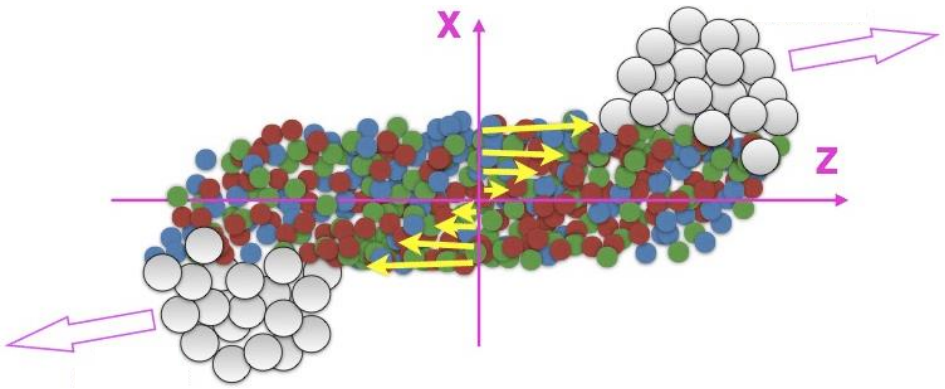
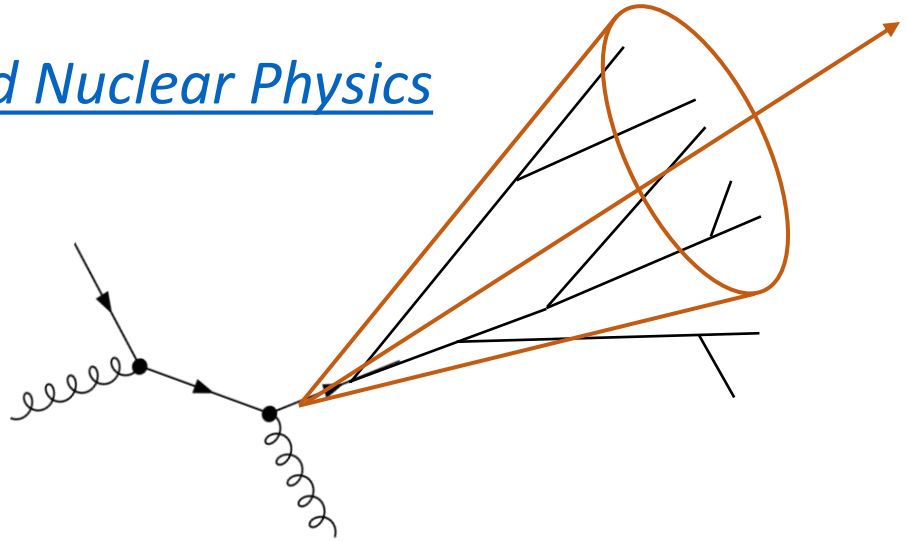
Exploring QCD dynamics using the jet invariant mass

Ezra D. Lesser (CERN)

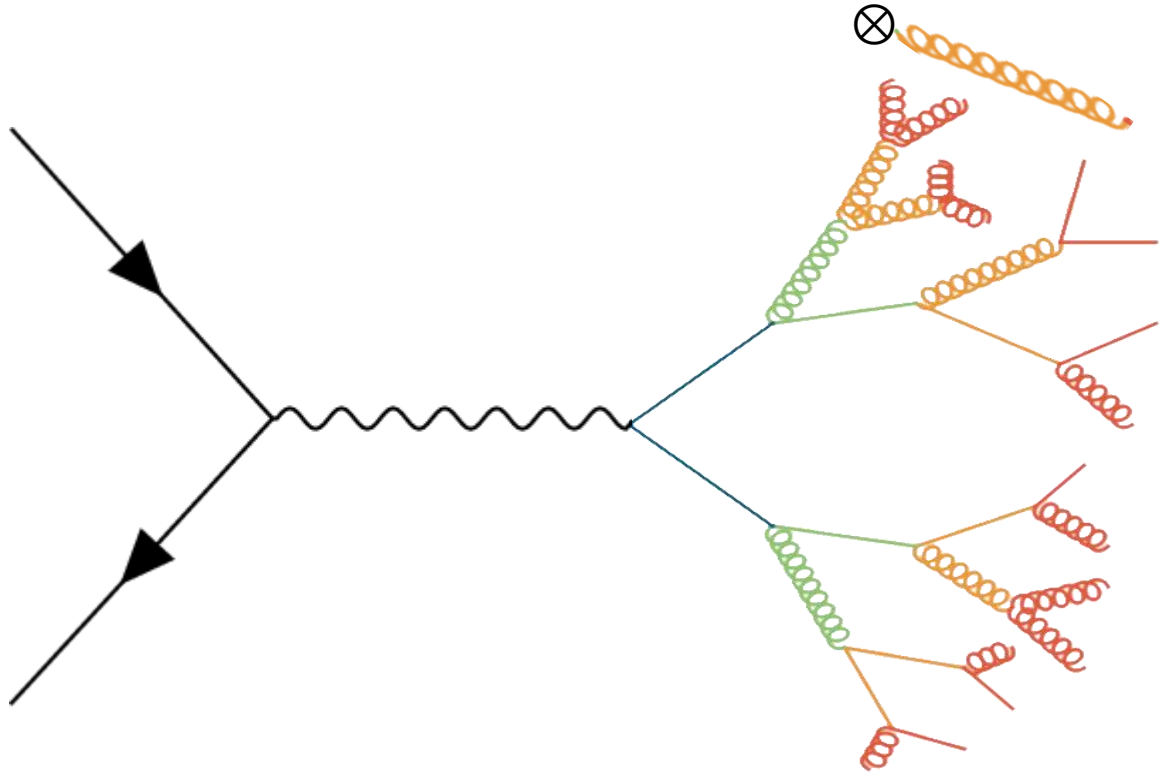
11 July 2024

10th International Conference on Quarks and Nuclear Physics





How do partons fragment?



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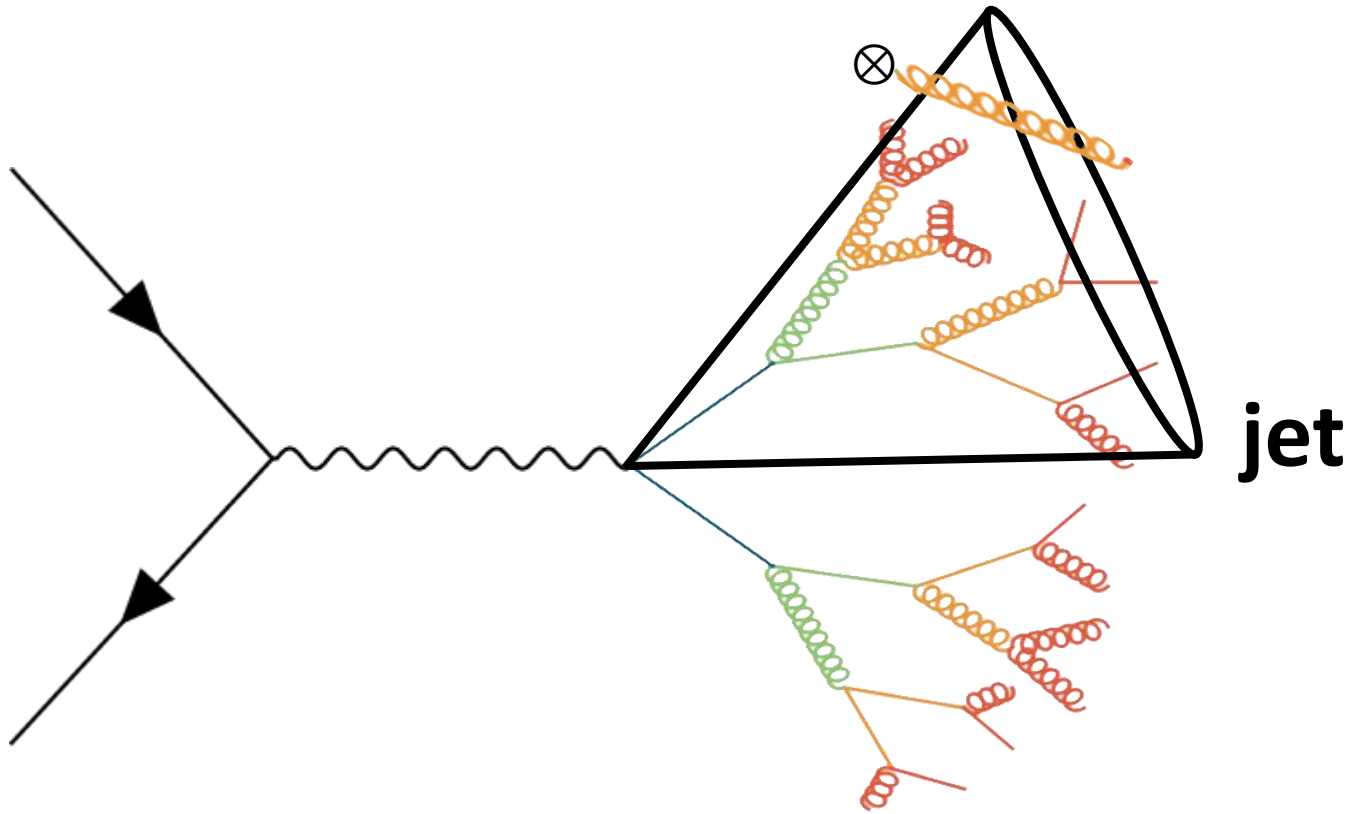

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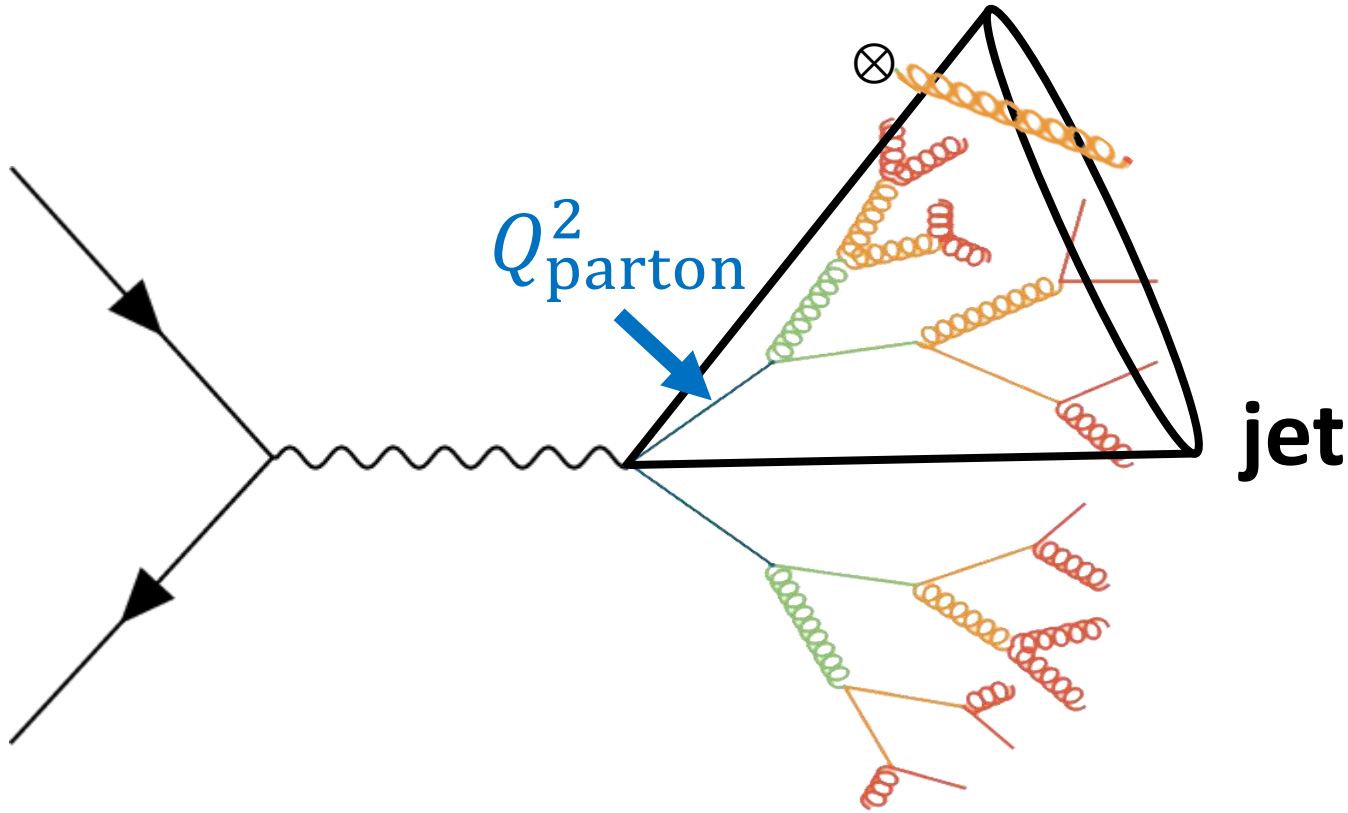

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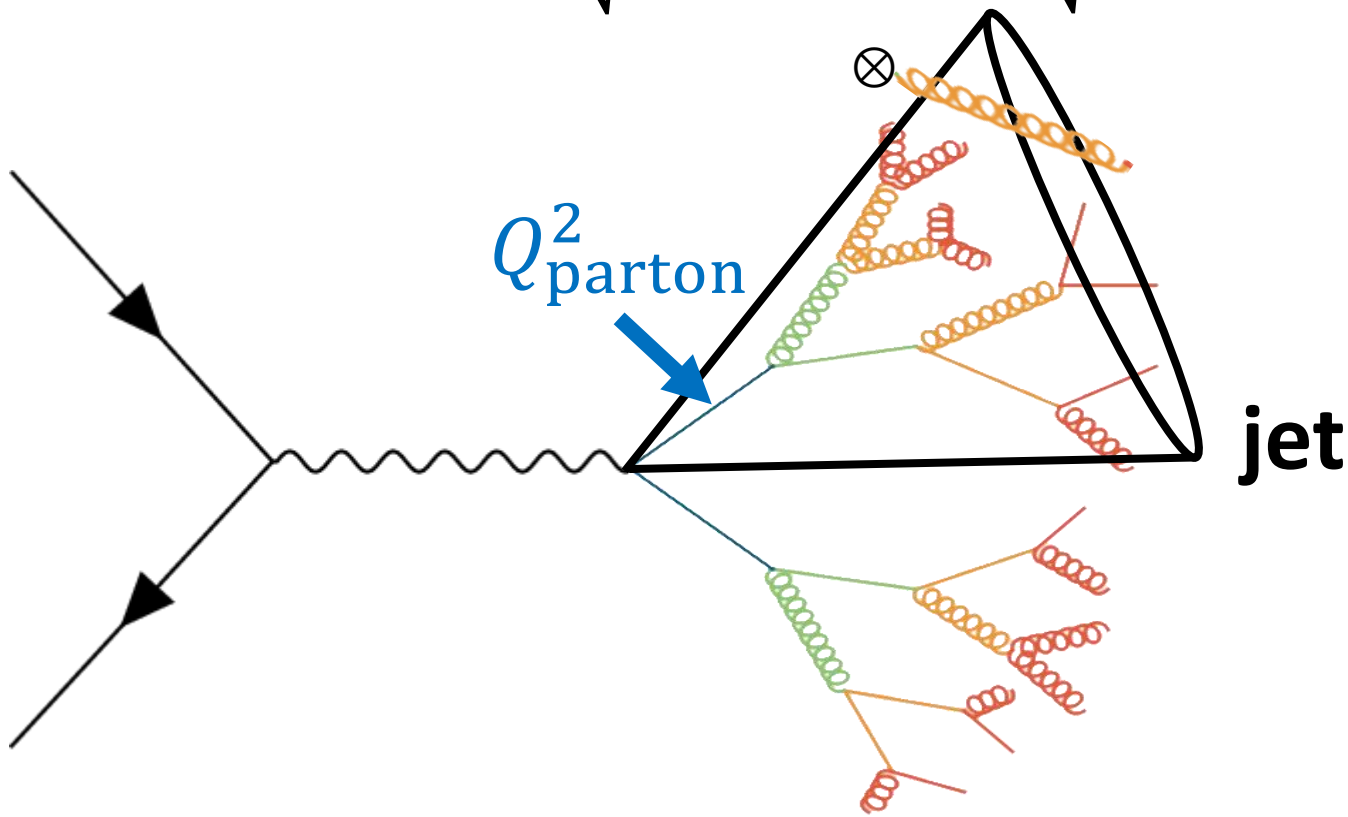
- **Invariant jet mass:** $m_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2} \approx \sqrt{Q_{\text{parton}}^2}$



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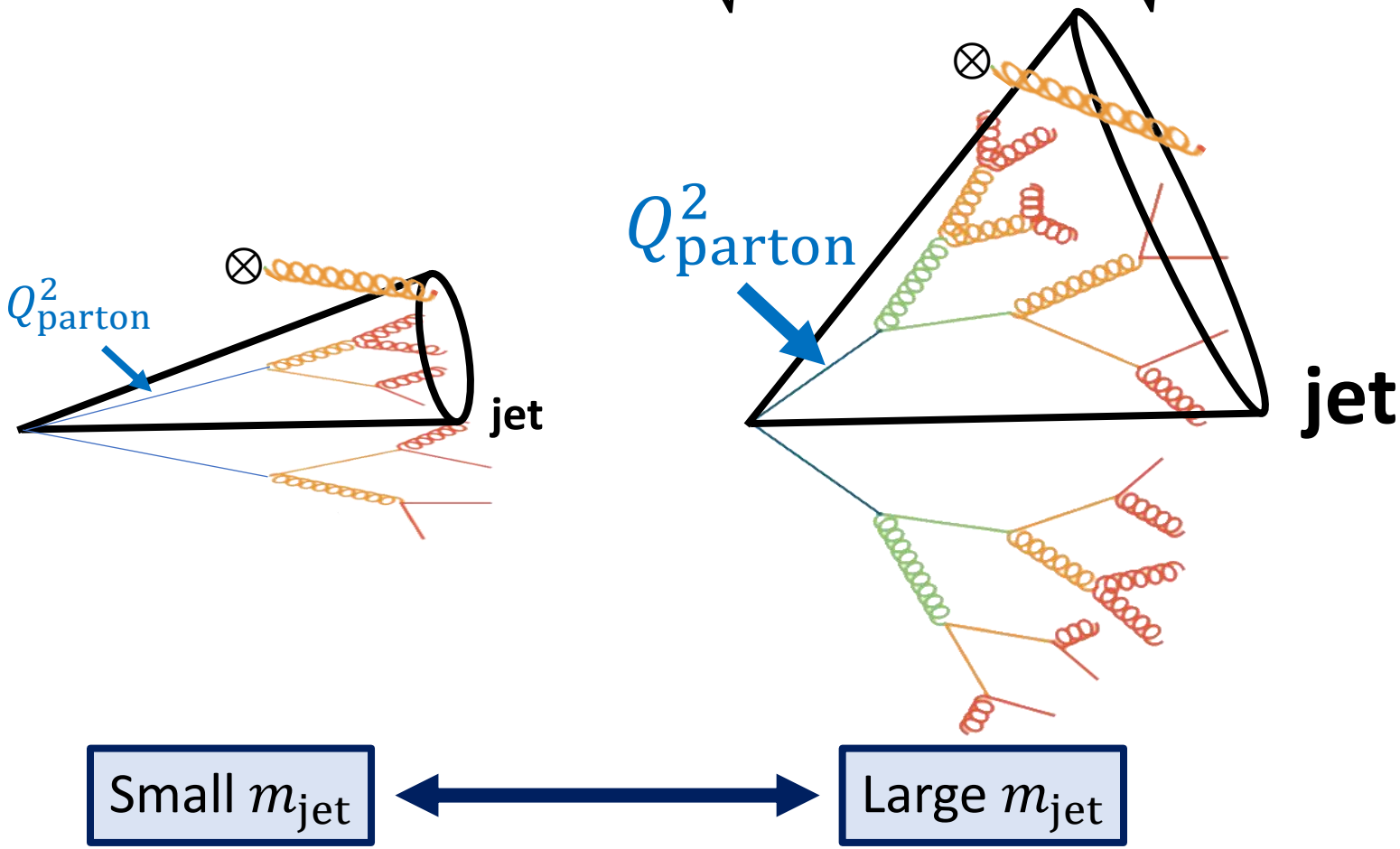

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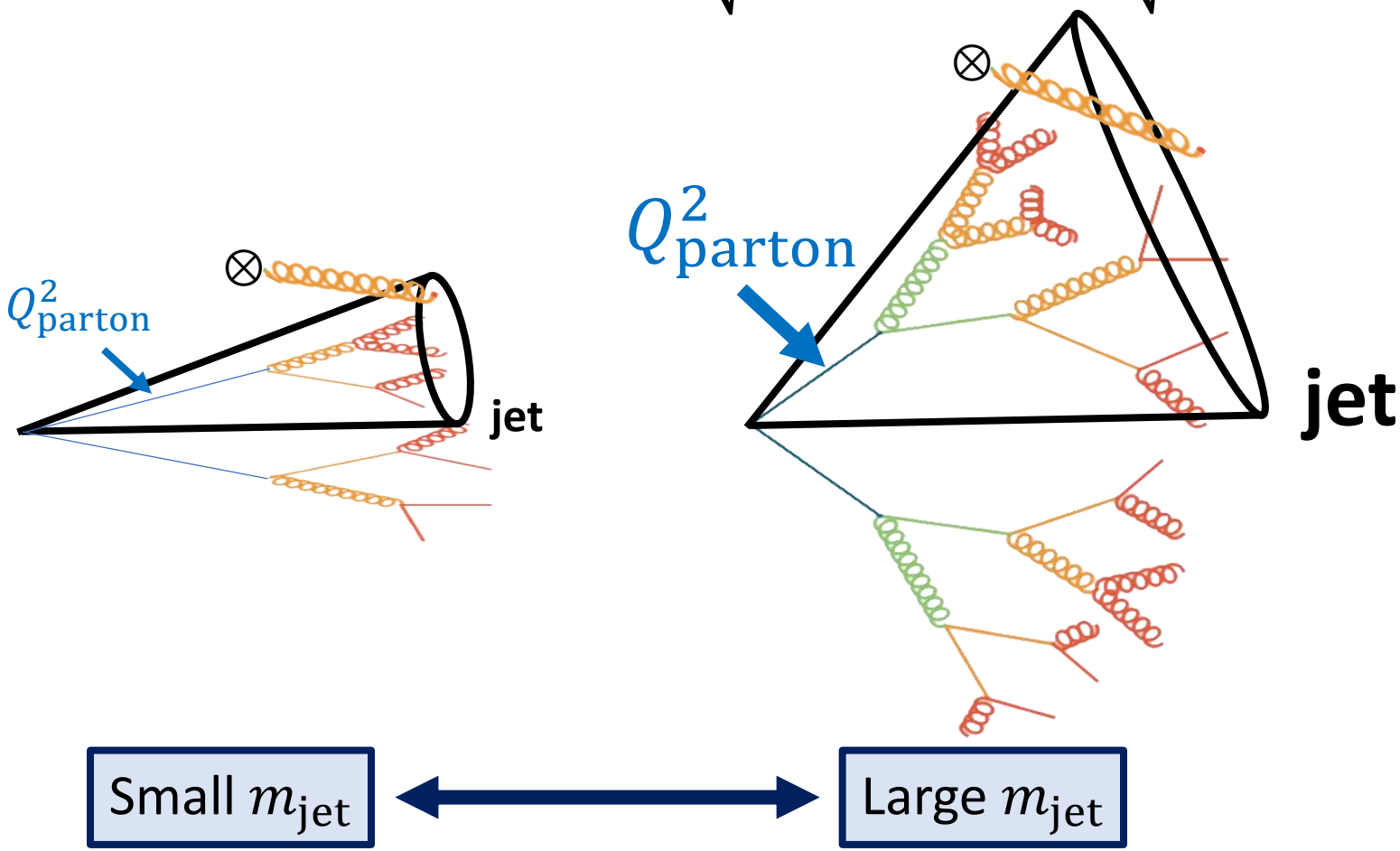

How does m_{jet} ($\sim Q_{\text{parton}}$) depend on $p_{\text{T,jet}}$?

Small m_{jet} ⟷ Large m_{jet}

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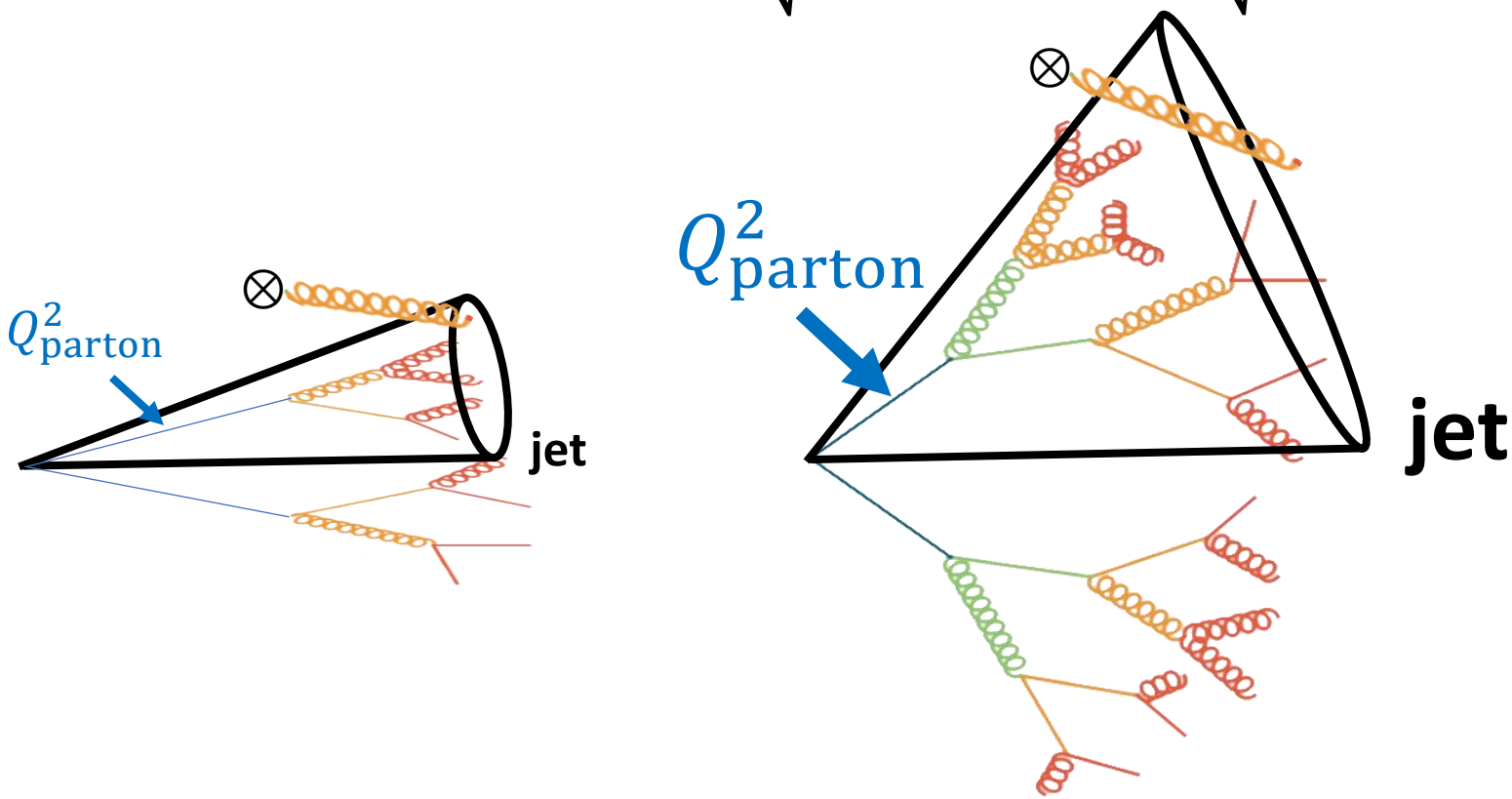
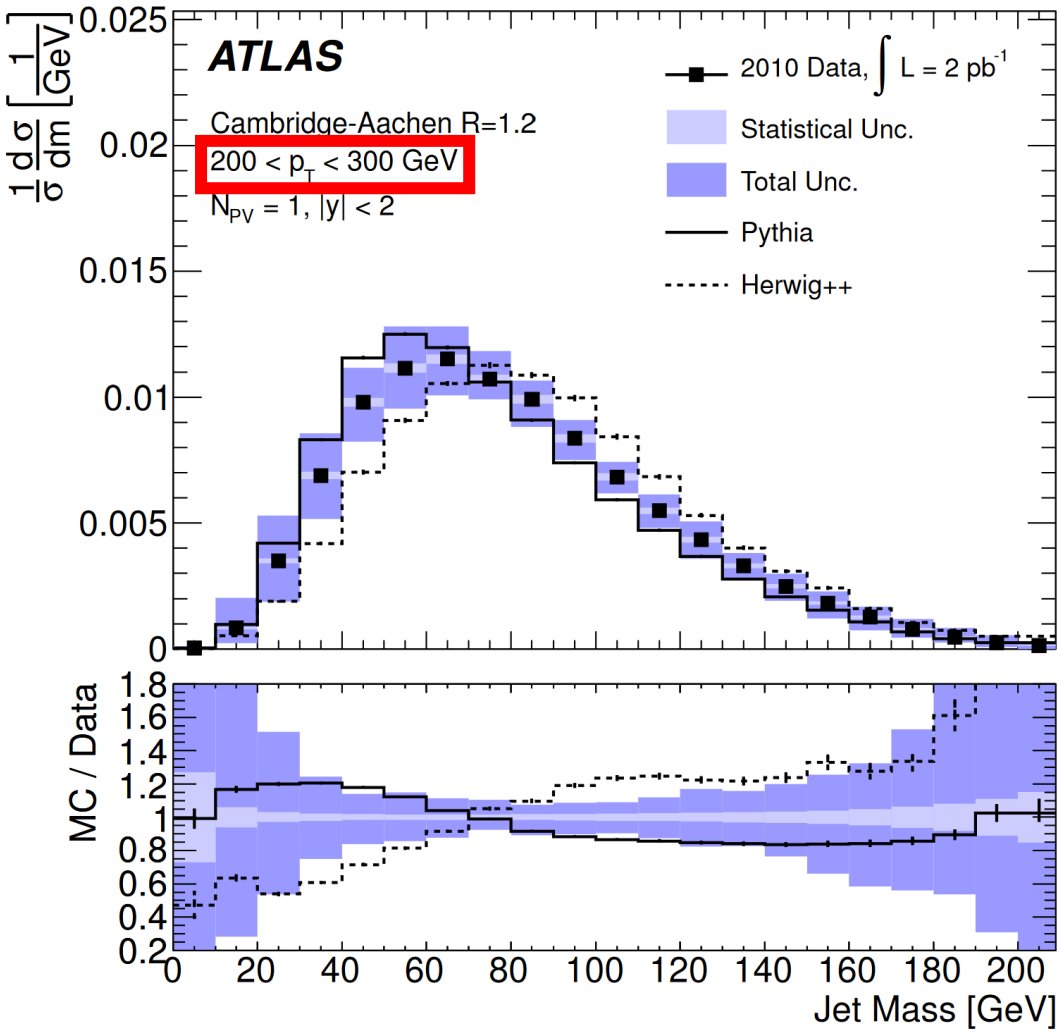


How does m_{jet} ($\sim Q_{\text{parton}}$) depend on $p_{\text{T,jet}}$?

How does theory compare to experiment?

