Antenna Subtraction and Its Recent Applications

James Currie

based on work with or by

Chen, Gehrmann, Gehrmann-De Ridder, Glover, Huss, Morgan, Niehues, Pires, Wells

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IP3

MC@NNLO

Coming Up

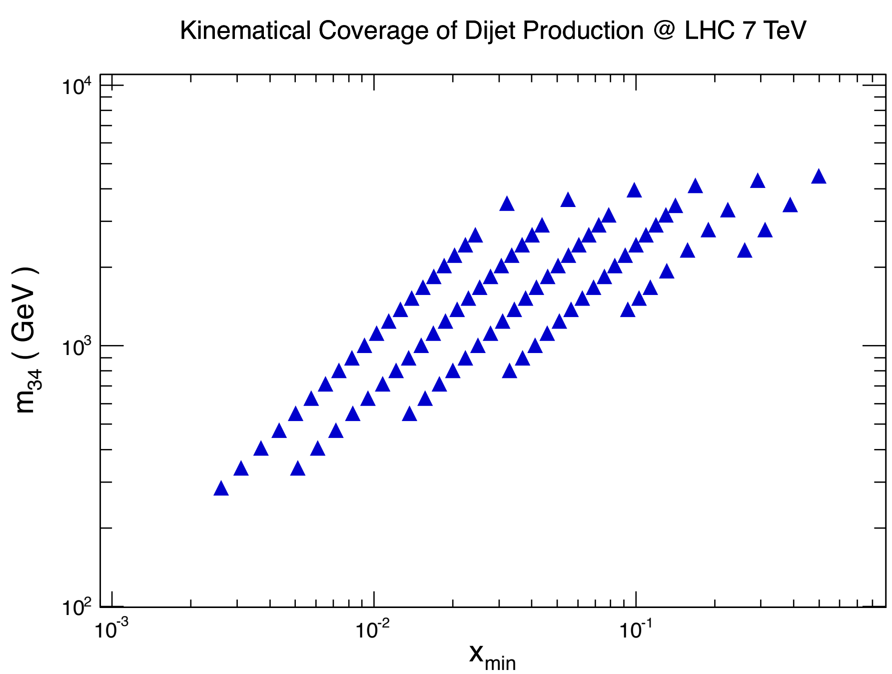
- Higher order corrections
- Antenna Subtraction
- Technicalities and possible improvements
- Recent applications of the method
- Looking to the future

Motivation for doing higher order calculations

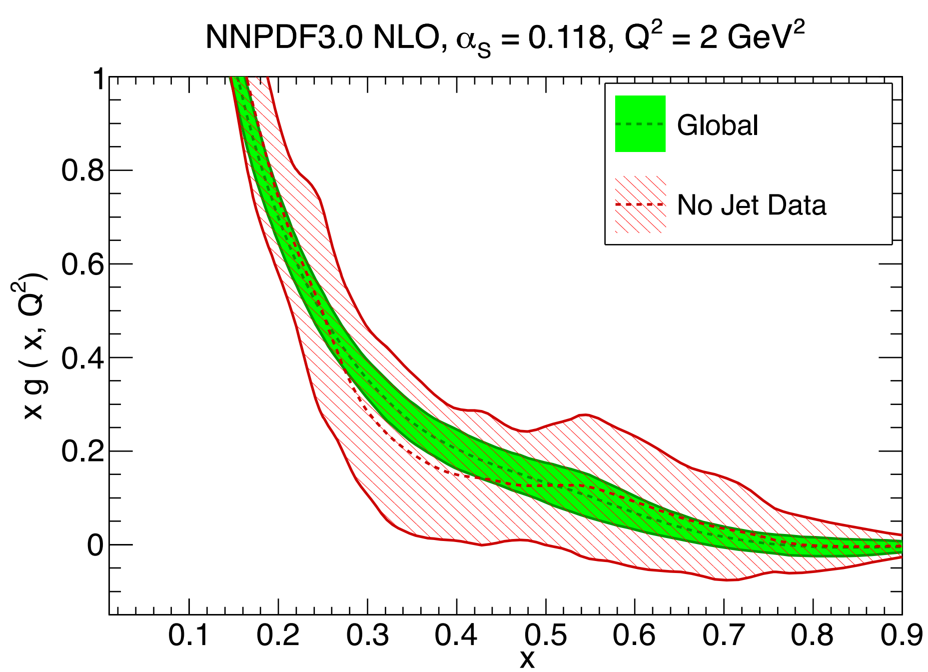
Constraining PDFs

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

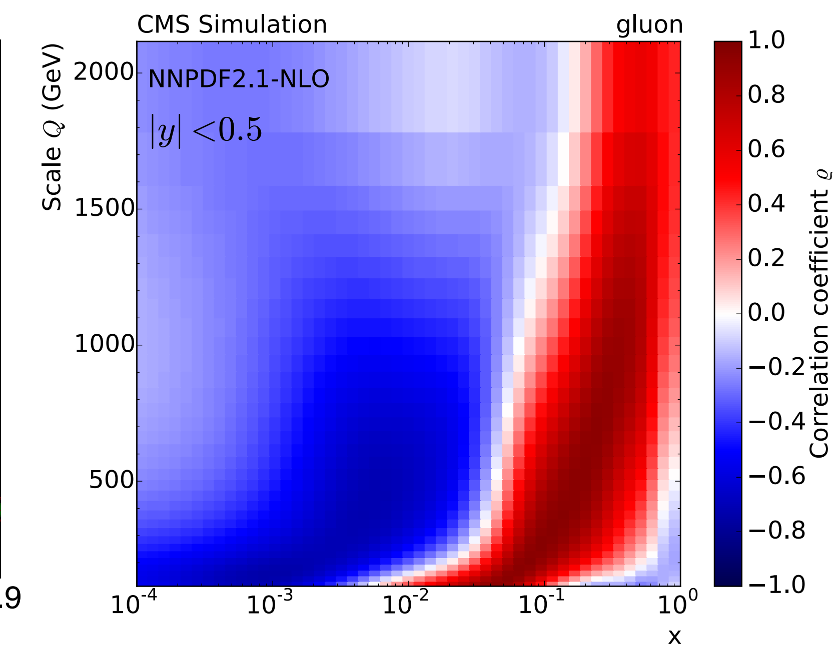
- LHC jets probe a wide range of x
- gluon PDF directly sensitive to jet data, especially at large x
- would like to consistently include NNLO jet data in NNLO PDF fits without using kinematically limited approximations



Rojo hep-ph [1410.7728]

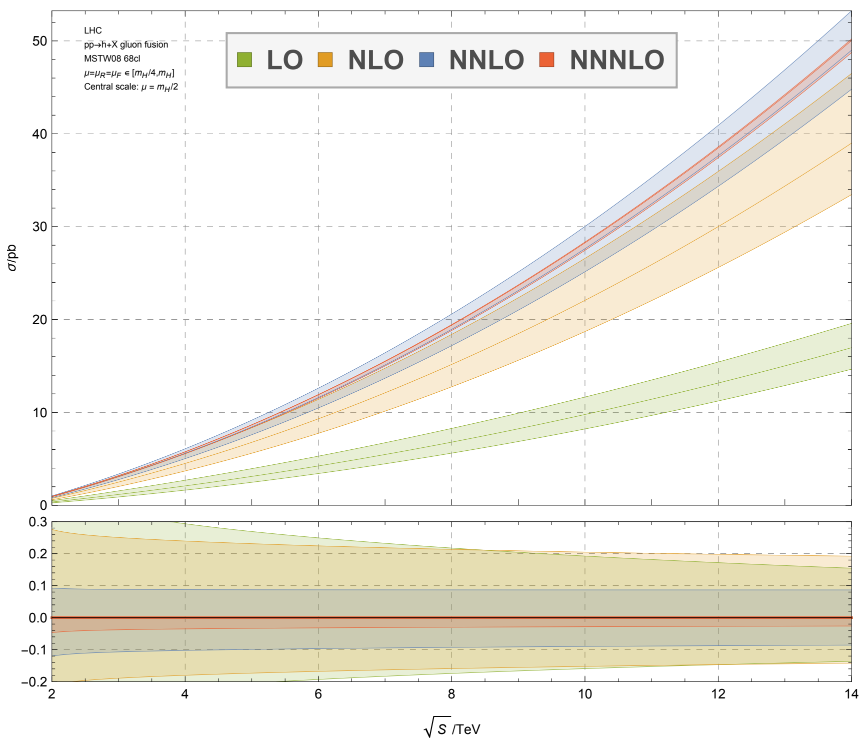


NNPDF collaboration hep-ph [1410.8849]

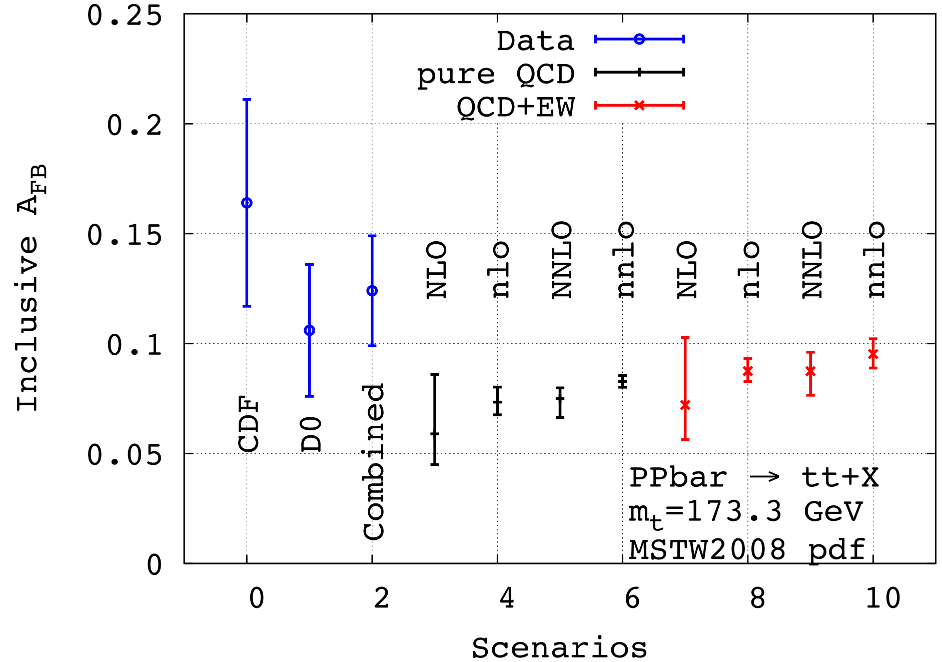


Rojo hep-ph [1410.7728]

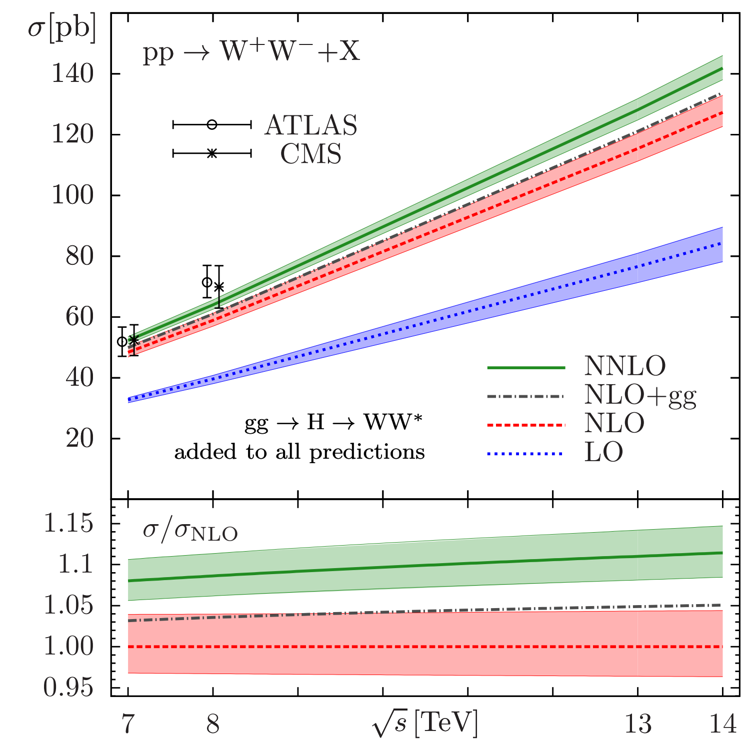
Discrepancies with data



Anastasiou, Duhr, Dulat, Herzog, Mistlberger



Czakon, Fiedler, Mitov



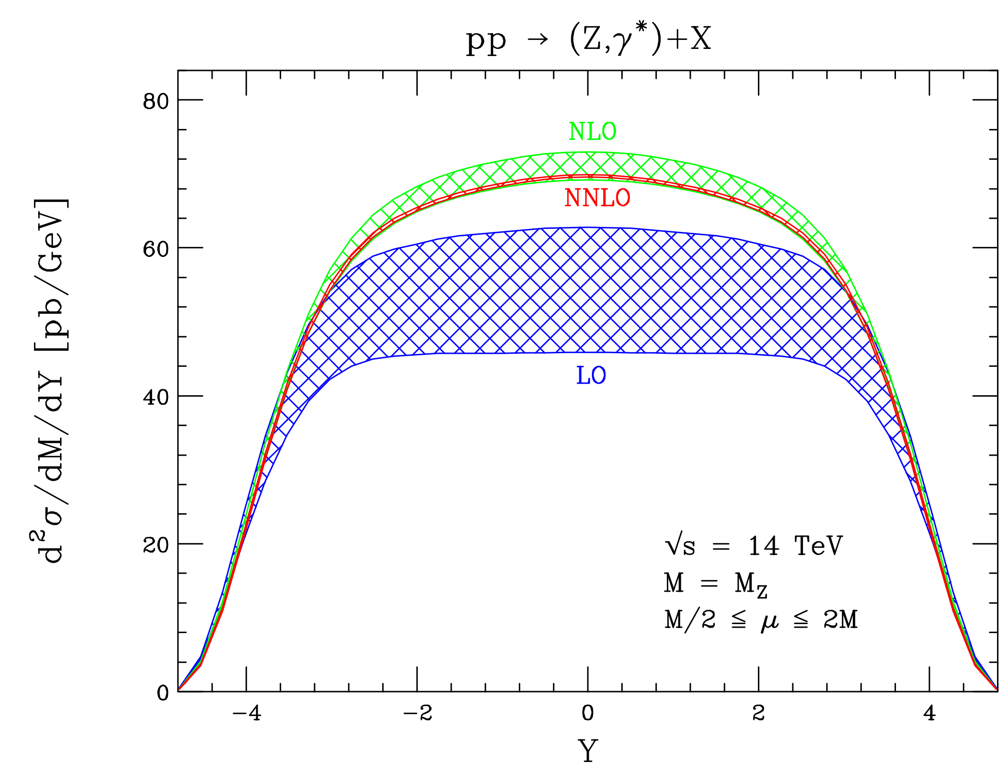
Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Ravlev, Tancredi

No BSM discovered yet… but plenty of BNLO

Theoretical Uncertainties

- Scale uncertainty one of the main obstacles, especially in jet veto and exclusive searches

- NNLO contains all features of calculation
  - initial-state radiation
  - non-trivial jet algorithm
  - all partonic channels
  - non-trivial physical scales

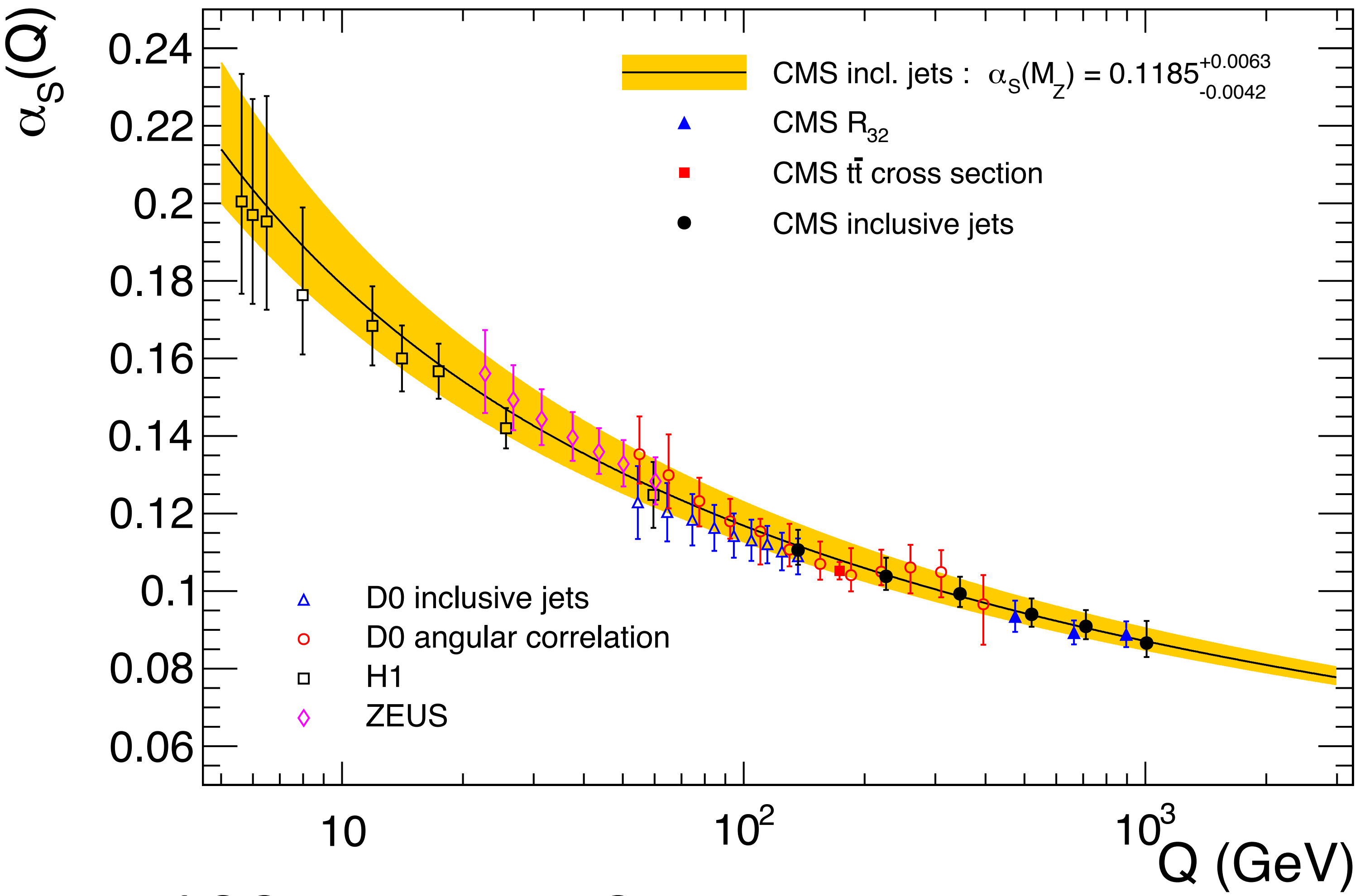


Anastasiou, Dixon, Melnikov, Petriello ’04

Strong Coupling

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

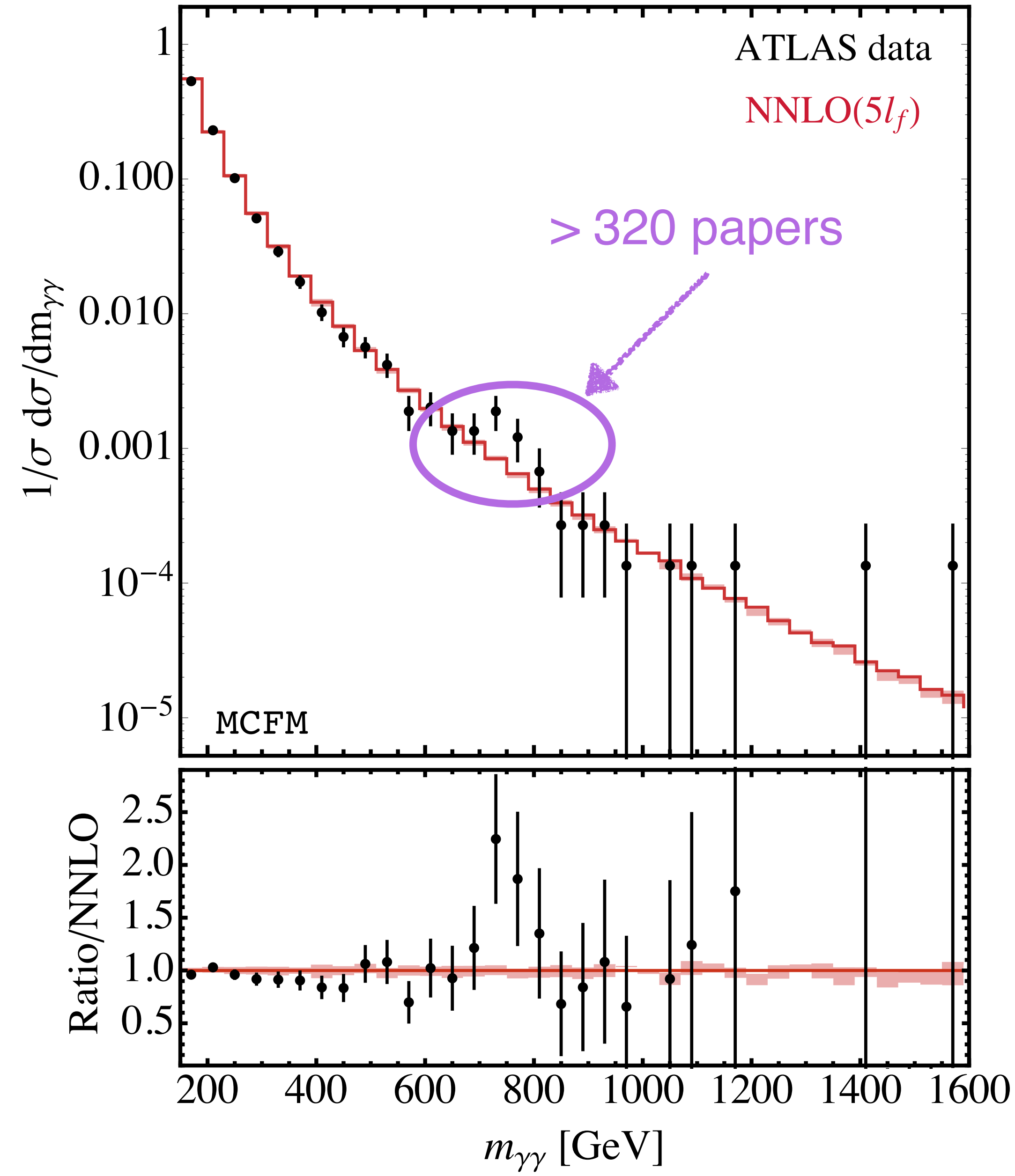


CMS hep-ex [1410.6765]

