QCD studies and Higgs searches at the LHC
part one

Sven-Olaf Moch

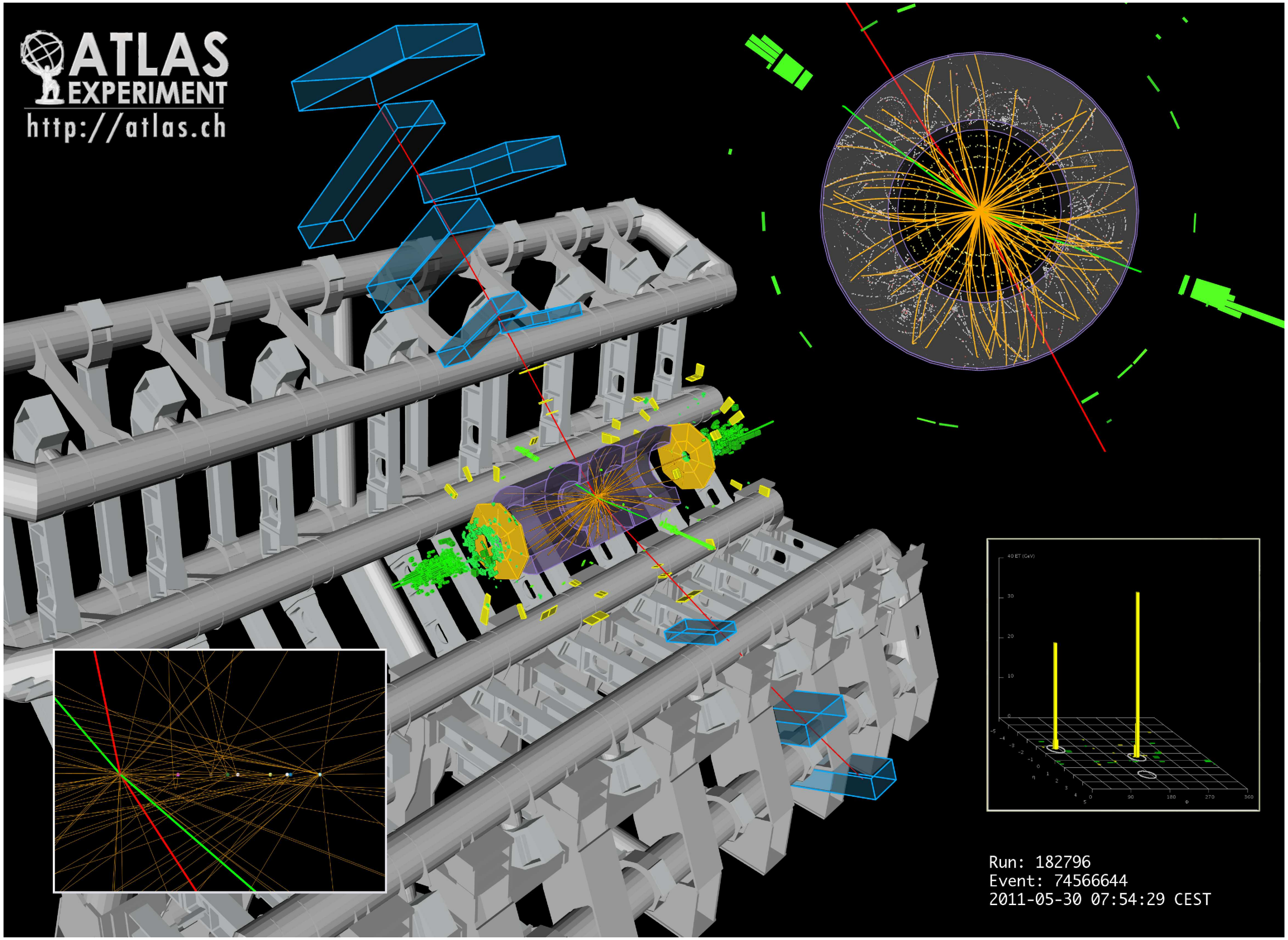
sven-olaf.moch@desy.de

DESY, Zeuthen

– CALC-2012, Dubna, July 28-29 2012 –

Hunt for the Higgs

- Higgs candidate event ($2e\,2\mu$ final state) in LHC run at $\sqrt{s} = 7$ TeV



Challenges

- Solve master equation

$$\text{new physics} = \text{data} - \text{Standard Model}$$

- LHC explores the energy frontier
  - searches require understanding of SM background
  - theory has to match or exceed accuracy of LHC data

Challenges

- Solve master equation

  new physics = data − Standard Model

- LHC explores the energy frontier
  - searches require understanding of SM background
  - theory has to match or exceed accuracy of LHC data

Perturbative QCD at Work

- QCD – the gauge theory of the strong interactions
- QCD covers dynamics in a large range of scales
  - asymptotically free theory of quarks and gluons at short distances
  - confining theory of hadrons at long distances
- Essential and established part of toolkit for discovering new physics
  - Tevatron and LHC
  - we no longer “test” QCD

Basic concepts of perturbative QCD

- Theoretical framework for QCD predictions at high energies relies on few basic concepts
  - infrared safety
  - factorization
  - evolution

Infrared safety

- Small class of cross sections at high energies and decay rates directly calculable in perturbation theory
- Infrared safe quantities
  - free of long range dependencies at leading power in large momentum scale Q Kinoshita '62; Lee, Nauenberg '64
- General structure of cross section
  - large momentum scale Q, renormalization scale μ

$$Q^2\,\hat{\sigma}\left(Q^2, \mu^2, \alpha_s(\mu^2)\right) = \sum_n \alpha_s^n\, c^{(n)}(Q^2/\mu^2)$$

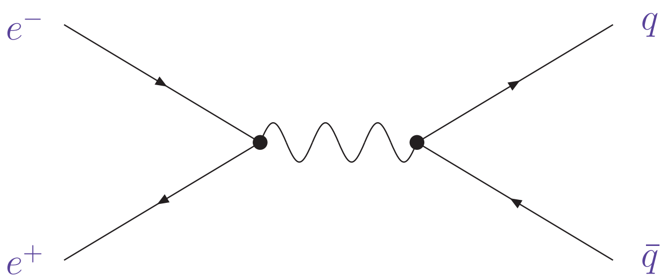
- Examples
  - total cross section in $e^+ e^-$-annihilation

$$R^{\rm had}(s) = \frac{\sigma(e^+ e^- \to \text{hadrons})}{\sigma(e^+ e^- \to \mu^+ \mu^-)}$$

  - jet cross sections in $e^+ e^-$-annihilation
  - total width of Z-boson

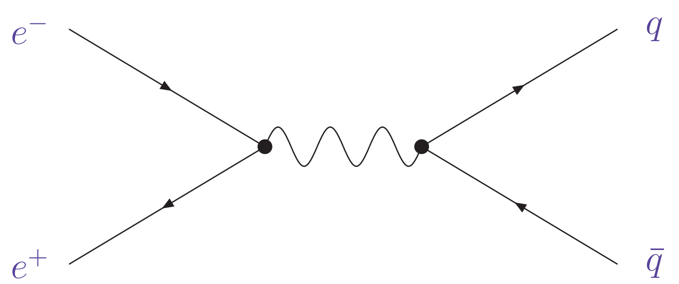
Soft and collinear singularities

- e^+e^--annihilation (massless quarks)
  - Born cross section $\sigma^{(0)} = \dfrac{4\pi\alpha^2}{3s}$

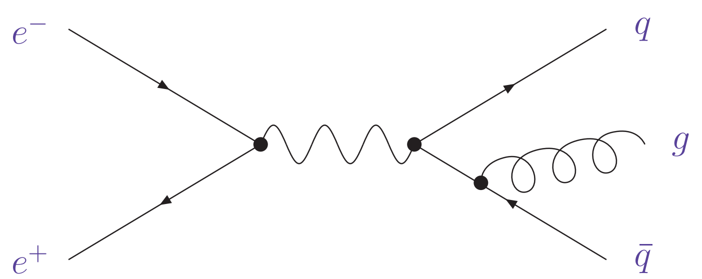


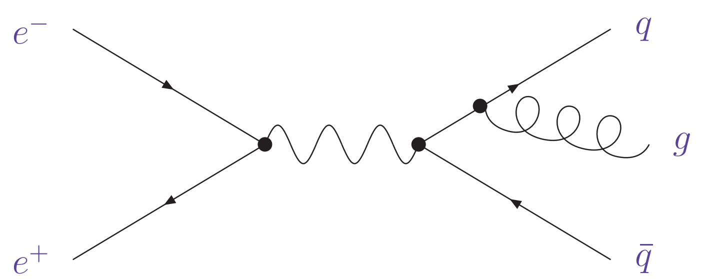
Soft and collinear singularities

- e^+e^--annihilation (massless quarks)
  - Born cross section $\sigma^{(0)} = \frac{4\pi\alpha^2}{3s}$



- Study QCD corrections (real emissions)



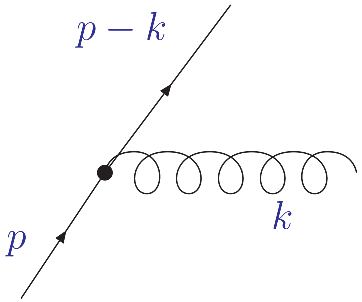


- Cross section
  - dimensional regularization $D = 4 - 2\epsilon$ (with $f(\epsilon) = 1 + \mathcal{O}(\epsilon^2)$)

$$\sigma^{q\bar{q}g} = \sigma^{(0)}\, 3 \sum_q e_q^2\, f(\epsilon)\, C_F\, \frac{\alpha_s}{2\pi} \int dx_1 dx_2\, \frac{x_1^2 + x_2^2 - \epsilon(2 - x_1 - x_2)}{(1-x_1)^{1+\epsilon}\,(1-x_2)^{1+\epsilon}}$$

- scaled energies $x_1 = 2\frac{E_q}{\sqrt{s}}$ and $x_2 = 2\frac{E_{\bar{q}}}{\sqrt{s}}$

- Soft and collinear divergencies ($0 \leq x_1, x_2 \leq 1$ and $x_1 + x_2 \geq 1$)



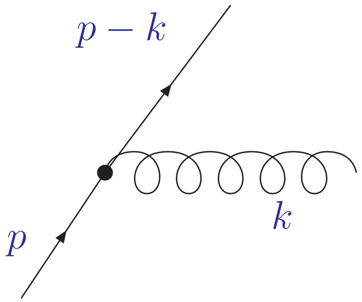
$$1 - x_1 = x_2 \frac{E_g}{\sqrt{s}} (1 - \cos\theta_{2g}) \text{ and}$$

$$1 - x_2 = x_1 \frac{E_g}{\sqrt{s}} (1 - \cos\theta_{1g})$$

- Integrate over phase space for real emission contributions

$$\sigma^{q\bar{q}g} \quad = \quad \sigma^{(0)}\, 3 \sum_q e_q^2\, f(\epsilon)\, C_F\, \frac{\alpha_s}{2\pi} \left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} + \mathcal{O}(\epsilon) \right)$$

