Fixed Order Jets for Run II

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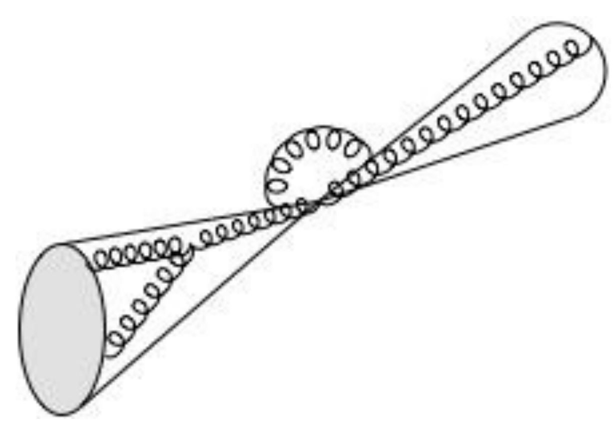


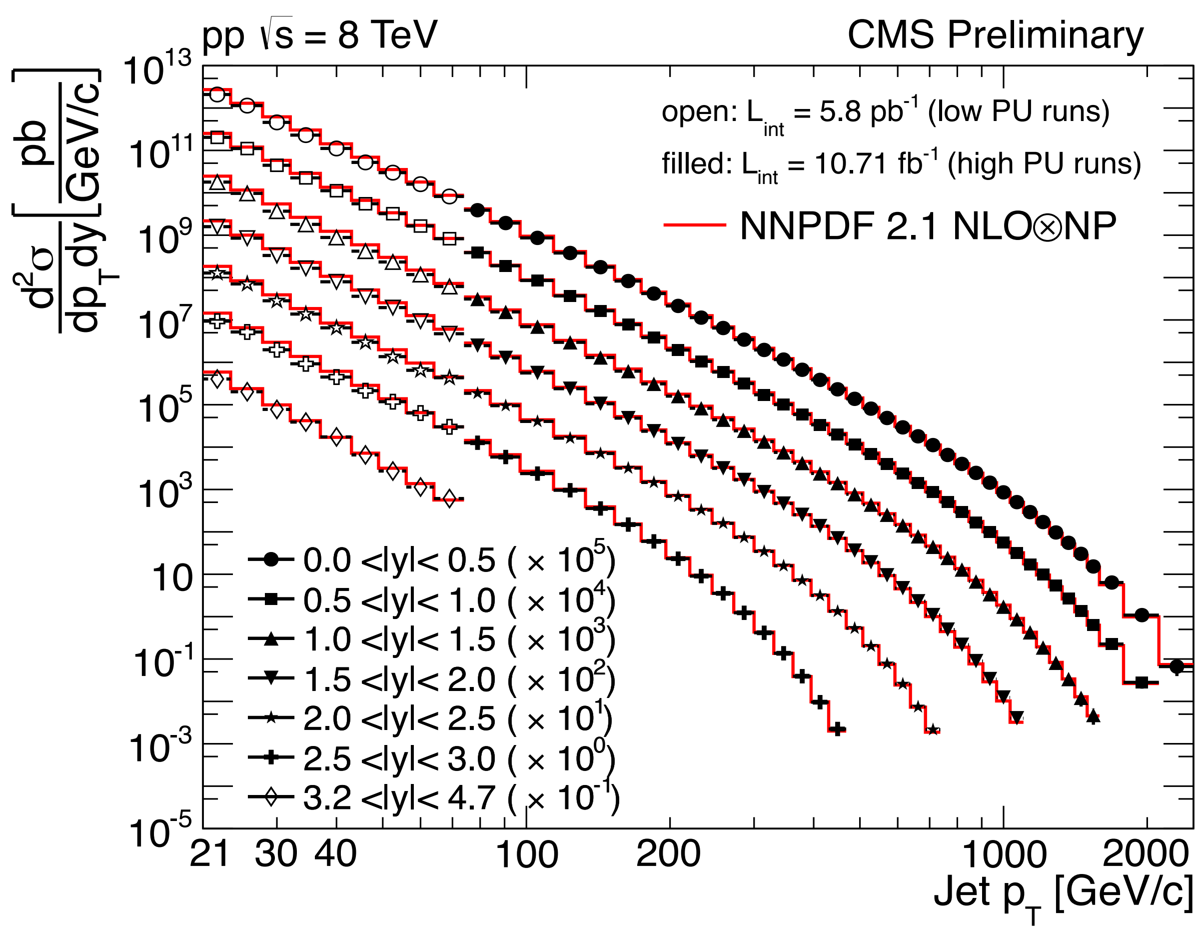
MC@NNLO

Jets at the LHC

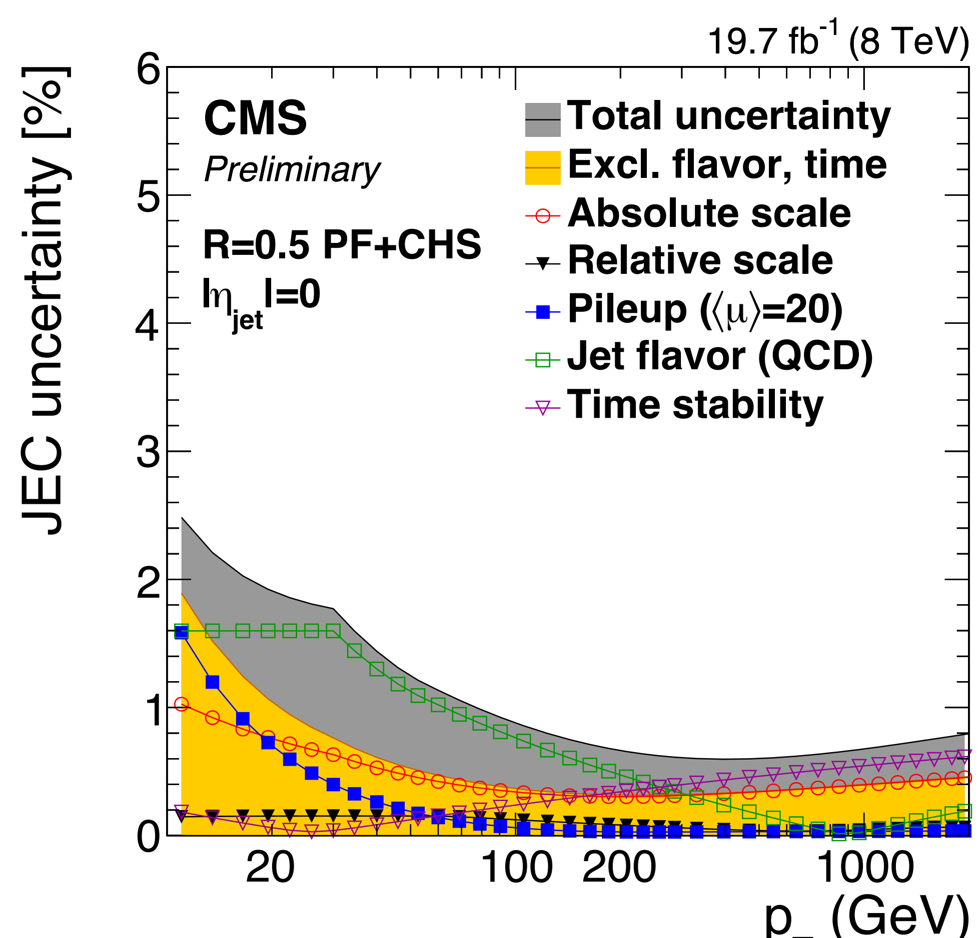
Ubiquitous and accurately measured at the LHC

