Quantum Chromodynamics

lecture III

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Belgian Dutch German summer school (BND 2012), Bonn, Sep 23, 2012

Plan

– Introduction to QCD
  Friday, September 21, 2012

– QCD at work: infrared safety, factorization and evolution
  Saturday, September 22, 2012

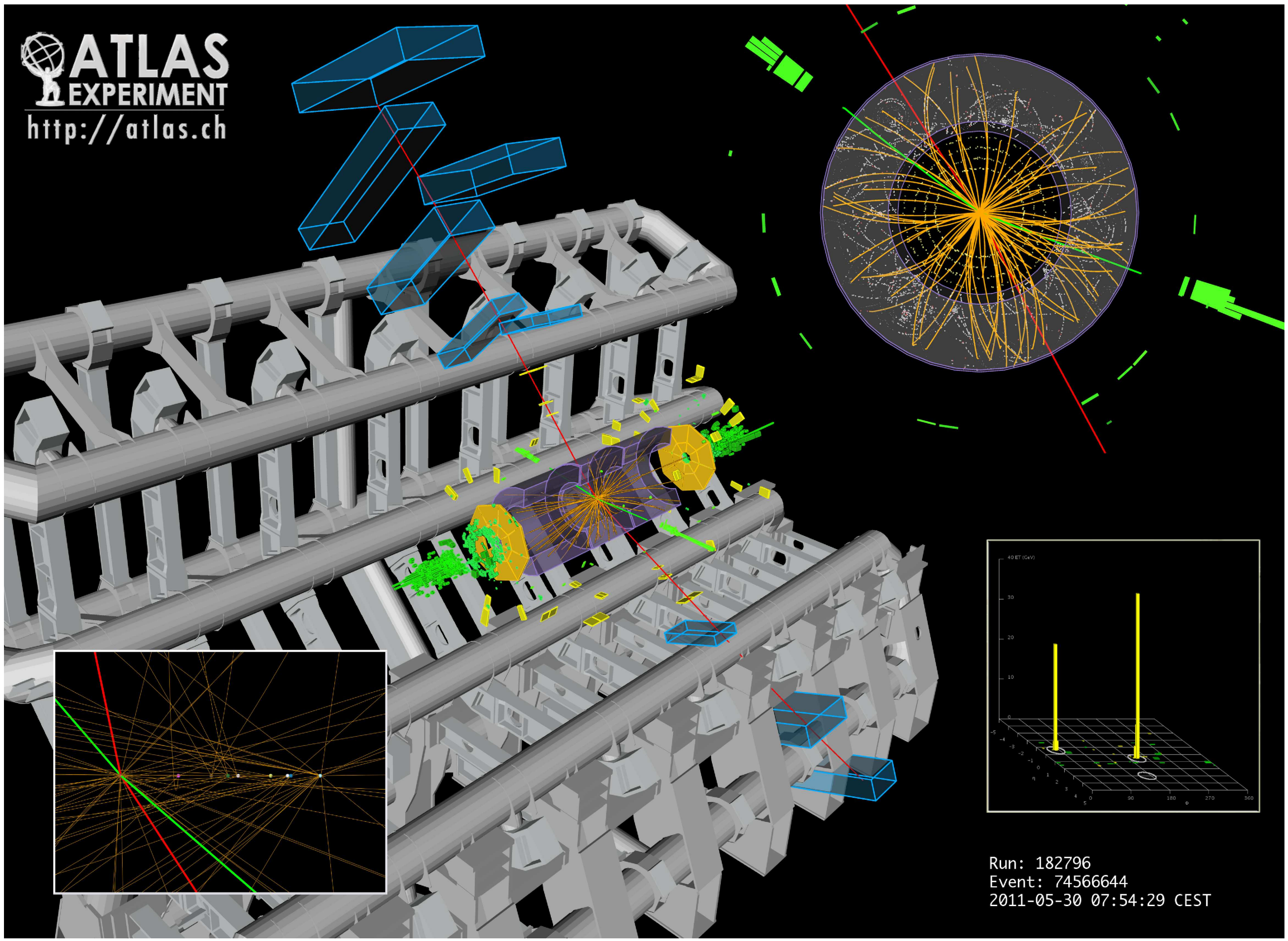
– *Higgs boson production*
  Sunday, September 23, 2012

– Gauge boson production and QCD jets
  Monday, September 24, 2012

– Top quark production
  Tuesday, September 25, 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

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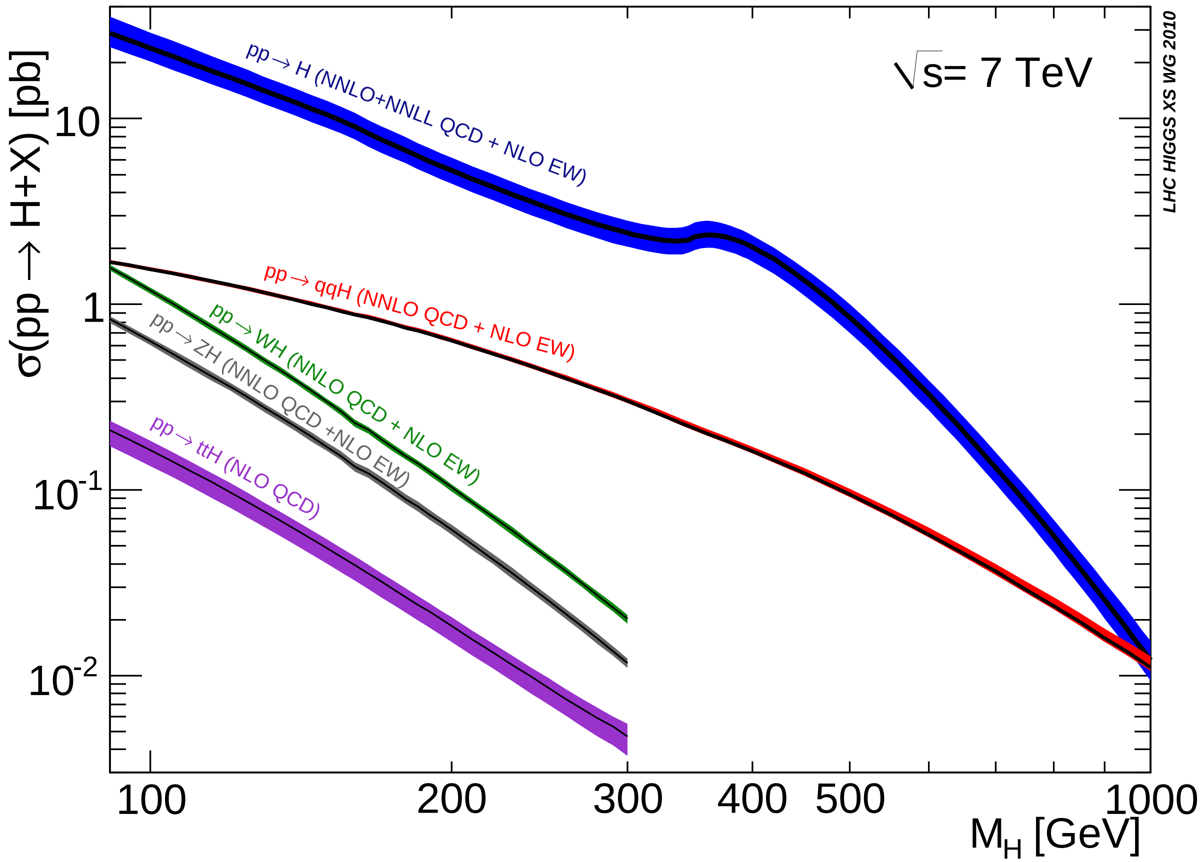
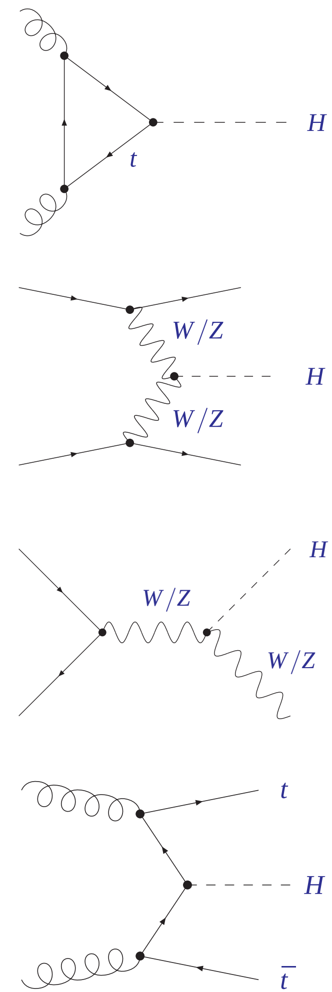
Higgs cross section

