QCD and EW corrections for V+jets DM backgrounds *

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LHCtheory ERC
final meeting
March 22-24 2017
CP3 Louvain

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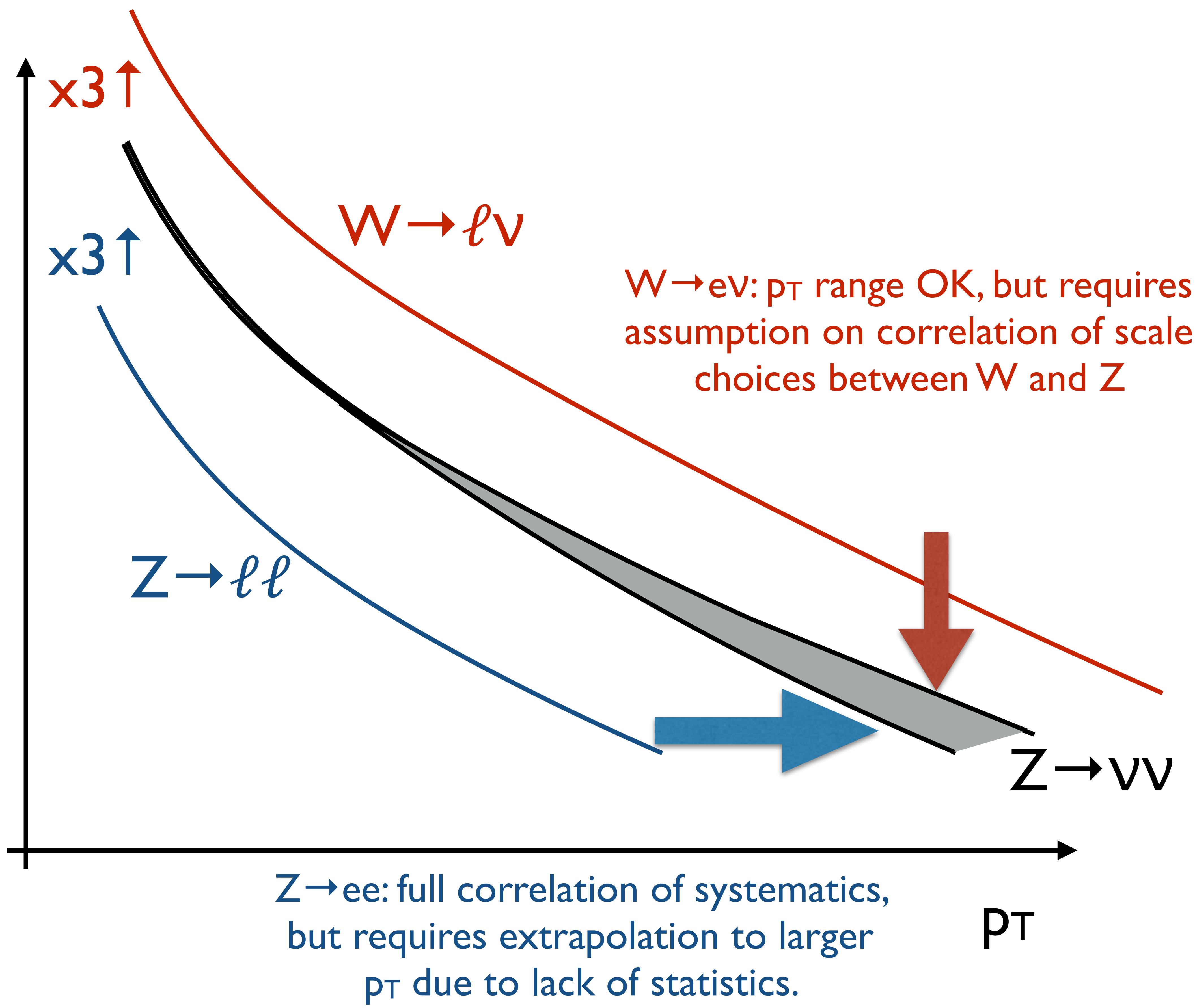
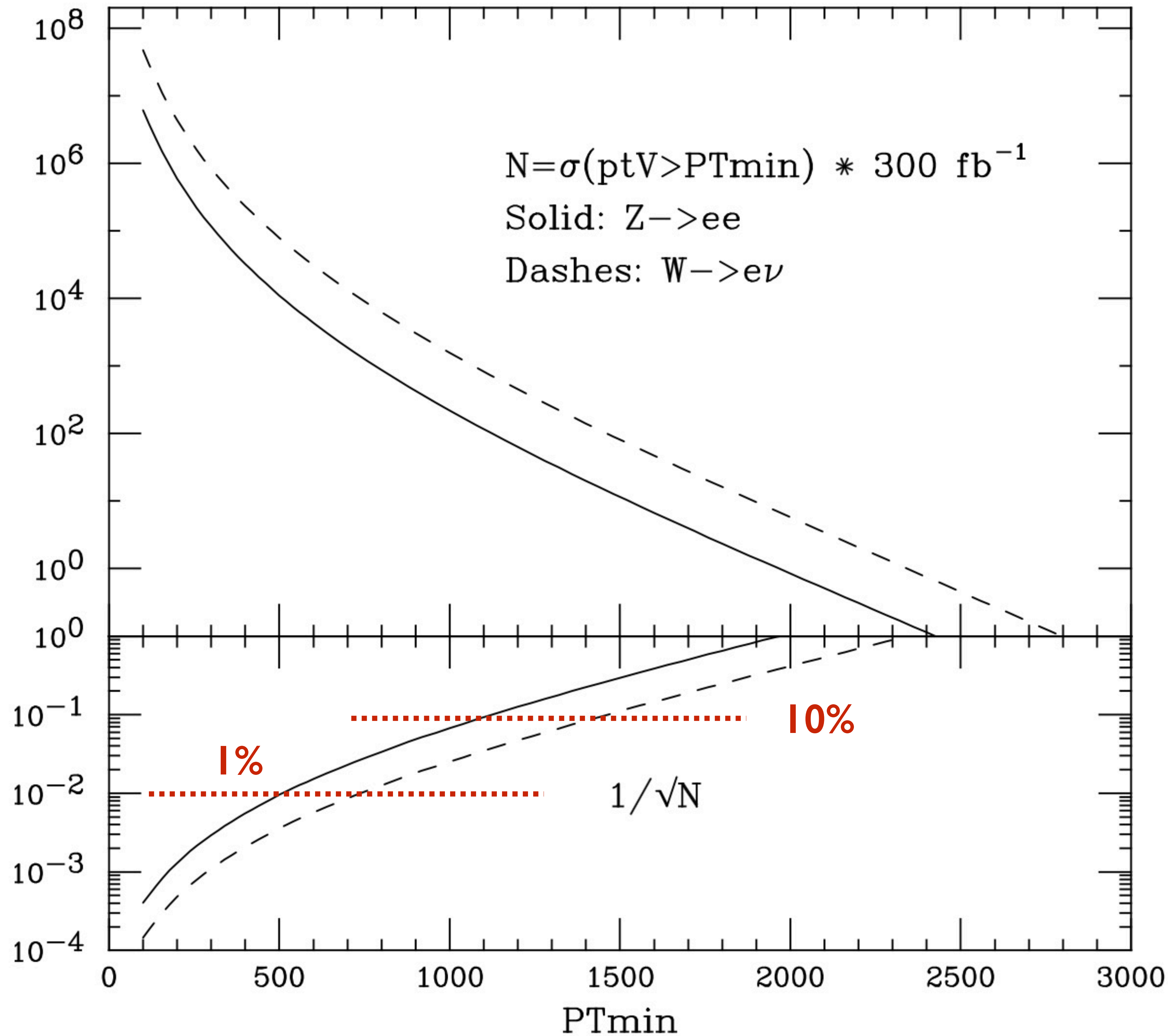
* to appear

Scope

- **Goal:** make maximal use of data on $p_T(W)$, $p_T(\gamma)$ and $p_T(Z\to\ell^+\ell^-)$ spectra to predict $Z\to\nu\nu$ backgrounds to DM search in MET +jet
- Assess theoretical systematics in extrapolating the MET bg from those data inputs:
  - QCD and EW corrections
  - focus on correlations (or lack thereof) between different processes
- Provide reweighting factors to modify the various MC $p_T(V)$ spectra:
  - allow the expts to efficiently cover the TH systematic range
  - parameterize TH syst in terms of nuisance param's, to "tune" TH predictions and syst's using data


x3↑
x3↑
W→ℓν
W→eν: pT range OK, but requires
assumption on correlation of scale
choices between W and Z
Z→ℓℓ
Z→νν
pT
Z→ee: full correlation of systematics,
but requires extrapolation to larger
pT due to lack of statistics.



