Charm & bottom cross sections in pp,p$\bar{p}$ collisions: data *vs* NNLO

Moriond QCD 2017

La Thuile – 27th March 2017

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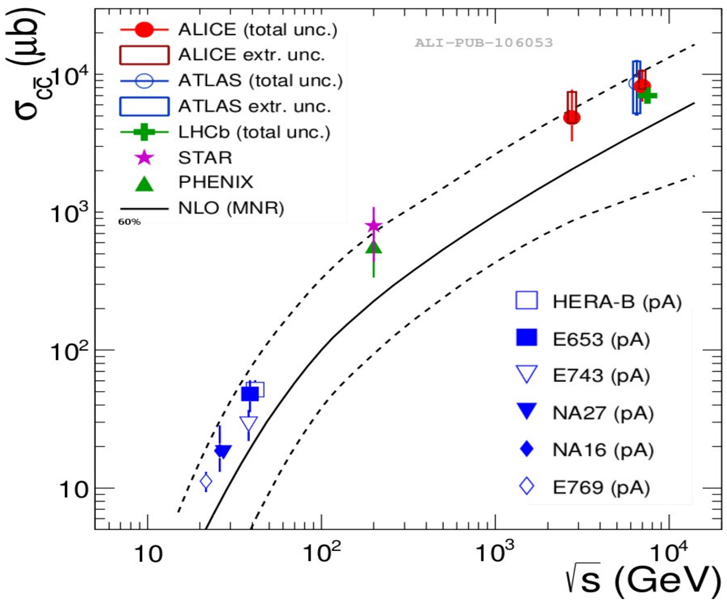
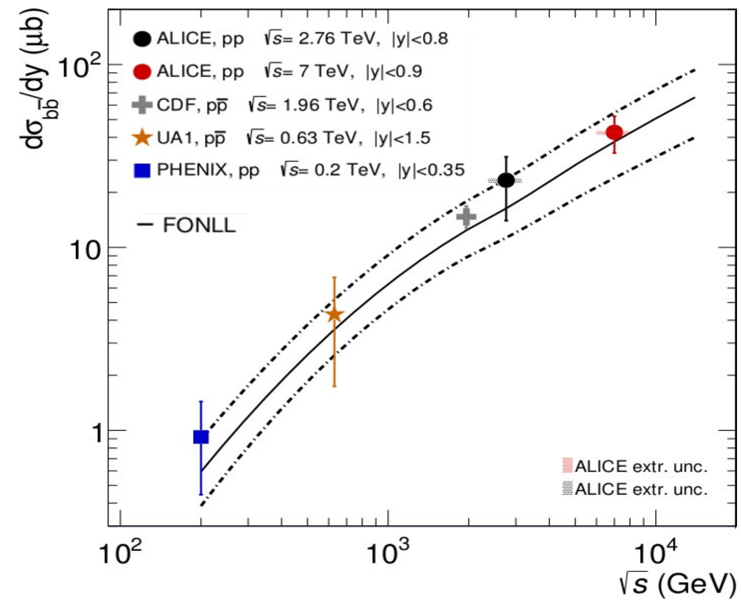
CERN

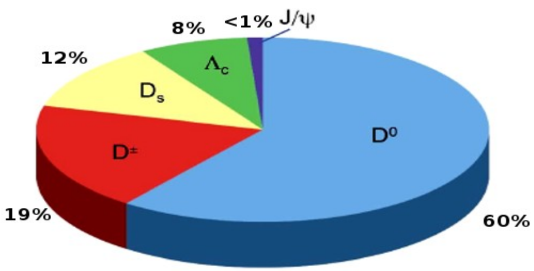
Charm & bottom production in pp,p$\bar{\text{p}}$ colls.

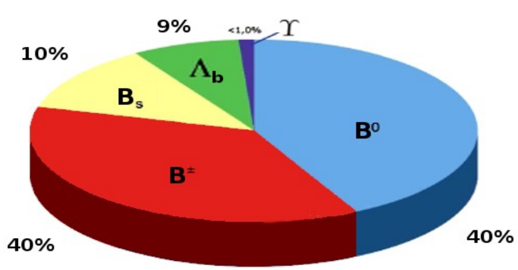
- Charm & bottom cross sections in pp collisions increase significantly with c.m. energy. At the LHC, they represent ~20%,~1% of σ_{inel}:





- Experimentally, one measures the c,b-quark fragmentation products (i.e. D,B mesons, Λ baryons) plus quarkonia bound states:





Most of total x-sections based on fraction of decay channels + model-dependent extrapolations over (p_T,y)

Calculation of heavy-Q x-sections in pp,p$\bar{\text{p}}$

- Charm/bottom/top production have intrinsic hard scales (m_Q ~ 1.7, 4.8, 173 GeV) that allow for application of pQCD framework to compute their cross sections.
- pQCD factorization theorem:

$$\sigma_{Q+X}[s, m_Q] \simeq \sum_{i,j} \int_0^1 \mathrm{d}x_i \int_0^1 dx_j\, f_i^A(x_i,\mu_F) f_j^B(x_j,\mu_F)\;\; \tilde{\sigma}_{ij\to Q+X}[x_i, x_j, m_Q, \mu_F, \mu_R]$$

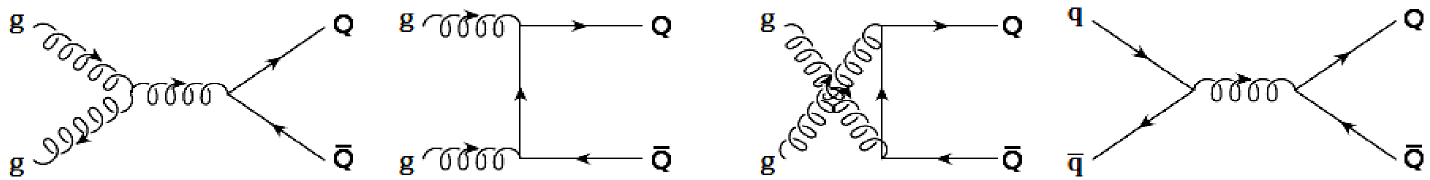
Sum over active flavours

Parton densities in proton: Evaluated at momentum fraction x & scale Q=μ_F

Partonic subprocesses cross sections, expanded in powers of α_s:

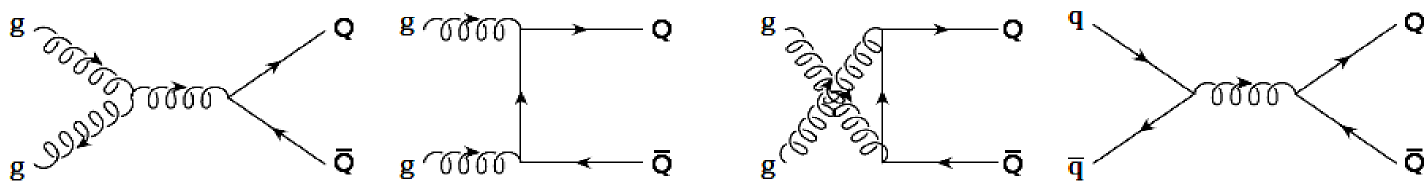
$$\tilde{\sigma}_{ij\to Q+X}[m_Q, \mu_F, \mu_R] = \frac{\alpha_s^2(\mu_R)}{m_Q^2}\left[\hat{\sigma}_{LO} + \alpha_s(\mu_R)\hat{\sigma}_{NLO} + \alpha_s^2(\mu_R)\hat{\sigma}_{NNLO} + \cdots\right]$$

- Cross sections clearly dominated by gluon-gluon fusion processes



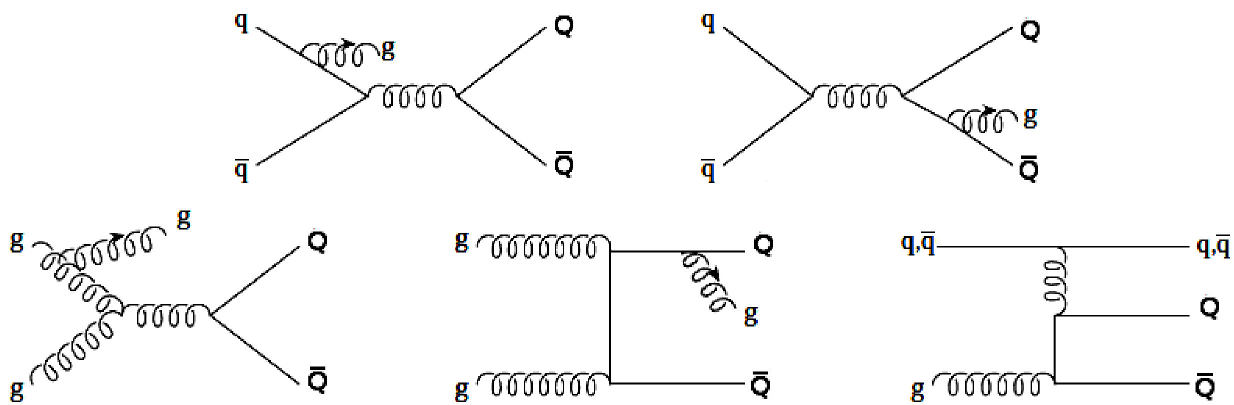
Heavy-Quark production in pp,p$\bar{p}$ (LO,NLO)

