NNLO Corrections to Dijet Production

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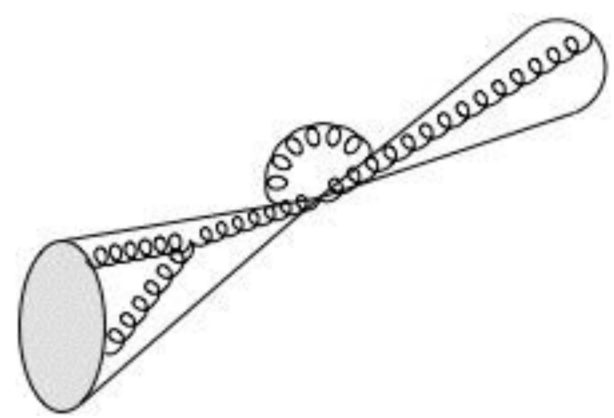
in direct collaboration with:

Nigel Glover (IPPP), João Pires (Milan) and Steven Wells (IPPP)



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IP3

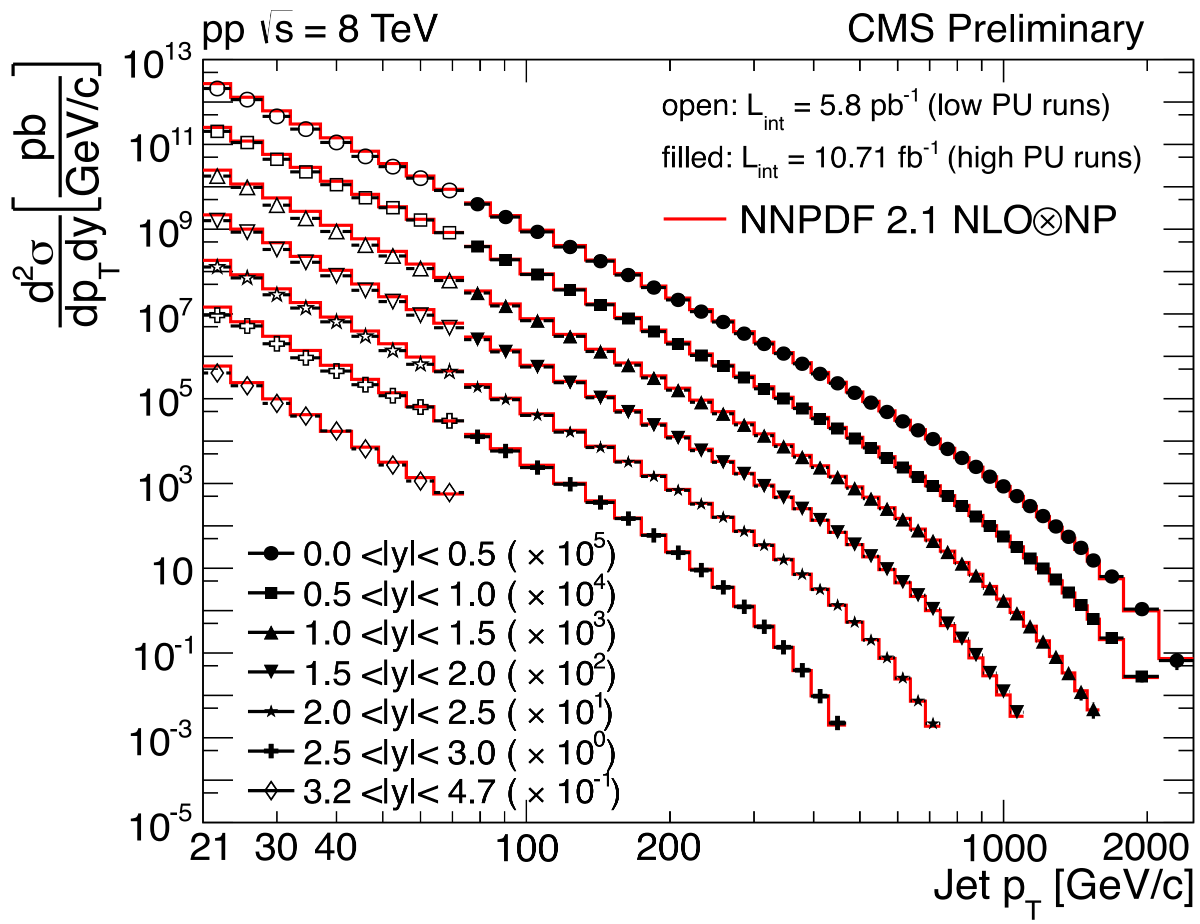
MC@NNLO

Jets at the LHC

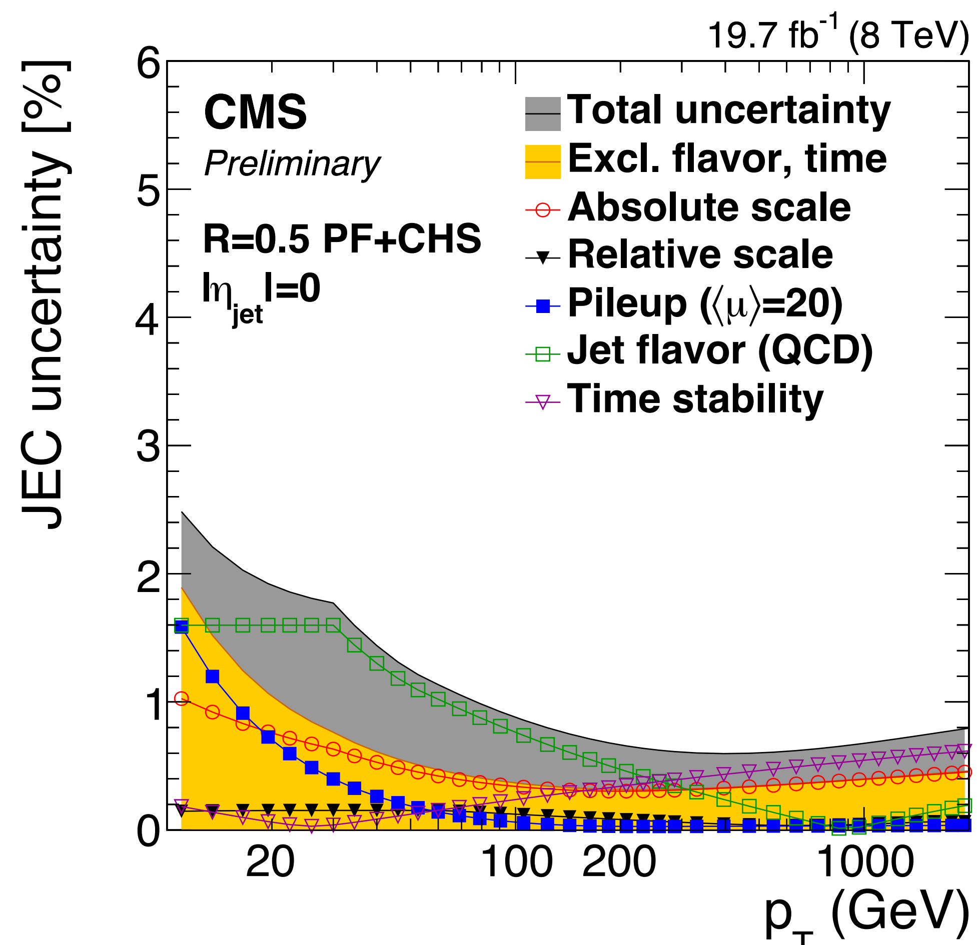
Ubiquitous and accurately measured at the LHC

