

# Theoretical predictions <sup>monojet</sup> for<sup>^</sup>DM backgrounds

John Campbell, Fermilab

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# Backgrounds from EXO-16-048-PAS

$E_T^{\text{miss}}$ (GeV)	Observed	Z $\rightarrow \nu\nu + \text{jets}$	W $\rightarrow \ell\nu + \text{jets}$	Top	Dibosons	Other	Total Bkg.
250-280	136865	79700 $\pm$ 2300	49200 $\pm$ 1400	2360 $\pm$ 200	1380 $\pm$ 220	1890 $\pm$ 240	134500 $\pm$ 3700
280-310	74340	45800 $\pm$ 1300	24950 $\pm$ 730	1184 $\pm$ 99	770 $\pm$ 120	840 $\pm$ 110	73400 $\pm$ 2000
310-340	42540	27480 $\pm$ 560	13380 $\pm$ 260	551 $\pm$ 53	469 $\pm$ 77	445 $\pm$ 63	42320 $\pm$ 810
340-370	25316	17020 $\pm$ 350	7610 $\pm$ 150	292 $\pm$ 28	301 $\pm$ 51	260 $\pm$ 39	25490 $\pm$ 490
370-400	15653	10560 $\pm$ 220	4361 $\pm$ 91	157 $\pm$ 17	198 $\pm$ 33	152 $\pm$ 26	15430 $\pm$ 310
400-430	10092	7110 $\pm$ 130	2730 $\pm$ 47	104 $\pm$ 12	133 $\pm$ 23	84 $\pm$ 15	10160 $\pm$ 170
430-470	8298	6110 $\pm$ 100	2123 $\pm$ 37	75.2 $\pm$ 7.9	110 $\pm$ 19	67 $\pm$ 11	8480 $\pm$ 140
470-510	4906	3601 $\pm$ 75	1128 $\pm$ 22	38.6 $\pm$ 5.3	75 $\pm$ 12	21.0 $\pm$ 3.9	4865 $\pm$ 95
510-550	2987	2229 $\pm$ 39	658 $\pm$ 12	18.5 $\pm$ 3.3	51.7 $\pm$ 9.5	12 $\pm$ 2.4	2970 $\pm$ 49
550-590	2032	1458 $\pm$ 27	398 $\pm$ 8	12.3 $\pm$ 2.6	35.9 $\pm$ 7.1	9.7 $\pm$ 1.9	1915 $\pm$ 33
590-640	1514	1182 $\pm$ 26	284 $\pm$ 7	5.5 $\pm$ 1.4	30.9 $\pm$ 5.7	2.6 $\pm$ 0.7	1506 $\pm$ 32
640-690	926	667 $\pm$ 15	151 $\pm$ 4	4.6 $\pm$ 1.7	16.7 $\pm$ 3.9	4.0 $\pm$ 0.8	844 $\pm$ 18
690-740	557	415 $\pm$ 12	90.4 $\pm$ 3.0	3.8 $\pm$ 1.5	15.6 $\pm$ 3.6	1.7 $\pm$ 0.4	526 $\pm$ 14
740-790	316	259 $\pm$ 9.6	55.2 $\pm$ 2.3	0.8 $\pm$ 0.5	9.14 $\pm$ 2.3	0.2 $\pm$ 0.1	325 $\pm$ 12
790-840	233	178 $\pm$ 7.1	35.3 $\pm$ 1.7	1.7 $\pm$ 0.8	5.35 $\pm$ 1.7	1.4 $\pm$ 0.3	223 $\pm$ 9
840-900	172	139 $\pm$ 6.2	25.2 $\pm$ 1.3	1.5 $\pm$ 1.2	2.52 $\pm$ 1.05	0.04 $\pm$ 0.03	169 $\pm$ 8
900-960	101	88.1 $\pm$ 4.9	14.7 $\pm$ 0.9	0.3 $\pm$ 0.3	3.88 $\pm$ 1.42	0.03 $\pm$ 0.02	107 $\pm$ 6
960-1020	65	73.8 $\pm$ 4.7	12.0 $\pm$ 0.8	0.4 $\pm$ 0.3	1.83 $\pm$ 0.92	0.02 $\pm$ 0.01	88.1 $\pm$ 5.3
1020-1090	46	42.6 $\pm$ 3.1	6.7 $\pm$ 0.6	0.0 $\pm$ 0.0	3.42 $\pm$ 1.33	0.01 $\pm$ 0.01	52.8 $\pm$ 3.9
1090-1160	26	21.5 $\pm$ 2.1	3.5 $\pm$ 0.4	0.0 $\pm$ 0.0	0.00 $\pm$ 0.00	0.01 $\pm$ 0.00	25.0 $\pm$ 2.5
		21.0 $\pm$ 2.2	3.3 $\pm$ 0.4	0.0 $\pm$ 0.0	1.07 $\pm$ 0.69	0.0 $\pm$ 0.00	25.5 $\pm$ 2.6
		22.5 $\pm$ 2.4	2.9 $\pm$ 0.3	0.0 $\pm$ 0.0	1.49 $\pm$ 0.91	0.0 $\pm$ 0.00	25.5 $\pm$ 2.6
Lots of recent work $\Rightarrow$							
discuss these at length							
400-430	2131	Z $\rightarrow \nu\nu + \text{jets}$	W $\rightarrow \ell\nu + \text{jets}$	Top	Dibosons	Other	Total Bkg.
		5300 $\pm$ 170	3390 $\pm$ 120	553 $\pm$ 54	396 $\pm$ 69	1	
		3720 $\pm$ 98	1823 $\pm$ 53	257 $\pm$ 27	261 $\pm$ 46	79	
		1911 $\pm$ 59	808 $\pm$ 28	101 $\pm$ 12	134 $\pm$ 25	25	
400-500	2131	1468 $\pm$ 45	521 $\pm$ 15	48.8 $\pm$ 5.7	107 $\pm$ 20	20.0 $\pm$ 3.6	2165 $\pm$ 55
500-600	521	388 $\pm$ 18	103.0 $\pm$ 5.1	10.7 $\pm$ 1.9	33.8 $\pm$ 7.0	1.76 $\pm$ 0.53	537 $\pm$ 23
600-750	225	151.0 $\pm$ 9.9	33.4 $\pm$ 2.3	1.9 $\pm$ 1.1	20.2 $\pm$ 4.5	1.05 $\pm$ 0.25	208 $\pm$ 11
750-1000	61	37.7 $\pm$ 3.7	7.09 $\pm$ 0.69	0.28 $\pm$ 0.25	10.2 $\pm$ 2.3	0.06 $\pm$ 0.03	55.3 $\pm$ 4.6

Mono  
jet

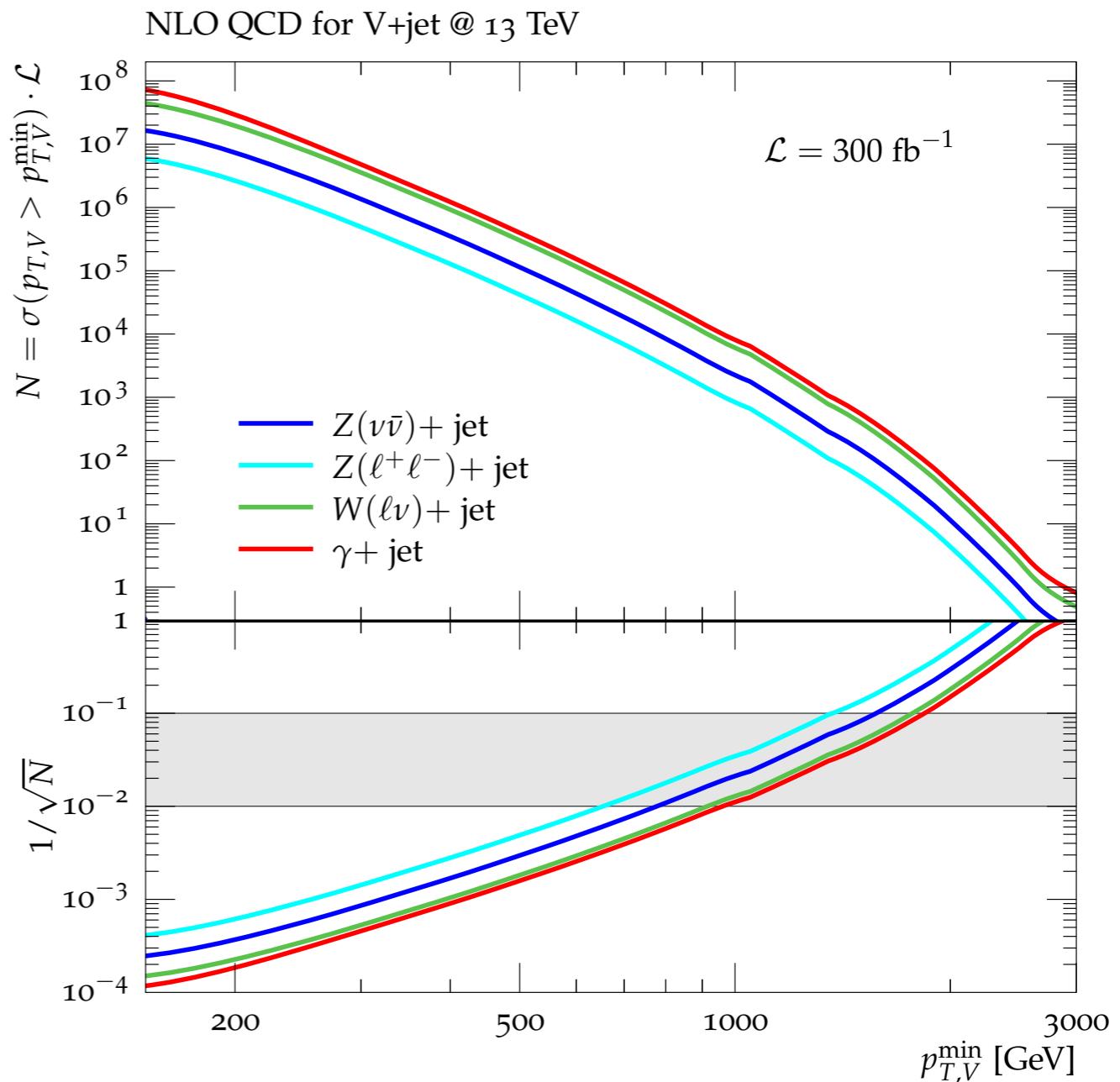
Less important  
and relatively  
well understood

Mono  
V

# Goal

- Ensure that the precision of the theoretical prediction is not the limiting factor in the experimental analysis.
- Based on statistical uncertainty alone ( $300 \text{ fb}^{-1}$ ):
  - sub-percent for few hundred GeV: control region  $\Rightarrow$  precision test
  - $\sim 3\%$  or smaller at  $p_T \sim 1 \text{ TeV}$
  - $\sim 10\text{-}30\%$  up to  $p_T \sim 2 \text{ TeV}$
- These goals can already be met and even surpassed!

Requires NNLO QCD, NLO EW and more – plus careful study of interplay of uncertainties between all V+jet processes



$\Rightarrow$  complementarity between measurements and searches

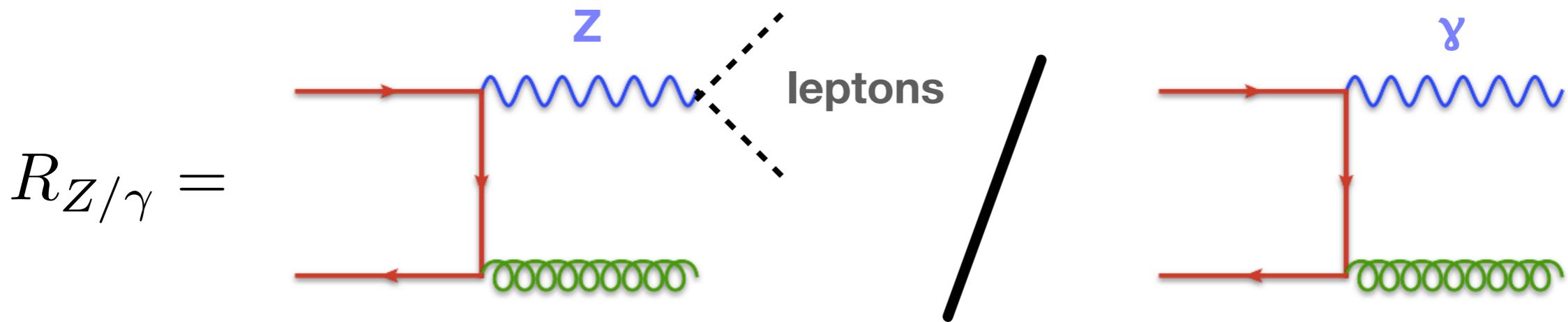


# Precision predictions for photon+jet

# Z/ $\gamma$ +jet ratio

- Excellent sample of events for calibrating V+jet backgrounds.