- Leading-order (LO) QCD processes:

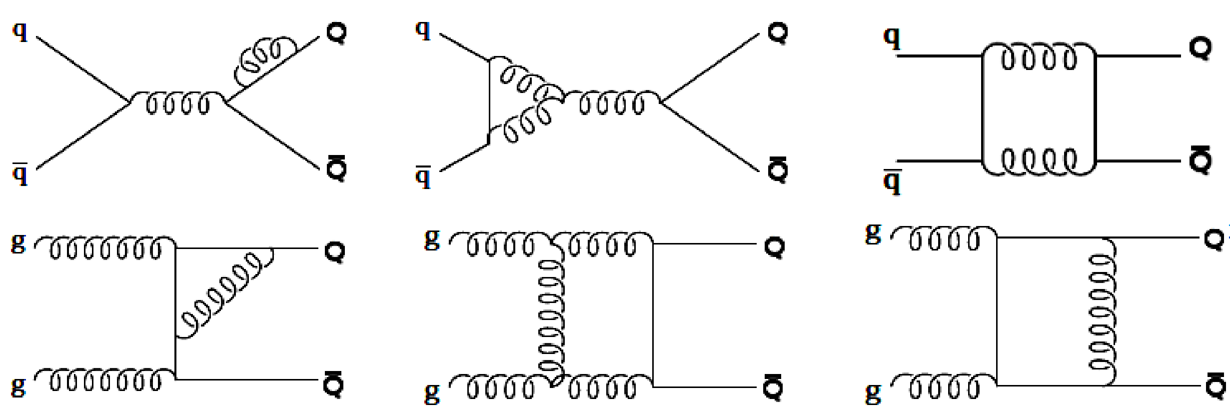


- Next-to-leading-order (NLO) QCD processes:

NLO real:



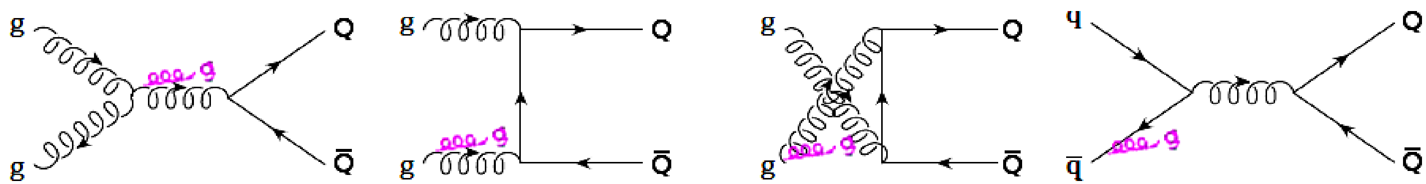
NLO virtual:



Mangano, Nason, Ridolfi, (MNR) ... [1992]

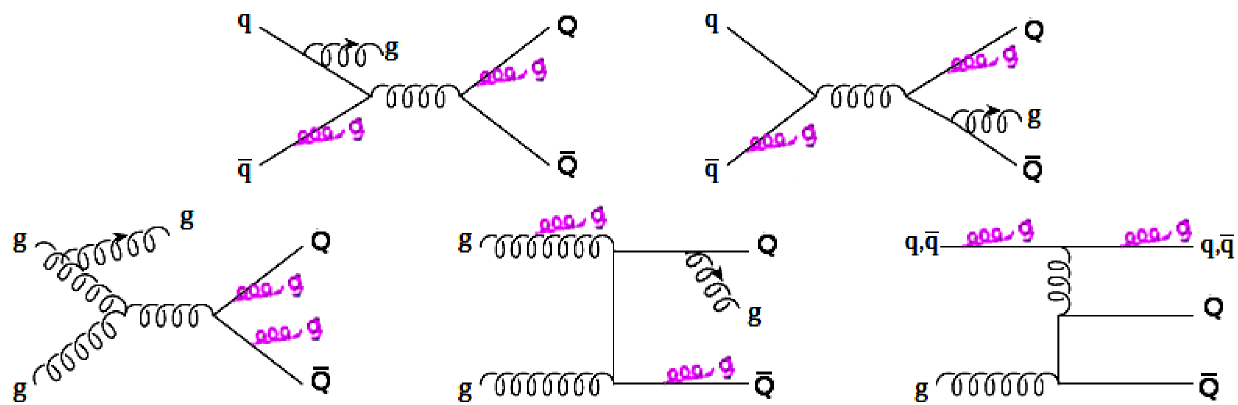
Heavy-Quark production in pp,p$\bar{p}$ (LO,NLO)

- LO + leading-log (LL) soft gluon resummation QCD processes:

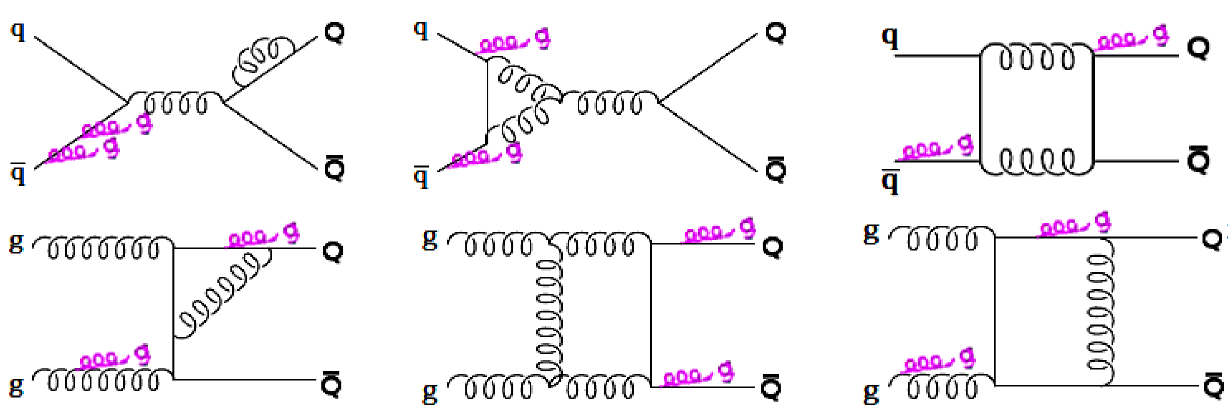


- NLO+ next-to-leading-log (NLL) soft gluon resummation QCD:

NLO real:



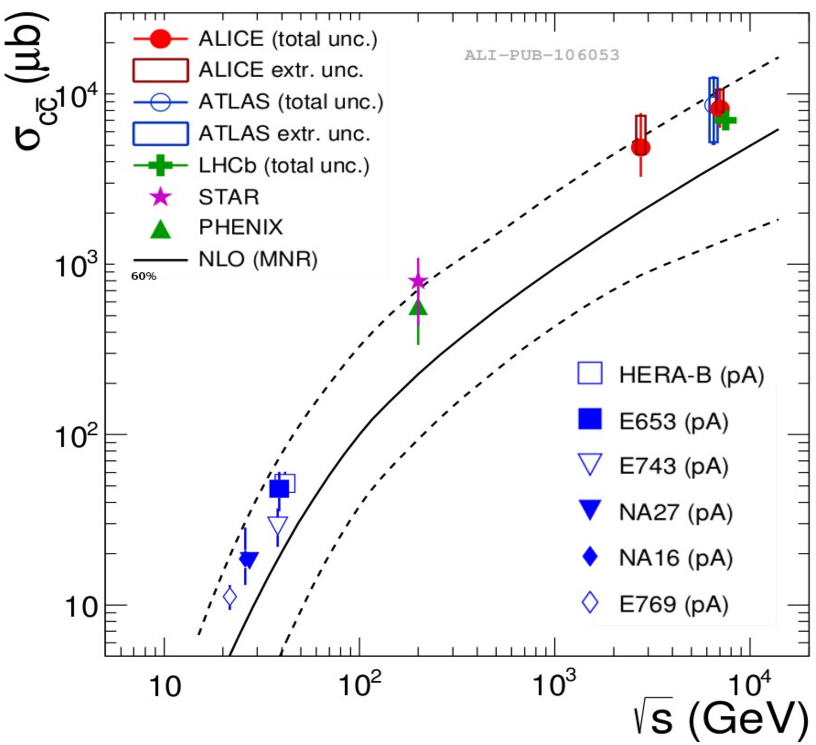
NLO virtual:

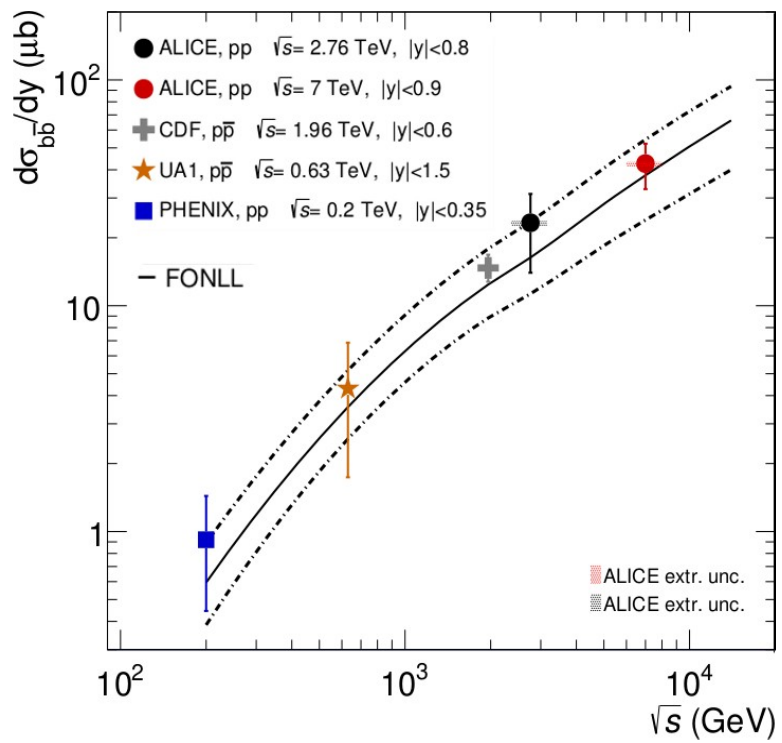


Mangano, Nason, Ridolfi
Cacciari, (FONLL)
Catani, Frixione, Mitov, Czakon,
…
[<2012]

Charm & bottom in pp,p$\bar{p}$: Data vs NLO+NLL

- pQCD predictions at NLO+NLL accuracy (MNR, FONLL) globally Reproduce the data. Better for bottom than for charm (charm measurements are at upper uncertainty band of the predictions):



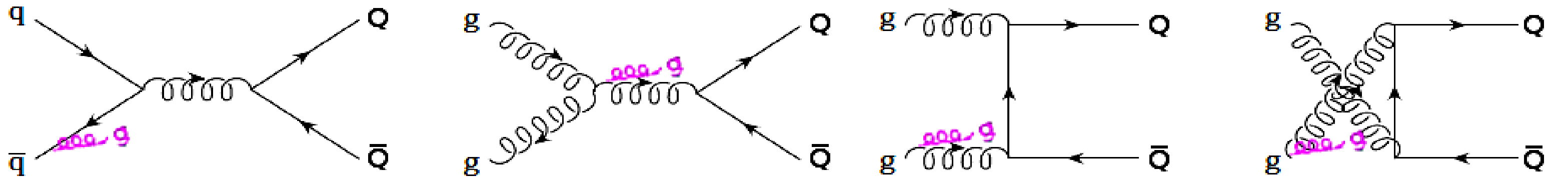


- pQCD predictions at NLO+NLL accuracy have still very large scale uncertainties: ~60% for ccbar (low m_c~1.67 GeV)

  ~35% for bbar (m_b~1.67 GeV)

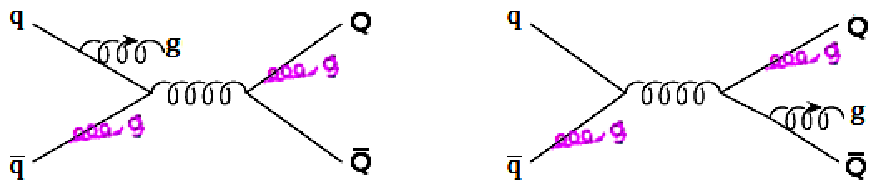
Heavy-Quark production in pp,p$\bar{p}$ (NNLO)

- LO + leading-log (LL) soft gluon resummation QCD processes:

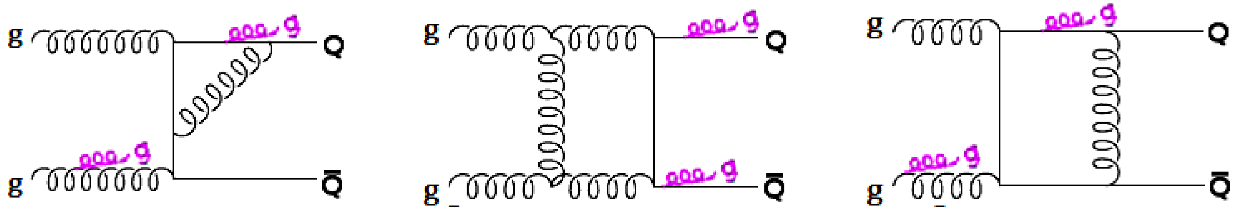


- NLO+ next-to-leading-log (NLL) soft gluon resummation QCD:

NLO real:

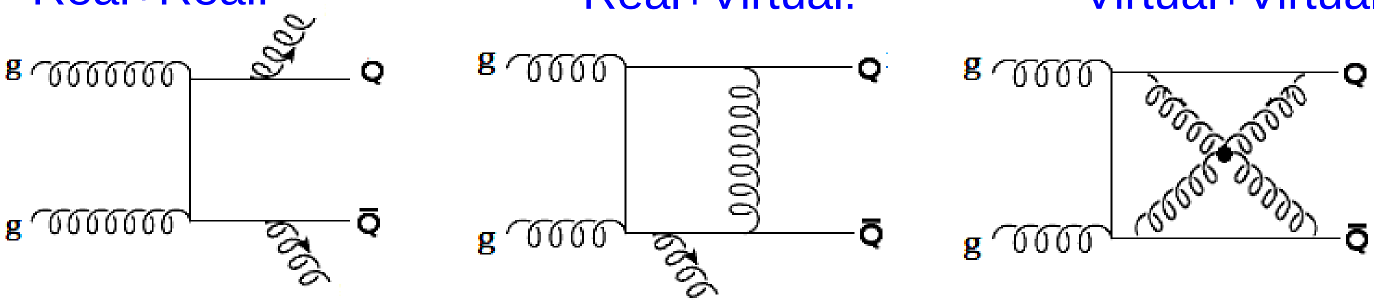


NLO virtual:



- NNLO+ next-to-leading-log (NLL) soft gluon resummation QCD:

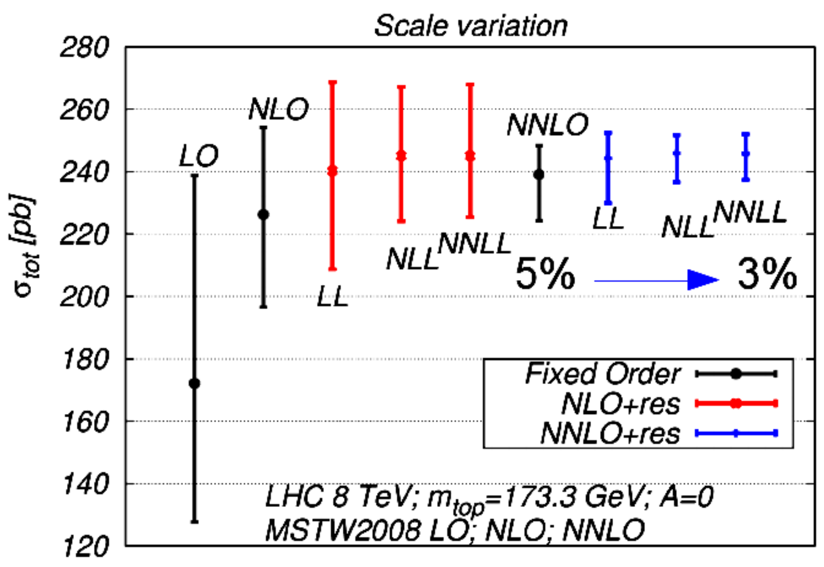
Real+Real: Real+Virtual: Virtual+Virtual:



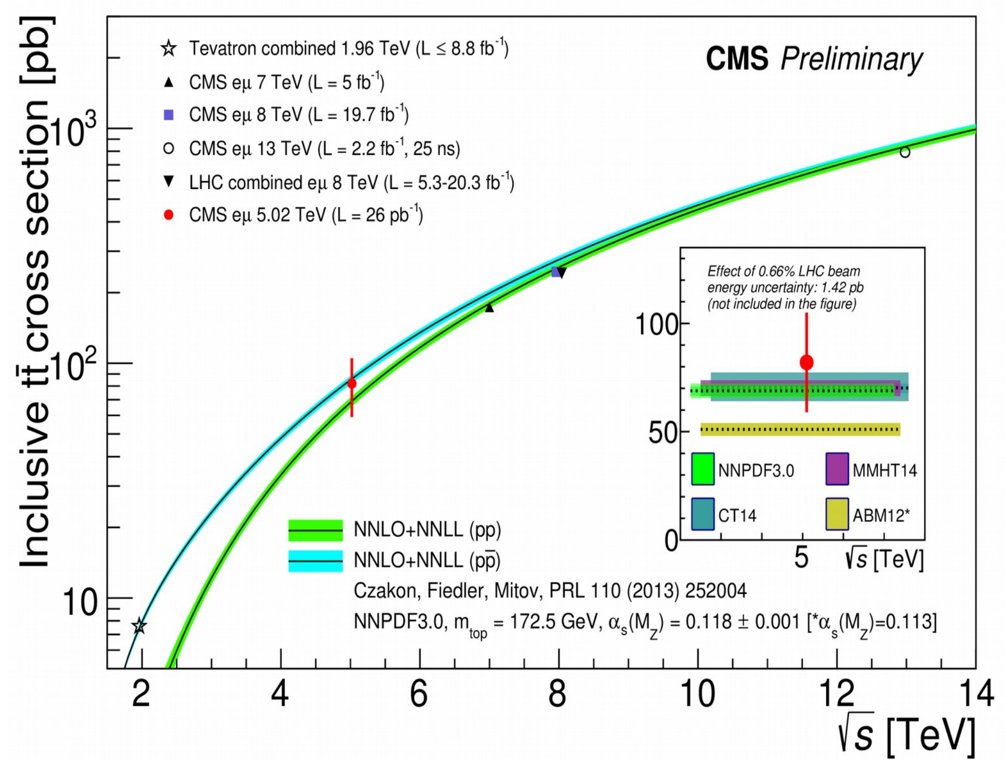
Mitov,Czakon *(Top++)*
Moch et al. *(HATHOR)*
…
[>2013]

$t\bar{t}$ production in pp,p$\bar{p}$: Data vs NNLO+NNLL

- Current state-of-the-art NNLO+NNLL calculations for ttbar agree very well with data and have very small scale uncertainties: 5%→3%



Mitov, Czakon et al. (Top++) 2013



- High precision of ttbar data & theory allows for accurate extractions of high-x gluon PDF and of the strong coupling α_s.
- Use Top++ (NNLO+NNLL) to compute cc,bb total cross sections?

$\sigma(c\bar{c},b\bar{b})$ at NNLO. Theoretical setup

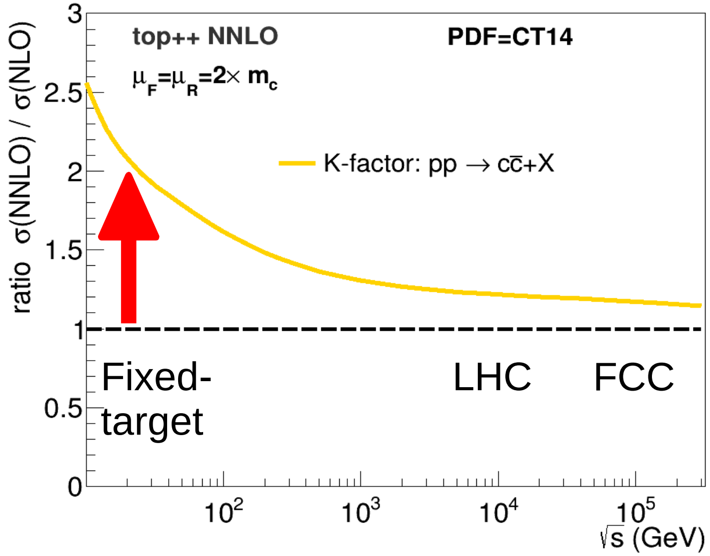
[Dd'E 2017, to be submitted]

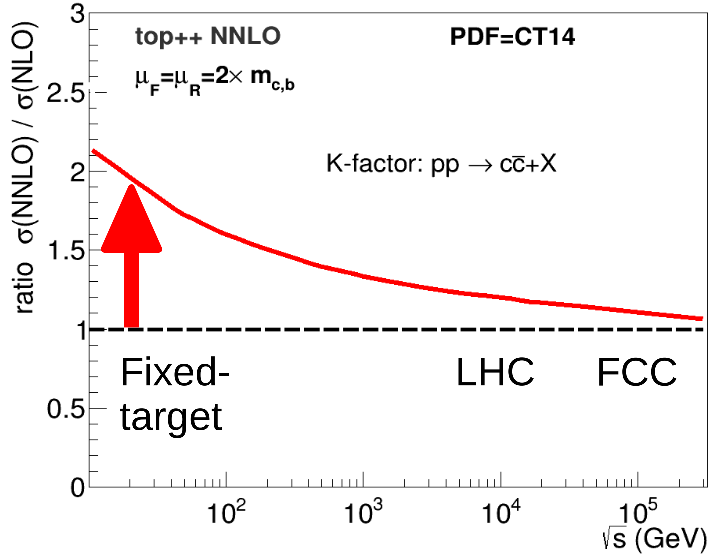
- Modified version of Top++:
  - Heavy-quark (pole) masses: m_c = 1.67 GeV, m_b=4.66 GeV
  - Active number of flavours: N_f = 3 (ccbar), 4 (bbbar)
- Model parameters:
  - Default scales: $\mu_F = \mu_R = 2\cdot m_{c,b}$ (Uncertainties: $\mu_F,\mu_R = [1,4]\times m_{c,b}$)
  - QCD coupling (PDF default): α_s = 0.118
  - PDFs (3, 4 flavour scheme. Interfaced via LHAPDF v6.1.6):

    CT14_NNLO (90% CL, 56 eigenvector sets, asymmetric)
    MMHT14_NNLO (68% CL, 50 eigenvector sets, asymmetric)
    ABMP16_NNLO (68% CL, 28 eigenvector sets, symmetric)
    NNPDF3.0_NNLO (68% CL, 100 replicas, symmetric)
  - Pure NNLO. NNLL gluon resummation not included (yet)
- Modified Top++ run for $\sqrt{s}$ of ~20 existing experimental data sets:
  - Charm: 11 measurements from $\sqrt{s}$=20 GeV (fixed-target) to 13 TeV (LHC)
  - Bottom: 8 measurements from $\sqrt{s}$=40 GeV (fixed-target) to 13 TeV (LHC)

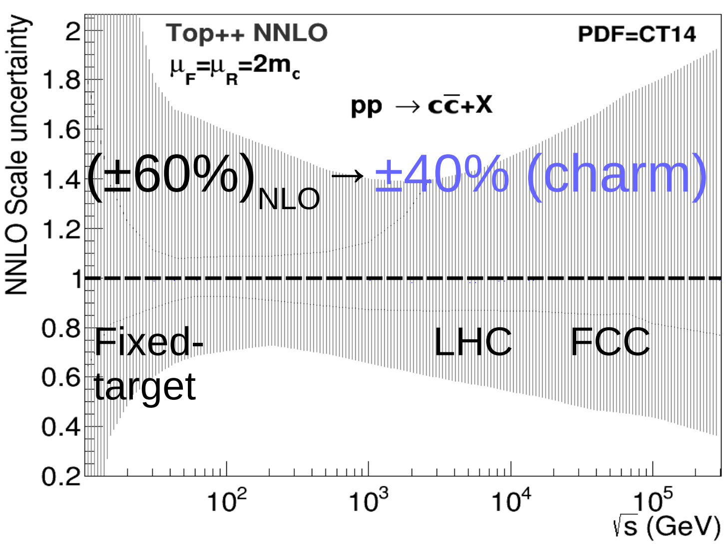
$\sigma(c\bar{c}, b\bar{b})$ results: NLO vs NNLO

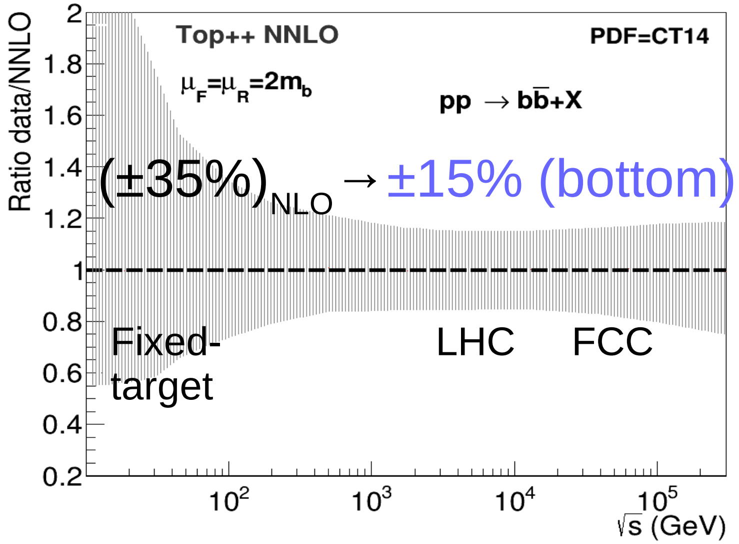
- Large charm & bottom K-factors : σ(NNLO/NLO)~2(fixed-target)–1.2(LHC)





