NNLO predictions for three-jet cross sections at the LHC

Rene Poncelet
in collaboration with Michal Czakon and Alexander Mitov
based on: 1907.12911 and 2106.05331

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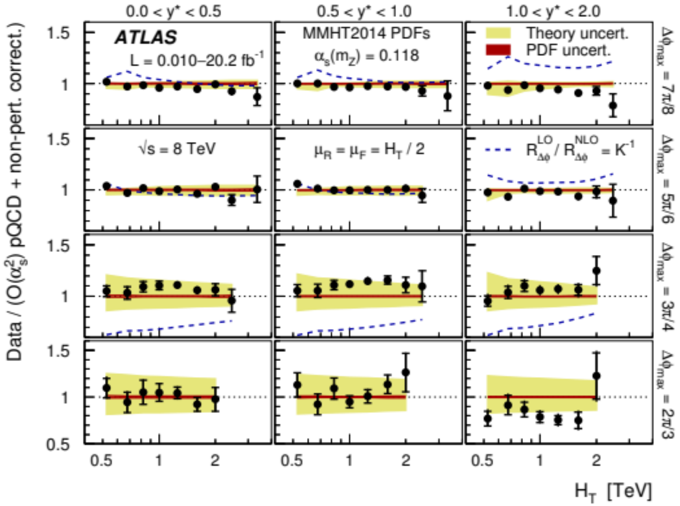
Jet observables at the LHC

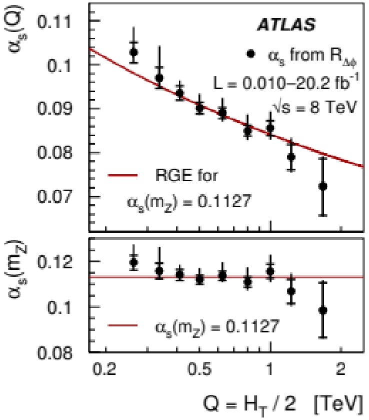
The LHC produces jets abundantly → many phenomenological applications

Tests of pQCD, α_s extraction:
R32 ratios, event-shapes

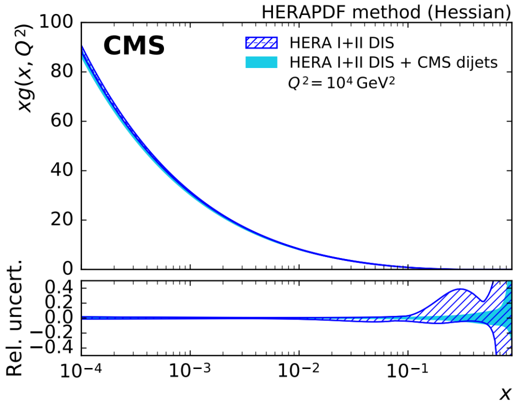
PDF determination:
Single inclusive,
Multi-differential dijet

BSM searches:
dijet mass

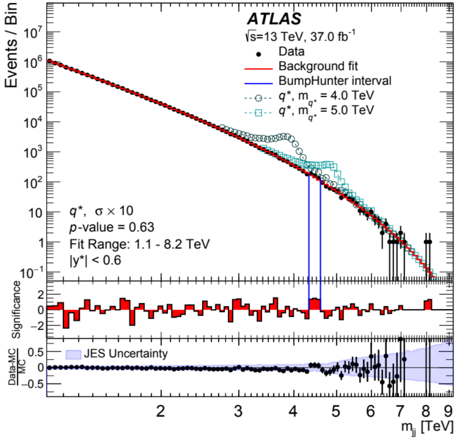




[1805.04691]



[1705.02628]



[1703.09127]

Precision theory required!

