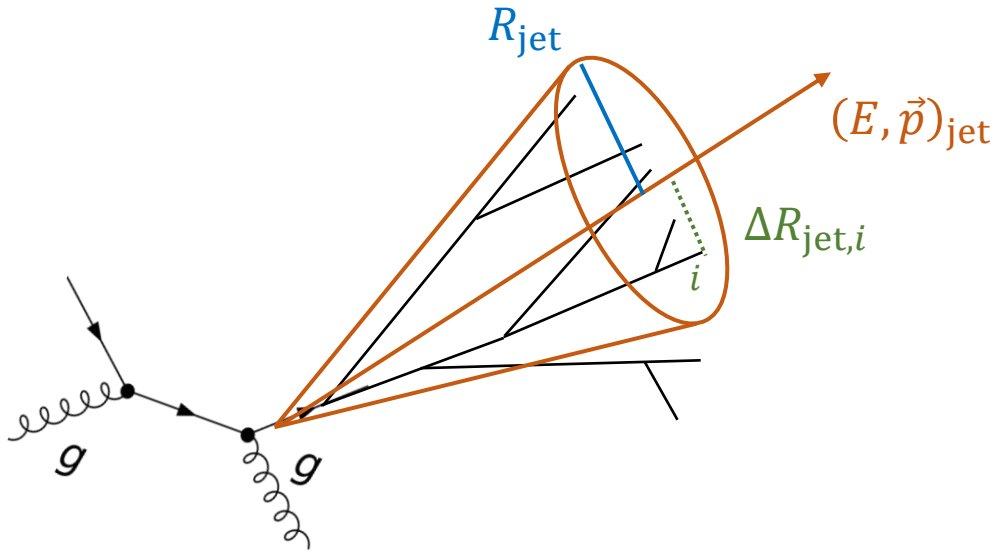
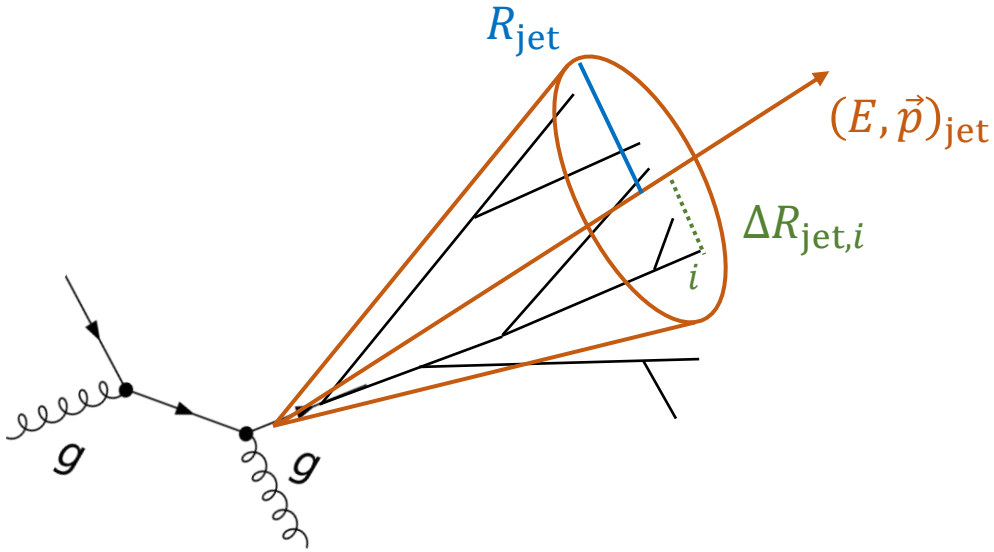
Jet fragmentation at the LHC (low-p_{T})

Ezra D. Lesser (CERN)

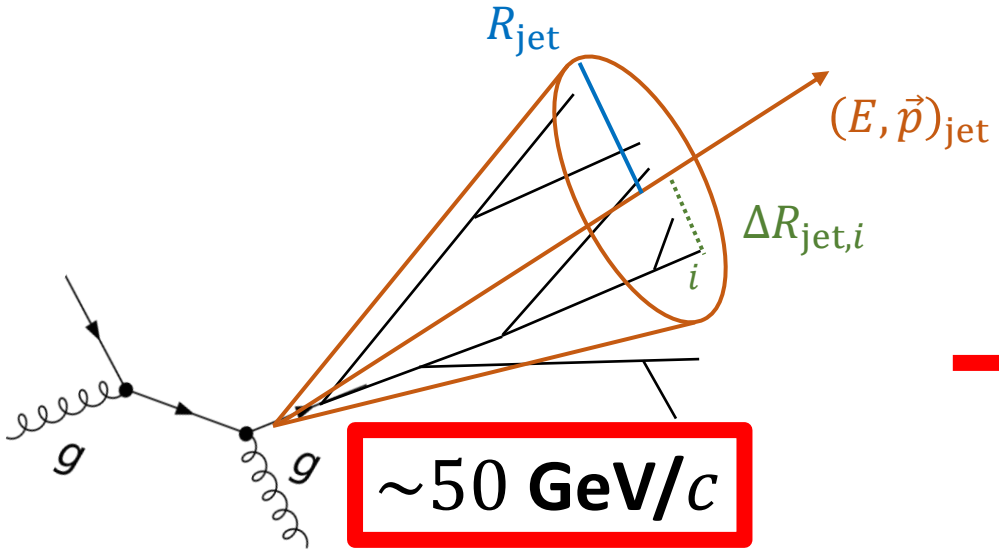
7 May 2024

Standard Model at the LHC // Rome, Italy



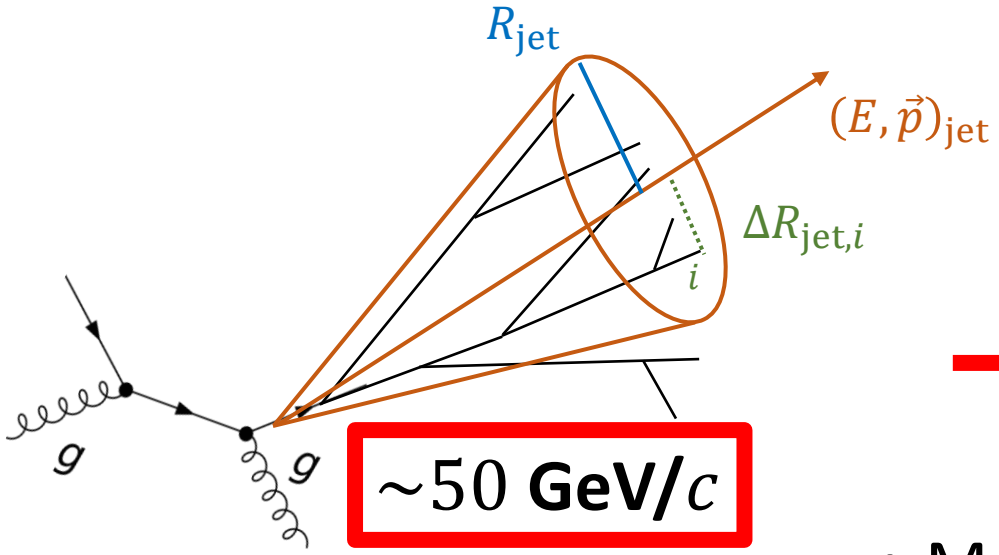

R_{jet}
$(E, \vec{p})_{\text{jet}}$
$\Delta R_{\text{jet},i}$
i
g
g

Low $p_{\mathrm{T}}^{\mathrm{jet}}$



High $p_{\mathrm{T}}^{\mathrm{jet}}$

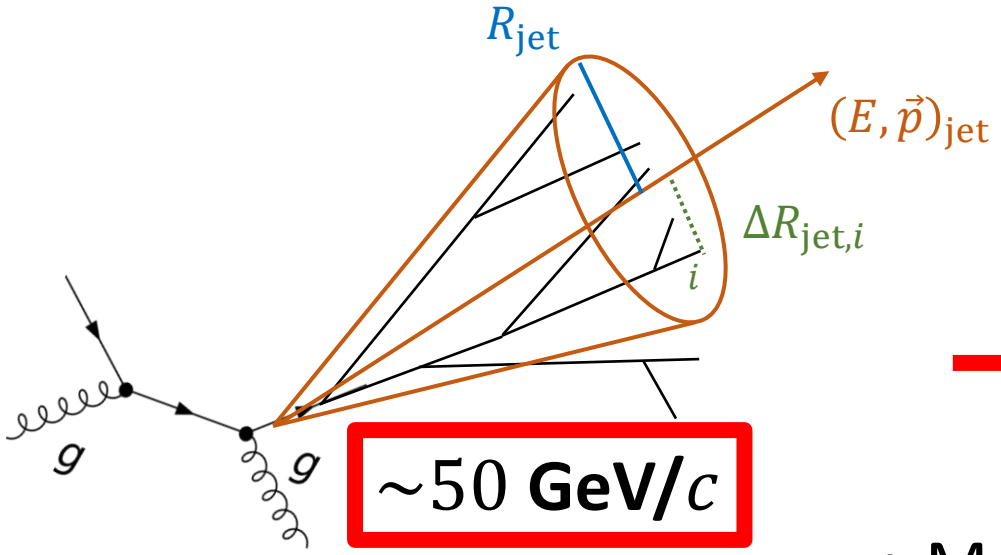
Low $p_{\mathrm{T}}^{\mathrm{jet}}$



High $p_{\mathrm{T}}^{\mathrm{jet}}$

- Much more **common**
- Much more **rare**

Low $p_{\mathrm{T}}^{\mathrm{jet}}$



High $p_{\mathrm{T}}^{\mathrm{jet}}$

- Much more **common**
- More **nonperturbative**

- Much more **rare**
- More **perturbative**

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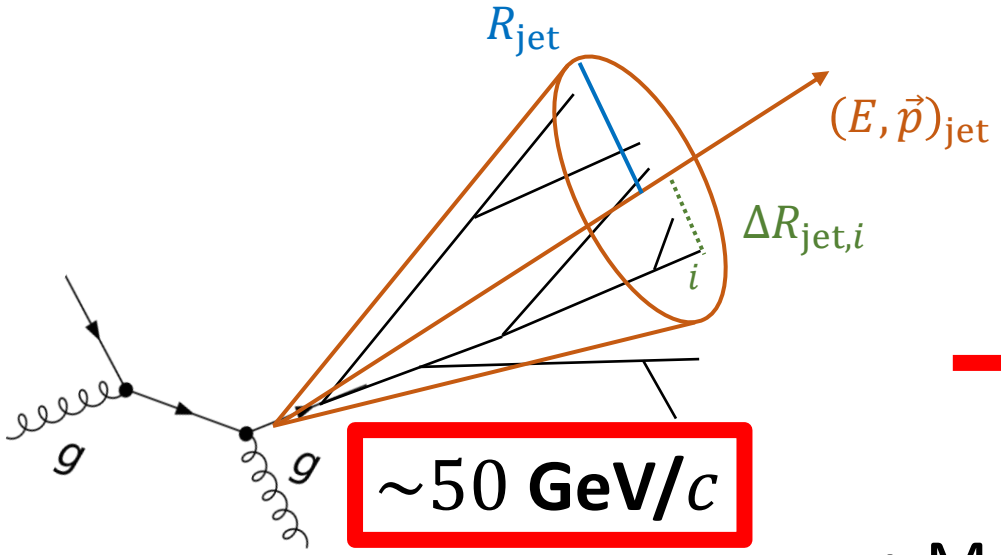
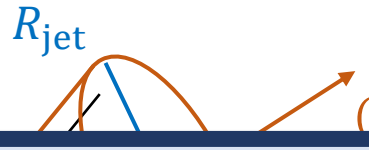


High $p_{\mathrm{T}}^{\mathrm{jet}}$

- Much more **common**
- More **nonperturbative**
- Sensitive to QCD and its backgrounds (e.g., "underlying event")

- Much more **rare**
- More **perturbative**
- Sensitive to rare SM processes (e.g., $\mathrm{H} \to \mathrm{b\bar{b}}$)



Low $p_{\mathrm{T}}^{\mathrm{je}}$ **gh** $p_{\mathrm{T}}^{\mathrm{jet}}$

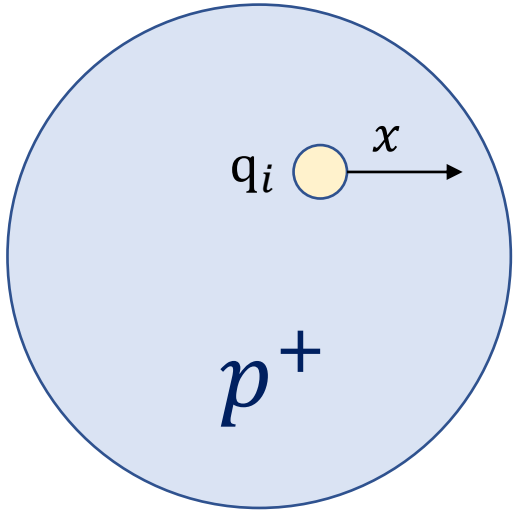
- Much m **are**
- More **nc** **ative**
- Sensitive re SM backgro g., $\mathrm{H} \to \mathrm{b\bar{b}}$) "underly

Despite these differences, jets **at any** p_{T} probe broad physical phenomena at a **variety of parton virtuality** Q^2

Understanding the jet life cycle

Understanding the jet life cycle

Parton Distribution Functions (PDFs)



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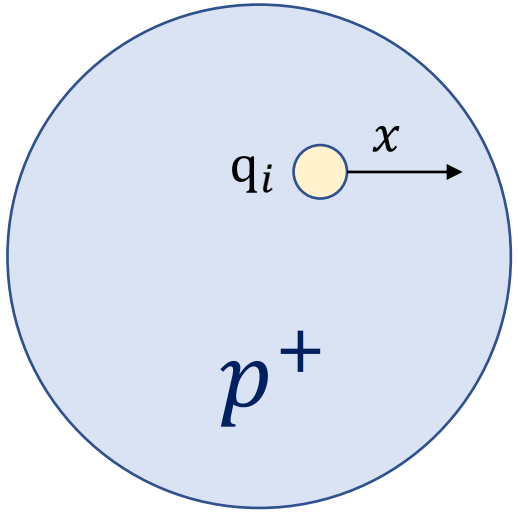
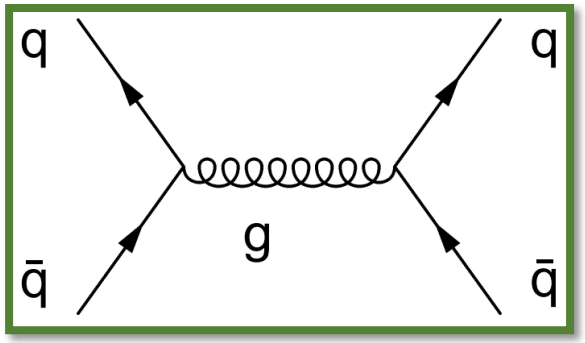


$\otimes$

Hard scattering process



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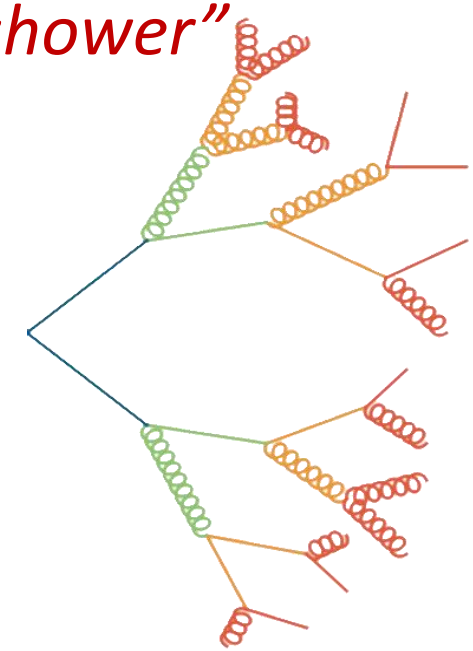
"Parton shower"



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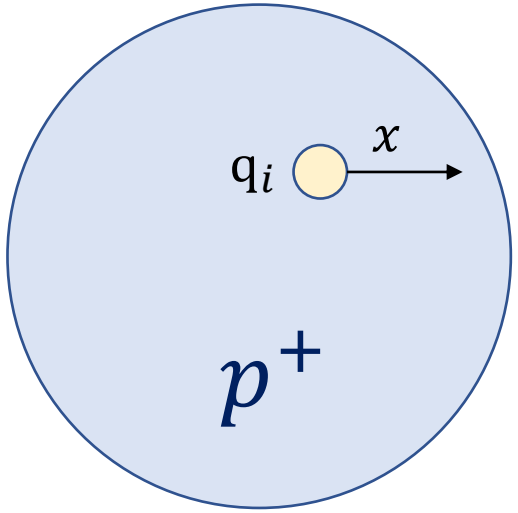

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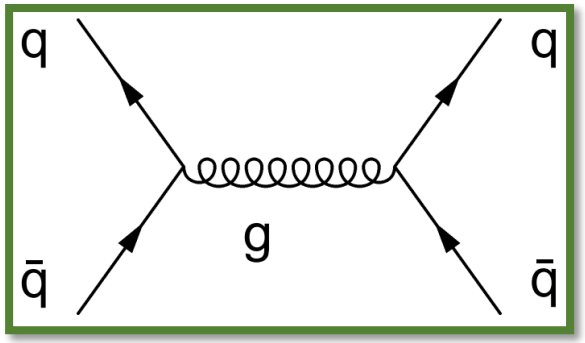

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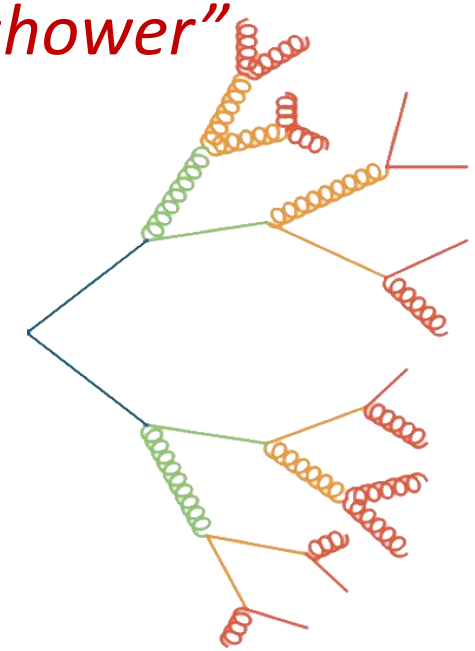

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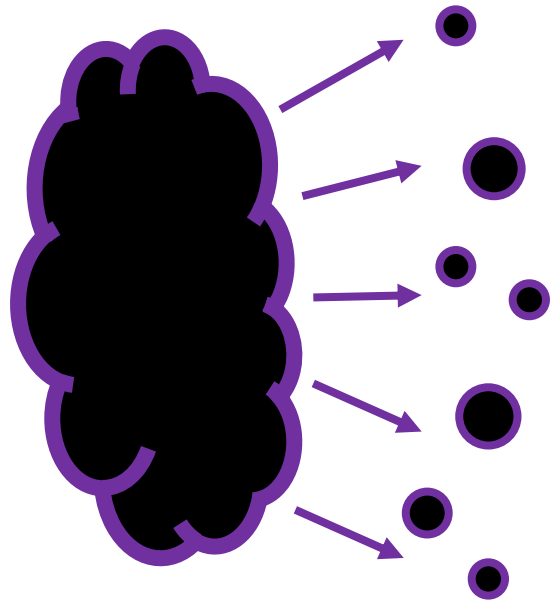
Hadronization



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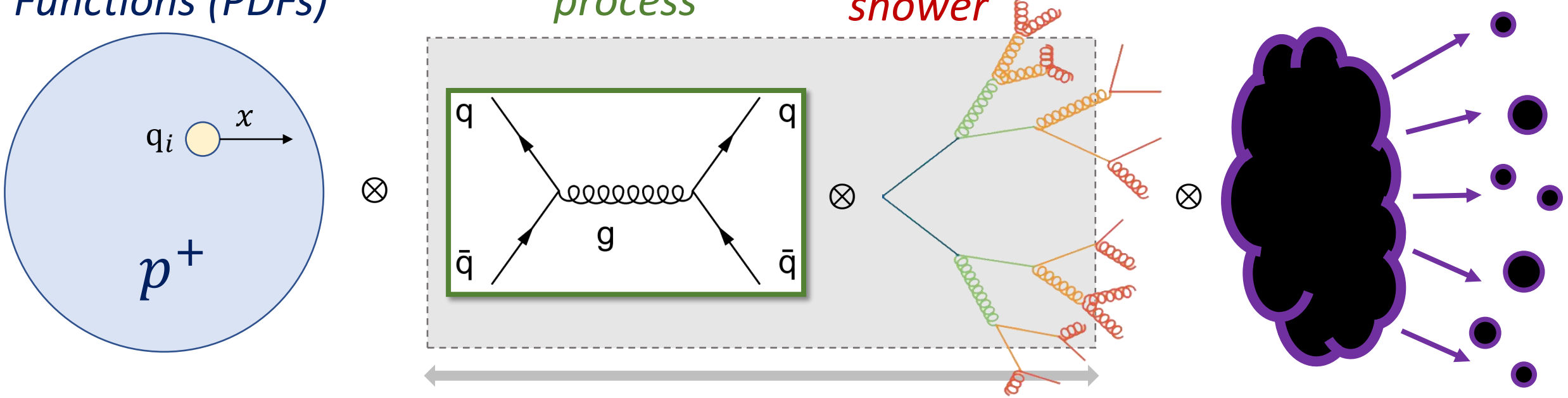

- How much of jet fragmentation is **perturbatively calculable**?

Understanding the jet life cycle

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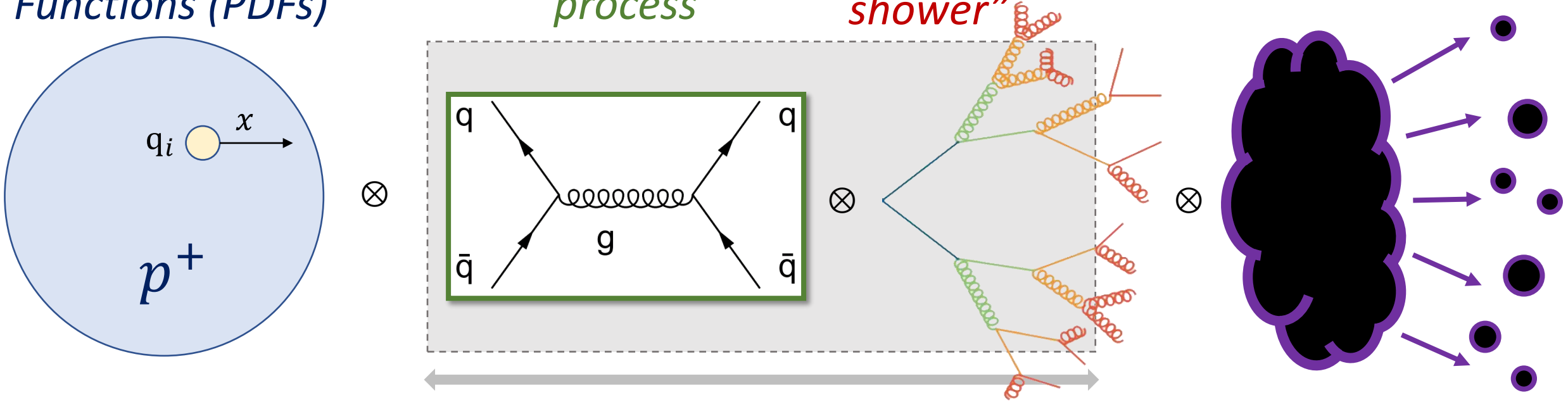

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- **What can experiments teach us** about each stage of jet formation and fragmentation?

Understanding the jet life cycle

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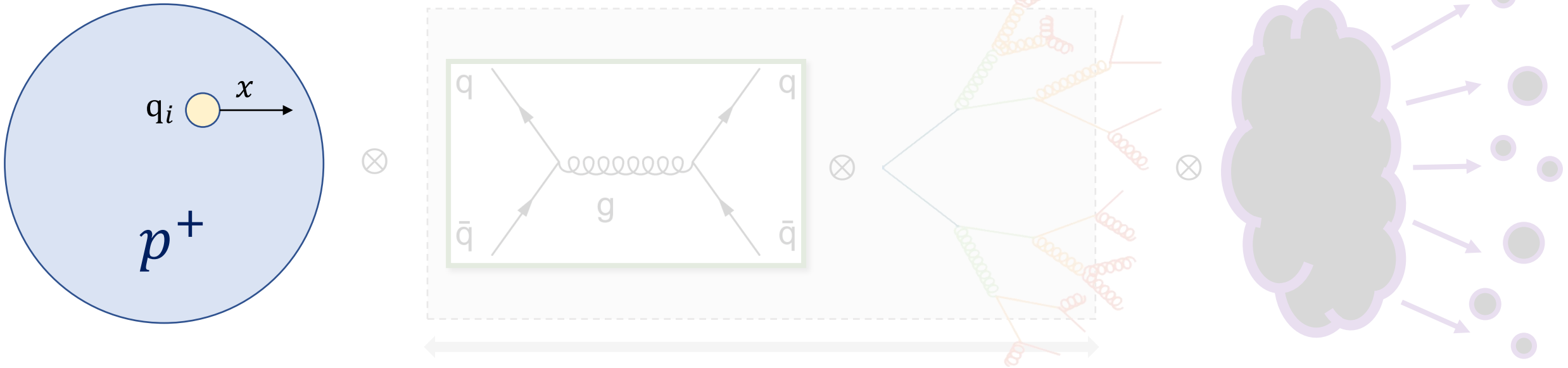

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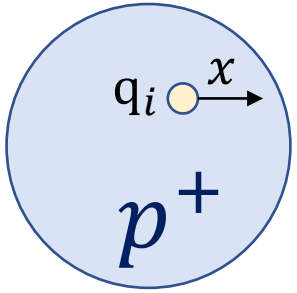
What's in a proton?



- **Intrinsic valence-like charm?** *i.e.,* ϵ term: $|p^+\rangle \propto |uud\rangle + \epsilon|uudc\bar{c}\rangle$

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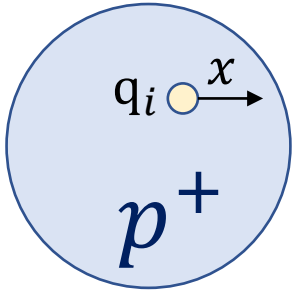

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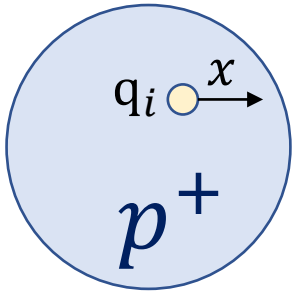

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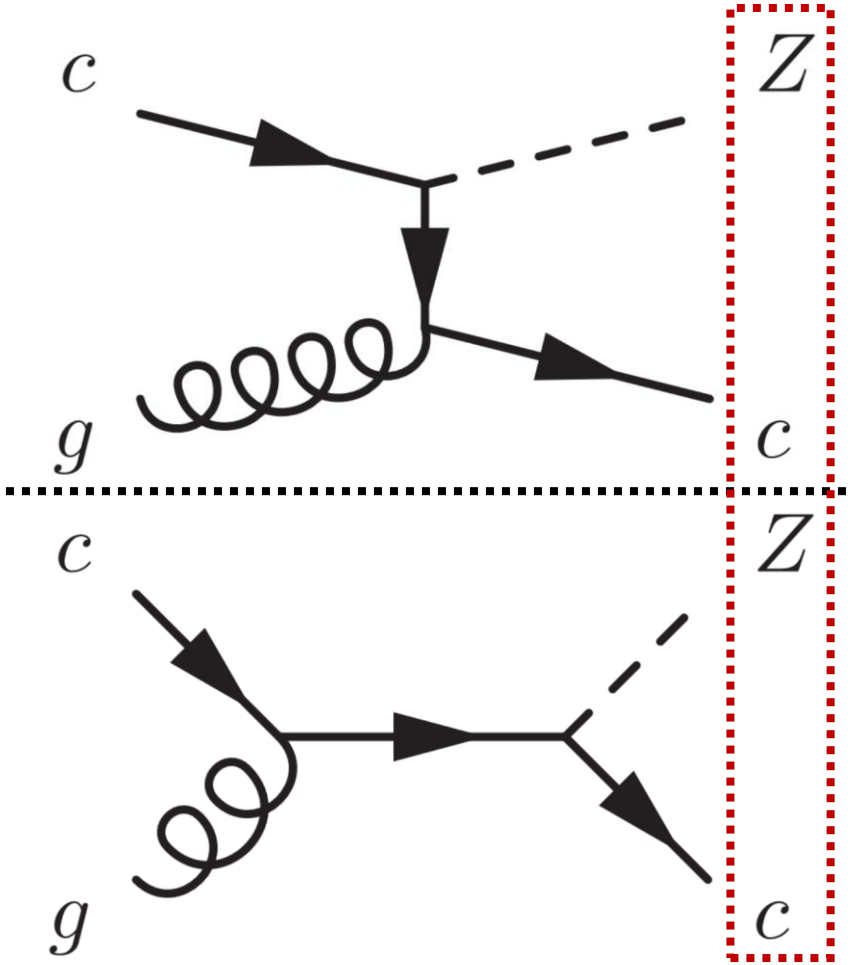

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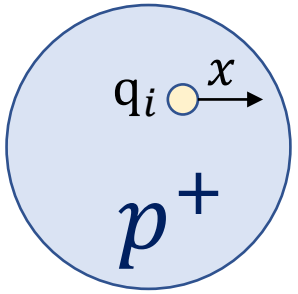

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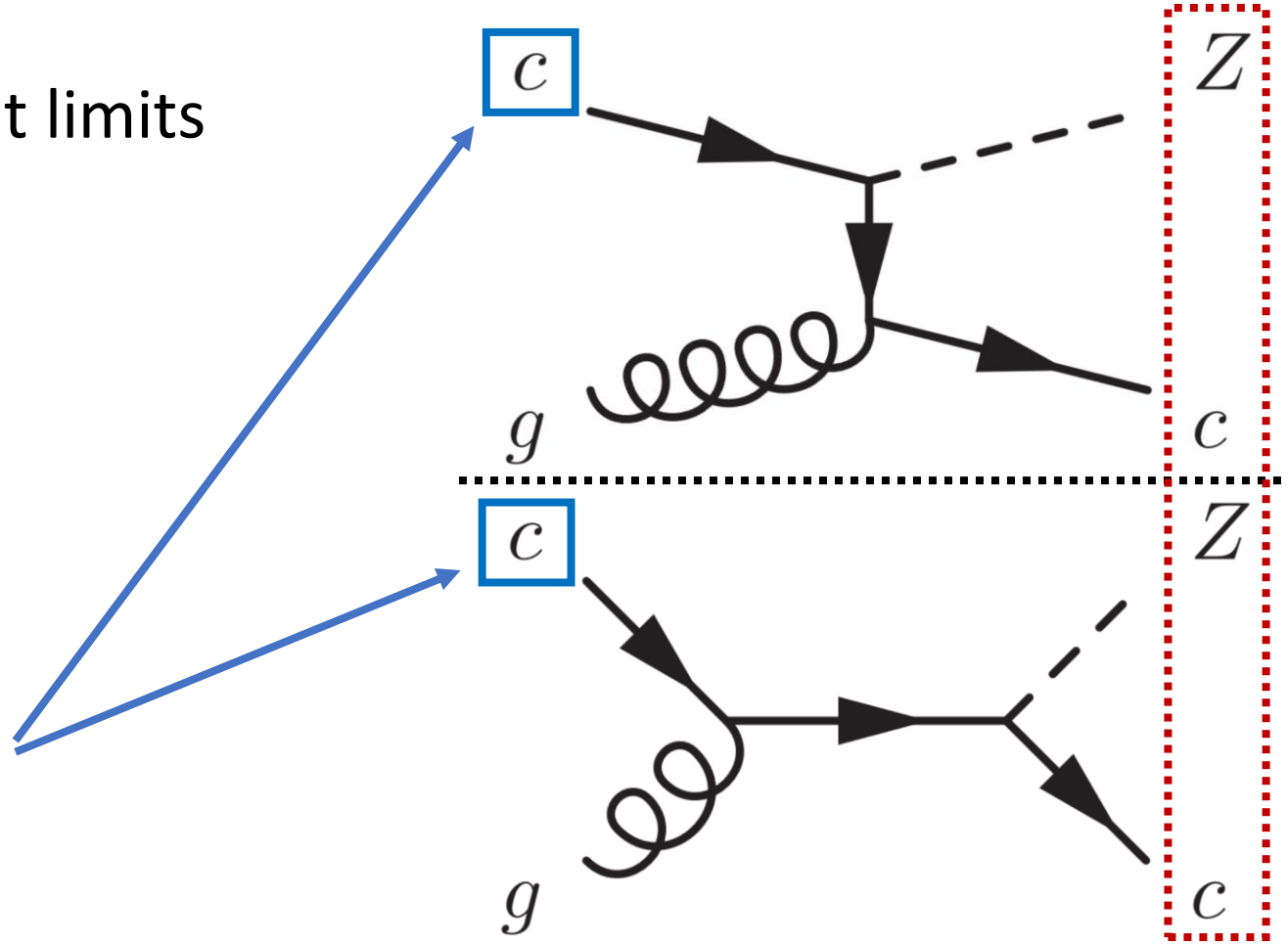
- **Purely gluon-like?**
  → *should disappear as* $x \to 1$



