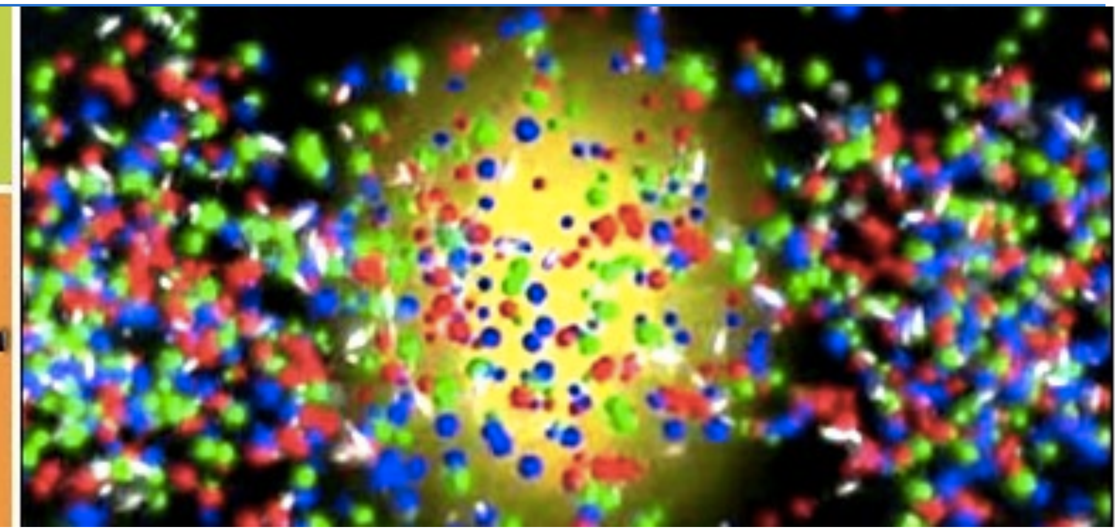
Dubna International Advanced
School of Theoretical Physics

Helmholtz International Summer School
"Physics of Heavy Quarks and Hadrons"
July 15-28, 2013, JINR, Dubna, Russia



The lessons of LHC
(Higgs boson and SUSY)

Dmitry Kazakov

BLTP JINR

The Higgs Boson

Questions:

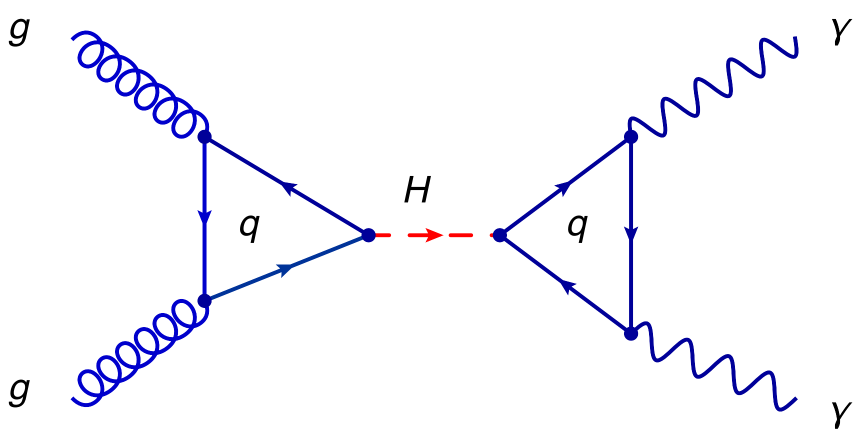
- Is it the Higgs boson?
- Is it the SM Higgs boson?
- Are there deviations from the SM?
- What are the alternatives?

Warning:

Statistics is still low for an ultimate judgement, be patient

Is it the Higgs boson? Is it 0^+ state?

Production and decay into γγ



L.Landau'48, C.-N.Yang'50

Spin= 0, ~~1/2~~, ~~1~~, ~~3/2~~, 2

Decay into WW

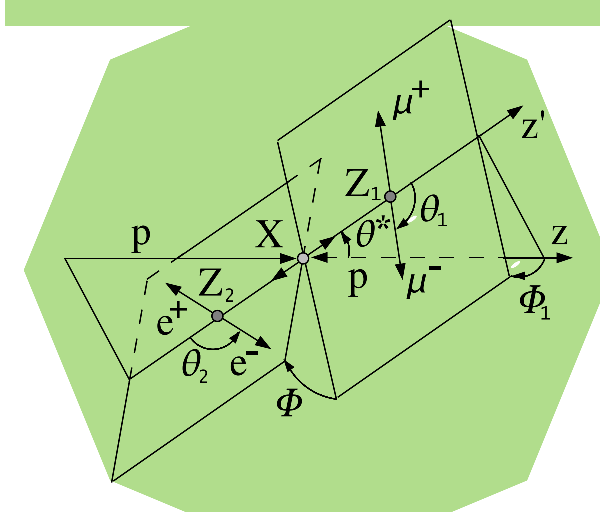
$$Ł = \frac{g^2}{4}(v+h(x))^2 W^+_\mu W^{-\mu}$$
$$= m_W^2 W^+_\mu W^{-\mu} + \frac{2m_W^2}{v} h\ W^+_\mu W^{-\mu} + \cdots$$

Decay into ZZ

$$Ł = A\frac{\alpha}{4\pi}\frac{1}{M} h\ F_{\mu\nu}F^{\mu\nu} + B\frac{\alpha}{4\pi}\frac{1}{M} h\ \epsilon_{\mu\nu\lambda\sigma}F^{\mu\nu}F^{\lambda\sigma}$$

Angular distribution

$$pp \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$$



Y.Gao et al'10, A.De Rujula et al'10

66% CL scalar

S.Baffoni et al, CMS'12

Is it the Higgs boson? Is it 0^+ state?

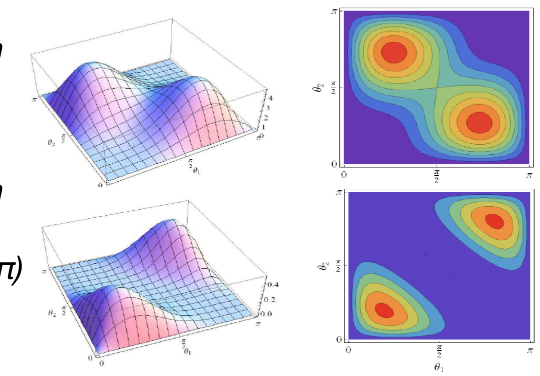
Preliminary results ATLAS/CMS

$$pp \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$$

G. Tonelli, CERN/INFN/UNIPI

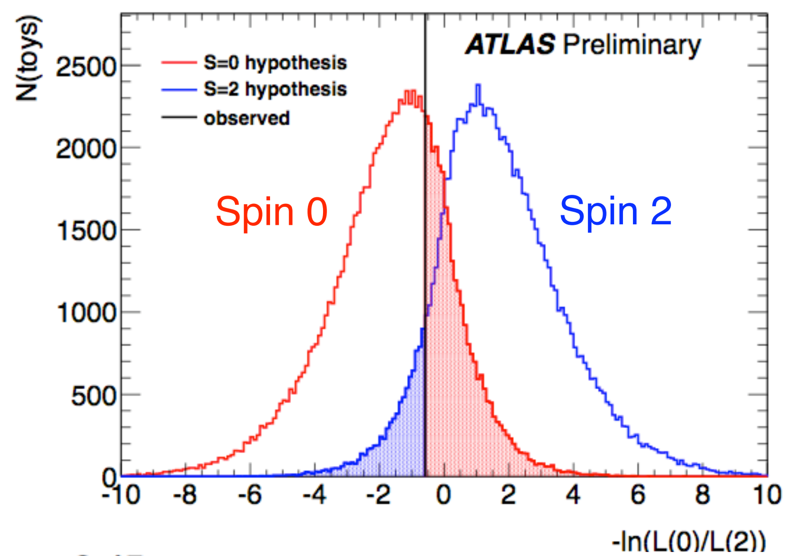
Polar angle distribution for $X_2 \to W^+W^-$

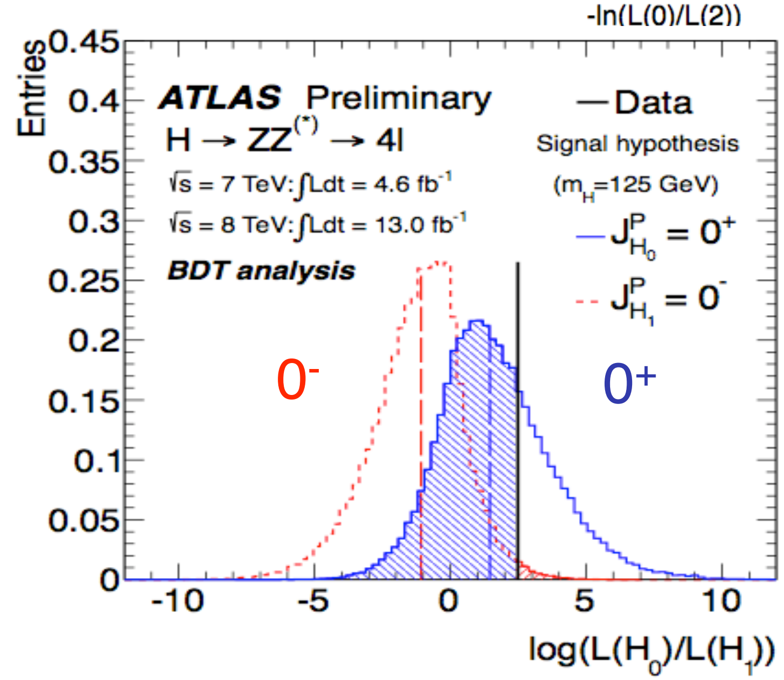
Polar angle distribution for $X_0 \to W^+W^-$ (for $\phi = \pi$)

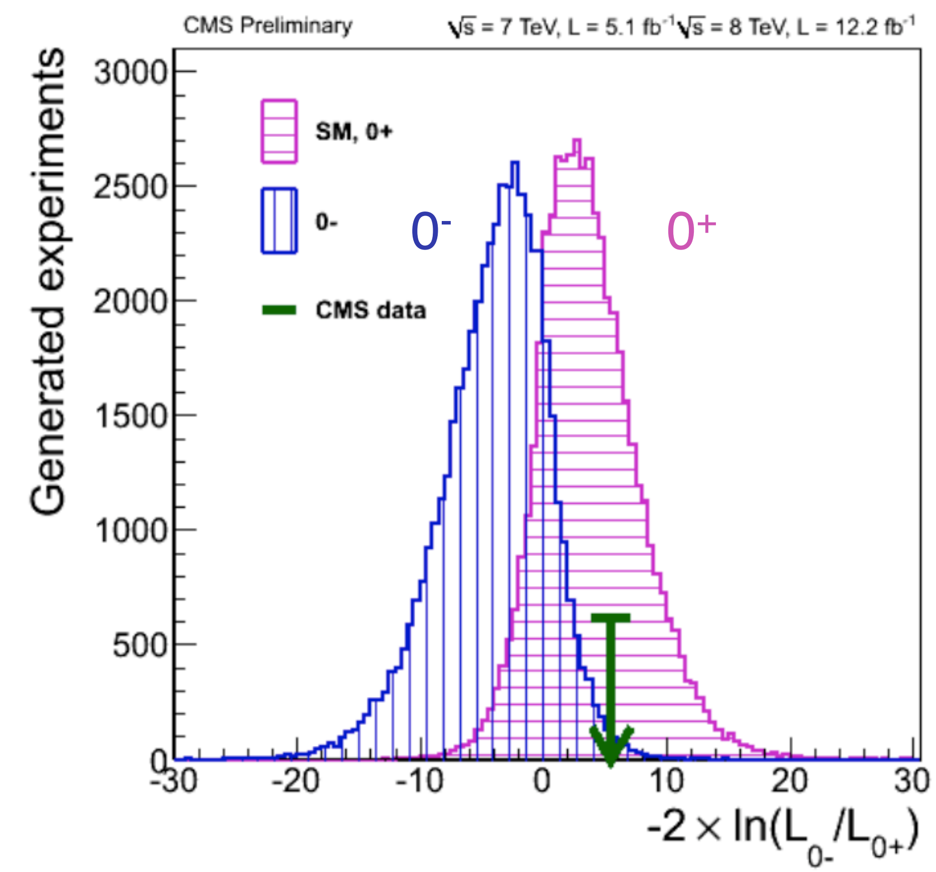


1) gg →X→γγ qq →X→γγ
spin-0: flat in cosθ*
spin-2: quartic in cosθ*

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$$

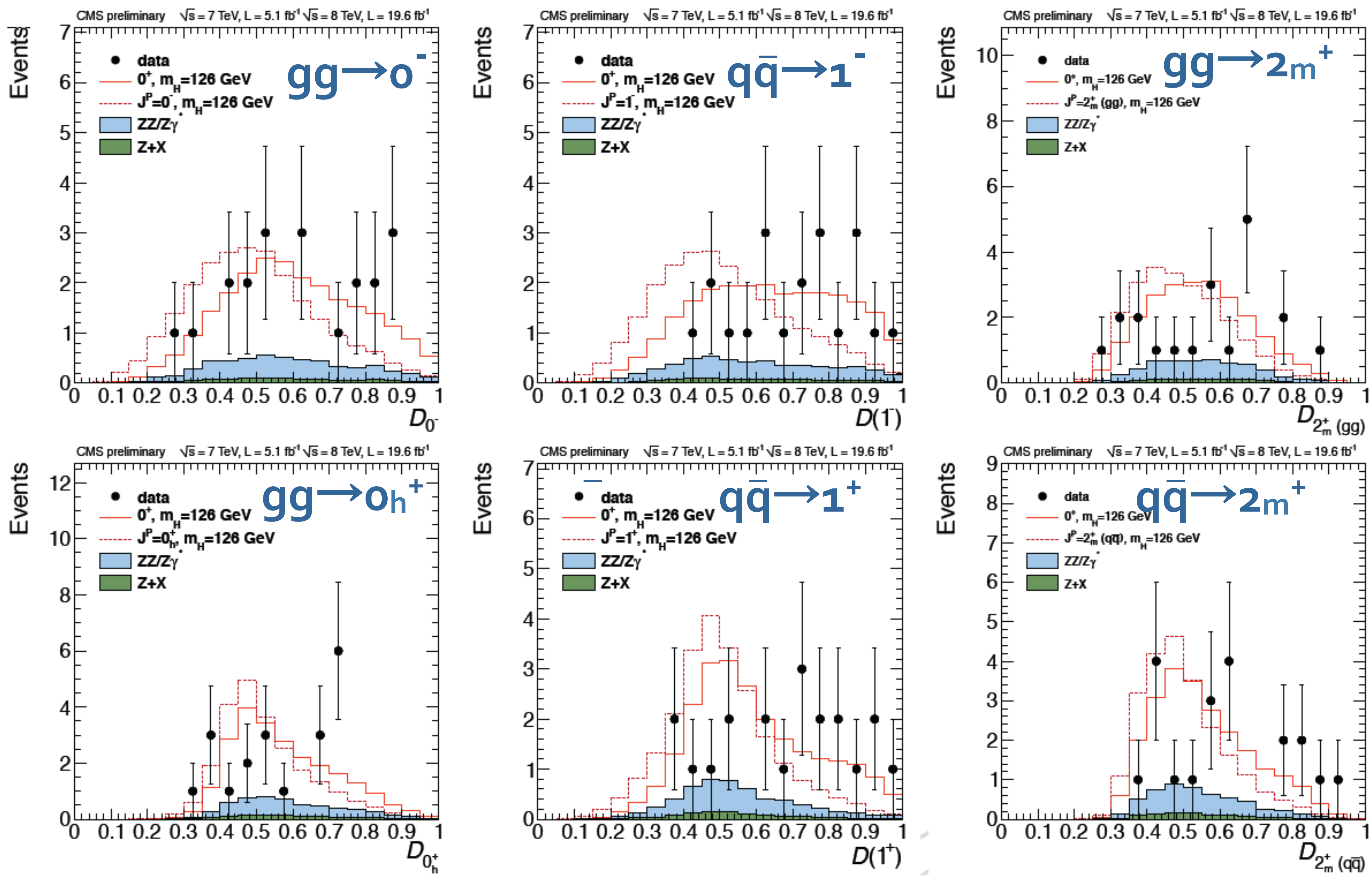




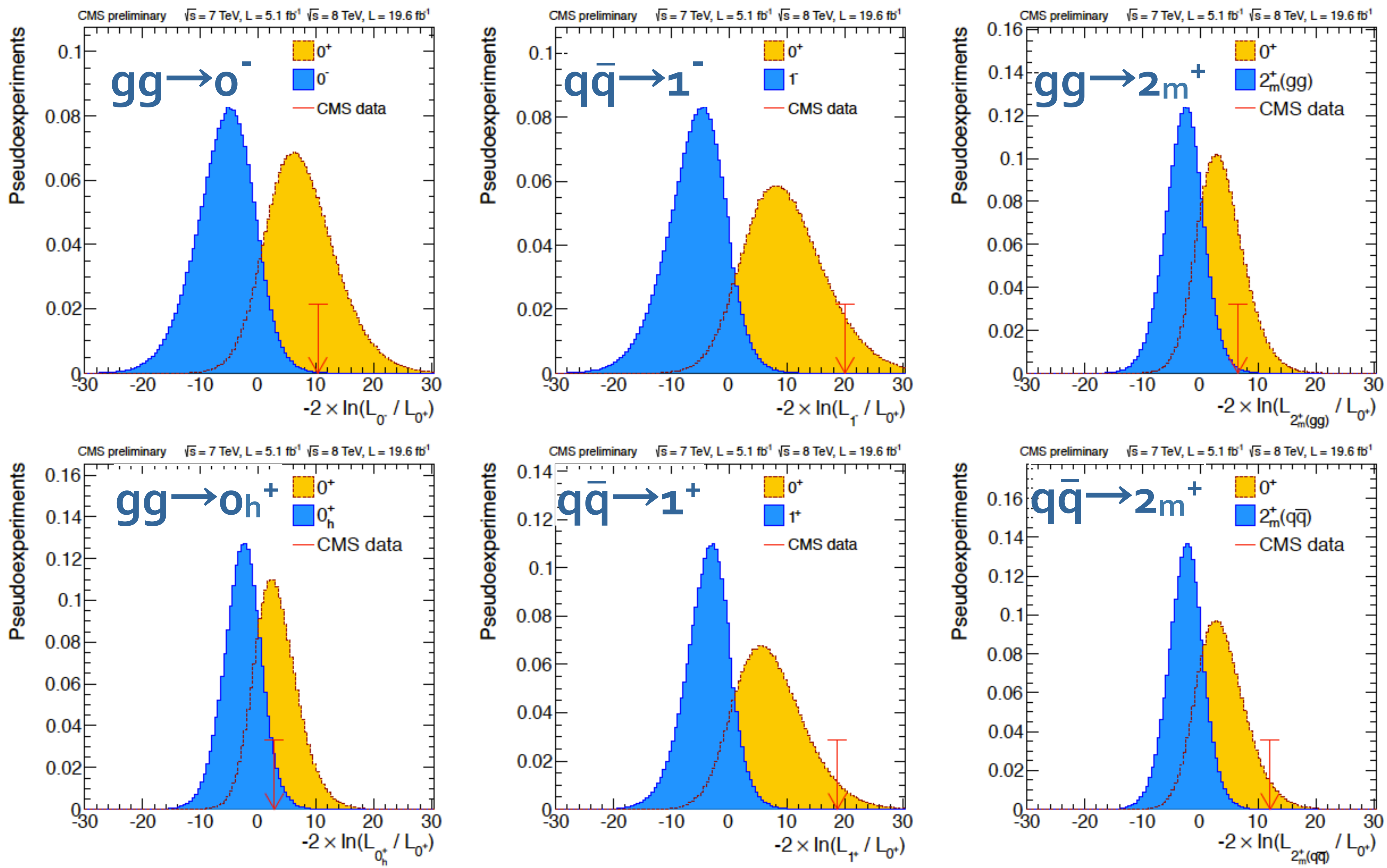


Preliminary results on scalar/pseudo-scalar; observation consistent with 0^+ (0^-) within **0.5 (2.45) σ.**