Data driven

Precision predictions

Resumption

Fixed order
perturbation theory

Parton-showers

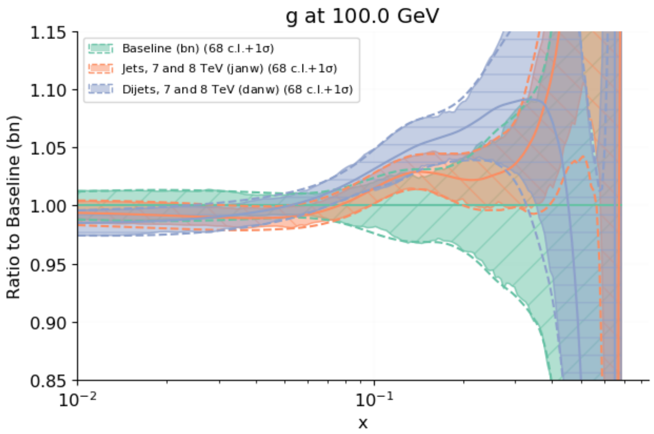
Precision theory predictions

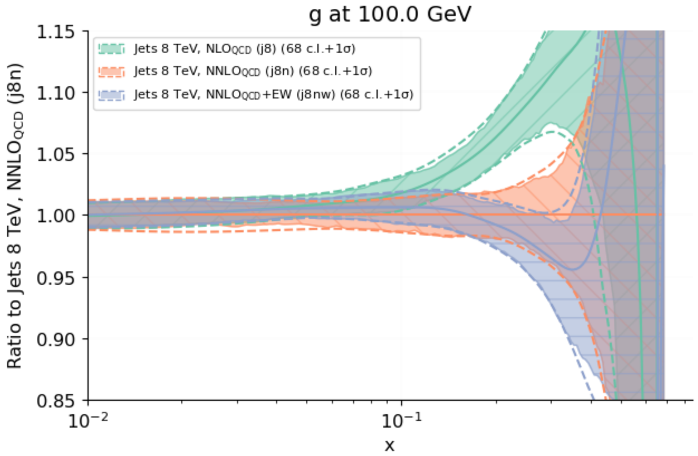
Parametric input:
PDFs and alphaS

Soft physics:
MPI, colour reconnection,
...

Fragmentation/hadronisation

Higher order pQCD: PDF fits with jets





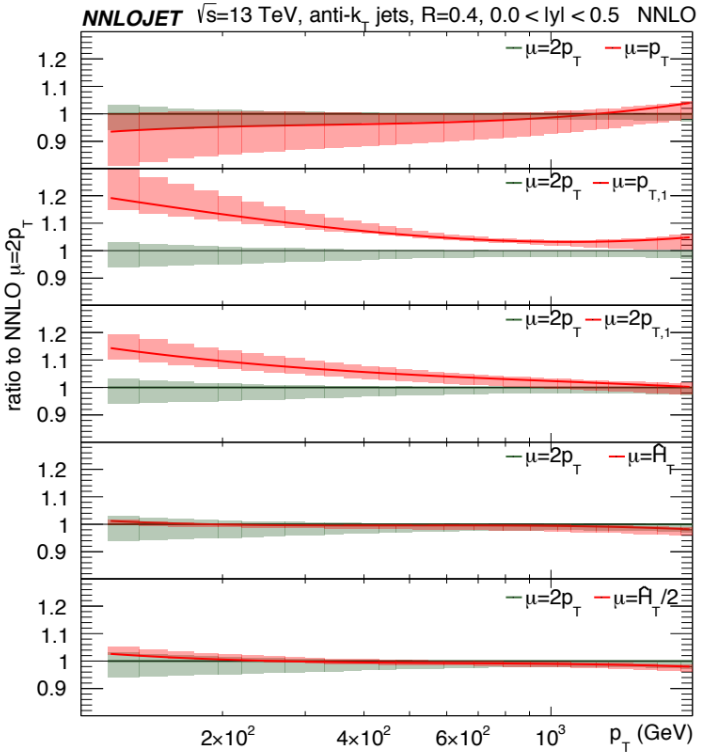
Idea (quite old actually [Giele'94]):

Here by a collaboration of NNLOJet and NNPDF [Khalek'20]:

Combine single inclusive and dijet triple differential measurements by ATLAS and CMS to constrain the large gluon-x

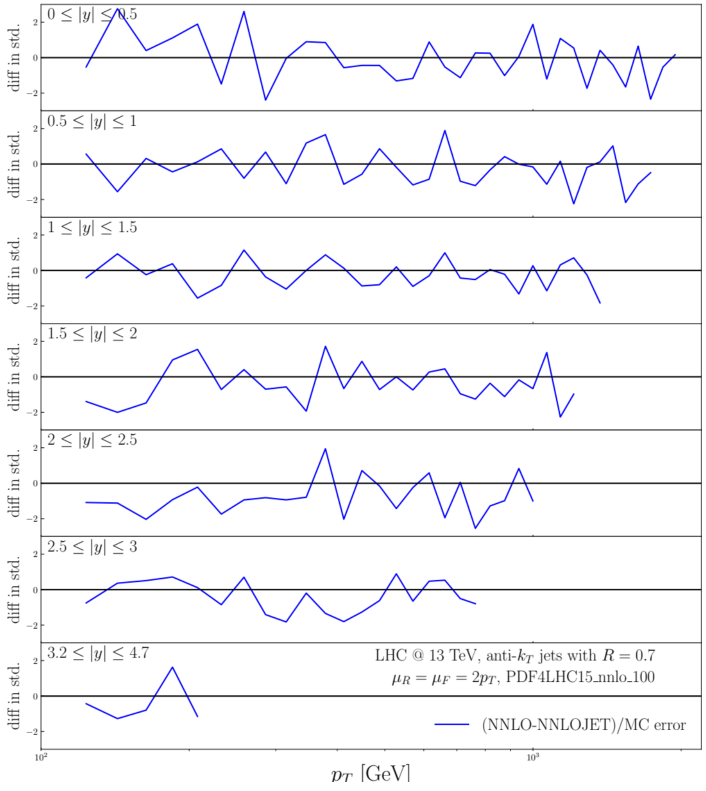
- Reduced uncertainty in large-x gluon PDF
- NNLO QCD corrections crucial to obtain consistent results between data sets
- NLO EW[Dittmaier'12] or full NLO corrections [Frederix'17,Reyer'19]

