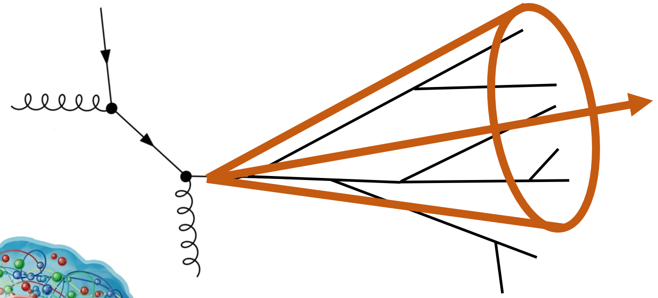
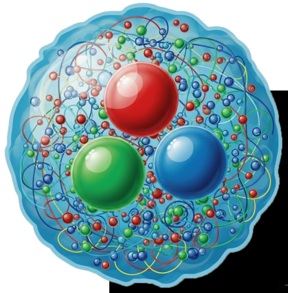
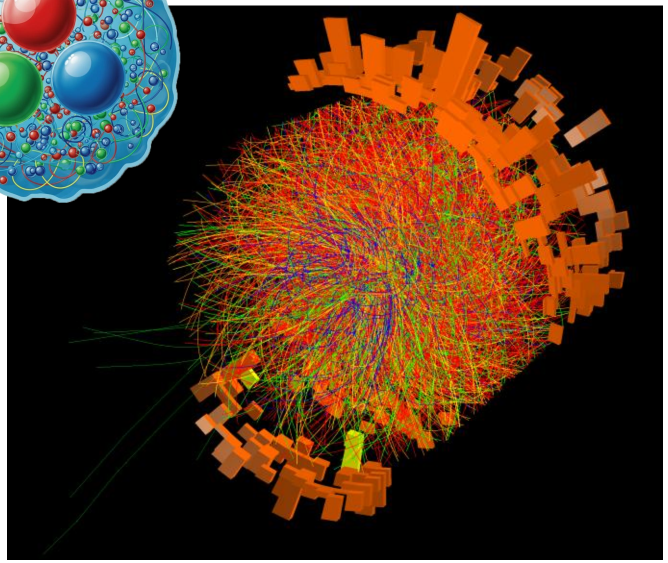
Unraveling QCD using hard probes in proton-proton and heavy-ion data



Ezra D. Lesser (CERN)

24 September 2025





Seminar – CCNU
Wuhan, China

Quantum ChromoDynamics

- **QCD** is the theory of the **strong nuclear interactions**

Quantum ChromoDynamics

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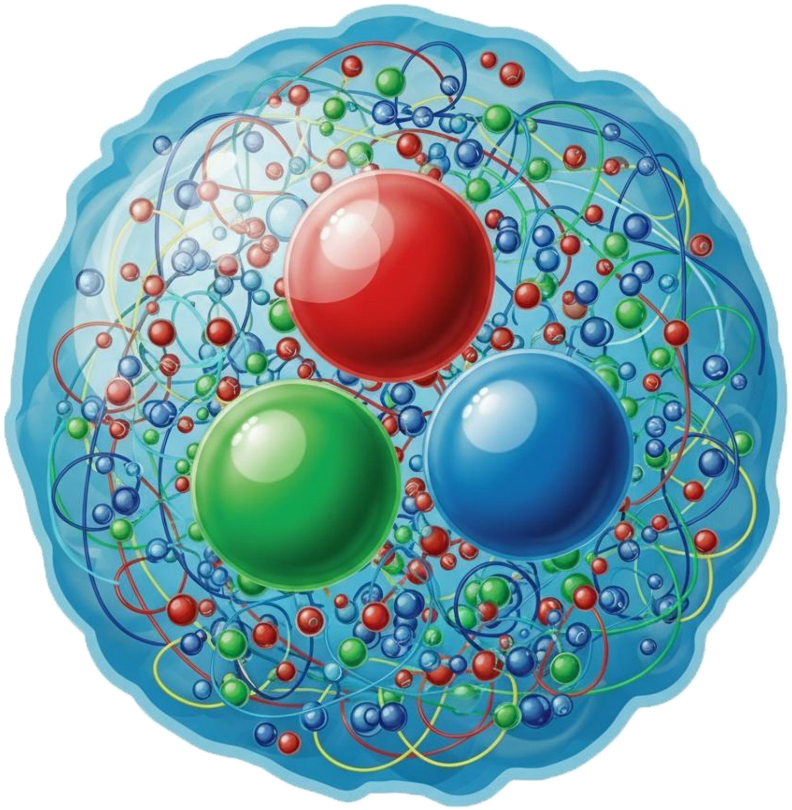

Formation of nucleons and their structure

Quantum ChromoDynamics

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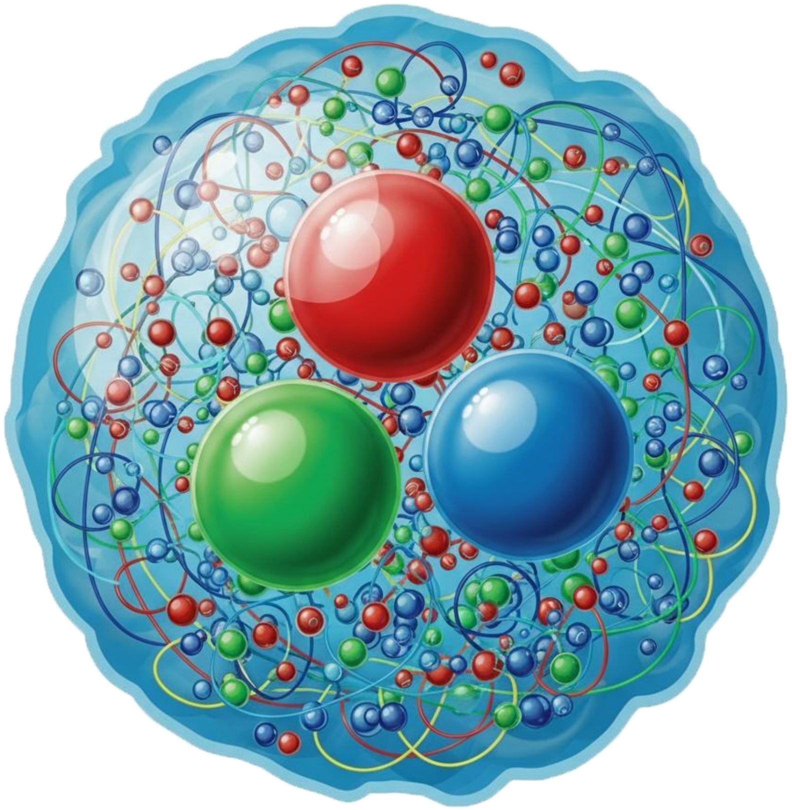
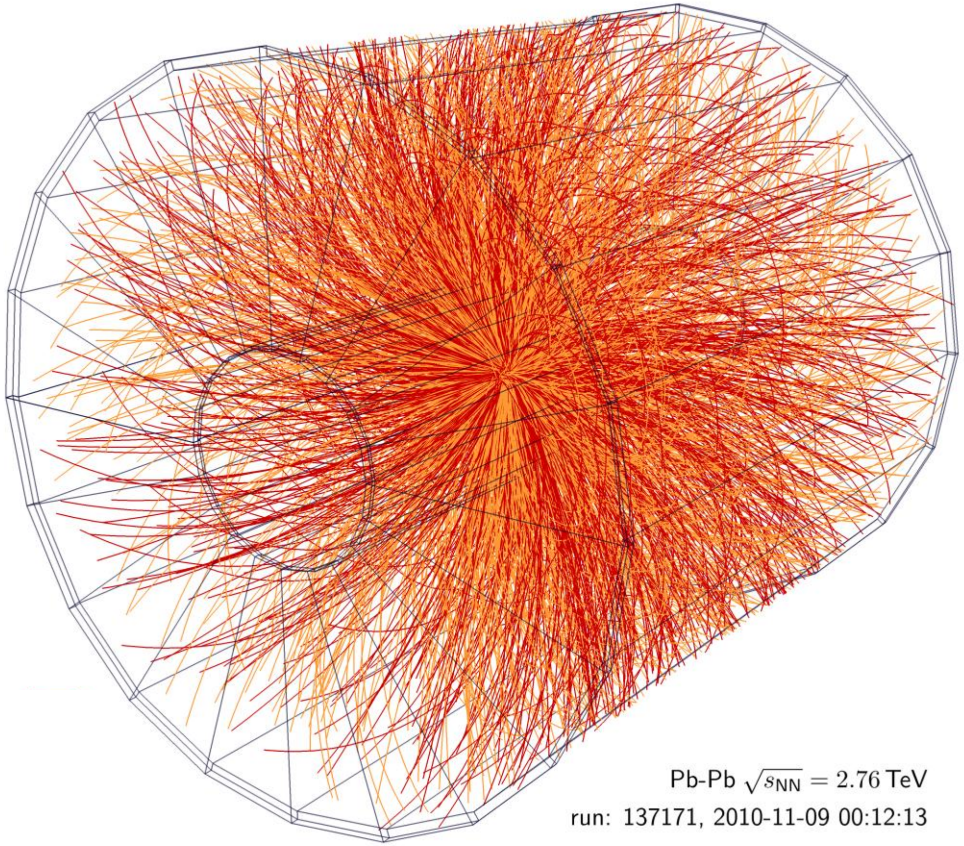


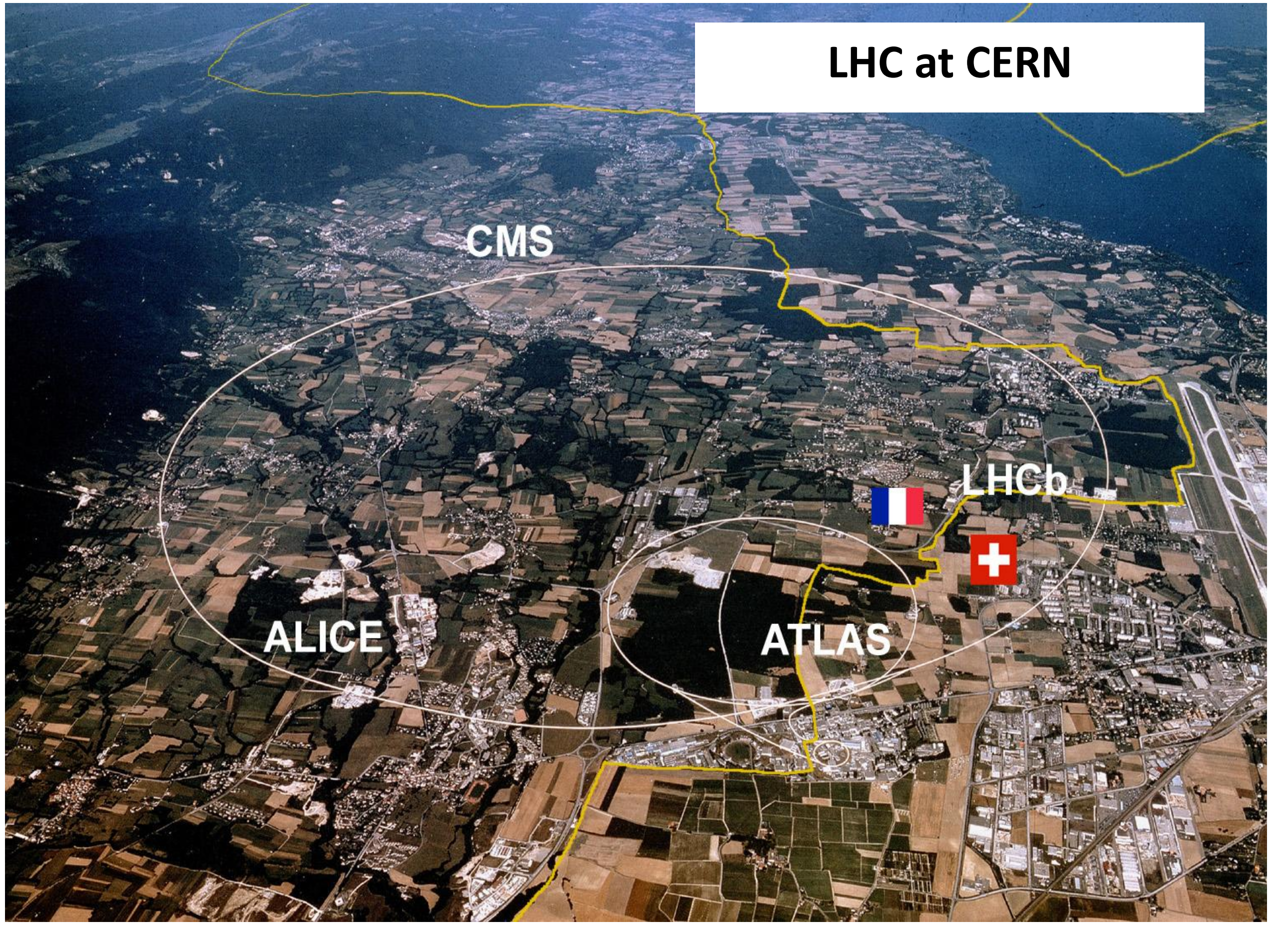
Formation of nucleons and their structure



Hot, dense conditions of the early universe

Quantum ChromoDynamics

- **QCD** is the theory of the **strong nuclear interactions**

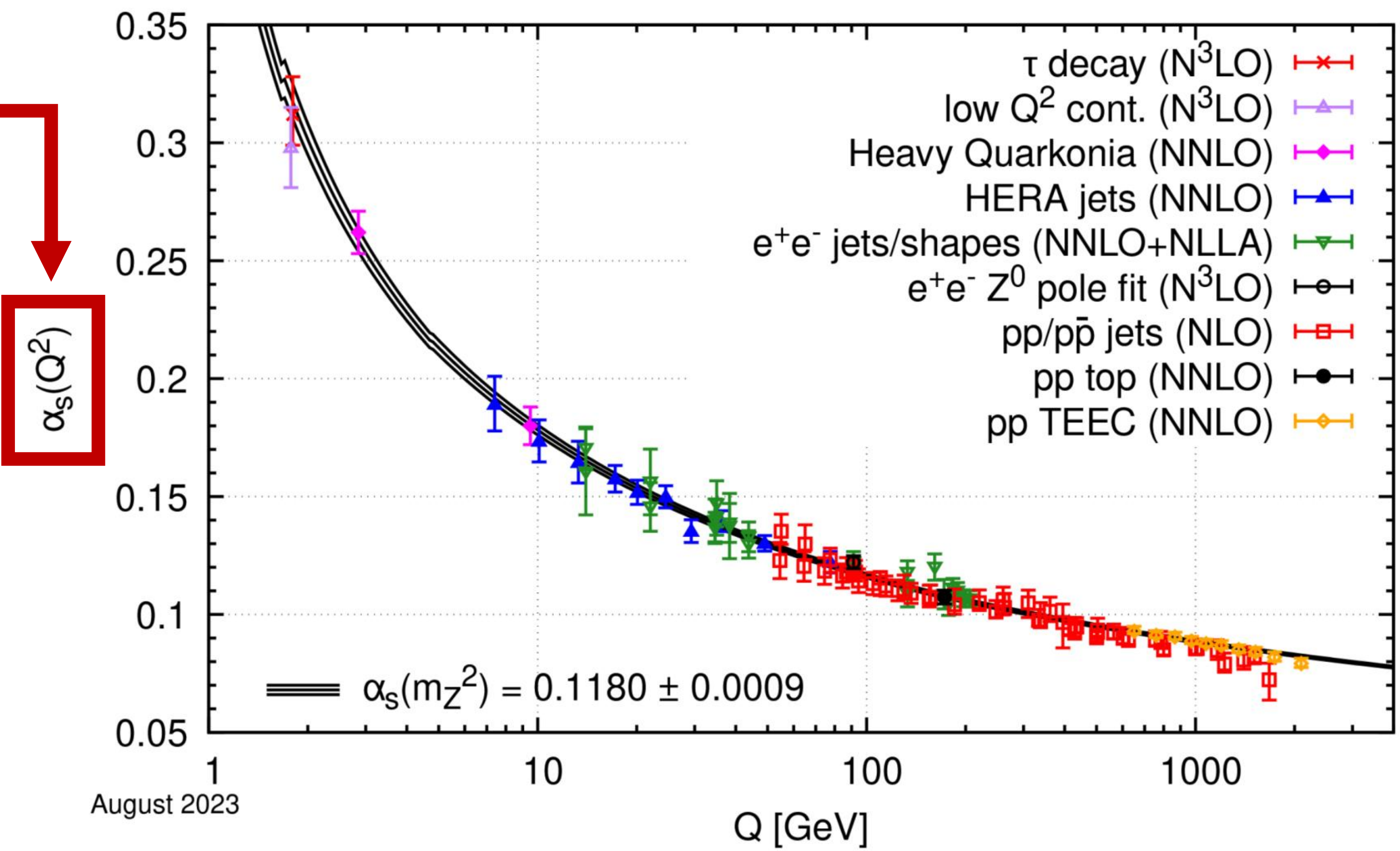


- We study **QCD** using particle colliders like the **Large Hadron Collider (LHC) at CERN**

- **Extreme energies** produce **hard probes** of the theory

Strength of the strong force

Strength of the strong force



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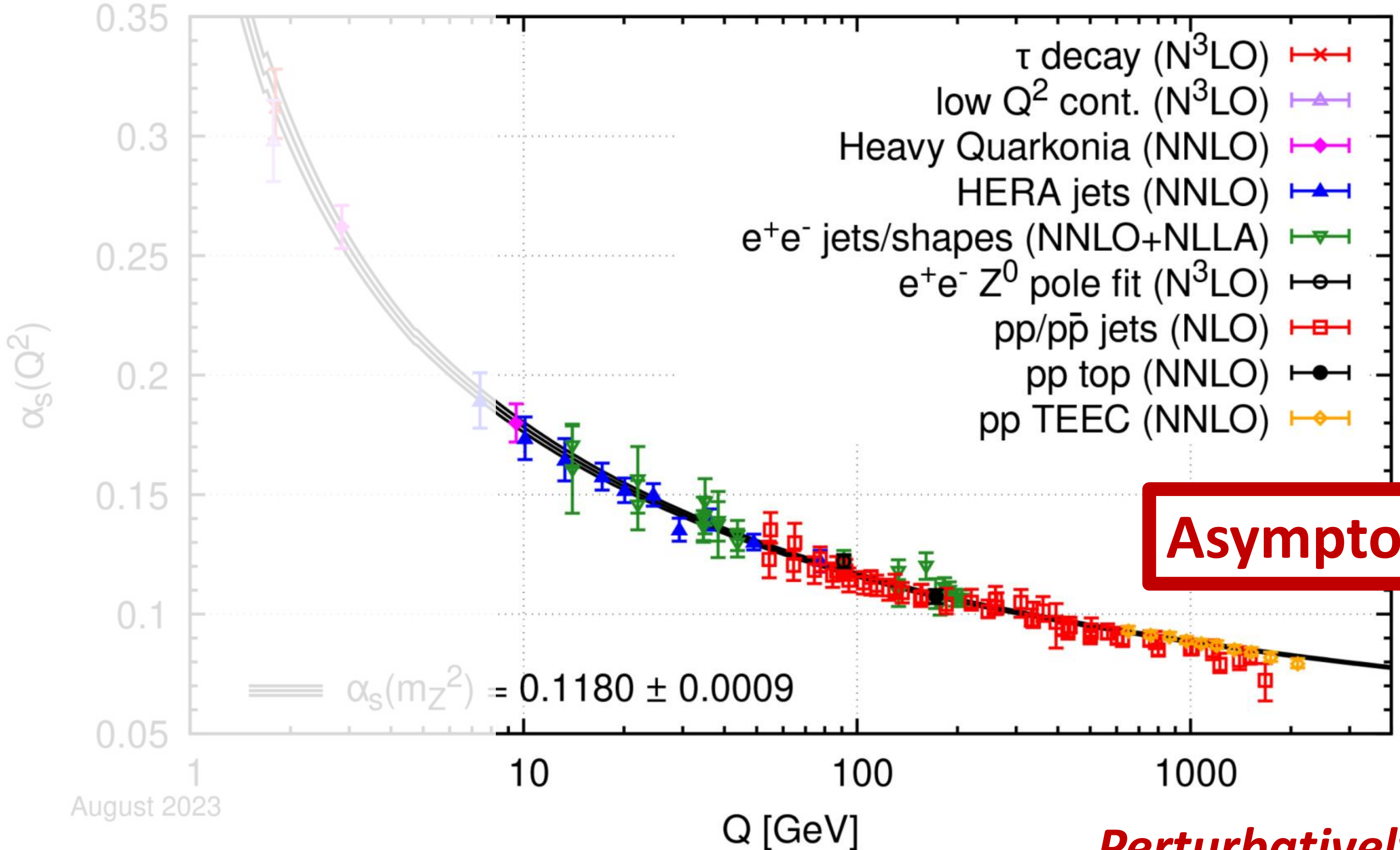
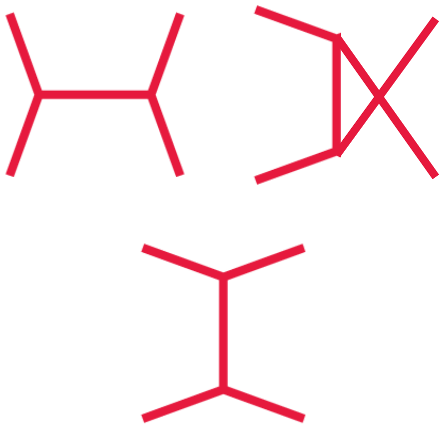
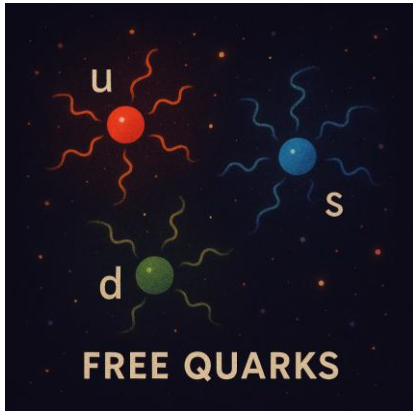
Strength of the strong force





Asymptotic freedom

Perturbatively calculable



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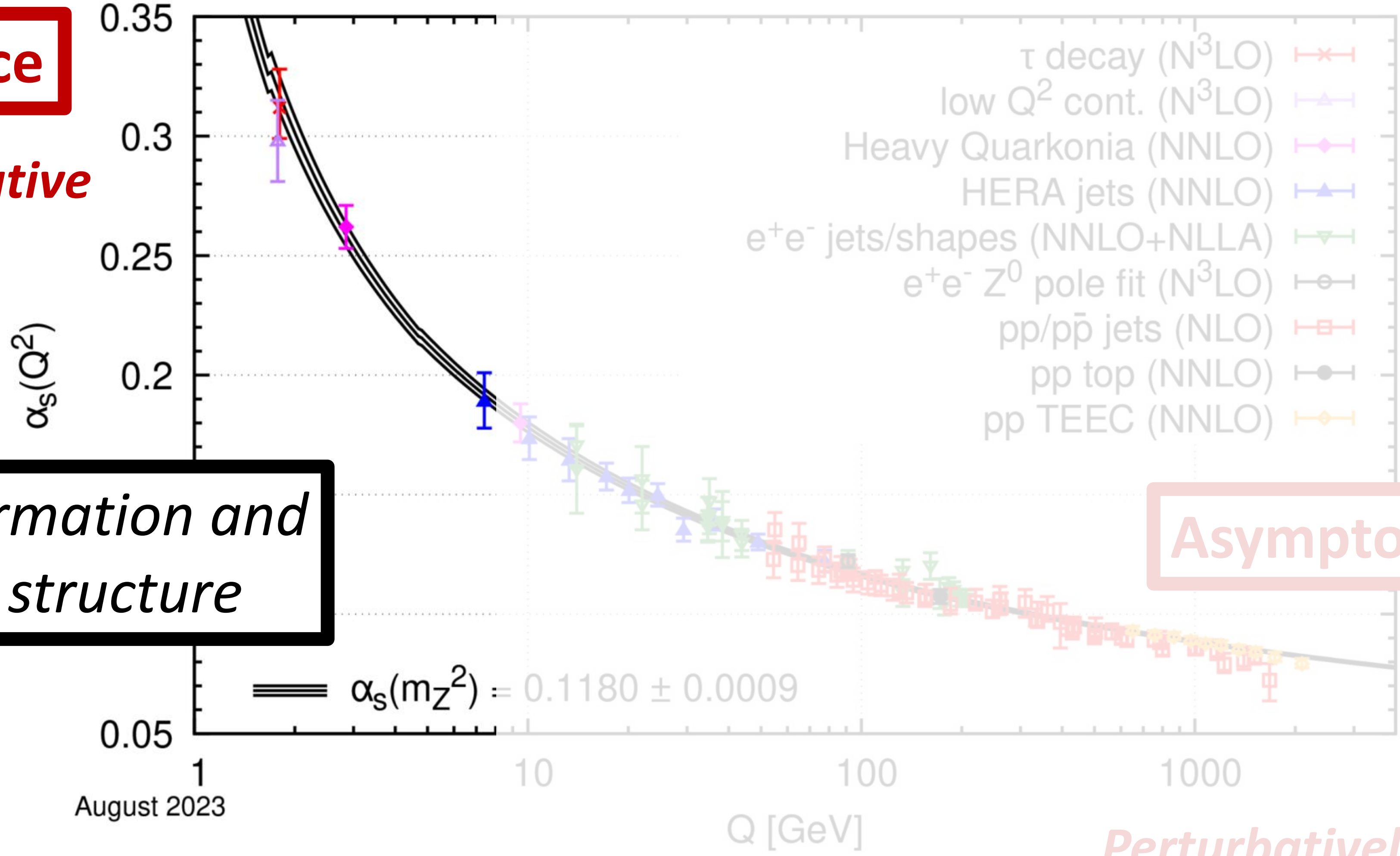
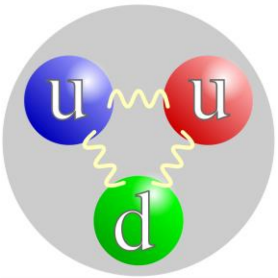
Strength of the strong force

Divergence

Nonperturbative



Hadron formation and internal structure



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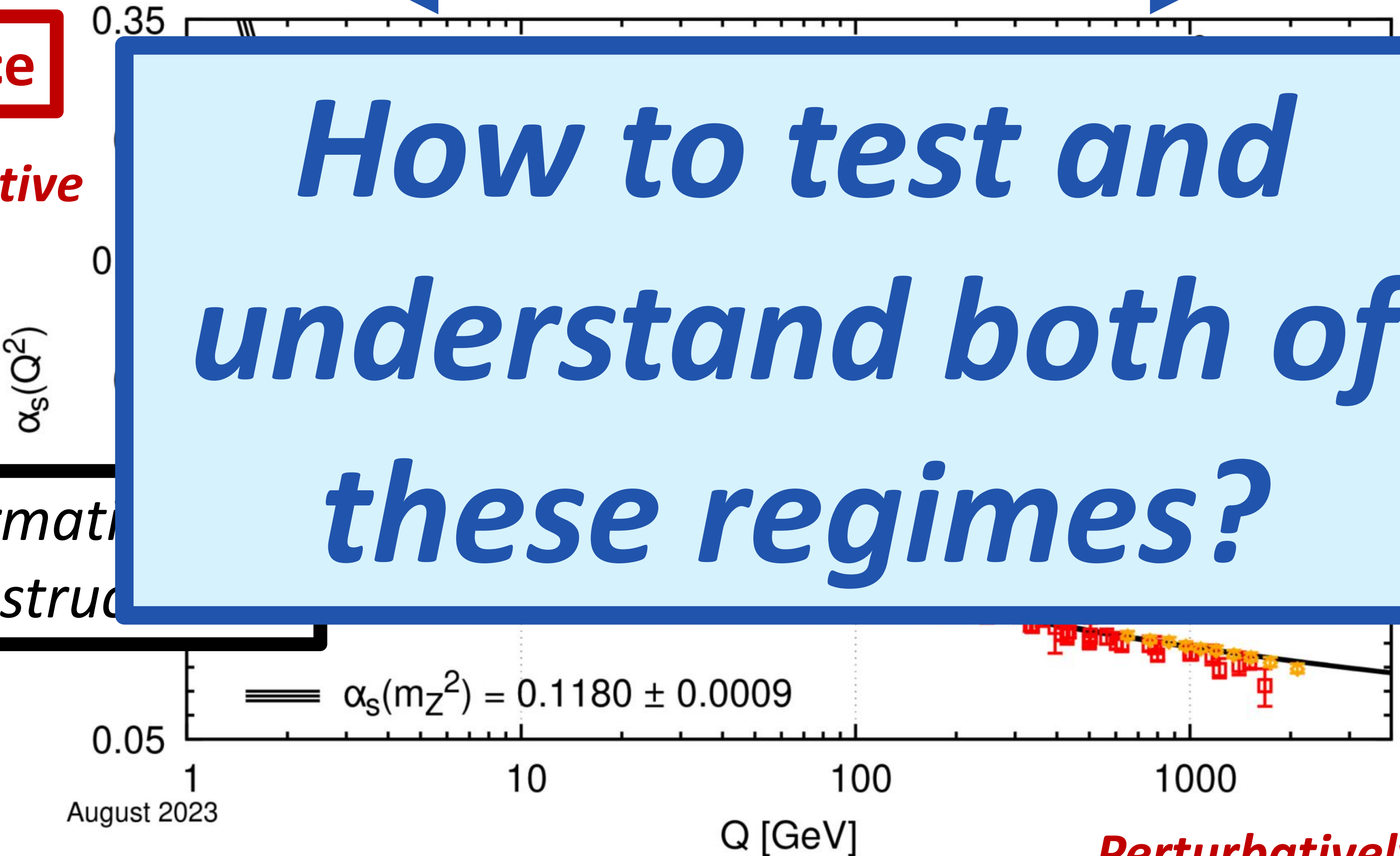
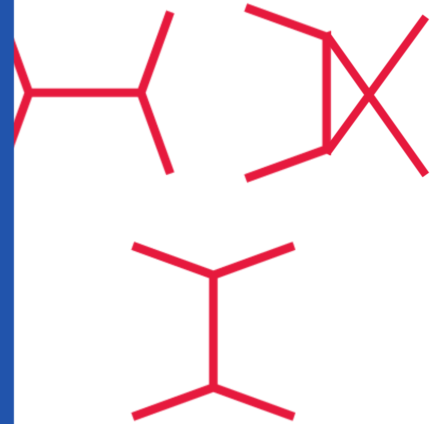
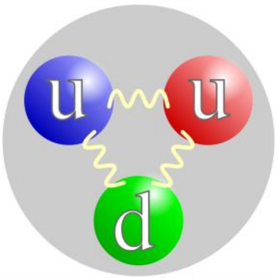


Hadron formati
internal struc

How to test and understand both of these regimes?



freedom



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Hard probes of QCD

- Produced by **high momentum-transfer processes**

Hard probes of QCD

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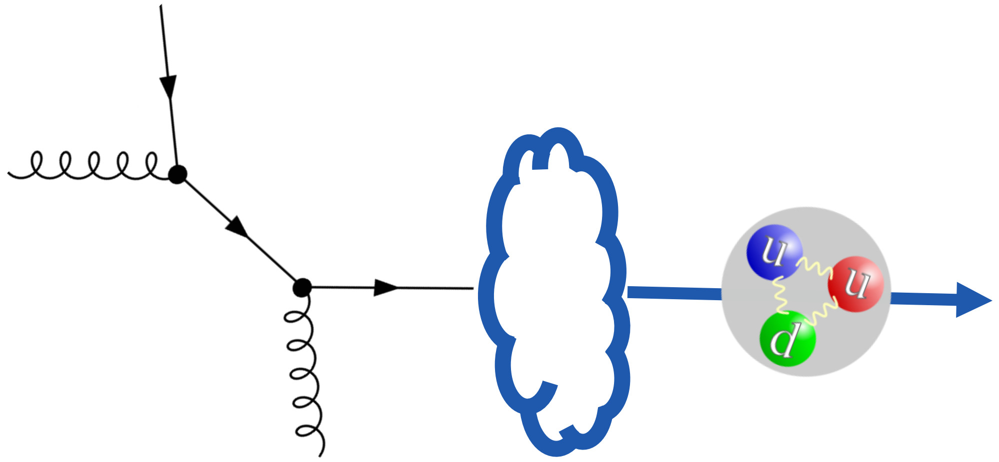
  - **High-p_{T} hadrons,** initiated by a hard scattering;



Hard probes of QCD

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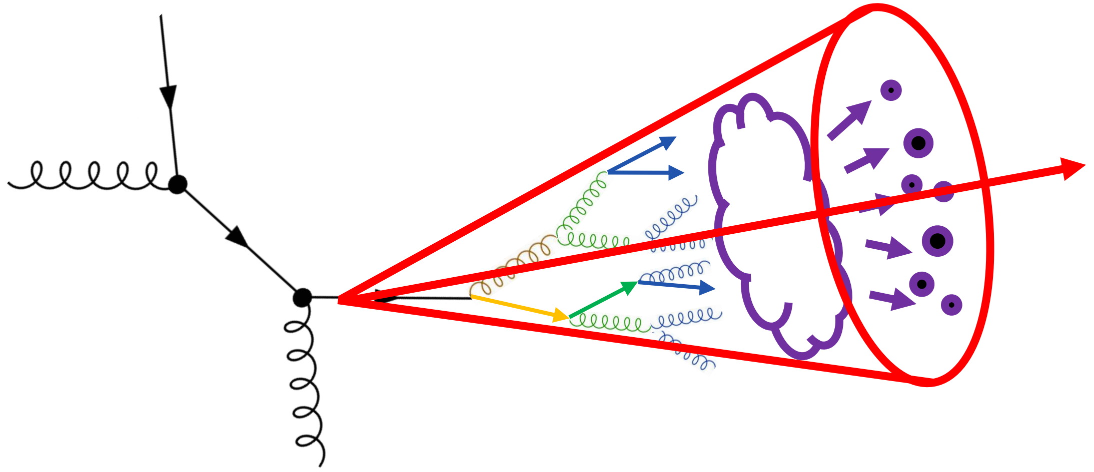
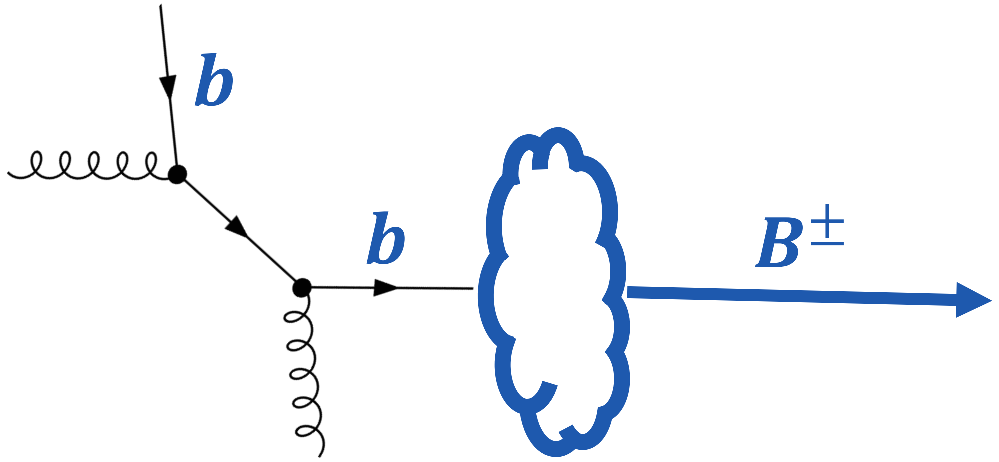


Hard probes of QCD

- Produced by **high momentum-transfer processes**
  - **High-p_{T} hadrons,** initiated by a hard scattering;
  - **Jets:** collimated sprays of particles;
  - **Heavy flavor (HF) hadrons**: particles with large masses, not found in ordinary nuclear matter



Hard probes of QCD

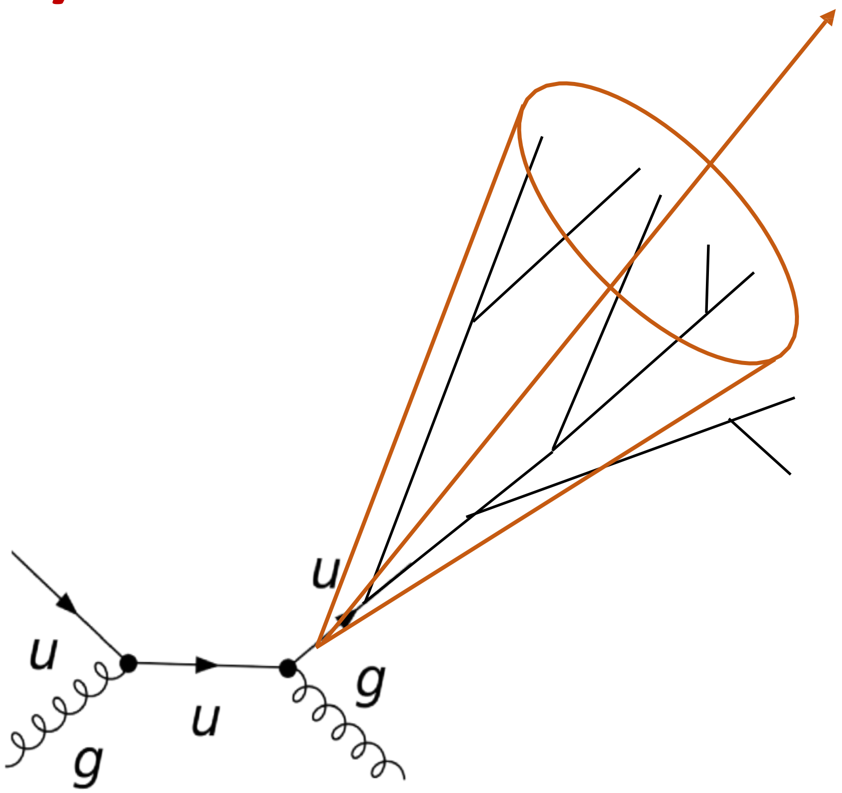
• P

These probes – and combinations of them – allow insight into QCD across different energy scales

found in ordinary nuclear matter

This talk: probing QCD in …

- **“vacuum” (proton-proton collisions)**



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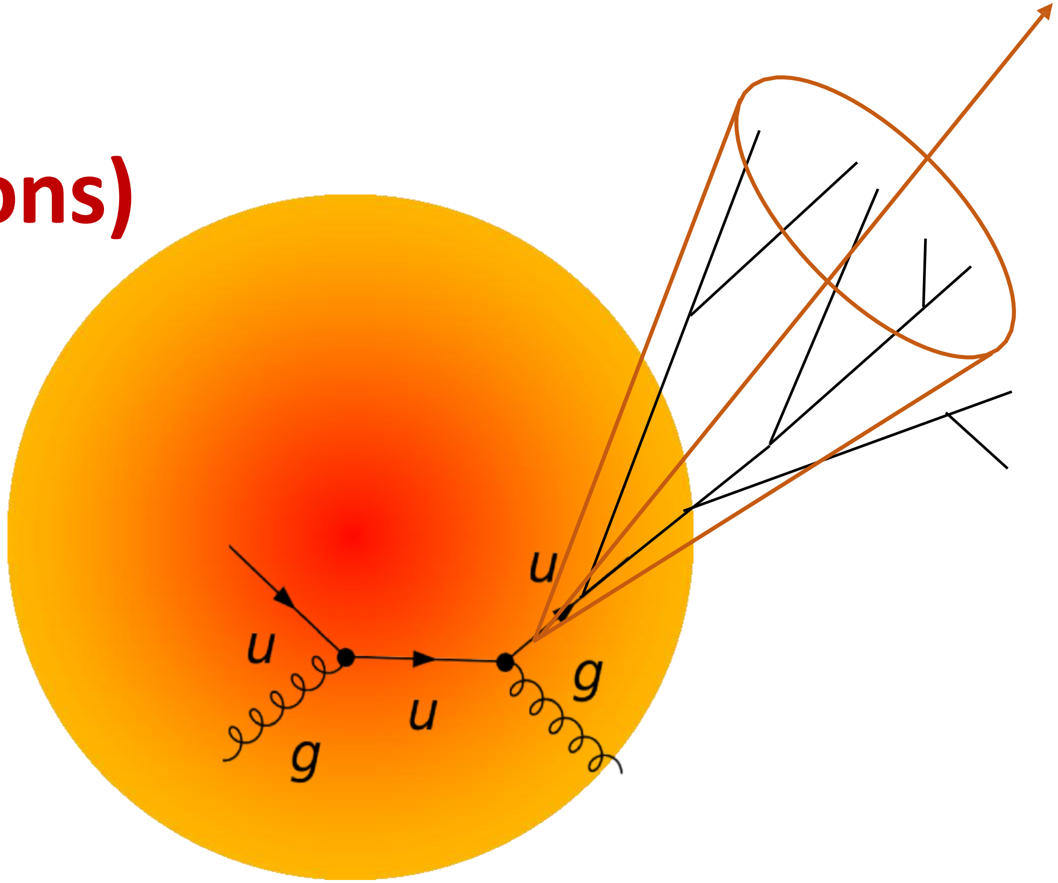
- “medium” (heavy-ion collisions)



This talk: probing QCD in …

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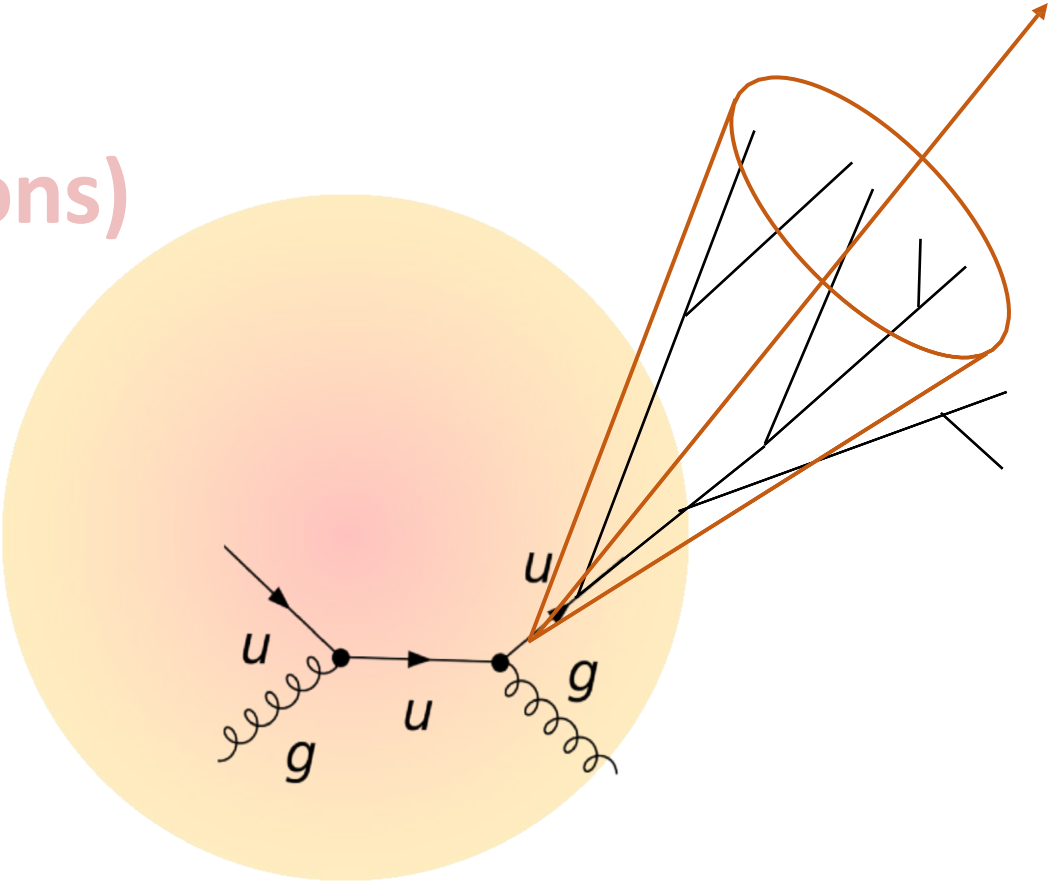
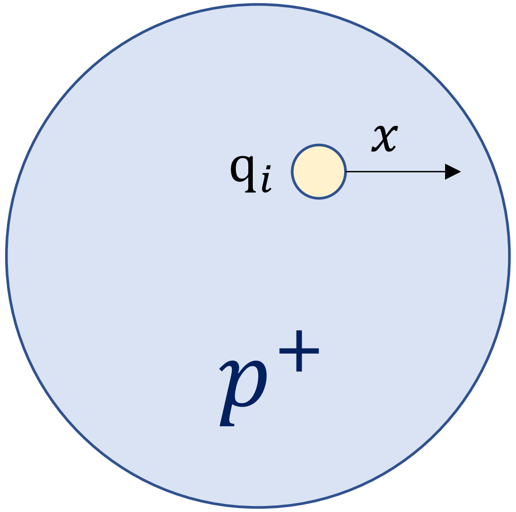


Breaking down a QCD event

Breaking down a QCD event

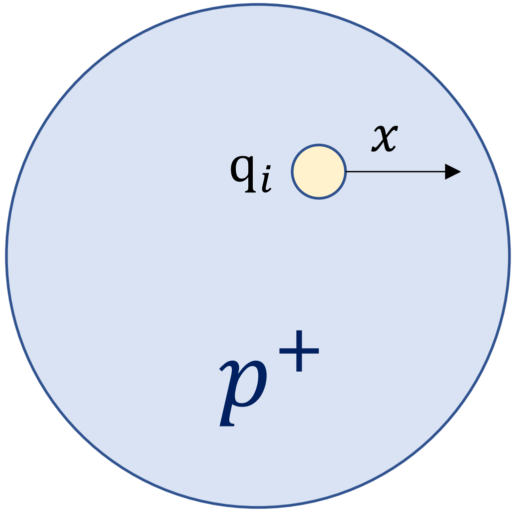
Parton Distribution Functions (PDFs)



Breaking down a QCD event

Parton Distribution Functions (PDFs)

Hard scattering process



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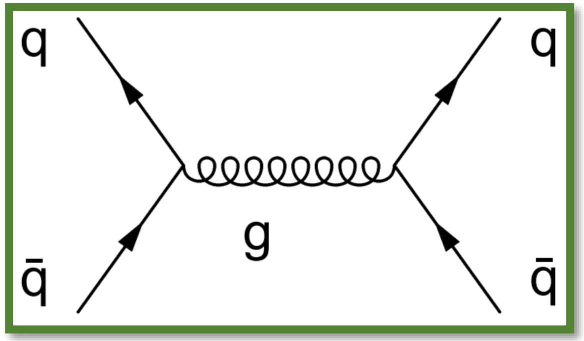

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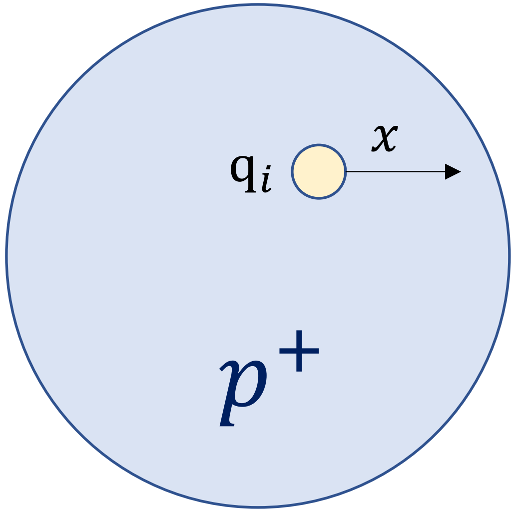

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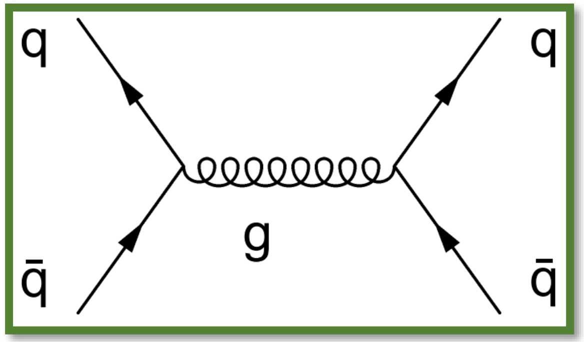

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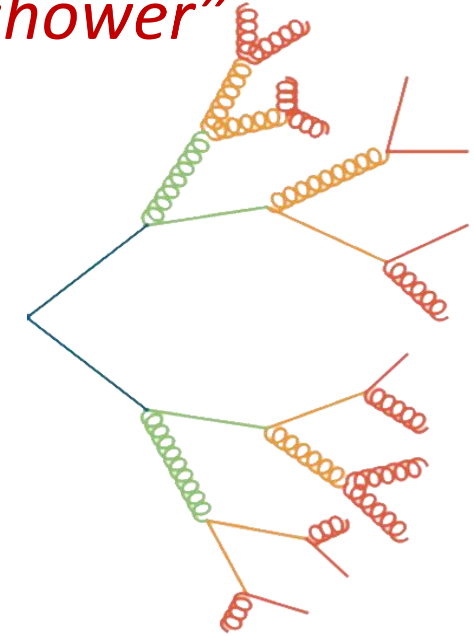
“Parton shower”



Breaking down a QCD event

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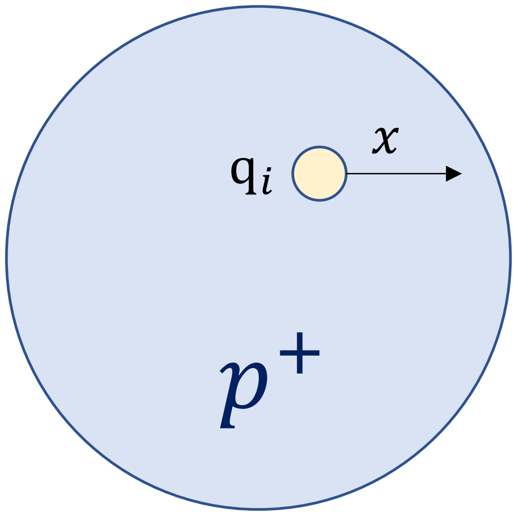
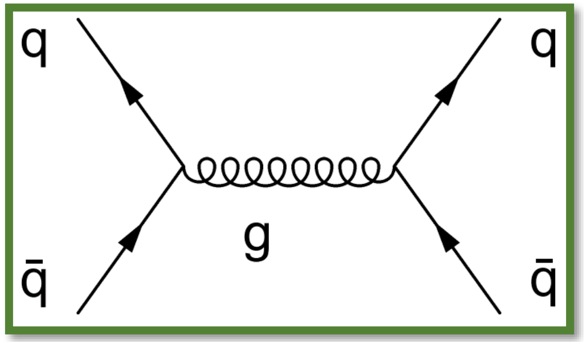


$\otimes$

Hard scattering process



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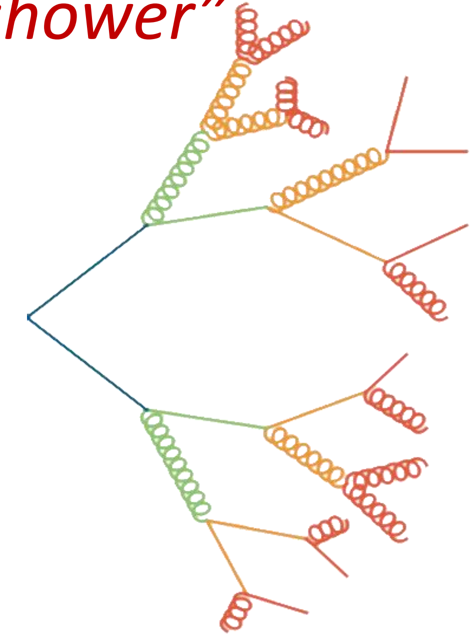

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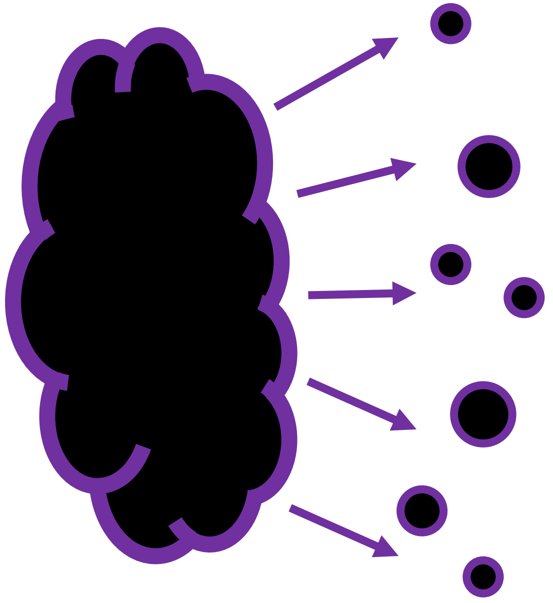
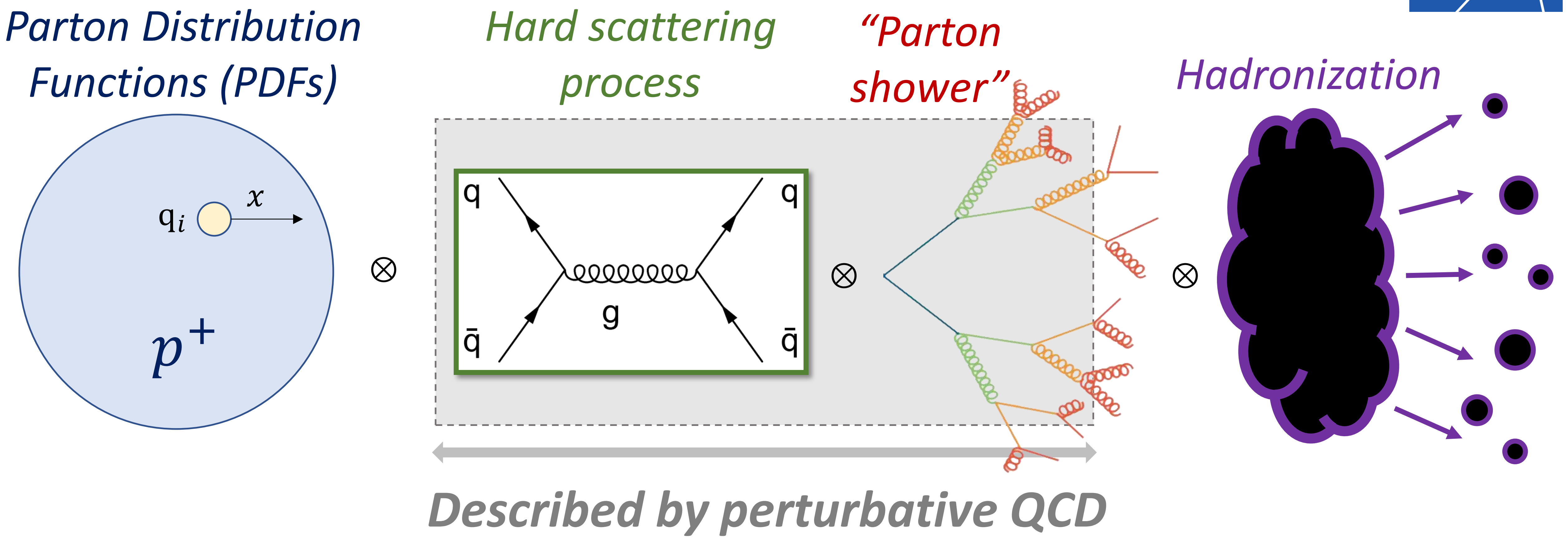
Hadronization

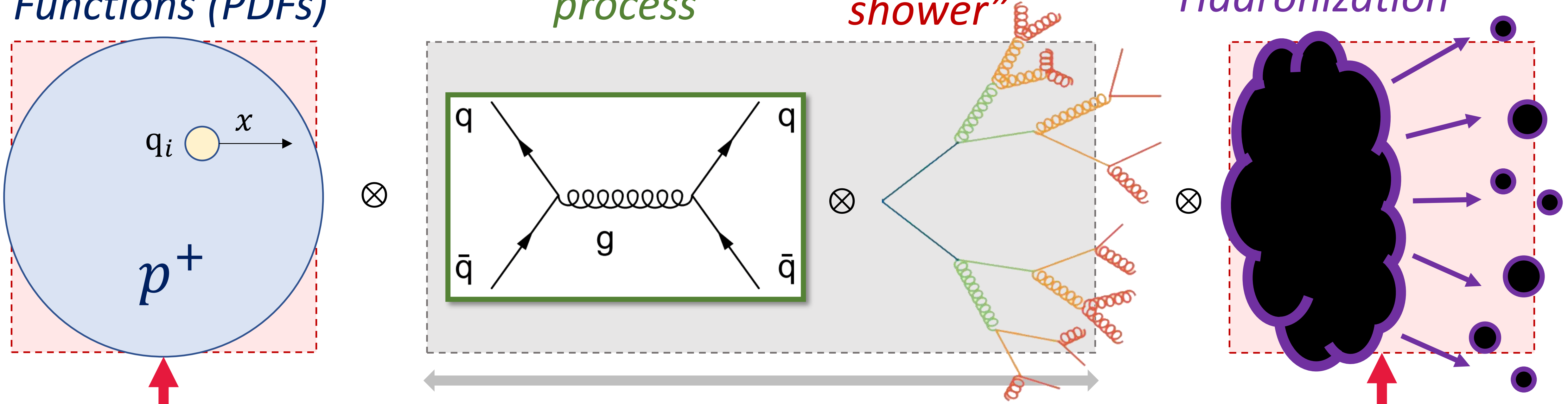


Breaking down a QCD event



Breaking down a QCD event

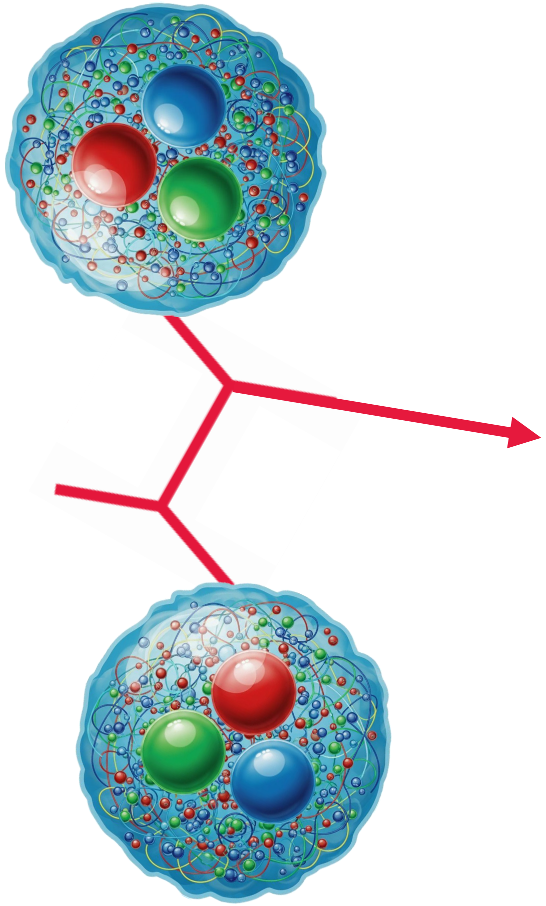
Parton Distribution Functions (PDFs) ⊗ *Hard scattering process* ⊗ *"Parton shower"* ⊗ *Hadronization*



Described by perturbative QCD

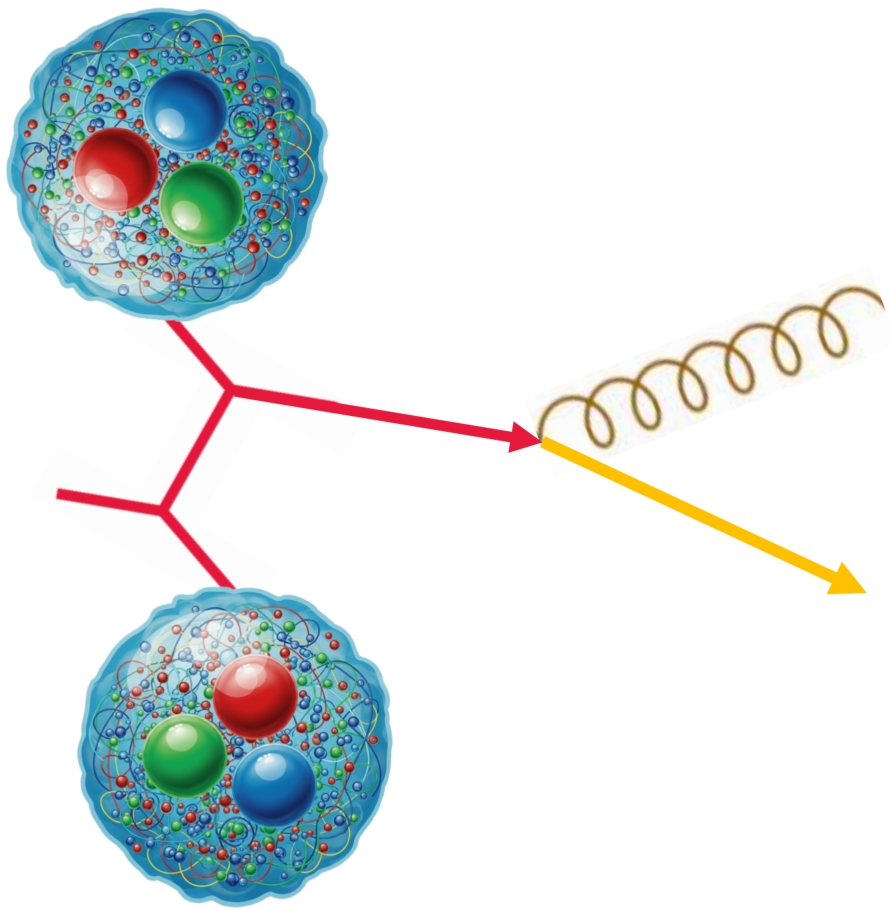
Nonperturbative QCD: extracted from experimental data

Jets as a QCD hard probe



$\boxed{\text{Energy scale } Q\text{:}}$ **High**

Jets as a QCD hard probe



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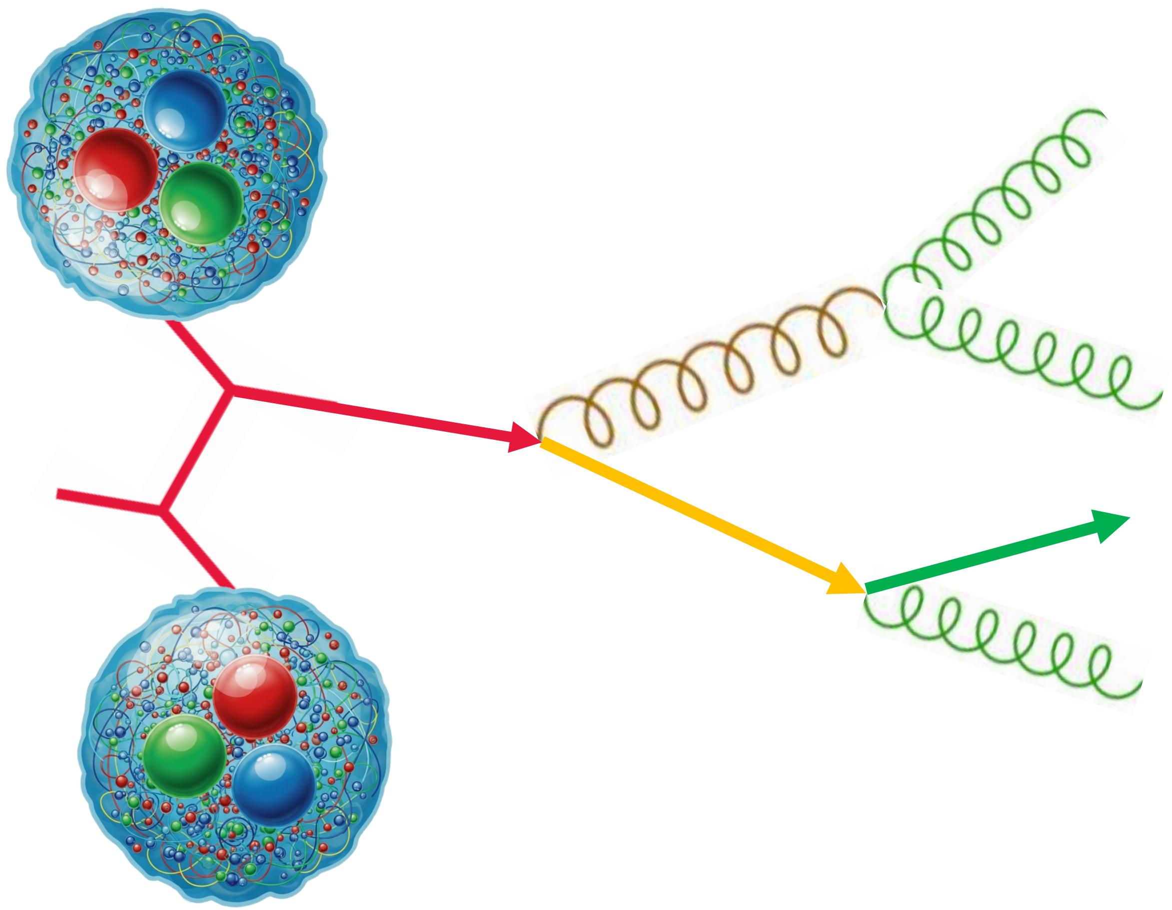

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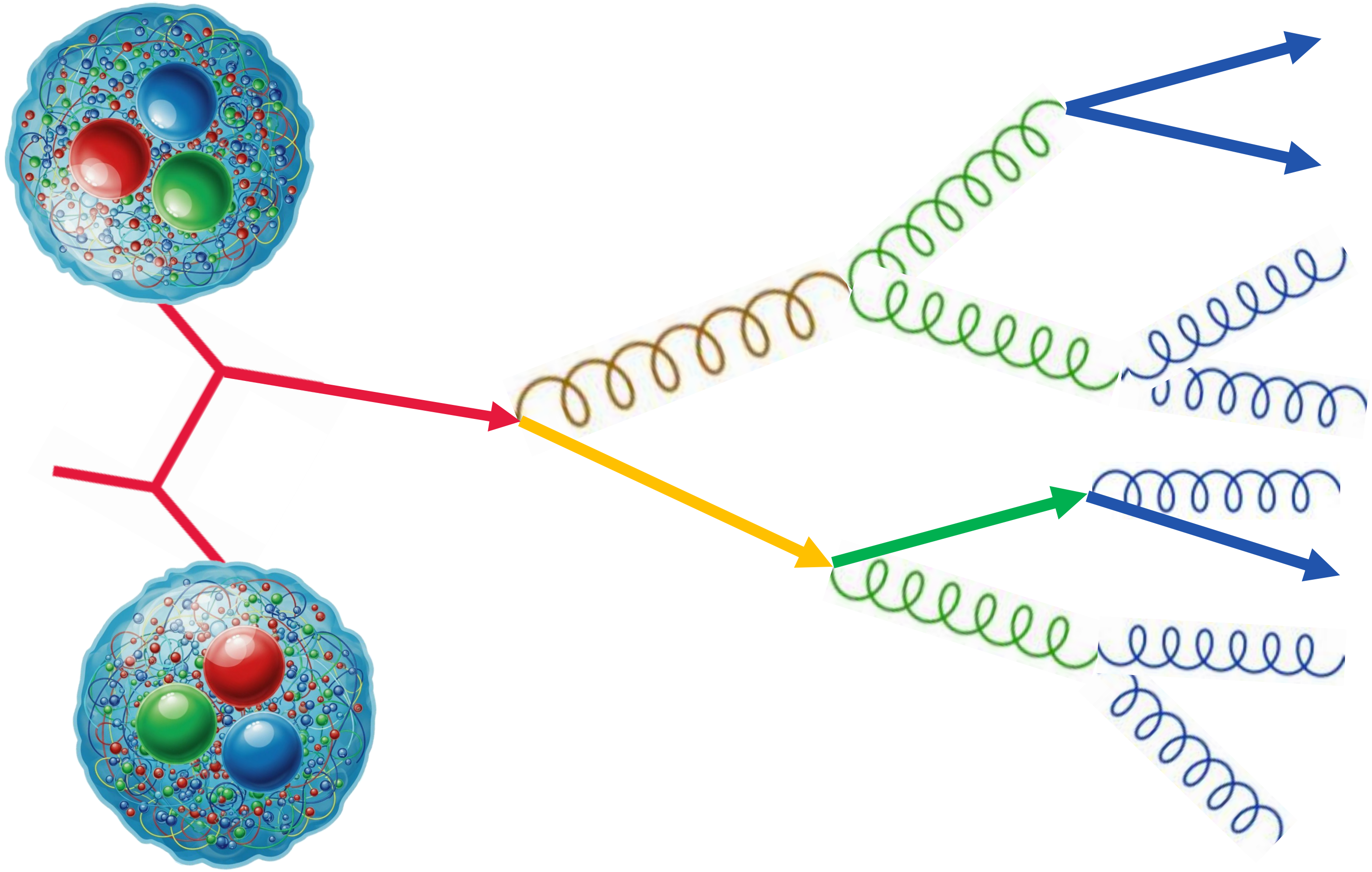

Energy scale Q: **High** → → → **Low**

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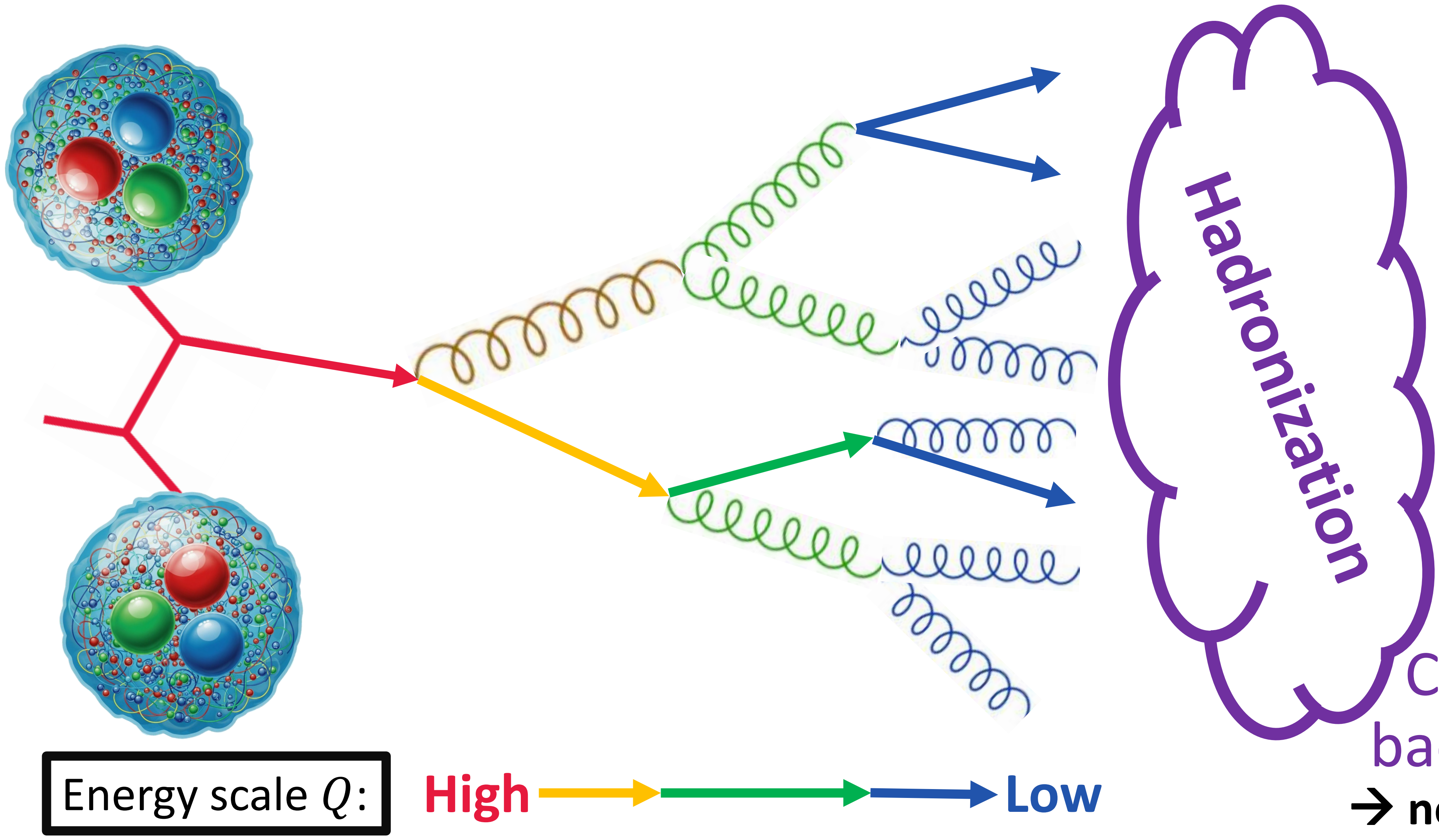
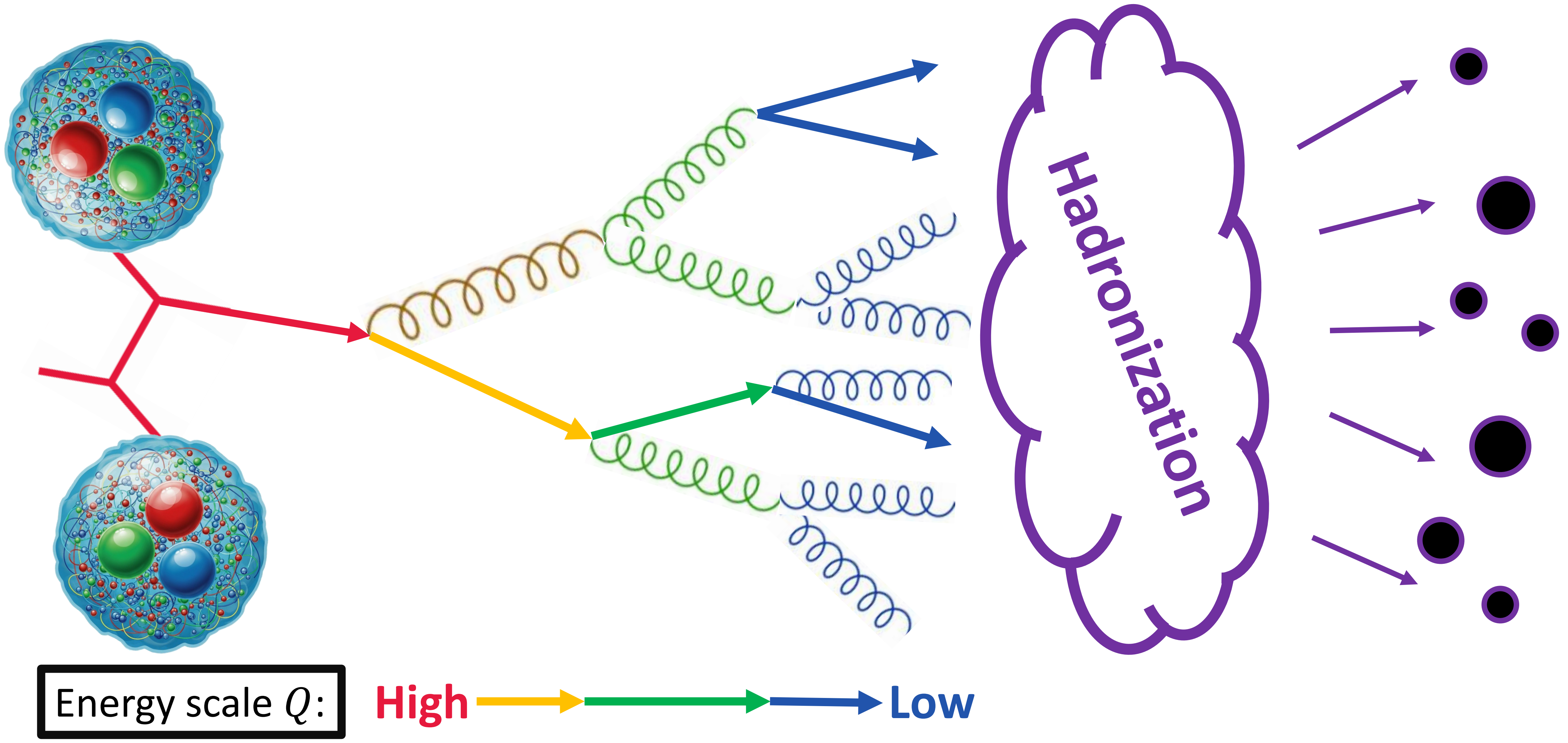