- very satisfying test of QCD and the LHC
- model independent probe of new physics

New Physics

- Bump hunting often uses data driven methods
- extrapolation to region with little data
- can fit rate and compare with precise SM prediction
- fit works well… bump survives until at least ICHEP



Campbell, Ellis, Li, Williams: 1603.02663

Methods at NLO

Main problem at NLO is extracting singularities… many ways to do this:

- Dipole subtraction [Catani, Seymour '96]
- FKS subtraction [Frixione, Kunszt, Signer '95]
- Sector decomposition [Hepp '67; Binoth, Heinrich '00]
- Phase space slicing [Giele, Glover '91]

Methods at NNLO

Main problem at NNLO is disentangling singularities

Most methods basically a generalization of NLO:

- Antenna subtraction [Kosower '03; Gehrmann, Gehrmann-De Ridder, Glover '05]
- CoLorFul subtraction [Del Duca, Somogyi, Trocsanyi '06] (dipoles)
- Sector-improved residue subtraction [Czakon '10] (FKS+sectors)
- qT and N-Jettiness subtraction [Catani, Grazzini '07; Gaunt, Stahlhofen, Tackmann, Walsh '15; Boughezal, Focke, Liu, Petriello '15] (slicing)

(not an exhaustive list)

Subtraction at NLO

No overlapping singularities so very simple structure

$$\mathrm{d}\sigma_{ab,NLO} = \int_{\Phi_{m+1}} \left[\mathrm{d}\sigma_{ab}^{R} - \mathrm{d}\sigma_{ab}^{S}\right] + \int_{\Phi_{m}} \left[\mathrm{d}\sigma_{ab}^{V} - \mathrm{d}\sigma_{ab}^{T}\right]$$

$$\mathrm{d}\sigma_{ab}^{T} = -\int_{1} \mathrm{d}\sigma_{ab}^{S} + \mathrm{d}\sigma_{ab}^{MF}$$

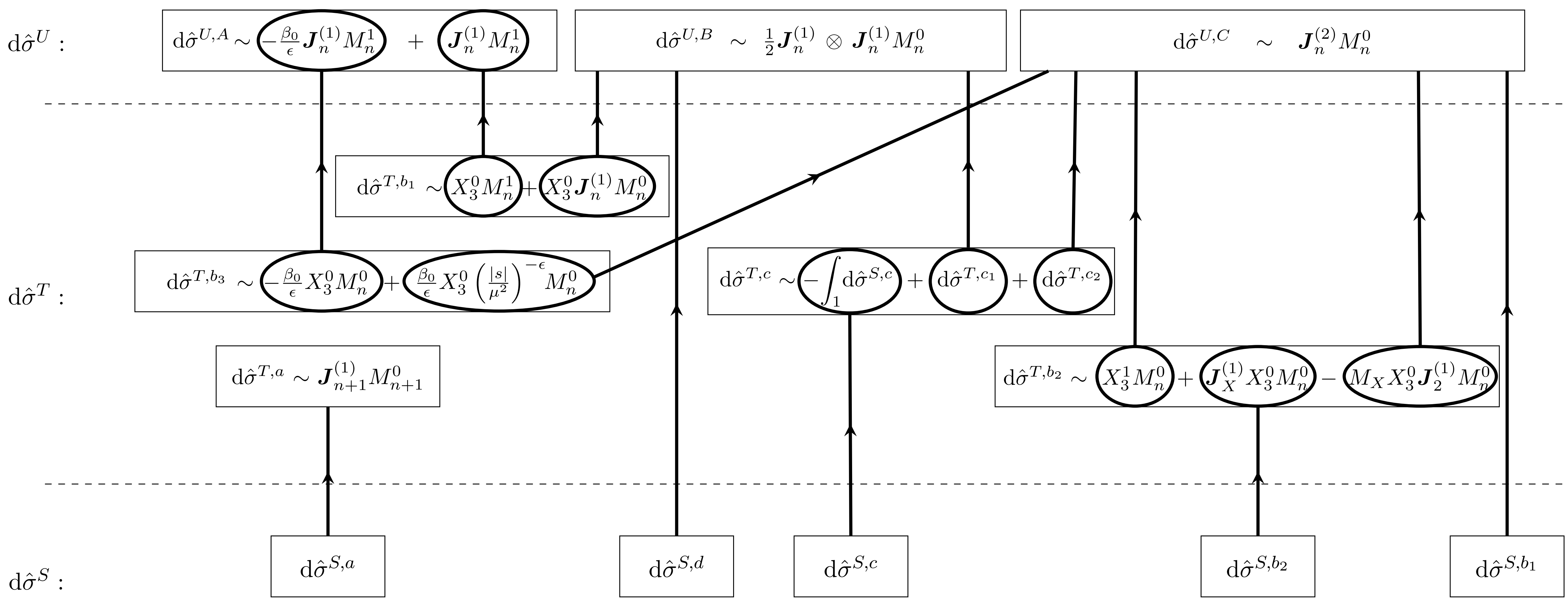
$$\mathrm{d}\sigma_{ab}^{S}$$

Subtraction at NNLO

At NNLO more terms to regulate

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

But real problem is dealing with intricate overlapping singularities



$d\hat{\sigma}^U$:
$d\hat{\sigma}^{U,A} \sim -\frac{\beta_0}{\epsilon}\boldsymbol{J}_n^{(1)}M_n^1 + \boldsymbol{J}_n^{(1)}M_n^1$
$d\hat{\sigma}^{U,B} \sim \frac{1}{2}\boldsymbol{J}_n^{(1)} \otimes \boldsymbol{J}_n^{(1)}M_n^0$
$d\hat{\sigma}^{U,C} \sim \boldsymbol{J}_n^{(2)}M_n^0$
$d\hat{\sigma}^{T,b_1} \sim X_3^0 M_n^1 + X_3^0\boldsymbol{J}_n^{(1)}M_n^0$
$d\hat{\sigma}^T$:
$d\hat{\sigma}^{T,b_3} \sim -\frac{\beta_0}{\epsilon}X_3^0 M_n^0 + \frac{\beta_0}{\epsilon}X_3^0\left(\frac{|s|}{\mu^2}\right)^{-\epsilon}M_n^0$
$d\hat{\sigma}^{T,c} \sim -\int_1 d\hat{\sigma}^{S,c} + d\hat{\sigma}^{T,c_1} + d\hat{\sigma}^{T,c_2}$
$d\hat{\sigma}^{T,a} \sim \boldsymbol{J}_{n+1}^{(1)}M_{n+1}^0$
$d\hat{\sigma}^{T,b_2} \sim X_3^1 M_n^0 + \boldsymbol{J}_X^{(1)}X_3^0 M_n^0 - M_X X_3^0\boldsymbol{J}_2^{(1)}M_n^0$
$d\hat{\sigma}^S$:
$d\hat{\sigma}^{S,a}$
$d\hat{\sigma}^{S,d}$
$d\hat{\sigma}^{S,c}$
$d\hat{\sigma}^{S,b_2}$
$d\hat{\sigma}^{S,b_1}$

Antenna Subtraction

Basic idea:

construct a counterterm that mimics the matrix element in all singular regions of phase space

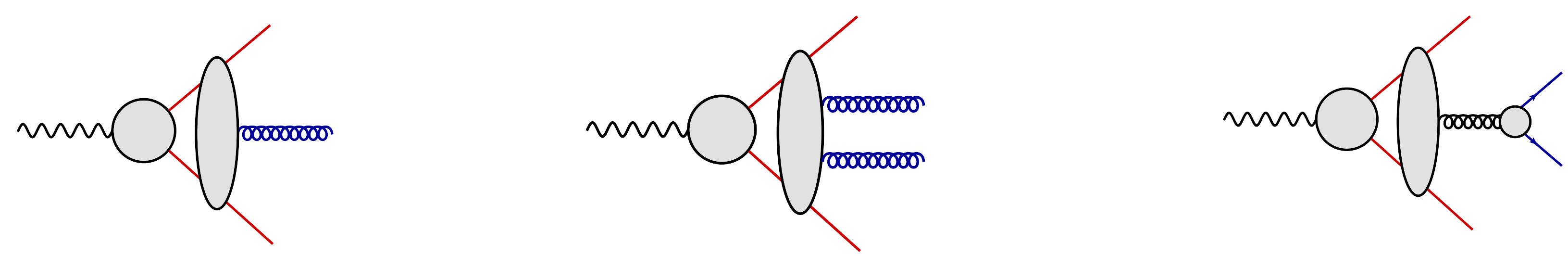
Antennae

Antenna functions built from matrix elements:

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

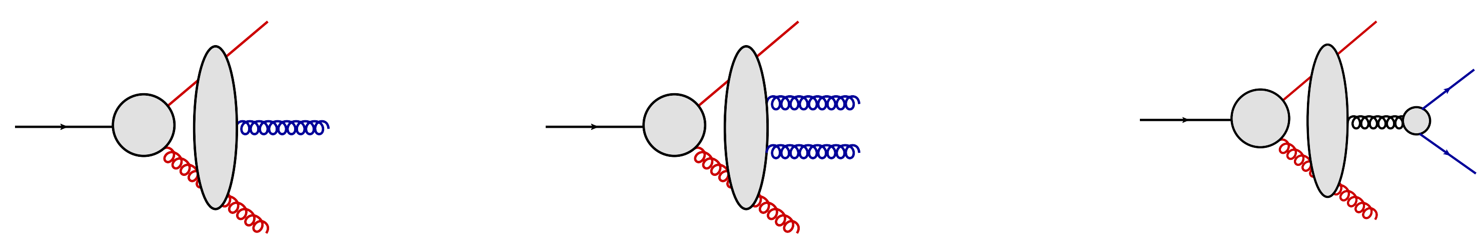
Quark-antiquark:

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



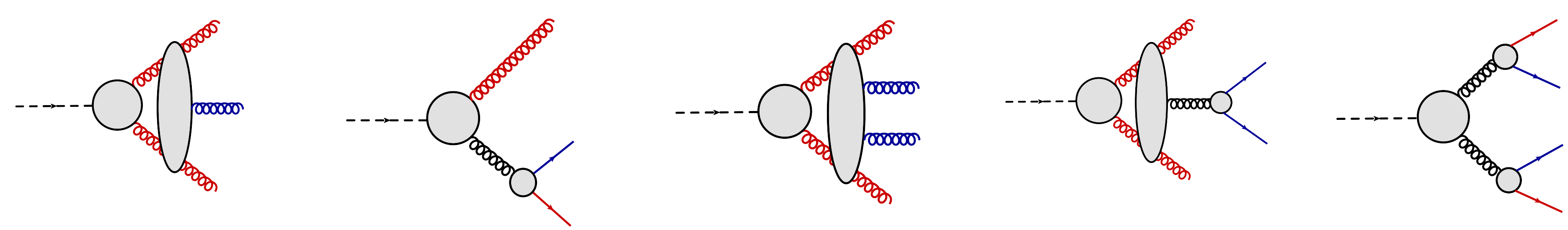
Quark-gluon:

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

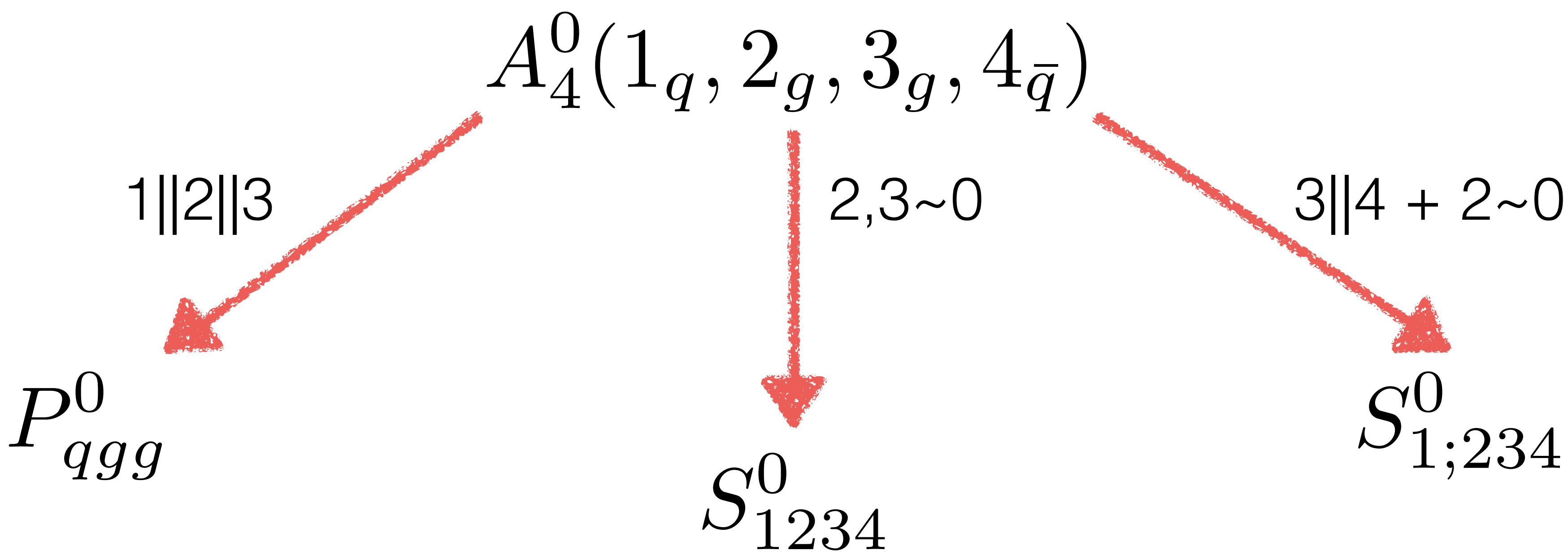


Gluon-gluon:

$H \to gg + \cdots$



Antenna mimics all singularities of QCD

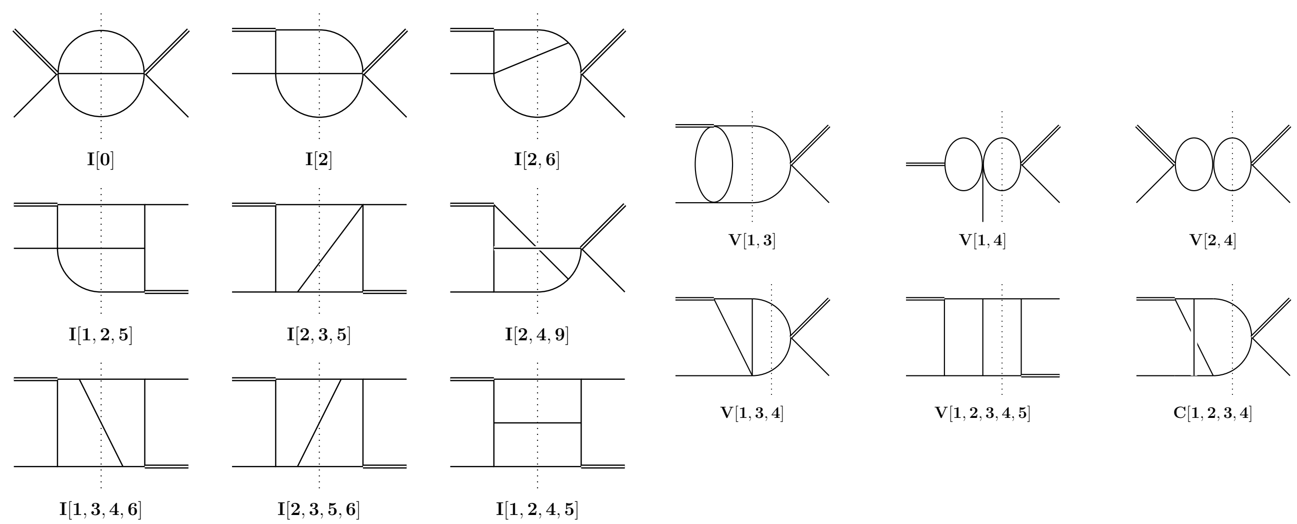


Phase space map smoothly interpolates momenta for reduced matrix element between limits

$$\widetilde{(123)} = xp_1 + r_1p_2 + r_2p_3 + zp_4$$
$$\widetilde{(234)} = (1-x)p_1 + (1-r_1)p_2 + (1-r_2)p_3 + (1-z)p_4$$

Integrating the Antennae

- Relate phase space integrals to multiloop integrals via optical theorem
- apply well developed techniques IBP, LI to masters

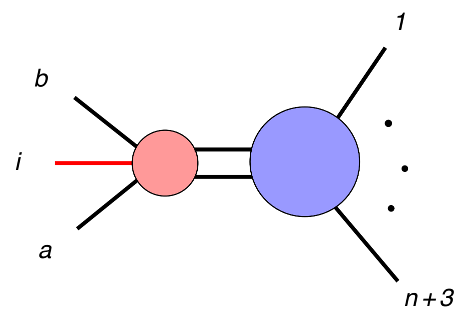


- all antennae in all crossings now successfully integrated:
  - Final-Final [Gehrman, Gehrmann-De Ridder, Glover ’04, ’05]
  - Initial-Final [Daleo, Gehrmann-De Ridder, Gehrmann, Luisoni ’10]
  - Initial-Initial [Gehrmann, Monni ’11; Boughezal, Gehrmann-De Ridder, Ritzmann ’11; Gehrmann, Ritzmann ’12]

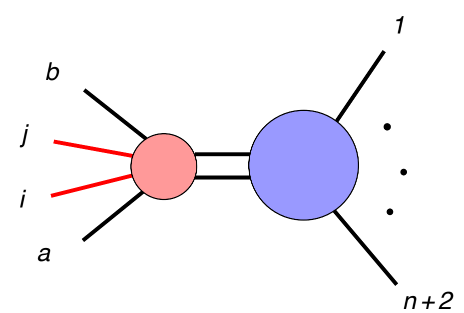
Double Real

Subtraction term constructed to remove:

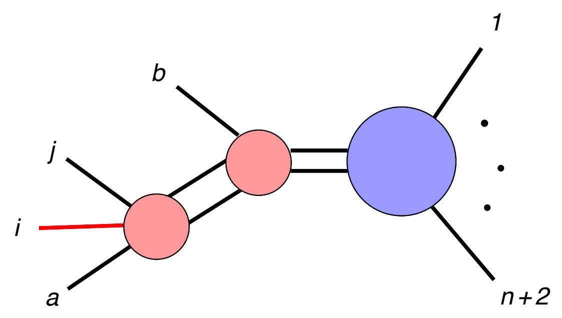
- single unresolved

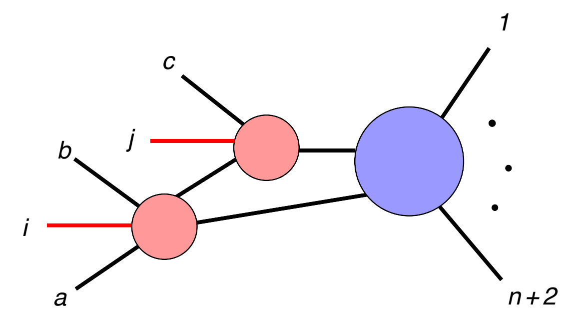


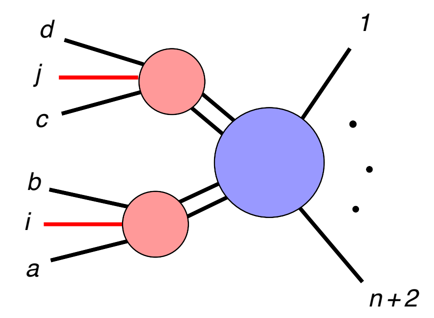
- colour connected double unresolved

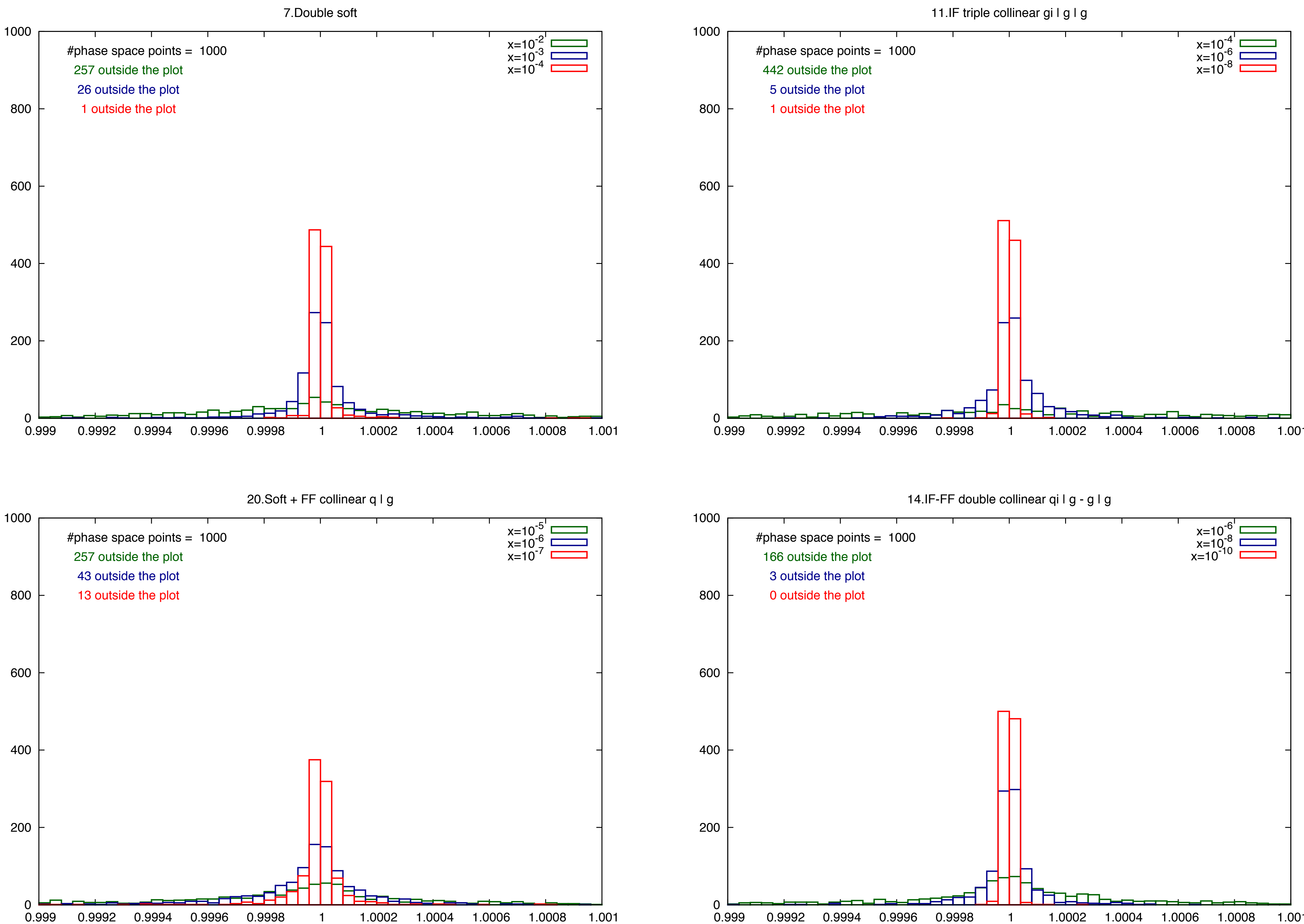


- over-subtraction in single and double unresolved limits









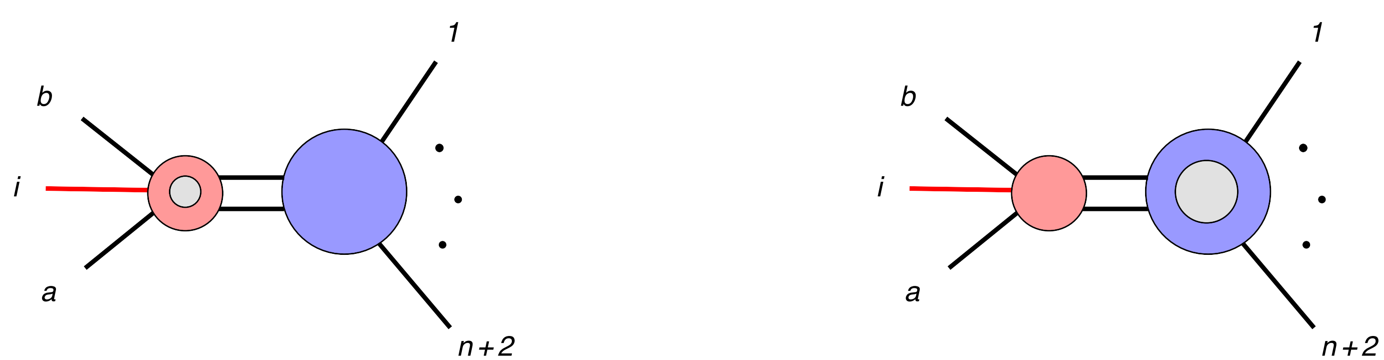
7.Double soft
#phase space points = 1000
257 outside the plot
26 outside the plot
1 outside the plot
x=10^-2
x=10^-3
x=10^-4
11.IF triple collinear gi l g l g
#phase space points = 1000
442 outside the plot
5 outside the plot
1 outside the plot
x=10^-4
x=10^-6
x=10^-8
20.Soft + FF collinear q l g
#phase space points = 1000
257 outside the plot
43 outside the plot
13 outside the plot
x=10^-5
x=10^-6
x=10^-7
14.IF-FF double collinear qi l g - g l g
#phase space points = 1000
166 outside the plot
3 outside the plot
0 outside the plot
x=10^-6
x=10^-8
x=10^-10
0
200
400
600
800
1000
0.999
0.9992
0.9994
0.9996
0.9998
1
1.0002
1.0004
1.0006
1.0008
1.001

Real Virtual

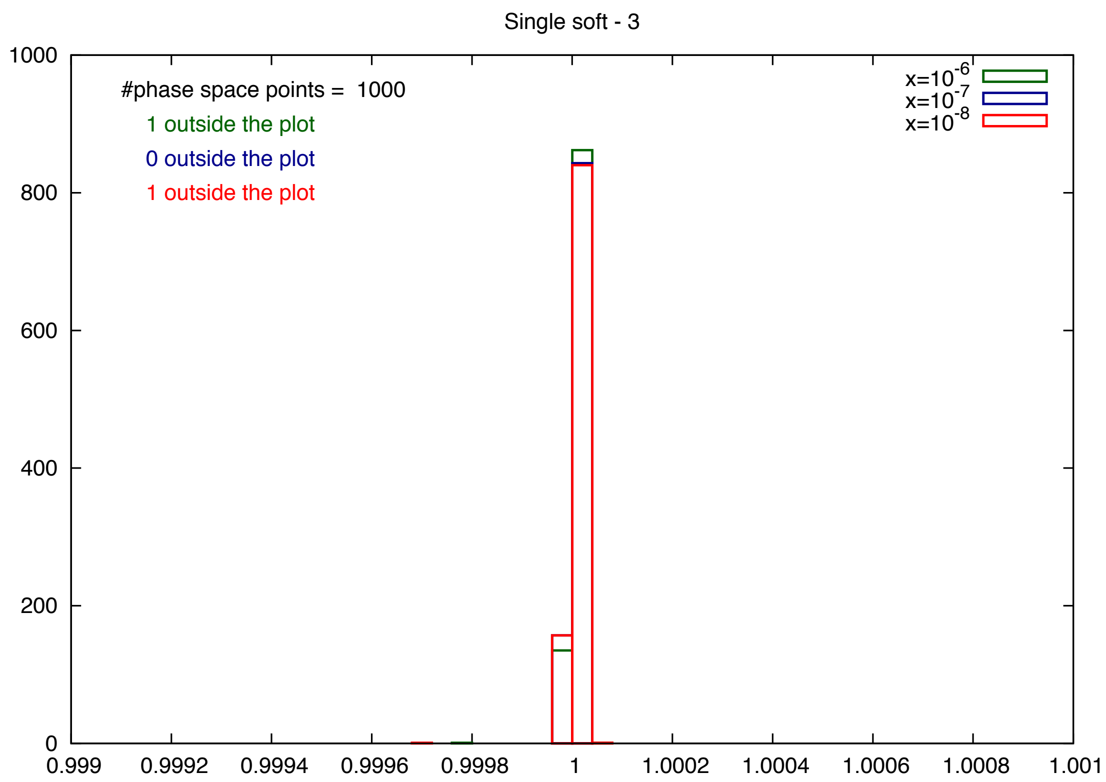
1. Analytic pole cancellation against 1-loop matrix element

$$2\mathrm{Re}\langle\mathcal{M}^0_{n+3}|\mathcal{M}^1_{n+3}\rangle + \boldsymbol{J}^{(1)}_{n+3}(1,\cdots,n+3;\epsilon)\langle\mathcal{M}^0_{n+3}|\mathcal{M}^0_{n+3}\rangle = \mathcal{O}(\epsilon^0)$$

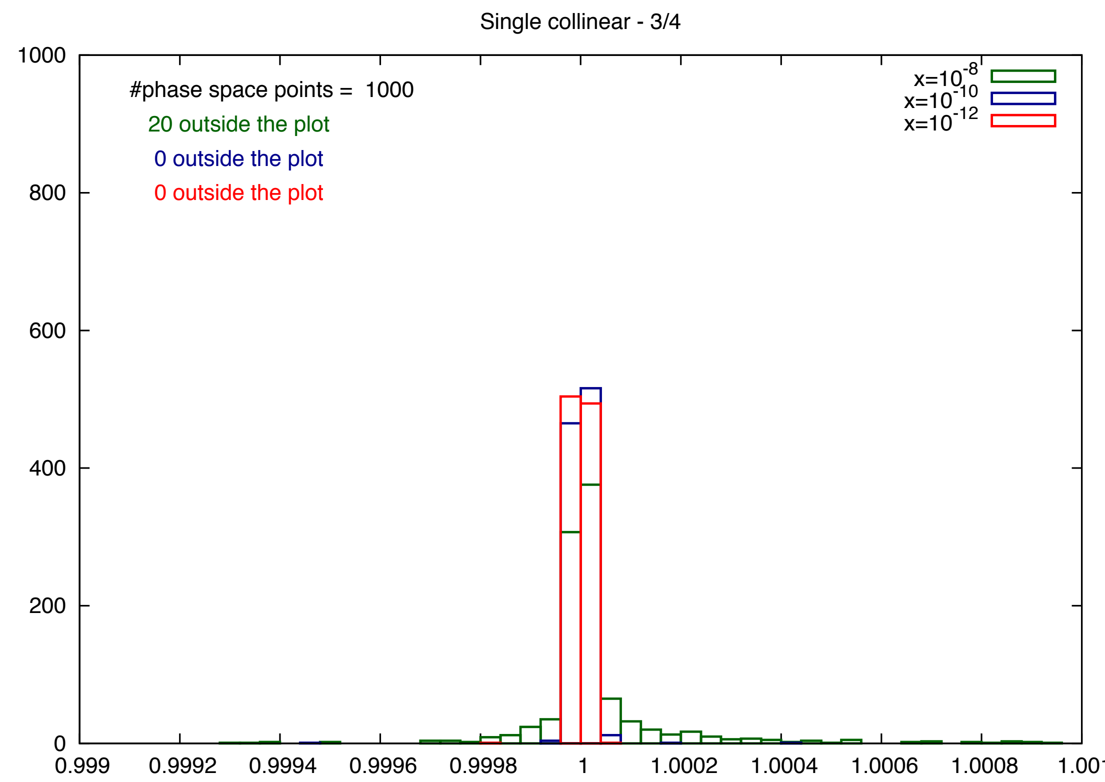
2. Only single unresolved limits



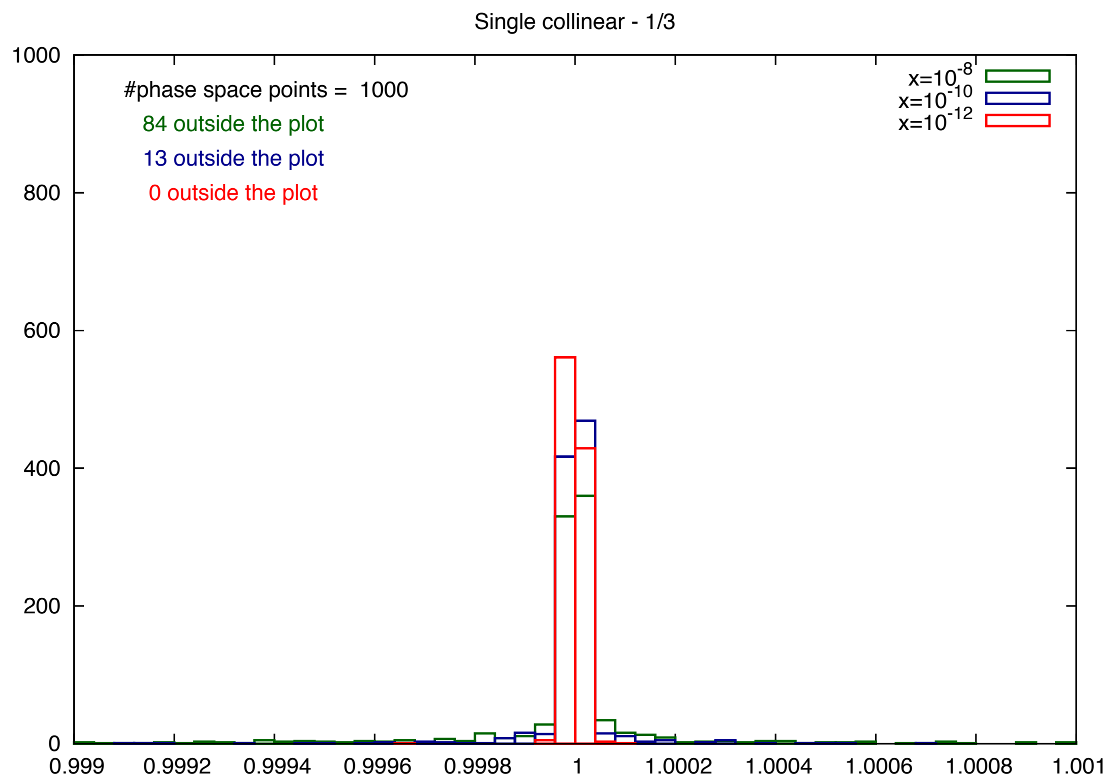
Single unresolved of (1) and poles of (2) also subtracted



Single soft - 3
#phase space points = 1000
1 outside the plot
0 outside the plot
1 outside the plot
x=10^-6
x=10^-7
x=10^-8



Single collinear - 3/4
#phase space points = 1000
20 outside the plot
0 outside the plot
0 outside the plot
x=10^-8
x=10^-10
x=10^-12



Single collinear - 1/3
#phase space points = 1000
84 outside the plot
13 outside the plot
0 outside the plot
x=10^-8
x=10^-10
x=10^-12

Double Virtual

Analytic pole cancellation against 2-loop and $(1\text{-loop})^2$ matrix element

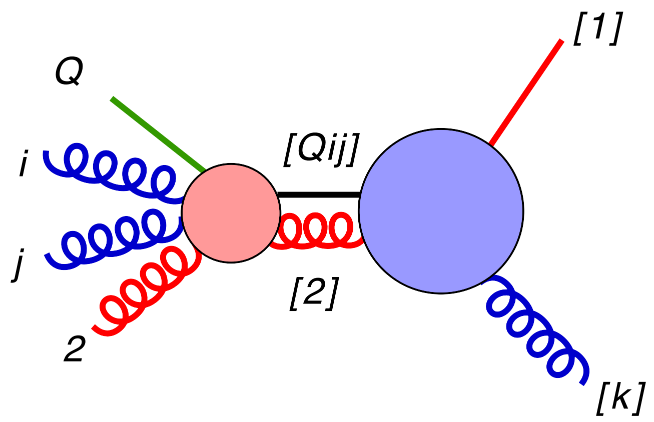
```
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoA4g2XU.frm
FORM 4.1 (Mar 13 2014) 64-bits                     Run: Wed May  4 18:13:43 2016
    #-

   poles = 0;

  19.40 sec out of 20.04 sec
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoA4g2YU.frm
FORM 4.1 (Mar 13 2014) 64-bits                     Run: Wed May  4 18:14:10 2016
    #-

   poles = 0;

  7.43 sec out of 7.50 sec
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoAh4g2XU.frm
FORM 4.1 (Mar 13 2014) 64-bits                     Run: Wed May  4 18:14:42 2016
    #-

   poles = 0;

  8.83 sec out of 8.88 sec
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoAh4g2YU.frm
FORM 4.1 (Mar 13 2014) 64-bits                     Run: Wed May  4 18:14:55 2016
    #-

   poles = 0;

  5.37 sec out of 5.41 sec
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoqgB2g2XU.frm
FORM 4.1 (Mar 13 2014) 64-bits                     Run: Wed May  4 18:15:25 2016
    #-

   poles = 0;
```

Disentangling initial-final collinear limits

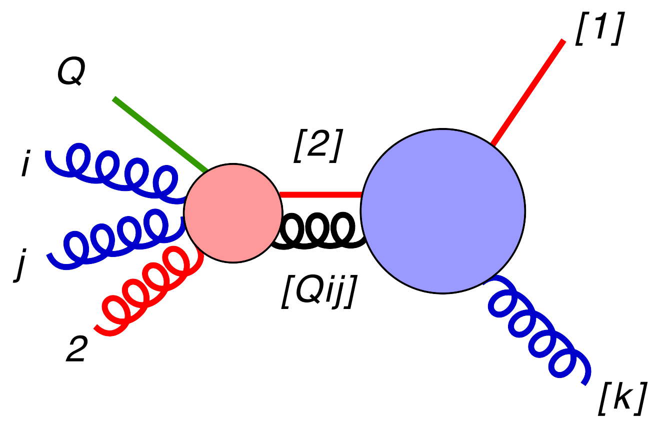
Additional complication with hadronic initial states

- phase space map smoothly interpolates between all limits
- smooth mapping between limits broken by reduced matrix element crossings

$$D_4^0(Q,i,j,2)M_4^0(1,k,\bar{2},(\widetilde{ijQ}))$$



$$D_4^0(Q,i,j,2)M_4^0(1,k,(\widetilde{ijQ}),\bar{2})$$



Can always be disentangled with the appropriate combination of antennae

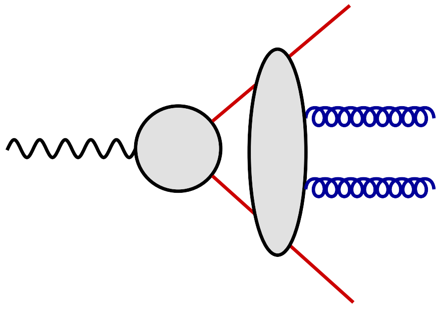
Better Antennae?

