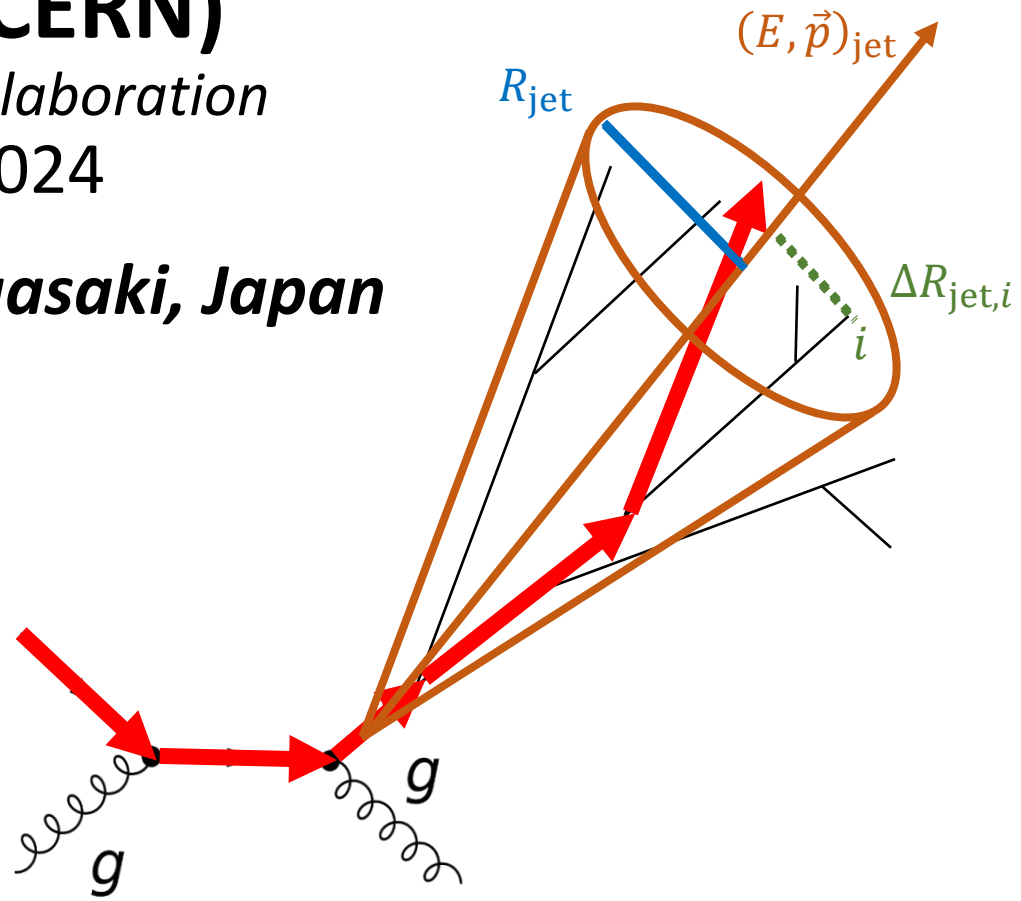
Probing QCD dynamics with jet substructure in LHCb kinematics

