γ + JET PRODUCTION AT NNLO

STANDARD MODEL AT THE LHC 2019

Universität Zürich[UZH]

MC@NNLO

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$\gamma +$ JET PRODUCTION AT THE LHC

- LHC experiments
  - γ production at high pT is classical hadron collider observable
    - Excellent detector sensitivity and large number of events
  - Recent experimental studies reach percent level accuracy.
    - ([ATLAS 1701.06882, 1801.00112, 1901.10075][CMS 1807.00782])
  - Background process of mono-jet, di-jet and BSM searches.
- Theory
  - High-pT γ is a probe to gluon and quark PDF already at LO QCD.
    - Not yet included in modern PDF analysis.
  - Require precise QCD and electroweak predictions from pQFT.
  - Rich phenomenology involving photon isolation and fragmentation.

STATUS OF THEORETICAL PREDICTIONS

- State-of-the-art precision of pQFT:
  - NNLO QCD corrections for γ + jet and inclusive γ production:
    - N-jettiness subtraction in MCFM : [1612.04333, 1703.10109]
    - Antenna subtraction in NNLOJET: [1904.01044] (this talk)
  - LO (1-loop) EW + 2-loop Sudakov-enhanced EW: [hep-ph/0508253]
  - NLO QCD + N3LL QCD threshold-resummation + LL EW Sudakov-resummation $\sim \log(M_V^2/p_T^2)$: [1606.02313]
  - Mixed NNLL QCD threshold-resummation + NLL EW Sudakov-resummation: [1305.4202, 1509.01961]
- Theory meets reality:
  - Measurements require isolated photon (finite accuracy of ECAL, π^0 decay etc).
  - NNLOJET (parton-level event generator) use realistic photon isolation procedure at NNLO QCD accuracy (this talk).

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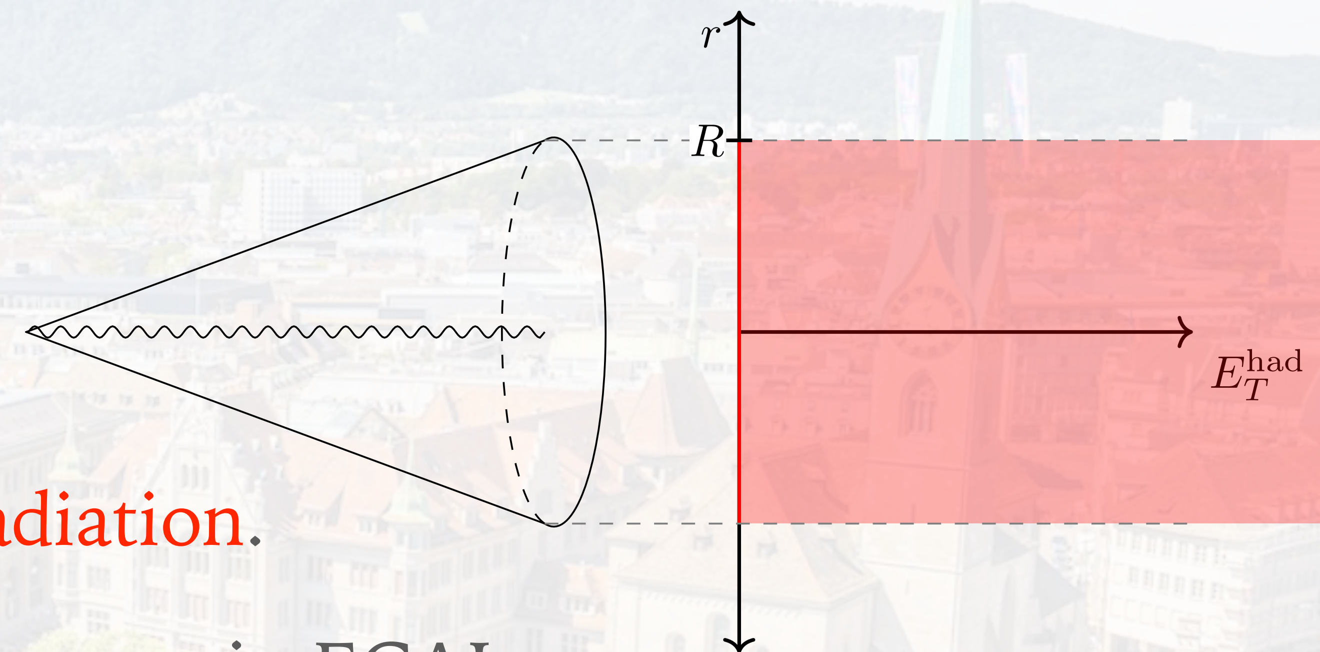
PHOTON ISOLATION

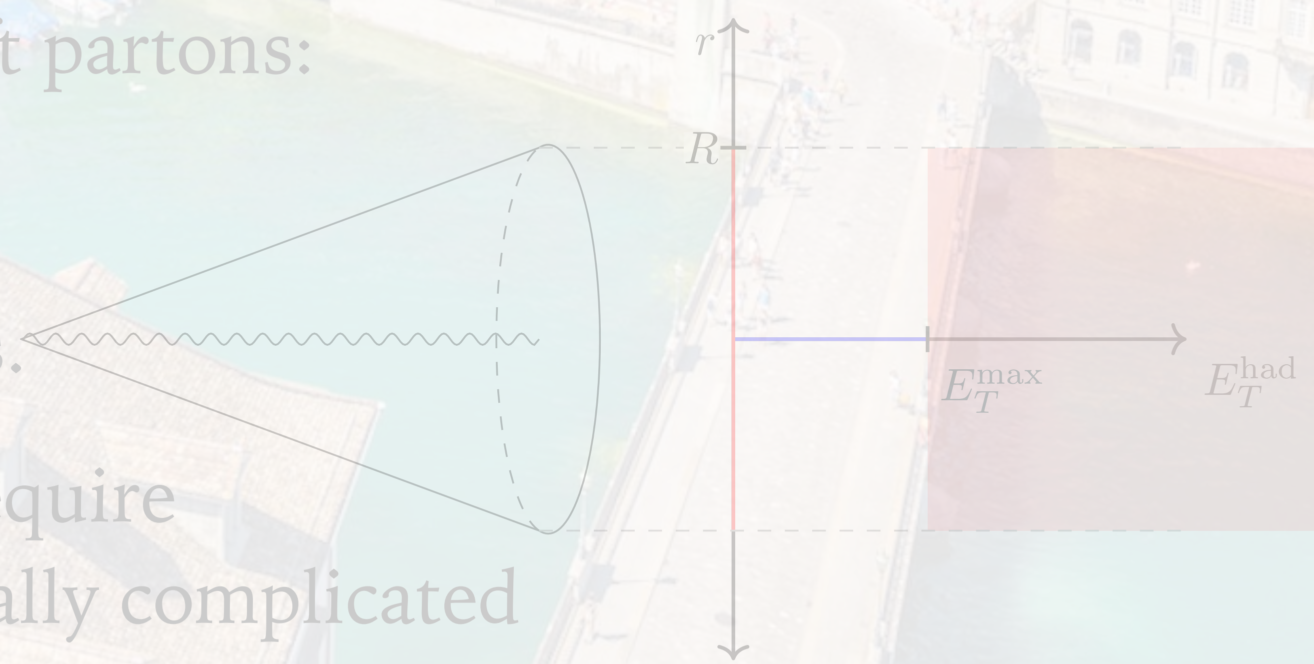
- Naive isolation:
  - No parton allowed within R:

$$E_T^{had} = E_T^{max} = 0$$



  - Theory: not IR safe for soft gluon radiation.
  - EXP: not feasible for absolute zero energy in ECAL.
- Fixed cone isolation
  - Apply threshold energy to allow soft partons:

$$E_T^{had} < E_T^{max} = \epsilon E_T^{\gamma} + E_T^{thres}$$



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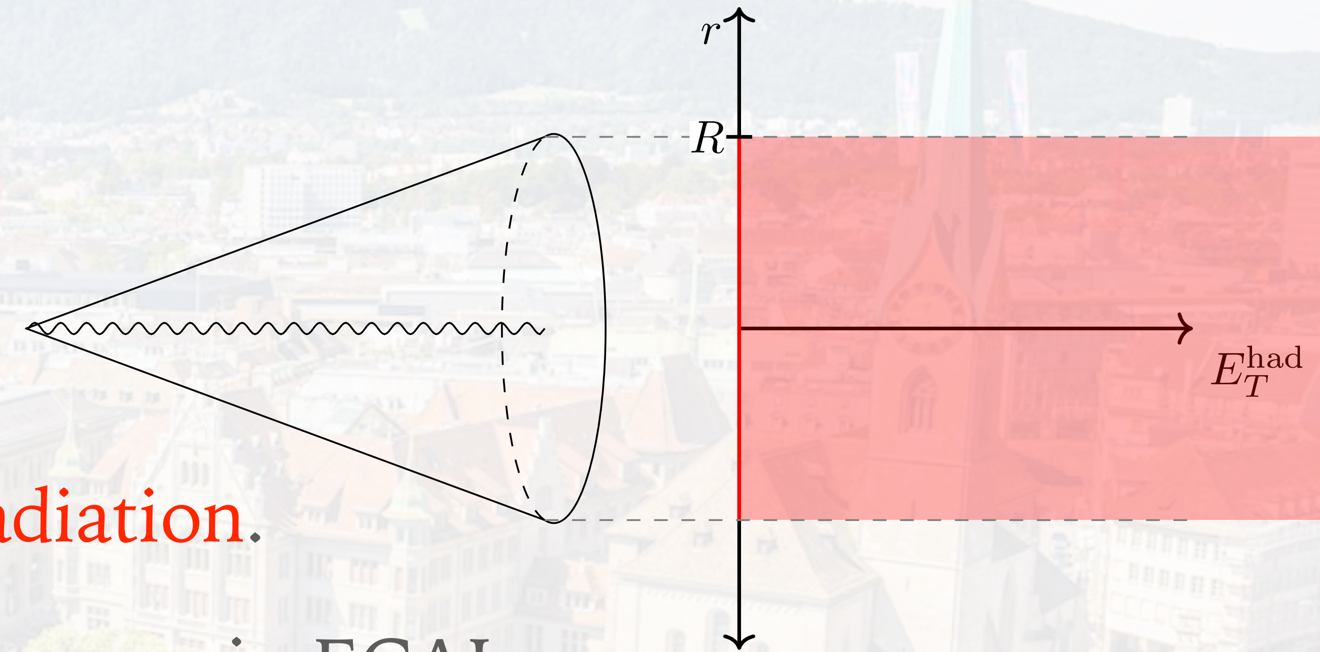

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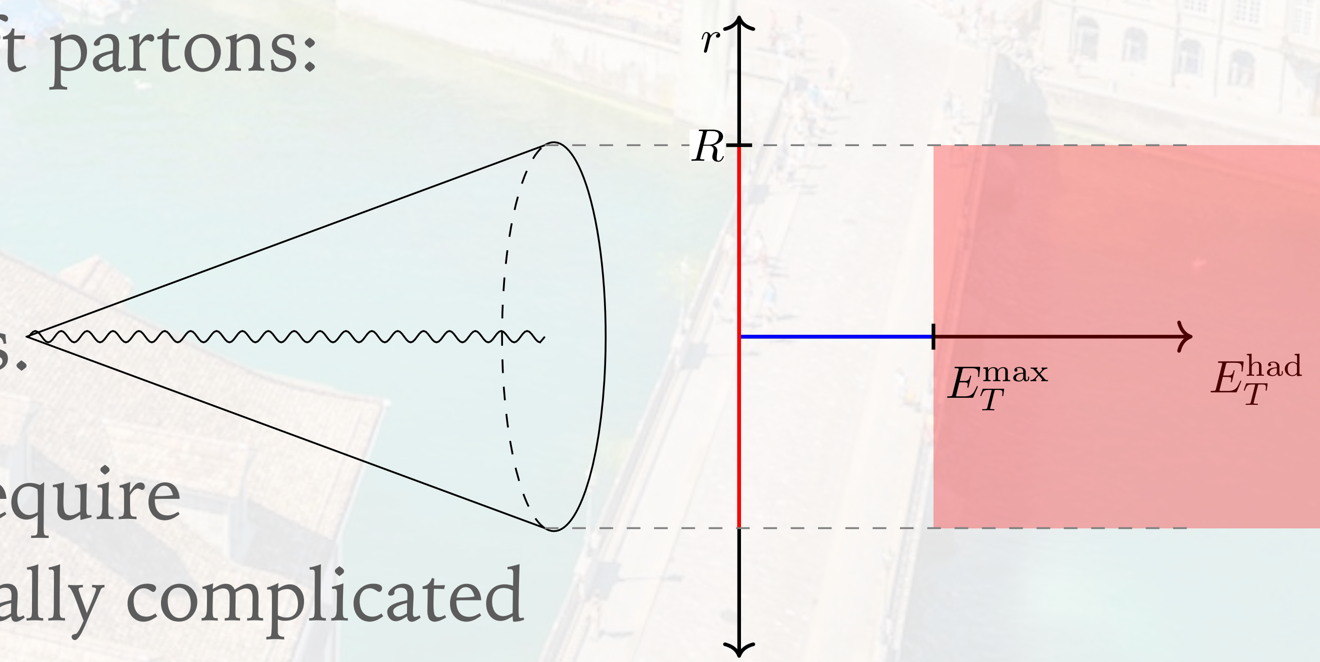