Higher order pQCD: lessons from dijet



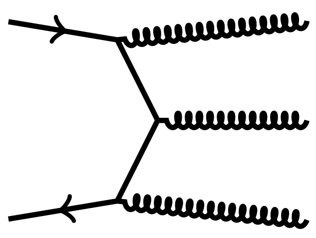
Detailed studies of **scale dependence**: Event-based choices vs. single jet choices [Currie'18]

Study of **sub-leading colour effects** in quark channels: smaller than **O(1%)** [Czakon'19]



Three jet production

Advances in perturbative QCD allow to tackle the most complicated 2→3 process



$pp \to ggg + X$

Bottlenecks:

- Double virtual amplitudes in leading colour approximation [Abreu'21]
- Handling of real radiation:
  - Sector-improved residue subtraction [Czakon'10'14'19] conceptually capable
  - Computationally very challenging! → O(1M CPUh)

Only Approximation made: $\mathcal{R}^{(2)}(\mu_R^2) = 2\,\mathrm{Re}\left[\mathcal{M}^{\dagger(0)}\mathcal{F}^{(2)}\right](\mu_R^2) + \left|\mathcal{F}^{(1)}\right|^2(\mu_R^2) \equiv \mathcal{R}^{(2)}(s_{12}) + \sum_{i=1}^{4} c_i \ln^i\left(\frac{\mu_R^2}{s_{12}}\right)$

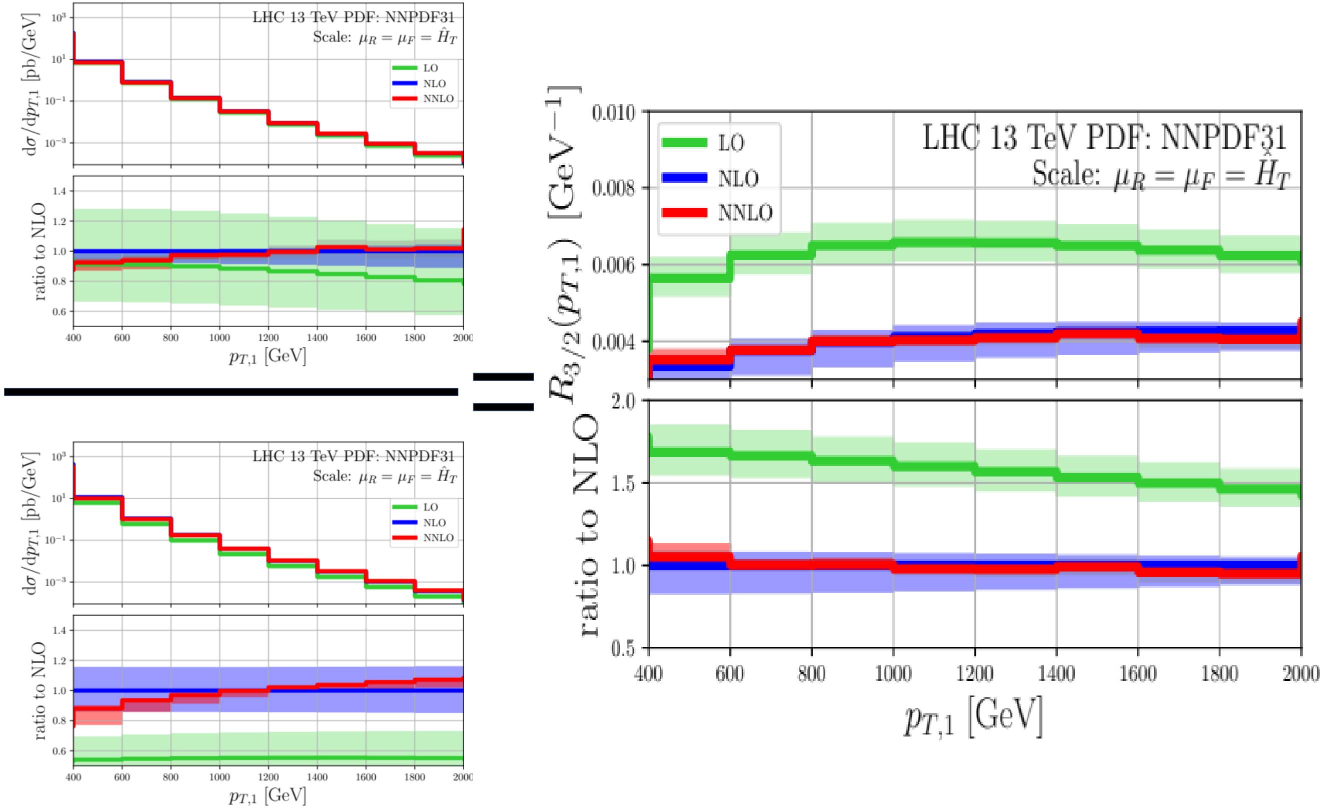
→ taken from [Abreu'21] $\mathcal{R}^{(2)}(s_{12}) \approx \mathcal{R}^{(2)l.c.}(s_{12})$