- Soft and collinear divergencies ($0 \leq x_1, x_2 \leq 1$ and $x_1 + x_2 \geq 1$)

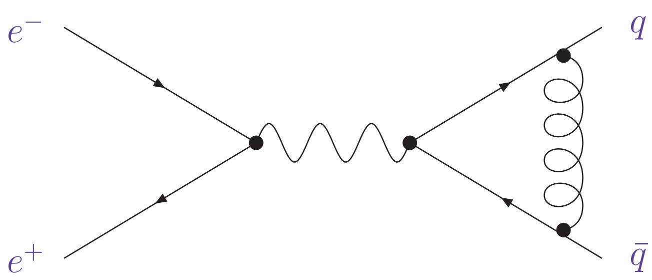


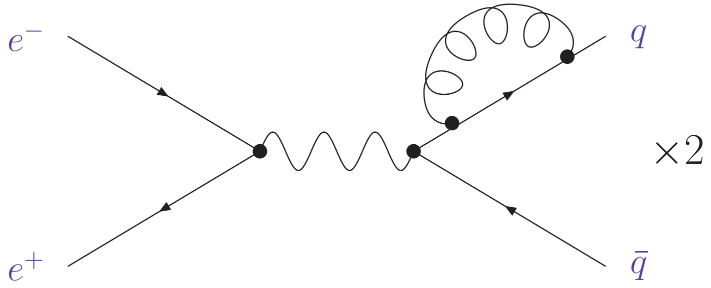
$$1 - x_1 = x_2 \frac{E_g}{\sqrt{s}}(1 - \cos\theta_{2g})$$ and
$$1 - x_2 = x_1 \frac{E_g}{\sqrt{s}}(1 - \cos\theta_{1g})$$

- Integrate over phase space for real emission contributions

$$\sigma^{q\bar{q}g} \quad = \quad \sigma^{(0)}\, 3 \sum_q e_q^2\, f(\epsilon)\, C_F\, \frac{\alpha_s}{2\pi} \left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} + \mathcal{O}(\epsilon)\right)$$

- Divergencies cancel against virtual contributions





$$\sigma^{q\bar{q}(g)} \quad = \quad \sigma^{(0)}\, 3 \sum_q e_q^2\, f(\epsilon)\, C_F\, \frac{\alpha_s}{2\pi} \left(-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 + \mathcal{O}(\epsilon)\right)$$

Infrared safety

- Total cross section ($R(s)$) is directly calculable in perturbation theory (finite)

$$R(s) \quad = \quad 3 \sum_q e_q^2 \left\{ 1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2) \right\}$$

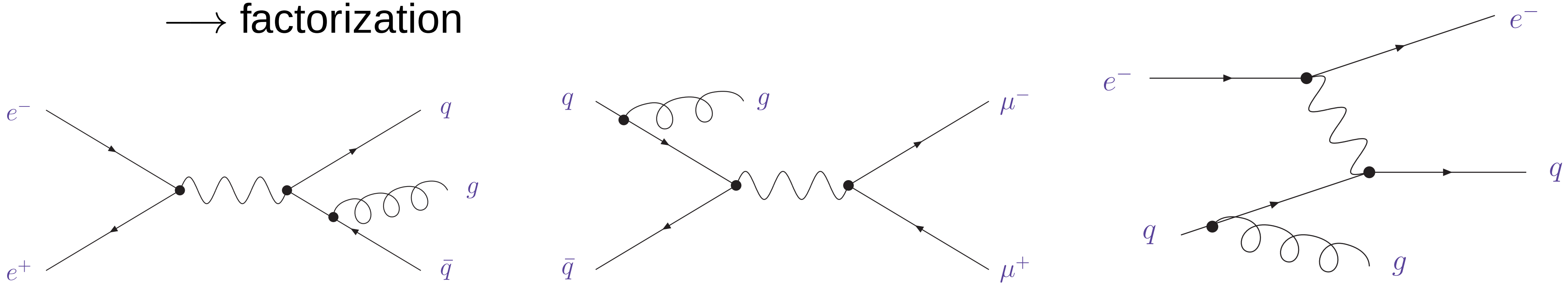
Infrared safety

- Total cross section ($R(s)$) is directly calculable in perturbation theory (finite)

$$R(s) \quad = \quad 3 \sum_q e_q^2 \left\{ 1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2) \right\}$$

Collinear singularities

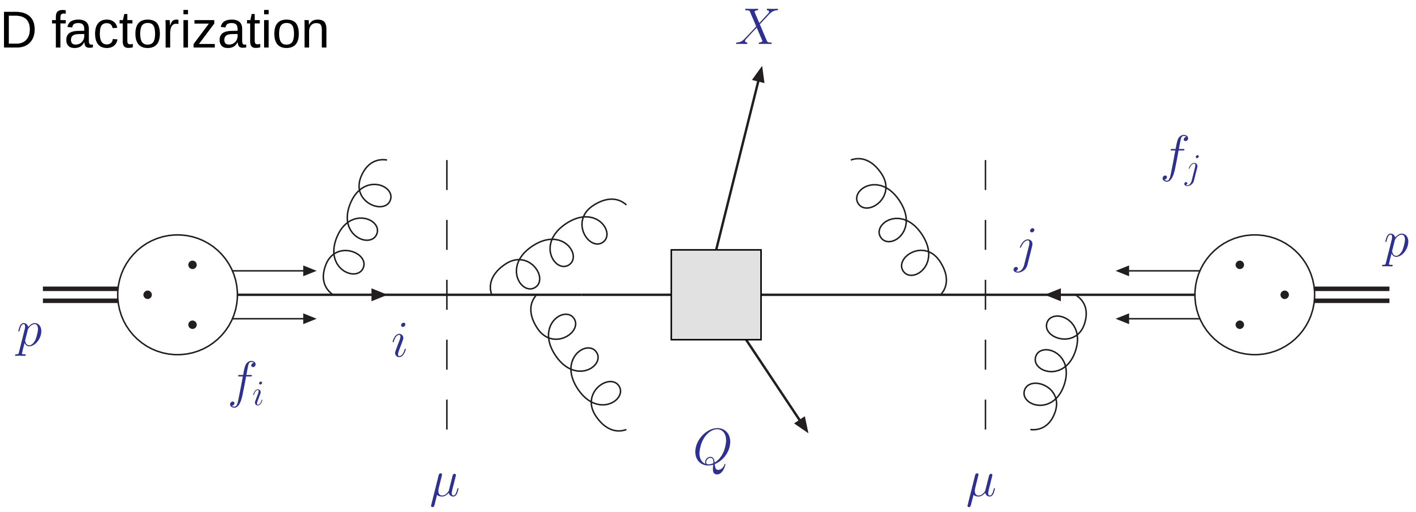
- Collinear divergencies remain for hadronic observables
  $\longrightarrow$ factorization



- Left: single-hadron inclusive e^+e^--annihilation (time-like kinematics)
- Center: Drell-Yan process in pp-scattering (space-like kinematics)
- Right: Deep-inelastic e^-p-scattering (space-like kinematics)

QCD factorization

- QCD factorization



$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - known to NLO, NNLO, ... ($\mathcal{O}(\text{few}\%)$ theory uncertainty)
- Non-perturbative parameters: parton distribution functions f_i, strong coupling α_s, particle masses m_X
  - known from global fits to exp. data, lattice computations, ...

Factorization

- Large class of hard-scattering reactions with initial state hadrons
  - cross section not infrared safe
  - dependent on quark and gluon degrees of freedom in hadron
  - sensitive to nonperturbative processes at long distances
- Factorization of cross section
  - infrared safe hard part $\hat{\sigma}_{\rm pt}$ calculable in perturbative QCD
  - nonperturbative function f determined from data
  - f parametrizes hadron structure
- General structure of cross section
  - large momentum scale Q, factorization scale μ

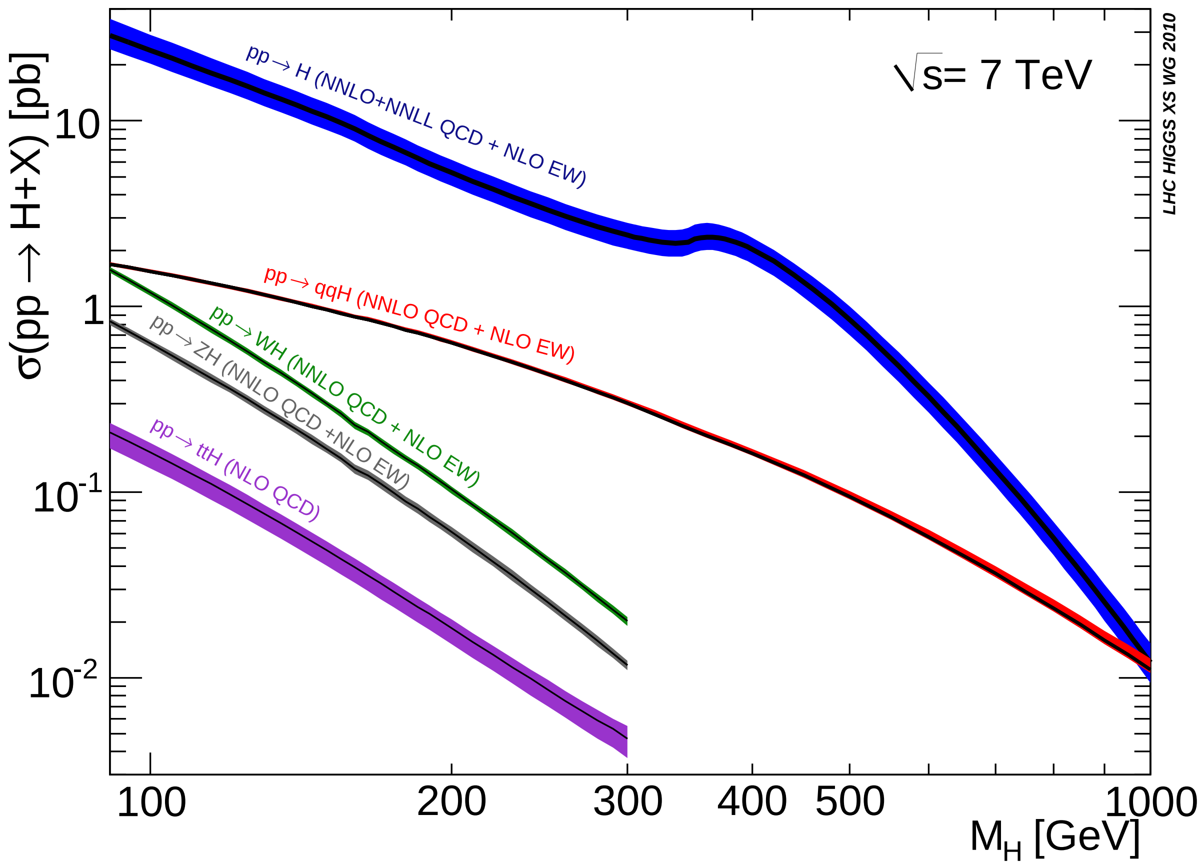
$$Q^2\, \sigma_{\rm phys}\, (Q) = \hat{\sigma}_{\rm pt}\, (Q/\mu, \alpha_s(\mu)) \,\otimes\, f\, (\mu)$$

