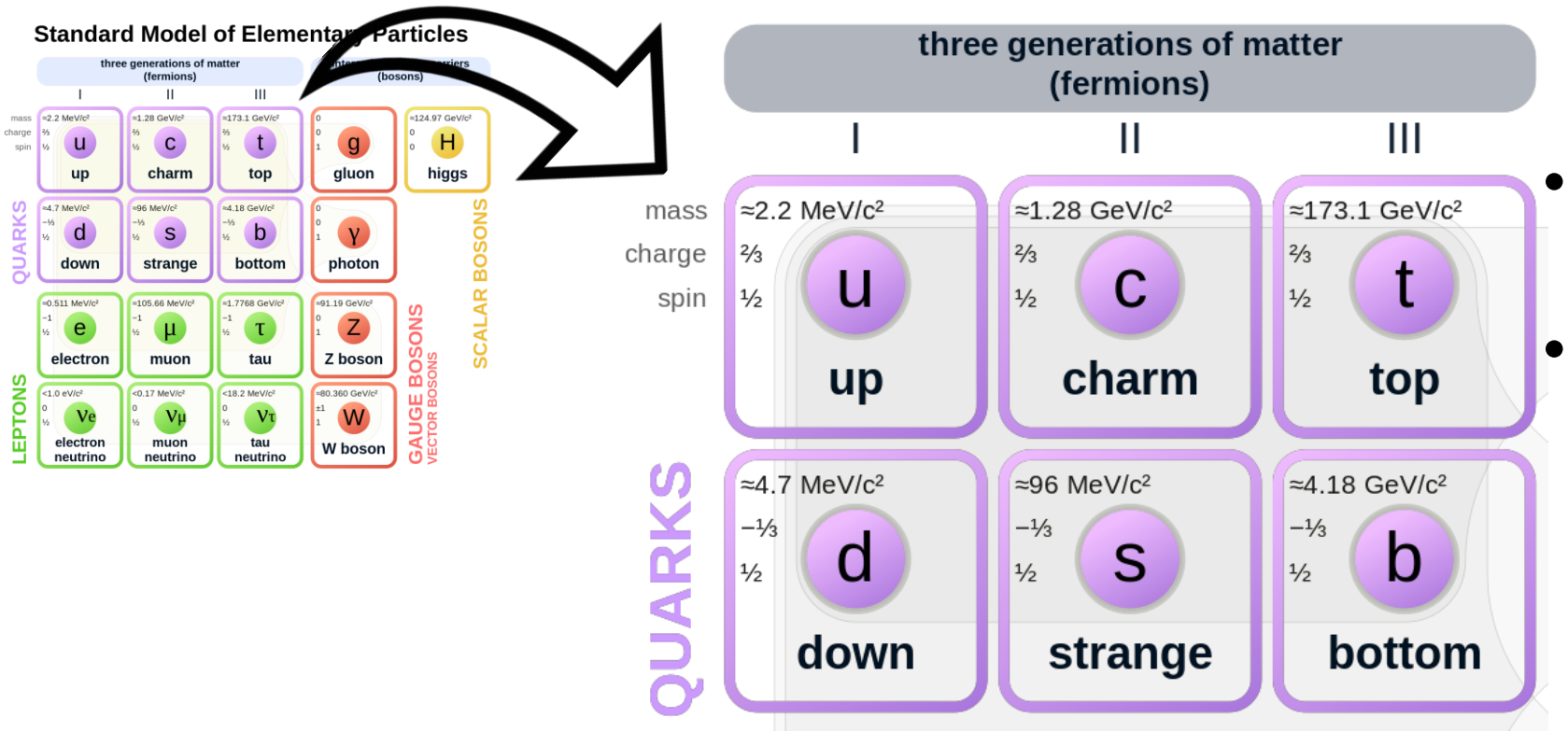
Obtaining high-precision predictions for top-pair production at the LHC in perturbative QCD

ANDRÉ ALVES

SUPERVISOR: JOÃO PIRES

SEPTEMBER 08, 2023

The top quark

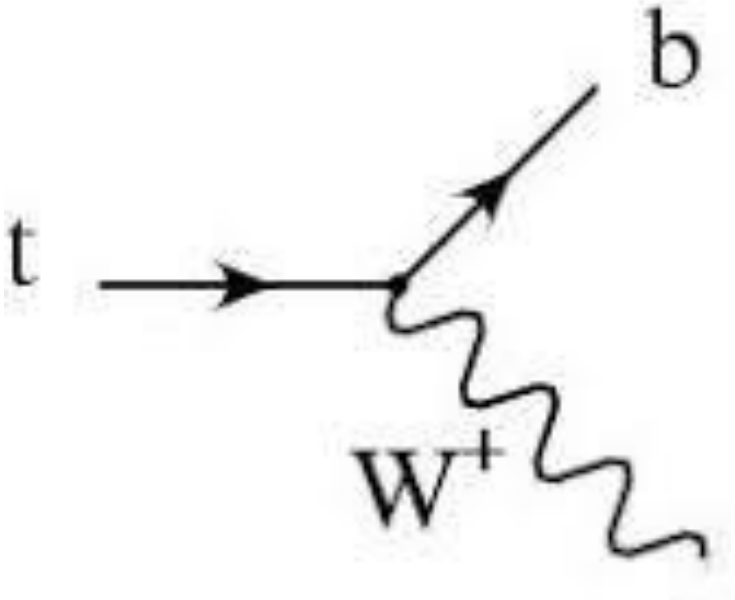


- **The heaviest particle**
- **Almost as massive as an atom of gold($\approx 180 GeV/c^2$)**

Top quark decay

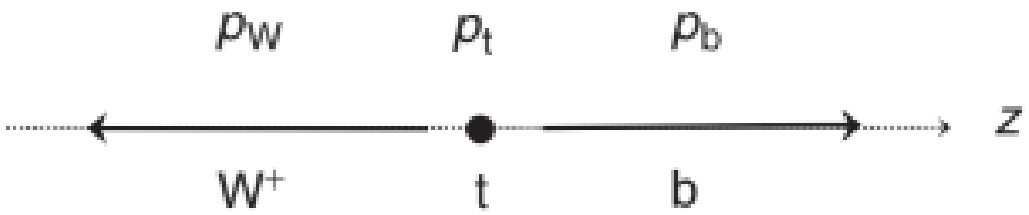
What is the most likely decay path?