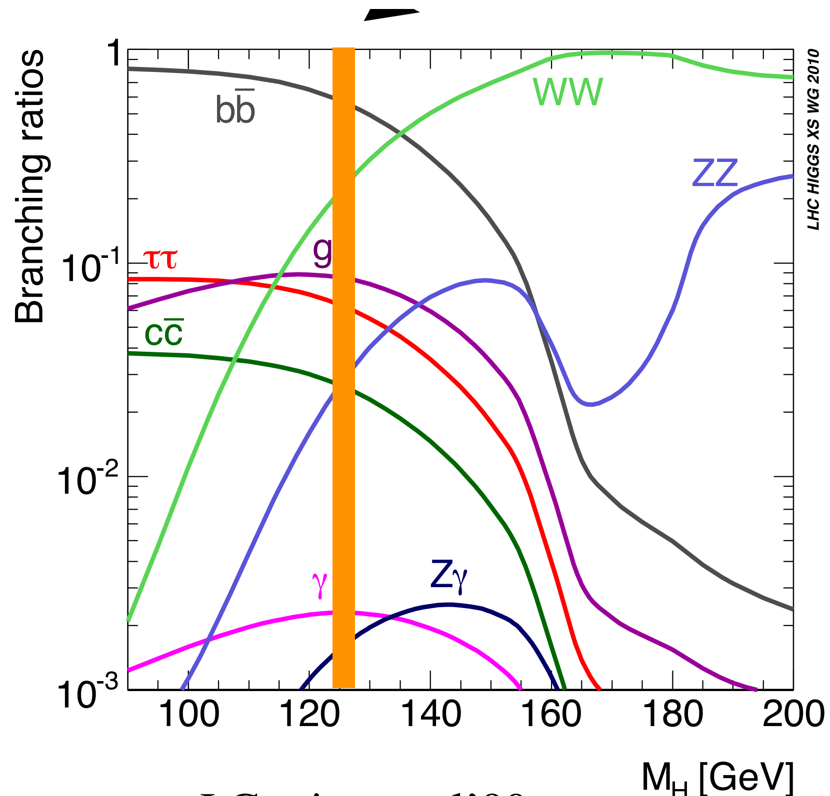
D_{JP} distributions (with D_{bkg}>0.5)



Spin-parity: test statistics



Decay modes



J.Gunion et al'90

for 126 GeV Higgs

$b\bar{b}$	56%	$\tau^+\tau^-$	6.2%	$\gamma\gamma$	0.23%
WW^*	23%	ZZ^*	2.9%	γZ	0.16%
gg	8.5%	$c\bar{c}$	2.8%	$\mu^+\mu^-$	0.02%

1. $\gamma\gamma$ decay mode: Observed (4.5 σ in ATLAS, 4.1 σ in CMS) .
2. ZZ^* decay mode: Observed (3.6 σ in ATLAS, 3.2 σ in CMS) .
3. WW^* decay mode: Observed (2.8 σ in ATLAS, 1.6 σ in CMS) .
4. $b\bar{b}$ decay mode: Observed (2.8 σ in CDF/D0 combination)
5. $\tau\bar{\tau}$ decay mode: Not observed yet

All these decays are consistent with the Higgs boson

Is it quantitatively consistent with the SM?

Is the Higgs Standard Model-like or not?

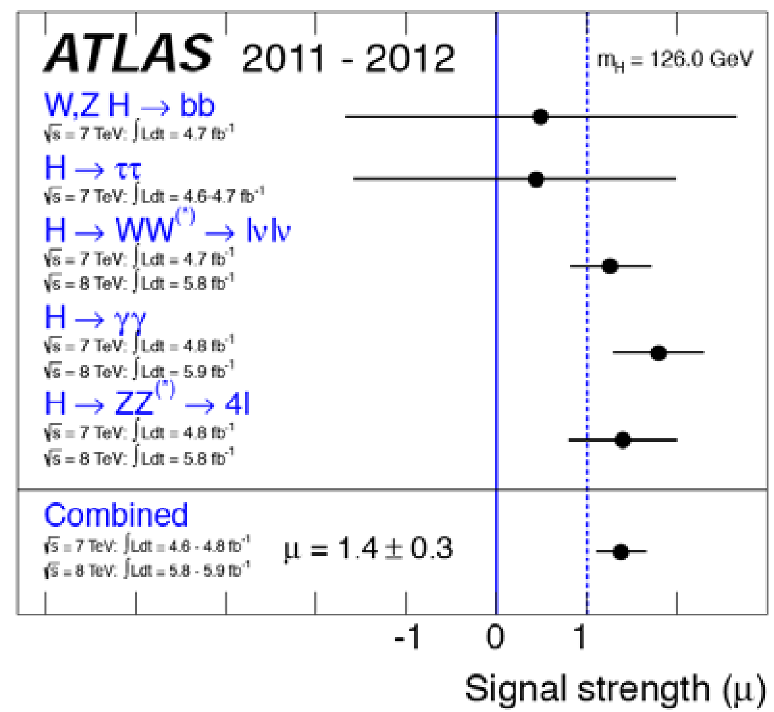
$$\mu = \sigma \cdot BR / (\sigma \cdot BR)|_{SM}$$

Conclusion (so far)

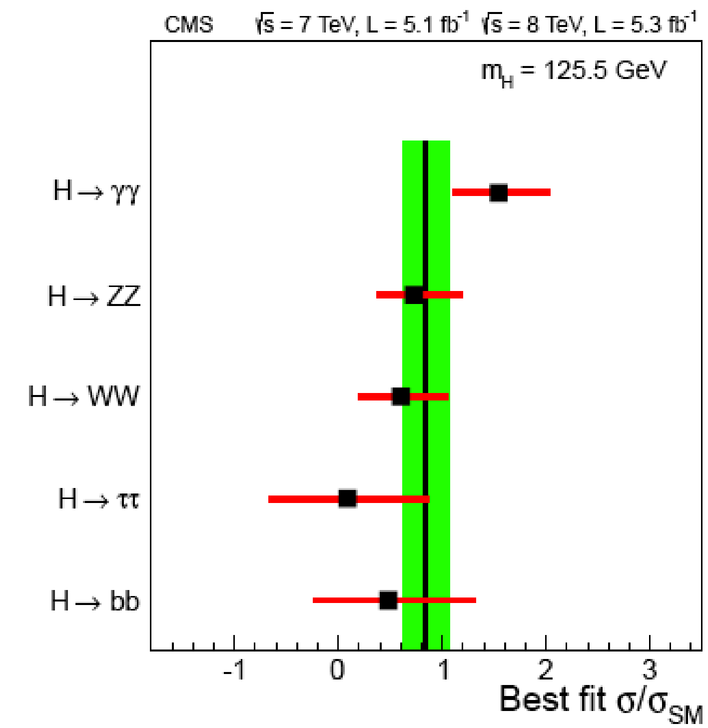
1. too much $\gamma\gamma$, $\mu_{ATLAS} = 1.8 \pm 0.5$
   $\mu_{CMS} = 1.56 \pm 0.43$
2. too few $b\bar{b}$, $\mu \sim 0.7$
3. no $\tau\bar{\tau}$
4. WW, ZZ about all right

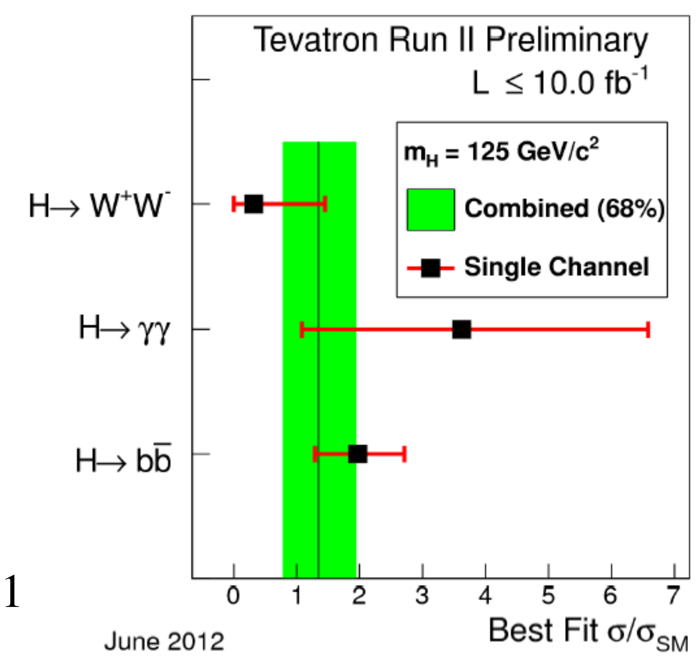
$$\begin{aligned} \mu(ZZ^{(*)} \to 4l)_{\text{ATLAS}} &= 1.4 \pm 0.6, \\ \mu(ZZ^{(*)} \to 4l)_{\text{CMS}} &= 0.7^{+0.4}_{-0.3}, \\ \mu(WW^{(*)} \to l\nu l\nu)_{\text{ATLAS}} &= 1.3 \pm 0.5, \\ \mu(WW^{(*)} \to l\nu l\nu)_{\text{CMS}} &= 0.6 \pm 0.4. \end{aligned}$$

G. Aad et al. [ATLAS]'12



S. Chatrchyan et al. [CMS]'12





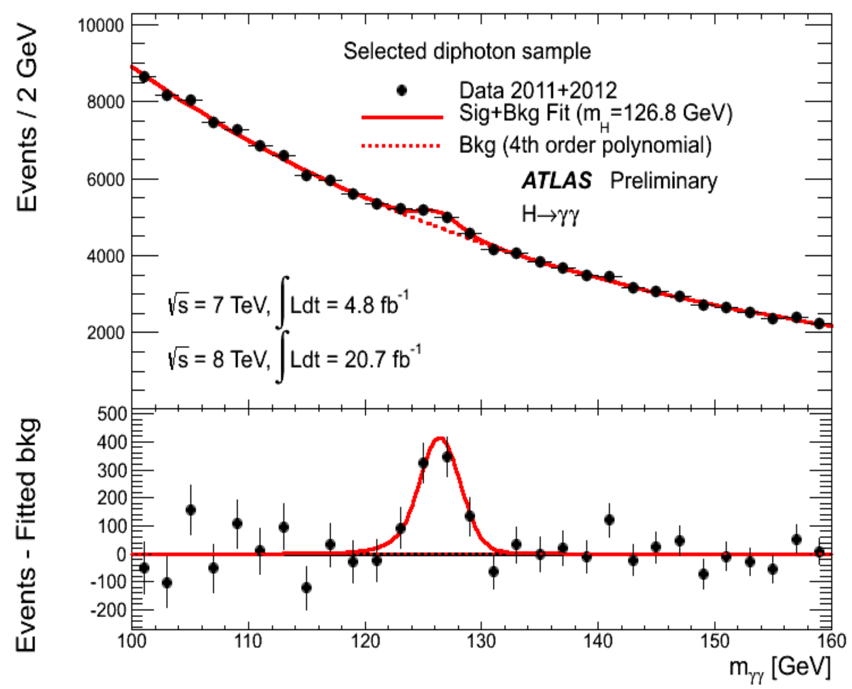
J. Haley et al, CDF/D0'12

Theoretical suggestions

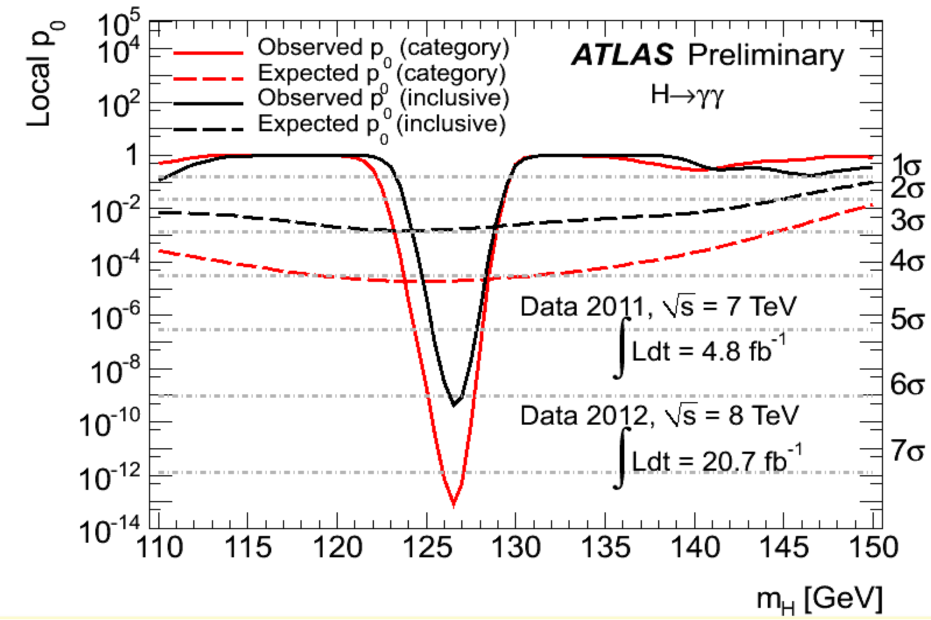
1. Extended Higgs sector — U.Ellwanger'11, J.Gunion et al'12
2. Colour singlet matter particles (stau) — M.Carena et al'11
3. New coloured matter particles (stop) — Z. Kang et al'11
4. Strongly interacting Higgs sector — J.Espinosa et al'12, F.Goertz et al'11

Higgs->γγ

- **Update from ATLAS**

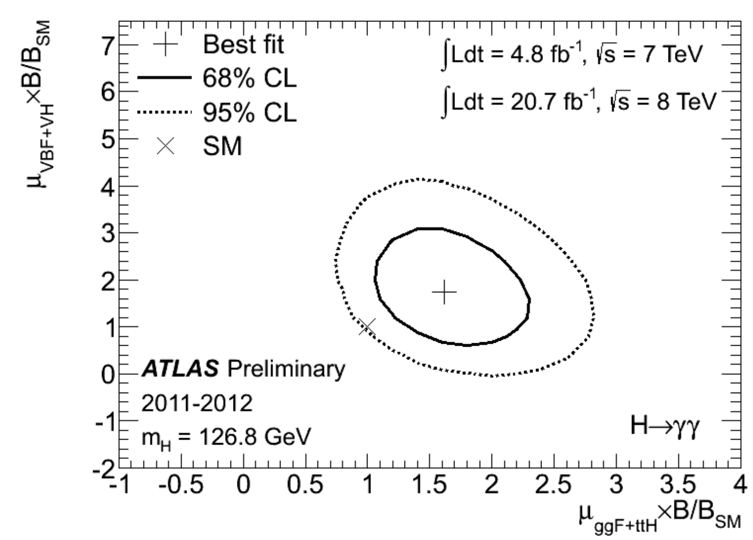


Mass window ~125 GeV with 90% signal: S/B~3%



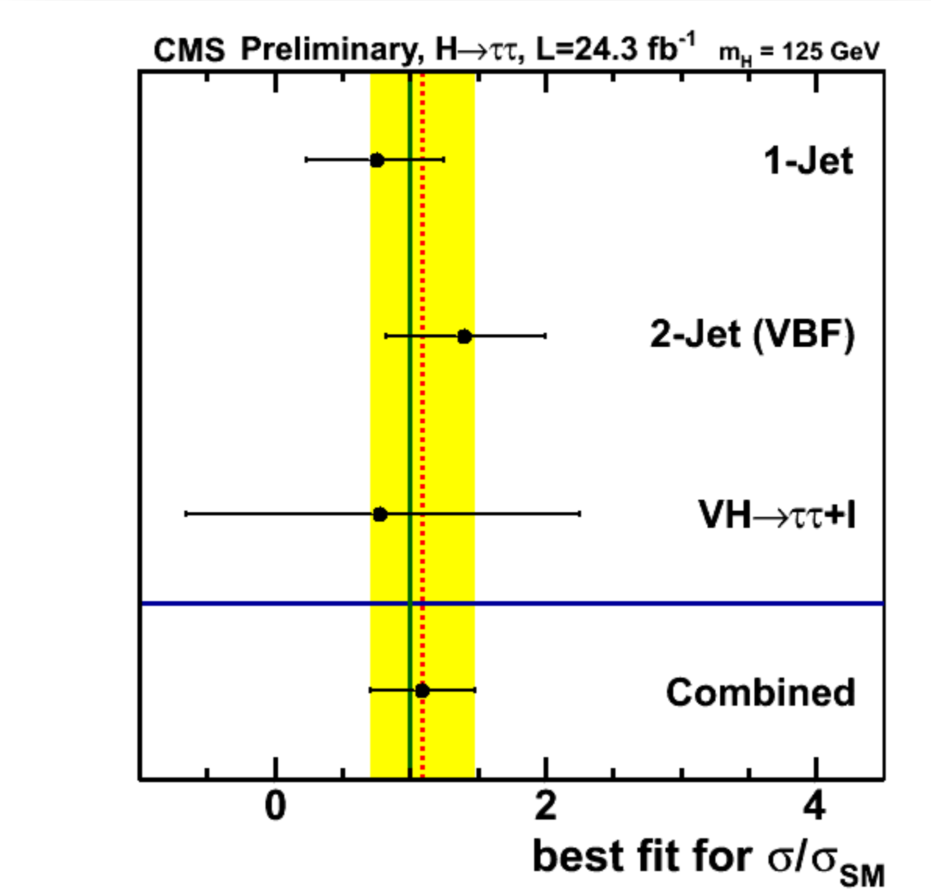
Significance; obs: 7.4σ; exp: 4.1σ

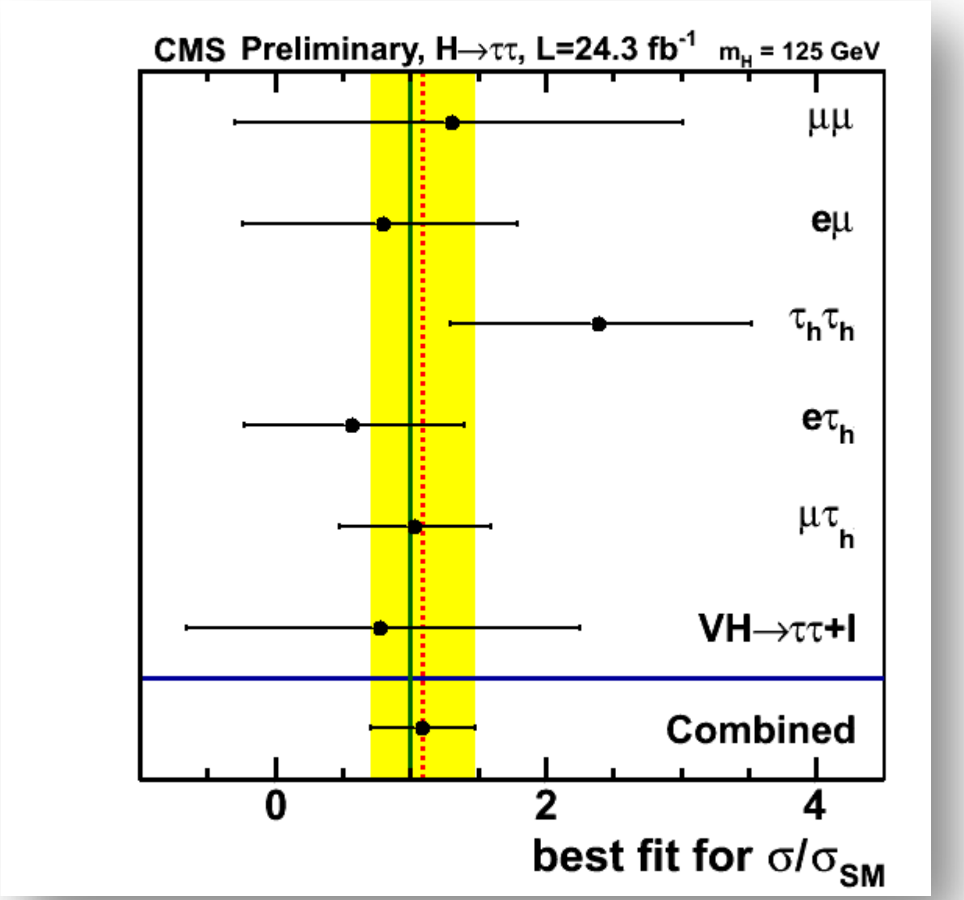
Mass: 126.8 ± 0.2(stat) ± 0.7(sys) GeV



Higgs->TT

- **Yields by "type" and by decay channel**





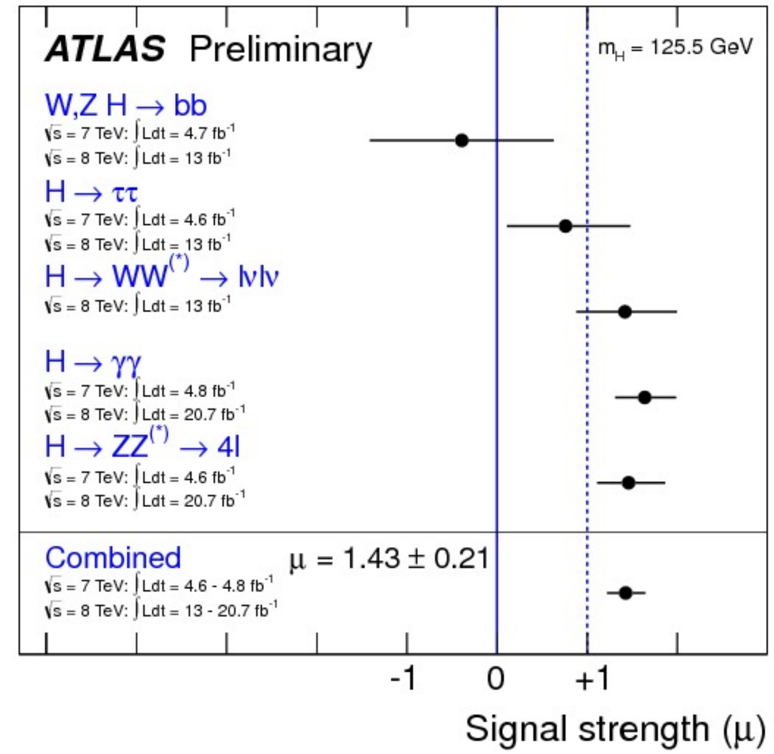
- Consistent picture across channels and categories
- Combined best-fit $\hat{\mu}$ of **1.1±0.4**

