Future prospects of α_s from jets at the LHC at NNLO

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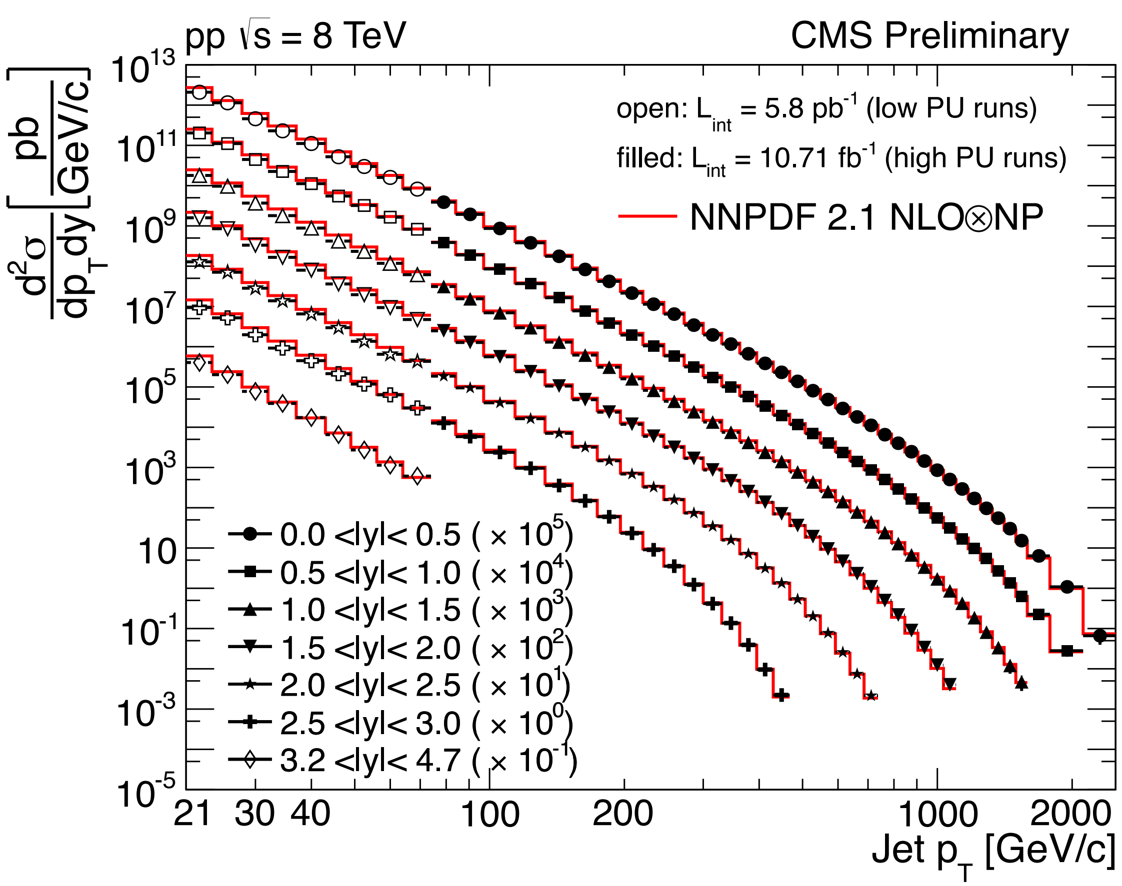
References:

- **Phys.Rev.Lett. 110 (2013) 16, 162003 A.Gehrmann-De Ridder, T. Gehrmann, N.Glover, JP**
- **JHEP 1304 (2013) 066 J.Currie, N.Glover, S.Wells**
- **JHEP 1401 (2014) 110 J.Currie, A.Gehrmann-De Ridder, N.Glover, JP**
- **PoS LL2014 (2014) 001 J.Currie, A.Gehrmann-De Ridder, T.Gehrmann, N.Glover, JP**
- **EPJ Web Conf. 90 (2015) 07005 JP**

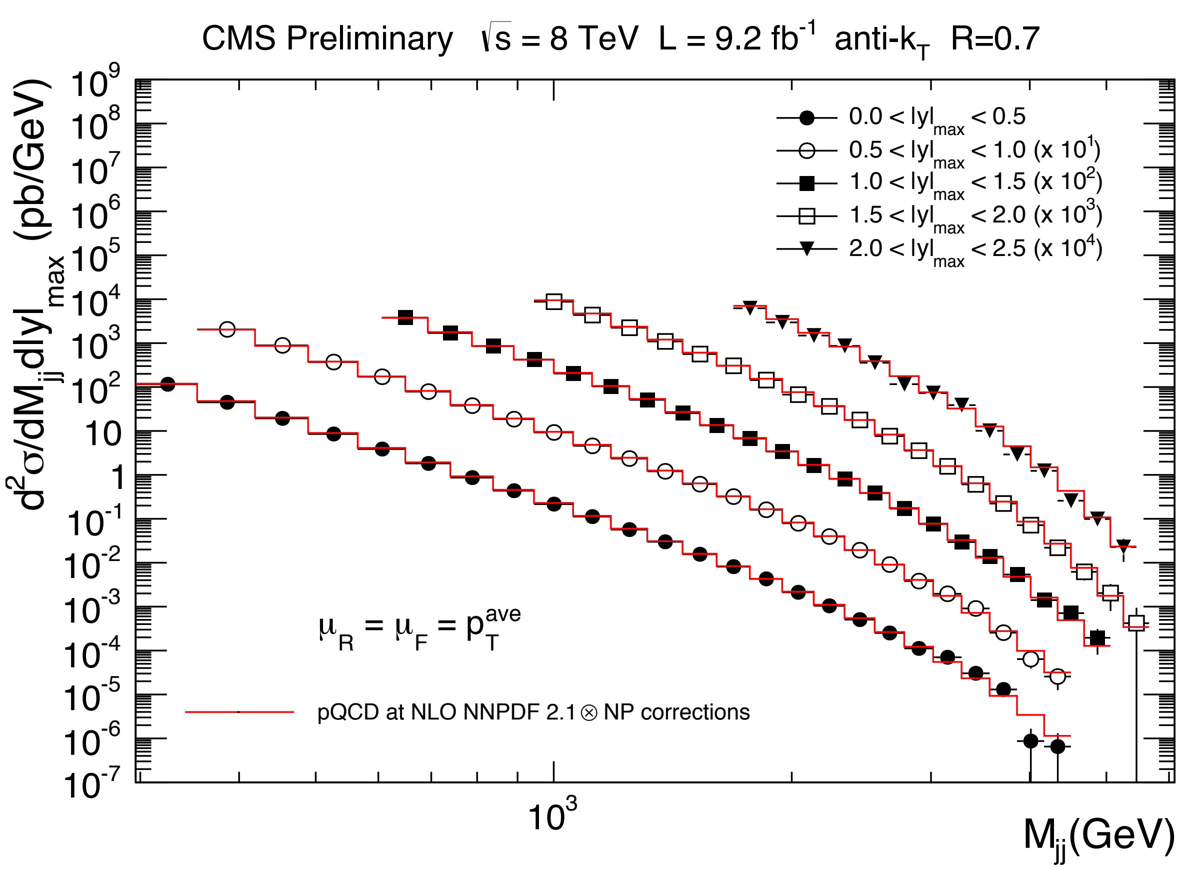
Jets at the LHC

- look at production of jets of hadrons with large transverse energy
- for sufficiently high transverse momentum $p_T > 20$ GeV high rates and clean and simple cross section definition

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T dy} = \frac{1}{\mathcal{L}} \frac{N_{jets}}{\Delta p_T \Delta y}$$



