Isolated photons at NNLO

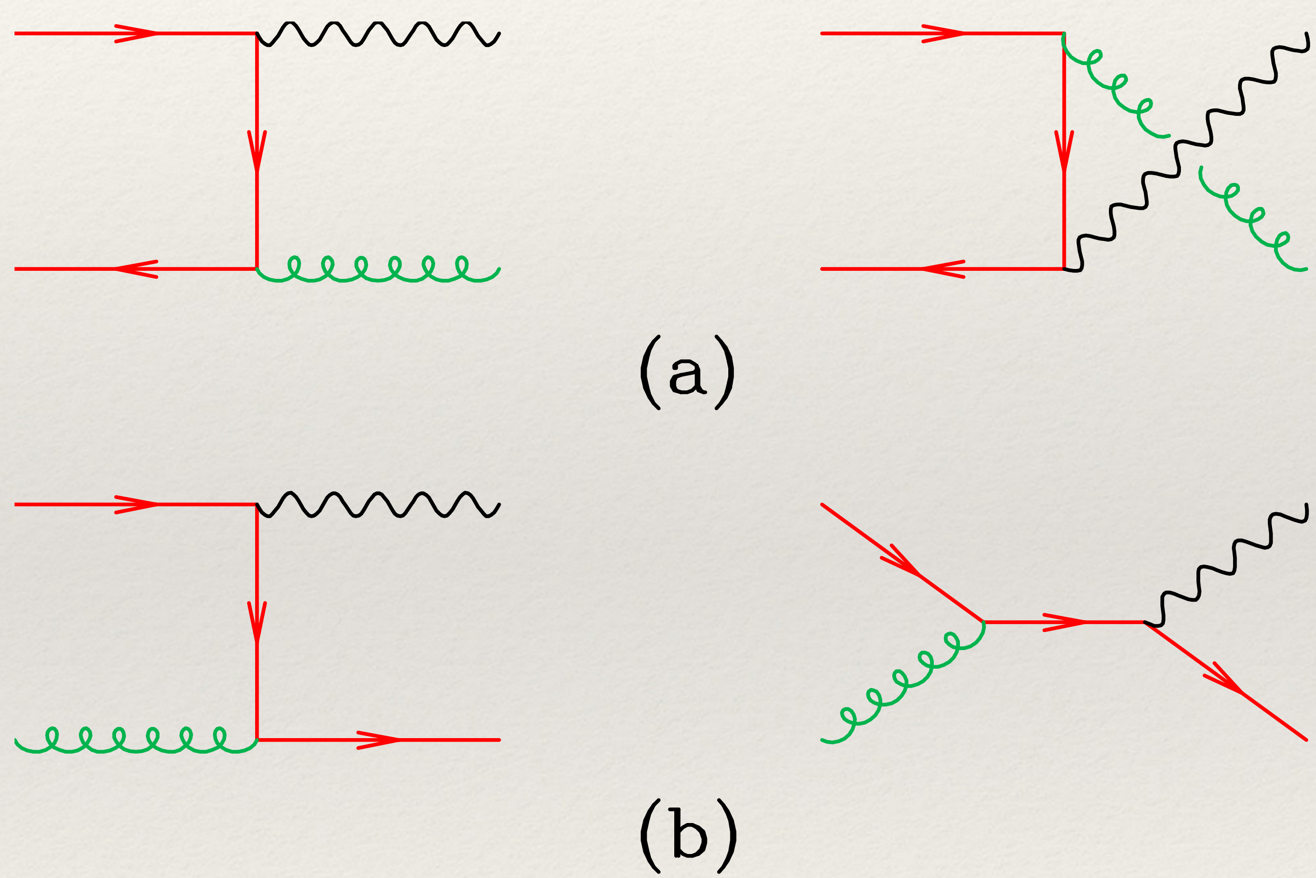
John Campbell, Keith Ellis, and Ciaran Williams

1612.04333: Direct photon production at next-to-next-to-leading order

1703.10109: Driving Miss Data:Going up a gear to NNLO

Motivation for Direct Photon Studies

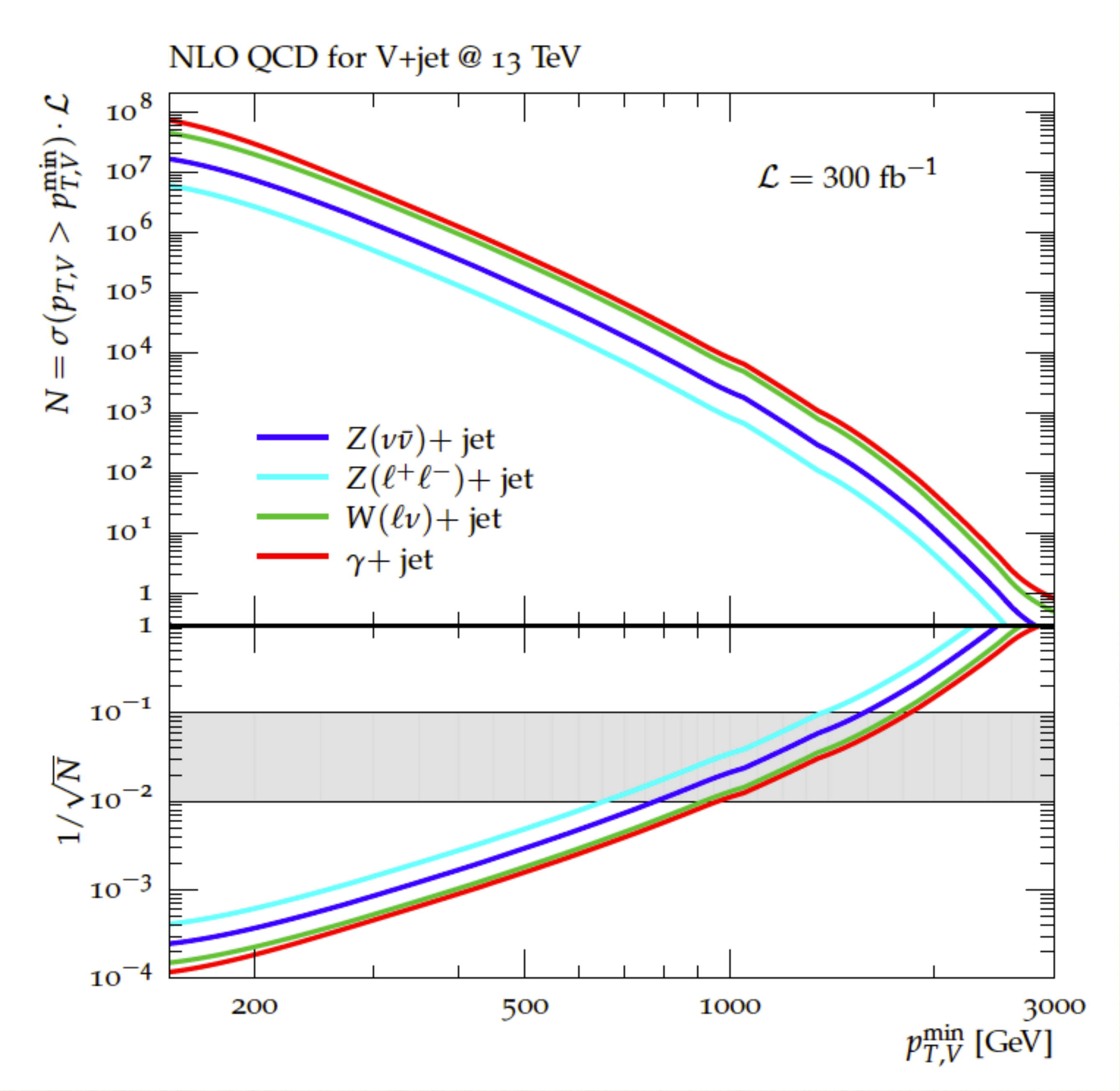
- Direct photon and photon + jet are interesting:-
  - In their own right as tests of the standard model
  - As a proxy for Z+jet processes, to estimate SM sources of jets+missing energy, especially at large jet p_T
  - As a probe of parton distributions, especially the gluon.



Production rate vs minimum p_T

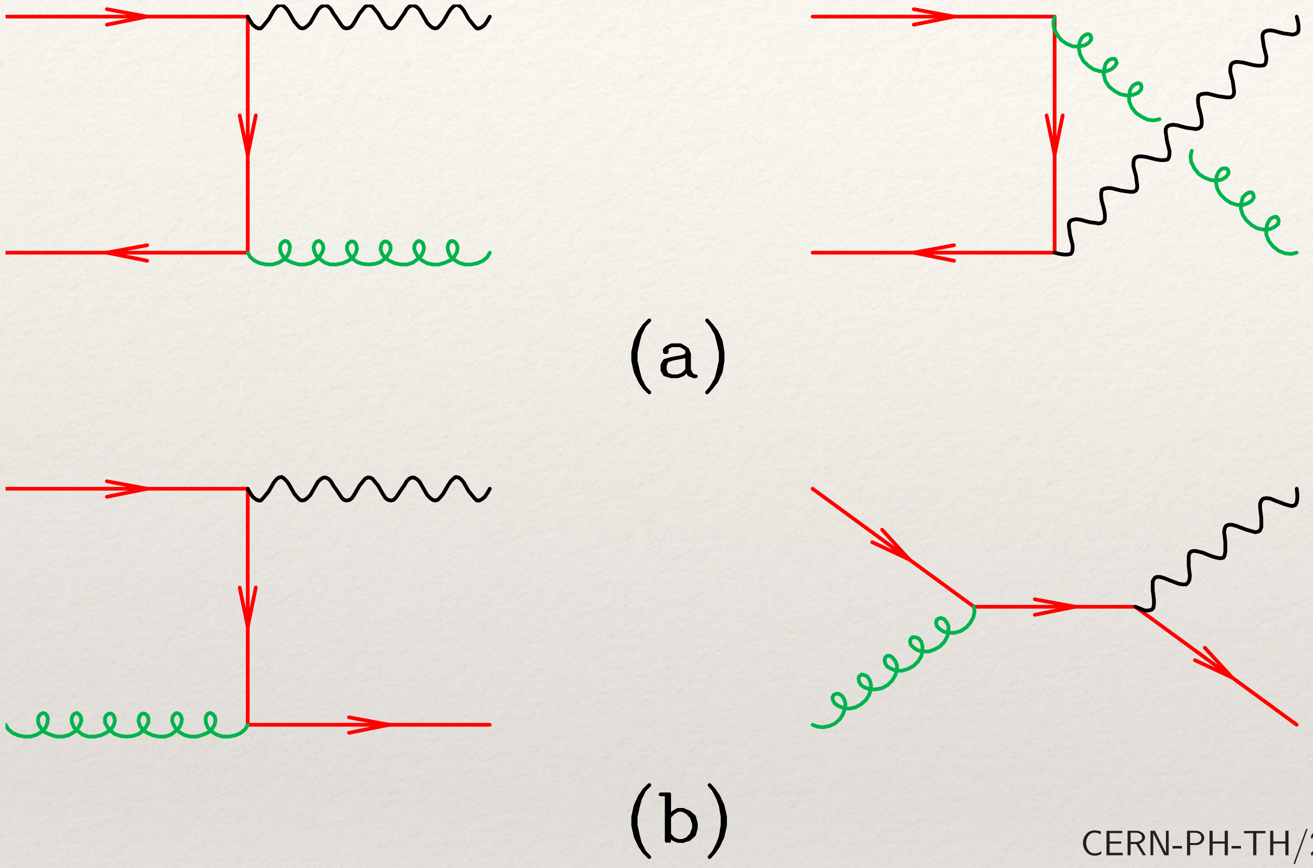
- Photon production is used to determine the shape of the MET spectrum (in the high energy region where the Z->$\mu^+\mu^-$ data runs out).

- Lower panel shows the expected statistical uncertainty in the data, which sets the goal for the theoretical uncertainty we should aim for at each p_T



Lindert et al., 1705.04664

Direct Photon and Parton PDFs



CERN-PH-TH/2013-006

The photon (+jet) process depends at LO on the gluon PDF. Additionally the process has high statistics and good phase space control (with control of photon p_T and rapidities), makes it a candidate for PDF fitting.