Small m_{jet} ⟷ Large m_{jet}

First look at the LHC (2010-2013)



JHEP 1205 (2012) 128

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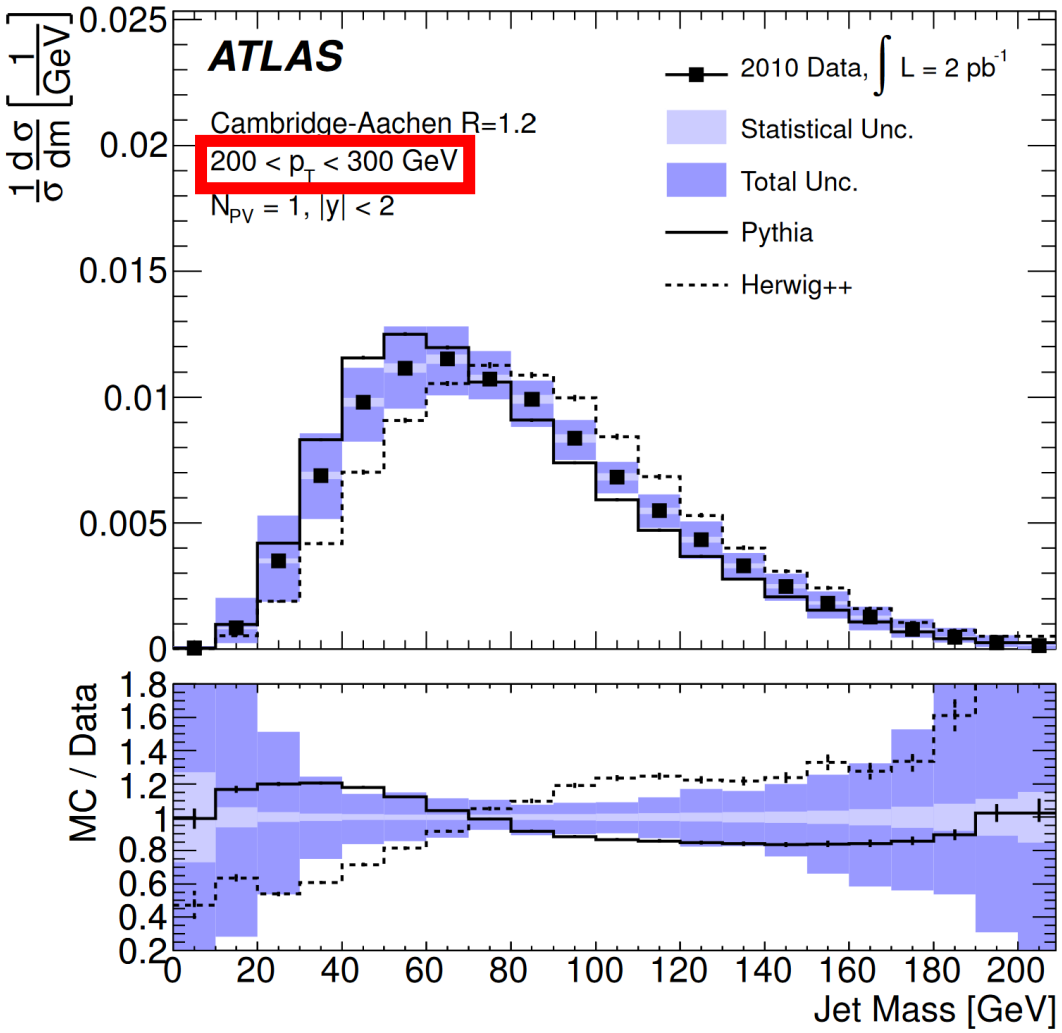
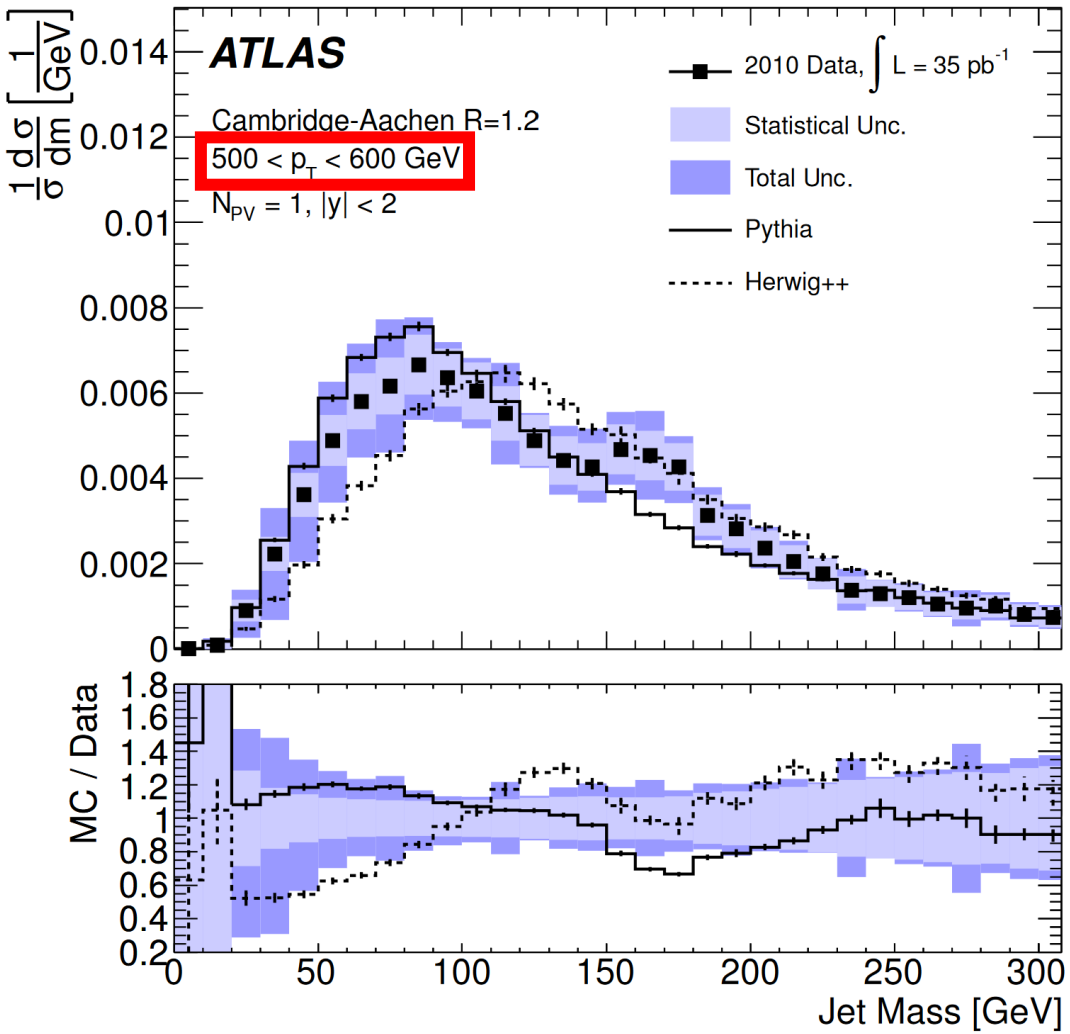
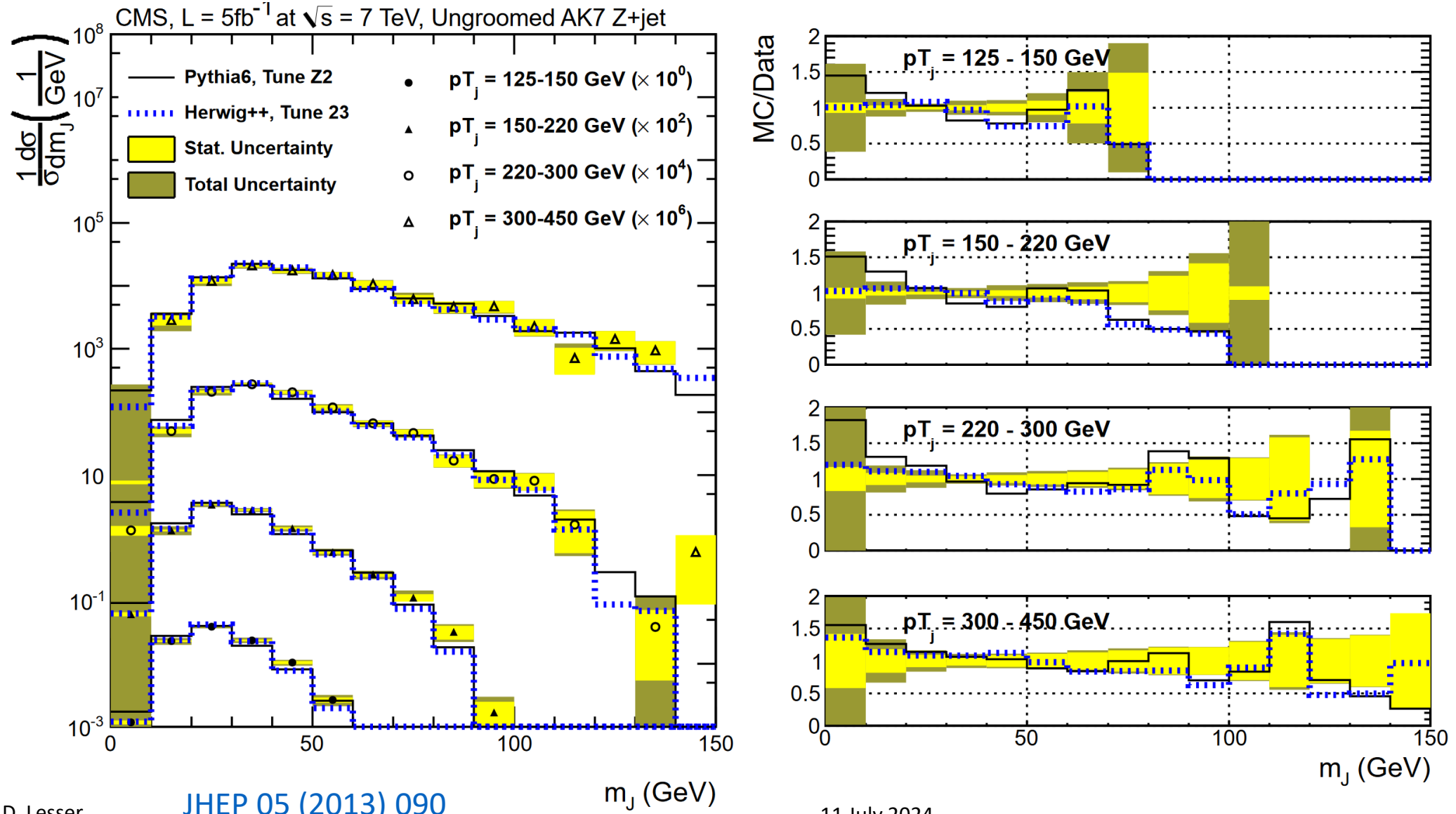




- Different energy scale, similar shape

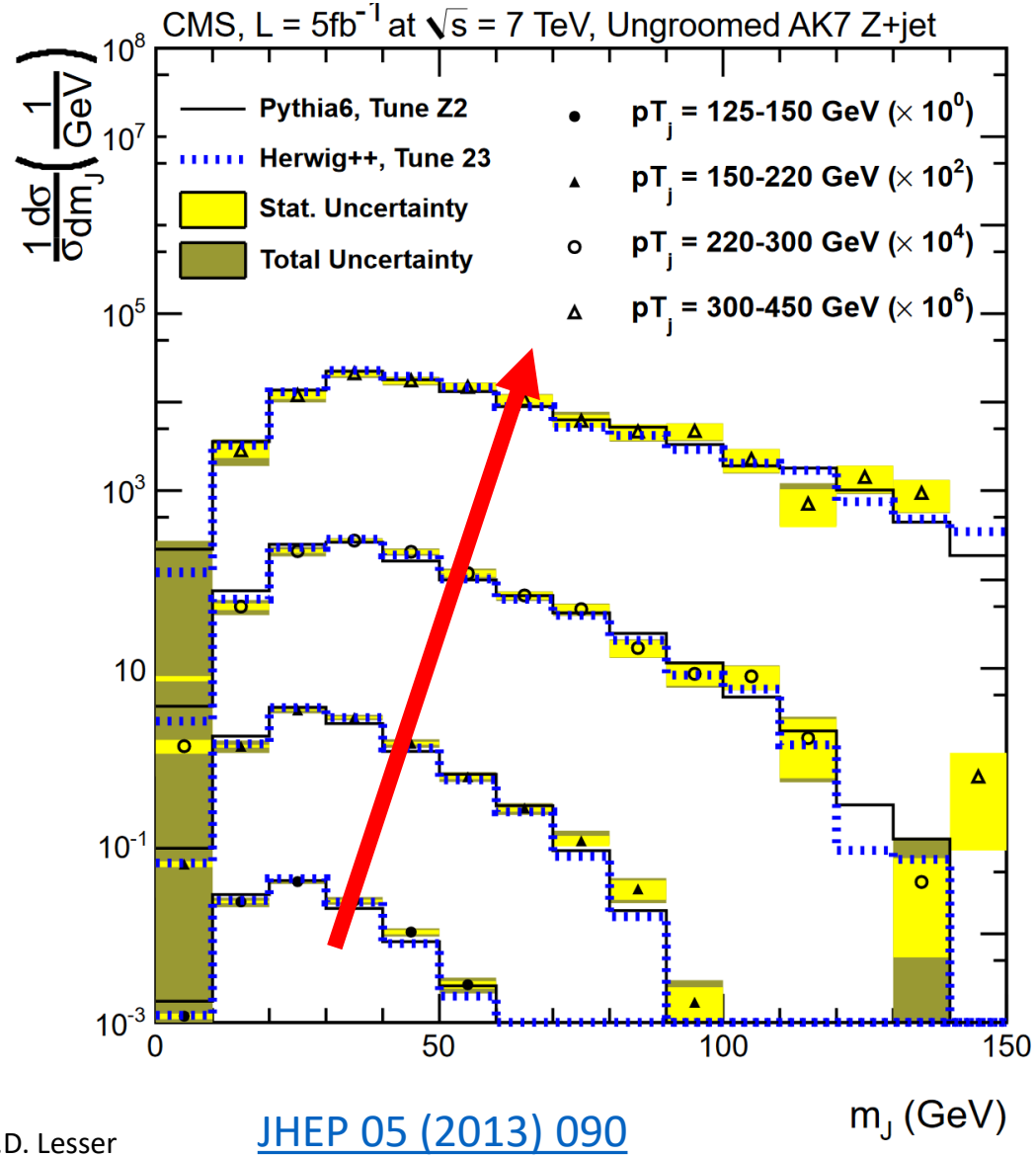
JHEP 1205 (2012) 128

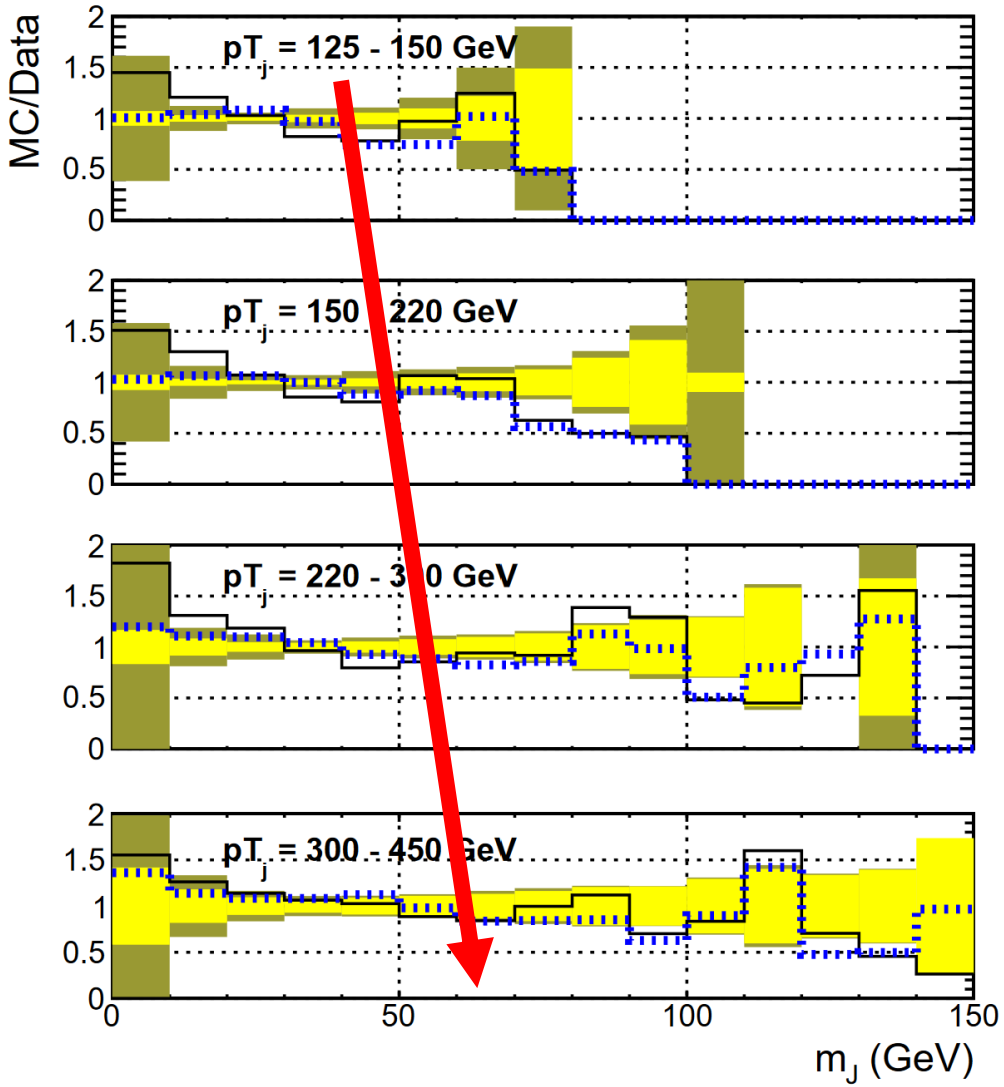
First look at the LHC (2010-2013)



JHEP 05 (2013) 090

First look at the LHC (2010-2013)

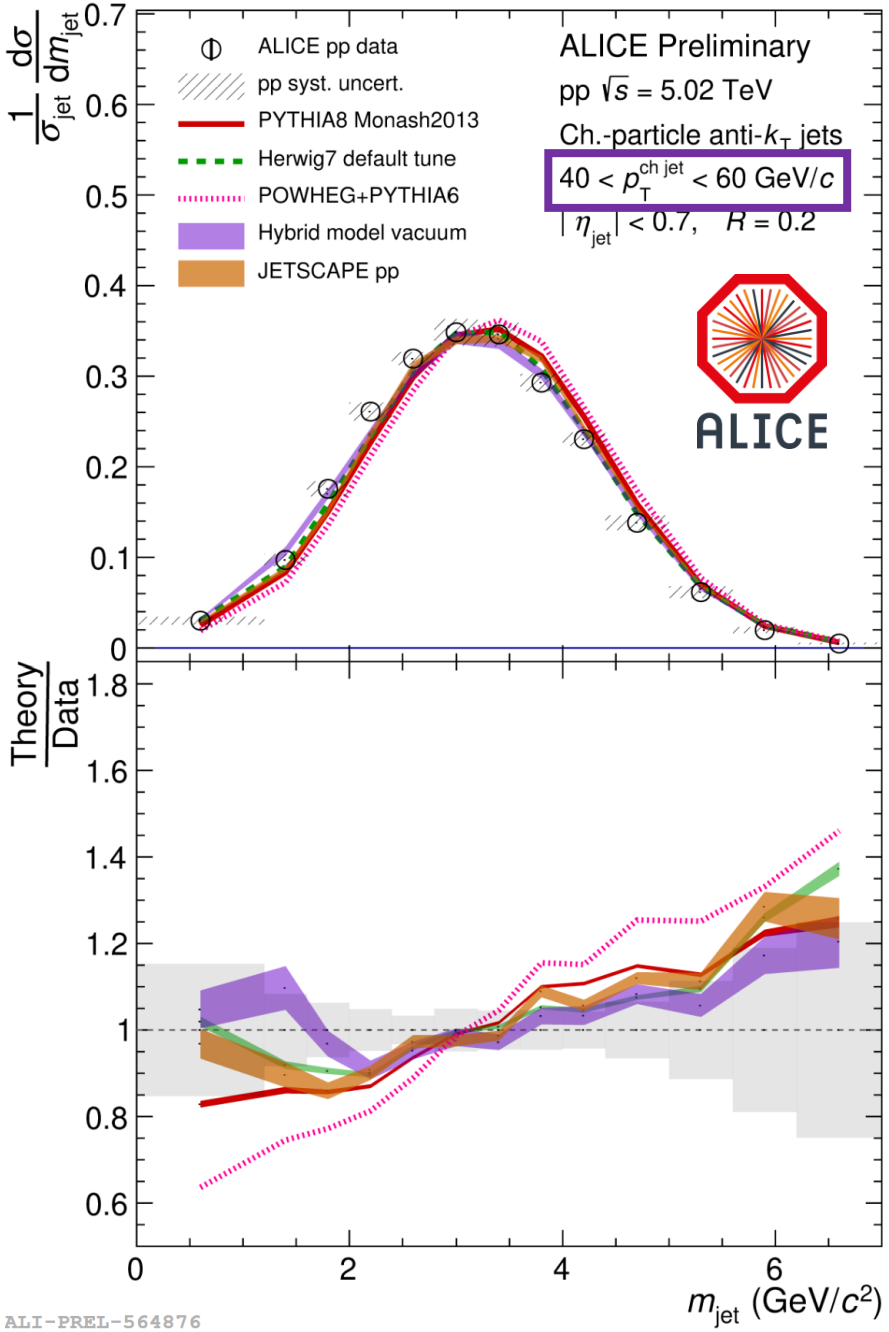


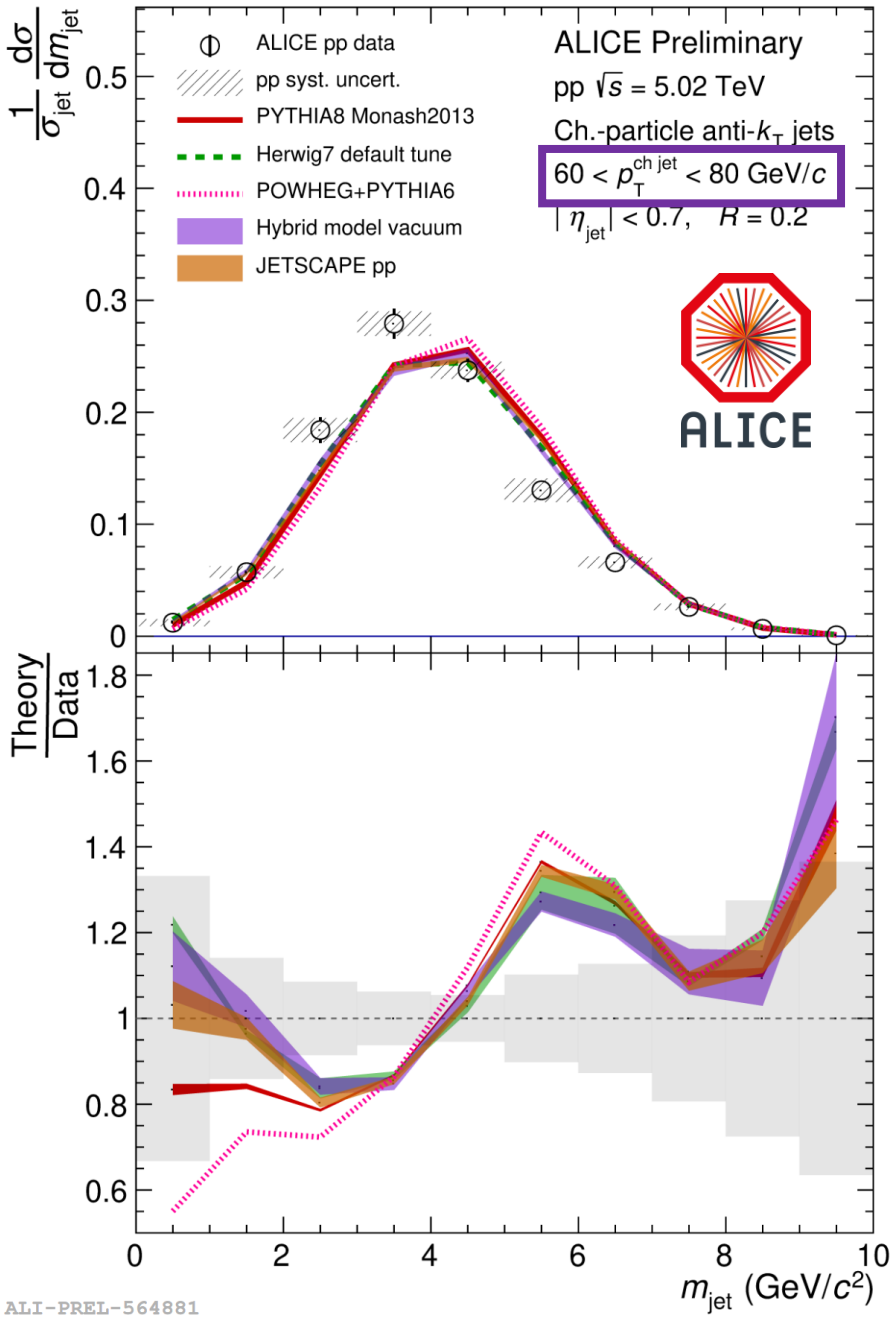


Larger variation between distributions at lower p_T?

[JHEP 05 (2013) 090]

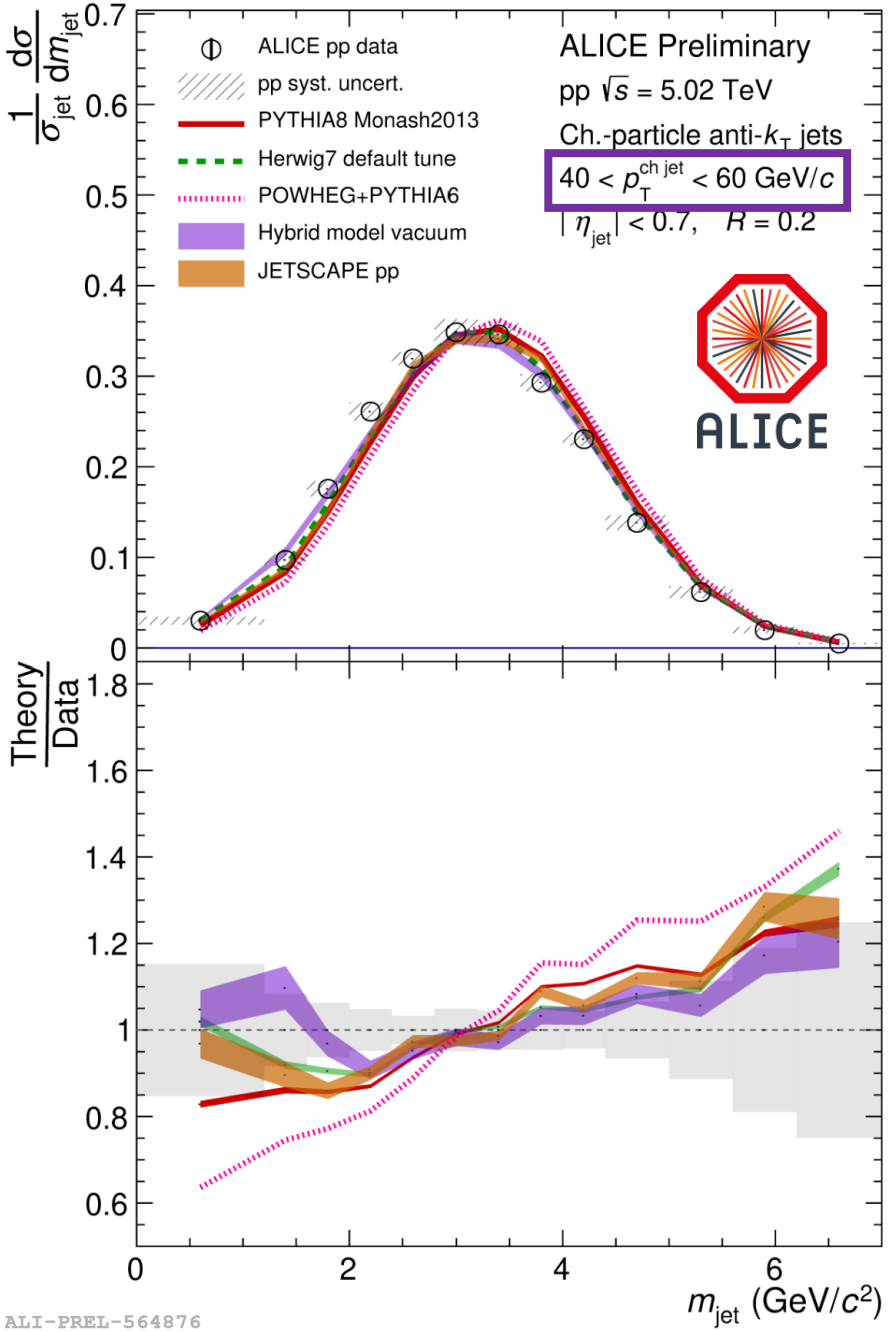
Lower $p_{T,jet}$

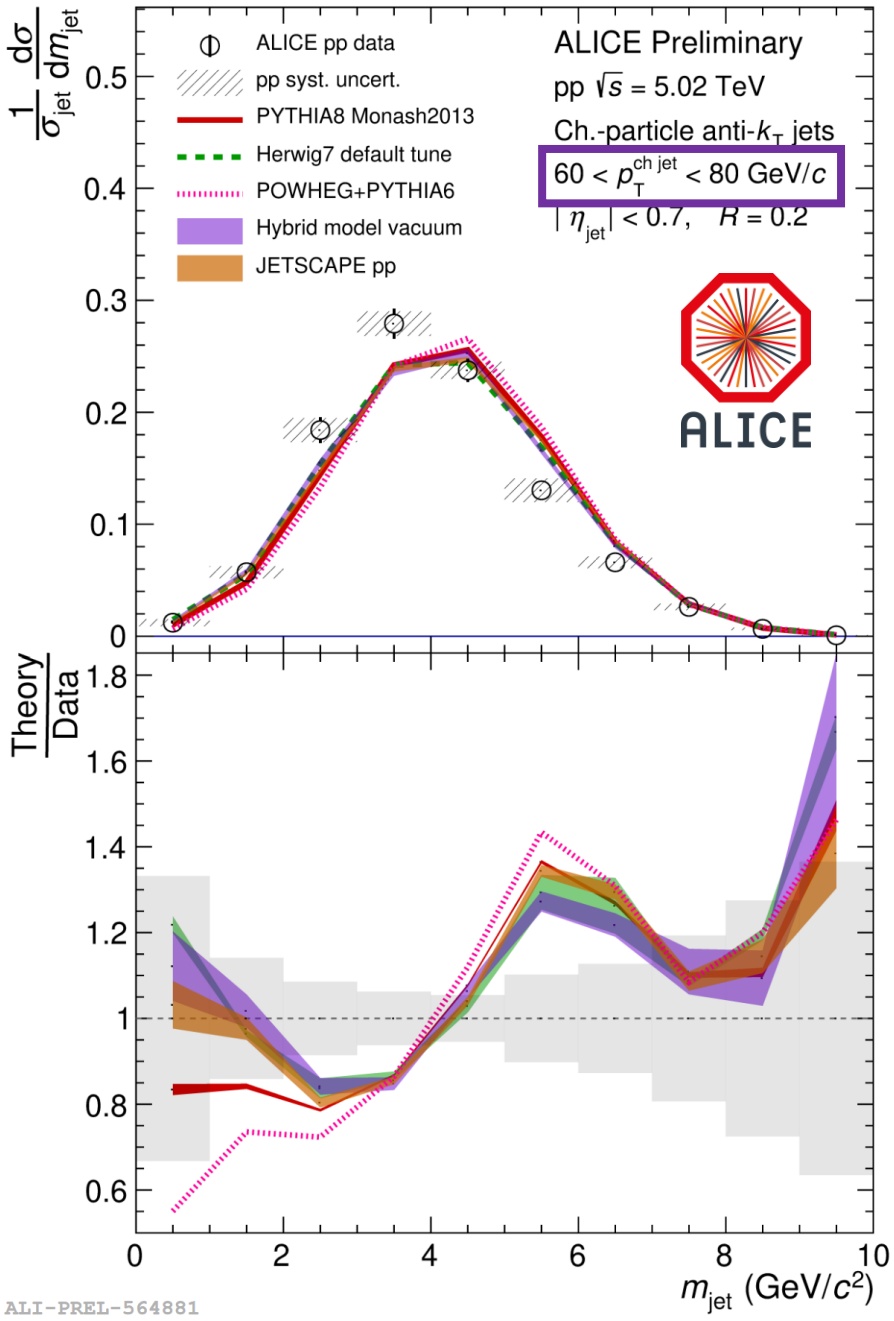




https://alice-figure.web.cern.ch/node/26502

Lower $p_{\mathrm{T,jet}}$

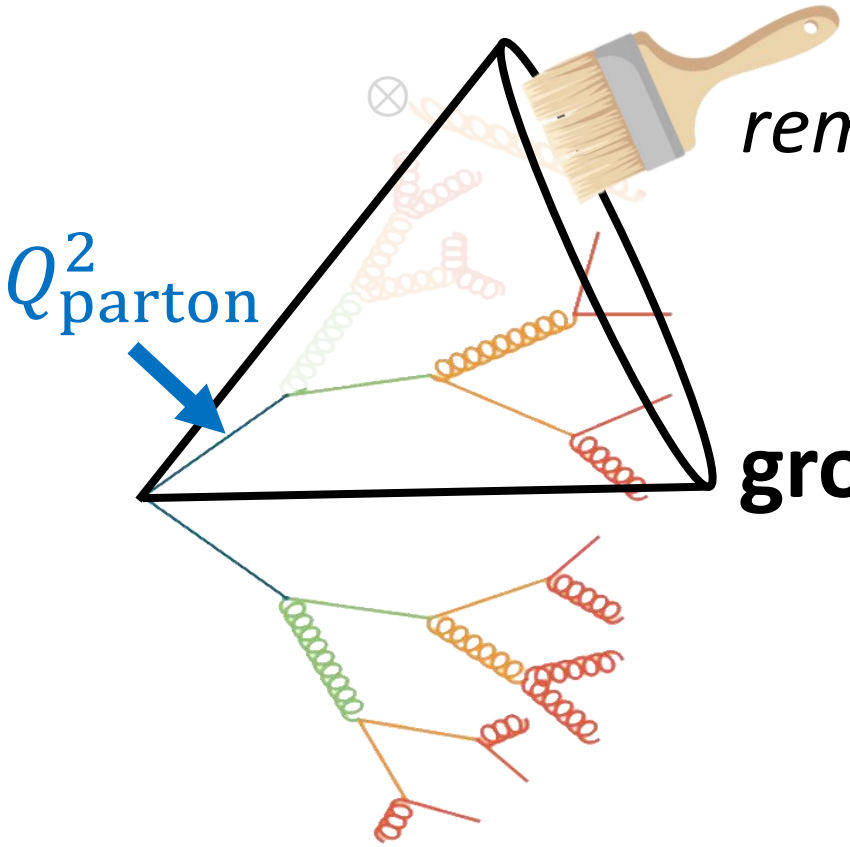




- Smaller tail than at higher $p_{\mathrm{T,jet}}$
- **Important baseline for Pb-Pb**