- ~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

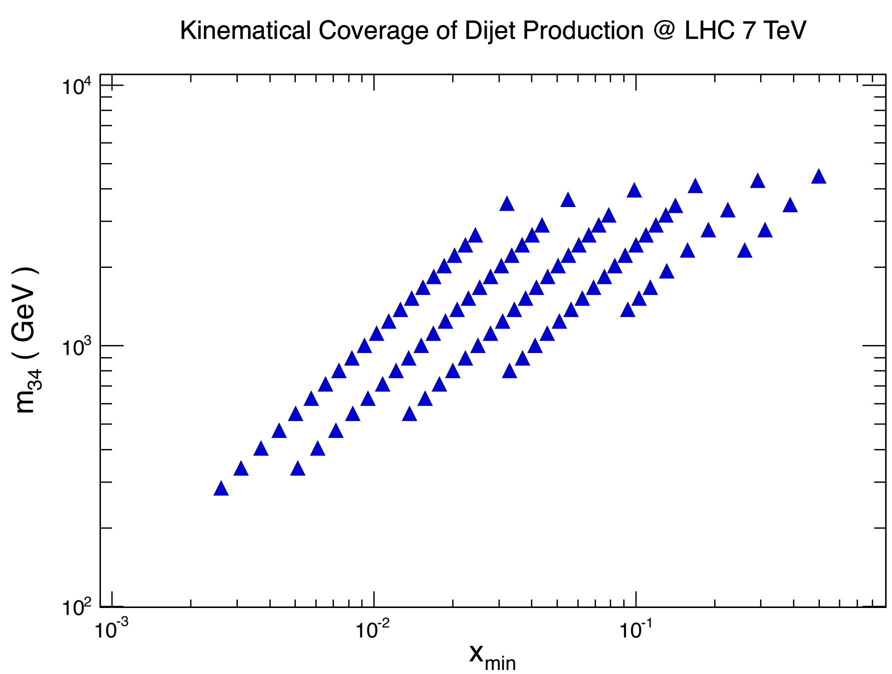


Weber/CMS, Radcor ‘15

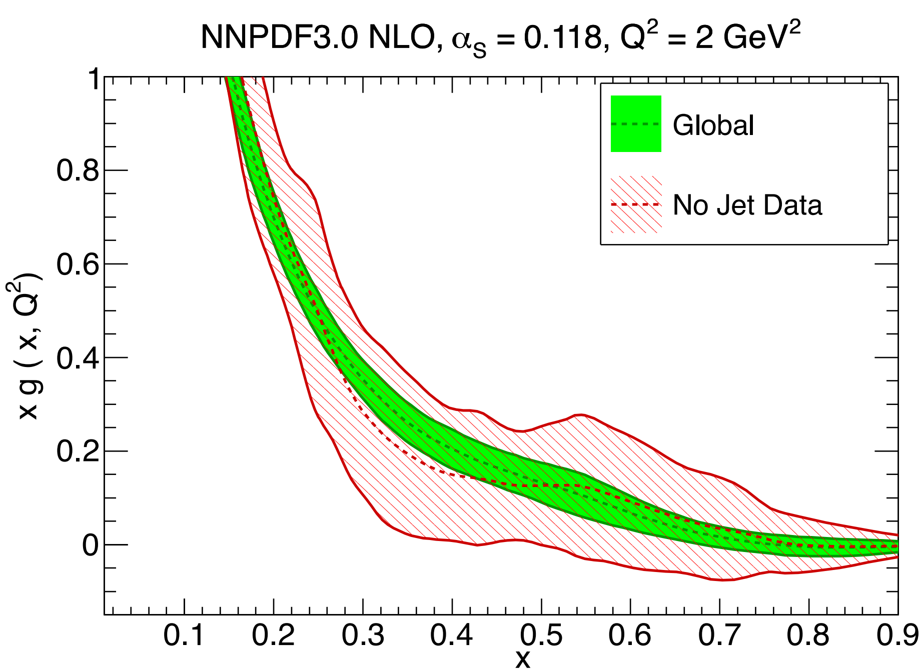
Jets and PDFs

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

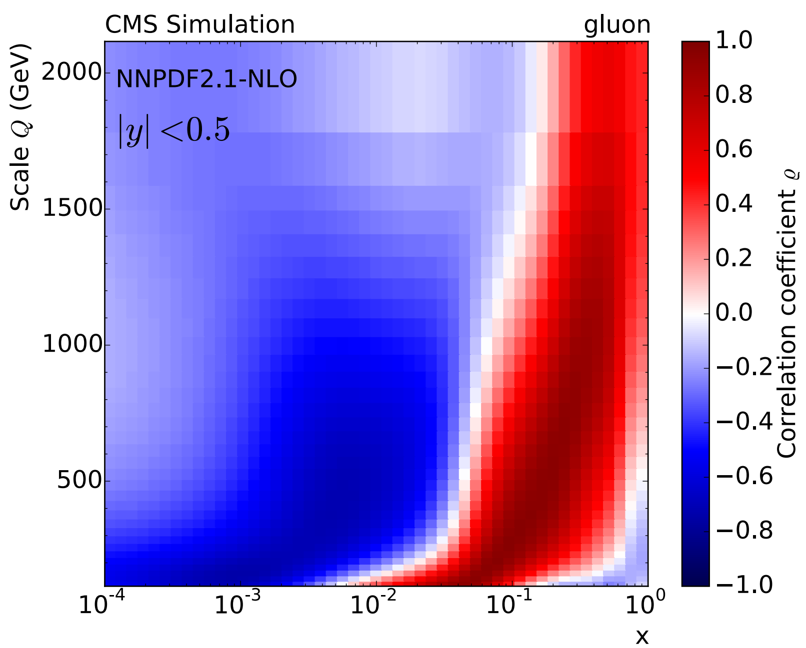
- LHC jets probe a wide range of x
- gluon PDF directly sensitive to jet data, especially at large x
- would like to consistently include NNLO jet data in NNLO PDF fits without using kinematically limited approximations



Rojo hep-ph [1410.7728]



NNPDF collaboration hep-ph [1410.8849]

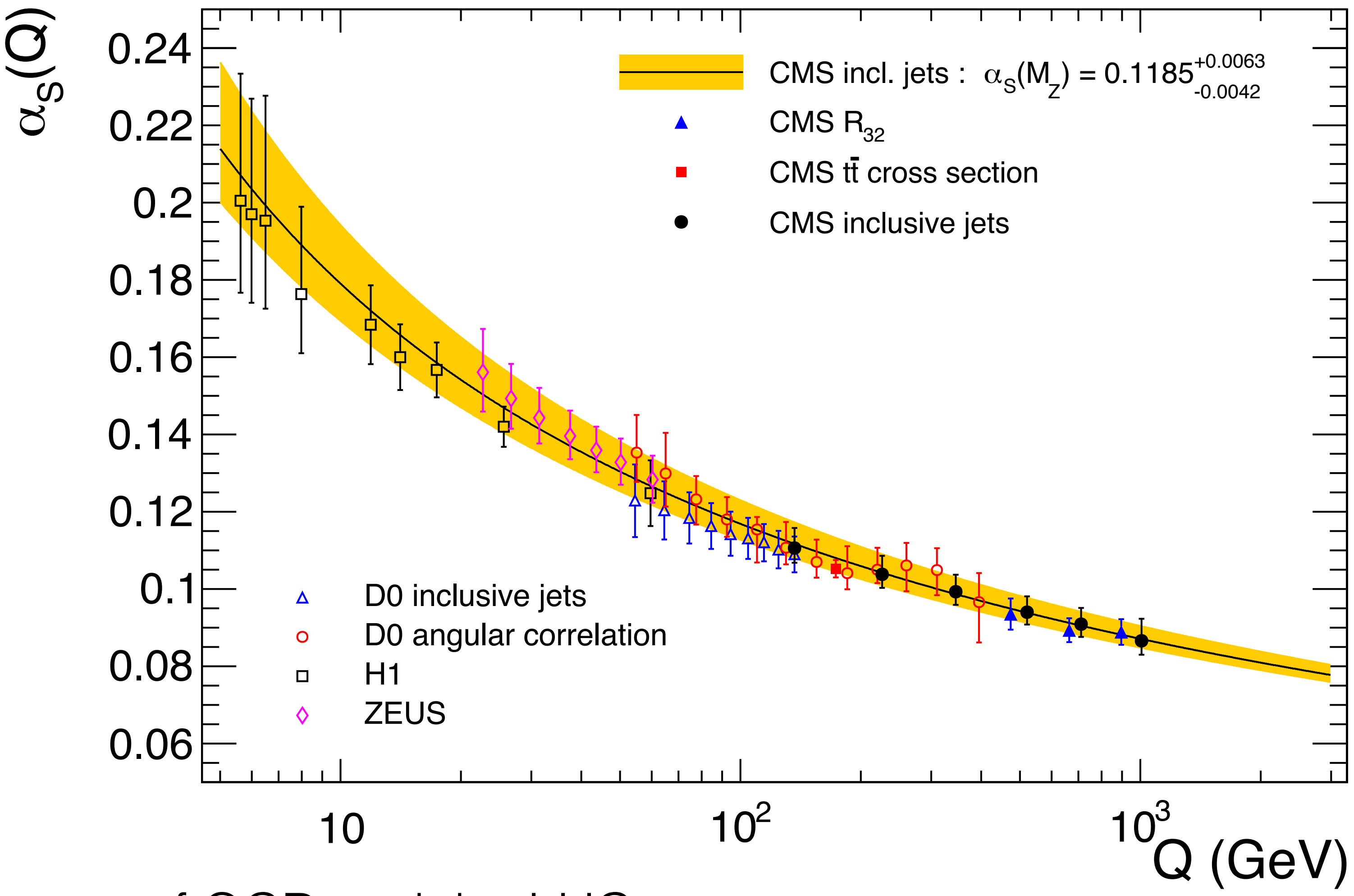


Rojo hep-ph [1410.7728]

Jets and α_s

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

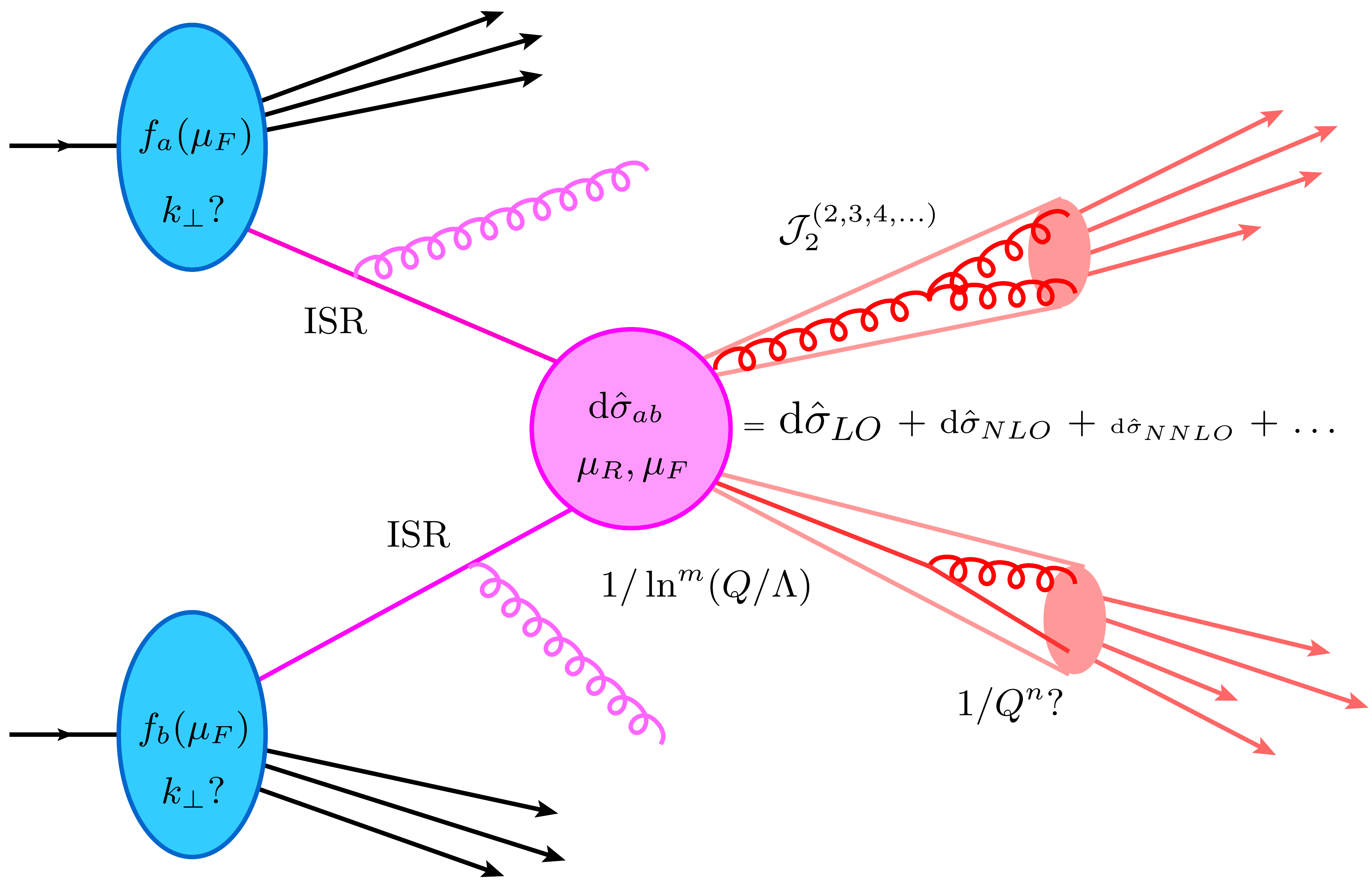
- $\alpha_s(M_Z)$ and running coupling from single experiment