CMS-PAS-FSQ-12-031



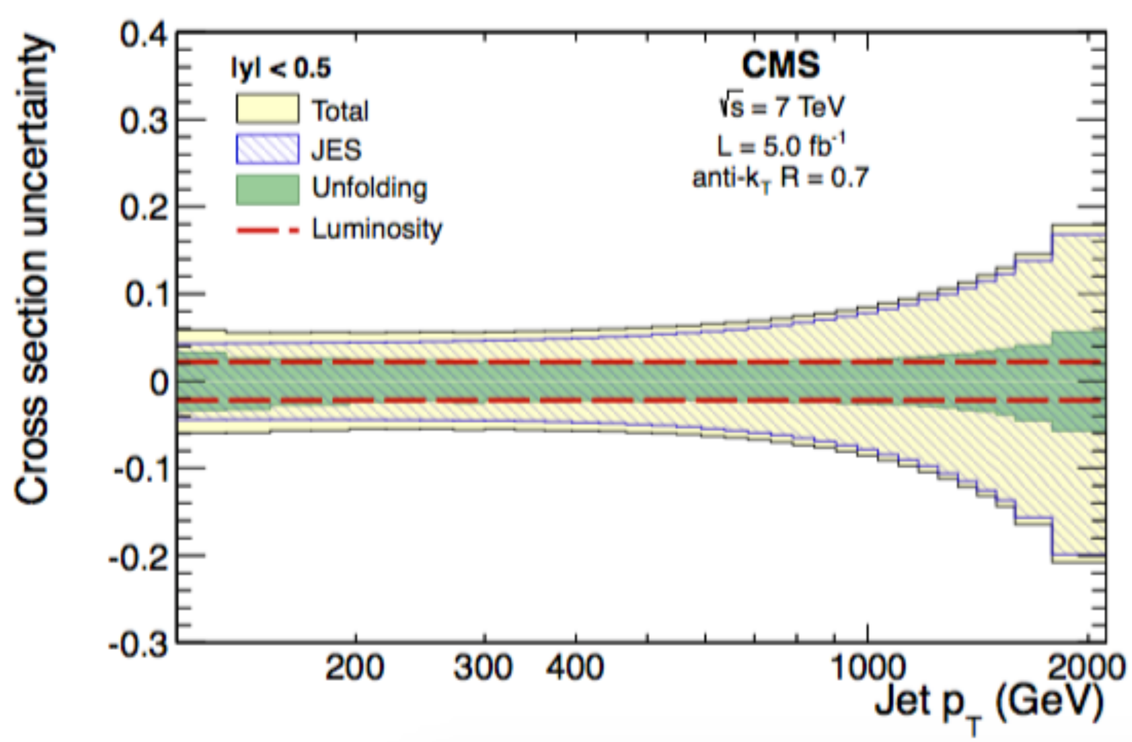
CMS-PAS-SMP-14-002

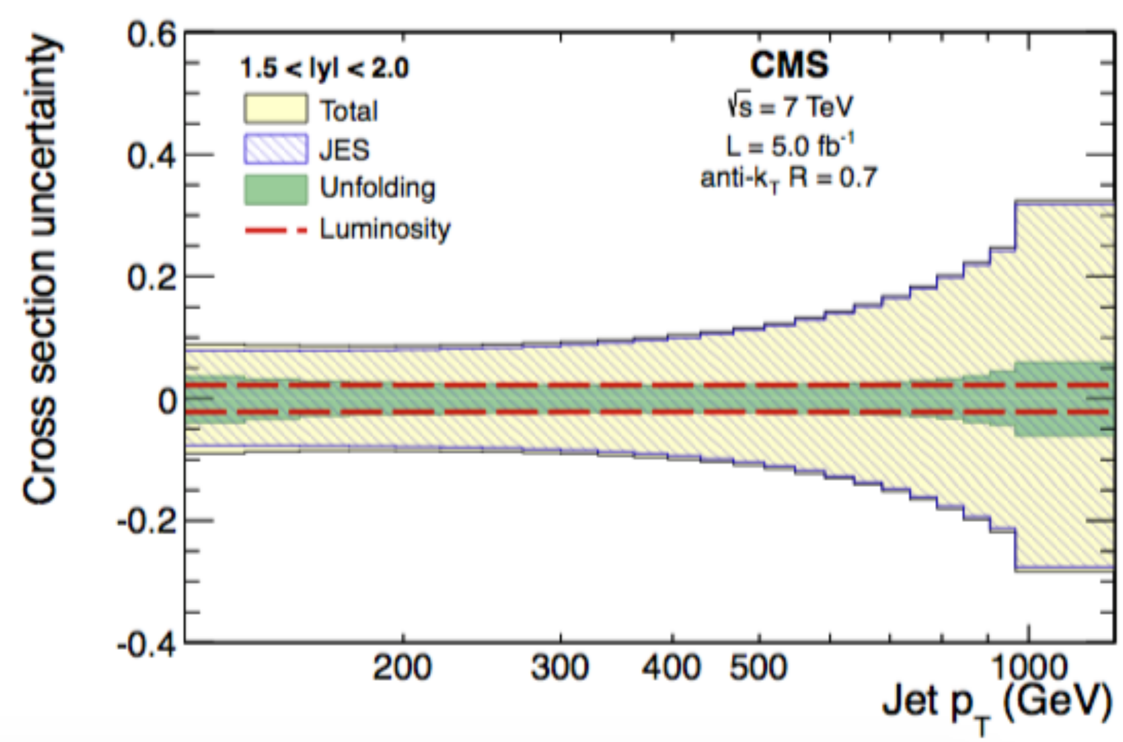
Jet cross section measurements

Collab.	Dataset	Measurement	anti-k_t R	Kinematic ranges
ATLAS	7 TeV, $\mathscr{L} = 17\ \mathrm{nb}^{-1}$	inclusive jet dijet mass	0.4 and 0.6	$(p_T/\mathrm{GeV} \geq 60) \otimes (\lvert y \rvert < 2.8)$ for dijet mass: $(p_T^{2nd}/\mathrm{GeV} \geq 30)$
ATLAS	7 TeV, $\mathscr{L} = 37\ \mathrm{pb}^{-1}$	inclusive jet dijet mass	0.4 and 0.6	$(p_T/\mathrm{GeV} \geq 20) \otimes (\lvert y \rvert < 4.4)$ for dijet mass: $(p_T^{1st}/\mathrm{GeV} \geq 30)$
ATLAS	7 TeV, $\mathscr{L} = 4.5\ \mathrm{fb}^{-1}$	inclusive jet	0.4 and 0.6	$(p_T/\mathrm{GeV} \geq 100) \otimes (\lvert y \rvert < 3.0)$
CMS	7 TeV, $\mathscr{L} = 34\ \mathrm{pb}^{-1}$	inclusive jet	0.5	$(p_T/\mathrm{GeV} \geq 18) \otimes (\lvert y \rvert < 3.0)$
CMS	7 TeV, $\mathscr{L} = 5\ \mathrm{fb}^{-1}$	inclusive jet dijet mass	0.7	$(p_T/\mathrm{GeV} \geq 100) \otimes (\lvert y \rvert < 2.5)$ $(p_T^{1st}/\mathrm{GeV} \geq 60$ and $p_T^{2nd}/\mathrm{GeV} \geq 30) \otimes (\lvert y \rvert < 2.5)$
CMS	7 TeV, $\mathscr{L} = 5\ \mathrm{fb}^{-1}$	inclusive jet jet p_T	0.7	$(35 \leq p_T/\mathrm{GeV} < 150) \otimes (3.2 < \lvert \eta^f \rvert < 4.7)$ in dijet evt.: $(\lvert \eta^c \rvert < 2.8)$
CMS	7 TeV, $\mathscr{L} = 5\ \mathrm{fb}^{-1}$	inclusive jet	0.5 and 0.7	$(p_T/\mathrm{GeV} \geq 56) \otimes (\lvert y \rvert < 3.0)$
prelim.	8 TeV, $\mathscr{L} = 10.71\ \mathrm{fb}^{-1}$	inclusive jet	0.7	$(p_T/\mathrm{GeV} \geq 80) \otimes (\lvert y \rvert < 3.0)$

[1510.01943]

- dominant systematic uncertainty JES ~ 1-2% corresponds to < 10% uncertainty on single inclusive x-sec





Observables for the determination of α_S at the LHC

- inclusive jet cross section $$\frac{d\sigma_{incl.jet}}{dp_T dy} \propto \alpha_s^2$$
  - NLO ✔ NNLO (partial)
- 3-jet to 2-jet inclusive cross section ratio $$\frac{d\sigma_{3jet/2jet}}{d\bar{p}_{T_{1,2}}} \propto \alpha_s$$
  - NLO ✔ NNLO ✗
- 3-jet mass cross section $$\frac{d\sigma_{3jet}}{dm_3 dy_{max}} \propto \alpha_s^3$$
  - NLO ✔ NNLO ✗
- top-quark pair production (A.Mitov's talk) $$\sigma_{t\bar{t}} \propto \alpha_s^2$$
  - NLO ✔ NNLO ✔

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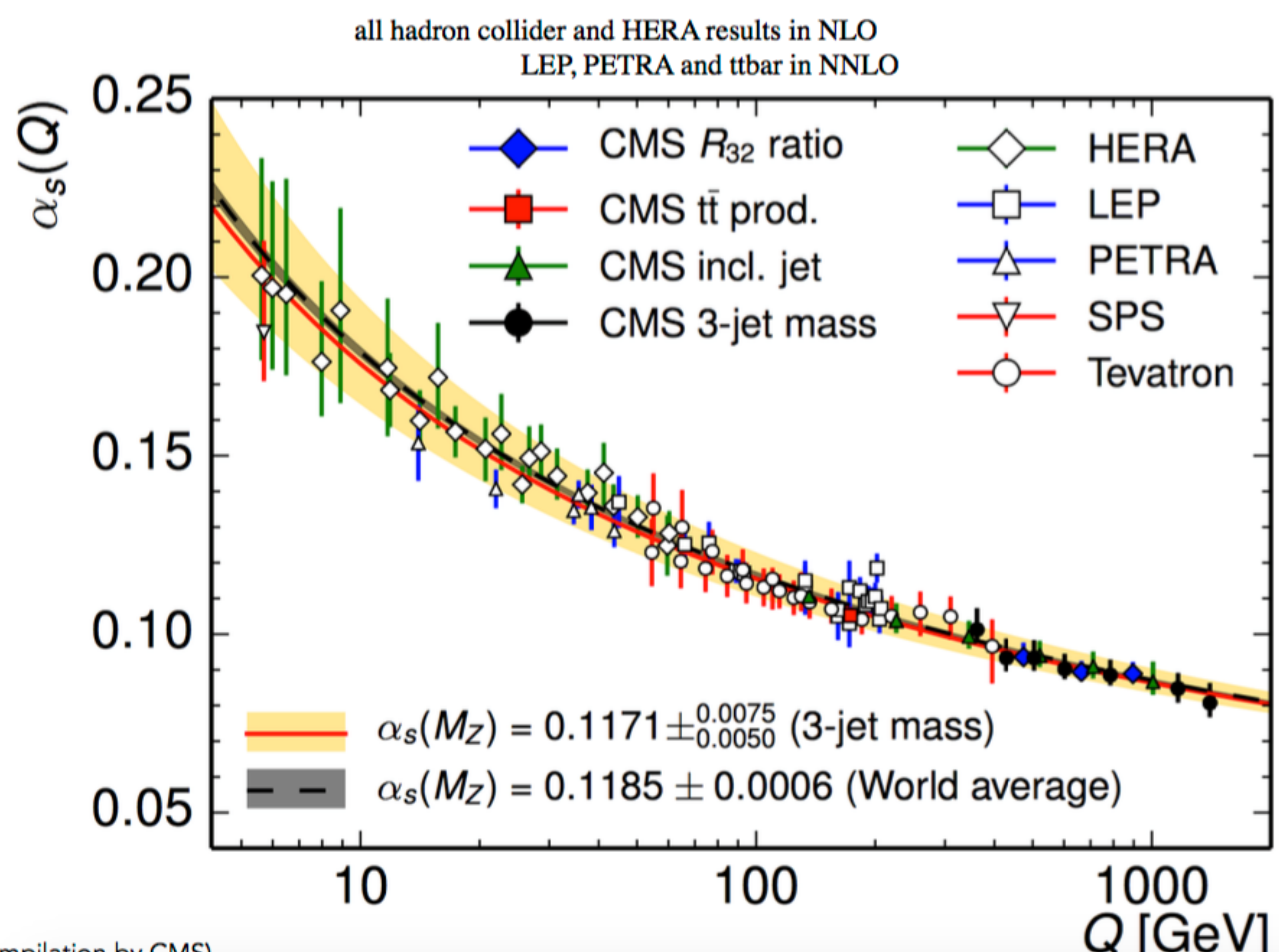
This talk