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix}$$



$$\mathbf{t \rightarrow bW^{+}}$$

Top quark lifetime



$$\Gamma_{fi} = \frac{p^*}{32\pi^2 m_a^2} \int |M_{fi}|^2 \, d\Omega$$

$$M = \frac{g_W}{\sqrt{2}} \epsilon_\mu^*(p_W) \bar{u}(p_b) \tfrac{1}{2} \gamma^\mu (1 - \gamma^5) u(p_t)$$

$$P_L = \tfrac{1}{2}(1 - \gamma^5)$$

$$p_t = (m_t, 0, 0, 0)$$

$$p_b = (p^*, 0, 0, p^*)$$

$$p_W = (E^*, 0, 0, -p^*)$$

$$E^{*2} = (p^*)^2 + m_W^2$$

$$u_\downarrow(p_b) \approx \sqrt{p^*} \begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix} \qquad u_1(p_t) = \sqrt{2m_t} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad u_2(p_t) = \sqrt{2m_t} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

$$\epsilon_+^*(p_W) = -\frac{1}{\sqrt{2}}(0, 1, -i, 0),$$

$$\epsilon_-^*(p_W) = \frac{1}{\sqrt{2}}(0, +1, +i, 0),$$

$$\epsilon_L^*(p_W) = \frac{1}{m_W}(-p^*, 0, 0, E^*)$$

Top quark lifetime

$$\mathcal{M}_1 = -g_{\mathrm{W}} \sqrt{2 m_{\mathrm{t}} \mathrm{p}^*},$$

$$\mathcal{M}_2 = -\frac{g_{\mathrm{W}}}{m_{\mathrm{W}}} \sqrt{m_{\mathrm{t}} \mathrm{p}^*} (E^* + \mathrm{p}^*)$$

$$\langle |\mathcal{M}^2| \rangle = \tfrac{1}{2} \left(|\mathcal{M}_1^2| + |\mathcal{M}_2^2| \right)$$

$$\Gamma(t \to bW^+) = \frac{G_F m_t^3}{8\sqrt{2}\pi} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + \frac{2m_W^2}{m_t^2}\right)$$

$$\tau_{\mathrm{t}} = 1/\Gamma_{\mathrm{t}} \approx 5 \times 10^{-25}\ \mathrm{s}$$

Strong force coupling constant, asymptotic freedom and muR

The interaction probability is proportional to the matrix element Squared and $|M|^2 \propto g^4$

$$\alpha_s = \frac{g_S^2}{4\pi}$$

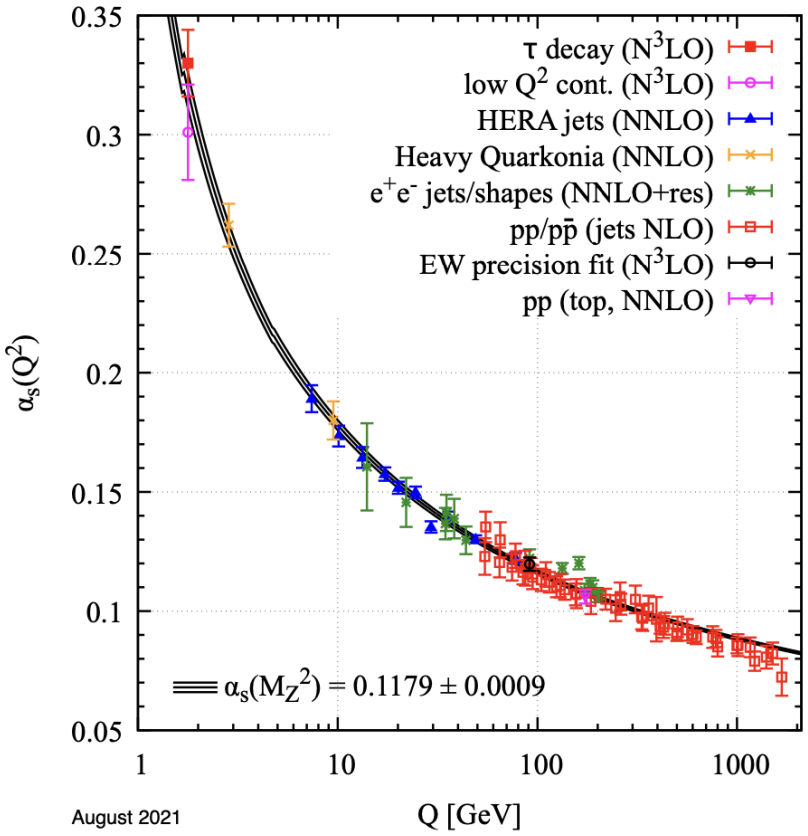
$\alpha(q^2 \approx 0) \sim 1/137 \approx 0{,}0073$

