Universum (Camille Flammarion, 1842-1925)

Physics at the Large Hadron Collider

Aleandro Nisati – INFN Rome

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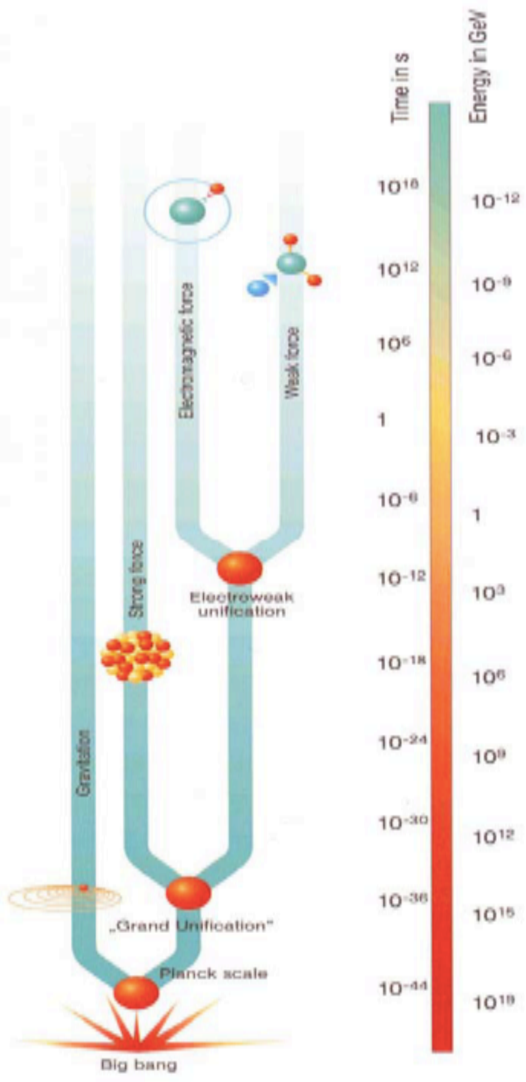
Overview

- Introduction
- The Large Hadron Collider
  - The general purpose experiments at LHC: ATLAS and CMS
- Standard Model measurements
- SM Higgs Boson searches
- BSM: SUSY and Exotics

Five outstanding issues in Standard Model

1. **Higgs mechanism**: What is the mechanism responsible for the electroweak symmetry breaking? Does the SM Higgs boson exist?
2. **Hierarchy**: Why gravity is so weak compared to the electroweak (EWK) force? It becomes strong for particles only at the Planck scale, around 10^{19} GeV, much above the EWK scale (10^{2} GeV, the energy scale dominating physics at low energies). What prevents quantities at the electroweak scale, such as the Higgs boson mass, from getting quantum corrections on the order of the Planck scale? Is the solution supersymmetry, extra-dimensions (or just anthropic fine-tuning)?
3. **Grand-Unification**: How do we unify the three different quantum mechanical fundamental interactions? How do we unify these with gravity?
4. **Dark Matter/Energy**: What's the origin of Dark Matter in the Universe? Does Supersymmetry explain DM?
5. **Matter antiMatter** in the Universe: What's the origin of this asymmetry?
6. …. Many more

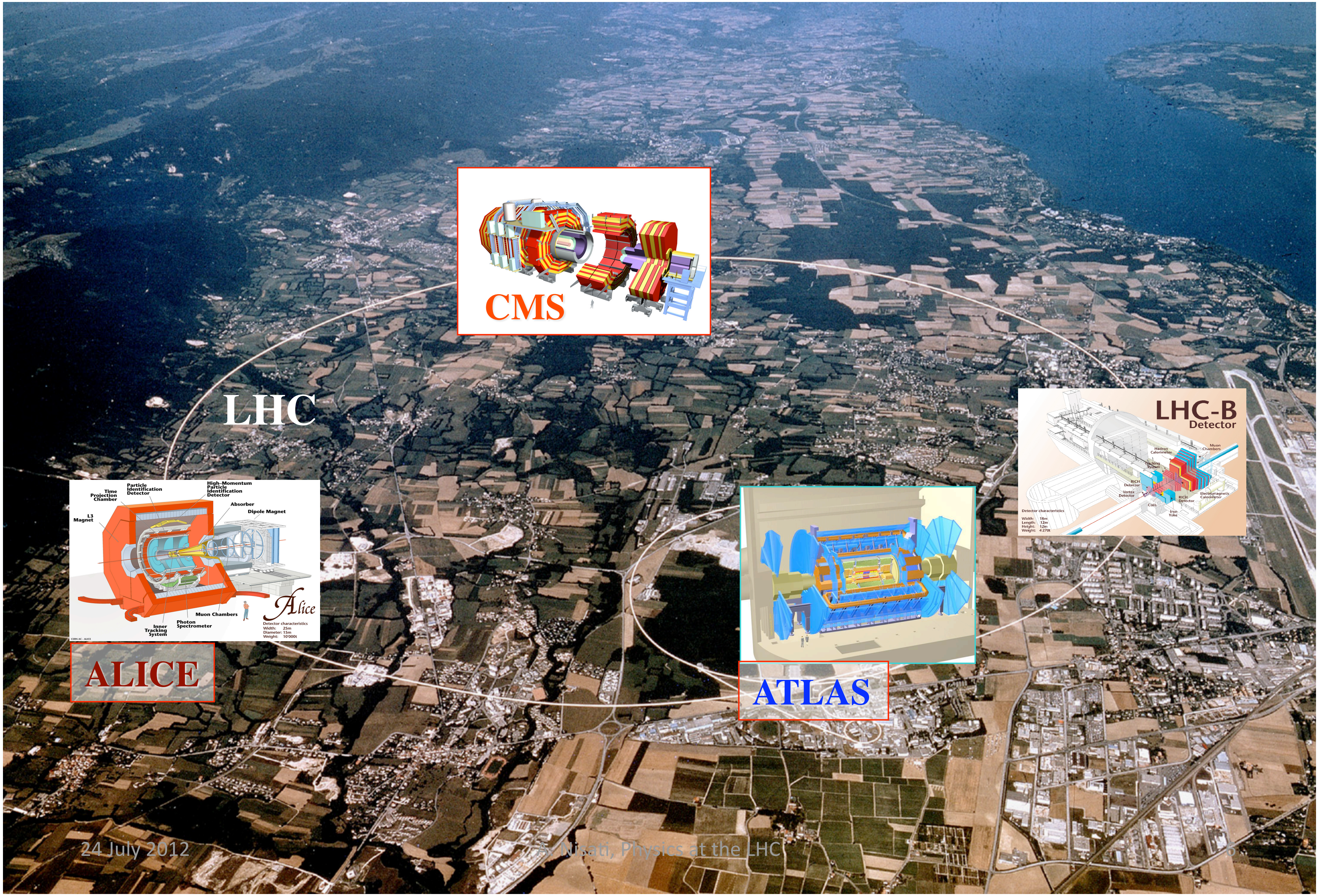


The scientific program of the Large Hadron Collider

- Investigate on the mechanism responsible for the EWK symmetry breaking:
  - Search for the SM Higgs boson
  - Search for BSM Higgs bosons
- Search for SUSY particles
- Search for Technicolor hadrons
- Search for Extra-Dimensions
- Study CP violations in heavy-flavour systems
- Test the SM at any possible level to get (direct/indirect) evidence of New Physics.
  - → Precision tests of the Standard Model
  - Don't be biased by the most trendy theory models: look at "360^{o}" for new physics signals

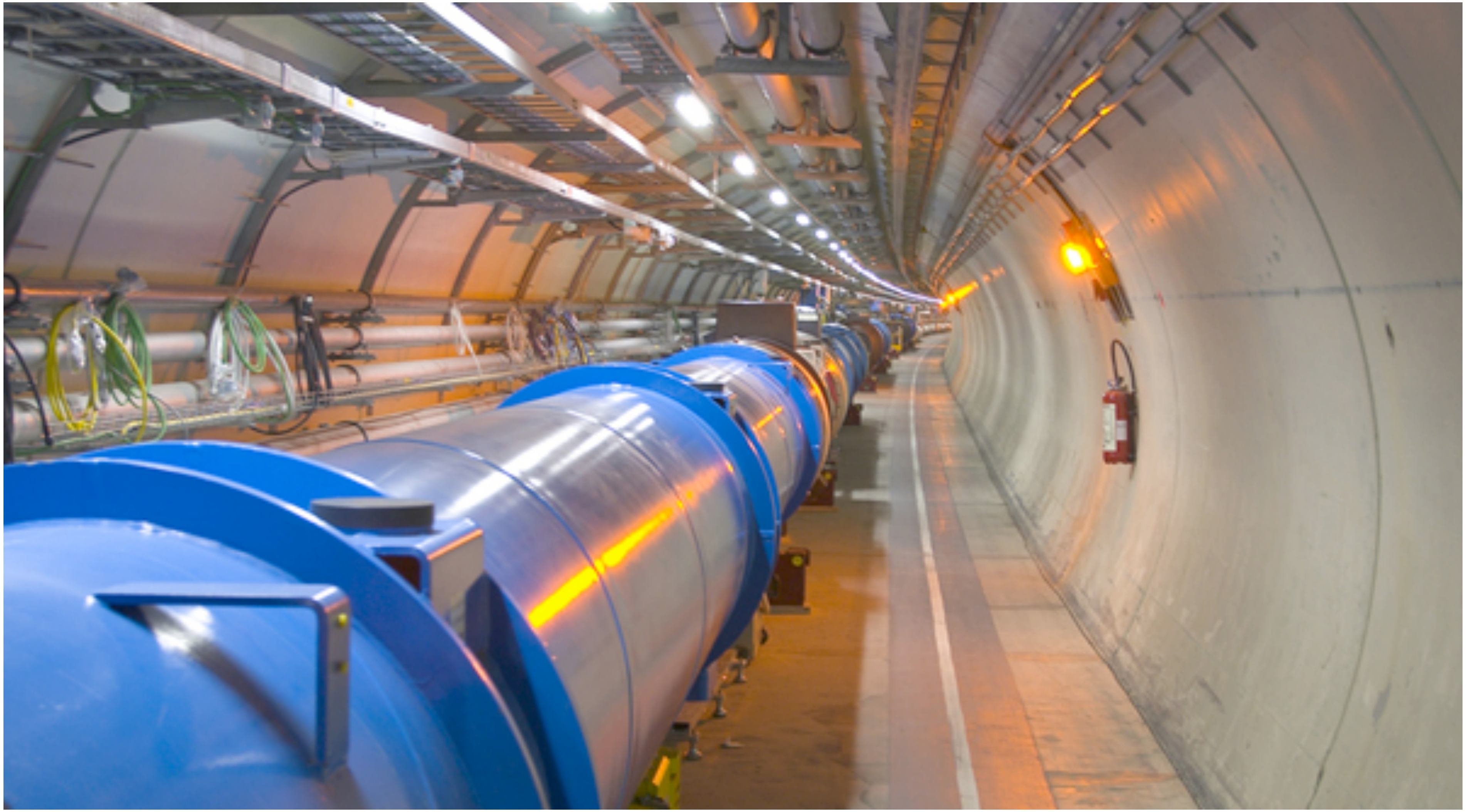
The Experiments at the LHC

The Experiments at the LHC



The Large Hadron Collider

proton-proton collider √s=14 TeV (nominal). In 2010,2011: √s=7 TeV

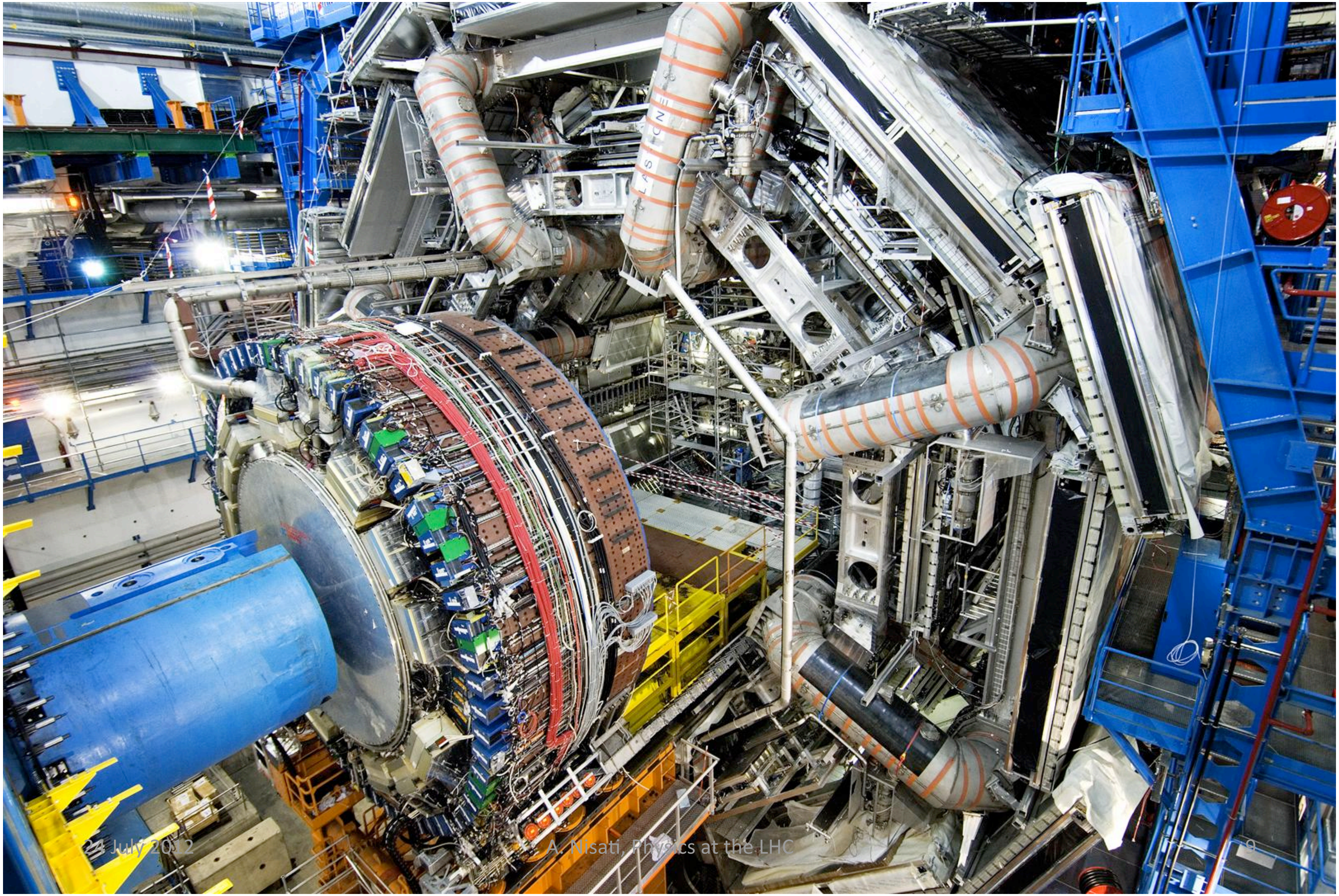


The Large Hadron Collider

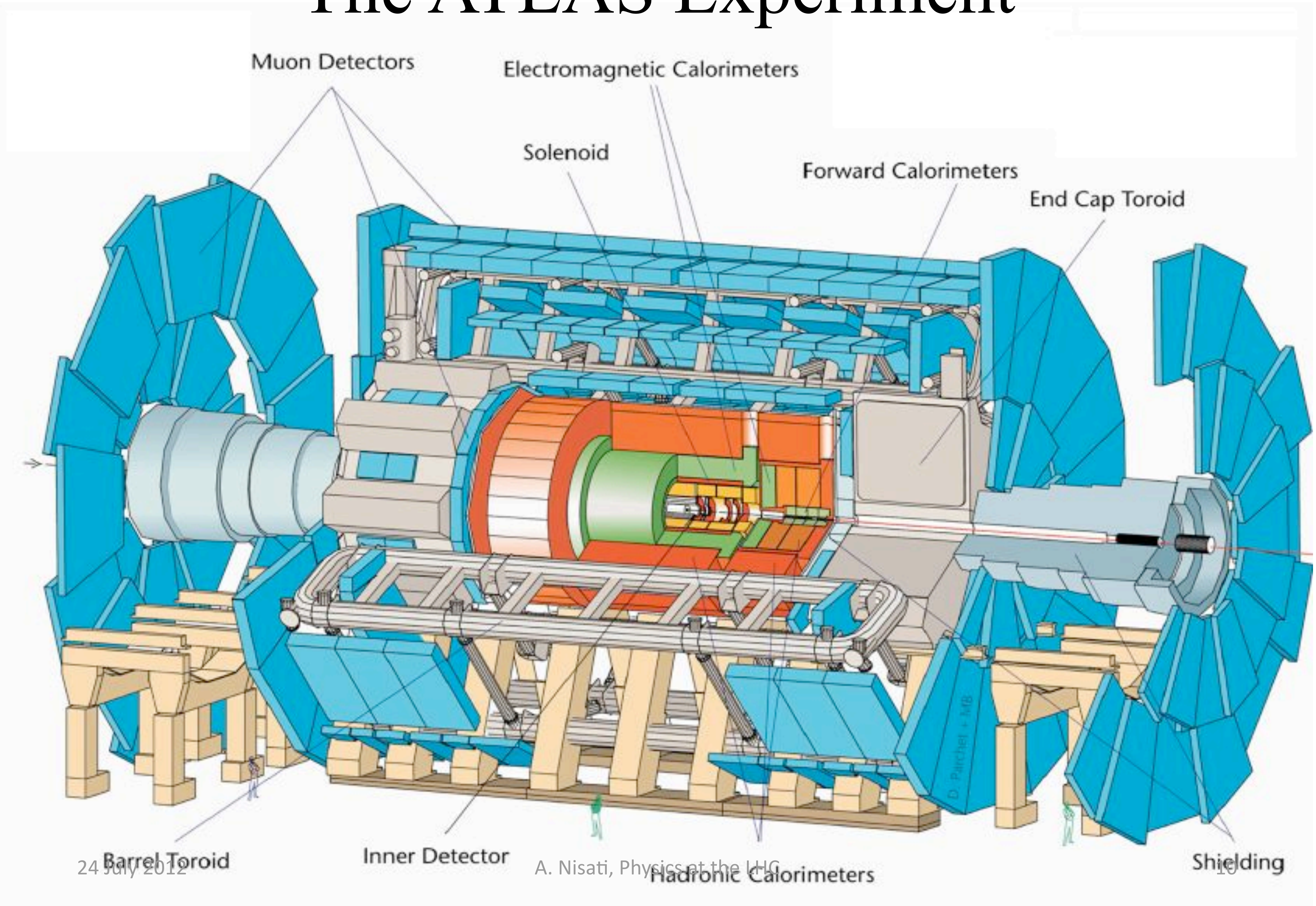
	2010	2011	2012(*)	Nominal
Energy [TeV]	3.5	3.5	4	7
β* [m] (IP1,IP2,IP5,IP8)	3.5, 3.5, 3.5, 3.5	1.5, 10, 1.5, 3.0	.6, 3,.6, .3	0.55, 10, 0.55, 10
Emittance [μm] (start of fill)	2.0 – 3.5	1.5 – 2.2		3.75
Transverse beam size at IP1&5 [μm]	60	28		16.7
Bunch population	1.2×10^{11} p	1.5×10^{11} p	1.6×10^{11} p	1.15×10^{11} p
Number of bunches	368	1380	1380	2808
Number of collisions (IP1 & IP5)	348	1318		-
Stored energy [MJ]	28	110		360
Peak luminosity [$cm^{-2}s^{-1}$]	2×10^{32}	3.65×10^{33}	6.66×10^{33}	1×10^{34}
Max delivered lum. (1 fill) [pb^{-1}]	6.23	122	237.32	-
Longest Stable Beams fill [hrs]	12:09	25:59	20:5	-

(*) records updated up to Jun 4th

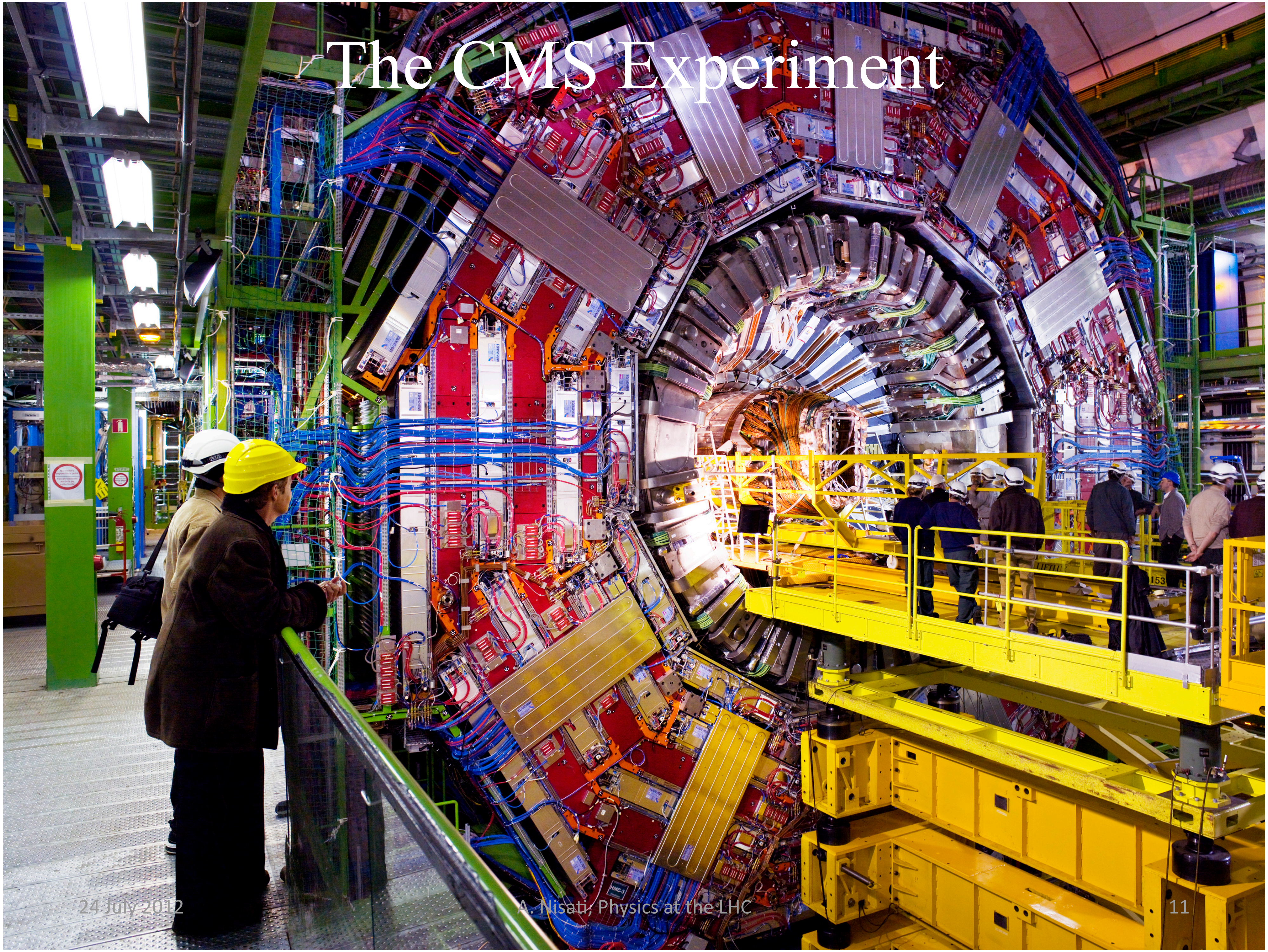
The ATLAS Experiment



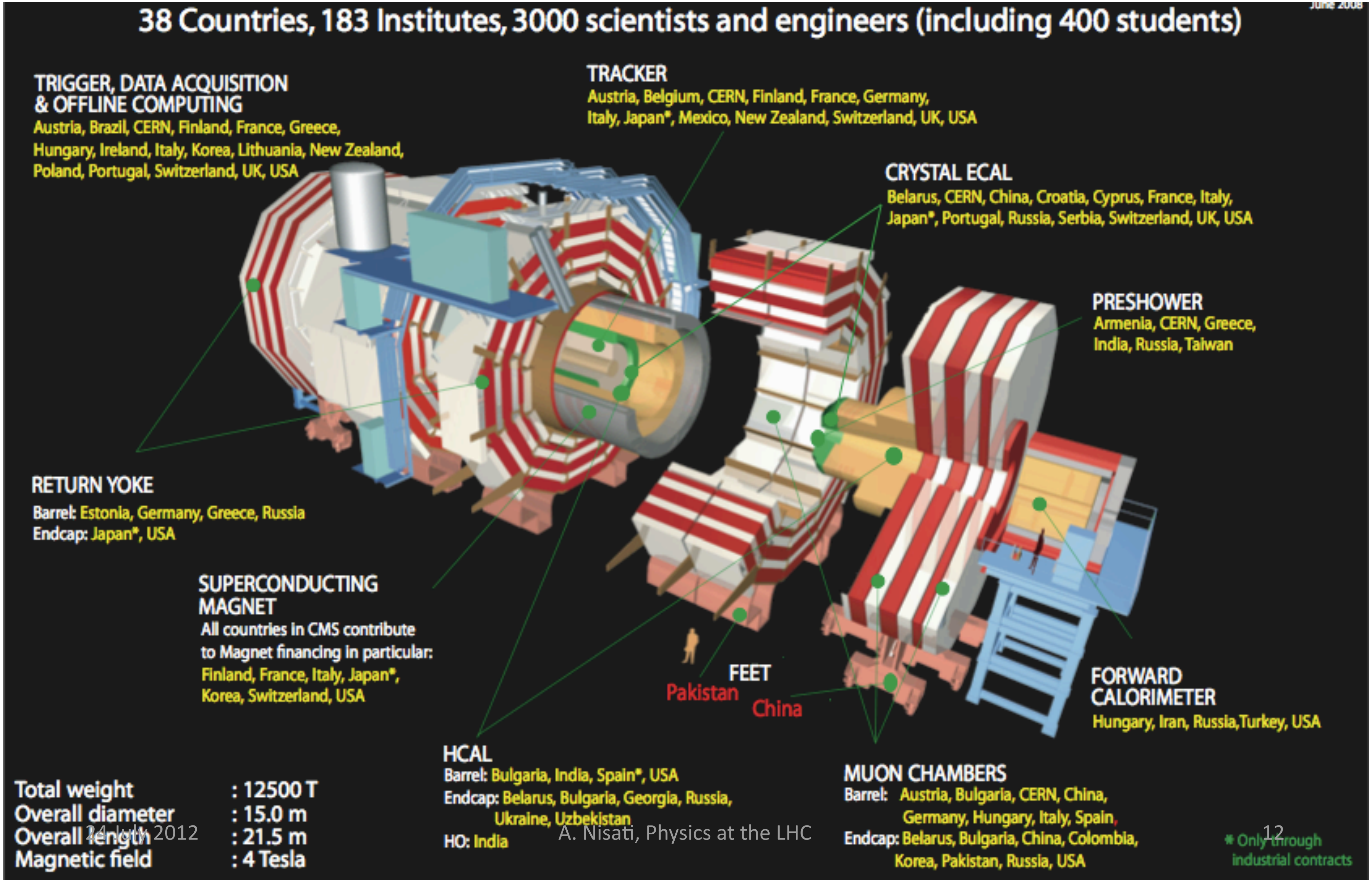
The ATLAS Experiment



The CMS Experiment

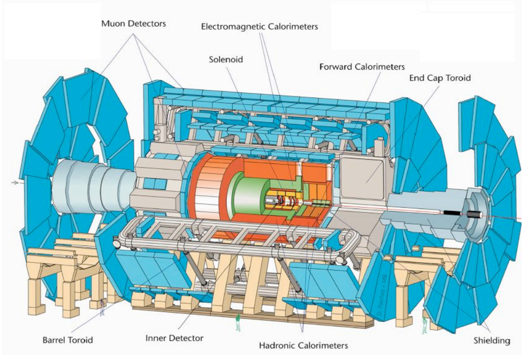


The CMS Experiment



ATLAS and CMS

ATLAS vs CMS



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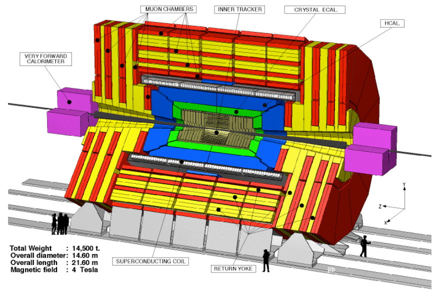
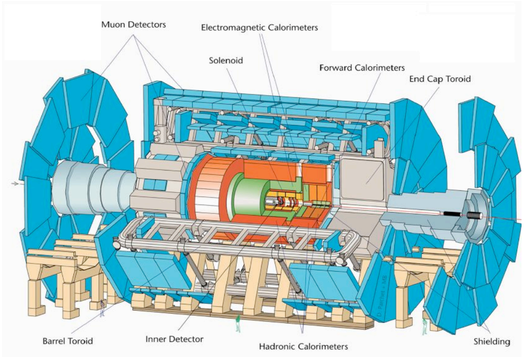
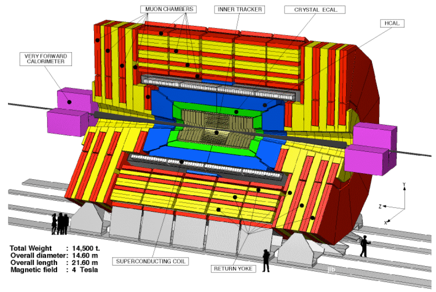


http://cmsinfo.web.cern.ch/cmsinfo/Detector/index.html

Magnetic field	2T solenoid Toroids: 0.5T barrel / 1T endcap	4T solenoid + return yoke
Tracker	Si pixels + strips = 3 + 4 layers (barrel) TRT Thickness: 0.4 - 2.0 X_0 $\sigma/p_T = 5 \times 10^{-4}\ p_T \oplus 0.01$	Si pixels + strips = 3 + 10 layers (barrel) All silicon Thickness: 0.4 - 1.8 X_0 $\sigma/p_T = 1.5 \times 10^{-4}\ p_T \oplus 0.005$
Muon system	3 stations RPC + TGC: triggers + φ meas. MDT + CSC: precision meas. σ/p_T = 2% @ 50 GeV σ/p_T = 10% @ 1 TeV	4 stations DT + CSC + RPC: triggers DT + CSC: precision + 2nd meas. σ/p_T = 1% @ 50 GeV σ/p_T = 5% @ 1 TeV

ATLAS vs CMS





EM calorimeter	Outside solenoid Lead+LAr sampling calo. $\sigma/E = 10\%/E^{1/2} \oplus 0.007$ Granularity $\Delta\eta \times \Delta\varphi$: 0.025 x 0.025	Inside solenoid $PbWO_4$ crystals total absorption calo. $\sigma/E = 2\text{-}5\%/E^{1/2} \oplus 0.005$ Granularity $\Delta\eta \times \Delta\varphi$: 0.0175 x 0.0175
Hadronic calorimeter	Outside solenoid Fe + scintillator / Cu+LAr (10 λ) $\sigma/E = 50\%/E^{1/2} \oplus 0.03$ Granularity $\Delta\eta \times \Delta\varphi$: 0.1 x 0.1 (barrel)	Inside solenoid Brass + scintillator (5.8 λ) $\sigma/E = 100\%/E^{1/2} \oplus 0.05$ Granularity $\Delta\eta \times \Delta\varphi$: 0.09 x 0.09 (barrel)
Trigger	L1 HLT: Region of Interest	L1: redundant muon trigger HLT

luminosity

- The rate of events N produced for a given physics reaction with cross section σ is

  $N = L \times \sigma$

  σ is independent from any parameter of the machine; it depends only on the physics process
- Dimensions: $L = [cm^{-2}][s^{-1}]$
- More in detail…: see next slide
- Some figures:
  - $L = 2\times10^{33}$ cm^{-2} s^{-1}: design value for Tevatron Run II
  - $L = \sim 10^{33}$ cm^{-2} s^{-1}: planned value for Tevatron Run II
  - $L = 10^{34}$ cm^{-2} s^{-1}: design value for LHC
- Assuming a data taking time in a year of 10^7 s, we have 100 fb^{-1} for LHC running at the nominal luminosity

luminosity

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

- **Nearly all the parameters are variable (and not independent)**
  - Number of particles per bunch N
  - Number of bunches per beam k_b
  - Relativistic factor (E/m_0) γ
  - Normalised emittance ε_n
  - Beta function at the IP β^*
  - Crossing angle factor F
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*

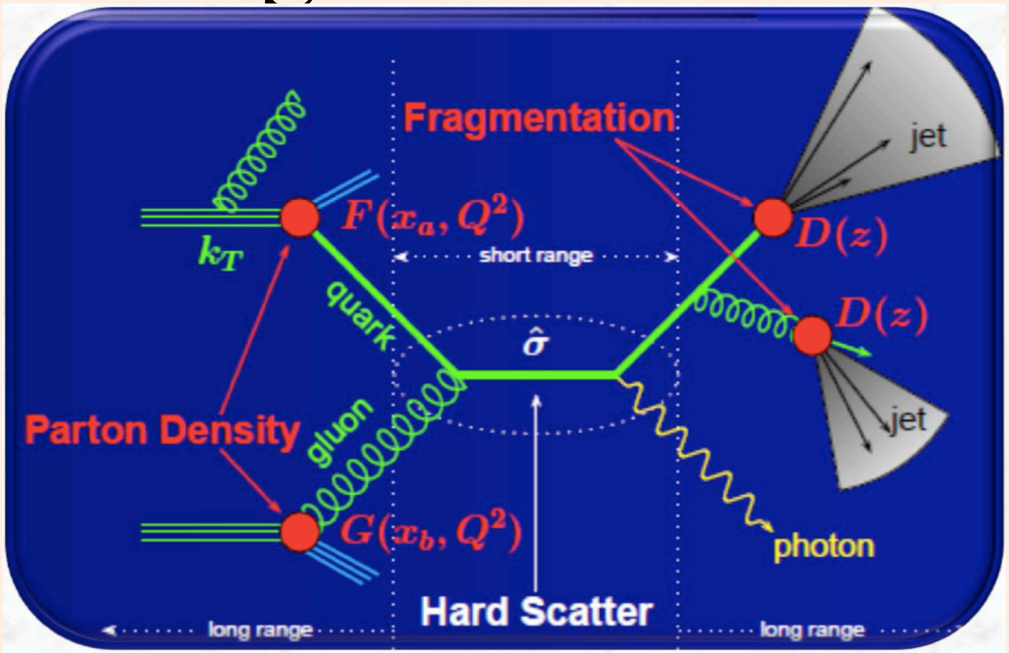
Intensity

Energy

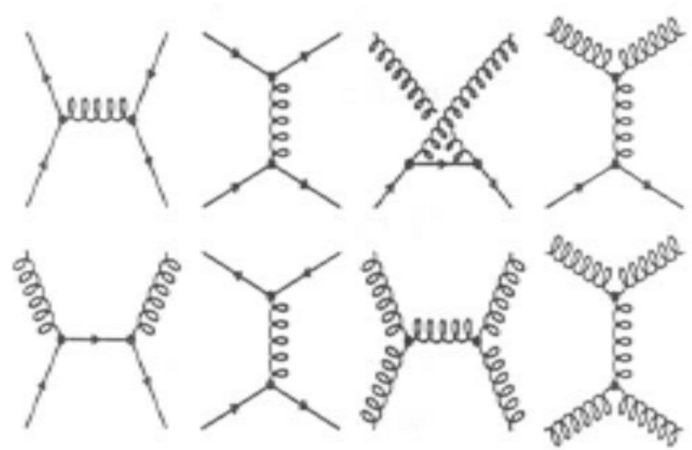
Interaction Region

$$F = 1 \Big/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

Scattering at a hadron collider

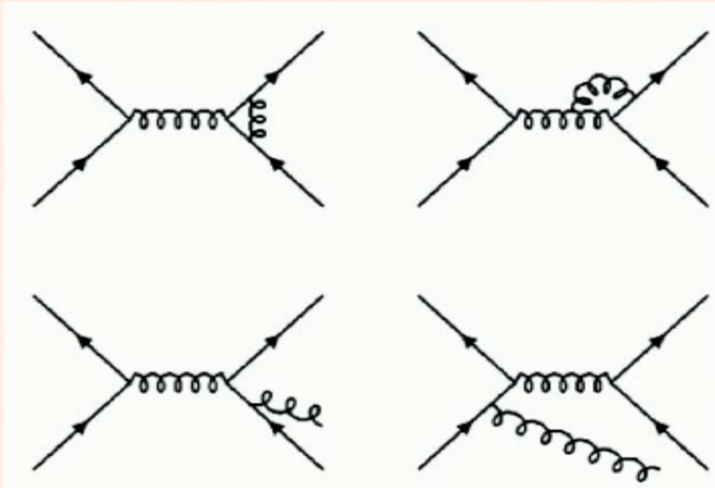


Dominant hard scattering processes: qq, qg and gg

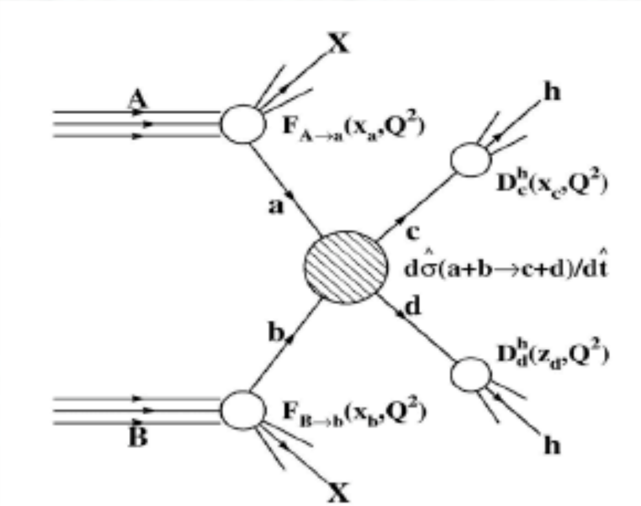


Leading Order (LO)

Next to Leading Order (NLO)



Calculation of cross sections



$$\sigma = \sum_{a,b} \int dx_a \; dx_b \; f_a \; (x_a, Q^2) \, f_b \; (x_b, Q^2) \; \hat{\sigma}_{ab} \; (x_a, x_b, \alpha_s)$$

Sum over initial partonic states a,b

$\hat{\sigma}_{ab} \equiv$ hard scattering cross section

$f_i \, (x, Q^2) \equiv$ parton density function

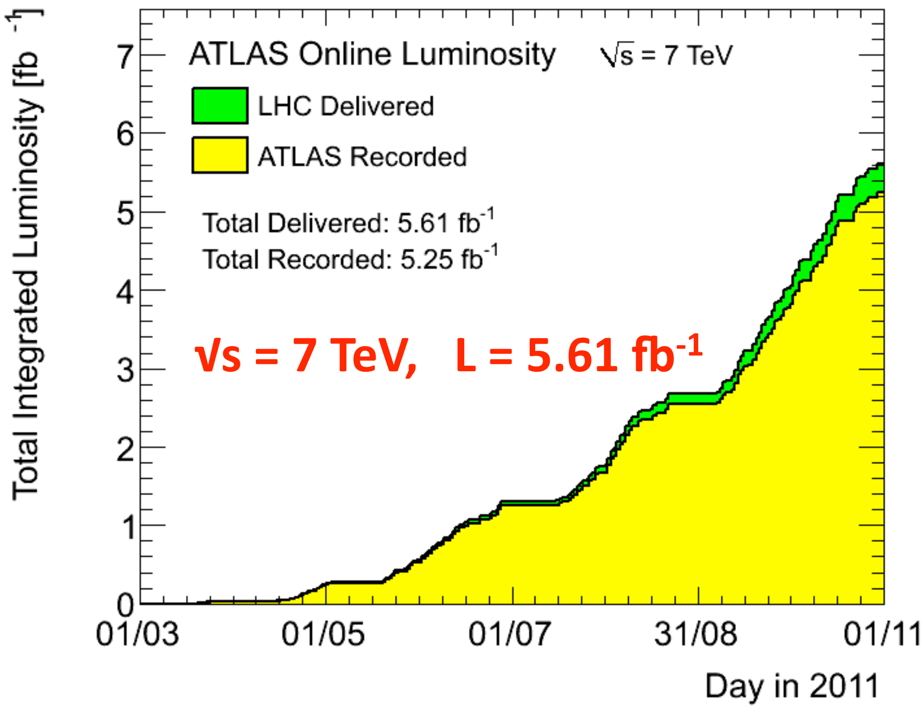
… + higher order QCD corrections (perturbation theory)
meanwhile available for many signal and background processes !

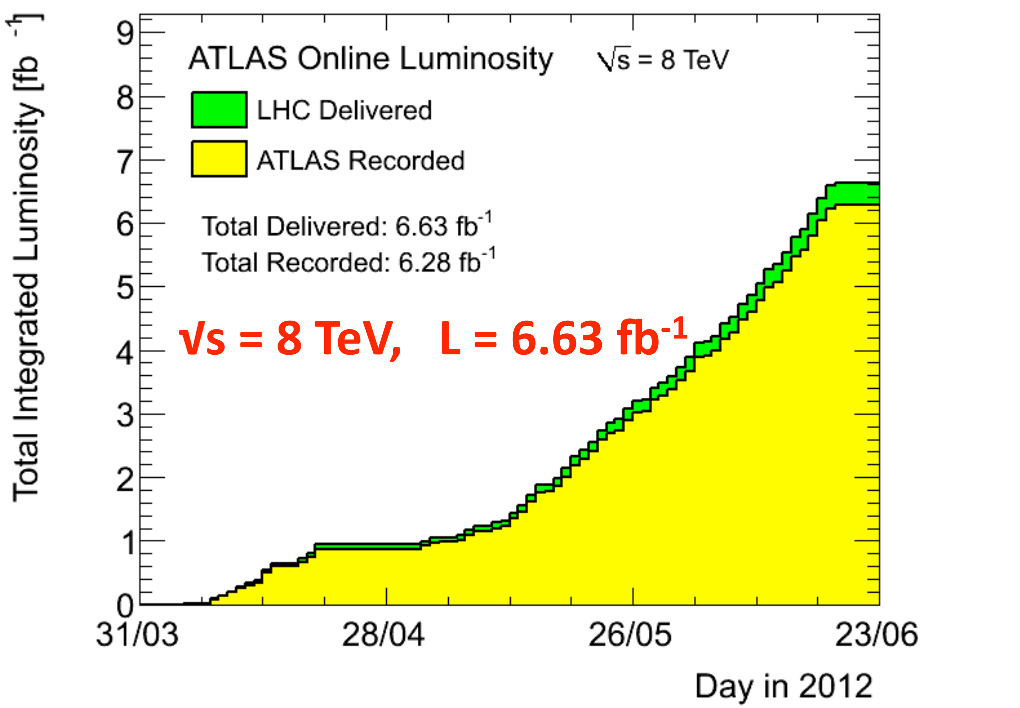
which for some processes turn out to be large
(e.g. Higgs production via gg fusion)

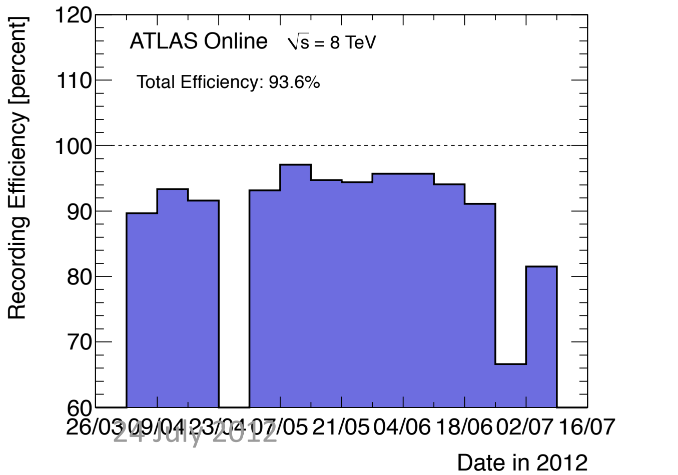
usually introduced as K-factors: $K_{[n]} = \sigma_{[n]} / \sigma_{[LO]}$

a few examples: Drell-Yan production of W/Z: $K_{NLO} \sim 1.2$
Higgs production via gg fusion: $K_{NLO} \sim 1.8$

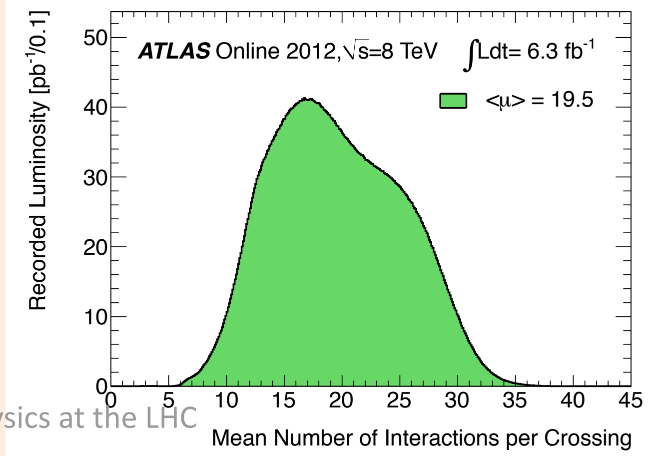
Total delivered luminosity in 2011 and up to 2012, June 20th





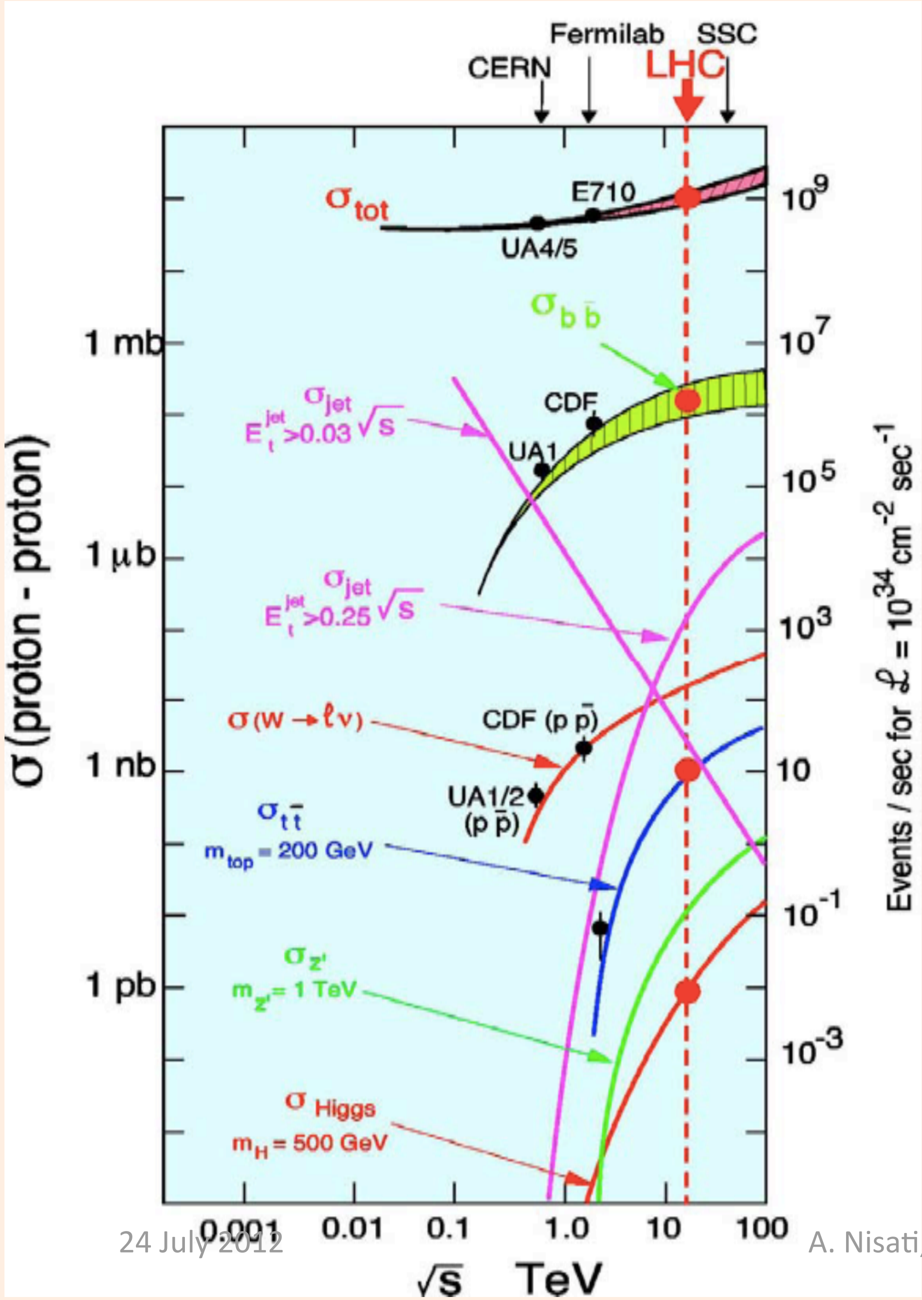


Similar figures for CMS



Event pile-up

Cross Sections and Production Rates



- Rates for nominal LHC
- Inelastic proton-proton inelastic collisions: 1 GHz
- bb pairs: 10 MHz
- tt pairs: 8 Hz
- W→eν: 150 Hz
- Z→ee: 15 Hz
- Higgs (m_H=120 GeV): 0.4 Hz

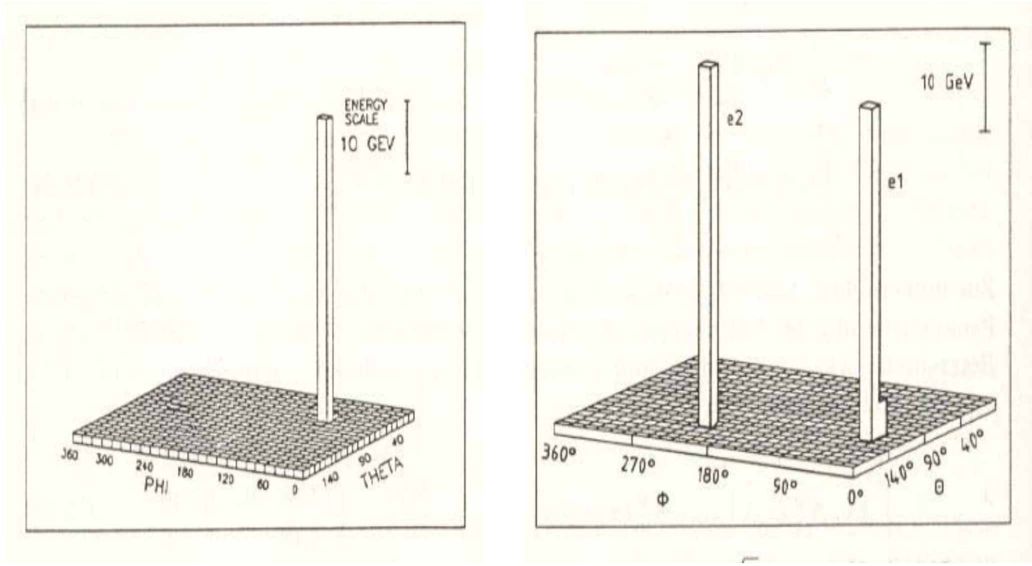
LHC is a factory of W/Z bosons, top and b-quarks,…

W and Z production at LHC

ATLAS

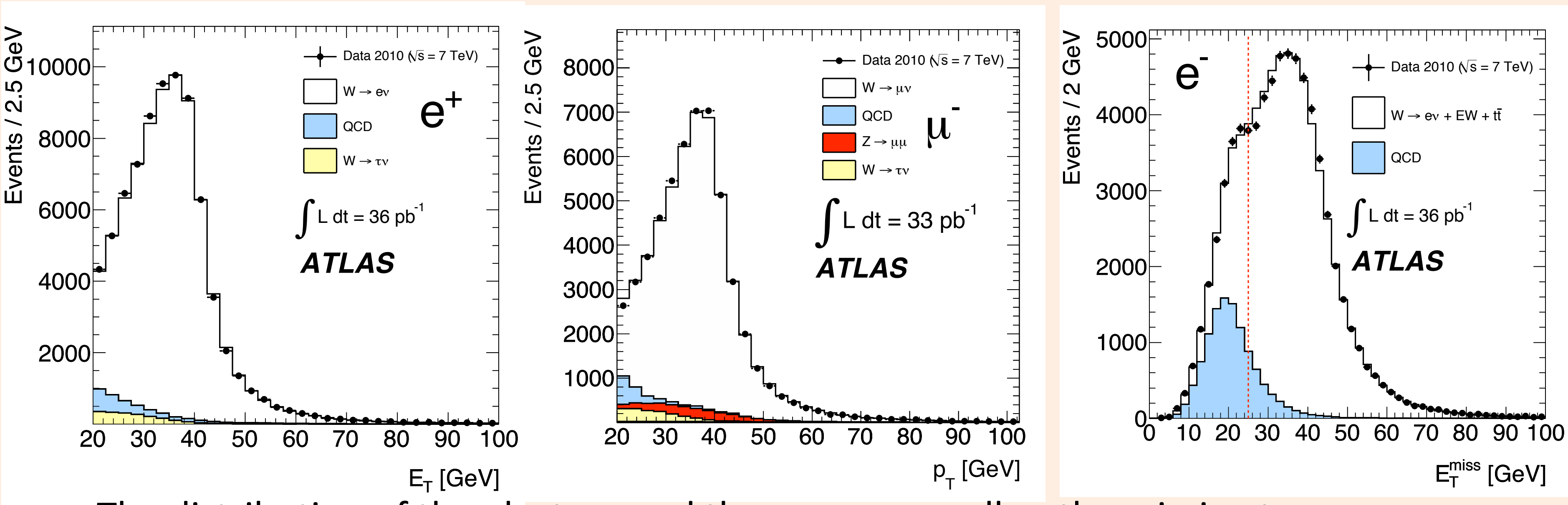
- The inclusive Drell-Yan production cross section measurement is an important test for Quantum ChromoDynamics (QCD). Theoretical calculations are available to NLO and NLLO.
- **Final states studied:**
  $W^{\pm} \rightarrow e^{\pm}\nu$; $W^{\pm} \rightarrow \mu^{\pm}\nu$
  $Z \rightarrow e^{-}e^{+}$; $Z \rightarrow \mu^{-}\mu^{+}$
- **W analysis**: based on the reconstruction and selection of ***isolated high-p_T leptons*** (e or μ) produced in association with ***large missing transverse energy E_T^{miss}***, and on the measurement of the associated ***transverse mass*** (see next box)
- **Z analysis**: is based on the reconstruction of ***two isolated high-p_T leptons***, and on the measurement of the associated ***invariant mass***