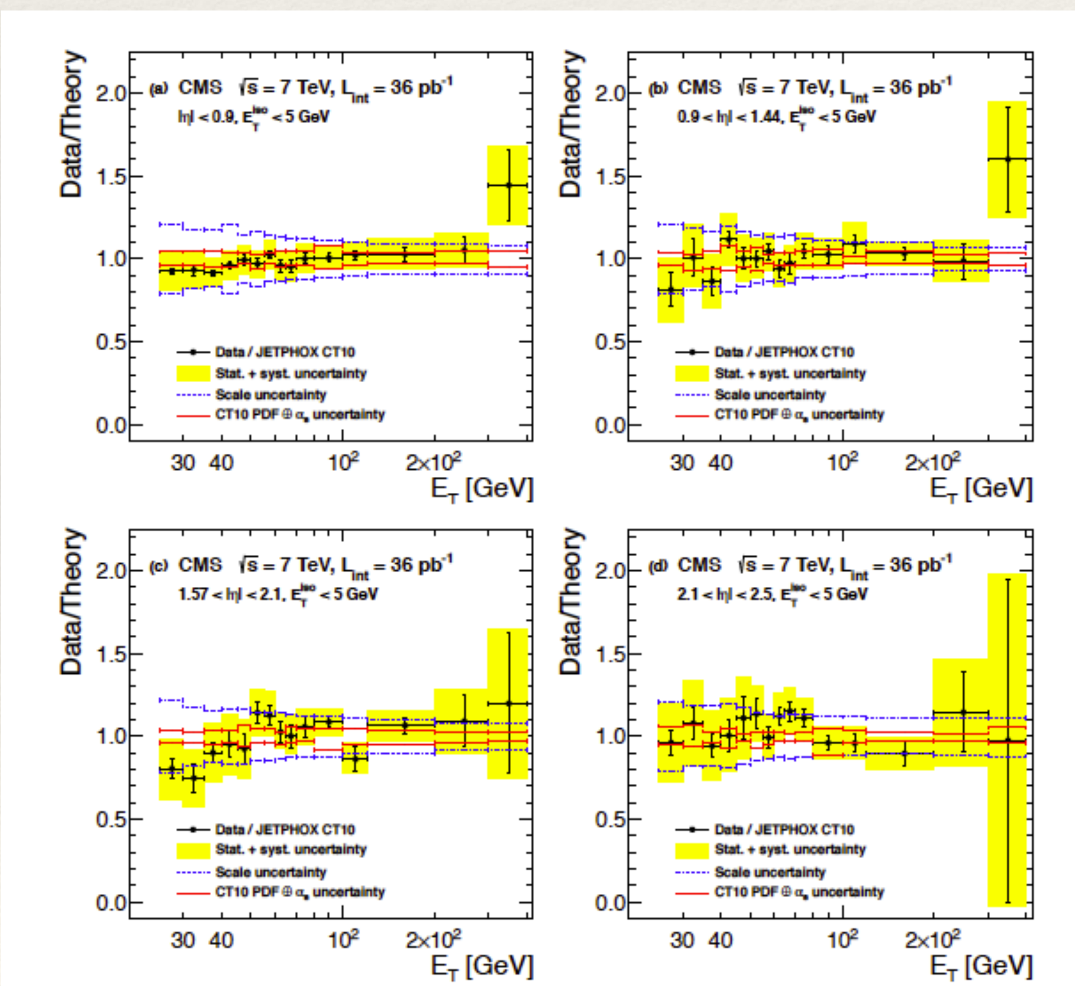
Sensitivity of the LHC isolated-γ+jet data to the parton distribution functions of the proton

1212.5511

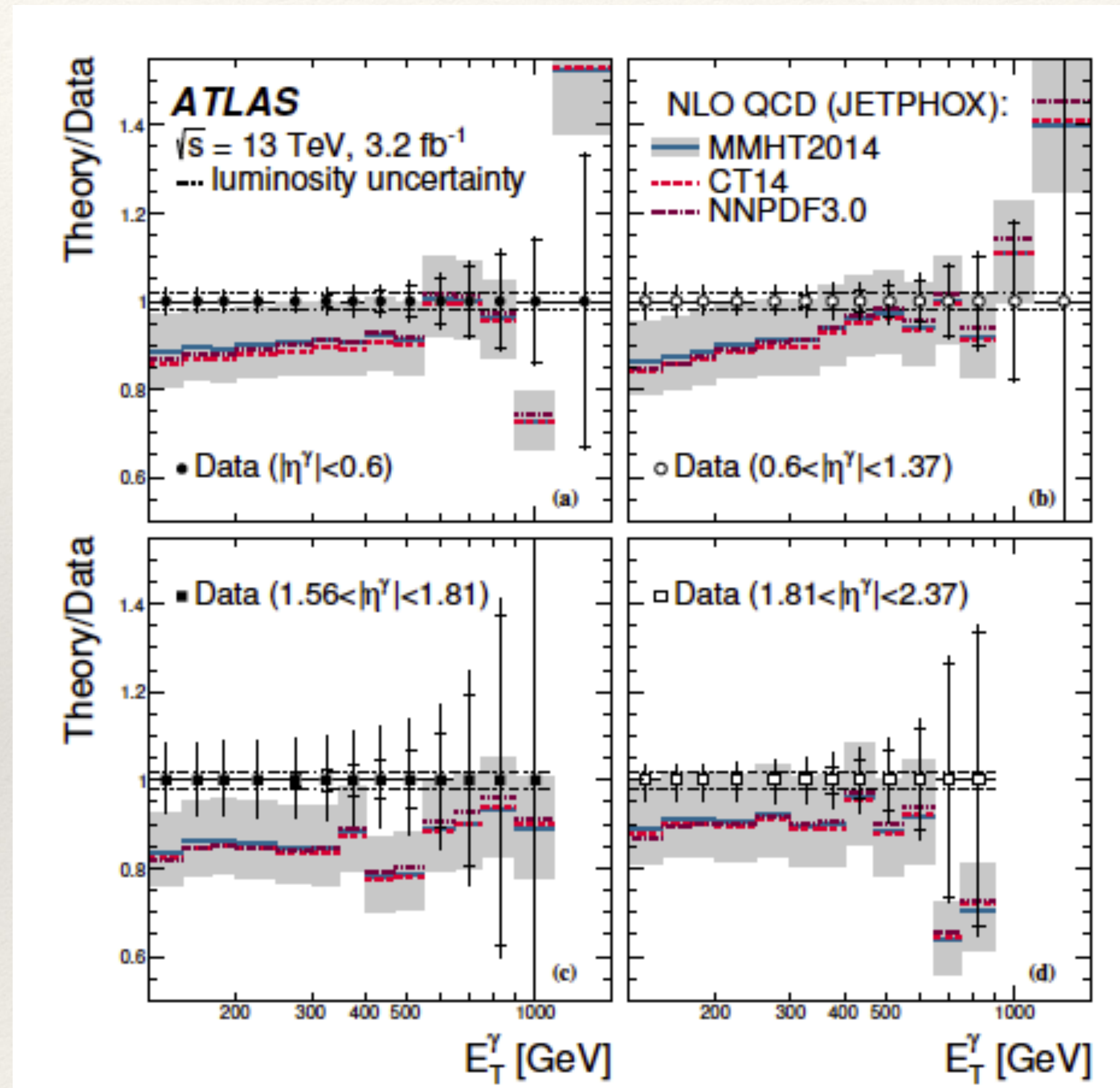
L. Carminati[1,2], G. Costa[1], D. d'Enterria[3], I. Koletsou[1],
G. Marchiori[4], J. Rojo[5], M. Stockton[6], F. Tartarelli[1]

Comparisons of data with NLO+PS

- In most bins the experimental accuracy is higher than the theoretical error
- At NLO theoretical error is dominated by scale variation.



CMS Measurements at 7 TeV, 1108.2044



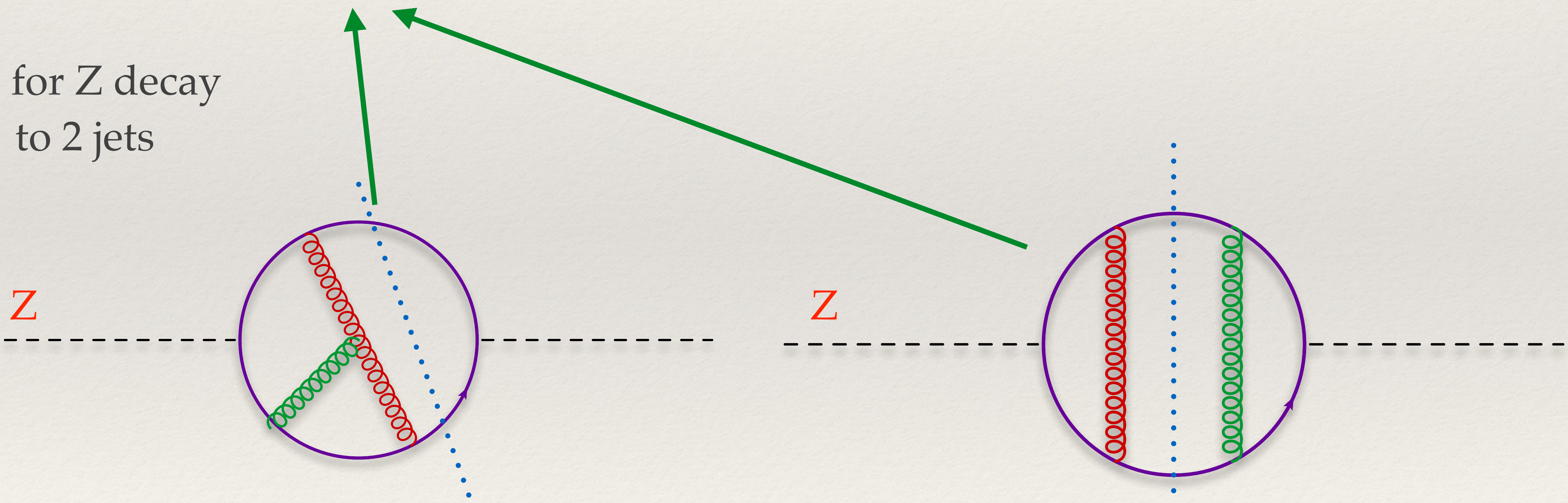
Atlas Measurements at 7,8 and 13 TeV, 1311.1440,1605,03495,1701.06882

Ingredients of a NNLO calculation

At NNLO we have to include three final state phase spaces of different dimensionality, (VV,RV,RR)

$$\sigma_{NNLO} = \int |\mathcal{M}_{VV}|^2 d^m\Phi + \int |\mathcal{M}_{RV}|^2 d^{m+1}\Phi + \int |\mathcal{M}_{RR}|^2 d^{m+2}\Phi$$

eg. for Z decay
to 2 jets



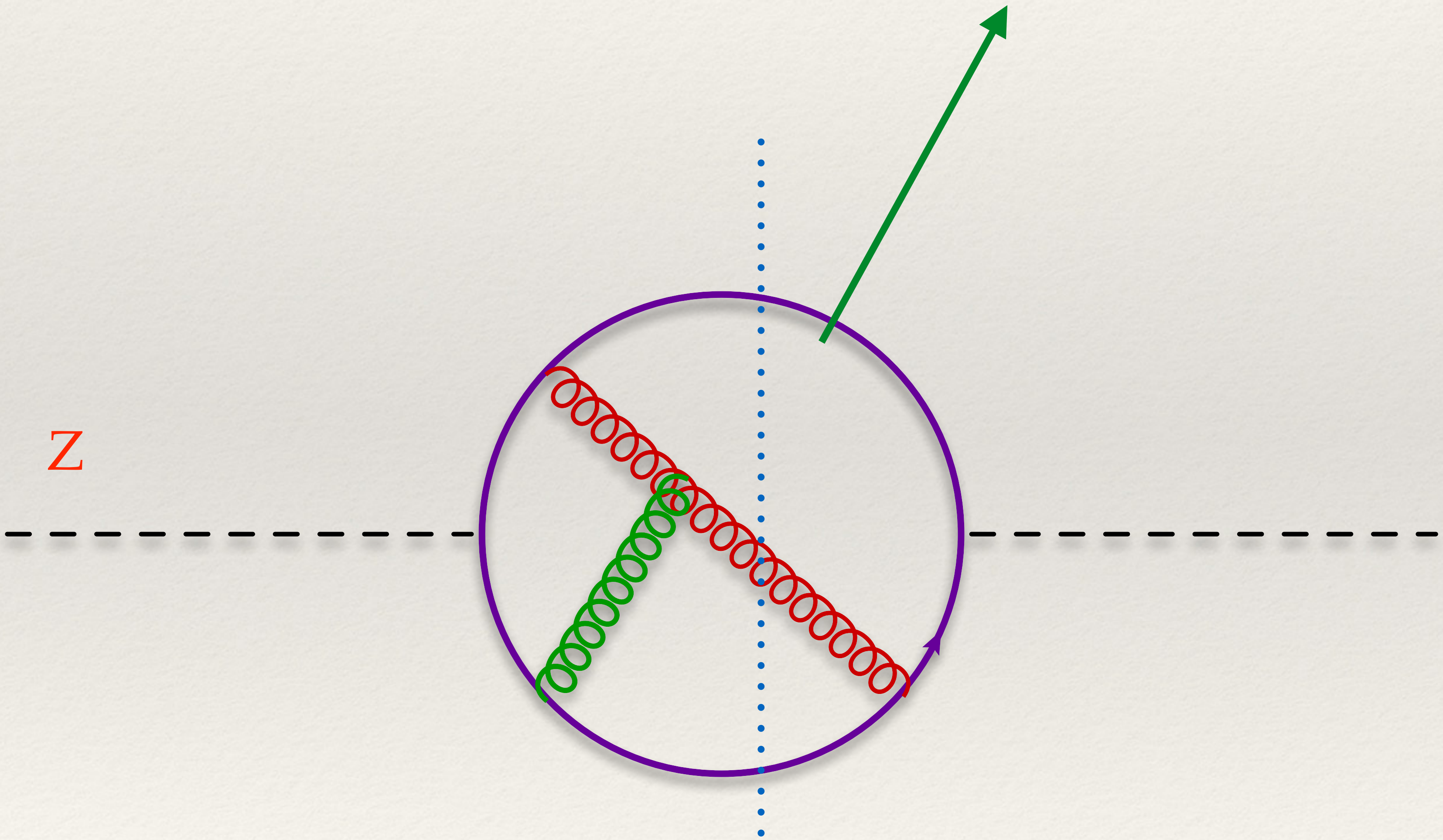
Two-loop double virtual

One-loop squared double virtual

Ingredients of a NNLO calculation

At NNLO we have three types of final state phase spaces

$$\sigma_{NNLO} = \int |\mathcal{M}_{VV}|^2 d^m\Phi + \int |\mathcal{M}_{RV}|^2 d^{m+1}\Phi + \int |\mathcal{M}_{RR}|^2 d^{m+2}\Phi$$