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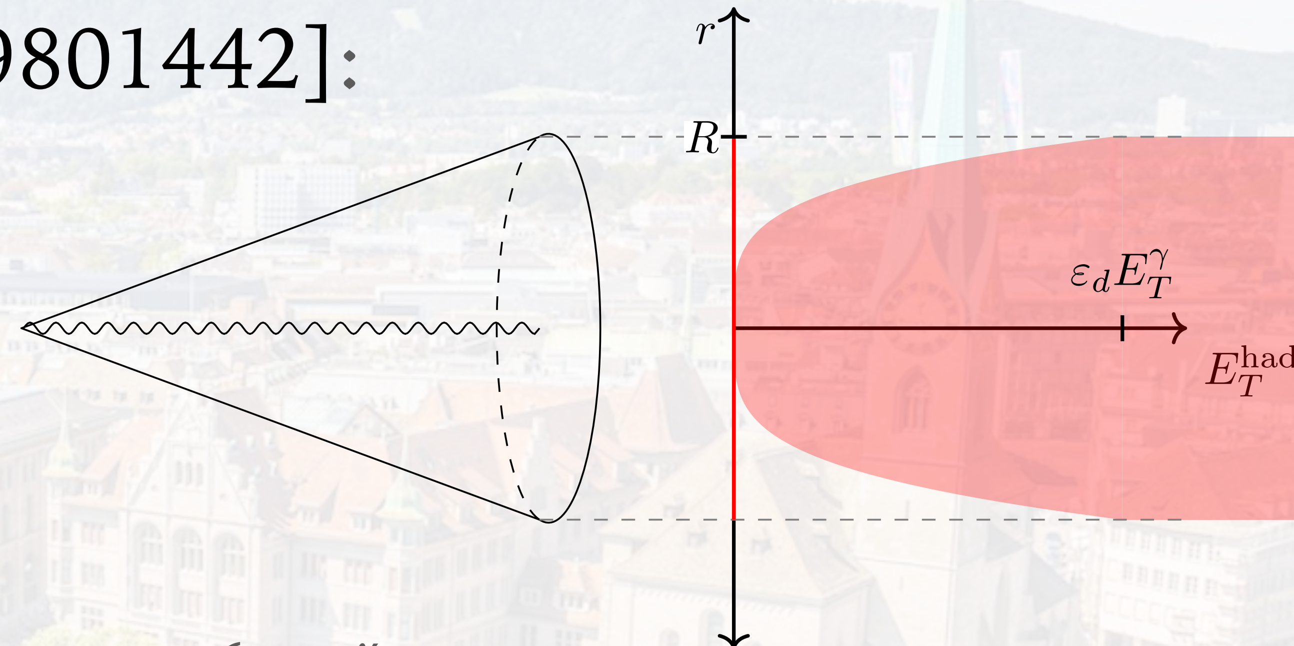
PHOTON ISOLATION

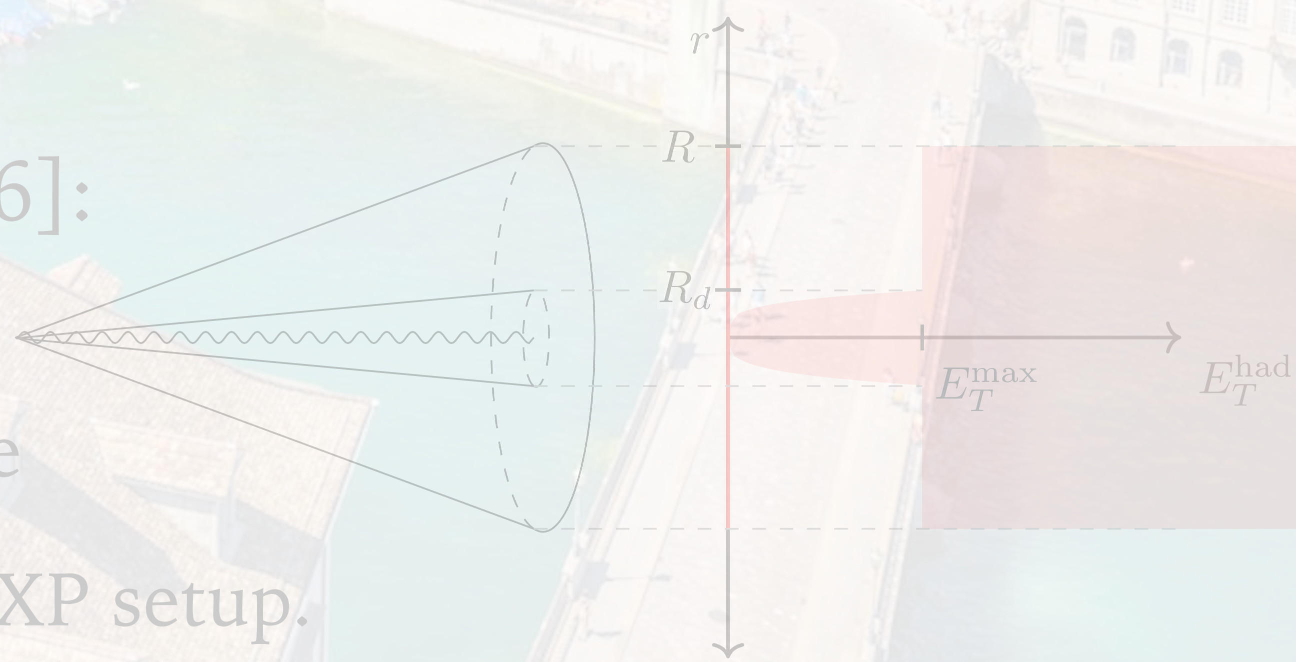
- Dynamic cone isolation [hep-ph/9801442]:
  - Cone-dependent threshold energy :
    For $0 < r_d < R$:

$$E_T^{had} < E_T^{max}(r_d) = \epsilon_d E_T^{\gamma} \left(\frac{1 - cos(r_d)}{1 - cos(R)} \right)^n$$



  - IR safe and fragmentation free: $E_T^{max}(r_d) = \begin{cases} \epsilon_d E_T^{\gamma} & (r_d \to R) \\ 0 & (r_d \to 0) \end{cases}$
  - Adjust ϵ_d, n to approximate mismatched region between fixed and dynamic cone isolation.