- ~1% JES corresponds to <10% uncertainty on single inclusive x-sec

Provides a rigorous test of QCD across a huge range of kinematic variables



CMS-PAS-FSQ-12-031

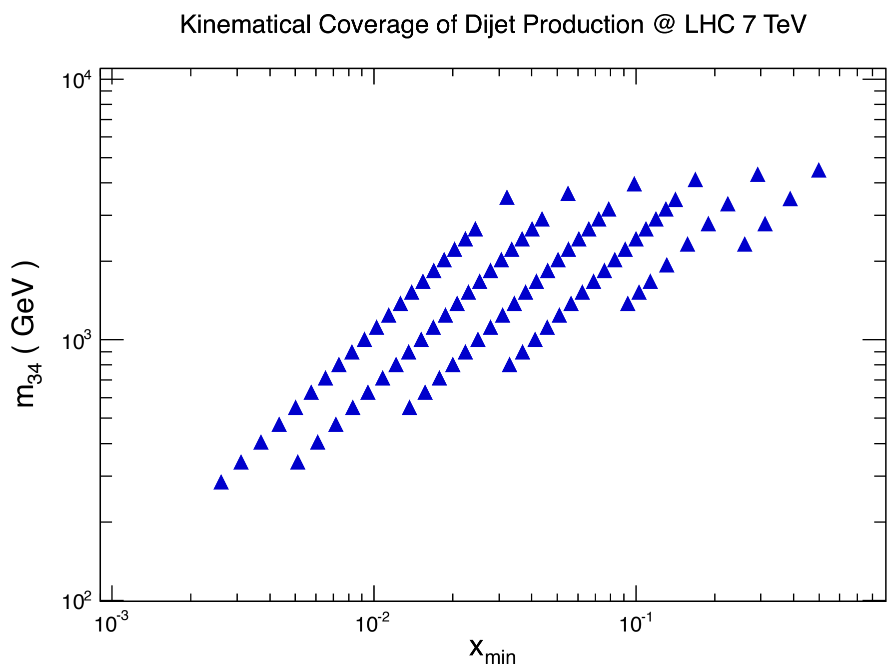


Weber, Monday

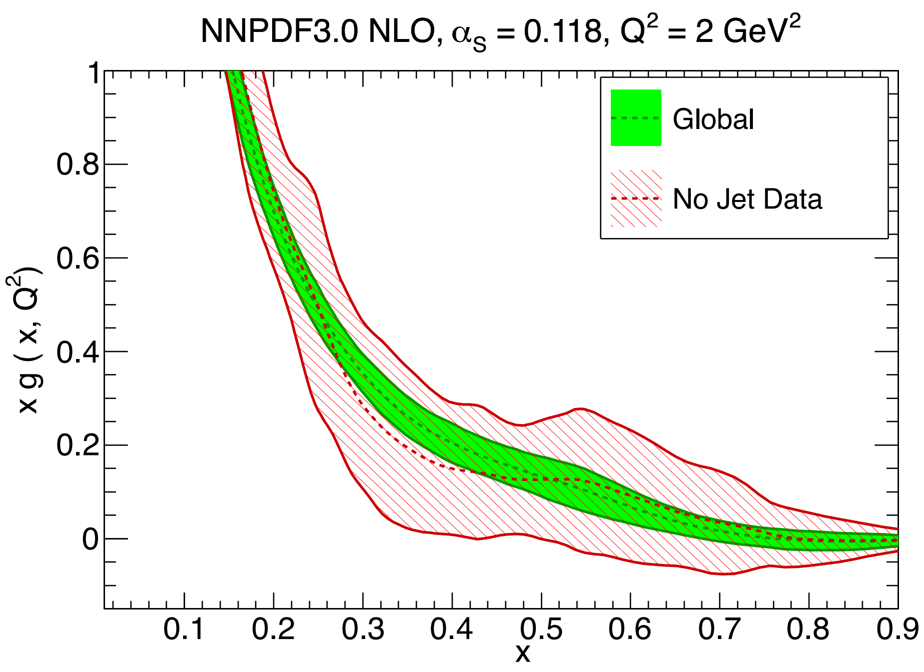
Jets and PDFs

LHC is mainly a gluon collider but gluon PDF is not well known:

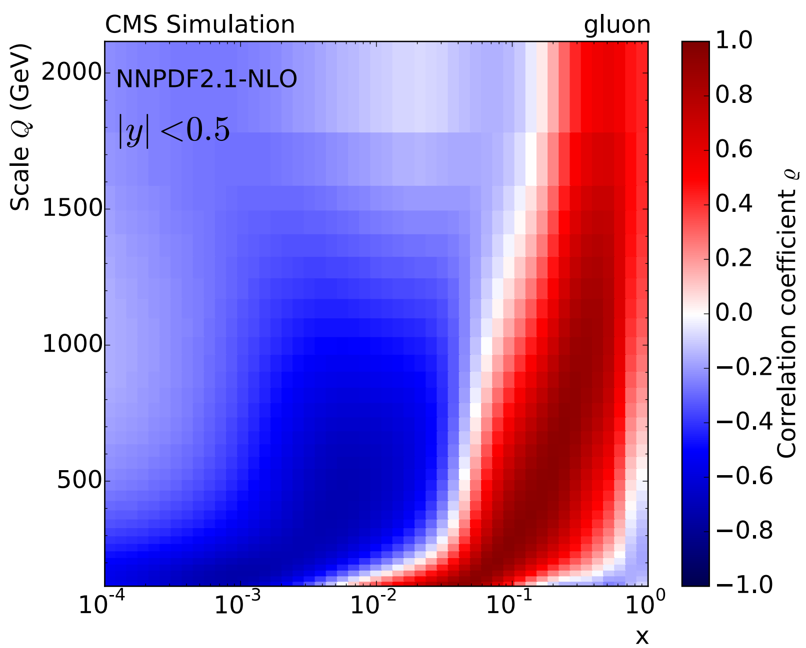
- LHC jets probe a wide range of x
- gluon PDF directly sensitive to jet data, especially at large x
- would like to consistently include NNLO jet data in NNLO PDF fits without using kinematically limited approximations



Rojo hep-ph [1410.7728]



NNPDF collaboration hep-ph [1410.8849]

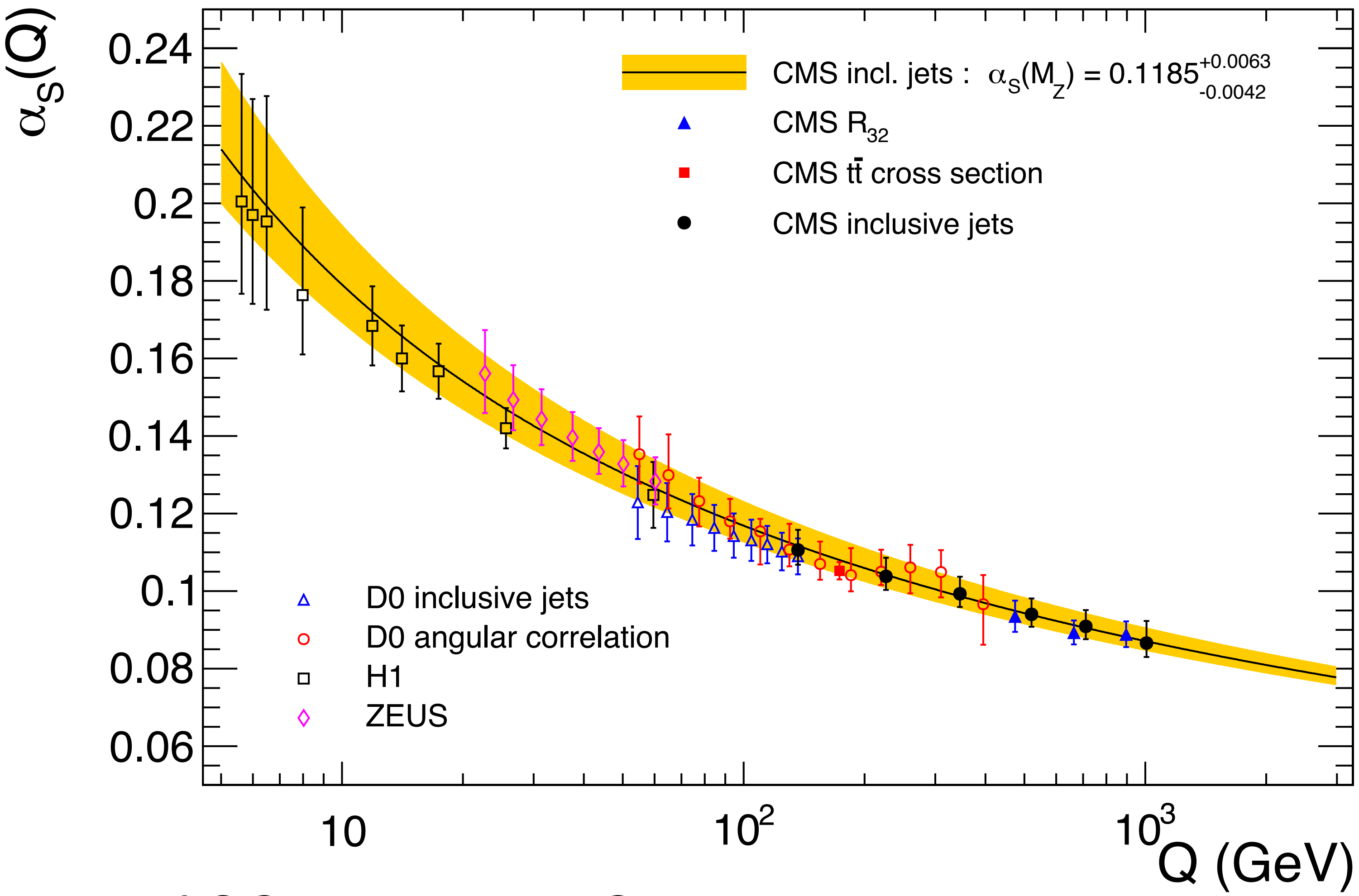


Rojo hep-ph [1410.7728]

Jets and α_s

Can use the single inclusive jet cross section to determine [CMS-PAS-SMP-12-028]:

- $\alpha_s(M_Z)$ and running coupling from single experiment

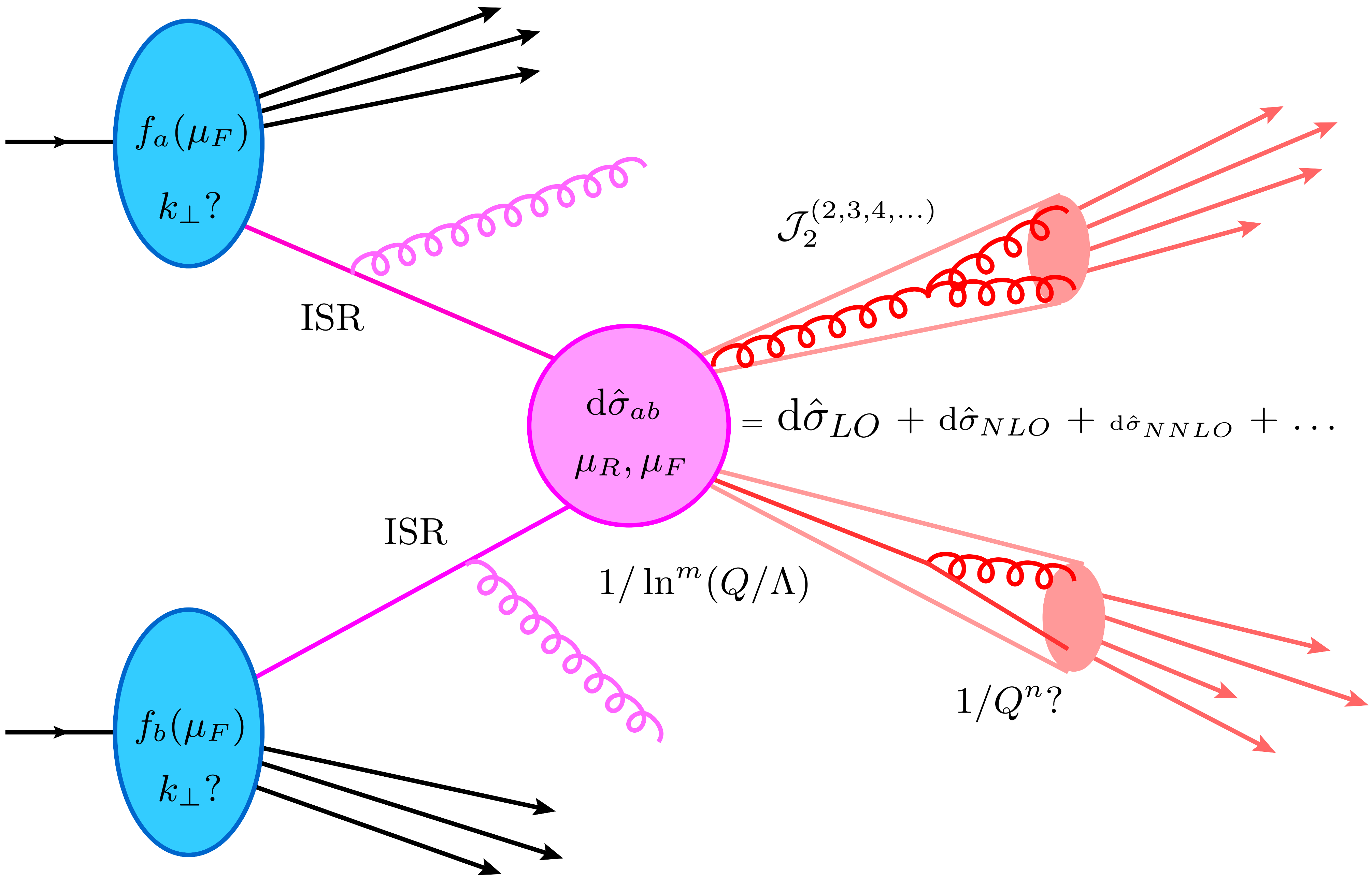


CMS hep-ex [1410.6765]

- very satisfying test of QCD and the LHC

- model independent probe of new physics

Why NNLO?



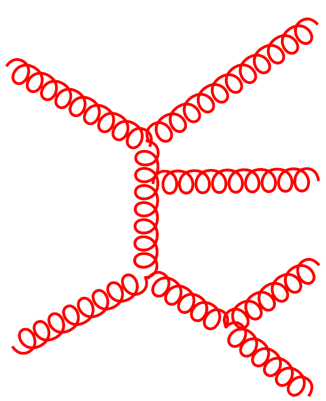
$f_a(\mu_F)$
$k_\perp$?
ISR
$\mathcal{J}_2^{(2,3,4,\ldots)}$
$\mathrm{d}\hat{\sigma}_{ab}$
μ_R, μ_F
$= \mathrm{d}\hat{\sigma}_{LO} + \mathrm{d}\hat{\sigma}_{NLO} + \mathrm{d}\hat{\sigma}_{NNLO} + \ldots$
ISR
$1/\ln^m(Q/\Lambda)$
$1/Q^n$?
$f_b(\mu_F)$
$k_\perp$?

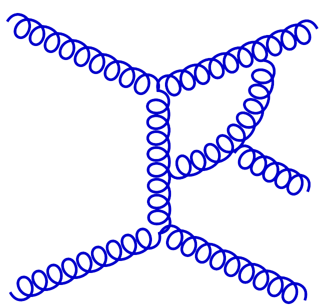
NNLO Subtraction

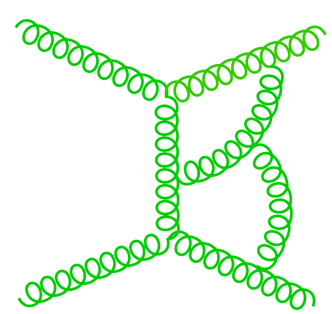
Unphysical intermediate quantities are divergent

- need to regulate with RR, RV and VV subtraction terms

$$\begin{aligned}\mathrm{d}\sigma_{ab,NNLO} &= \int_{\Phi_{m+2}} \mathrm{d}\sigma^{RR}_{ab,NNLO} \\ &+ \int_{\Phi_{m+1}} \mathrm{d}\sigma^{RV}_{ab,NNLO} + \mathrm{d}\sigma^{MF,1}_{ab,NNLO} \\ &+ \int_{\Phi_{m}} \mathrm{d}\sigma^{VV}_{ab,NNLO} + \mathrm{d}\sigma^{MF,2}_{ab,NNLO}\end{aligned}$$





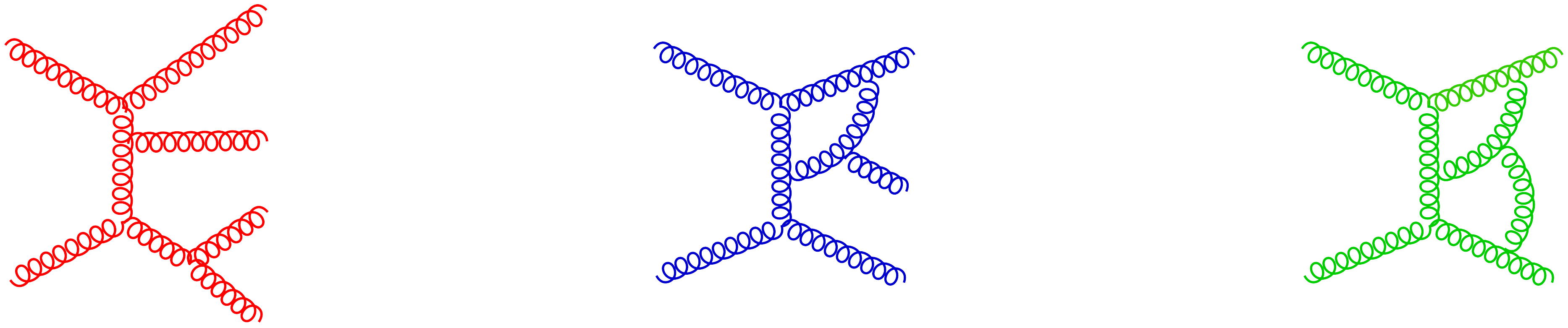


NNLO Subtraction

Unphysical intermediate quantities are divergent

- need to regulate with RR, RV and VV subtraction terms

$$\begin{aligned} \mathrm{d}\sigma_{ab,NNLO} &= \int_{\Phi_{m+2}} \left[\mathrm{d}\sigma^{RR}_{ab,NNLO} - \mathrm{d}\sigma^{S}_{ab,NNLO}\right] \\ &+ \int_{\Phi_{m+1}} \left[\mathrm{d}\sigma^{RV}_{ab,NNLO} - \mathrm{d}\sigma^{T}_{ab,NNLO}\right] \\ &+ \int_{\Phi_{m}} \left[\mathrm{d}\sigma^{VV}_{ab,NNLO} - \mathrm{d}\sigma^{U}_{ab,NNLO}\right] \end{aligned}$$



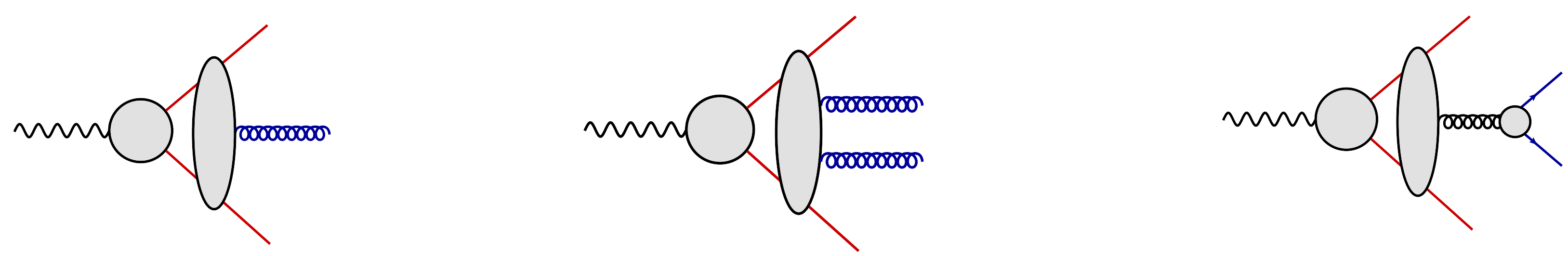
Antenna Subtraction

Antenna functions built from matrix elements:

$$X_3^0(i,j,k) \sim \frac{|\mathcal{M}_3^0(i,j,k)|^2}{|\mathcal{M}_2^0(I,K)|^2}, \qquad X_4^0(i,j,k,l) \sim \frac{|\mathcal{M}_4^0(i,j,k,l)|^2}{|\mathcal{M}_2^0(I,L)|^2}$$