Motivation

- experimental tests of perturbative QCD at the TeV scale, asymptotic freedom

$$\mu_R^2 \frac{\mathrm{d}\alpha_s}{\mathrm{d}\mu_R^2} = \beta(\alpha_s) = -\left(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \ldots\right)$$



(compilation by CMS)

Motivation

- reduce world average α_s uncertainty by including LHC inclusive jet collider data at NNLO
- improve Higgs cross section measurements (Luminita Mihaila's talk)

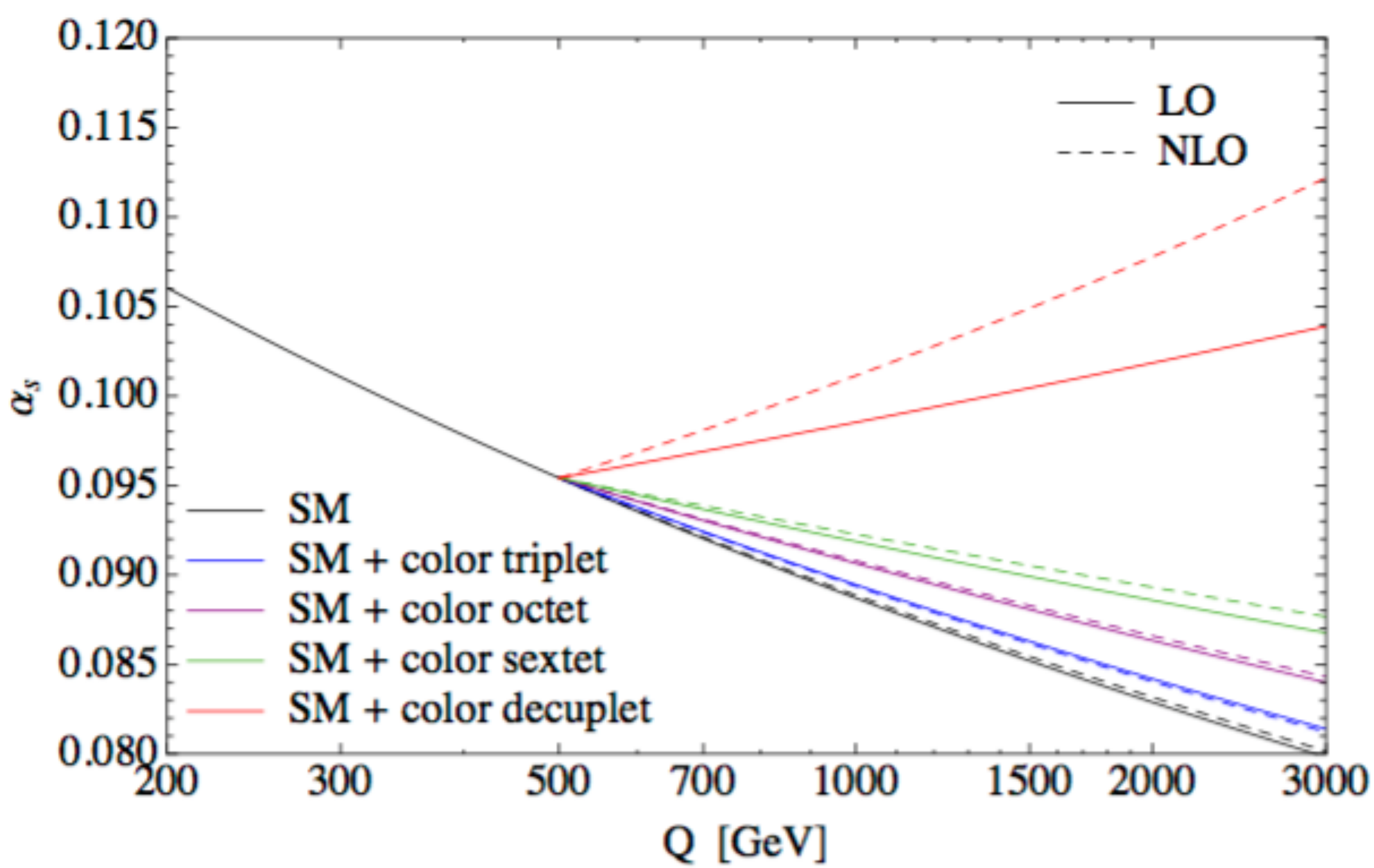
Uncertainties (update of [LHC HXSWG 2013] for $\sqrt{s} = 14$ TeV)

Process	Cross section(pb)	Scale(%)		$\delta\alpha_s$(%)
ggH	49.87	-2.61	+ 0.32	$\pm$ 3.7
VBF	4.15	-0.4	+ 0.8	$\pm$ 0.7
WH	1.474	-0.6	+ 0.3	$\pm$ 0.9
ZH	0.863	-1.8	+ 2.7	$\pm$ 0.9
ttH	0.611	-9.3	+ 5.9	$\pm$ 3.0

Motivation

- provide model independent exclusions on BSM models which predict a different running (Francesco Sannino's talk)

$$\frac{\alpha_s(Q)}{\alpha_s^{SM}(Q)} \approx 1 + \frac{n_{eff}}{3\pi}\alpha_s(m_X)\log\left(\frac{Q}{m_X}\right)$$

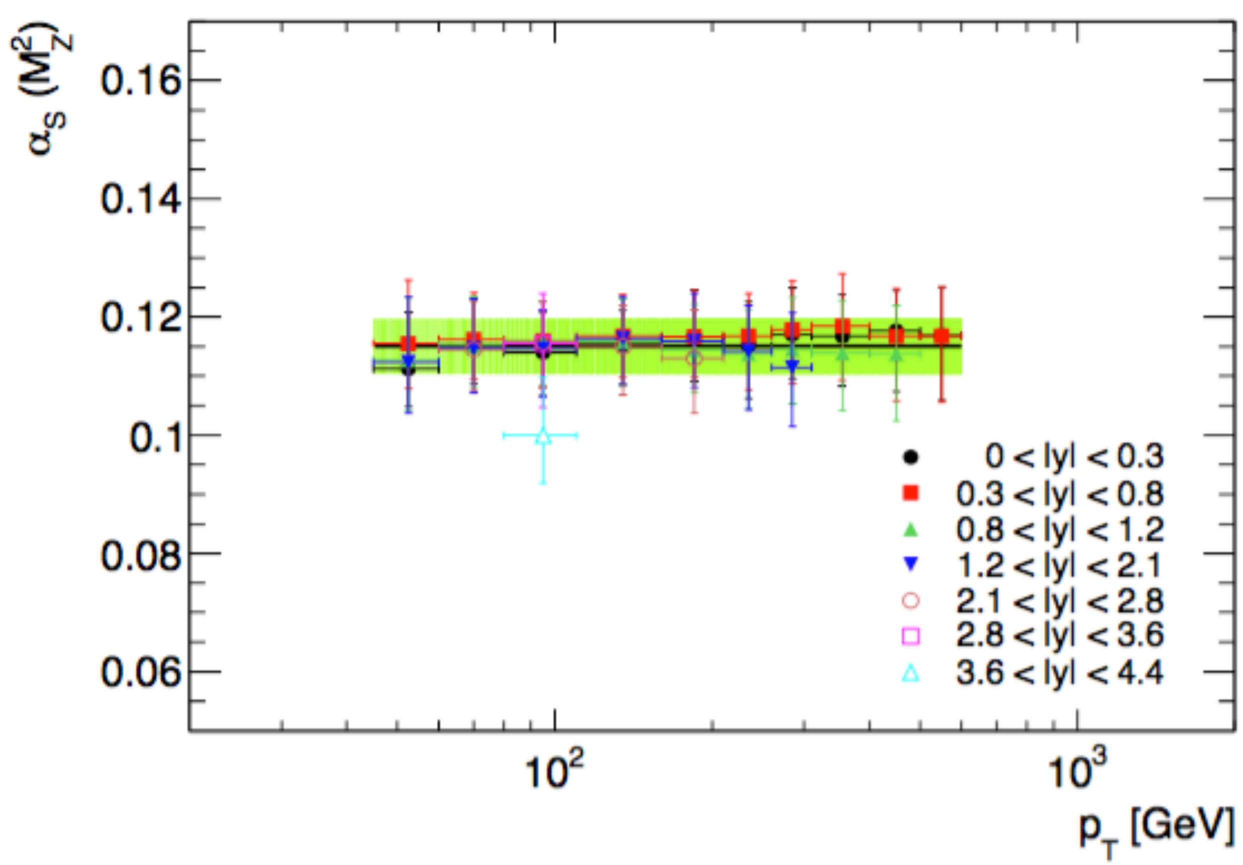


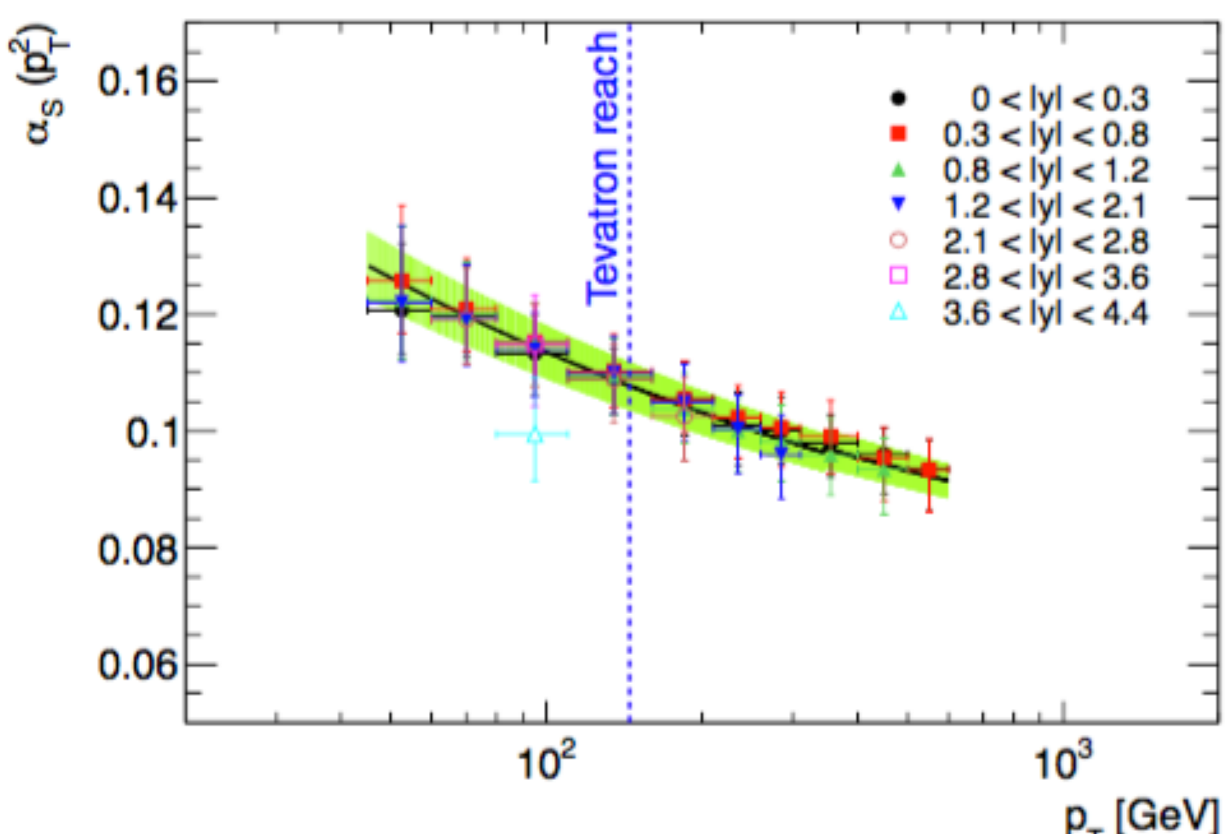
ATLAS dataset L=37pb^{-1} $\sqrt{s}$=7 TeV