Three jet production - R32(pT1)

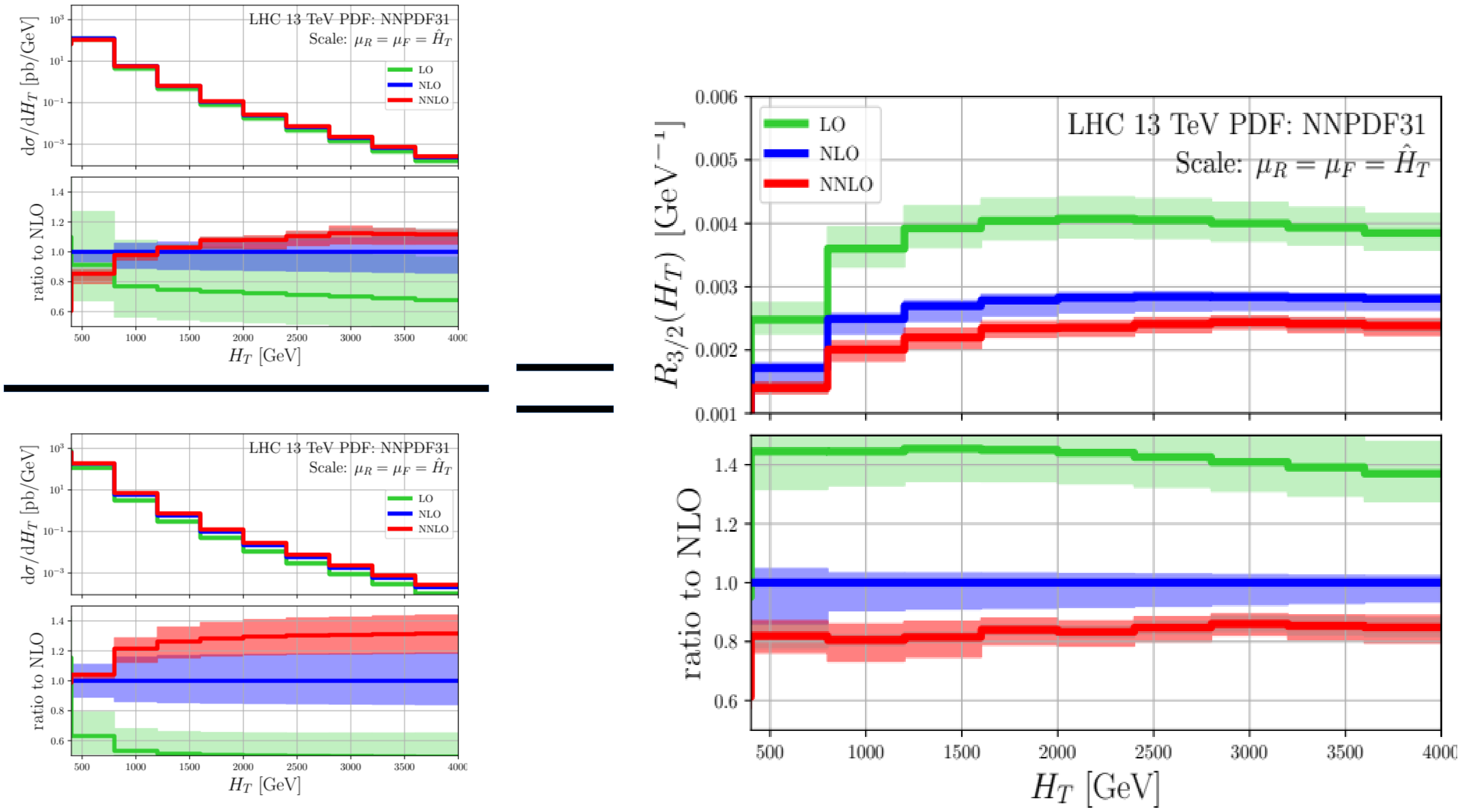
- LHC @ 13 TeV, NNPDF31
- Require at least three (two) jets:
  - $p_T(j) > 60$ GeV and $|y(j)| < 4.4$
  - $H_{T,2} = p_T(j_1) + p_T(j_2) > 250$ GeV
- Scales:

$$\mu_R = \mu_F = \hat{H}_T = \sum_{\text{partons}} p_T$$

$$R_{3/2}(X, \mu_R, \mu_F) = \frac{\mathrm{d}\sigma_3(\mu_R, \mu_F)/\mathrm{d}X}{\mathrm{d}\sigma_2(\mu_R, \mu_F)/\mathrm{d}X}$$



Three jet production - R32(HT)



$$H_T = \sum_{\text{jets}} p_T$$

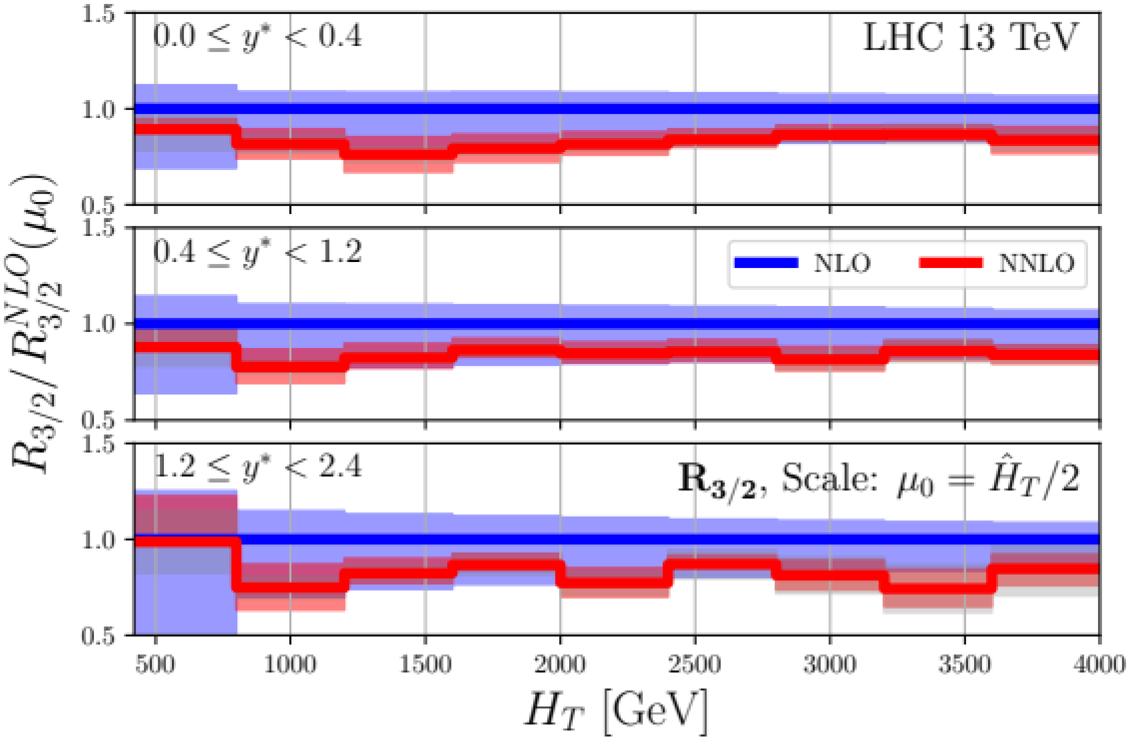
Scale dependence correlated in ratio

→ reduction of scale dependence

→ flat k-factor

→ scale bands in ratio barely overlap

Three jet production – R32(HT,y*)



Double differential w.r.t. $y^* = |y(j_1) - y(j_2)|/2$

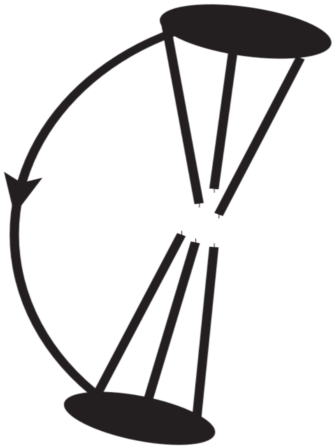
Different central scale choice: $\hat{H}_T/2$