Computation time is limited mainly by the subtraction term

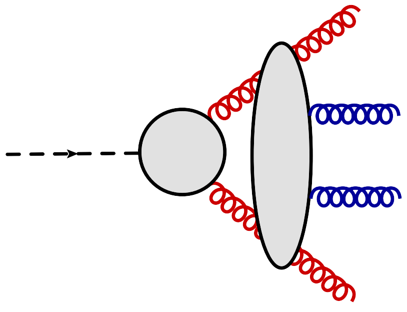
- many calls to libraries and PS maps due to many terms
- many (most) terms in the subtraction are to cancel spurious limits

Worth investigating if it is possible to define antennae with more focussed properties

- cf. quark-antiquark antenna (no spurious limits)



- with gluon-gluon antenna (unresolved "hard" radiators)



Colour Space

Antenna are colour stripped objects:

- contain all singularities
- analytic integration is the hard part

Overall singularity structure best organised in colour space:

- can dress colour stripped functions with charges
- algorithmic approach —> automation along the lines of Catani-Seymour

$$X_3^0(i,j,k)\langle\mathcal{M}_n^0|\mathcal{M}_n^0\rangle \to X_3^0(i,j,k)\langle\mathcal{M}_n^0|\boldsymbol{T}_{(\widetilde{ij})}\cdot\boldsymbol{T}_{(\widetilde{jk})}|\mathcal{M}_n^0\rangle$$

Recent Applications

- pp->2J (gluons only) [Gehrmann, Gehrmann-De Ridder, Glover, Pires ‘12]
- pp->H+J [Chen, Gehrmann, Glover, Jaquier ’14, ‘16]
- pp->Z+J [Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan ’15; ‘16]
- ep->(2+1)J [Currie, Gehrmann, Niehus 1605.XXXX]
- pp->2J (all channels) [Currie, Glover, Pires 160Z.XXXX]

H+J

Phenomenologically interesting:

- dominated by scale uncertainty
- necessary for accurate differential properties of Higgs

3 independent calculations exist:

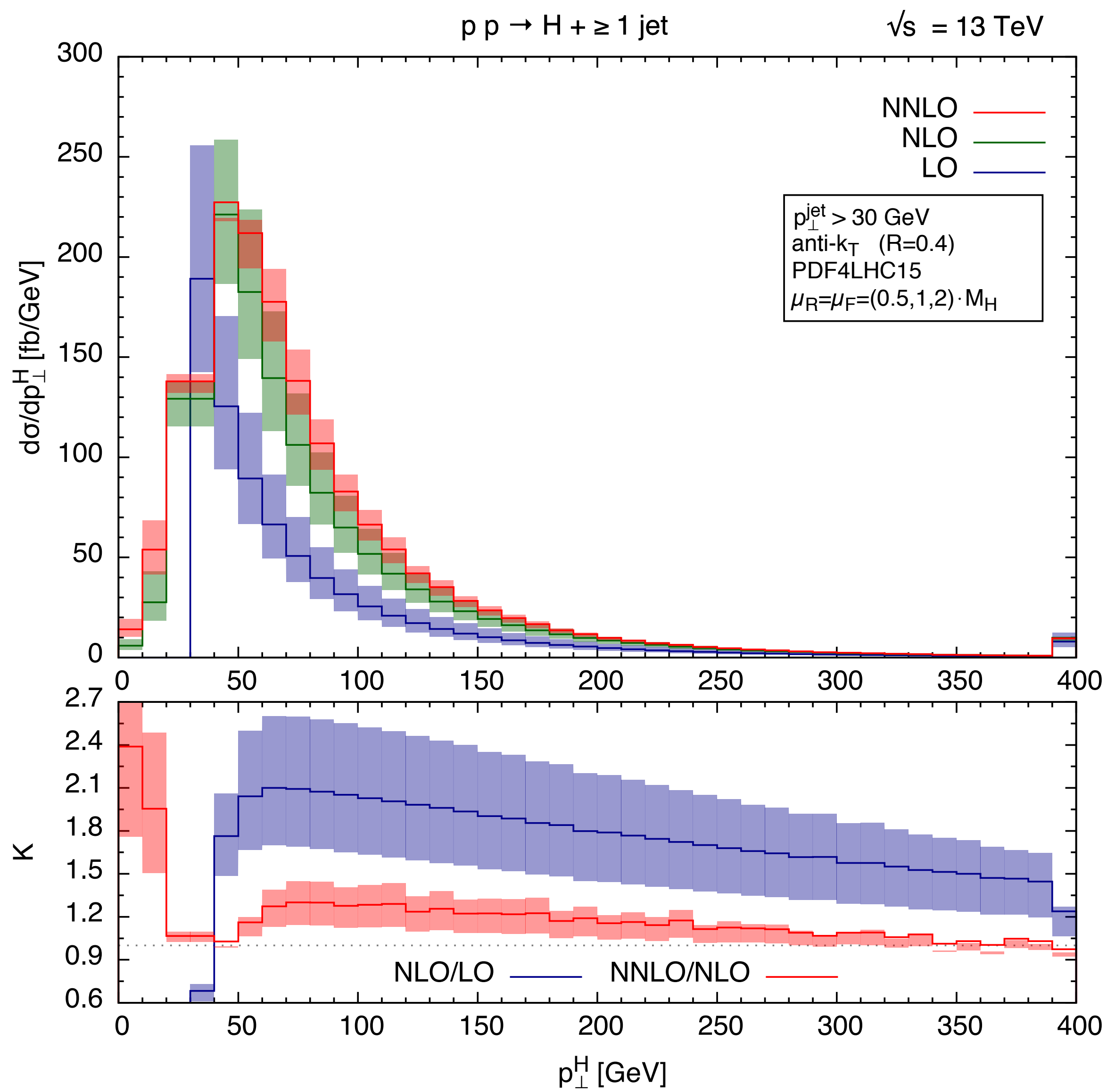
$$\sigma^{NNLO}_{antenna} = 9.44^{+0.59}_{-0.85}\ \mathrm{fb}$$

$$\sigma^{NNLO}_{sectors} = 9.45^{+0.58}_{-0.82}\ \mathrm{fb}$$

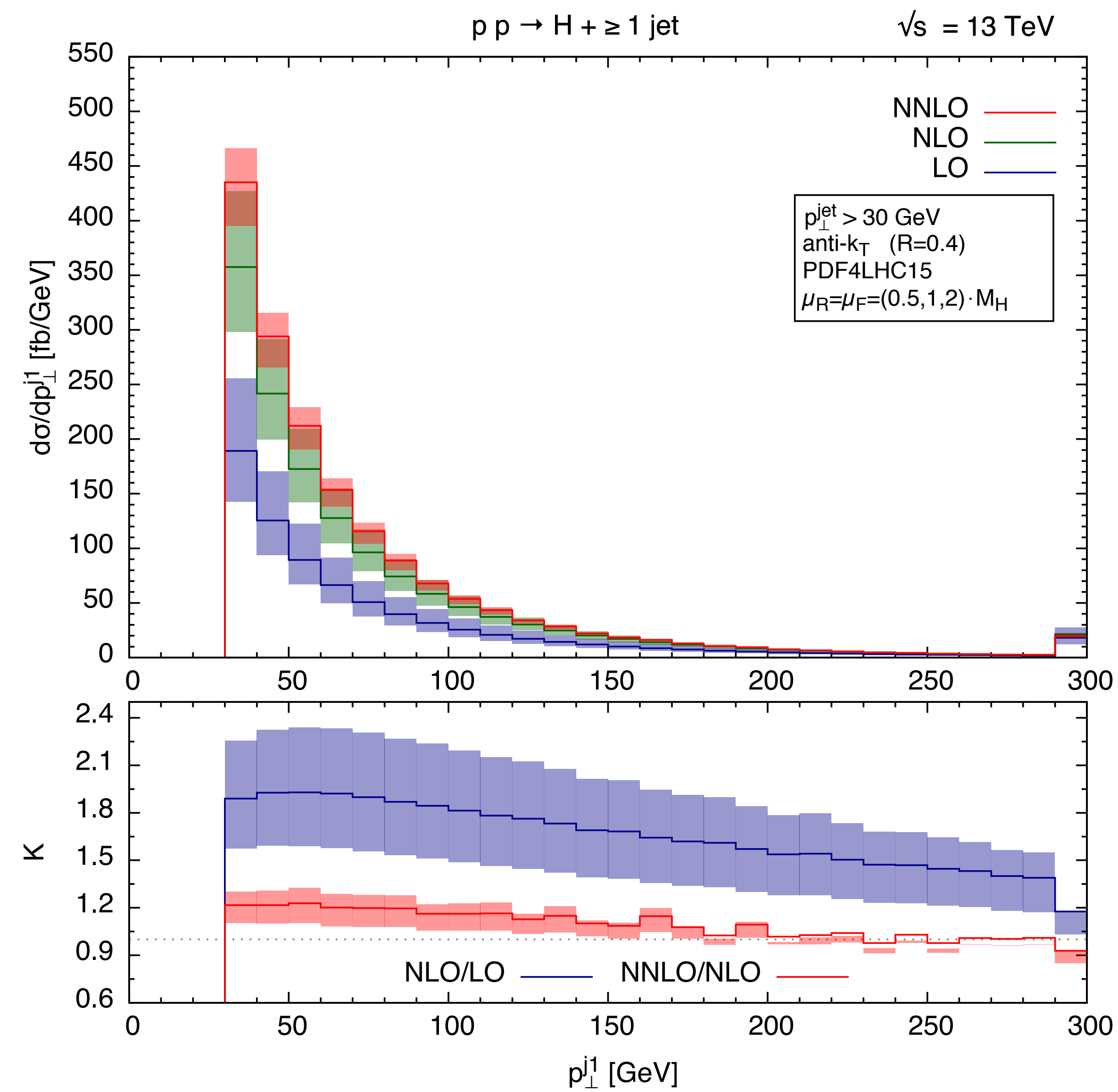
- Antennae [Chen, Gehrmann, Glover, Jaquier '14, '16]
- Sectors [Boughezal, Caola, Melnikov, Petriello, Schulze '13; Caola, Melnikov, Shultz '15]
- N-Jettiness [Boughezal, Focke, Giele, Liu, Petriello '15]

Provides testbed for comparison between main methods for the first time!

pT

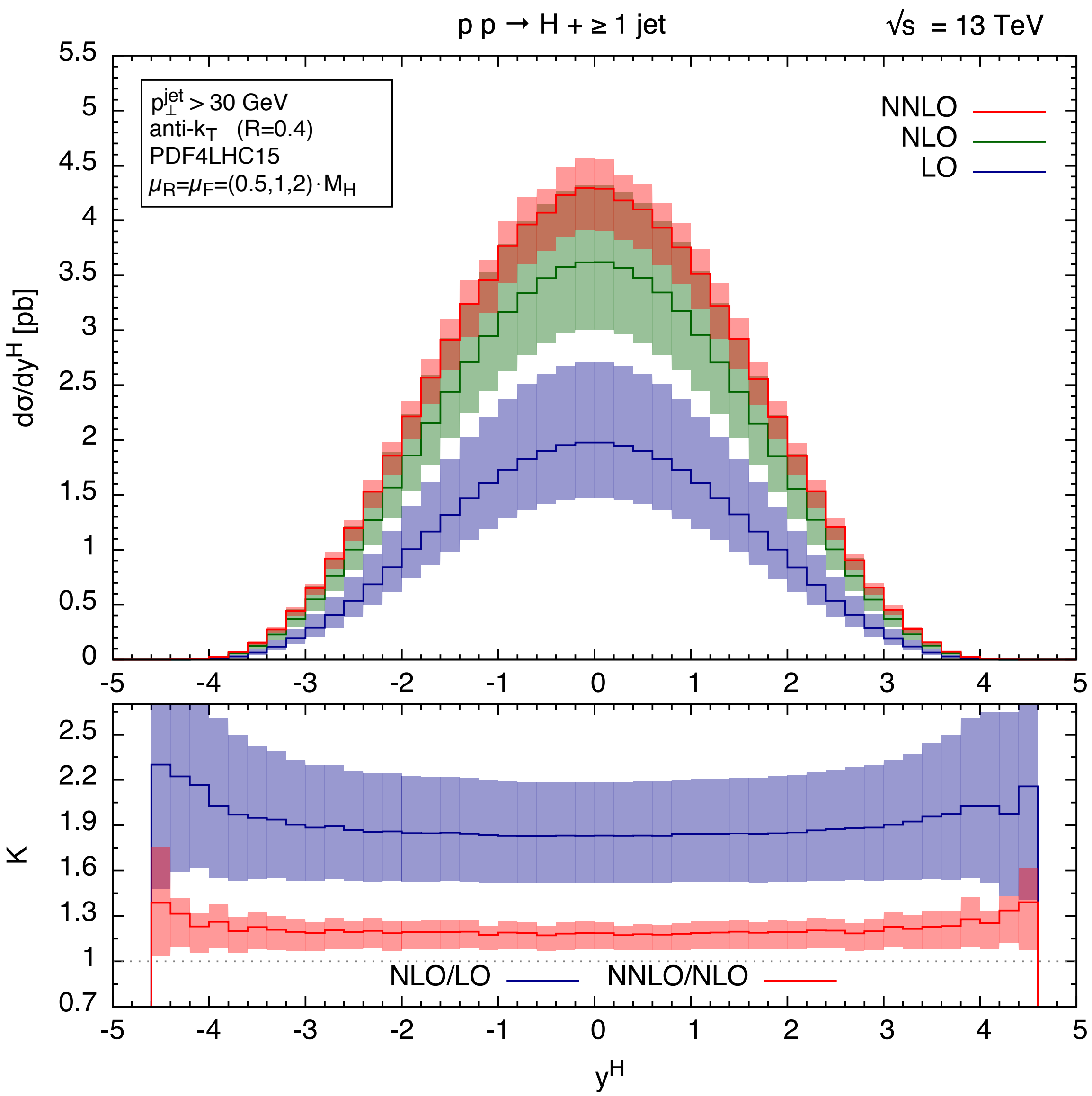

p p → H + ≥ 1 jet
√s = 13 TeV
NNLO
NLO
LO
$p_\perp^{jet}$ > 30 GeV
anti-k_T (R=0.4)
PDF4LHC15
$\mu_R=\mu_F=(0.5,1,2)\cdot M_H$
$d\sigma/dp_\perp^H$ [fb/GeV]
K
NLO/LO
NNLO/NLO
$p_\perp^H$ [GeV]

Higgs

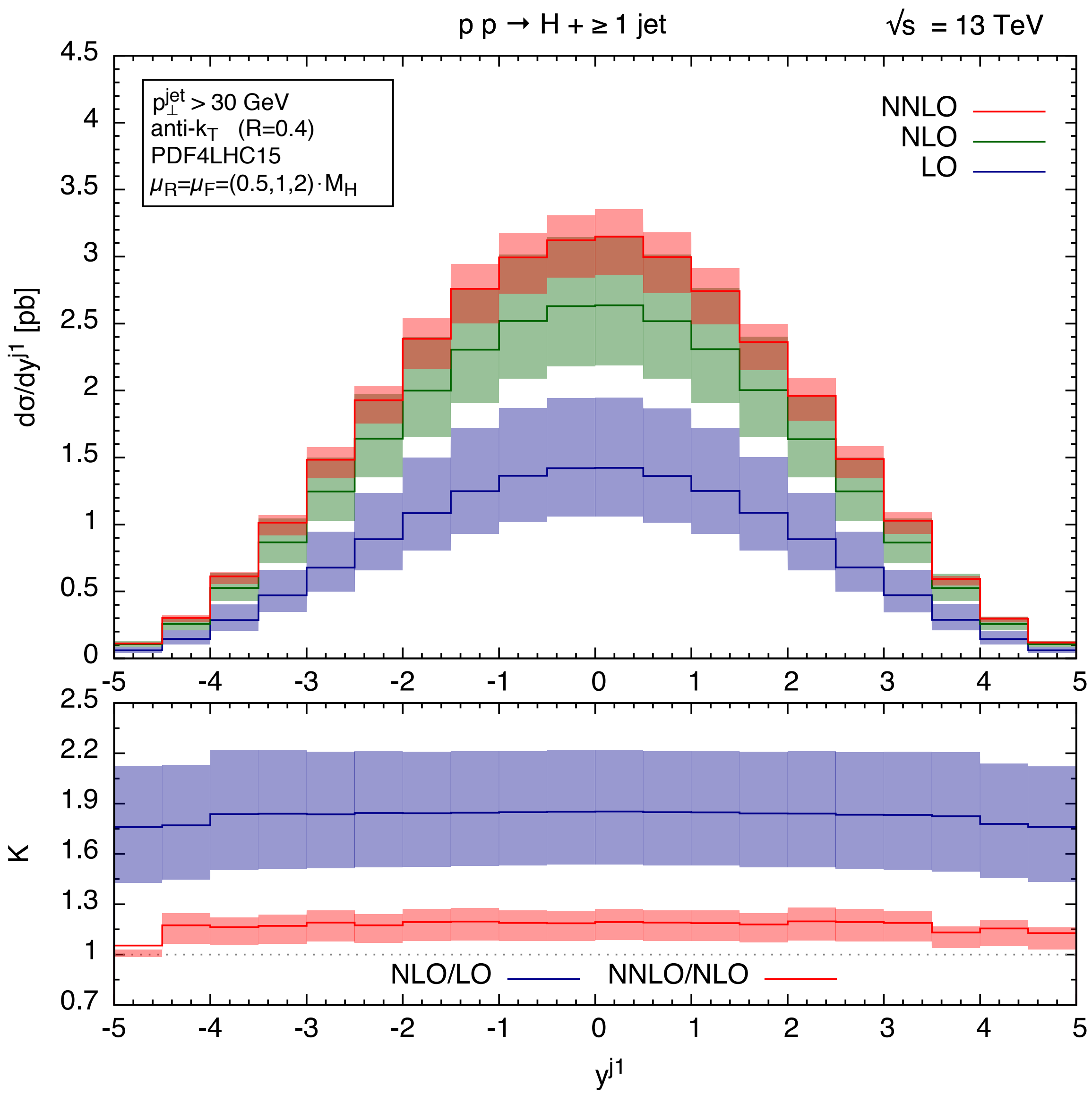

p p → H + ≥ 1 jet
√s = 13 TeV
NNLO
NLO
LO
$p_\perp^{jet}$ > 30 GeV
anti-k_T (R=0.4)
PDF4LHC15
$\mu_R=\mu_F=(0.5,1,2)\cdot M_H$
$d\sigma/dp_\perp^{j1}$ [fb/GeV]
K
NLO/LO
NNLO/NLO
$p_\perp^{j1}$ [GeV]

