



PRECISE PREDICTIONS FOR THE PRODUCTION OF JETS IN DIS

Alexander Huss

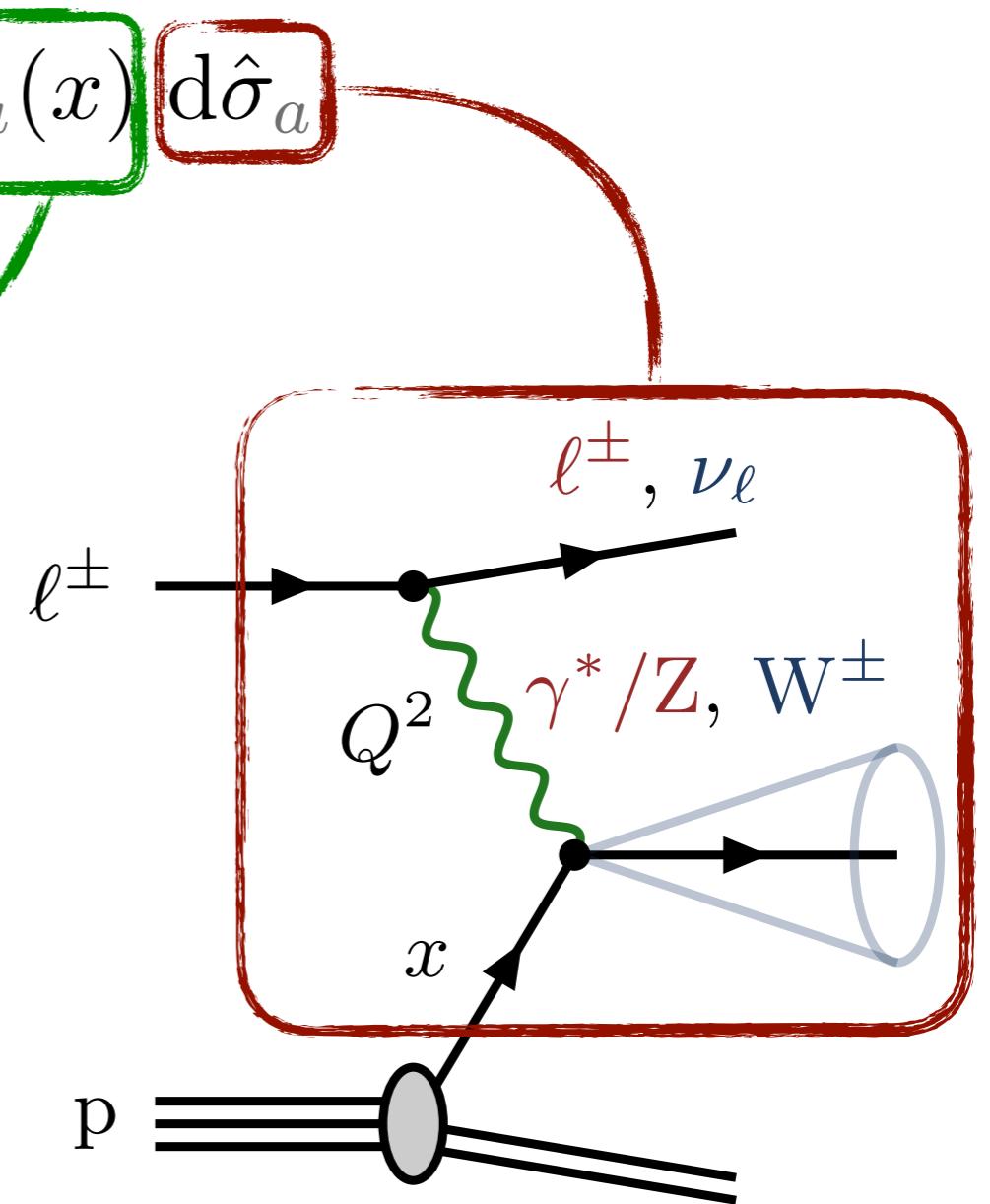
with Nigel Glover, Thomas Gehrmann, Jan Niehues, Duncan Walker, Andreas Vogt

DEEP INELASTIC SCATTERING

- Focus: perturbative QCD to DIS jet production

$$d\sigma = \sum_a \int_0^1 dx [f_a(x) d\hat{\sigma}_a]$$

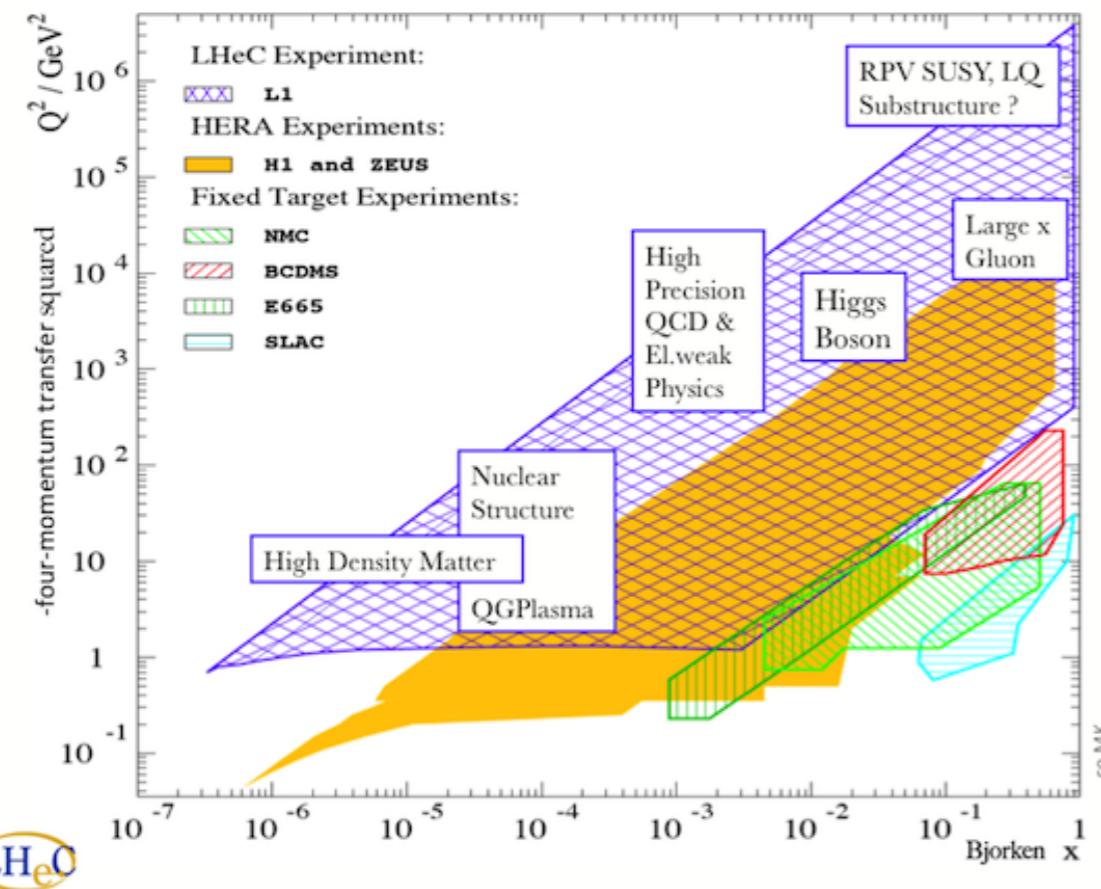
- very precise probe of the proton structure (PDFs)
(talks in WG1)
- independent variables: (x, Q^2)
 - γ^*/Z neutral current (NC)
 - W^\pm charged current (CC)



THE EXPERIMENTS

HERA's legacy...