https://alice-figure.web.cern.ch/node/26502

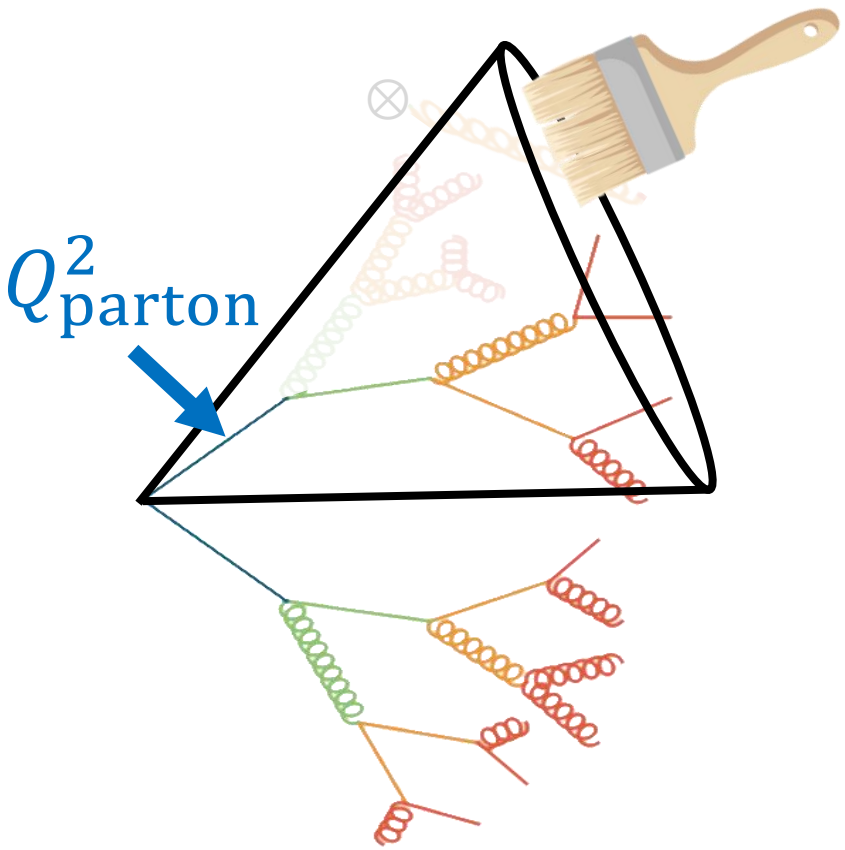
Groomed jet mass

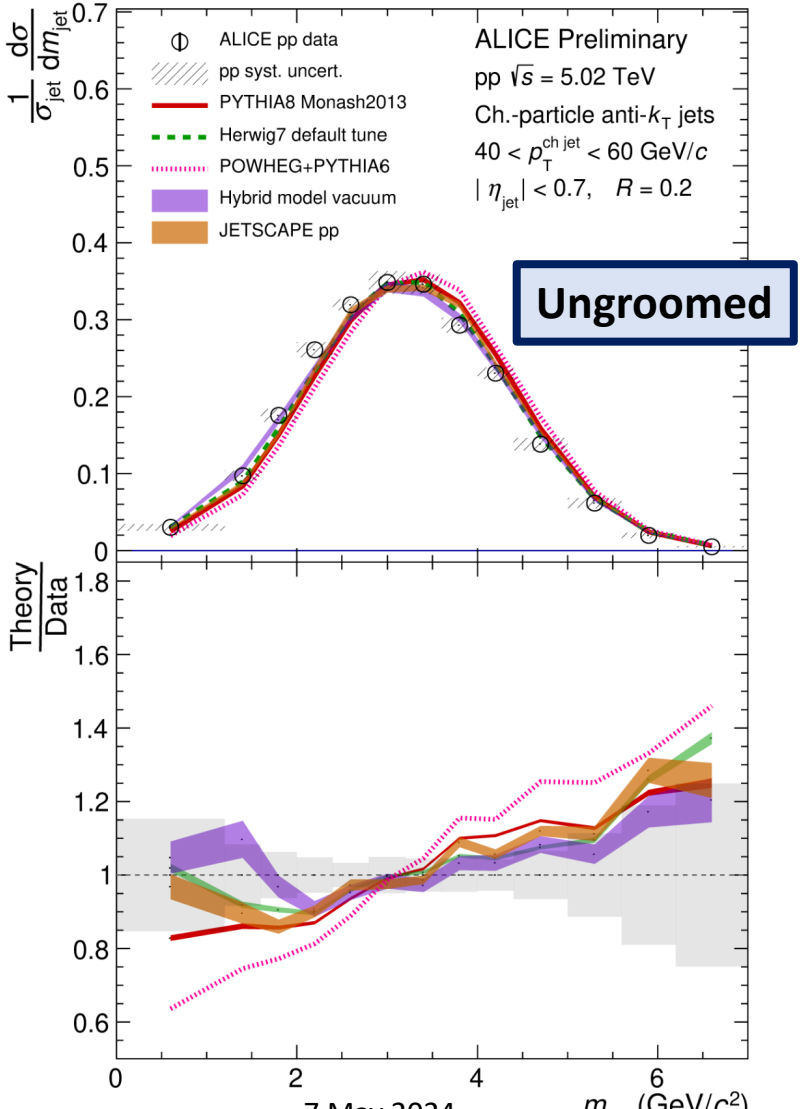


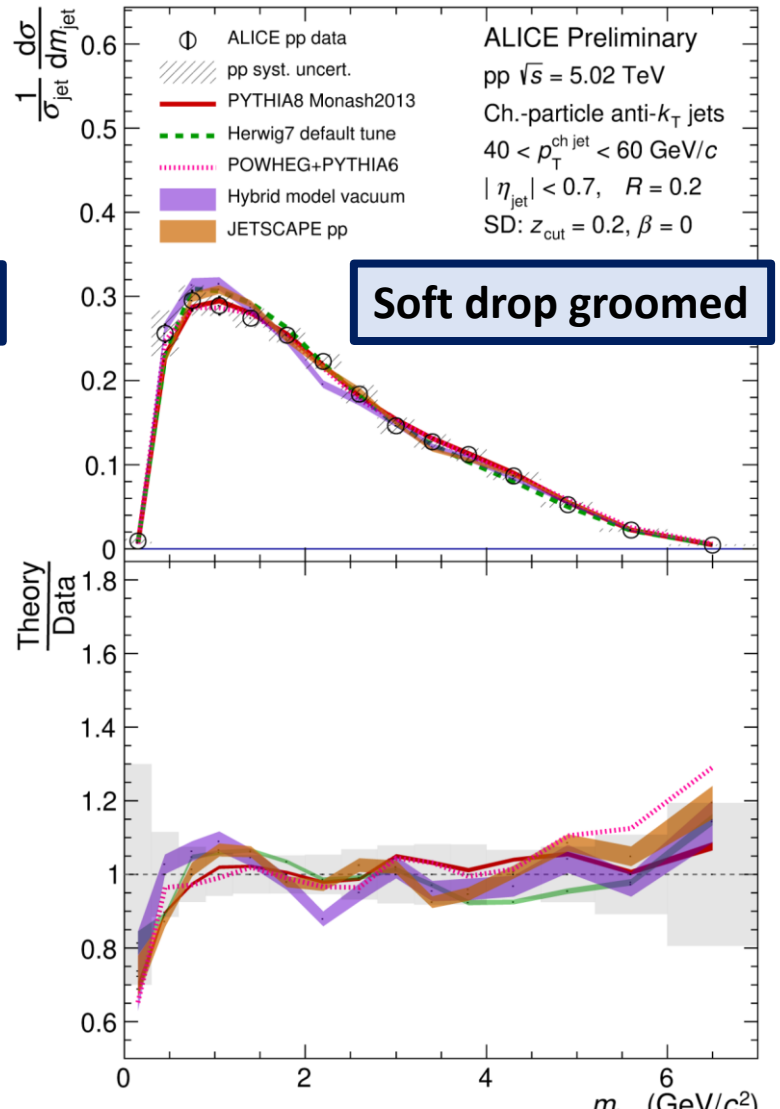
remove soft, wide-angle radiation

groomed jet

Groomed jet mass







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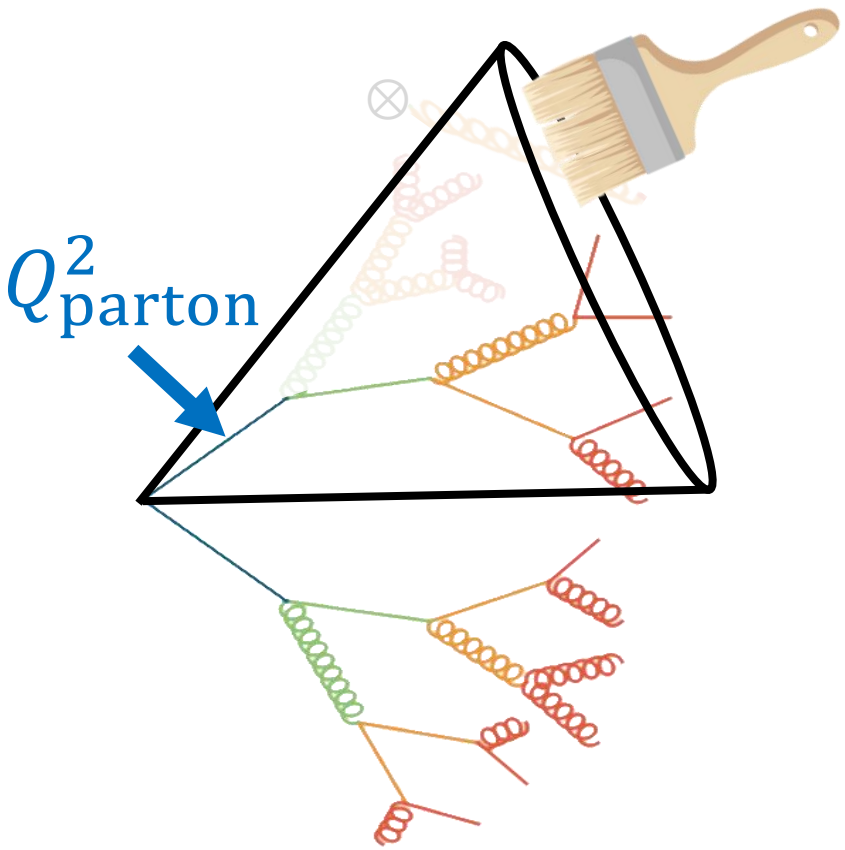
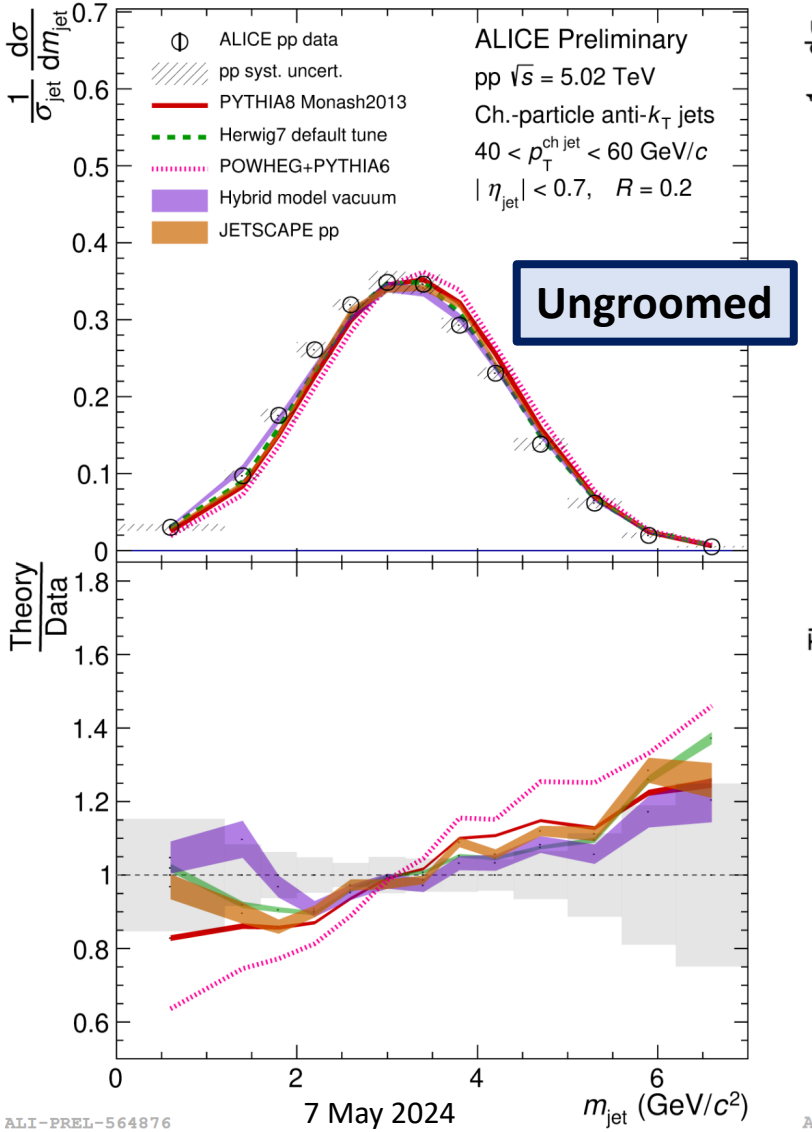
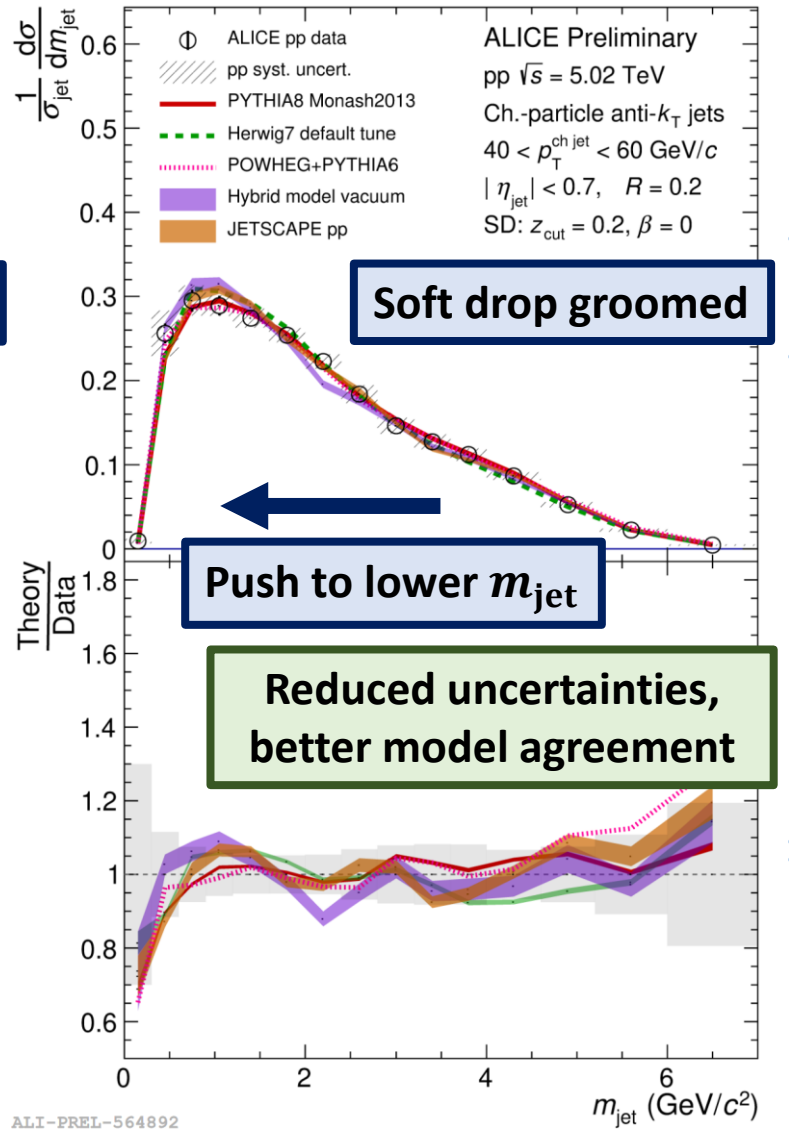




Ungroomed



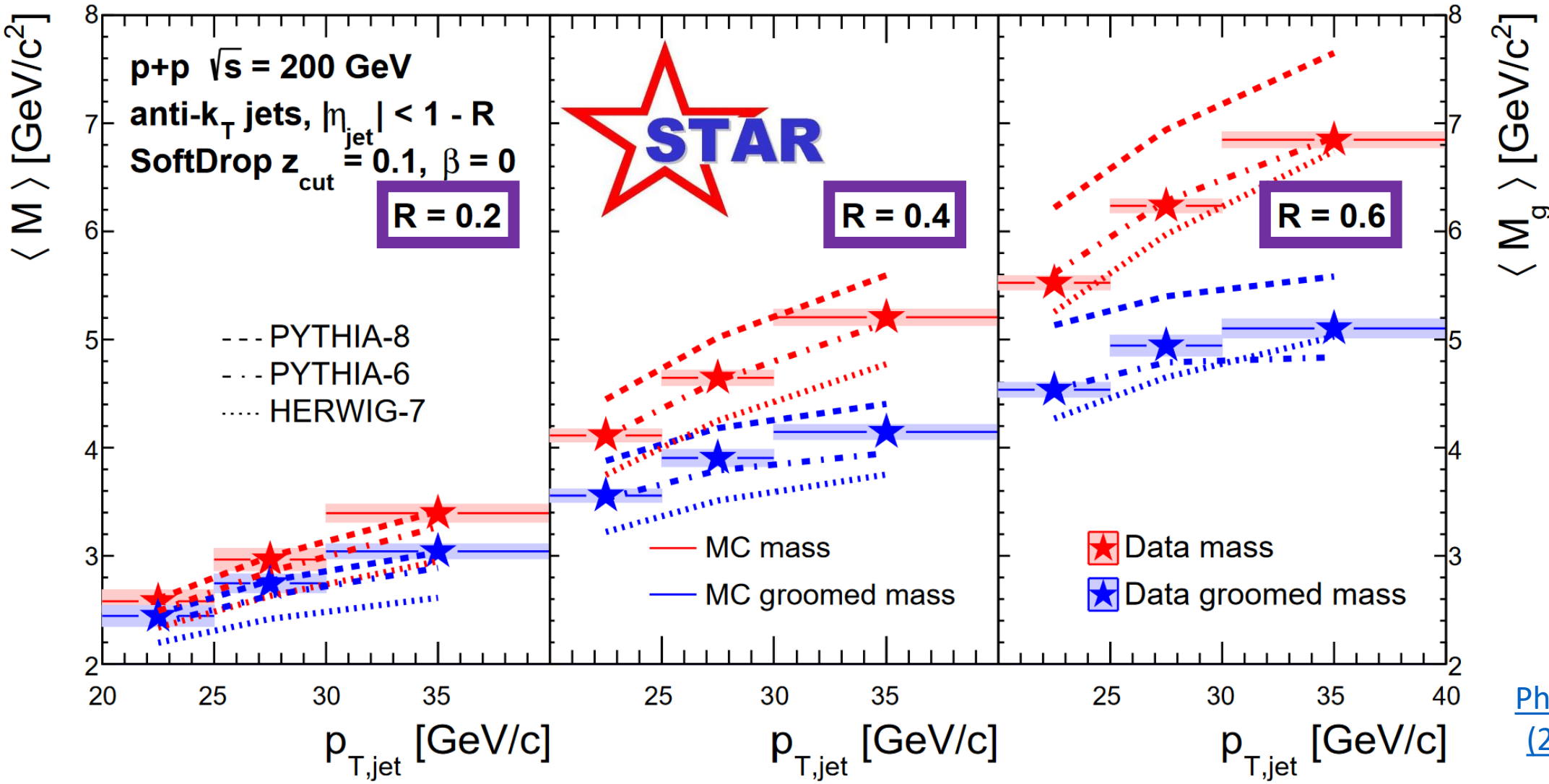
Soft drop groomed

Push to lower m_{jet}

Reduced uncertainties, better model agreement

https://alice-figure.web.cern.ch/node/26502

(Un)groomed jet mass at RHIC



Phys. Rev. D 104 (2021) 052007

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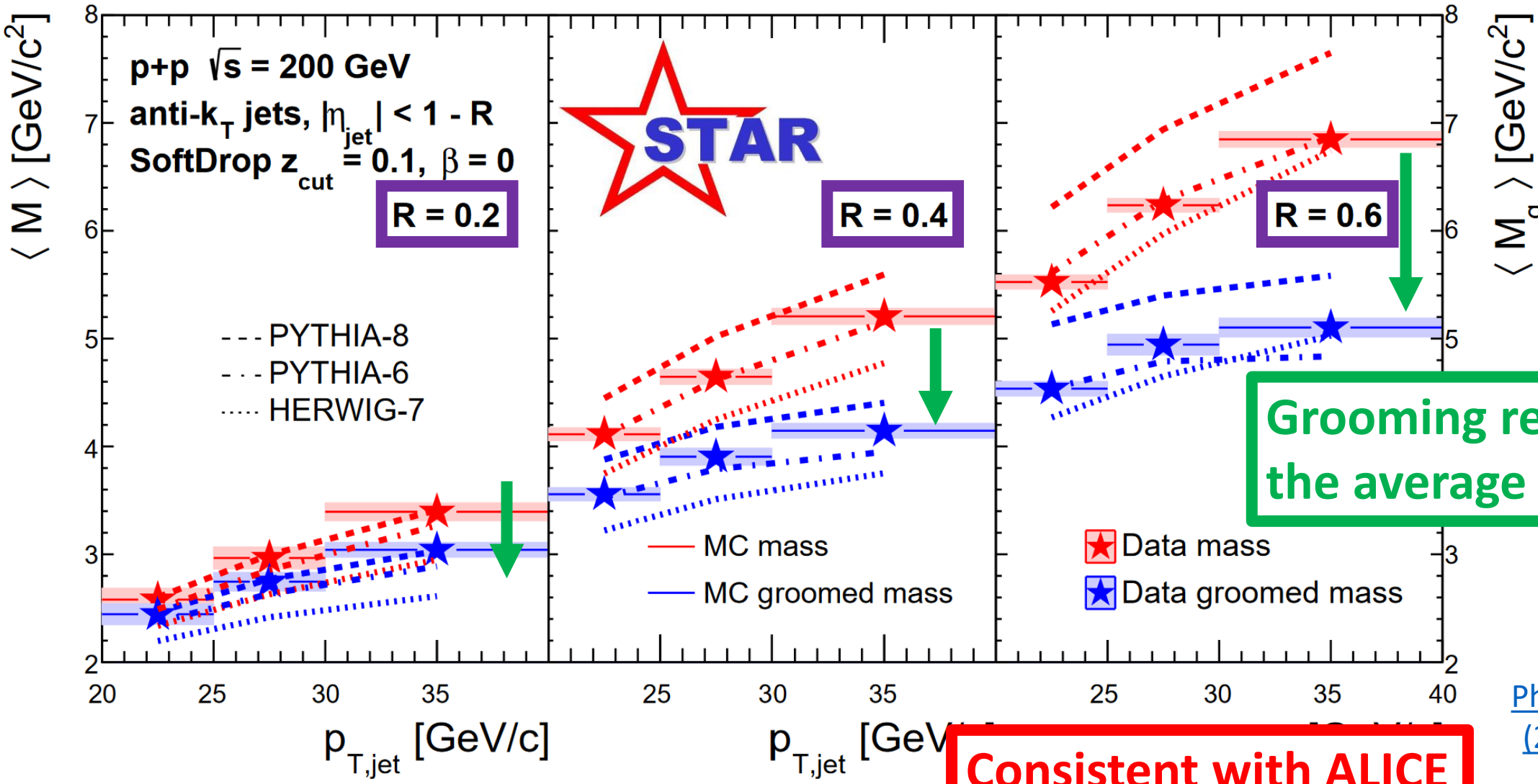

Grooming reduces the average jet mass

Consistent with ALICE

Phys. Rev. D 104 (2021) 052007

Where to go from here?