Three jet production – azimuthal decorrelation

Kinematic constraints on the azimuthal separation between the two leading jets (φ12)

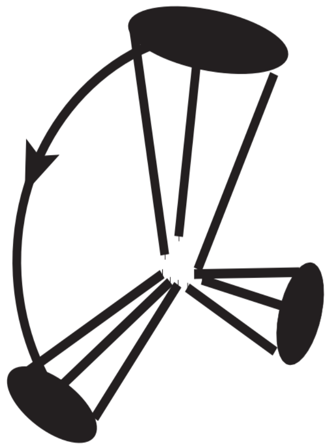
Dijet:

φ12 = π



Trijet:

φ12 > 2/3π



φ12 sensitive to the jet multiplicity:

2j: φ12 = π

3j: φ12 > 2/3π

4j: unconstrained

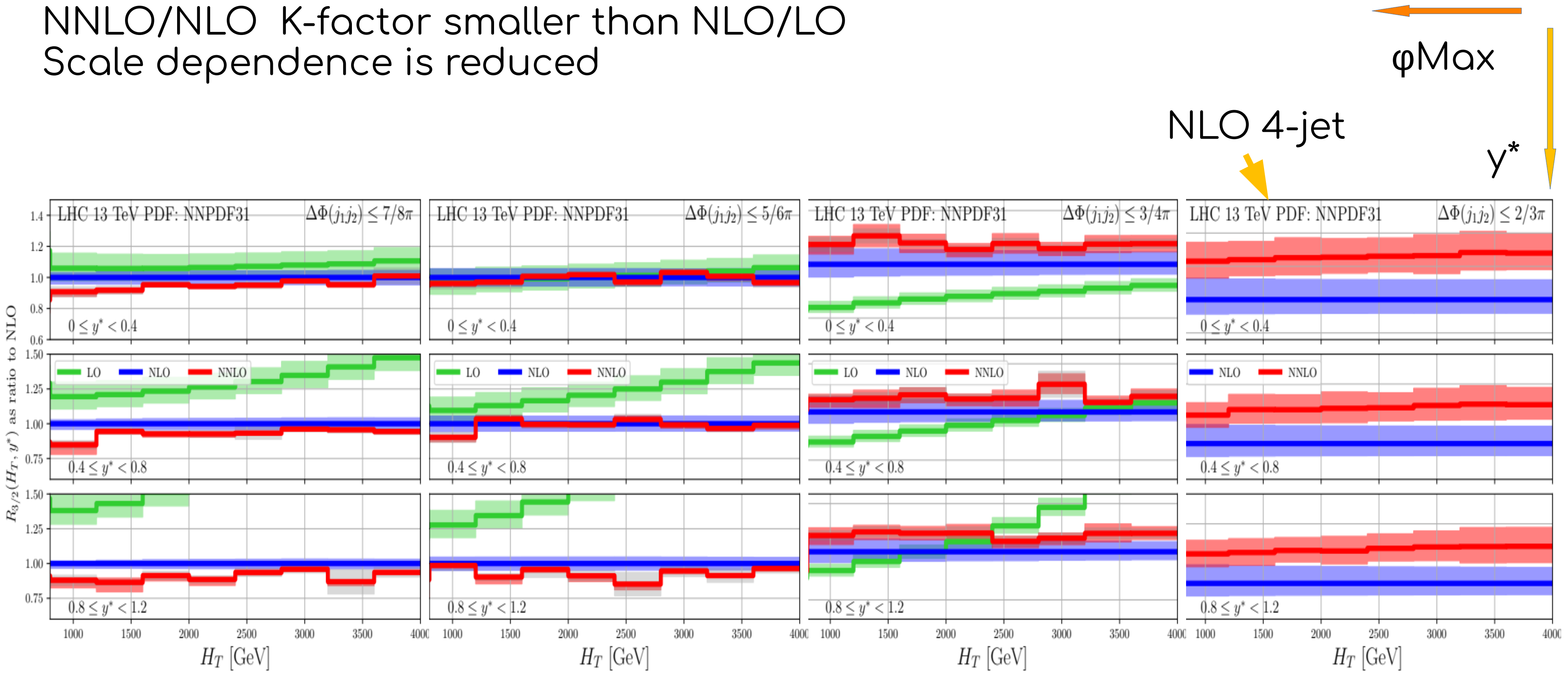
Study of the ratio

R32(HT,y*,φMax) =
(dσ3(φ<φMax)/dHT/dy*)/(dσ2/dHT/dy*)