<1% precision directly from Z→ee data up to pt~500 GeV

>10% stat. uncertainty on Z→νν bg rate for pt>~1300 GeV

so the critical region where we want to get %-level TH systs is around 500-1 TeV

QCD

- All procs available to NNLO. PDF syst with Lux
- Assume as reference full correlation in the scale choice for W and Z processes. Parameterize deviations from full correlation with nuisance param's
- Further param's to model range of functional forms for p_T-dependence of ren/fact scales
- Define systematics using NLO results, validate with NNLO

Example

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{N}^k\mathrm{LO\,QCD}}(\vec{\mu}) \quad = \quad K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x,\vec{\mu})\,\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0).$$

$$\mu_{R,0} = \mu_{F,0} = \mu_0 = \hat{H}'_{\mathrm{T}}/2, \qquad \hat{H}'_{\mathrm{T}} = E_{\mathrm{T},V} + \sum_{i\in\{\mathrm{q,g},\gamma\}} |p_{\mathrm{T},i}|$$

$$E^2_{\mathrm{T,Z}} = p^2_{\mathrm{T},\ell^+\ell^-} + m^2_{\ell^+\ell^-}, \qquad E^2_{\mathrm{T,W}} = p^2_{\mathrm{T},\ell\nu} + m^2_{\ell\nu} \qquad E^2_{\mathrm{T},\gamma} = p^2_{\mathrm{T},\gamma}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{N}^k\mathrm{LO\,QCD}}(\vec{\varepsilon}_{\mathrm{QCD}}) \quad = \quad \left[K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) + \sum_{i=1}^{3}\varepsilon_{\mathrm{QCD},i}\,\delta^{(i)}K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x)\right] \times \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0).$$

- $\varepsilon^i_{\mathrm{QCD}}$ (i=1,2,3): nuisance param's to describe **scale, shape, process** syst's
- gaussian dist'ed, 1σ range = [–1,1]

Scale syst $\delta^{(1)}$

$$
\begin{aligned}
K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) &= \frac{1}{2}\left[K^{(V,\max)}_{\mathrm{N}^k\mathrm{LO}}(x) + K^{(V,\min)}_{\mathrm{N}^k\mathrm{LO}}(x)\right],\\
\delta^{(1)} K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) &= \frac{1}{2}\left[K^{(V,\max)}_{\mathrm{N}^k\mathrm{LO}}(x) - K^{(V,\min)}_{\mathrm{N}^k\mathrm{LO}}(x)\right],
\end{aligned}
$$

$$
\begin{aligned}
K^{(V,\max)}_{\mathrm{N}^k\mathrm{LO}}(x) &= \max\left\{K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x,\vec{\mu}^{(k)}_i)\middle|0 \le i \le 6\right\},\\
K^{(V,\min)}_{\mathrm{N}^k\mathrm{LO}}(x) &= \min\left\{K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x,\vec{\mu}^{(k)}_i)\middle|0 \le i \le 6\right\}.
\end{aligned}
$$

$$
\begin{aligned}
\frac{\vec{\mu}^{(1)}_i}{\mu_0} &= (1,1),(2,2),(0.5,0.5),(2,1),(1,2),(1,0.5),(0.5,1),\\
\frac{\vec{\mu}^{(2)}_i}{\mu_0} &= (1,1),(4,4),(0.25,0.25),(4,1),(1,4),(1,0.25),(0.25,1)
\end{aligned}
$$

Shape syst $\delta^{(2)}$

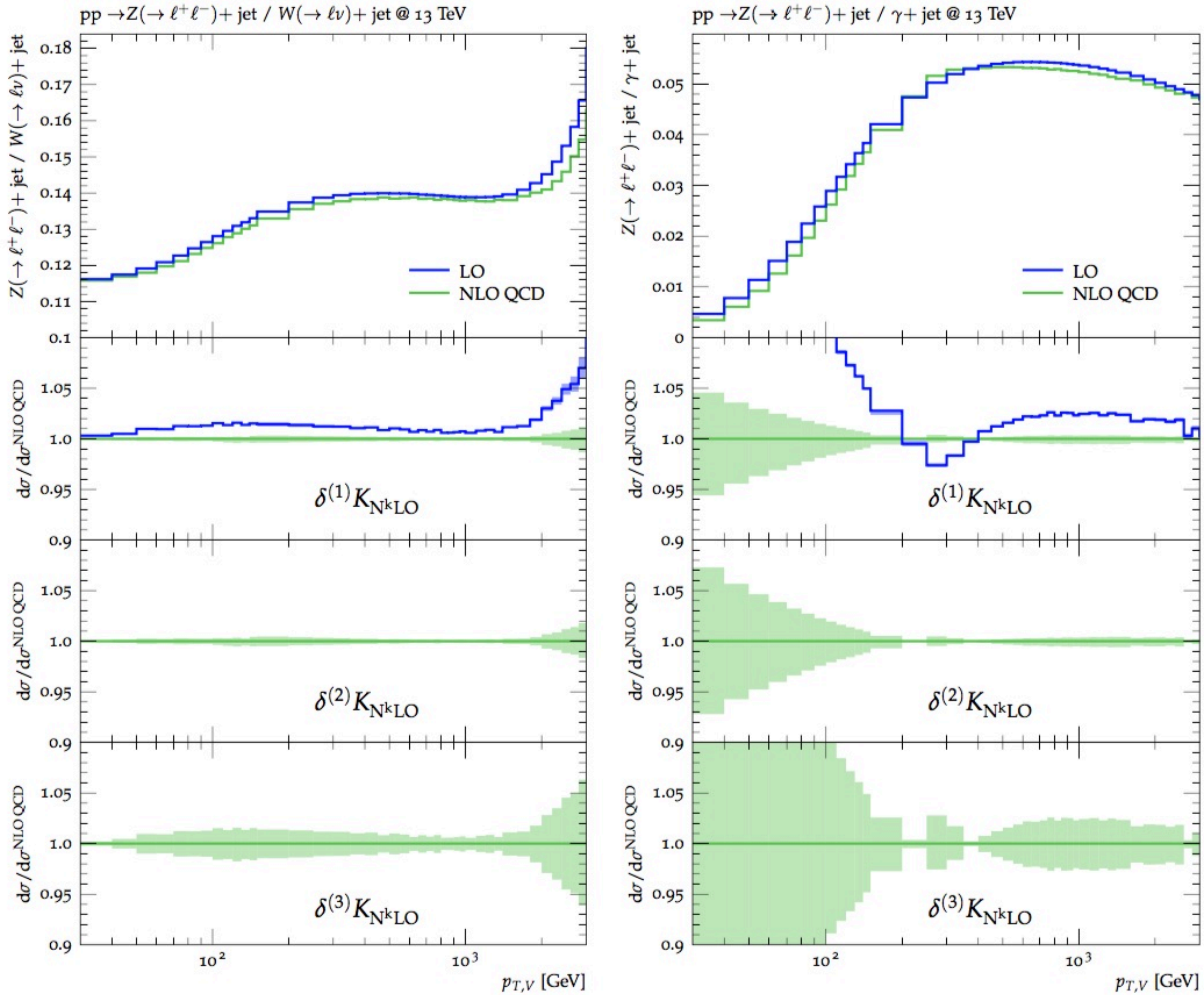
$$
\delta^{(2)} K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = \omega_{\mathrm{shape}}(x)\,\delta^{(1)} K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x), \qquad \omega_{\mathrm{shape}}(x) = \tanh\left[\ln\left(\frac{p_{\mathrm{T}}}{p_{\mathrm{T},0}}\right)\right] = \frac{p_{\mathrm{T}}^2 - p_{\mathrm{T},0}^2}{p_{\mathrm{T}}^2 + p_{\mathrm{T},0}^2},
$$

$$
p_{\mathrm{T},0} = 650\,\mathrm{GeV}
$$

Process dep syst $\delta^{(3)}$

$$
\delta^{(3)} K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = \Delta K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) - \Delta K^{(Z)}_{\mathrm{N}^k\mathrm{LO}}(x) \qquad \Delta K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x)/K^{(V)}_{\mathrm{N}^{k-1}\mathrm{LO}}(x) - 1
$$

Preliminary results



EW

- All procs available to NLO
- Include leading Sudakov logs beyond NLO
- Use finite NLO EW contributions to assign systematics from missing subleading NNLO (and beyond) corrections
- Mixed QCD-EW: multiplicative correction as reference. OK for Sudakov logs part, use difference between mult vs additive prescription for sub-log corrections to assign systematics

