Precision QCD: Experimental status

Rencontres du Vietnam

“Precision theory for LHC & future colliders”

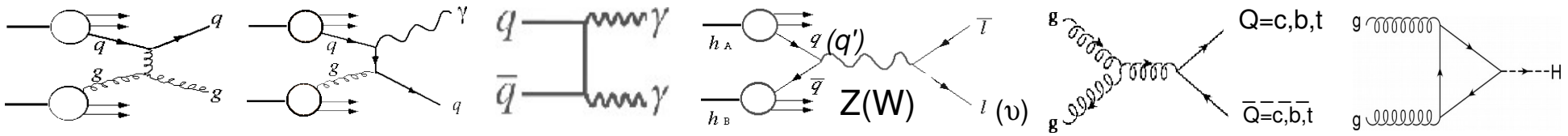
Quy Nhon (Vietnam)

25th Sept–1st Oct. 2016

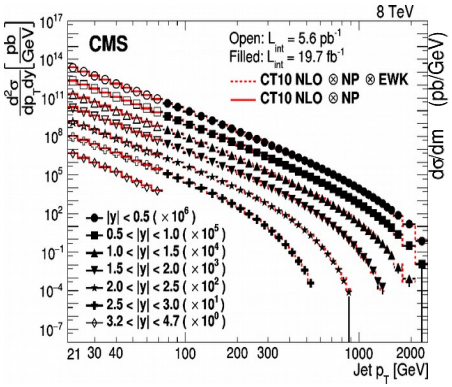
David d'Enterria (CERN)

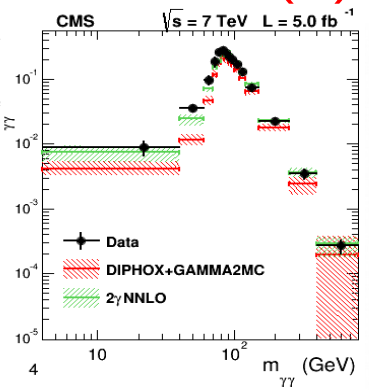
Precision QCD at the LHC: Outline

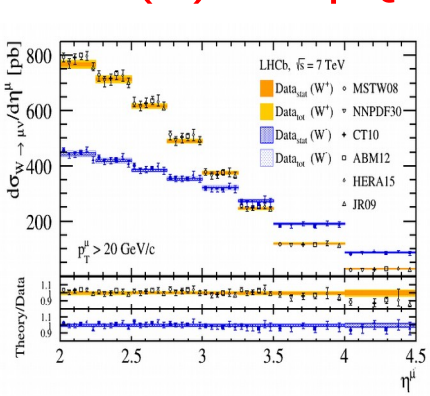
- Introduction. Observables: Jets, (di)photons, W,Z bosons, heavy-Q, Higgs

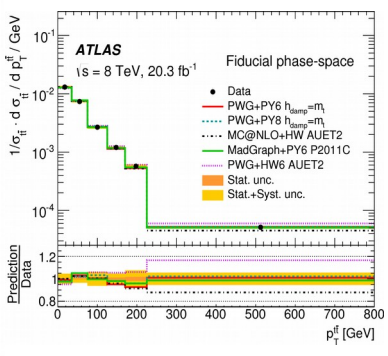


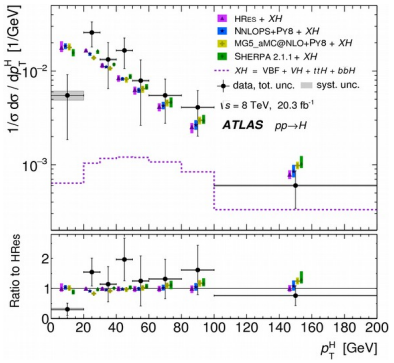
- Data vs. state-of-the-art (N)NLO+(N)NLL pQCD:



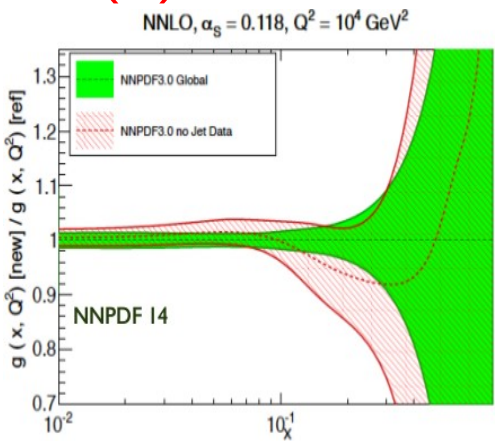


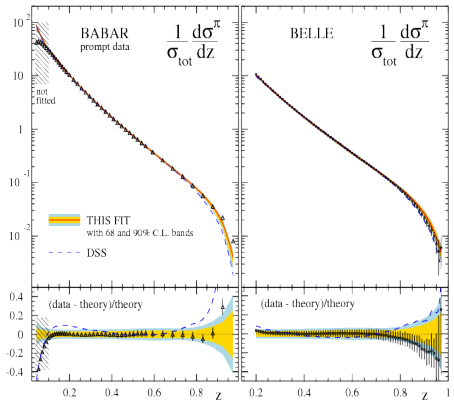




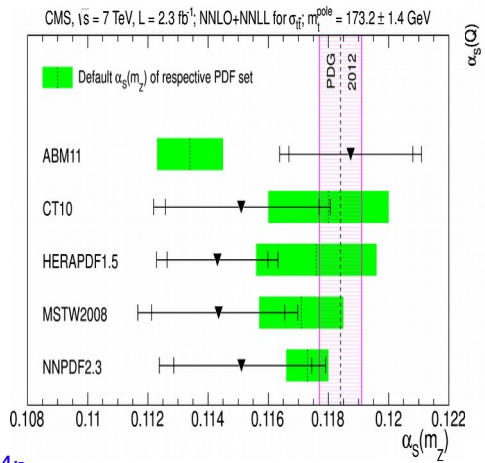


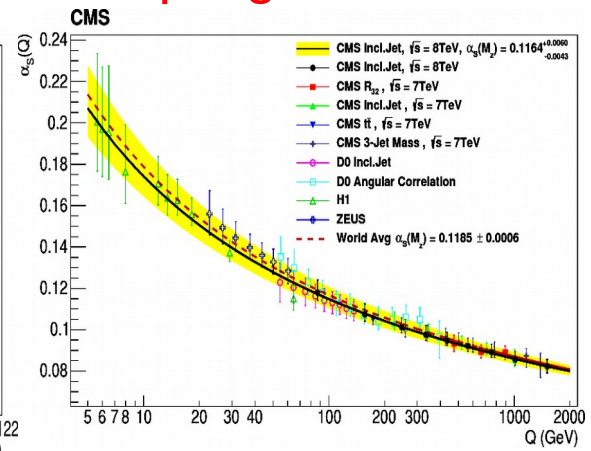
- (N)NLO PDFs & FFs improvements:





- (N)NLO QCD coupling extraction:





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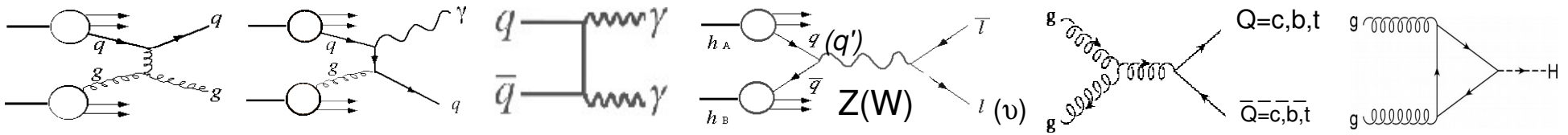

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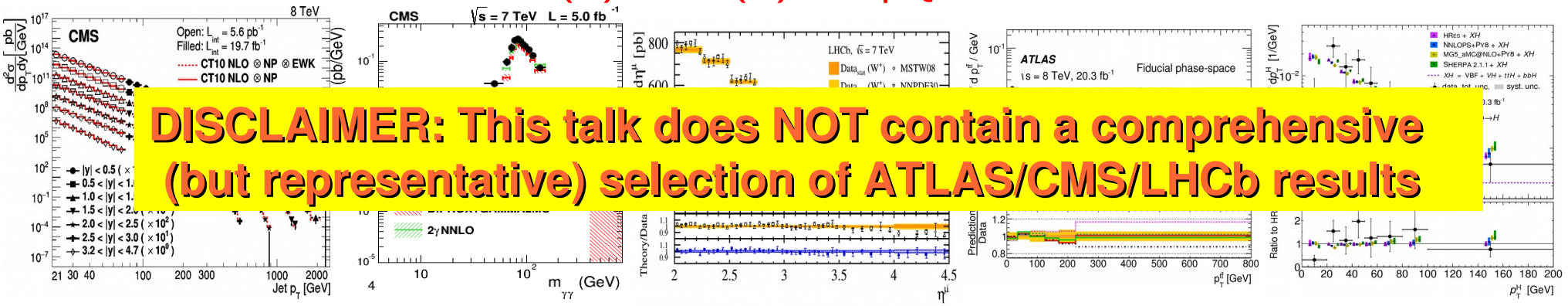

DISCLAIMER: This talk does NOT contain a comprehensive (but representative) selection of ATLAS/CMS/LHCb results

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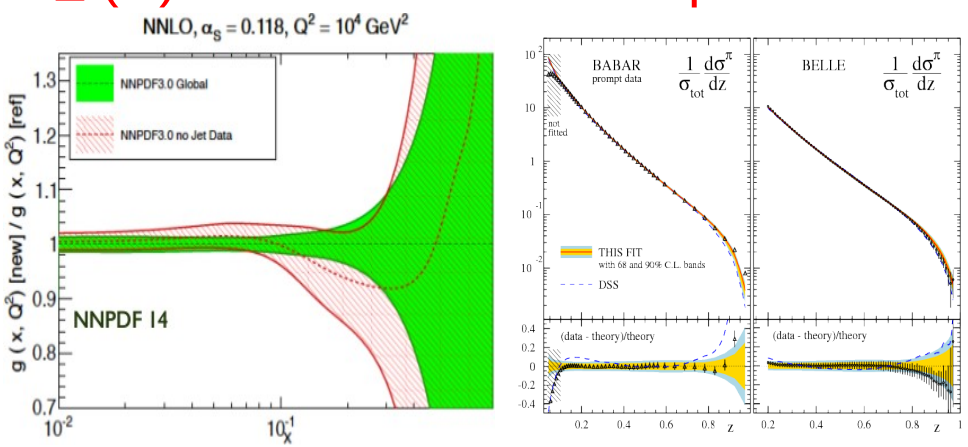

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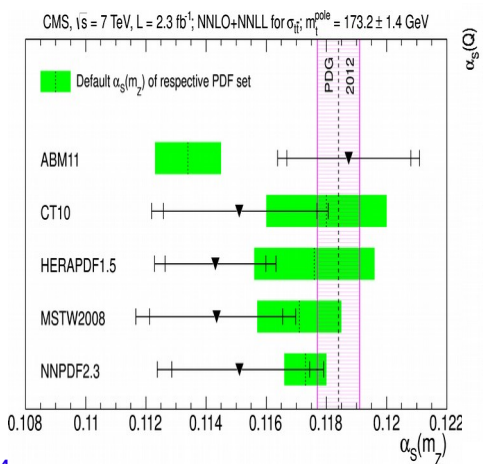
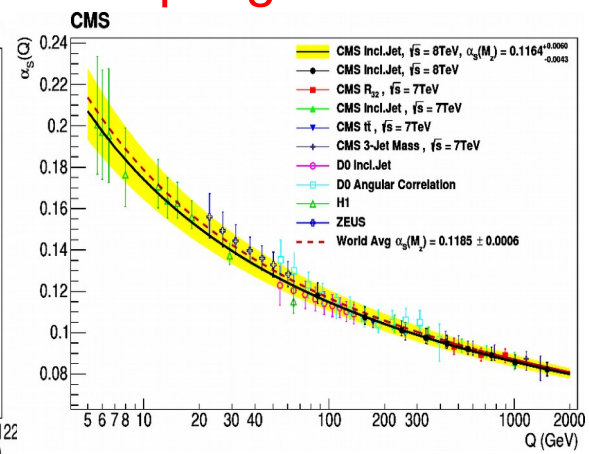
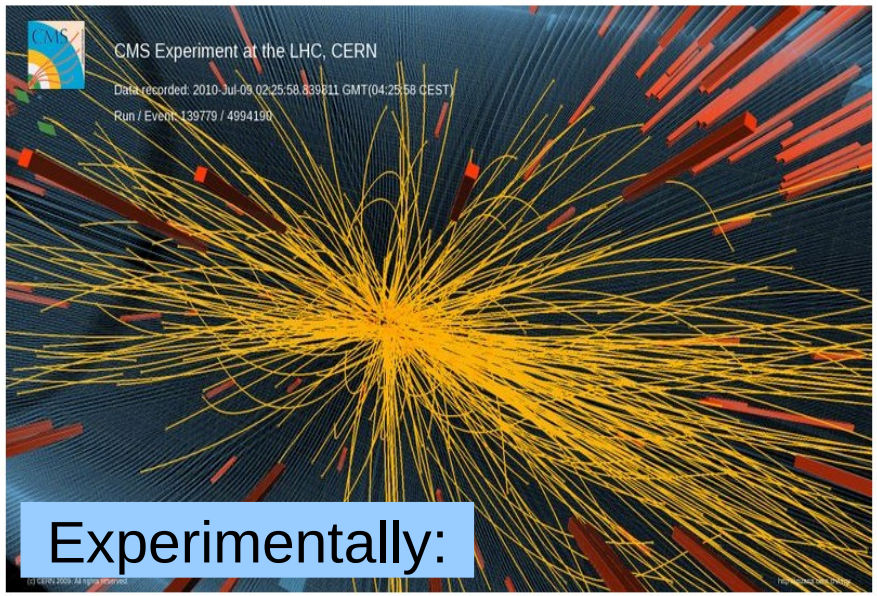
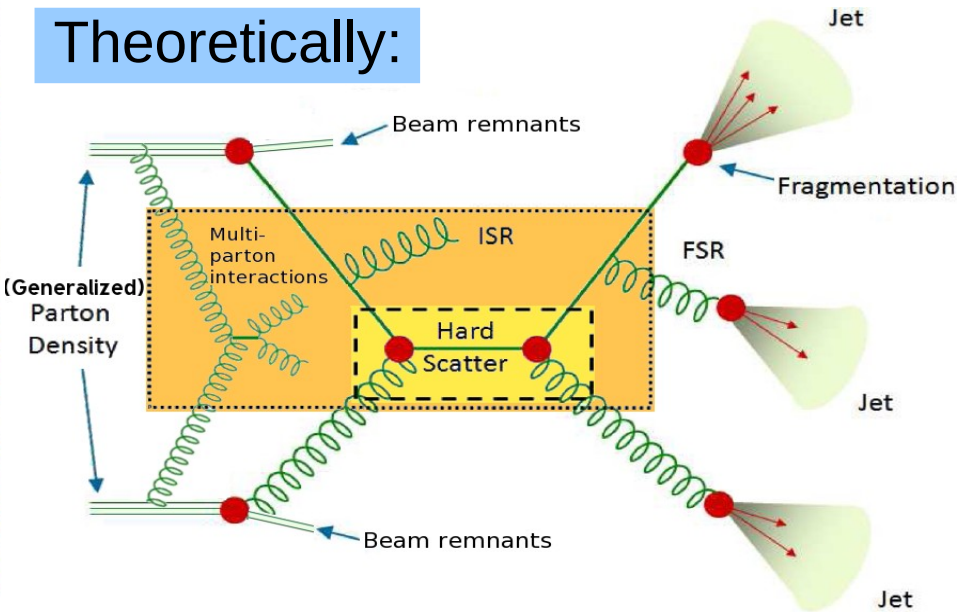




(Almost) All LHC p-p physics "is" QCD physics





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, color reconnection, diffractive scattering,...

- High-precision (experimental & theoretical) studies of QCD are key to understand production/properties of all (B)SM particles at the LHC

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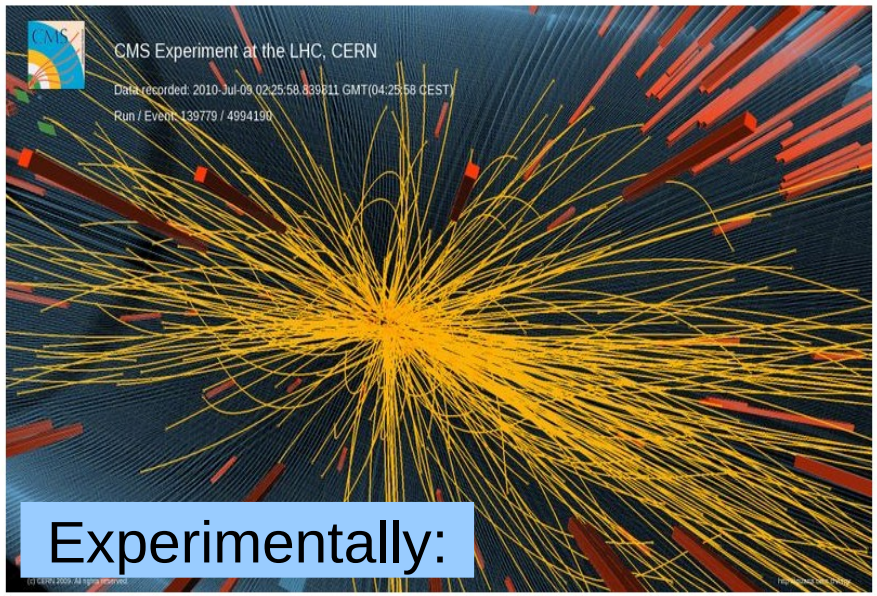
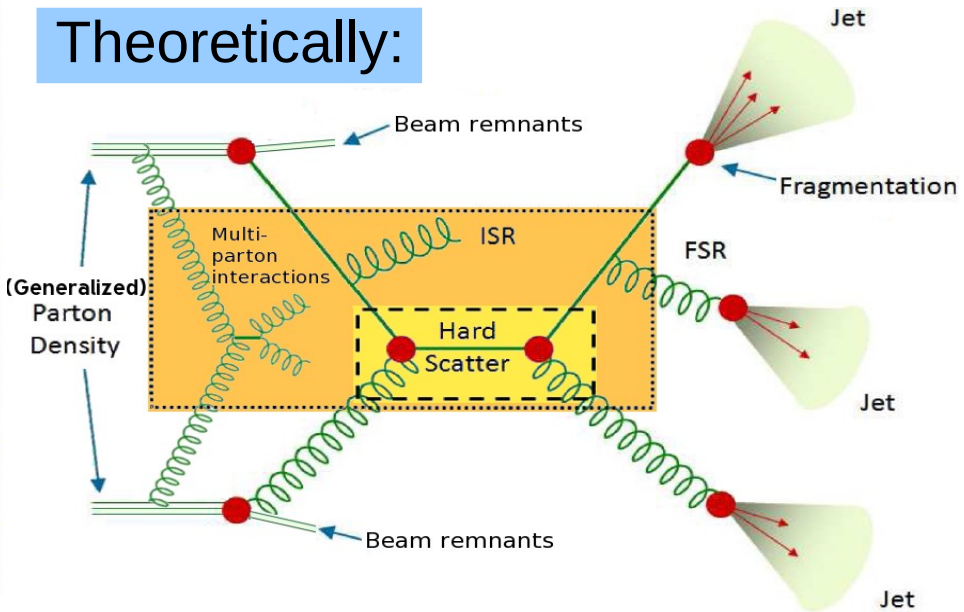


Theoretically:



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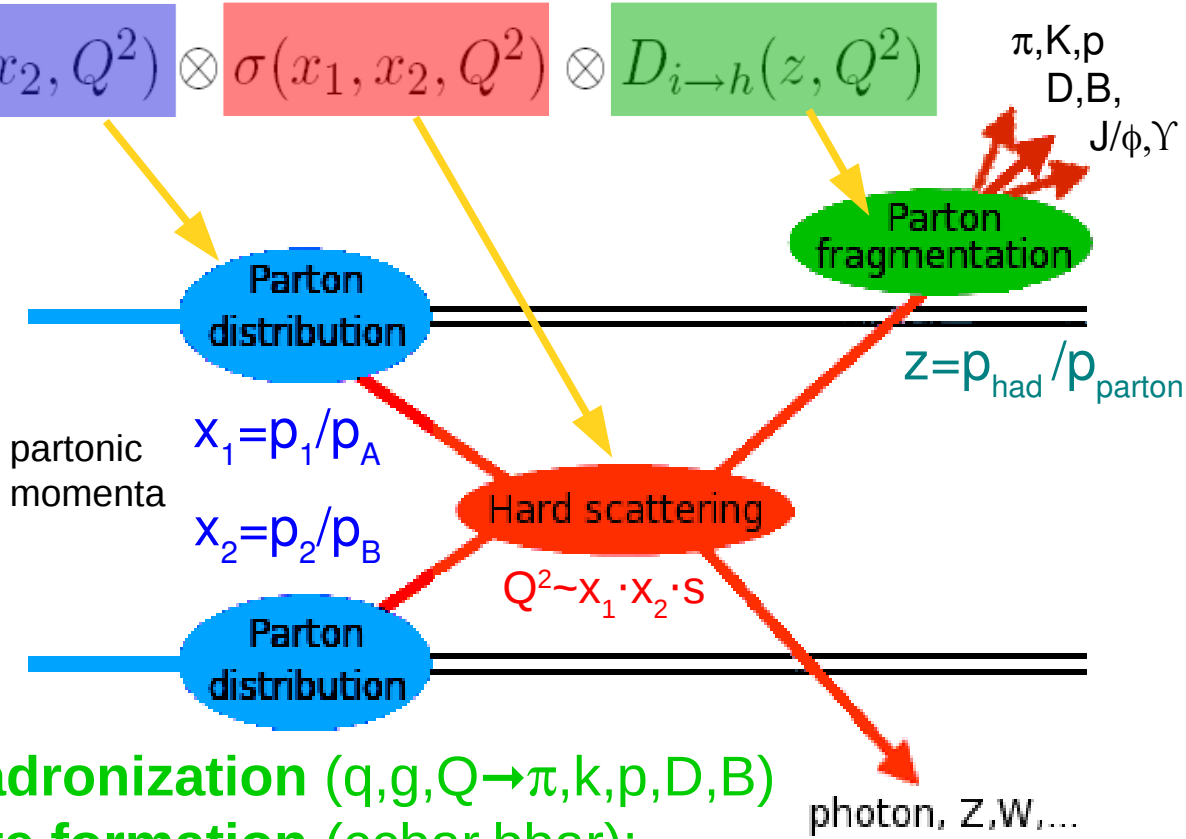
[Not yet high-precision TH/EXP QCD]

- High-precision (experimental & theoretical) studies of QCD are key to understand production/properties of all (B)SM particles at the LHC

Master formula for pQCD 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):

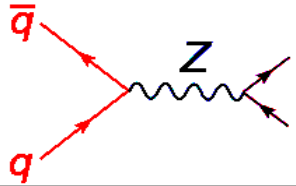
Universal FFs fitted from data + DGLAP evolution

- NOTE: *Transverse parton density (key for MPI/UE/DPS) not accounted for.*

pQCD 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):

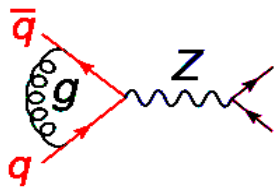
LO

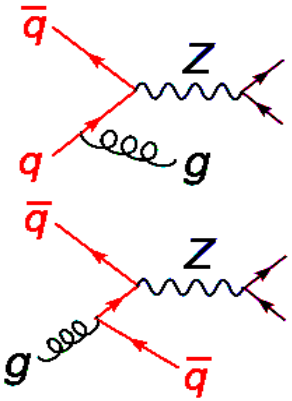


O(1-10) diagrams

(scale) TH uncert.~50-100%

NLO





O(100) diagrams

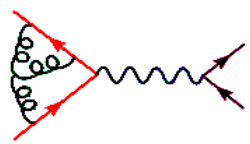
(scale) TH uncertainty~20%

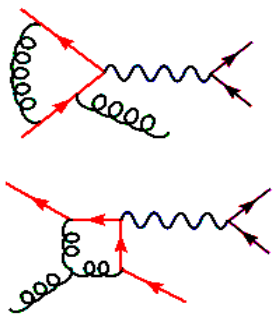
pp → jets+X (upcoming NNLO)

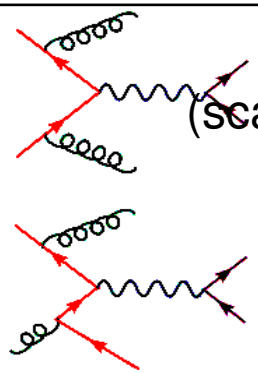
pp → $c\bar{c}$,$b\bar{b}$+X; W+Q

pp → γ+X

NNLO







O(10³) diagrams

(scale) TH uncert.~1–5%

pp → W,Z+X (+jet,+γ)

pp → VV+X (V=W,Z)

pp → γ γ +X

pp → ttbar+X, t+X

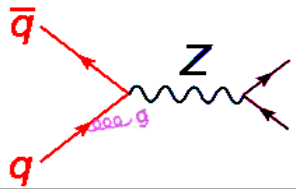
pp → H+X=jets,V,ttbar

First-ever N³LO: gg→H+X (~10⁵ diags. ~5% uncert.)

pQCD x-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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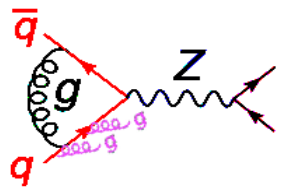

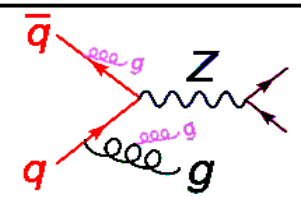

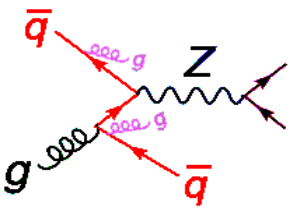

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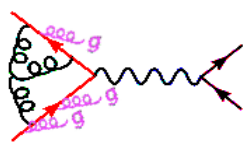

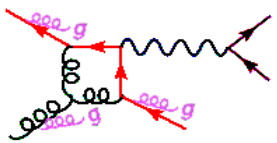

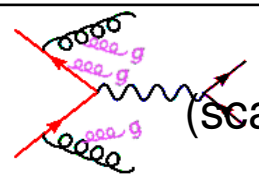

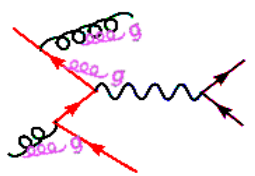

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pp → ttbar+X, t+X

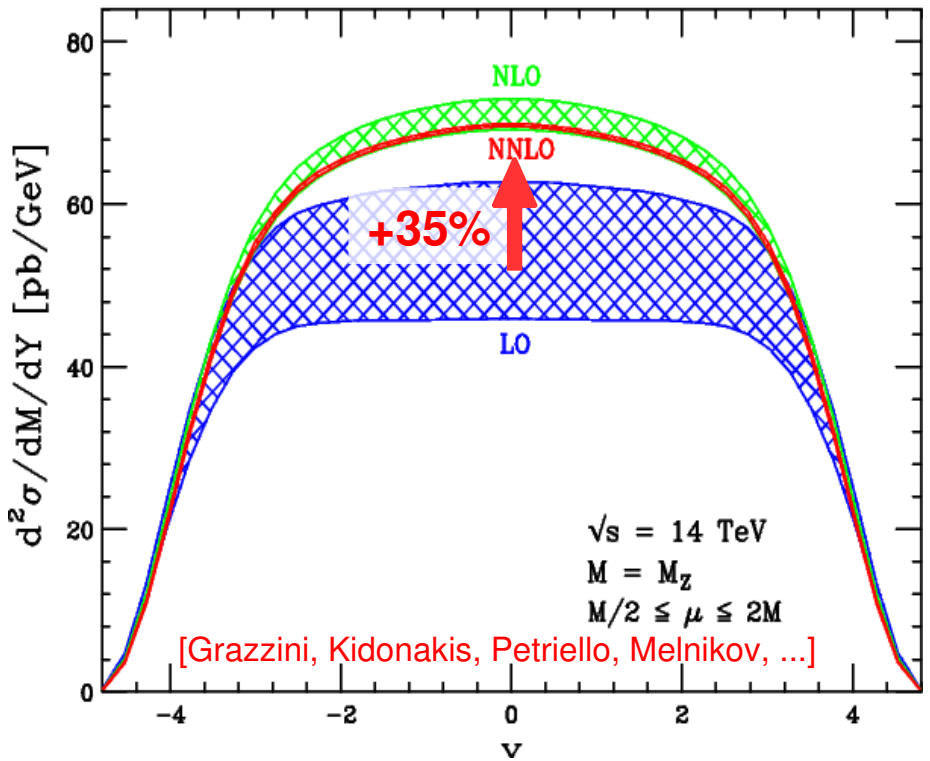
pp → H+X=jets,V,ttbar

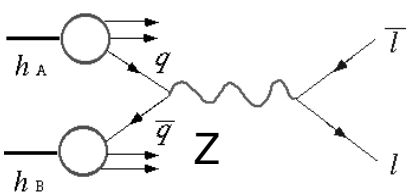
(State-of-the-art calculations include also QED+EWK corrs: $\alpha_s^2 \approx \alpha$)

pQCD x-sections: Higher-order corrs. (examples)

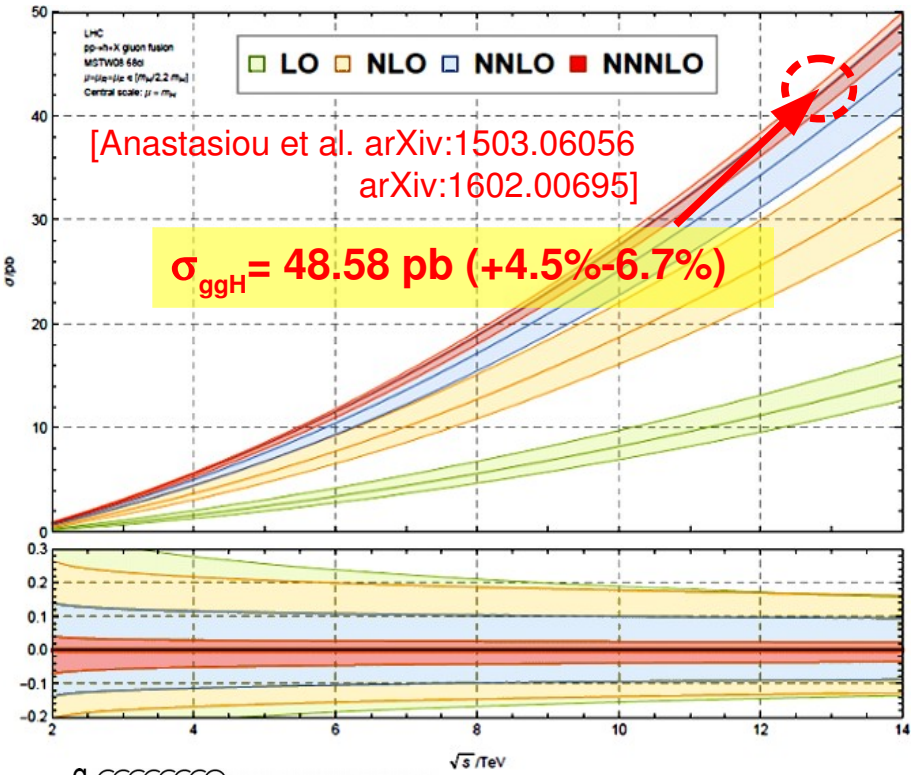
- Theory calculations with increasing # of real emissions + virtual corrections:
  (i) (usually) increased x-sections, (ii) reduced theoretical uncertainties