- 42 data points in the p_T range 45 GeV to 600 GeV of the inclusive jet p_T cross section
- theoretical prediction: NLO QCD with non-perturbative corrections
- large systematic uncertainty of the fit due to jet radius choice followed by JES and missing higher NNLO order

$$\alpha_s(M_Z) = 0.1151 \pm 0.0001\,(\mathrm{stat}) \pm 0.0047\,(\mathrm{sys}) \pm 0.0014\,(\mathrm{p_T\ range}) \pm 0.0060\,(\mathrm{jet\ size})\ ^{+0.0044}_{-0.0011}\,(\mathrm{scale})\ ^{+0.0022}_{-0.0015}\,(\mathrm{PDF\ choice}) \pm 0.0010\,(\mathrm{PDF\ eig})\ ^{+0.0009}_{-0.0034}\,(\mathrm{NP\ corrections})\,.$$

B.Malaescu, P.Starovoitov[1203.5416]





CMS dataset L=5fb^{-1} $\sqrt{s}$=7 TeV

- 133 data points in the p_T range 114 GeV to 2116 GeV and 5 rapidity bins with $|y| < 2.5$ of the inclusive jet p_T cross section R=0.7
- theoretical prediction: NLO QCD and EW corrections with non-perturbative corrections
- theoretical uncertainties limit the achievable precision

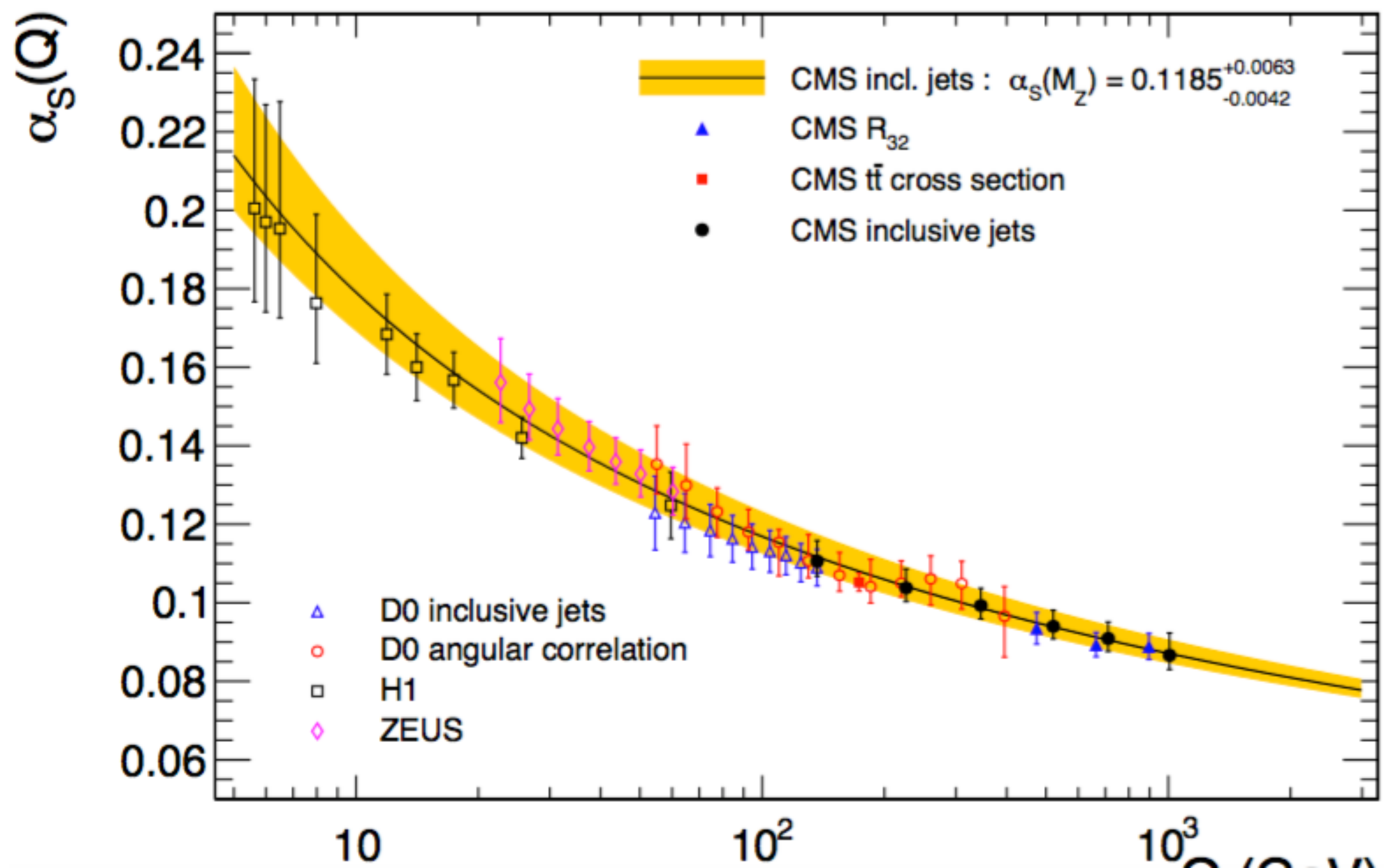
$$\alpha_s(M_Z) = 0.1185 \pm 0.0019(\mathrm{exp})^{+0.0060}_{-0.0037}(\mathrm{theo})$$

$\|y\|$ range	No. of data points	$\alpha_S(M_Z)$	χ^2/n_{dof}
$\|y\| < 0.5$	33	$0.1189 \pm 0.0024\,(\mathrm{exp}) \pm 0.0030\,(\mathrm{PDF}) \pm 0.0008\,(\mathrm{NP})^{+0.0045}_{-0.0027}\,(\mathrm{scale})$	16.2/32
$0.5 \leq \|y\| < 1.0$	30	$0.1182 \pm 0.0024\,(\mathrm{exp}) \pm 0.0029\,(\mathrm{PDF}) \pm 0.0008\,(\mathrm{NP})^{+0.0050}_{-0.0025}\,(\mathrm{scale})$	25.4/29
$1.0 \leq \|y\| < 1.5$	27	$0.1165 \pm 0.0027\,(\mathrm{exp}) \pm 0.0024\,(\mathrm{PDF}) \pm 0.0008\,(\mathrm{NP})^{+0.0043}_{-0.0020}\,(\mathrm{scale})$	9.5/26
$1.5 \leq \|y\| < 2.0$	24	$0.1146 \pm 0.0035\,(\mathrm{exp}) \pm 0.0031\,(\mathrm{PDF}) \pm 0.0013\,(\mathrm{NP})^{+0.0037}_{-0.0020}\,(\mathrm{scale})$	20.2/23
$2.0 \leq \|y\| < 2.5$	19	$0.1161 \pm 0.0045\,(\mathrm{exp}) \pm 0.0054\,(\mathrm{PDF}) \pm 0.0015\,(\mathrm{NP})^{+0.0034}_{-0.0032}\,(\mathrm{scale})$	12.6/18
$\|y\| < 2.5$	133	$0.1185 \pm 0.0019\,(\mathrm{exp}) \pm 0.0028\,(\mathrm{PDF}) \pm 0.0004\,(\mathrm{NP})^{+0.0053}_{-0.0024}\,(\mathrm{scale})$	104.1/132

CMS collaboration [1410.6765]

CMS dataset L=5fb^{-1} $\sqrt{s}$=7 TeV

- running of the strong coupling investigated by refitting six p_T bins in the range Q=136-1007 GeV



CMS collaboration [1410.6765]