- Hybrid cone isolation [1611.07226]:
  - Small dynamical cone of R_d to eliminate fragmentation dependence
  - Fixed cone with $R^2 \gg R_d^2$ to mimic EXP setup.



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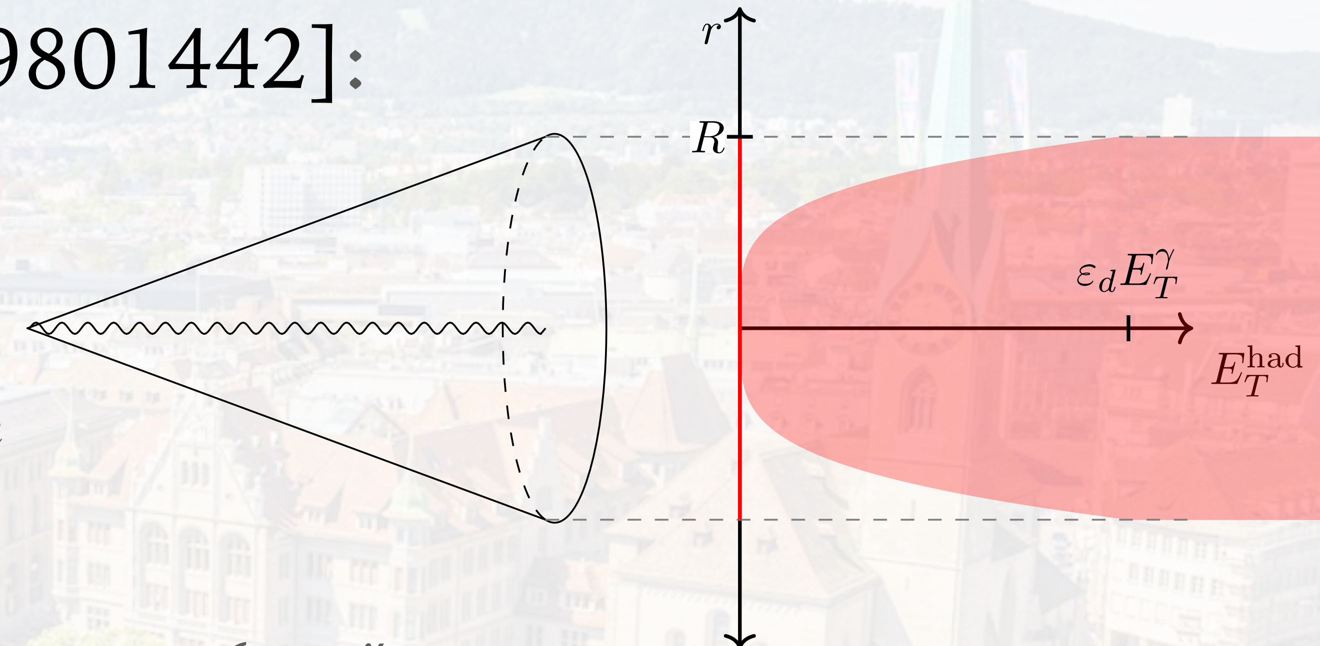

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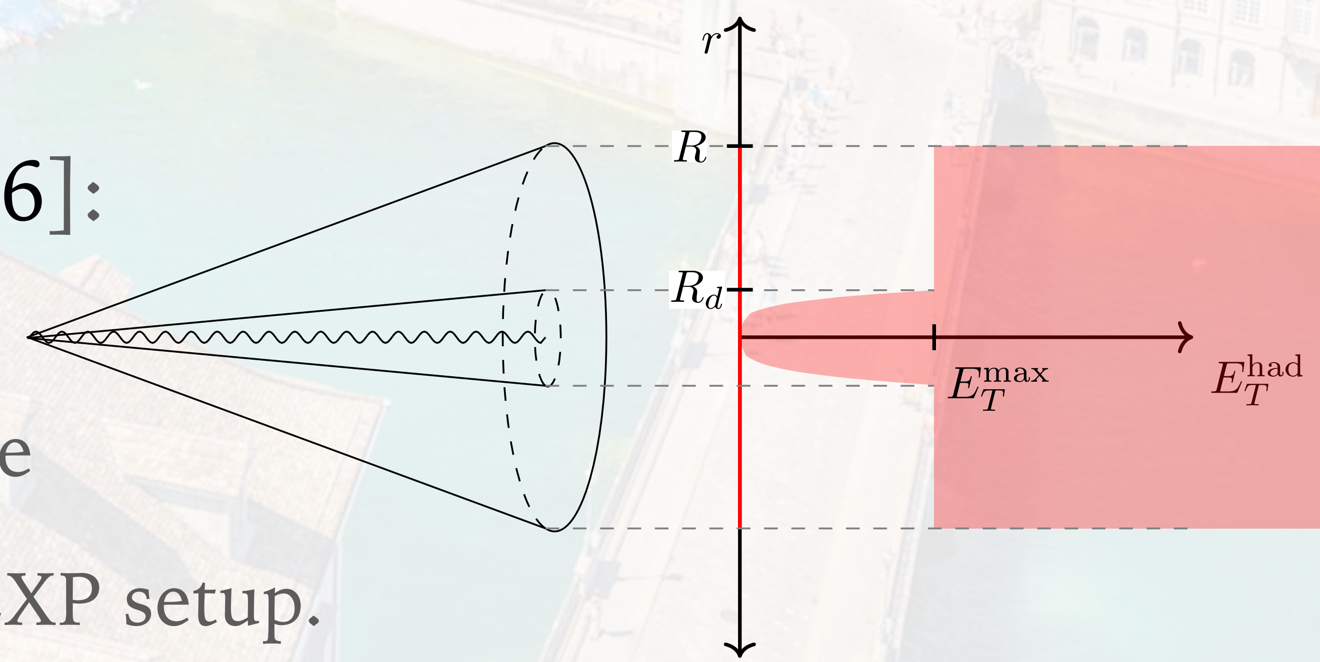

γ+ JET @ NNLO IN NNLOJET

XC, T. Gehrmann, N. Glover, M. Höfer, A. Huss

- NNLO QCD framework for γ + jet
  - Implementation of fixed/dynamic/hybrid (default) cone isolation algorithms
  - Implementation of matrix elements (MEs) up to NNLO in analytic form
    - Tree and 1-loop MEs numerically validated against OpenLoops [1111.5206]
    - 2-loop MEs based on di-jet colour-sub-leading amplitudes [hep-ph/0101304, hep-ph/0304168]
    - NLO cross sections for $\gamma + J$ and $\gamma + JJ$ validated against SHERPA [1611.07226, 0811.4622, 1207.5030]
  - Antenna subtraction terms based on $Z + J$ @ NNLO [1507.02850, 1605.04295]
- Parton-level event generator
  - Dynamical scale choices: $E_T^\gamma, H_T^{jet}, H_T^{parton}$
  - Flexible fiducial selection criterion: $p_T^\gamma, p_T^j, y^\gamma, y^j, R^{\gamma j}, m^{\gamma j}$