Jet

Rapidity

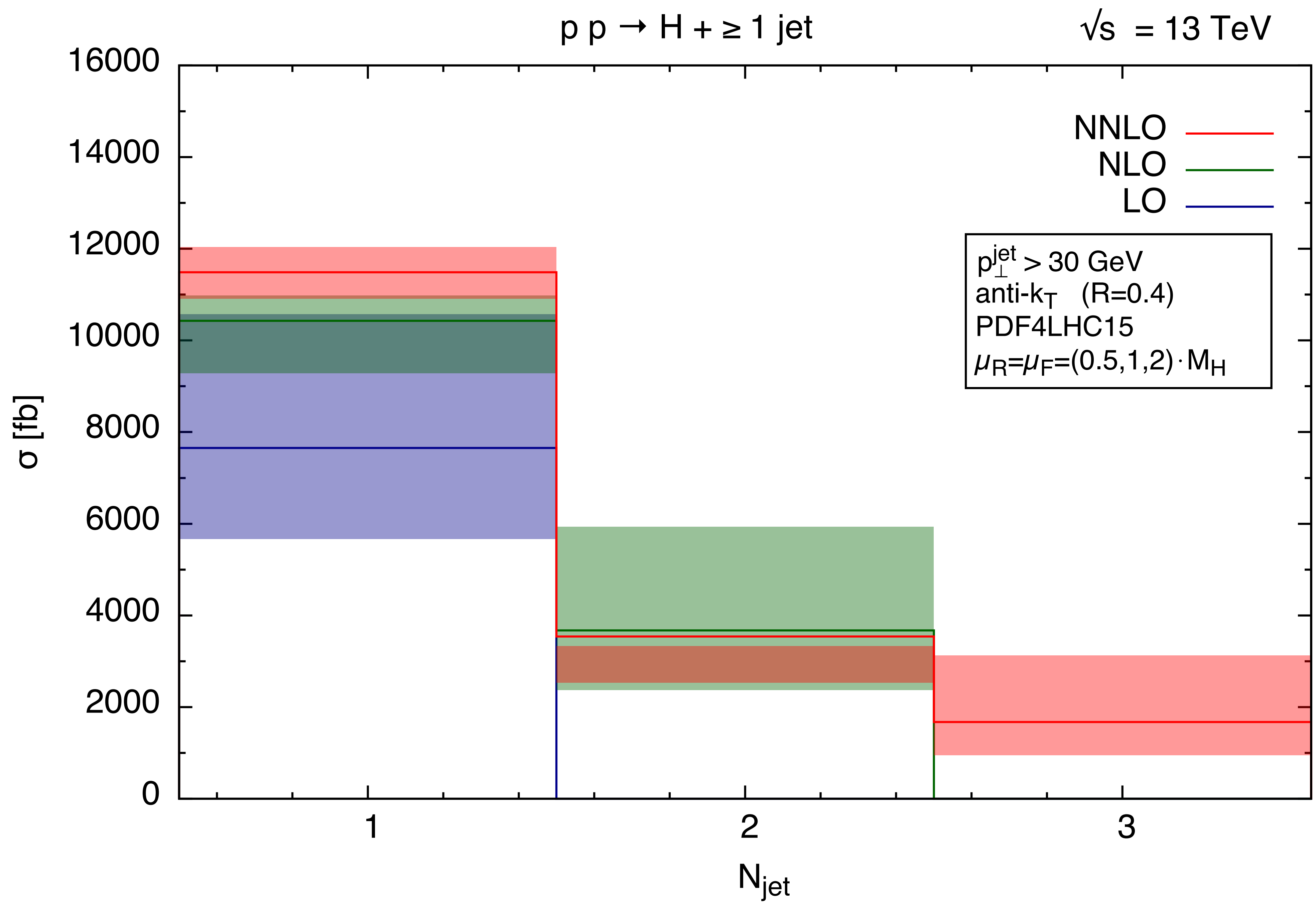


Higgs



Jet

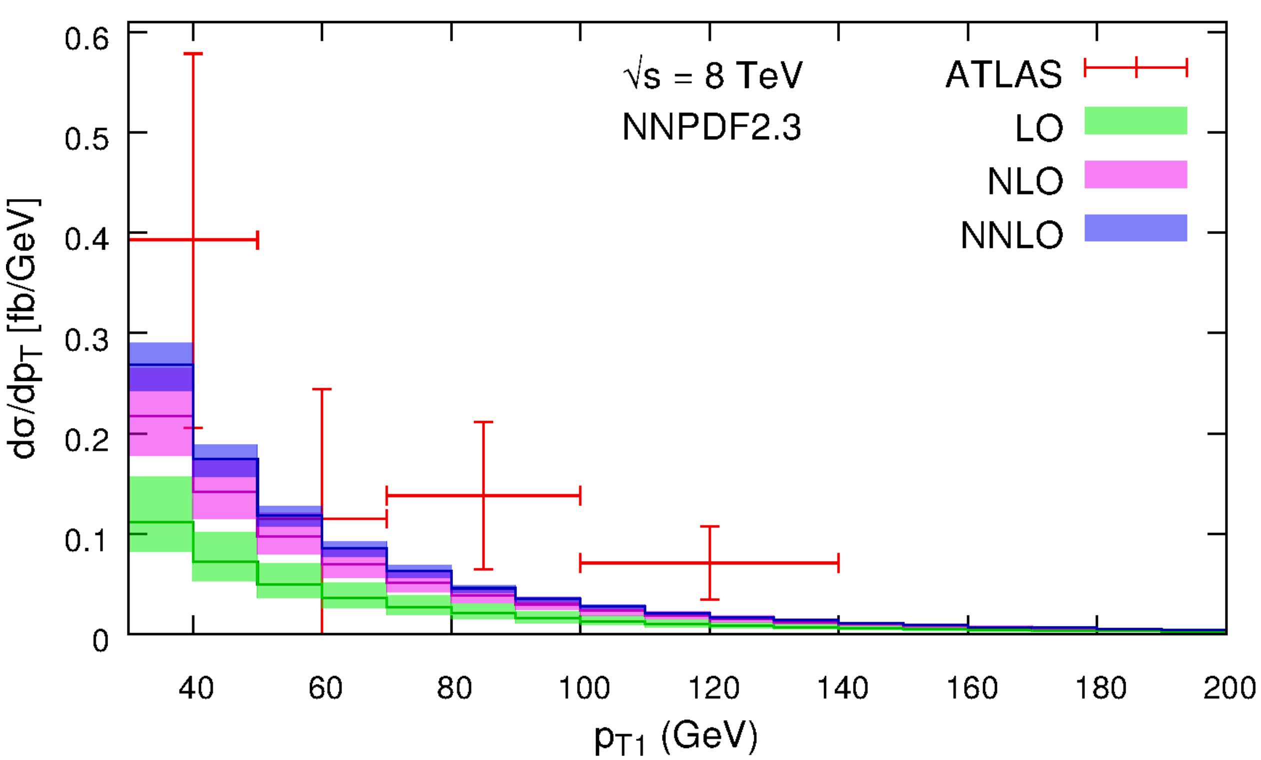
Exclusive

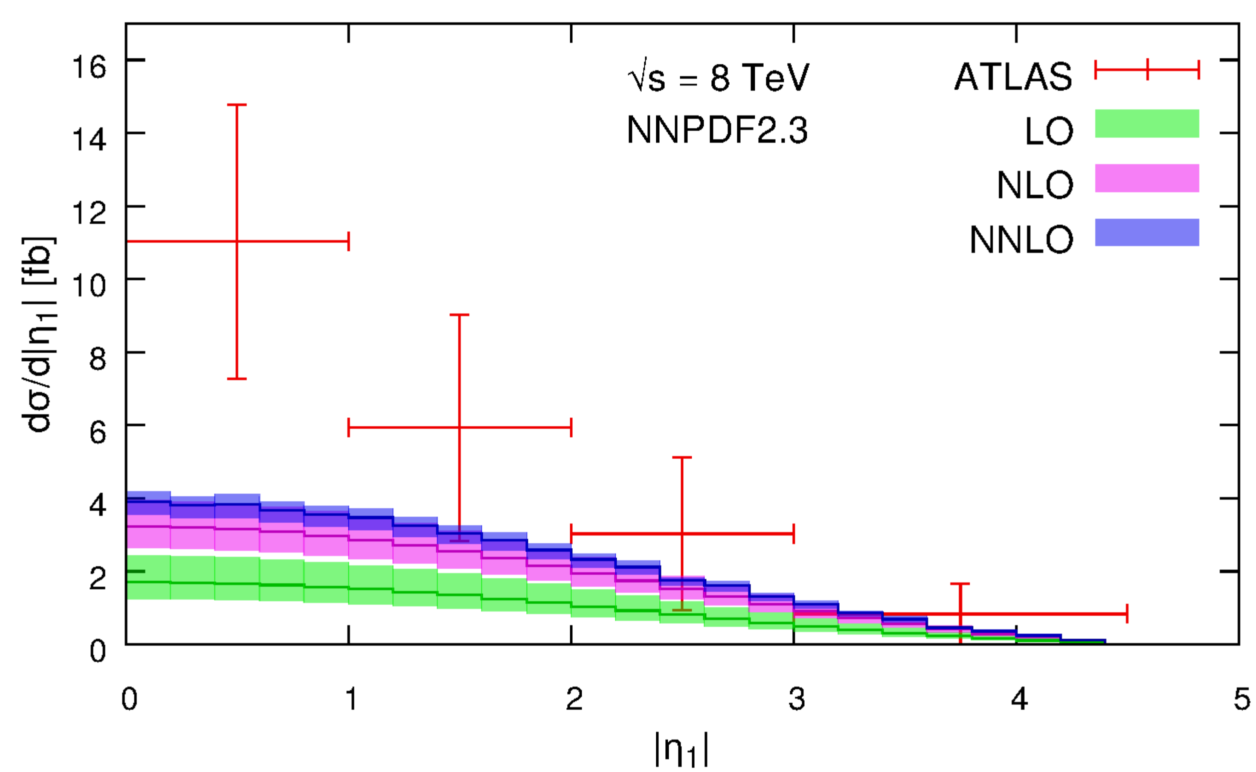


p p → H + ≥ 1 jet
√s = 13 TeV
16000
14000
12000
10000
8000
6000
4000
2000
0
σ [fb]
1
2
3
N_jet
NNLO
NLO
LO
p⊥^jet > 30 GeV
anti-k_T (R=0.4)
PDF4LHC15
μR=μF=(0.5,1,2)·MH

Data

- H+J NNLO prediction still undershoots data (Atlas)
- errors are reasonably large
- finite mass effects probably small ~2-3% @NLO [Harlander, Neumann, Ozeren, Wiesemann '12]

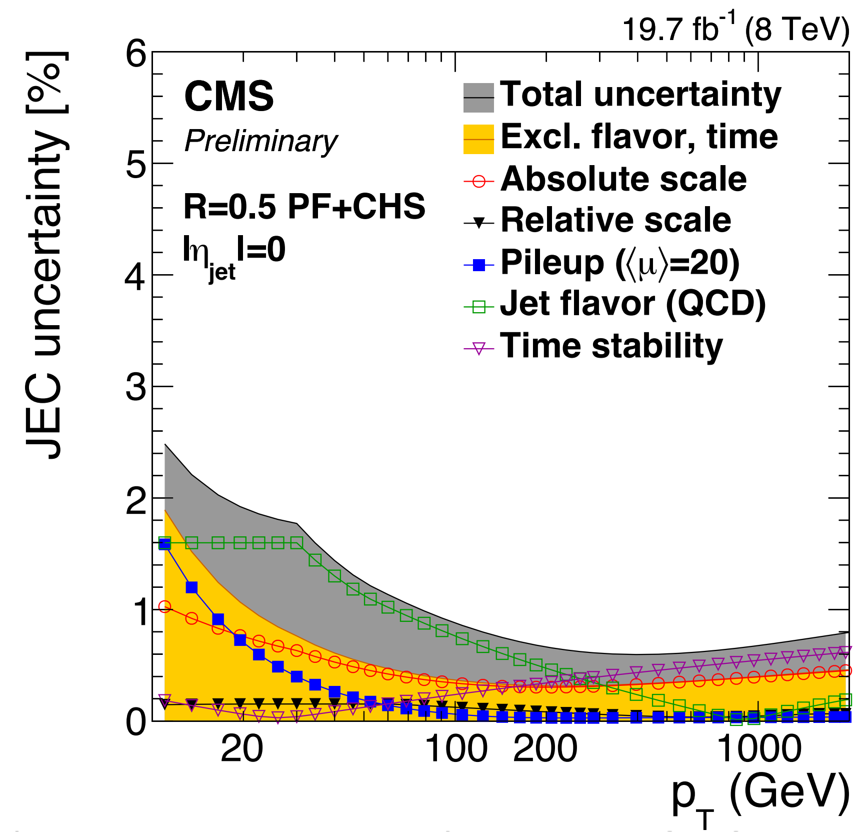




Z+J

Phenomenologically interesting signal:

- clean leptonic signature
- good handle on Jet Energy Scale
- inclusive Z p_T large discrepancy with data



CMS-DP-2015/044

Theoretically interesting calculation:

- significant NLO K-factors and scale uncertainty
- completely independent implementation using N-Jettiness [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello.'15; Boughezal, Liu, Petriello.'16]
- another opportunity to compare methods and give reliable results for comparison with data

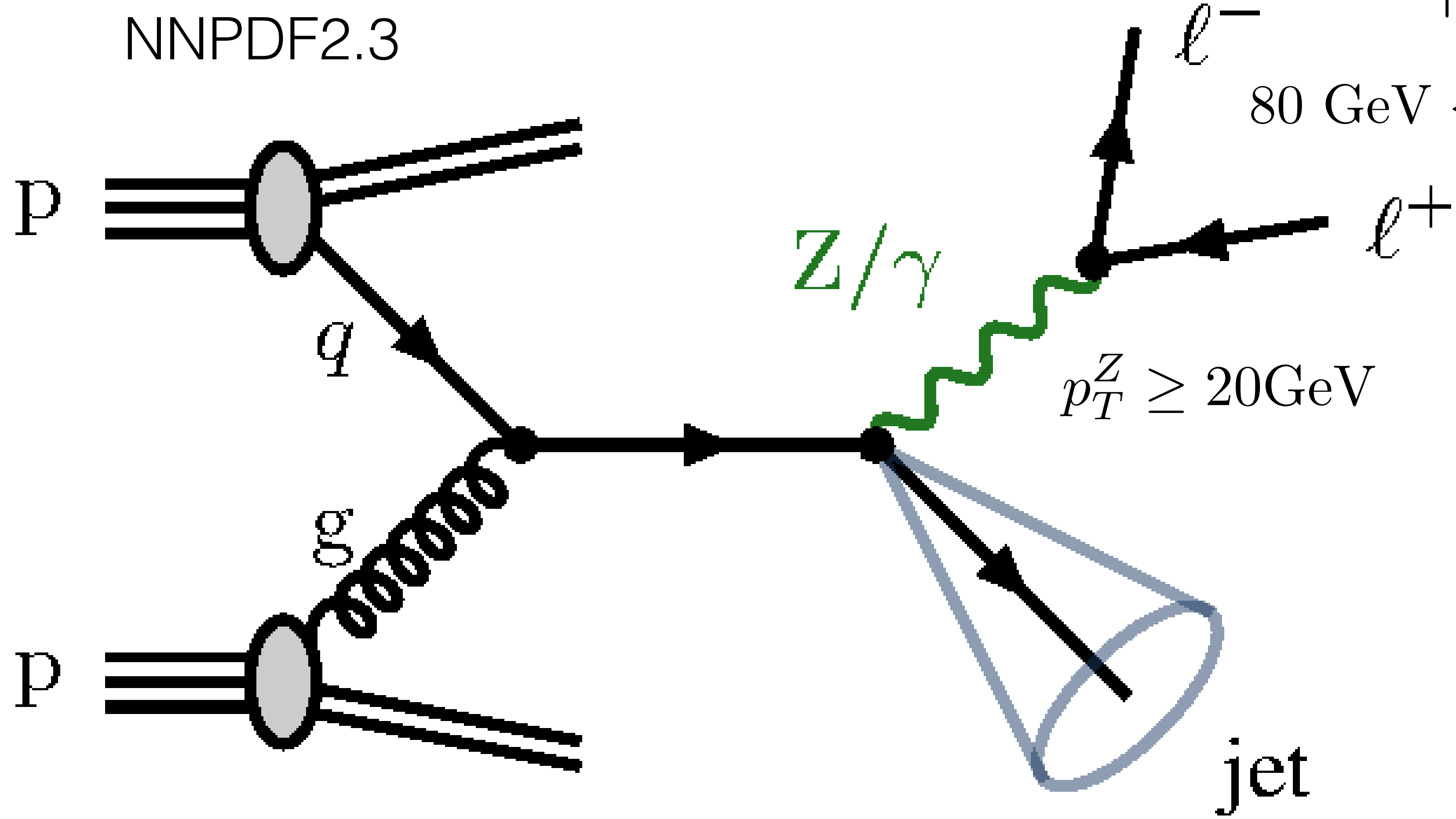
Setup-Z+≥1J

NNPDF2.3

$|y^{\ell}| < 5$

$80\ \mathrm{GeV} < m_{\ell\ell} < 100\ \mathrm{GeV}$

8 TeV



$p_T^Z \geq 20\mathrm{GeV}$

$$\mu_R = \mu_F = \sqrt{m_{\ell\ell}^2 + p_{T,Z}^2} \times \left[\frac{1}{2}, 1, 2\right]$$

p_T>30 GeV
R=0.5
y<3

Total cross section

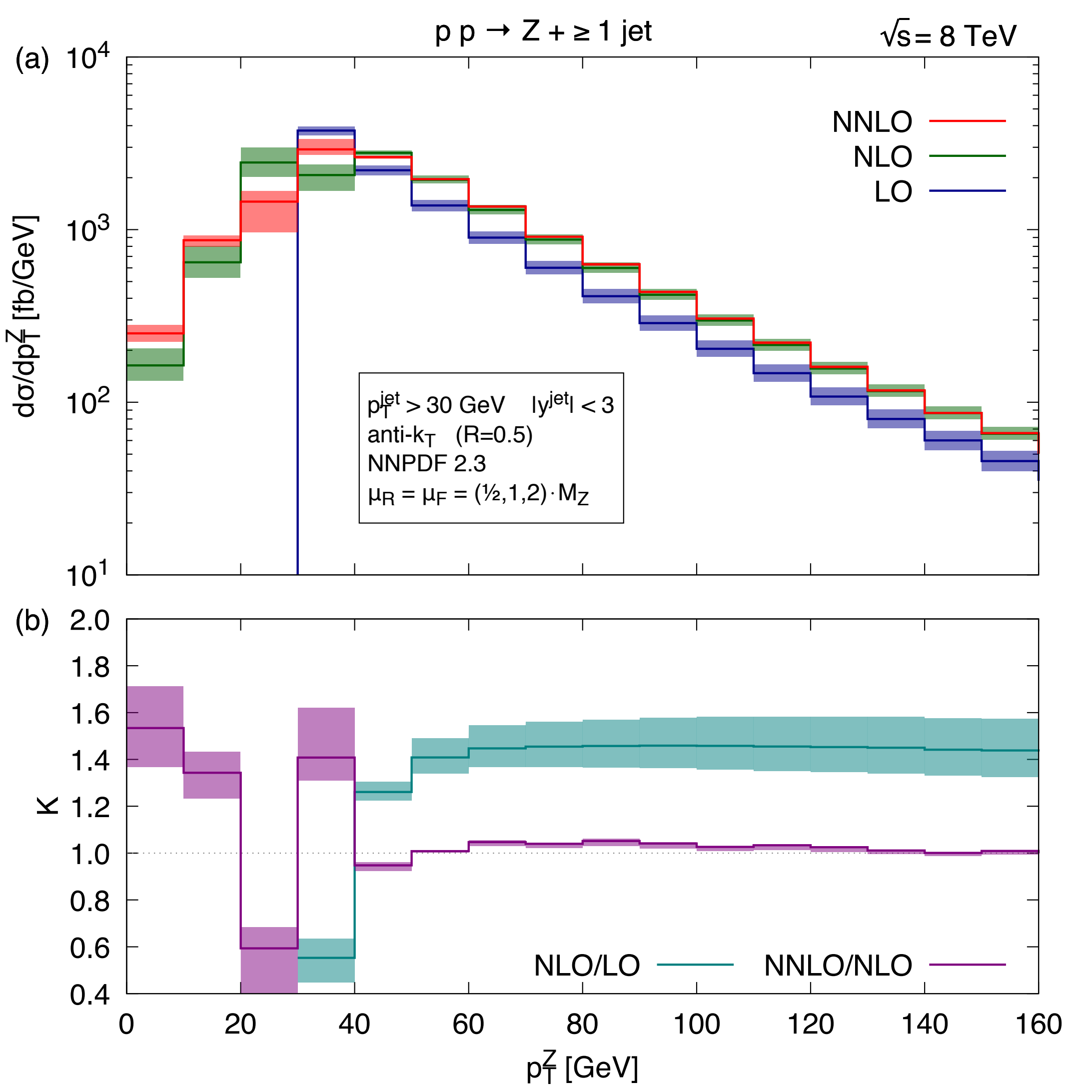
$$\sigma_{LO} = 103.6^{+7.7}_{-7.5}\ \text{pb}$$

$$\sigma_{NLO} = 144.4^{+9.0}_{-7.2}\ \text{pb} \qquad +40\%$$

$$\sigma_{NNLO} = 145.8^{+0.0}_{-1.2}\ \text{pb} \qquad +1\%$$

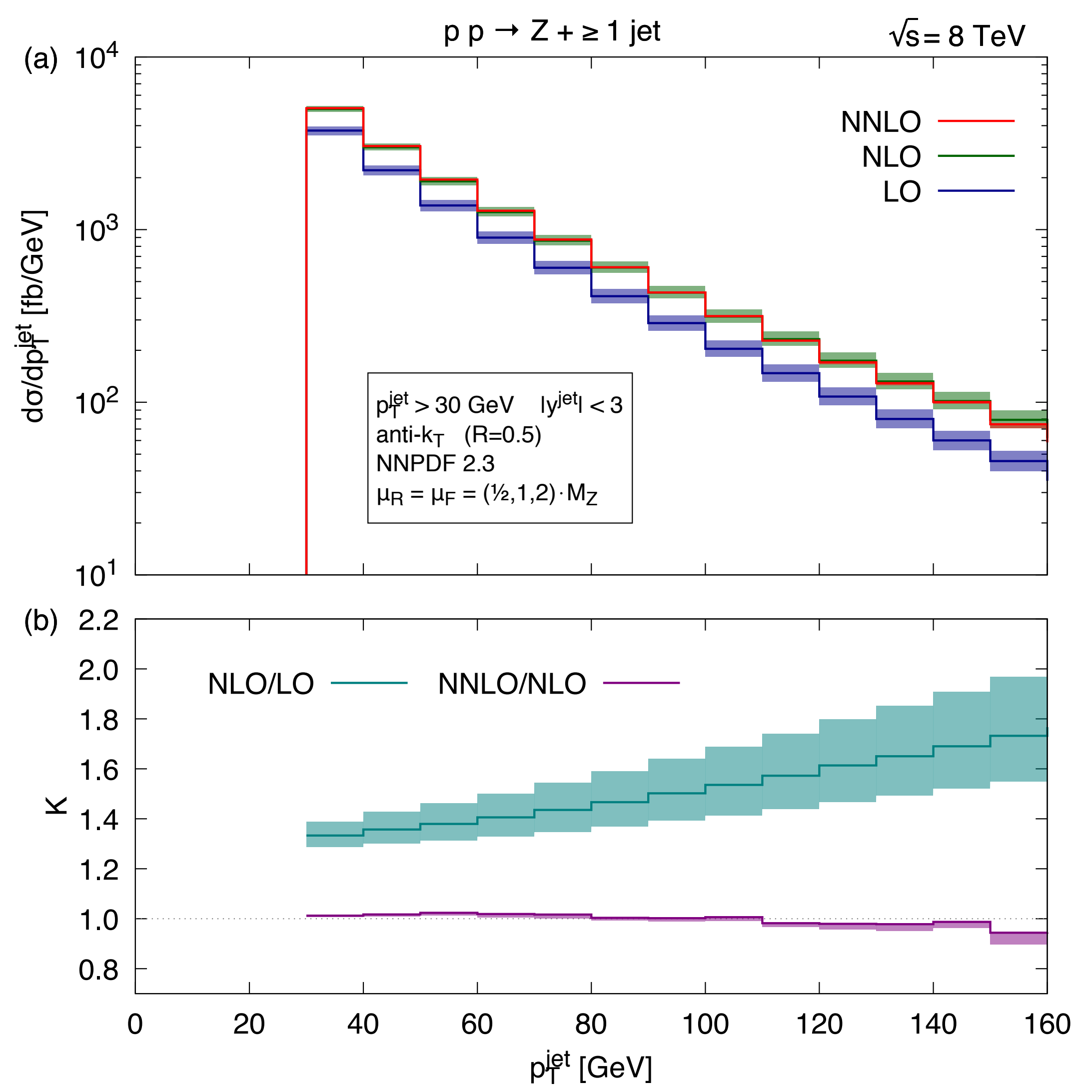
- All channels included from NLO onwards
- NNLO stabilizes perturbative series
- scale uncertainty significantly reduced

pT



p p → Z + ≥ 1 jet
√s = 8 TeV
(a)
NNLO
NLO
LO
dσ/dp$_T^Z$ [fb/GeV]
p$_T^{jet}$ > 30 GeV |y^{jet}| < 3
anti-k$_T$ (R=0.5)
NNPDF 2.3
μ$_R$ = μ$_F$ = (½,1,2)·M$_Z$
(b)
K
NLO/LO
NNLO/NLO
p$_T^Z$ [GeV]