Cross section for Higgs production at the LHC

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





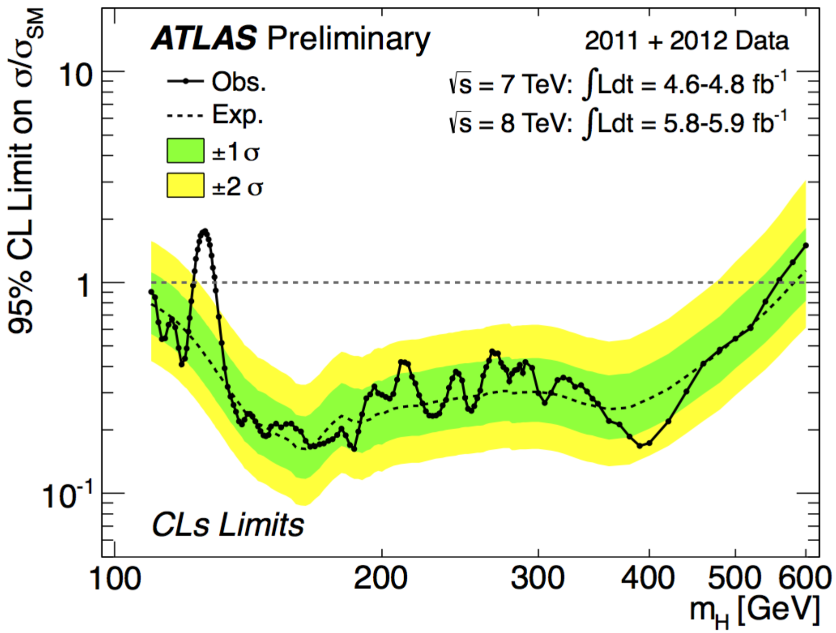
gg-fusion

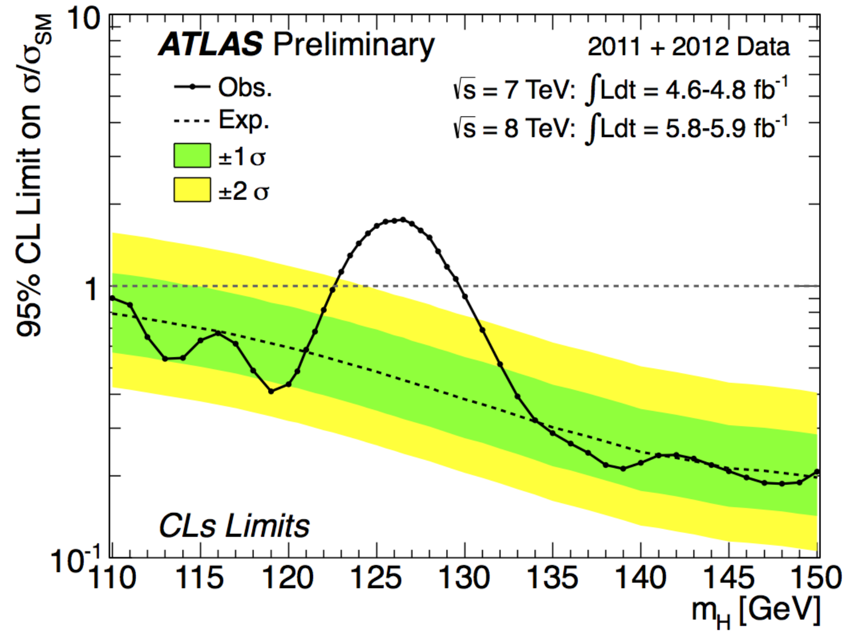
weak boson fusio

Higgs strahlung

$t\bar{t}H$-channel

Higgs discovery at LHC



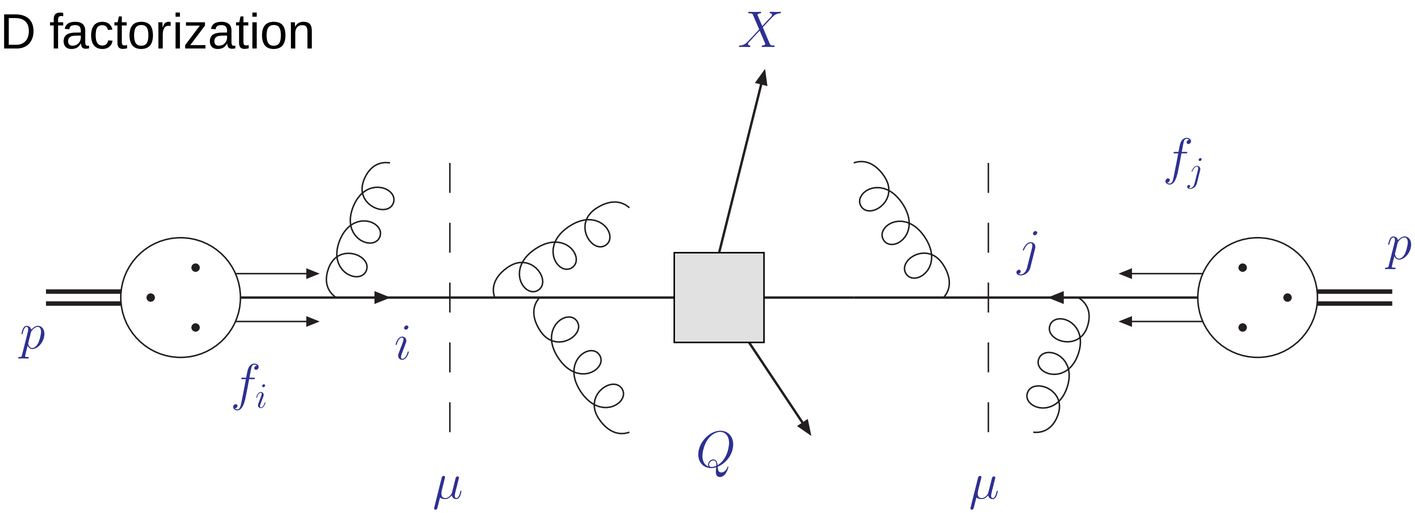


Atlas coll. July 2012

- 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

QCD factorization

- QCD factorization

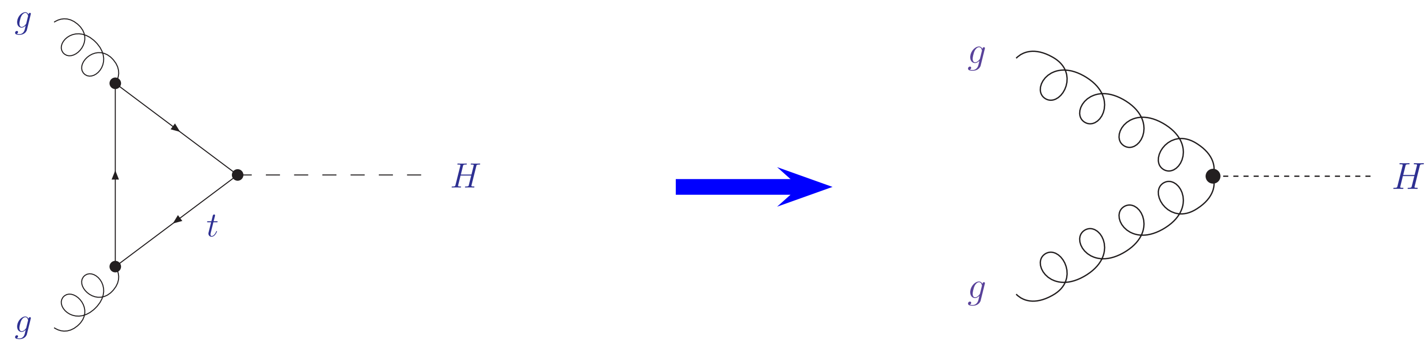


$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- 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, ...

gg-fusion

Effective theory



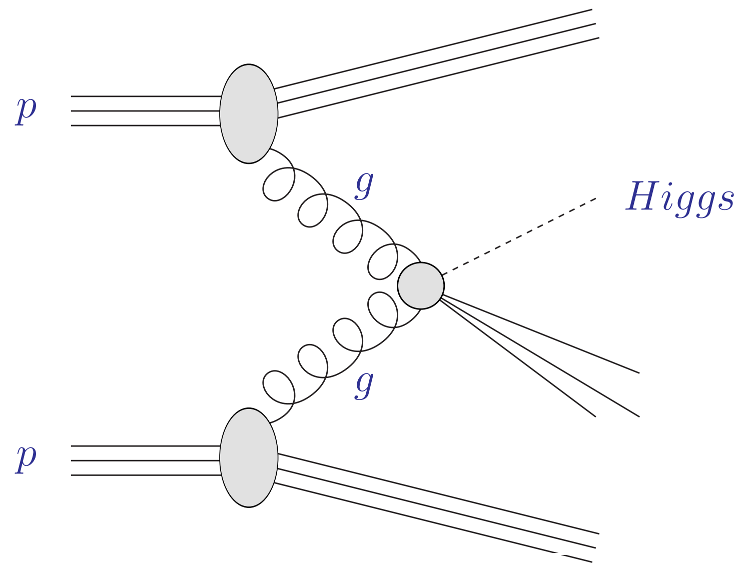
- Integration of top-quark loop (finite result)
  - decay width $H \to gg$ ($m_q = 0$ for light quarks, m_t heavy)

