Top pair production at the LHC through NNLO QCD and NLO EW

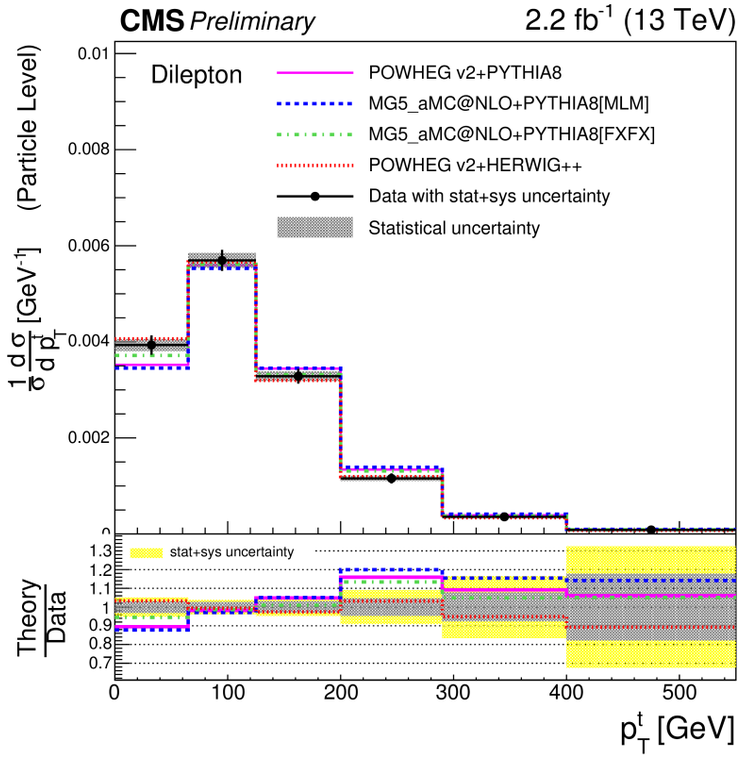
Marco Zaro
LPTHE - Université Pierre et Marie Curie, Paris VI

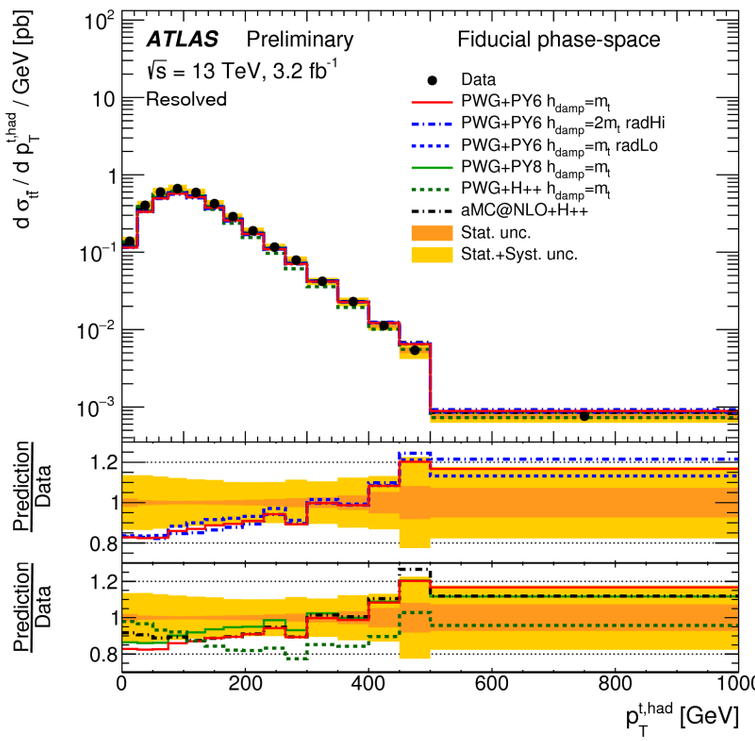
based on M. Czakon, D. Heymes, A. Mitov, D. Pagani, I. Tsinikos, MZ, arXiv:1705.04105

