HEP theory group: results of the past 12 months

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UNIVERSITY OF CAMBRIDGE

The theory group

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Junior group leader
Korea

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Faculty
Kraków

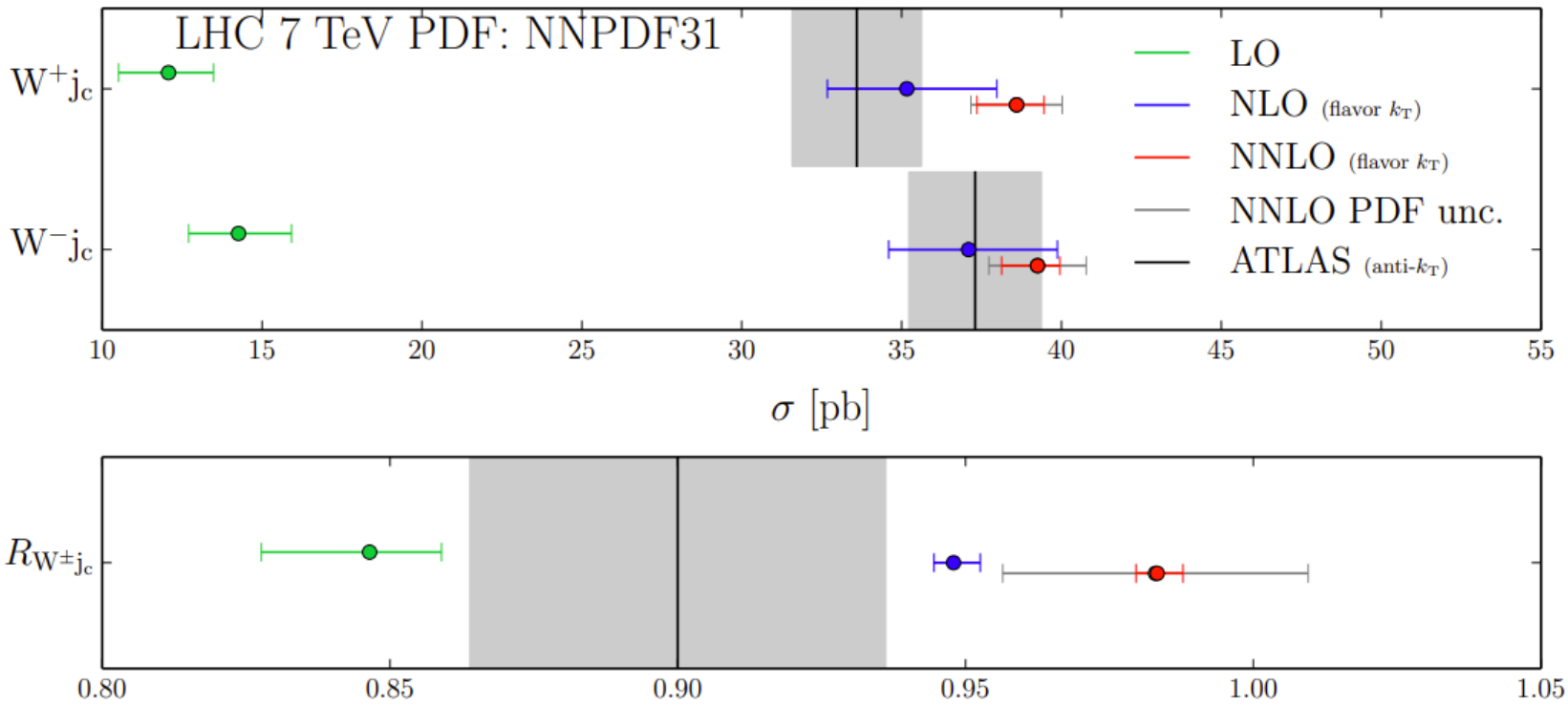
The theory group

PhD student
Aachen
↓

W+c-jet: introduction

- Processes: $p\,p \to \mu^+ \nu_\mu j_c + X$ and $p\,p \to \mu^- \overline{\nu}_\mu j_c + X$
- At Born level: $s\,g \to \mu \nu_\mu c +$ off-diagonal CKM contributions
- $\Rightarrow$ Sensitivity to strange PDF!
- First analysis at NNLO: arXiv:2011.01011
- Compared to ATLAS data (arXiv:1402.6263)
- Only off-diagonal contribution included: V_{cd} at LO
- Used flavour-k_T to define charm jet

W+c-jet: previous results



$$R^{\mathrm{LO,unc.}}_{\mathrm{W^\pm j_c}} = 0.84646(4)^{+25.4\%}_{-22.0\%}, \quad R^{\mathrm{NLO,unc.}}_{\mathrm{W^\pm j_c}} = 0.9479(3)^{+9.8\%}_{-8.6\%}, \quad R^{\mathrm{NNLO,unc.}}_{\mathrm{W^\pm j_c}} = 0.983(5)^{+3.5\%}_{-3.7\%}$$

W+c-jet: previous conclusions

"[...] The inclusion of the NNLO corrections leads to a significant reduction of the theoretical uncertainty due to missing higher-order terms. A remarkable feature of this process is that at this order, the PDF uncertainty is consistently larger than the scale one. For this reason this process offers excellent opportunities for high-quality fitting of the strange quark PDF and possibly even the $s\bar{s}$ asymmetry of the proton. [...] The data for the plus signature tends to be lower than the NNLO QCD predictions. We have discussed three sources for this discrepancy: the different jet algorithms used in our computation and in the experimental analysis, EW corrections which are not accounted for in this work, and the need for inclusion of higher-order QCD corrections to quark-mixing effects mediated by off-diagonal CKM matrix elements. [...]"

W+c-jet: second study (arXiv:2212.00467)

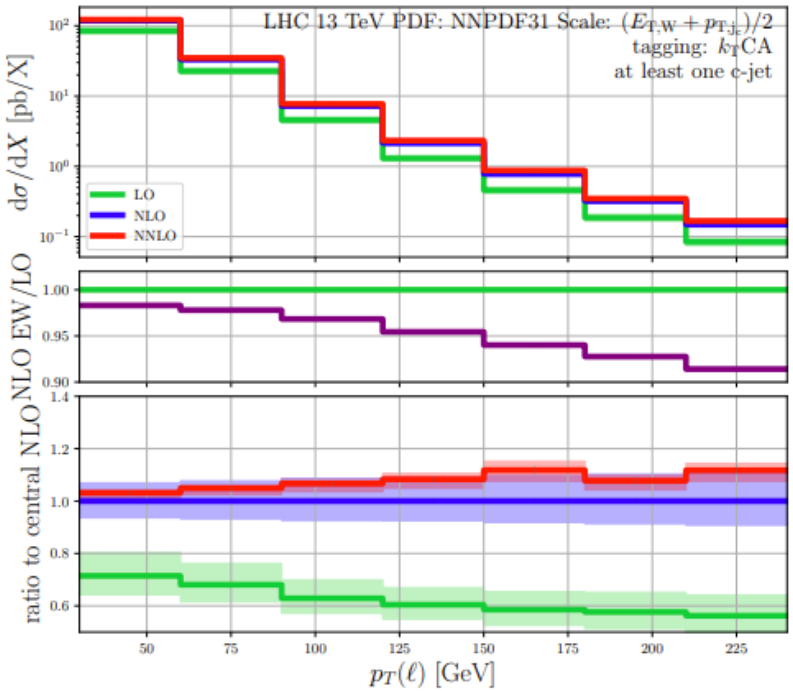
- Second study of W+c-jet
- Abstract:

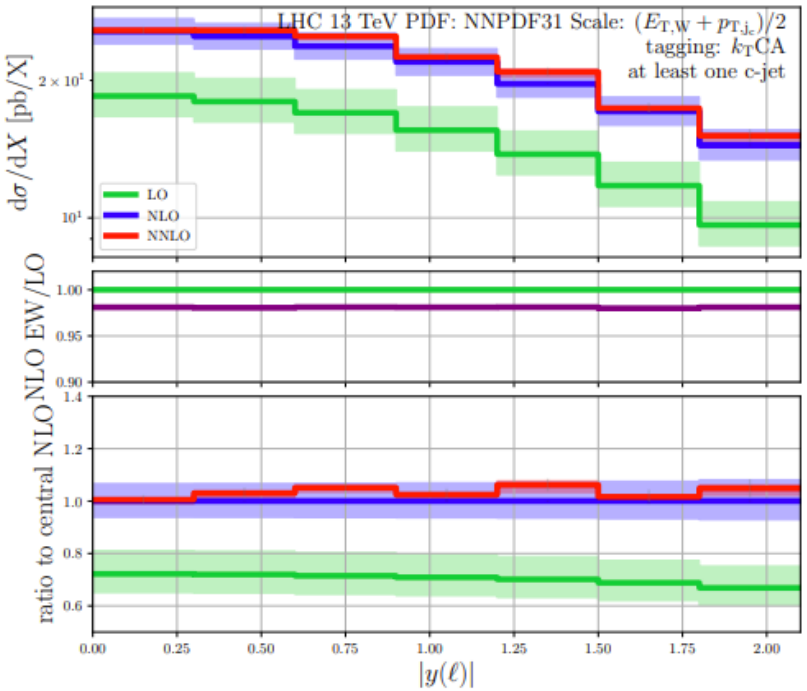
"State-of-the-art analyses of W+c-jet production at the LHC require precise predictions. In the present work, we study in detail the impact of off-diagonal CKM elements up to next-to-next-to leading order in QCD, the influence of flavored jet algorithms, and the size of electroweak corrections. In addition, we also investigate phenomenological aspects related to the exact definition of the process. We find that all these effects can be of the order of several per cent for both the fiducial cross section and differential distributions. They are, therefore, very relevant for the interpretation of current and upcoming measurements."

W+c-jet: results of second study (arXiv:2212.00467)

Electroweak corrections

Order	$\sigma_{\mathrm{W}^+\mathrm{j_c}}$ [pb]	$\sigma_{\mathrm{W}^-\mathrm{j_c}}$ [pb]	$R_{\mathrm{W}^\pm\mathrm{j_c}} = \sigma_{\mathrm{W}^+\mathrm{j_c}}/\sigma_{\mathrm{W}^-\mathrm{j_c}}$
NLO EW	117.399(2)	111.627(2)	0.95084(2)
$\delta_{\text{NLO EW}}$ [%]	−1.93	−1.92	−0.01

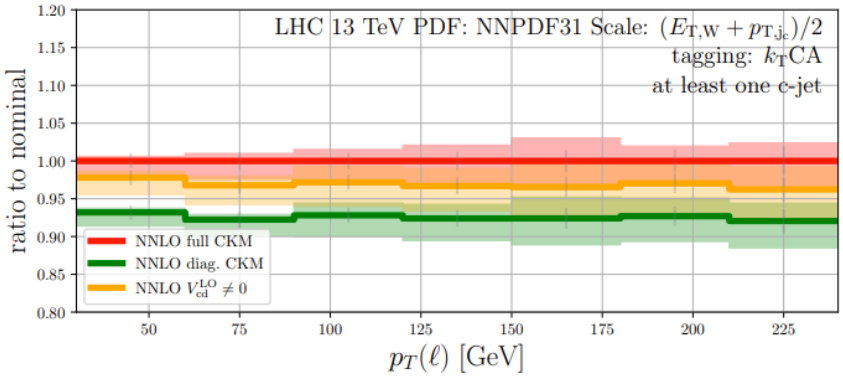


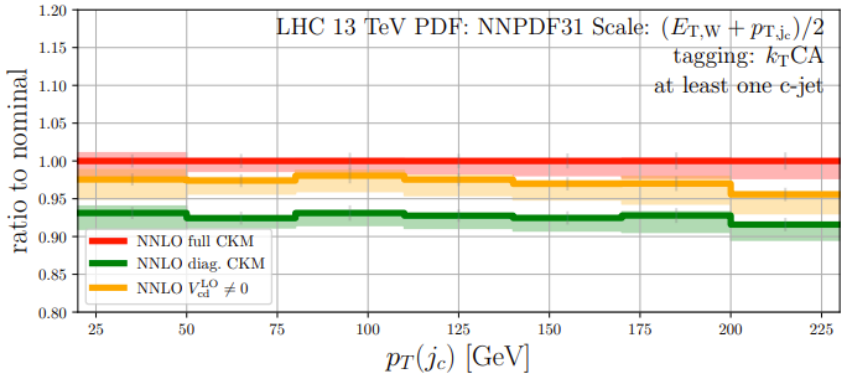


W+c-jet: results of second study (arXiv:2212.00467)