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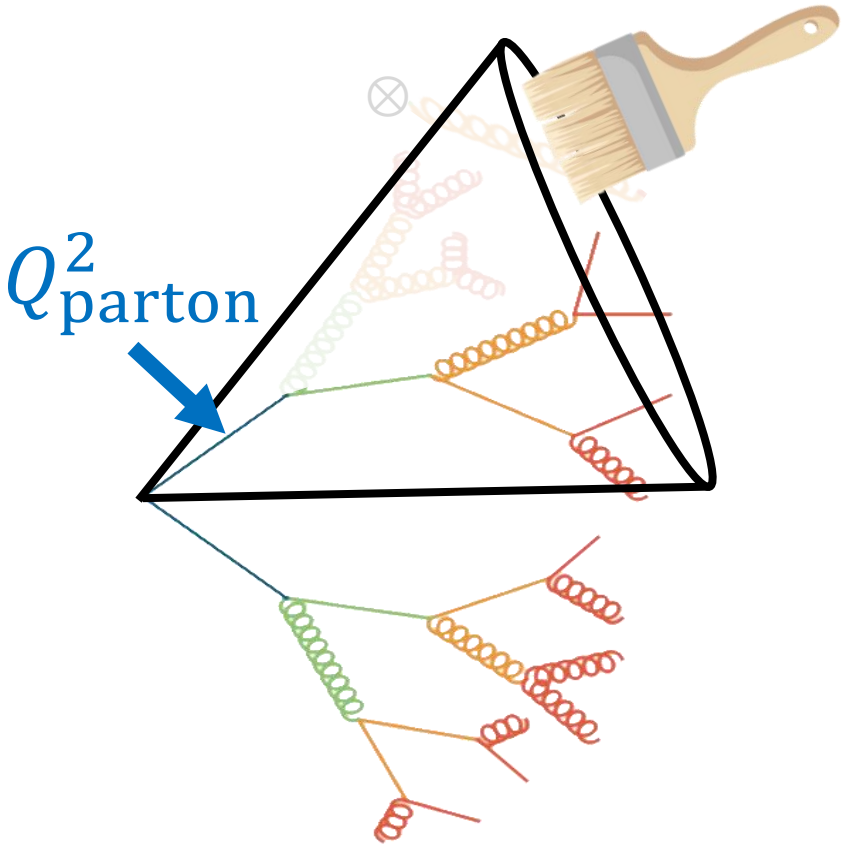

- Groomed jet mass has now been calculated at **NNLO + NNNLL**
  - *Comparisons between* ***experimental results & theory?***

[Phys. Lett. B 809 (2020) 135704]

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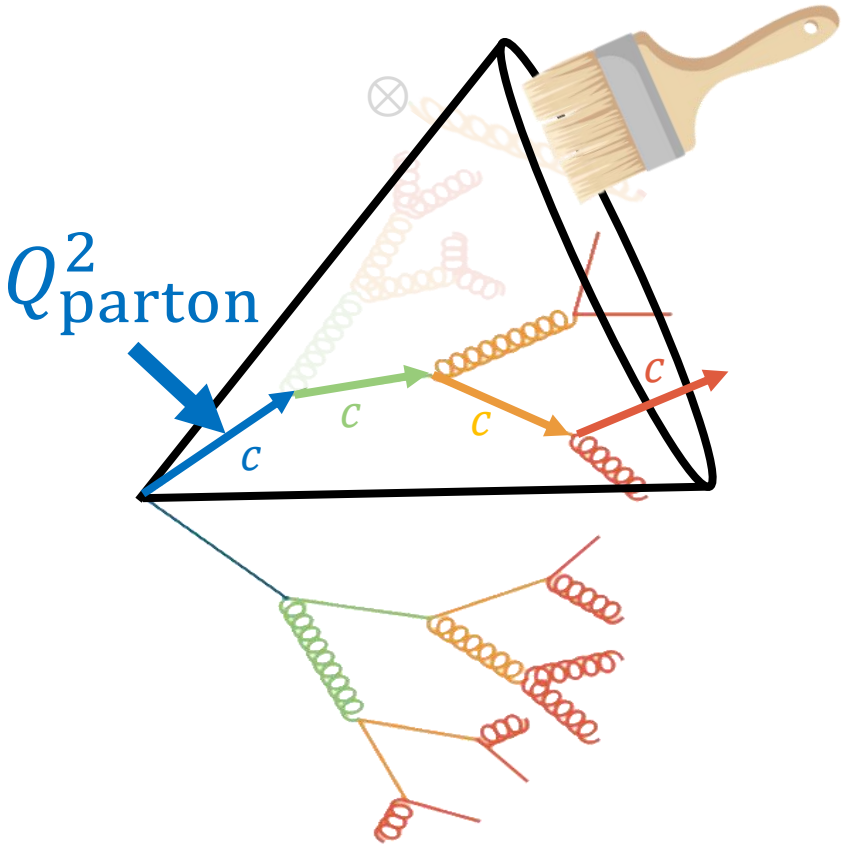

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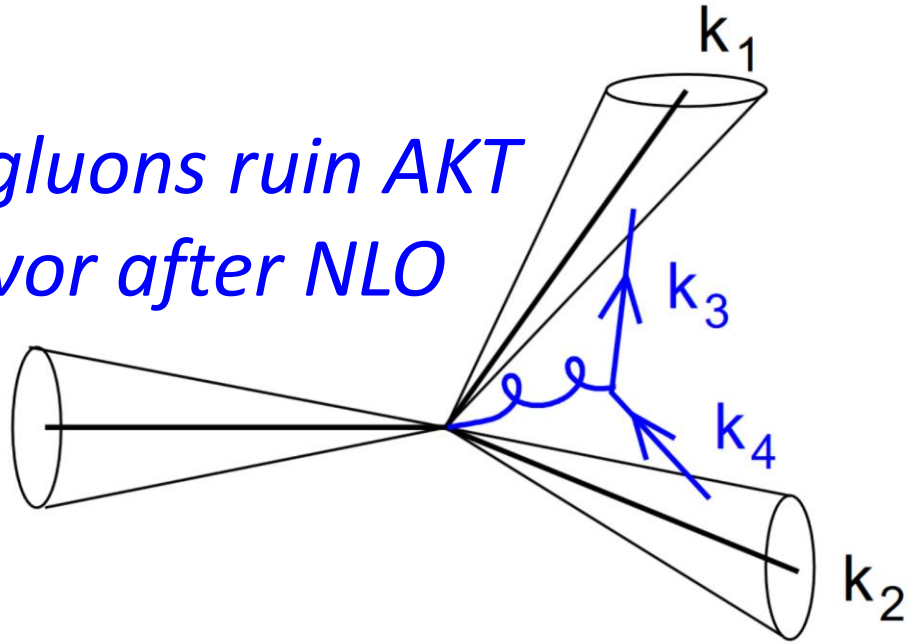
  - *Comparisons between* ***experimental results & theory?***
- Test the **flavor dependence** of QCD fragmentation / **parton mass**

Phys. Lett. B 809 (2020) 135704

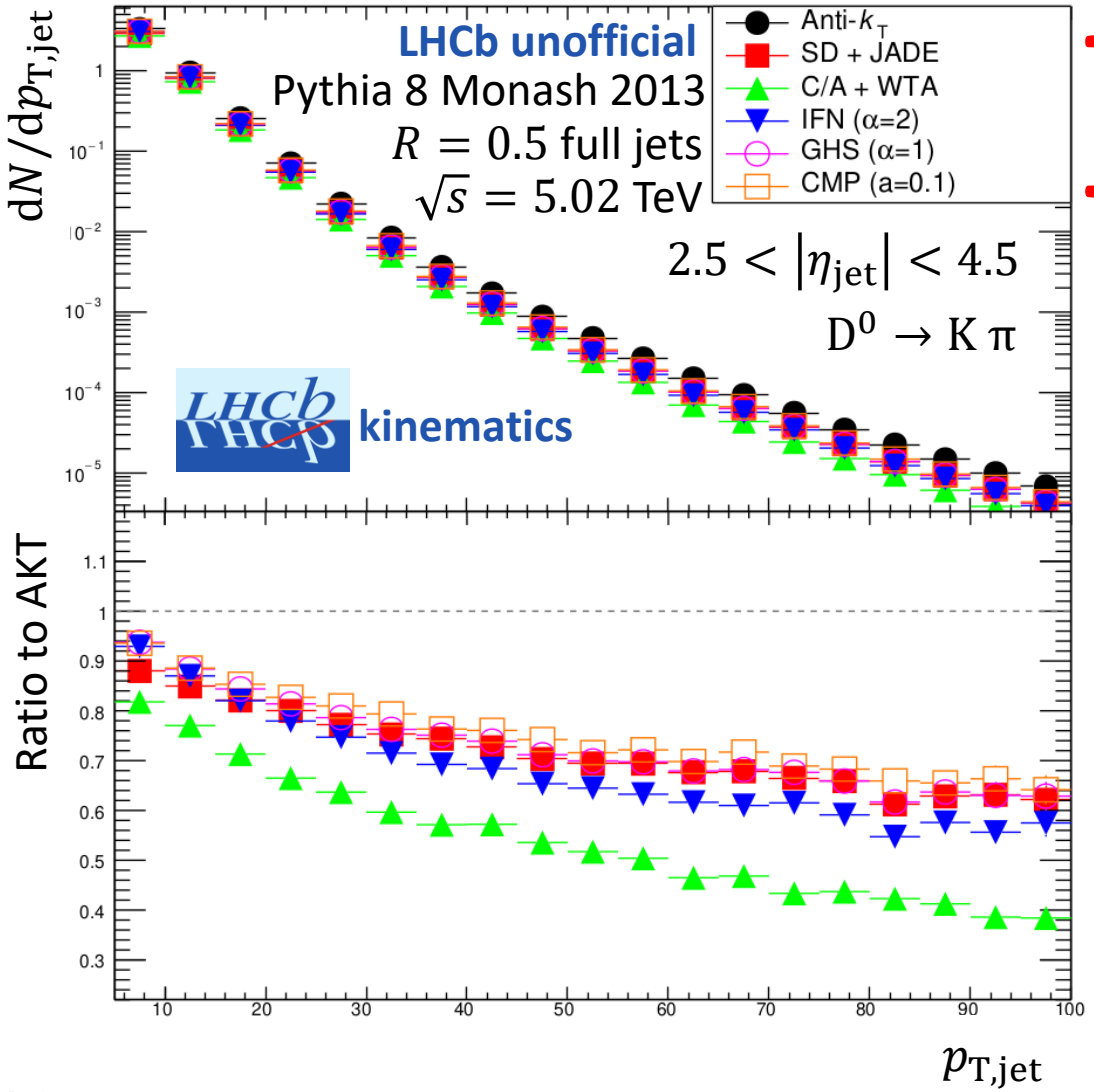
High precision with heavy flavor

Soft gluons ruin AKT flavor after NLO



Eur. Phys. J. C 47 (2006) 113-124

High precision with heavy flavor



New flavor-tagging algorithms calculable beyond NLO

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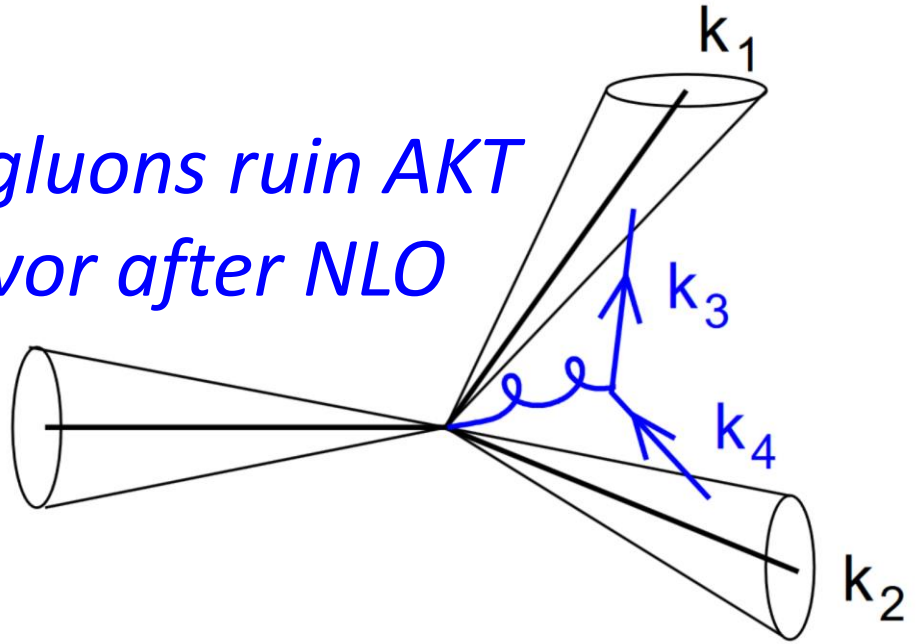

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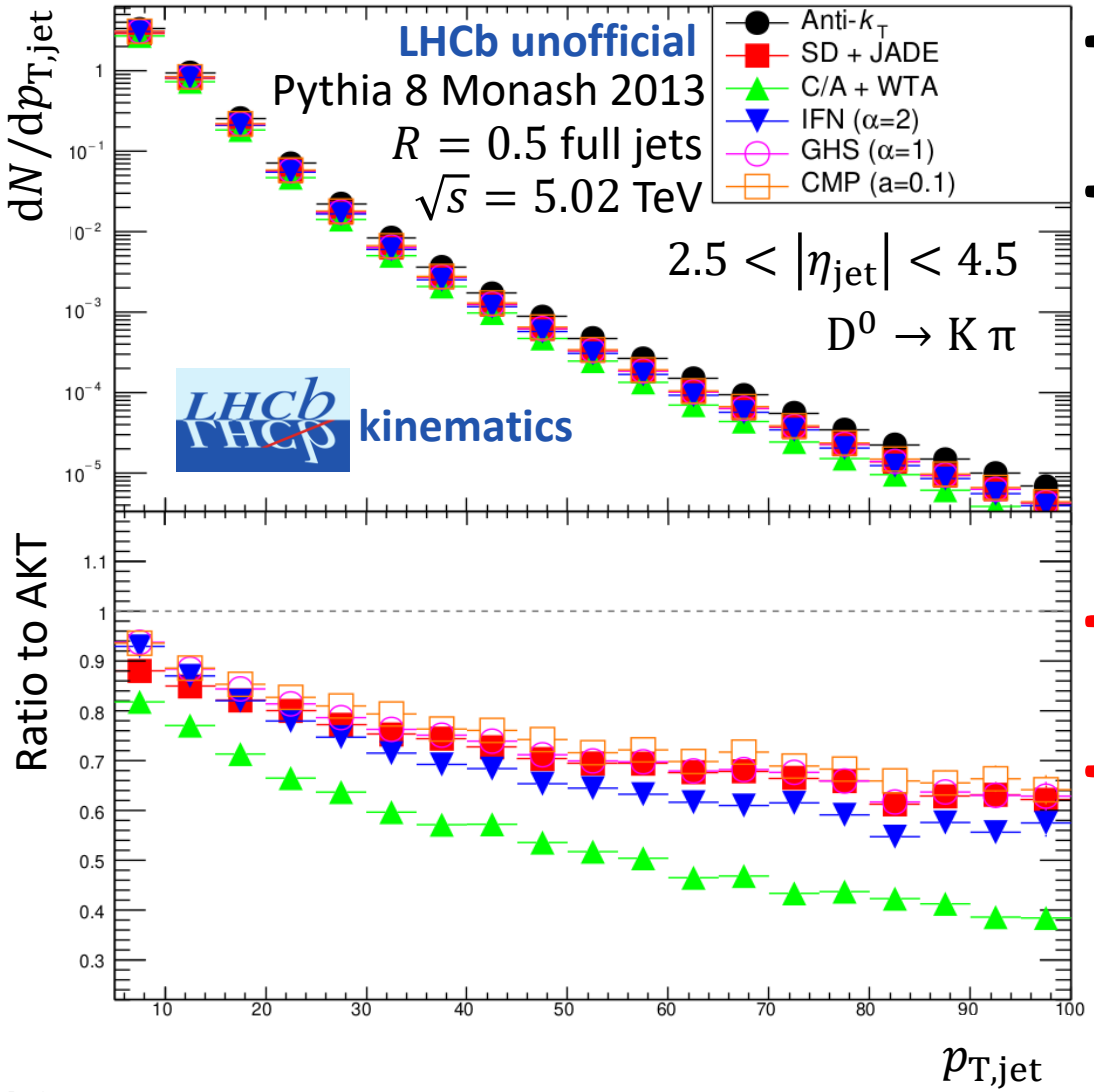
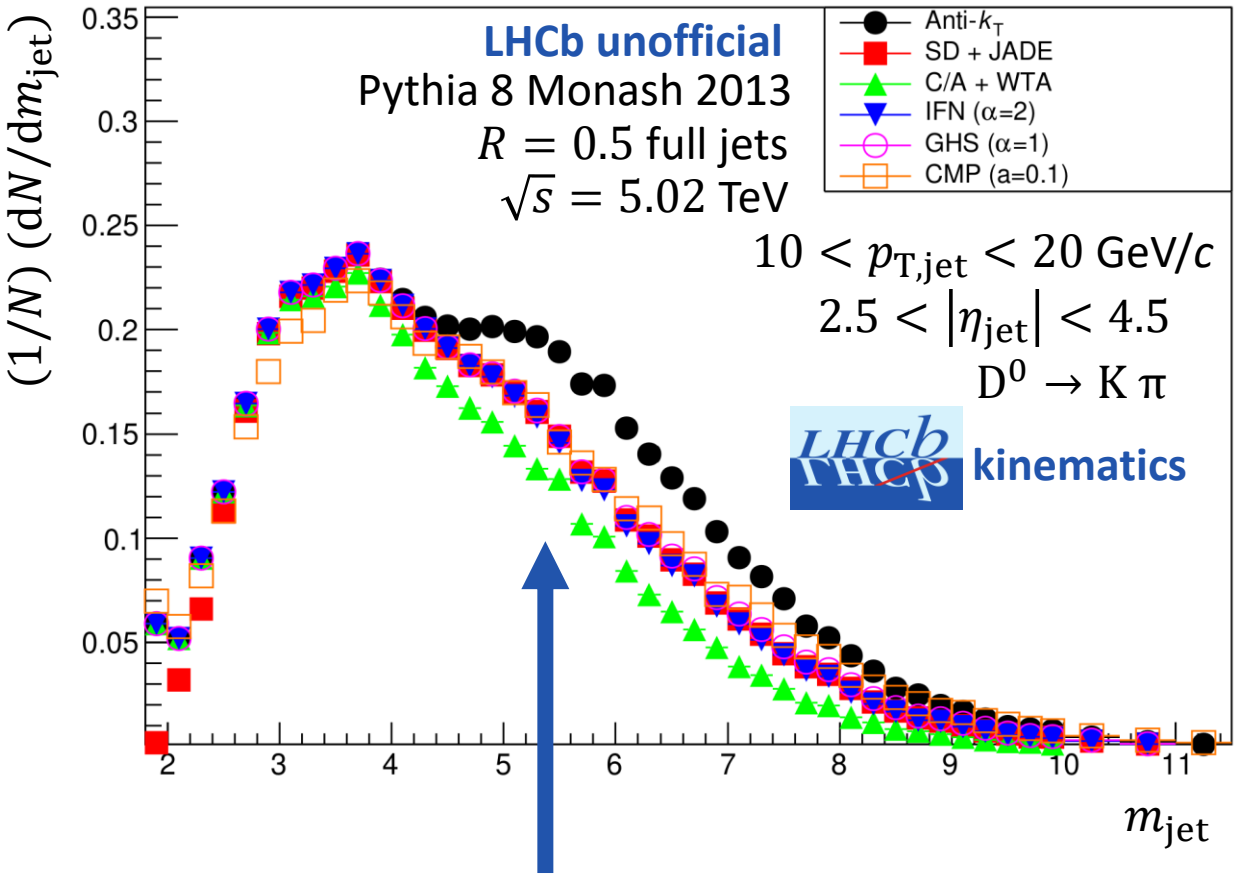


New flavor-tagging algorithms calculable beyond NLO

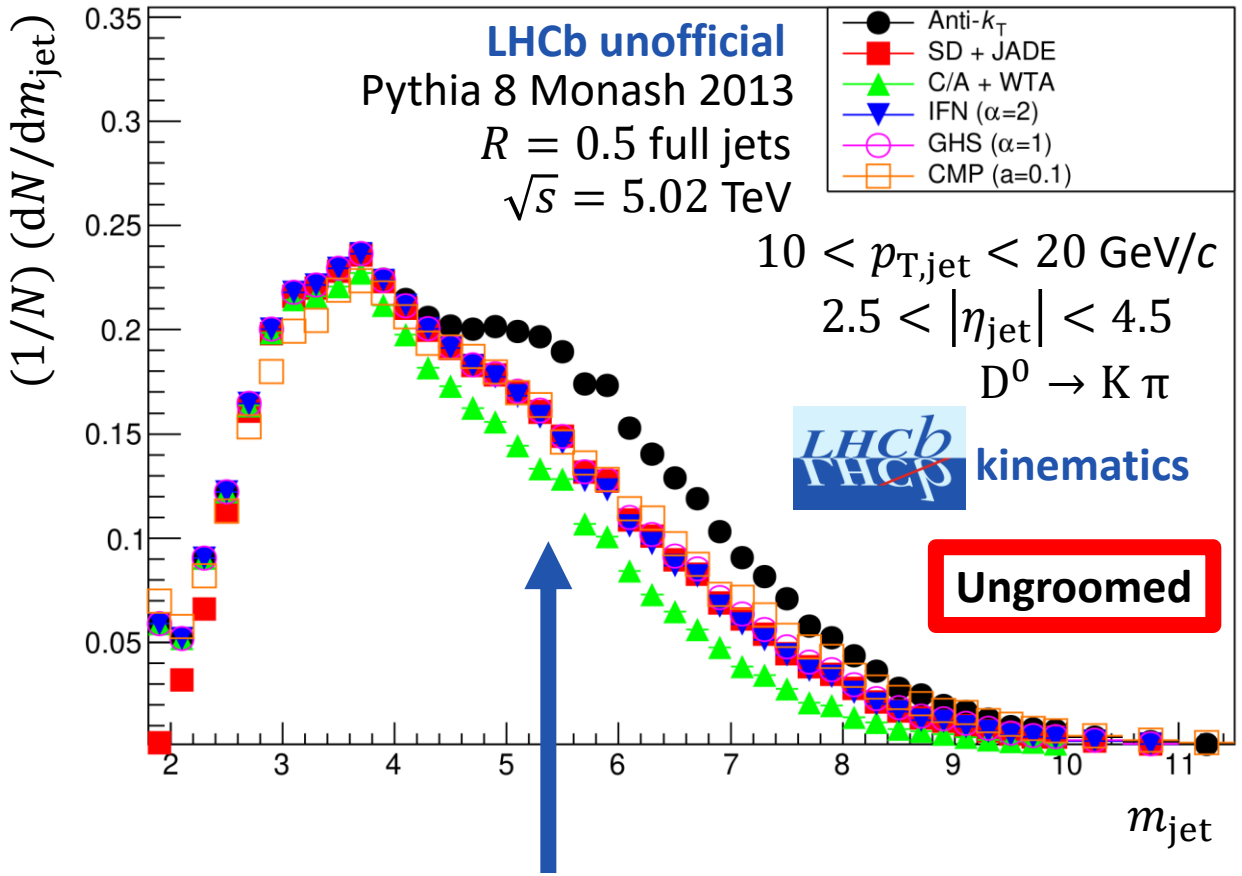
Jets with two HF hadrons

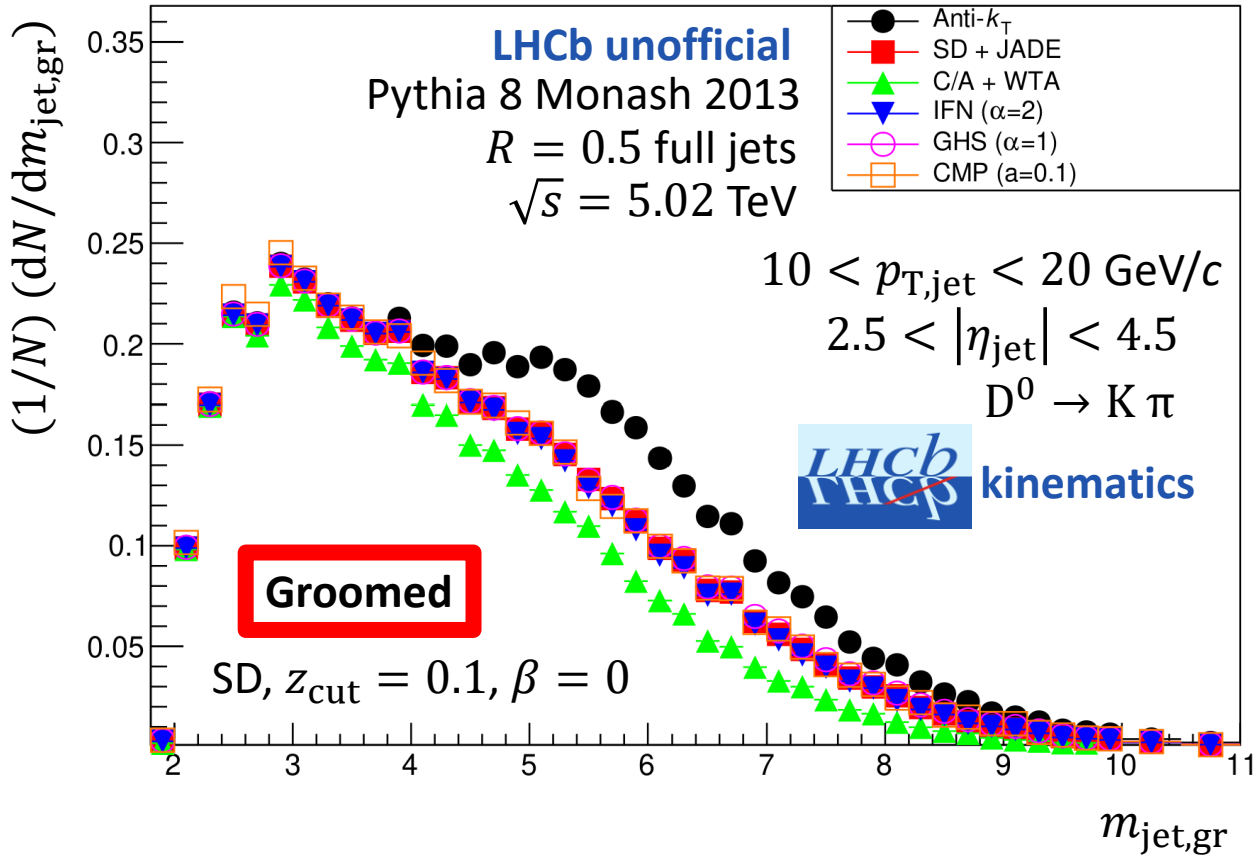
High precision with heavy flavor



New flavor algorithms remove second mass peak

High precision with heavy flavor

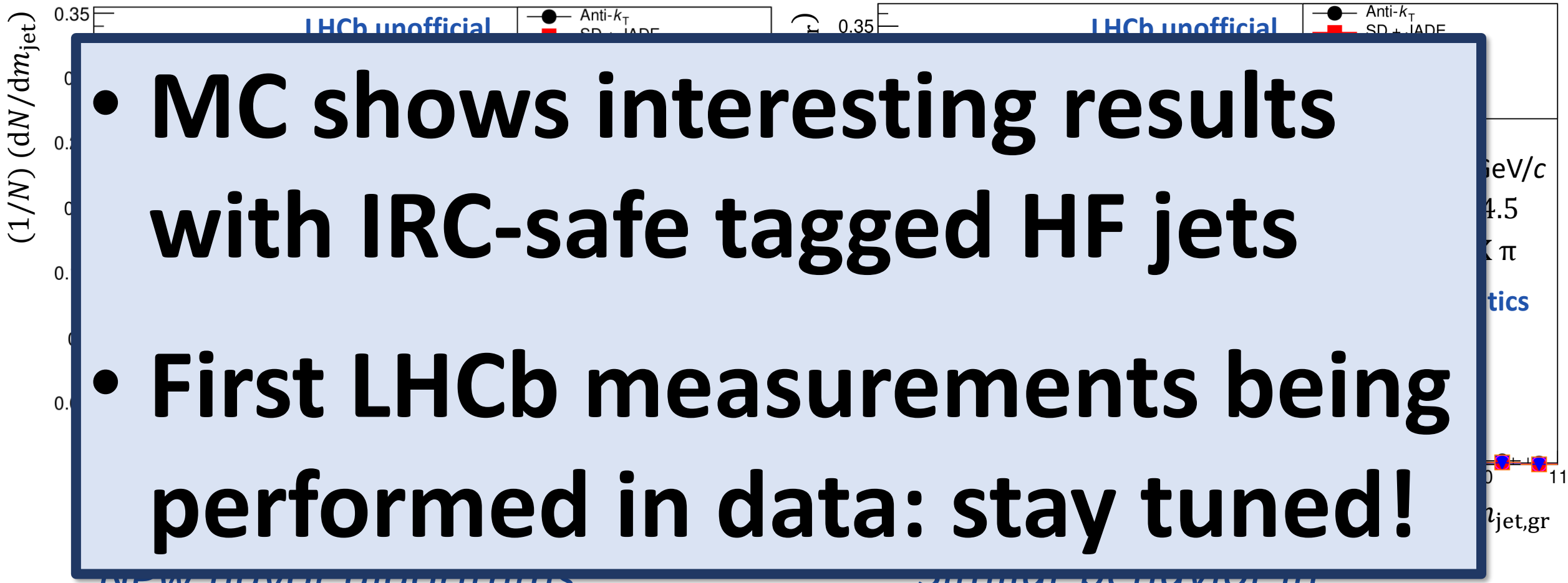




New flavor algorithms remove second mass peak

Similar behavior in groomed jets

High precision with heavy flavor



- **MC shows interesting results with IRC-safe tagged HF jets**
- **First LHCb measurements being performed in data: stay tuned!**

New flavor algorithms remove second mass peak

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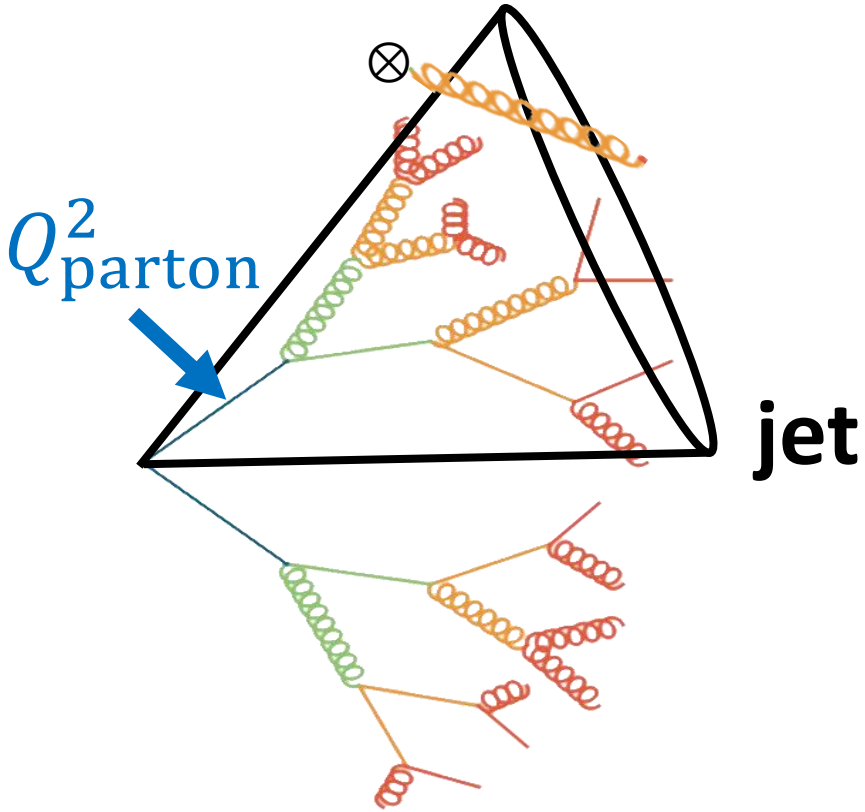

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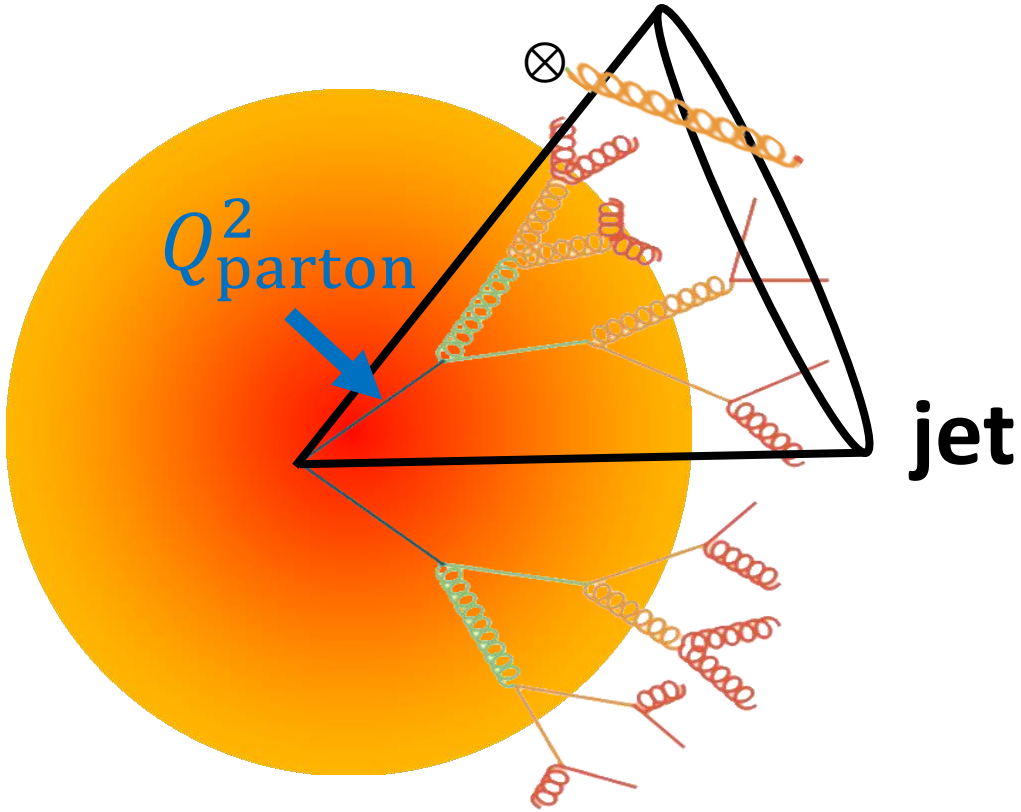