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

- 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 $HG^{\mu\nu\,a}\,G^a_{\mu\nu}$ 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 $\hat{\sigma}_{ij\to H}$

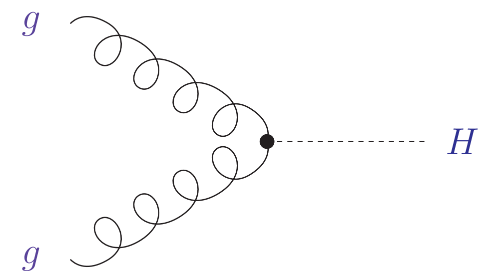
$$\hat{\sigma}_{ij\to H} = \underbrace{\alpha_s^2 \Big[\hat{\sigma}^{(0)}_{ij\to H} + \alpha_s\, \hat{\sigma}^{(1)}_{ij\to H}}_{} + \alpha_s^2\, \hat{\sigma}^{(2)}_{ij\to H} + \ldots \Big]$$

NLO: standard approximation (large uncertainties)

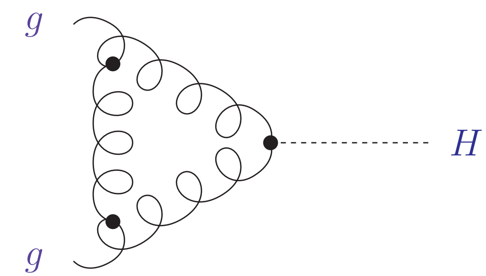
Radiative corrections in a nutshell

- 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 $D = 4 - 2\epsilon$

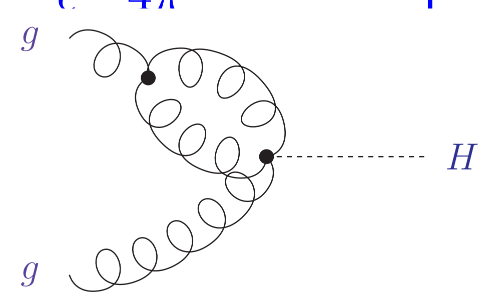


$$\hat{\sigma}^{(1),v}_{gg \to H} \quad = \quad C_A \, \frac{\alpha_s}{4\pi} \, \delta(1-x) \left(\frac{\mu^2}{m_H^2} \right)^{\epsilon} \left(- \frac{2}{\epsilon^2} + 7\, \zeta_2 + \mathcal{O}(\epsilon) \right)$$

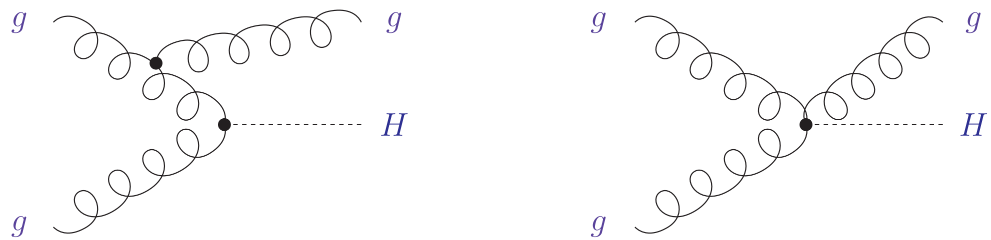
  - additional contribution from renormalization of effective operator

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

  - 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

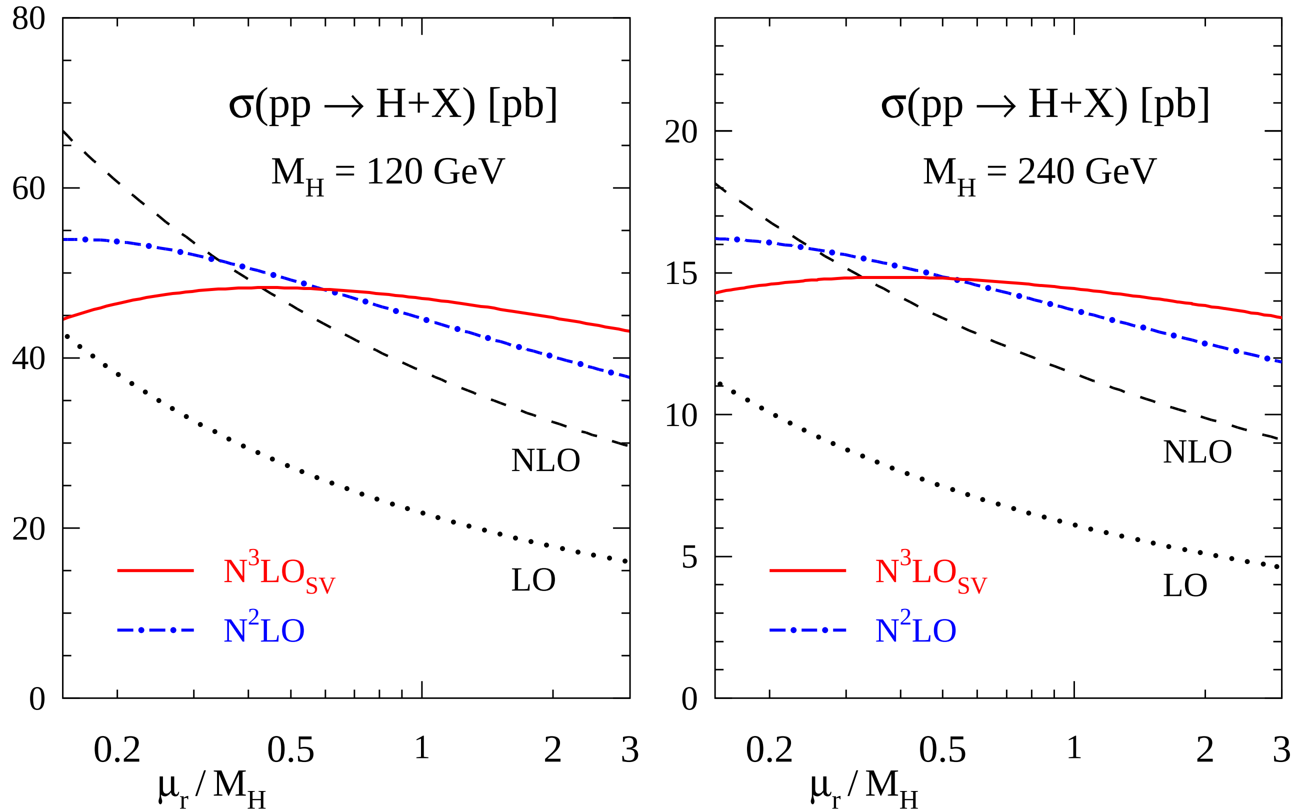
$$\hat{\sigma}_{gg\to H}^{(1),\mathrm{bare}} \quad = \quad \frac{\alpha_s}{4\pi} \left(\frac{\mu^2}{m_H^2}\right)^{\epsilon} \left\{ \frac{1}{\epsilon}\, 2\, P_{gg}^{(0)}(x) + \hat{\sigma}_{gg\to H}^{(1)}(x) + \mathcal{O}(\epsilon) \right\}$$