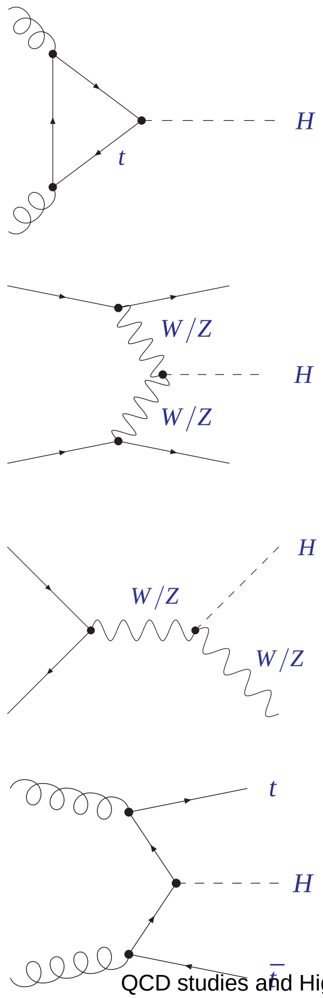
  - convolution $\otimes$ in suitable kinematical variables
- Factorization
  - generalization of operator product expansion

Higgs cross section

Cross section for Higgs production at the LHC

- Dominant channels for Higgs boson production LHC Higgs XS WG '10





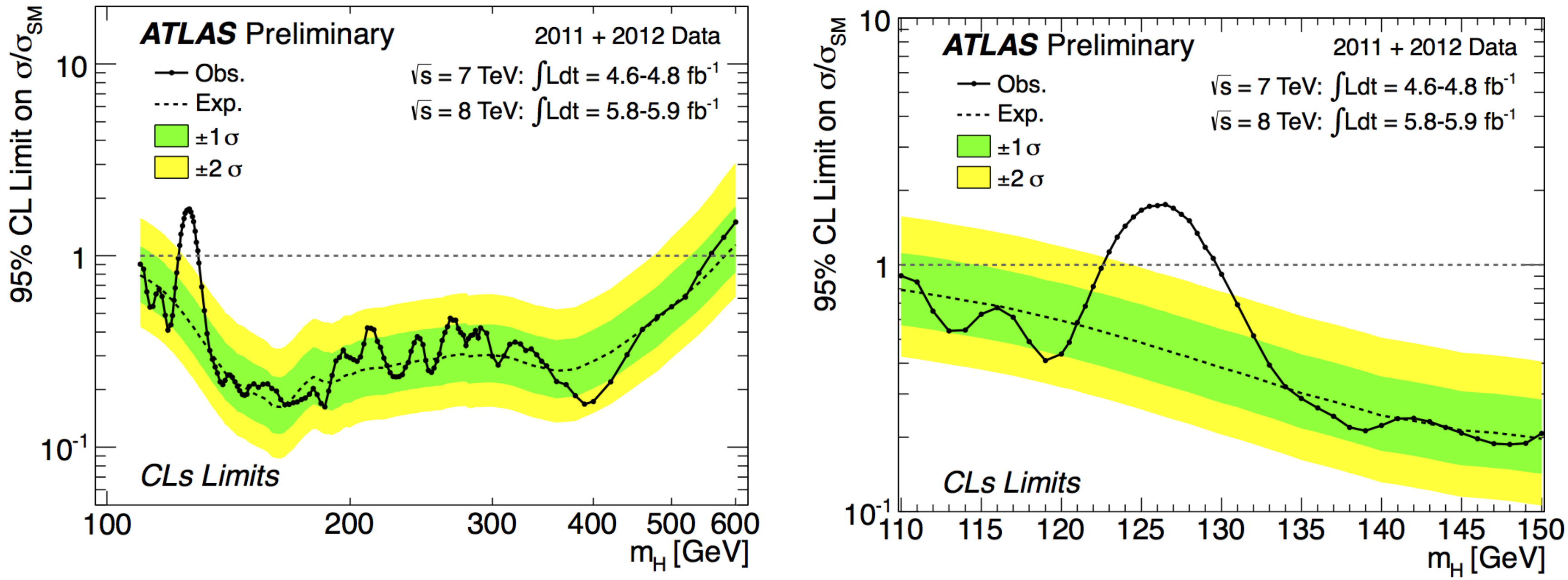
gg-fusion

weak boson fusion

Higgs strahlung

$t\bar{t}H$-channel

Higgs discovery at LHC

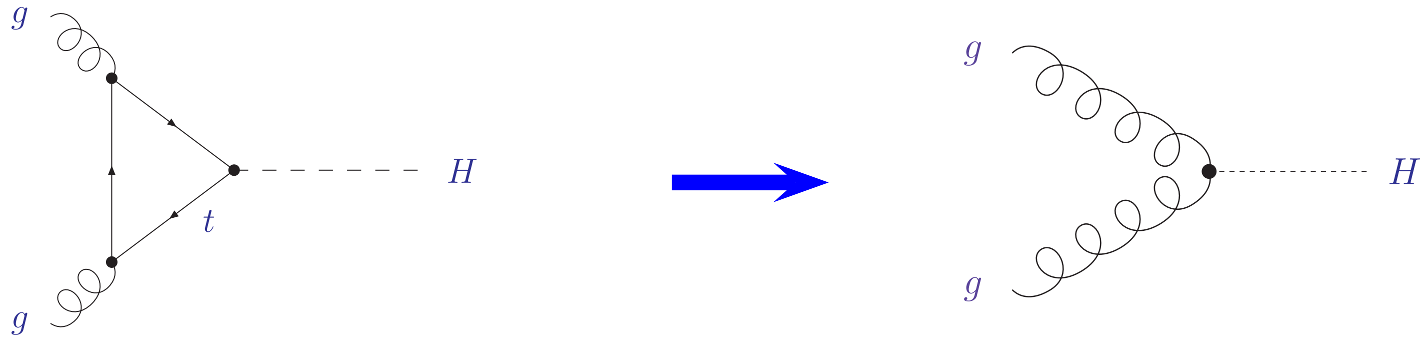


Atlas coll. July 2012

- Higgs mass in the range $m_H = 125$ GeV
  - Higgs search driven predominantly by $gg \to H$
  - current range of excluded Higgs masses at Tevatron optimistic and consequences for LHC interesting

gg-fusion

Effective theory

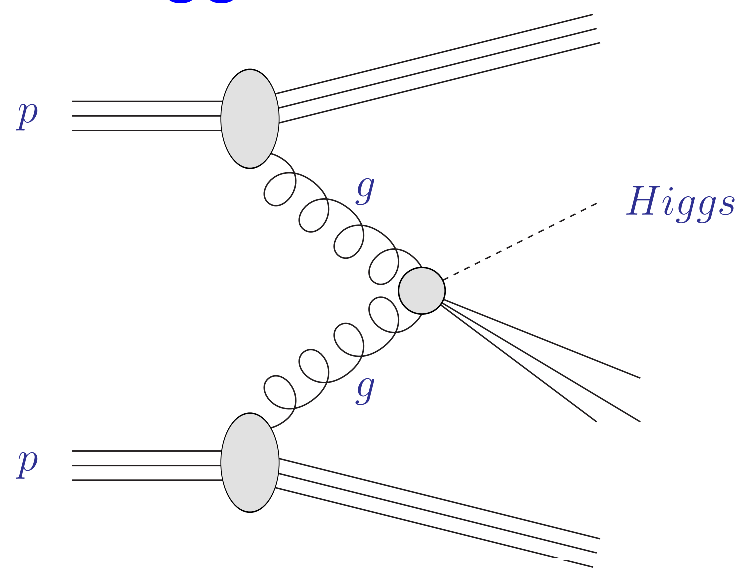


- Integration of top-quark loop (finite result)
  - decay width $H \to gg$ ($m_q = 0$ for light quarks, m_t heavy)

$$\Gamma_{H \to gg} = \frac{G_\mu \, m_H^3}{64 \sqrt{2} \, \pi^3} \, \alpha_s^2 \, f\left(\frac{m_H^2}{4 m_t^2} \right)$$

- Effective theory in limit $m_t \to \infty$; Lagrangian $\mathcal{L} = -\frac{1}{4} \, \frac{H}{v} \, C_H \, G^{\mu\nu\,a} \, G^a_{\mu\nu}$
  - operator $H G^{\mu\nu\,a} \, G^a_{\mu\nu}$ relates to stress-energy tensor
  - additional renormalization proportional to QCD β-function required
    Kluberg-Stern, Zuber '75; Collins, Duncan, Joglekar '77

QCD corrections to ggF



- Hadronic cross section $\sigma_{pp\to H}$ with $\tau = m_H^2/S$
  - renormalization/factorization (hard) scale $\mu = \mathcal{O}(m_H)$

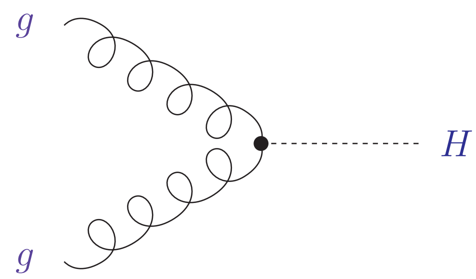
$$\sigma_{pp\to H} = \sum_{ij} \int_\tau^1 \frac{dx_1}{x_1} \int_{x_1}^1 \frac{dx_2}{x_2} f_i\left(\frac{x_1}{x_2},\mu^2\right) f_j\left(x_2,\mu^2\right) \hat{\sigma}_{ij\to H}\left(\frac{\tau}{x_1},\frac{\mu^2}{m_H^2},\alpha_s(\mu^2)\right)$$

- Partonic cross section $\hat{\sigma}_{ij\to H}$

$$\hat{\sigma}_{ij\to H} \quad = \quad \underbrace{\alpha_s^2 \Big[\, \hat{\sigma}^{(0)}_{ij\to H} + \alpha_s\, \hat{\sigma}^{(1)}_{ij\to H}}_{} \; + \; \alpha_s^2\, \hat{\sigma}^{(2)}_{ij\to H} \; + \; \ldots \Big]$$

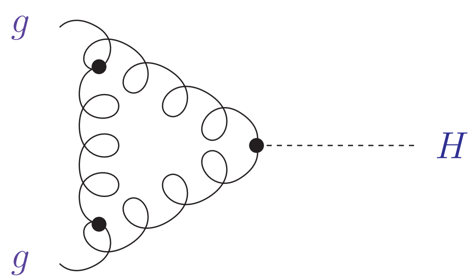
NLO: standard approximation (large uncertainties)