Bern et al, [arXiv:1106.1423](#); Ask et al, [arXiv:1107.2803](#)



ratio of quark-boson couplings

$$\approx \left( R_u + \frac{R_d - R_u}{1 + \frac{Q_u^2}{Q_d^2} \frac{\langle u \rangle}{\langle d \rangle}} \right) [\text{Br}(Z \rightarrow \ell^-\ell^+) \times \mathcal{A}]$$

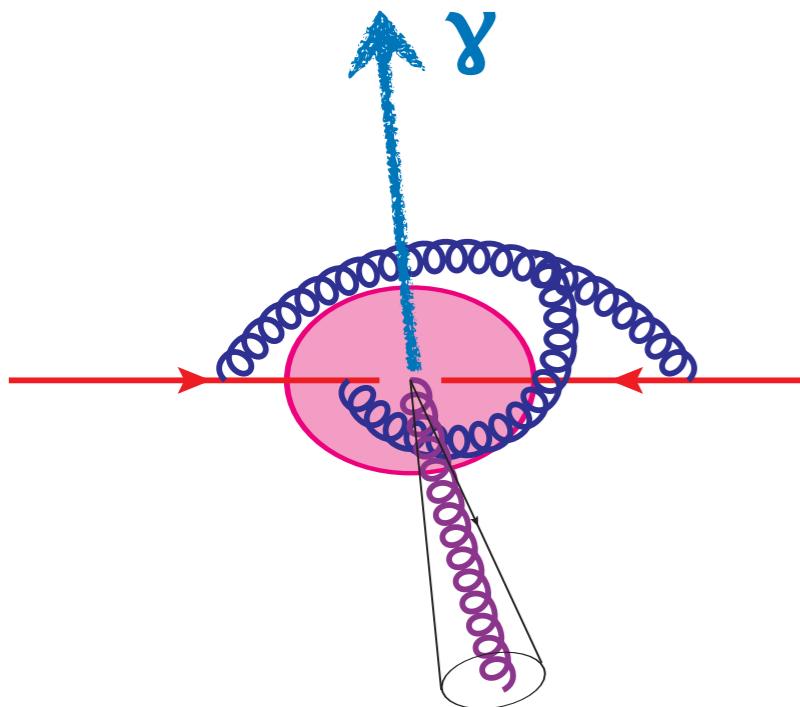
acceptance for leptons

pdf values at typical  $x=2p_T/\sqrt{s}$

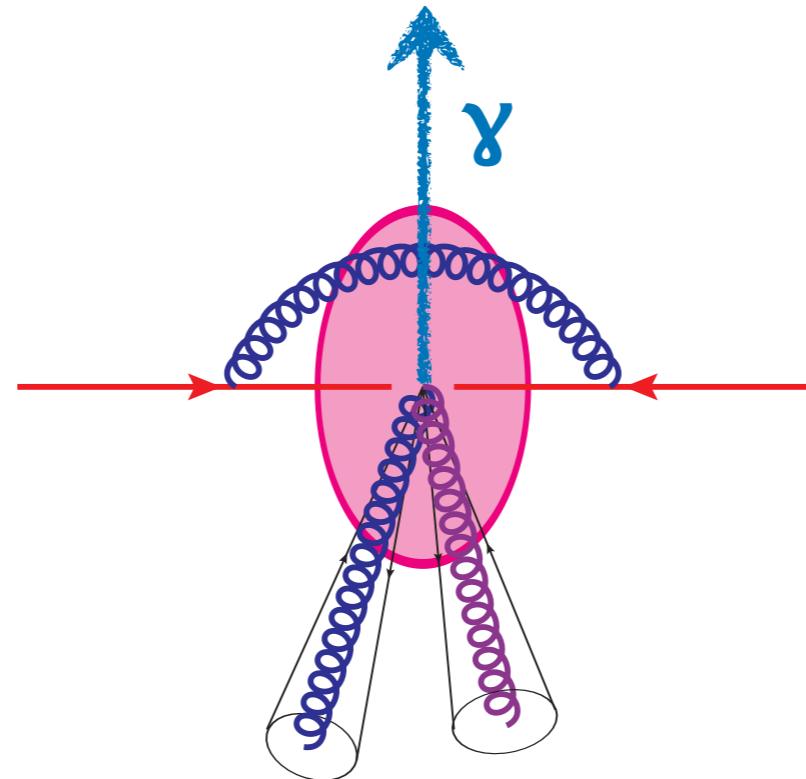
⇒ expect plateau at high transverse momentum as  $\langle u \rangle / \langle d \rangle \rightarrow \infty$

# Sketch of NNLO calculation

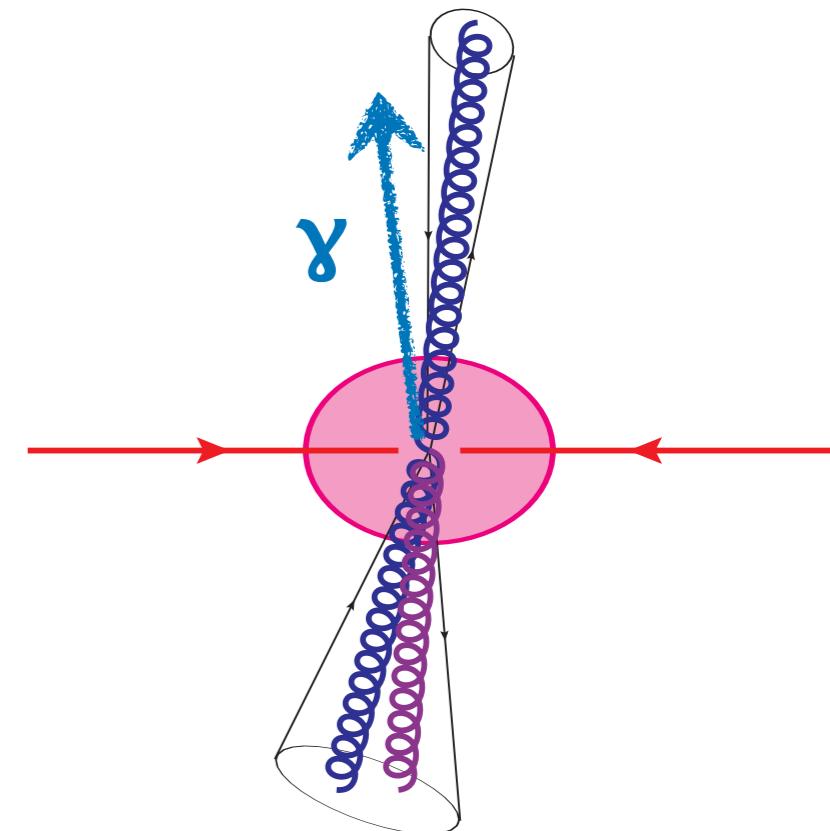
Pure virtual, e.g. 2-loop diagrams (Born topology)



Real-virtual, 1-loop with an additional parton



Real-real, two additional partons



- Two main challenges:
  - calculation of 2-loop diagrams with multiple scales;
  - method for isolating singularities and cancelling between contributions.

[for a recent overview see:  
[G. Zanderighi @ EPS2017](#)]

2-loop amplitudes from Anastasiou et al, [arXiv:0201274](#)

N-jettiness slicing, Boughezal et al, [arXiv:1504.02131](#); Gaunt et al, [arXiv:1505.04794](#).

# Setup

- Most important input parameter: electromagnetic coupling.
  - Use the “ $a(0)$ ” scheme for compatibility with separate calculation of NLO EW effects in this scheme:  $\alpha|_{\gamma+j} = \alpha(0) = 1/137.036$
- Use “smooth cone” (“Frixione”) isolation criterion in order to make NNLO calculation tractable.  
[Frixione, arXiv:9801442](#)

$$\sum p_T^{\text{had}}(R) < 0.025 \times p_T^\gamma \left( \frac{1 - \cos R}{1 - \cos 0.4} \right)^2 \quad \forall R < 0.4 .$$

(parameter choices)

- Quantify impact of this choice by comparison at NLO using traditional isolation and fragmentation functions.

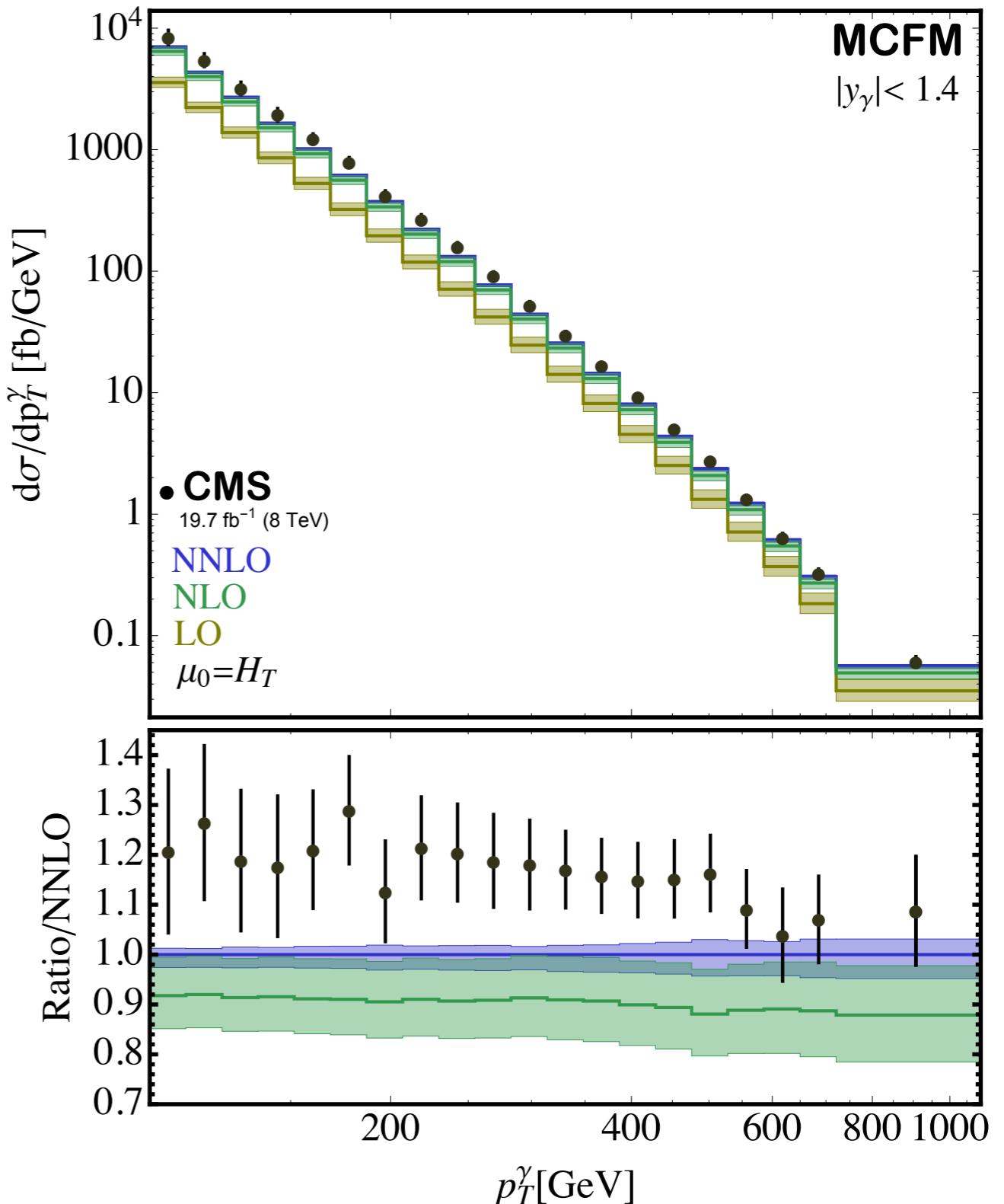
# Comparison at 8 TeV

- Adopt [CMS analysis](#) cuts.
- Perturbative uncertainty:  
6-point scale variation with  
central choice of  $H_T$

$$\mu_R = r H_T, \quad \mu_F = f H_T$$

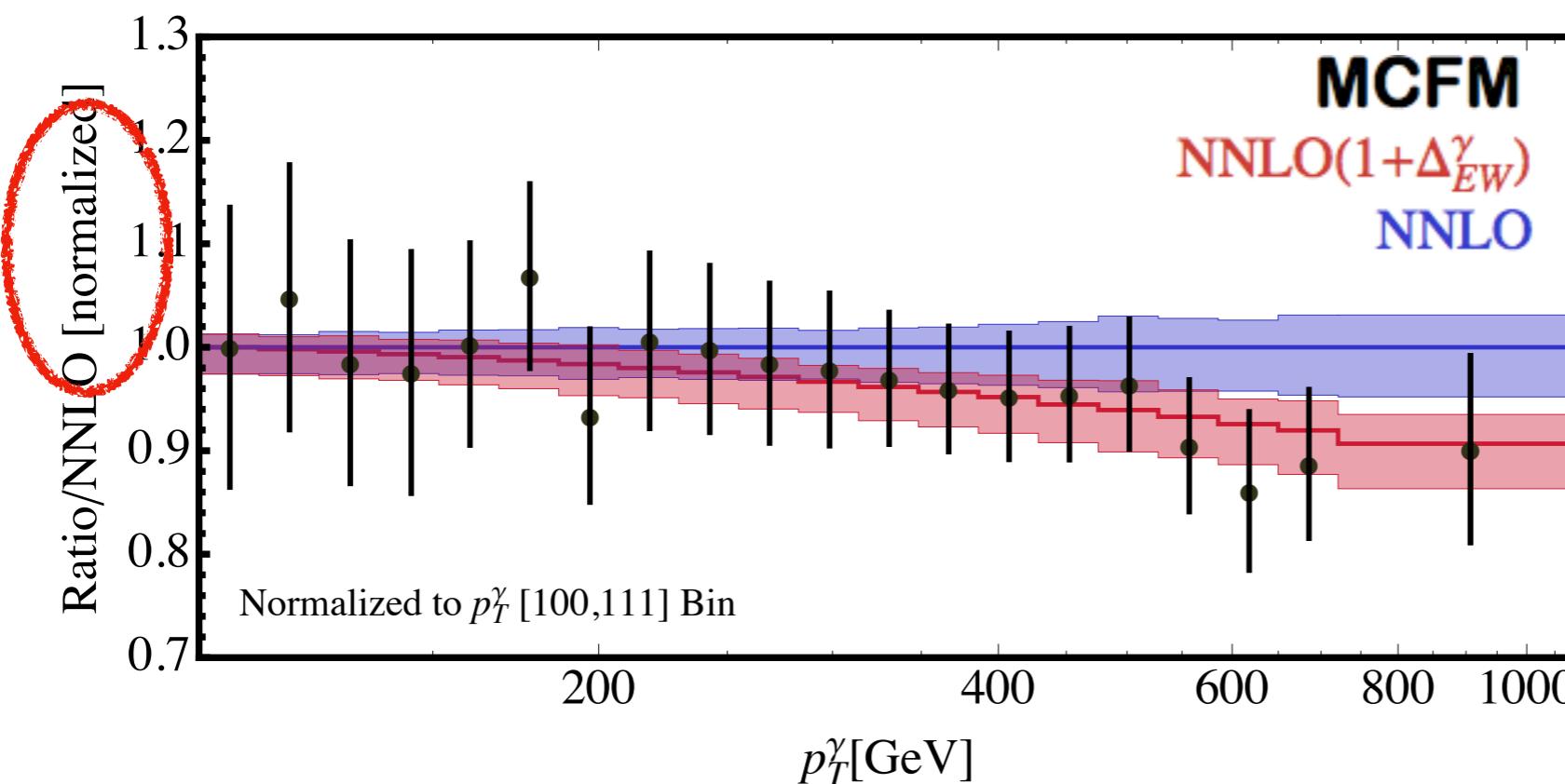
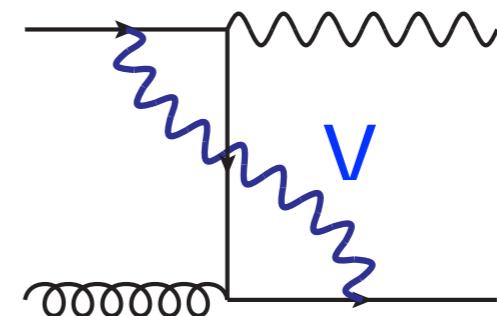
$$r, f \in (\frac{1}{2}, 1, 2) \text{ and } rf \neq 1$$