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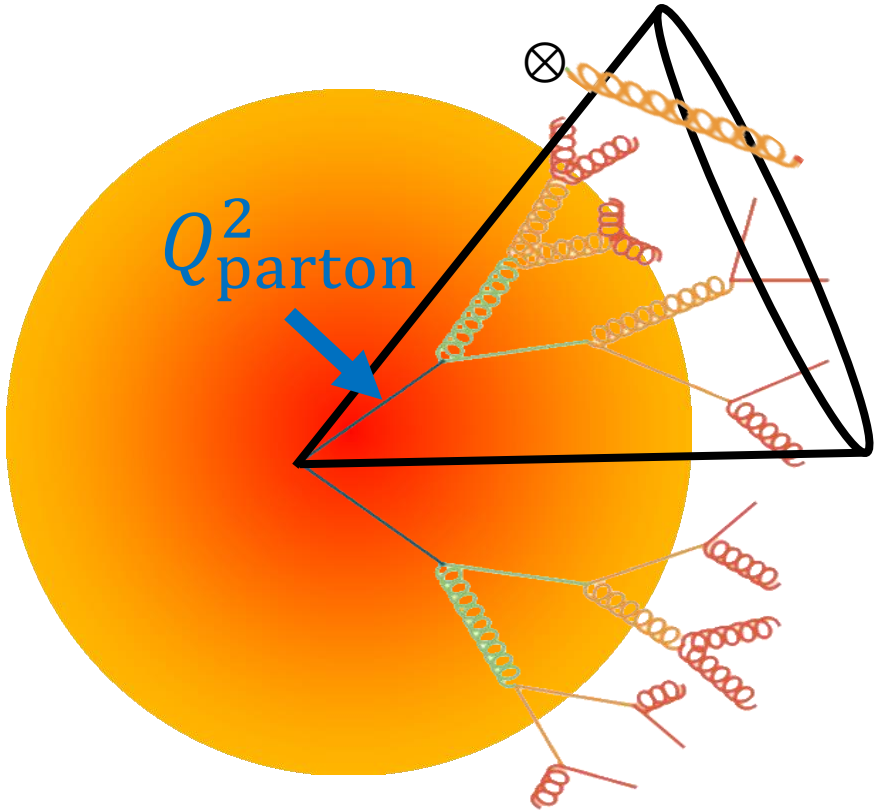
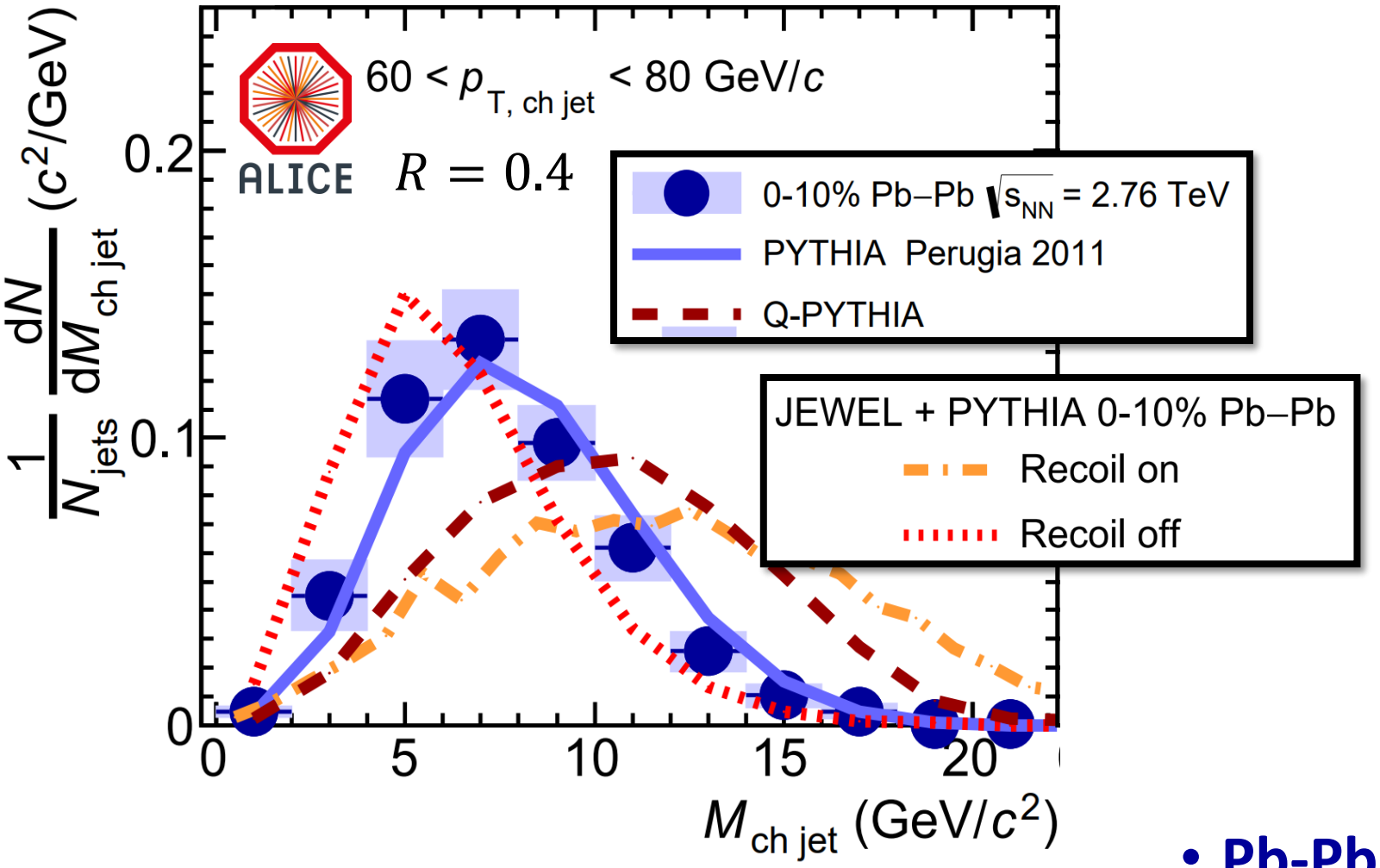


jet

- ***Broadening*** vs. ***narrowing***?
- ***Coherent*** vs. ***incoherent*** scattering?
- ***Resolution scale*** of quarks & gluons?
- Wide-angle ***Rutherford scattering***?
- Medium's ***degrees of freedom***?

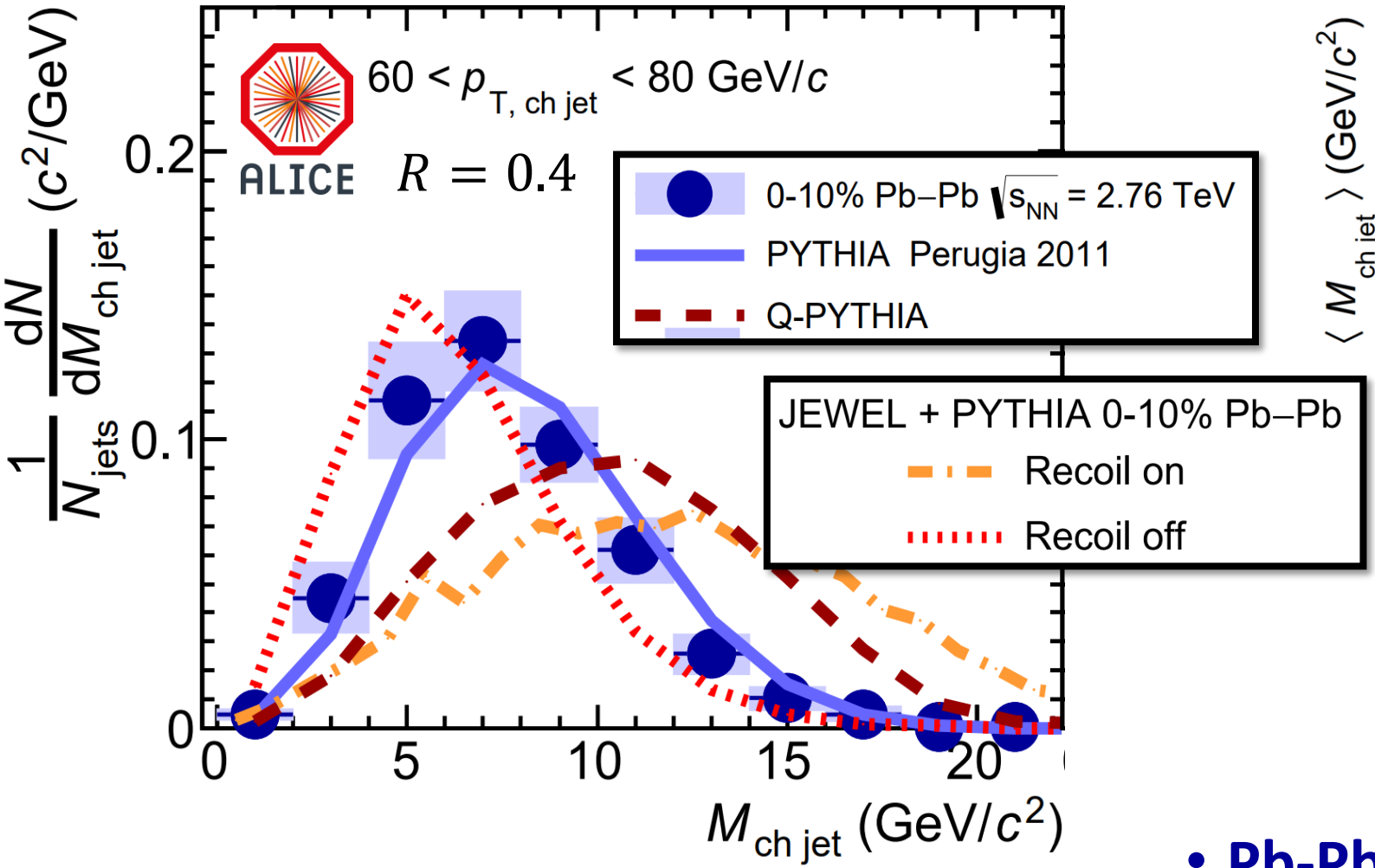
Jet mass in Pb-Pb

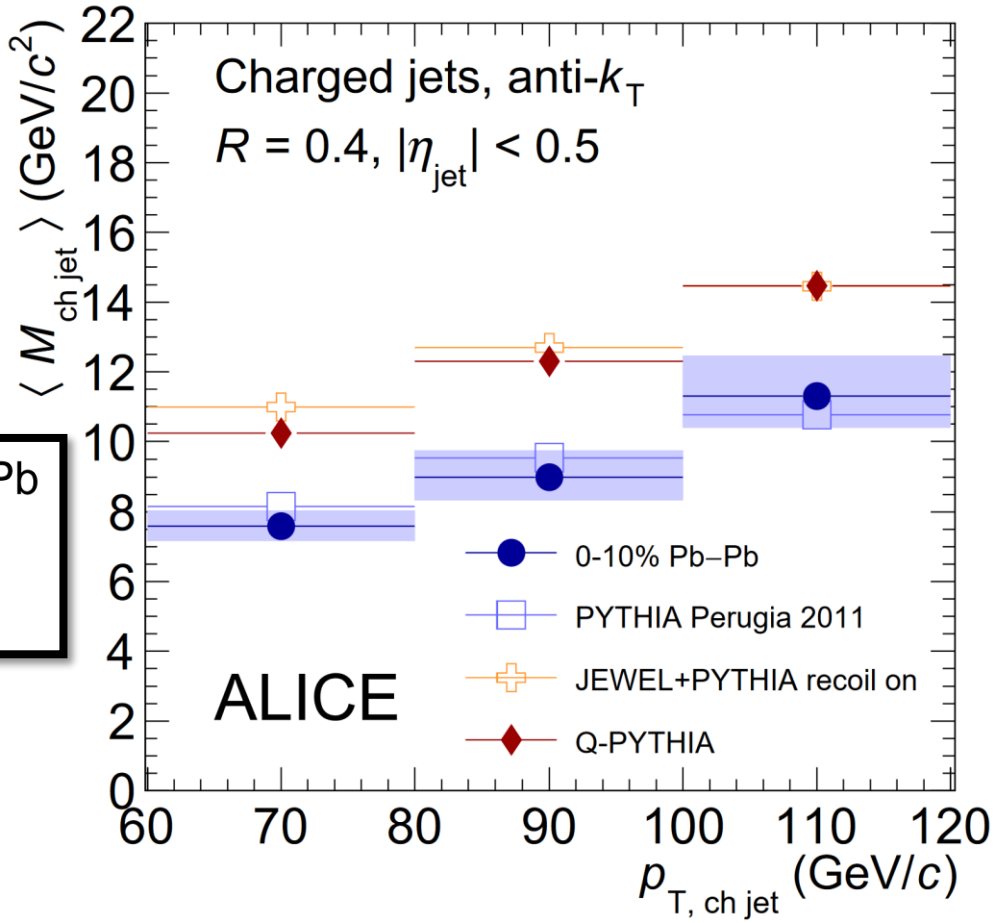


- **Pb-Pb data & PYTHIA pp agree…!**

Phys. Lett. B 776 (2018) 249-264

Jet mass in Pb-Pb





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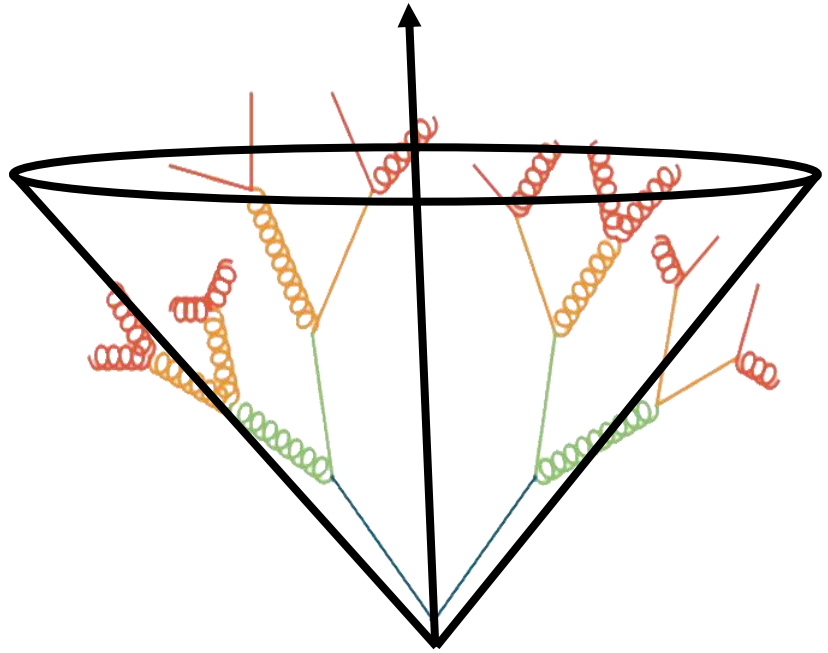
From mass to angularities

Jet angularities:

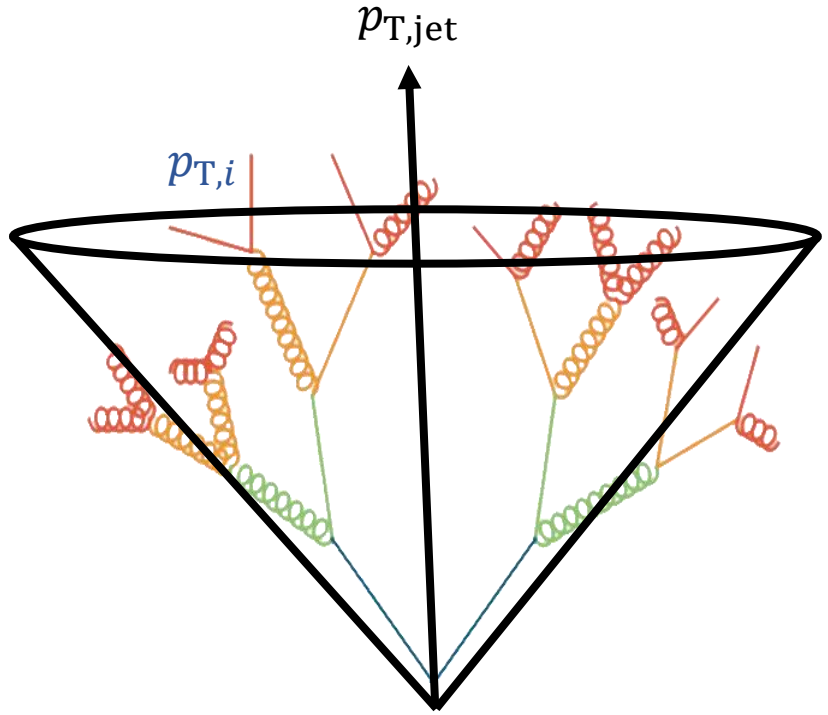
$$\lambda_\alpha = \sum_{i \in \text{jet}} \dots$$



From mass to angularities

Jet angularities:

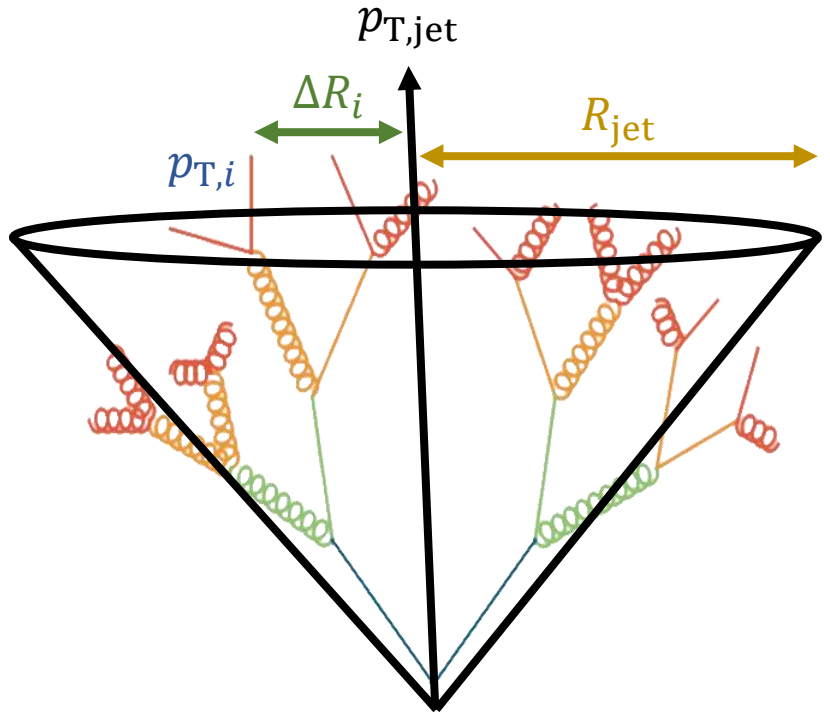
$$\lambda_\alpha = \sum_{i \in \text{jet}} \frac{p_{\text{T},i}}{p_{\text{T,jet}}} \quad \ldots$$



From mass to angularities

Jet angularities:

$$\lambda_\alpha = \sum_{i \in \text{jet}} \frac{p_{\text{T},i}}{p_{\text{T,jet}}} \left(\frac{\Delta R_i}{R_{\text{jet}}} \right)^\alpha$$



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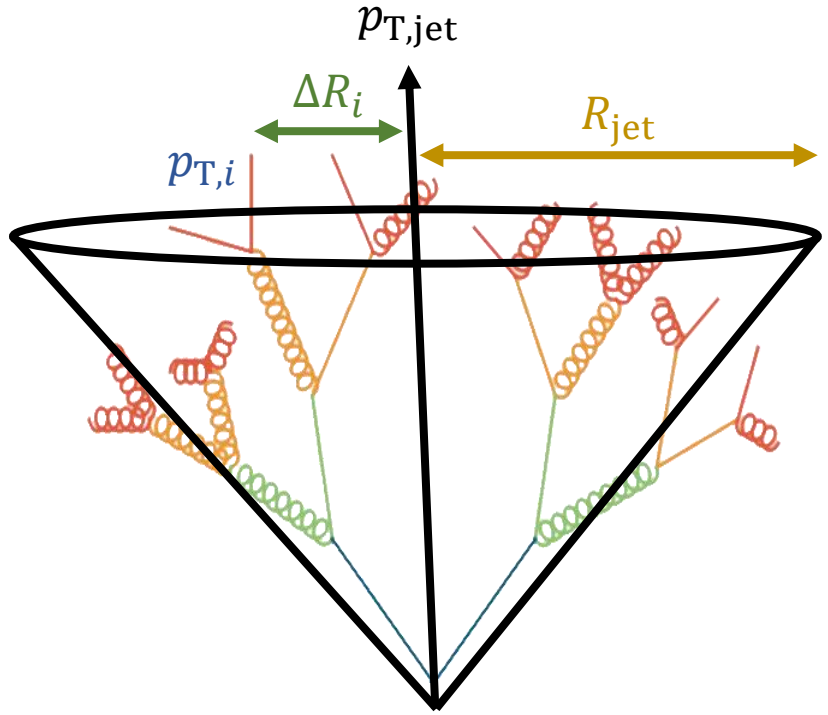
$$\lambda_\alpha = \sum_{i \in \text{jet}} \frac{p_{\text{T},i}}{p_{\text{T,jet}}} \left(\frac{\Delta R_i}{R_{\text{jet}}} \right)^\alpha$$

α ← *free parameter*

free parameter → R_{jet}

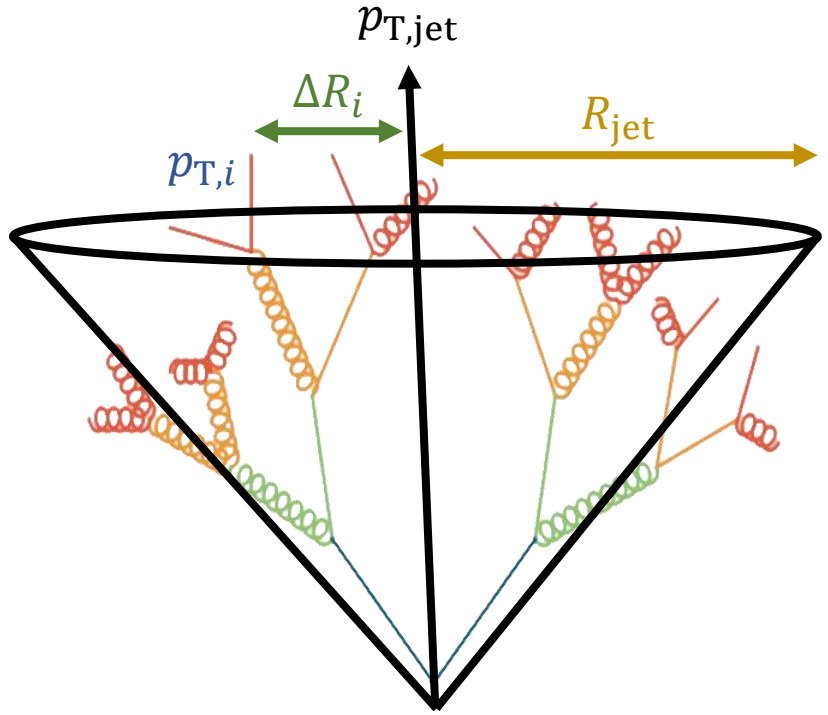


From mass to angularities

Jet angularities:

$$\lambda_\alpha = \sum_{i \in \text{jet}} \frac{p_{\text{T},i}}{p_{\text{T,jet}}} \left(\frac{\Delta R_i}{R_{\text{jet}}} \right)^\alpha = \sum_{i \in \text{jet}} z_i \theta_i^\alpha$$

"Where is the p_{T} inside the jet?"

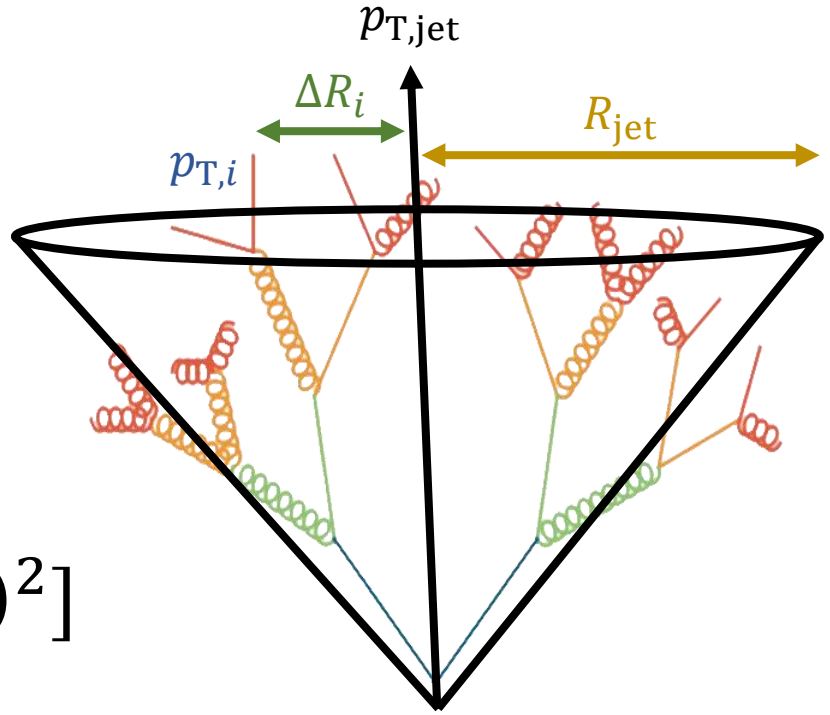


From mass to angularities

Jet angularities:

$$\lambda_\alpha = \sum_{i \in \text{jet}} \frac{p_{\text{T},i}}{p_{\text{T,jet}}} \left(\frac{\Delta R_i}{R_{\text{jet}}} \right)^\alpha = \sum_{i \in \text{jet}} z_i \theta_i^\alpha$$

"Where is the p_{T} inside the jet?"



Jet girth: $g = R * \lambda_1$

Jet thrust:

$$\lambda_2 = \left(\frac{m}{R p_{\text{T}}} \right)^2 + O[(\lambda_2)^2]$$

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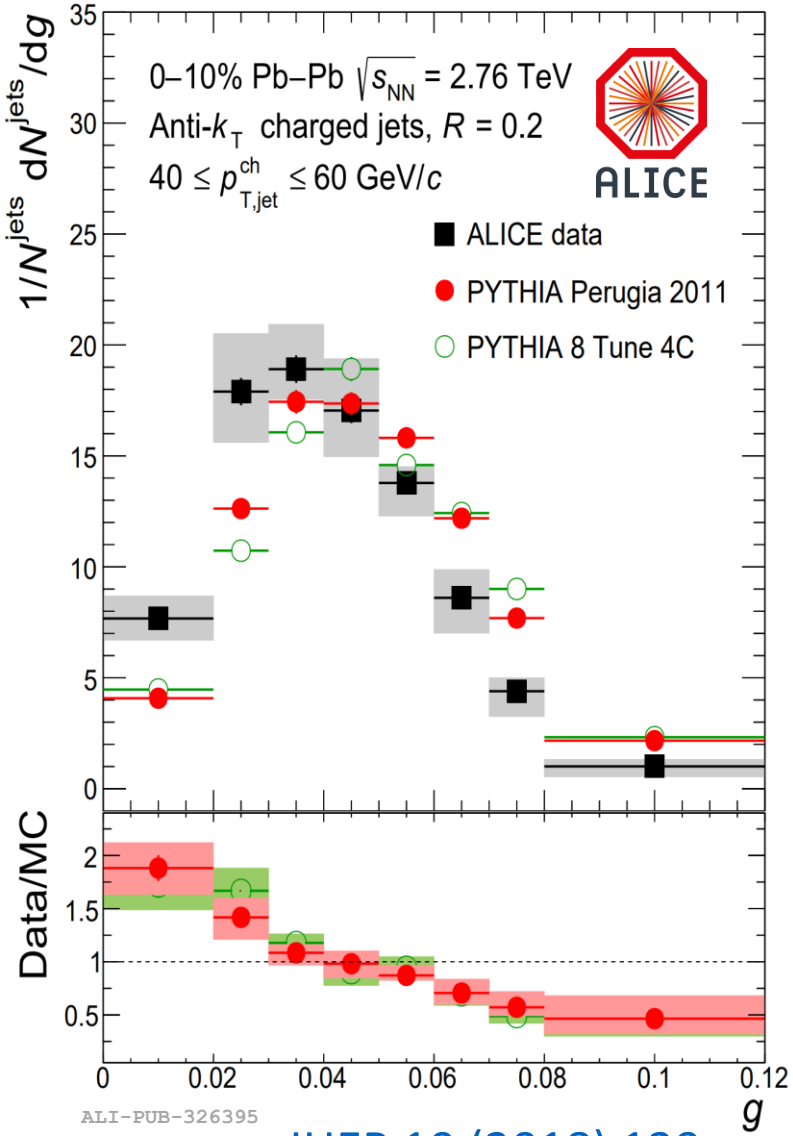

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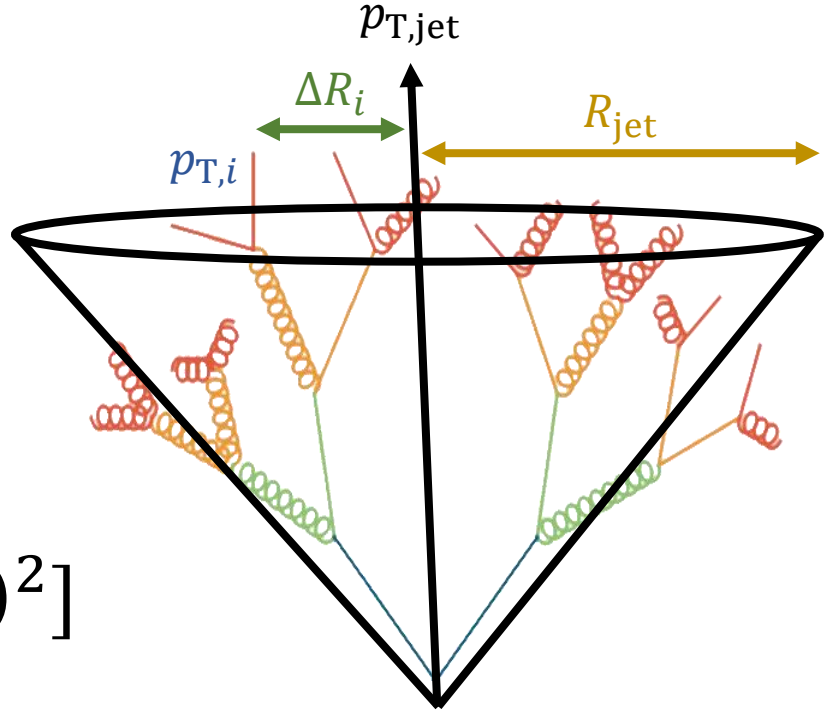