LHC Top Working Group meeting, June 6th 2017, CERN

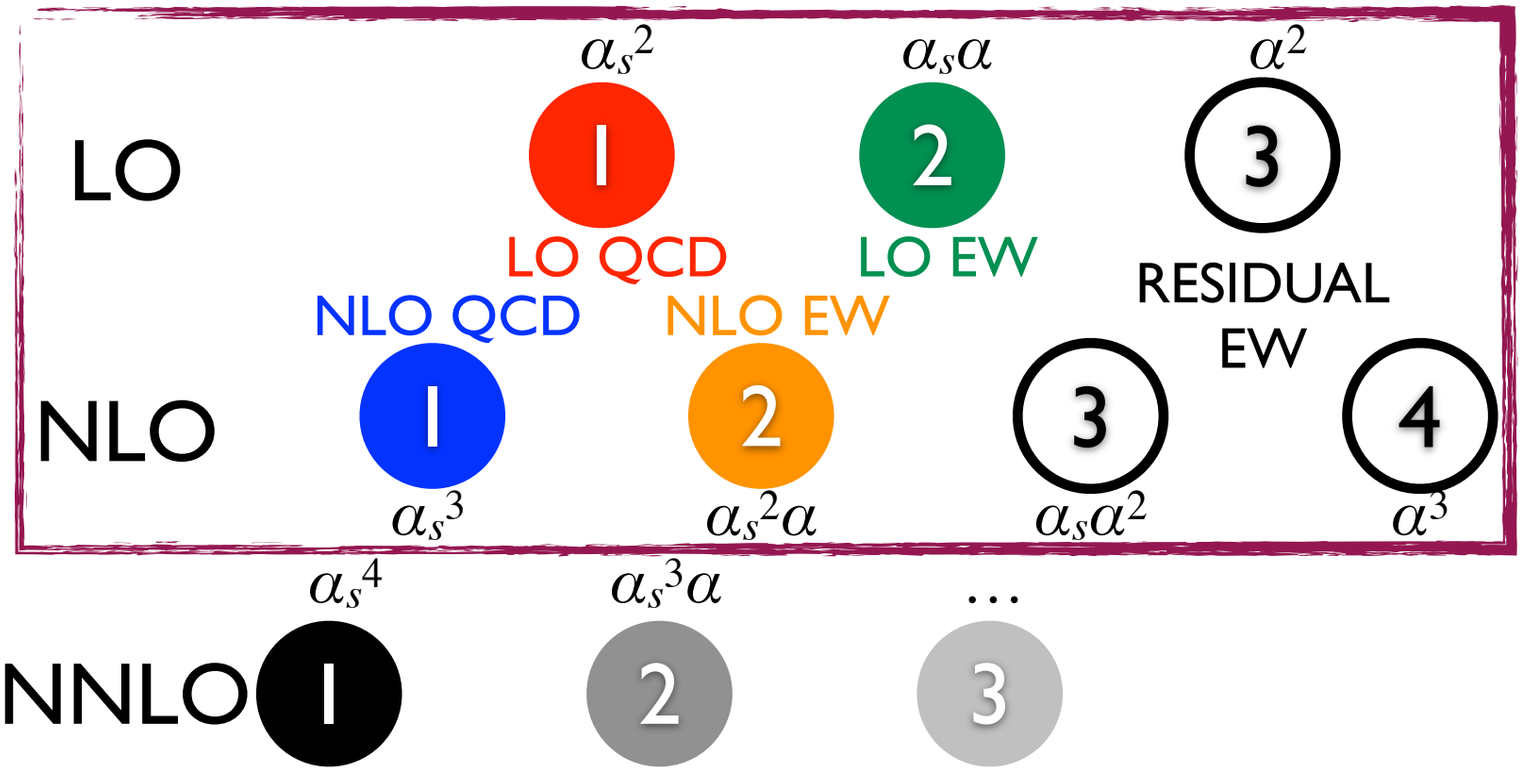
Motivation

- Top pair production enters almost all LHC analyses, either as a signal, as a background or via PDF fits and MC-tunes
- NLO-accurate MCs do a decent job, still there is some tension with data
- The decreasing exp. uncertainties call for better predictions: NNLO and NLO EW mandatory
- Unlike QCD corrections, the EW ones bring two new features, which can be relevant for boosted tops and high-p_T searches:
  - Sudakov suppression (negative) and photon-initiated contributions (positive)
- Need for a consistent combination of NNLO QCD and NLO EW corrections





Higher-order corrections to $t\bar{t}$ production



- NLO EW corrections to $t\bar{t}$ have been known for years, but they remain a hot topic