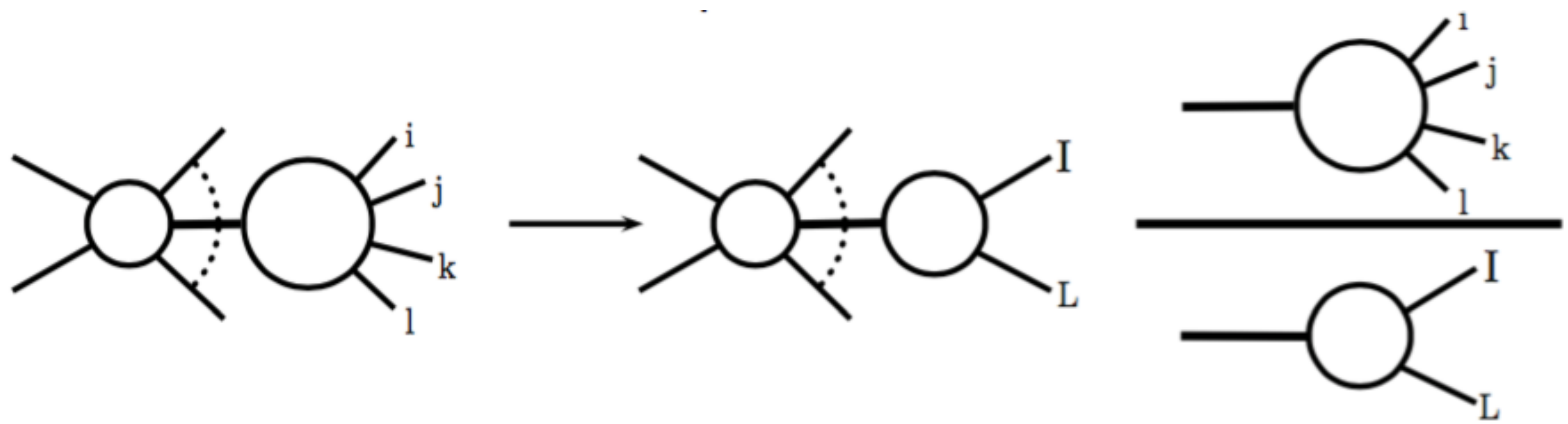
Towards inclusive jet production at NNLO

$$\mathrm{d}\hat{\sigma}_{NNLO} = \int_{\mathrm{d}\Phi_4} \mathrm{d}\sigma_{NNLO}^{RR} + \int_{\mathrm{d}\Phi_3} \mathrm{d}\sigma_{NNLO}^{RV} + \int_{\mathrm{d}\Phi_2} \mathrm{d}\sigma_{NNLO}^{VV}$$

- six parton tree level + five parton one-loop + four parton two-loop QCD scattering matrix elements
- explicit infrared poles from loop integrations
- implicit poles in phase space regions for single and double unresolved emission
- procedure to extract the IR singularities and assemble all the pieces in a parton-level generator
- differential cross sections → kinematics of the final state intact to apply arbitrary phase space cuts

Antenna subtraction at NNLO

- universal factorisation of both color ordered matrix elements and the (m+2)- particle phase space → colour connected unresolved partons



$$|M_{m+4}(\ldots,i,j,k,l,\ldots)|^2\ J(\{p_{m+4}\})\ \longrightarrow |M_{m+2}(\ldots,I,L,\ldots)|^2\ J(\{p_{m+2}\})\ \cdot X_4^0(i,j,k,l)$$

$$\mathrm{d}\hat{\sigma}_{NNLO} = \int_{\mathrm{d}\Phi_4}(\mathrm{d}\sigma^{RR}_{NNLO} - \mathrm{d}\sigma^{S}_{NNLO}) + \int_{\mathrm{d}\Phi_3}(\mathrm{d}\sigma^{RV}_{NNLO} - \mathrm{d}\sigma^{T}_{NNLO}) + \int_{\mathrm{d}\Phi_2}(\mathrm{d}\sigma^{VV}_{NNLO} - \mathrm{d}\sigma^{U}_{NNLO})$$

- pure gluon process involves identity preserving initial-state collinear singularities only

- mixed gluon-quark processes involves both identity preserving and identity changing initial state collinear singularities and their overlap

Antenna subtraction at NNLO

Checks on the NNLO pp→j+X calculation:

- subtraction terms correctly approximate the matrix elements in all unresolved configurations of partons *j,k*

$$\boxed{\mathrm{d}\hat{\sigma}^{RR,RV}_{NNLO} \xrightarrow{\forall\{j,k\},\{j\}\to 0} \mathrm{d}\hat{\sigma}^{S,T}_{NNLO}}$$

- local (pointwise) analytic cancellation of all IR explicit poles when integrated subtraction terms are combined with one and two-loop matrix elements

$$\boxed{\mathcal{P}oles\left(\mathrm{d}\hat{\sigma}^{RV}_{NNLO} - \mathrm{d}\hat{\sigma}^{T}_{NNLO}\right) = 0}$$

$$\boxed{\mathcal{P}oles\left(\mathrm{d}\hat{\sigma}^{VV}_{NNLO} - \mathrm{d}\hat{\sigma}^{U}_{NNLO}\right) = 0}$$

- allows the computation of multiple differential distributions in a single program run

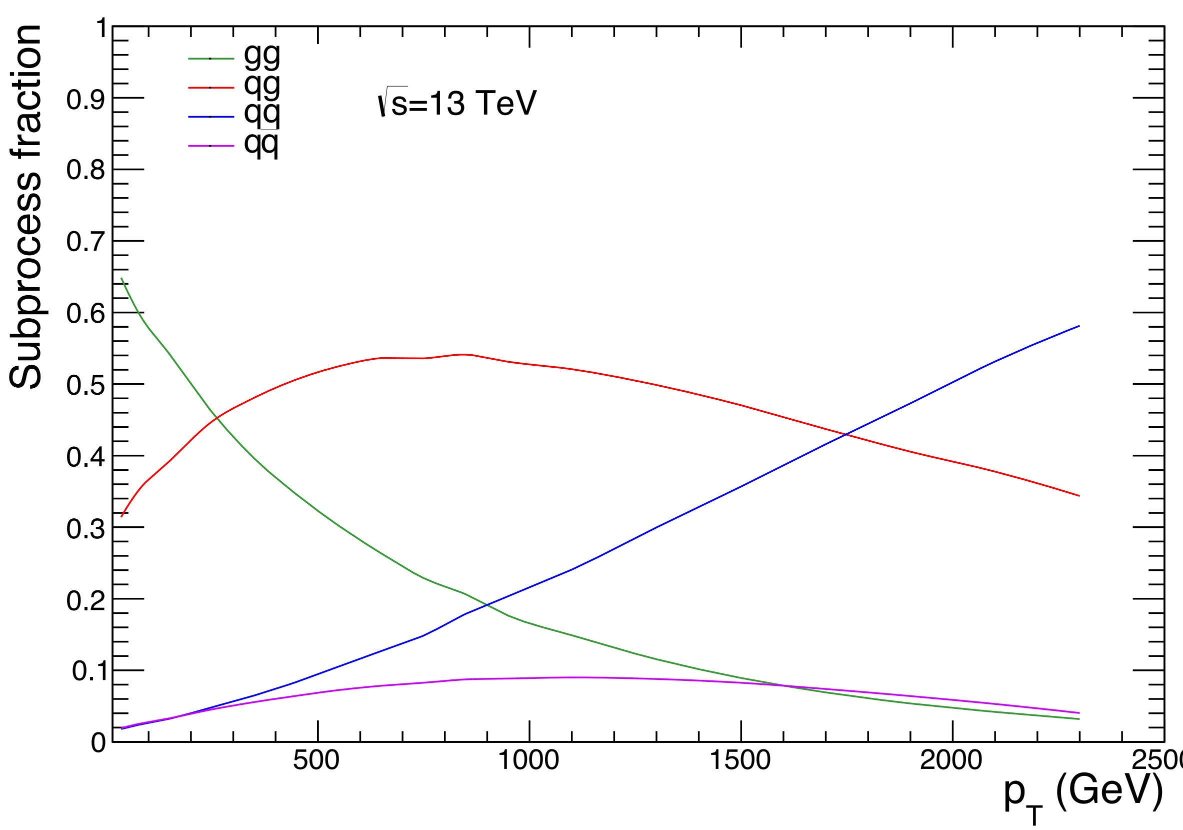
Numerical setup

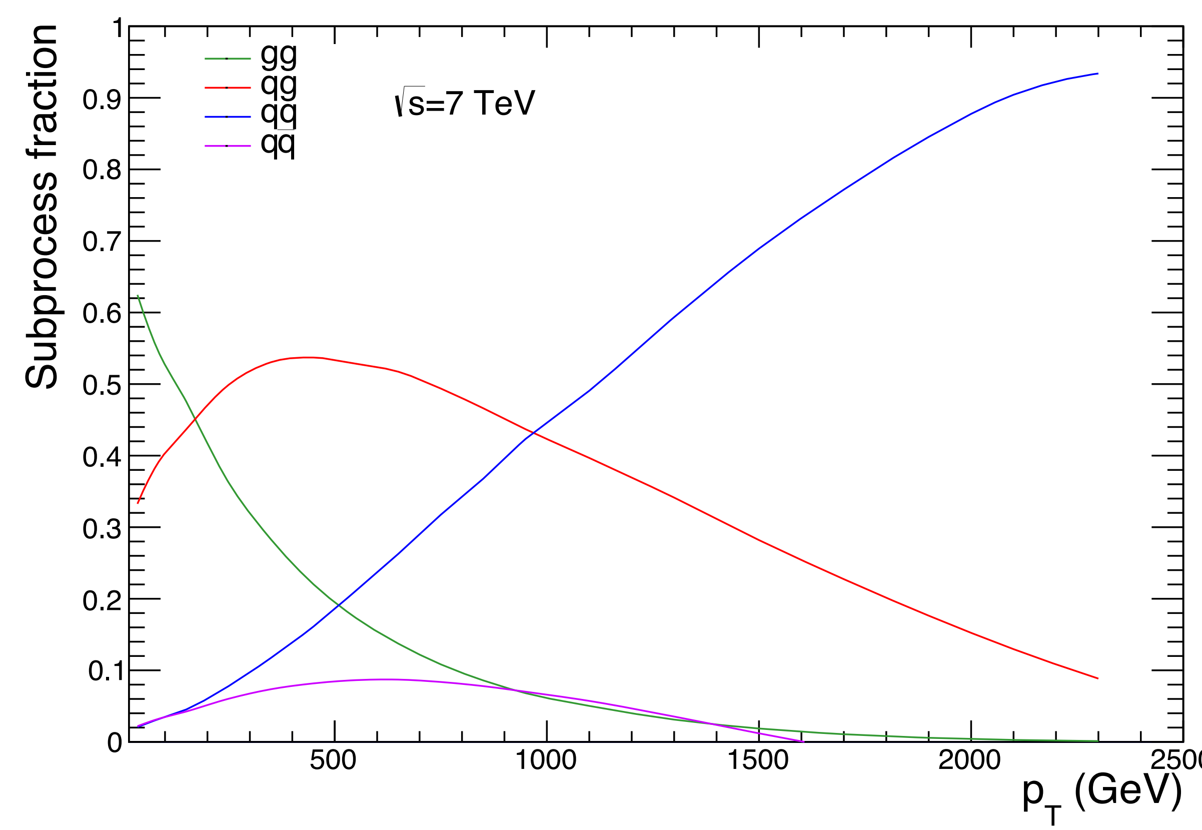
- $\sqrt{s}$ = 13 TeV
- NNPDF3.0_nnlo_as_0118
- jets reconstructed using anti-k_T algorithm with R=0.4
- central scale choice $\mu_R=\mu_F=p_T$
- LO and NLO cross sections are all channels at all colour levels