$\alpha_s(q^2 \approx 0) \sim 1$

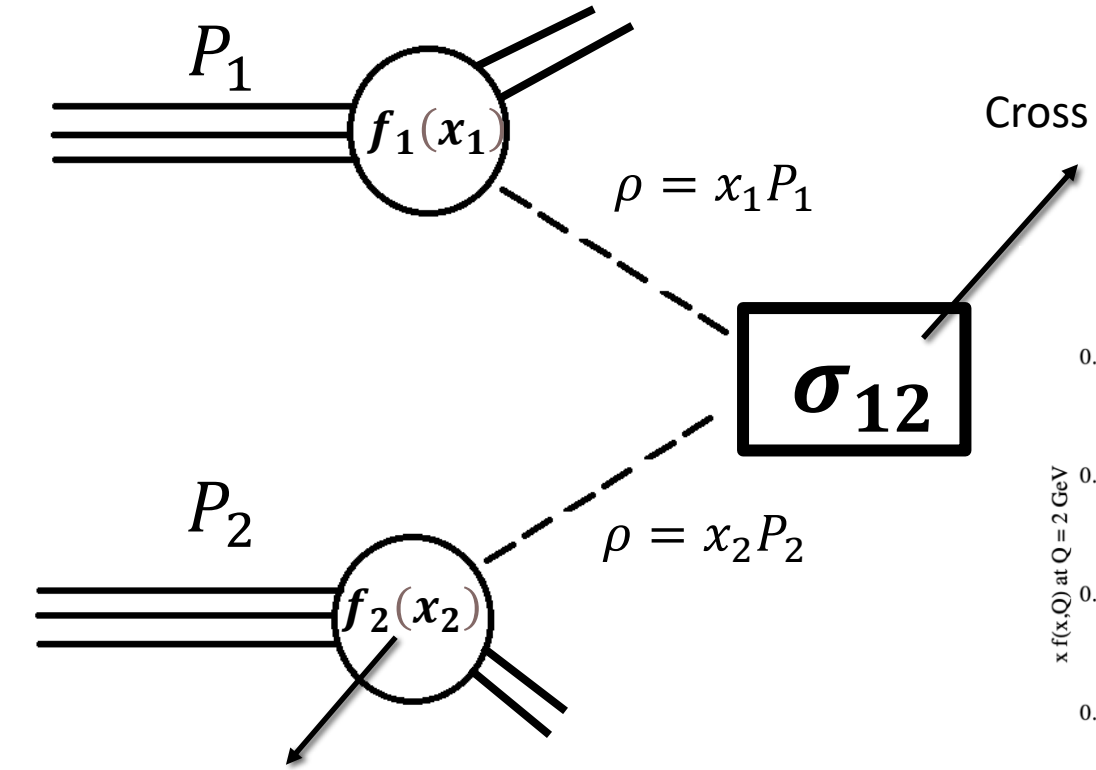
$\alpha_s(m_Z^2) \sim 0{,}118$

Renormalization scale

$\alpha_s = \alpha_s(q, \mu_R)$

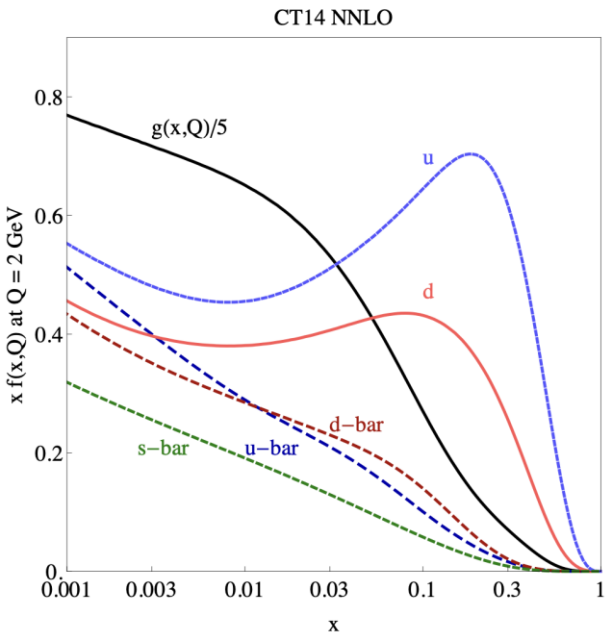


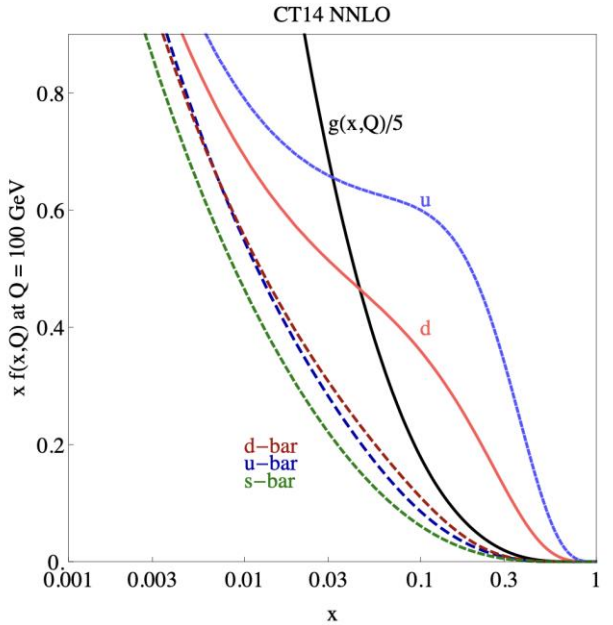
PDF and factorization scale



Parton density function

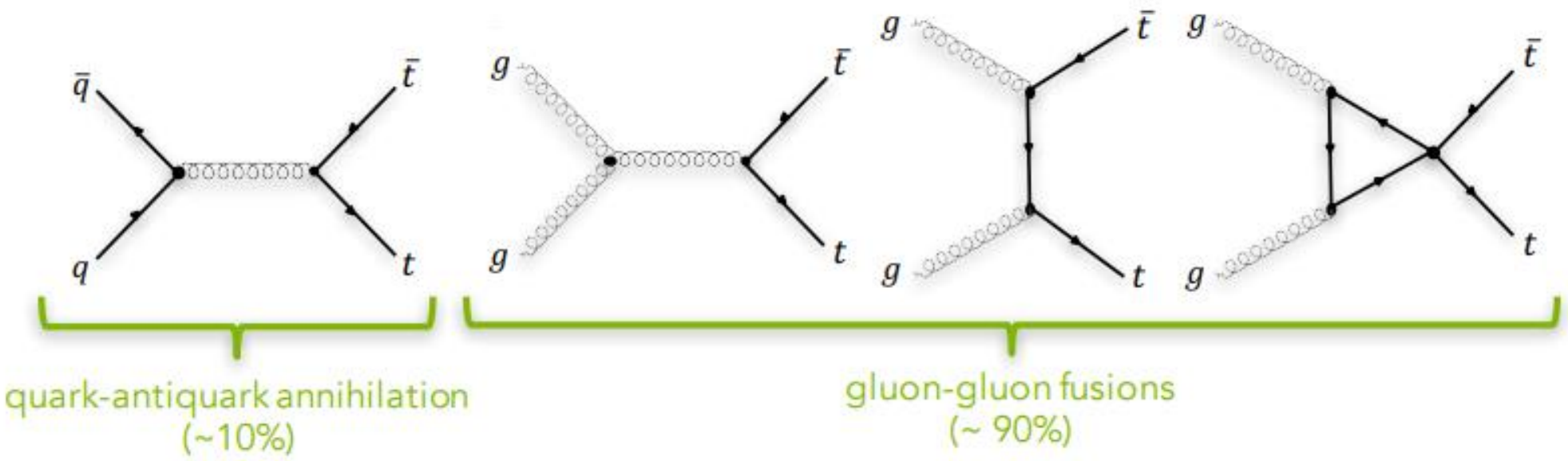