Radiative corrections in a nutshell



- Leading order
  - partonic cross section $x = \tau/x_1$

    $\hat{\sigma}^{(0)}_{gg\to H} = \delta(1-x)$

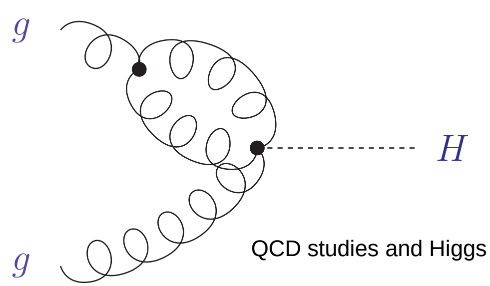


- Next-to-leading order
  - virtual correction (time-like kinematics)
    (infrared divergent; proportional to Born)
  - dimensional regularization $D = 4 - 2\epsilon$

$$\hat{\sigma}^{(1),v}_{gg\to H} = C_A \frac{\alpha_s}{4\pi} \delta(1-x) \left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} \left(-\frac{2}{\epsilon^2} + 7\,\zeta_2 + \mathcal{O}(\epsilon)\right)$$

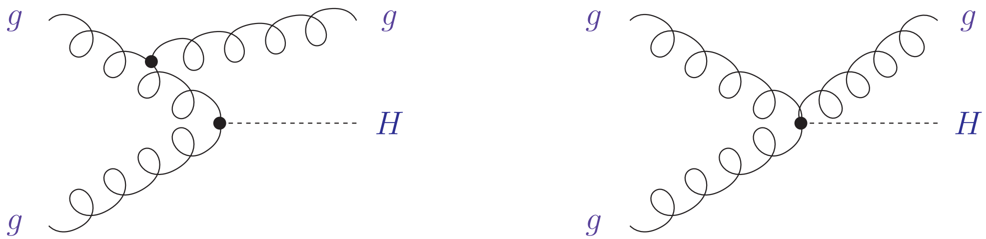
  - additional contribution from renormalization of effective operator

$$\alpha_s^{\text{bare}} = \alpha_s^{\text{ren}} \left\{ 1 - \frac{\beta_0}{\epsilon} \frac{\alpha_s^{\text{ren}}}{4\pi} + \mathcal{O}(\alpha_s^2) \right\}$$



  - massless tadpoles vanish
    in dimensional regularization

- Next-to-leading order



  - add real and virtual corrections $\hat{\sigma}^{(1)}_{gg\to H} = \hat{\sigma}^{(1),r}_{gg\to H} + \hat{\sigma}^{(1),v}_{gg\to H}$
  - collinear divergence remains splitting functions $P^{(0)}_{gg}$

$$\hat{\sigma}^{(1)}_{gg\to H} = \frac{\alpha_s}{4\pi}\left(\frac{\mu^2}{m_H^2}\right)^{\epsilon}\Bigg\{$$

$$\frac{1}{\epsilon}\,C_A\left(\frac{8}{1-x}+\frac{8}{x}-8(2-x+x^2)+\frac{22}{3}\delta(1-x)\right)-\frac{1}{\epsilon}\,n_f\,\frac{4}{3}\delta(1-x)$$

$$+C_A\left(16\frac{\ln(1-x)}{1-x}+\left(\frac{22}{3}+8\zeta_2\right)\delta(1-x)-16x(2-x+x^2)\ln(1-x)\right.$$

$$\left.-8\frac{(1-x+x^2)^2}{1-x}\ln(x)-\frac{22}{3}(1-x)^3\right)$$

$$+\mathcal{O}(\epsilon)\Bigg\}$$

- Structure of NLO correction
  - absorb collinear divergence $P_{gg}^{(0)}$ in renormalized parton distributions

$$\hat{\sigma}_{gg\to H}^{(1),\mathrm{bare}} = \frac{\alpha_s}{4\pi} \left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} \left\{ \frac{1}{\epsilon}\, 2\, P_{gg}^{(0)}(x) + \hat{\sigma}_{gg\to H}^{(1)}(x) + \mathcal{O}(\epsilon) \right\}$$

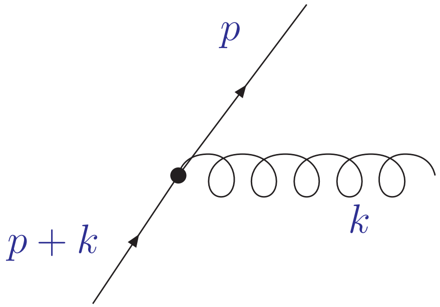
$$g^{\mathrm{ren}}(\mu_F^2) = g^{\mathrm{bare}} - \frac{\alpha_s}{4\pi}\, \frac{1}{\epsilon}\, P_{gg}^{(0)}(x) \left(\frac{\mu^2}{\mu_F^2}\right)^{\epsilon}$$

  - partonic (physical) structure function at factorization scale μ_F

$$\hat{\sigma}_{gg\to H} = \delta(1-x) + \frac{\alpha_s}{4\pi} \left\{ \hat{\sigma}_{gg\to H}^{(1)}(x) - \ln\left(\frac{m_H^2}{\mu_F^2}\right) 2\, P_{gg}^{(0)}(x) \right\}$$

Resummation

- Large logarithmic corrections soft/collinear regions of phase space



$$\frac{1}{(p+k)^2} = \frac{1}{2p\cdot k} = \frac{1}{2E_q E_g(1-\cos\theta_{qg})}$$

$$\alpha_s \int d^4k \frac{1}{(p+k)^2} \longrightarrow \alpha_s \int dE_g\, d\sin\theta_{qg} \frac{1}{2E_q E_g(1-\cos\theta_{qg})}$$

$$\longrightarrow \alpha_s \ln^2(\dots)$$

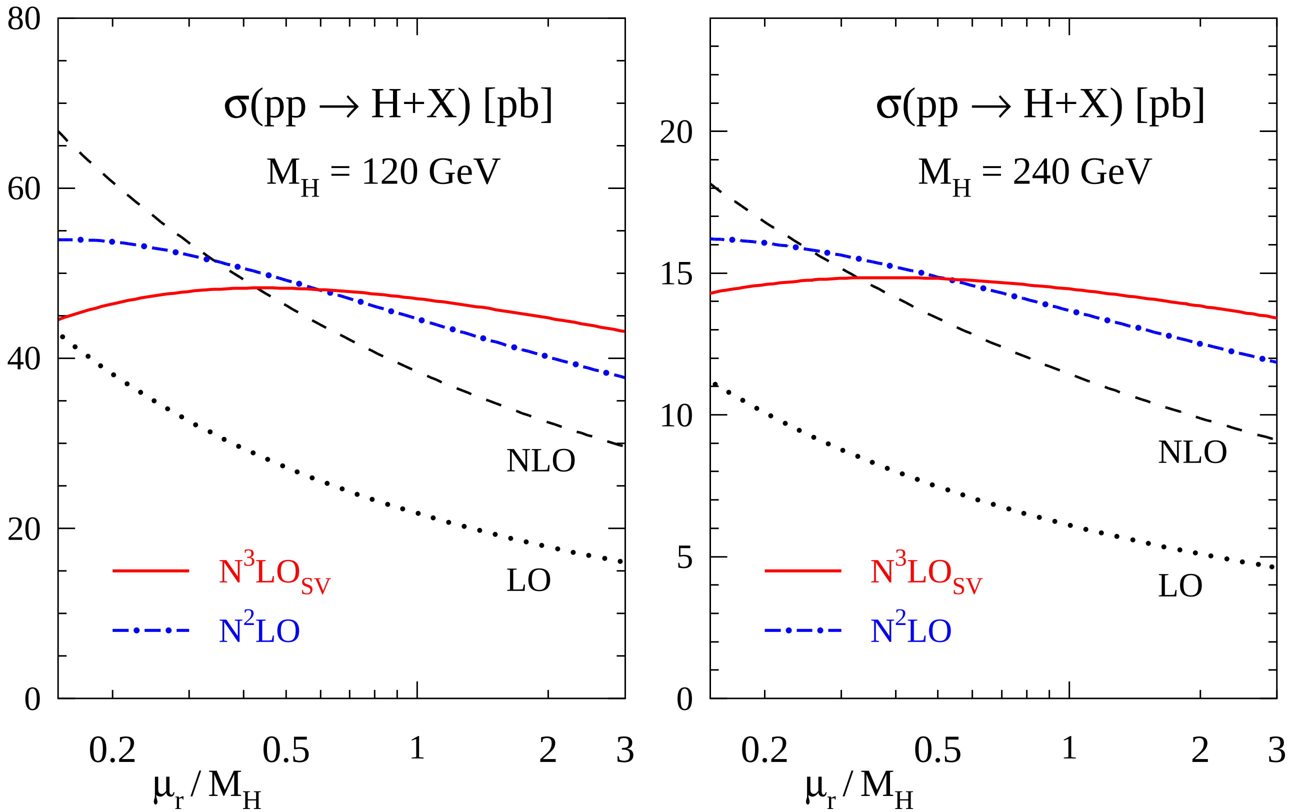
- Resummation
  - reorganize perturbative expansion $\longrightarrow$ stability
  - generating functional for higher orders of perturbation theory

$$\begin{aligned} \mathcal{O} &= 1 + \alpha\left(\ln^2 + \ln + 1\right) + \alpha^2\left(\ln^4 + \ln^3 + \ln^2 + \ln + 1\right) + \dots \\ &= \left(1 + \alpha\, 1 + \alpha^2\, 1 + \dots\right)\exp\left(\alpha\ \ln^2 + \alpha\ \ln + \alpha^2\ \ln + \dots\right) \end{aligned}$$

- Higgs cross section $\hat\sigma_{gg\to H}$ with $x = \dfrac{M_H^2}{s}$ ($x \simeq 1$ close to threshold)