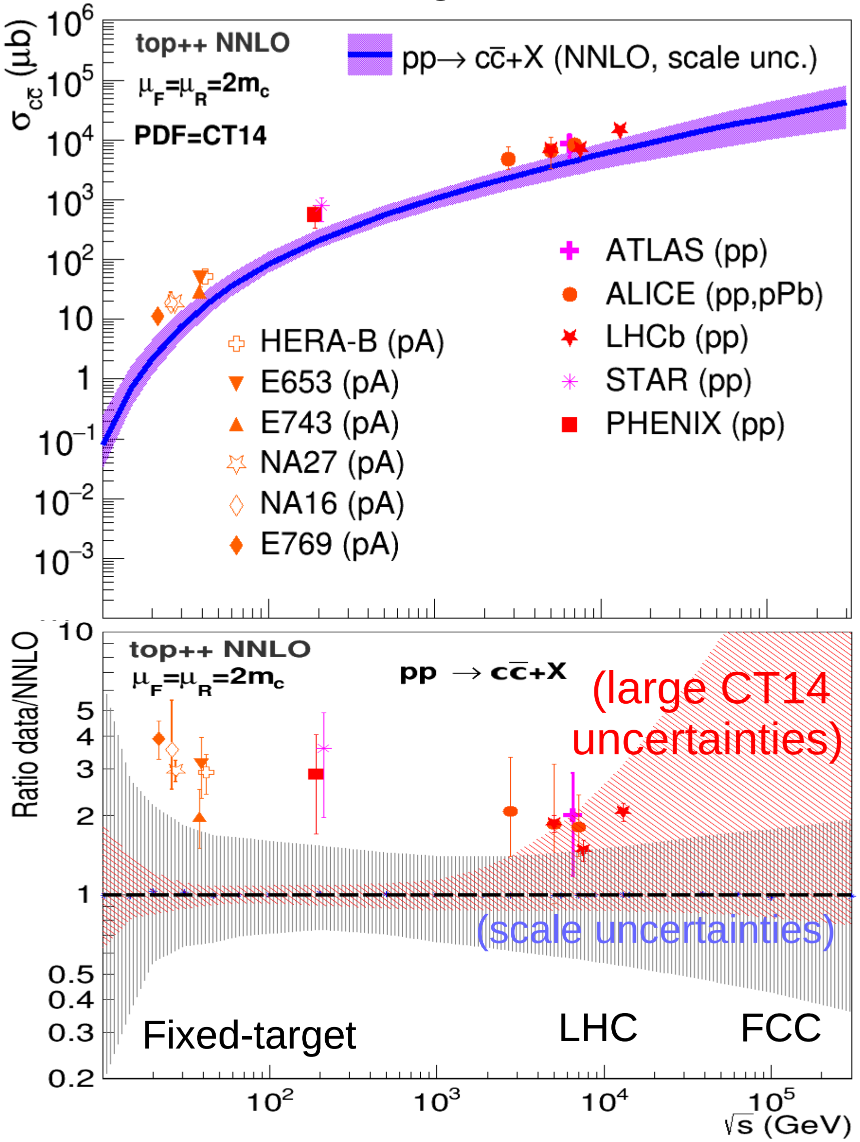
- Reduced NLO→NNLO scale uncertainties:



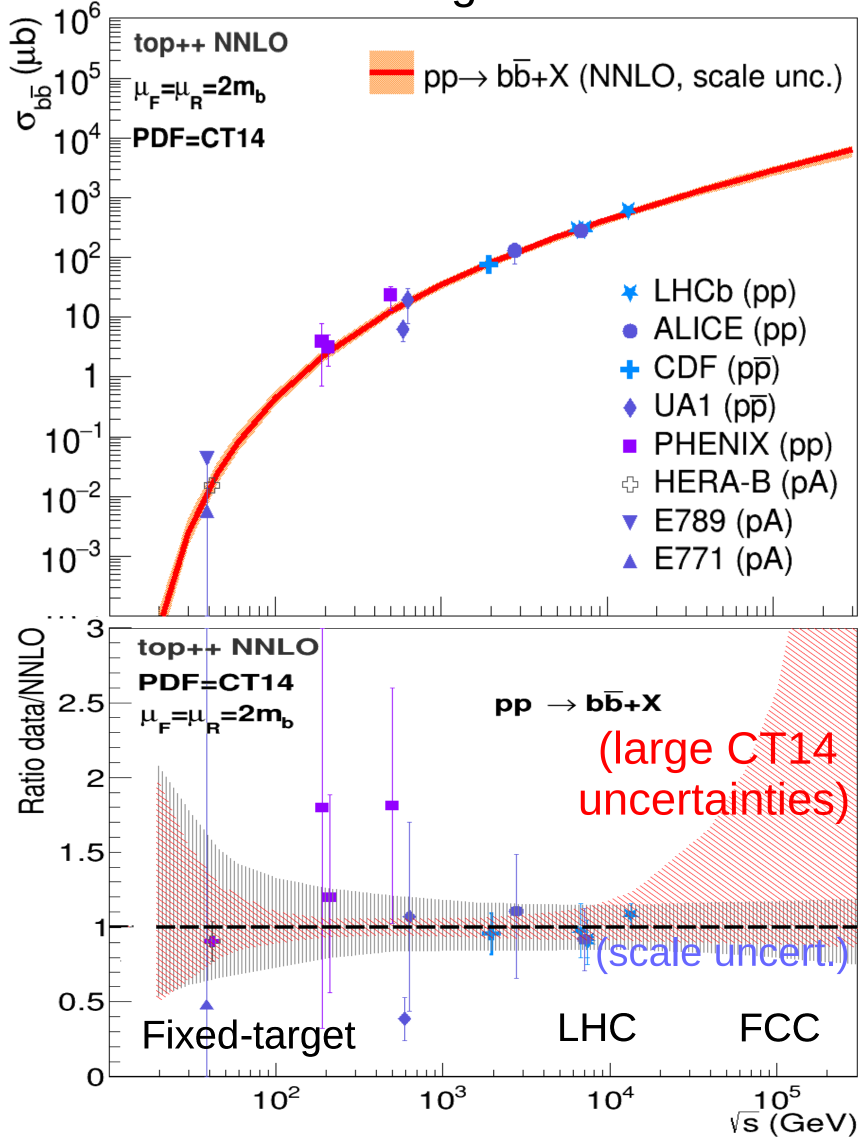


$\sigma(c\bar{c}, b\bar{b})$: Data vs. NNLO (CT14 PDF)

- **Charm**: Data ×2 theory, but agreement within large uncertainties

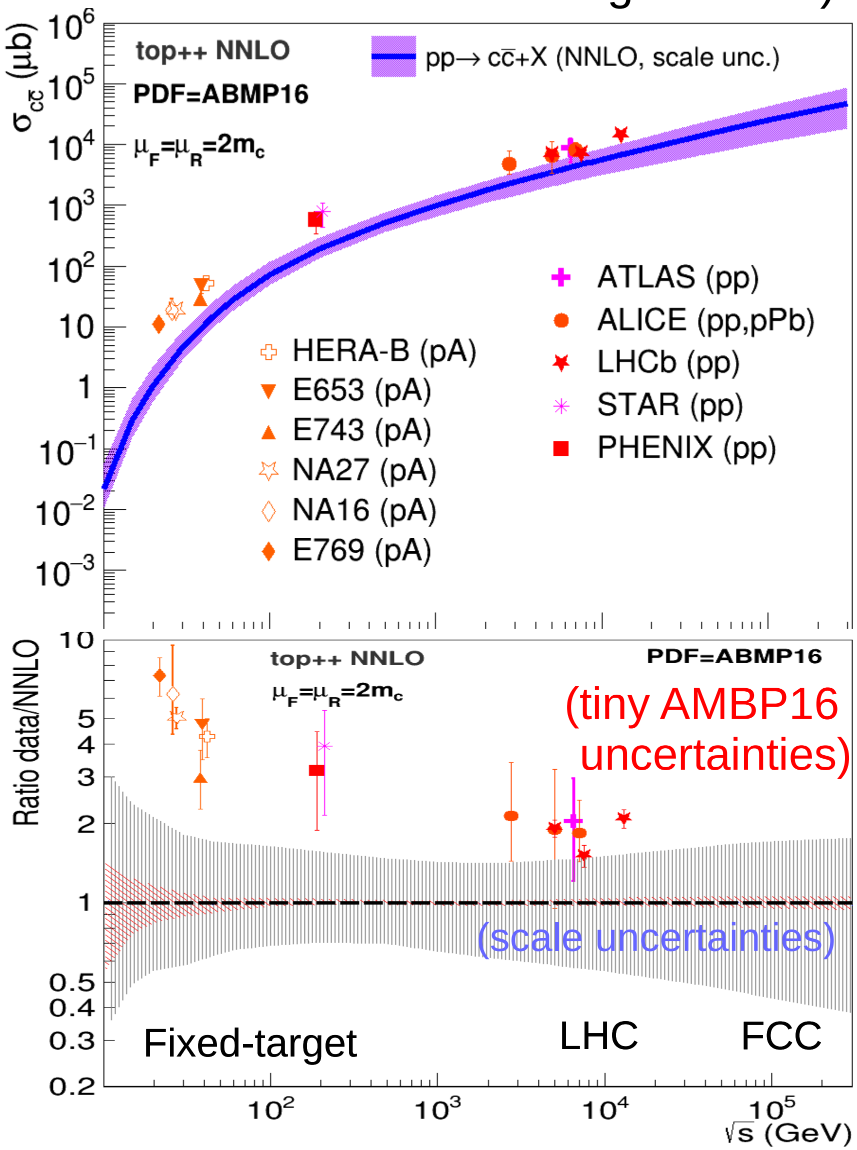


- **Bottom**: Very good agreement at all √s within large uncertainties



σ(cc̄,bb̄): Data vs. NNLO (ABMP16 PDF)

- Charm: Data ×2–5 theory (agreement for LHC within large uncert.)



