J/ψ production at NLO with a scale-dependent Color Evaporation Model

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in collaboration with

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Quarkonia production

Color-evaporation model (CEM); 1977; Fritzsch, Halzen:

Numerous non-perturbative gluon emissions $\Rightarrow$ quantum states of the $Q\bar{Q}$ pair and the quarkonium H can be different

Color-singlet model (CSM); $\sim$1980; Chang, Berger and Jones, Baier and Ruckl:

Quantum state of the pair does not evolve between its production and its hadronisation.

Color-octet mechanism (COM) **and NRQCD** 1997; Bodwin, Braaten, and Lepage.

Takes into account CS and CO $Q\bar{Q}$ states:

$$\sigma^H = \sum_{Q\bar{Q}(n)} \hat{\sigma}[Q\bar{Q}(n)]\langle 0|\mathscr{O}^H_{Q\bar{Q}(n)}|0\rangle$$

- All based on a factorization hypothesis.

The color evaporation model

Several interesting features:

- Simple implementation and only one non-perturbative parameter.
- Relatively good description of data (in particular for integrated cross sections).

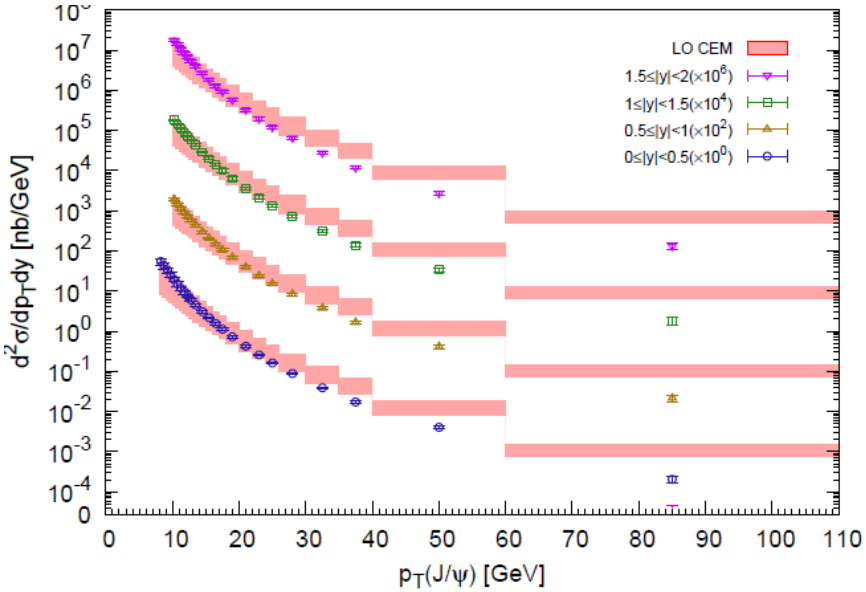
$$\frac{d\sigma}{dp_t} = F_{J/\psi} \int_{2m_c}^{2m_{D^0}} \frac{d\sigma^{Q\bar{Q}}}{dm_{Q\bar{Q}} dp_t} dm_{Q\bar{Q}}$$

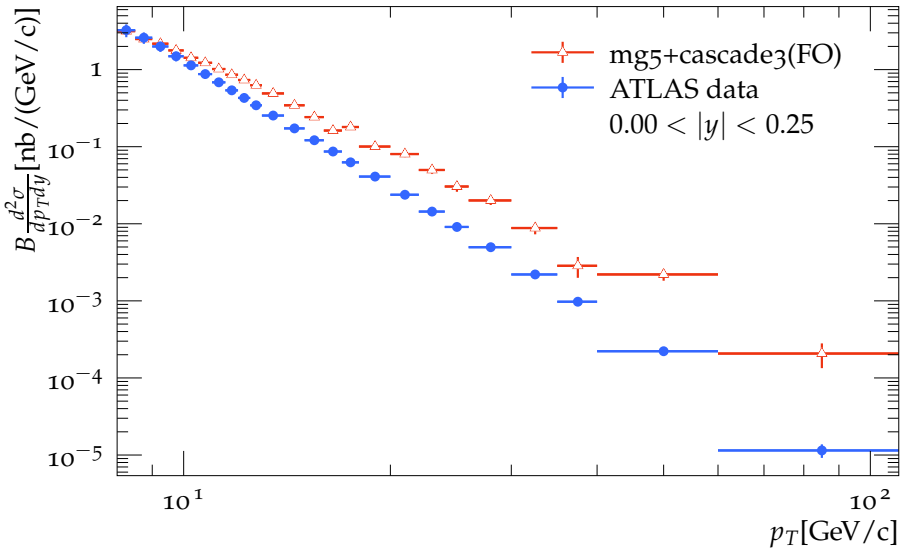
Improved CEM (*Y.-Q. Ma and R. Vogt, PRD 94 (2016) 11 114029*):

$$\frac{d\sigma}{d^3p} = F_{J/\psi} \int_{m_{J/\psi}}^{2m_{D^0}} \frac{d\sigma^{Q\bar{Q}}}{dm_{Q\bar{Q}} dp^3_{Q\bar{Q}}} \delta^3 \left(p - \frac{m_{J/\psi}}{m_{Q\bar{Q}}} p_{Q\bar{Q}} \right) dm_{Q\bar{Q}},$$

The improved CEM gives better results for ratios of quarkonia.

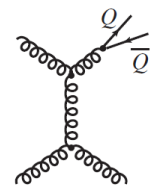
However... CEM at NLO





Lansberg, Phys.Rept. 889 (2020) 1-106

Main issue: Spectrum too hard. Due to some NLO contributions $gg \to gQ\bar{Q}$ scaling as $1/p_t^4$.



Our main goals:

1. Solve this issue.
2. Compare with LO results obtained with the k_t-factorization $\to$ discussion of the formalism.

Proposed solution

- Include the dependence on μ ($Q\bar{Q}$ evolution):

$$d\hat{\sigma}_{ab\to Q\bar{Q}}(x_1 x_2 s, q_t; \mu) \otimes d_{Q\bar{Q}}(\mu, \mu_0) \otimes D^{\text{CEM}}_{Q\bar{Q}\to J/\psi}(\mu_0)$$

Discussed by Kang, Lee, Ma, Qiu, Sterman and Watanabe in the framework of NRQCD.

Interests of our work:

- CEM = useful model. It would be nice if it worked better for p_t distributions.
- Estimation of the impact of the FF evolution with μ.
- Discussion on different k_t-factorization formalisms.