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
$1/\ln^m(Q/\Lambda)$
$1/Q^n$?
$f_b(\mu_F)$
$k_\perp$?

Why NNLO?

NNLO is first order which:

- gives useful estimate of theoretical scale error
- contains all elements of physics in the process
- can begin to probe NP effects
- allows consistent use of NNLO PDFs

Should be the Run II standard wherever possible

- reduces (over) dependence on approximations

NNLO Run II Marketplace

	local subtraction	analytic	pp collisions	final-state jets	scalable final state
Antenna Subtraction	✗ + $\frac{✓}{\epsilon^n}$	✓	✓	✓	✓
STRIPPER	✓	✗	✓	✓	✓
q Subtraction	✗	✓	✓	✗	✓ / ✗
N-Jettiness	✗	✓	✓	✓	✓ / ✗

Slicing Techniques

Extended to NNLO by clever new slicing parameters

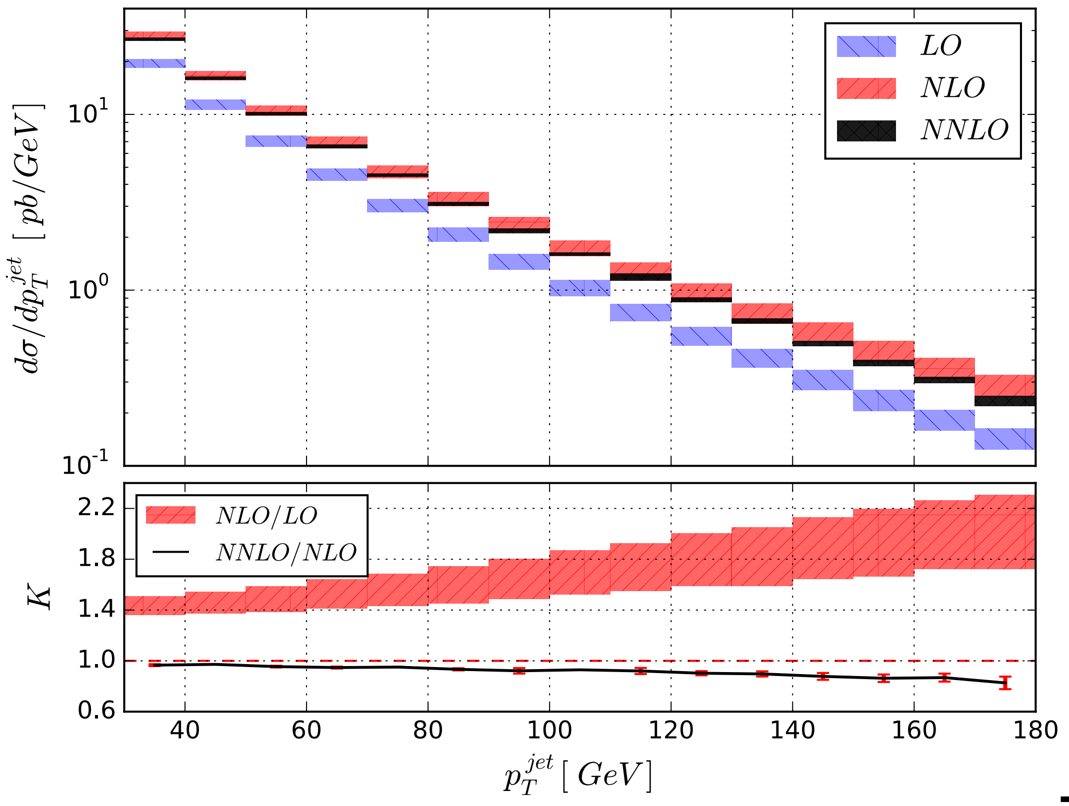
Define a kinematic cut on the phase space:

- evaluate cross section above cut with NLO techniques
- cross section below cut approximated by resummation inspired function

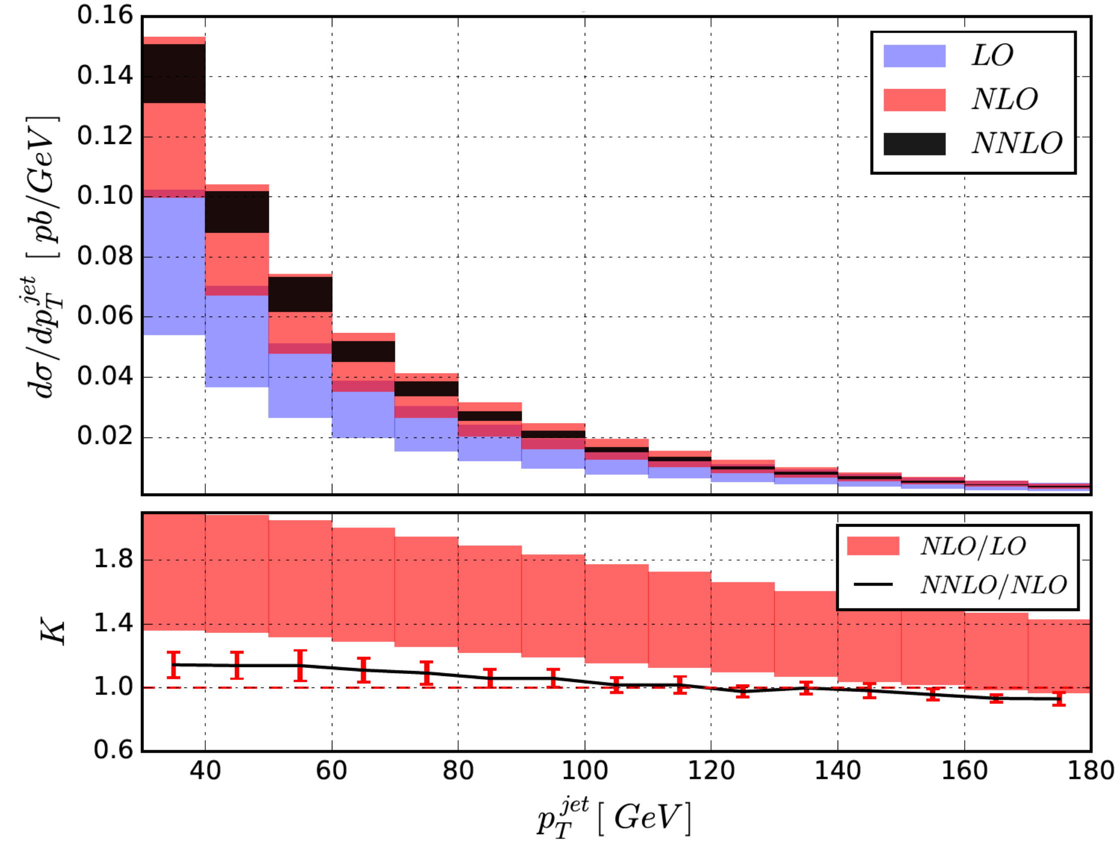
Prime examples are q_T [Catani, Grazzini] and N-Jettiness [Bougezhal, Focke, Liu, Petriello; Gaunt, Stahlhofen,Tackmann, Walsh]

- need to check cut independence
- already several implementations H+j, W+j, Z+j [Bougezhal, Focke, Liu, Petriello, Campbell, Ellis, Giele]
- interesting to compare this very new technique with other methods