- **W Selection:**
  - **One lepton p_T > 20 GeV in $|\eta|$<2.5**
  - **E_T^{miss} > 25 GeV**
  - **Background (<10%): largest: $W \rightarrow \tau\nu$; $Z \rightarrow \tau\tau$; ttbar, QCD jets**
- **The cross section is measured in a *fiducial kinematic region***



"lego-plot" of a W→eν and Z→ee event
In UA1, UA2 experiments at the SppS (1982)

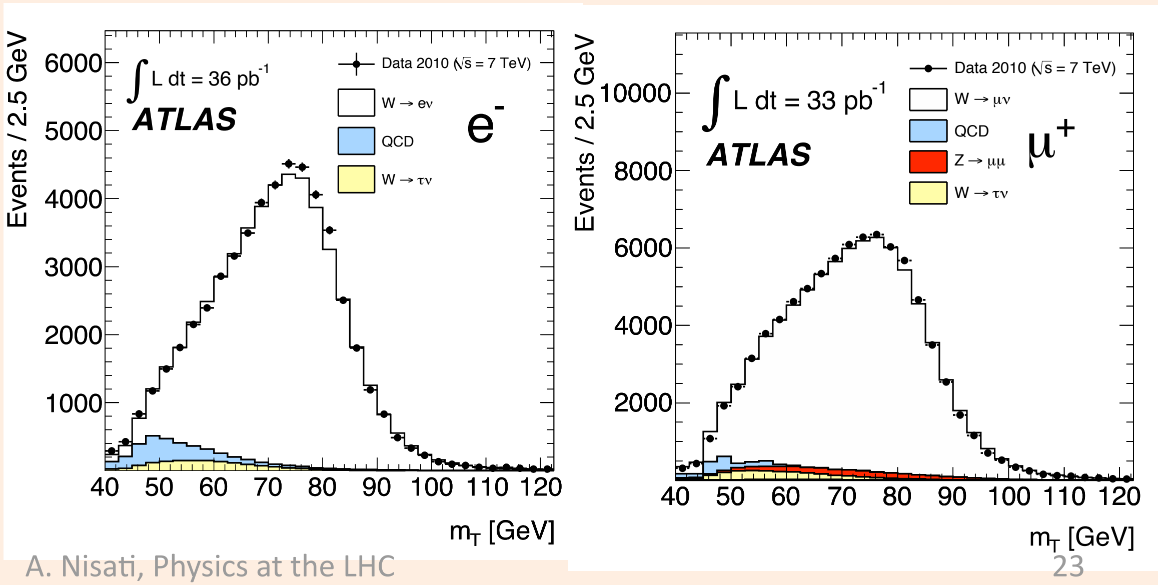
W production at LHC



The distribution of the electron and the muon, as well as the missing transverse energy

The transverse mass

$$m_T = \sqrt{2 \cdot P_T^l \cdot P_T^{miss} (1 - \cos\Delta\phi^{l,\upsilon})}$$



W production at LHC

- Measure the cross section:

$$\sigma_{tot} = \frac{1}{A_{W/Z}} \cdot \frac{N - B}{C_{W/Z} L_{\text{int}}}$$

- Where:
  - **N** is the number of selected candidate events
  - **B** is the number of background events
  - $\mathbf{C_{W/Z}}$ is the efficiency/ correction factor within the fiducial region
  - $\mathbf{A_{W/Z}}$ is the cross-section extrapolation from the fiducial region to the "full" kinematic region
  - $\mathbf{L_{int}}$ is the analysed integrated luminosity

- $C_{W/Z}$ takes into account the reconstruction and identification efficiencies of the physics objects used in the event selection, as well as the event selection acceptance: $C_{W/Z} = N_{MC,rec,sel}/N_{MC,gen,cut}$
- $A_{W/Z}$ defines the acceptance of the fiducial region; it is defined as $A_{W/Z} = \sigma_{fid}/\sigma_{tot} = N_{MC,gen,cut}/N_{MC,gen,all}$
  - estimated with Monte Carlo analysis

W production at LHC

- Systematic uncertainties must be taken into account to the estimate of B, $C_{W/Z}$, $A_{W/Z}$ and L_{int}
- Results (for muon final states):

ATLAS

	N	B	$C_{W/Z}$	$A_{W/Z}$
W^+	84514	6600 ± 600	0.796 ± 0.016	0.495 ± 0.008
W^-	55234	5700 ± 600	0.779 ± 0.015	0.470 ± 0.010
$W^\pm$	139748	12300 ± 1100	0.789 ± 0.015	0.485 ± 0.007
Z	11709	86 ± 32	0.782 ± 0.007	0.487 ± 0.010

TABLE VII. *Number of observed candidates N and expected background events B, efficiency and acceptance correction factors for the W and Z muon channels. Efficiency scale factors used to correct the simulation for differences between data and MC are included in the $C_{W/Z}$ factors. The given uncertainties are the quadratic sum of statistical and systematic components. The statistical uncertainties on the $C_{W/Z}$ and $A_{W/Z}$ factors are negligible.*

- **Background uncertainties: it is evaluated with a combination of Monte Carlo predictions and measurements from data;**
- **It depends on the channel under study, but in general it is at the 2-3% level**
- **Relative uncertainties are 10% for W/Z to tau final states, and 20-40% for QCD**

Uncertainties on $A_{W/Z}$ ATLAS

	A	$\delta A^{\rm pdf}_{\rm err}$	$\delta A^{\rm pdf}_{\rm sets}$	$\delta A_{\rm hs}$	$\delta A_{\rm ps}$	$\delta A_{\rm tot}$
Electron channels						
W^+	0.478	1.0	0.7	0.9	0.8	1.7
W^-	0.452	1.5	1.1	0.2	0.8	2.0
$W^\pm$	0.467	1.0	0.5	0.6	0.8	1.5
Z	0.447	1.7	0.6	0.2	0.7	2.0
Muon channels						
W^+	0.495	1.0	0.8	0.6	0.8	1.6
W^-	0.470	1.5	1.1	0.3	0.8	2.1
$W^\pm$	0.485	1.0	0.5	0.4	0.8	1.5
Z	0.487	1.8	0.6	0.2	0.7	2.0

TABLE II. *Acceptance values (A) and their relative uncertainties (δA) in percent for W and Z production in electron and muon channels. The various components of the uncertainty are defined in the text. The total uncertainty ($\delta A_{\rm tot}$) is obtained as the quadratic sum of the four parts.*

W production at LHC

- Systematic uncertainties must be taken into account to the estimate of B, $C_{W/Z}$, $A_{W/Z}$ and L_{int}
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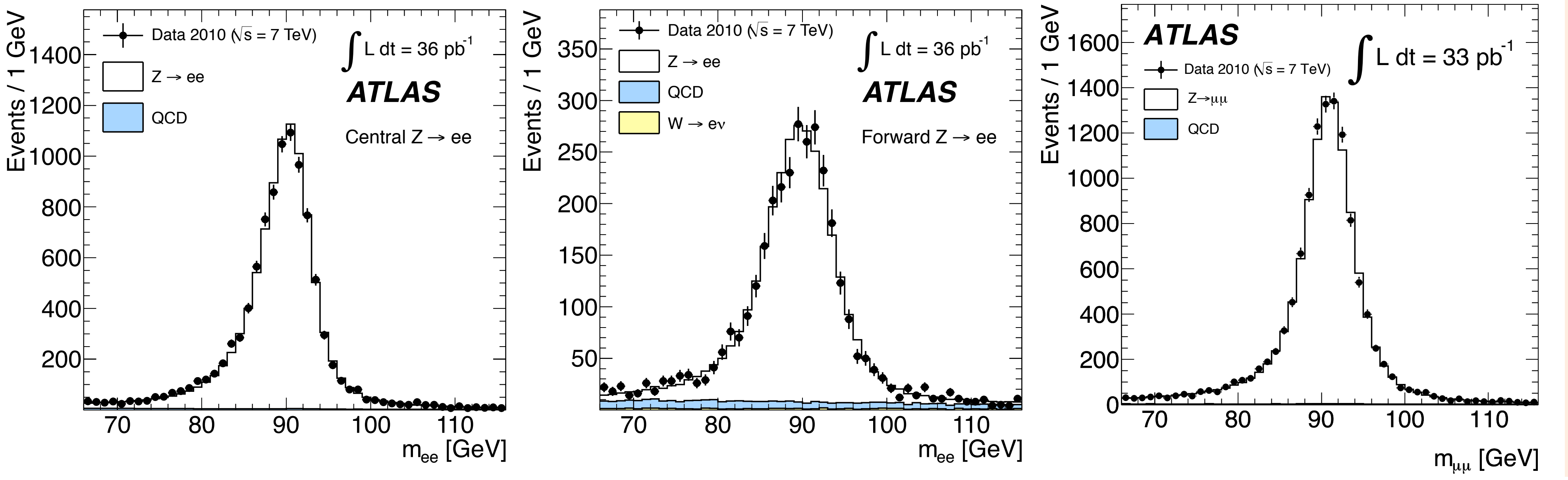
Uncertainties on $C_{W/Z}$

ATLAS

	$\delta\sigma_{W\pm}$	$\delta\sigma_{W+}$	$\delta\sigma_{W-}$	$\delta\sigma_Z$
Trigger	0.5	0.5	0.5	0.1
Muon reconstruction	0.3	0.3	0.3	0.6
Muon isolation	0.2	0.2	0.2	0.3
Muon p_T resolution	0.04	0.03	0.05	0.02
Muon p_T scale	0.4	0.6	0.6	0.2
QCD background	0.6	0.5	0.8	0.3
Electroweak+$t\bar{t}$ background	0.4	0.3	0.4	0.02
E_T^{miss} resolution and scale	0.5	0.4	0.6	-
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.8	0.8	0.7	0.3
Total experimental uncertainty	1.6	1.7	1.7	0.9
$A_{W/Z}$ theoretical uncertainty	1.5	1.6	2.1	2.0
Total excluding luminosity	2.1	2.3	2.6	2.2
Luminosity		3.4		

TABLE IX. *Summary of relative systematic uncertainties on the measured integrated cross sections in the muon channels in per cent. The efficiency systematic uncertainties are partially correlated between the trigger, reconstruction and isolation terms. This is taken into account in the computation of the total uncertainty quoted in the table. The theoretical uncertainty on $A_{W/Z}$ applies only to the total cross section.*

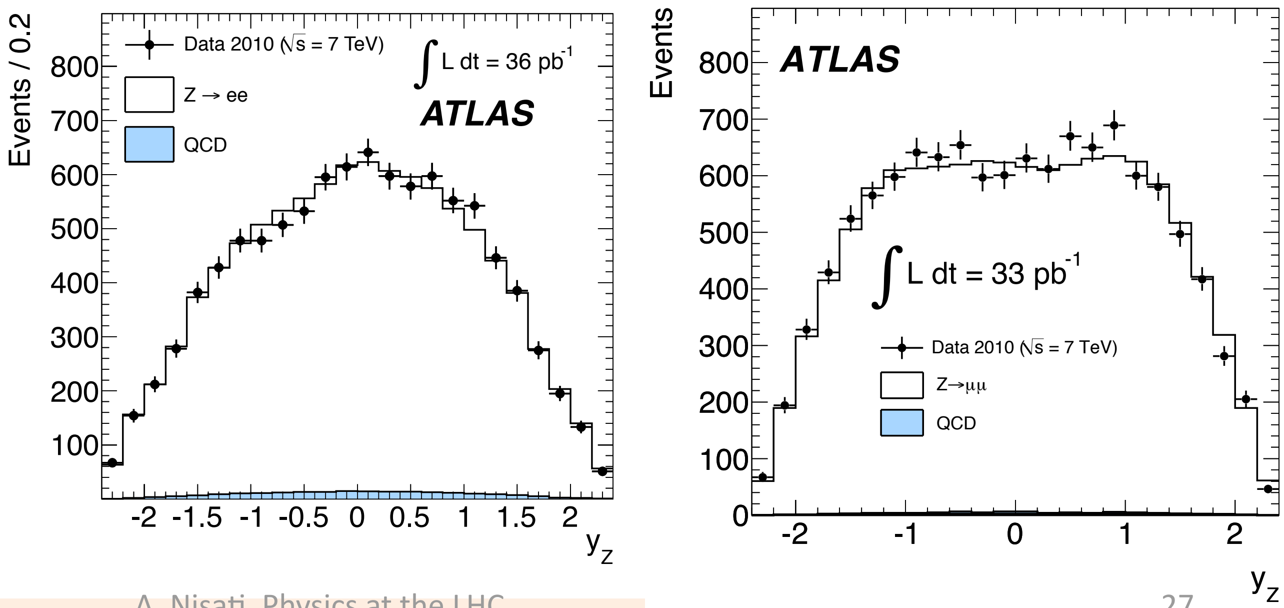
Z production at the LHC



Z selection:

two leptons p_T > 20 GeV in $|\eta|$<2.5

Background (<2%): mainly QCD, Z→ττ



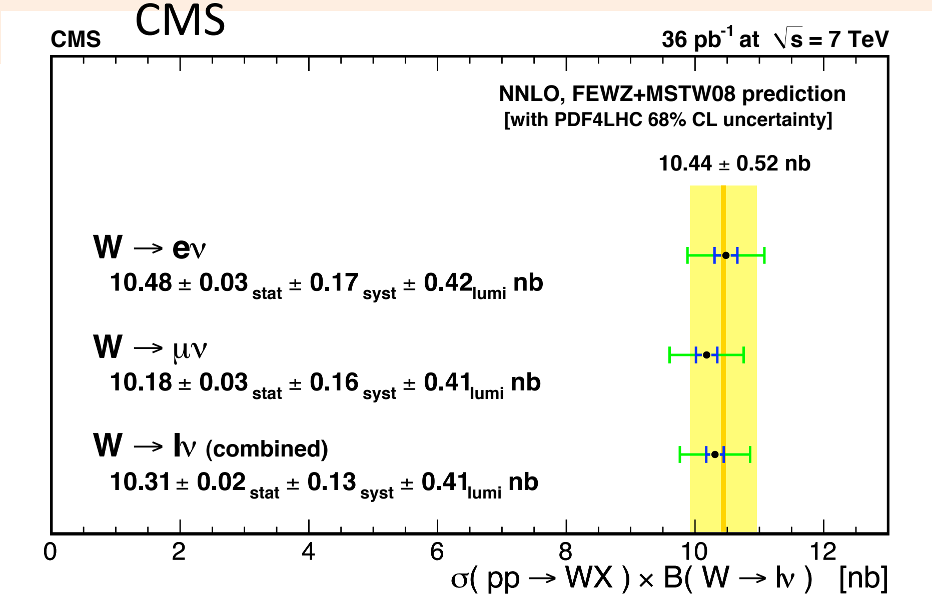
W production at LHC: results

ATLAS

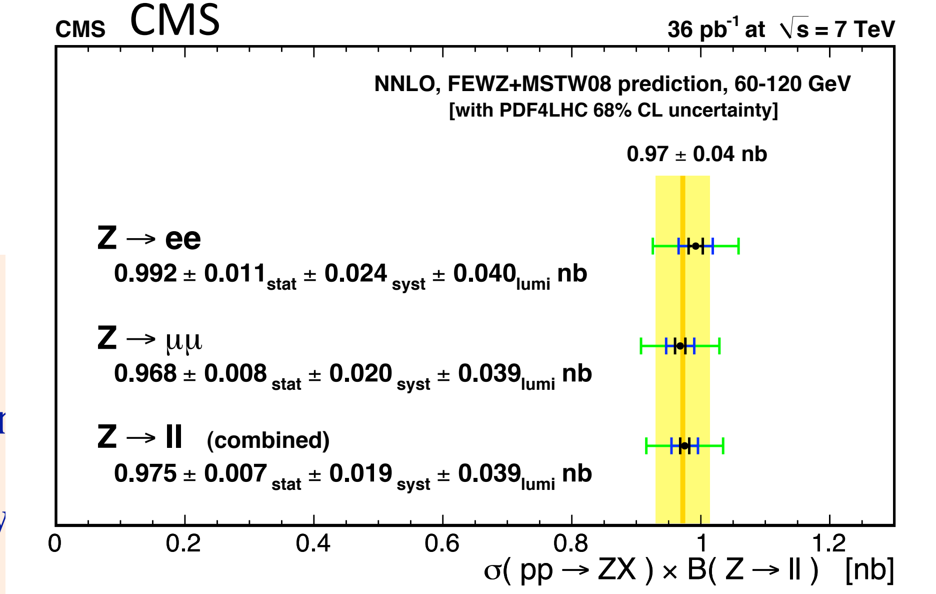
	$\sigma_W^{tot} \cdot BR(W \to \ell\nu)$ [nb]
	sta, sys, lum, acc
W^+	$6.048 \pm 0.016 \pm 0.072 \pm 0.206 \pm 0.096$
W^-	$4.160 \pm 0.014 \pm 0.057 \pm 0.141 \pm 0.083$
$W^\pm$	$10.207 \pm 0.021 \pm 0.121 \pm 0.347 \pm 0.164$
	$\sigma_{Z/\gamma^*}^{tot} \cdot BR(Z/\gamma^* \to \ell\ell)$ [nb], $66 < m_{\ell\ell} < 116$ GeV
	sta, sys, lum, acc
Z/γ^*	$0.937 \pm 0.006 \pm 0.009 \pm 0.032 \pm 0.016$

TABLE XII. *Combined total cross sections times leptonic branching ratios for W^+, W^-, W and Z/γ^* production. The uncertainties denote the statistical (sta), the experimental systematic (sys), the luminosity (lum), and the extrapolation (acc) uncertainties.*

CMS



CMS

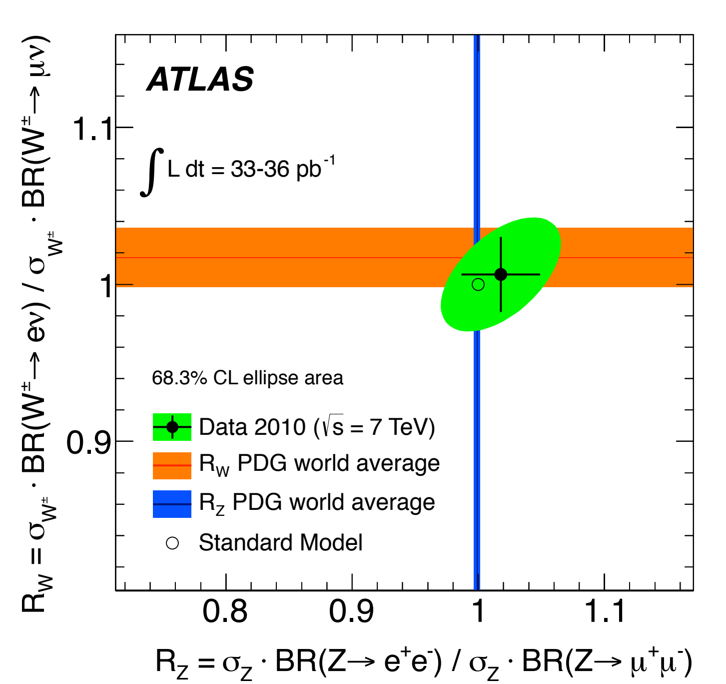


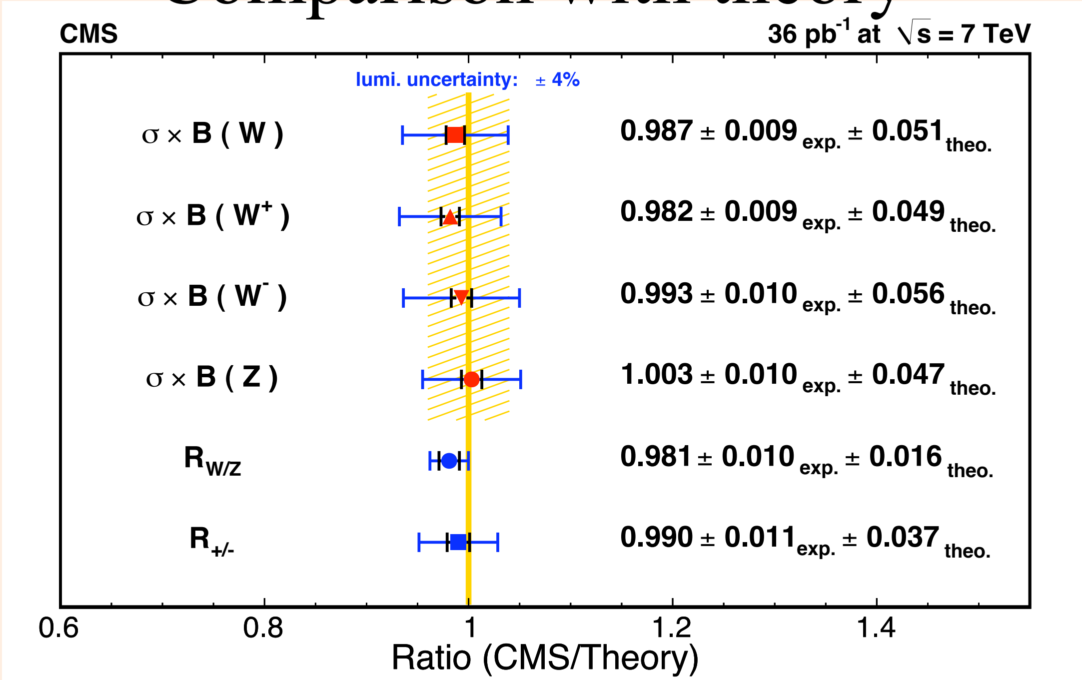
Very similar results from CMS

Data are well described by NNLO QCD calculation
[C.R. Hamberg et al., Nucl. Phys. B359 (1991) 343]
In both experiments precision is already limited by systematic uncertainties

W production at LHC: results

- Lepton Universality
- Comparison with theory



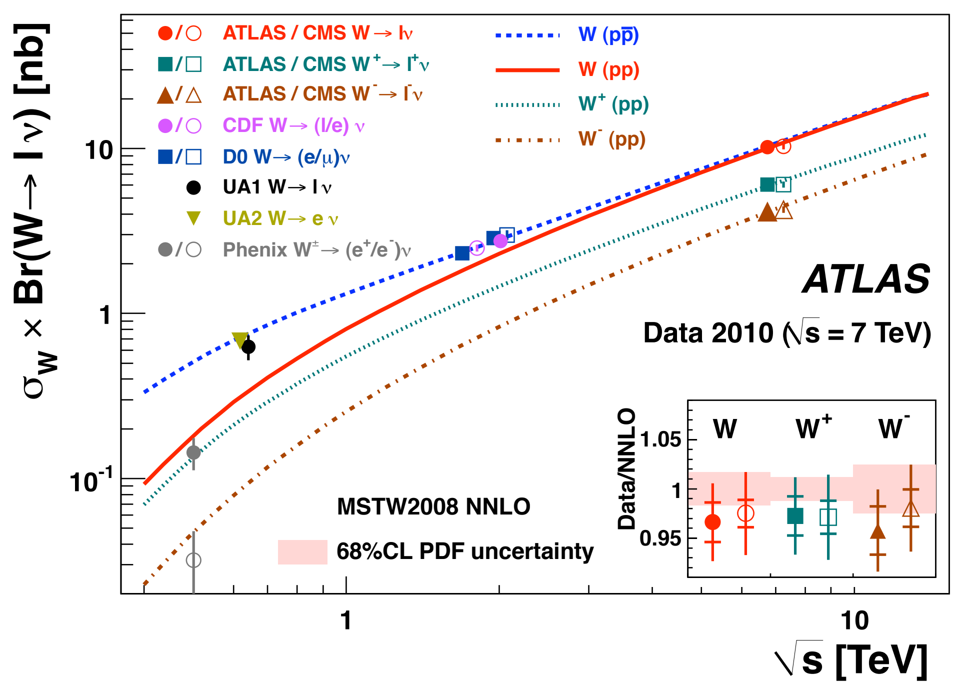


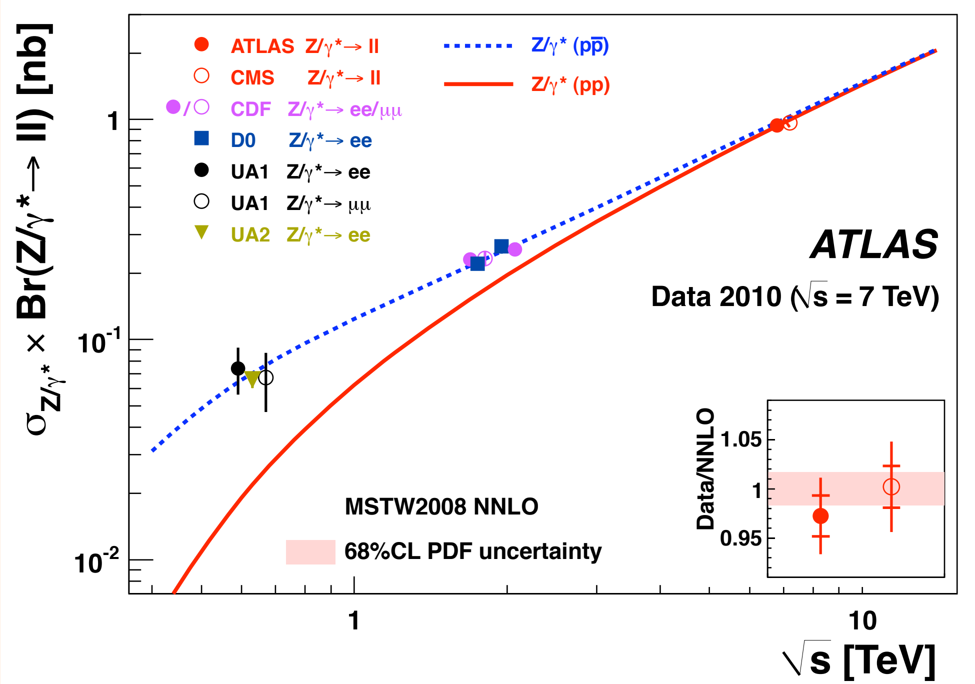
$$R_W = \frac{\sigma_W^e}{\sigma_W^\mu} = \frac{Br(W \to e\nu)}{Br(W \to \mu\nu)}$$
$$= 1.006 \pm 0.004\,(\mathrm{sta}) \pm 0.006\,(\mathrm{unc}) \pm 0.022\,(\mathrm{cor})$$
$$= 1.006 \pm 0.024.$$

$$R_Z = \frac{\sigma_Z^e}{\sigma_Z^\mu} = \frac{Br(Z \to ee)}{Br(Z \to \mu\mu)}$$
$$= 1.018 \pm 0.014\,(\mathrm{sta}) \pm 0.016\,(\mathrm{unc}) \pm 0.028\,(\mathrm{cor})$$
$$= 1.018 \pm 0.031.$$

Ratio of CMS measurement to theory expectations. The experimental uncertainty is the sum in quadrature of the statistical and the systematic uncertainties not including the uncertainty on the extrapolation to the full acceptance due to parton density functions.

W production at LHC: results

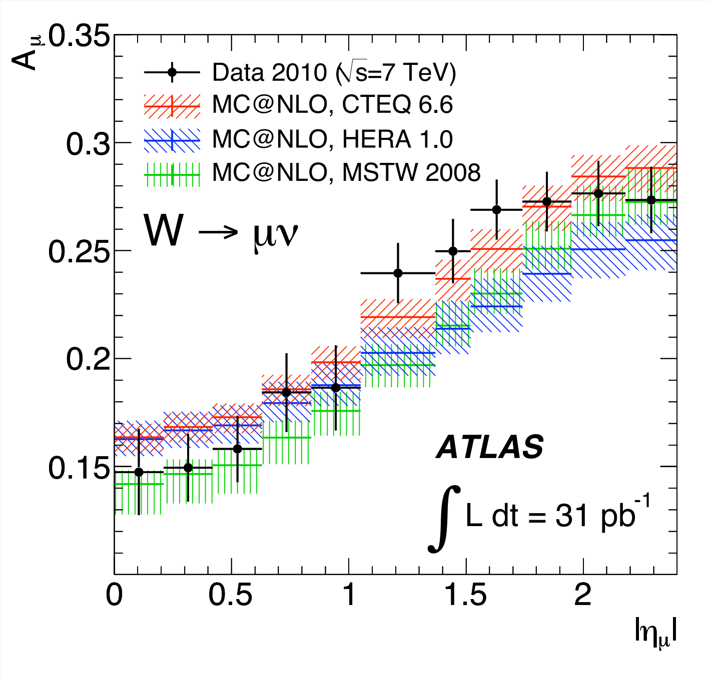


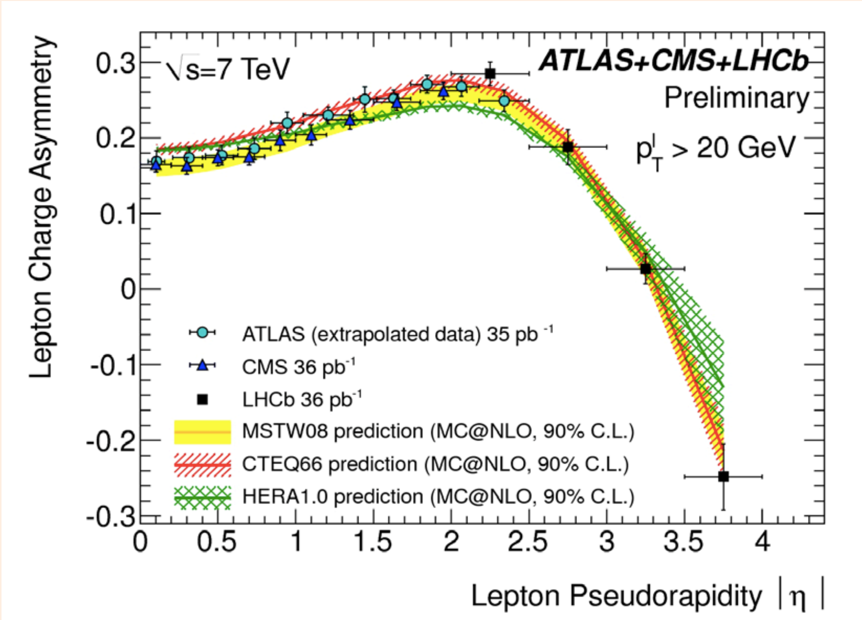


The measured values of σ(W,Z) times BR(W→lν,Z→ll) for W^+, W^- for their sum and for Z compared to the theoretical predictions based on NNLO QCD calculations using the MSTW 2008 PDF set. Results are shown for the combined electron-muon channels.

W asymmetry

- Define asymmetry: $A_\mu = \dfrac{d\sigma_{W_{\mu^+}}/d\eta_\mu - d\sigma_{W_{\mu^-}}/d\eta_\mu}{d\sigma_{W_{\mu^+}}/d\eta_\mu + d\sigma_{W_{\mu^-}}/d\eta_\mu}$
- In pp collision is sensitive to the valence quarks versus sea antiquark densities
- Currently assumed to be the same in PDF parametrizations

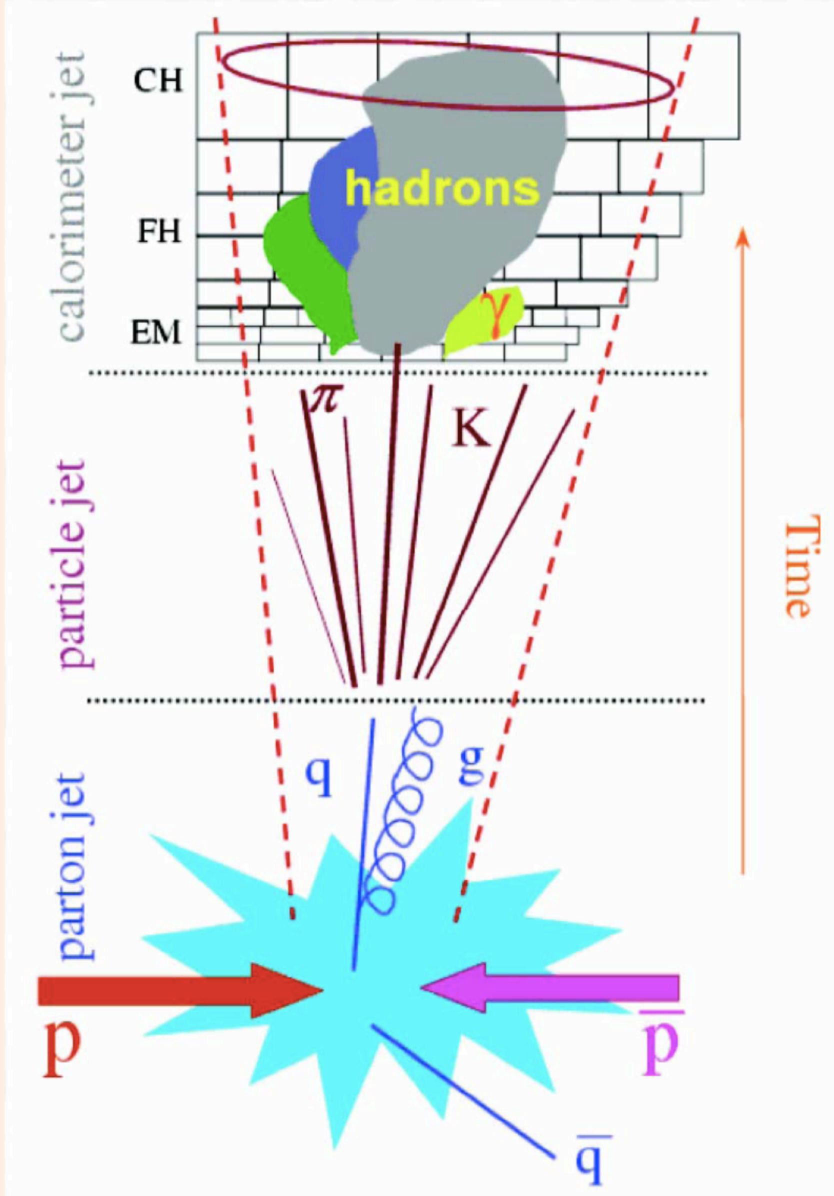




Combination covers huge kinematic range

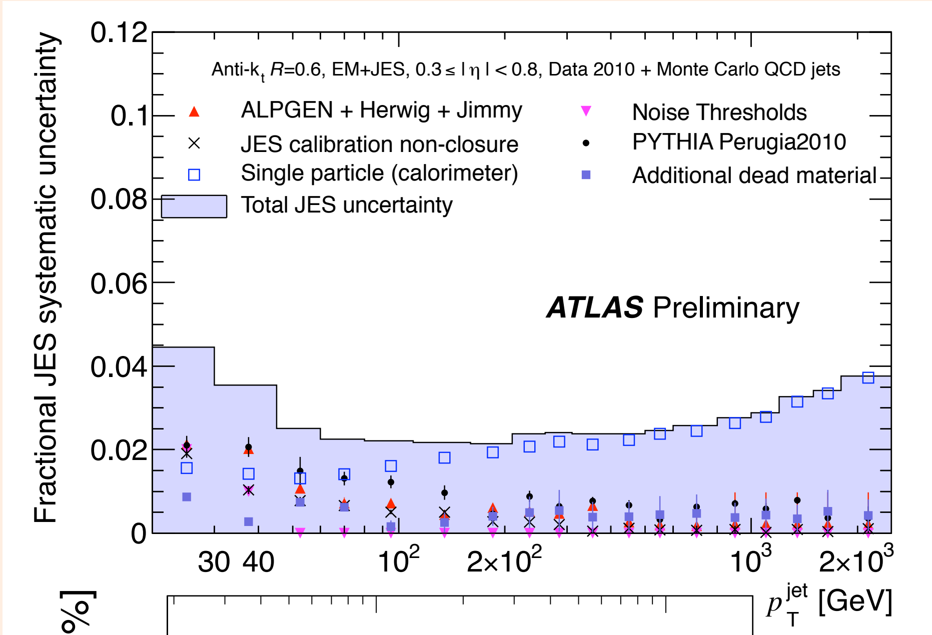
Jet reconstruction and energy measurements

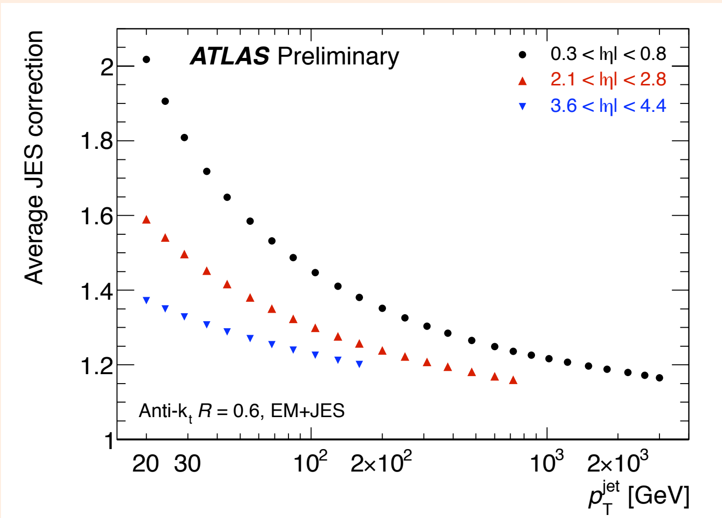
- A jet is not a well defined object (parton shower, fragmentation, detector response)
- The detector response is different for electrons/photons, and for hadrons
- One needs an algorithm to define a jet and to measure its energy
  - Conflicting requirements between experiment and theory
- Correct the reconstructed jet energy to account for losses of fragmentation particles, event pile-up, material effects, etc etc

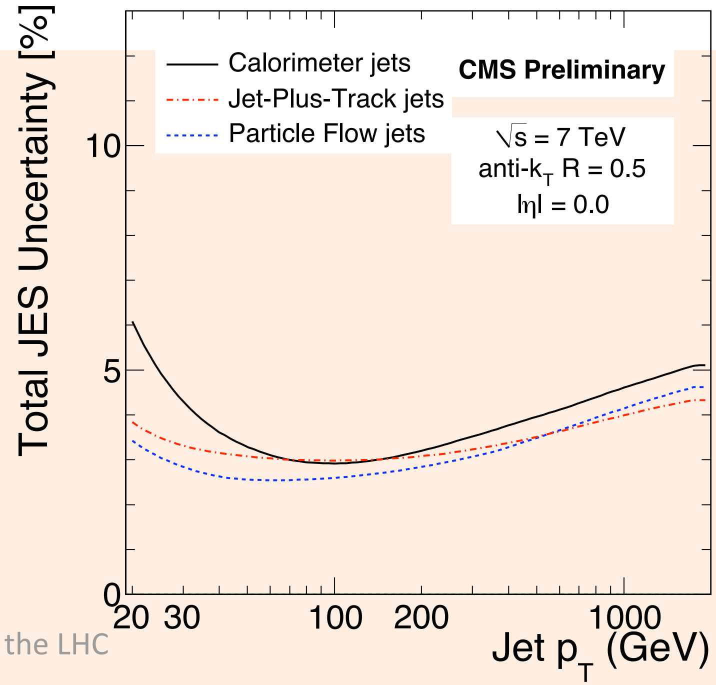


Jet calibration

- Correct the raw reconstructed jet energy to restore the energy at the "particle level"
- The jet calibration procedure relies on MC analysis, as well as on test beam and in-situ measurements
- ATLAS/CMS Jet Energy Scale Uncertainties are at the level of ~2.5-4% for central jets with ET<1 TeV;

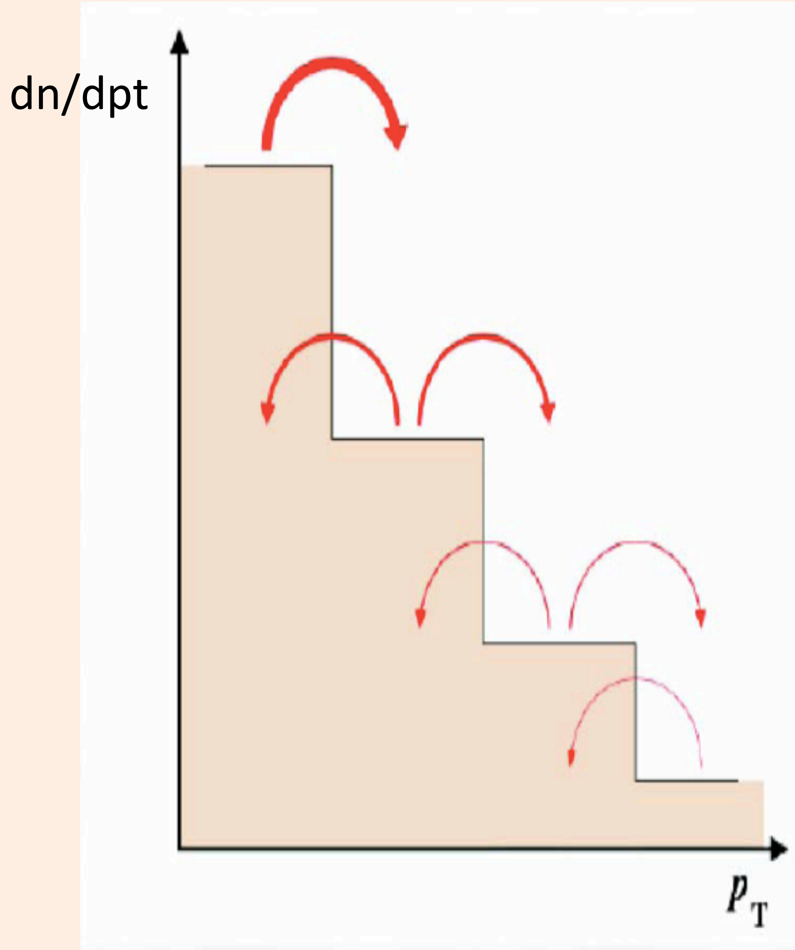






Jet measurement

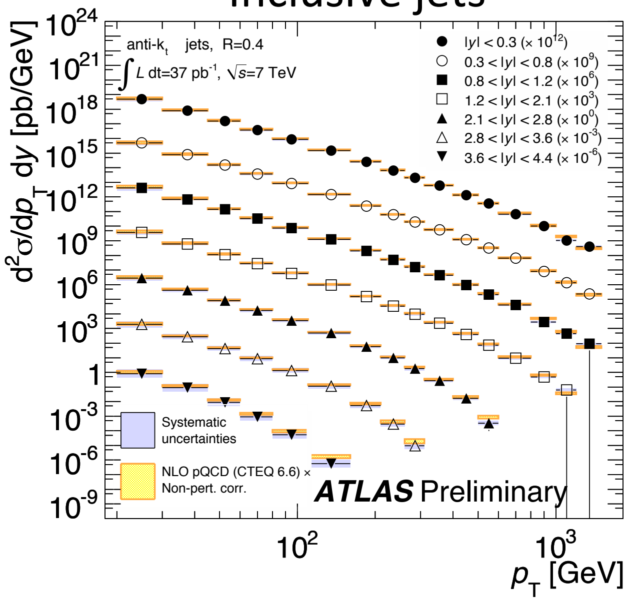
- Measure $d^2\sigma / dp_T d\eta = N / (\varepsilon \cdot L \cdot \Delta p_T \cdot \Delta\eta)$
- It's a counting experiment, so "simple"
- However effects due to the non perfect jet energy reconstruction, JES and Jet Energy resolution (JER), induce biases to steeply falling spectra such as those of the jet p_T distribution
- Physics results should be corrected for such effects



Inclusive jet and dijet cross section

Mainly based on 2010 data

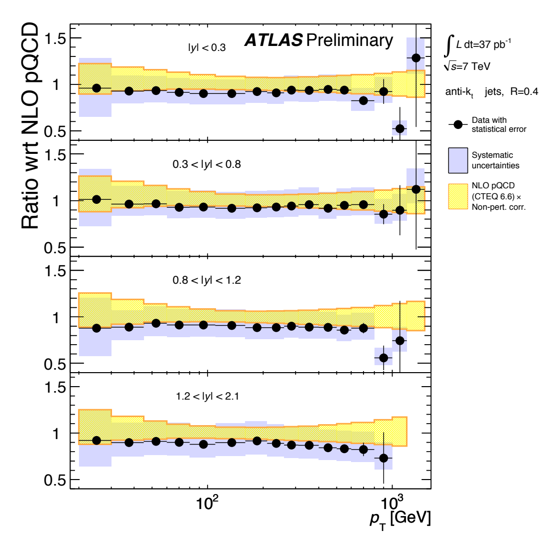
Inclusive jets



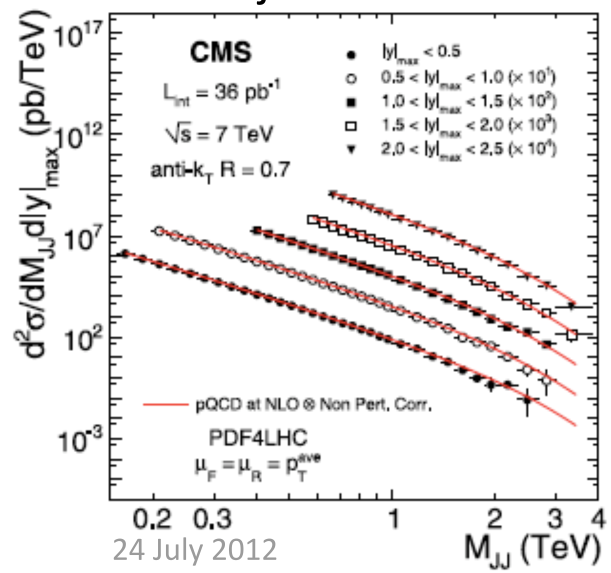
Inclusive jet cross section; p_T to > 1 TeV, |y|<4.4
Cross sections vary by 10^{10} over p_T range measured

Experimental uncertainties ~ 10 – 20%

data are compared to NLO pQCD calculations to which non-perturbative corrections have been applied.
Agreement of data with predictions within uncertainties

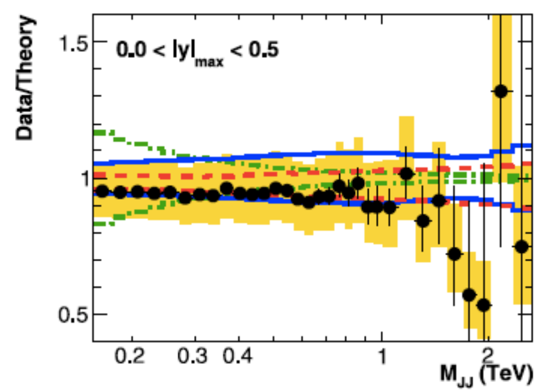


dijets



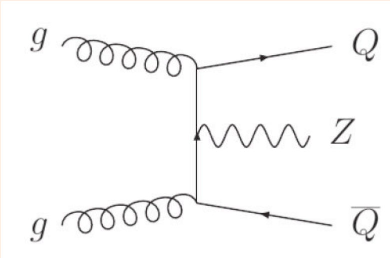
Dijet cross section as a function of m_{jj} and $|y_{max}|$;
Data up to m_{jj} ~ 4 TeV; ($m_{jj}/\sqrt{s}$=0.57) in 5 intervals of $|y_{max}|$
Cross sections varies by ~10^7 over mass range measured

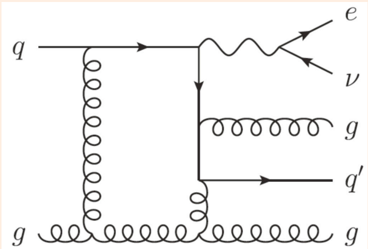
CMS



Data and predictions in good agreement within systematic uncertainties of 10-15%

QCD aspects in W/Z produced with jets



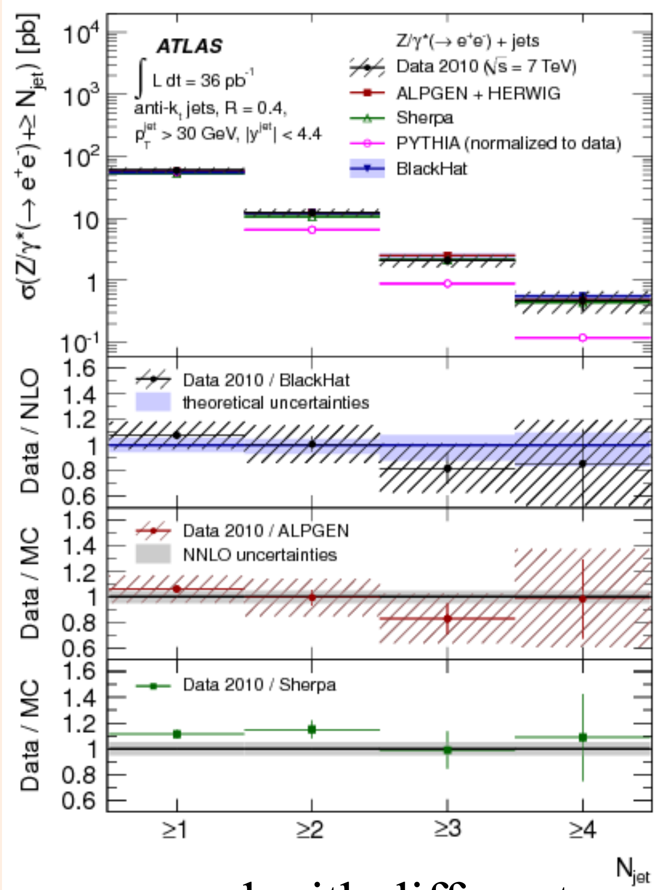


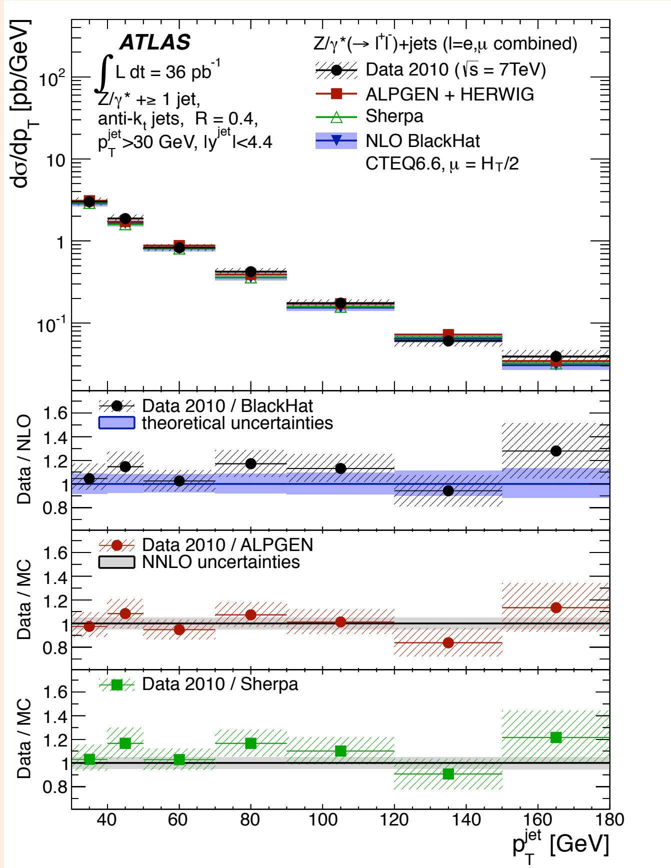
1. Important test of perturbative QCD in high p_T region (jet multiplicities, p_T spectra, etc)
2. W/Z+jets one of the most severe backgrounds for many new physics searches
3. Important for performance studies

- Final states considered: W +jtes, Z+jets, W+b,Z+b,W +c
- Studies based on whole 2010 statistics : 33-36pb^{-1} (uncertainty on luminosity between 3.4% and 3.8%)
- Final states with e/μ considered (plots shown indifferently for one or the other channels: similar conclusions)