Ezra D. Lesser (CERN)
on behalf of the LHCb Collaboration
25 September 2024

Hard Probes 2024 // Nagasaki, Japan



b-quark production at the LHC

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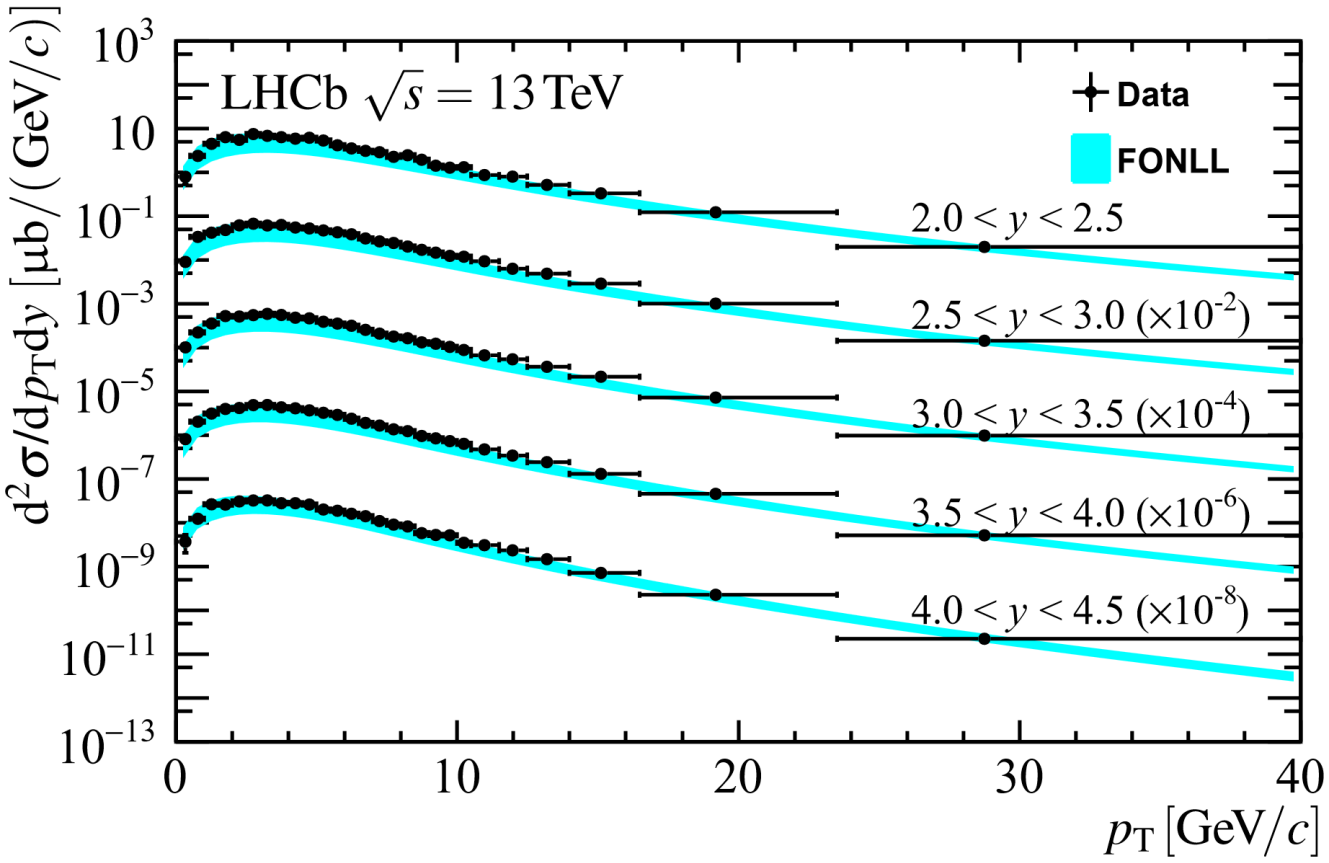
$B^{\pm}$ double-differential cross-sections



LHCb Collab., *JHEP* 12 (2017) 026

- b-hadron spectra have been studied with excellent precision by the LHC experiments