Connect partons back into hadrons

→ **nonperturbative QCD**

Jets as a QCD hard probe



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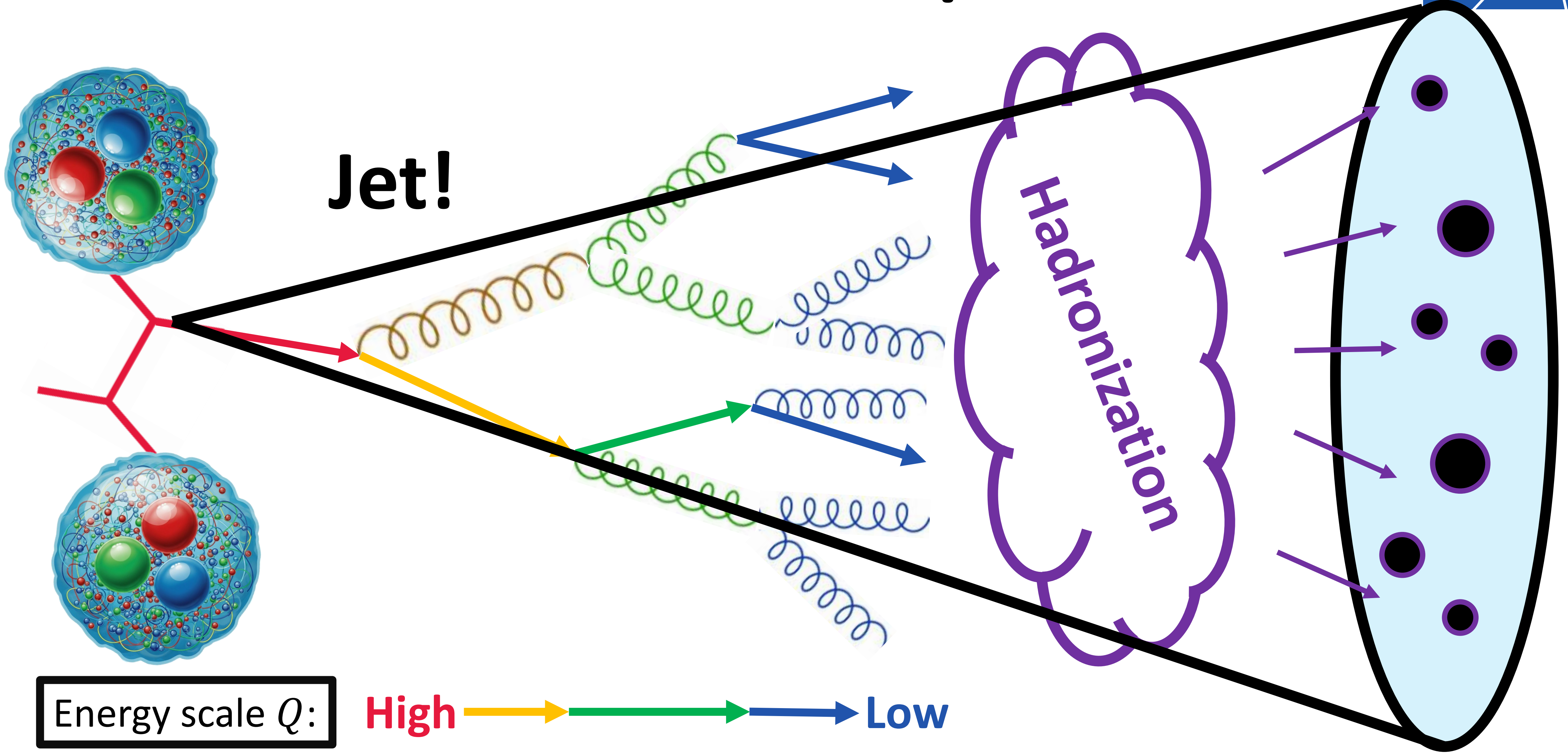

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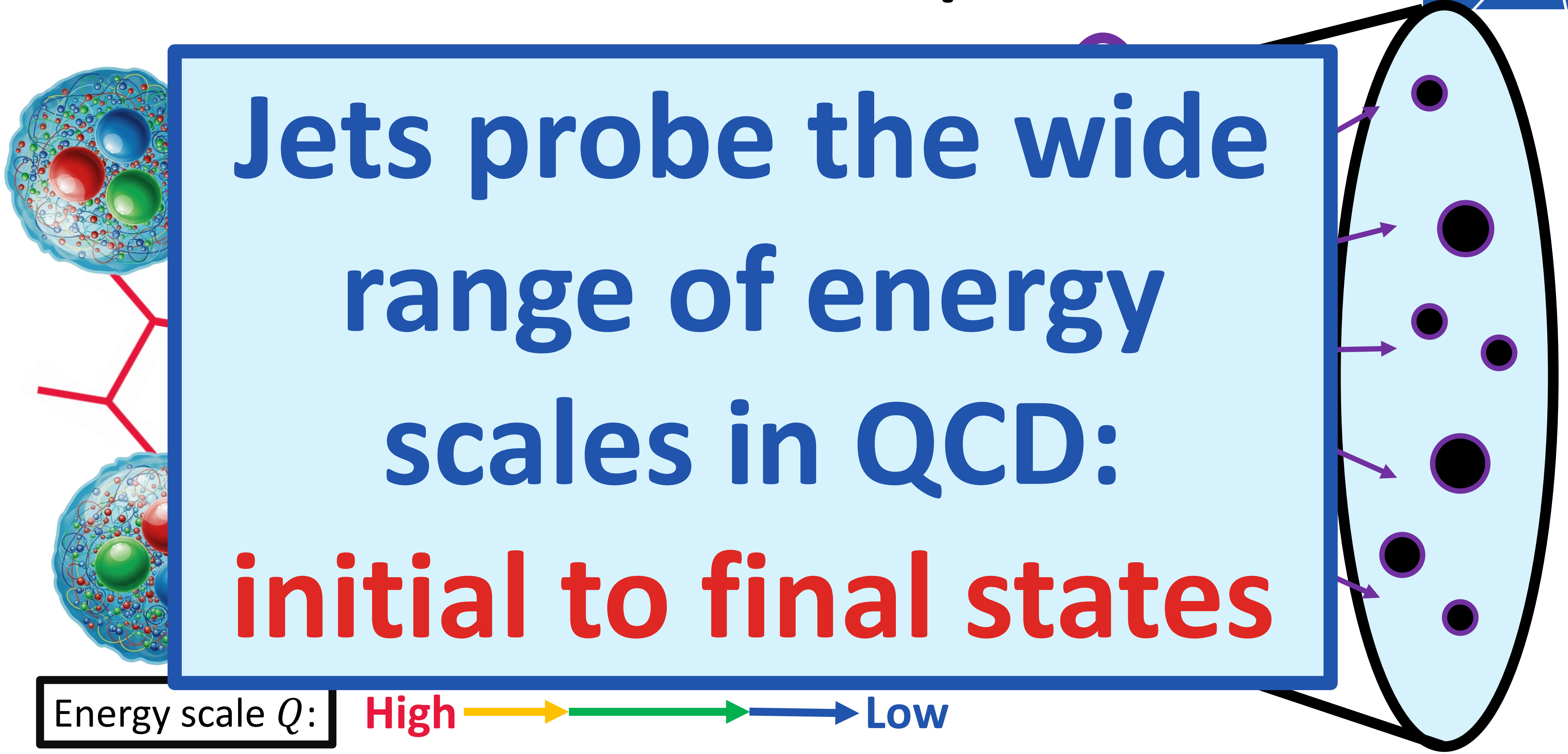
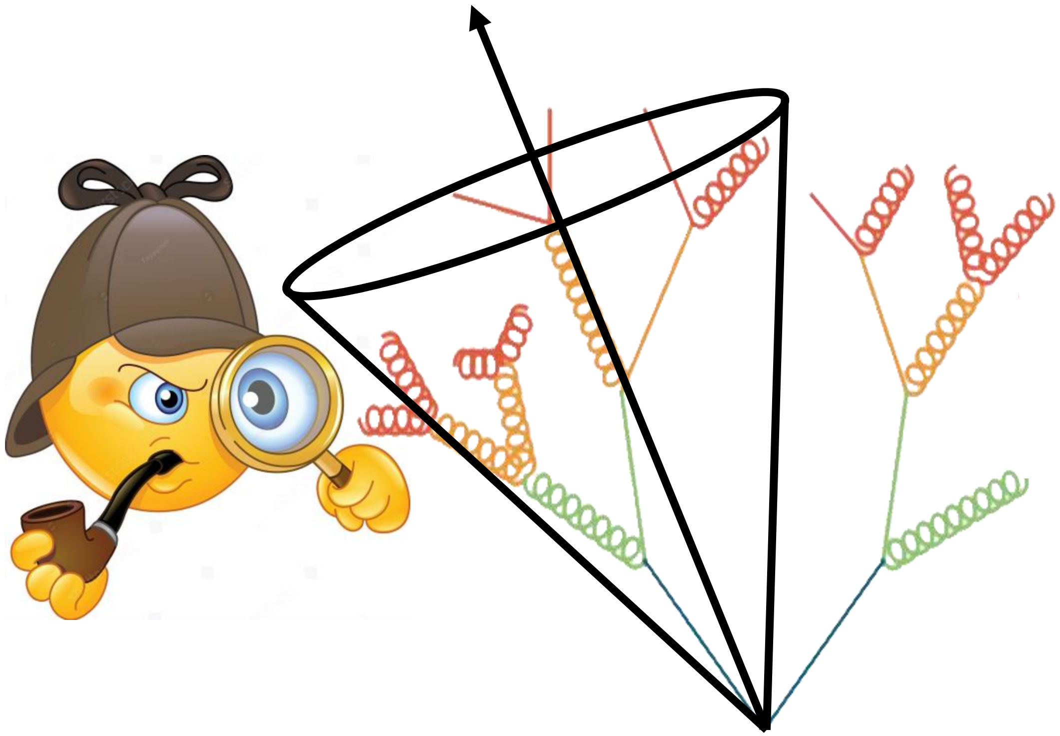


Jets probe the wide range of energy scales in QCD: initial to final states

Energy scale Q: High → → → Low

A flexible probe of QCD

- Jets and **jet substructure observables** can therefore be "tuned" to study specific processes of QCD



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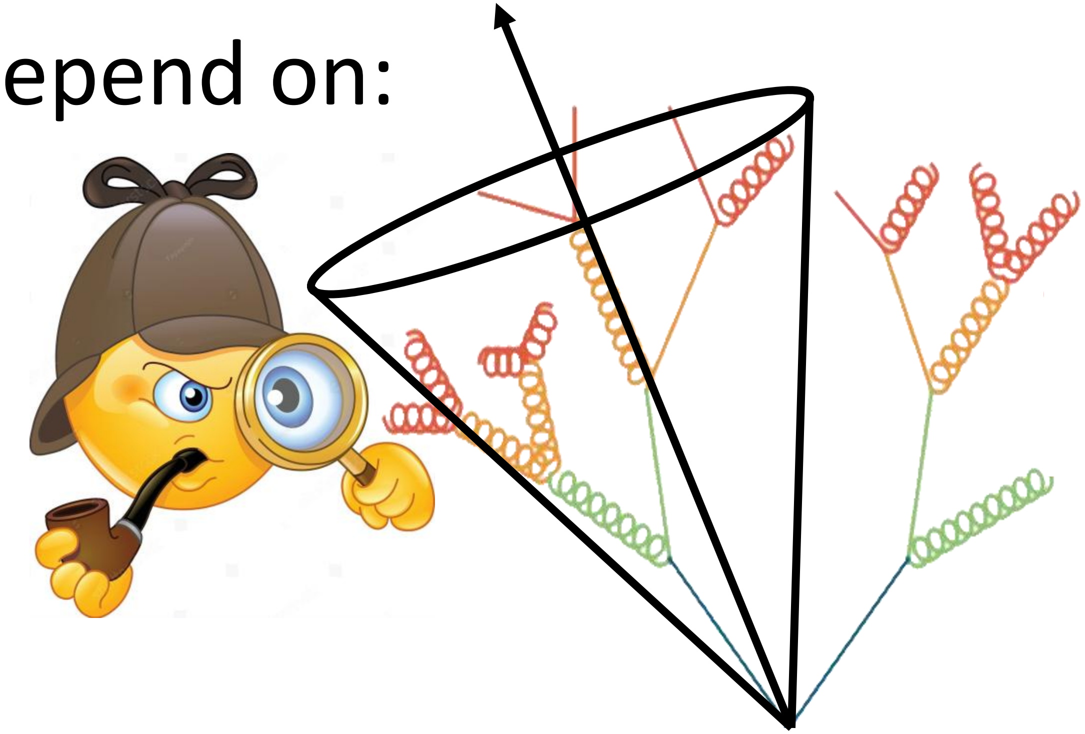

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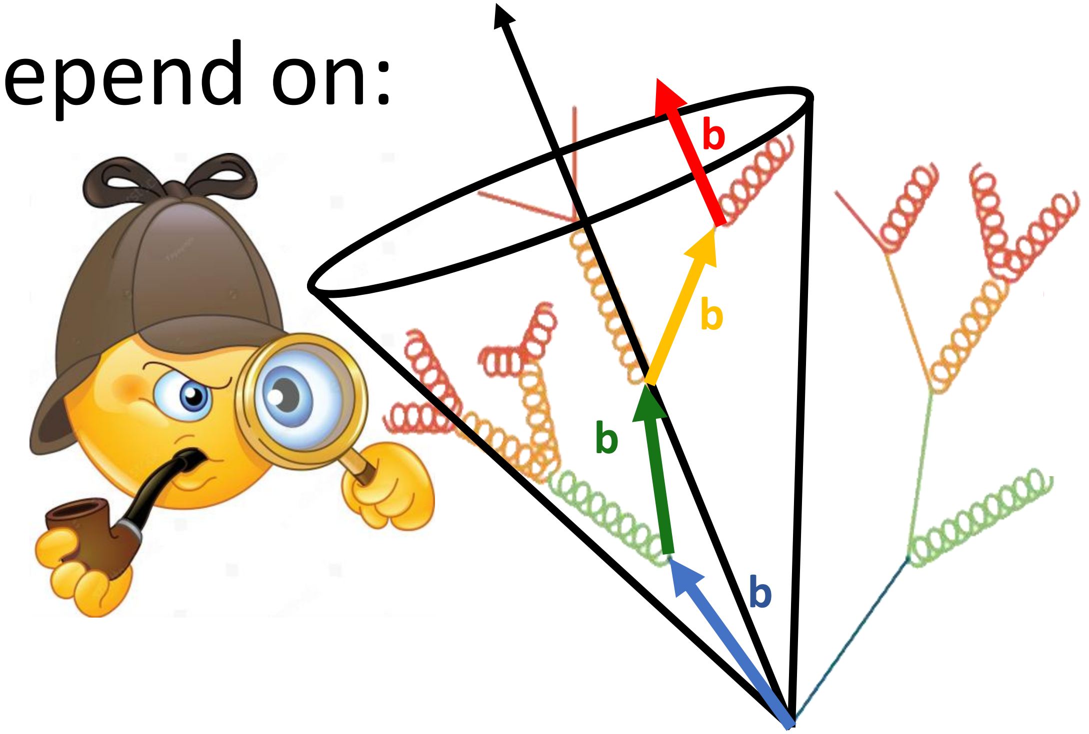
- How does the jet fragmentation depend on:
  - Parton ***flavor***?



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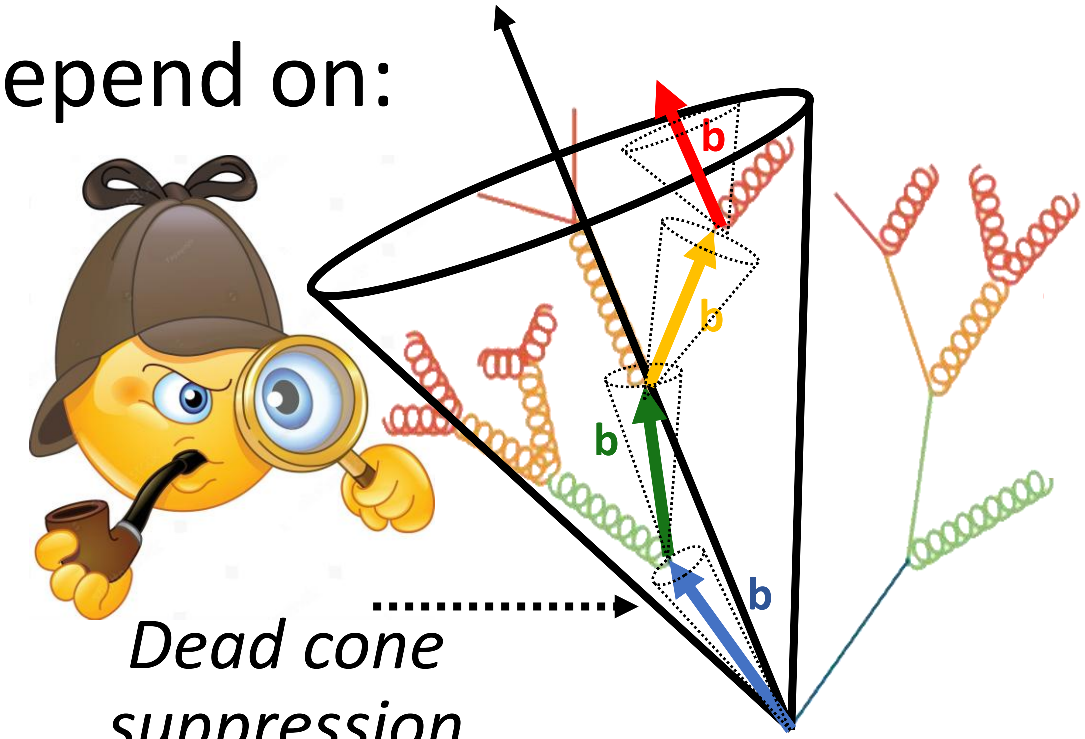

Dead cone suppression

J. Phys. **G17** (1991) 1602

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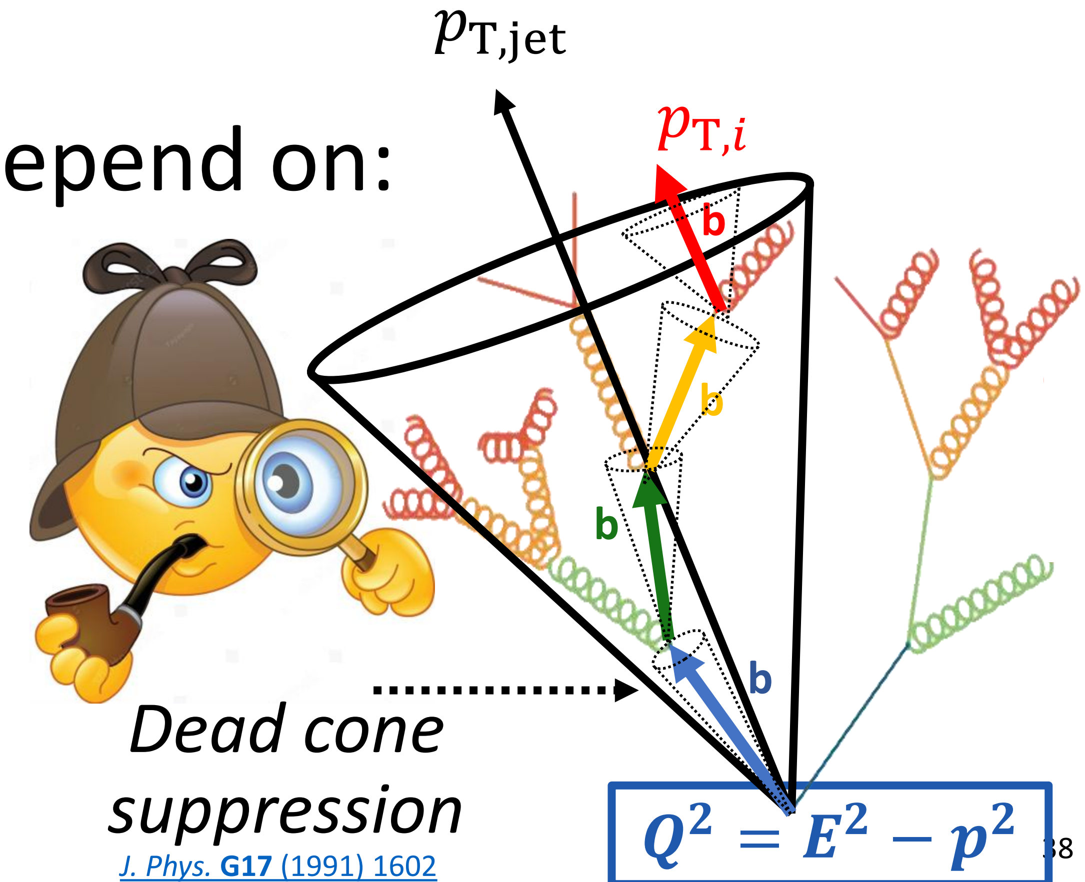

[*J. Phys.* **G17** (1991) 1602](#)

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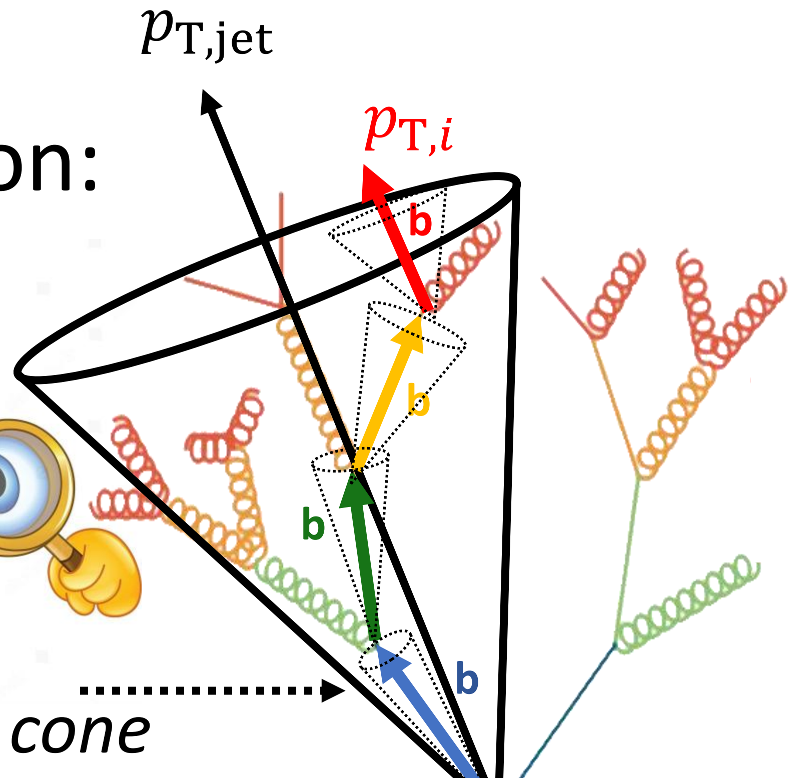
- **How well can QCD predict these effects in data?**



Dead cone suppression

$$\boldsymbol{Q^2 = E^2 - p^2}$$

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Criteria for calculability

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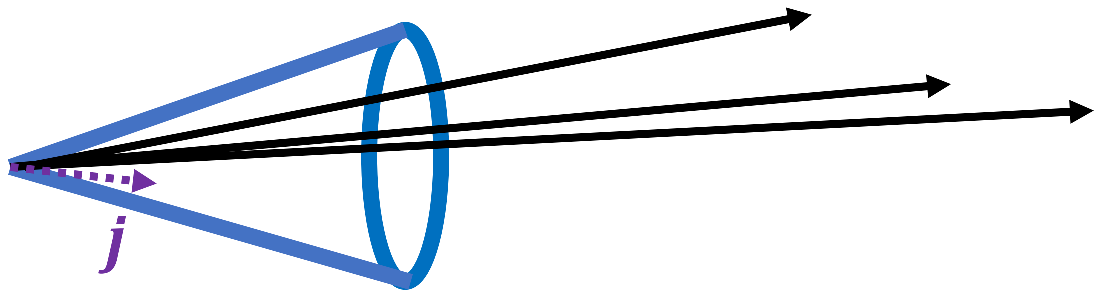
Infra-Red safety:
the jet/observable should not change if **a low-momentum ($p \approx 0$) particle j** is added to the event/jet



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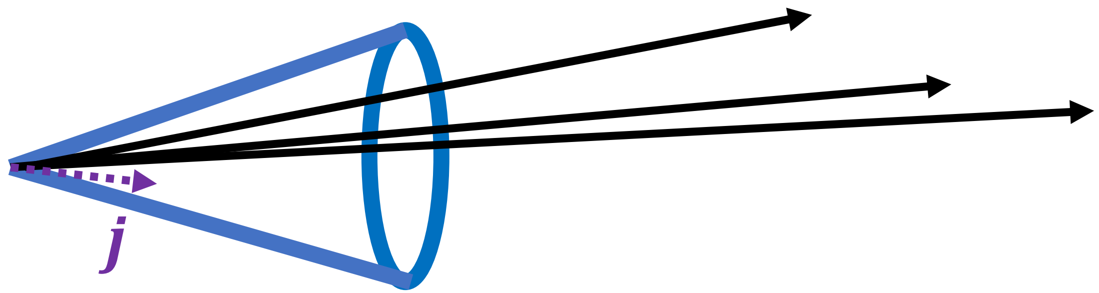

Collinear safety:
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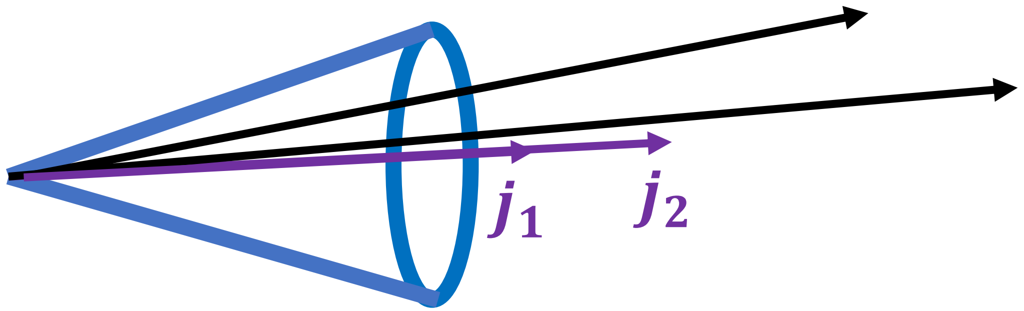

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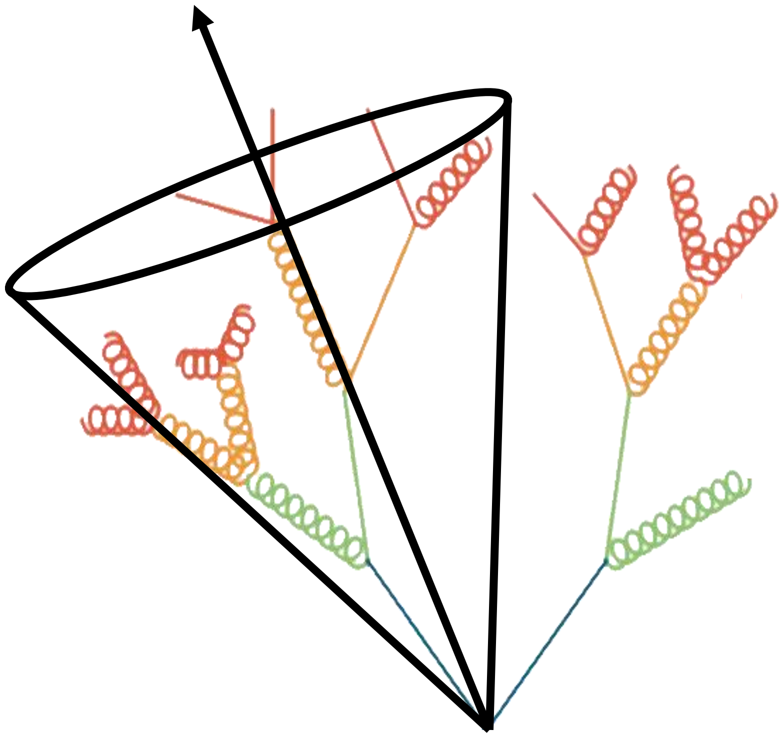
IRC-safe → well-defined path to calculation

Generalized jet angularities

- **IRC-safe jet observables** dependent on constituent $\boldsymbol{p}_{\mathbf{T}}$ and **angle**

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



Generalized jet angularities

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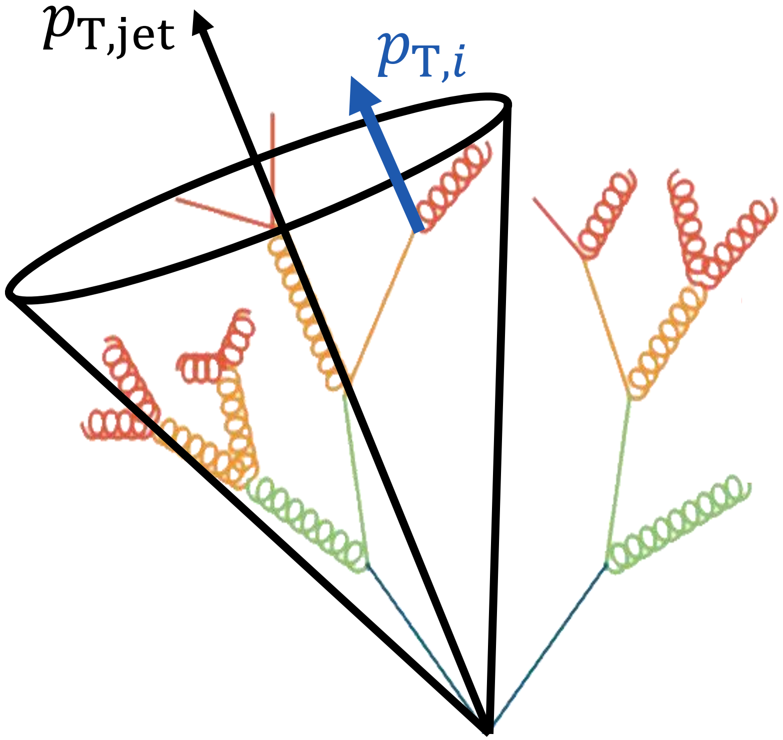
$$\lambda_\alpha = \sum_{i \in \text{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \;\; \cdots$$



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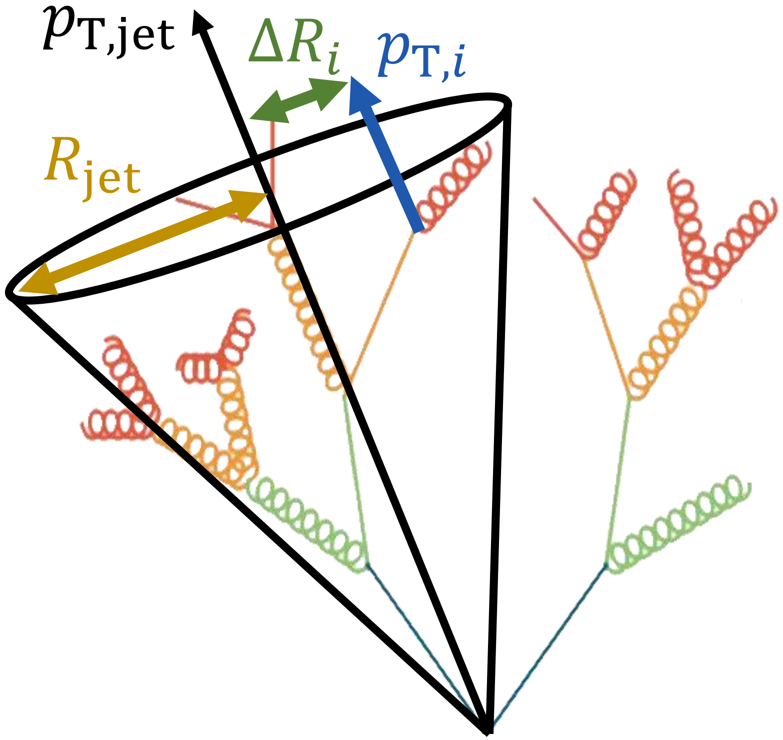

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free parameter

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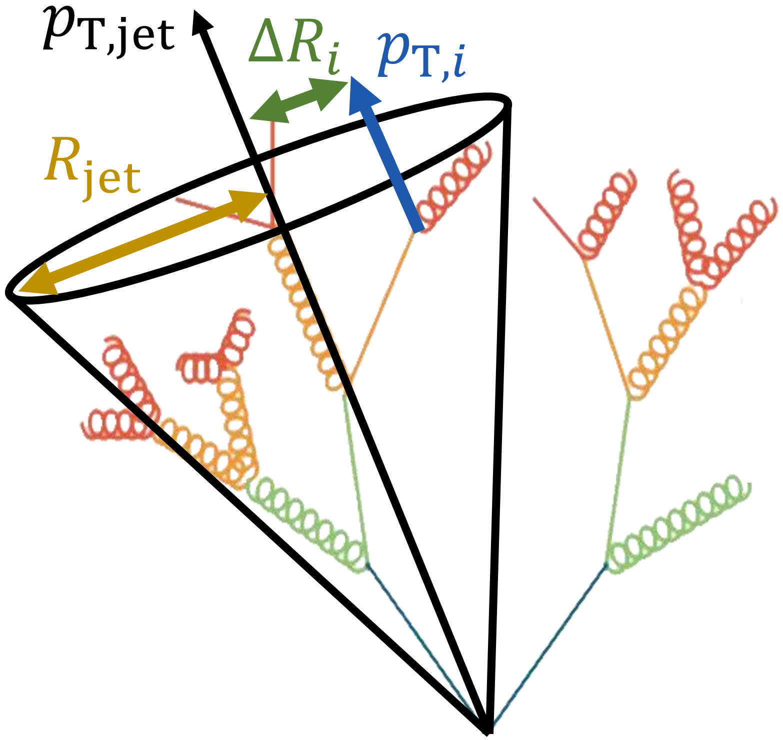

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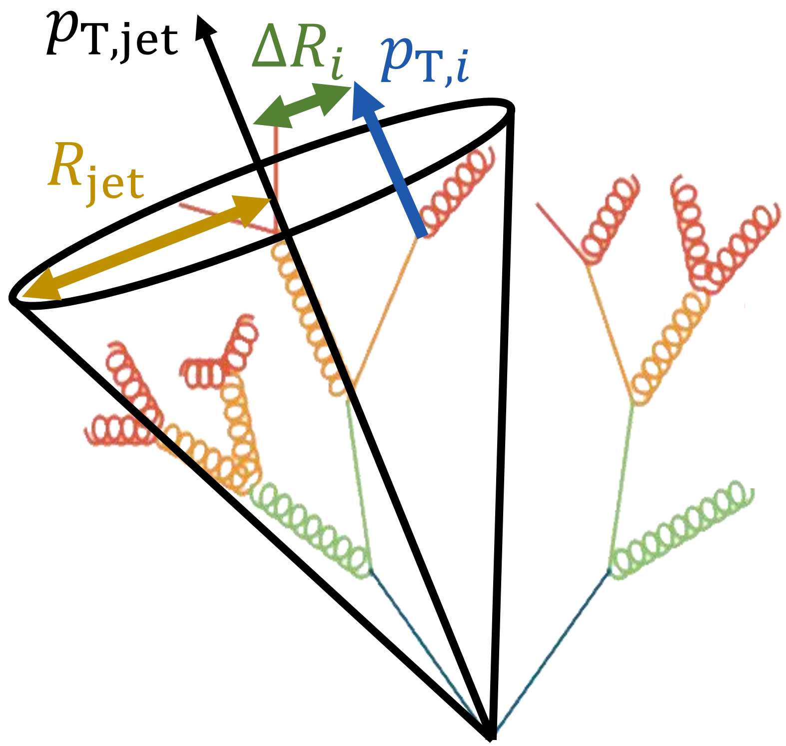
$$= \sum_{i\in\mathrm{jet}} z_i \theta_i^\alpha$$

"Where is the p_T inside the jet?"



Generalized jet angularities

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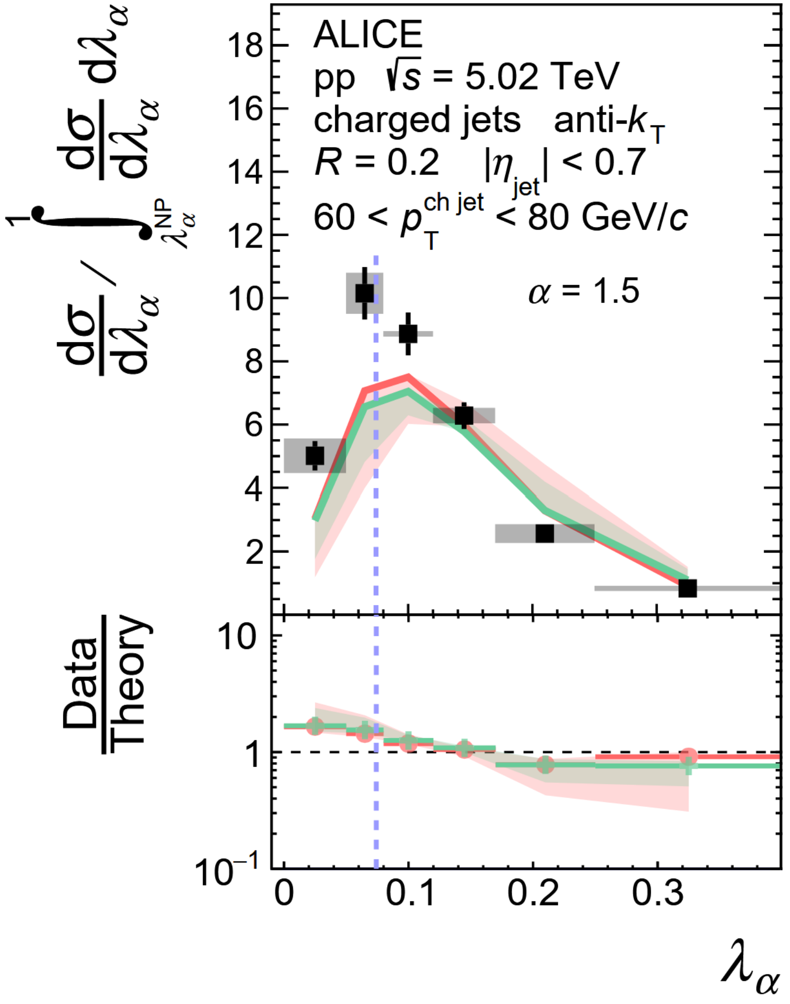
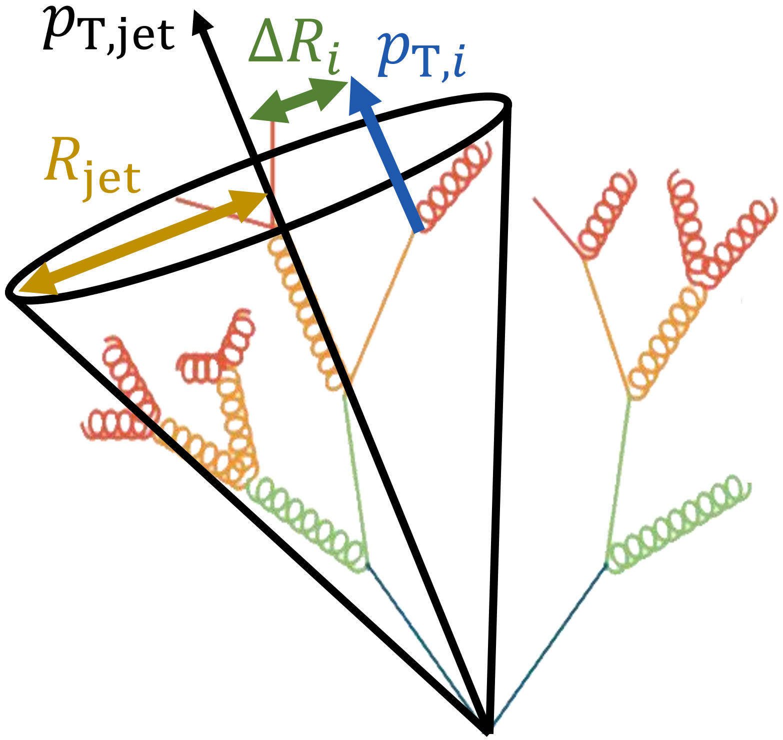


$$\lambda_\alpha = \sum_{i\in\mathrm{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}\left(\frac{\Delta R_i}{R_\mathrm{jet}}\right)^\alpha$$

$$= \sum_{i\in\mathrm{jet}} z_i\theta_i^\alpha$$

"Where is the p_T inside the jet?"



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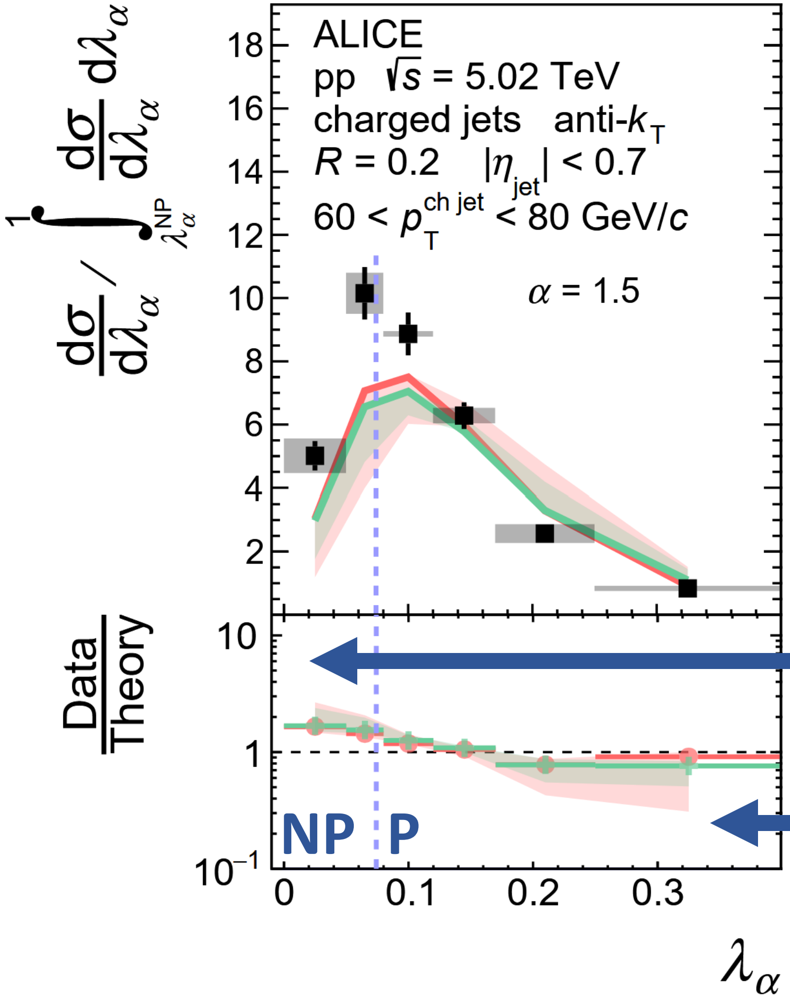

$$\lambda_\alpha = \sum_{i\in \text{jet}} \frac{p_{T,i}}{p_{T,\text{jet}}} \left(\frac{\Delta R_i}{R_{\text{jet}}}\right)^\alpha = \sum_{i\in\text{jet}} z_i \theta_i^\alpha$$

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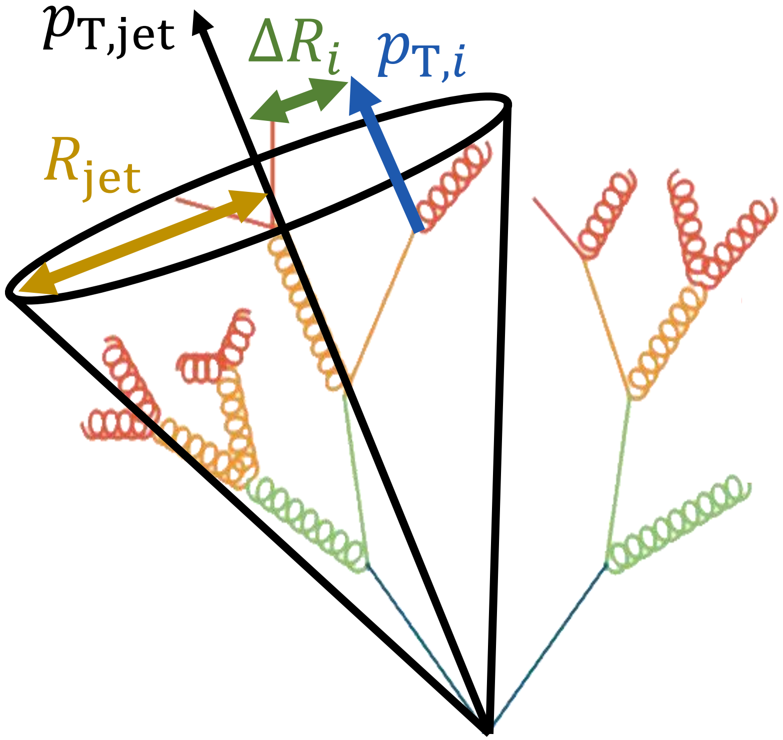

Nonperturbative region

Perturbative region

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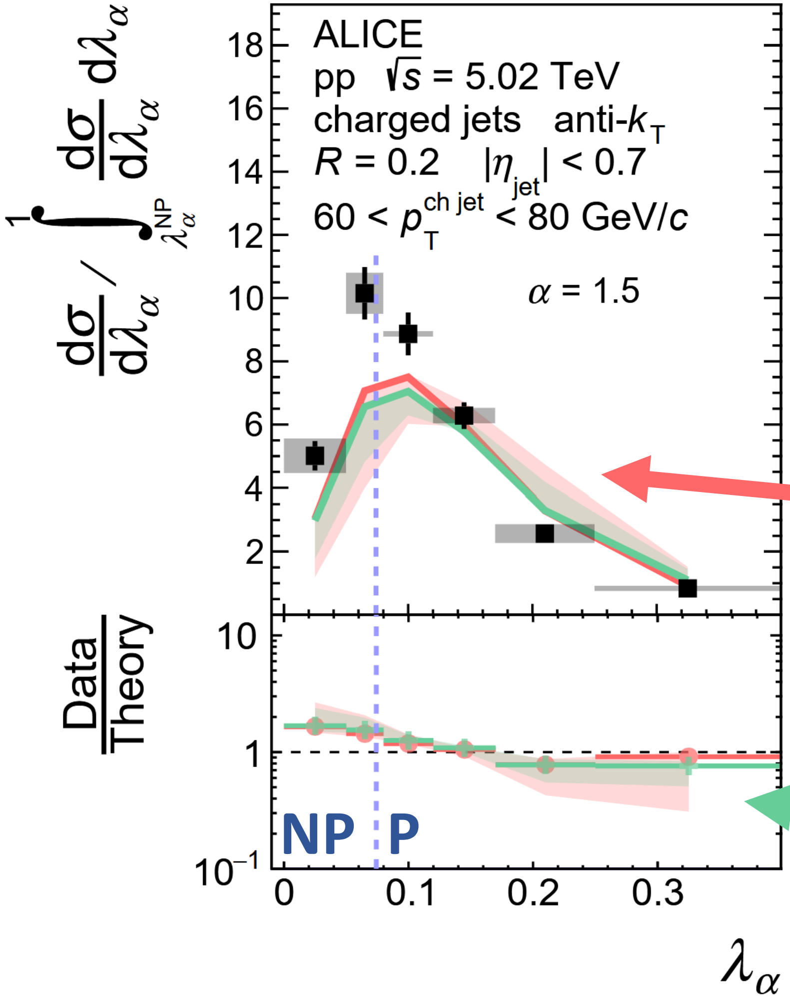

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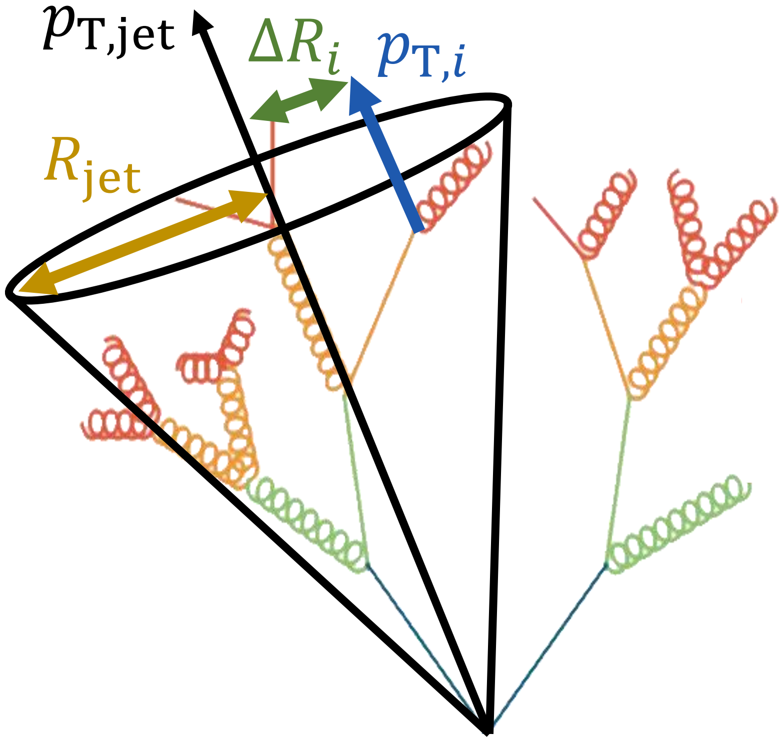

Direct QCD predictions

Reasonable agreement with experimental data

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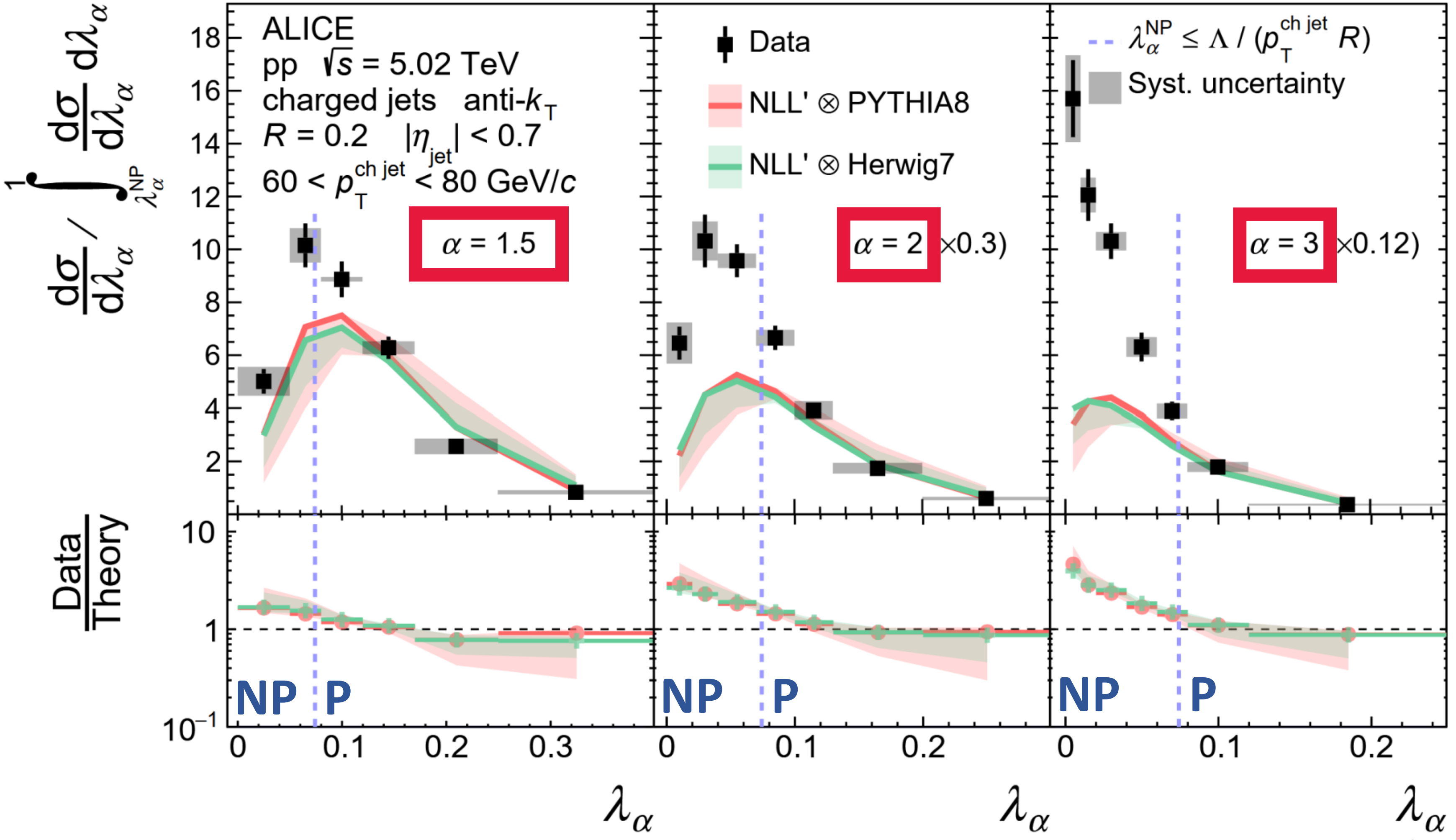

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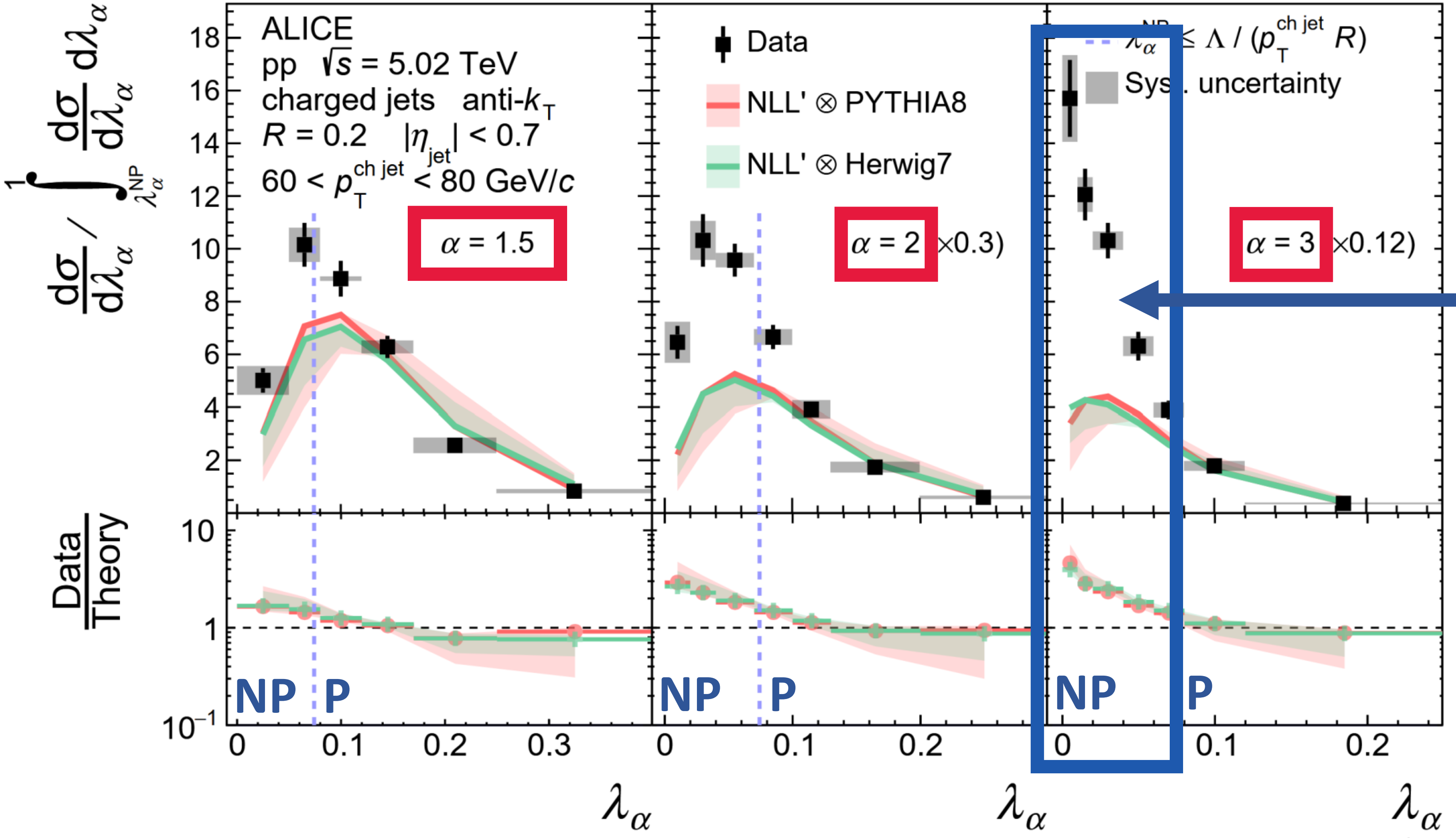

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Breakdown of predictions at larger values of α

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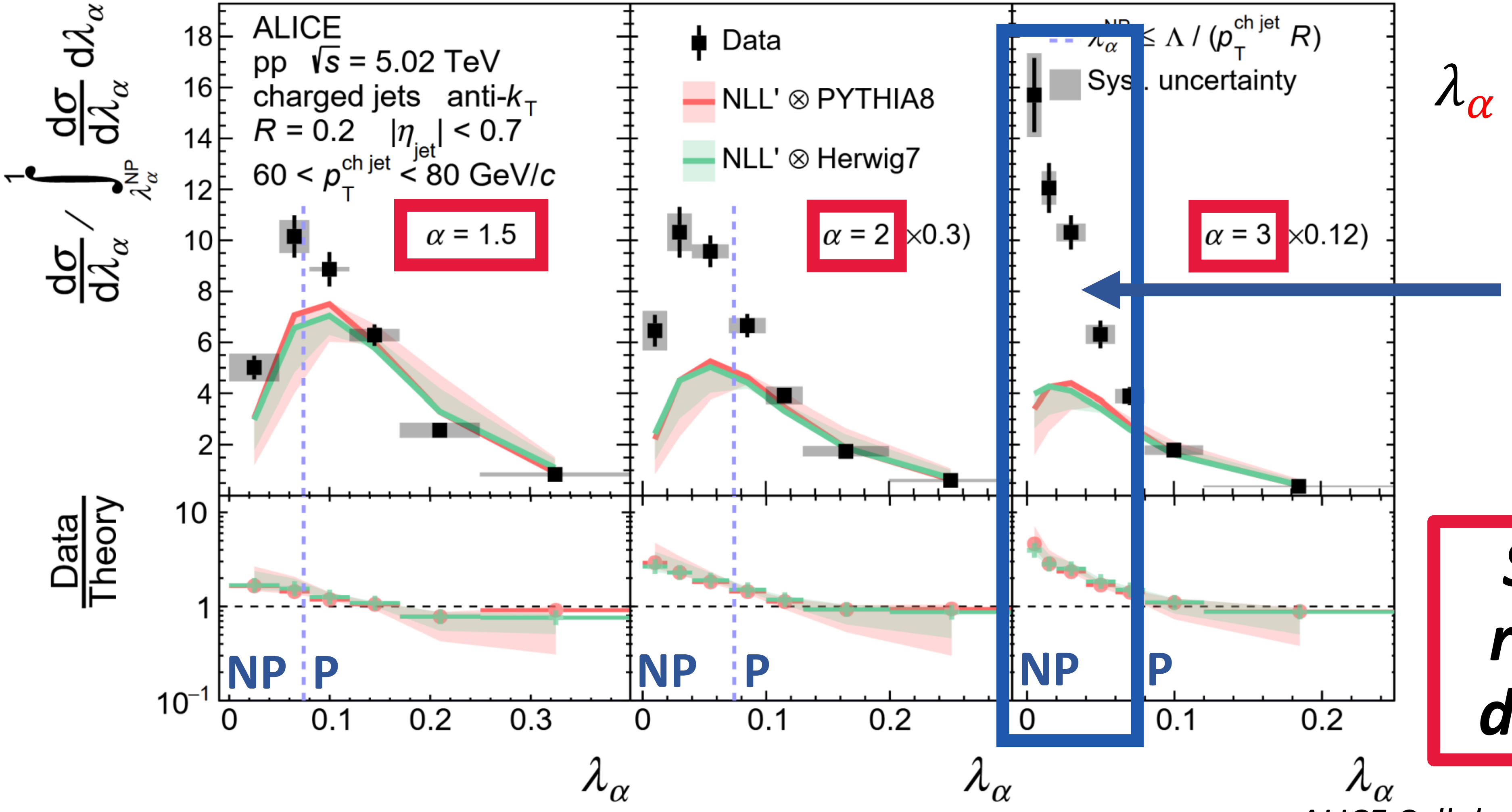

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Breakdown of predictions at larger values of α

Soft, wide angle radiation is more difficult to predict

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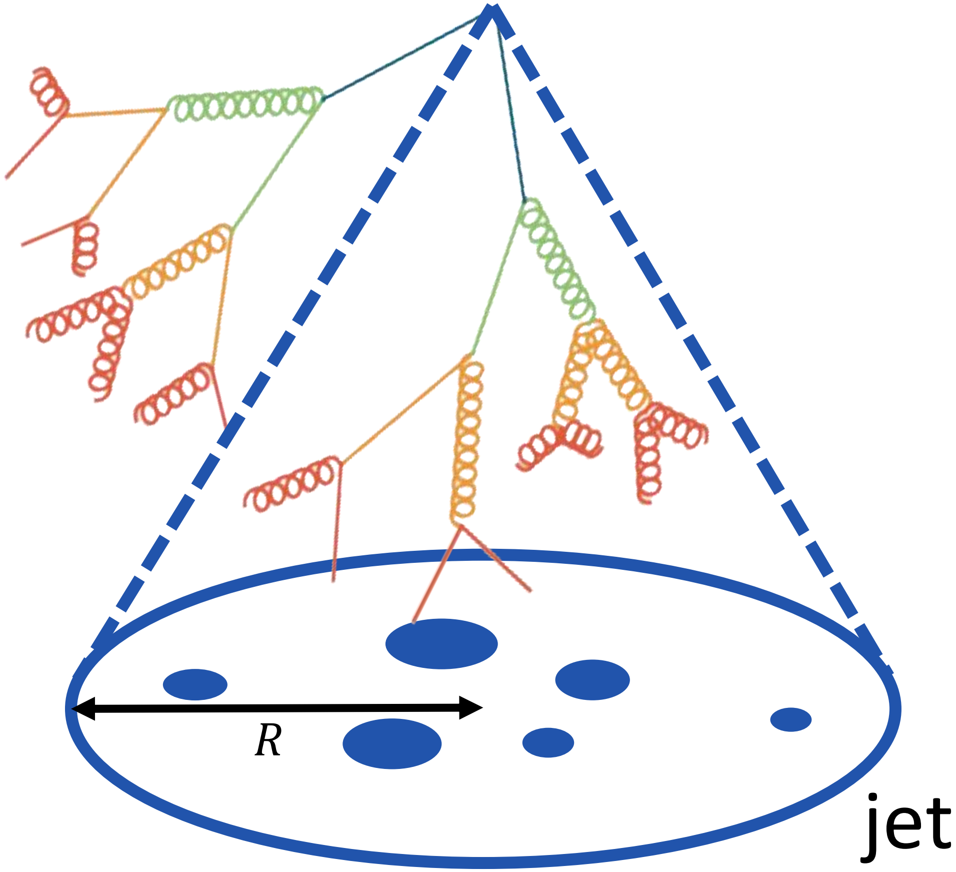
Going deeper: jet grooming



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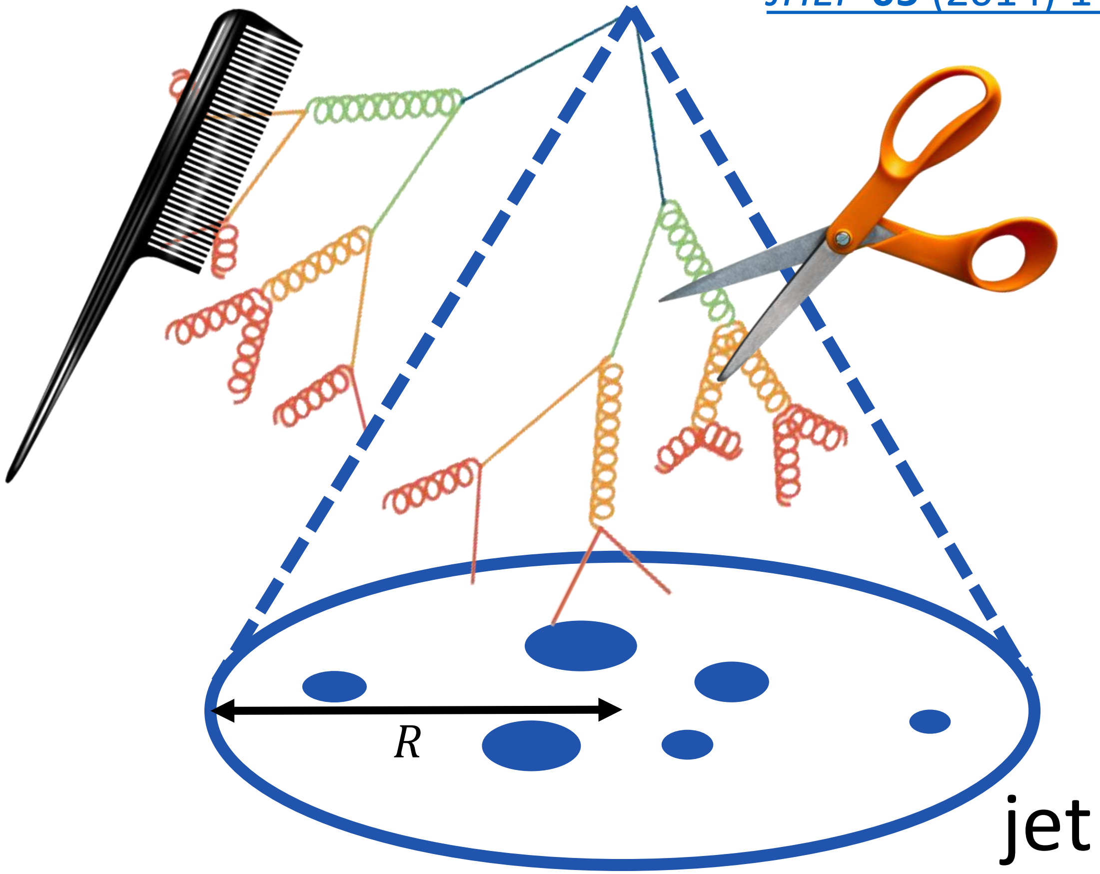
Larkoski, Marzani, Soyez, Thaler
[*JHEP* **05** (2014) 146]



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Larkoski, Marzani, Soyez, Thaler
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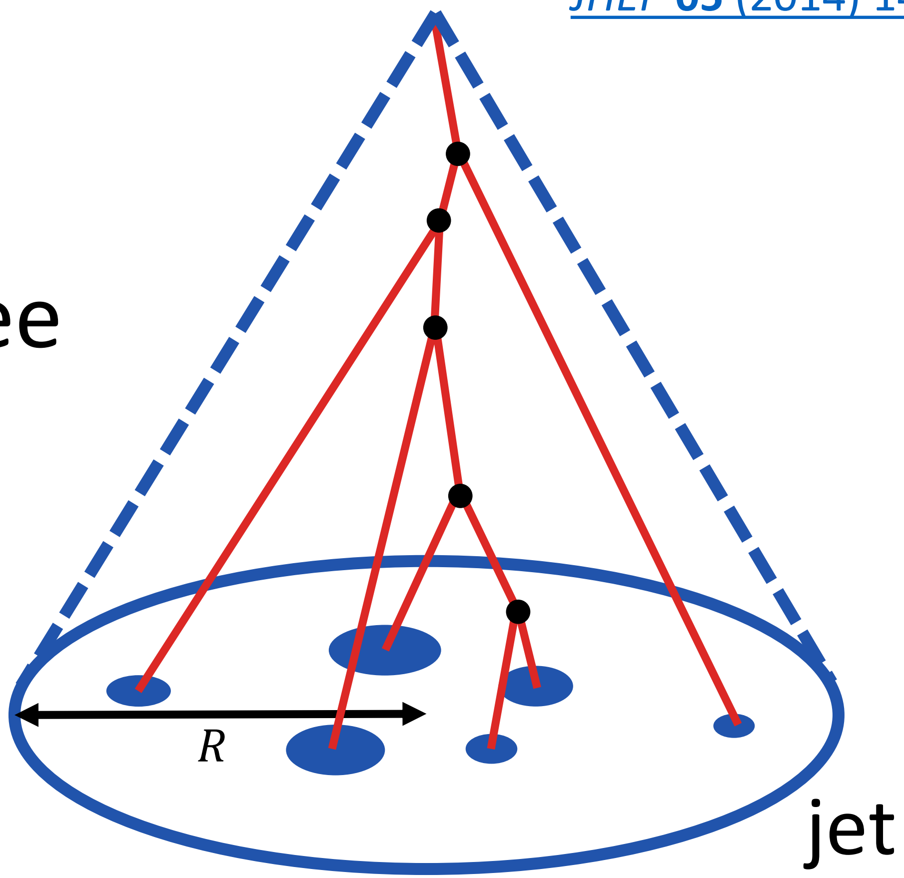

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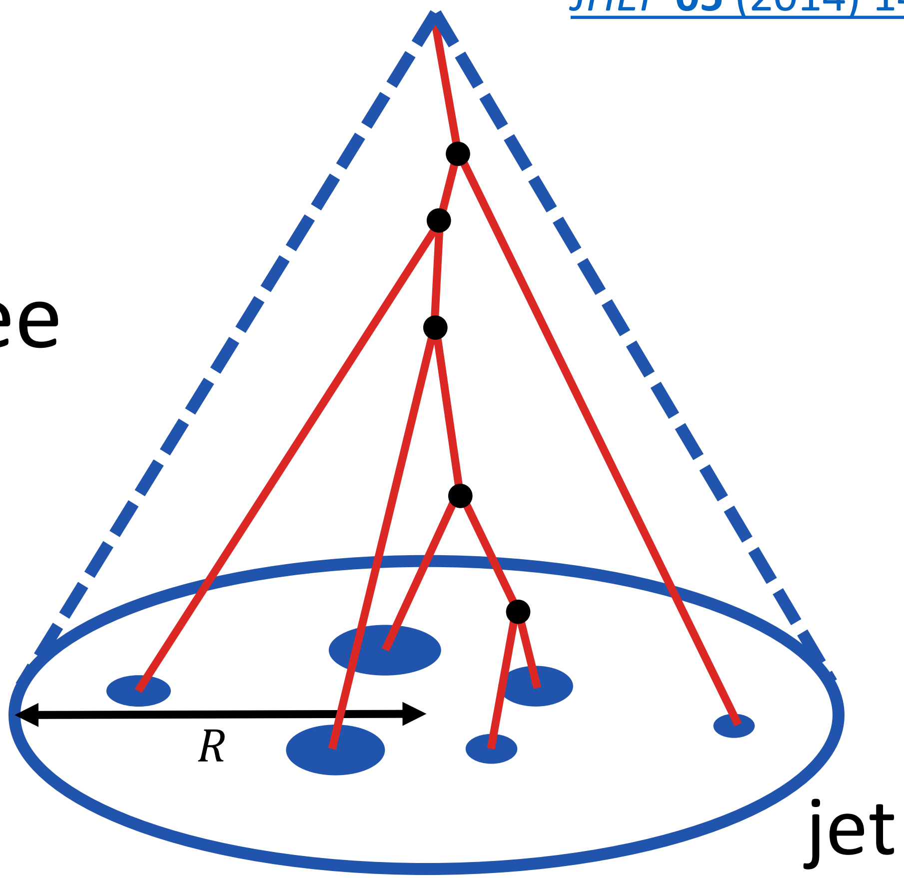
- Trim branches until the **Soft Drop condition** is satisfied:

$$\boxed{\frac{\min(p_{\mathrm{T}1}, p_{\mathrm{T}2})}{p_{\mathrm{T}1} + p_{\mathrm{T}2}} \overset{?}{>} z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}}$$

Larkoski, Marzani, Soyez, Thaler
JHEP **05** (2014) 146



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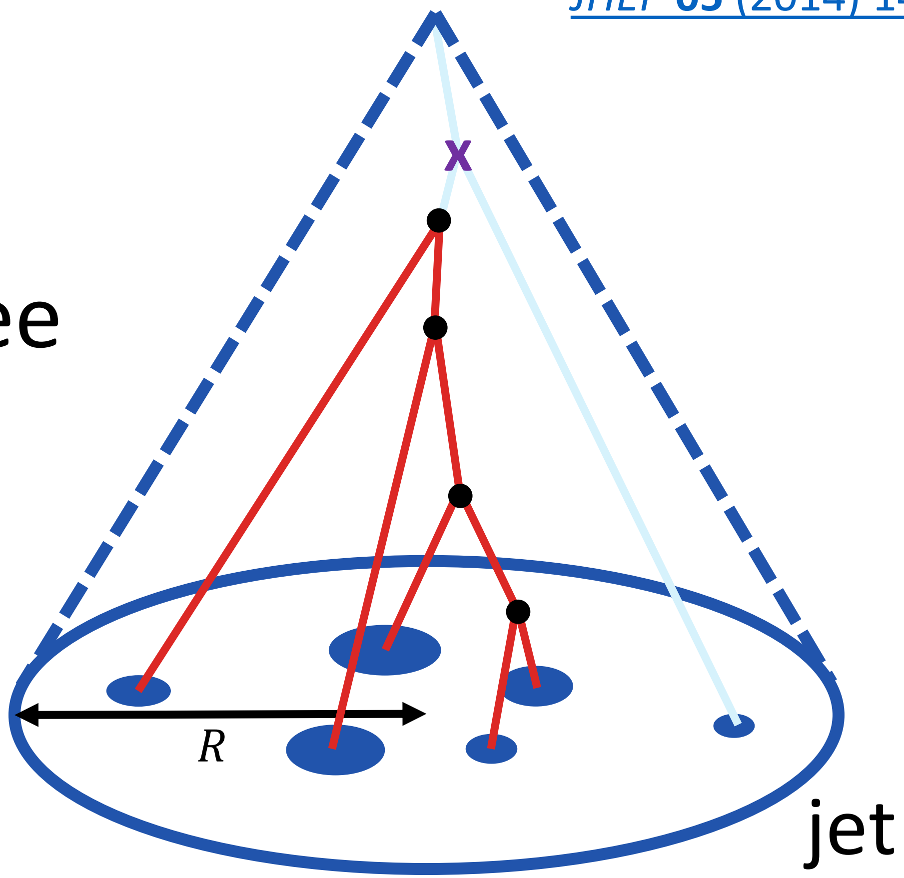

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Larkoski, Marzani, Soyez, Thaler
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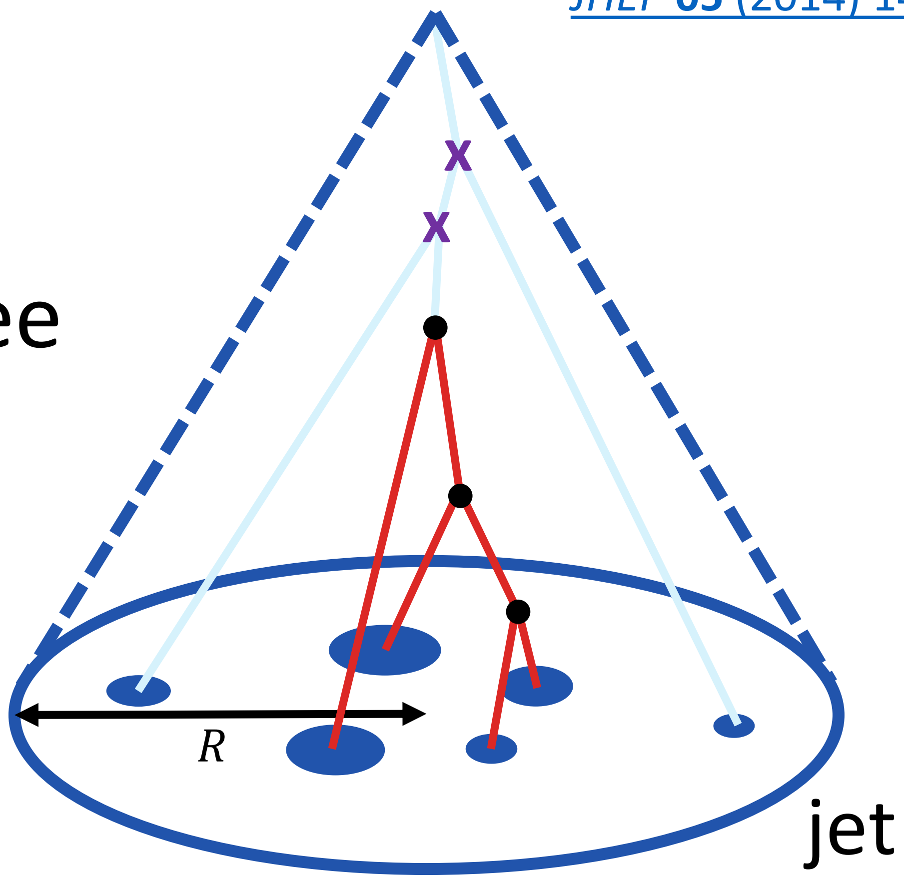