- Scale uncertainty from  
 $\sim 10\%$  (NLO) to  $\sim 3\%$  (NNLO).
- Data/theory high; **shape?**



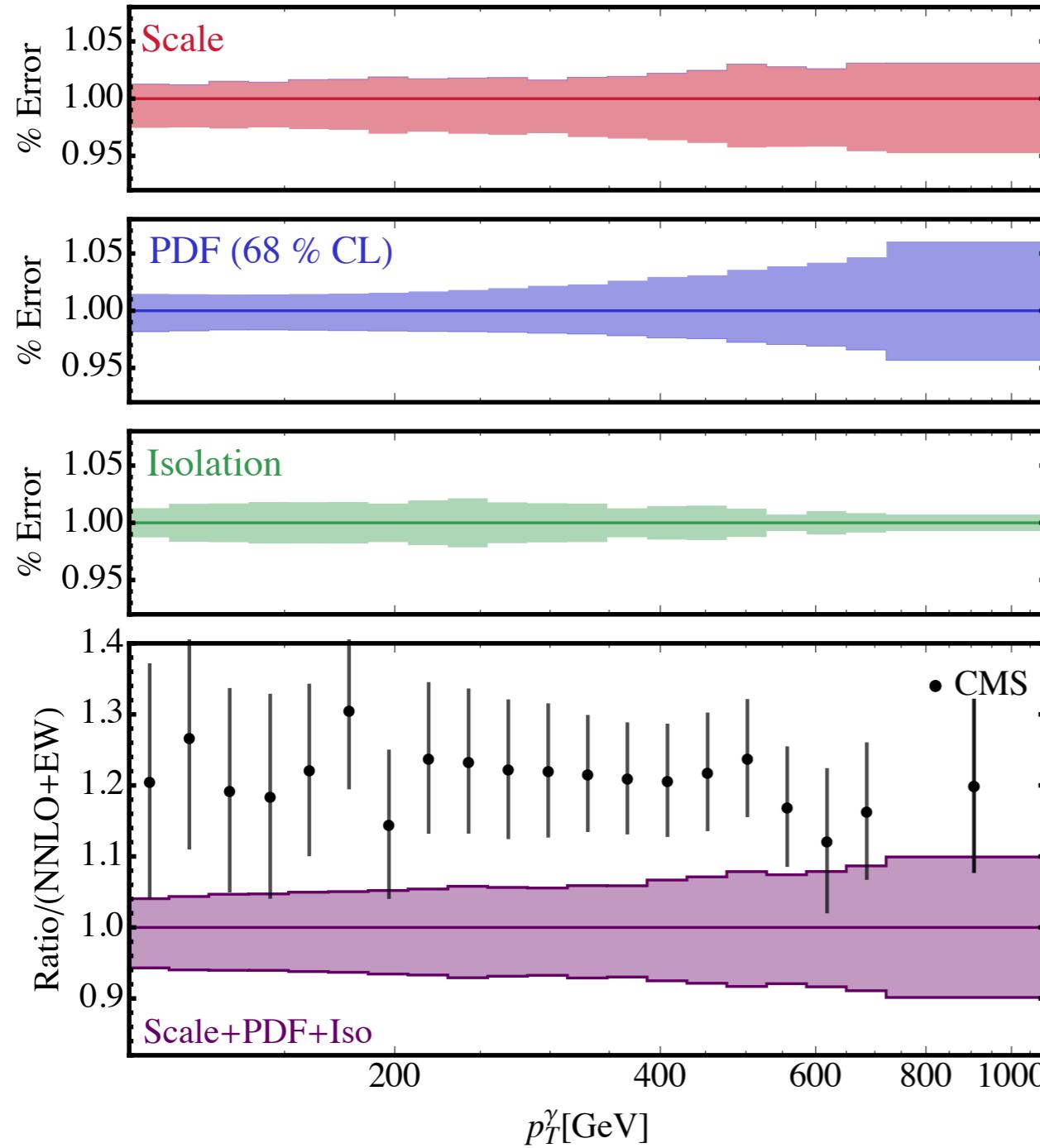
# Inclusion of EW Sudakov effects

- At high  $p_T$ , EW corrections are enhanced by Sudakov logarithms with the leading form  $\log^2(M_V/p_T)$ .
- Easily incorporated through approximate form that captures high-energy behavior, multiplying NNLO result. [Kuhn et al, arXiv:0508253](#)



- Lowers prediction at high  $p_T$ .
- Better agreement with shape of data.

# Detailed study of uncertainty



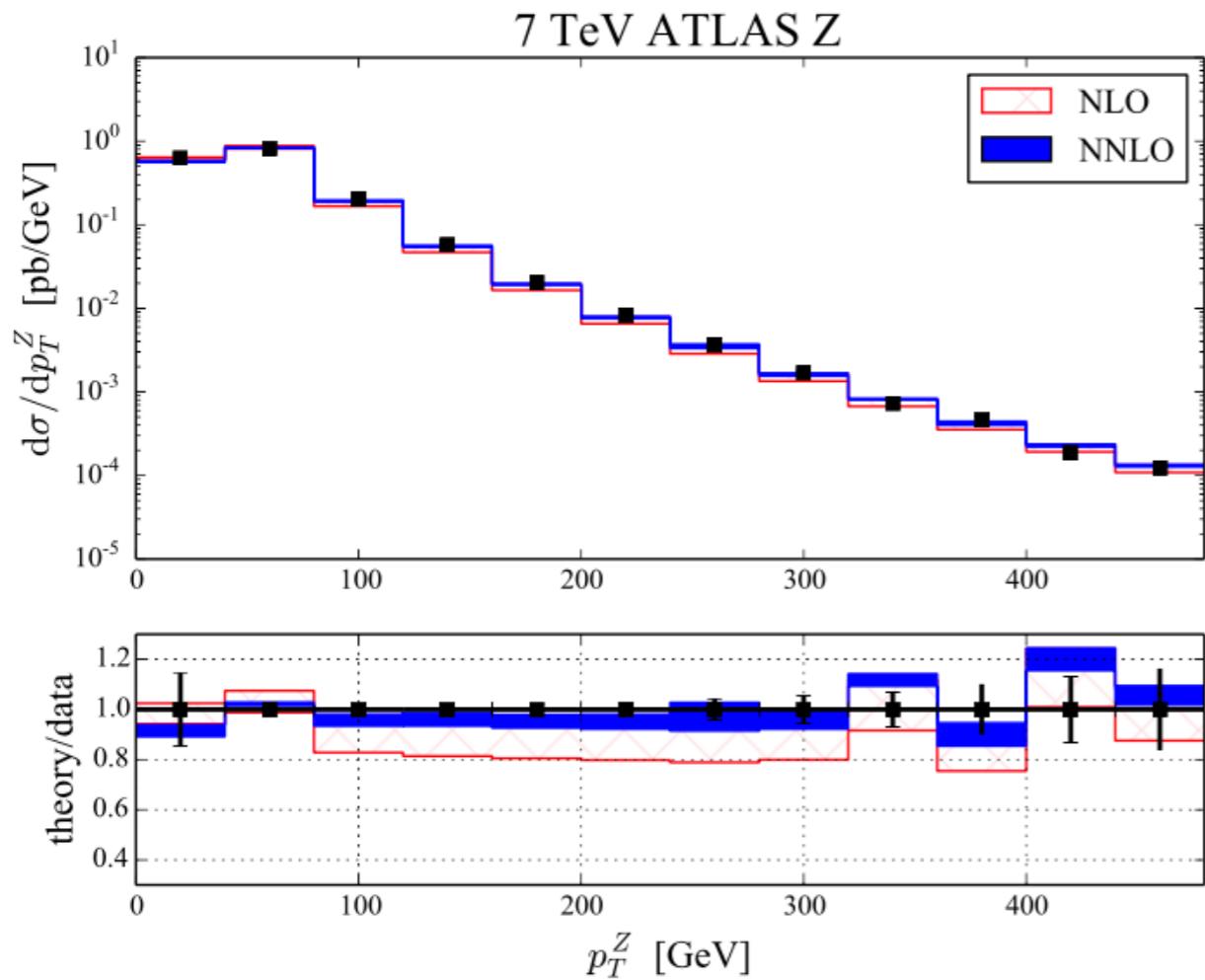
- Scale variation (as before).
- 68% CL PDF uncertainty in CT14, using LHAPDF.
- Difference between smooth cone and parton-level version of experimental isolation.
  - conservative: multiply by two, allow excursion in both directions.

⇒ **tension remains**

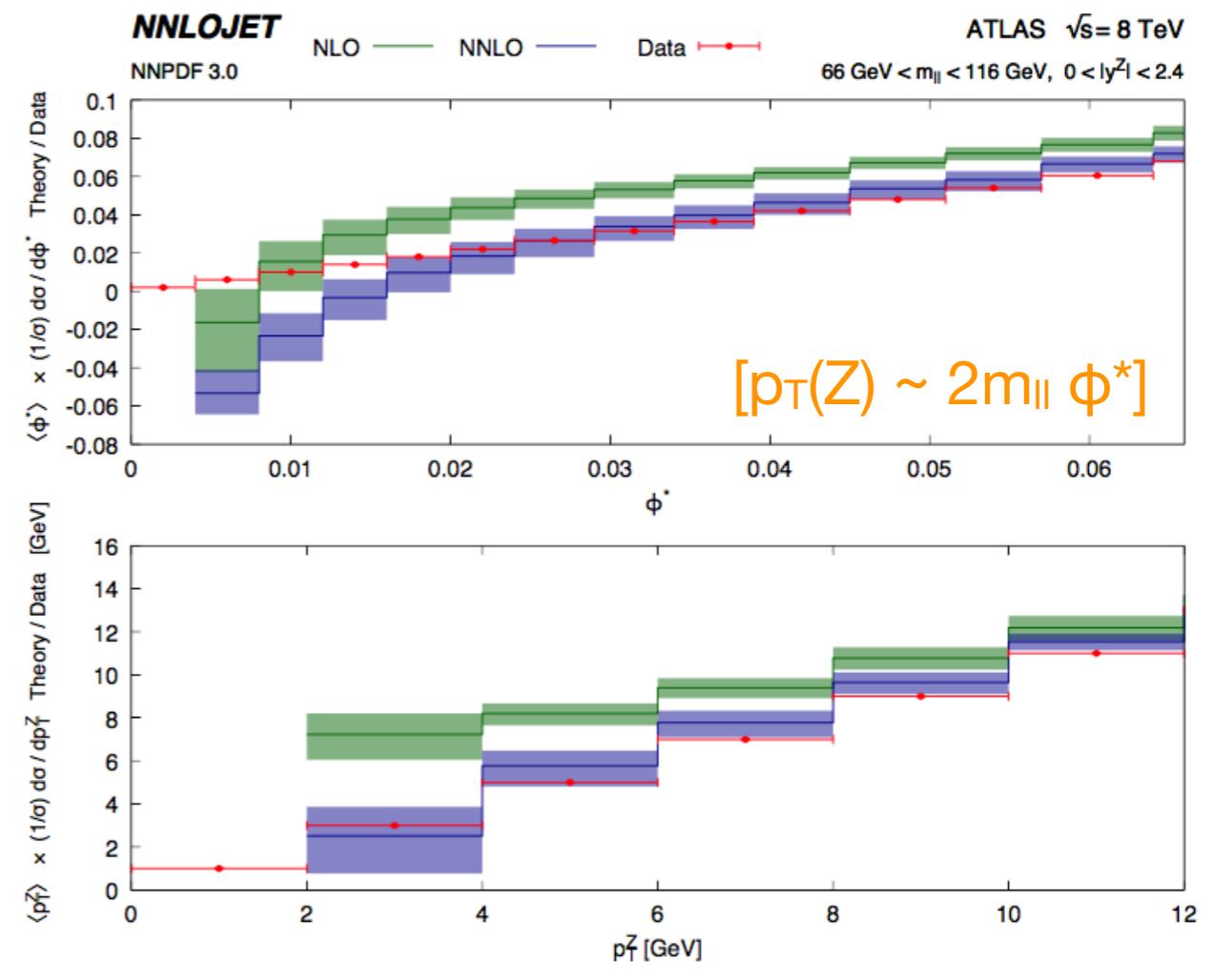
(level higher than quoted luminosity uncertainty 2.6%)

# Z+jet at NNLO

- NNLO results for Z+jet also available from two groups.