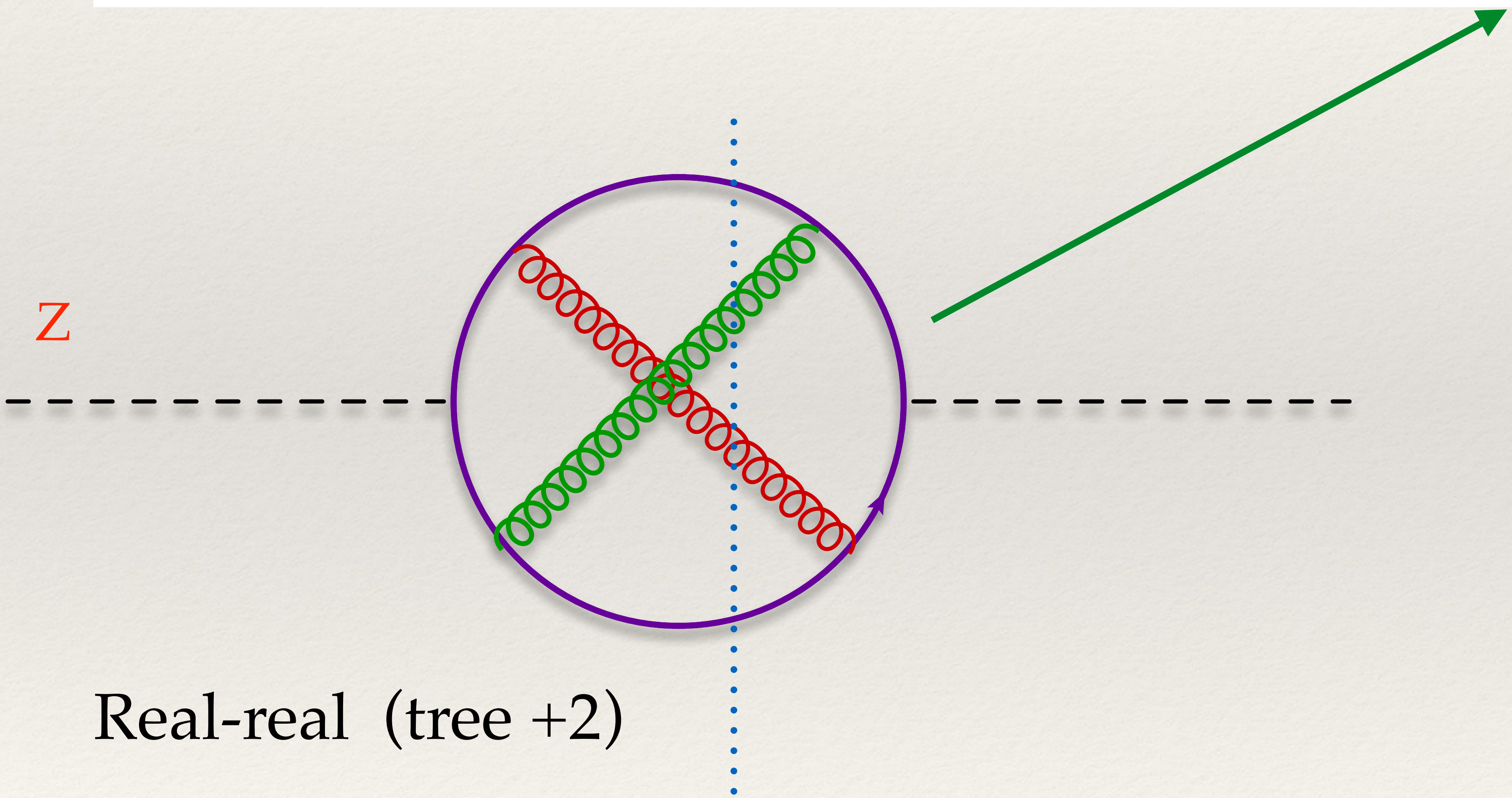


Real-virtual (one-loop +1) x (real + 1)

Ingredients of a NNLO calculation

At NNLO we have three types of final state phase spaces

$$\sigma_{NNLO} = \int |\mathcal{M}_{VV}|^2 d^m\Phi + \int |\mathcal{M}_{RV}|^2 d^{m+1}\Phi + \int |\mathcal{M}_{RR}|^2 d^{m+2}\Phi$$

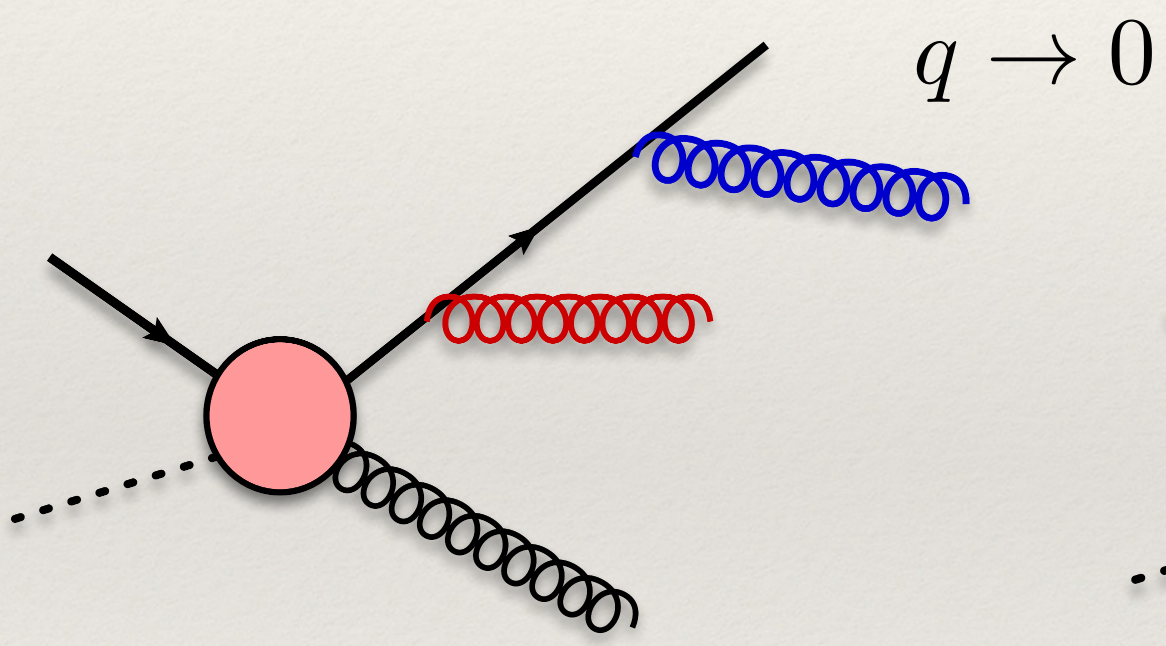


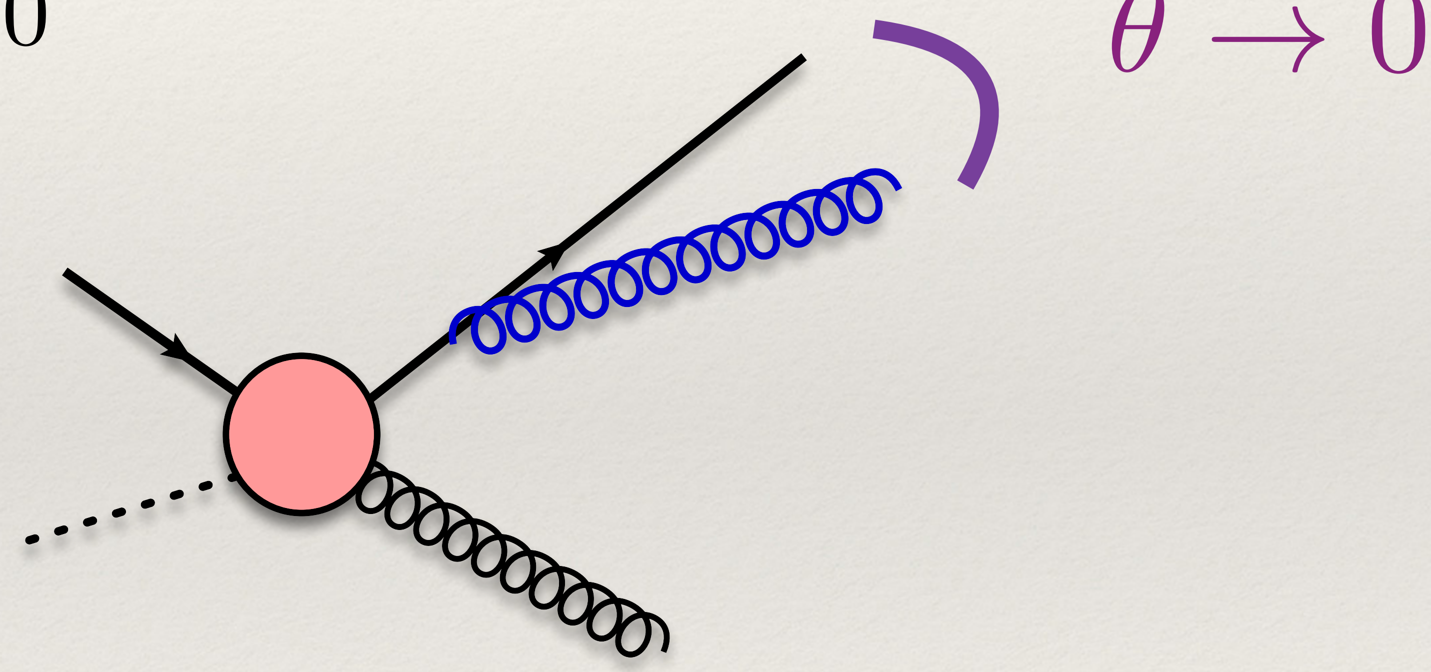
Real-real (tree +2)

Divergences

All of our contributions (VV, RV, RR) are divergent in the soft and collinear regions.

There are two types of singularities in real matrix elements,





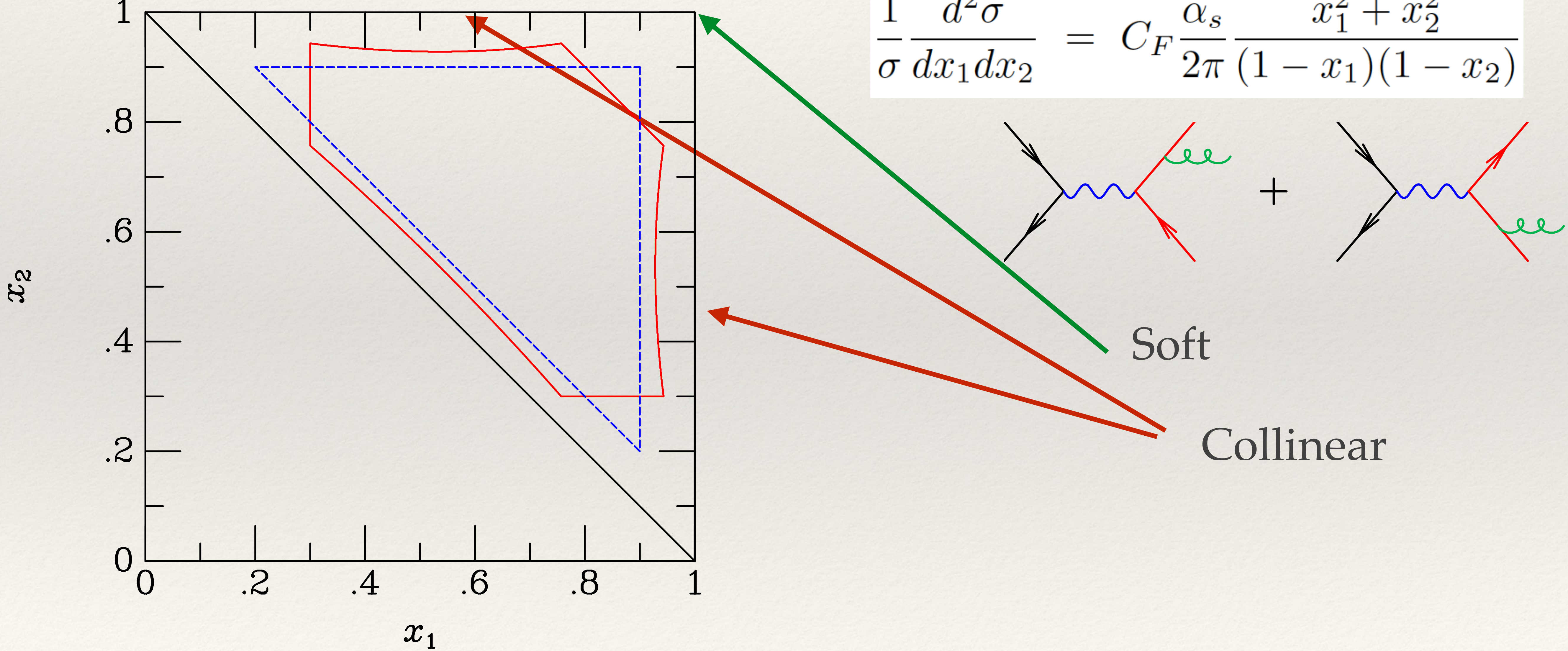
Soft (particle momenta vanishes)

Collinear (angle between two massless particles vanishes)

Slicing methods

A simple way of dealing with the IR singularities is phase space slicing (eg. Sterman-Weinberg 1977)

$$\frac{1}{\sigma}\frac{d^2\sigma}{dx_1 dx_2} = C_F \frac{\alpha_s}{2\pi}\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$



Colour neutral final states

For color neutral final states the transverse momentum of the recoiling EW particles determines the double and singly unresolved regions of phase space. (Catani Grazzini 07)

$$\sigma_{NNLO} = \int dq_T \frac{d\sigma}{dq_T}\theta(q_T^{cut} - q_T) + \int dq_T \frac{d\sigma}{dq_T}\theta(q_T - q_T^{cut})$$