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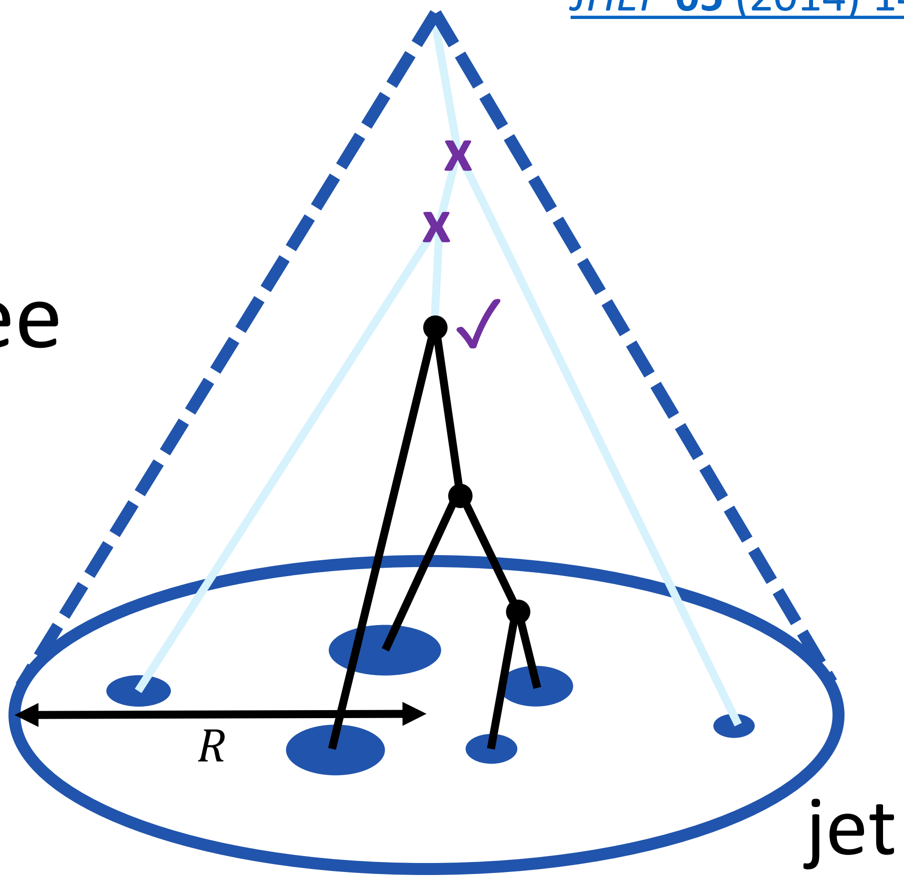
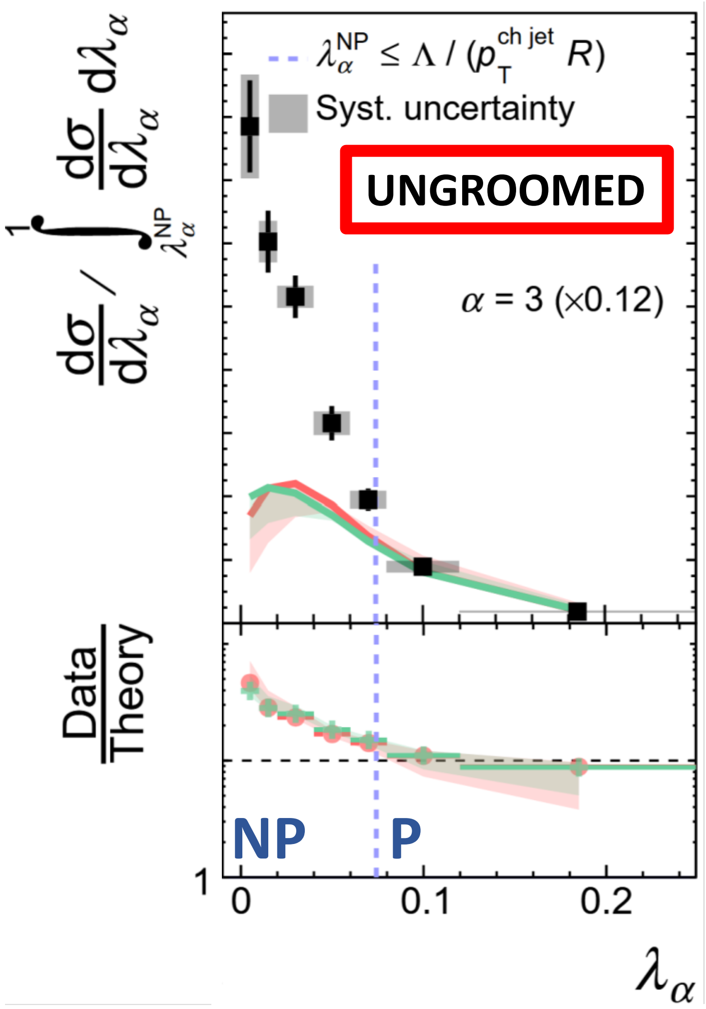
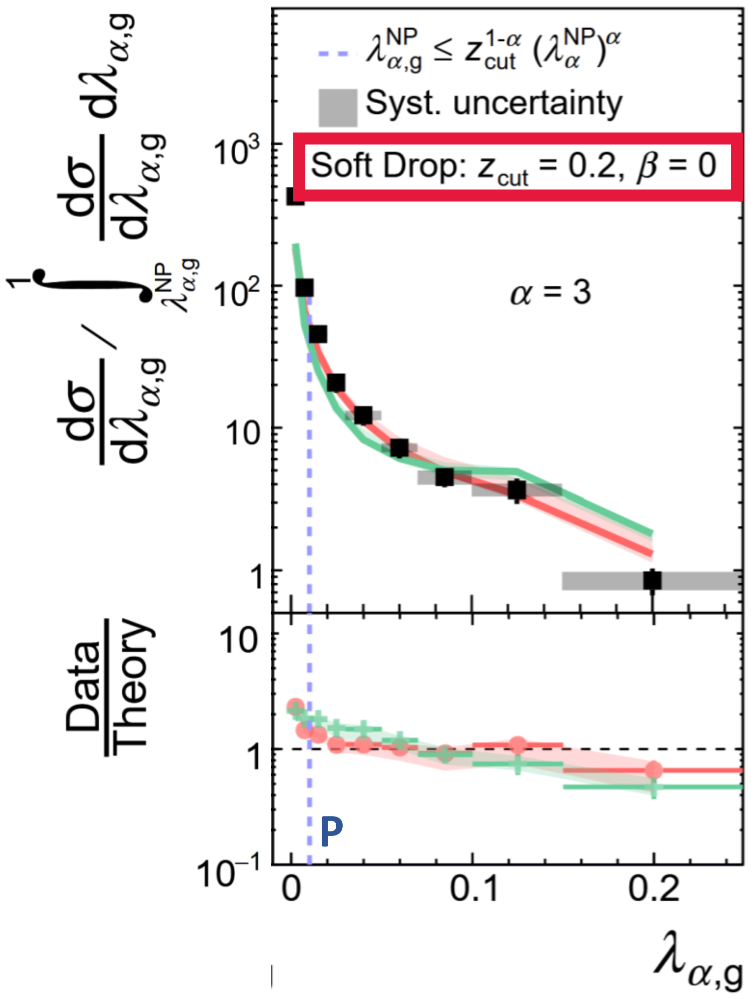


Groomed jet angularities

- **IRC-safe jet observables** dependent on constituent p_{T} and **angle**





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

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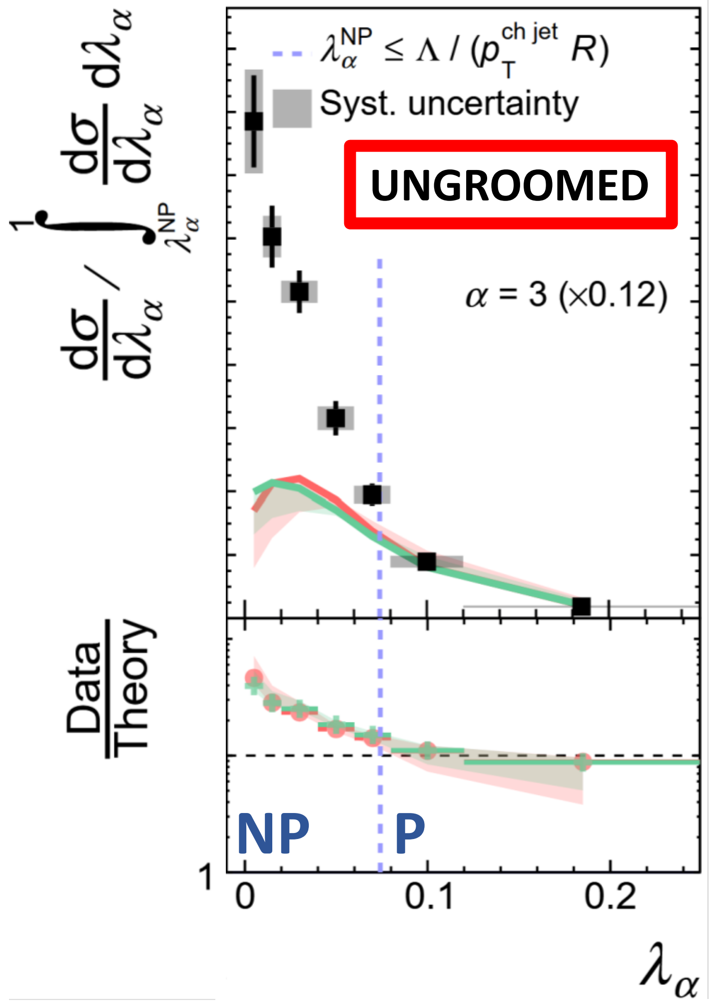

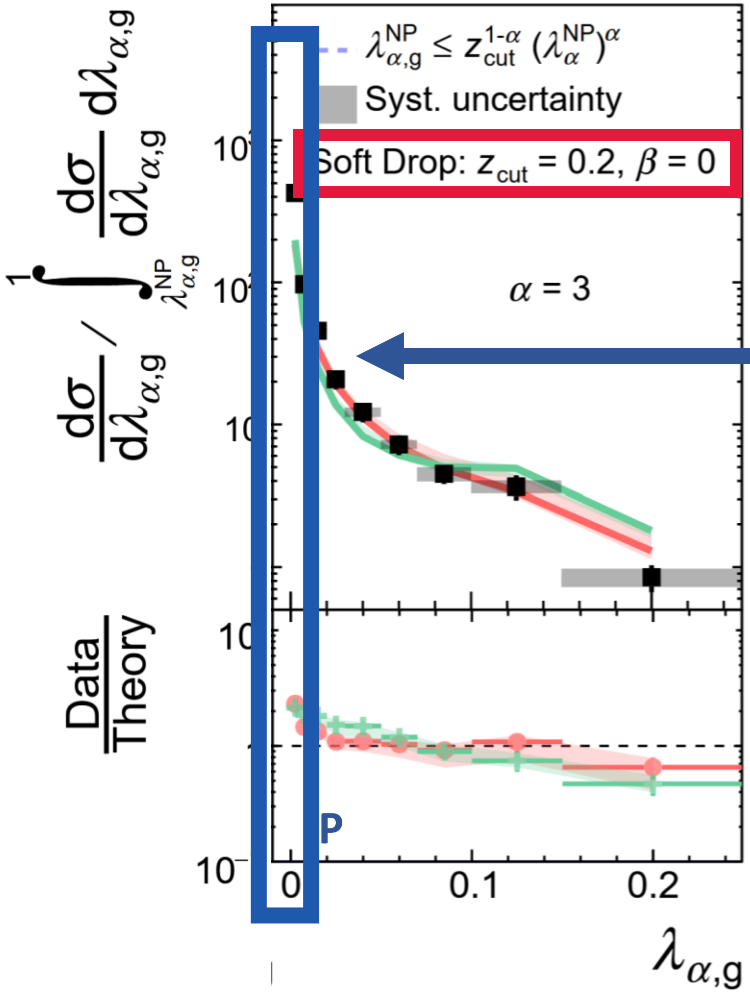

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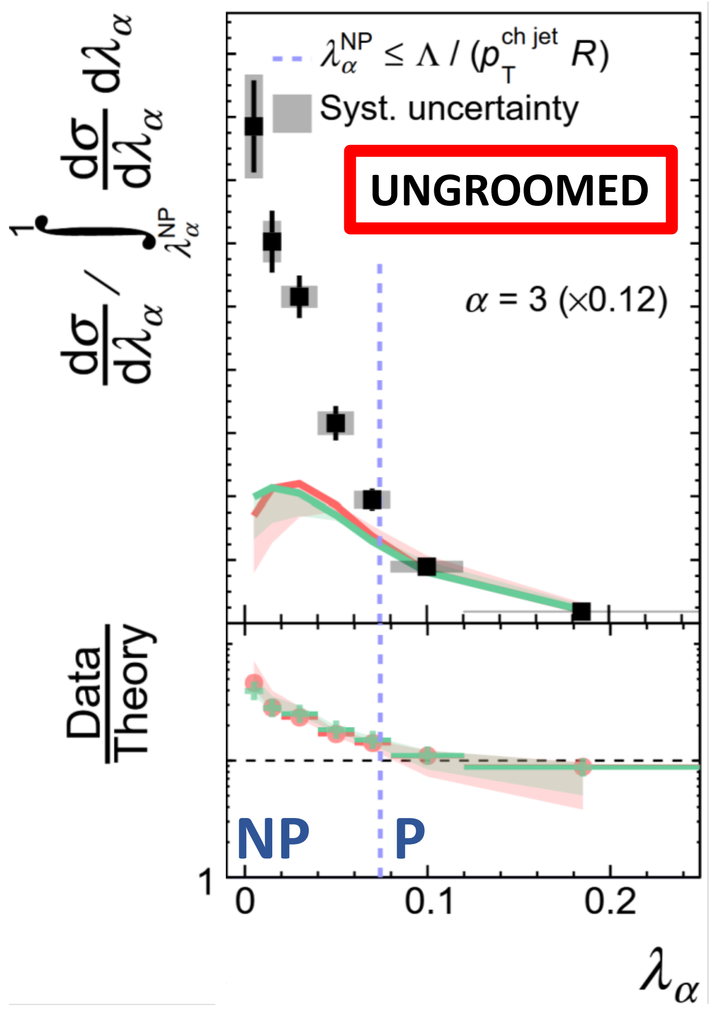

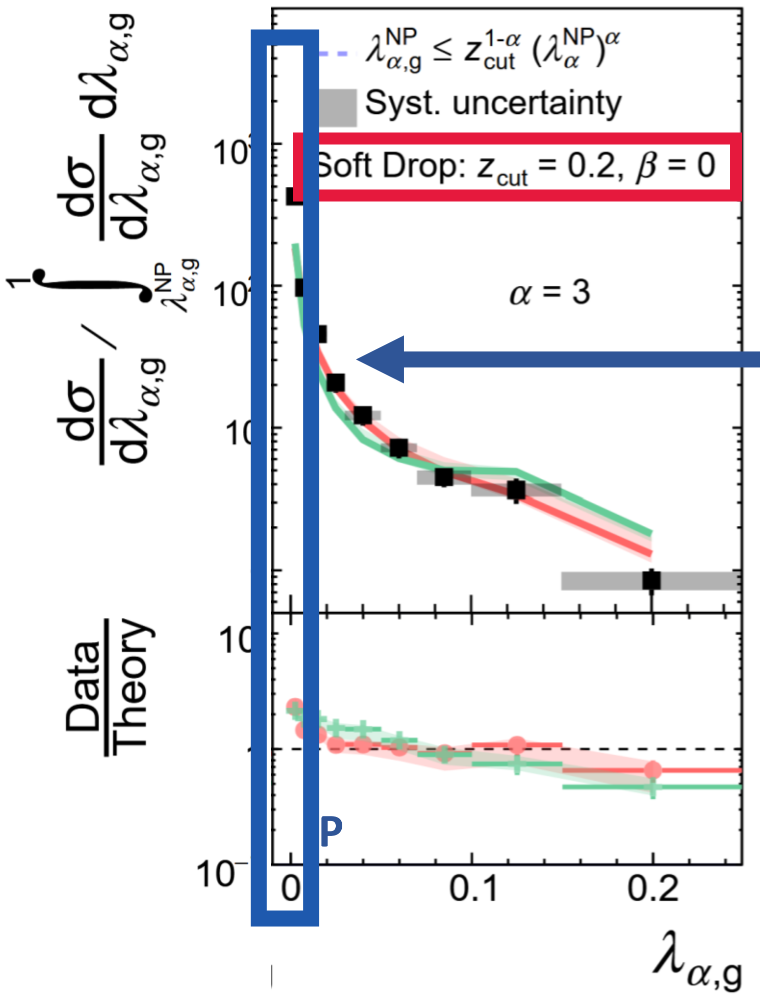

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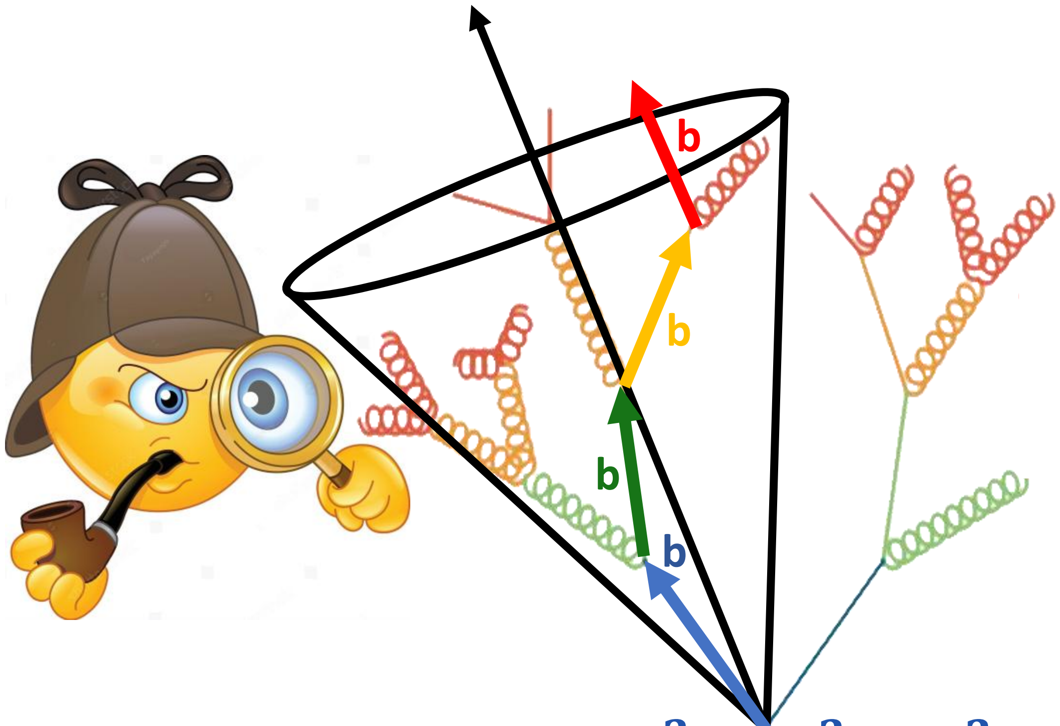
Nonperturbative region is reduced

Grooming improves constraints on perturbative QCD

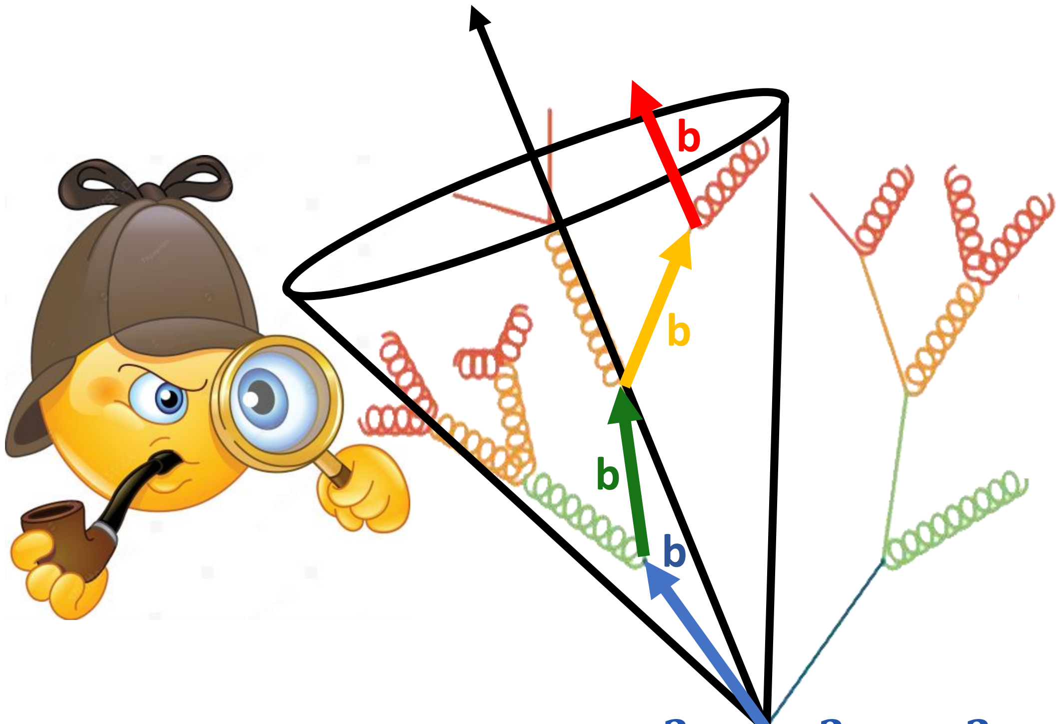
Mass & virtuality dependence



$$Q^2 = E^2 - p^2$$

Mass & virtuality dependence

- How does the **jet formation** depend on the **mass m_b** and the **virtuality Q^2** of its initiating parton?



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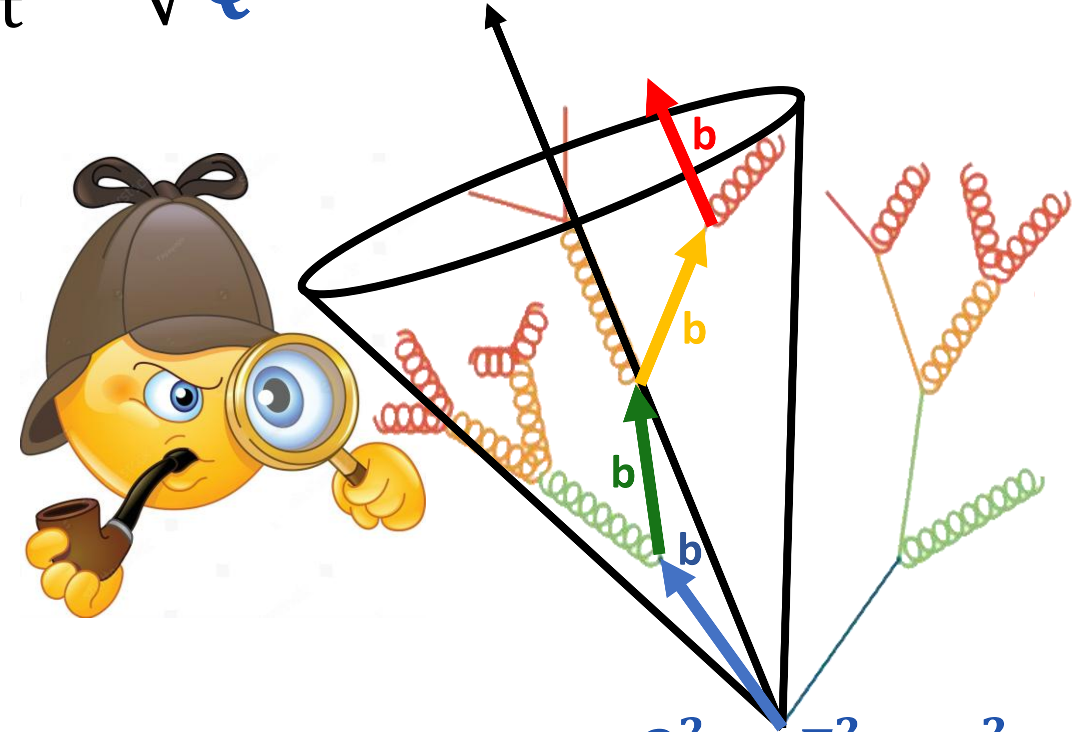

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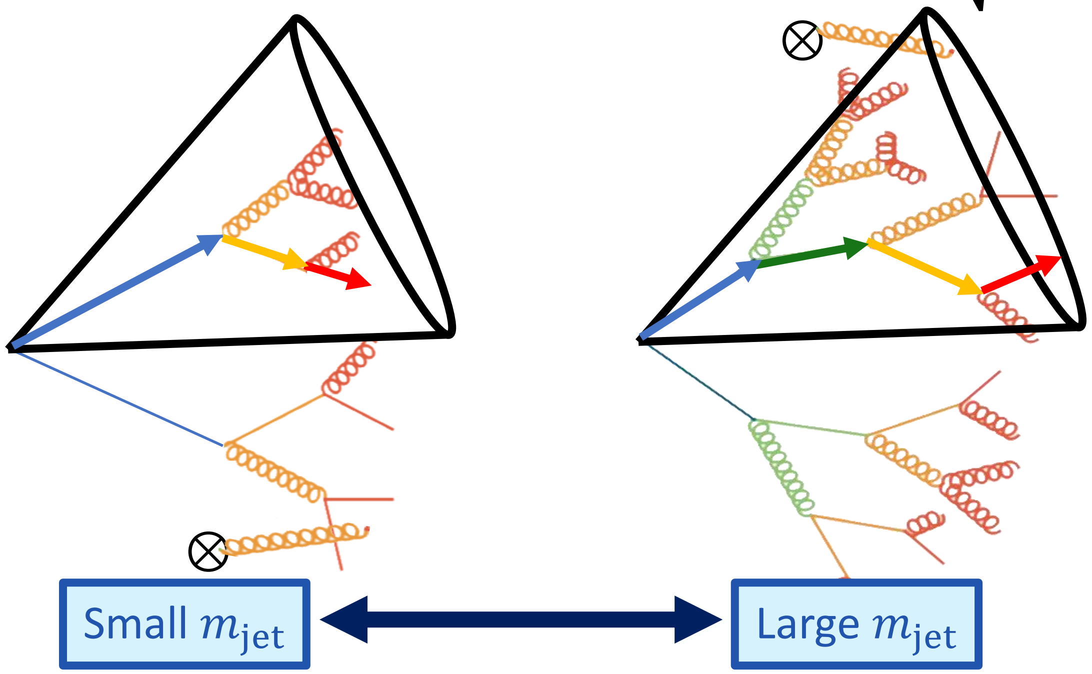
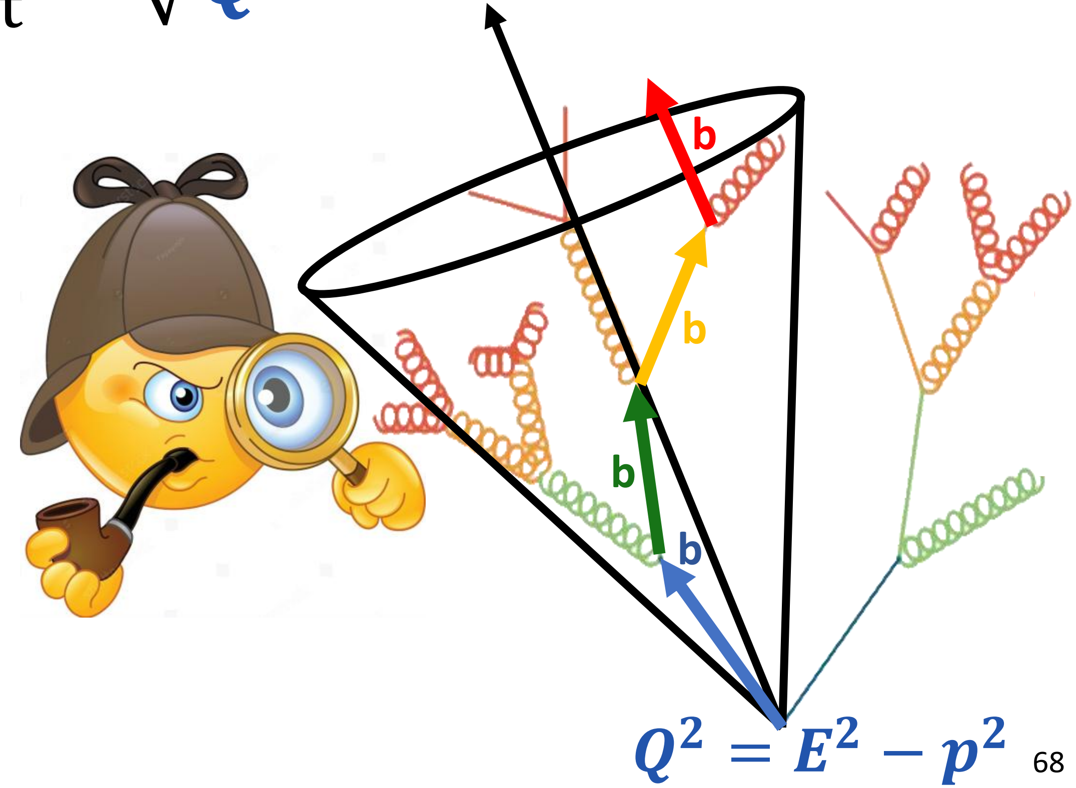
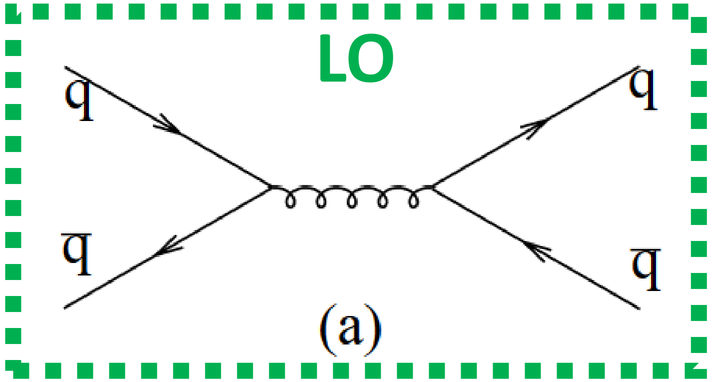




Flavor definition problem



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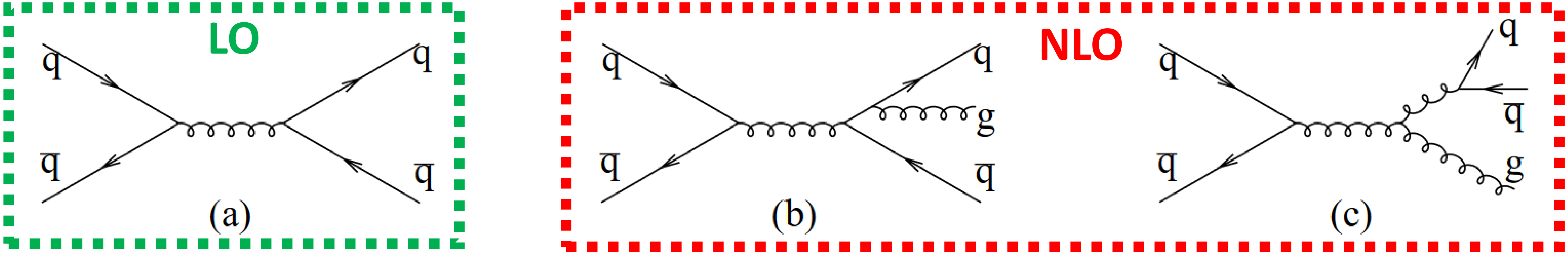

- **Cannot separate $q\bar{q} \rightarrow q\bar{q}g$ corrections to gg and $q\bar{q}$ at Born level**

Banfi, Salam, Zanderighi
EPJC 47 (2006) 113-124

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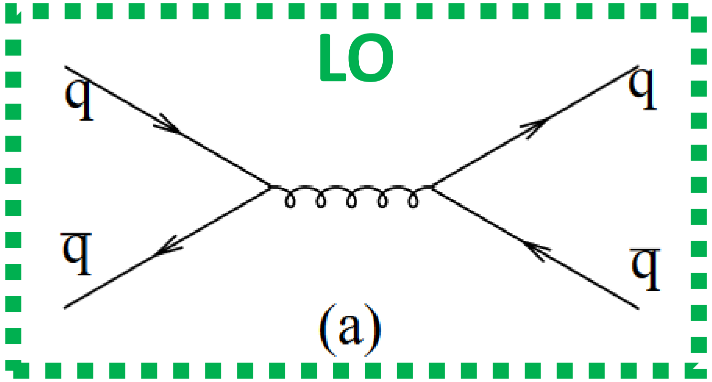

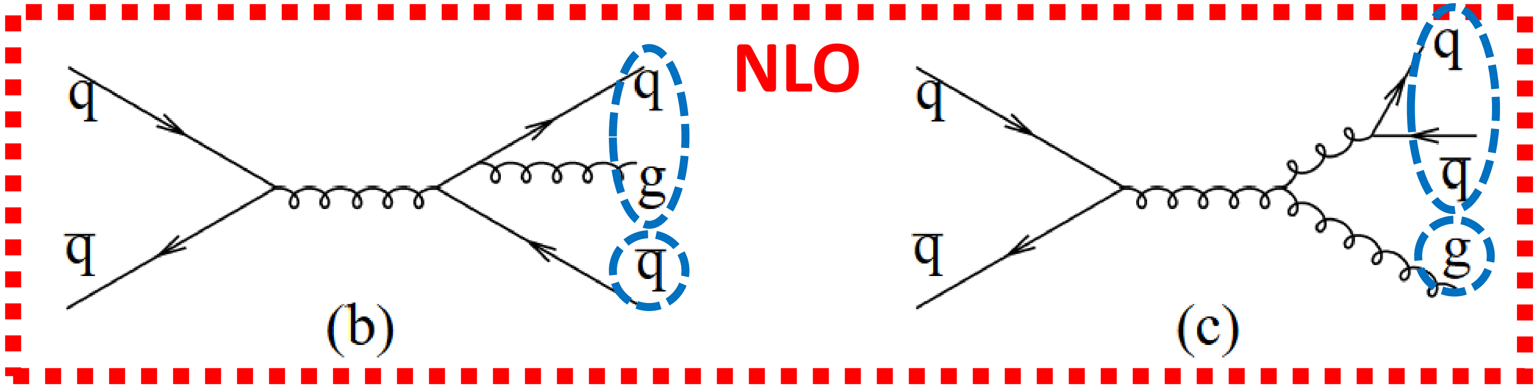

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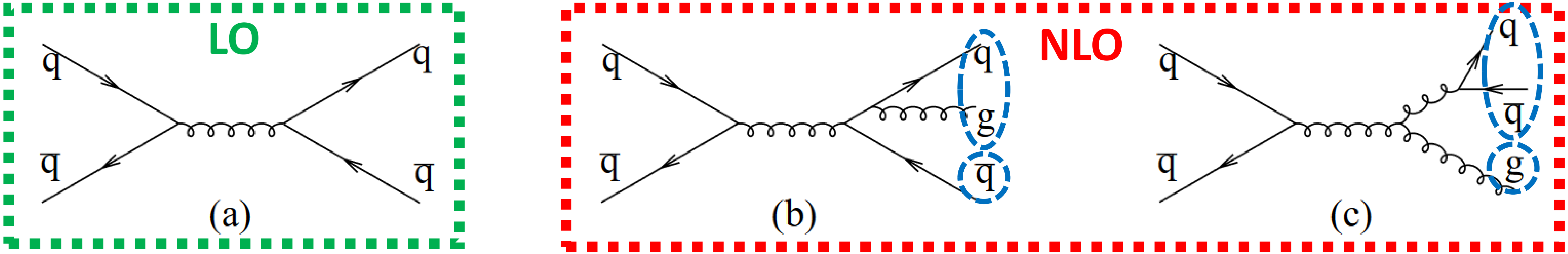

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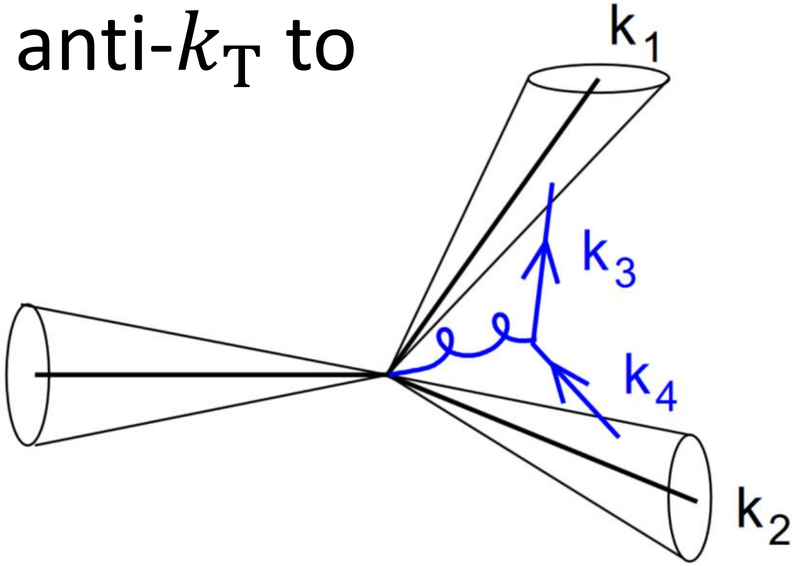
- **But soft gluons ruin this at NNLO**



Banfi, Salam, Zanderighi
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Theoretically safe flavor tagging

- Traditional flavor tagging is **<u>not well-defined past NLO</u>**

Banfi, Salam, Zanderighi
[*Eur. Phys. J.* **C47** (2006) 113-124]

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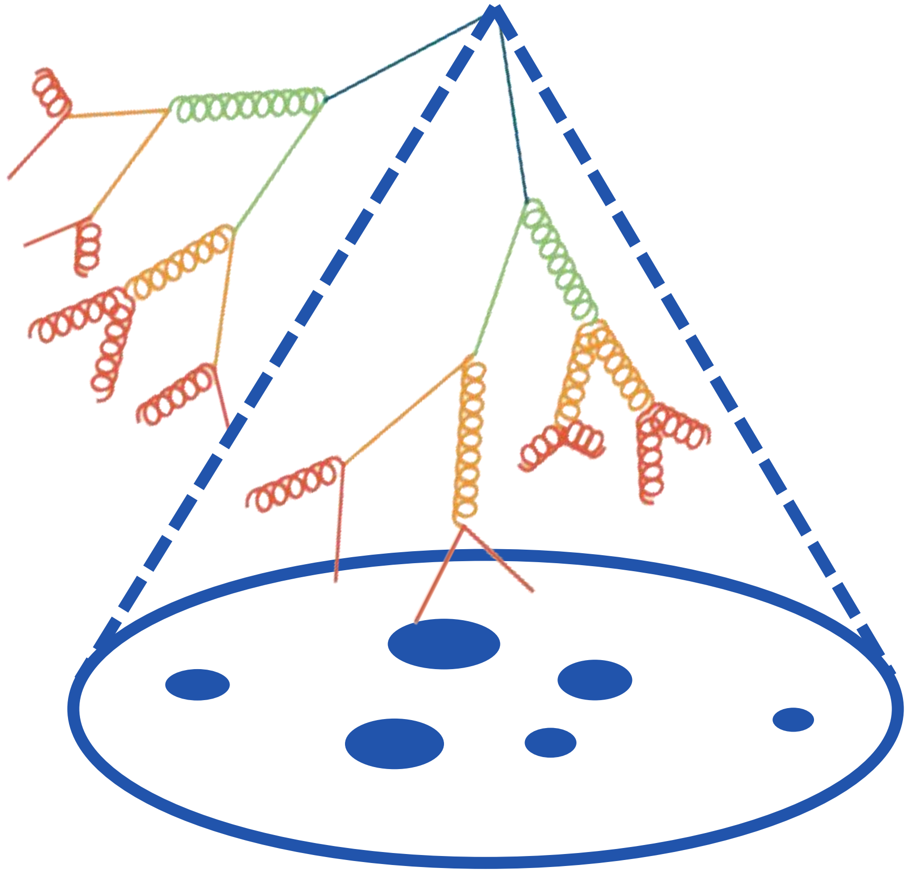

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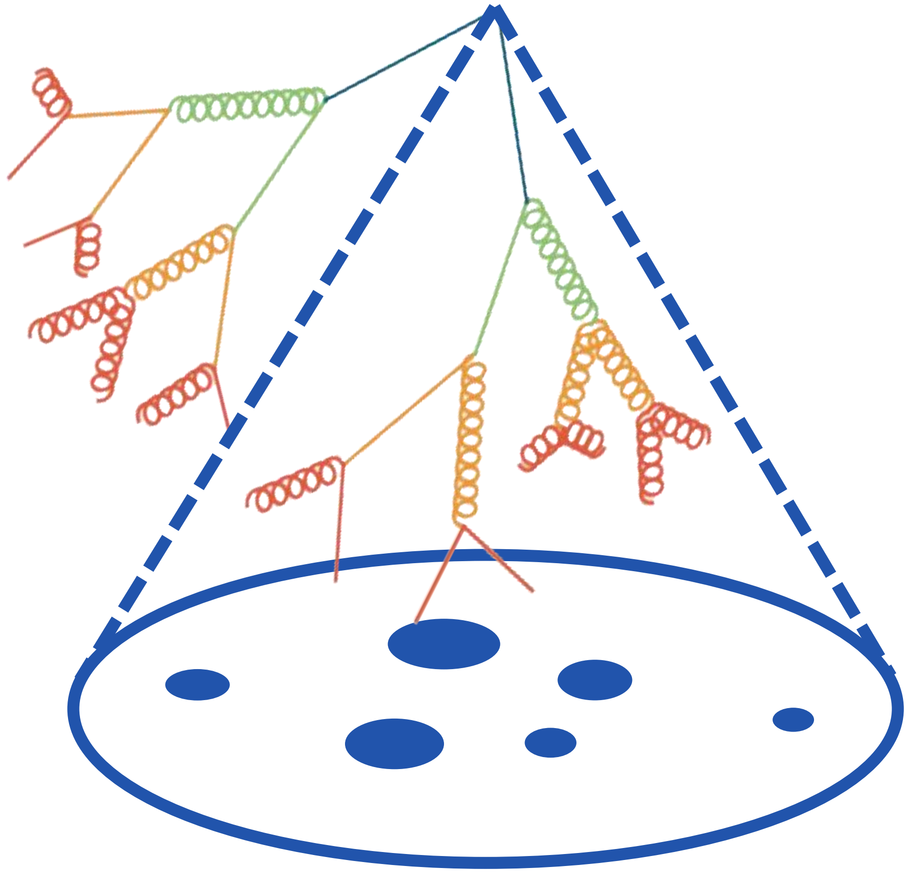
- Utilize new **“Winner-Take-All”** flavor-tagging algorithm

Caletti, Larkoski, Marzani, Reichelt
[*JHEP* **10** (2022) 158]



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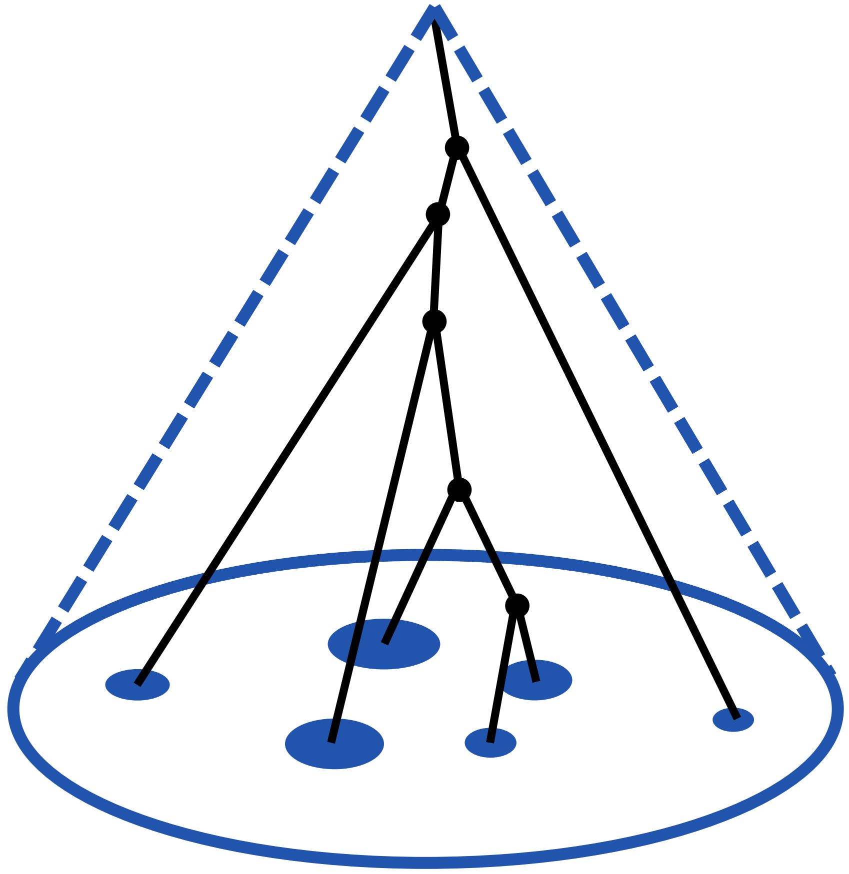
JHEP **10** (2022) 158

  - **Recluster** into angularly-ordered tree



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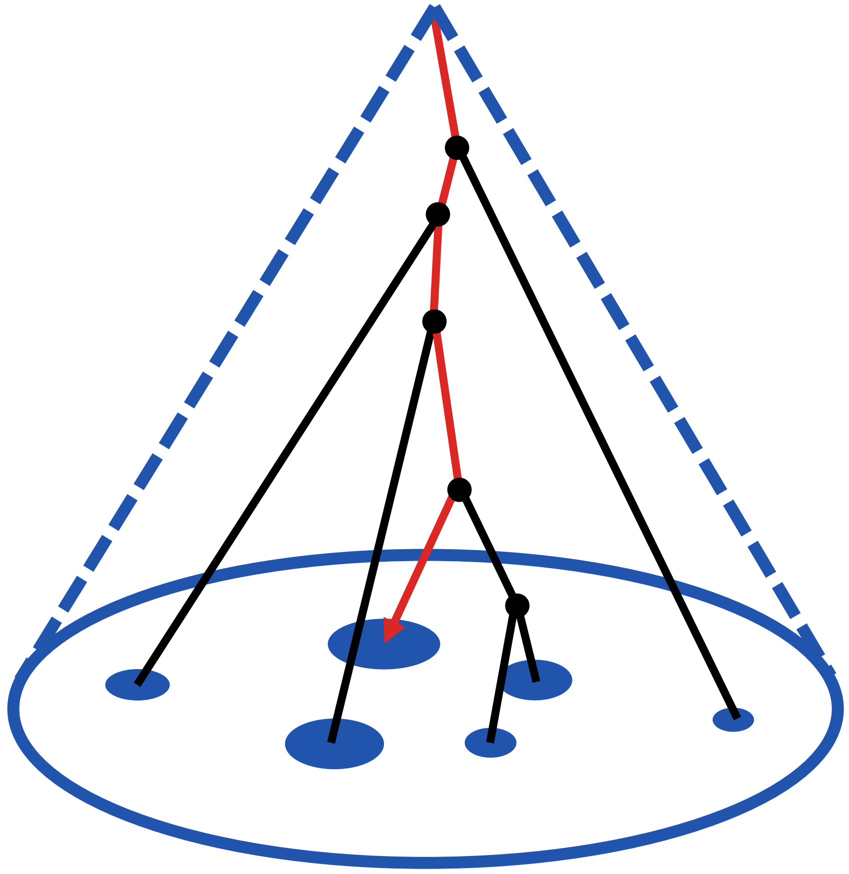
  - **Recluster** into angularly-ordered tree
  - **Follow** the hardest branch



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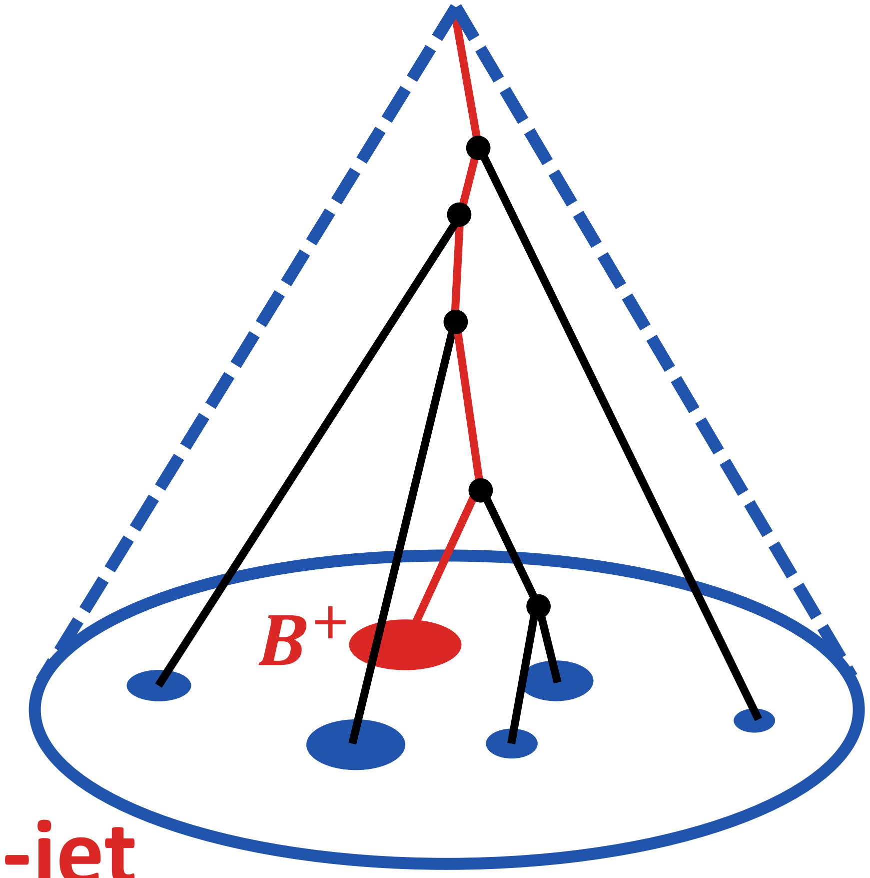
  - **Recluster** into angularly-ordered tree
  - **Follow** the hardest branch
  - **Define** flavor by particle along the axis



***b*-jet**

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Caletti, Larkoski, Marzani, Reichelt
[*JHEP* **10** (2022) 158]

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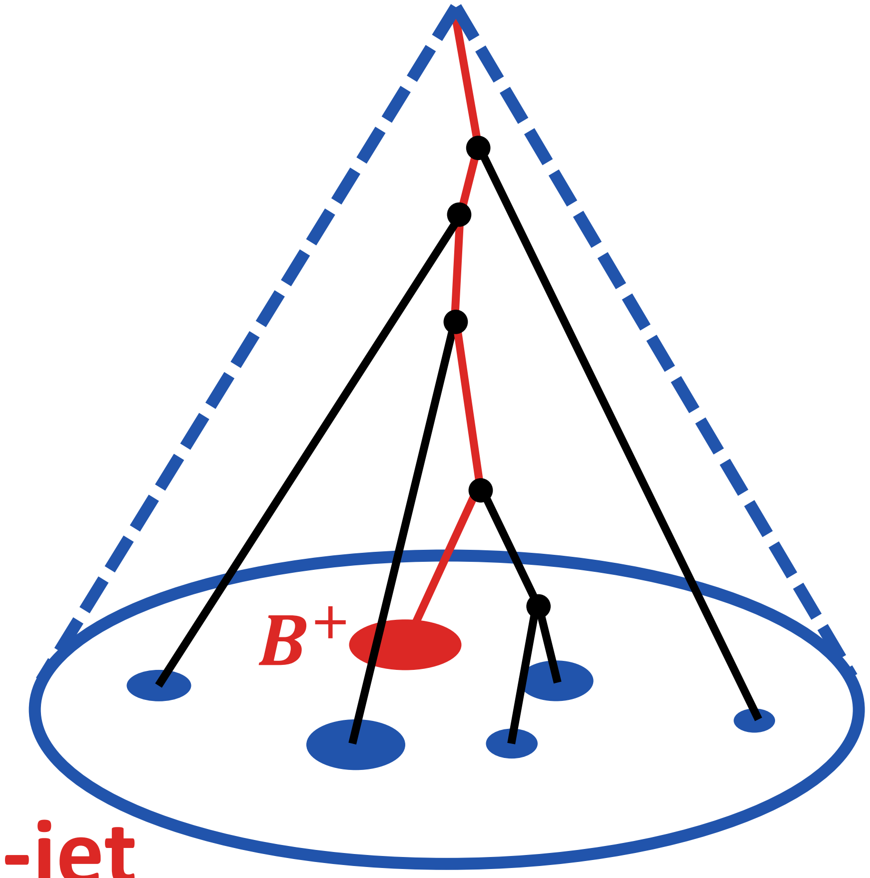
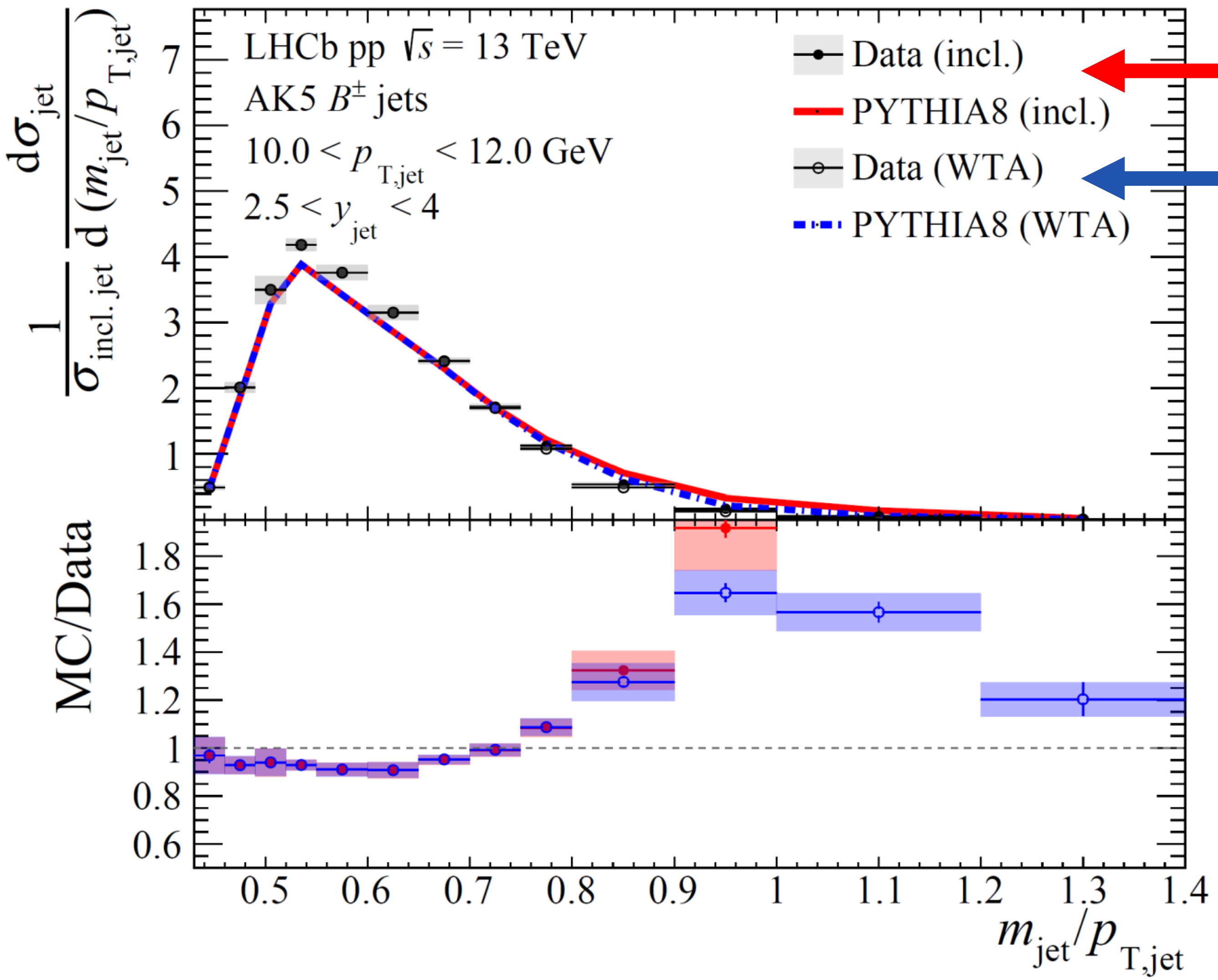
  - **Define** flavor by particle along the axis

- **Calculable to any perturbative order!**



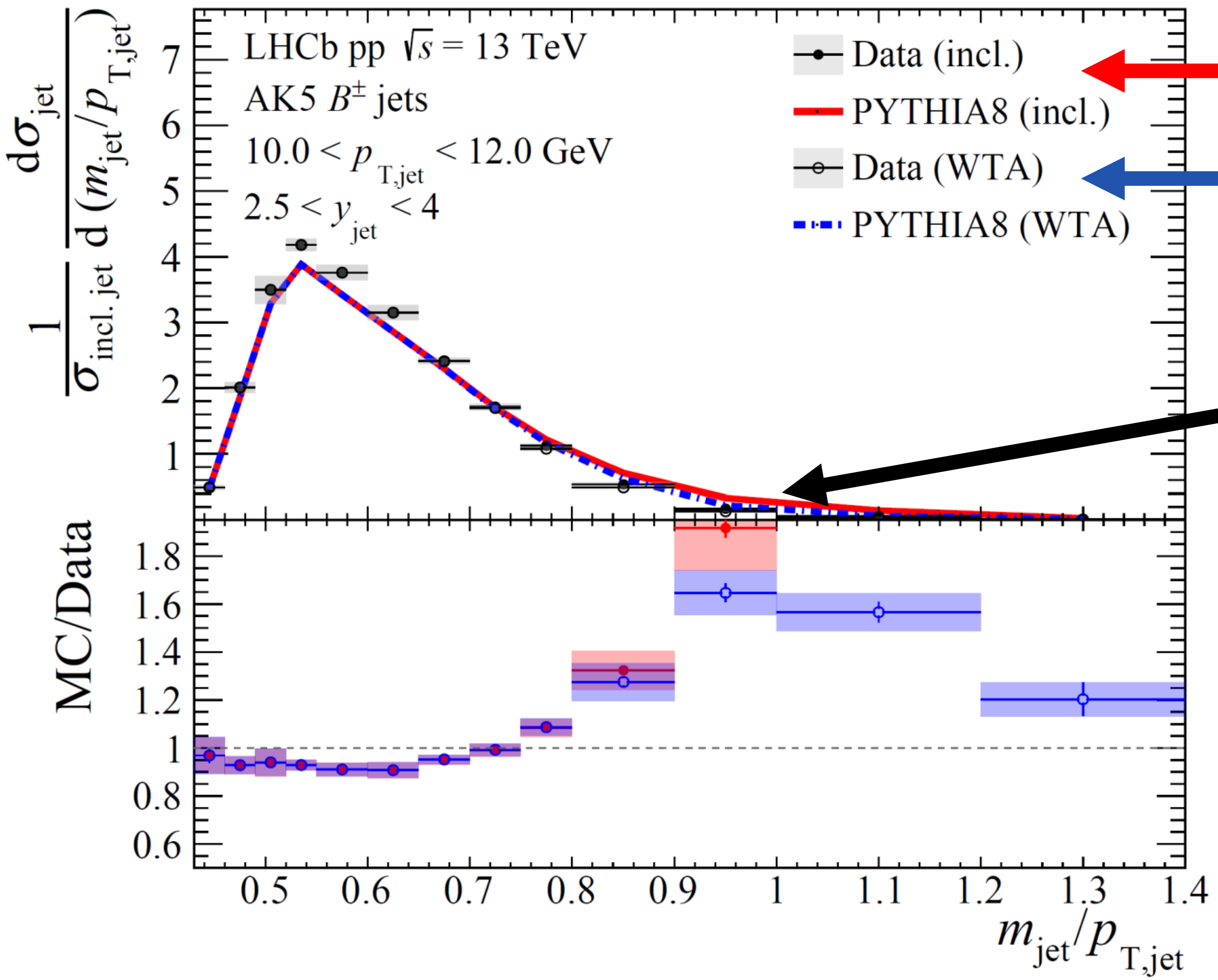
b-jet invariant mass



No WTA tagging requirement

WTA tagging required

b-jet invariant mass



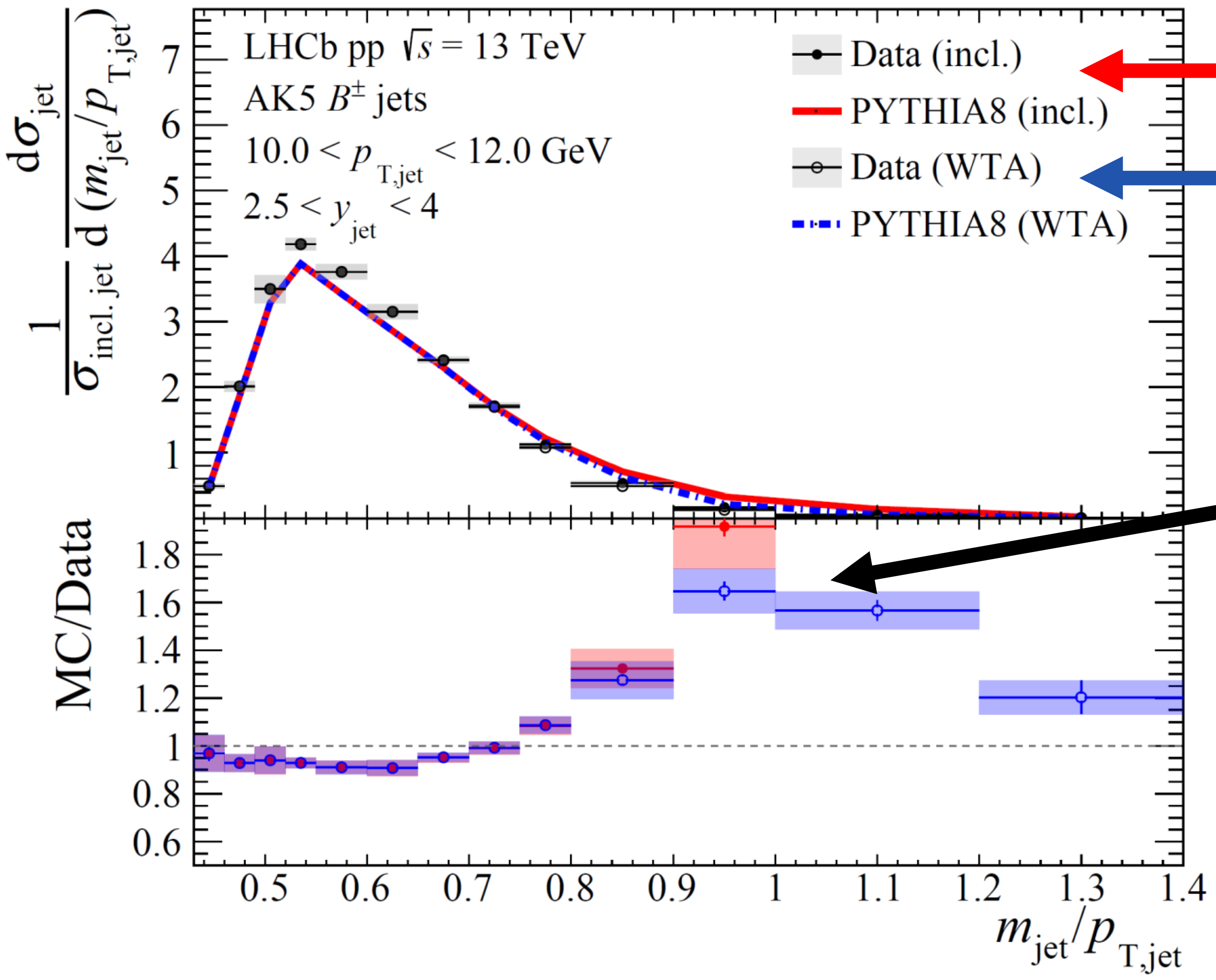
No WTA tagging requirement

WTA tagging required

Slight reduction in tails

These entries are coming primarily from $g \rightarrow b\bar{b}$

b-jet invariant mass



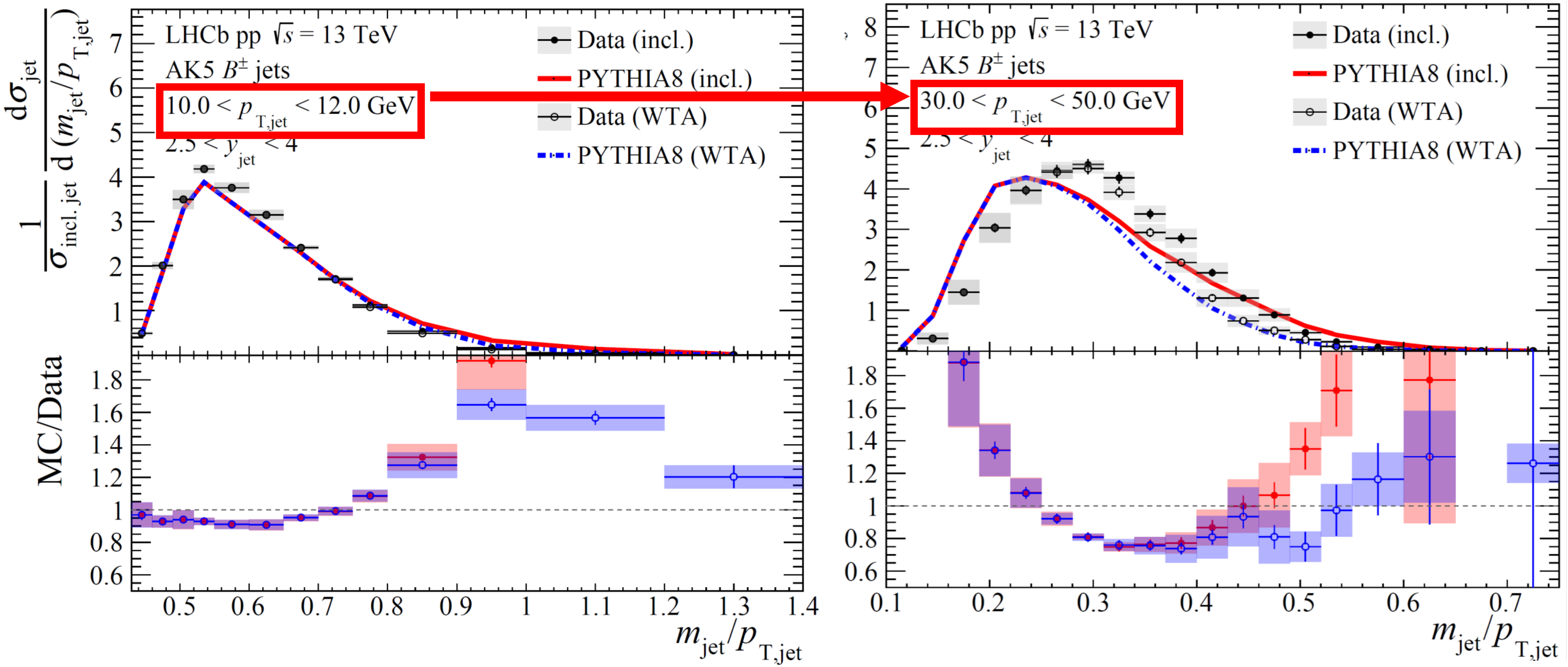
No WTA tagging requirement

WTA tagging required

Significant deviations from Pythia 8.186 MC

Worse for no-WTA: **Pythia splitting function poorly describes $b\bar{b}$ production?**

b-jet invariant mass



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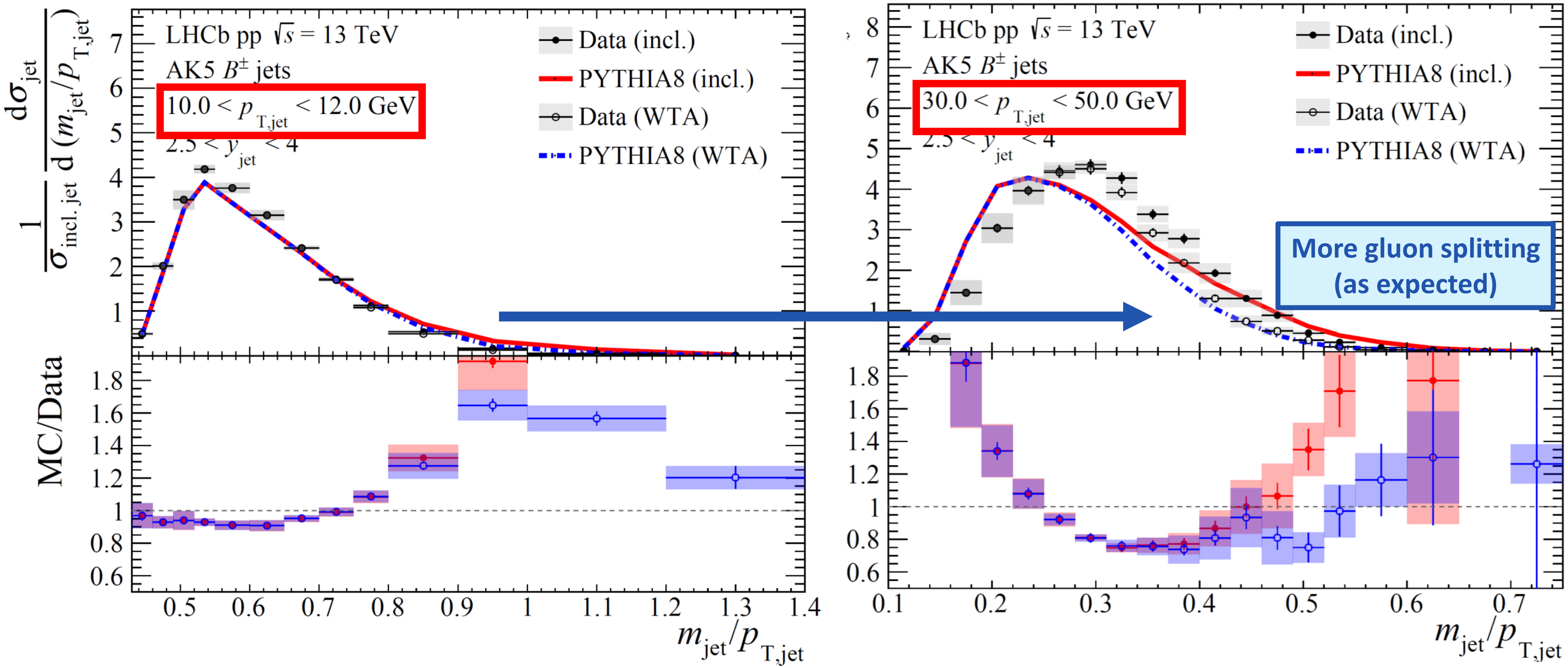

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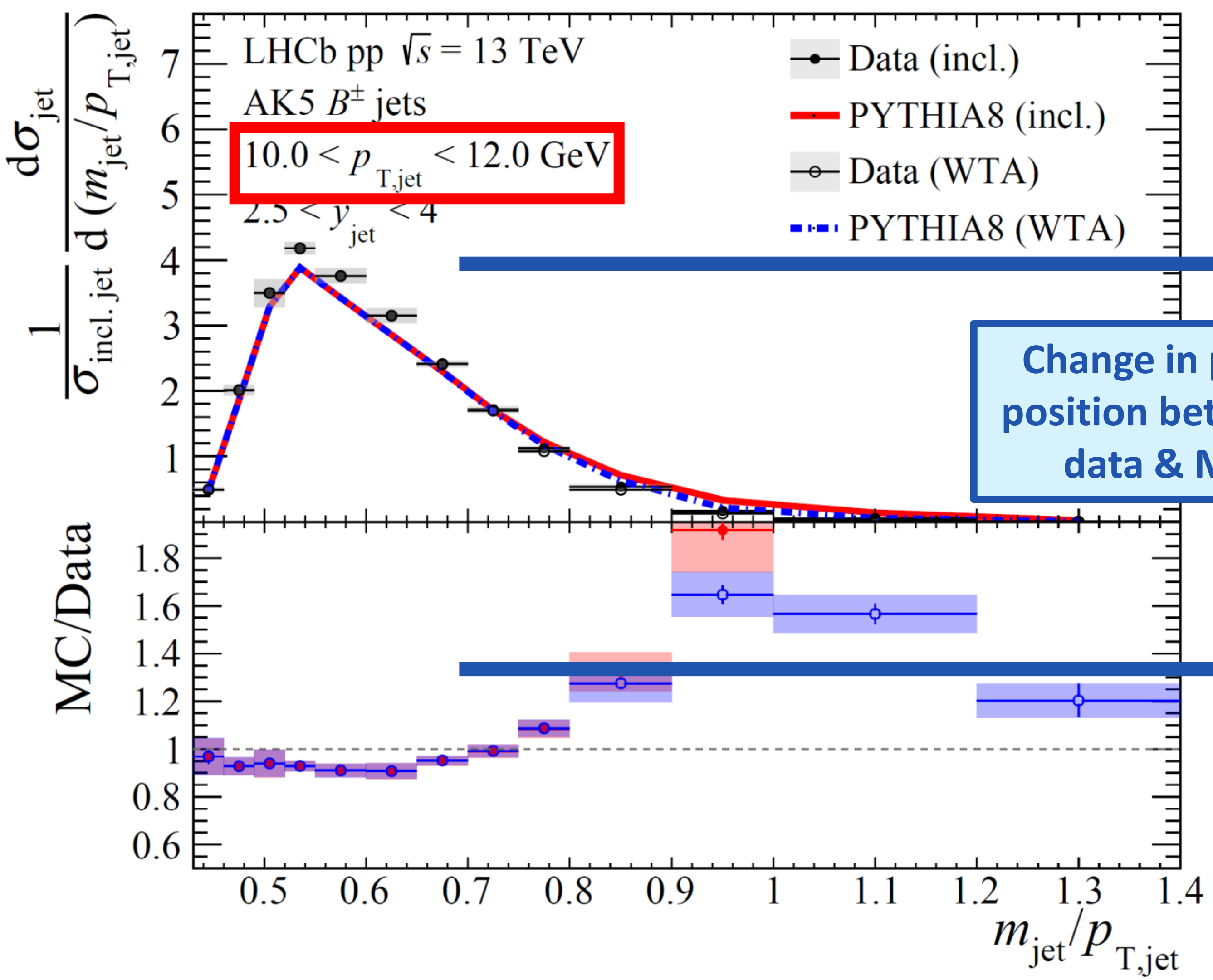

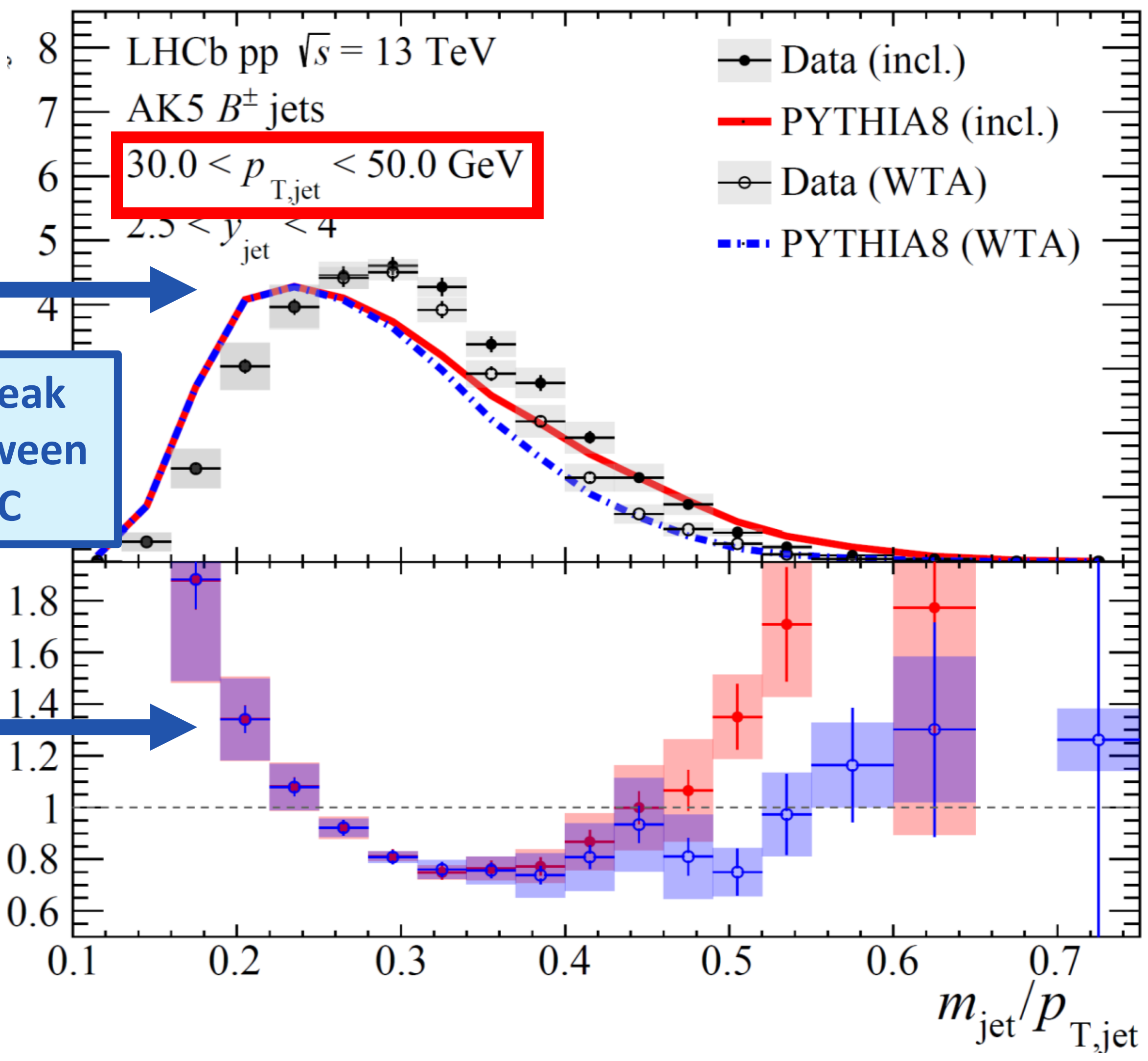

Change in peak position between data & MC

 arXiv:2505.11955 (accepted to *Phys. Lett. B.*)

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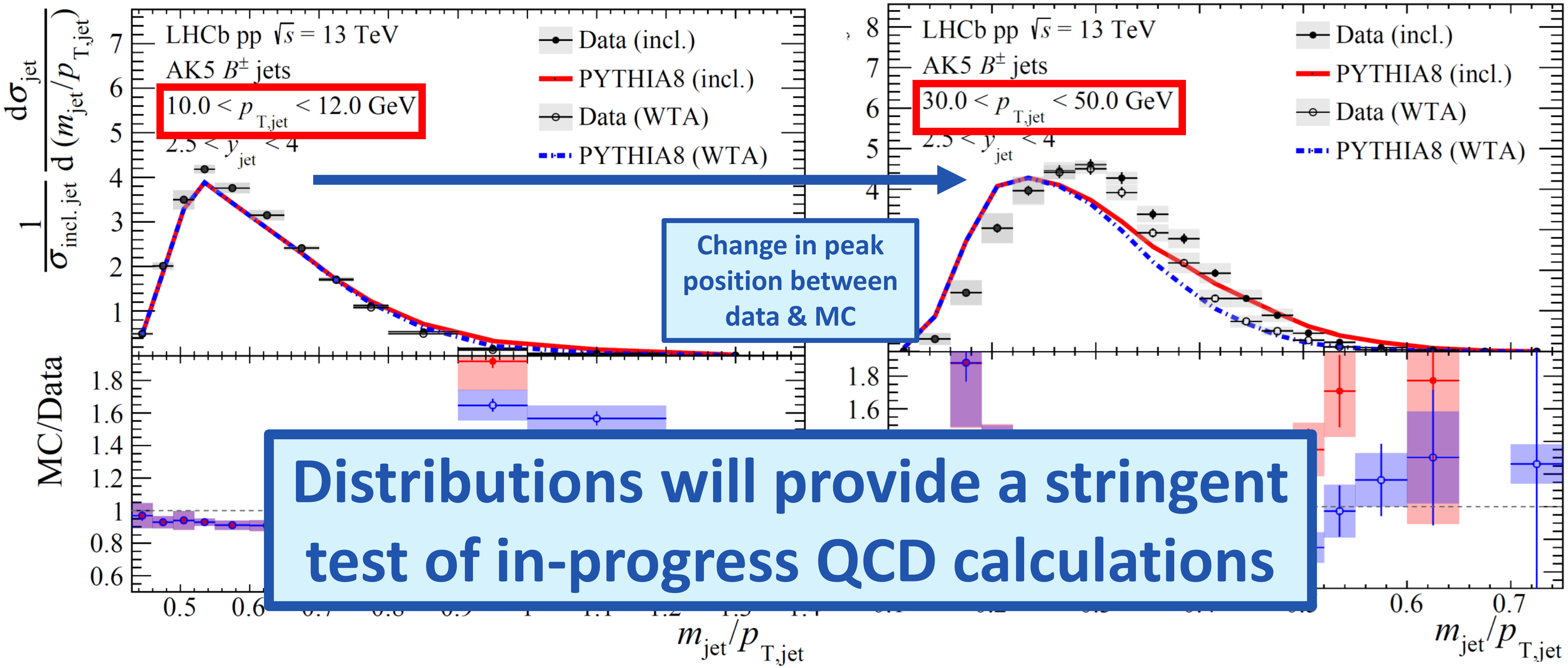
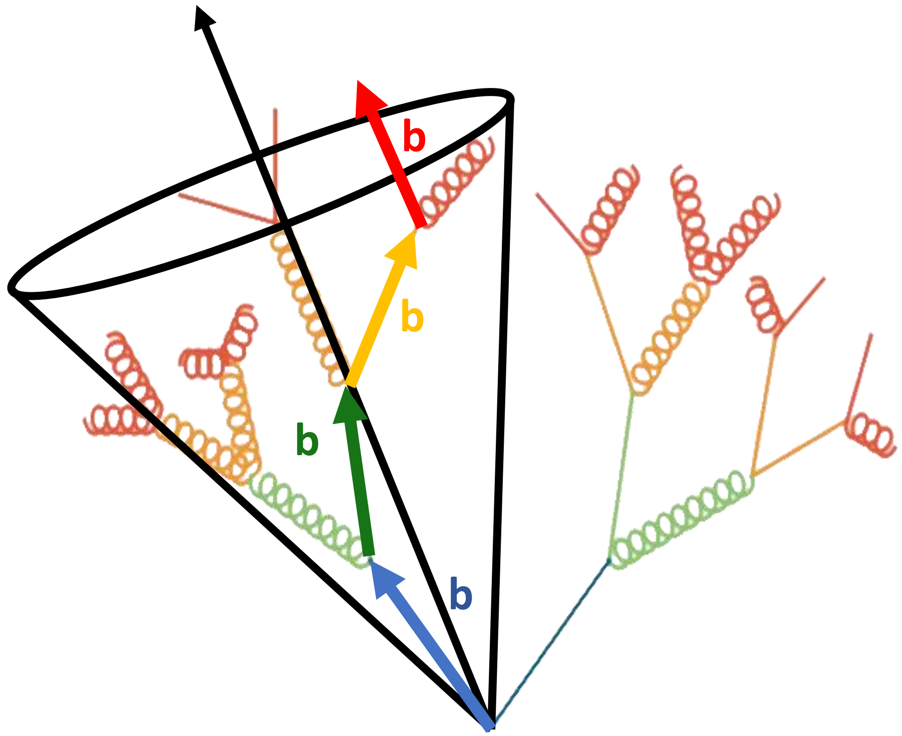


Distributions will provide a stringent test of in-progress QCD calculations

Mass effects on fragmentation?