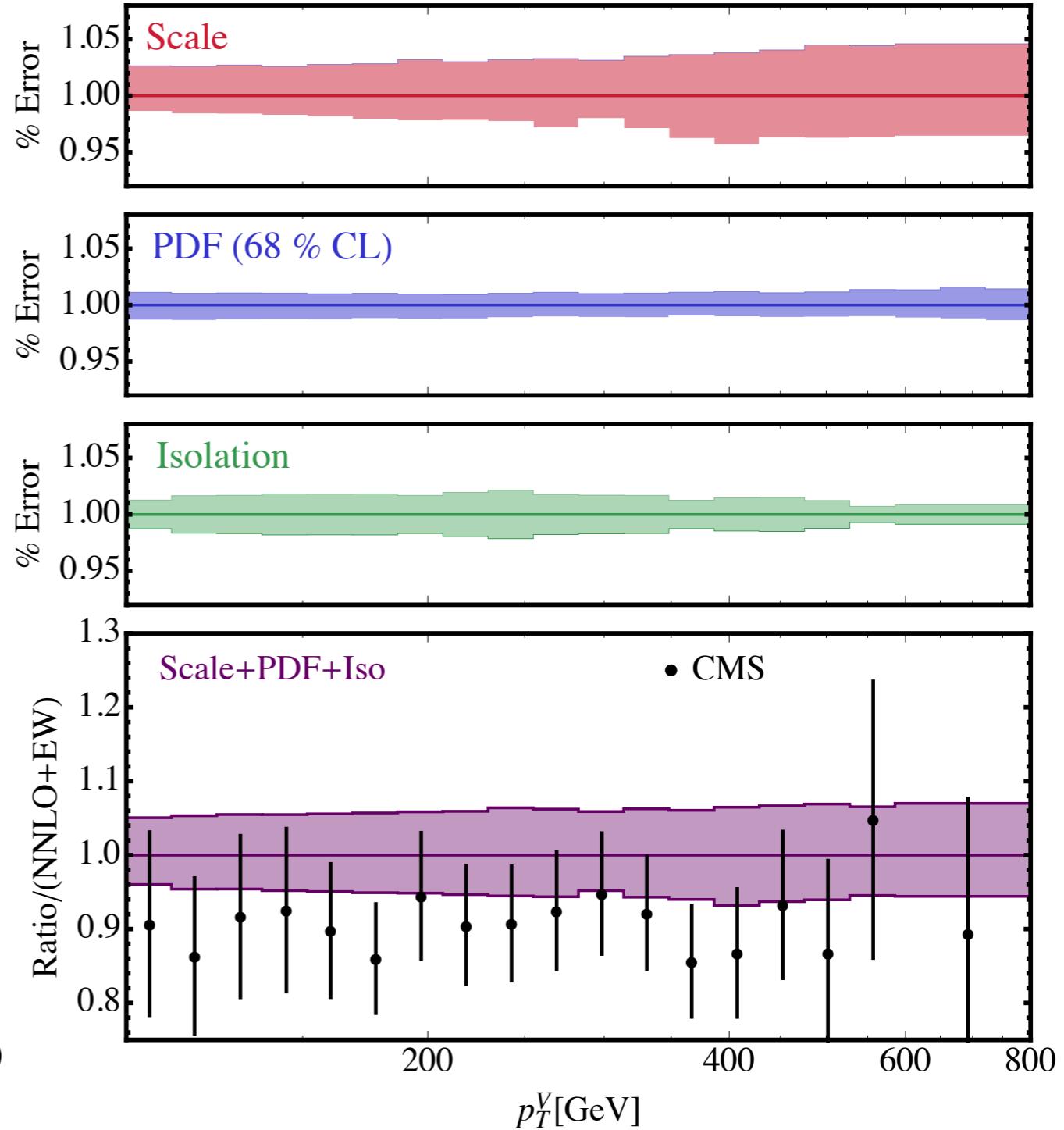
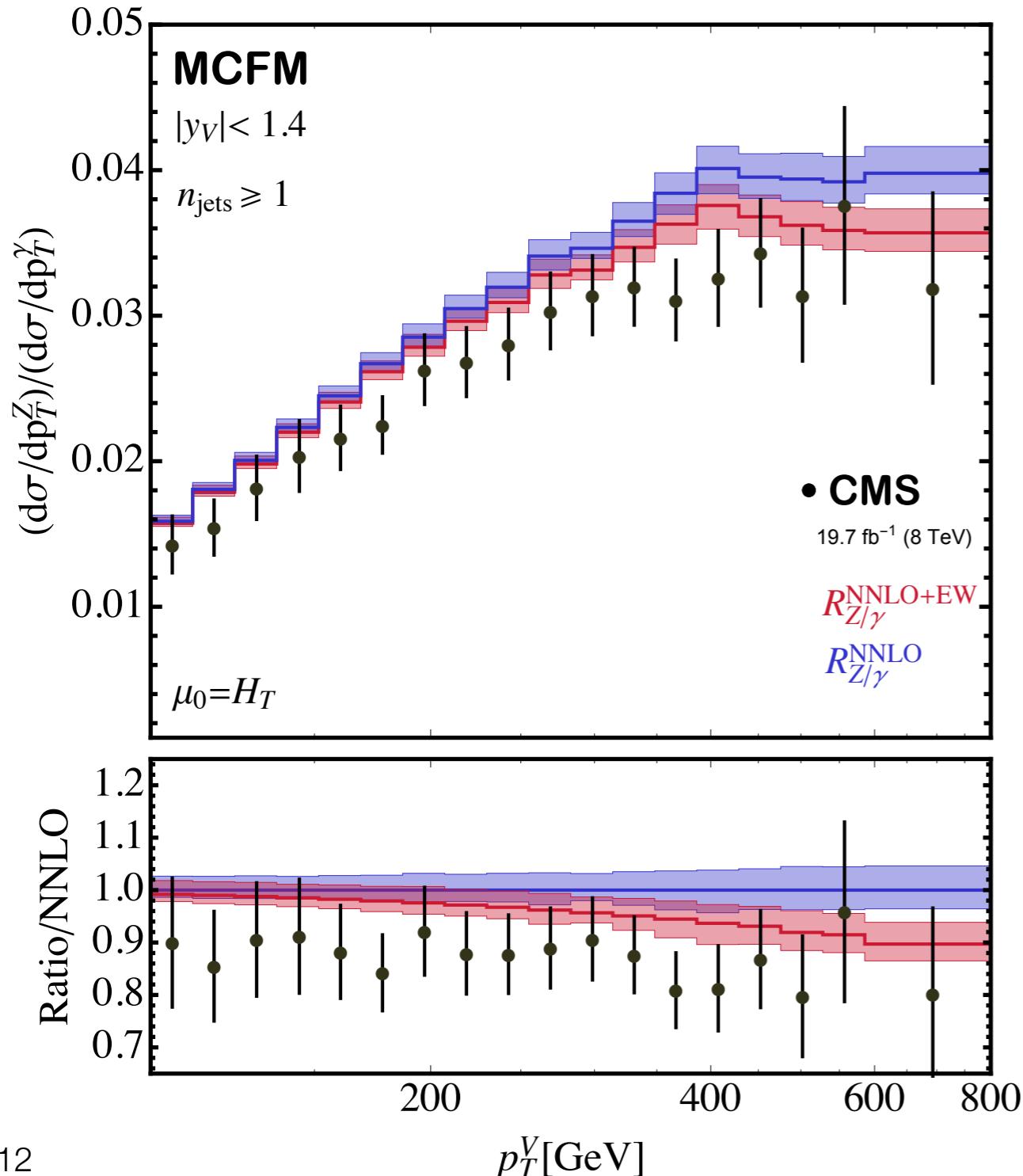
Boughezal et al,  
[arXiv:1512.01291](https://arxiv.org/abs/1512.01291), [arXiv:1602.05612](https://arxiv.org/abs/1602.05612), ...

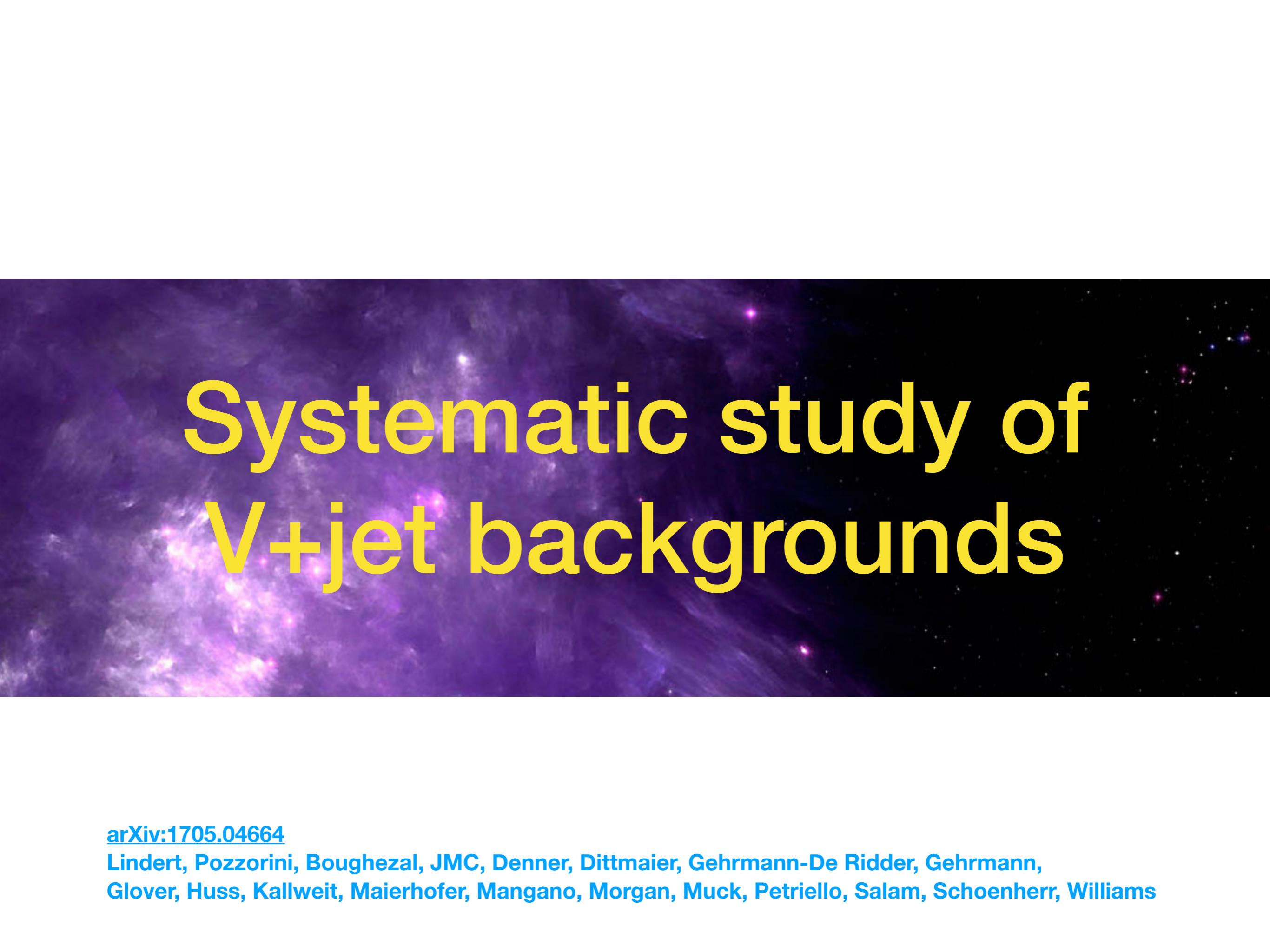


Gehrmann-De Ridder et al,  
[arXiv:1507.02850](https://arxiv.org/abs/1507.02850), [arXiv:1610.01843](https://arxiv.org/abs/1610.01843), ...

- Boughezal et al. implemented in MCFM, so easily combined for ratio prediction.

# Results for Z/ $\gamma$ ratio





# Systematic study of V+jet backgrounds

[arXiv:1705.04664](https://arxiv.org/abs/1705.04664)

Lindert, Pozzorini, Boughezal, JMC, Denner, Dittmaier, Gehrman-De Ridder, Gehrman,  
Glover, Huss, Kallweit, Maierhofer, Mangano, Morgan, Muck, Petriello, Salam, Schoenherr, Williams

# Overview

- Detailed study at NLO QCD+EW, also including central results from NNLO QCD.
  - study of uncertainties performed at NLO QCD only.
  - NNLO QCD used to check correctness of procedure at NLO and stability of predictions.
  - future work to propagate all uncertainties from full NNLO calculations.
- With NNLO QCD in hand to provide confidence, uncertainty estimate from NLO QCD turns out to be sufficient for tails with  $300 \text{ fb}^{-1}$ .
  - but will be nice to take advantage of NNLO QCD at lower values of  $p_T$ , for verification of modeling.
  - eventually will require NNLO QCD and more study to do better.

# Master formula

(Z) Gehrmann-De Ridder et al, [arXiv:1610.01843](#); Currie et al, [arXiv:1301.4693](#), ...