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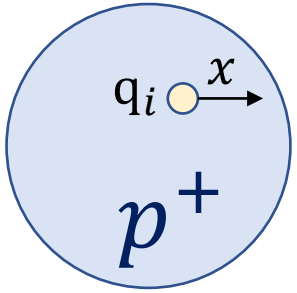

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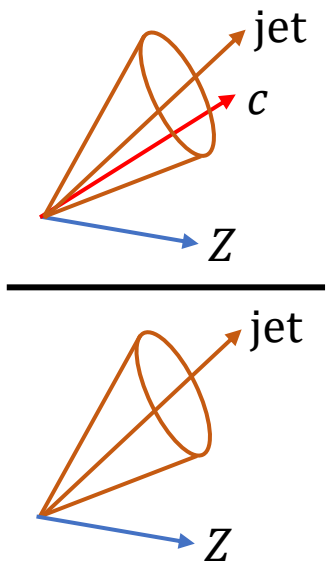
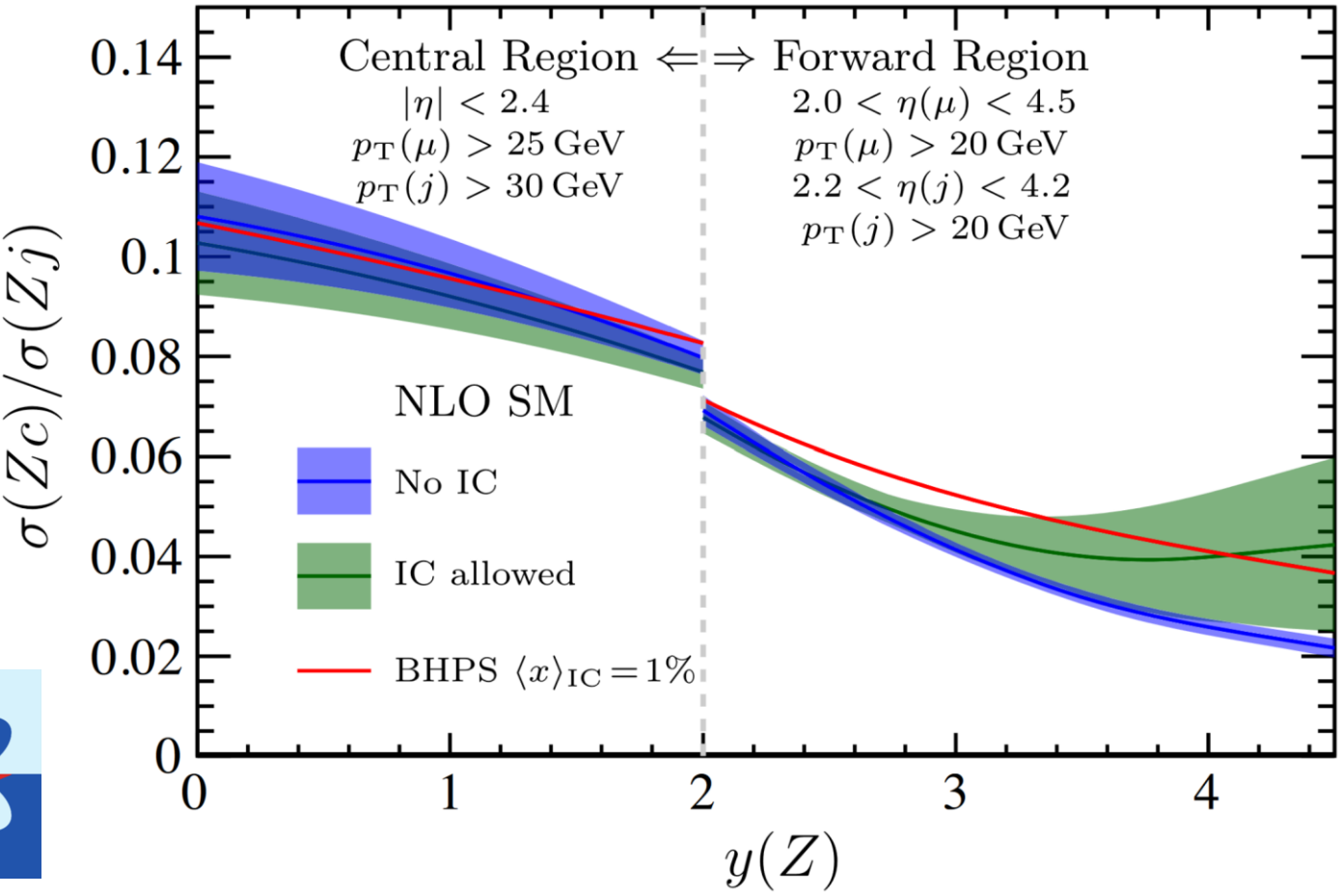
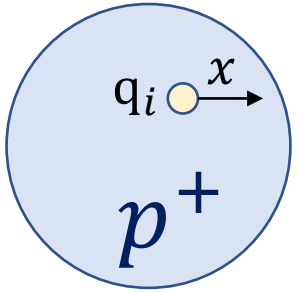




- Largest difference expected between **no-IC** and **IC** at large $y(Z)$

What's in a proton?



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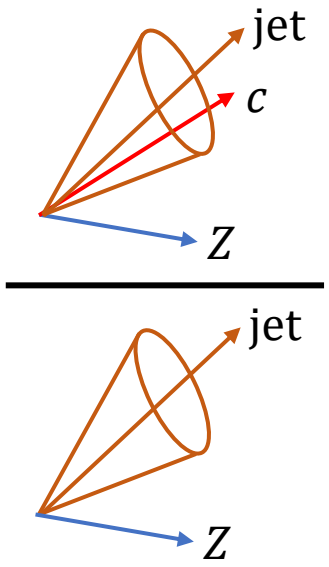
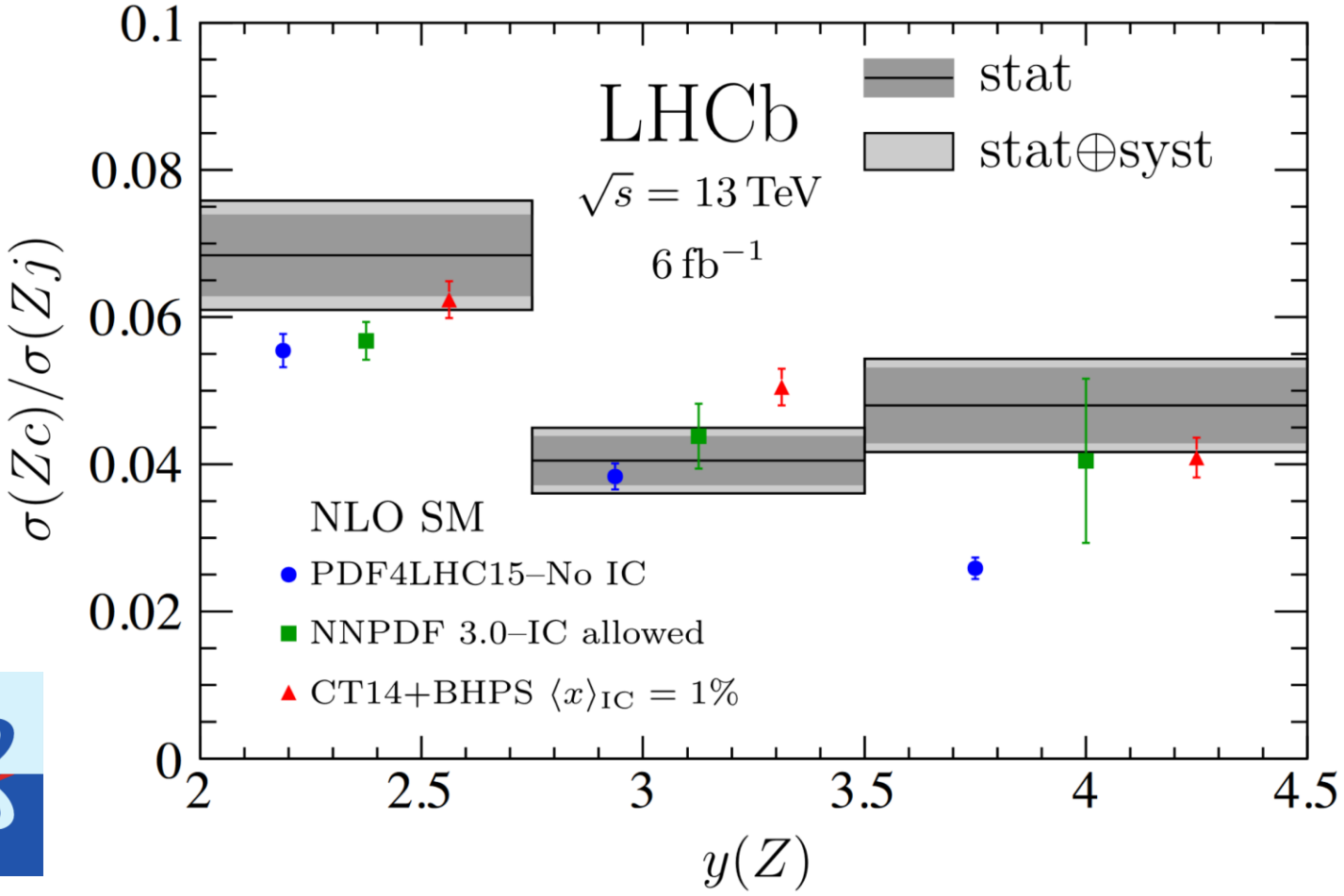
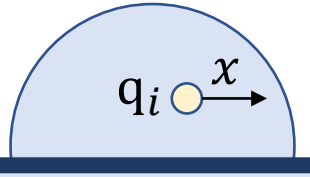




- Largest difference expected between **no-IC** and **IC** at large $y(Z)$
- **Significant tension with no-IC model** at large $y(Z)$

PRL 128 (2022) 082001

What's in a proton?

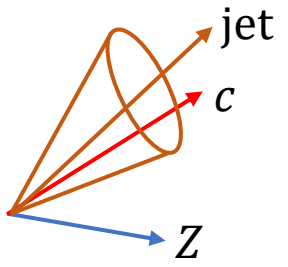


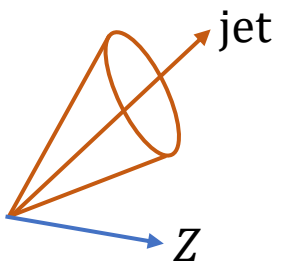
- **Intrin**

$dc\bar{c}\rangle$

ifference
l between
d **IC** at
$Z)$

nt tension
IC model
$y(Z)$





- **Update global PDFs using data at large y?**
- **Intrinsic charm at 3σ**

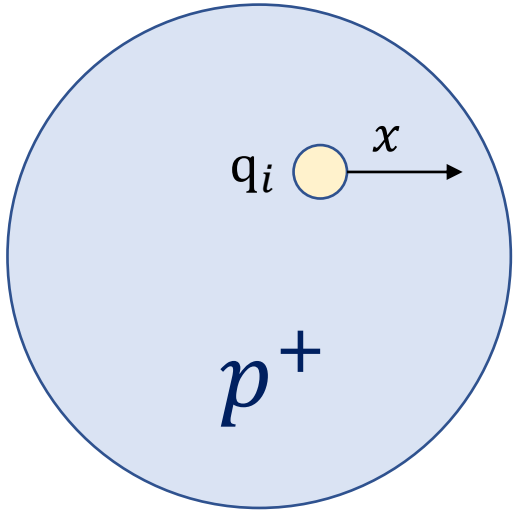
  Nature 608, 483-487 (2022)

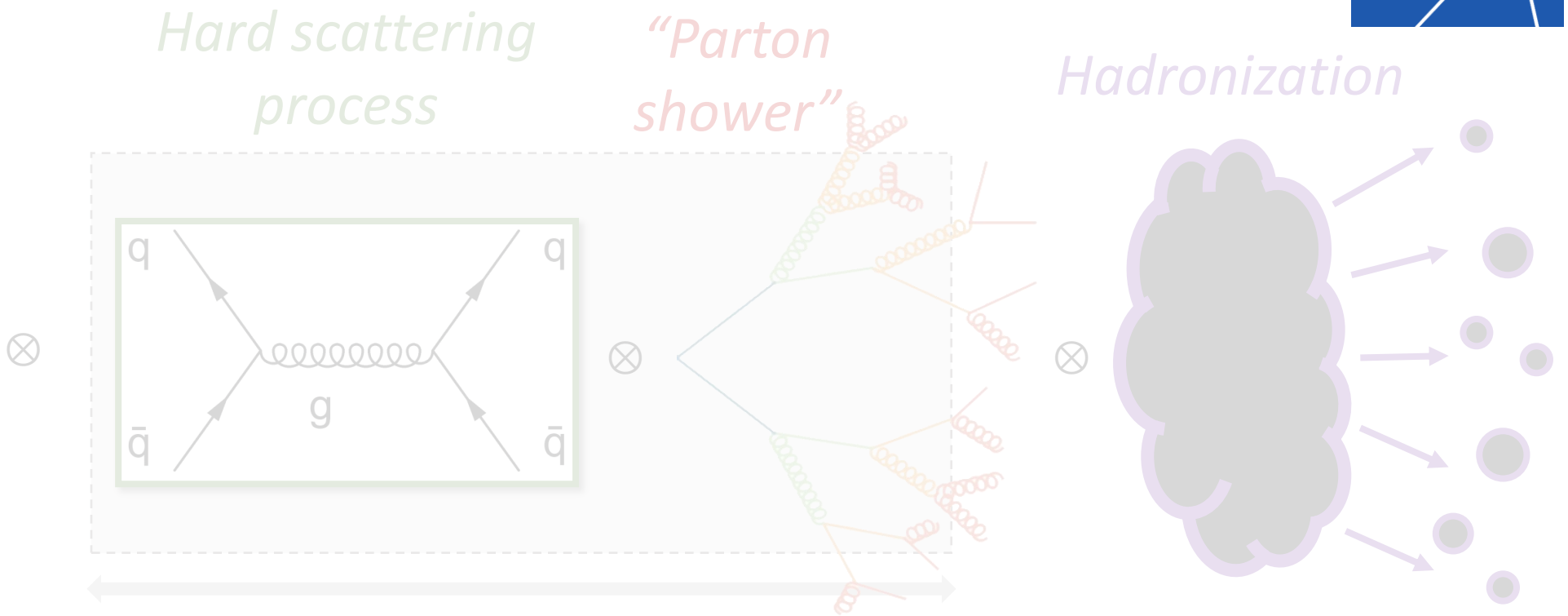
- **More studies with Z+c?**

$y(Z)$

Understanding the jet life cycle

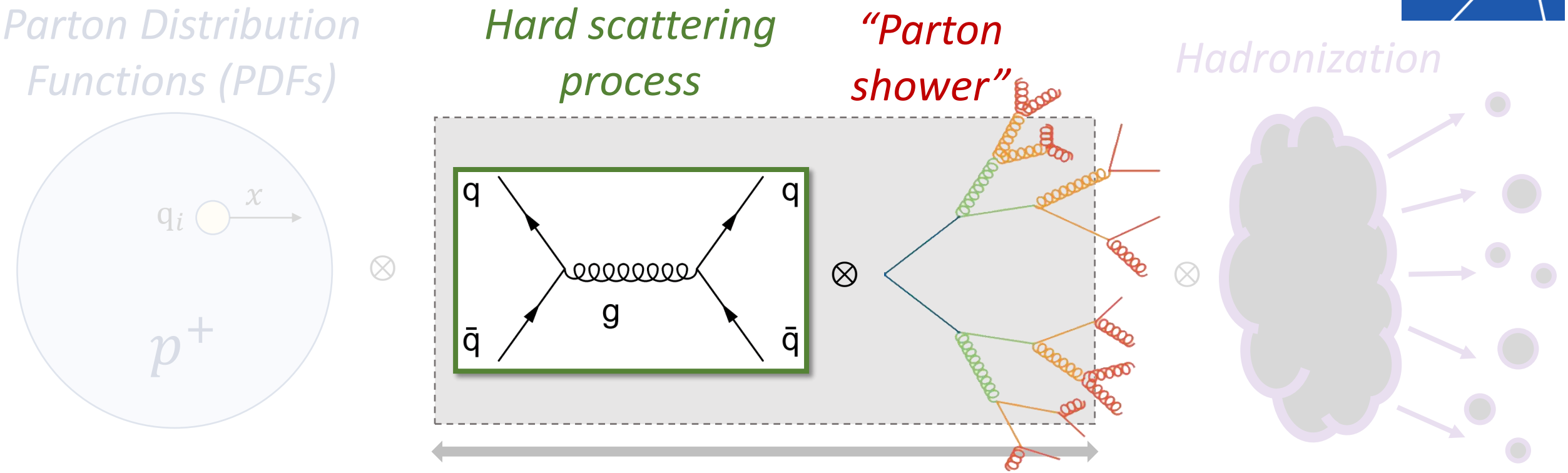
Parton Distribution Functions (PDFs)





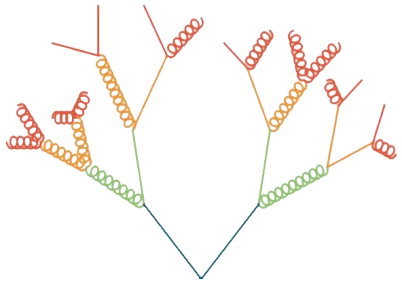
- What is the **initial state** of the collision?

Understanding the jet life cycle



- What is the **initial state** of the collision?
- How does QCD turn **quarks and gluons** into **jets**?

Probing parton emissions



- **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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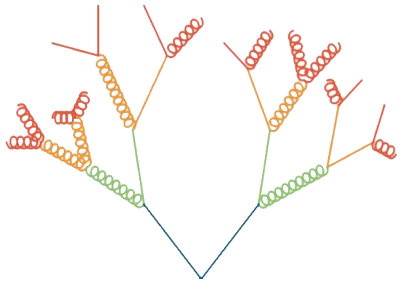

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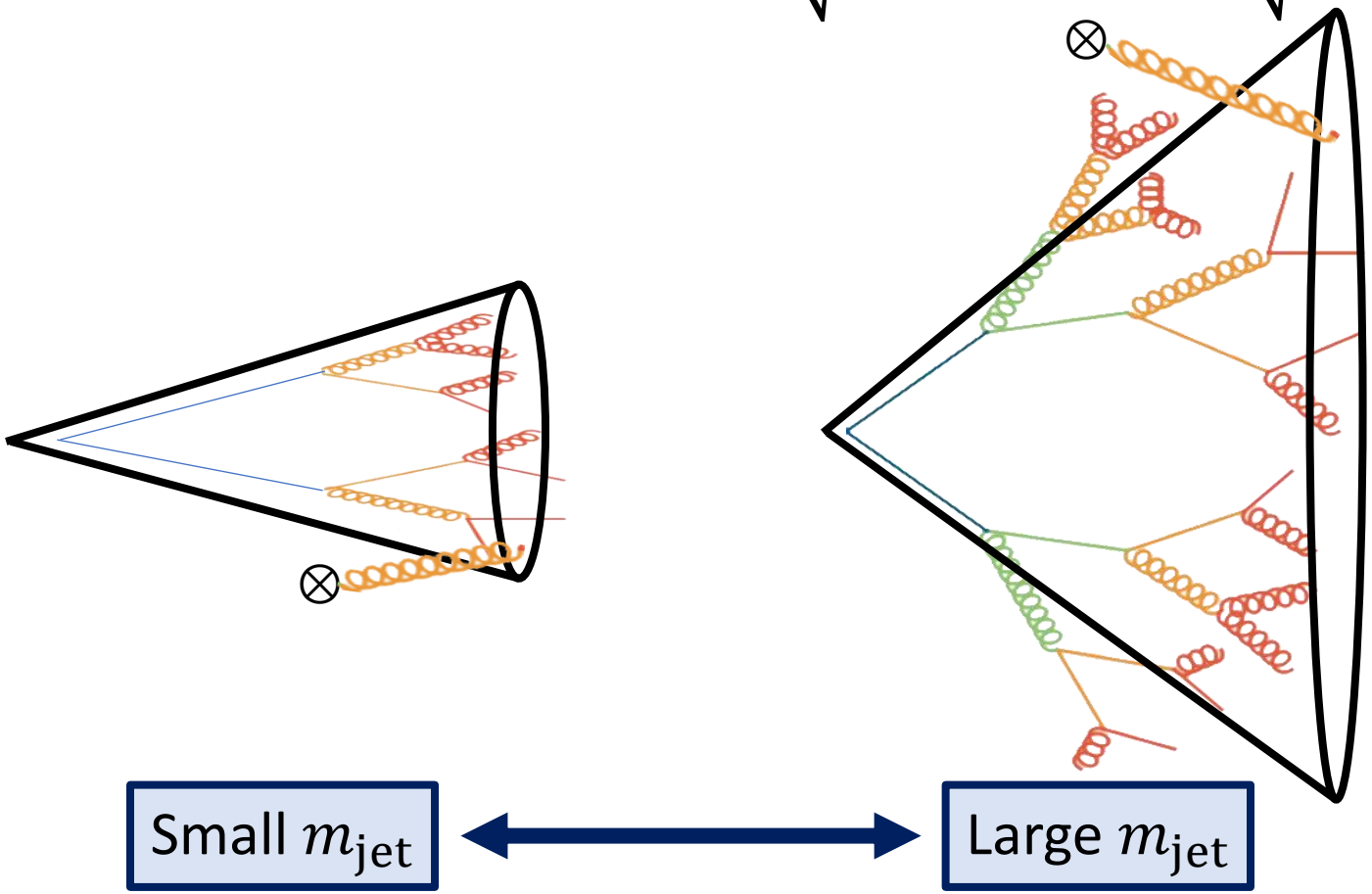
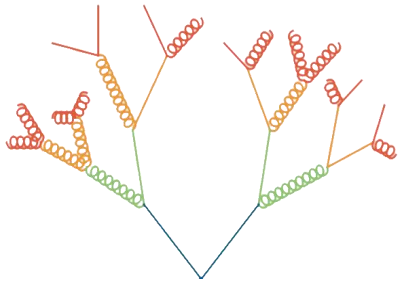


Small m_{jet} ⟷ Large m_{jet}

Probing parton emissions



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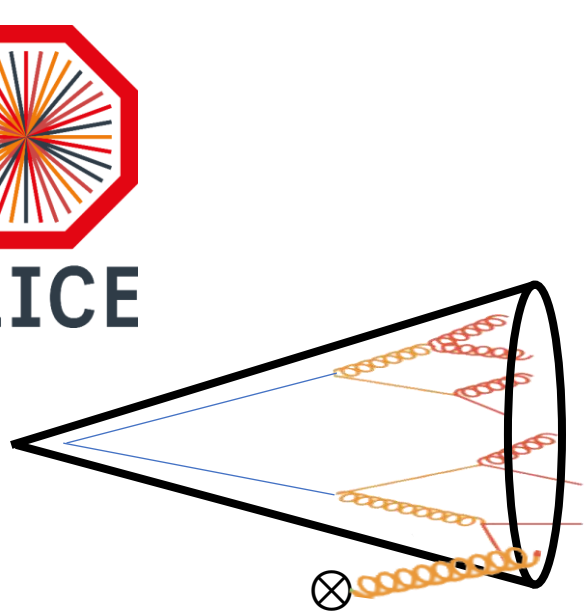

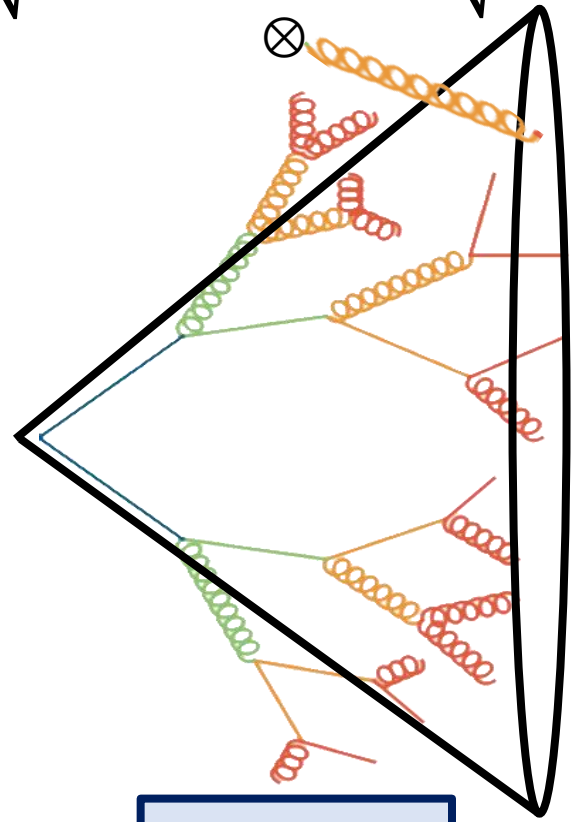

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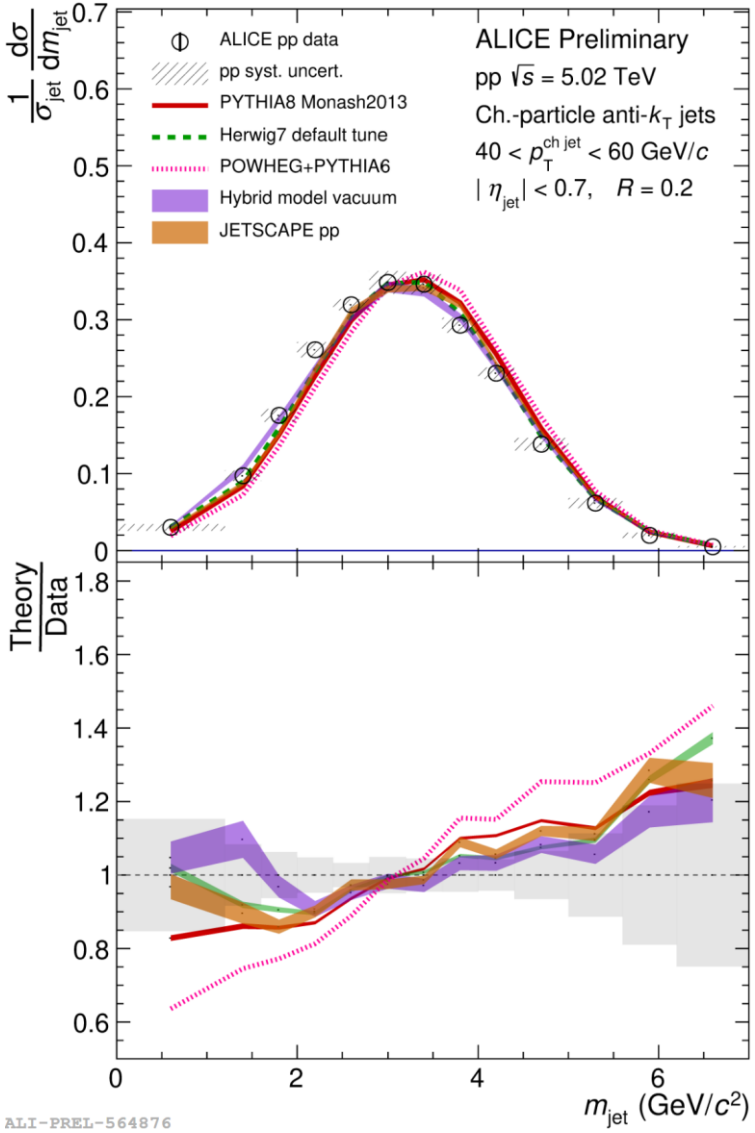
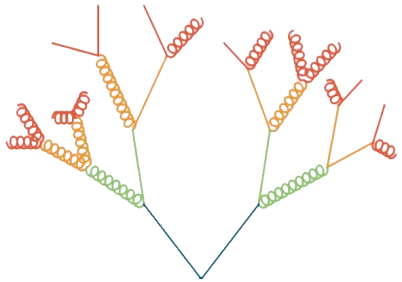


https://alice-figure.web.cern.ch/node/26502

Probing parton emissions



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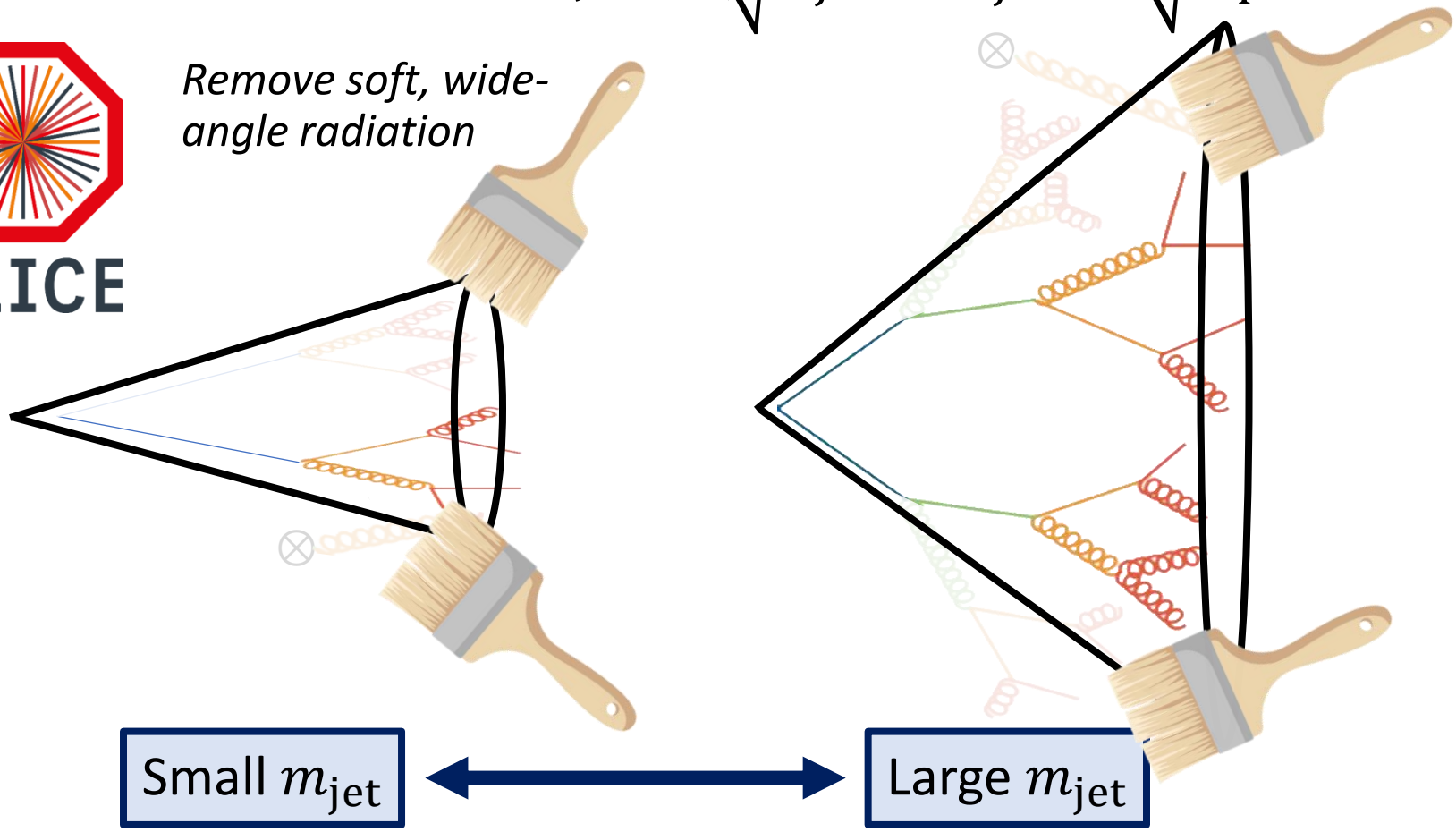
Remove soft, wide-angle radiation