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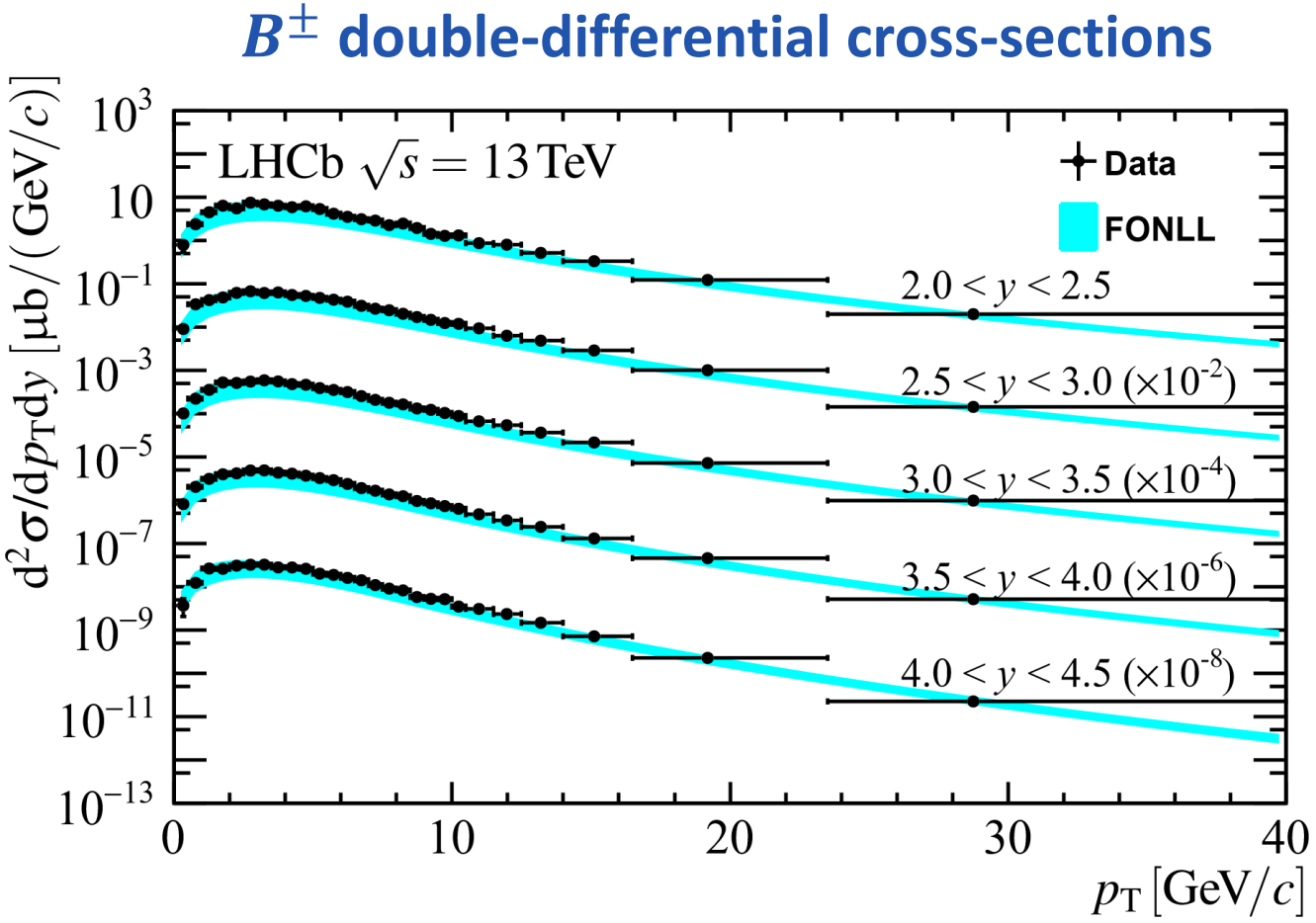
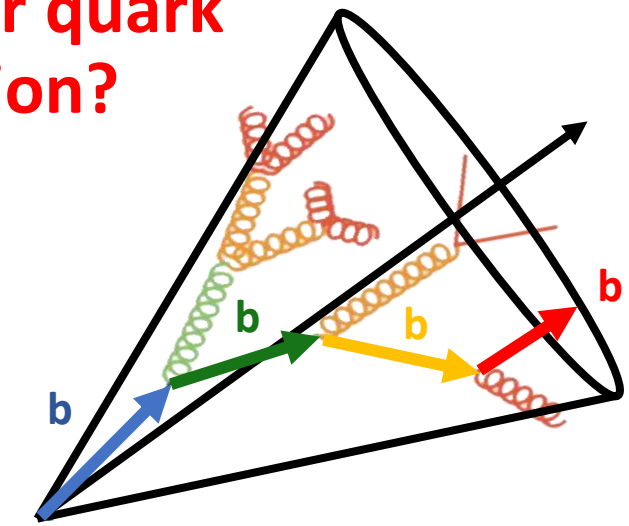