(W) Boughezal et al, [arXiv:1504.02131](#), [arXiv:1602.06965](#)

(γ) JMC, Ellis, Williams, [arXiv:1612.04333](#), [arXiv:1703.10109](#)

Kallweit et al, [arXiv:1412.5157](#),  
[arXiv:1511.08692](#)

Perturbative QCD  
prediction at NLO or NNLO

Electroweak corrections, exact at  
NLO, dominant NNLO effects

$$\frac{d}{dp_T} \sigma_{\text{TH}}^{(V)} = \frac{d}{dp_T} \sigma_{\text{QCD}}^{(V)} + \frac{d}{dp_T} \Delta \sigma_{\text{EW}}^{(V)} + \frac{d}{dp_T} \Delta \sigma_{\text{mix}}^{(V)} + \frac{d}{dp_T} \sigma_{\gamma-\text{ind.}}^{(V)}.$$

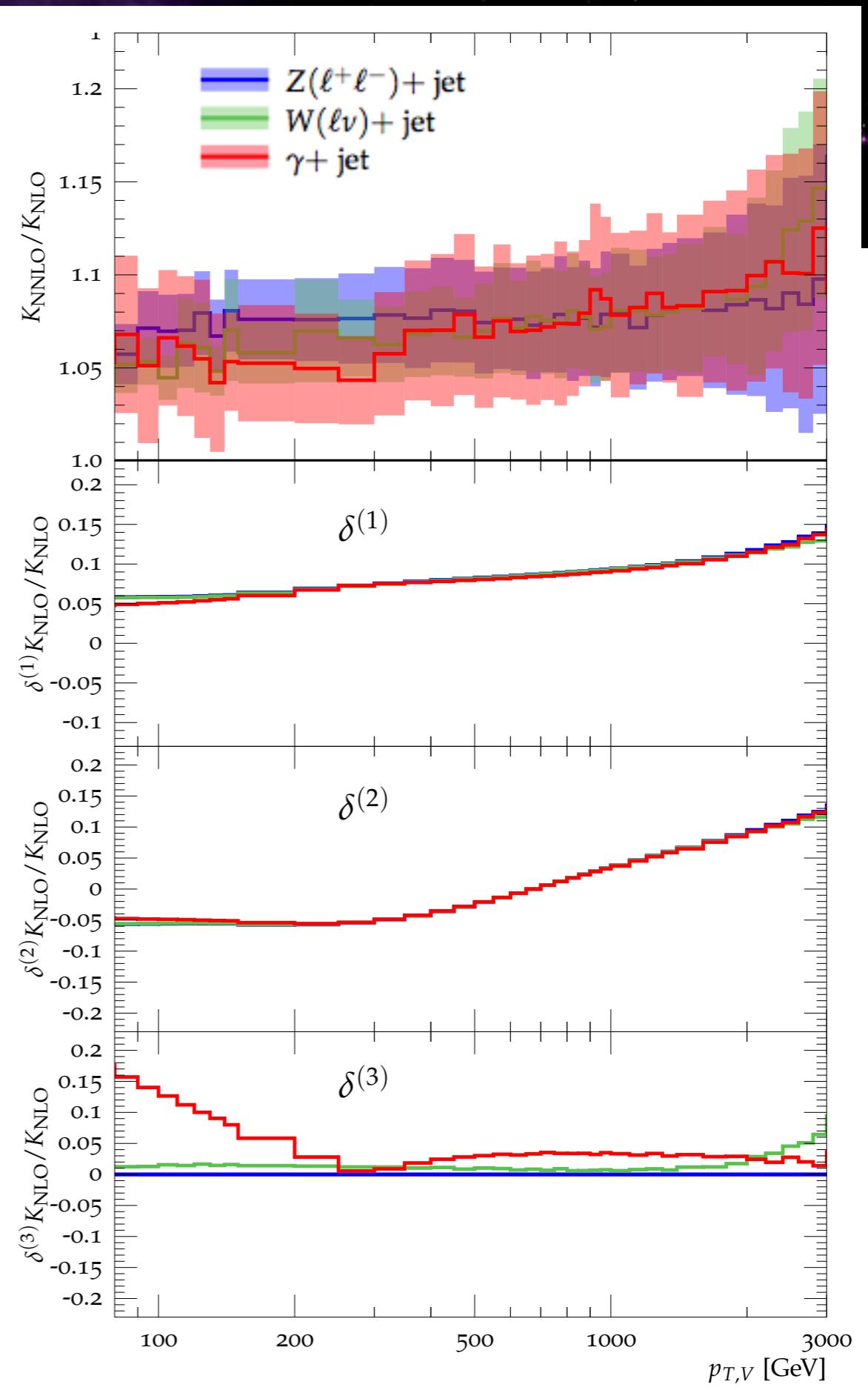
Factorized combination of mixed  
QCD and EW effects,  $\mathcal{O}(\alpha\alpha_s)$

Photon-induced  
contributions

- Important to control all these contributions *and* their associated uncertainty budgets.
  - focussing on region  $p_T \gtrsim 200$  GeV, neglecting important systematic effects at low  $p_T$ .

# QCD uncertainty

- NLO scale uncertainty  $\delta^{(1)}$ : 5-15%
- Shape uncertainty bounded by scale variation  $\delta^{(2)}$ : 5-15%
- Correlation between processes ~ difference between K-factors  $\delta^{(3)}$ : < 2% in general
  - fundamental difference between photons and Z below 200 GeV.
  - W+jet and Z+jet differ by ~ 5% at high  $p_T$ .
- NNLO scale uncertainty 2-6% (room for future improvement ...)

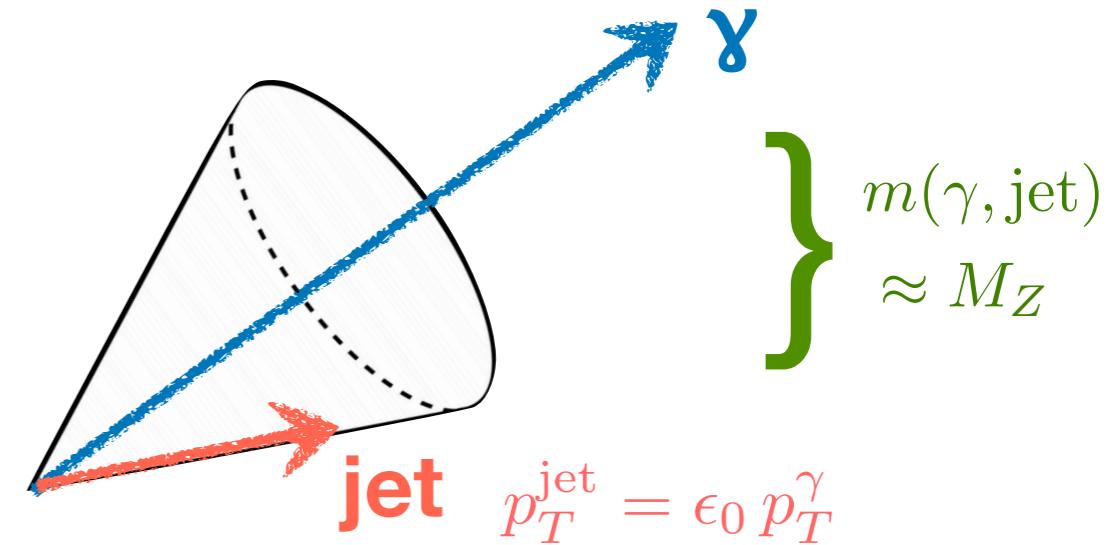


# Photon subtlety

- Use Frixione isolation prescription (as earlier) but with dynamic cone radius:

$$\sum p_T^{\text{had}}(R) < \epsilon_0 \times p_T^\gamma \left( \frac{1-\cos R}{1-\cos R_{\text{dyn}}} \right) \quad \forall R < R_{\text{dyn}}$$

$$R_{\text{dyn}}(p_{T,\gamma}, \epsilon_0) = \min \left\{ 1, \frac{M_Z}{p_{T,\gamma} \sqrt{\epsilon_0}} \right\}$$



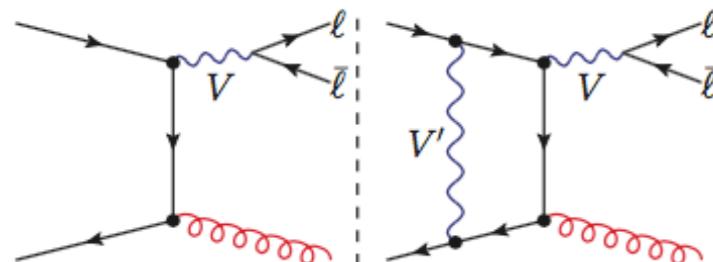
- Photon just satisfying criterion leads to photon-jet invariant mass  $\sim M_Z$ .

- regulates collinear singularities in similar fashion to W/Z+jet, enhancing similarity between processes.
- Take **additional uncertainty** based on standard Frixione setup: at most 10% over interesting ( $p_T > 200$  GeV) range.

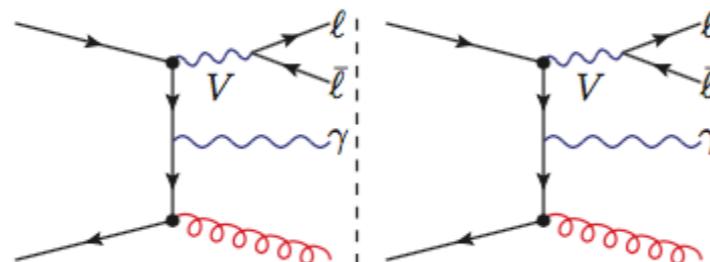


# Electroweak corrections

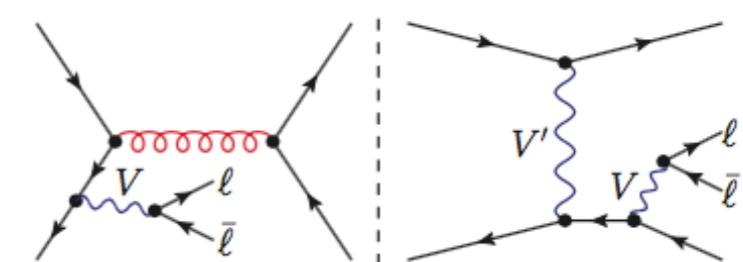
Kallweit et al, arXiv:1511.08692



(a) Virtual  $\mathcal{O}(\alpha_S \alpha^3)$  correction



(b) Real  $\mathcal{O}(\alpha_S \alpha^3)$  correction



(c) Real  $\mathcal{O}(\alpha_S \alpha^3)$  correction

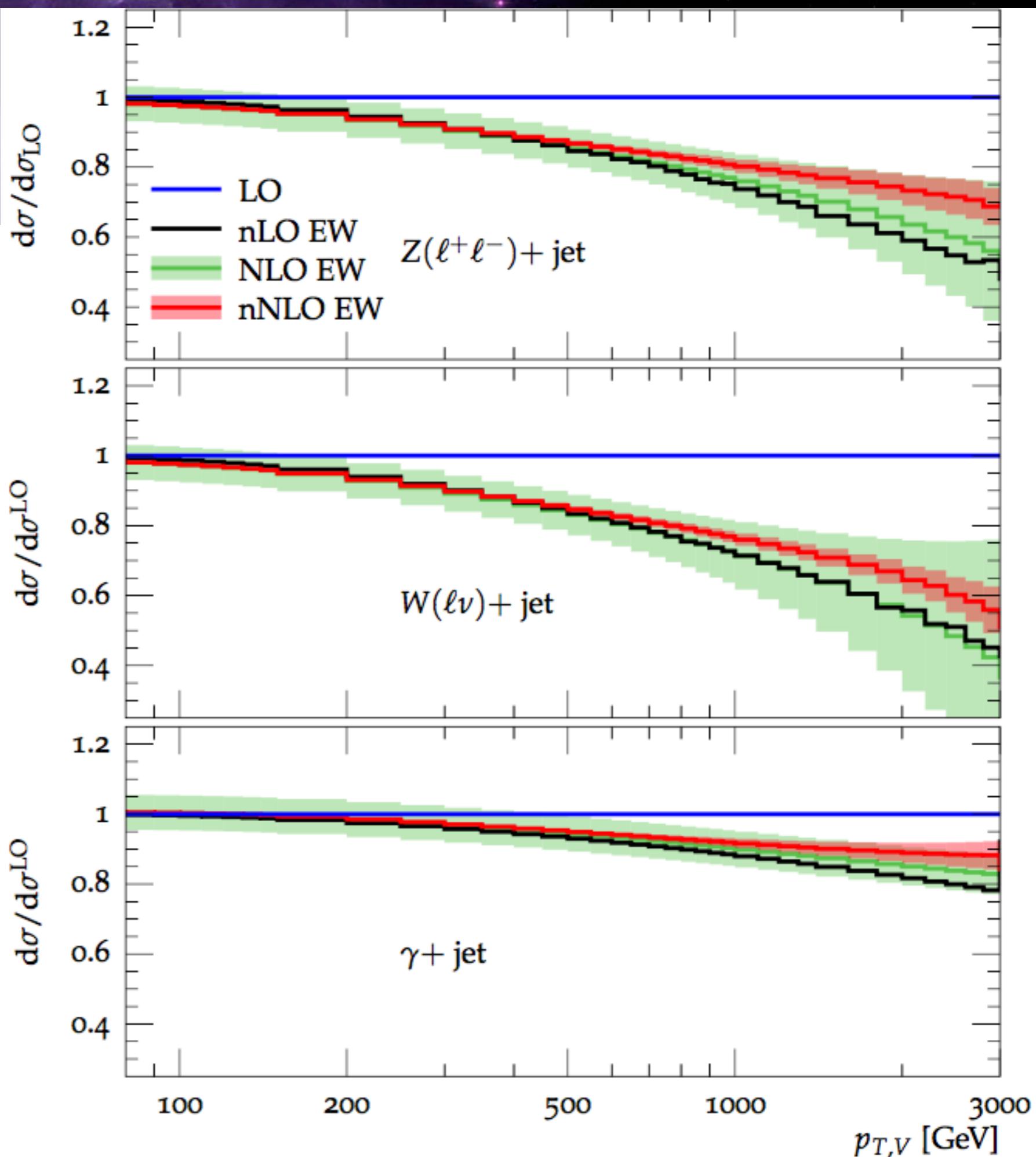
- Exact NLO EW corrections including off-shell effects and radiation in vector boson decays; use “dressed” leptons.
- Dominant part of NNLO, from Sudakov-enhanced contributions, “nNLO”. Kuhn et al, arXiv:0708.0476, ...