NNLO

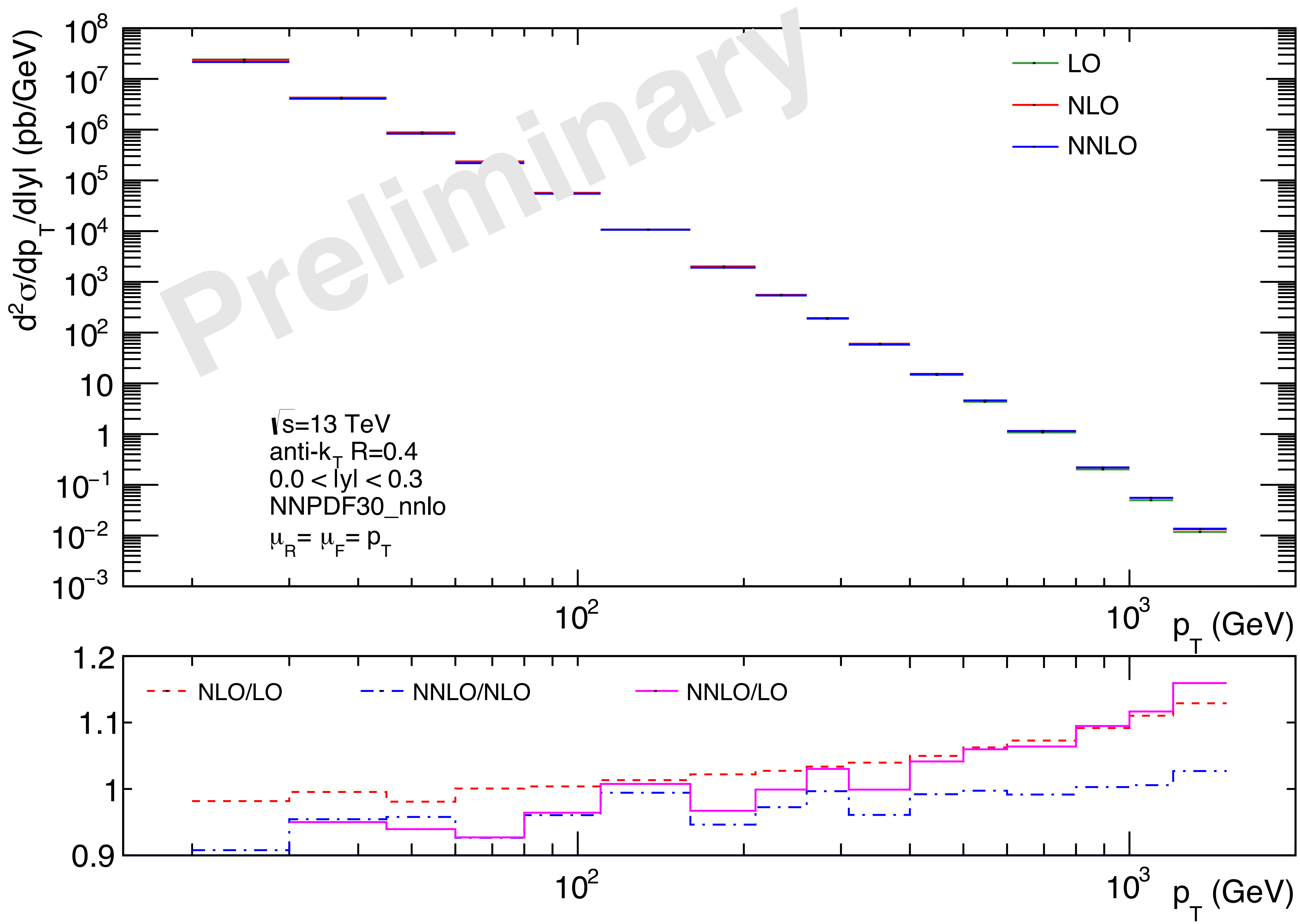
- N^2 corrections to *gg*
- NN_F corrections to *gg*
- N^2 corrections to *qg*
- N^2 corrections to $q\bar{q}$ not included
- At low to moderate p_T *gg*+*qg* dominate
- *qq* results in preparation

NNLO contributions	perturbative order
$gg \to gggg$	tree-level (RR)
$gg \to q\bar{q}gg$	tree-level (RR)
$qg \to qggg$	tree-level (RR)
$q\bar{q} \to gggg$	tree-level (RR)
$gg \to ggg$	one-loop (RV)
$gg \to q\bar{q}g$	one-loop (RV)
$qg \to qgg$	one-loop (RV)
$q\bar{q} \to ggg$	one-loop (RV)
$gg \to gg$	two-loop (VV)
$gg \to q\bar{q}$	two-loop (VV)
$qg \to qg$	two-loop (VV)
$q\bar{q} \to gg$	two-loop (VV)