Z+jets: measurements

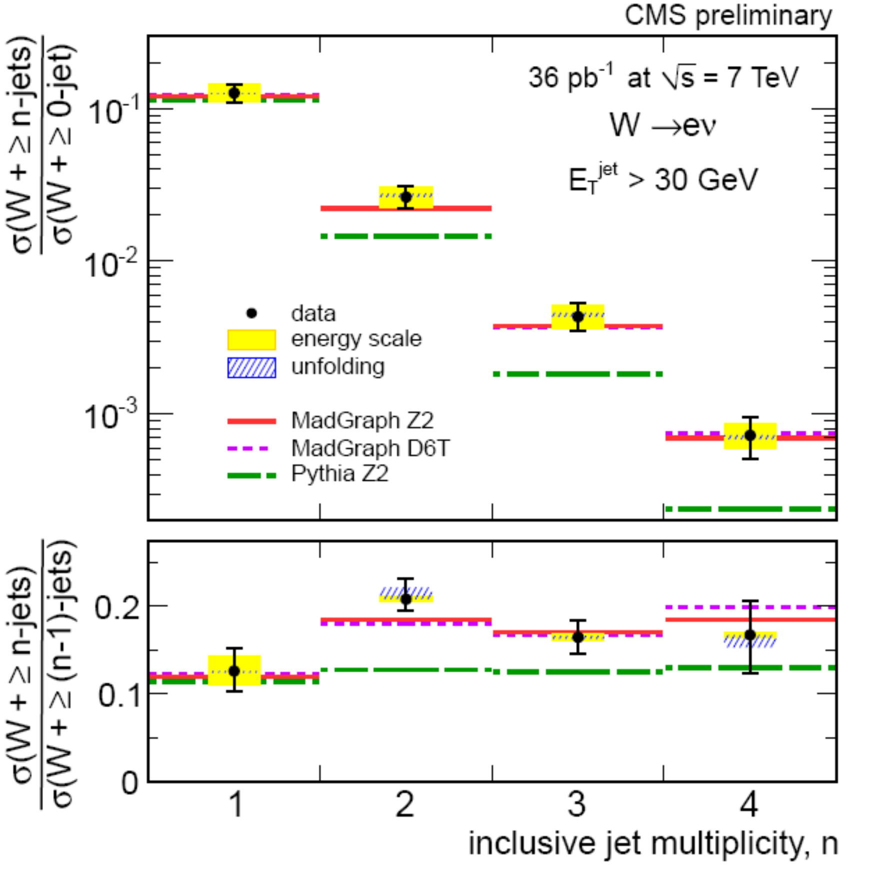
- Subtraction of main sources of background
  - Electroweak (dibosons, W+jets, ttbar, Z→ττ, QCD multijets): shapes derived from simulation
- Relative proportion of signal/ background derived from a fit to m_{ll}

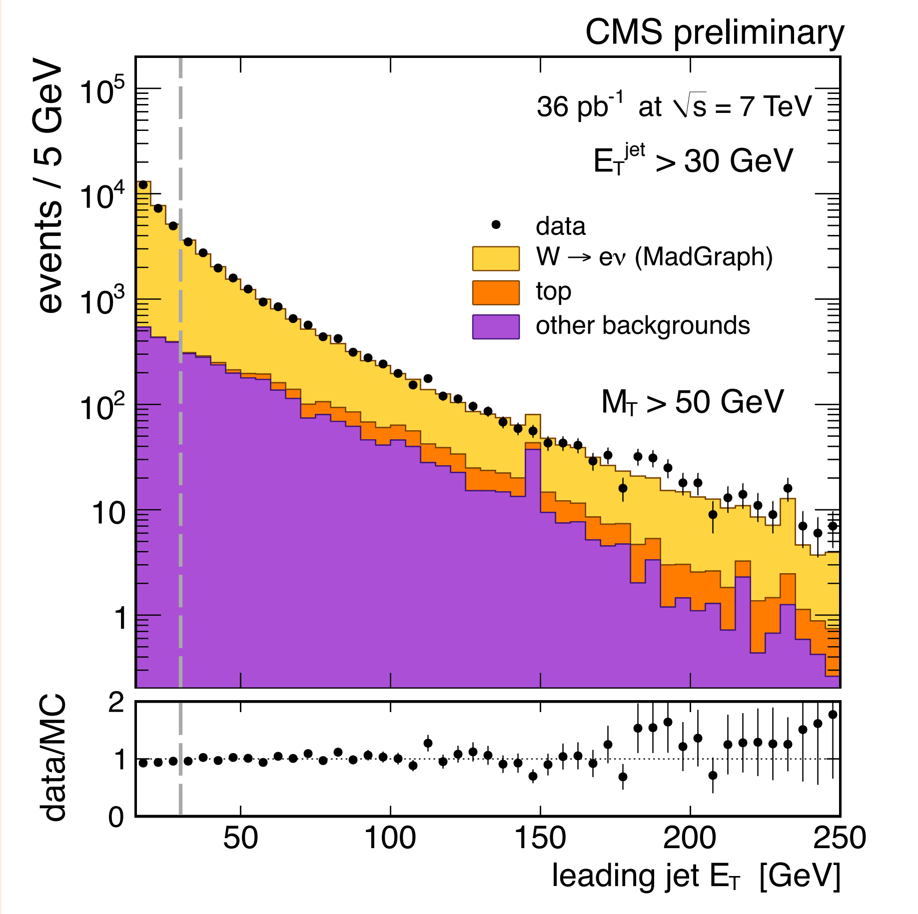




- Fiducial cross section compared with different generators corrected for parton to hadron effects and QED effects
- Pythia (LO pQCD) does not reproduce the data (even rescaled for Njet=1)
- Correct description of data is given by
  - Alpgen/Sherpa: LO matrix element for multipartonic final states
  - BlackHat: NLO pQCD calculations up to Njet=3 (LO for Njet=4)

W+jets measurement





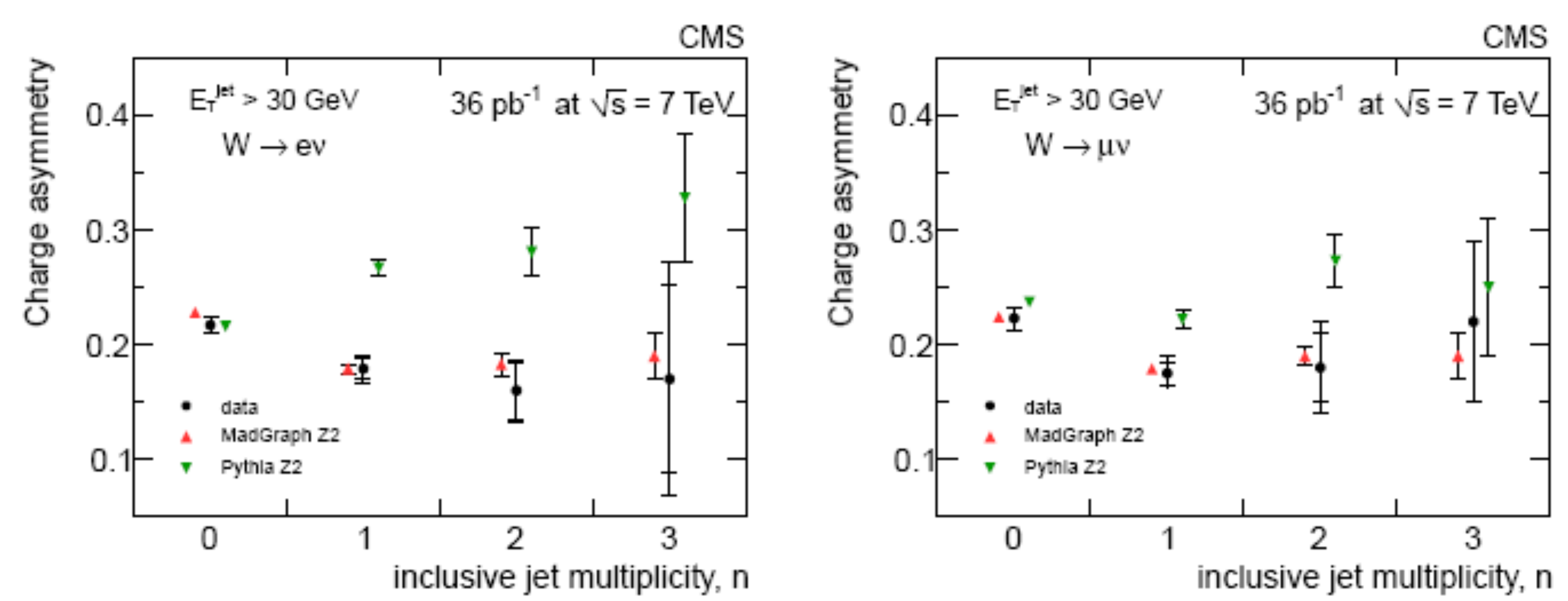
Left: inclusive jet multiplicity cross section ratio

Right: Distribution of the leading jet transverse energy in W events

Electrons only. Same level of precision with μ

W+jets: charge asymmetry

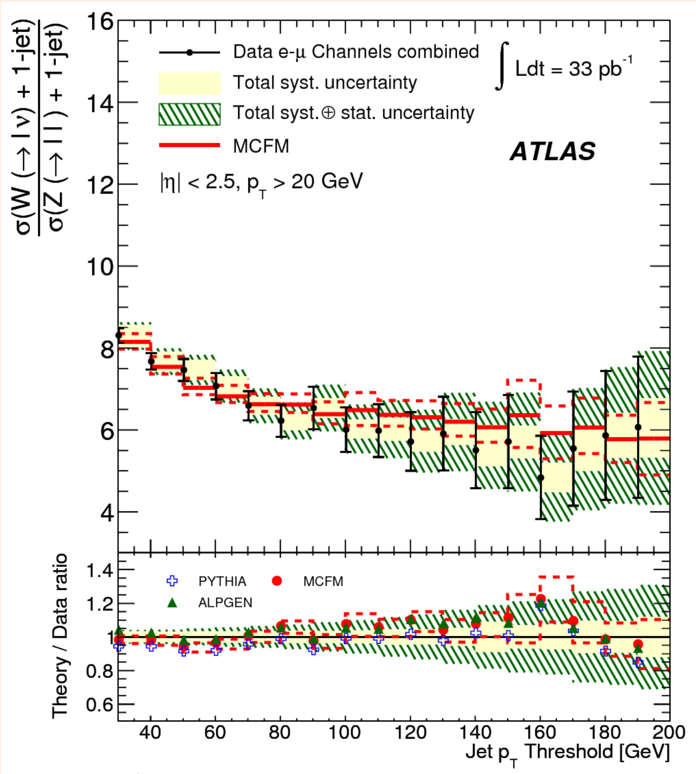
$$A_W = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)}$$

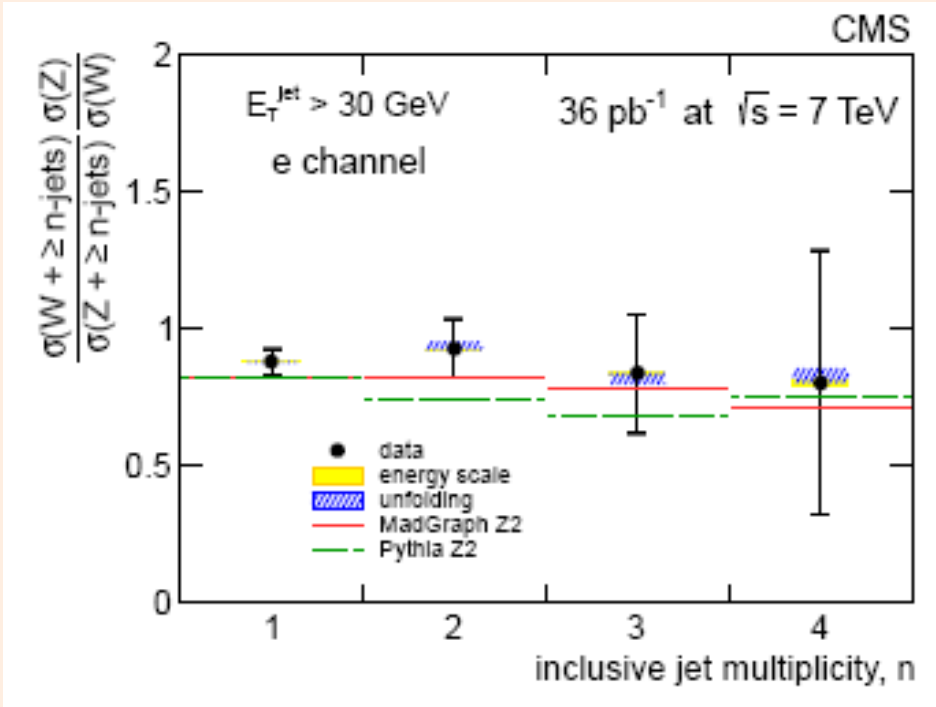


- Pythia not able to describe A_W asymmetry for n ≥ 1 jet
- W charge asymmetry well described by MadGraph.
  - Systematic errors includes: uncertainty on jet energy scale, difference of efficiencies for positive and negative leptons and charge misidentification (lower than 1% for e and 1‰ for μ).

W+jets/Z+jets ratio

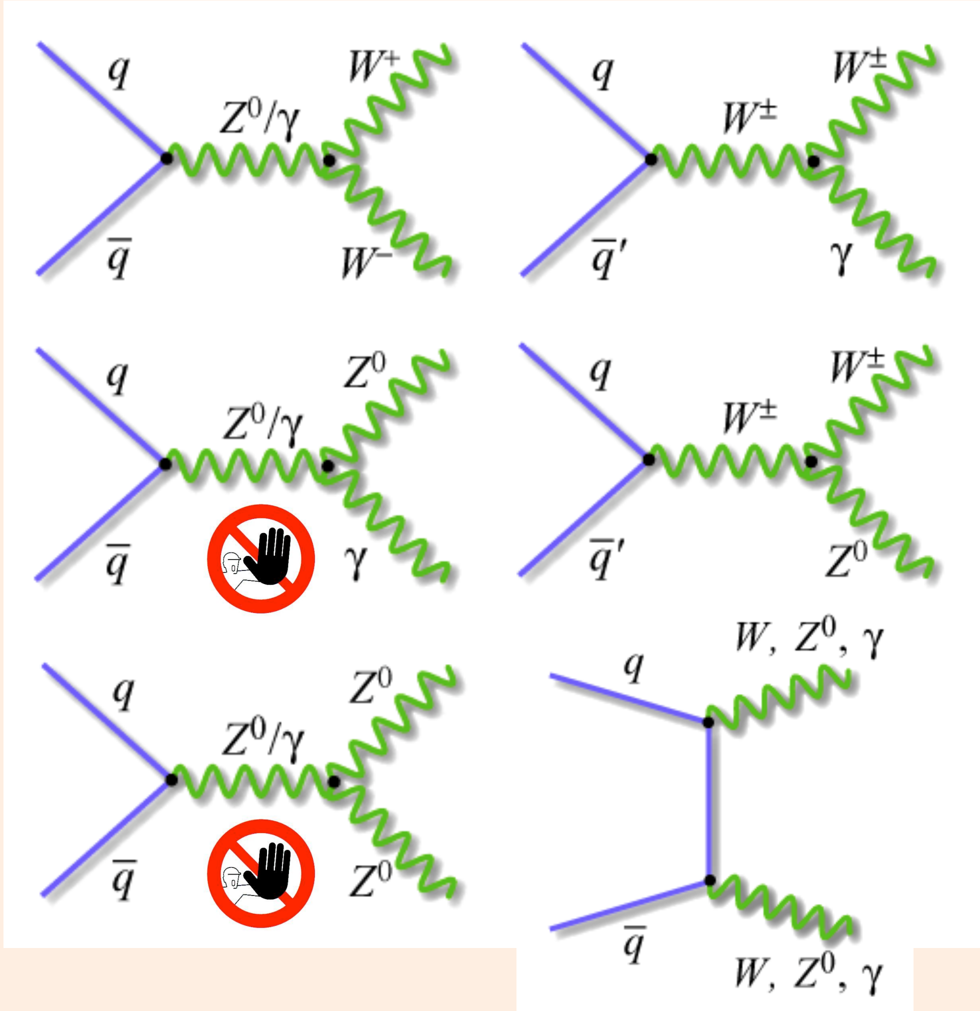
- Stringent test of standard model with a reduced systematic error:
  - cancellations of different sources of systematic errors : jet energy scale, jet energy resolution, lepton efficiency (partially), generator.
  - ATLAS (1 jet only): 4-6% total systematic error (vs ~13-15% in V + ≥ 1jets).
- Event selection/background subtraction/unfolding very similar to the single boson analysis:
  - Experimental results well described by the different generators.





Diboson production

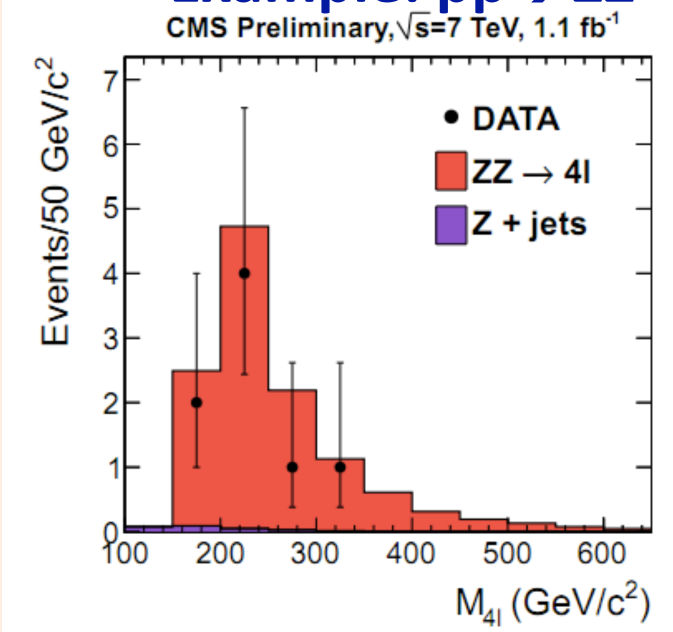
- Important test of the Standard Model, sensitivity to self-interactions between bosons: WW, γγ, ZZ,WZ,Wγ,Zγ
- Important backgrounds to Higgs and BSM processes
- Measure:
  - Production cross-section
  - Triple Gauge Couplings (TGCs)



Diboson production

- Event selection:
- Based on the reconstruction of high-p_T isolated leptons (e,μ,τ; >20 GeV), photons (>20 GeV) and large transverse missing energy (>10 GeV)
- Cuts on m_{ll} (>20 GeV) and/or m_T(>20 GeV) where appliable
- Main backgrounds
  - W,Z+jets (+fake leptons)
  - ttbar
  - QCD jets

Example: pp→ZZ



source	uncertainty
trigger	1.5%
lepton identification	3%
lepton isolation	2%
lepton energy scale	1%
τ reconstruction	6%
τ energy scale	3%

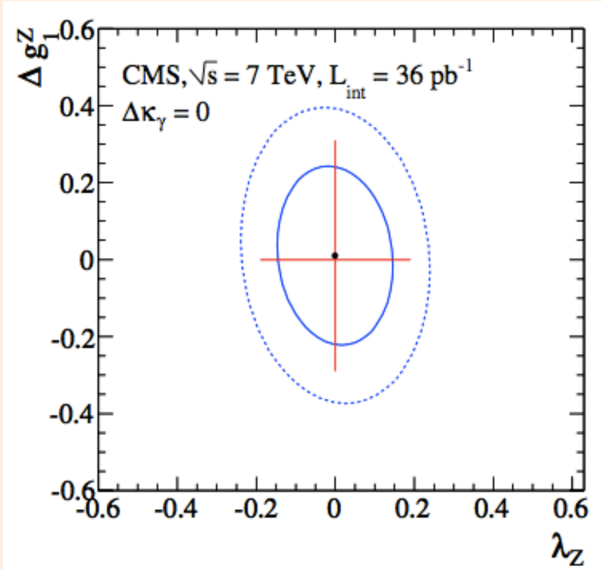
$$\sigma(pp \to ZZ + X) = 3.8^{+1.5}_{-1.2}(\text{stat.}) \pm 0.2(\text{sys.}) \pm 0.2(\text{lumi.})\ \text{pb}$$

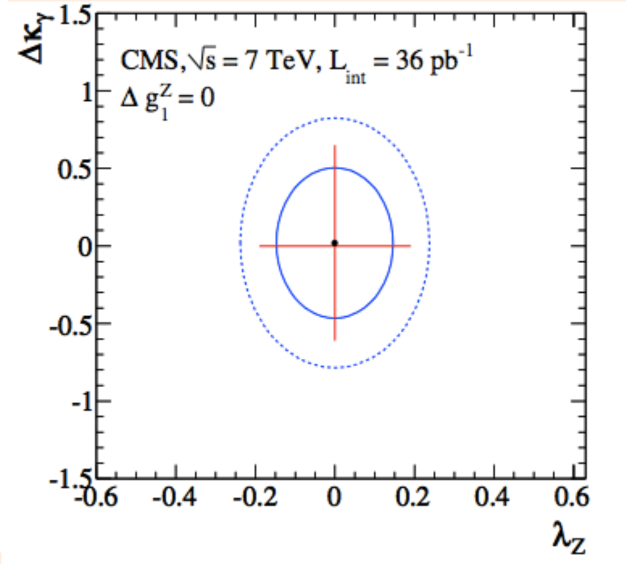
Anomalous couplings

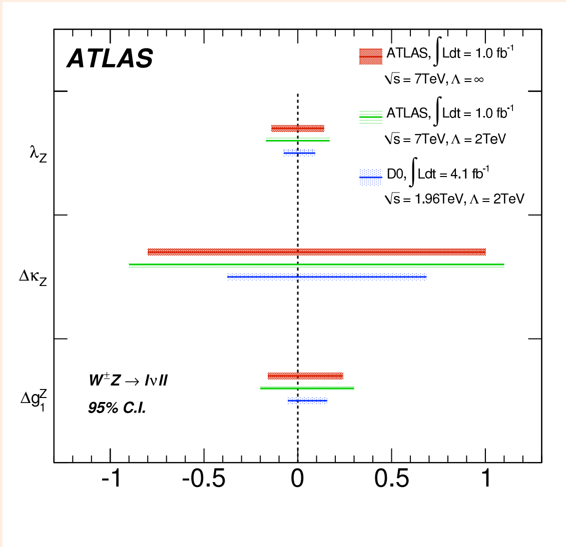
- Study the couplings of Vector Bosons
- This is sensitive to possible New Physics
- Start from the most generic TGC Lagrangian: described by 14 independent parameters
- Invoke CP invariance and EM gauge invariance 14→5 parameters: λ_γ, λ_Z; g_1^Z, k_γ, k_Z;
- Allowed by SM:
  - $\lambda_\gamma, \lambda_{Z=0}$; $g_1^Z = k_\gamma = k_Z = 1$;
  - γ/Z→WW
  - W→Wγ
  - W→WZ
- Forbidden by SM ("neutral vertices"):
  - γ/Z→ZZ or Zγ
- → measure these gauge coupling parameters to verify the SM predictions

TGCs

- Measure the diboson cross section production
- Express this as a function of the gauge coupling parameters free
- Measure the gauge couplings and compare with SM

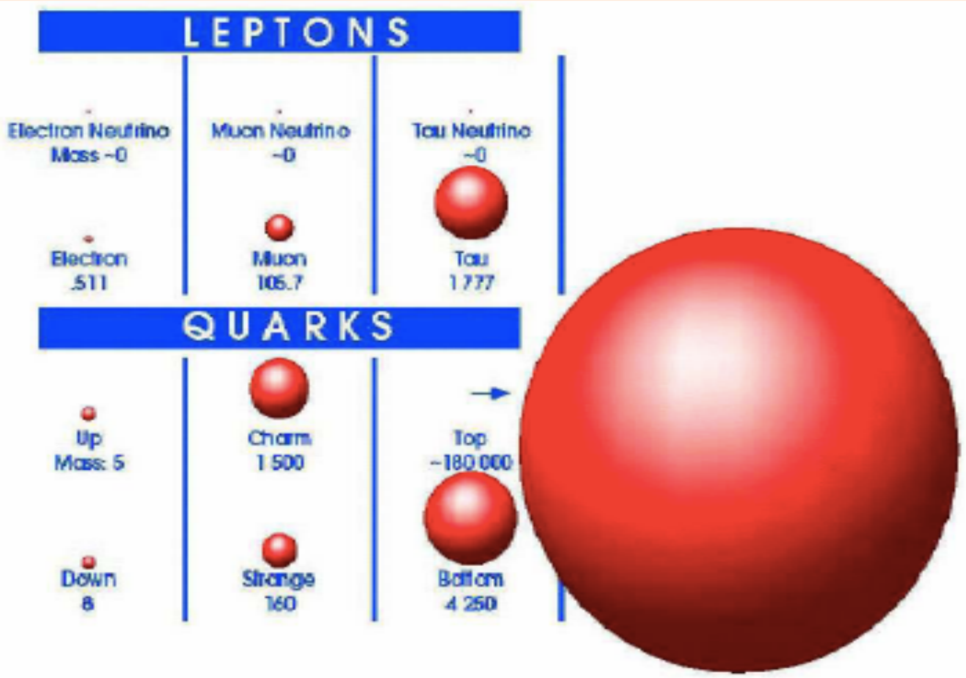






- **LHC TGC measurements competitive with Tevatron**
- **More data will improve the accuracy of these estimates**
- **Current results don't show any significant anomaly**

Top quark physics

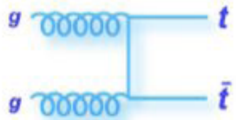


- Why the top quark is so important?
- → many reasons…

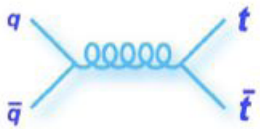
- Mass: it is more than 35 times heavier than the 2nd heaviest quark (the b-quark). why?
- Its Yukawa coupling is very close 1: why? Special role in the electroweak symmetry breaking mechanism?
- we still know little about its properties: mass, spin, charge, decay time, Yukawa coupling, …
- Its decay time, $\tau \sim 10^{-25}$ s, does not allow to hadronize: → no top-quark hadrons!
- Its production at the LHC represent one of the most severe backgrounds to New Physics searches
- It may serve as a window to New Physics searches!

Top quark production at the LHC

- Gluon fusion (dominant at LHC)



- Quark-antiquark annihilation



	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%

For $m_t = 172.5$ GeV

$\sqrt{s} = 1.96$ TeV: $\sigma(pp \to t\bar{t})_{NNLOapprox} = 7.46^{+0.48}_{-0.67}$ pb

$\sqrt{s} = 7$ TeV: $\sigma(pp \to t\bar{t})_{NNLOapprox} = 164.6^{+11.4}_{-15.7}$ pb

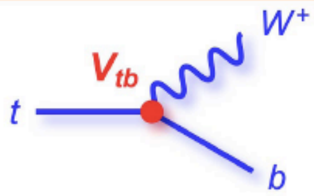
.

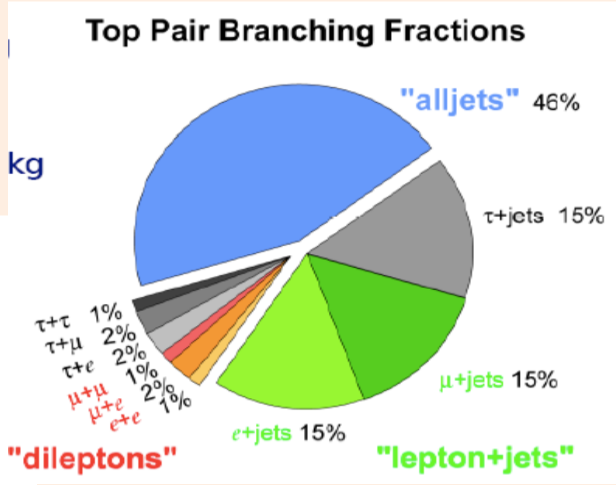
Lanenfeld et al. PRD 80, 054009 (2009)
Aliev et al., Comp. Phys. Comm. 182, 1034 (2011)
Kidonakis, Phys. Rev. D82, 114030 (2010)
Ahrens et al., JHEP 1009, 097 (2010) arXiv:1105.5824

- NLO corrections completely known
- NNLO partly known

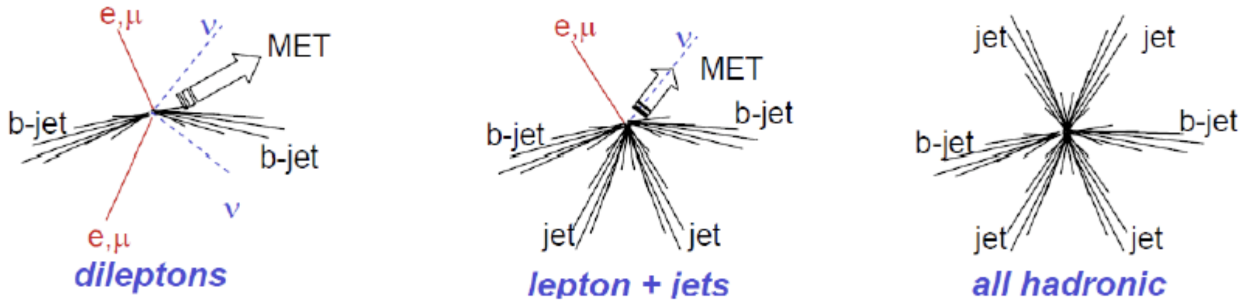
Top production and decay

- Top decays before it can hadronize
  - almost exclusively t->Wb

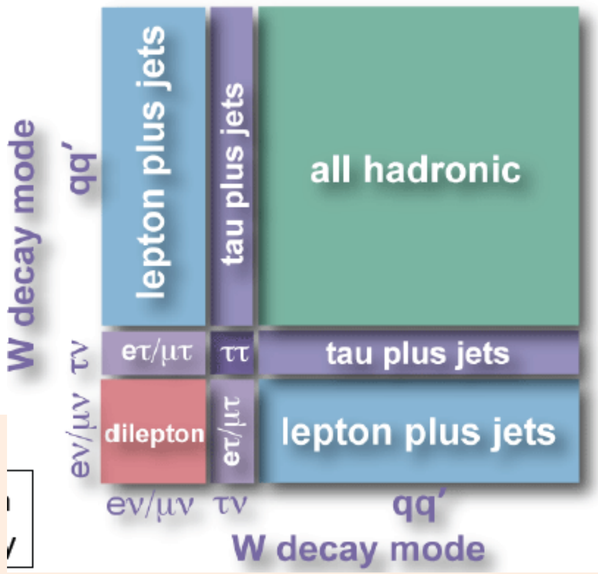




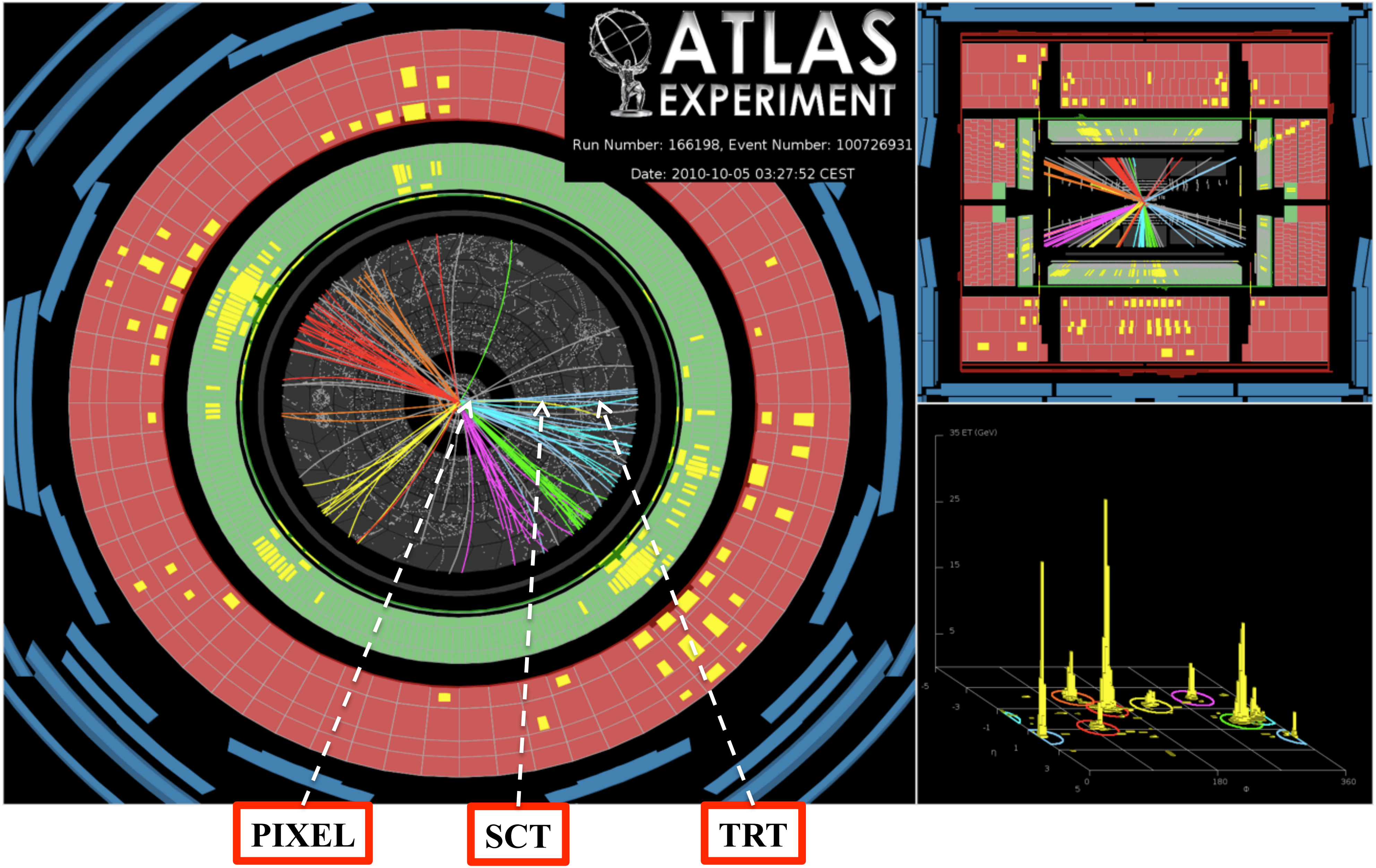
- Top pair event classification according to W decays



	dileptons	lepton + jets	all hadronic
Branching ratio:	~5%	~30%	~46%
Backgrounds:	few (mainly Z+jets)	moderate (mainly W+jets)	huge (mainly QCD)

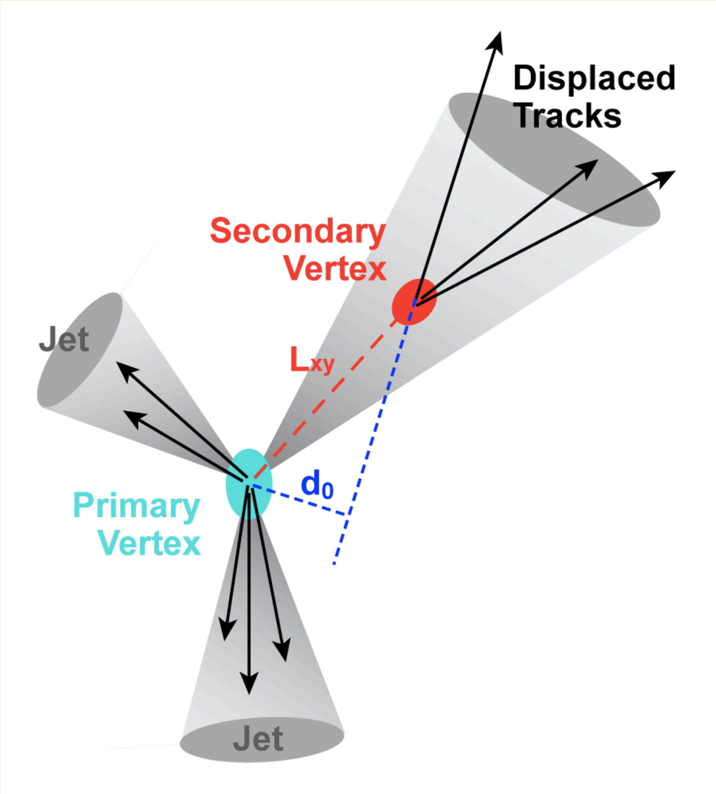


b-tagging

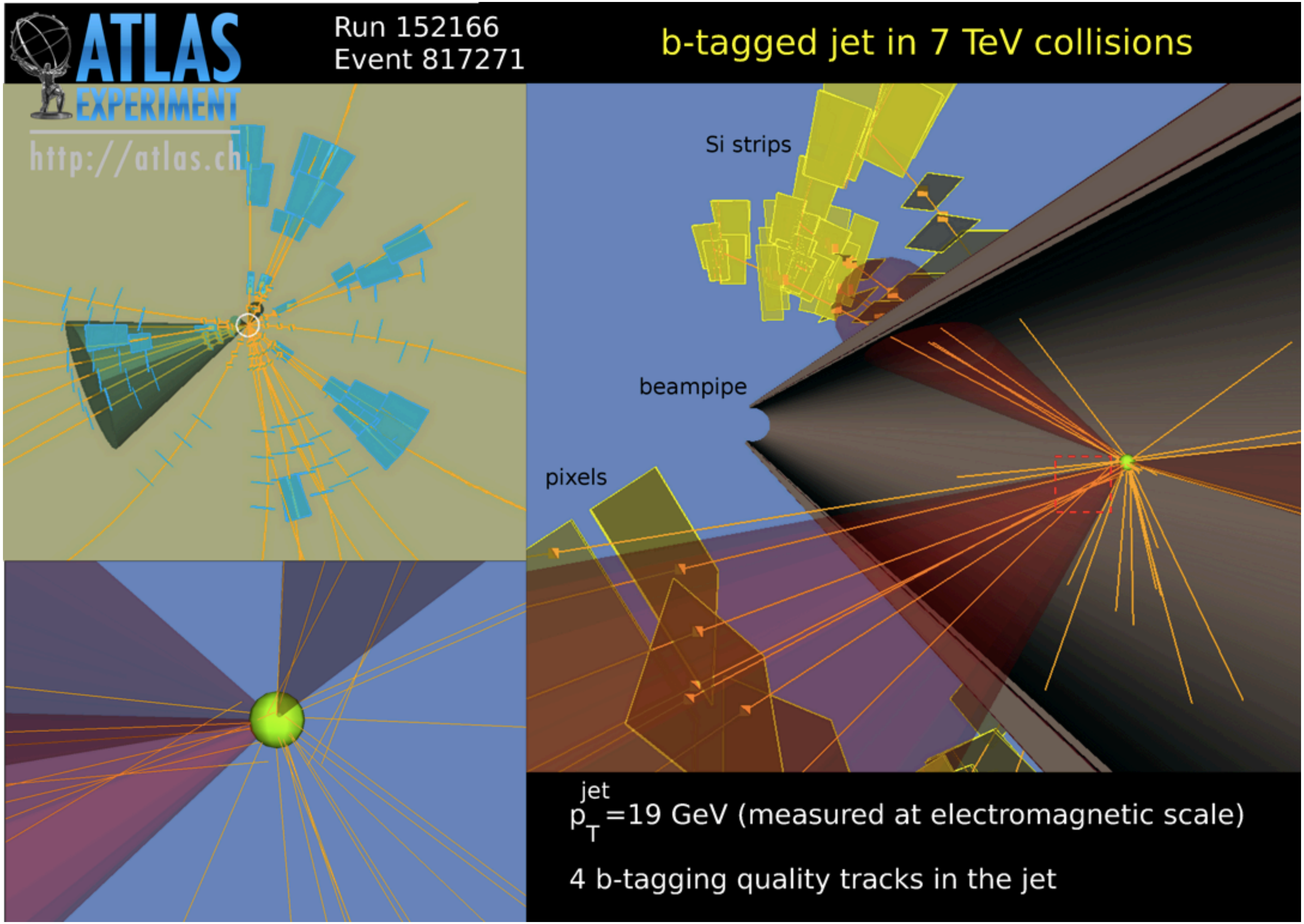

ATLAS
EXPERIMENT
Run Number: 166198, Event Number: 100726931
Date: 2010-10-05 03:27:52 CEST
35 ET (GeV)
25
15
5
η
Φ
0
180
360
PIXEL
SCT
TRT

b-tagging

- The goal: identify jets originating from b-quark fragmentation

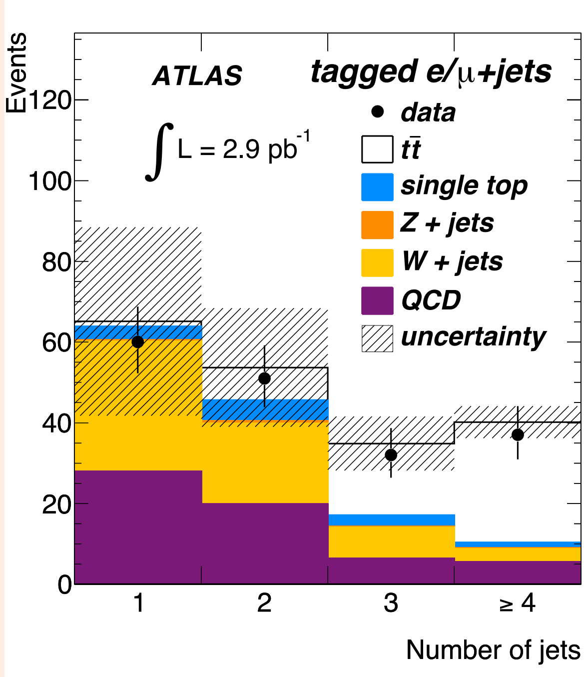


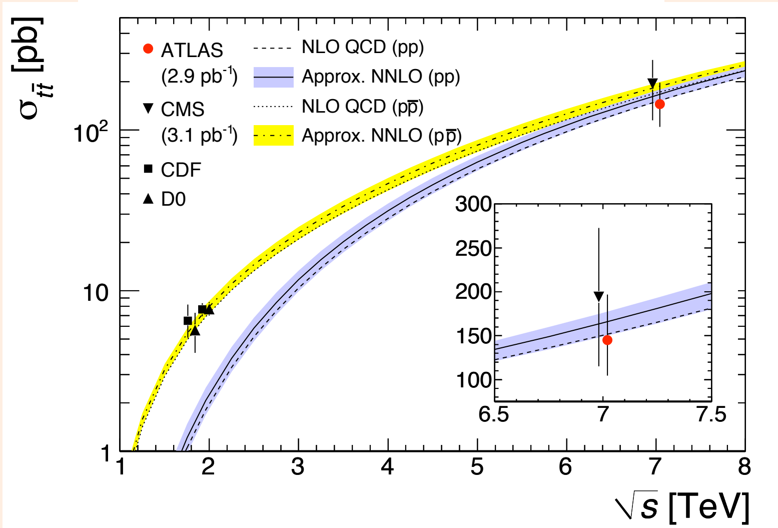
- B-tagging exploits the properties of b-hadrons:
  - High-mass (~ 5 GeV)
  - Long lifetime (~1.5 ps, cτ ~ 0.45 mm) → a b-hadron in a 50 GeV jet flies on average ~ 3 mm before decaying!
- Experimentally relies on:
  - Detecting soft lepton in jets
  - Measuring tracks with large impact parameter
  - Reconstruction secondary vertices displaced from the Primary Vertex


ATLAS EXPERIMENT
http://atlas.ch
Run 152166
Event 817271
b-tagged jet in 7 TeV collisions
Si strips
beampipe
pixels
p_T^{jet}=19 GeV (measured at electromagnetic scale)
4 b-tagging quality tracks in the jet

ttbar production in lepton+jet final states

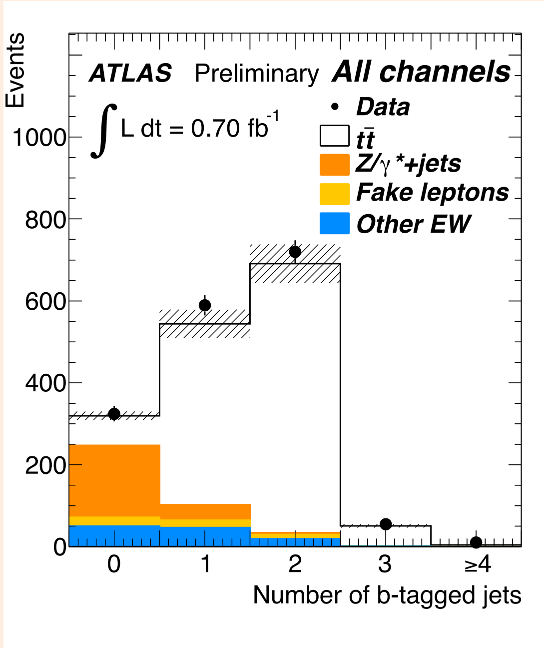
- First measurement, studying lepton+jets+MET
- Event selection:
  - Lepton trigger
  - One identified lepton (e,μ) with $p_T > 20$ GeV
  - MET > 35 GeV (rejects QCD background)
  - $m_T > 25$ GeV (to select W→lν final states)
  - At least one jet with $p_T > 25$ GeV, $|\eta|<2.5$
  - B-tagging: at least on jet b-tagged;
    - SV0 algorithm used
    - Efficiency of 50% for ttbar events
    - Light-jet acceptance: 0.01-0.002 (20<pt<200 GeV)





ttbar production in dilepton final states

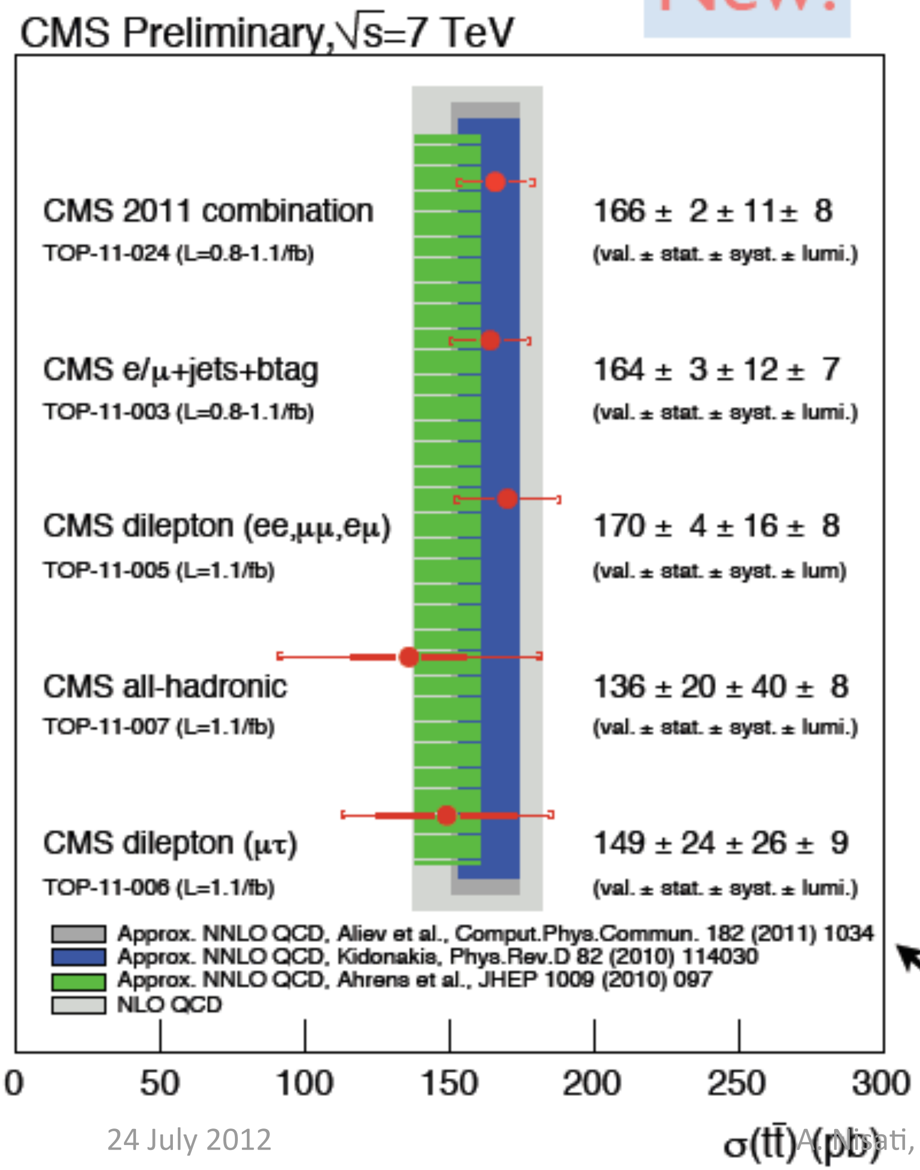
- Event selection:
  - exactly two oppositely-charged lepton candidates (ee,eμ,μμ)
  - at least two jets with p_T > 25 GeV and $|\eta|<2.5$
  - $m_{ll}>15$ GeV to reject heavy flavour background
  - ee, μμ final states: m_Z-15 GeV $<m_{ll}<m_Z$-15 GeV and MET>60 GeV
  - eμ final states: H_T (sum of leptons and jets p_T)> 130 GeV
- Perform the analysis with/without the requirement of at least one selected jet to be b-tagged



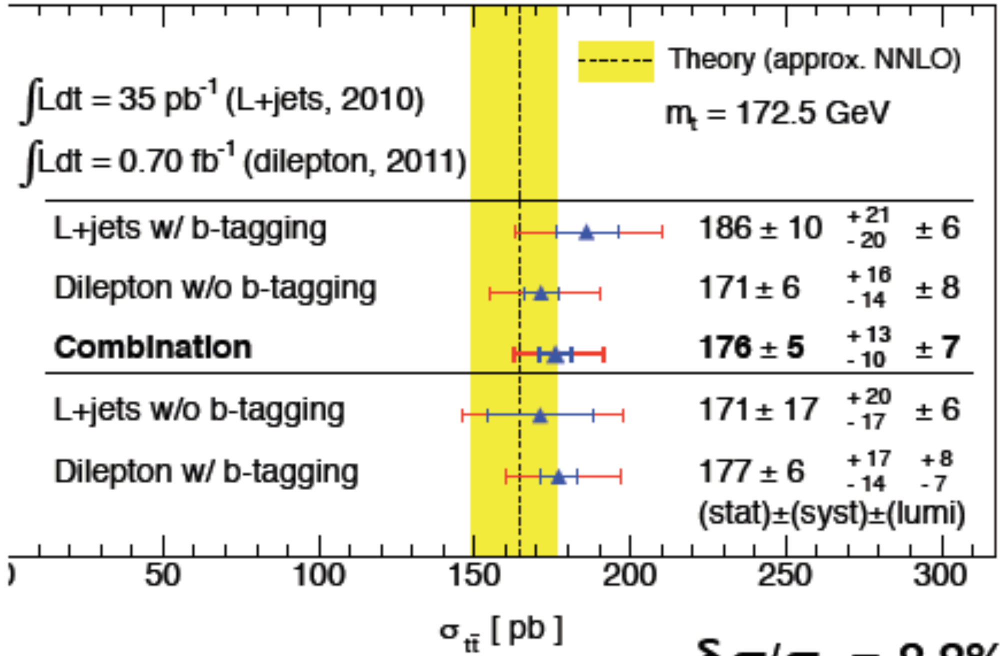
Multiplicity distribution of b-tagged jets in ee + μμ + eμ events. Contributions from diboson and single top-quark events are summarized as 'Other EW'.

Combined cross section

(CMS-TOP-11-024) New!