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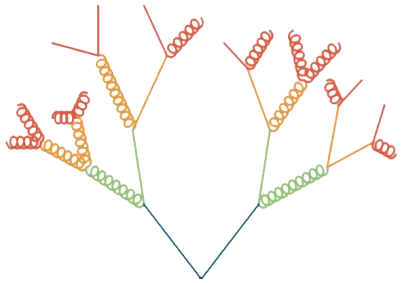

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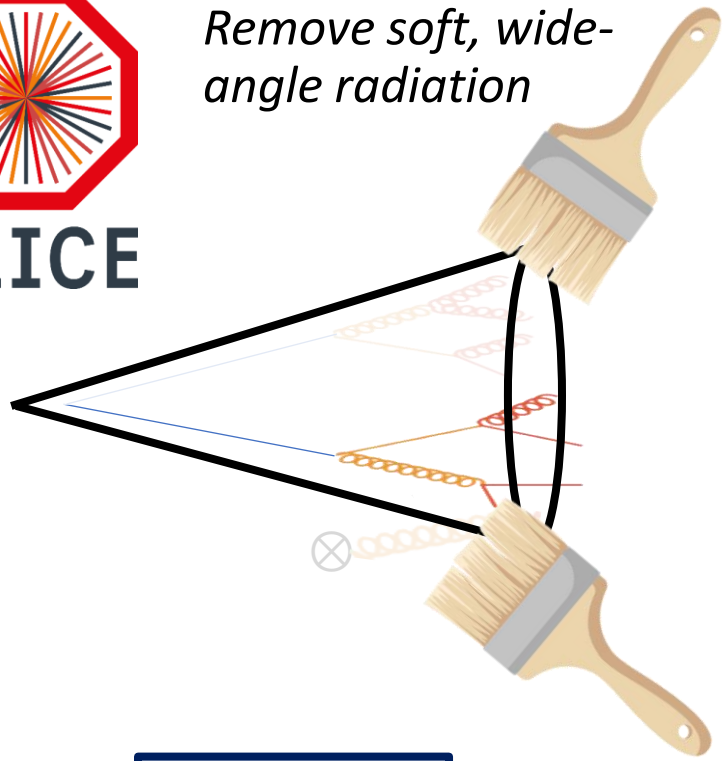
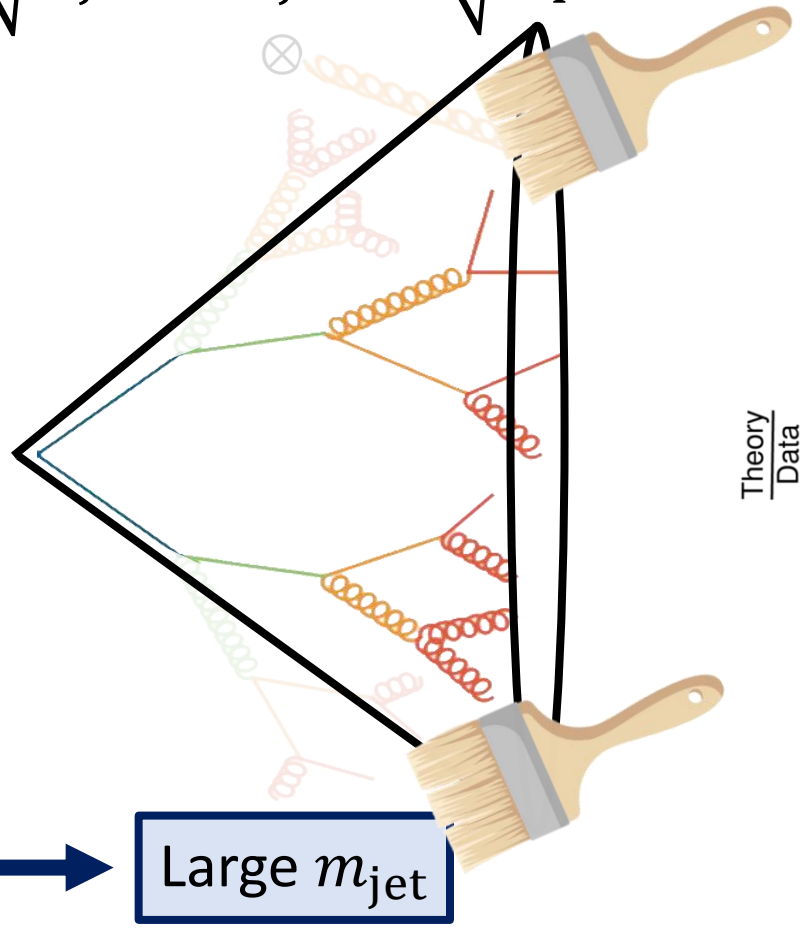
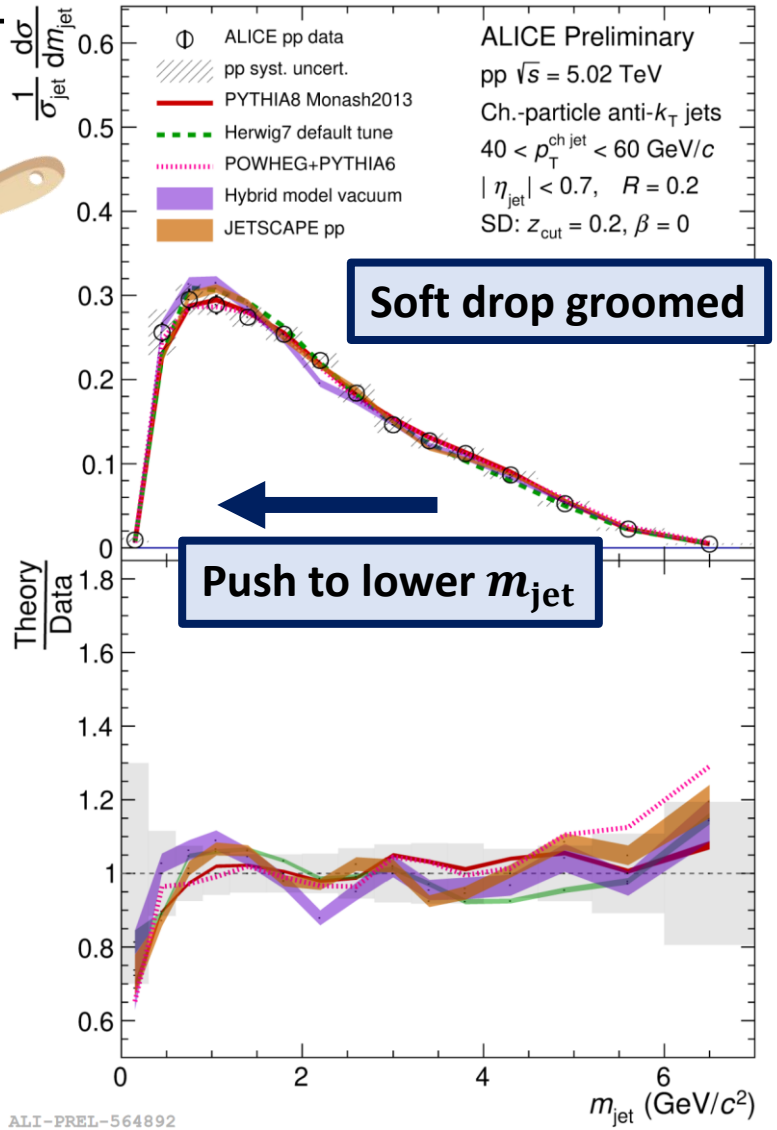




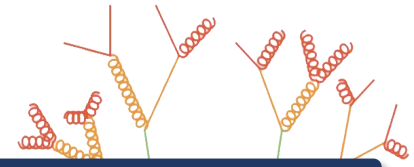
Small m_{jet} ⟷ Large m_{jet}



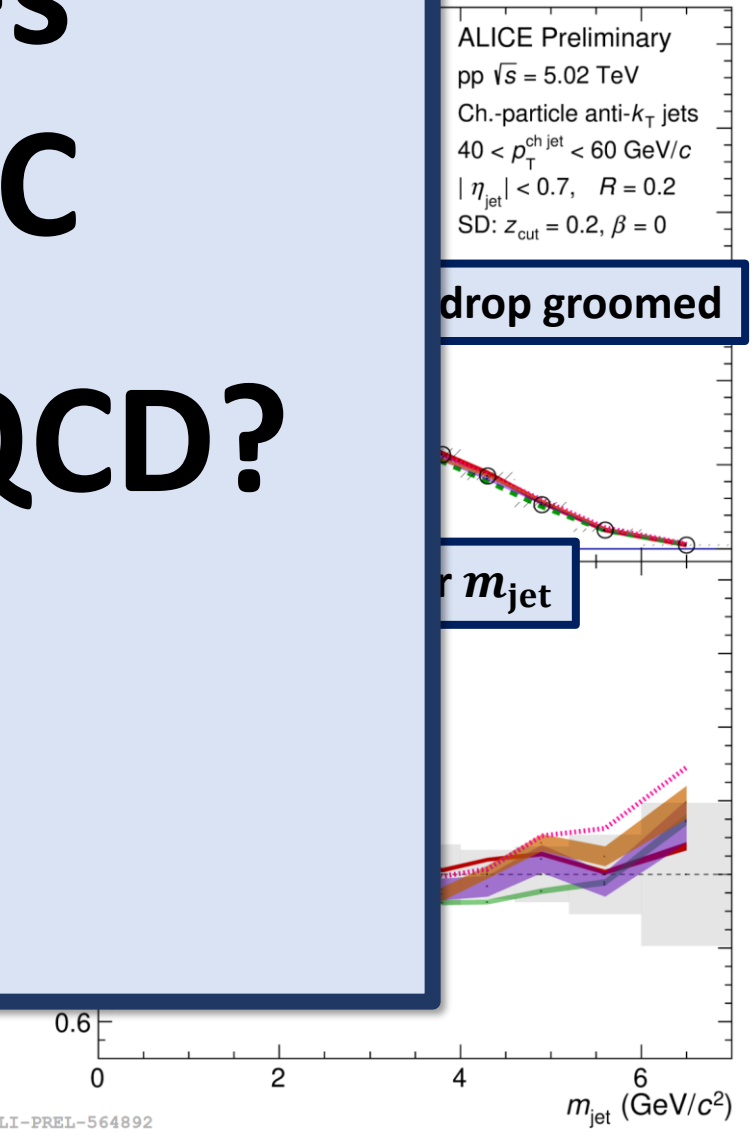
https://alice-figure.web.cern.ch/node/26502

Probing parton emissions

- **Invariant**



- **Grooming improves agreement with MC**
- **Comparisons to pQCD?**
- **Reduce systematic uncertainties?**



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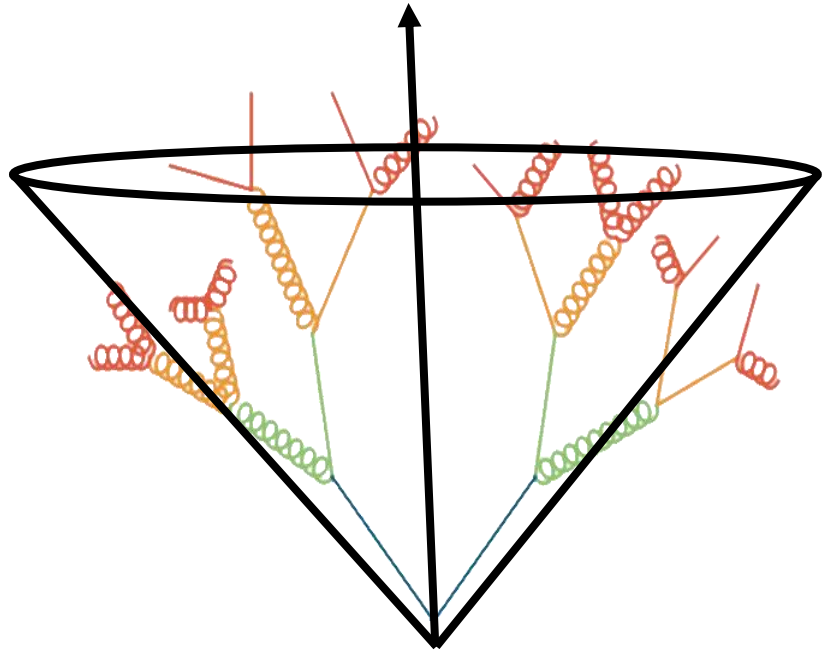
Small m_{jet} ⟷ Large m_{jet}

From mass to angularities

Jet angularities:

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

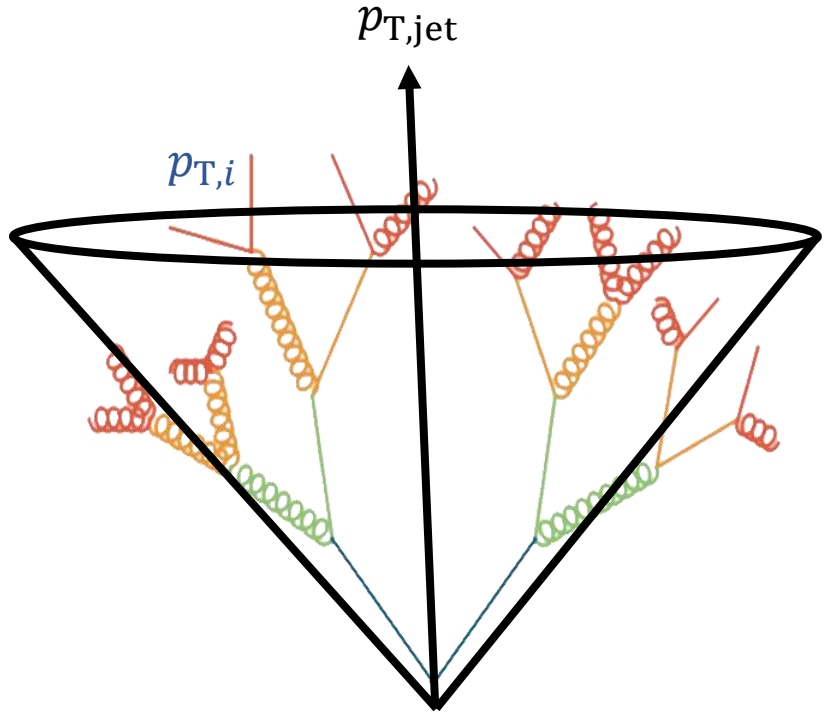


https://alice-figure.web.cern.ch/node/26561

From mass to angularities

Jet angularities:

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

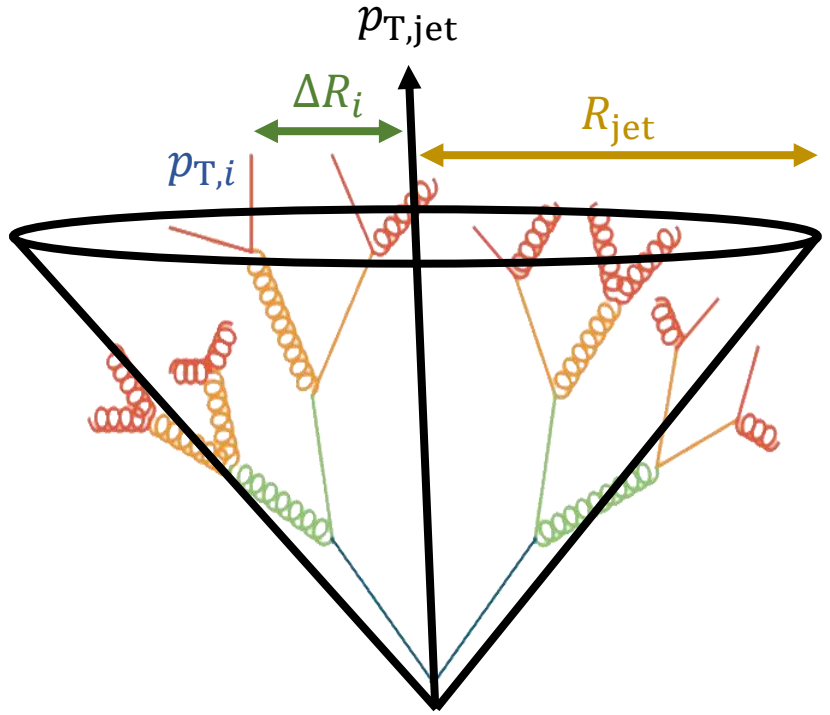


https://alice-figure.web.cern.ch/node/26561

From mass to angularities

Jet angularities:

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



https://alice-figure.web.cern.ch/node/26561

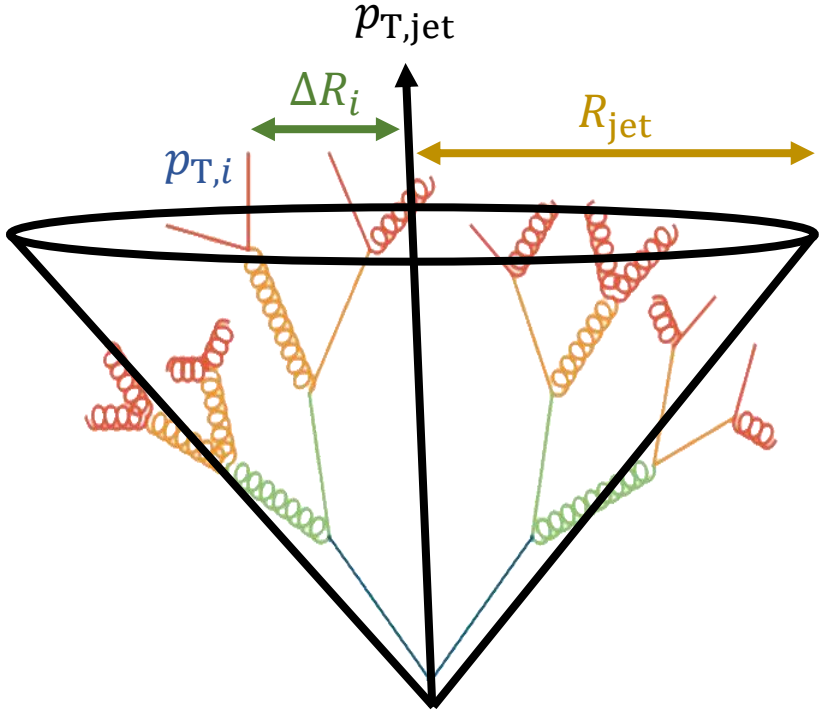
From mass to angularities

Jet angularities:

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

α ← *free parameter*

free parameter → R_{jet}



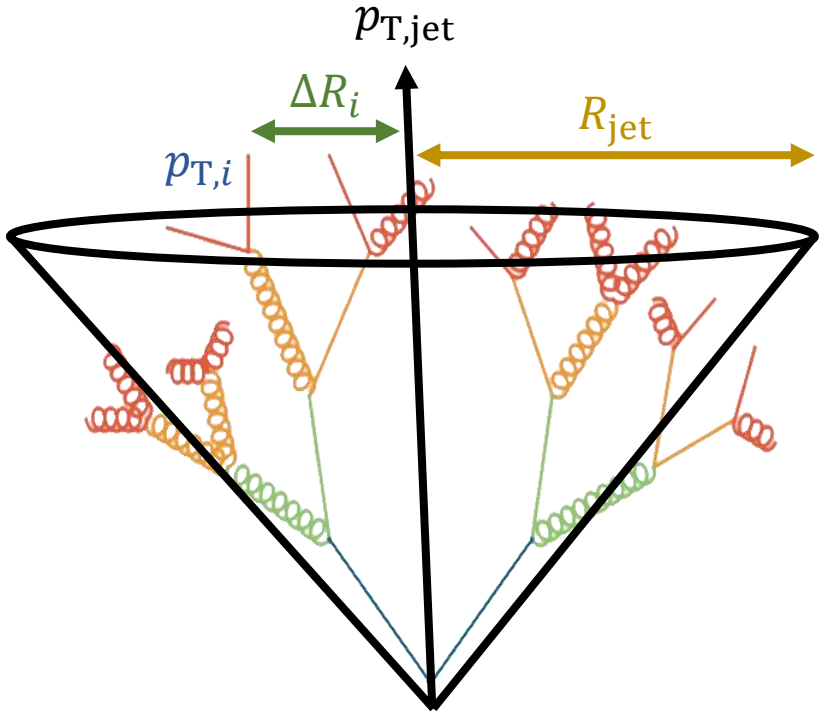
https://alice-figure.web.cern.ch/node/26561

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?"



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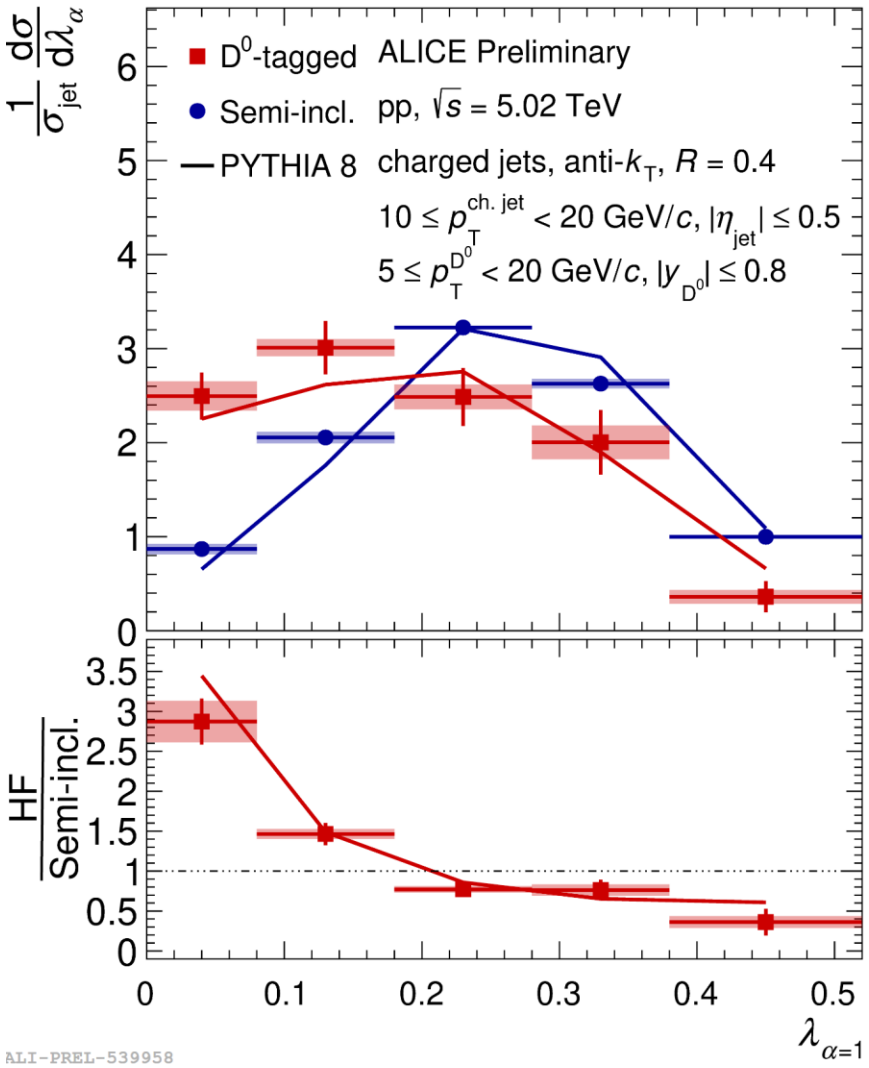
From mass to angularities



Jet angularities:

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

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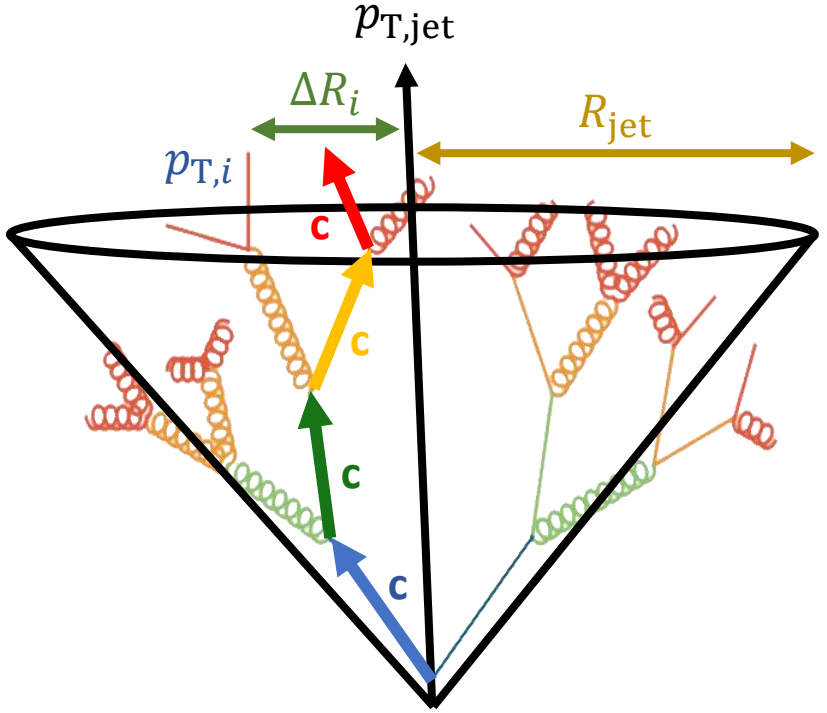
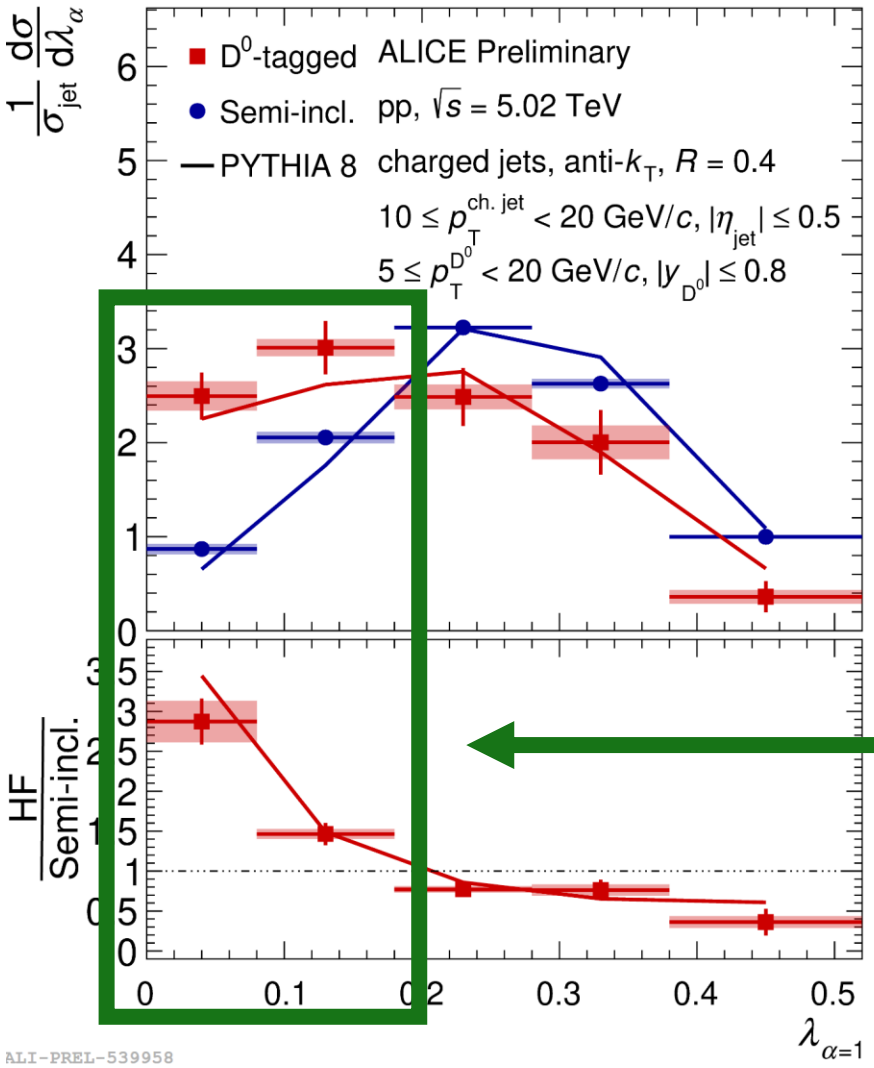


From mass to angularities

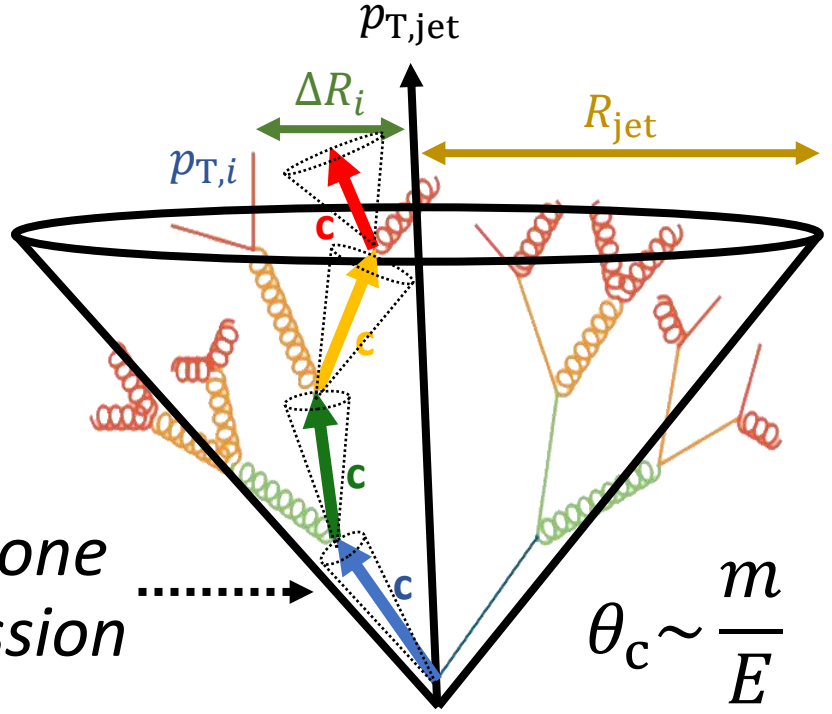


Jet angularities:

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

Charm enhanced at small λ_α!

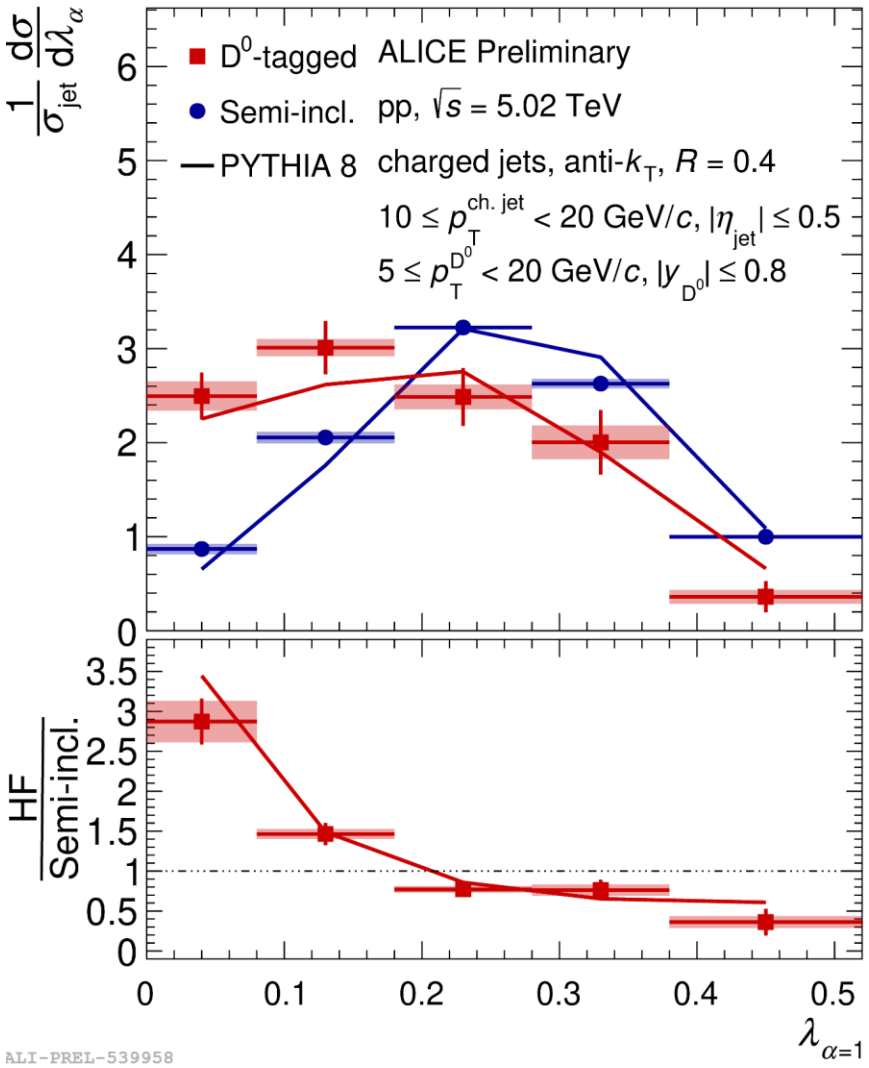
"Where is the p_T inside the jet?"