With y* = |y1-y2|/2

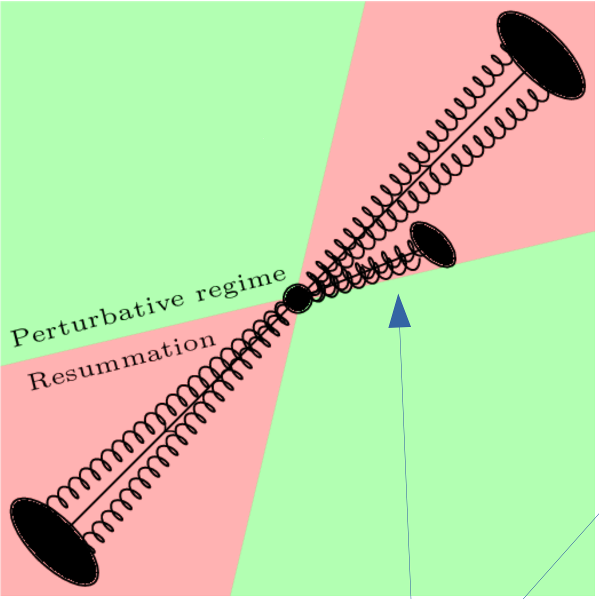
Three jet production – R32(HT,y*,φMax)

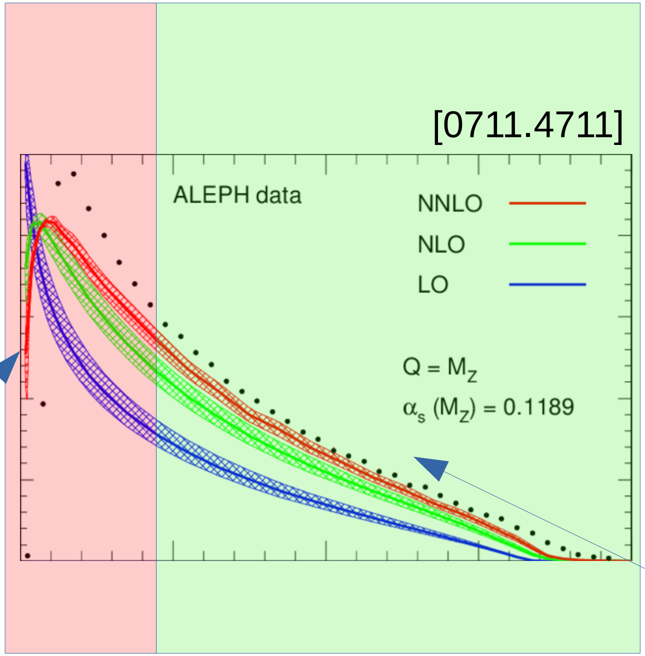
NNLO/NLO K-factor smaller than NLO/LO
Scale dependence is reduced