- 1994-2007: HERA I & II
 - ▶ e^\pm (27.5 GeV)
 - ▶ p (460-920 GeV)
 - ▶ *large* set of jet data



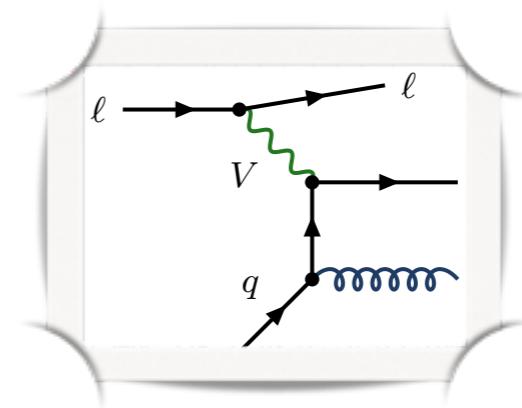
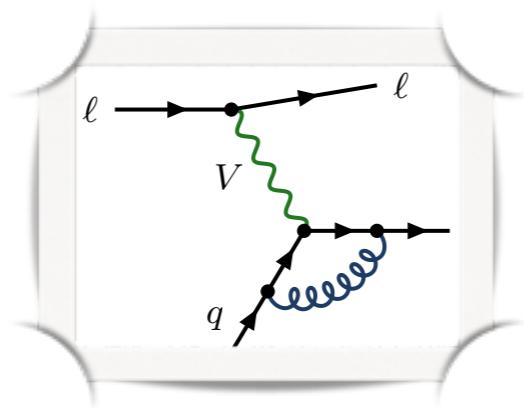
...and the future?

- LHeC / FCCep ($\sqrt{s} = 1.3 / 3.5 \text{ TeV}$)
- precision QCD (talk by C. Gwenlan)
 - ▶ $\delta a_s \sim 0.1\%$, PDFs $\sim 1\%$
- Higgs: disentangle WWH & ZHH

DIS @ NLO

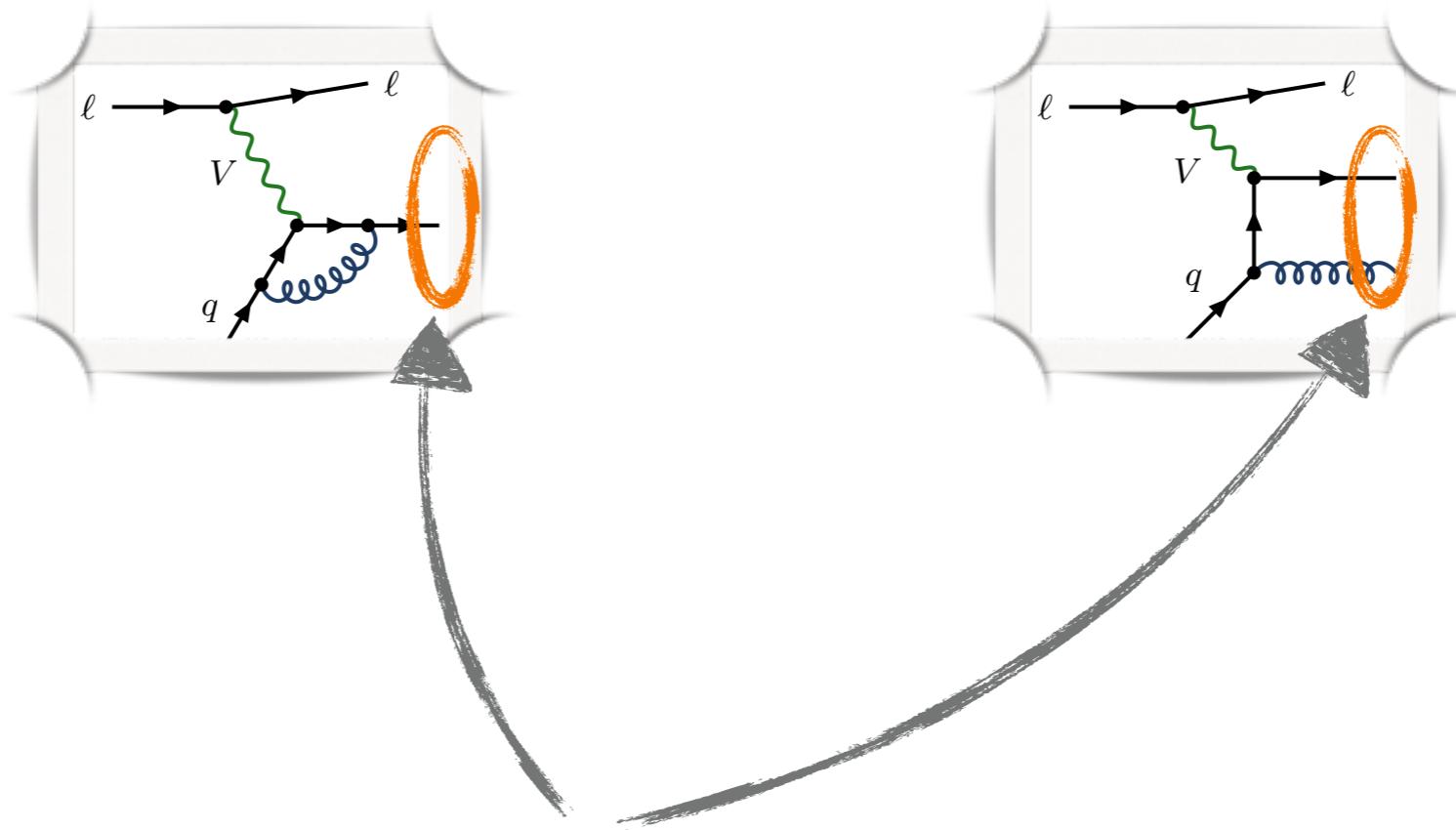
$$d\hat{\sigma}_a^{\text{NLO}} = \int_{\Phi_m} d\sigma_a^V$$

$$+ \int_{\Phi_{m+1}} d\sigma_a^R$$



INCLUSIVE DIS

$$d\hat{\sigma}_a^{\text{NLO}} = \int_{\Phi_m} d\sigma_a^V + \int_{\Phi_{m+1}} d\sigma_a^R$$



- **inclusive:** integrate over “ X ” (can do it analytically!)
- only lepton kinematics: (x, Q^2)

INCLUSIVE DIS: THE STRUCTURE FUNCTION

$$d\hat{\sigma}_a^{\text{NLO}} = \int_{\Phi_m} d\sigma_a^V + \int_{\Phi_{m+1}} d\sigma_a^R$$
$$\frac{c_2}{\epsilon^2} + \frac{c_1}{\epsilon^1} + c_0^V$$
$$-\frac{c_2}{\epsilon^2} - \frac{c_1}{\epsilon^1} + c_0^R$$



Structure Functions: F_L , F_2 , F_3

- inclusive: integrate over “ X ” (can do it analytically!)
- only lepton kinematics: (x, Q^2)

GOING DIFFERENTIAL

$$d\hat{\sigma}_a^{\text{NLO}} = \int_{\Phi_m} d\sigma_a^V \mathcal{F}_{\text{jet}}(\{p\}_m) + \int_{\Phi_{m+1}} d\sigma_a^R \mathcal{F}_{\text{jet}}(\{p\}_{m+1})$$

- differential: resolve “**X**” & study jets
 - a_s extraction, PDF constraints, ...

GOING DIFFERENTIAL

$$d\hat{\sigma}_a^{\text{NLO}} = \int_{\Phi_m} d\sigma_a^V \mathcal{F}_{\text{jet}}(\{p\}_m) + \int_{\Phi_{m+1}} d\sigma_a^R \mathcal{F}_{\text{jet}}(\{p\}_{m+1})$$



$$\frac{c_2}{\epsilon^2} + \frac{c_1}{\epsilon^1} + c_0^V$$

analytical integration unfeasible!

- differential: resolve “X” & study jets
- a_s extraction, PDF constraints, ...



GOING DIFFERENTIAL

$$d\hat{\sigma}_a^{\text{NLO}} = \int_{\Phi_m} d\sigma_a^V \mathcal{F}_{\text{jet}}(\{p\}_m) + \int_{\Phi_{m+1}} d\sigma_a^R \mathcal{F}_{\text{jet}}(\{p\}_{m+1})$$



$$\frac{c_2}{\epsilon^2} + \frac{c_1}{\epsilon^1} + c_0^V$$

INFRARED SUBTRACTION @ NLO

- Dipole subtr.
- FKS subtr.
- ...

- differential: resolve “X” & study jets
- α_s extraction, PDF constraints, ...

GOING DIFFERENTIAL

$$d\hat{\sigma}_a^{\text{NLO}} = \int_{\Phi_m} d\sigma_a^V \mathcal{F}_{\text{jet}}(\{p\}_m) + \int_{\Phi_{m+1}} d\sigma_a^R \mathcal{F}_{\text{jet}}(\{p\}_{m+1})$$



$$\frac{c_2}{\epsilon^2} + \frac{c_1}{\epsilon^1} + c_0^V$$

INFRARED SUBTRACTION @ NNLO

- *Antenna subtr.* 
- CoLorFul subtr.
- q_T slicing (talk by M. Wiesemann)
- Stripper
- τ_N slicing
- Projection-to-Born
- Nested soft-collinear subtr.
- Local analytic subtr. (talk by G. Pelliccioli)
- ...