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

  - partonic (physical) structure function at factorization scale μ_F

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

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

Resummation

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

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

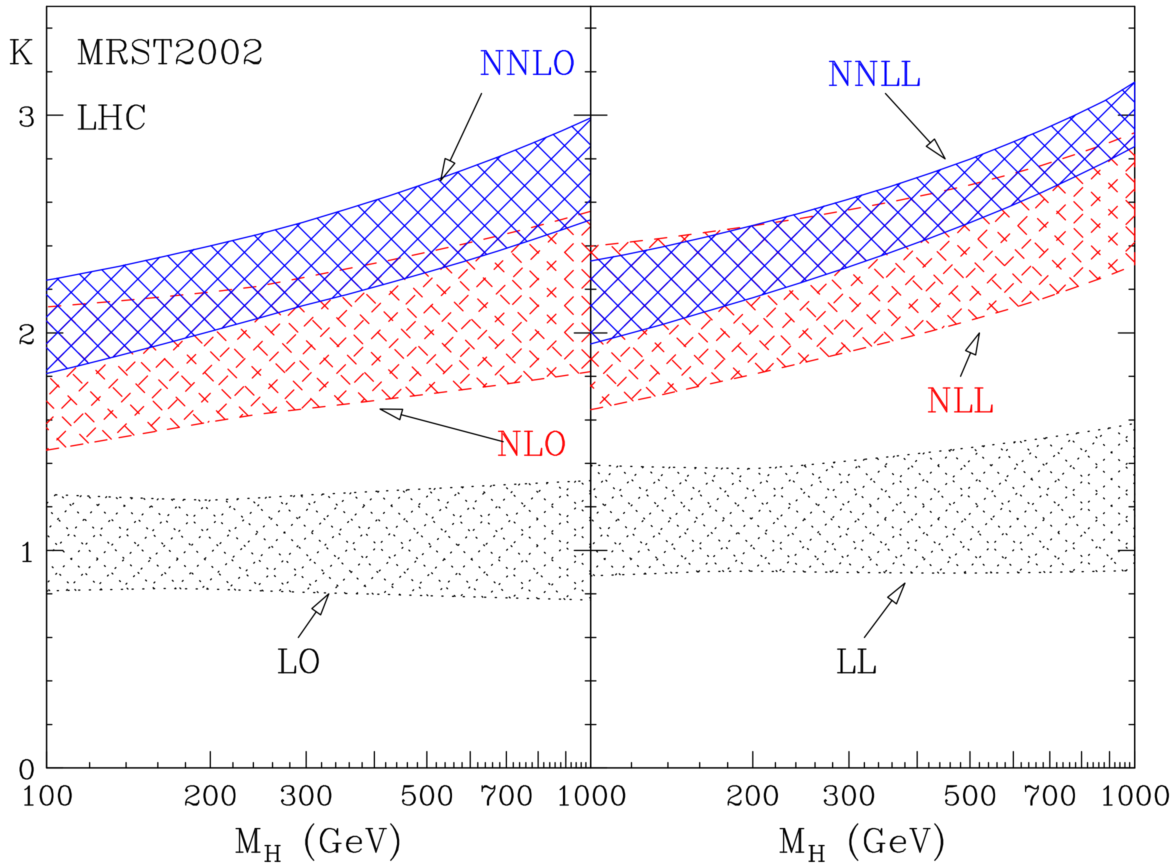
- Recall large double logarithms at NLO

$$\hat{\sigma}^{(1)}_{gg\to H} = \frac{\alpha_s}{4\pi}\left(\frac{\mu^2}{m_H^2}\right)^\epsilon \Bigg\{$$
$$\frac{1}{\epsilon} C_A \left(\frac{8}{1-x} + \frac{8}{x} - 8(2-x+x^2) + \frac{22}{3}\delta(1-x)\right) - \frac{1}{\epsilon} n_f \frac{4}{3}\delta(1-x)$$
$$+ C_A \left(16\frac{\ln(1-x)}{1-x} + \left(\frac{22}{3} + 8\zeta_2\right)\delta(1-x) - 16x(2-x+x^2)\ln(1-x)\right.$$
$$\left. -8\frac{(1-x+x^2)^2}{1-x}\ln(x) - \frac{22}{3}(1-x)^3\right) + \mathcal{O}(\epsilon)\Bigg\}$$

- Threshold resummation to all orders with standard technology

$$\hat{\sigma}^N_{gg\to H} = (1 + \alpha_s\, g_{01} + \alpha_s^2\, g_{02} + \ldots)\cdot \exp\left(G^N\right) + \mathcal{O}(N^{-1}\ln^n N)$$

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

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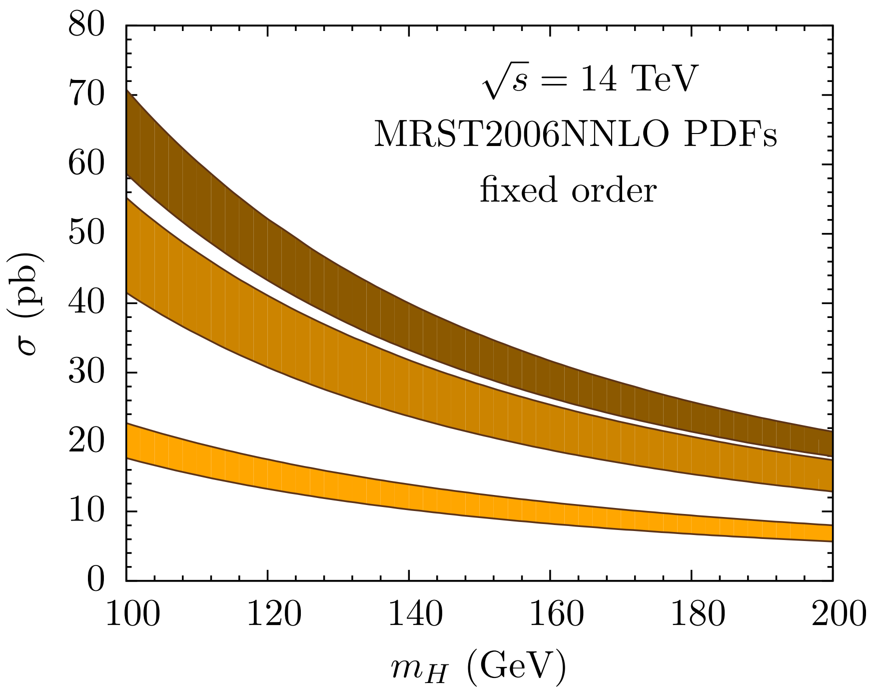