Our framework

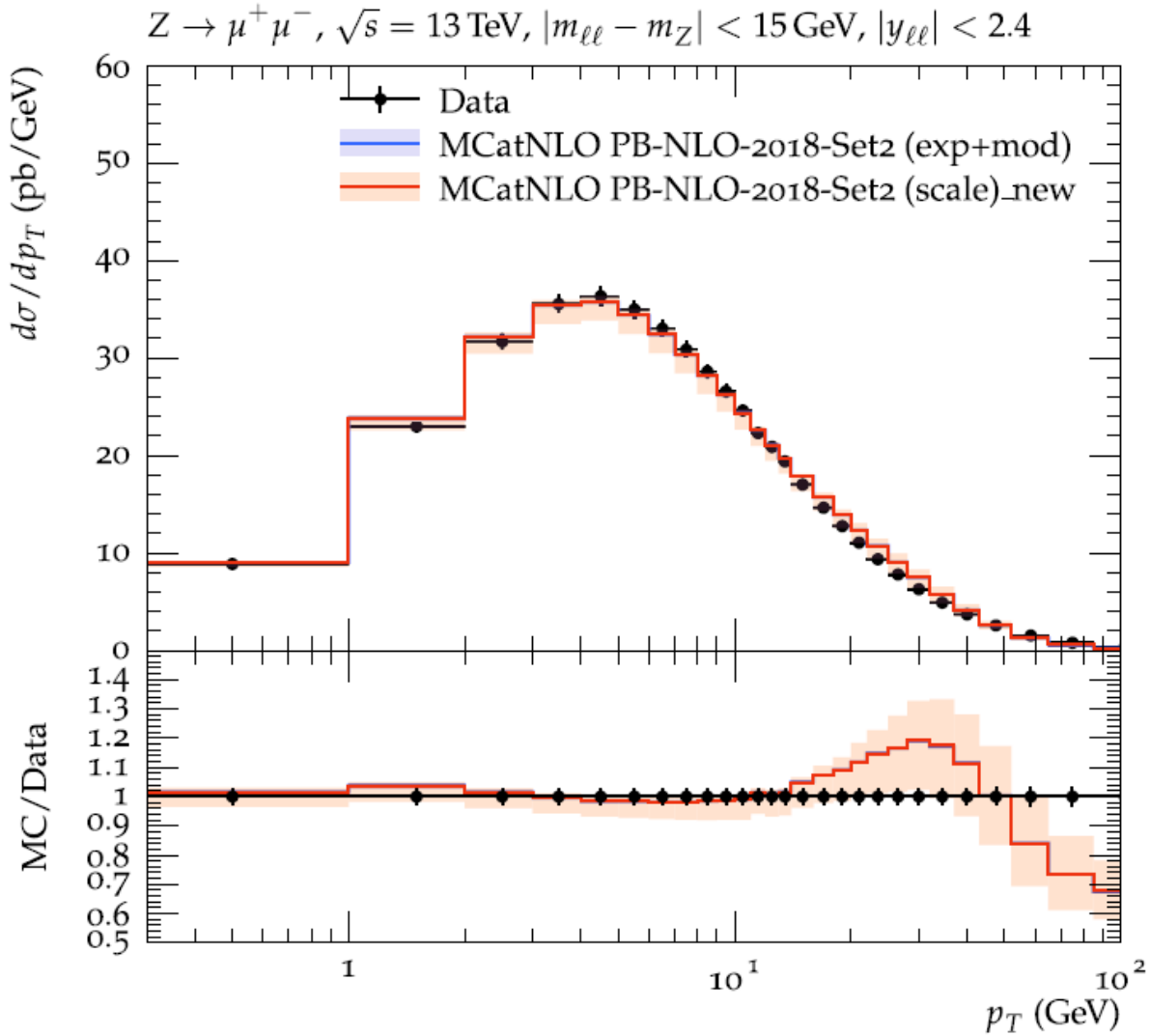
$$\frac{d\sigma(pp \to J/\psi + X)}{dx_1 dx_2 d^2p_t}(s, x_1, x_2, p_t) = \sum_{a,b} \int d^2k_{1t} d^2k_{2t} F_{a/p}(x_1, k_{1t}; \mu)$$

$$\times F_{b/p}(x_2, k_{2t}; \mu) d\hat{\sigma}_{ab\to Q\bar{Q}}(x_1 x_2 s, q_t; \mu) \otimes d_{Q\bar{Q}}(\mu, \mu_0, z) \otimes D^{\text{CEM}}_{Q\bar{Q}\to J/\psi}(\mu_0)$$

1. $pp \to c\bar{c} + X$ at NLO: Madgraph5_aMC@NLO and Parton-Branching (PB) UPDFs (through CASCADE3). *$\hat{\sigma}_{ab\to Q\bar{Q}}$ includes only part of the LP contributions scaling as $1/p_t^4$ $\to$ affects the value of $F_{J/\psi}$.*
2. $Q\bar{Q}$ evolution: Timelike parton shower with PYTHIA6. Initial scale $\mu_i = \mu = m_t$. *c and $\bar{c}$ evolved independently (approximate evolution).*
3. CEM applied at scale $\sim m_{J/\psi}$. We use $F_{J/\psi} = 0.014$, *Lansberg, Phys.Rept. 889 (2020) 1-106 (madgraph used in this paper).*

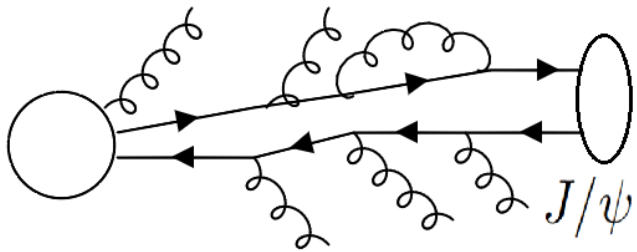
Our framework

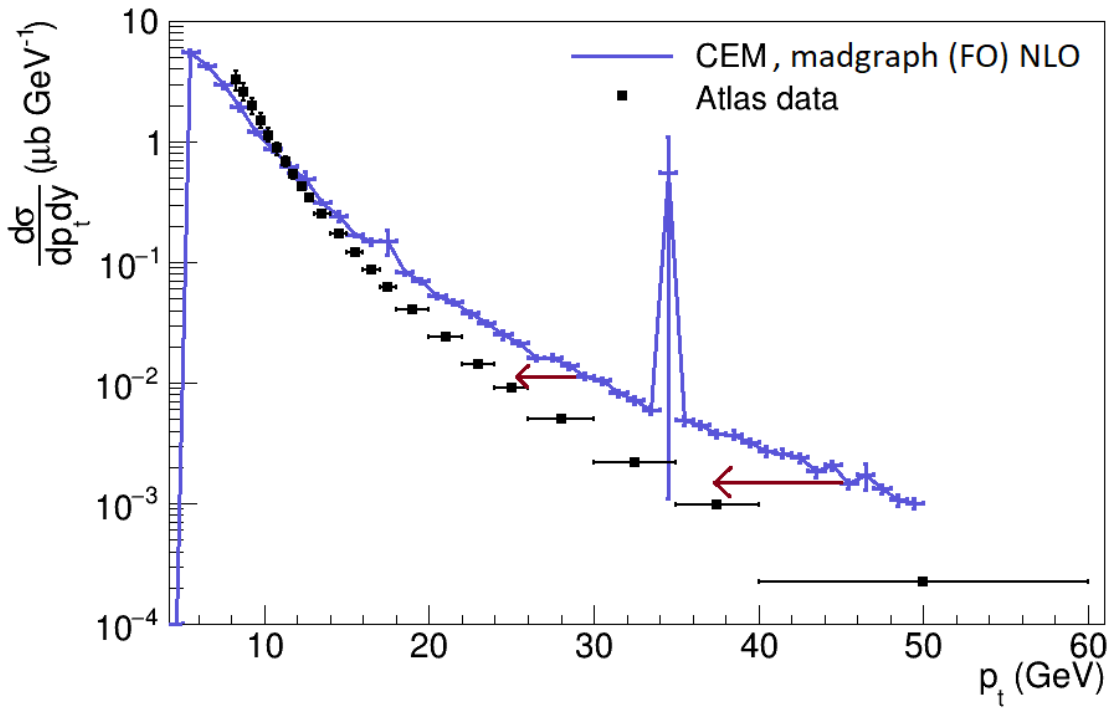
Used for Drell-Yan data, *Bermudez Martinez et al., Eur. Phys. J. C (2020) 80:598.*