Signal Strength

- **Parameter of interest : μ (global)**

⇒ μ = 1.43 ± 0.16 (stat) ± 0.14 (sys)

Council Dec 2012 μ = 1.35 ± 0.19 (stat) ± 0.15 (sys)

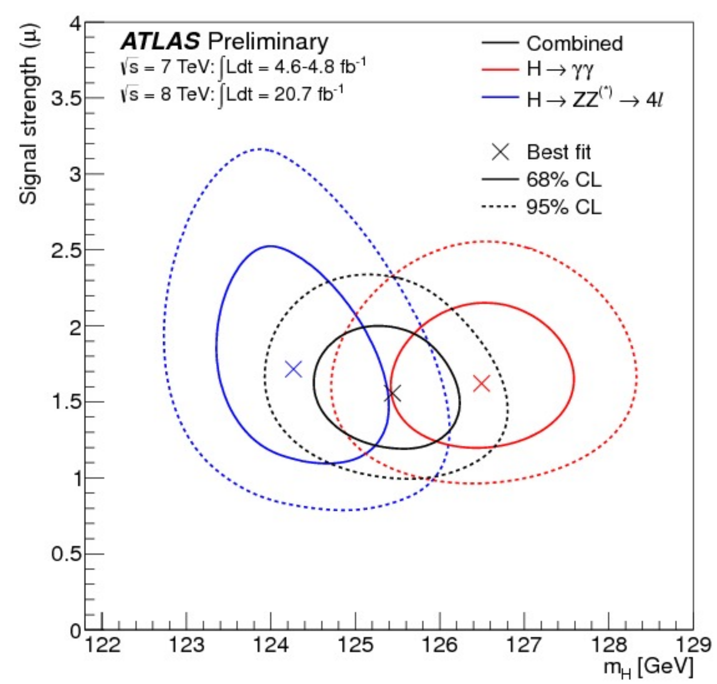


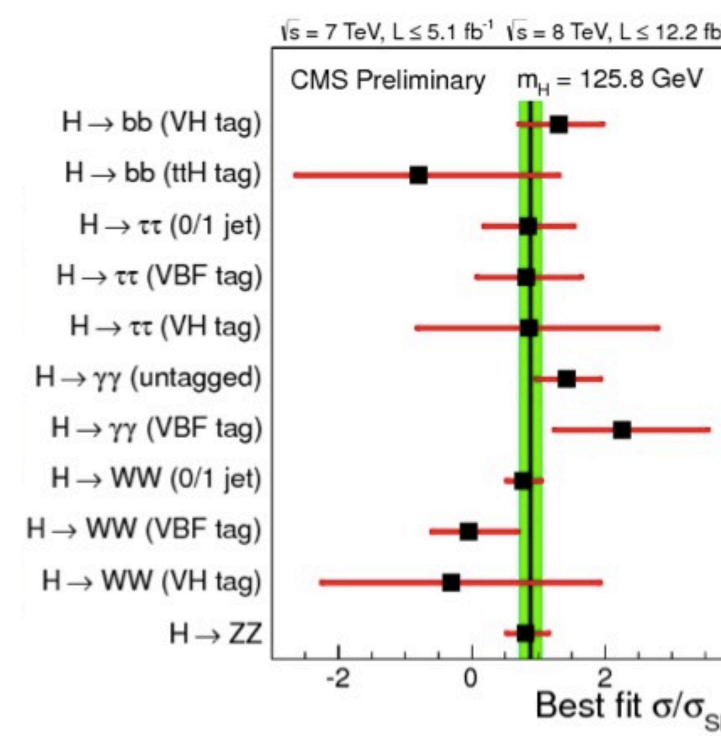
at m_H = 125.5

[124.5-126.5]:
μ ± 4%

- **Consistency tests**
  - **global μ with SM: 3%**
    - 11% with rectangular QCD scale and parton dist functions
  - **5 μ_i with SM: 8%**
  - **5 μ_i with 1.43: 32%**

- **μ, m_H contours**
  - **γγ**
  - **4l**
  - **combined**





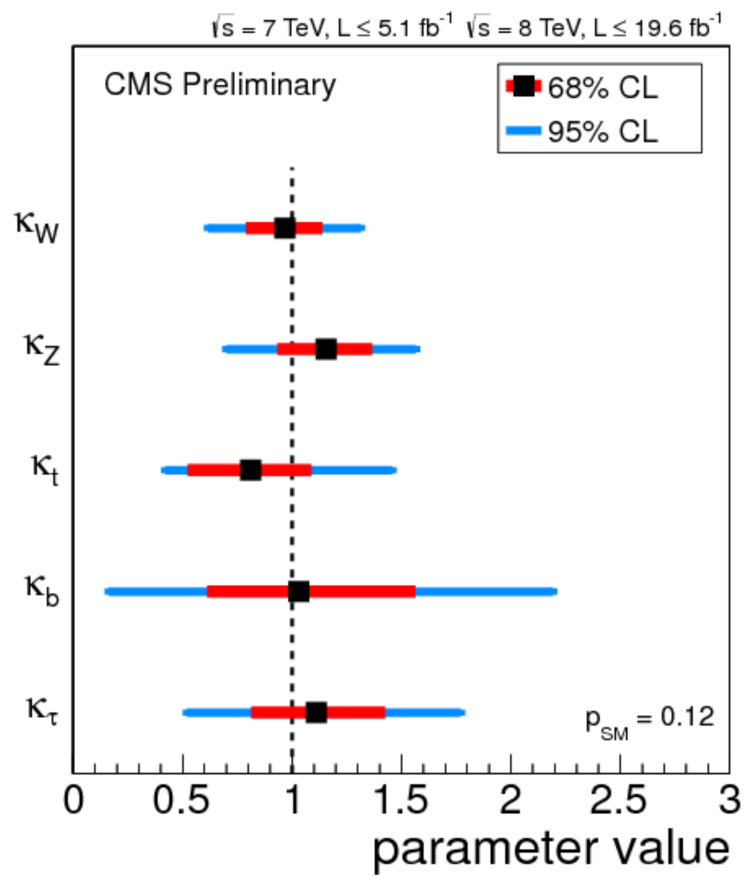
σ/σ_{SM} = 0.88 +/- 0.21

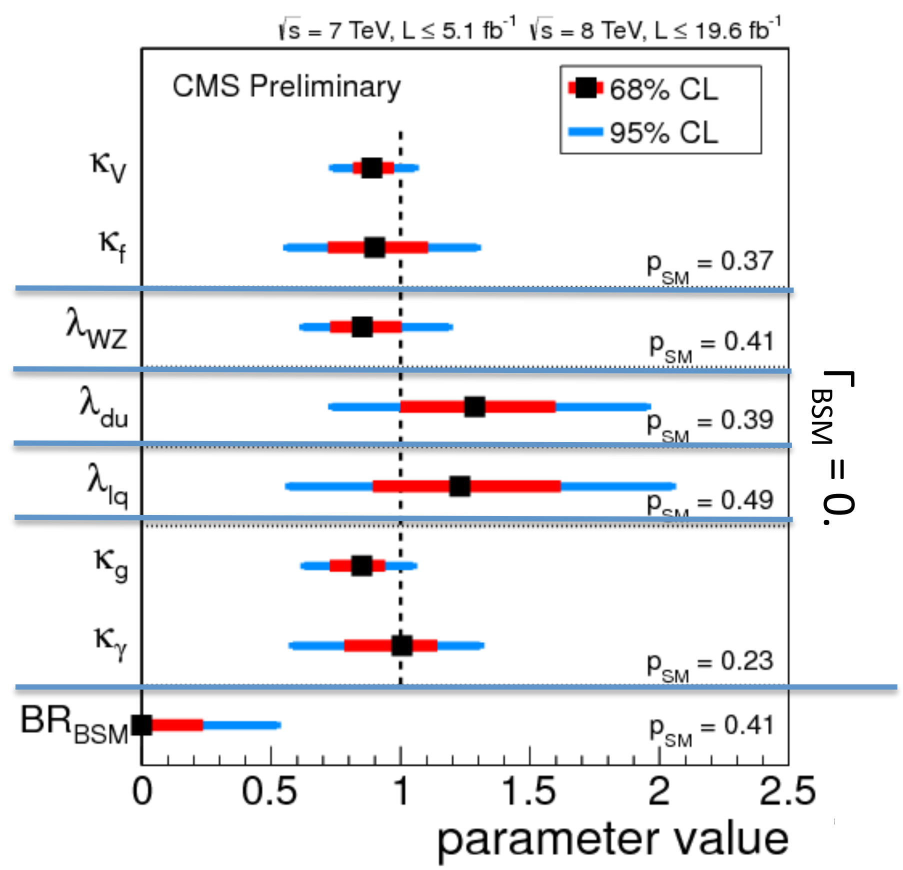
Bruno Mansoulié (IRFU-CEA), Moriond-EW, March 2013

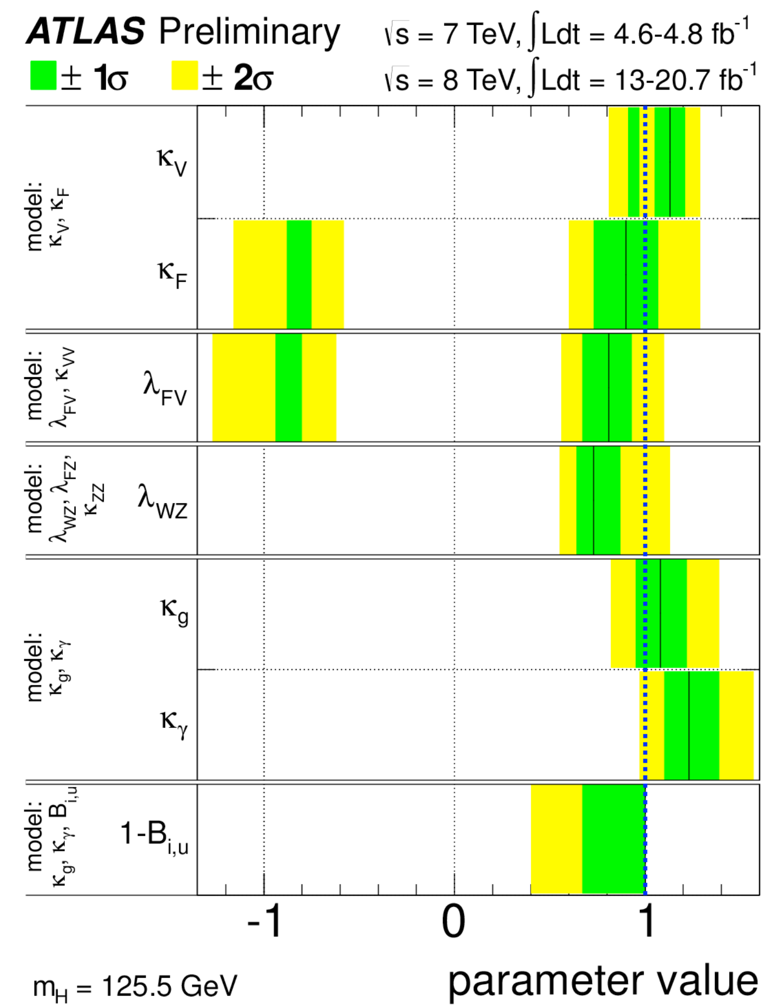
The couplings?

- LHC XS WG benchmark models (arxiv:1209.0040):
  - Fermionic vs bosonic couplings: κ_V κ_f
  - Search for asymmetries: λ_{WZ}, λ_{du}, λ_{lq}
  - Search for new physics in loops: κ_g κ_γ BR_{BSM}

Summary of all searches for coupling deviations

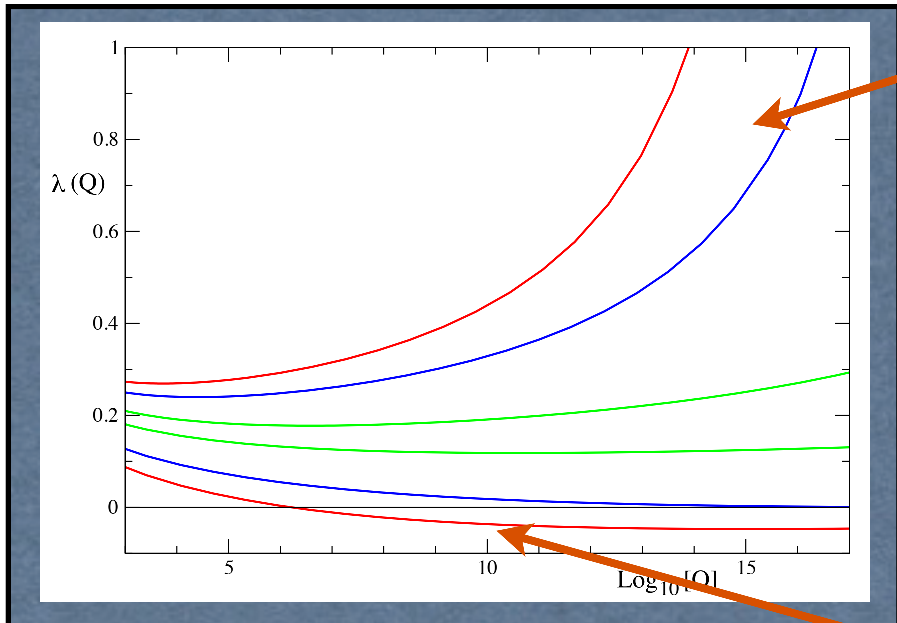






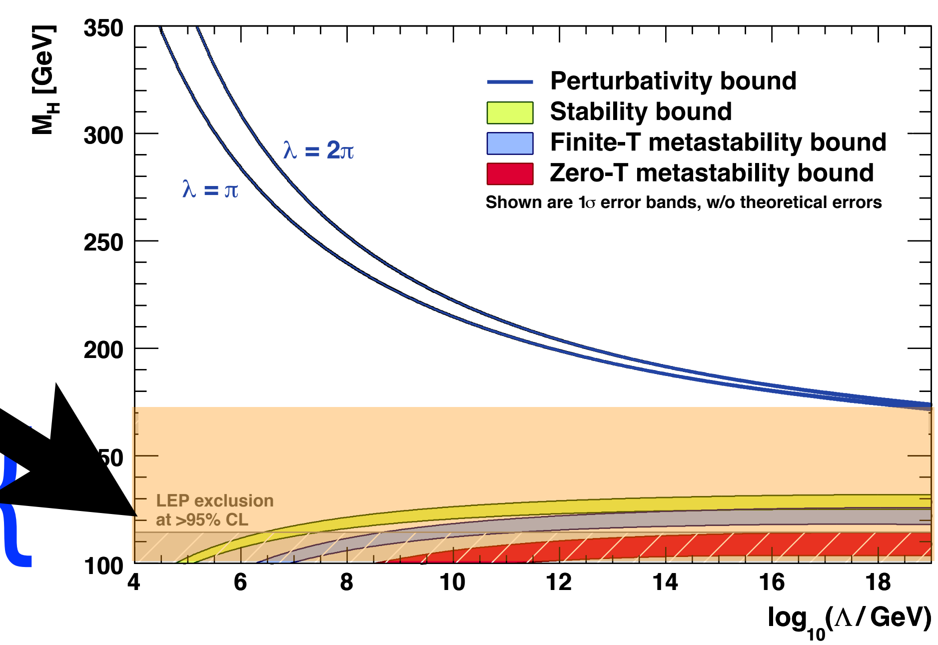
Theoretical Bounds on the Higgs mass in SM

Running of the Higgs coupling



Demanding λ not too large (keep perturbativity)
not too negative that desstabilizes the Higgs potential

A.Pomarol et al'11



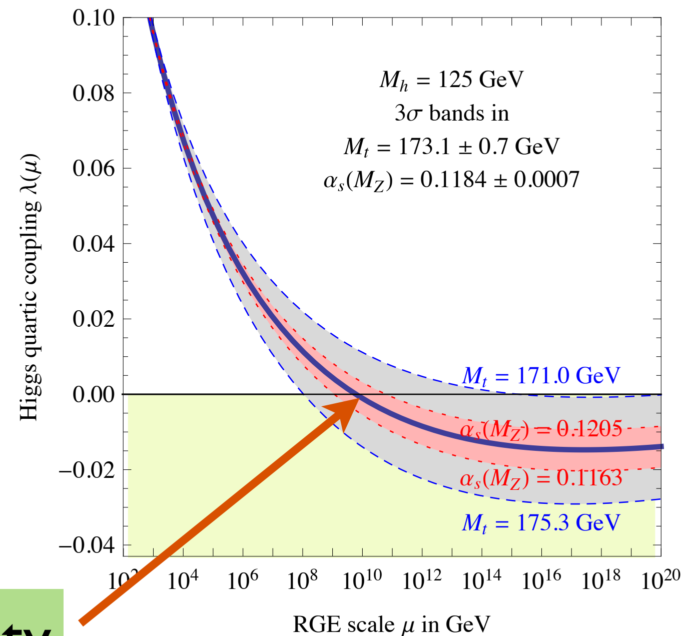
A 125 GeV Higgs is in this window!