Obtained from the Collins-Soper-Sterman factorization theorem for small q_T

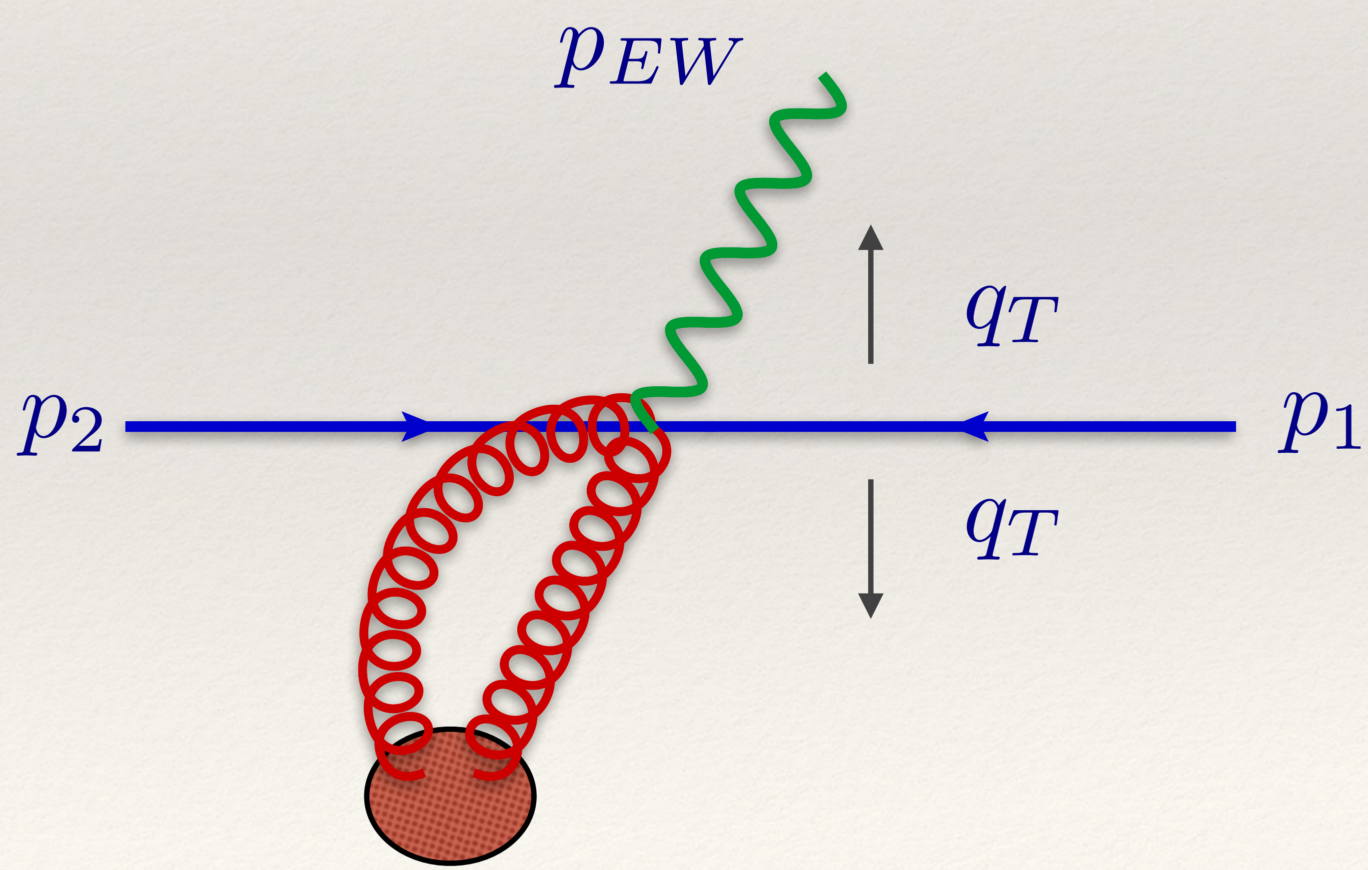
This is an NLO cross section for one additional parton extrapolated to q_T^{cut}

Q_T slicing

For color neutral final states the transverse momentum of the recoiling EW particles determines the double and singly unresolved regions of phase space. (Catani Grazzini hep-ph/0703012)

$$\sigma_{NNLO} = \int dq_T \frac{d\sigma}{dq_T} \theta(q_T^{cut} - q_T) + \int dq_T \frac{d\sigma}{dq_T} \theta(q_T - q_T^{cut})$$

This method fails for processes with colored partons in the final state , so we have consider slicing using the global event-shape jet-veto parameter, called N-jettiness.



N-jettiness

N-jettiness is an global event shape variable, designed to veto final state jets (Stewart, Tackmann, Waalewijn)

$$\mathcal{T}_N(\Phi_M) = \sum_{k=1}^{M} \min_i \left\{ \frac{2q_i \cdot p_k}{Q_i} \right\}$$

N=Number of final state jets

M=Number of final state partons

Momentum of final state jets and two beam momenta

A hard scale (e.g. Energy of jets)

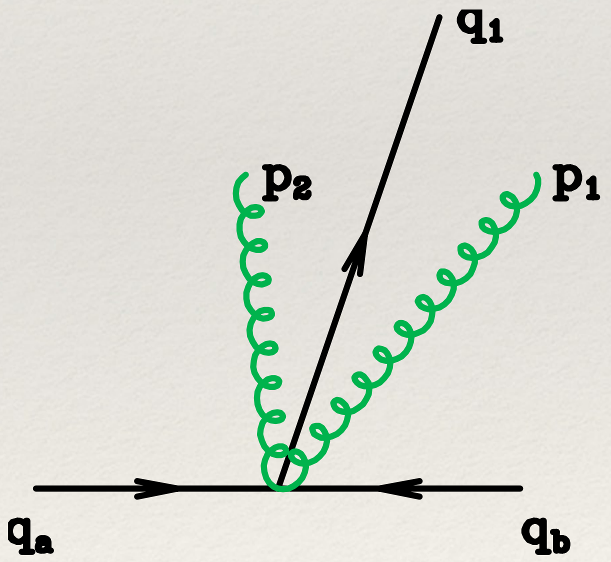
All final state partons

Zero and one jet cases, τ_0, τ_1

- Here we are concerned mainly with τ_0, τ_1.
- Direction q_1 defined by a jet algorithm.

$$\tau_0 = \sum_{k=1}^{M} \min\left\{ \frac{2q_a.p_k}{Q_a}, \frac{2q_b.p_k}{Q_b} \right\}$$

$$\tau_1 = \sum_{k=1}^{M} \min\left\{ \frac{2q_a.p_k}{Q_a}, \frac{2q_b.p_k}{Q_b}, \frac{2q_1.p_k}{Q_1} \right\}$$



N-jettinesss slicing

The method can be used as a regularization scheme, (Boughezal et al, 1505.03893, Gaunt et al, 1505.04794) using N-jettiness to separate the doubly and singly unresolved regions.

$$\sigma_{NNLO} = \int d\Phi_N |\mathcal{M}_N|^2 + \int d\Phi_{N+1} |\mathcal{M}_{N+1}|^2 \theta_N^<$$

$$+ \int d\Phi_{N+2} |\mathcal{M}_{N+2}|^2 \theta_N^< + \int d\Phi_{N+1} |\mathcal{M}_{N+1}|^2 \theta_N^>$$

$$+ \int d\Phi_{N+2} |\mathcal{M}_{N+2}|^2 \theta_N^>$$

(green) = Below the cut (can use factorization theorem)

(red) = Above the cut (can use NLO code)

Below cut region

Factorization theorem valid in the below cut region based on SCET,

(Stewart et al, 1004.2489).

Beam functions, describes radiation collinear *to initial state*

Jet functions, describes radiation collinear to final state jets

$$\sigma(\tau_N < \tau_N^{cut}) = \int H \otimes B \otimes B \otimes S \otimes \left[\prod_n^N J_n\right] + \mathcal{O}(\tau_N^{cut})$$

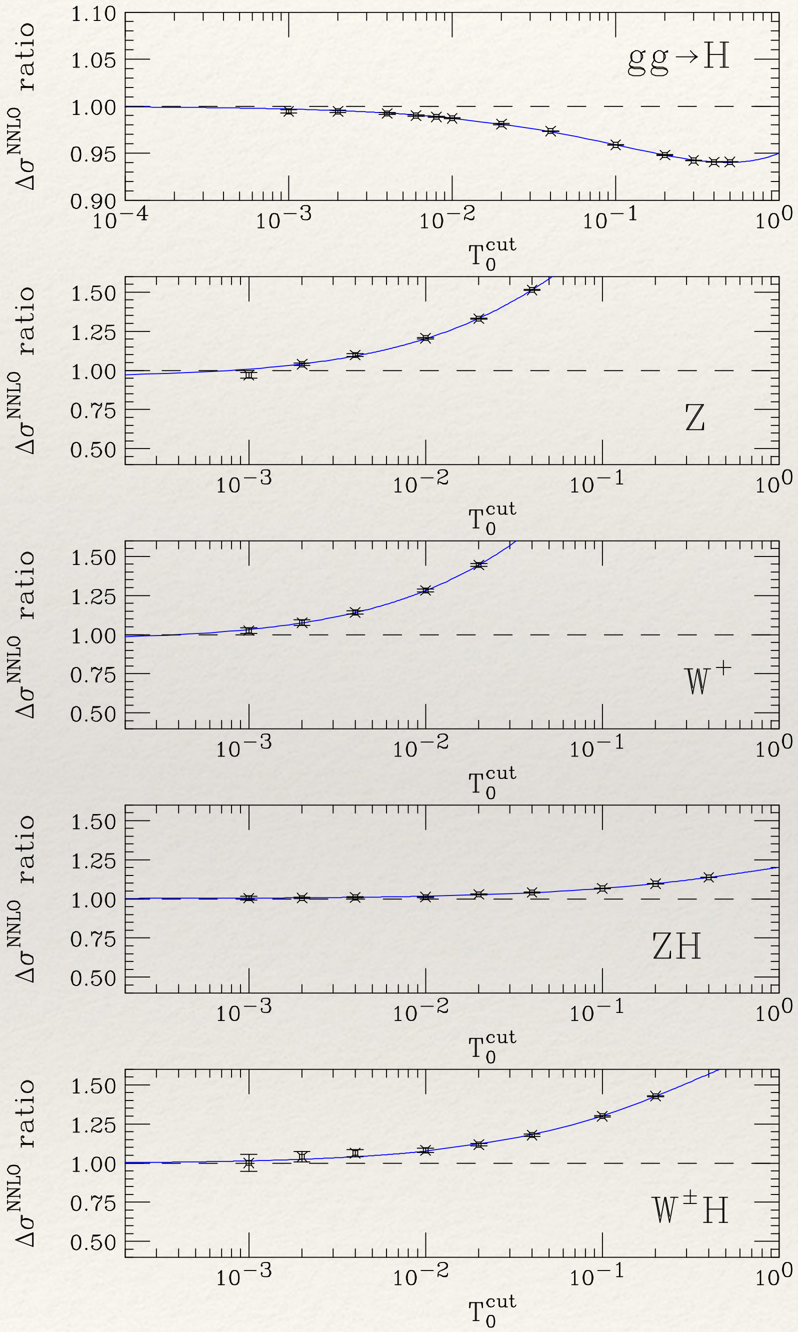
Potential power corrections

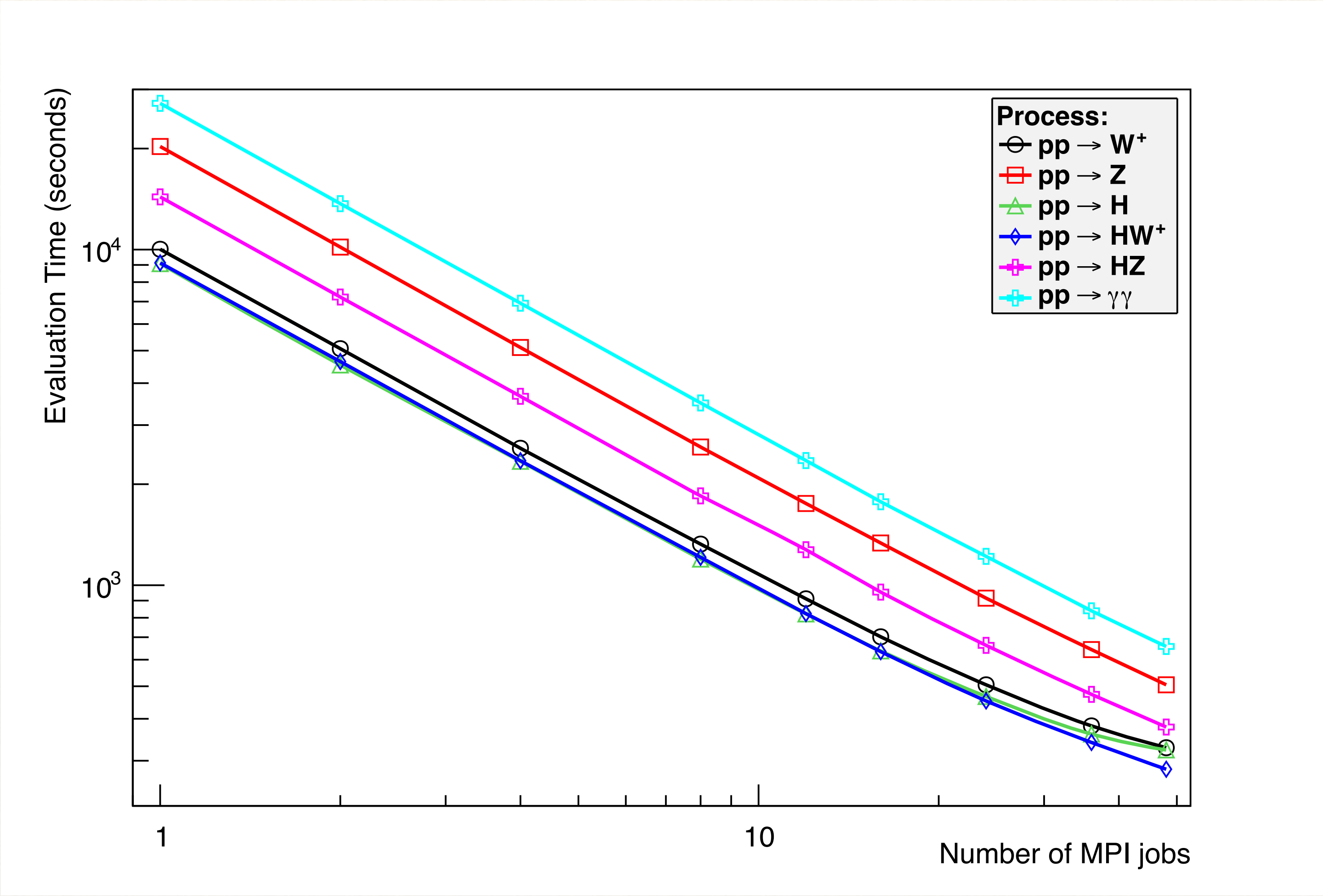
Hard function, includes 2-loop virtual

Soft function, describes soft radiation

- B@NNLO : Gaunt, Stahlhofen, Tackmann (1401.5478,1405.1044)
- S@NNLO : Boughezal, Liu, Petriello (1504.02540)
- J@NNLO : Becher Neubert (hep-ph/0607228), Becher, Bell (1008.1936)