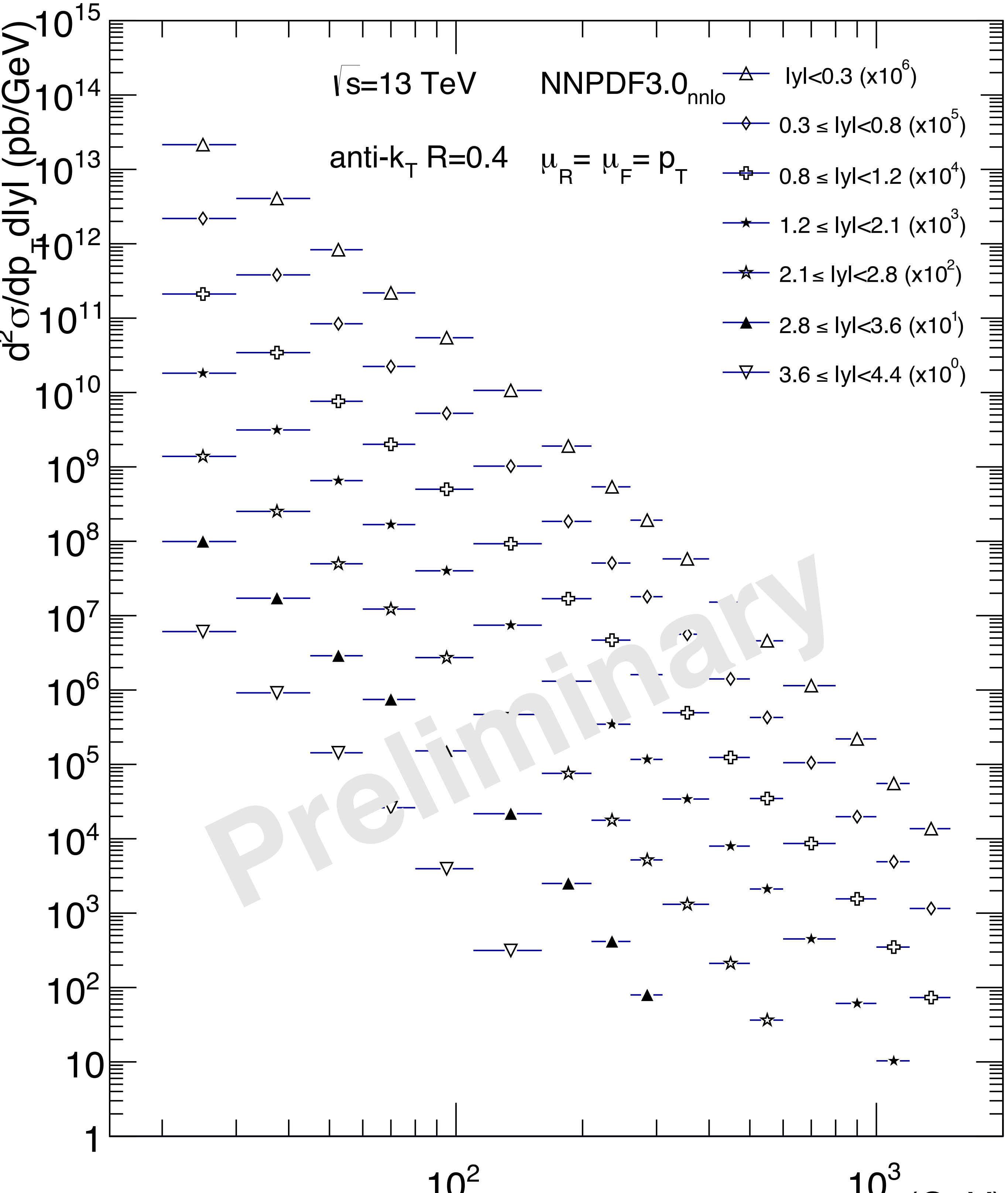


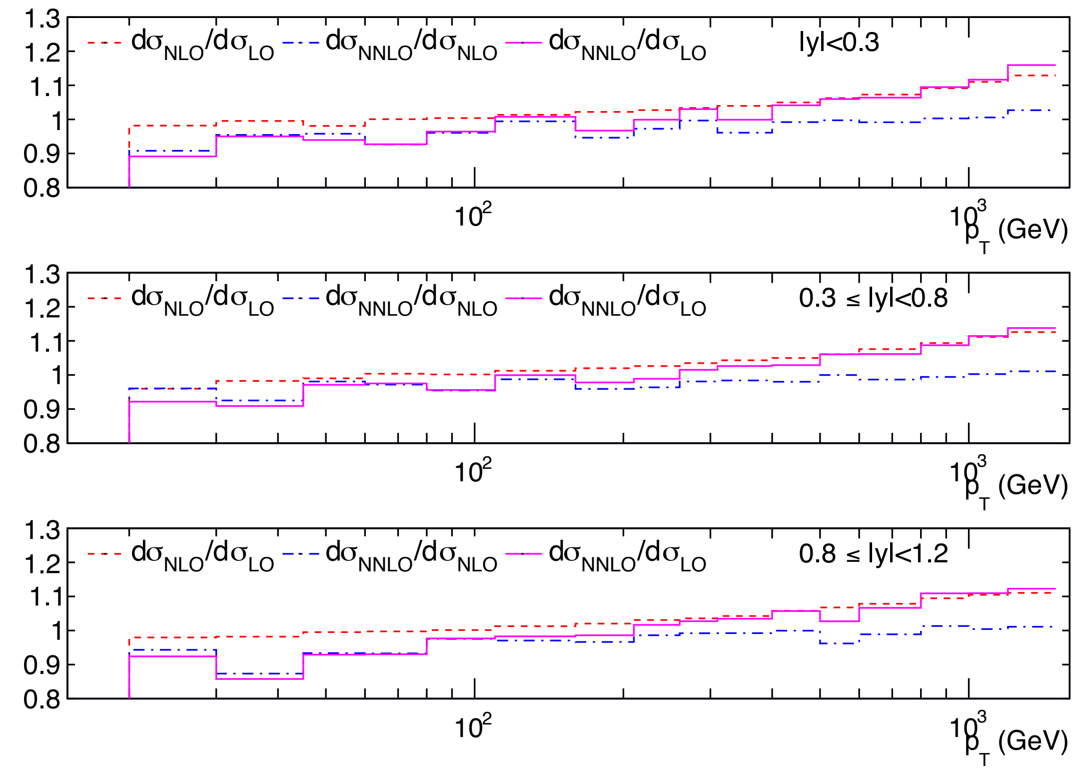
Inclusive jet p_T distribution at NNLO



- moderate corrections of -10% that rise to 1% at high-p_T with respect to NLO

Double differential inclusive jet p_T distribution at NNLO

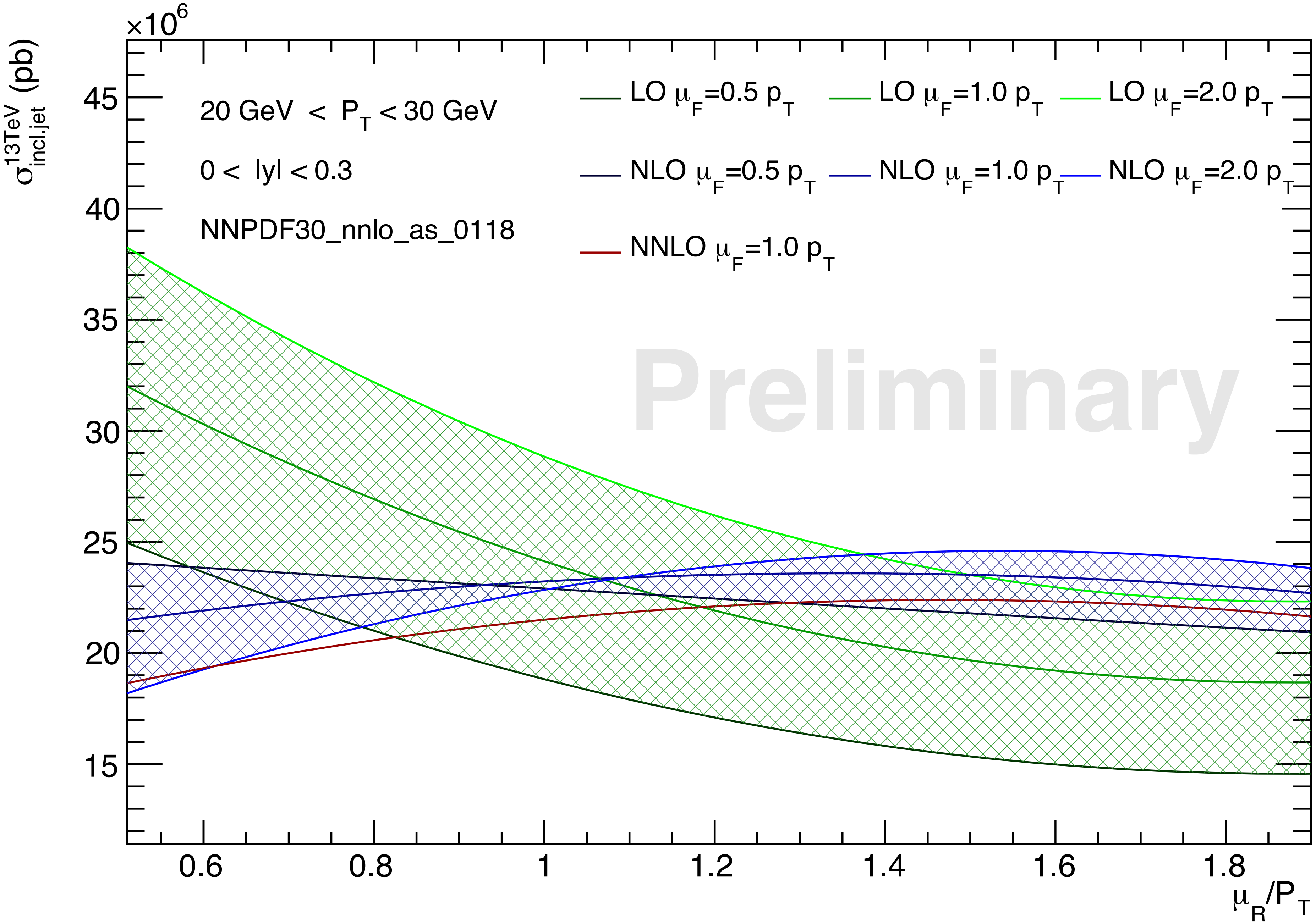




Double differential *k*-factors

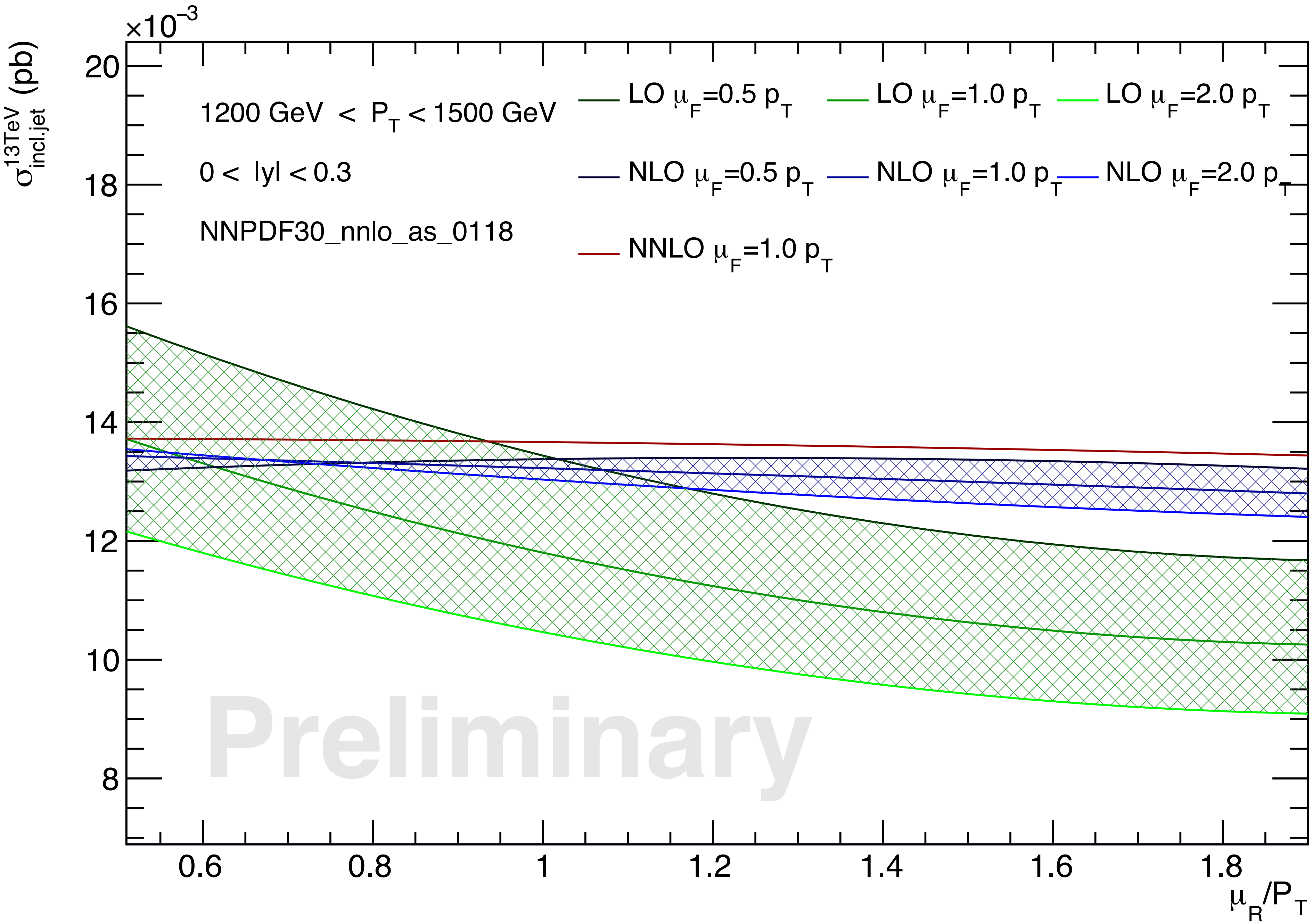
- NNLO prediction reduced between 10% and 1% with respect to the NLO cross section
- similar behaviour between the rapidity slices

Scale dependence of the inclusive jet p_T cross section



- at LO 45% theory uncertainty due to scale → 15% at NLO
- reduced at NNLO but μ_R variation only
- NNLO prediction inside the NLO scale variation band

Scale dependence of the inclusive jet p_T cross section



- at high p_T flat scale dependence of the NNLO cross section
- NNLO cross section outside the NLO scale variation band