Only a small window
in the Higgs mass
makes the SM consistent
all the way to the Planck scale

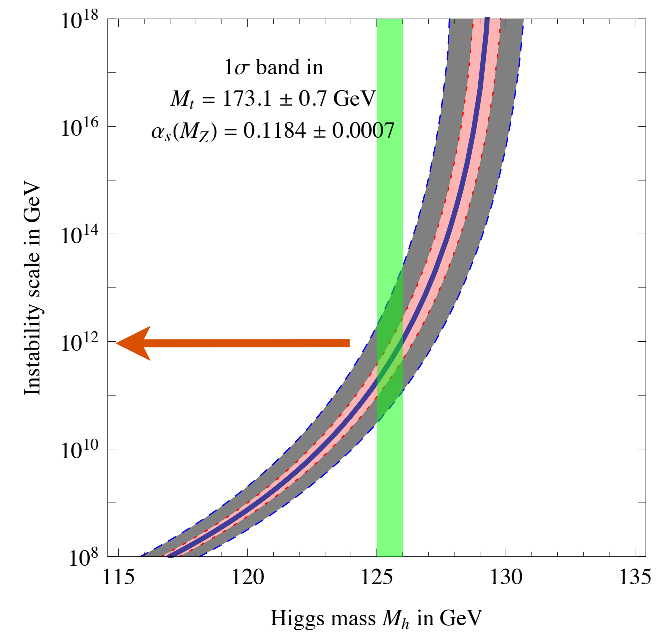
Stability of the Electroweak Vacuum

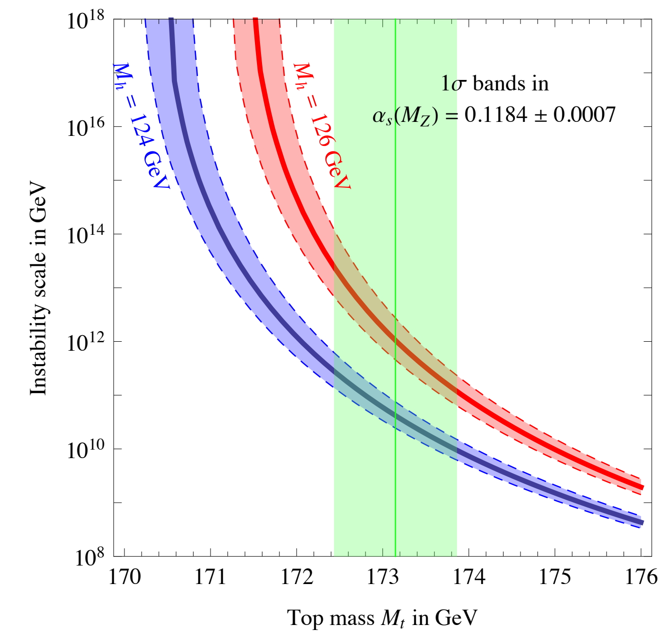
The running of the Higgs coupling $\lambda(\mu)$

G.Degrassi et al'12 arXiv:1205.6497 M.Zoller'12



instability

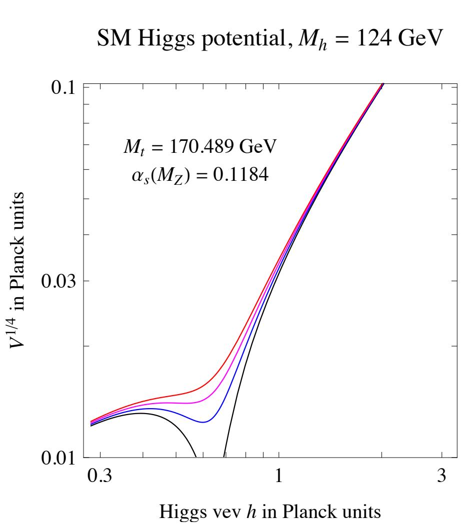


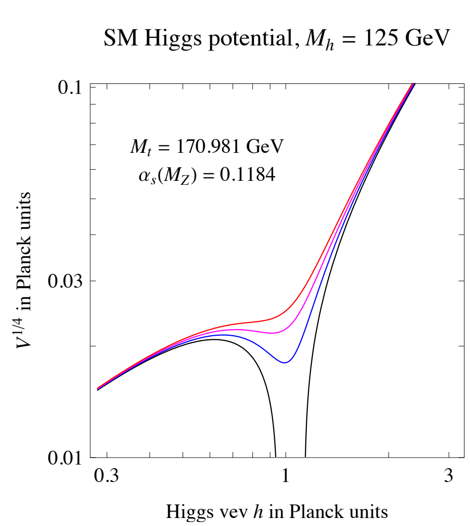


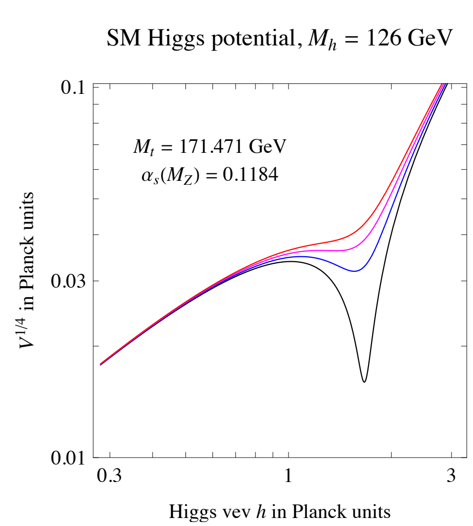
$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}\ .$$

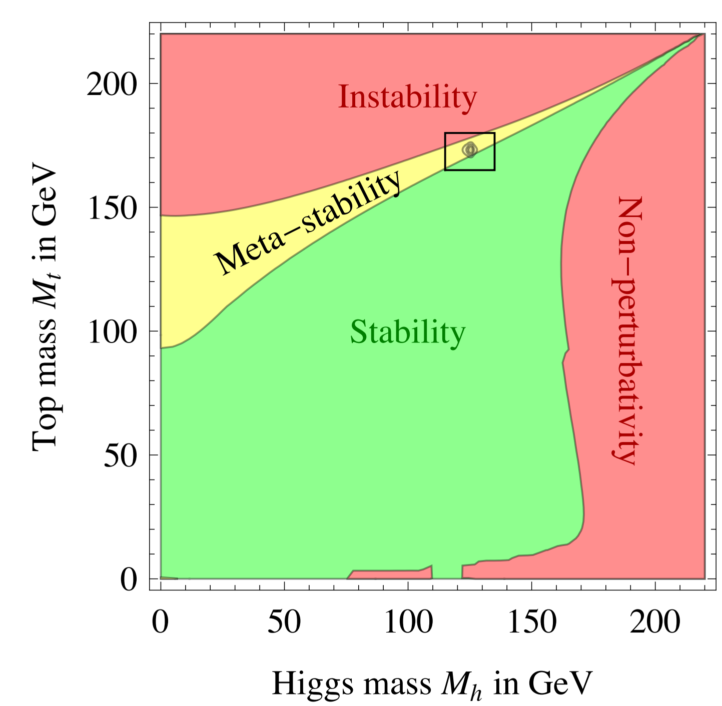
$$M_h > 129.4 \pm 1.8\ \ \mathrm{GeV}.$$

Effective potential









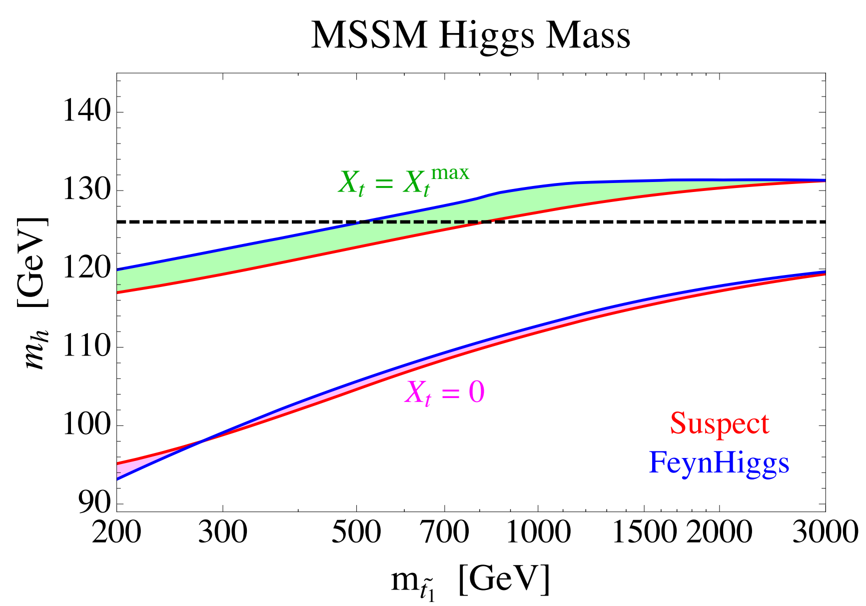
вторник, 23 июля 13 г.

Higgs v SUSY

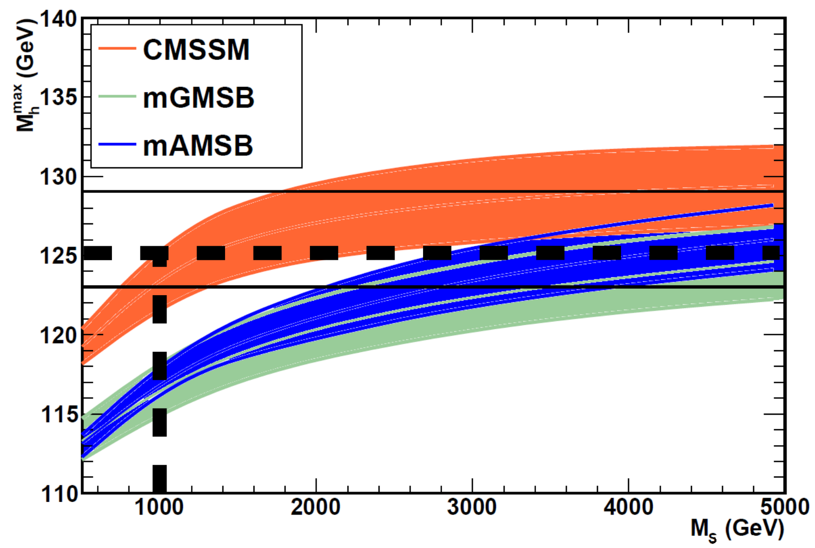
$$m^2_{Higgs} = M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_s^4}{m_t^4} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right] + 2 - loop$$

$$M_S^2 = \tilde{m}_{t_1}\tilde{m}_{t_2} \qquad X_t = A_t - \mu\cot\beta$$

from JHEP 1204 (2012) 131

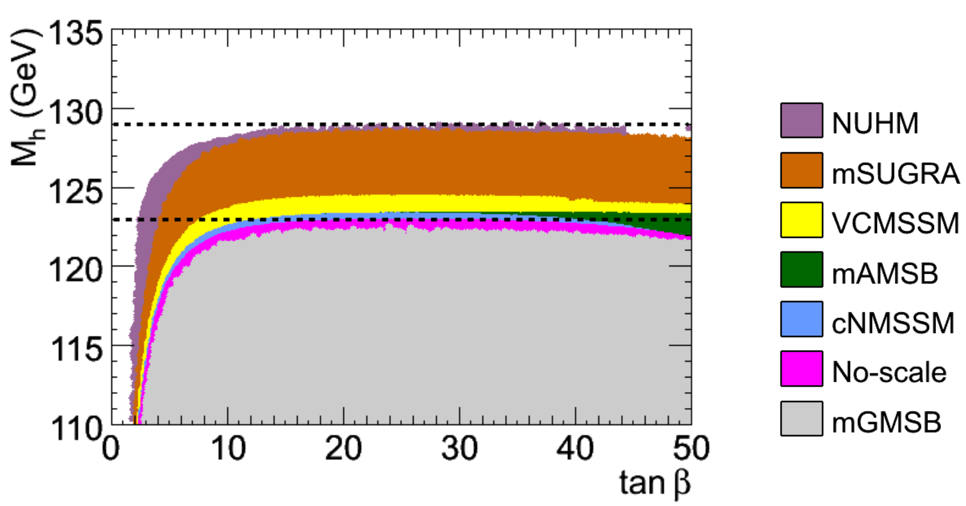


from arXiv:1207.1348

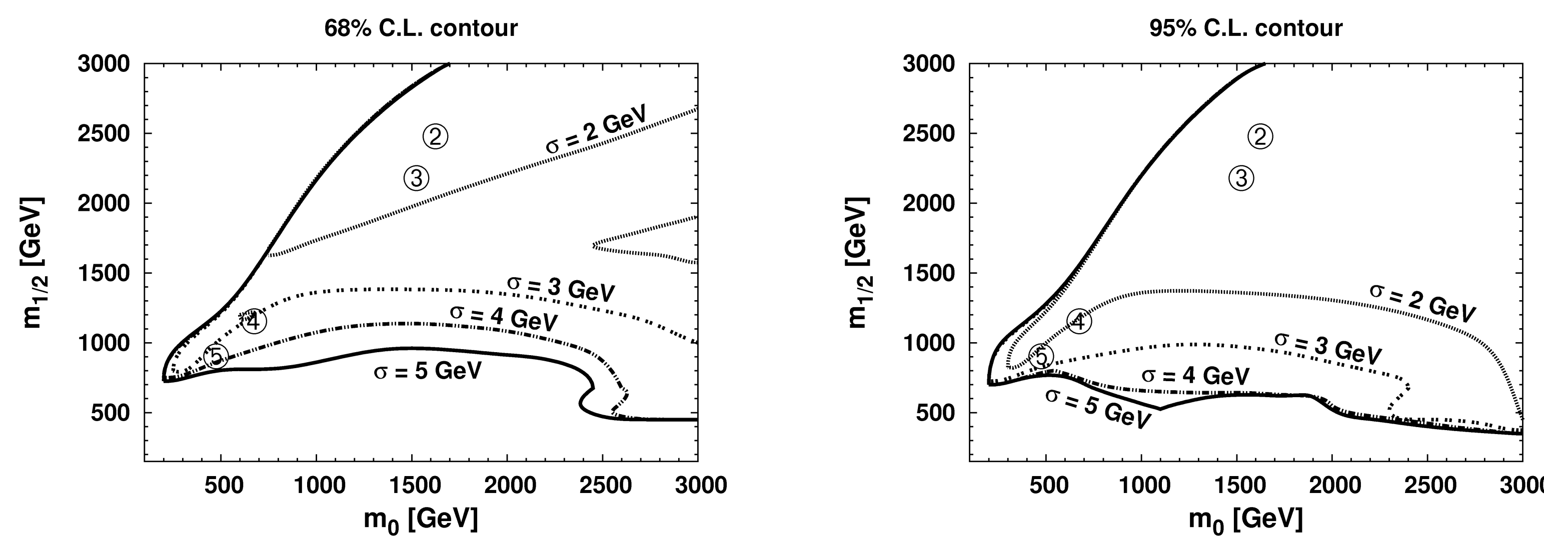


Resume

1. MSSM has already troubles to accomodate 126 GeV Higgs
2. Needs M_S ~ 1TeV
3. Large part of the parameter space is closed



A. Arbey et al'12



W. de Boer et al'12

Two Higgses or One Higgs?

Higgs Bosons at 98 and 125 GeV at LEP and LHC

G. Belanger et al'12

M.Drees'12

LEP $e^+e^- \to Zh, \quad h \to b\bar{b}$ $m_h \approx 98$ GeV

LHC $pp \to h \to \gamma\gamma$ $m_h \approx 126$ GeV

Possible explanation within NMSSM h,H

- 2σ LEP excess is inconsistent with the SM being only about 10 – 20% of the rate for the SM Higgs but might be consistent within SUSY model

Scenario	m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	$m_{H^\pm}$	$m_{\tilde{\chi}_1^0}$	Ωh^2	LSP singlino	LSP Higgsino	$R_{gg}^{h_2}(\gamma\gamma)$
I	99	124	311	140	302	295	76	0.099	18%	75%	1.62
II	97	124	481	217	473	466	92	0.026	20%	74 %	1.53
III	99	126	993	147	991	989	115	0.099	75%	25%	1.14

Two Higgs Bosons in the interval 123-128 GeV

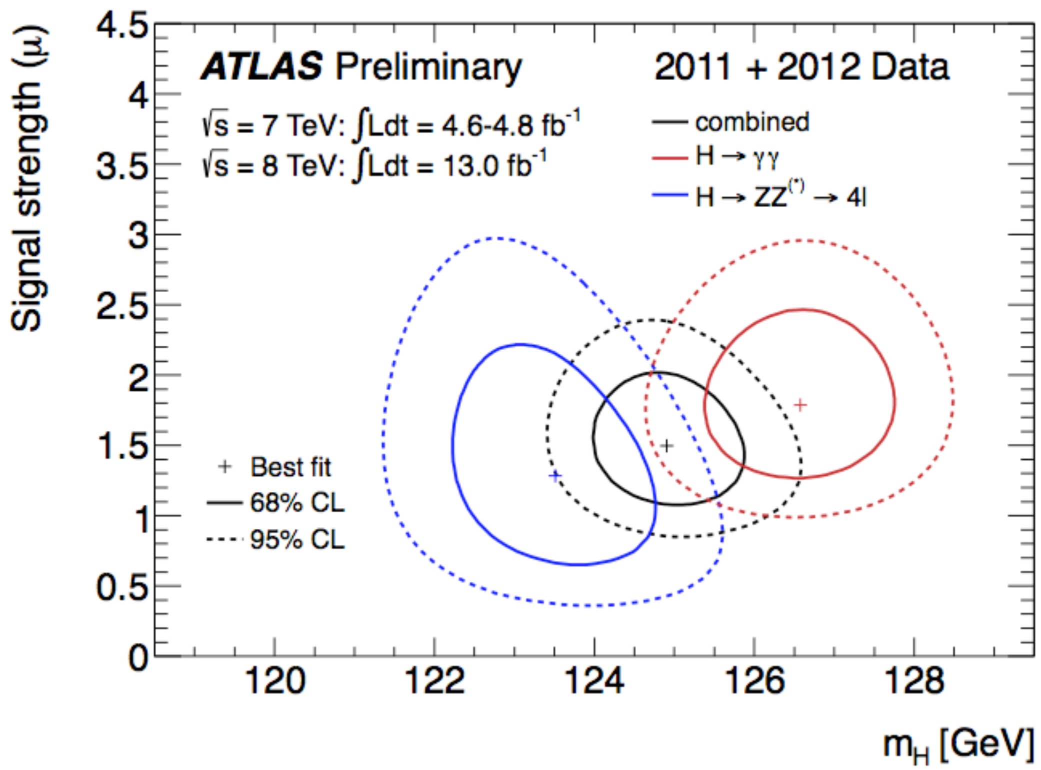
J.Gunion et al'12

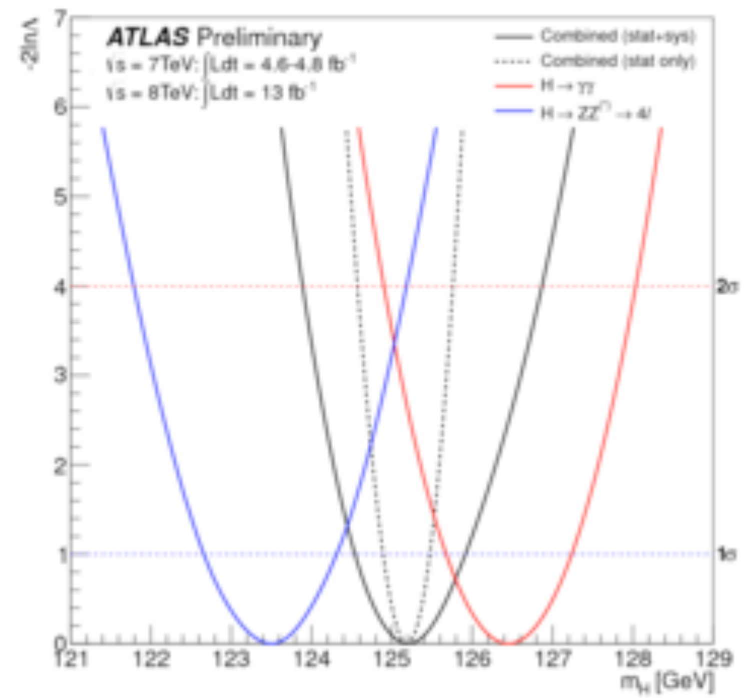
- Two CP even Higgses of the NMMSM are degenerate.
- Large rates (relative to $gg \to h_{SM} \to \gamma\gamma$ or $gg \to h_{SM} \to ZZ \to 4l$) for $gg \to h_{1,2} \to \gamma\gamma$ and $gg \to h_{1,2} \to ZZ \to 4l$ are possible when either one rate is large or the sum is large

m0 ∈ [0.9,1.3] TeV, $m_{1/2}$ ∈ [500,700] GeV, A0 ∈ [−1.8, −1.0] TeV, A_κ ∈ [−400, −250] GeV, A_λ ∈ [−600, −400] GeV, mS (GUT) ∈ [1.4, 2.2] TeV, m_{H_u} (GUT) ∈ [2,2.2] TeV and m_{H_d}(GUT) ∈ [0.7,1.2] TeV

Two Higgs Bosons at ATLAS?