Full CKM effects

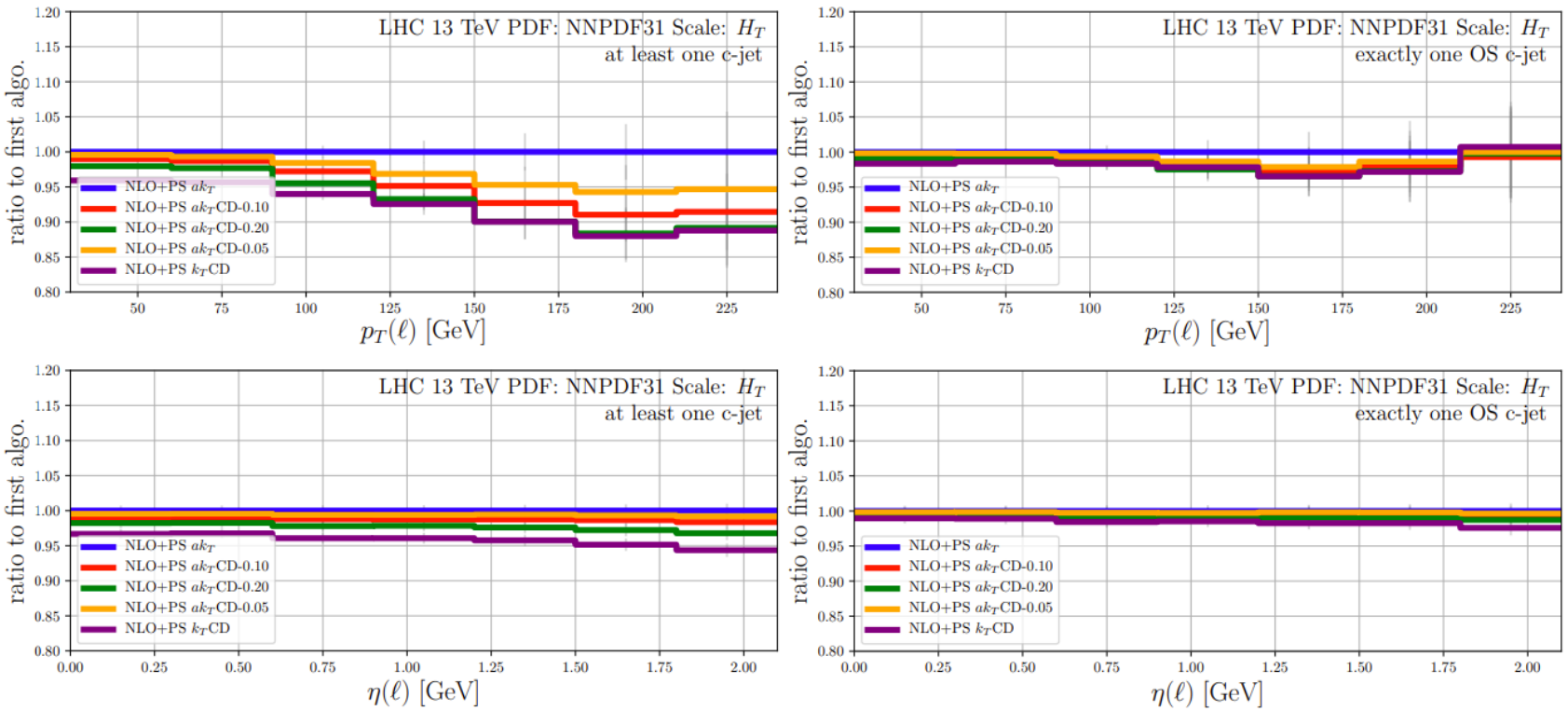
σ_{NNLO} [pb]	full CKM	$V_{cd}^{\text{LO}} \neq 0$	no CKM
+	$168.6(8)^{+0.7\%\ +3.8\%(\text{PDF})}_{-2.1\%\ -3.8\%(\text{PDF})}$	$164.4(8)^{+1.0\%\ +3.9\%(\text{PDF})}_{-2.4\%\ -3.9\%(\text{PDF})}$	$156.7(8)^{+0.7\%\ +4.2\%(\text{PDF})}_{-2.1\%\ -4.2\%(\text{PDF})}$
-	$173.9(1.9)^{+0.6\%\ +3.7\%(\text{PDF})}_{-1.8\%\ -3.7\%(\text{PDF})}$	$168.5(1.9)^{+1.0\%\ +3.8\%(\text{PDF})}_{-2.2\%\ -3.8\%(\text{PDF})}$	$156.7(1.9)^{+0.5\%\ +4.2\%(\text{PDF})}_{-1.6\%\ -4.2\%(\text{PDF})}$





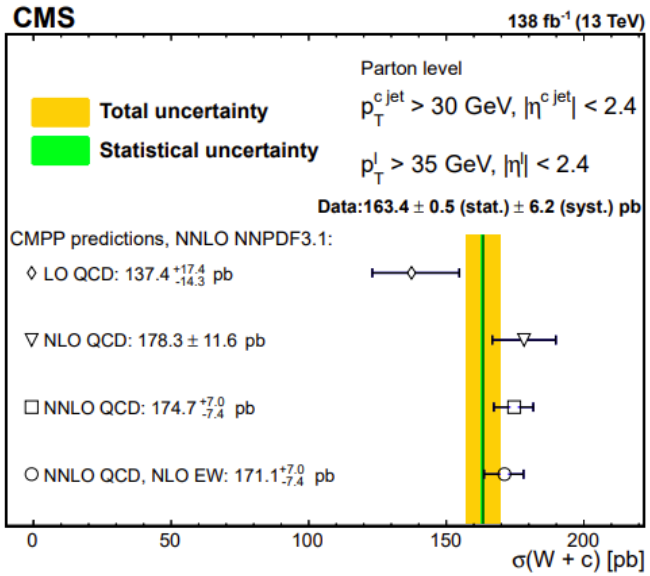
W+c-jet: results of second study (arXiv:2212.00467)

Differences between jet algorithms



W+c-jet: CMS study (arXiv:2308.02285)

- Recent CMS analysis
- New results compared to NNLO predictions

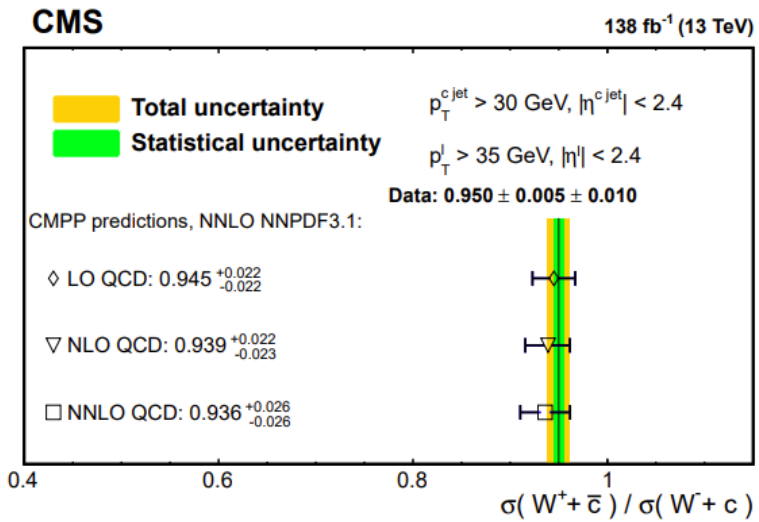


QCD order	EW order	σ^{OS}_{W+c}	σ^{SS}_{W+c}	σ^{OS-SS}_{W+c}	Δ^{OS-SS}_{stat}	Δ^{OS-SS}_{scales}	Δ^{OS-SS}_{PDF}	Δ^{OS-SS}_{Total}
LO	LO	137.4	0	137.4	±0.1	$^{+16.6}_{-13.3}$	±5.1	$^{+17.4}_{-14.3}$
NLO	LO	182.4	4.1	178.3	±0.3	$^{+9.3}_{-9.4}$	±6.8	$^{+11.6}_{-11.6}$
NNLO	LO	182.9	8.2	174.7	±1.0	$^{+1.2}_{-2.8}$	±6.8	$^{+7.0}_{-7.4}$
NNLO	NLO	179.1	8.0	171.1	±1.0	$^{+1.2}_{-2.8}$	±6.8	$^{+7.0}_{-7.4}$