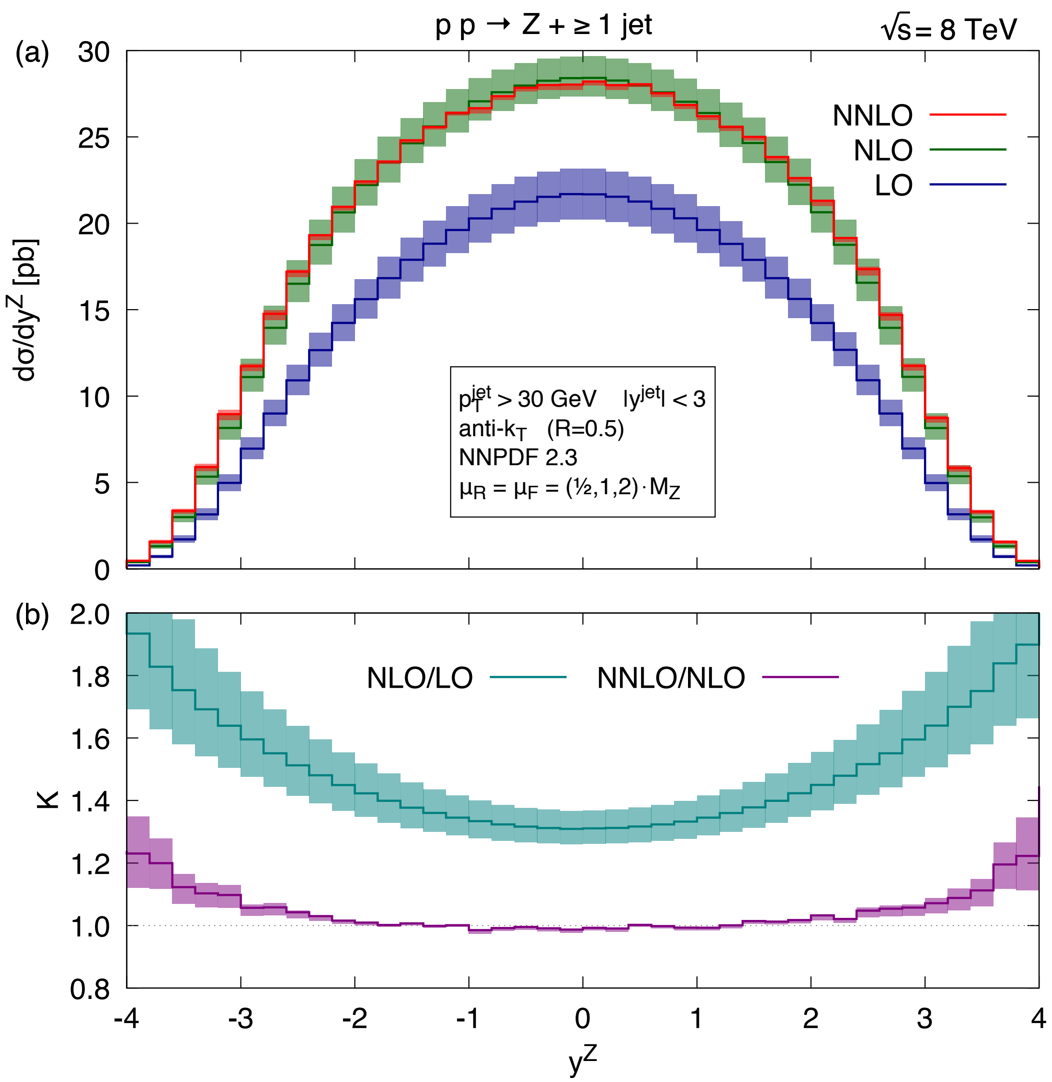
Z



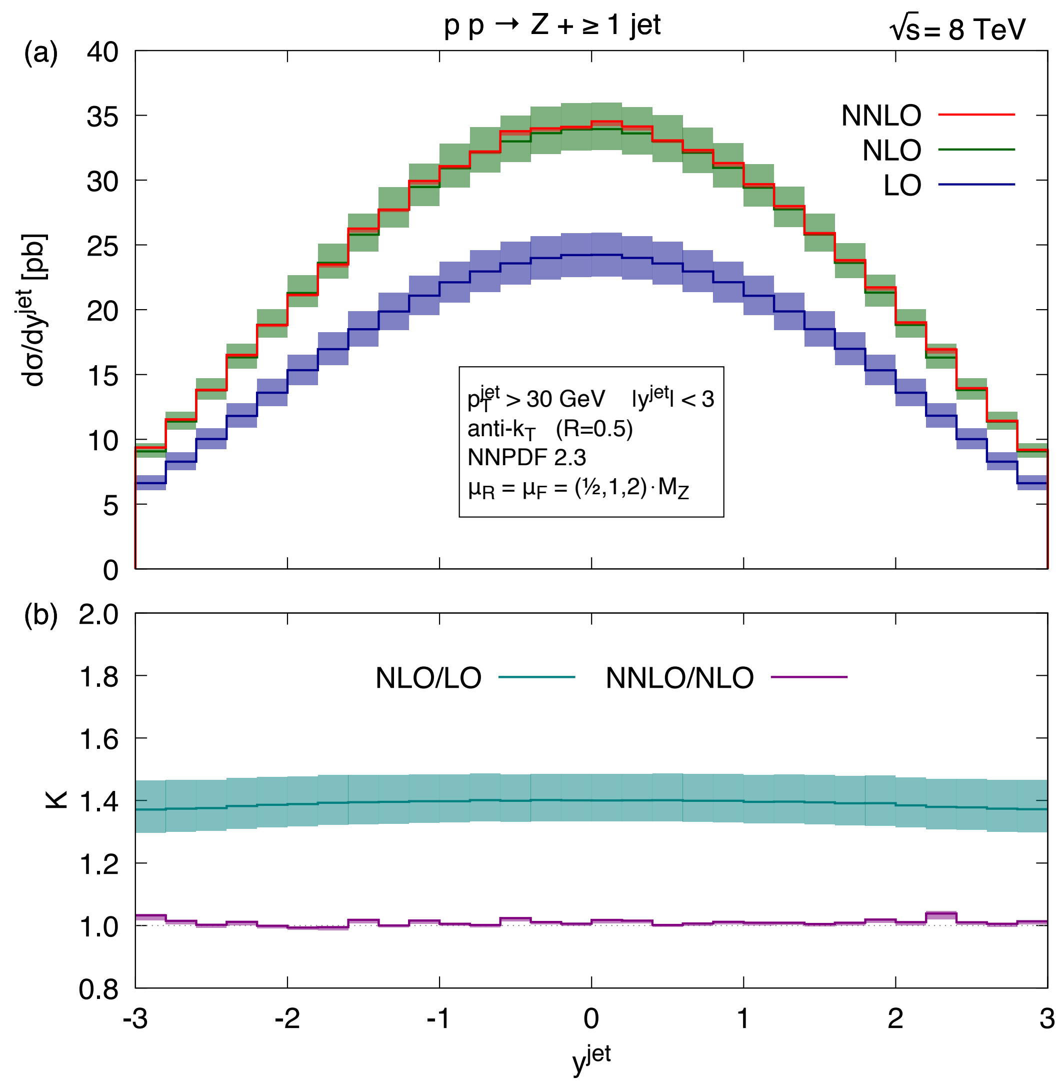
p p → Z + ≥ 1 jet
√s = 8 TeV
(a)
NNLO
NLO
LO
dσ/dp$_T^{jet}$ [fb/GeV]
p$_T^{jet}$ > 30 GeV |y^{jet}| < 3
anti-k$_T$ (R=0.5)
NNPDF 2.3
μ$_R$ = μ$_F$ = (½,1,2)·M$_Z$
(b)
K
NLO/LO
NNLO/NLO
p$_T^{jet}$ [GeV]

Jet

Rapidity



Z



Jet

NNLO dramatically improves Z+J prediction:

- total cross section central value stabilized
- NNLO/NLO K-factors mostly flat
- scale uncertainty significantly reduced
- NNLO/NLO K-factors $\lesssim$5% for distributions

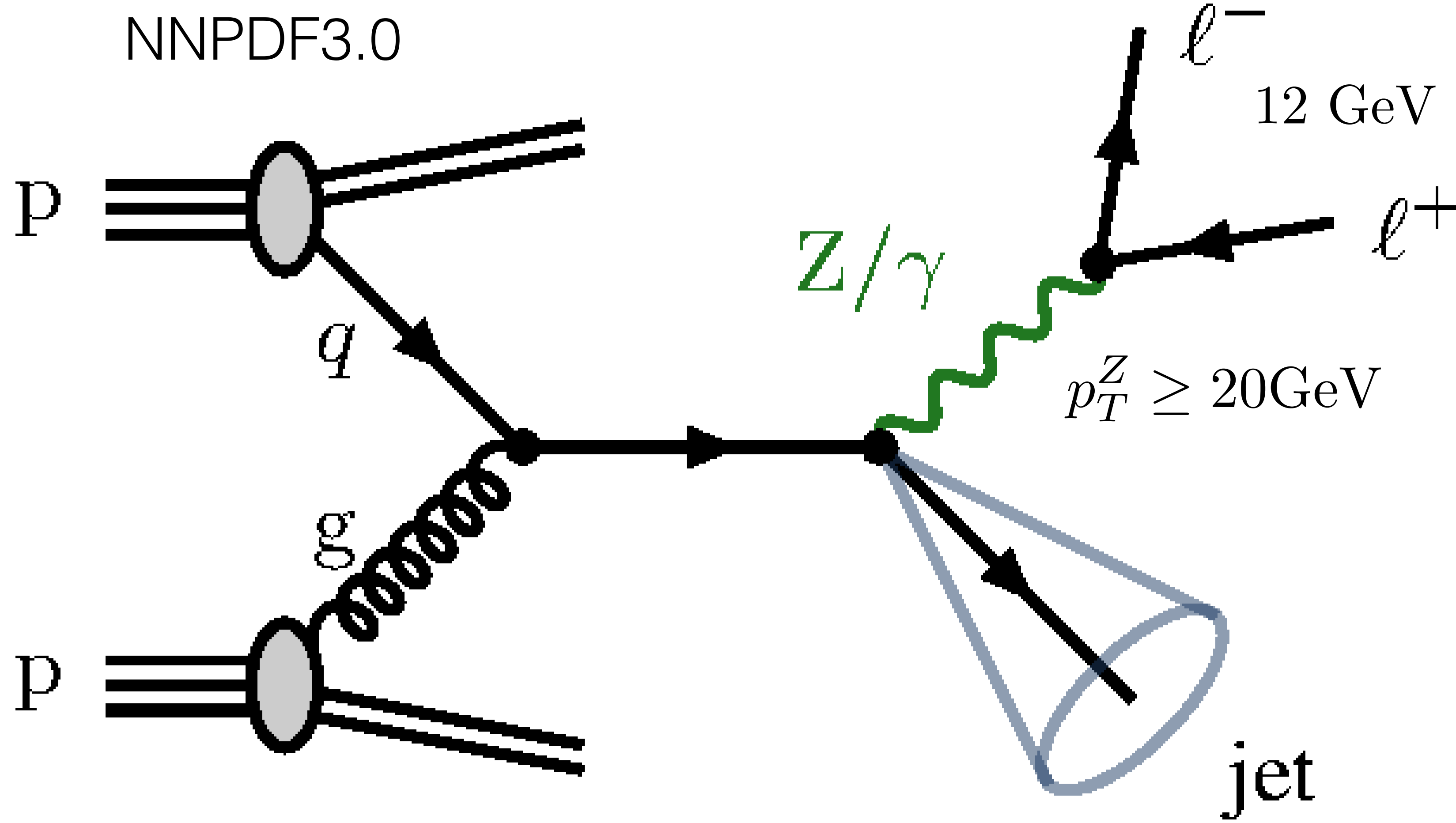
Setup-inclusive Z

$p_T^{\ell_1} \geq 20 \text{ GeV}$

$|y^{\ell^\pm}| < 2.4$

NNPDF3.0

$12 \text{ GeV} < m_{\ell\ell} < 150 \text{ GeV}$



$p_T^{\ell_2} \geq 10 \text{ GeV}$

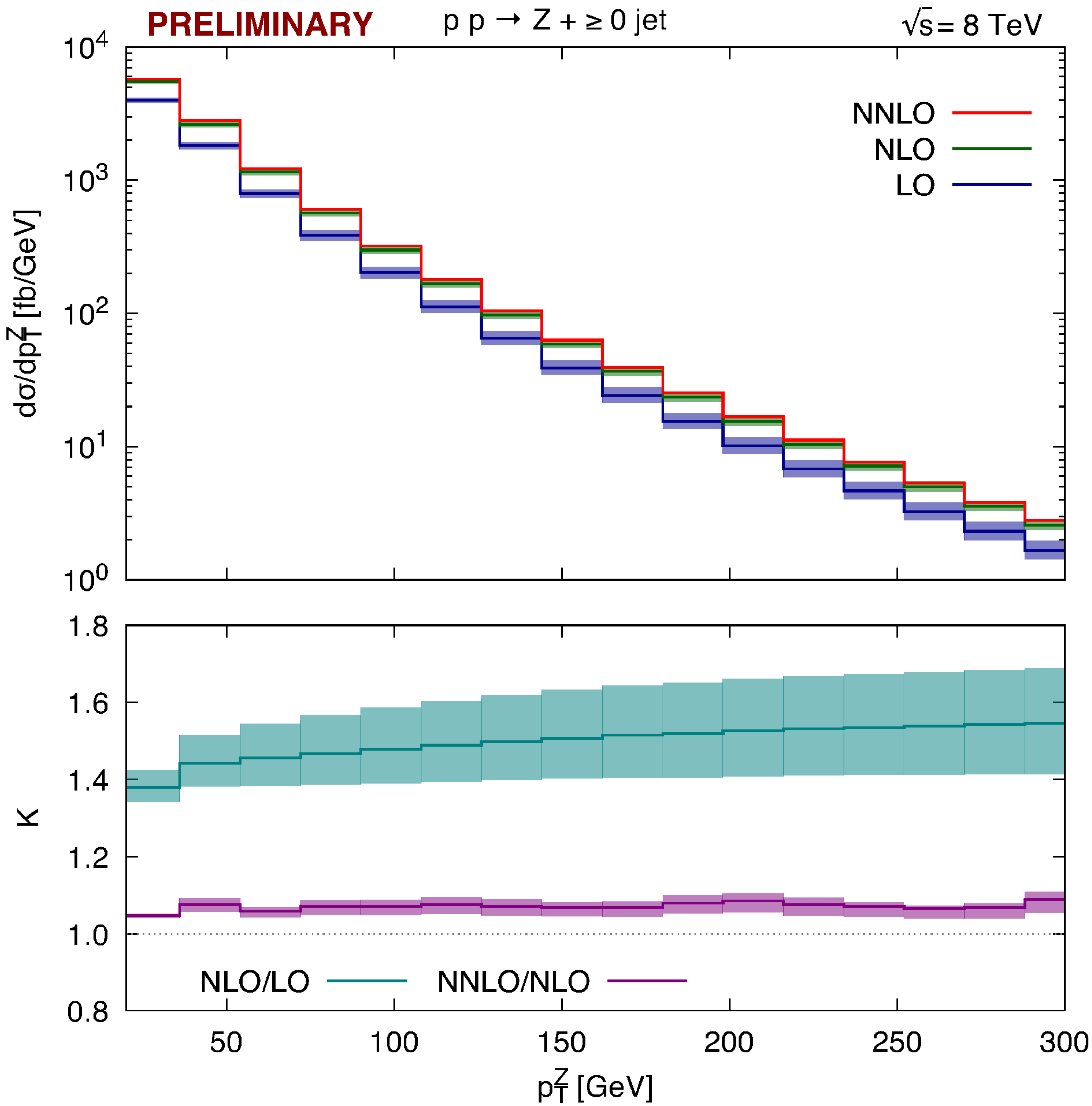
$p_T^Z \geq 20\text{GeV}$

8 TeV

$$\mu_R = \mu_F = \sqrt{m_{\ell\ell}^2 + p_{T,Z}^2} \times \left[\frac{1}{2}, 1, 2\right]$$

Fully inclusive in QCD radiation

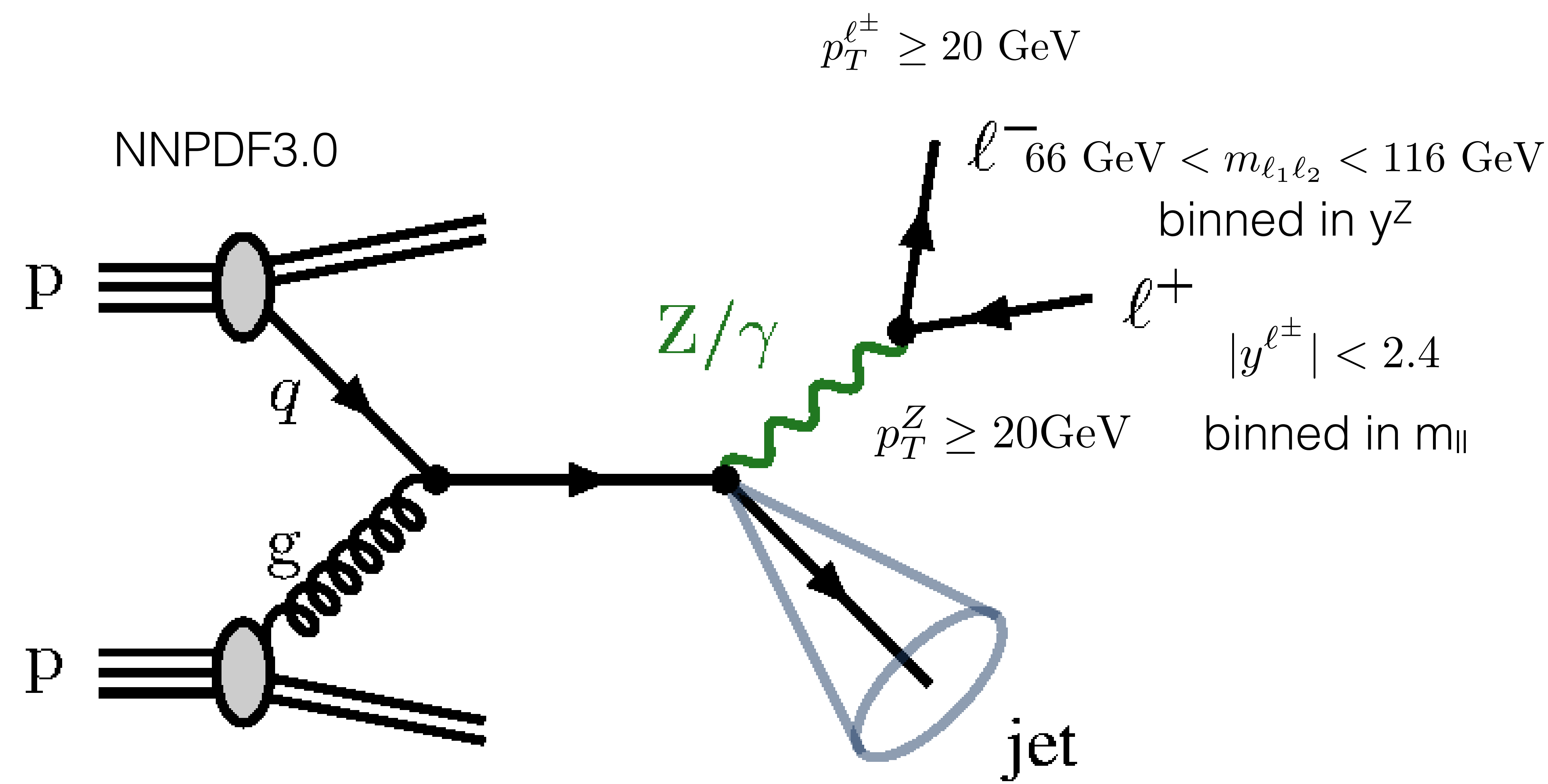
- large NLO corrections 40-60%
- moderate NNLO corrections 5-10%
- significantly improved scale uncertainty
- essentially flat K-factor