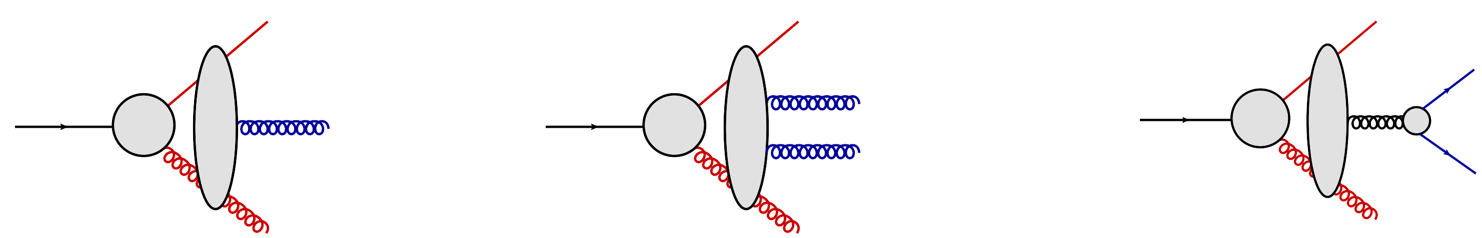
Quark-antiquark:

$\gamma^* \to q\bar{q} + \cdots$



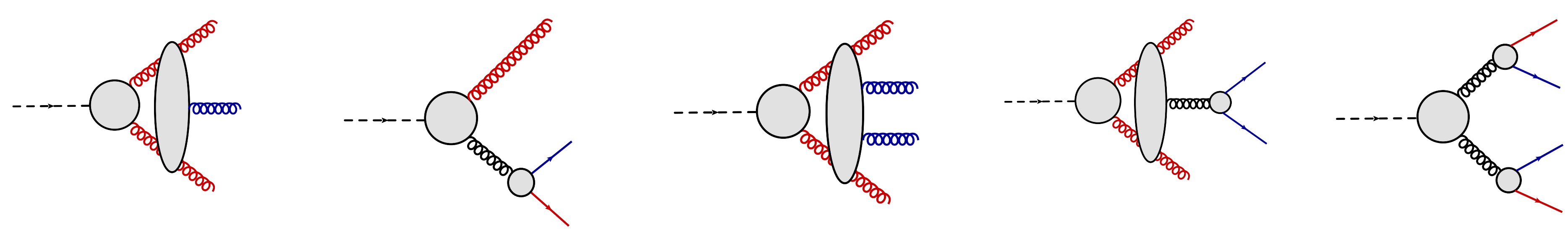
Quark-gluon:

$\bar{\chi}^0 \to \tilde{g}g + \cdots$



Gluon-gluon:

$H \to gg + \cdots$



Where to start?

pp⇒2j at NNLO is a complicated calculation:

- many crossings and colour factors to consider
- up to four massless partons in the final state means a large number of (overlapping) unresolved limits

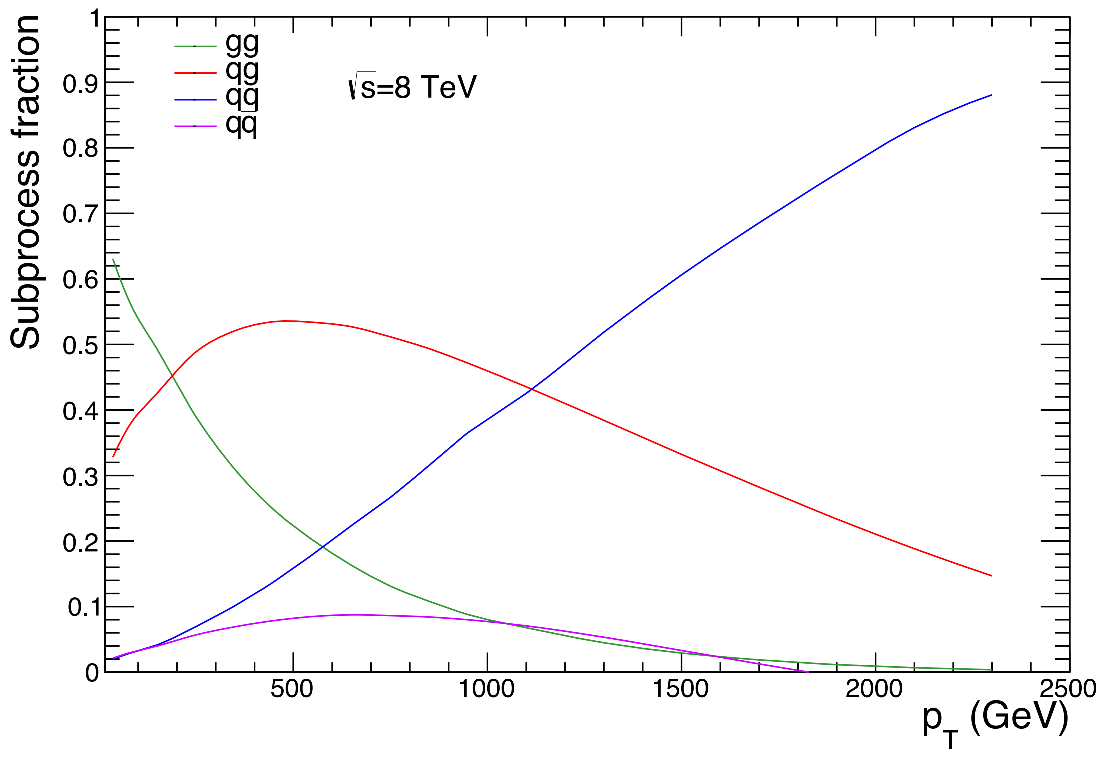
Start by considering:

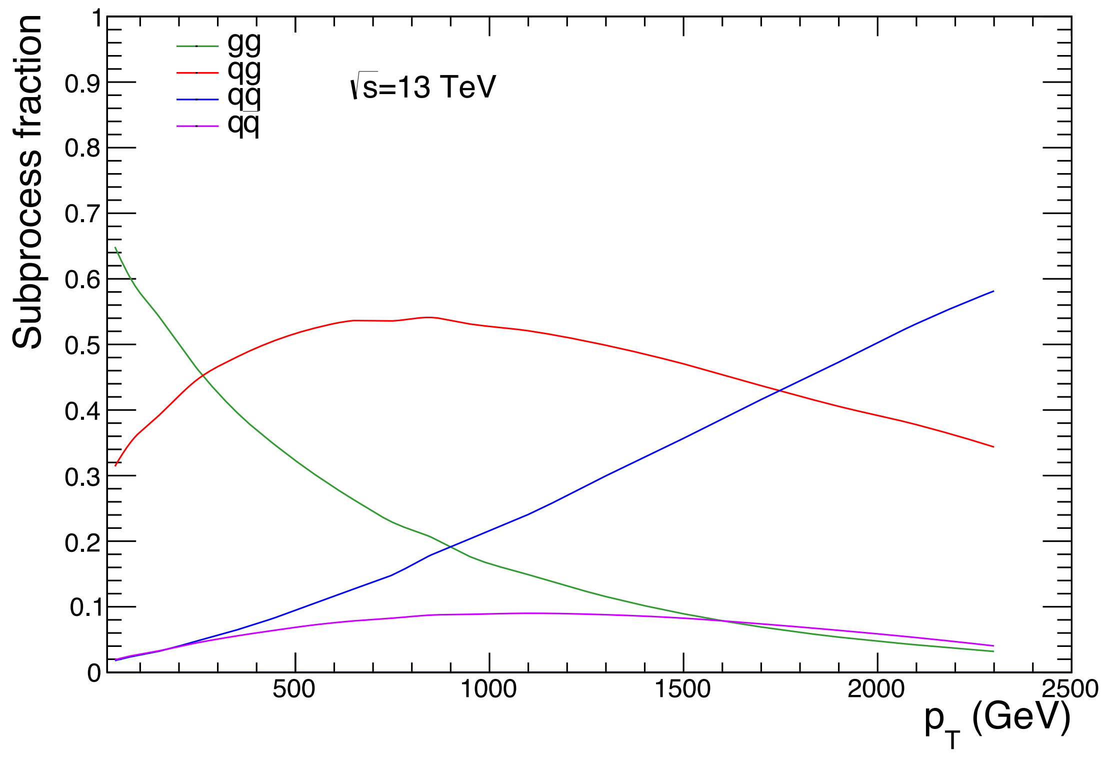
- what are the most important channels?
- what are the most important colour factors in each channel?