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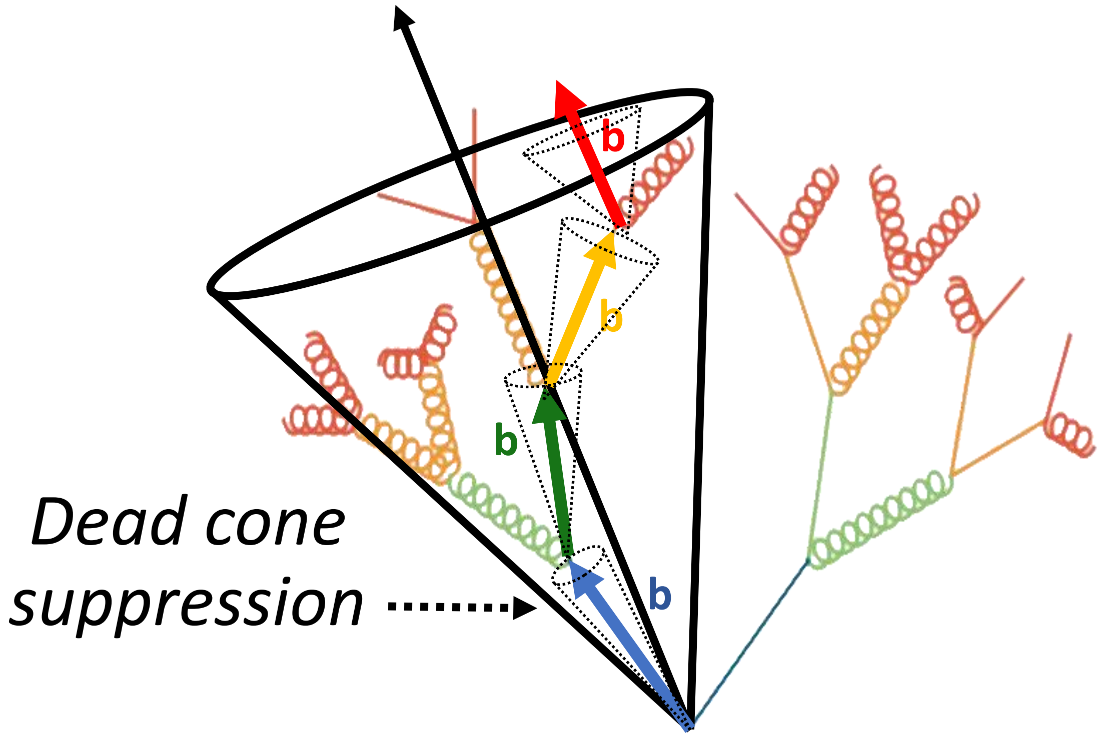
Dokshitzer, Khoze, Troyan
J. Phys. **G17** (1991) 1602



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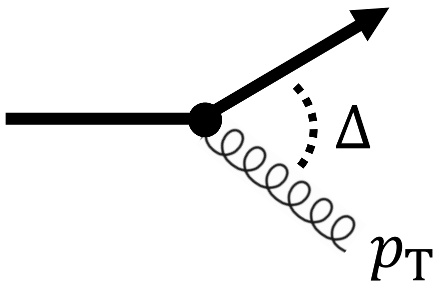

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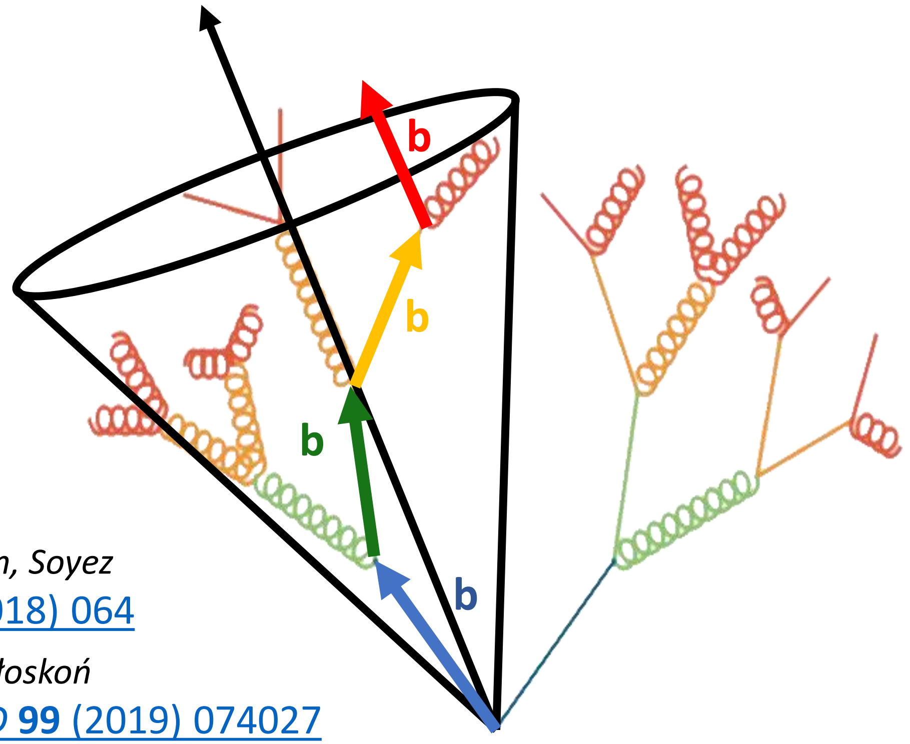

Dreyer, Salam, Soyez
[*JHEP* **12** (2018) 064]

Cunqueiro, Płoskoń
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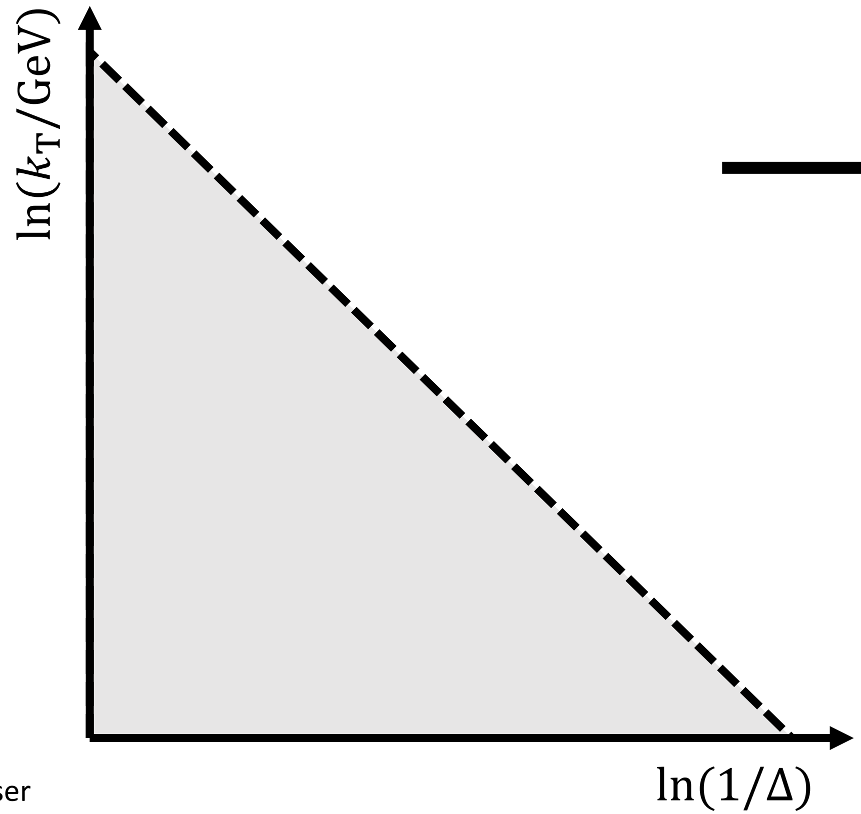

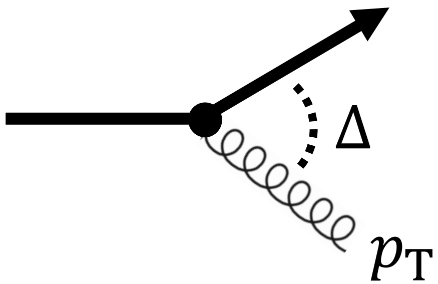

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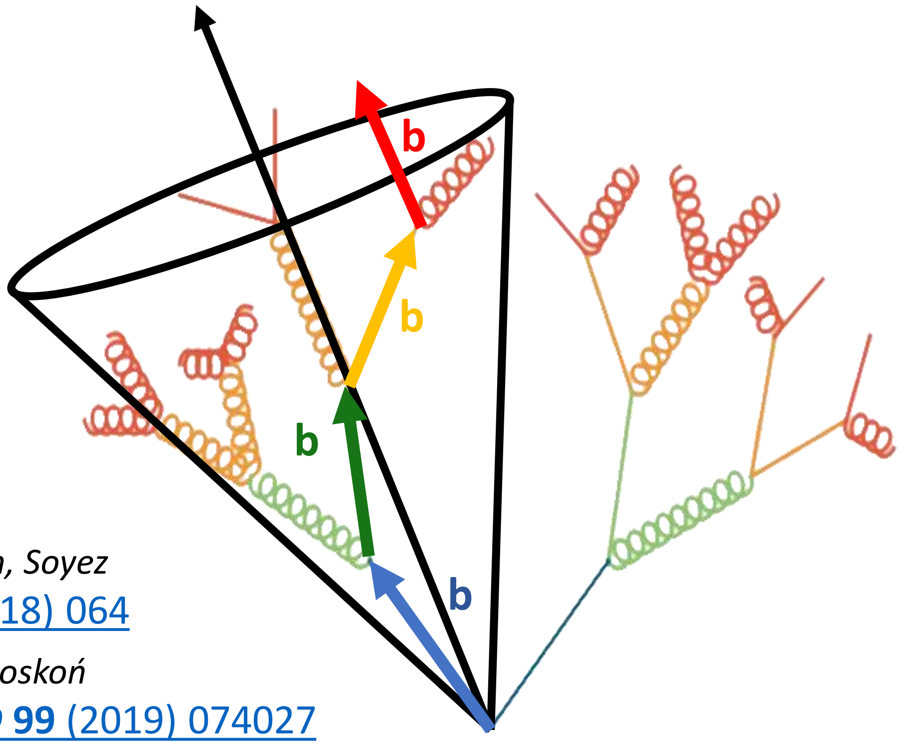

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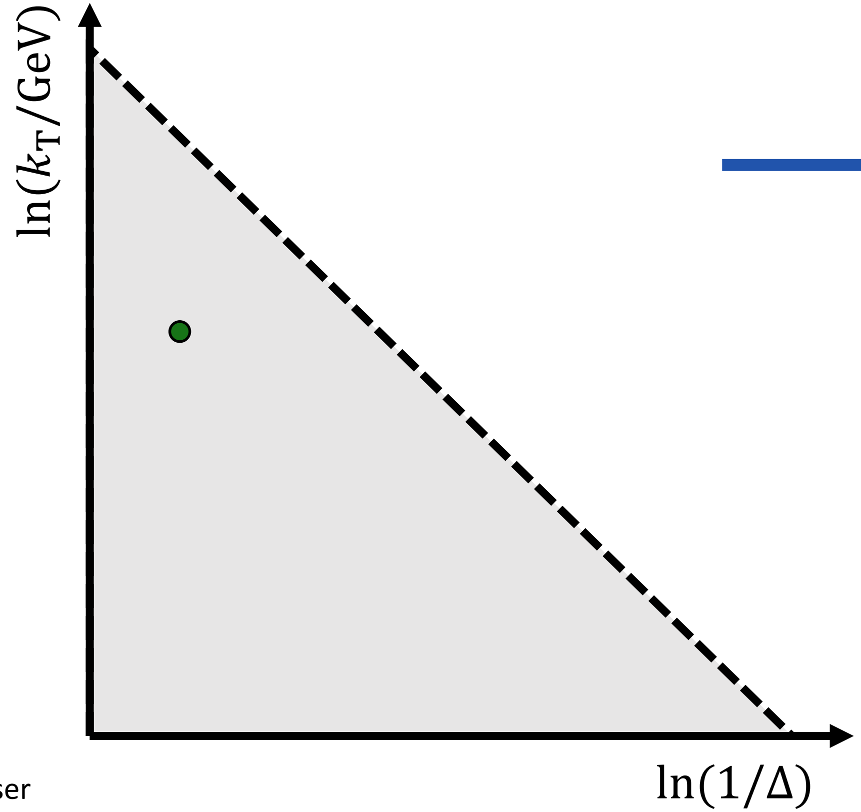

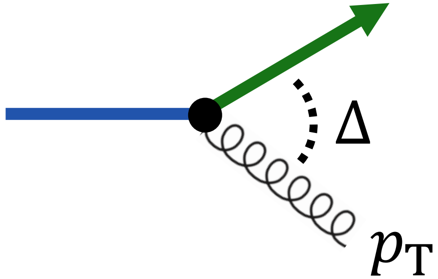

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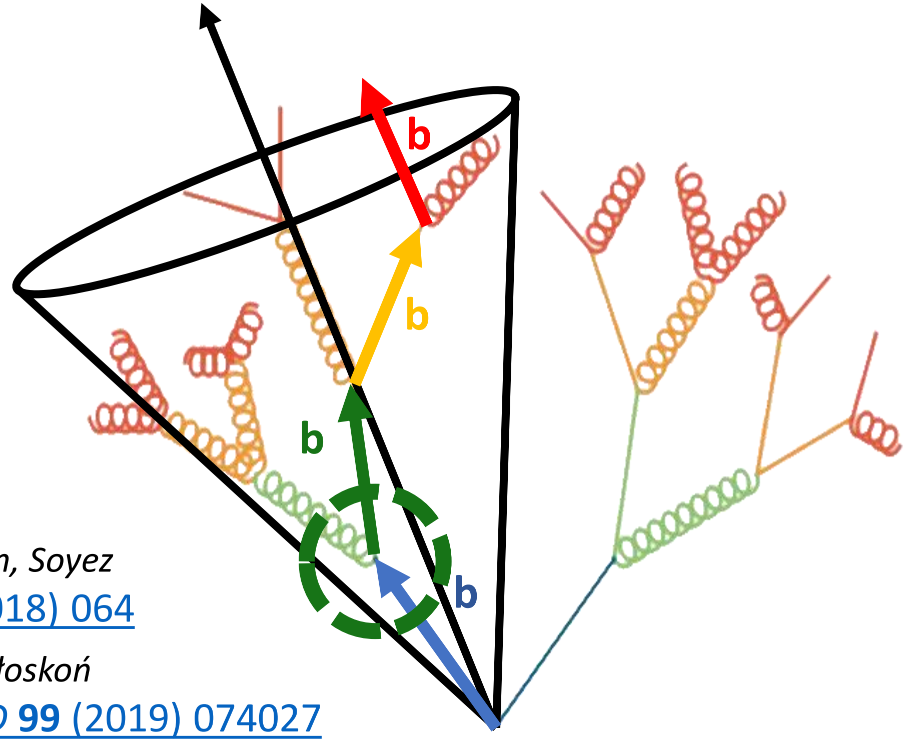

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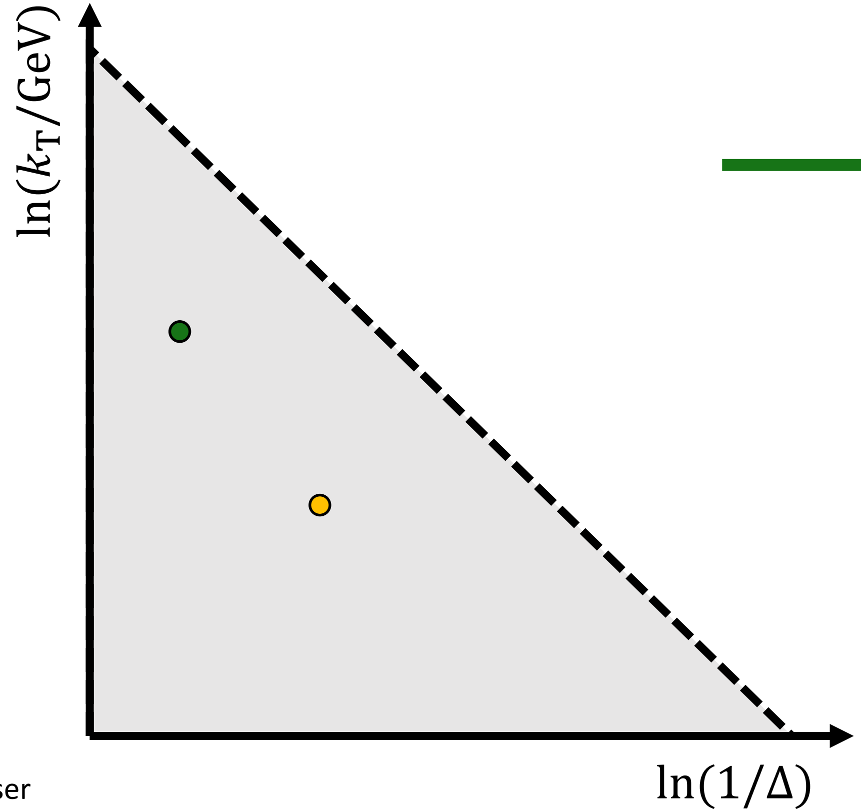

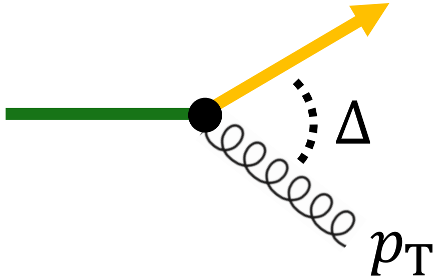

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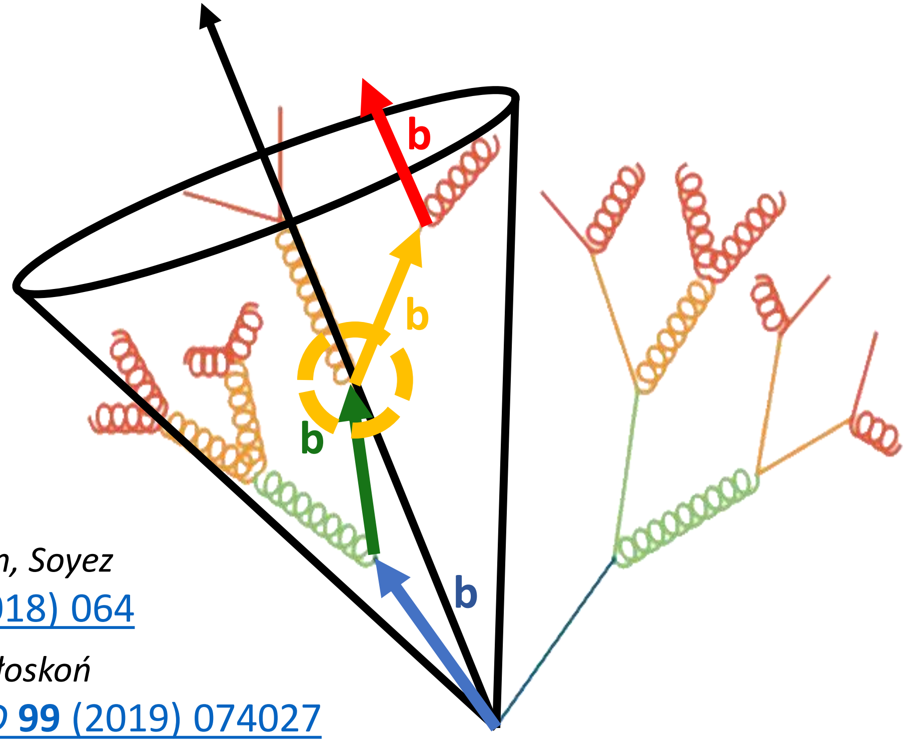

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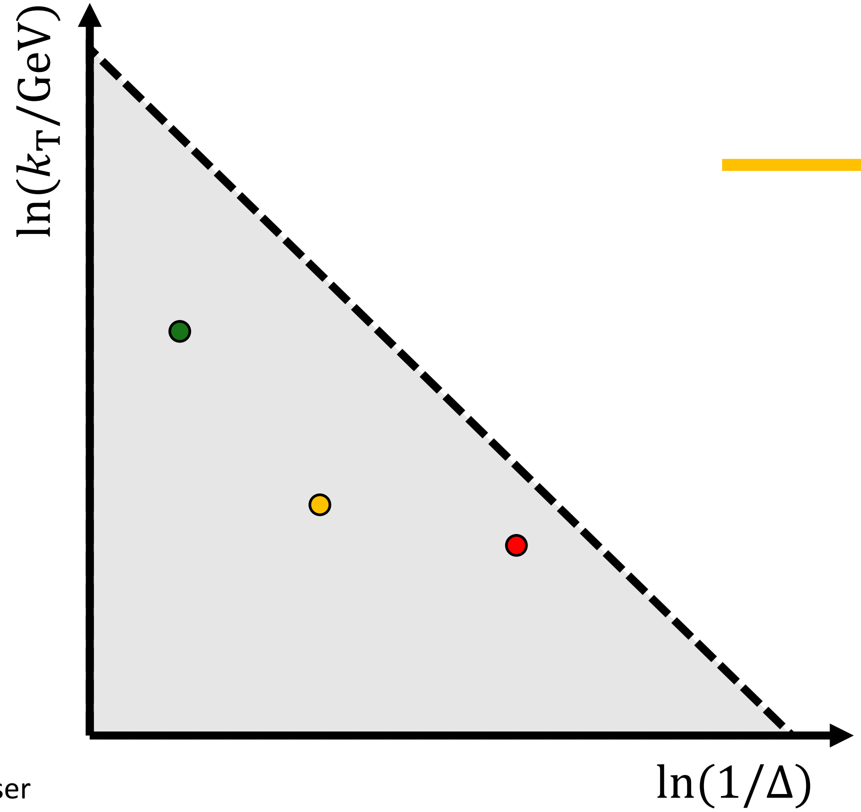

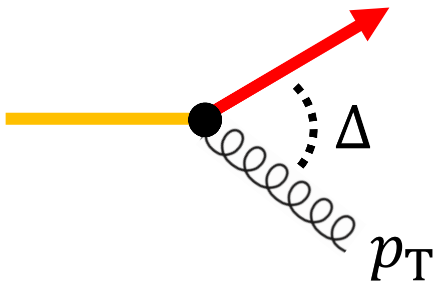

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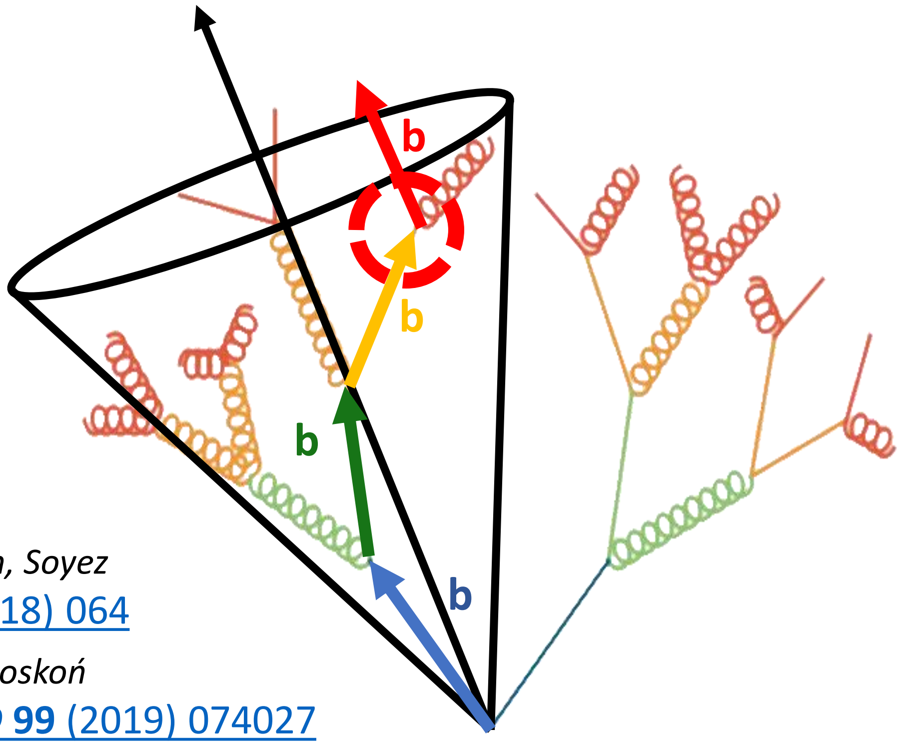

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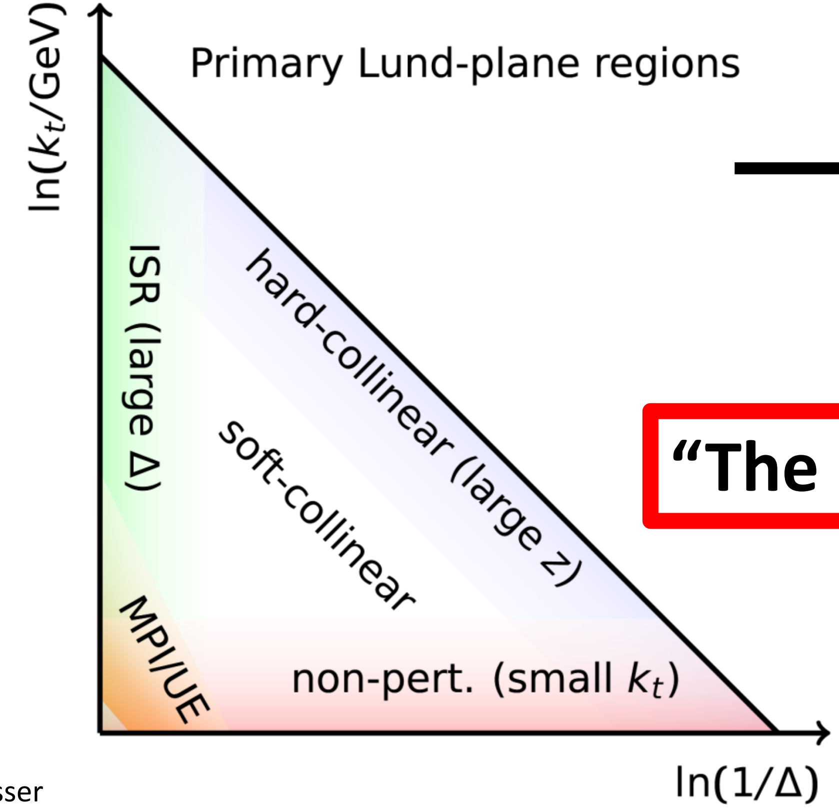

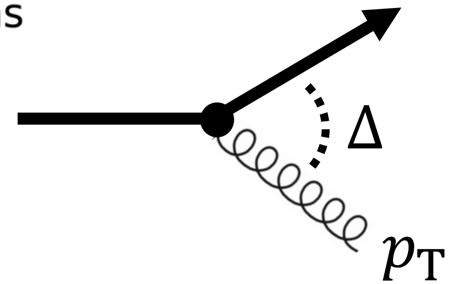

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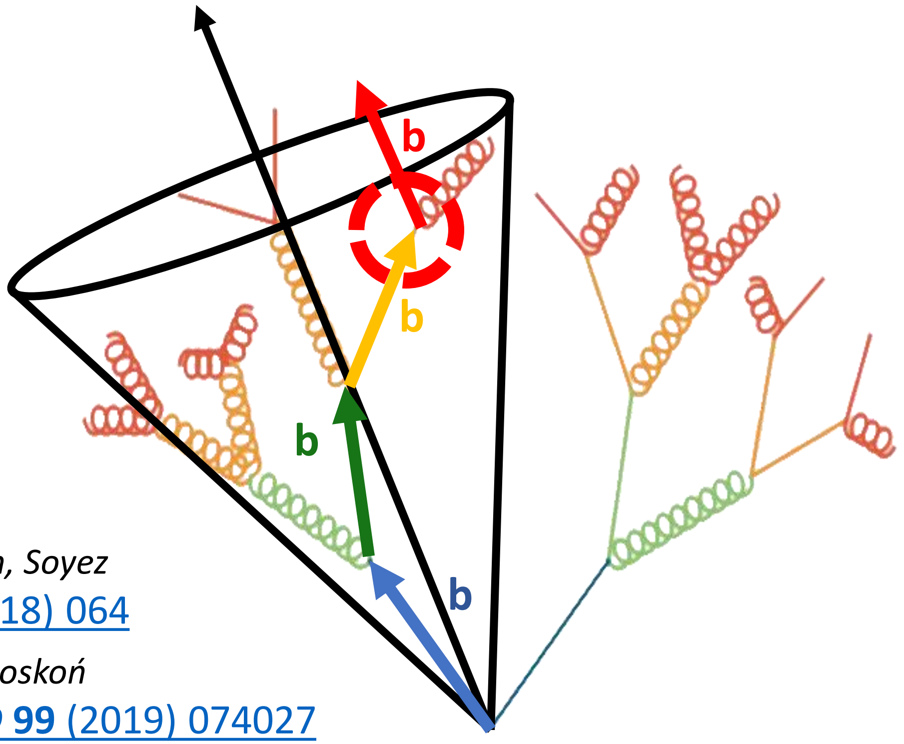
"The Lund jet plane"



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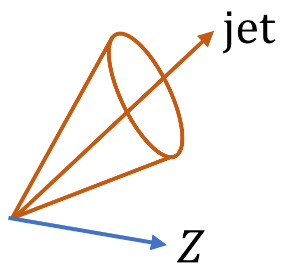
Light **vs. HF** q Lund jet plane

- Light-quark enriched sample obtained using Z + jet sample



Light vs. HF q Lund jet plane

arXiv:2505.23530
(accepted to *Phys. Rev. D*)

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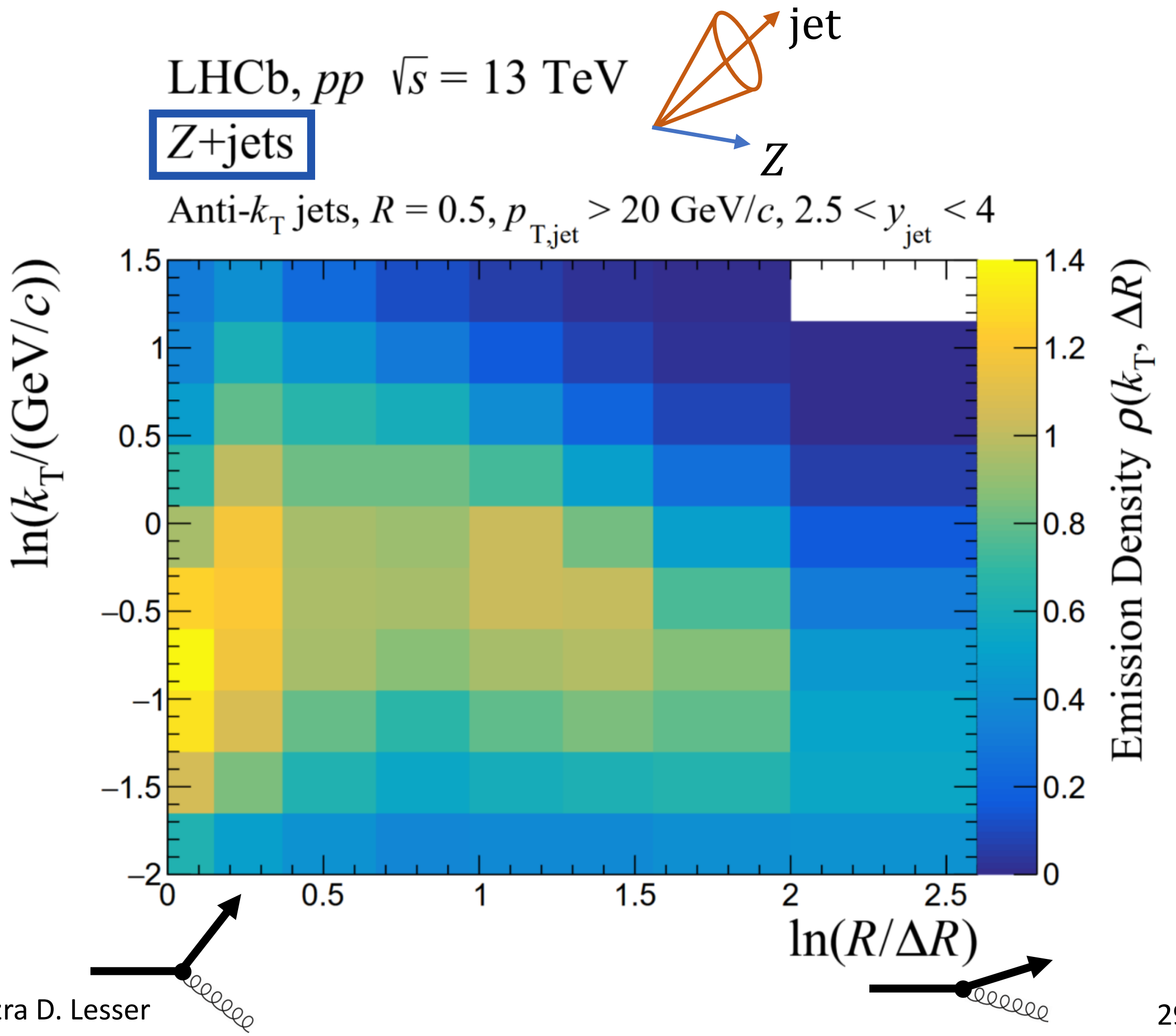

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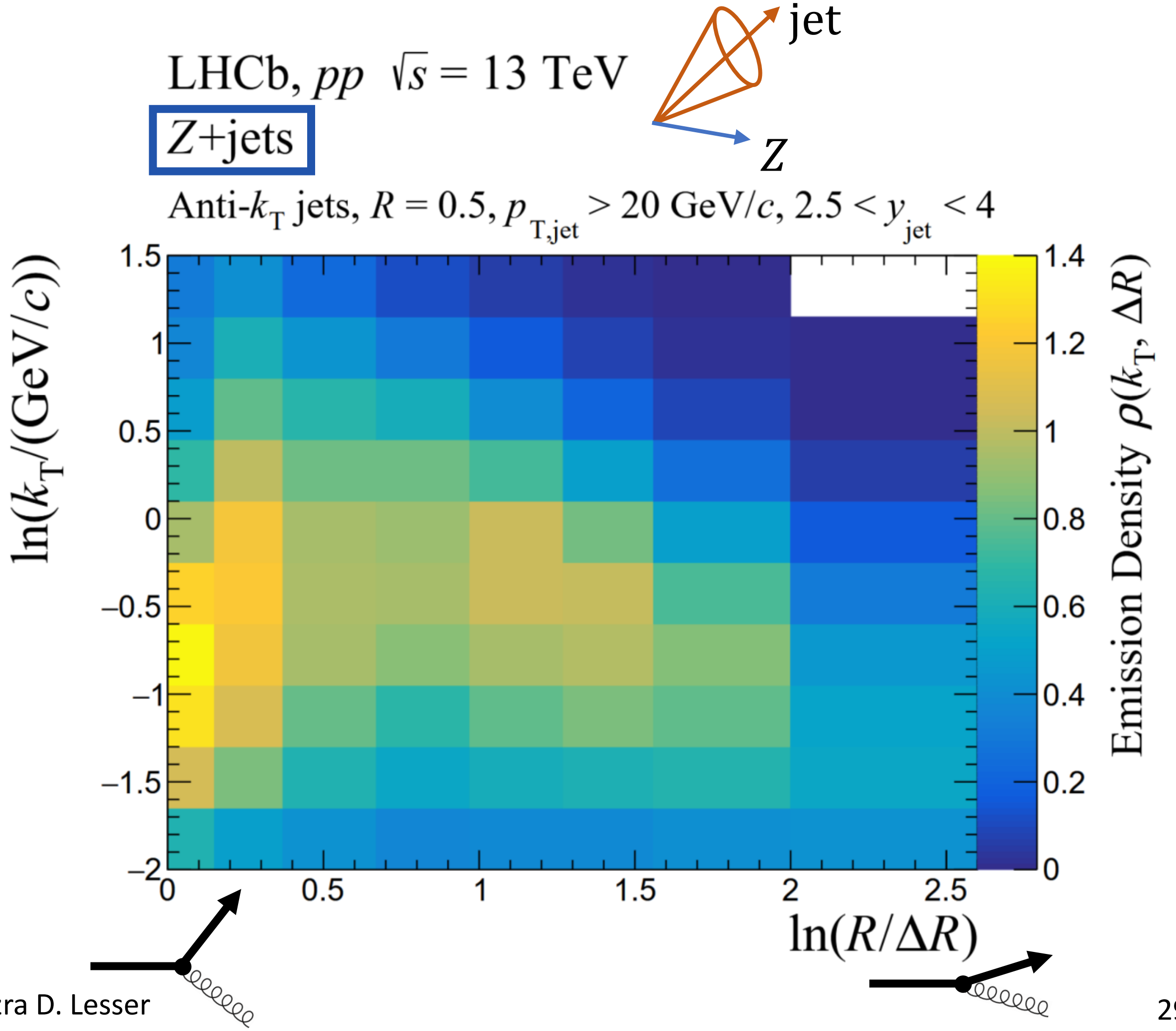

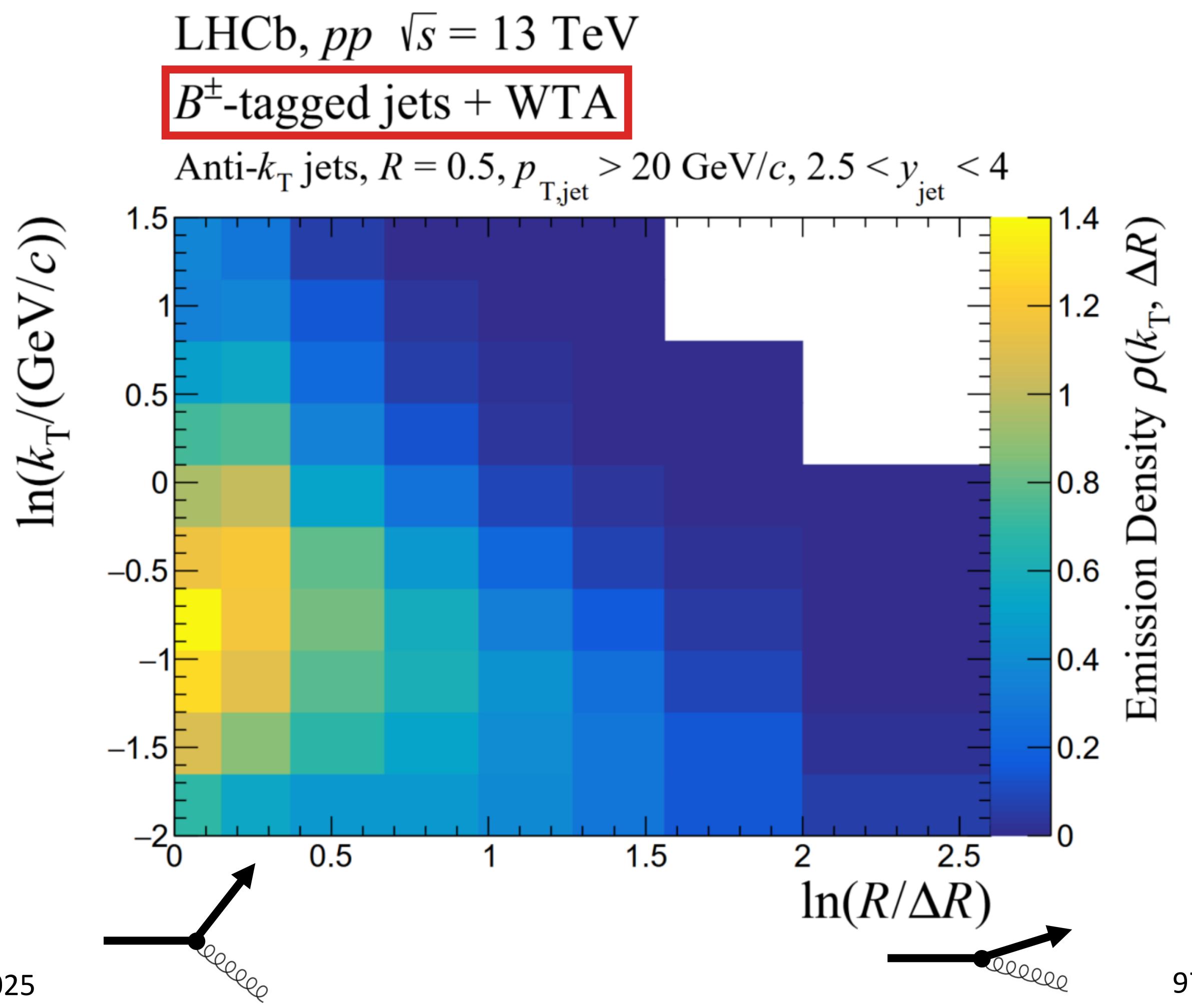

Light vs. HF q Lund jet p

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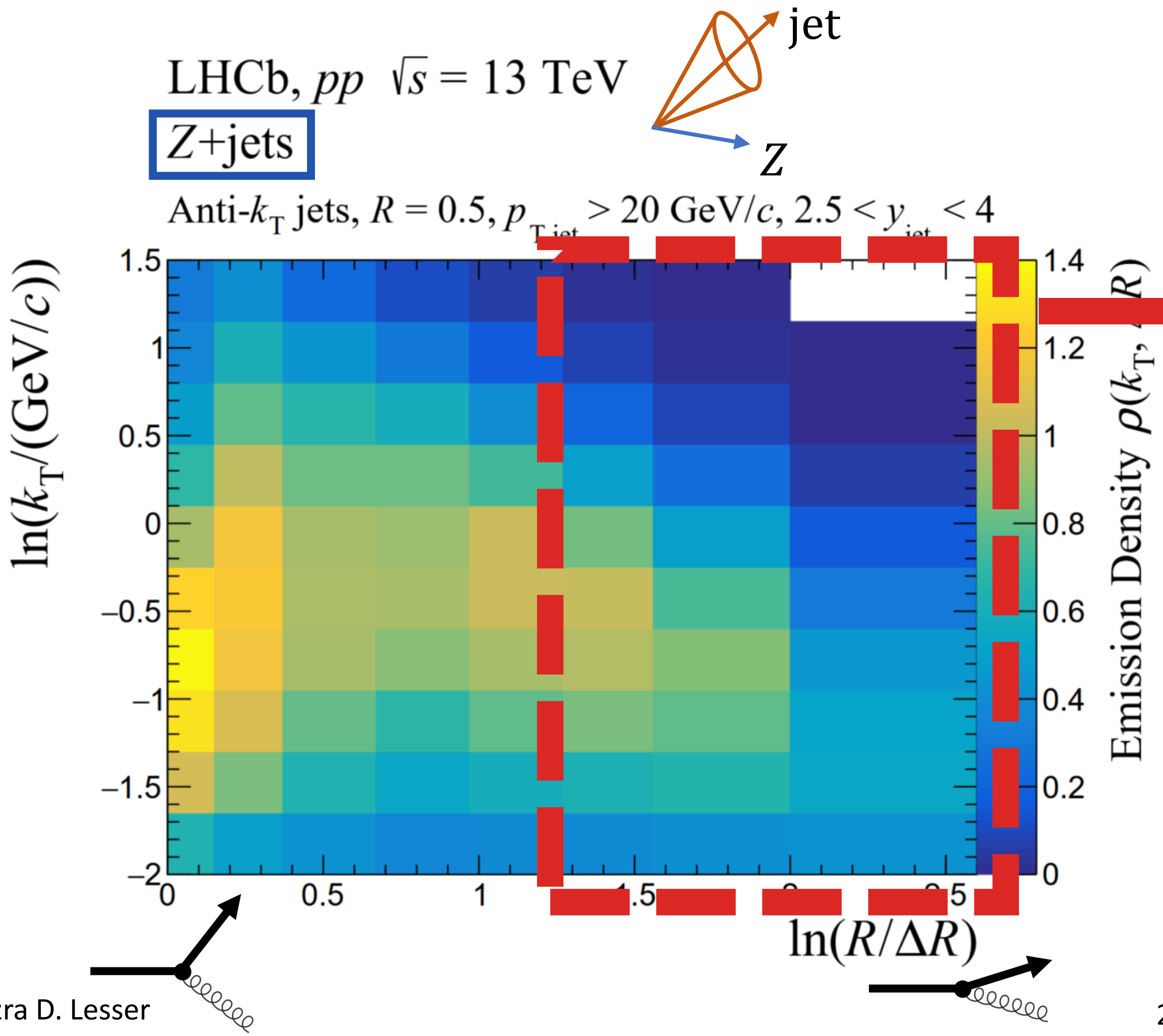
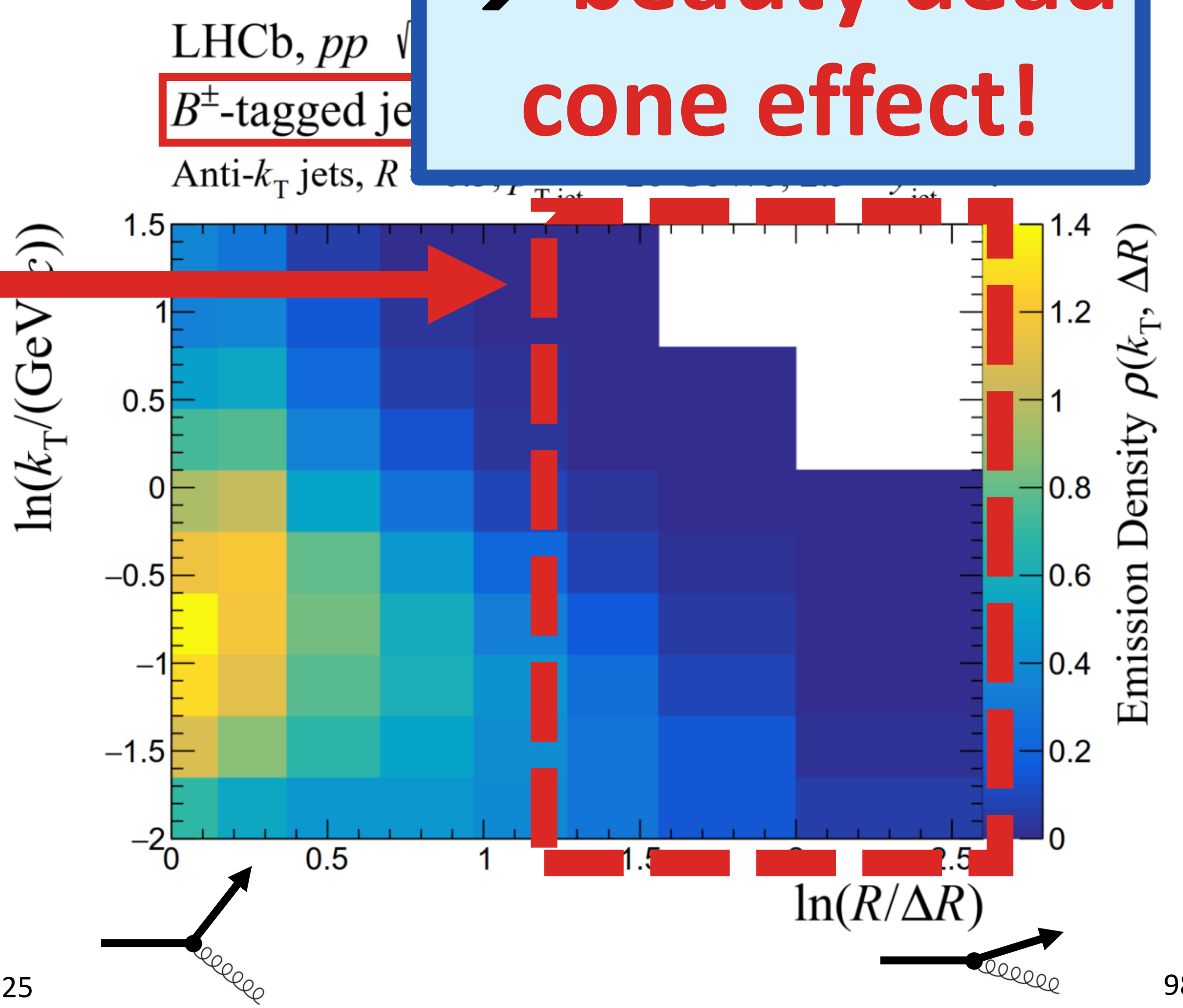
Suppression at small angles → beauty dead cone effect!





Slicing the Lund jet plane

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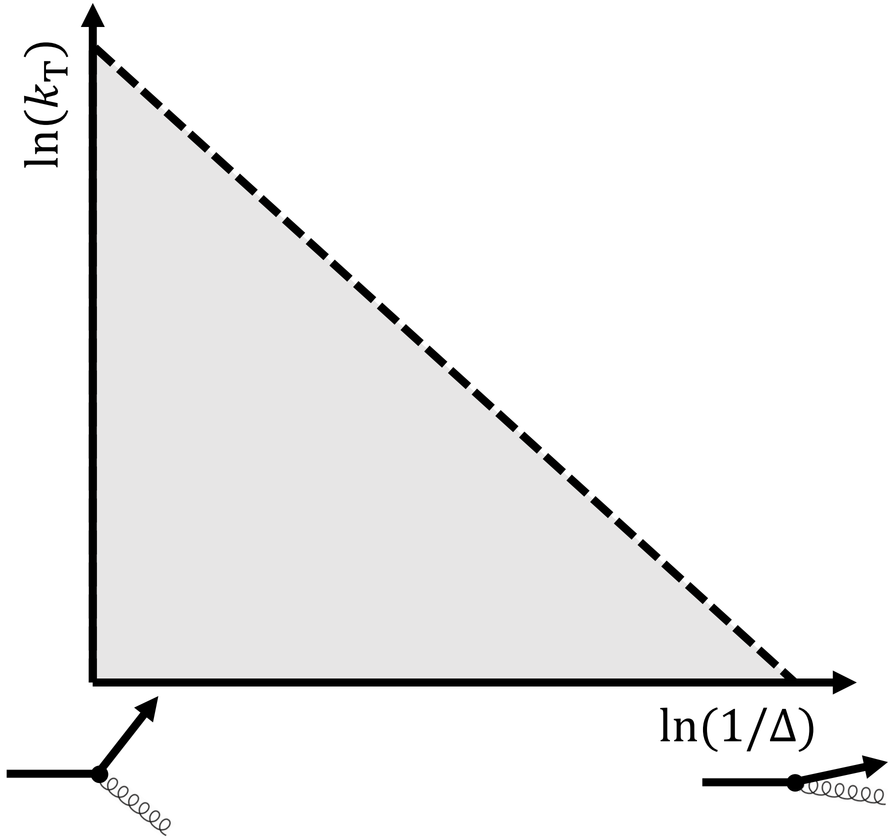

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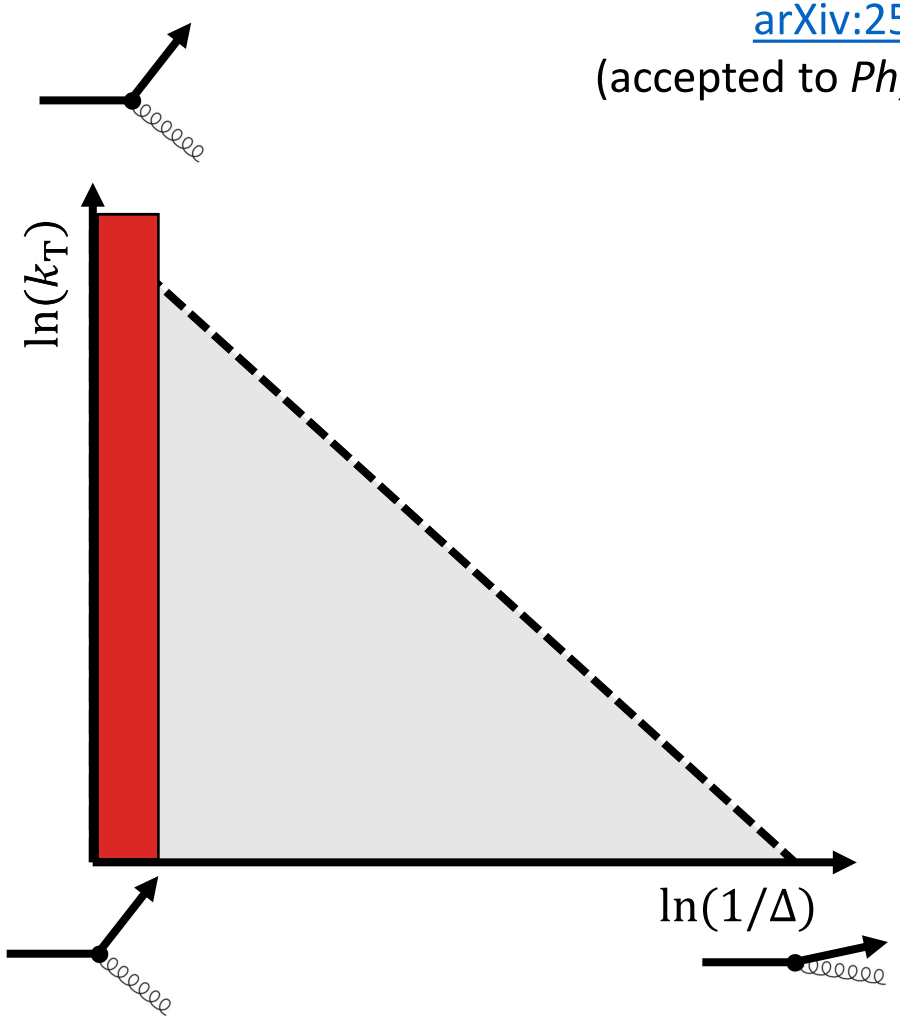

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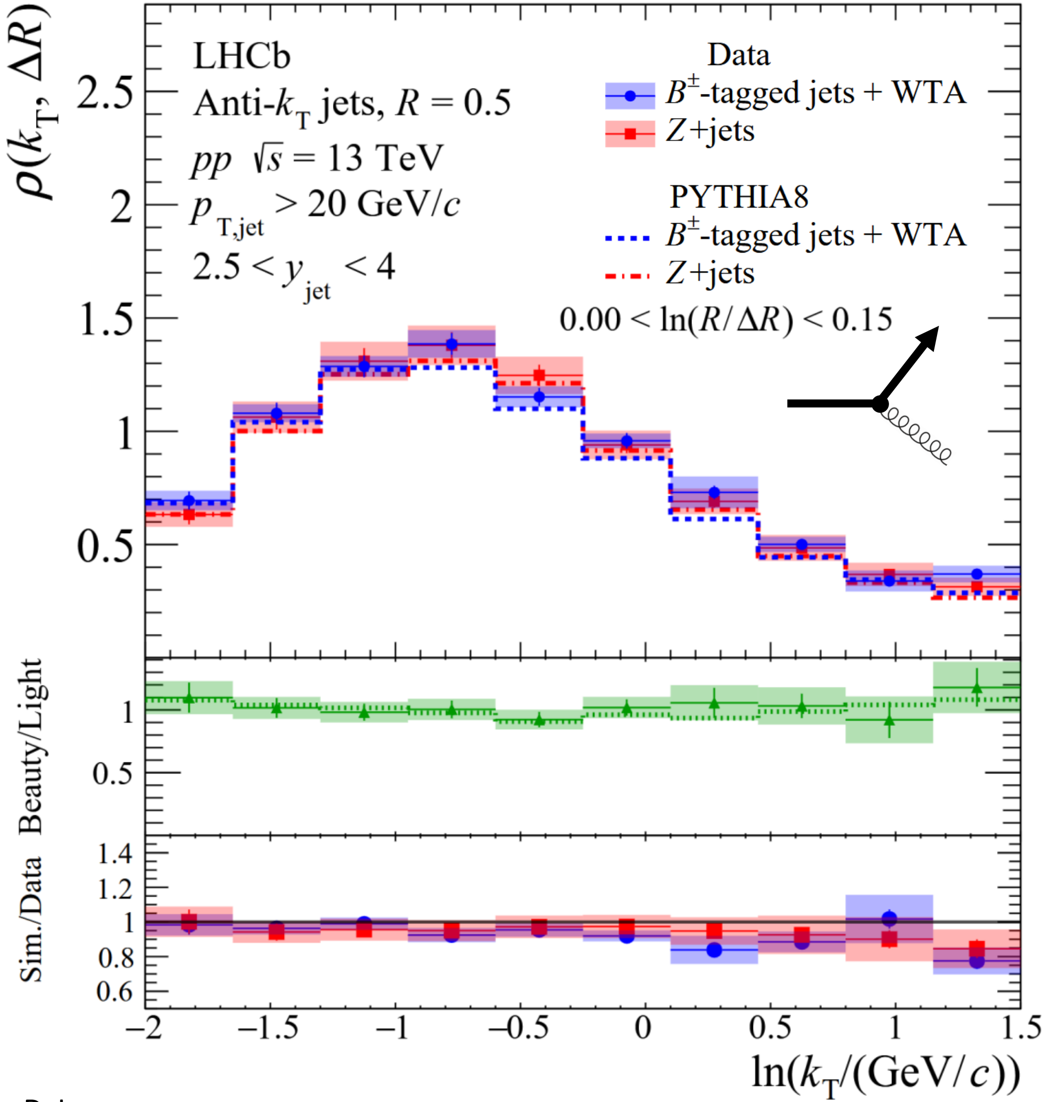
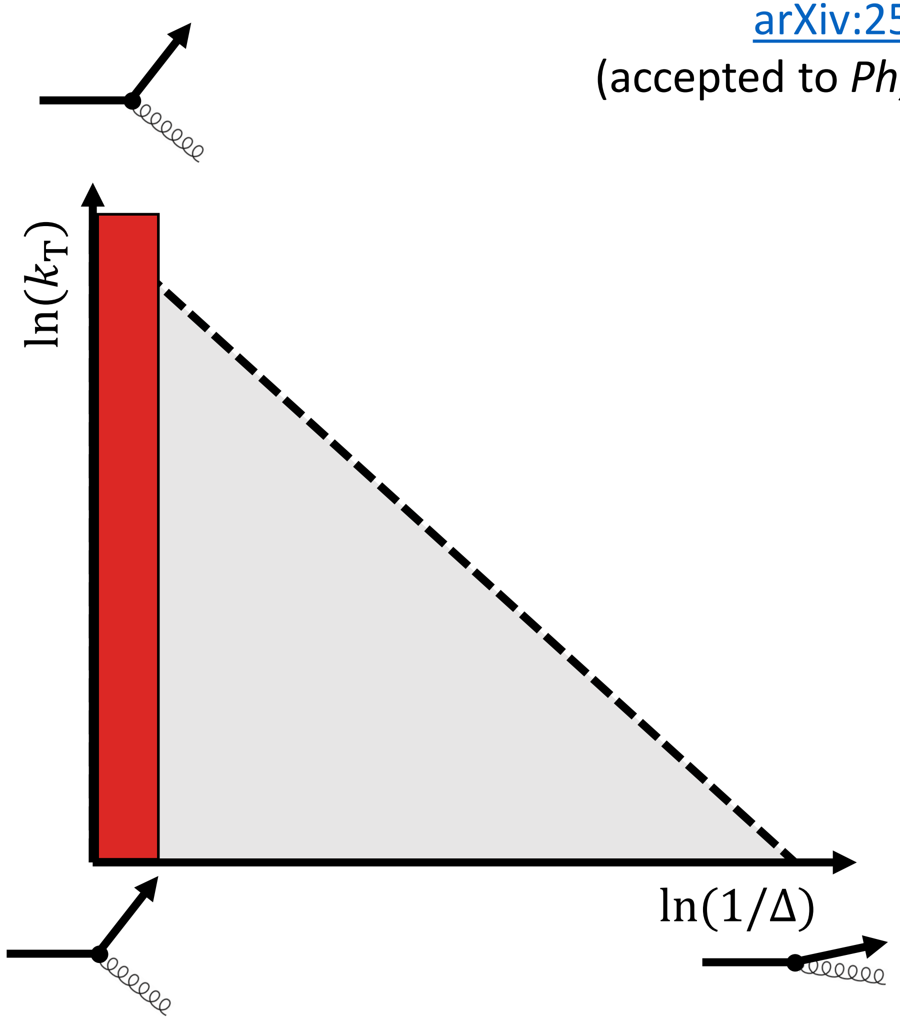


← ***Dead cone modification***

← ***Pythia 8 agreement***



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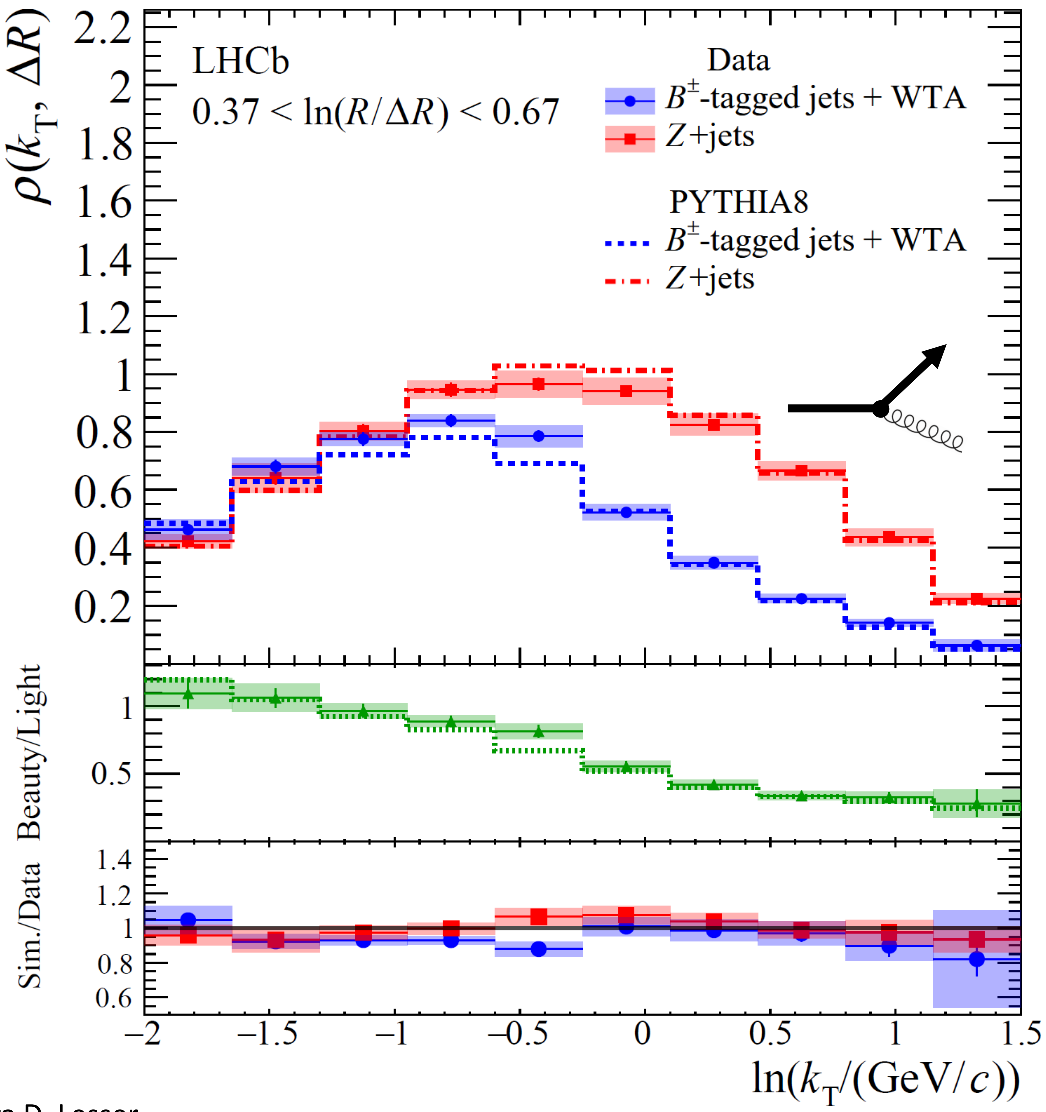

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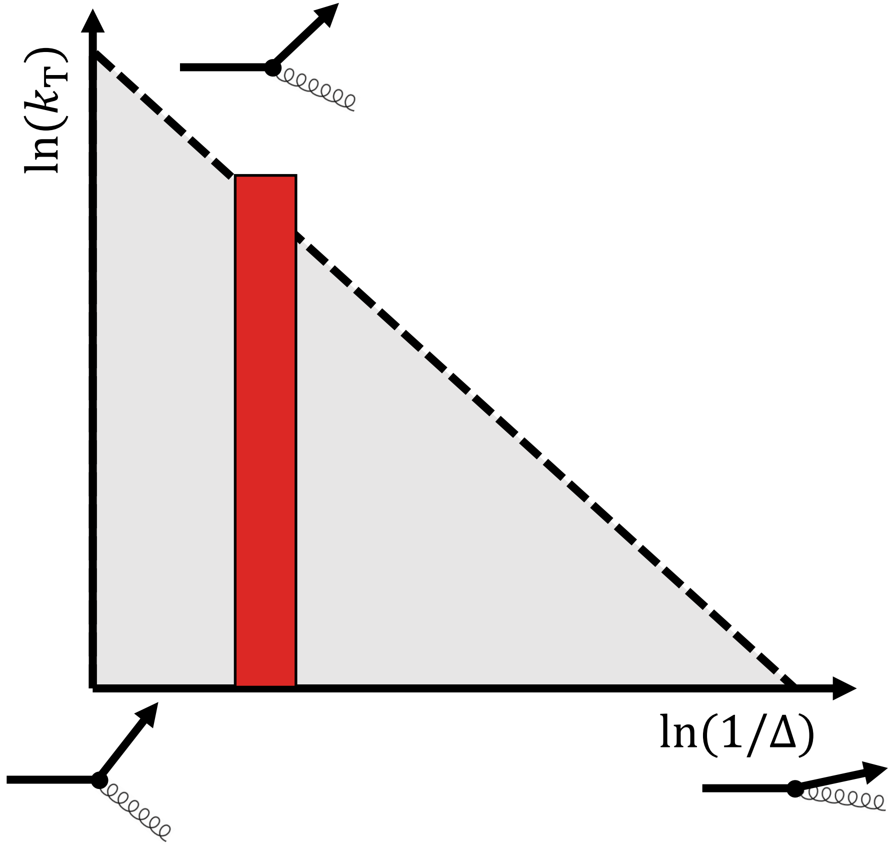

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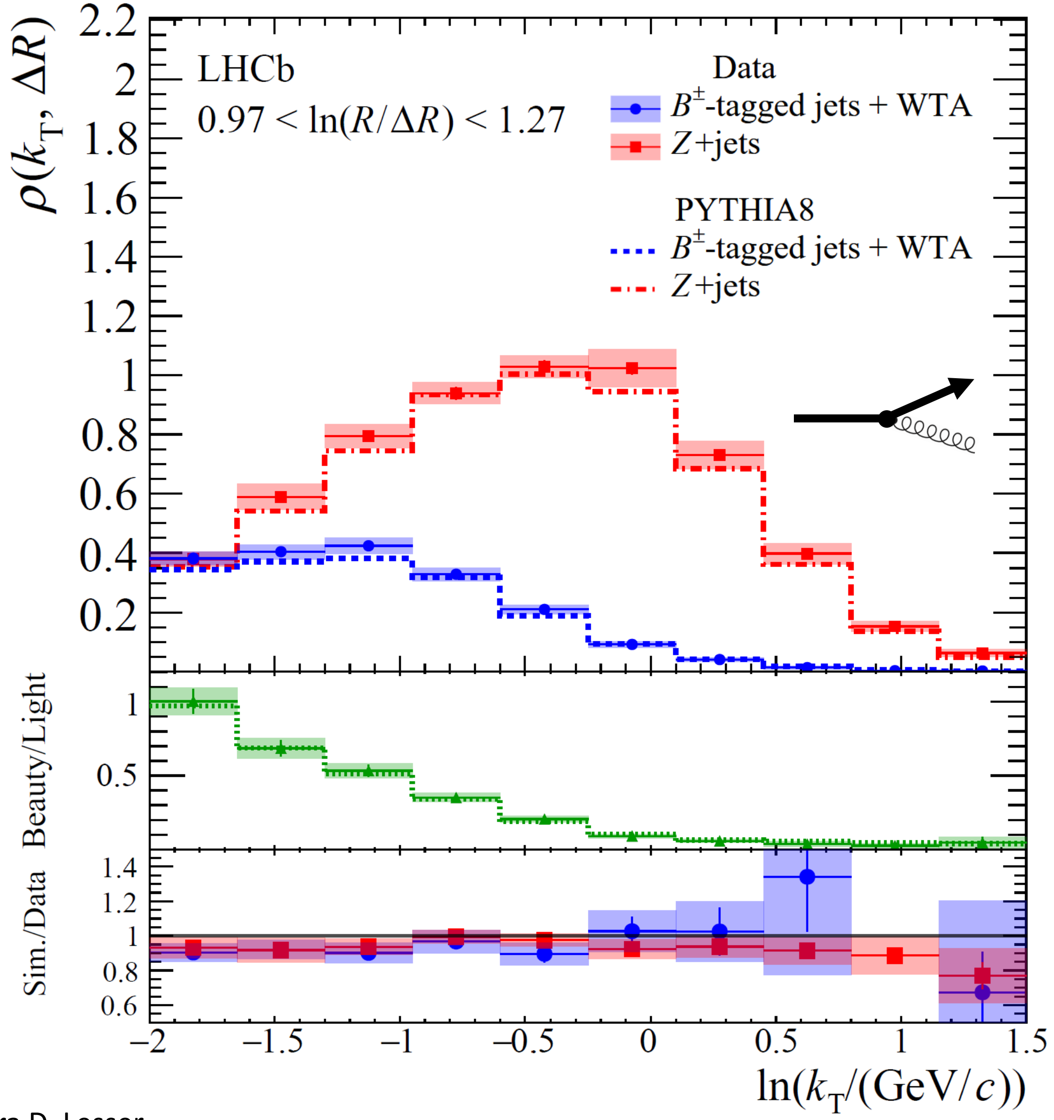