Setup-inclusive Z-ATLAS cuts

NNPDF3.0

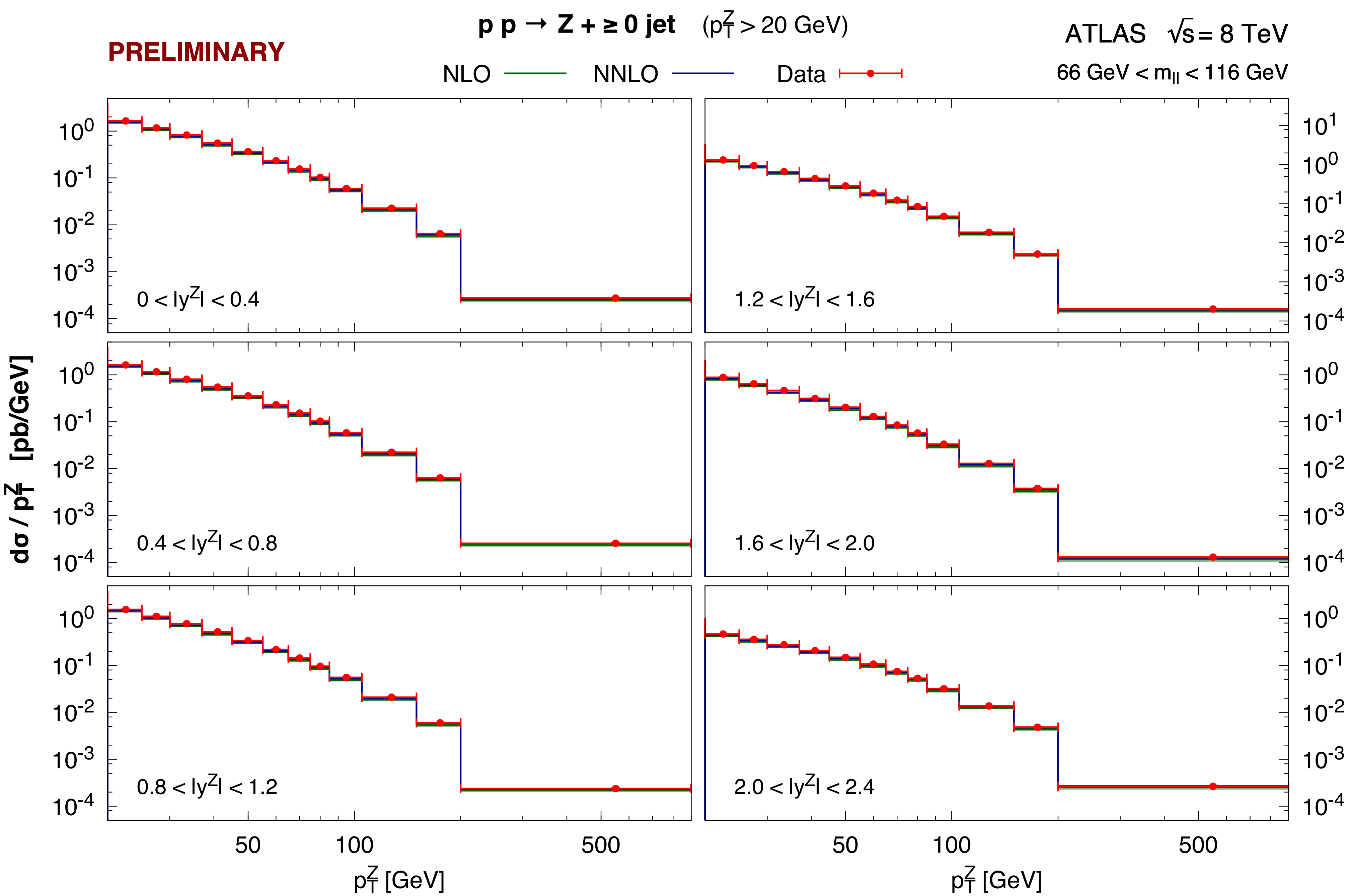
8 TeV



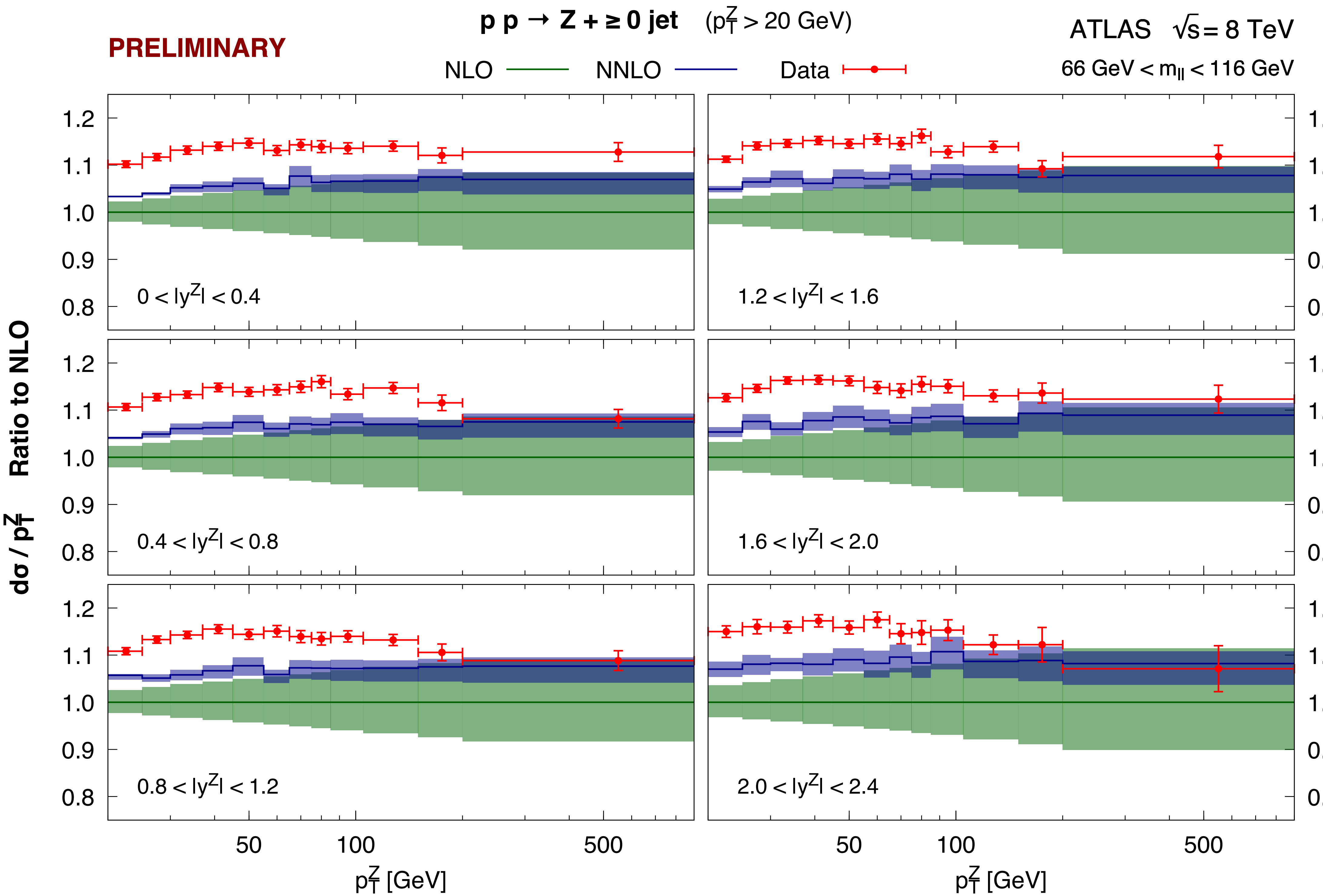
$$\mu_R = \mu_F = \sqrt{m_{\ell\ell}^2 + p_{T,Z}^2} \times \left[\frac{1}{2}, 1, 2\right]$$

Fully inclusive in QCD radiation

$\mathrm{d}\sigma/\mathrm{d}p_T^Z$ binned in y^Z

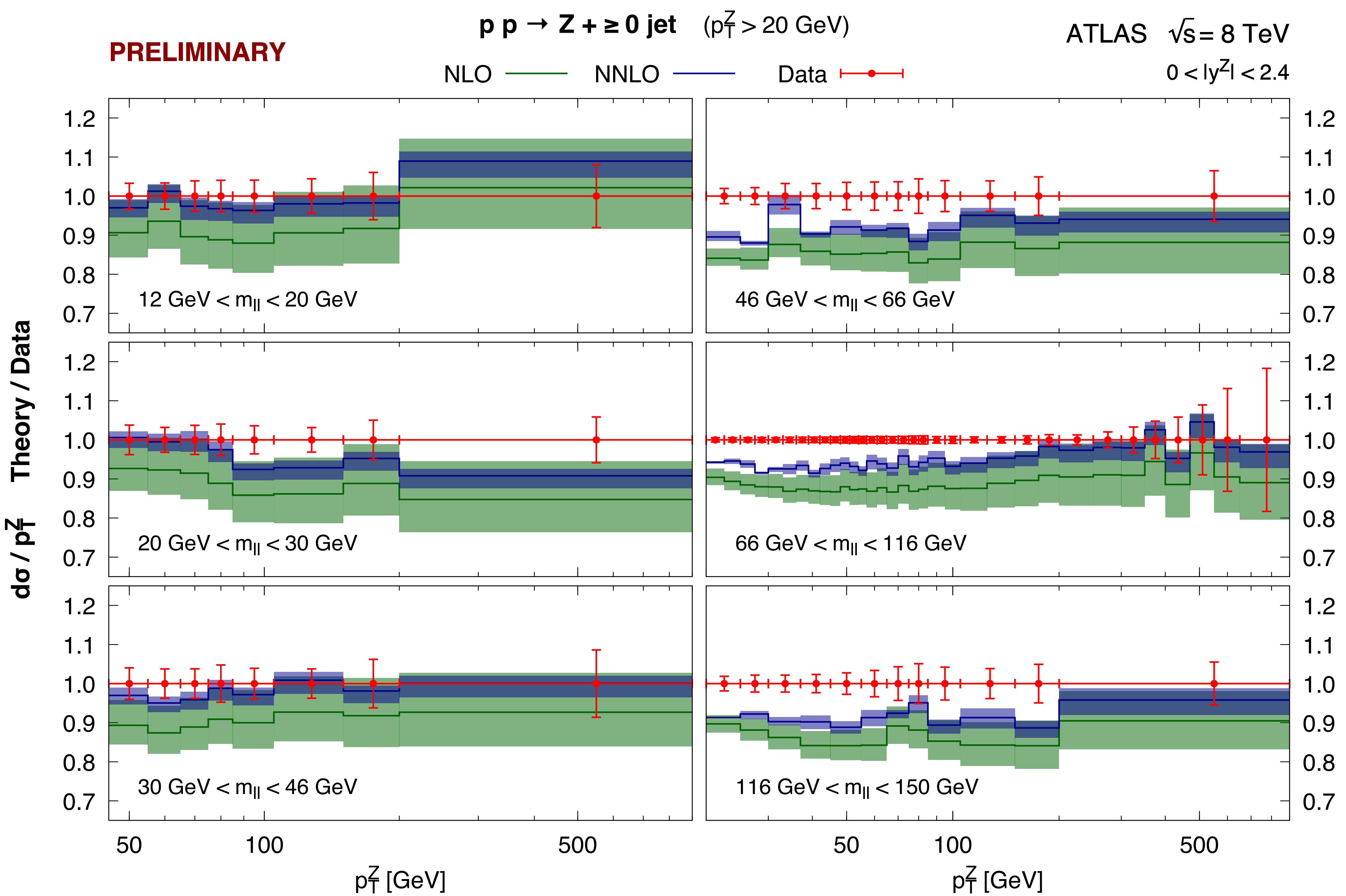


Ratio to NLO



p p → Z + ≥ 0 jet (p$_T^Z$ > 20 GeV)
PRELIMINARY
ATLAS √s = 8 TeV
66 GeV < m$_{ll}$ < 116 GeV
NLO
NNLO
Data
dσ / p$_T^Z$ Ratio to NLO
0 < |y^Z| < 0.4
1.2 < |y^Z| < 1.6
0.4 < |y^Z| < 0.8
1.6 < |y^Z| < 2.0
0.8 < |y^Z| < 1.2
2.0 < |y^Z| < 2.4
p$_T^Z$ [GeV]
p$_T^Z$ [GeV]