- differential: resolve “X” & study jets
- a_s extraction, PDF constraints, ...

GOING DIFFERENTIAL

$$d\hat{\sigma}_a^{\text{NLO}} = \int_{\Phi_m} d\sigma_a^V \mathcal{F}_{\text{jet}}(\{p\}_m) + \int_{\Phi_{m+1}} d\sigma_a^R \mathcal{F}_{\text{jet}}(\{p\}_{m+1})$$



$$\frac{c_2}{\epsilon^2} + \frac{c_1}{\epsilon^1} + c_0^V$$

INFRARED SUBTRACTION @ N³LO

- q_T slicing
- *Projection-to-Born*



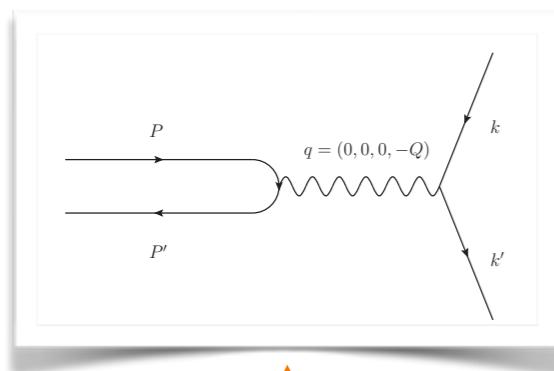
- differential: resolve “X” & study jets
- a_s extraction, PDF constraints, ...

DIS DI-JET PRODUCTION AT NNLO

DIO DISPI E KOBOSHIMA ET AL.

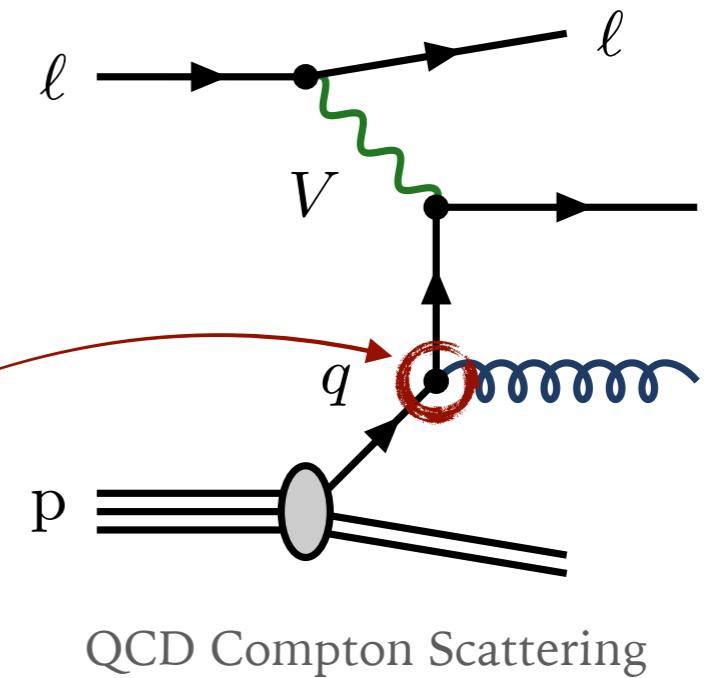
DI-JET PRODUCTION

- $\#(\text{jets}) \geq 2$
or Breit Frame

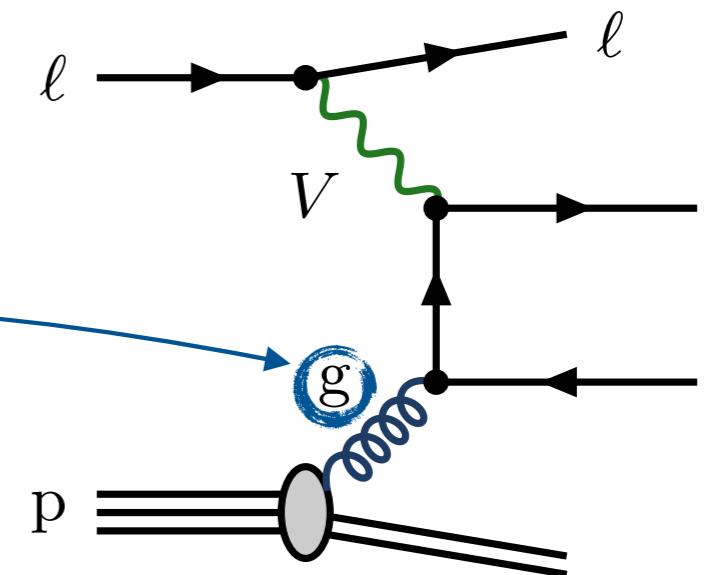


↑
partonic recoil

- direct sensitivity to α_s
- rare handle on gluon PDF at HERA



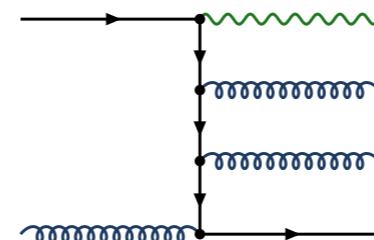
QCD Compton Scattering



Boson-Gluon Fusion

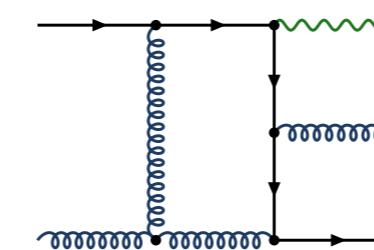
DIS_{2J} @ NNLO

$$\sigma_{\text{NNLO}} = \int_{\Phi_{Z+3}} d\sigma_{\text{NNLO}}^{\text{RR}}$$



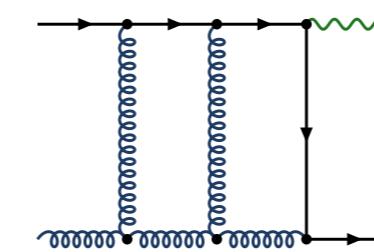
- ▶ single-unresolved
- ▶ double-unresolved

$$+ \int_{\Phi_{Z+2}} d\sigma_{\text{NNLO}}^{\text{RV}}$$



- ▶ single-unresolved
- ▶ $1/\epsilon^2, 1/\epsilon$

$$+ \int_{\Phi_{Z+1}} d\sigma_{\text{NNLO}}^{\text{VV}}$$



- ▶ $1/\epsilon^4, 1/\epsilon^3, 1/\epsilon^2, 1/\epsilon$

\sum finite (Kinoshita–Lee–Nauenberg & factorization)

Non-trivial cancellation of infrared singularities

DIS_{2J} @ NNLO USING ANTENNA SUBTRACTION

$$\sigma_{\text{NNLO}} = \int_{\Phi_{Z+3}} \left(d\sigma_{\text{NNLO}}^{\text{RR}} - d\sigma_{\text{NNLO}}^{\text{S}} \right)$$

$$+ \int_{\Phi_{Z+2}} \left(d\sigma_{\text{NNLO}}^{\text{RV}} - d\sigma_{\text{NNLO}}^{\text{T}} \right)$$

$$+ \int_{\Phi_{Z+1}} \left(d\sigma_{\text{NNLO}}^{\text{VV}} - d\sigma_{\text{NNLO}}^{\text{U}} \right)$$