(ATLAS-CONF-2011-108)



$\delta\sigma/\sigma$ = 8.8%

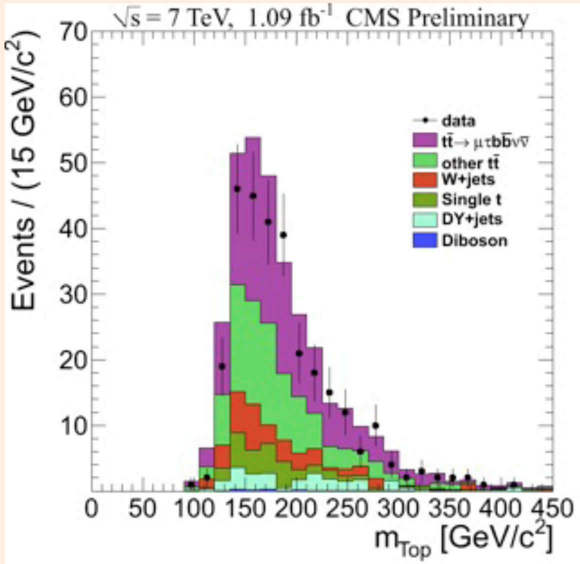
$$176 \pm 5(\text{stat.}) \pm {}^{13}_{10}(\text{syst.}) \pm 7(\text{lumi})$$

$\delta\sigma/\sigma$ = 8%

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2(\text{stat.}) \pm 10.6(\text{syst}) \pm 7.8(\text{lumi.})\ \text{pb}$$

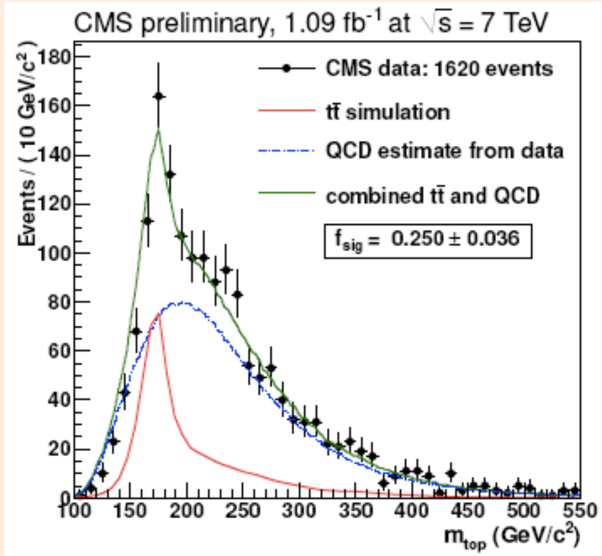
ttbar production in other final states

- **μ+τ final state**
  - Event selection
    - Only one isolated muon pT > 20/25 GeV (CMS ATLAS)
    - At least two jets
    - MET > 40/30 GeV (CMS/ATLAS)
    - HT > 200 GeV (ATLAS)
    - One b-tagging
    - At least one tau jet
    - Opposite sign of muon and tau jet



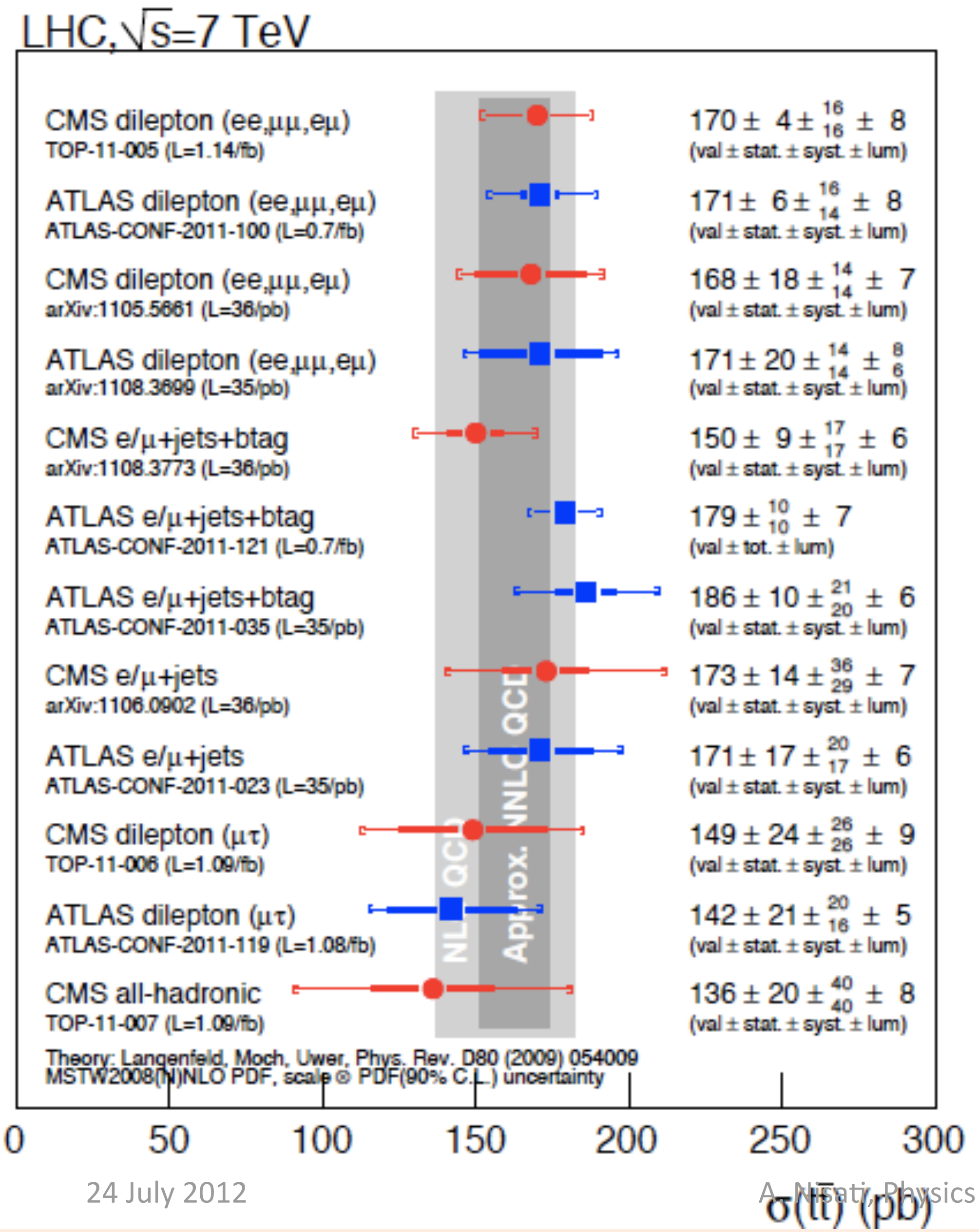
σ=148.7±23.6(stat.)±26.0(syst.)±8.9(lumi.)pb

- **hadronic final state**
  - Large branching fraction: 45%
  - Event selection
    - Select events with 6 high-p_T jets
    - At least two b-tagged jets
    - Cuts on MET (ATLAS)
    - Measure QCD jet background from data



σ=136±20(stat.)±40(syst.)±8(lumi.)pb

ttbar production cross section summary

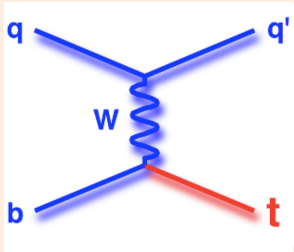


Comments

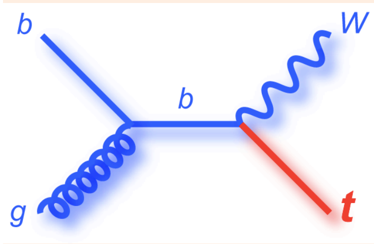
- Most precise value now ~ 7%. Systematics & Lumi
- NNLO approximation's precision now being challenged (also for Tevatron measurements)
- No new combinations yet but LHC-wide combination group set up → O(5%)?
- More results upcoming for TOP2011

Single top

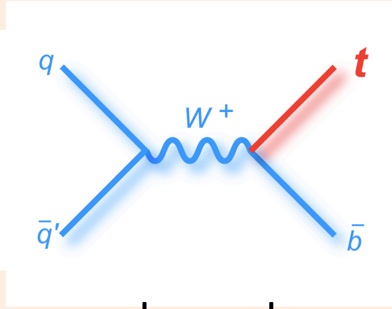
- Important measurement of the Standard Model
  - Establish different production channels
  - Compare with SM predictions
- Search for new phenomena
  - FCNC
  - W'
  - H+
  - 4th generation
  - …



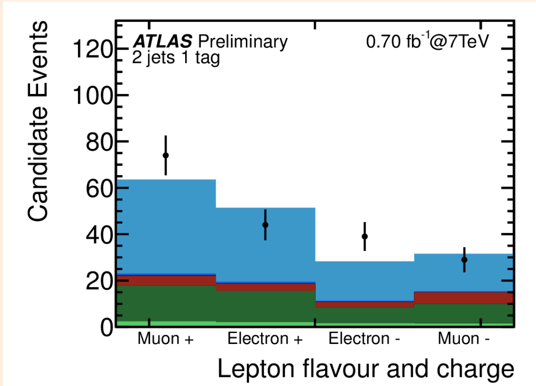
t-channel
σ=64.2±2.6 pb



Wt-channel
σ=15.6±1.3 pb



s-channel
σ=4.6±0.2 pb



ATLAS, t-channel: candidates after event selection

$90 \pm 9^{+31}_{-20}$ pb (cut) 7.6 σ
$105 \pm 7^{+36}_{-30}$ pb (NN)

22^{+9}_{-7} pb (stat $\oplus$ syst.)
2.7 σ obs.
$(1.8 \pm 0.9)\ \sigma$ exp.

Expected limit $\sigma_t(s) < 20.5$ pb
Observed limit $\sigma_t(s) < 26.5$ pb
~5 x SM cross section (4.6 pb)

Present single top production cross section measurements in agreement with Standard Model predictions

Top mass

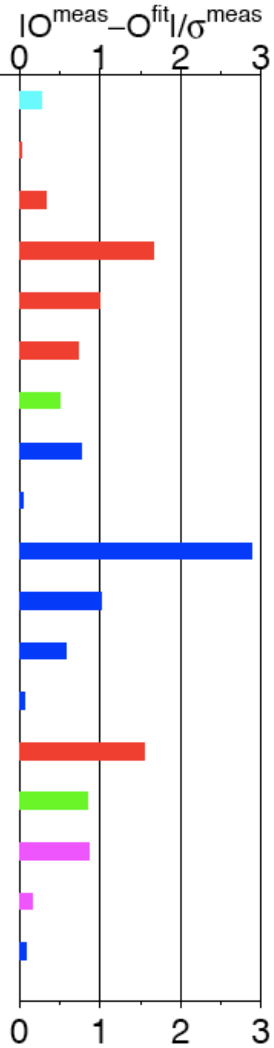
- Global electroweak fit
- Based, on a number of experimental observables; for ZFITTER they are 18, see left table
  - Each observable is calculated in the Standard Model as a function of $\Delta\alpha_{had}(m_Z^2)$; $\alpha_S(m_Z)$; m_Z; m_{top}; m_{Higgs};
- The W-mass is calculated as:

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F sin^2\Theta_W}}$$

- Taking into account the radiative corrections:

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F sin^2\Theta_W}\frac{1}{1-\Delta r}}$$

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4



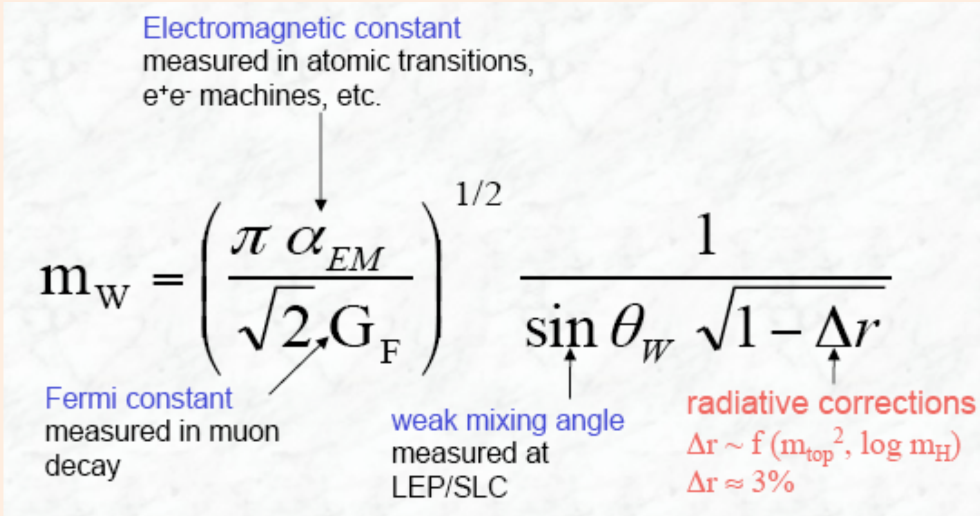
July 2010

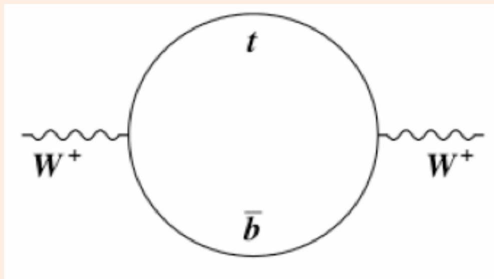
Top mass

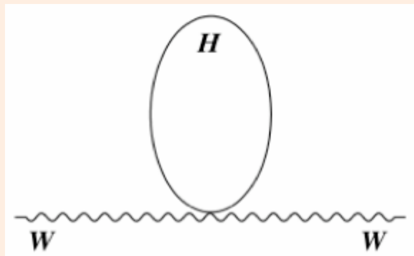
- Radiative corrections are proportional to m^2_{top}, and on $\log(m_H)$

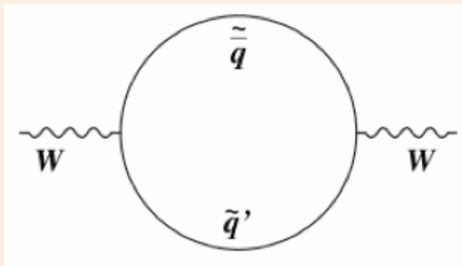
$$\Delta\rho \approx \frac{3\sqrt{2}G_F}{16\pi^2} M_{top}^2$$

- ➔ **precise measurements of m_{top} and m_W constraint the SM Higgs boson mass**
- Additional contributions may come from other new still unseen particles: e.g. SUSY

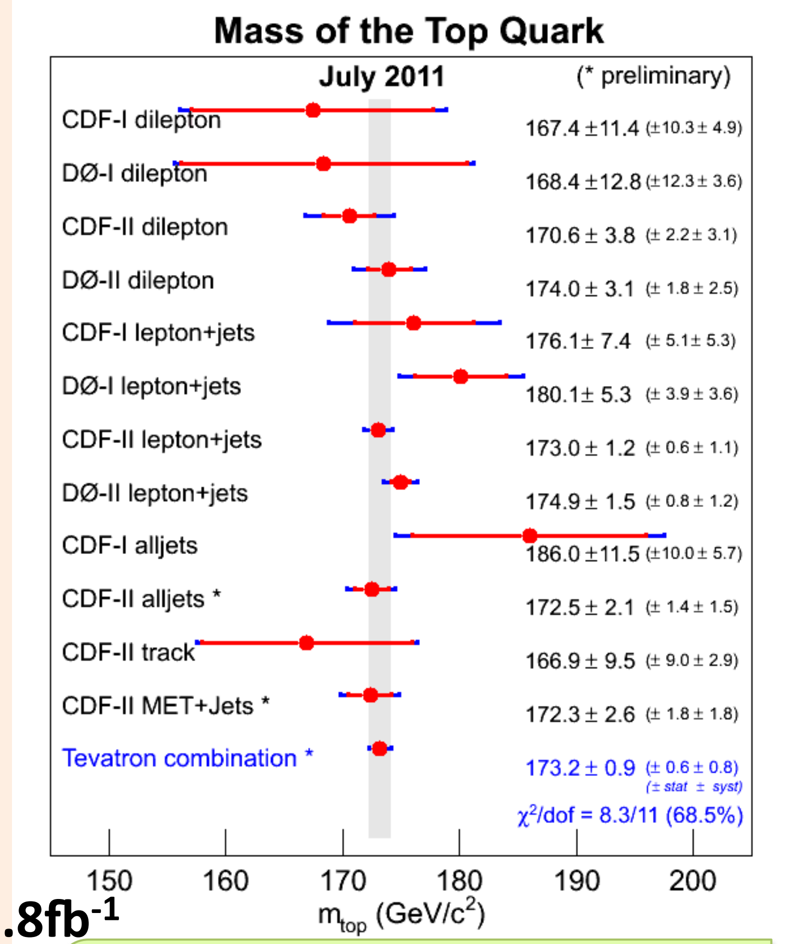




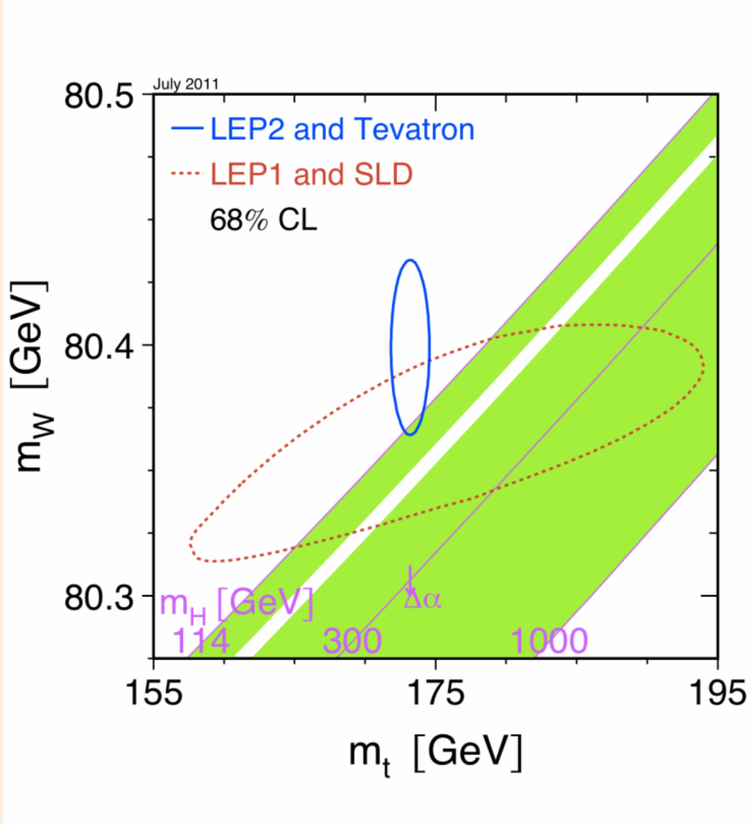




Top mass – Tevatron



3.6-5.8fb^{-1}



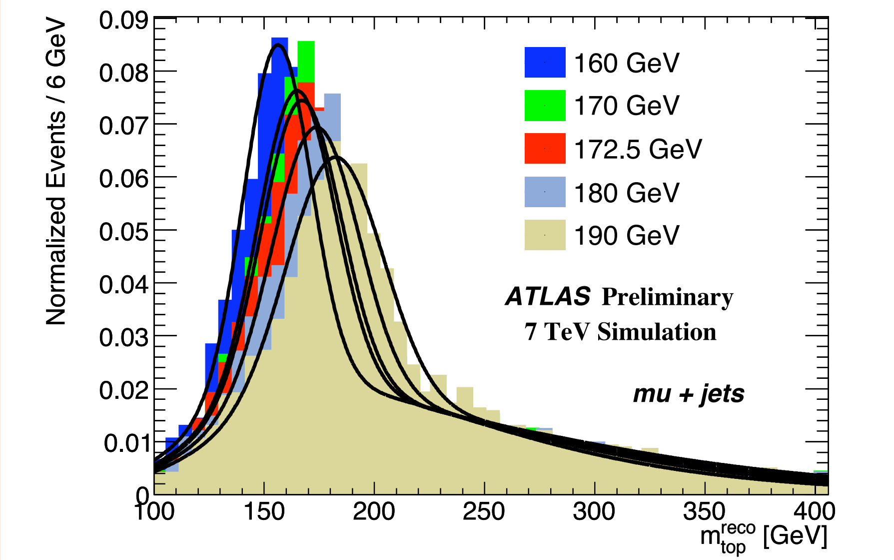
m_{top} = 173.2±0.9 GeV

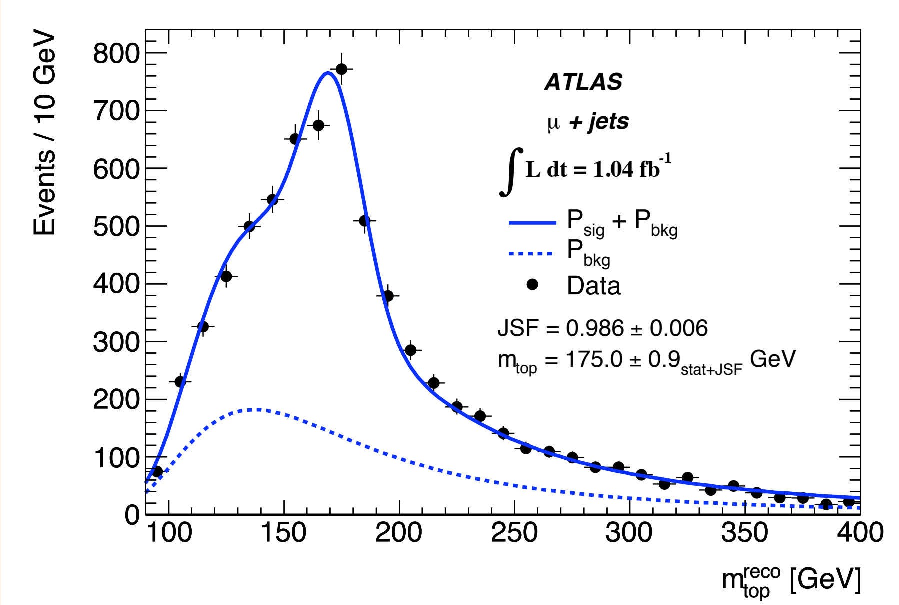
Top mass - LHC

- Example: 2-D template method: fit simultaneously the top quark mass and the Jet Energy Scale (JES)

$$\chi^2 = \left[\frac{E_{j1}(1-\alpha_1)}{\sigma_1}\right]^2 + \left[\frac{E_{j2}(1-\alpha_2)}{\sigma_2}\right]^2 + \left[\frac{M_{jj}(\alpha_1,\alpha_2)-m_W}{\Gamma_W}\right]^2$$

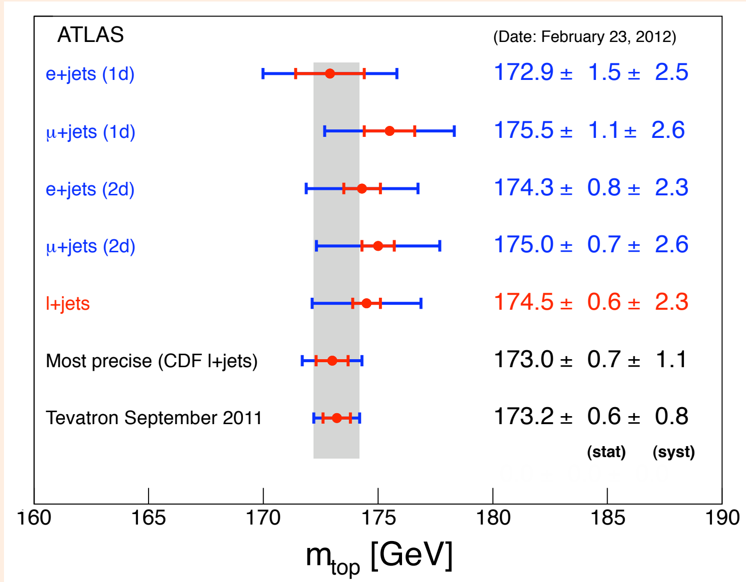
- Make "templates" of Monte Carlo background and signal events with different top mass hypothesis
- Fit data to templates using maximum likelihood fit

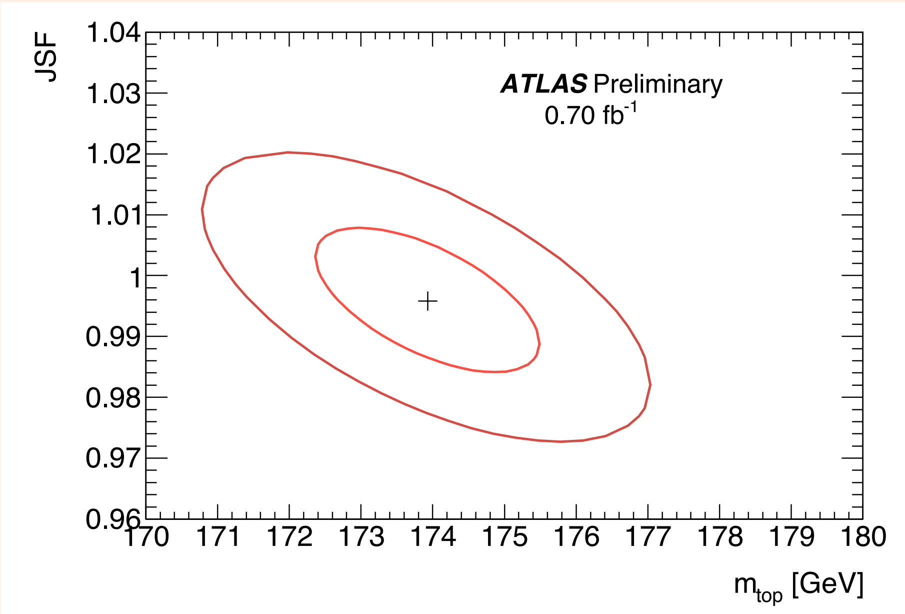


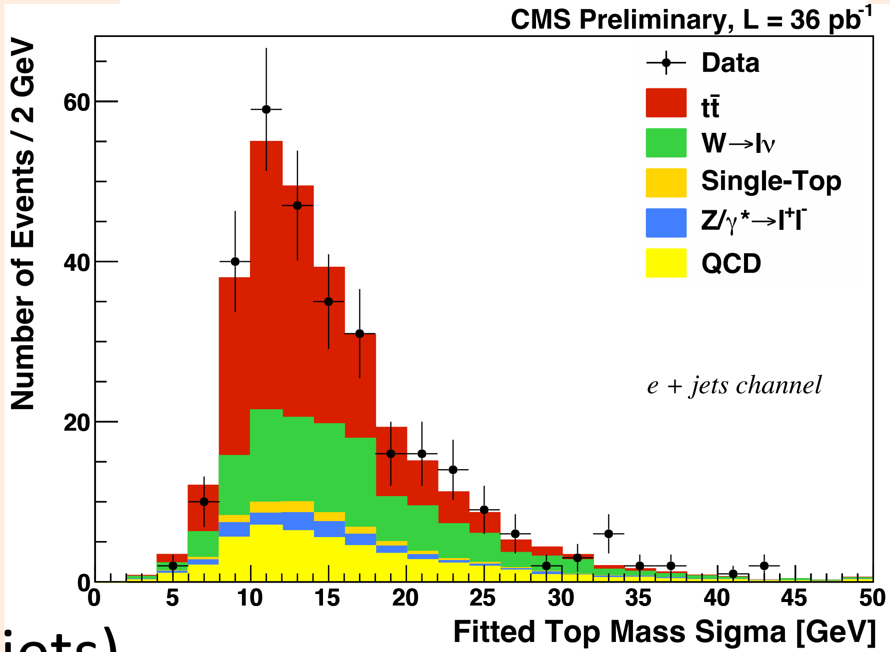


Top mass - LHC

- Results:
  - JES-m_{top} (bottom left)
  - m_{top} summary (top-right)
  - CMS top mass measurement: use l+jets events, but use a kinematic fit to the ttbar system decay to extract the top mass





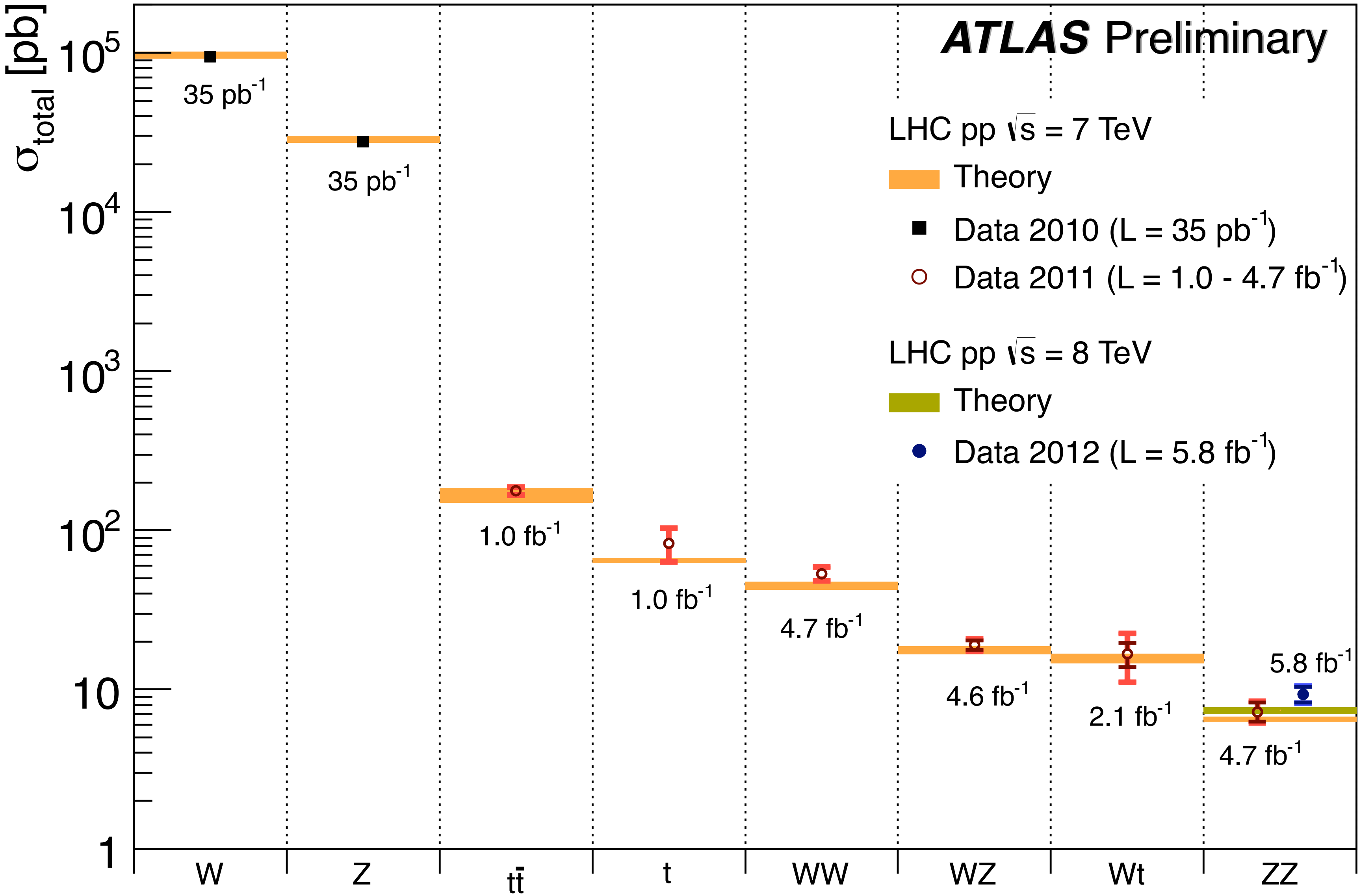


CMS : m_t = 172.6 ± 0.6 ± 1.2 GeV (μ+jets)

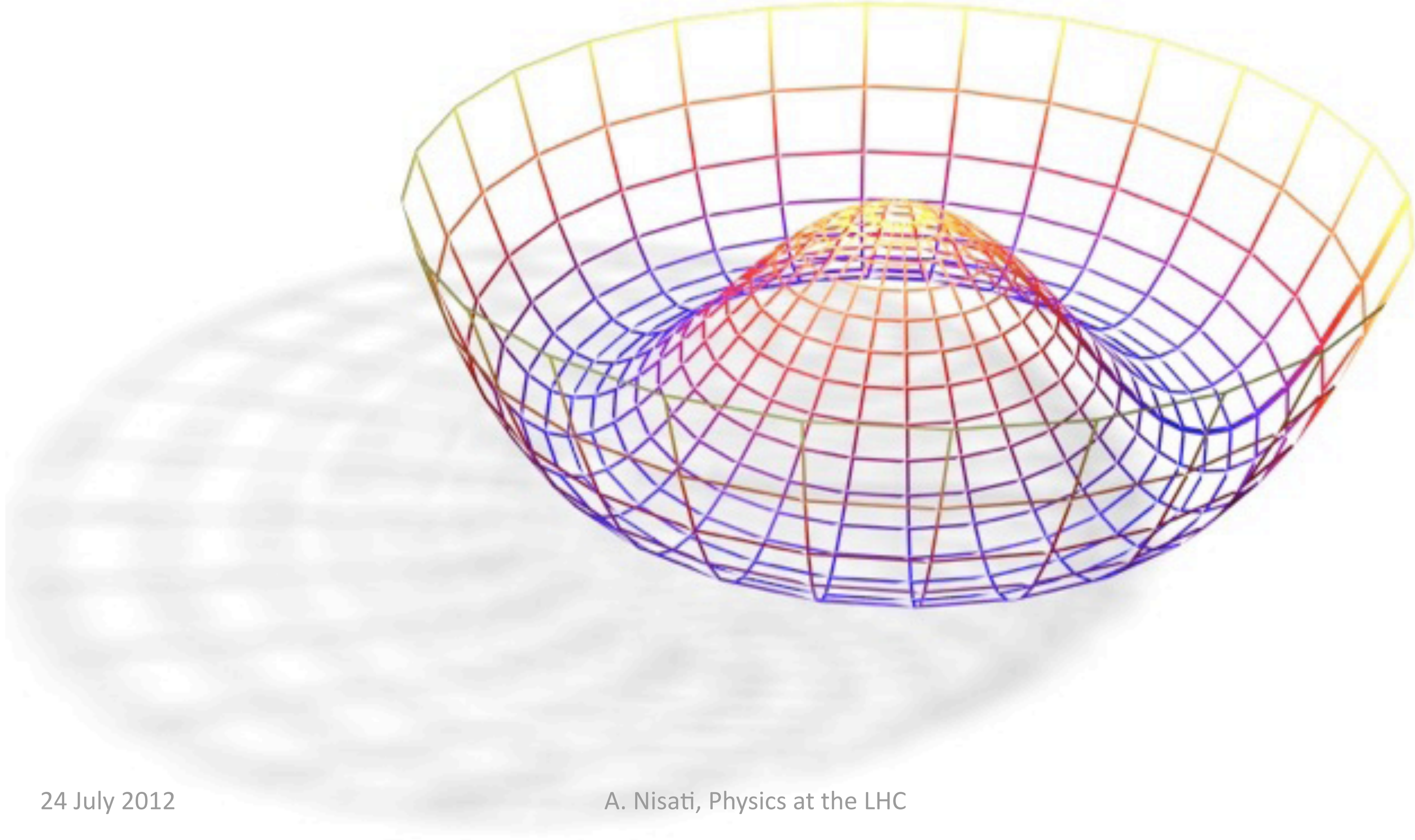
ATLAS: m_t = 174.5 ± 0.6 ± 2.3 GeV (l+jets L=1.04/fb)

ATLAS+CMS: m_t = 173.3 ± 0.5 ± 1.3 GeV (L=4.9/fb)

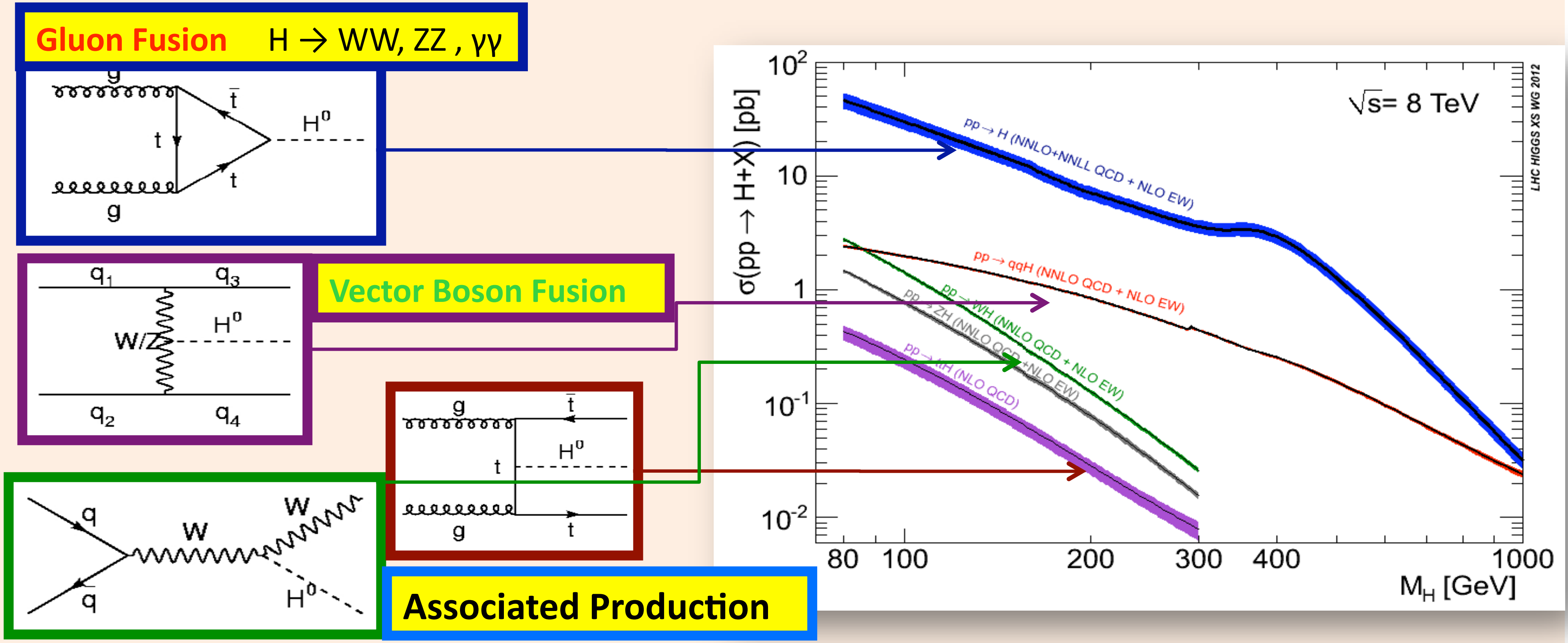
Standard Model – summary



Standard Model Higgs boson search



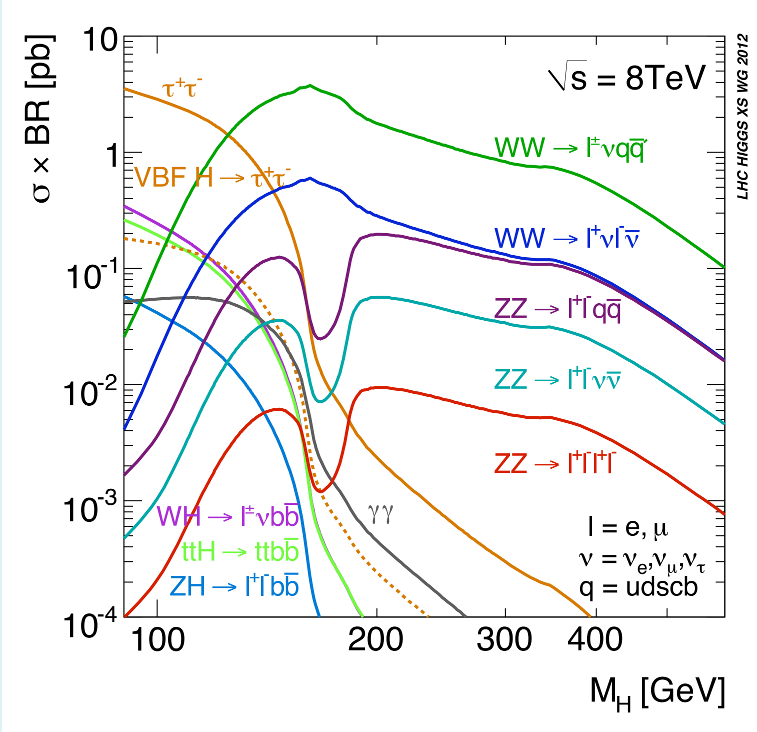
SM Higgs production at the LHC



- Gluon fusion is the dominant mechanism for Higgs production at present hadron colliders
  - At LHC this is x10 higher than at Tevatron!
- Associated production is also important: qqH, VH, ttH

Higgs cross-sections

- **H→γγ**: rare channel, but the best for low mass
- **H→WW$^{(*)}$**:
  - →lνlν: very important in the intermediate mass range
  - → lνqq: highest rate, important at high mass
- **H→ZZ$^{(*)}$**:
  - → 4l: golden channel
  - → llνν: good for high mass
  - → llbb: also high mass
- **H→ττ**: good signal/ background, important at low mass, rare
- Associated prod. **H→ bb-bar**
  - ttH, WH, ZH
  - It is useful for the discovery
  - It is very important for Higgs property studies if SM Higgs is discovered

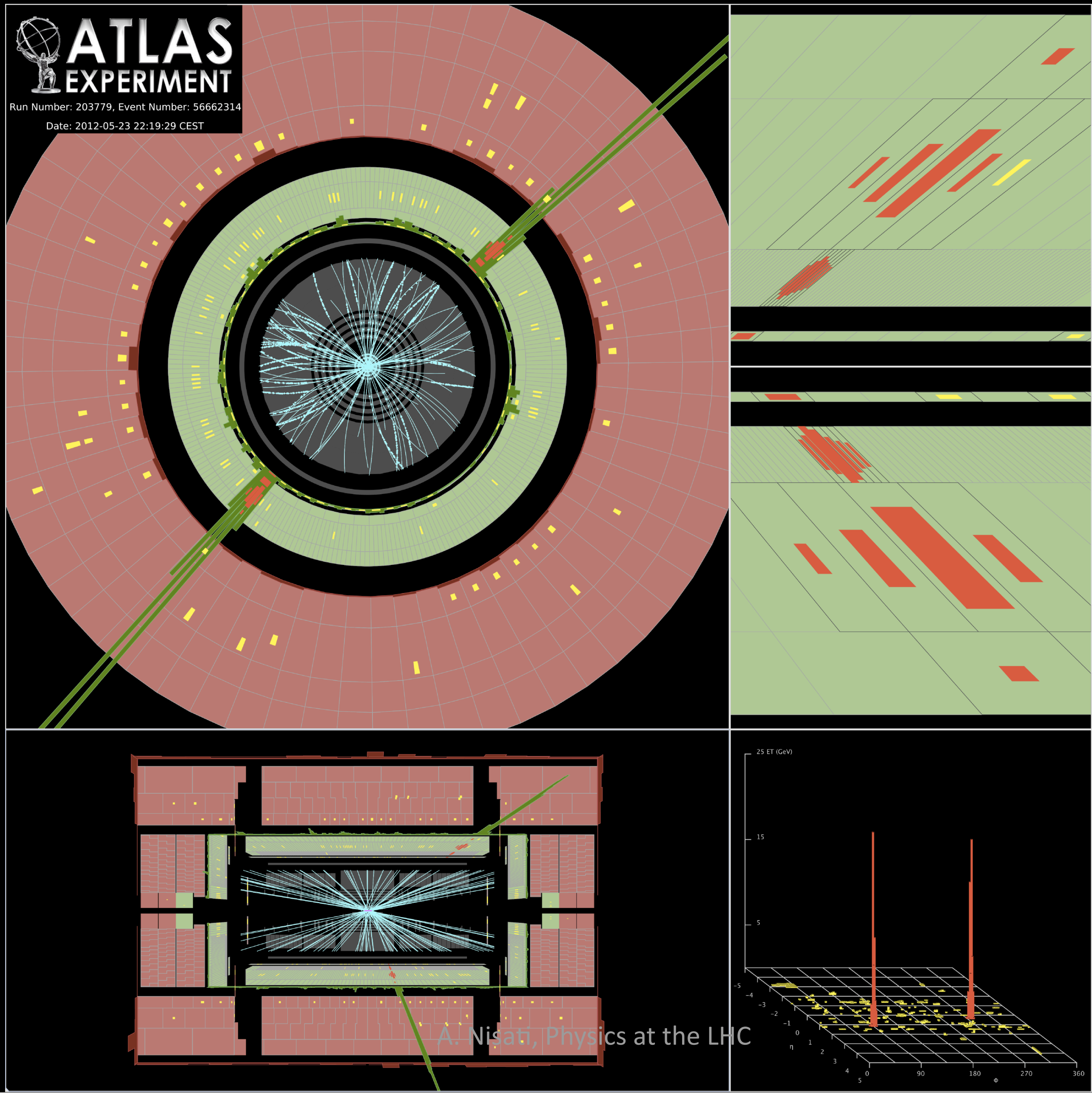


Events expected to be produced with √s= 8 TeV, L=1 fb^{-1}

m_H, GeV	WW→lνlν	ZZ→4l	γγ
120	159	1.9	54
150	485	5.9	22
300	124	5.7	0.05

Data sample analysed: L ~4.8 (2011) + 5.9 fb^{-1}(2012)

H→γγ

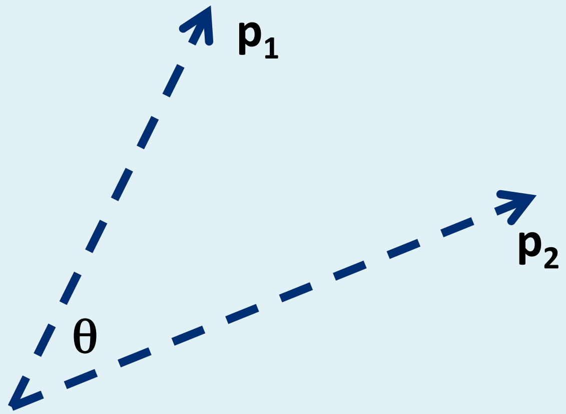

ATLAS
EXPERIMENT
Run Number: 203779, Event Number: 56662314
Date: 2012-05-23 22:19:29 CEST

H→γγ

Mass reconstruction

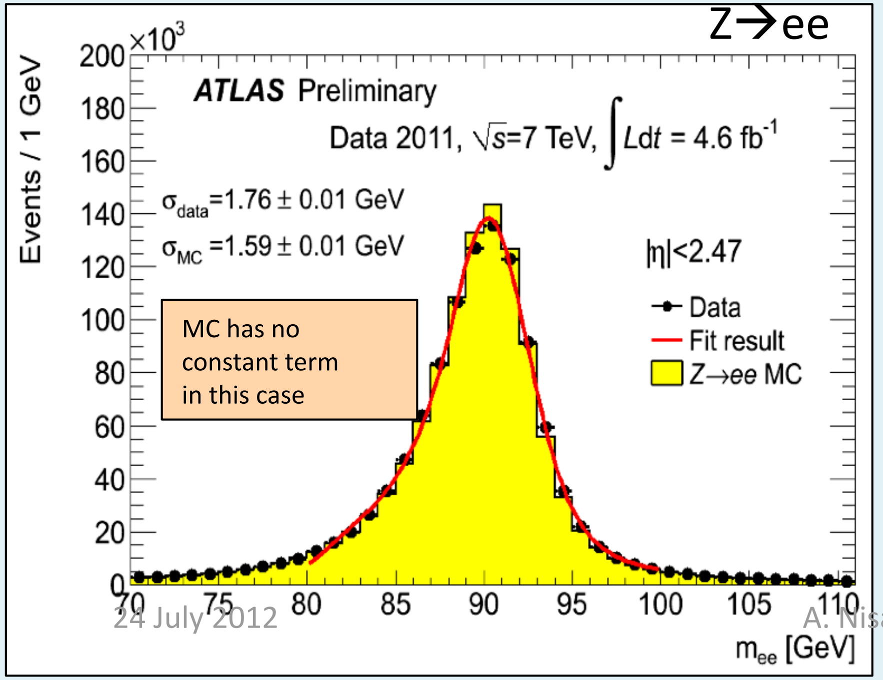
$m^2 = 2\mathbf{P_1 P_2}(1\text{-}\cos\vartheta)$

$\delta m/m = (1/\sqrt{2})(\delta P/P) \oplus (1/2)\, \delta\vartheta/(\tan\vartheta/2)$



It is important to measure the photon momentum in space with high resolution:

- → accurate measurement of the photon energy
- → accurate measurement of the photon direction of flight



Electron scale and resolution transported to photons using MC
(systematics few % from material effects)

Present understanding of calorimeter E response
(from Z, J/ψ → ee, W→ eν data and MC):

- **Energy scale at m_Z known to ~ 0.5%**
- **Linearity better than 1% (over few GeV-few 100 GeV)**
- **"Uniformity" (constant term of resolution):** 1% (barrel) -1.7 % (end-cap)

$H \rightarrow \gamma\gamma$

Mass reconstruction

$m^2 = 2P_1P_2(\mathbf{1\text{-}cos\vartheta})$

$\delta m/m = (1/\sqrt{2})(\delta P/P) \oplus (1/2)\, \delta\vartheta/(\tan\vartheta/2)$

It is important to measure the photon momentum in space with high resolution:

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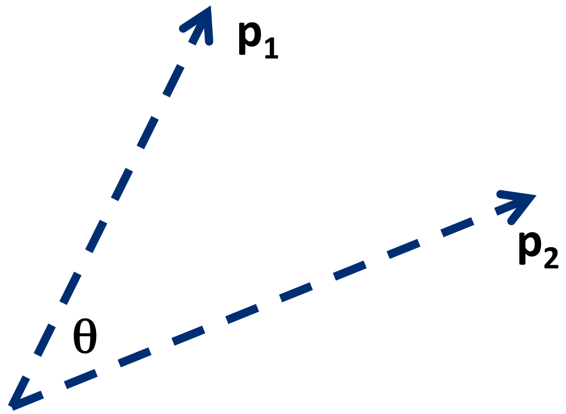
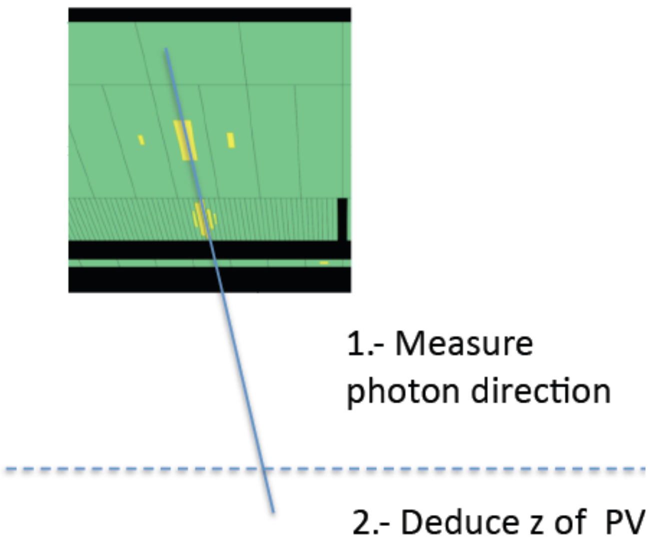
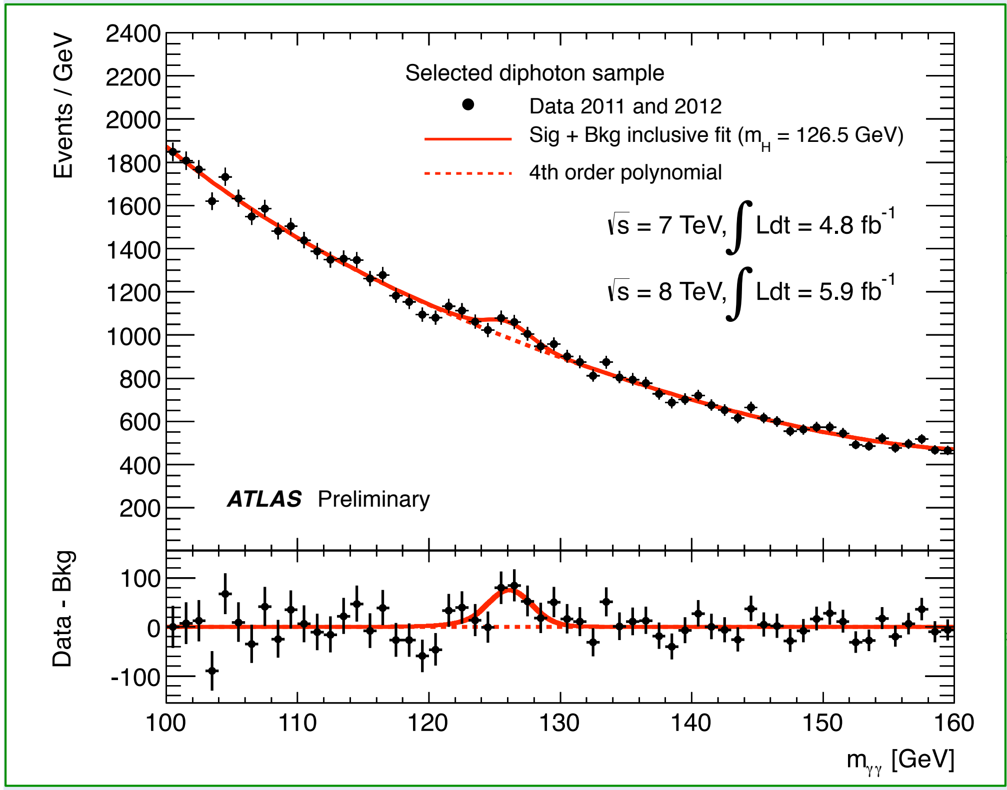


- ATLAS:
  - high energy resolution
  - Measure the photon direction using the longitudinal segmentation of the LAr calorimeter, and fit the $\gamma\gamma$ production vertex using the pp beam line



- CMS:
  - very high energy resolution
  - Measure the photon direction using the impact point measured by the crystal calorimeter, and the hard-scattering proton-proton vertex ➔ requires correct vertex identification in presence of large pile-up

H→γγ: results



# of events selected: 35271

m_H = 126.5 GeV

Category	σ_{CB} [GeV]	FWHM [GeV]	Observed [N_{evt}]	S [N_{evt}]	B [N_{evt}]
Inclusive	1.63	3.87	3693	100.4	3635
Unconverted central, low p_{Tt}	1.45	3.42	235	13.0	215
Unconverted central, high p_{Tt}	1.37	3.23	15	2.3	14
Unconverted rest, low p_{Tt}	1.57	3.72	1131	28.3	1133
Unconverted rest, high p_{Tt}	1.51	3.55	75	4.8	68
Converted central, low p_{Tt}	1.67	3.94	208	8.2	193
Converted central, high p_{Tt}	1.50	3.54	13	1.5	10
Converted rest, low p_{Tt}	1.93	4.54	1350	24.6	1346
Converted rest, high p_{Tt}	1.68	3.96	69	4.1	72
Converted transition	2.65	6.24	880	11.7	845
2-jets	1.57	3.70	18	2.6	12

p_{Tt} is the diphoton transverse momentum orthogonal to the diphoton thrust axis in the transverse plane

Photon reconstruction and identification efficiency: 65%(95%) for 25(80) GeV p_T

Overall Higgs boson selection efficiency: ~38%

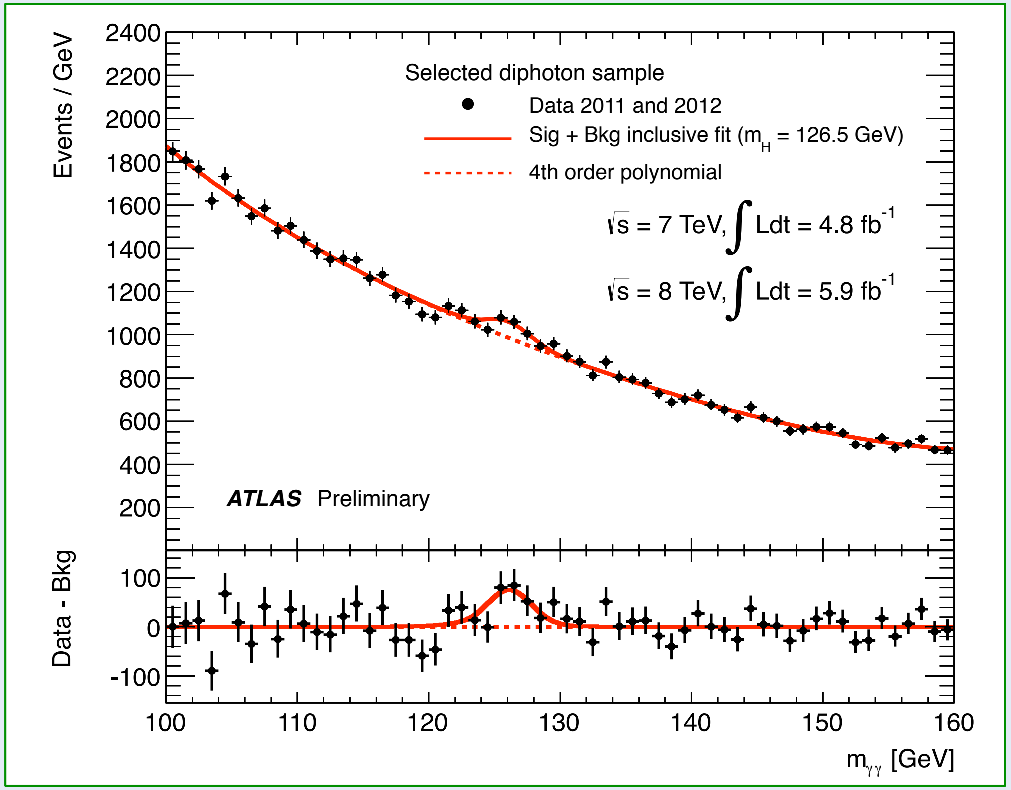
$\sqrt{s}$	m_H	$\mathcal{B}(H \to \gamma\gamma)$	$\sigma(pp \to H)$	$\sigma(gg \to H)$	σ_{VBF}
7 TeV	125 GeV	2.3×10^{-3}	17.5 pb	15.3 pb	1.2 pb
8 TeV	125 GeV	2.3×10^{-3}	22.3 pb	19.5 pb	1.6 pb

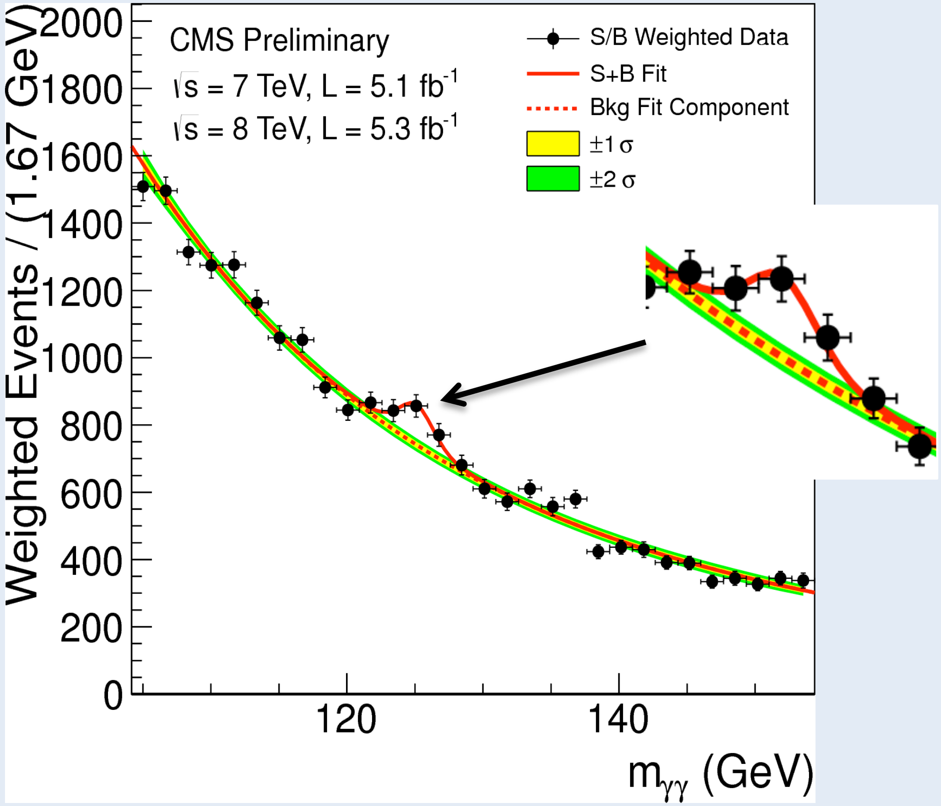
Background composition

$\sqrt{s}$	$\gamma\gamma$	γj	jj	Drell-Yan
7 TeV	(78 ± 4) %	(19 ± 3) %	(2 ± 1) %	(1.4 ± 0.1) %
8 TeV	(74 ± 3) %	(22 ± 2) %	(3 ± 1) %	(0.8 ± 0.1) %

γj + jj << γγ irreducible (purity ~ 76%)

H→γγ: ATLAS and CMS results





Background model is extracted **directly from data**, both in ATLAS and CMS.