Proof of principle with known colour singlet production processes





Code is public and can be downloaded from mcfm.fnal.gov

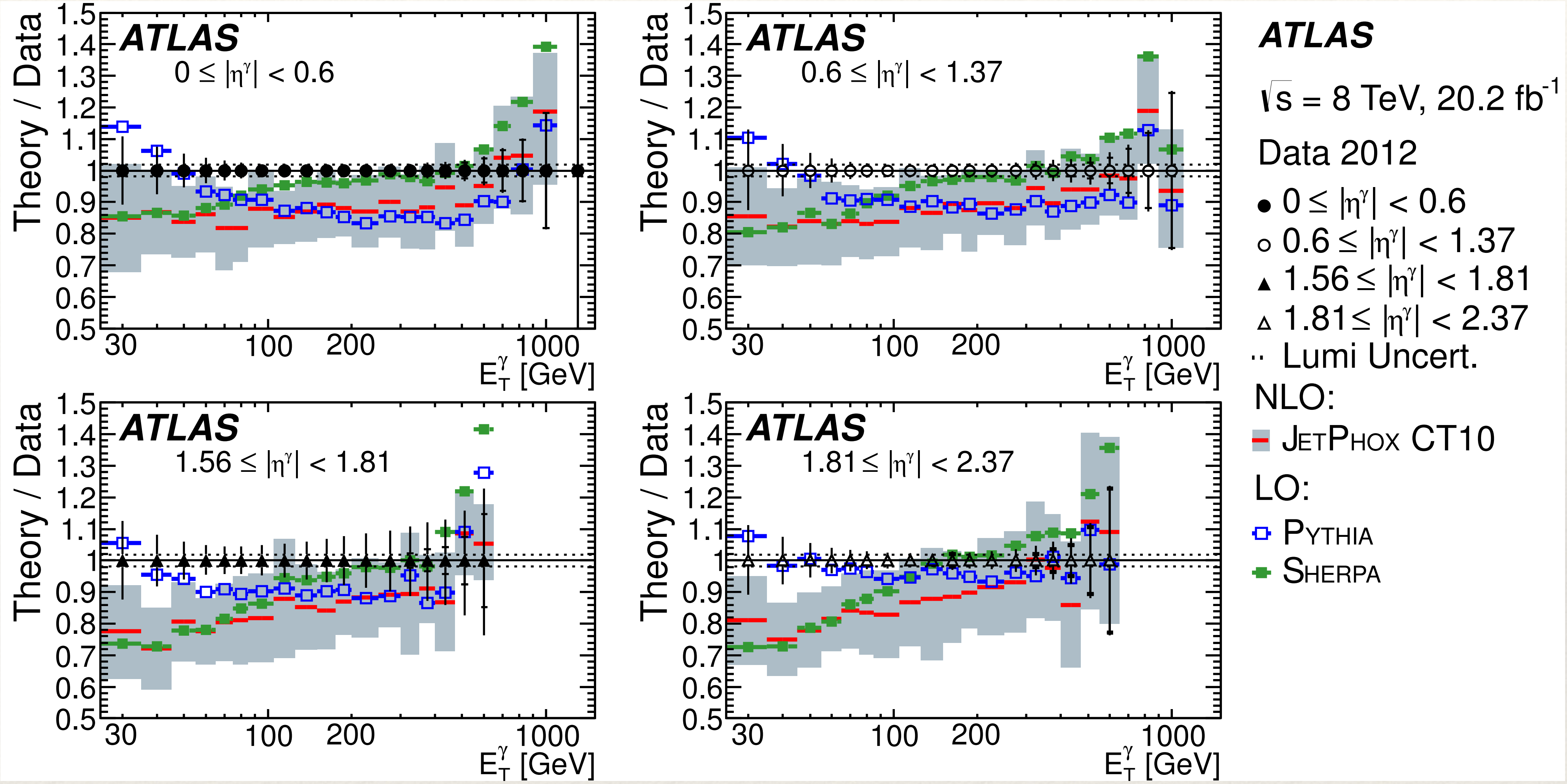
Results can be compared with numerically more inclusive results.

Boughezal et al, 1605.08011

Inclusive photons

- This somewhat more challenging than say, Z production because the existence of a photon at large p_T, mandates a colored parton in the final state.
- So we use a hybrid of τ_0 and τ_1.

Comparison of 8 TeV data with LO & NLO



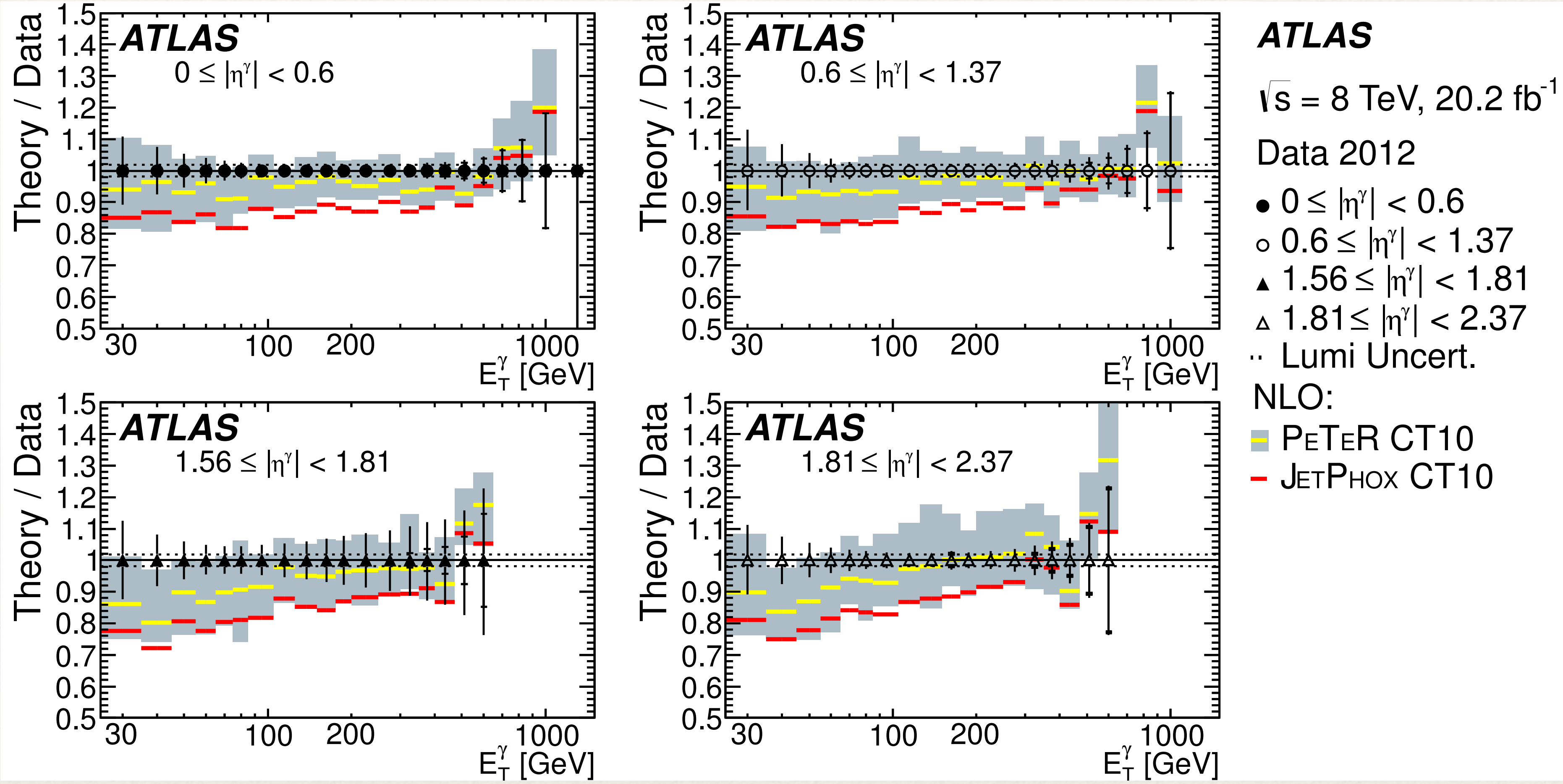
NLO uncertainty is large, but tension with data appears.

ATLAS 1605.03495

Adding threshold resummation+EW

Including threshold resummation + EW corrections improves things slightly, but theoretical errors are still large, compared to ATLAS errors.

PeTeR:Becher, Lorentzen, Schwartz,1206.6115

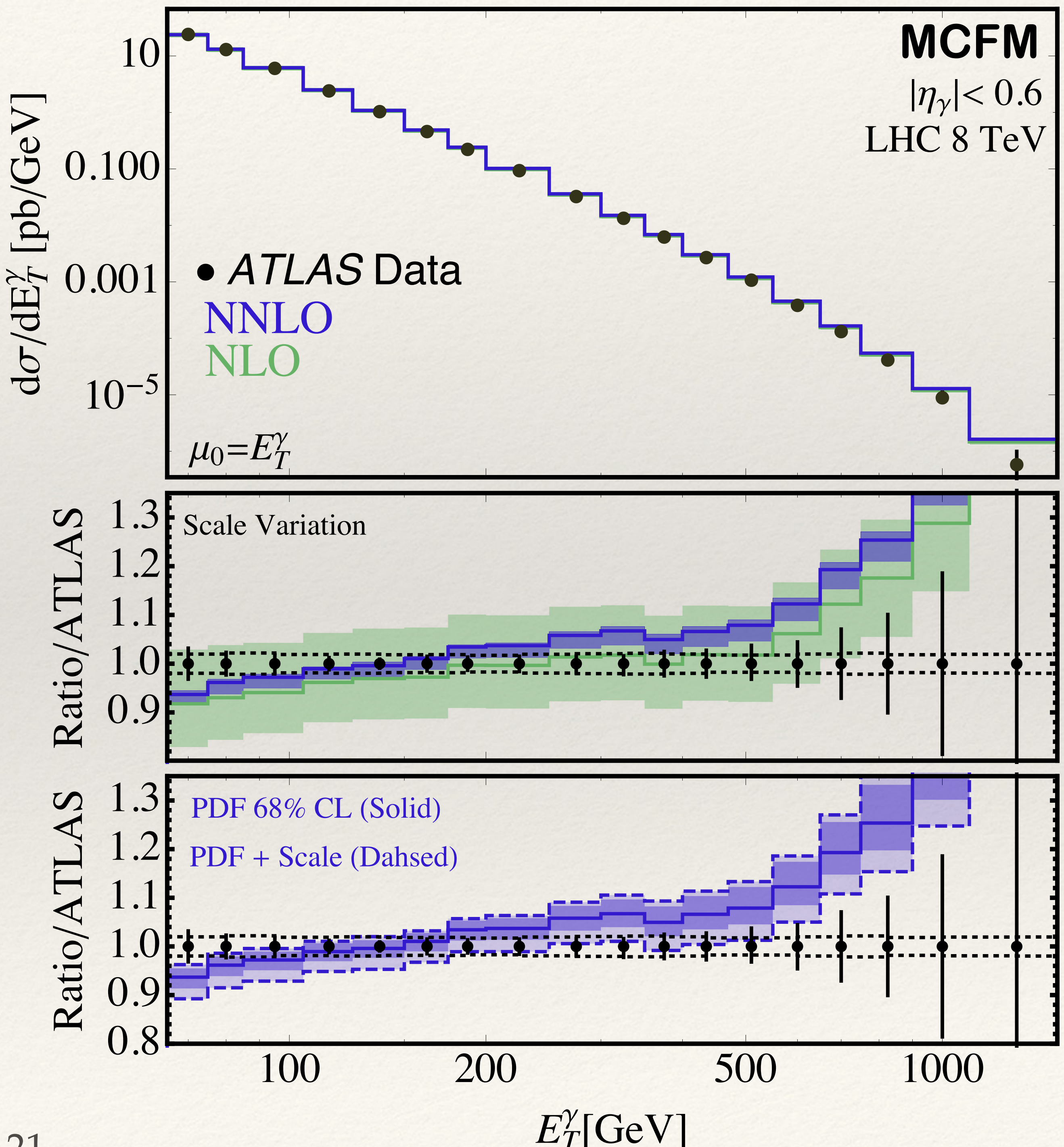


$$\alpha_{PETER} = \frac{1}{127.9}$$

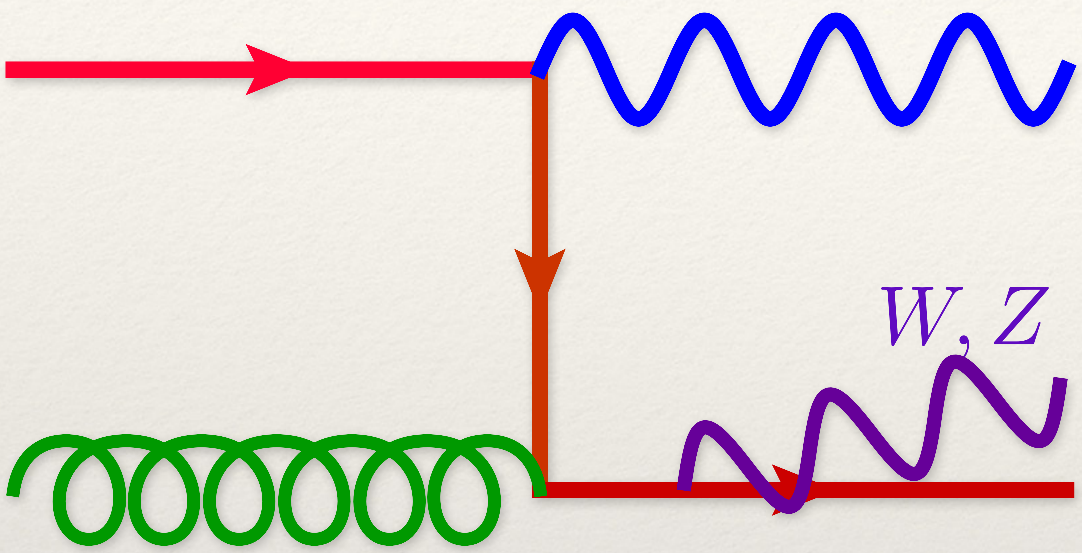
Warning: $$\alpha_{JETPHOX} = \frac{1}{137}$$

Comparison of data with MCFM

- Comparison at NLO and NNLO.
- With larger alpha NLO does a much better job than JETPHOX.
- Scale variation at NNLO is now comparable to data error.
- However at NNLO the shape is not so well described, especially at the highest pT's.