- ▶ $d\sigma_{\text{NNLO}}^{\text{S}}, d\sigma_{\text{NNLO}}^{\text{T}}$:
mimic $d\sigma_{\text{NNLO}}^{\text{RR}}, d\sigma_{\text{NNLO}}^{\text{RV}}$
in unresolved limits
- ▶ $d\sigma_{\text{NNLO}}^{\text{T}}, d\sigma_{\text{NNLO}}^{\text{U}}$:
analytic cancellation of poles in $d\sigma_{\text{NNLO}}^{\text{RV}}, d\sigma_{\text{NNLO}}^{\text{VV}}$

$$\sum \quad \text{finite} \quad - 0$$

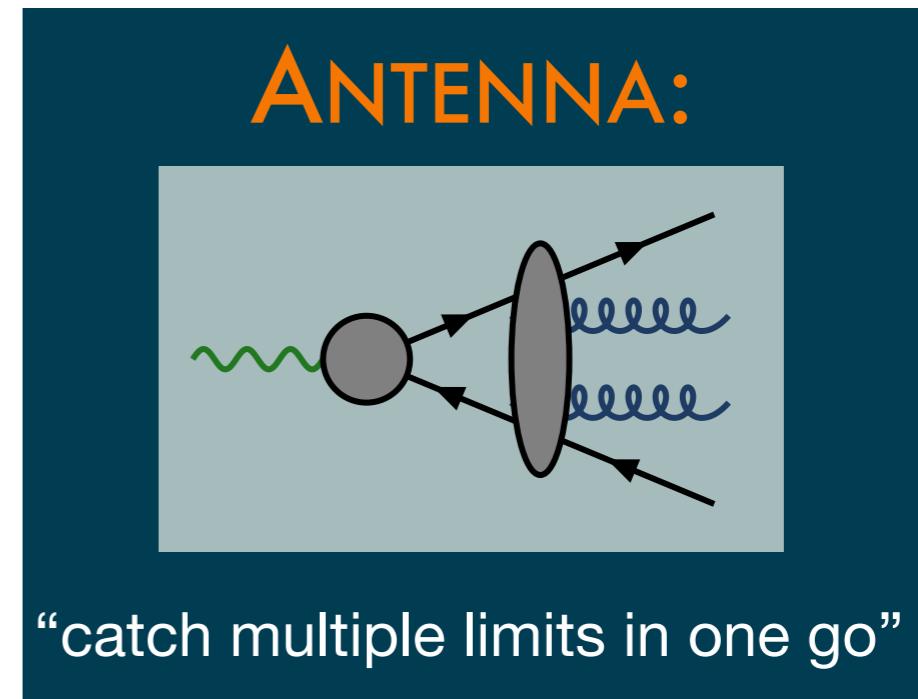
⇒ each line suitable for numerical evaluation in $D = 4$

DIS_{2J} @ NNLO USING ANTENNA SUBTRACTION

$$\sigma_{\text{NNLO}} = \int_{\Phi_{Z+3}} \left(d\sigma_{\text{NNLO}}^{\text{RR}} - d\sigma_{\text{NNLO}}^{\text{S}} \right)$$

$$+ \int_{\Phi_{Z+2}} \left(d\sigma_{\text{NNLO}}^{\text{RV}} - d\sigma_{\text{NNLO}}^{\text{T}} \right)$$

$$+ \int_{\Phi_{Z+1}} \left(d\sigma_{\text{NNLO}}^{\text{VV}} - d\sigma_{\text{NNLO}}^{\text{U}} \right)$$

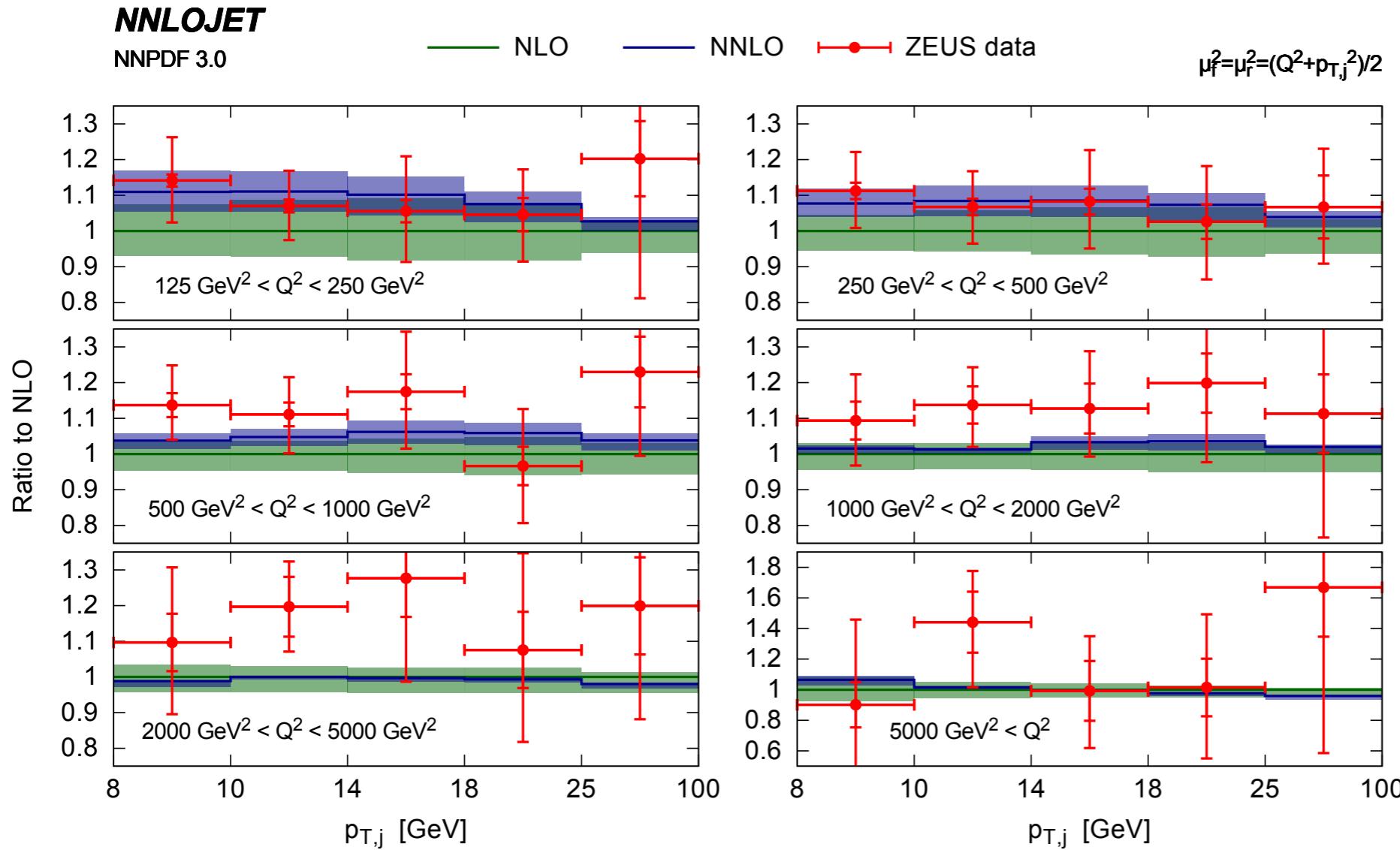


$$\sum \quad \text{finite} \quad - 0$$

⇒ each line suitable for numerical evaluation in $D = 4$

INCLUSIVE JETS IN THE BREIT FRAME (NC DIS_{2J})

[Currie, Gehrmann, AH, Niehues '17]

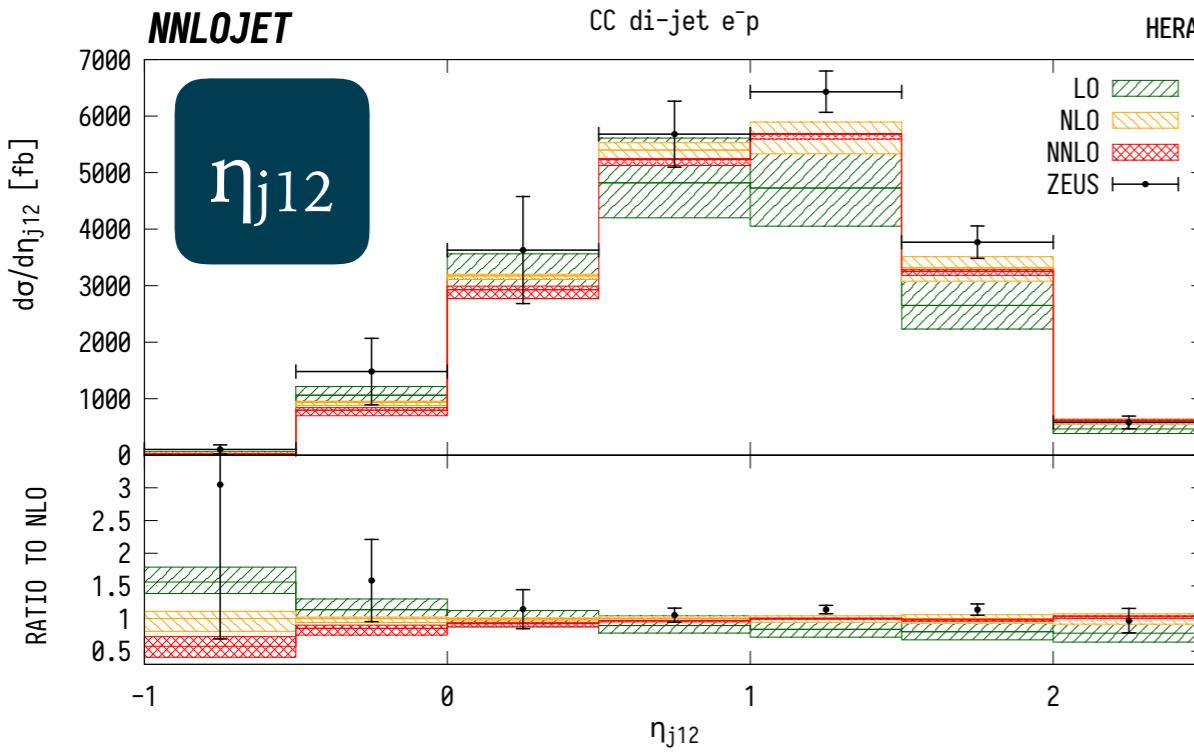


already used:

- *a_s extraction*
(talk by D. Britzger)
- *PDF fits*
(talk by A. Sarkar)

- sizeable corrections in lower Q^2 bins (better description of data)
- high- Q^2 bins: small NNLO corrections + reduction of scale uncert.