- **Different analytical functions are studied to describe the background invariant mass distribution. Some examples:**
  - **exponential function**
  - **polynomial function**
  - **5th order polynomial function**

Sum of mass distributions for each event class, weighted by S/B

B is integral of background model over a constant signal fraction interval

In order to maximize the sensitivity to the search the events are classified in categories, and analyzed independently

H→γγ: systematic uncertainties

ATLAS

Signal yield	
Theory	**~ 20%**
Photon efficiency	**~ 10%**
Background model	**~ 10%**
Categories migration	
Higgs pT modeling	**Up to ~ 10%**
Conv/uncovertyed γ	**Up to ~ 6%**
Jet Energy Scale	**Up to ~ 20% (2j/ VBF)**
Underlying event	**Up to ~ 20% (2j/ VBF)**
photon	
H→γγ mass resolution	**~ 14%**
Photon Energy scale	**~ 0.6%**

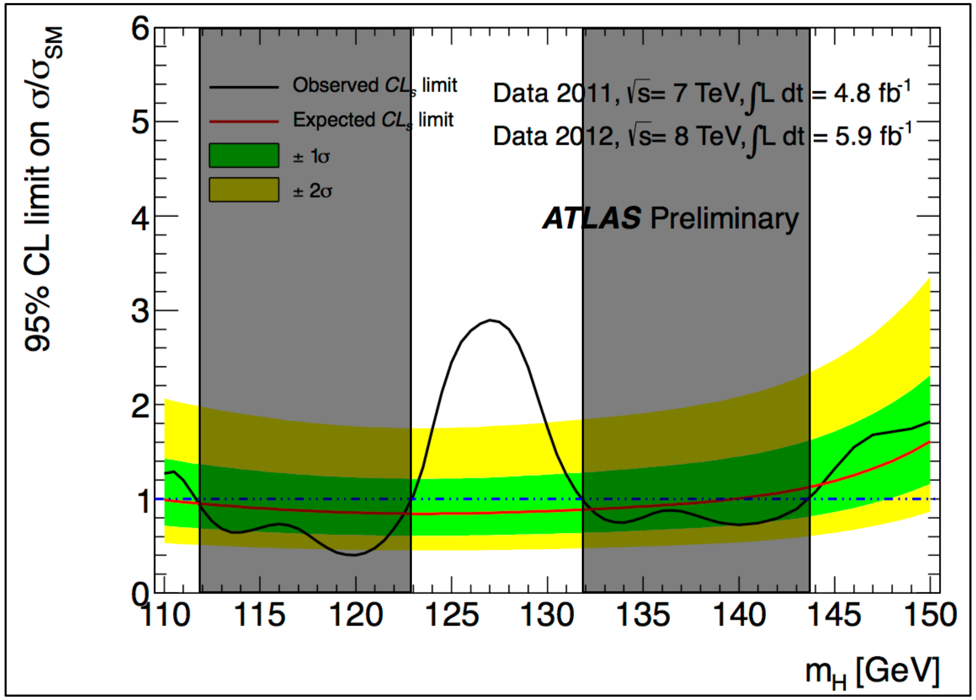
Category	Parametrization	Uncertainty [N_{evt}] $\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV
Inclusive	4th order pol.	7.3	10.6
Unconverted central, low p_{Tt}	Exp. of 2nd order pol.	2.1	3.0
Unconverted central, high p_{Tt}	Exponential	0.2	0.3
Unconverted rest, low p_{Tt}	4th order pol.	2.2	3.3
Unconverted rest, high p_{Tt}	Exponential	0.5	0.8
Converted central, low p_{Tt}	Exp. of 2nd order pol.	1.6	2.3
Converted central, high p_{Tt}	Exponential	0.3	0.4
Converted rest, low p_{Tt}	4th order pol.	4.6	6.8
Converted rest, high p_{Tt}	Exponential	0.5	0.7
Converted transition	Exp. of 2nd order pol.	3.2	4.6
2-jets	Exponential	0.4	0.6

Background modeling uncertainties

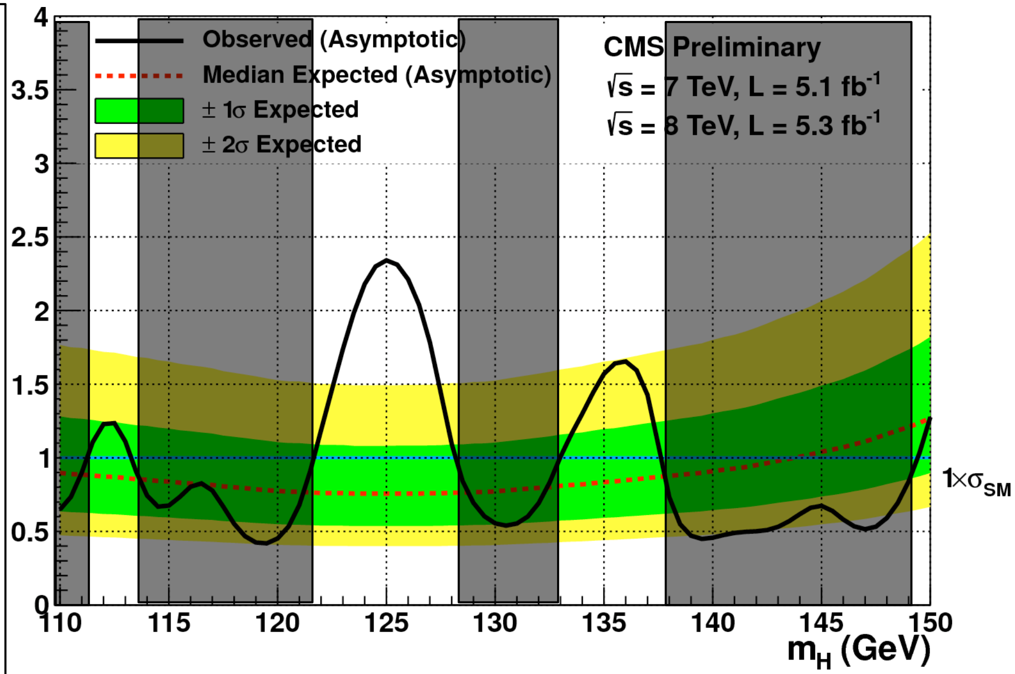
Fit background distribution predicted by RESBOS with the chosen background parametrization adopted to describe the data; Max deviation of background model from expected background distribution taken as systematic uncertainty

H→γγ: exclusion limits

ATLAS



CMS



ATLAS

Excluded (95% CL):

112-122.5 GeV, 132-143 GeV

Expected: 110-139.5 GeV

CMS

Excluded (95% CL):

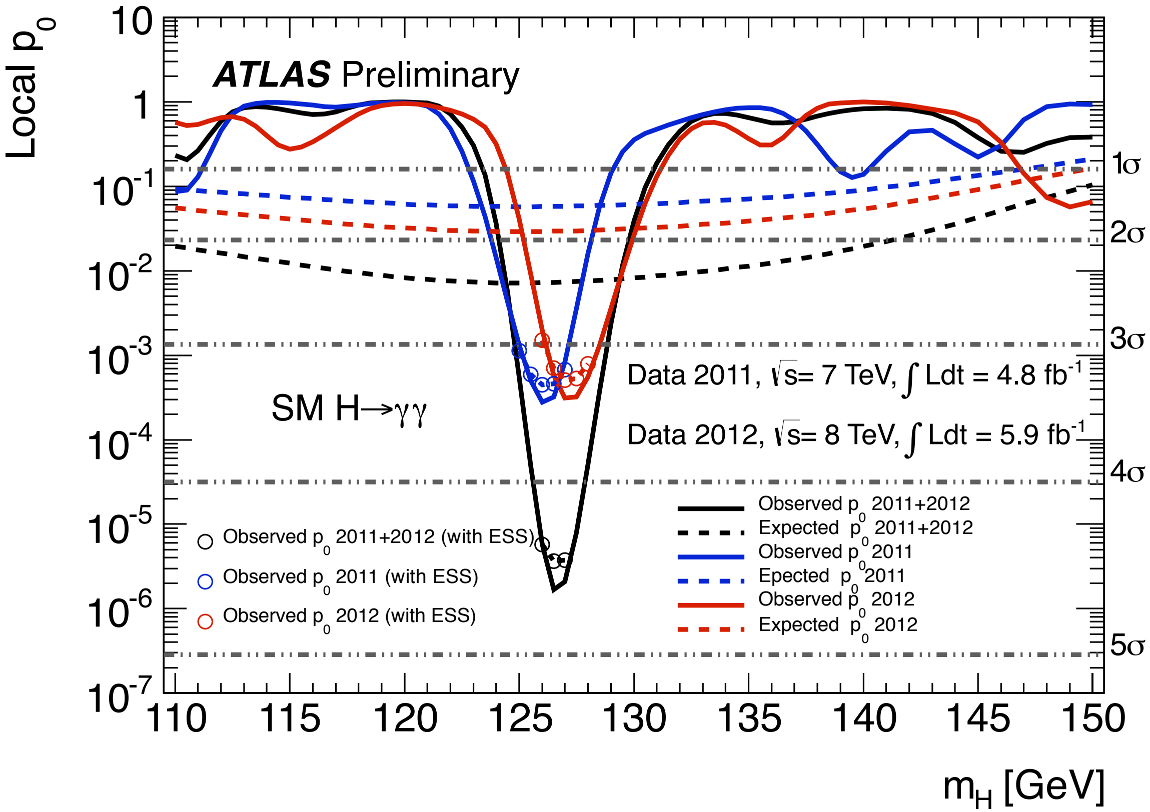
114-121, 129-132, 138-149 GeV

H→γγ: analysis of the excess

- We observe an excess of events in the mass interval between 122 and 132 GeV
- Analysis its consistency with a pure background fluctuation
  - Quite complex statistical analysis
  - In first approximation you can evaluate the statistical significance of the event excess by evaluating:

    $\mathbf{N\sigma = (N_{data} - N_{backg})/\sqrt{N_{backg}}}$
  - But this does not use the full information available:
    - Shape od the excess
    - excess observed in different categories

H→γγ: analysis of the excess



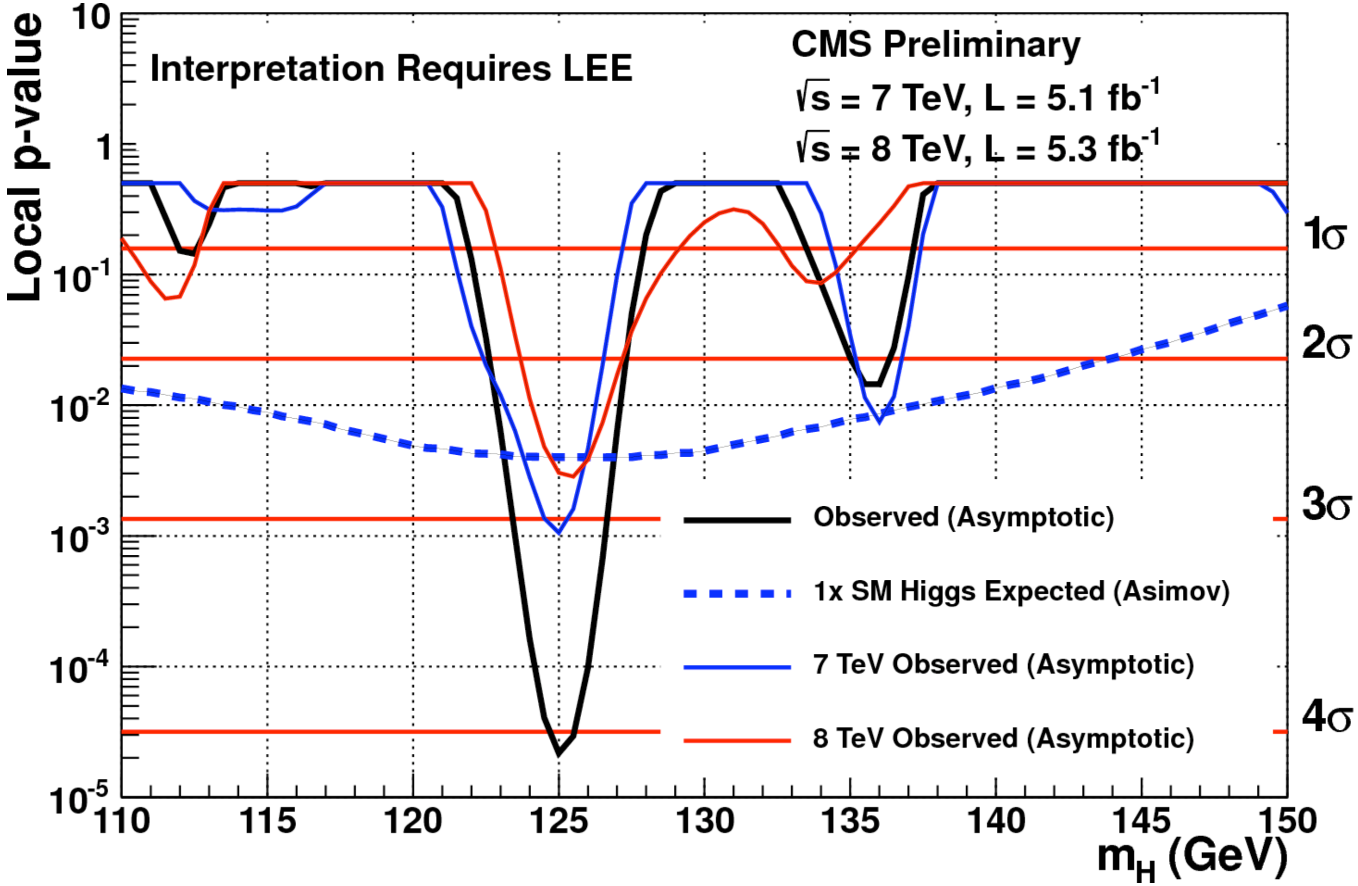
p_0 is the probability for the background to produce a fluctuation at least as large as the one observed in data (and in our case assumes that the relative signal strength between event classes follows SM predictions)

Points indicate impact of 0.6% uncertainty on photon energy scale: ~ 0.1 sigma

Data sample	m_H of max deviation	local p-value	local significance	expected from SM Higgs
2011	126 GeV	3×10^{-4}	3.5 σ	1.6 σ
2012	127 GeV	3×10^{-4}	3.4 σ	1.9 σ
2011+2012	126.5 GeV	2×10^{-6}	4.5 σ	2.4 σ

Global 2011+2012 (including LEE over 110-150 GeV range): 3.6 σ

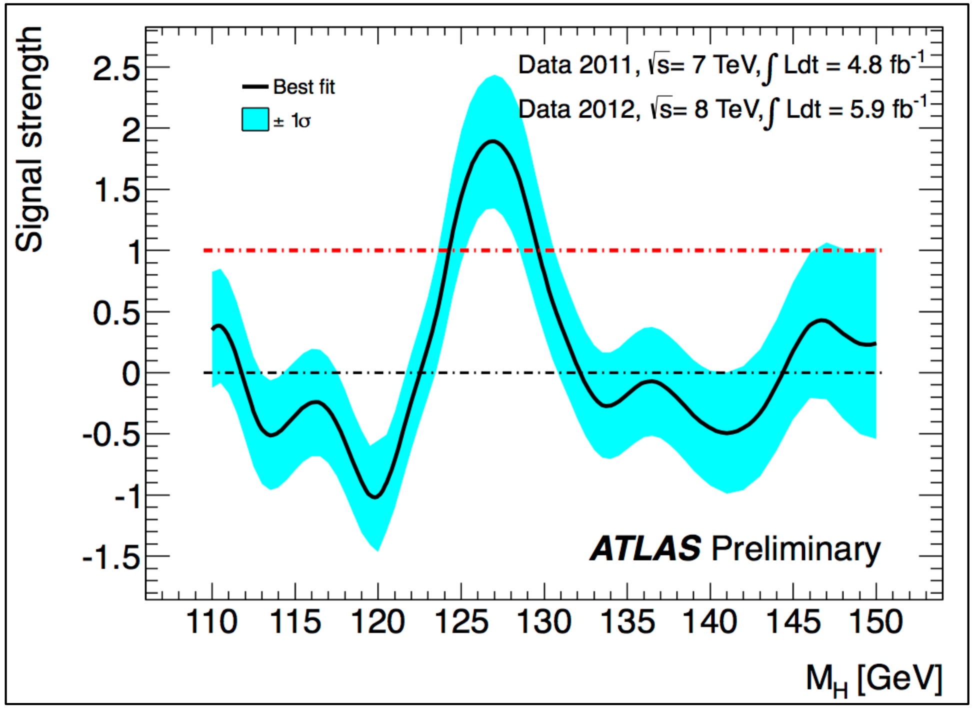
H→γγ: analysis of the excess

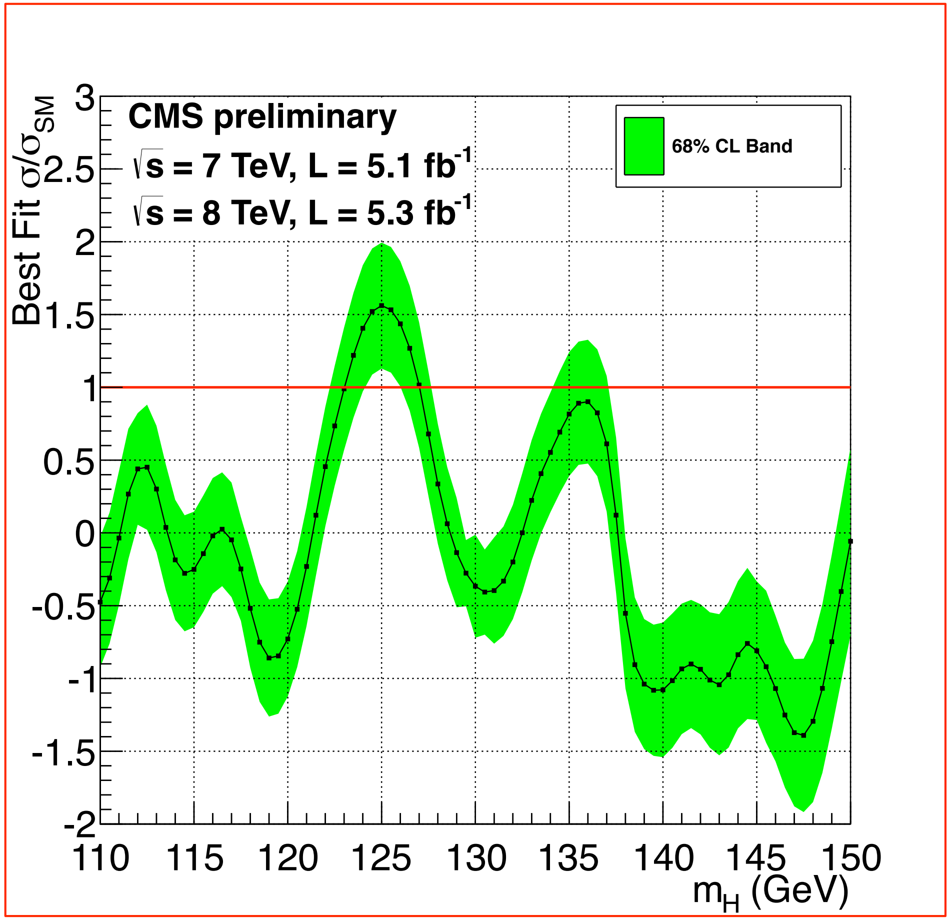


- Minimum local p-value at 125 GeV with a local significance of 4.1 σ
- Similar excess in 2011 and 2012
- Independent cross check analyses give similar results
- Global significance in the full search range (110-150 GeV) 3.2 σ

H→γγ: signal strength

Fit signal strength and normalized to SM Higgs expectation at given m_H (μ)

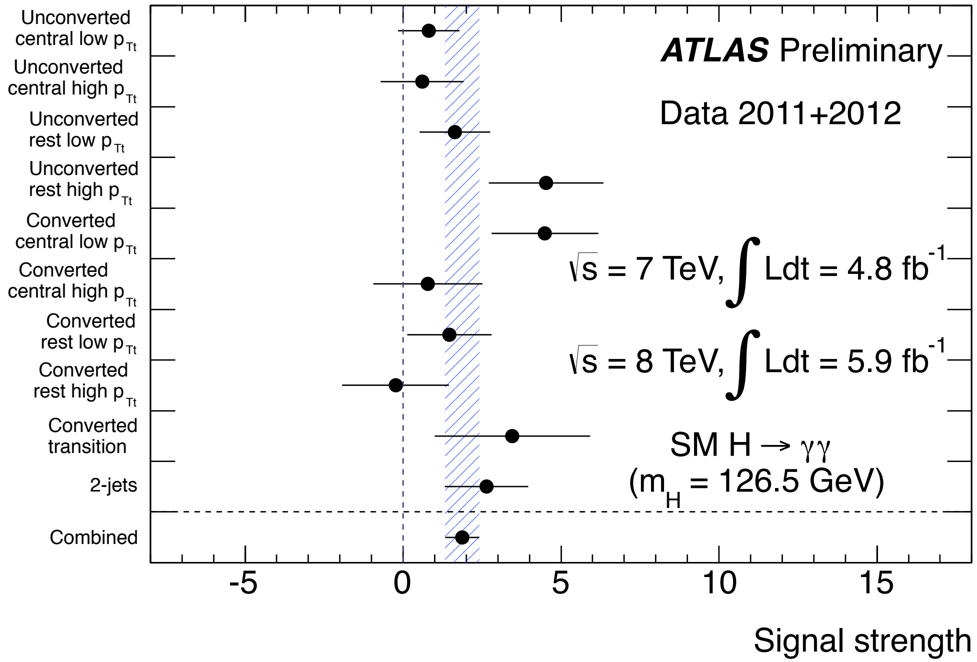


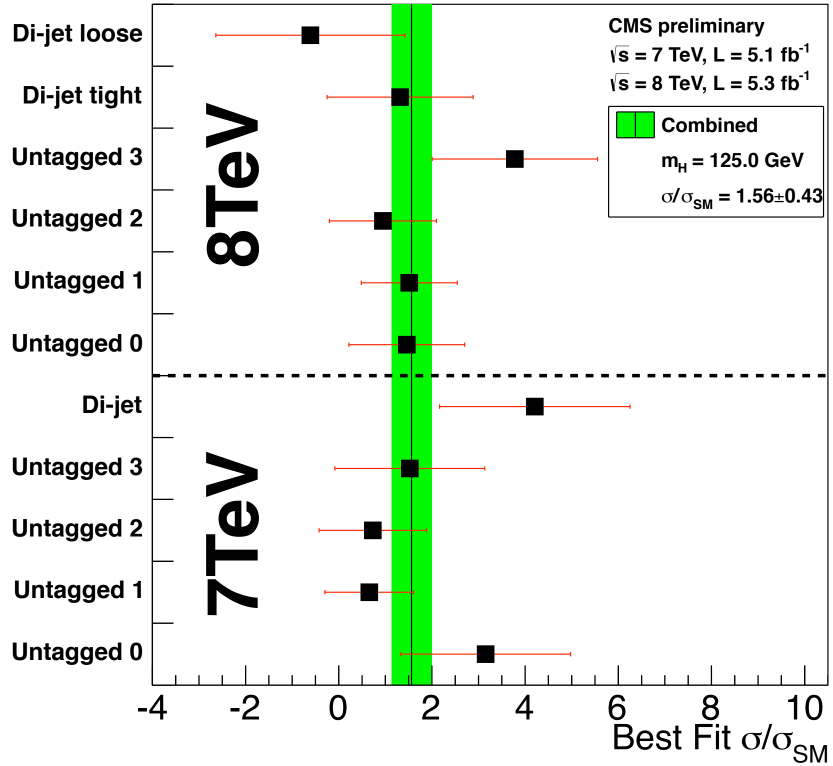


ATLAS: Best-fit value at 126.5 GeV: μ=1.9 ± 0.5

CMS: Combined best fit signal strength σ/σ_{SM} = 1.56±0.43 x SM, consistent with SM.

H→γγ: signal strength



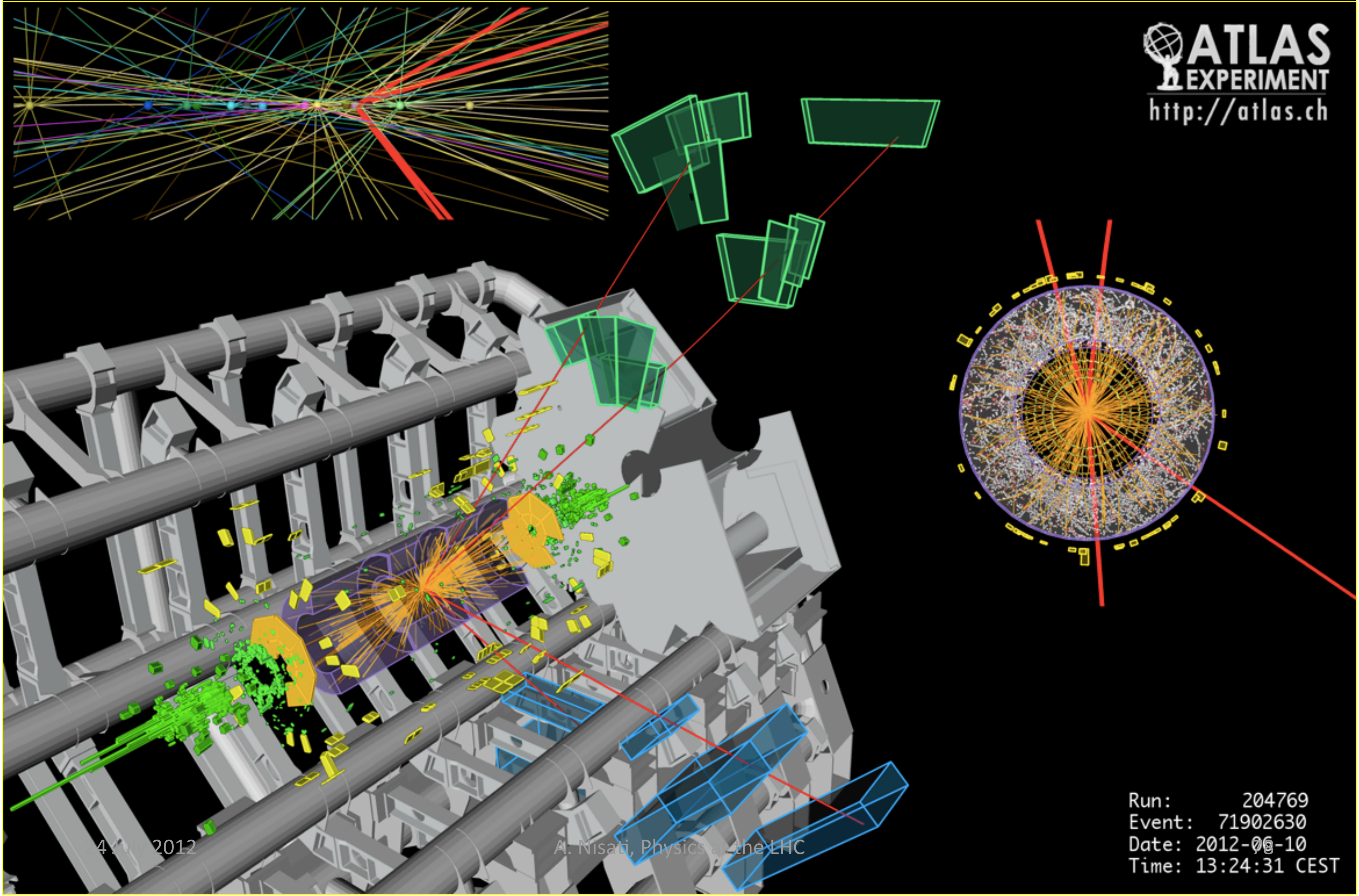


Categories in agreement within uncertainties

ATLAS: Best-fit value at 126.5 GeV: $\mu = 1.9 \pm 0.5$

CMS: Combined best fit signal strength σ/σ_{SM} = 1.56±0.43 x SM, consistent with SM.

H→ZZ(*)→ 4 leptons



$H \rightarrow ZZ^{(*)} \rightarrow$ 4 leptons

- **Small cross section × BR: $\sigma \times BR \sim$ 2-5 fb**
- However:
  - **mass can be fully reconstructed** → events would cluster in a (narrow) peak
  - **large signal-to-background ratio**: S/B ~ 1
- **Event Selection:**
  - **4 leptons: $p_T^{1,2,3,4}$ > 20,20,7,7 GeV;**
  - **$m_{12} = m_Z \pm 15$ GeV; m_{34} > 15-60 GeV (depending on m_H) [ATLAS]**
- **Main backgrounds:**
  - $ZZ^{(*)}$ (irreducible)
  - $m_H < 2m_Z$: Zbb, Z+jets, tt with two leptons from *b/q-jets* → *lepton*
- Suppressed with isolation and impact parameter cuts on two softest leptons
- Signal acceptance x efficiency: ~ 15 % for $m_H \sim$ 125 GeV

Crucial experimental aspects:

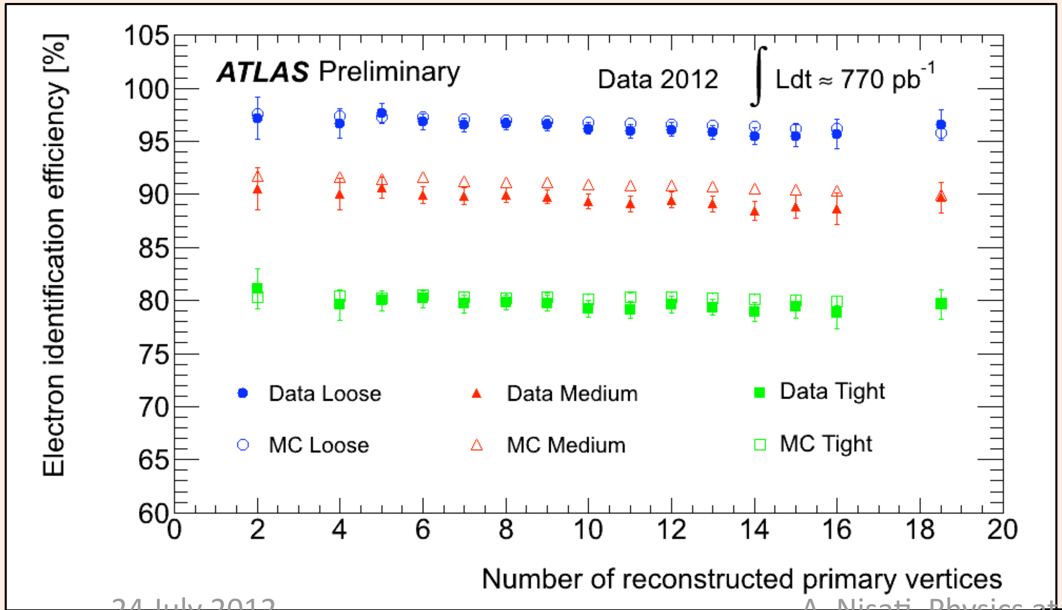
- **High lepton reconstruction and identification efficiency down to lowest p_T**
- **Good lepton energy/momentum resolution**
- **Good control of reducible backgrounds (Zbb, Z+jets, tt) in low-mass region:**
  - **→ cannot rely on MC alone (theoretical uncertainties, b/q-jet → lepton modeling, ..)**
  - **→ need to compare MC to data in background-enriched control regions (but: low statistics ..)**
- **→ Conservative/stringent p_T and m(ll) cuts used at this stage**

ATLAS: Electron and muon performance

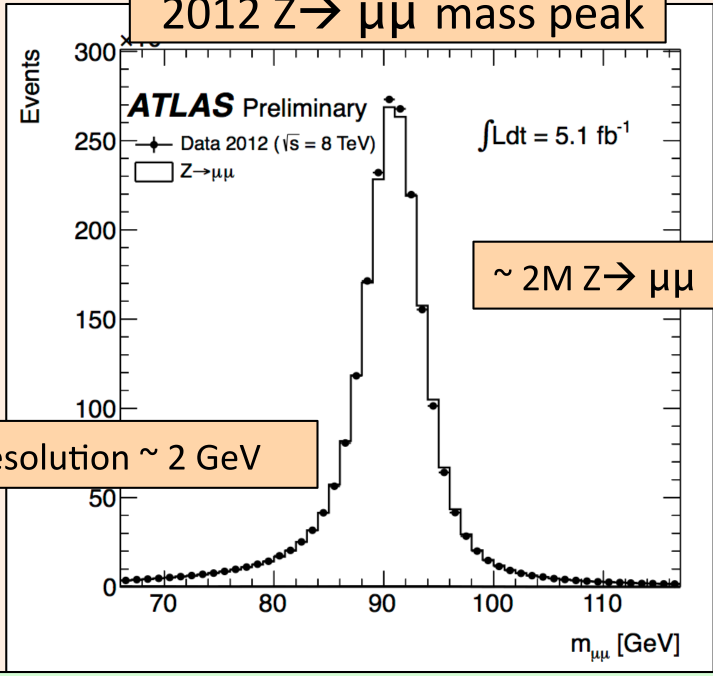
Identification efficiency from
J/ψ → ll, W → lν, Z→ ll data samples

Crucial to understand low-p_T electrons (affected by material) with data

Variation of electron efficiency with pile-up (cuts not re-tuned yet) well modeled by simulation: from Z→ ee data and MC samples



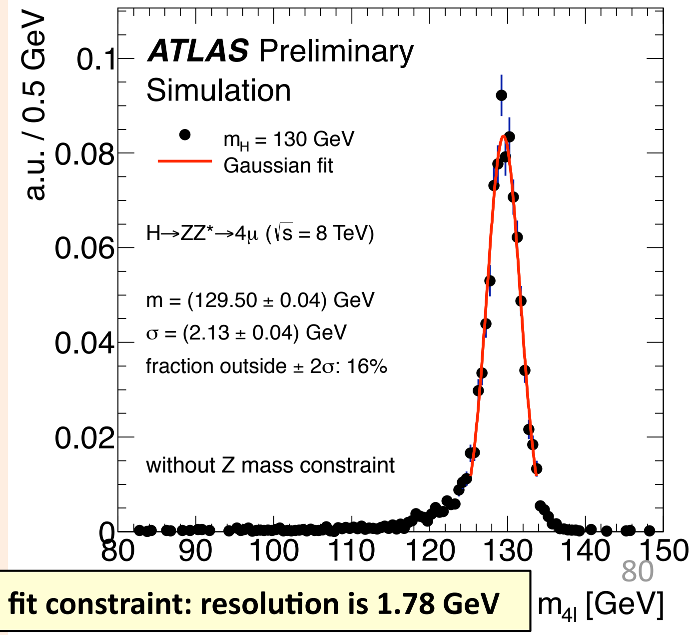
2012 Z→ μμ mass peak



~ 2M Z→ μμ

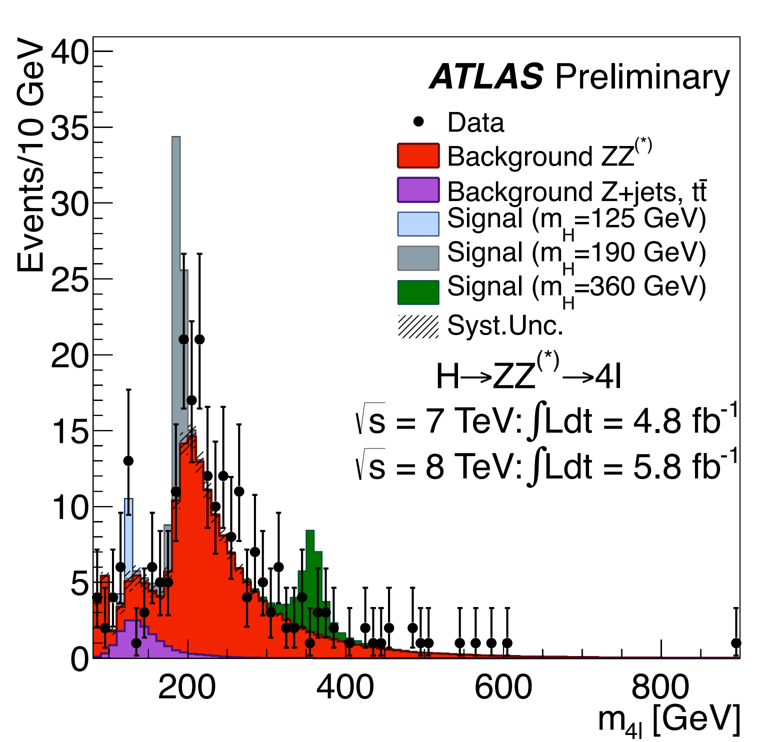
Mass resolution ~ 2 GeV

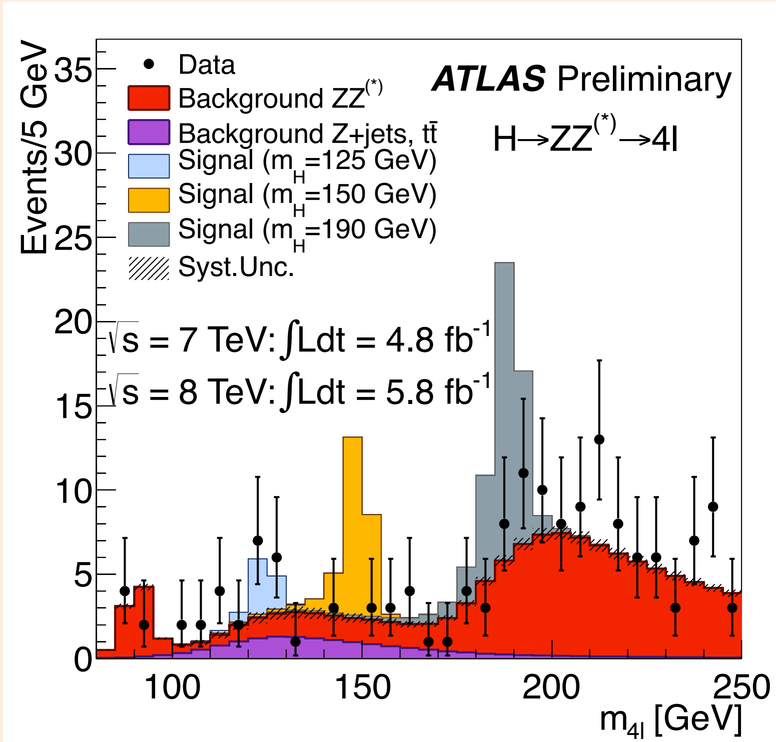
H→ 4μ mass resolution: 2.13 GeV
Event fraction in ±2σ: ~ 84%



With mass fit constraint: resolution is 1.78 GeV

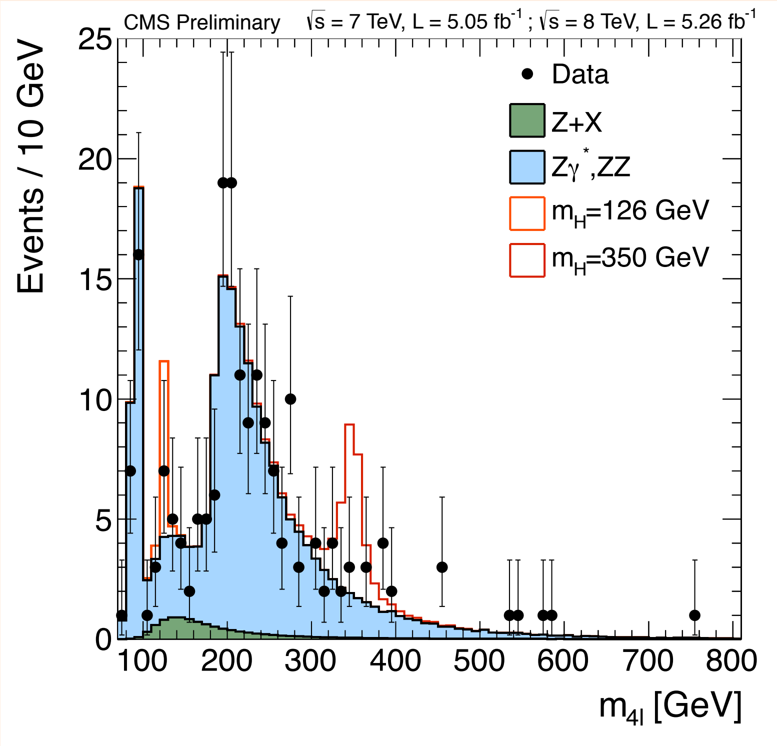
H→ZZ$^{(*)}$→ 4 leptons: ATLAS

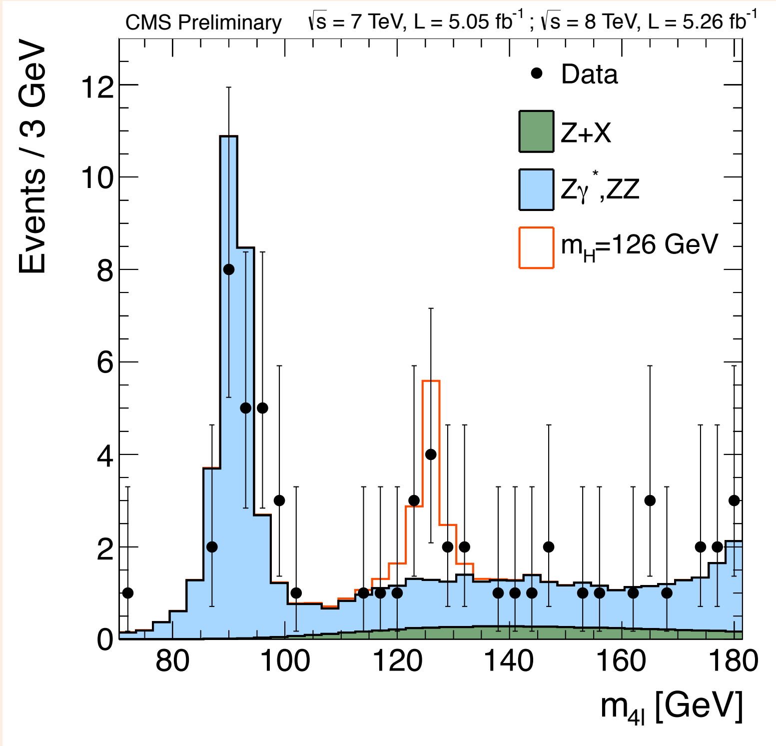




Dataset	2011	2012	2011+2012
Expected background	2.1 ± 0.3	2.9 ± 0.4	5.1 ± 0.8
Expected signal	2.0 ± 0.3	3.3 ± 0.5	5.3 ± 0.8
data	4	9	13

H→ZZ$^{(*)}$→ 4 leptons: CMS

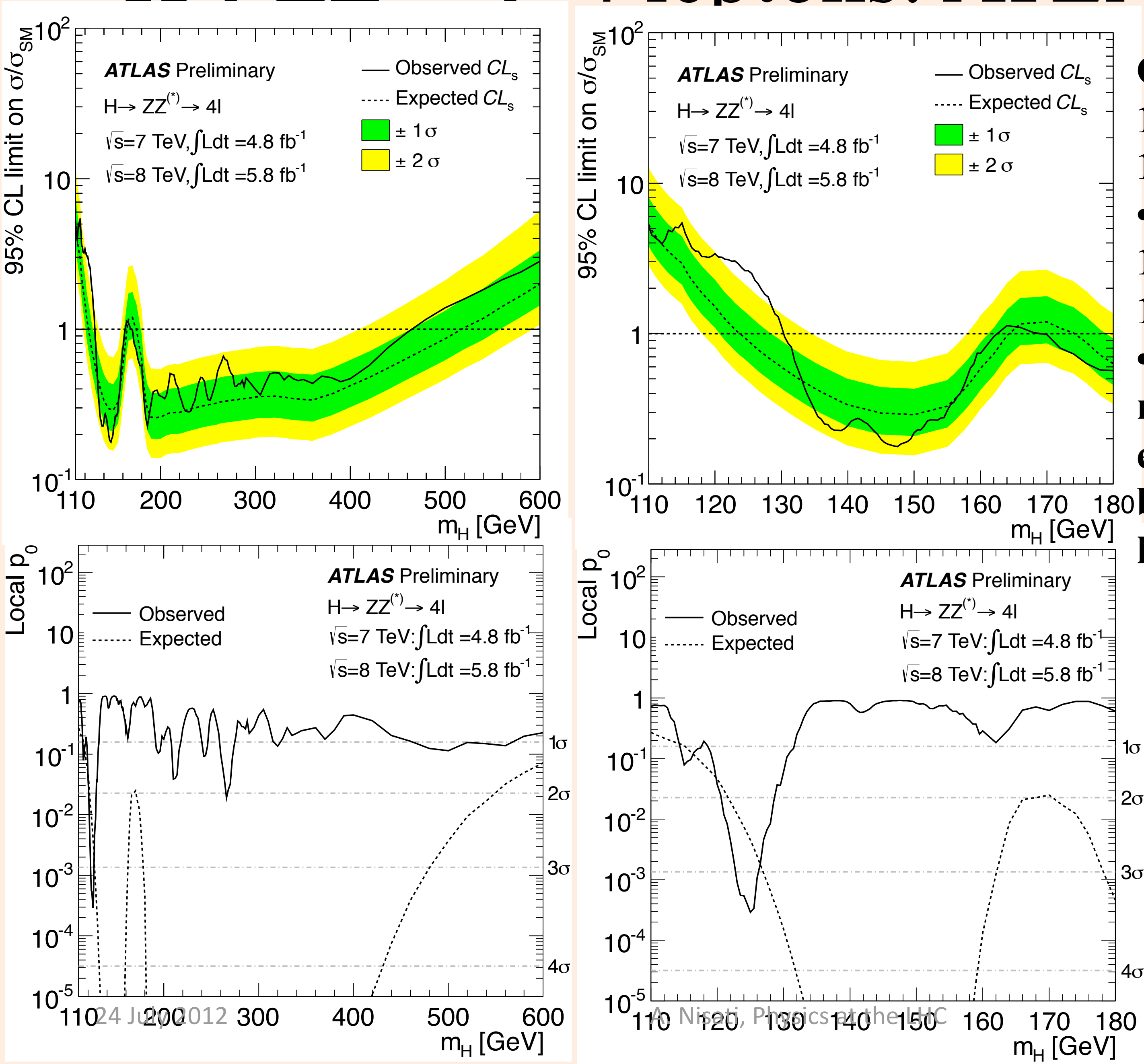




Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.5 ± 1.0
Z+X	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds	$3.9^{+1.1}_{-0.8}$	$6.6^{+0.9}_{-0.8}$	$9.5^{+2.0}_{-1.6}$	$19.9^{+2.4}_{-2.0}$
$m_H = 120\,\mathrm{GeV}$	0.8 ± 0.2	1.6 ± 0.3	1.9 ± 0.5	4.4 ± 0.6
$m_H = 126\,\mathrm{GeV}$	1.5 ± 0.5	3.0 ± 0.6	3.8 ± 0.9	8.3 ± 1.2
$m_H = 130\,\mathrm{GeV}$	2.1 ± 0.7	4.1 ± 0.8	5.4 ± 1.3	11.6 ± 1.6
Observed	6	6	9	21

