Hard QCD at the LHC

2016 Aspen Winter Conf. Particle Physics

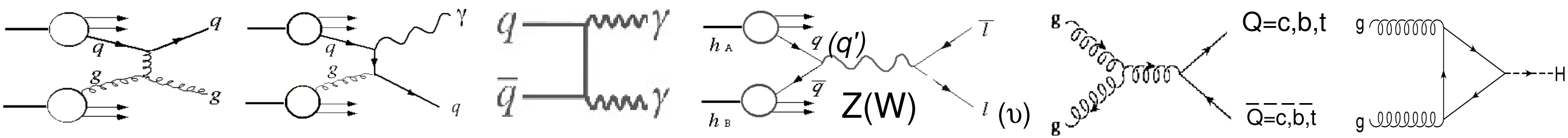
"Particle Phys. on the Verge of Discovery?"

Aspen (CO), 10th–15th Jan. 2016

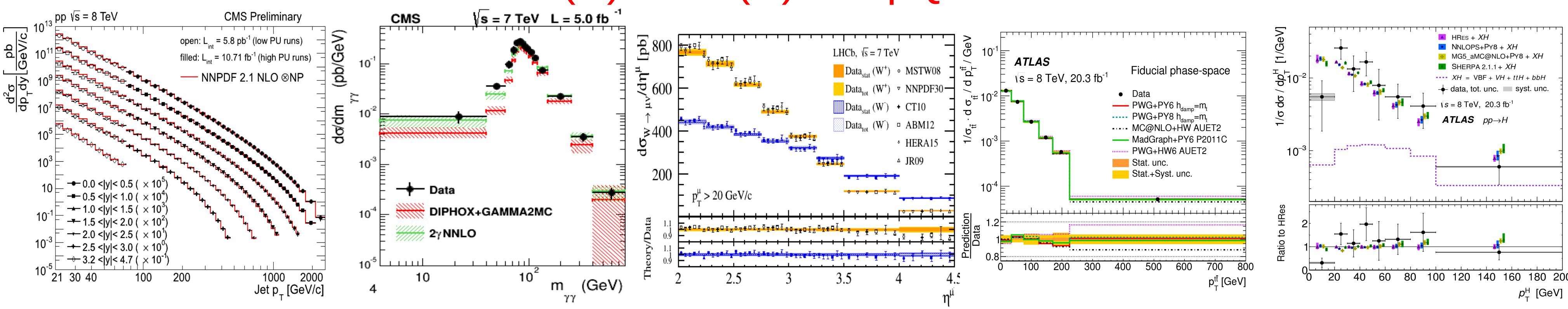
David d'Enterria (CERN)

Hard QCD at the LHC: Outline

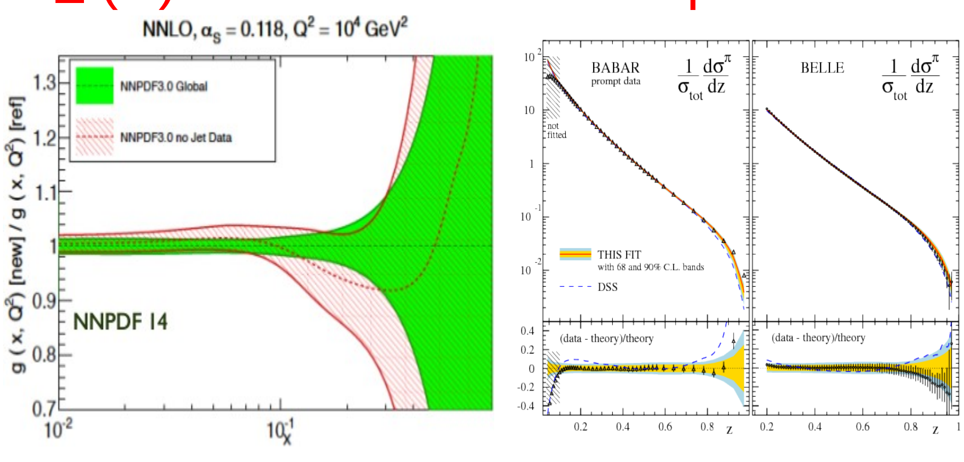
■ Introduction. Observables: Jets, (di)photons, W,Z bosons, heavy-Q, Higgs



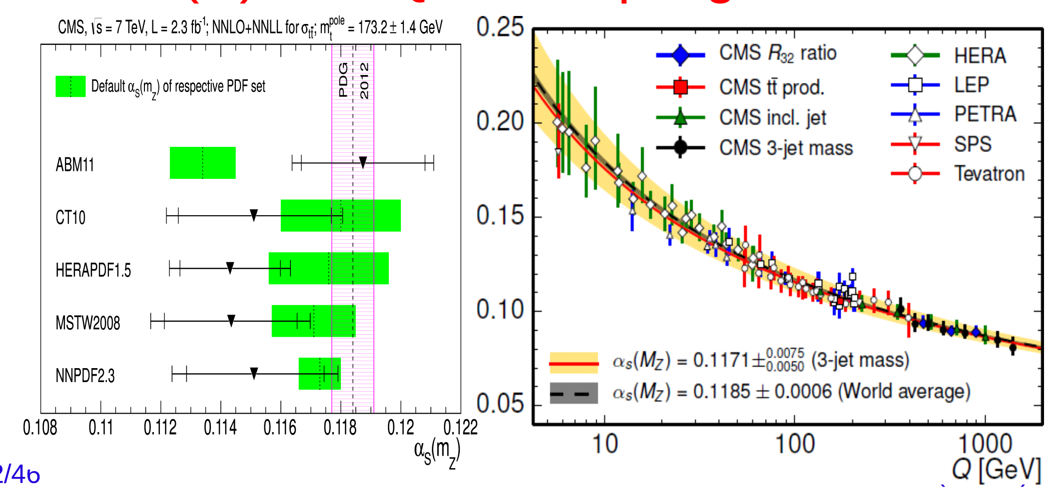
■ Data vs. state-of-the-art (N)NLO+(N)NLL pQCD:



■ (N)NLO PDFs & FFs improvements:



■ (N)NLO QCD coupling extraction:



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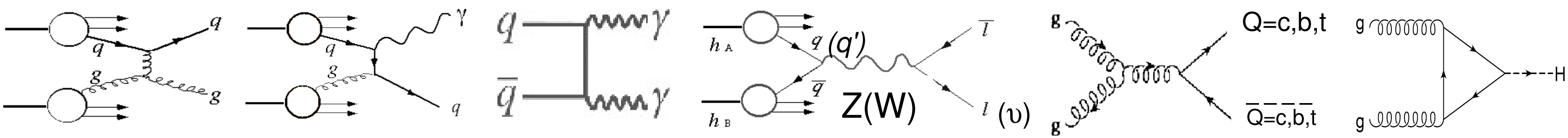

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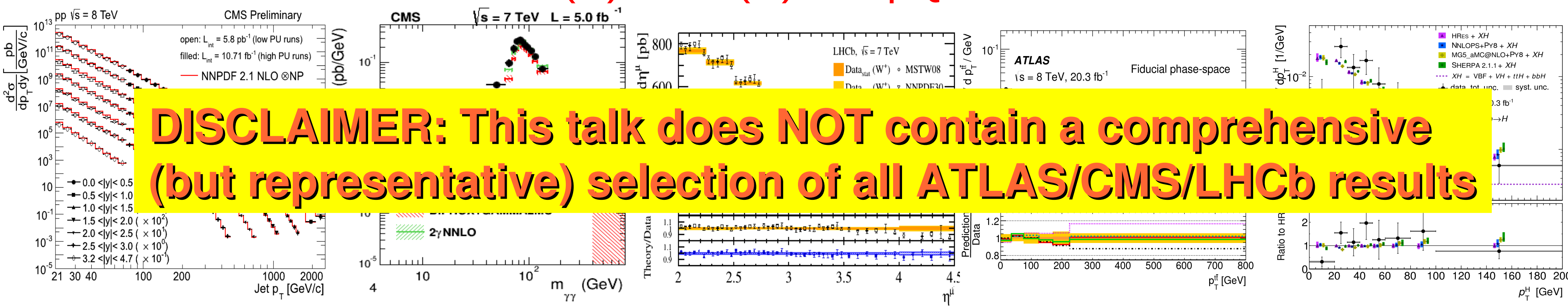

DISCLAIMER: This talk does NOT contain a comprehensive (but representative) selection of all ATLAS/CMS/LHCb results

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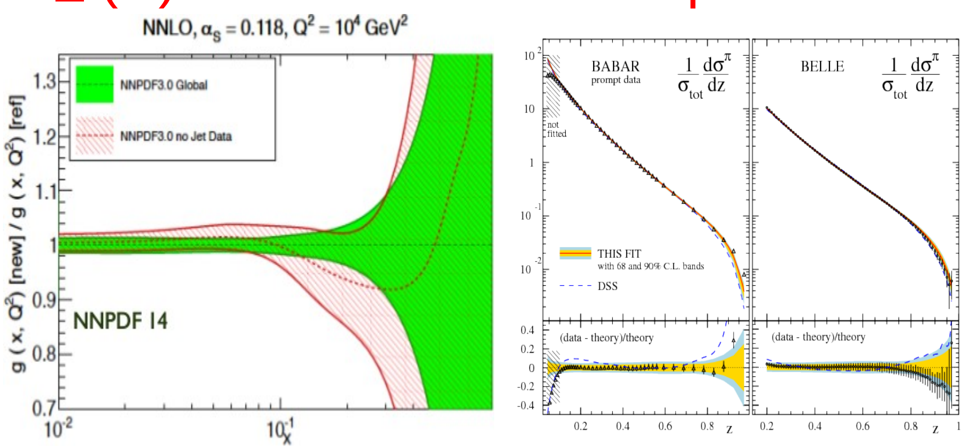

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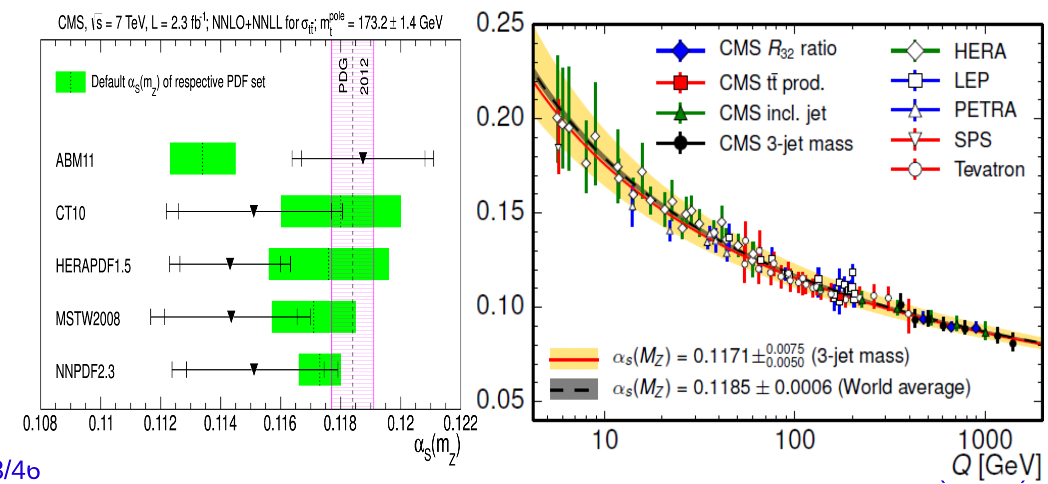
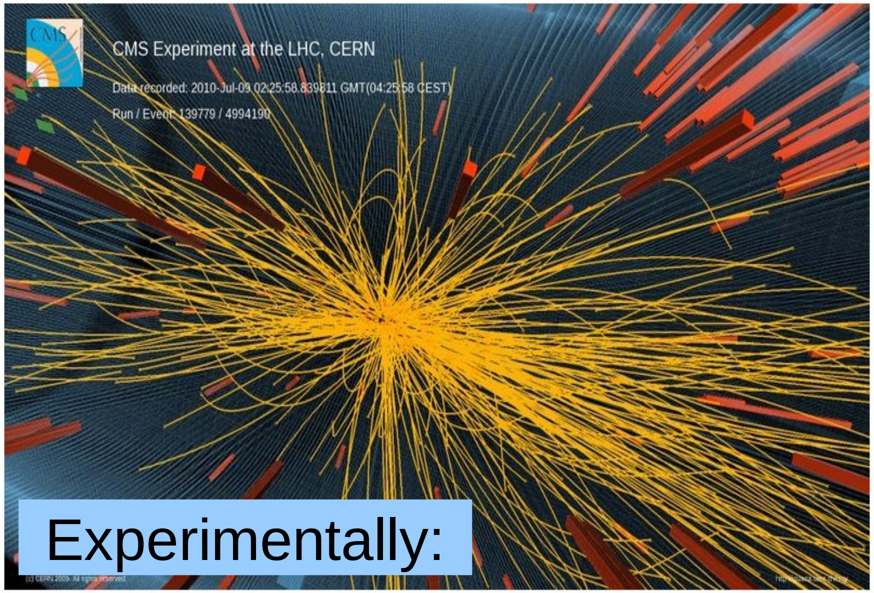
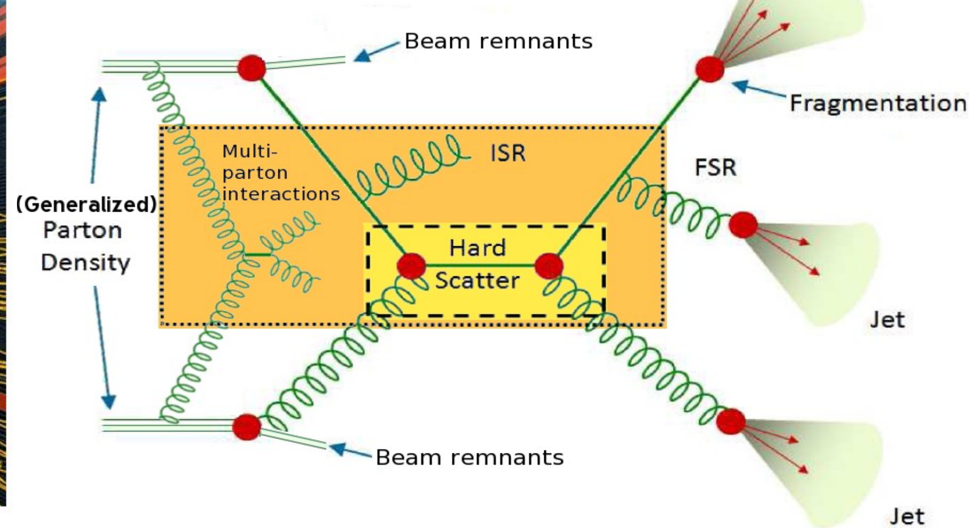


"All" LHC p-p physics "is" QCD physics



Theoretically:



Full Quantum Cromodynamics at work :

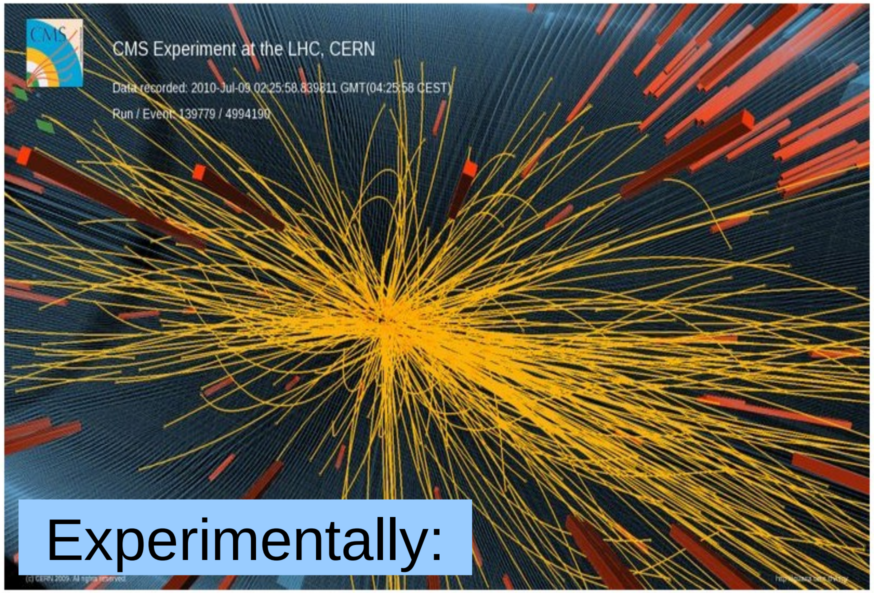
(1) Hard scattering (large p_T,mass): perturbative matrix elements, DGLAP evol., Resummations, Parton Distribution Functions, Fragmentation Functions

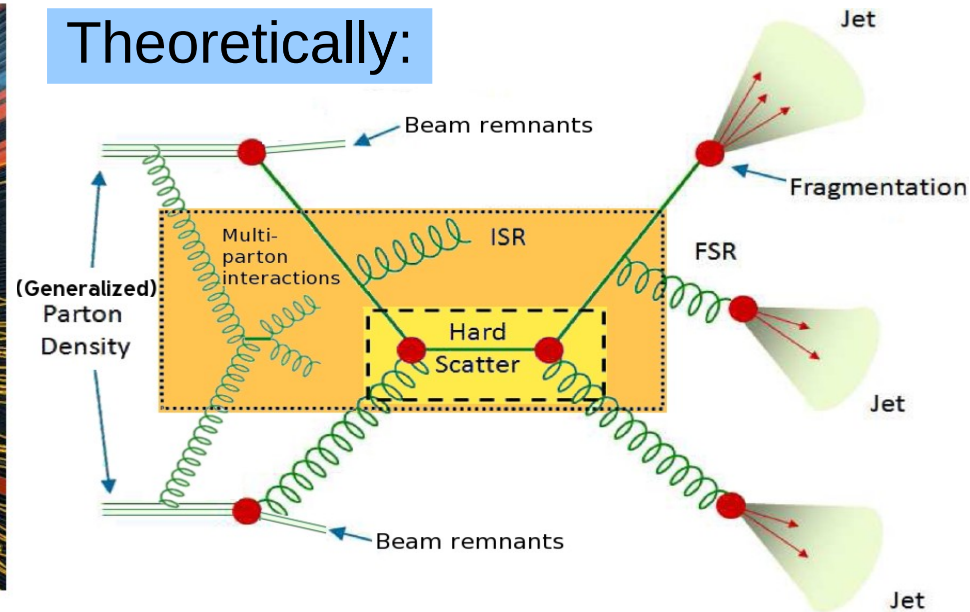
(2) Semi-hard dynamics: Multiparton interactions, Generalized PDFs

(3) Soft: Beam remnants, diffractive scatterings,...

- High-precision (experimental & theoretical) studies of QCD are key to understand production of all (B)SM signals & bckgds at the LHC:

"All" LHC p-p physics "is" QCD physics





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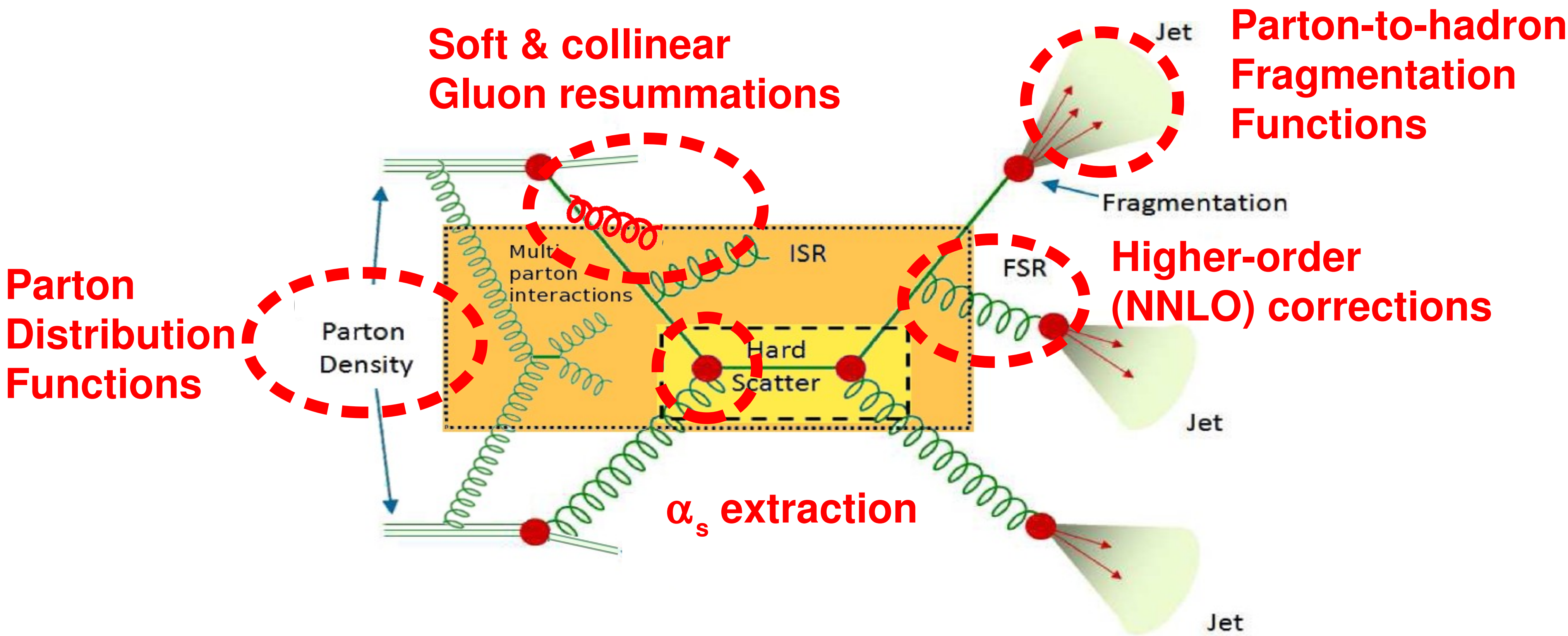
(3) Soft: Beam remnants, diffractive scatterings,... [Douglas M Schaefer, Friday]

- High-precision (experimental & theoretical) studies of QCD are key to understand production of all (B)SM signals & bckgds at the LHC:

Organization of the talk

- What have learned from the hard QCD data at the LHC about...

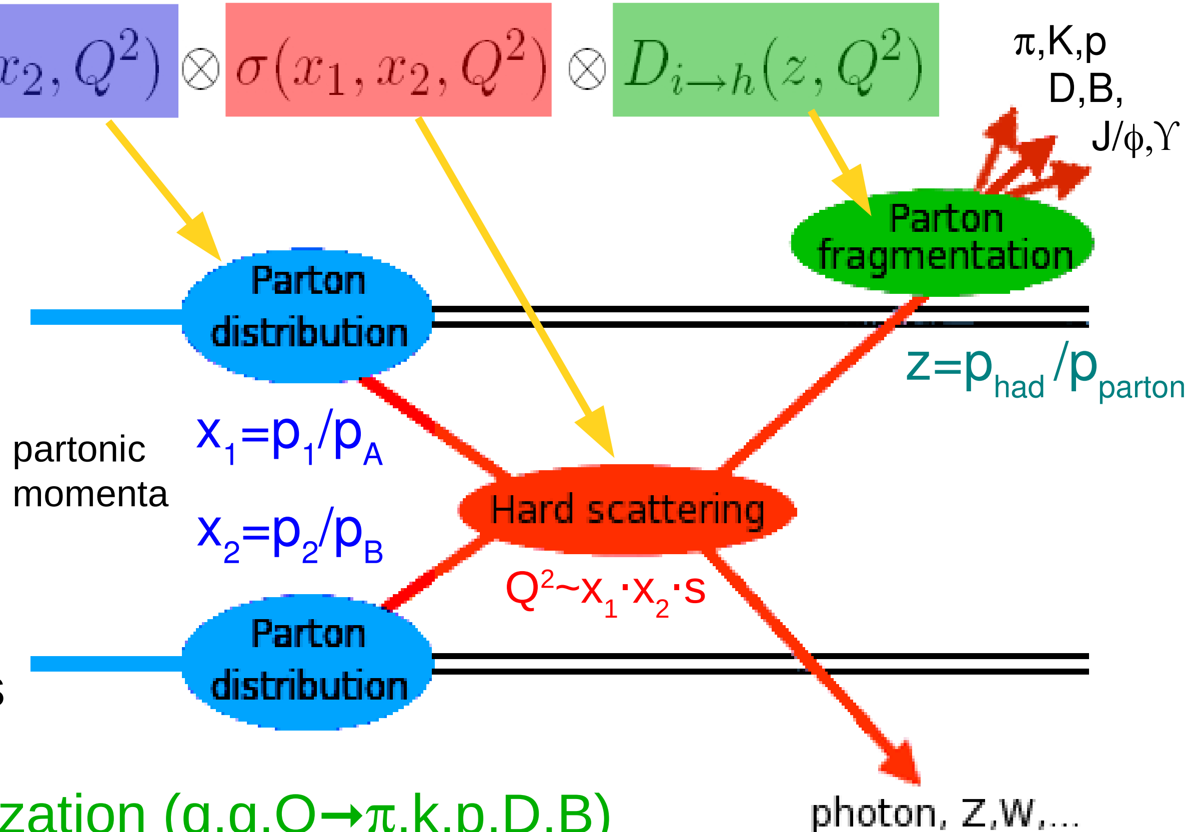


- The total and differential cross sections for <u>any</u> new particle(s) at the LHC (SUSY, DM, Z', S(750)...) are affected by such crucial hard QCD ingredients.

"Master formula" for hard QCD cross sections

- Collinear factorization for hard process cross sections in p-p collisions: Convolution of non-perturbative objects + parton-parton matrix elements:

$$\sigma^{AB\to h} = f_A(x_1,Q^2)\otimes f_B(x_2,Q^2)\otimes\sigma(x_1,x_2,Q^2)\otimes D_{i\to h}(z,Q^2)$$



1) Initial state:

Universal PDFs fitted from data + DGLAP evolution

2) Hard scattering:

Matrix elements computed at (N)NLO in α_s expansion + (N)NLL resummation of logs

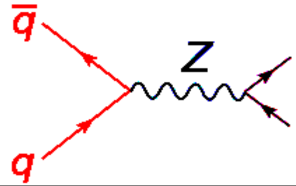
3) Final-state hadronization (q,g,Q→π,k,p,D,B) or bound-state formation (ccbar,bbar):

Universal FFs fitted from data + DGLAP evolution

Hard x-sections: Perturbative α_s expansion

- Theoretical cross section calculations obtained via α_s expansion with increasing # of real parton emissions (legs) + virtual corrections (loops):

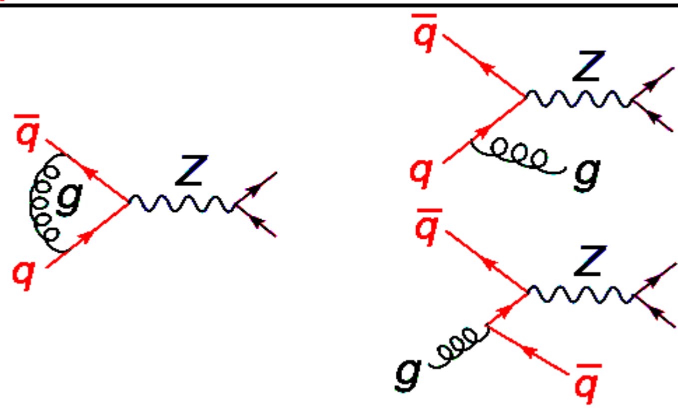
LO



O(1-10) diagrams

TH uncert.~50-100%

NLO



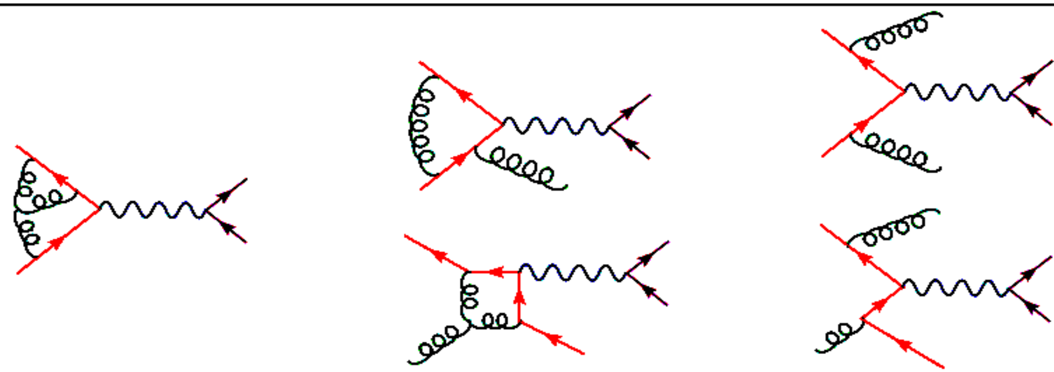
O(100) diagrams

TH uncertainty~20%

pp → jets+X (upcoming NNLO)

pp → γ+X

NNLO



O(1.000) diagrams

TH uncert.~5%

pp → W,Z+X (+jet)

pp → γ γ +X

pp → ttbar+X

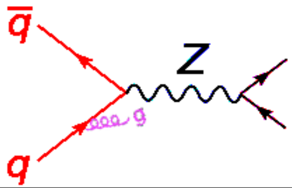
pp → H+X=jets,V,ttbar

First-ever N^3LO: gg→H+X (~10^5 diags. ~2% uncert.)