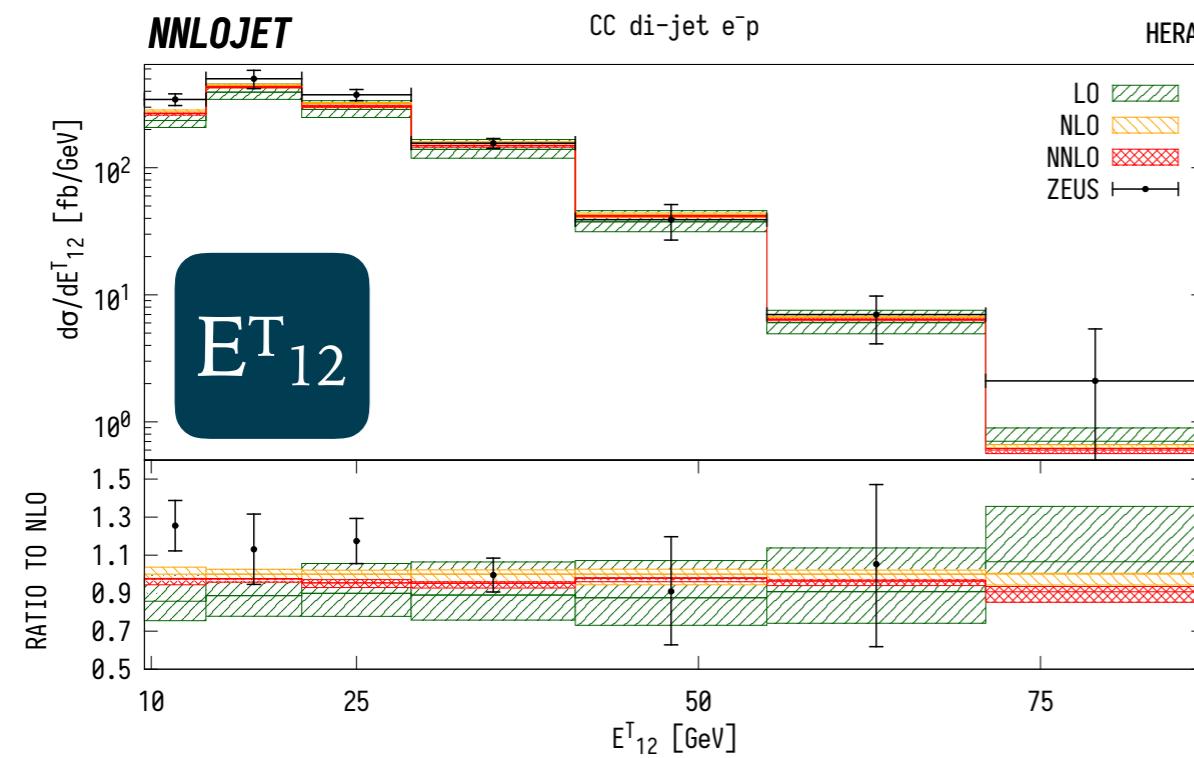
DI-JETS (CC DIS_{2J})



[Niehues, Walker '18]

➤ CC: flavour information

➤ NLO → NNLO
typically $\times 2$ reduction
in scale uncertainties



➤ negative corrections
@ low η_{j12}

DIS JET PRODUCTION AT N³LO

DIOSEL + KOBOSCHI + WILHELM

DIS_{1J} @ NLO

$$d\hat{\sigma}_a^{\text{NLO}} = \int_{\Phi_m} d\sigma_a^V \mathcal{F}_{\text{jet}}(\{p\}_m) + \int_{\Phi_{m+1}} d\sigma_a^R \mathcal{F}_{\text{jet}}(\{p\}_{m+1})$$

- differential: resolve final-state partons
 - rich theoretical testing ground

DIS_{1J} @ NLO USING PROJECTION-TO-BORN

$$\begin{aligned} d\hat{\sigma}_a^{\text{NLO}} = & \int_{\Phi_m} d\sigma_a^V \mathcal{F}_{\text{jet}}(\{p\}_m) + \int_{\Phi_{m+1}} d\sigma_a^R \mathcal{F}_{\text{jet}}(\{p\}_{m+1 \rightarrow m}) \\ & + \int_{\Phi_{m+1}} d\sigma_a^R \left\{ \mathcal{F}_{\text{jet}}(\{p\}_{m+1}) - \mathcal{F}_{\text{jet}}(\{p\}_{m+1 \rightarrow m}) \right\} \end{aligned}$$

- differential: resolve final-state partons
 - rich theoretical testing ground

DIS_{1j} @ NLO USING PROJECTION-TO-BORN

$$\hat{d\sigma}_a^{\text{NLO}} = \boxed{\int_{\Phi_m} d\sigma_a^V \mathcal{F}_{\text{jet}}(\{p\}_m) + \int_{\Phi_{m+1}} d\sigma_a^R \mathcal{F}_{\text{jet}}(\{p\}_{m+1 \rightarrow m})}$$
$$+ \int_{\Phi_{m+1}} d\sigma_a^R \left\{ \mathcal{F}_{\text{jet}}(\{p\}_{m+1}) - \mathcal{F}_{\text{jet}}(\{p\}_{m+1 \rightarrow m}) \right\}$$

(SF @ NLO) + (DIS_{2j} @ LO)

- differential: resolve final-state partons
- rich theoretical testing ground

DIS_{1J} @ N³LO USING PROJECTION-TO-BORN

DIS 2 jet
@ NNLO

[Currie, Gehrmann, Niehues '16]
[Currie, Gehrmann, AH, Niehues '17]
CC: [Niehues, Walker '18]

Projection-to-Born



[Cacciari, et al. '15]

DIS structure
function
@ N³LO

[Moch, Vermaseren, Vogt '05]