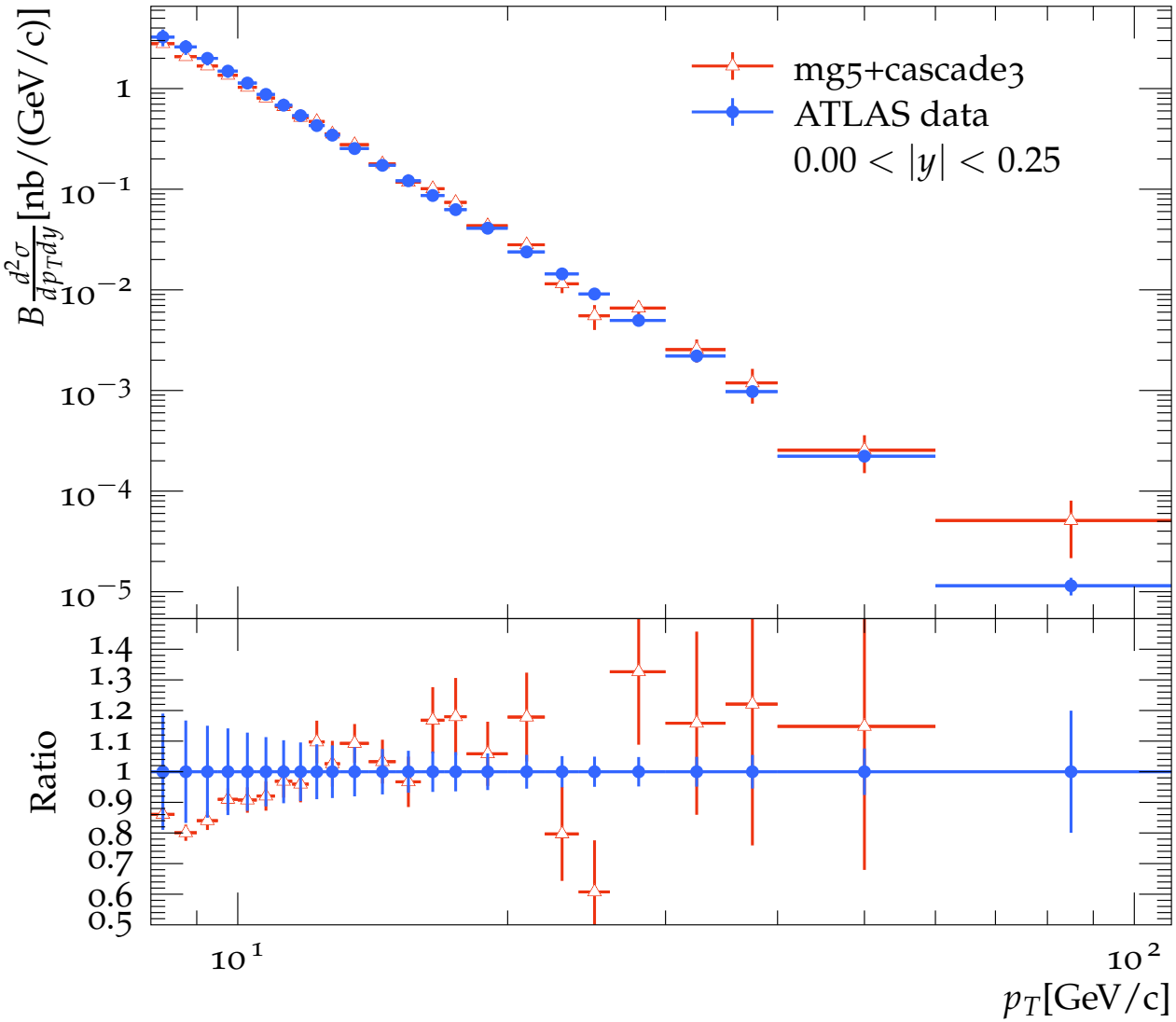
Consequences of the evolution

- Mixing of color-singlet and color-octet states.
- Vacuum energy loss: Higher $p_t \Rightarrow$ longuer cascade $\Rightarrow$ larger shift of p_t. $1/p_t^4 \to m_Q^2/p_t^4\mu^2$.





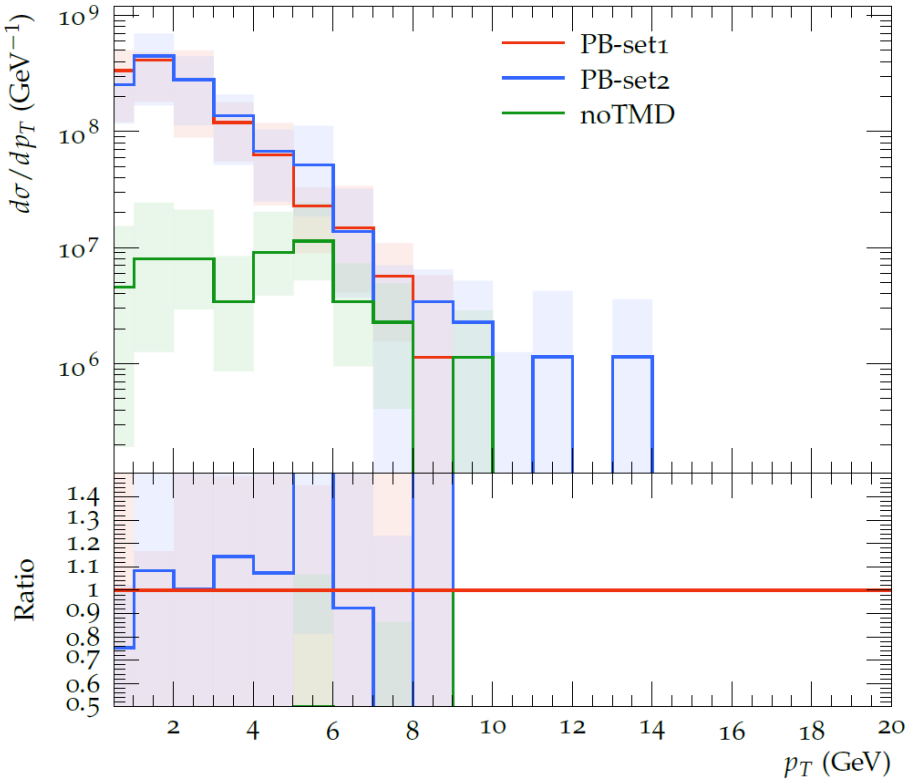
Results at large p_t: ATLAS, 8 TeV



Effect of the Parton Branching UPDFs negligible at large p_t.