Dead cone suppression ⋯⋯▸

$$\theta_c \sim \frac{m}{E}$$

From mass to angularities



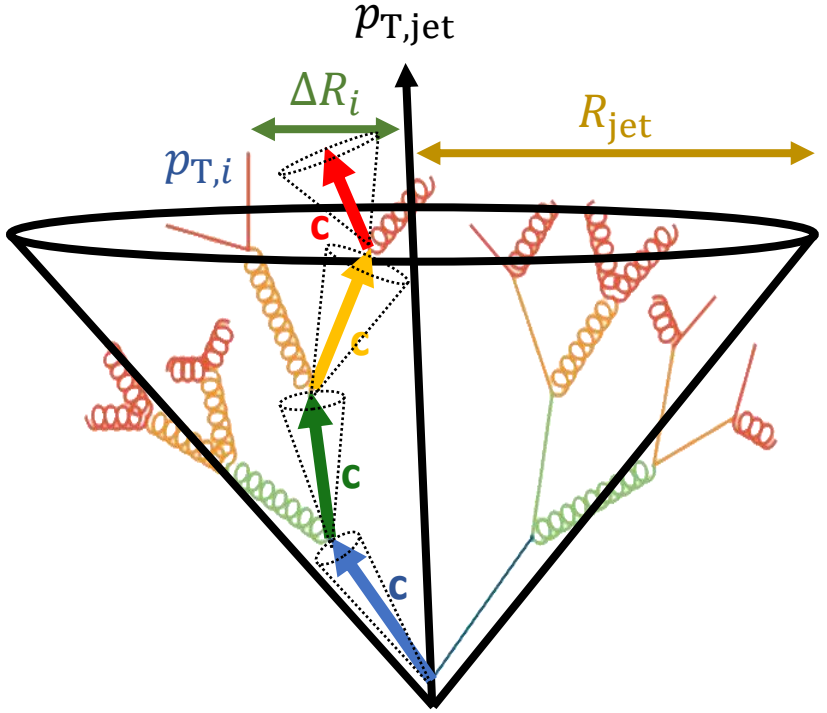
Jet angularities:

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

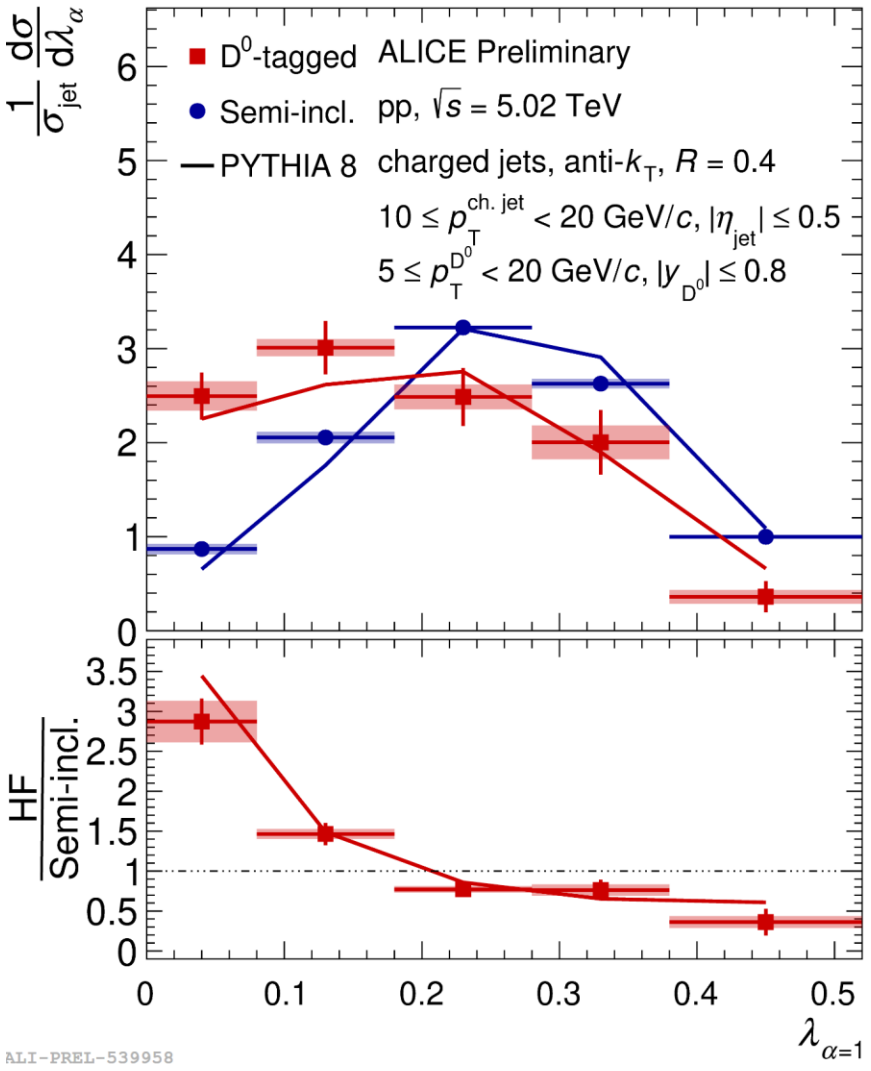
How to separate?

- *Mass effects*
- *Quark vs. gluon fragmentation*

"Where is the p_T inside the jet?"



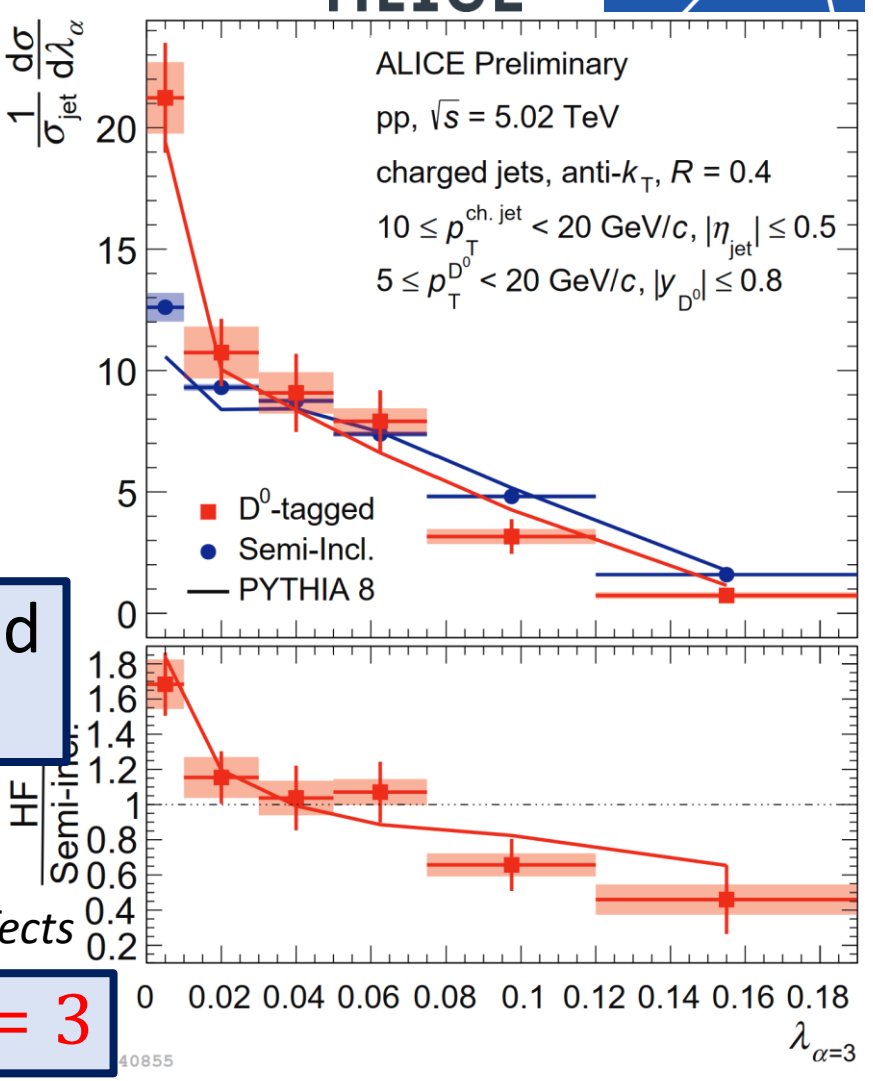
From mass to angularities



Jet angularities:

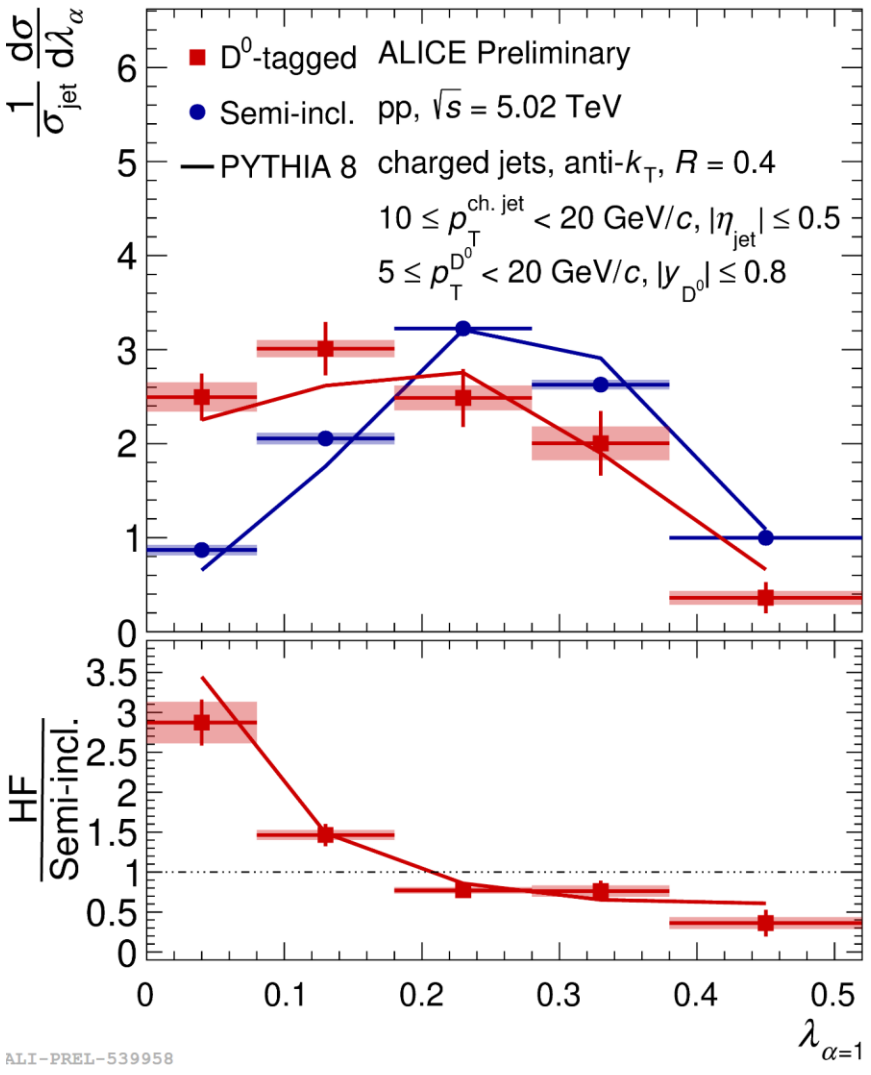
$$\lambda_\alpha = \sum_{i \in \text{jet}} \frac{p_{\text{T},i}}{p_{\text{T,jet}}} \left(\frac{\Delta R_i}{R_{\text{jet}}}\right)^\alpha = \sum_{i \in \text{jet}} z_i \theta_i^\alpha$$

Increased α → increased angular weighting



mass effects — $\alpha = 1$ ⟷ $\alpha = 3$ — *Casimir color effects*

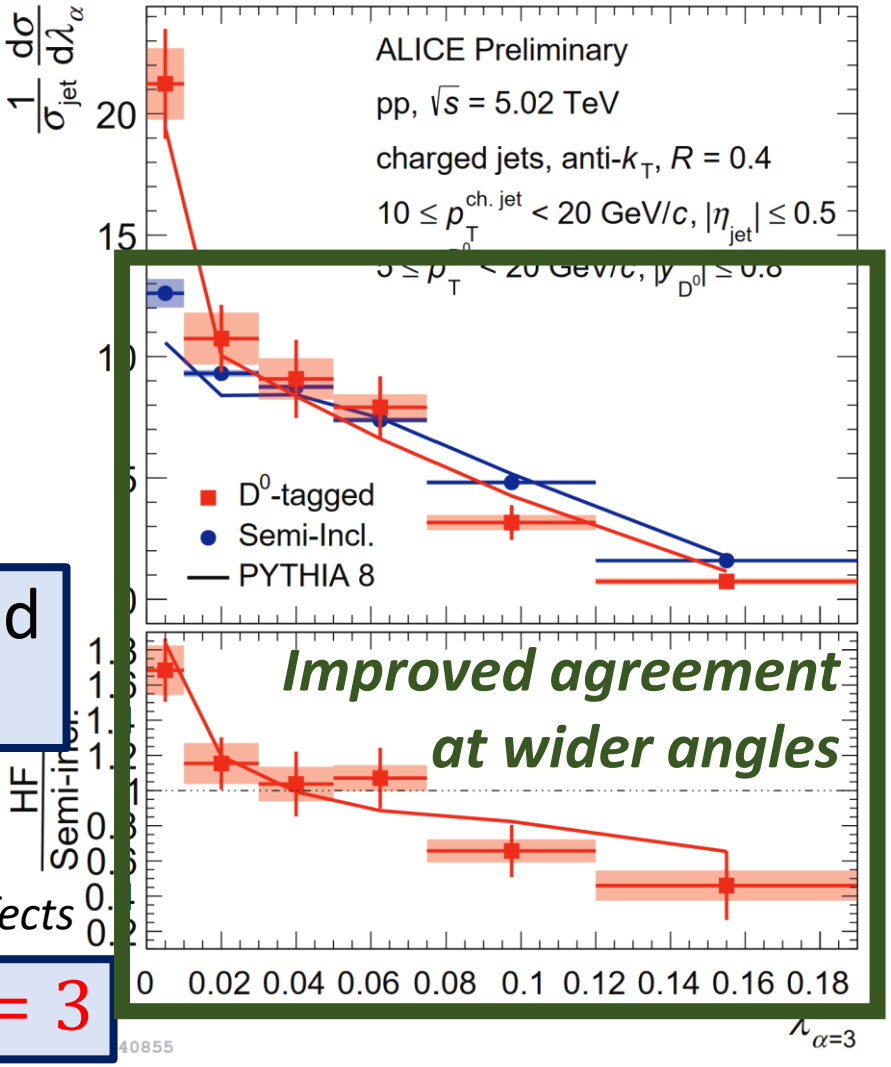
From mass to angularities



Jet angularities:

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

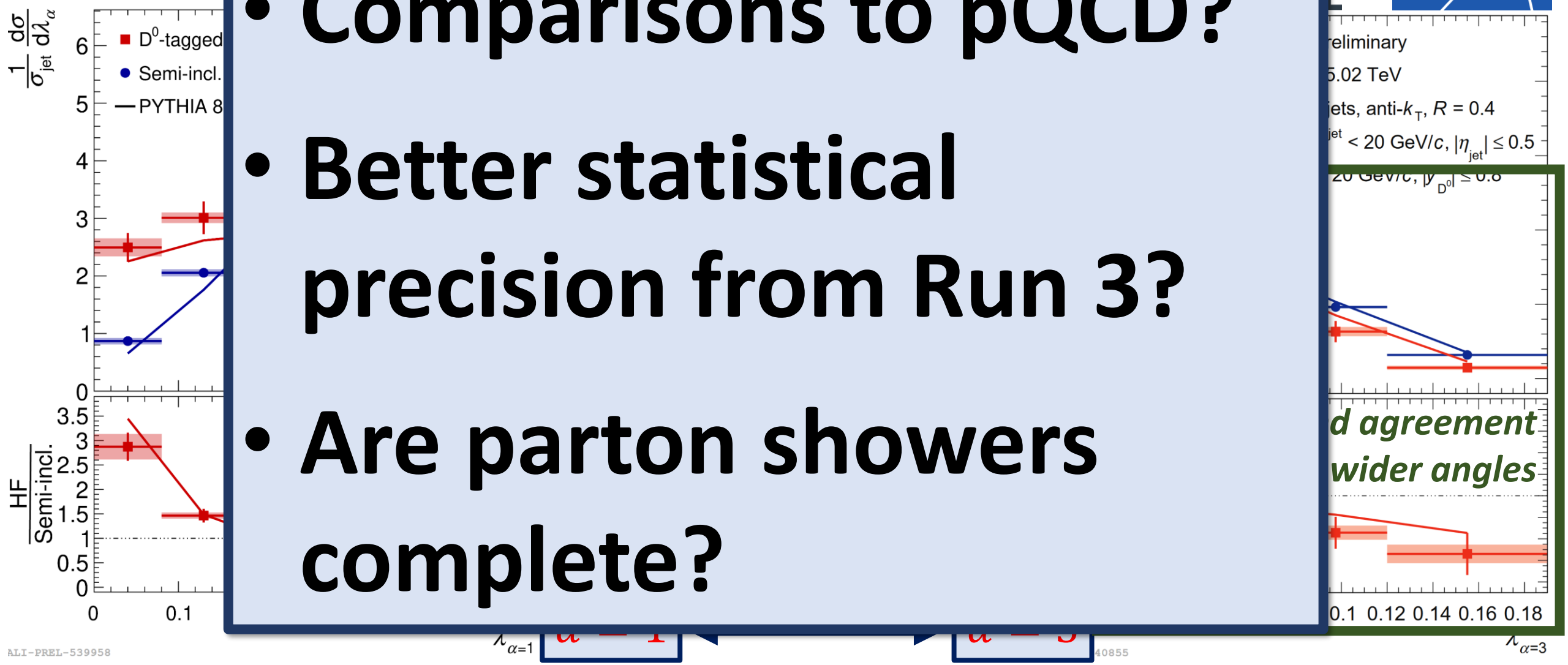
Increased α → increased angular weighting



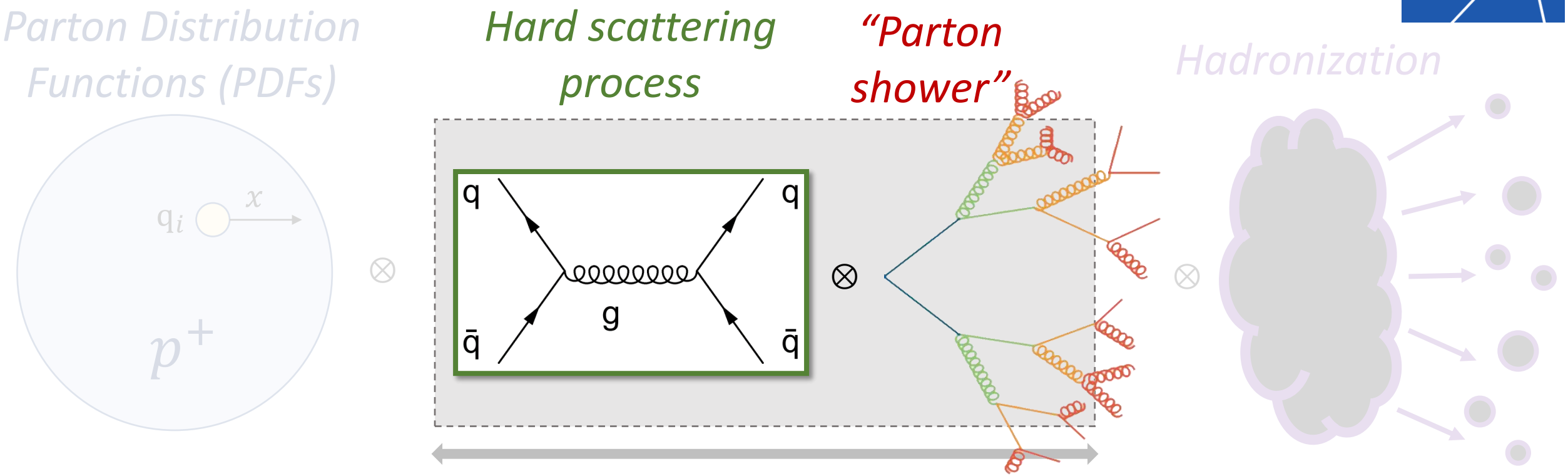
mass effects — $\alpha = 1$ ⟷ $\alpha = 3$ — *Casimir color effects*

From mass to angularities

- **Comparisons to pQCD?**
- **Better statistical precision from Run 3?**
- **Are parton showers complete?**

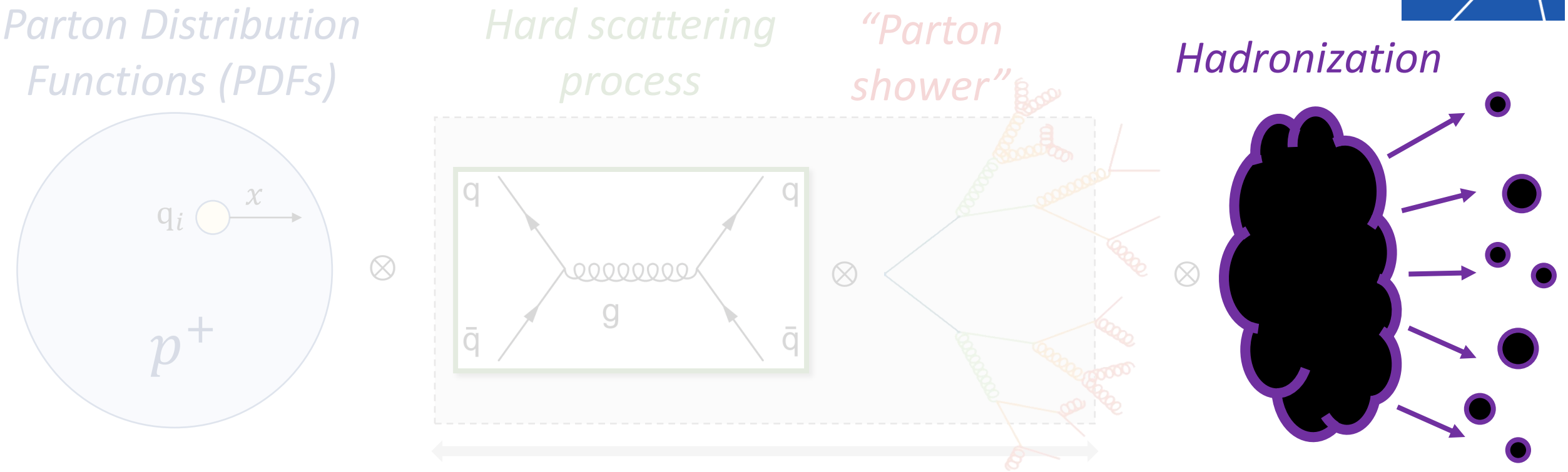


Understanding the jet life cycle



- Test **parton fragmentation** in **perturbative** QCD

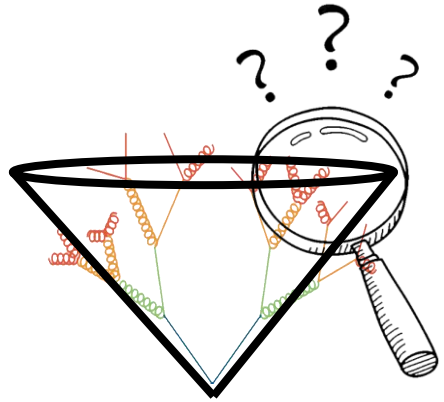
Understanding the jet life cycle



- Test **parton fragmentation** in **perturbative** QCD
- Probe **hadron fragmentation** in **nonperturbative** QCD

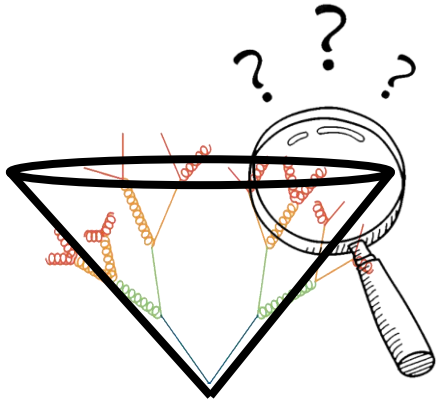
Studying jet constituents

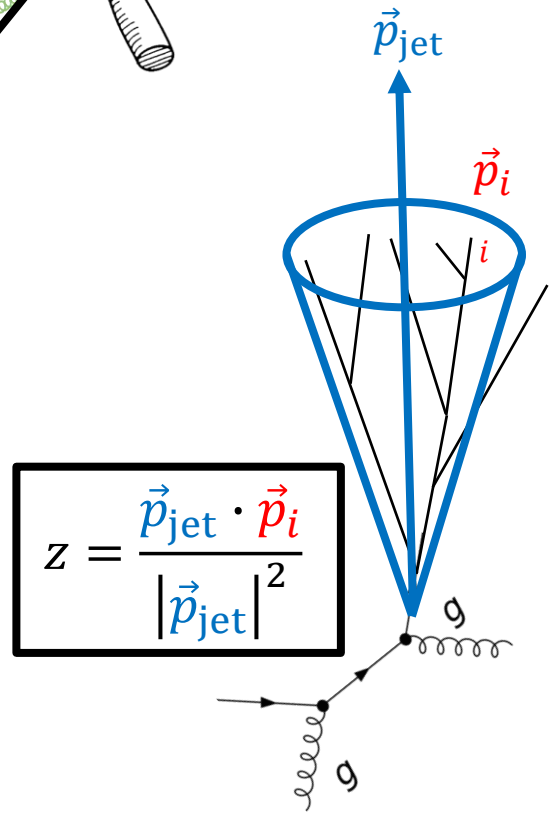
- What hadrons are produced inside of jets?



Studying jet constituents

- What hadrons are produced inside of jets?

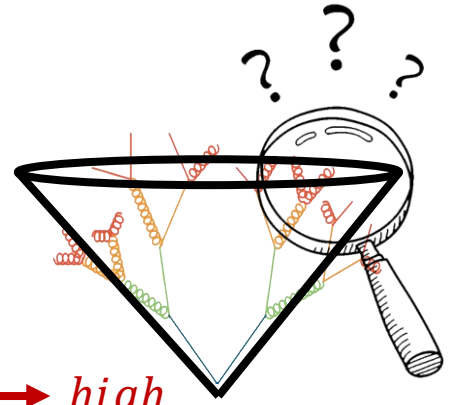




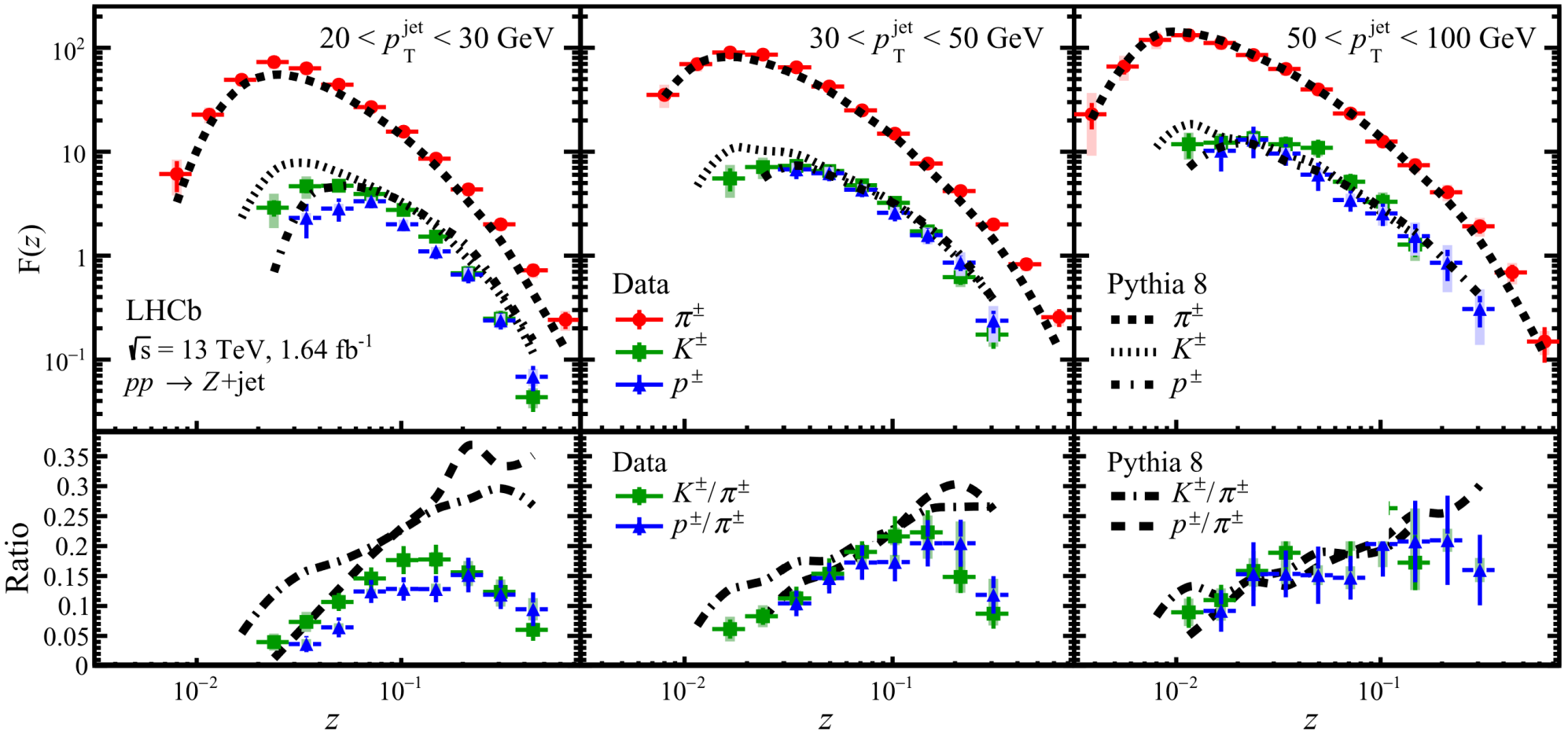
$$z = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_i}{\left|\vec{p}_{\text{jet}}\right|^2}$$

Studying jet constituents

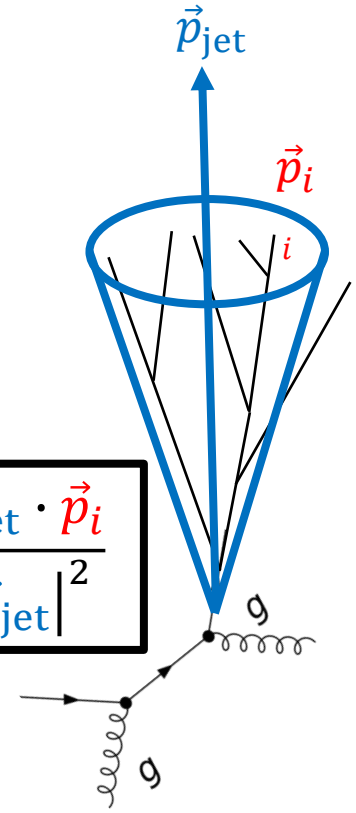
- What hadrons are produced inside of jets?