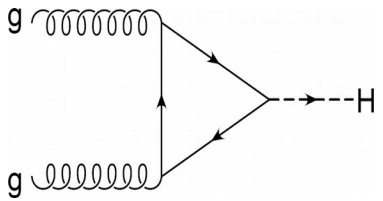
$\sigma(pp \to Z,\gamma^*)$ at NNLO:





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



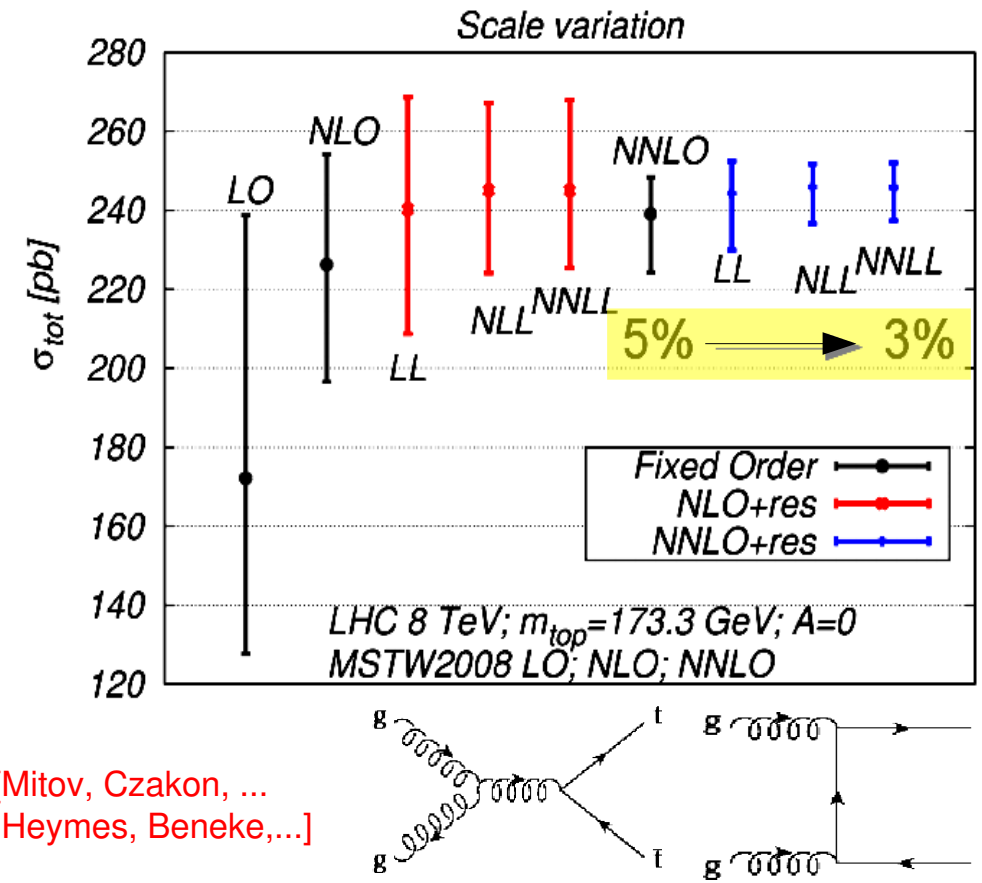


+10^5 diagrams more

pQCD x-sections: Resummation (examples)

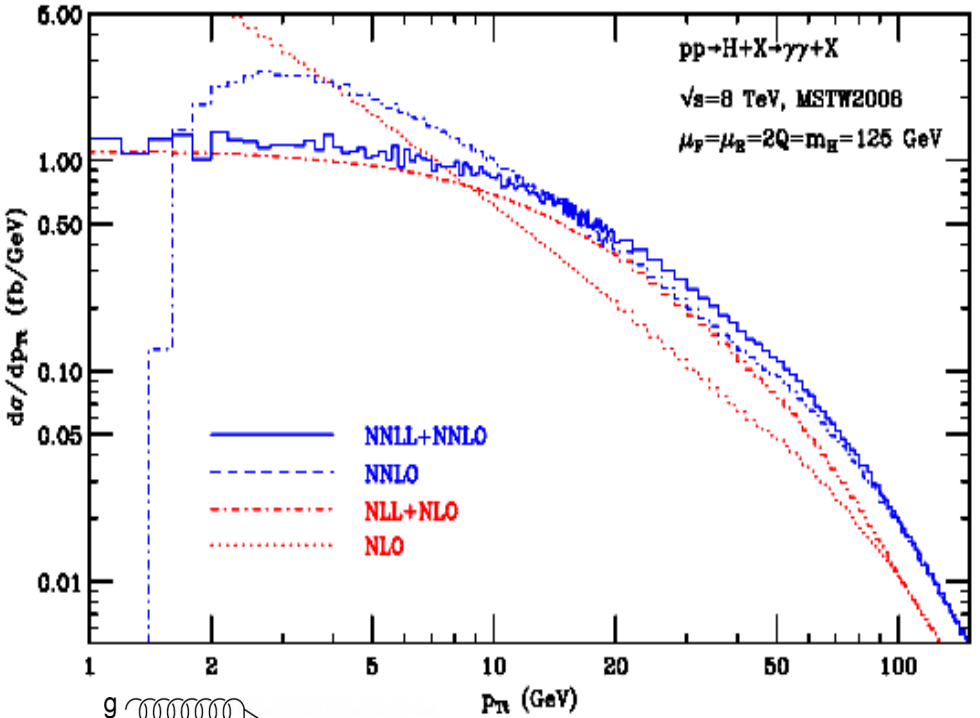
- Theory calculations include increasing # of real emissions + virtual corrections:
  + soft & collinear log resummations: (i) (usually) increased x-sections,
  (ii) reduced theoretical uncertainties, (iii) Improved p_T differential distributions:

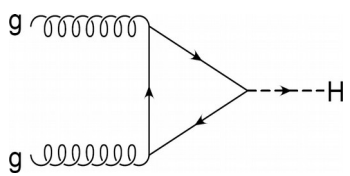
$\sigma(pp \to ttbar)$ at NNLO+NNLL:



[Mitov, Czakon, ... Heymes, Beneke,...]

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

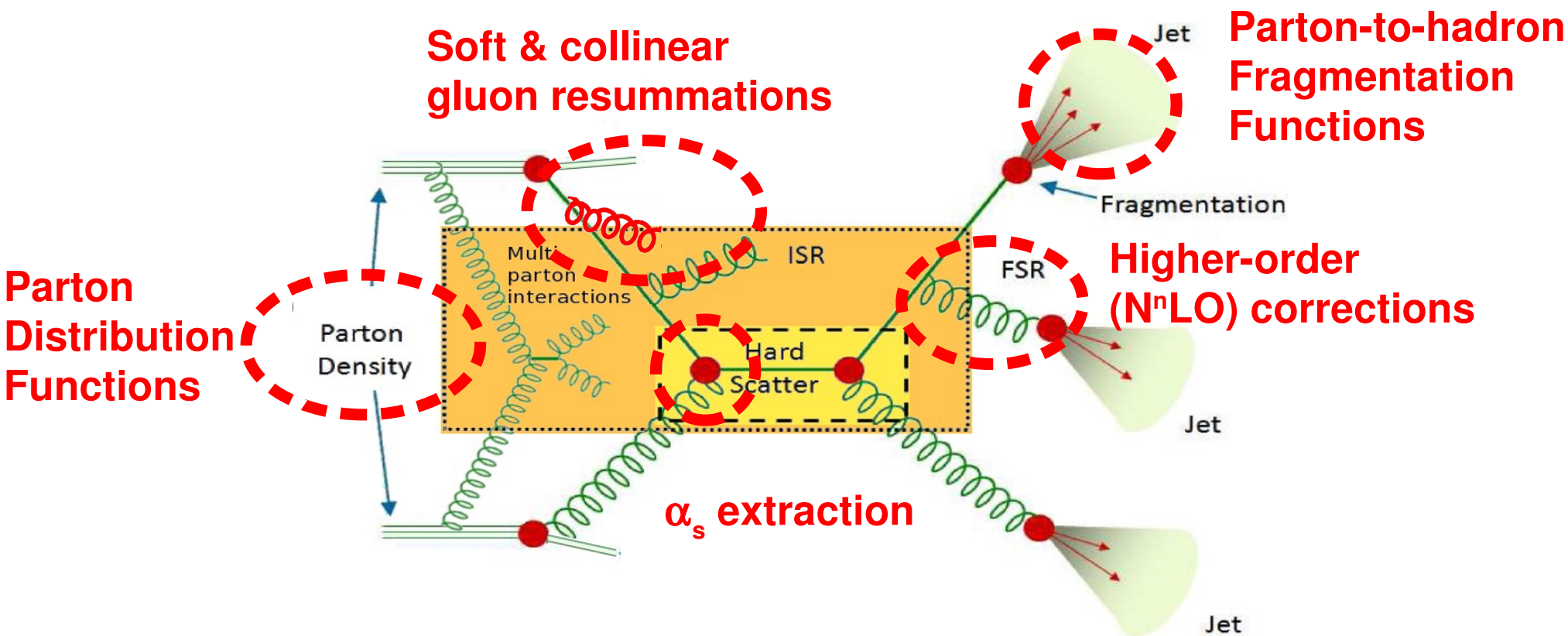




[DeFlorian et al. arXiv:1203.6321]

Organization of the talk

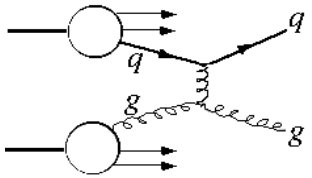
- What have we learned from the hard QCD data at the LHC about...

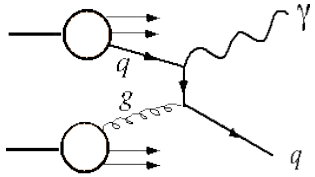


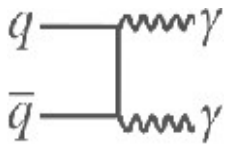
- <u>All precision observables</u> depend chiefly on all these pQCD ingredients, e.g.: i) BSM (SUSY, DM, Z'..) resonances on high-x PDF, ii) m_W on resummations, iii) m_{top} (via σ_{tt}) on higher-order corrs, iv) b,c Yukawas on α_s, ...

Precision QCD: LHC Data

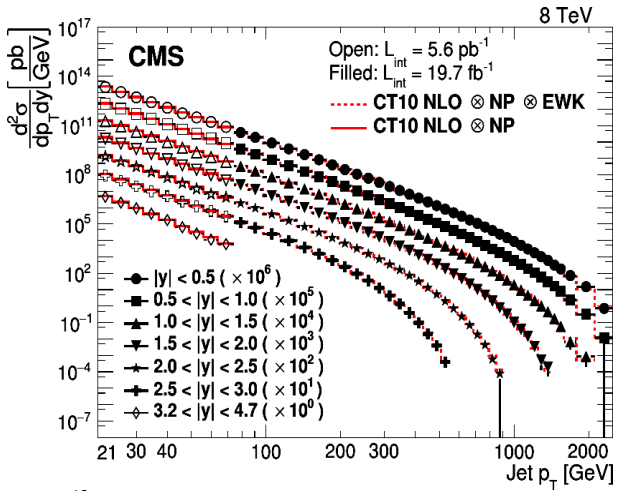
Wealth of precision QCD data: jets, γ, diphotons

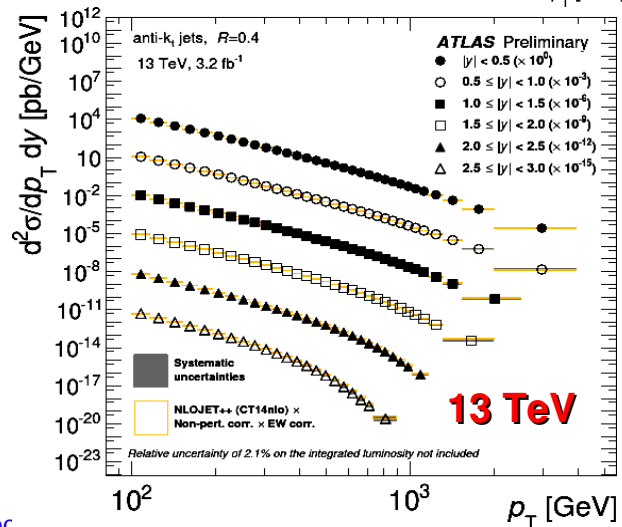






■ √s=2.76,7,8,13 TeV (central):





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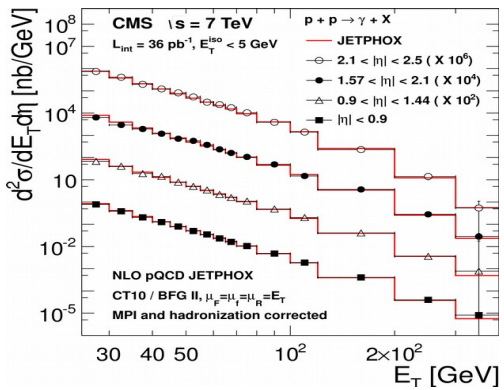
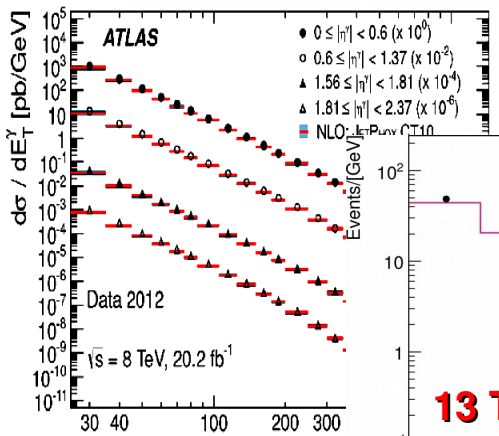
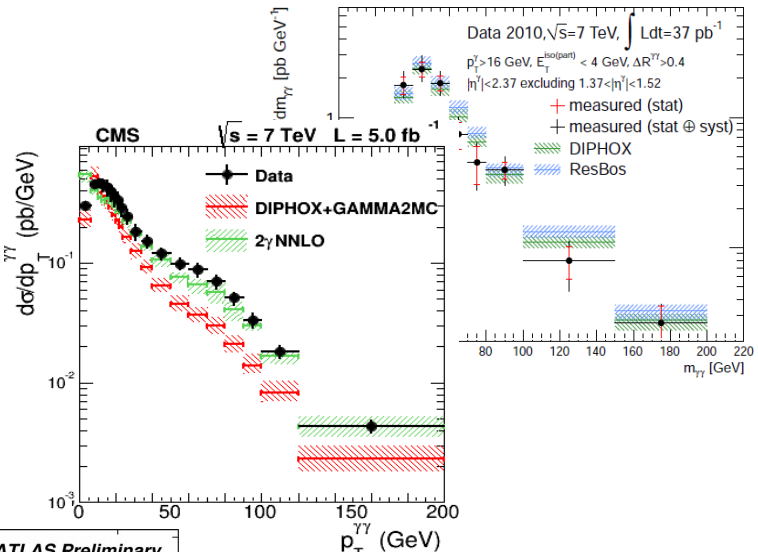
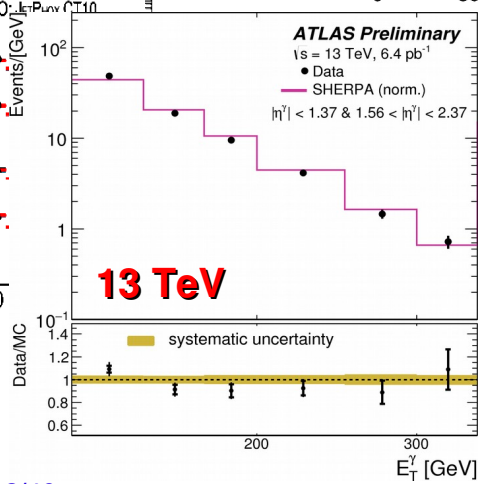
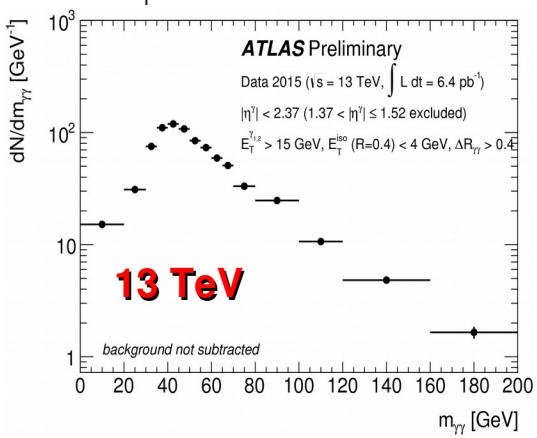




■ √s=7,8,13 TeV (central):

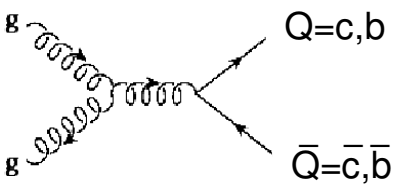


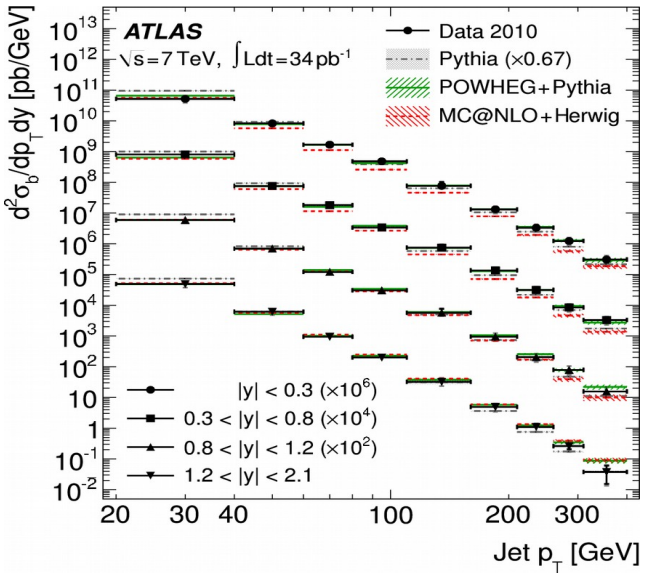


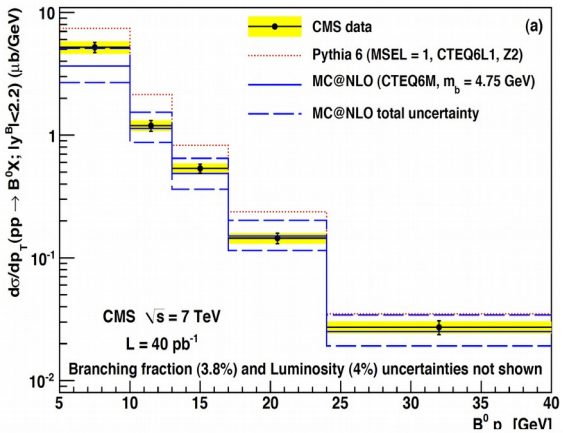


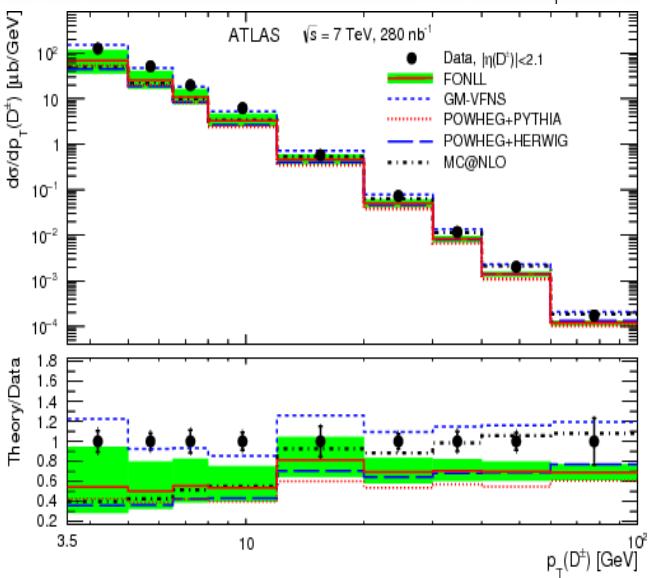
Wealth of precision QCD data: charm, bottom

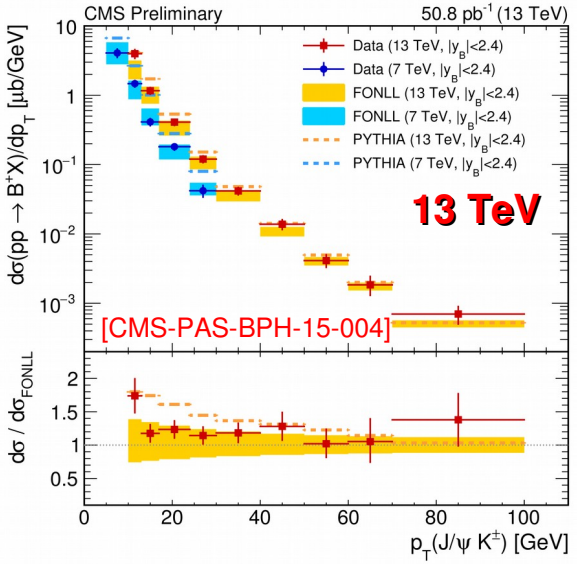
■ √s = 7, 8, 13 TeV (central rapidities):





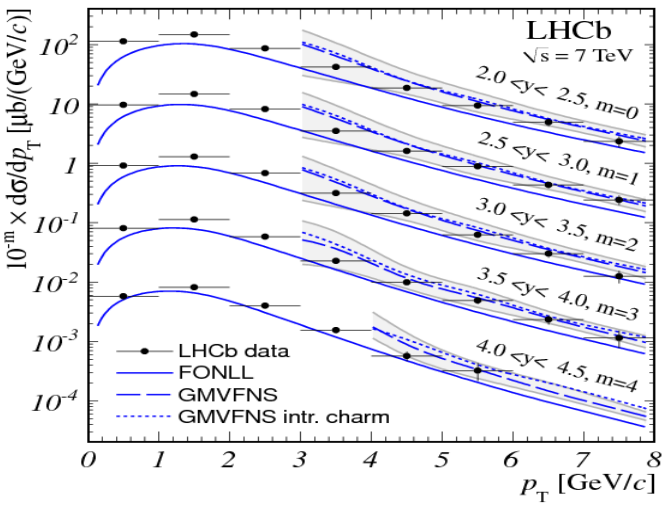




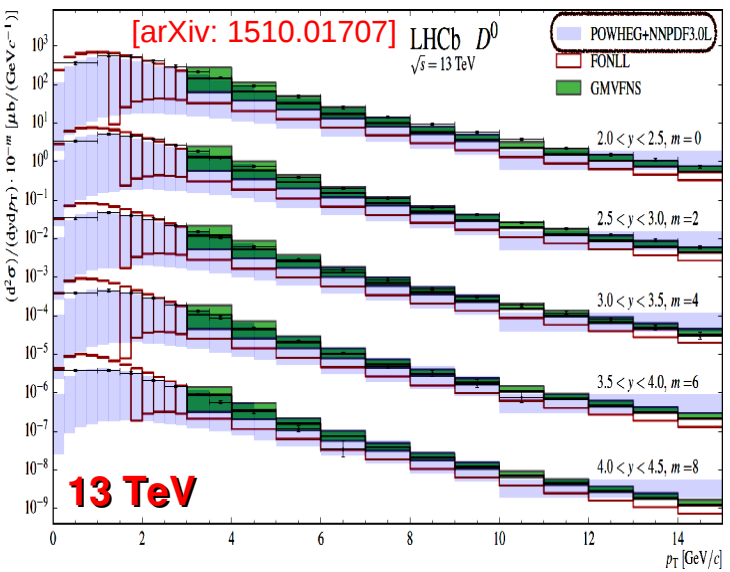


■ √s = 7, 8, 13 TeV (forward):

[NPB871 (2013) 1]

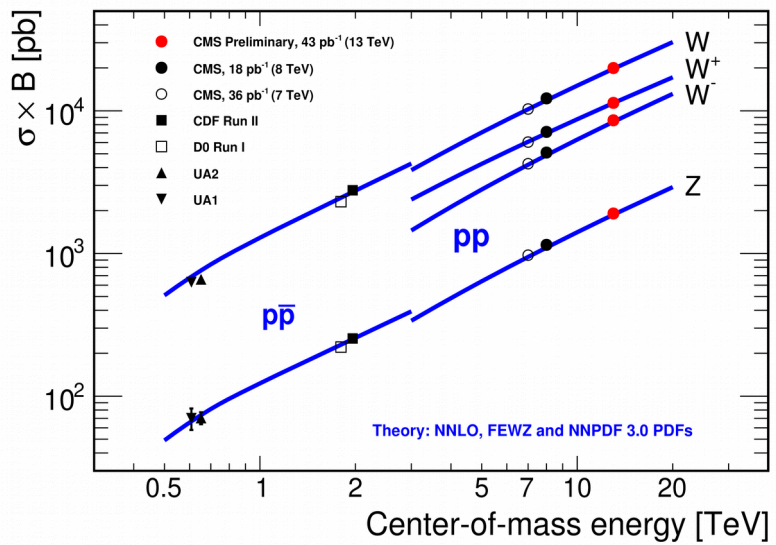


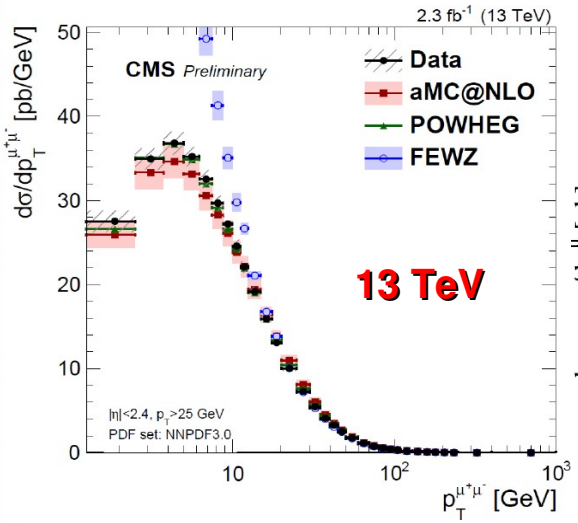
[arXiv: 1510.01707]

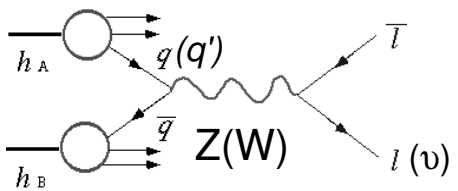


Wealth of precision QCD data: W, Z bosons

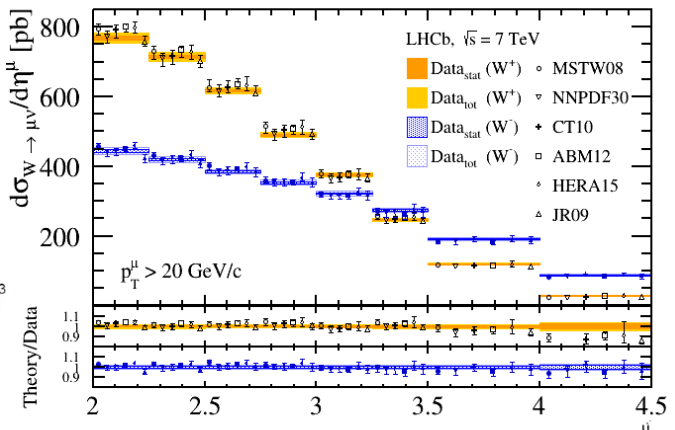
- √s = 7, 8, 13 TeV (central rapidities):



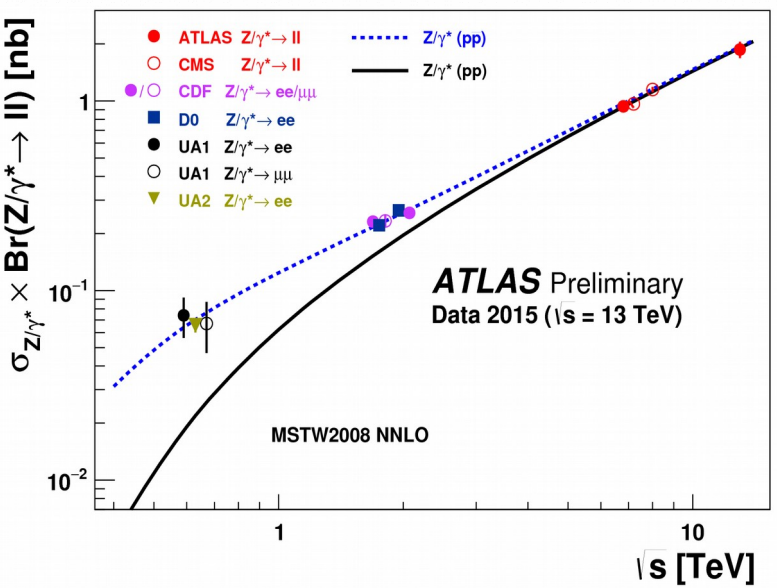


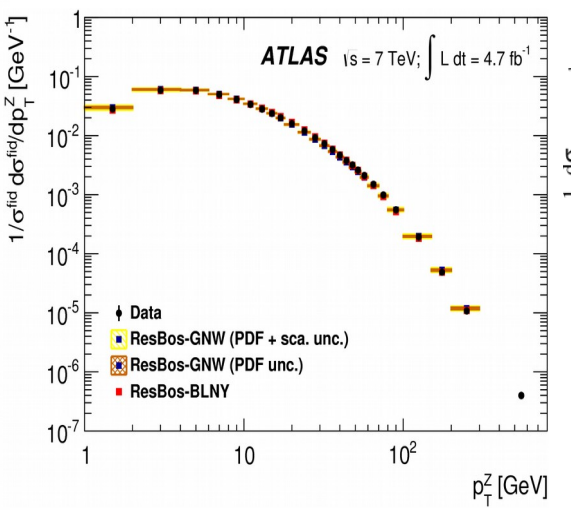


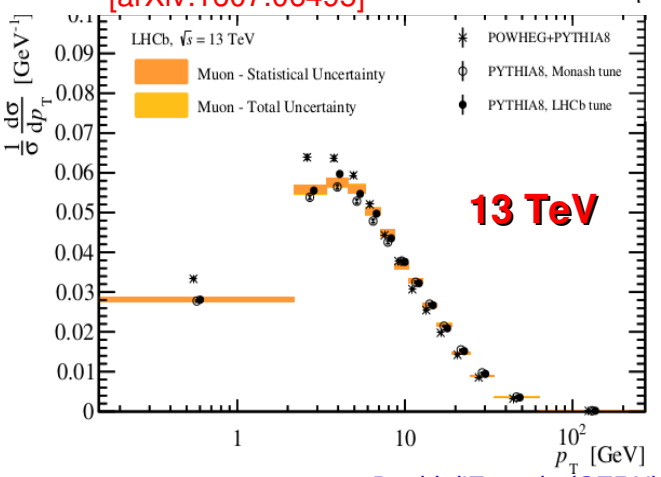
- √s = 7, 8, 13 TeV (forward):



[arXiv:1607.06495]