Example

$$K^{(V)}_{\mathrm{TH}}(x,\vec{\varepsilon}_{\mathrm{QCD}},\vec{\varepsilon}_{\mathrm{EW}},\varepsilon_{\mathrm{mix}}) = K^{(V)}_{\mathrm{TH},\otimes}(x,\vec{\varepsilon}_{\mathrm{QCD}},\vec{\varepsilon}_{\mathrm{EW}}) + \varepsilon_{\mathrm{mix}}\,\delta K^{(V)}_{\mathrm{mix}}(x),$$
$$= \left[K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) + \sum_{i=1}^{3}\varepsilon_{\mathrm{QCD},i}\,\delta^{(i)}K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x)\right]$$
$$\times\left[1+\kappa^{(V)}_{\mathrm{EW}}(x)+\sum_{i=1}^{3}\varepsilon^{(V)}_{\mathrm{EW},i}\,\delta^{(i)}\kappa^{(V)}_{\mathrm{EW}}(x)\right]+\varepsilon_{\mathrm{mix}}\,\delta K^{(V)}_{\mathrm{mix}}(x),$$

Beyond NNLL syst $\delta^{(1)}$

$$\delta^{(1)}\kappa^{(V)}_{\mathrm{EW}}(x) = \delta\kappa^{(V)}_{\mathrm{NNLO\,Sud}}(x) = \frac{2}{3}\kappa^{(V)}_{\mathrm{NLO\,EW}}(x)\,\kappa^{(V)}_{\mathrm{NNLO\,Sud}}(x)$$

α^2 log^2 syst $\delta^{(2)}$

$$\delta^{(2)}\kappa^{(V)}_{\mathrm{EW}}(x) = 0.05\,\kappa^{(V)}_{\mathrm{NLO\,EW}}(x)$$

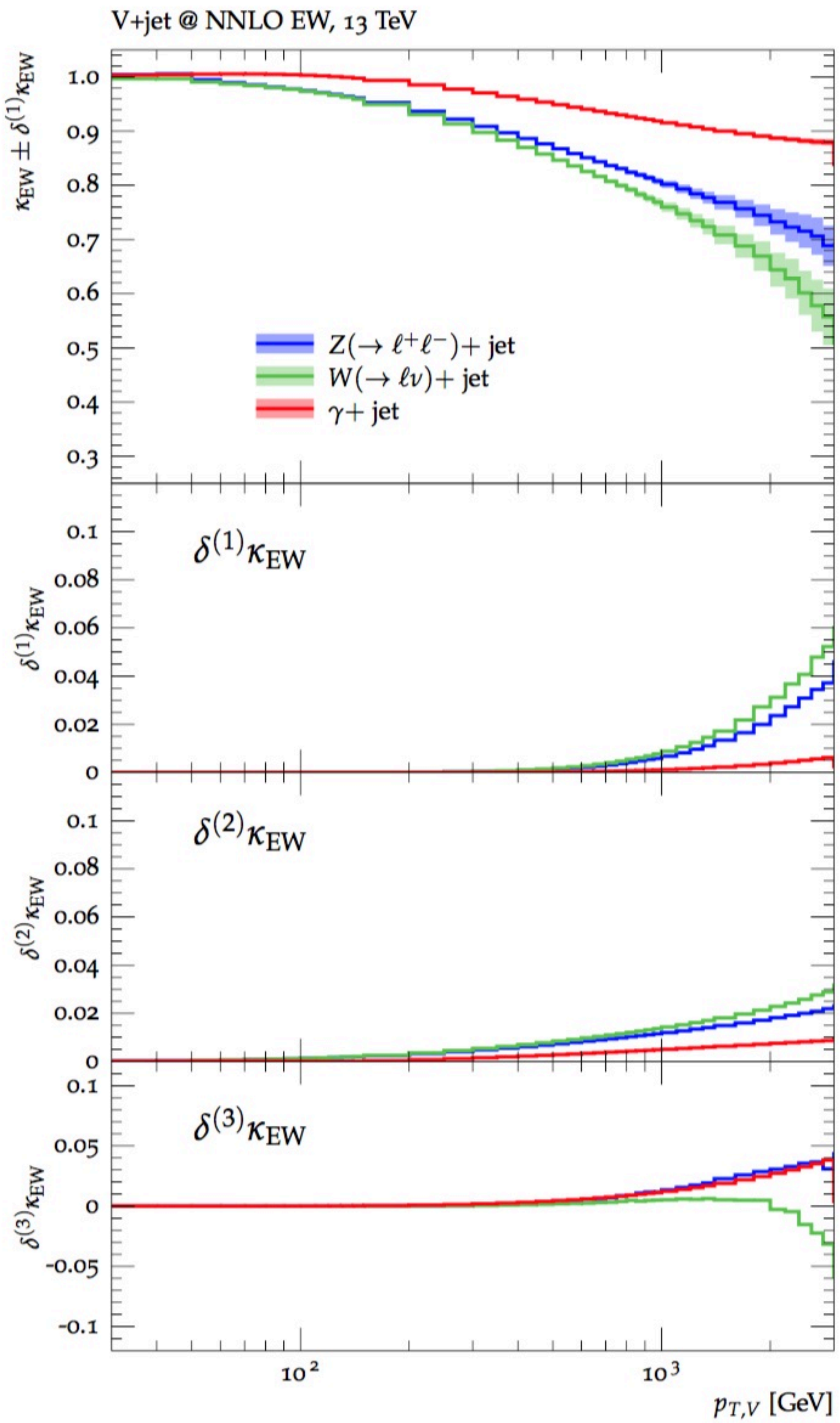
(this is ~equivalent to $\delta^{(2)}_{\mathrm{hard}} \le \frac{0.05\pi}{\alpha}\delta^{(1)}_{\mathrm{hard}} \simeq 20\,\delta^{(1)}_{\mathrm{hard}}$)

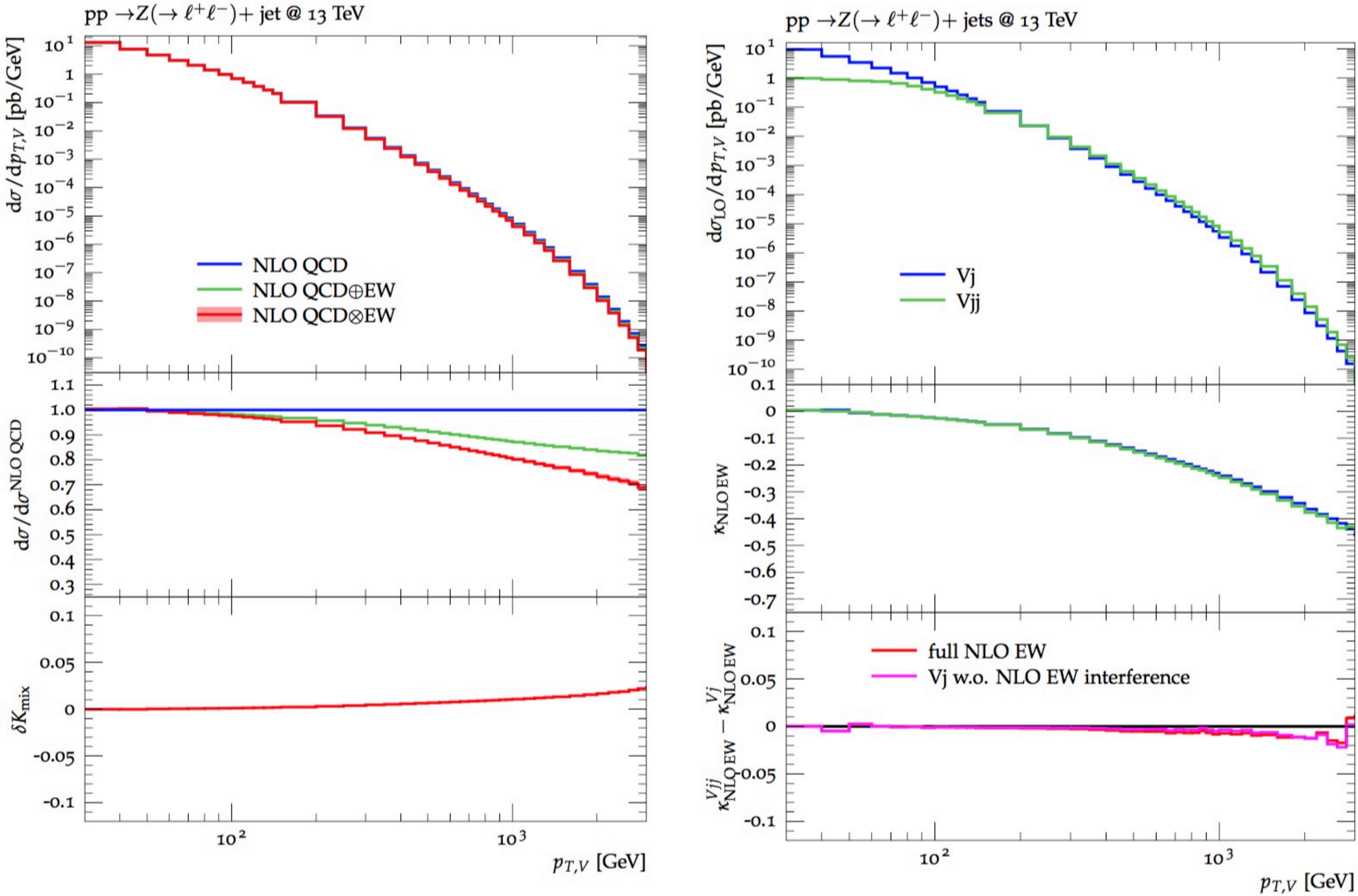
Non-sudakov NNLO syst $\delta^{(3)}$

$$\delta^{(3)}\kappa^{(V)}_{\mathrm{EW}}(x) = \kappa^{(V)}_{\mathrm{NNLO\,Sud}}(x) - \frac{1}{2}[\kappa^{(V)}_{\mathrm{NLO\,EW}}(x)]^2$$