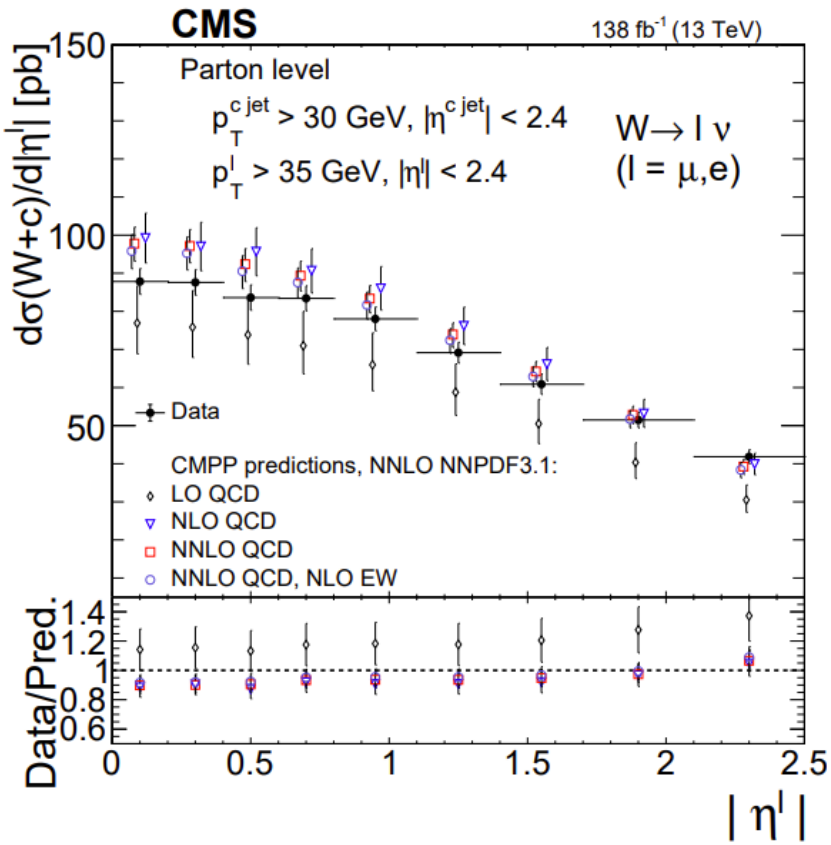
CMS: $163.4 \pm 0.5\,(\text{stat}) \pm 6.2\,(\text{syst})$ pb

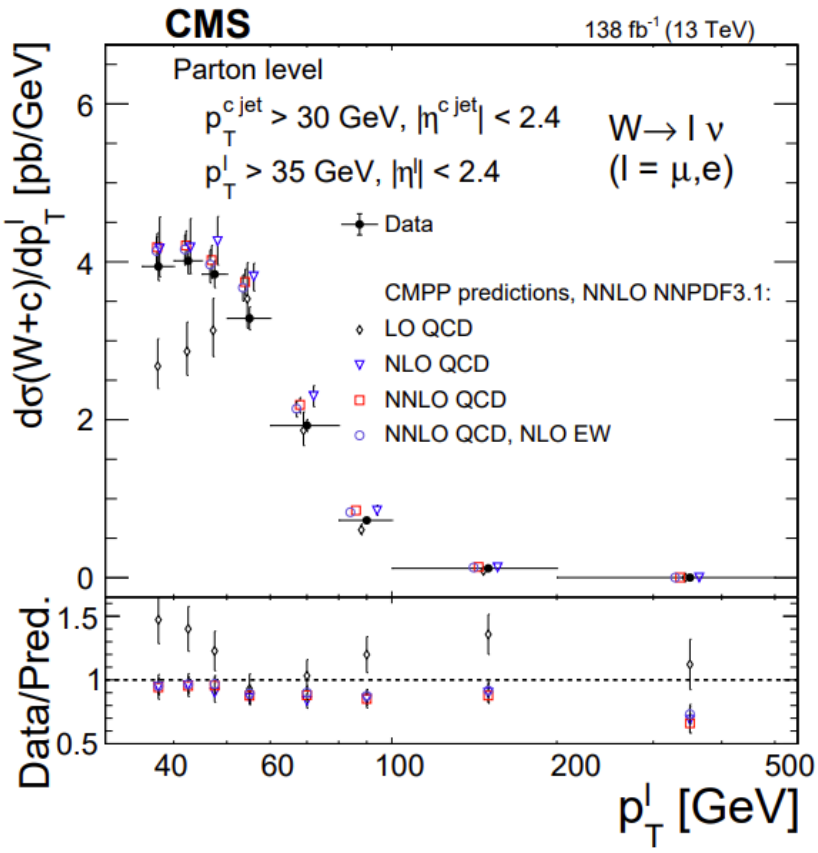
QCD order	$R_c^{\pm}$	Δ_{stat}	Δ_{scales}	Δ_{PDF}	Δ_{Total}
LO	0.945	±0.001	±0.001	±0.022	±0.022
NLO	0.939	±0.004	±0.002	±0.023	±0.023
NNLO	0.936	±0.011	±0.002	±0.023	±0.026

CMS: $0.950 \pm 0.005\,(\text{stat}) \pm 0.010\,(\text{syst})$



W+c-jet: CMS study (arXiv:2308.02285)

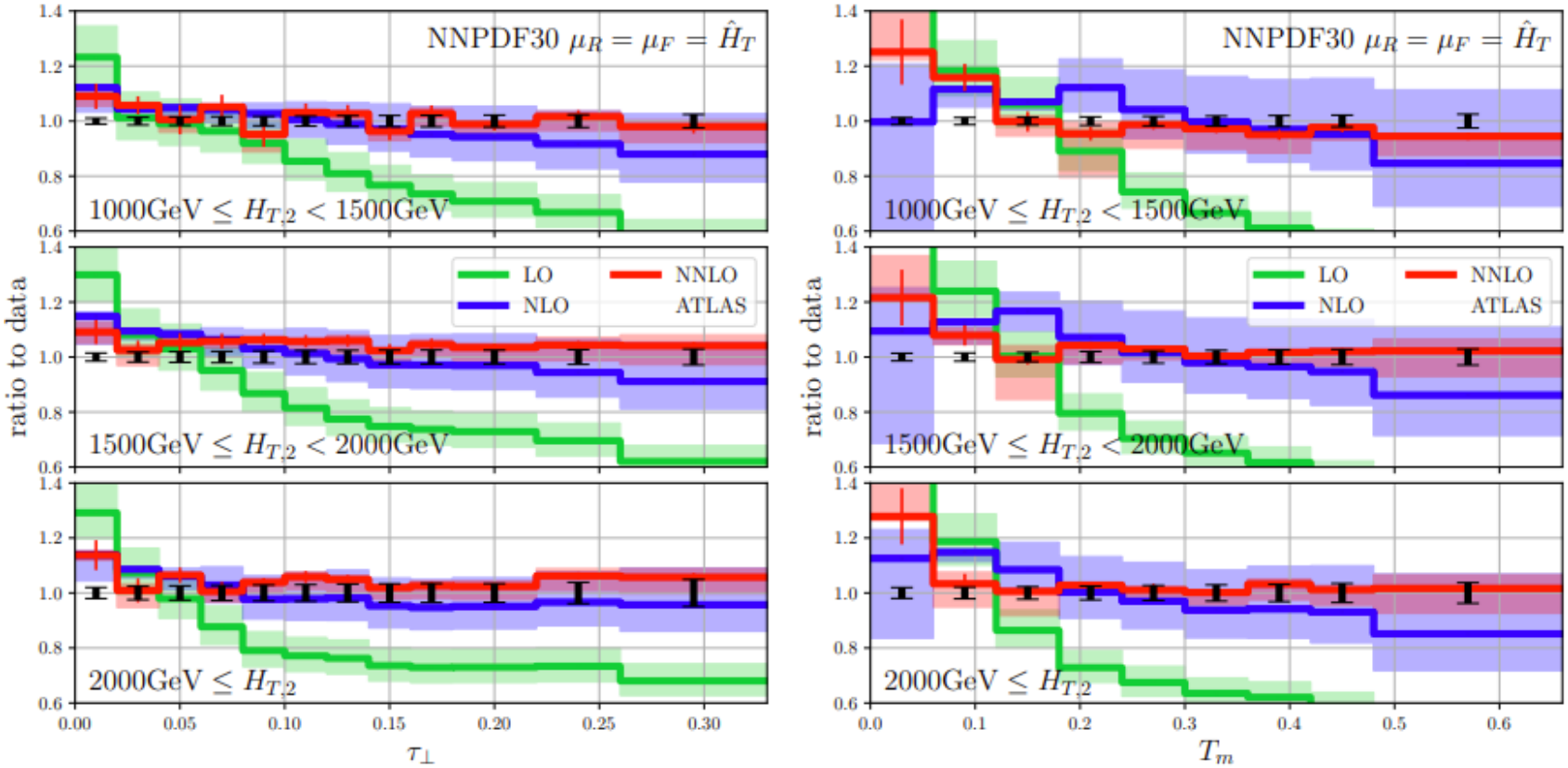




Event shapes: introduction

- Processes: $p\,p \to 2j + X$ and $p\,p \to 3j + X$
- 3-jet at NNLO: first computed in arXiv:2106.05331
- Typically: ratios of 3-jet and 2-jet cross sections
- Reveal details of QCD and are correlated with α_s
- arXiv:2301.01086: comparison to ATLAS (arXiv:2007.12600)