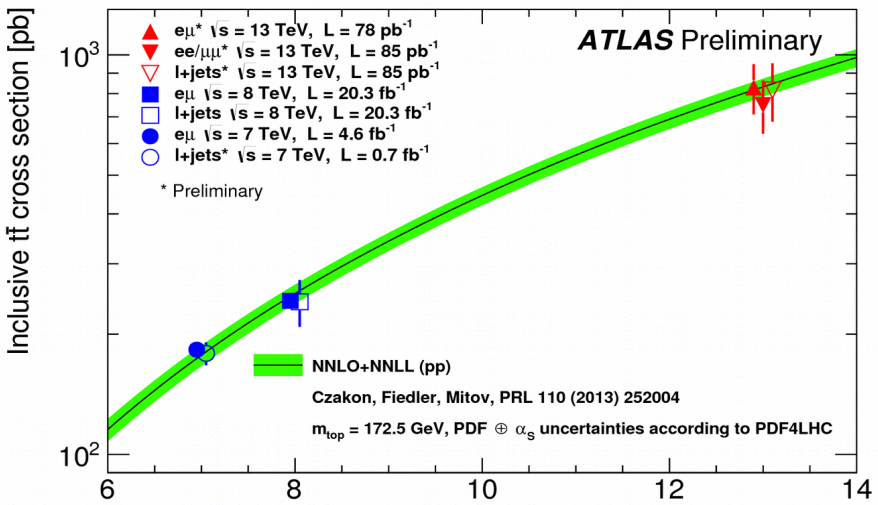


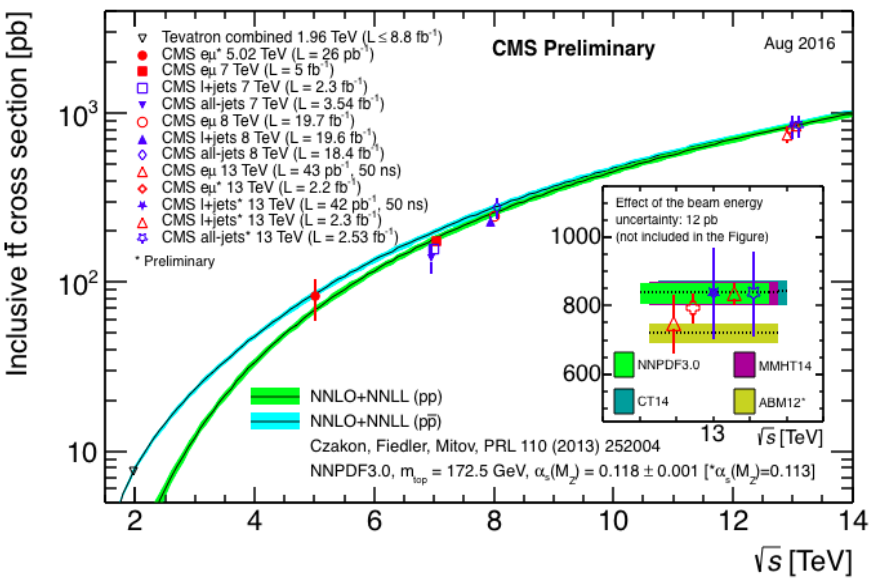


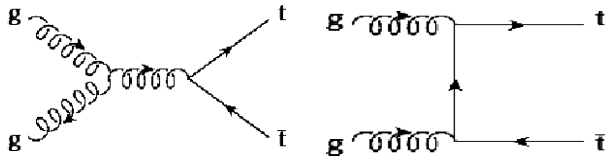


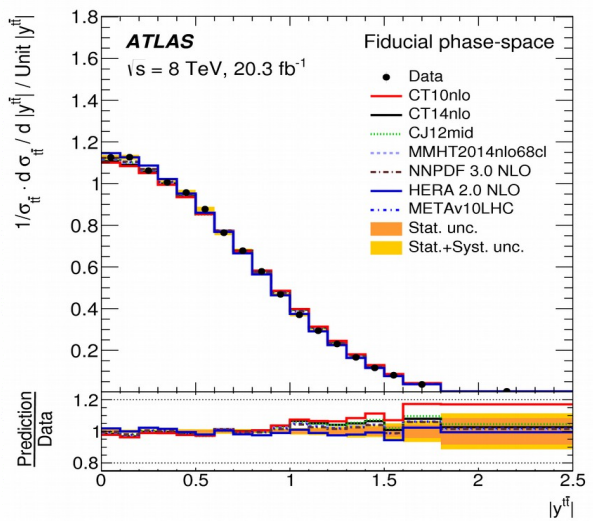
Wealth of precision QCD data: top-pairs

- √s = 5,7,8,13 TeV (central rapidities):

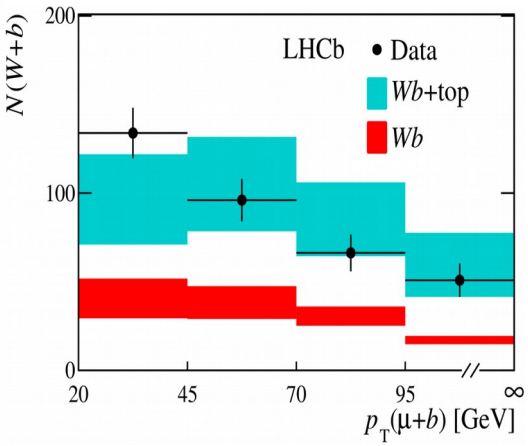


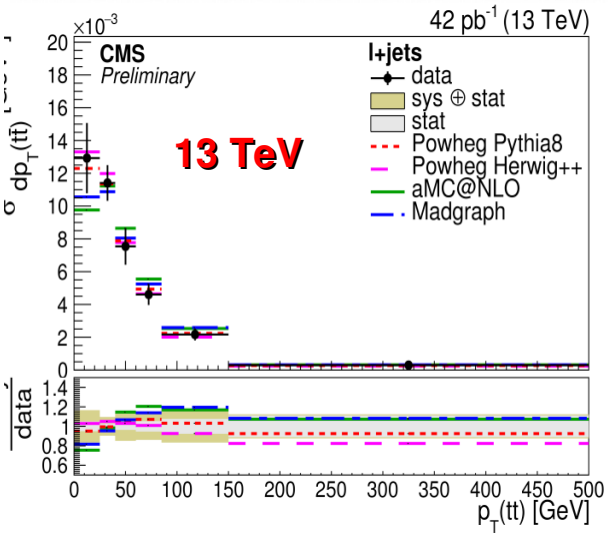


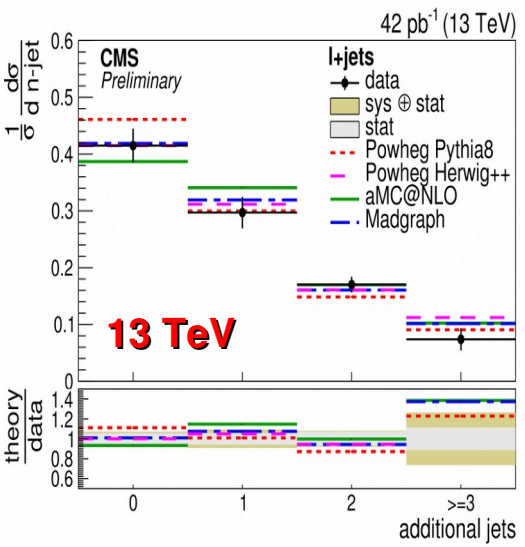




- √s = 7, 8 TeV (forward):

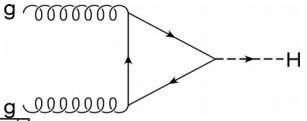


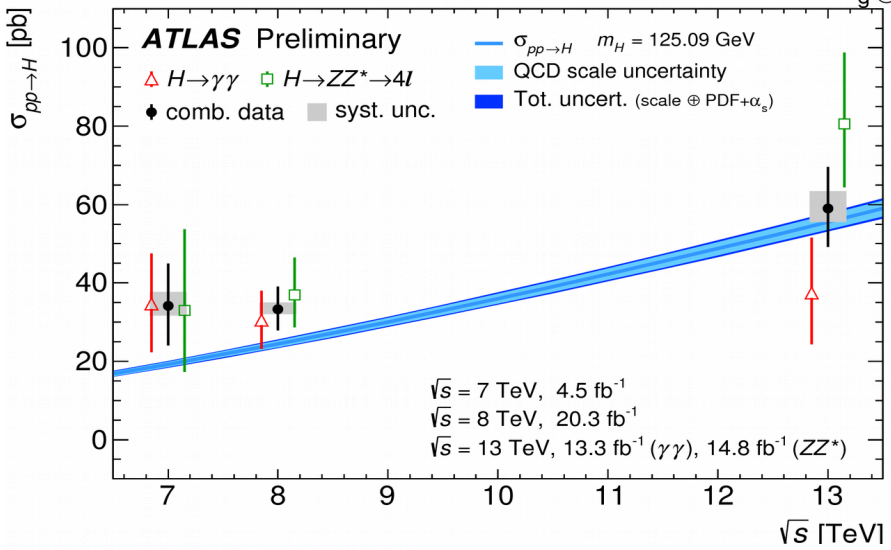


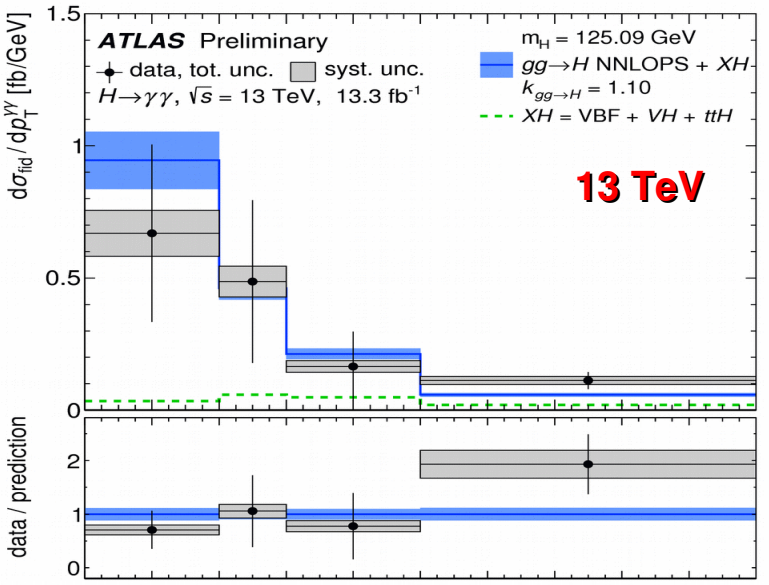


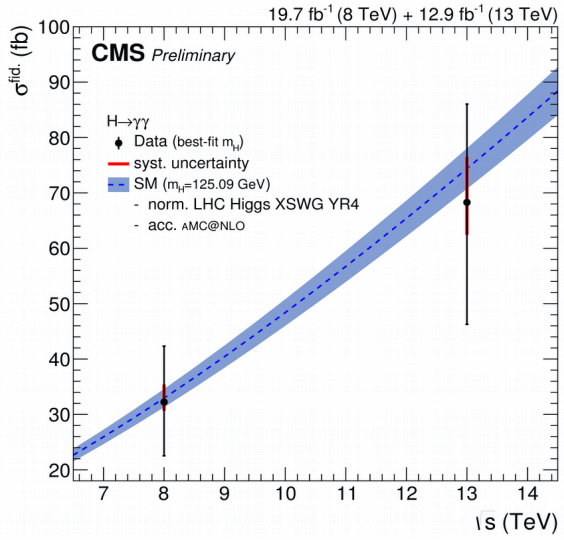
Wealth of hard QCD data: Higgs boson

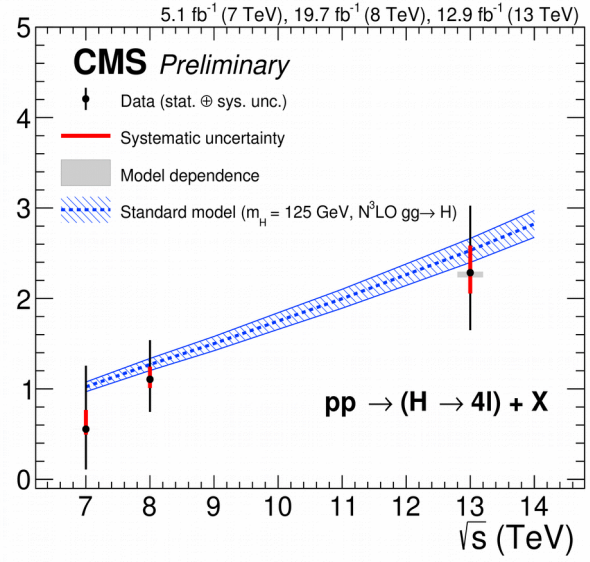
- √s = 7,8,13 TeV (central rapidities):

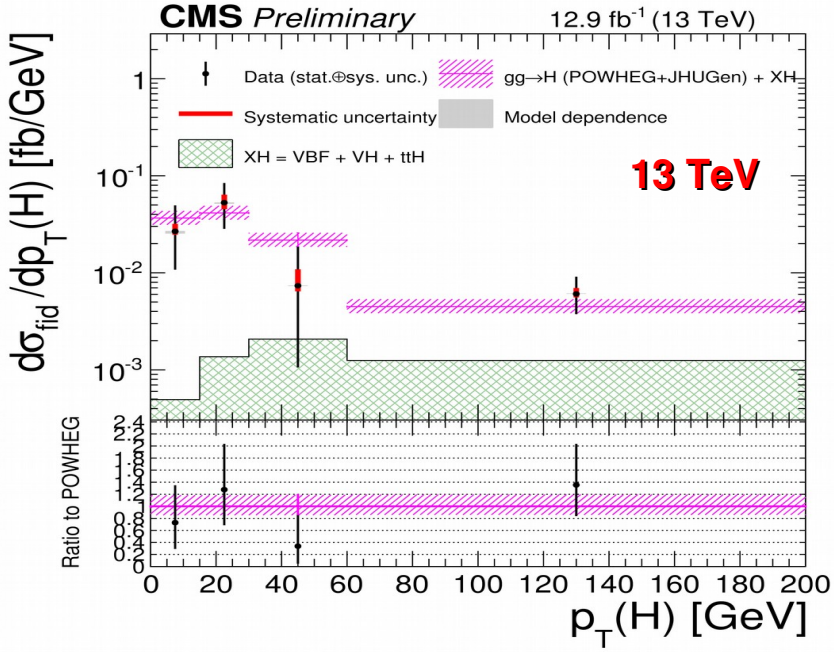




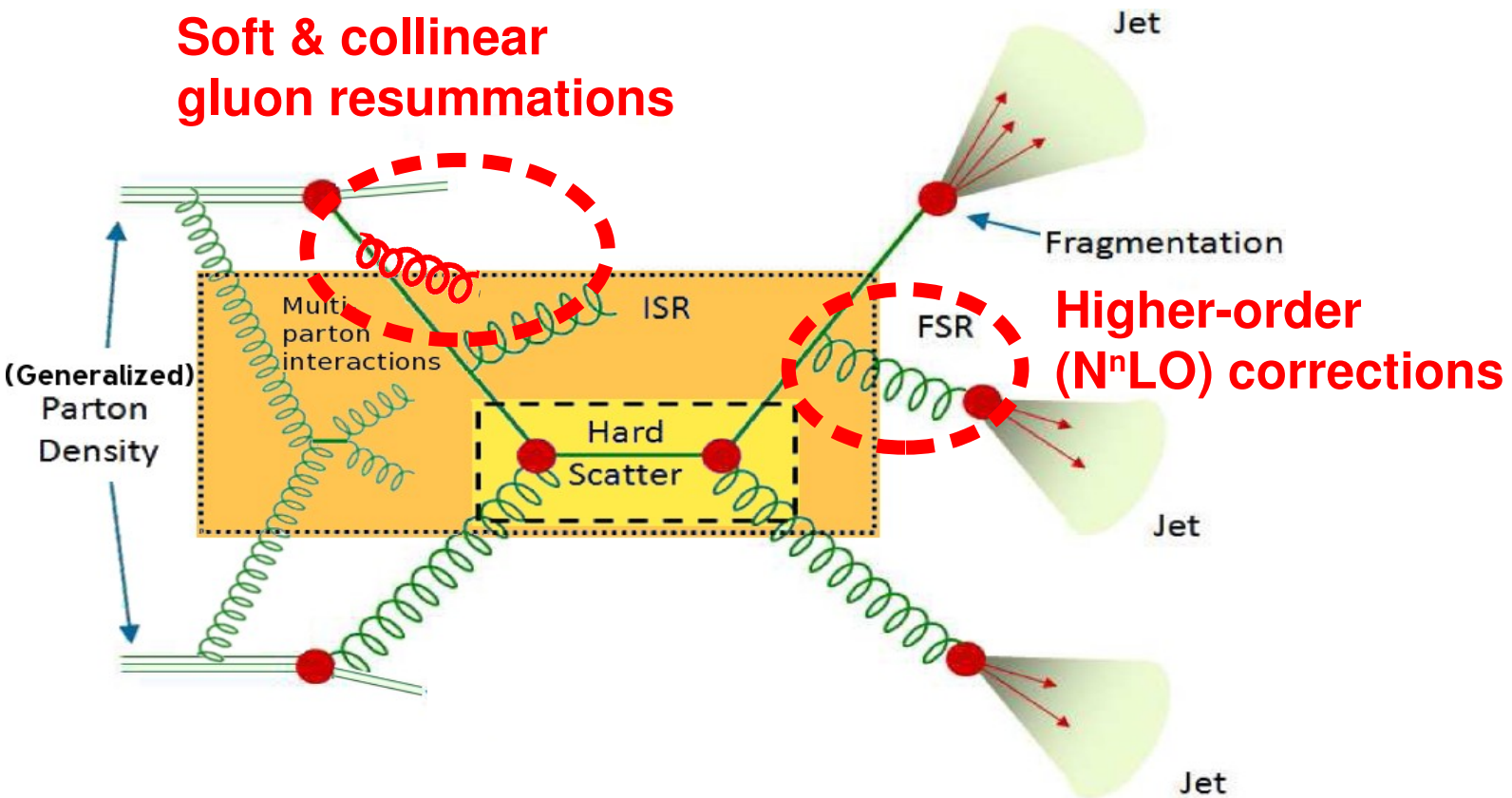






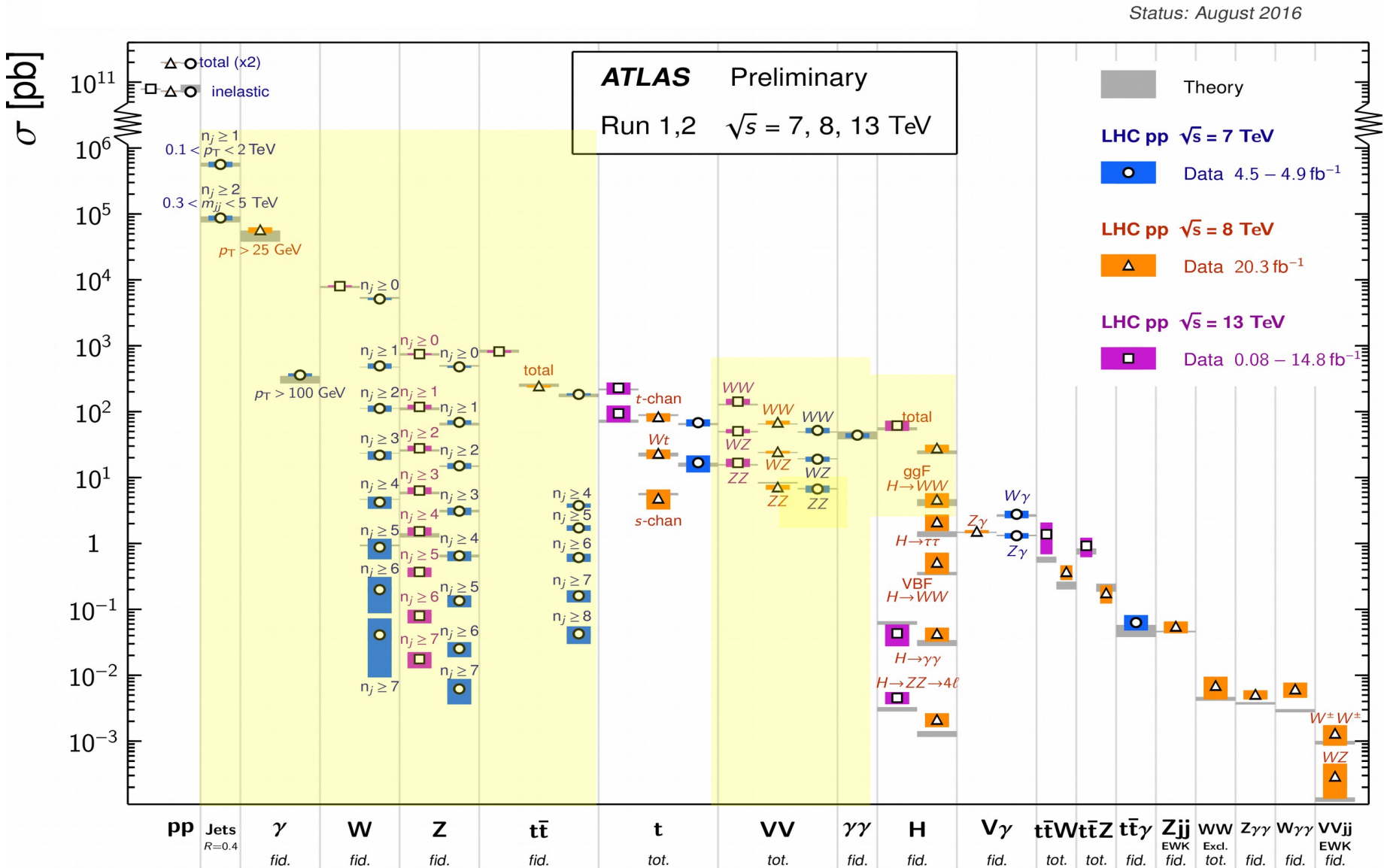


Higher-order & resummations



Total hard cross sections: Data vs. pQCD

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



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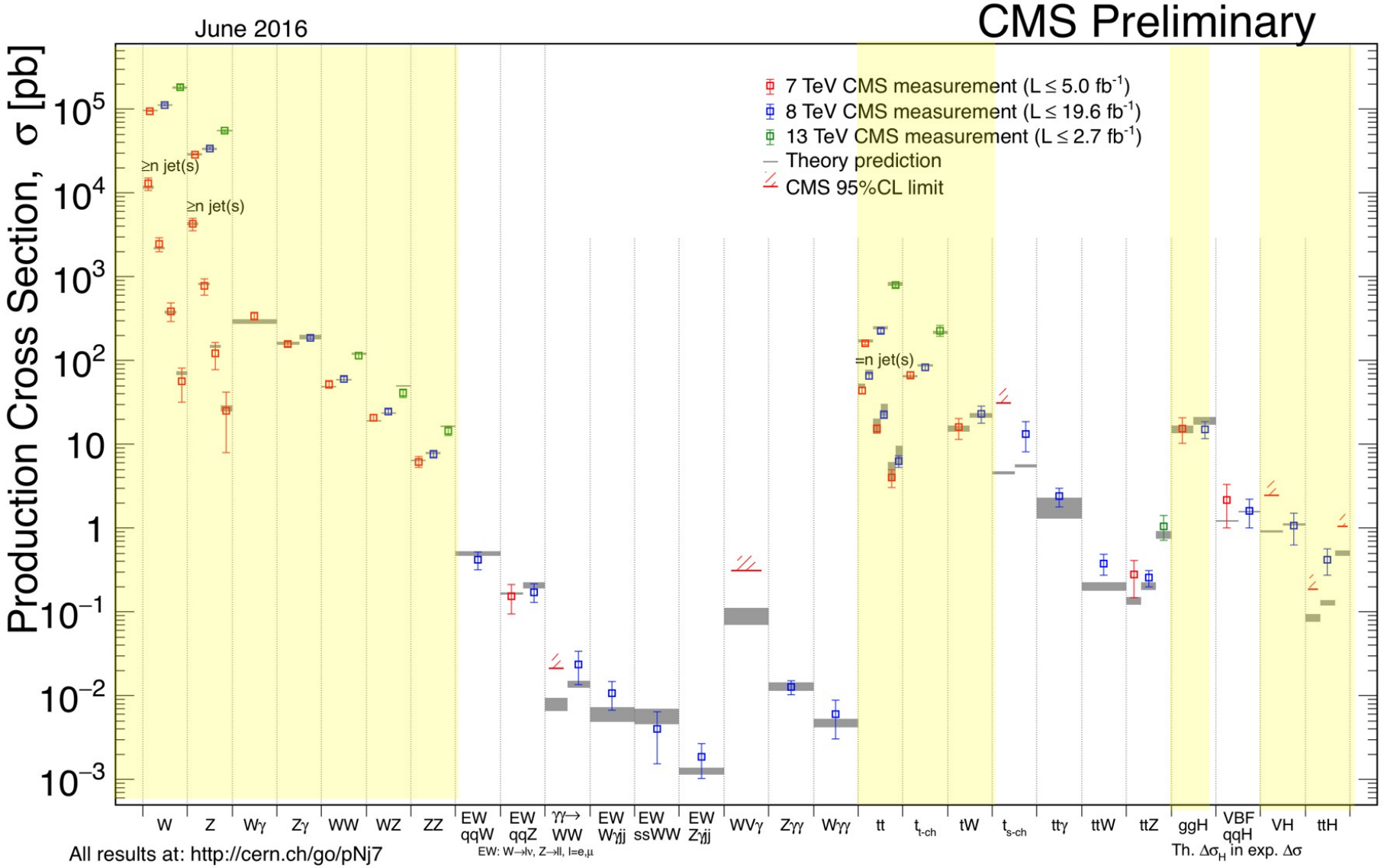
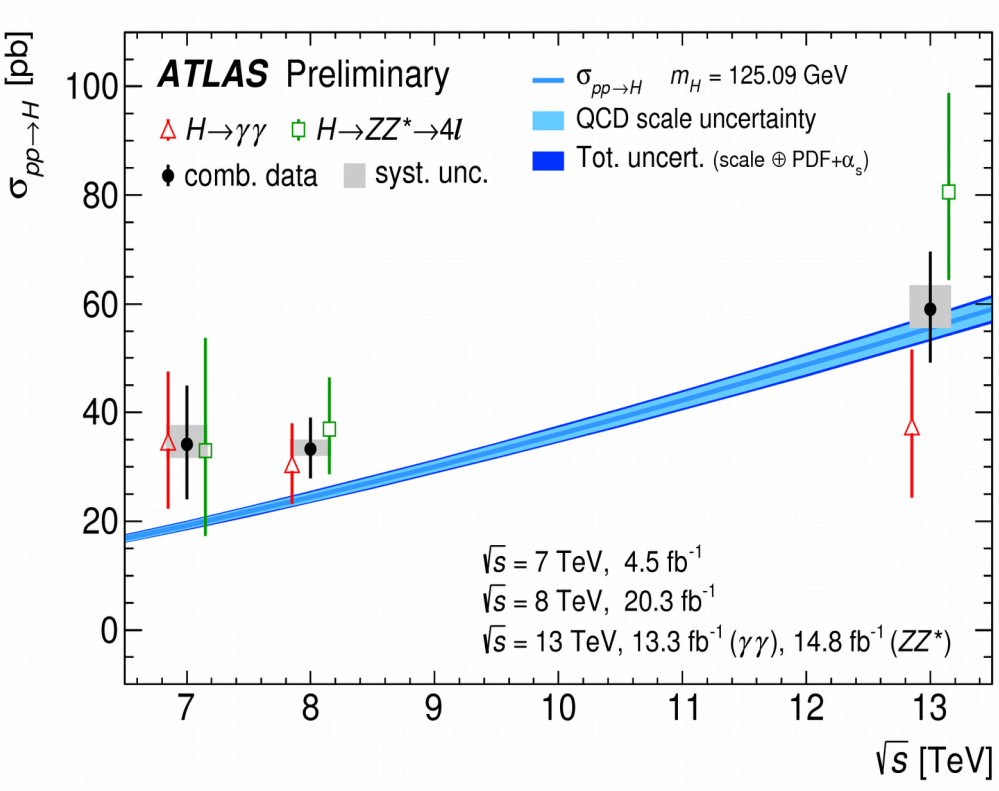


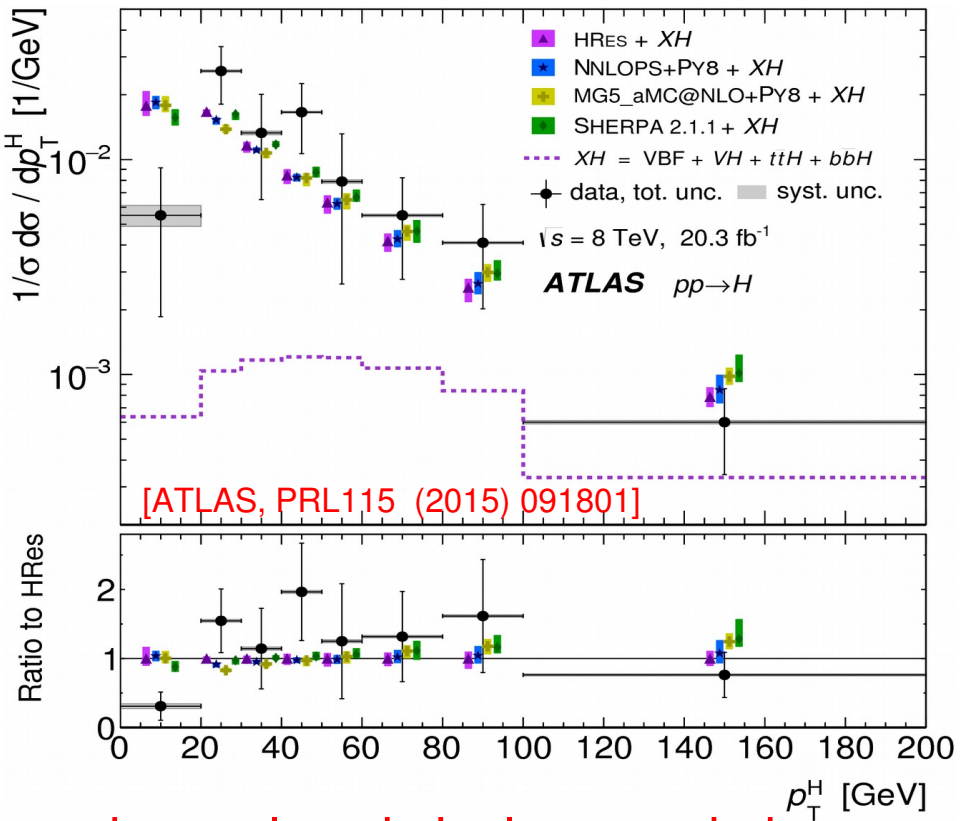
Higgs x-sections: Data vs. NNLO+NNLL

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

Higgs $\sigma(pp \to H)$ vs N^3LO:



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



- Decent agreement within still large experimental statistical uncertainties

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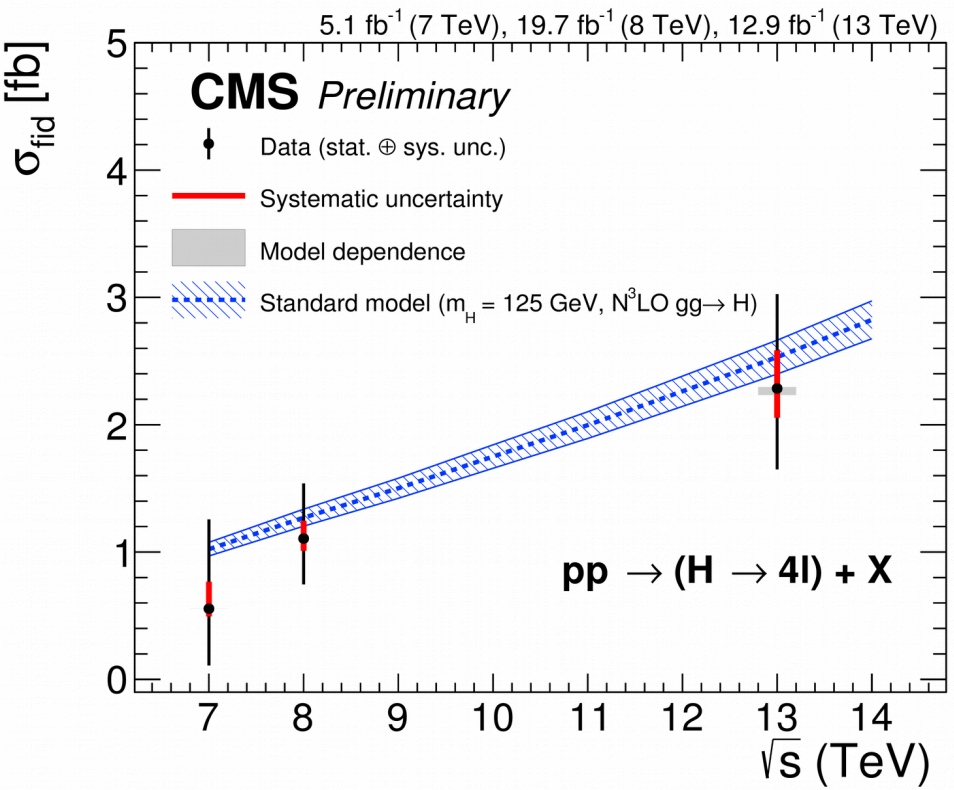

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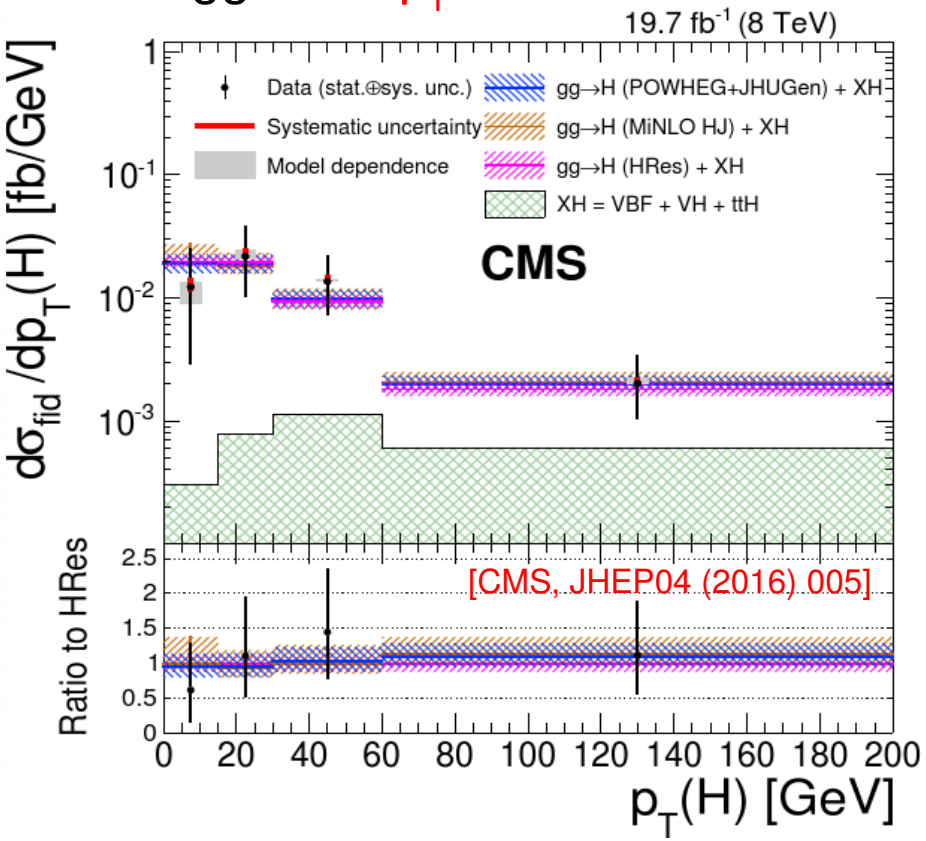
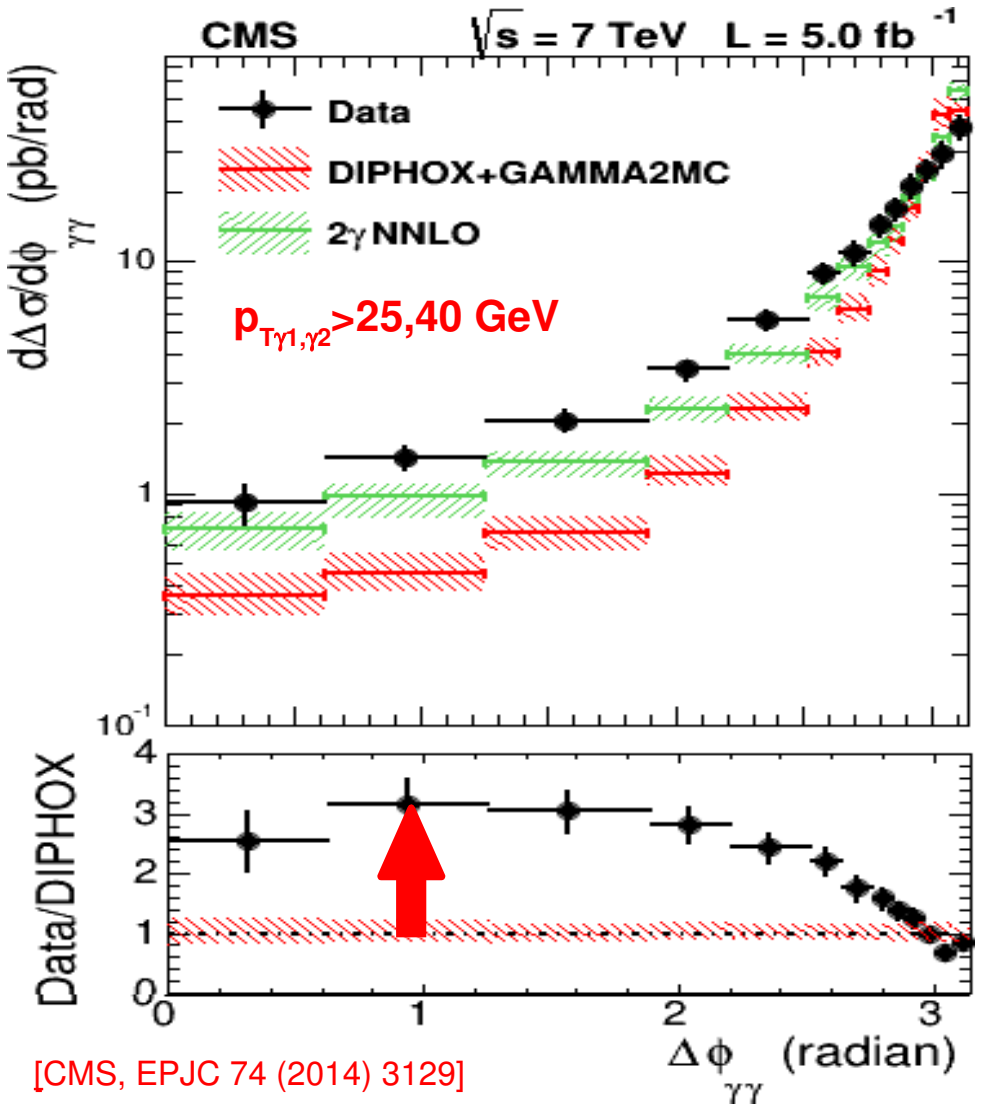


- Decent agreement within still large experimental statistical uncertainties

Diphoton x-sections: Role of NNLO corrections

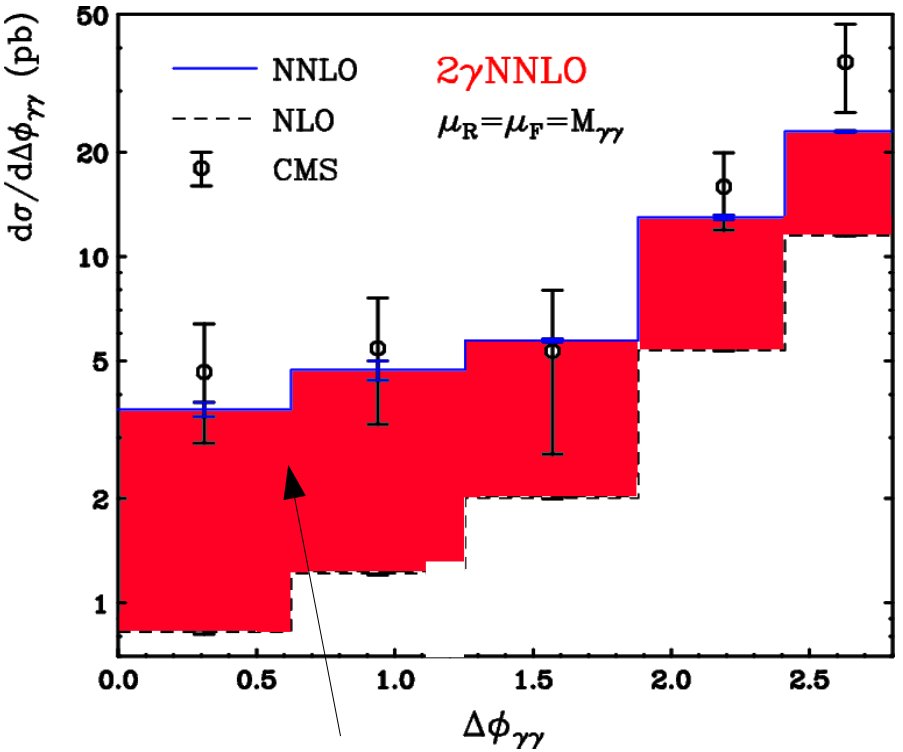
- NLO largely underestimates increasingly collinear γ's ($\Delta\varphi<2.5$):



[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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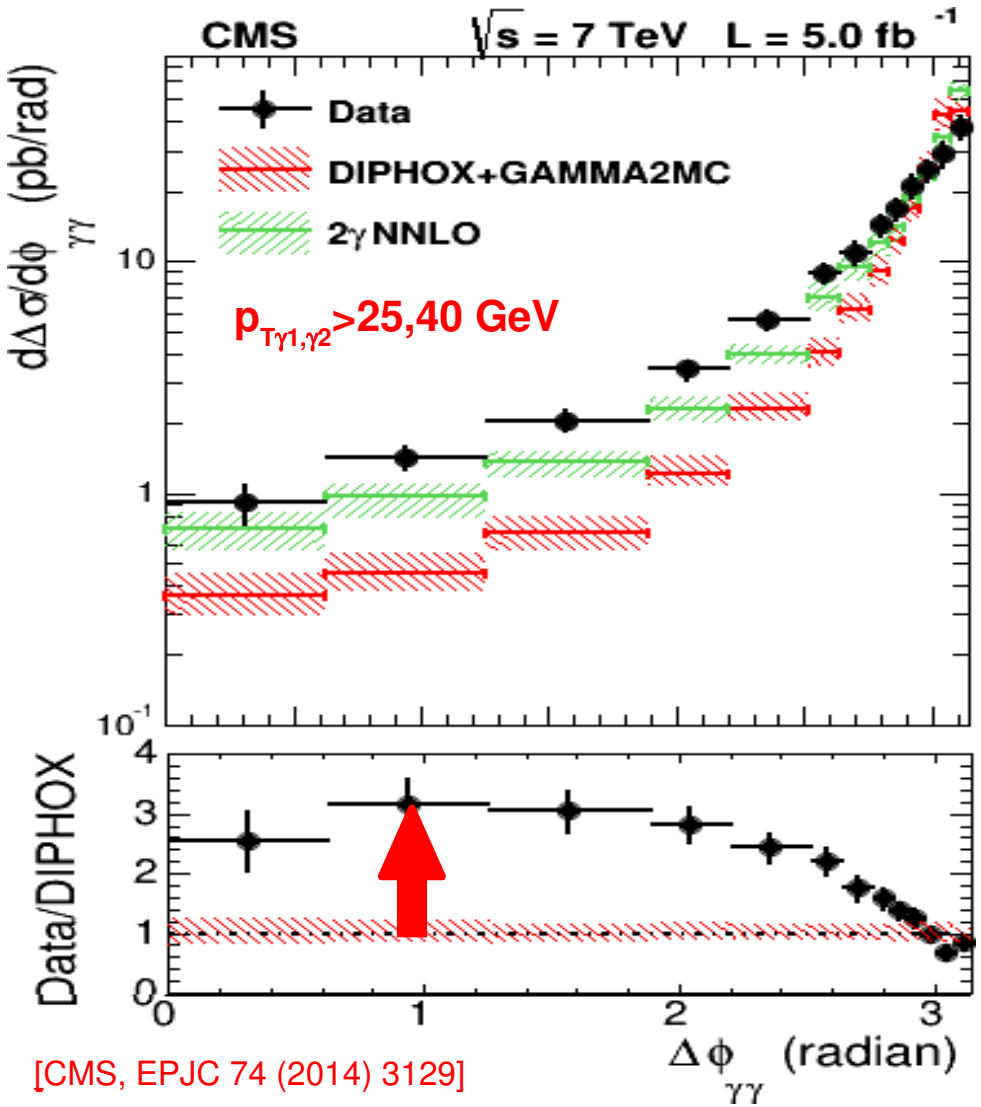

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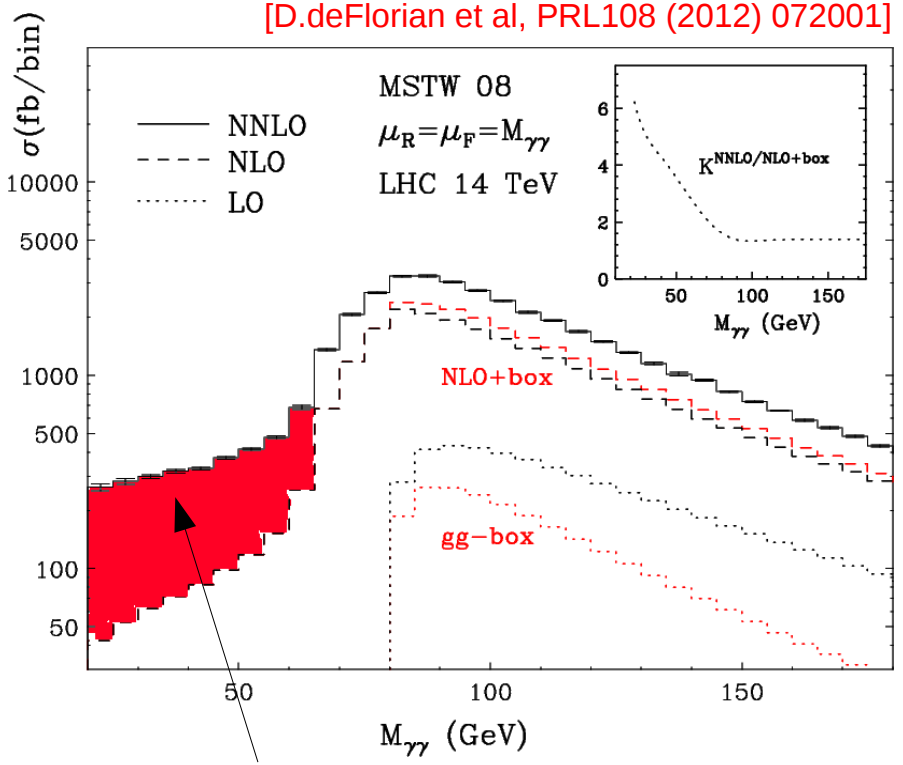
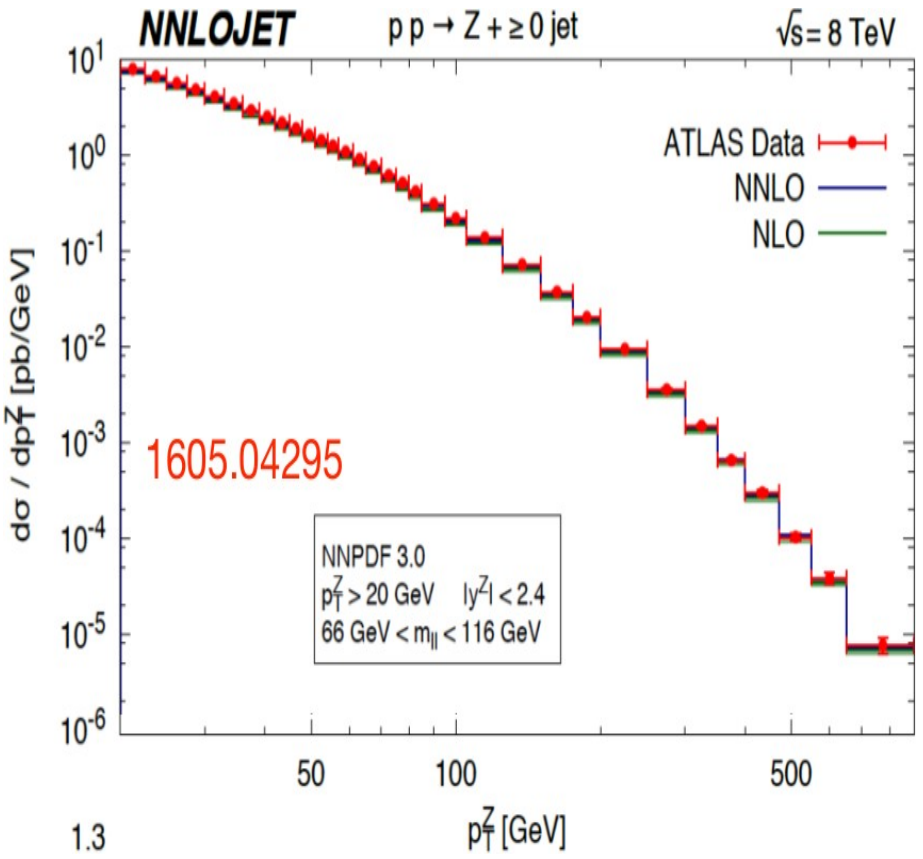


Enhanced NNLO production of collinear γ's (e.g. qq →qqγγ) "fills" out relevant regions of phase-space.

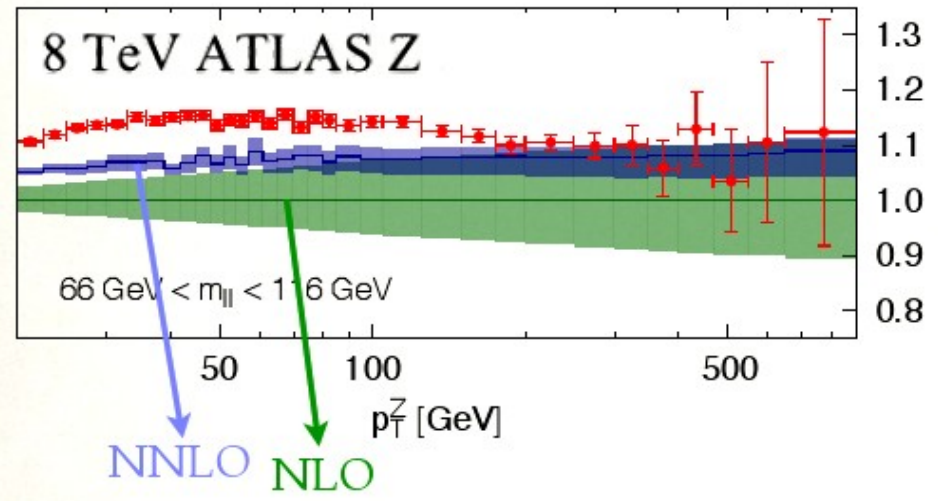
Z+j boson x-sections: Role of NNLO corrections

- Z yields at high p_T are ~10% underestimated by NLO.
- NNLO-data diff.: <5% at high-p_T

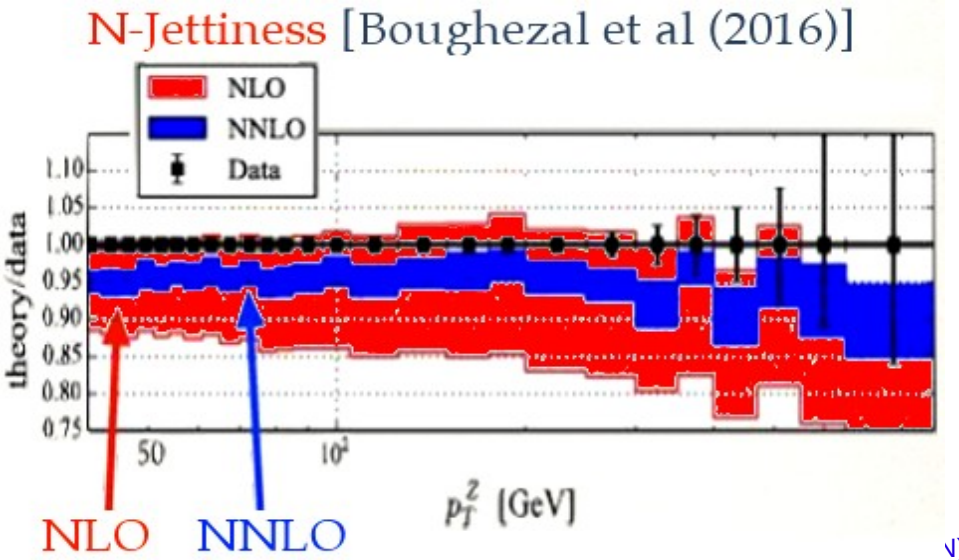
& much reduced scale uncertainties:



Antenna [Gehrmann-de Ridder et al (2016)]

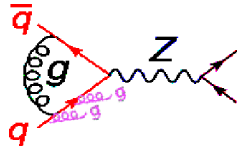


N-Jettiness [Boughezal et al (2016)]

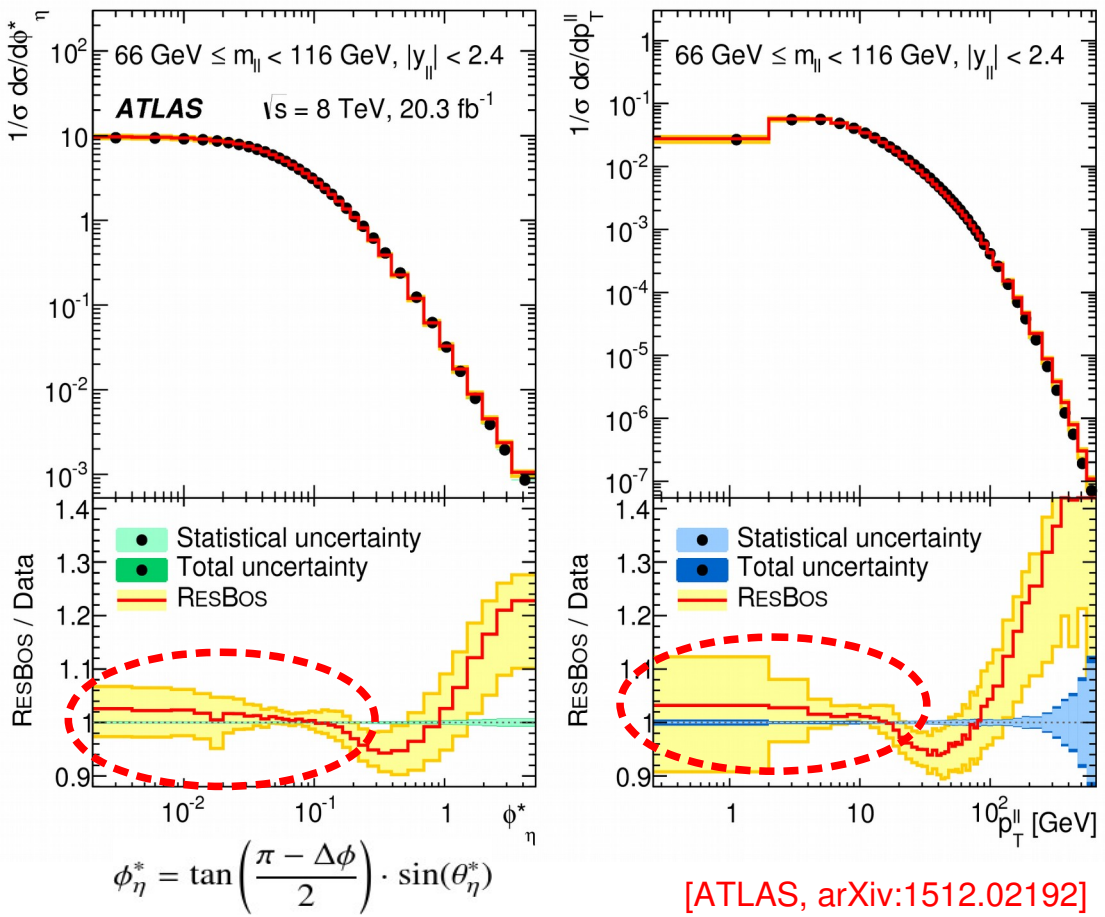


Z boson x-sections: Role of resummations

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



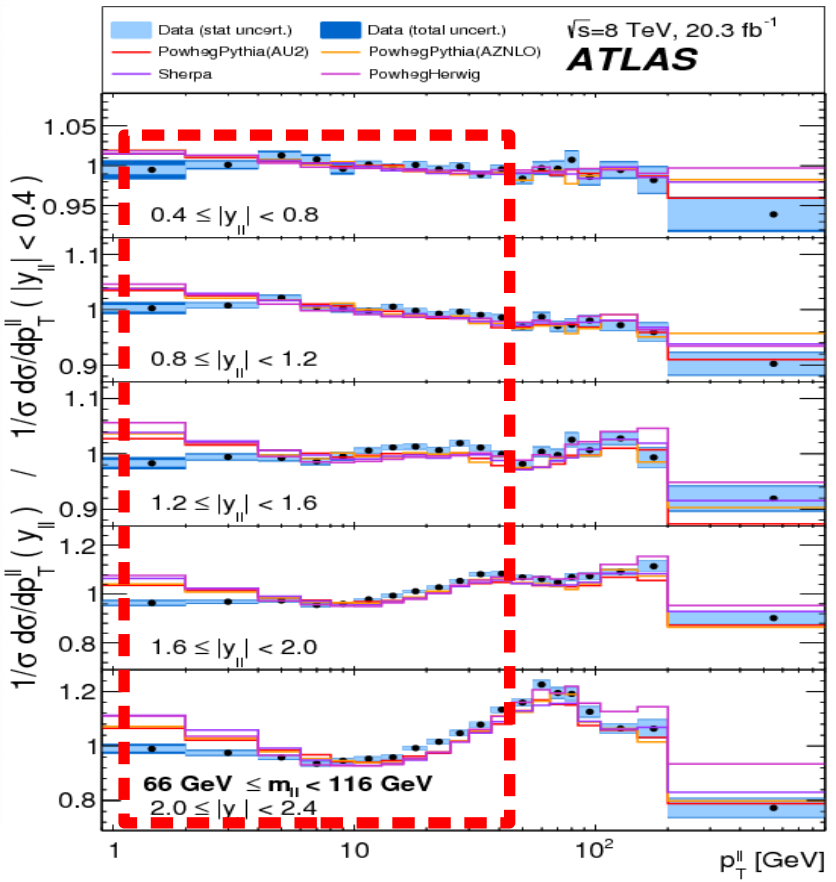
- NLO+NNLL resummations are crucial to reproduce the Z spectra at low-p_T:



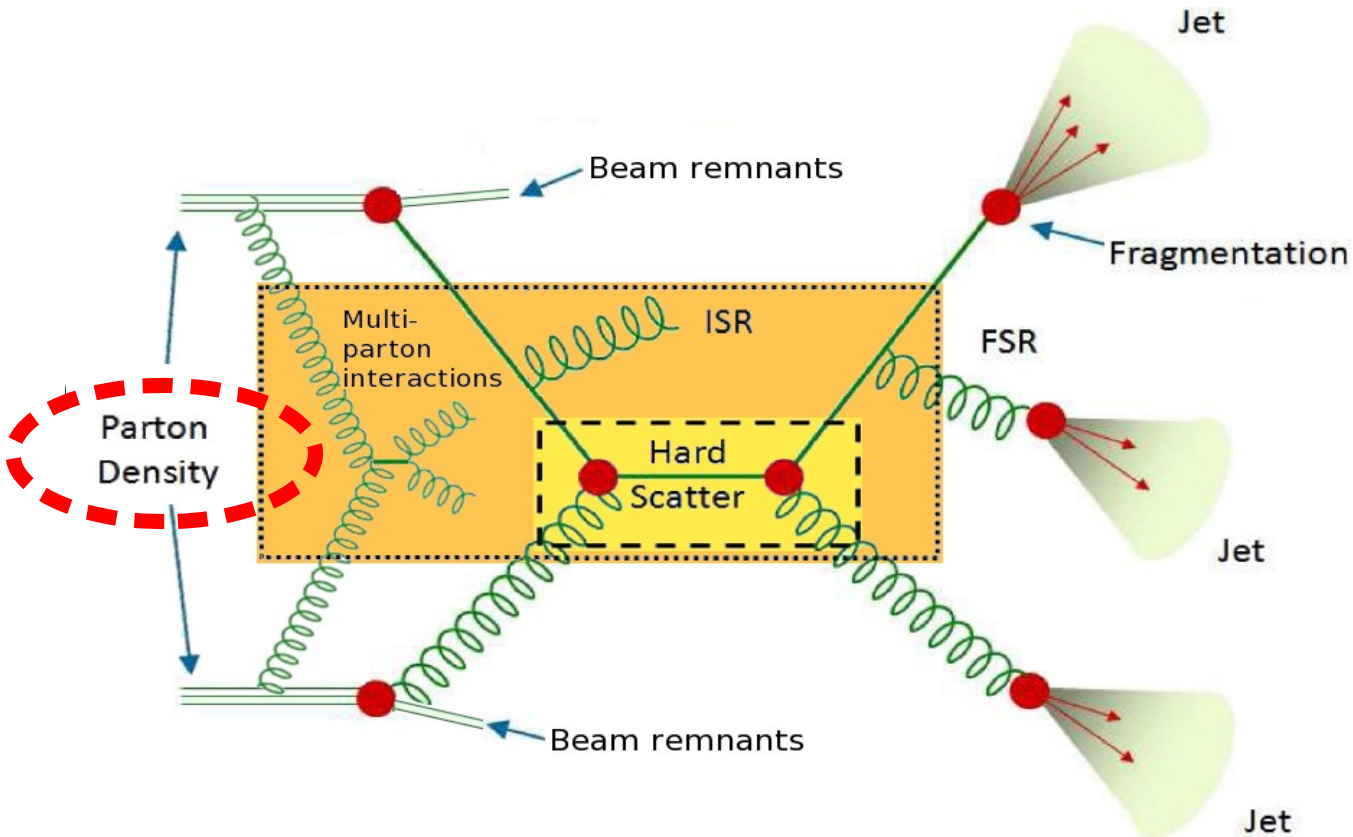
$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta^*_\eta)$$

[ATLAS, arXiv:1512.02192]