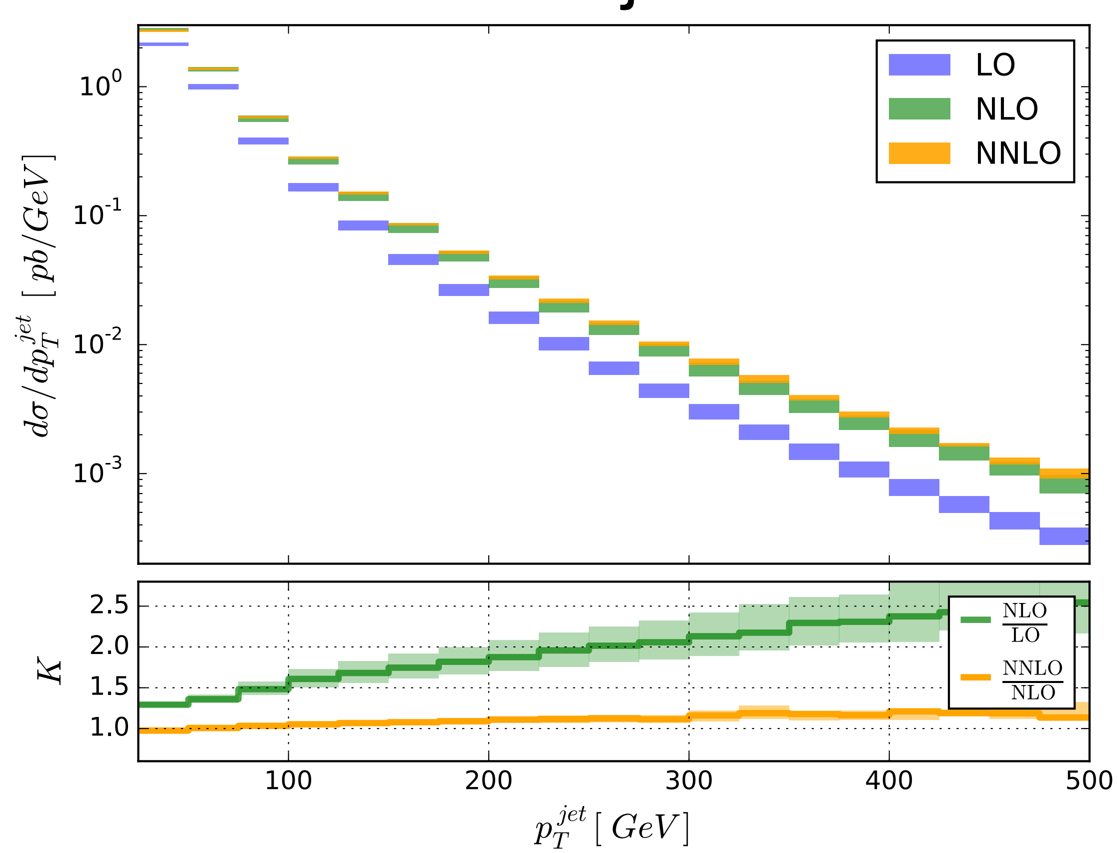
W+j


LO
NLO
NNLO
NLO/LO
NNLO/NLO
$d\sigma/dp_T^{jet}$ [pb/GeV]
K
p_T^{jet} [GeV]

H+j


LO
NLO
NNLO
NLO/LO
NNLO/NLO
$d\sigma/dp_T^{jet}$ [pb/GeV]
K
p_T^{jet} [GeV]

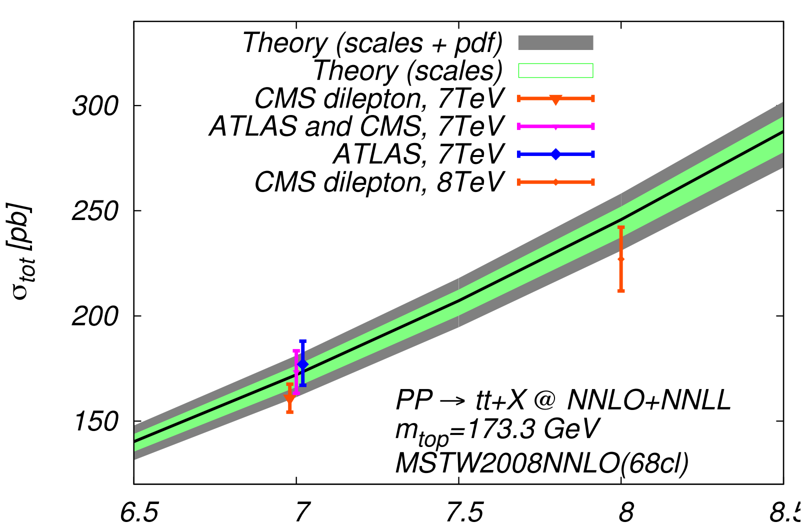
Z+j


LO
NLO
NNLO
NLO/LO
NNLO/NLO
$d\sigma/dp_T^{jet}$ [pb/GeV]
K
p_T^{jet} [GeV]

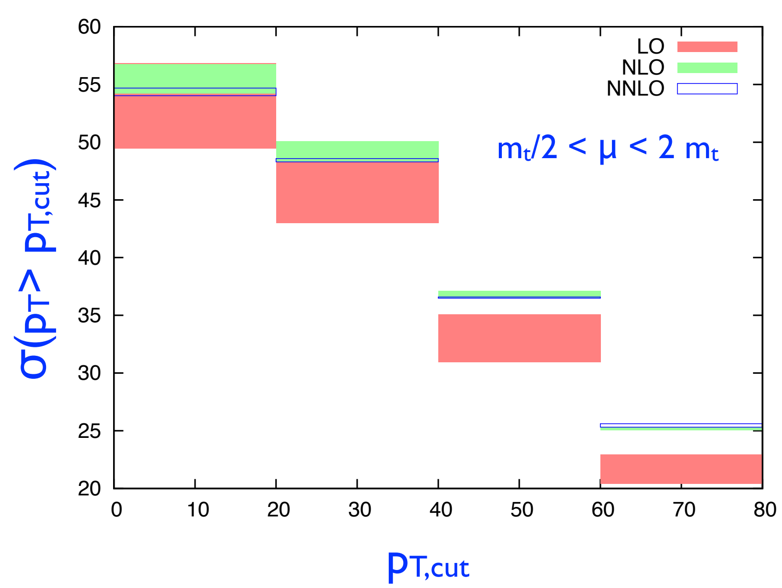
Sector Improved Numerical Subtraction

Generalizes FKS + sector decomposition to NNLO with smart phase space decomposition

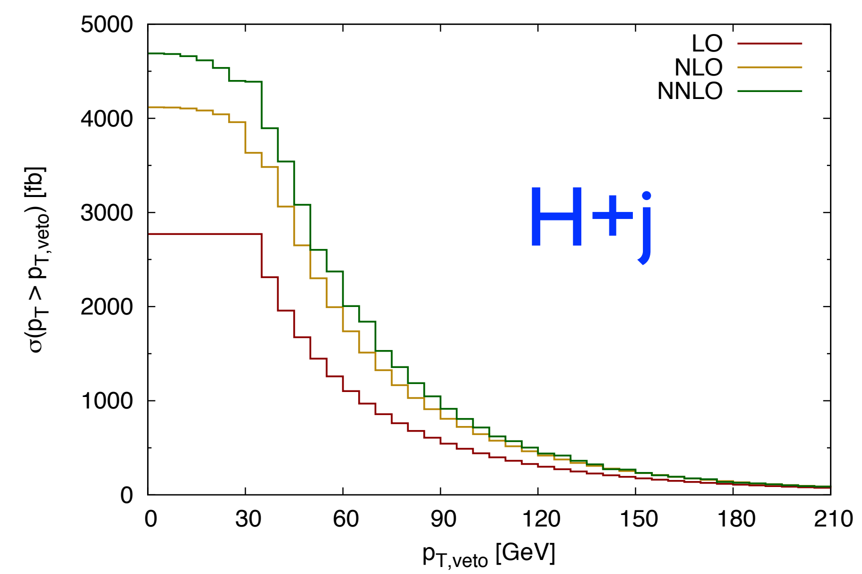
- general algorithm in d-dimensions [Czakon,Fielder, Heymes, Mitov]
- requires only the known singular functions and matrix elements



[Czakon, Fielder, Mitov]



[Burcherseifer, Caola, Melnikov]



[Boughezal, Caola, Melnikov, Petriello, Shultz]

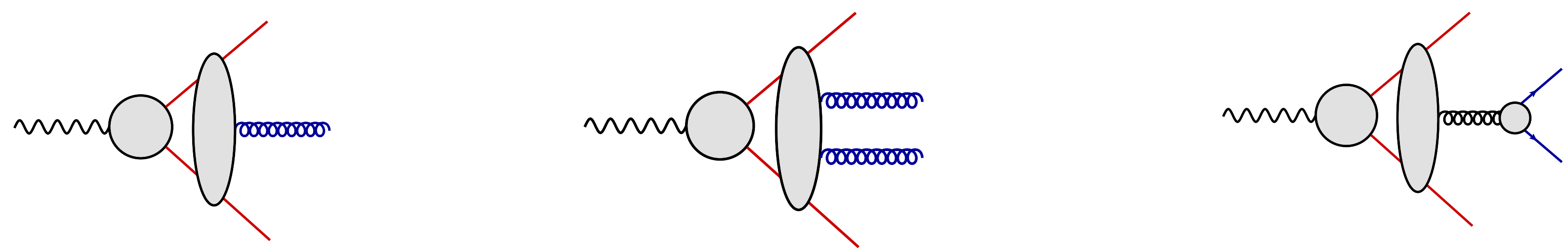
- need to show numerical pole cancellation
- can be computationally expensive, need for efficient code

Antenna Subtraction

Generalizes dipole subtraction to NNLO with antenna functions

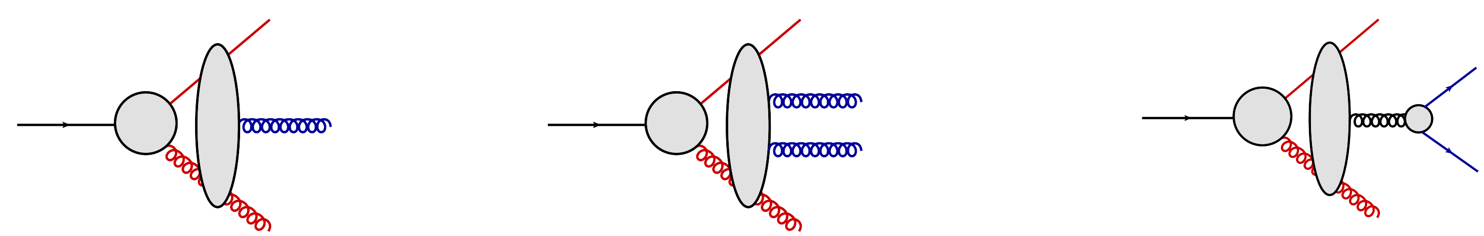
Quark-antiquark:

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



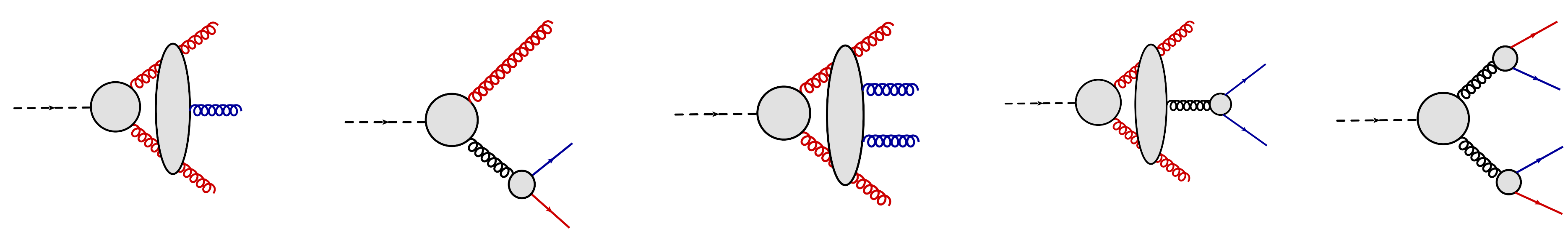
Quark-gluon:

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



Gluon-gluon:

$H \to gg + \cdots$

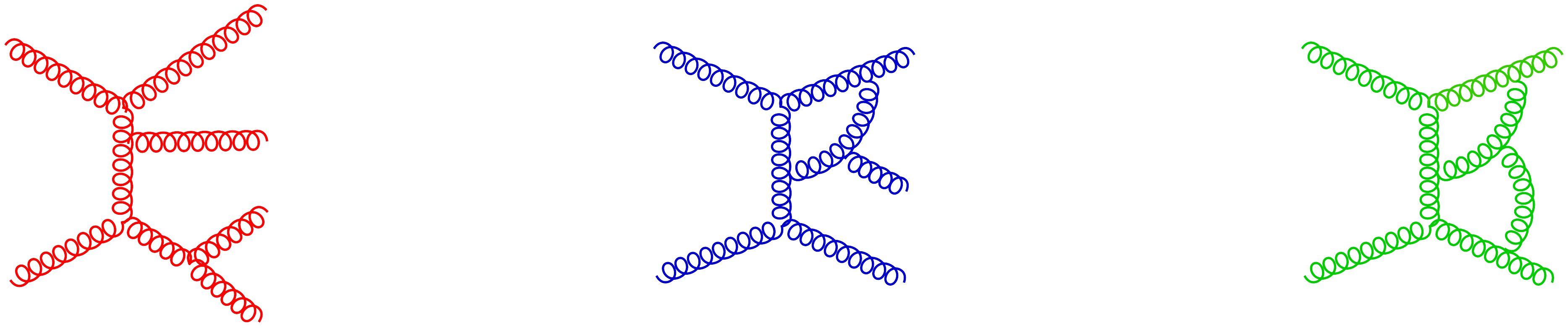


Antenna Subtraction

Unphysical intermediate quantities are divergent

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

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

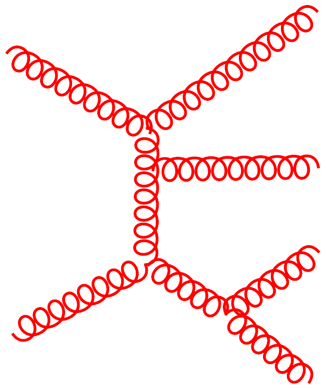
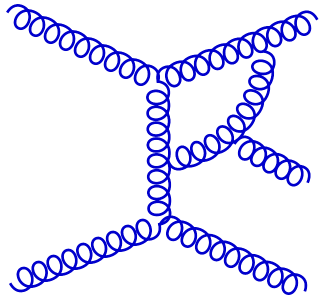
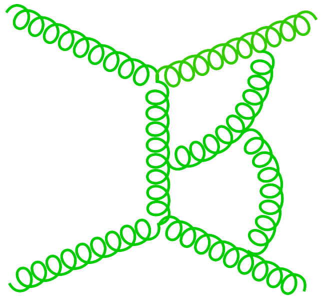


Antenna Subtraction

Unphysical intermediate quantities are divergent

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

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

Unintegrated antennae mimic divergences of RR, RV

$$A_4^0(q,g,g,\bar{q}) \to P_{qgg}^0,\ S_{ijkl}^0,\ P_{gg}^0,\ P_{qg}^0,\ S_{ijk}^0\ \ldots$$

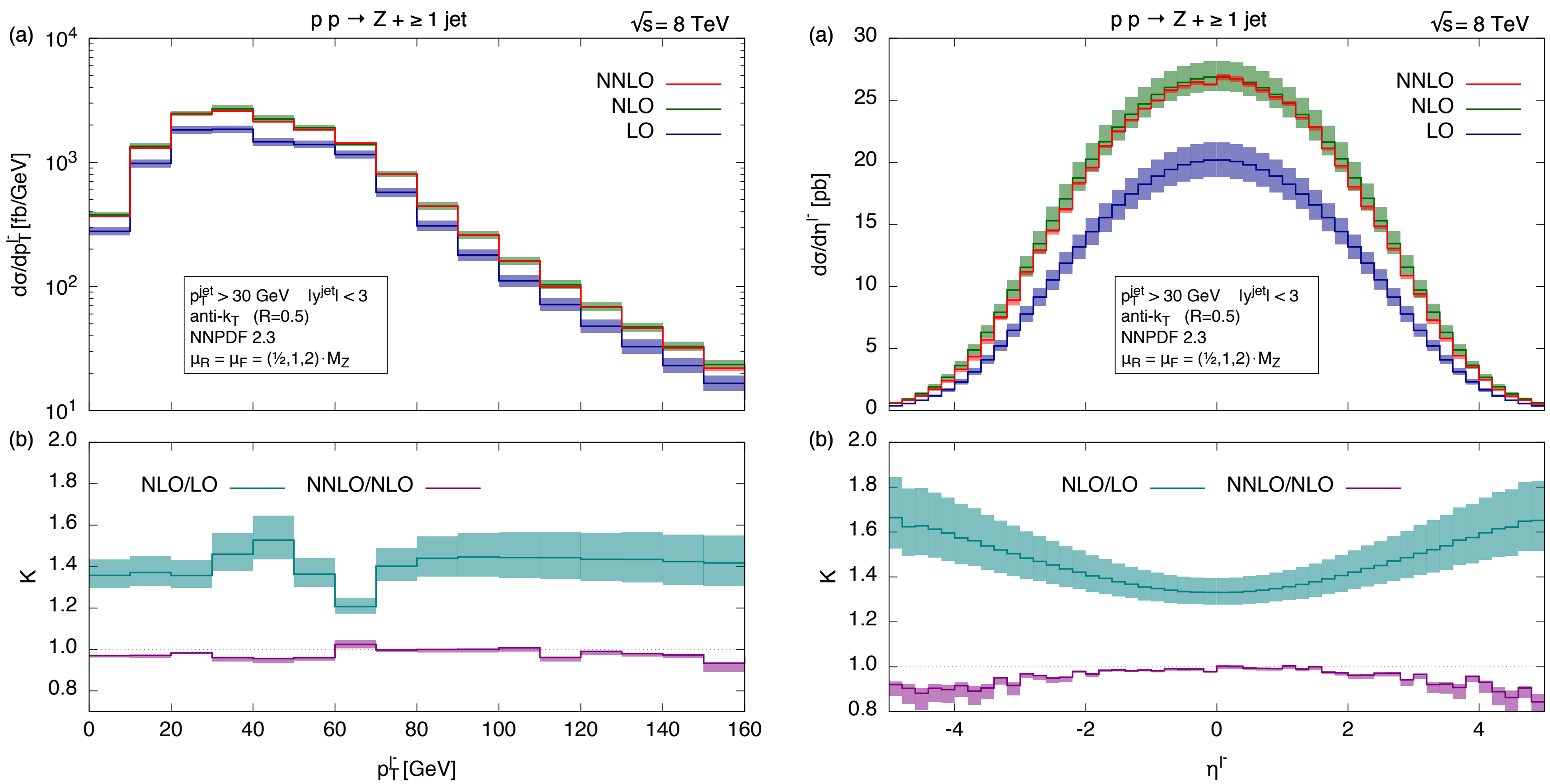
Integrated antennae match pole structure of RV, VV

$$\mathcal{A}_3^0(s_{ij}) = \boldsymbol{I}_{q\bar{q}}^{(1)}(s_{ij},\epsilon) + \mathcal{O}(\epsilon^0)$$