low ← $p_{\mathrm{T}}^{\mathrm{jet}}$ → high



$$z = \frac{\vec{p}_{\mathrm{jet}} \cdot \vec{p}_i}{\left|\vec{p}_{\mathrm{jet}}\right|^2}$$



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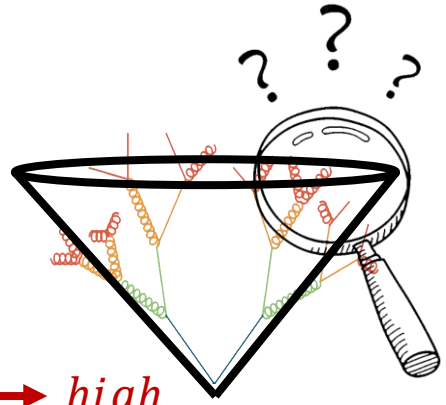
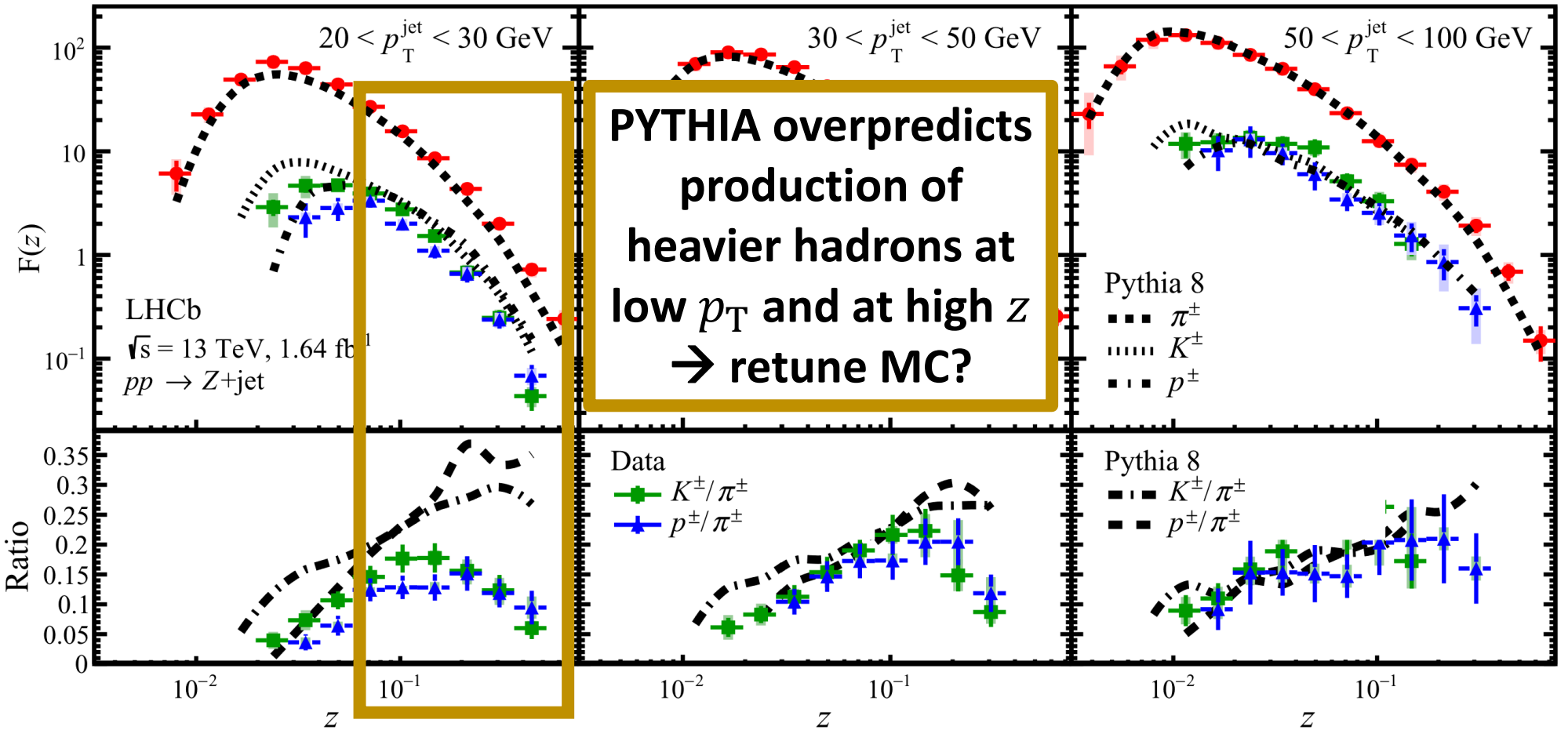
Studying jet constituents

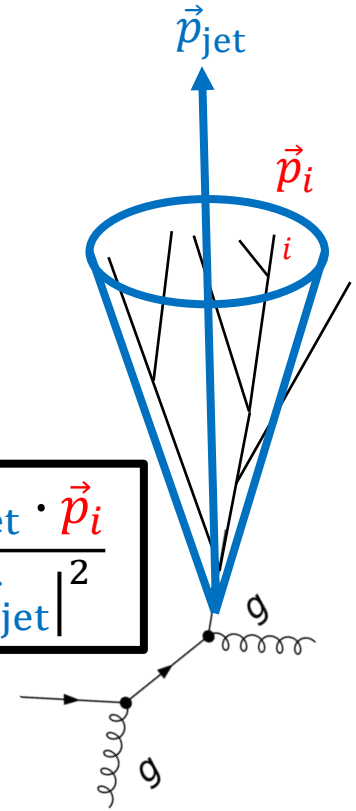
- What hadrons are produced inside of jets?



low ← $p_{\mathrm{T}}^{\mathrm{jet}}$ → high



PYTHIA overpredicts production of heavier hadrons at low p_{T} and at high z → retune MC?



$$z = \frac{\vec{p}_{\mathrm{jet}} \cdot \vec{p}_i}{\left|\vec{p}_{\mathrm{jet}}\right|^2}$$

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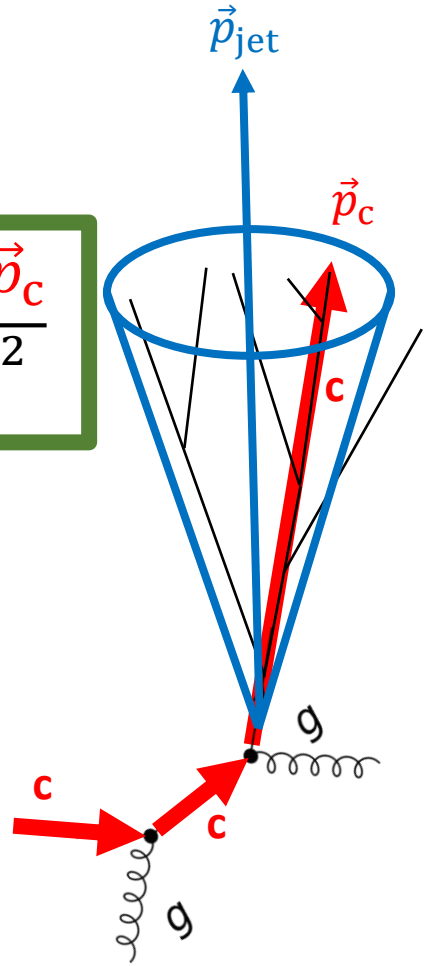
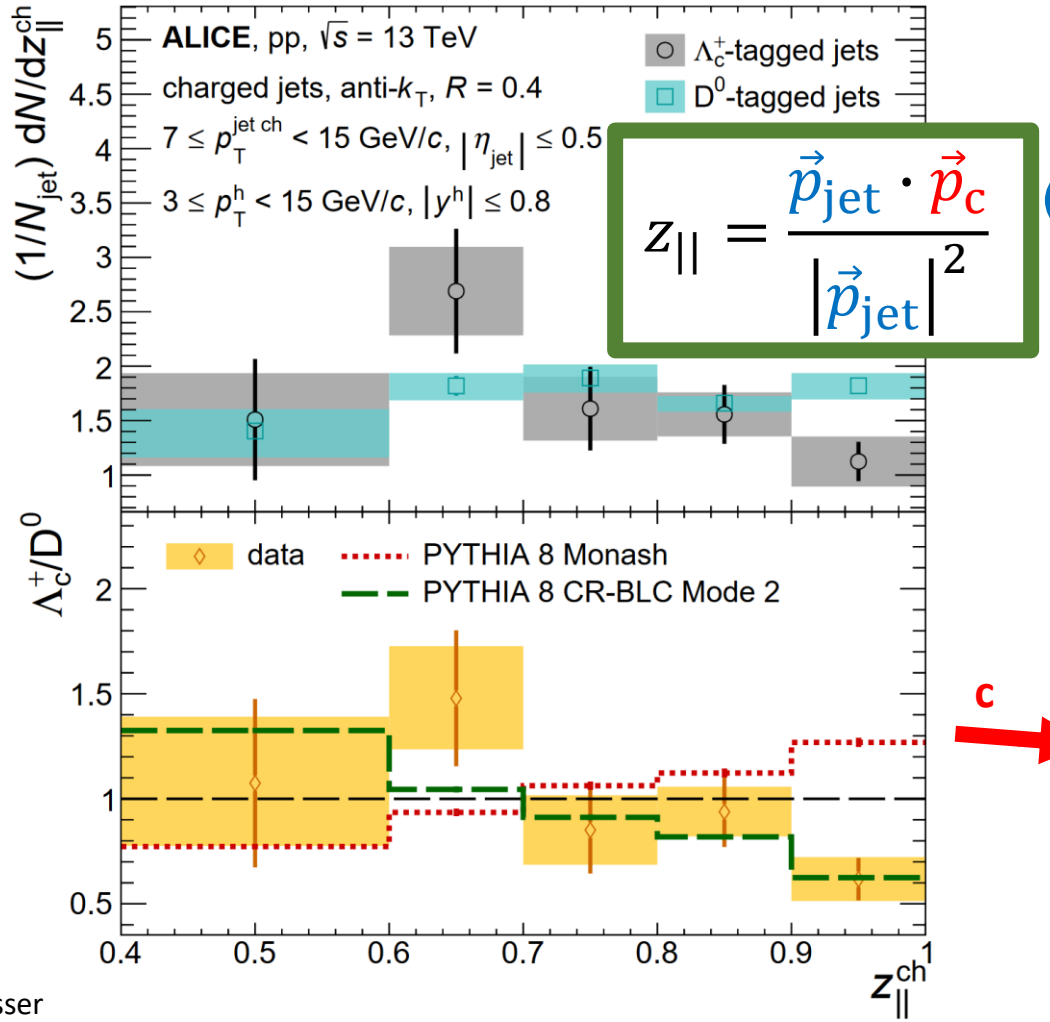
Charm quark fragmentation

$$z_{||} = \frac{\vec{p}_{\mathrm{jet}} \cdot \vec{p}_{\mathrm{c}}}{\left|\vec{p}_{\mathrm{jet}}\right|^2}$$

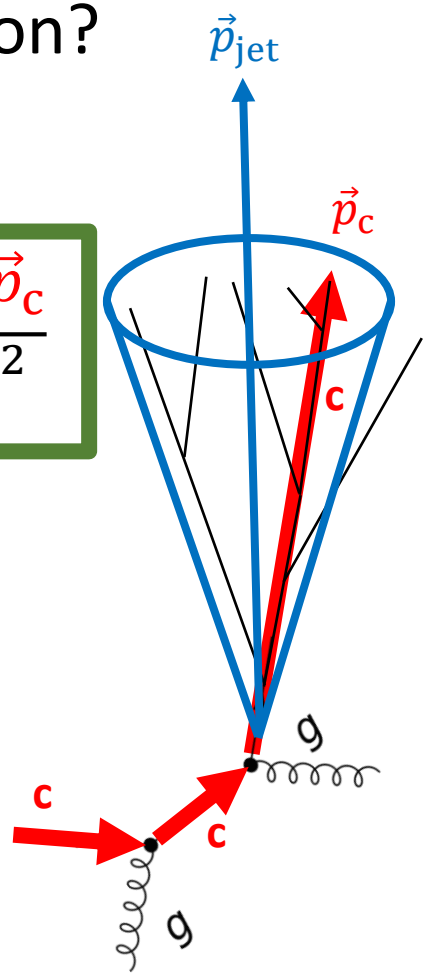


Charm quark fragmentation

- Λ_c^+ baryon **softer** than D^0 meson?



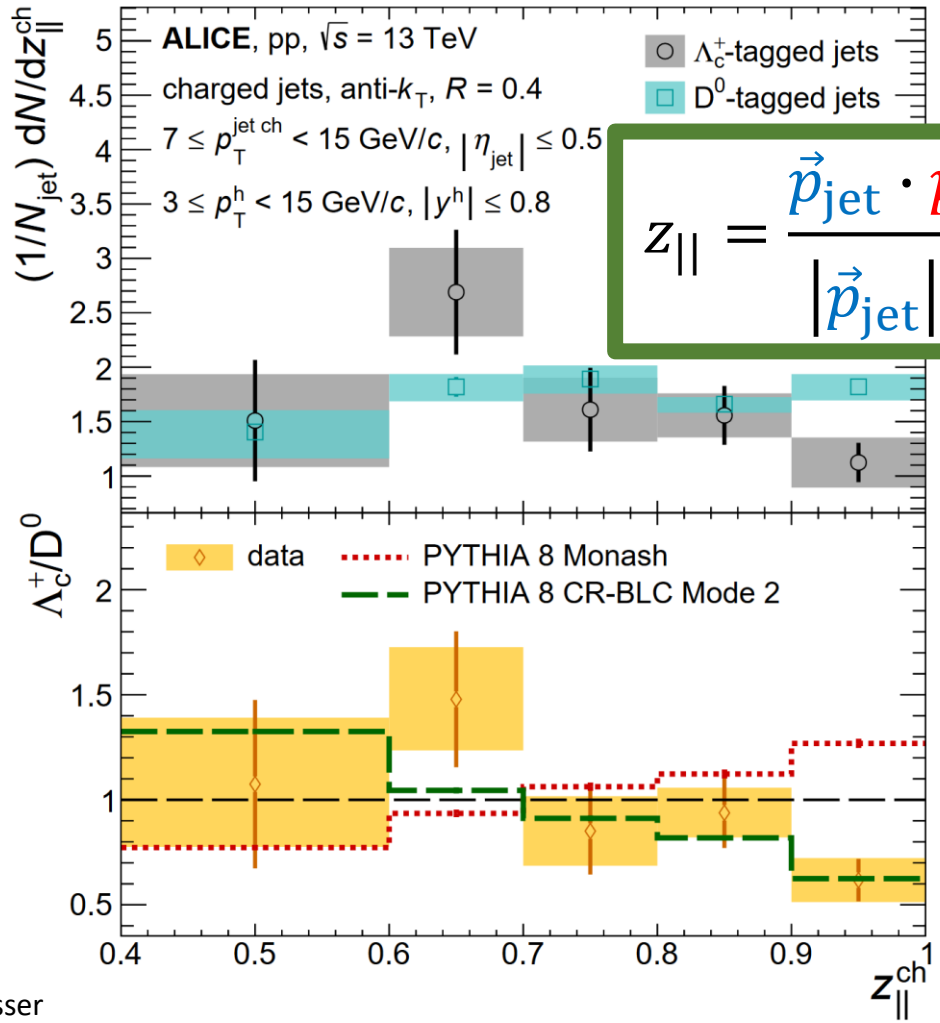
$$z_{\parallel} = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{c}}}{|\vec{p}_{\text{jet}}|^2}$$



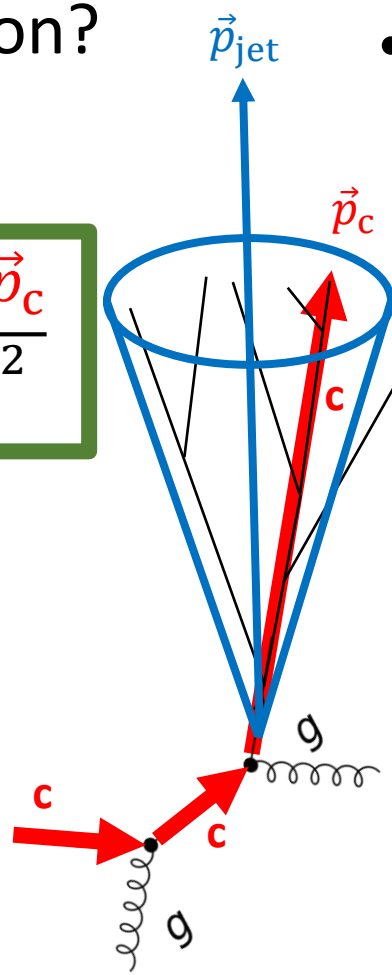
Phys. Rev. D 109 (2024) 072005

Charm quark fragmentation

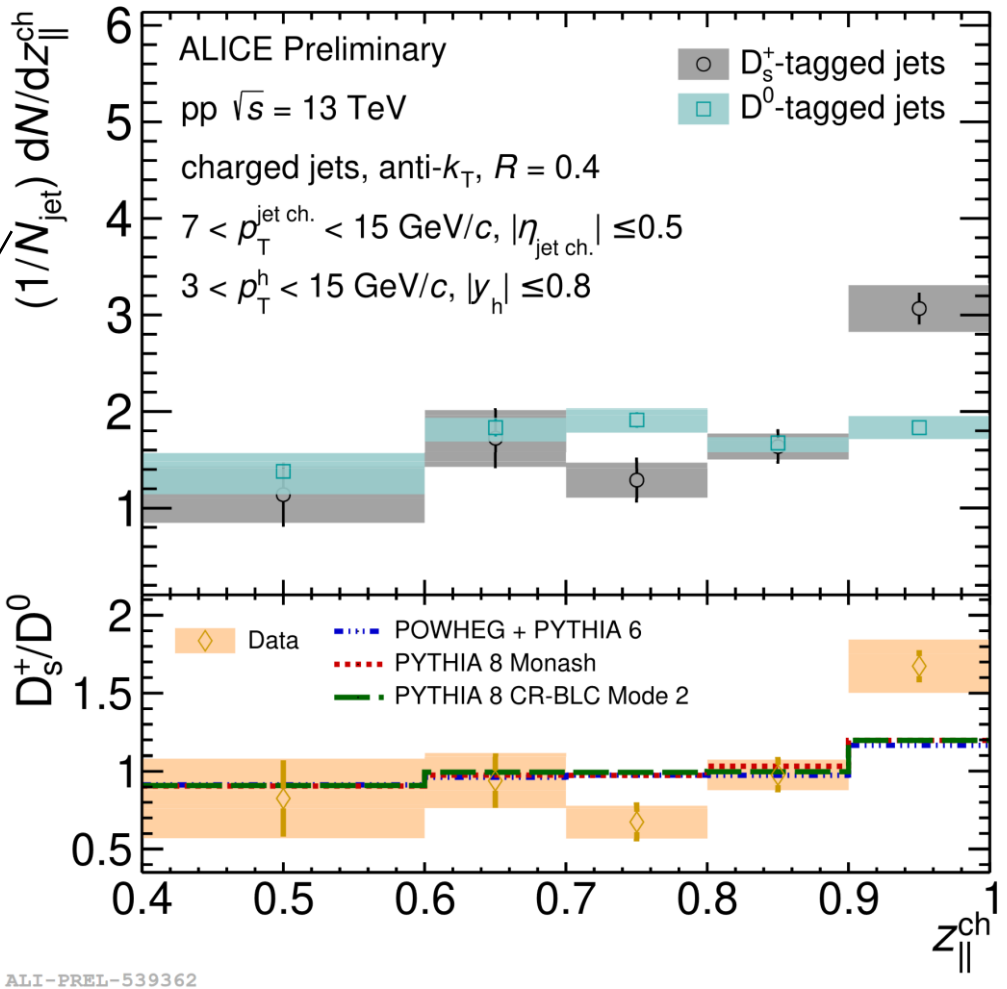
- Λ_c^+ baryon **softer** than D^0 meson?



$$z_{\parallel} = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{c}}}{|\vec{p}_{\text{jet}}|^2}$$



- D_s^+ meson **harder** than D^0 meson?



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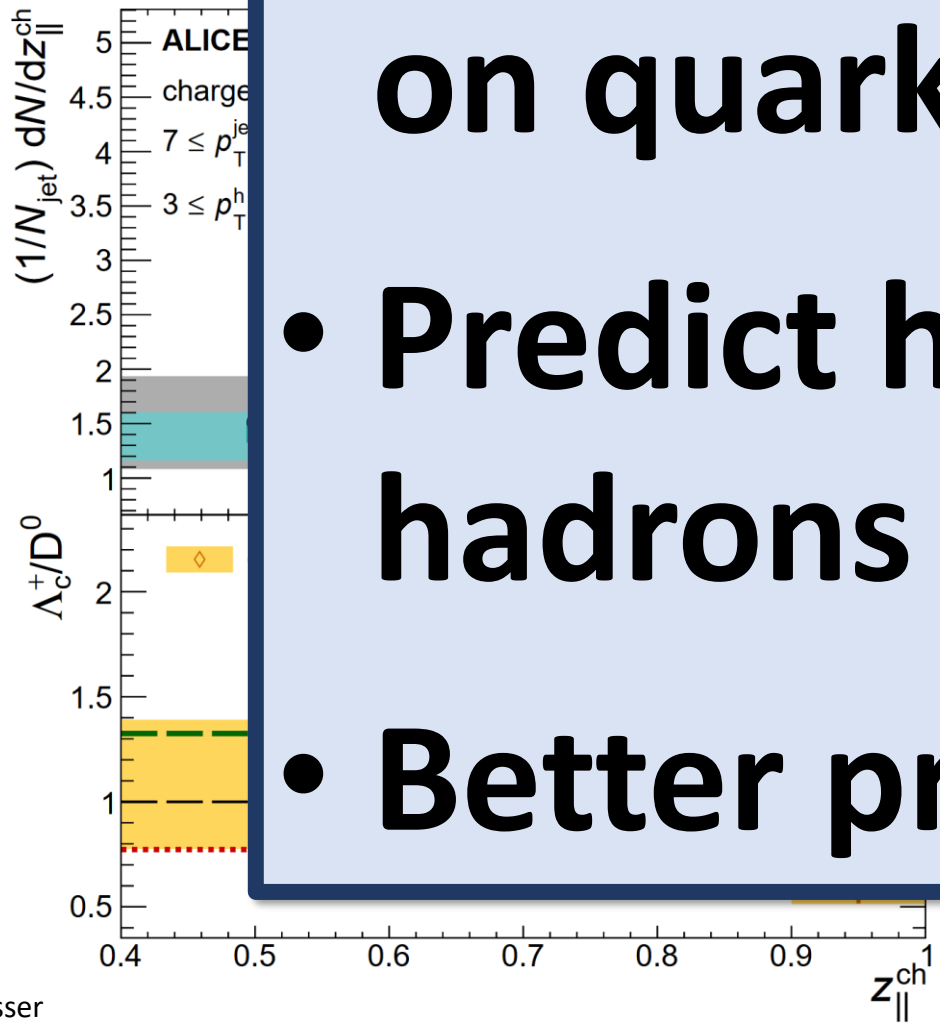
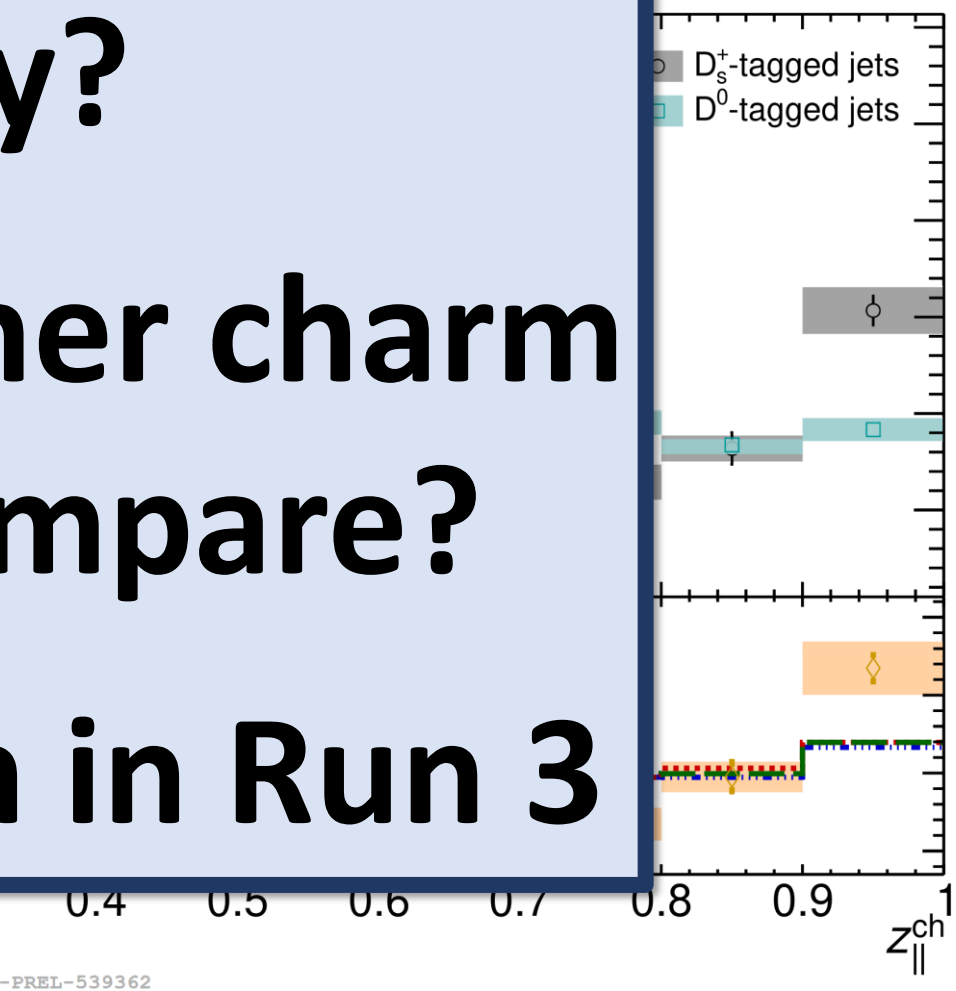
https://alice-figure.web.cern.ch/node/26379

Charm quark fragmentation

- Λ_c^+ bary … D^0 meson?

- **Coalescence depends on quark energy?**
- **Predict how other charm hadrons will compare?**
- **Better precision in Run 3**





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https://alice-figure.web.cern.ch/node/26379

Bottom-tagged jets

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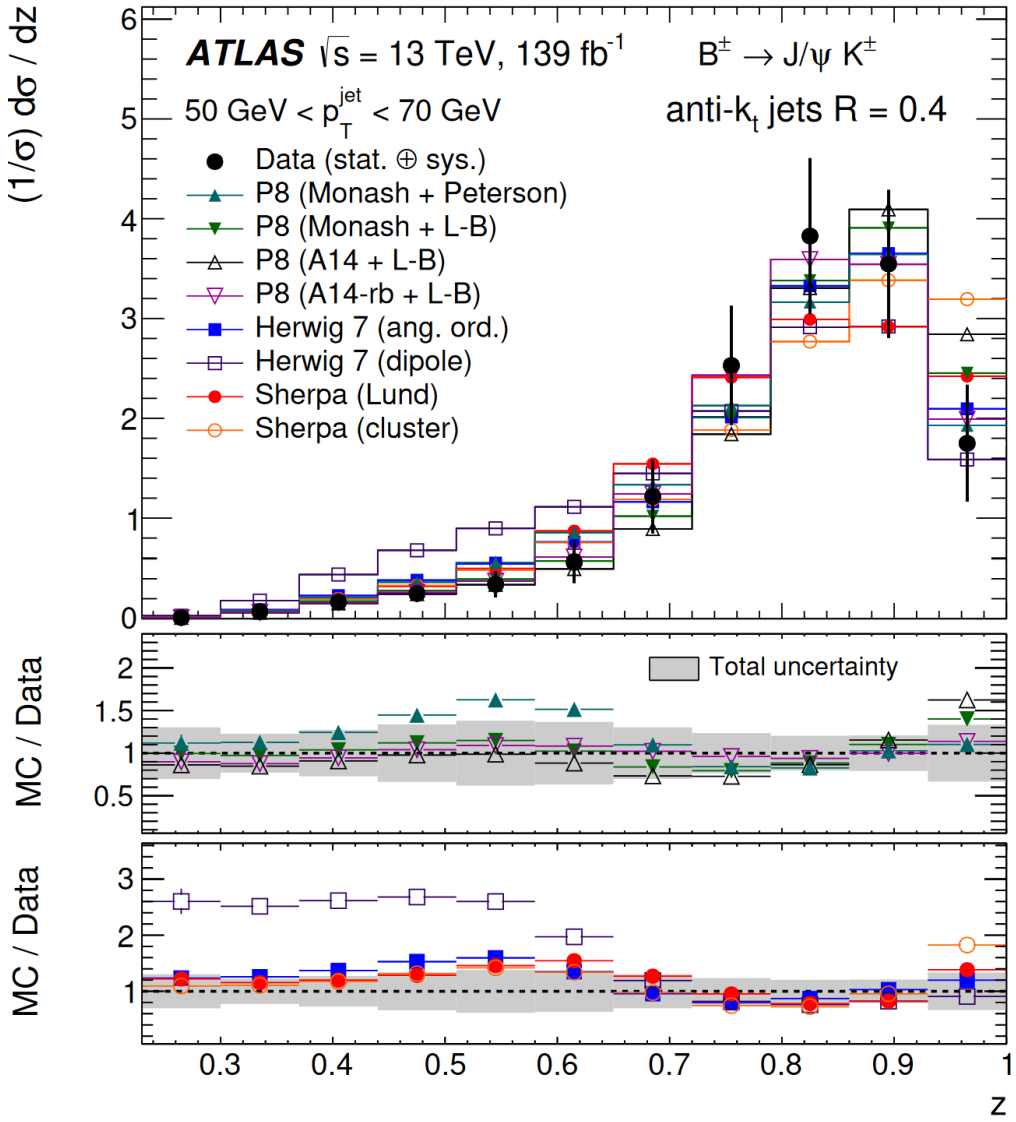
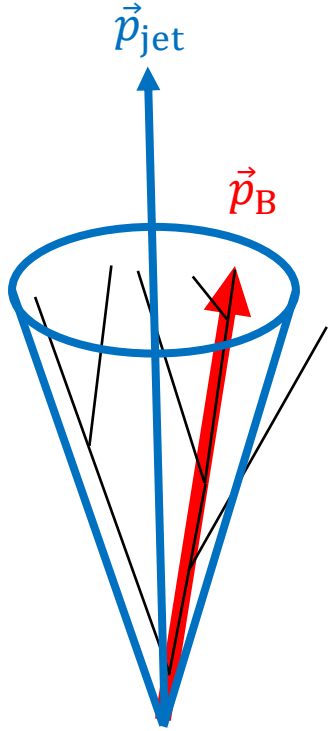
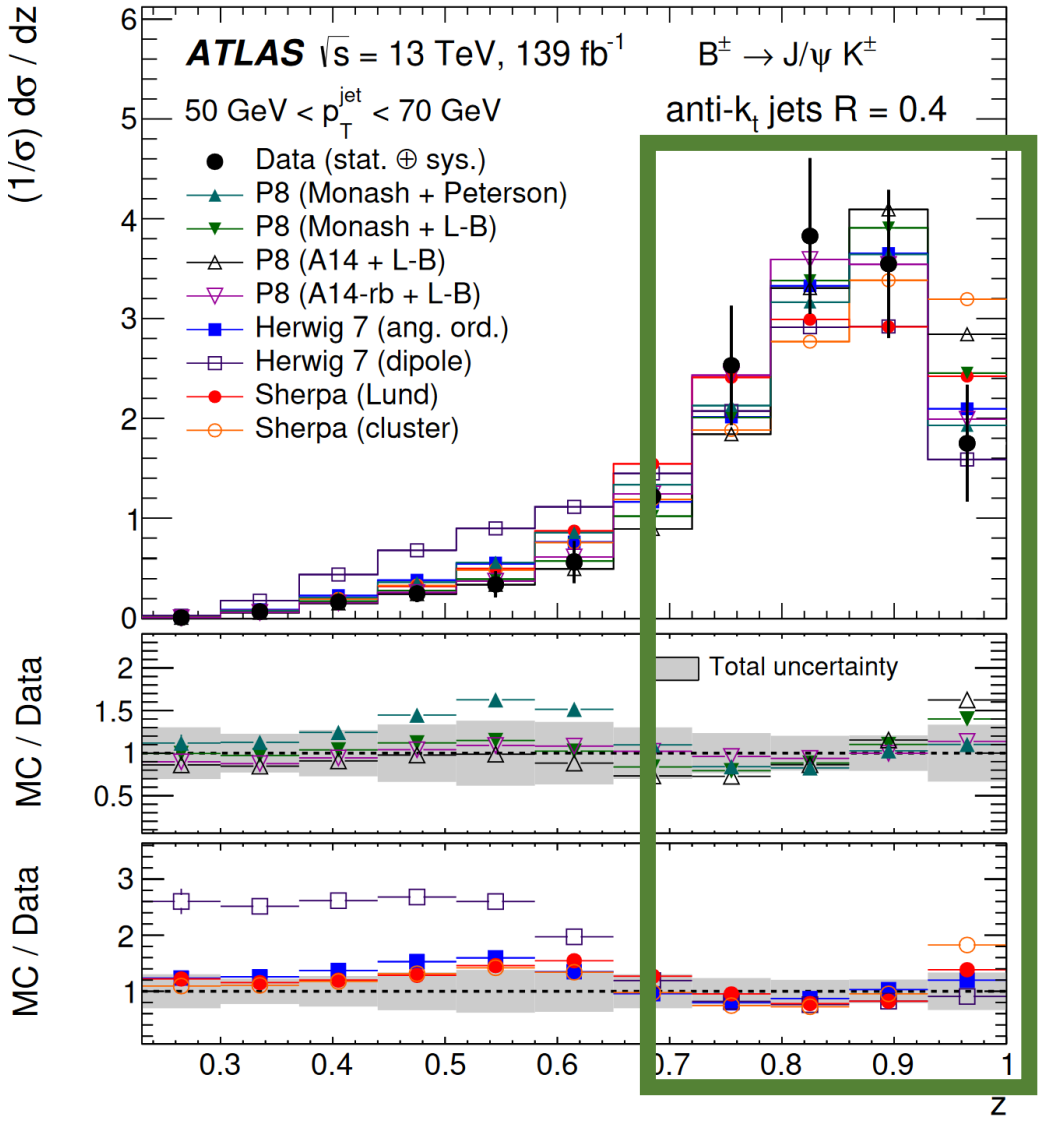


$$z = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_B}{\left|\vec{p}_{\text{jet}}\right|^2}$$