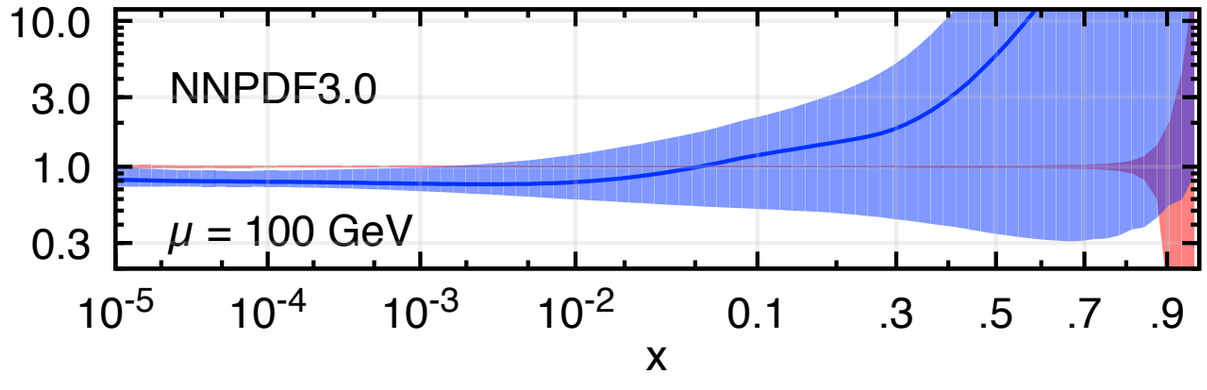
  Weak: Beenakker et al., Nu.Ph.B.411(1994), Kuhn et al., hep-ph/0610335 & arXiv:1305.5773, Bernreuther et al., hep-ph/0508091, Campbell et al., arXiv:1608.03356; QED+$g\gamma$ LO: Hollik et al., arXiv:0708.1697; FB asymmetry: Hollik et al., arXiv:1107.2606, Kuhn et al., arXiv:1109.6830, Manohar et al., arXiv:1201.3926, Bernreuther et al., arXiv:1205.6580; NLO+EW +decay (NWA): Bernreuther et al., arXiv:1003.3926; EW with γ-initiated: Pagani et al, arXiv:1606.01915; EW to $e^+\mu^-\nu\nu b\bar{b}$: Denner et al., arXiv:1607.05571
- We combine the NNLO QCD corrections with the complete LO and NLO corrections and we study the effect on differential observables in $t\bar{t}$ production

  Czakon, Mitov, Heymes arXiv:1511.0049 & 1606.03350

Setup of the calculation

- We use the following input-parameters
  m_t=173.3 GeV, m_W=80.385GeV, m_Z=91.1876 GeV, m_H=125.0 GeV
- EW corrections are computed in the G_μ scheme, with
  G_μ=1.1663787 · 10^{-5} GeV^{-2}
- Factorization and renormalisation scales are set to
  $\mu=m_T(t/\bar{t})/2$ for $p_T(t/\bar{t})$, $\mu=H_T/4$ for all other observables Czakon et al, arXiv:1606.03350
- A 5FS is employed throughout the computation
- EW corrections are computed with a development branch of `MadGraph5_aMC@NLO`; NNLO QCD corrections with `Top++`
- We use the LuxQED PDF set for our reference predictions, and compare with NNPDF3.0QED. These PDF sets provide a photon density obtained with different methodologies Manohar et al, 1607.04266; NNPDF Coll. arXiv:1410.849 & 1308.0598

See also Pagani, Tsinikos, MZ, arXiv:1606.01915 for a study of the photon-PDF effects in $t\bar{t}$ production