$$f_p = f_p\left(x_p, \mu_F\right)$$





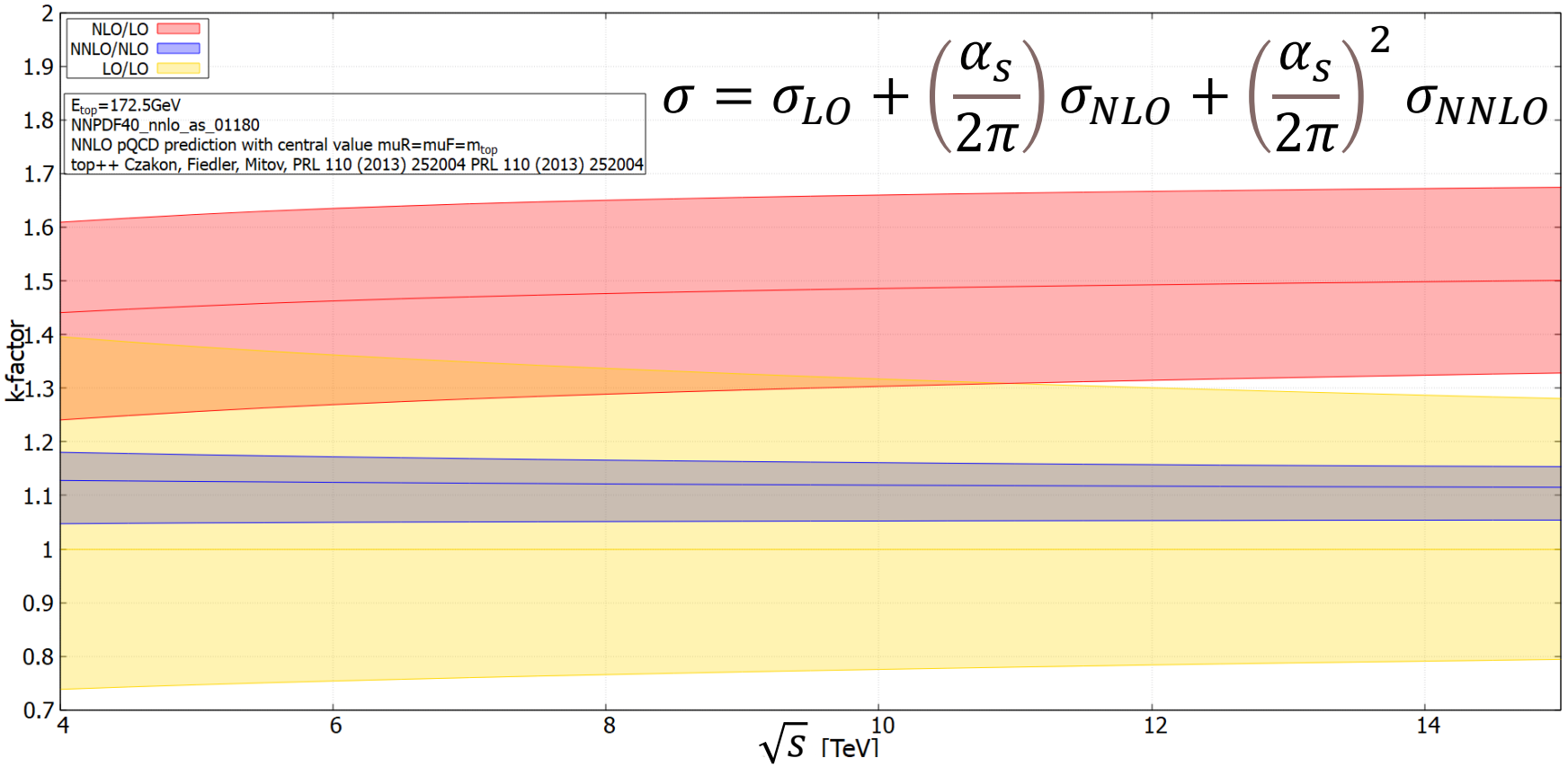
Top quark production at the LHC

Proton-Proton collisions



https://cds.cern.ch/record/2314658/files/ATL-PHYS-SLIDE-2018-190.pdf

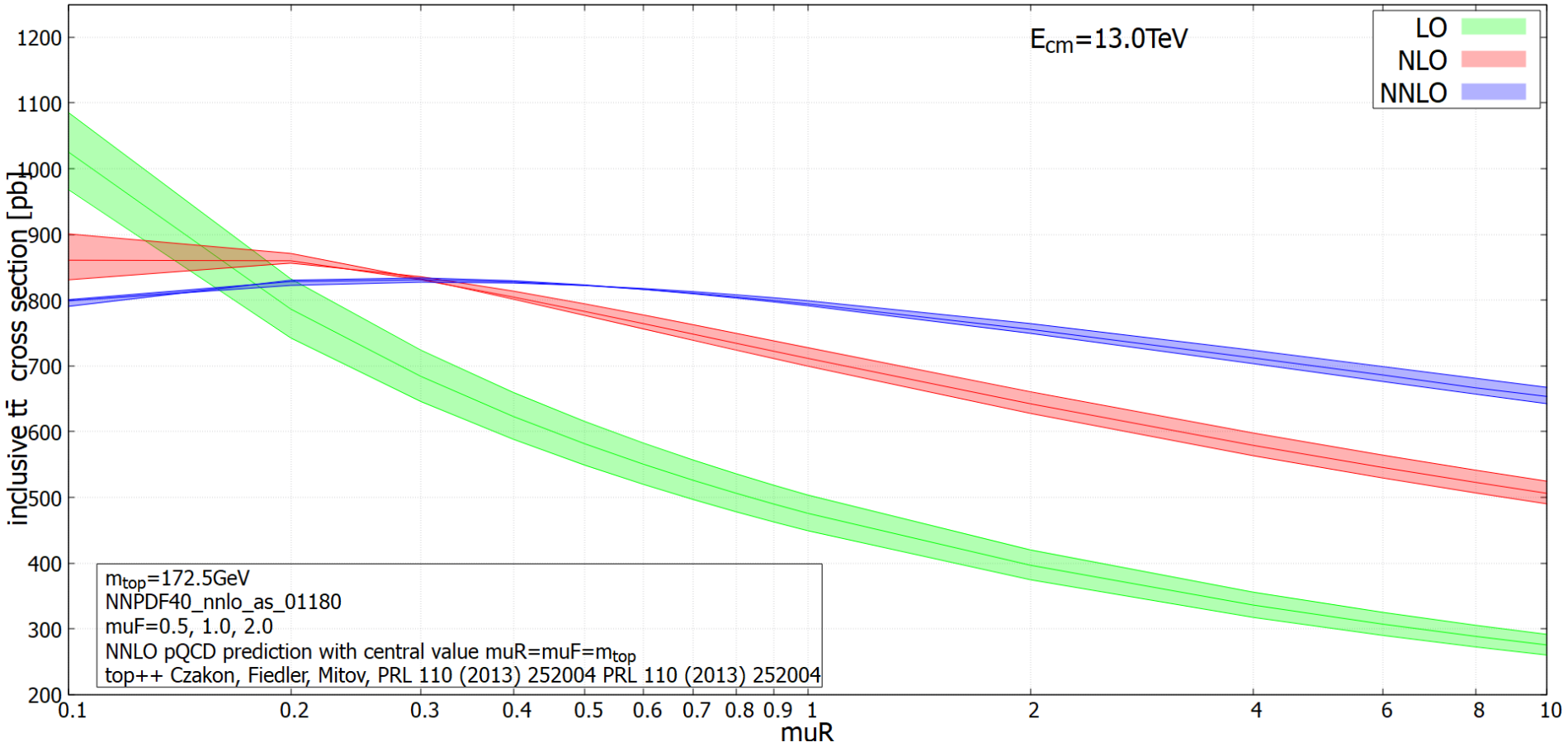
Perturbative expansion $pp \rightarrow t\bar{t}$