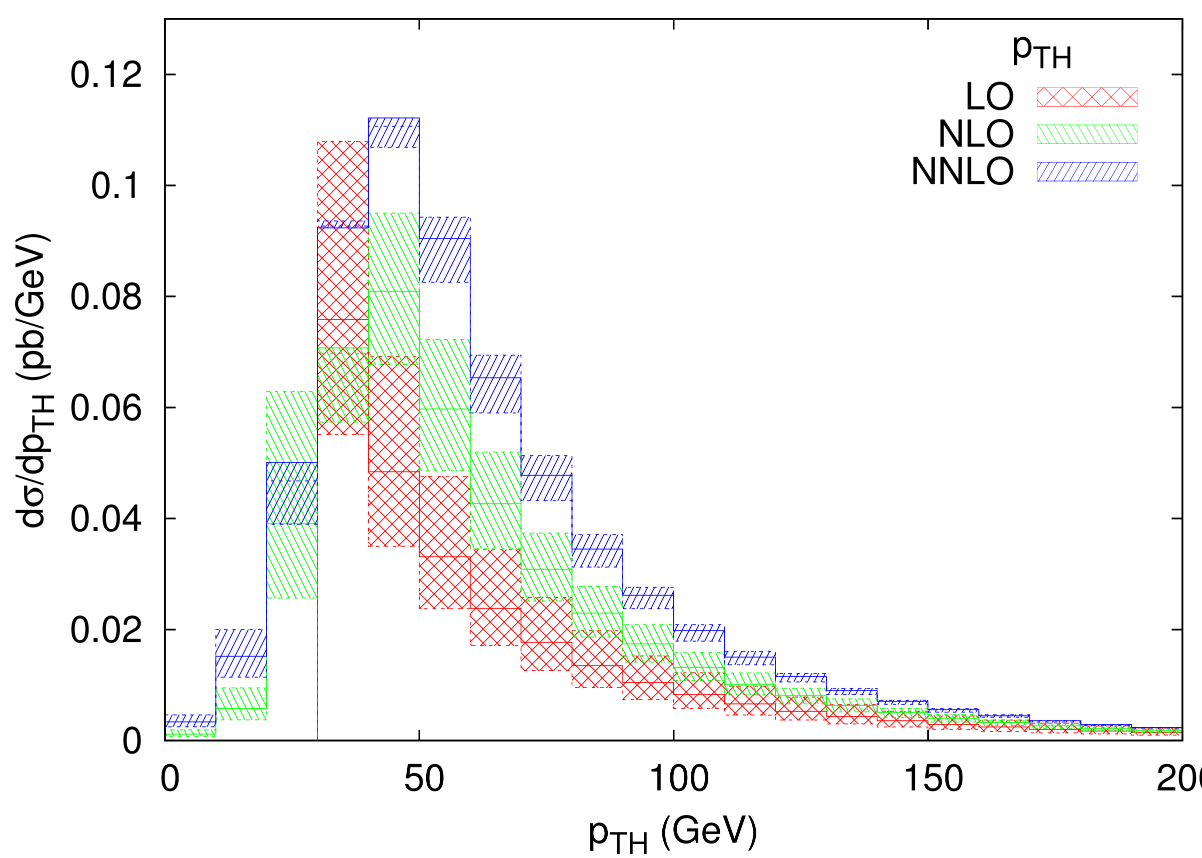
Result is IR finite cross sections:

- analytic pole cancellation
- can be used for an arbitrary number of legs
- implemented in several calculations, e^+e^- ->3j, H+j, Z+j, 2j

  [Chen, Currie, Gehrmann, Gehrmann-de Ridder, Glover, Huss, Jaquier, Morgan, Pires, Wells]



p p → Z + ≥ 1 jet
√s = 8 TeV
(a)
(b)
NNLO
NLO
LO
NLO/LO
NNLO/NLO
$p_T^{jet} > 30$ GeV $|y^{jet}| < 3$
anti-k_T (R=0.5)
NNPDF 2.3
$\mu_R = \mu_F = (½,1,2)\cdot M_Z$
$d\sigma/dp_T^{l^-}$ [fb/GeV]
$d\sigma/d\eta^{l^-}$ [pb]
K
$p_T^{l^-}$ [GeV]
η^{l^-}



p_{TH}
LO
NLO
NNLO
$d\sigma/dp_{TH}$ (pb/GeV)
p_{TH} (GeV)

Dijets

pp$\Rightarrow$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

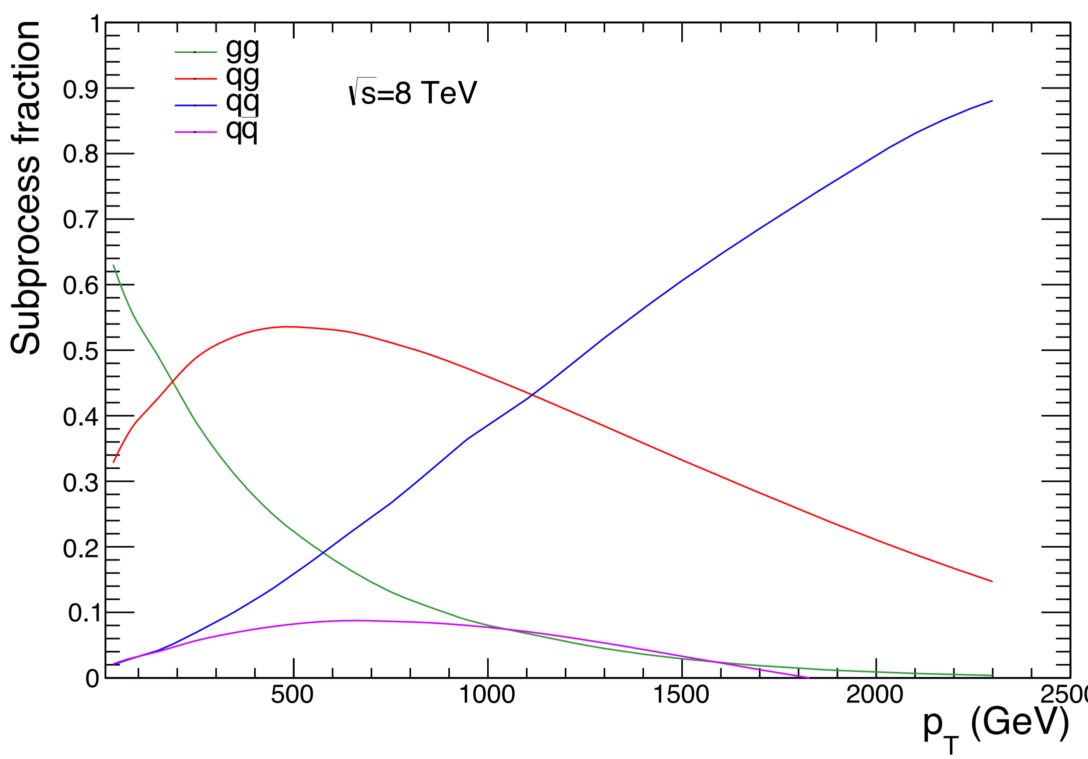
Start by considering:

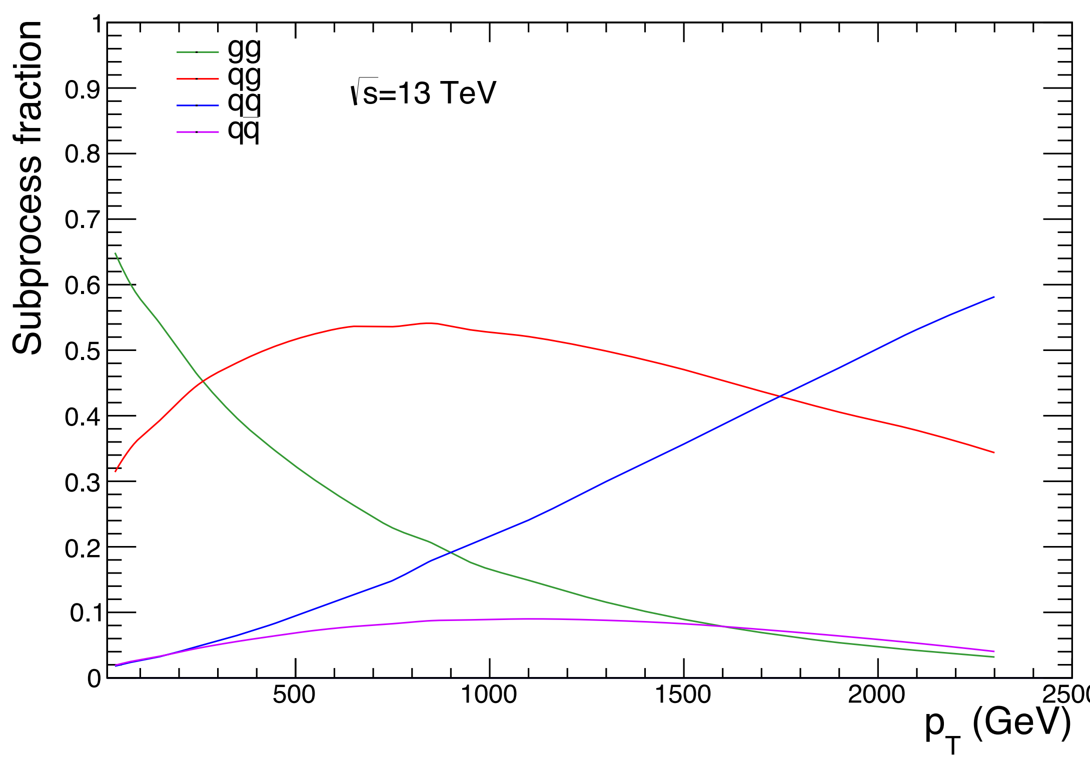
- what are the most important channels?
- what are the most important colour factors in each channel?