Mixed EW-QCD syst $\delta^{(\mathrm{mix})}$

$$\delta K^{(V)}_{\mathrm{mix}}(x) = 0.1\left[K^{(V)}_{\mathrm{TH},\oplus}(x,\vec{\mu}_0) - K^{(V)}_{\mathrm{TH},\otimes}(x,\vec{\mu}_0)\right]$$


V+jet @ NNLO EW, 13 TeV
$\kappa_{EW} \pm \delta^{(1)}\kappa_{EW}$
$Z(\to \ell^+\ell^-)$+ jet
$W(\to \ell\nu)$+ jet
γ+ jet
$\delta^{(1)}\kappa_{EW}$
$\delta^{(2)}\kappa_{EW}$
$\delta^{(3)}\kappa_{EW}$
10^2
10^3
$p_{T,V}$ [GeV]

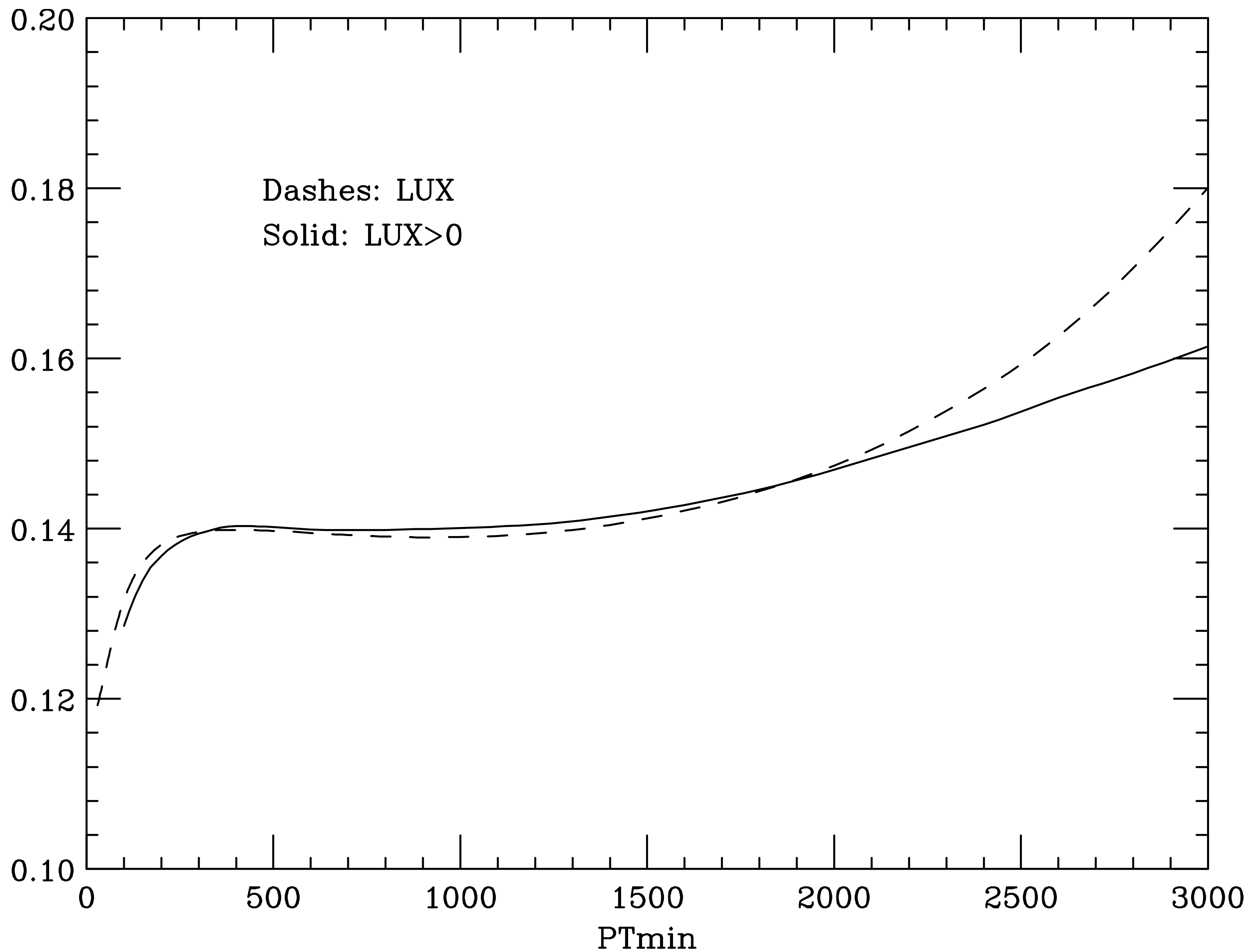


pp →Z(→ ℓ⁺ℓ⁻)+ jet @ 13 TeV
dσ/dp_{T,V} [pb/GeV]
NLO QCD
NLO QCD⊕EW
NLO QCD⊗EW
dσ/dσ^{NLO QCD}
δK_mix
p_{T,V} [GeV]
pp →Z(→ ℓ⁺ℓ⁻)+ jets @ 13 TeV
dσ_LO/dp_{T,V} [pb/GeV]
Vj
Vjj
κ_NLO EW
κ^{Vjj}_{NLO EW} − κ^{Vj}_{NLO EW}
full NLO EW
Vj w.o. NLO EW interference
p_{T,V} [GeV]