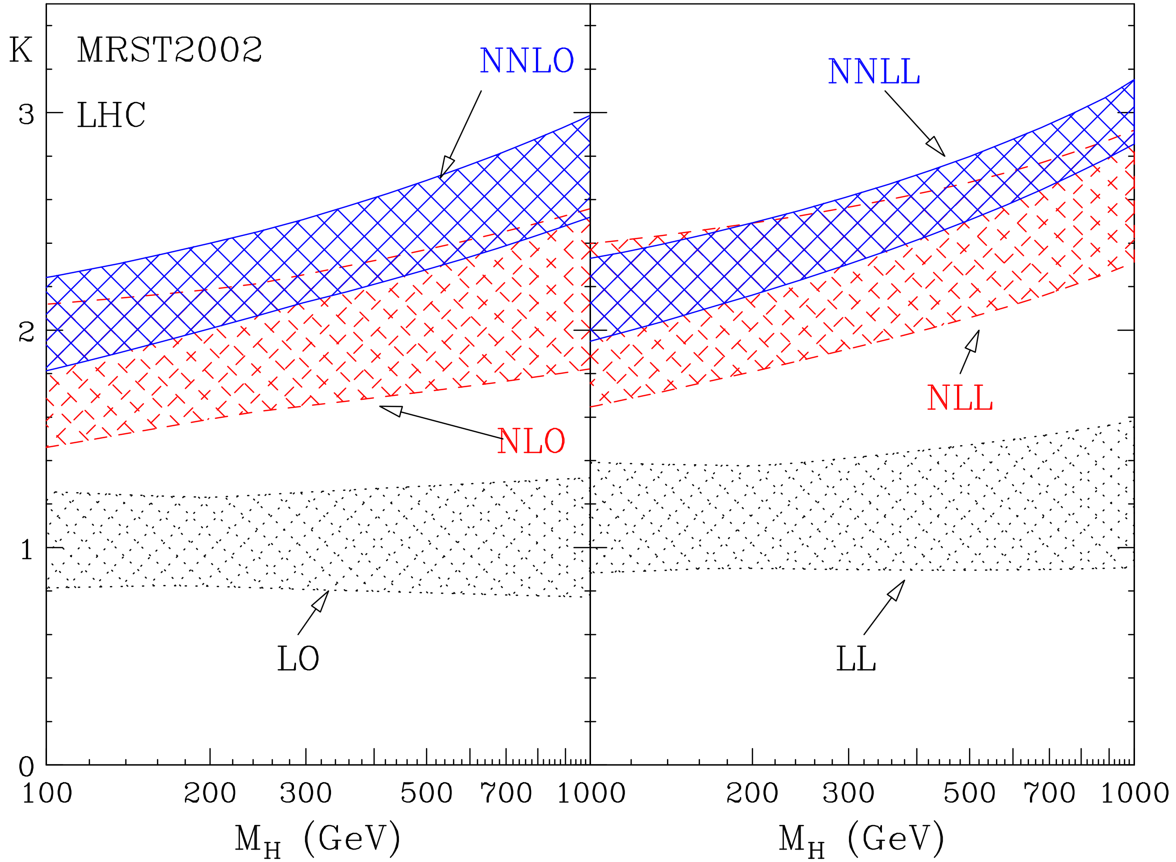
$$\alpha_s^n \left(\frac{\ln^{2n-1}(1-x)}{1-x}\right)_+ \longleftrightarrow \alpha_s^n\ \ln^{2n}(N)$$

Inclusive cross section



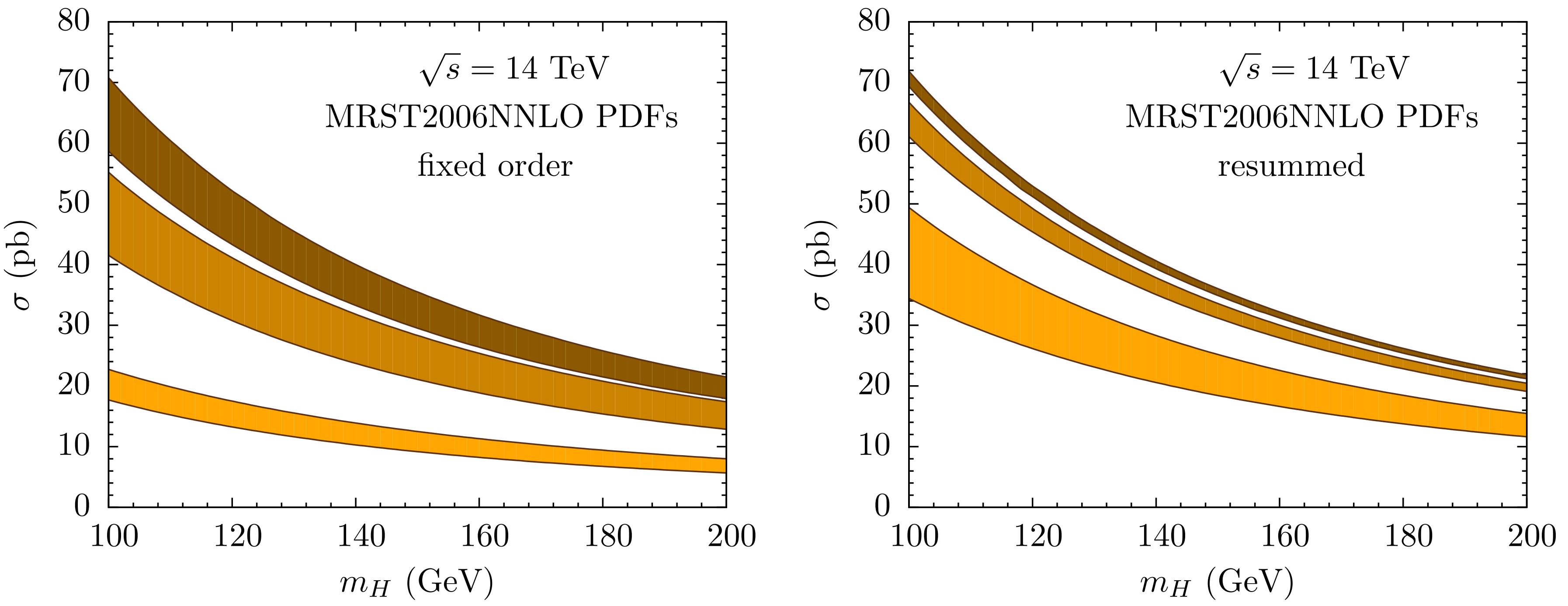
- Apparent convergence of perturbative expansion
  - NNLO corrections still large
    Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03
  - improvement through complete soft N^3LO corrections S.M., Vogt '05
    or NNLL resummtion Catani, de Florian, Grazzini, Nason '03, Ahrens et al. '10
- Perturbative stability under renormalizaion scale variation

Total Higgs cross section and resummation



- Cross section at LHC with scale variation:
  fixed order predictions (left) and resummed perturbation series (right)
  - NNLO corrections
    Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03
  - NNLL resummation
    Catani, Grazzini, de Florian, Nason '03, Ahrens et al. '10

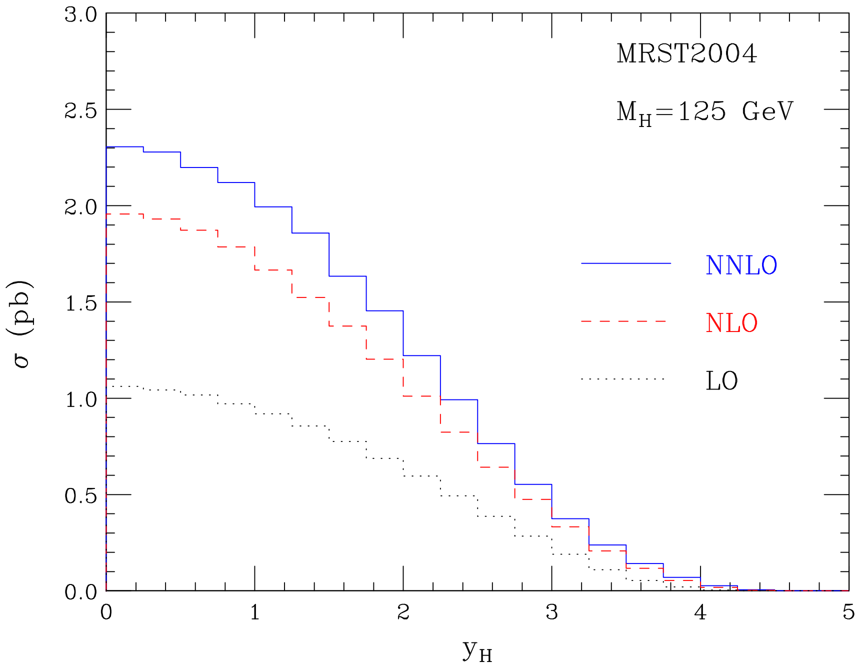
Total Higgs cross section and resummation

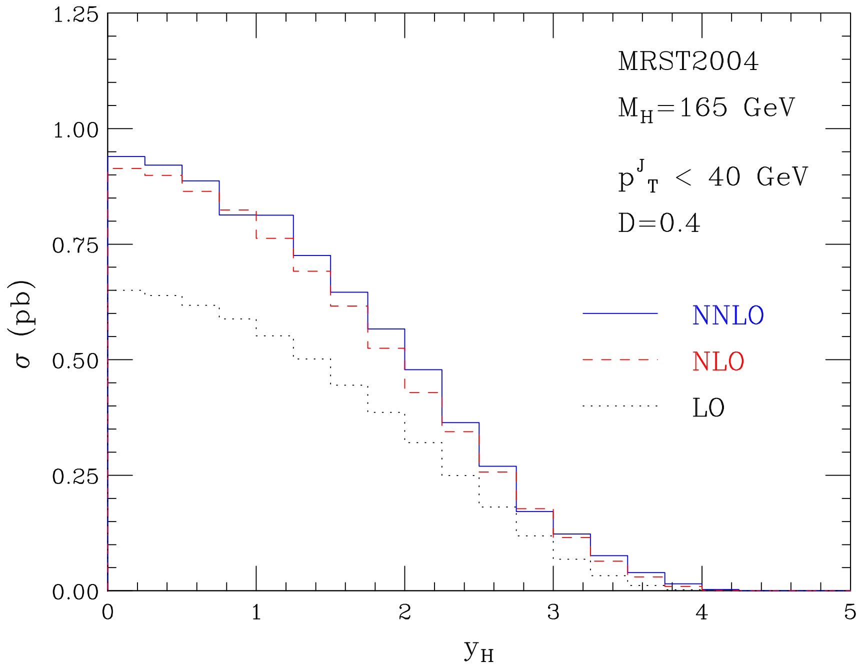


- Cross section at LHC with scale variation:
  fixed order predictions (left) and resummed perturbation series (right)
  - NNLO corrections
    Harlander, Kilgore ‘02; Anastasiou, Melnikov ‘02; Ravindran, Smith, van Neerven ‘03
  - NNLL resummation (lots of activity in the last years)
    Catani, Grazzini, de Florian, Nason ‘03, Ahrens et al. ‘10

gg fusion (fully exclusive)