Mass window:
From 110 to 160 GeV

H→ZZ$^{(*)}$→ 4 leptons: ATLAS results

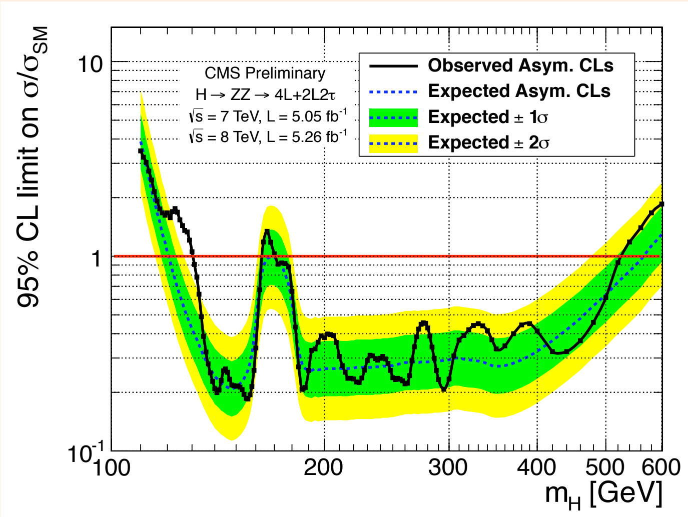


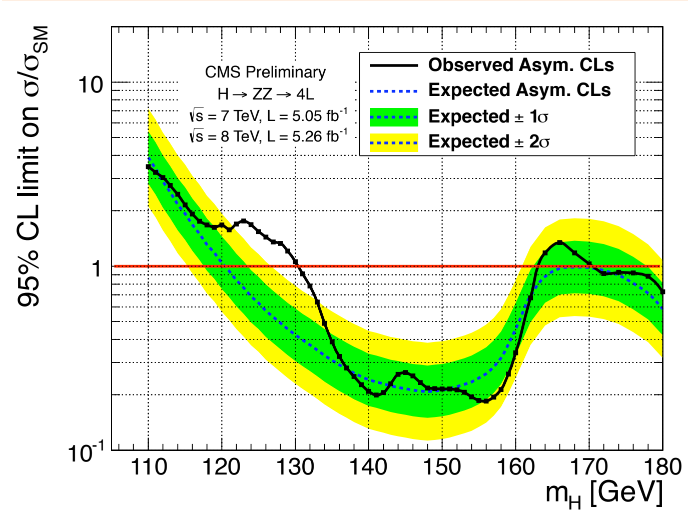
Observed exclusion :
131-162 GeV and
170 - 460 GeV

- **Expected exclusion :**
124-164 GeV and
176 - 500 GeV
- **For m_H ~120-130 GeV much weaker limit than expected in the background-only hypothesis**

- 7 TeV (2011): 2.3σ at 125 GeV, expected 1.5σ
- 8 TeV (2012): 2.7σ at 125.5 GeV, expected 2.1σ
- **Combined: 3.4σ at m_H=125 GeV, expected 2.6σ**

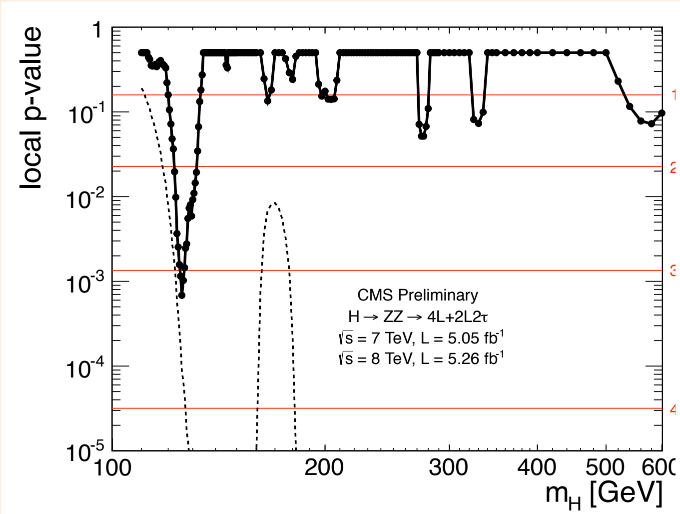
H→ZZ$^{(*)}$→ 4 leptons: CMS results

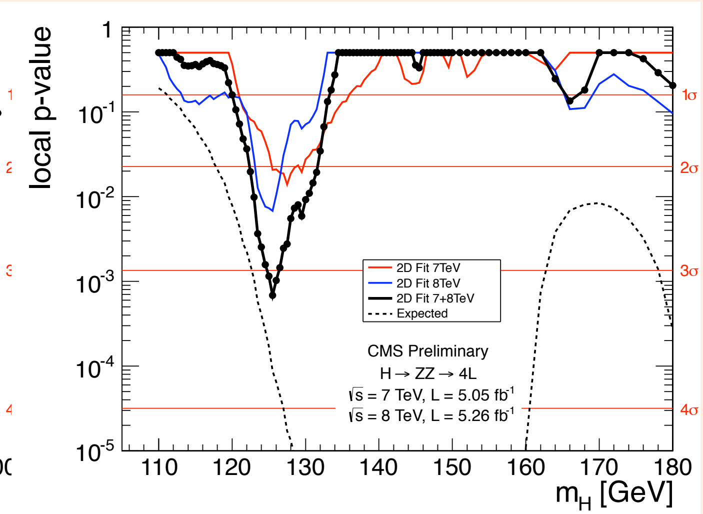




Observed exclusion : 131-162 GeV and 172-530 GeV

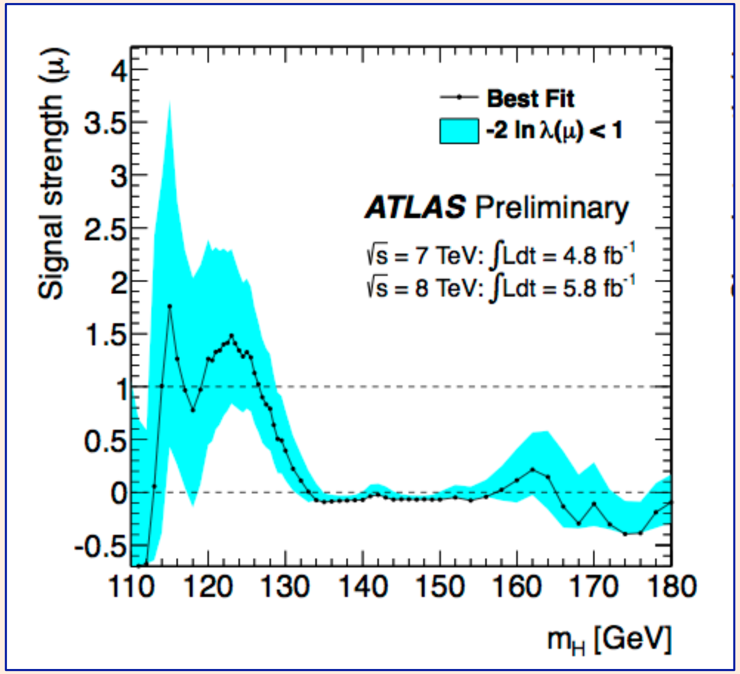
- **Expected exclusion : 121-550 GeV**
- **For m_H ~120-130 GeV much weaker limit than expected in the background-only hypothesis**



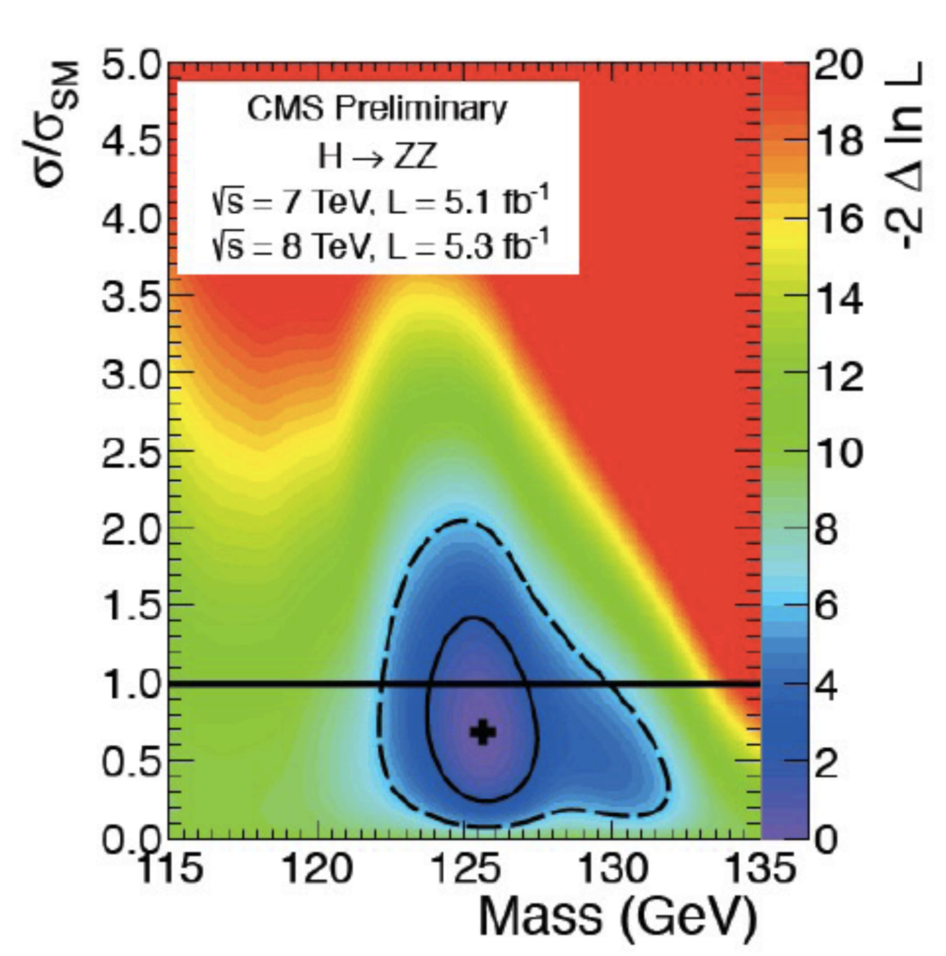


- **Combined local significance: 3.2σ at m_H=125.5 GeV, expected 3.8σ**

H→ZZ$^{(*)}$→ 4 leptons: signal strengths

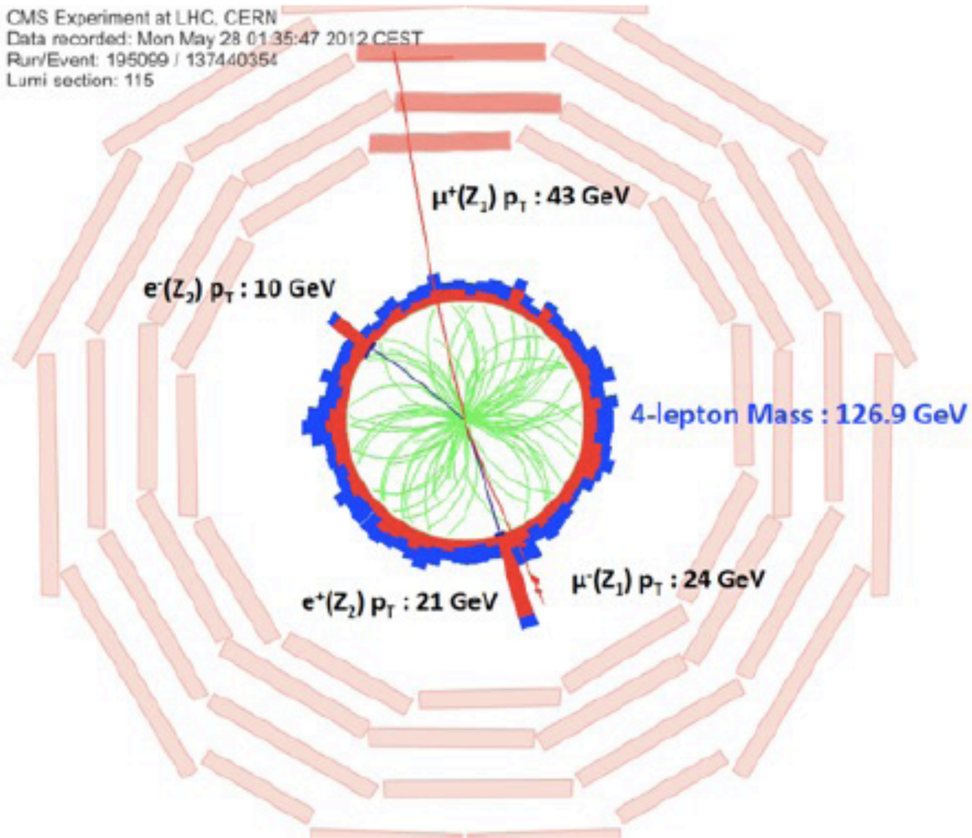


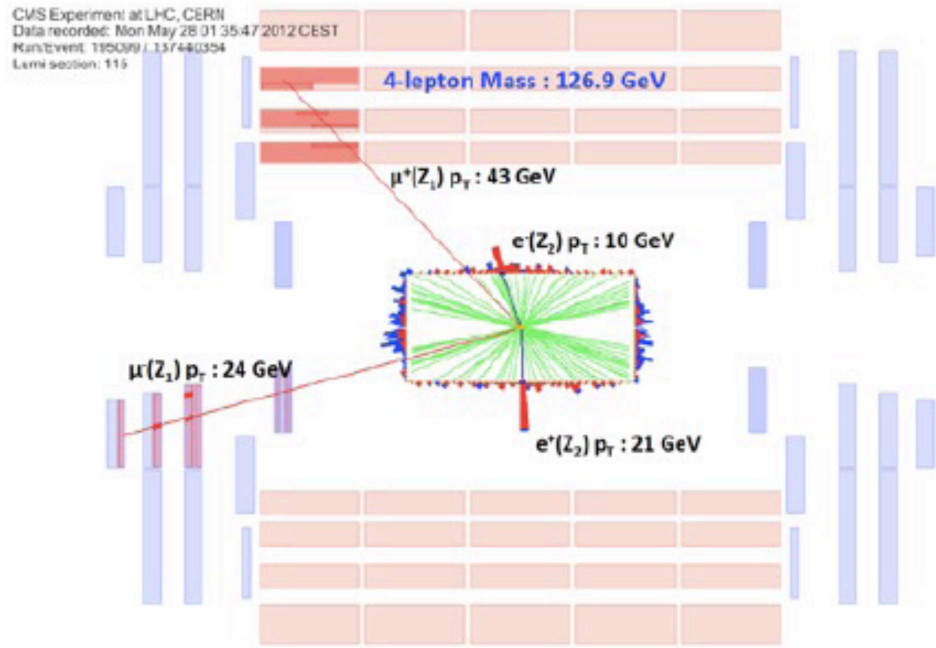
Best-fit value at 125 GeV: μ=1.3 ± 0.6

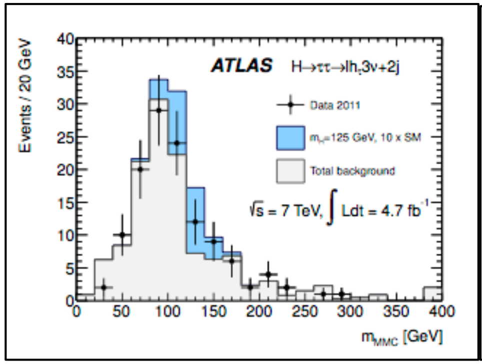


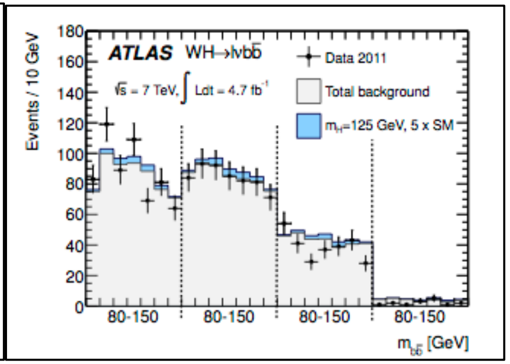
Likelihood scan performed on full dataset
Global minimum of likelihood:
M(4l) = 125.6 ± 1.2 GeV
μ = 0.7 ± 0.4 (signal strength)
Ellipses indicate 68% and 95% CL contours

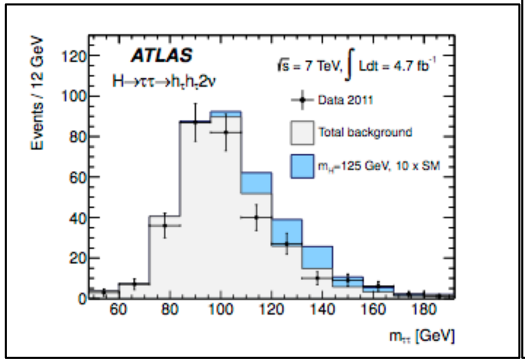
H→ZZ$^{(*)}$→ 4 leptons: a CMS event

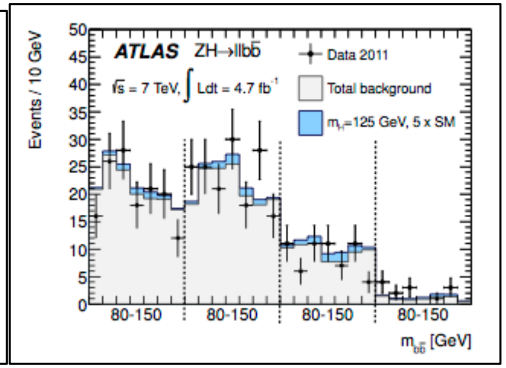








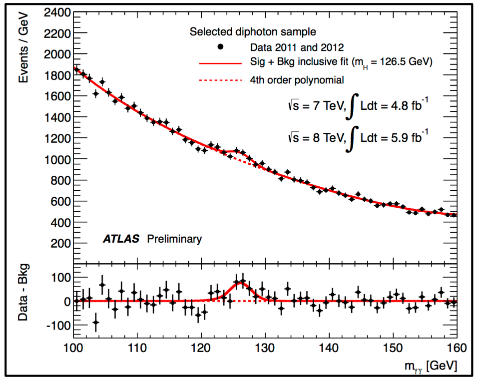


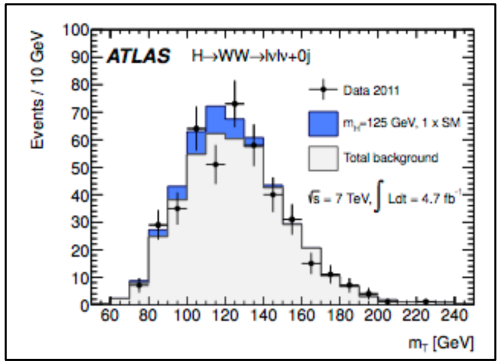


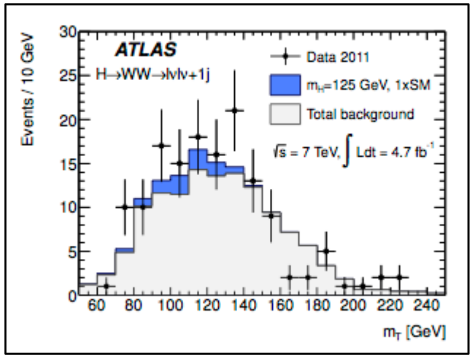
Many other channels have been studied with 2011 data or being studied with 2012 data

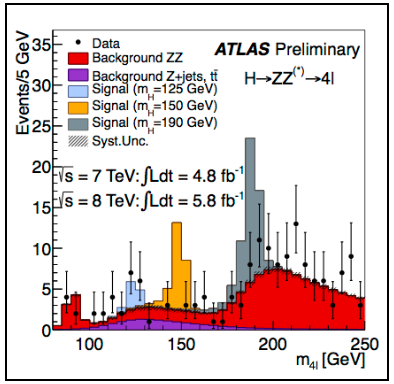
Combining all channels together:

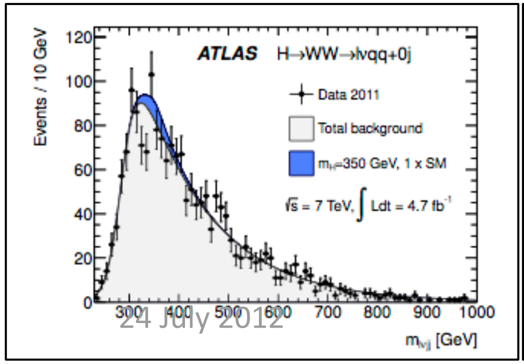
- ❑ H→ γγ, 4l: full 2011 and 2012 datasets (~ 10.7 fb^{-1}) and improved analyses
- ❑ all other channels (H→ WW$^{(*)}$→ lνlν, H→ ττ, WH→ lνbb, ZH→ llbb, ZH→ ννbb, ZZ → llνν, H→ ZZ → llqq; H→ WW→lνqq): full 2011 dataset (up to 4.9 fb^{-1})

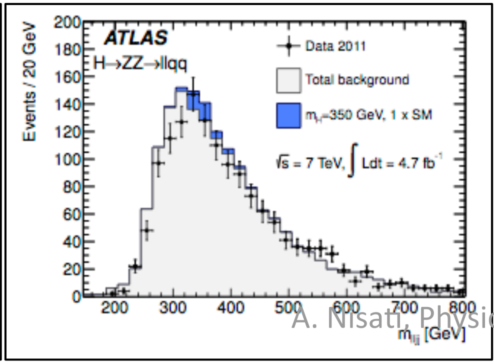


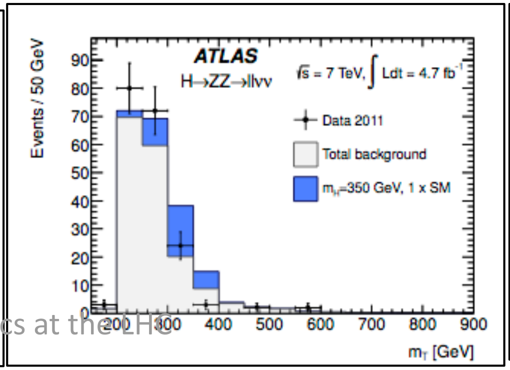


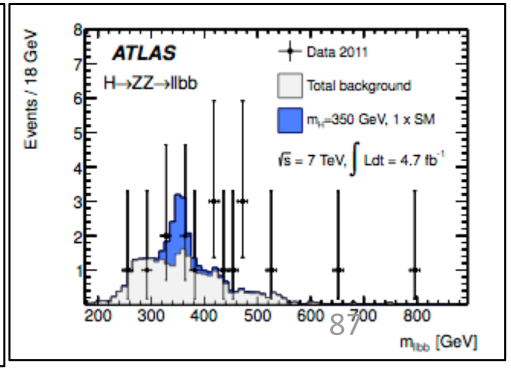








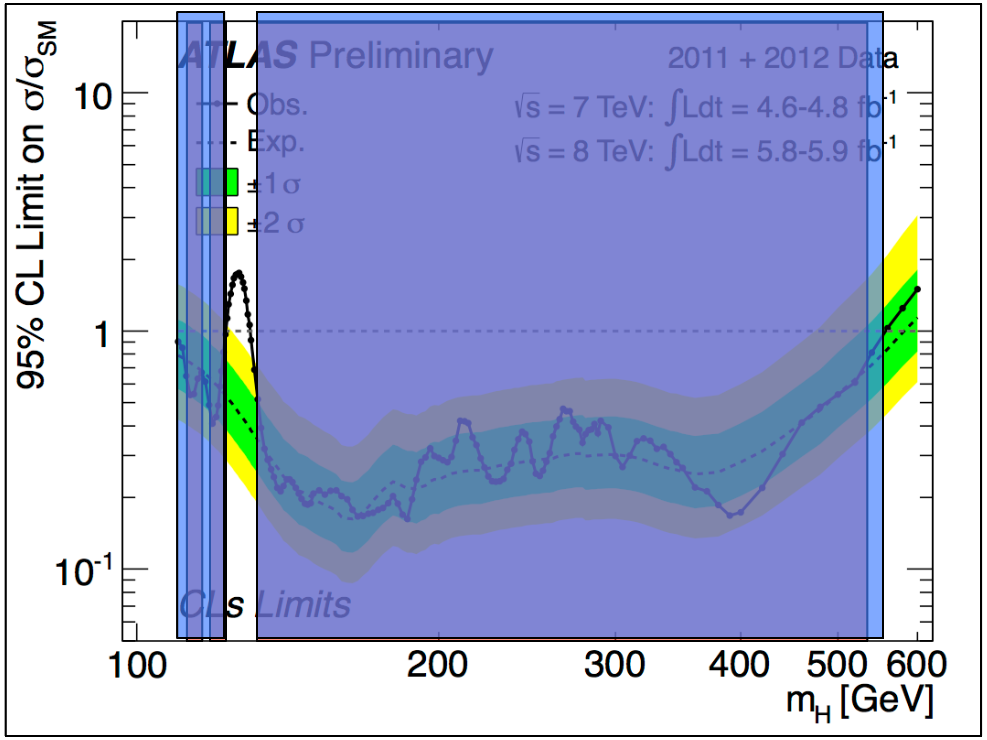


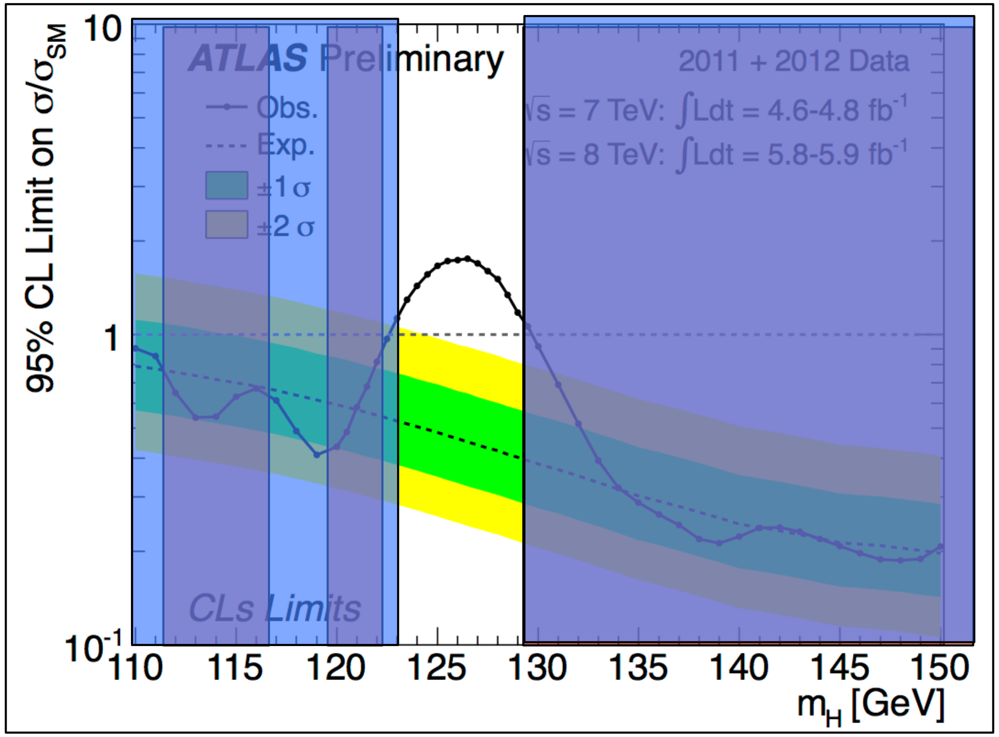


Combined results : ATLAS exclusion limits

Previous ATLAS results

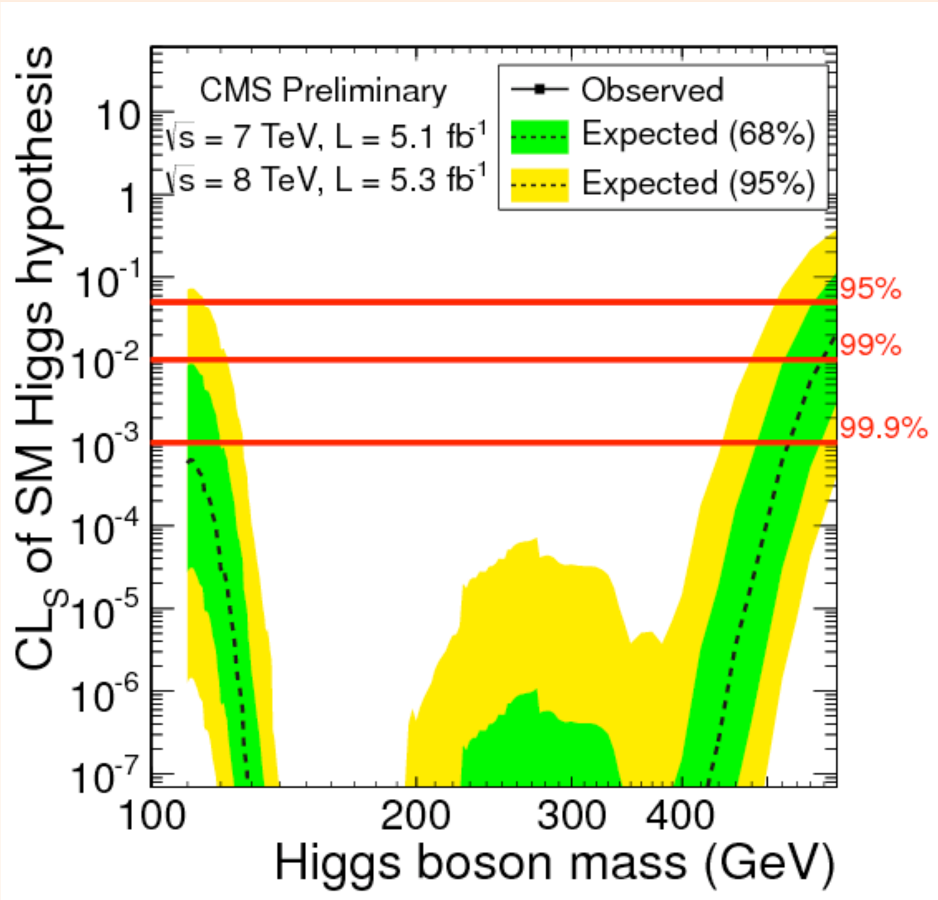
ATLAS today

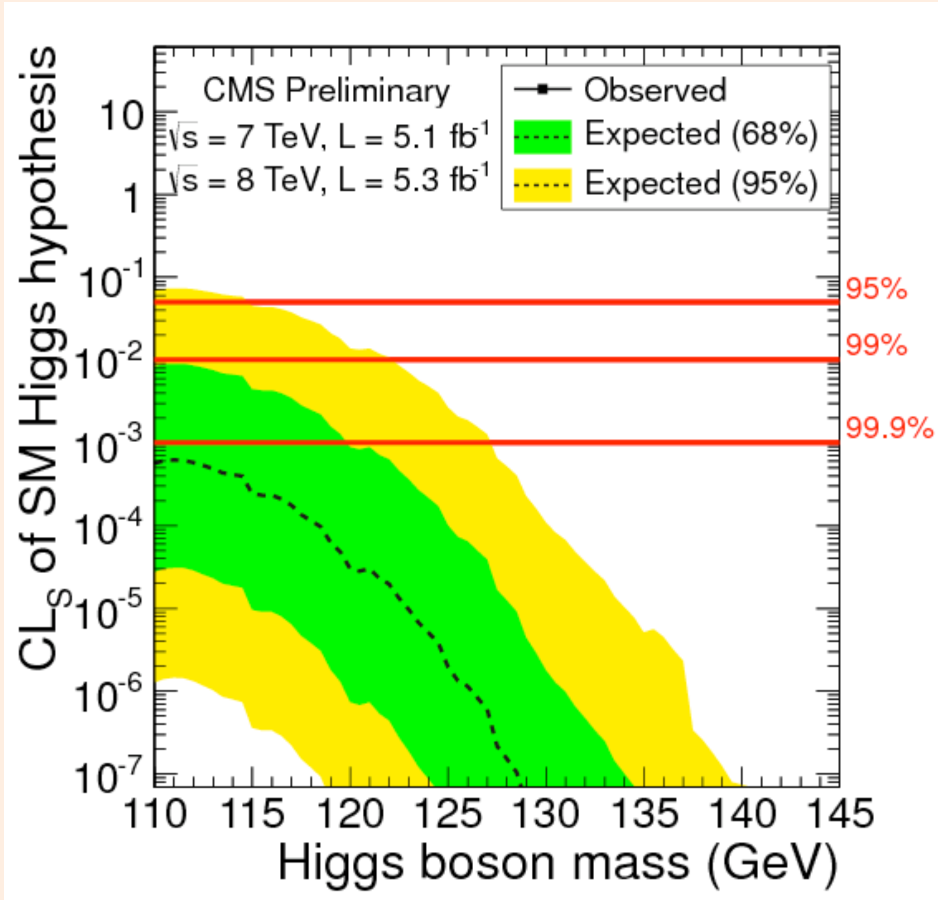




Excluded at 95% CL	**110-122.6 129.7-558 GeV**
Excluded at 99% CL	**111.7-121.8 GeV 130.7-523 GeV**
Expected at 95% CL if no signal	110-582 GeV

Combined results : CMS exclusion limits



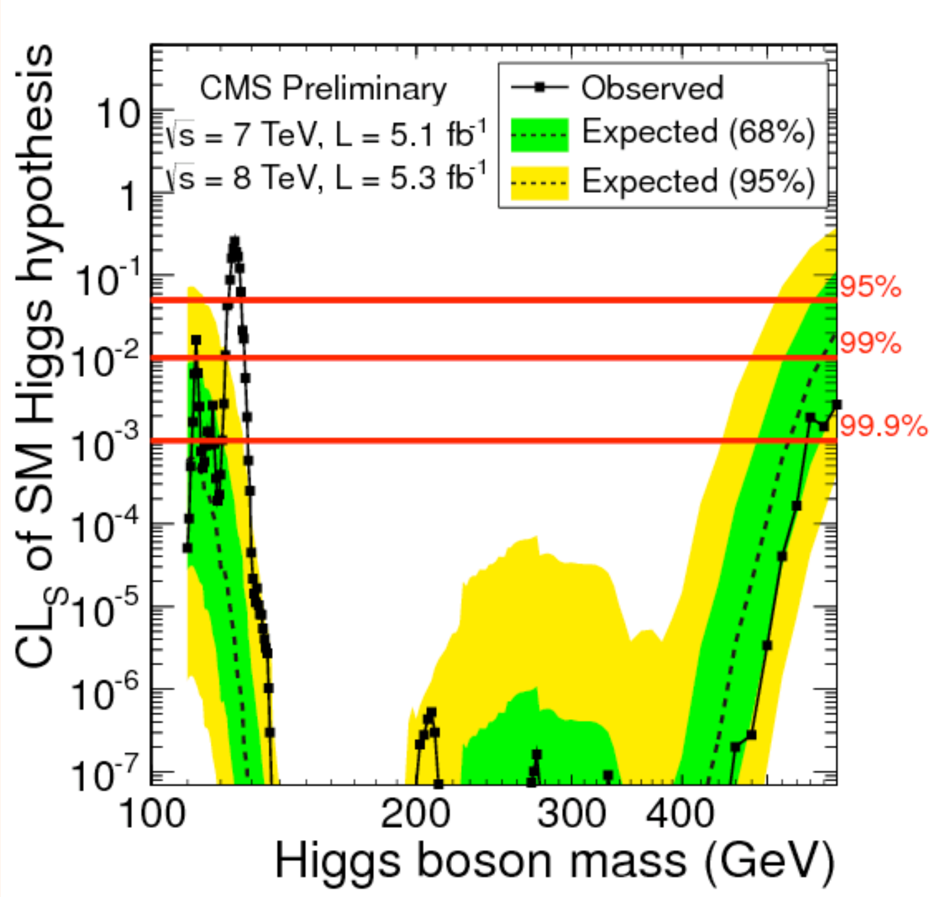


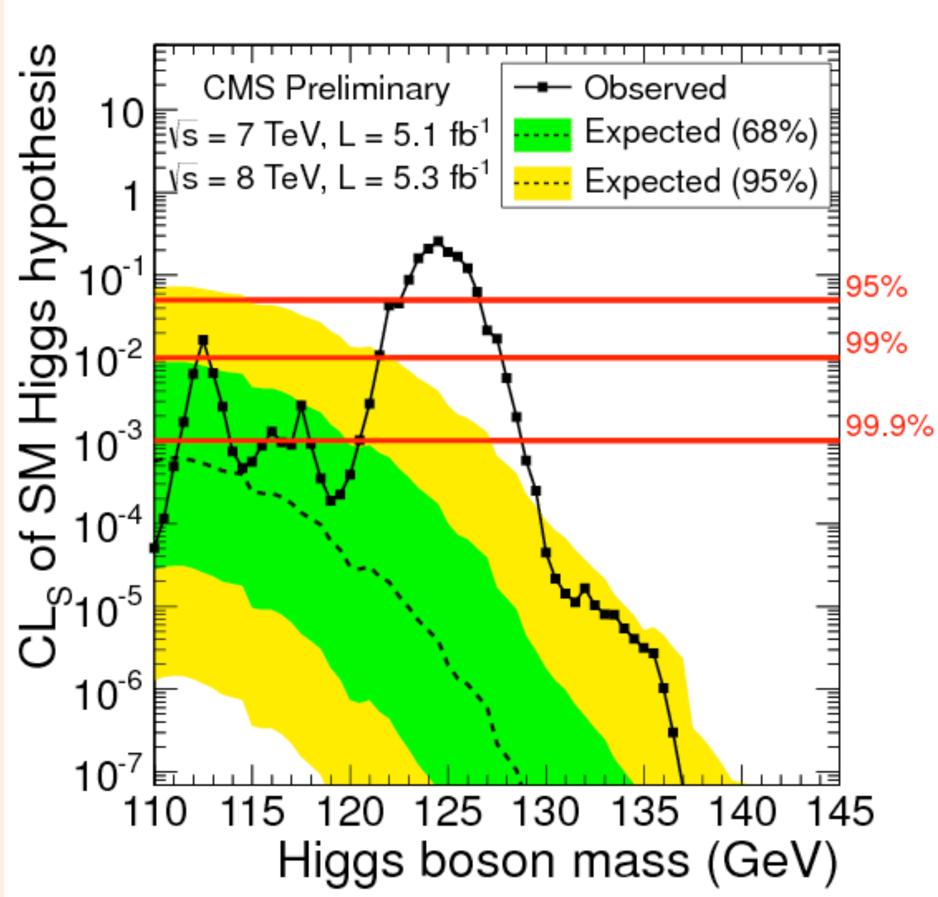
Expected in absence of SM Higgs boson: **110 – 600 GeV at 95% CL**

110 – 580 GeV at 99% CL

110 – 520 GeV at 99.9%CL

Combined results : CMS exclusion limits

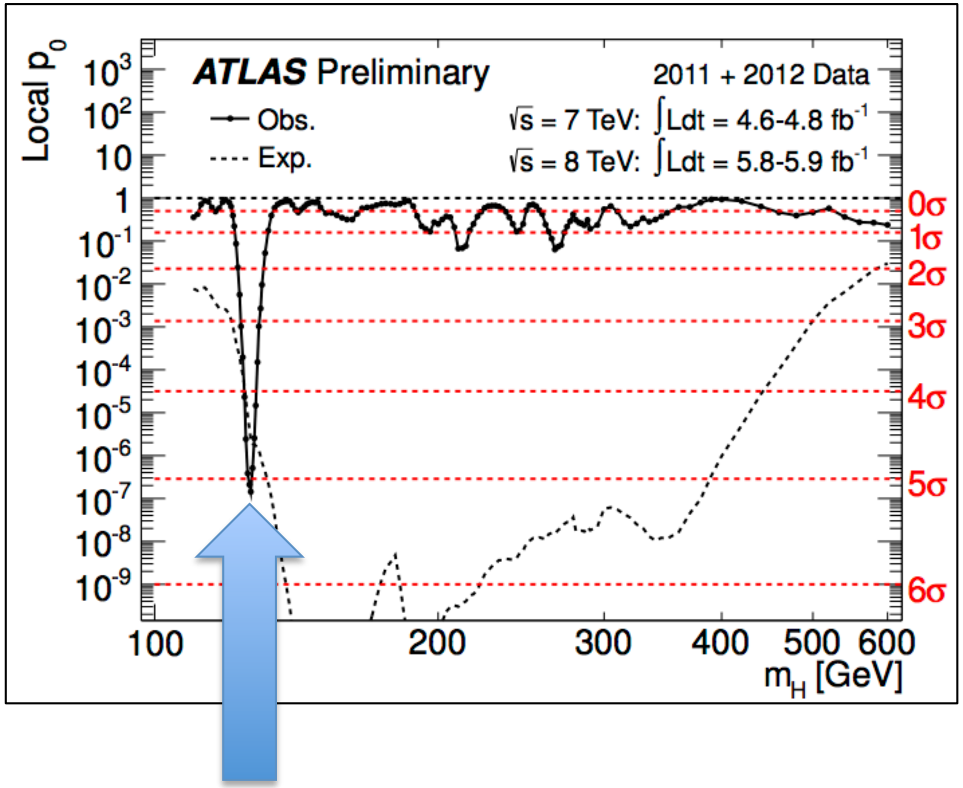


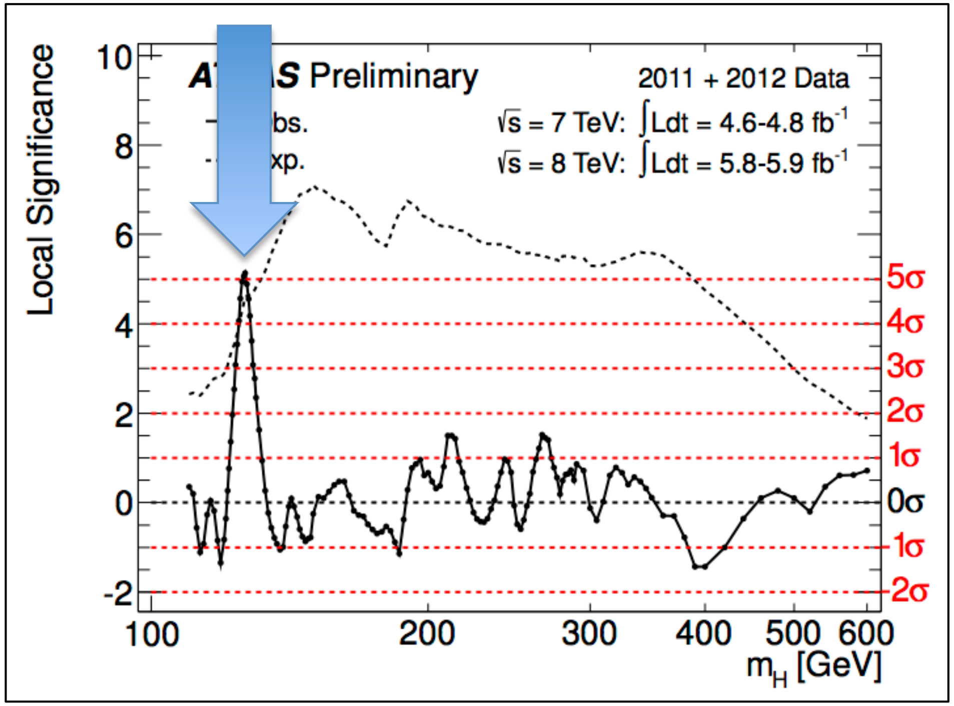


<u>Observed</u>: 110 – 122.5 [...] 127 – 600 GeV at 95% CL

110 - 112 .. 113 – 121.5 [...] 128 – 600 GeV at 99% CL

Combined results : event excess - ATLAS

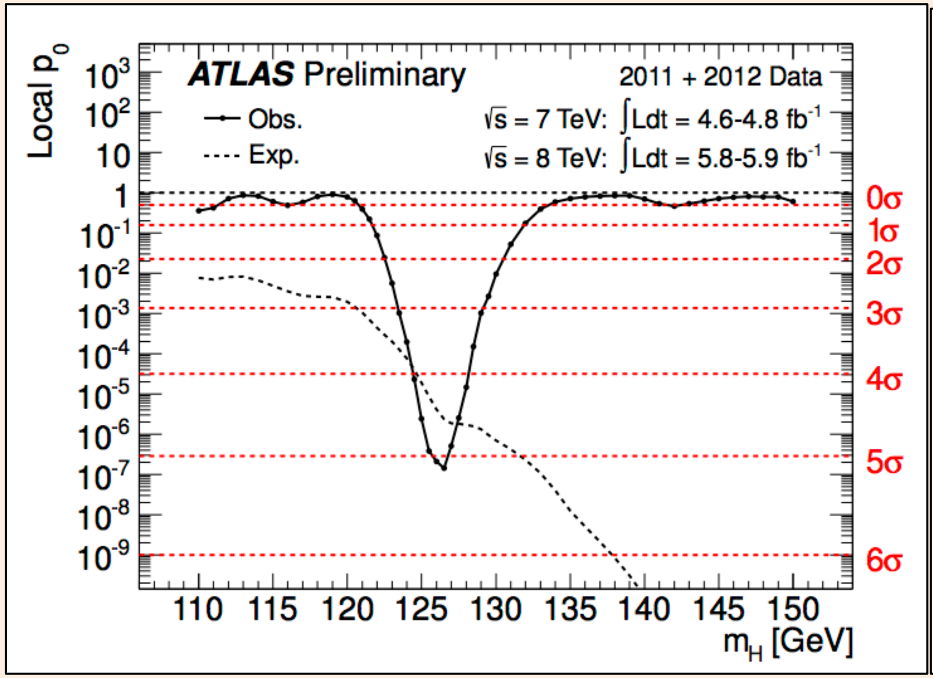


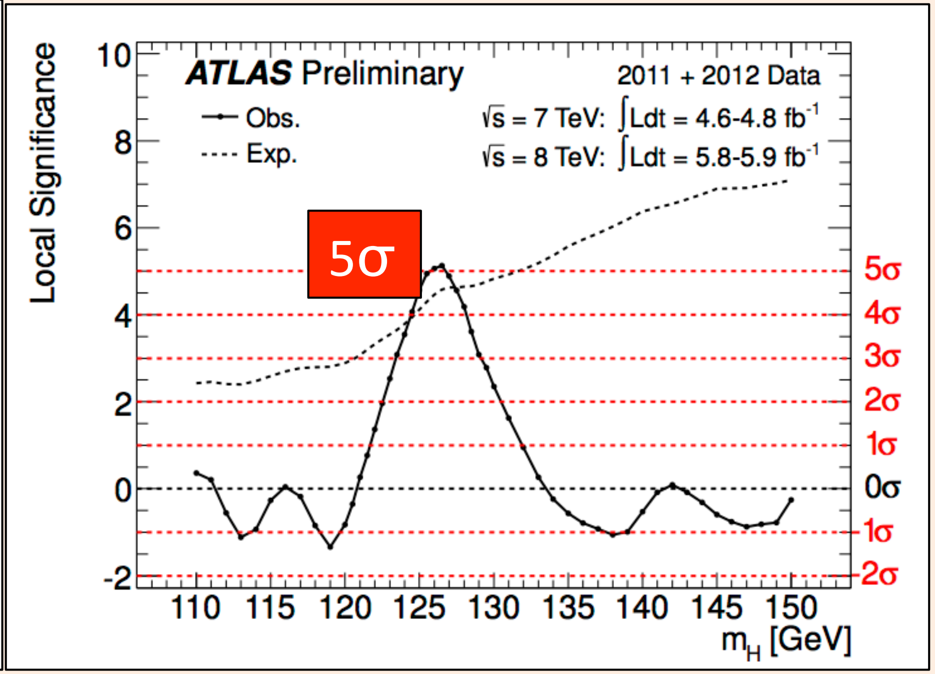


Excellent consistency (better than 2σ !) of the data with the background-only hypothesis over full mass spectrum

except in one region

Combined results : event excess - ATLAS

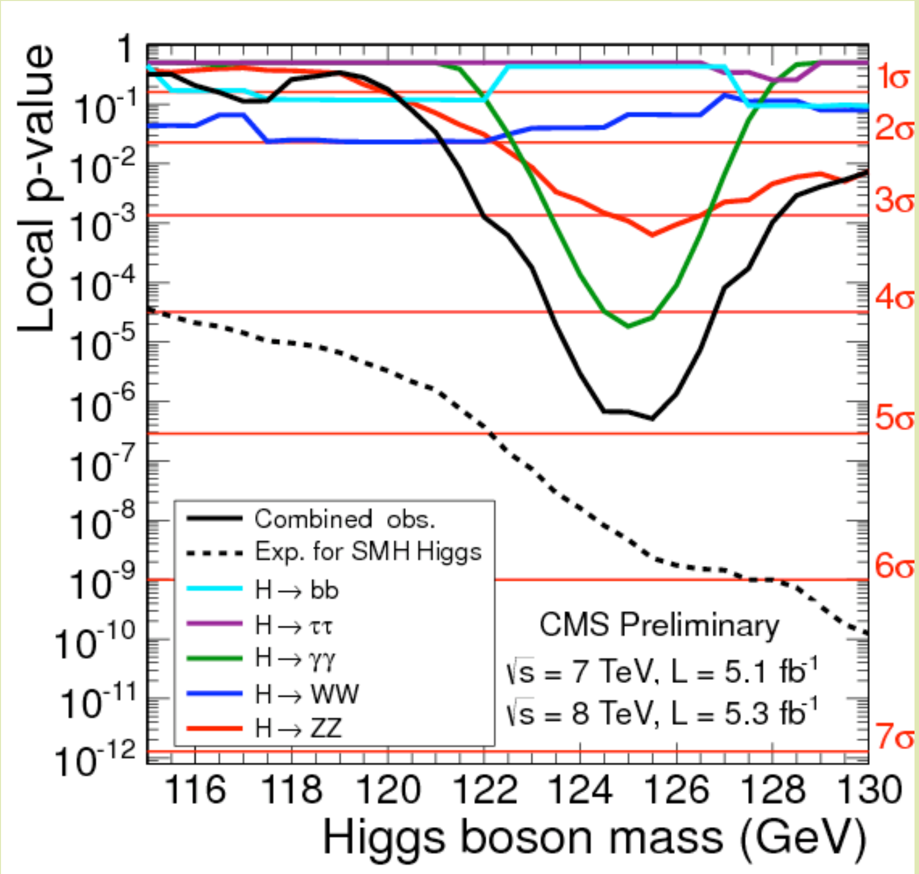




Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	**5.0 σ**
Probability of background up-fluctuation	3 x 10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

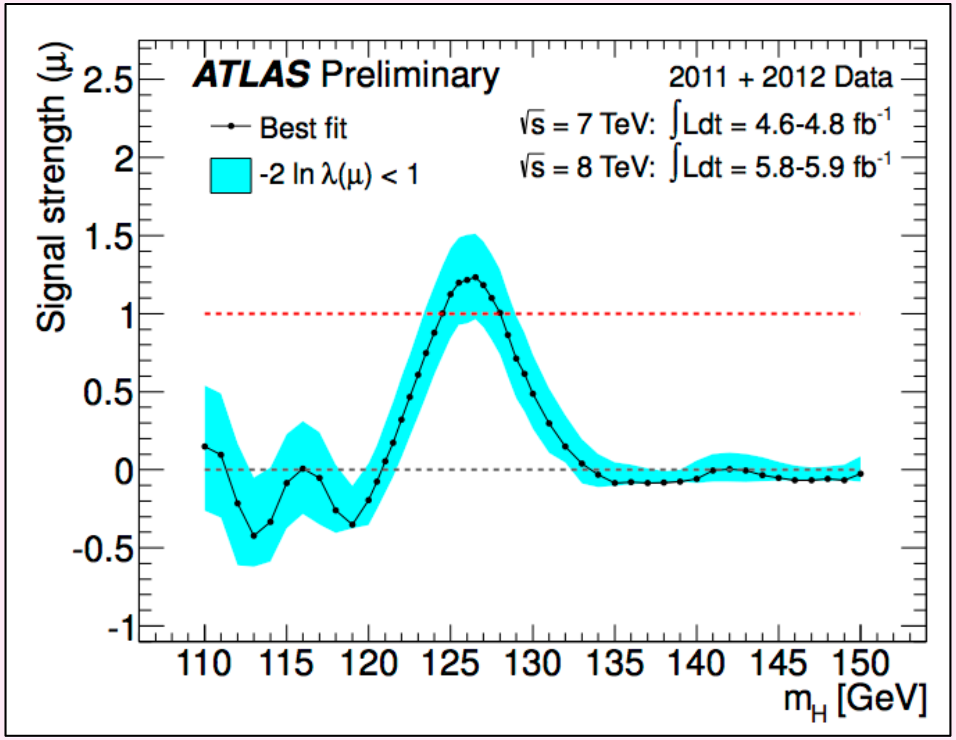
Combined results : event excess - CMS

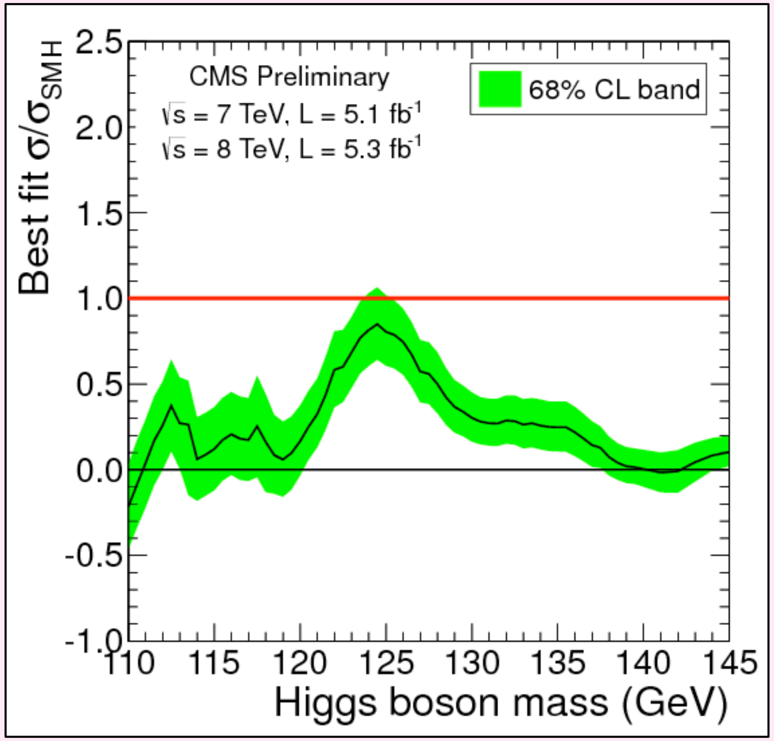


- **all channels together: comb. significance: 4.9 σ**
- **expected significance for SM Higgs: 5.9 σ**