Electroweak effects

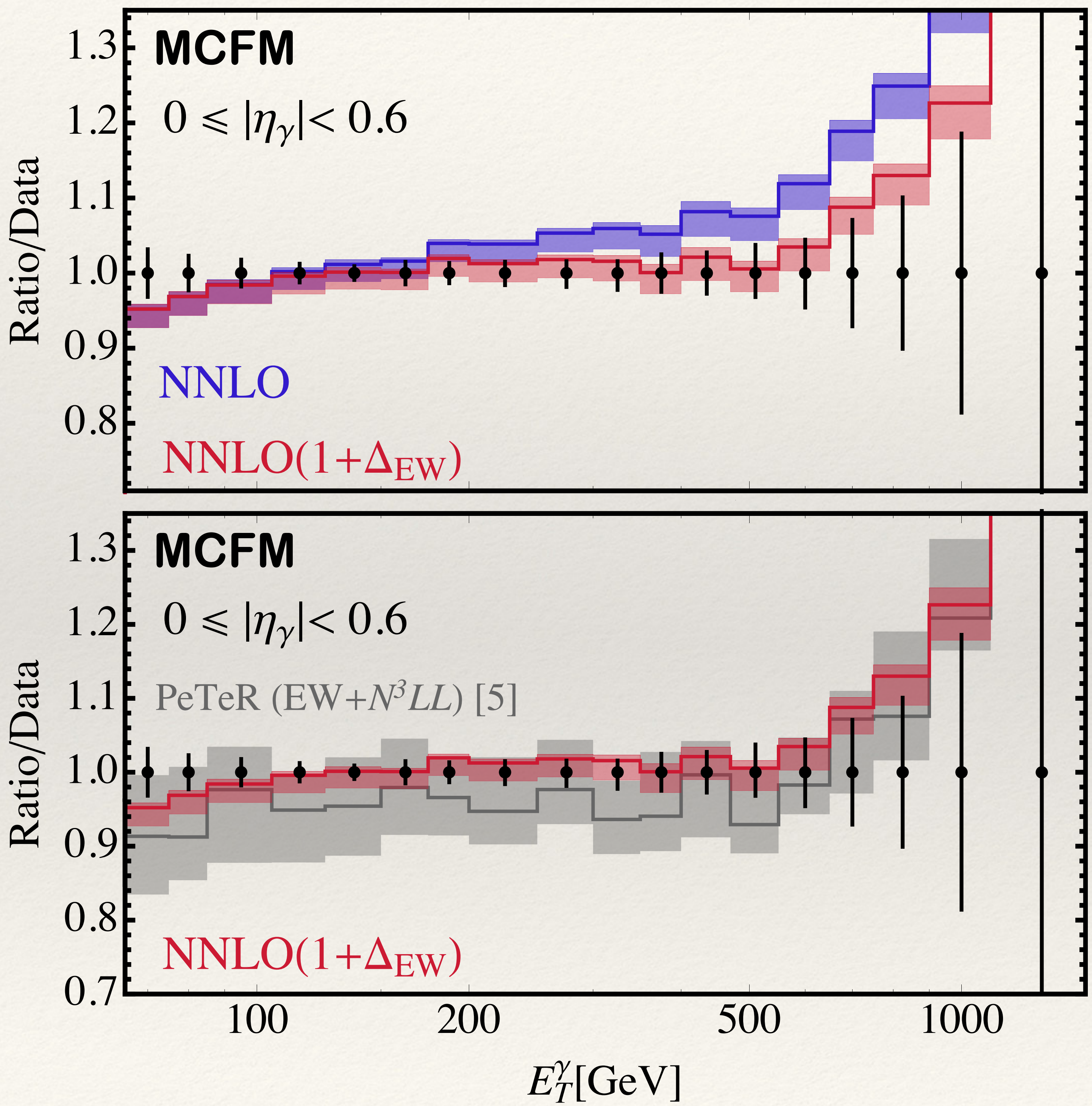


If the scale of the process is > 1 TeV, then EW effects should be important.

We take the parameterization for the photon p_T spectrum of the LL Sudakov, EW corrections presented by Kuhn, Kulesza, Pozzorini, and Schulze 05′

This allows us to do a fair comparison to PeTeR, which includes the same EW resummation.

MCFM+EW vs PeTeR

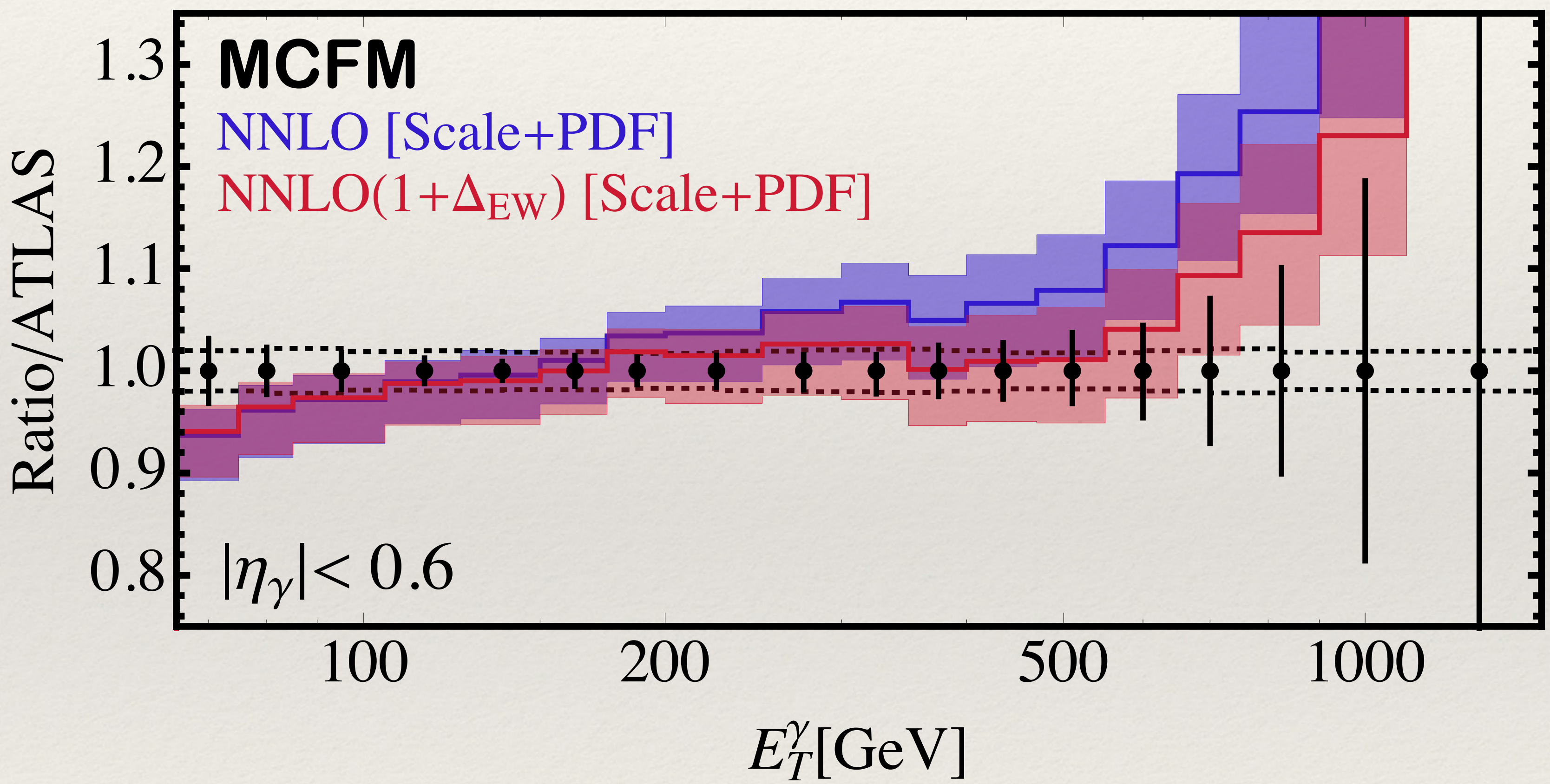


NNLO and EW together do a better job of describing the data

The estimate of the theoretical error is now comparable to experiment
and better than that obtained with N^3LL.

PDF errors

- NNLO+EW is in good agreement with the data



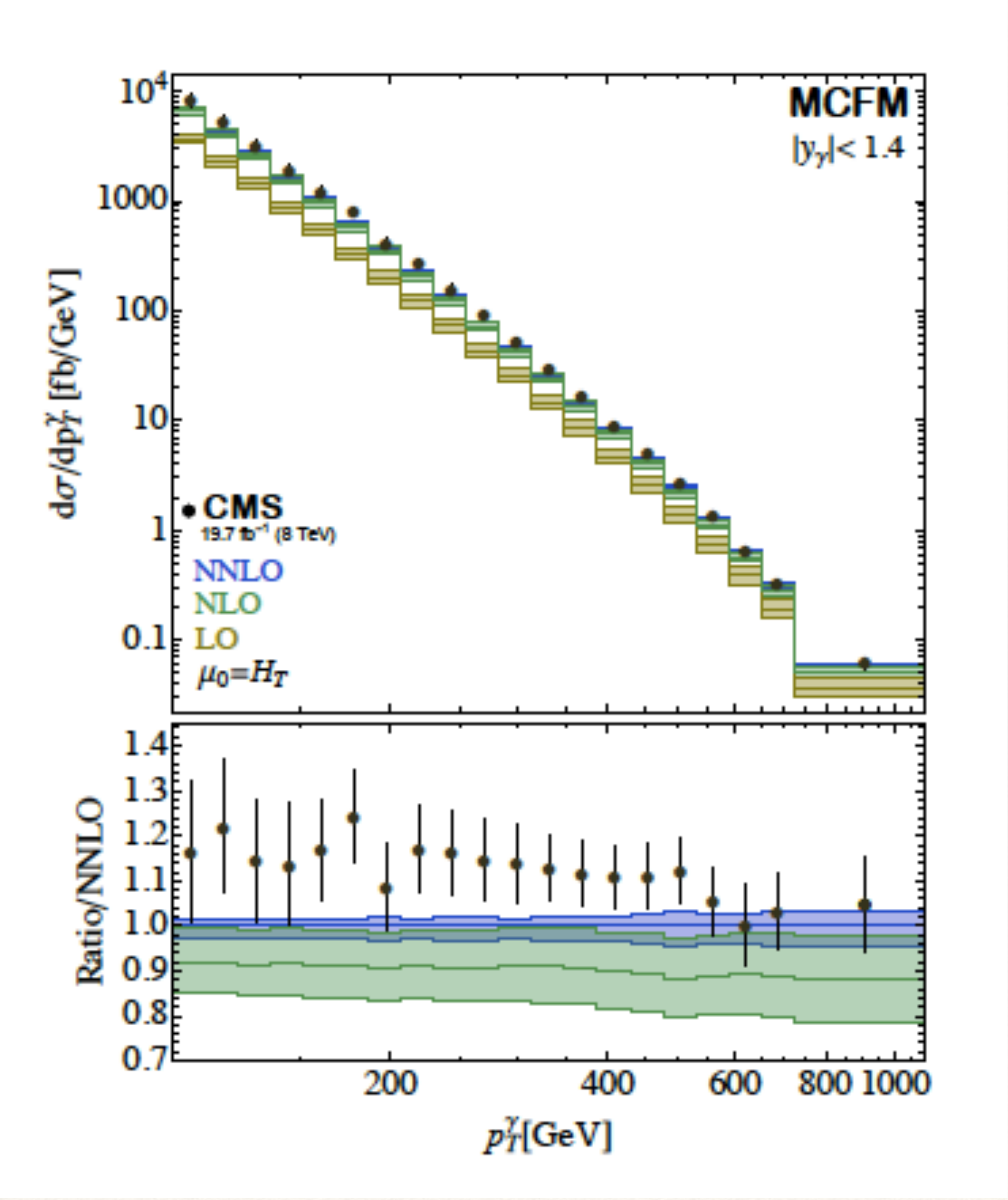
- the large PDF errors highlight how useful this channel will be to constrain PDFs at LHC

"Driving miss data"

- The aim of this work is to investigate the role of γ+jet data as a proxy for Z+jet, to estimate rates for MET+Jet, especially at large pT
- We first investigate agreement of theory with γ+jet data
- Ratio (γ+2j)/(γ+j)
- And then finally, the ratio (l^+l^-+j)/(γ+j)