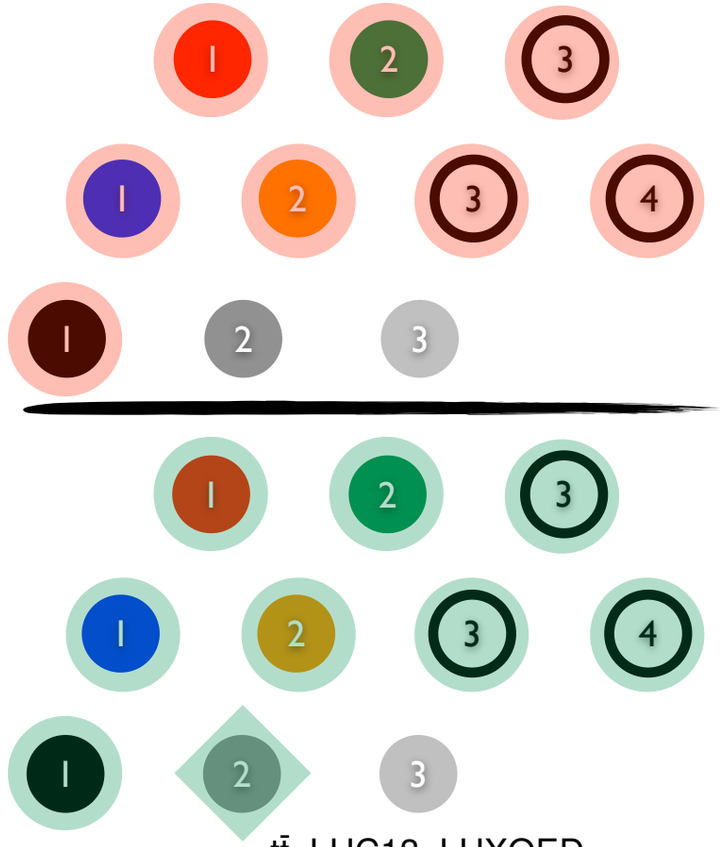
Combination of NNLO QCD and EW corrections

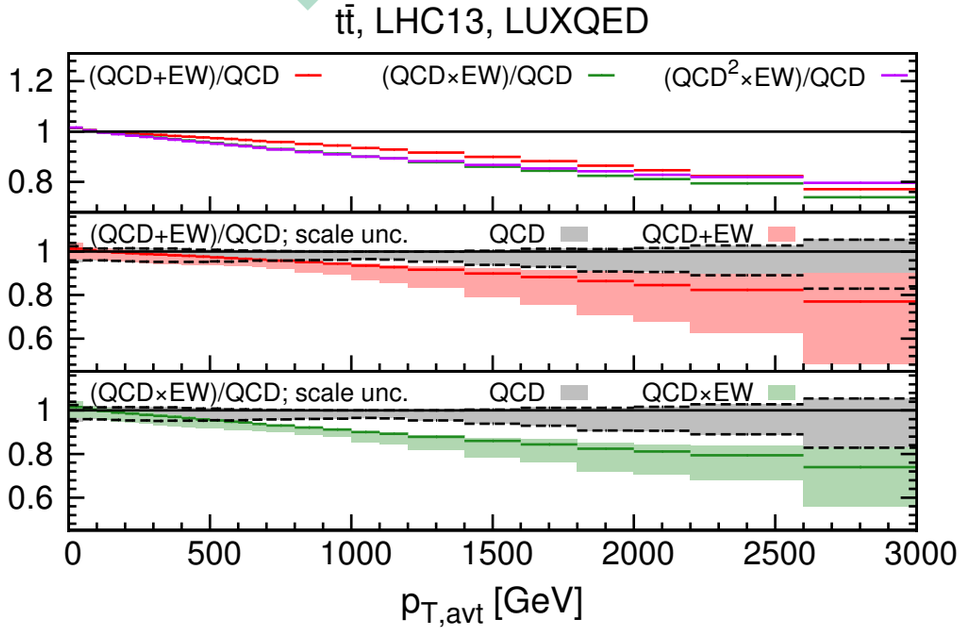
- The most straightforward way to combine EW and QCD corrections is an *additive* combination: simply add the two: $\Sigma_{\mathrm{QCD+EW}} \equiv \Sigma_{\mathrm{QCD}} + \Sigma_{\mathrm{EW}}$
  - Only terms which are known exactly are included
  - NLO EW corrections have LO-like scale variations: where they are large, they induce very large uncertainties
- Alternatively, one can try to guess subleading terms ($\alpha_s{}^3\alpha$) via a *multiplicative* combination

$$\Sigma_{\mathrm{mixed}} \equiv \Sigma_{\mathrm{NNLO,2}} \sim \Sigma_{\mathrm{NLO\ QCD}} \times \Sigma_{\mathrm{NLO\ EW}}/\Sigma_{\mathrm{LO}}$$