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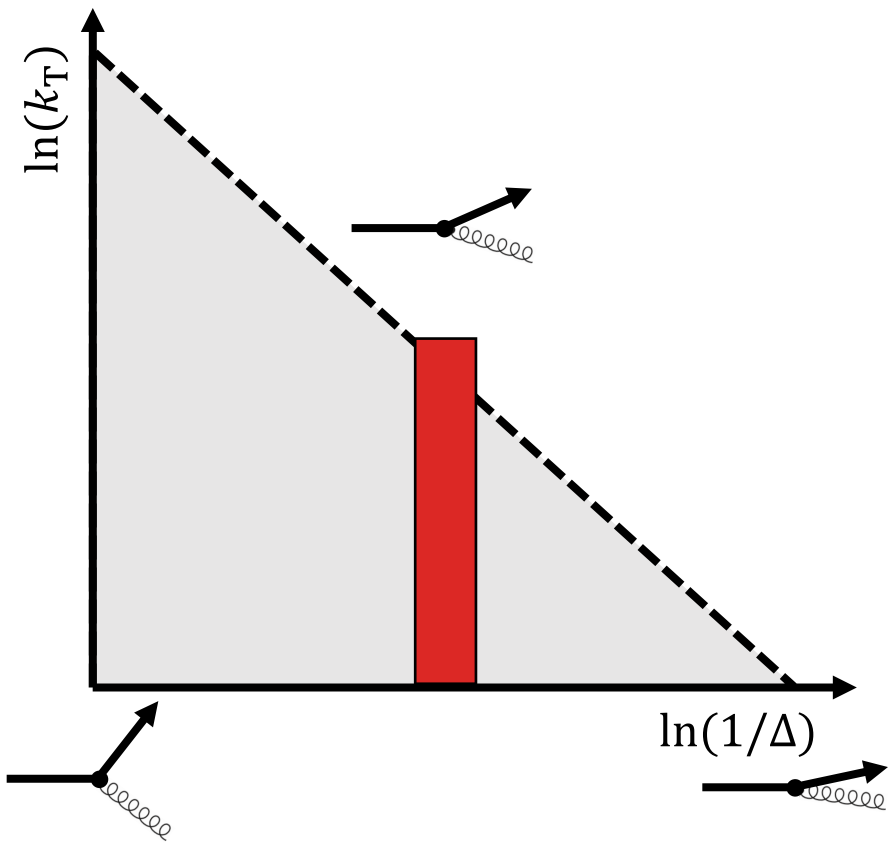

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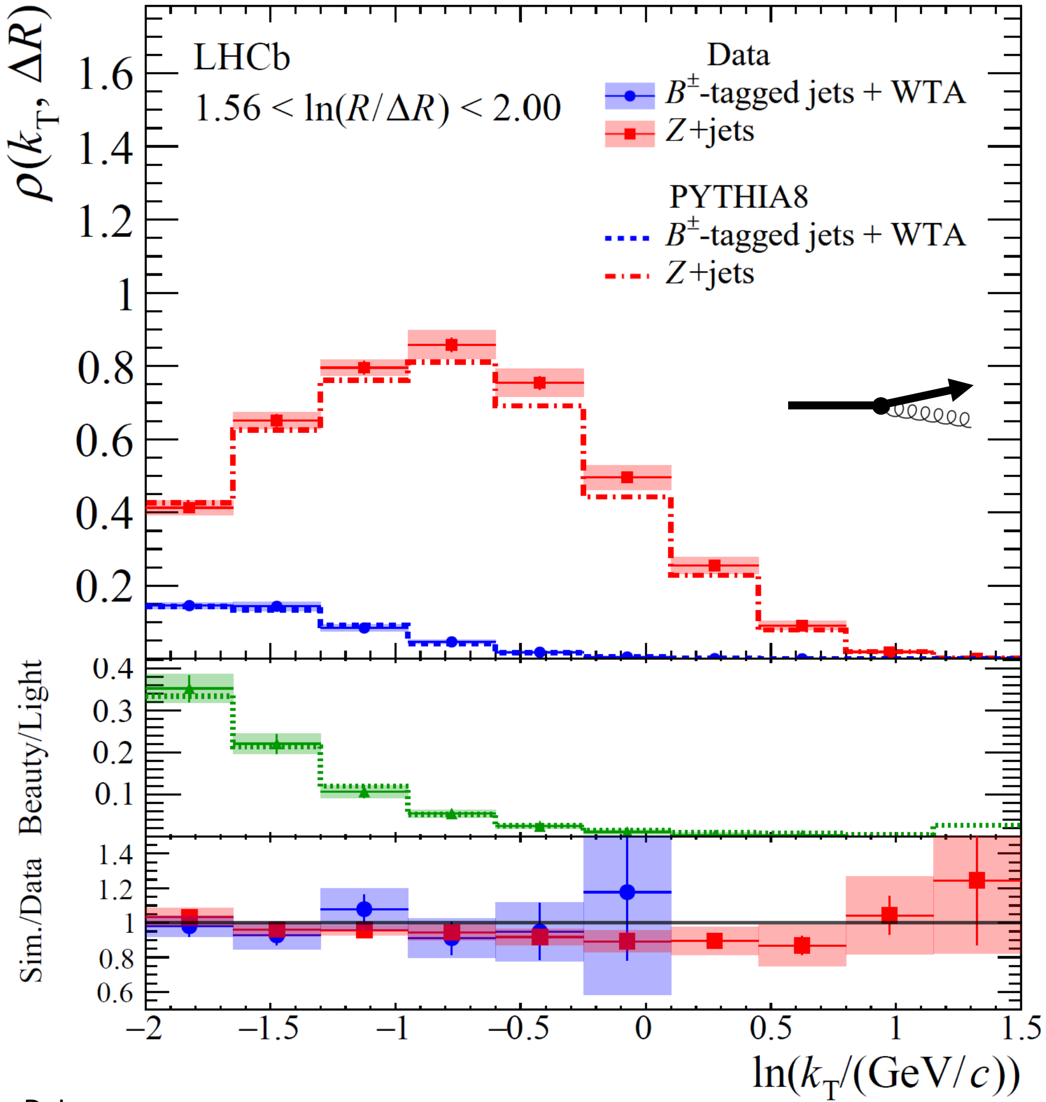

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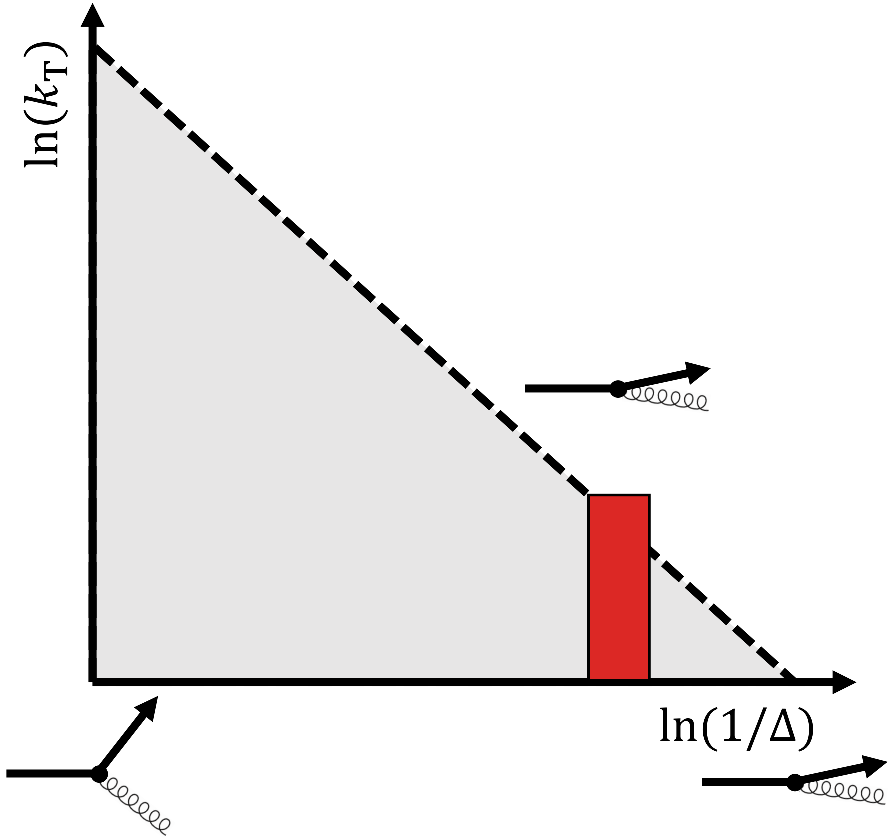
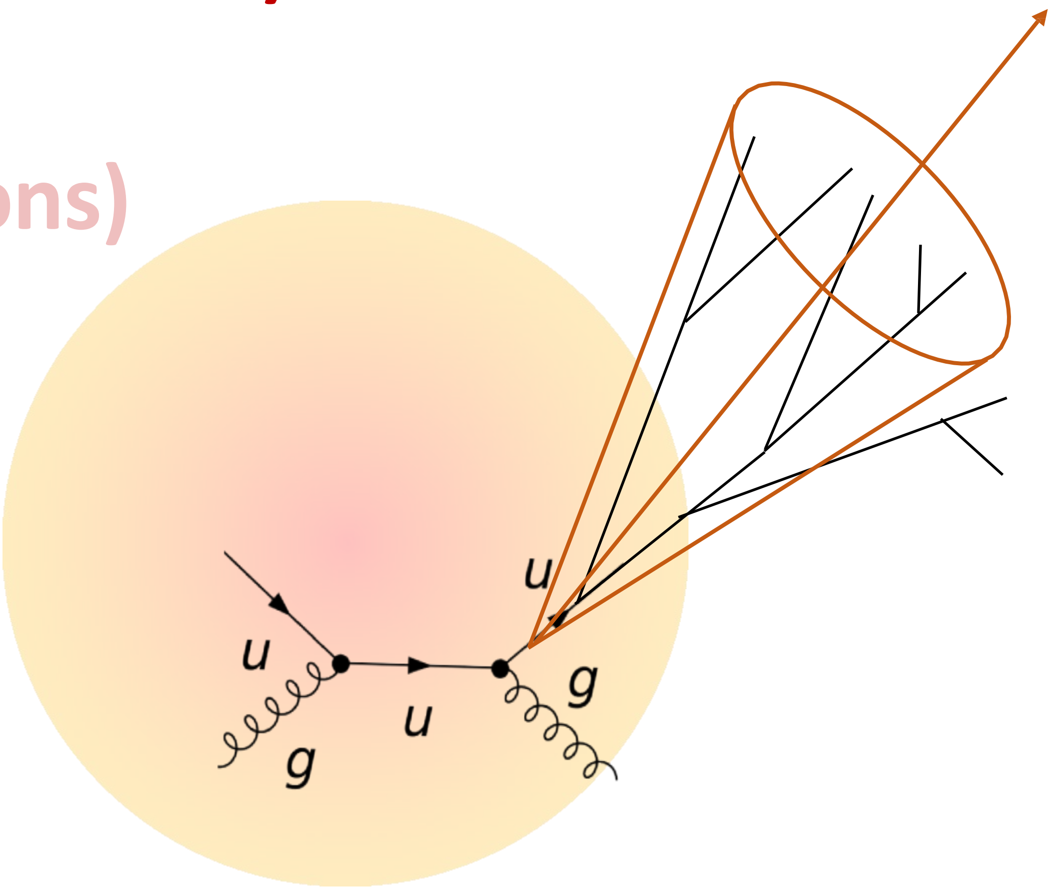


This talk: probing QCD in …

- **“vacuum” (proton-proton collisions)**
- “medium” (heavy-ion collisions)



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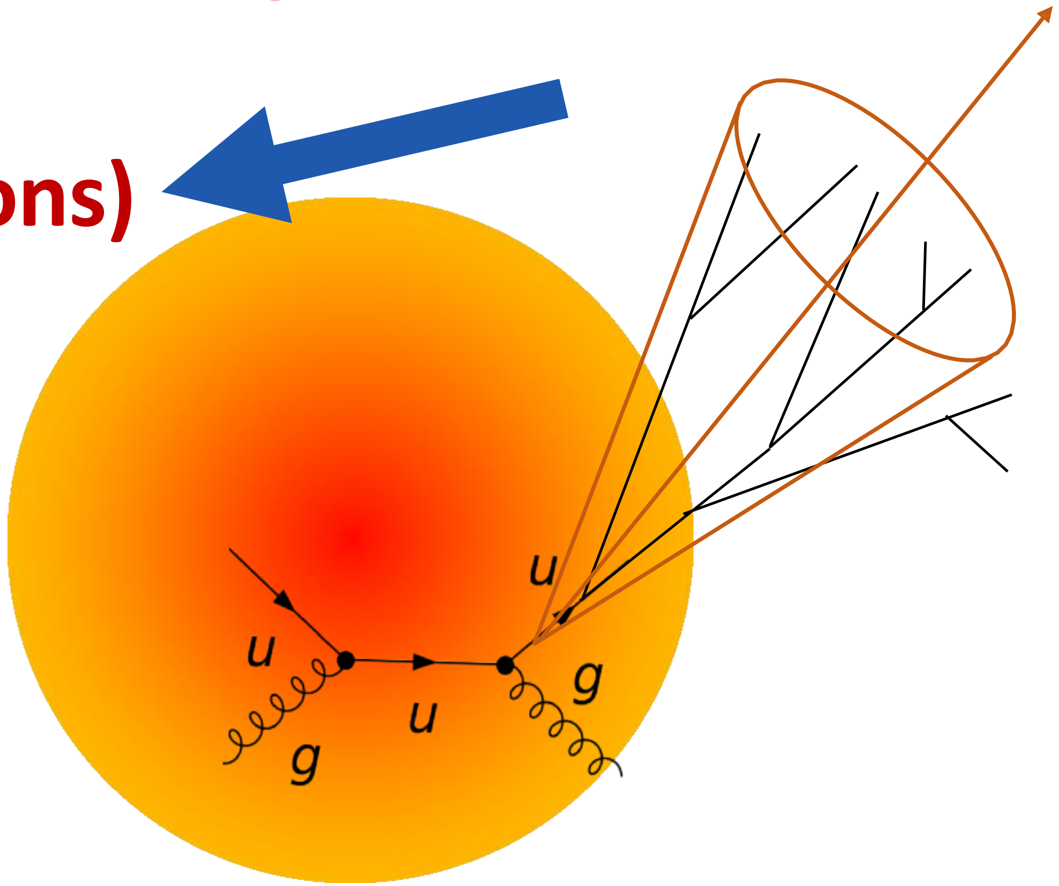
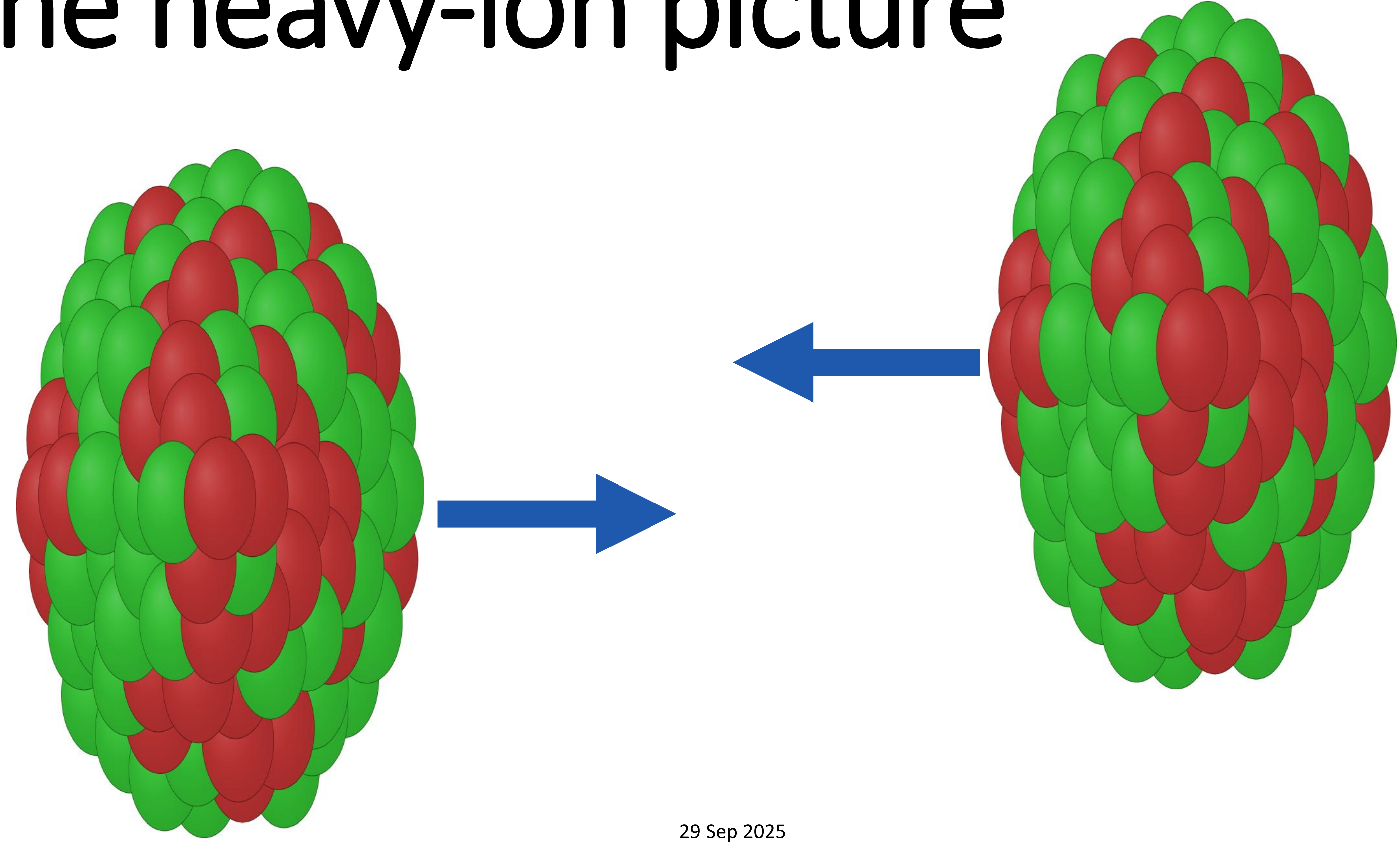


The heavy-ion picture



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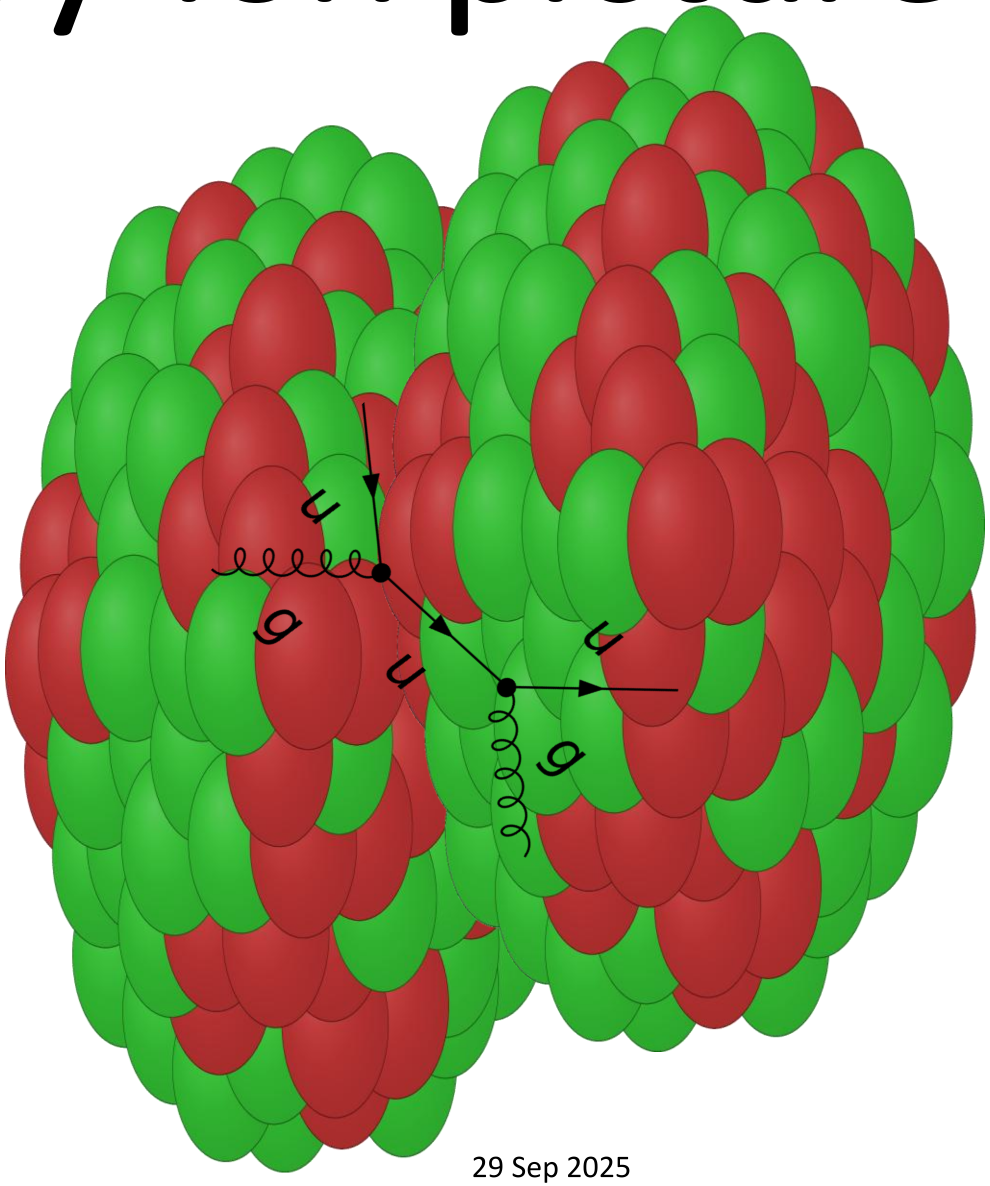

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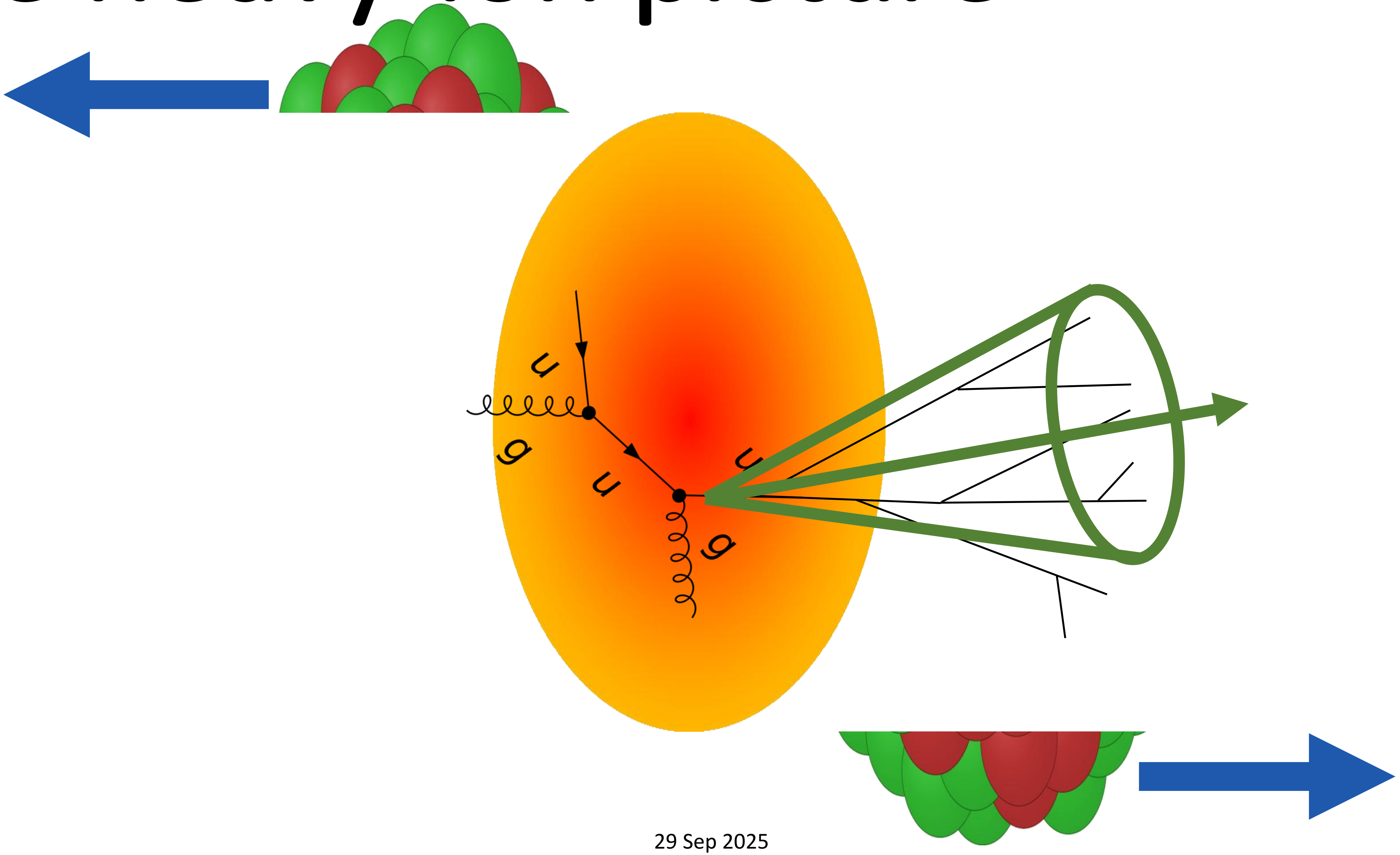

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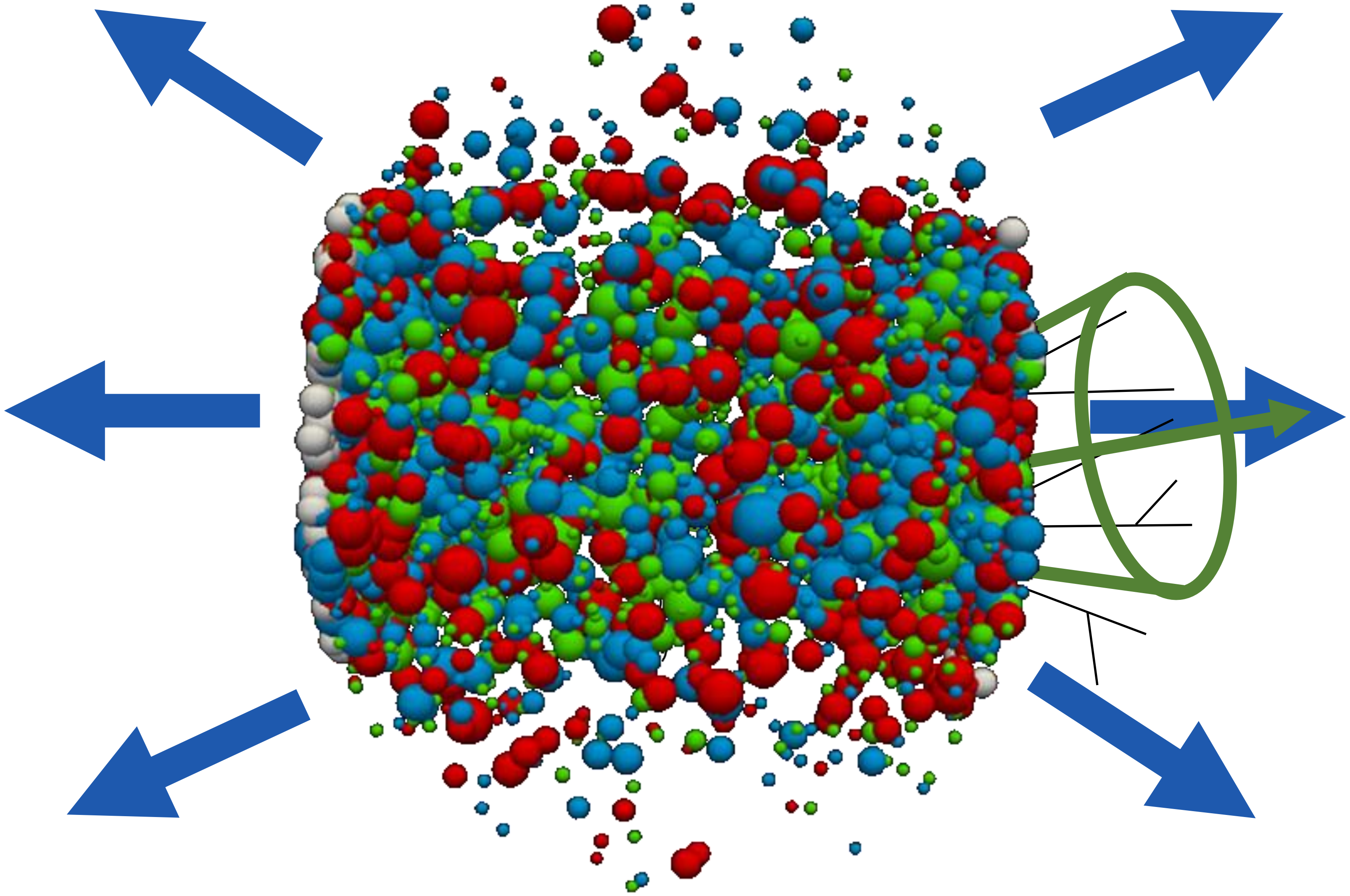

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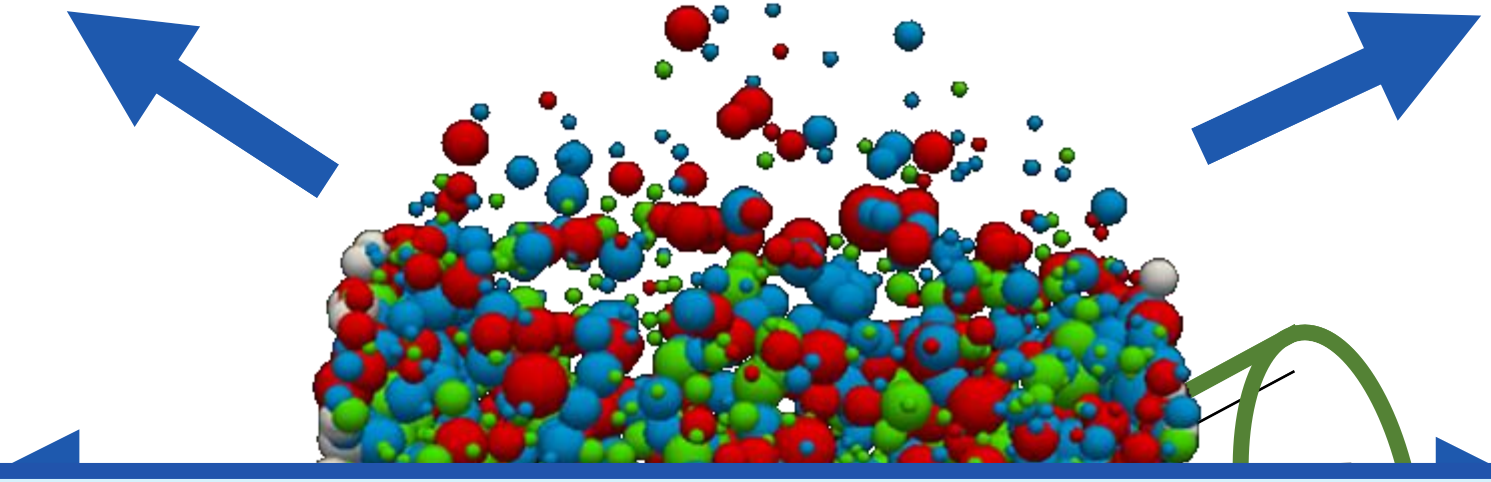
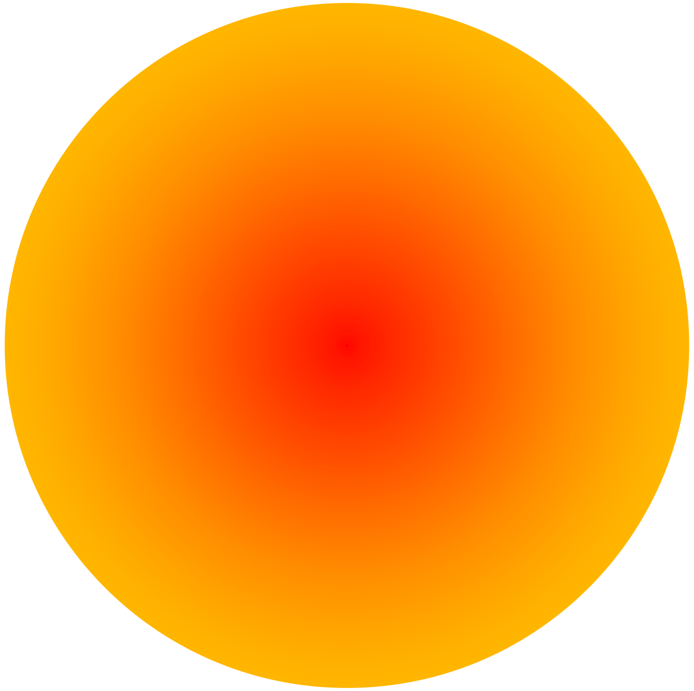


What can we learn about QCD from hard probes produced in heavy-ion collisions?

Many-body QCD in medium

- **Very challenging to study!**
  - Dynamics never (yet) derived from first-principles QCD
  - Competing phenomenological effects



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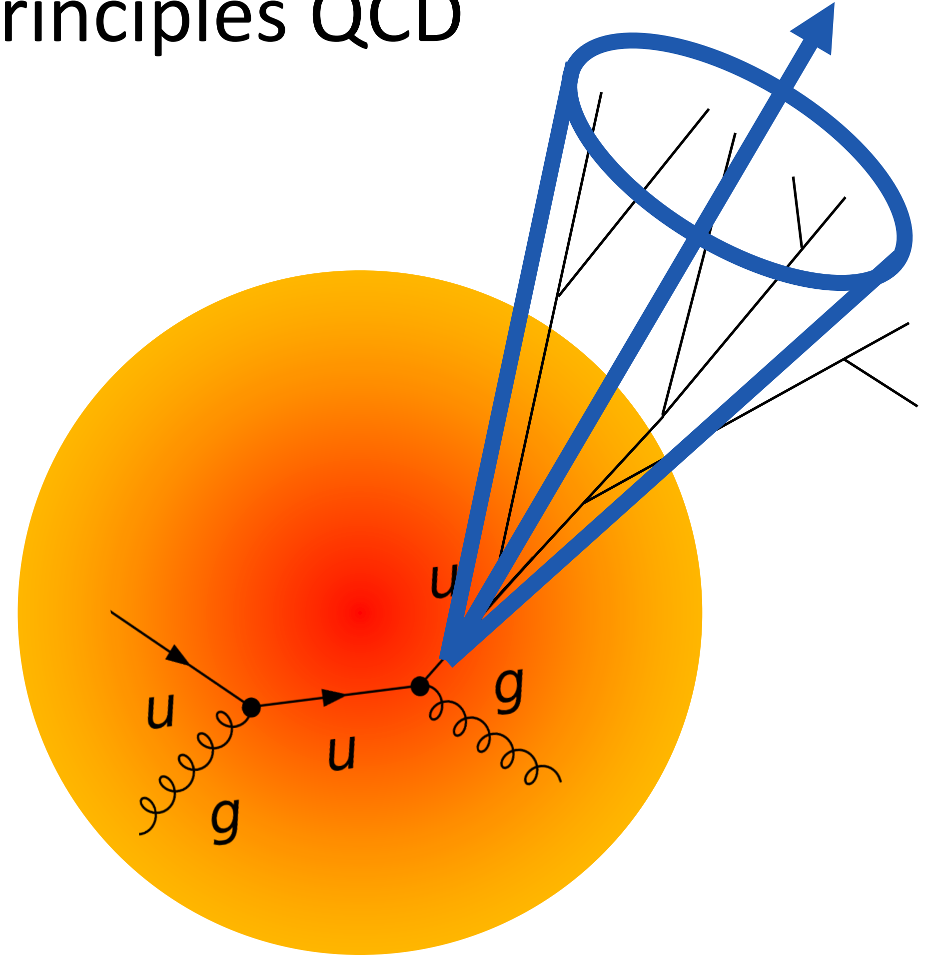

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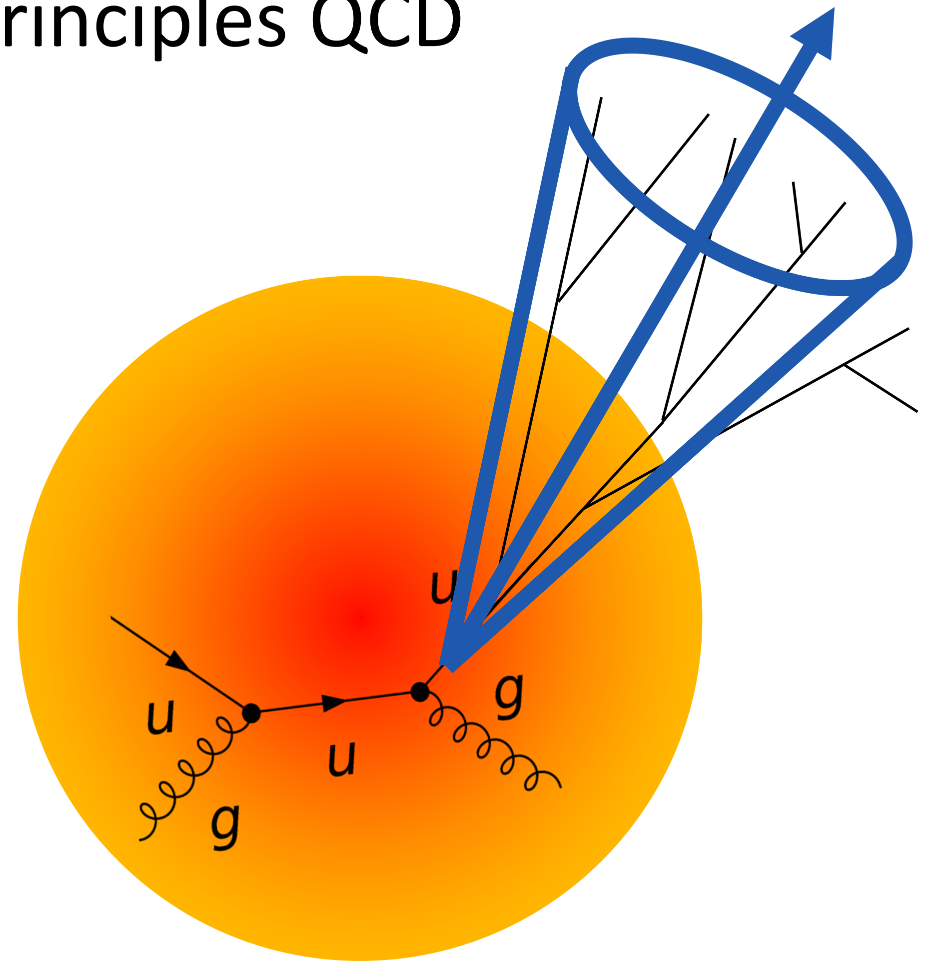

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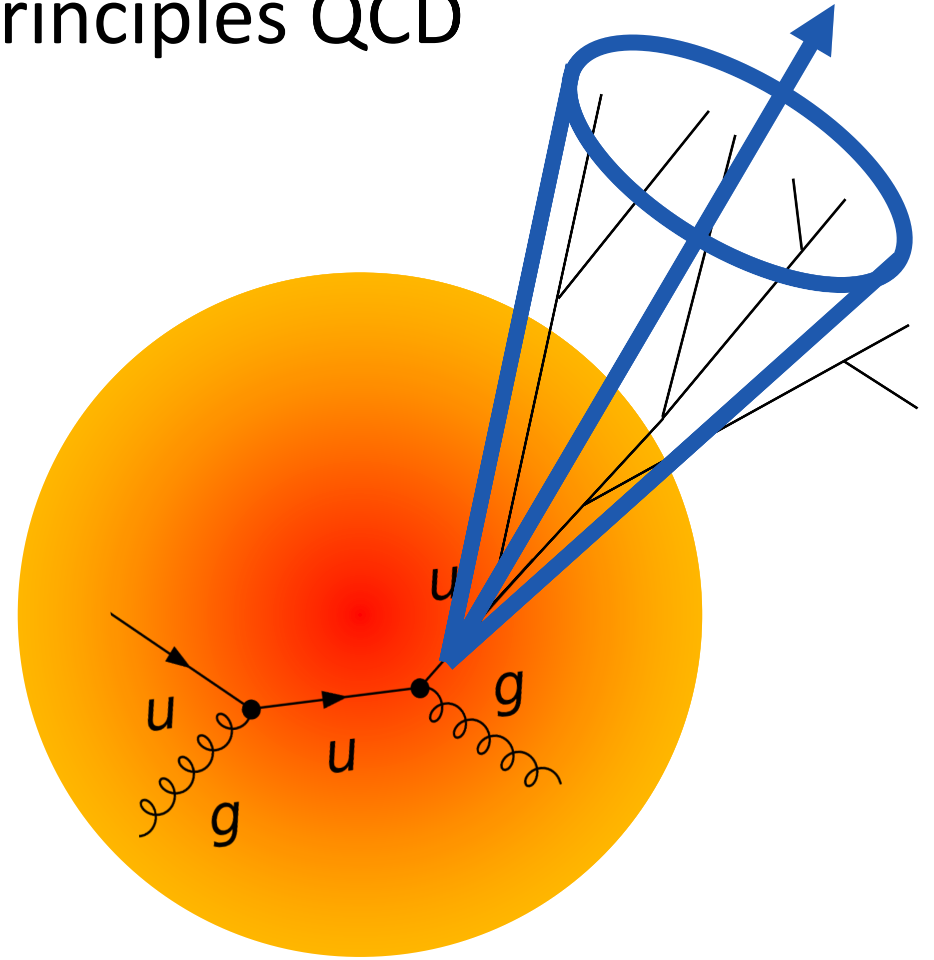

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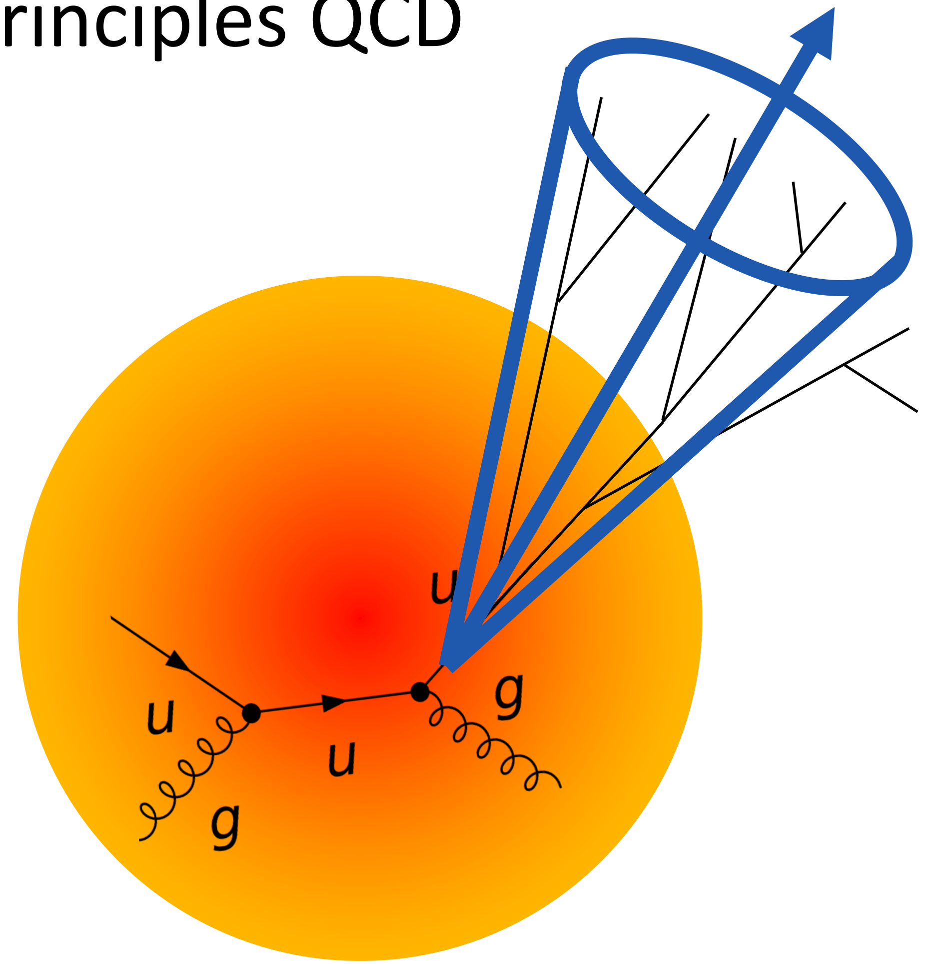

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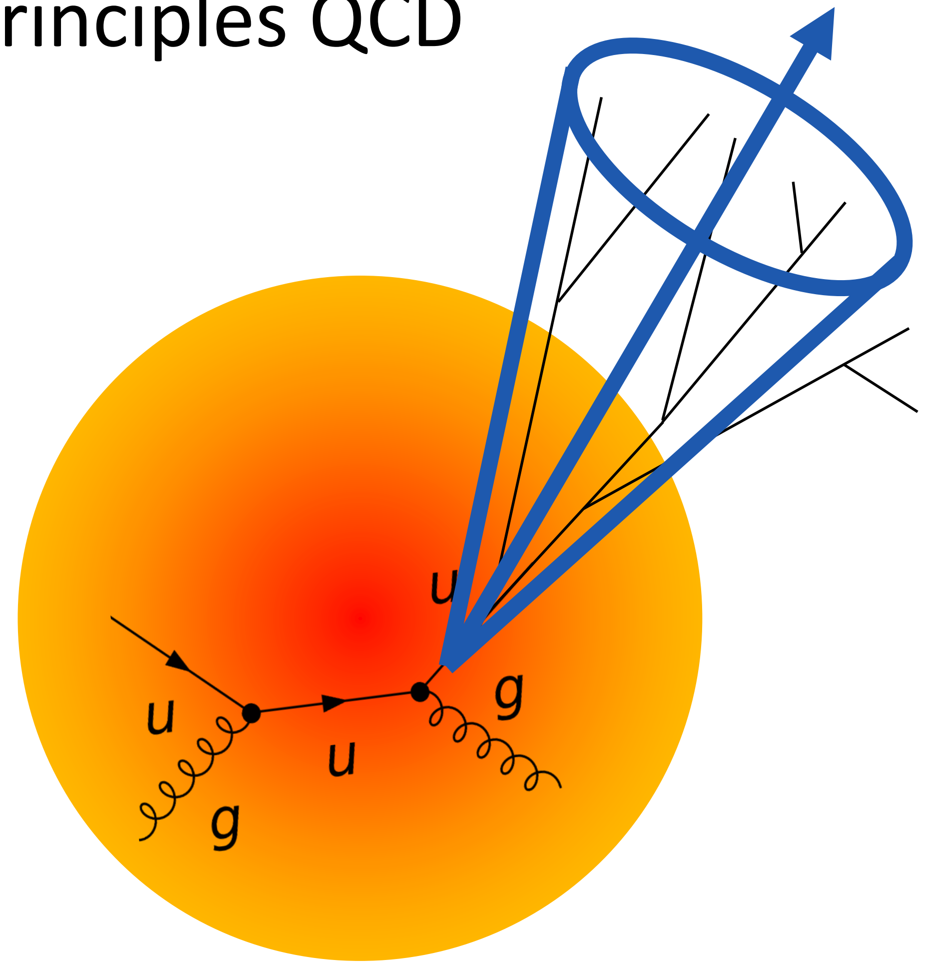
- Medium's degrees of freedom?



In-medium jet modification

- How does the QCD medium affect jet formation?

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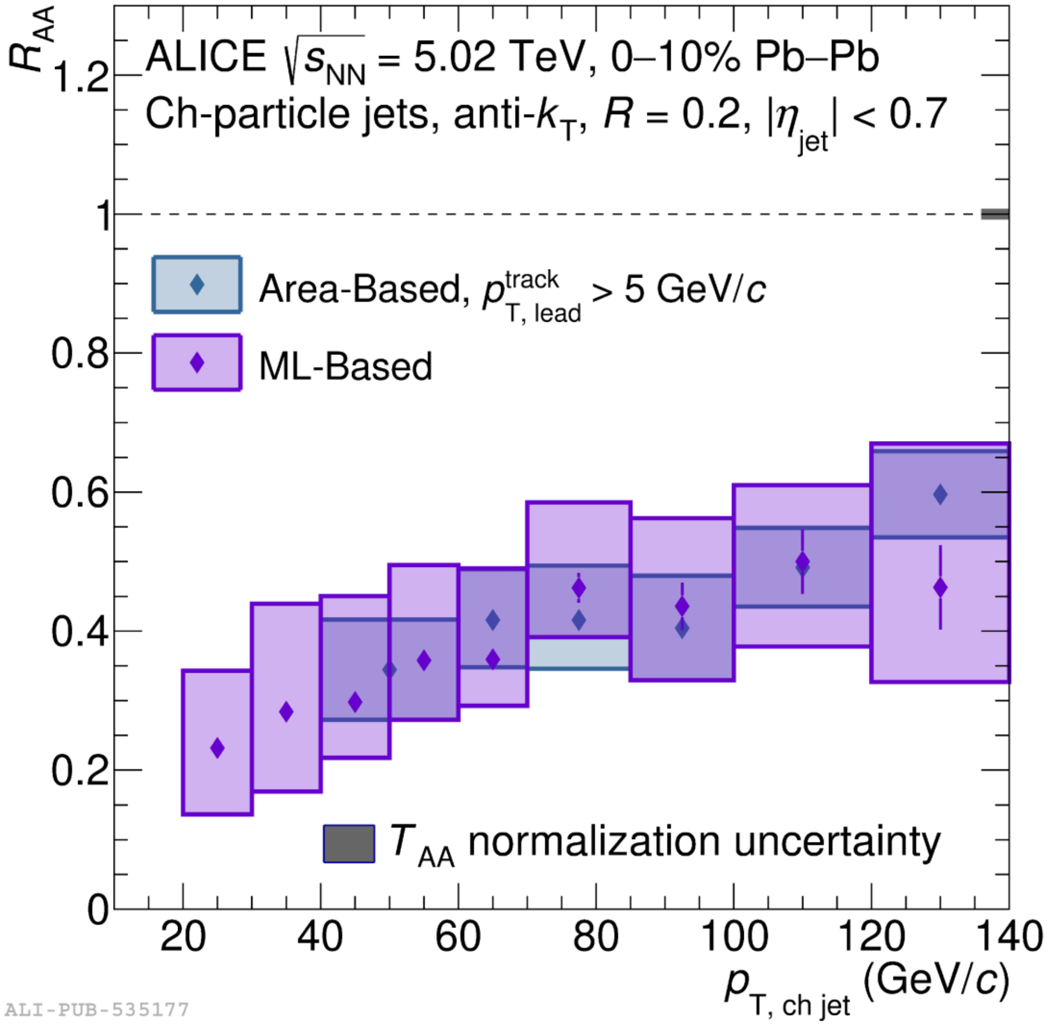

$$\boxed{R_{AA} \sim \frac{\text{jet yield in AA}}{\text{jet yield in pp}}}$$

- $R_{AA} < 1 \quad \rightarrow$ **jets are "quenched"**

ALICE Collaboration,
Phys. Lett. B **849** (2024) 138412

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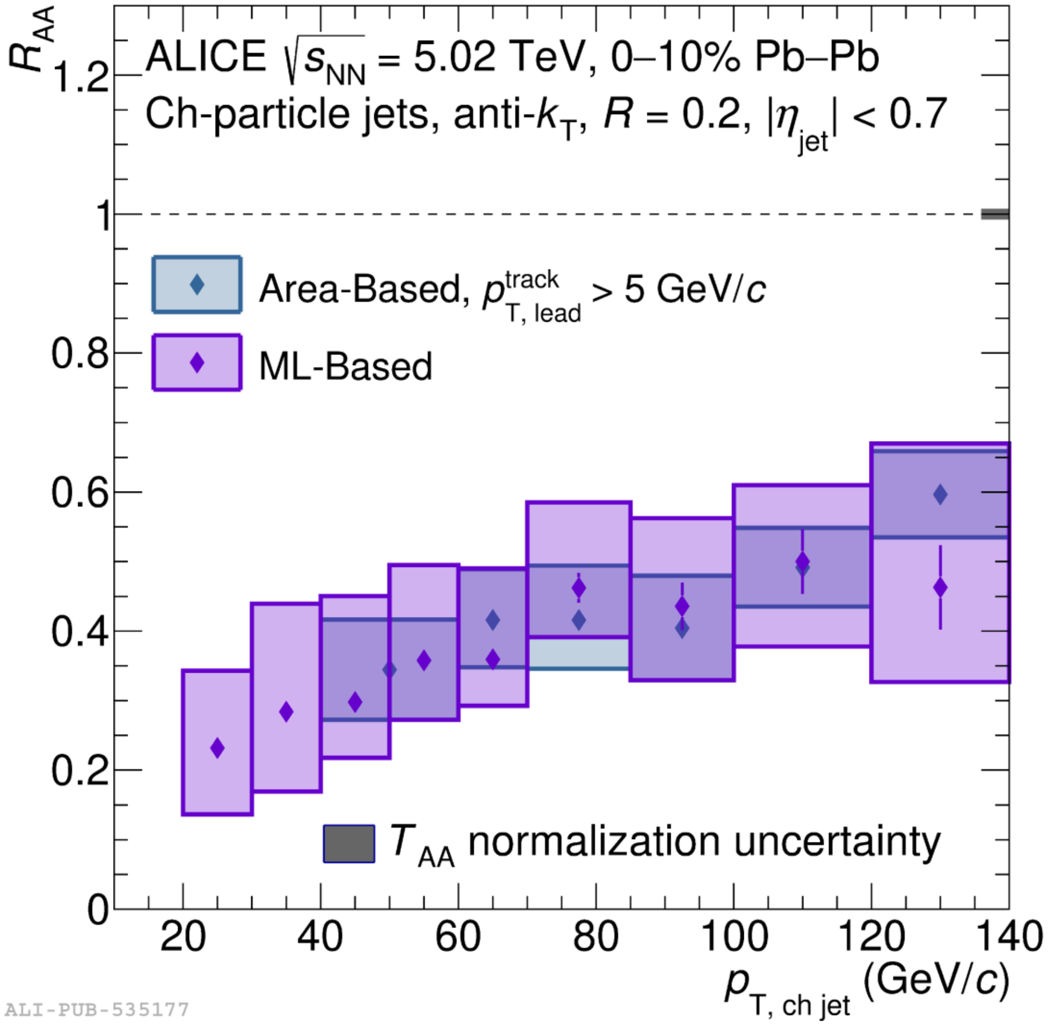

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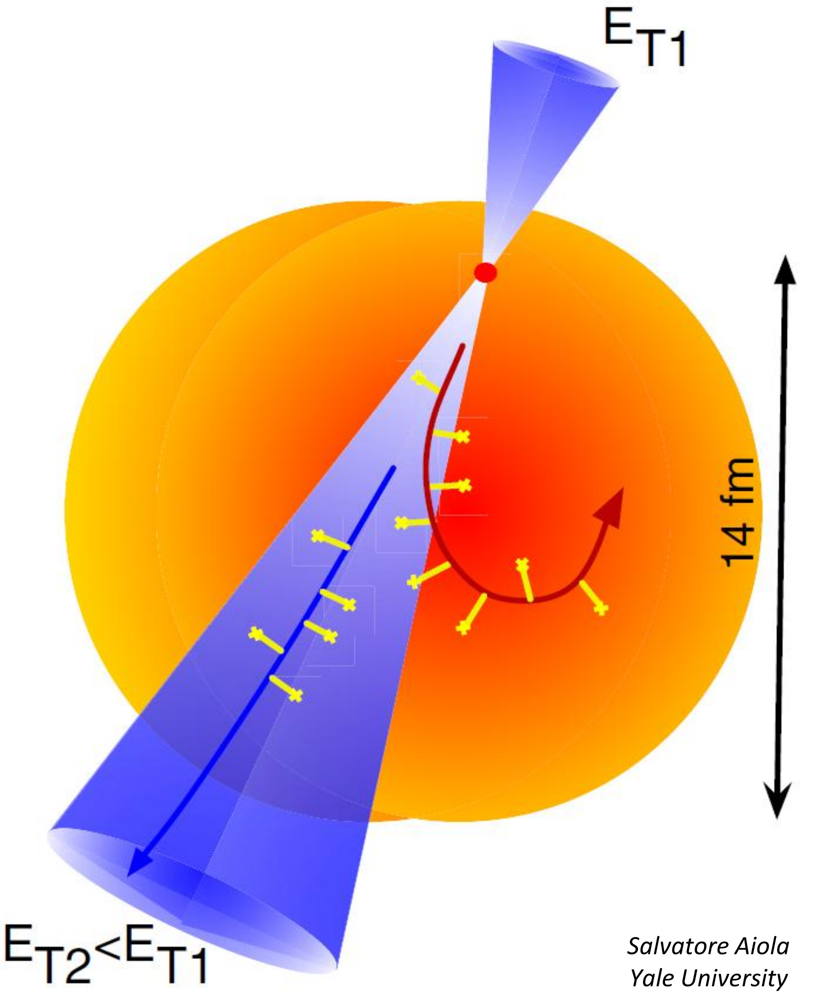

Salvatore Aiola
Yale University

- **Jet substructure** gives insight into the microscopic modification

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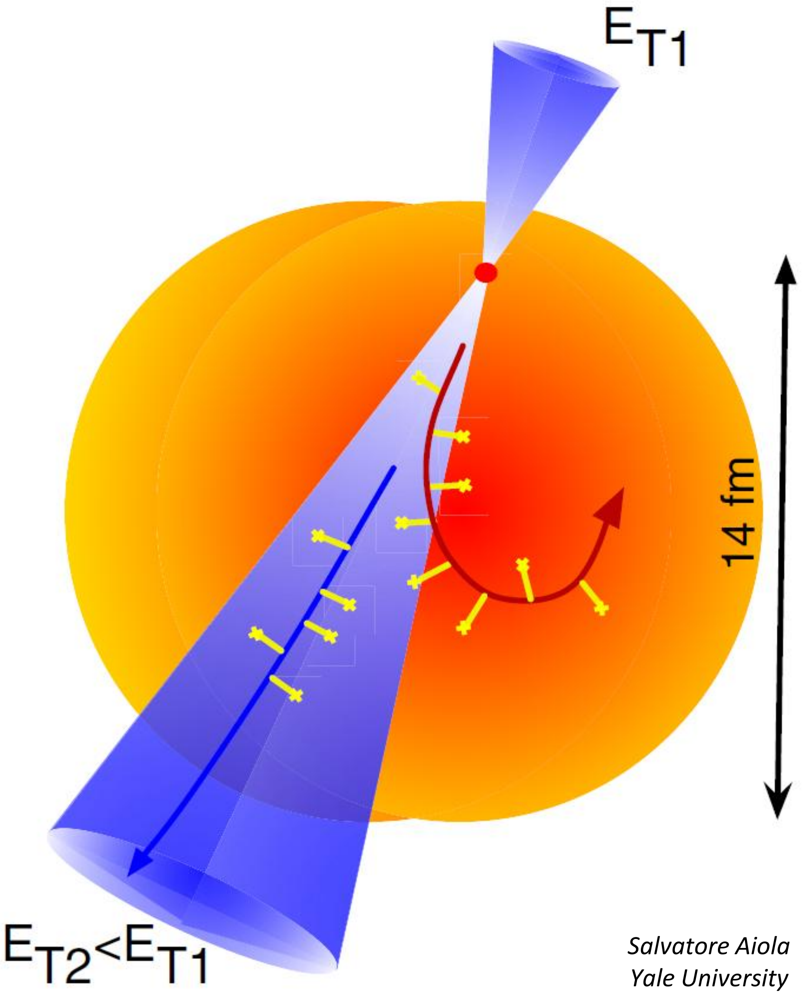

Salvatore Aiola
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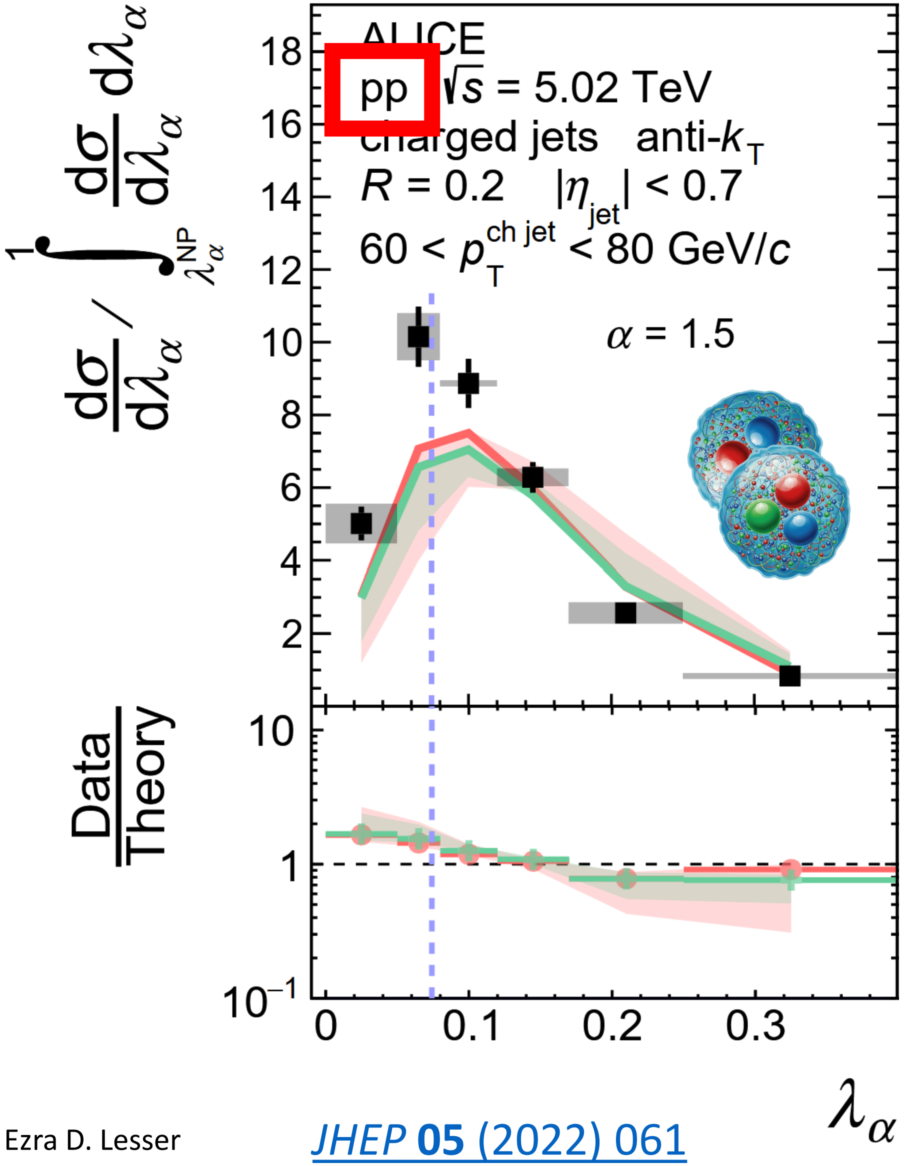
- **Jet substructure** gives insight into the microscopic modification

- Choose jet observables based on the desired physics probe

Jet quenching in angularities



[JHEP **05** (2022) 061]

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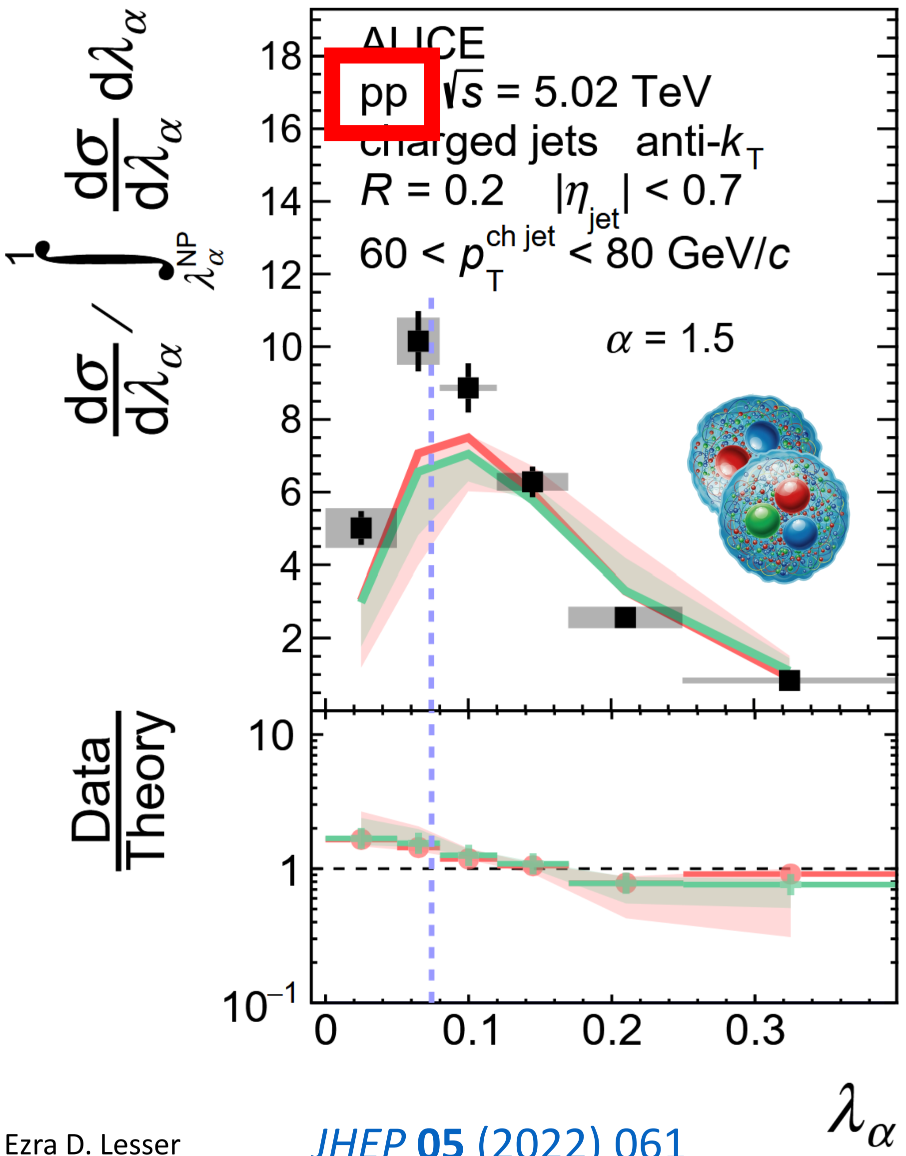

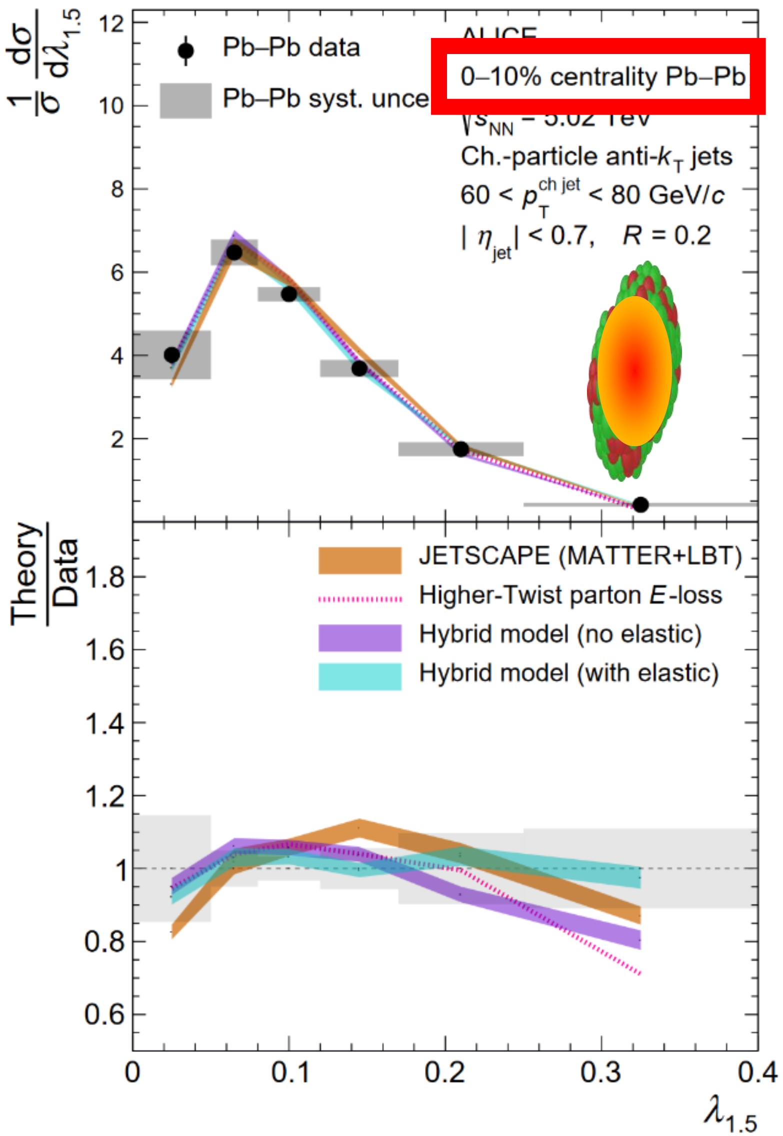

JHEP **05** (2022) 061

Phys. Lett. B **864** (2025) 139409 and ALICE-PUBLIC-2024-004

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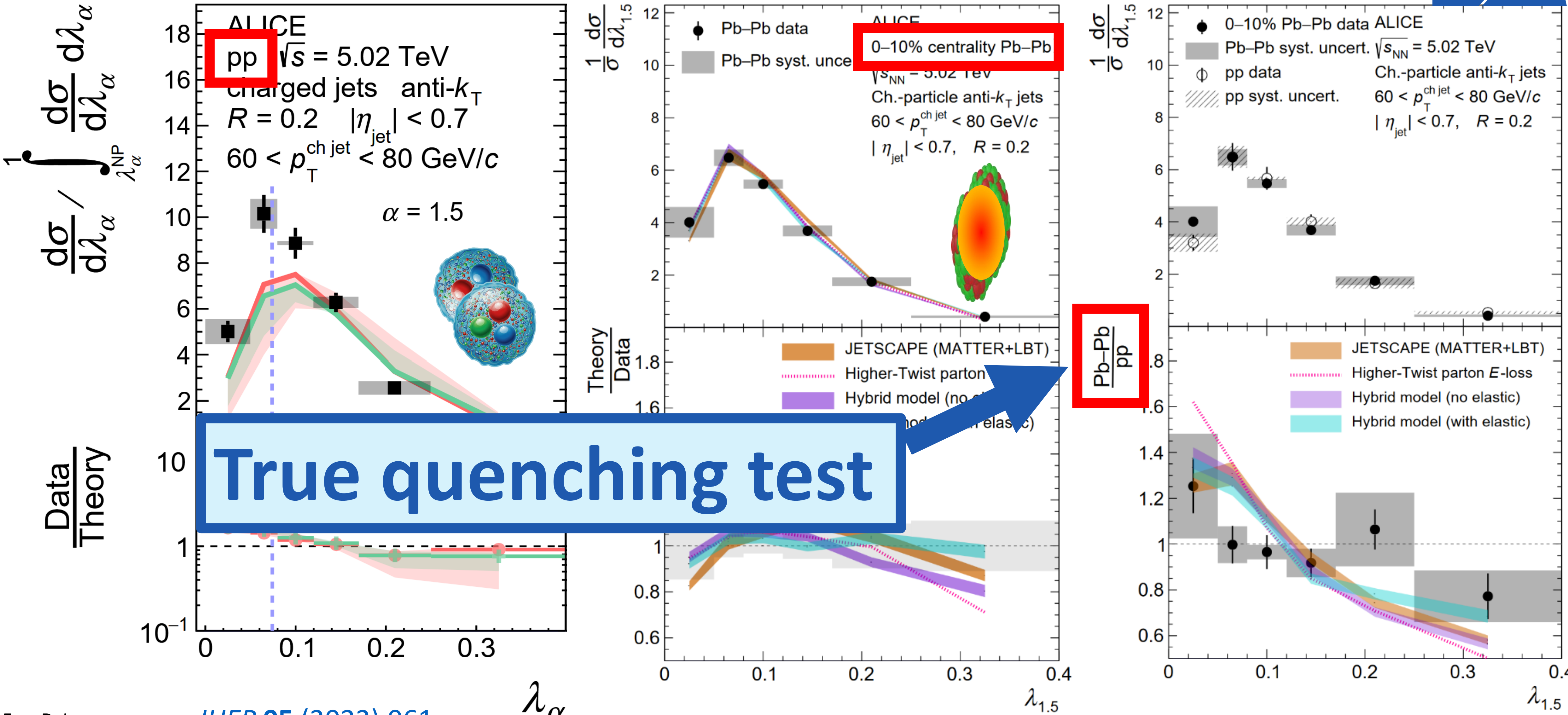

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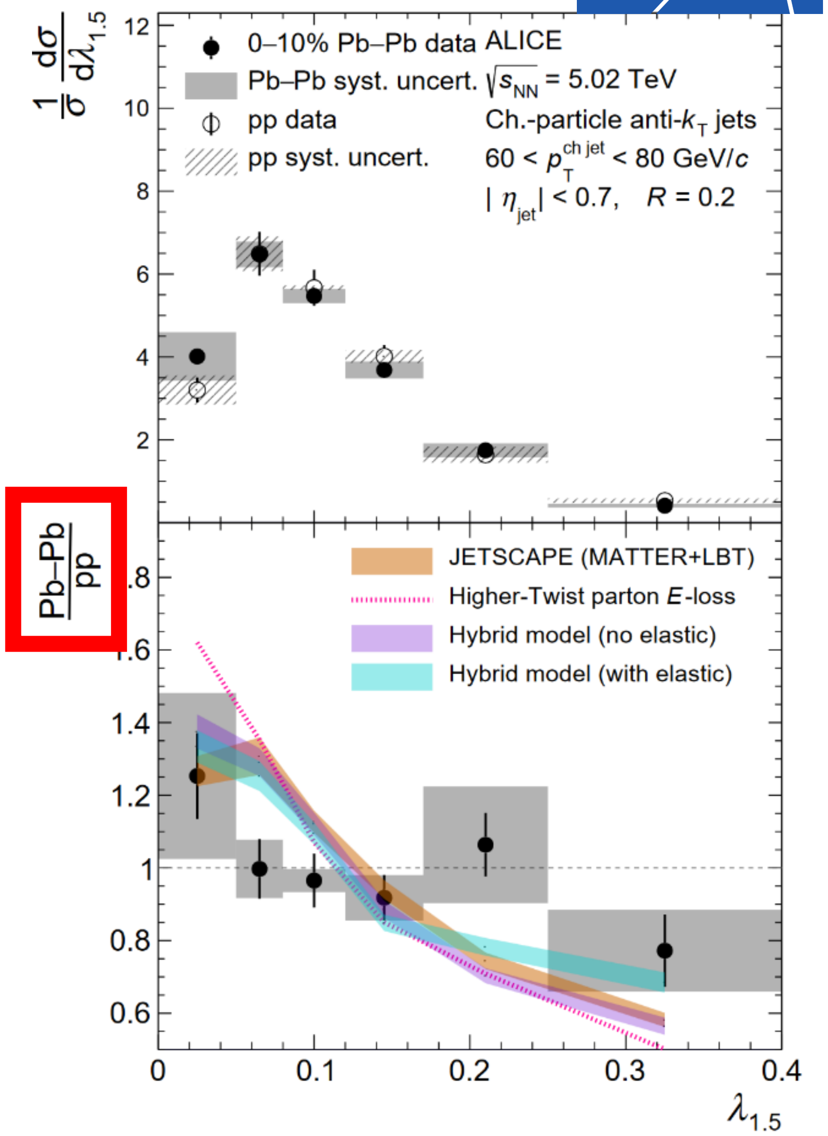