- Two Higgs Bosons in the interval 123-128 GeV





$$m_H = 123.5 \pm 0.9\ (stat)\ ^{+0.4}_{-0.2}\ (syst)\ \mathrm{GeV} \quad m_H = 126.6 \pm 0.3\ (stat) \pm 0.7\ (syst)\ \mathrm{GeV}$$

$$m_H = 125.2 \pm 0.3\ (stat)\ \pm\ 0.6\ (syst)\ \mathrm{GeV}$$

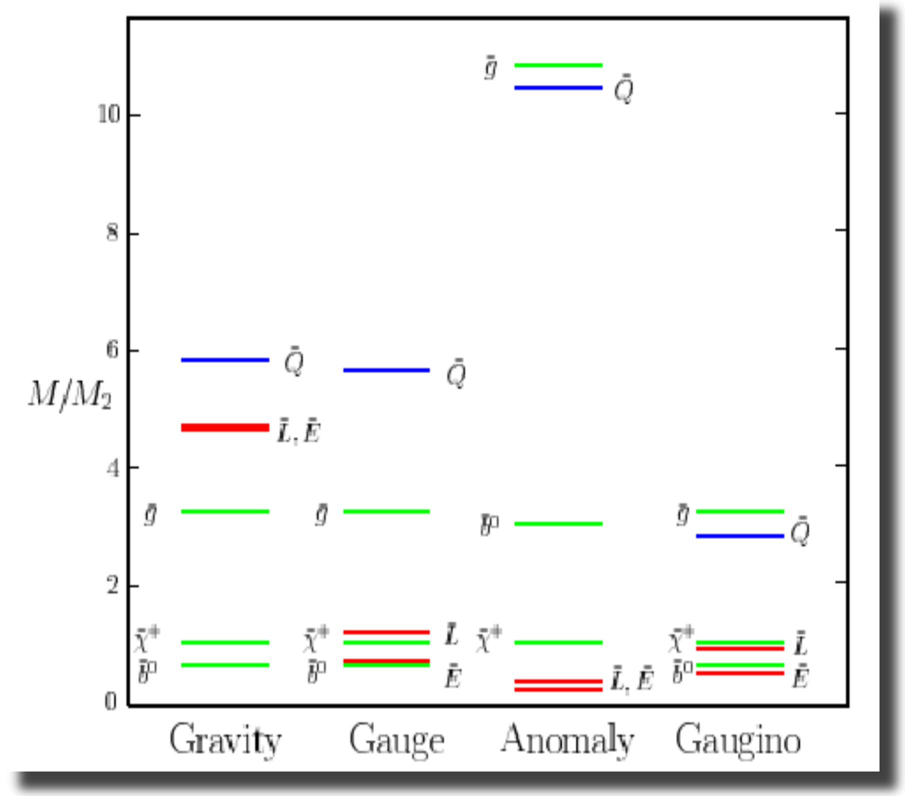
NO the measurements of the mass in the two channels are each other compatible (2.3-2.7σ) and everything is compatible with what CMS observes.

Supersymmetry

What SUSY?

- MSSM
- CMSSM
- mSUGRA
- mGMSB
- mAMSB
- NUHM
- NMSSM
- No Scale
- ...

Superparticle spectrum



SUSY at TeV scale:

- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explains the electroweak symmetry breaking

SUSY:

- Provides unification with gravity
- Provides the Dark matter candidate

Search for SUSY Manifestation

Particle Phys

- Direct production at colliders at high energies
- Indirect manifestation at low energies
  - Rare decays ($B_s \to s\gamma,\ B_s \to \mu^+\mu^-, B_s \to \tau\nu$)
  - g-2 of the muon
- Search for long-lived SUSY particles

Astro Phys (if SUSY DM)

- Relic abundancy of Dark Matter in the Universe
- DM annihilation signal in cosmic rays
- Direct DM interaction with nucleons

Nothing so far ...

Exp and Theor Framework

Two ways to present and analyse data:

1. High energy input:
introduce universal parameters at high energy scale (GUT)
Example $m_0,\ m_{1/2},\ A_0,\ \tan\beta$ of MSSM

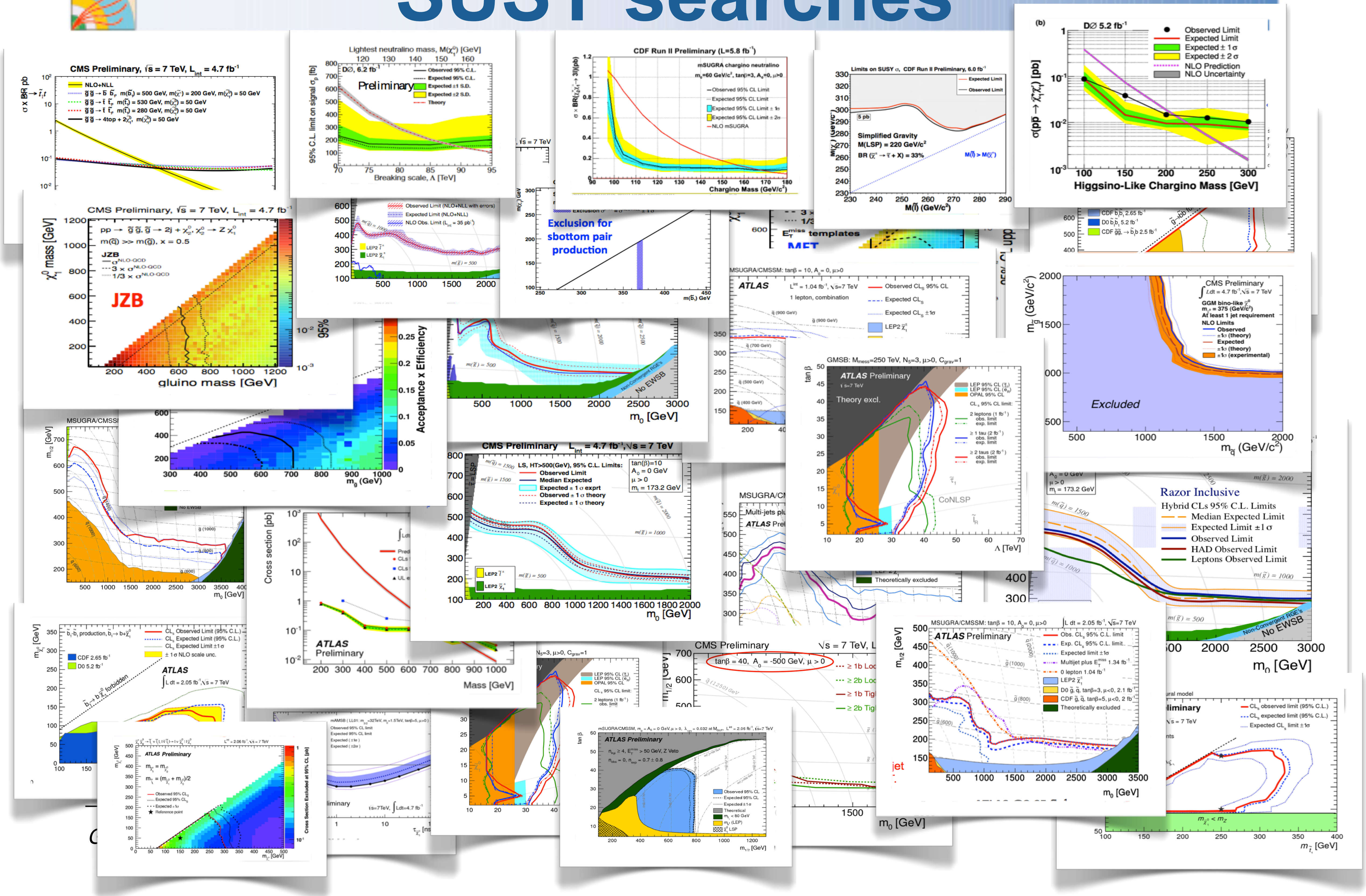
Advandage: small number of universal parameters for all masses
Disadvantage: strictly model dependent (MSSM, NMSSM, etc)

2. Low energy input:
use low energy parameters like masses of superpartners
Example $\tilde{m}_g,\ \tilde{m}_q,\ \tilde{m}_\chi$ or $m_A, \tan\beta$

Advandage: less model dependent
Disadvantage: many parameters, process dependent

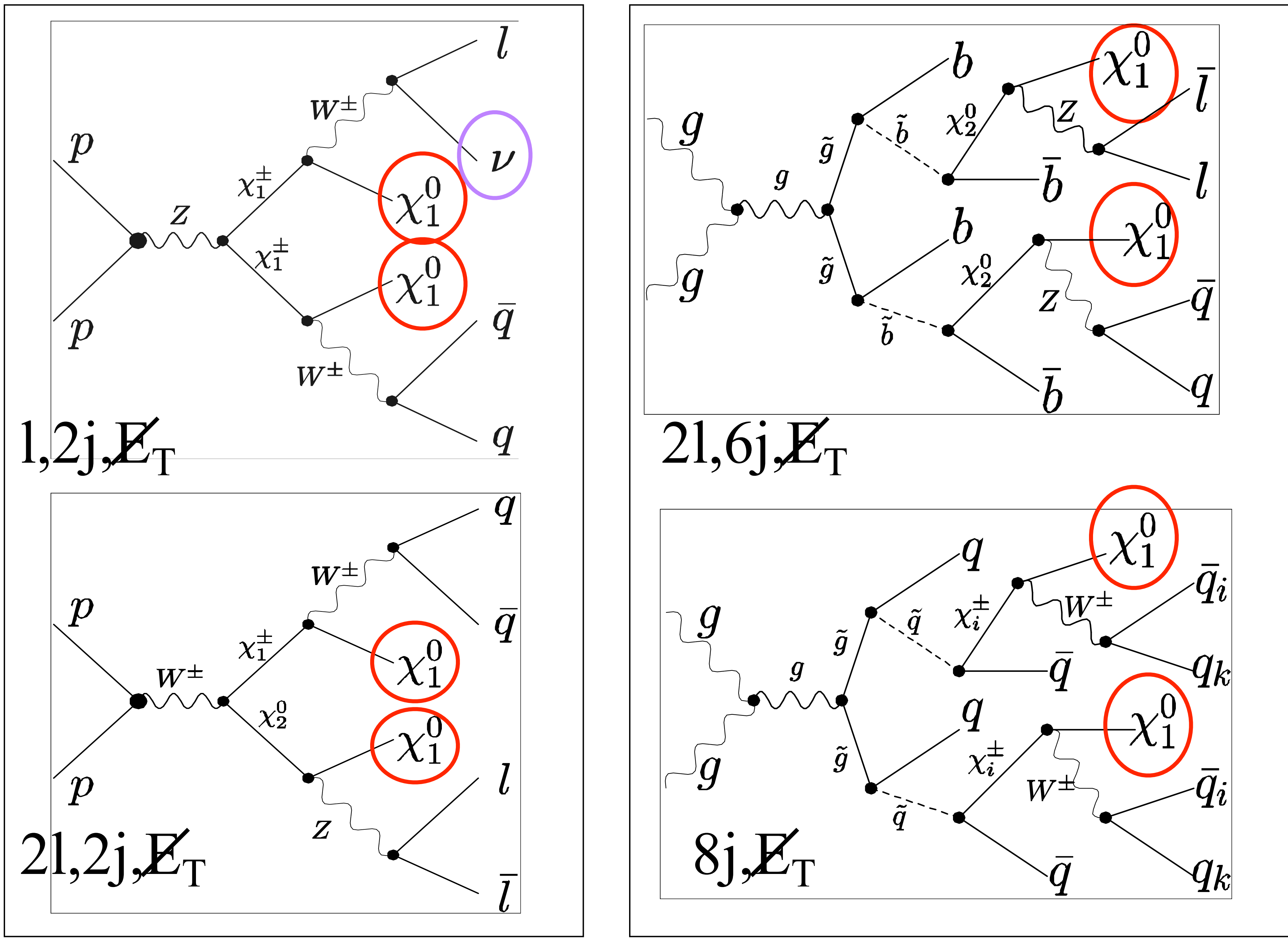
Both approaches are used

SUSY searches



Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's

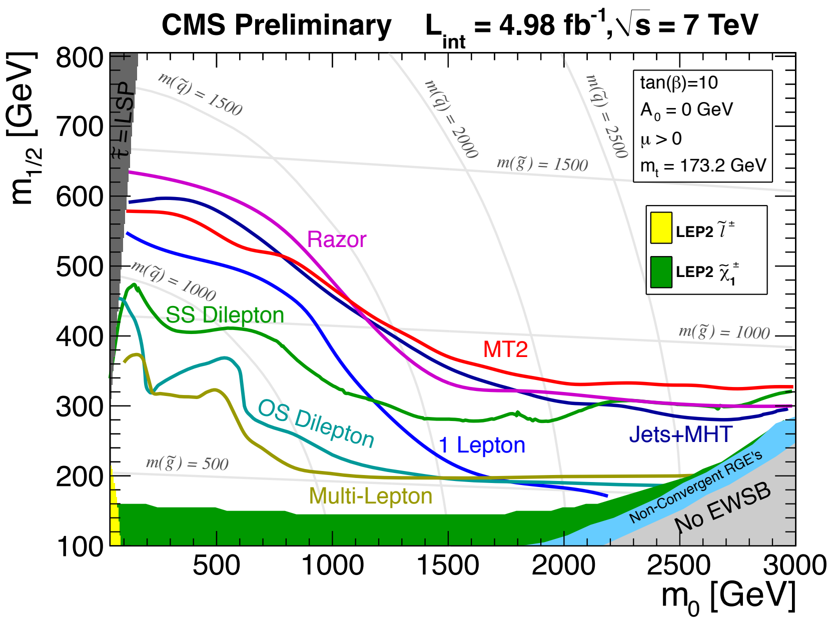


Strong int's

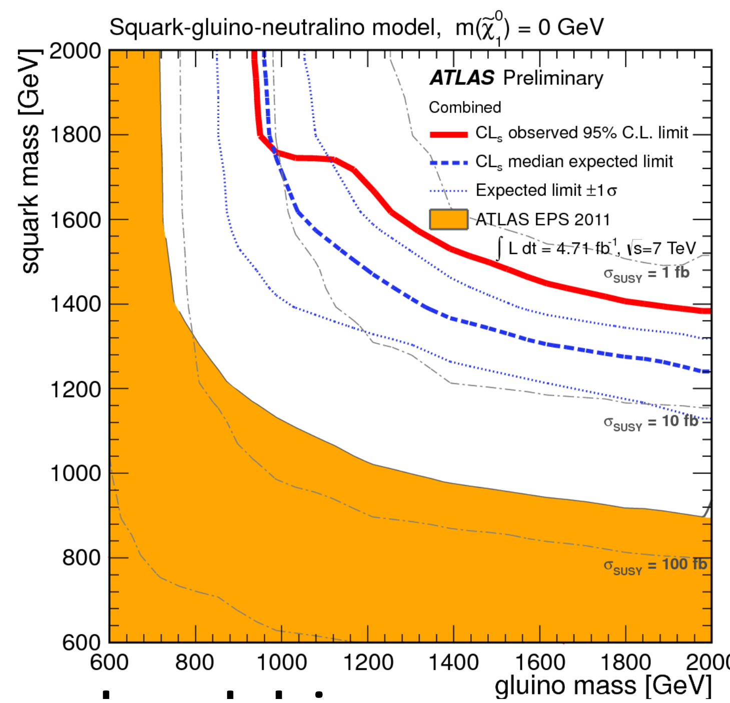
Typical SUSY signature: Missing Energy and Transverse Momentum