**contained in NLO**       $\delta_{\text{Sud}}^{(1)} = \sum_{i,j} C_{2,ij}^{(1)} \ln^2 \left( \frac{Q_{ij}^2}{M^2} \right) + C_1^{(1)} \ln^1 \left( \frac{Q^2}{M^2} \right),$

**“nNLO”**       $\delta_{\text{Sud}}^{(2)} = \sum_{i,j} C_{4,ij}^{(2)} \ln^4 \left( \frac{Q_{ij}^2}{M^2} \right) + C_3^{(2)} \ln^3 \left( \frac{Q^2}{M^2} \right) + \mathcal{O} \left[ \ln^2 \left( \frac{Q^2}{M^2} \right) \right]$

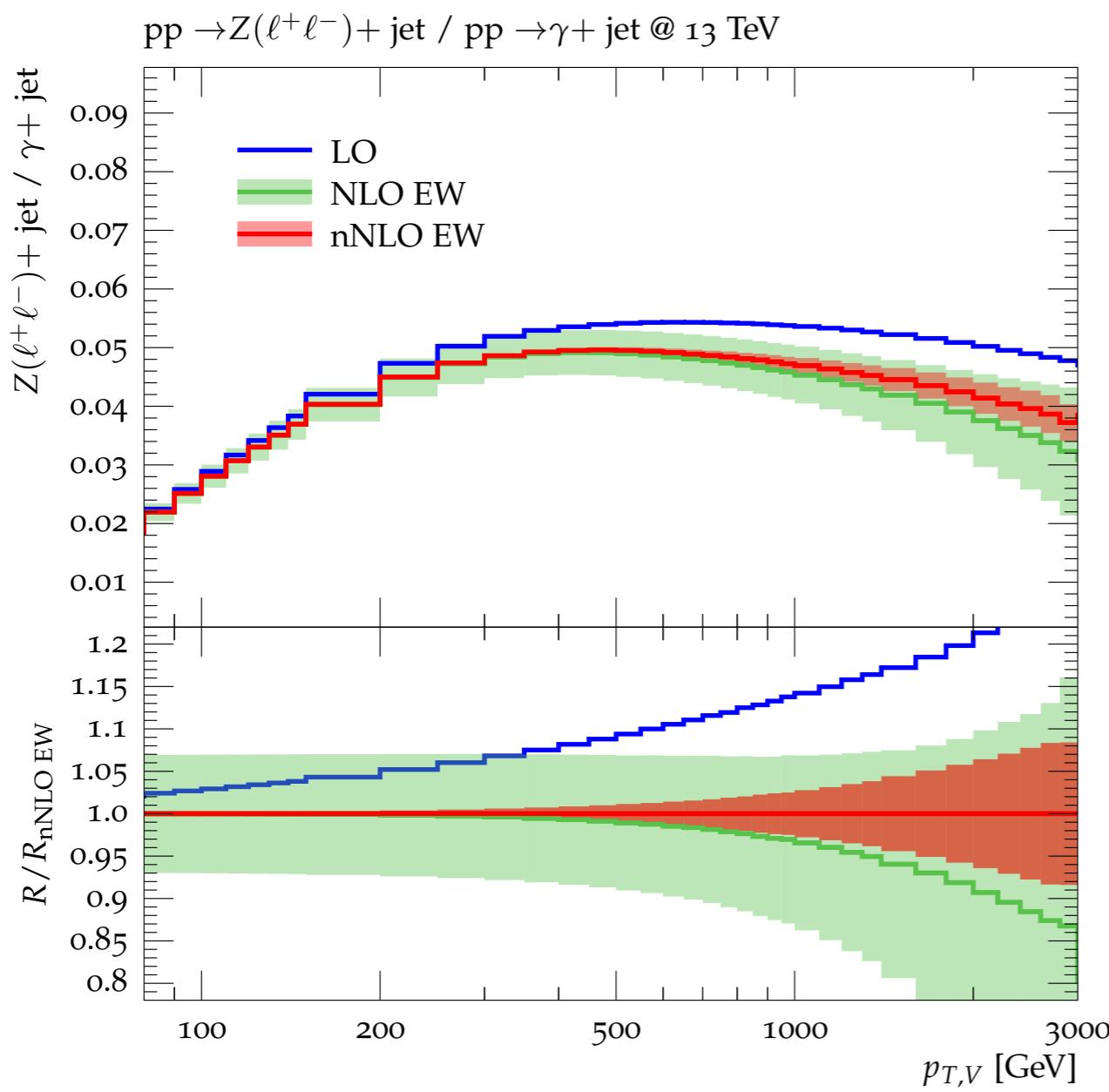
# Impact

- For W/Z huge impact in tail: as large as -50%!
- Not as large for  $\gamma$ +jet (sensitivity to EW charges).
- Sudakov works well at NLO.
- Correction from nNLO is positive.  
**→ total uncertainty at nNLO is ~7% in multi-TeV region**

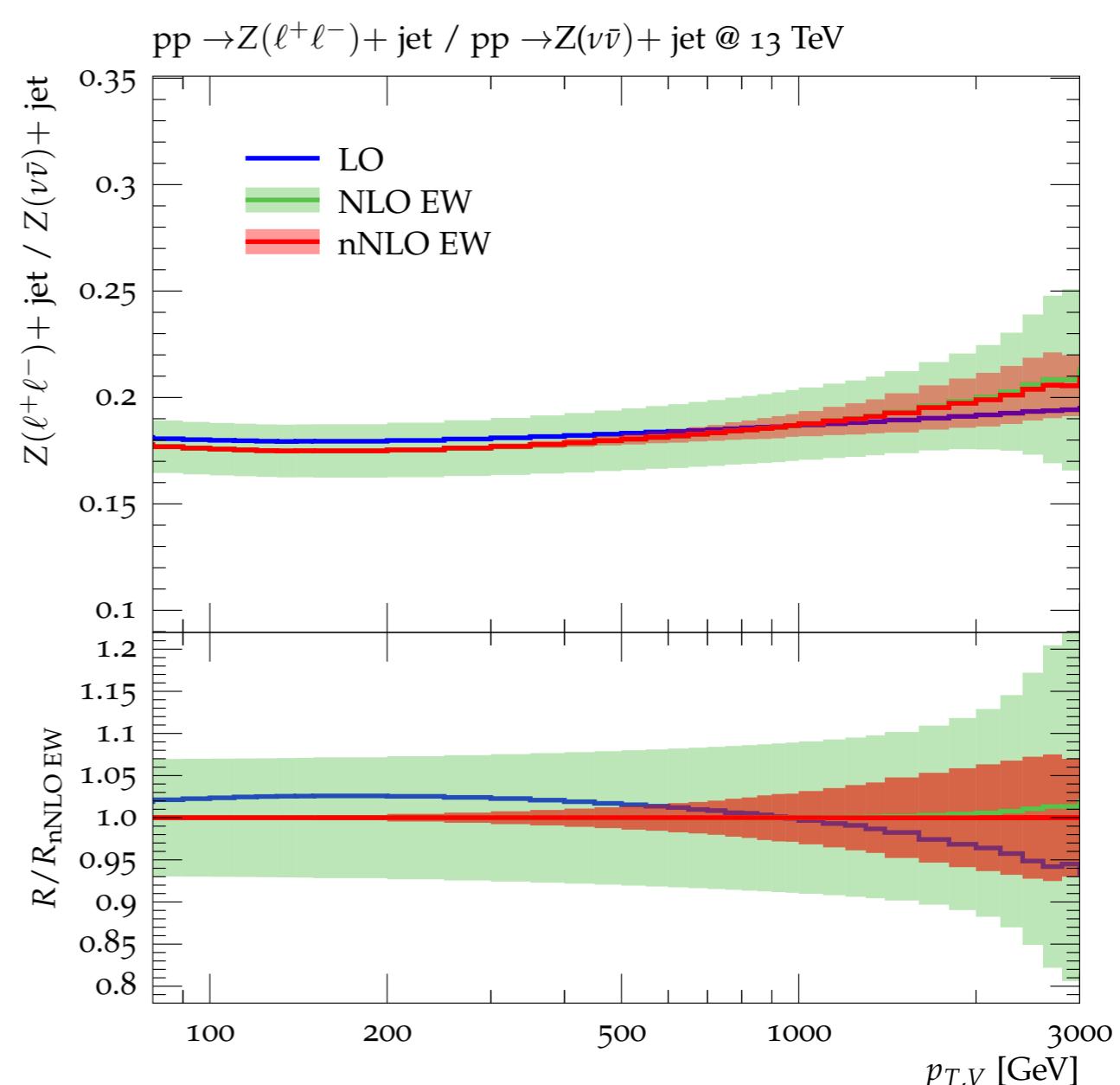


# EW effect on ratios

$Z(\ell\ell)/\text{photon}$

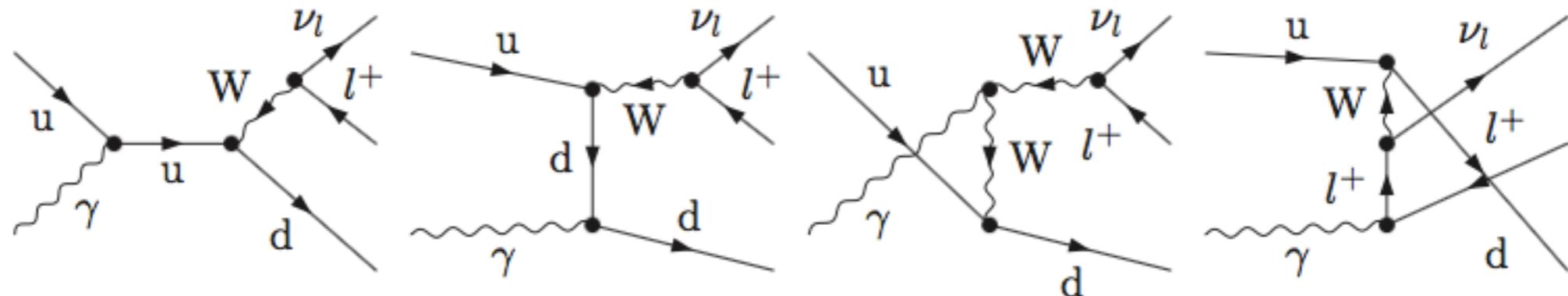


$Z(\ell\ell)/Z(\nu\bar{\nu})$



# Photon-induced contributions

Denner et al, arXiv:0906.1656; Kallweit et al, arXiv:1511.08692



- Non-negligible effect from photon-induced contributions, especially for  $W$ +jet production (from t-channel  $W$  diagrams).
  - included up to NLO QCD (i.e. dressing LO diagrams above).
- Secondary (smaller) effect from modifying quark and gluon PDFs through solution of DGLAP equations including QED.

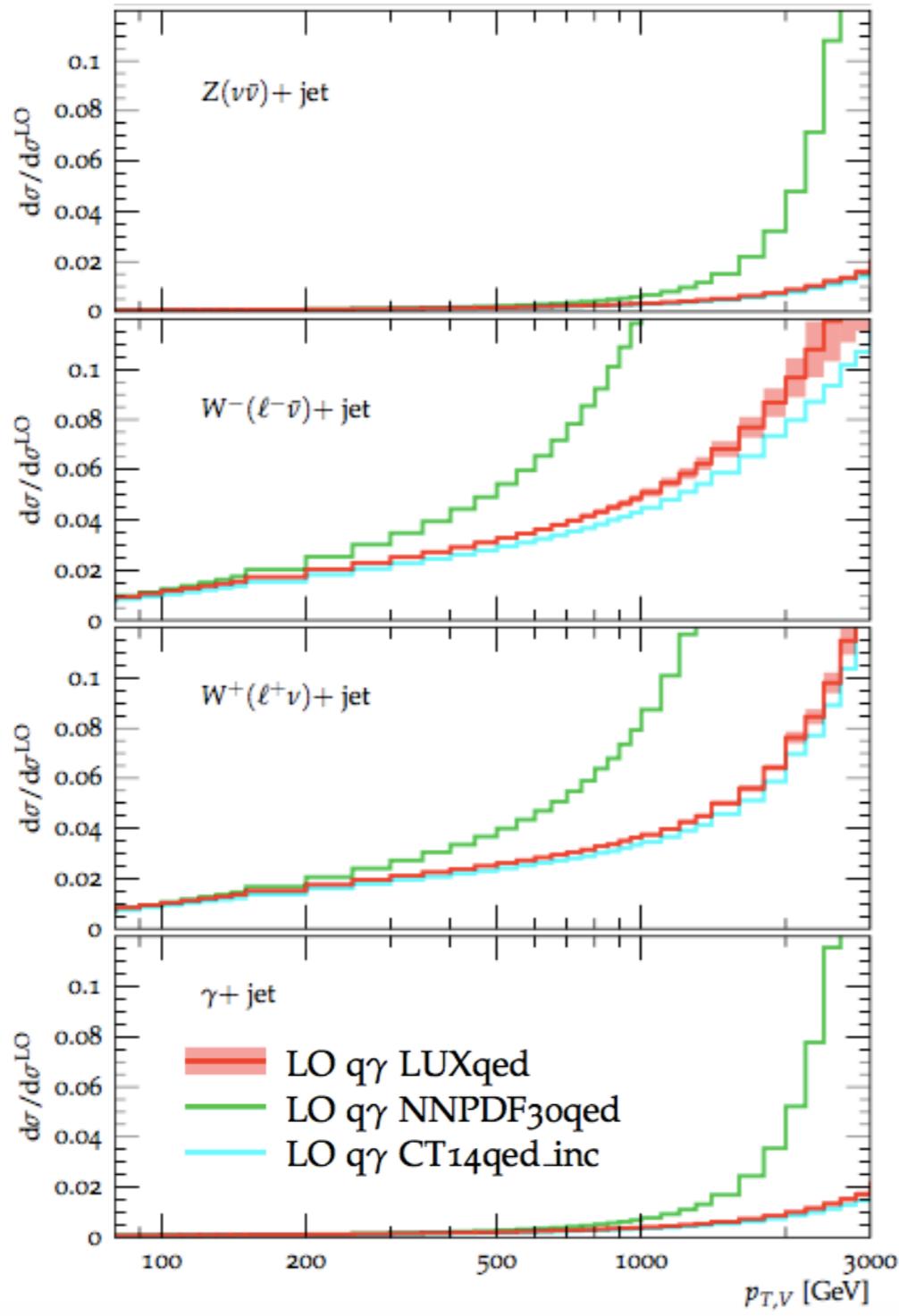
**LUXqed** Manohar et al, arXiv:1607.04266  
**model-independent, data-driven**