Small and intermediate p_t

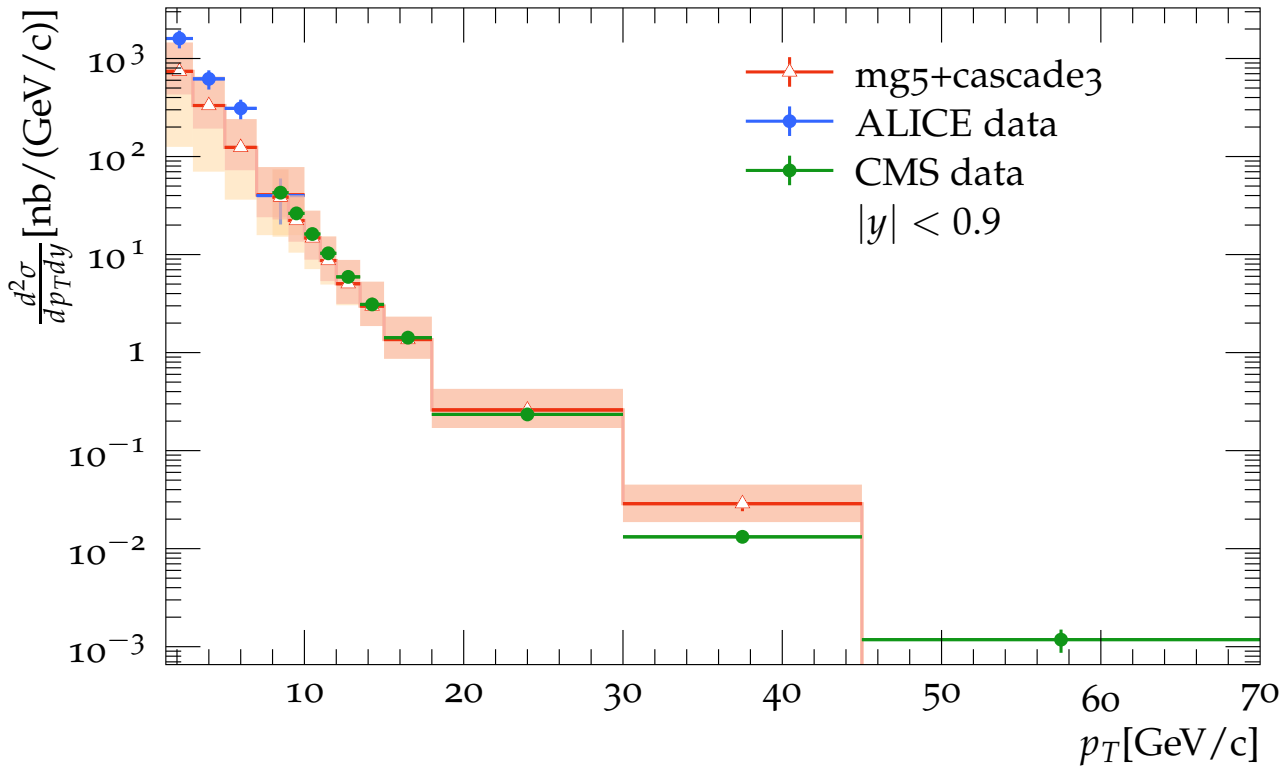
Kinematical region where the intial transverse momentum does matter.



- LO contributions with $k_t = 0$ do not contribute $\Rightarrow$ Green line shows NLO contr. only.
- NLO starts to dominate at $p_t \sim 8$ GeV (depends on your UPDFs).

Results at small and intermediate p_t

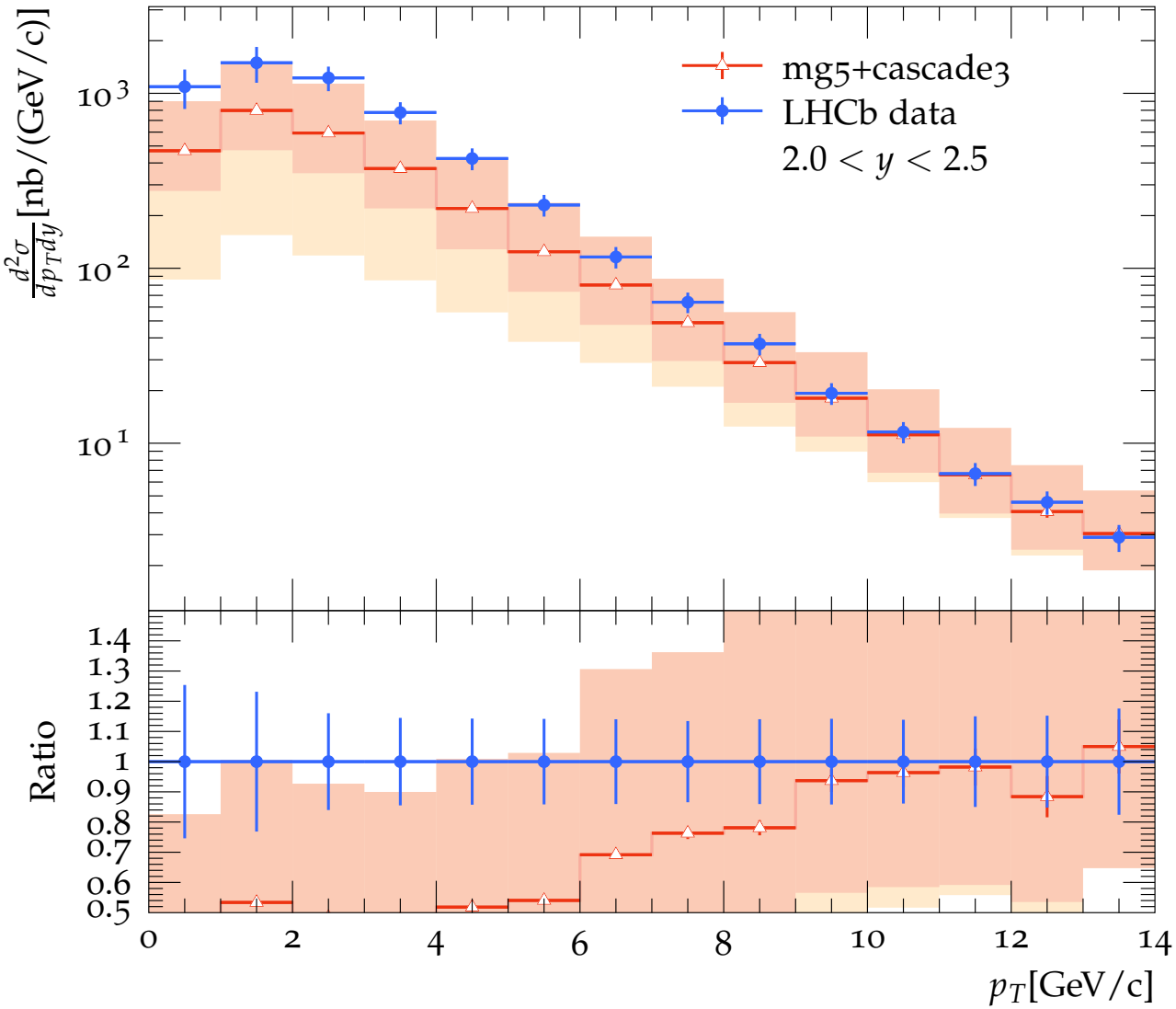
- Theoretical uncertainties obtained by varying the factorization/renormalization scales.