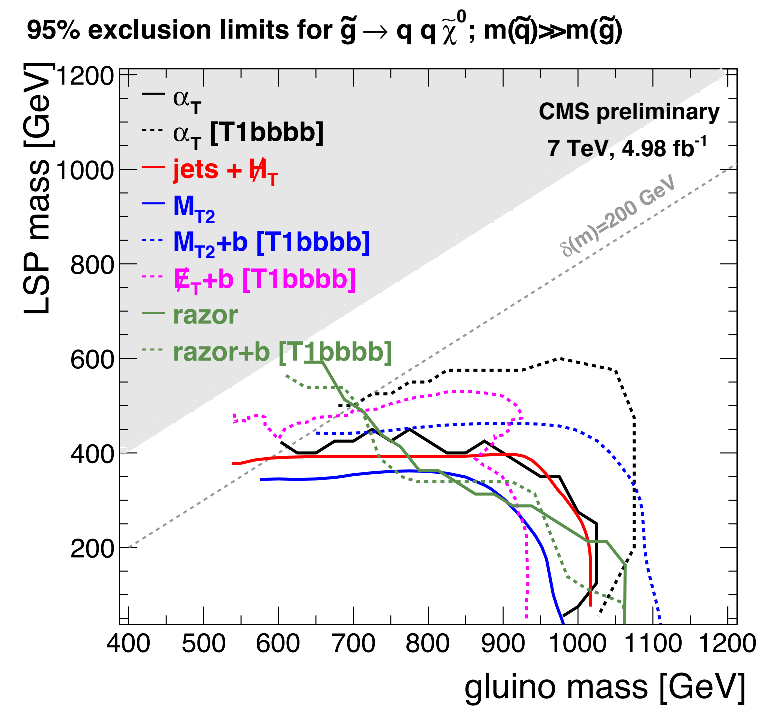
The Progress of LHC

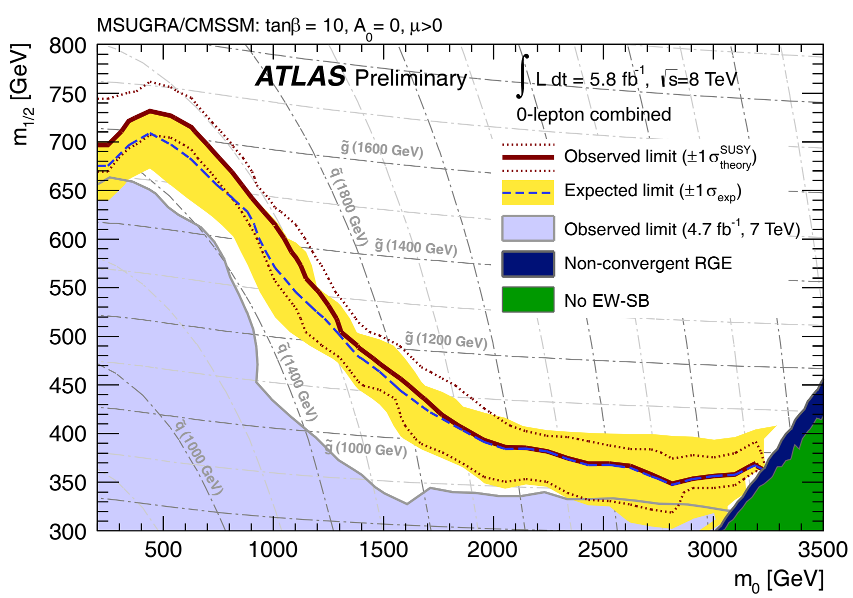
CMS CMSSSM summary

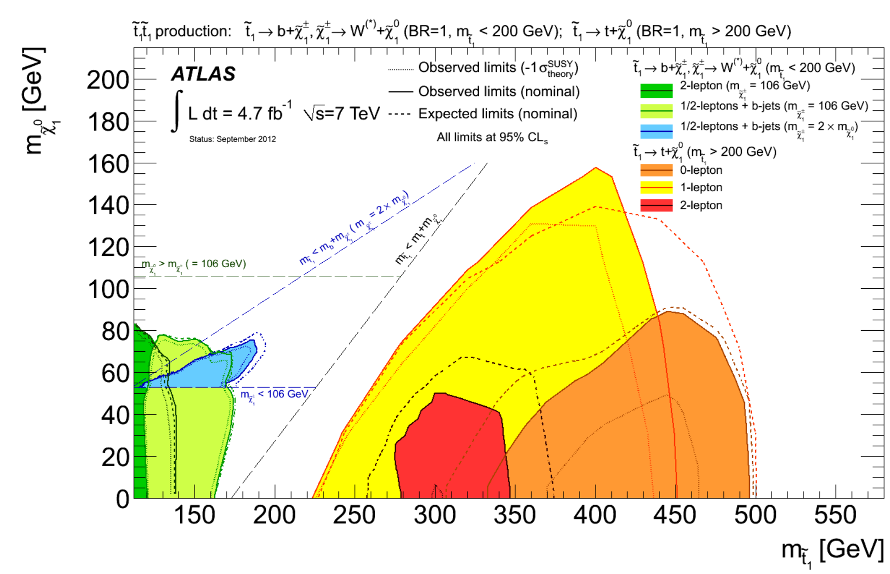


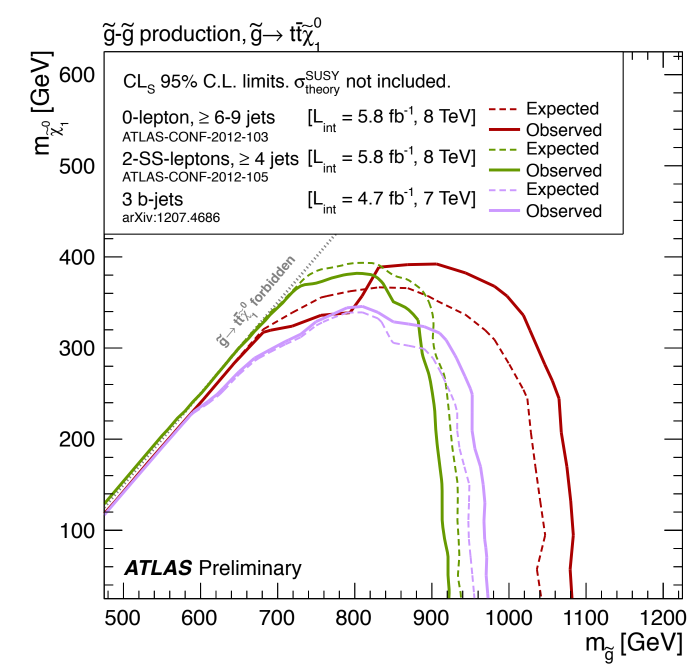
Look for squarks and gluinos with direct decays to SM+LSP









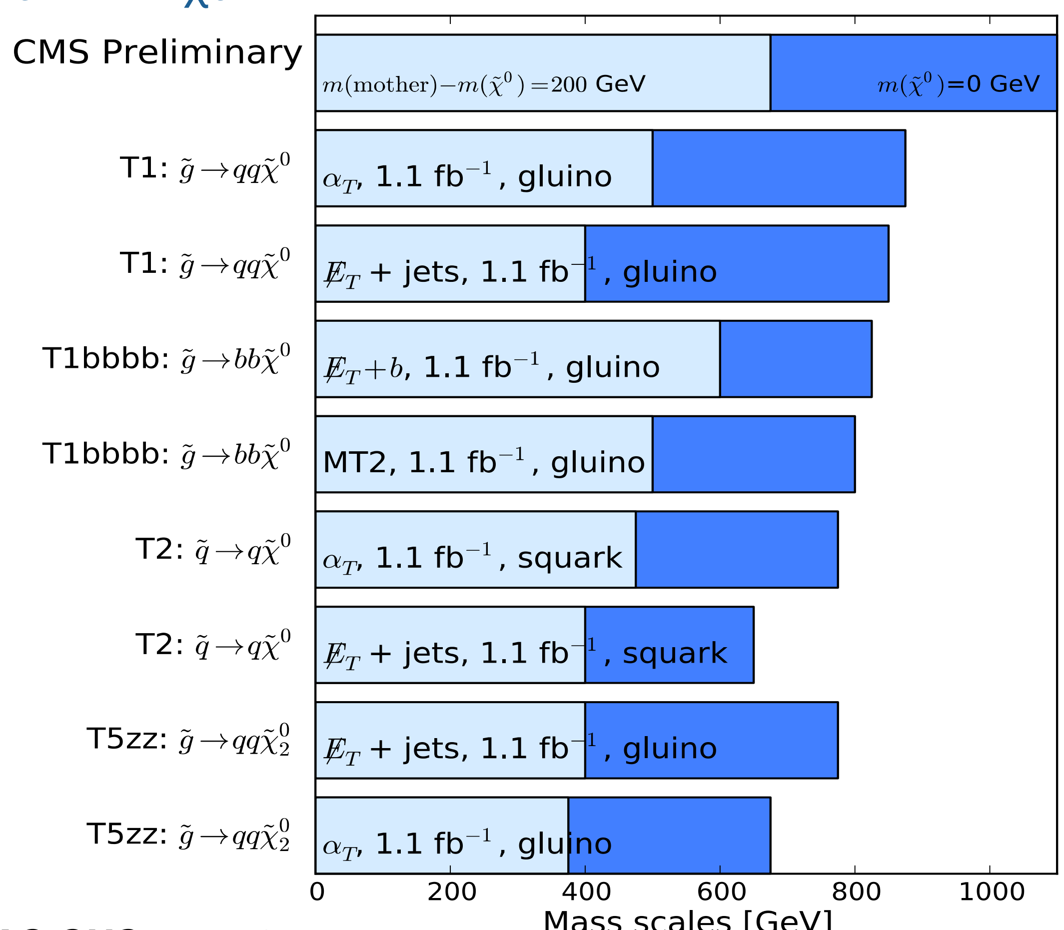


$\tilde{m}_g > 1000\ GeV$

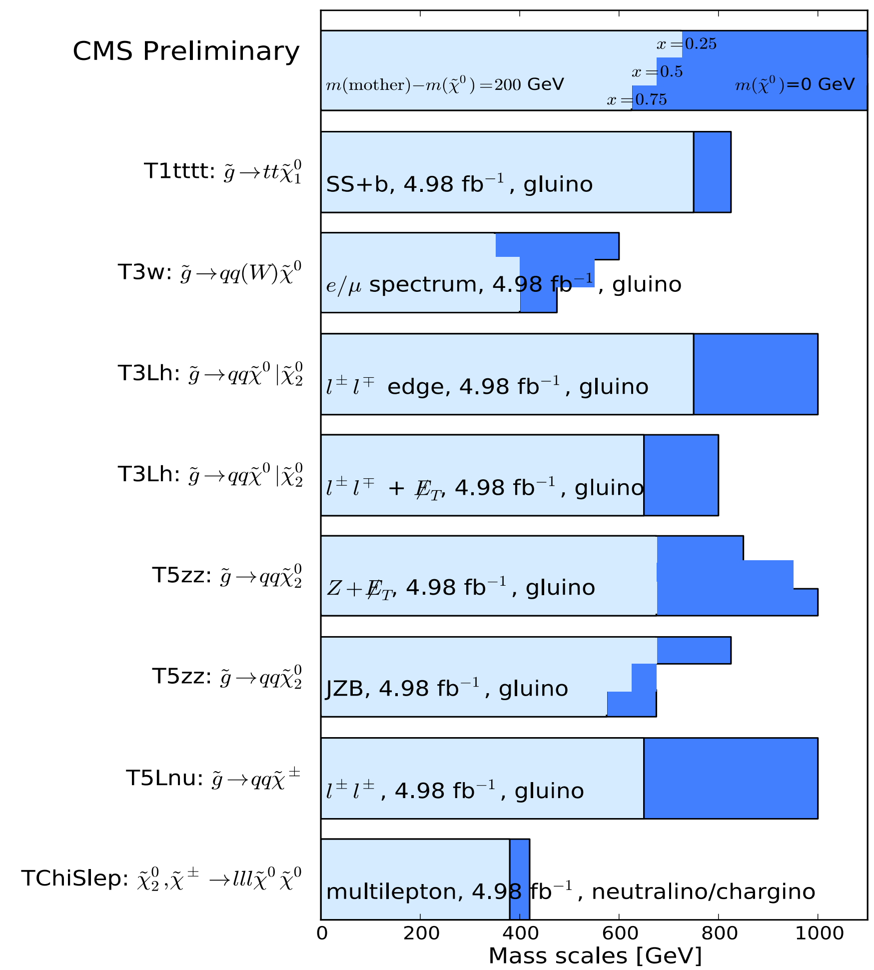
$\tilde{m}_q > 1400\ GeV$

SUSY in simplified models

Hadronic (left) and leptonic (right) SUSY searches in simplified SUSY models. Exclusion limits for gluino and squark masses, for $m_{\chi 0}$ = 0 GeV (dark blue) and $m_{mother} - m_{\chi 0}$= 200 GeV (light blue).



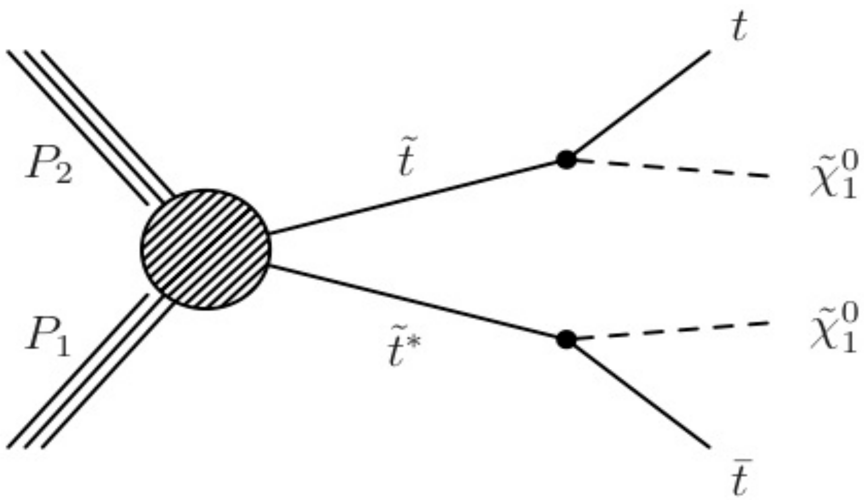
CMS-PAS-SUS-11-016

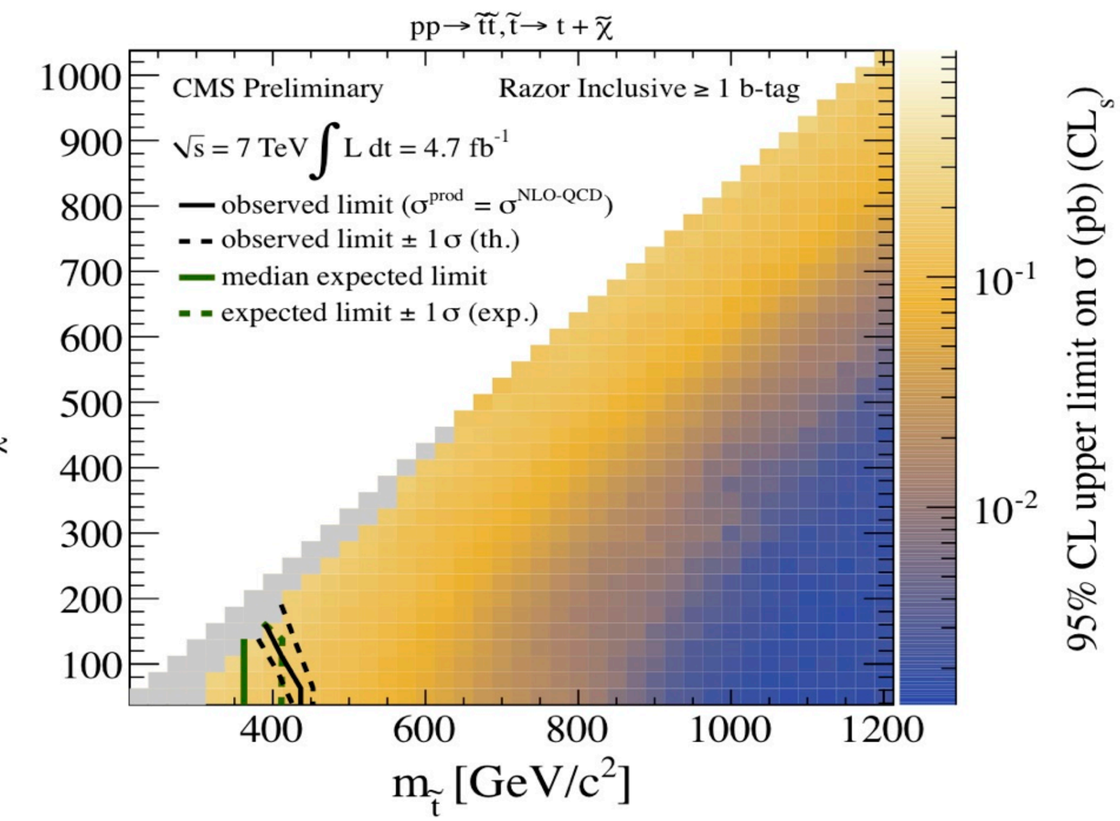


SUSY is not dead (yet). It might still hide in low MET/low HT events. More complicated models are under investigation→ more challenging searches. For some it is hard to even get the data on tape.

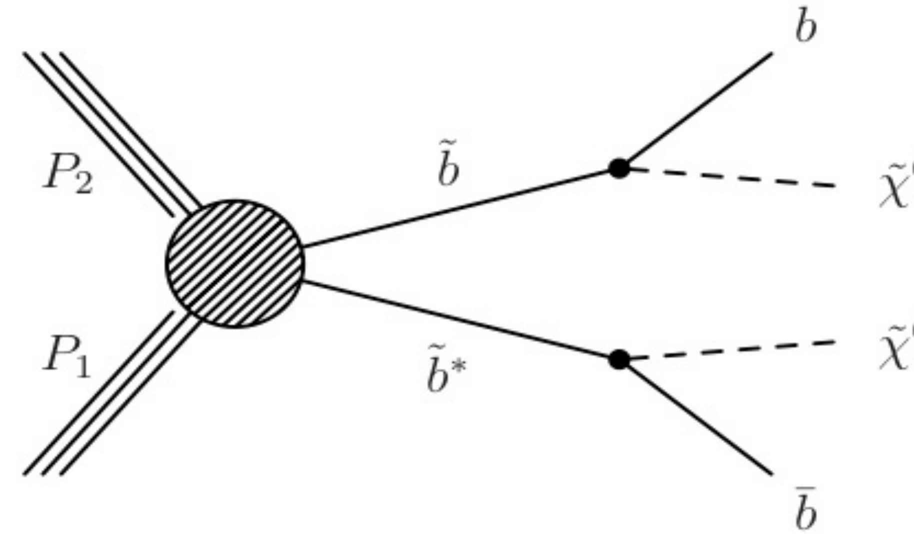
CMS stop and sbottom searches

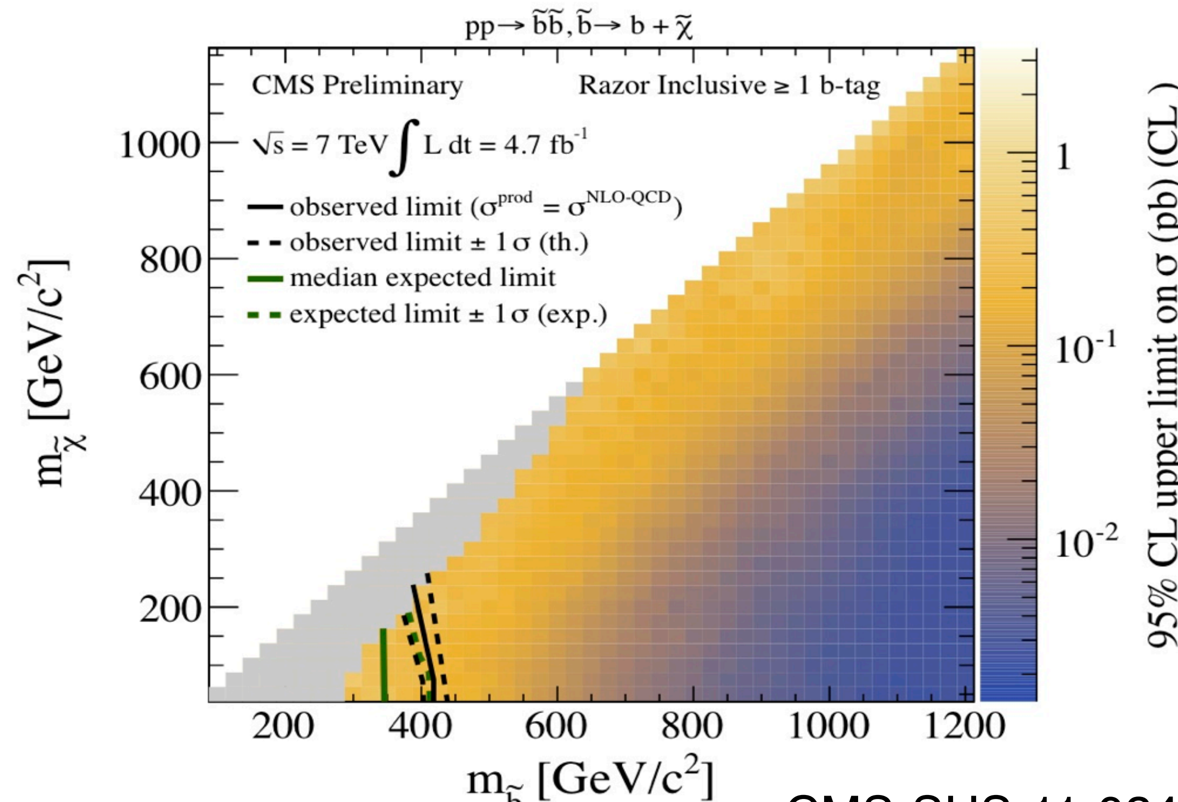
Di-stop production resulting in 2 top quarks +MET final states