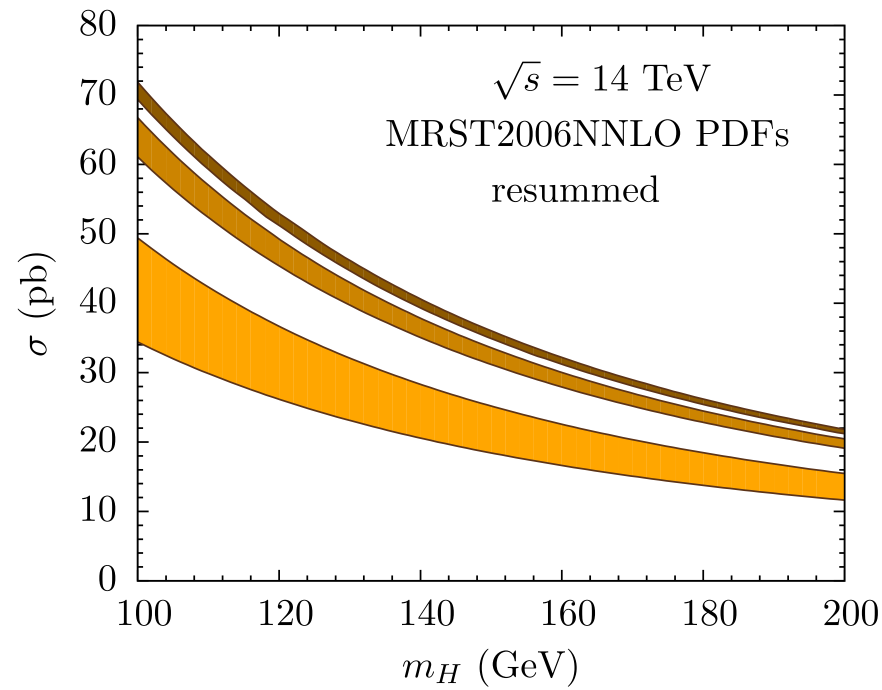

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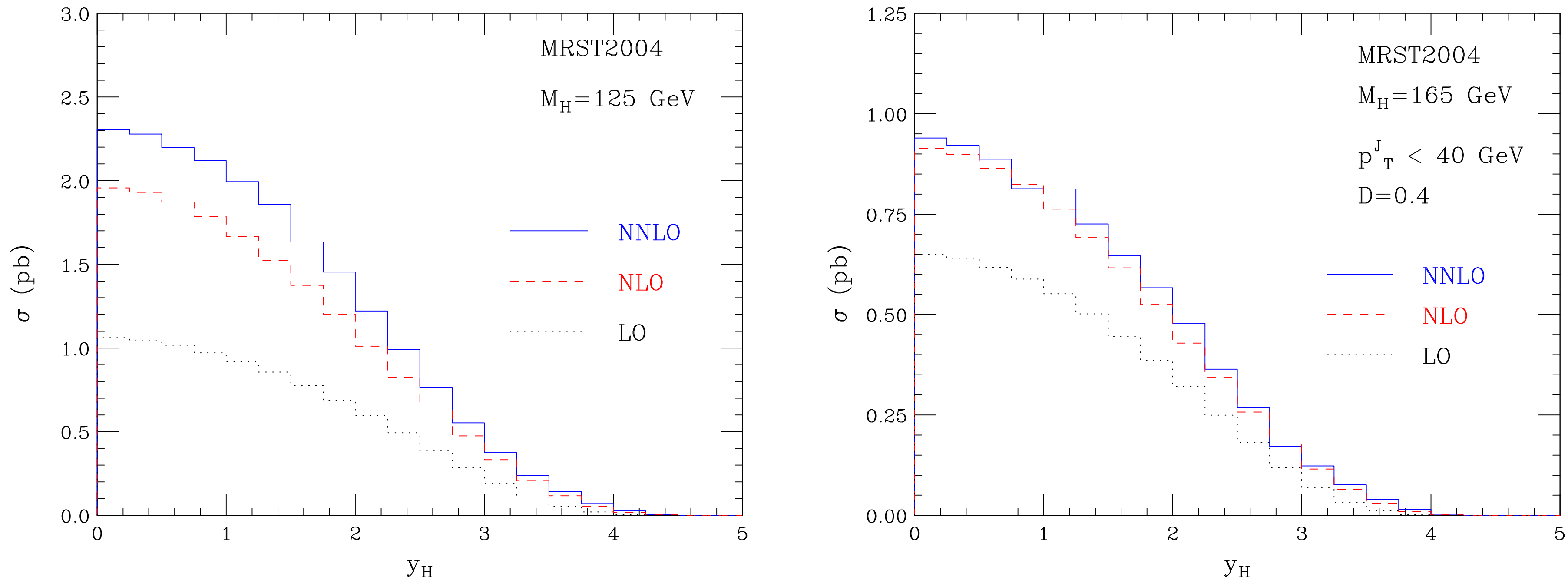
  - NNLL resummation (lots of activity in the last years)

    Catani, Grazzini, de Florian, Nason ‘03, Ahrens et al. ‘10

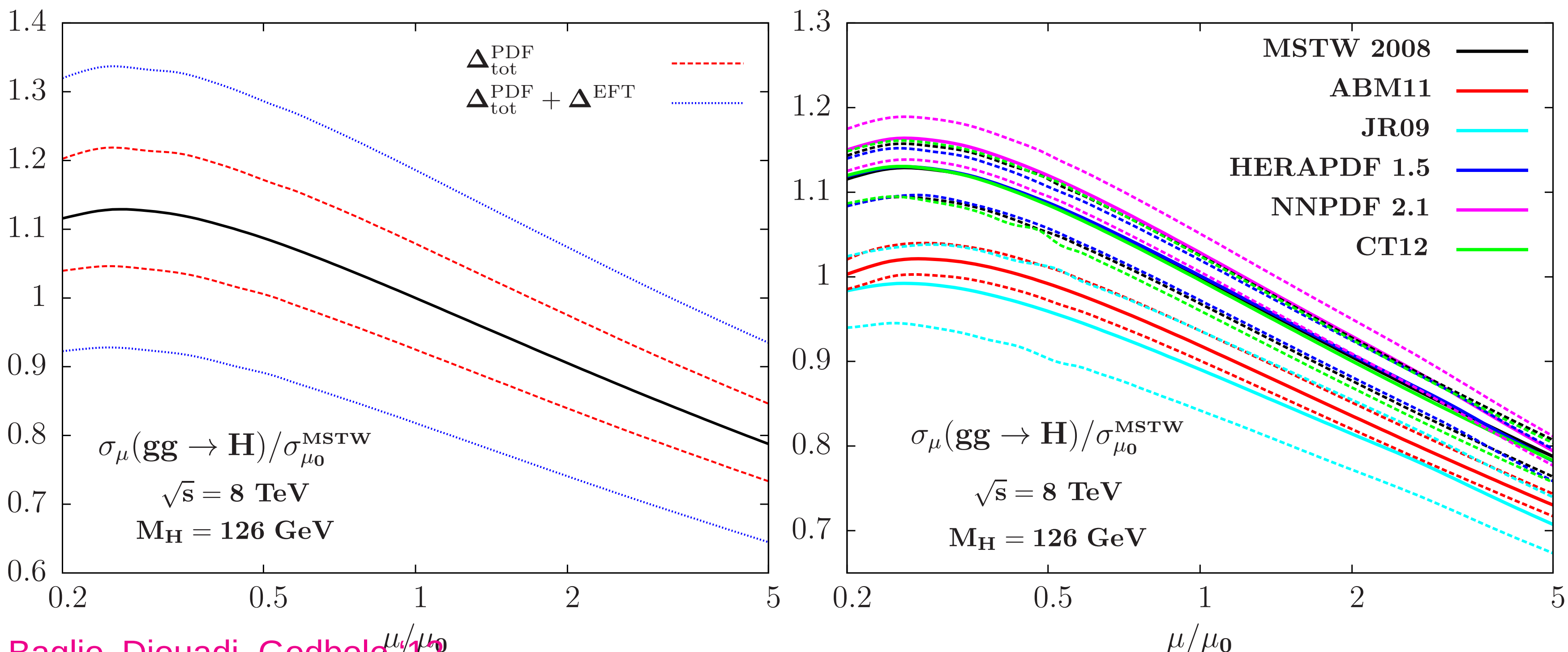
gg fusion (fully exclusive)

- 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 $D = 0.4$)

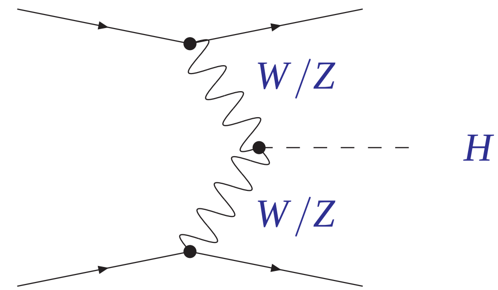
PDF dependence of gg-fusion cross section at LHC



Baglio, Djouadi, Godbole '12

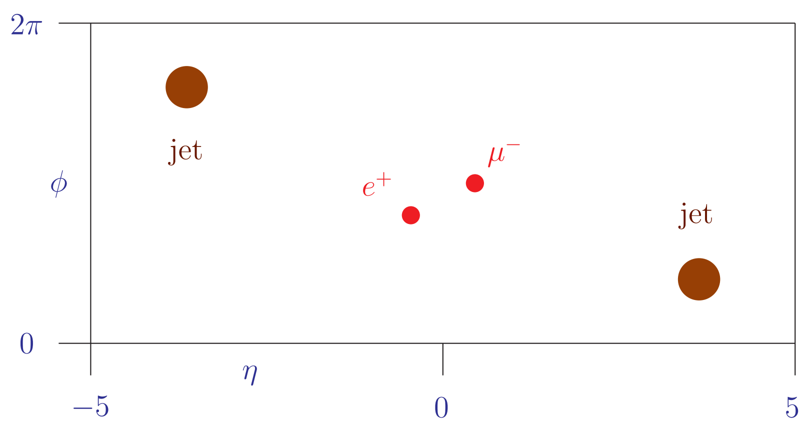
- PDFs uncertainty
  - PDFs (gluon at large x) largest single source of uncertainty
  - PDF uncertainty estimates by LHC Higgs XS WG too optimistic
- Linear addition of errors
  - PDF uncertainty and error due to effective theory:
    $\Delta\sigma = \Delta\sigma_{\rm PDF} + \Delta\sigma_{\rm EFT}$

Vector-boson fusion



- Second largest rate at LHC (WWH coupling)

Signatures

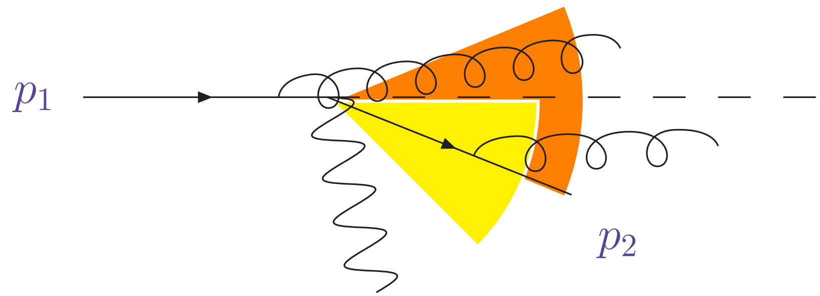


- WW, ZZ fusion $\longrightarrow$ Higgs is color singlet
  - two hard (forward) tagging jets (visible in detector)
  - no (or small) hadronic activity between tagging jets
  - color connection between forward jet and proton remnant
  - Higgs decay in the central rapidity region

Perturbative QCD corrections

Where is the hadronic activity ?