Channels

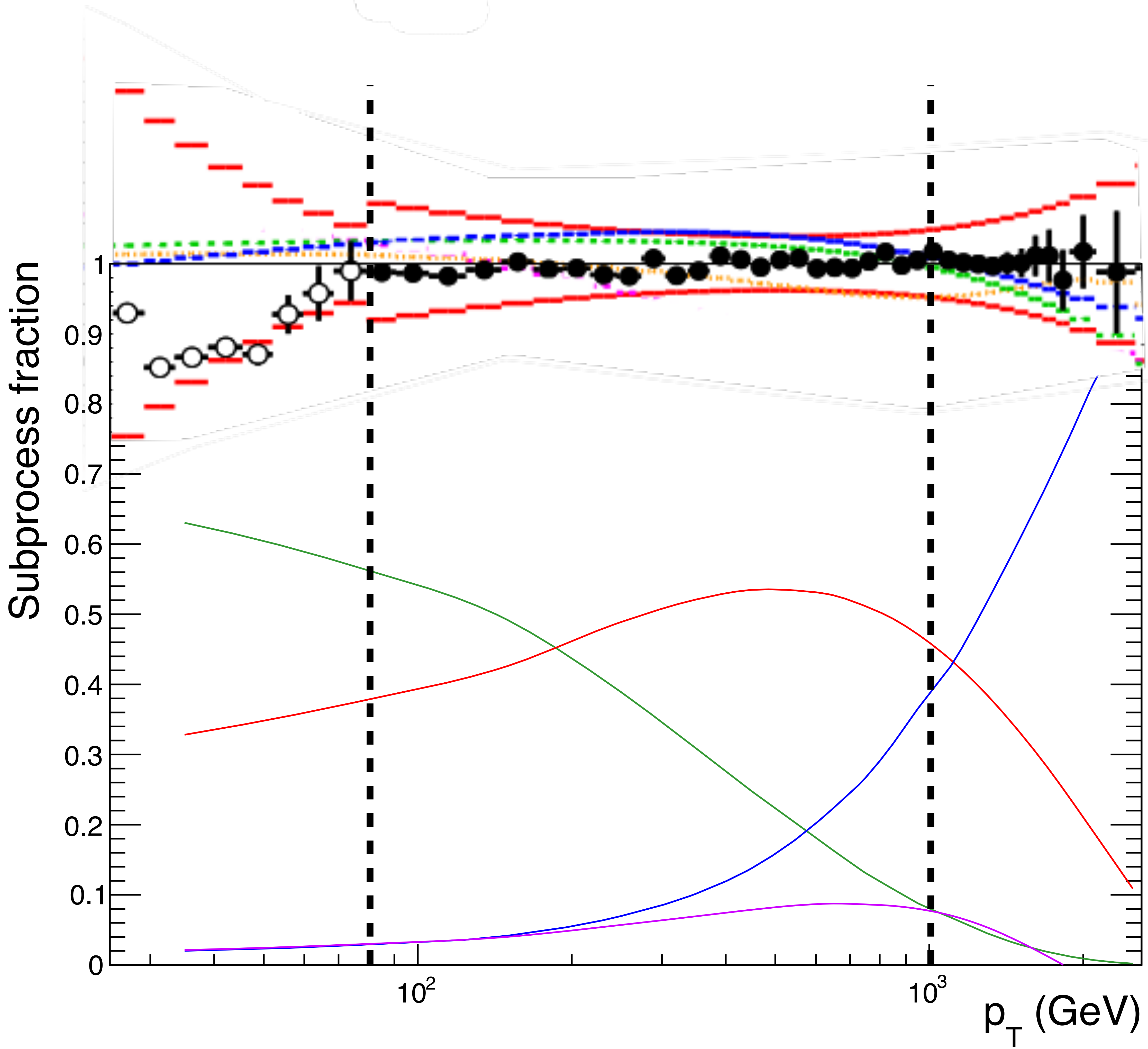
At low to moderate p_T the gluonic initial-states (gg+qg) dominate

At high p_T quark scattering becomes important





In this talk we will focus on gg+qg; qq results in preparation



Subprocess fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^2
10^3
p_T (GeV)

gg channel

Start with the double real all-gluon contribution [Glover, Pires '10]:

- six gluon matrix element [Mangano, Parke, Xu '87; Berends, Giele '87]:

$$|\mathcal{M}_6^0|^2 = \sum_{\text{perms}} A_6^0(1,2,i,j,k,l)$$

- "single unresolved" subtraction term:

$$f_3^0(2,i,j)\ A_5^0(1,\bar{2},(\widetilde{ij}),k,l)$$

- "double unresolved" subtraction term:

$$F_4^0(2,i,j,k)\ A_4^0(1,\bar{2},(\widetilde{ijk}),l)$$

- "spurious unresolved" subtraction term:

$$f_3^0(2,i,j)\ f_3^0((\widetilde{ij}),k,l)\ A_4^0(1,\bar{2},(\widetilde{(\widetilde{ij})(kl)}))$$

Real-virtual correction [Glover, Pires '12]:

- one-loop five gluon matrix element [Bern, Dixon, Kosower '93]

$$|\mathcal{M}_5^1|^2 = \sum_{\text{perms}} A_5^1(1,2,i,j,k)$$

- pole subtraction term:

$$\boldsymbol{J}^{(1)}(1,2,i,j,k)\ A_5^0(1,2,i,j,k)$$

- single unresolved subtraction term:

$$f_3^0(2,i,j)\ A_4^1(1,\bar{2},(\widetilde{ij}),k) + f_3^1(2,i,j)\ A_4^0(1,\bar{2},(\widetilde{ij}),k)$$

- spurious pole/single unresolved subtraction term:

$$\boldsymbol{J}^{(1)}(2,i)\ f_3^0(i,j,k)\ A_4^0(1,\bar{2},(\widetilde{ij}),(\widetilde{jk}))$$

Double virtual correction [Gehrmann, Gehrmann de-Ridder, Glover, Pires '13]

- two-loop matrix elements [Glover, Oleari, Tejeda-Yeomans '01]
-]:

$$|\mathcal{M}_4^2|^2 = \sum_{\text{perms}} A_4^2(1,2,i,j)$$

- double virtual subtraction term:

$$
\begin{aligned}
&+ \boldsymbol{J}^{(1)}(1,2,i,j)\; A_4^1(1,2,i,j) \\
&+ \frac{1}{2}\boldsymbol{J}^{(1)}(1,2,i,j) \otimes \boldsymbol{J}^{(1)}(1,2,i,j)\; A_4^0(1,2,i,j) \\
&+ \boldsymbol{J}^{(2)}(1,2,i,j)\; A_4^0(1,2,i,j)
\end{aligned}
$$

- analogous to well known IR pole structure [Catani '98]
- structure is universal and generalizable to higher multiplicities

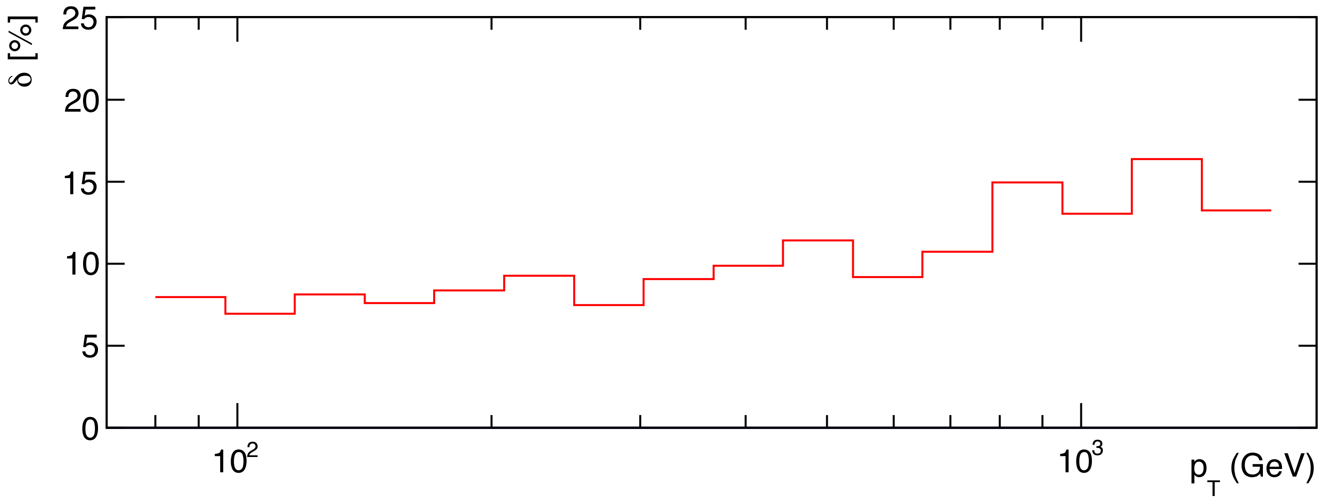
Sub-leading colour all-gluon correction [JC, Glover, Pires '14]:

- posed an interesting theoretical challenge
- antenna subtraction designed for squared partial amplitudes
- sub-leading colour RR and RV gluon scattering built from interferences

$$\mathcal{A}_6^{0,\dagger}(\sigma)\left[\mathcal{A}_6^0(\sigma') + \mathcal{A}_6^0(\sigma'') + \mathcal{A}_6^0(\sigma''')\right]$$

$$\mathcal{A}_5^{0,\dagger}(\sigma)\ \mathcal{A}_5^1(\sigma')$$

The method worked well and produced a small correction



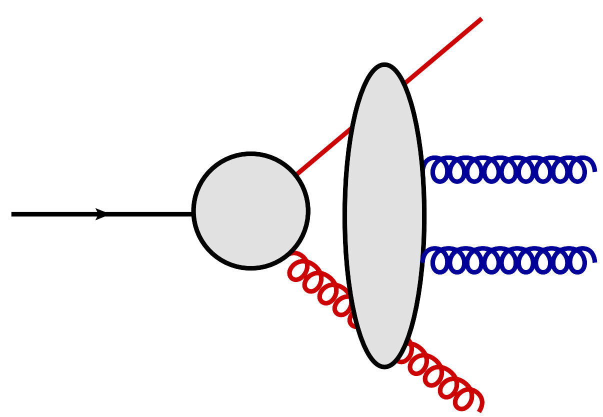
qg channel

Very important channel over a wide range of p_T:

- main missing component for jets up to ~1 TeV

Also presents interesting theoretical challenges:

- antennae interpolate between many limits with a smooth momentum map
- not always desirable when factoring onto physically different matrix elements



$$\times \quad M_{qg} \quad \text{or} \quad M_{q\bar{q}}$$

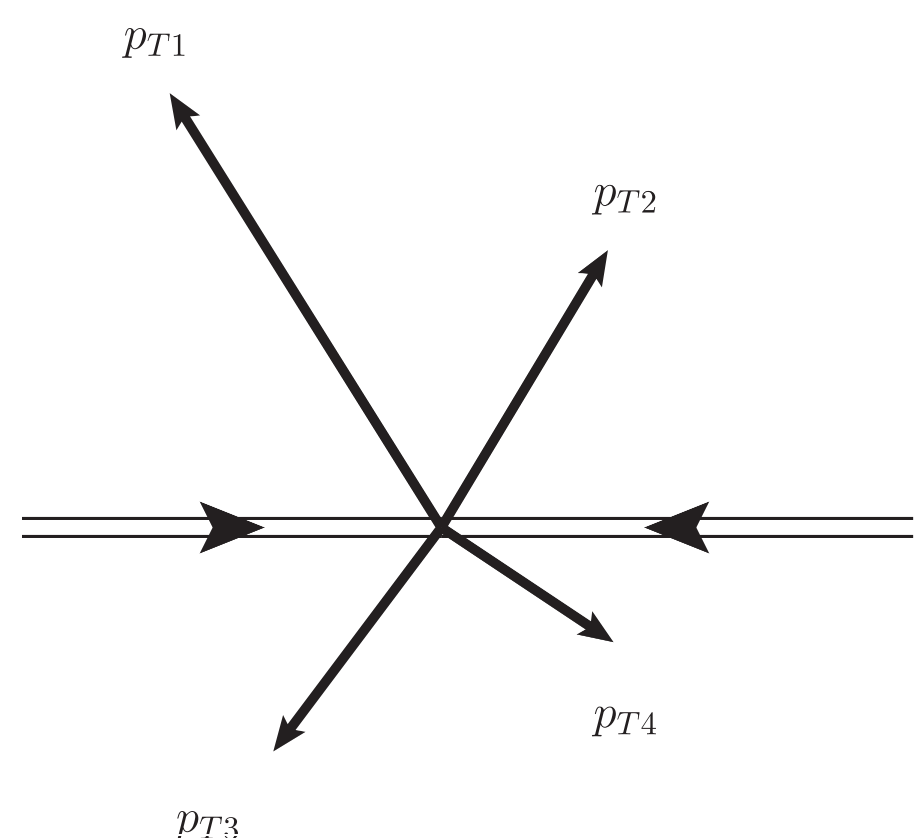
Limits can be disentangled successfully and systematically