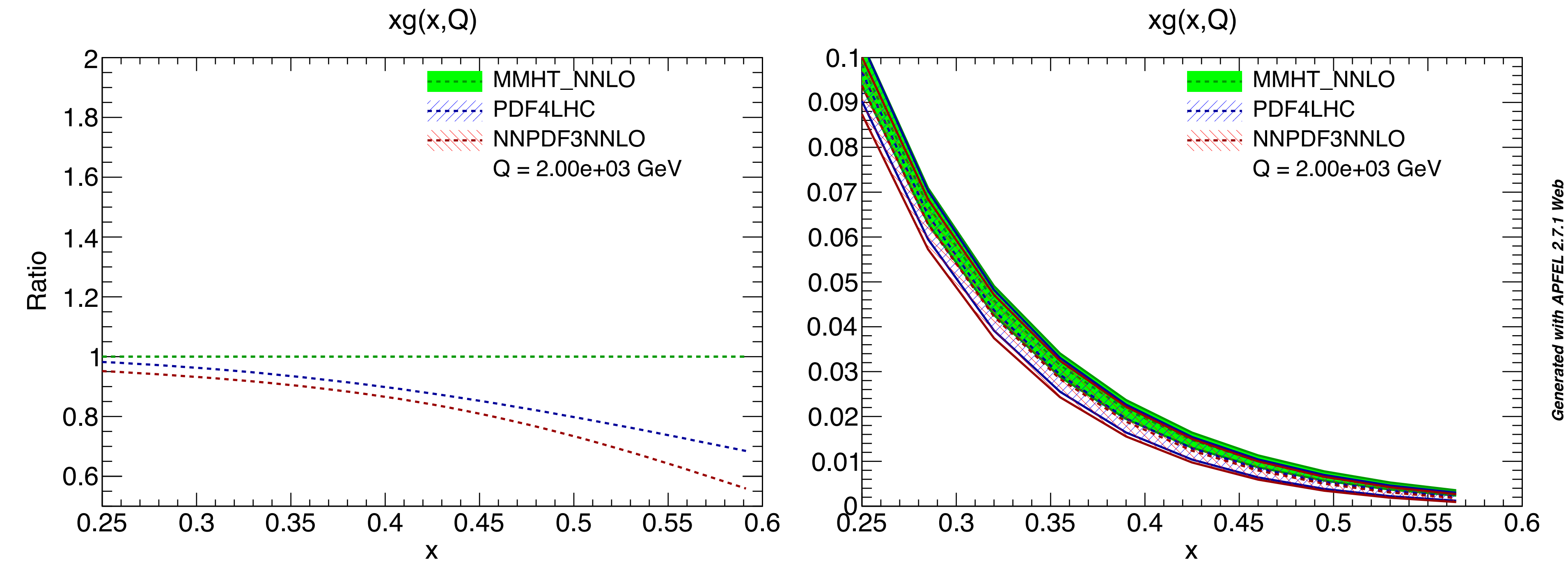
PDF syst's issues

Ratio of Z/W production rates at large pT

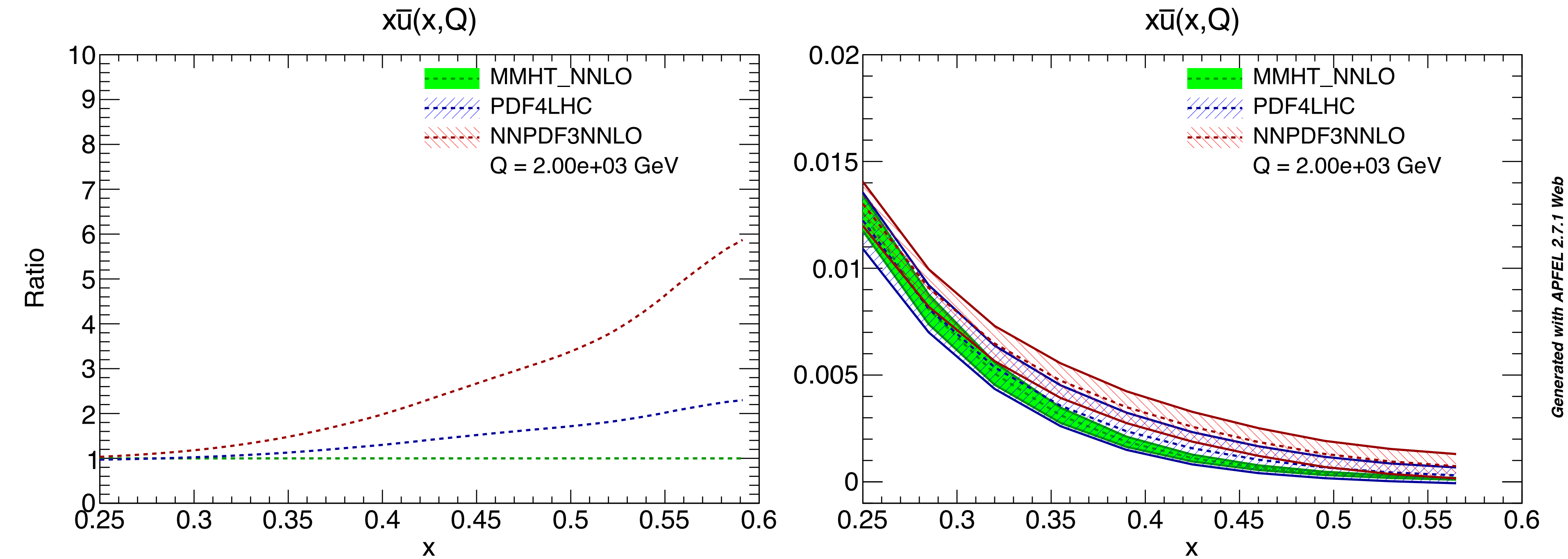
$$\sigma(Z,\, p_T > P_{Tmin}) \;\; / \;\; \sigma(W,\, p_T > P_{Tmin})$$



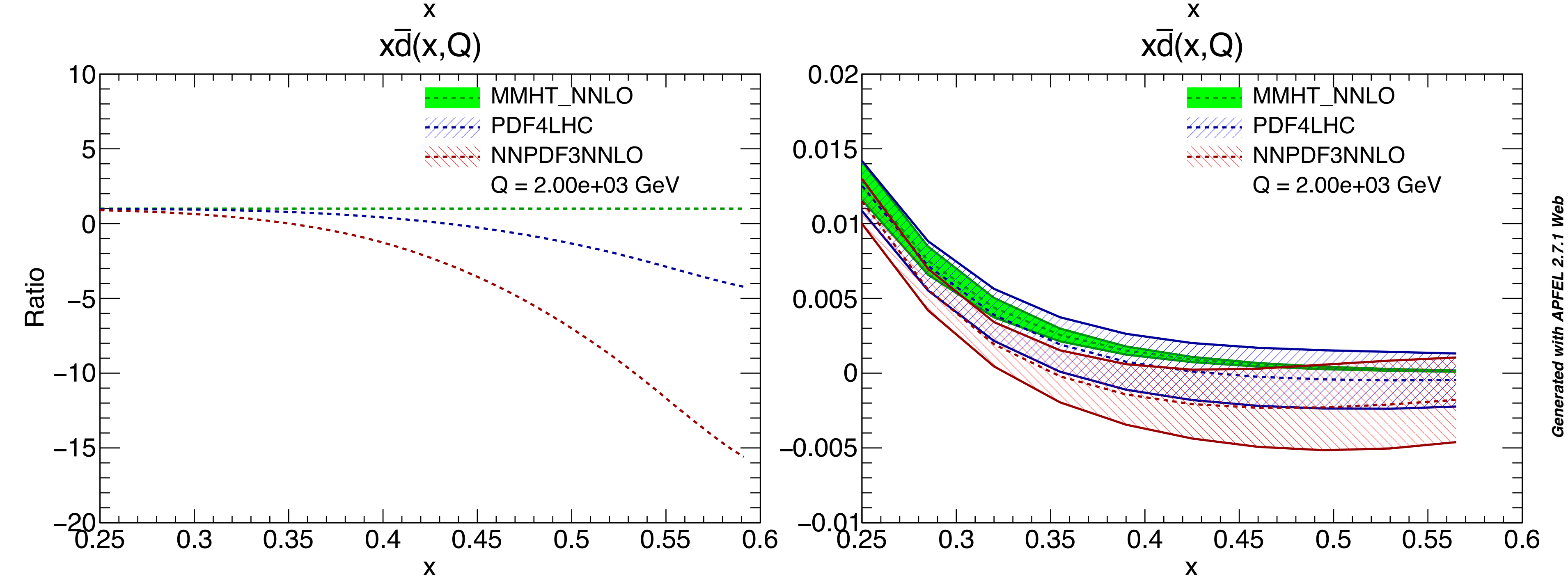
The solid line is obtained by setting to 0 individual flavours when their PDF turns negative (this is what I label, here and later, LUX>0). All plots here and in the following at LO



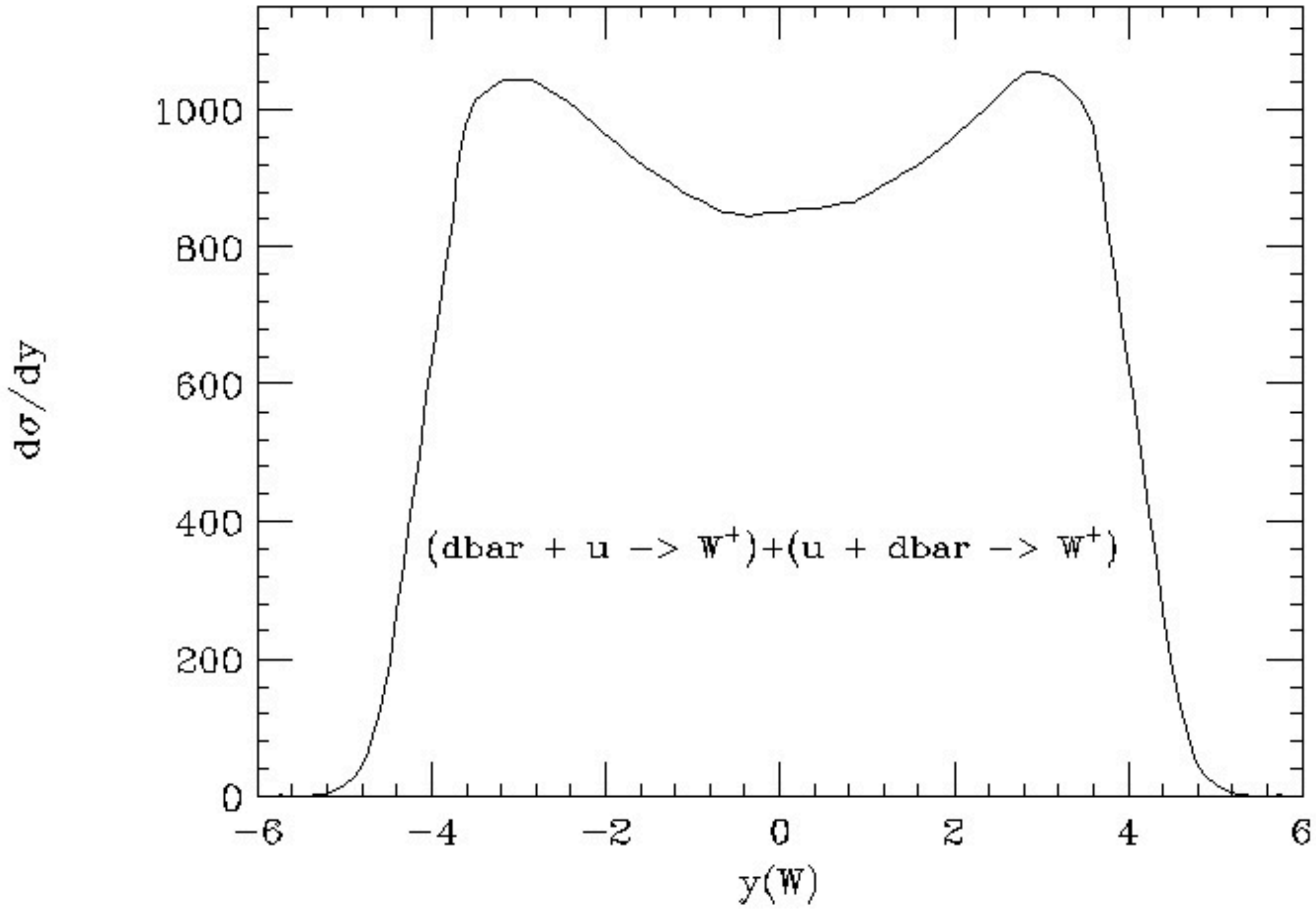
The gluon density is rather well behaved. It stays positive in the range shown here, and there is a mild difference between MMHT and NNPDF (PDF4LHC combines these two plus CT14, and it's always located in between MMHT and NNPDF)