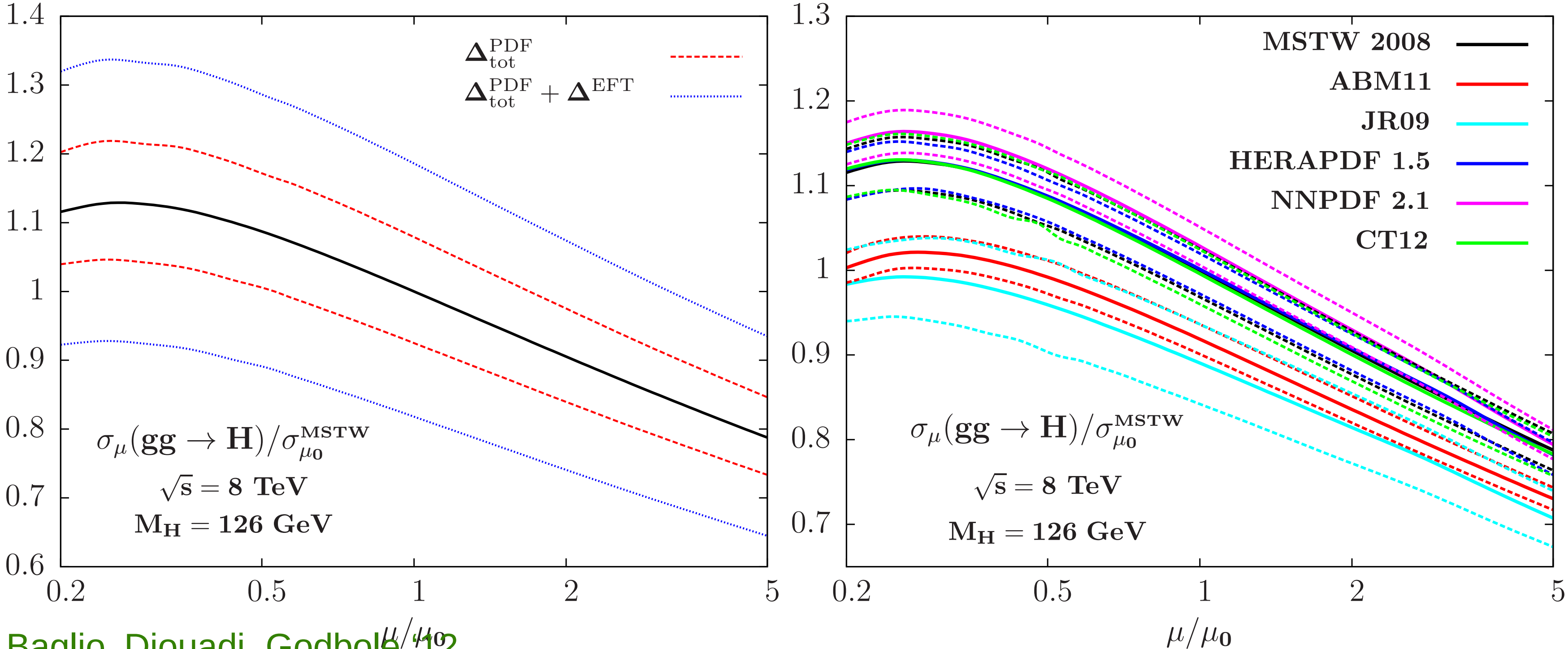
- Bin-integrated Higgs rapidity distribution including decay $H \to \gamma\gamma$
  - QCD corrections up to NNLO Anastasiou, Melnikov, Petriello '05
  - fast parton level Monte Carlo HNNLO Catani, Grazzini '07





- Impact of kinematical cuts on higher order corrections (LHC $\sqrt{s} = 14$ TeV)
  - left: Higgs mass $M_h = 125$ GeV, no cuts on p_t of jets
  - right: Higgs mass $M_h = 165$ GeV and veto on jets with $p_t > 40$ GeV (k_t algorithm for jet reconstruction with jet size $D = 0.4$)

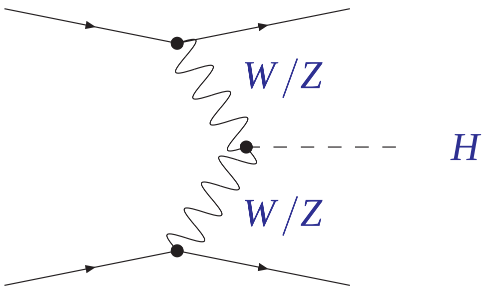
PDF dependence of gg-fusion cross section at LHC



Baglio, Djouadi, Godbole '12

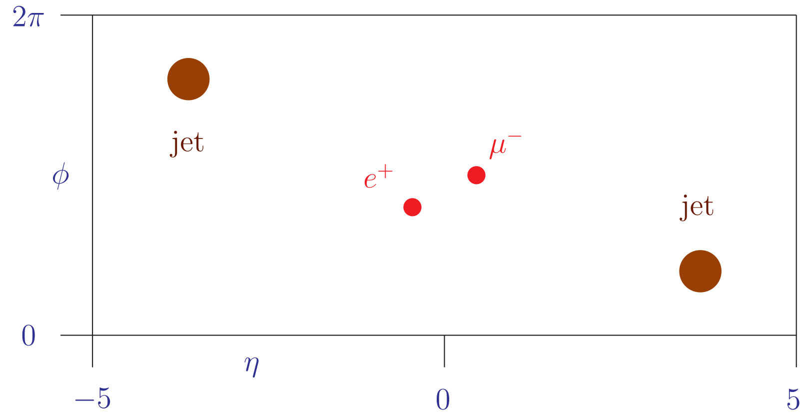
- PDFs uncertainty
  - PDFs (gluon at large x) largest single source of uncertainty
  - PDF uncertainty estimates by LHC Higgs XS WG too optimistic
- Linear addition of errors
  - PDF uncertainty and error due to effective theory:
    $\Delta\sigma = \Delta\sigma_{\rm PDF} + \Delta\sigma_{\rm EFT}$

Vector-boson fusion



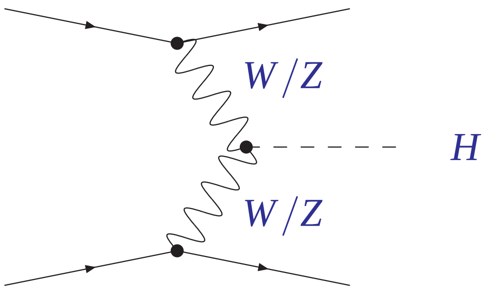
- Second largest rate at LHC (WWH coupling)

Signatures



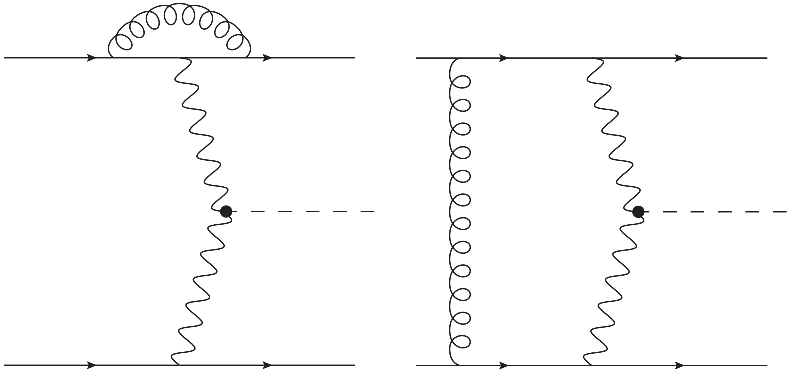
- WW, ZZ fusion $\longrightarrow$ Higgs is color singlet
  - two hard (forward) tagging jets (visible in detector)
  - no (or small) hadronic activity between tagging jets
  - color connection between forward jet and proton remnant
  - Higgs decay in the central rapidity region

Vector-boson fusion

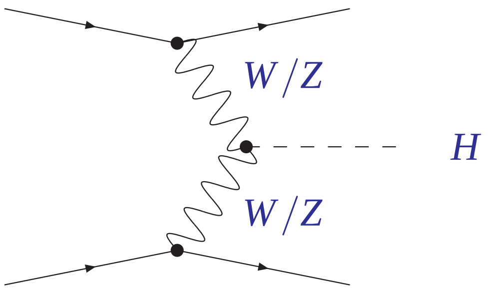


- Second largest rate at LHC (WWH coupling)

- NLO QCD radiative corrections

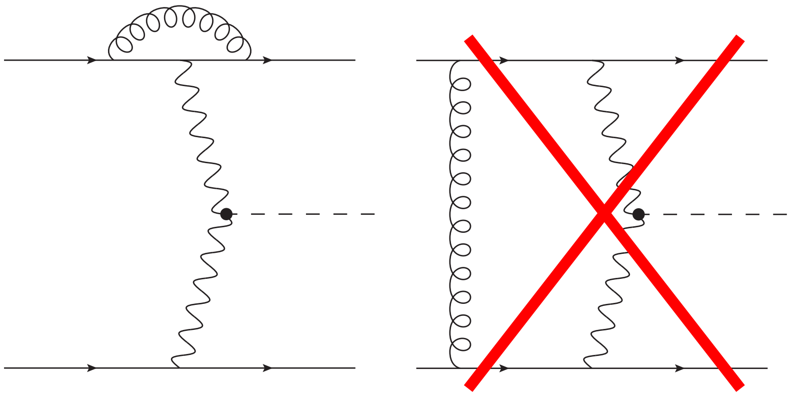


Vector-boson fusion

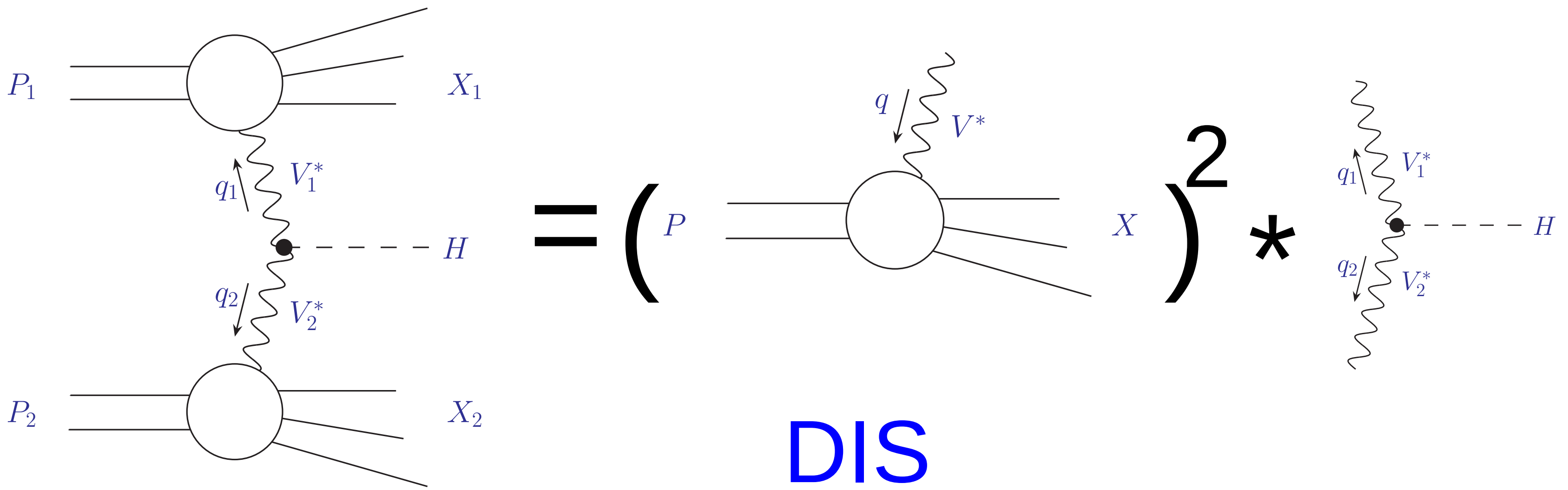


- Second largest rate at LHC (WWH coupling)

- NLO QCD corrections factorize
(color conservation eliminates t-channel gluon in squared ME)