COMPARE WITH 13 TEV DATA

- Available measurements at 13 TeV:

ATLAS	$pp \to \gamma + X$	$3.2\ \text{fb}^{-1}$	[1701.06882]
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CMS	$pp \to \gamma + X\ /\ \gamma + j$	$2.26\ \text{fb}^{-1}$	[1807.00782]

- Fiducial selection criterion in [1801.00112]:
  - Jets algorithm: anti-kT jet $R^j = 0.4,\ \ p_T^j > 100\ GeV,\ \ |y^j| > 2.37,\ \ N_j \geq 1$
  - Photon isolation (fixed): $R = 0.4,\ \ E_T^{had} < E_T^{max} = 4.2 \times 10^{-3} E_T^{\gamma} + 10$ GeV
  - Photon fiducial: $p_T^{\gamma} > 125\ GeV,\ \ |y^{\gamma}| < 1.37\ or\ 1.56 < |y^{\gamma}| < 2.36,\ \ R^{\gamma j} > 0.8$
- Additional setup in NNLOJET [1904.01044]:
  - Photon isolation (hybrid): $R_d = 0.1,\ \ \epsilon_d = 0.1,\ \ n = 2$
  - PDF set: NNPDF3.1 [1706.00428] and NNPDF3.0 [1401.8849]
  - Central scale of $\mu_R = \mu_F = p_T^{\gamma}$ with 7-point scale variations

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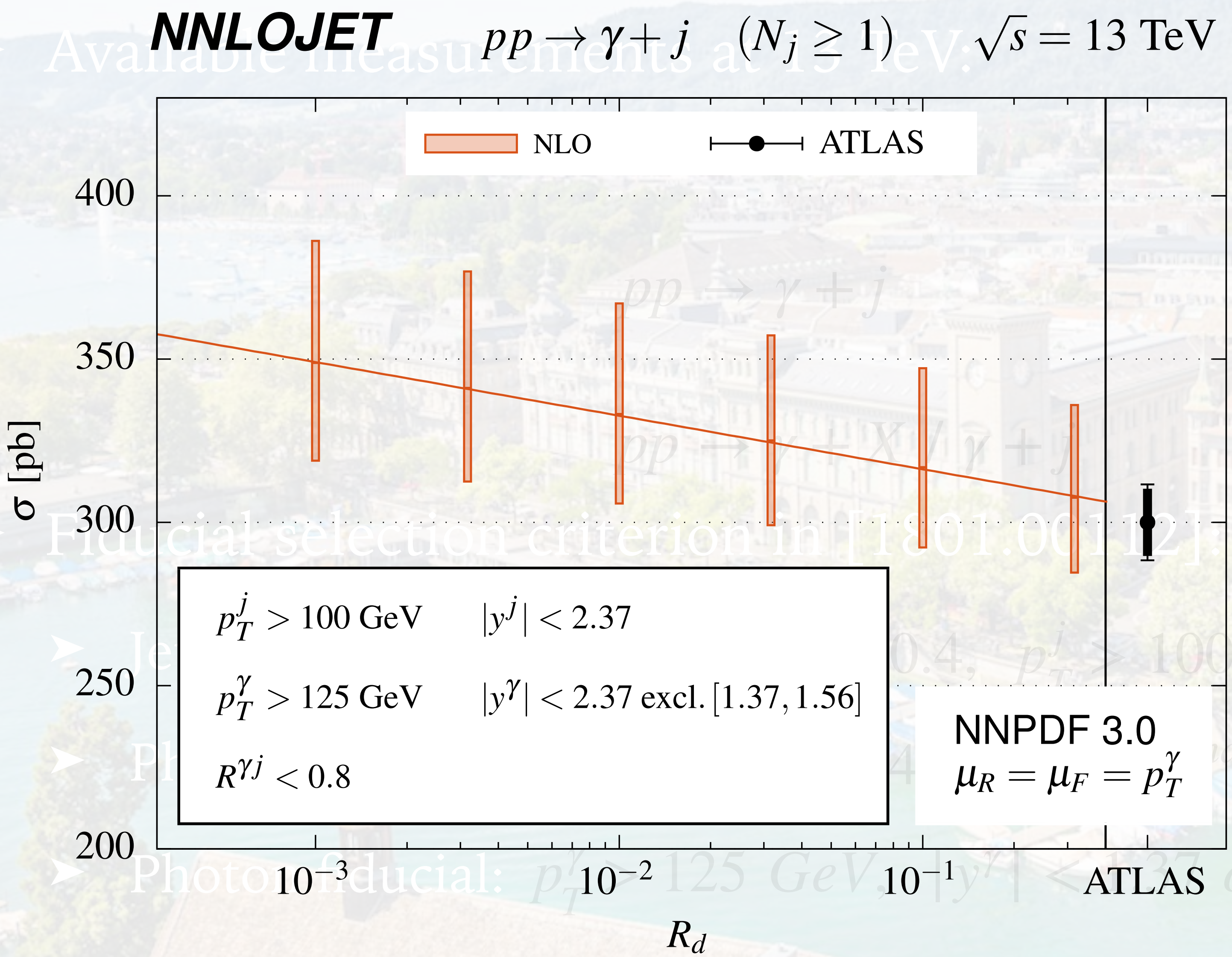

- Current choices of R_d, ϵ_d, n
  - Values recommended in ATLAS at matrix-element level
  - Need more analysis from both EXP and Theory for various isolation setups.
- Constrain of R_d
  - Match EXP choice: $R_d^2 \ll R^2$
  - From NLO: [hep-ph/0204023]