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

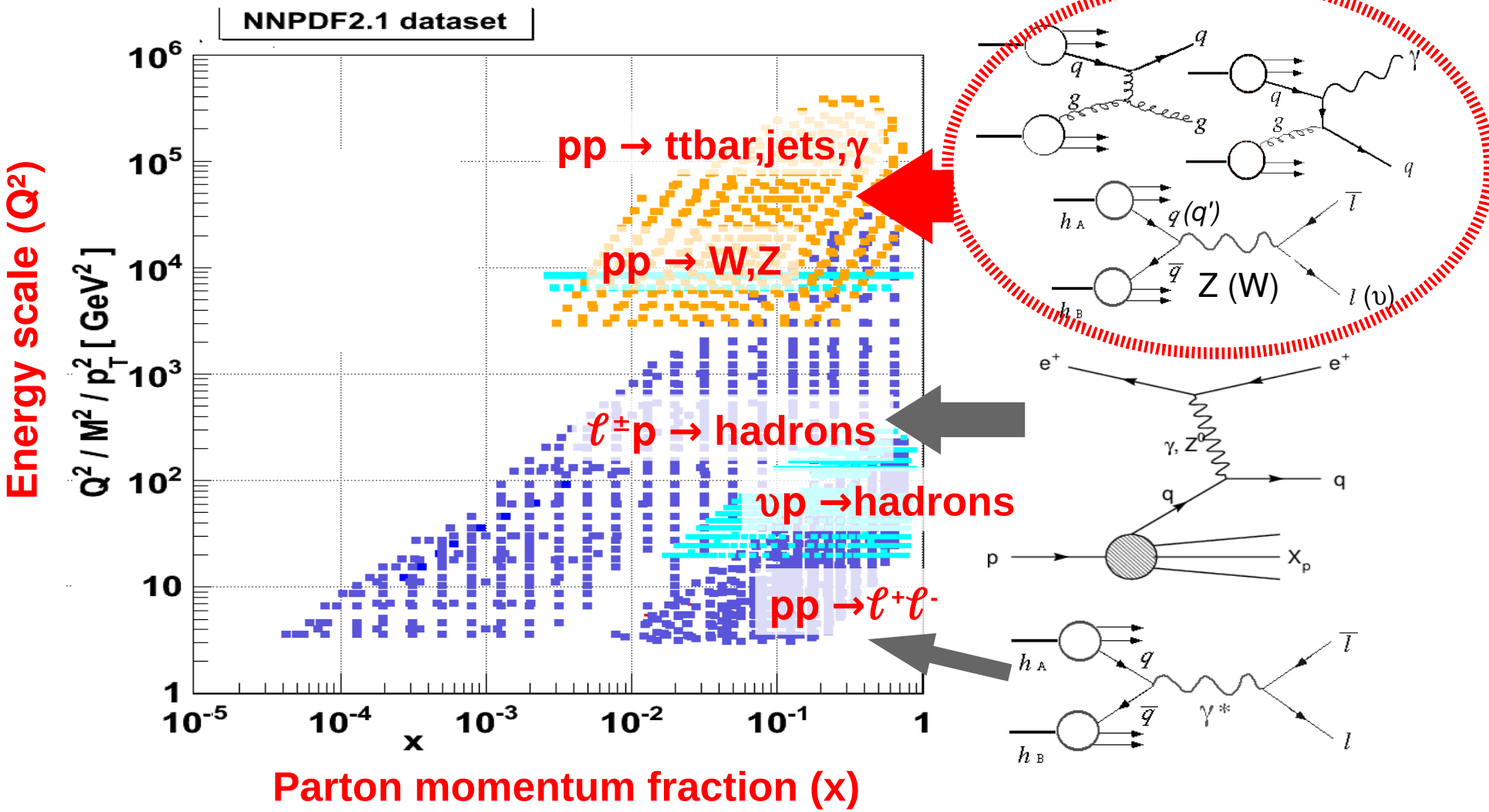


Parton distribution functions



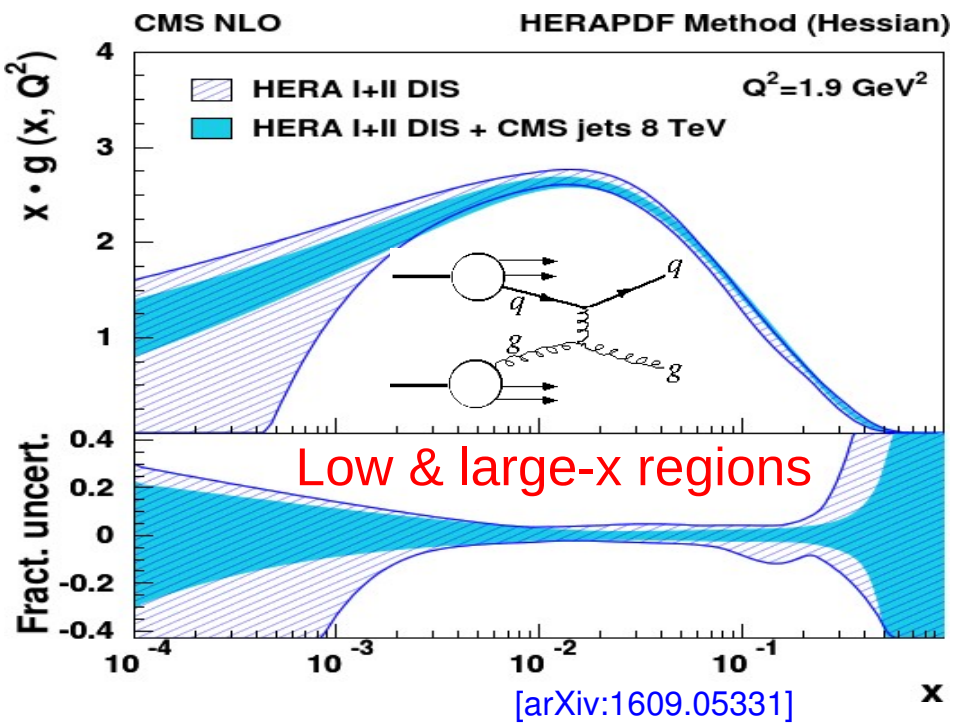
Extraction of PDFs via global fits

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

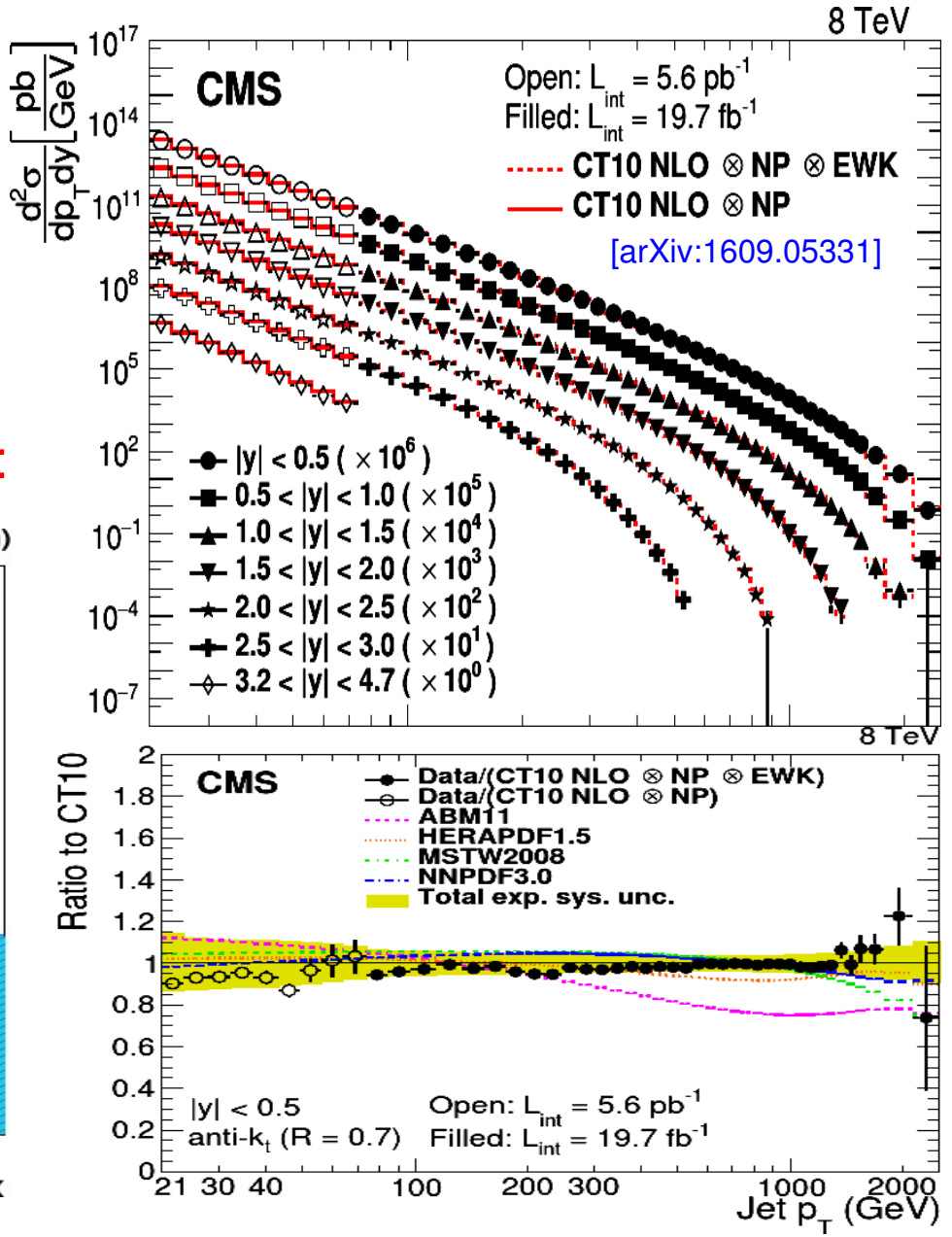


Gluon PDF constraints from jets

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

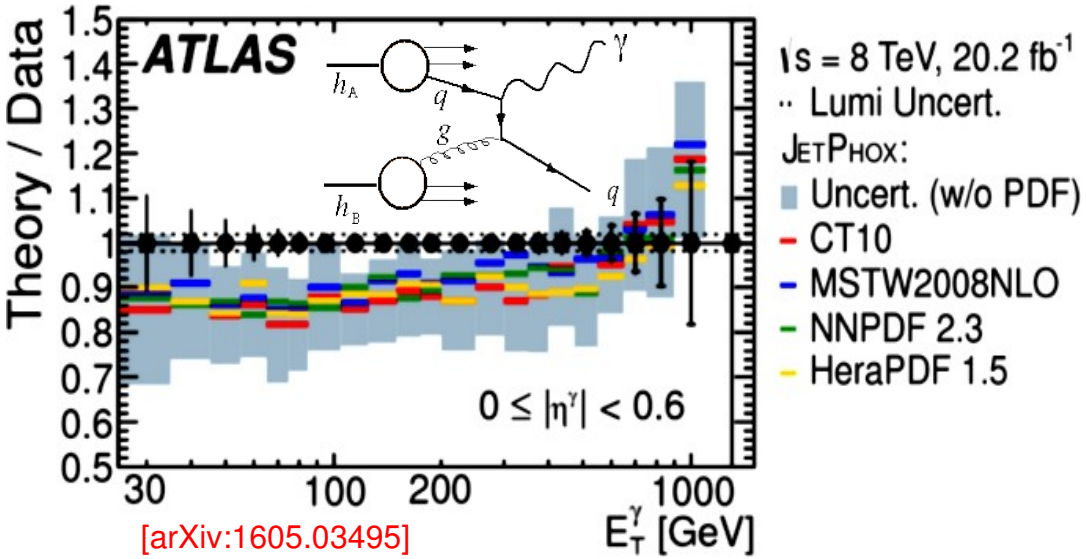


[arXiv:1609.05331]



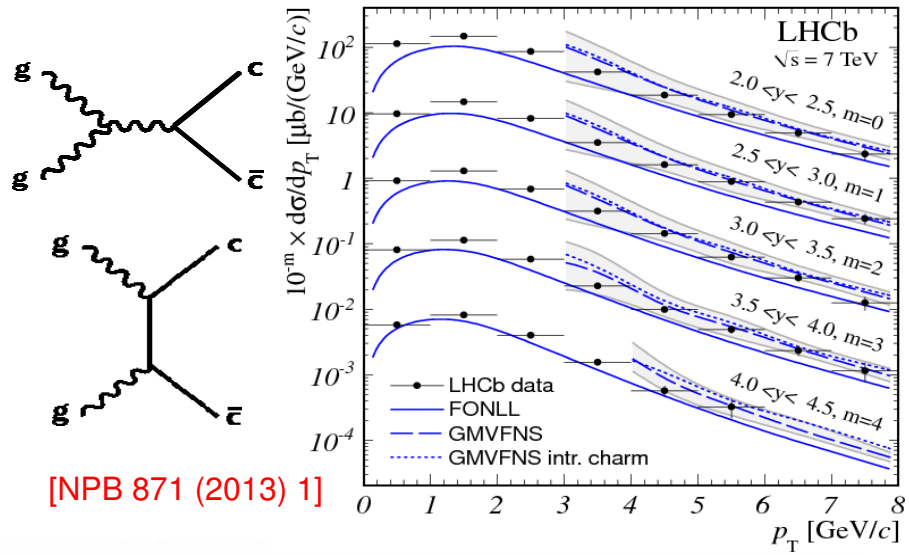
Gluon PDF constraints from γ, charm, t-tbar

- Isolated photon p_T spectra:



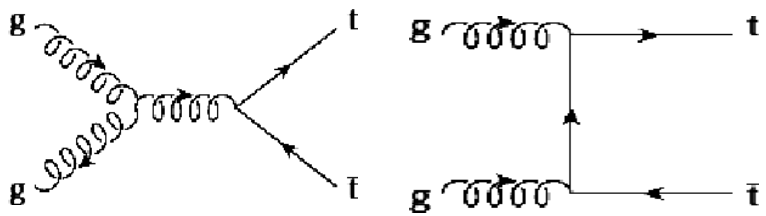
[arXiv:1605.03495]

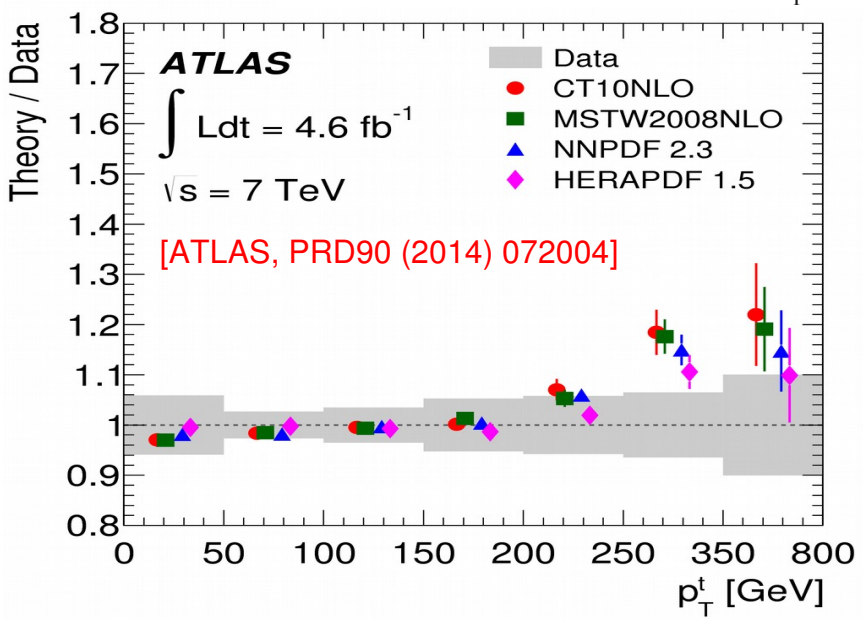
- Forward D-mesons (LHCb):



[NPB 871 (2013) 1]

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

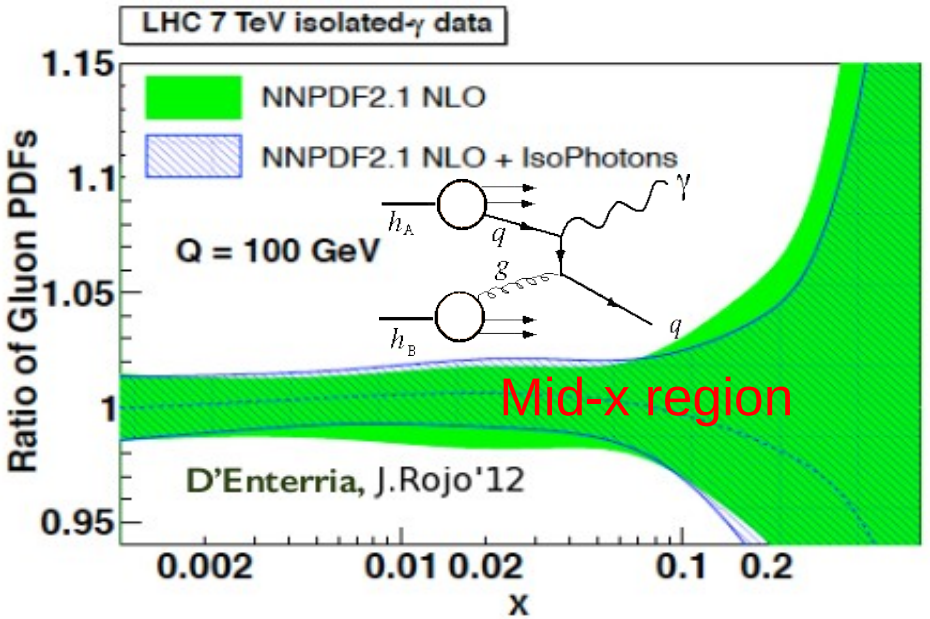




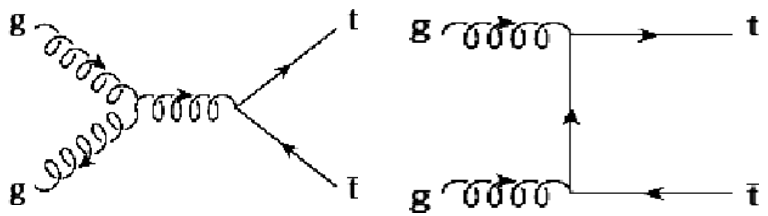
[ATLAS, PRD90 (2014) 072004]

Gluon PDF constraints from γ, charm, t-tbar

- Isolated photon p_T spectra:

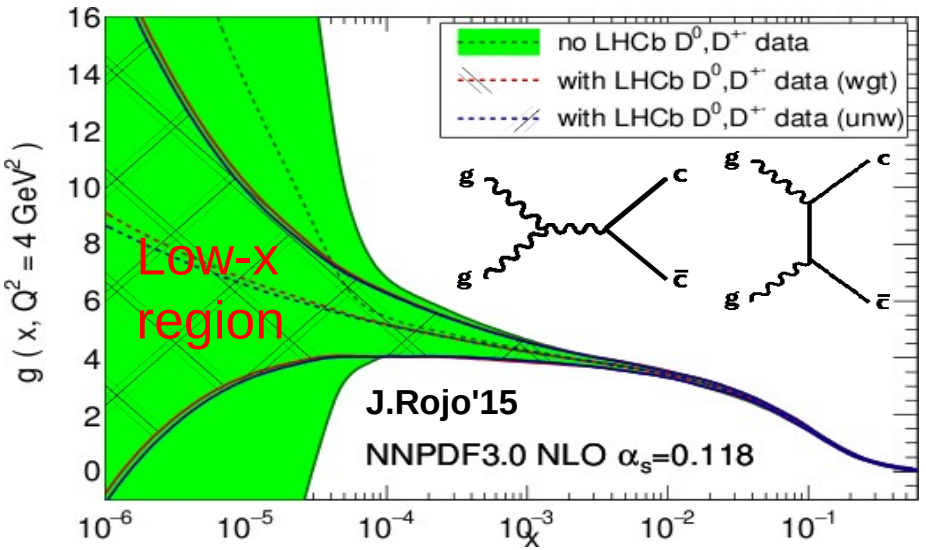


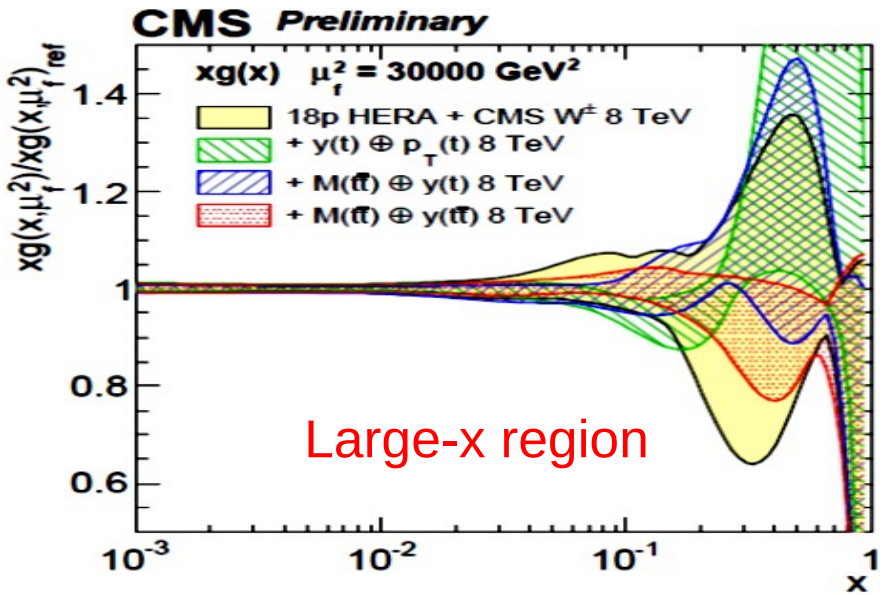
- Top-pair differential x-sections (NNLO):



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

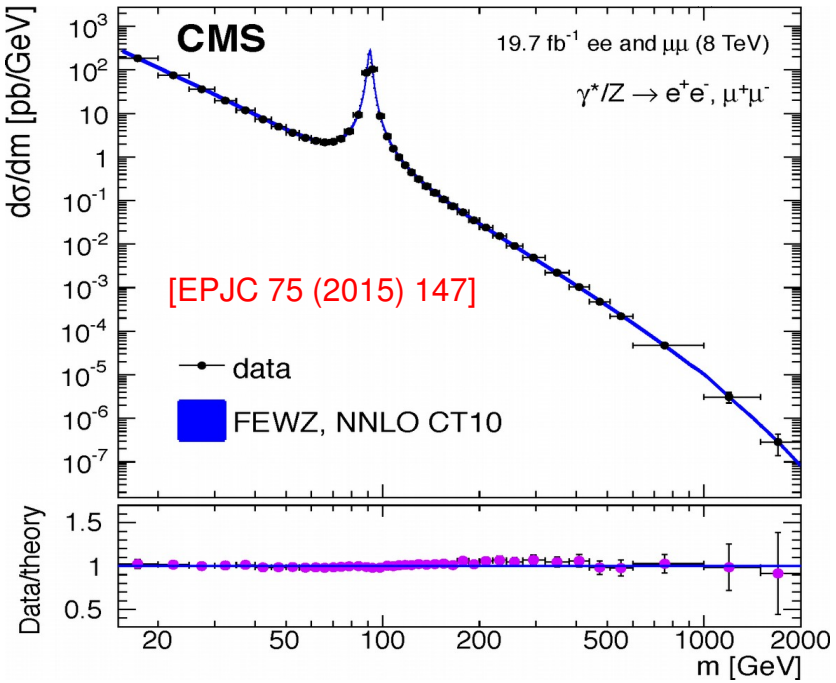
- Forward D-mesons (LHCb):

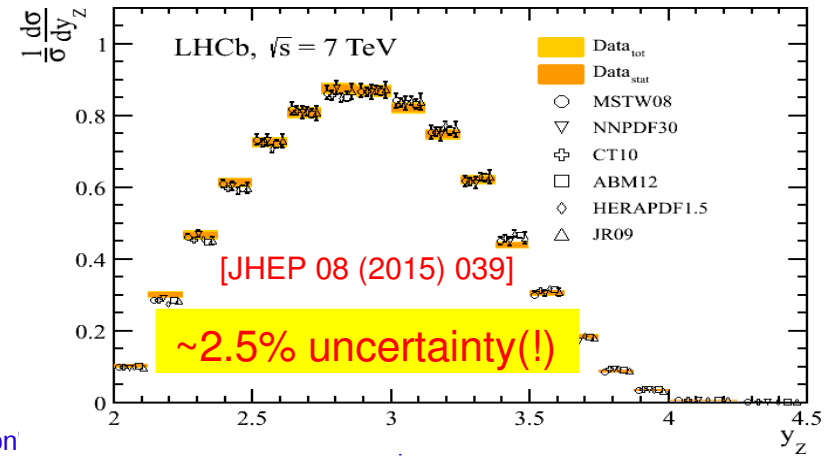


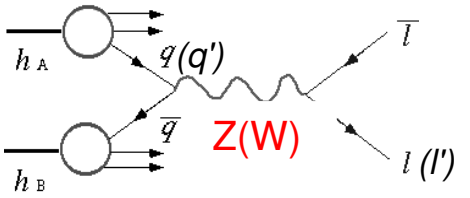


Quark PDF constraints from W, Z "std. candles"

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

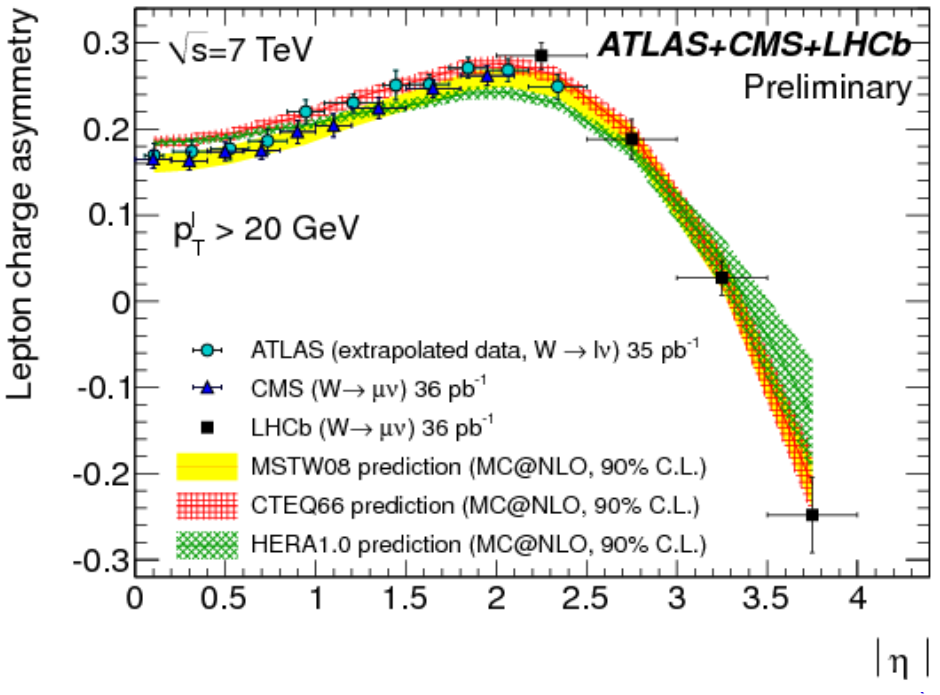






- W electron charge asymmetry vs |η| measured to ~1%. Many uncertainties cancel in ratio. Constrains u/d PDF ratio

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



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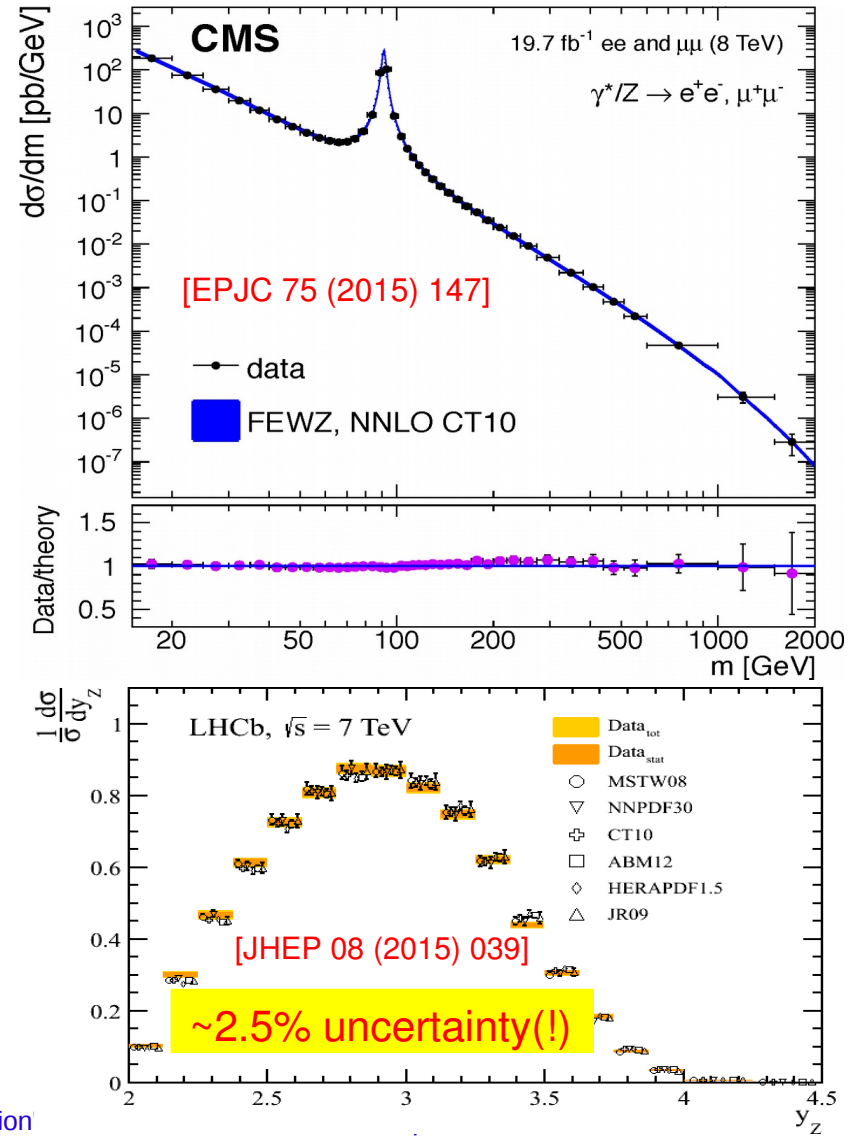