- QCD radiation predominantly in direction of incoming partons (angular ordering)



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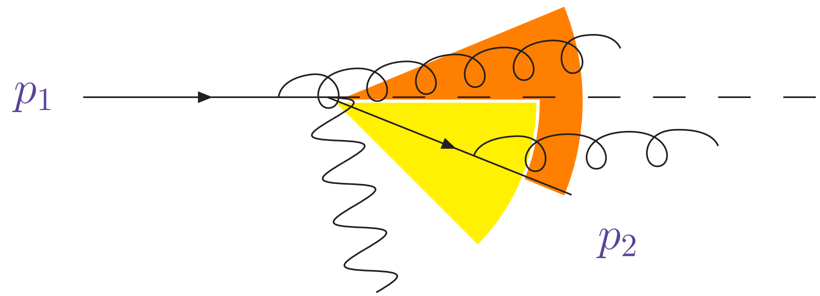
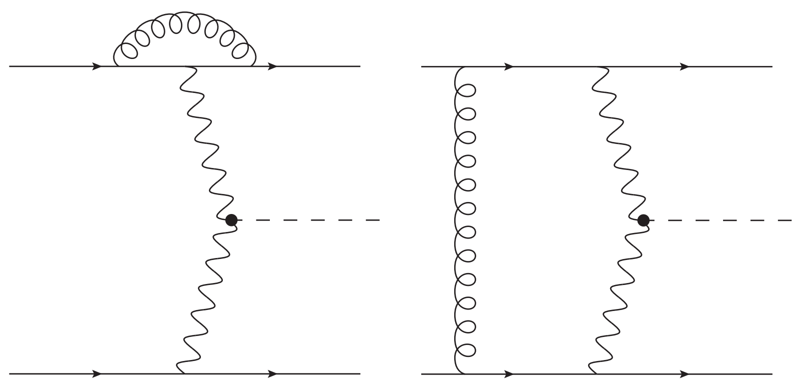


- NLO QCD radiative corrections



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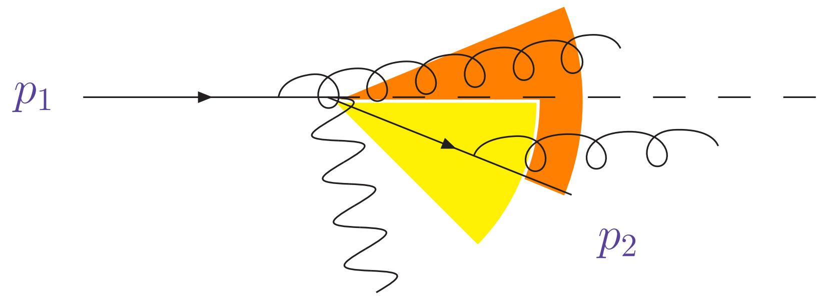
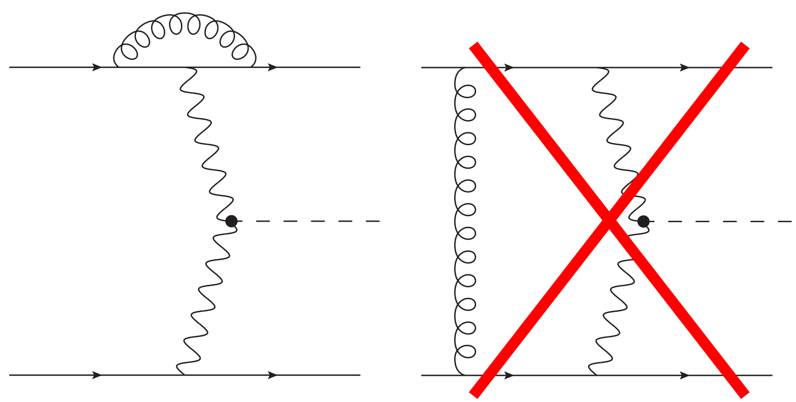
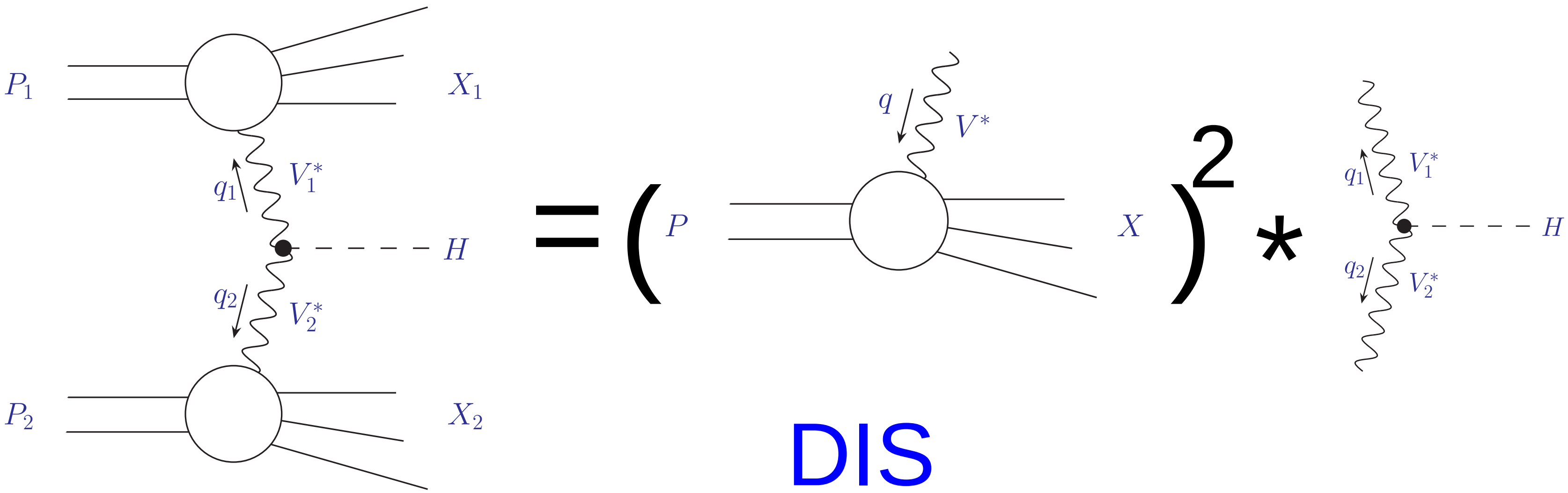


- NLO QCD corrections factorize (color conservation eliminates t-channel gluon in squared ME)