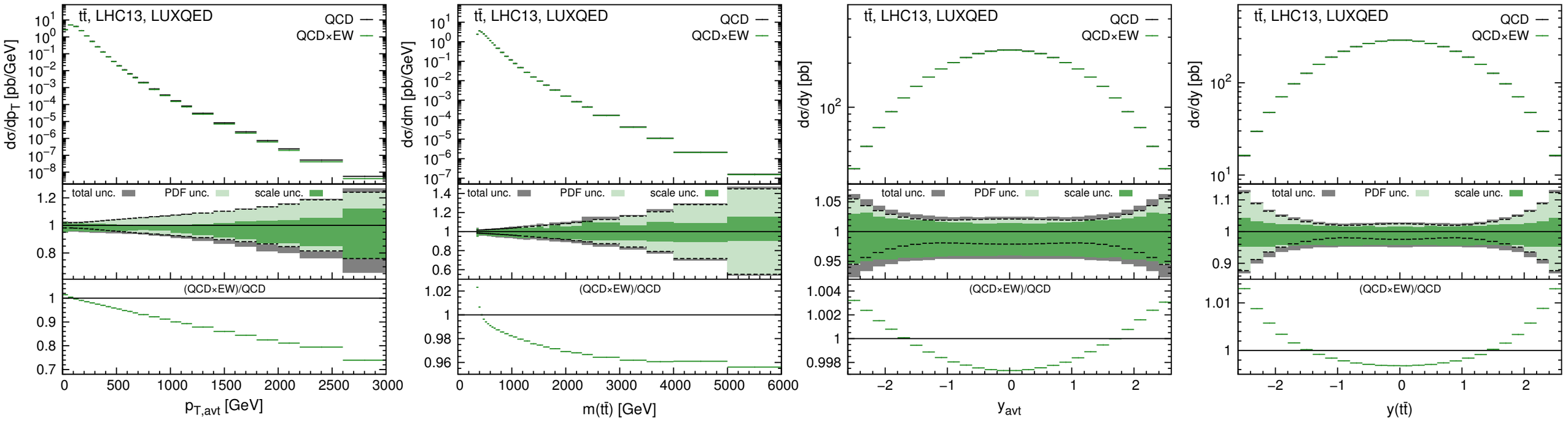
$$\Sigma_{\mathrm{QCD\times EW}} \sim \Sigma_{\mathrm{QCD+EW}} + \Sigma_{\mathrm{mixed}}$$

  - The $\alpha_s{}^3\alpha$ term is included in an approximate manner
  - The multiplicative combination works well when QCD corrections are dominated by soft-emissions and EW corrections by Sudakov logs → It is the case for $t\bar{t}$!
- For our reference results the multiplicative combination will be employed