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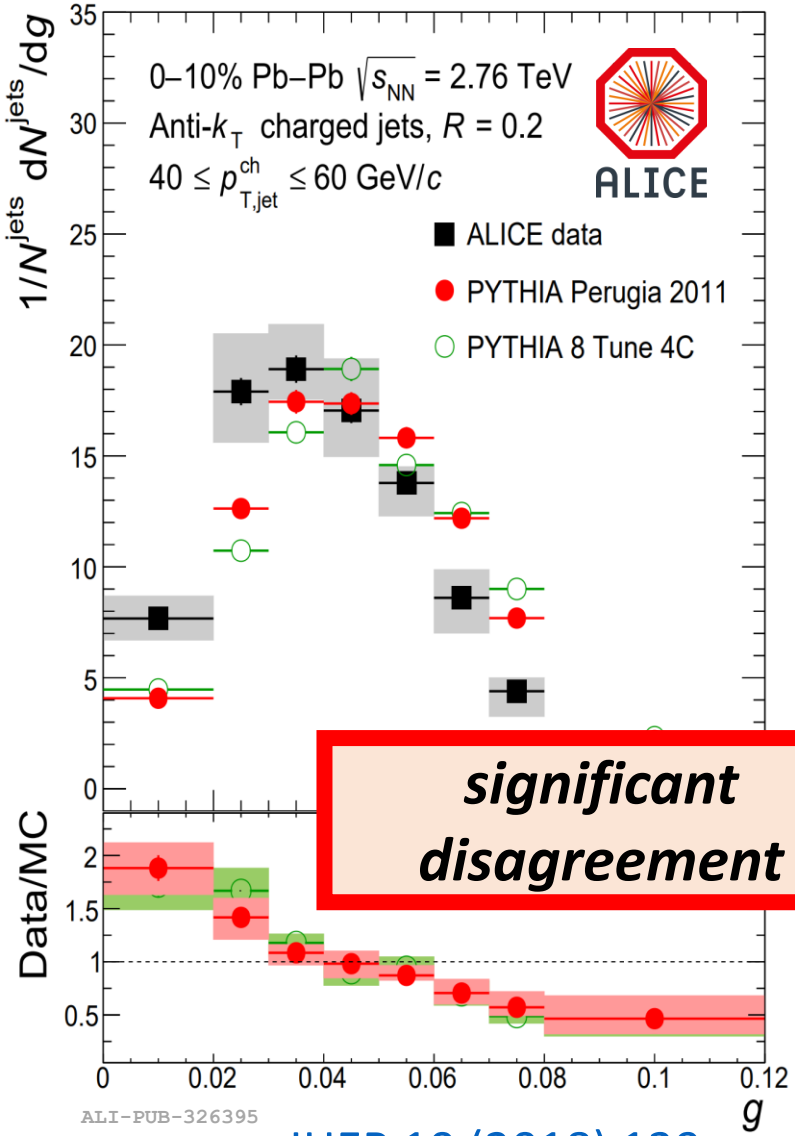
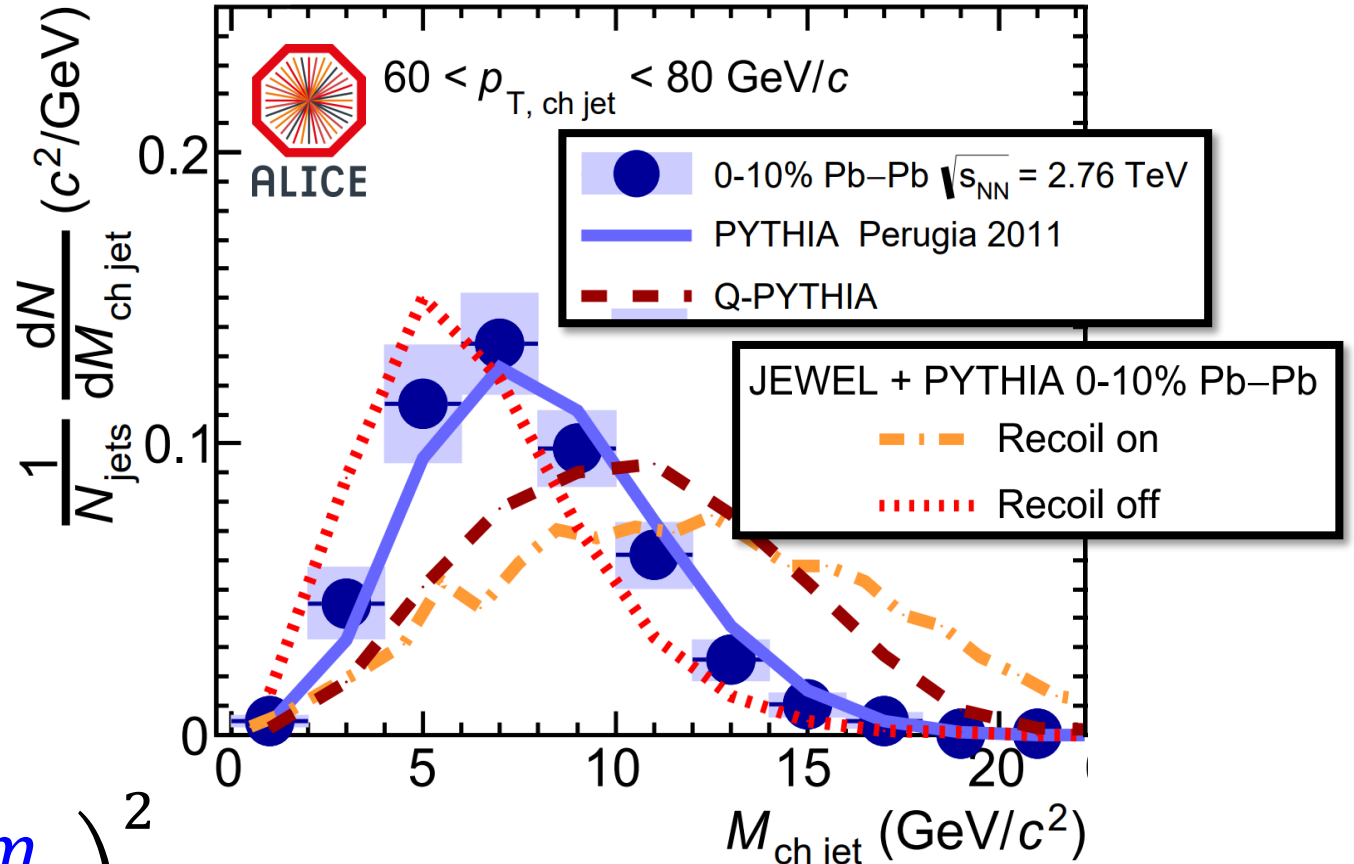


significant disagreement



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No significant disagreement

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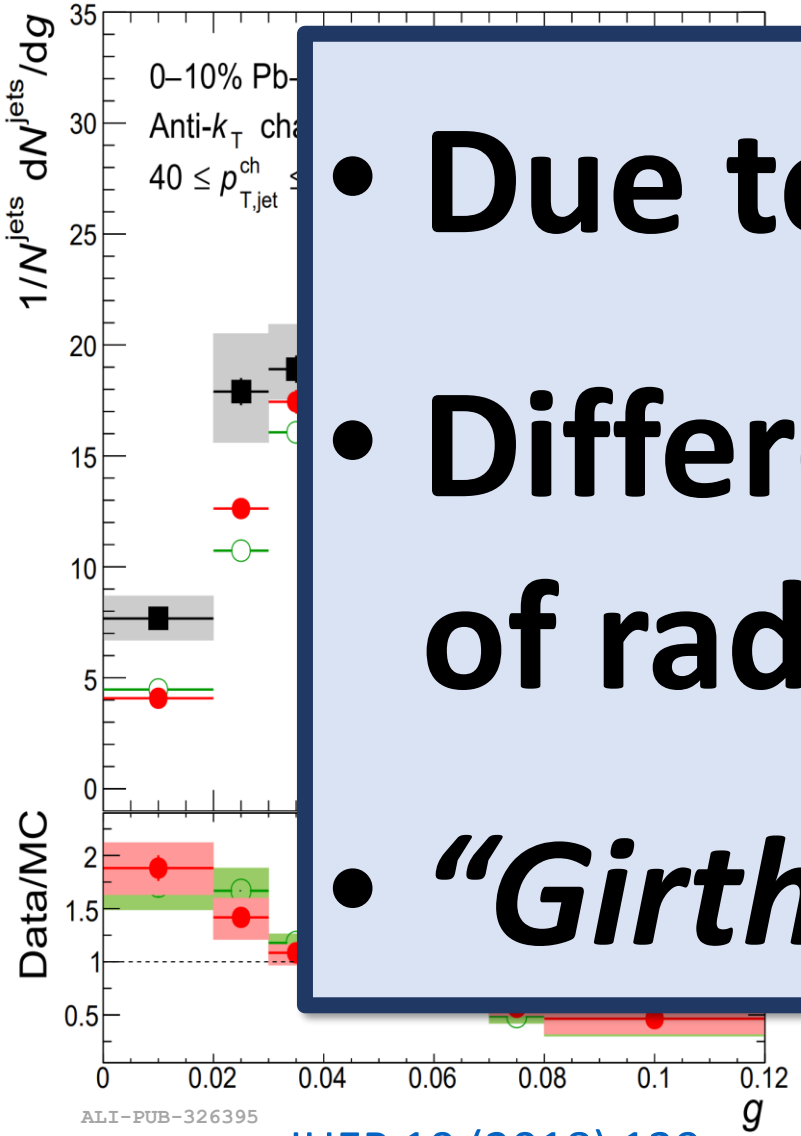
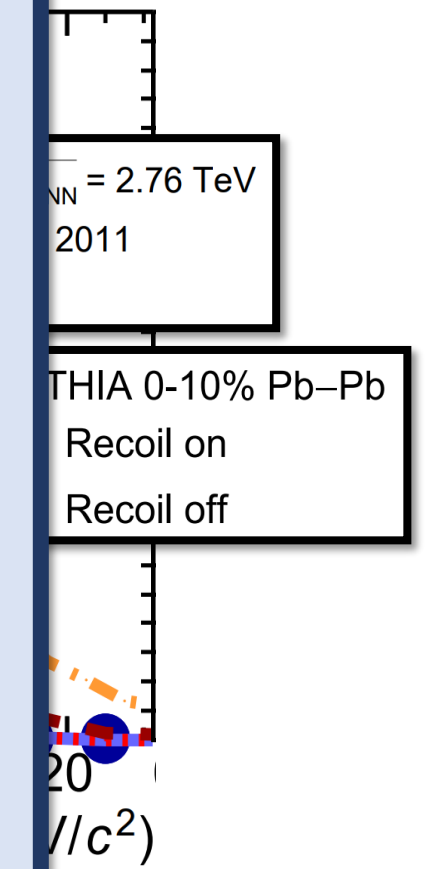
Phys. Lett. B 776 (2018) 249-264

From mass to angularities



- **Due to different $p_{\mathrm{T}}^{\mathrm{jet}}$? R?**
- **Difference in the angles of radiation probed?**
- ***"Girth-mass puzzle"***



(Rp_{T})

ignificant disagreement

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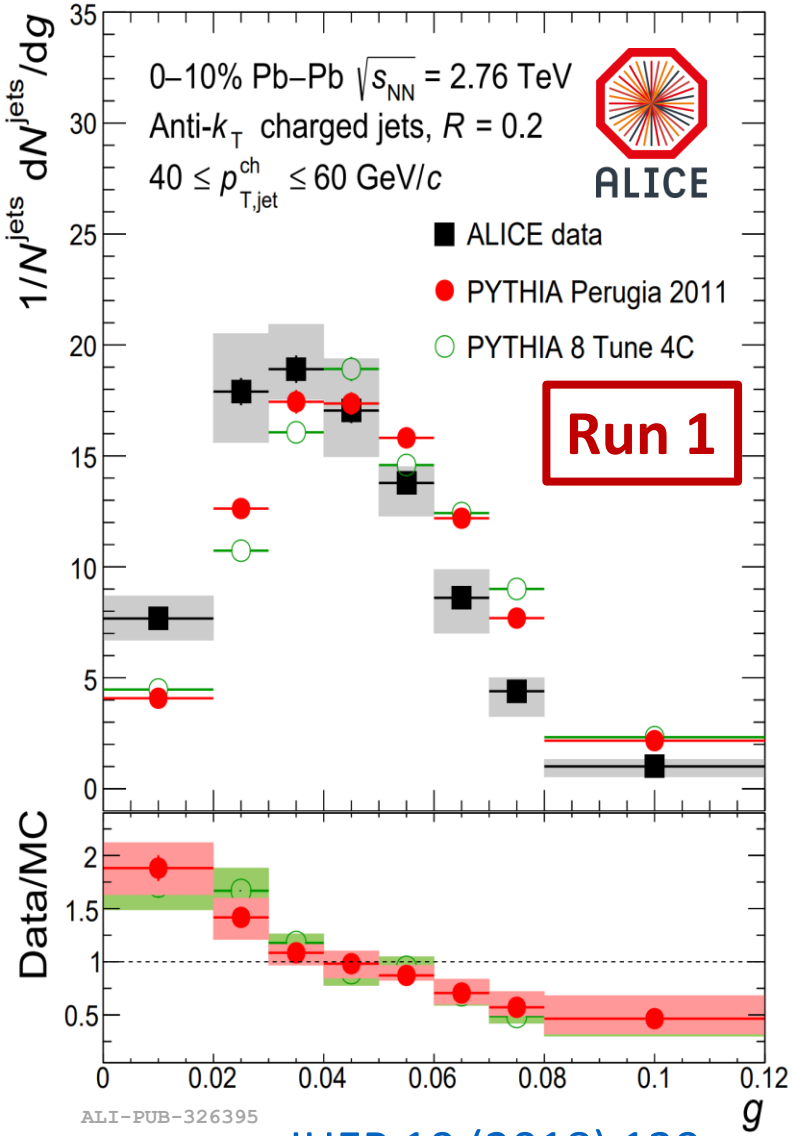

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$$g = \lambda_1 * R$$

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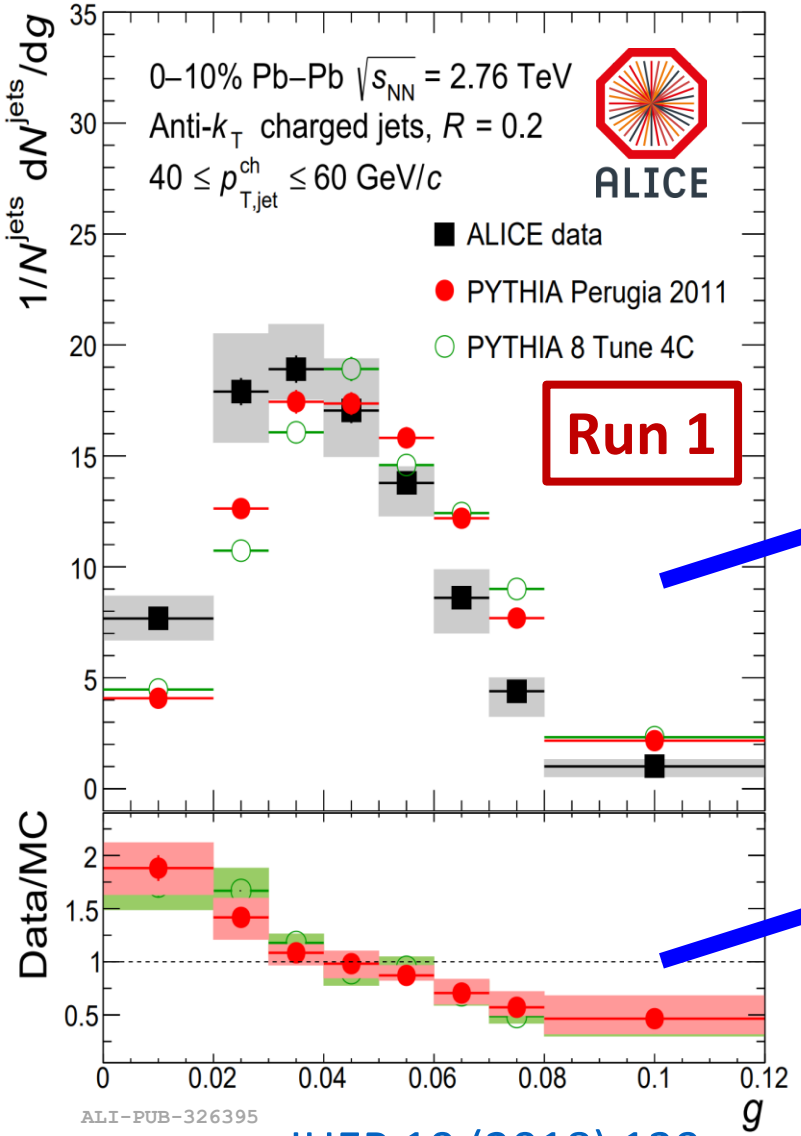
New run 2 girth study



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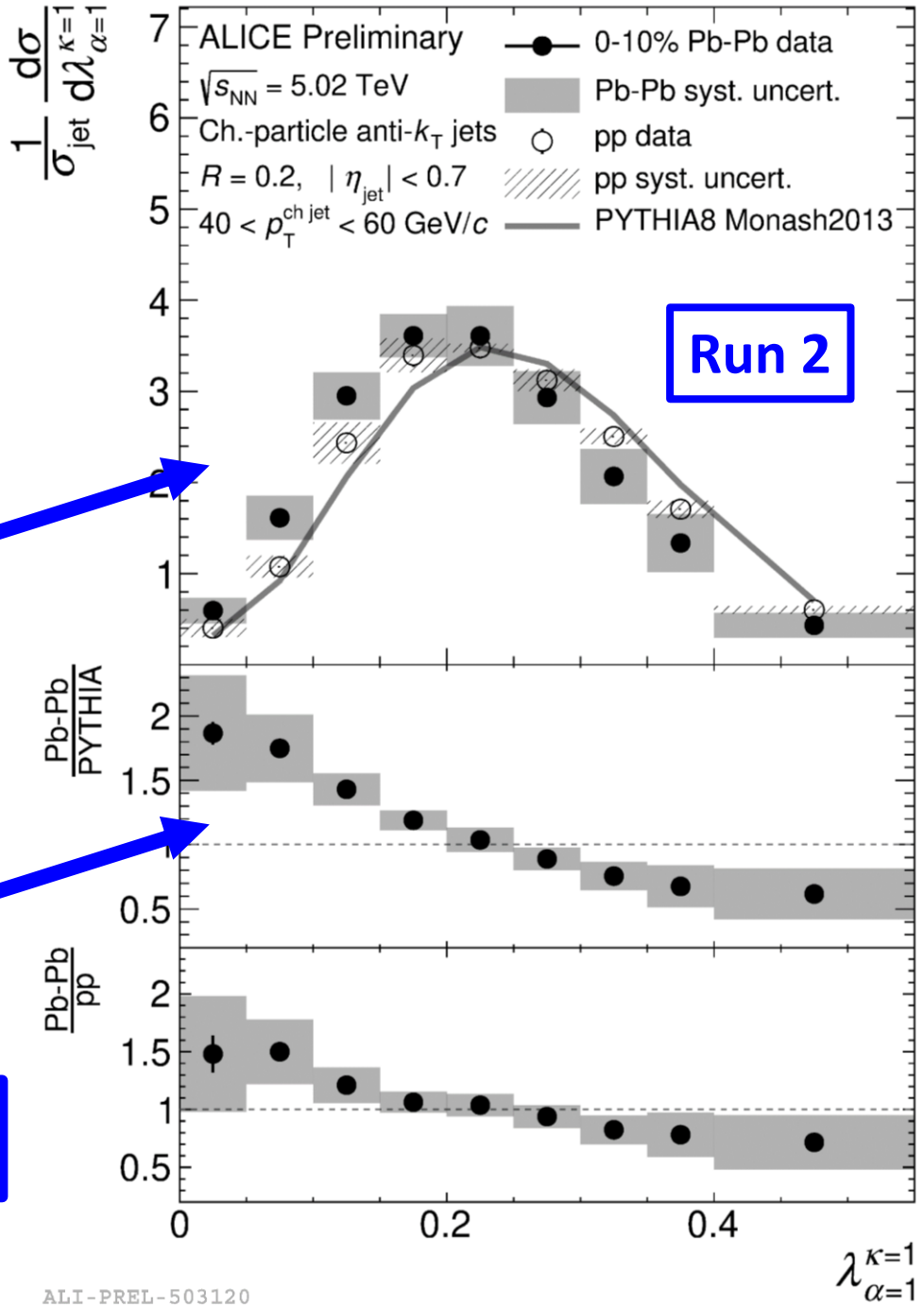

https://alice-figure.web.cern.ch/node/21570

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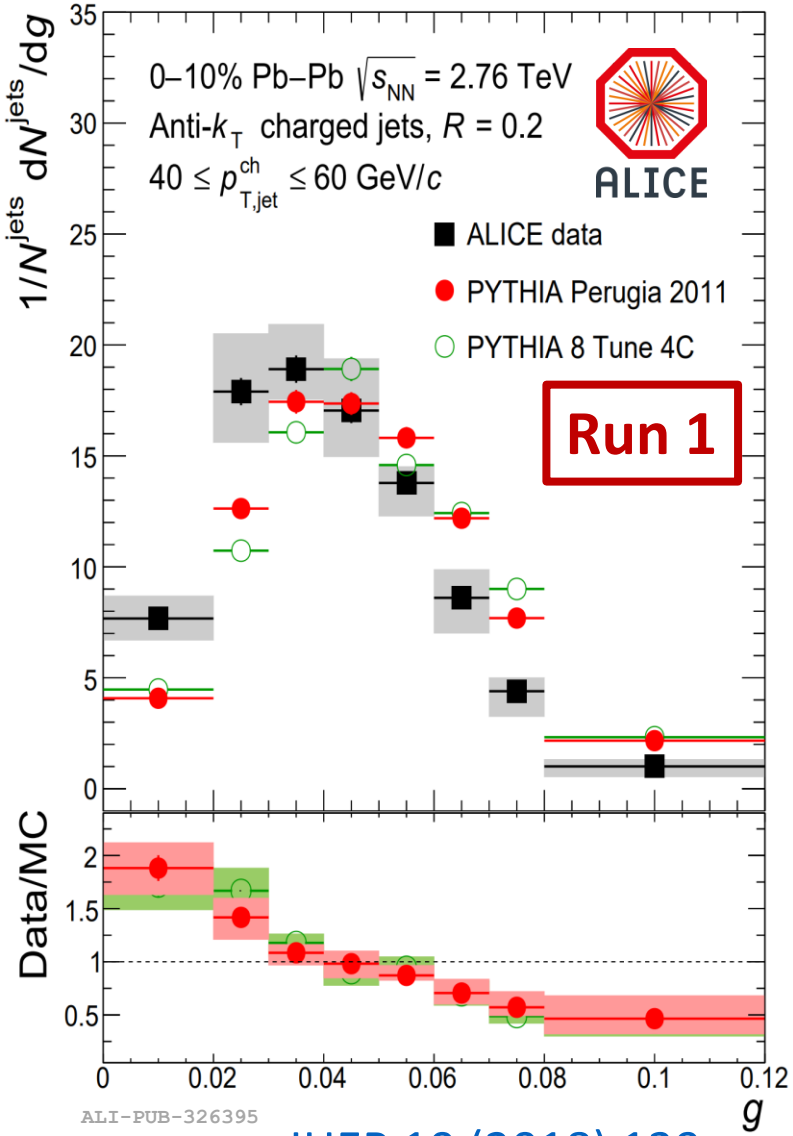

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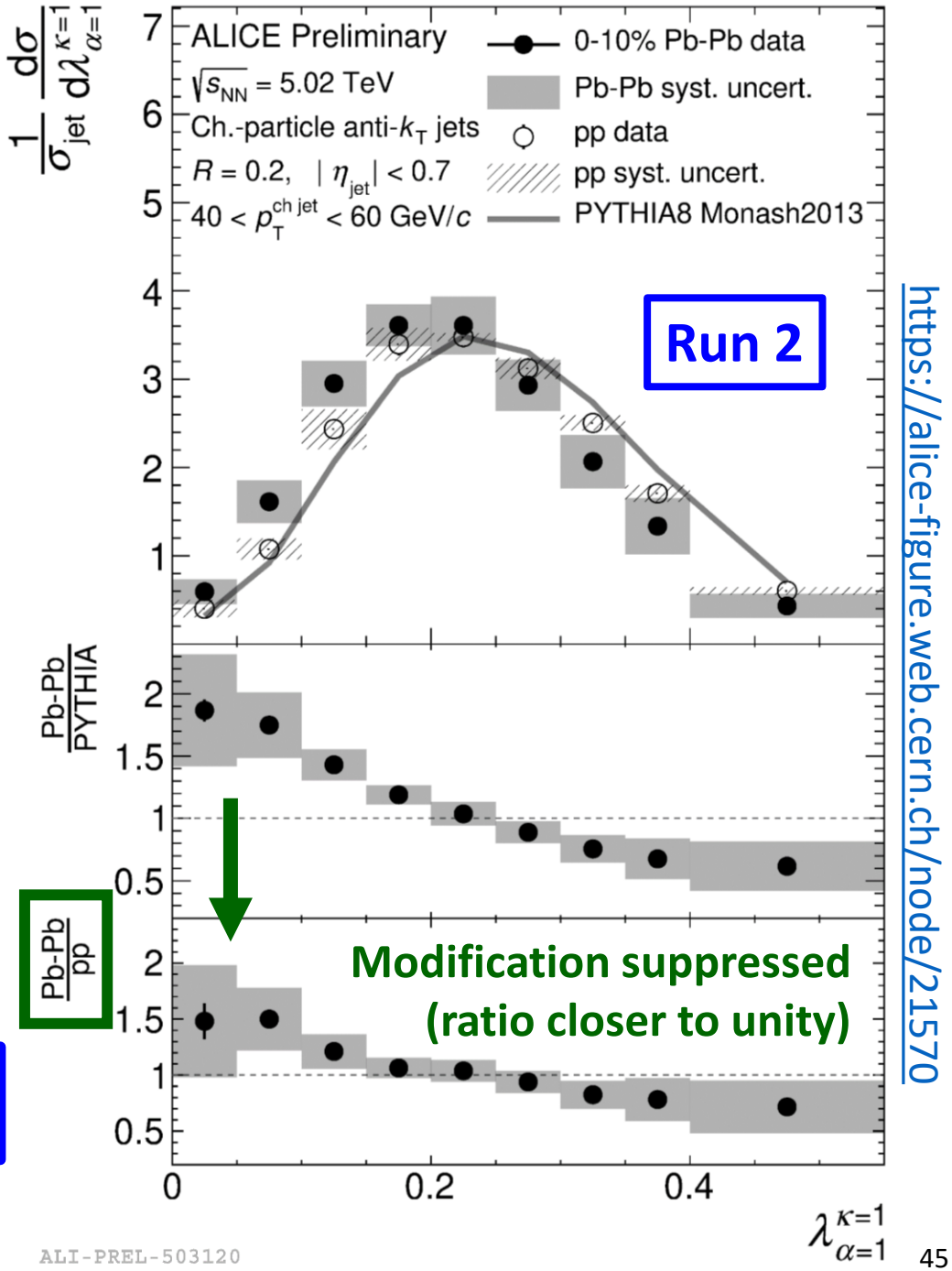

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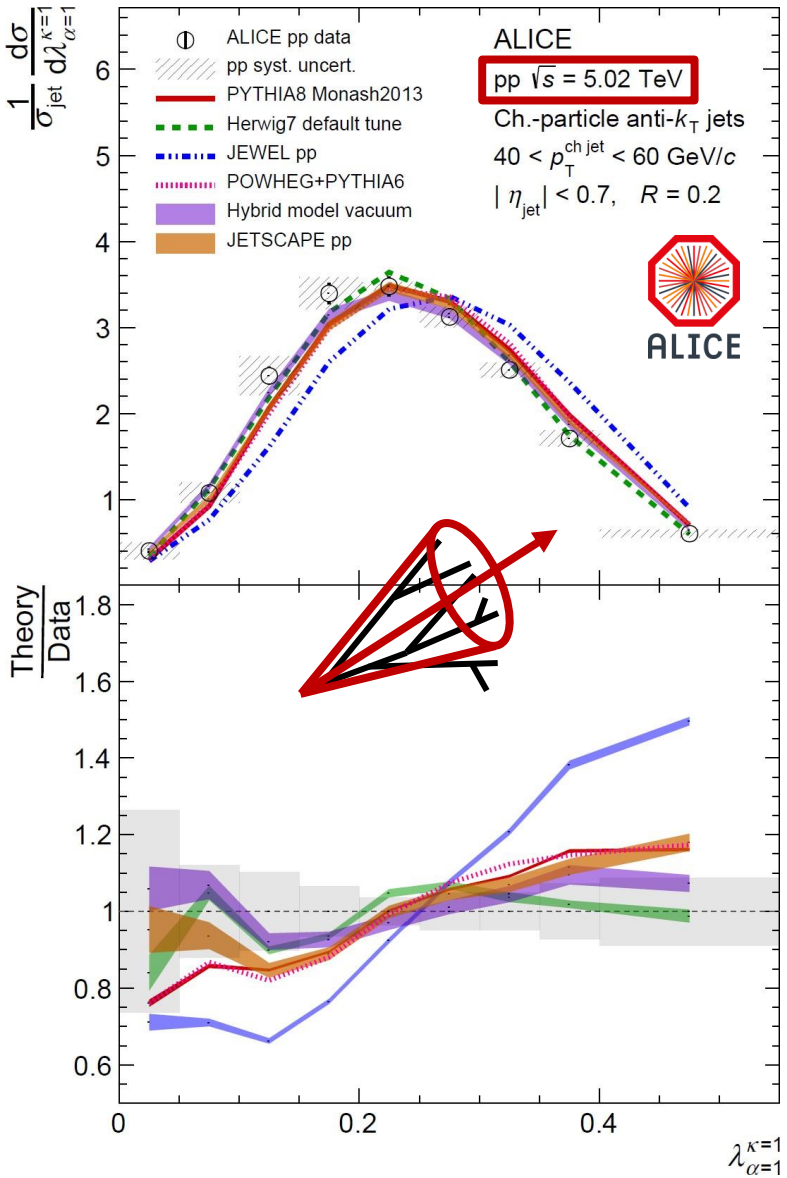
QCD fragmentation modifications