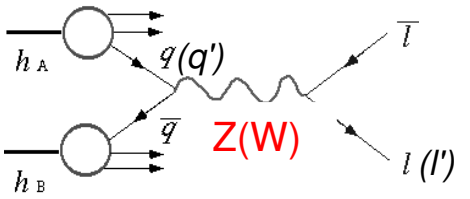

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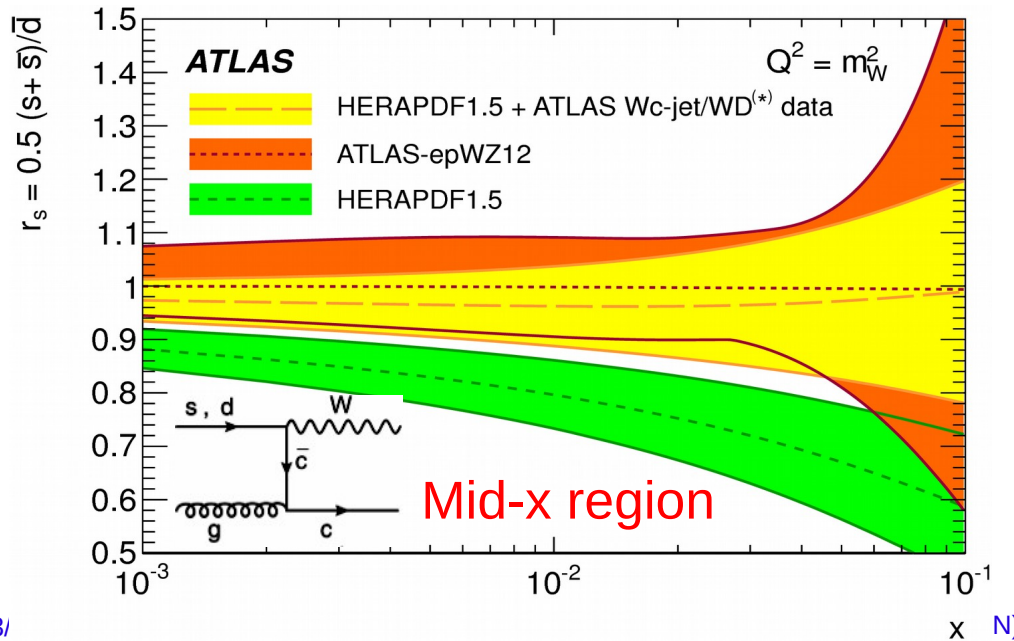
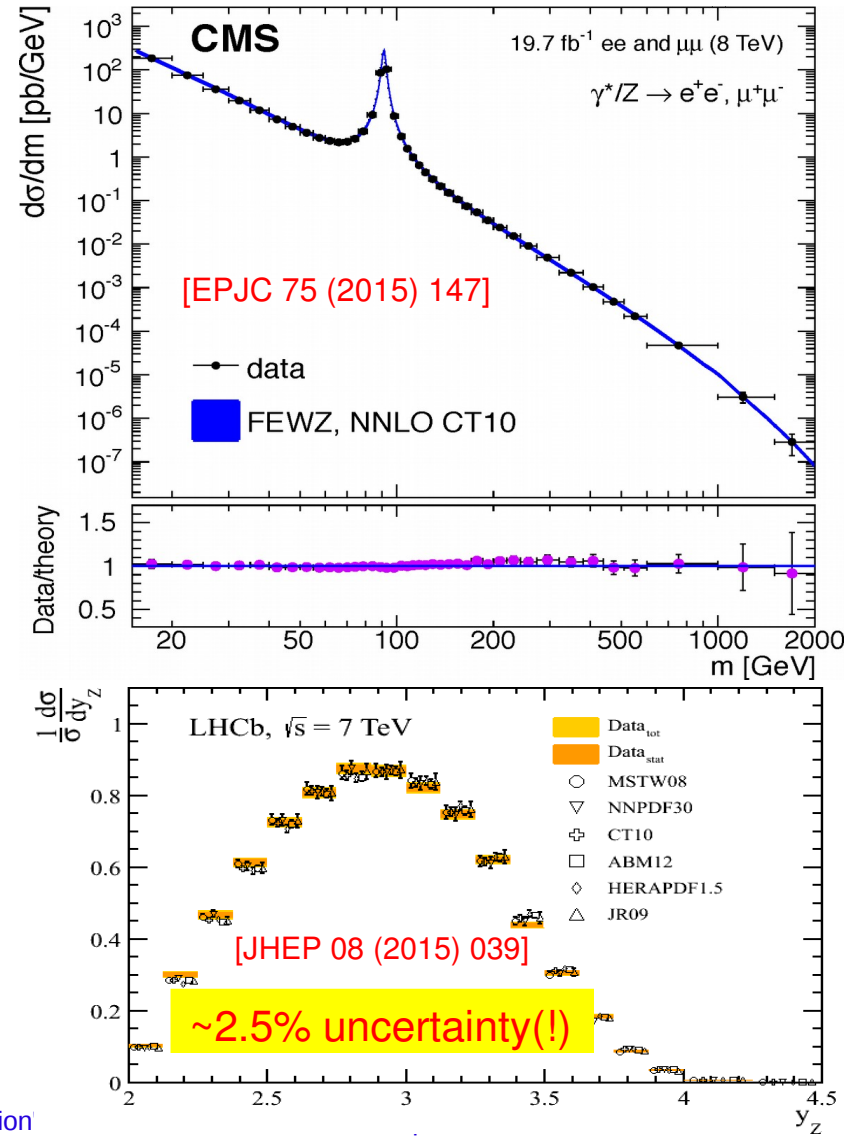
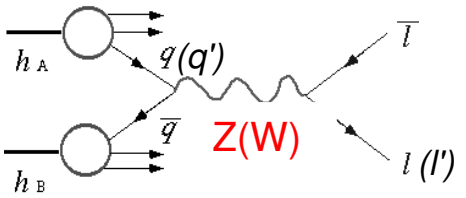
- W+charm constrains s/d PDF ratio:



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

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





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

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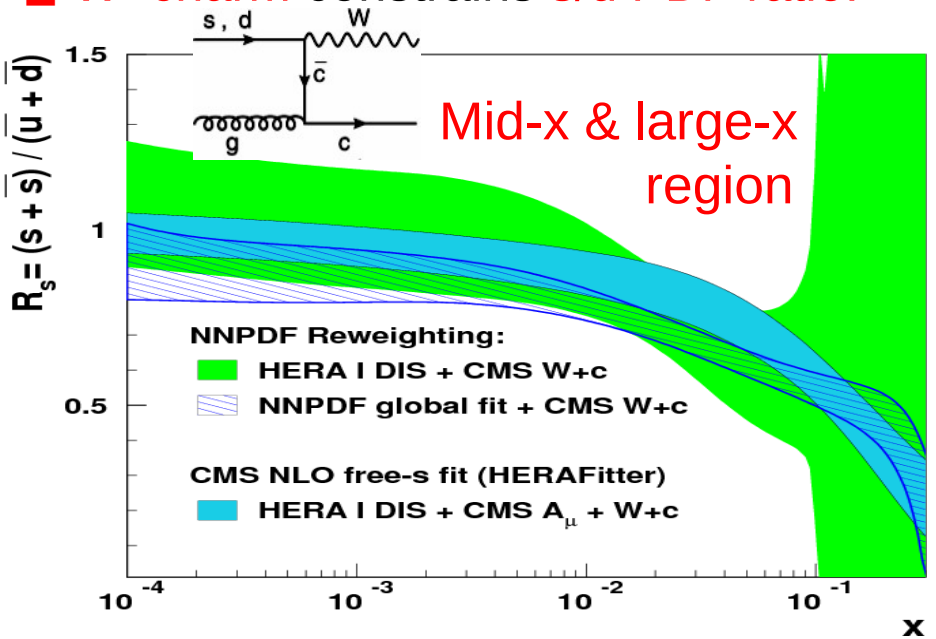
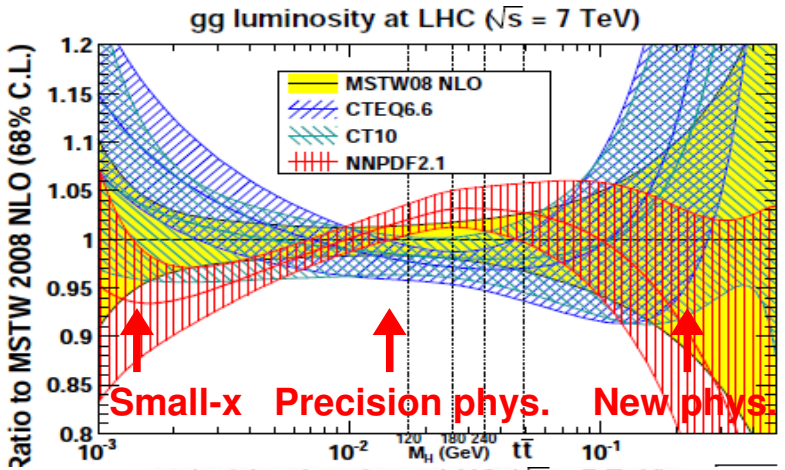


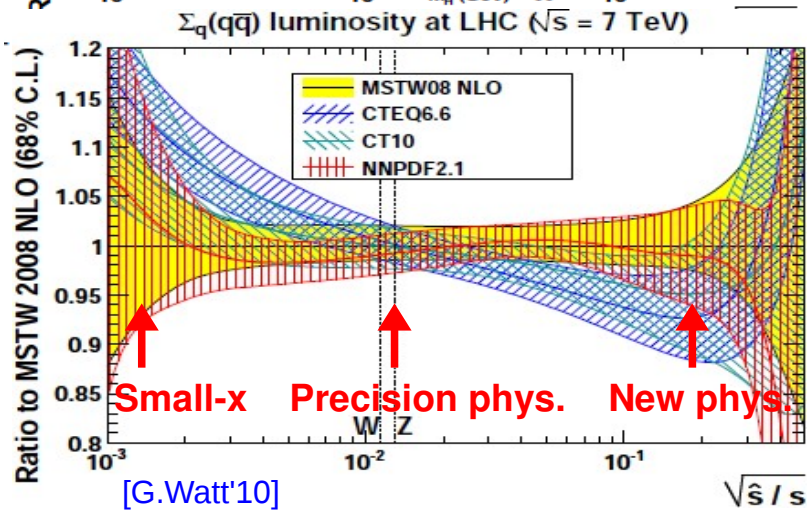
Updated PDF sets with LHC Run-1 data

- 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-&post-LHC Run-1 (biggest mods. from PDF benchmarking):

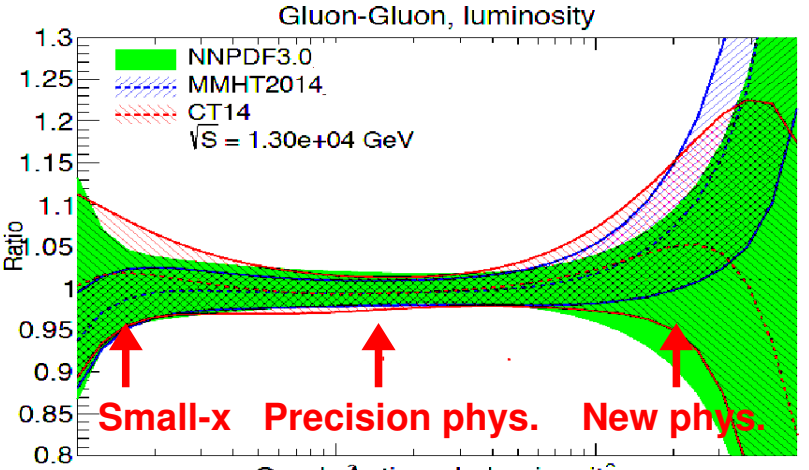
GLUONS

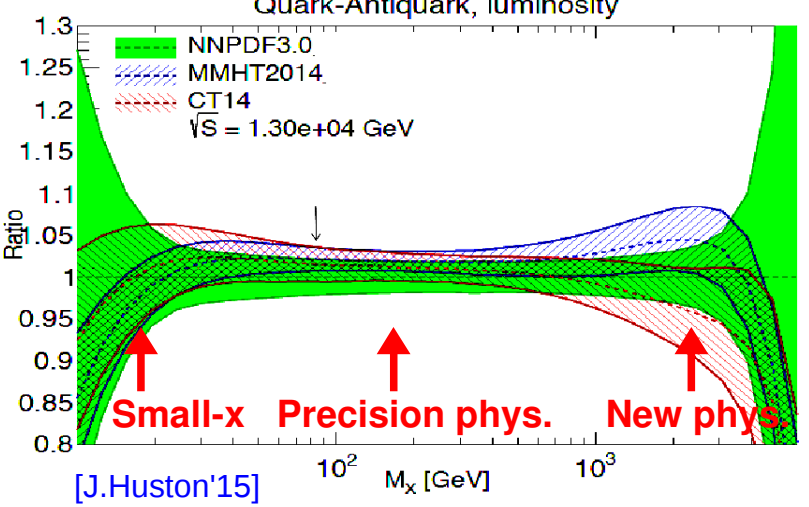


QUARKS



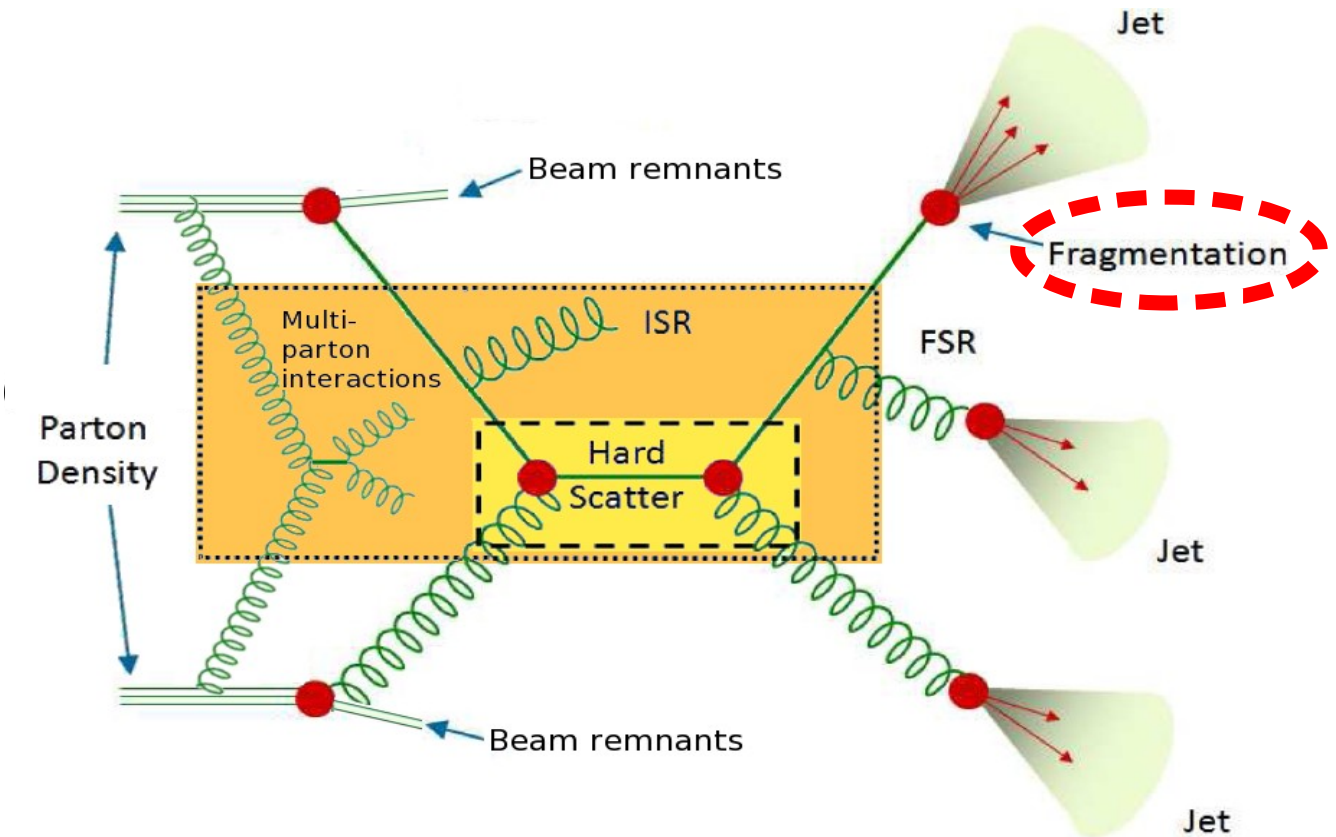
[G.Watt'10]





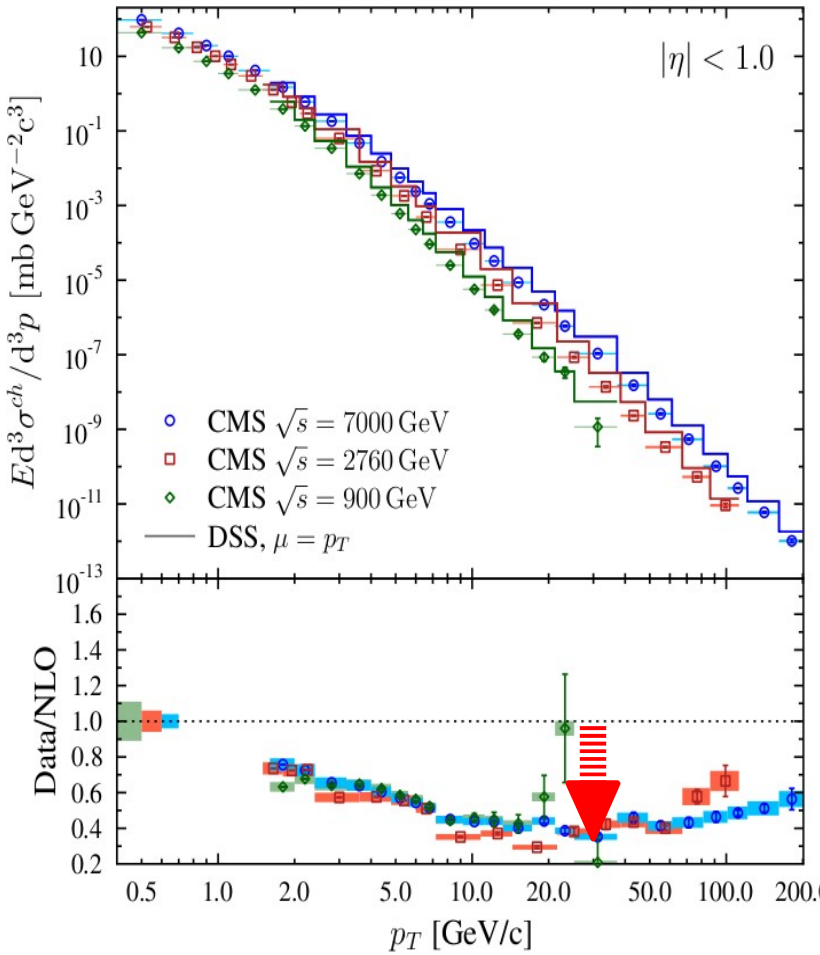
[J.Huston'15]

Parton fragmentation functions



High-p_T hadron spectra vs. NLO

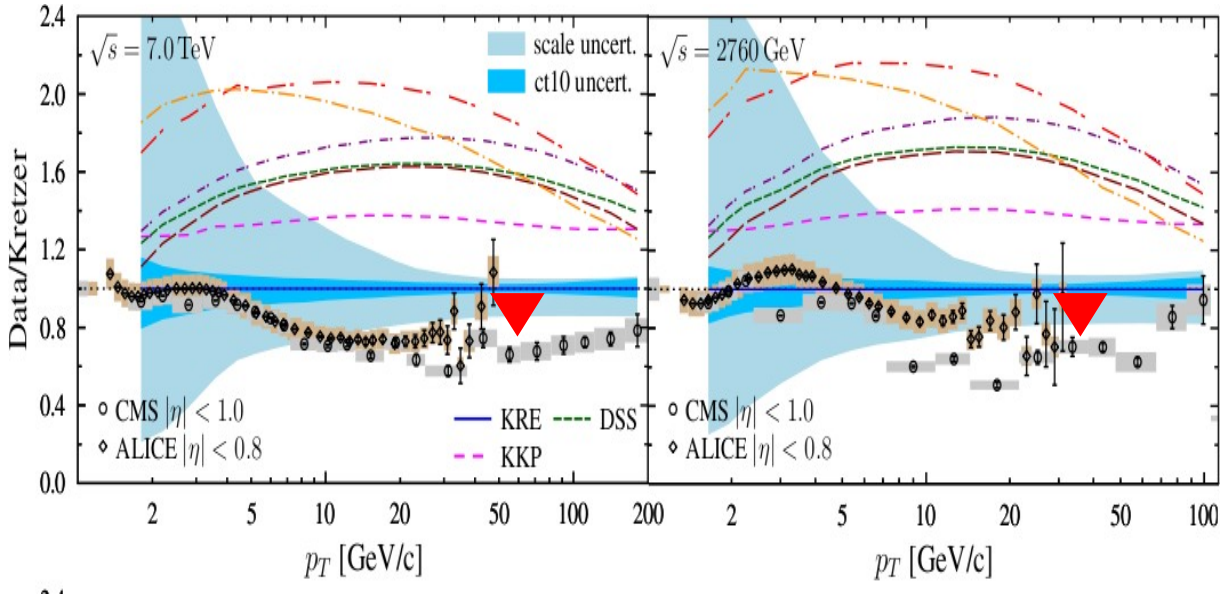
- NLO pQCD overpredicts high-p_T hadron cross sections by factor $\times 2$:



- All Fragmentation Functions (FFs) fail.

  Disagreement increases from $\sqrt{s}$=0.9 to 7 TeV

- "Old" Kretzer FF shows best agreement:



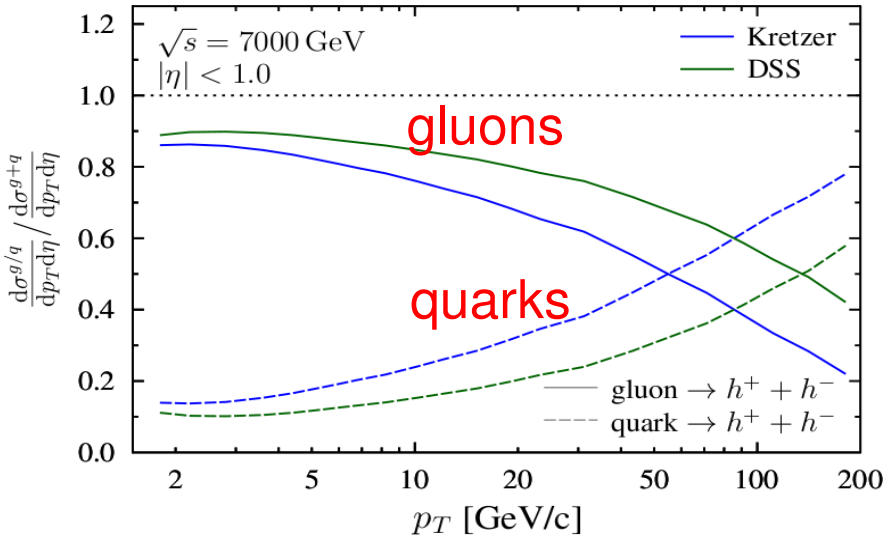
[Dd'E. et al, NPB883 (2014) 615]

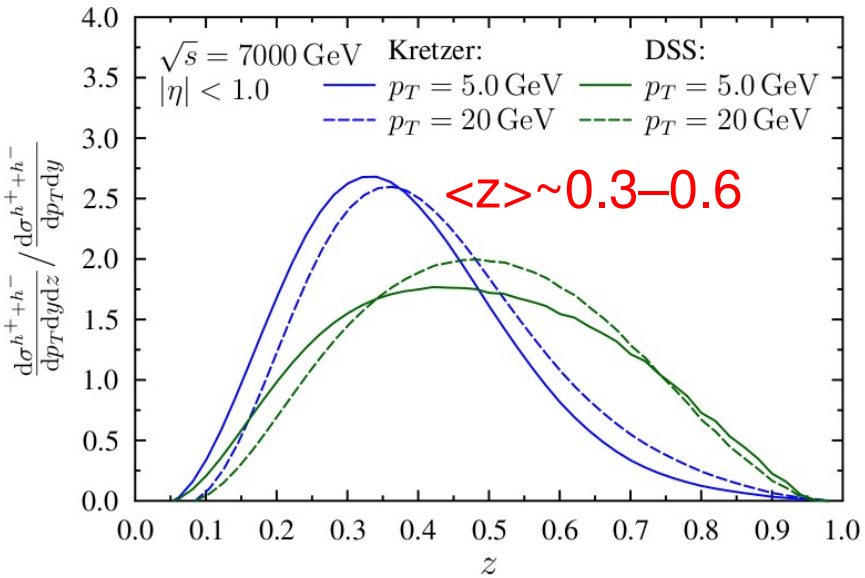
- Same NLO calculations reproduce well high-p_T jet and photon spectra:

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

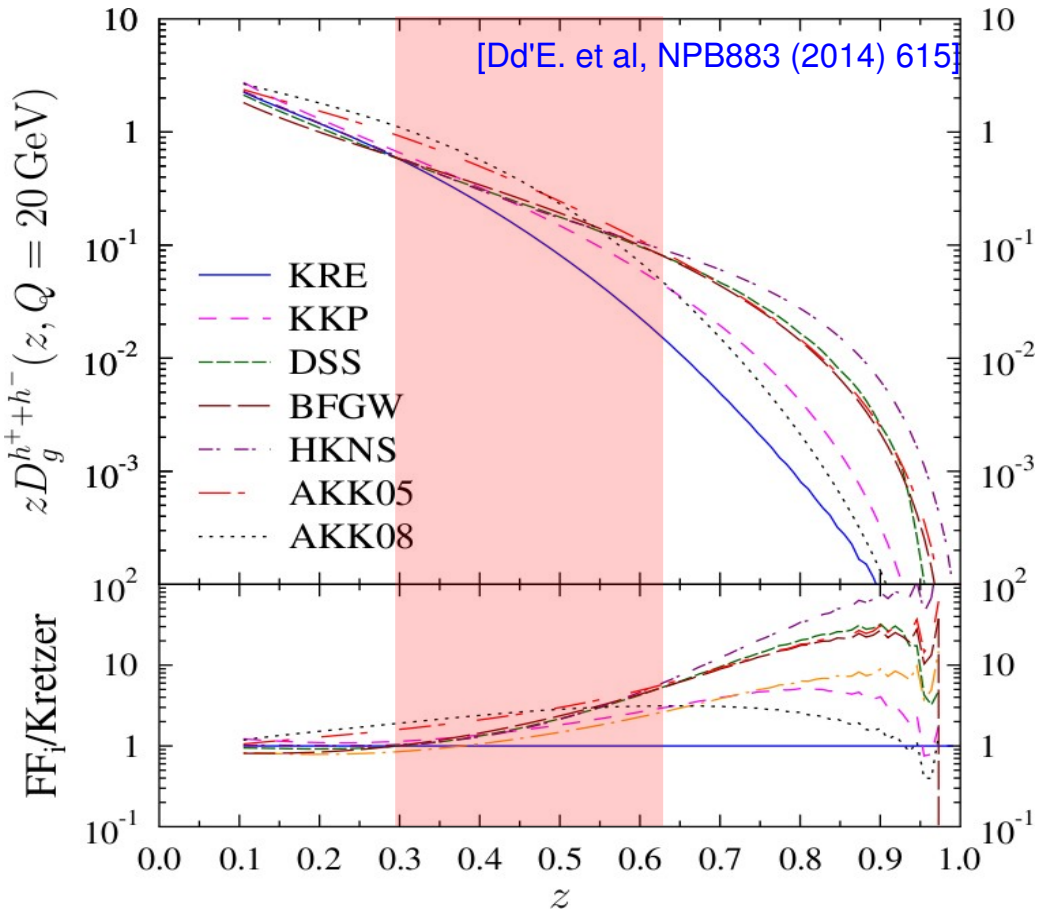
Badly-known gluon-to-hadron FFs

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





Very large differences on gluon-to-hadron FFs

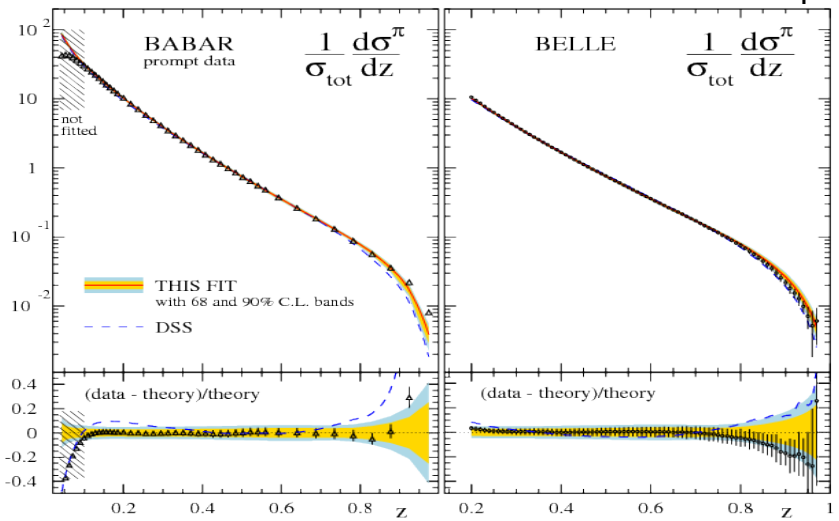


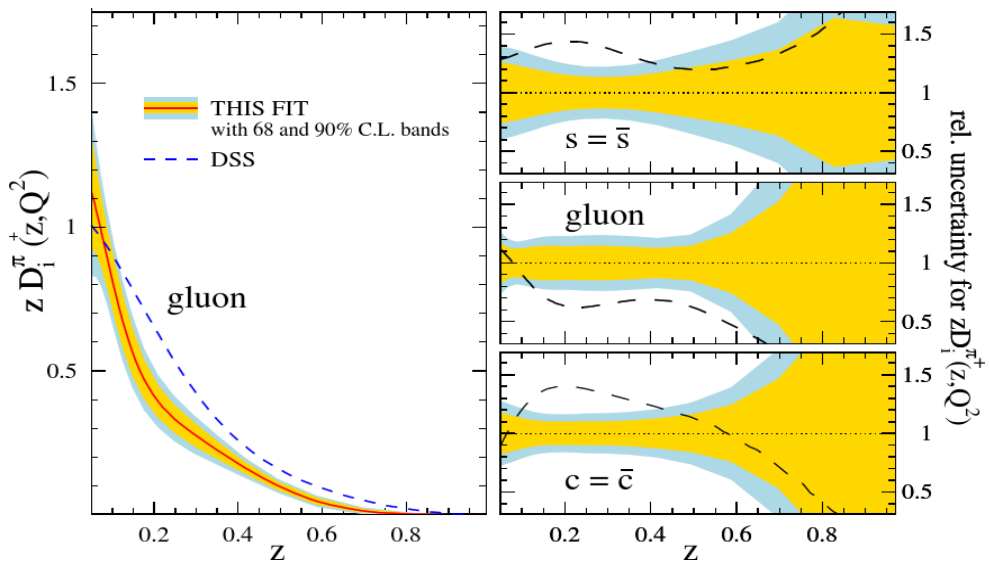
- Current NLO gluon FFs are too hard. Need to refit them with newer data.