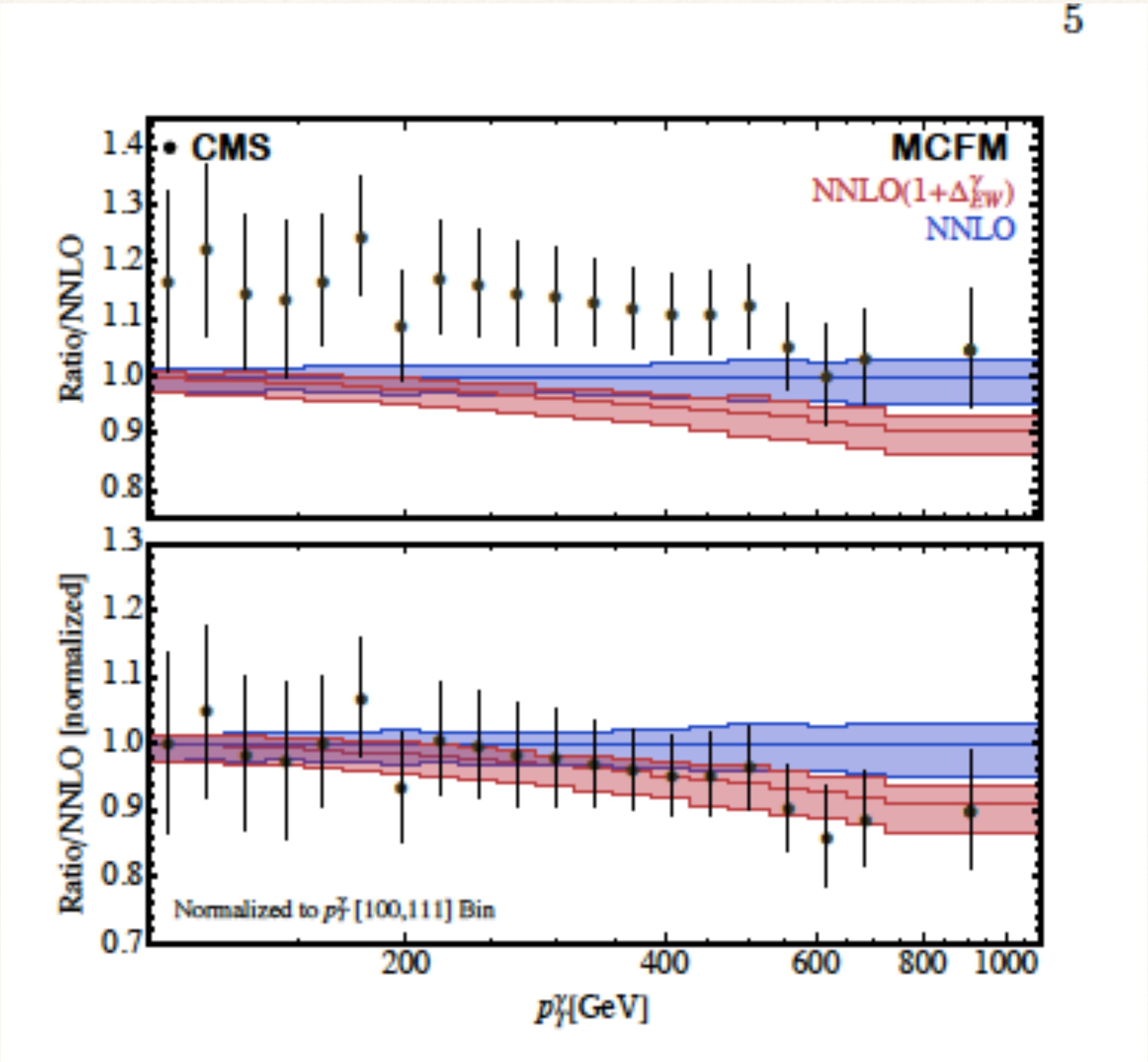
γ+jet data

- Comparison to CMS data
  1505.06520
- small pt dependence in NNLO/NLO K-factor
- Scale variation of order 2-3% at NNLO, vs 8-10% at NLO



γ+jet data +EW effects

- Adding electroweak effects, (Becher et al, 1305.4202,1509.01961) normalization worsens, but shape improves

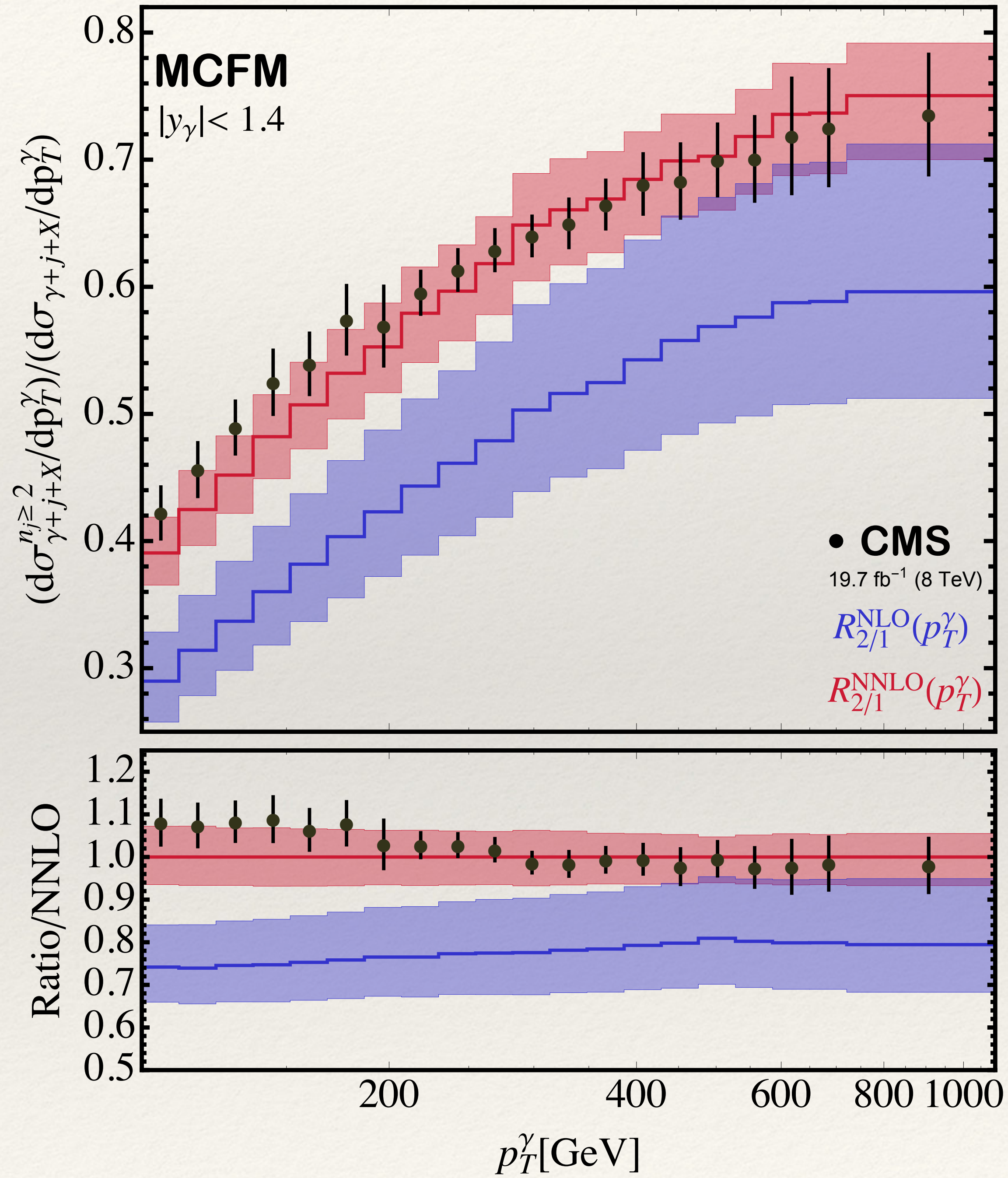


$(\gamma+2j)/(\gamma+j)$

- Using our NLO and NNLO calculation for γ+j we can calculate,

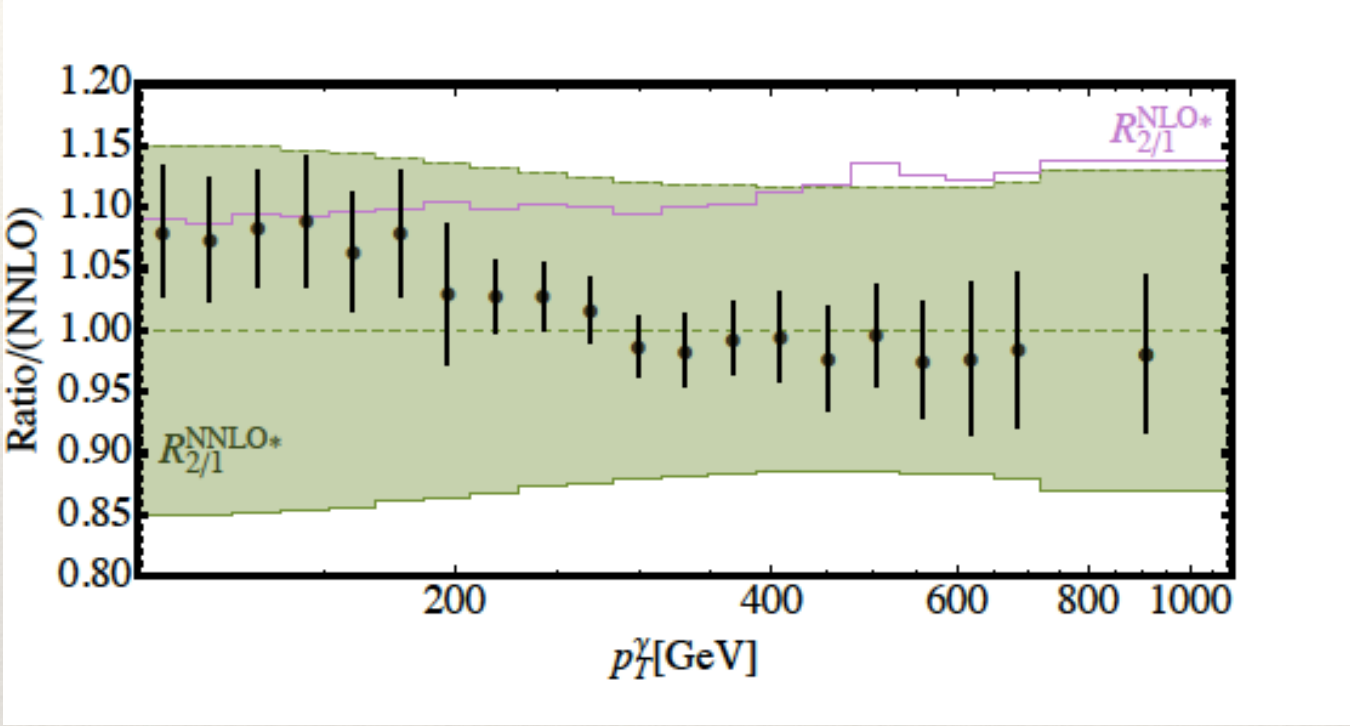
$$R_{2/1}(p_T^\gamma) = \frac{\alpha_s^2 \sum_{k=0}^{n_2} \alpha_s^k \, d\sigma_{\gamma+2j}^{(k)}/dp_T^\gamma}{\alpha_s \sum_{k=0}^{n_1} \alpha_s^k \, d\sigma_{\gamma+j}^{(k)}/dp_T^\gamma} .$$

- for n_1=1(NLO) and n_1=2(NNLO), where n_2=n_1-1



$(\gamma+2j)/(\gamma+j)$

- Introducing an estimate for the uncalculated NNLO term in the two jet rate we find that the expected range encompasses both the NLO prediction and the data.



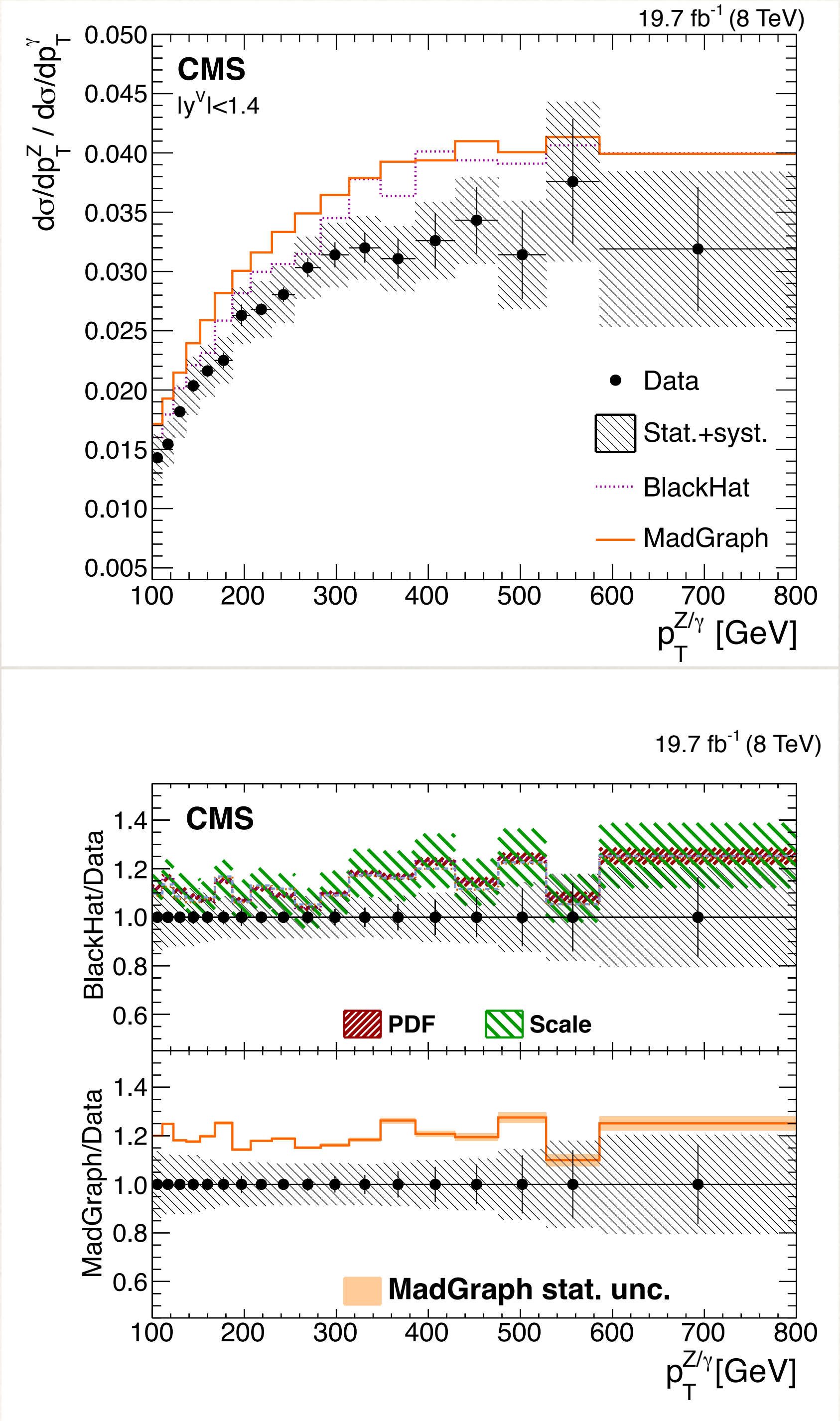
$(l^+l^-+j)/(\gamma+j)$

$$R_{Z/\gamma} = \left(R_u + \frac{R_d - R_u}{1 + \frac{Q_u^2}{Q_d^2}\frac{\langle u \rangle}{\langle d \rangle}} \right) [\mathrm{Br}(Z \to \ell^-\ell^+) \times \mathcal{A}]$$