Event shapes: results (arXiv:2301.01086)

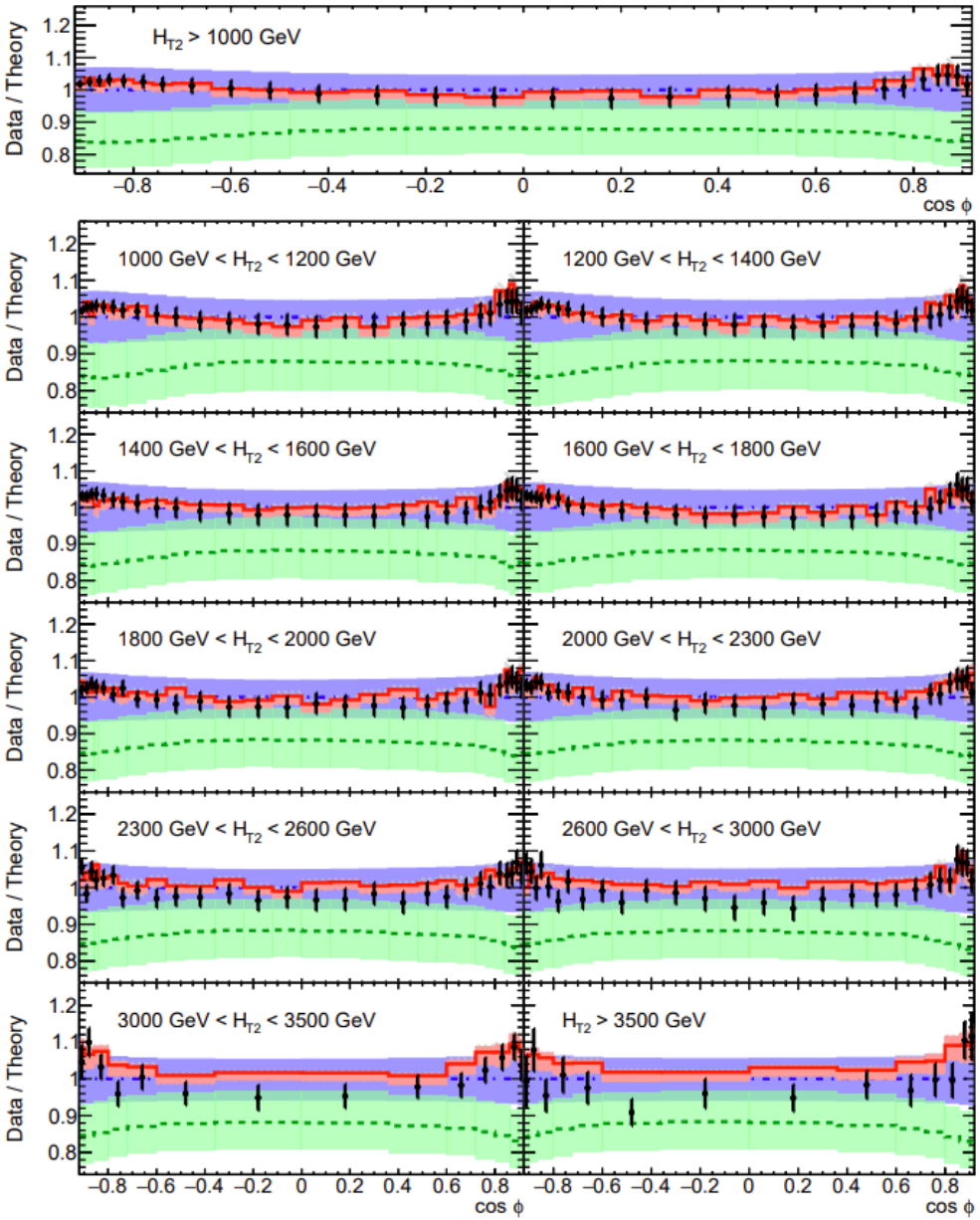


$$\tau_\perp = 1 - T_\perp\,, \quad T_\perp = \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_\perp|}{\sum_i |\vec{p}_{T,i}|}\,, \quad \text{and} \quad T_m = \frac{\sum_i |\vec{p}_{T,i} \times \hat{n}_\perp|}{\sum_i |\vec{p}_{T,i}|}\,.$$

Event shapes: new ATLAS analysis (arXiv:2301.09351)

- Soon thereafter: a new ATLAS analysis
- Comparison to NNLO predictions provided by Alex, René & friends
- Used to extract α_s at high scales: up to $\sim$ 2 TeV!
- Computational cost: $\mathcal{O}(10^{13})$ events $\Leftrightarrow$ $\mathcal{O}(100$ million CPUh$)$
- Thankfully done using ATLAS resources...

Event shapes: new ATLAS analysis (arXiv:2301.09351)



ATLAS

Particle-level TEEC

$\sqrt{s}$ = 13 TeV; 139 fb^{-1}

anti-k_t $R = 0.4$

$p_T > 60$ GeV

$|\eta| < 2.4$

$\mu_{R,F} = \hat{H}_T$

$\alpha_s(m_Z) = 0.1180$

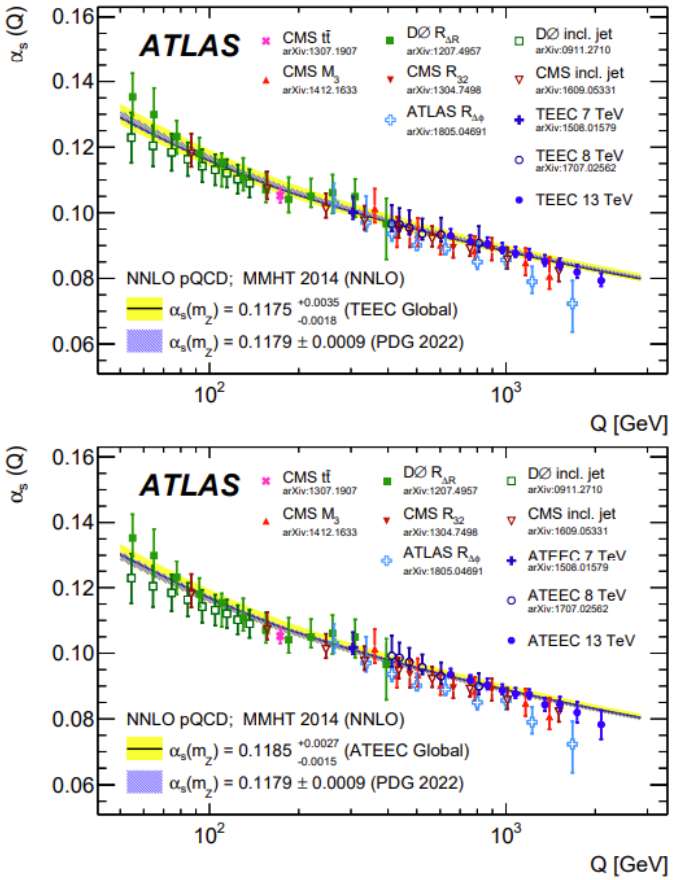
MMHT 2014 (NNLO)