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- **Higher-Twist parton energy loss** exhibits slight tension in the tails *S.-Y. Chen, B.-W. Zhang, et al.* *Chin. Phys. C* **45** (2021) 2, 024102
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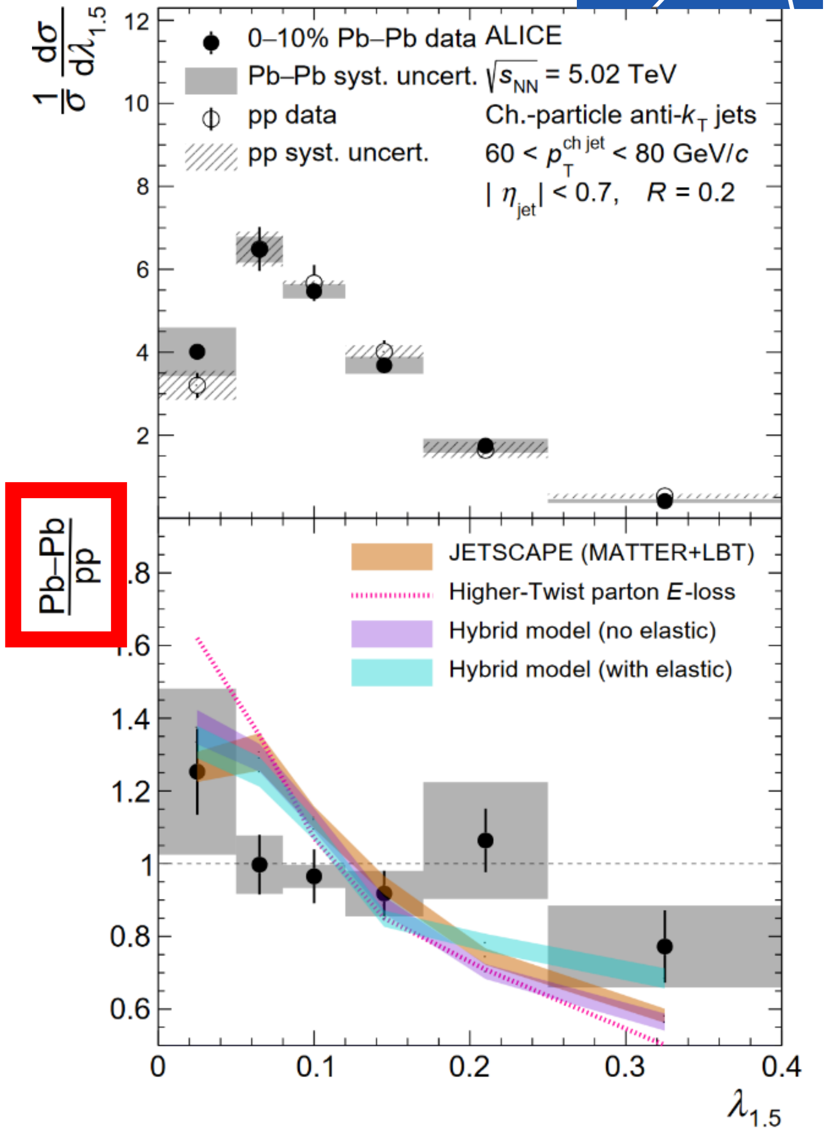

Phys. Lett. B **864** (2025) 139409 and ALICE-PUBLIC-2024-004

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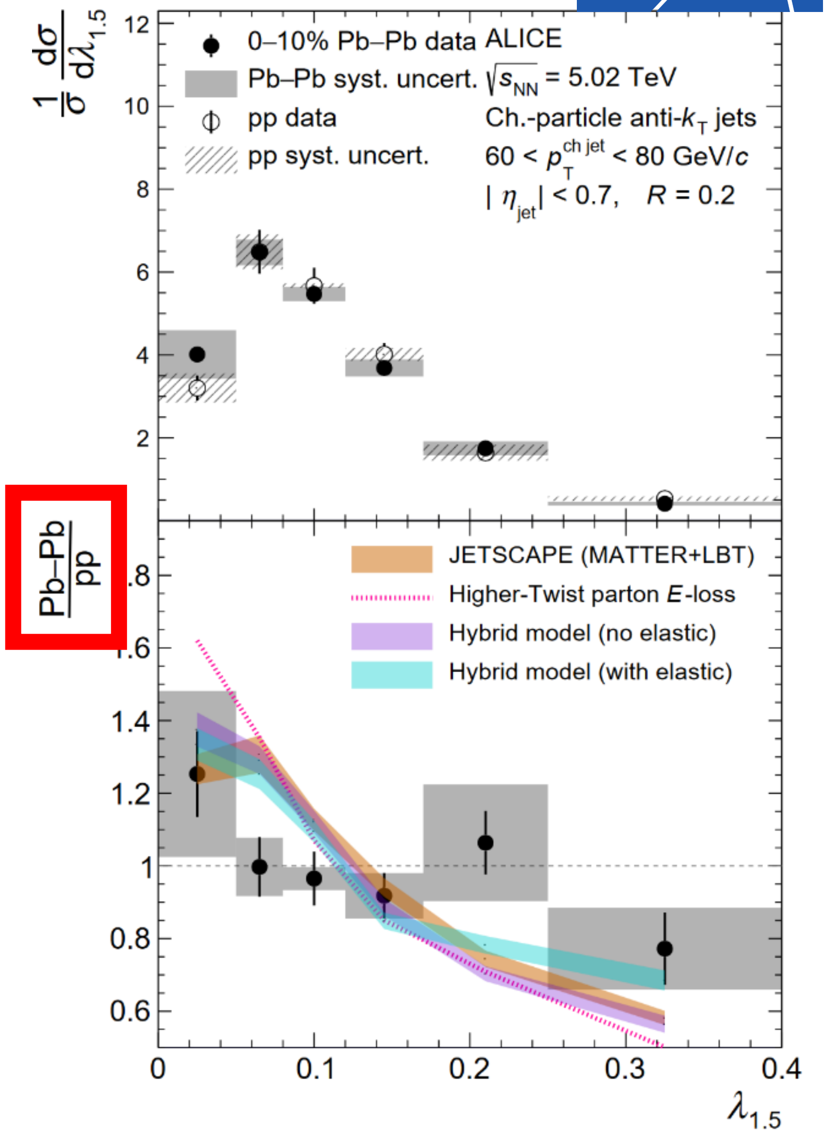
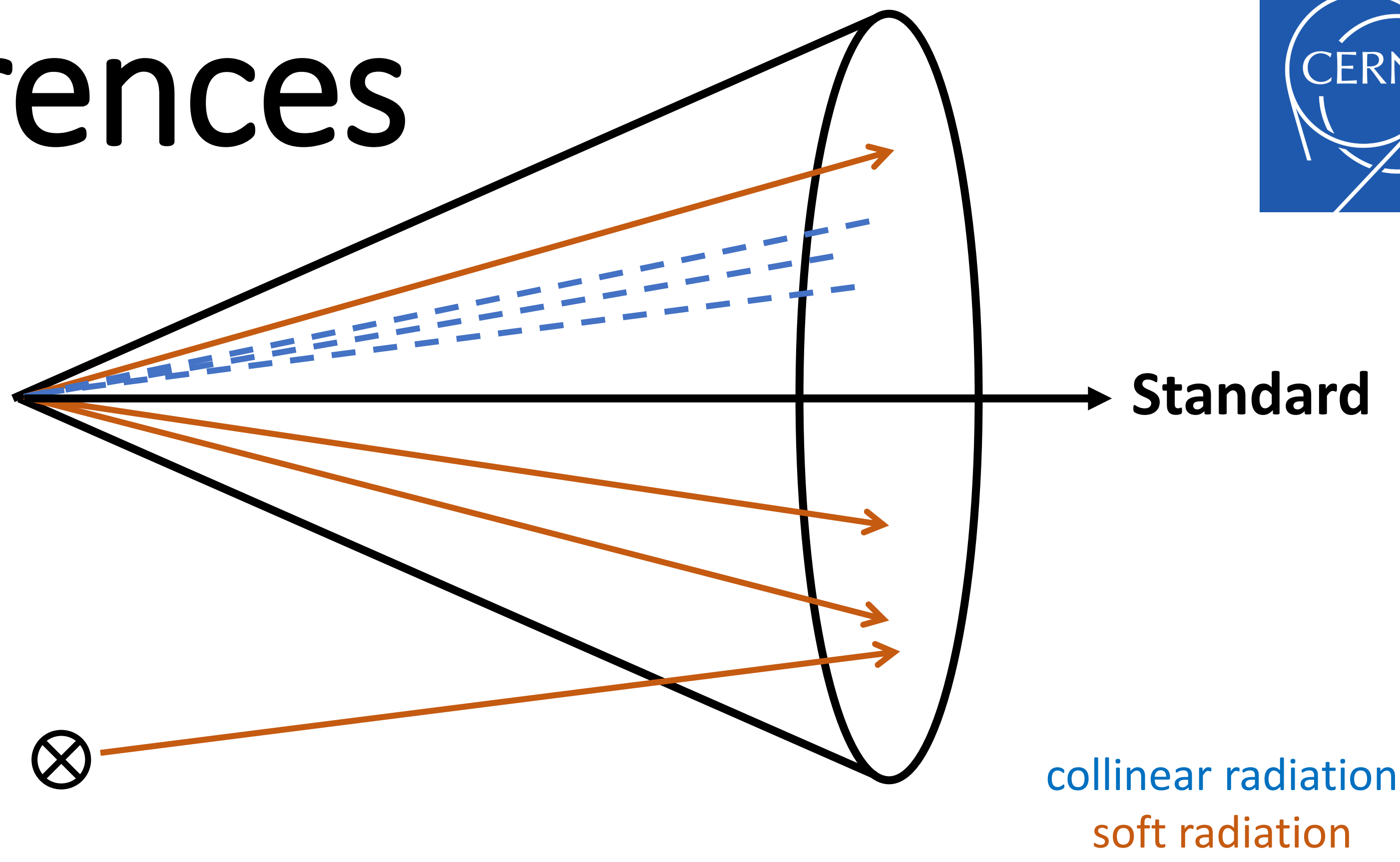
- Measurements across α and p_{T}: **broad constraints on theoretical models**



Phys. Lett. B **864** (2025) 139409 and ALICE-PUBLIC-2024-004

Jet-axis differences

- **Standard**: anti-k_{T} jet with E-scheme recombination



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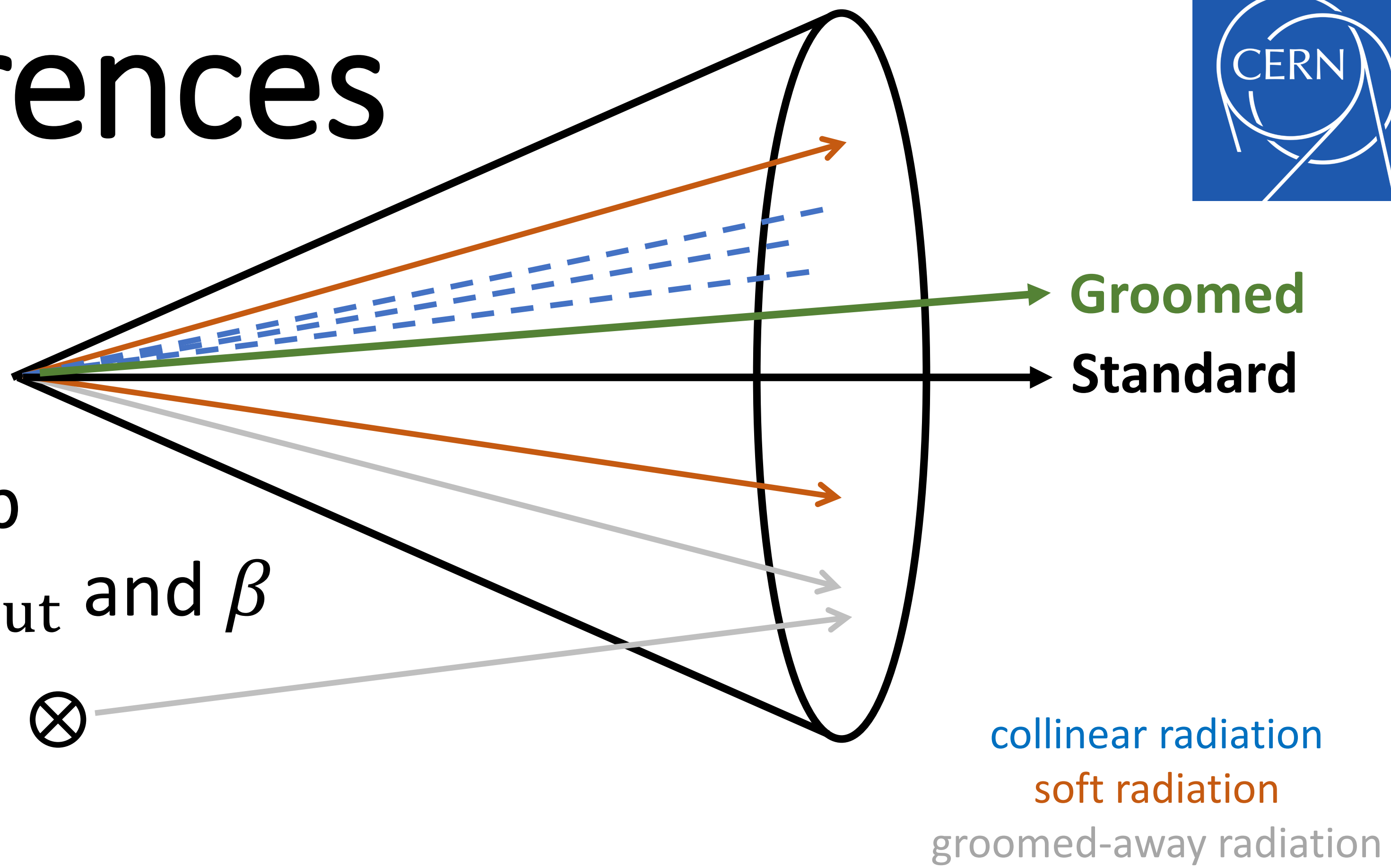

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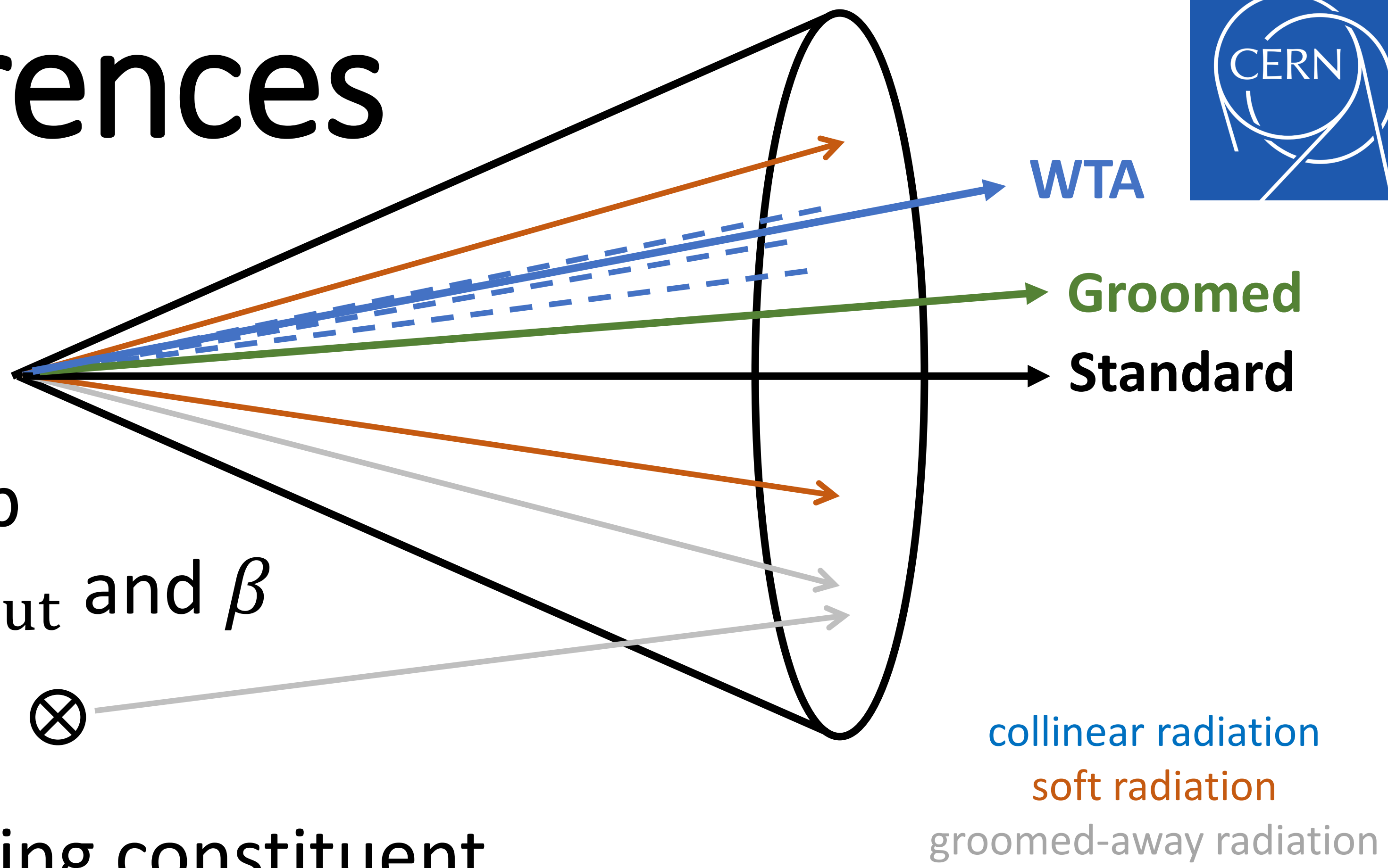

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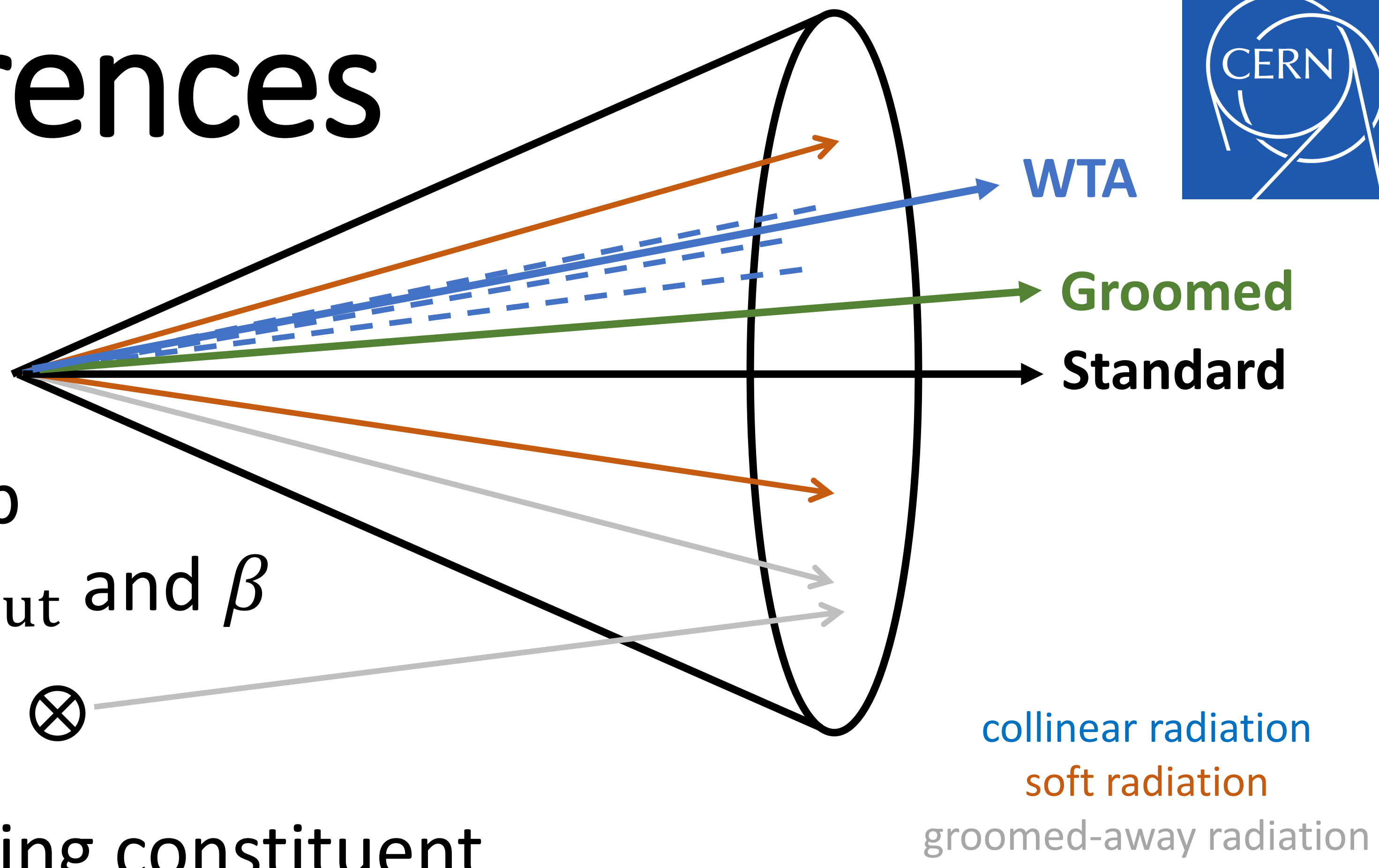

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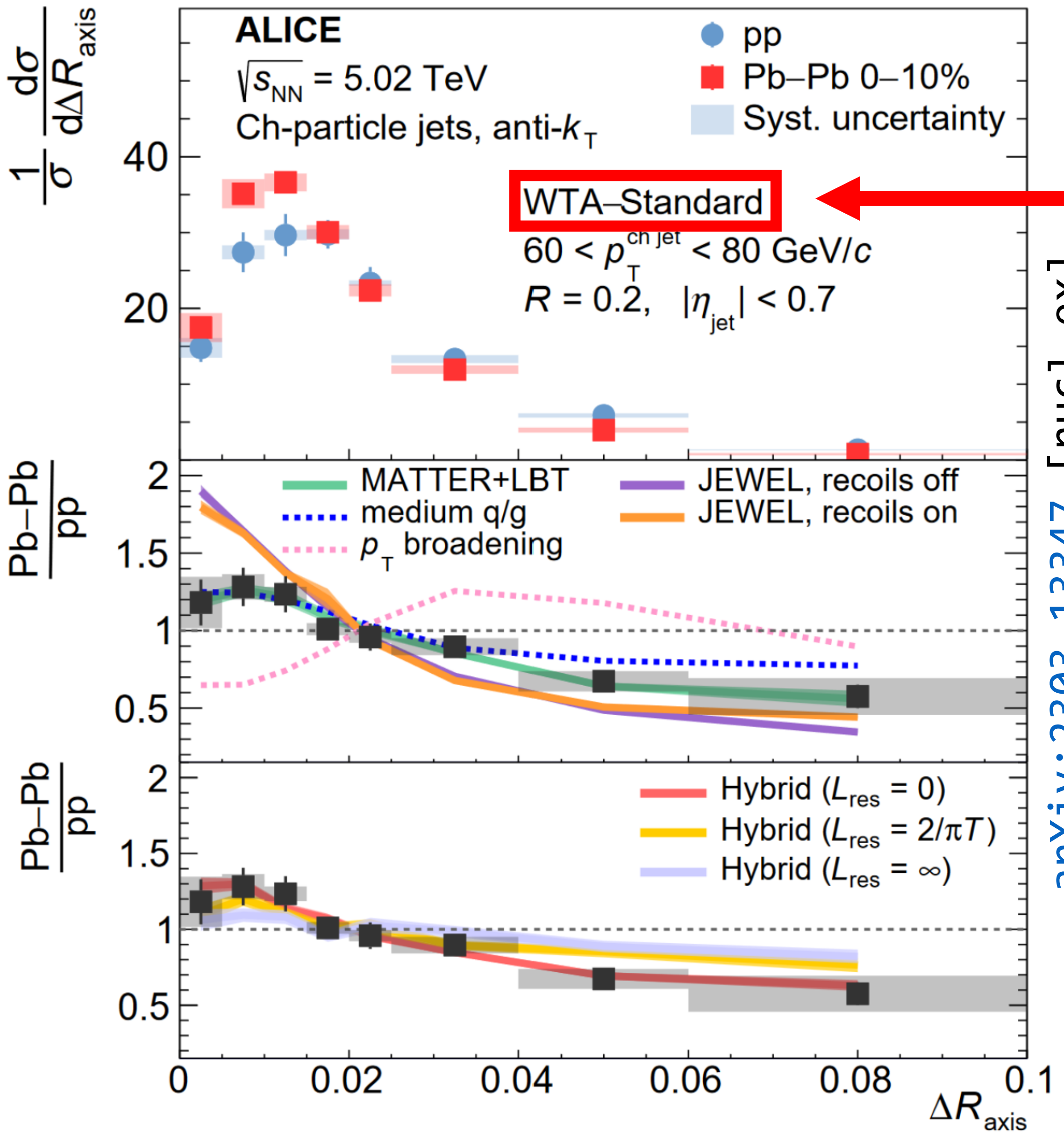
- **Groomed**: apply Soft Drop with different values of z_{cut} and β
- **Winner-Take-All (WTA)**: jet axis is given by its leading constituent
- Calculate the angular separation: $\Delta R_{\mathrm{axis}} = \sqrt{\Delta y^2 + \Delta\phi^2}$
- IRC-safe observable sensitive to **soft radiation, TMDs, and PDFs**

Cal, Neill, Ringer, Waalewijn [JHEP **04** (2020) 211]

Jet axis differences in Pb-Pb vs. pp



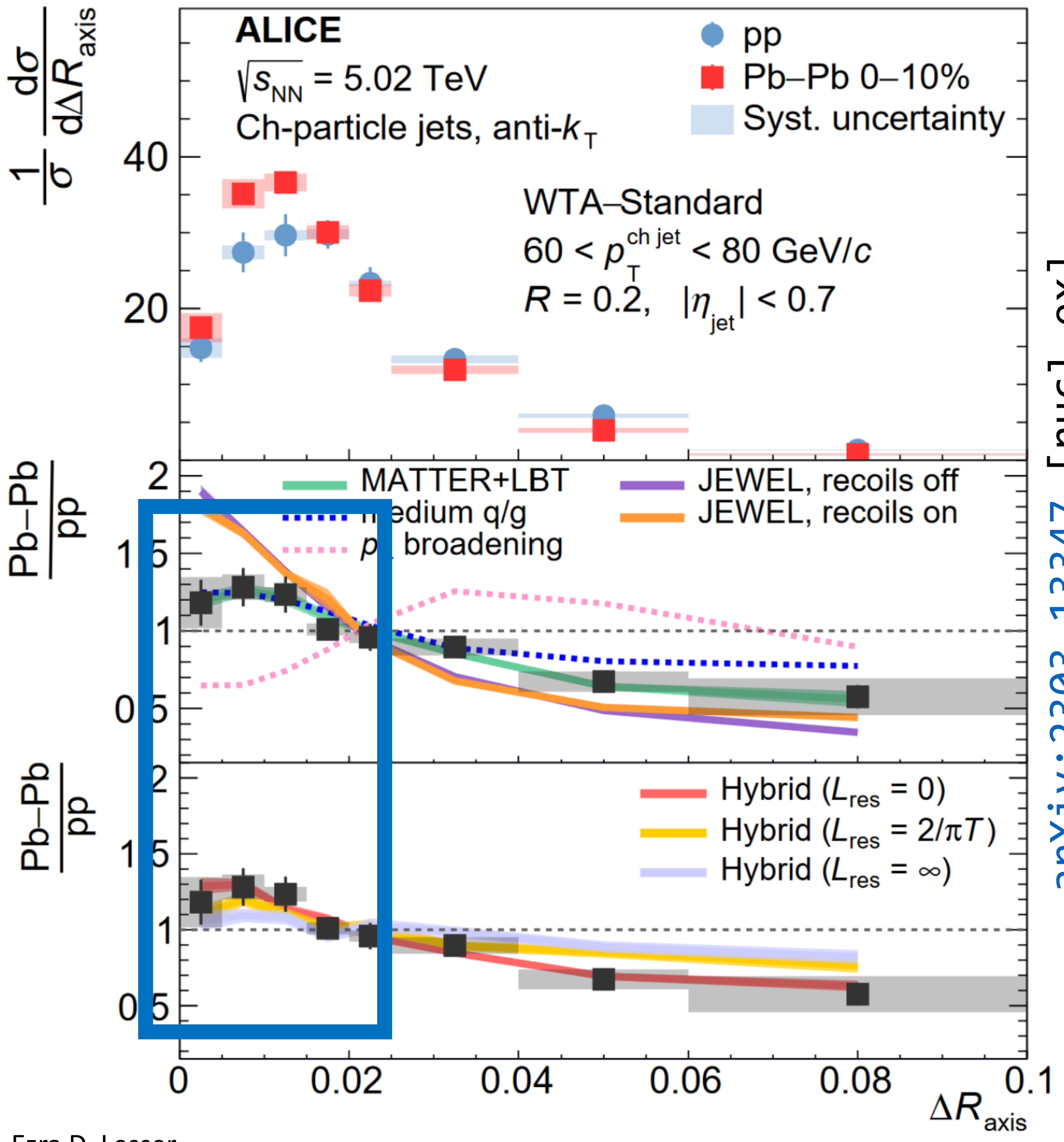
[nucl-ex] arXiv:2303.13347

Standard (E-scheme)

vs.

Winner-Take-All

Jet axis differences in Pb-Pb vs. pp



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  - *Consistent with "narrowing"*

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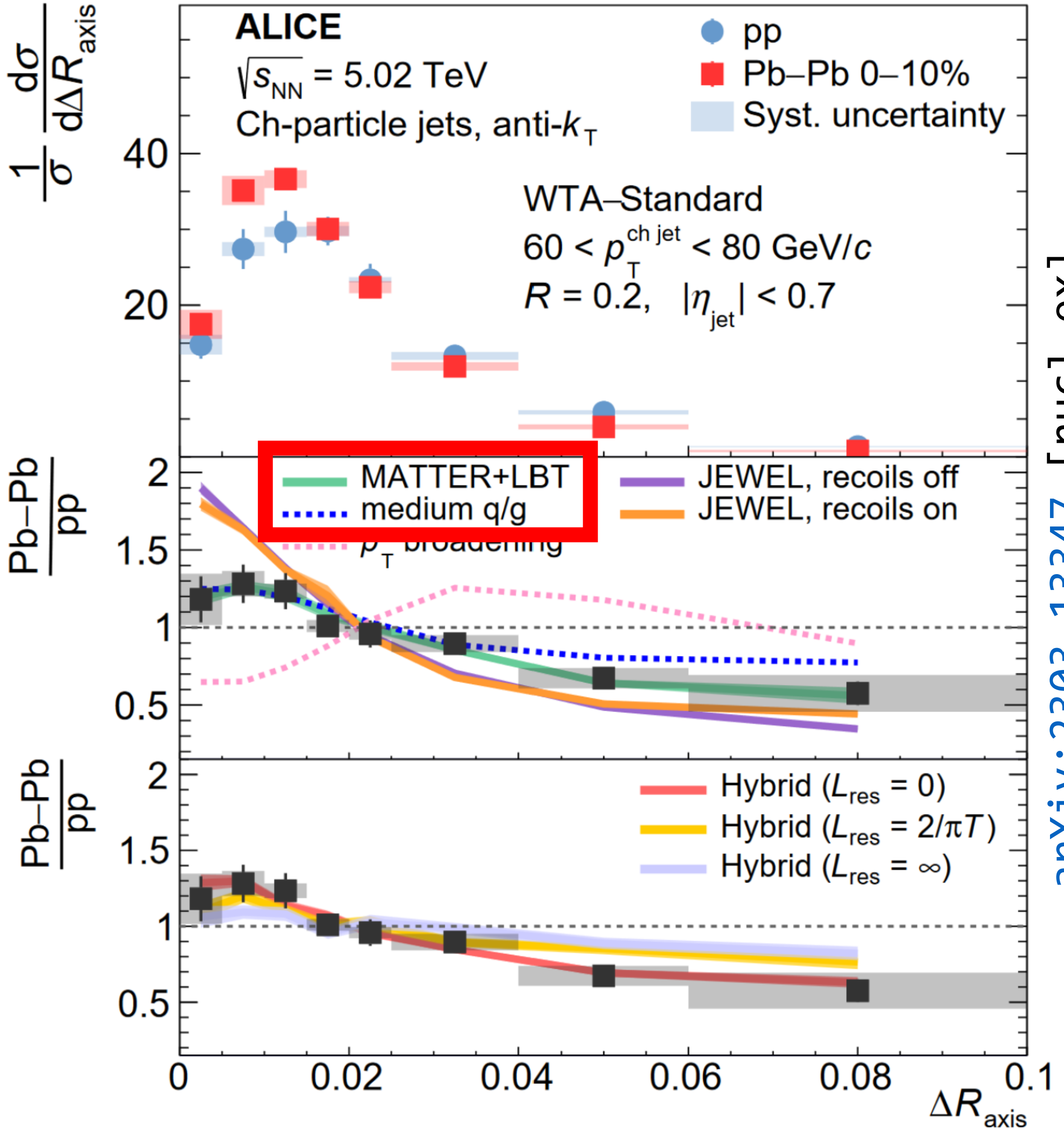

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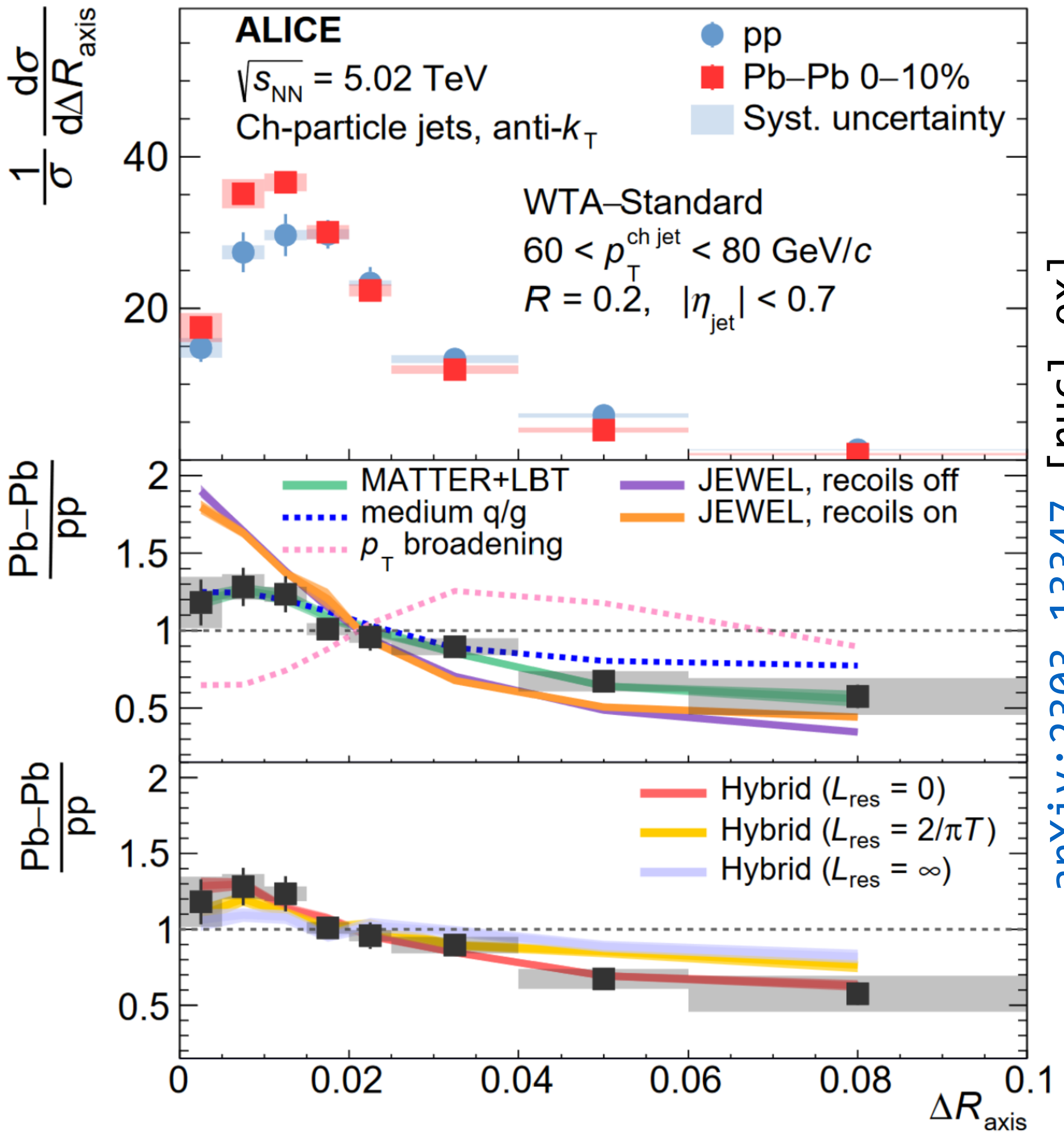

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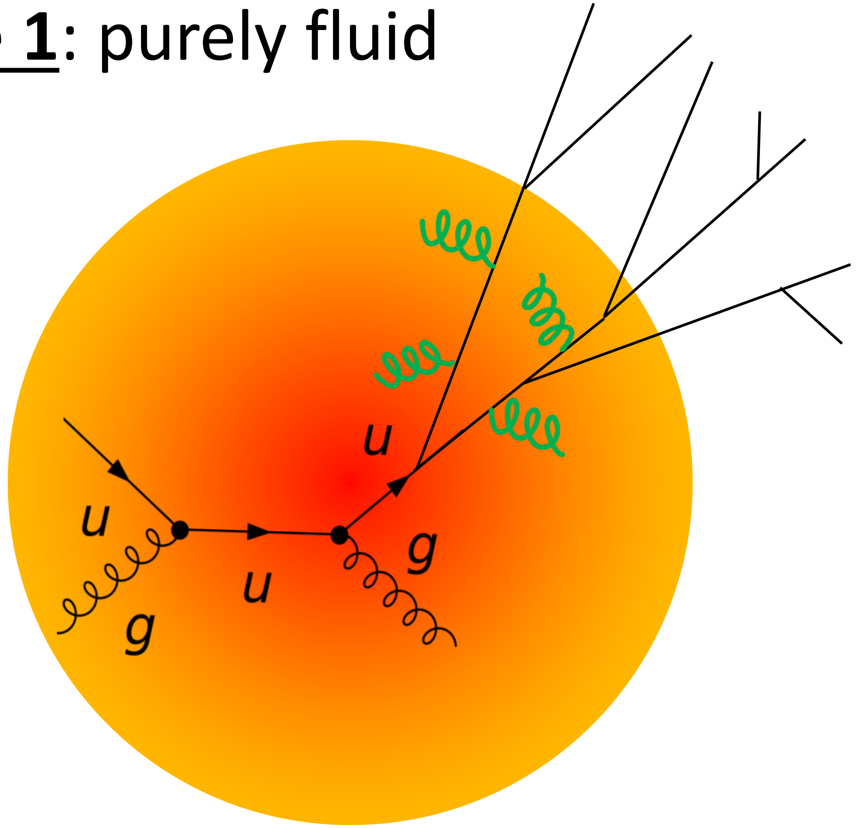
- **Quenched jet axes are more similar** than vacuum jets
  - *Consistent with "narrowing"*
- Agreement with **JETSCAPE (MATTER+LBT)** and **medium q/g modification** calculations
- Preference towards **zero resolution length of the medium** in Hybrid model

→ **Consistent with other models?**

Multiple hard interactions in QGP?

Picture 1: purely fluid

D'Eramo, Rajagopal, Yin
JHEP **01** (2019) 172



Jet fragmentation
+ medium-induced emissions

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D'Eramo, Rajagopal, Yin
JHEP **01** (2019) 172

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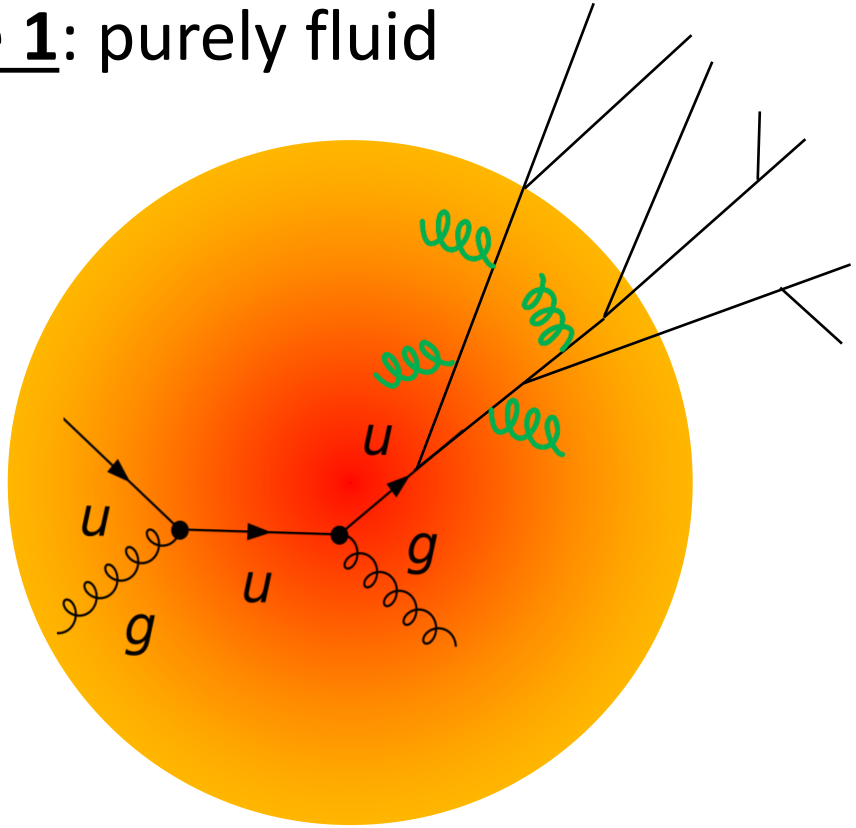

Jet fragmentation
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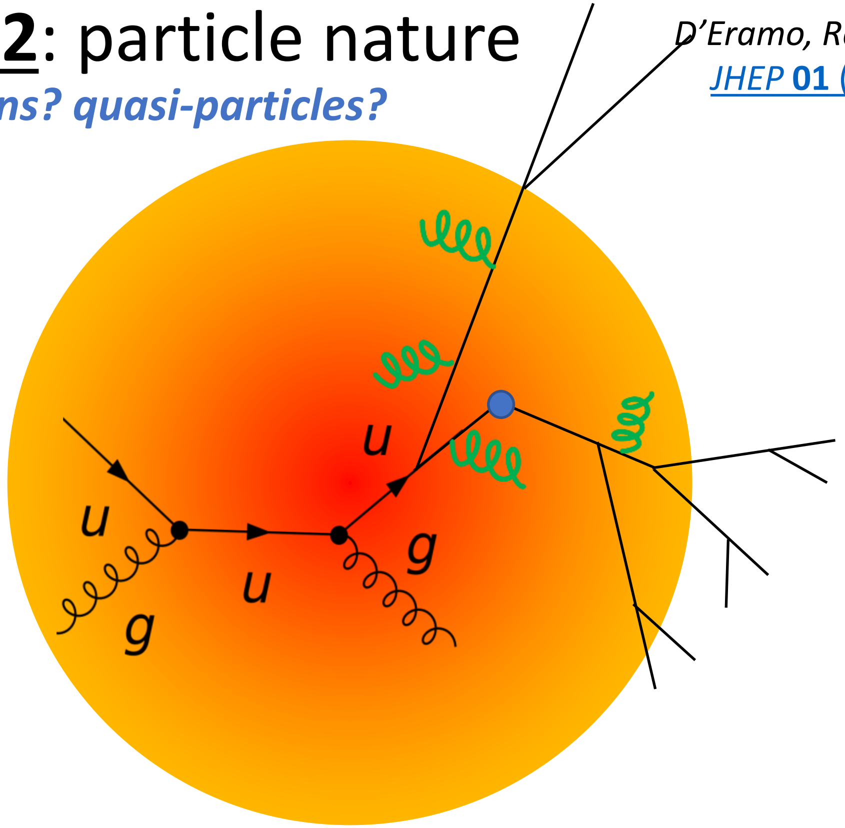
Picture 2: particle nature
partons? quasi-particles?



Jet fragmentation
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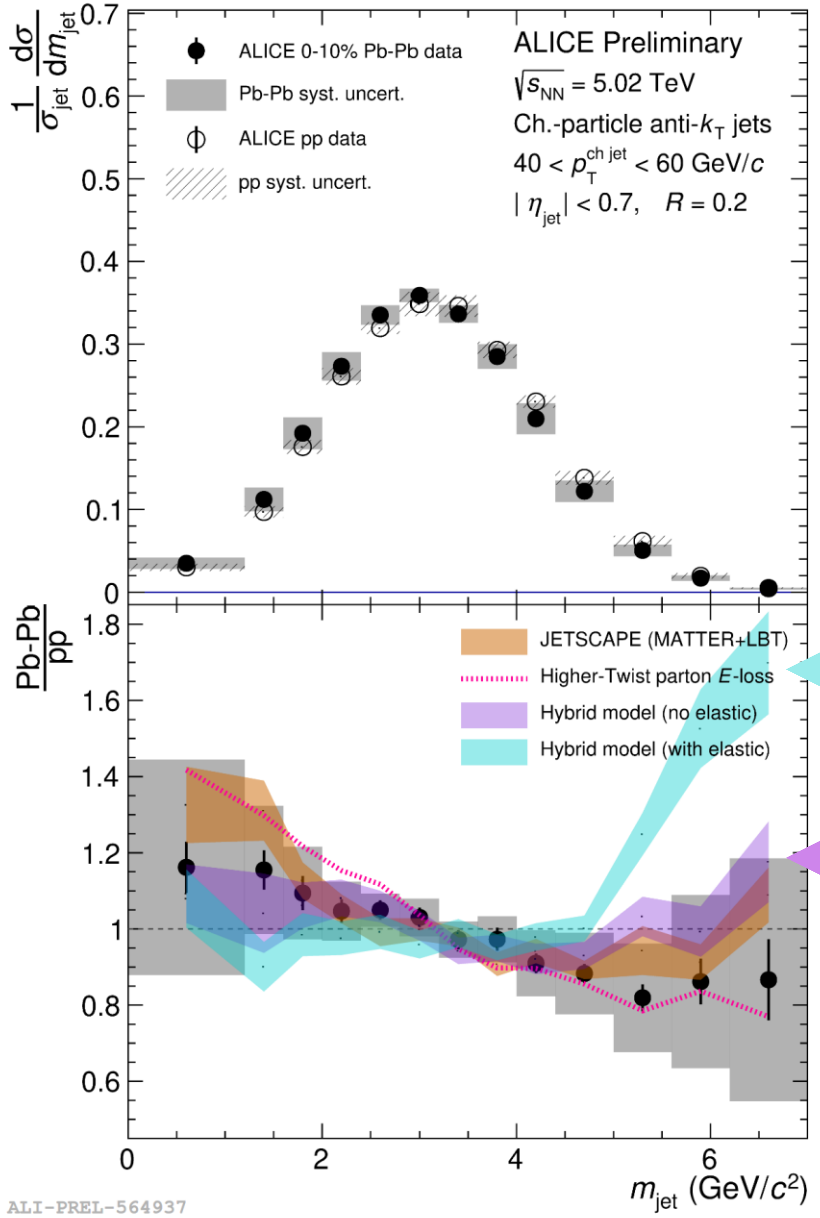
+ elastic Molière scattering?

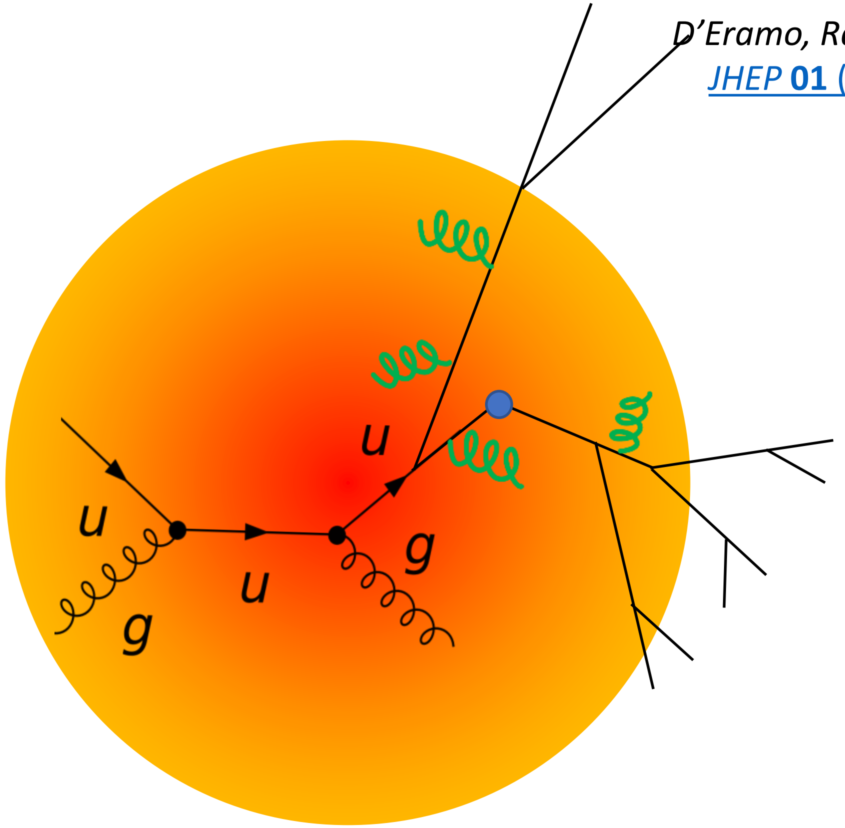
Multiple hard interactions in QGP?



With Molière

No Molière

D'Eramo, Rajagopal, Yin
JHEP **01** (2019) 172



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Phys. Lett. B **864** (2025) 139409 and ALICE-PUBLIC-2024-004

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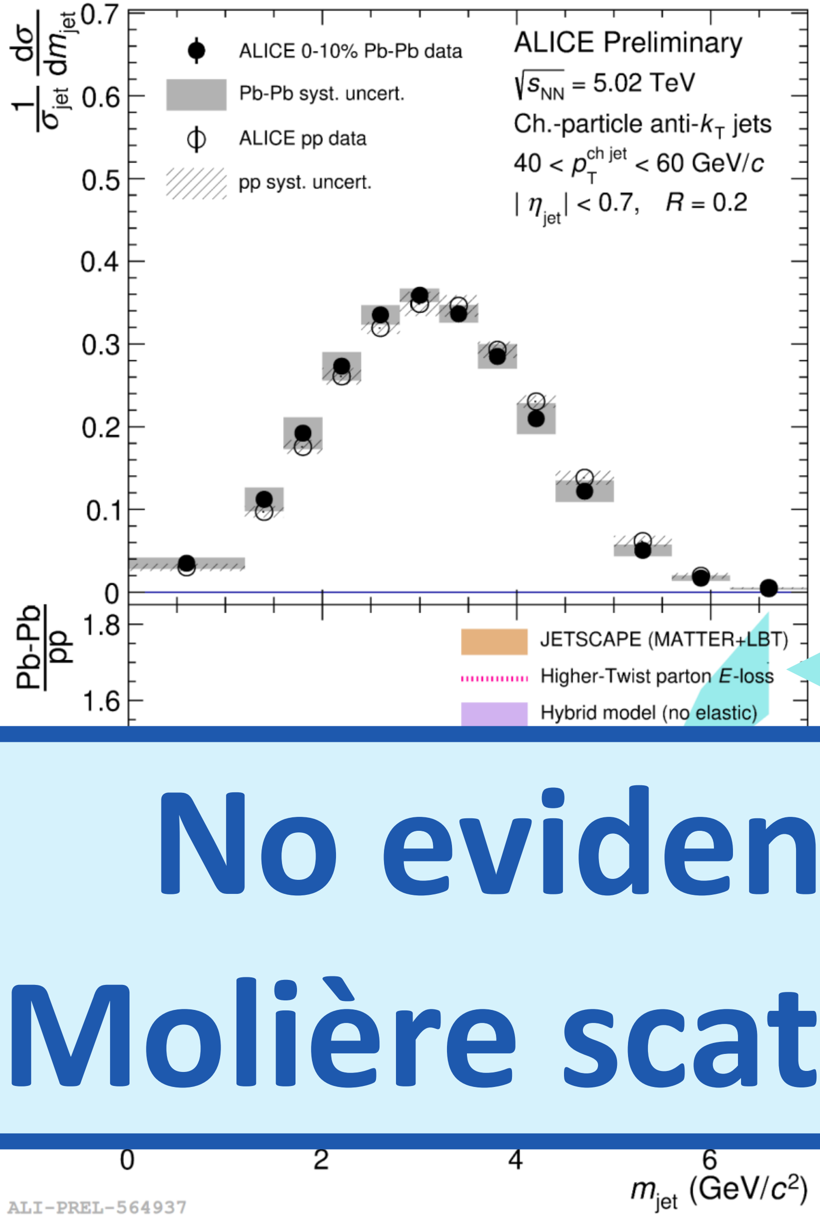

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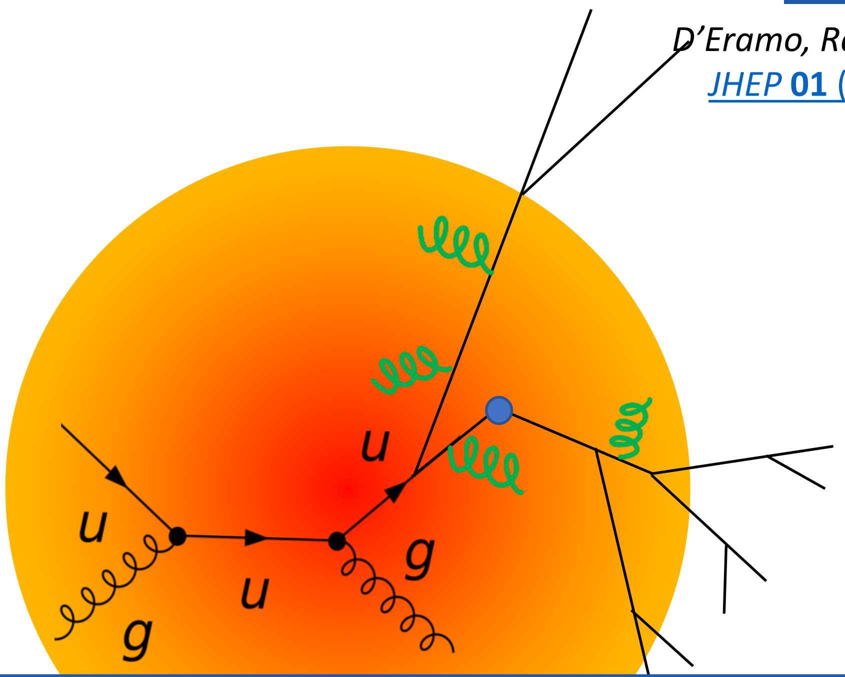
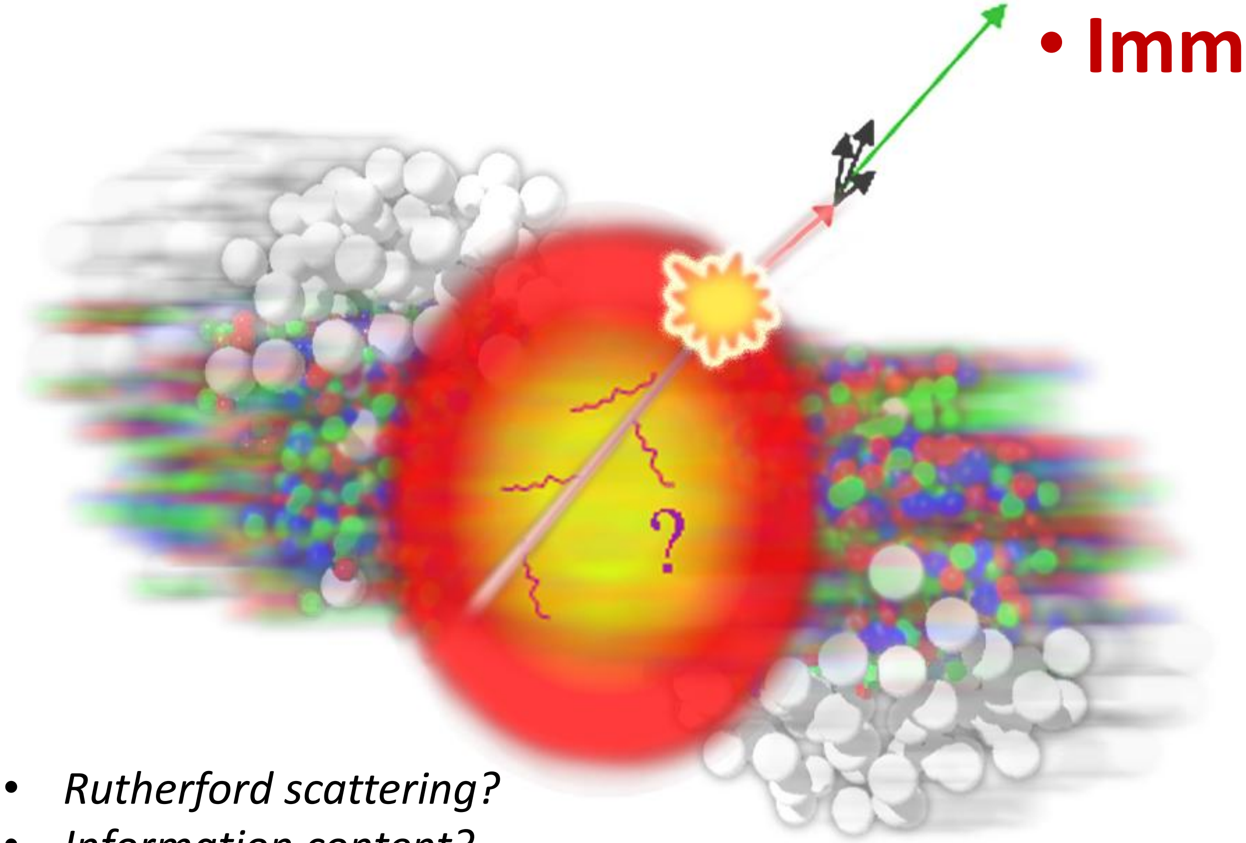
D'Eramo, Rajagopal, Yin
JHEP **01** (2019) 172



No evidence for in-medium Molière scattering in this model

How hard must a probe be?

- Low-p_{T} jets (< 40 GeV/c) **challenging in QGP**
  - **Immense uncorrelated background**



- *Rutherford scattering?*
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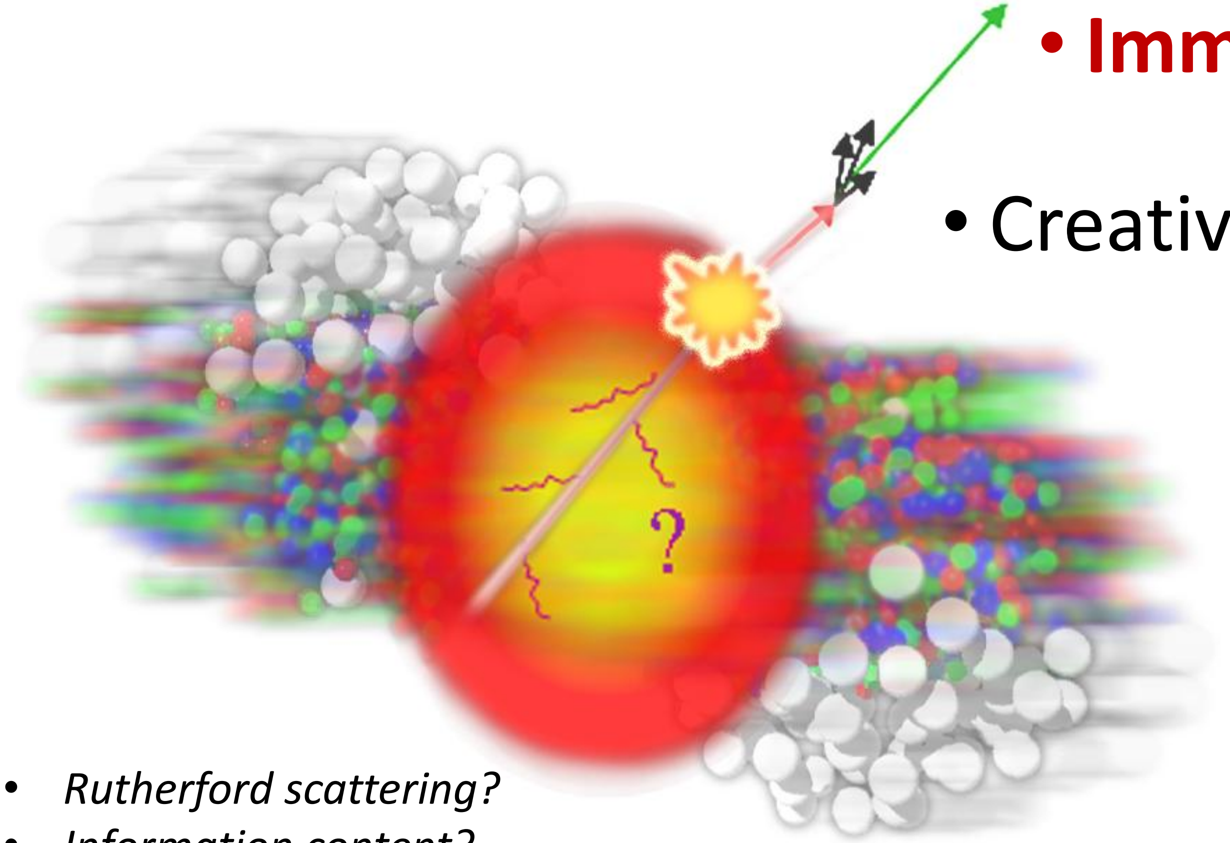
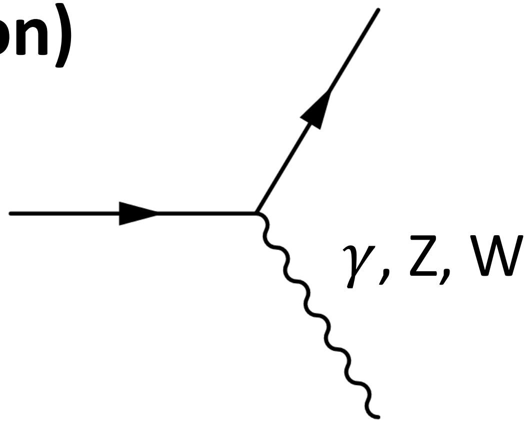


- Rutherford scattering?
- Information content?

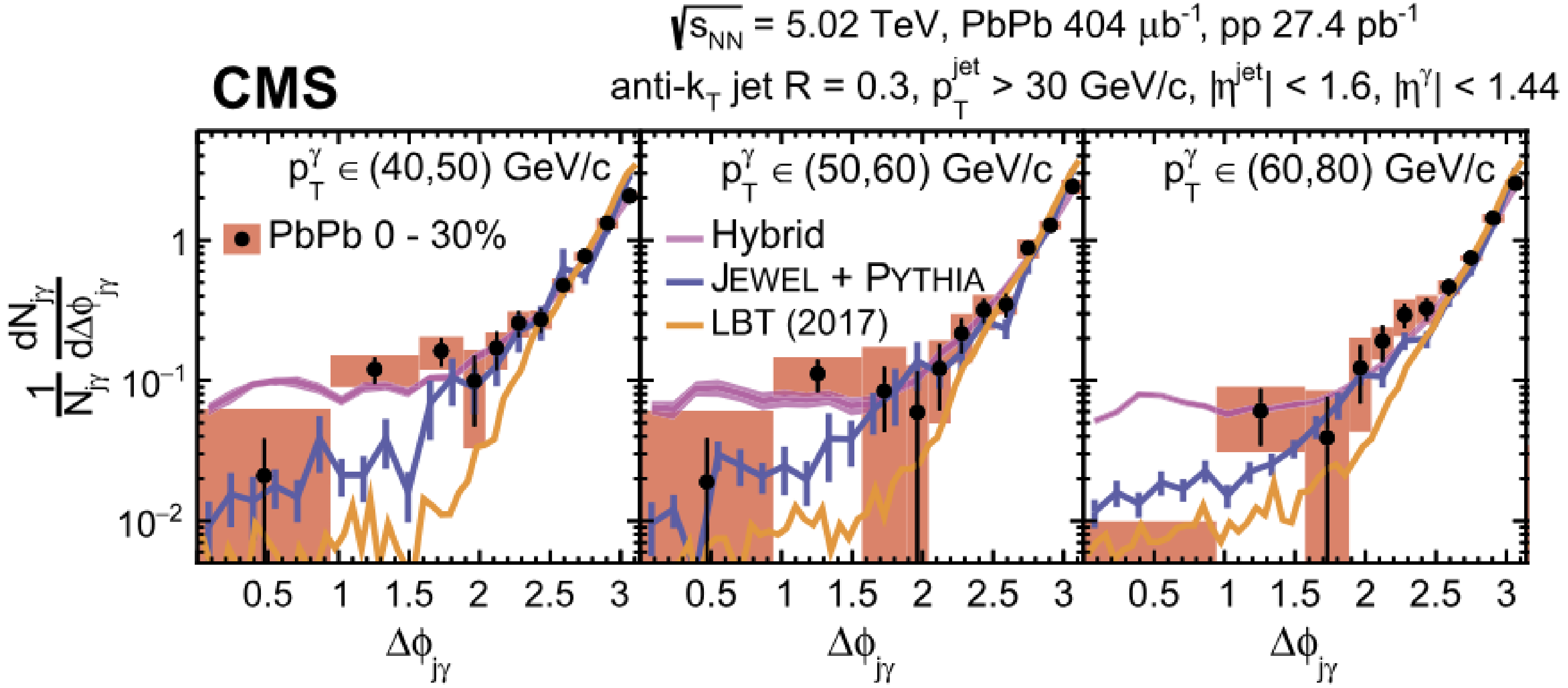
- Creative solution:

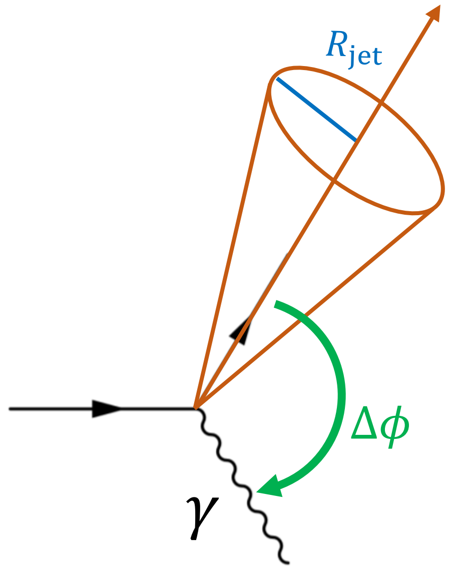
Tagging jets using a **transverse probe (e.g. EW boson)**



... or another **semi-hard hadron**

Photon-tagged jet correlations





Phys. Lett. B **785** (2018) 14-39

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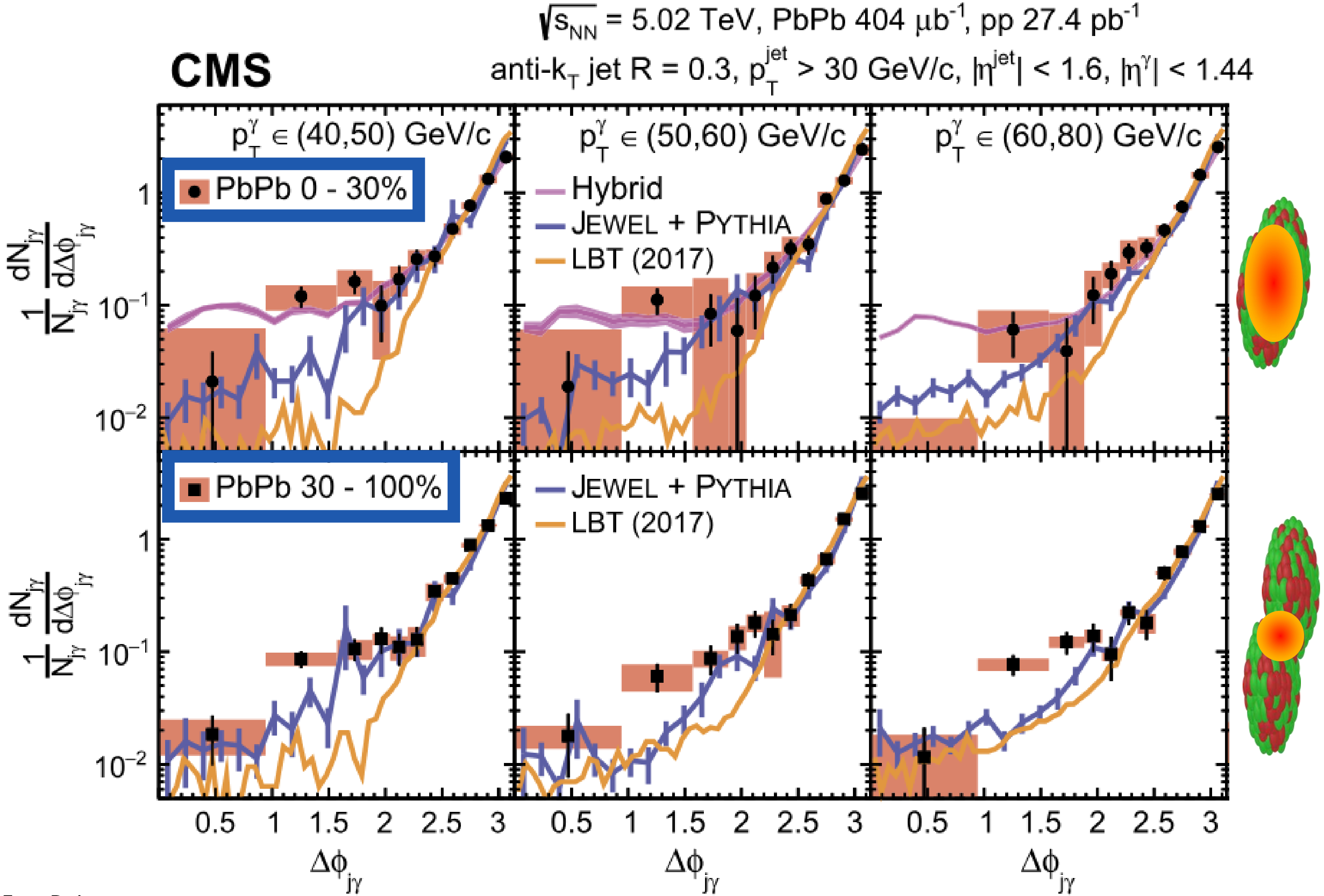

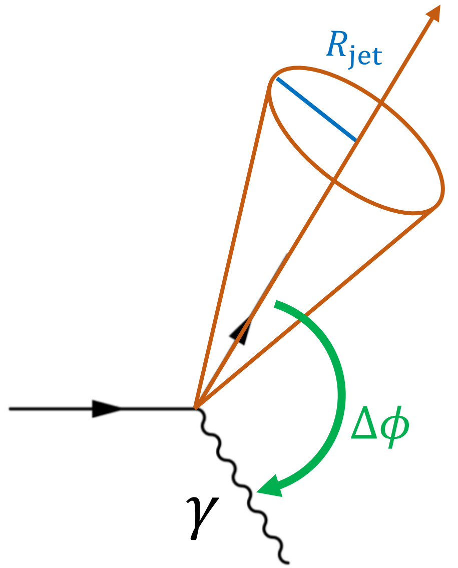

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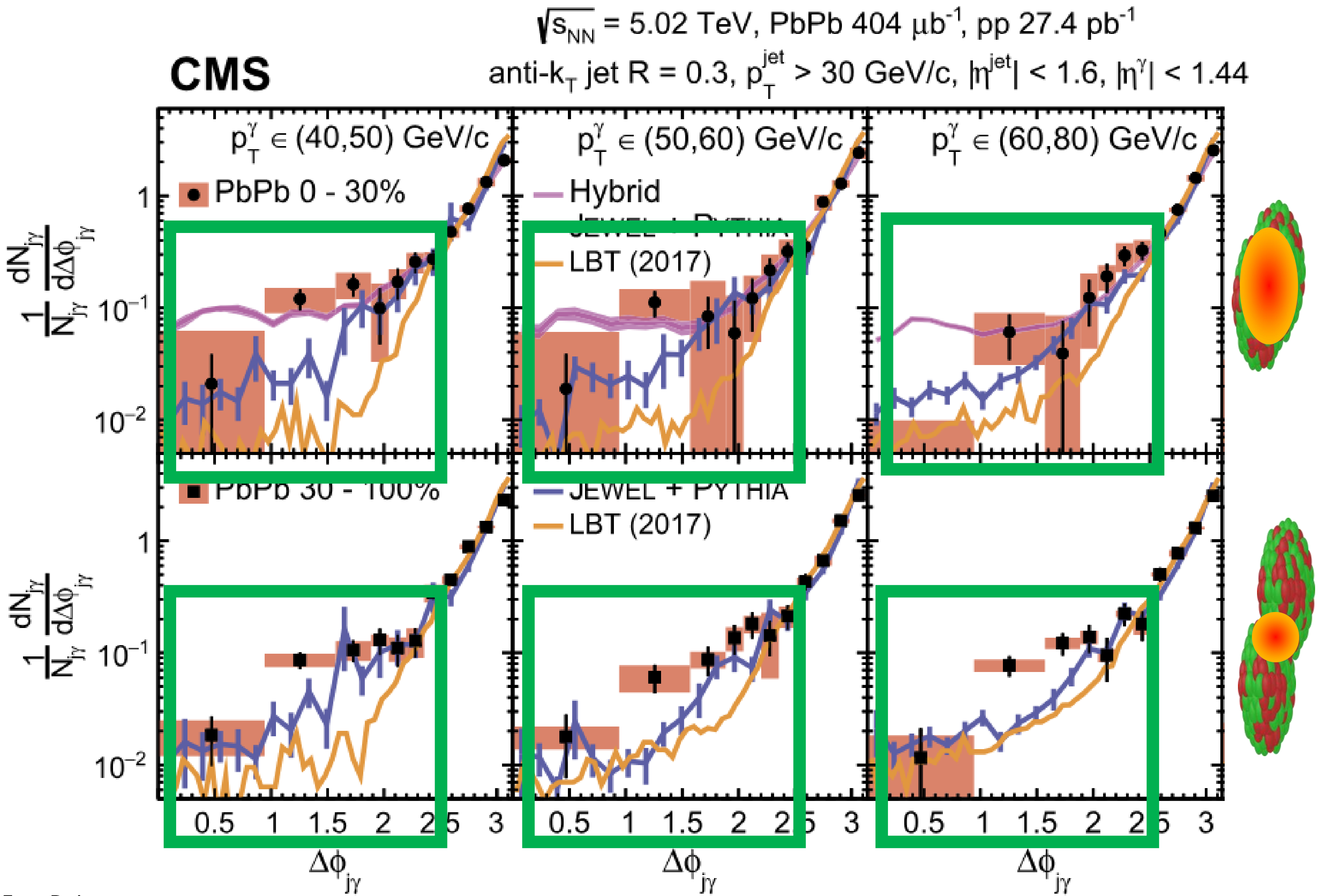
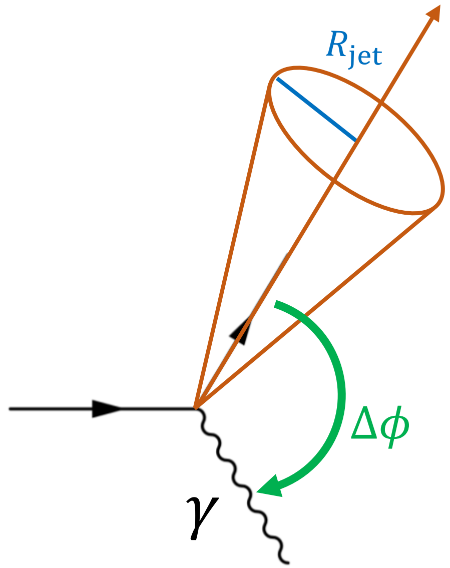
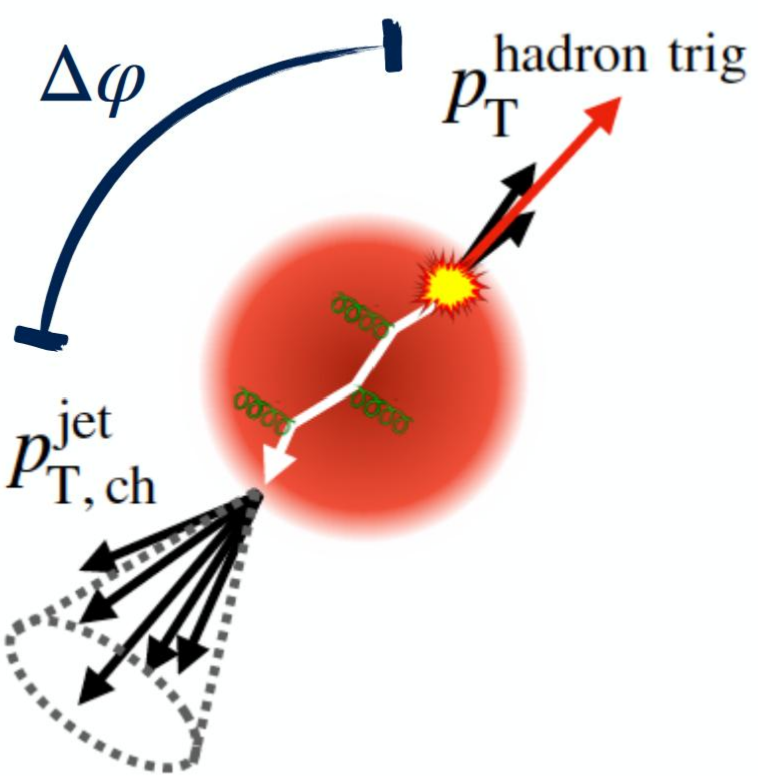




- **Hint of second peak at smaller $\Delta\phi$?**
- Tension with models → scattering effect?