Hard cross sections: Soft gluon resummations

- Theory calculations with increasing # of real emissions + virtual corrections + soft & collinear log resummations (improves p_T differential distributions):

LO
+LL



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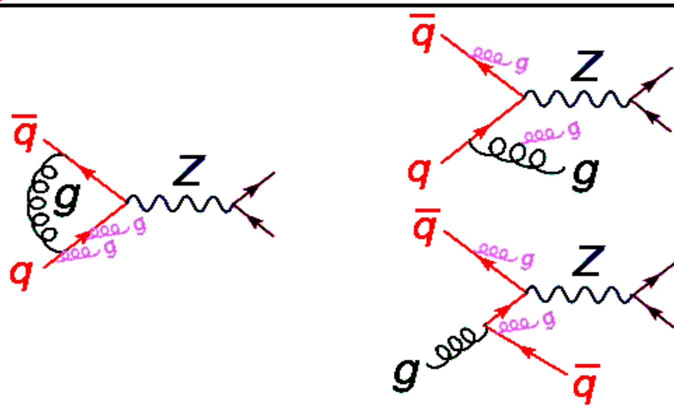
NLO
+NLL



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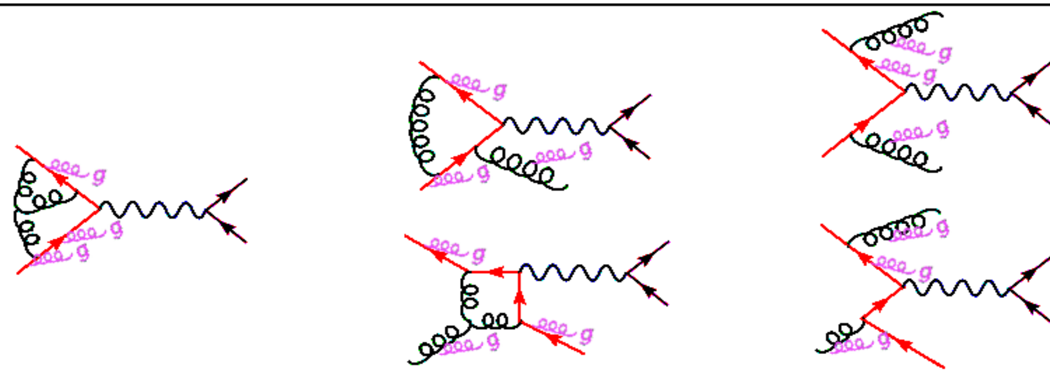


O(1.000) diagrams

TH uncert.~5%

pp→W,Z+X (+jet)

pp→γ γ +X

pp→ttbar+X

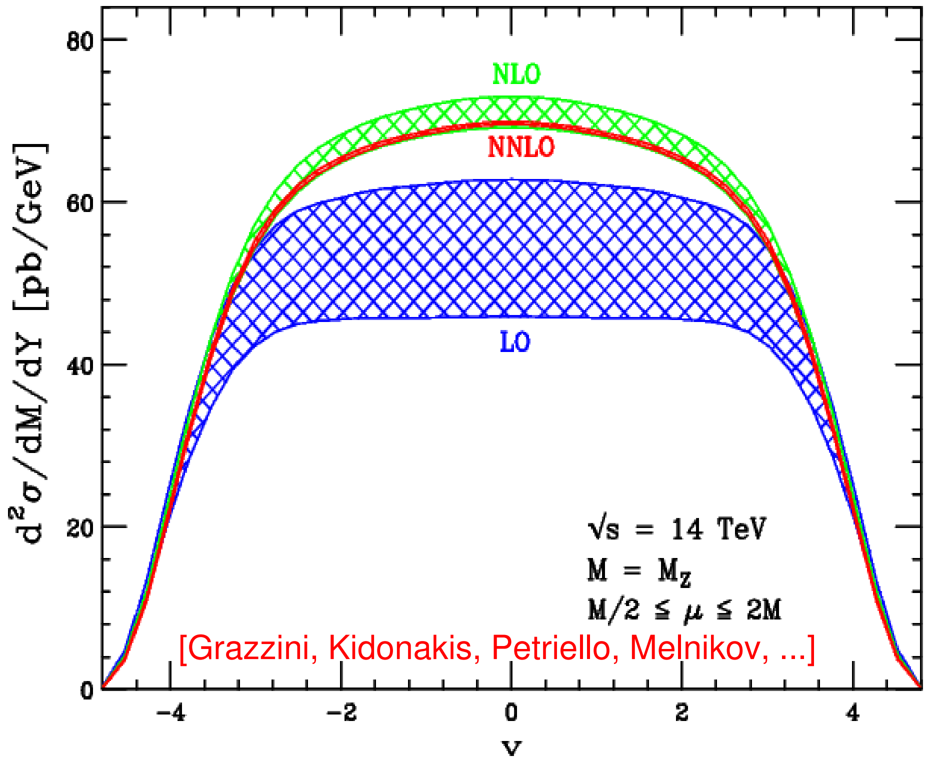
pp→H+X=jets,V,ttbar

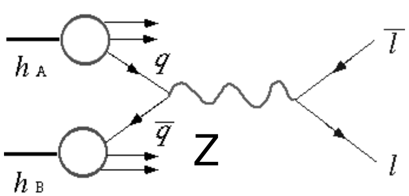
(State-of-the-art pQCD calculations include also QED+EWK corrections)

Hard cross sections: Higher-order corrections

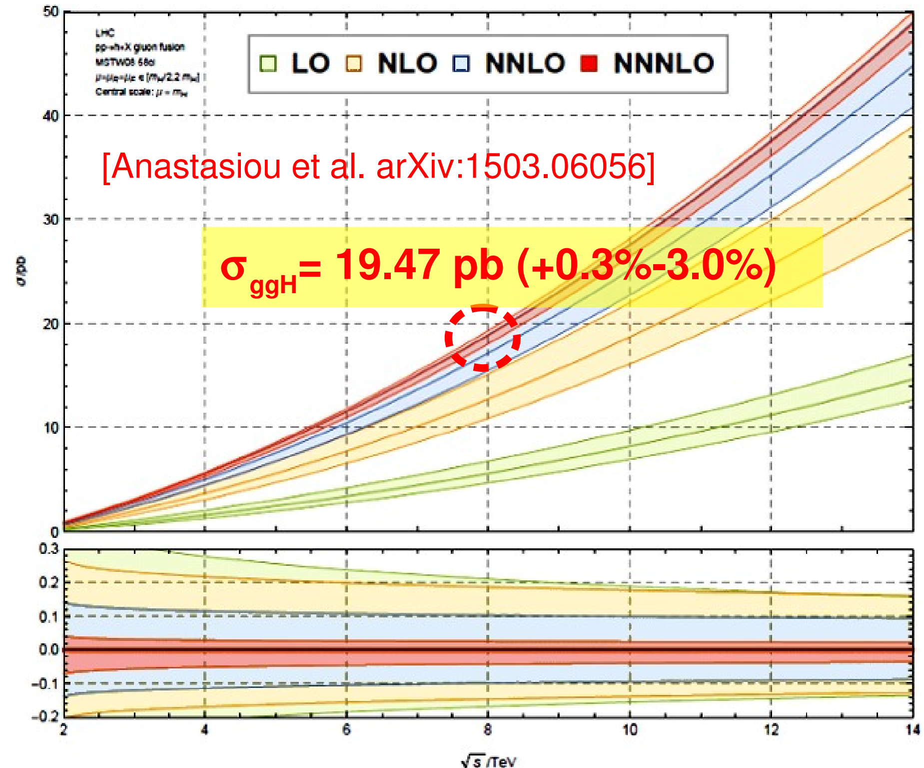
- Theory calculations with increasing # of real emissions + virtual corrections: (i) (usually) increased x-sections, (ii) reduced theoretical uncertainties

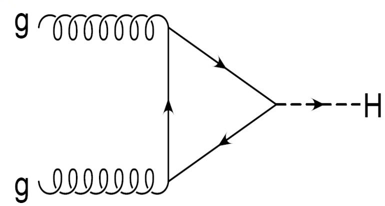
$\sigma(pp \to Z,\gamma^*)$ at NNLO:





Higgs $\sigma(gg \to H)$ at N^3LO:



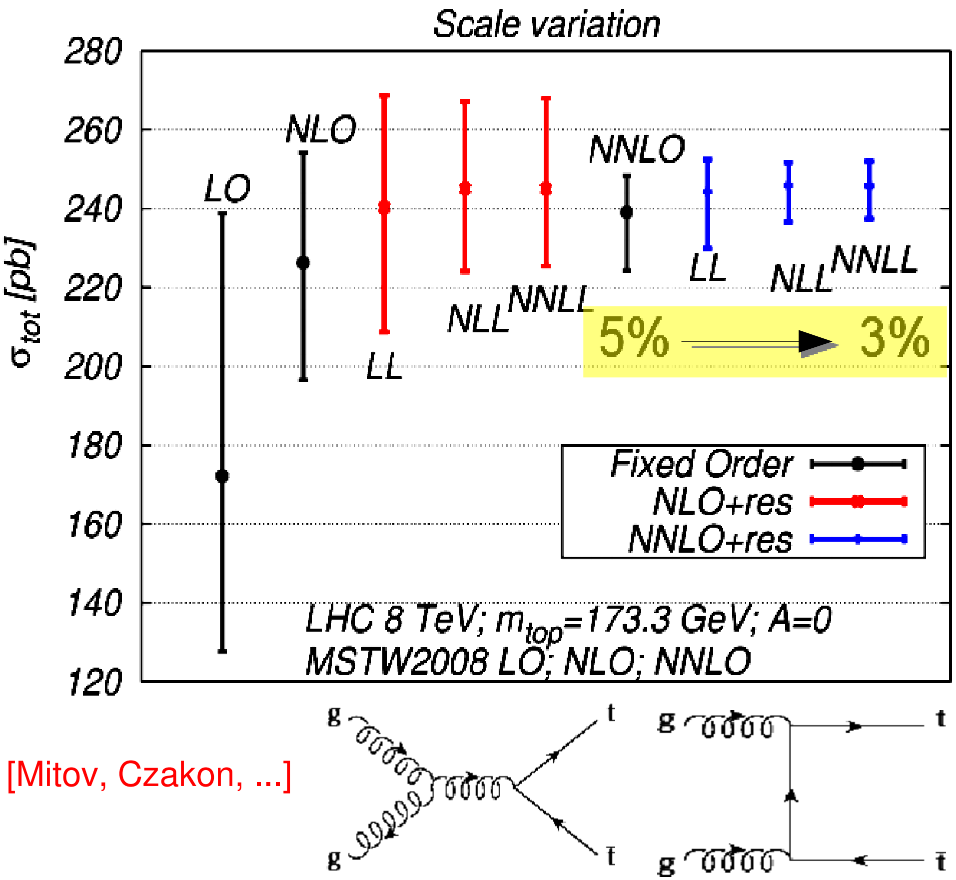


$+10^5$ diagrams more

Hard cross-sections: Resummations

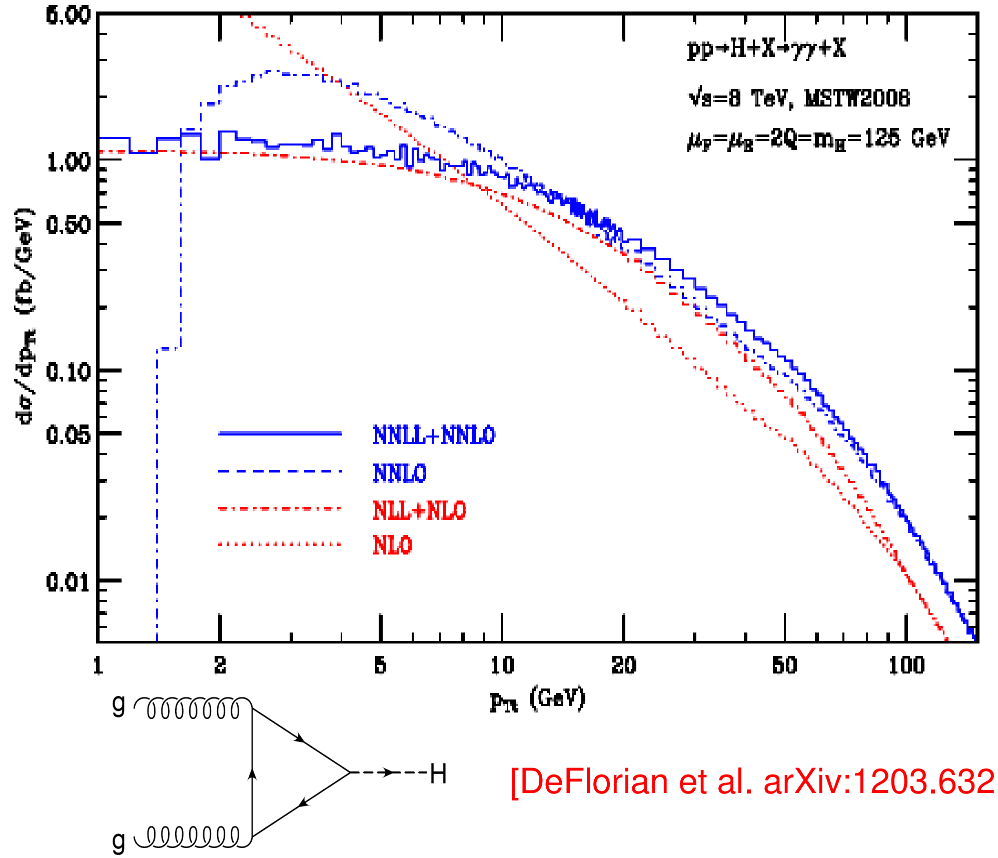
- Theory calculations include increasing # of real emissions + virtual corrections: + soft & collinear log resummations: (i) (usually) increased x-sections, (ii) reduced theoretical uncertainties, (iii) Improved p_T differential distributions:

$\sigma(pp\to ttbar)$ at NNLO+NNLL:



[Mitov, Czakon, ...]

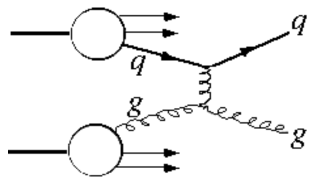
Higgs $d\sigma/dp_T$ at NNLO+NNLL:

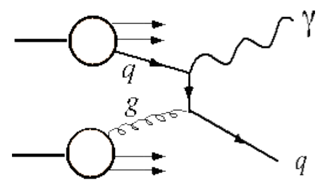


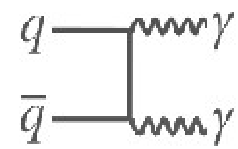
[DeFlorian et al. arXiv:1203.6321]

Hard QCD: LHC Data

Wealth of hard QCD data: jets, γ, diphotons







- √s=2.76,7,8,13 TeV (central):
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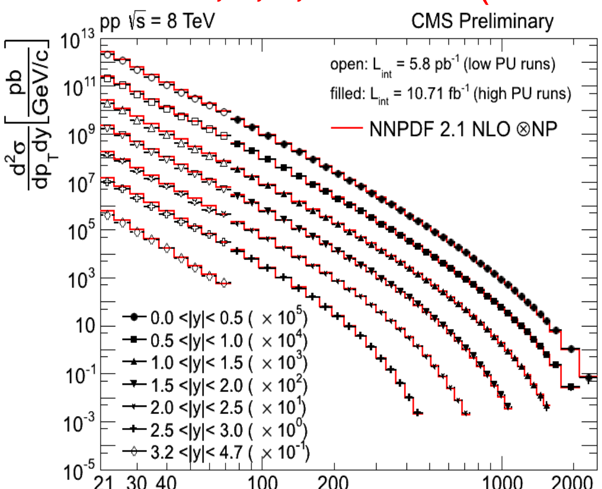
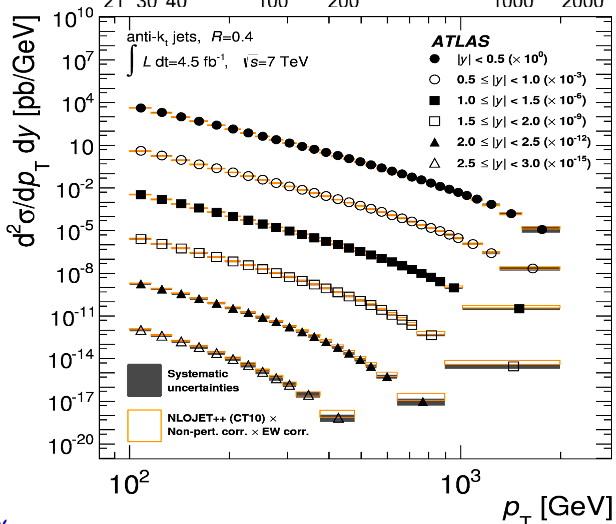
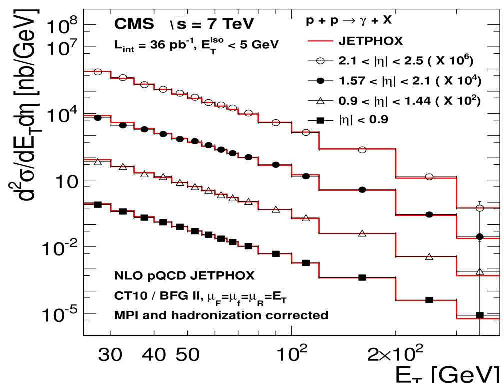
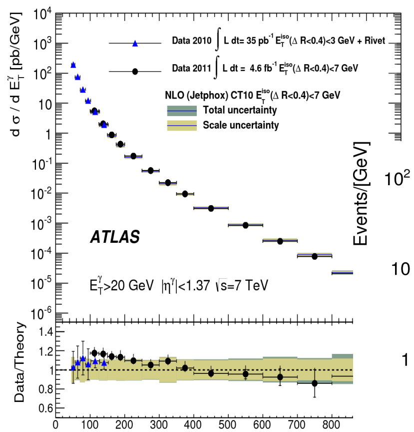
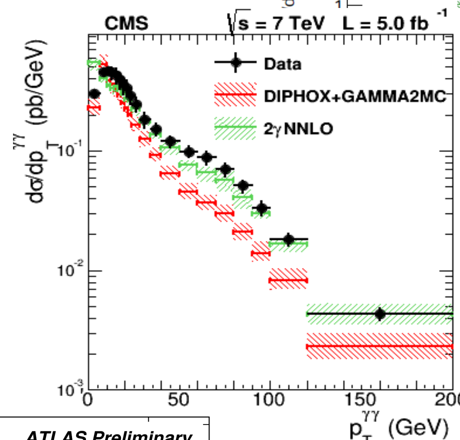
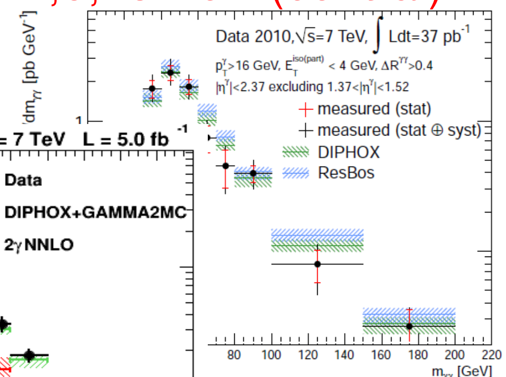


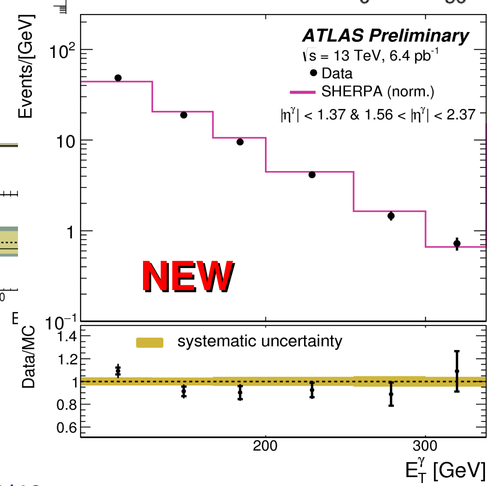


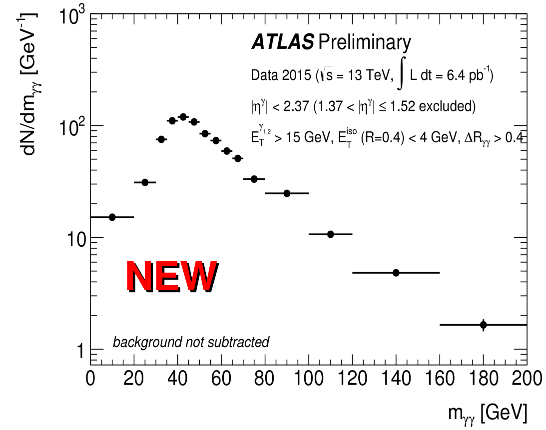






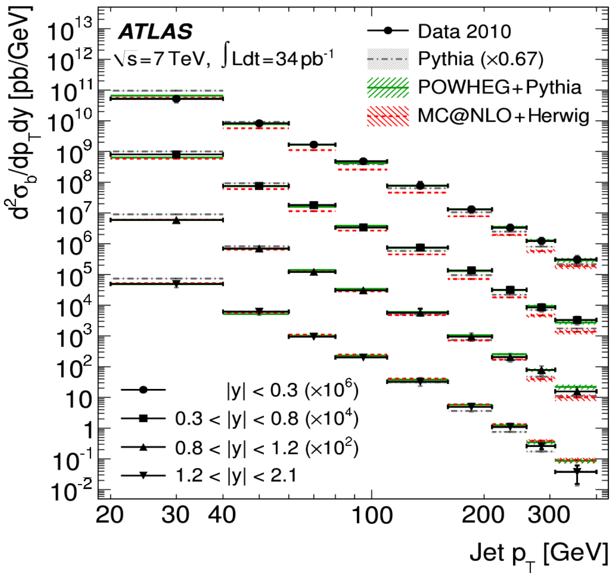


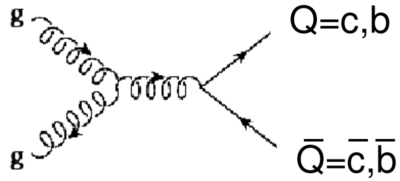


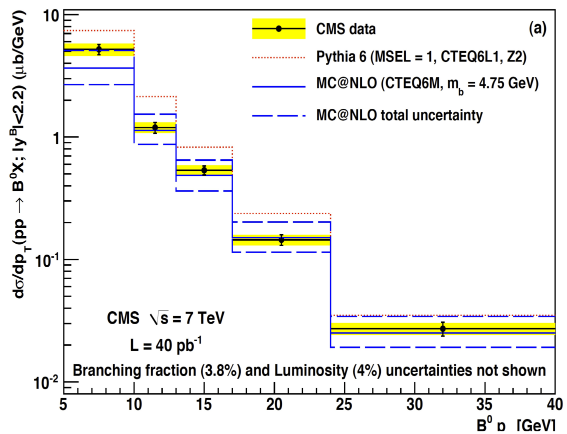


Wealth of hard QCD data: charm, bottom

- $\sqrt{s}$ = 7, 8, 13 TeV (central rapidities):

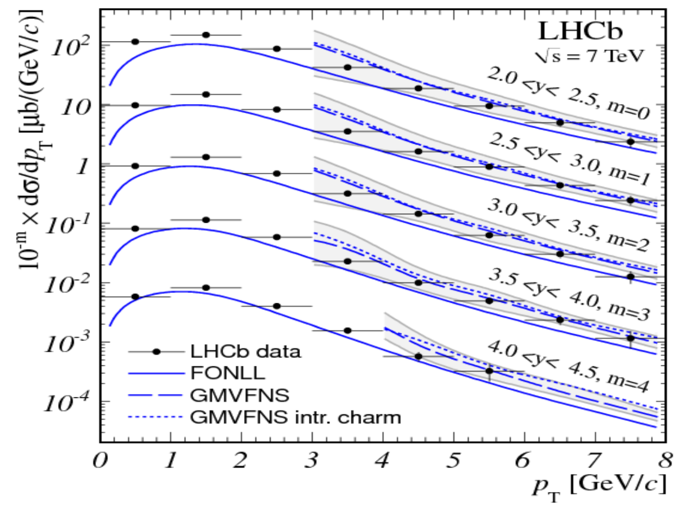


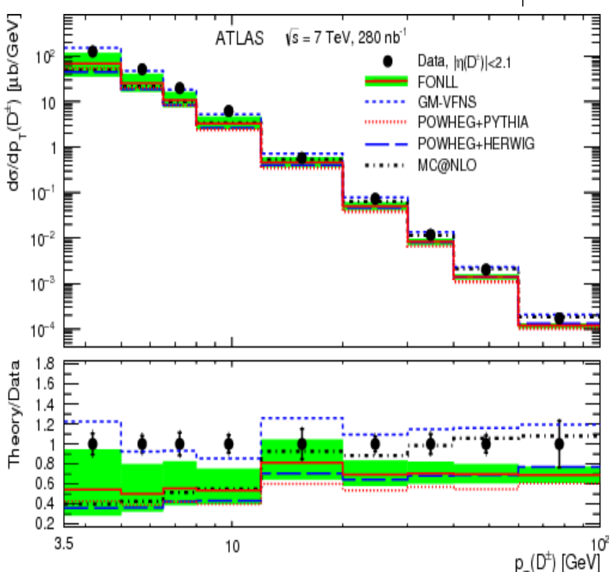


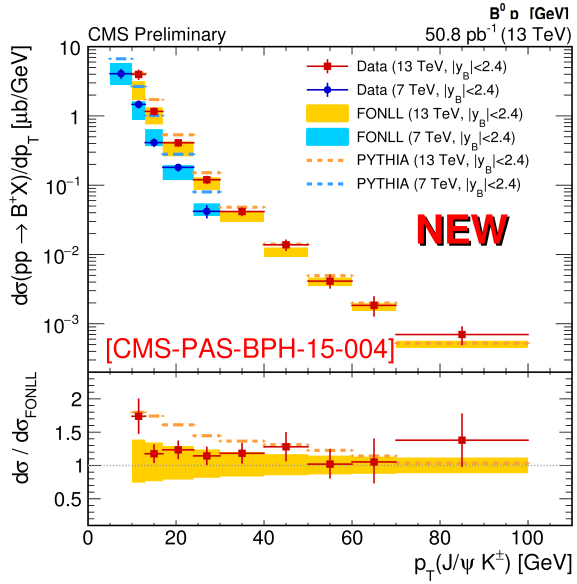


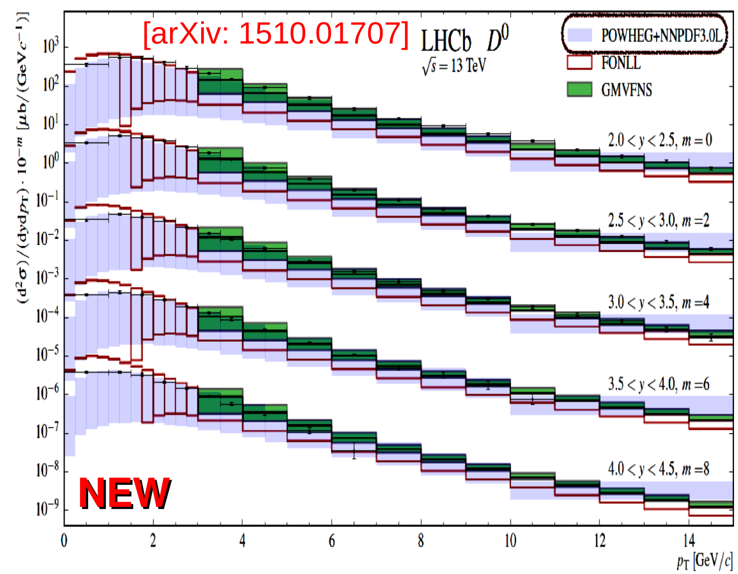
- $\sqrt{s}$ = 7, 8, 13 TeV (forward):

[NPB871 (2013) 1]



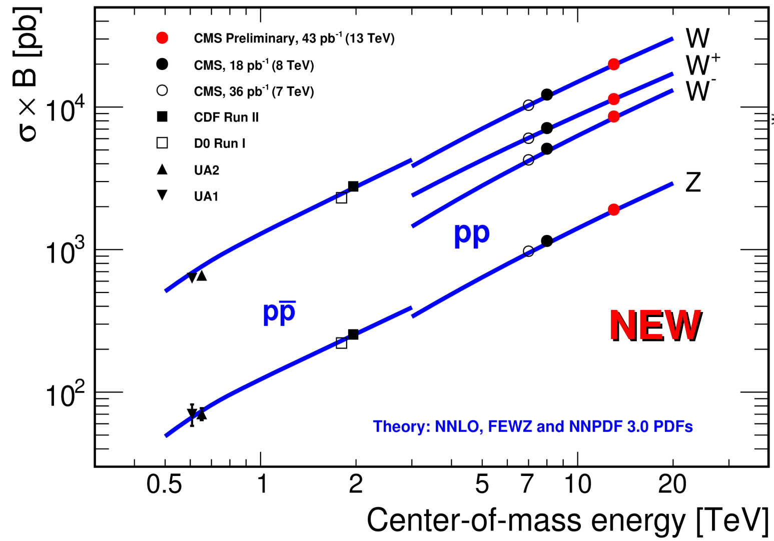


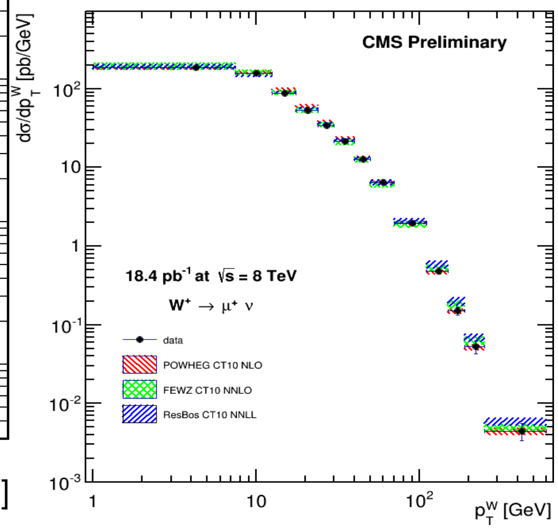


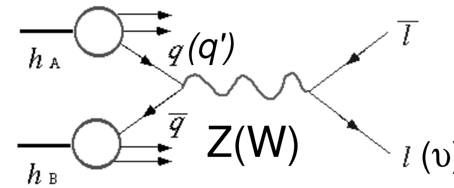


Wealth of hard QCD data: W, Z bosons

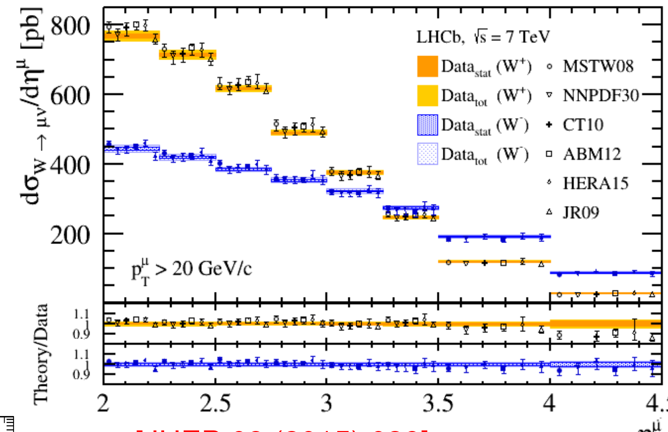
■ √s = 7, 8, 13 TeV (central rapidities):



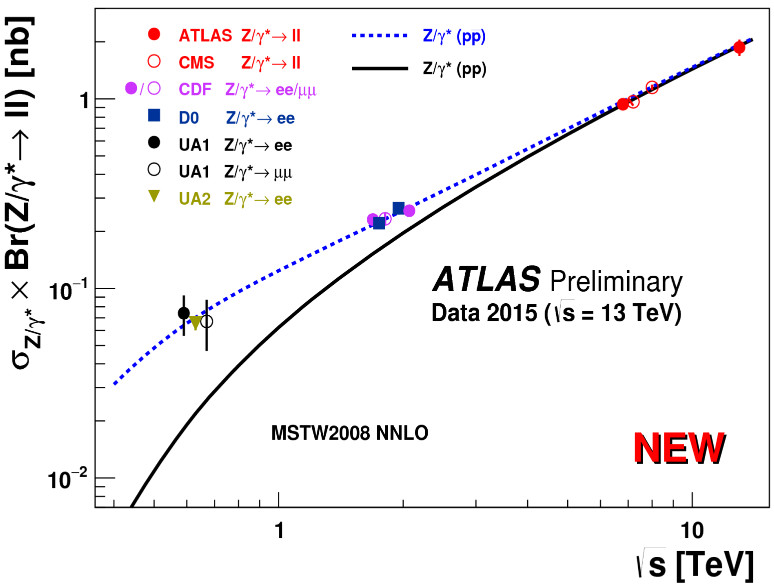


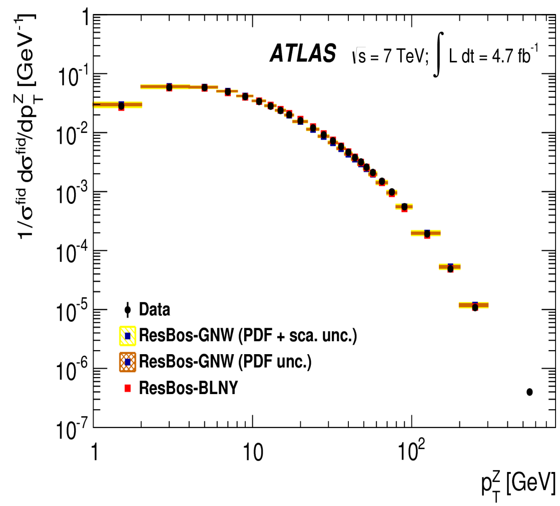


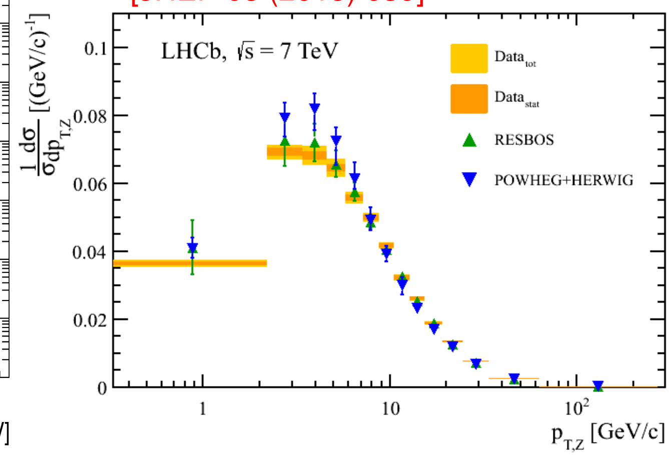
■ √s = 7, 8 TeV (forward):