Di-sbottom production resulting in 2 b quarks +MET final states

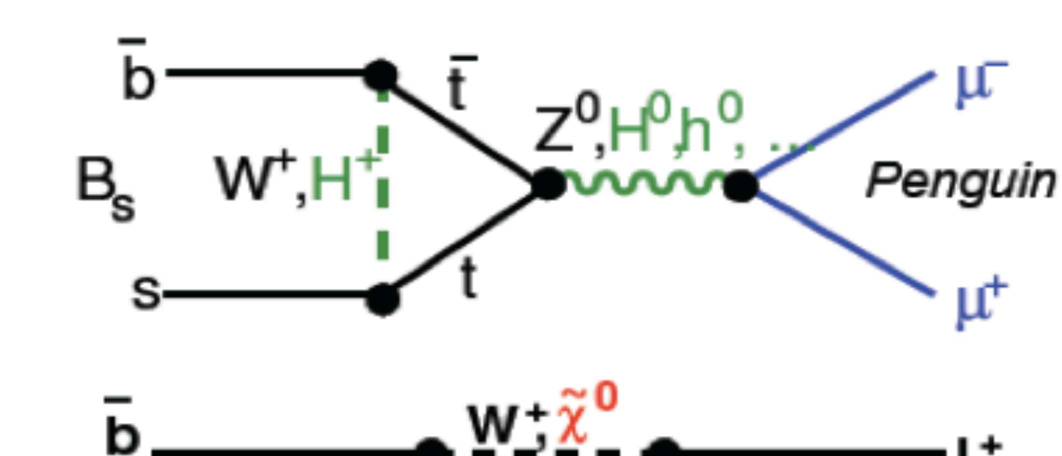




CMS-SUS-11-024

Probing SUSY with $B_{s,d} \to \mu^+\mu^-$

- Decays highly suppressed in SM
  - Forbidden at tree level
  - $b \to s(d)$ FCNC transition only through penguin and box diagrams
  - Helicity suppressed by factors of (m_μ/



$$Br[B_s \to \mu\mu] \; = \; \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1 - \frac{4m_l^2}{m_B^2}}$$

$$\left[\left(1 - \frac{4m_l^2}{m_B^2}\right) \left| \frac{(C_S - C_S')}{(m_b + m_s)} \right|^2 + \left| \frac{(C_P - C_P')}{(m_b + m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A - C_A') \right|^2 \right]$$

$$C_S \simeq \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left(\frac{\tan^3\beta}{\sin^2\theta_W}\right) \left(\frac{m_b m_\mu m_t \mu}{M_W^2 M_A^2}\right) \frac{\sin 2\theta_{\tilde{t}}}{2} \left(\frac{m_{\tilde{t}_1}^2 \log\left[\frac{m_{\tilde{t}_1}^2}{\mu^2}\right]}{\mu^2 - m_{\tilde{t}_1}^2} - \frac{m_{\tilde{t}_2}^2 \log\left[\frac{m_{\tilde{t}_2}^2}{\mu^2}\right]}{\mu^2 - m_{\tilde{t}_2}^2} \right)$$

Enhancement

Suppression

Electroweak, g-2, and Dark Matter constraints

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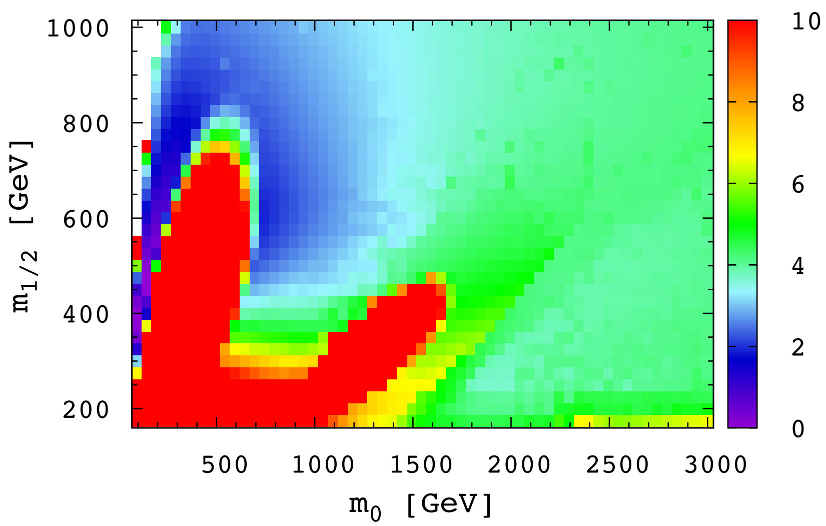
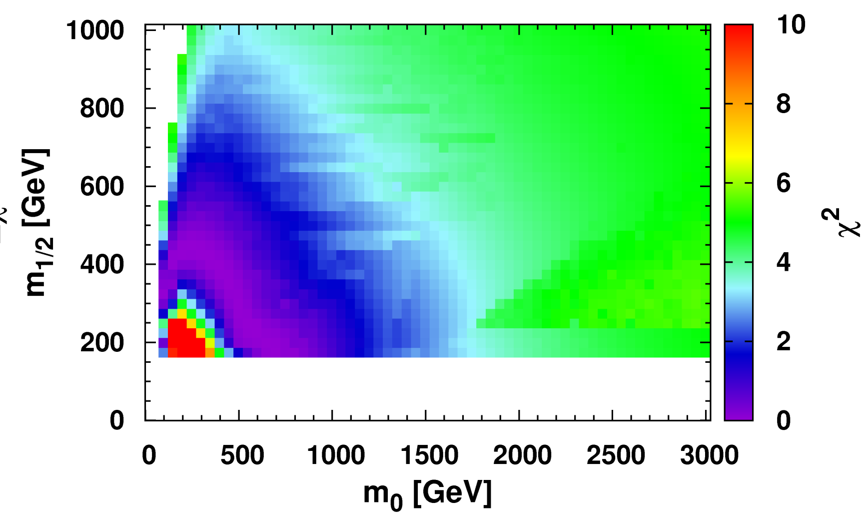
95% CL exclusion

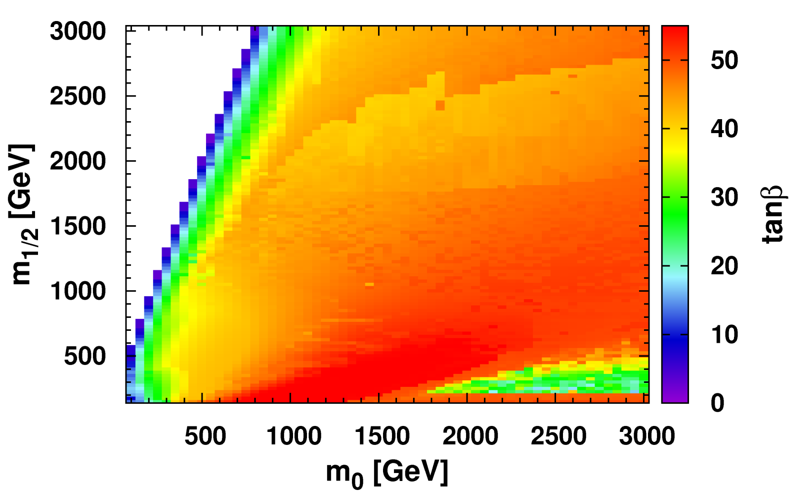


$B_s \to s\gamma,\ B_s \to \mu^+\mu^-,\ B_s \to \tau\nu$

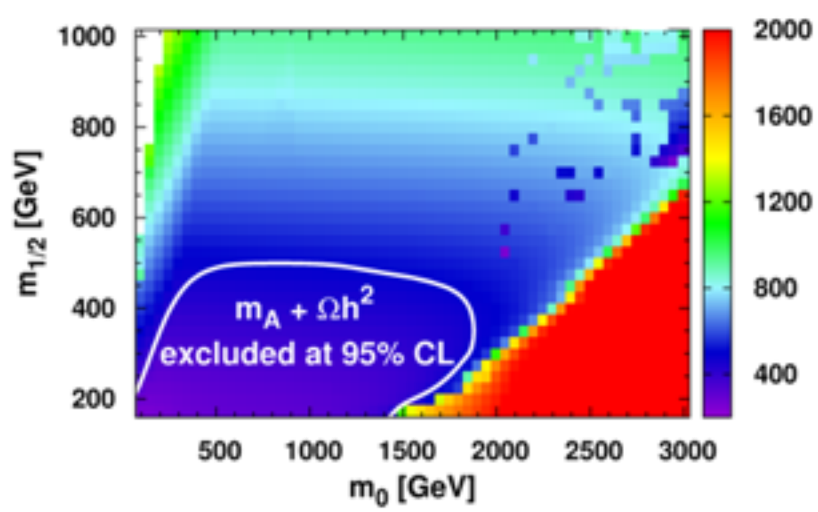


muon $g-2$

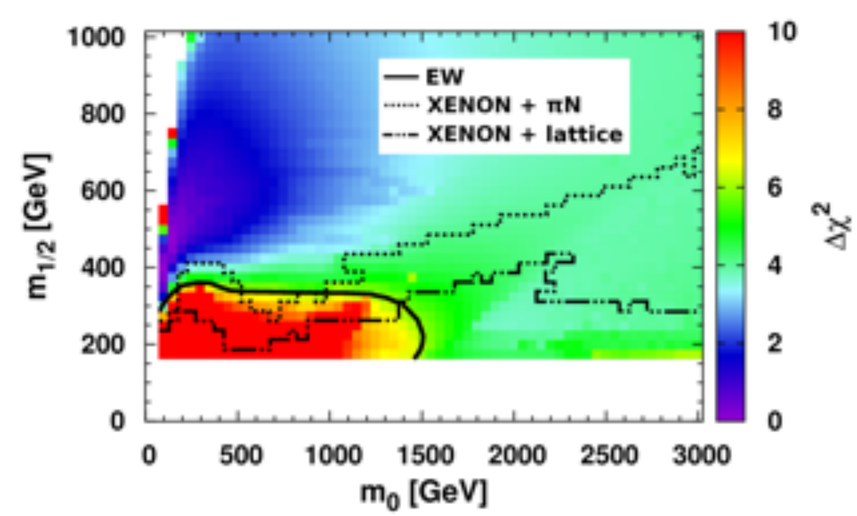
Constraint	Data
Ωh^2	0.113 ± 0.004
$b \to X_s\gamma$	$(3.55 \pm 0.24) \cdot 10^{-4}$
$B_u \to \tau\nu$	$(1.68 \pm 0.31) \cdot 10^{-4}$
Δa_μ	$(302\ \pm\ 63(exp)\ \pm\ 61(theo)) \cdot 10^{-11}$
$B_s^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^- < 4.5 \cdot 10^{-9}$
m_h	$m_h > 114.4$ GeV
m_A	$m_A > 480$ GeV for $\tan\beta \approx 50$
ATLAS	$\sigma_{had}^{SUSY} < 0.003 - 0.03$ pb
CMS	$\sigma_{had}^{SUSY} < 0.005 - 0.03$ pb
XENON100	$\sigma_{\chi N} < 8 \cdot 10^{-45} - 2 \cdot 10^{-44} cm^2$