Channels

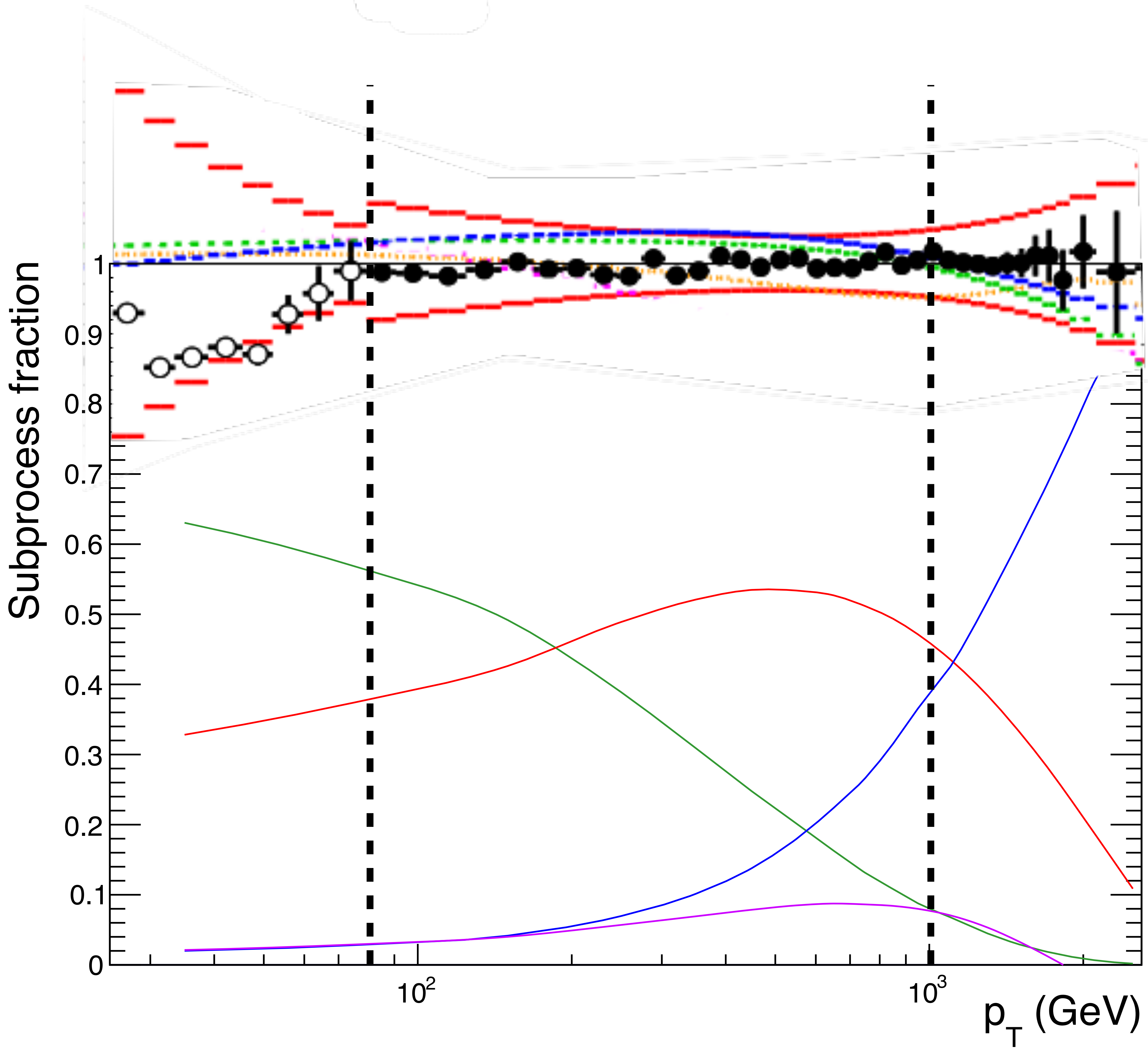
At low to moderate p_T the gluonic initial-states (gg+qg) dominate

At high p_T quark scattering becomes important





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

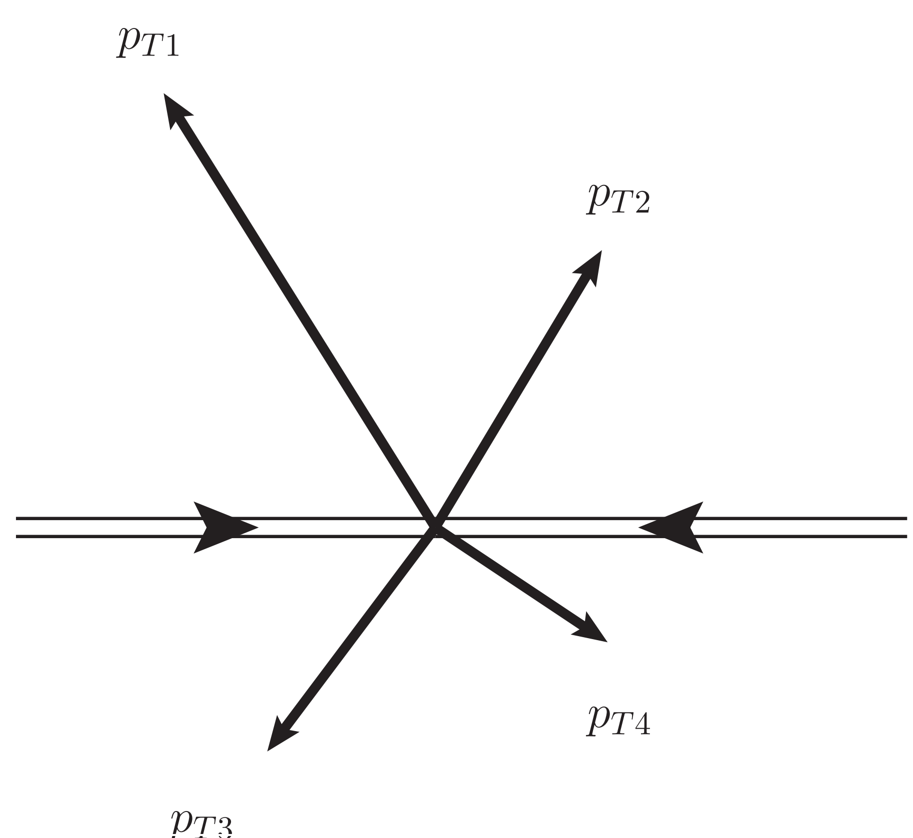


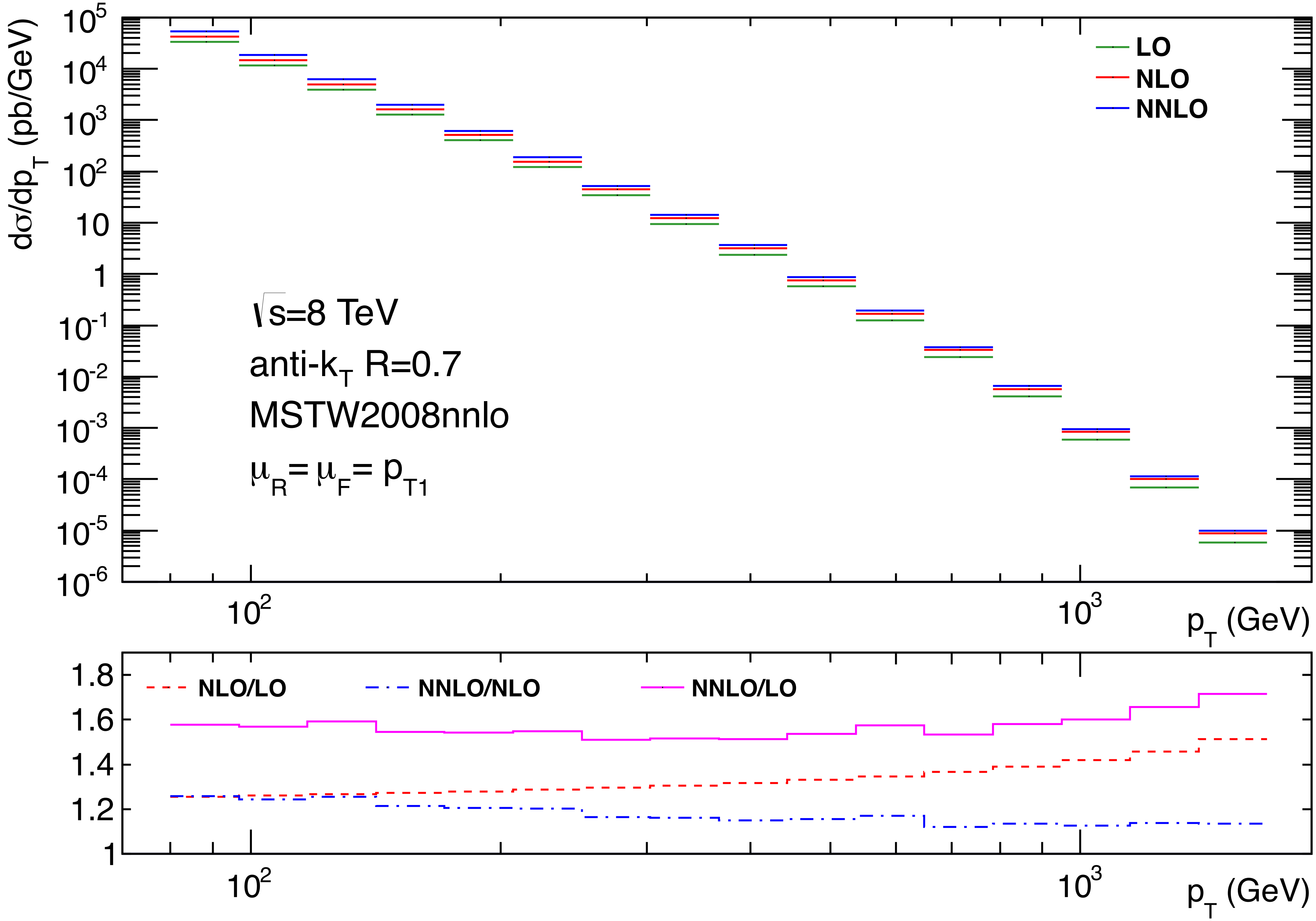
Subprocess fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^2
10^3
p_T (GeV)

Results Part I

The following results are for:

- gluons only subprocess
- leading colour contribution
- accept jets with $p_T > 20$ GeV
- rapidity cut $|y| < 4.4$
- scale $\mu = \mu_F = p_{T1}$
- anti-k_T jet algorithm R=0.7
- MSTW2008nnlo
- $\sqrt{s} = 8$ TeV