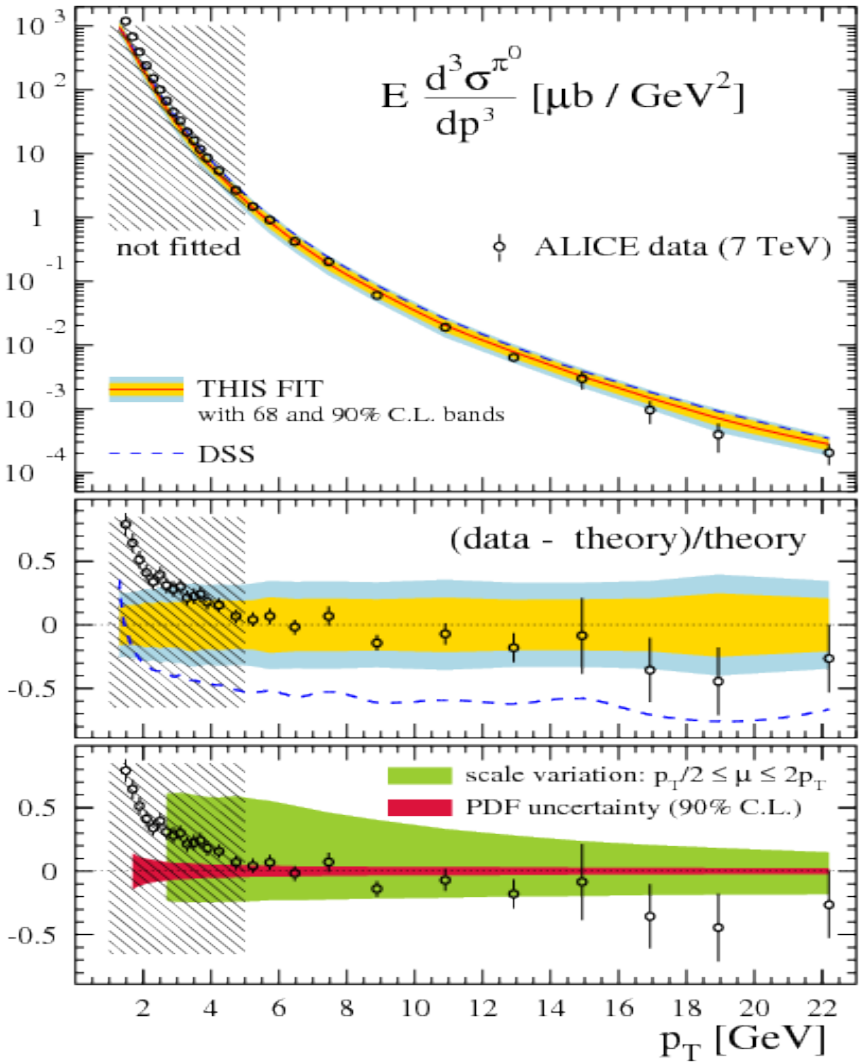
Improved gluon-to-hadrons FFs

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

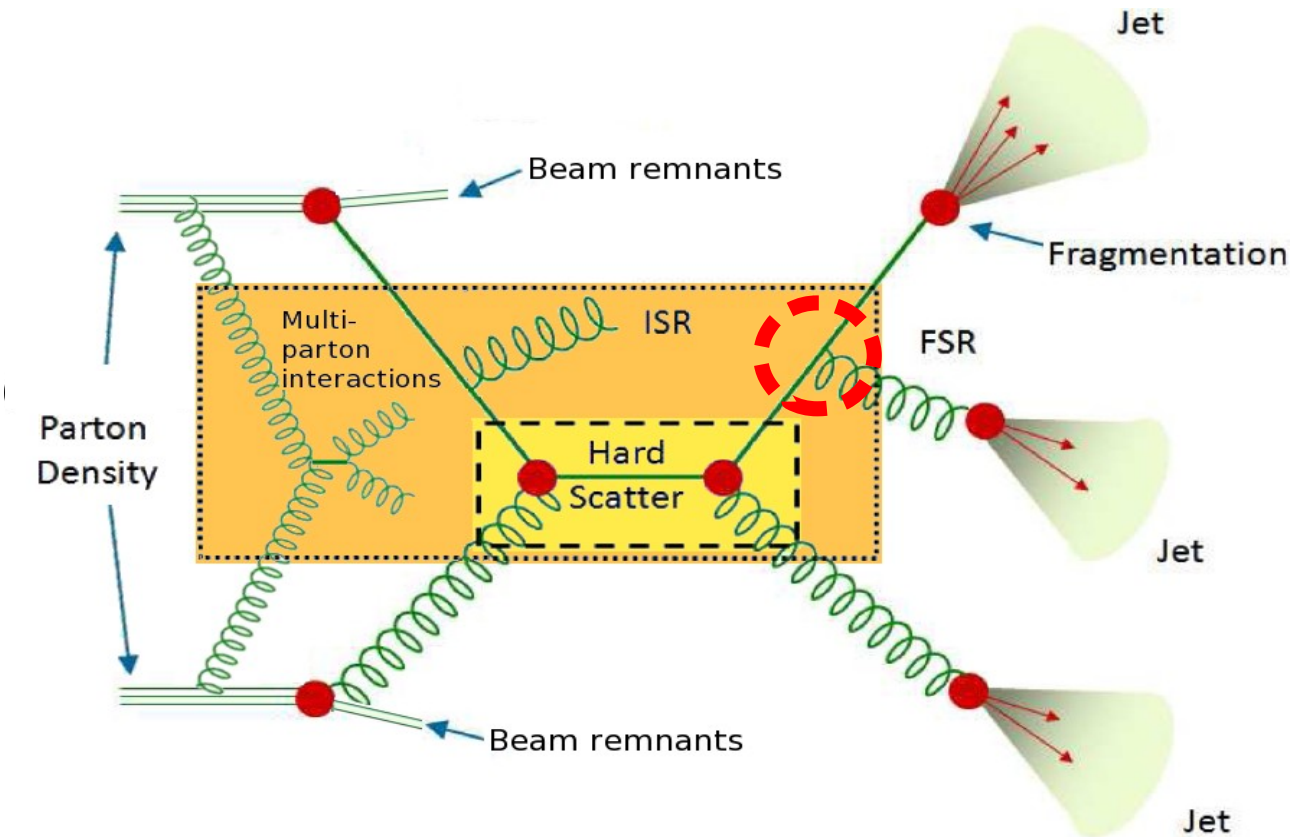
[DeFlorian et al, PRD91 (2015) 014035]







Strong coupling determination

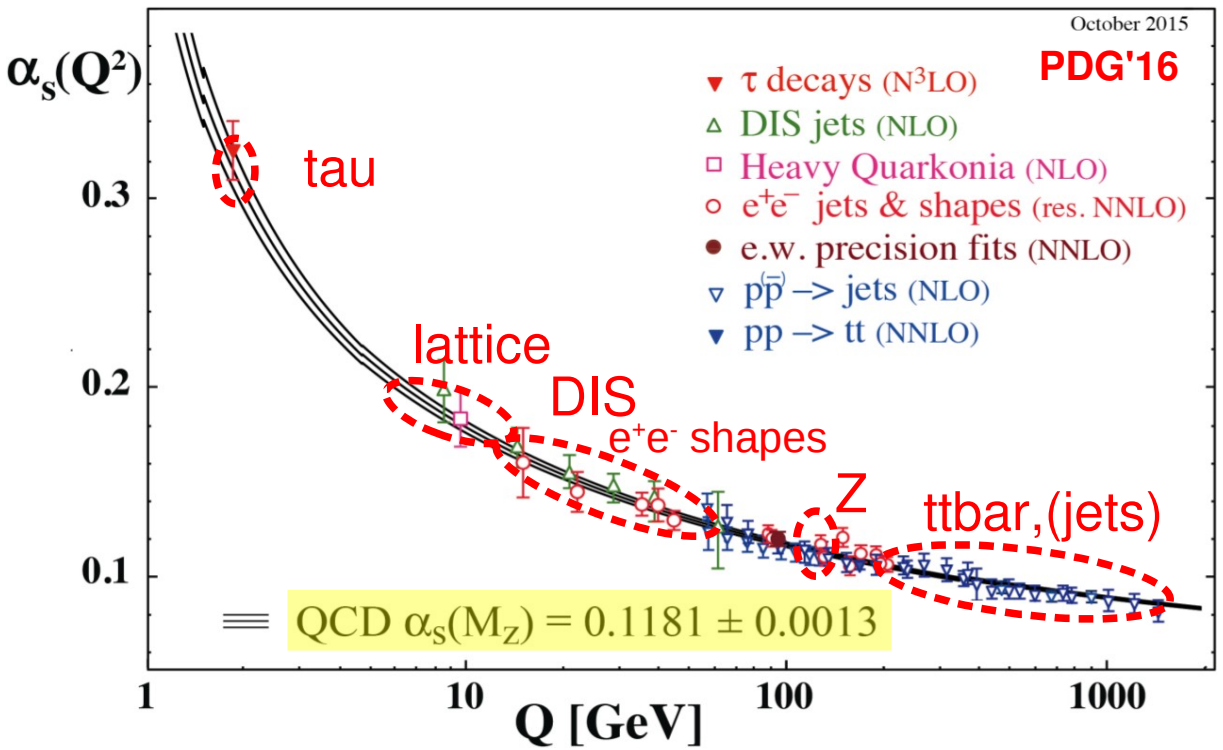


Determination of the QCD coupling α_s

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 $\Lambda \sim 0.2$ 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 colored sector, GUT).

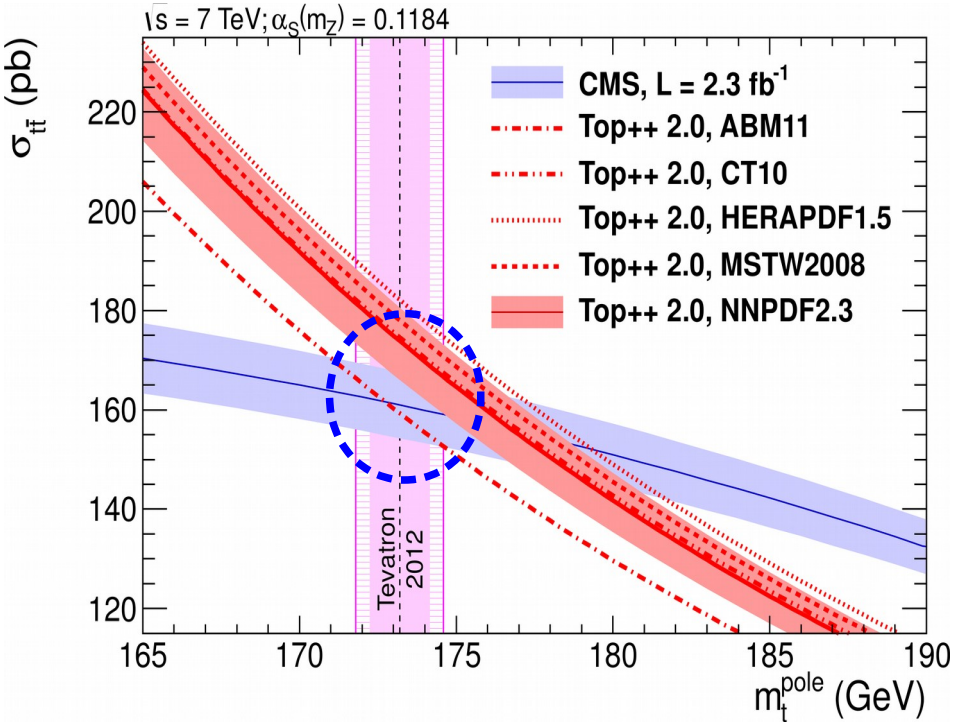
- Determined through comparison of various experimental (ee, ep, pp) observables to associated pQCD predictions at (at least) NNLO accuracy.



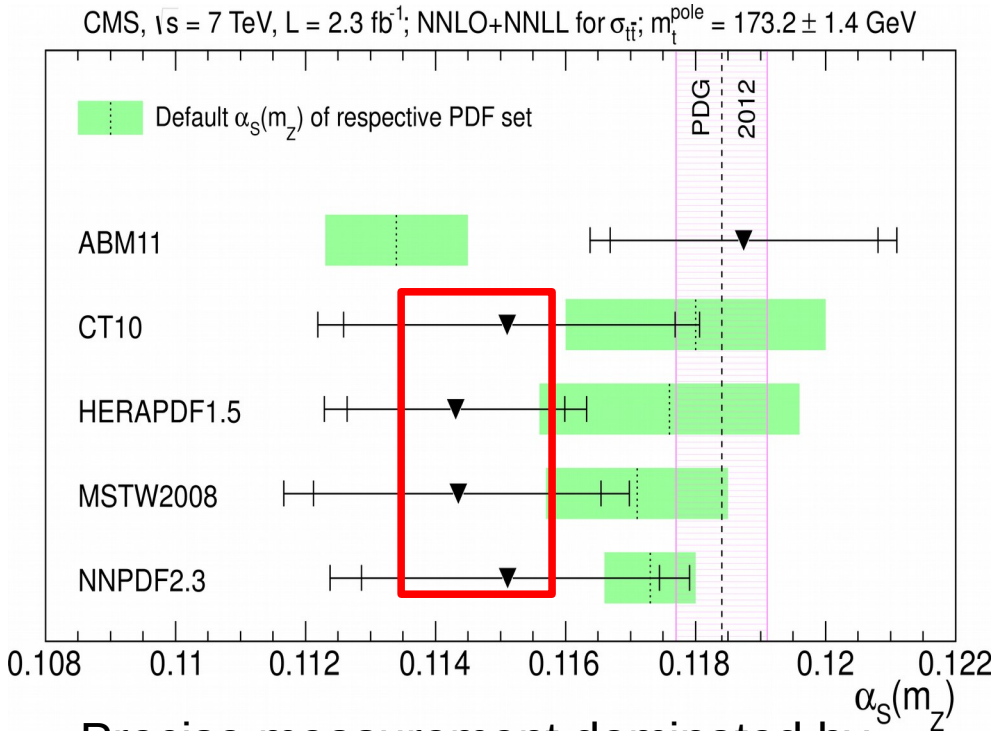
QCD coupling from t-tbar cross sections

- 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]



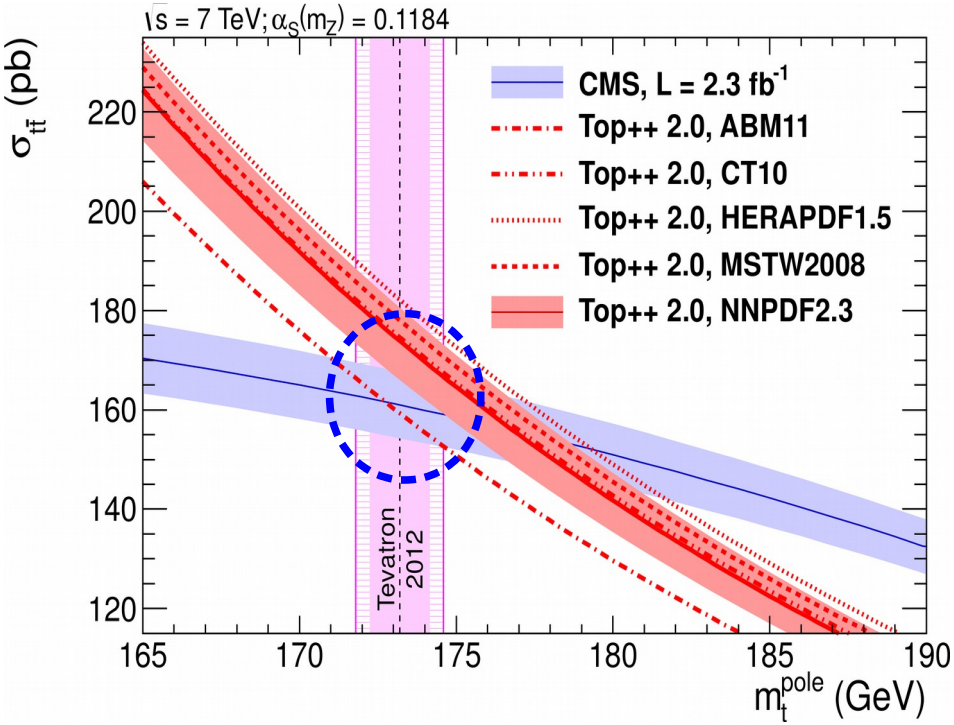
Precise measurement dominated by associated PDF uncertainty (±2.5%)

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

QCD coupling from t-tbar cross sections

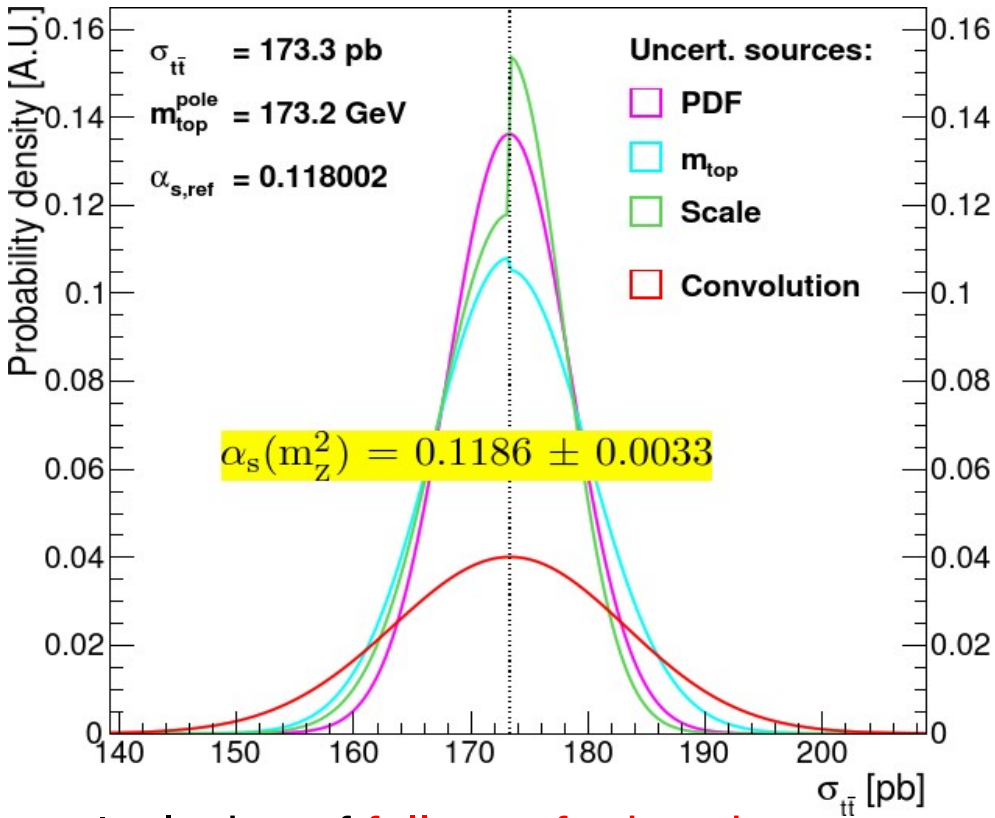
- Total top-antitop cross section (theoretically known at NNLO+NNLL) is the 1st p-p collider observable to constrain α_s at NNLO accuracy:

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



[CMS, PLB 728 (2014) 496]

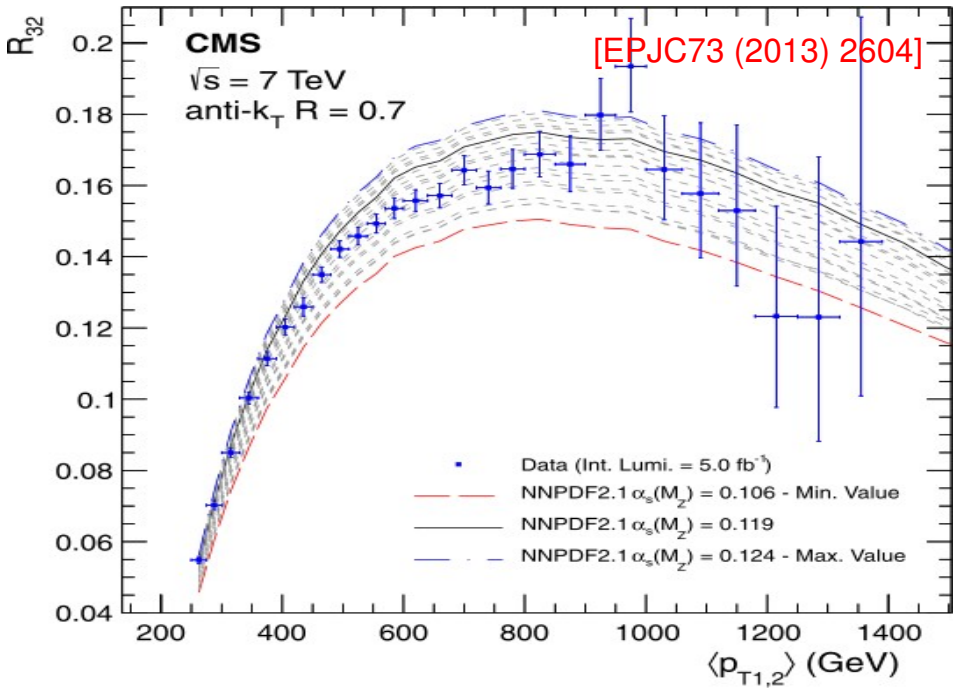
[G.Salam et al. arXiv:1512.05194]

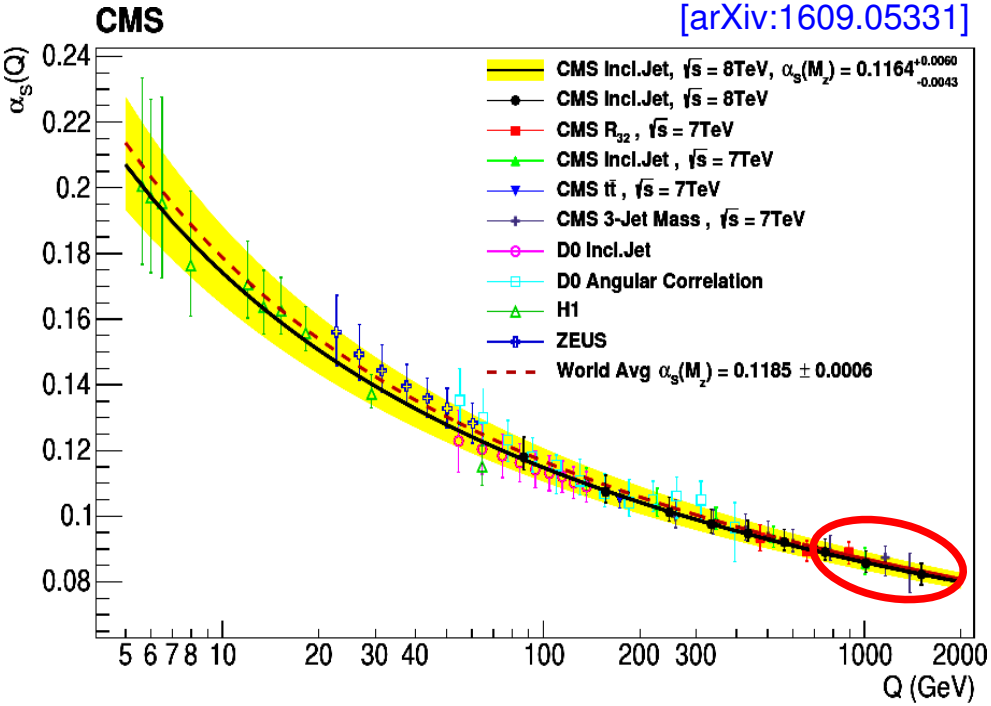


Inclusion of full set of t-tbar data increases the extracted $\alpha_s(m_Z)$ value.

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:





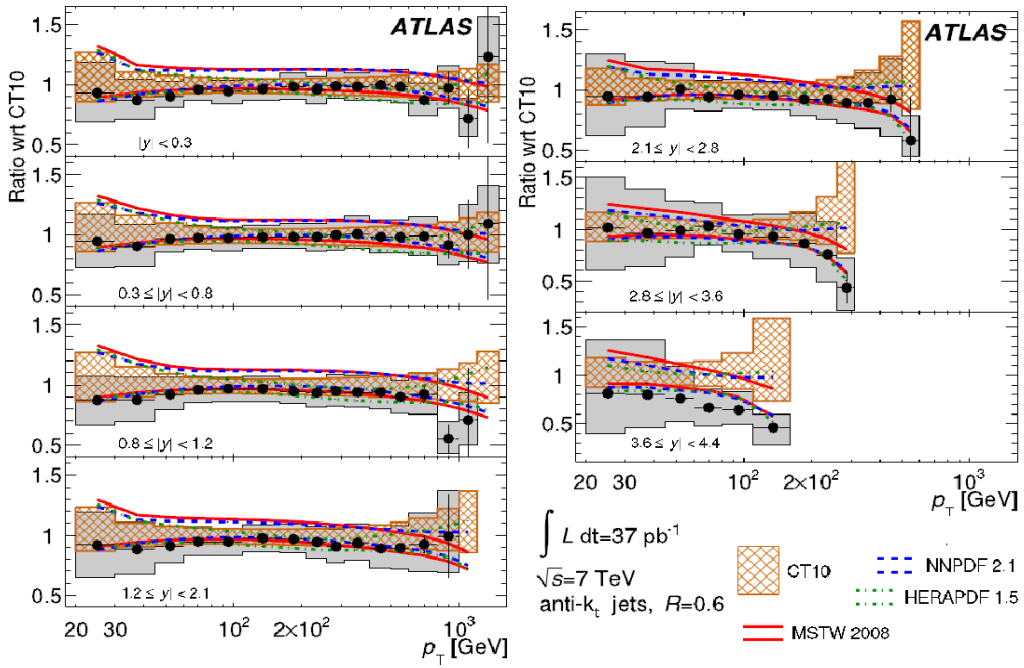
$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF}) \pm 0.0050\,(\text{theory})$$

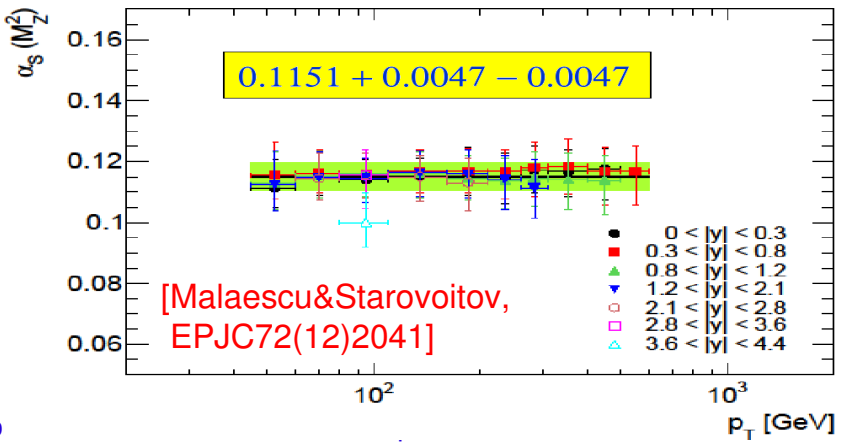
$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp}) \,^{+0.0060}_{-0.0037}\,(\text{theo})$$

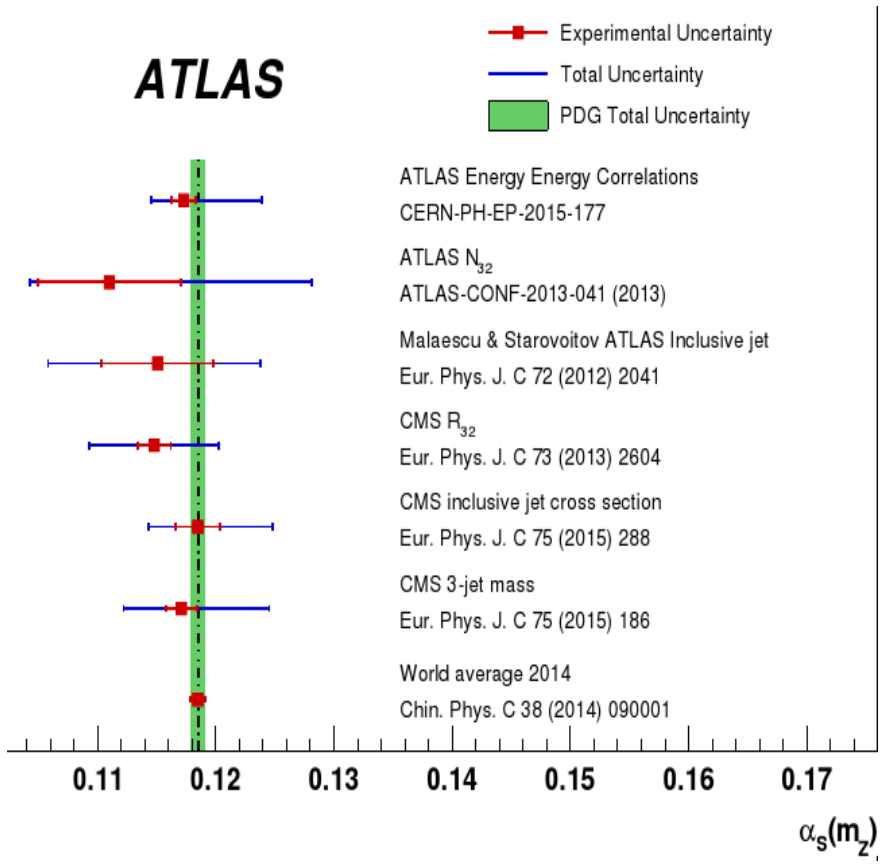
- Measurements dominated by TH uncertainty: PDF & (asym.) scale uncertainty.

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):





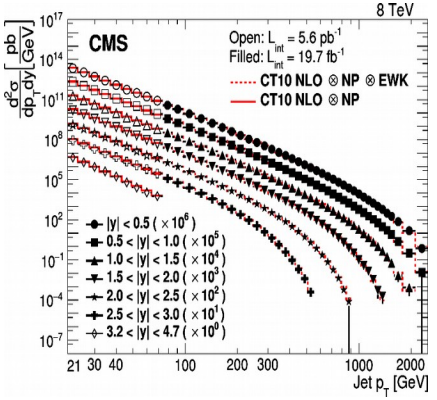


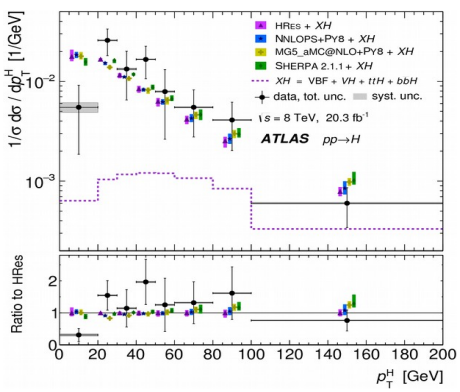
Upcoming jet x-sections NNLO calculations will provide improved α_s extractions.