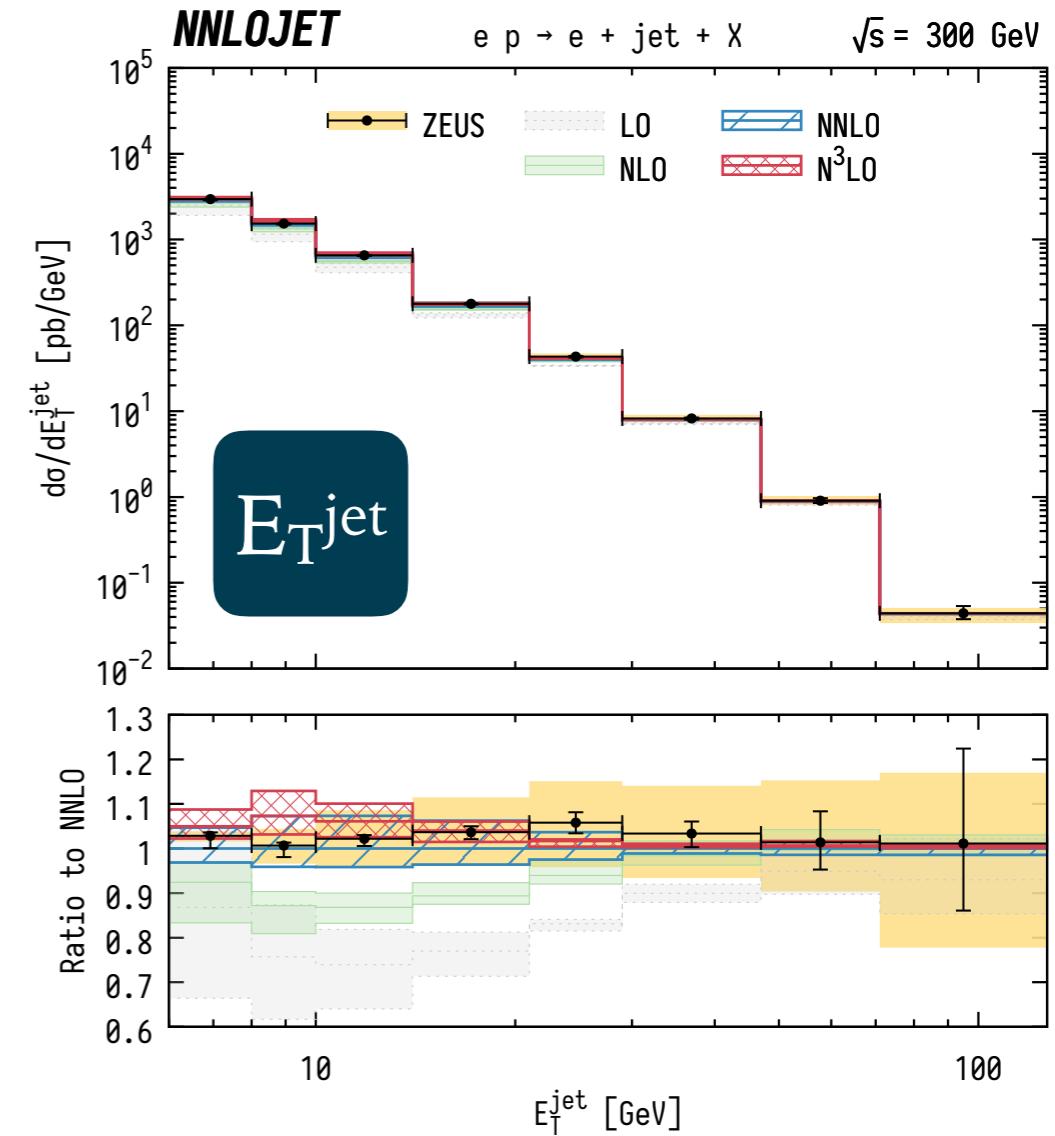
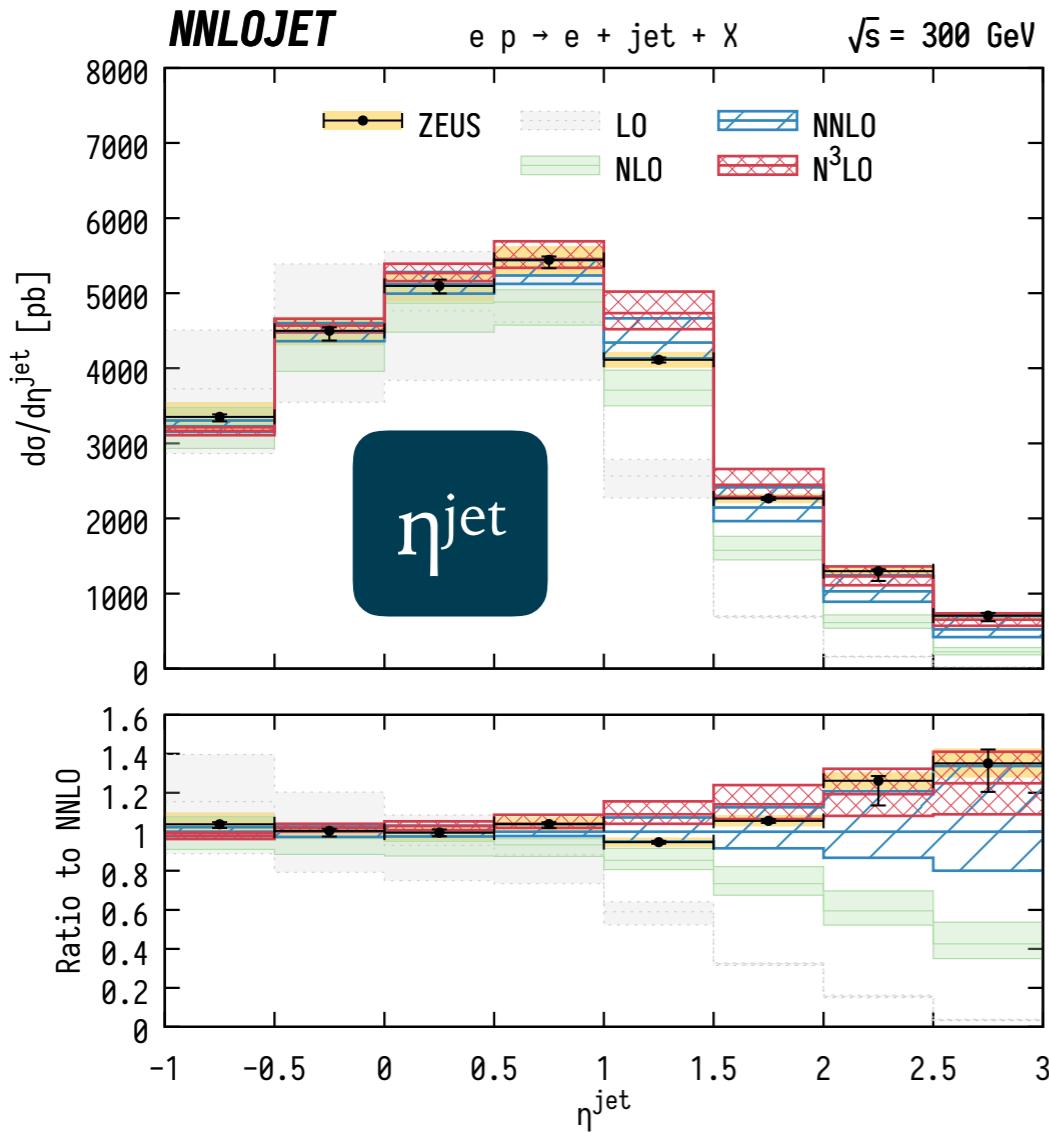
=

DIS fully
differential @ N³LO

[Currie, Gehrmann, Glover, AH, Niehues, Vogt. '18]
CC: [Gehrmann, Glover, AH, Niehues, Walker, Vogt '18]

INCLUSIVE JETS (NC DIS_{1J})