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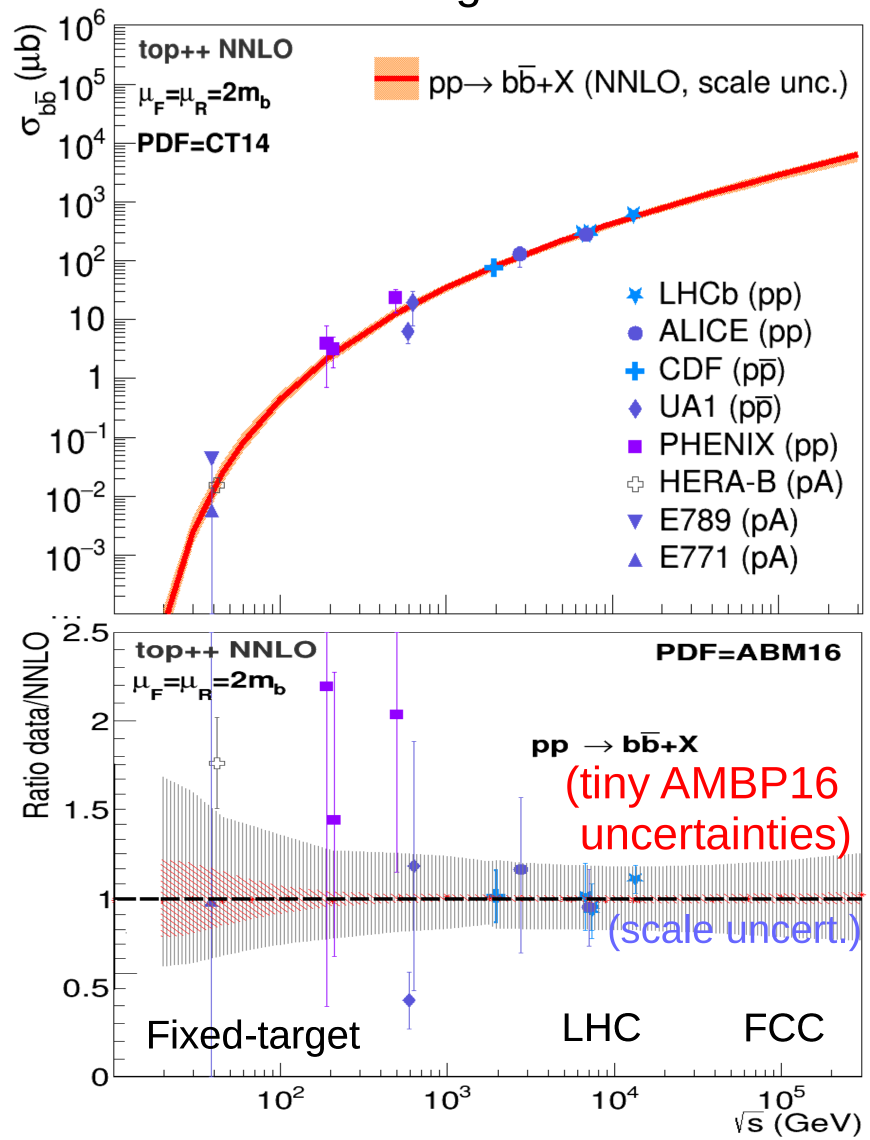
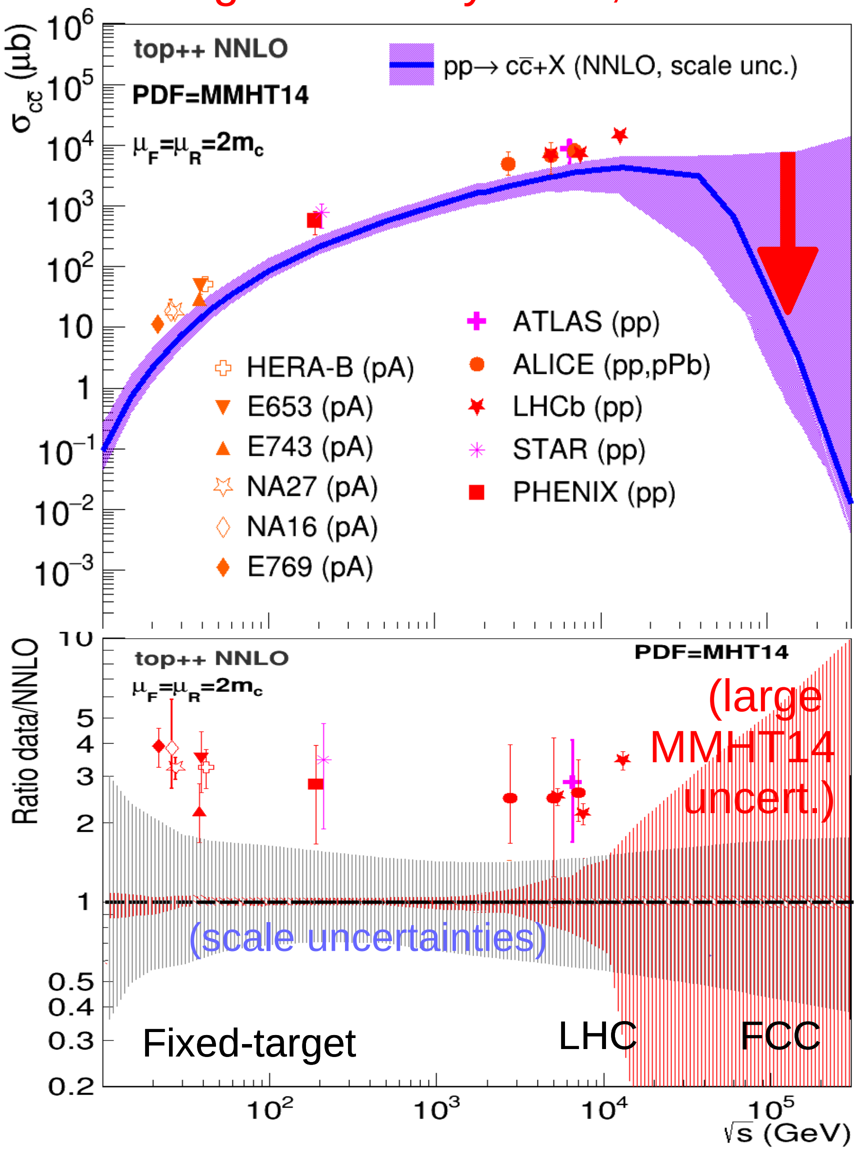


σ($c\bar{c}$,$b\bar{b}$): Data vs. NNLO (MMHT14 PDF)

- **Charm**: Data ×2.5 theory (negative gluon at very low x, √s>30 TeV)