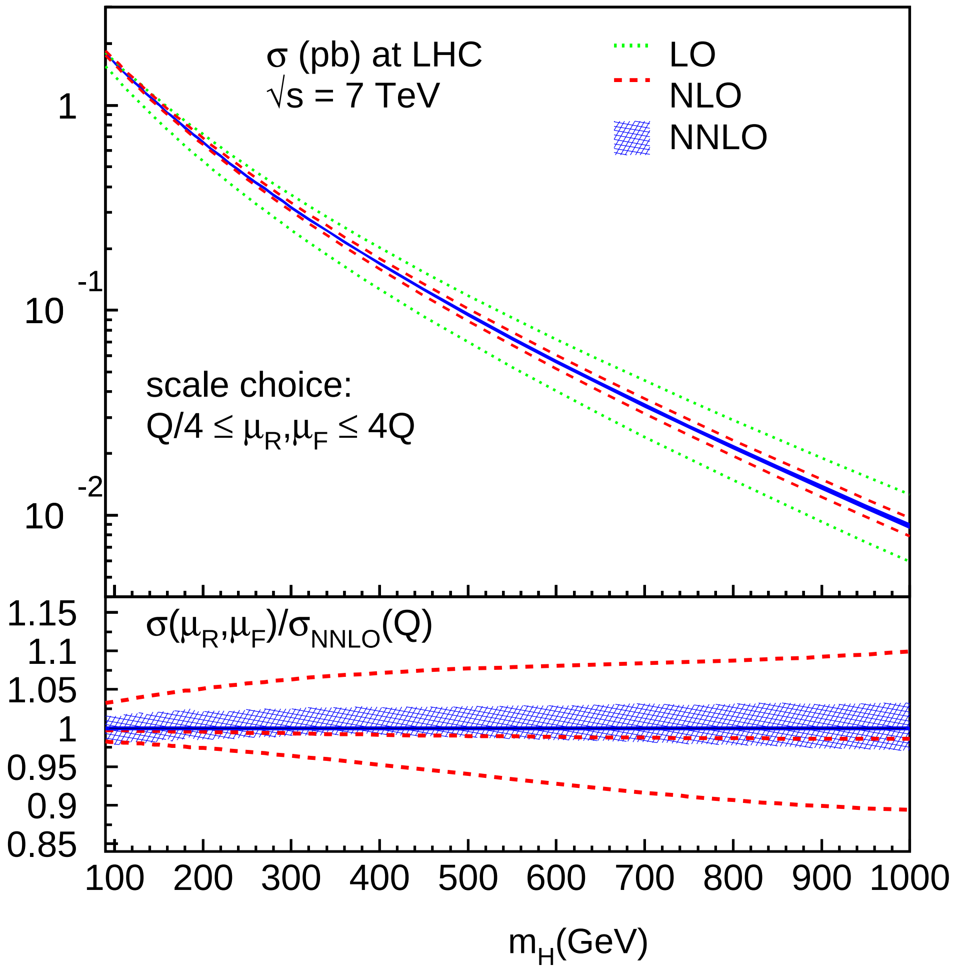


Exact factorization



- 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

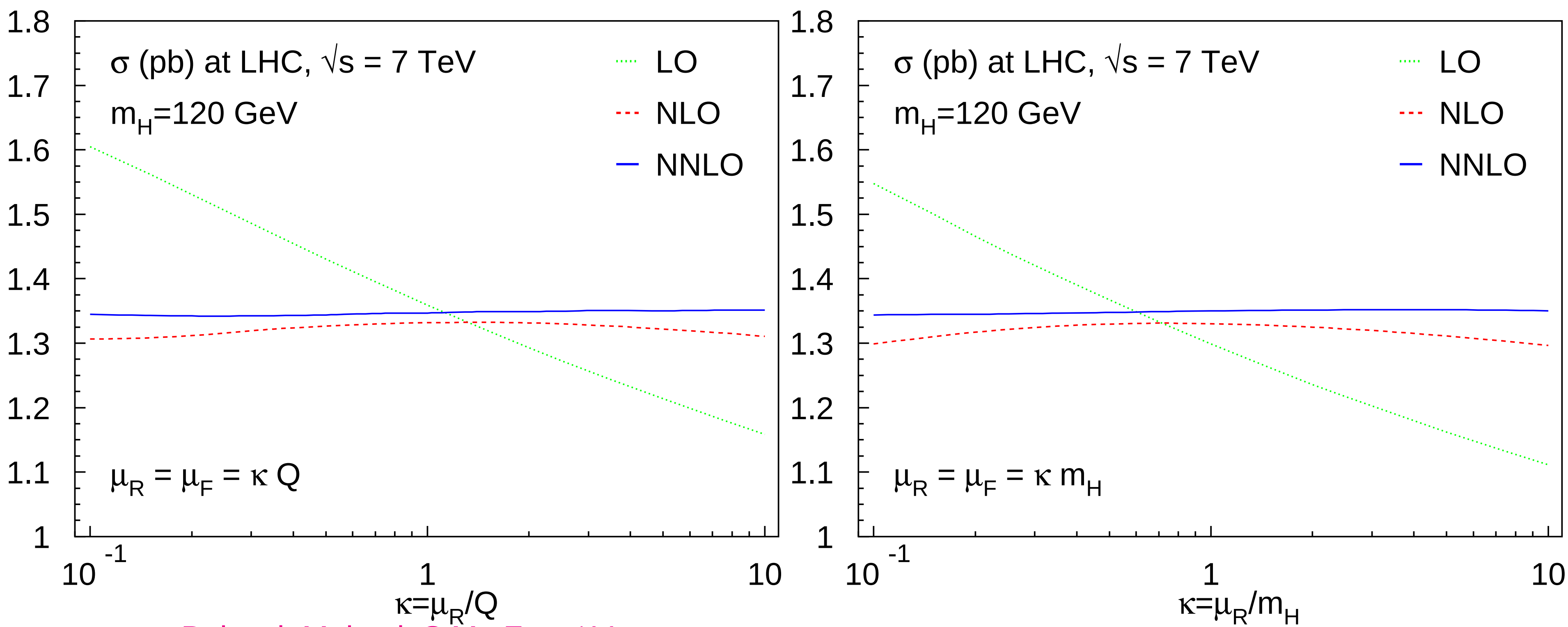
VBF cross section at LHC



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

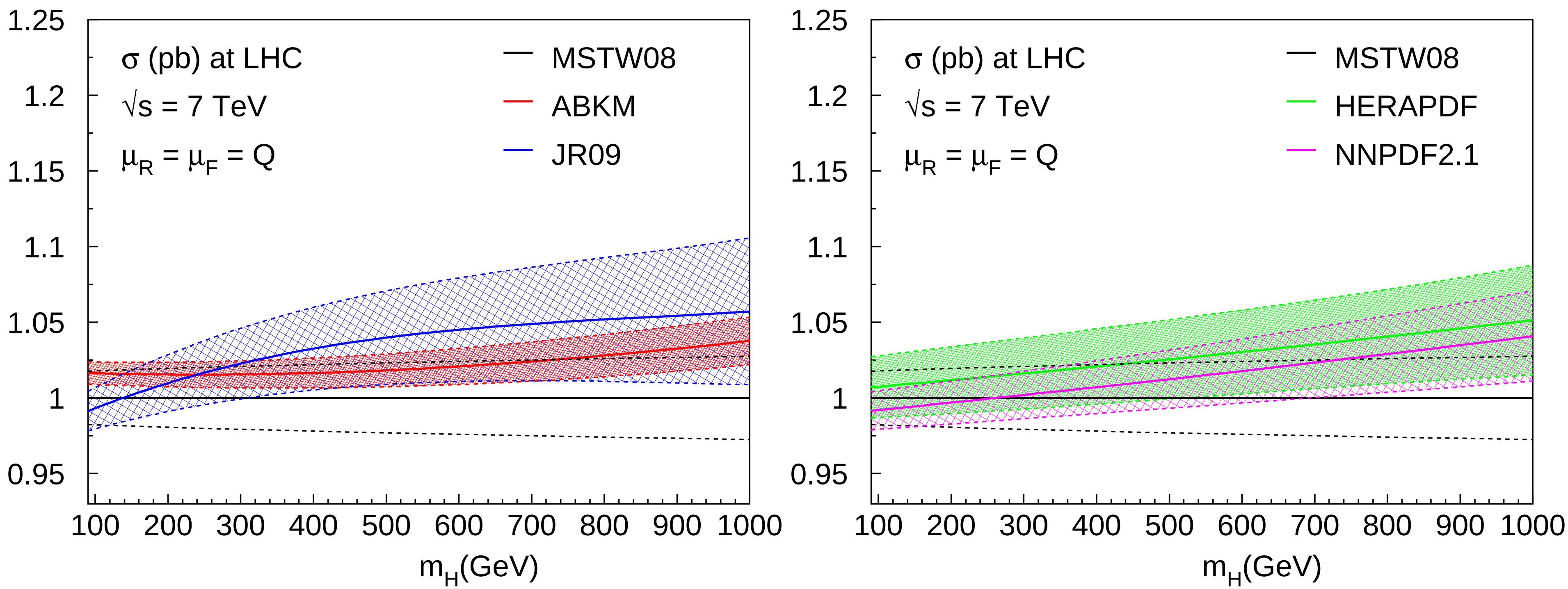
Scale stability at NNLO



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

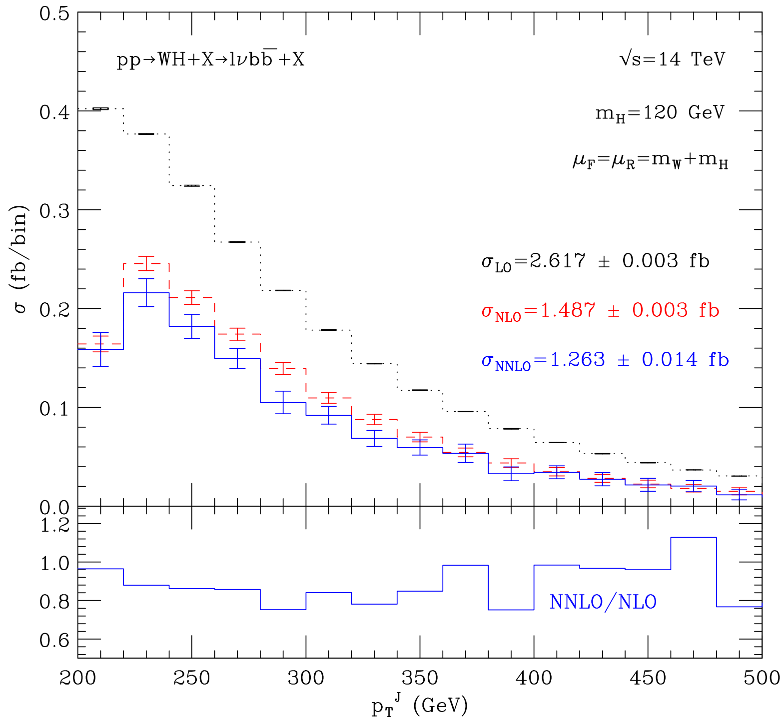


Bolzoni, Maltoni, S.M., Zaro '11

- 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

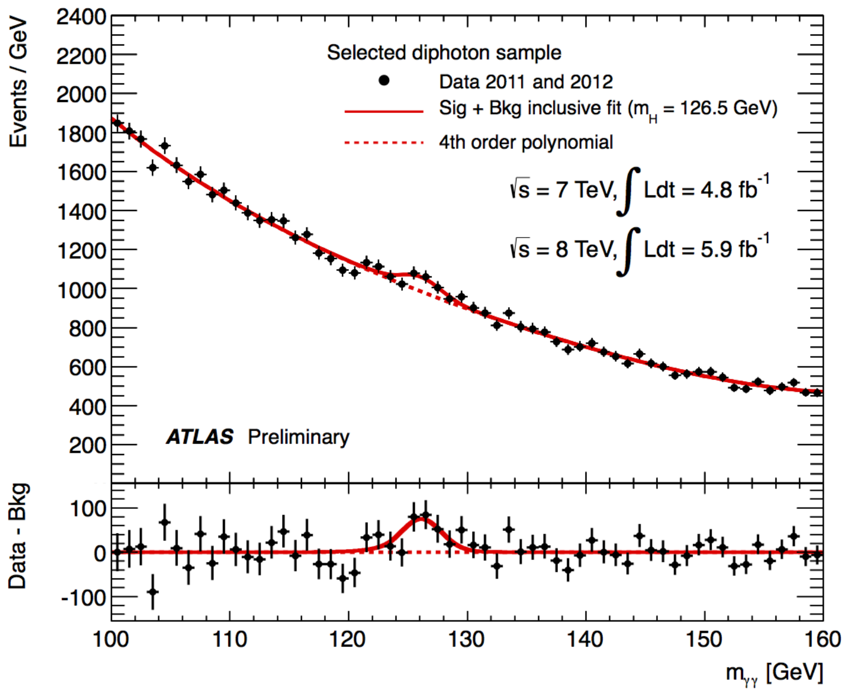
WH production (fully exclusive) Ferrara, Tramontana, Grazzini '11

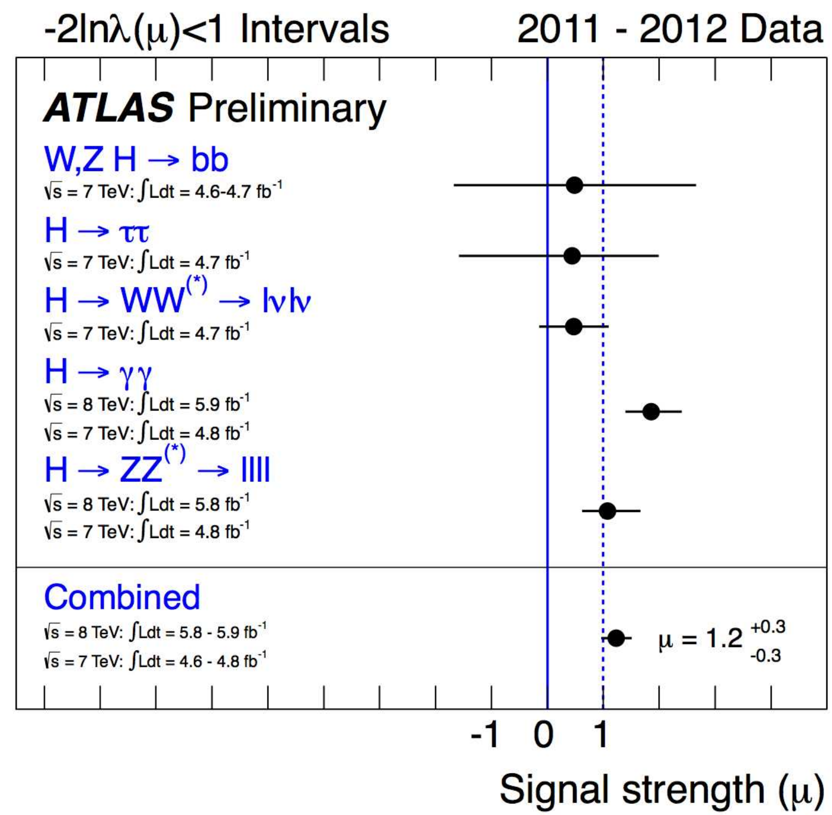


- Scale dependence at the 1% level both at NLO and NNLO