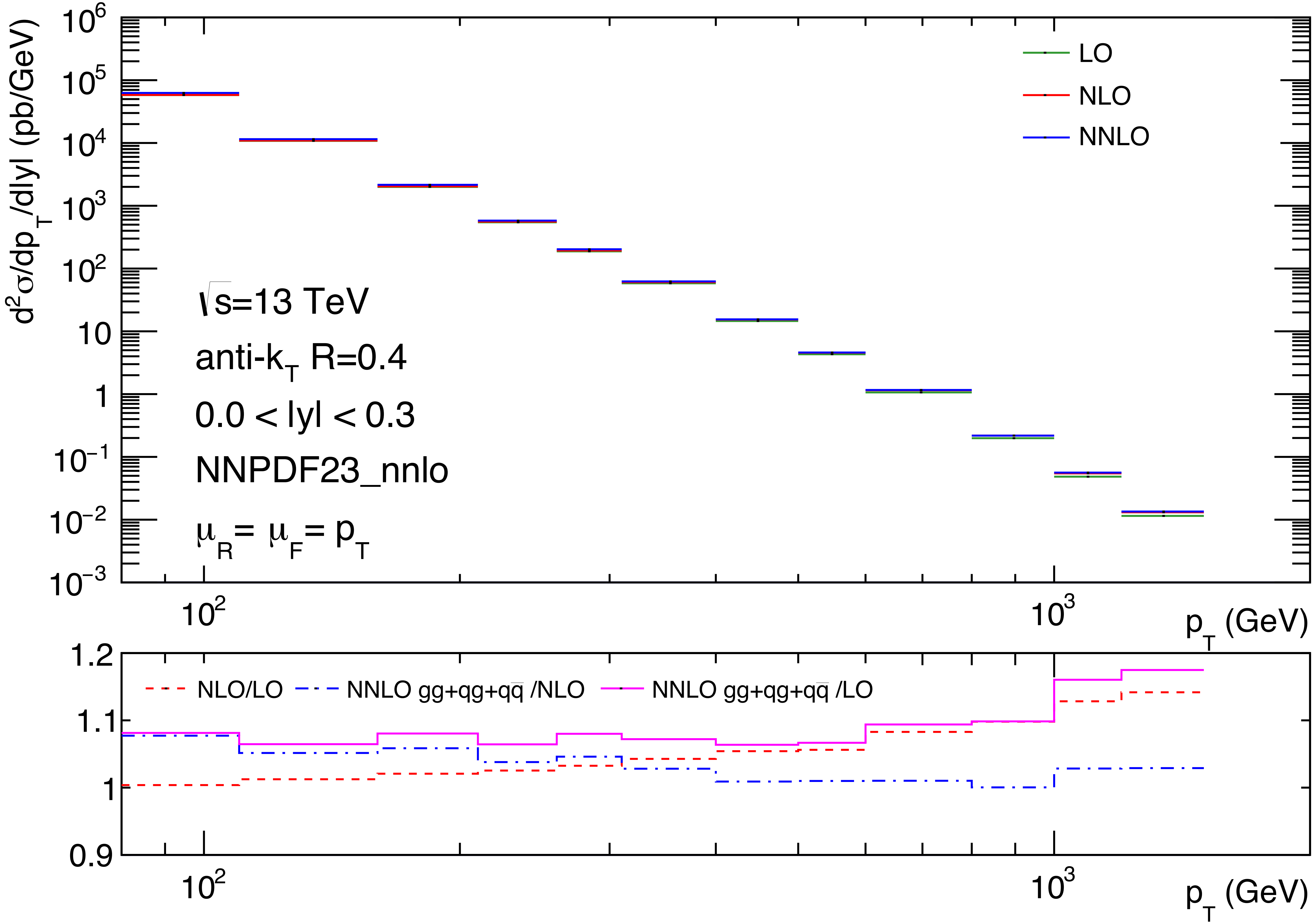
Results

The following results are for gg+qg+q$\overline{\mathbf{q}}$⇒2j at 13 TeV

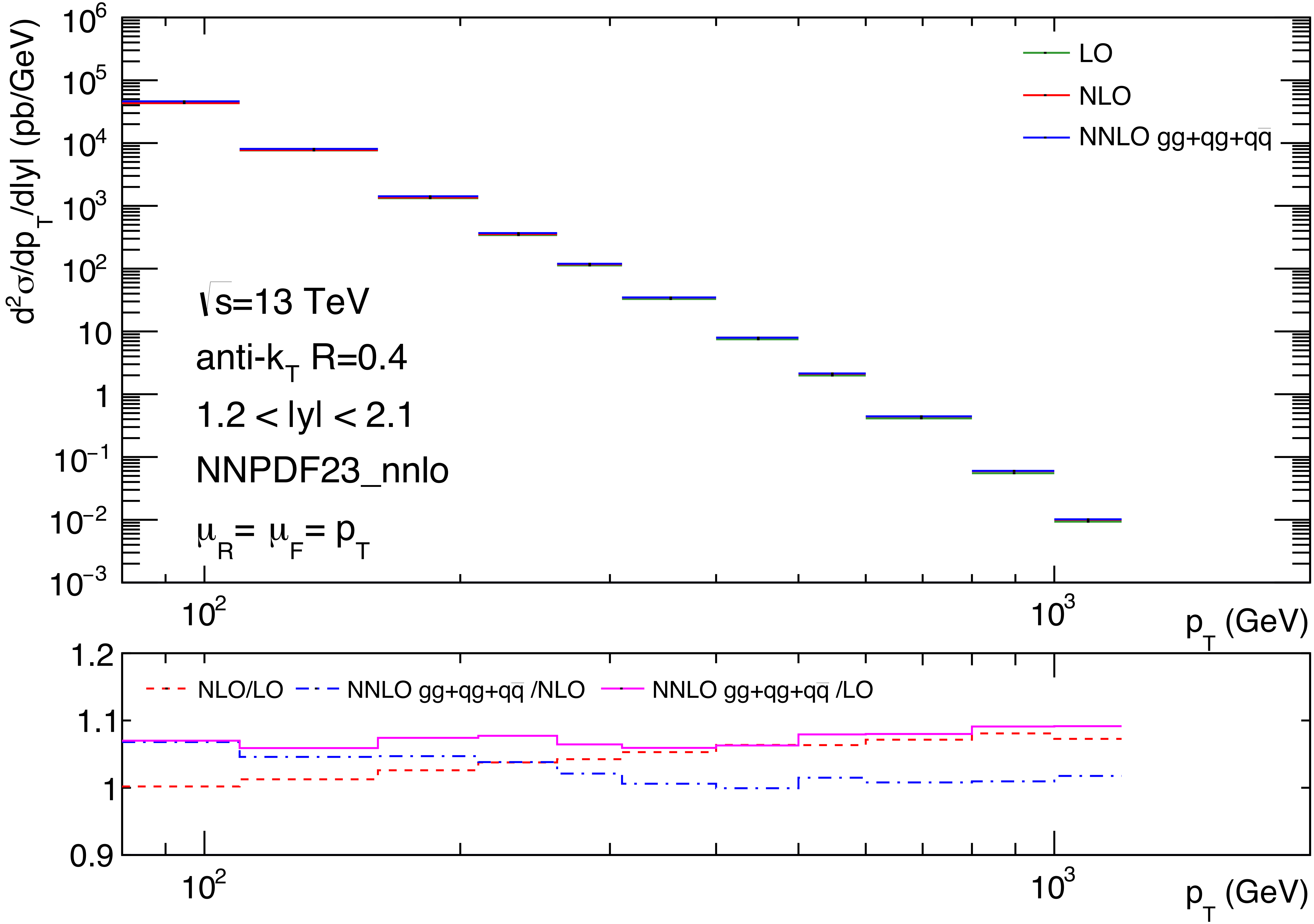
Setup:

- NNPDF2.3_NNLO
- accept jets with p_T > 80 GeV
- rapidity cut |y| < 4.4
- scale μ = μ_F = p_T rather than p_{T1}
- anti-k_T jet algorithm R=0.4



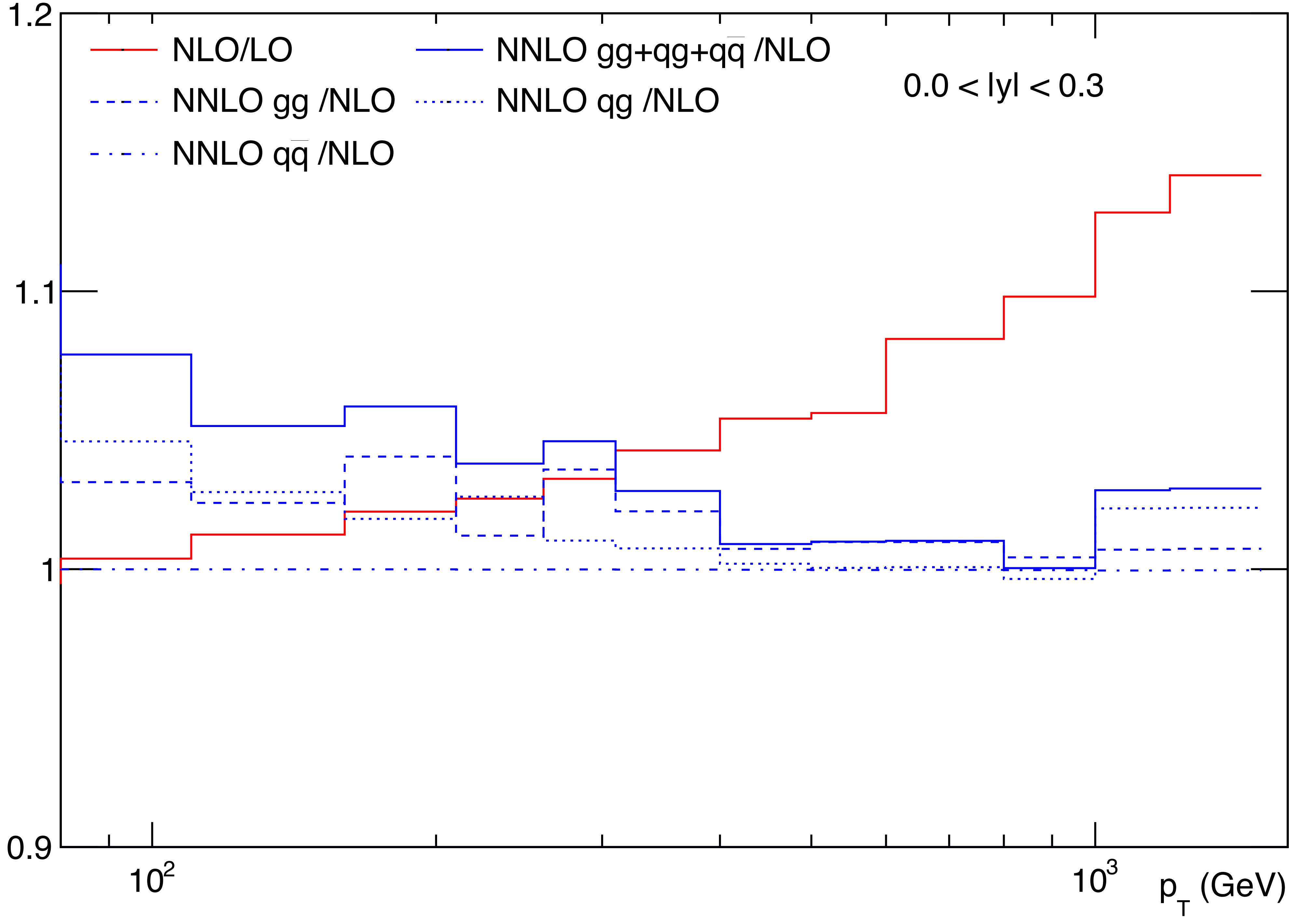


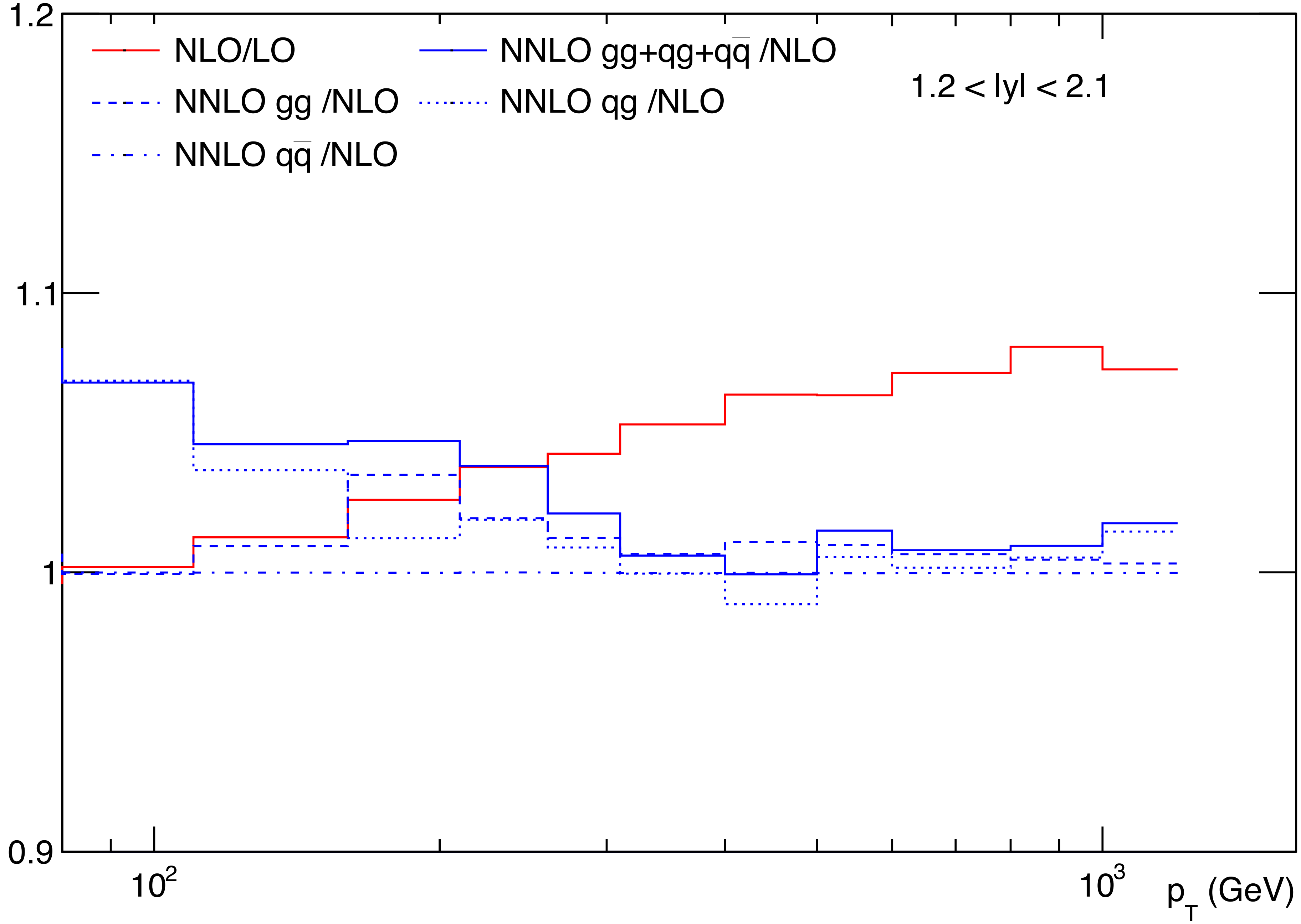
LO
NLO
NNLO
$d^2\sigma/dp_T/d|y|$ (pb/GeV)
$\sqrt{s}$=13 TeV
anti-k_T R=0.4
0.0 < |y| < 0.3
NNPDF23_nnlo
$\mu_R = \mu_F = p_T$
p_T (GeV)
NLO/LO
NNLO gg+qg+q$\bar{q}$ /NLO
NNLO gg+qg+q$\bar{q}$ /LO
p_T (GeV)