    $\sigma \sim \log(1/R_d),\ R_d \to 0$
  - Neither too small nor too large

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- Compare ATLAS differential distributions at 13 TeV [1801.00112]:
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  - $|cos(\theta^*)|$

$$\left(cos(\theta^*) = tanh\frac{\Delta y^{\gamma j}}{2} \right)$$

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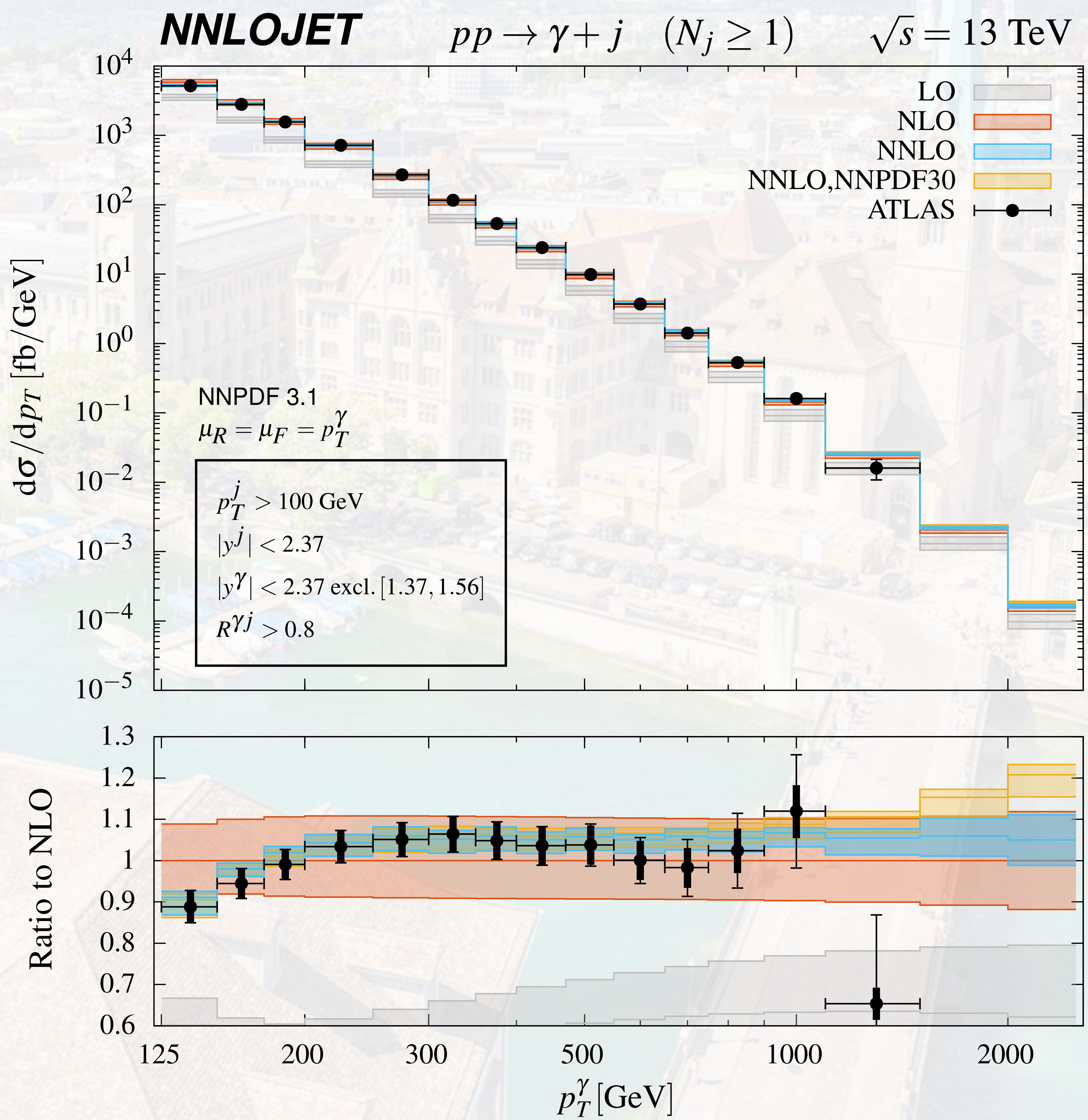

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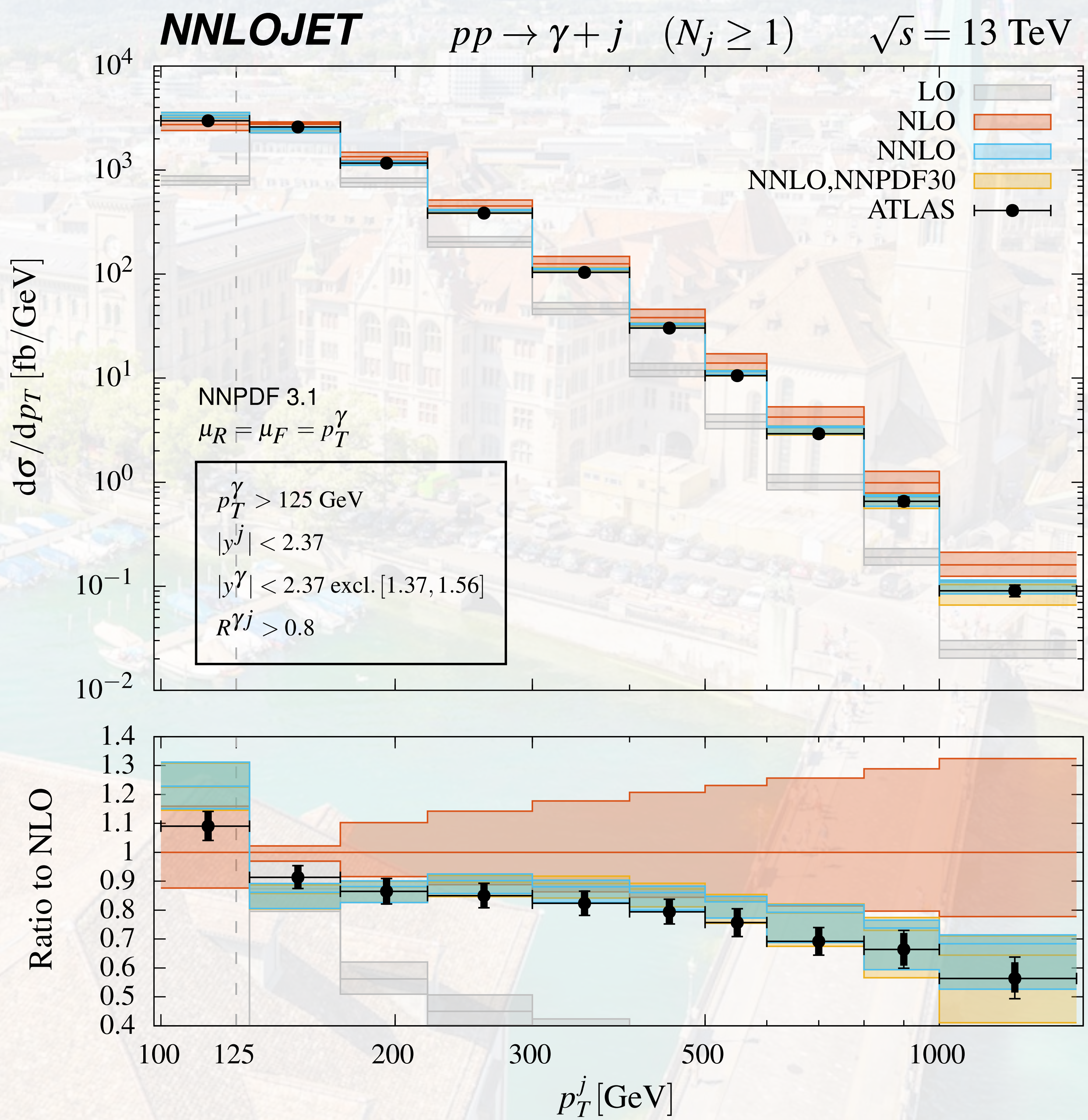