[JHEP 08 (2015) 039]

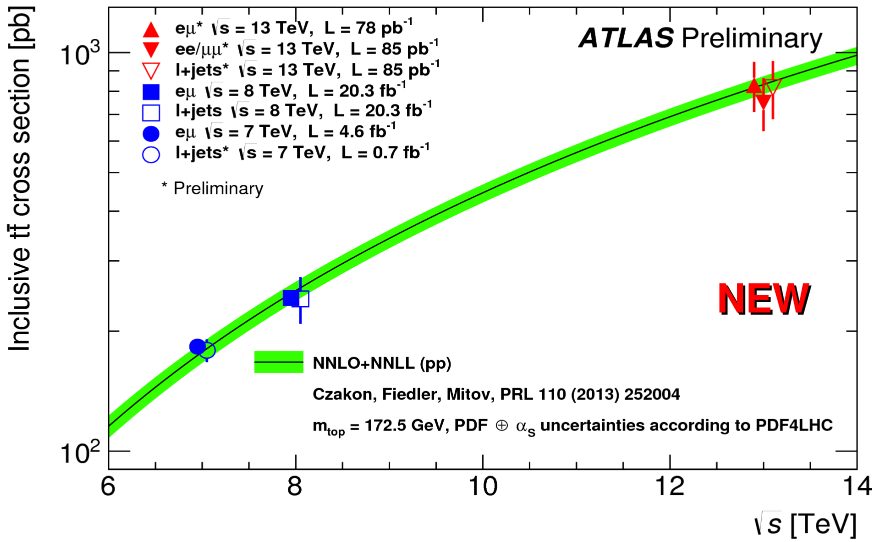


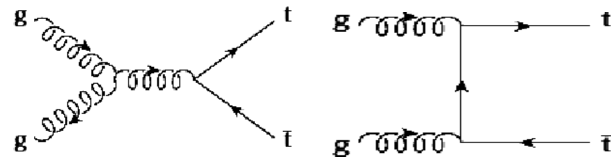


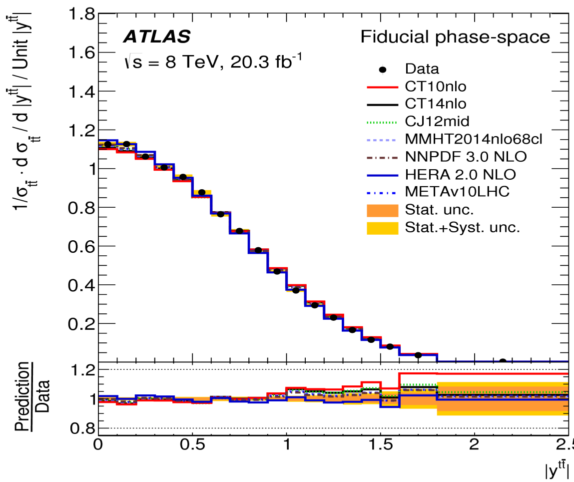


Wealth of hard QCD data: top-pairs

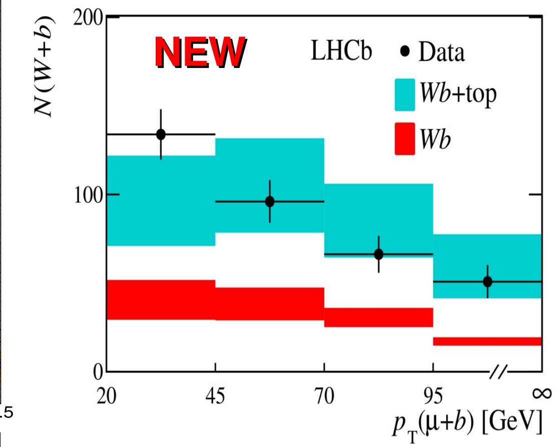
■ √s = 7, 8, 13 TeV (central rapidities):

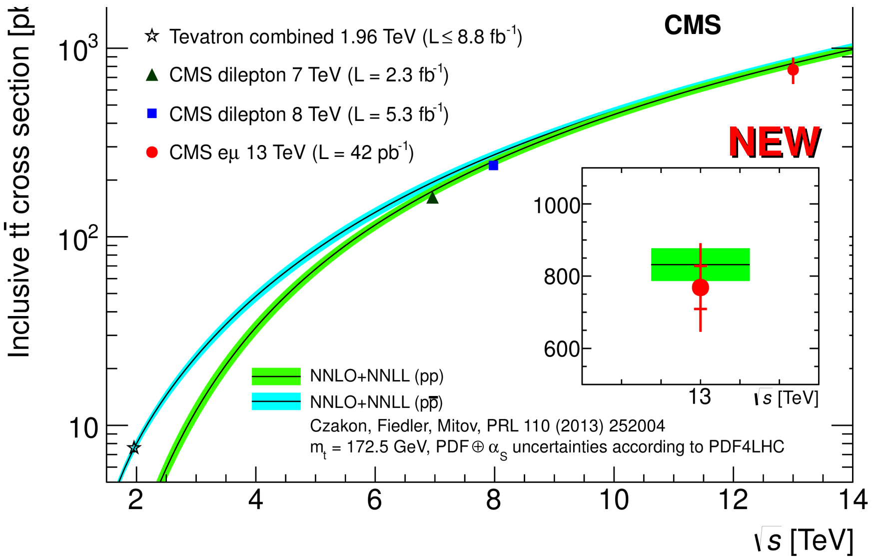


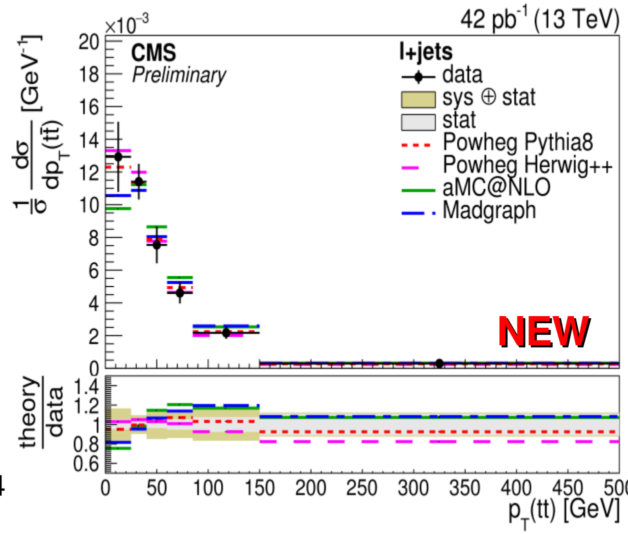


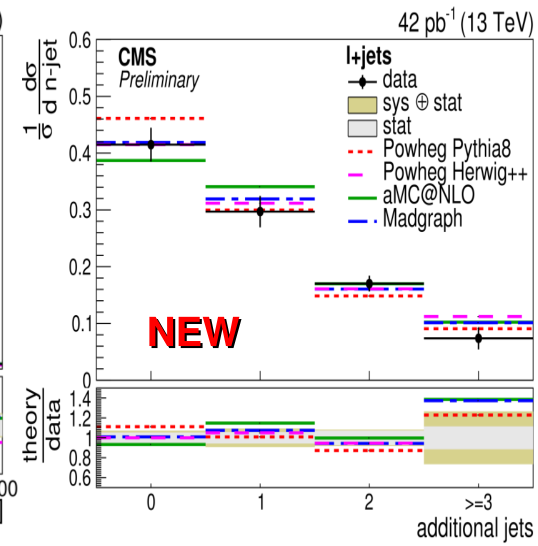


■ √s = 7, 8 TeV (forward):



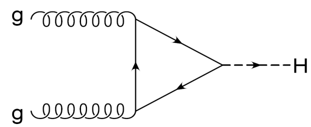


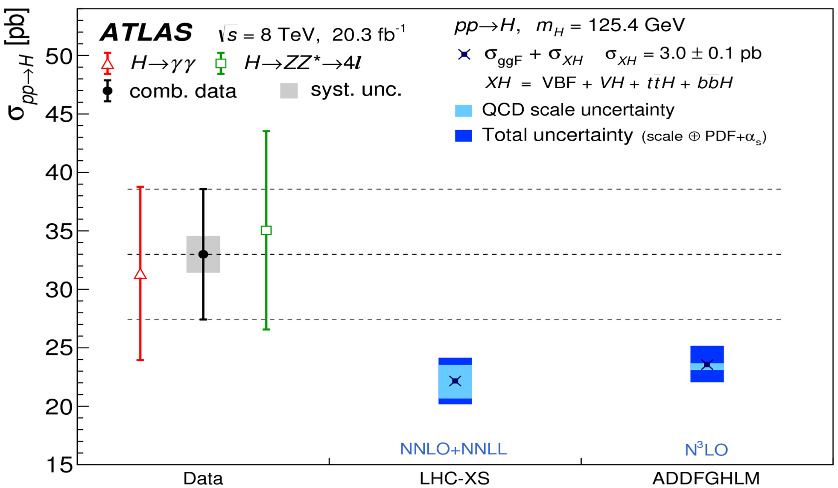


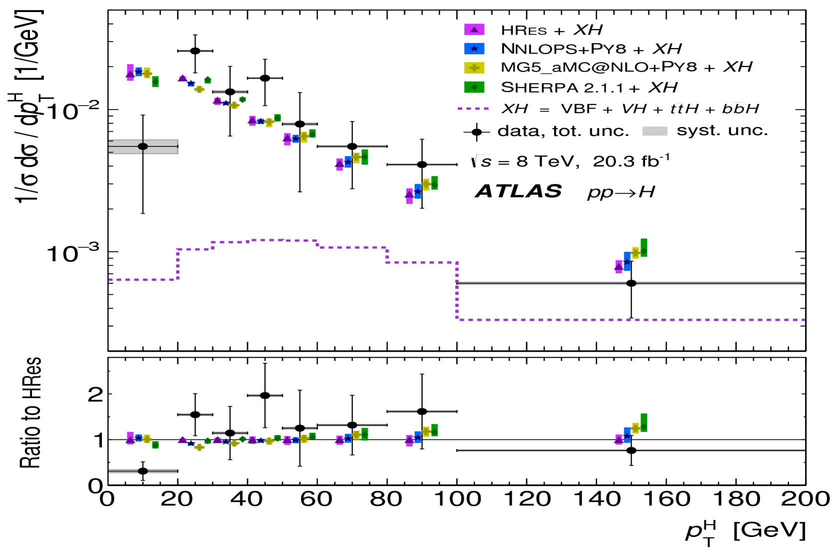


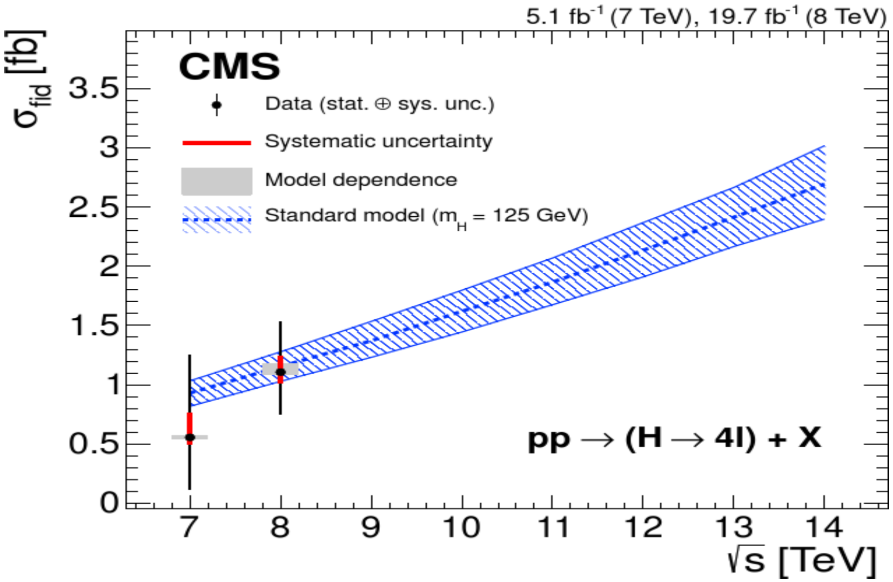
Wealth of hard QCD data: Higgs boson

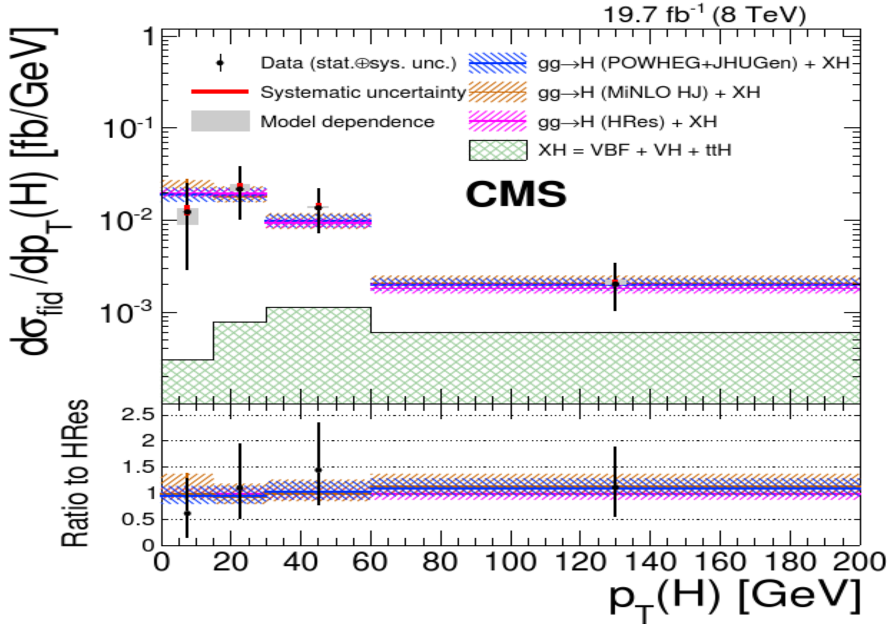
- √s = 7, 8 TeV (central rapidities):



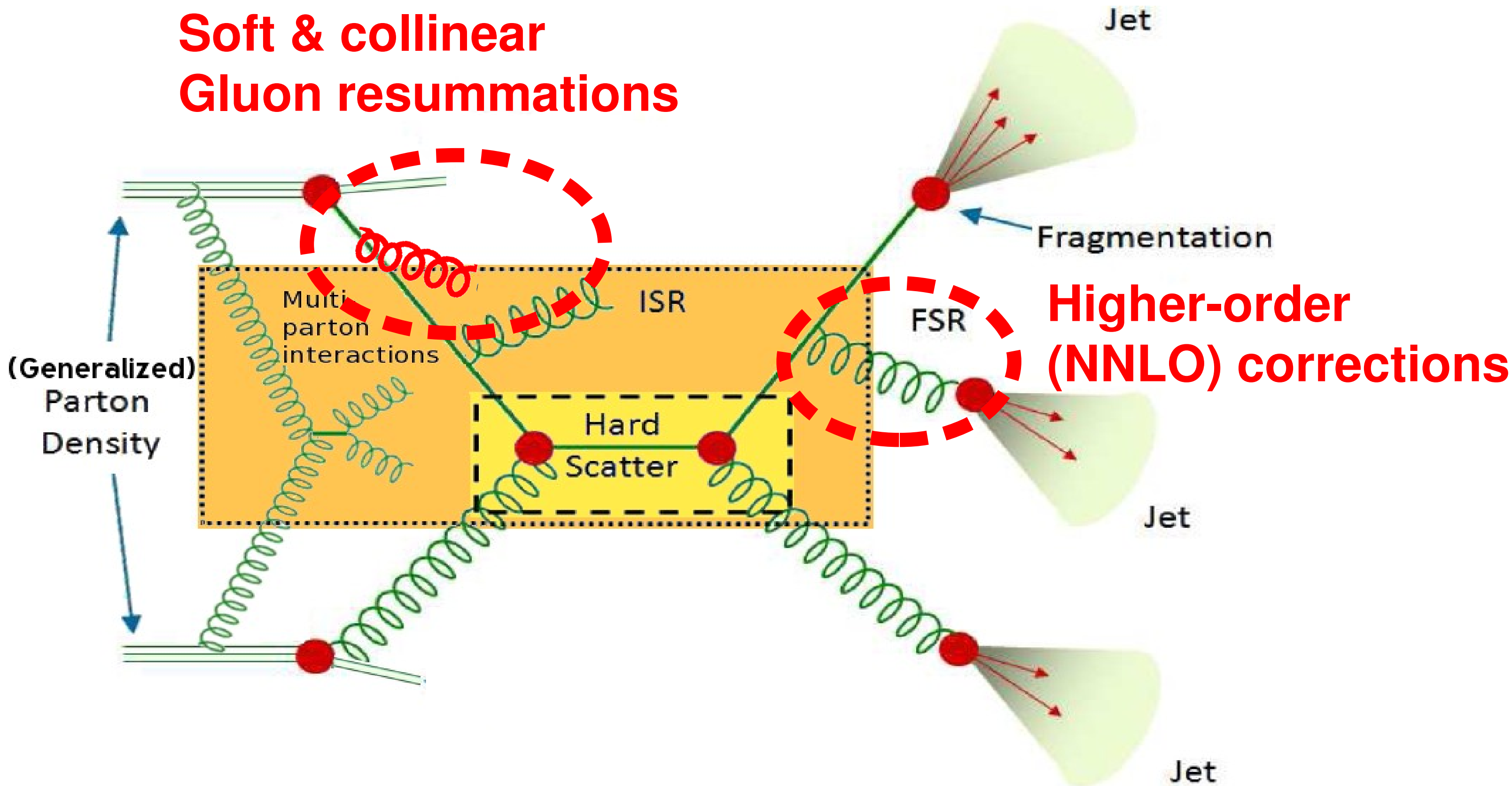






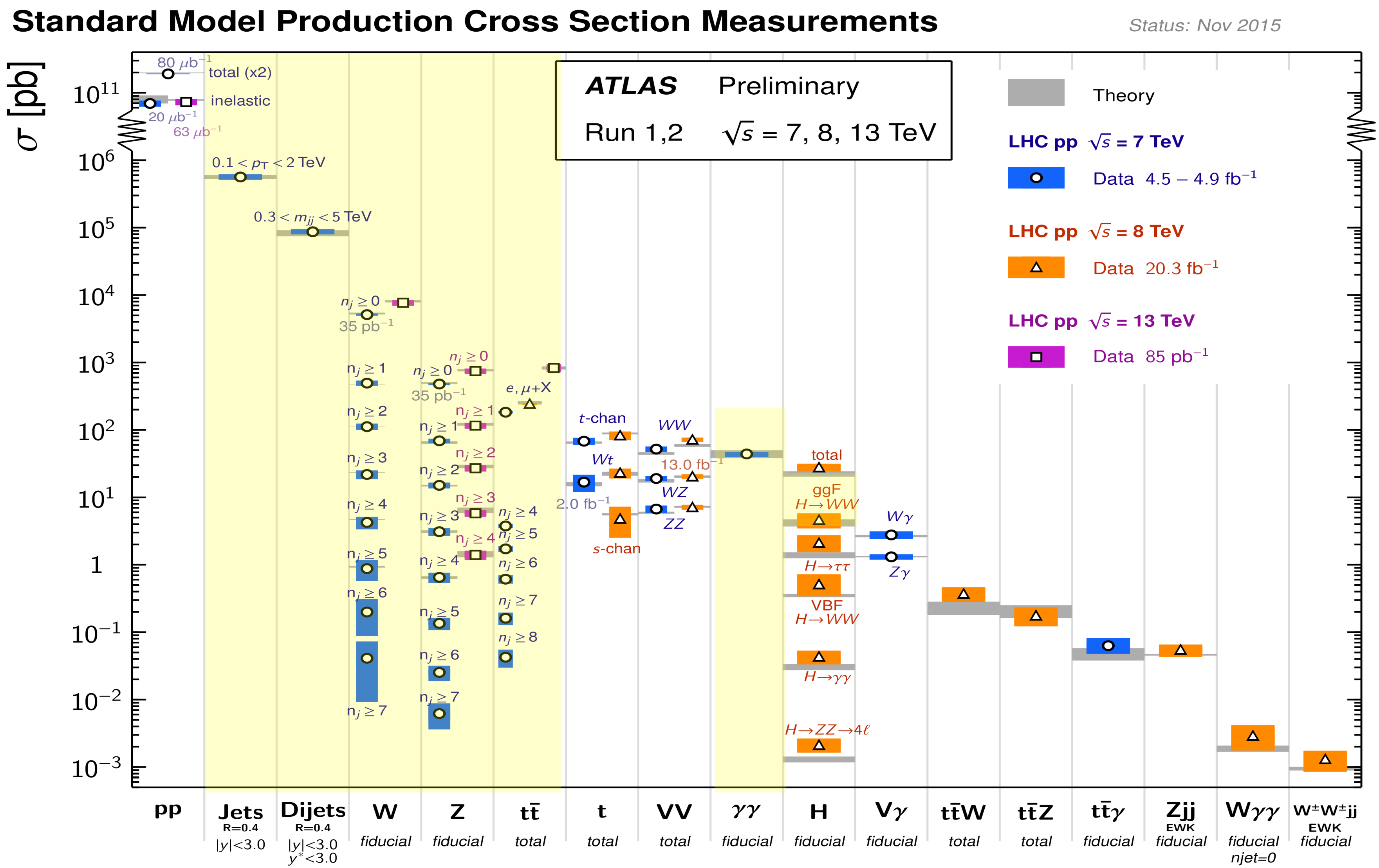


Higher-order & resummations



Total hard cross sections: Data vs. pQCD

- NNLO calculations in excellent agreement with all measured total x-sections:



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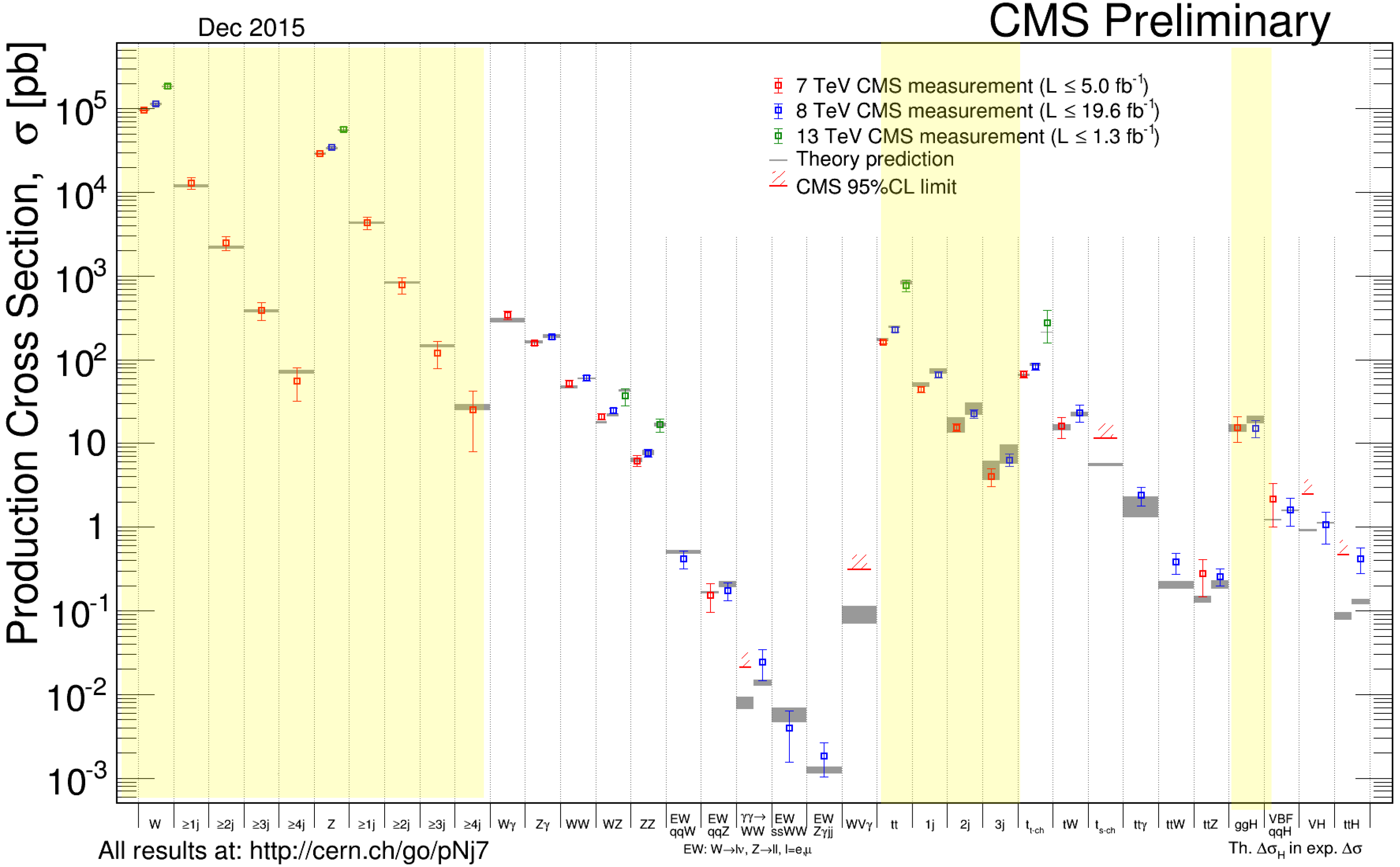
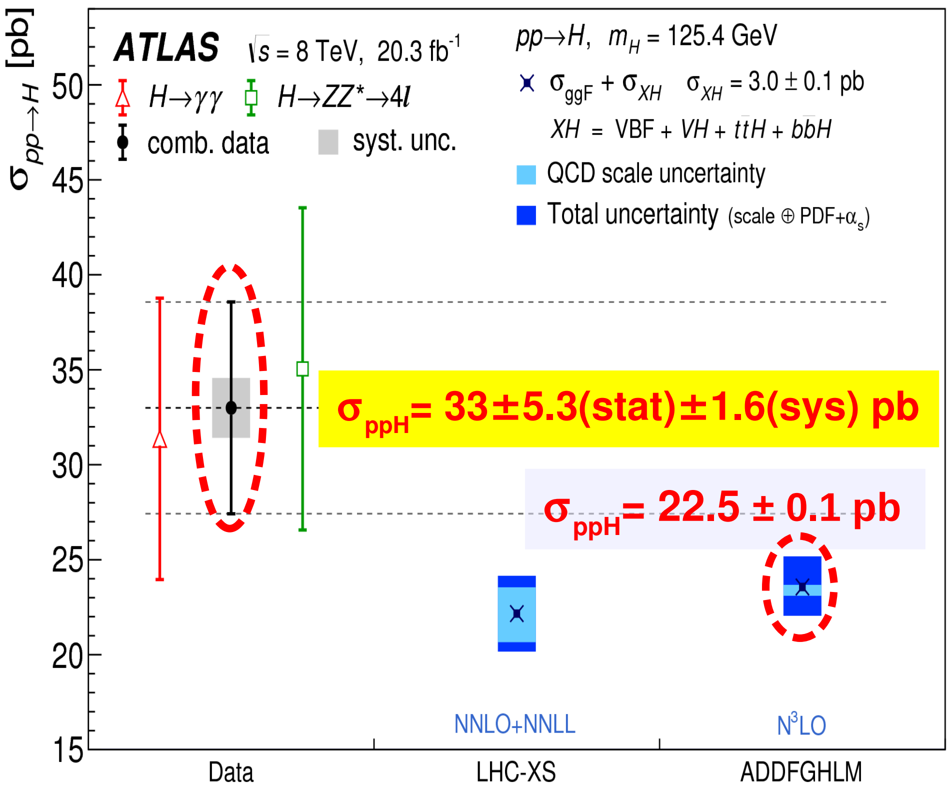


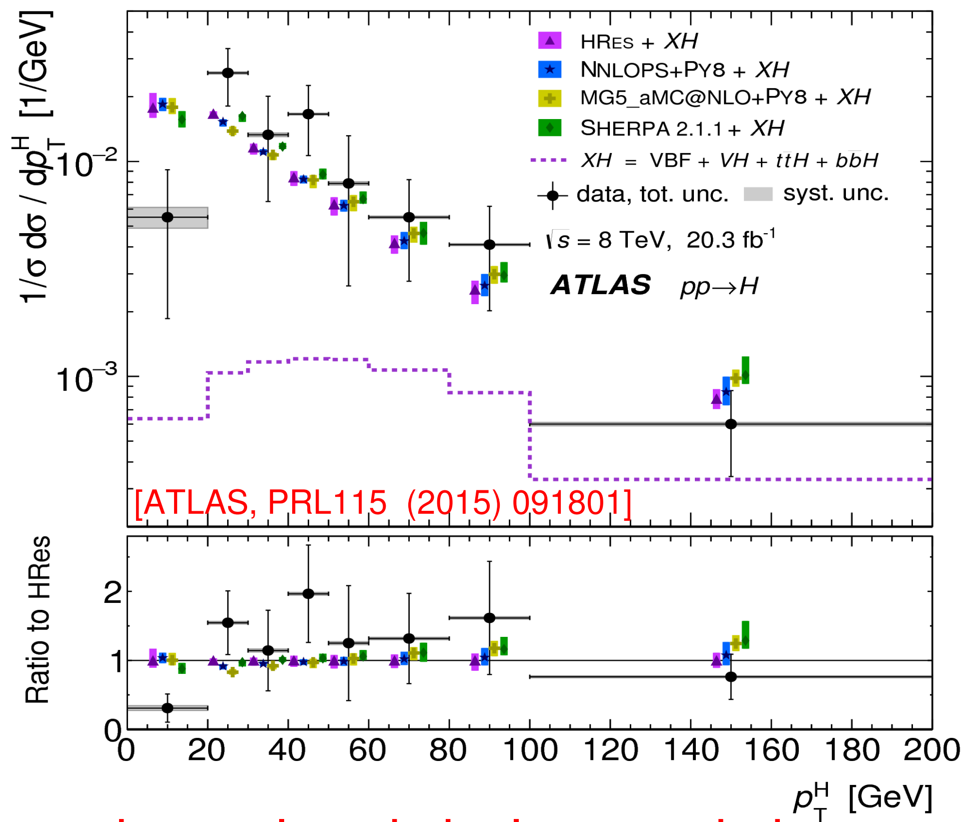
Higgs x-sections: Data vs. NNLO+NNLL

- Theory calculations include increasing # of real emissions + virtual corrections + soft & collinear log resummations (improves p_T differential distributions).
- Higgs production is paradigmatic example:

Higgs $\sigma(pp\rightarrow H)$ vs N^{2,3}LO:



Higgs $d\sigma/dp_T$ vs NNLO+NNLL:



- Decent agreement within still large experimental statistical uncertainties

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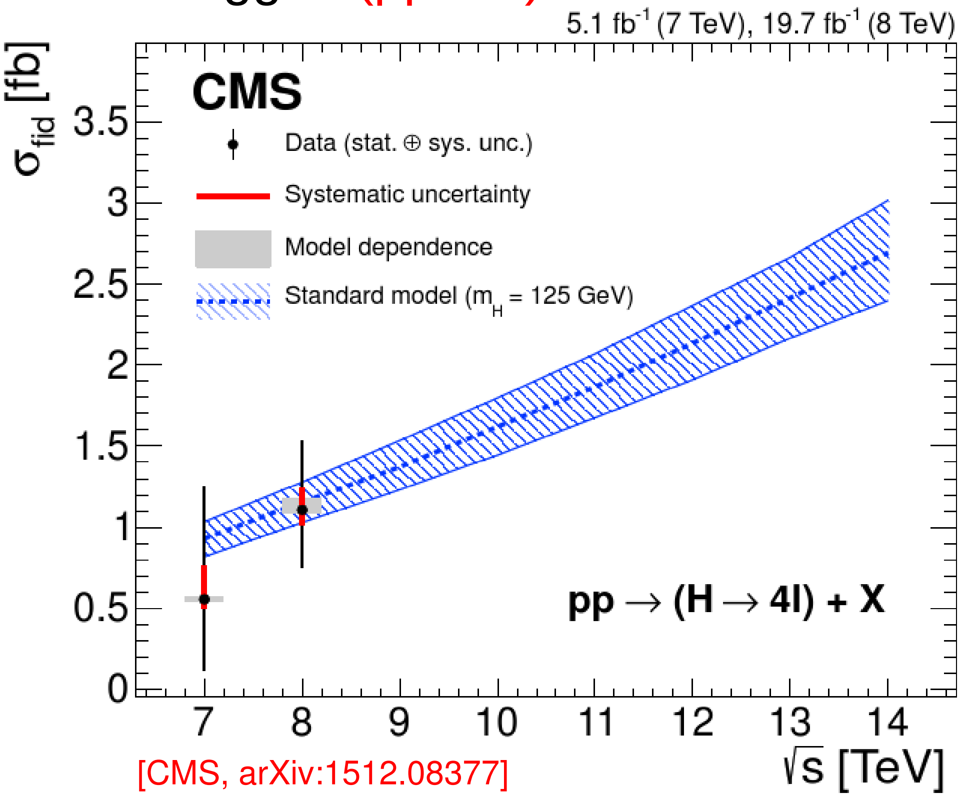

[CMS, arXiv:1512.08377]

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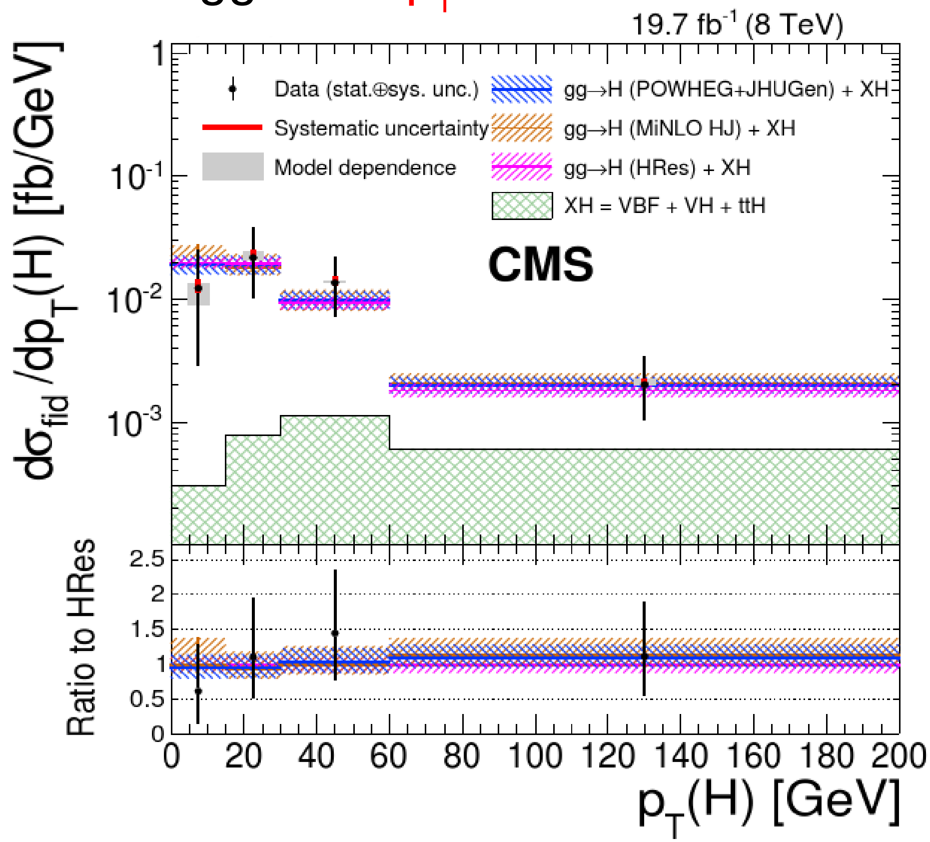
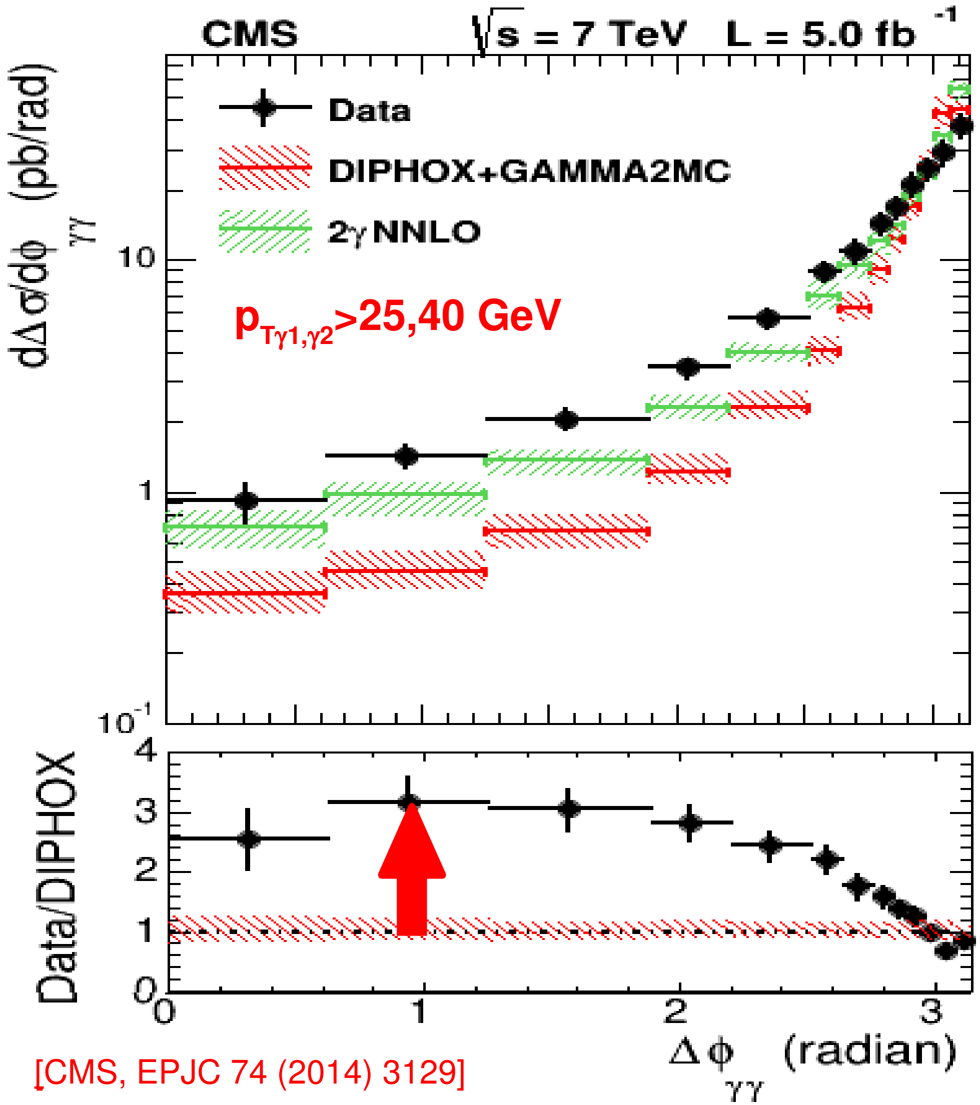


- Decent agreement within still large experimental statistical uncertainties

Diphoton x-sections: Role of NNLO corrections

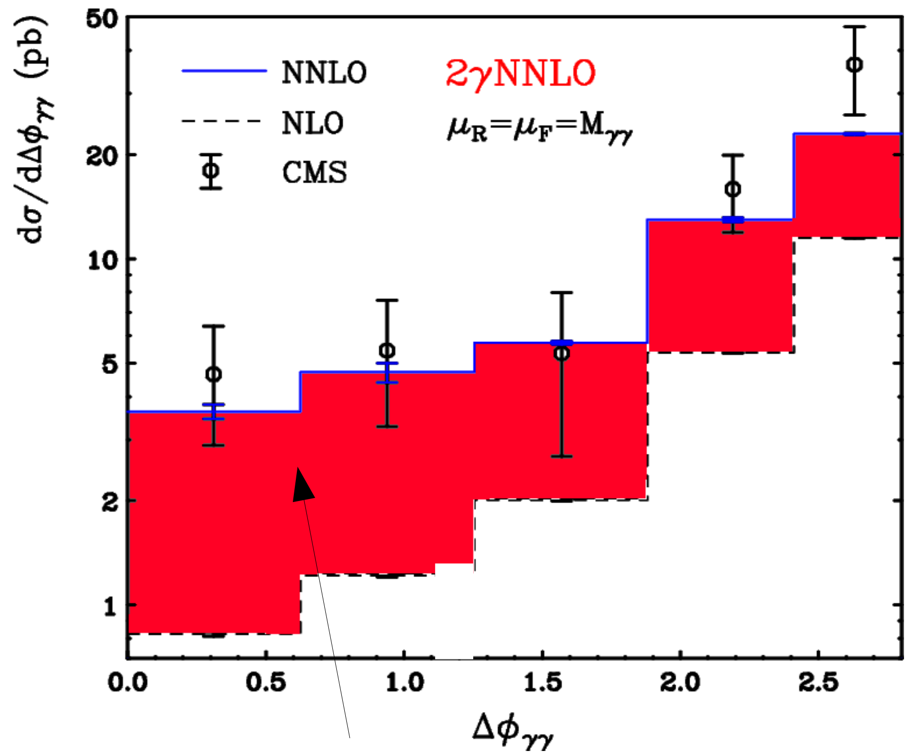
- NLO largely underestimates increasingly collinear γ's (Δφ<2.5):



[CMS, EPJC 74 (2014) 3129]

- Cured by latest state-of-the-art NNLO diphoton calculations:

[D.deFlorian et al, PRL108 (2012) 072001]



Enhanced NNLO production of collinear γ's (e.g. qq →qqγγ).
When γ–γ not back-to-back: NLO~1st order

Diphoton x-sections: Role of NNLO corrections

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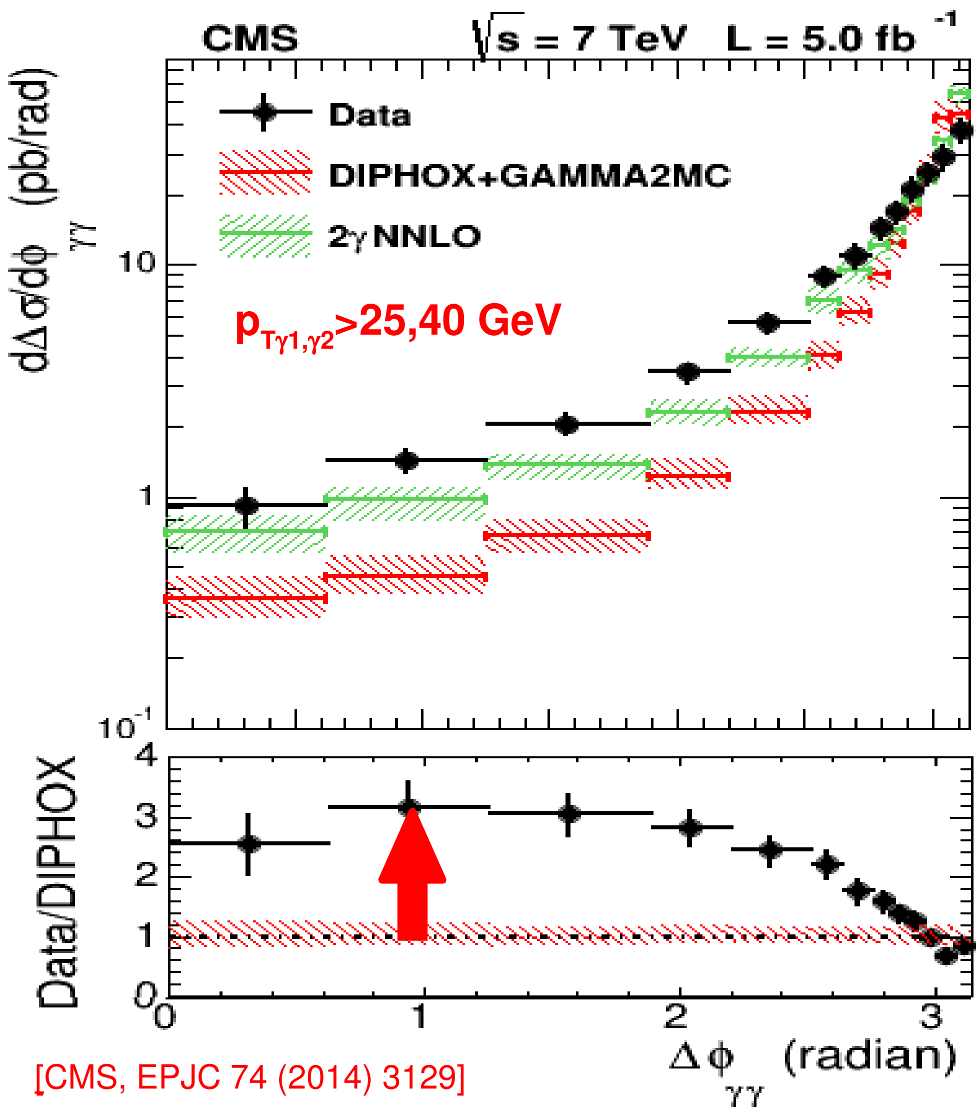

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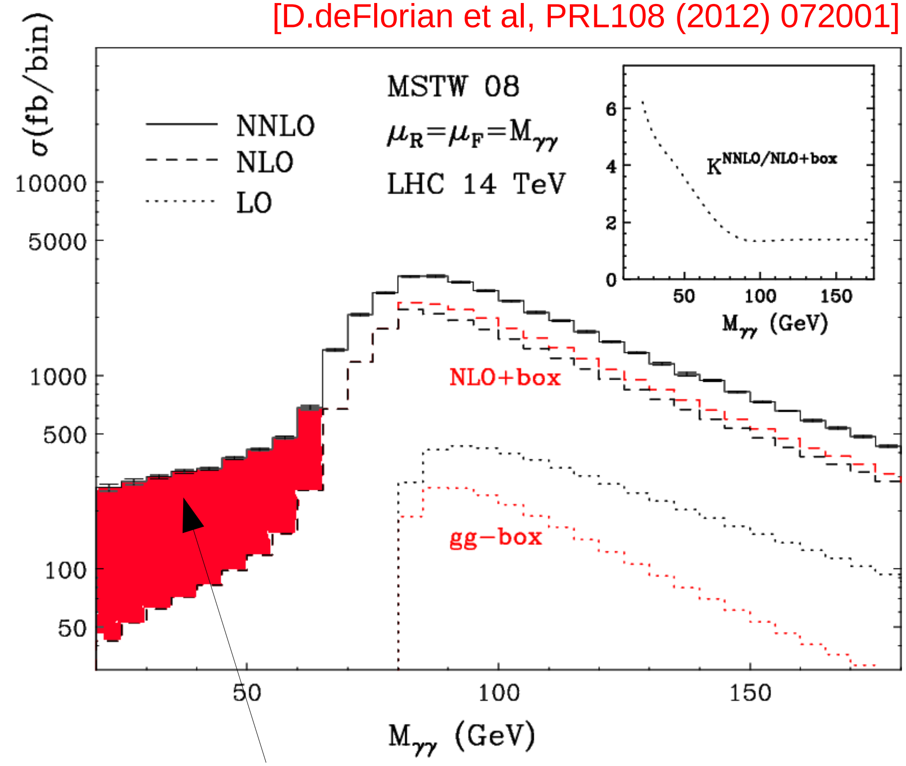
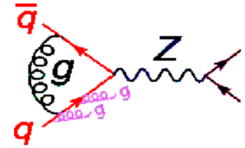


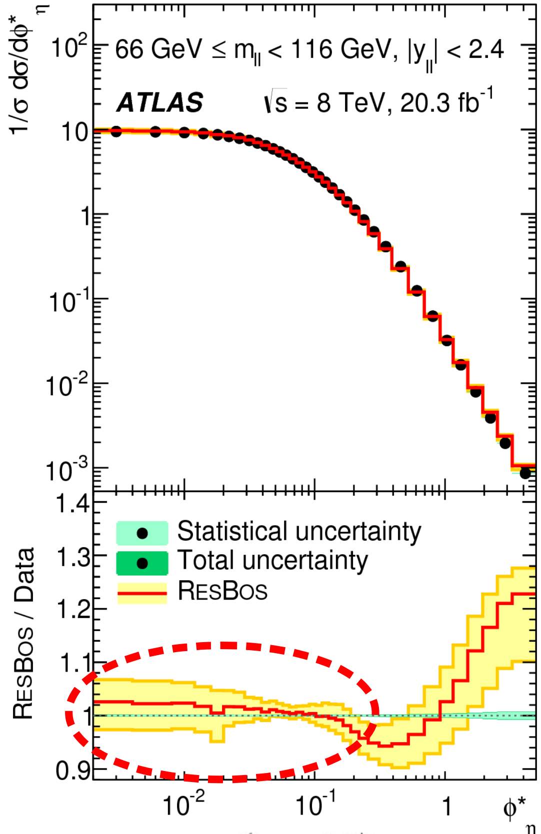
Enhanced NNLO production of collinear γ's (e.g. qq →qqγγ) "fills" out relevant regions of phase-space.

Z boson x-sections: Role of resummations

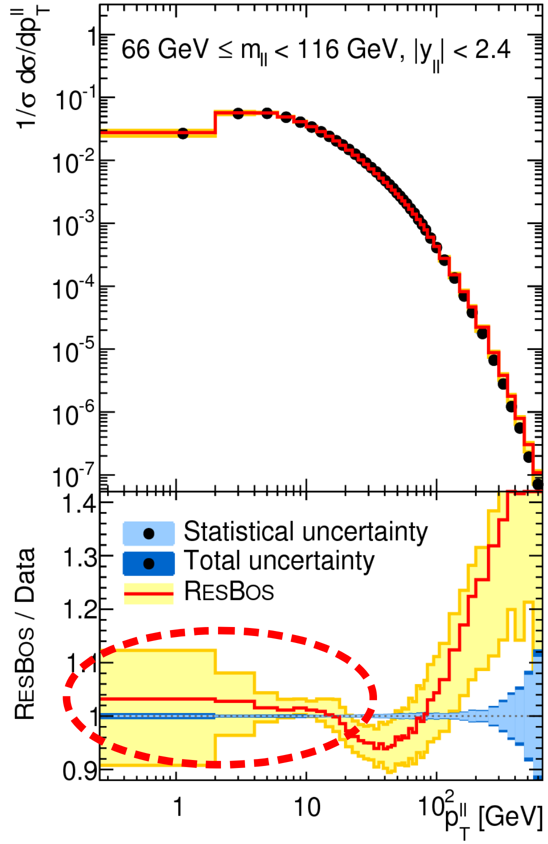
- Very precise differential measurement (uncert. <1% in ϕ^*_η) strongly constrains modeling of soft/collinear gluon emission.



- NLO+NNLL resummations are crucial to reproduce the Z spectra at low-p_T:

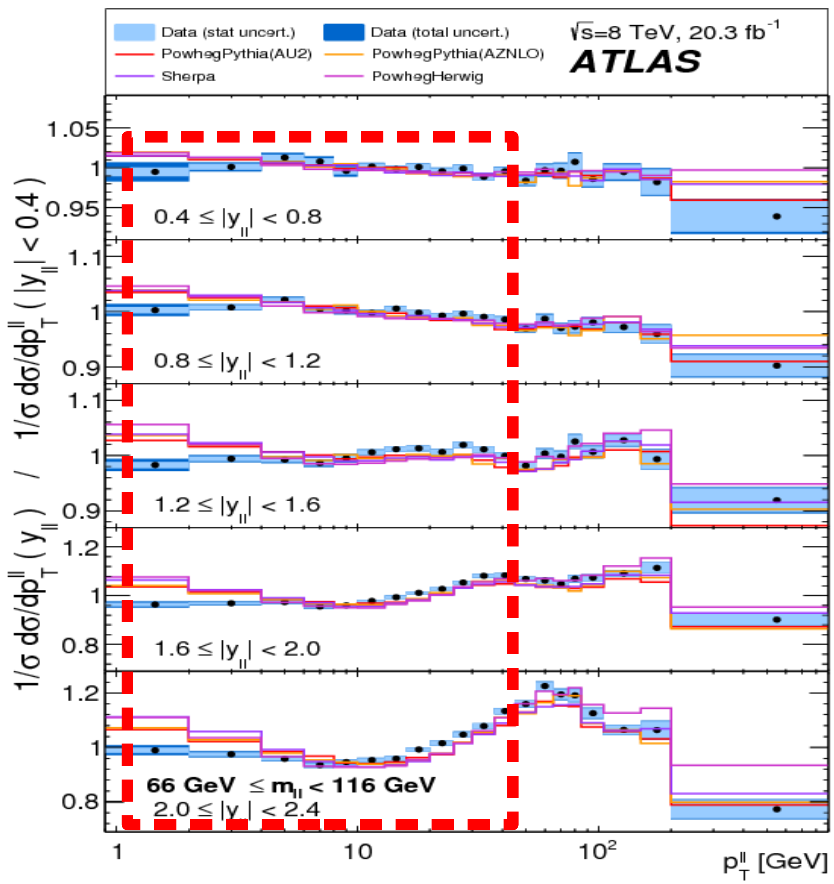


$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta^*_\eta)$$



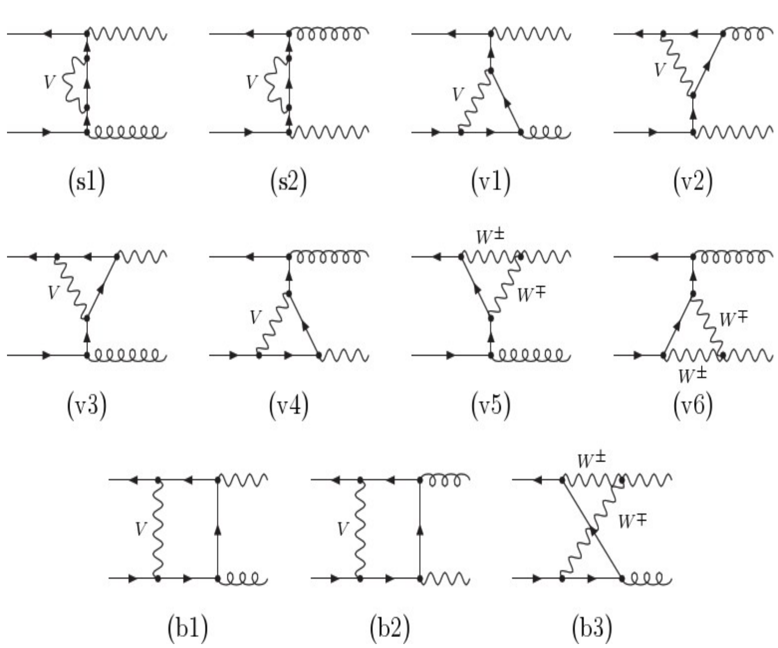
[ATLAS, arXiv:1512.02192]

- NLO+parton-showers (effective LL or NLL*) also reproduce well low-p_T spectra:

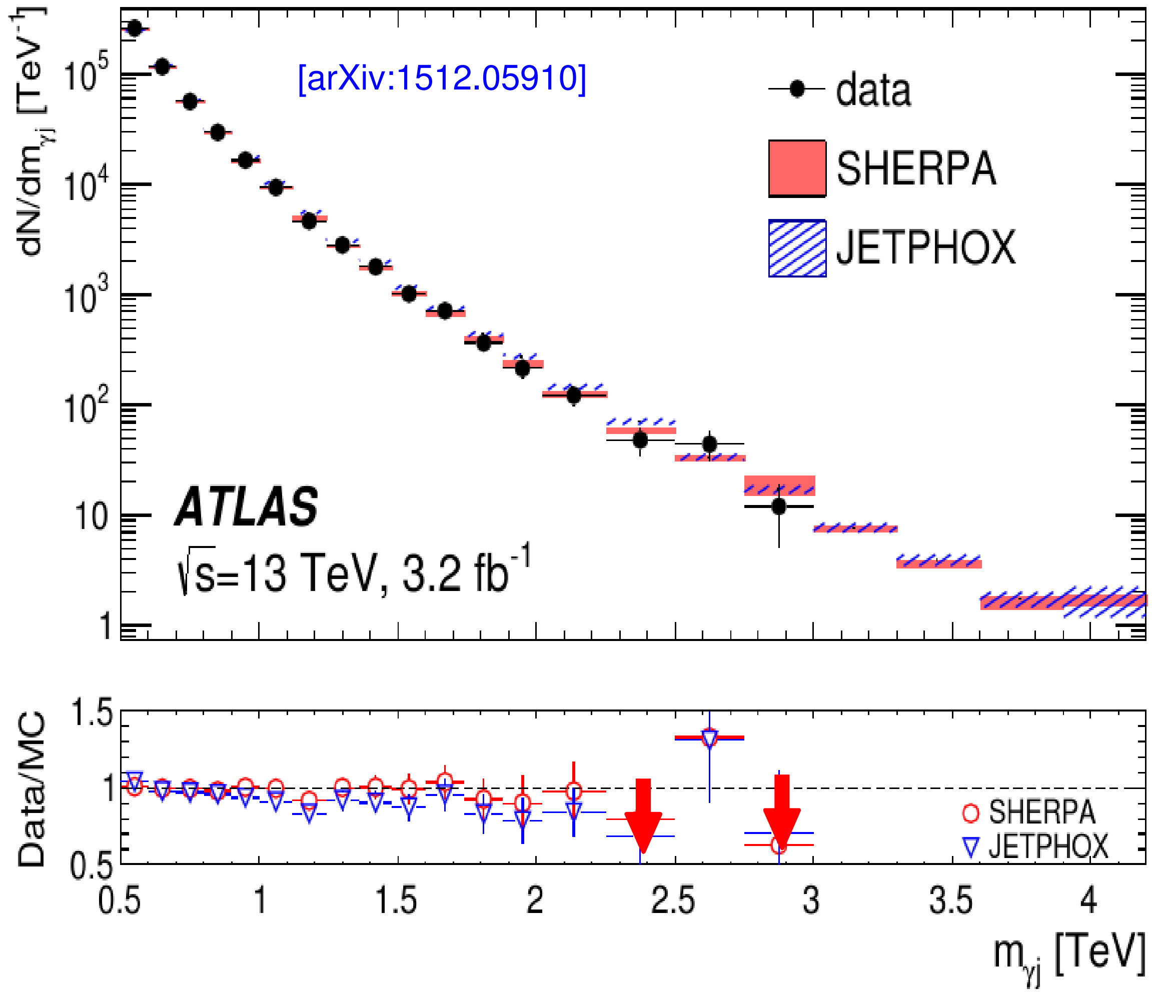


γ+jet x-sections: Role of ewk corrections

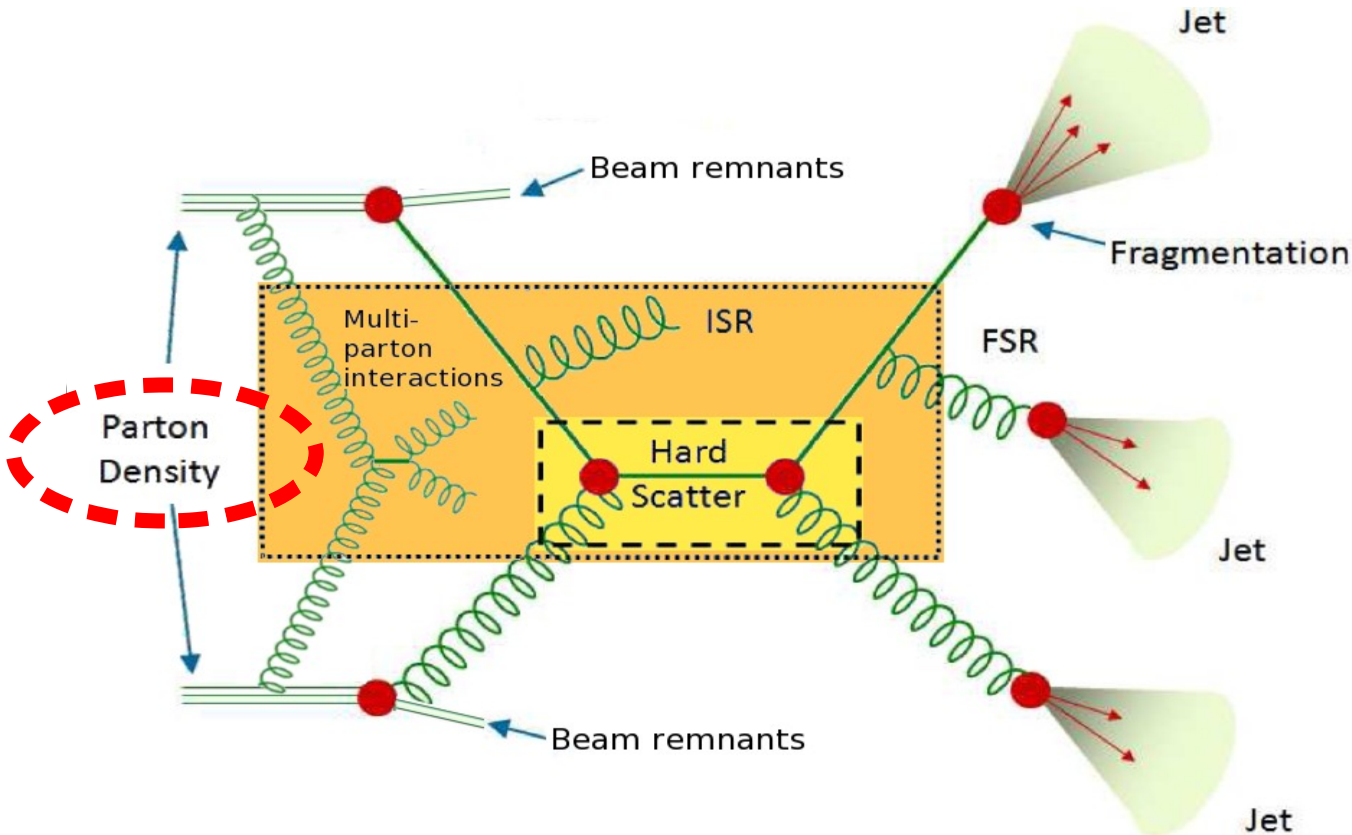
- At high energies, negative W,Z corrections increasingly reduce by O(10-30%) the γ x-sections. Explanation of the data/theory<1 for $m_{\gamma j}$>1.5 TeV?