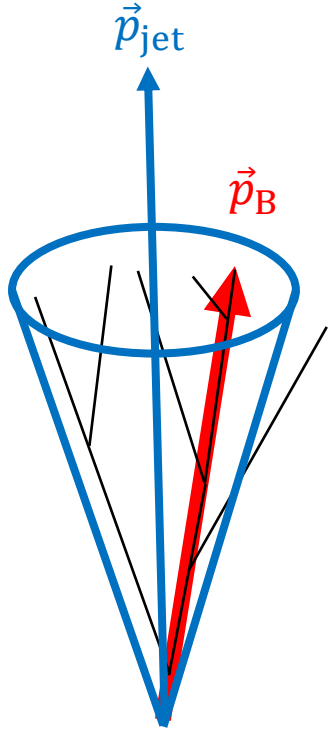
Bottom-tagged jets

JHEP 12 (2021) 131



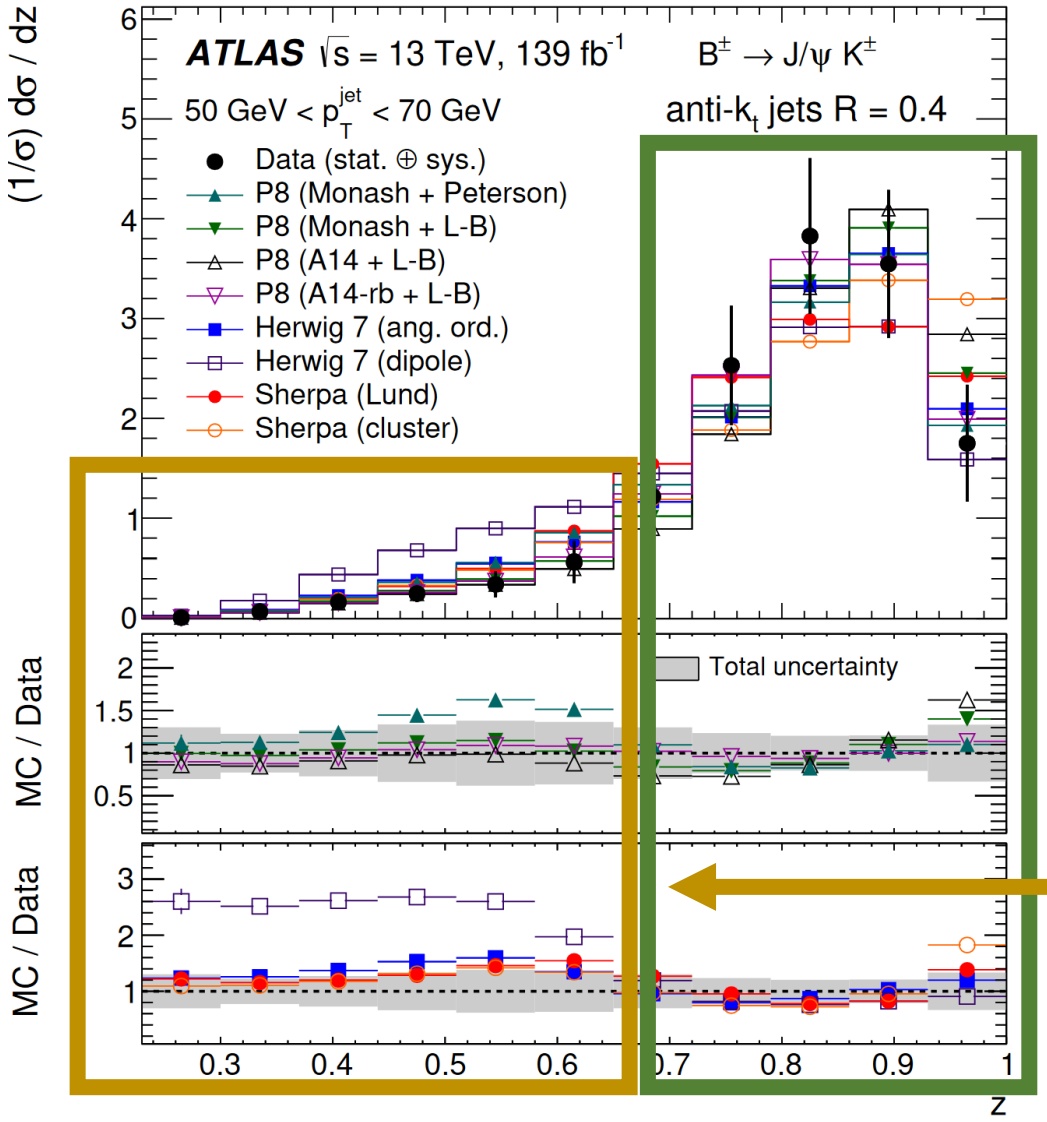
Peak at large z well-described by models at medium jet p_{T}

$$z = \frac{\vec{p}_{\mathrm{jet}} \cdot \vec{p}_B}{\left|\vec{p}_{\mathrm{jet}}\right|^2}$$



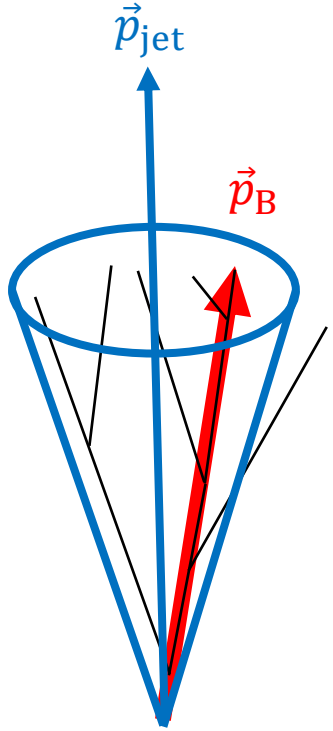
Bottom-tagged jets

JHEP 12 (2021) 131



Peak at large z well-described by models at medium jet p_{T}

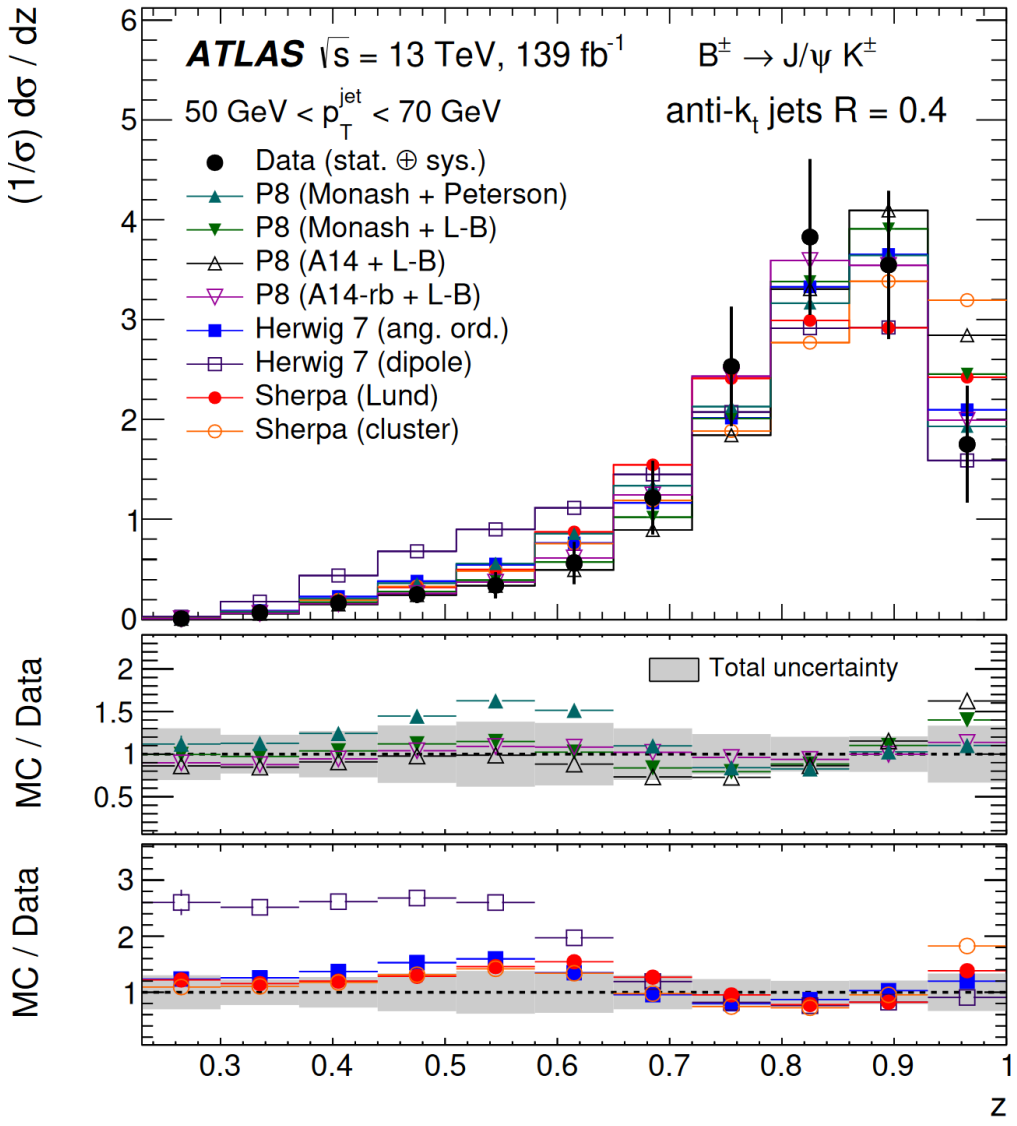
$$z = \frac{\vec{p}_{\mathrm{jet}} \cdot \vec{p}_B}{\left|\vec{p}_{\mathrm{jet}}\right|^2}$$

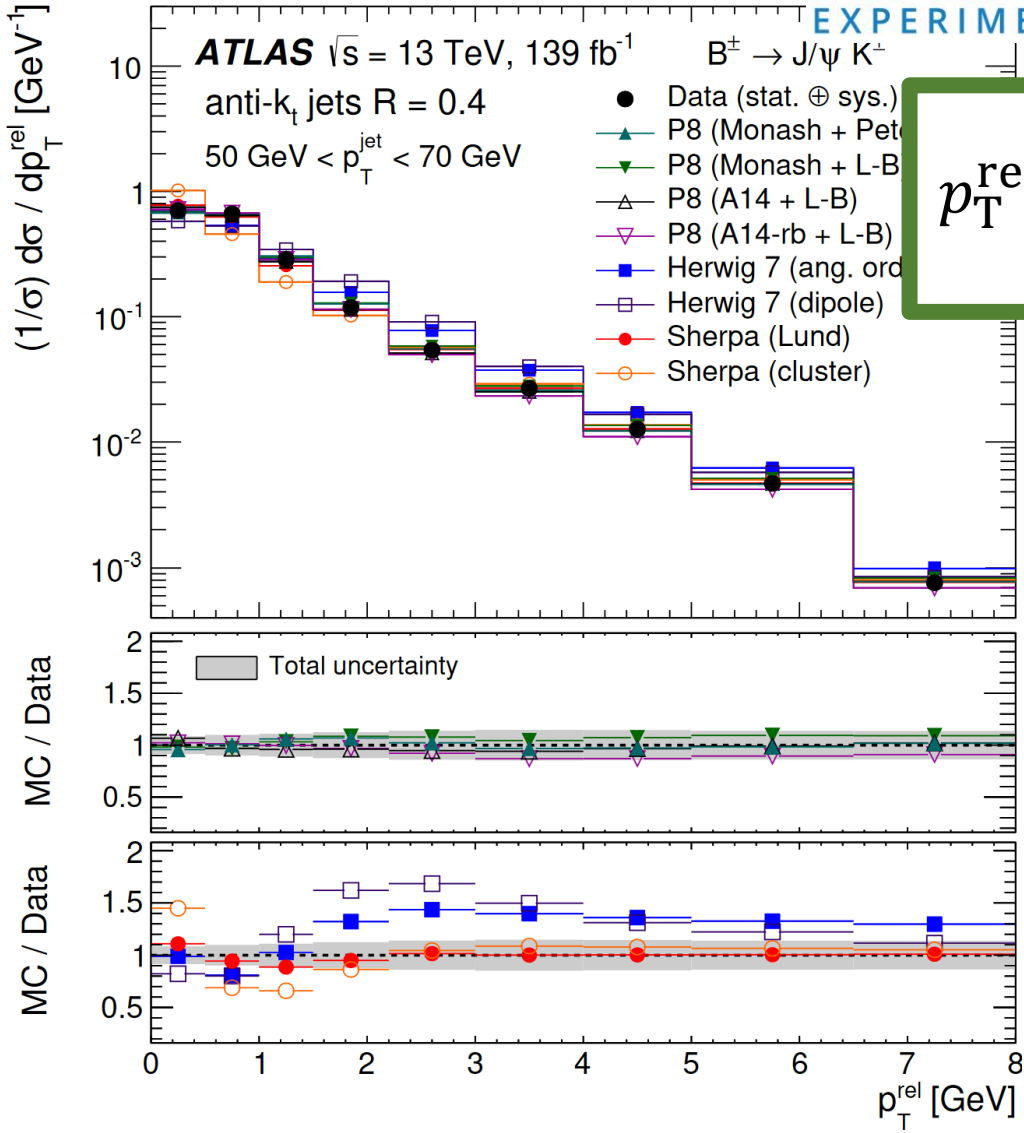


Gluon-splitting ($g \to b\bar{b}$) overestimated by some MC models

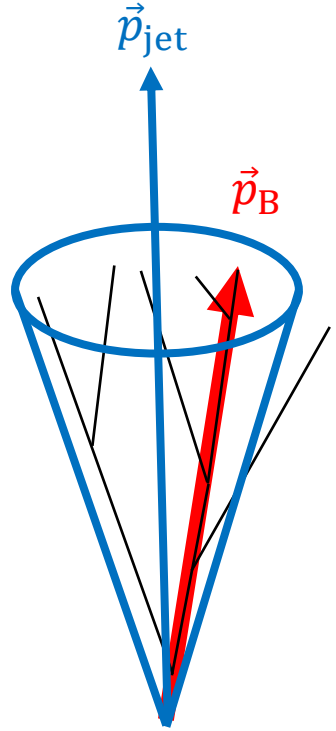
Bottom-tagged jets

[JHEP 12 (2021) 131](#)





$$p_{\mathrm{T}}^{\mathrm{rel}} = \frac{\left|\vec{p}_B \times \vec{p}_{\mathrm{jet}}\right|}{\left|\vec{p}_{\mathrm{jet}}\right|^2}$$



Bottom-tagged jets

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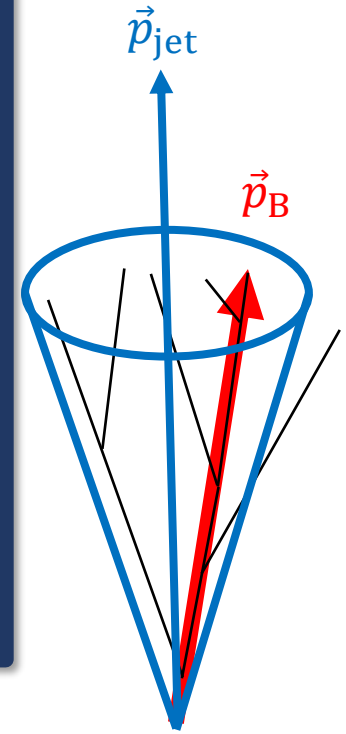
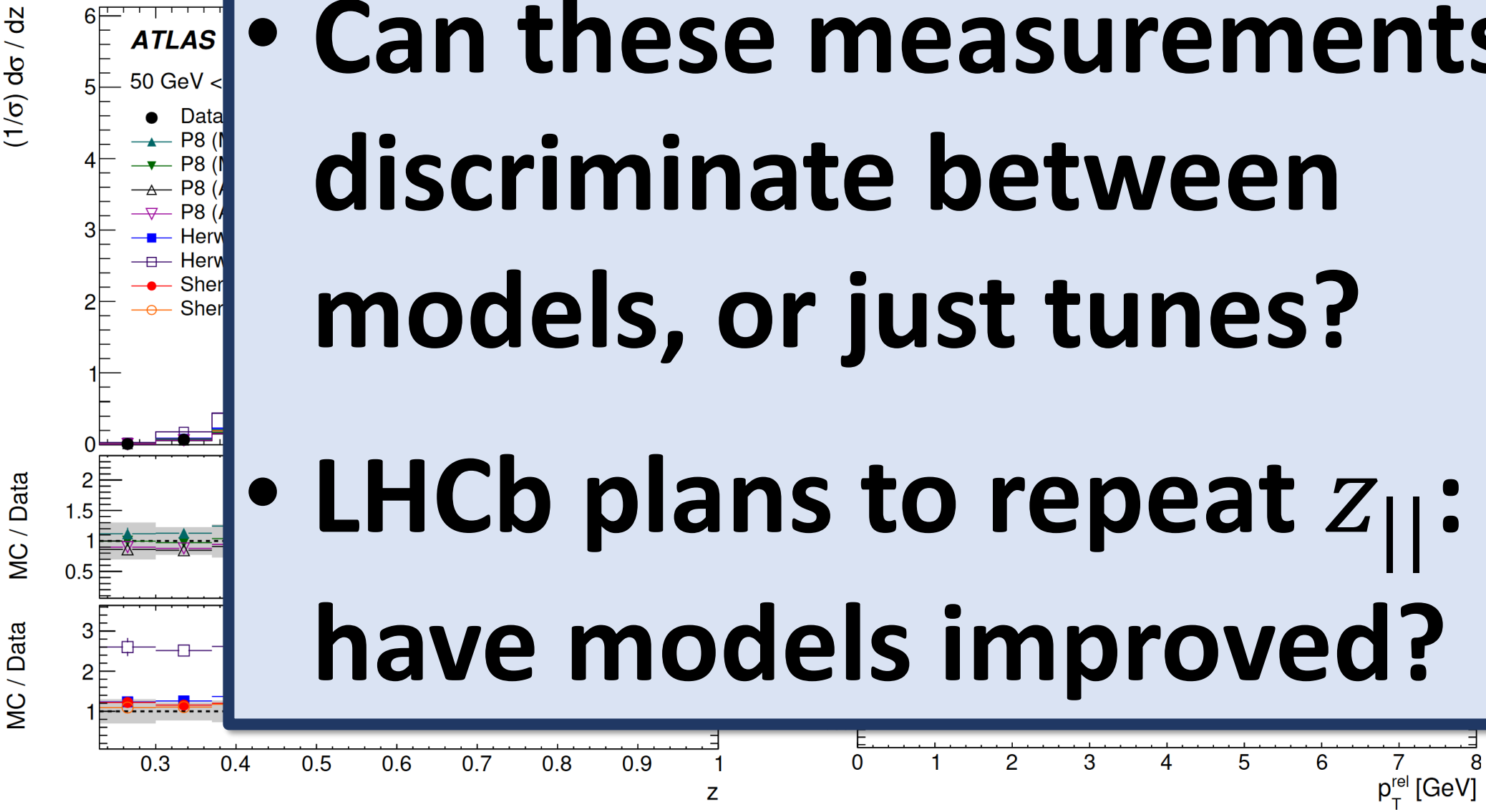
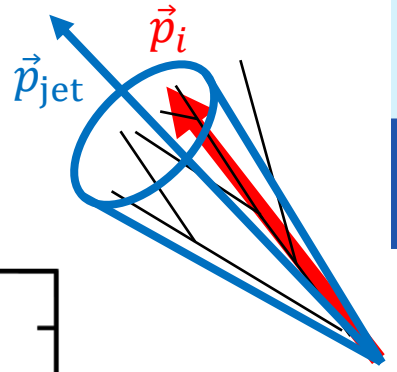
- **Can these measurements discriminate between models, or just tunes?**
- **LHCb plans to repeat $z_{||}$: have models improved?**

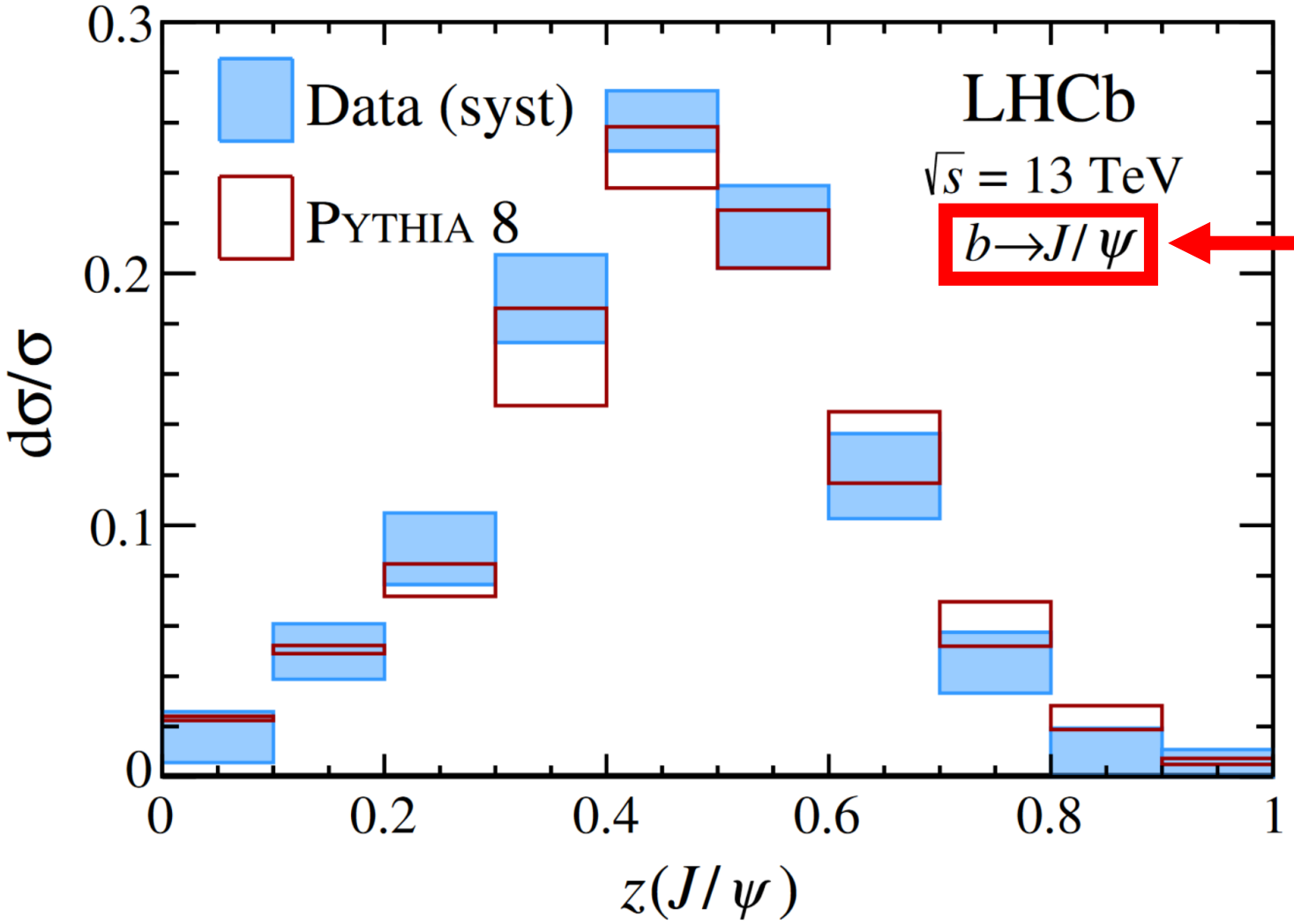
$$\frac{|\vec{p}_B \times \vec{p}_{\text{jet}}|}{|\vec{p}_{\text{jet}}|^2}$$





Charmonium in jet?





- **Non-prompt decays**: agreement with MC

[PRL 118 (2017) 192001]

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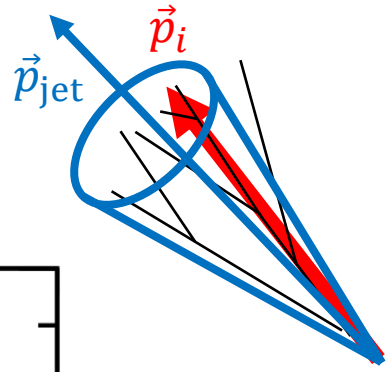
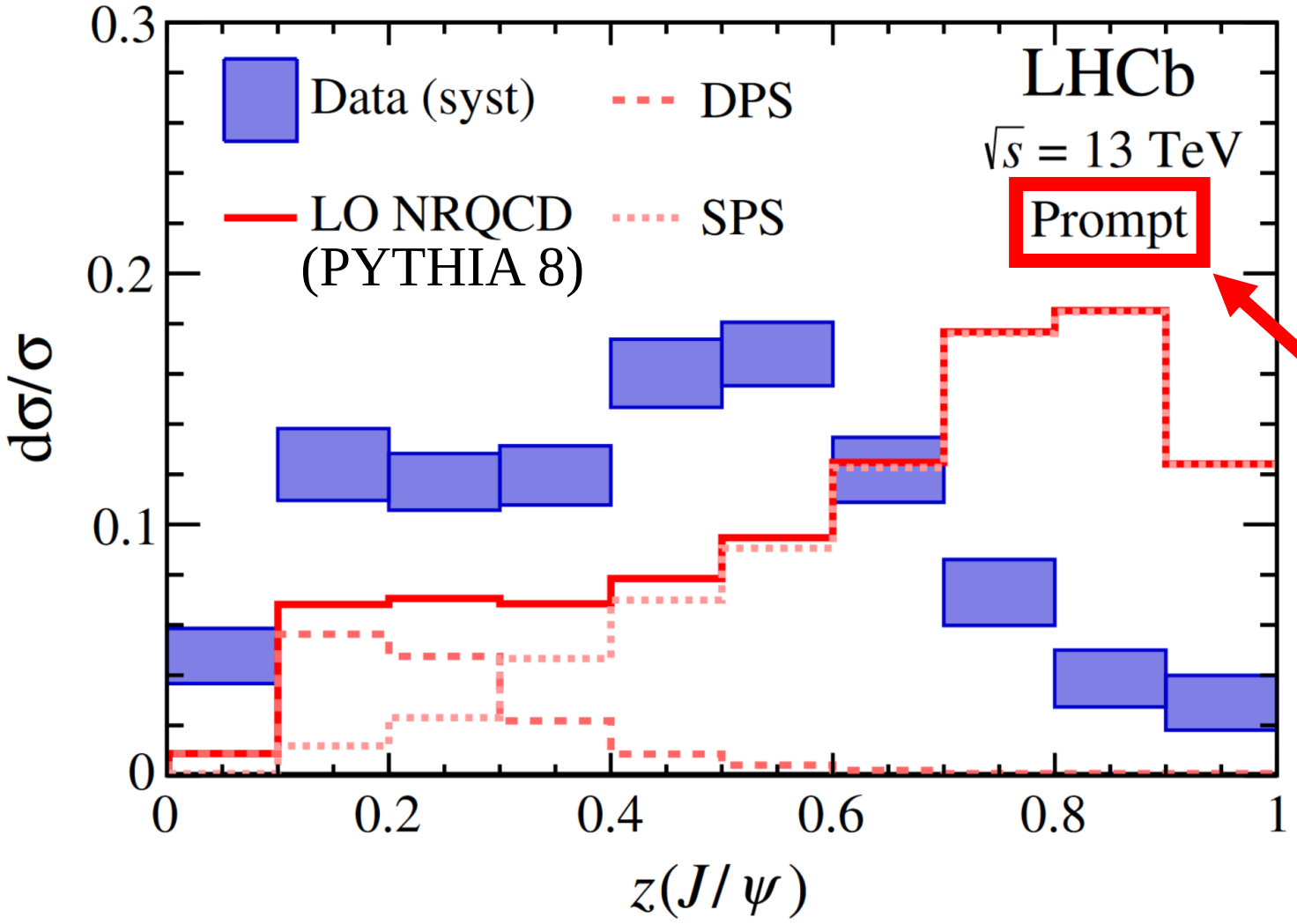
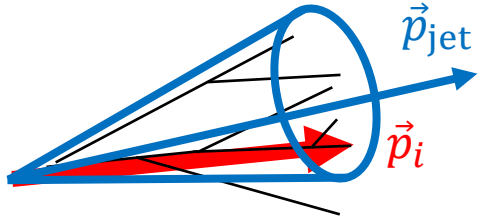


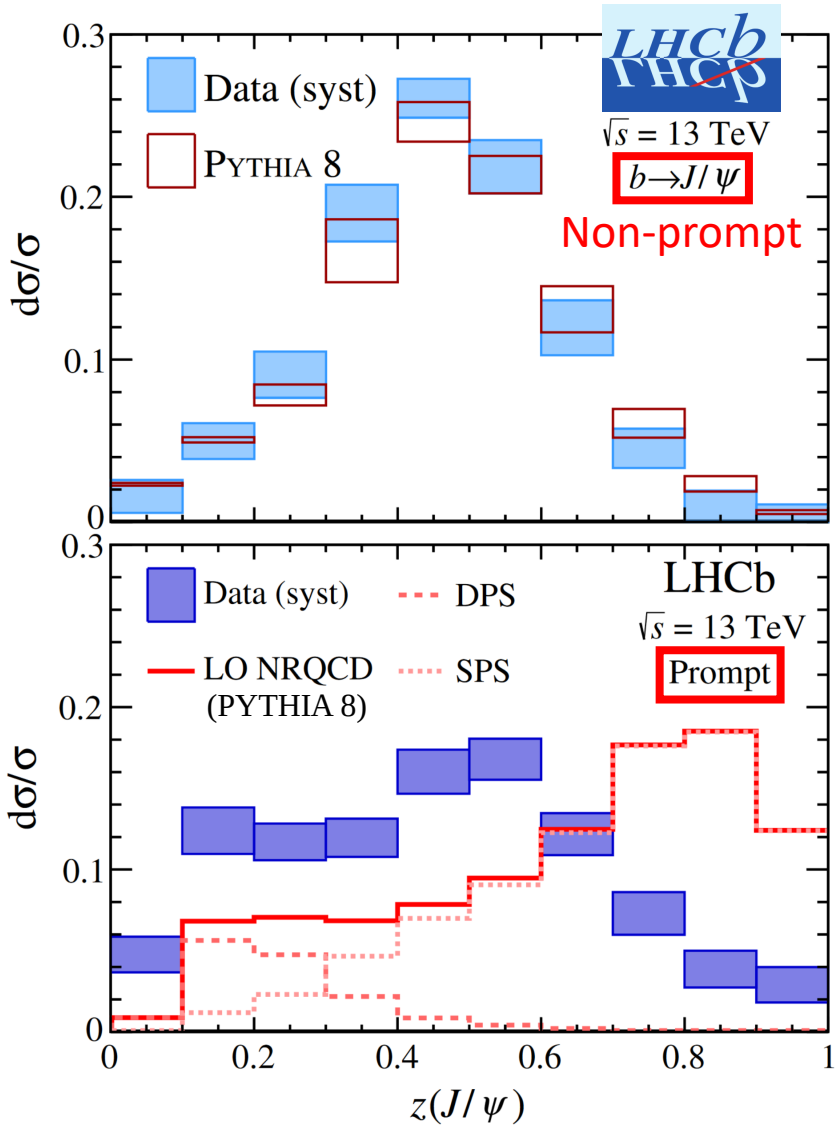


- **Non-prompt decays**: agreement with MC
- **Prompt J/ψ**: tension with MC predictions

[PRL 118 (2017) 192001]

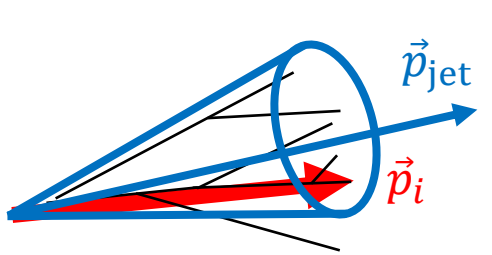
Charmonium in jet?