- Almost independent from $\sqrt{s}$

- $\sigma_{NLO} \sim 45\% - 50\%$
- $\sigma_{NNLO} \sim 12\%$
- Converges quickly

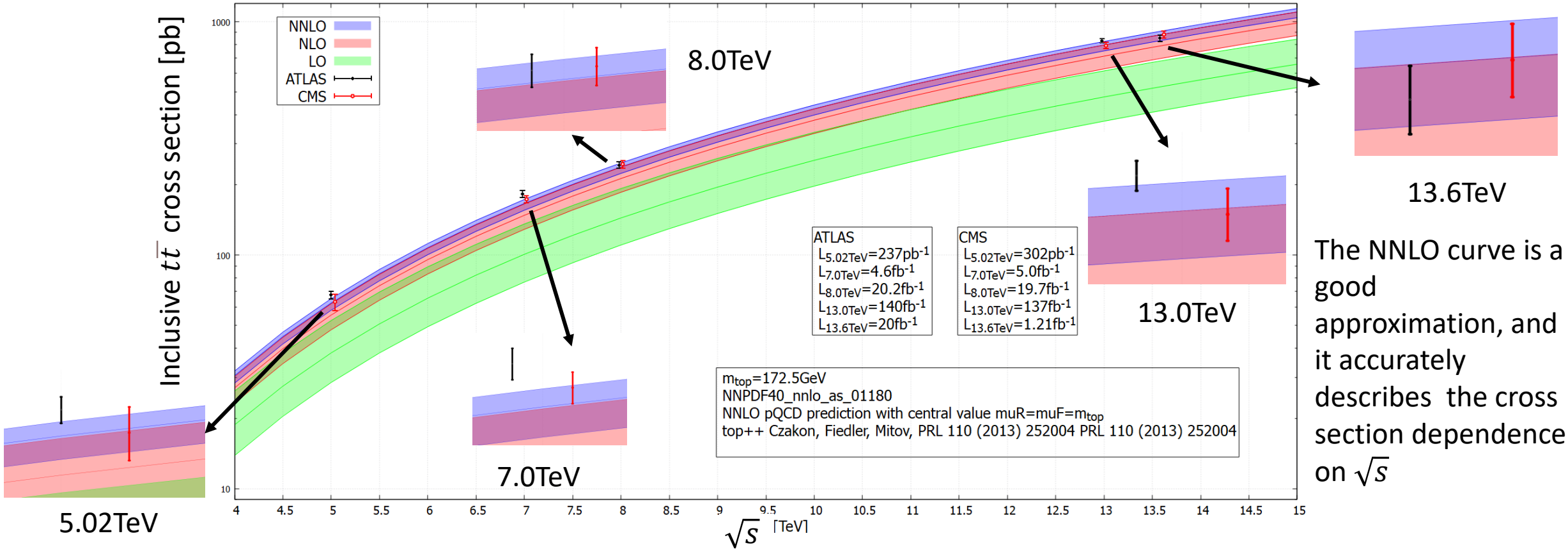
Theory uncertainty from renormalization and factorization scales