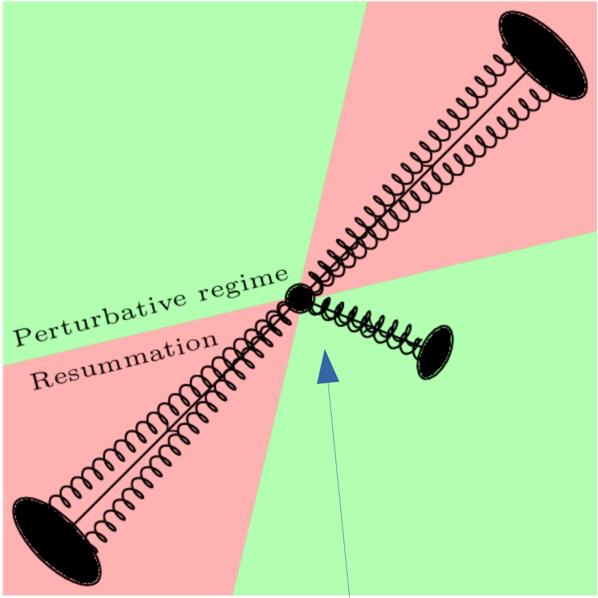


Event-shapes regimes

Typically event-shapes measure departure from N hard jet case







Anisotropic, 2-prong like

Sensitivity to resummation, non-perturbative effects

Example: 1-Thrust at LEP

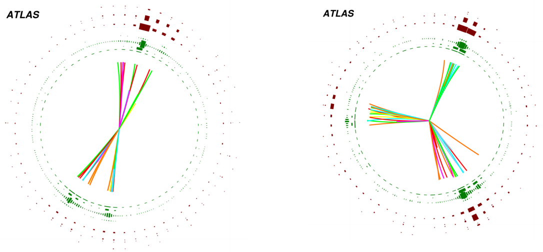
Isotropic, multi-jet

Sensitive to hard matrix elements

Event-shapes at the LHC

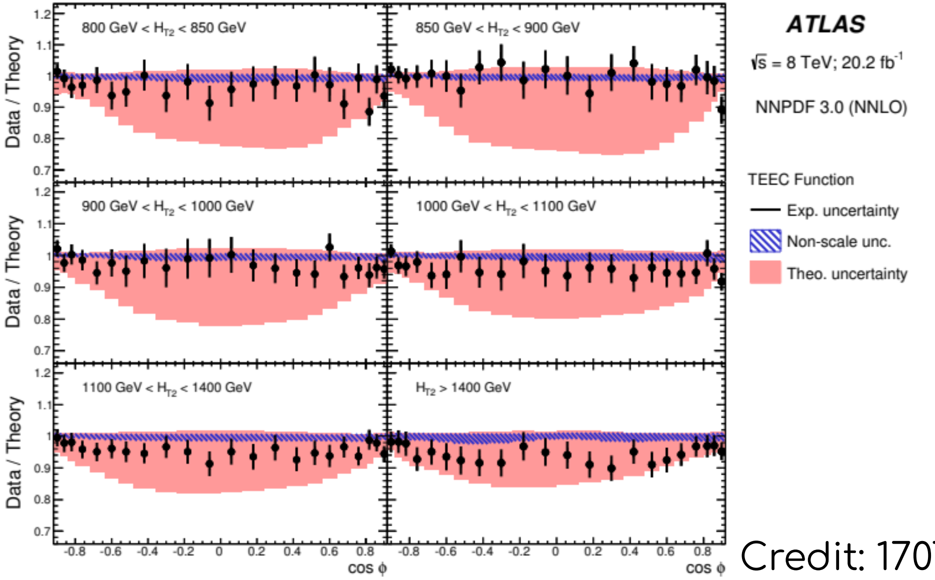
Event-shapes are measured using multi-jet events
→ three jet is the leading contribution

Credit: ATLAS 2007.12600



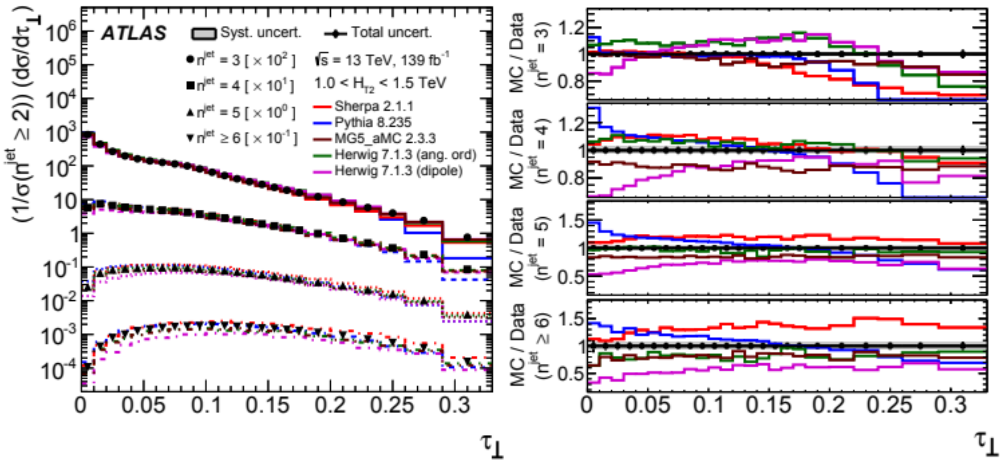
TEEC (Transverse Energy-Energy Correlation)

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\perp,i}E^A_{\perp,j}}{\left(\sum_k E^A_{T,k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$



Credit: 1707.02562

Transverse Thrust: $\tau_T = 1 - \frac{\sum_i |\vec{p}_{T,i}\cdot\hat{n}|}{\sum|\vec{p}_{T,i}|}$



Summary and Outlook

Jet rates with the sector-improved residue subtraction framework

- Full NNLO QCD predictions for di-jet production available
  → scale choice important
  → sub-leading colour contributions small
- Three jets @ the LHC:
  - First predictions available with approximate two-loop contribution!
    → improved scale dependence and stabilized K-factors
    → pT spectra, HT, double differential
  - Real radiation for 2→3 can be handled.
    But efficiency is a concern and needs some attention!

Many interesting applications ahead! → Event-shapes
Stay tuned!

Thank you for your attention!