Hadron-jet acoplanarity



- Look for a **trigger track (TT)** within some p_T range, and then **study jets in $\Delta\phi$ from TT**

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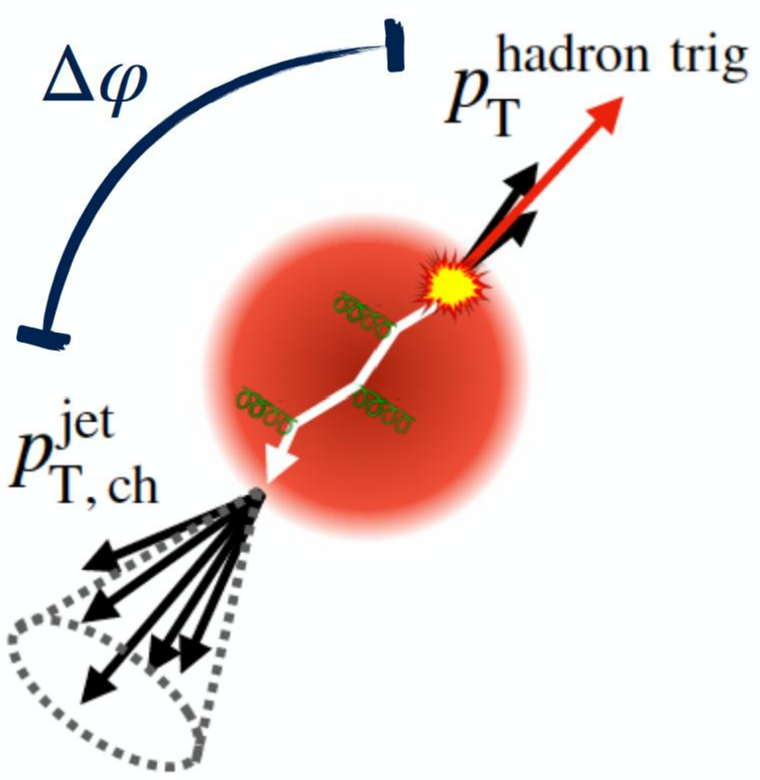

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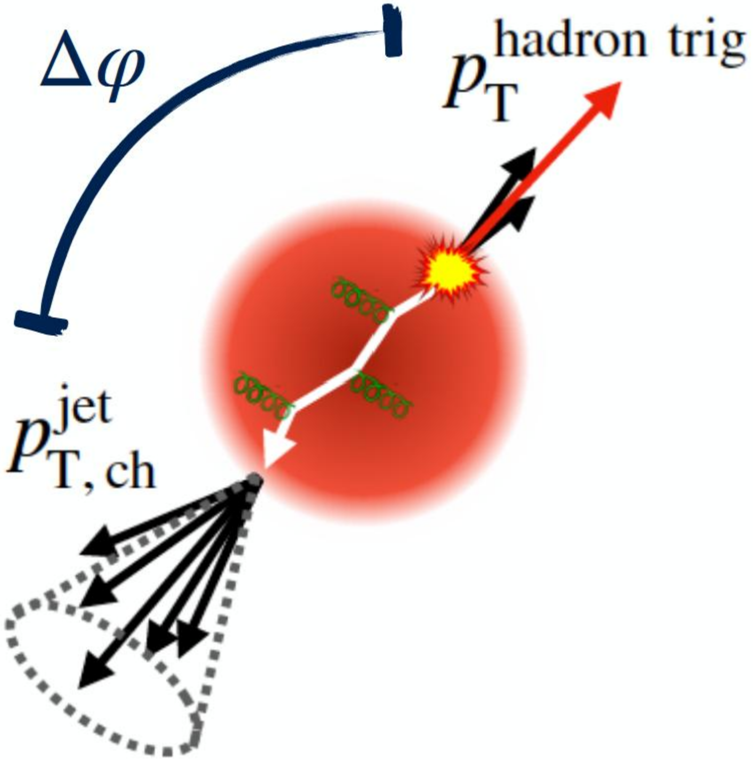

- Look for a **trigger track (TT)** within some p_T range, and then **study jets in $\Delta\phi$ from TT**
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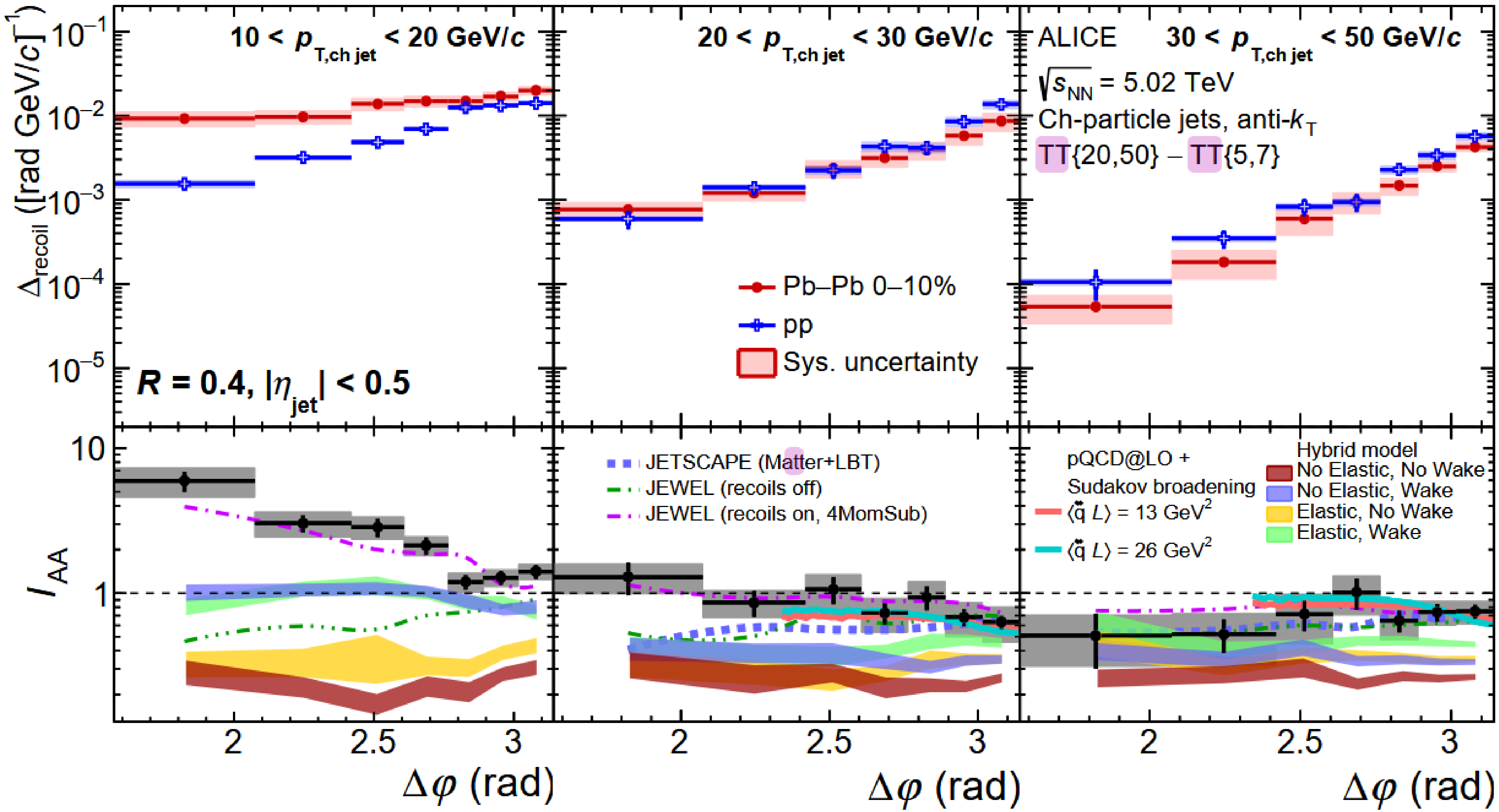
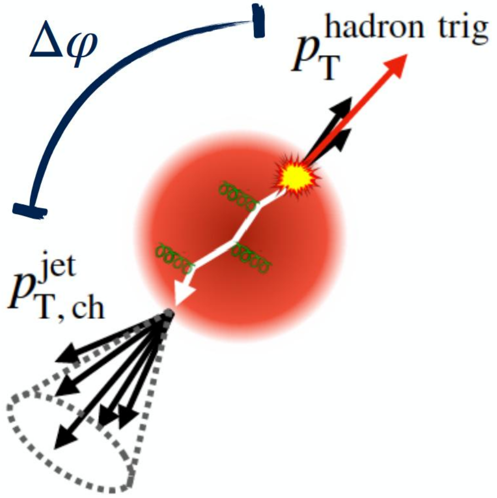
- **Subtract "reference" (low-p_T) TT distribution from "signal" (high-p_T) TT distribution** to correct for uncorrelated effects: left with Δ_{recoil} observable

Hadron-jet acoplanarity





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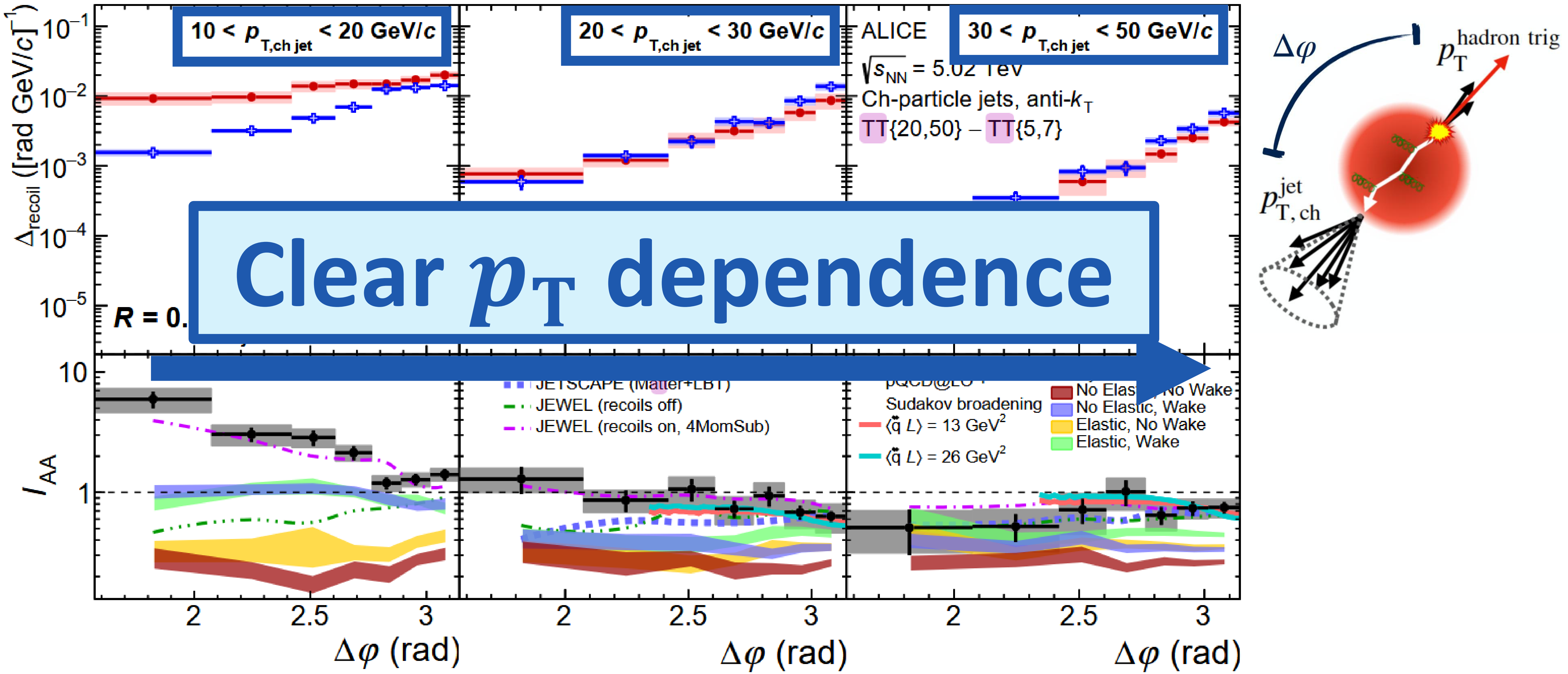
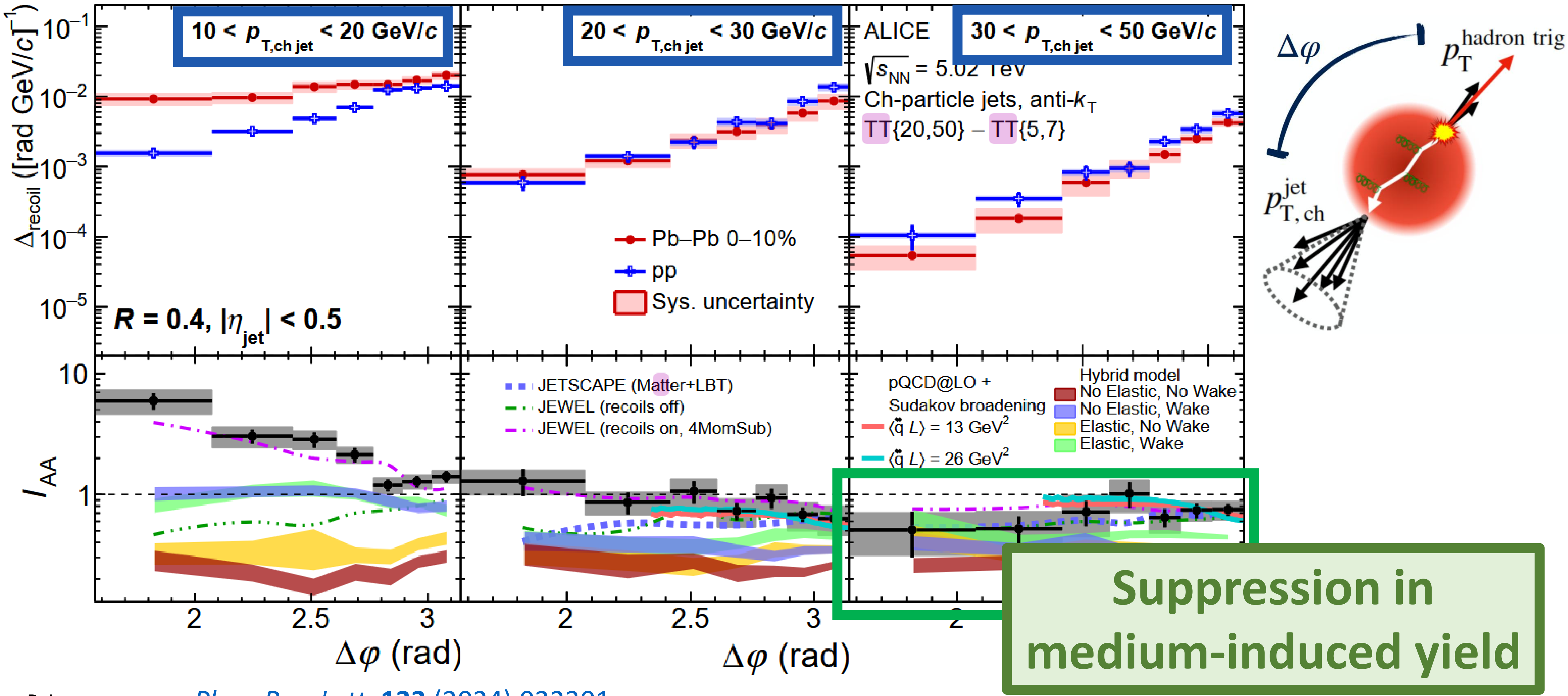


Clear p_T dependence

Hadron-jet acoplanarity



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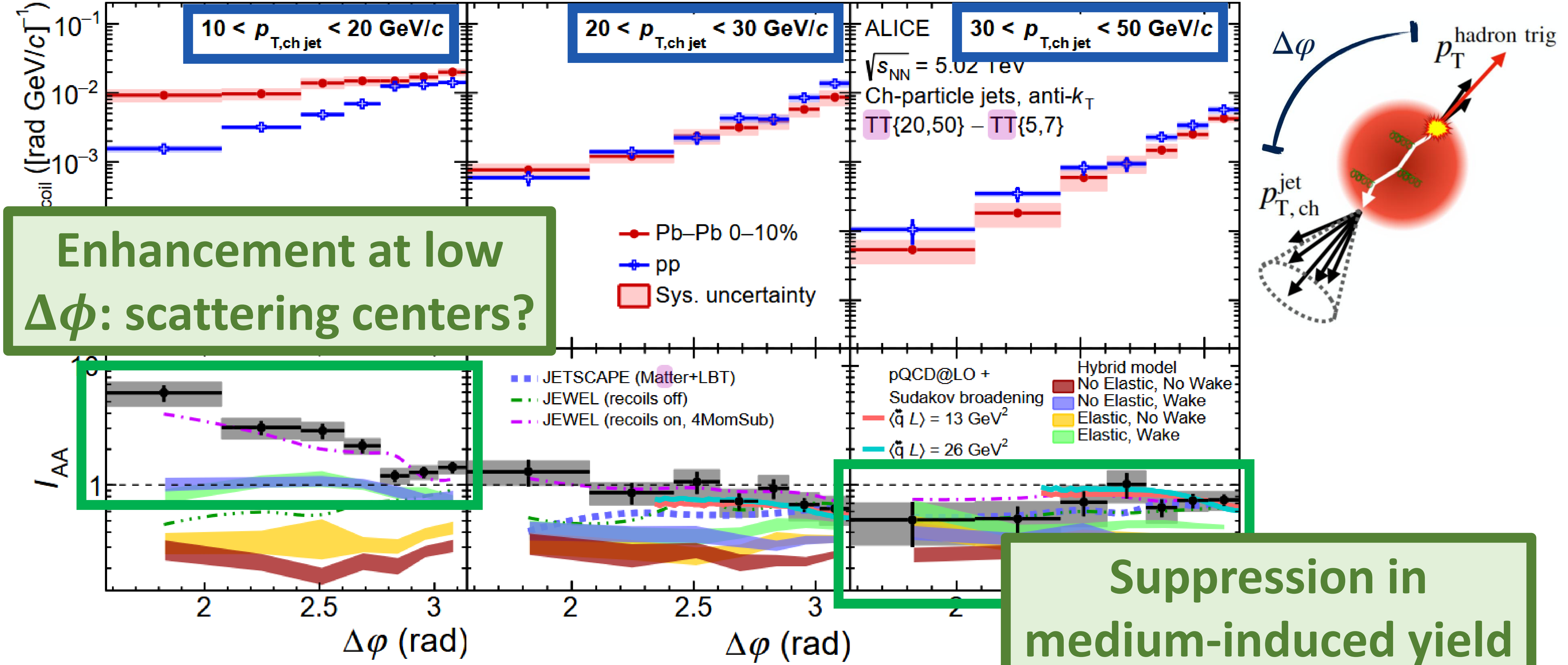

Enhancement at low $\Delta\phi$: scattering centers?

Suppression in medium-induced yield

Summary

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- **Diverse and growing opportunities for future LHC measurements!**

Backup

Durham (k_T) jet family

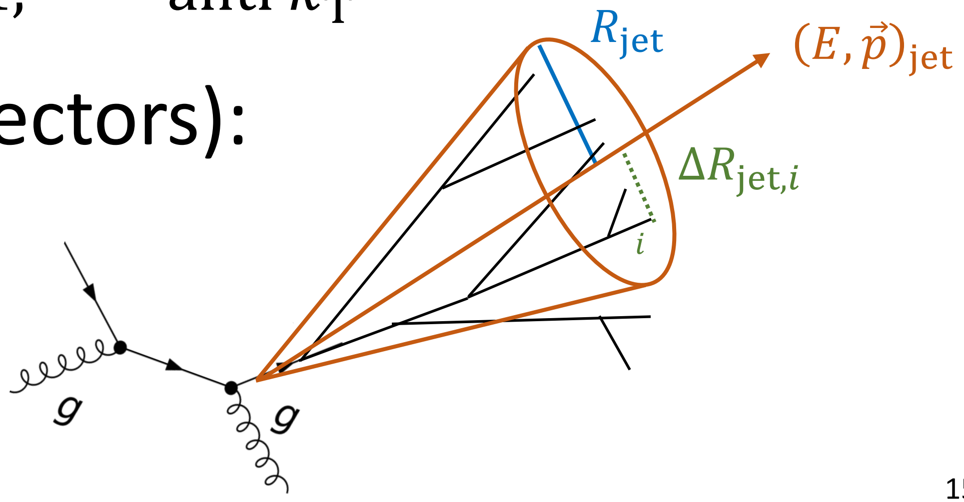
- Jets are reconstructed from **Particle Flow objects** using a sequential recombination algorithm
  - From an **IRC-safe** class of algorithms
  - **Soft-resilient**: shape is not strongly affected by soft, wide-angle radiation

$$d_{ij} = \min\left(k_{\mathrm{T}i}^{2p}, k_{\mathrm{T}j}^{2p}\right)\frac{\Delta_{ij}^2}{R^2}$$
$$d_{i\mathrm{B}} = k_{\mathrm{T}i}^{2p}$$

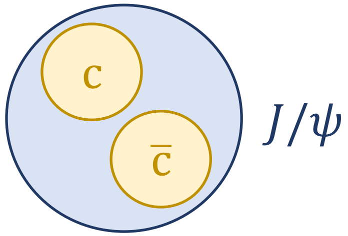
$$p = \begin{cases} 1, & (\text{"inclusive"})\ k_\mathrm{T} \\ 0, & \text{Cambridge/Aachen} \\ -1, & \text{anti } k_\mathrm{T} \end{cases}$$

- ***E*-scheme** recombination (adding four vectors):

$$(E,\vec{p})_\mathrm{jet} = \sum_{i\in\mathrm{jet}} (E,\vec{p})_i$$



Heavy quarkonium in jets



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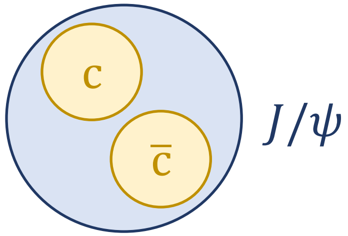

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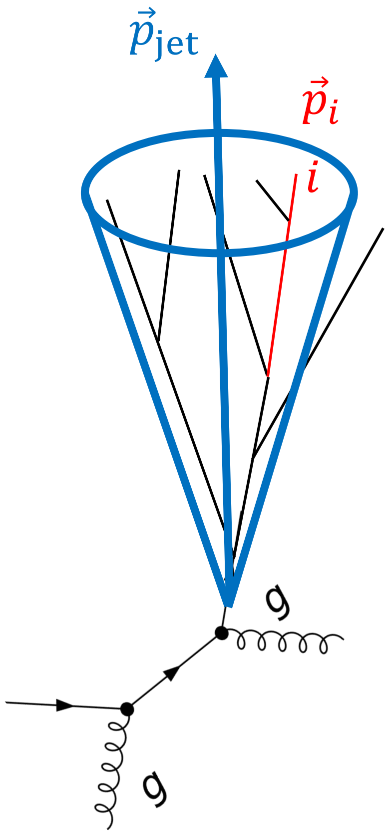
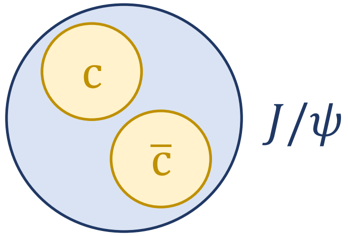


$$z = \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}$$

particle momentum fraction

Heavy quarkonium in jets



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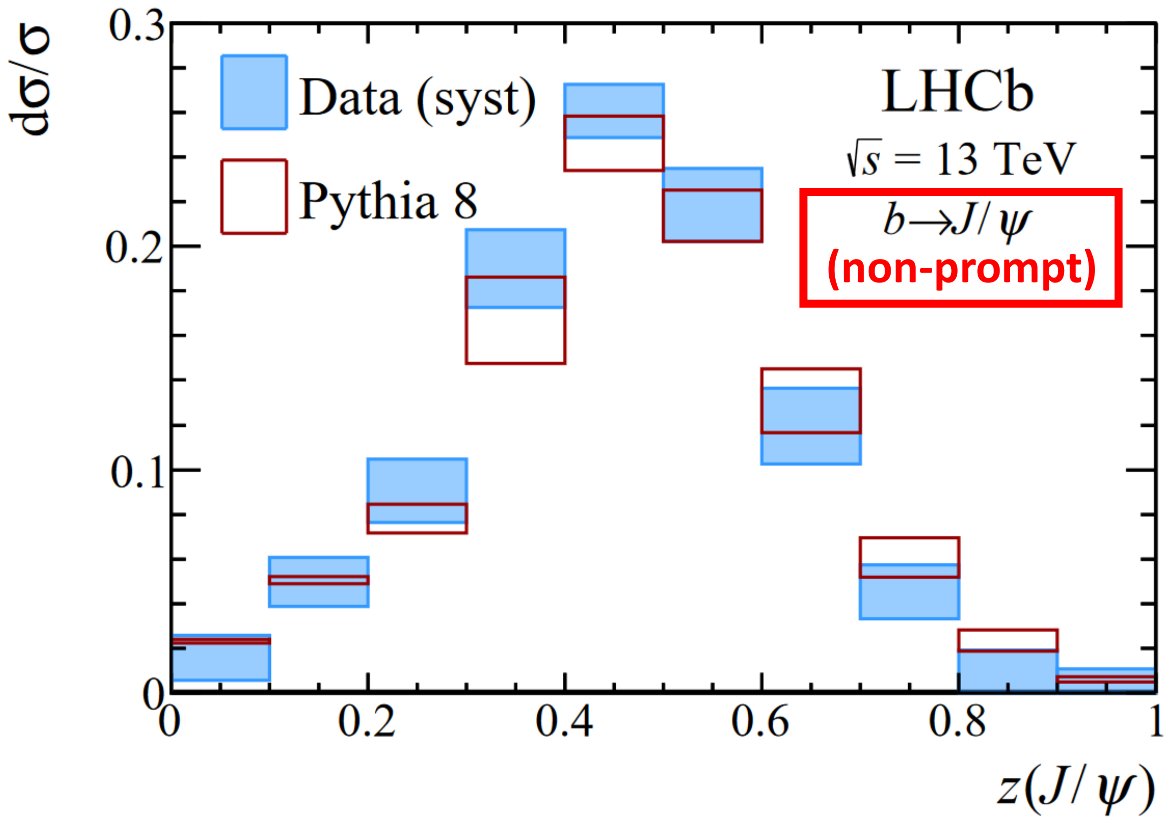
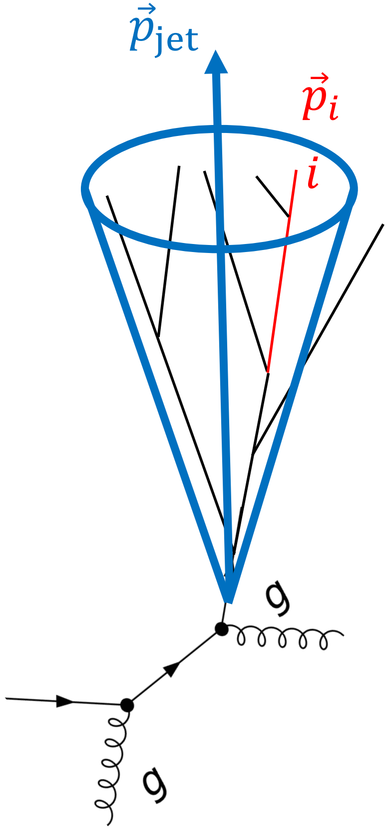


- Both **prompt** and **non-prompt (feed-down)** contributions



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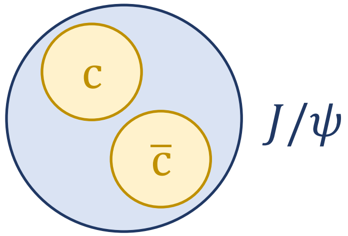
[*Phys. Rev. Lett.* **118** (2017) 192001]

Heavy quarkonium in jets



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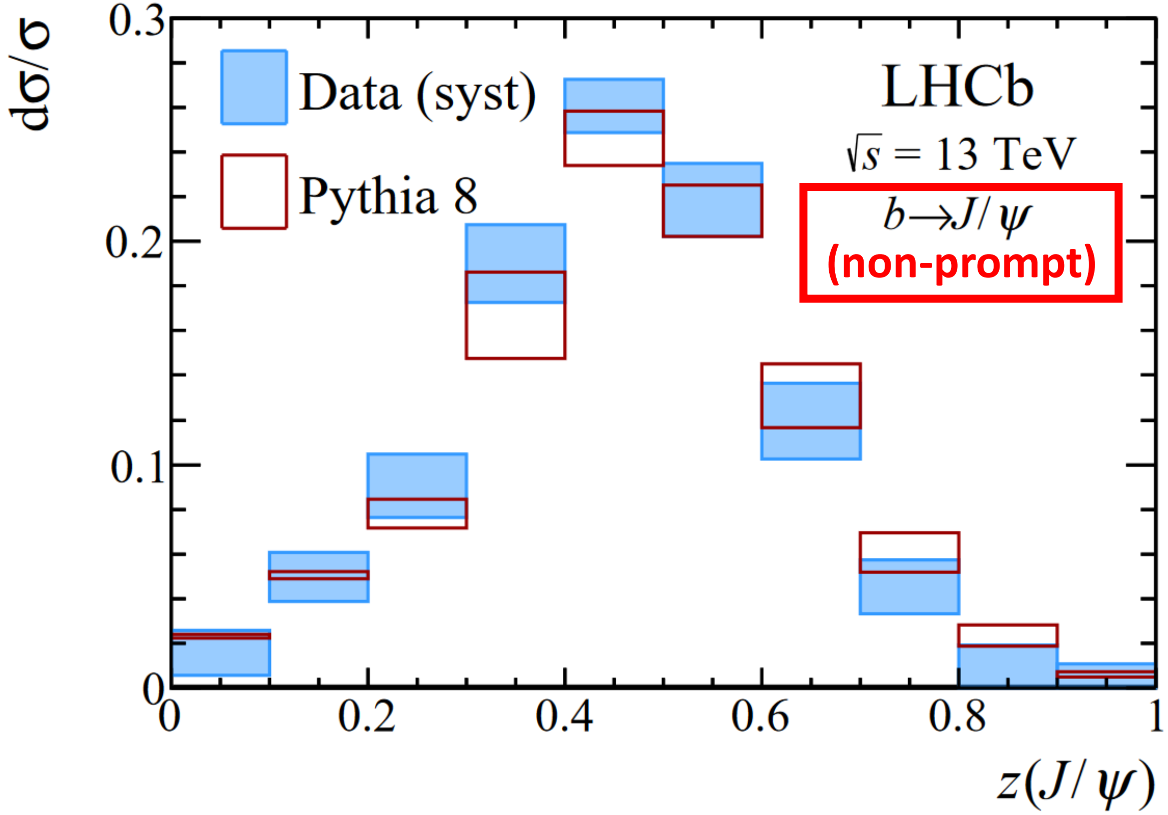

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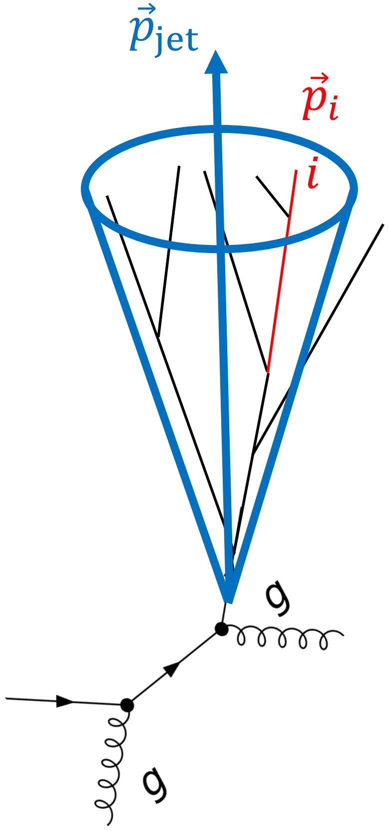
- Charmonium from b decays only carries $\sim$50% of jet energy
  → **surrounded by b-jet fragmentation**



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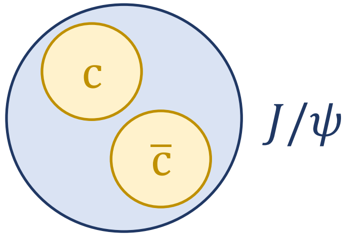

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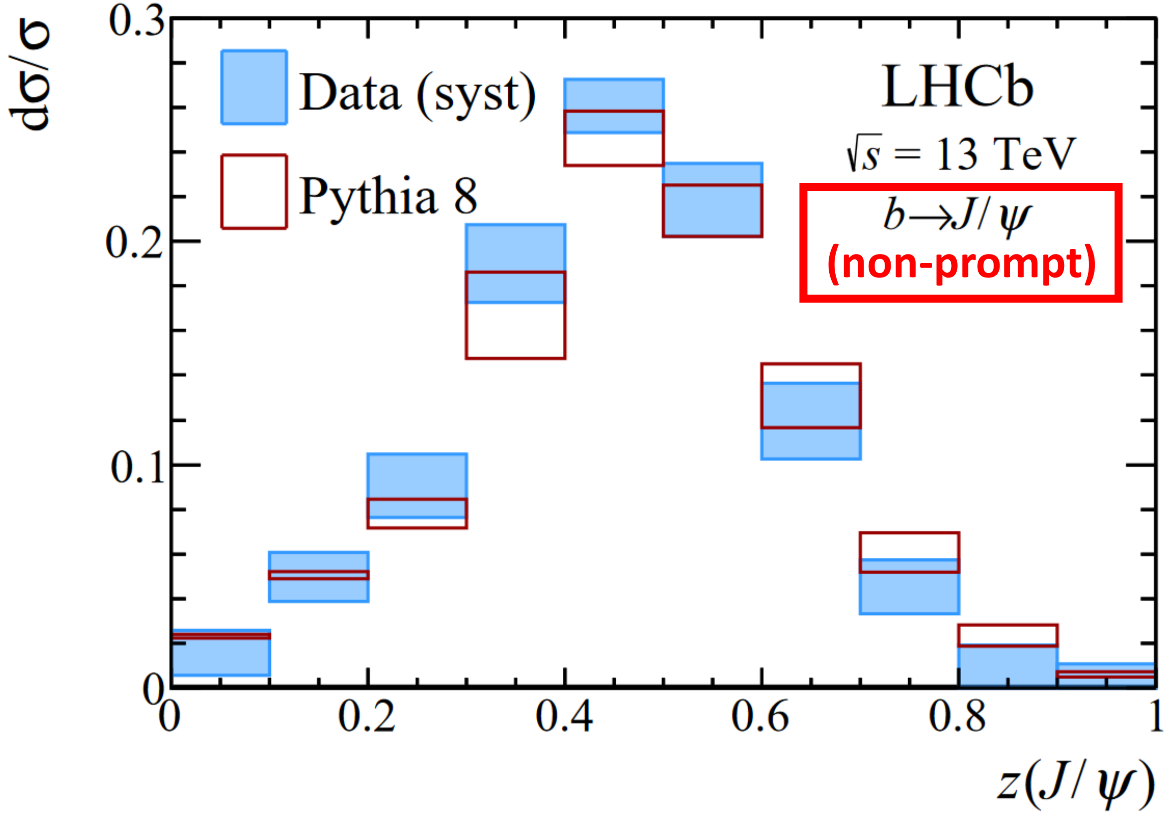
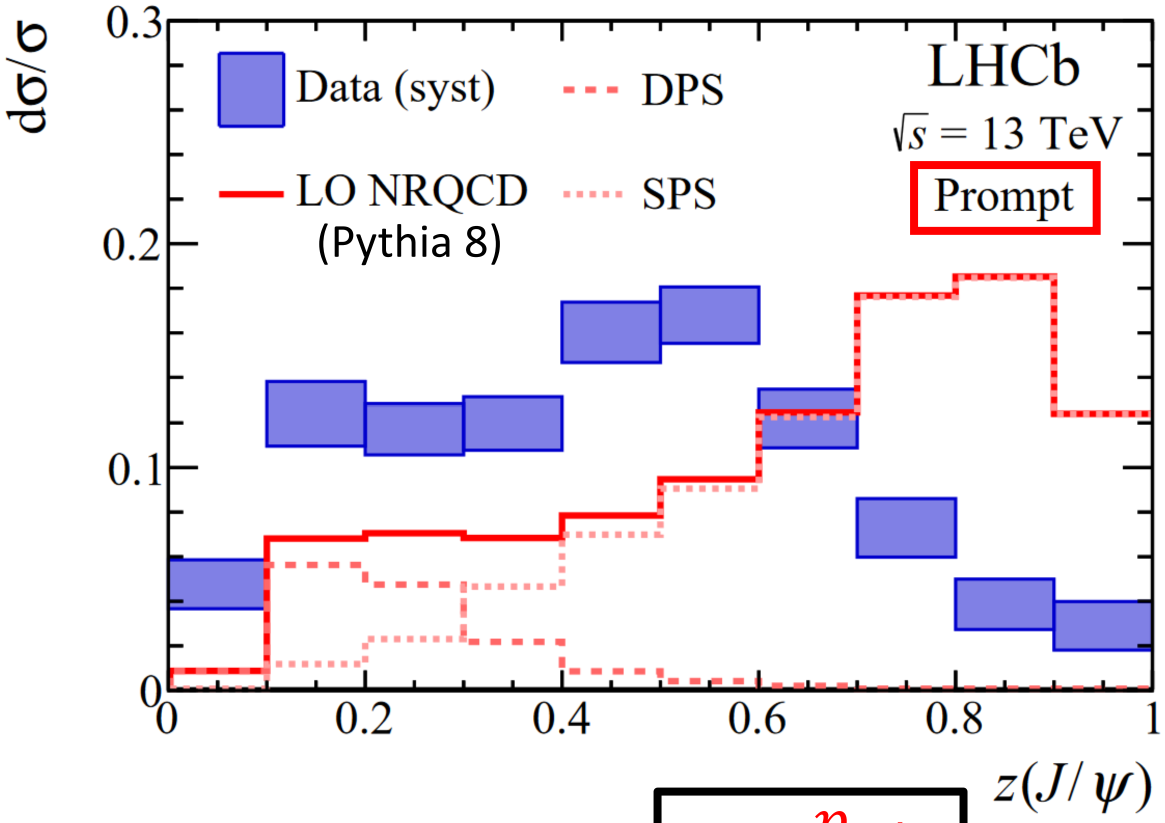
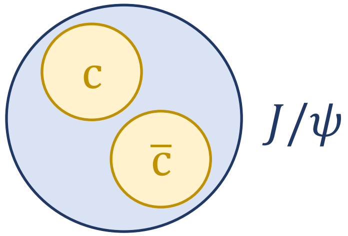




particle momentum fraction $z = \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}$

Phys. Rev. Lett. **118** (2017) 192001

Heavy quarkonium in jets



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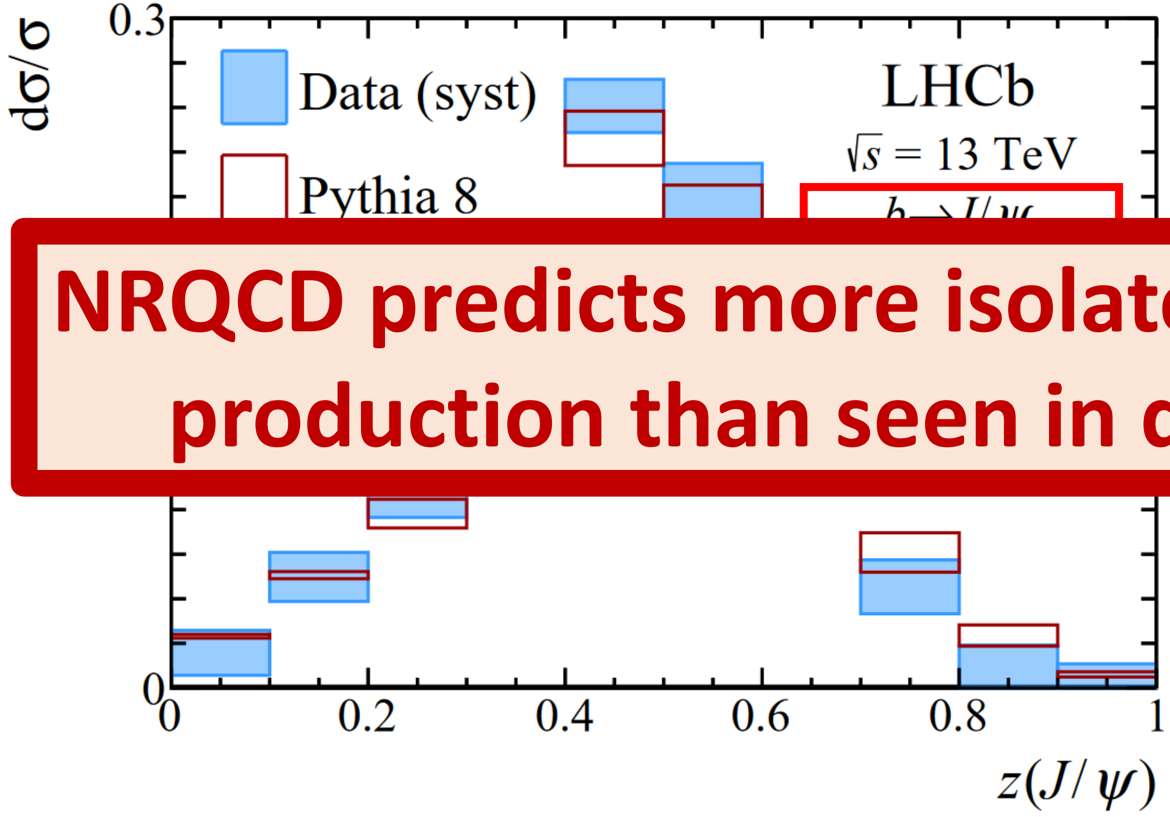
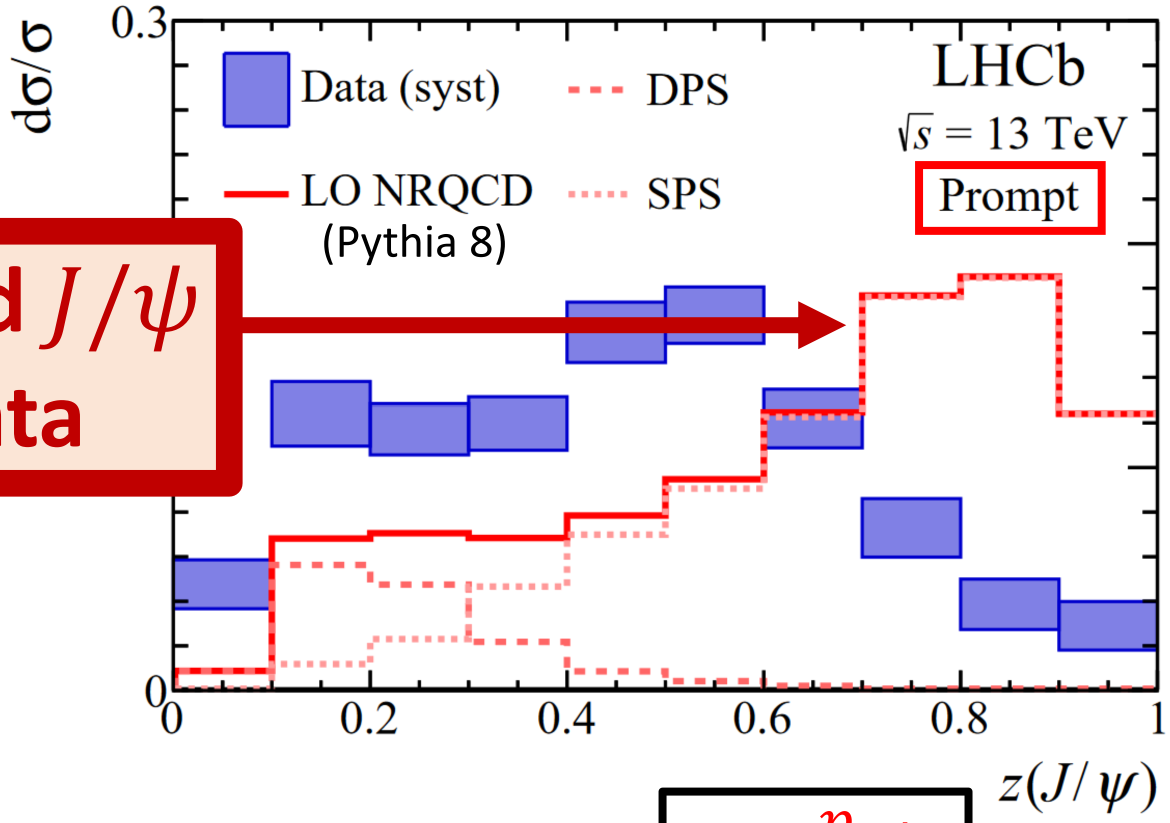


NRQCD predicts more isolated J/ψ production than seen in data



particle momentum fraction $z = \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}$

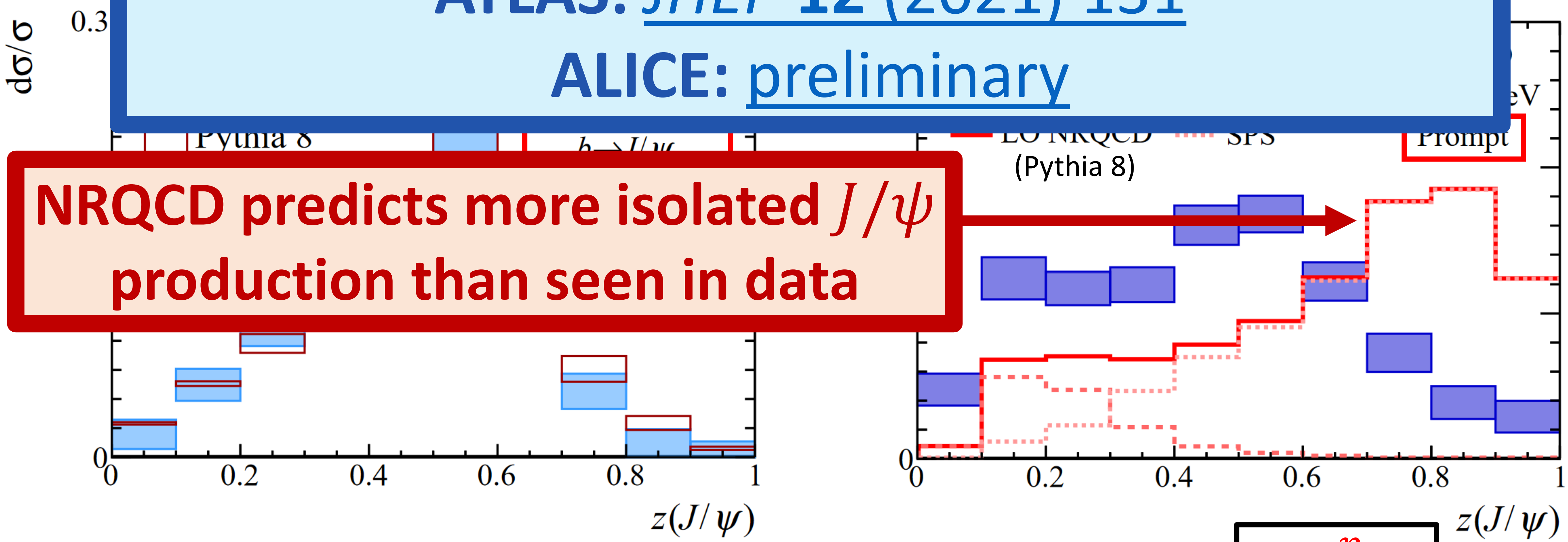
Phys. Rev. Lett. **118** (2017) 192001

This *same result* also observed by:

CMS: *Phys. Lett.* **B825** (2021) 136842

ATLAS: *JHEP* **12** (2021) 131

ALICE: preliminary



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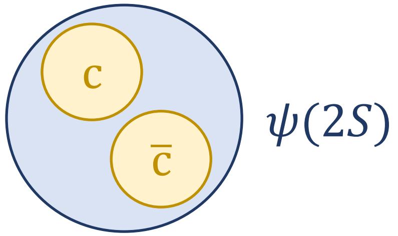
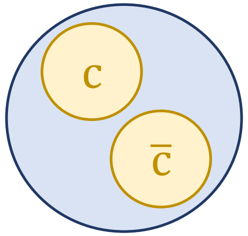
Heavy quarkonia in jets



- How are heavy $q\bar{q}$ pairs such as $\psi(2S)$ produced according to QCD?

Heavy quarkonia in jets



$\psi(2S)$

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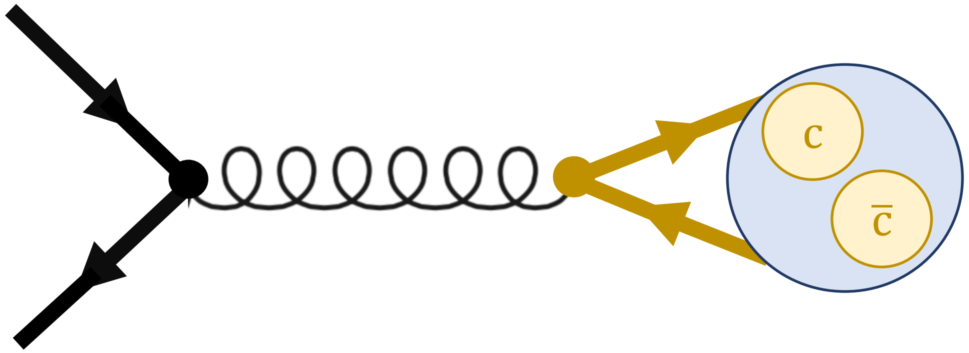
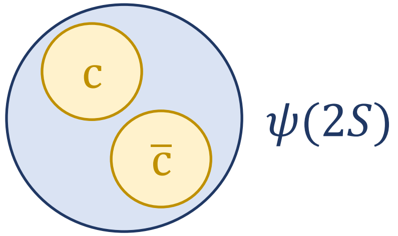
1) Prompt production

(LO NRQCD picture)



$\psi(2S)$

Heavy quarkonia in jets



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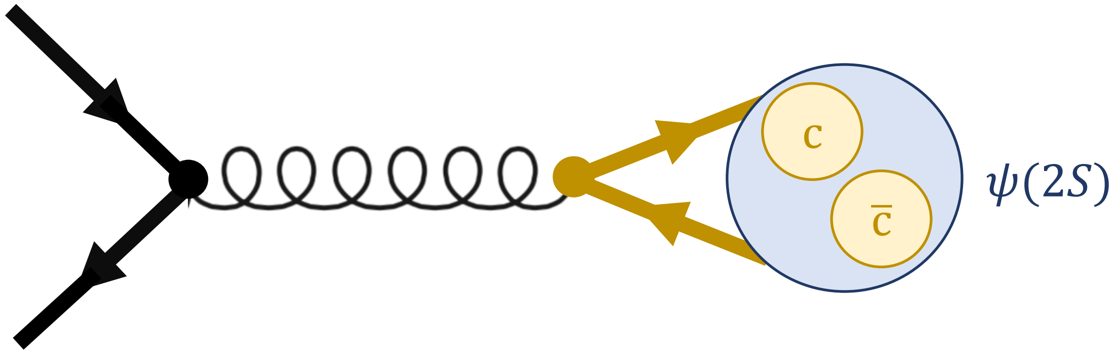
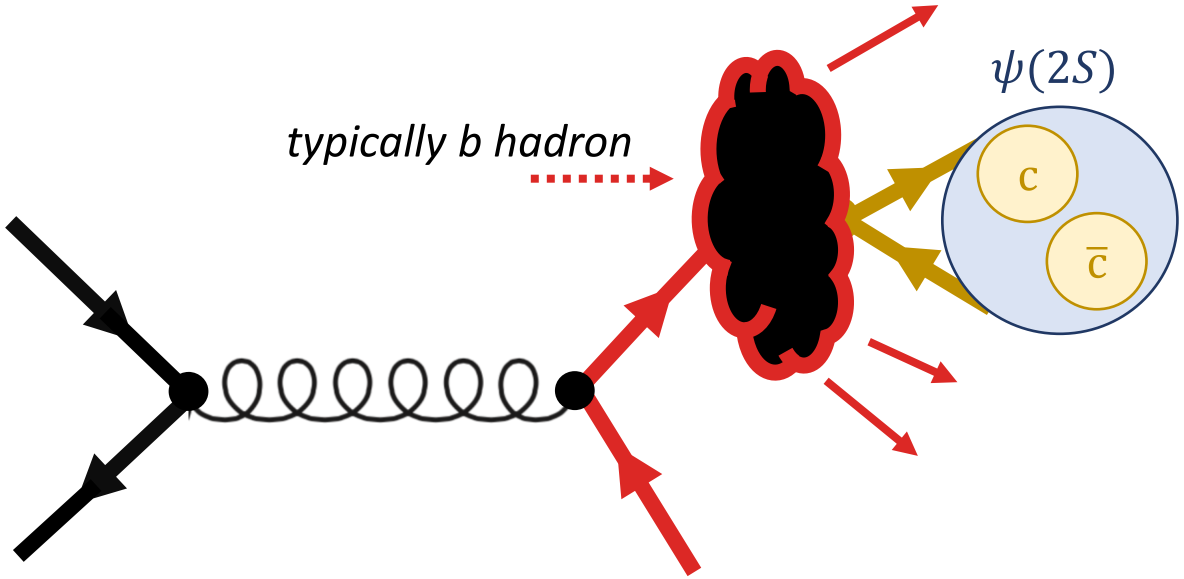
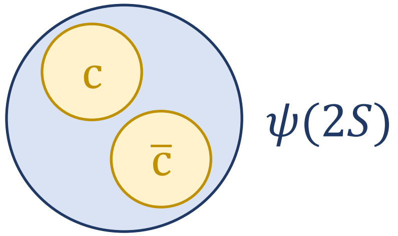


2) Non-prompt production



Heavy quarkonia in jets



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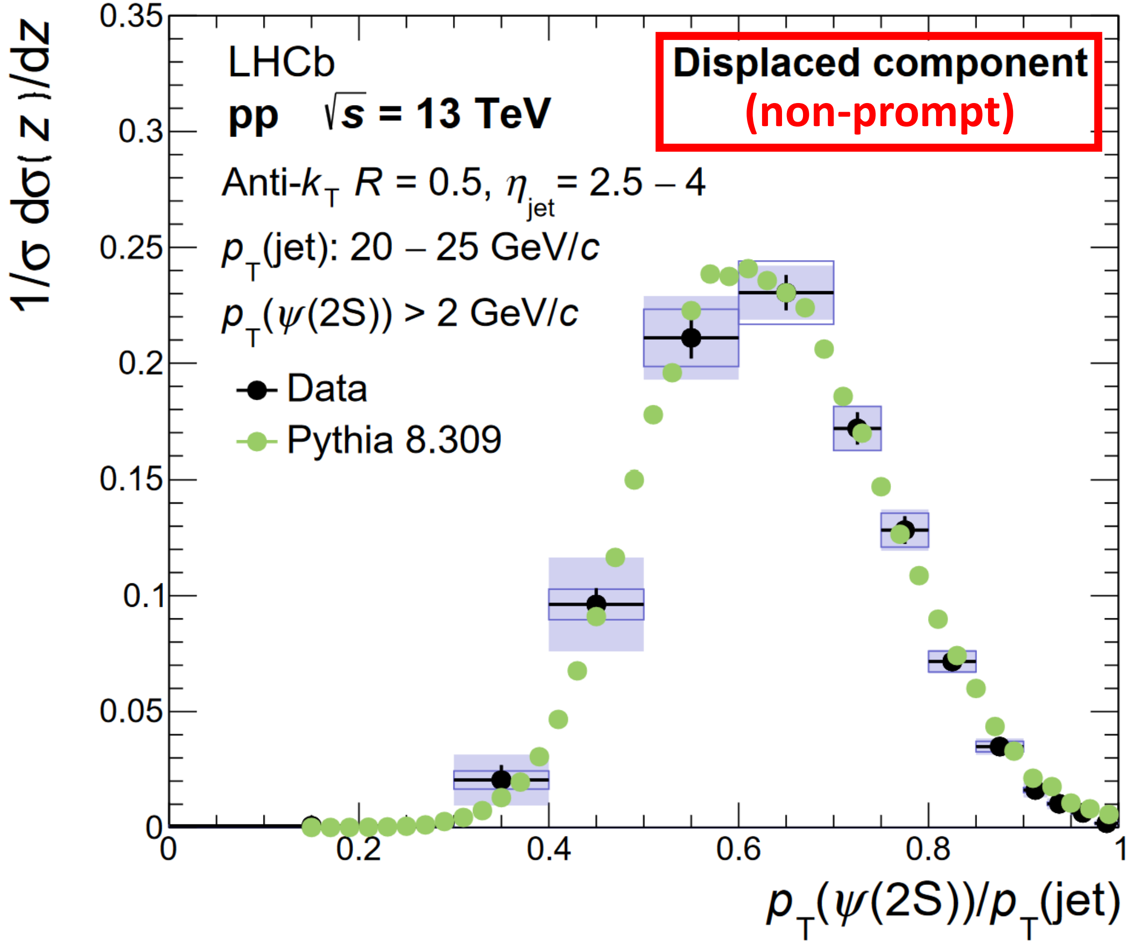

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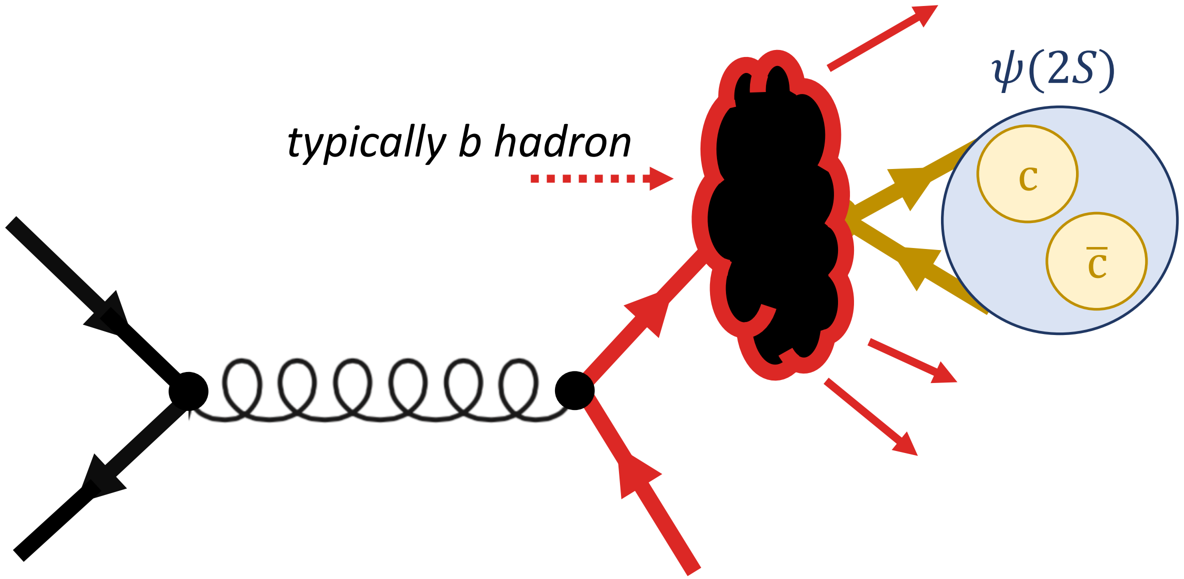

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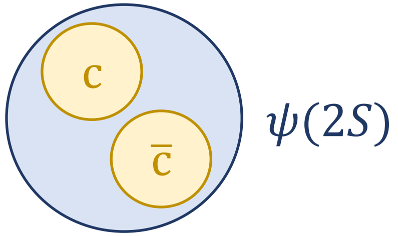

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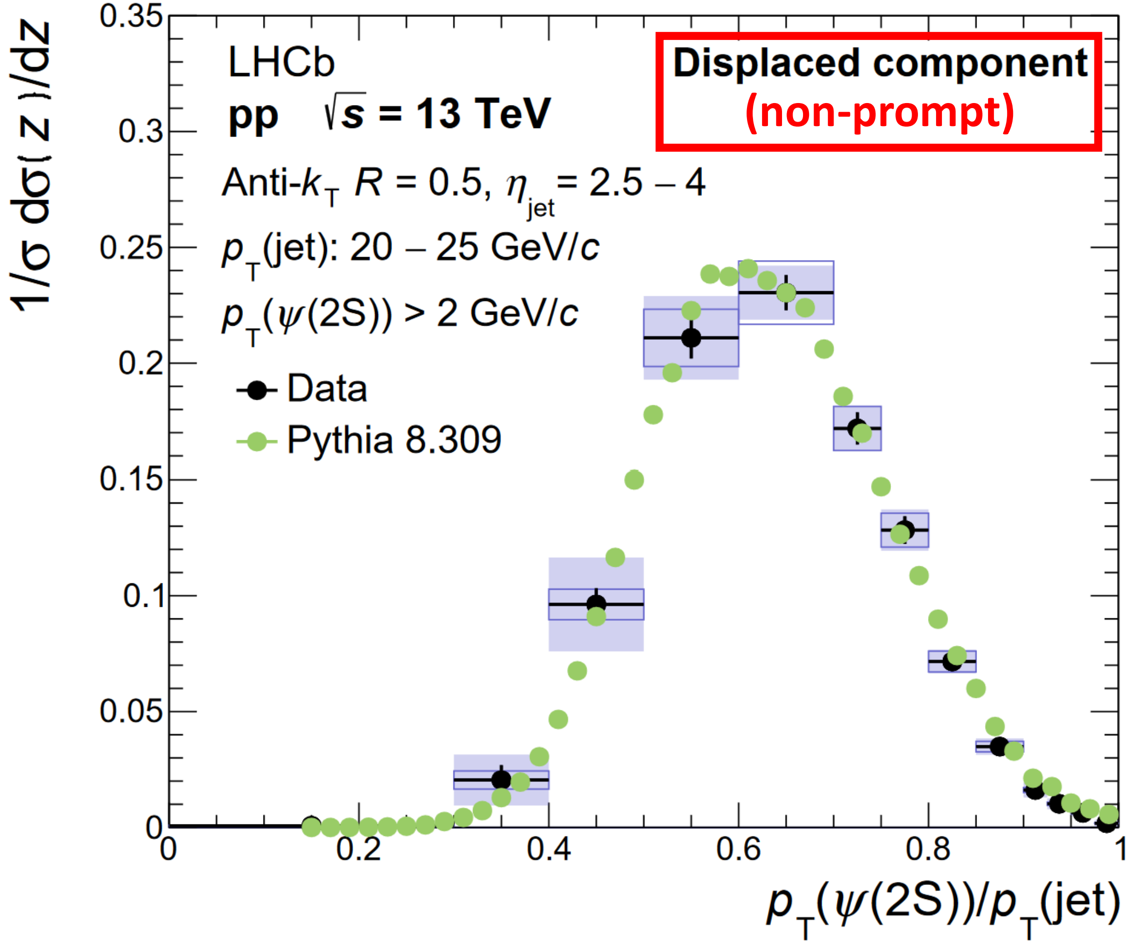
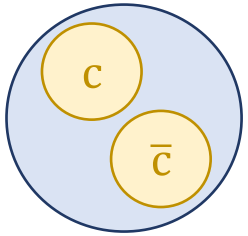


- Displaced $\psi(2S)$ carries $\sim 60\%$ of jet transverse momentum
- **Good agreement** between data and simulation

Heavy quarkonia in jets



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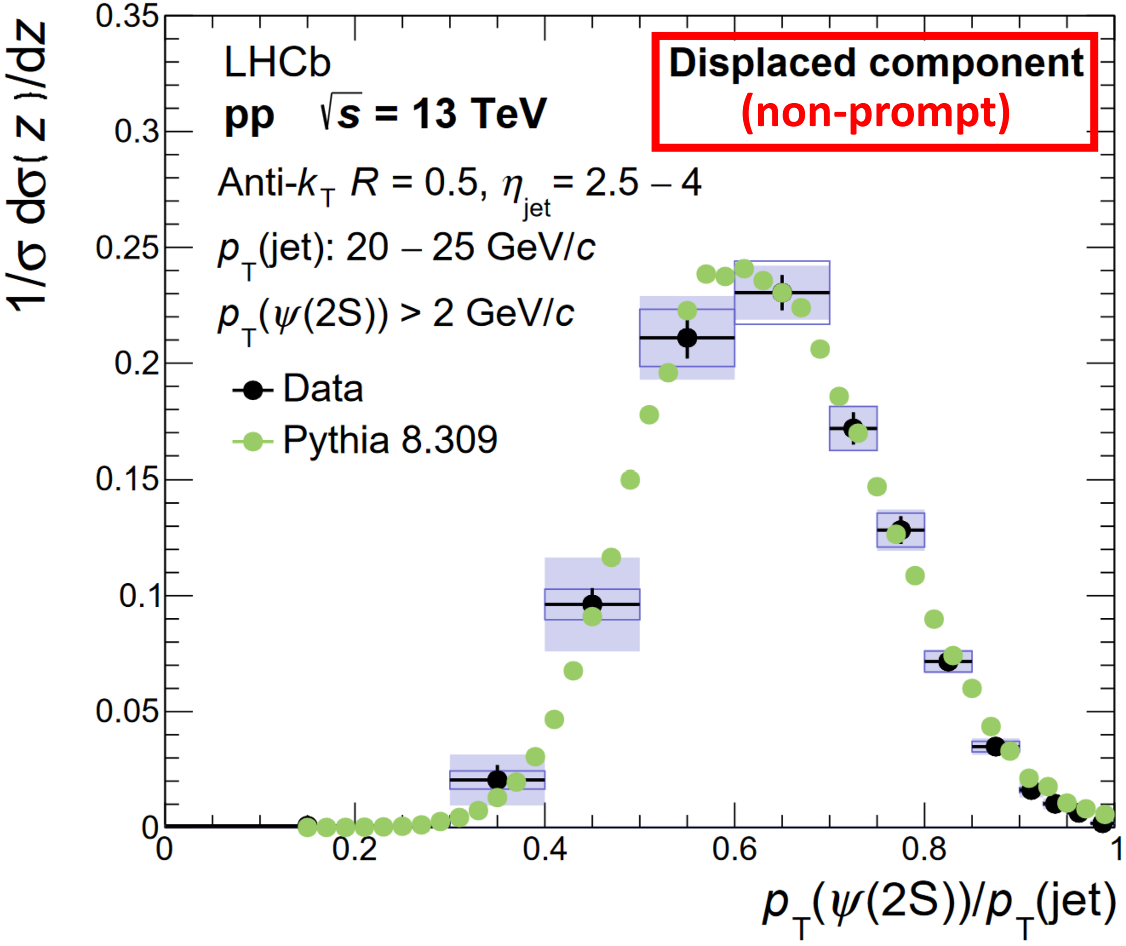
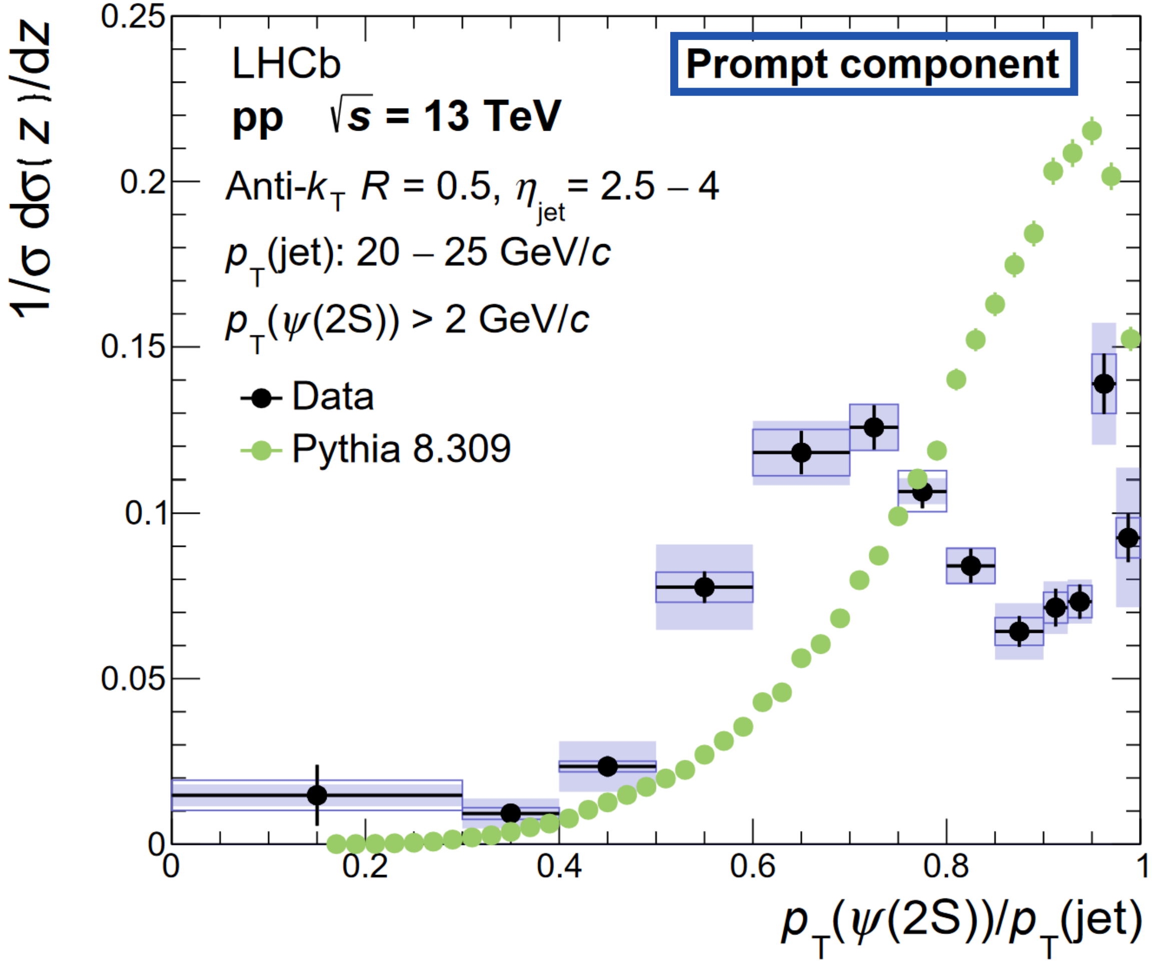
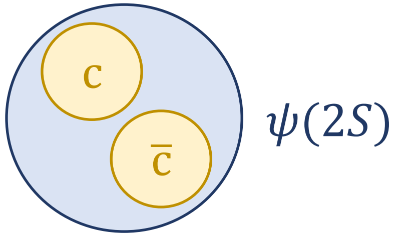




Heavy quarkonia in jets



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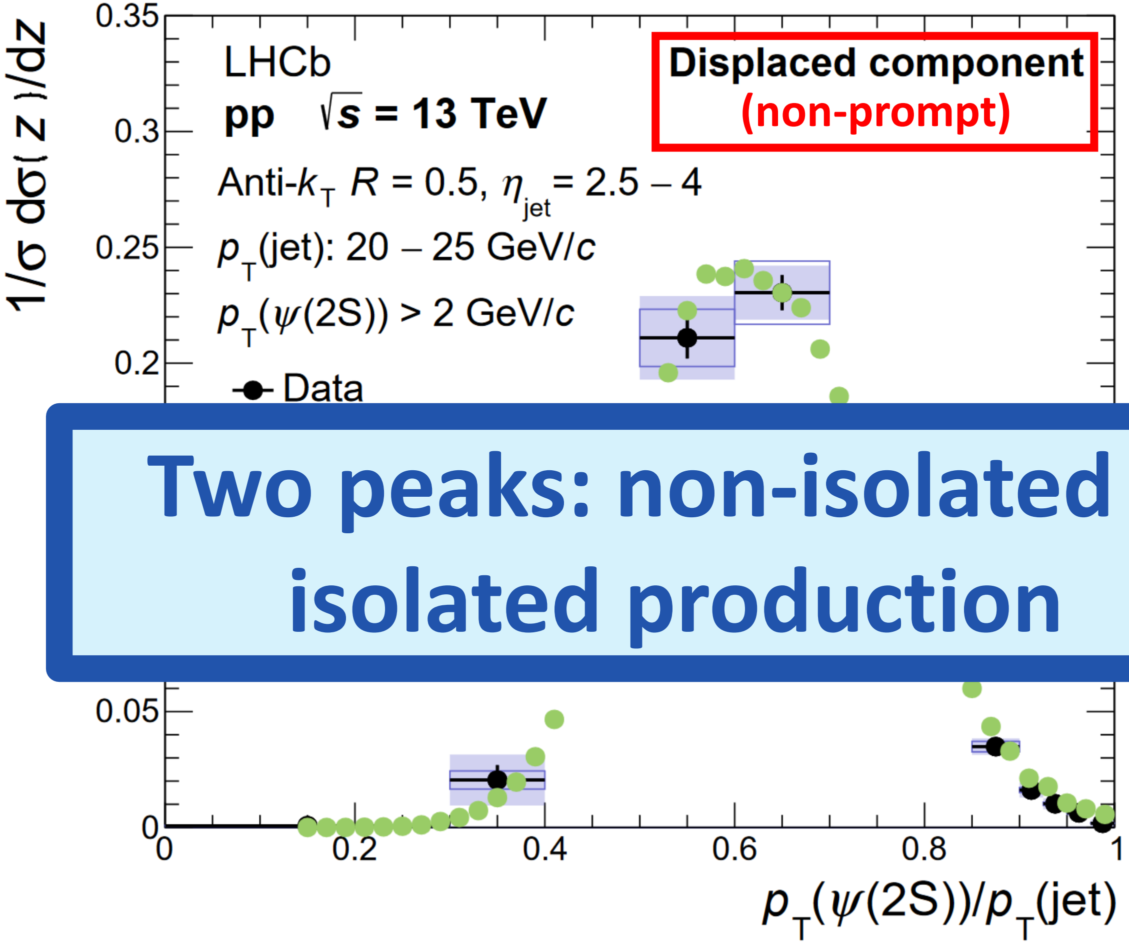
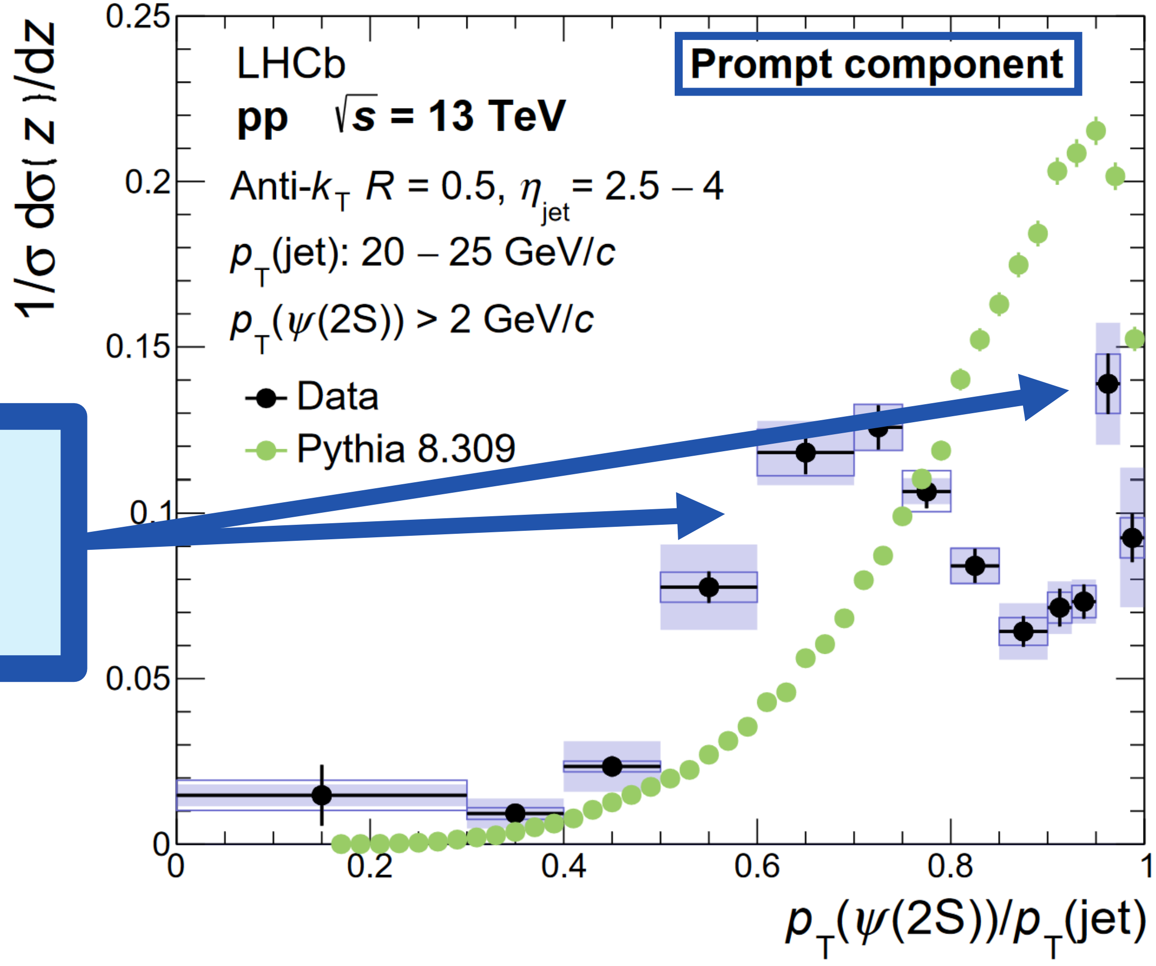
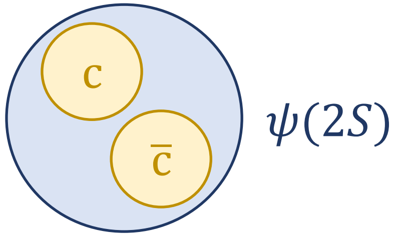