$$R_q = \frac{v_q^2 + a_q^2}{4 \sin^2\theta_w \cos^2\theta_w Q_q^2}$$

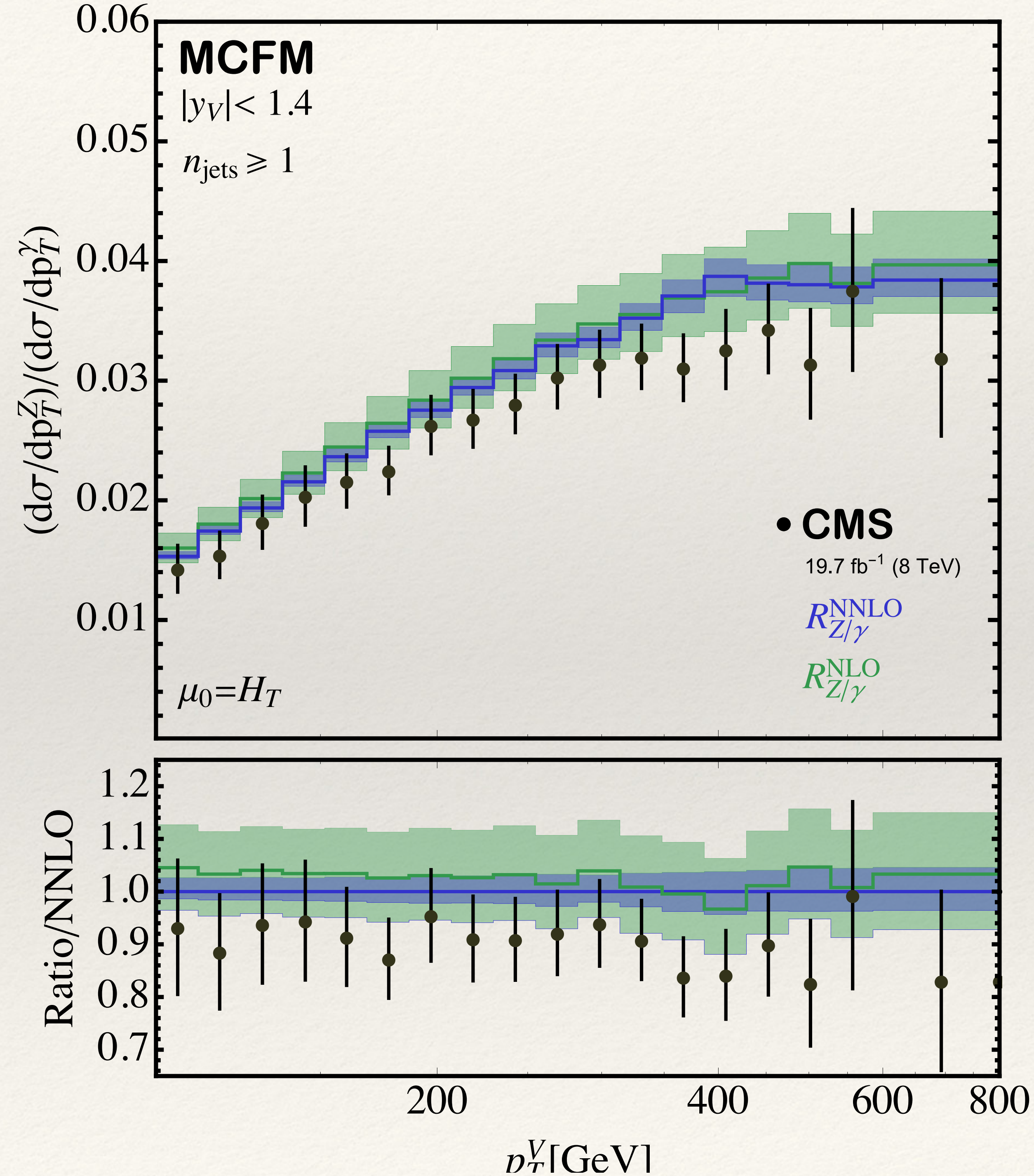
- At high p_T, ($x \to 1$, $\langle d \rangle / \langle u \rangle \to 0$), ratio is expected to reach an asymptotic value proportional to R_u

$$R_u \sim 0.90, \quad R_d \sim 4.7$$



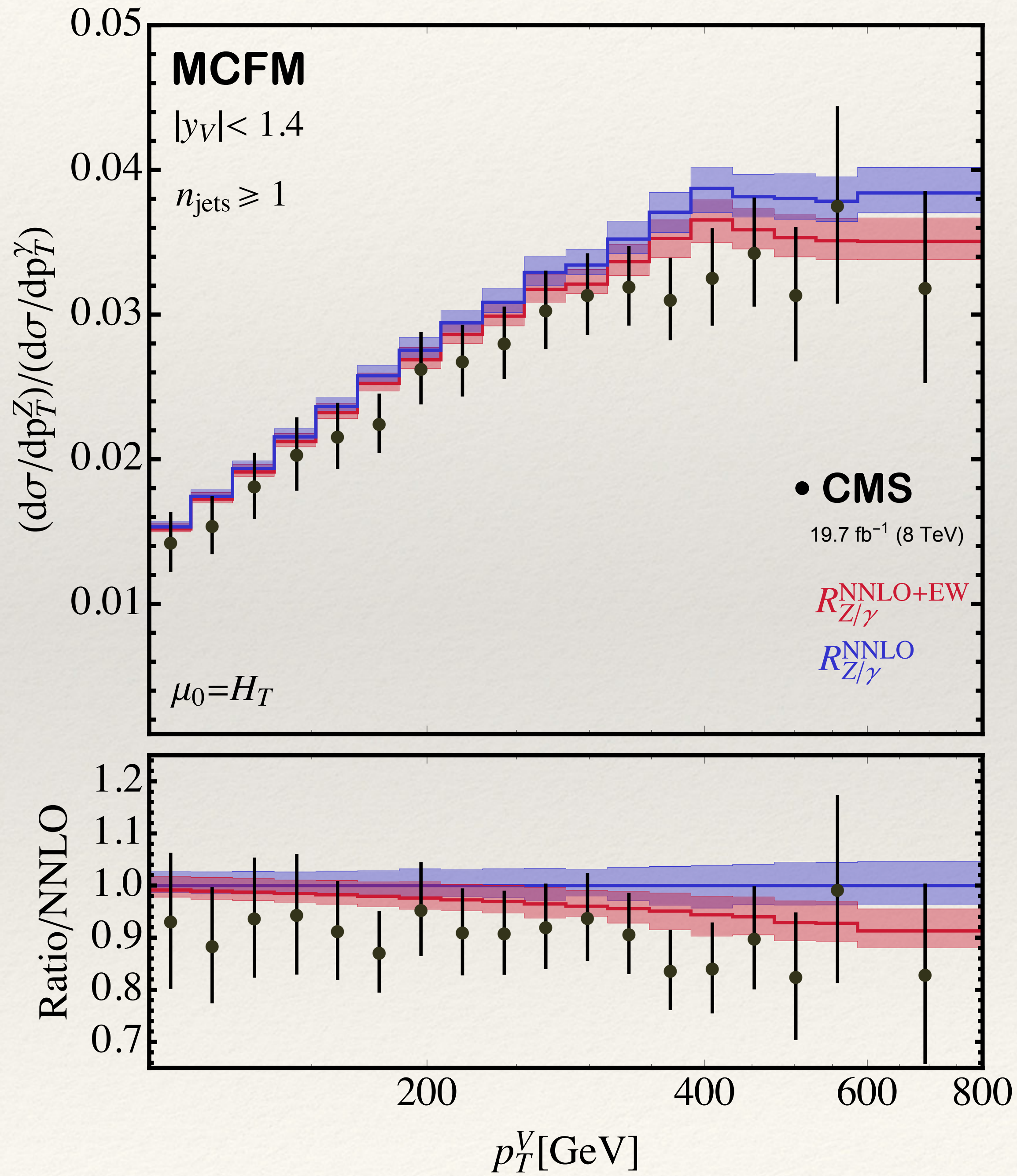
$(l^+l^-+j)/(\gamma+j)$

- NNLO effects reduce the ratio, especially at lower values of p_T



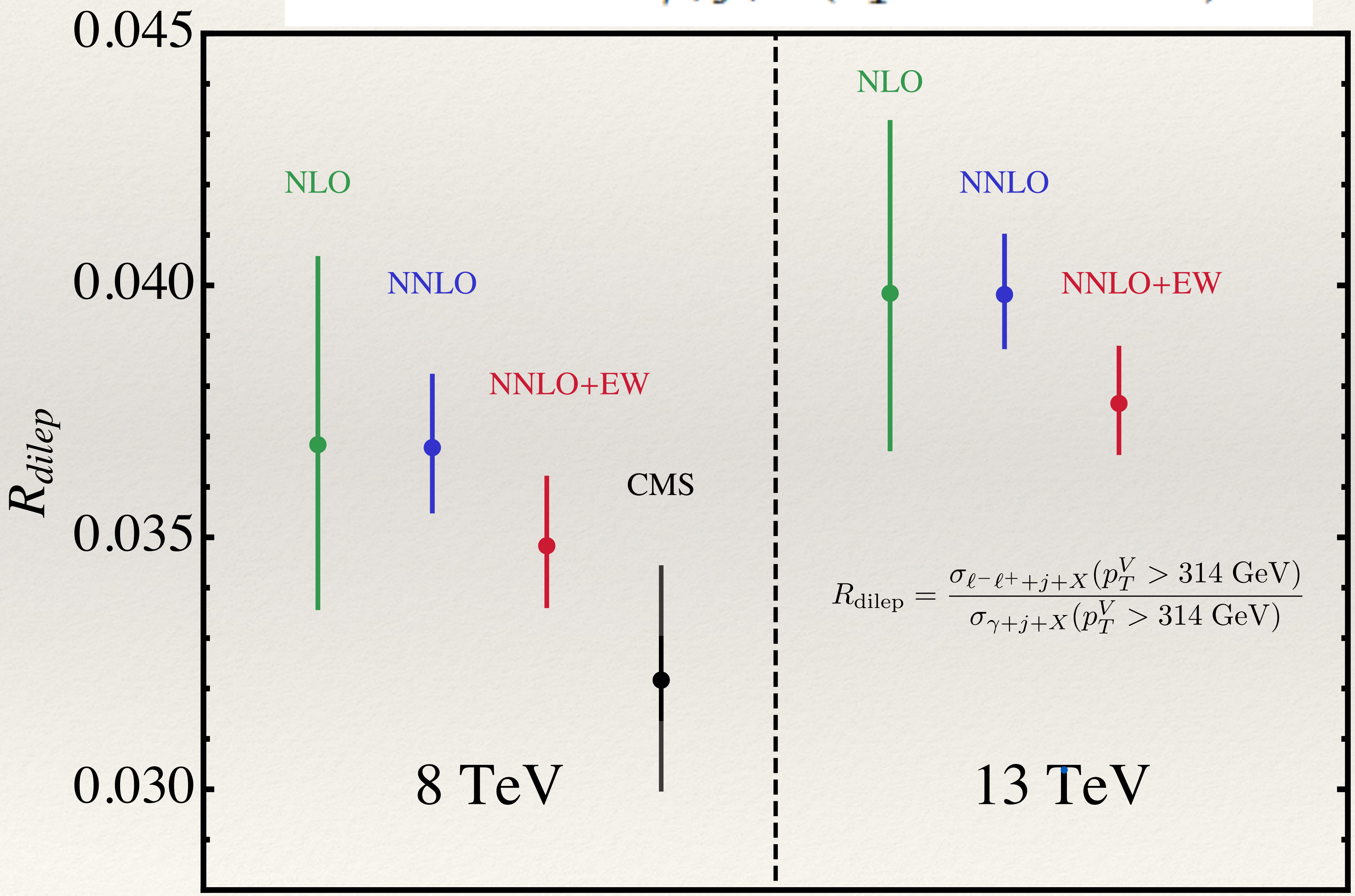
(l+l-+j)/(γ+j)+EW

- Include EW effects
- Since electroweak corrections do not change the Z+j and γ+j processes in the same way, the ratio is modified, by as much as 7% in the high p_T bins



Asymptotic estimate for ratio

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



- Projection for this ratio at 13 TeV

Conclusions

- The precision of NNLO is needed by the data in direct photon studies and allows for interesting phenomenology to be undertaken.
- NNLO QCD is becoming the standard for 2->2 processes at the LHC, albeit with a few caveats.
- I have presented NNLO predictions for photon processes γ +X, γ +j+X and considered the effect of electroweak corrections.
- Also computed the (Z+j)/(γ +j) ratio at NNLO+EW and compared to 8 TeV CMS data. This ratio can be used to extract the MET+jets shape in searches.