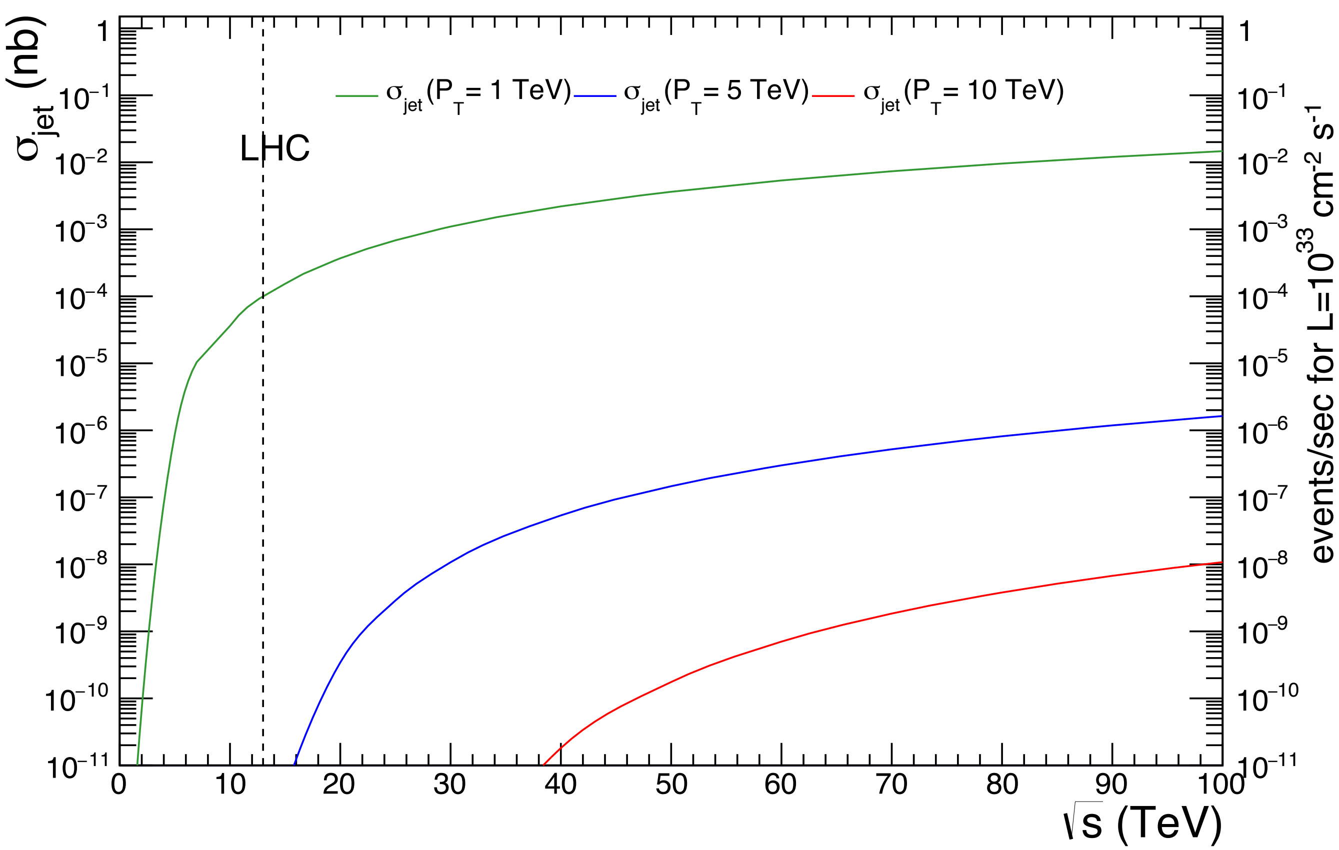
Conclusions

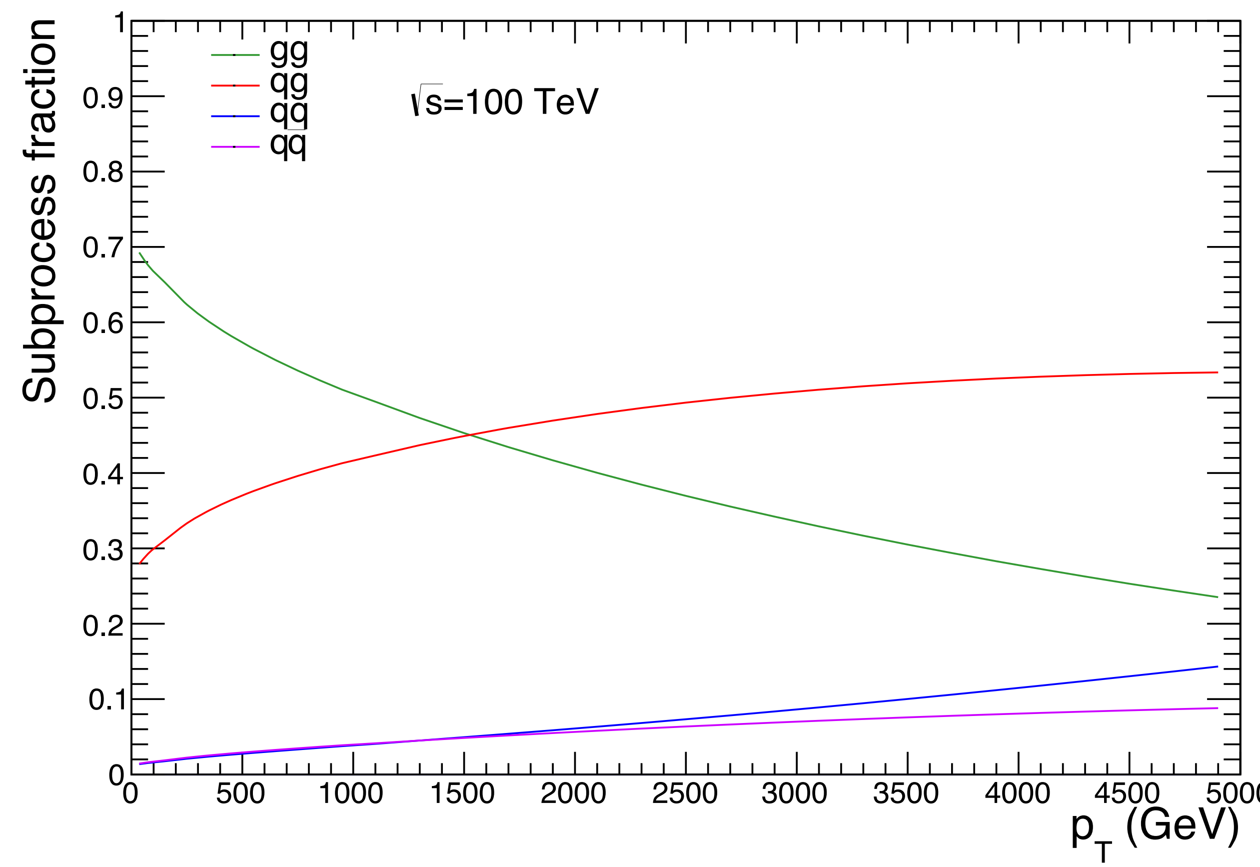
- LHC jet data can provide an access to the determination of α_s at the TeV scale
- current theoretical uncertainties at NLO limit the achievable precision in α_s
- huge effort in consolidating the NNLO results in automated framework

Future work

- completion of remaining channels
- delivery of the results late 2015/early 2016
- interface NNLO computation to APPLgrid and fastNLO
- perform refined scale variation studies
- deliver NNLO results at different jet sizes R=0.4 and R=0.7

At a future pp √s=100 TeV collider





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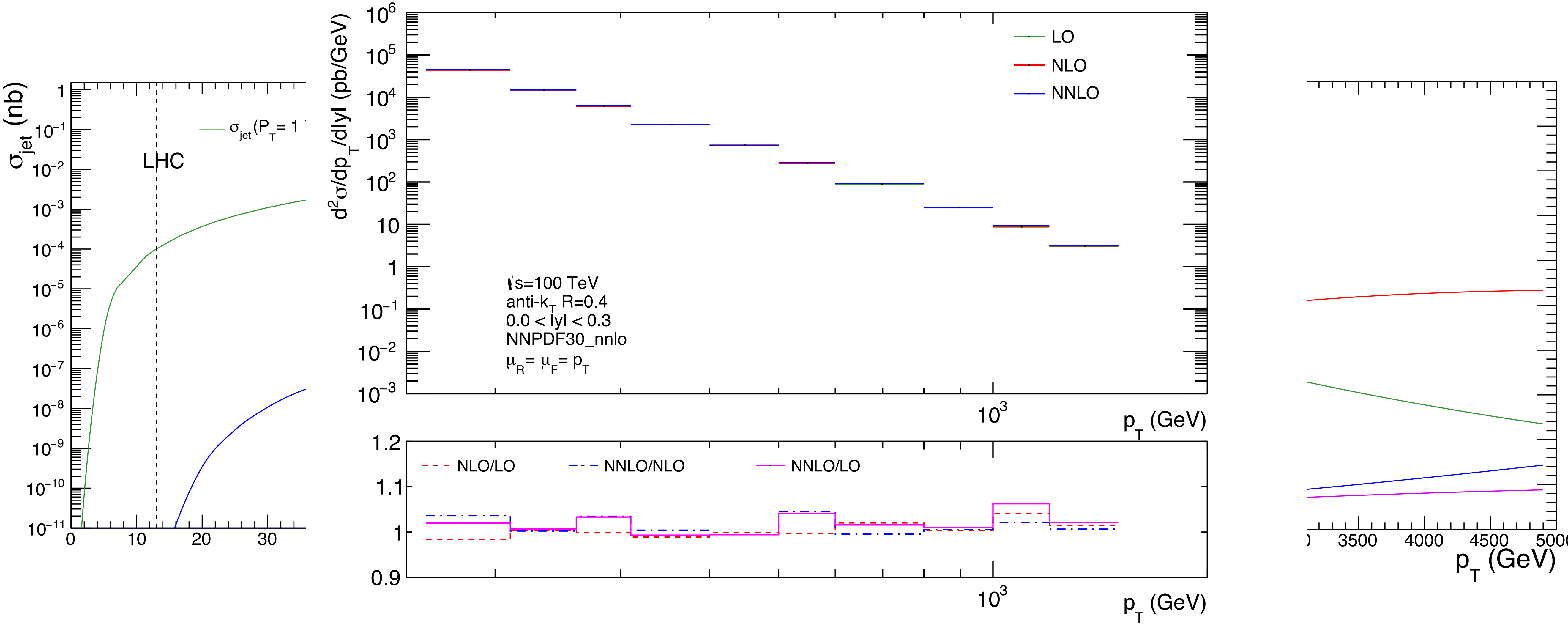

NNLO N^2 gluons only term gives moderate corrections