Signal strength

Combined results: fitted signal strength



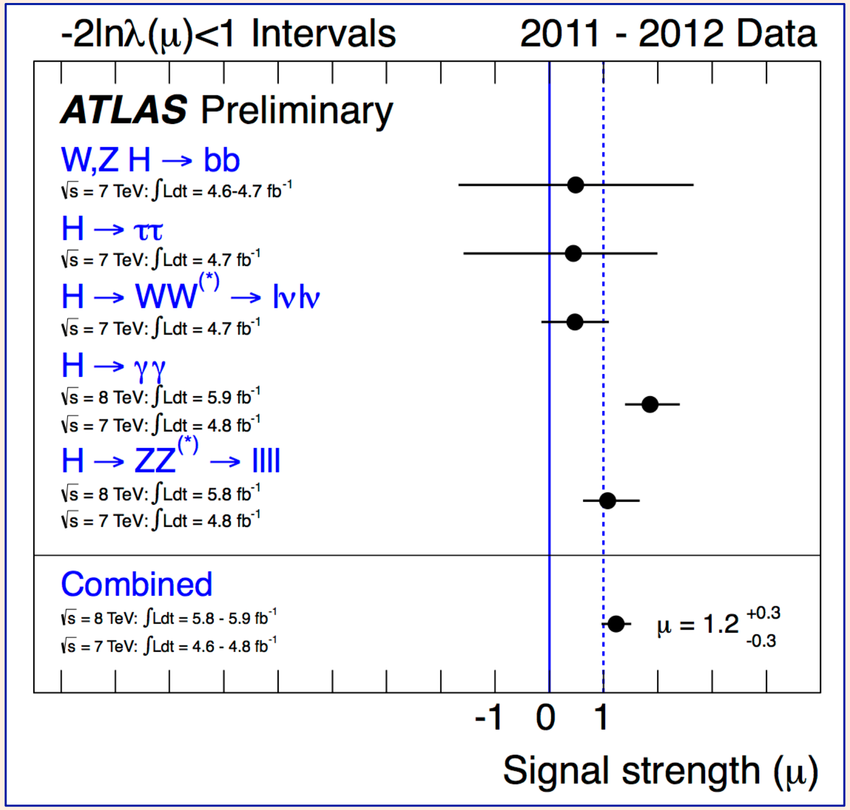


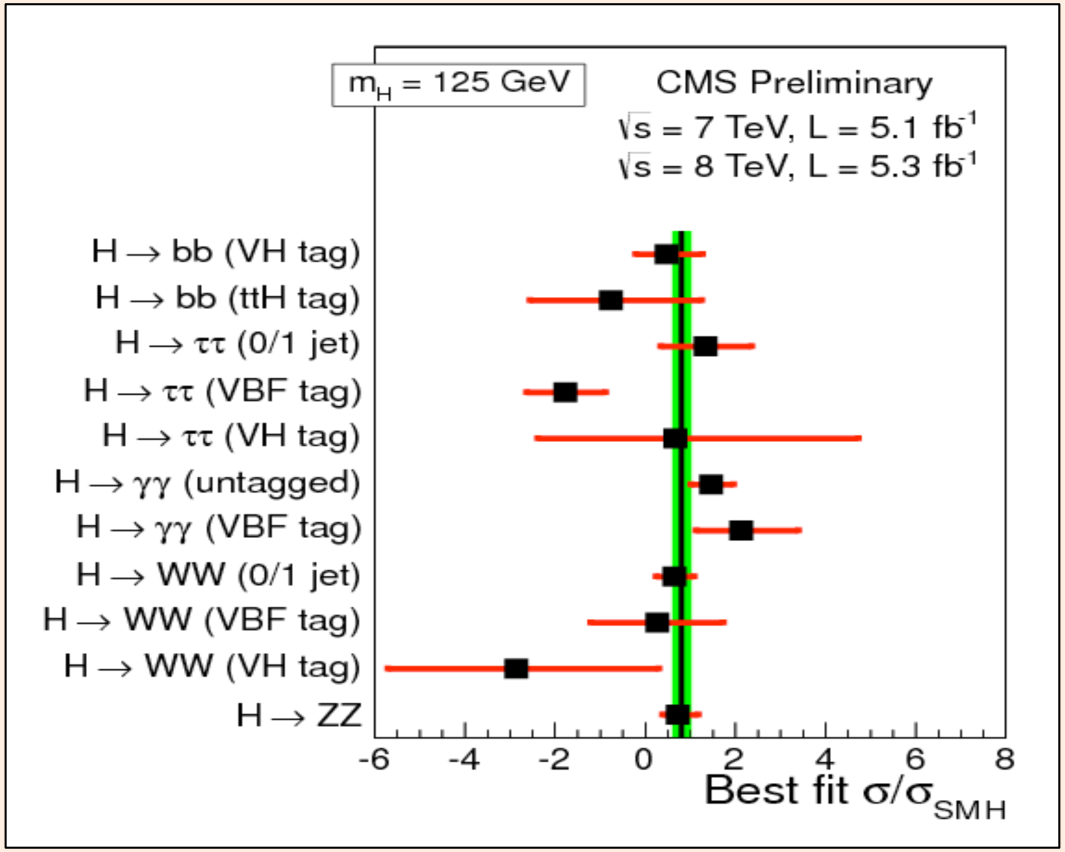
Best-fit value at 126.5 GeV:
$\mu = 1.2 \pm 0.3$

Best-fit value at 125 GeV:
$\mu = 0.80 \pm 0.22$

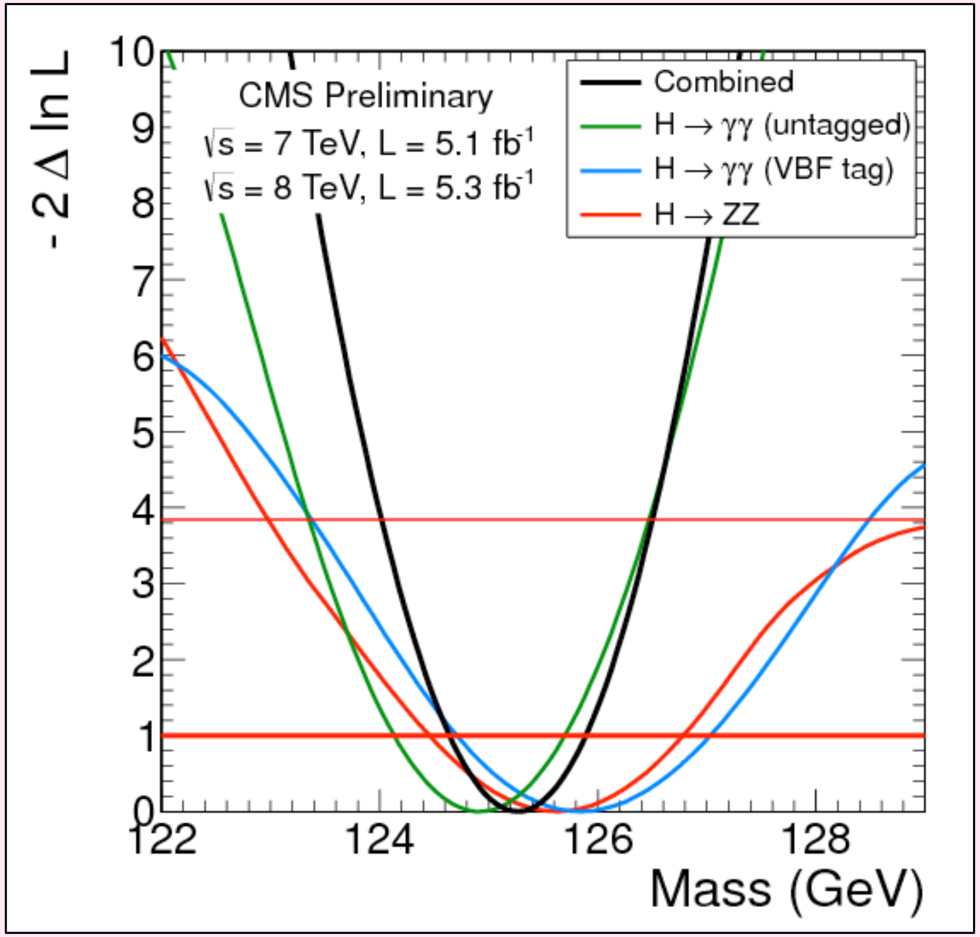
Good agreement with the expectation for a SM Higgs within the present statistical uncertainty

Signal strength





Signal mass



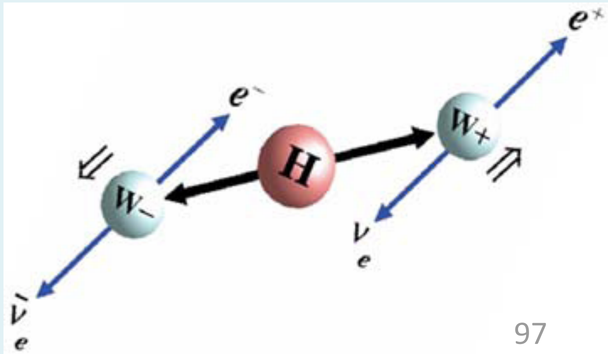
To reduce model dependence,
allow for free cross sections
in three channels
and fit for the common mass:

$m_X = 125.3 \pm 0.6$ GeV

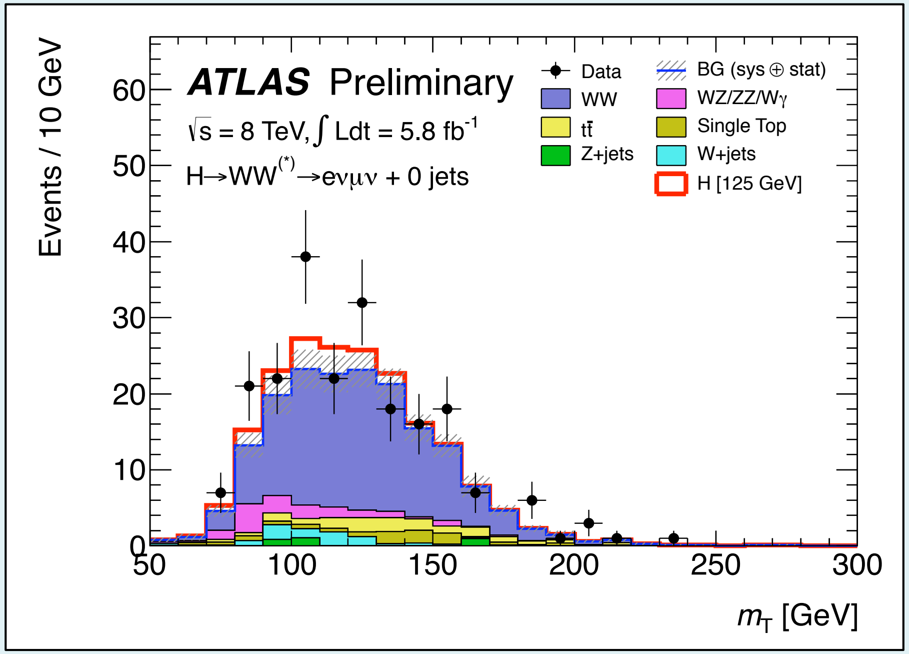
Recent results from ATLAS on WW(*)→lνlν using also 2012 data

- The most sensitive process for $130 < m_H < 200$ GeV
- But also one of the most challenging channels: complete reconstruction of the invariant mass of this final system is not possible because the production of neutrinos
- Largest background is the irreducible WW SM production
  - But also Drell-Yan and top process when looking to final states associated to one jet
- Select events with two high-p_T opposite sign leptons and large transverse missing energy (E_t^{miss}), produced in association of 0, 1 and 2 jets

- After E_T^{miss} cut, divide the events in three categories:
  1. Events with 0 jets with p_T>25 GeV and $|\eta|<4.5$
  2. Events with 1 jet with p_T>25 GeV and $|\eta|<4.5$;
  3. Events with 2 jet with p_T>25 GeV and $|\eta|<4.5$;
- Apply topological cuts (m^{ll}, p_T^{ll}, $\Delta\varphi^{ll}$)
- Reconstruct and study the transverse mass m_T

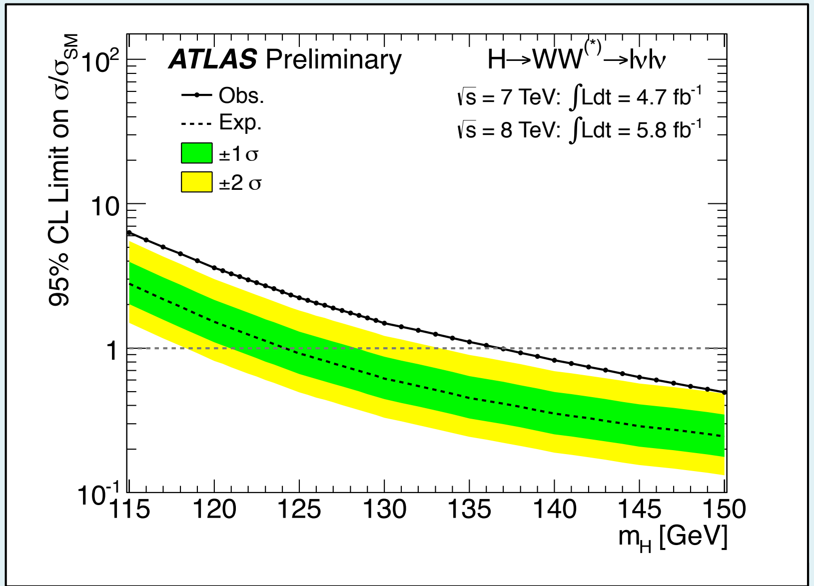


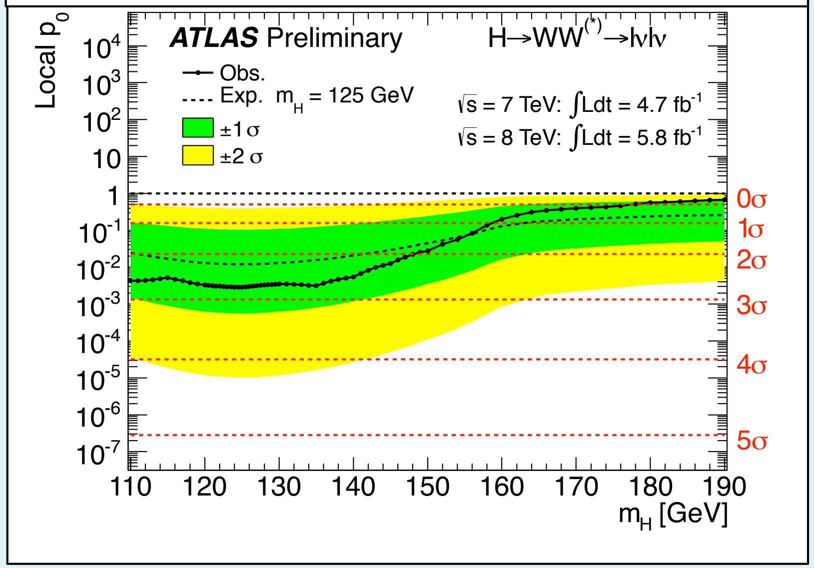
Recent results from ATLAS on WW(*)→lνlν using also 2012 data



Transverse mass m_T distribution in the H+0 jet (a, b) and H + 1 jet (c, d) channels, for events satisfying all criteria. The plot shows the events with a subleading muon.

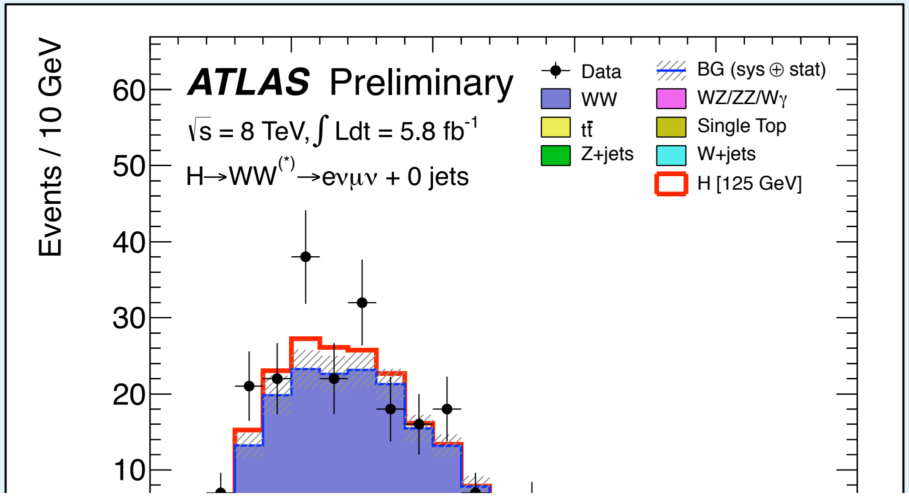
The W+jets background is estimated directly from data and WW and top backgrounds are scaled to use the normalisation derived from control regions described in the text. The hashed area indicates the total uncertainty on the background prediction.

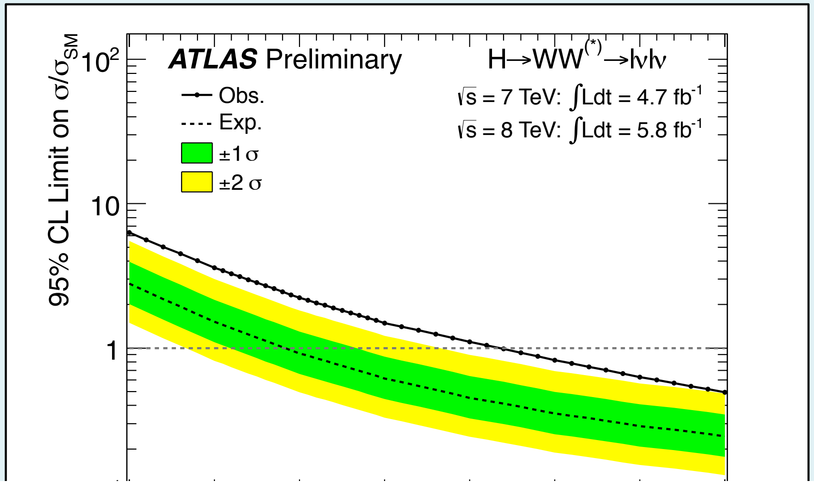




An excess of 2.8 sigma is observed

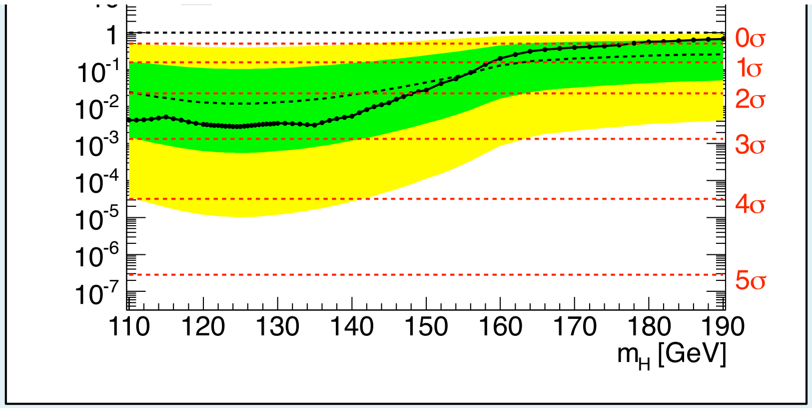
Recent results from ATLAS on WW$^{(*)}$→lνlν using also 2012 data





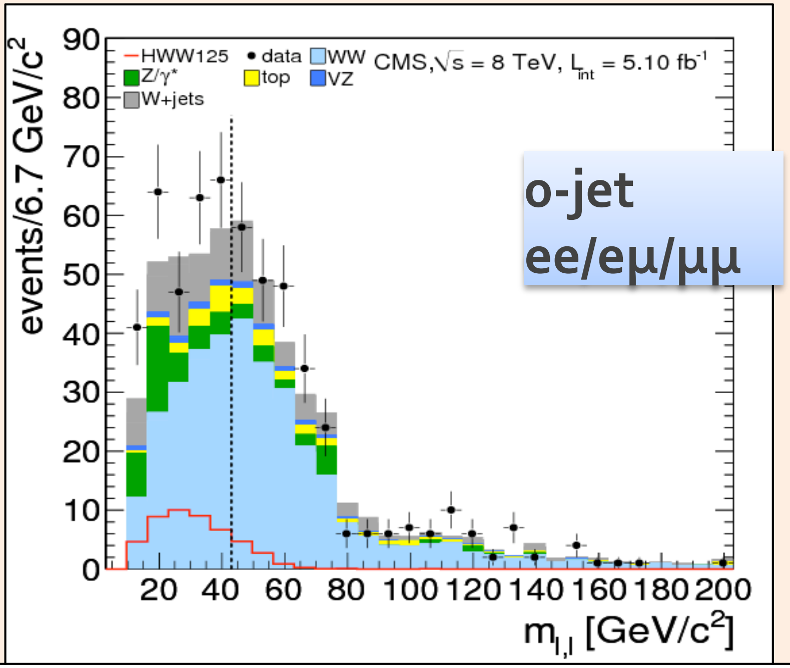
THESE RESULTS ARE NOT USED IN THE PRESENTED ATLAS COMBINATION

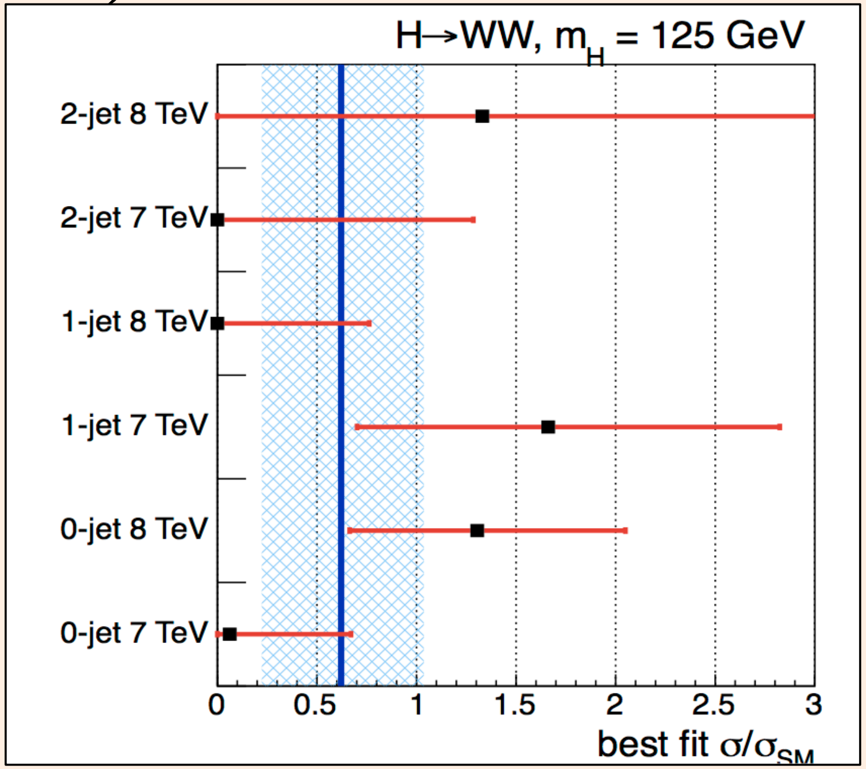
events satisfying all criteria. The plot shows the events with a subleading muon.
The W+jets background is estimated directly from data and WW and top backgrounds are scaled to use the normalisation derived from control regions described in the text. The hashed area indicates the total uncertainty on the background prediction.

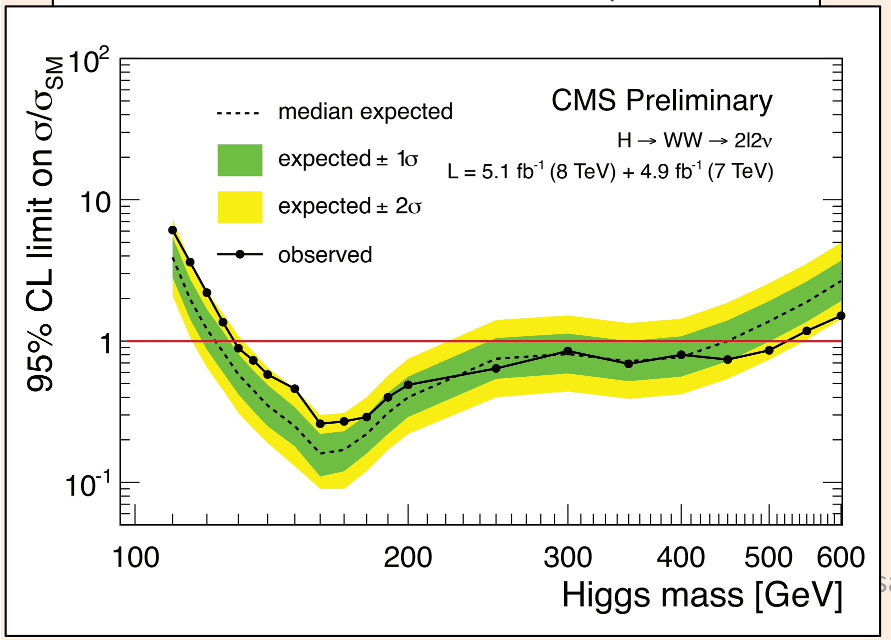


An excess of 2.8 sigma is observed

CMS: $WW^{(*)} \rightarrow l\nu l\nu$







Plot top left: 8 TeV data for the 0-jet category; the result shows some excess

Plot top right: signal strength

Plot bottom left: exclusion limit

THESE RESULTS ARE USED IN THE PRESENTED CMS COMBINATION

Conclusions

Preliminary results on searches for a SM Higgs boson using the ~ 4.9/fb of 7 TeV data collected in 2011, and the ~5.8/fb of 8 TeV data collected in 2012 are available

The invariant mass interval range $100 < m_H < 600$ GeV has been investigated
CMS: exclude at 95% CL the whole mass range **except $122.5 < m_H < 127$ GeV**
ATLAS: exclude at 95% CL the whole mass range **except $122.6 < m_H < 129.7$ GeV**

An excess of events with significance
5.0 sigma by ATLAS at m = 126.5 GeV and
4.9 sigma by CMS at m = 125.0 GeV
is observed

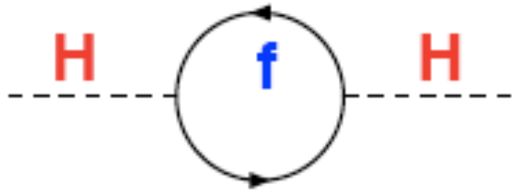
- This excess is driven by the final states γγ and 4-lepton in ATLAS and CMS
- Preliminary very recent results from ATLAS show a 3.2 sigma excess in the channel $WW^{(*)} \rightarrow l\nu l\nu$
- The fitted signal strength is 1.2±0.30 (ATLAS) and 0.8±0.22 (CMS)

Beyond Standard Model searches

The Hierarchy problem - 1

- **The question: why the weak force is ~ 10^{32} times stronger than the gravitational force?**
  - **$F \sim 1/[M^2_{Pl} \bullet r^2]$; $M_{Pl} = 1.22\times10^{19}$ GeV ⇔ $M_H \sim 10^2$ GeV**
- Both forces involve constants of nature:
  - The Fermi's constant
  - The Newton's constant
- In the Standard Model the quantum corrections to the Fermi constant appear unnaturally large, unless a delicate cancellation between the bare value of this constant and its quantum corrections take place (**fine-tuning**)

$$\Delta M_H^2 \equiv$$



$$\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2$$

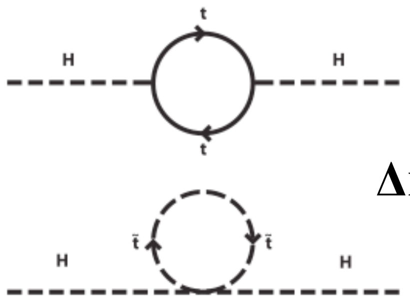
  - More technically the question is why the Higgs boson mass is so much lighter than the Planck mass (or the Grand Unification energy)

The Hierarchy problem - 2

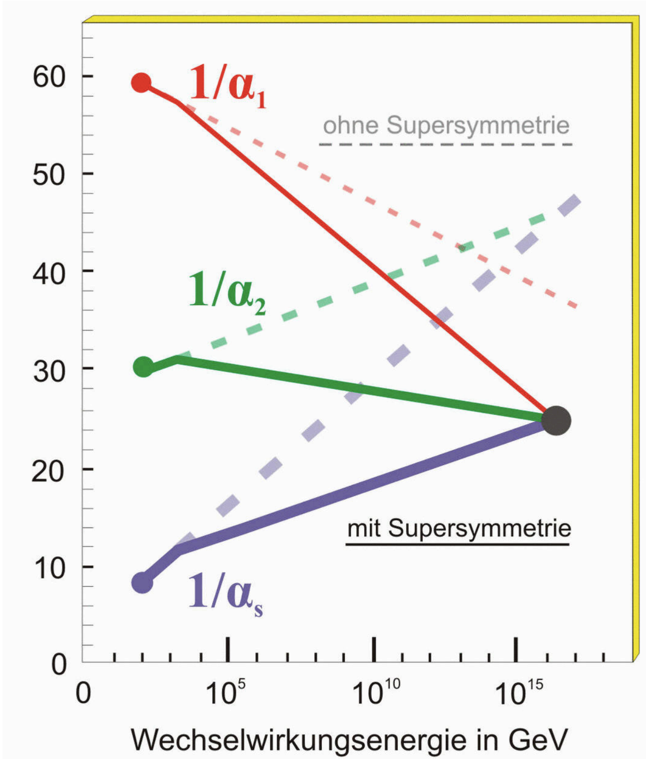
- **Three main avenues** for solving the hierarchy problem:
- ***Supersimmetry***
  - *A set of new (light) SUSY particles cancel the divergence*
- ***Extra dimensions***
  - *There is a cut-off at the ~TeV scale where gravity sets in; in other words the "actual" gravity constant is larger then the one observed (or the Planck mass is much smaller)*
- ***Strong interactions/compositness***
  - *The Higgs is not an elementary scalar particle*
  - *The Higgs emerges as a Nambu-Goldostone boson of a strongly interacting sector*

Supersymmetry

- Supersymmetry provides a natural mechanism to keep small quantum corrections to the Higgs boson mass
- Supersymmetry provides a natural candidate for dark matter (the lightest supersymmetric particle)
- Supersymmetry facilitates the grand-unification of the em, weak and strong couplings
- Supersymmetry is an "extension" of the SM, it is consistent with the observed data



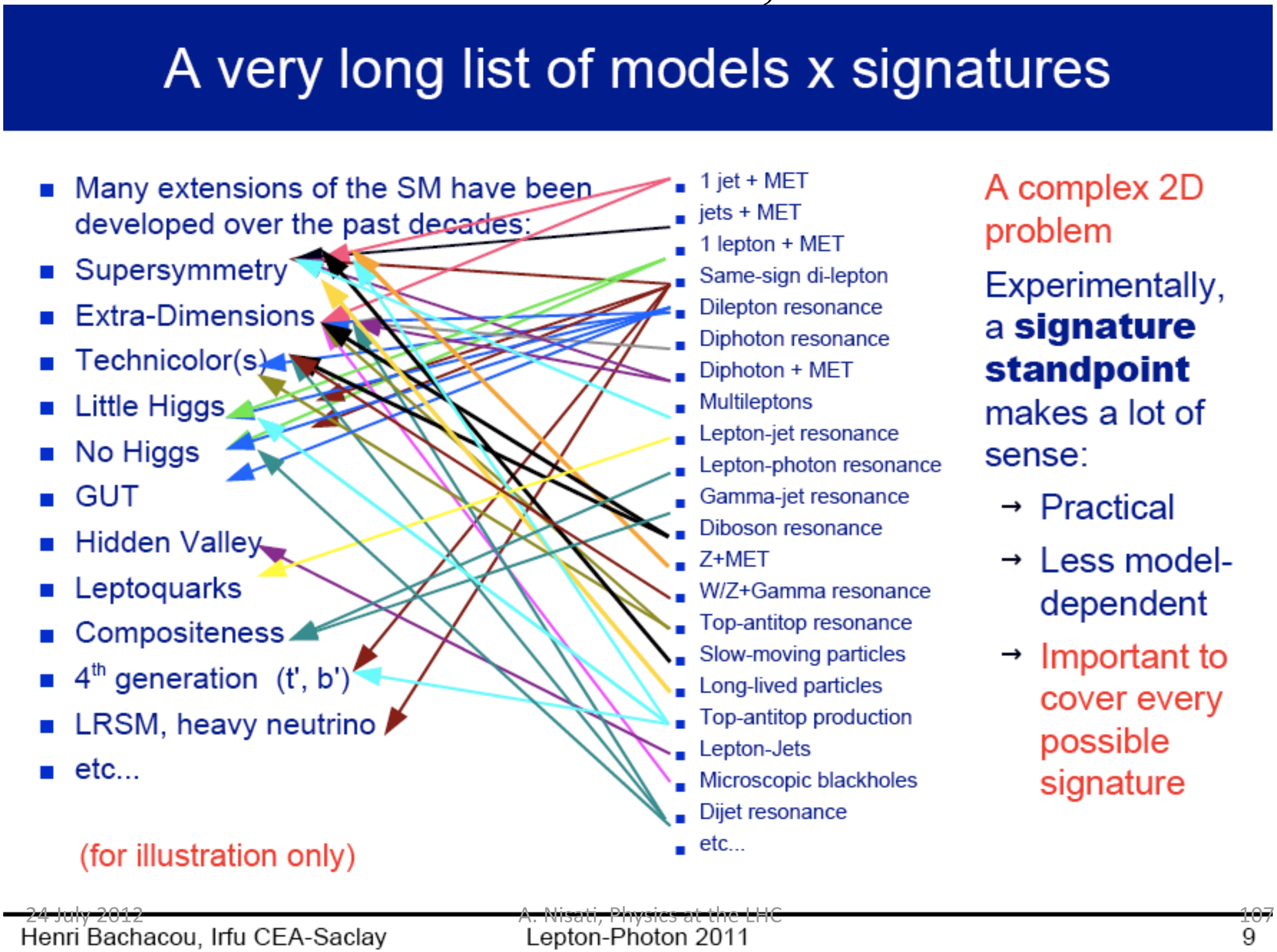
$\Delta m = f(m^2_B - m^2_F)$



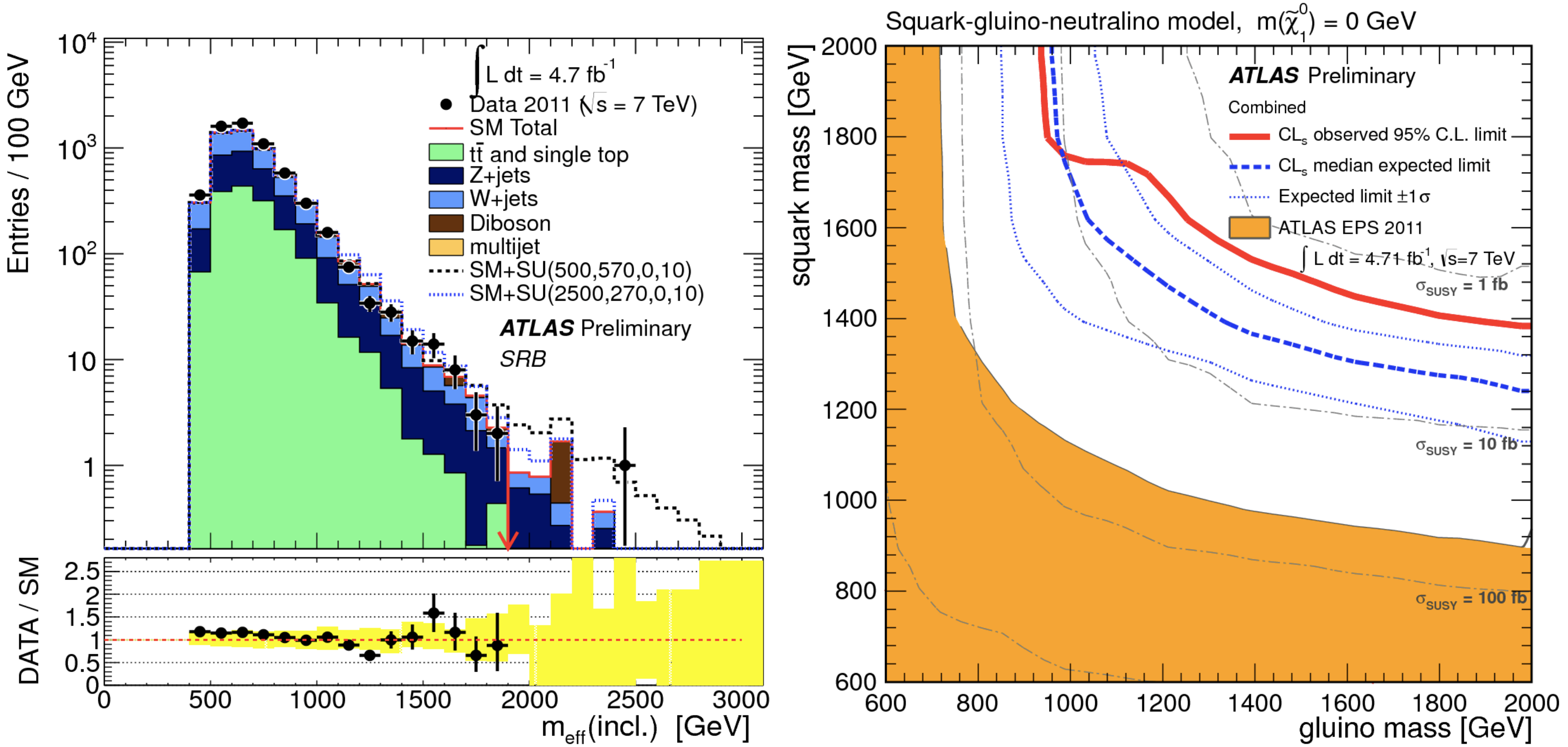
Strategy for SUSY searches at the LHC

- Search for excesses in multijet + no-lepton + missing transverse energy events
- Search for excesses in single lepton, opposite sign dilepton, same sign dilepton, taus, in association with jets and missing transverse energy
- Look for special features (γ's, long lived sleptons)
- End-point analyses, global fit → SUSY model parameters

If we found an excess, is it SUSY?

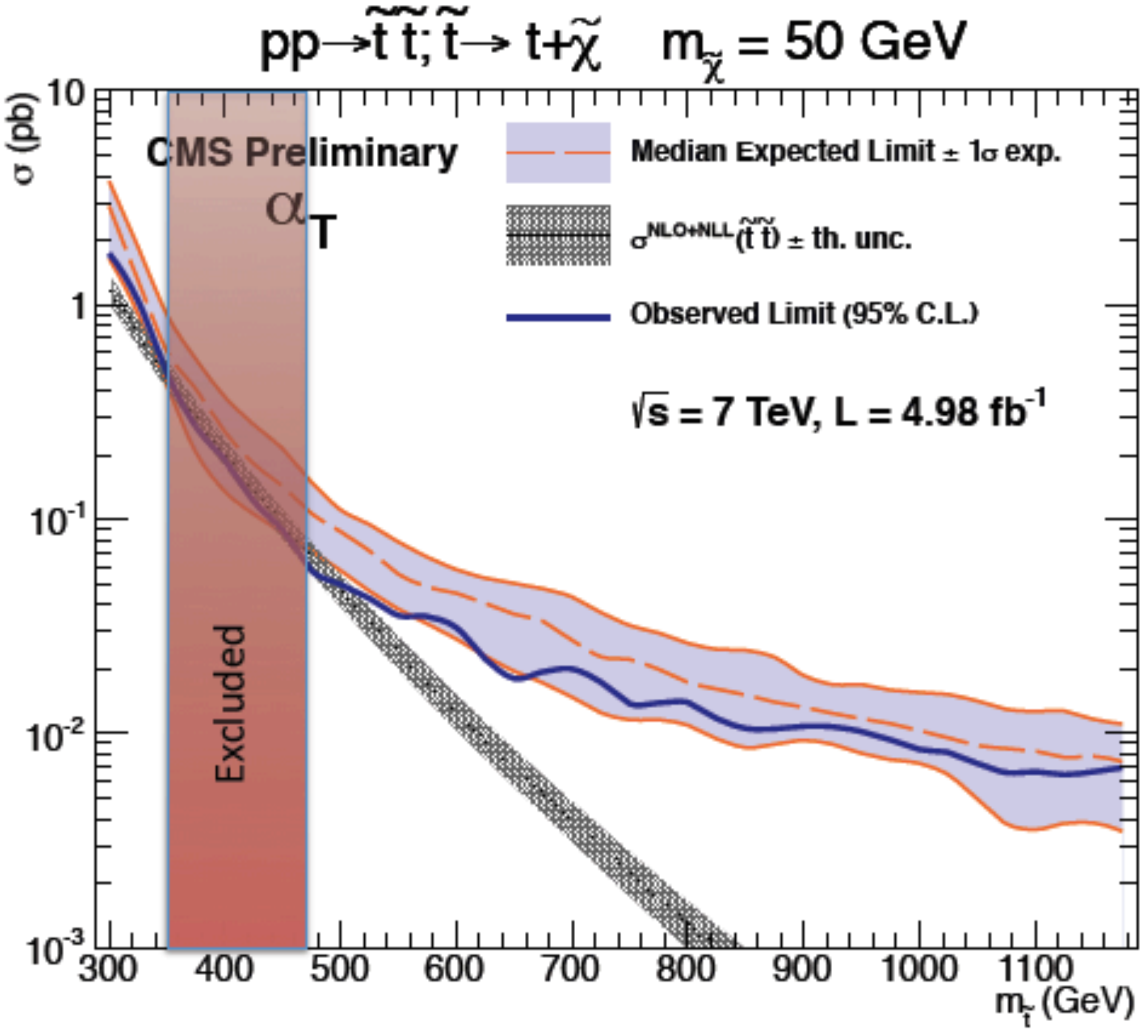


ATLAS: jets + transverse missing energy



- Search for strong production of squarks and gluinos
- Very strong limits from counting experiment:
  - for msquark=mgluino m > ~1.4 TeV @ 95% C.L.
- Dominant background from Z→νν+jets
- Limits do not apply to stop/sbottom production

CMS limits on stop production

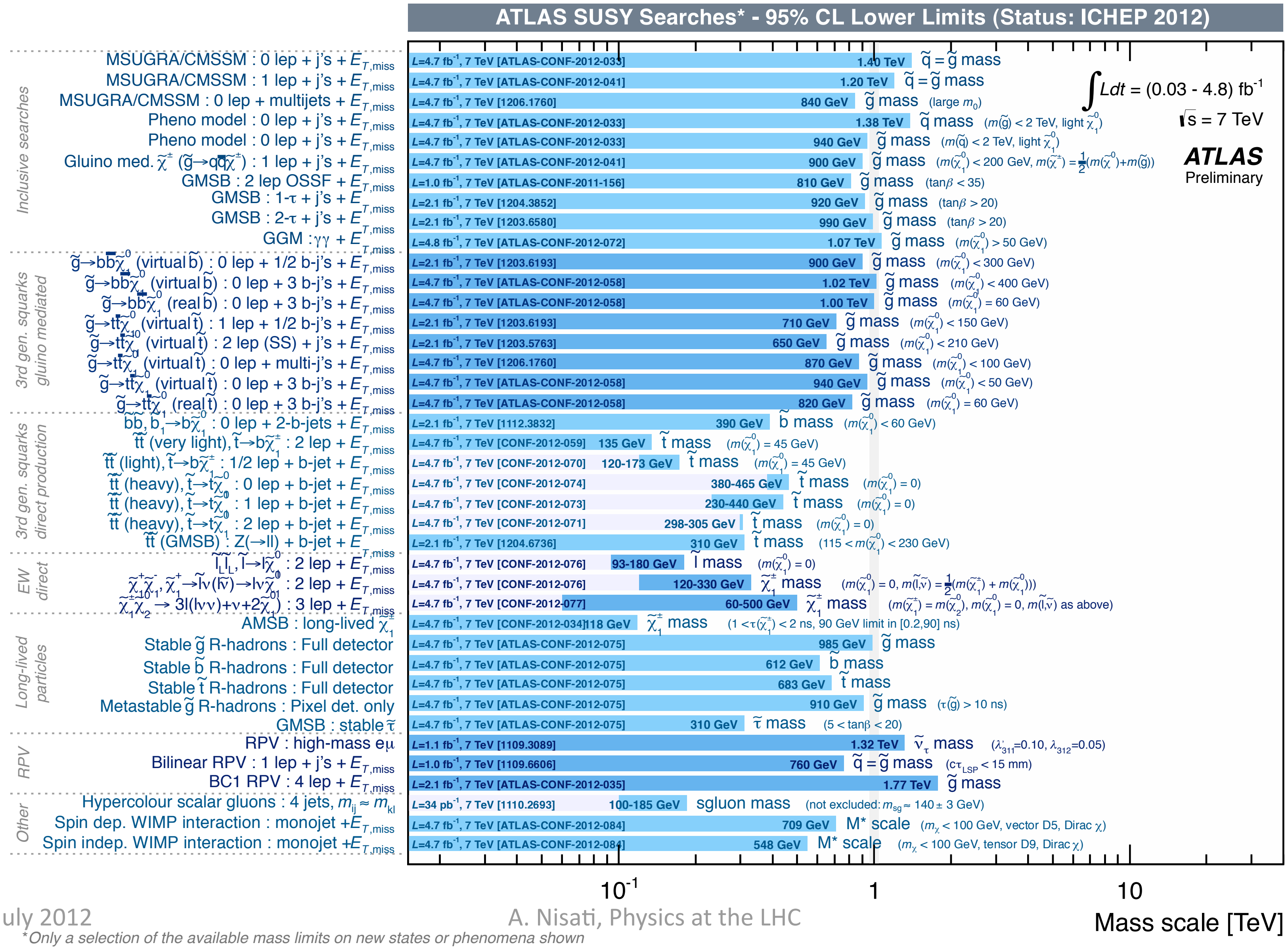


Sensitivity will improve rapidly with more data

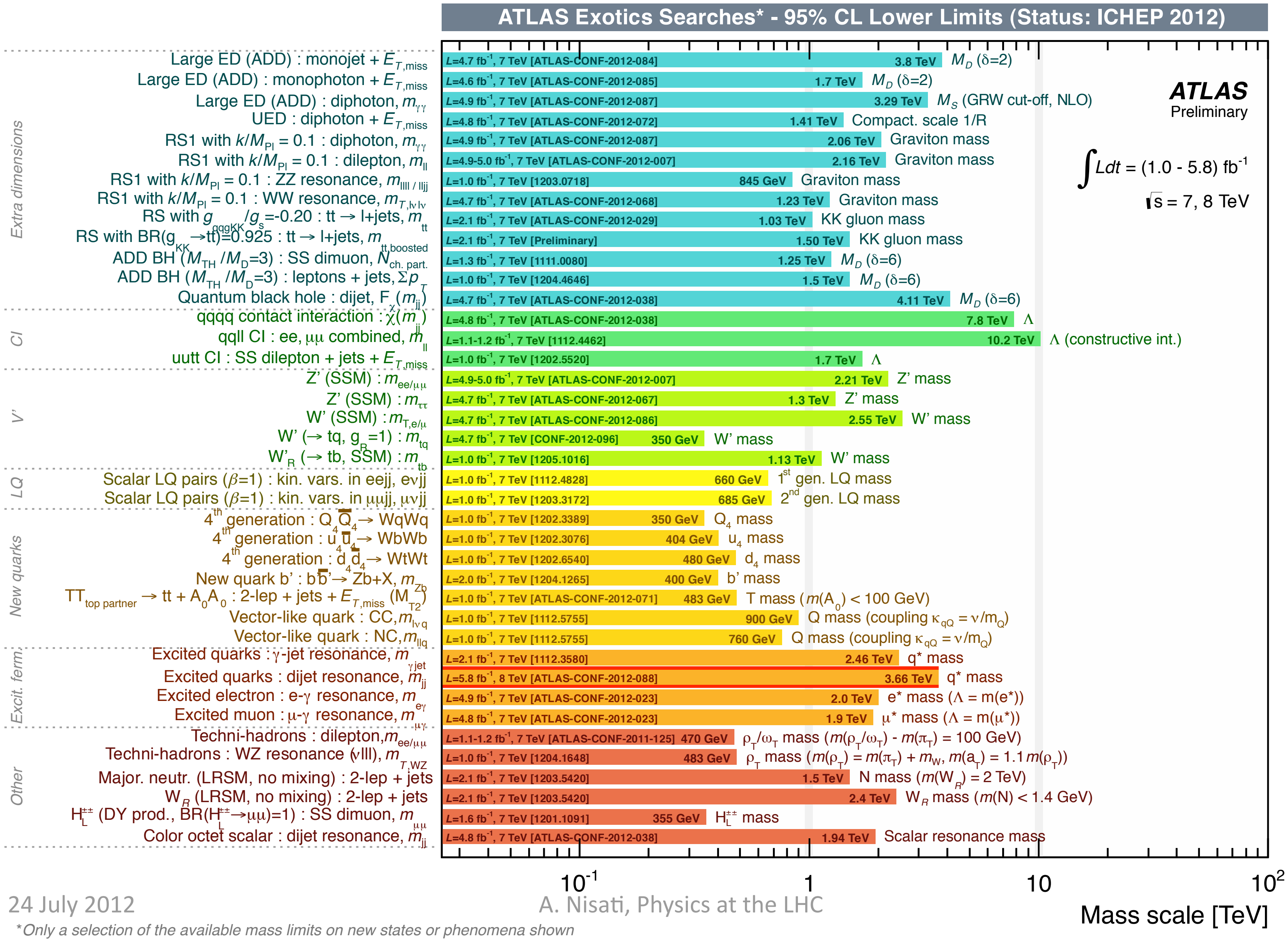
The hierarchy problem: non SUSY solutions

- **Extra Dimensions theories**:
  - **Kaluza-Klein** model (1921)
  - **Large Extra Dimensions**, or ADD model (Nima Arkani-Hamed, Savas Dimopoulos and Gia Dvali, 1998)
  - **Universal Extra Dimensions** (UED, 2001)
  - **Randall-Sundrum** model (1999)
  - **DGP Model** (Gia Dvali, Gregory Gabadadze and Massimo Porrati; 2000)