**NNPDF30qed** Ball et al, arXiv:1308.0598  
**model-independent, data-driven, suffers from large uncertainties**

**CT14qed\_inc** Schmidt et al, arXiv:1509.02905  
**non-pert. model, some data constraints**

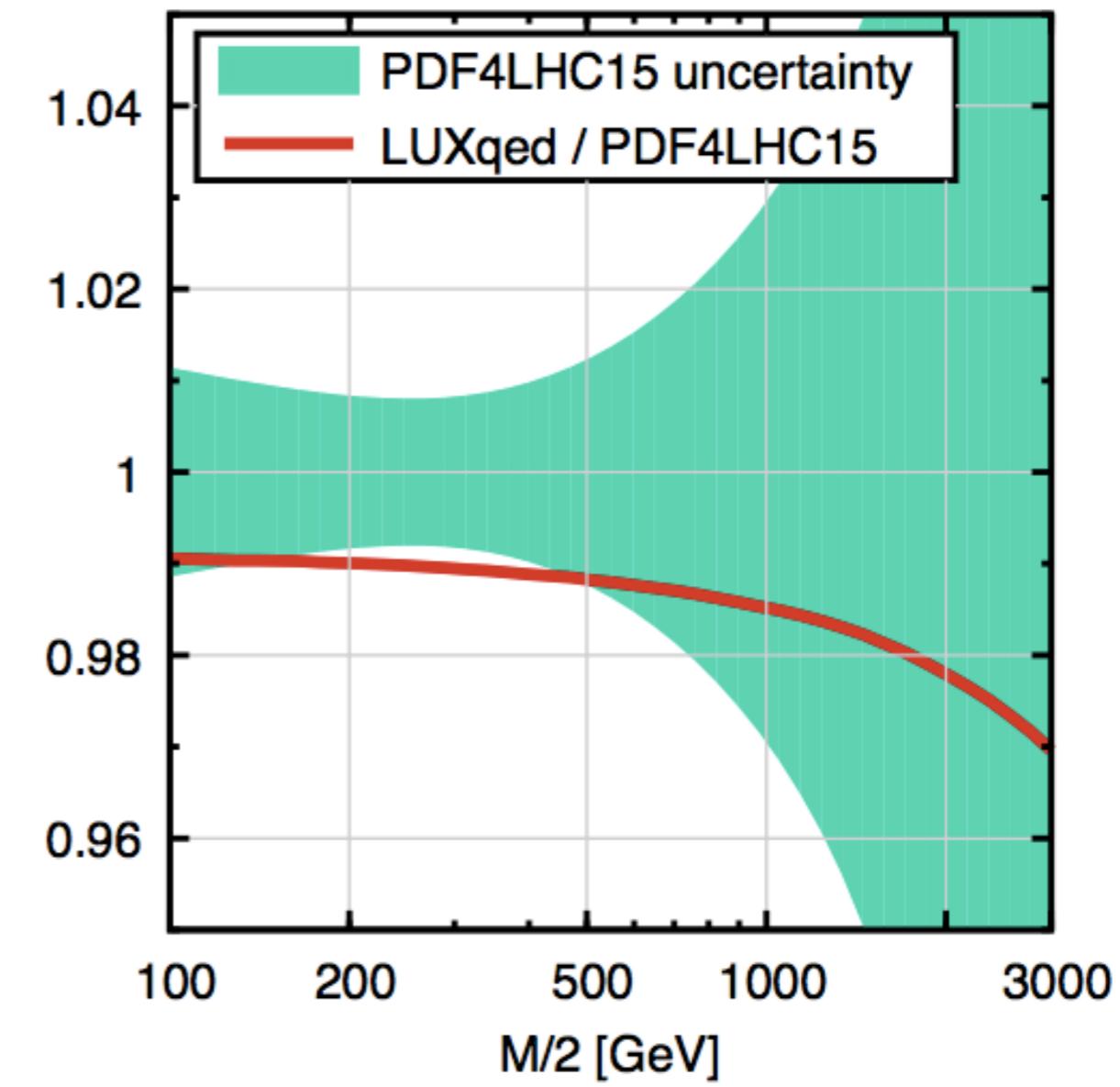


# Photon impact



$$2 \sum_i (\mathcal{L}_{gq_i} + \mathcal{L}_{g\bar{q}_i})$$

QED effects on ( $g\Sigma$ ) luminosity



# Mixed corrections

- No explicit calculation of mixed  $\mathcal{O}(\alpha\alpha_s)$  corrections.
- However, some information known:
  - factorization of Sudakov-enhanced contributions from QCD.
  - some kinematic regions support reliability of factorization.
  - factorization preserves level and hierarchy of scale dependence.
- Thus combine QCD and EW effects by treating as factorized:

$$K_{\text{TH},\otimes}^{(V)}(x, \vec{\mu}) = K_{\text{N}^k\text{LO}}^{(V)}(x, \vec{\mu}) \left[ 1 + \kappa_{\text{EW}}^{(V)}(x) \right]$$

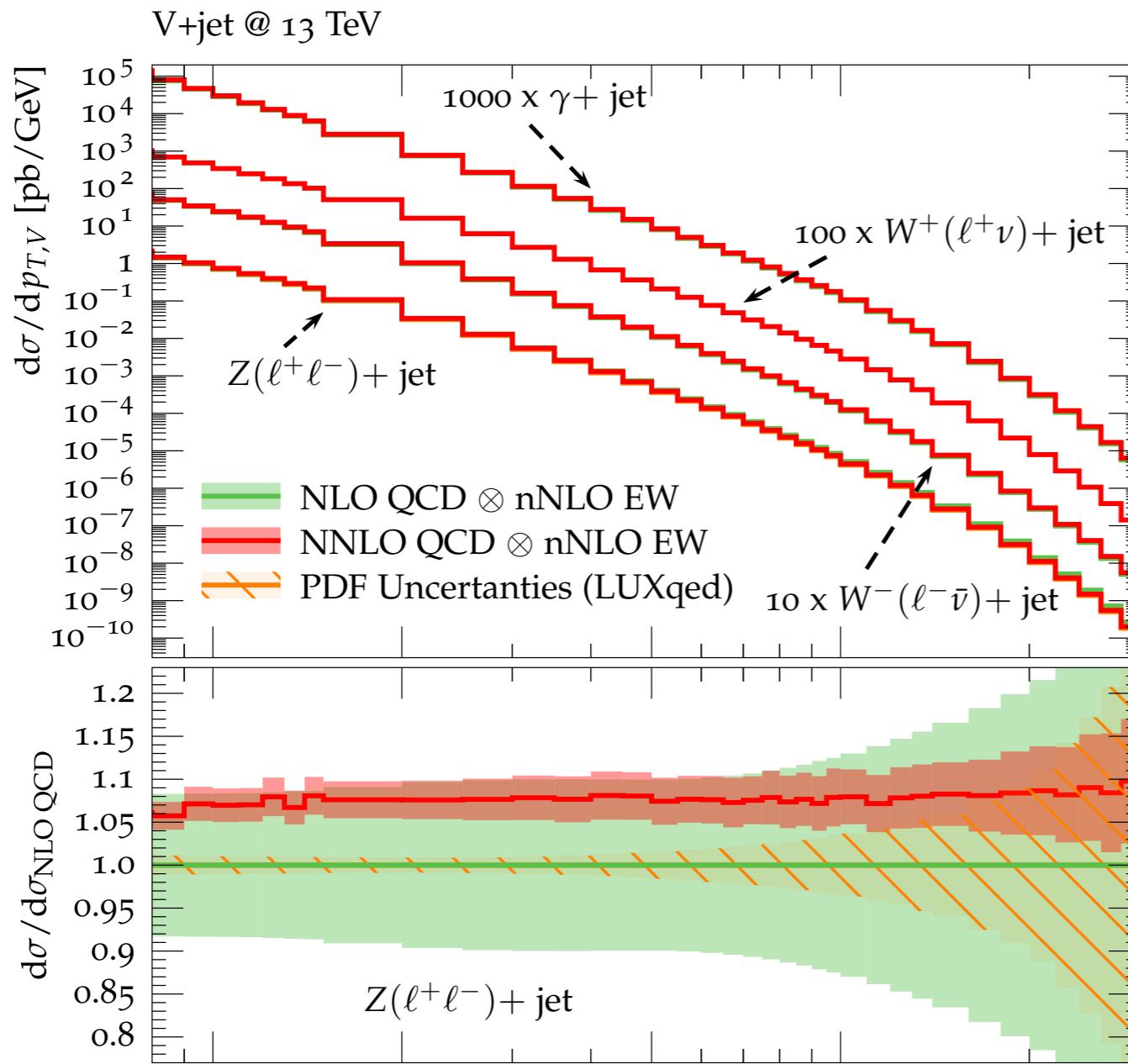
- Estimate uncertainty by scaling difference with simply adding:

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

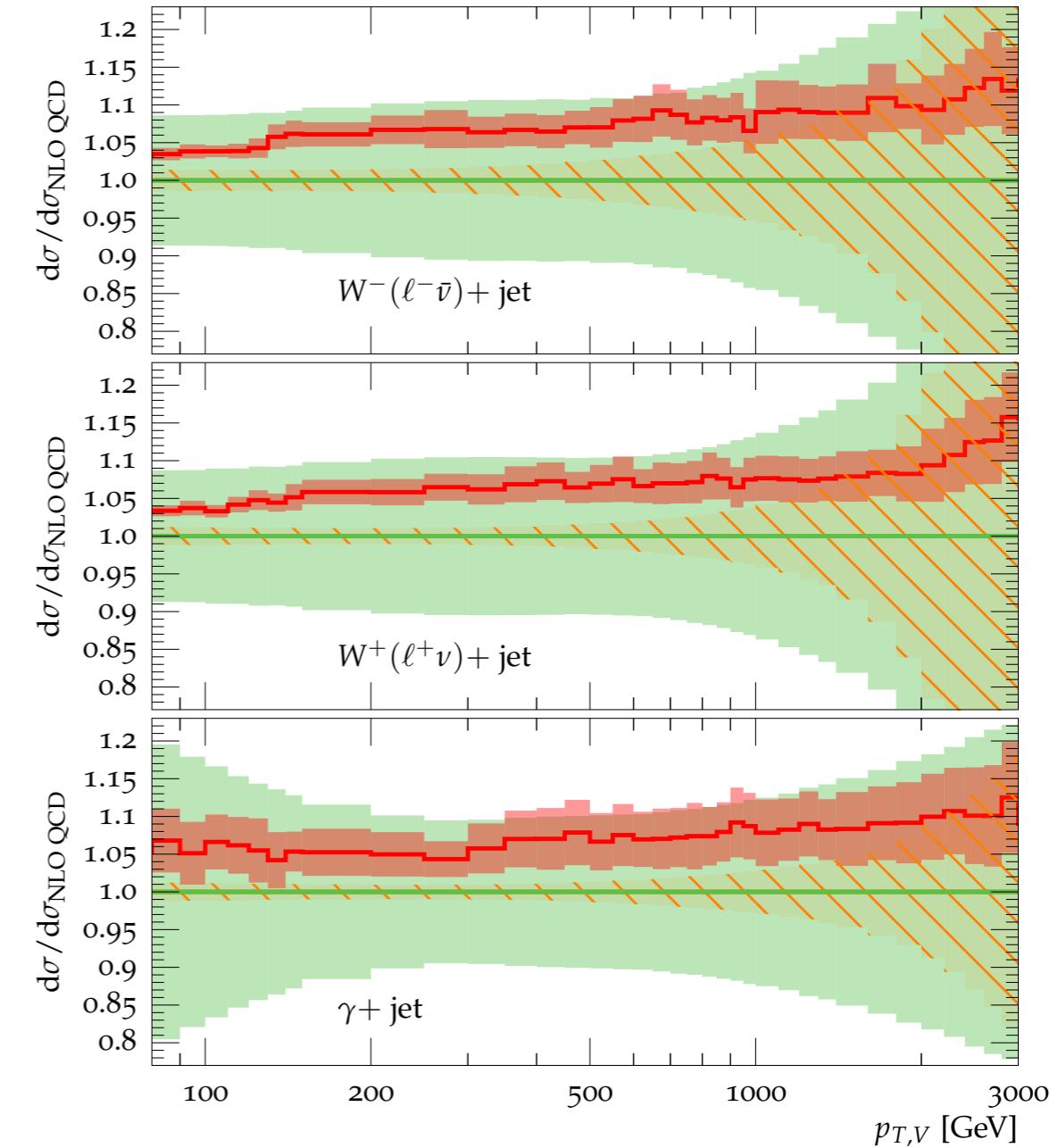
**⇒ combination uncertainty is 0.5 - 3.5% at 3 TeV**



# Final results



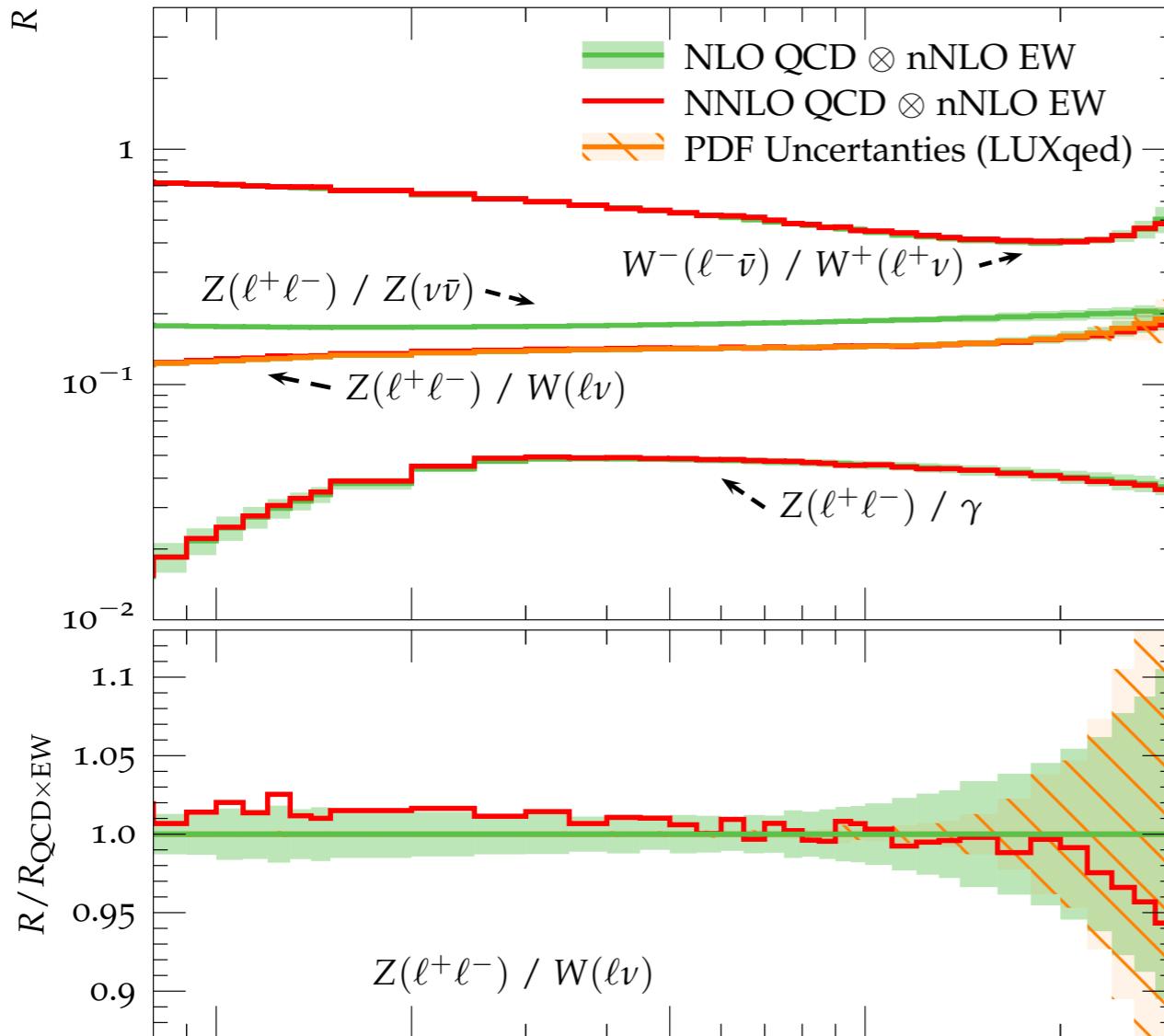
All NLO uncertainties combined in quadrature (NLO), except for PDFs