[J.H.Kuhn et al., JHEP 0603 (2006) 059]

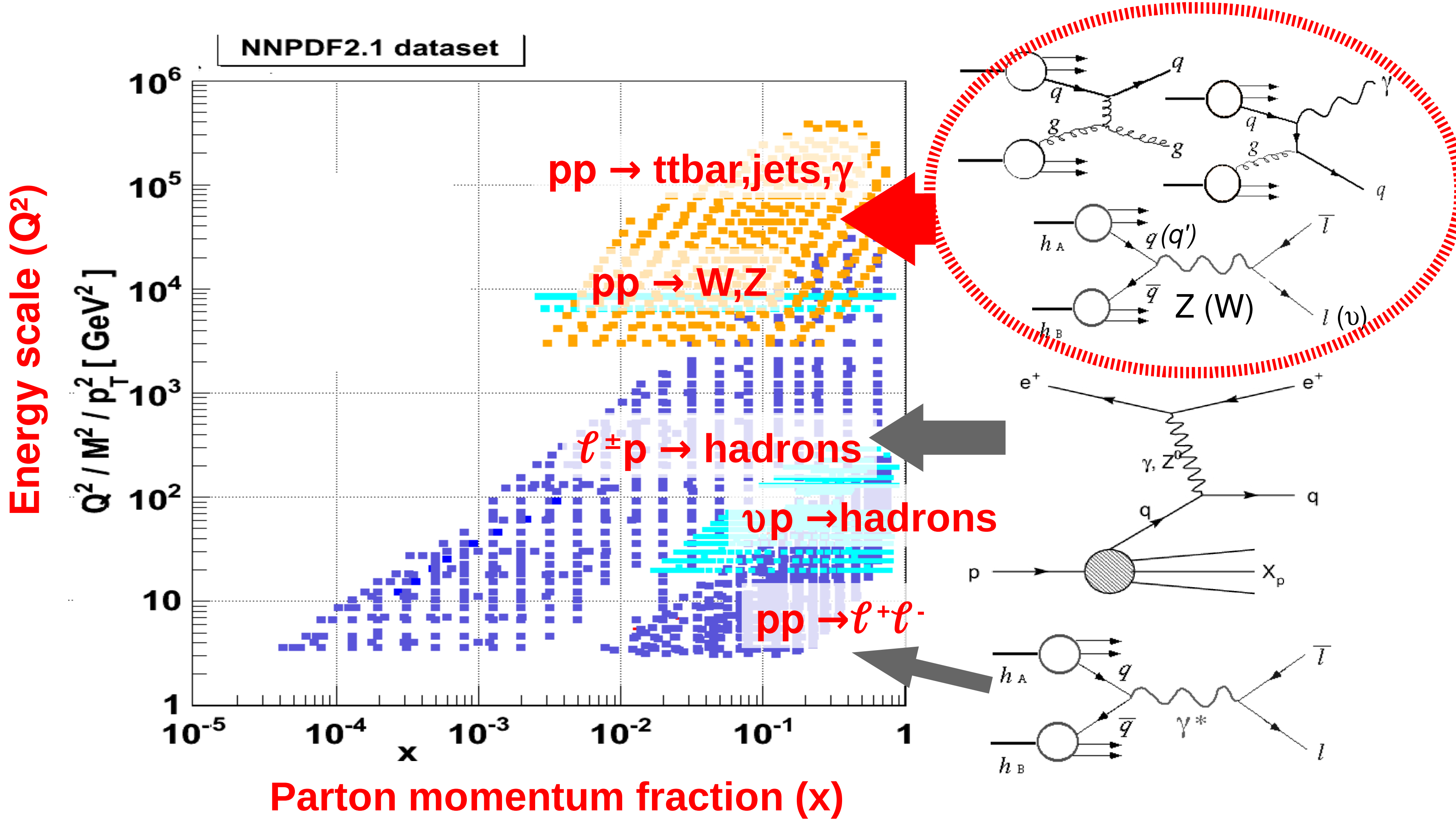


Parton distribution functions



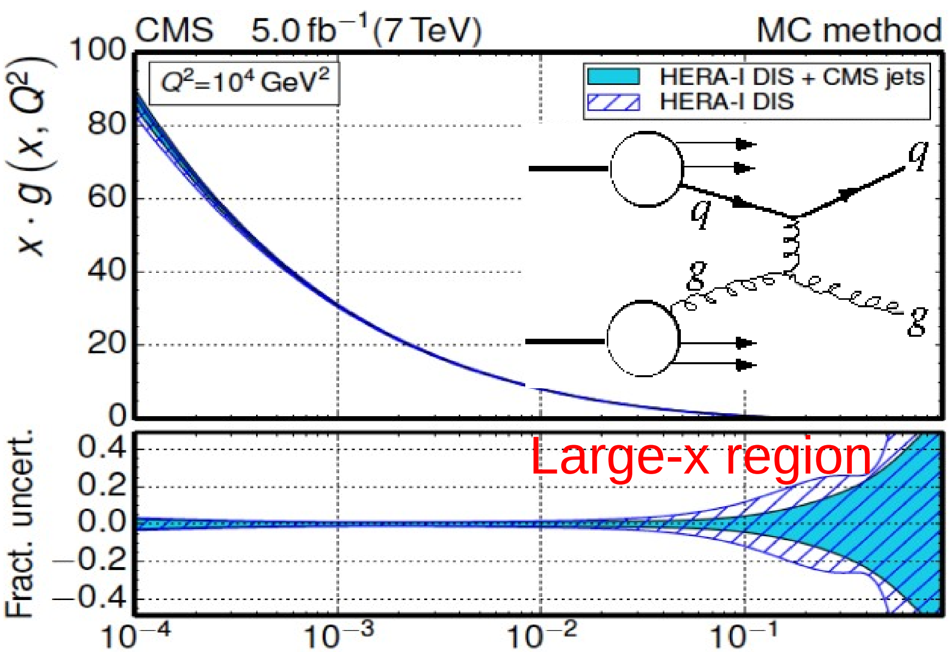
Extraction of PDFs via global fits

- Fixed-target & collider DIS ($\ell^{\pm}$,υ-p) and p-p data: $\sigma_{data} \sim \sigma_{partons} \otimes PDF_{(fitted)}$

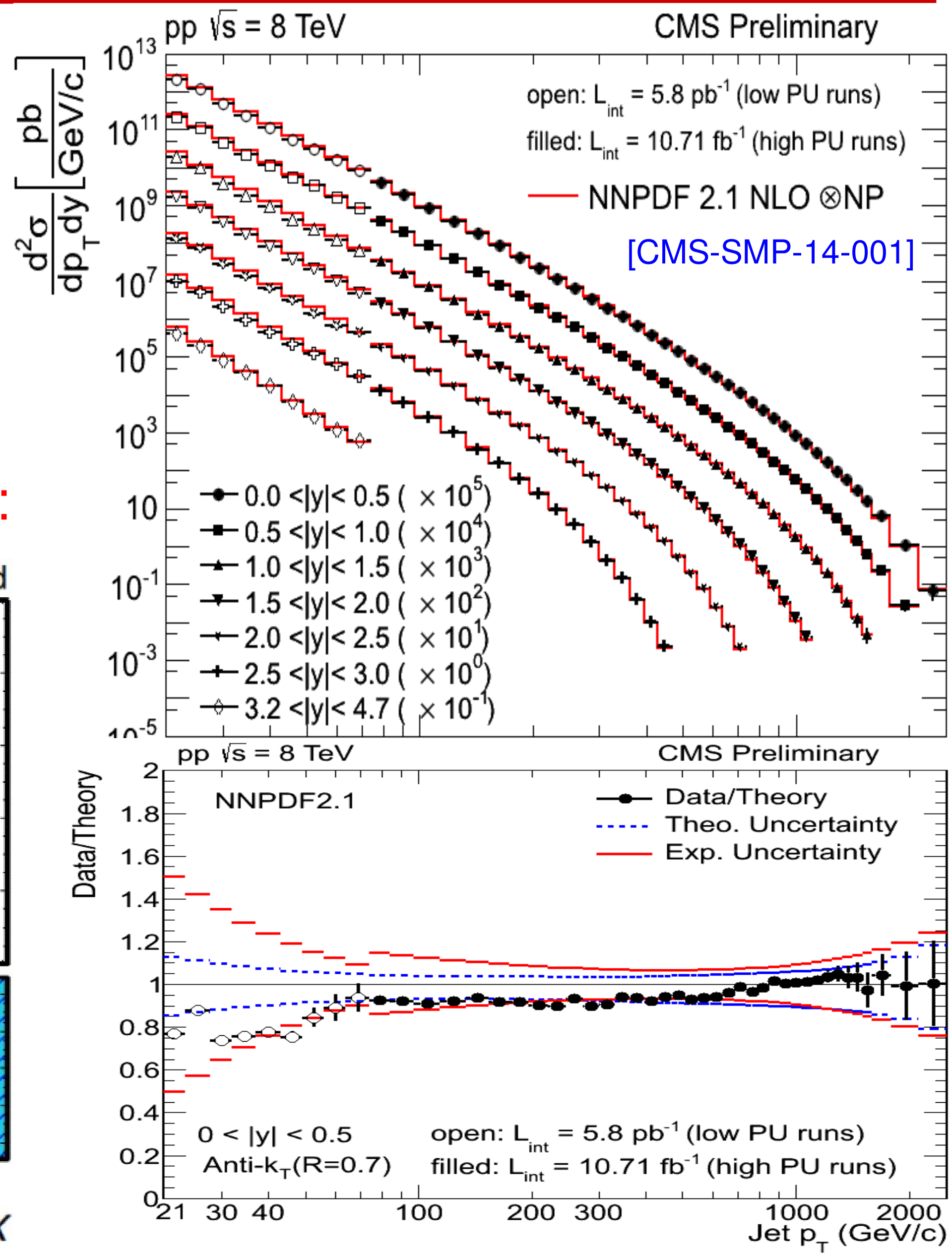


Gluon PDF constraints from jets

- Inclusive jet p_T spectra:
  p_T = 20 GeV up to 2–3 TeV
  Exp. uncertainty: ~10% (JES)
- NLO pQCD describes data over 14 orders-magnitude !
- Improved knowledge of gluon PDF:

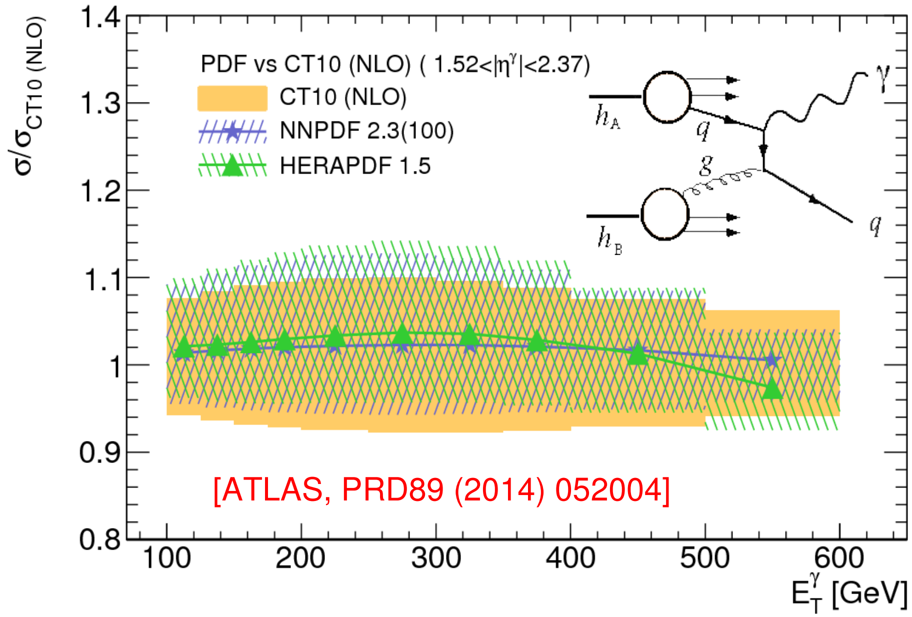


[CMS,EPJC 75 (2015) 186]



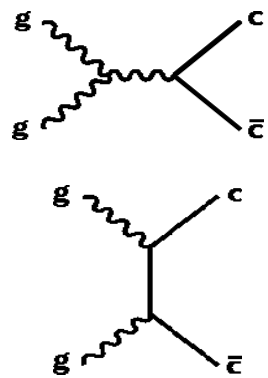
Gluon PDF constraints from γ, charm, t-tbar

- Isolated photon p_T spectra:

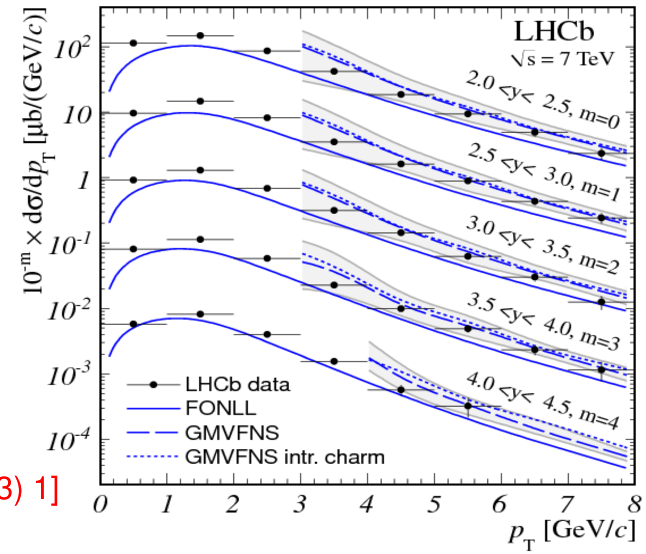


[ATLAS, PRD89 (2014) 052004]

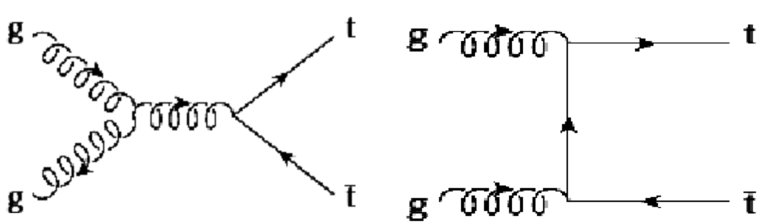
- Forward D-mesons (LHCb):

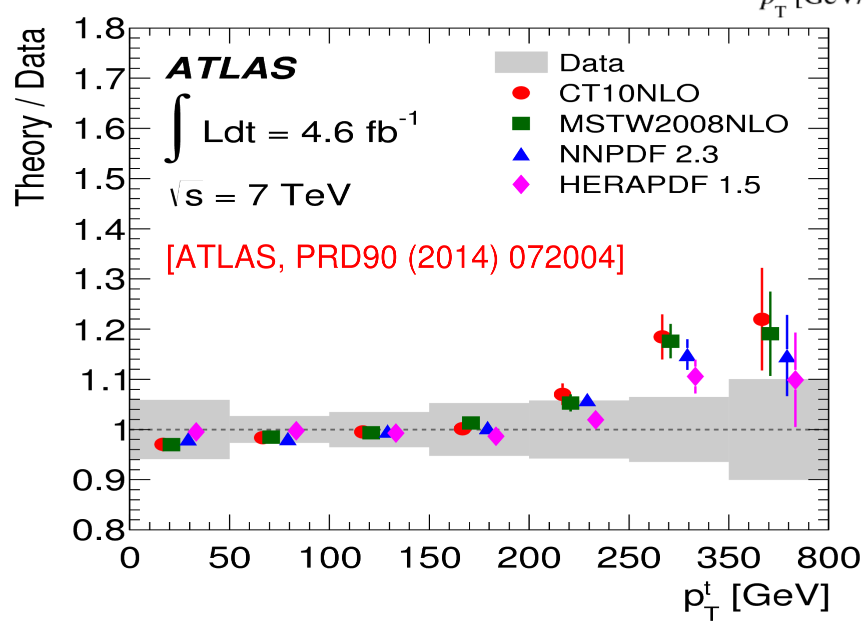


[NPB 871 (2013) 1]



- Top-pair differential x-sections (NNLO):





[ATLAS, PRD90 (2014) 072004]

Gluon PDF constraints from γ, charm, t-tbar

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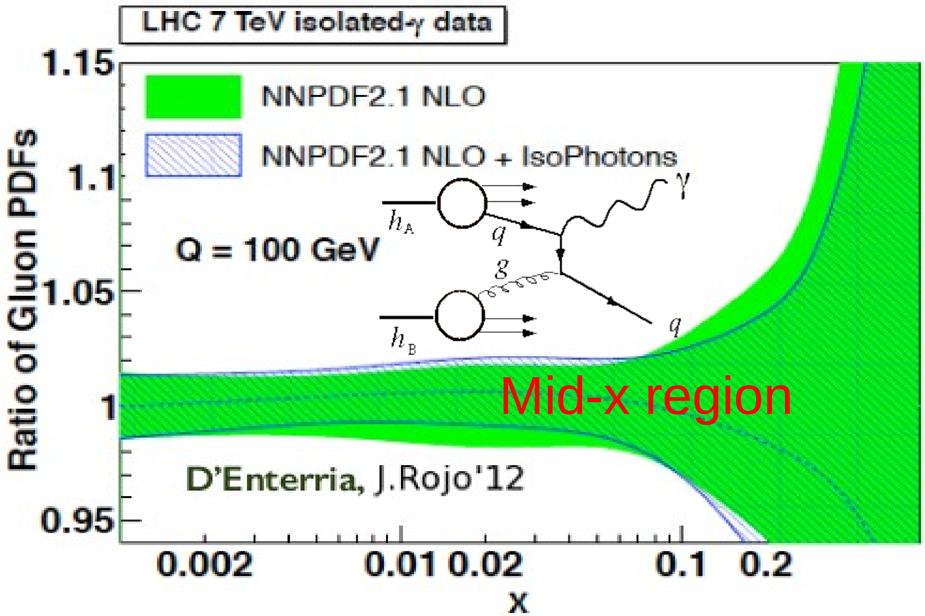

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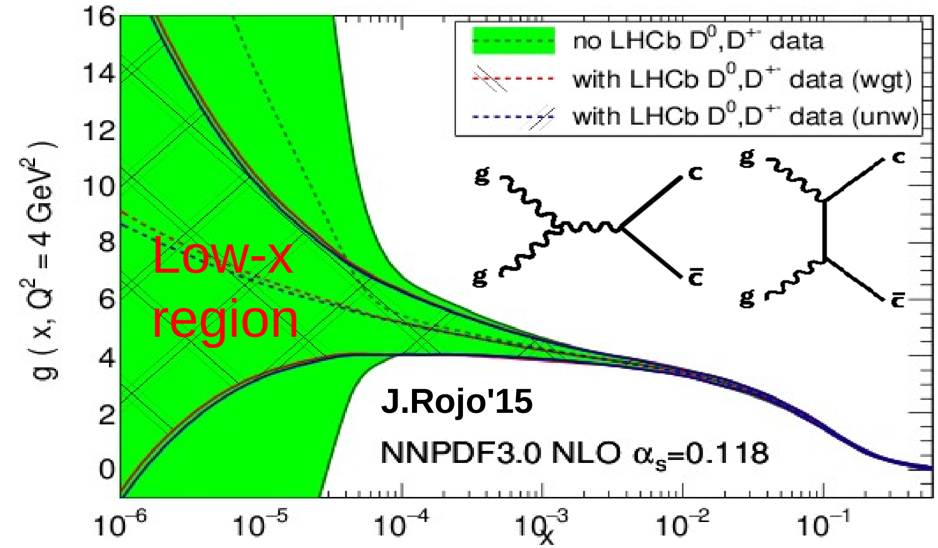

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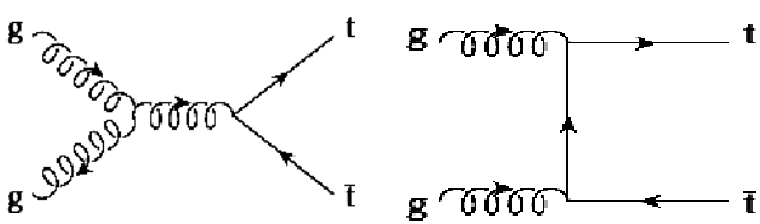
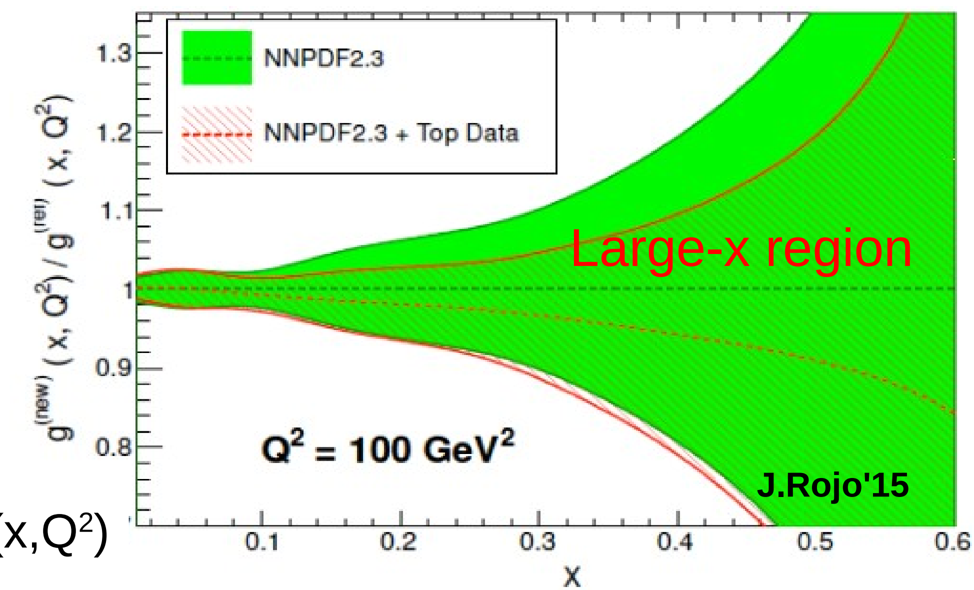
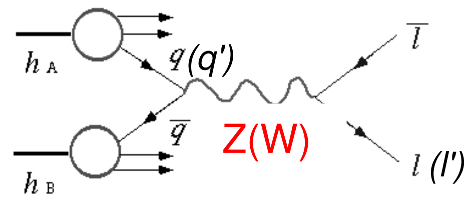


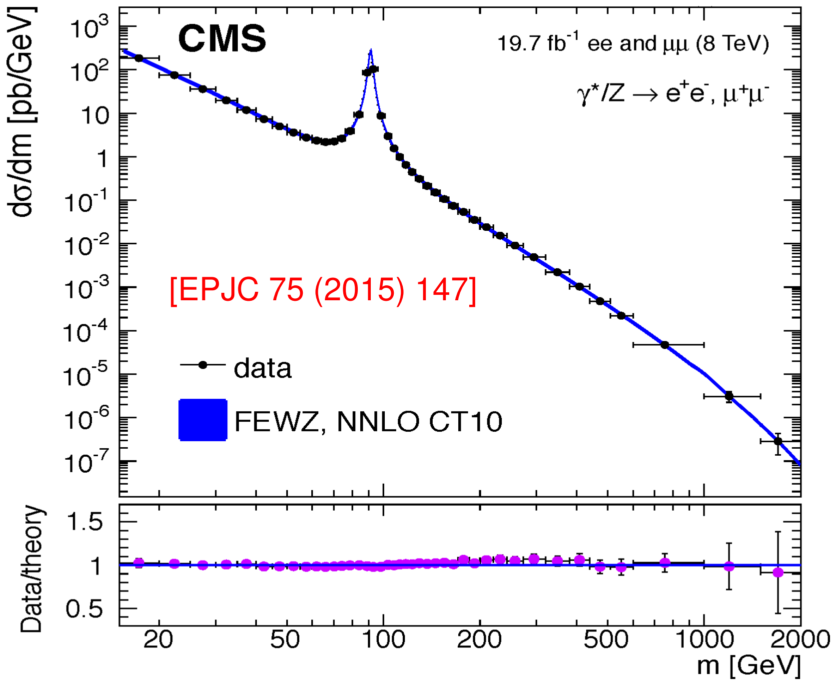


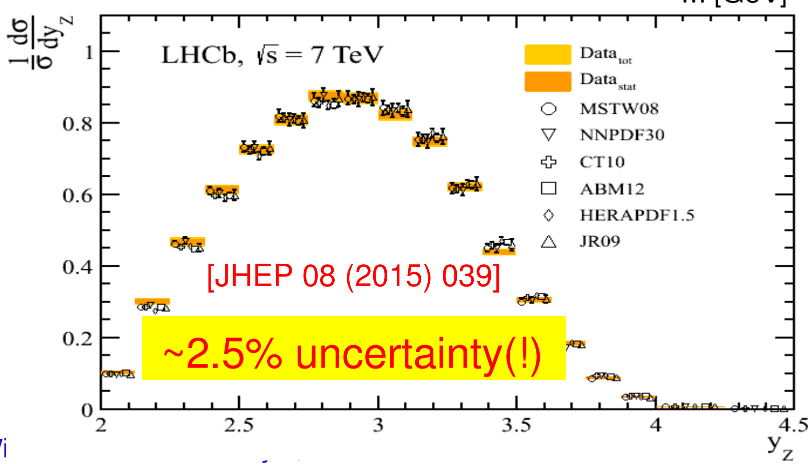
- Reduced gluon uncertainties at different (x,Q^2)

Quark PDF constraints from W, Z “std. candles”

- Differential DY+Z x-section in accord with NNLO over 9 orders-of-magnitude & forward:

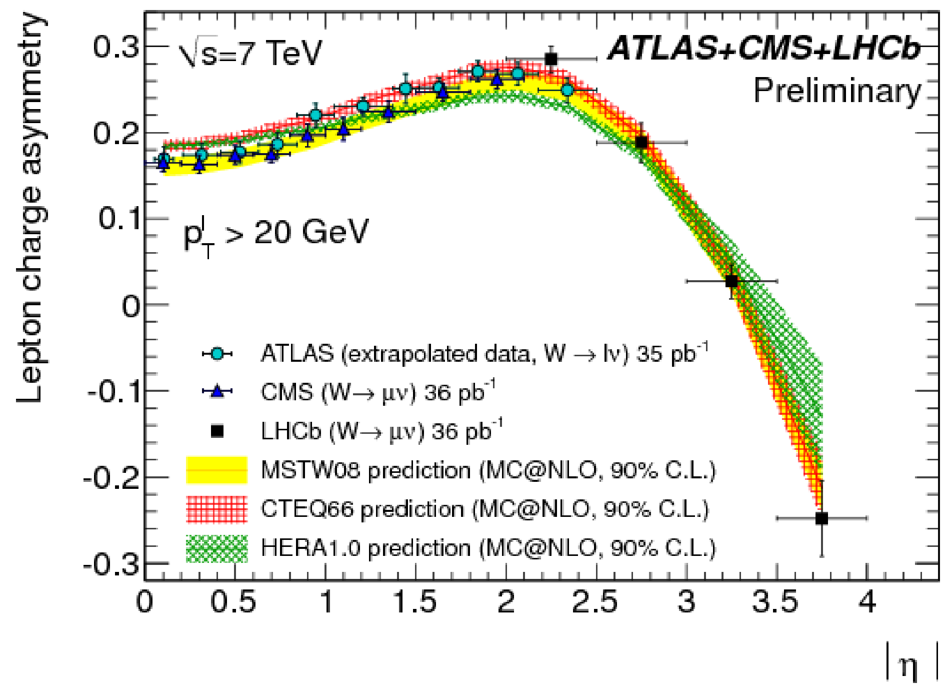






- W electron charge asymmetry vs |η| measured to ~1%. Many uncertainties cancel in ratio. Constrains u/d PDF ratio

$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$



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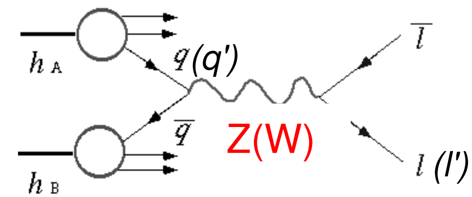

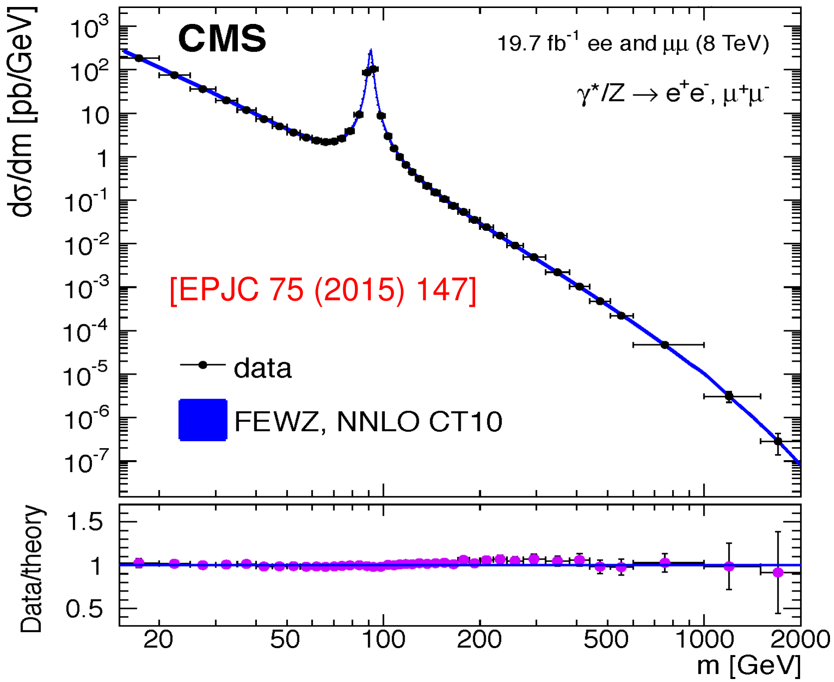

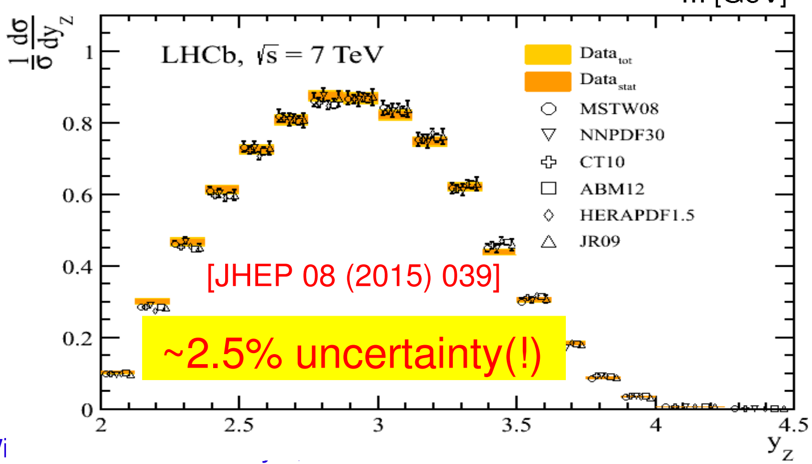

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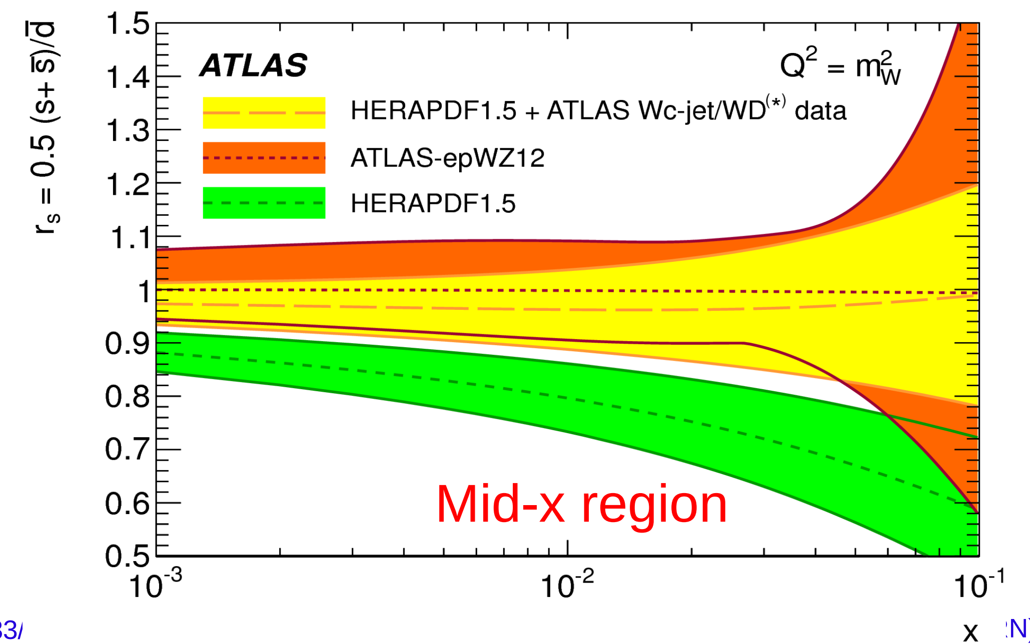