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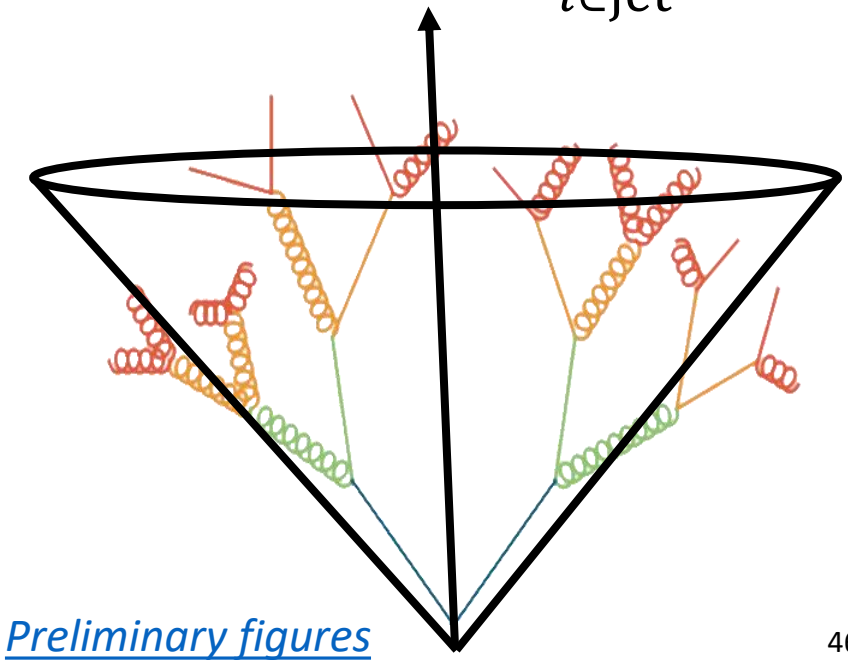
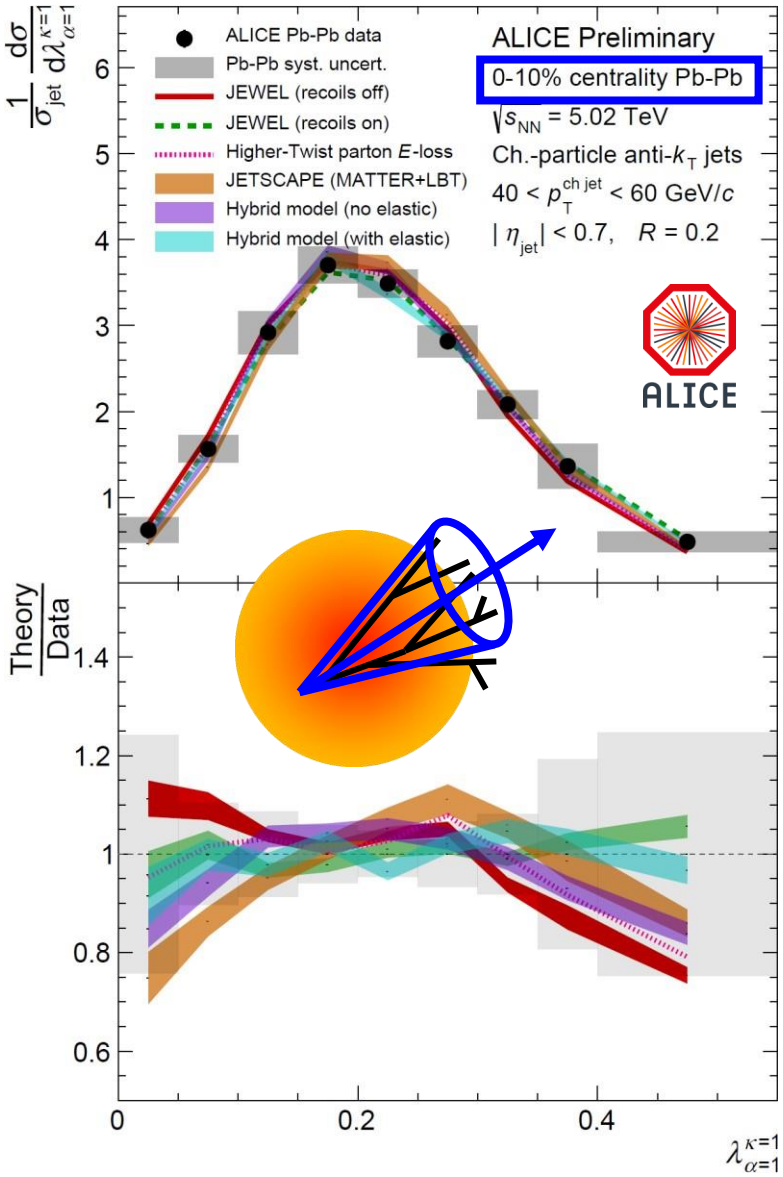
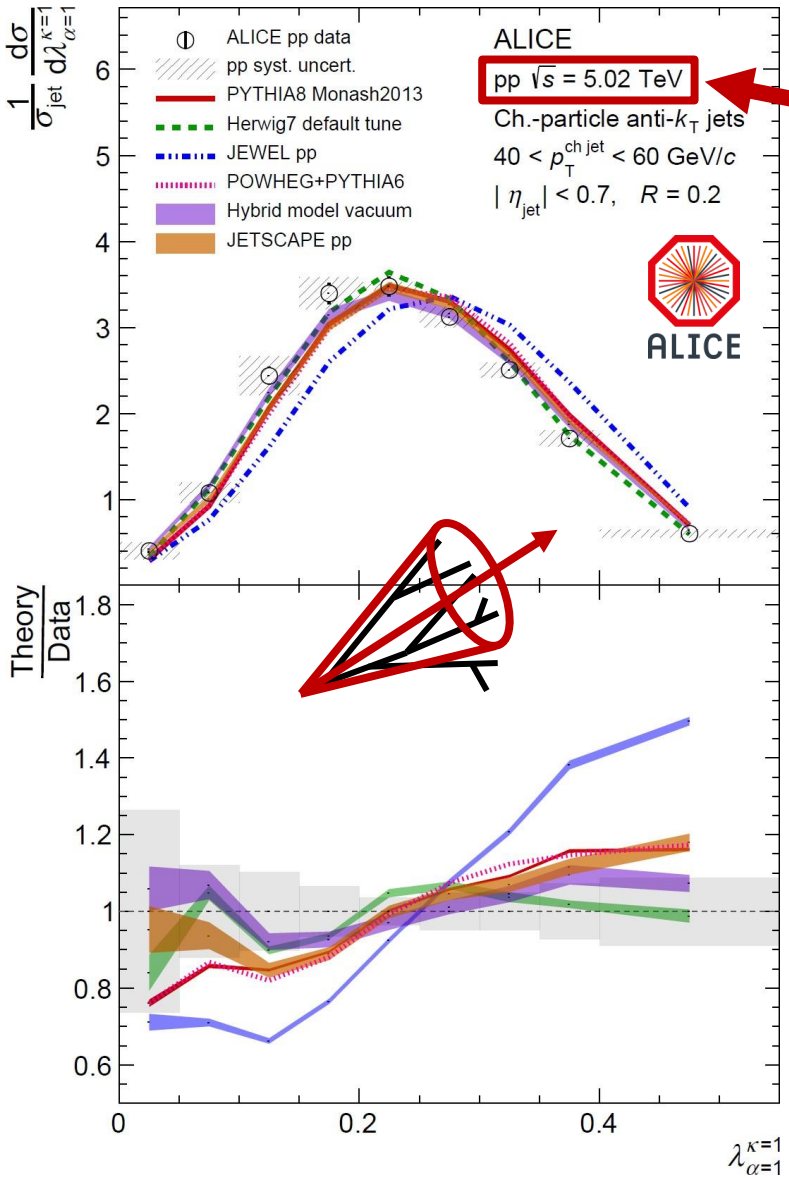


Preliminary figures

QCD fragmentation modifications





Run 2 pp baseline for AA quenching

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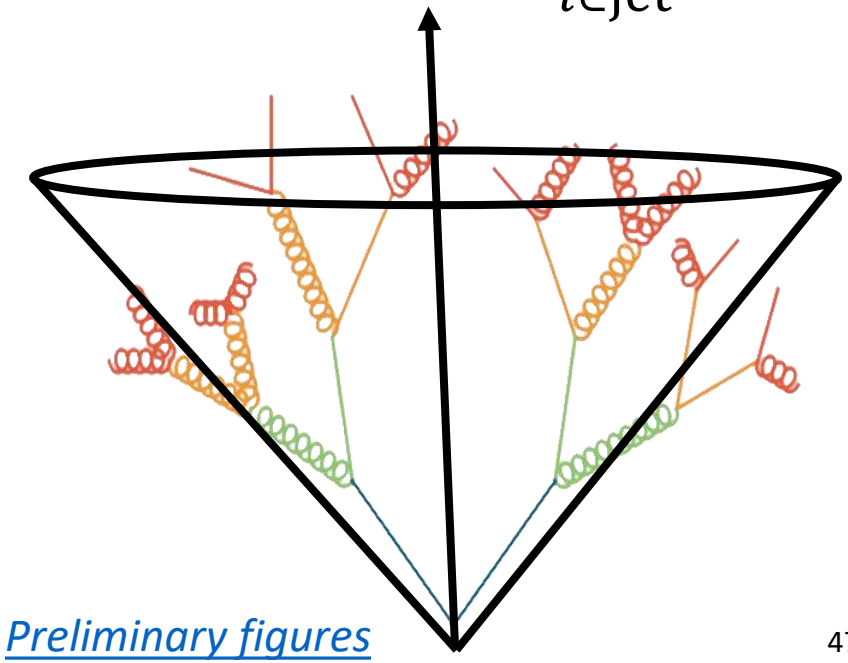

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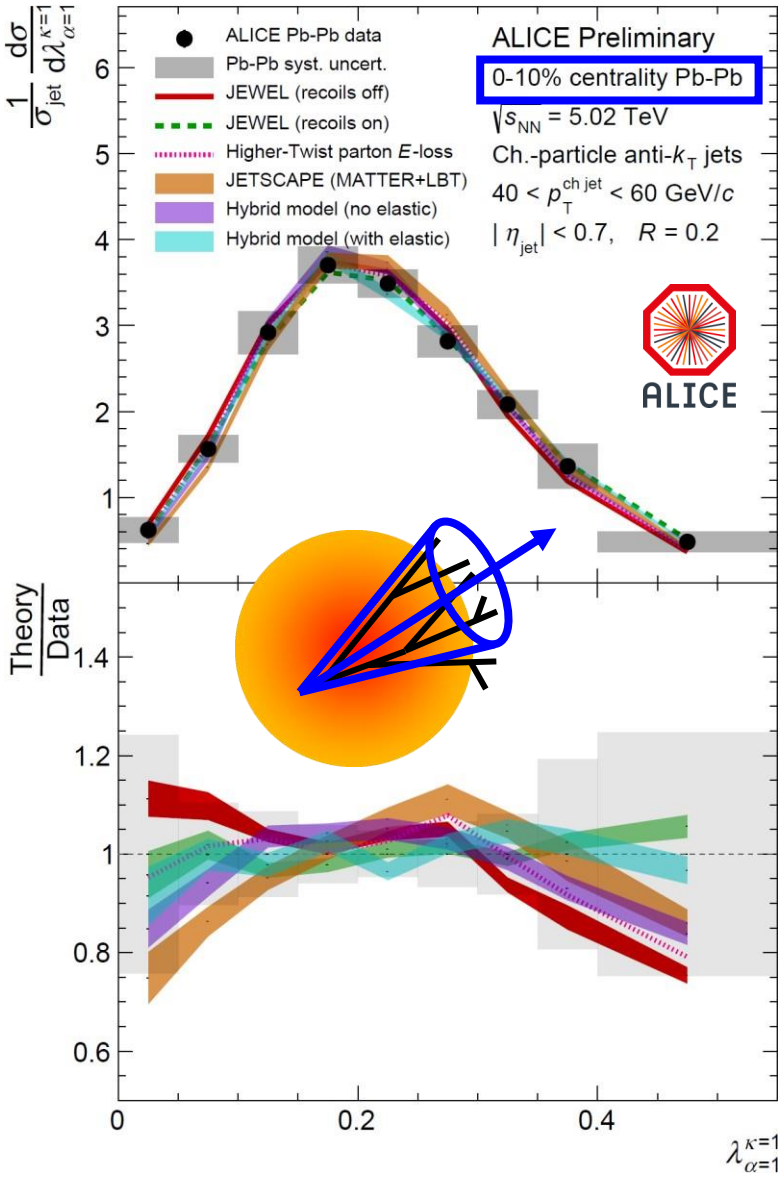

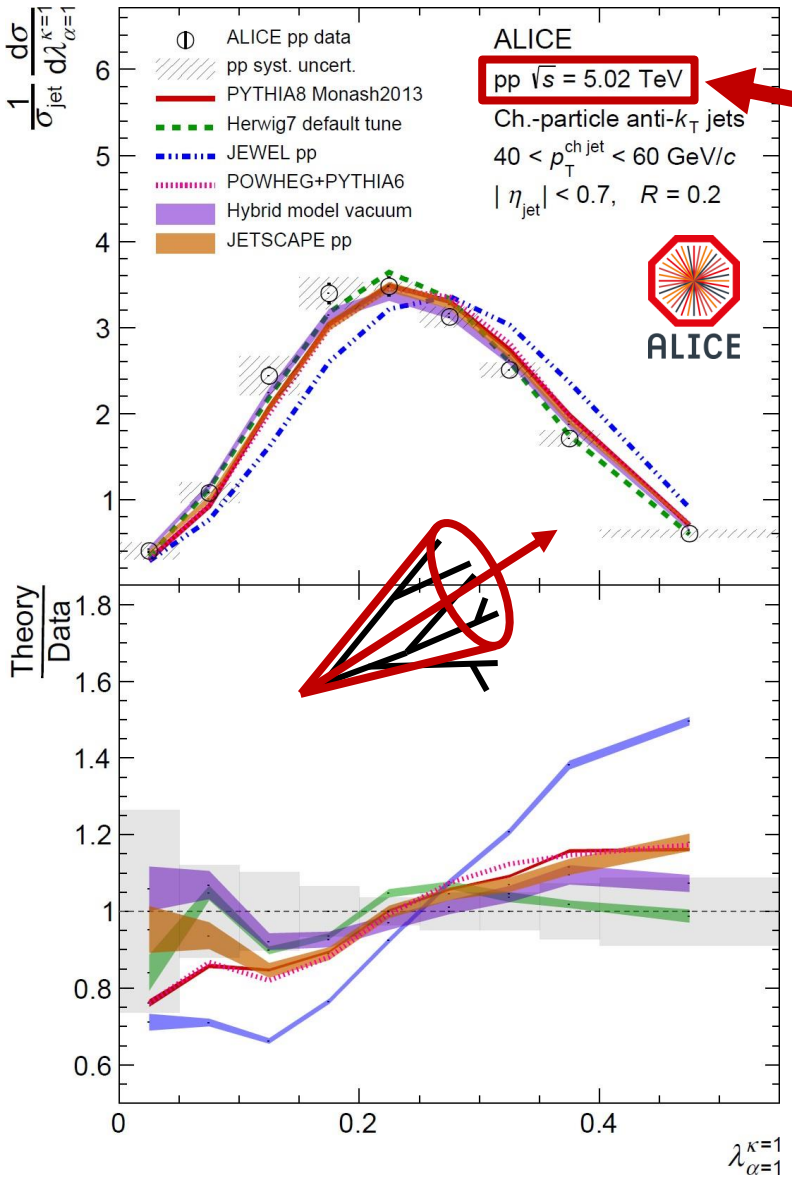

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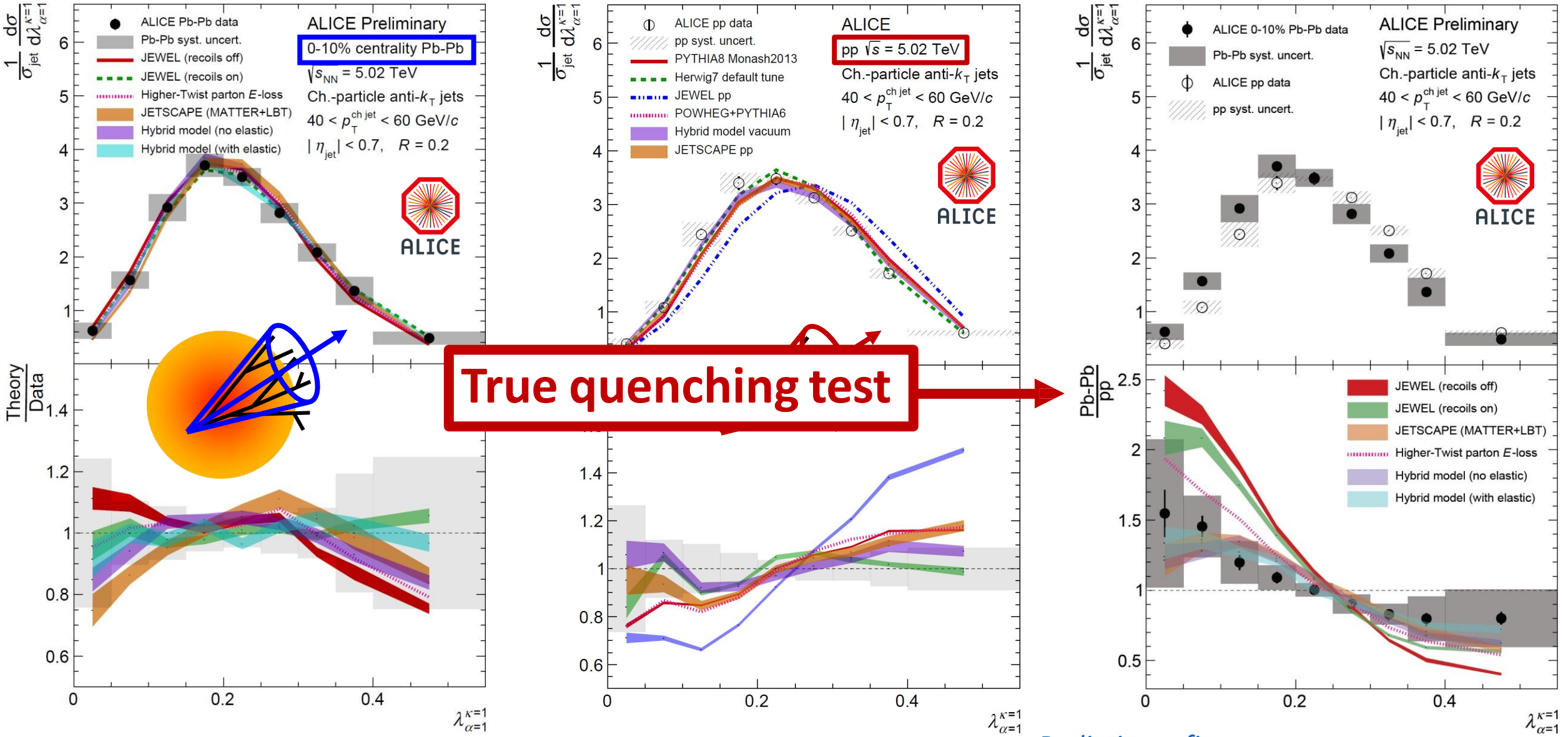
Some models exhibit more tension in pp baseline than in AA

Preliminary figures

QCD fragmentation modifications



True quenching test

Preliminary figures

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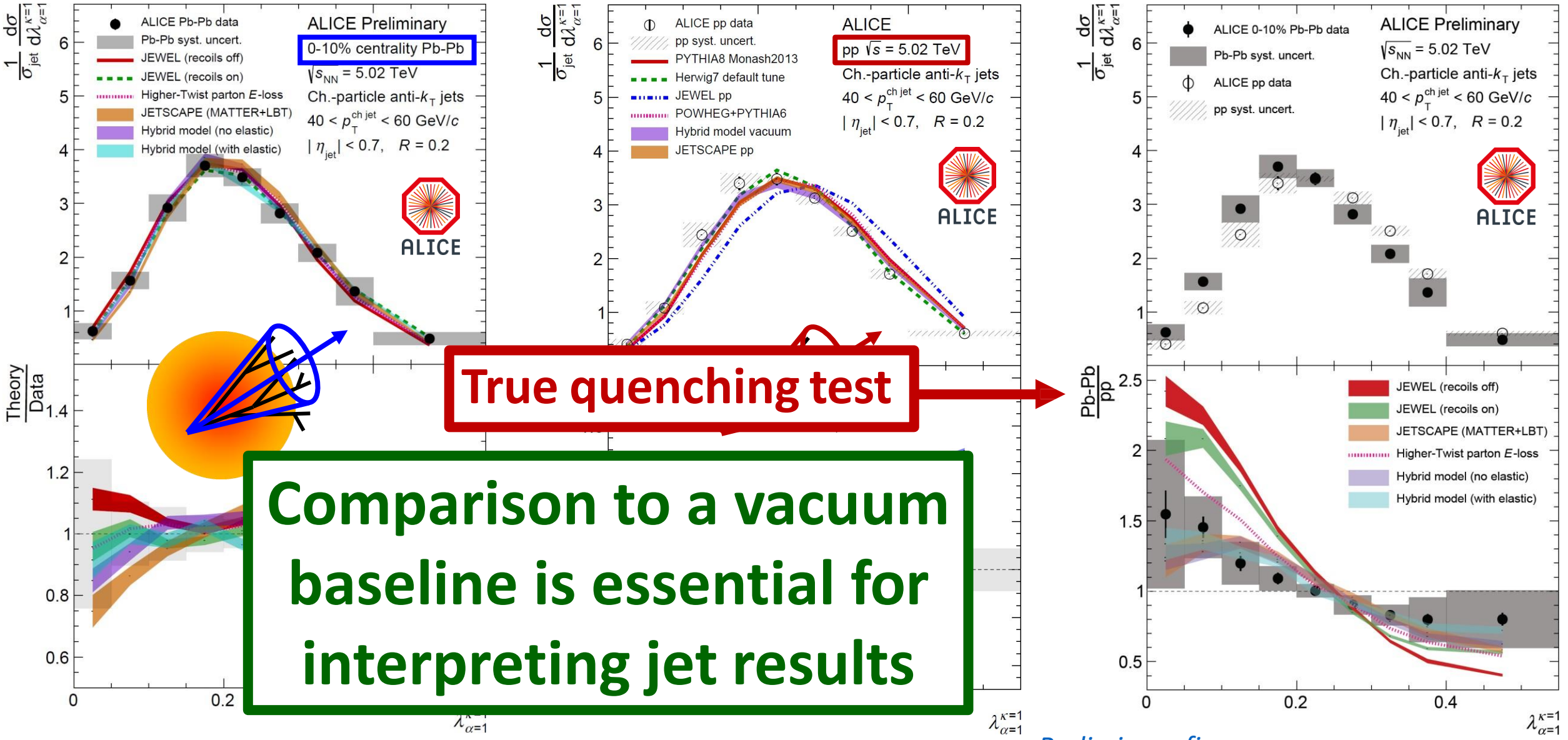

True quenching test

Comparison to a vacuum baseline is essential for interpreting jet results

Preliminary figures

QCD observable sensitivity

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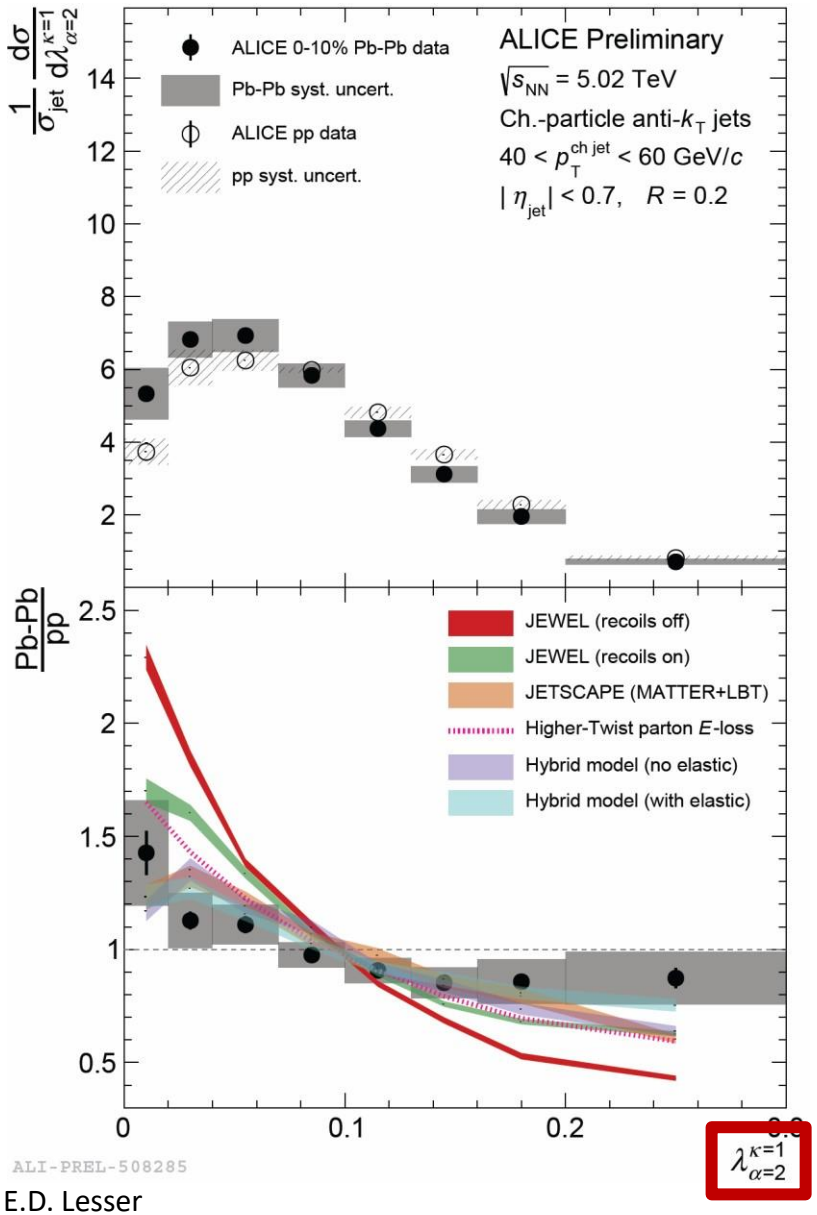

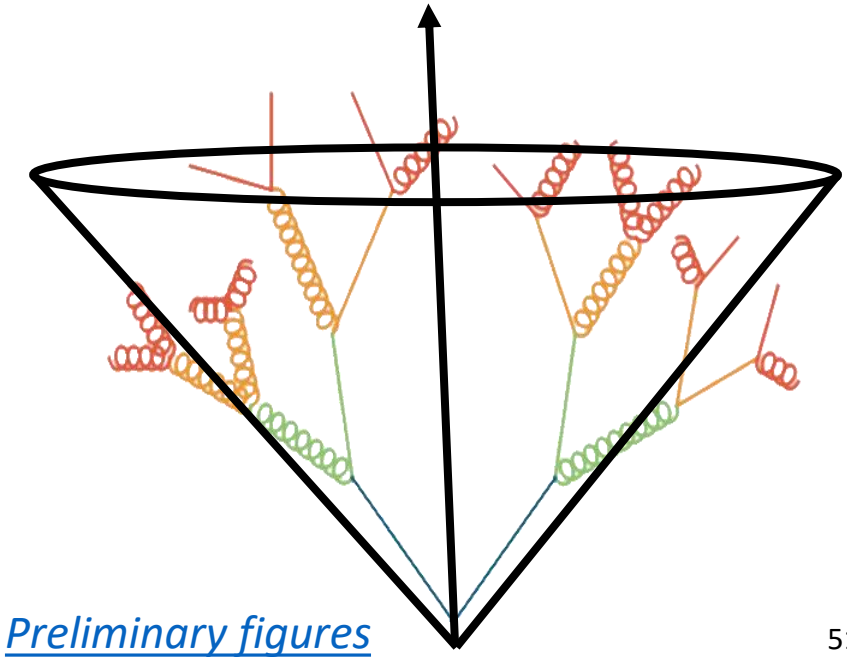

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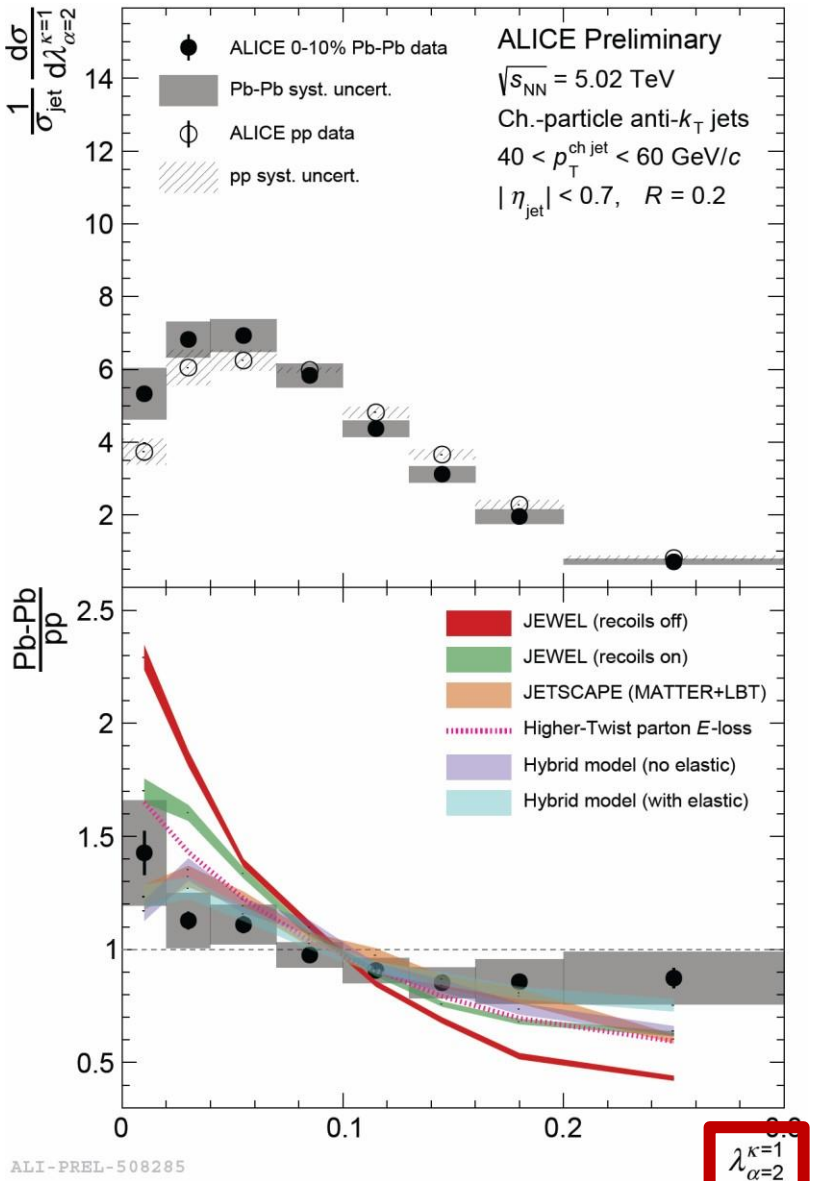

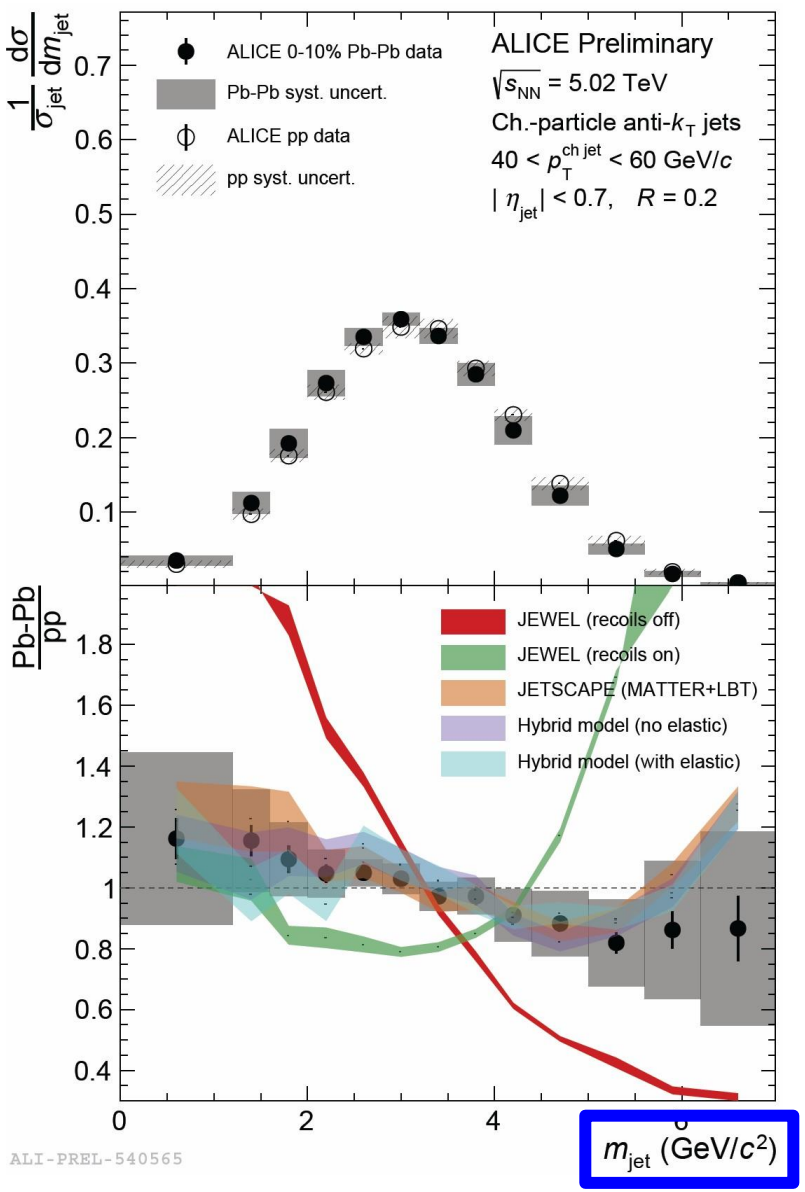

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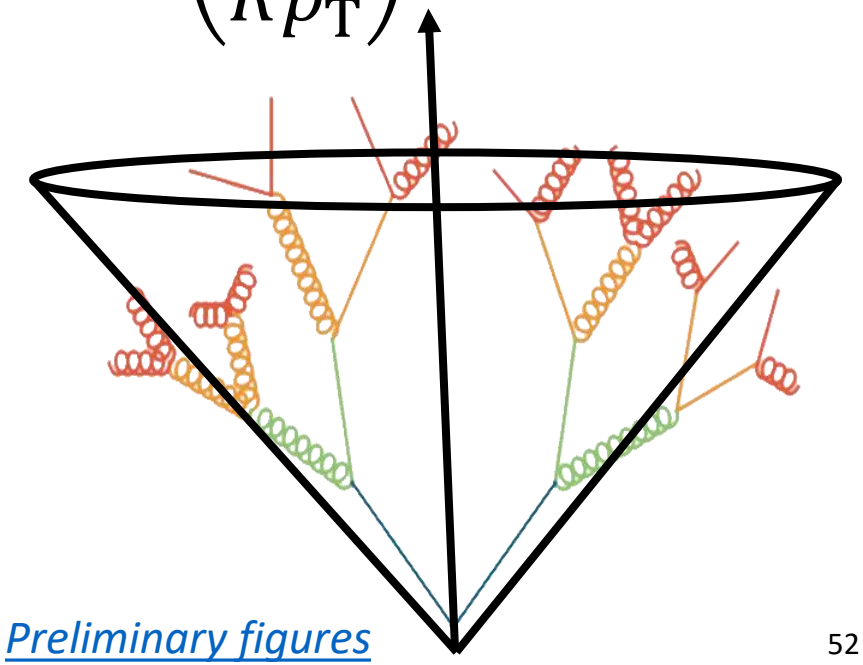