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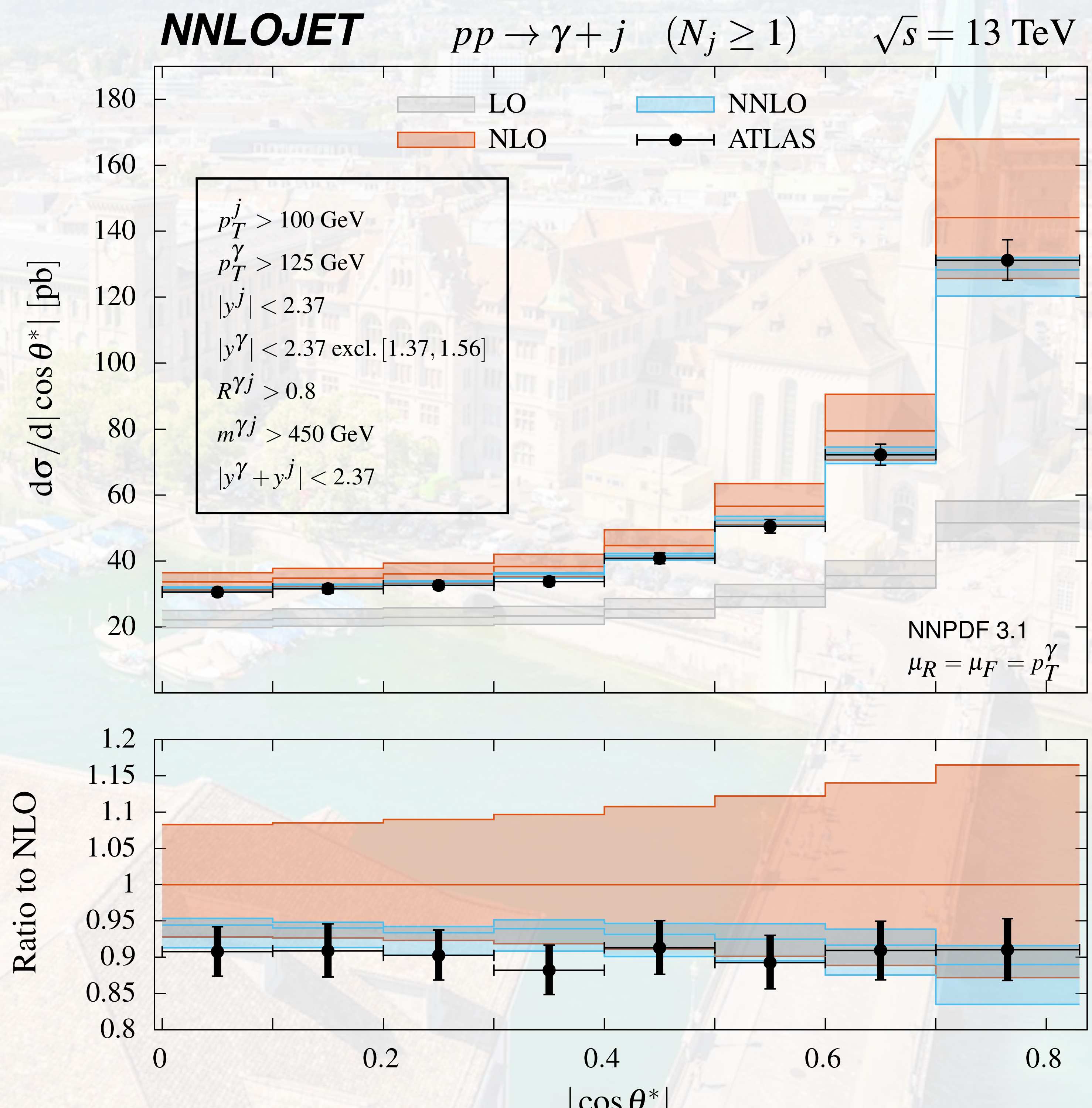