Quark PDF constraints from W, Z "std. candles"

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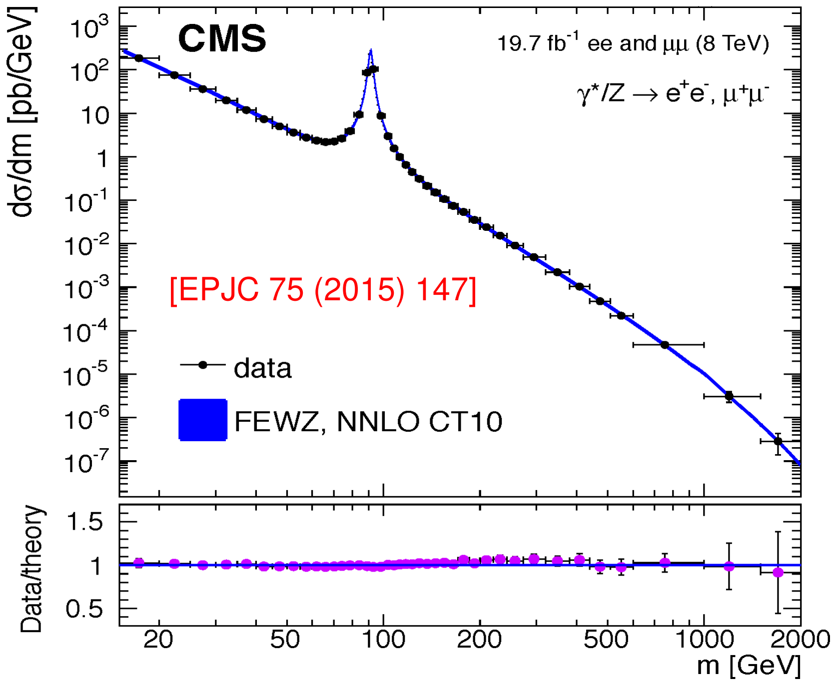

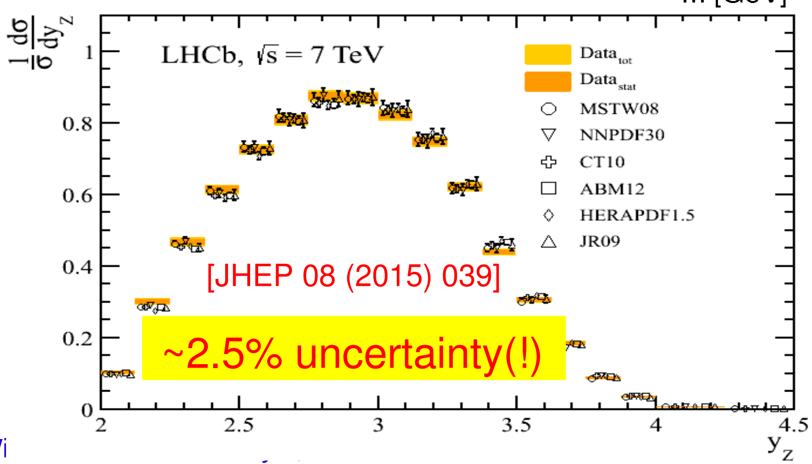

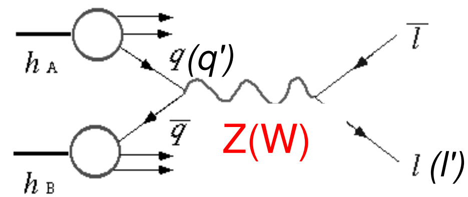

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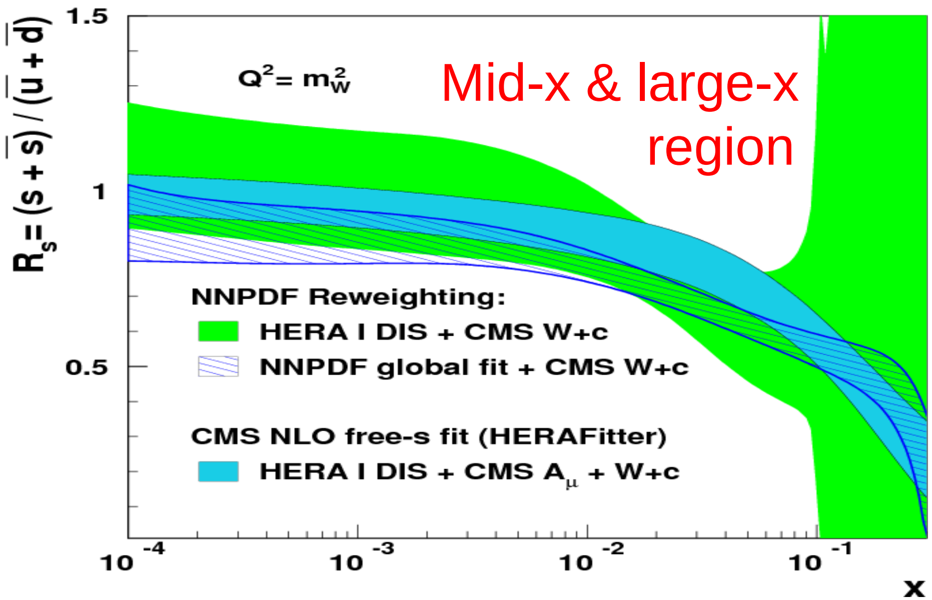


Updated PDF sets with LHC Run-1 data

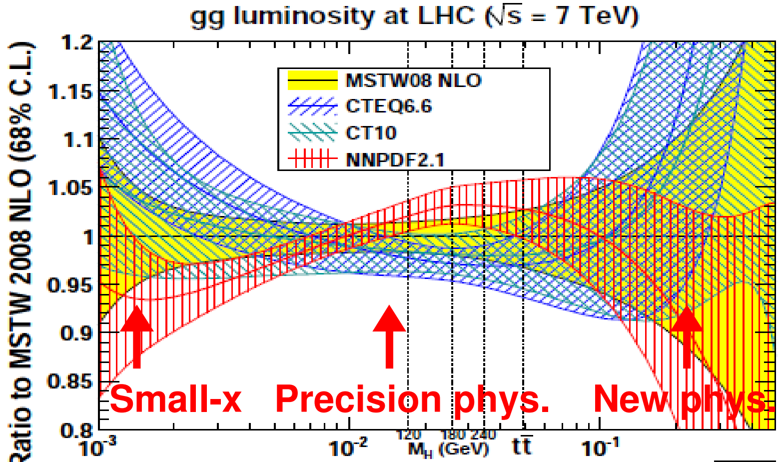
- Run-1 data constraints: New generation PDFs (global fit) for Run-2:

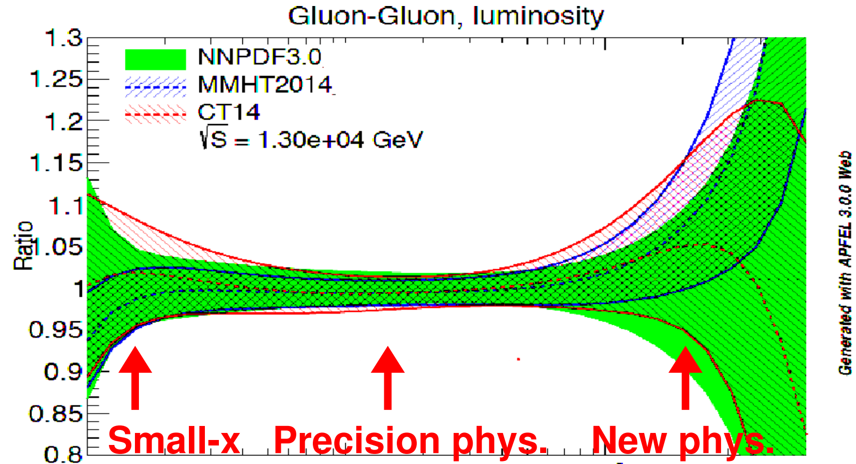
  NNPDF2.0 → NNPDF3.0   MSTW08 → MMHT14

  CT10 → CT14   HERAPDF1.0 → HERAPDF2.0

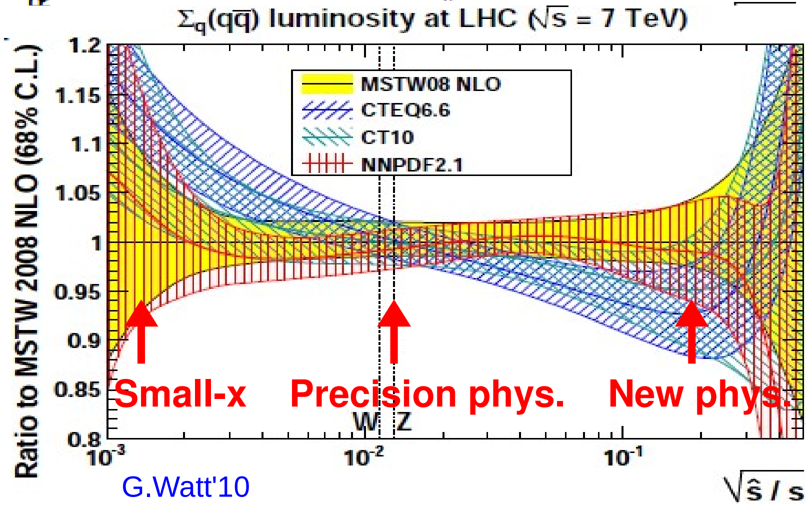
- Parton-parton luminosities pre- and post-LHC Run-1:

GLUONS

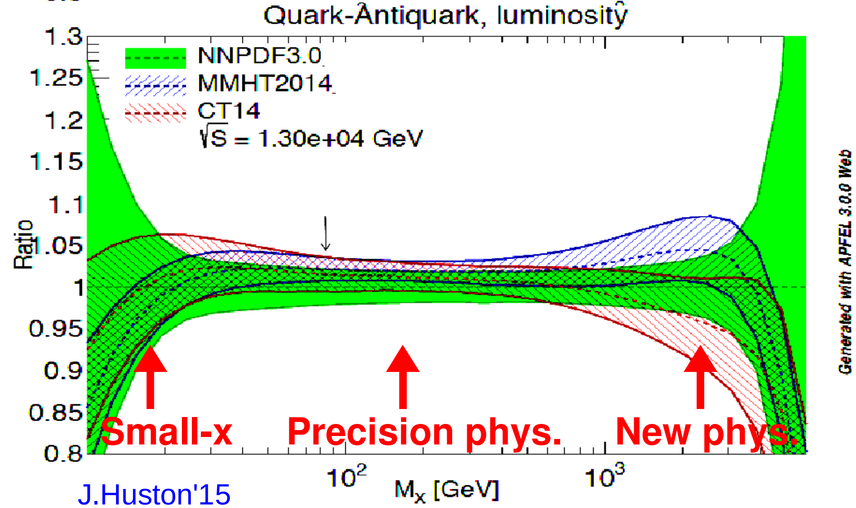




QUARKS

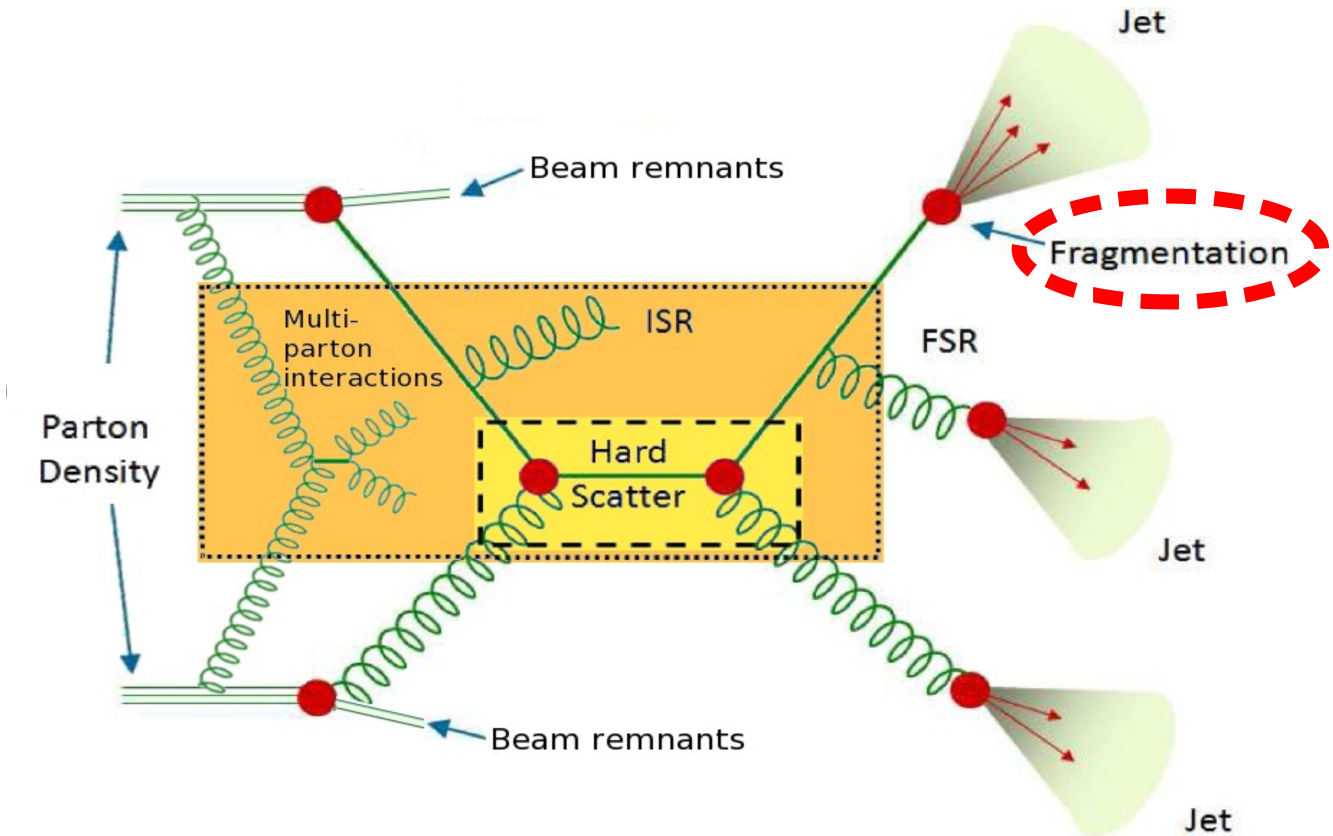


G.Watt'10



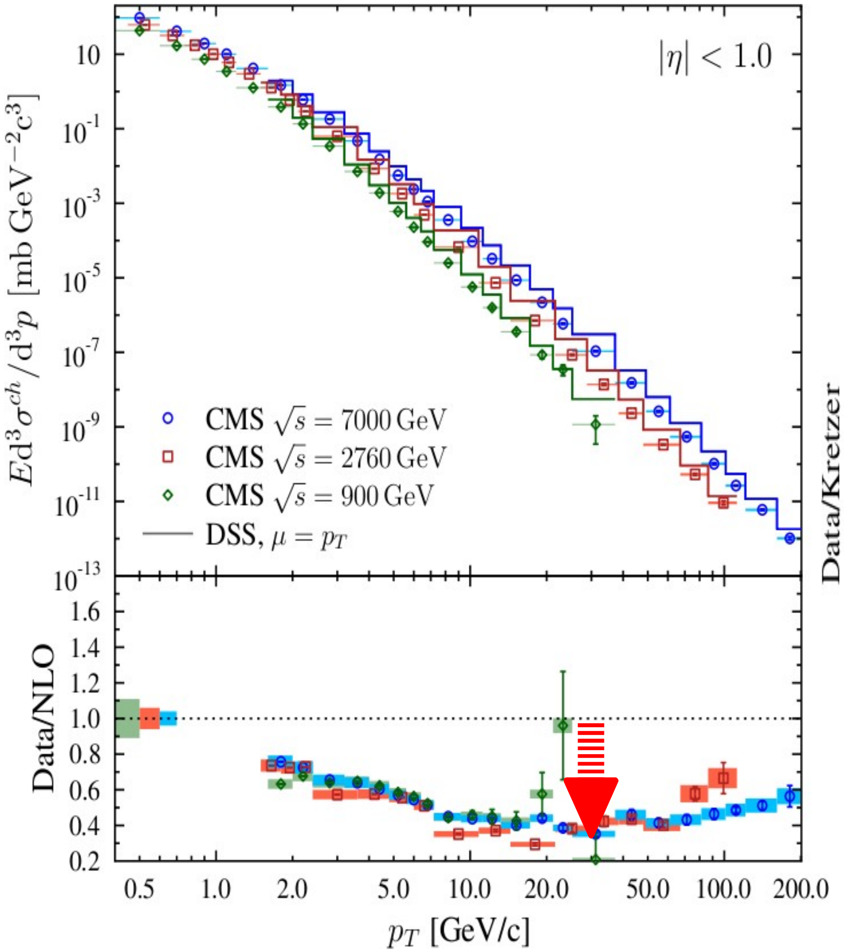
J.Huston'15

Parton fragmentation functions



High-p_T hadron spectra vs. NLO

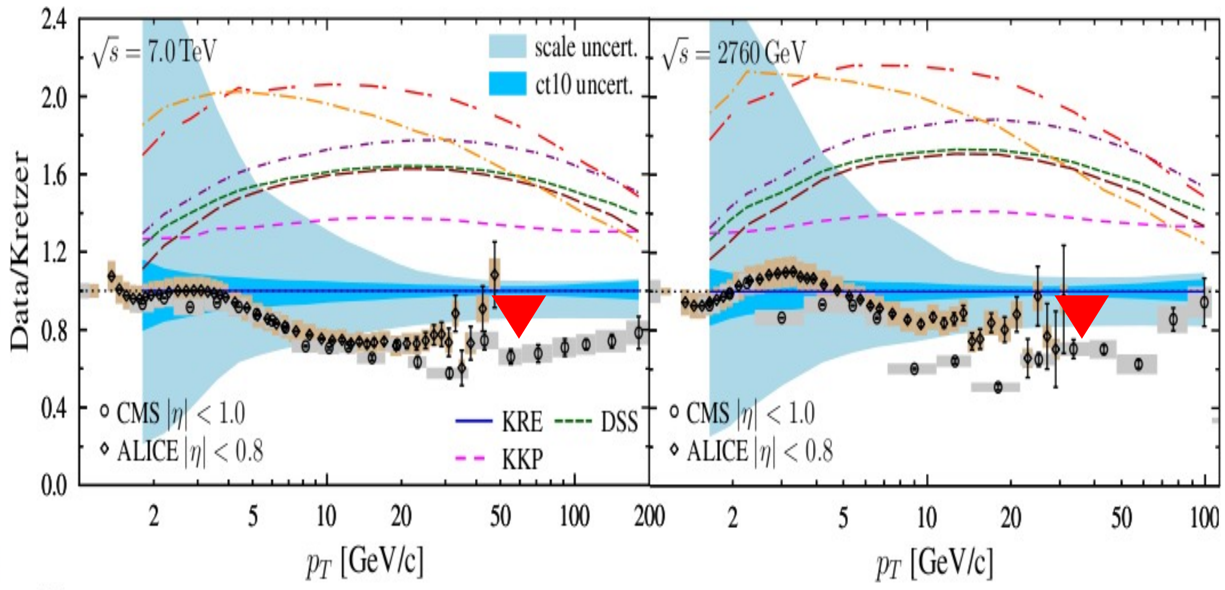
- NLO pQCD overpredicts high-p_T hadron cross sections by factor ×2:



- All Fragmentation Functions (FFs) fail.

  Disagreement increases from √s=0.9 to 7 TeV

- "Old" Kretzer FF shows best agreement:



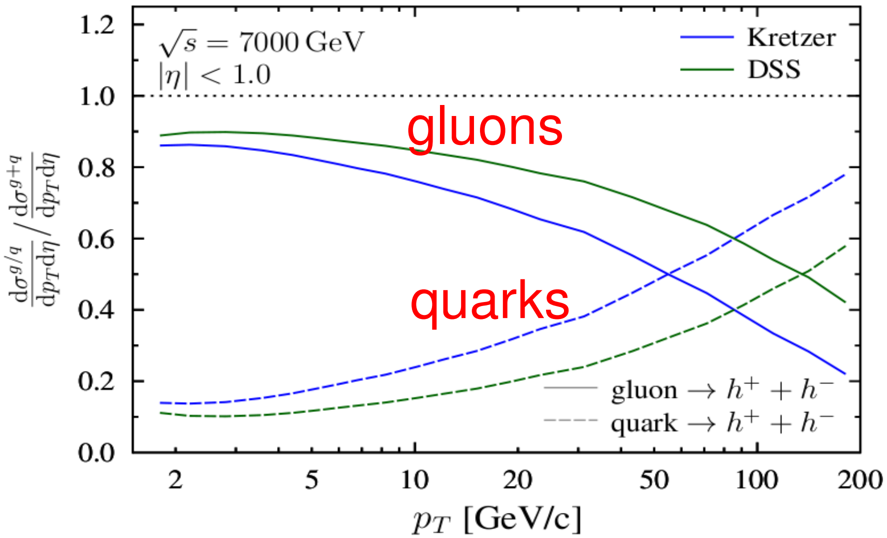
[Dd'E et al, NPB883 (2014) 615]

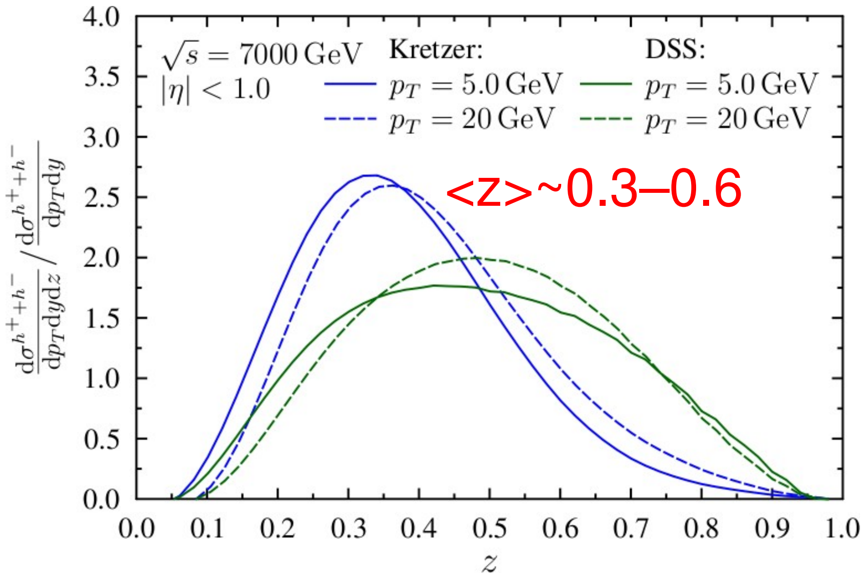
- Same NLO calculations reproduce well high-p_T jet and photon spectra:

  Problems in current parton-to-hadron FFs obtained from $e^+e^- \rightarrow$ hadrons data.

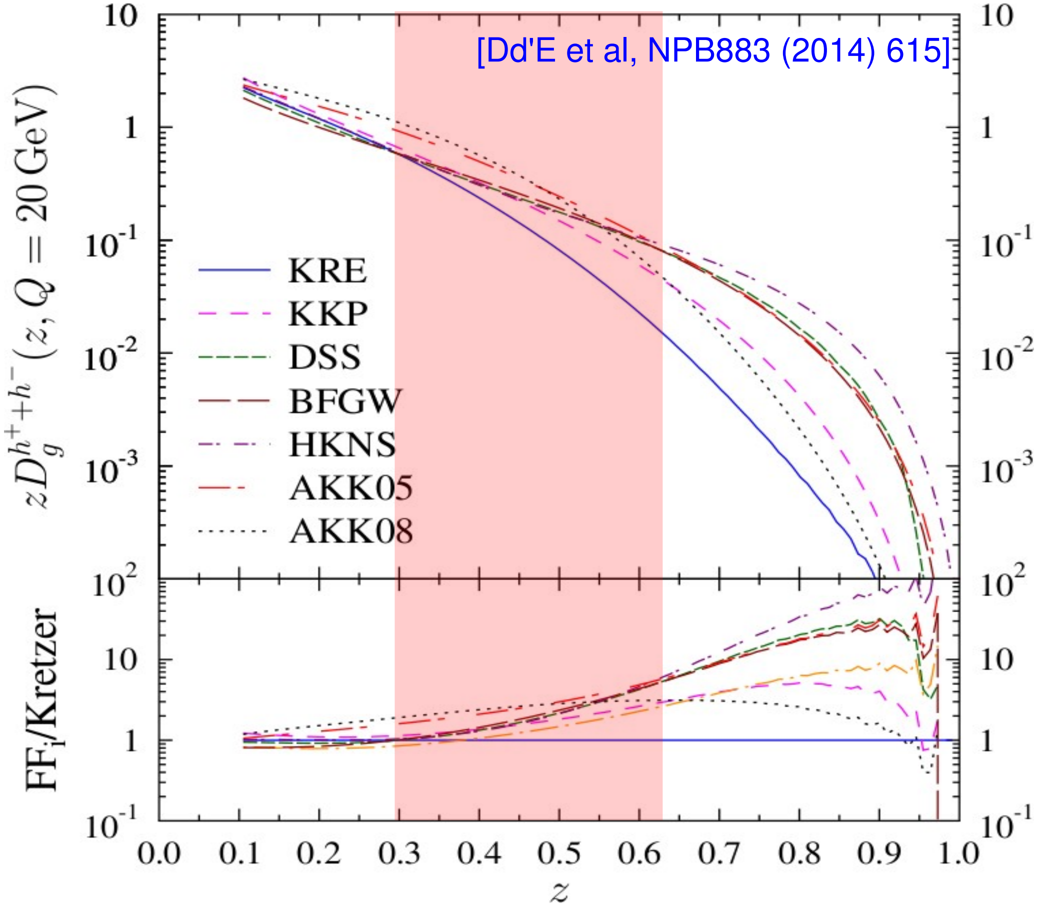
Badly-known gluon-to-hadron FFs

- **Dominant gluon** production&fragmentation **up to p_T~50 GeV** with **<z>~0.3–0.6**





Very large differences on gluon-to-hadron FFs

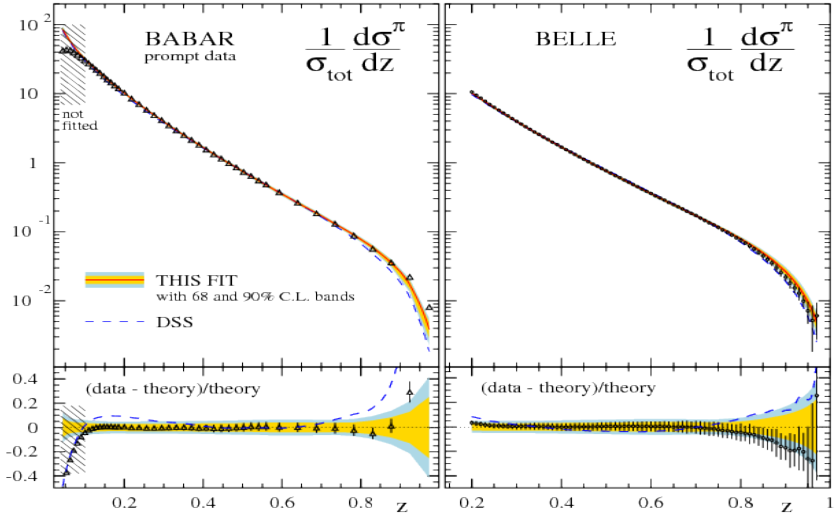


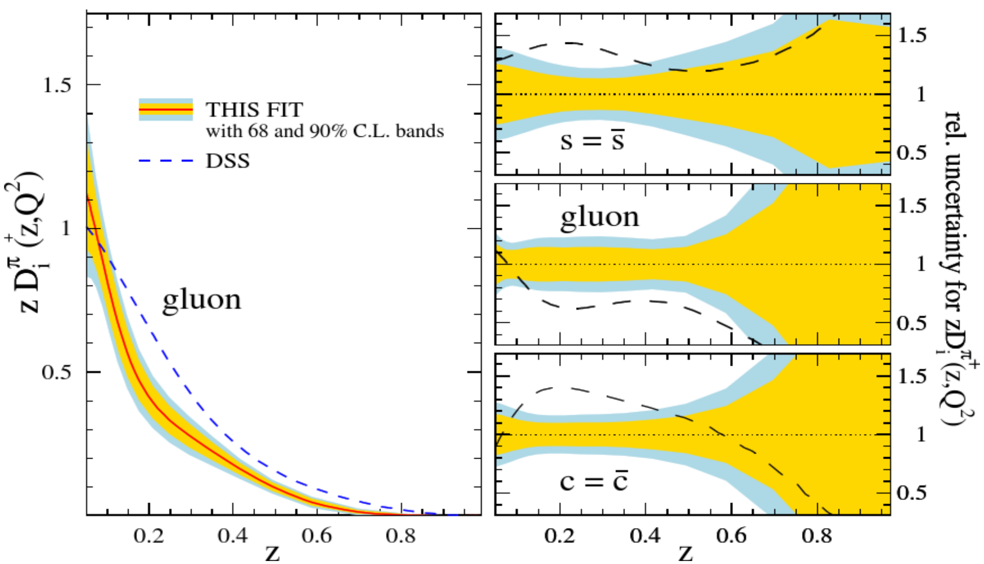
- Current NLO **gluon FFs are too hard**. Need to **refit them** with newer data.