ubar is also positive, but it's much more uncertain, with the ratio between NNPDF and MMHT reaching 5 at x=0.5. Notice there is ~ a factor of 10 between ubar and g (ubar/g~0.1), as expected

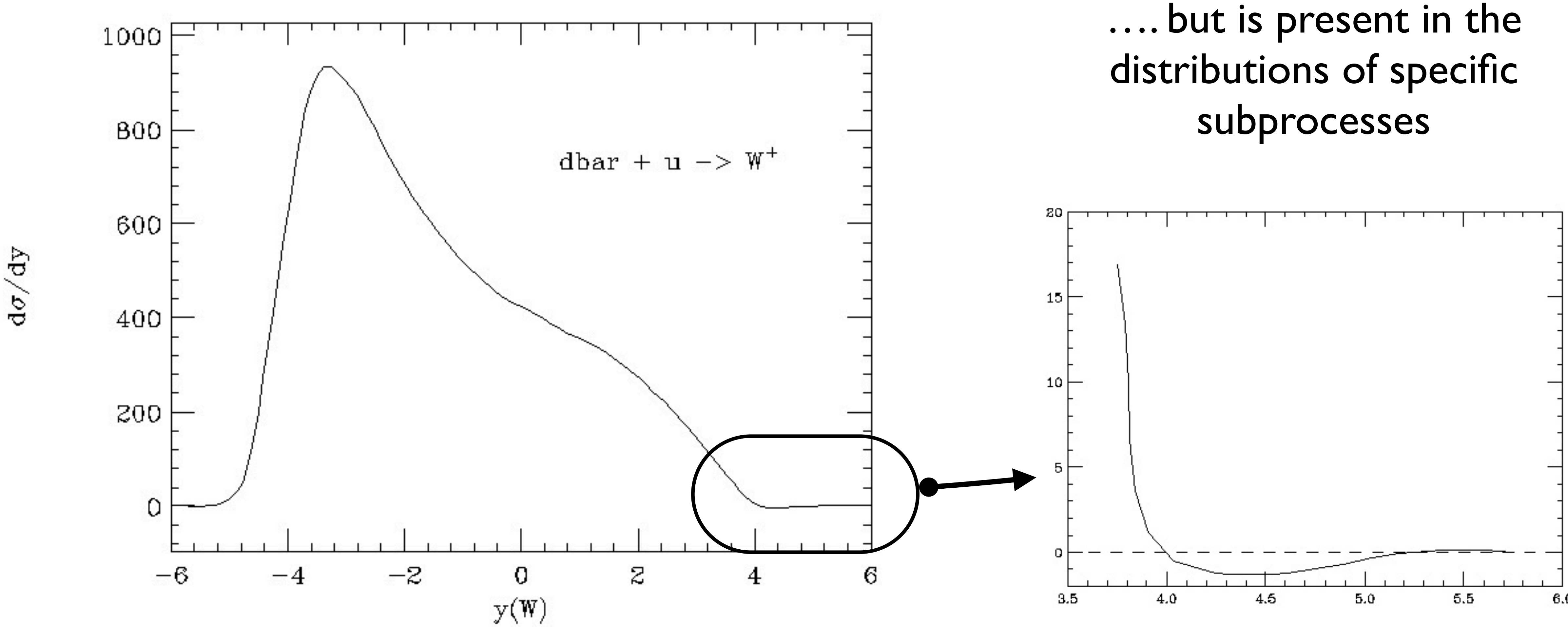


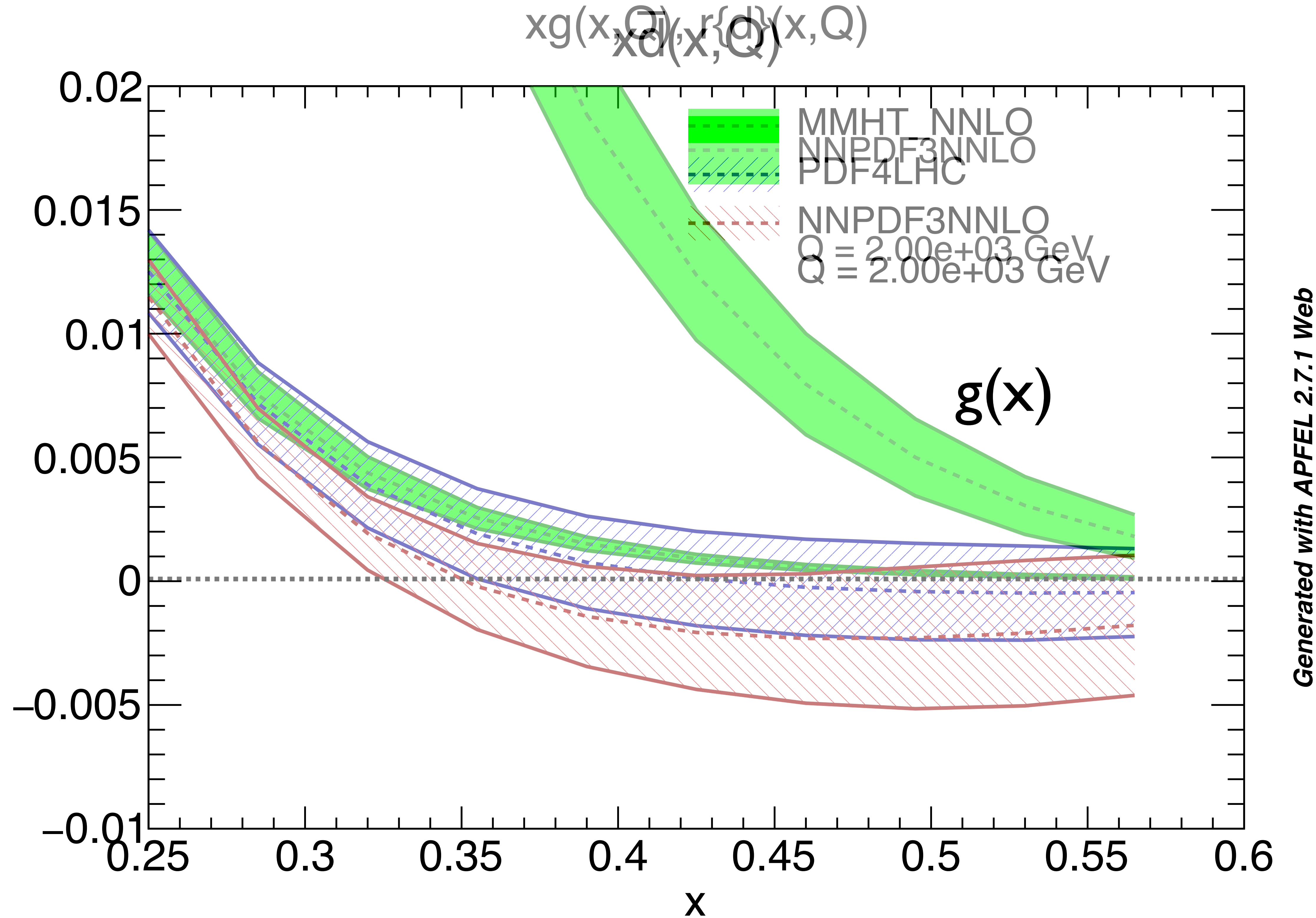
dbar becomes negative for NNPDF above x~0.35. Its absolute value remains almost constant, and therefore the ratio NNPDF/MMHT grows large at large x. PDF4LHC reflects this behavior. Close inspection shows that within the uncertainty band |dbar(x)| can be > g(x)