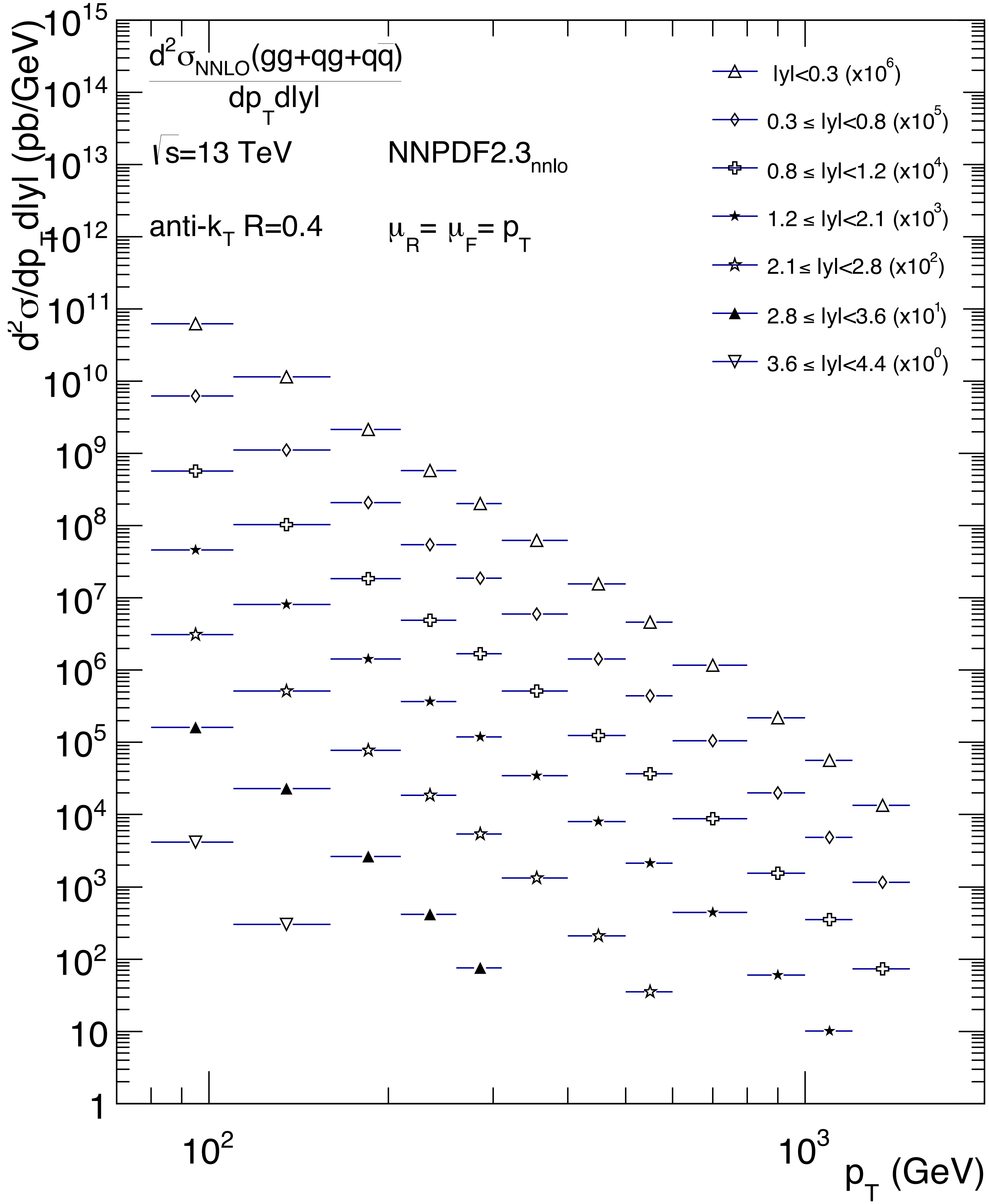


LO
NLO
NNLO gg+qg+q$\bar{q}$
$\sqrt{s}$=13 TeV
anti-k_T R=0.4
1.2 < |y| < 2.1
NNPDF23_nnlo
$\mu_R = \mu_F = p_T$
$d^2\sigma/dp_T/d|y|$ (pb/GeV)
p_T (GeV)
NLO/LO
NNLO gg+qg+q$\bar{q}$ /NLO
NNLO gg+qg+q$\bar{q}$ /LO
p_T (GeV)

K-factors

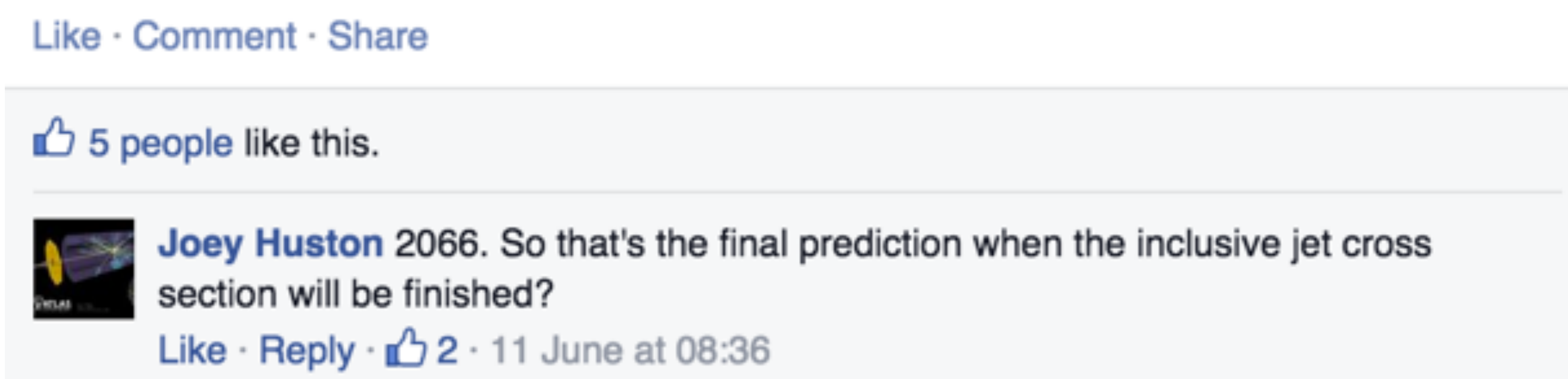

1.2
1.1
1
0.9
10^2
10^3
p_T (GeV)
NLO/LO
NNLO gg+qg+q$\bar{q}$ /NLO
NNLO gg /NLO
NNLO qg /NLO
NNLO q$\bar{q}$ /NLO
0.0 < lyl < 0.3


NLO/LO
NNLO gg+qg+q$\bar{q}$ /NLO
NNLO gg /NLO
NNLO qg /NLO
NNLO q$\bar{q}$ /NLO
1.2 < lyl < 2.1
1.2
1.1
1
0.9
10^2
10^3
p_T (GeV)



$\frac{d^2\sigma_{NNLO}(gg+qg+q\bar{q})}{dp_T d|y|}$
$\sqrt{s}$=13 TeV
NNPDF2.3$_{nnlo}$
anti-k$_T$ R=0.4
$\mu_R = \mu_F = p_T$
|y|<0.3 (x10^6)
0.3 ≤ |y|<0.8 (x10^5)
0.8 ≤ |y|<1.2 (x10^4)
1.2 ≤ |y|<2.1 (x10^3)
2.1≤ |y|<2.8 (x10^2)
2.8 ≤ |y|<3.6 (x10^1)
3.6 ≤ |y|<4.4 (x10^0)
$d^2\sigma/dp_T d|y|$ (pb/GeV)
p_T (GeV)

Where to go now?



A few things remain to be included in our study:

- quark scattering for high p_T jets (results in preparation)
- leading N_F corrections in all channels (in preparation)
- sub-leading colour probably insignificant and can be dropped without compromising phenomenology
- updated scale variation (in preparation)
- upgrade of the Monte Carlo and interface to APPLgrid/n-tuples

Summary

Antenna subtraction is a flexible and powerful IR subtraction scheme

We have used this method to calculate the NNLO correction to jet production at the LHC:

- updated gluon scattering results at 13 TeV
- added the new and significant quark-gluon channel
- we observe that the new qg channel dominates for moderate p_T
- NNLO corrections up to ~8% of the NLO decreasing with p_T
- quark-quark channel and N_F results in preparation