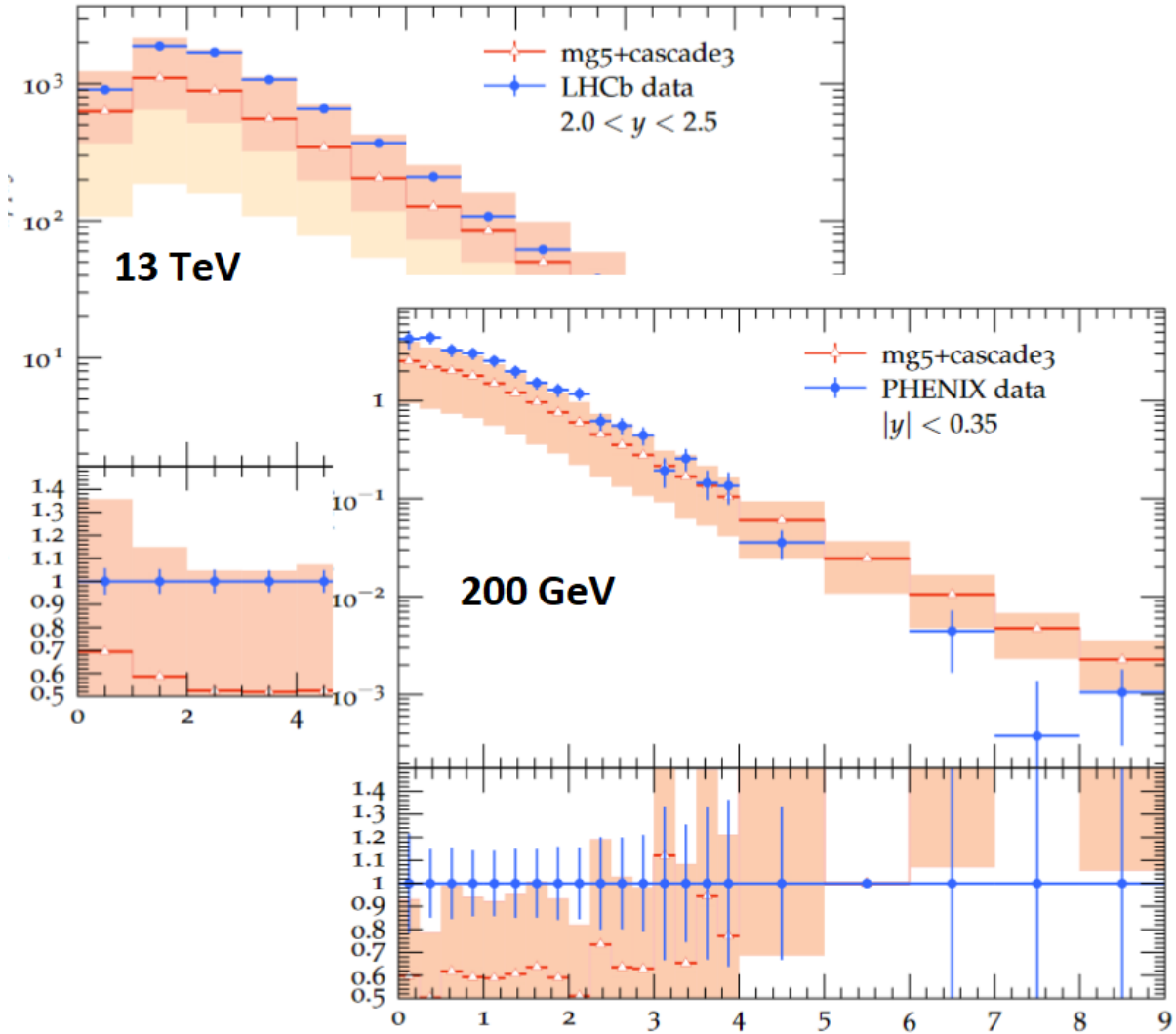
- Our central values underestimate a bit small p_t data (but in agreement within uncertainties).
- Data at 7 TeV.

Results at small and intermediate p_t

- Comparison with LHCb data at 7 TeV: Similar results.



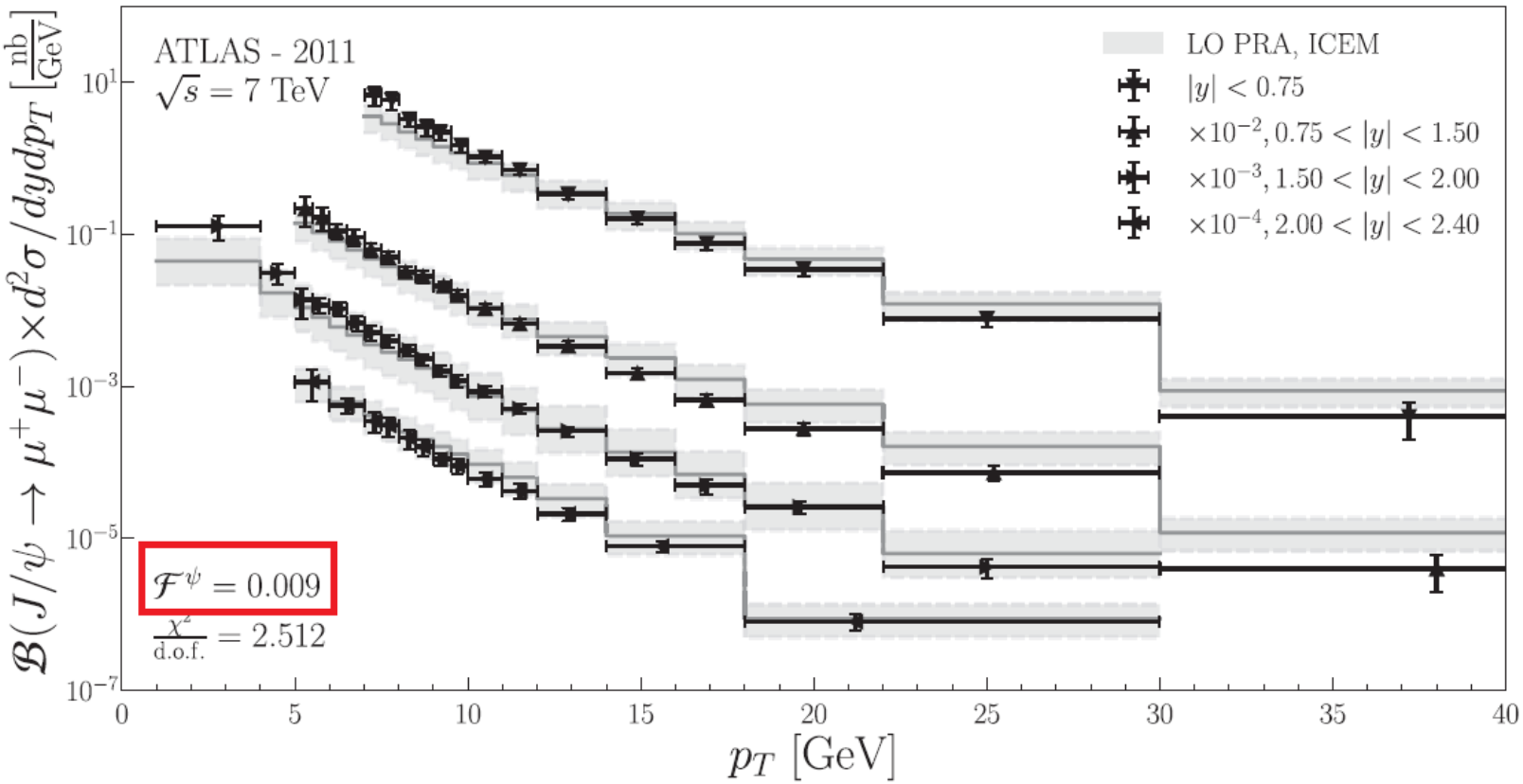
Universality of $F_{J/\psi}$



- All obtained with $F_{J/\psi} = 0.014$. As expected, $F_{J/\psi}$ looks universal.