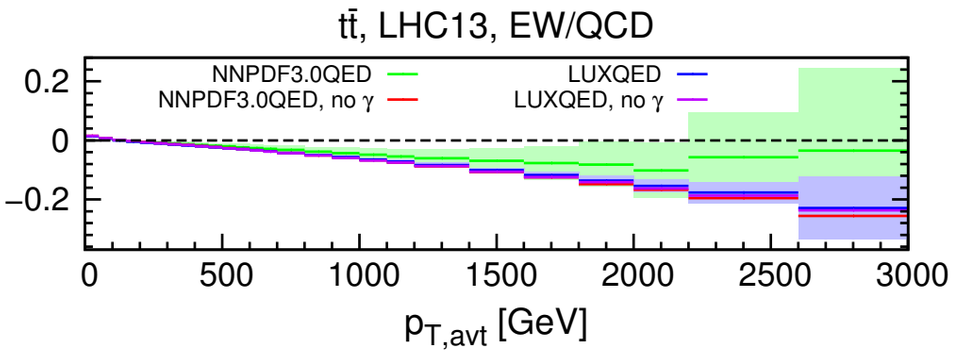


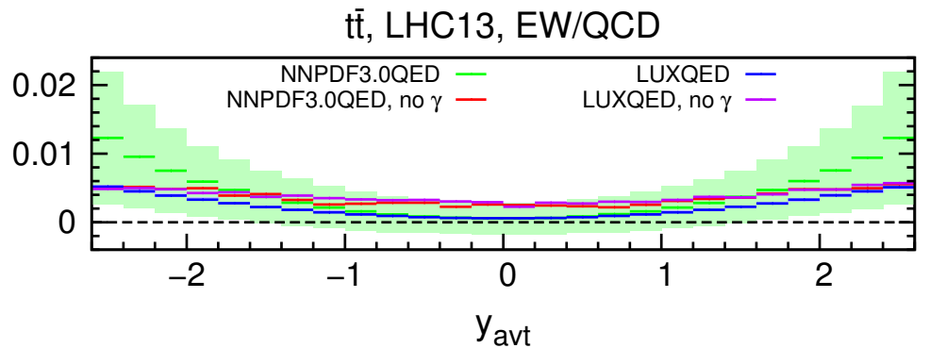
Results

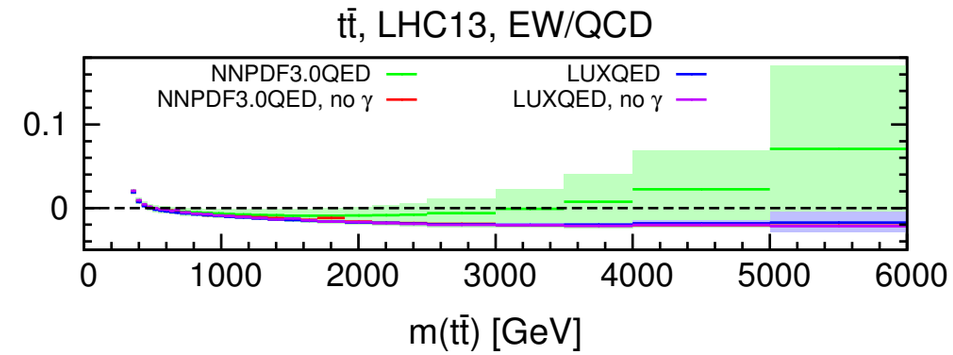


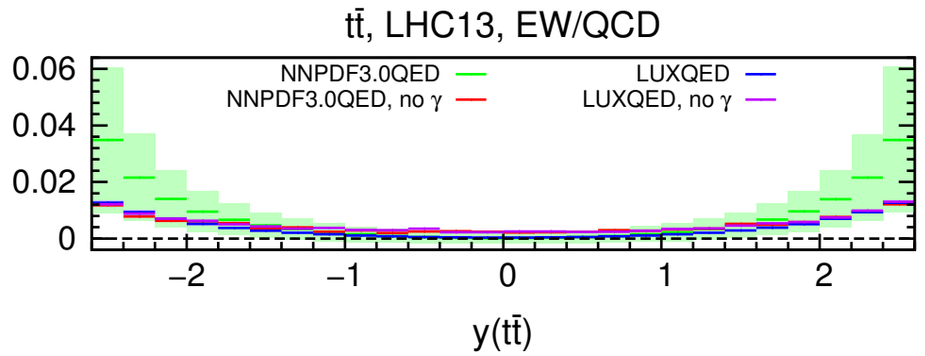
- EW corrections have the largest effect on the top p_T (up to -25% at 3 TeV). Comparable with scale uncertainties from p_T>500 GeV. EW corrections on the invariant mass are smaller, and almost negligible on the rapidity of the top and of the pair
- Note that theoretical uncertainties are dominated, in many regions, by PDFs