Data

LO

NLO

NNLO



HighTEA (arXiv:2304.05993)*

- Database of precomputed "Theory Events"
  - **Equivalent to a full fledged computation**
  - Currently this means partonic fixed order events
  - Extensions to included showered/resummed/hadronized events is feasible

Not so new idea:
LHE [Alwall et al '06],
Ntuple [BlackHat '08'13],

- Analysis of the data through an user interface
  - Easy-to-use
  - Fast
  - Flexible:
    - Observables from basic 4-momenta
    - Free specification of bins
    - Renormalization/Factorization Scale variation
    - PDF (member) variation
    - Specify phase space cuts

https://www.precision.hep.phy.cam.ac.uk/hightea

HighTEA: **High energy Theory Event Analyser**

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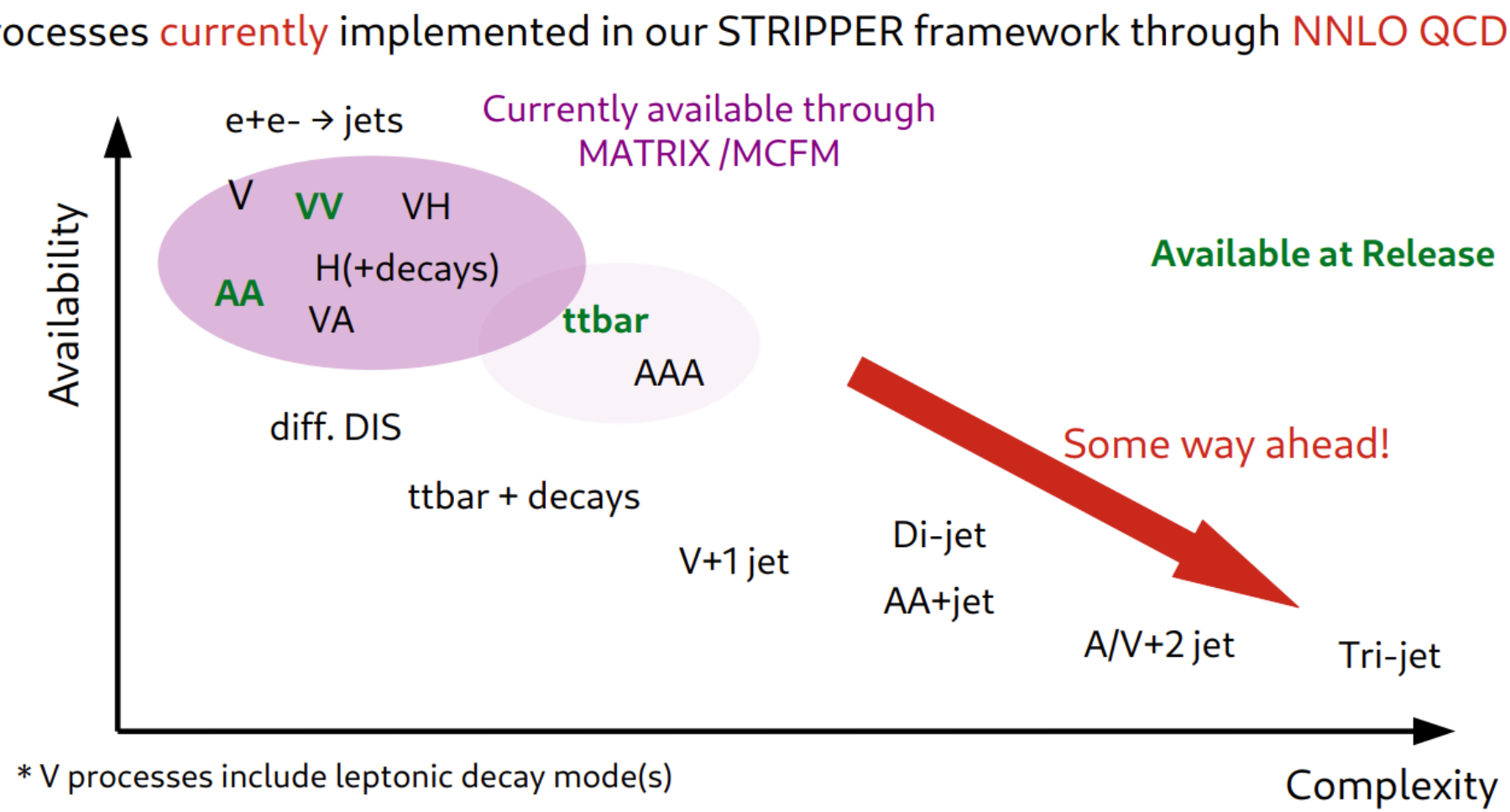
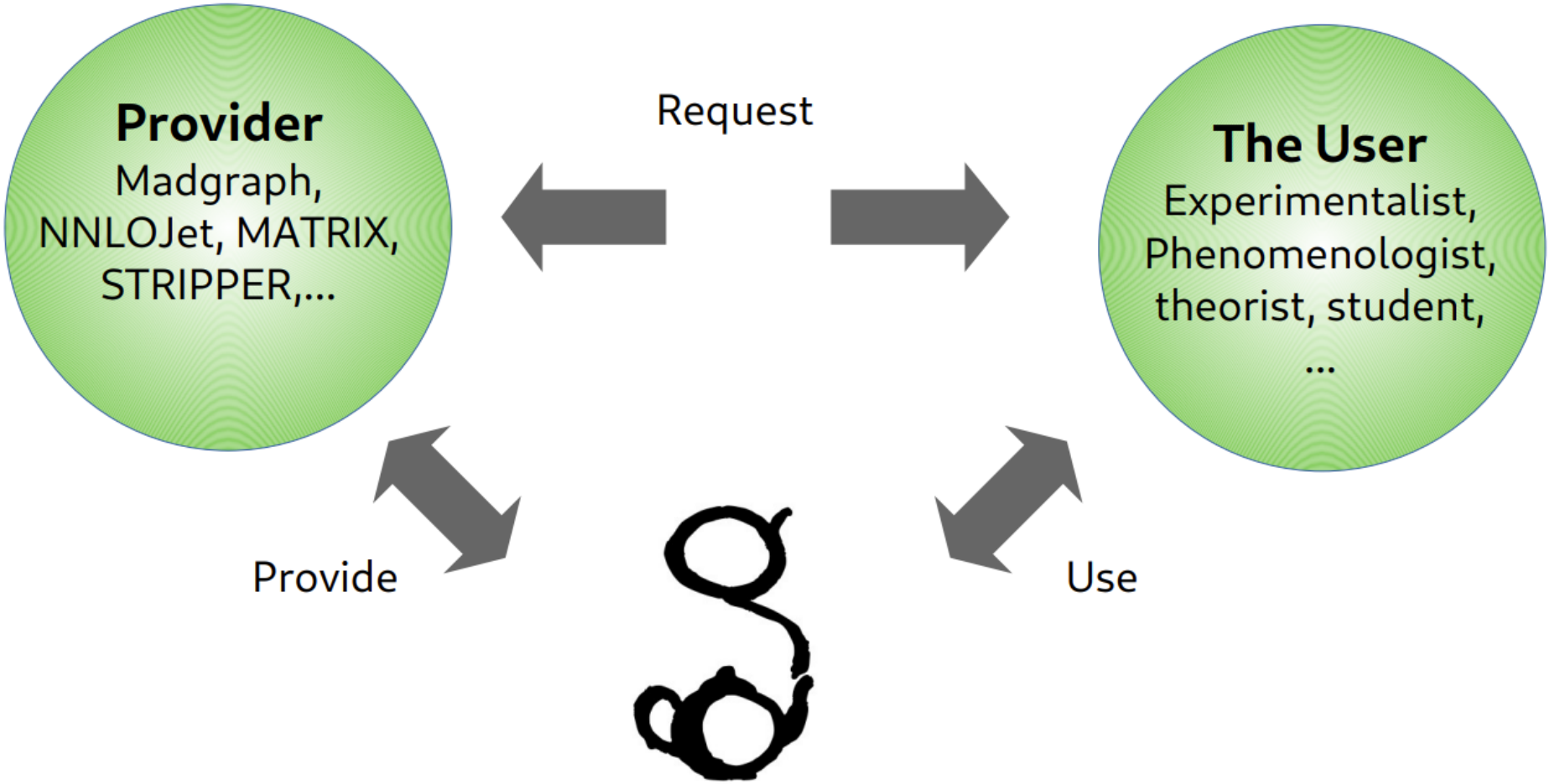
*Collage of slides by René Poncelet