Reduction of dependence on muR and muF with higher perturbative order

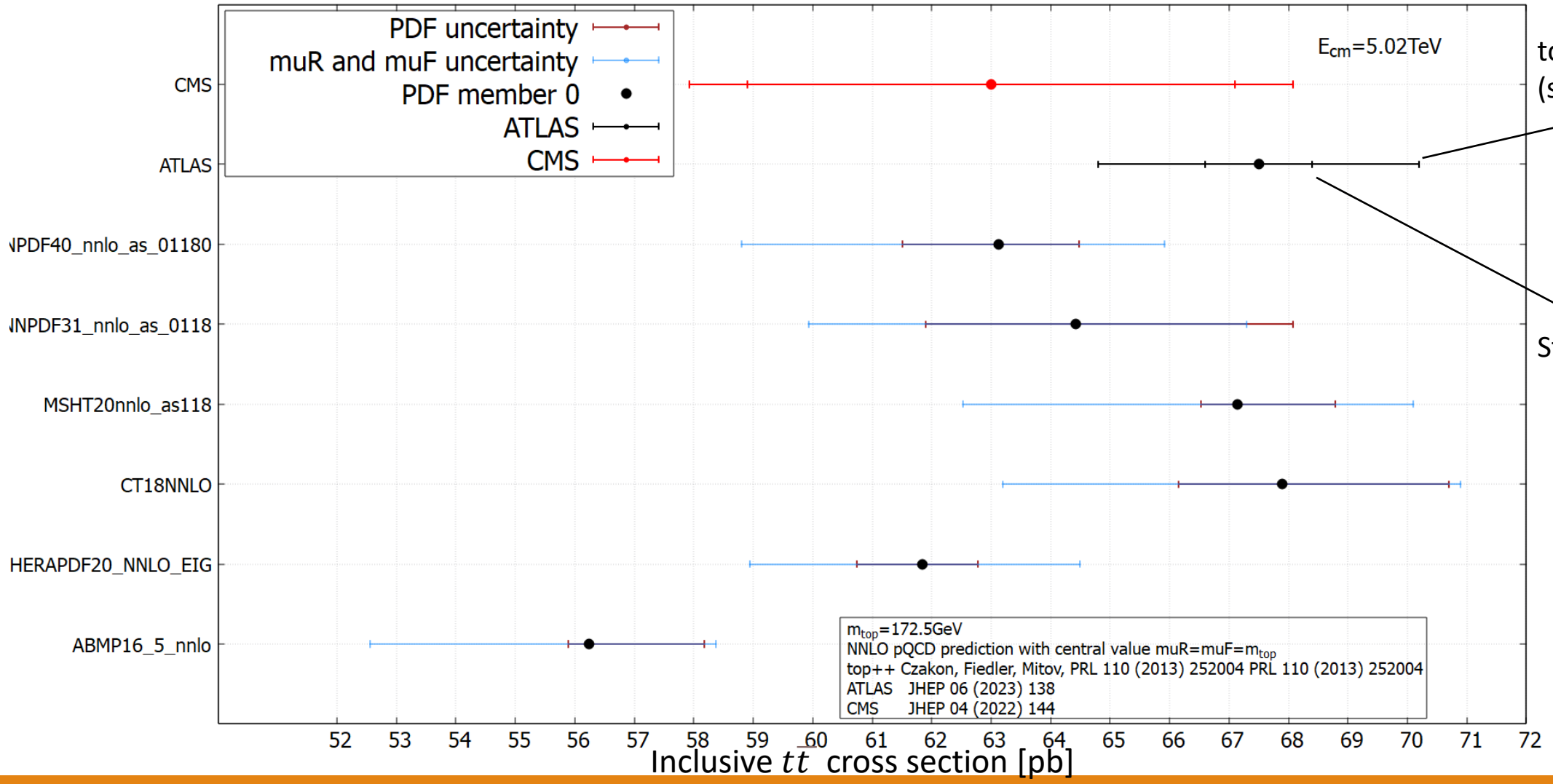
Variation of muF by a factor of 2

Prediction vs ATLAS and CMS measurement



The NNLO curve is a good approximation, and it accurately describes the cross section dependence on $\sqrt{s}$