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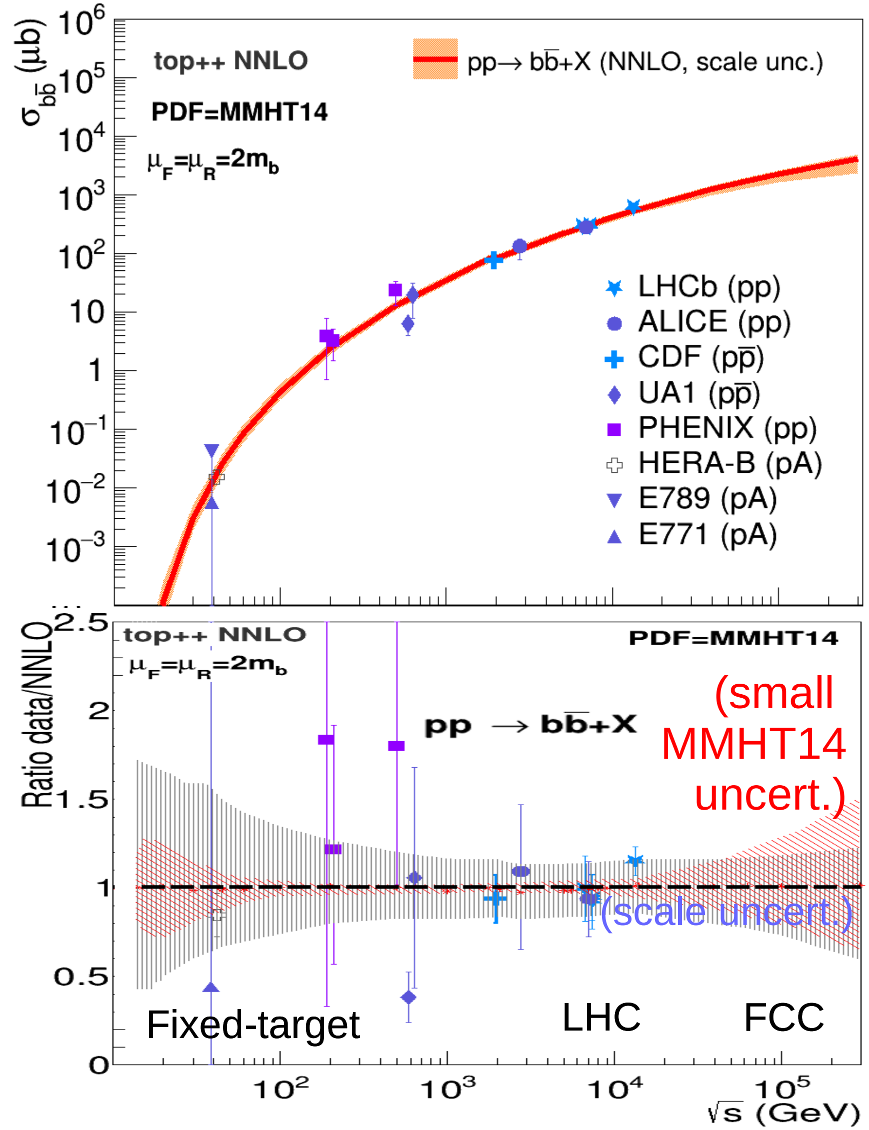
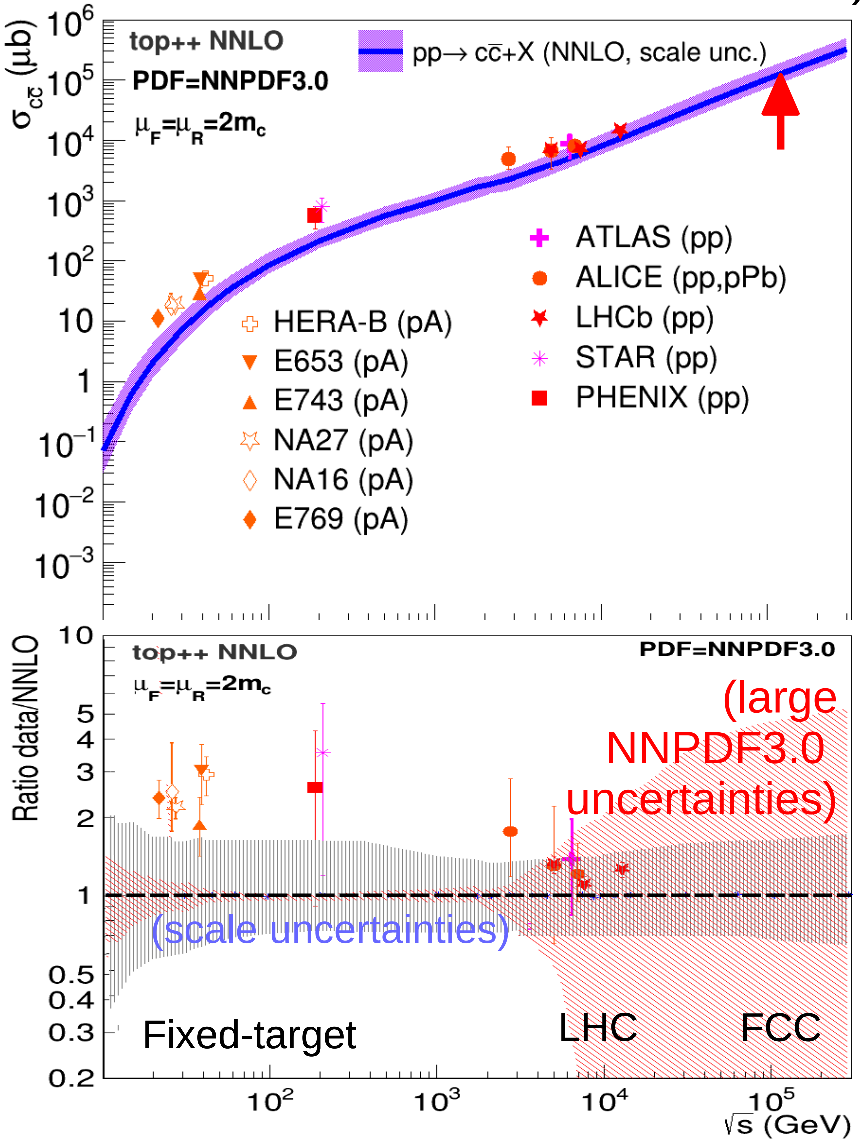


$\sigma(c\bar{c}, b\bar{b})$: Data vs. NNLO (NNPDF3.0 PDF)

- Charm: Data ×2 theory (agreement within uncert. but "kink" at √s>10 TeV)



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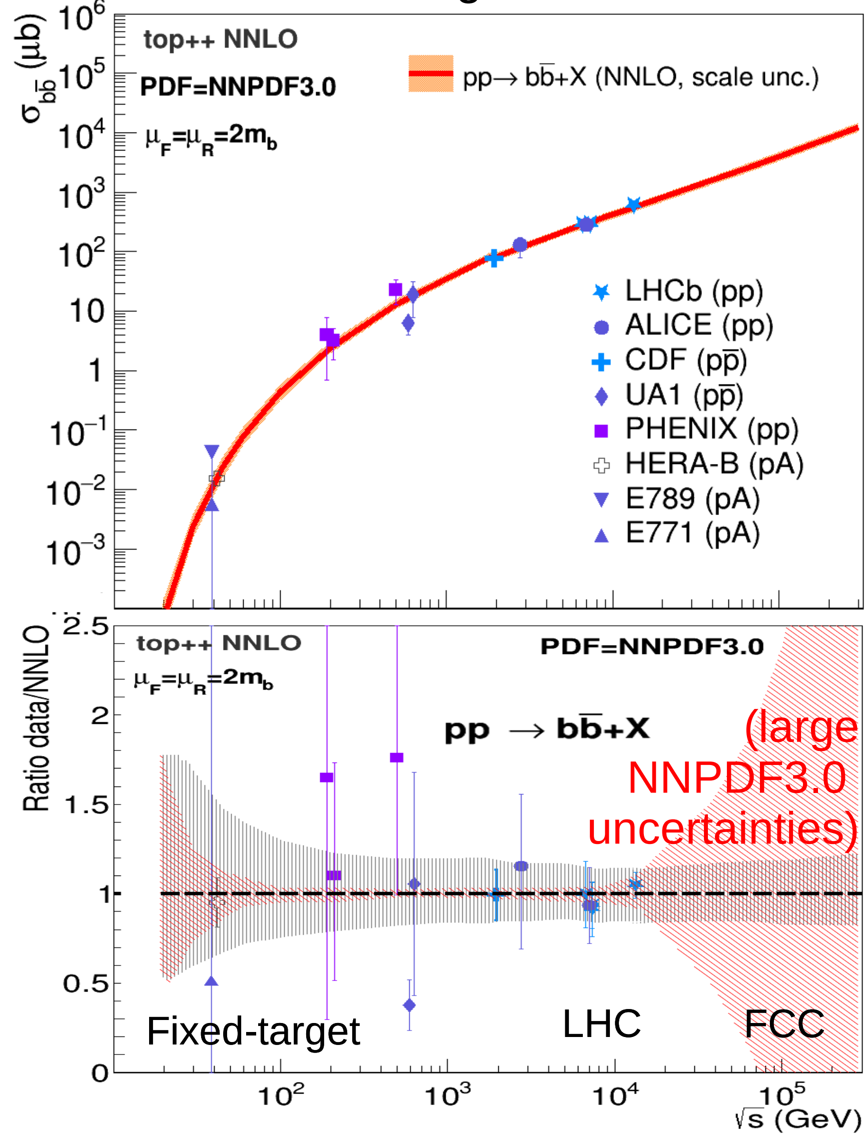
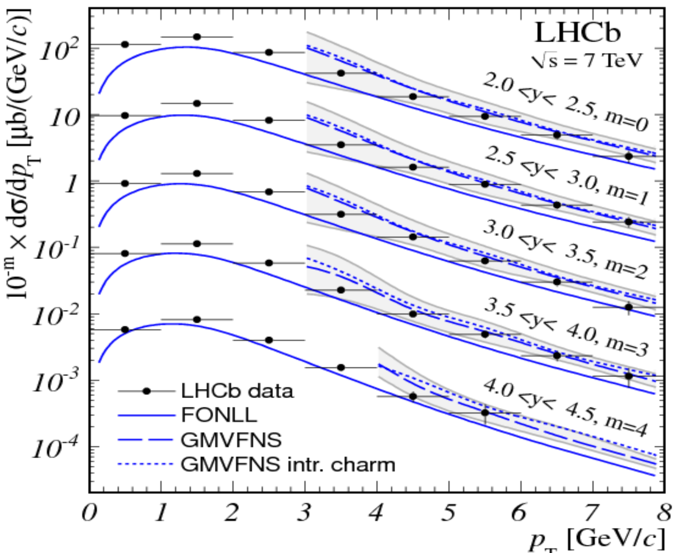
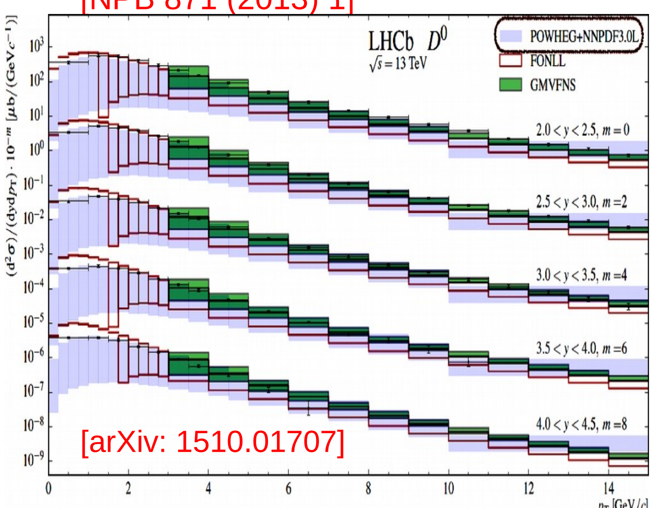