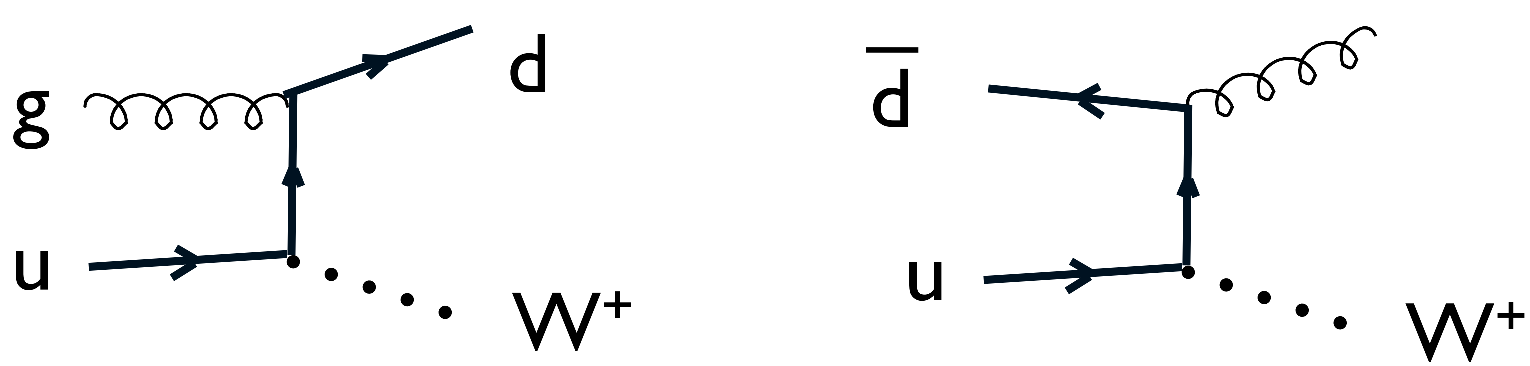


impact of negative PDF not evident from inclusive W spectra….