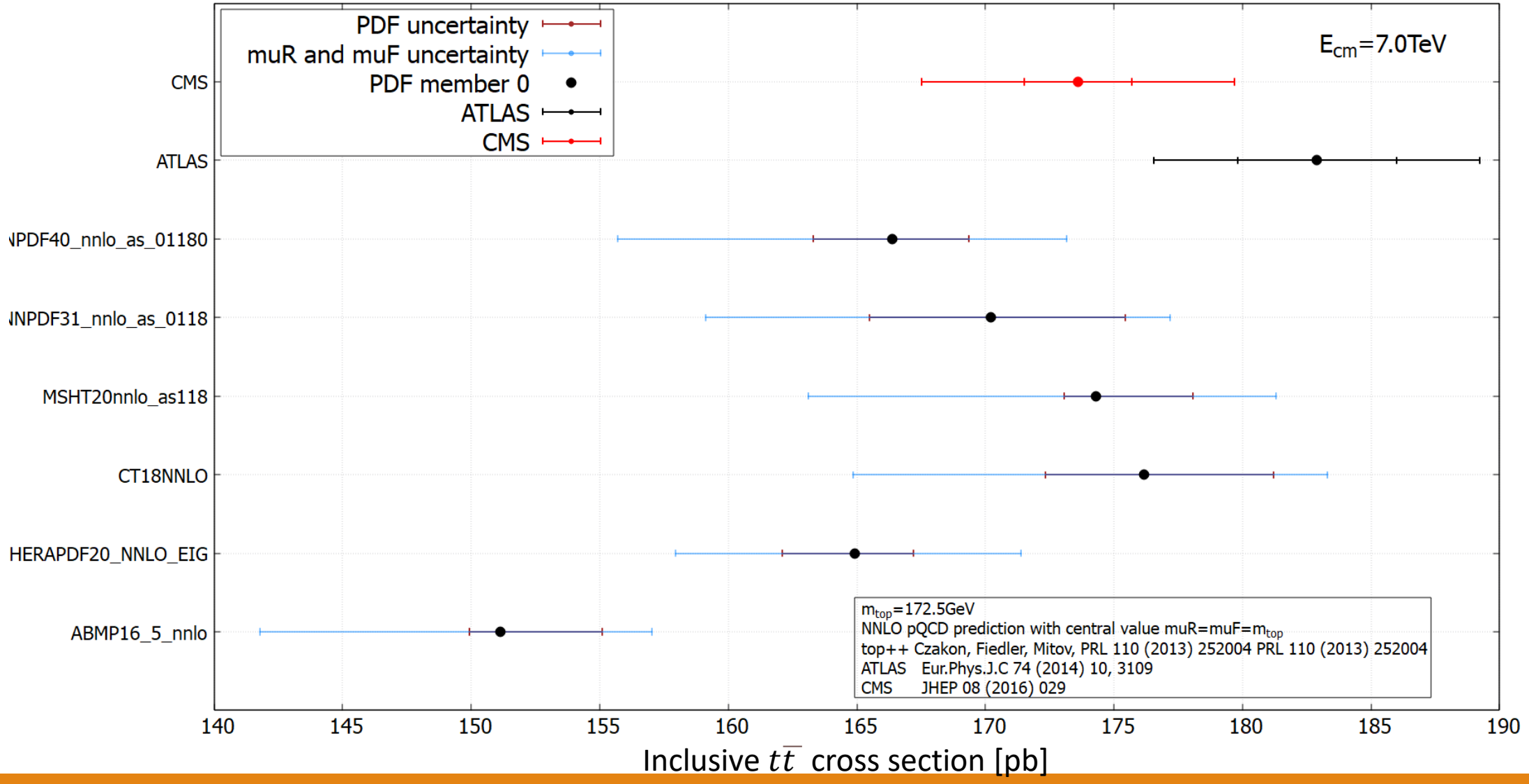
PDF uncertainty 5.02TeV



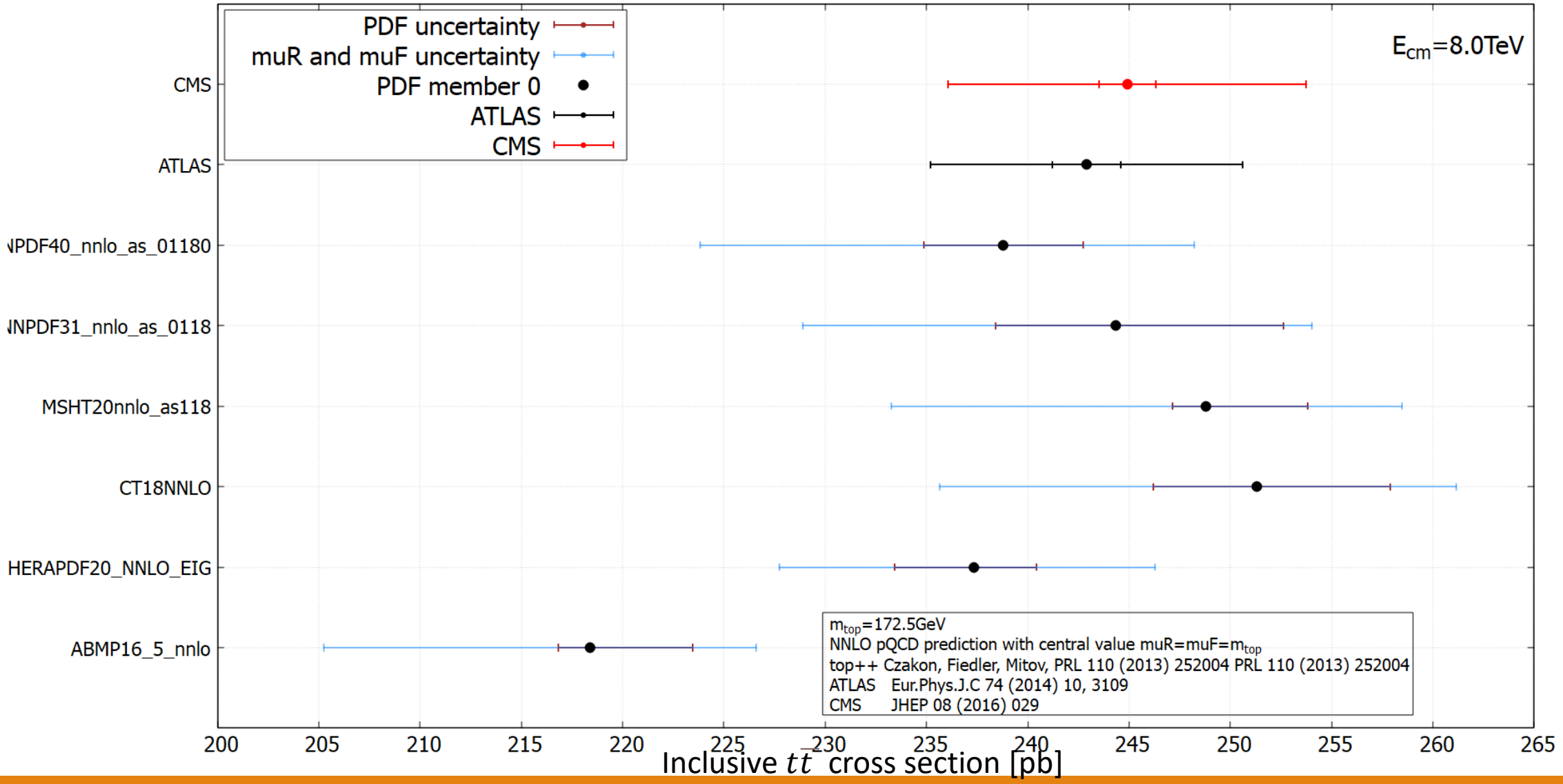
total error
(stat+syst+lumi)