Discussion on "classical" k_t-factorization calculations

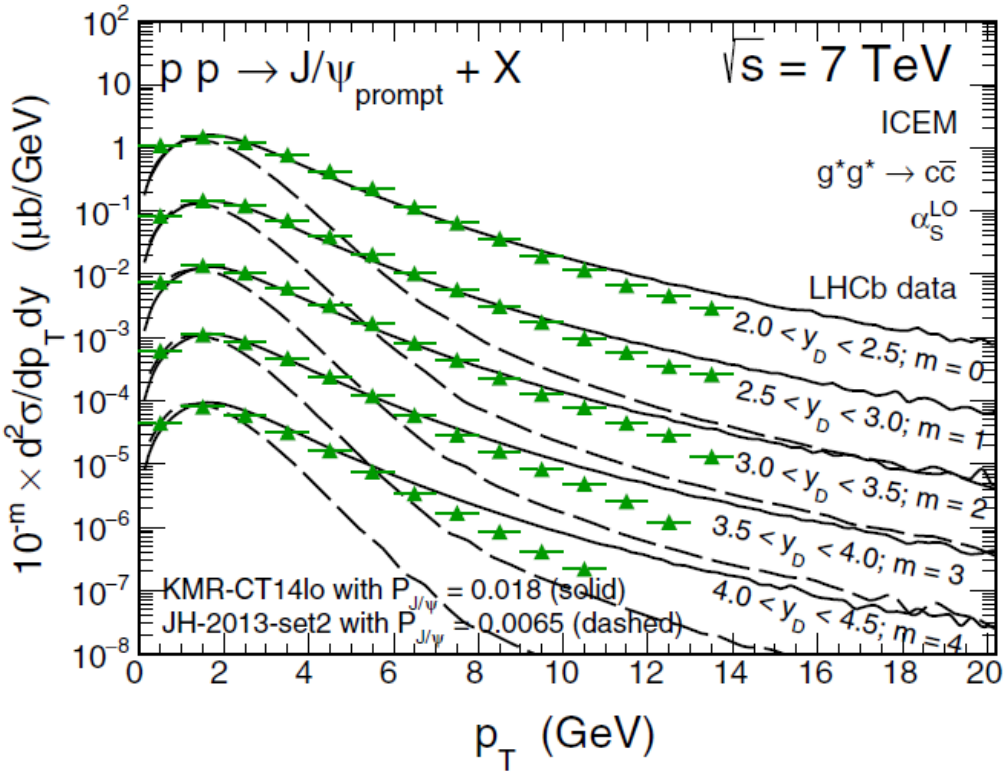
LO calculations with off-shell cross section, KMR UPDFs and the improved CEM: *Chernyshev, Saleev: PRD 106, 114006 (2022)*



- $F_{J/\psi}$ not universal, even in the range $\sqrt{s} \in [0.2, 13]$ TeV.
- Spectrum dictated only by UPDFs: a bit too hard?

Discussion on "classical" k_t-factorization calculations

Maciuła, Szczurek, Cisek, PRD 99 (2019) 054014



- Strong dependence on the choice of UPDFs: inconclusive
- Beyond LO? Matched cross section:
  $\sigma = (\sigma_{\text{HEF}} + \text{sub. of LO CF}) + (\sigma_{\text{collinear}} + \text{sub. small x})$

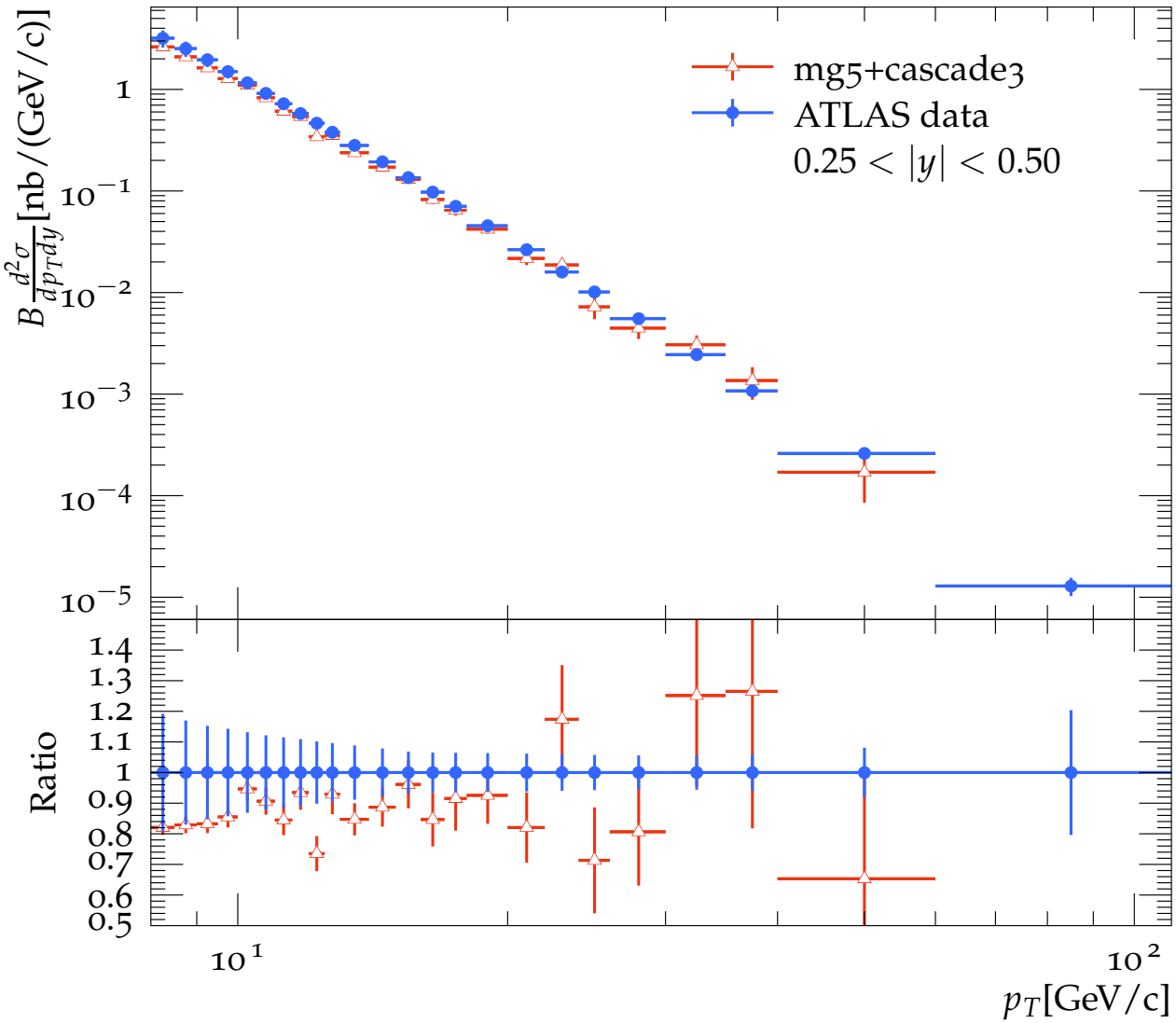
$\Rightarrow$ Large p_t (x not that small) mainly dictated by the NLO $\sigma_{\text{collinear}}$.

Conclusion

- Color Evaporation Model at NLO + scale dependence: Good agreement with data (in particular at moderate and large p_t).
- Strong impact of the evolution: Suggests that a new determination of LDME may be necessary (some of the LDME are negative, leading to negative cross sections).
- Hard to interpret LO k_t-factorization calculations for this observable. Going beyond seems necessary.