HighTEA (arXiv:2304.05993)**



**Slide shamelessly stolen from René Poncelet

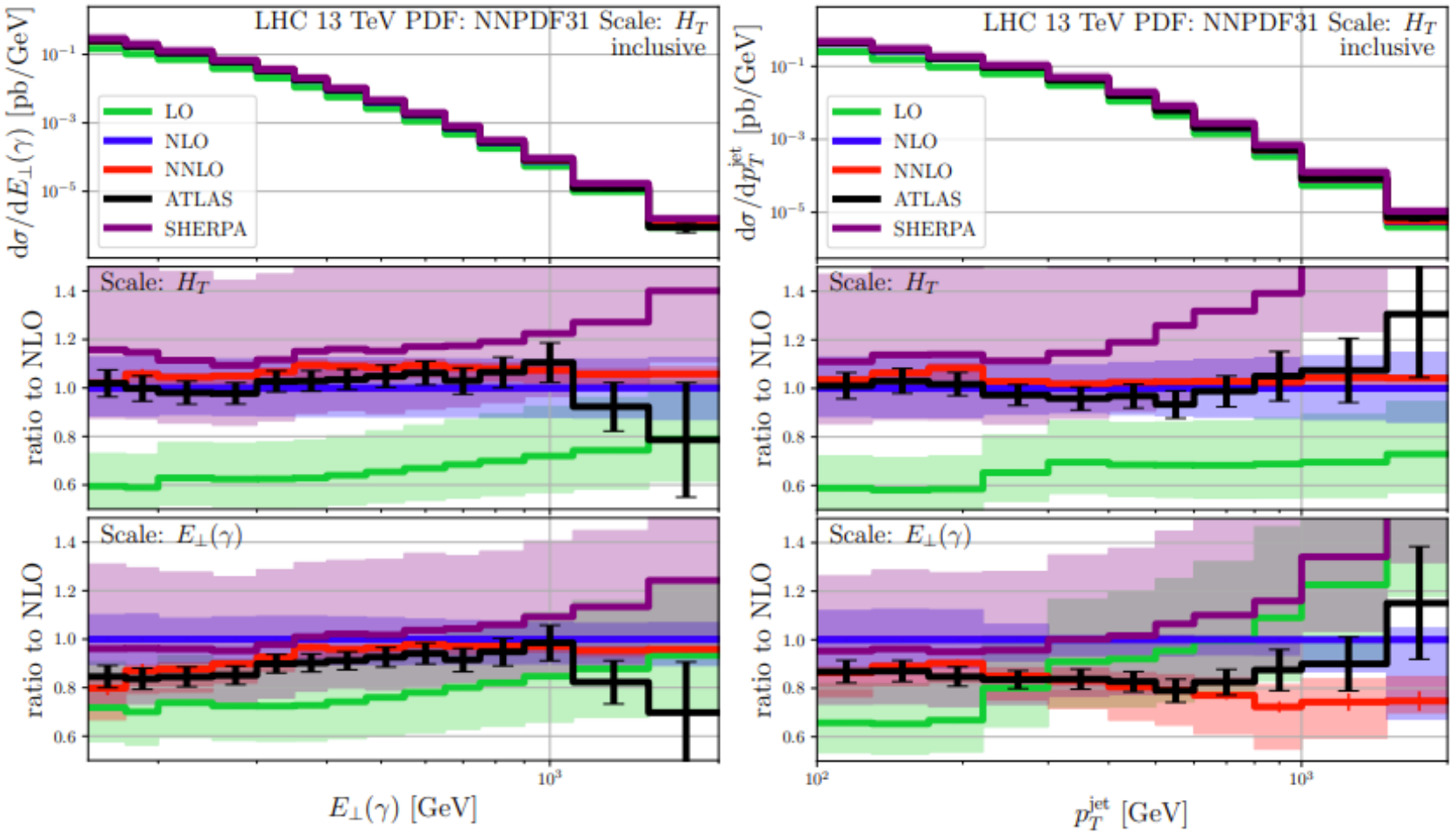
The HighTEA vision*



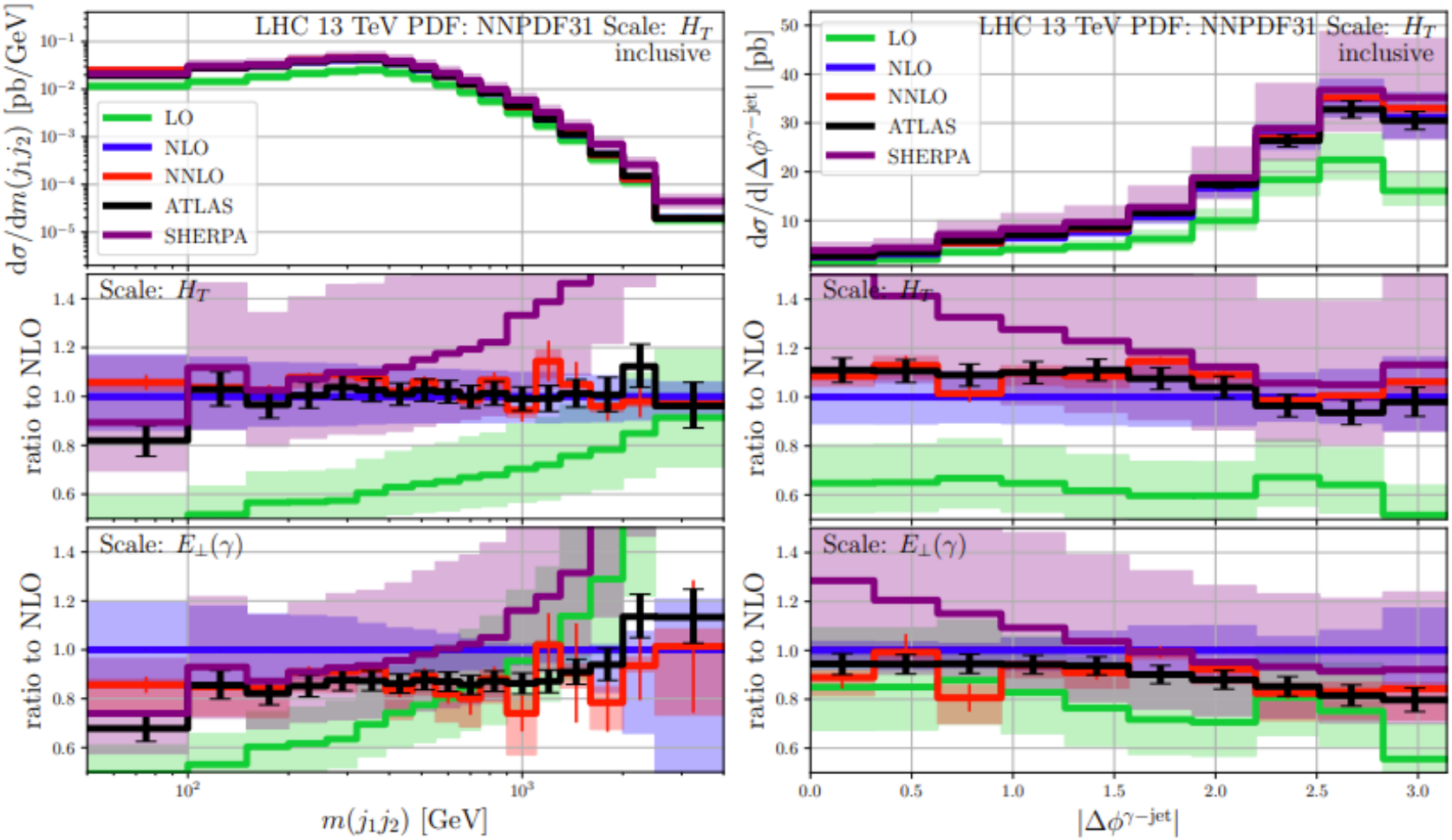
*Another slide stolen from René Poncelet

Photon + dijet (arXiv:2304.06682)

- First NNLO computation of $p\,p \to A\,j\,j + X$ at full colour
- Results compared to ATLAS data (arXiv:1912.09866)



Photon + dijet (arXiv:2304.06682)

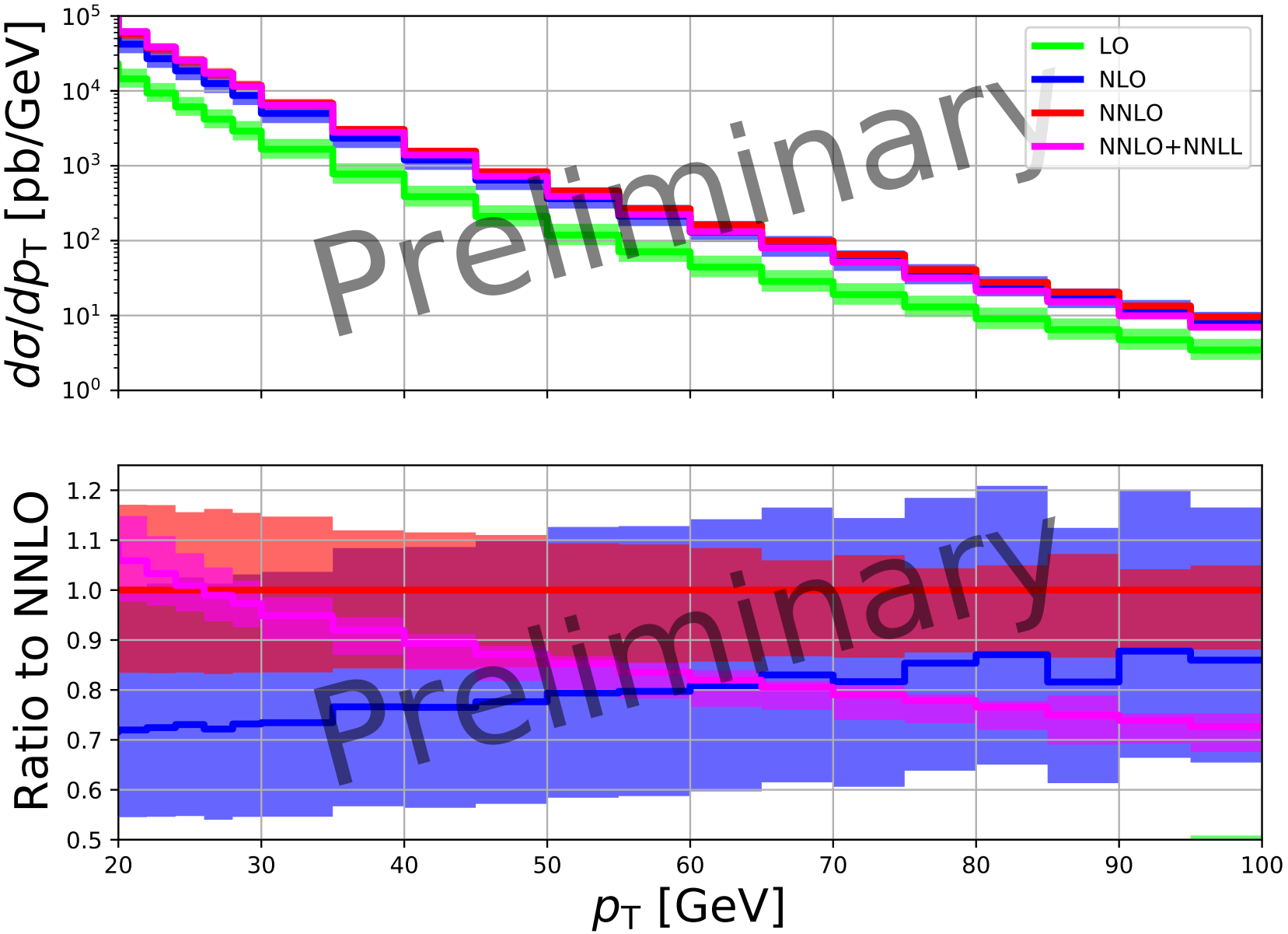


But what about myself?

Open bottom production

- A wealth of data from the Tevatron and S$p\bar{p}$S on open bottom production
- Processes considered:
  $p\,\bar{p} \to b + X$
  $(\hookrightarrow B \;/\; \mu \;/\; J/\psi \;/\; \psi(2S))$
  $p\,\bar{p} \to 2b + X$
  $(\hookrightarrow 2B \;/\; 2\mu)$
- Previous comparisons to theory: NLO(+NLL)
  Cacciari, Greco, Nason (1998)
- Consistently found data/theory $\approx 1.5 \pm 0.5$ (th.)
  (initially data/theory ≈ 3 before theory improvements)
- We can do better: NNLO+NNLL!

Preliminary results: b-quark p_T-spectrum at NNLO+NNLL



Conclusion & outlook

- Many new NNLO results
- Many new comparisons to data
- In general: better agreement and smaller uncertainties
- New results will enable future reduction of strange PDF uncertainties
- New extractions of α_s
- Generally: high-precision tests of QCD!
- Many exciting projects under way, including (but not limited to) hadron-level predictions for various LHC processes at NNLO