$\tan\beta$ fit of DM abundance

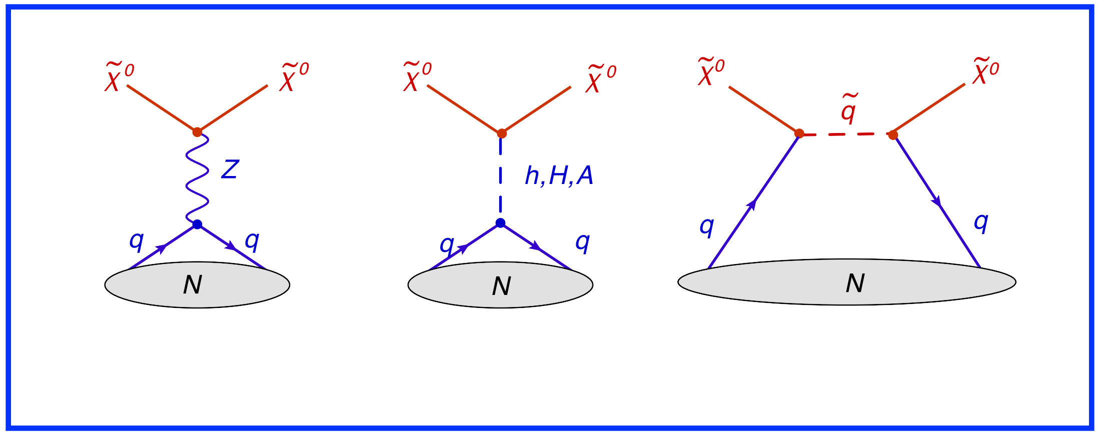


Dark matter abundance

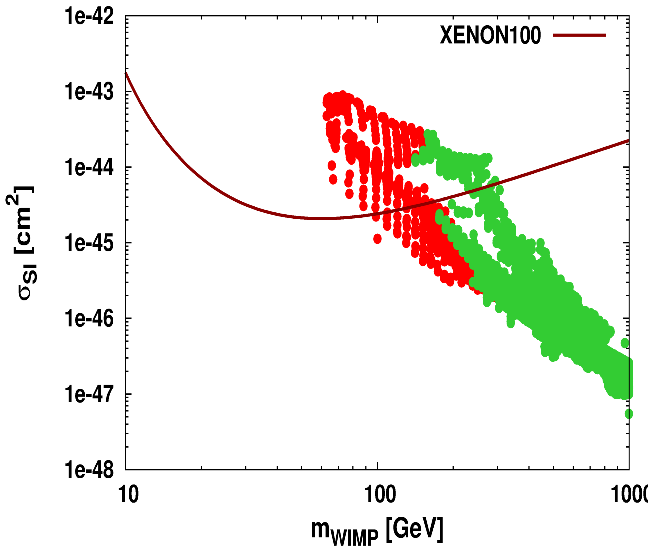


Direct DM search

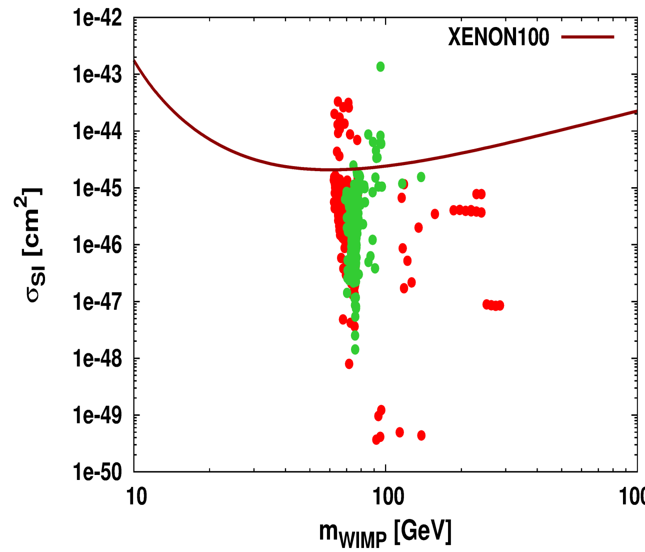
DM Nucleons Interaction

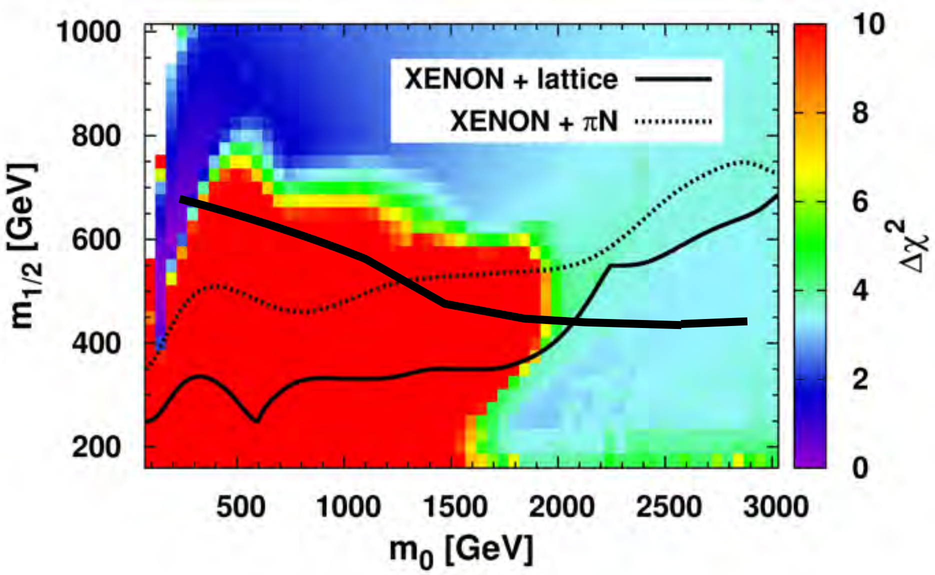


MSSM



NMSSM



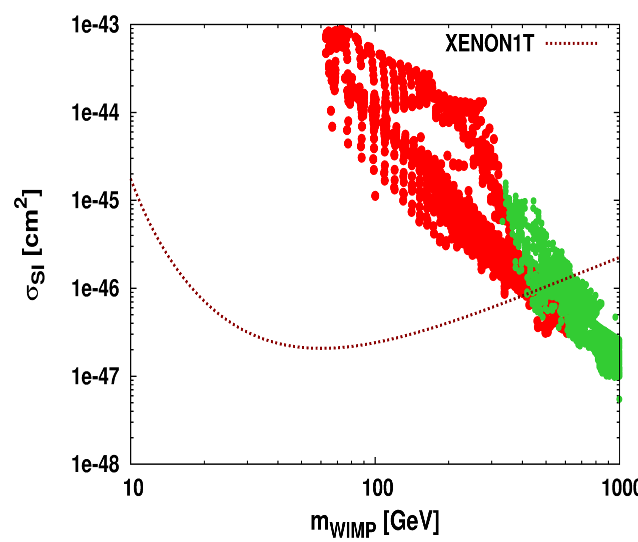


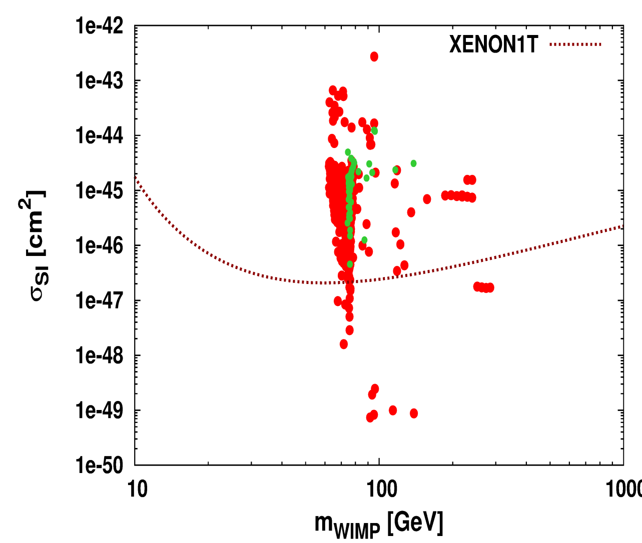
MSSM

Direct DM search

Red points - excluded by LHC

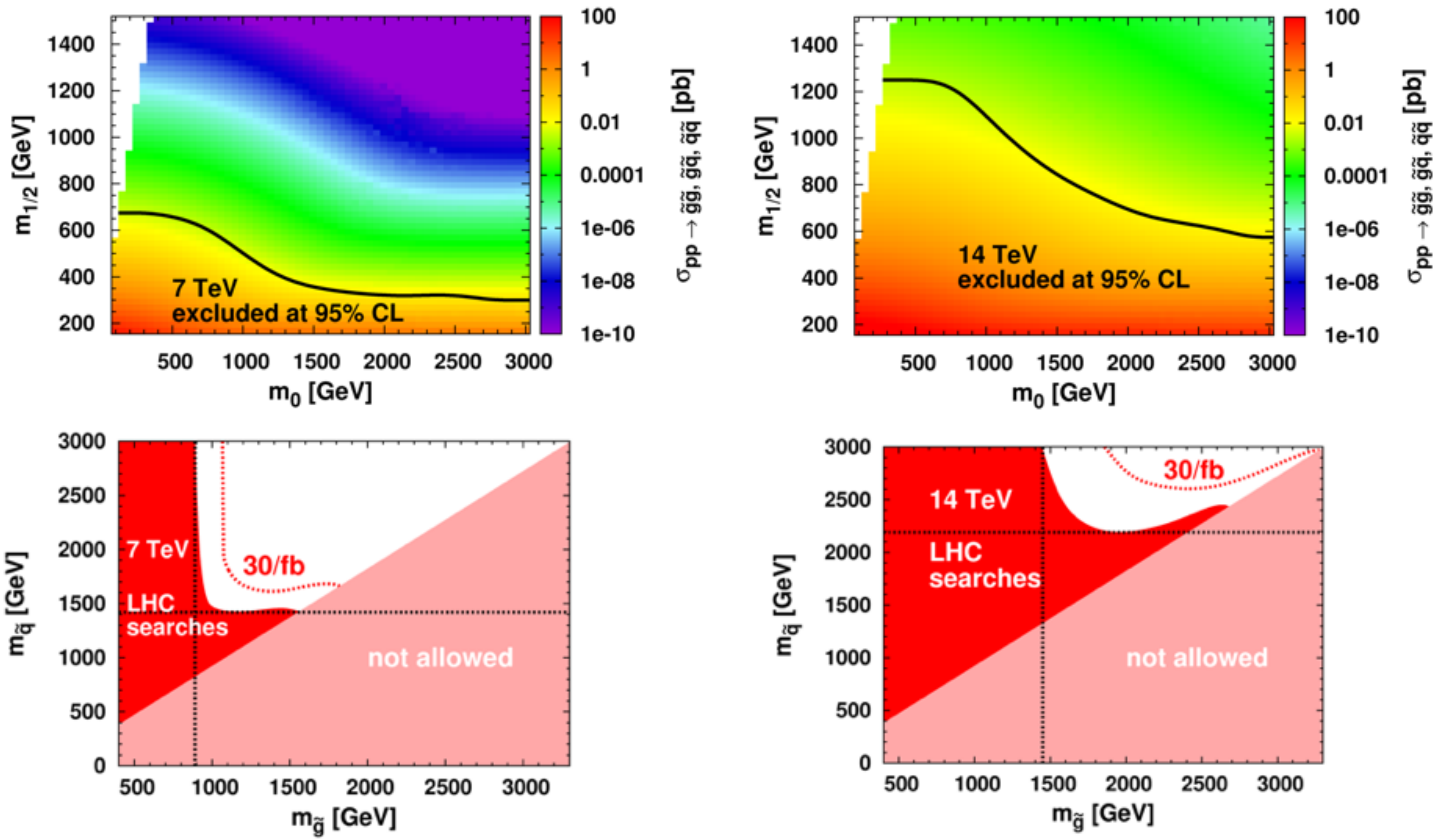
XENON100+LHC 8





XENON1T+LHC 14

LHC Reach at 7 and 14 TeV

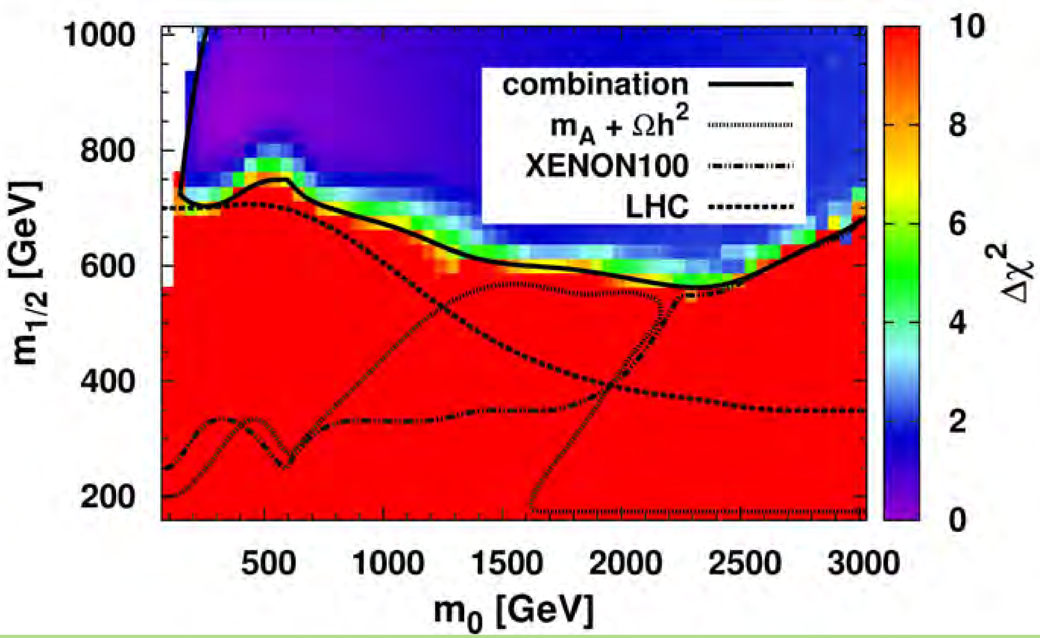


Energy is more important than luminosity

Combined Fit to all Data

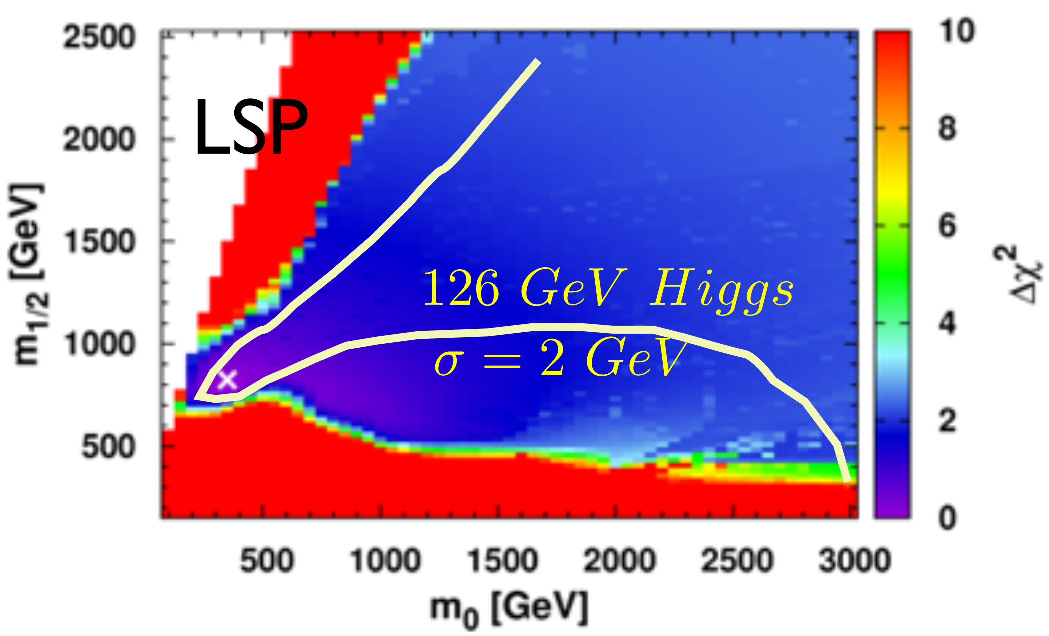
W.de Boer, C.Beskidt, D.K.'11'12

MSSM



without 125 GeV Scalar

The values of $\tan\beta$ and A0 are adjusted



with 125 GeV Scalar

Larger scale for $m_{1/2}$

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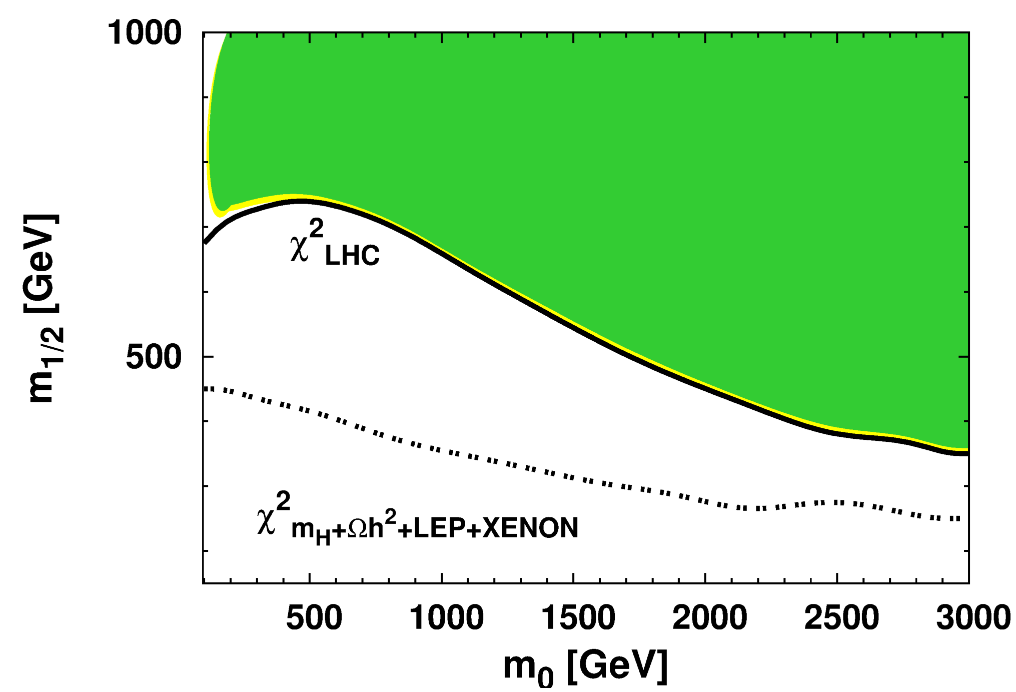
NMSSM



Conclusion

SUSY today:

- No signal so far, but do not give up
- There is still plenty of room for SUSY
- Interpretations of searches are model dependent
- LHC run at 14 TeV might be crucial for low energy SUSY

- Give me something better and I will stick to it

Concluding Remarks

The Higgs Boson:

- Everything is developing as expected
- Wait till the end of the run
- It looks like the Higgs boson so far

SUSY:

- No signal so far, but do not give up
- There is still plenty of room for SUSY

LHC:

- Excellent performance, new results are ahead

Linear Collider:

- It is time to think of it again as a precision physics and discovery machine

Discovery Machine

$$e^+e^- \to X_{New}(+Y_{SM})$$

Precision Machine

$$e^+e^- \to SM$$

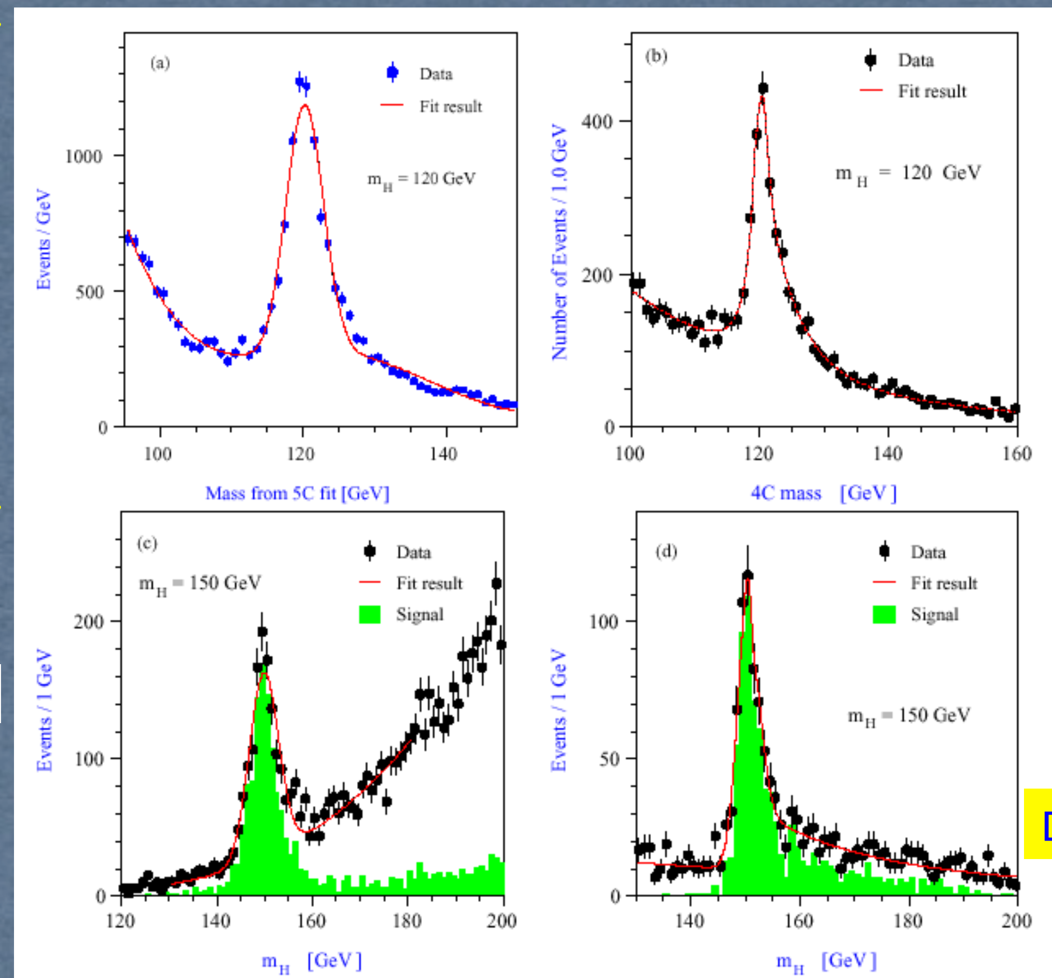
Precision physics of Higgs bosons

ee -> HZ diff. decay channels

m_H = 120 GeV

$\rightarrow b\bar{b}q\bar{q}$

$\rightarrow q\bar{q}\ell^+\ell^-$



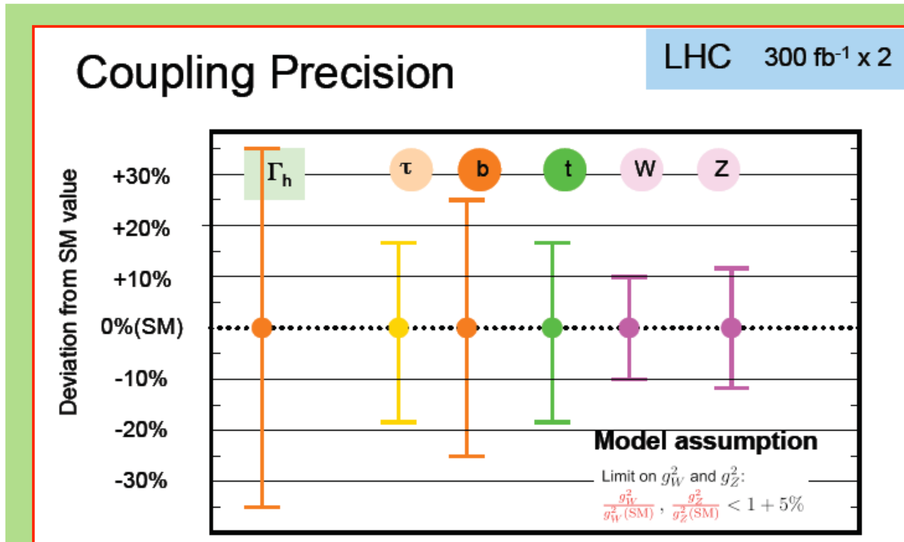
Dm_H = 40 MeV

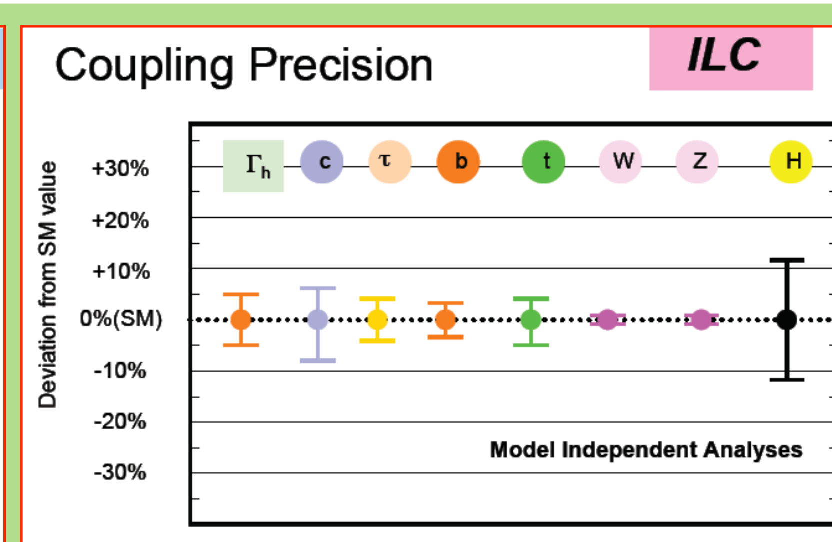
m_H = 150 GeV

$\rightarrow W^+W^-q\bar{q}$

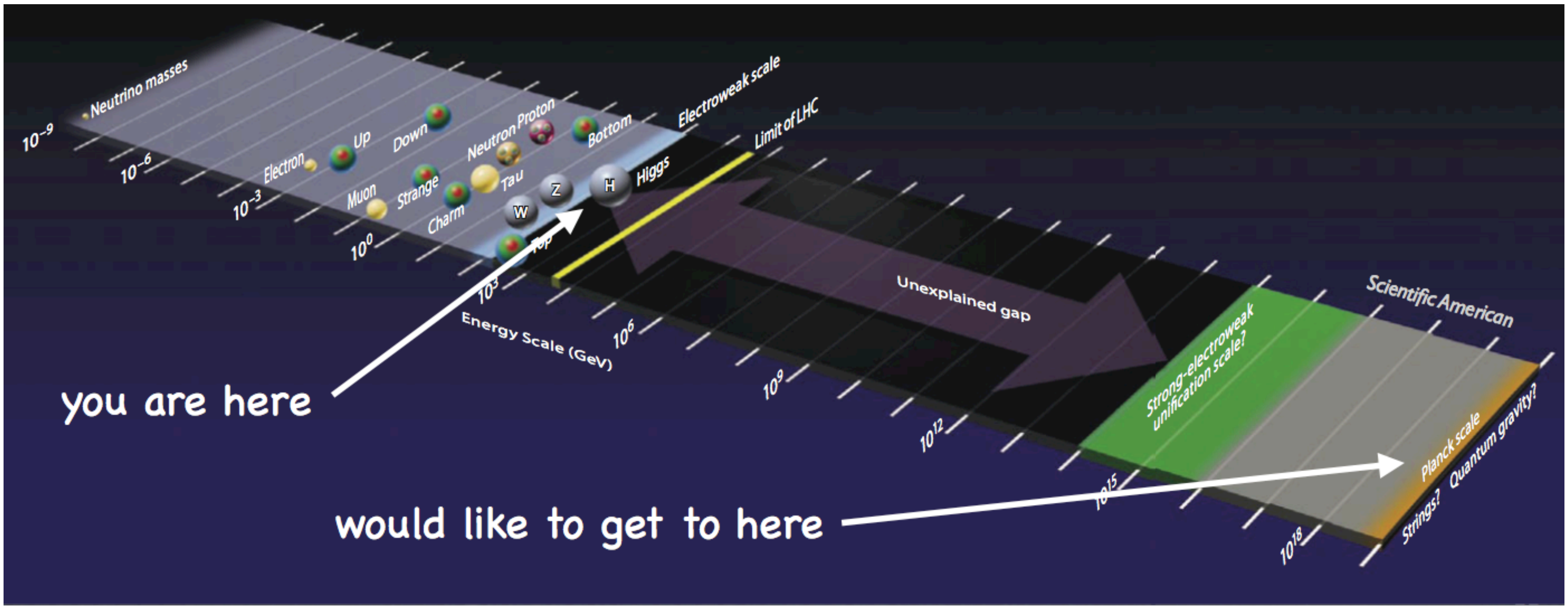
$\rightarrow W^+W^-\ell^+\ell^-$

Dm_H = 70 MeV





HEP Scale


Neutrino masses
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Electron
Up
Down
Muon
Strange
Charm
Neutron Proton
Tau
Bottom
W
Z
H
Higgs
Top
Electroweak scale
Limit of LHC
Energy Scale (GeV)
Unexplained gap
Strong-electroweak unification scale?
Planck scale
Strings? Quantum gravity?
Scientific American
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The End