Thank you for your attention

Backup: ATLAS data 8 TeV



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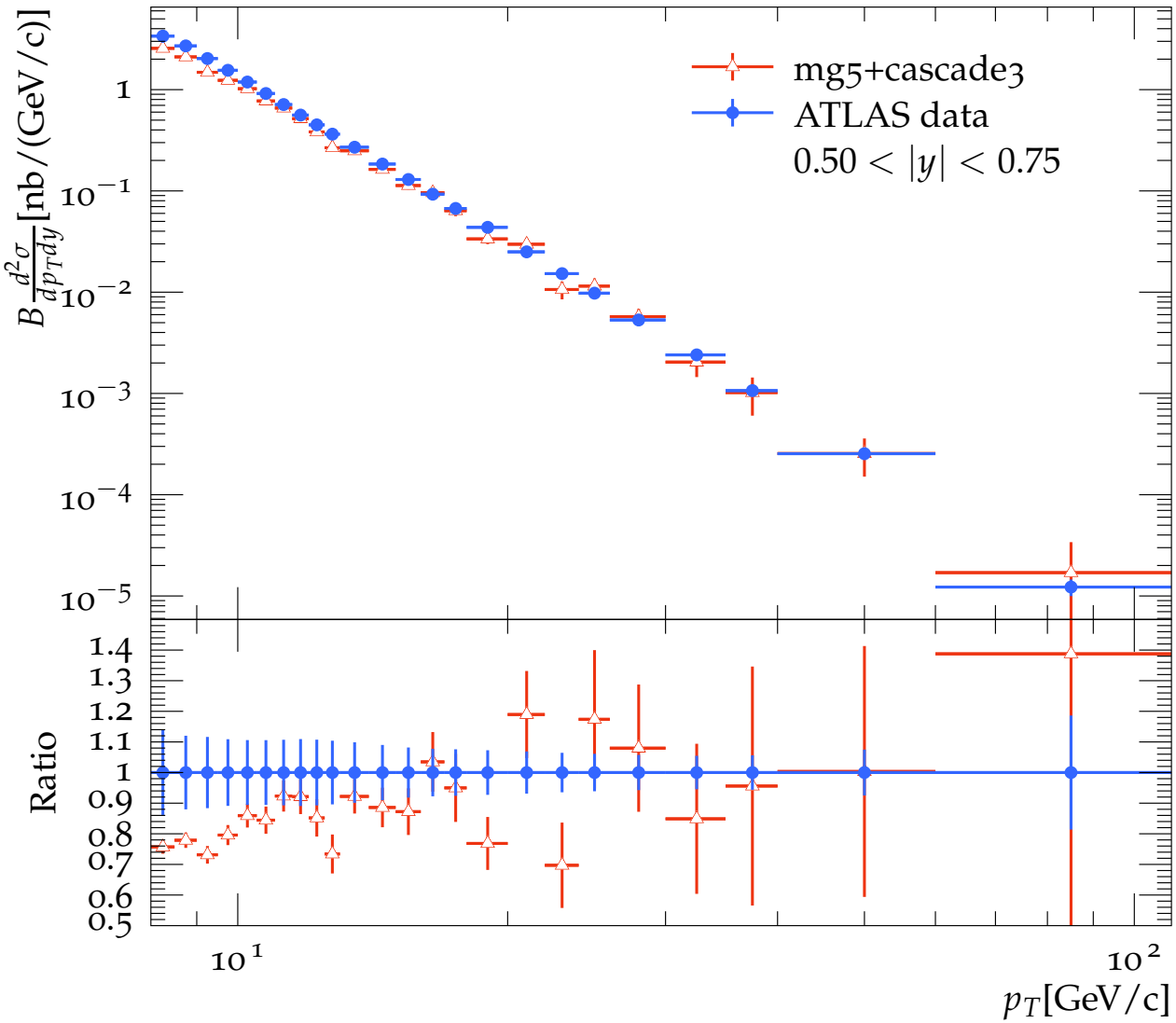

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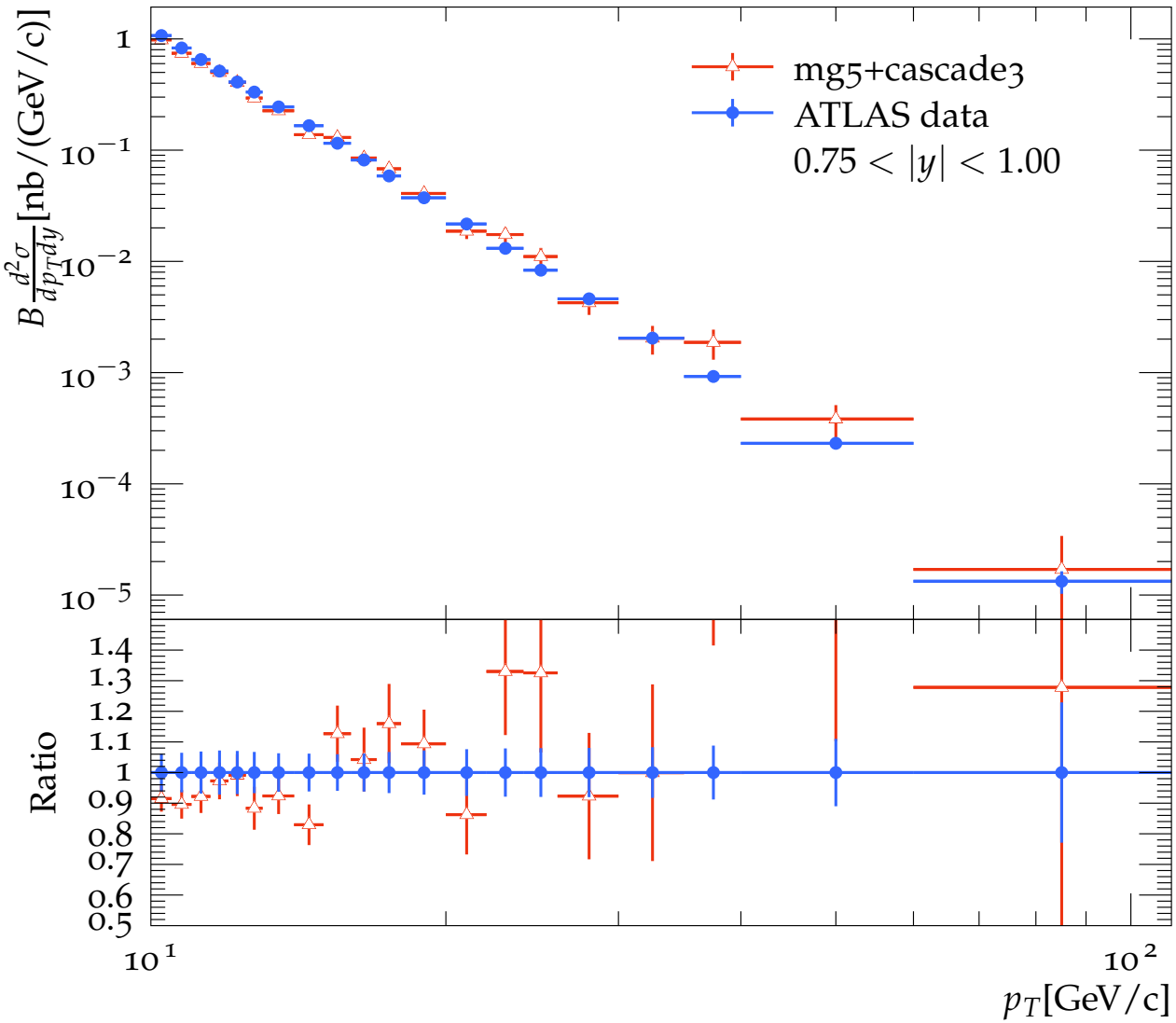