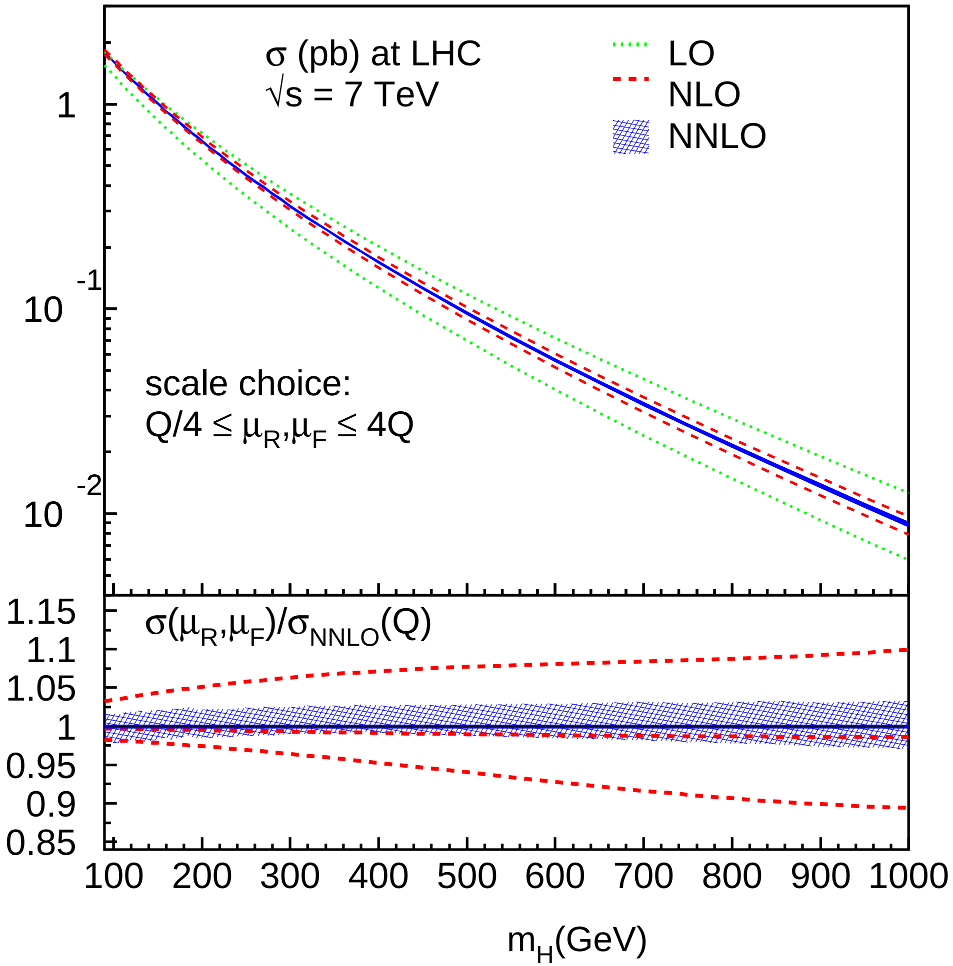
Exact factorization



DIS

- Deep-inelastic scattering building block of cross section with structure functions F_1, F_2 and F_3
- Exact factorization at NLO: so-called strucure function approach
  Han, Valencia, Willenbrock ‘92
- Structure function approach is NOT exact at NNLO in QCD
  - but can be still considered a good approximation, holds to $\mathcal{O}(1\%)$
  - NNLO QCD corrections to F_1, F_2 and F_3 long known
    Kazakov, Kotikov ‘88; Zijlstra, van Neerven ’92; S.M., Vermaseren ‘99

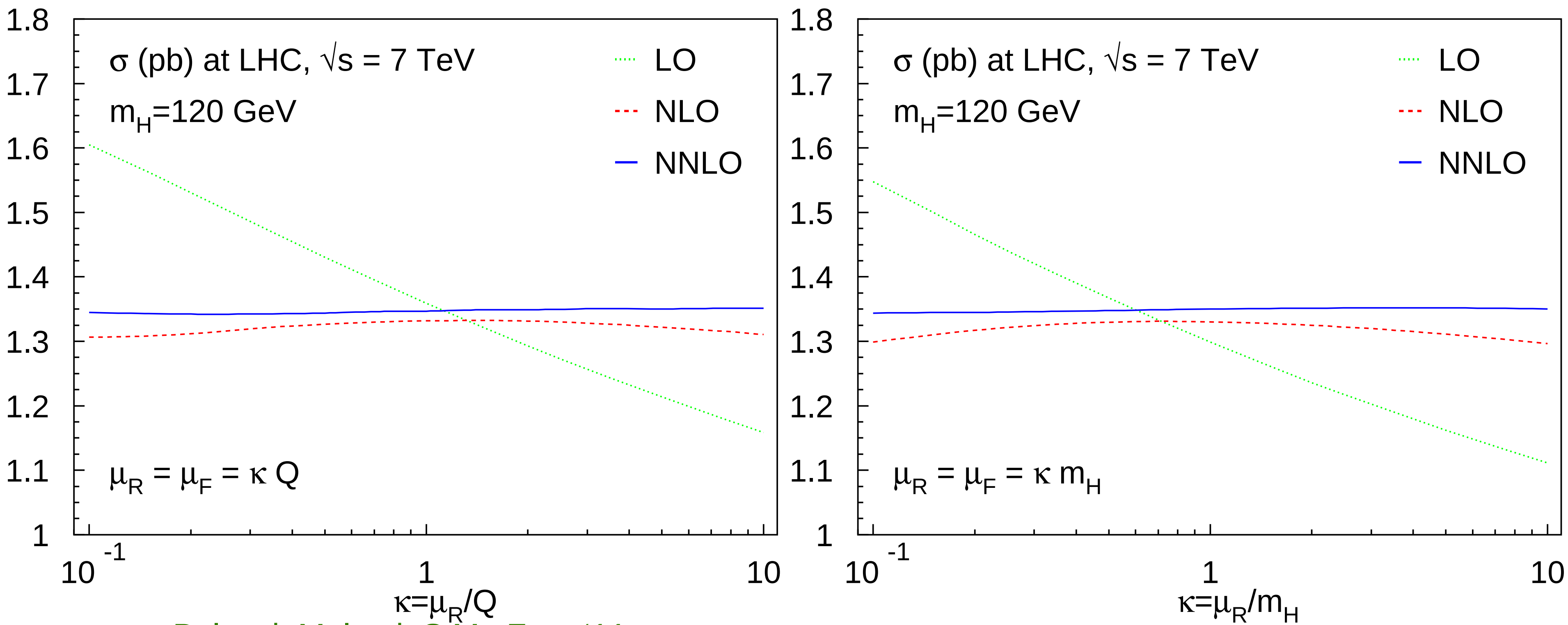
VBF cross section at LHC



Bolzoni, Maltoni, S.M., Zaro '11

- VBF at NNLO
- QCD corrections at second order small
  - apparent convergence
- NNLO results very stable at 2% against QCD scales variation (uniformly over the full mass range)
- Significant reduction of theoretical uncertainty

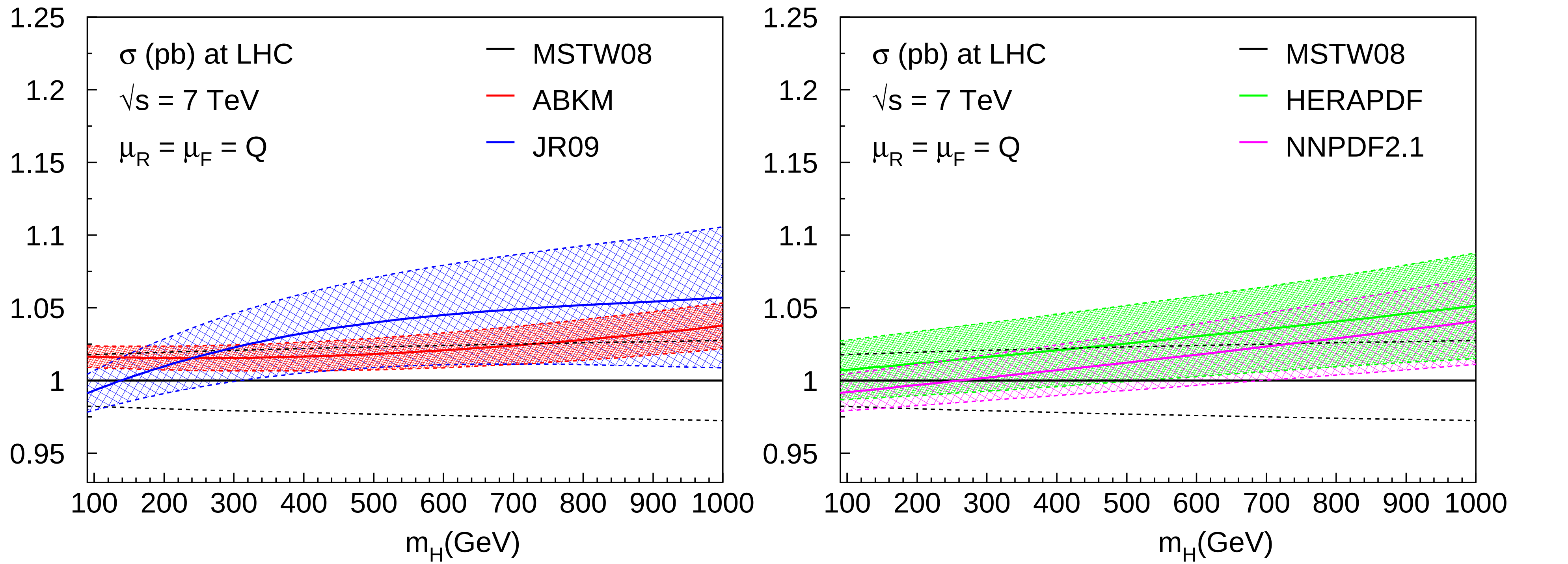
Scale stability at NNLO



Bolzoni, Maltoni, S.M., Zaro '11

- VBF cross sections displays very good scale stability at NNLO over large range for $\mu_R = \mu_F$ preferred (minimal sensitivity)
- Scale choice $\mu_R = \mu_F \simeq Q$ preferred (minimal sensitivity)