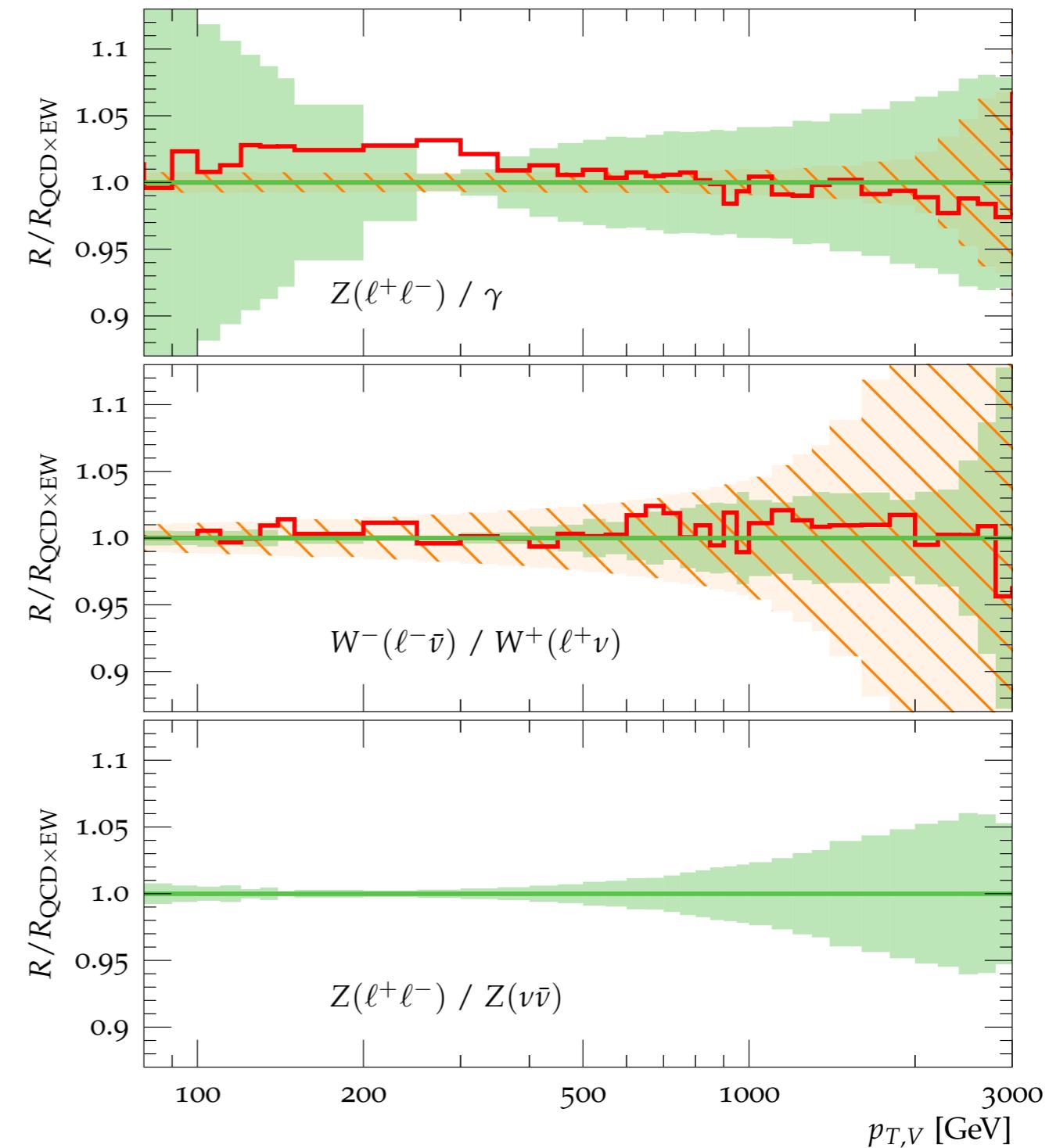
[NNLO: scale uncertainty only]

# Bottom line

V+jet ratios @ 13 TeV



**Many uncertainties cancel,  
< 5% up to 1-2 TeV, very  
stable from NLO to NNLO**



# Summary

- Huge amount of work to complete all relevant NNLO QCD calculations and perform thorough analysis of error budget at NLO QCD+EW, stimulated by and in concert with experiments.
- NLO QCD and EW predictions and uncertainties tabulated versus  $p_T(V)$ , available as data files from LPCC DM WG page:

<http://lpcc.web.cern.ch/content/dark-matter-wg-documents>

- Intended to be propagated to an experimental analysis by reweighting MC event sample with only loose cuts, inclusive of all radiation.
  - MC sample must be reweighted to central predictions.
  - heavy reliance on other observables, especially ones relating to jets, will invalidate predictions and study would need to be extended.
- A full NNLO analysis requires further study; since scale dependence drives uncertainty, might reduce by about a factor of two.
- Need for similar theory-wide effort on backgrounds for other searches?

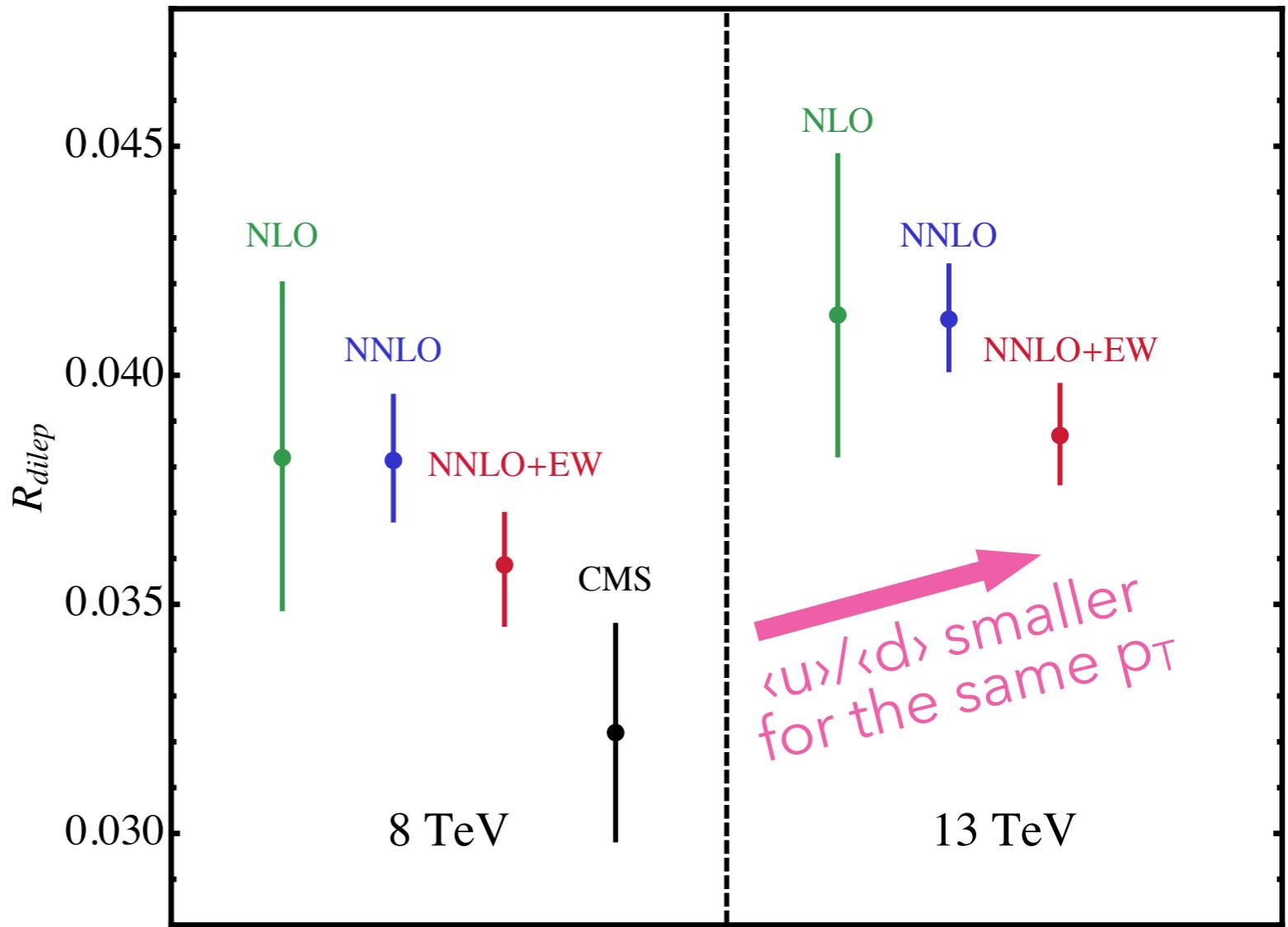
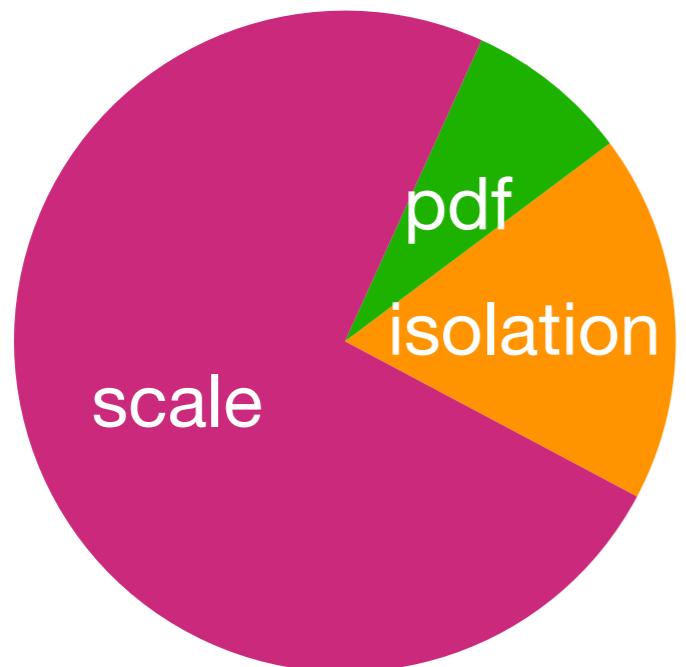




# Backup

# High- $p_T$ cross-section

- Mild tension with 8 TeV data.
- Theoretical uncertainty budget on  $R_{dilep}$  small overall (4%), dominated by scale.



$$R_{dilep} = \frac{\sigma_{\ell^-\ell^++j+X}(p_T^V > 314 \text{ GeV})}{\sigma_{\gamma+j+X}(p_T^V > 314 \text{ GeV})}$$

# QCD uncertainties

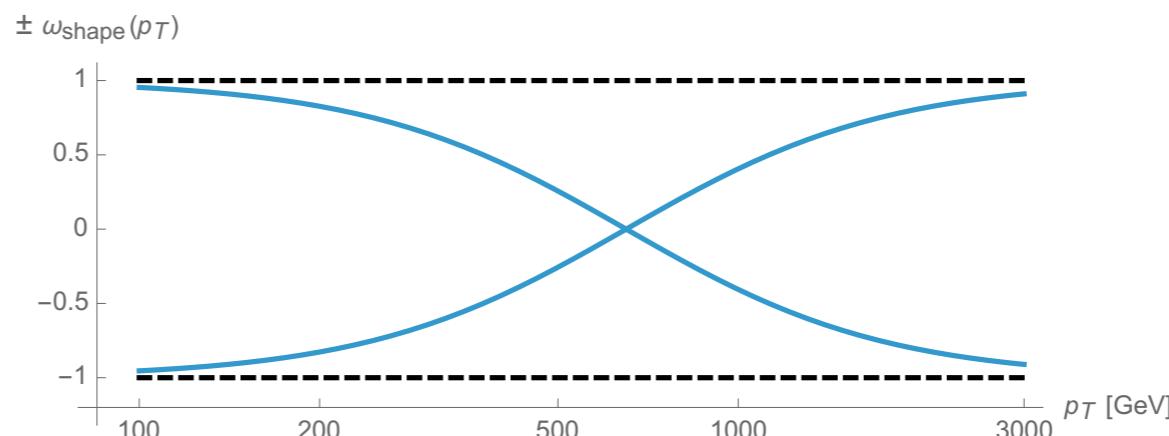
- Six-point symmetrized scale variation (about  $H_T/2$ ) expressed via K-factor:

$$\delta^{(1)} K_{N(N)LO}^{(V)}(x) = \frac{1}{2} \left[ K_{N(N)LO}^{(V,\max)}(x) - K_{N(N)LO}^{(V,\min)}(x) \right]$$

- Conservatively apply additional shape uncertainty:

$$\delta^{(2)} K_{NLO}^{(V)}(p_T) = \omega_{\text{shape}}(p_T) \delta^{(1)} K_{NLO}^{(V)}(p_T),$$

- reference scale of 650 GeV (middle of range).
- at most an additional  $\sqrt{2}$  on scale uncertainty



- Additional estimate of correlation between all V+jet processes.

$$\delta^{(3)} K_{NLO}^{(V)}(p_T) = \Delta K_{NLO}^{(V)}(p_T) - \Delta K_{NLO}^{(Z)}(p_T).$$

- compare K-factors with Z+jet; choice of reference process has small impact on correlations.