Summary of SUSY searches

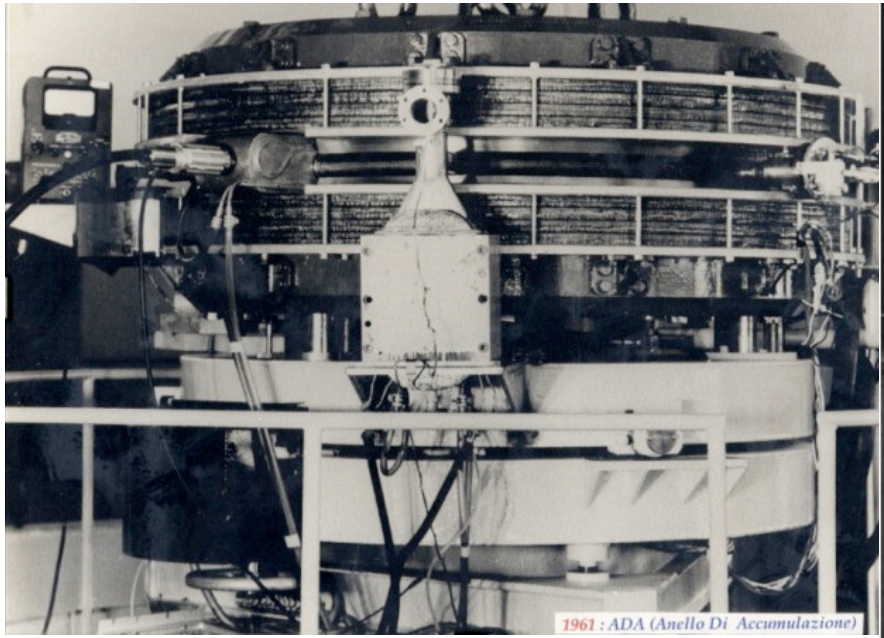


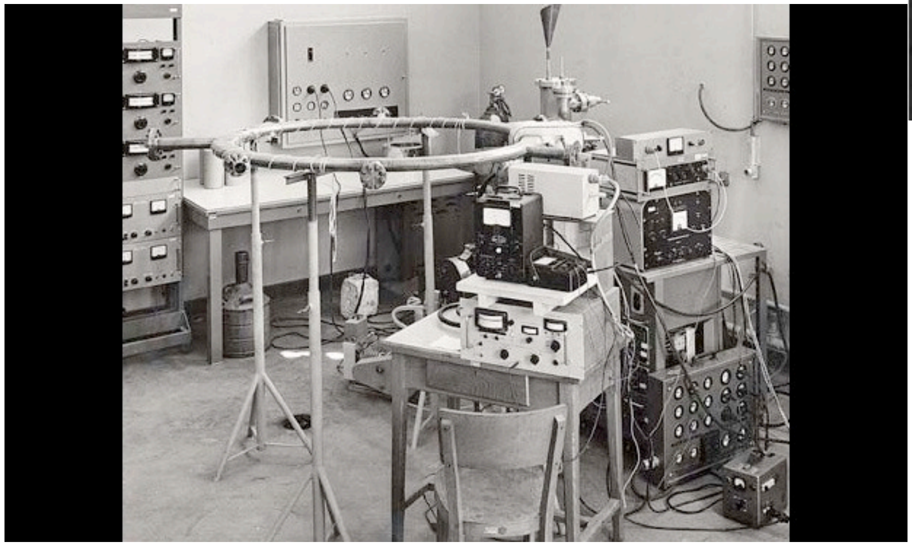
Summary of Exotics searches



backup

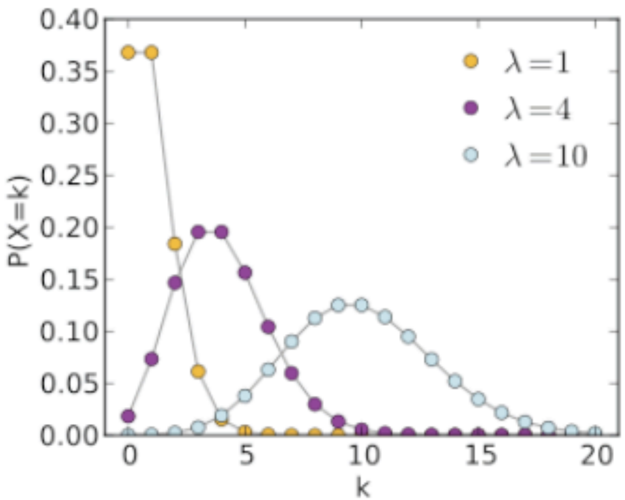
The 50 years of AdA





Top left: AdA
Top right: Bruno Touschek and Edoardo Amaldi
Bottom left: AdA: the vacuum chamber

Event pileup



- given an average number of interactions, the number of PU events per bunch-crossing is expected to have roughly a poissonian distribution

multiply the luminosity (per bunch) by the minimum bias cross-section (71.3 mb) gets the expected rate per bunch:

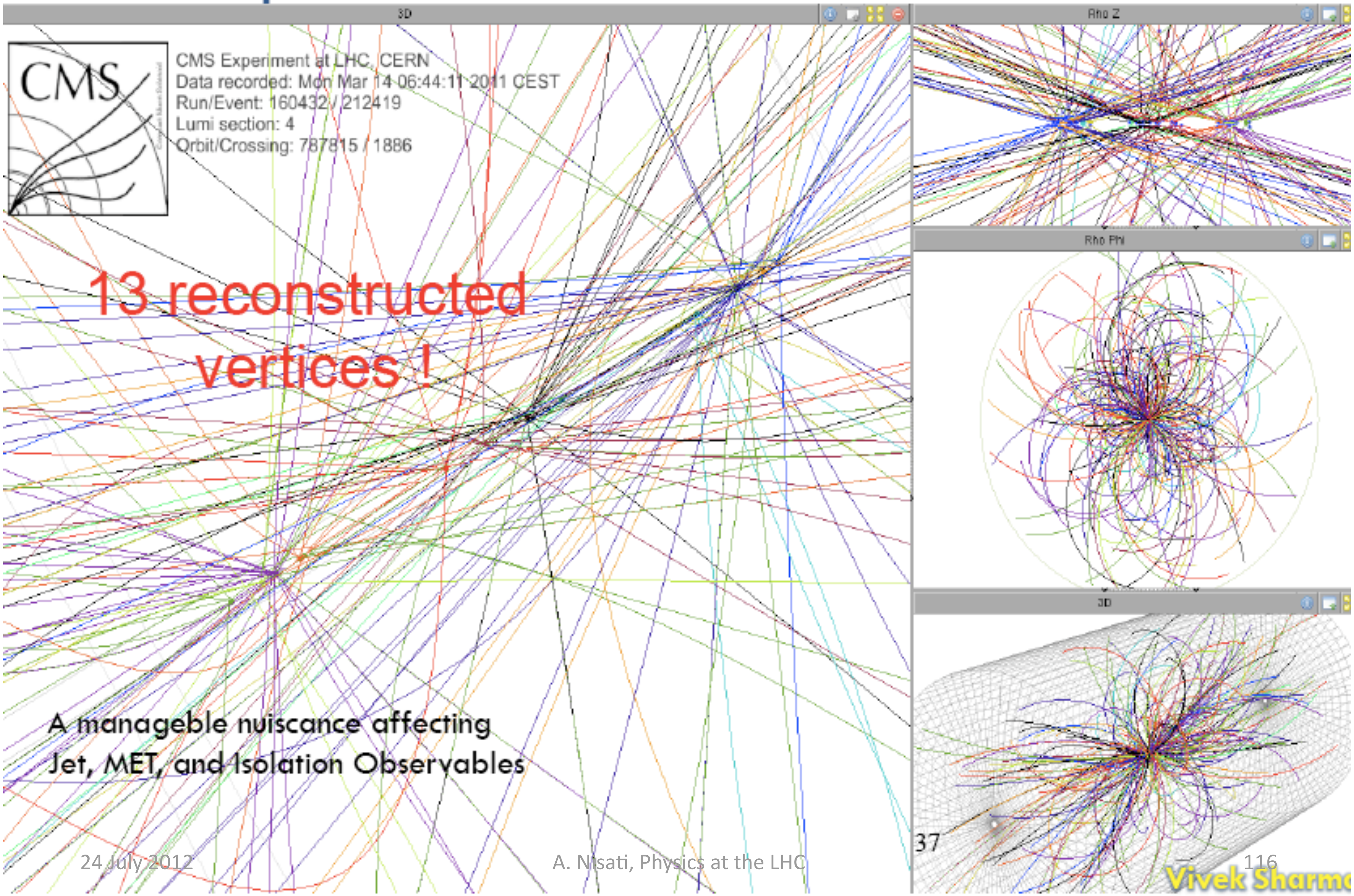
$$\mathrm{Rate}_{\mathrm{pileup}_{\mathrm{xing,ls}}} = \mathscr{L}_{\mathrm{xing,ls}} \cdot \sigma_{\mathrm{minimum\ bias}}$$

divide by the revolution frequency of a bunch to get the number of PU events:

$$\mathscr{N}_{\mathrm{pileup}_{\mathrm{xing,ls}}} = \frac{\mathscr{L}_{\mathrm{xing,ls}} \cdot \sigma_{\mathrm{minimum\ bias}}}{\mathrm{cirulation\ rate}}$$

calculate average distributions over longer periods, weighting by the luminosities

Pileup: A New Feature in 2011 Data

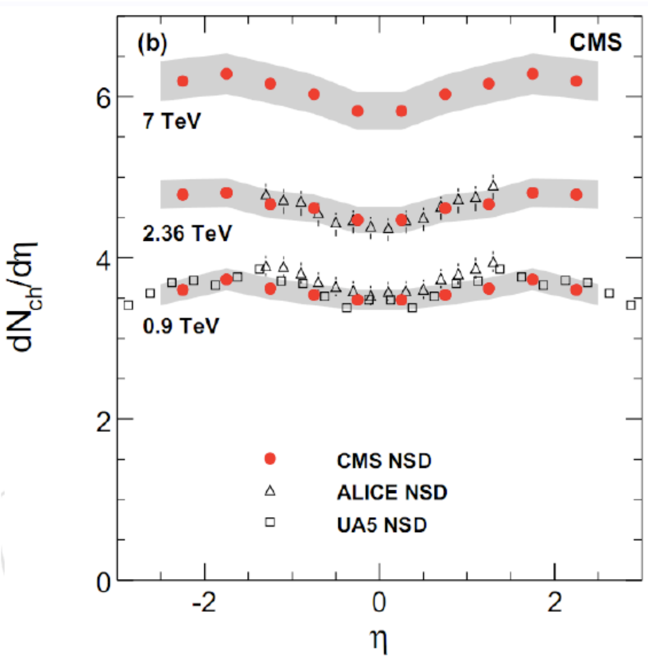


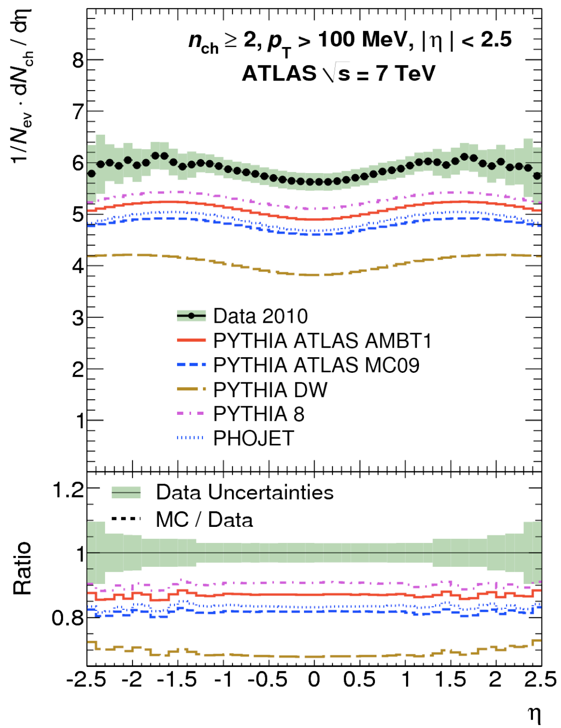
“soft interactions” at the LHC

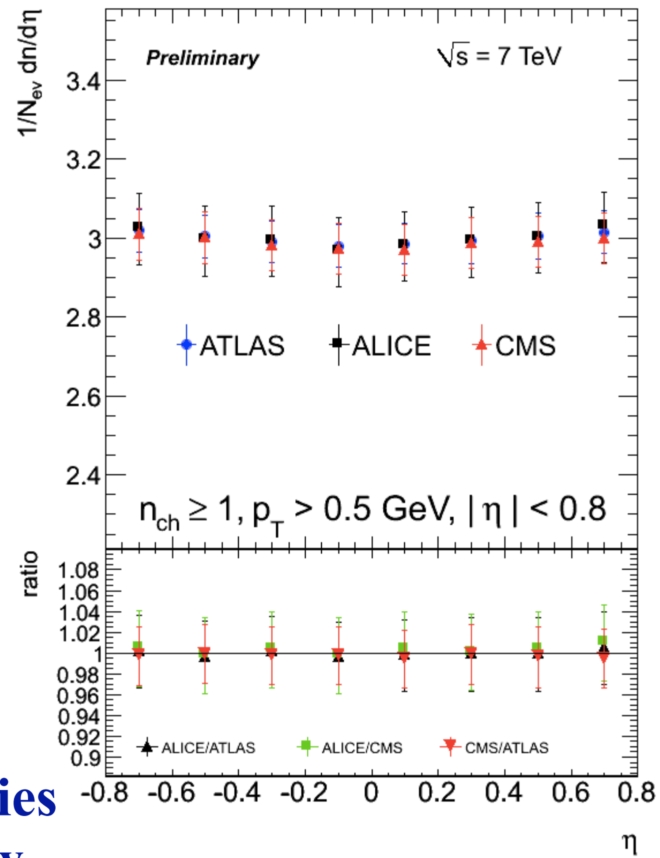
- The large majority of the pp collisions are **soft**
  - No “perturbative” predictions
  - Need to model them in a phenomenological approach
- Use Monte Carlo (MC) description to correct the data for the detector effect

- Inclusive particle spectra
- Particle multiplicities
- Strange particle production
- Inclusive cross section
- “Gap” cross section
- Underlying event
- 2-particle correlations
- Monte Carlo tuning

Charged particle spectra

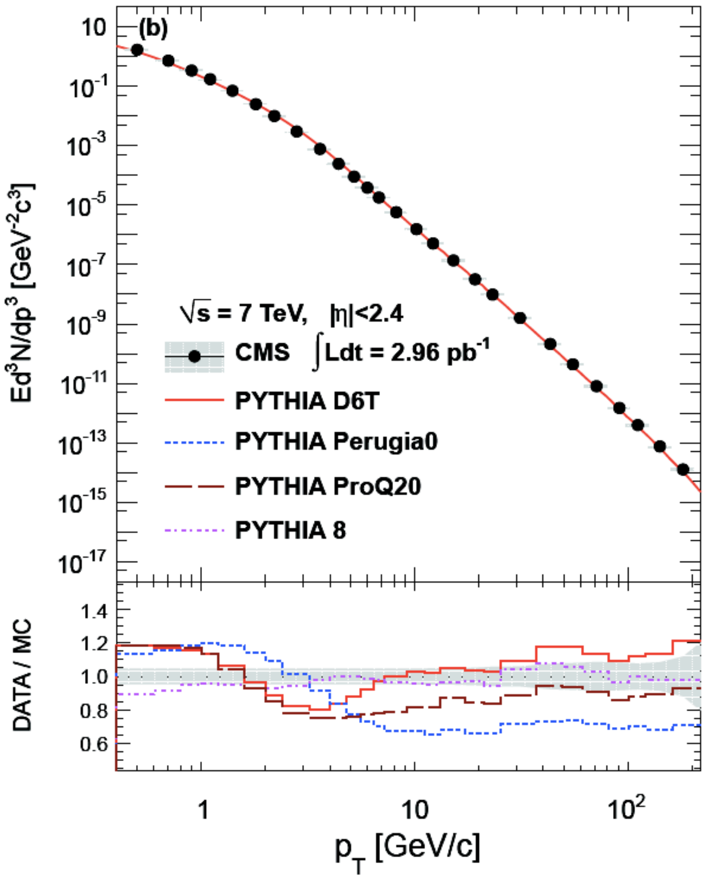


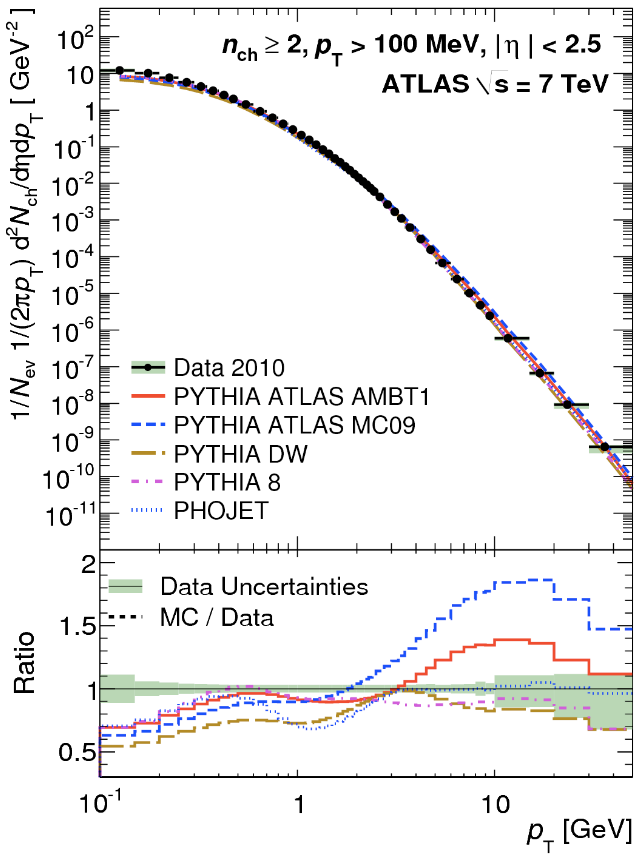




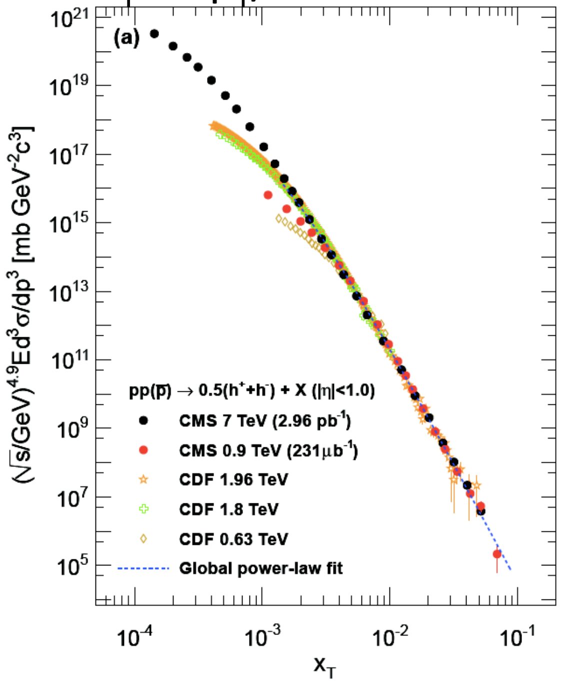
- **Several event selections, pt/h acceptances, energies**
  - **Very high particle production at increasing energy**
  - **MC predictions are globally too low, specially pre-LHC tunes**
- **MBUEWG : common set of event Sel. + acceptance**
  - **excellent agreement between exp.**
  - **useful for tuning**

Charged particle spectra



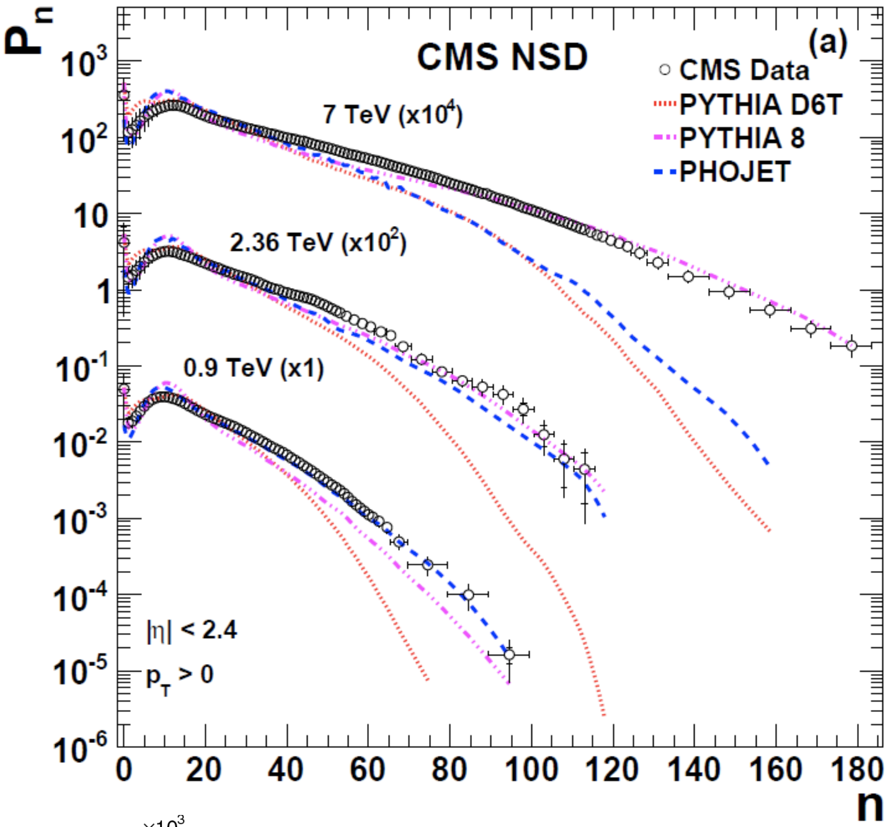


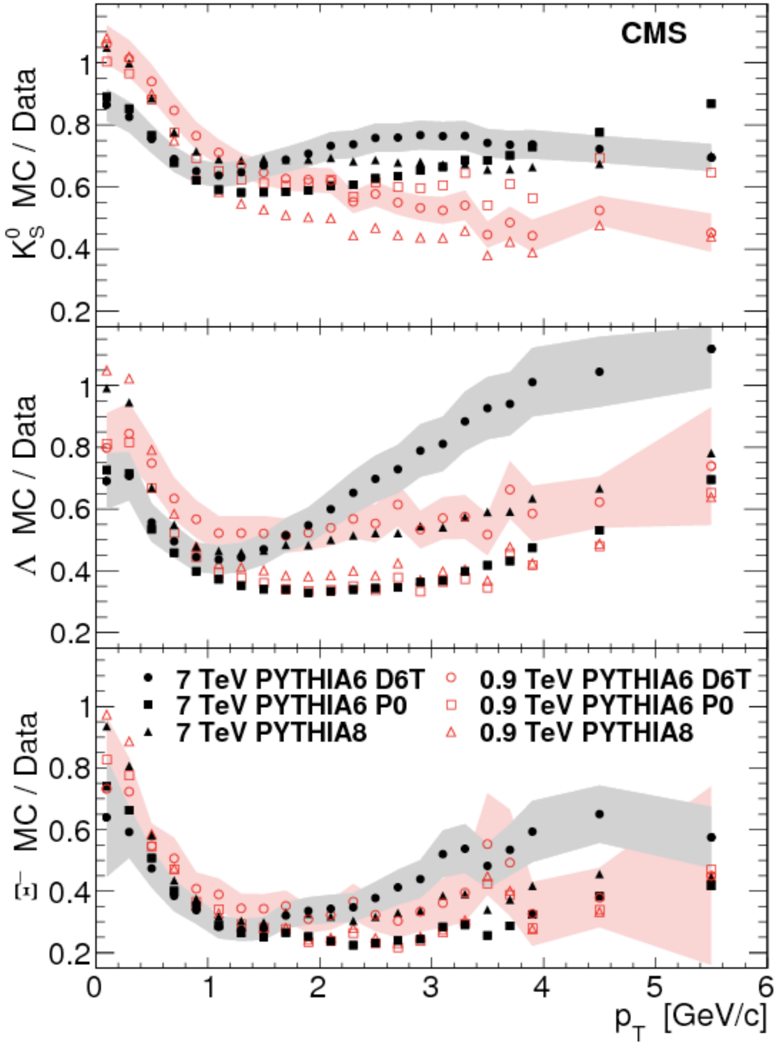
$x_T = 2p_T/\sqrt{s}$

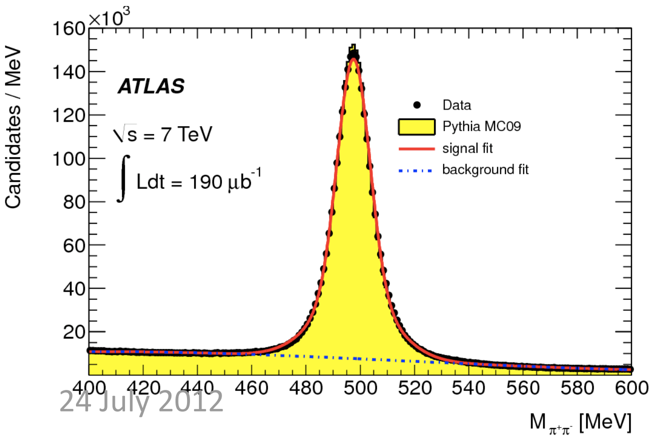


- **Again, several event selections, pT/h acceptances, energies**
  - **Pre-LHC tunes tend to predict too strong events**
  - **Simple xT scaling allows to derive pT spectrum at 2.76TeV, useful for HI**
- **analysis, like jet quenching**

Multiplicities – strange particle production







QCD aspects in W/Z produced with jets

Leptons	ATLAS	CMS
P_t lower cut	>20 GeV	>20(1st) / 10(2nd)GeV
η coverage	e:|η| <2.47 (1.37-1.52 excl.) μ: |η| < 2.4	e:|η| <2.5 (1.44-1.56 excl.) μ: |η| < 2.1
Trigger/reco efficiencies	e: 94% μ: ~85% (T) 90% (R)	e: 80%(1st)/95% (2nd) μ: 85%

Jets	ATLAS	CMS
Anti kt	R = 0.4	R = 0.5
P_t lower cut	P_t>30 GeV (W+ J : 20)	P_t>30 GeV
η coverage	|η| < 2.8	|η| < 2.4
Jet energy scale uncertainty	4-8% (P_t & η depend.)	3-6% (P_t & η depend.)
Lepton-jet sep.	R_{lj} > 0.5	R_{lj} > 0.3

Pileup concerns:

simulated by superimposing minimum bias event generated by Pythia.

CMS treatment:

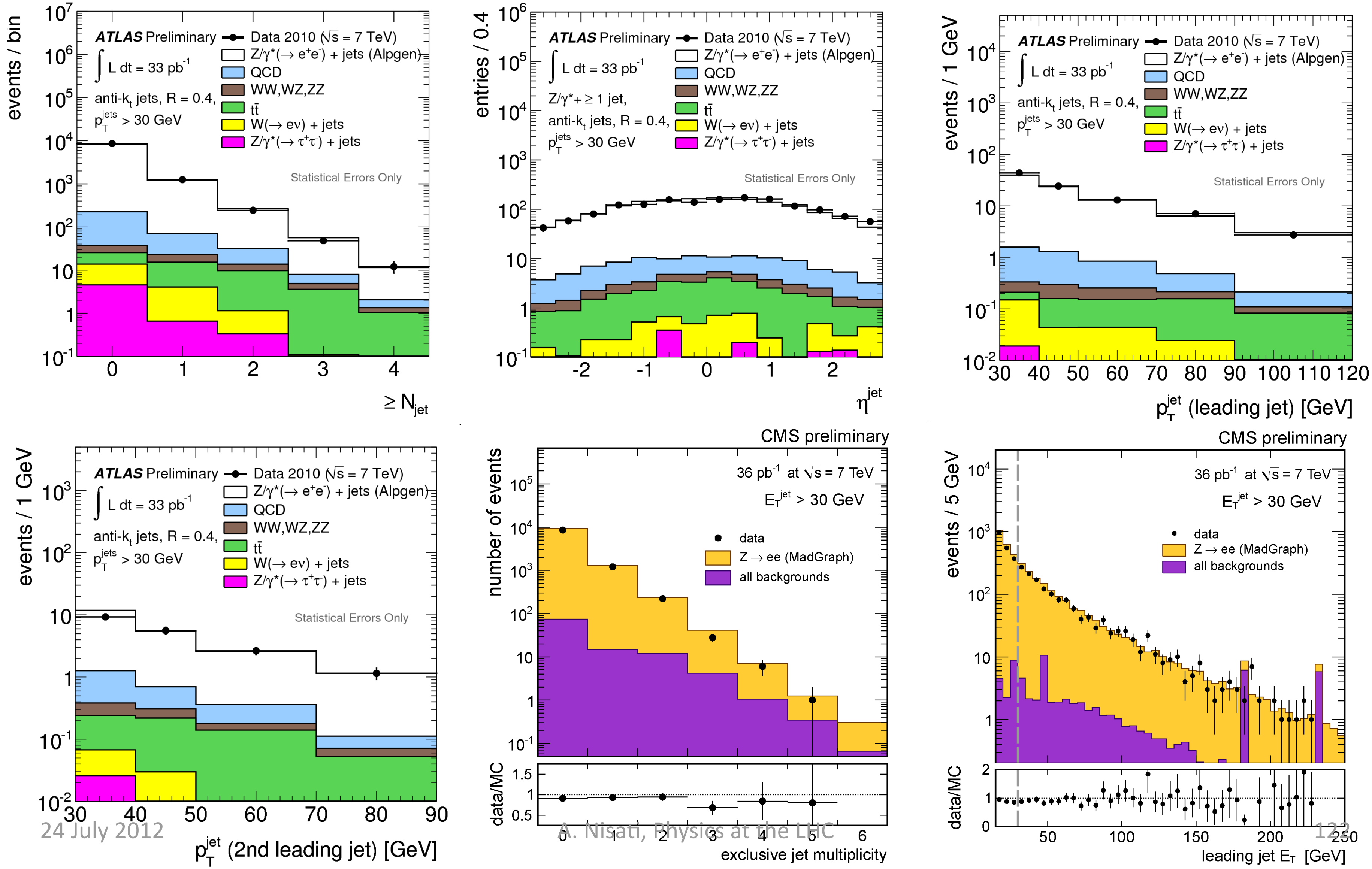
subtraction of an event energy density not related to the hard interaction, estimated as r = median (p_t^{jet}/area(jet))

ATLAS treatment:

reject jets with less than 75% of charged tracks associated to primary vertex (JVF: jet vertex fraction) Jet energy scale uncertainty increased to take into account the additional energy

W,Z+jets: control plots

2 opposite charged leptons with invariant mass in range 60-120(66-116) GeV.



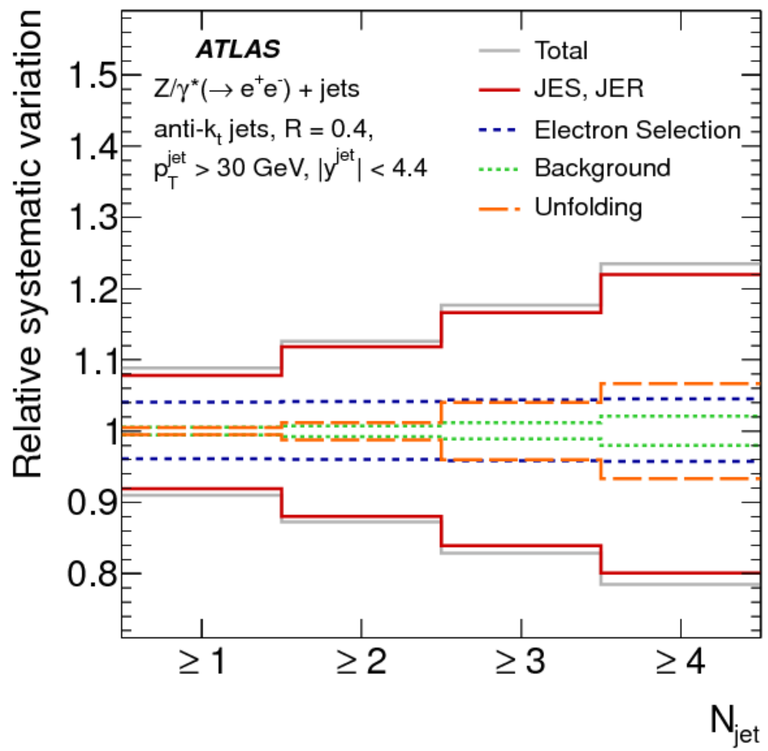
Z+jets: measurements

- Fiducial cross section not corrected for acceptance to avoid model dependence (acceptance within lepton/jet fiducial and kinematic cuts beforementioned).

$$\frac{d\sigma}{d\alpha} = \frac{N_{data} - N_{background}}{\int L dt} \times U(\alpha)$$

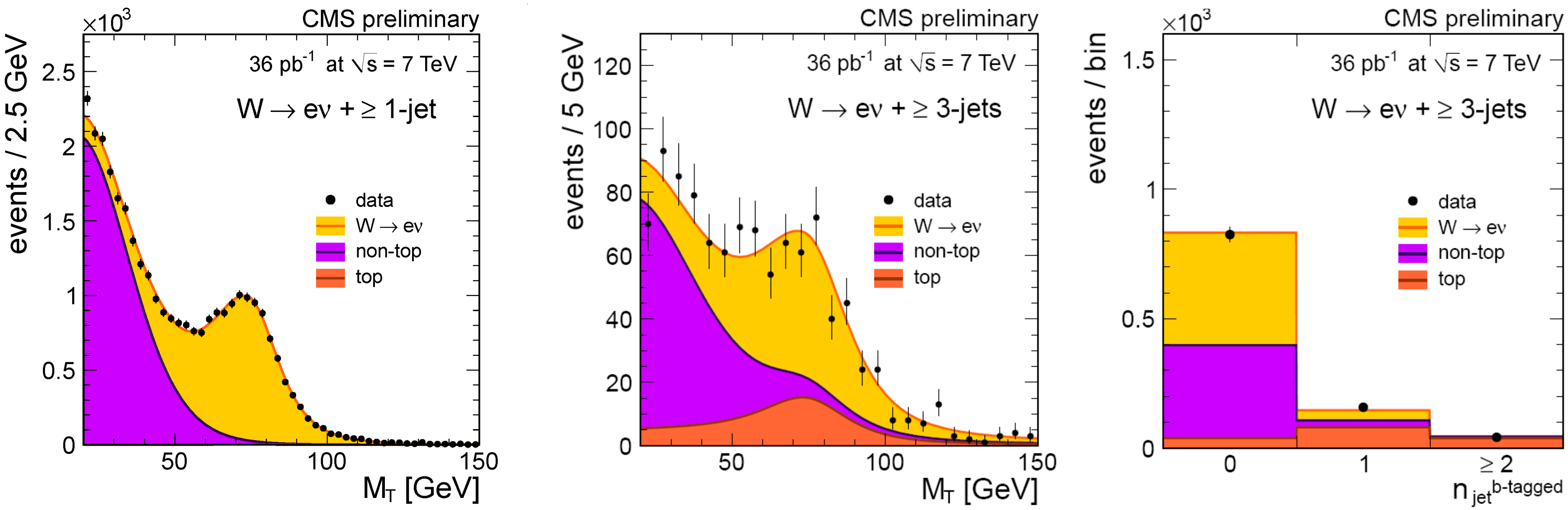
Unfolding coefficient to correct for detector effects: efficiencies (trigger/ reconstruction/selection), resolution.
α: p_t^{jet} , N_{jets}

Source	ATLAS	CMS
Jet energy scale	10-20%	8-16%
Pile up	4%	
Unfolding	5-7%	Not avail.
Lepton selection	5-6%	2-10%
QCD background	2%	-
Jet energy resolution	<1%	<1%
Total	13-24%	10-25%



W+jets measurement

- Background treatment very similar to Z+jets analysis:
  - Shapes derived from simulation except the QCD multijets derived from data in ATLAS (for the electron final state).
  - Global fit of E_t^{miss} (ATLAS) / M_t+$n_{b\text{-}jet}$(CMS) to derive level of background.

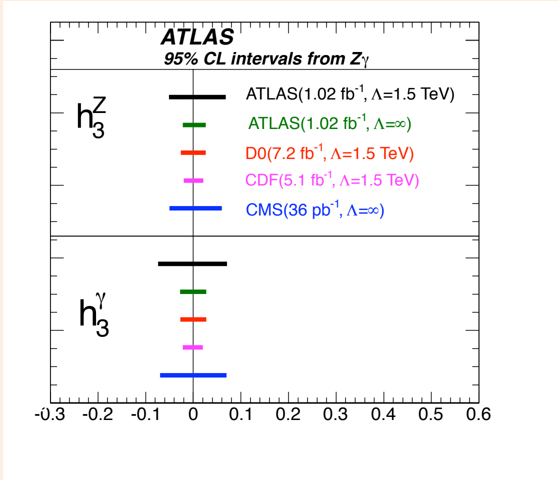


- Unfolding method used again to derive fiducial cross sections:
  - Systematic error still dominated by jet energy scale (additional contributions by jet energy resolution/lepton energy scale/ E_t^{miss}).
  - Systematic error largely dominant (vs statistical one) for n=1;2.

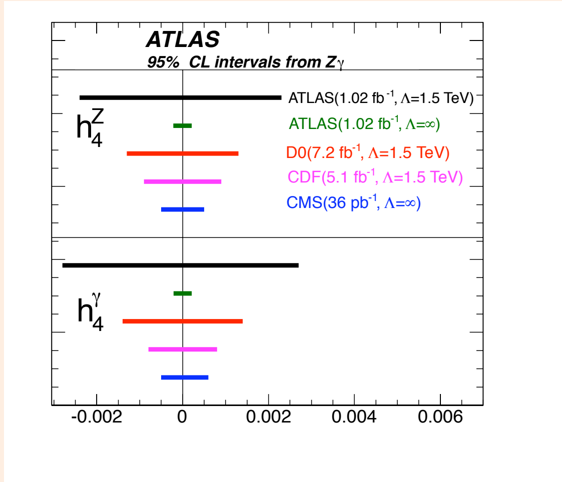
TGCs

- Measure the diboson cross section production
- Express this as a function of the gauge coupling parameters free
- Measure the gauge couplings and compare with SM

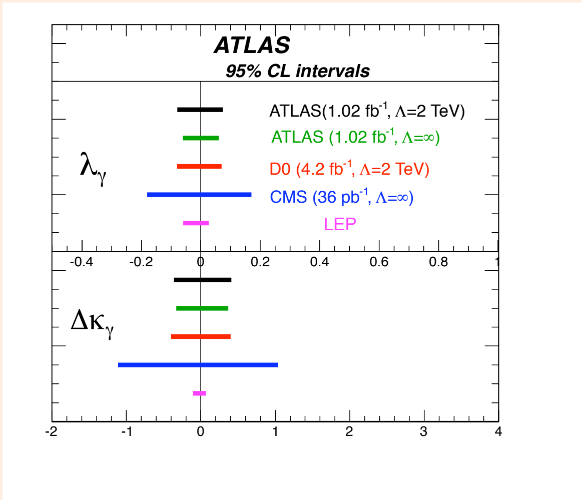
ZZγ and Zγγ vertices



ZZγ and Zγγ vertices



WWγ vertex



LHC TGC measurements competitive with Tevatron.

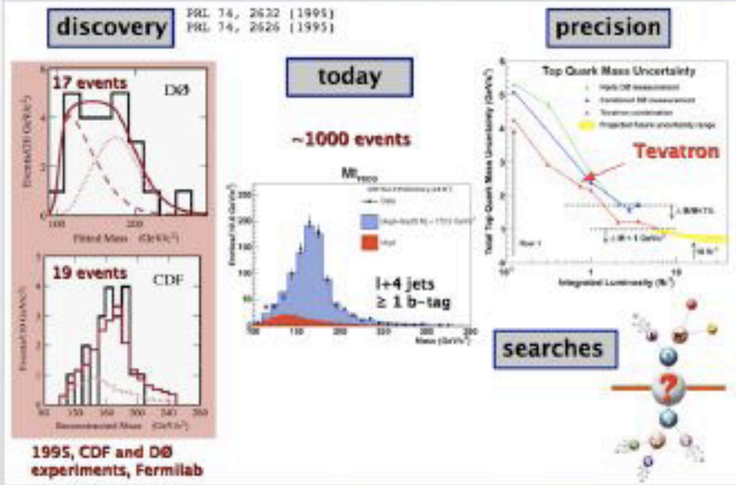
More data will improve the accuracy of these estimates

Current results don't show any significant anomaly

Short History of TOP

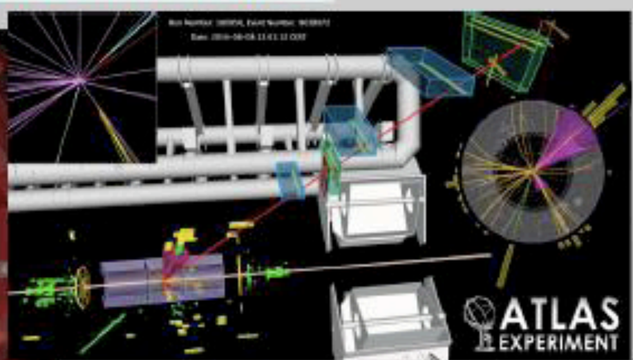
1995: Discovery of the top quark

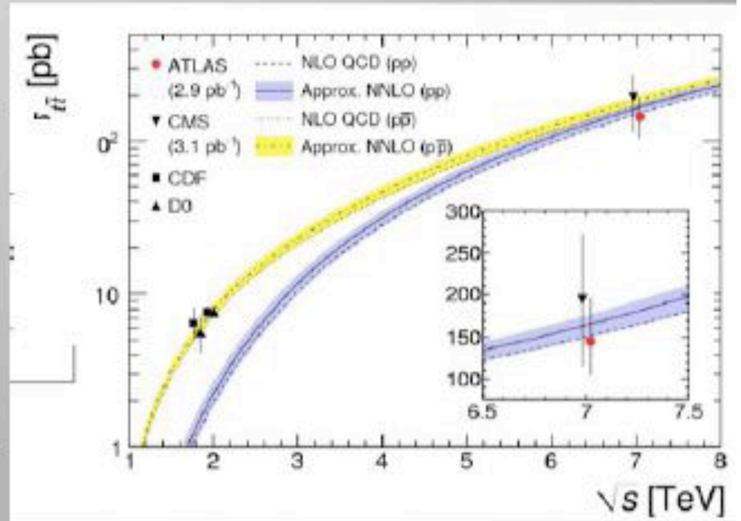
- in 1995 D0 and CDF observed and excess of events consistent with $p\bar{p} \to t\bar{t} \to W^+bW^-\bar{b}$



2009: Discovery of the single top production

July 2010: First top in Europe

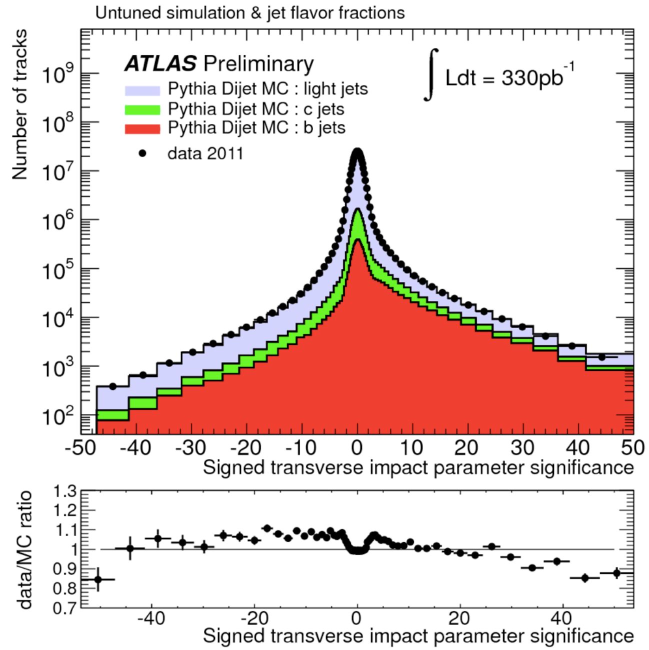




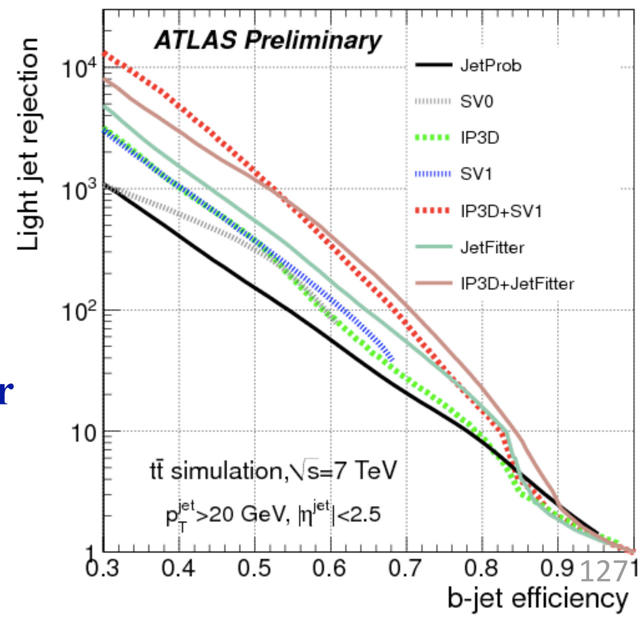
By end 2010: LHC top measurements

b-tagging algorithms

- *Several algorithms of different complexity and performance are employed*
- **JetProb** (IP based): it signs the transverse and longitudinal impact parameters of tracks with respect to the primary vertex. It also build a probability that the tracks in the jet originate from the primary vertex
- **SV0** (SV based): it reconstruct the inclusive vertex formed by the decay products of the b-hadron, including products of the eventual subsequent c-hadron decay
- **IP3D**: likelihood ratio using transverse and longitudinal IP distributions;
- **SV1**: likelihood ratio using mass, energy fraction and number of two-tracks vertices insecondary vertex
- **JetFitter** (multivertex fit): neural network aiming at reconstucting both B and D decay vertices
- Combination of some of the above methods



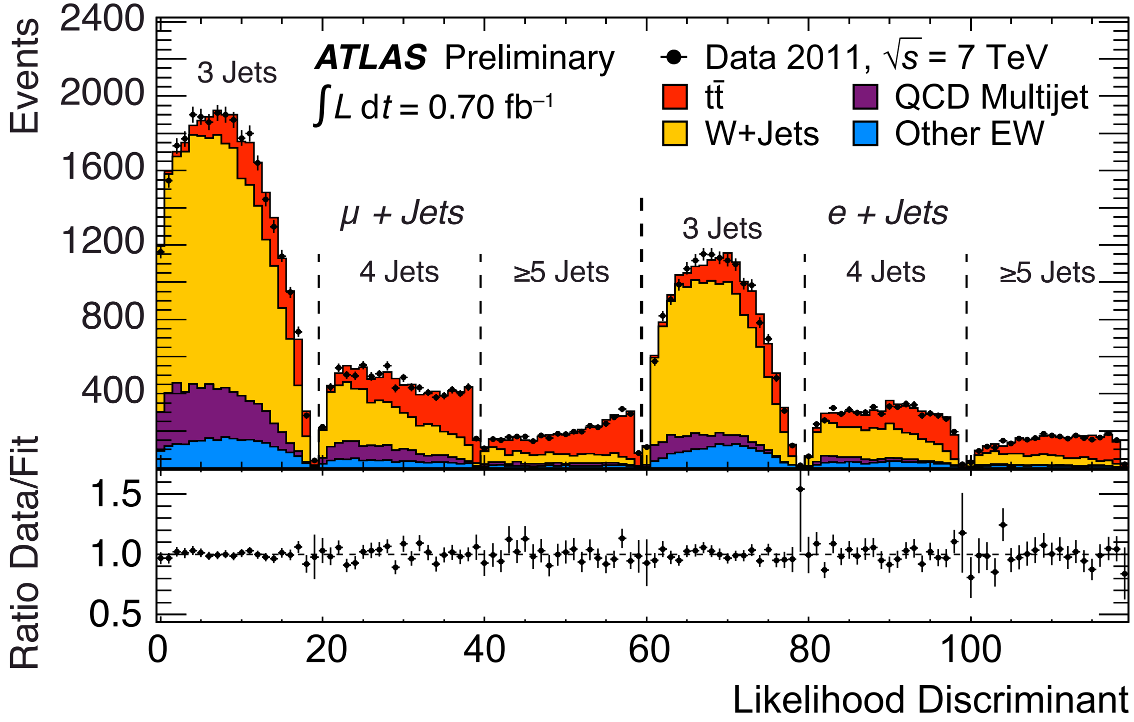
Light-jet rejection as a function of the b-jet tagging efficiency for the early tagging algorithms (JetProb and SV0) and for the high performance algorithms, based on simulated top-antitop events.



ttbar production in lepton+jet final states

- Recent study of lepton+jets final states using 0.7 fb^{-1}.

ATLAS-CON-2011-121

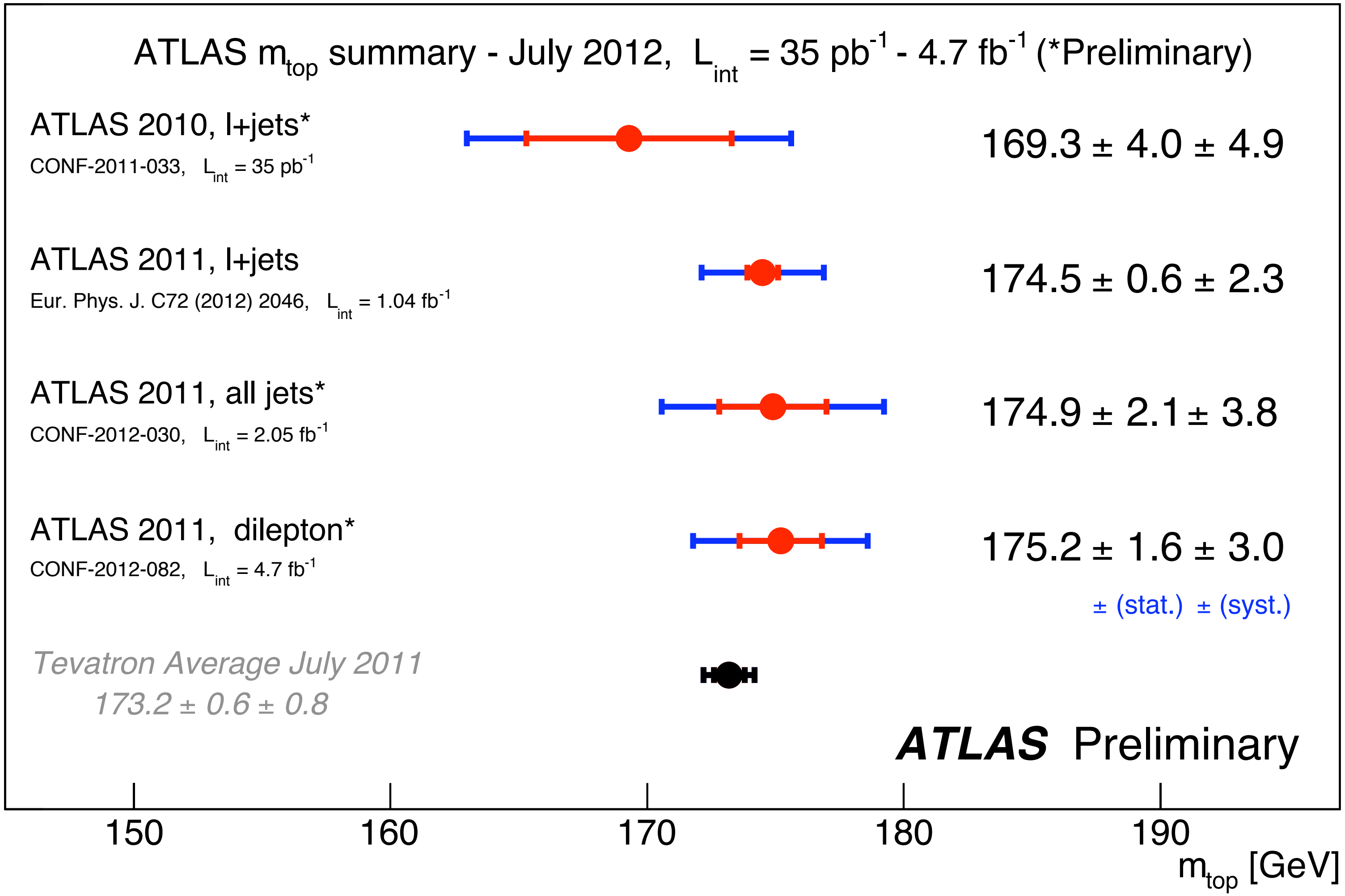


- Main systematic uncertainties:
  - MC Signal generator
  - Jet Energy Scale
  - ISR+FSR
- Likelihood Discriminant : study lepton eta, highest jet p_T, event aplanarity, HT

$$\mathcal{L}(\vec{\beta},\vec{\delta}) = \prod_{k=1}^{120} \mathcal{P}(\mu_k, n_k) \times \prod_j \mathcal{G}(\beta_j, \Delta_j) \times \prod_i \mathcal{G}(\delta_i, 1)$$

β=free parameter, δ=nuisance parameter

σ(comb.)=179.0±3.9(stat.)±9.0(syst.)±6.6(lumi.) pb   δσ/σ = 6.6%


ATLAS m_{top} summary - July 2012, L_{int} = 35 pb^{-1} - 4.7 fb^{-1} (*Preliminary)
ATLAS 2010, l+jets*
CONF-2011-033, L_{int} = 35 pb^{-1}
169.3 ± 4.0 ± 4.9
ATLAS 2011, l+jets
Eur. Phys. J. C72 (2012) 2046, L_{int} = 1.04 fb^{-1}
174.5 ± 0.6 ± 2.3
ATLAS 2011, all jets*
CONF-2012-030, L_{int} = 2.05 fb^{-1}
174.9 ± 2.1 ± 3.8
ATLAS 2011, dilepton*
CONF-2012-082, L_{int} = 4.7 fb^{-1}
175.2 ± 1.6 ± 3.0
± (stat.) ± (syst.)
Tevatron Average July 2011
173.2 ± 0.6 ± 0.8
ATLAS Preliminary
150
160
170
180
190
m_{top} [GeV]