Updated NNPDF3.0 (NLO) low-x gluon

- Forward D-mesons (LHCb) probe gluon down to $x \sim 10^{-6}$:

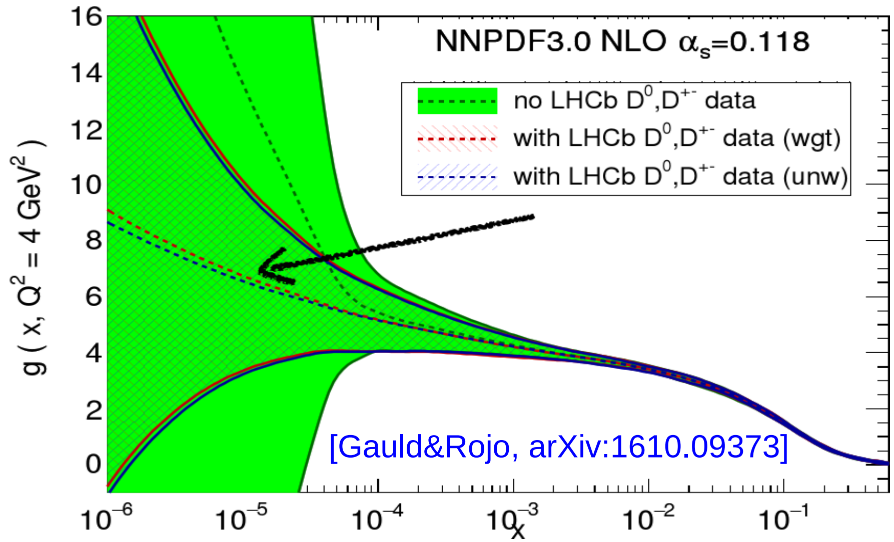


[NPB 871 (2013) 1]



- 5,7,13 TeV D-meson data fitted with FONLL calculations (GM-VFN scheme):

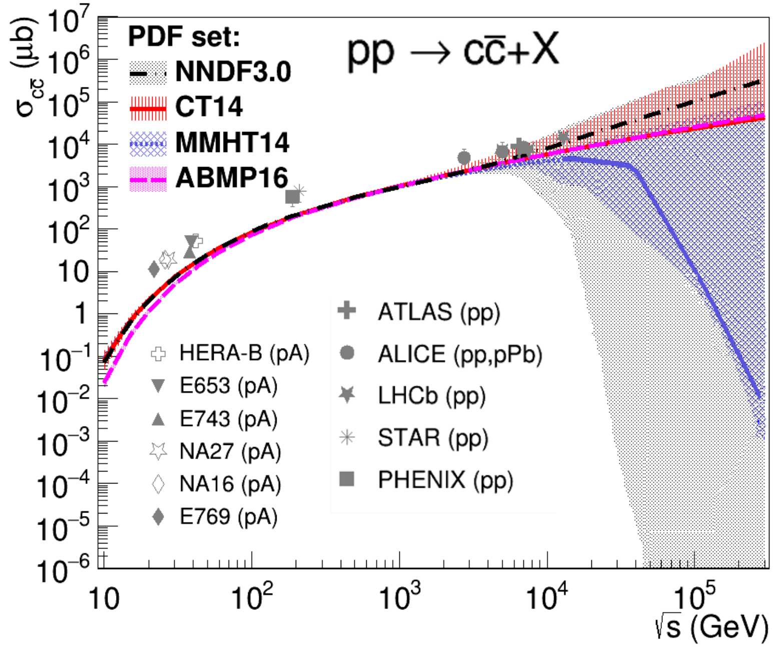
  - Updated analysis based on **normalized cross-sections at 5, 7 and 13 TeV** and **cross-section CoM energy ratios** (avoiding double counting)
  - Good description of all datasets, **compatible pull on the small-x gluon** except the R13/7 ratio
  - The $N^5+N^7+N^{13}$ combination leads to a **reduction of the small-x gluon PDF errors by an order of magnitude**!



- Future NNPDF low-x gluon will cure σ(cc) high-$\sqrt{s}$ “kink” & reduce uncertainties

Summary

- First-ever calculation of NNLO total charm and bottom cross sections in hadronic collisions (using modified version of Top++):
  - ✓ Large K-factors: σ(NNLO/NLO) ~ 2(fixed-target)–1.2(LHC)
  - ✓ Reduced scale uncertainties:
    Charm: $\pm(60\%)_{NLO} \rightarrow \pm(40\%)_{NNLO}$ Bottom: $\pm(35\%)_{NLO} \rightarrow \pm(15\%)_{NNLO}$
- Agreement with data (20 measurements from 20 GeV to 10 TeV), within large (PDF & exp.) uncertainties, though central exp. charm x-section still ×2–3 above theory.
- Very strong sensitivity to low-x gluon PDF (esp. charm). Predictions above LHC have uncontrolled behaviours and/or very large uncertainties:
  – CT14 gluon seems best behaved overall
  – AMBP16 underestimates most low-$\sqrt{s}$ data.
  – MMHT14 gluon dives to zero above ~30 TeV
  – NNPDF3.0 gluon best agreement w/ data (but unphysical slope change & huge uncertainties at ~10 TeV)



- At $\sqrt{s}$~300 TeV, $\sigma_{cc} \sim \sigma_{inel}$: Impact on μ,ν of most energetic cosmic-rays showers

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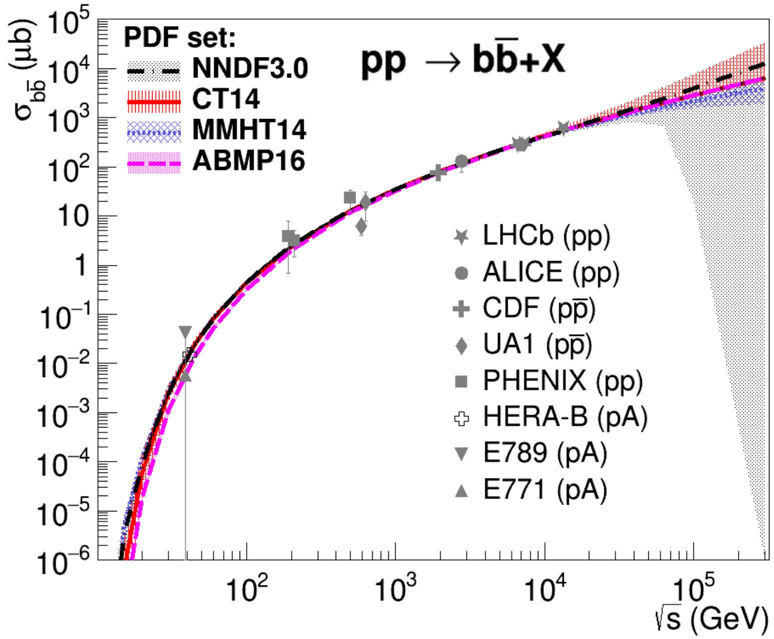

- Bottom x-sections well behaved for all PDFs up to ~100 TeV.

Backup slides