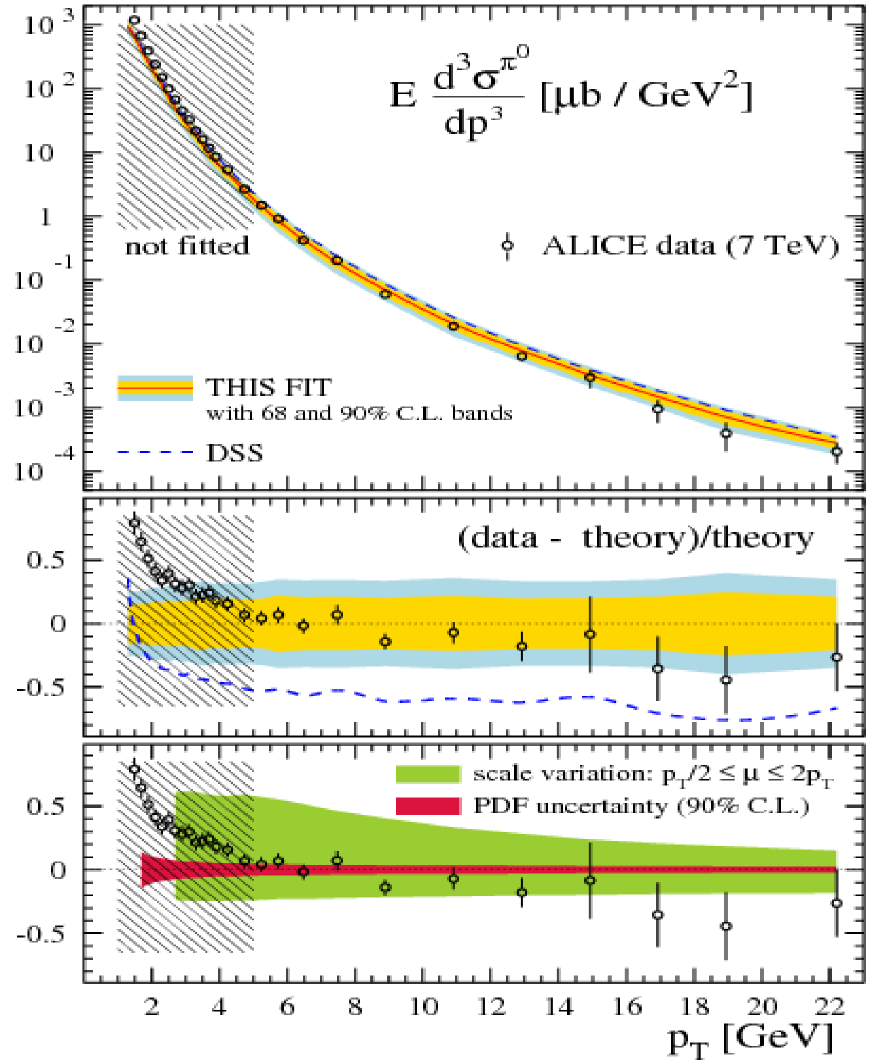
Improved gluon-to-hadrons FFs

- Refitting of recent BaBar/Belle $e^+e^- \rightarrow$ hadrons data yields softer FFs & better agreement with high-p_T LHC hadron spectra:

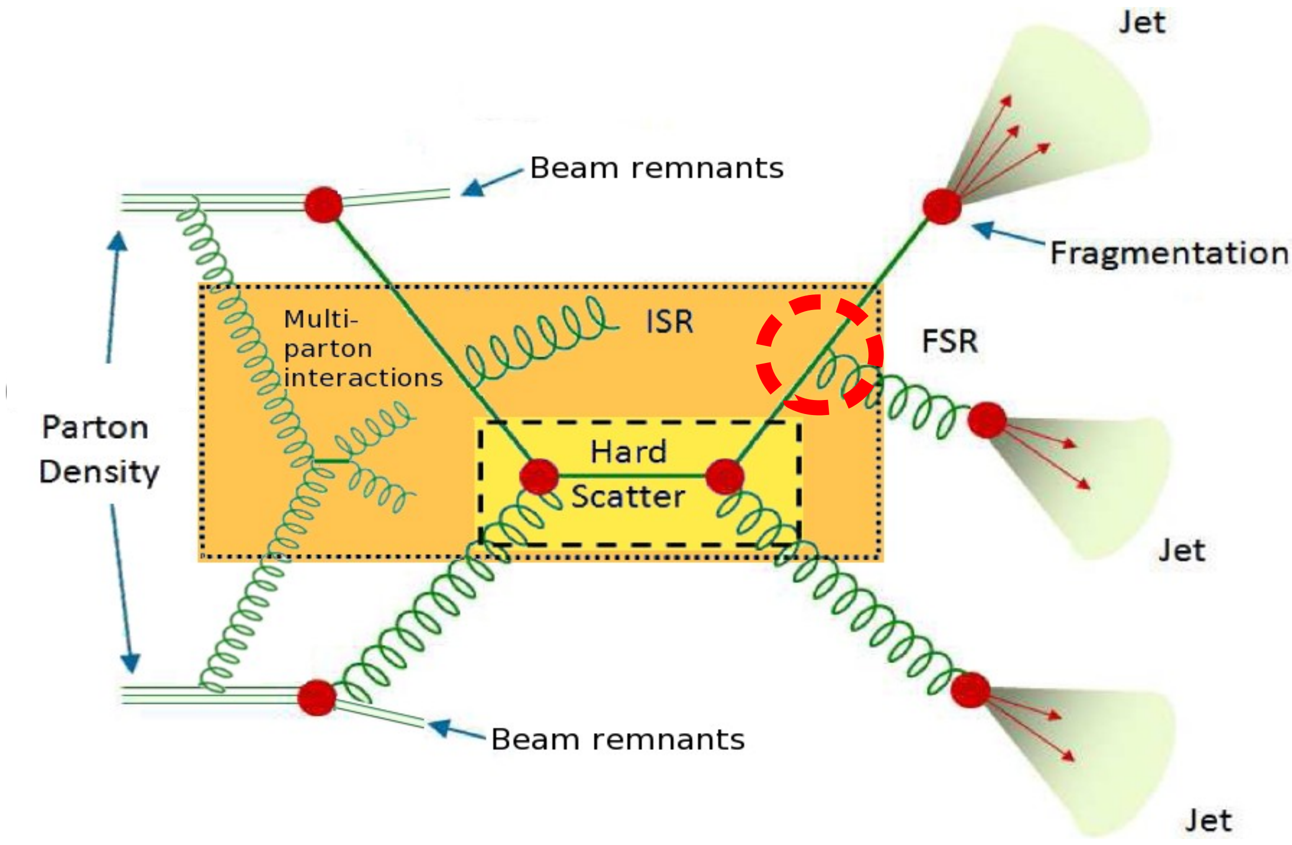
[DeFlorian et al, PRD91 (2015) 014035]







Strong coupling determination

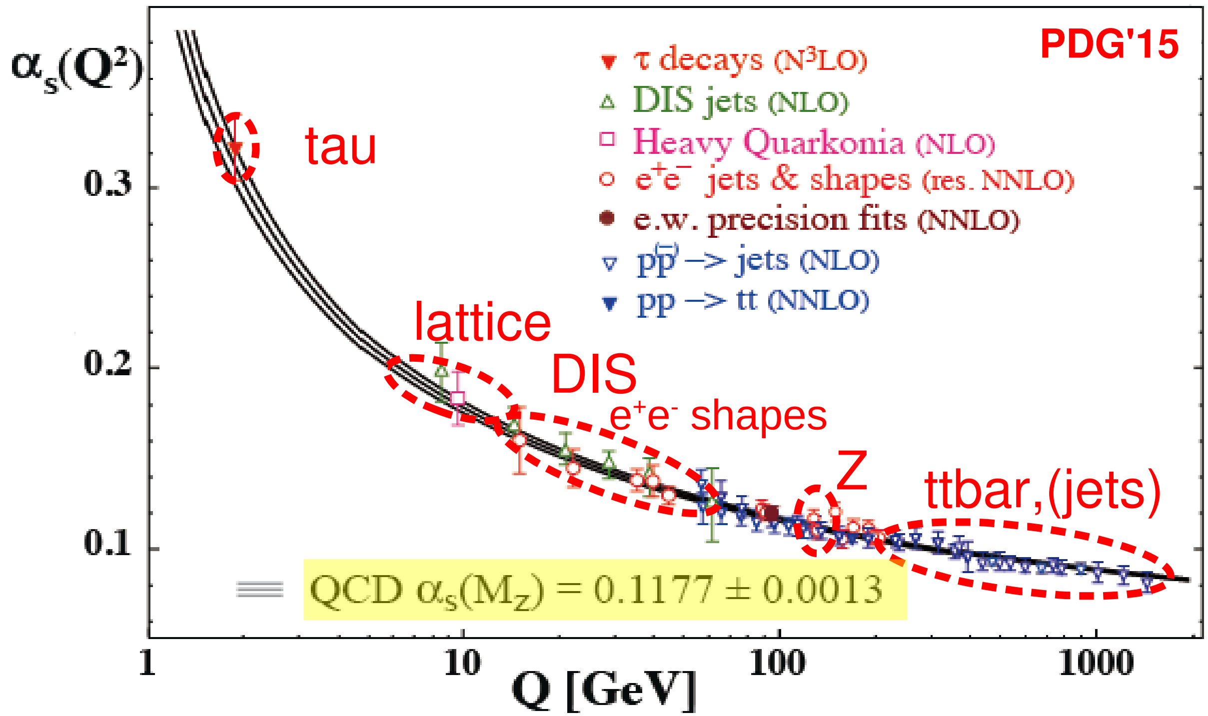


Determination of the QCD coupling α_s

α_s = Single free parameter in QCD (in the $m_q \to 0$ limit). Determined at a given reference scale (usually m_Z). Decreases as $\sim 1/\ln(Q^2/\Lambda^2)$, with $\Lambda \sim 0.25$ GeV

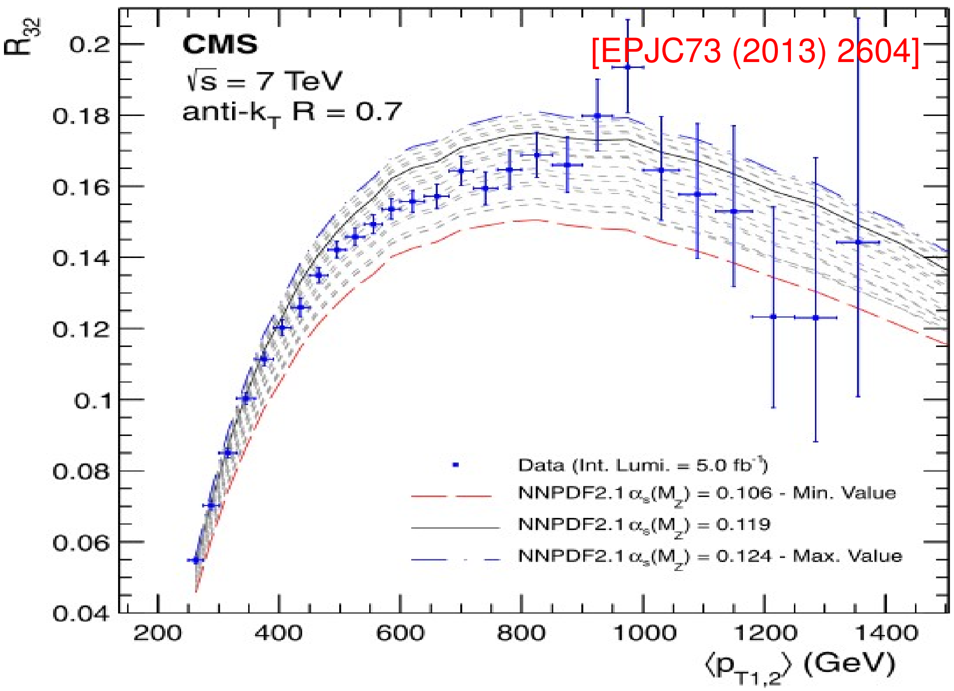
- Least precisely known of all couplings: $\delta\alpha_s \sim 1\%(!)$, $\delta\alpha \sim 3\cdot10^{-10}$, $\delta G_F \sim 5\cdot10^{-8}$, $\delta G \sim 10^{-5}$
- Impacts all LHC cross-sections.
- Key for precise SM studies. Uncertainties: ±4% σ(ggH), ±7% H→cc, ±4% H→gg
- BSM physics (e.g. new coloured sectors).

- Determined through comparison of various experimental (ee, ep, pp) observables to associated pQCD predictions at NNLO accuracy.

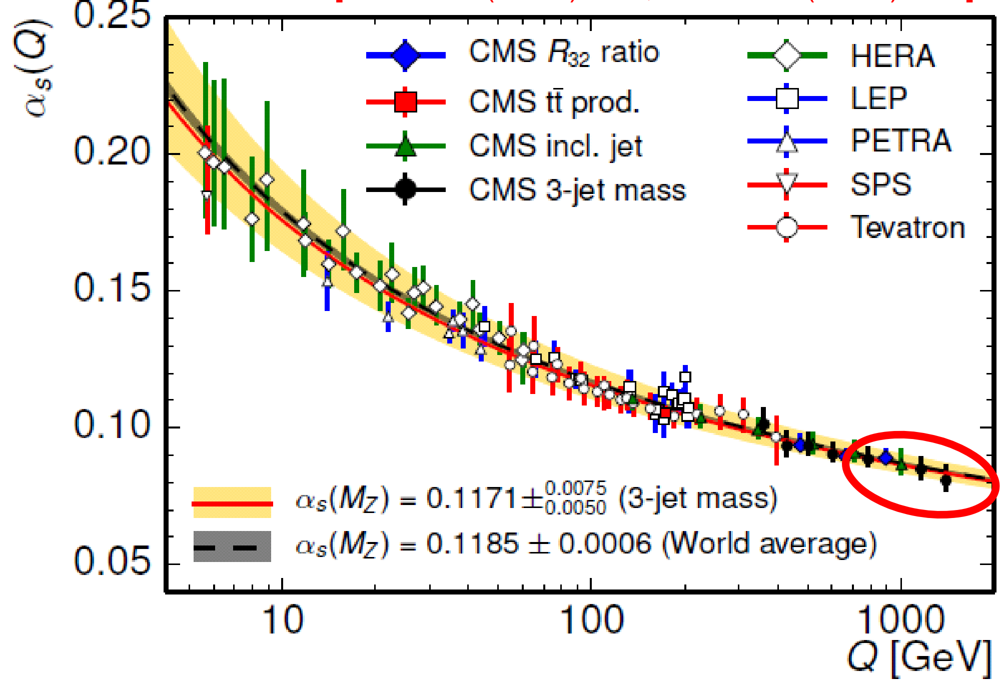


QCD coupling from jet observables (CMS)

- Ratio of 3-jets of 2-jets, 3-jet mass & inclusive jets x-sections constrain α_s (at NLO accuracy only) up to so-far unprobed scales Q ~ 1.4 TeV:



[EPJC 75 (2015) 288, EPJC 75 (2015) 186]



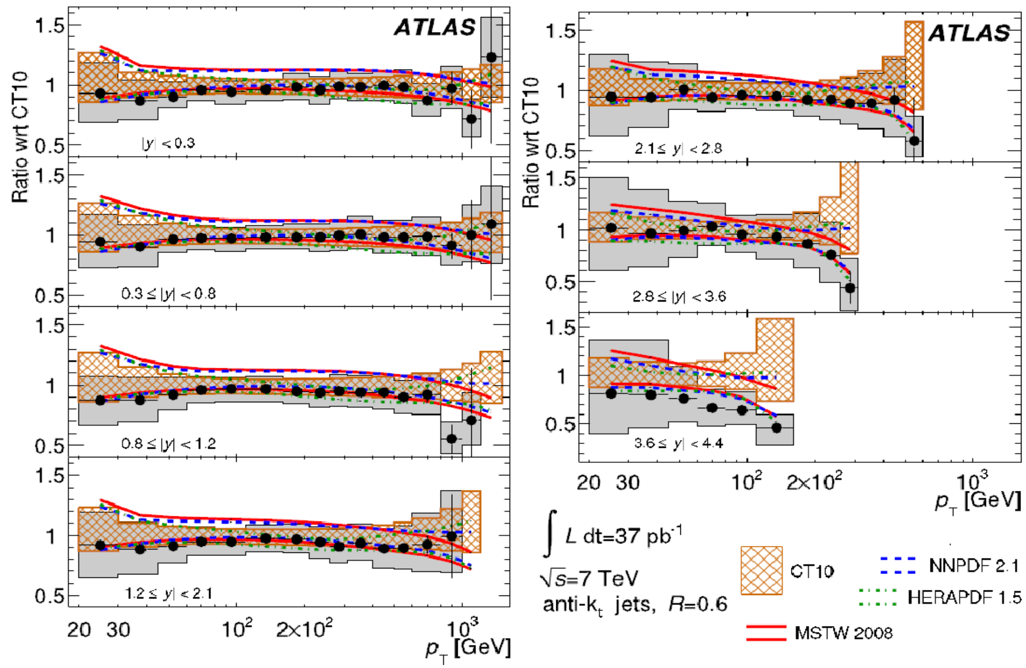
$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF}) \pm 0.0050\,(\text{theory})$$

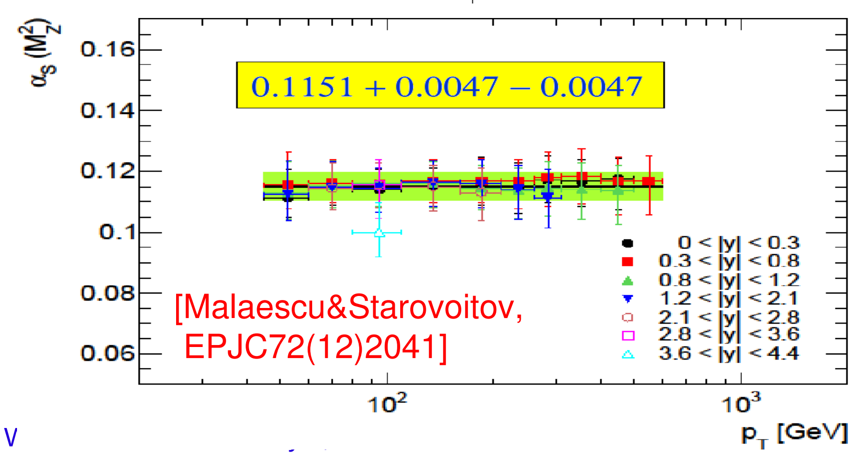
$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp})\,^{+0.0060}_{-0.0037}\,(\text{theo})$$

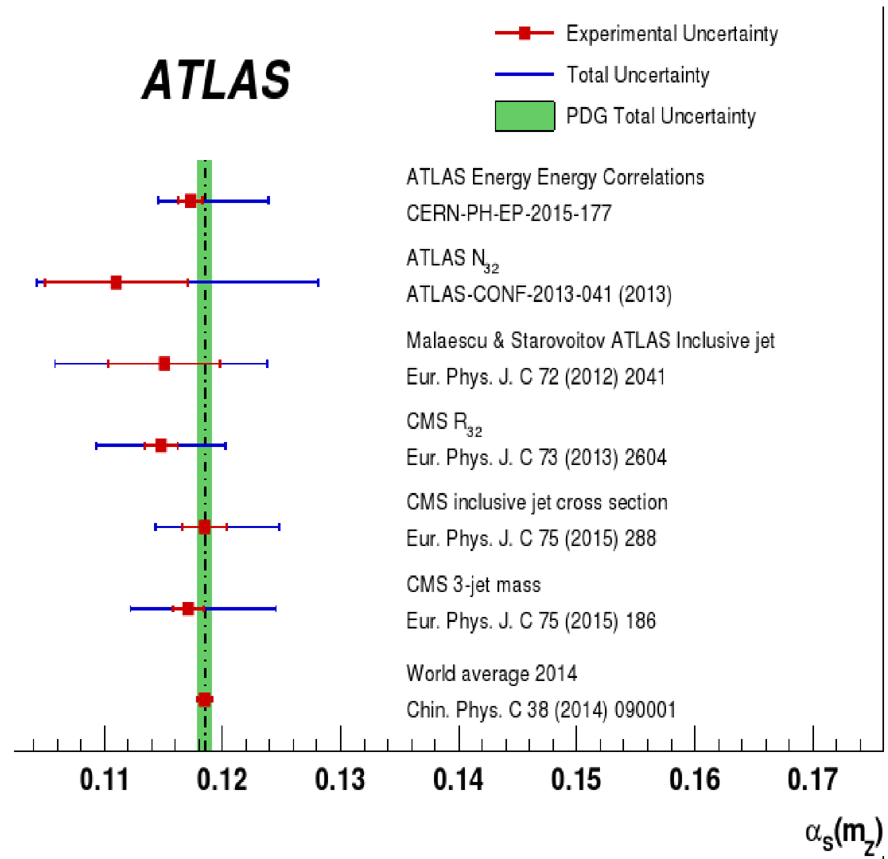
- Measurements dominated by TH uncertainty: PDF & (asym.) scale uncertainty.

QCD coupling from jet observables (ATLAS)

- Ratio of 3-jets of 2-jets, 3-jet mass & inclusive jets x-sections as well as angular correlations in multijet events constrain α_s (at NLO accuracy):





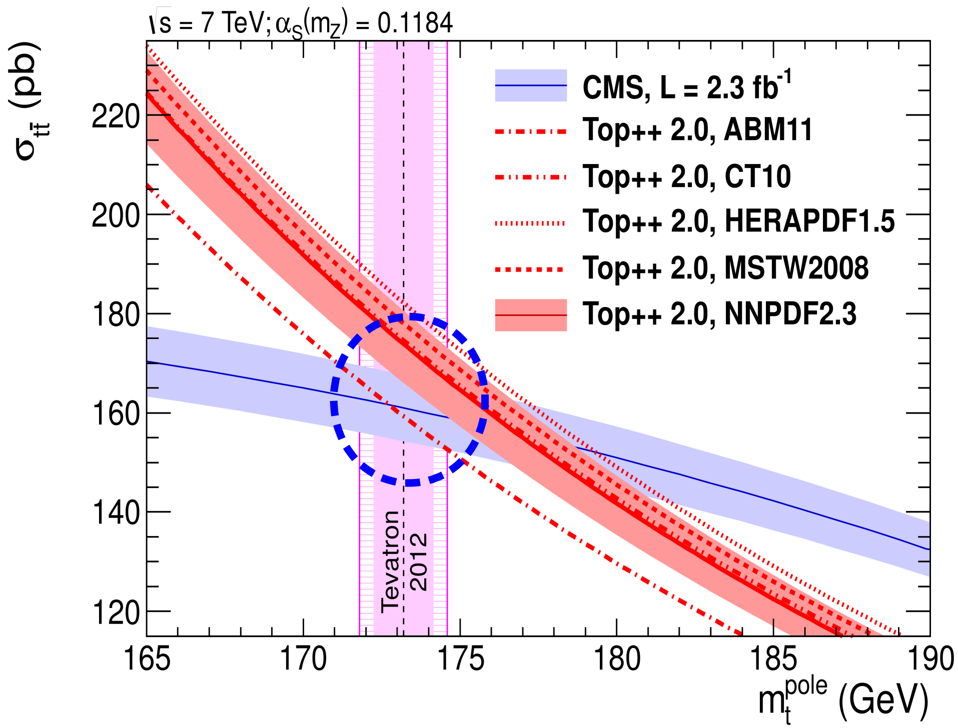


Upcoming jet x-sections NNLO calculations will provide improved α_s extractions.

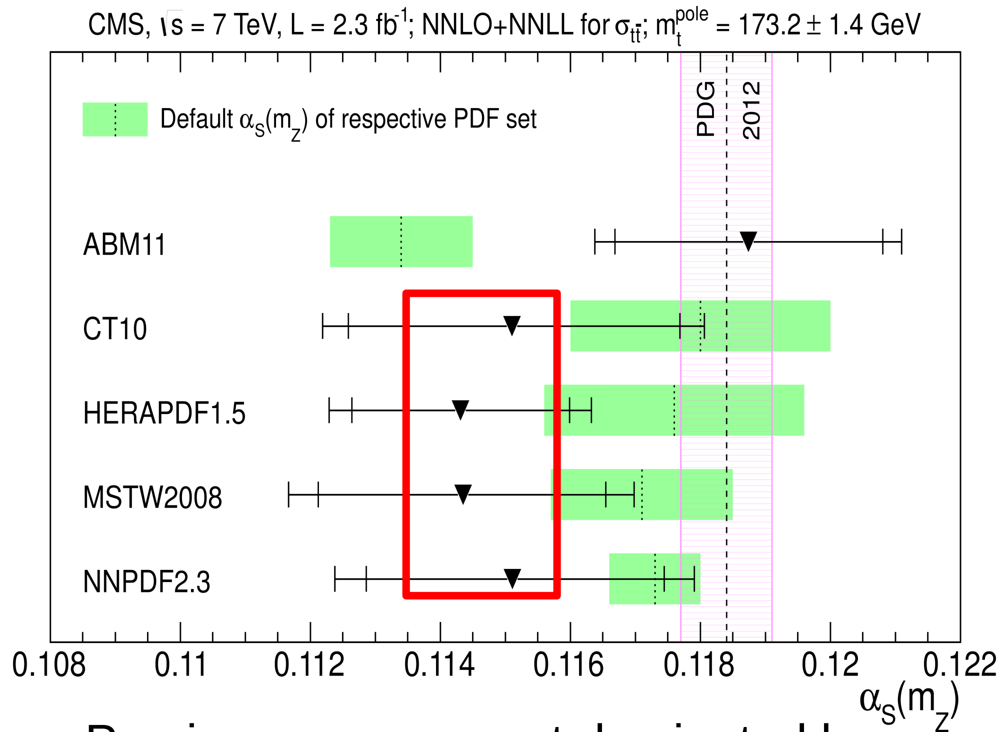
QCD coupling from t-tbar cross sections

- Total top-antitop cross section (theoretically known at NNLO+NNLL) is the 1st p-p collider observable to constrain α_s at NNLO accuracy:

Data-theory x-section comparison for varying PDF+α_s as a function of m_{top}:



[CMS, PLB 728 (2014) 496]



Precise measurement dominated by associated PDF uncertainty (±2.5%)

$$\alpha_s(M_Z^2) = 0.1151^{+0.0028}_{-0.0027}$$

QCD coupling from t-tbar cross sections

- Total top-antitop cross section (theoretically known at NNLO+NNLL) is the 1st p-p collider observable to constrain α_s at NNLO accuracy:

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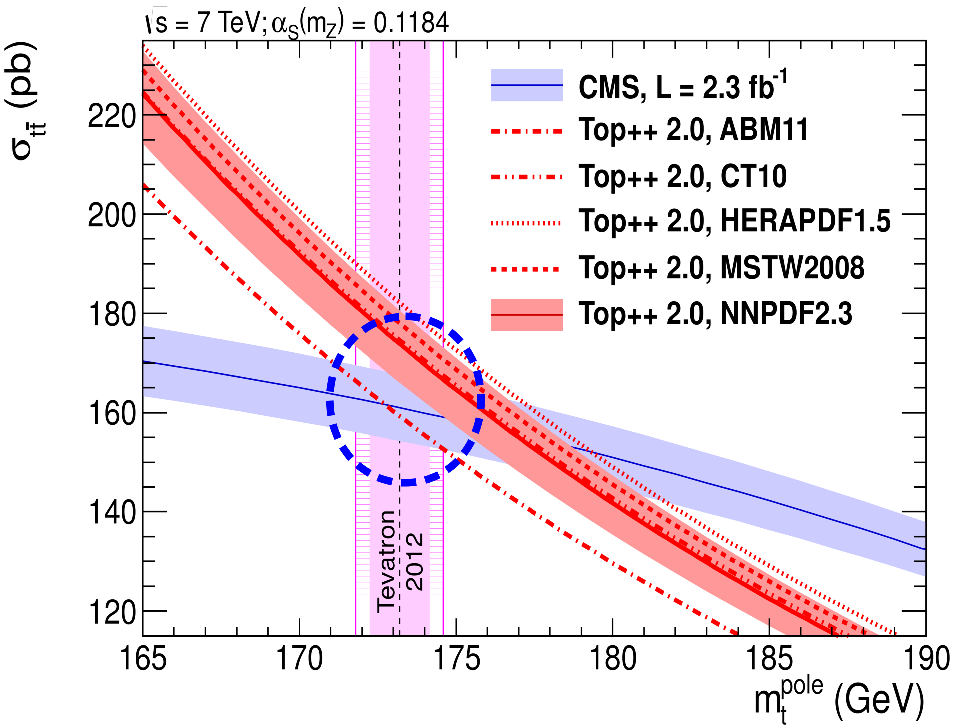
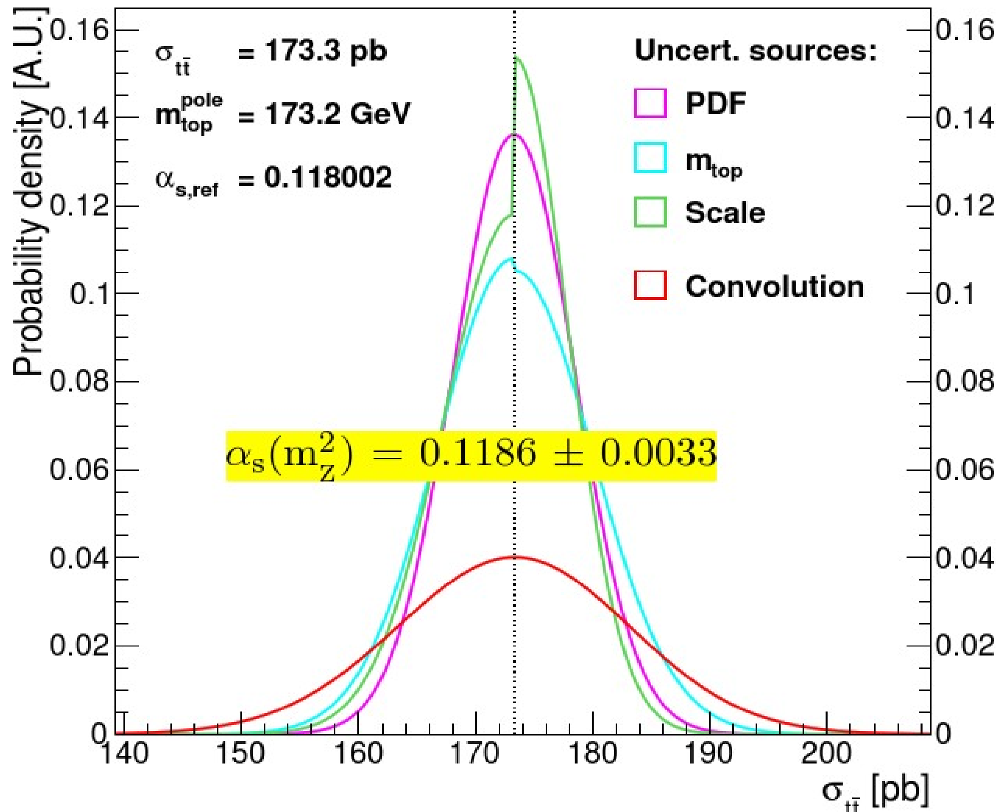


[CMS, PLB 728 (2014) 496]

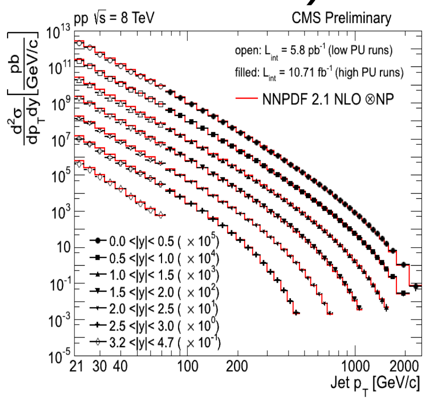
[G.Salam et al. arXiv:1512.05194]

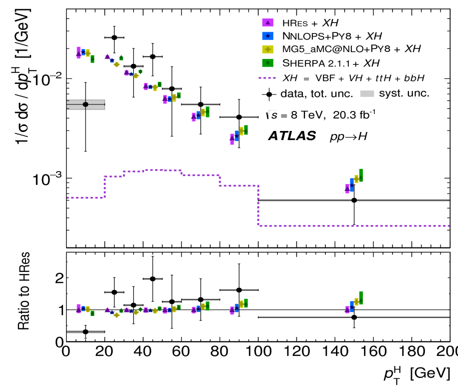


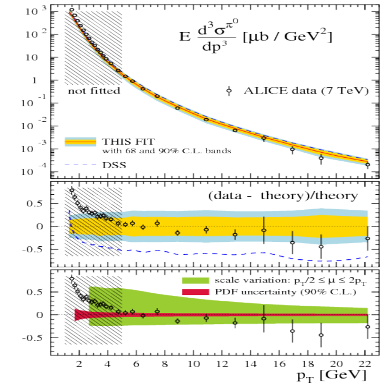
Inclusion of full set of t-tbar data increases the extracted $\alpha_s(m_Z)$ value.