$\mathrm{d}\sigma/\mathrm{d}p_T^Z$ binned in m$_{ll}$



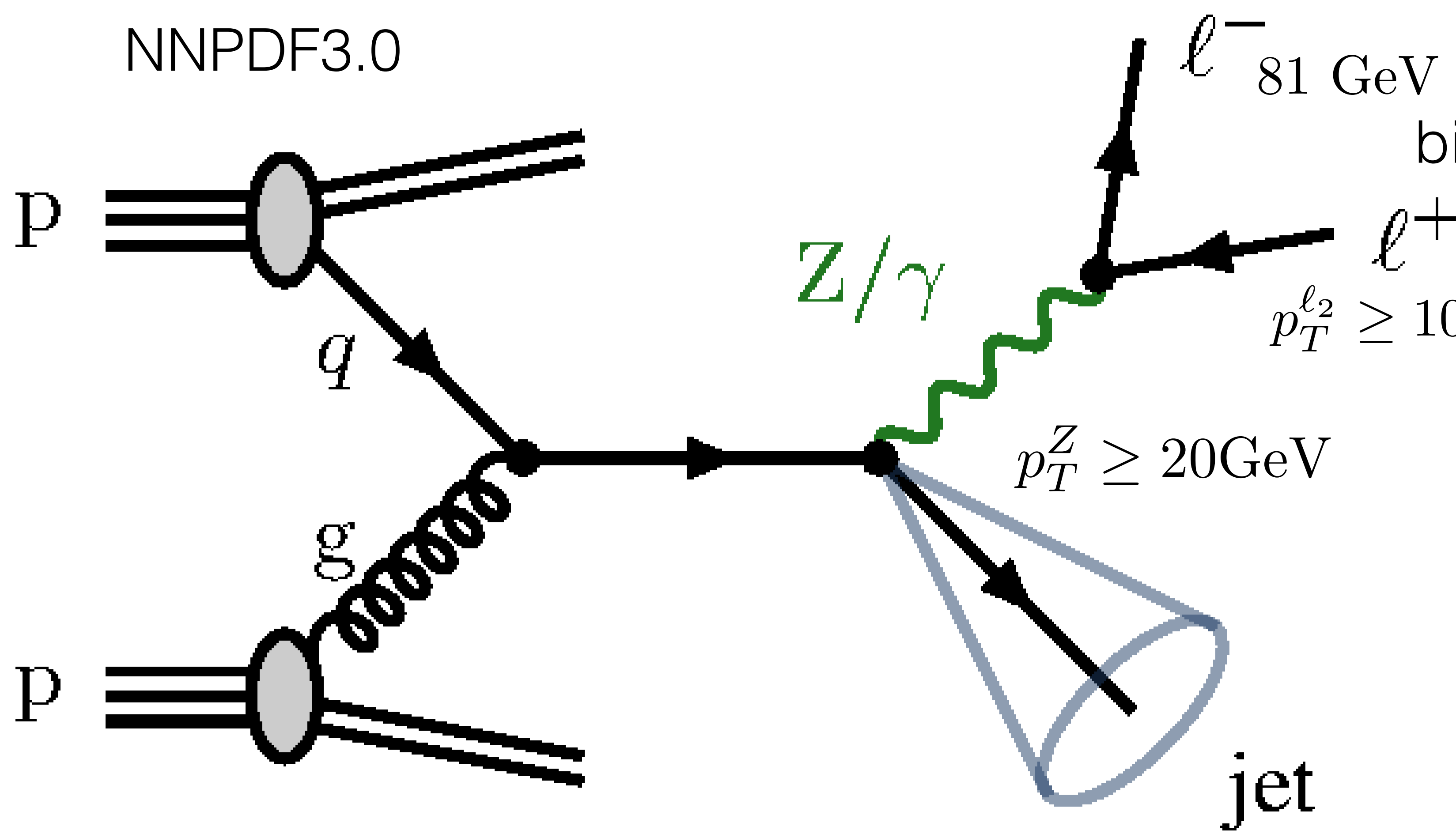
Setup-inclusive Z-CMS cuts

$p_T^{\ell_1} \geq 25~\text{GeV},~~|y^{\ell_1}| < 2.1$

NNPDF3.0

$81~\text{GeV} < m_{\ell\ell} < 101~\text{GeV}$

binned in y^Z



$p_T^{\ell_2} \geq 10~\text{GeV},~~|y^{\ell_2}| < 2.4$

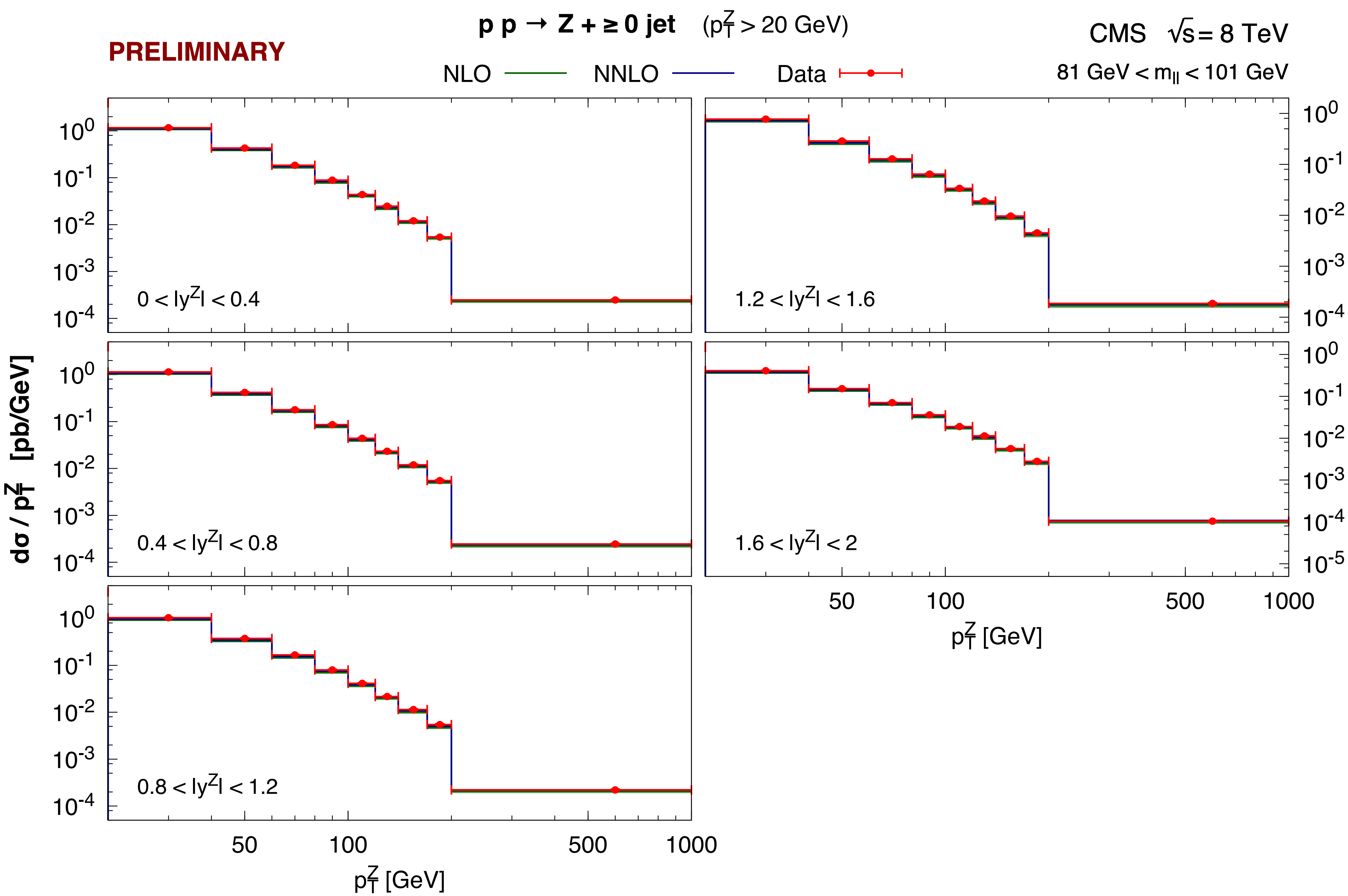
8 TeV

$p_T^Z \geq 20\text{GeV}$

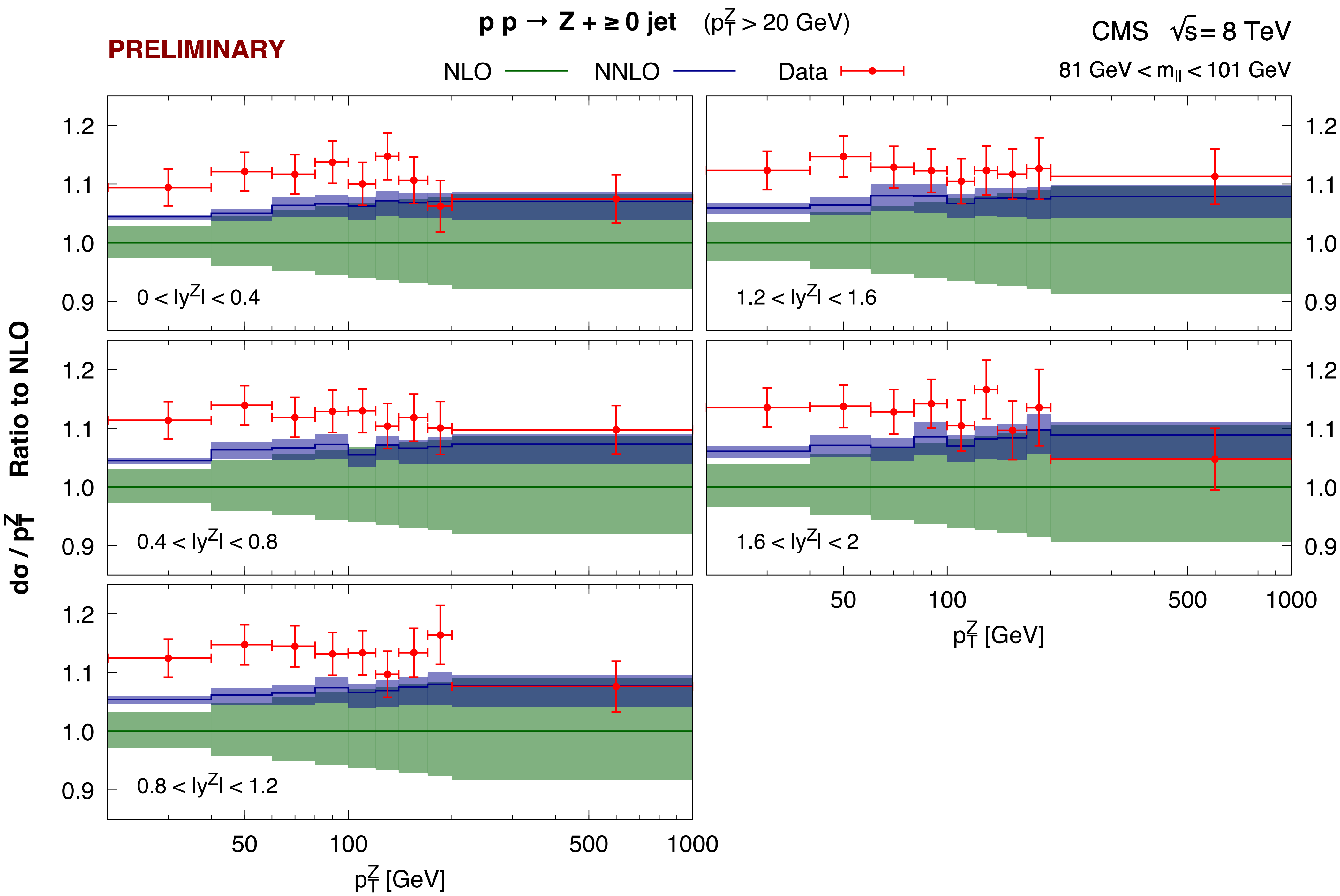
$$\mu_R = \mu_F = \sqrt{m_{\ell\ell}^2 + p_{T,Z}^2} \times \left[\frac{1}{2}, 1, 2\right]$$

Fully inclusive in QCD radiation

$\mathrm{d}\sigma/\mathrm{d}p_T^Z$ binned in y^Z



Ratio to NLO



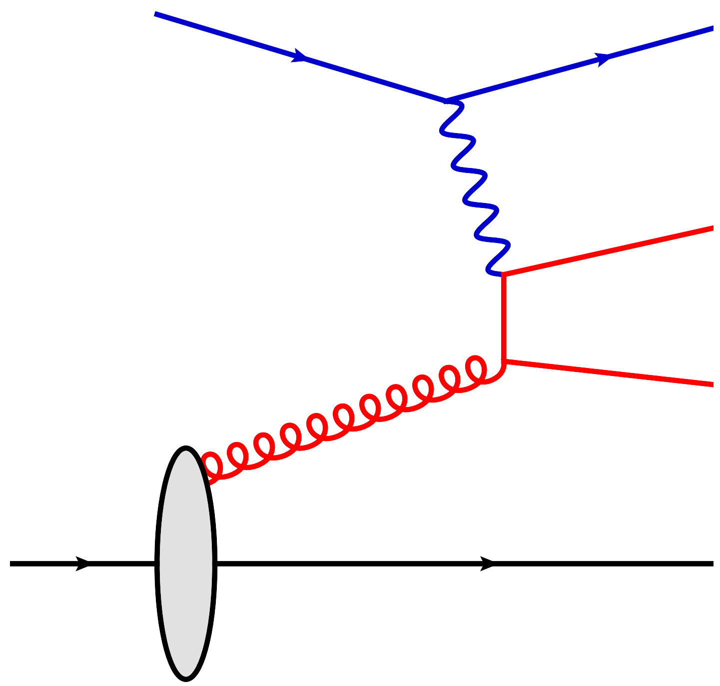
PRELIMINARY
p p → Z + ≥ 0 jet (p$_T^Z$ > 20 GeV)
CMS √s = 8 TeV
81 GeV < m$_{ll}$ < 101 GeV
NLO
NNLO
Data
dσ / p$_T^Z$ Ratio to NLO
0 < |y^Z| < 0.4
1.2 < |y^Z| < 1.6
0.4 < |y^Z| < 0.8
1.6 < |y^Z| < 2
0.8 < |y^Z| < 1.2
0.9
1.0
1.1
1.2
50
100
500
1000
p$_T^Z$ [GeV]

- moderate NNLO corrections (in the right direction!)
- reduces tension with data
- scale variation significantly reduced
- clarifies the theoretical challenge for resolving with data

DIS (2+1)J

DIS is not just a way of approximating VBF Higgs!

- wealth of data used extensively for quark PDFs
- (2+1)J directly sensitive to gluon
- would like to include NNLO consistently into PDF fits



Setup

Cuts and parameters as set out in [1406.4709]:

- HERA lab frame $-1 < \eta_j < 2.5$
- Breit frame $5 \text{ GeV} < p_T < 50 \text{ GeV}$

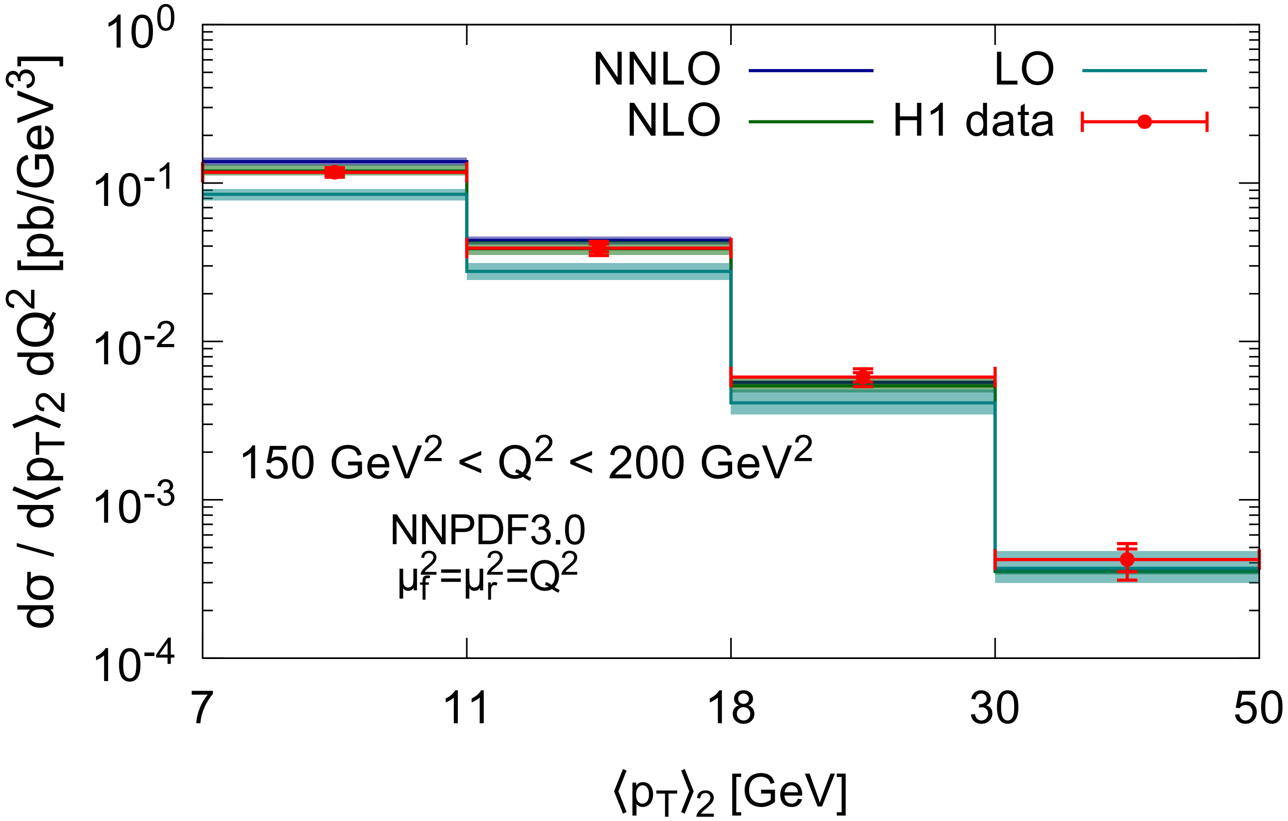
$$m_{12} > 16 \text{ GeV}$$

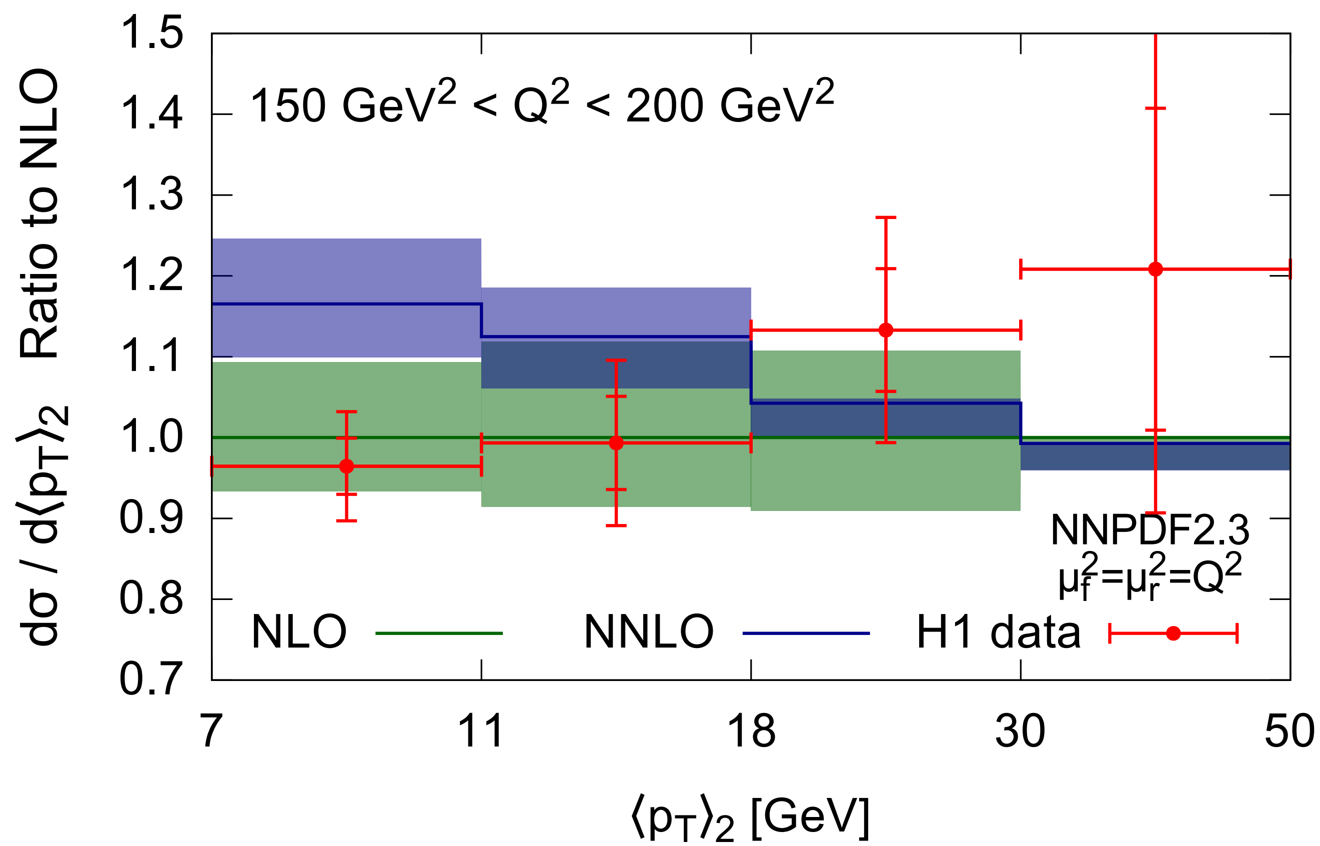
Dijet and Trijet observables:

$$\langle p_T \rangle_2 = \frac{1}{2}\left(p_T^{j_1} + p_T^{j_2}\right) \qquad \xi_2 = x\left(1 + \frac{m_{12}^2}{Q^2}\right)$$

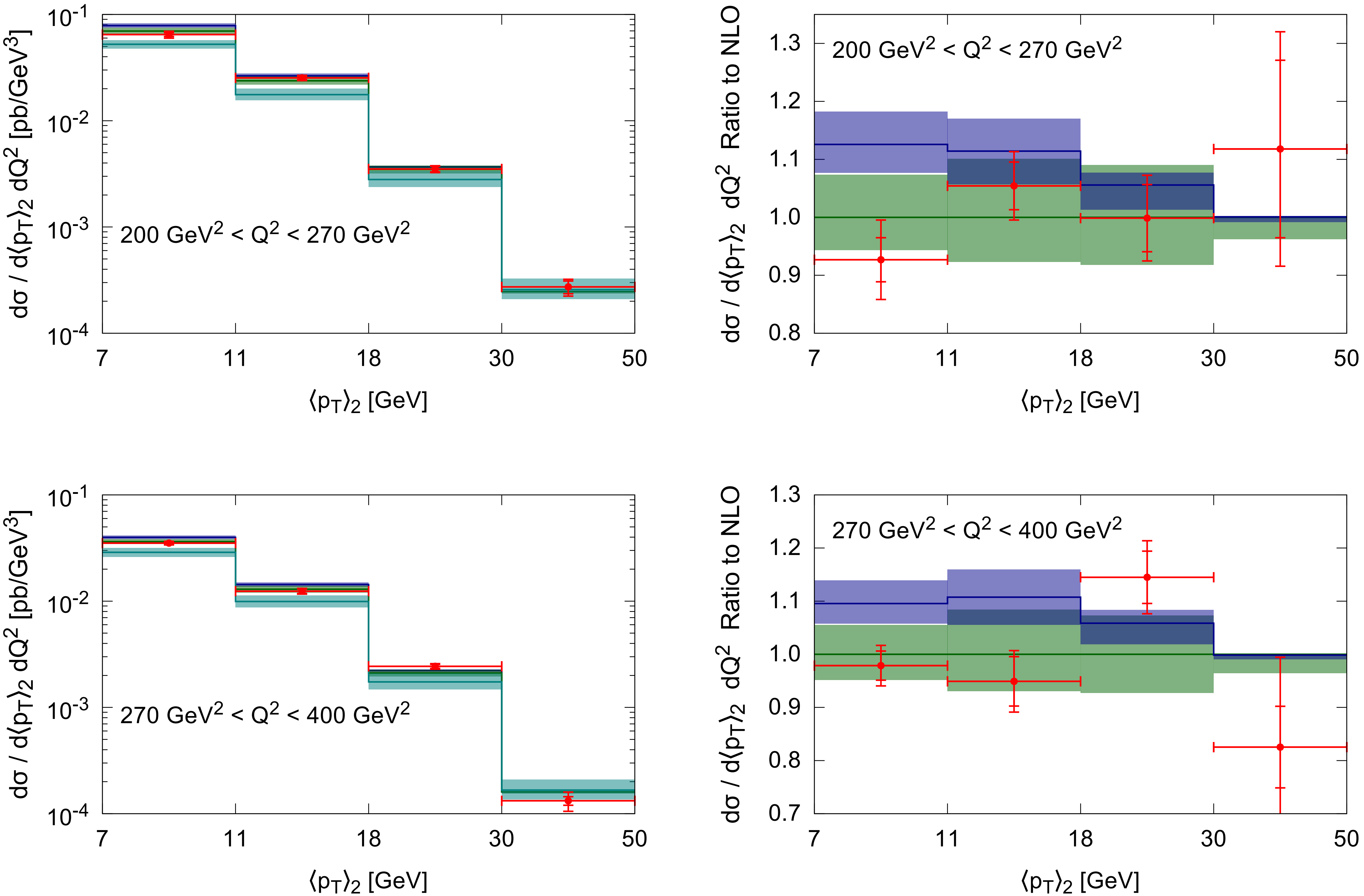
$$\langle p_T \rangle_3 = \frac{1}{2}\left(p_T^{j_1} + p_T^{j_2} + p_T^{j_3}\right) \qquad \xi_3 = x\left(1 + \frac{m_{123}^2}{Q^2}\right)$$

$\langle p_T \rangle_2$





- significant reduction in scale uncertainty ≲5%, below experimental errors
- suffers from Sudokov shoulder in lowest bin due to selection cuts



200 GeV^2 < Q^2 < 270 GeV^2
270 GeV^2 < Q^2 < 400 GeV^2
dσ / d⟨p$_T$⟩$_2$ dQ^2 [pb/GeV^3]
dσ / d⟨p$_T$⟩$_2$ dQ^2 Ratio to NLO
⟨p$_T$⟩$_2$ [GeV]

Future applications

Would like to improve experimental analysis:

- symmetric p_T and m_{12} cut causing problems
- would like asymmetric cuts on leading and subleading jets

Program ready to be applied to other setups:

- intermediate and low Q^2 ranges

View to phenomenology:

- determination of α_s
- refit PDFs using DIS dijet data

Dijet

- So far published gluons-only full colour [Gehrmann, Gehrmann-De Ridder, Glover, Pires ’12; Currie, Gehrmann-De Ridder, Glover, Pires ’13]
- recently migrated to *NNLOJET* framework
- completed for all channels (gg, qg, $\bar{q}$g, q$\bar{q}$, qq, qQ, q$\bar{Q}$) at leading colour-leading N_F
  - i.e N^2, NN_F & N_F^2 NNLO corrections to LO
- currently running and checking results
- hope to have public results imminently for phenomenology

NNLOJET

All calculations now housed within single basic framework:

- completely standalone code at LO, NLO, NNLO
- fully differential parton level event generator
- many processes now included:
  - H($\gamma\gamma$)+ 0,1,2 jets
  - Z(l^+l^-)+ 0,1 jet
  - DIS dijet
  - LHC+Tevatron dijet
- development and validation of the code ongoing, adding new process

Future Projects

- further refinement of the method to improve efficiency
- H+J new decay channels
- Dijet phenomenology, PDF fits
- H+2j in HEFT @ NNLO
  - same subtraction terms as dijet, need amps
- pp->3J
  - no new ingredients needed for subtraction, need amps
  - $R_{3/2}$ at NNLO hadron collider a real possibility

Summary

Antenna subtraction has moved on from a proof of principle to full blown phenomenology:

- implemented in standalone parton-level event generator *NNLOJET*
- powerful, general and analytic method for producing NNLO accurate distributions
- many processes of interest now complete or nearing completion
- method can cope with exciting new processes without extension
- comparison of NNLO fixed order with data now a reality at LHC