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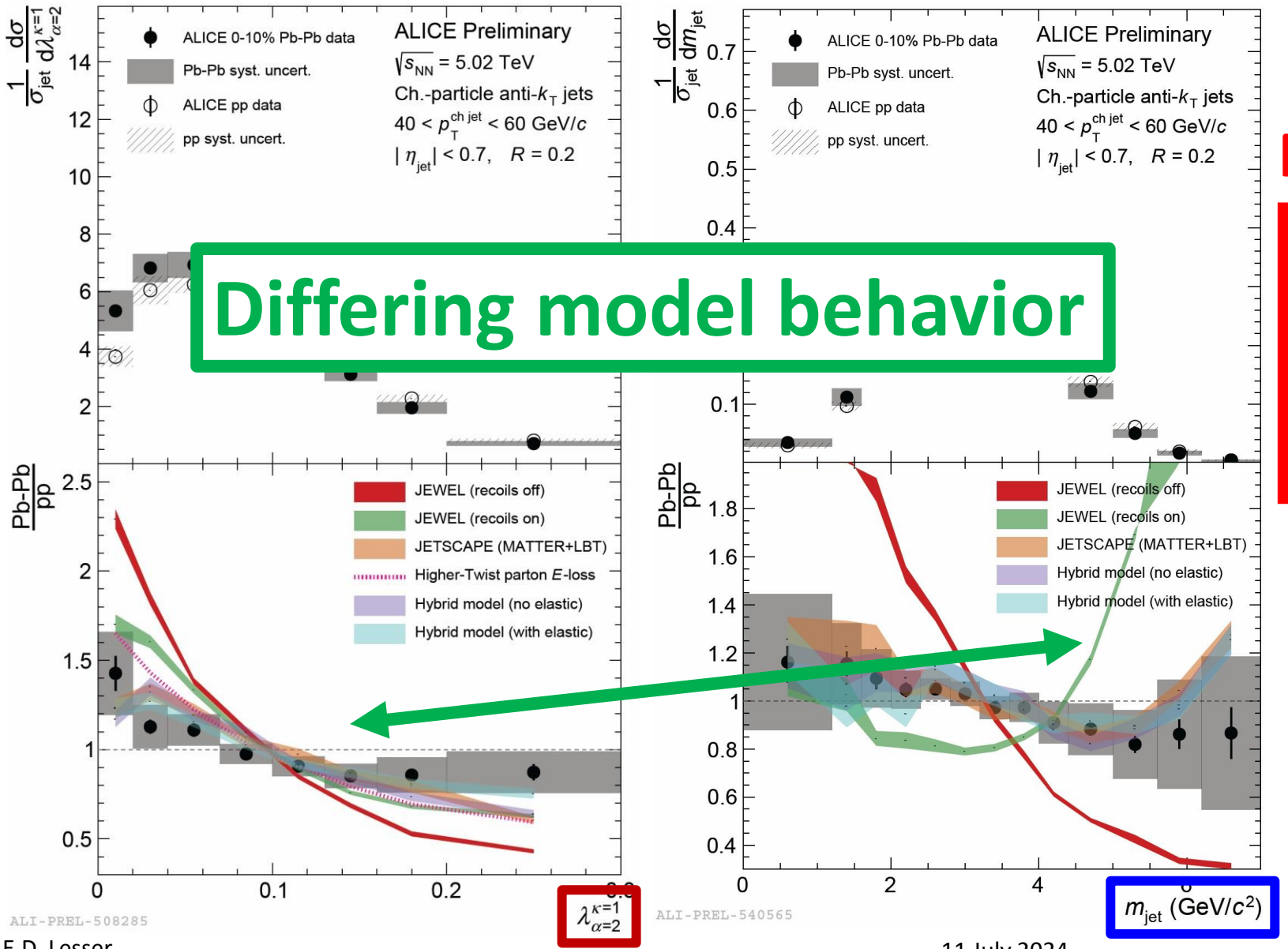

Differing model behavior

Not useful for low-p_T jets

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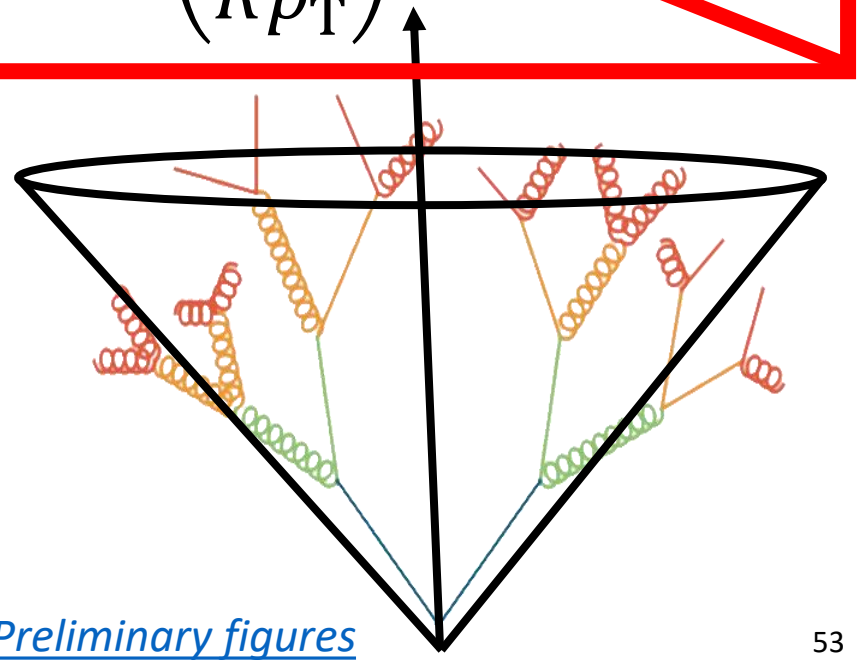

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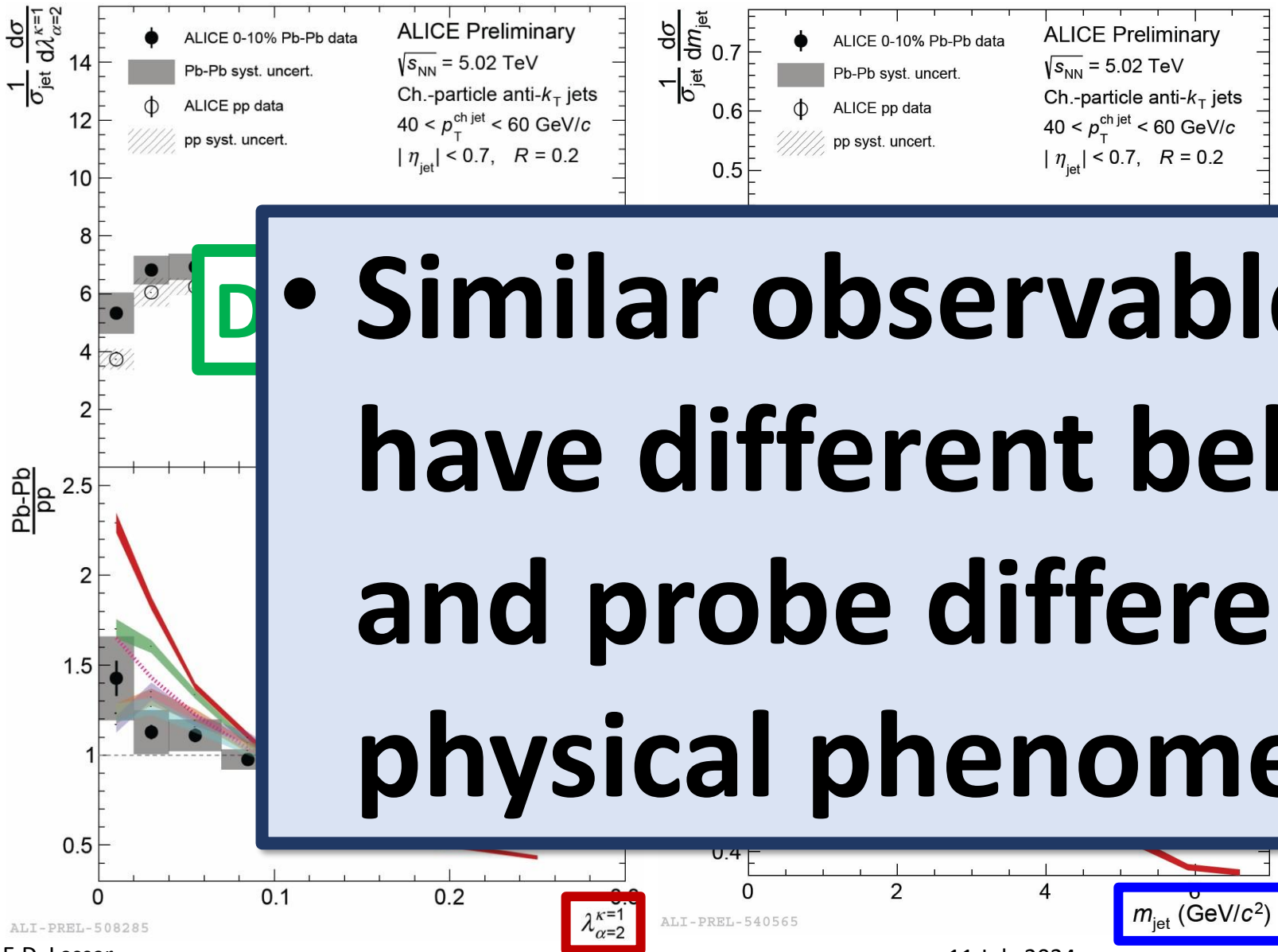
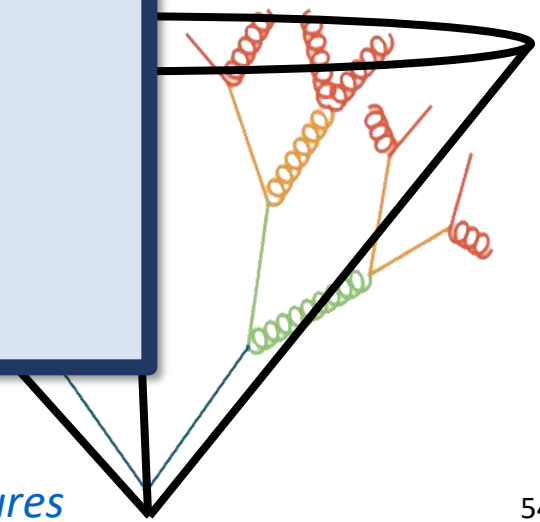


Not useful for low-p_T jets

relation:

$+ \mathcal{O}[(\lambda_2)^2]$

- **Similar observables can have different behavior and probe different physical phenomena**



Conclusions

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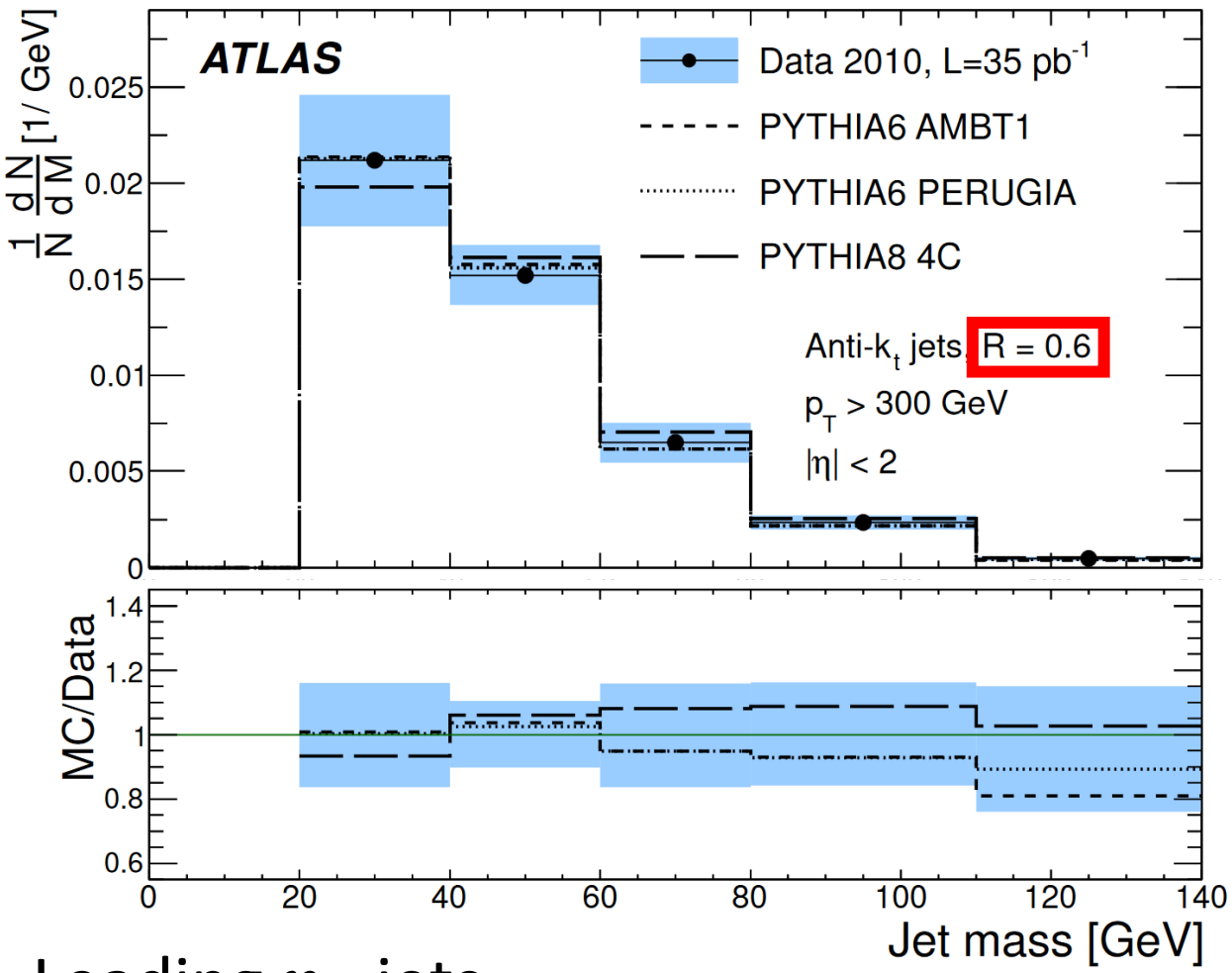
- Excellent opportunity to study **QCD flavor dependence** and to test recent theoretical developments at unprecedented precision

Backup

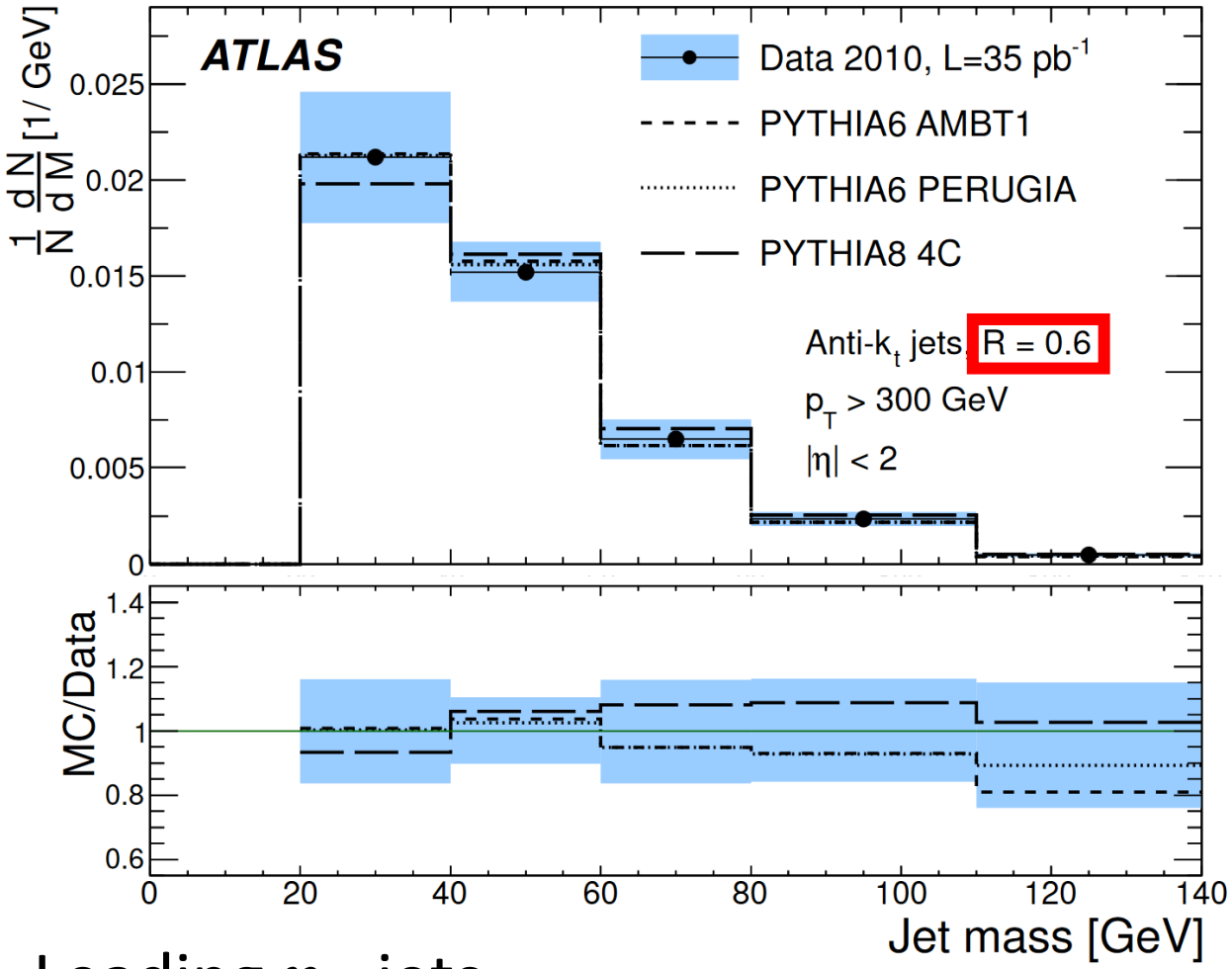
First look at the LHC (2010-2013)

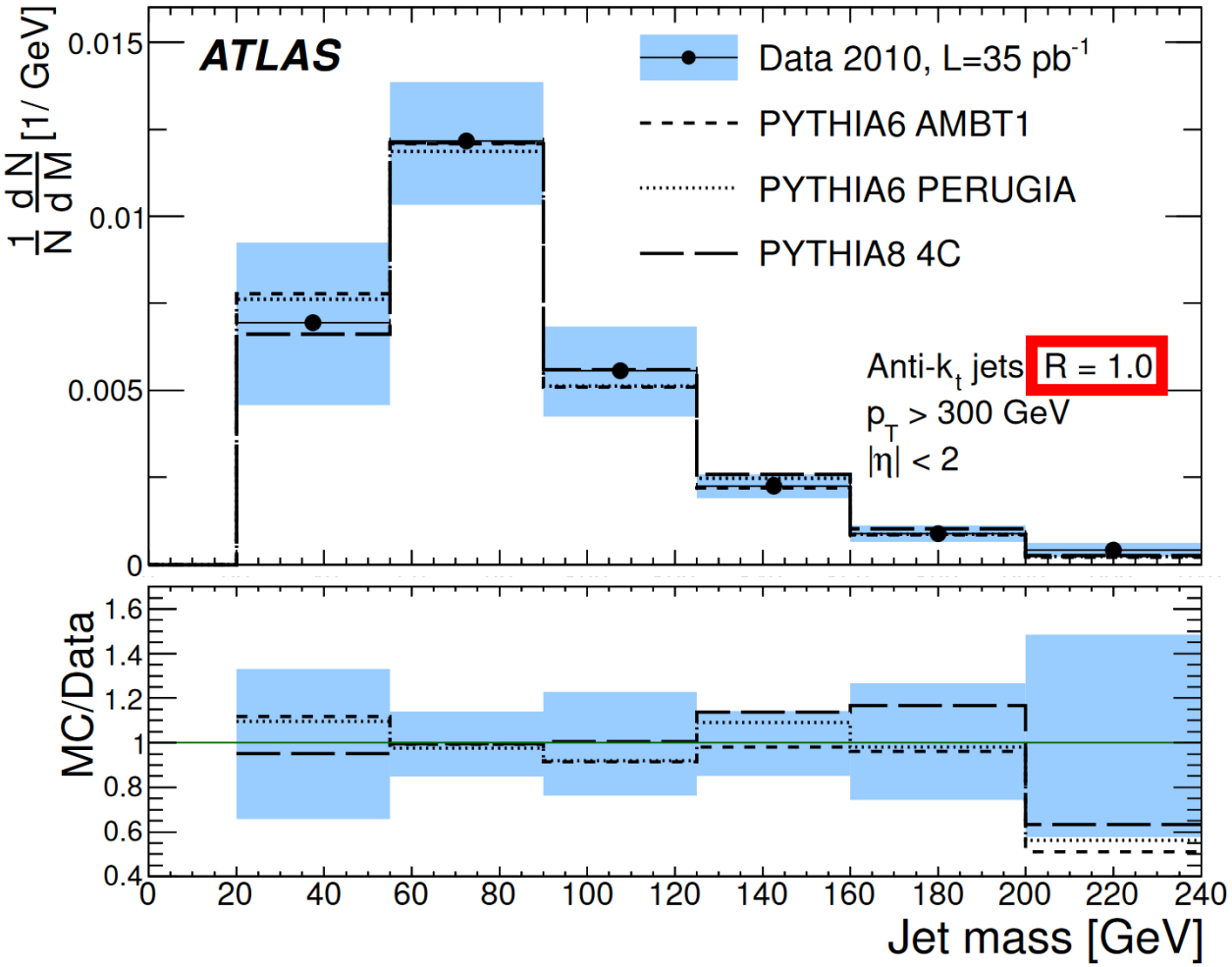


Leading p_{T} jets

[Phys. Rev. D 86 (2012) 072006]

First look at the LHC (2010-2013)





Leading p_{T} jets

- different R → different jets; different shape?

[Phys. Rev. D 86 (2012) 072006]

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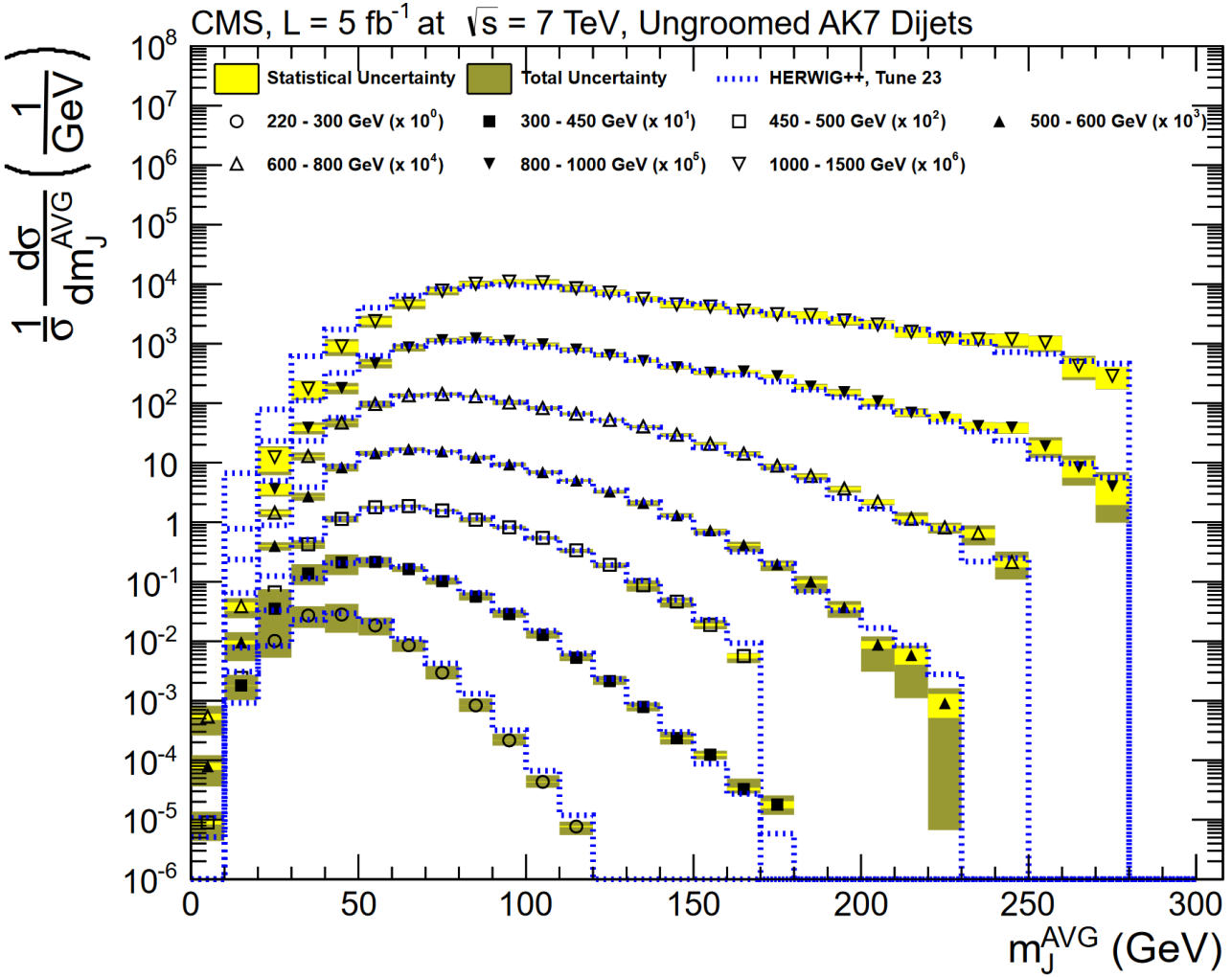

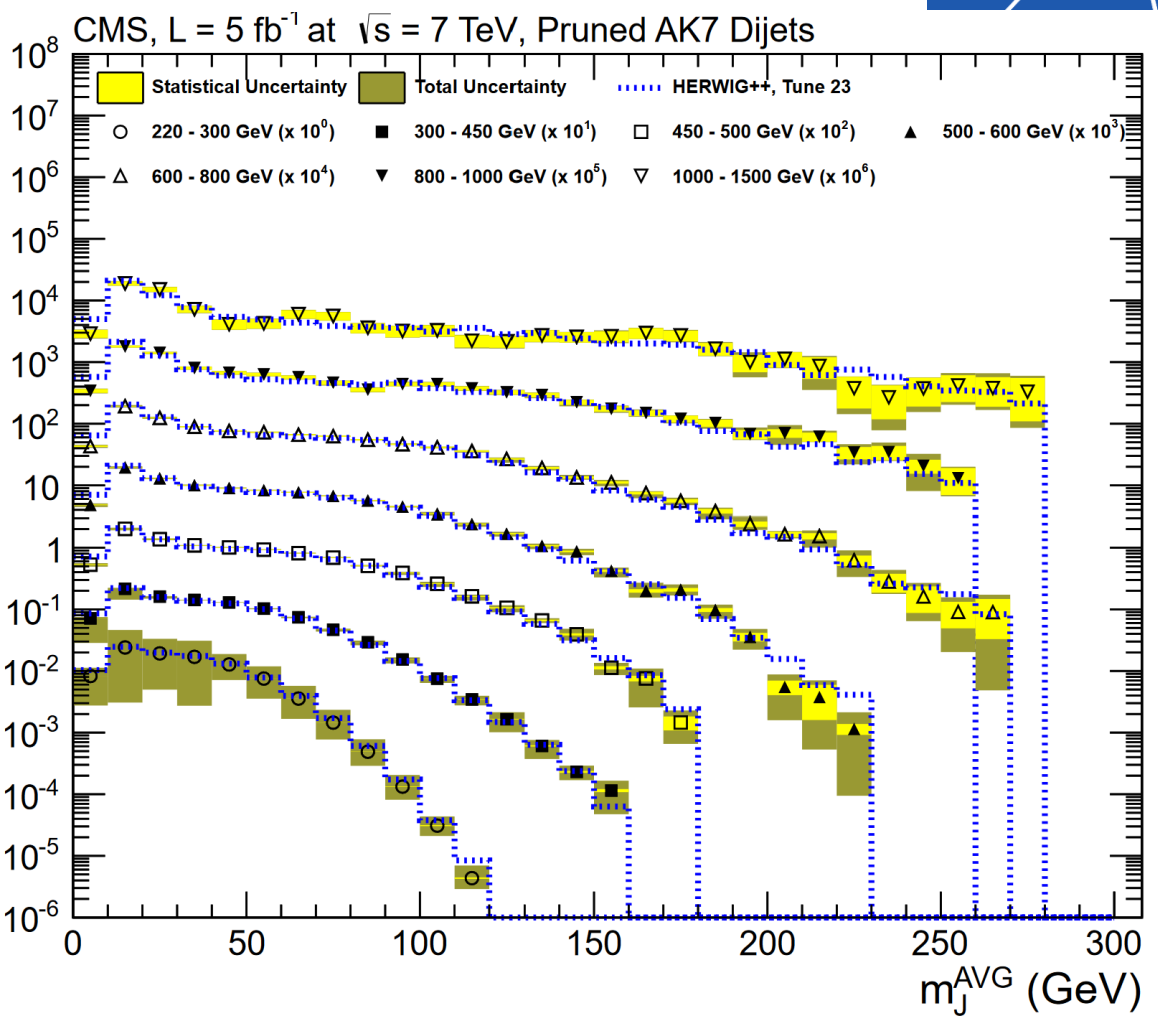

JHEP 05 (2013) 090

- Groomed vs ungroomed