- LHC $\sqrt{s} = 14$ TeV: lepton $p_t > 30$ GeV, $|y| < 2.5$ and $p_t^{miss} > 30$ GeV; require $p_t^W > 200$ GeV; (cone alg. with $R = 1.2$)
  - one fat jet with $p_t > 200$ GeV (and $b\bar{b}$-pair), $|y| < 2.5$; no other jet with $p_t > 20$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

LHC measurements

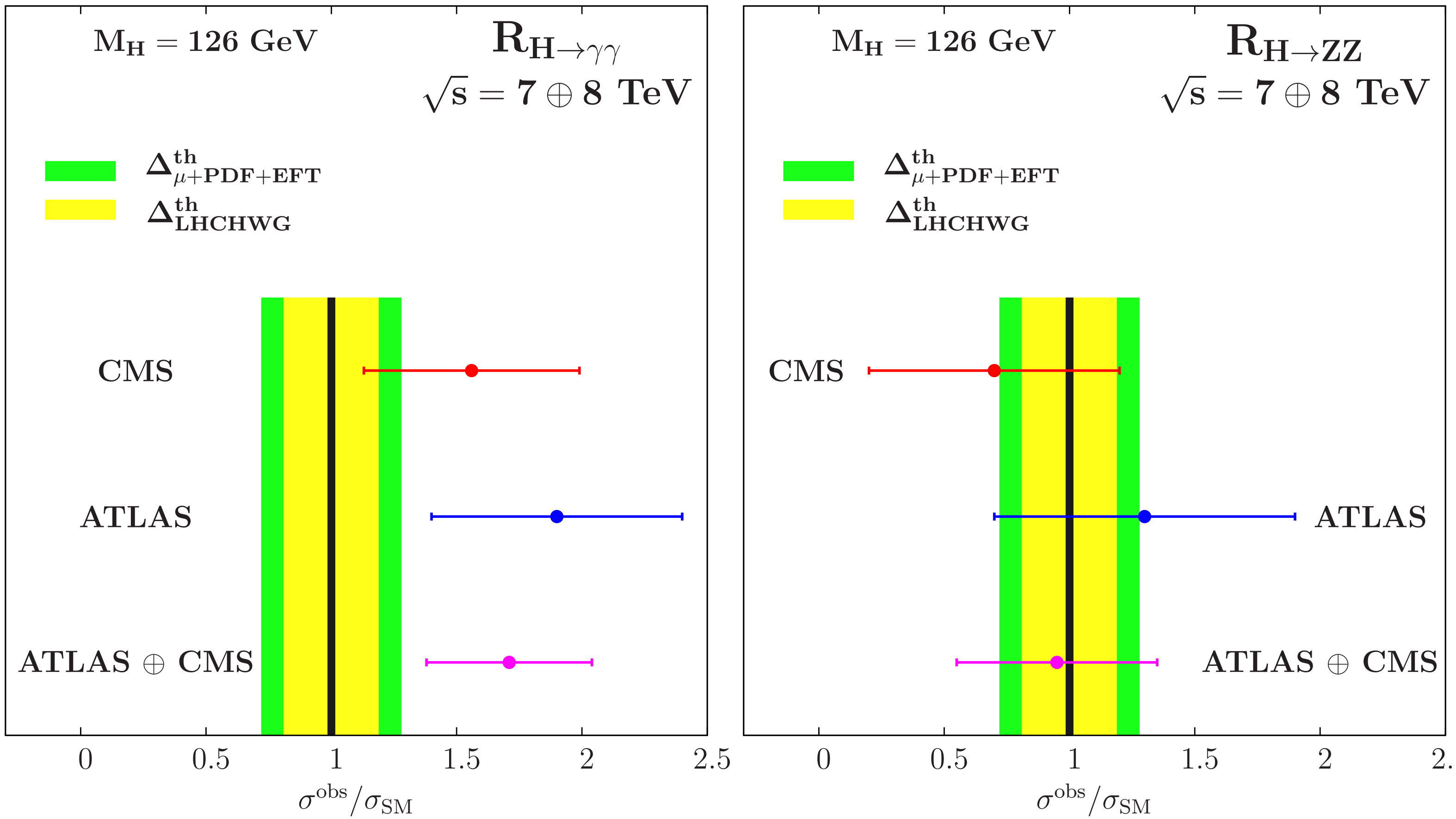
Atlas coll. July 2012





- 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 III)

Standard Model

- Successful experimental program at LHC relies crucially on detailed understanding of Standard Model processes
- QCD at work
  - illustration of factorization, infrared safety and evolution for $gg \to H$
  - resummation of large logarithms near threshold

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