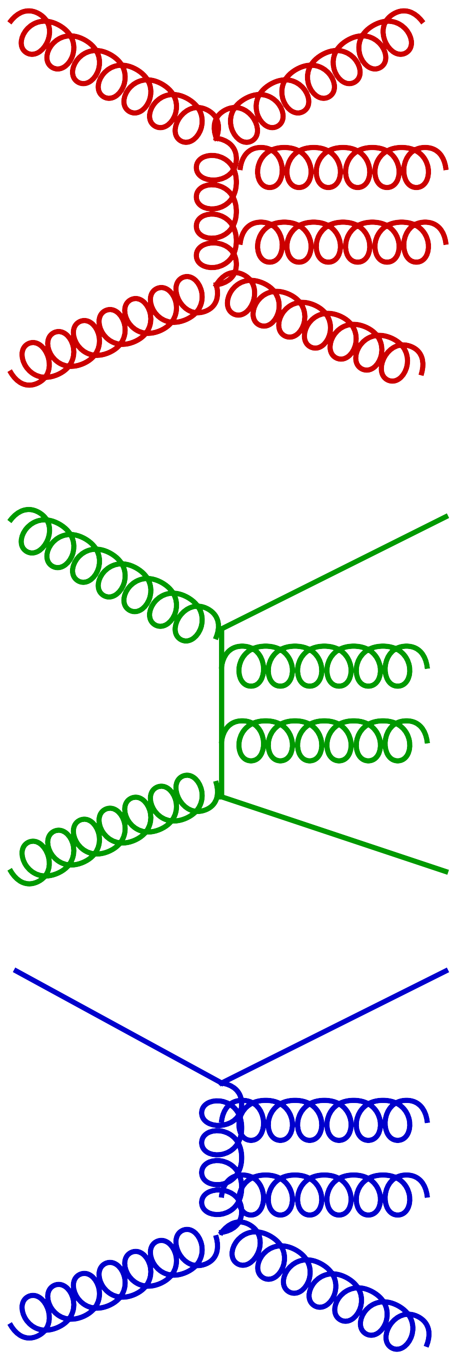


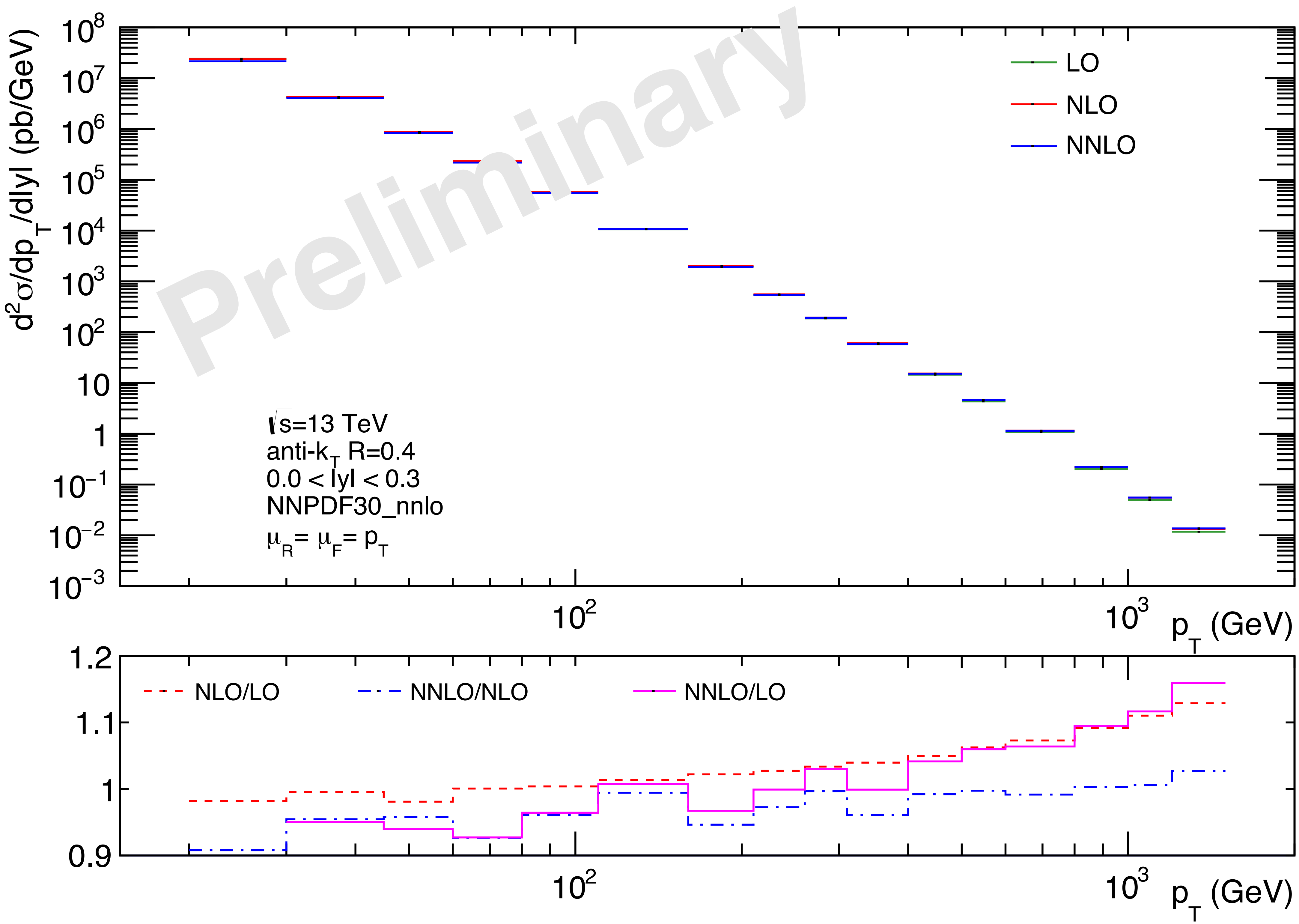
15-25% NNLO correction relative to gluons only NLO

Results Part II

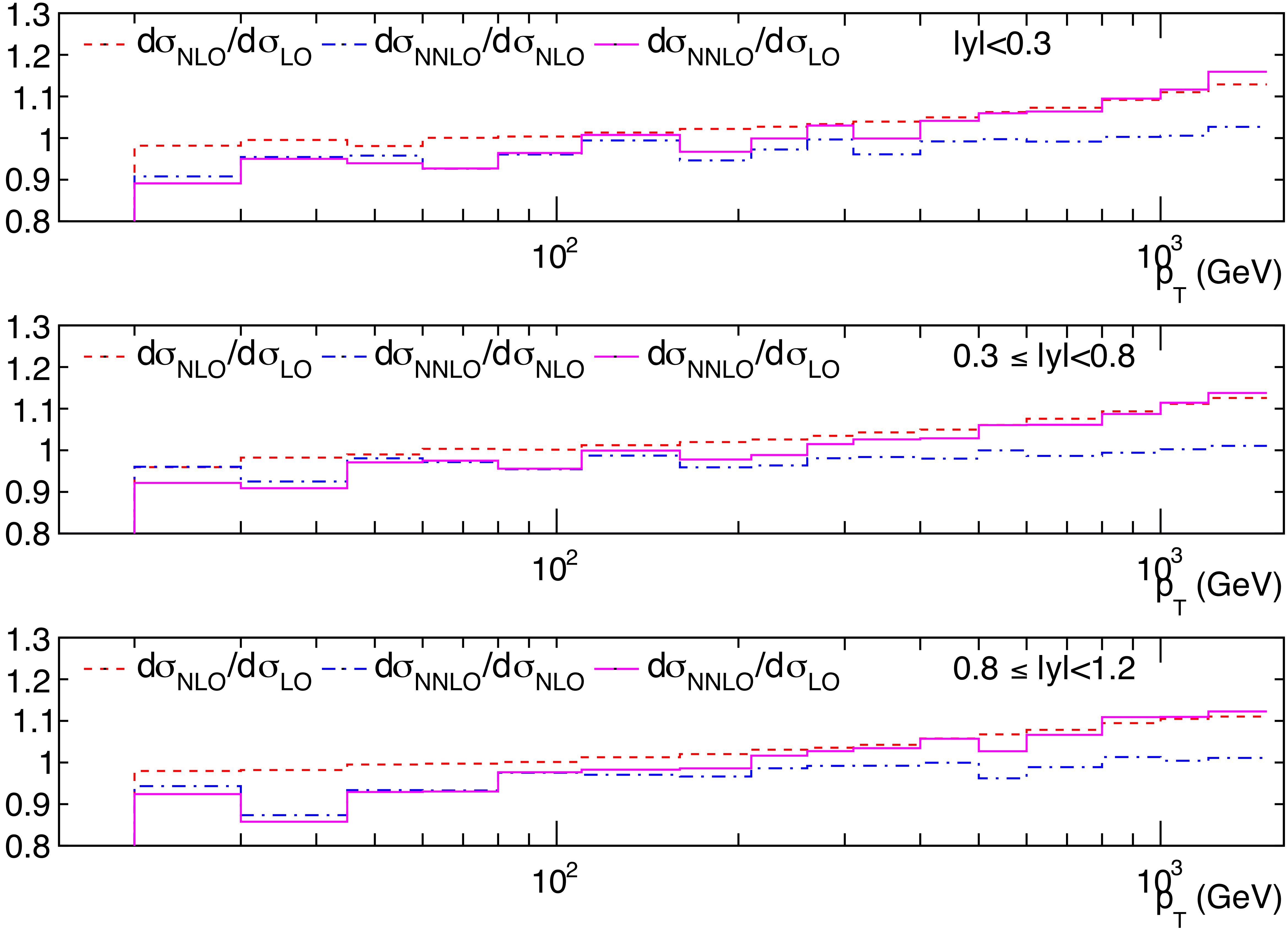
In recent runs make a number of changes:

- scale $\mu = \mu_F = p_T$, not p_{T1}
- NNPDF3.0_as_0118
- R=0.4
- normalize K-factors to *full* NLO
- include more channels and colour factors
  - N^2 corrections to gg
  - $N\,N_F$ corrections to gg
  - N^2 corrections to qg
- $\sqrt{s} = 13$ TeV





-9% to +1% NNLO correction relative to full NLO



dσNLO/dσLO
dσNNLO/dσNLO
dσNNLO/dσLO
|y|<0.3
0.3 ≤ |y|<0.8
0.8 ≤ |y|<1.2
1.3
1.2
1.1
1
0.9
0.8
10^2
10^3
pT (GeV)

Conclusions

Predictions look very different from old results:

- new scale choice p_T
- new channels: $N\,N_F$ gg and N^2 qg
- run II energies, smaller R
- K-factors now quoted with reference to full NLO

New features to be added soon:

- $N\,N_F$ correction to qg + N_F^2 correction to gg and qg
- N^2, $N\,N_F$, N_F^2 corrections to qq channel - high pT jets

These new features will change the results again; then we can talk about physics!

Summary

- Several impressive tools available for NNLO jet studies
- Phenomenology is moving very quickly
- Focus is shifting from developing techniques to exploiting power of NNLO calculations
- Computationally demanding, need to think about how best to use them
- bring on the Run II data!