PDF dependence of VBF cross section at LHC

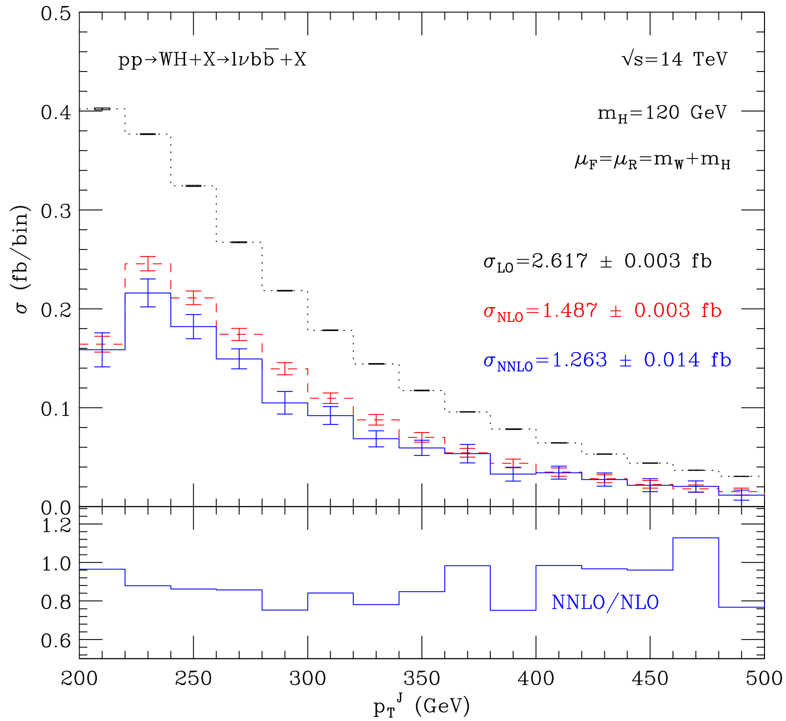


Bolzoni, Maltoni, S.M., Zaro '11

- PDF uncertainty
  - moderate for small Higgs masses $\mathcal{O}(\pm 2\%)$
  - increasingly larger for heavy Higgs bosons up to $\mathcal{O}(\pm 10\%)$

Higgs strahlung

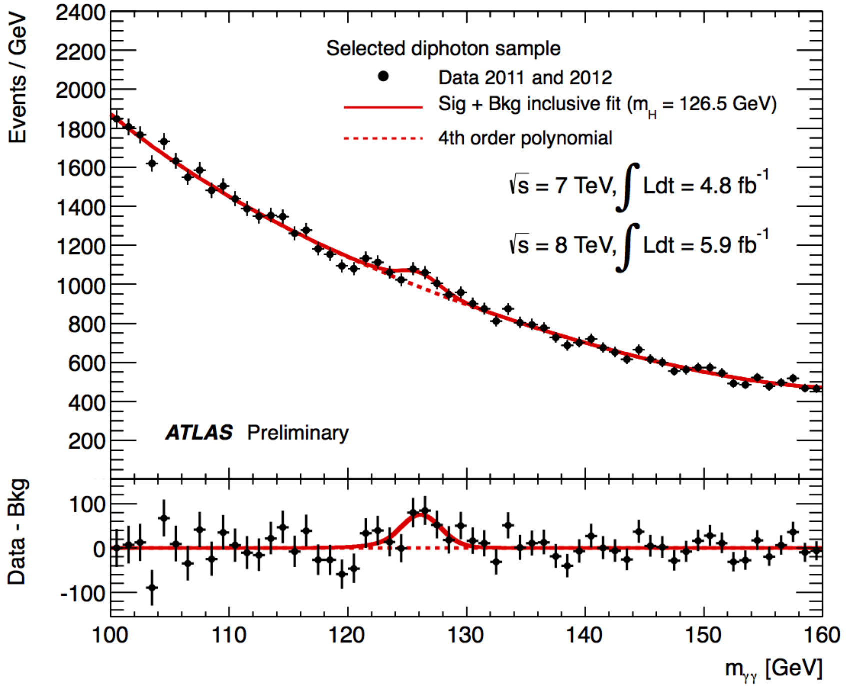
WH production (fully exclusive) Ferrara, Tramontana, Grazzini '11

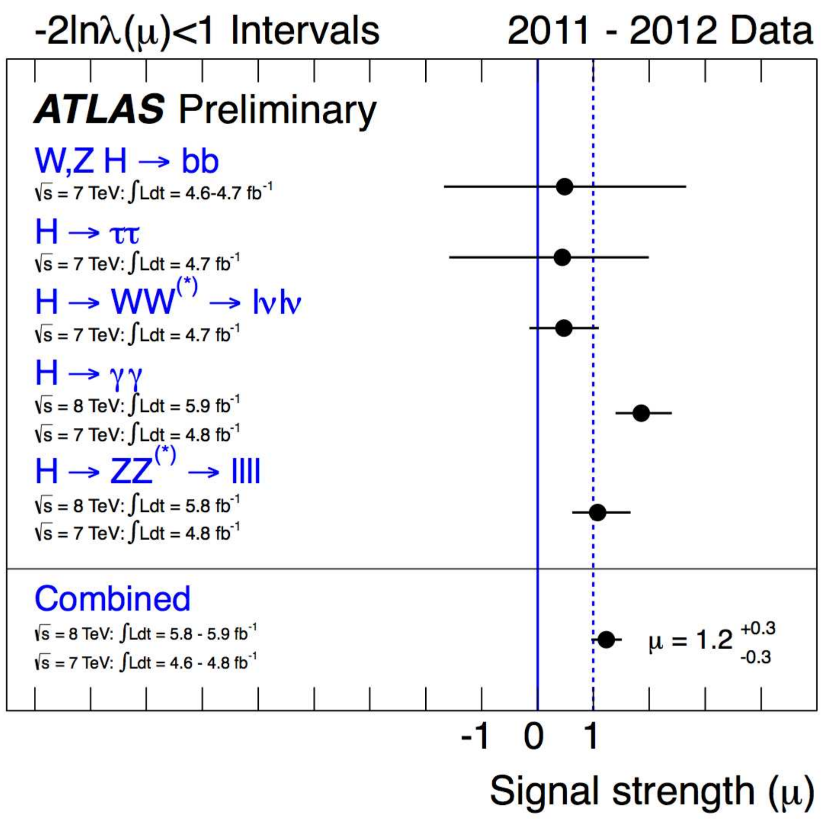


- Scale dependence at the 1% level both at NLO and NNLO
- LHC $\sqrt{s} = 14$ TeV: lepton $p_t > 30$ GeV, $|y| < 2.5$ and $p_t^{miss} > 30$ GeV; require $p_t^W > 200$ GeV; (cone alg. with $R = 1.2$)
  - one fat jet with $p_t > 200$ GeV (and $b\bar{b}$-pair), $|y| < 2.5$; no other jet with $p_t > 20$ GeV and $|y| < 5$

LHC measurements

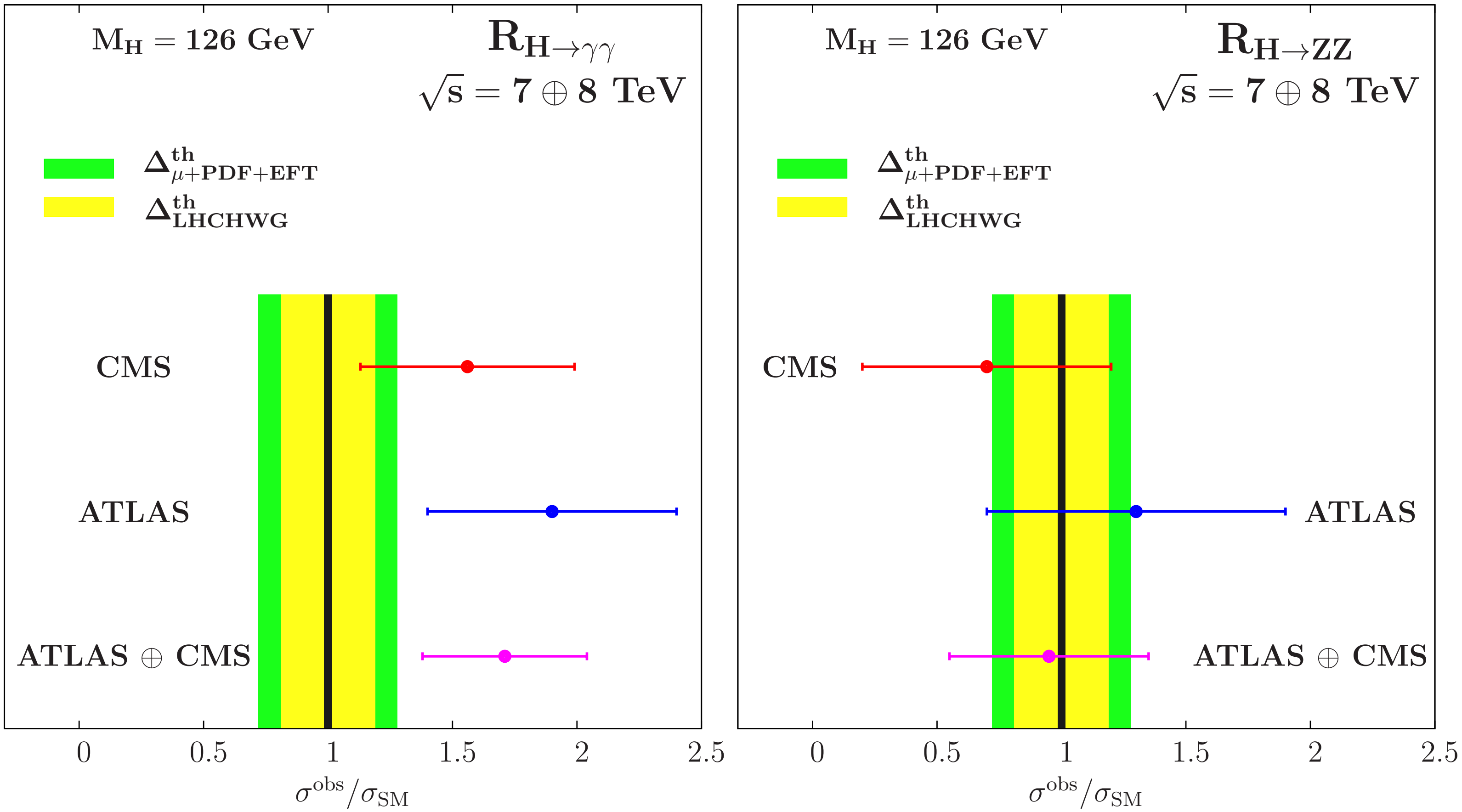
Atlas coll. July 2012





- Measured $H \to \gamma\gamma$ decay mode (left)
- Signal strength of all analyzed decay modes normalized to SM expectation (right)
- Agreement with SM for $H \to ZZ$; excess of $H \to \gamma\gamma$ (new physics ?)

Theory uncertainty



- Theory uncertainty of SM expectations revisited Baglio, Djouadi, Godbole '12
  - ratios $R_{XX} = \sigma^{obs}_{H\to XX}/\sigma^{SM}_{H\to XX}$
  - larger PDF uncertainties and linear addition of errors
- Excess of $H \to \gamma\gamma$ due to optimistic error estimates by Atlas and CMS

Summary (part I)

Standard Model

- Successful experimental program at LHC relies crucially on detailed understanding of Standard Model processes
- QCD at work
  - concepts of factorization, infrared safety, evolution

Higgs measurements

- Precision predictions for Higgs production at LHC available
  - radiative corrections (higher orders) important
  - essential to control theory uncertainties
  - non-perturbative parameters currently source of largest differences for Higgs cross section predictions