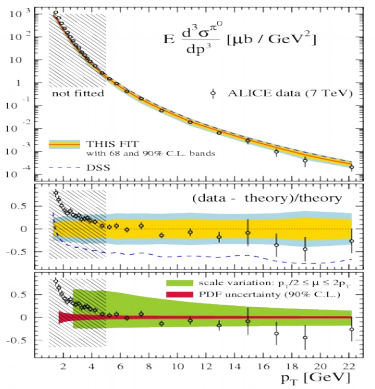
Summary: Precision QCD at the LHC

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

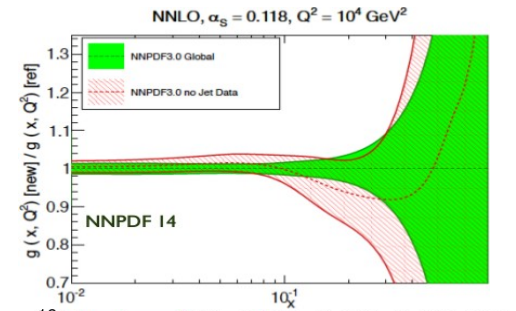
- Good data–pQCD (N)NLO+(N)NLL accord for total and differential cross sections:

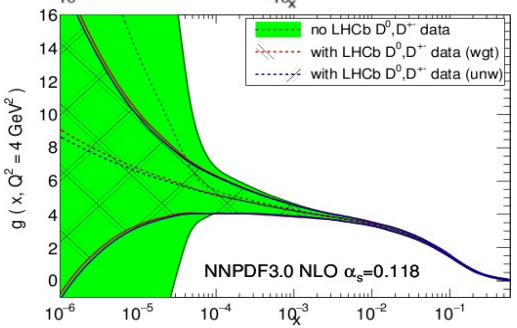


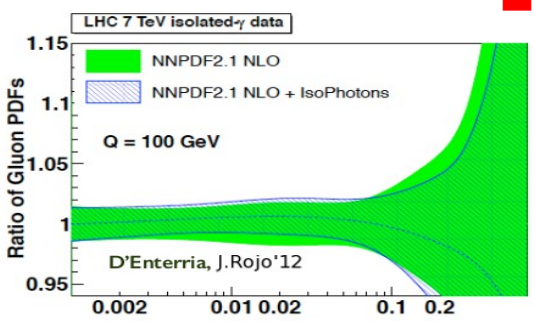


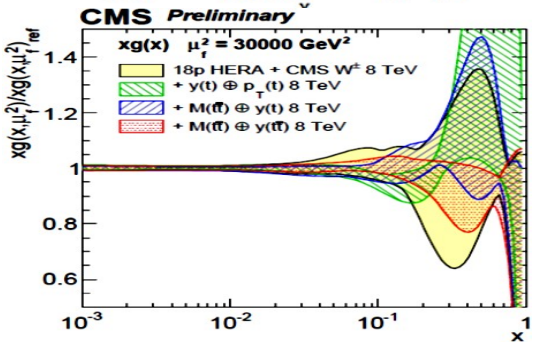


- Improved (N)NLO PDFs via jets, γ, W,Z, charm, ttbar:



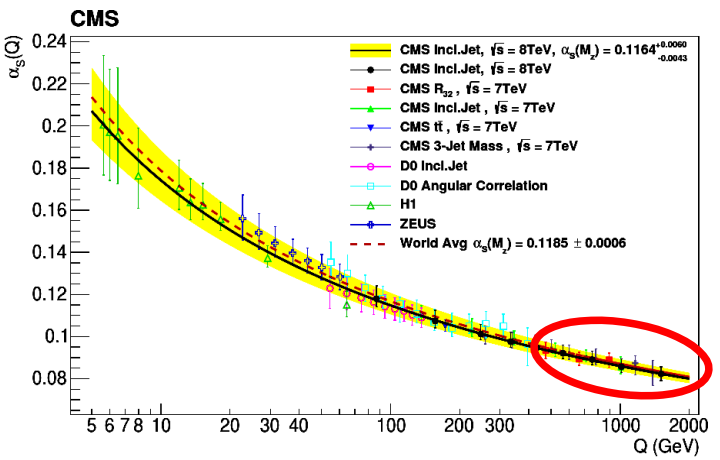






- Refitted (N)NLO gluon-to-hadron FFs

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

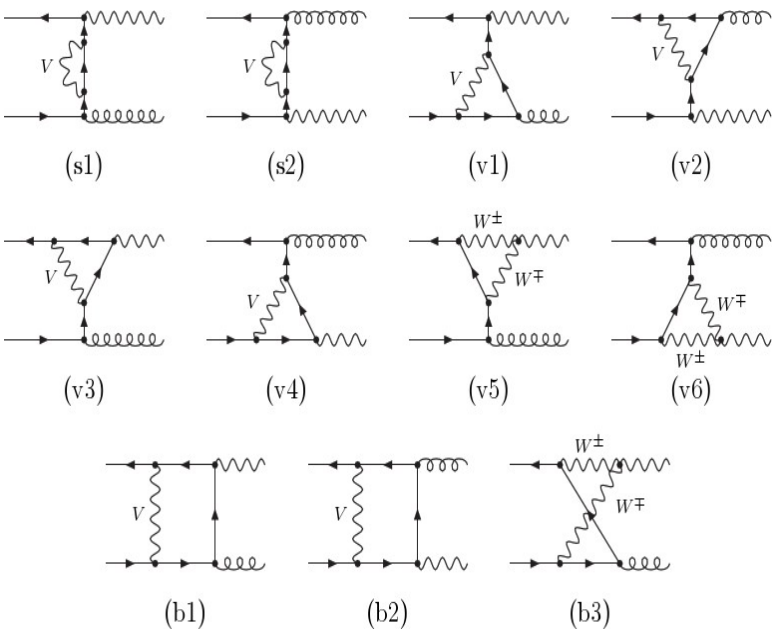


- EXP/TH pQCD precision <5% = Cornerstone for all (B)SM signals & bckgds. studies.

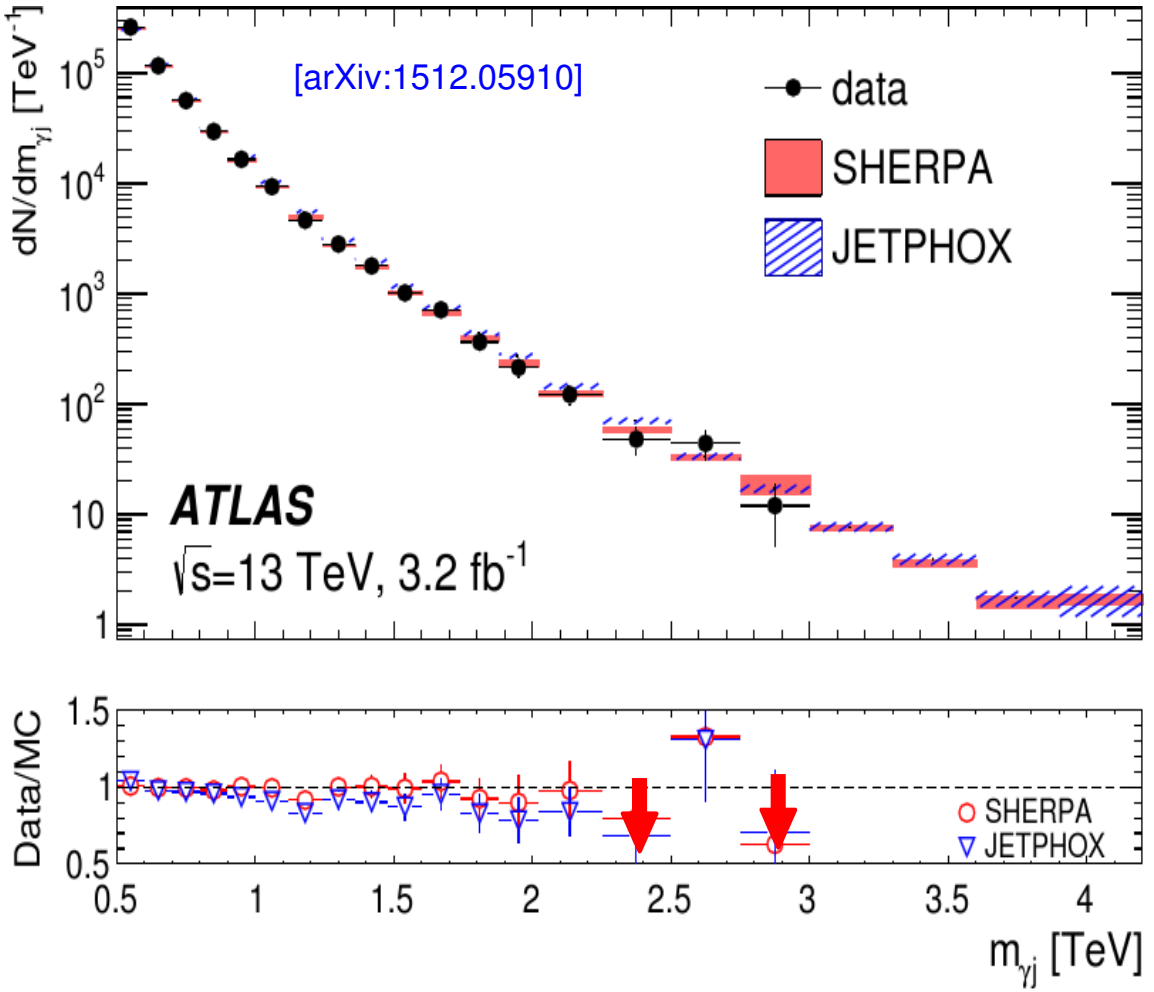
Back up slides

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?



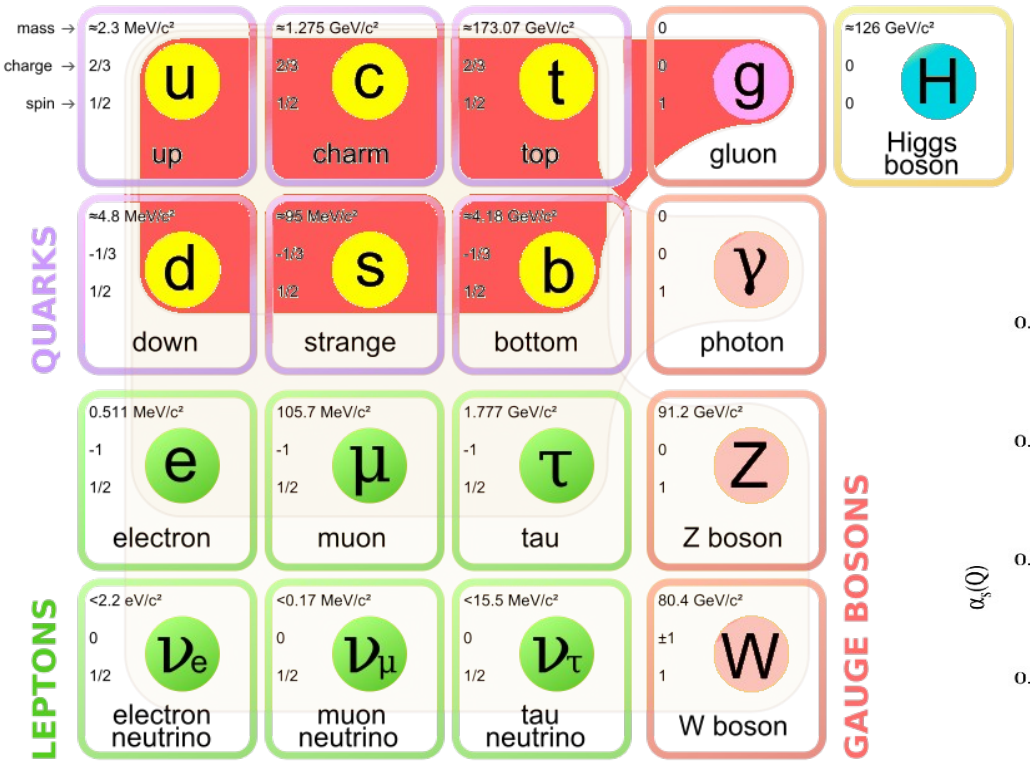
[J.H.Kuhn et al., JHEP 0603 (2006) 059]



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 :

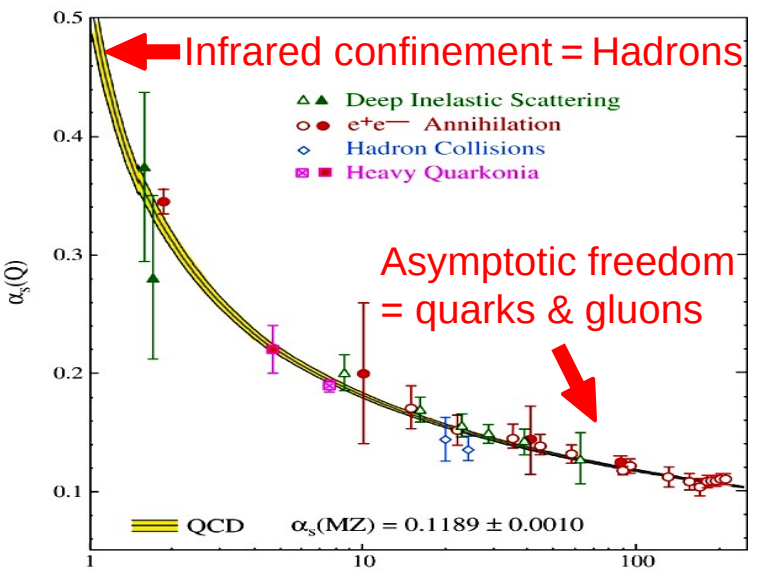


$$\mathcal{L} = \underbrace{-\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu}}_{\text{Gluon dynamics}} + \sum_f \underbrace{\bar{\psi}_i^{(f)} (i D_\mu - m_f) \psi_i^{(f)}}_{\text{Quark-gluon dyn.+quark mass}}$$

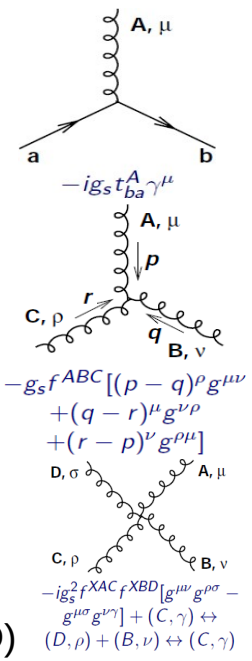
$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f^{abc} A^b_\mu A^c_\nu$$

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

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: $SU_c(3)$]

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

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

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

[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:

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

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

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

- Gauge-boson field strength tensors:

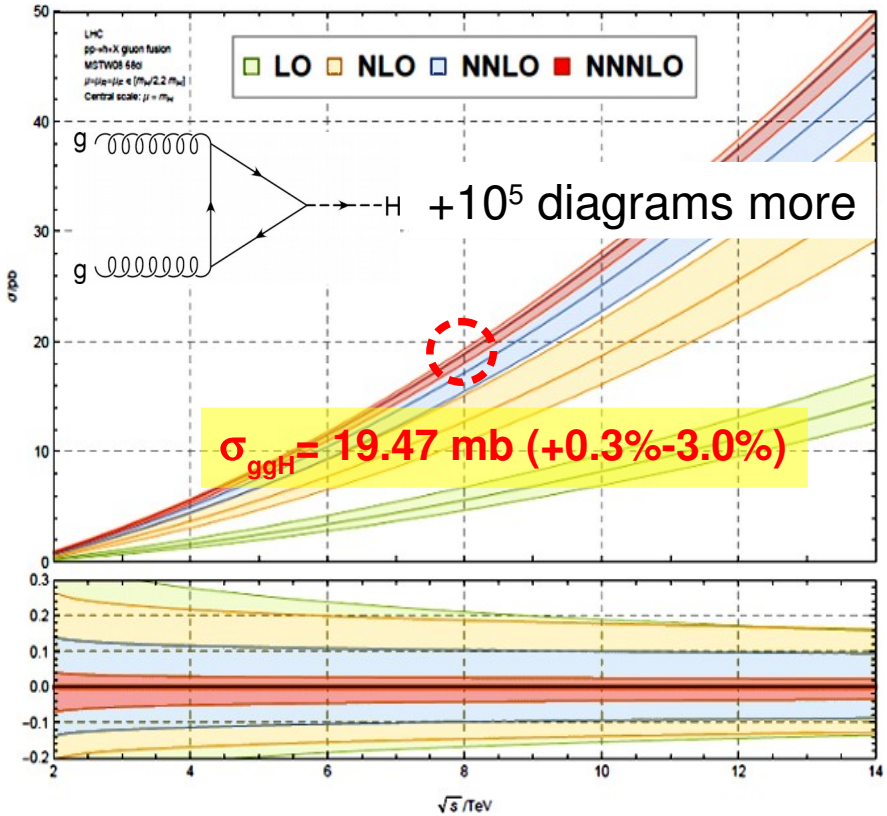
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu + ig_2(\mathbf{W}_\mu \mathbf{W}_\nu - \mathbf{W}_\nu \mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu \mathbf{G}_\nu - \partial_\nu \mathbf{G}_\mu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

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

Higgs cross sections: pQCD predictions

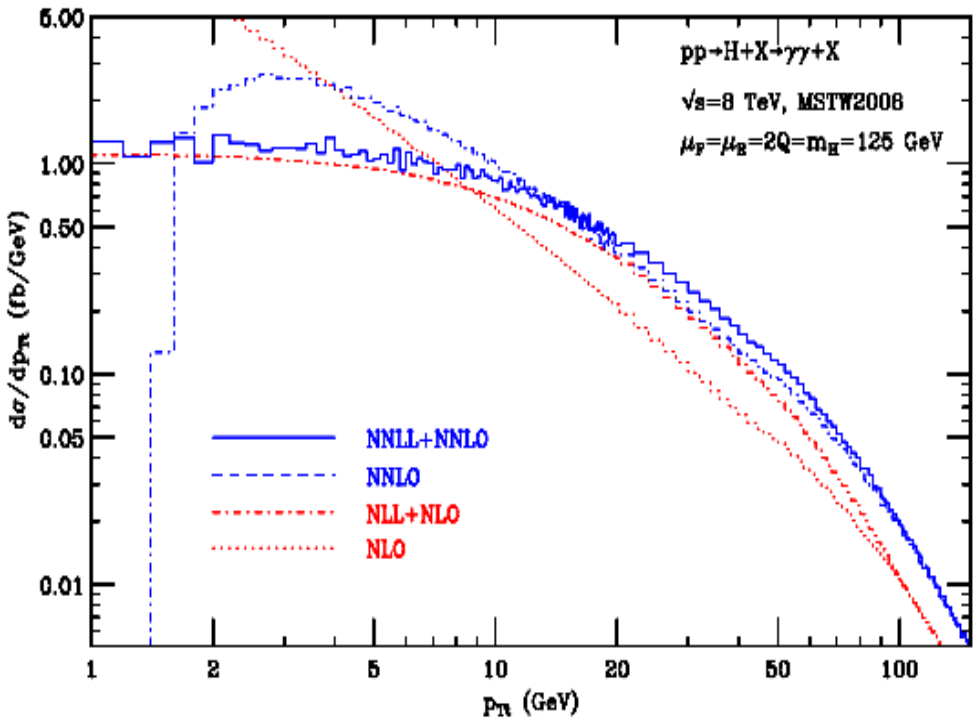
- Theory calculations include increasing # of real emissions + virtual corrections + soft&collinear log resummations (improves p_T differential distributions).
- Higgs production is paradigmatic example:

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



[Anastasiou et al. arXiv:1503.06056]

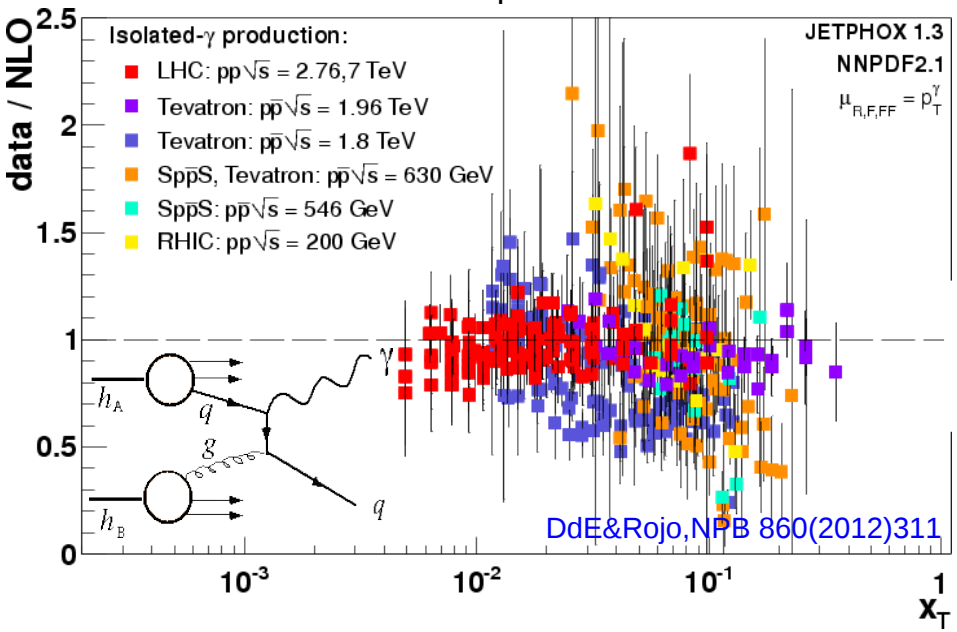
Higgs $d\sigma/dp_T$ at NNLO+NNLL:



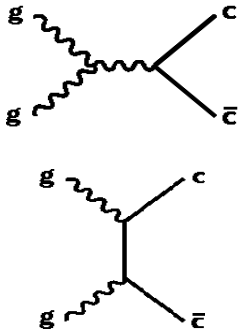
[DeFlorian et al. arXiv:1203.6321]

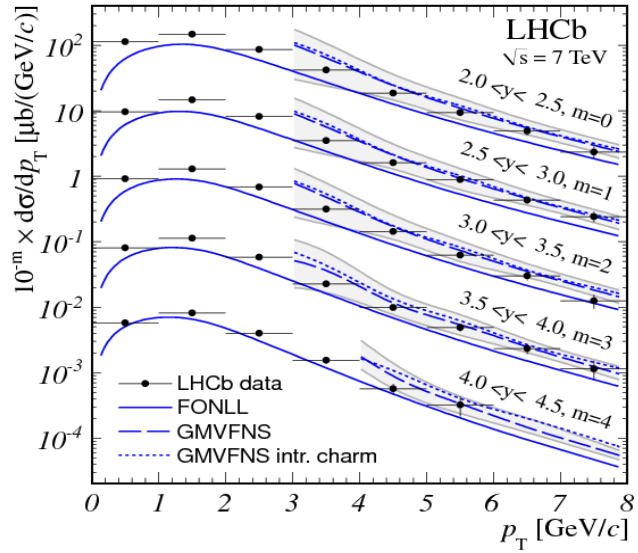
Gluon PDF constraints via LHC γ, charm, t-tbar

- Isolated photon p_T spectra:

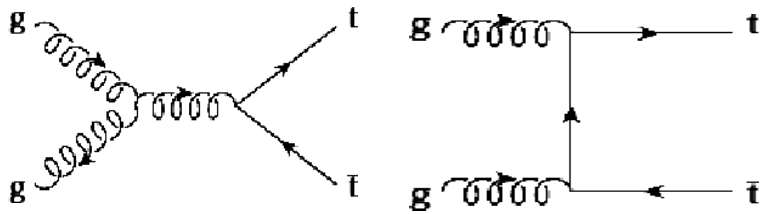


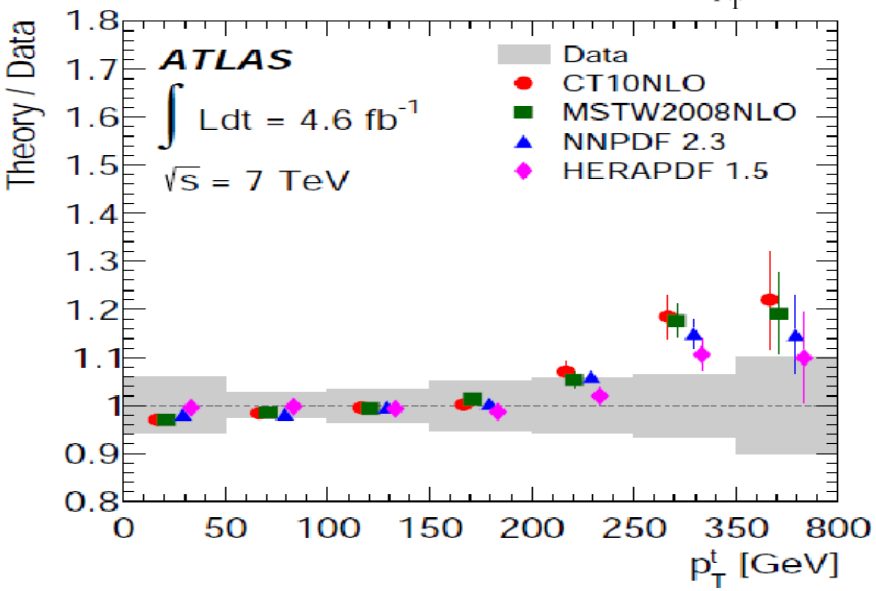
- Forward D-mesons (LHCb):





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





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

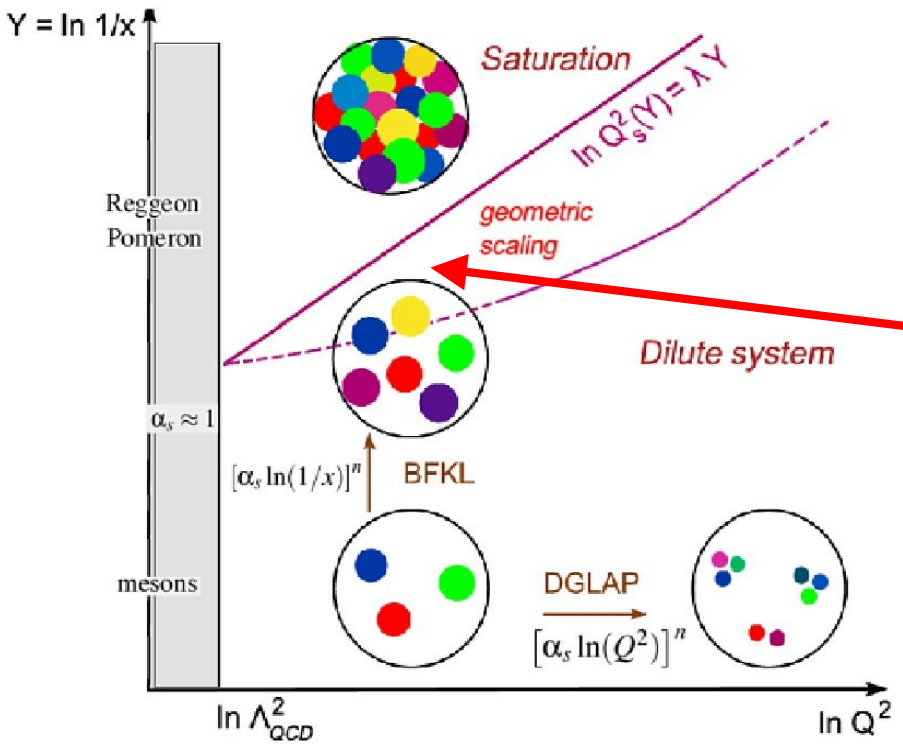
Searches of "Beyond DGLAP" evolution

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

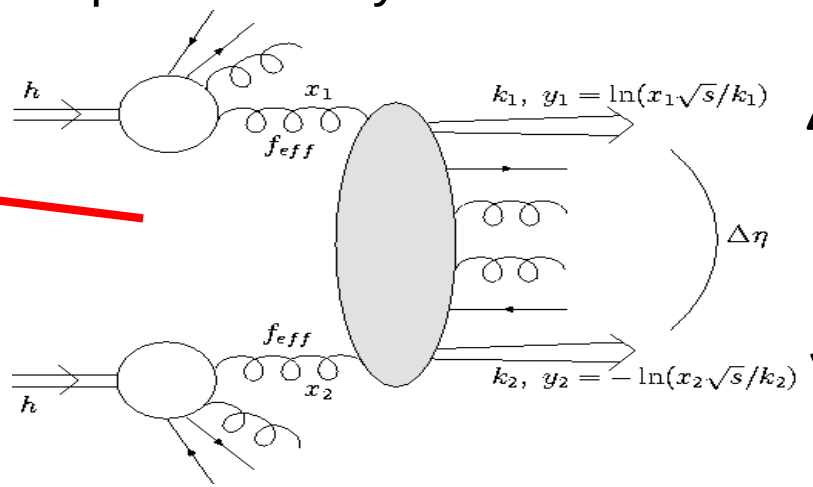
  $f(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$ [fixed-order PDFs, collinear factorization]

- 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:

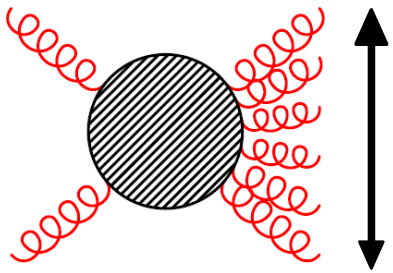


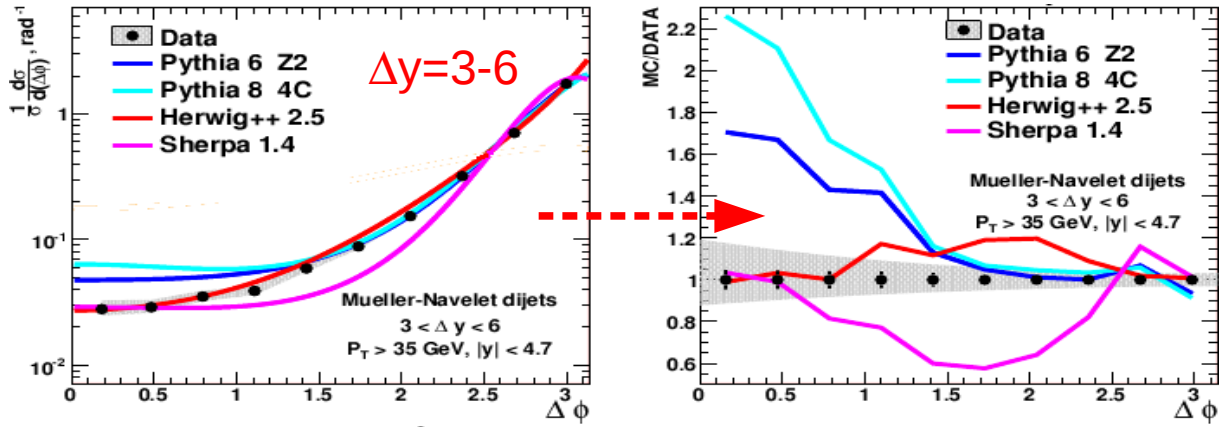
$\Delta\eta \sim 10$ (Atlas,CMS)

- Extra radiation in rapidity ?
- Enhanced azimuthal decorrelation ?

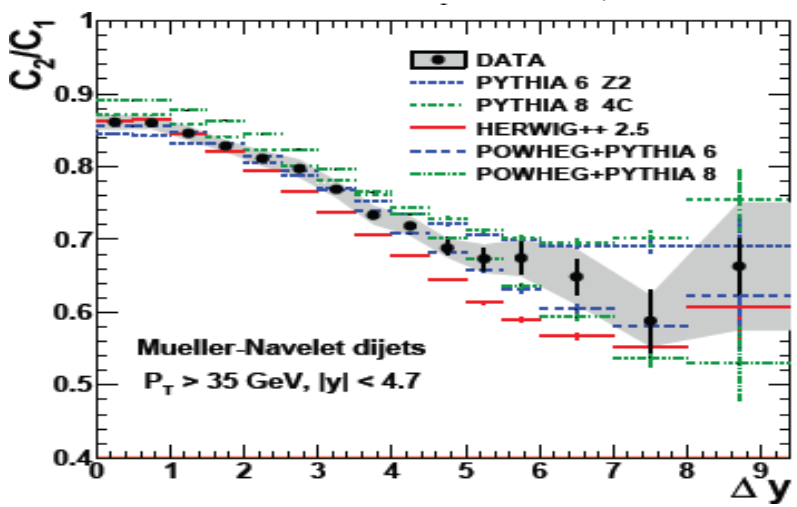
“Beyond DGLAP” in LHC Mueller-Navelet dijets?

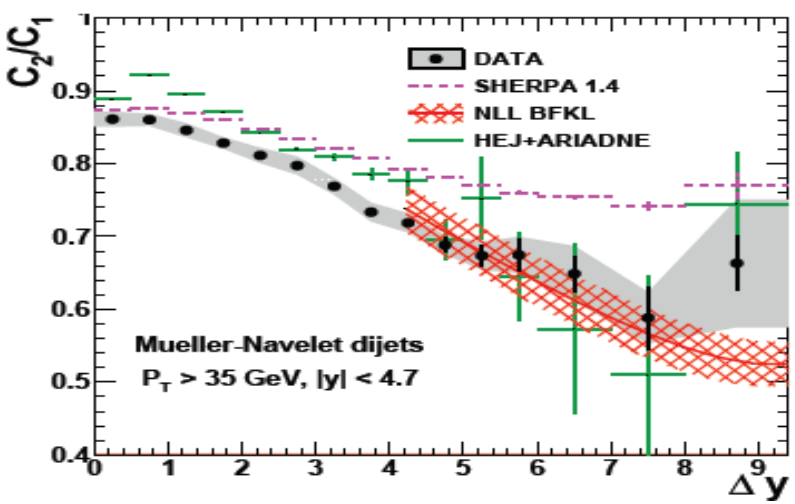
- MN dijet azimuthal decorrelations over large Δy:
  Absolute Δφ distributions & ratio moments vs Δy





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





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