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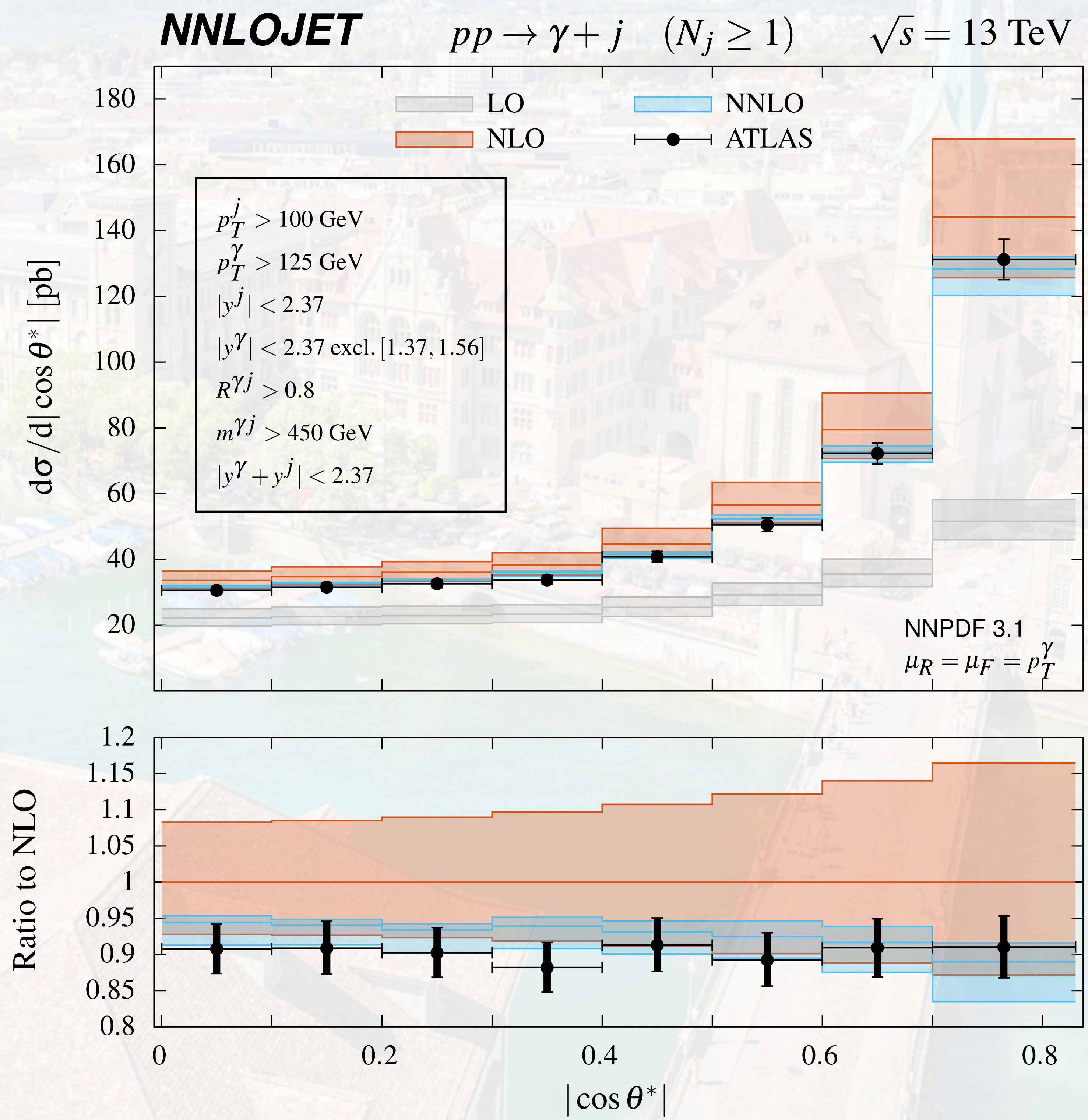

CONCLUSION AND OUTLOOK

- Independent NNLO calculation for isolated photon and photon+jet production at the LHC.
- Hybrid cone isolation gives more realistic description of isolated photon in LHC measurements.
- NNLO QCD corrections reduce theory uncertainties and agree better with data (both normalisation and shape).

- Other important correction to be included: EW corrections ✓, threshold resummation ⊗, Sudakov resummation ⊗, small R_d resummation ⊗
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Thank You for Your Attention

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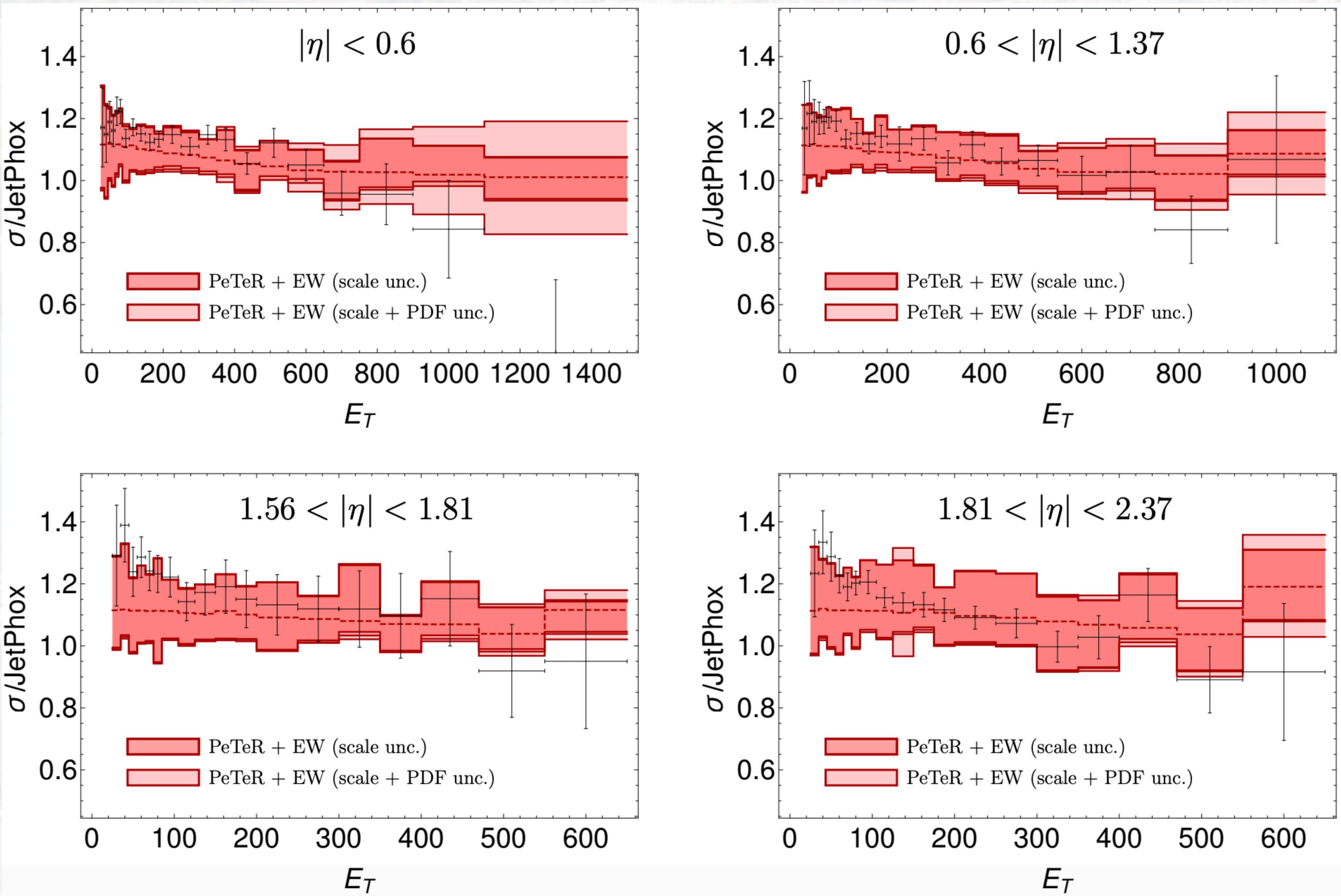

PeTeR [1606.02313]:

NLO QCD

NLO fragmentation

N3LL Thres-resummation

LL EW-resummation

Normalised to JetPhox:

[hep-ph/0204023]

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