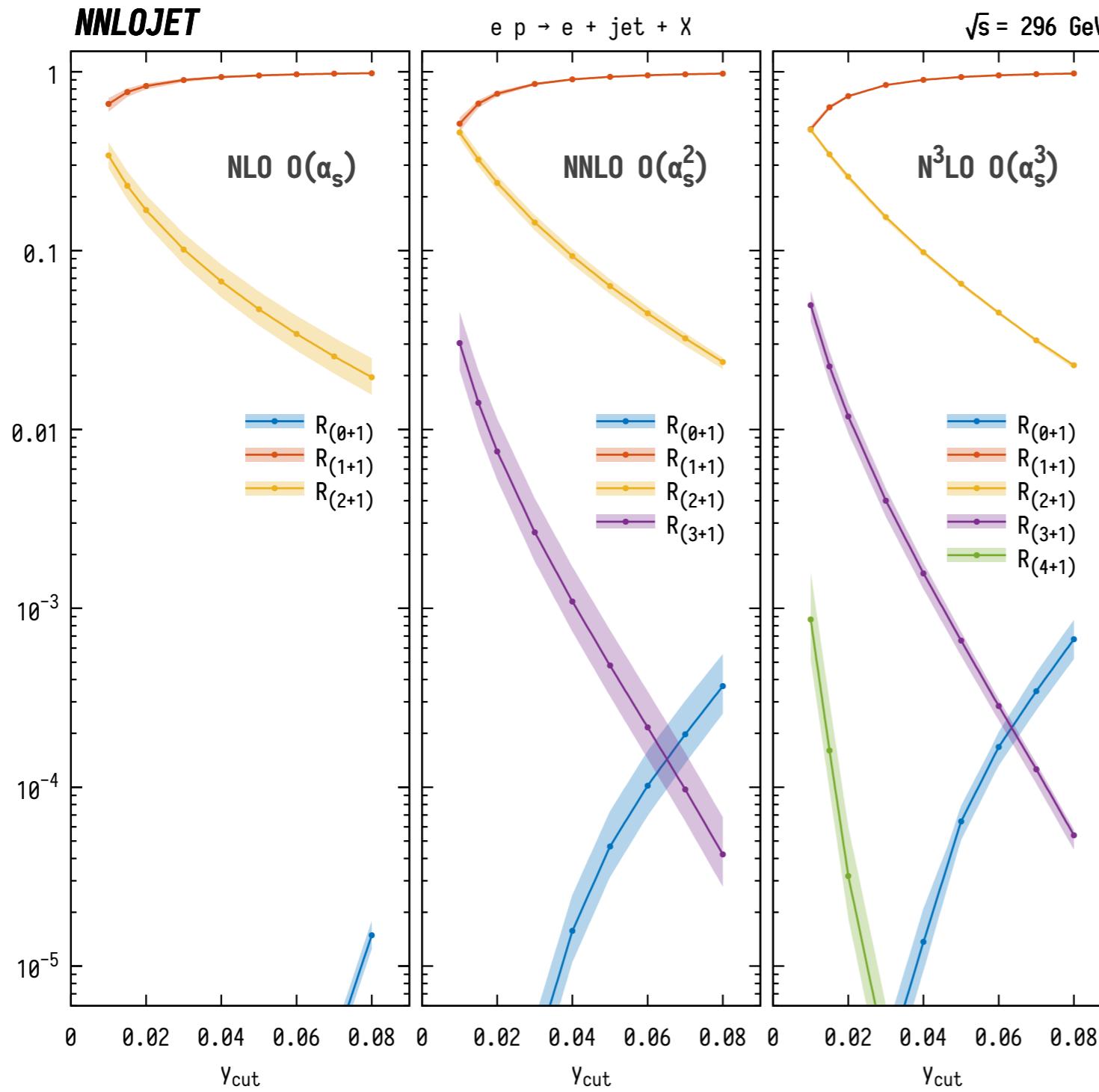
[Currie, Gehrmann, Glover, AH, Niehues, Vogt. '18]



- for the first time: **overlapping bands** (agreement with data)
- reduction of scale uncertainties

JET RATES (NC DIS_{1J})

[Currie, Gehrmann, Glover, AH, Niehues, Vogt. '18]



Jet rates:

$$R_{(n+1)} = N_{(n+1)} / N_{\text{tot}}$$

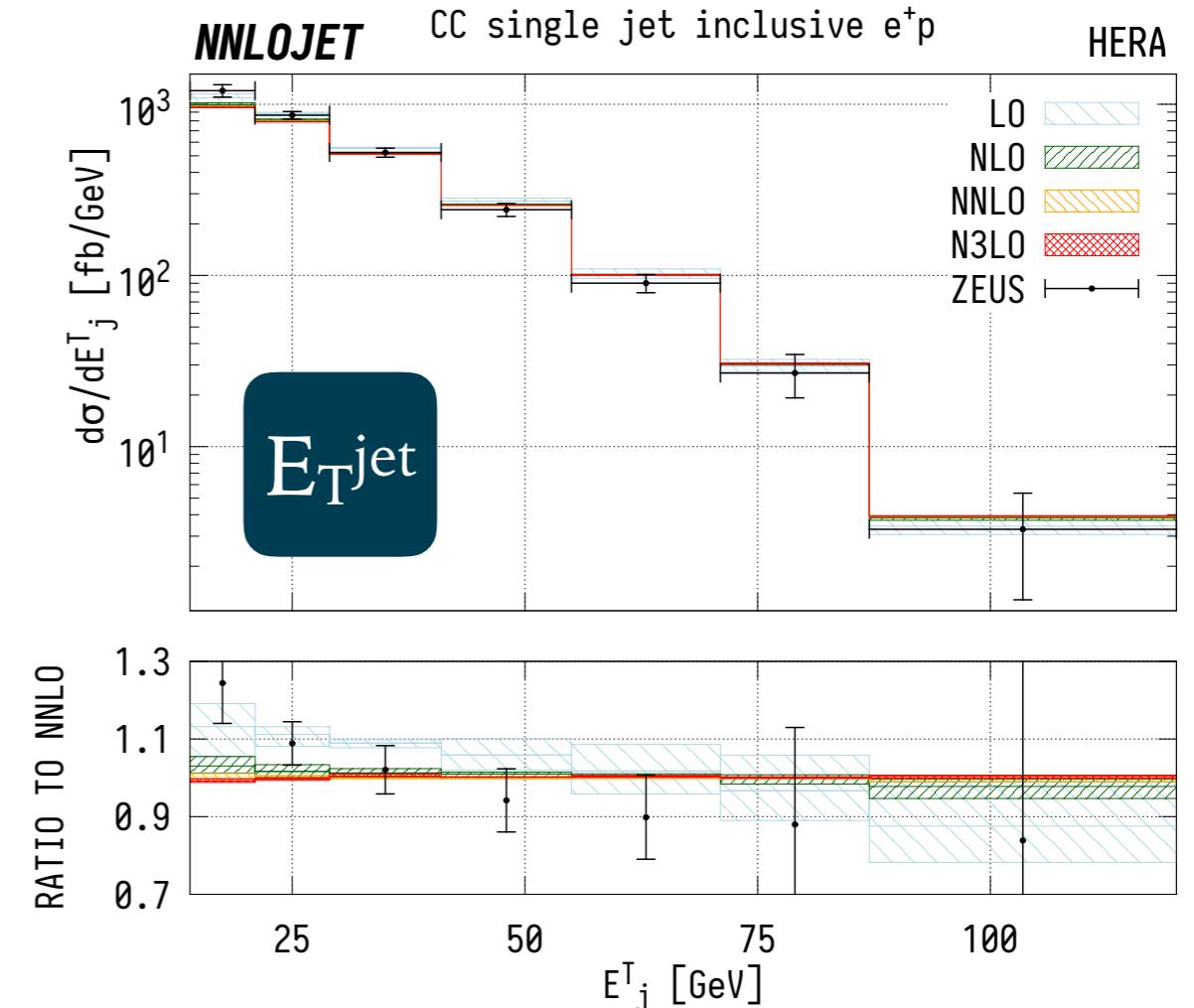
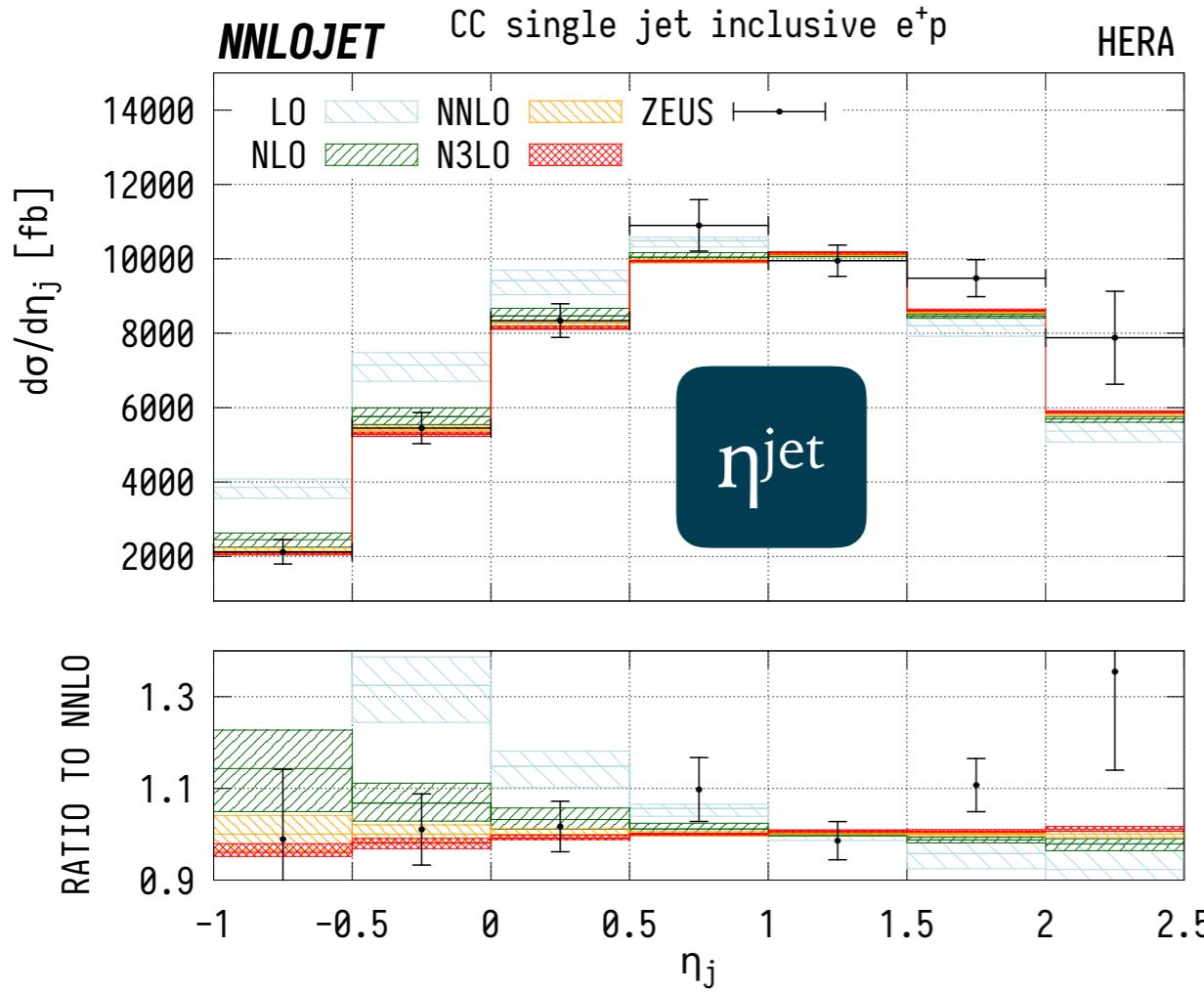
JADE algorithm