…. but is present in the distributions of specific subprocesses

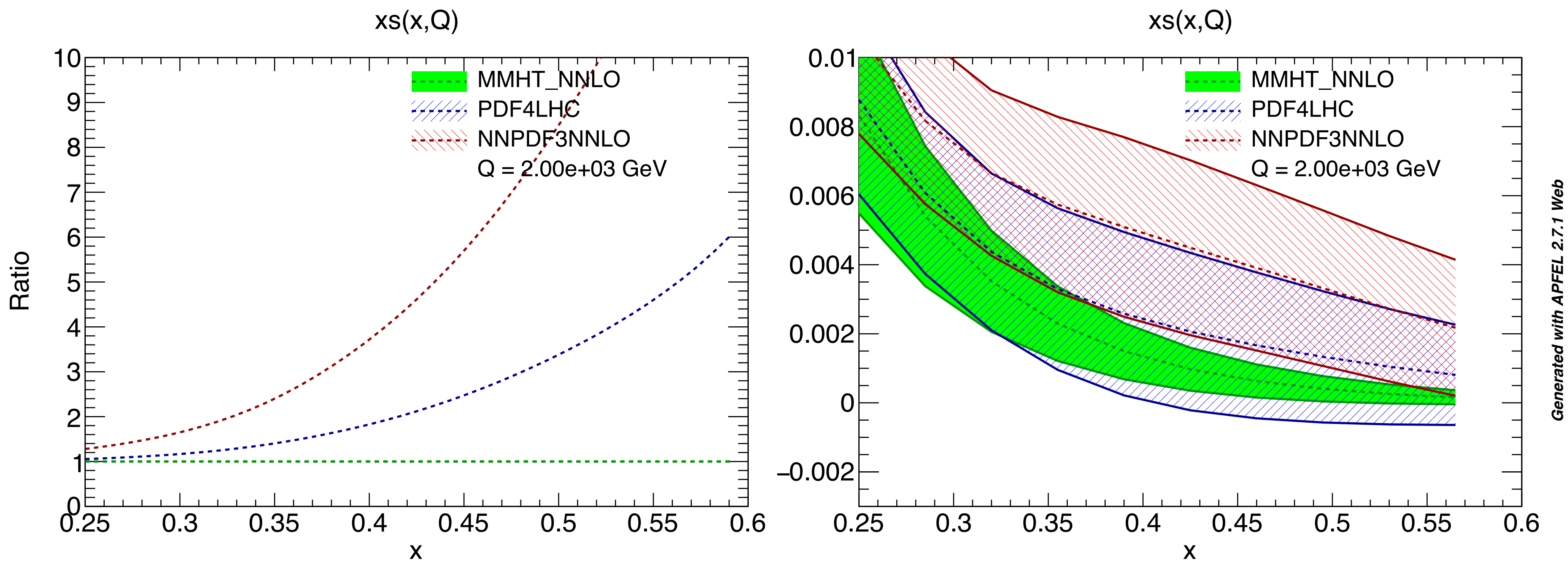




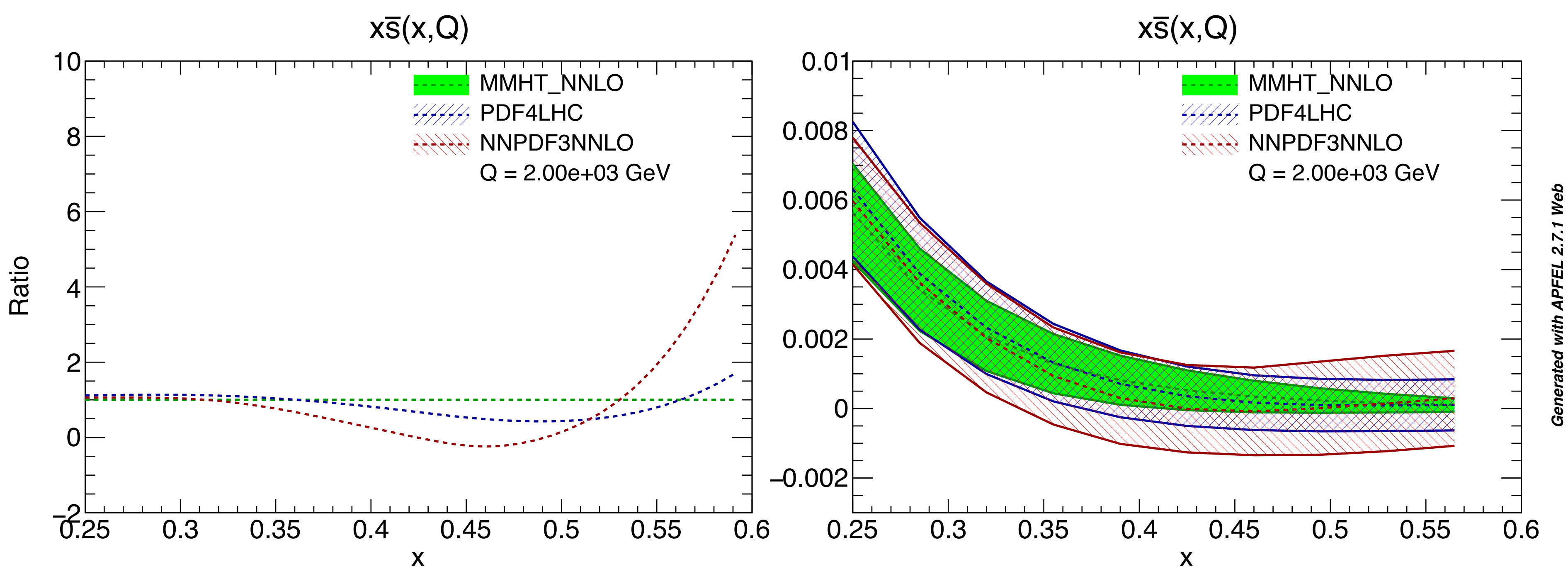


$\sim f_u * [f_g + f_{\bar{d}}]$

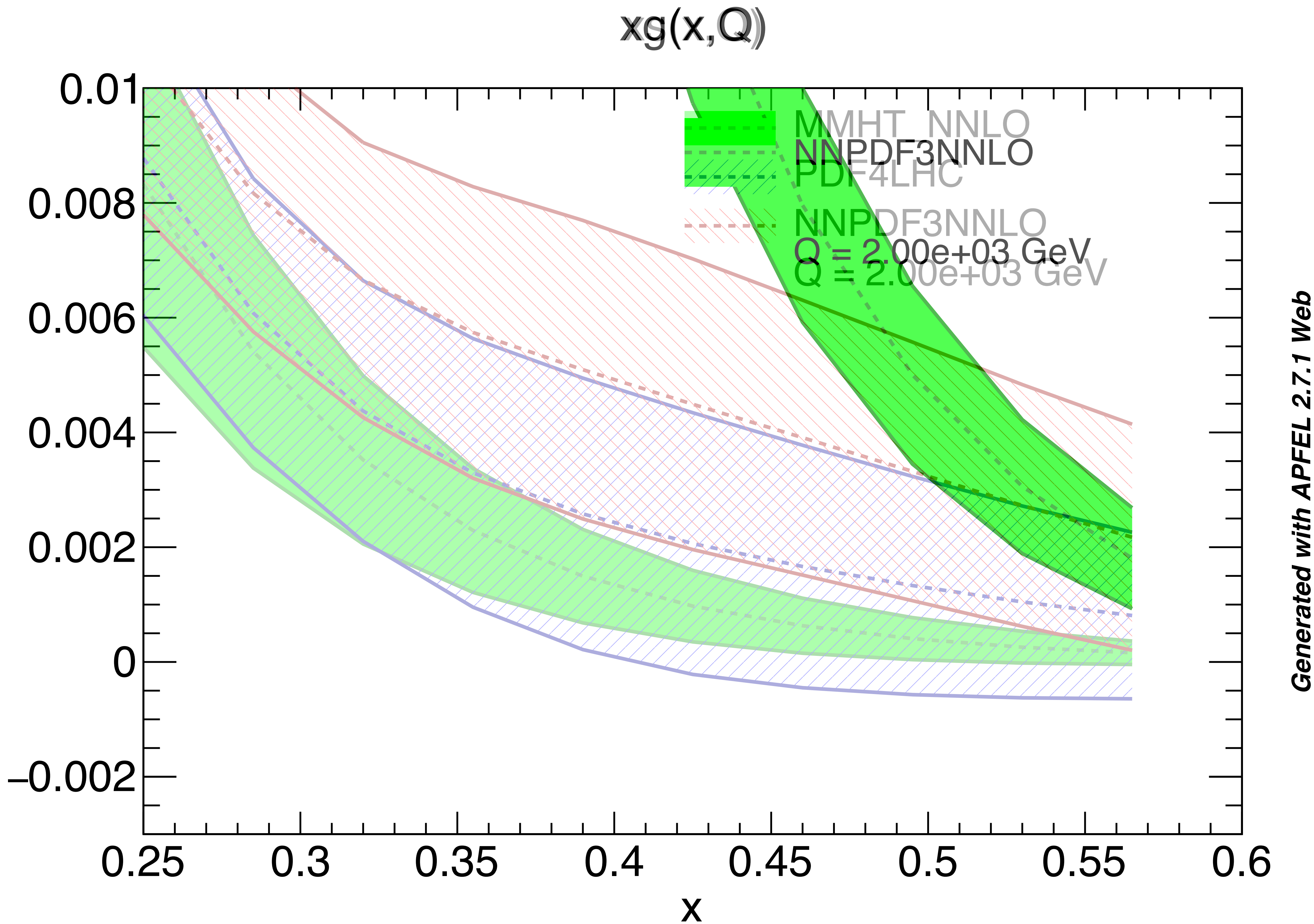
< 0 at large pt !!



The strange behaves like the ubar. It's positive, but NNPDF (and as a consequence PDF4LHC) grows a lot and has a huge uncertainty

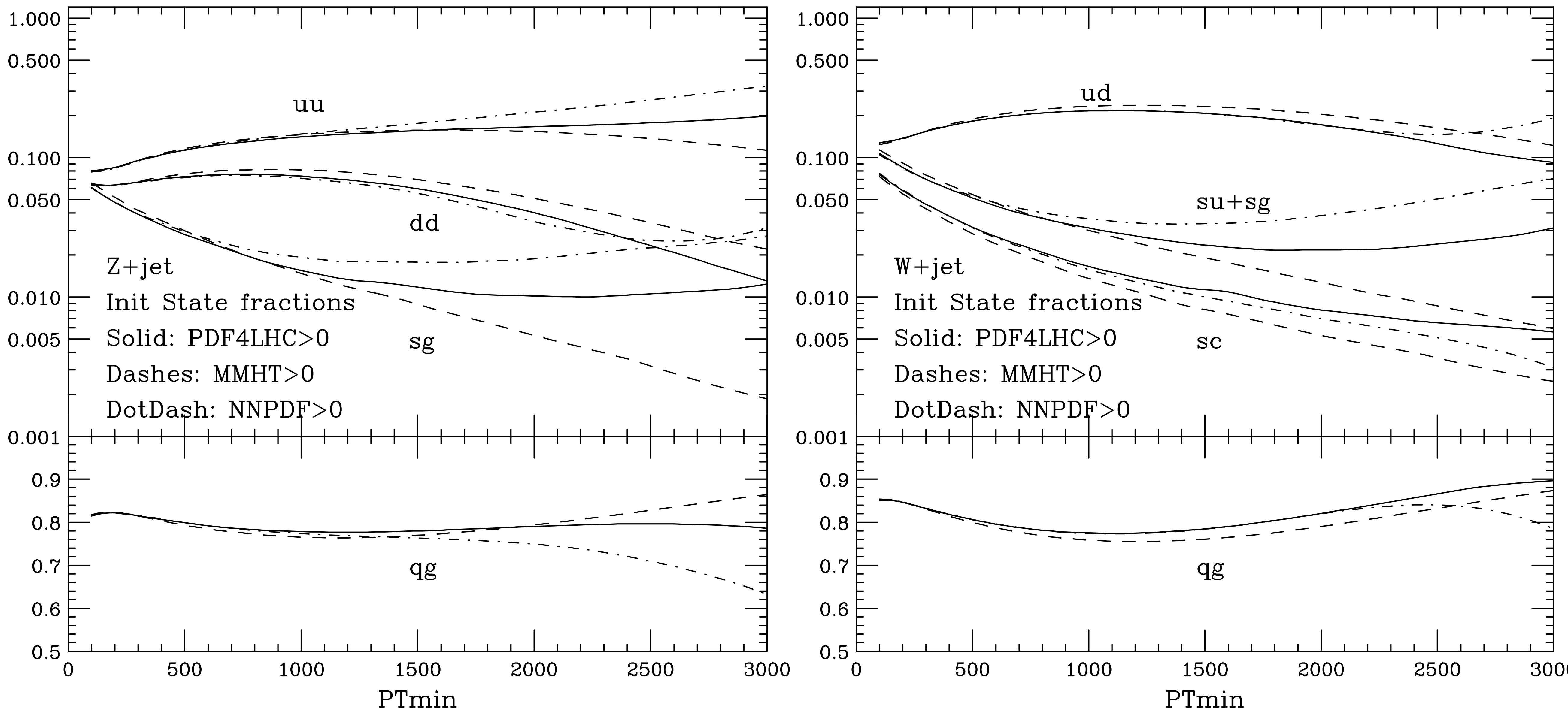


The antistrange of MMHT is very similar to the strange. For NNPDF it's totally different, and goes negative. Overall there isn't really a justification for this behaviour


xg(x,Q)
0.01
0.008
0.006
0.004
0.002
0
−0.002
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
x
MMHT_NNLO
NNPDF3NNLO
PDF4LHC
NNPDF3NNLO
Q = 2.00e+03 GeV
Q = 2.00e+03 GeV
Generated with APFEL 2.7.1 Web

s(x) > g(x) for x>~ 0.5

Fractional contributions of different initial states, for different PDF sets (LO and positive PDFs)



Notice the different shapes of the qg contribution for Z and W spectra.

Notice also the big PDF dependence of these fractions. In particular the huge spread of the processes involving a strange quark, which at large pt can vary between few permille (MMHT) and several percent (NNPDF). PDF4LHC is in between, but it's likely to be greatly pulled by NNPDF

Differences would be enhanced allowing for negative PDFs

Remarks

- There is probably room to reduce the PDF systematics at large x, even in absence of data, by using general principles of consistency
- PDFs can in principle be negative, but must lead to positive results for physical observables.
- Most effects pointed out here would not be revealed by usual large-x observables used for fits, like jet or top rates, or inclusive W charge asymmetry, but could then affect specific quantities like high-pt V, or very high mass DY
- "Gedanken observables" could be envisaged to impose positivity (e.g. large mass W', with flavour specific couplings: u dbar $\rightarrow W'^{+}$, u sbar $\rightarrow W'^{+}$, g s $\rightarrow$ s*, ...)
- Are there general criteria that can be added? E.g.
  - gluon > sea?
  - s vs sbar?