Summary: Hard-QCD at the LHC

- Wealth of (differential, central & fwd) data: Jets, (di)γ, W,Z, heavy-Q, Higgs

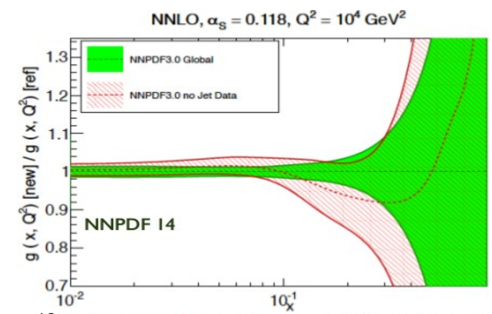


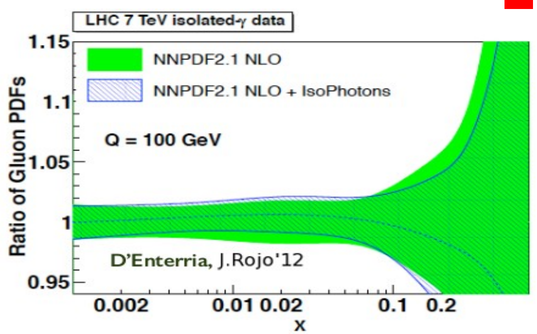


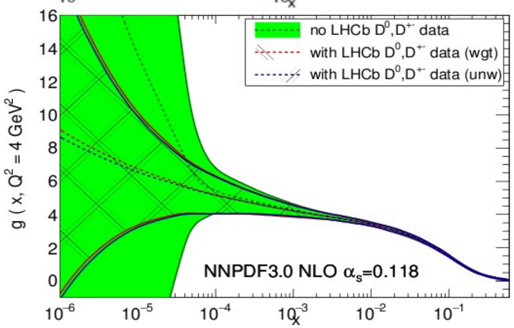


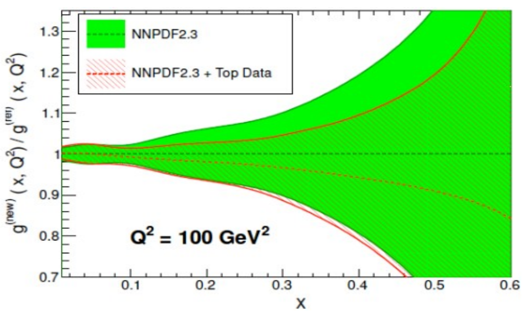
- Good data–pQCD (N)NLO+(N)NLL accord for total and differential cross sections:

- Improved (N)NLO PDFs via jets, γ, W,Z, charm, ttbar:



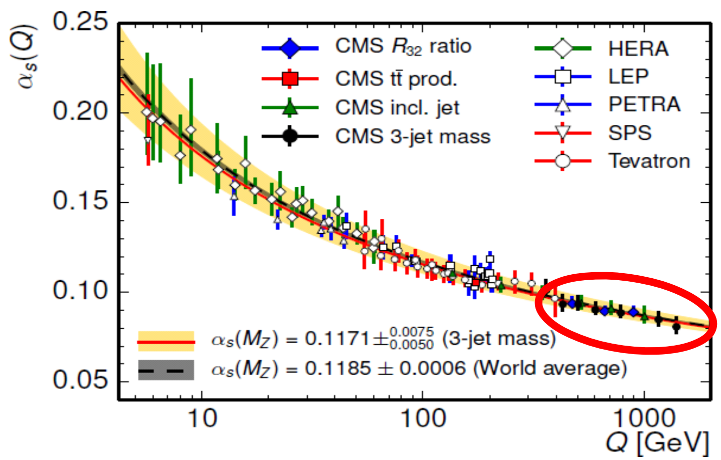






- Refitted (N)NLO gluon-to-hadron FFs

- High-precision α_s extractions (asymptotic freedom tested up to ~2 TeV)



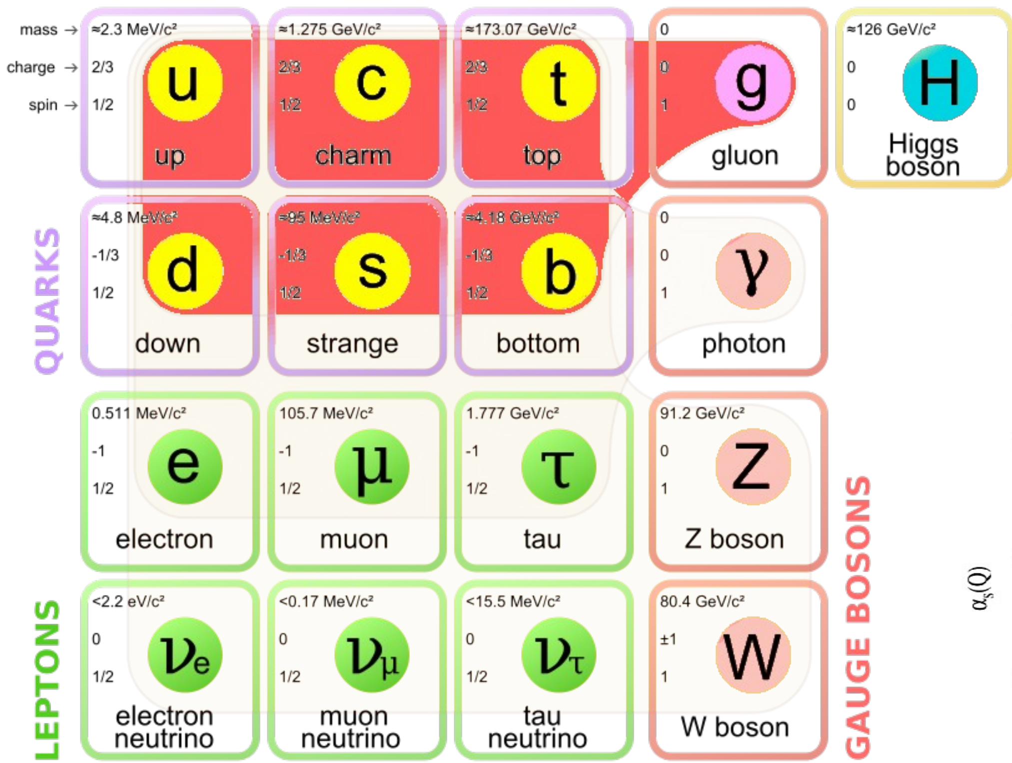
- Hard-QCD precision ~5% = Cornerstone for all (B)SM signals & bckgds. studies.

Back up slides

Quantum Chromodynamics

- Quantum Field Theory describing the strong interaction between quarks & gluons via local gauge symmetry: non-Abelian SU(3) color group

QCD sector in the Standard Model :



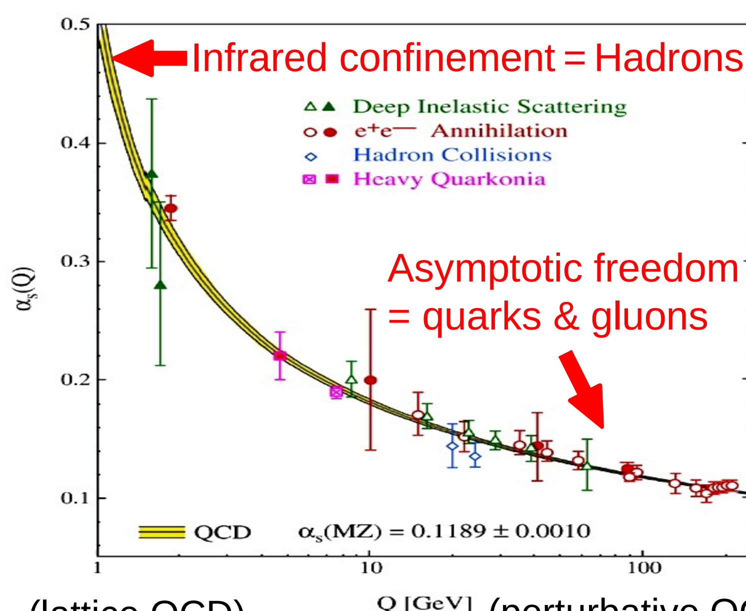
$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + \sum_f \bar{\psi}^{(f)}_i (i D_\mu - m_f) \psi^{(f)}_i$$

Gluon dynamics | Quark-gluon dyn.+quark mass

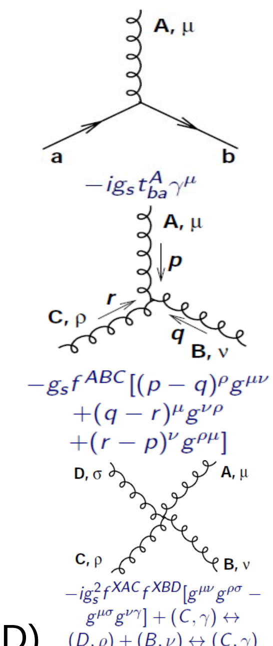
$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f^{abc} A^b_\mu A^c_\nu$$

$$D_\mu = \partial_\mu \pm i g_s t_a A^a_\mu$$

QCD coupling constant



(lattice QCD) (perturbative QCD)



Quantum Chromodynamics

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: $SU_c(3)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right]$$

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right]$$

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

- Gauge-fermion dynamics via covariant derivatives:

$$D_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}, \quad D_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L\\ d_L\end{pmatrix},$$

$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R,$$

$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

- Gauge-boson field strength tensors:

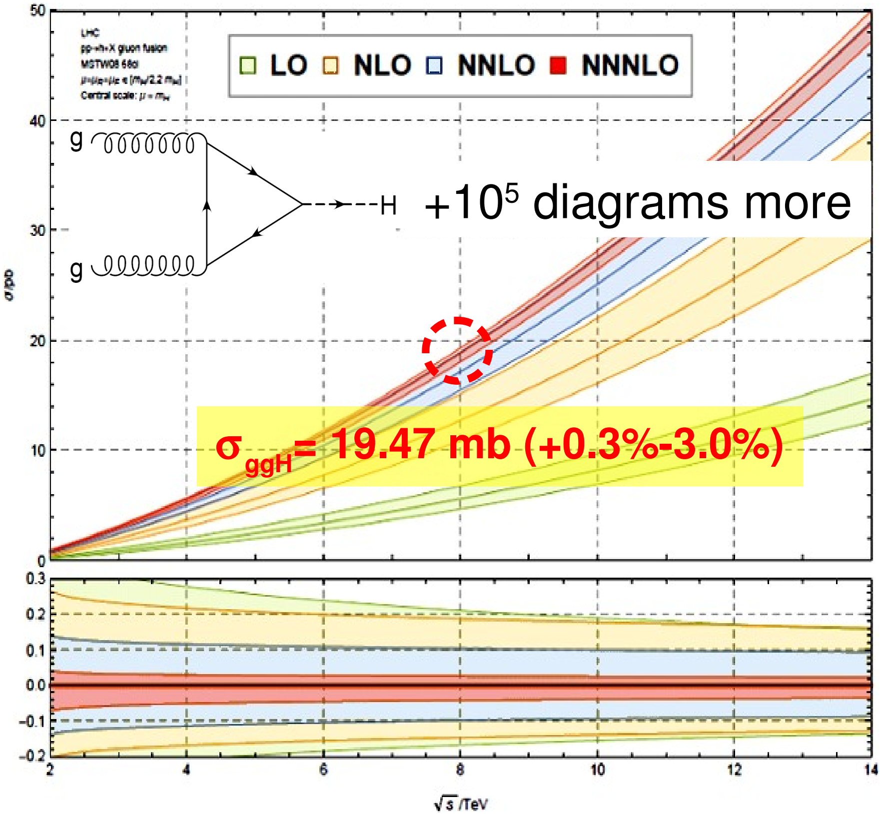
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu).$$

«Issues»: no CP-violation (axion?), confinement, non-perturbative structure/dynamics,...

Higgs cross sections: pQCD predictions

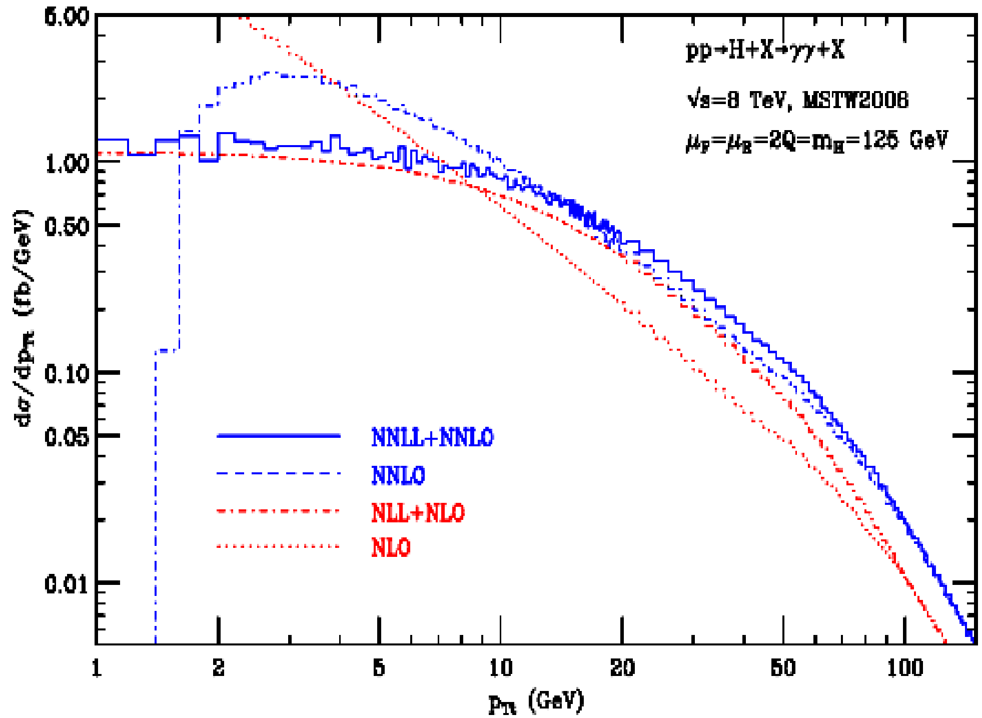
- Theory calculations include increasing # of real emissions + virtual corrections + soft&collinear log resummations (improves p_T differential distributions).
- Higgs production is paradigmatic example:

Higgs $\sigma(gg\to H)$ at N^{3}LO:



[Anastasiou et al. arXiv:1503.06056]

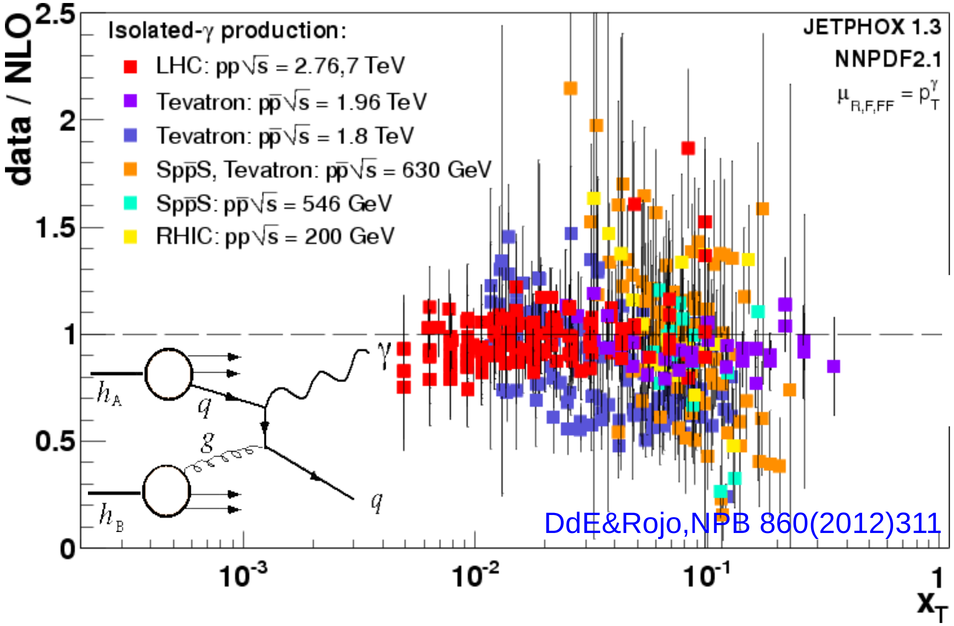
Higgs $d\sigma/dp_T$ at NNLO+NNLL:



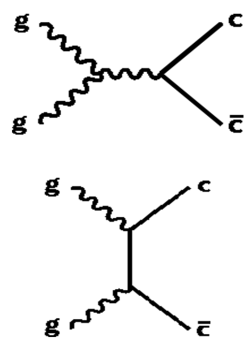
[DeFlorian et al. arXiv:1203.6321]

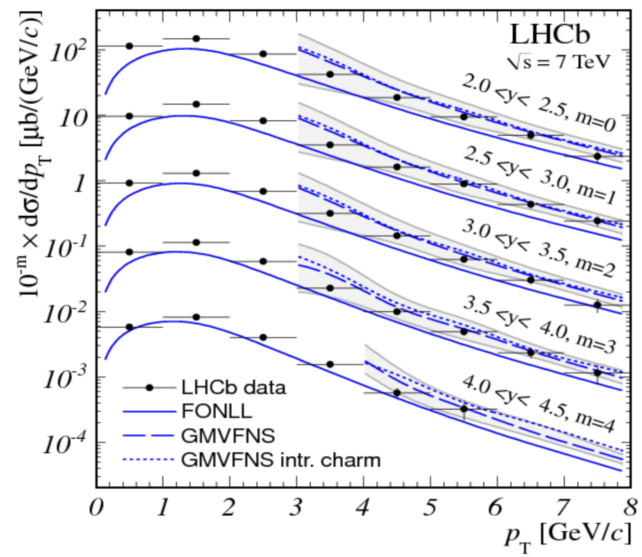
Gluon PDF constraints via LHC γ, charm, t-tbar

- Isolated photon p_T spectra:

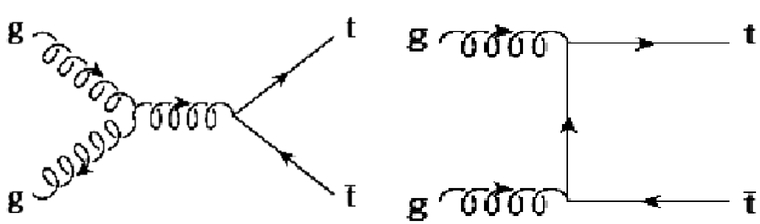


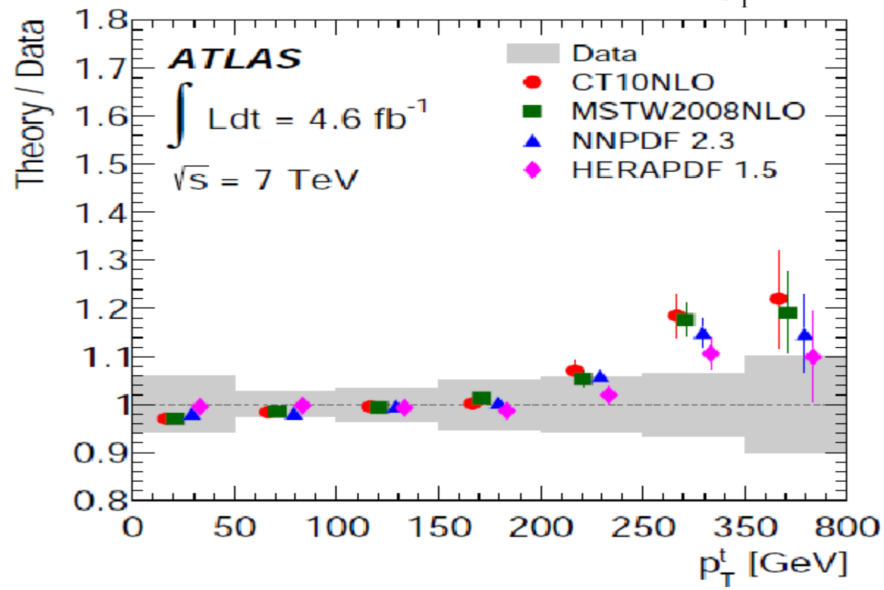
- Forward D-mesons (LHCb):





- Top-pair total x-sections (NNLO):





Reduced gluon uncertainties at different (x,Q^2)

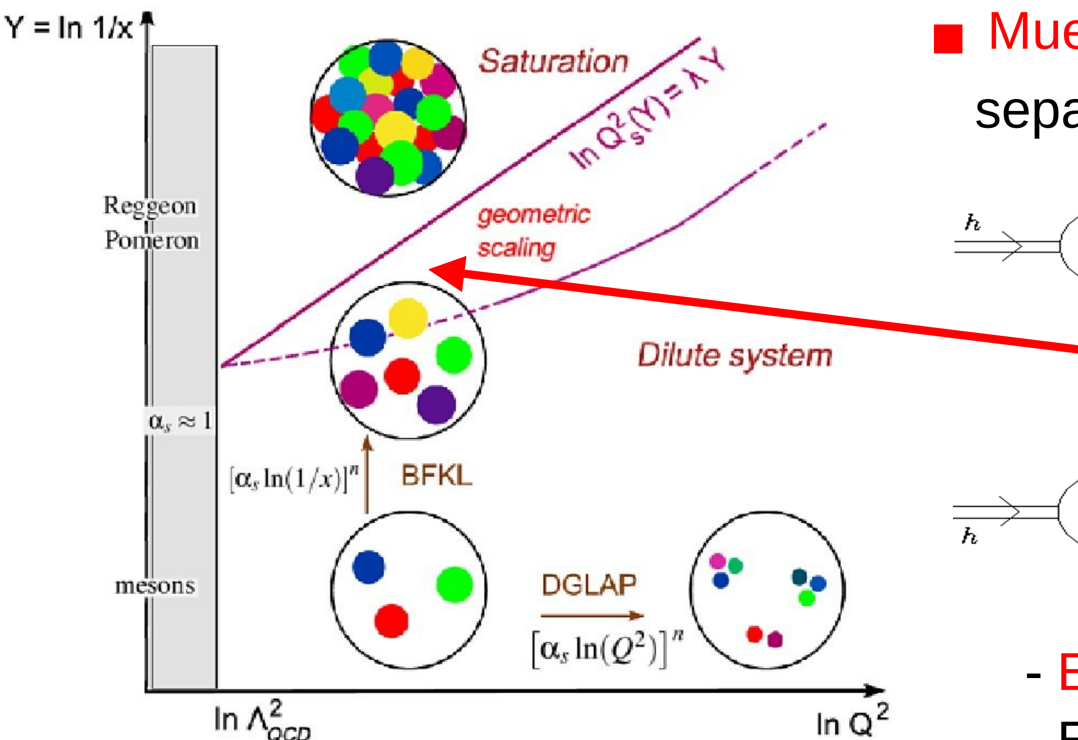
Searches of "Beyond DGLAP" evolution

- DGLAP equations describe parton radiation as a function of Q^2:

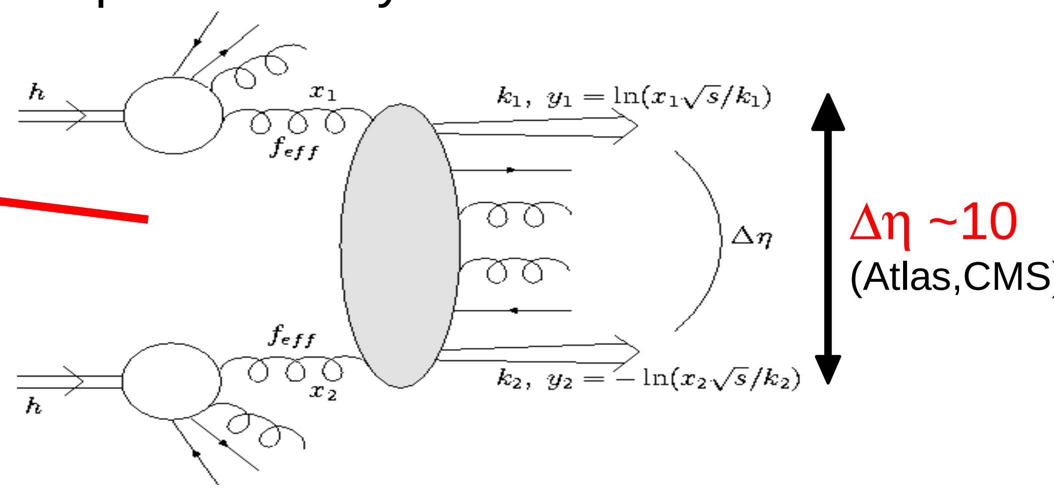
  $f(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$ [fixed-order PDFs, collinear factorization]

- BFKL, saturation evolutions: At low-x & mid Q^2, parton emission in p_L,η

  $f(x) \sim \alpha_s \ln(1/x)^n$ [uPDFs, k_T-factorization]



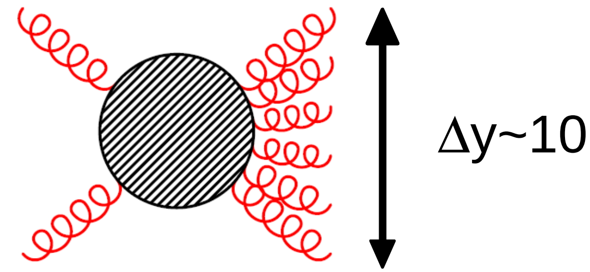
- Mueller-Navelet dijets with large y separation very sensitive to BFKL:

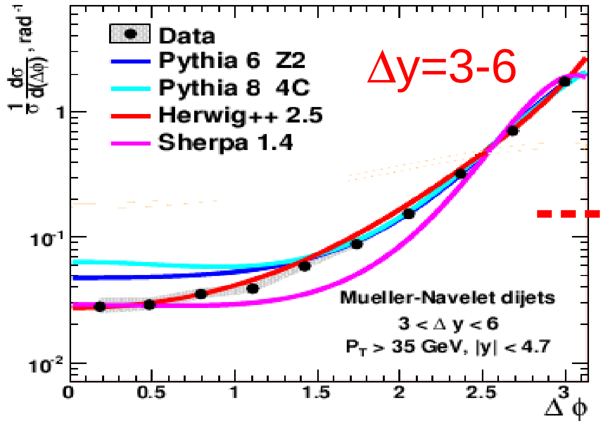


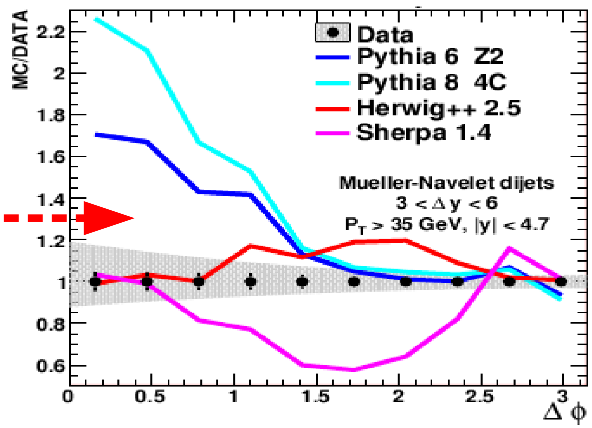
- Extra radiation in rapidity ?
- Enhanced azimuthal decorrelation ?

"Beyond DGLAP" in LHC Mueller-Navelet dijets?

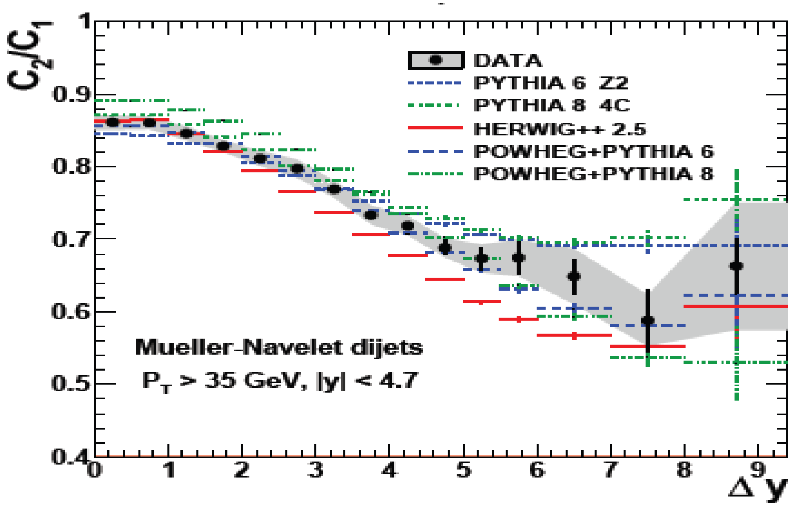
- MN dijet azimuthal decorrelations over large Δy: Absolute $\Delta\varphi$ distributions & ratio moments vs Δy

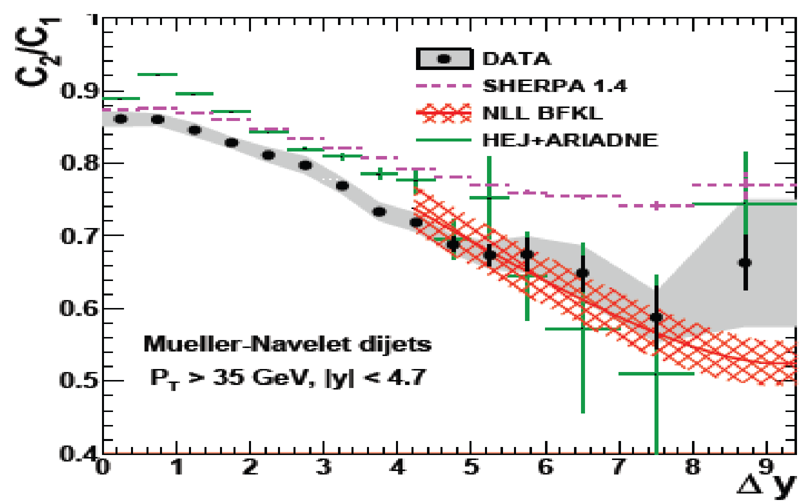






- HERWIG = DGLAP + (N)LL parton-shower not doing bad ...





- Latest NLL+ BFKL also consistent with results... Final word at lower p_T ?