→ cluster partons if:

$$\frac{2E_i E_j (1 - \cos \theta_{ij})}{W^2} < y_{\text{cut}}$$

INCLUSIVE JETS (CC DIS_{1J})

[Gehrman, Glover, AH, Niehues, Walker, Vogt '18]



- for the first time: **overlapping bands** (agreement with data)
- reduction of scale uncertainties

SUMMARY & OUTLOOK

- **DIS** — precise probe of the proton structure & QCD
 - PDF constraints, a_s extraction, ...
- current **state of the art**: (**DIS_{2j} @ NNLO**) & (**DIS_{1j} @ N³LO**)
 - substantially reduced theory uncertainties & better convergence
 - improved description of the data
- **precise QCD predictions essential to...**
 - fully exploit **HERA** measurements (calculations already being used)
 - match demands of **future colliders** (LHeC, FCCep)
- calculations & techniques also useful for **LHC**:
 - (**VBF @ N³LO**) — VBF \simeq (DIS_{1j})²
 - (**ggH @ N³LO**) — **Projection-to-Born**: numerical stability & performance



❤️ *APPLfast*
► (*talk by M. Sutton*)

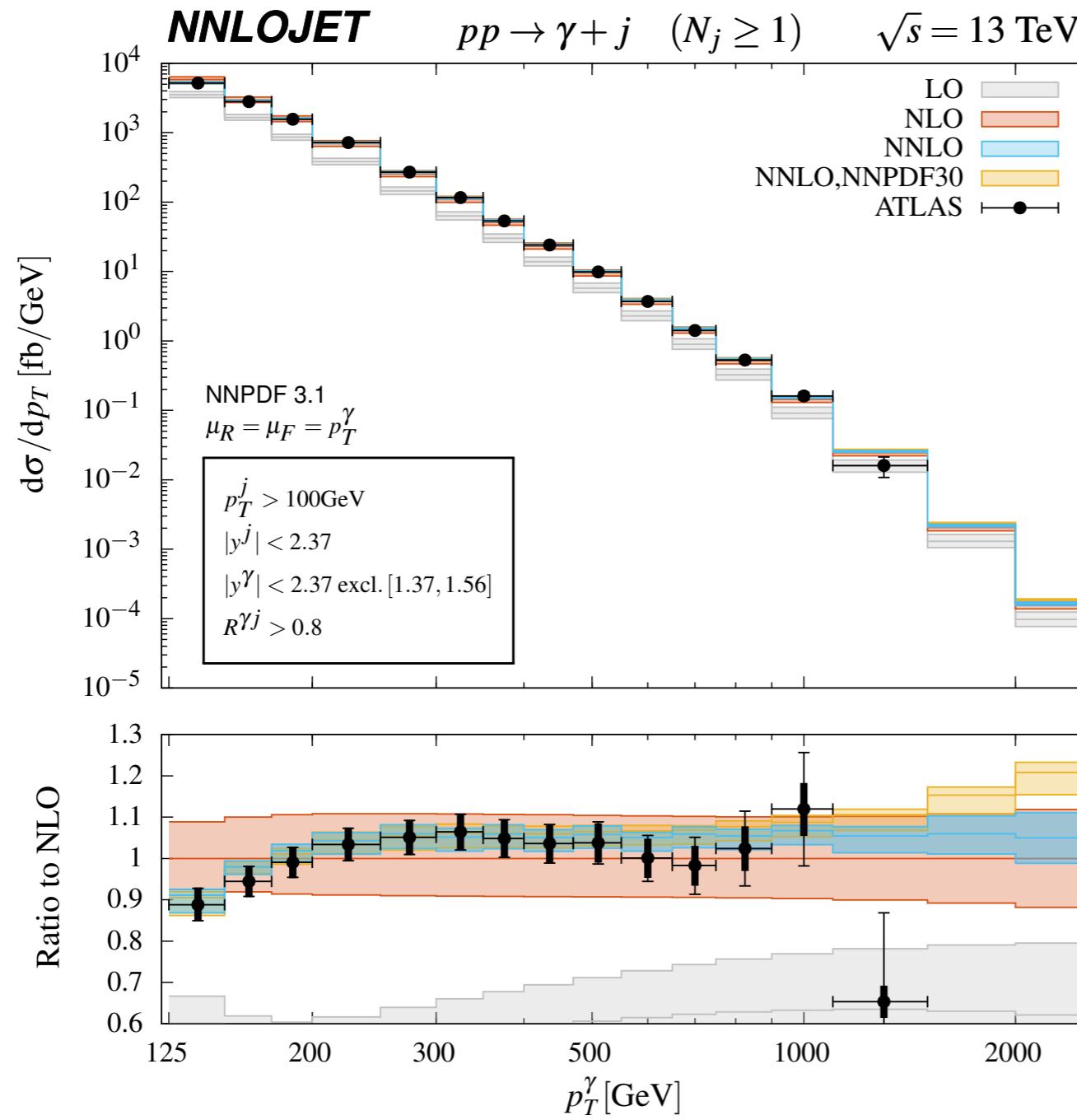
X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld, A. Gehrmann-De Ridder,
T. Gehrmann, E.W.N. Glover, M. Höfer, AH, I. Majer, J. Mo, T. Morgan, J. Niehues,
J. Pires, D. Walker, J. Whitehead

Processes computed using the antenna subtraction method

- $\text{pp} \rightarrow V$ @ NNLO
- $\text{pp} \rightarrow V + j$ @ NNLO
- $\rightarrow V \rightarrow \ell\bar{\ell}$ ($V = Z/\gamma^*, W^\pm$)
- $\text{pp} \rightarrow \text{jets}$ ($i'M\text{-NEW}$, jets, 2j) @ NNLO
- $\text{pp} \rightarrow \gamma + j$ @ NNLO
- $\text{ep} \rightarrow 1j$ @ $N^3\text{LO}$
- $\text{ep} \rightarrow 2j$ @ NNLO
- $e^+e^- \rightarrow 3 \text{ jets}$ @ NNLO
- $\text{pp} \rightarrow H$ (ggH) @ $N^3\text{LO}$
- $\text{pp} \rightarrow H + j$ (ggH) @ NNLO
- $\text{pp} \rightarrow H + 2j$ (VBF) @ NNLO
- $\rightarrow H \rightarrow \gamma\gamma, \tau\tau, V\gamma, VV$
- $\text{pp} \rightarrow VH$ @ NNLO
- $\rightarrow H \rightarrow bb$
- ...

PHOTON + JET @ 13 TeV

[Chen, Gehrmann, Glover, Höfer, AH '19]



hybrid isolation

NLO (~ 1)

- +40% corrections
- $\pm 10\%$ uncertainties

NNLO

- $\sim 5\%$ corrections
- *shape distortions*
- $\lesssim 5\%$ uncertainties

- previous NNLO calculation
 τ_N [Campbell, Ellis, Williams '17]
(dynamical cone isol.)

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THANK YOU!