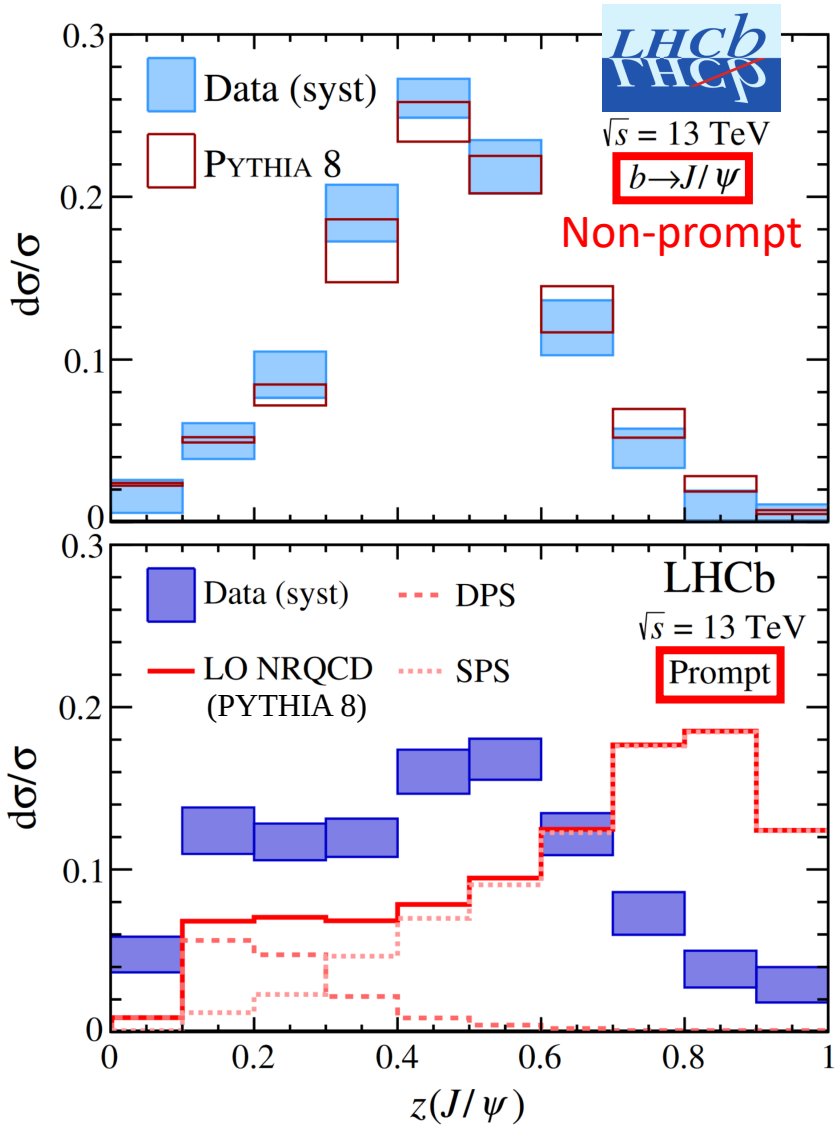




[PRL 118 (2017) 192001]

Charmonium in jet?





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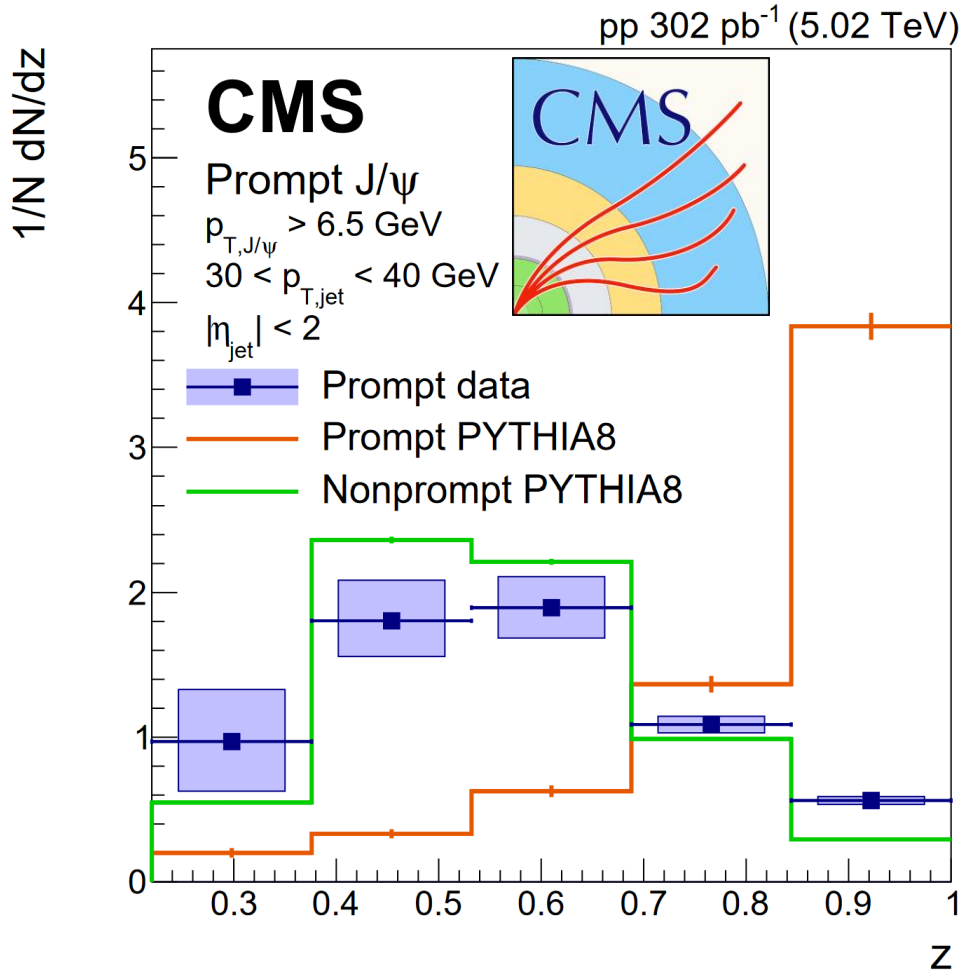
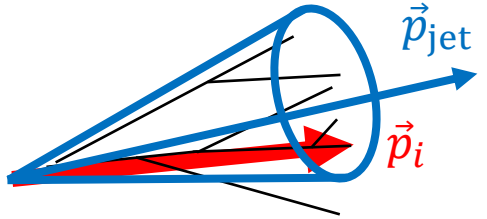
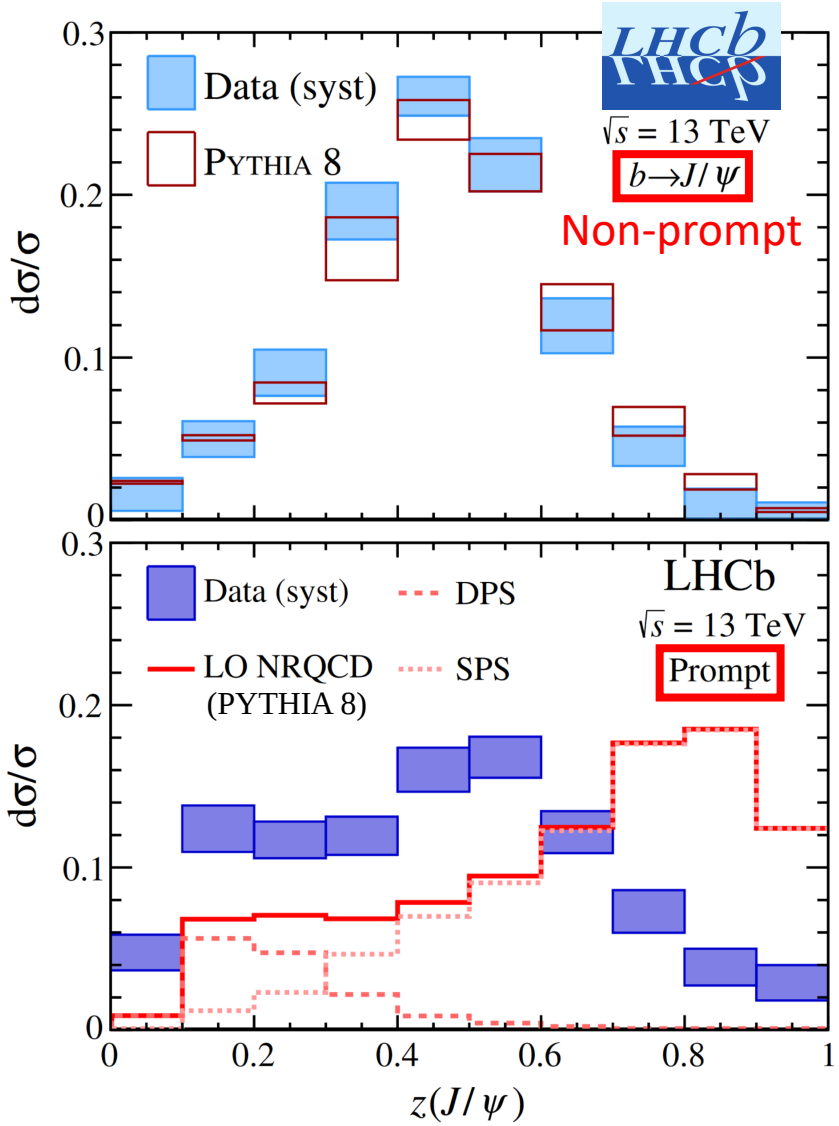


[Phys. Lett. B 825 (2021) 136842]

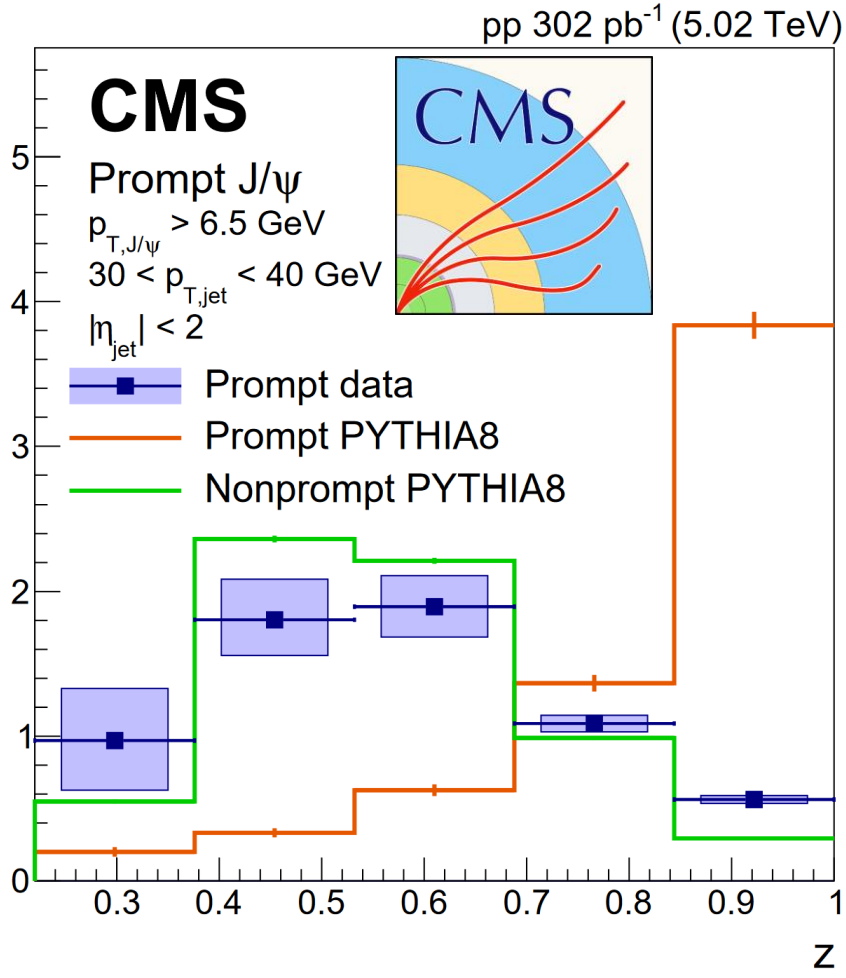
Charmonium in jet?





Similarity between mid- and forward-rapidity jets

CMS: "data show a relatively large degree of surrounding jet activity, indicative of J/ψ production inside of parton showers."



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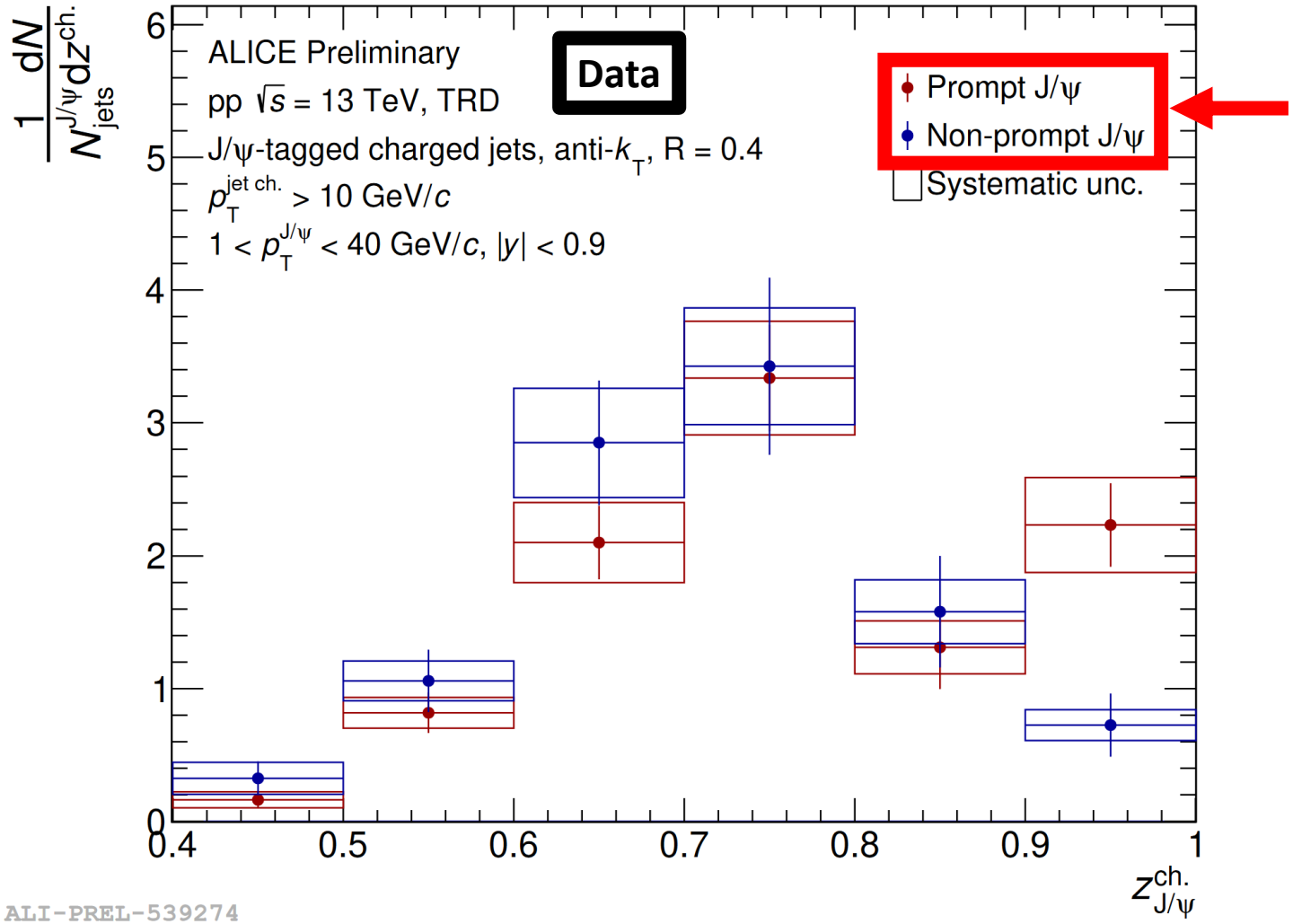
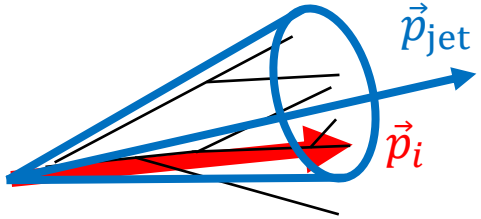
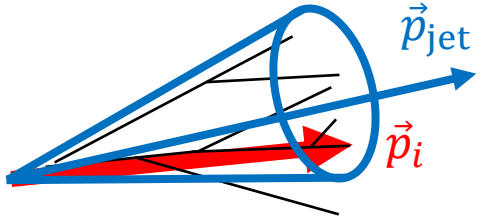


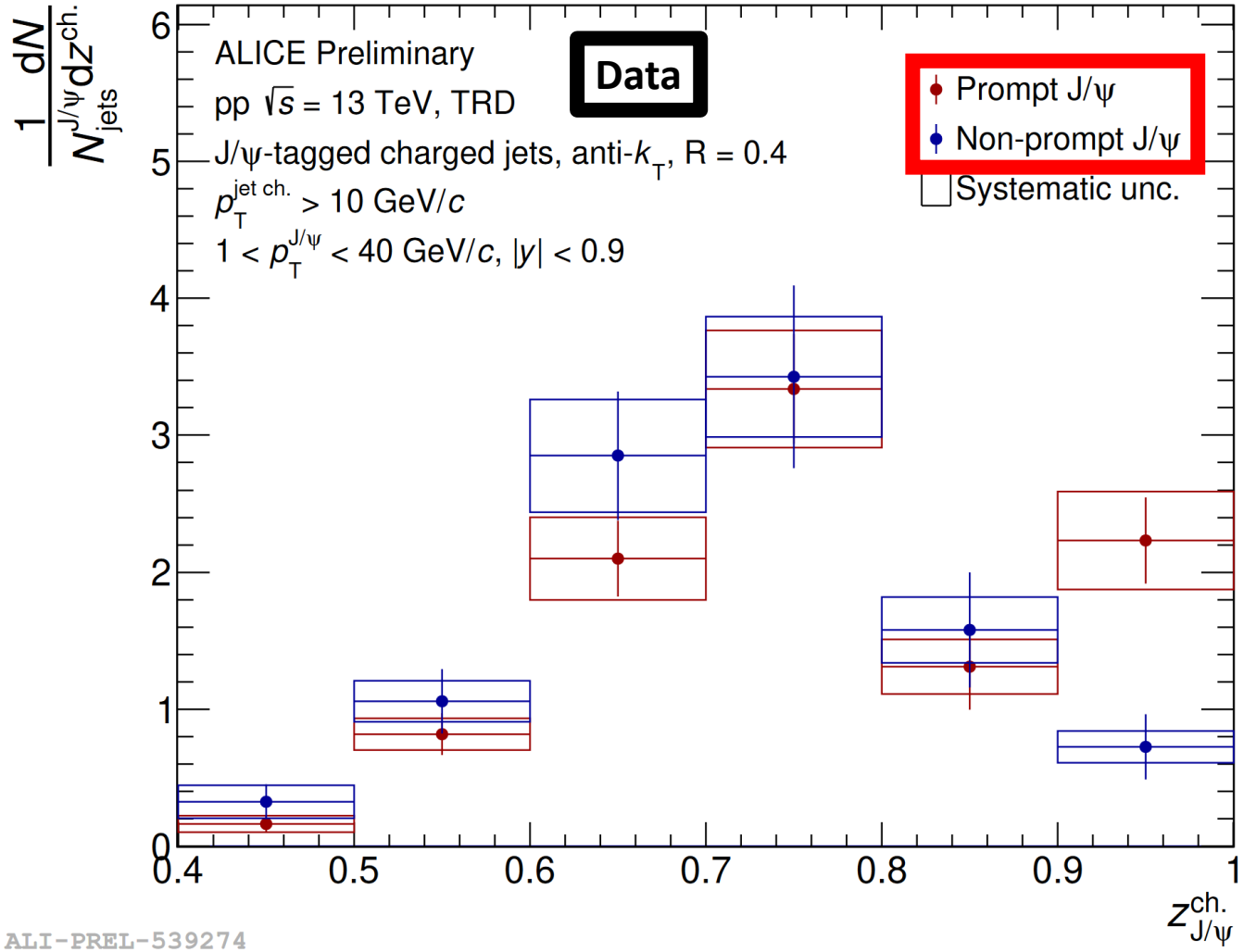
ALI-PREL-539274



https://alice-figure.web.cern.ch/node/26481

Charmonium in jet?





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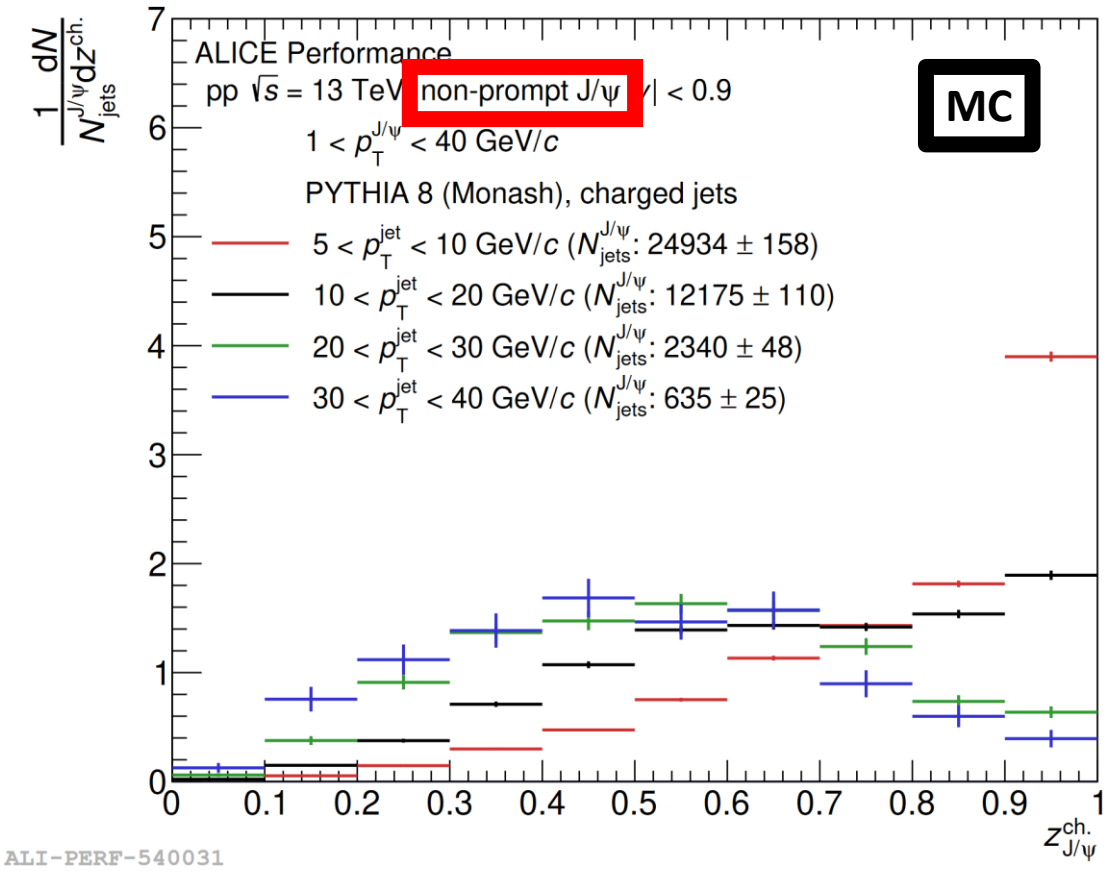
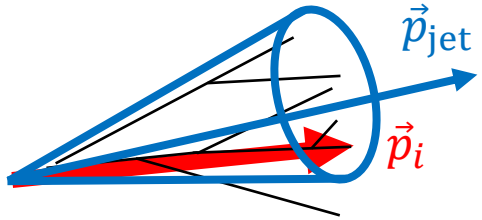
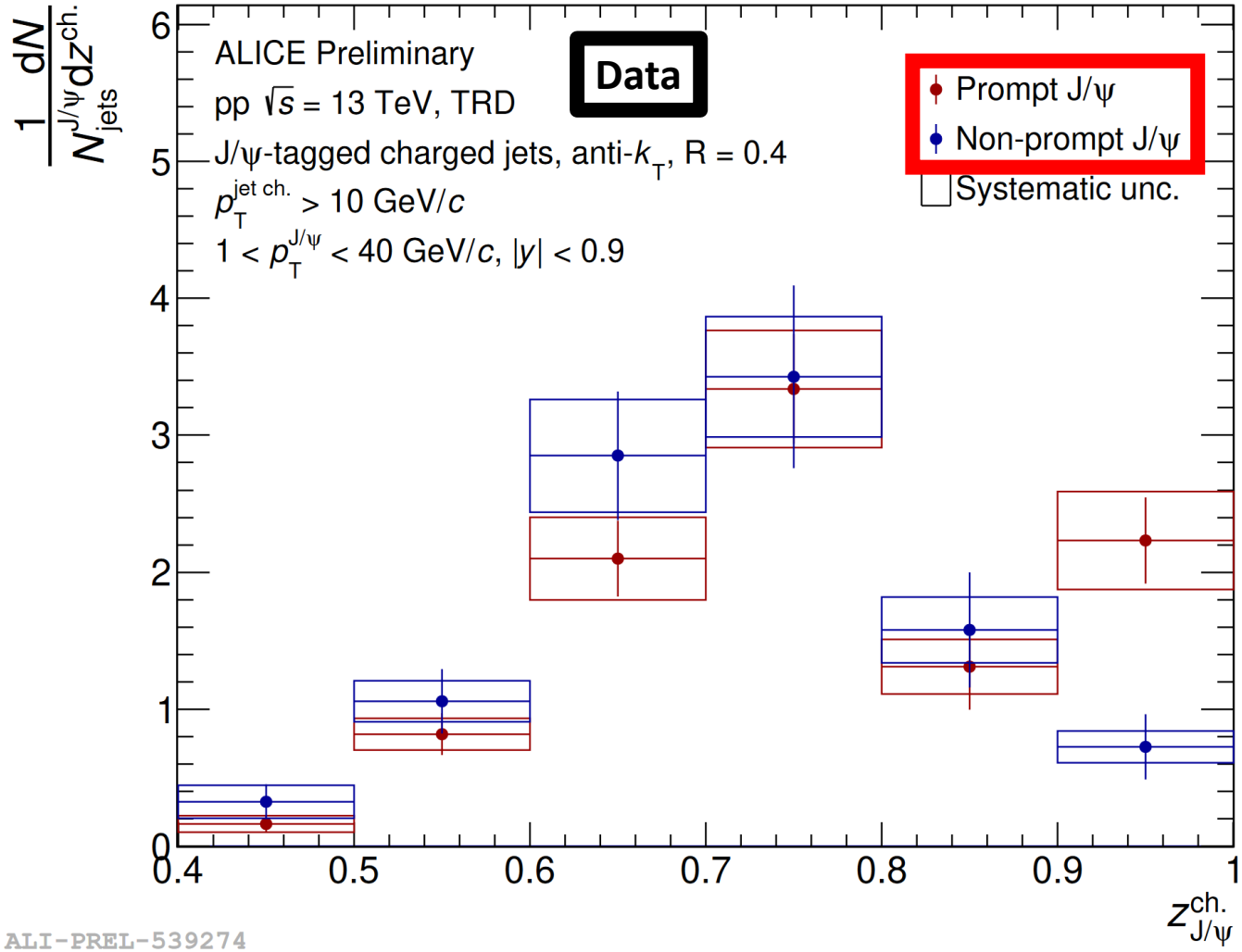


ALI-PERF-540031

https://alice-figure.web.cern.ch/node/26481

Charmonium in jet?