Statistical error

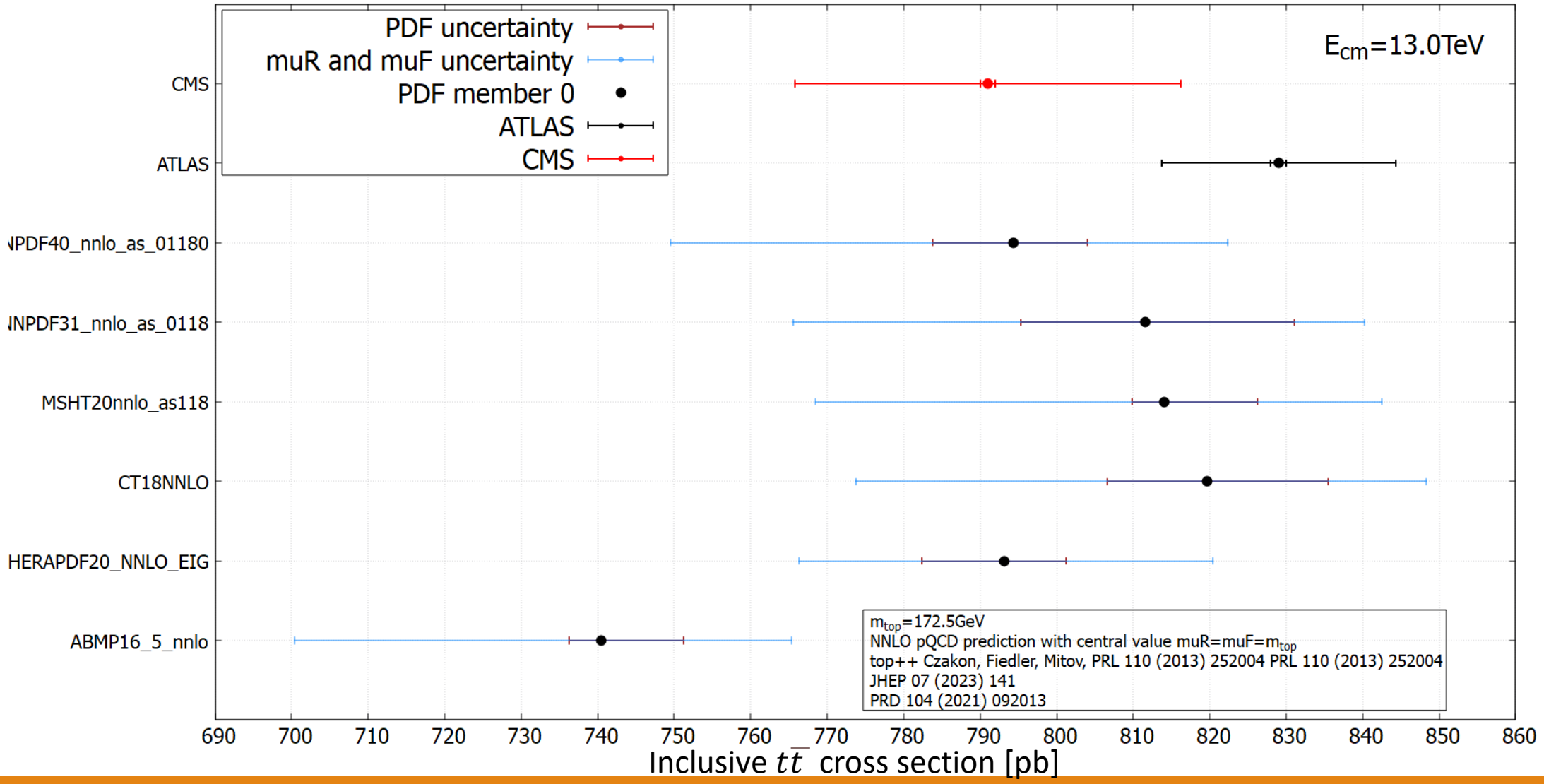
PDF uncertainty 7.0TeV



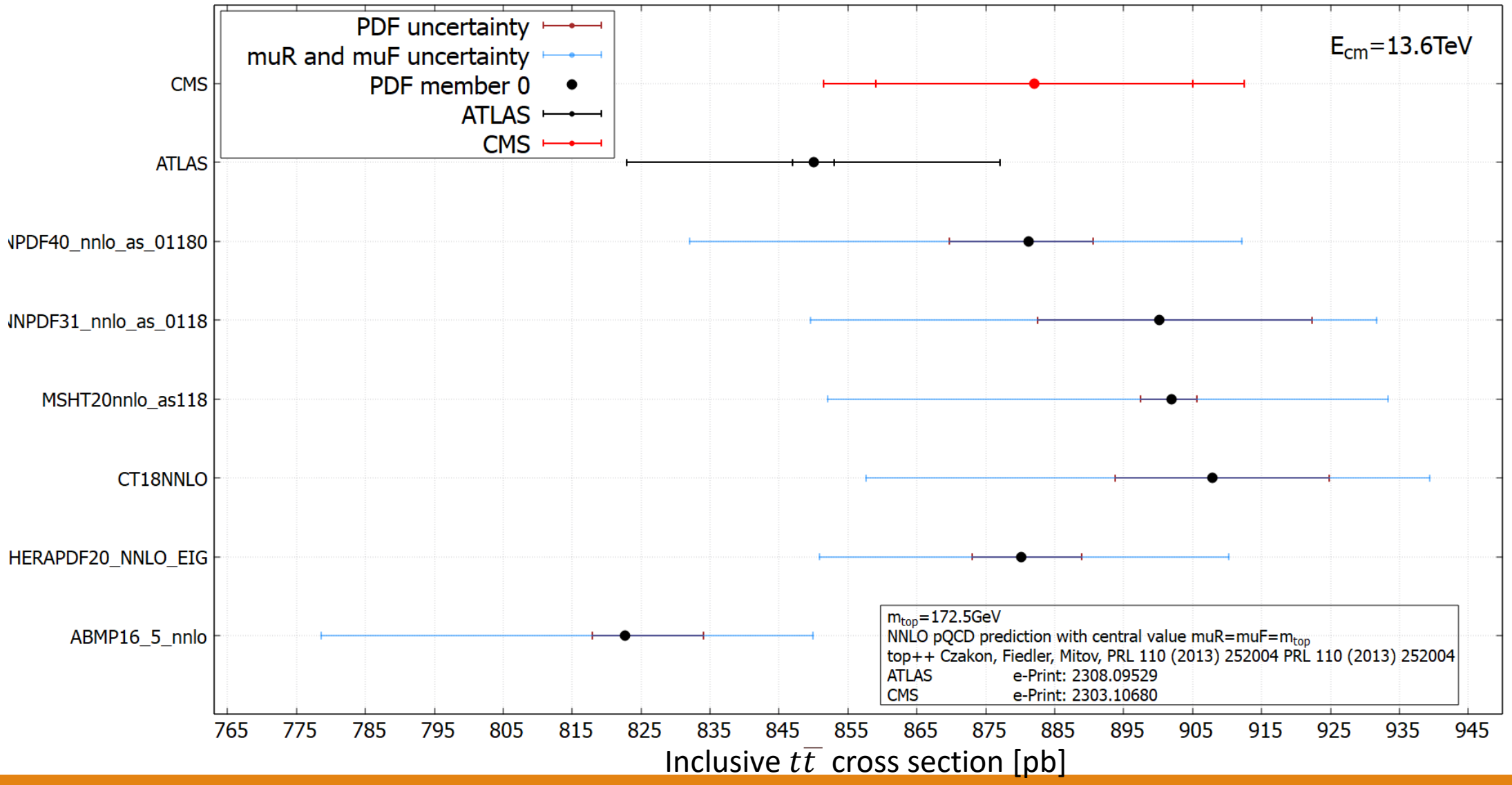
PDF uncertainty 8.0TeV



PDF uncertainty 13.0TeV



PDF uncertainty 13.6TeV



Conclusion

- The experimental results agree with the theoretical predictions, the standard model can predict the cross section in perturbative QCD accurately
- In LO, the error can reach 40%, in NLO 20% but in NNLO only 5%
- PDF and muR and muF error usually under 5%
- Next step would be to study the differential $t\bar{t}$ cross-section as a function of the invariant mass of the top-quark pair, $m_{t\bar{t}} = (p_t + p_{\bar{t}})^2$.