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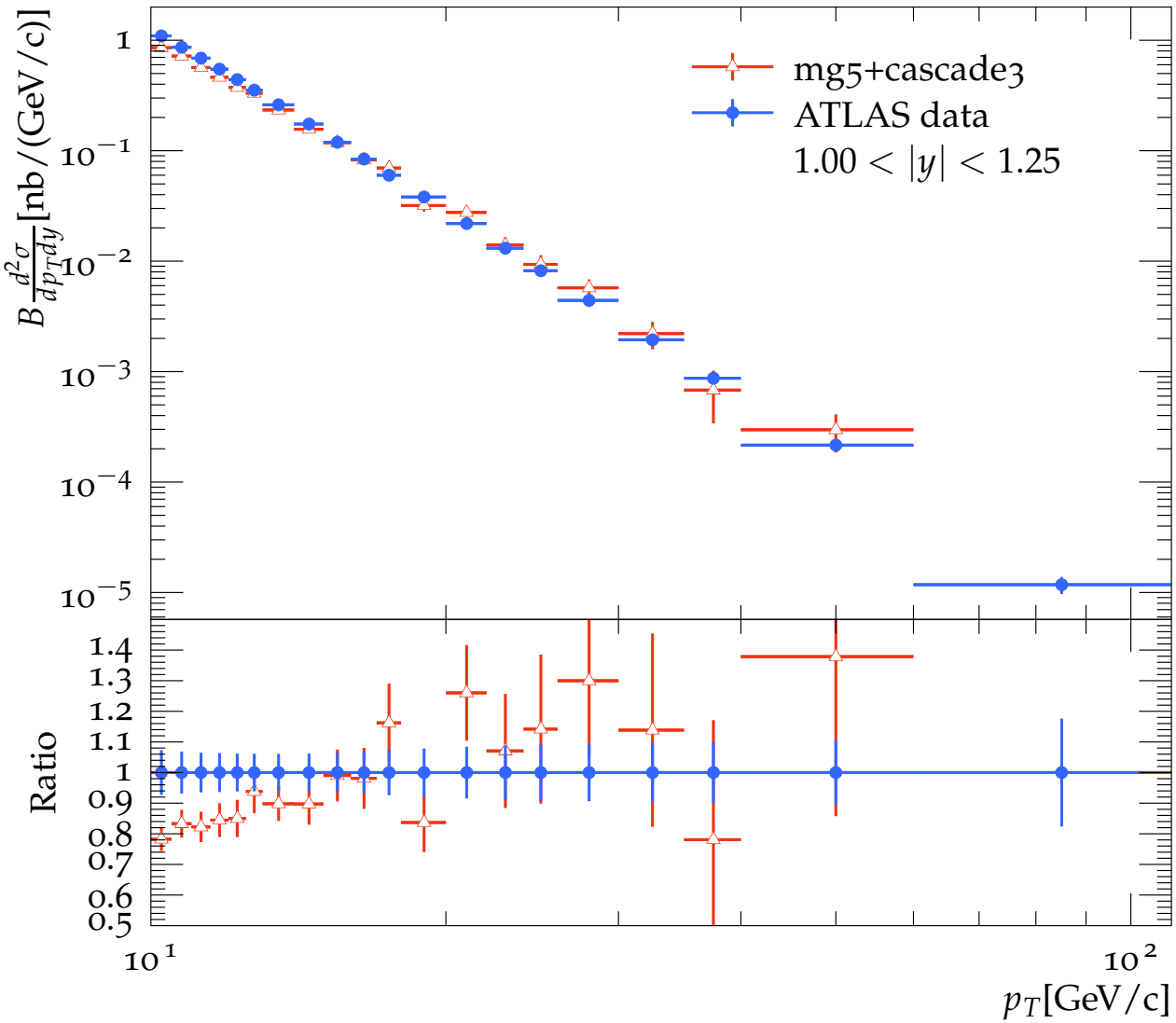

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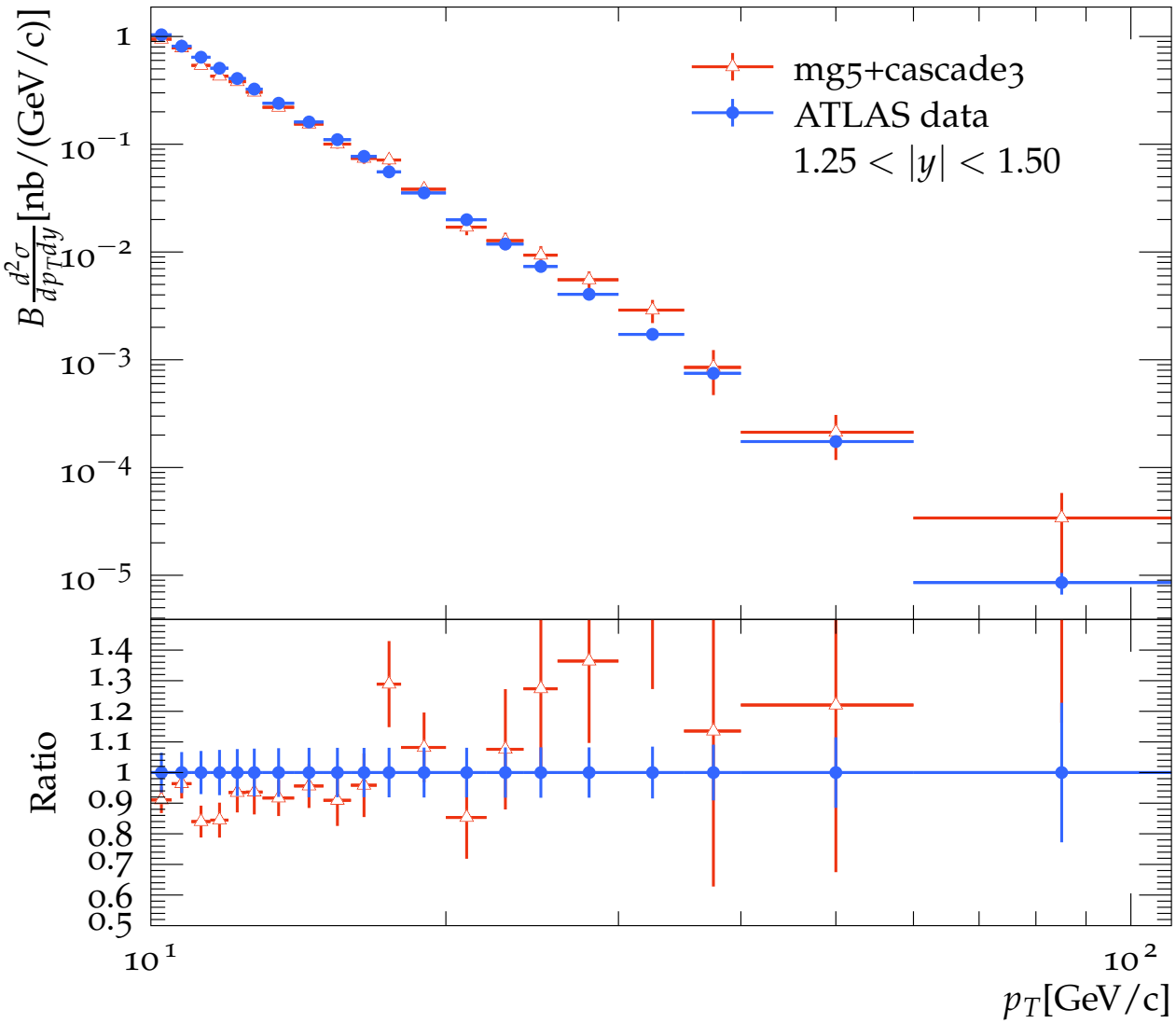

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