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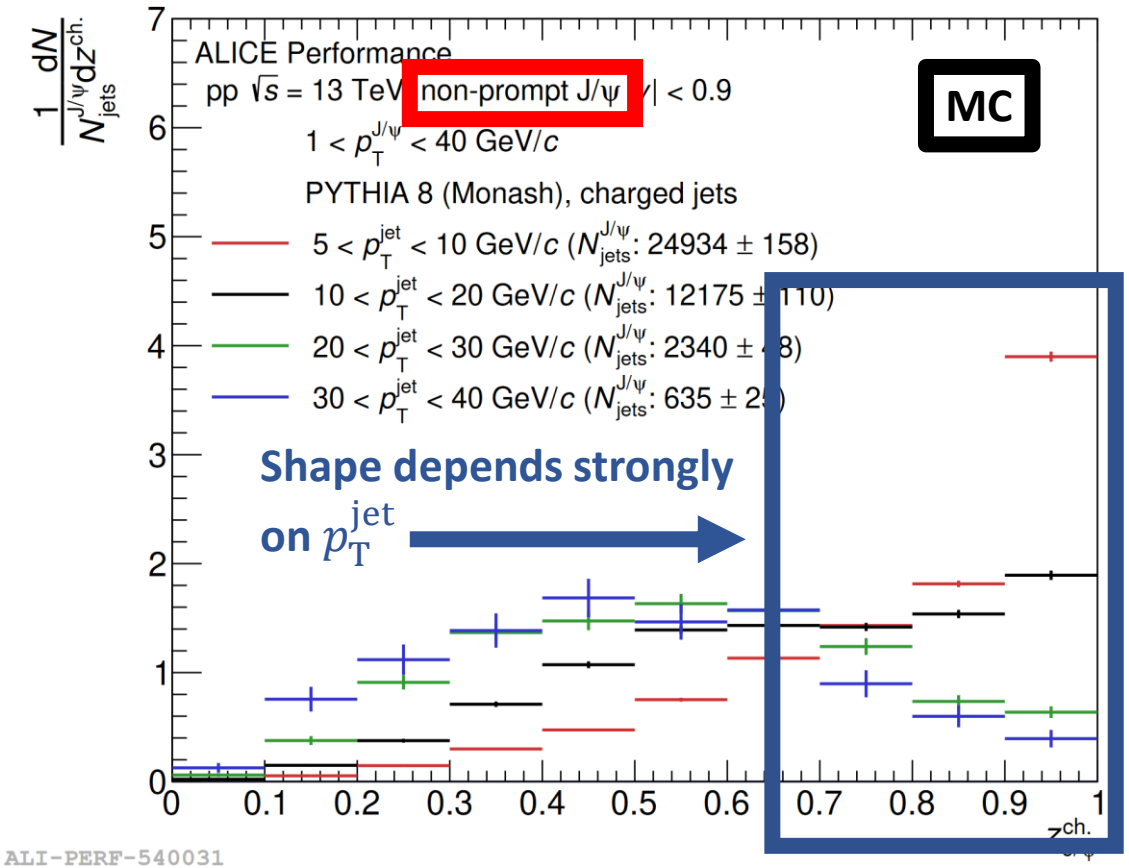

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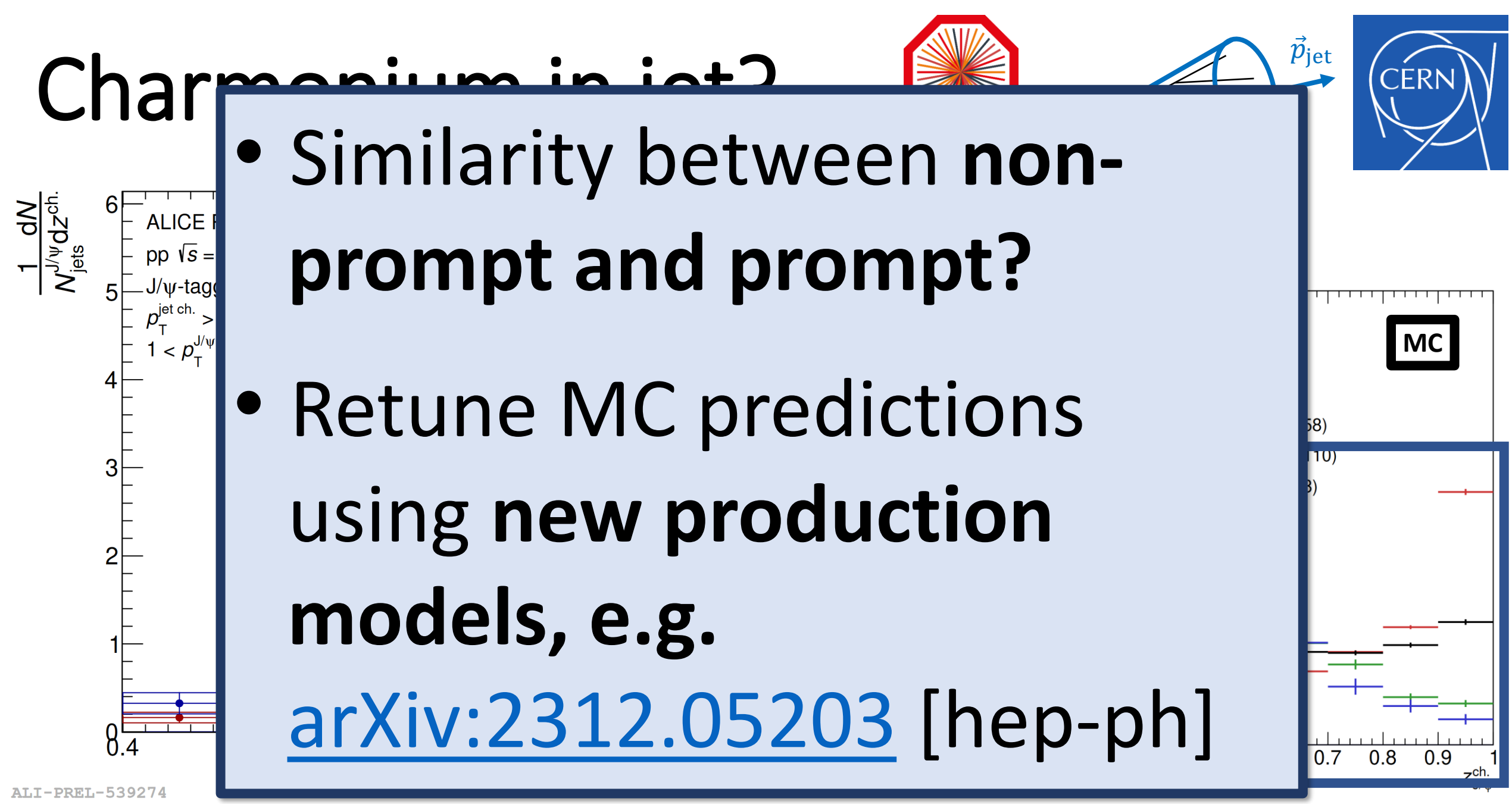

- Similarity between **non-prompt and prompt?**
- Retune MC predictions using **new production models, e.g.** arXiv:2312.05203 [hep-ph]

What we've learned

- **Jet fragmentation** is an excellent probe for QCD at all energy scales

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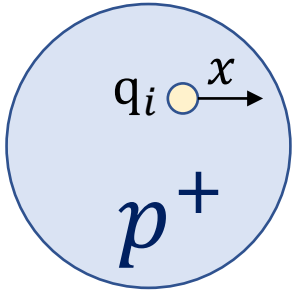
  - Systematically probe nonperturbative effects such as hadronization

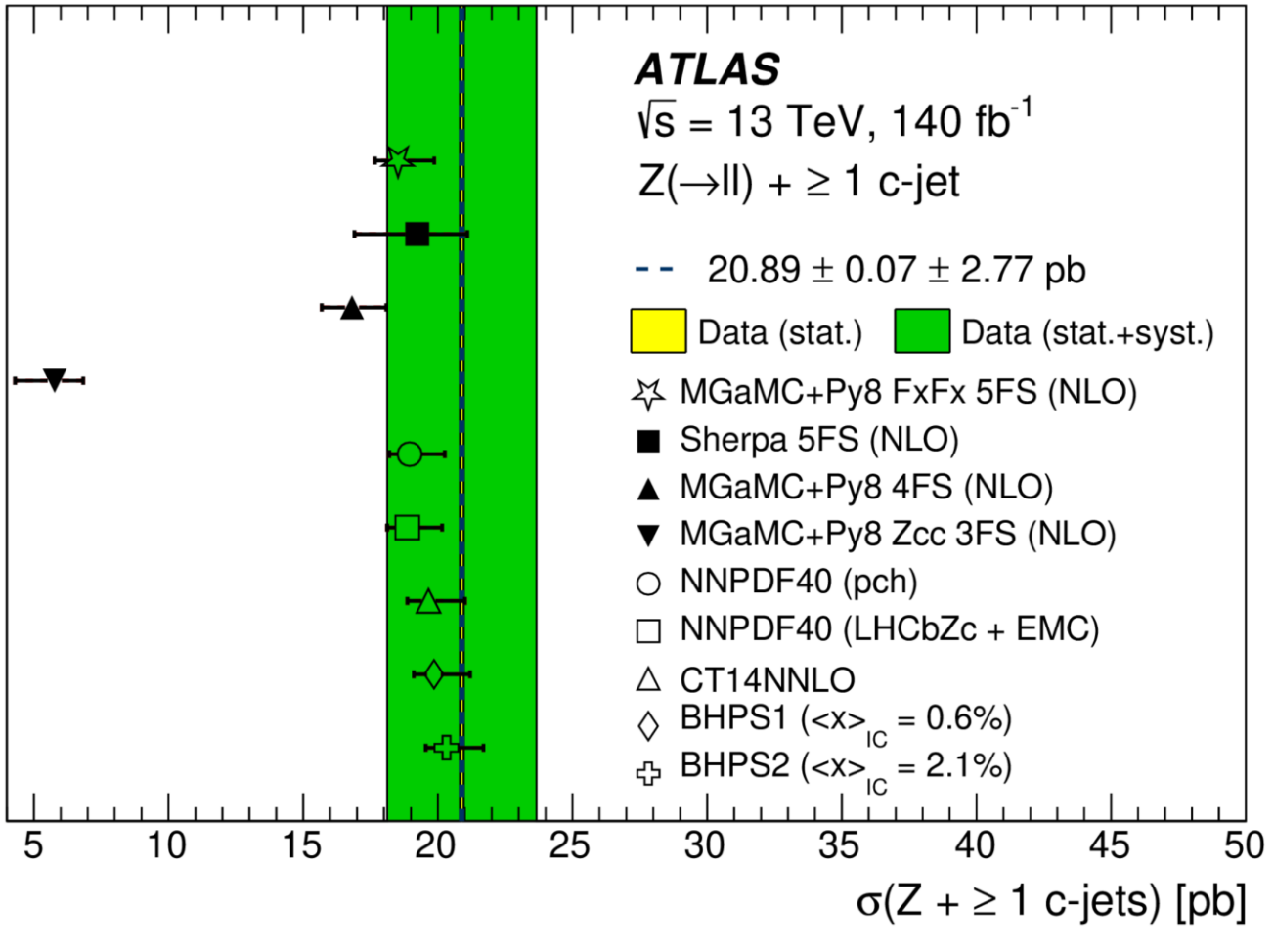
Backup

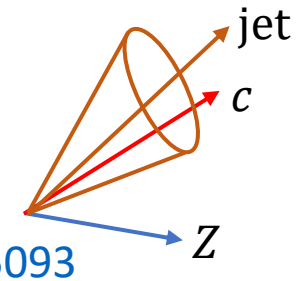
What's in a proton?



- **Intrinsic valence-like charm?** *i.e.,* ϵ term: $|p^+\rangle \propto |uud\rangle + \epsilon|uudc\bar{c}\rangle$

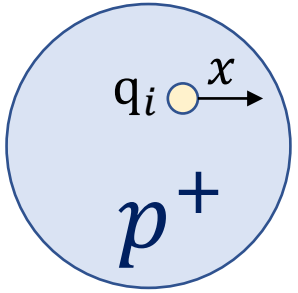
- **New ATLAS result!**





https://arxiv.org/abs/2403.15093

What's in a proton?



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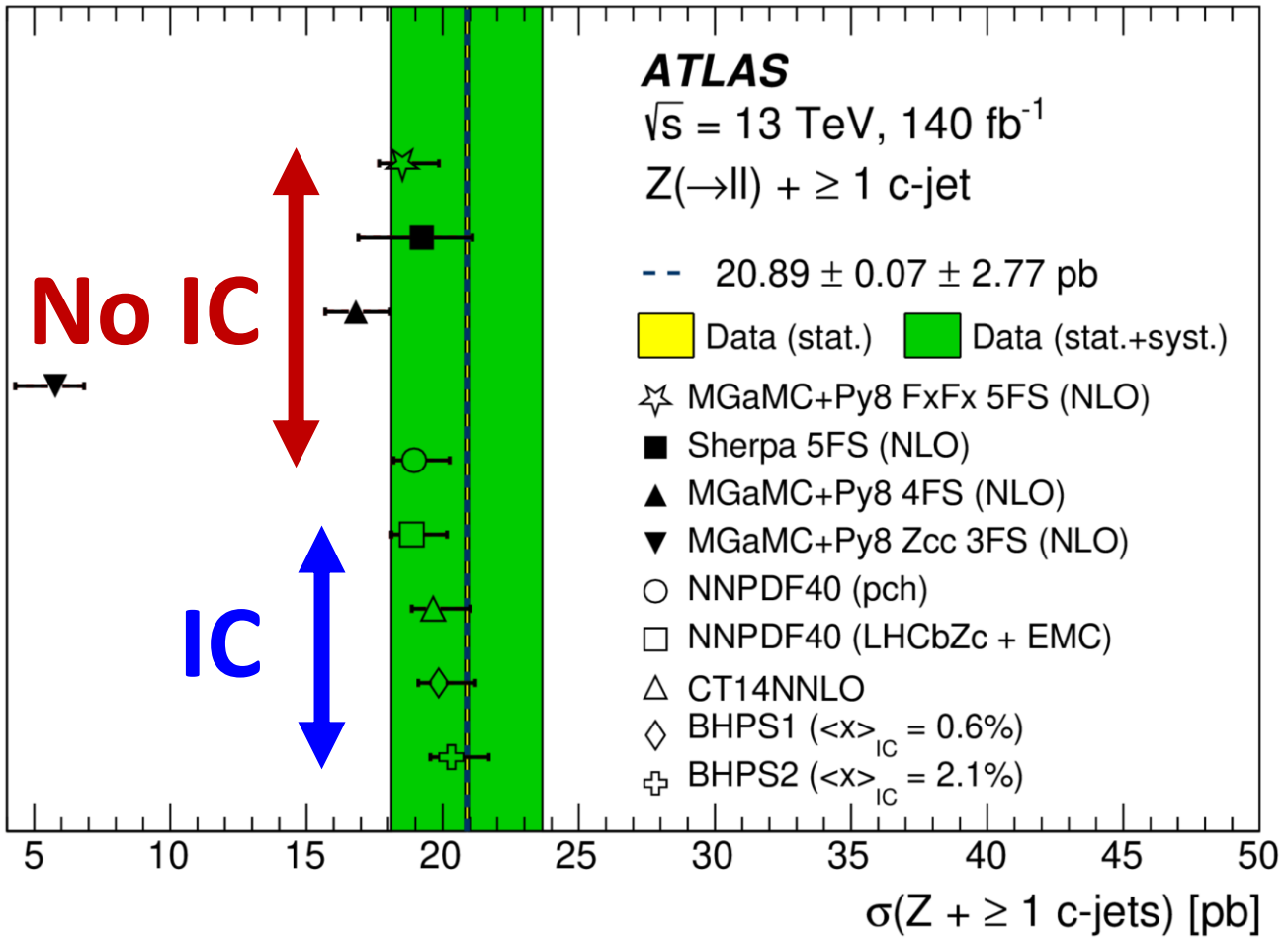

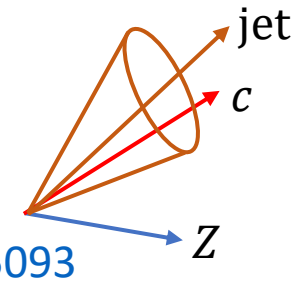

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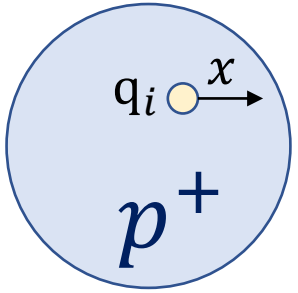
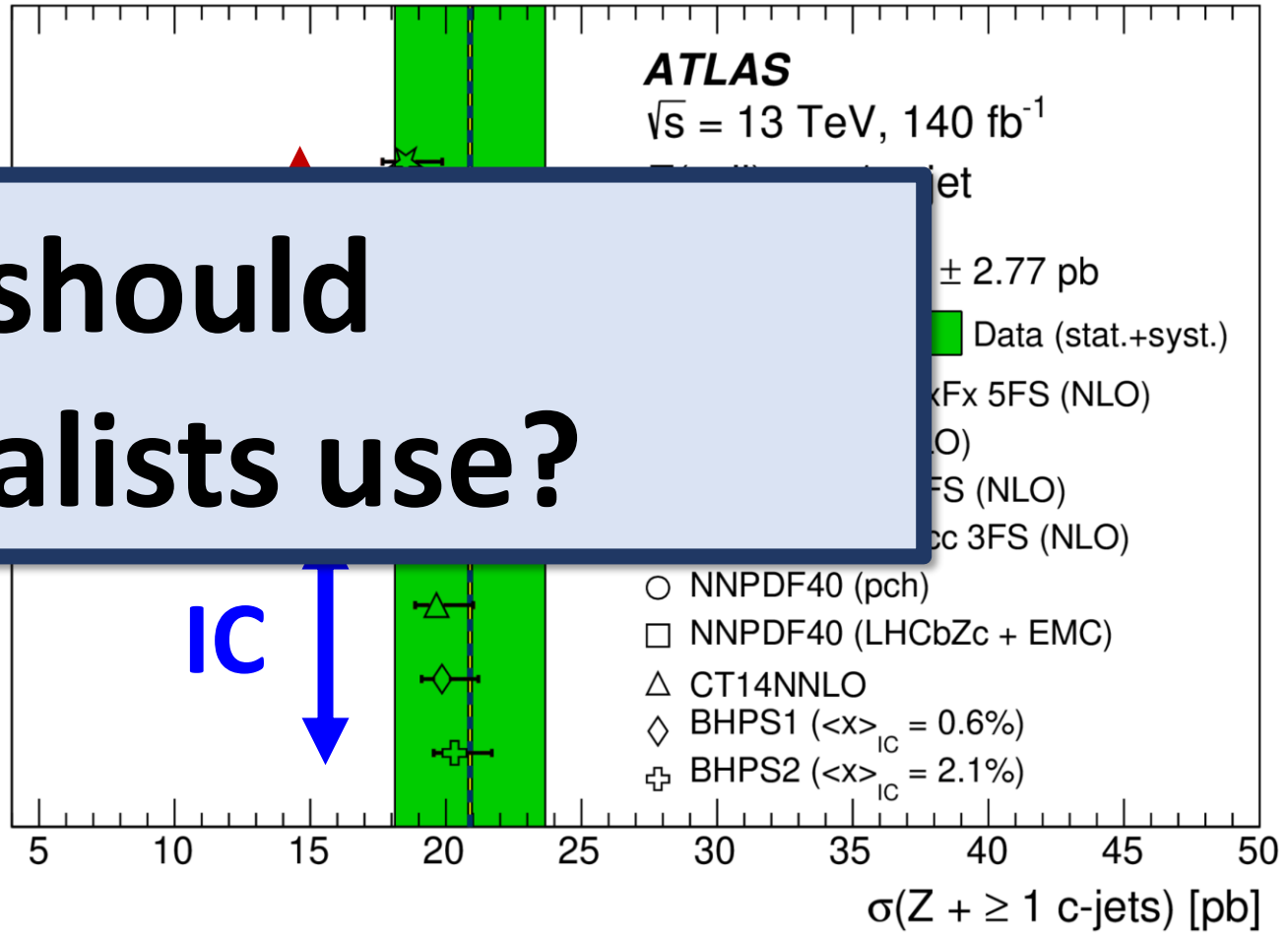


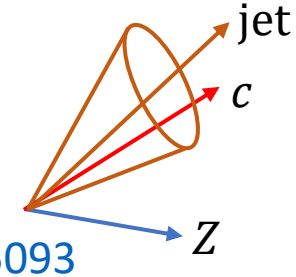
- **Intrinsic valence-like charm?** *i.e.,* ϵ term: $|p^+\rangle \propto |uud\rangle + \epsilon|uudc\bar{c}\rangle$

- **New ATLAS result!**

- **Which PDF should experimentalists use?**

- **No evidence observed for IC in central rapidity**





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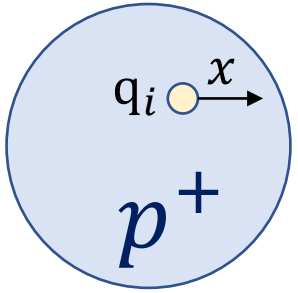

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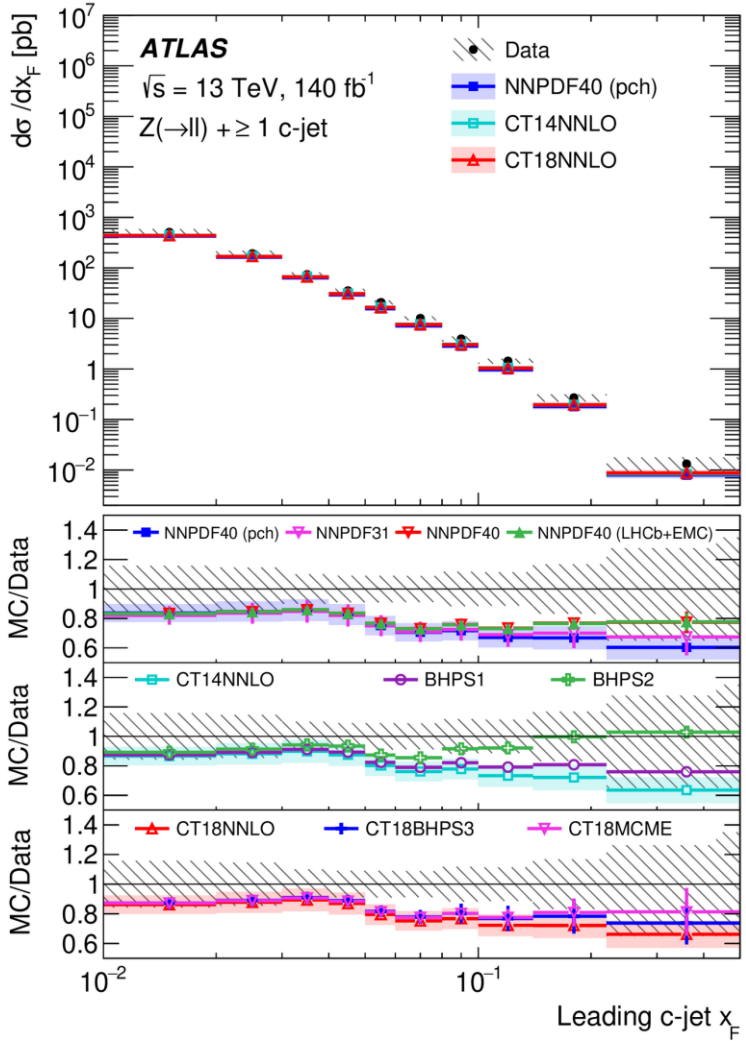
- **Models within uncertainties**

$$x_{\mathrm{F}}(\mathrm{c}) = \frac{2|p_z(\mathrm{c})|}{\sqrt{s}}$$



https://arxiv.org/abs/2403.15093

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

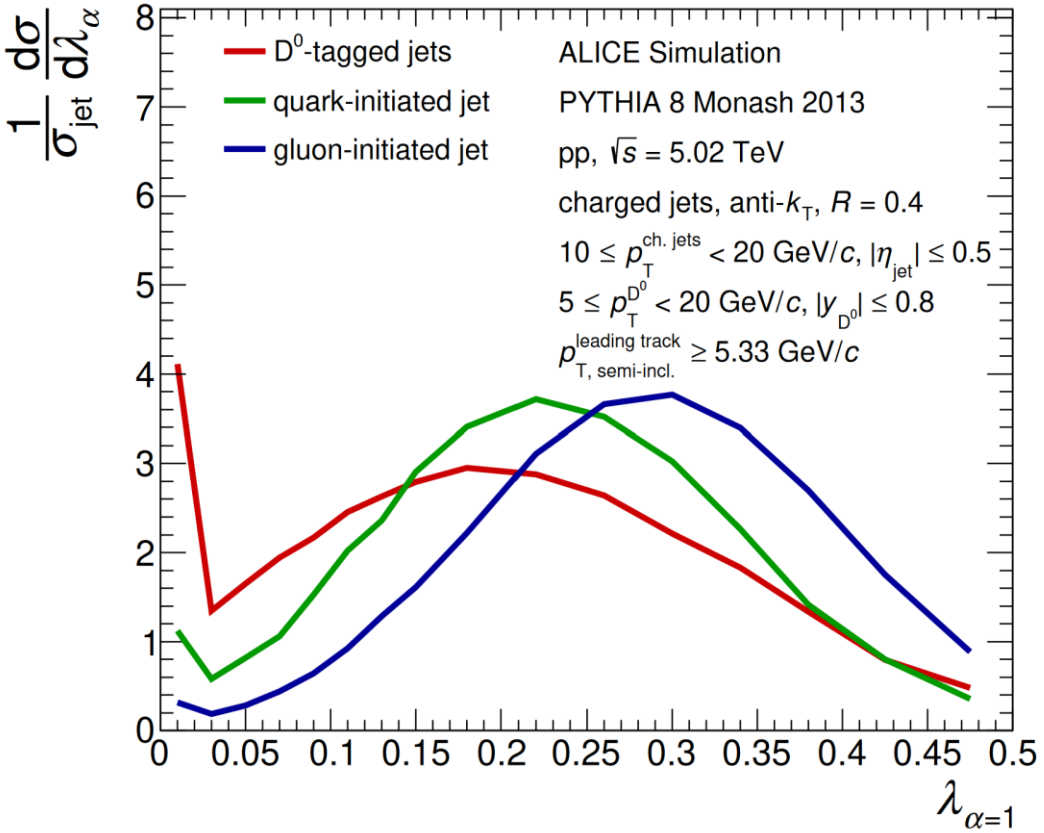
mass effects

$\alpha = 1$

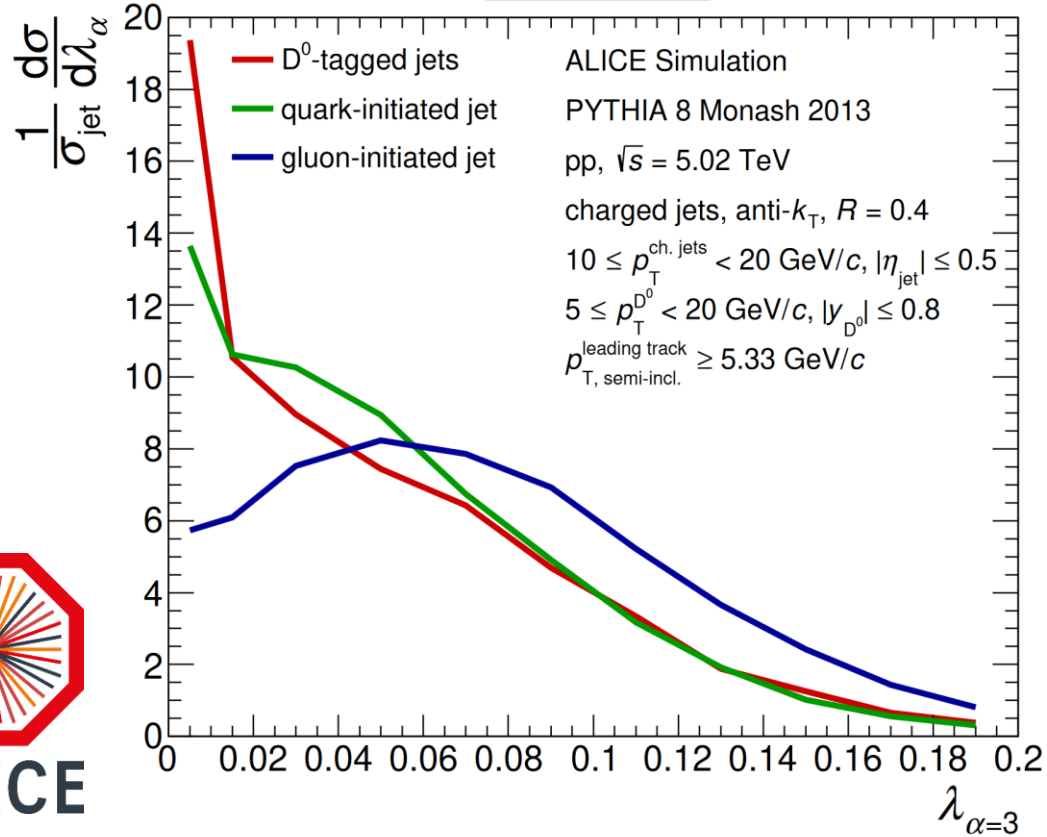
Increased α → increased angular weighting

Casimir color effects

$\alpha = 3$



ALI-SIMUL-540830



ALI-SIMUL-540839

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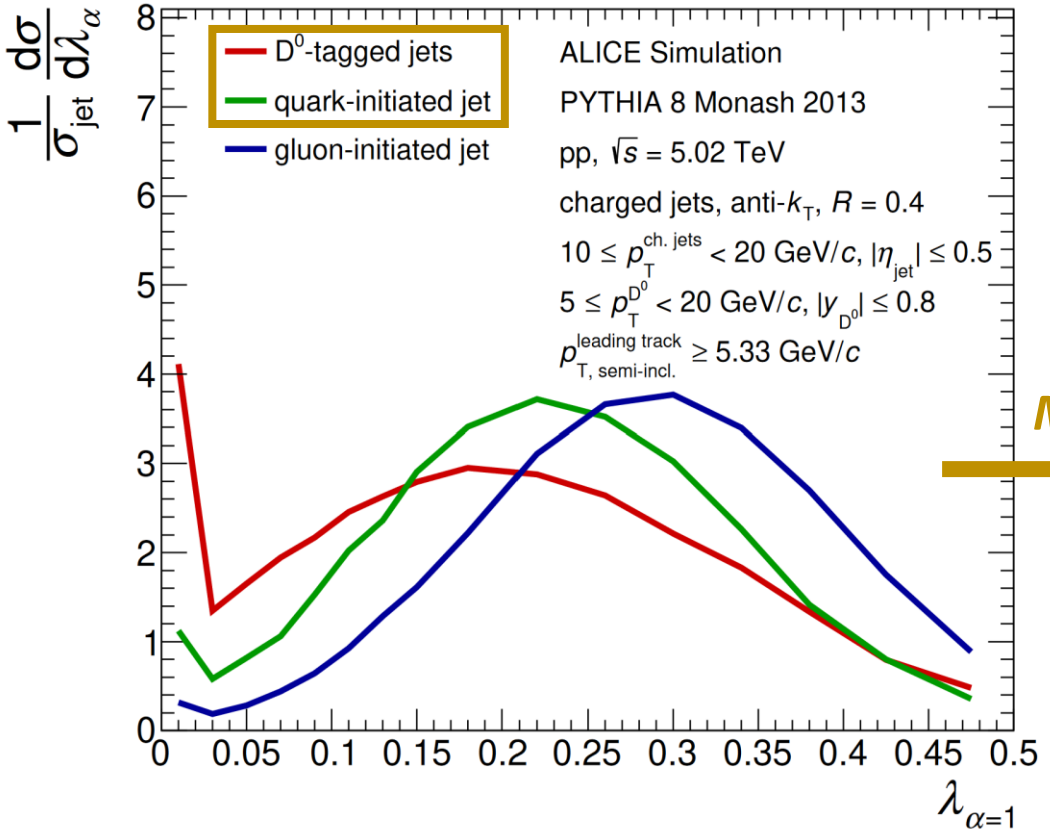
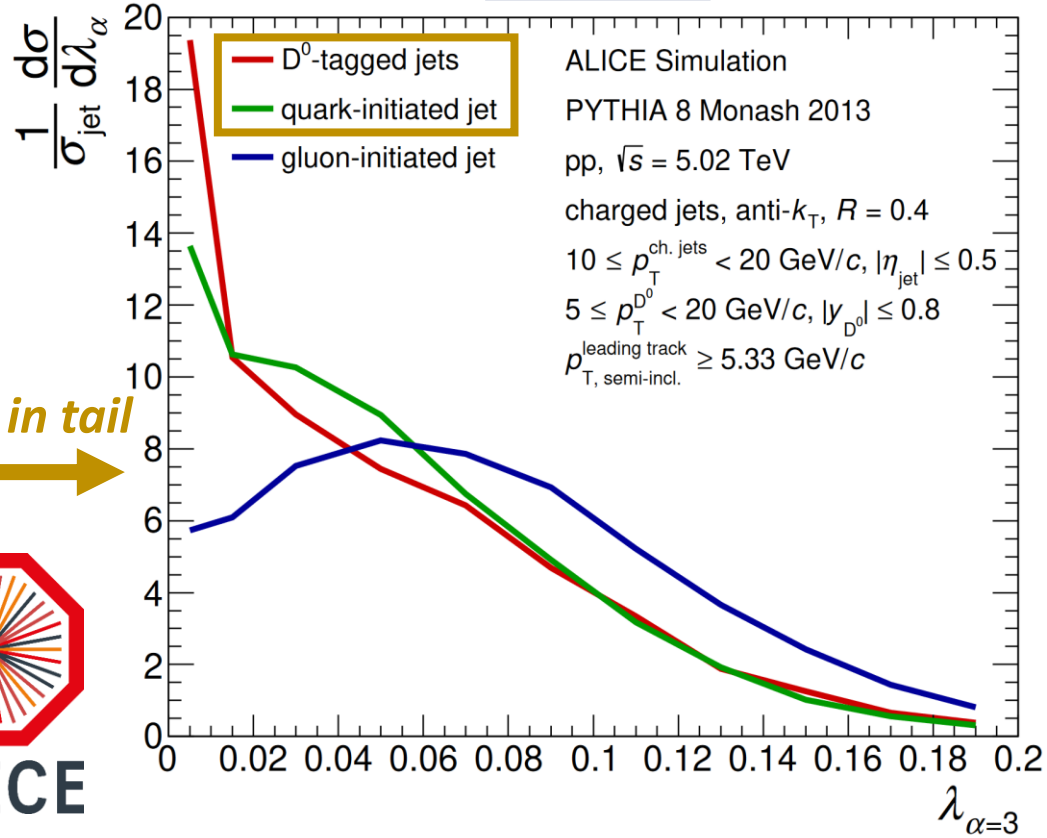


ALI-SIMUL-540830

Mass effects reduced in tail



ALI-SIMUL-540839