Two peaks: non-isolated & isolated production

Heavy quarkonia in jets



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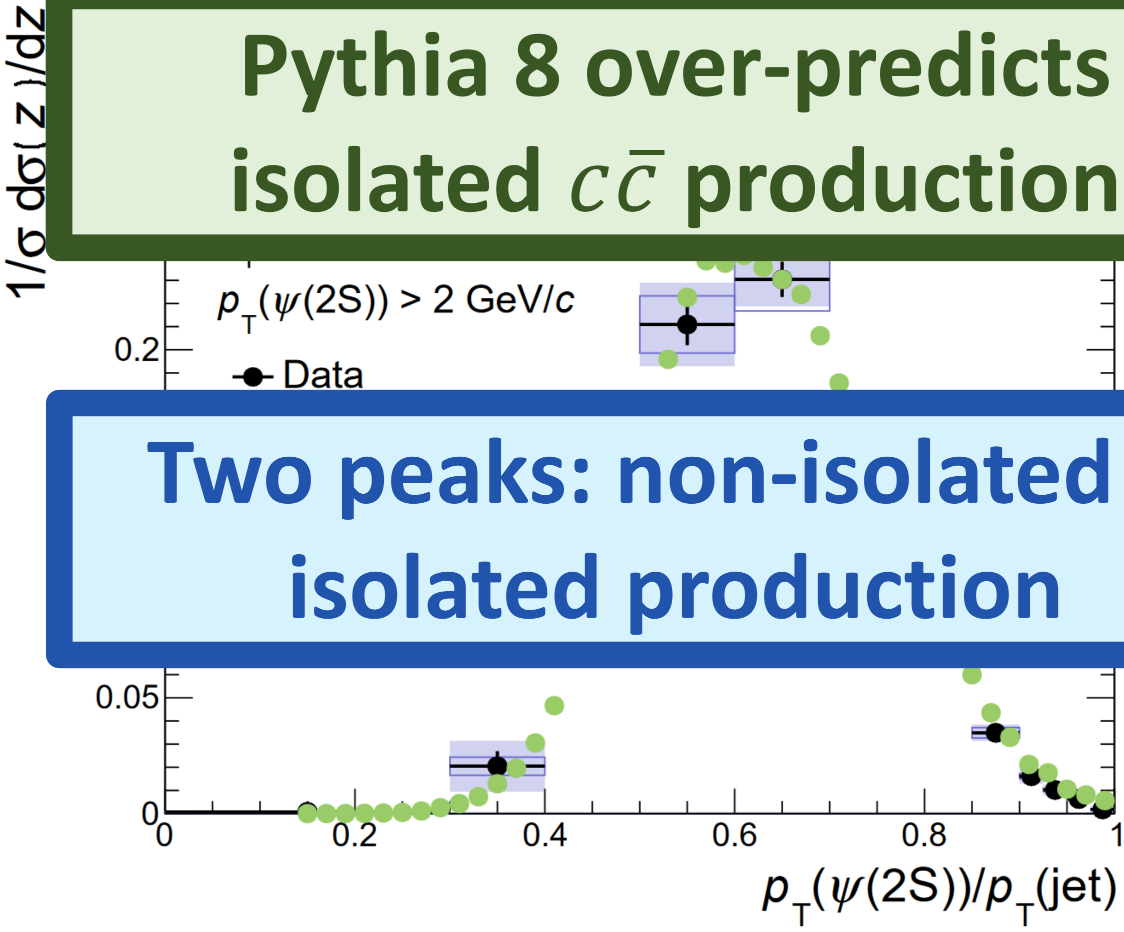
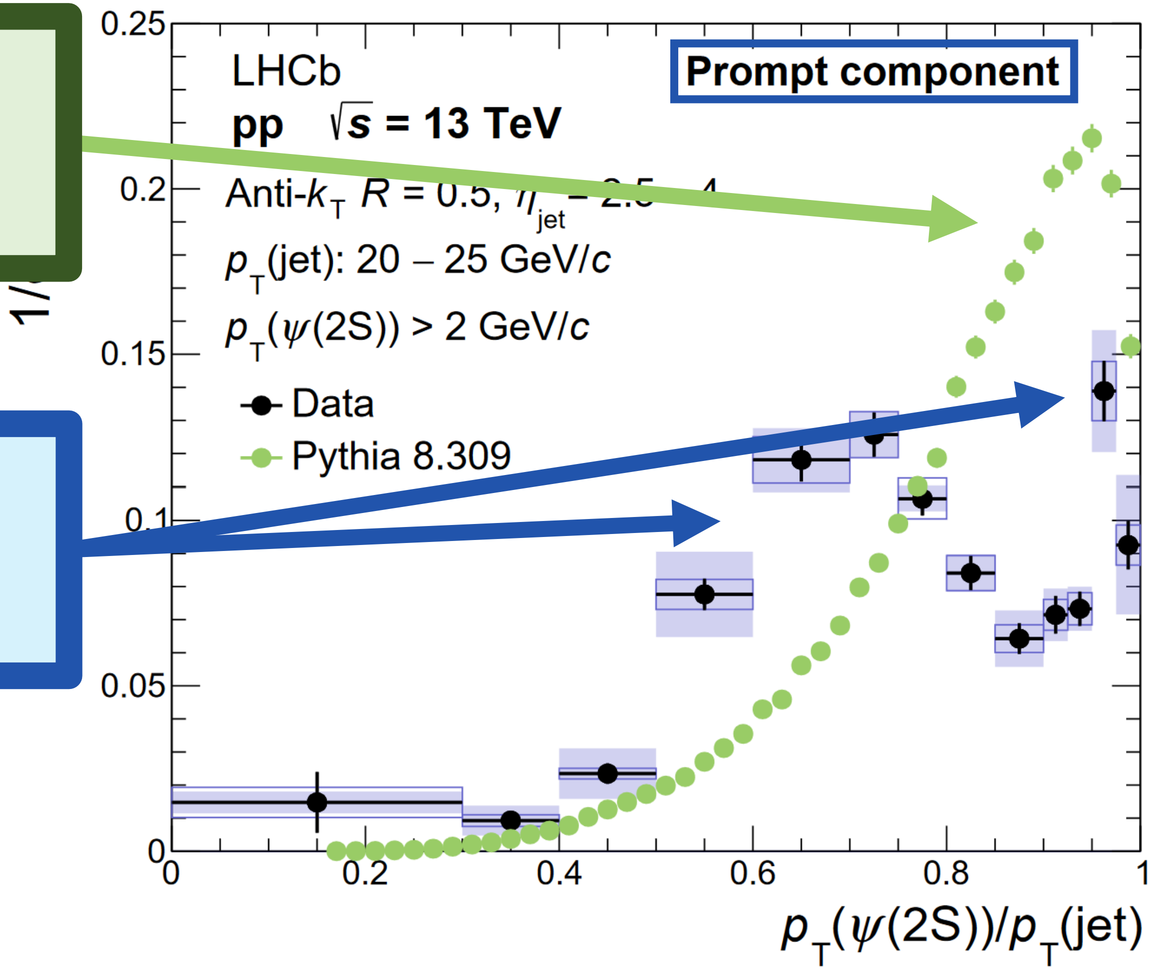


Pythia 8 over-predicts isolated $c\bar{c}$ production

Two peaks: non-isolated & isolated production



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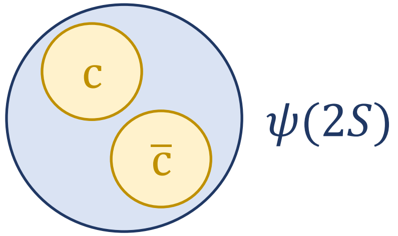

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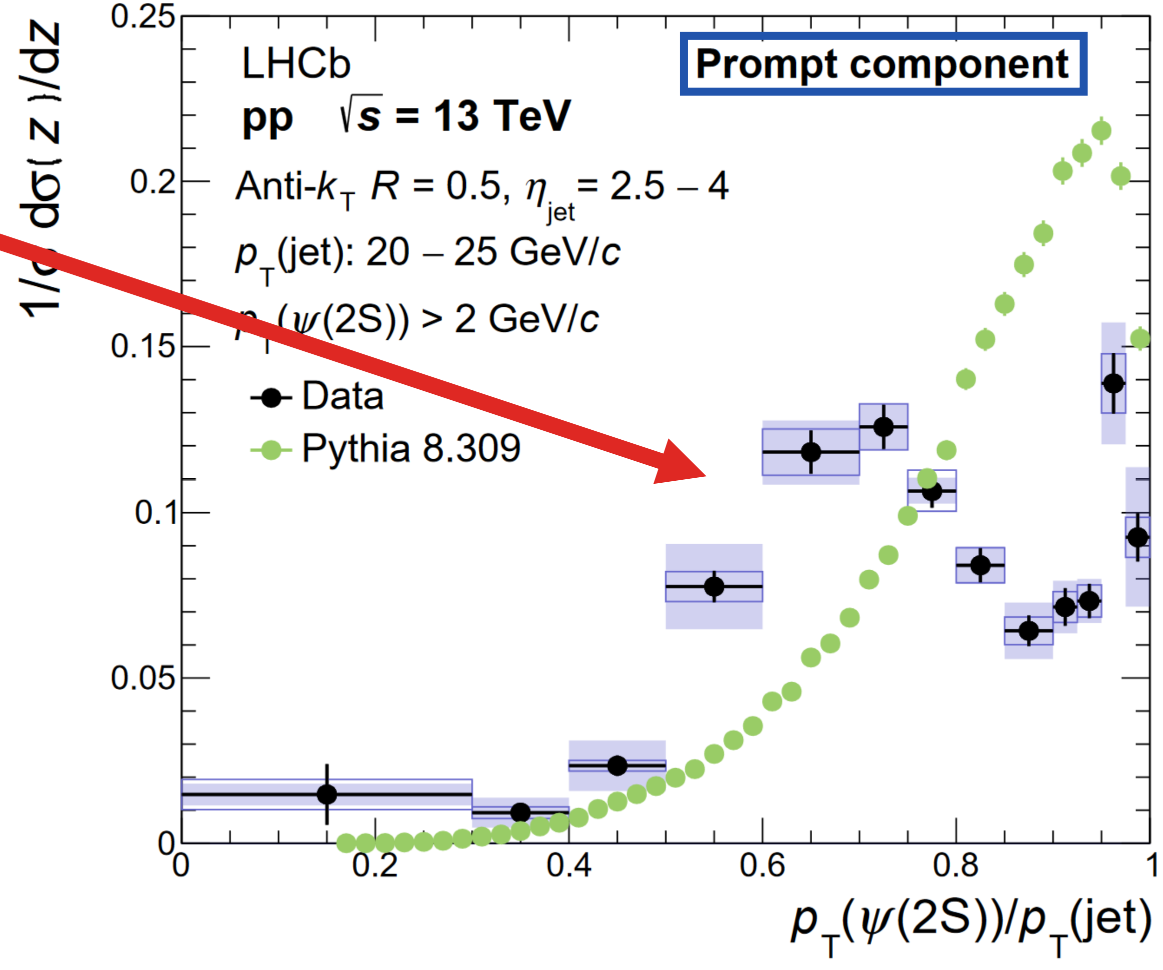
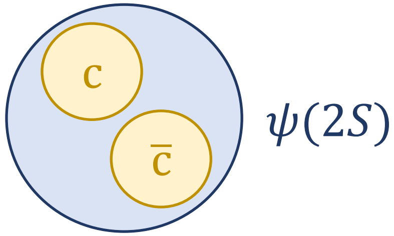


Heavy quarkonia in jets



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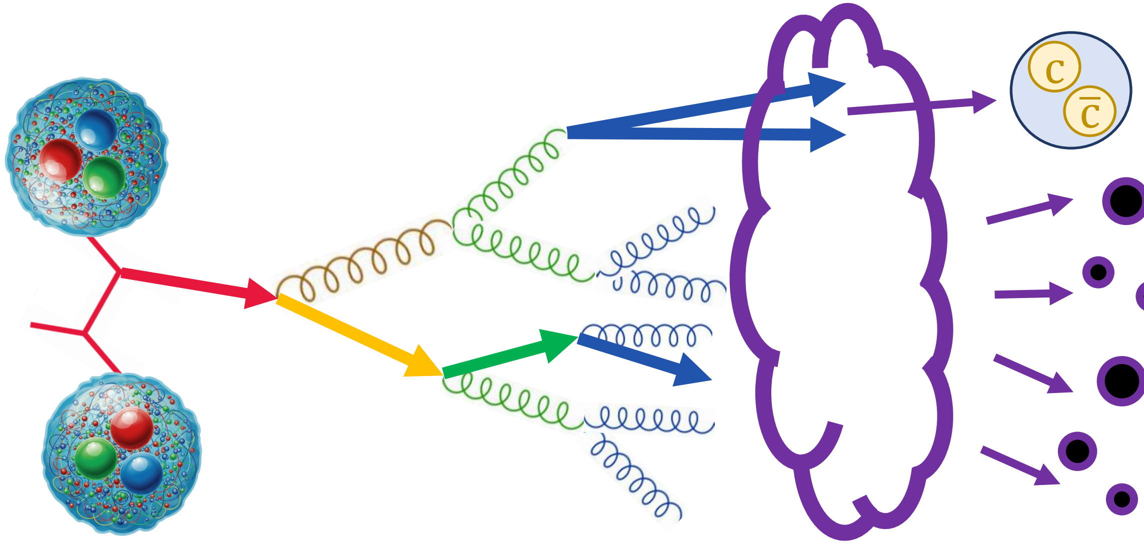
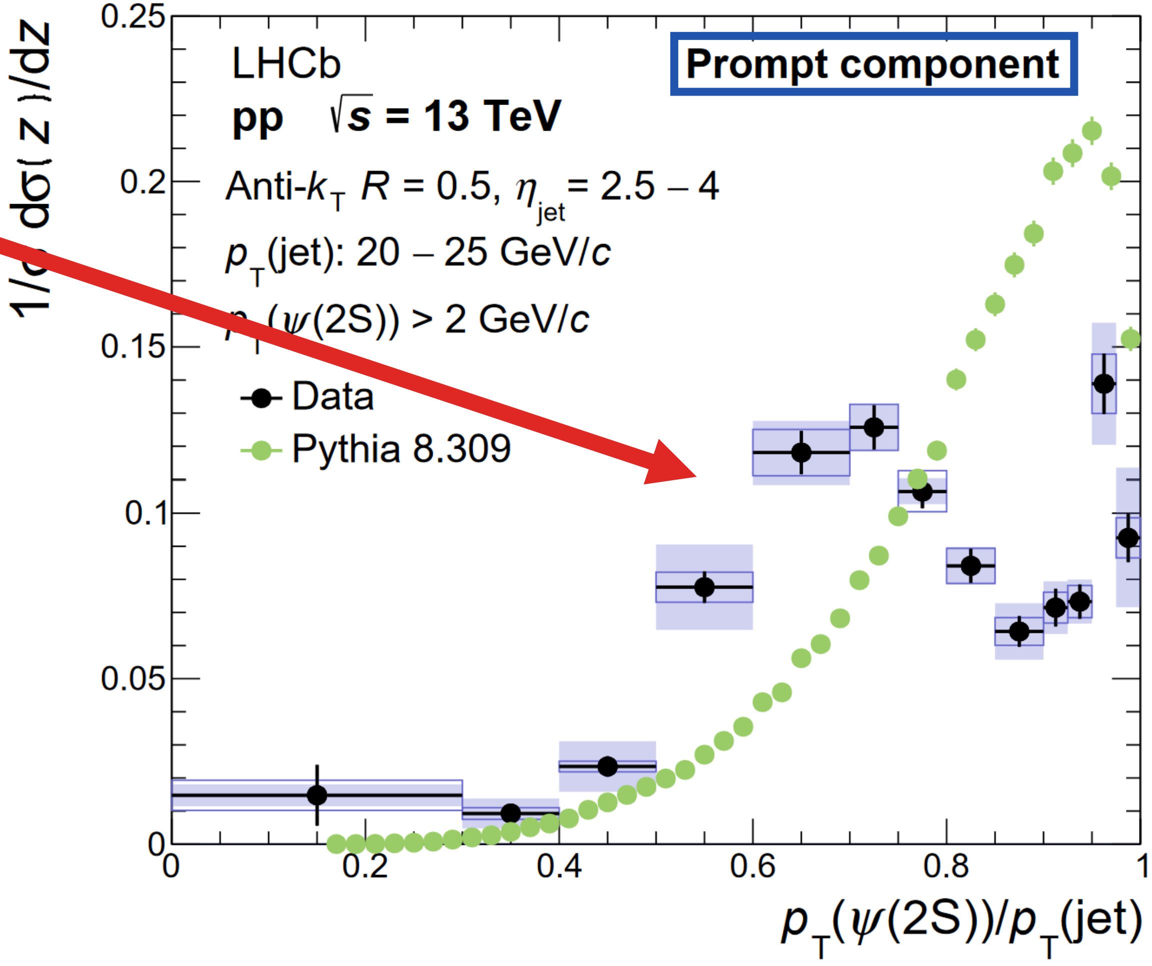
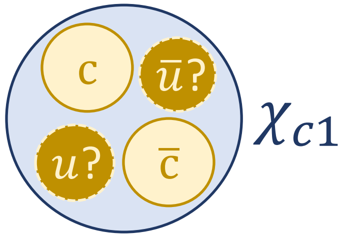


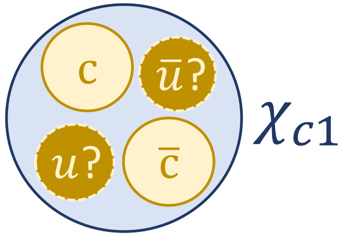


Higher mass states



- How is **tetraquark /** $D\overline{D}^*$ **molecule** candidate $\chi_{c1}(3872)$ produced?

Higher mass states



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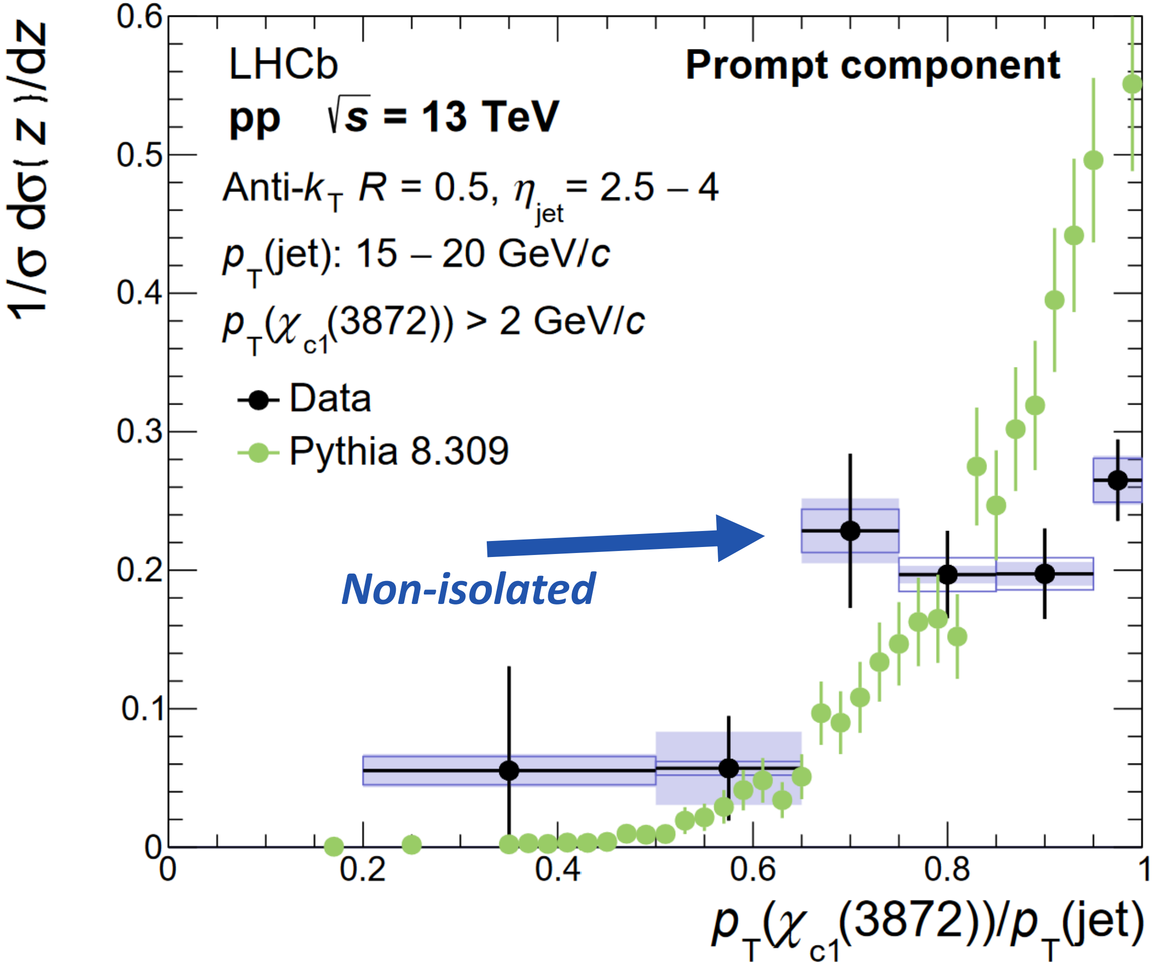
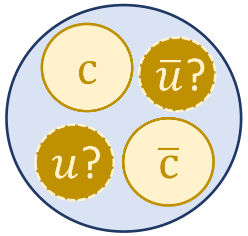


Eur. Phys. J. C **85** (2025) 562

Higher mass states



χ_{c1}

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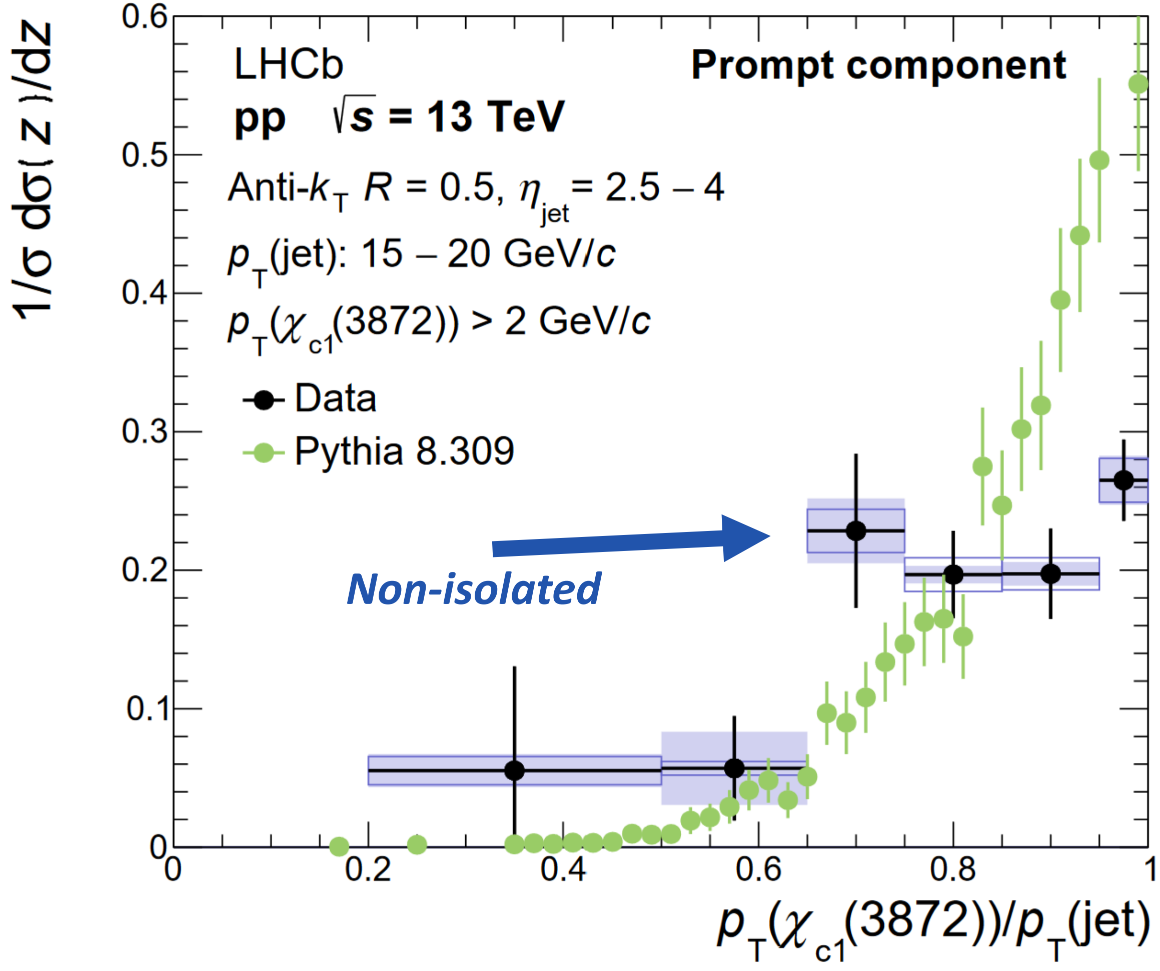

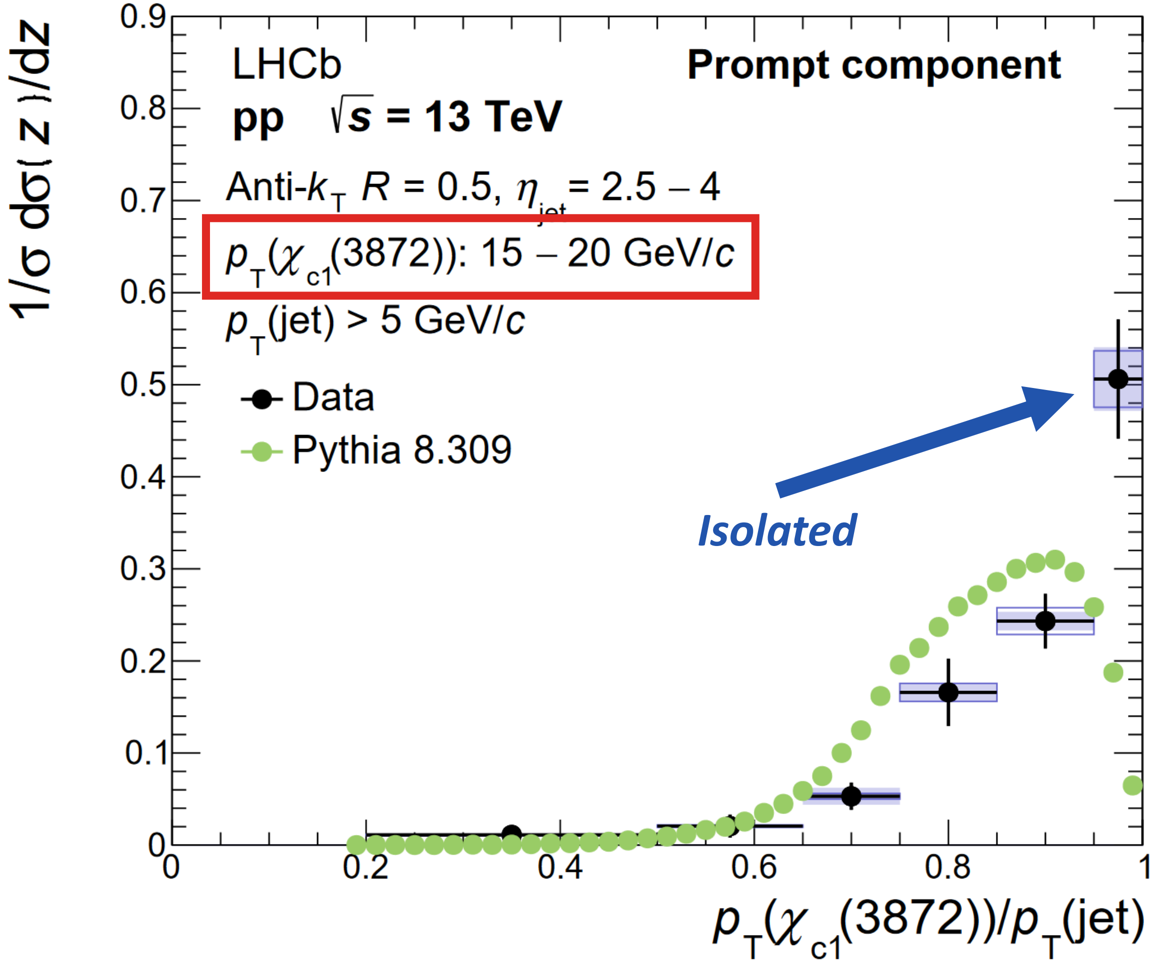

Eur. Phys. J. C **85** (2025) 562

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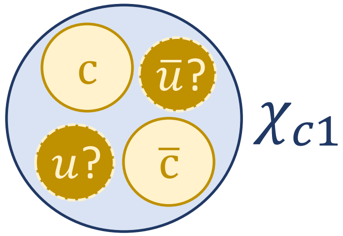

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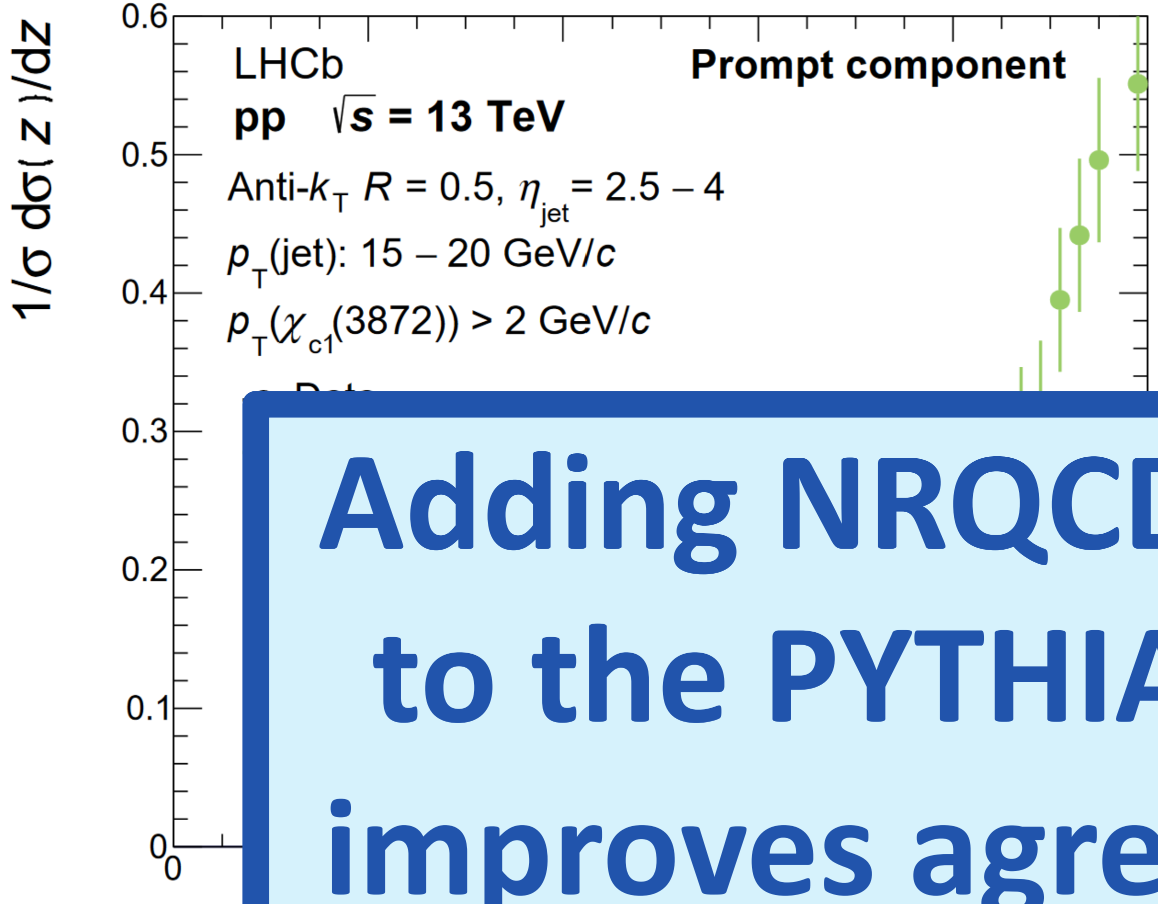
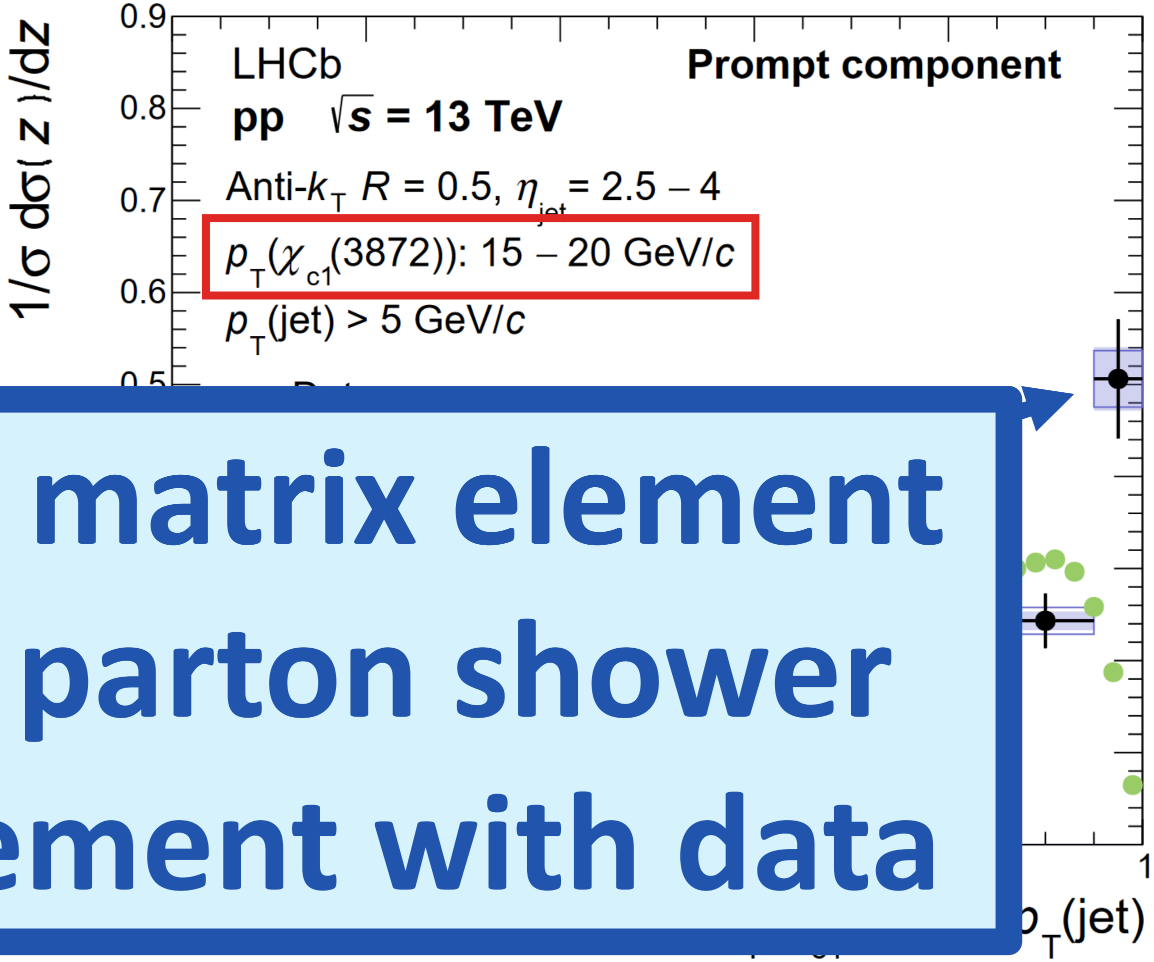
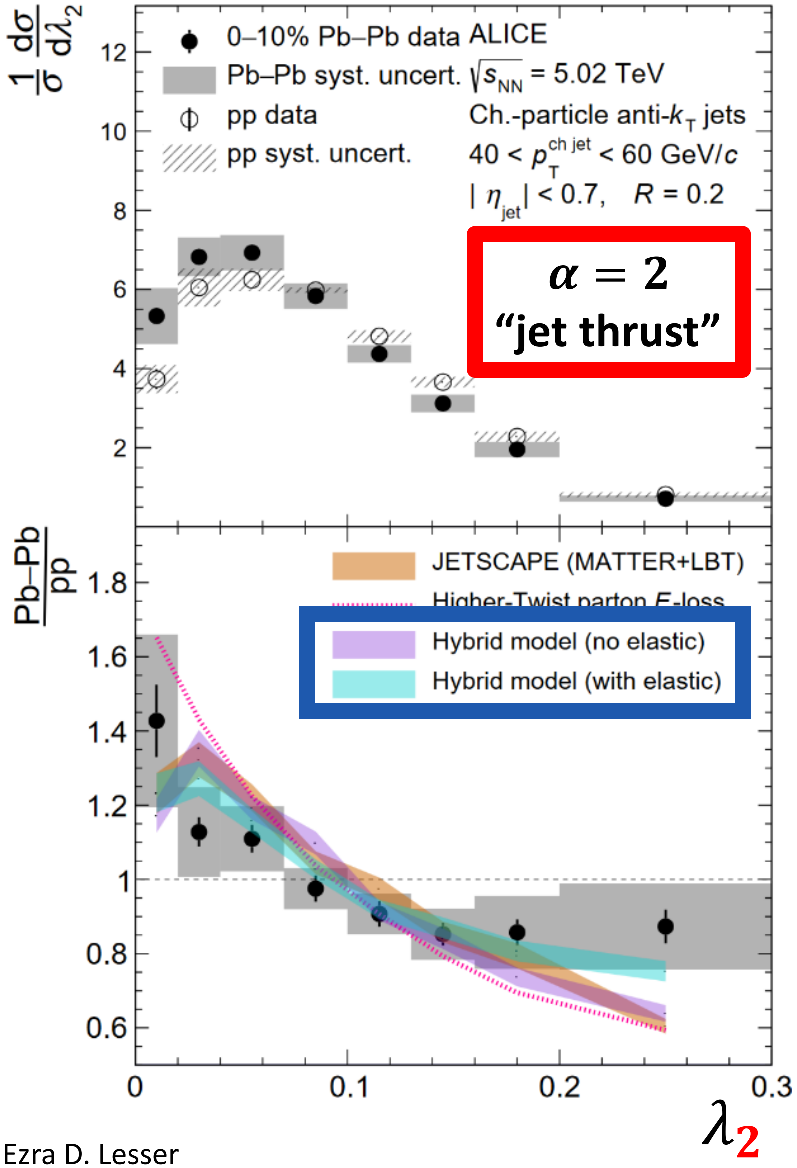




Adding NRQCD matrix element to the PYTHIA parton shower improves agreement with data

 [*Eur. Phys. J. C* **85** (2025) 562] [*Eur. Phys. J. C* **84** (2024) 432]

Jet quenching in angularities



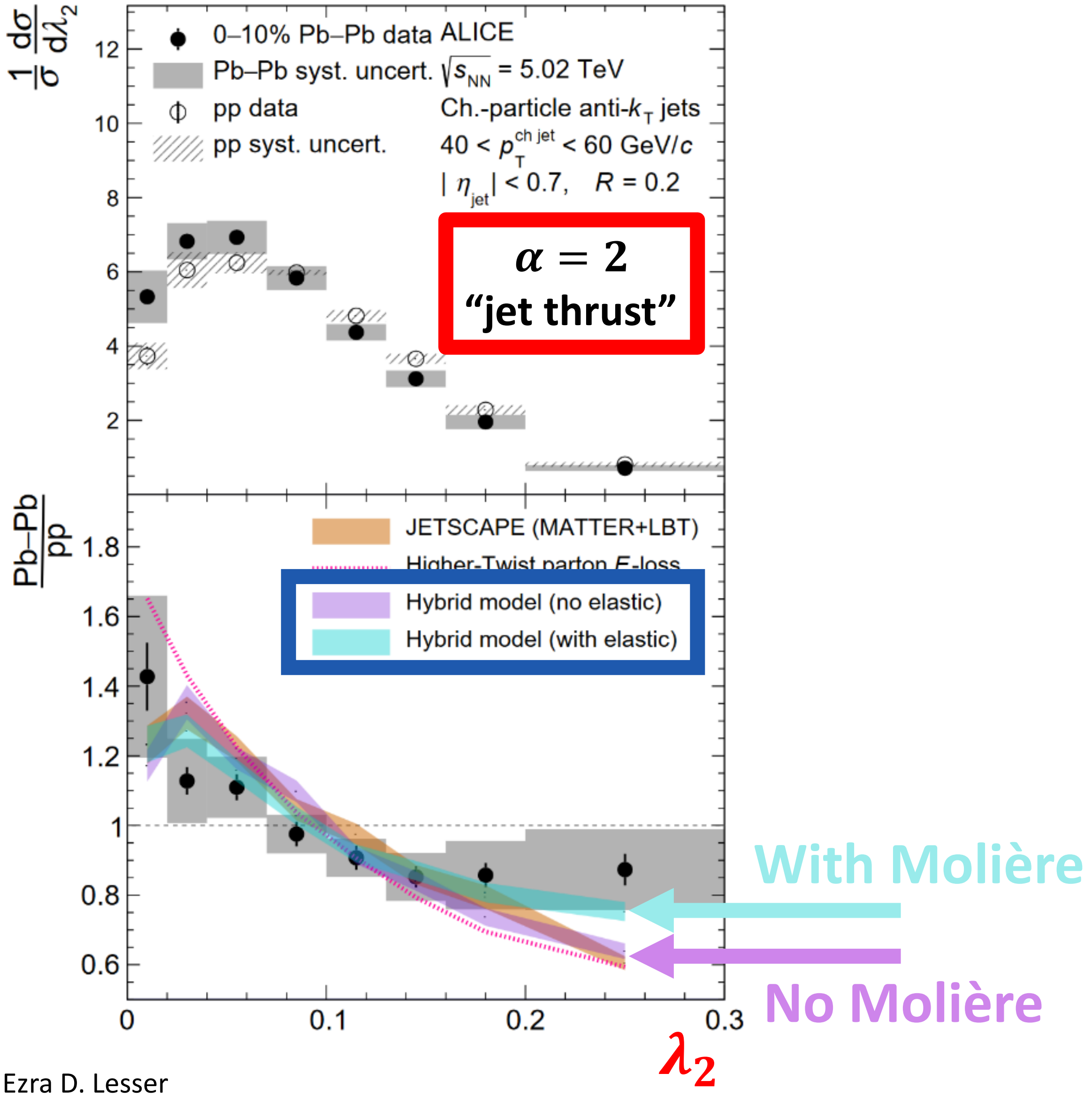
Hybrid model: vacuum predictions + strong QGP modifications based on **AdS/CFT correspondence**

D. Pablos, et al., JHEP **10** *(2014) 019*

- with / without elastic **Molière scattering**

F. D'Eramo, K. Rajagopal, Y. Yin JHEP **01** *(2019) 172*

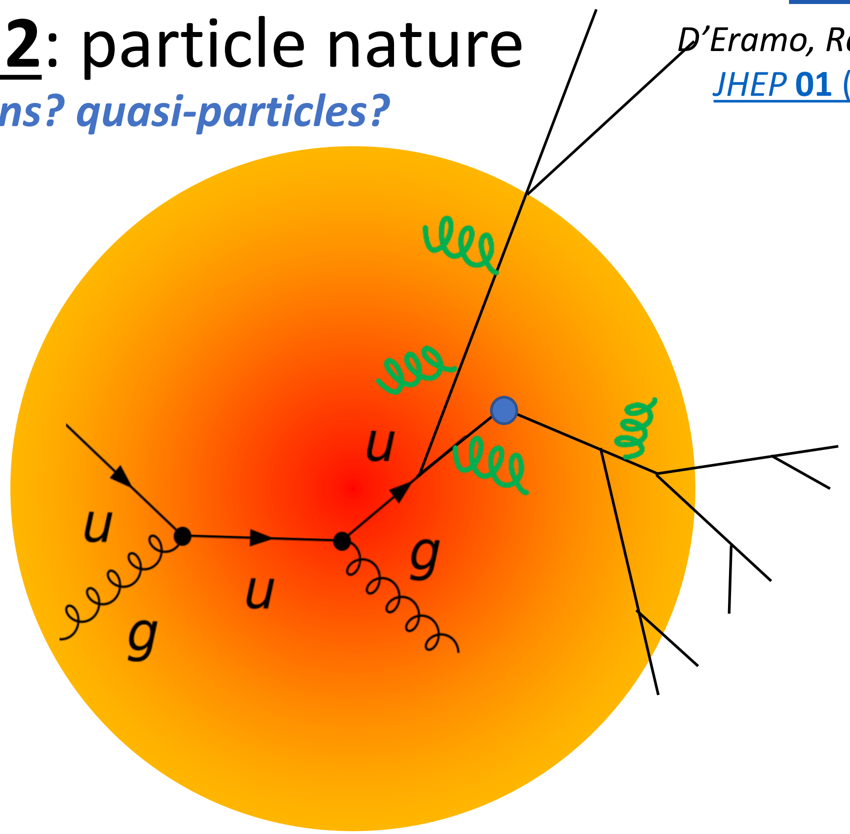
Multiple hard interactions in QGP?



Picture 2: particle nature

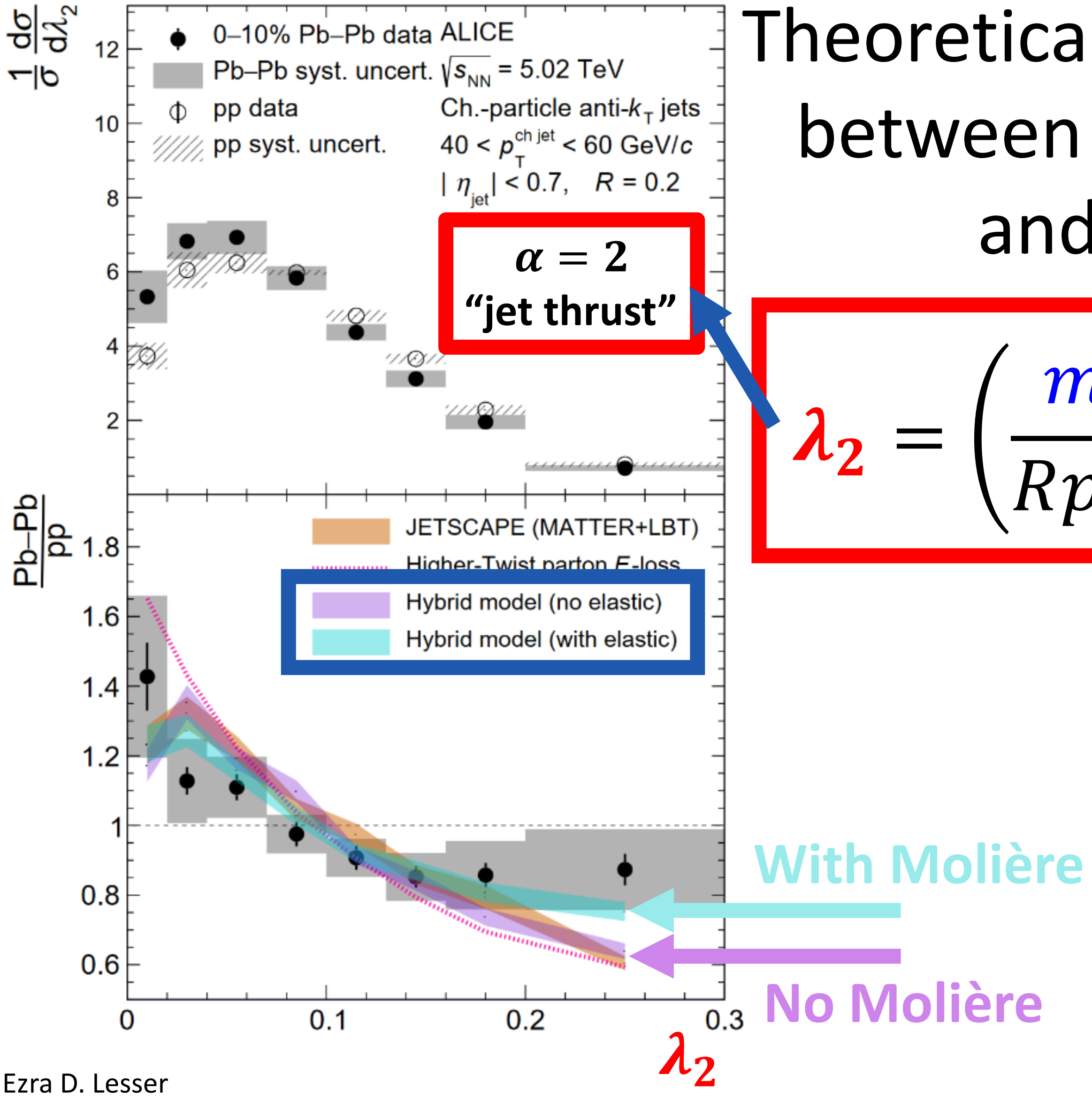
partons? quasi-particles?

D'Eramo, Rajagopal, Yin
JHEP **01** (2019) 172



Jet fragmentation
+ medium-induced emissions
+ elastic Molière scattering?

Multiple hard interactions in QGP?

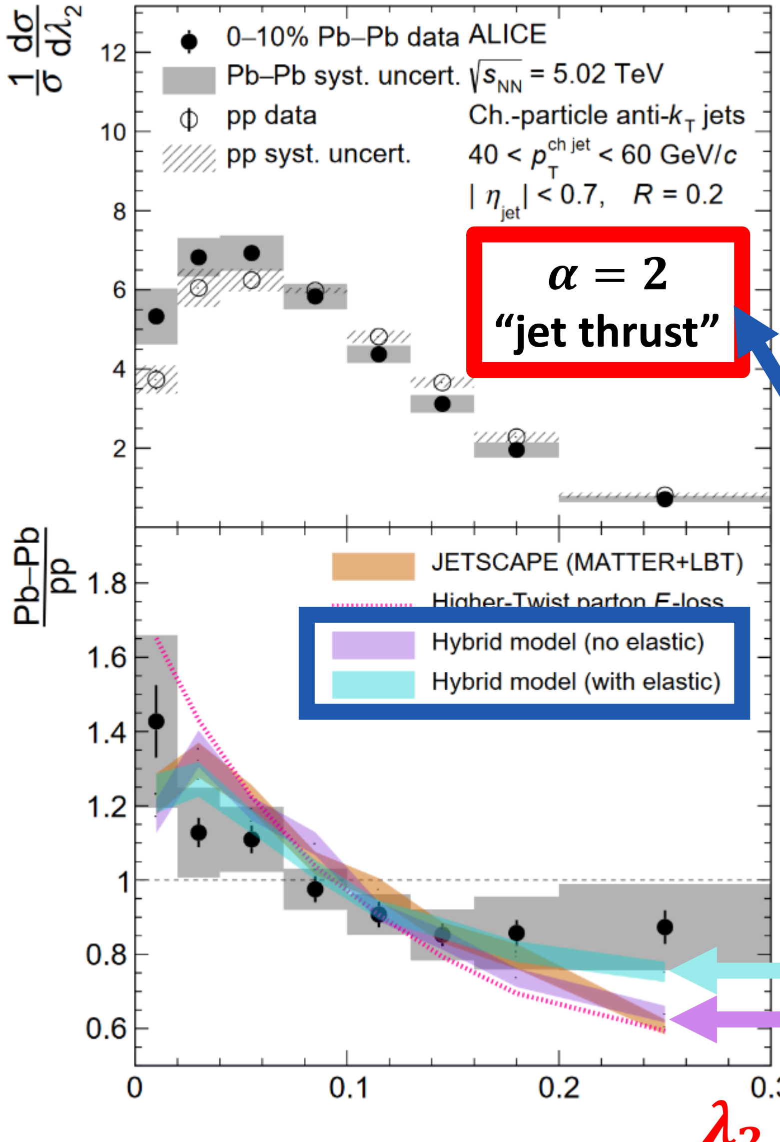


Theoretical correspondence between **jet angularities** and **jet mass:**

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

JHEP 1804 (2018) 110

Multiple hard interactions in QGP?



$\alpha = 2$
"jet thrust"

λ_2

Theoretical correspondence between **jet angularities** and **jet mass:**

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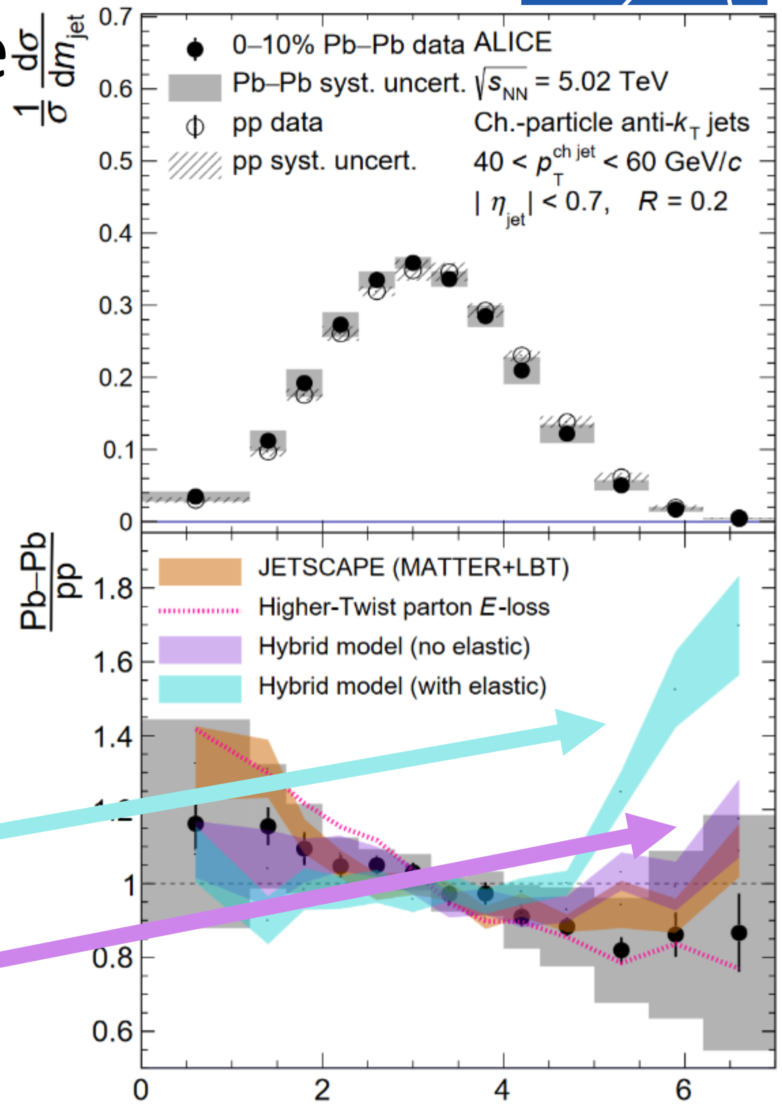
JHEP 1804 (2018) 110

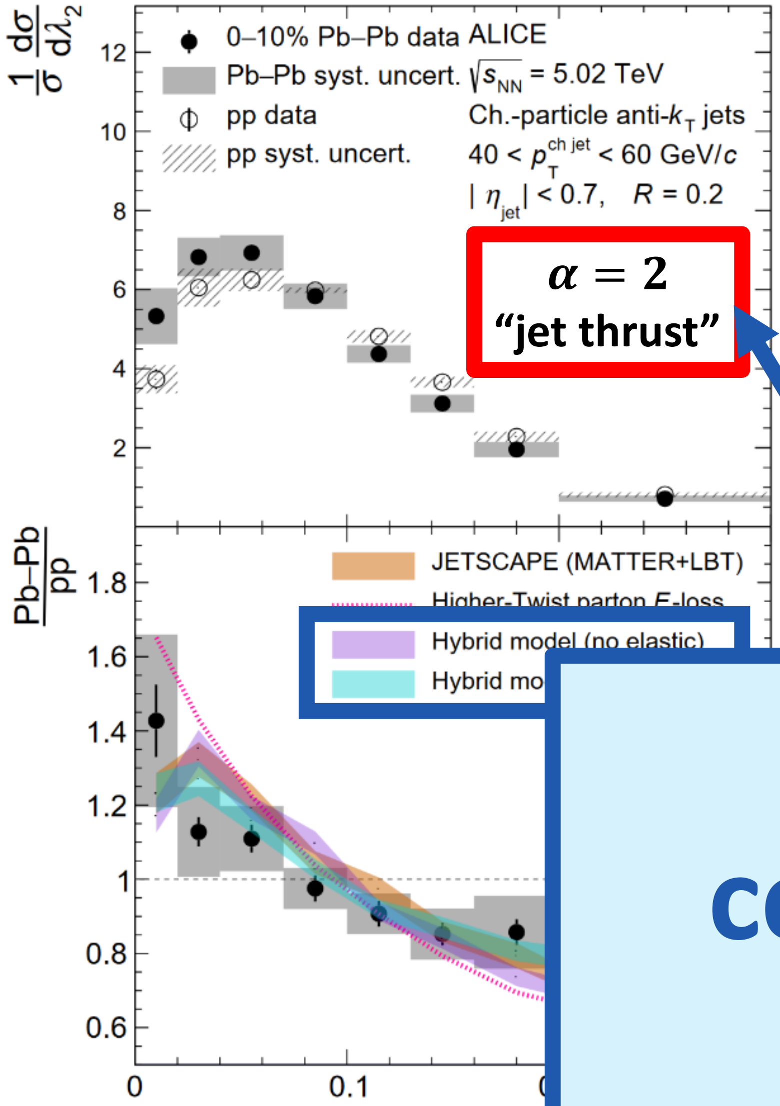
With Molière

No Molière



m_{jet} (GeV/c)

Multiple hard interactions in QGP?



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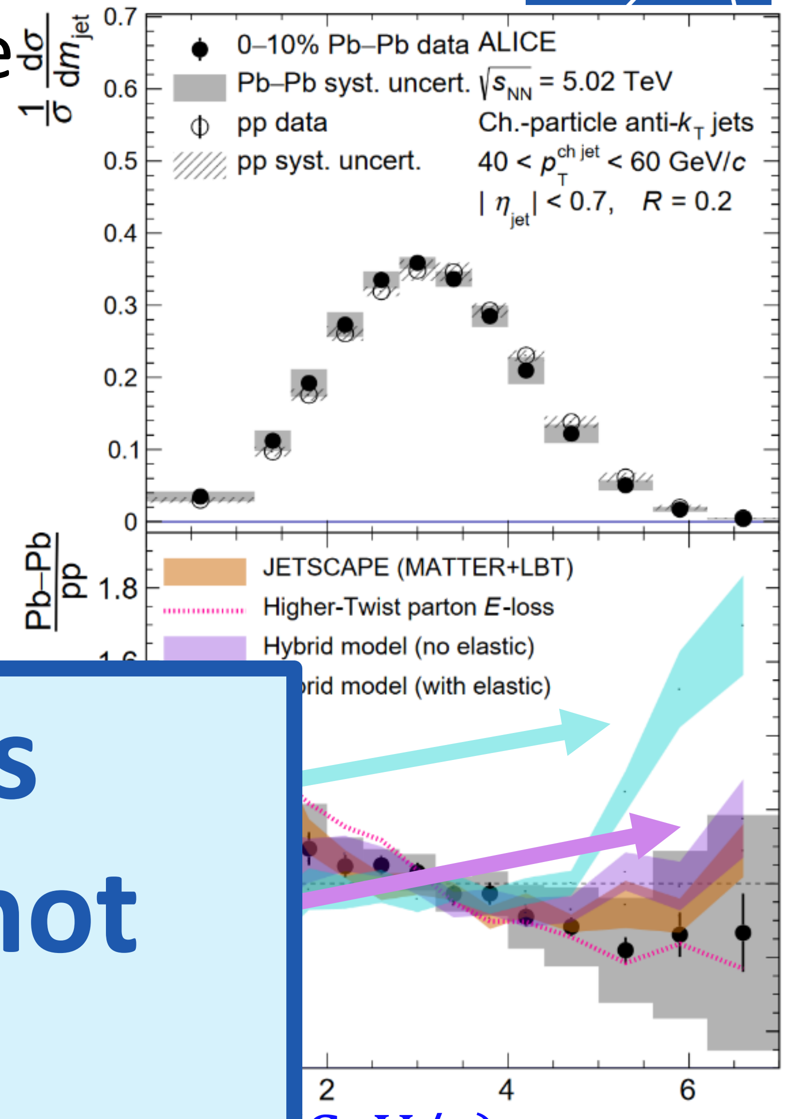
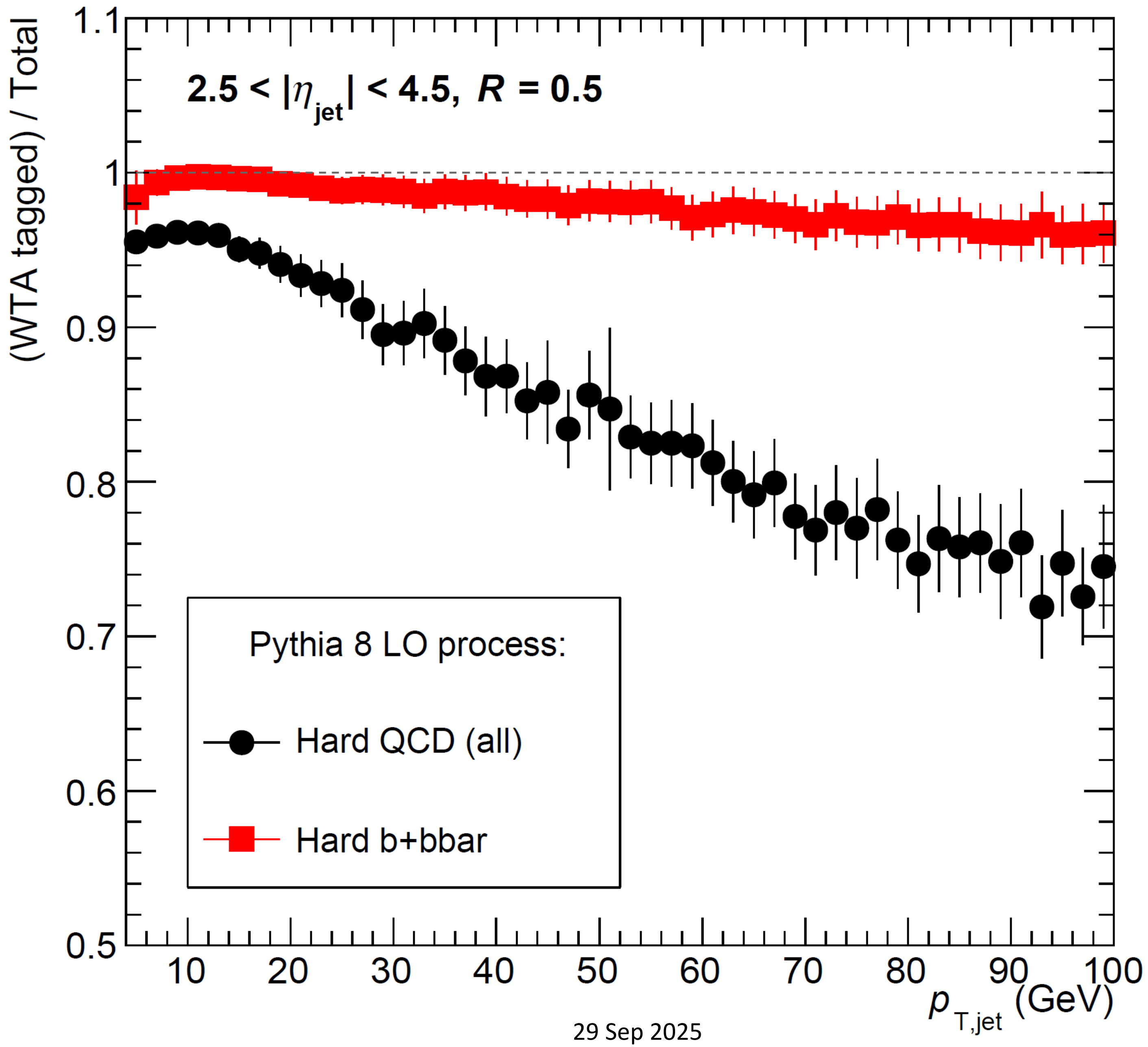
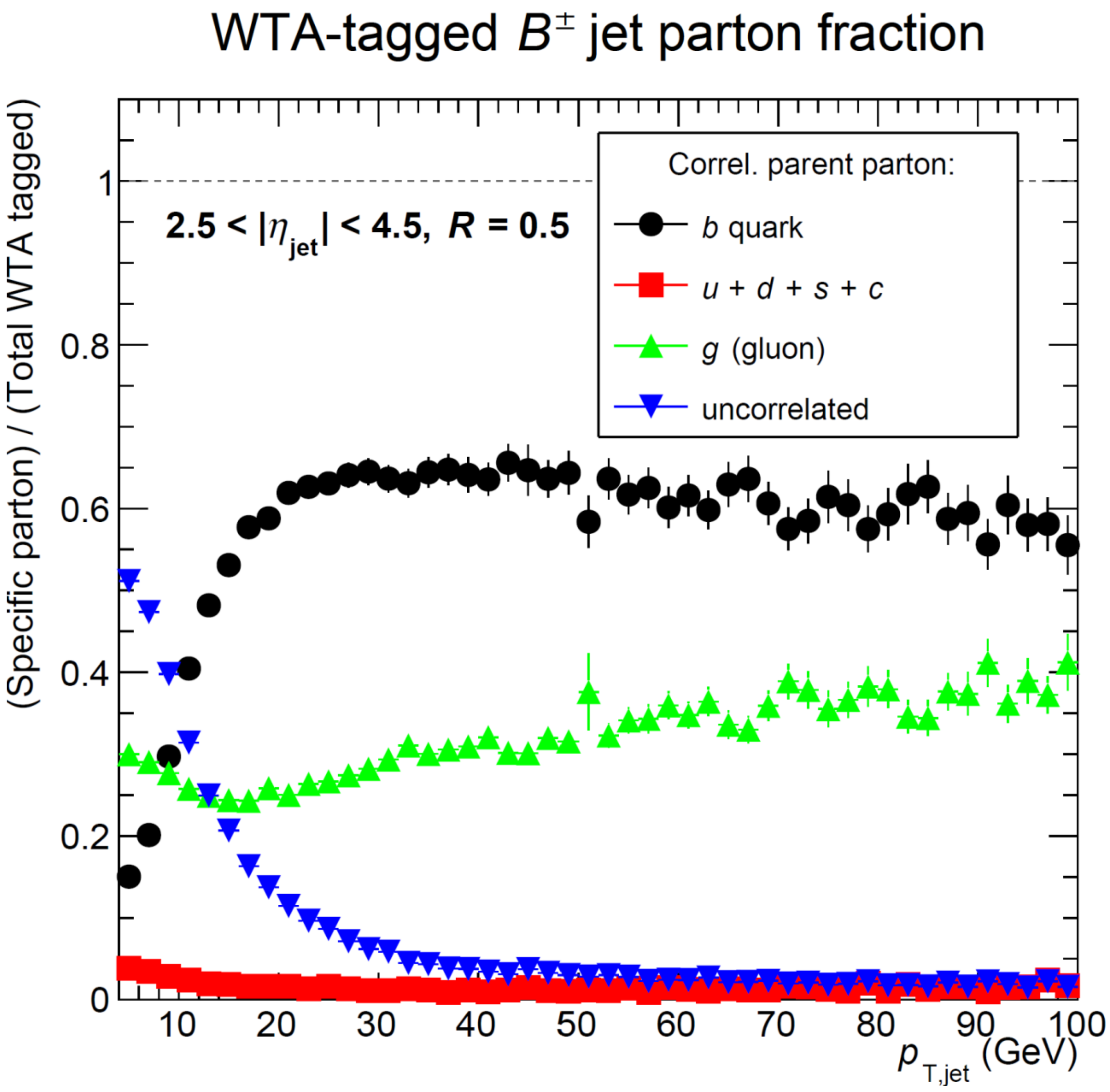
JHEP 1804 (2018) 110

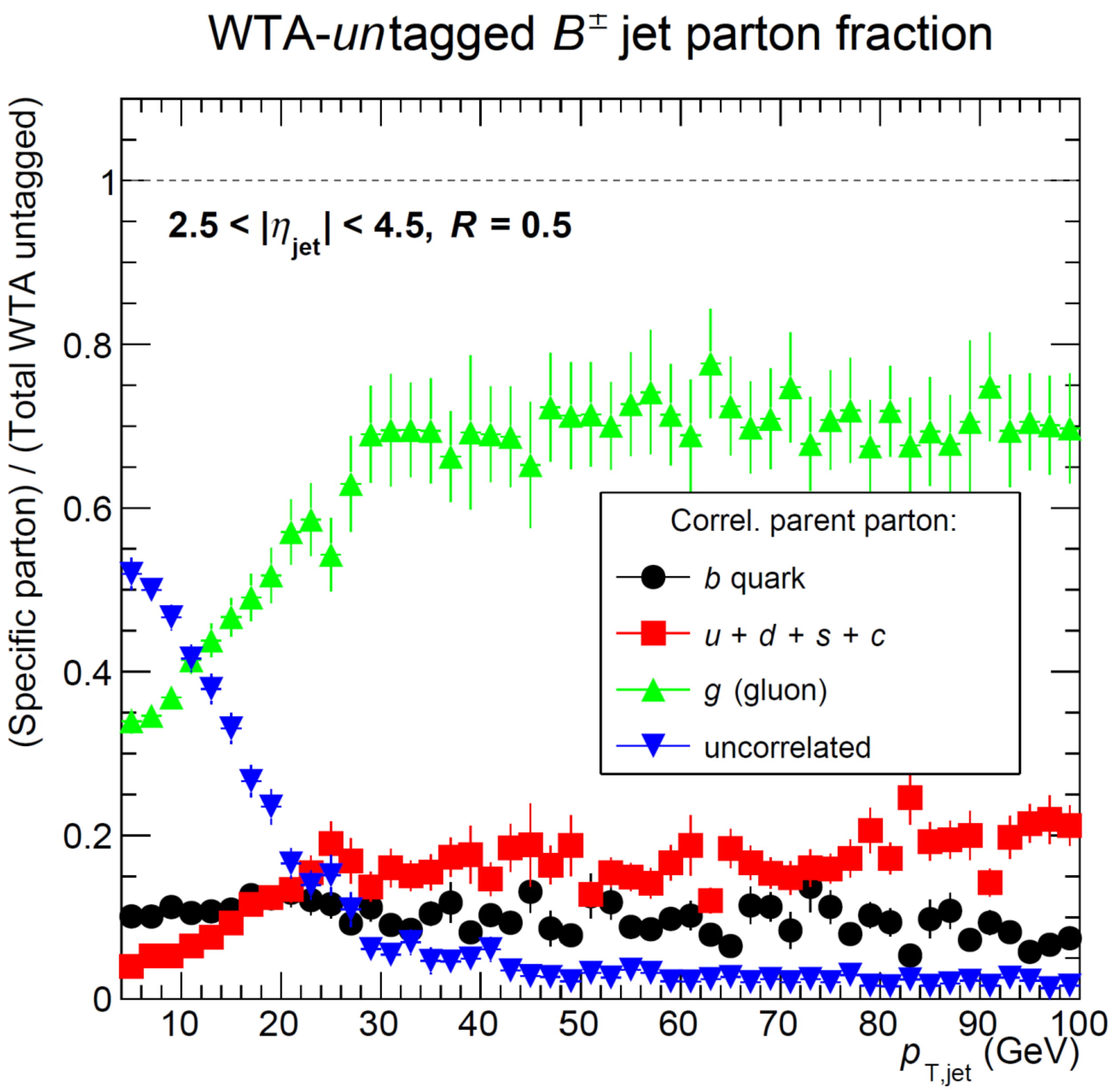


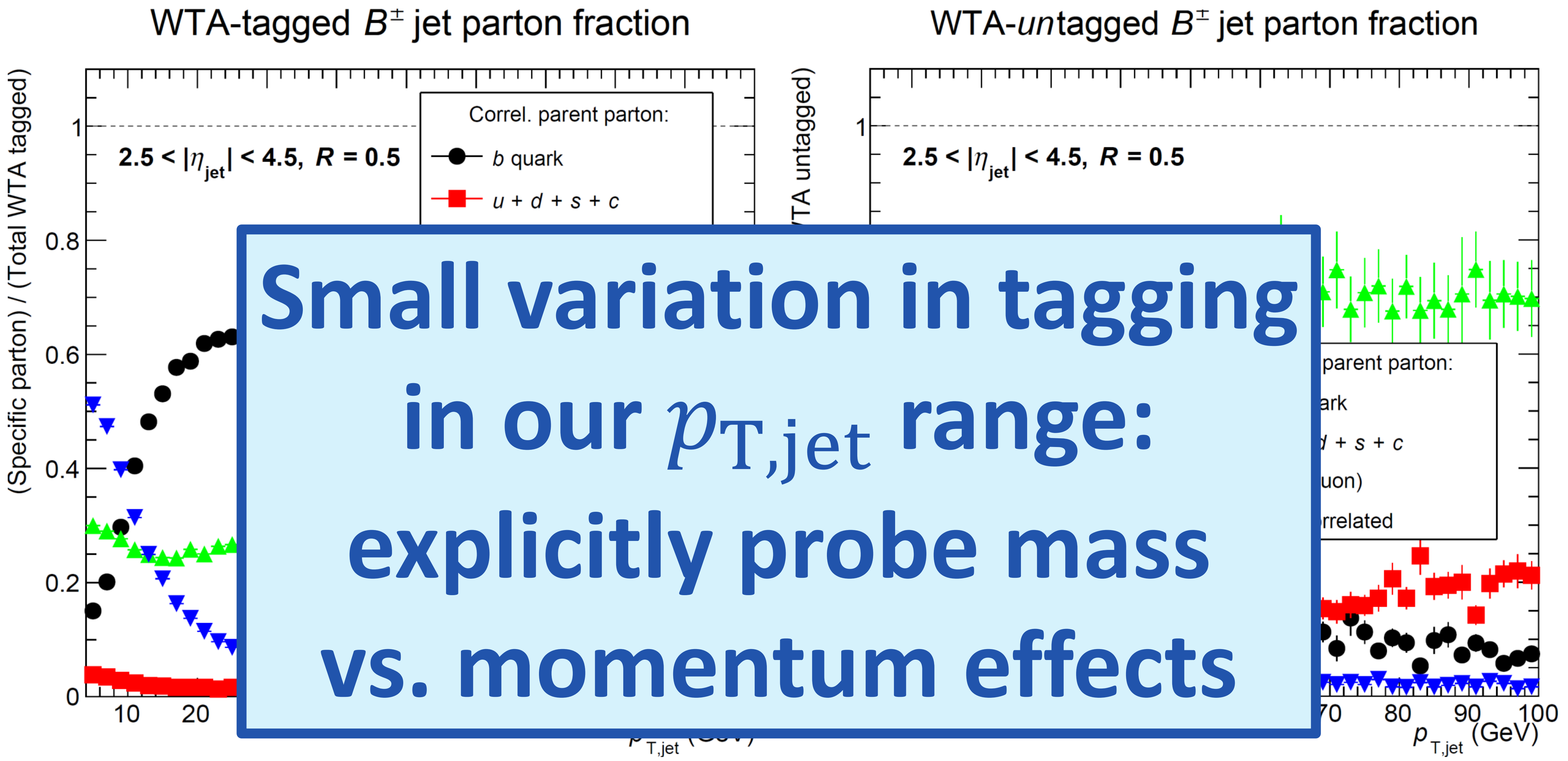
Inconsistency: this correspondence is not useful at low p_{T}

WTA tagging fraction for jets with $B^{\pm}$




WTA-tagged $B^{\pm}$ jet parton fraction
(Specific parton) / (Total WTA tagged)
$2.5 < |\eta_{\mathrm{jet}}| < 4.5$, $R = 0.5$
Correl. parent parton:
b quark
$u + d + s + c$
g (gluon)
uncorrelated
$p_{\mathrm{T,jet}}$ (GeV)
0
0.2
0.4
0.6
0.8
1
10
20
30
40
50
60
70
80
90
100


WTA-*un*tagged $B^{\pm}$ jet parton fraction
(Specific parton) / (Total WTA untagged)
$2.5 < |\eta_{\mathrm{jet}}| < 4.5$, $R = 0.5$
Correl. parent parton:
b quark
$u + d + s + c$
g (gluon)
uncorrelated
$p_{\mathrm{T,jet}}$ (GeV)
0
0.2
0.4
0.6
0.8
1
10
20
30
40
50
60
70
80
90
100



Small variation in tagging in our $p_{\text{T,jet}}$ range: explicitly probe mass vs. momentum effects