Photon PDF effects



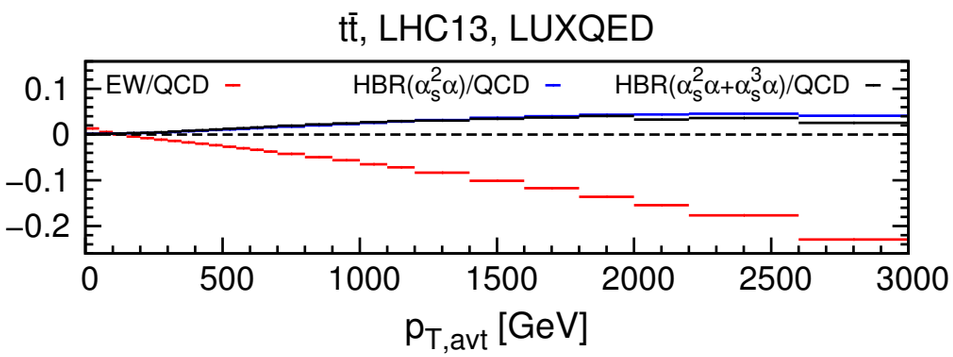


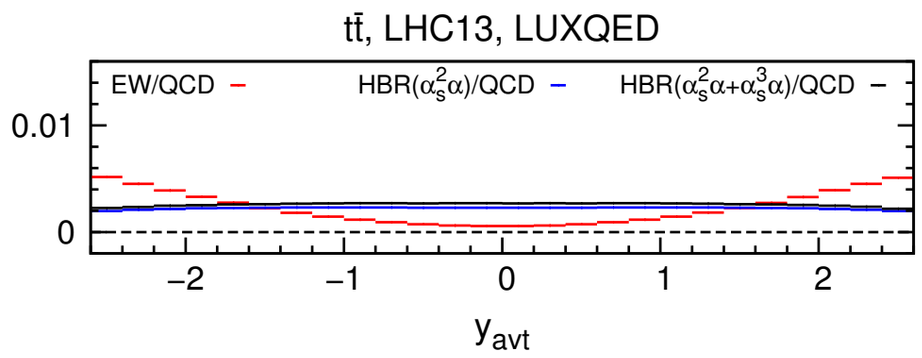


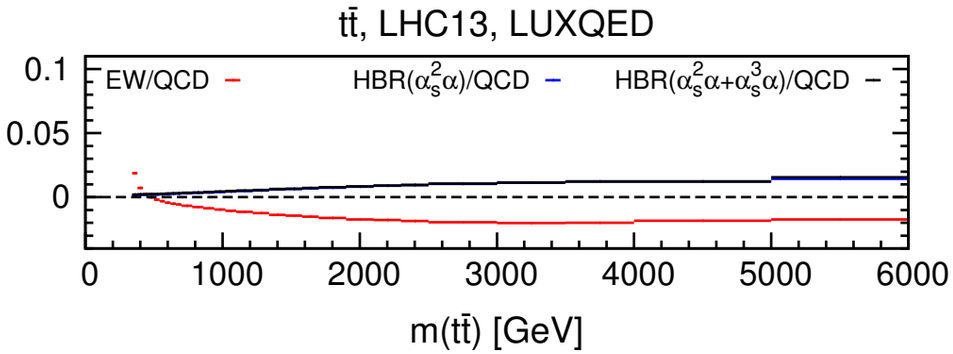


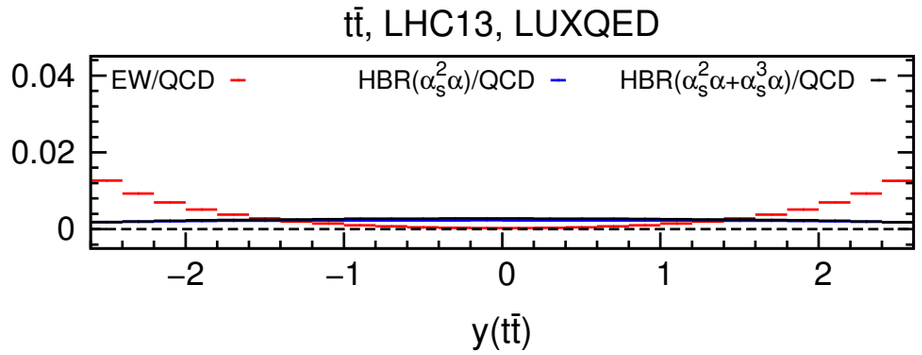
- As it has been shown in 1606.01915, the photon density from NNPDF gives large effects, which even compensate the Sudakov suppression at large p_T's, with a large uncertainties.
- On the other hand, the photon density from LuxQED gives very small effects in $t\bar{t}$ production, compatible with what one gets by setting the photon PDF to zero

Radiation of extra Heavy Bosons









- The real-radiation of heavy bosons (W/Z/H) is of the same perturbative orders of NLO EW corrections
- It is a finite contributions, which is also subtracted from the $t\bar{t}$ cross section in experimental analyses
- In principle, one may wonder if it compensates EW corrections, in particular Sudakov effects
- In practice, their contribution remains small or very small

Conclusion and outlook

- We have provided a consistent combination of NNLO QCD and NLO EW corrections (including all subleading contributions at LO and NLO)
- A multiplicative combination is employed, which approximates the term at order $\alpha_s^3 \alpha$
- Results, including differential K-factors and rates for 8 and 13 TeV and raw histograms data are publicly available at
  http://www.precision.hep.phy.cam.ac.uk/results/ttbar-nnloqcd-nloew/

- EW K-factor is expected to be very stable e.g. with different PDFs; one can obtain predictions at NNLO QCD + EW for any PDF set by using FastNLO tables for the QCD part Czakon, Heymes, Mitov, arXiv:1704.08551
- Coming soon: combination of NNLO QCD and EW corrections for the top asymmetry at the Tevatron and at the LHC

Extra slides: Additive vs multiplicative