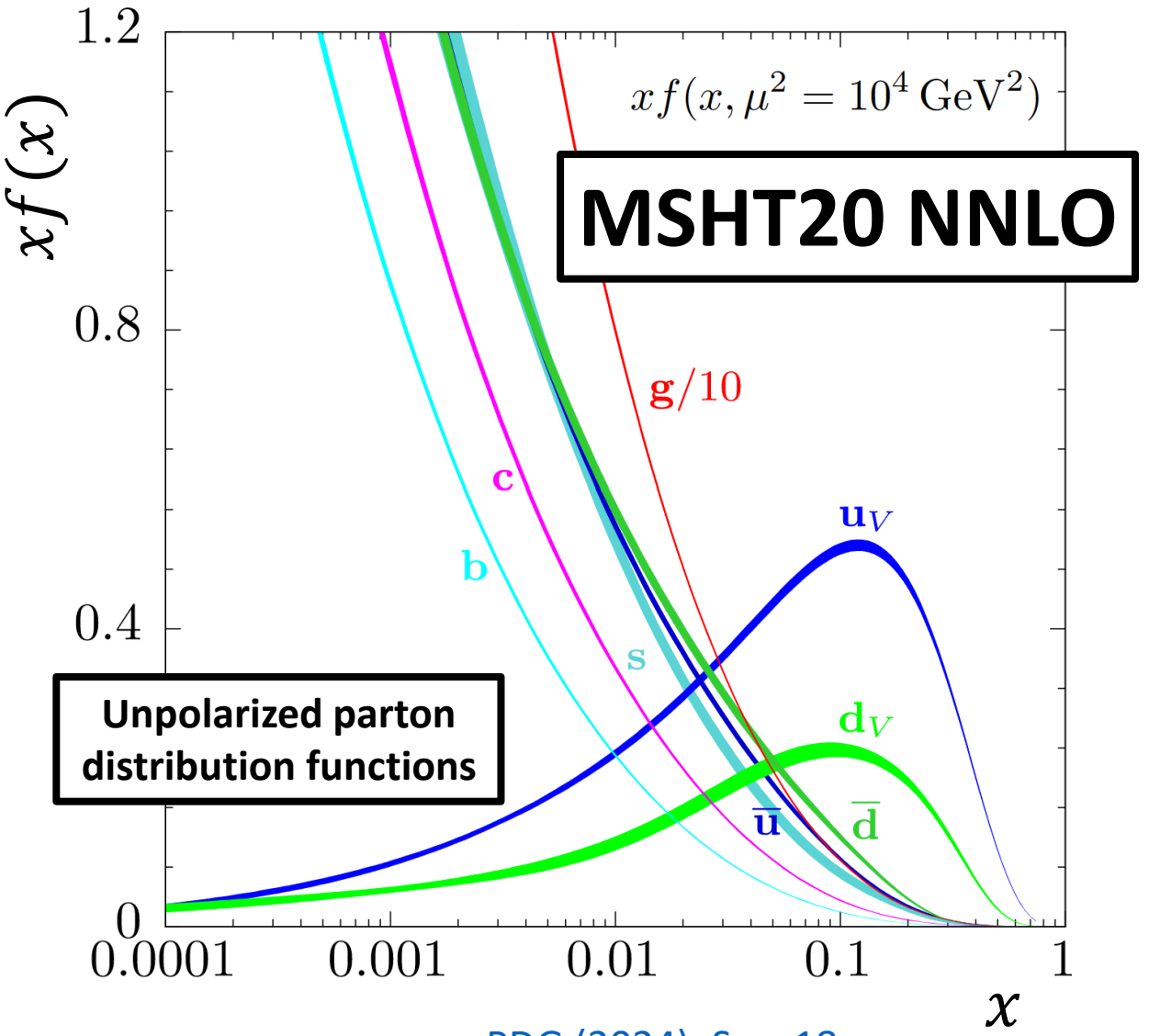
LHCb Collab., *JHEP* 12 (2017) 026

- b-hadron spectra have been studied with excellent precision by the LHC experiments
- What can we learn about **heavy-flavor quark fragmentation?**



b-quark production at the LHC

- No inherent b-quark component in the proton wavefunction



PDG (2024), Sec. 18

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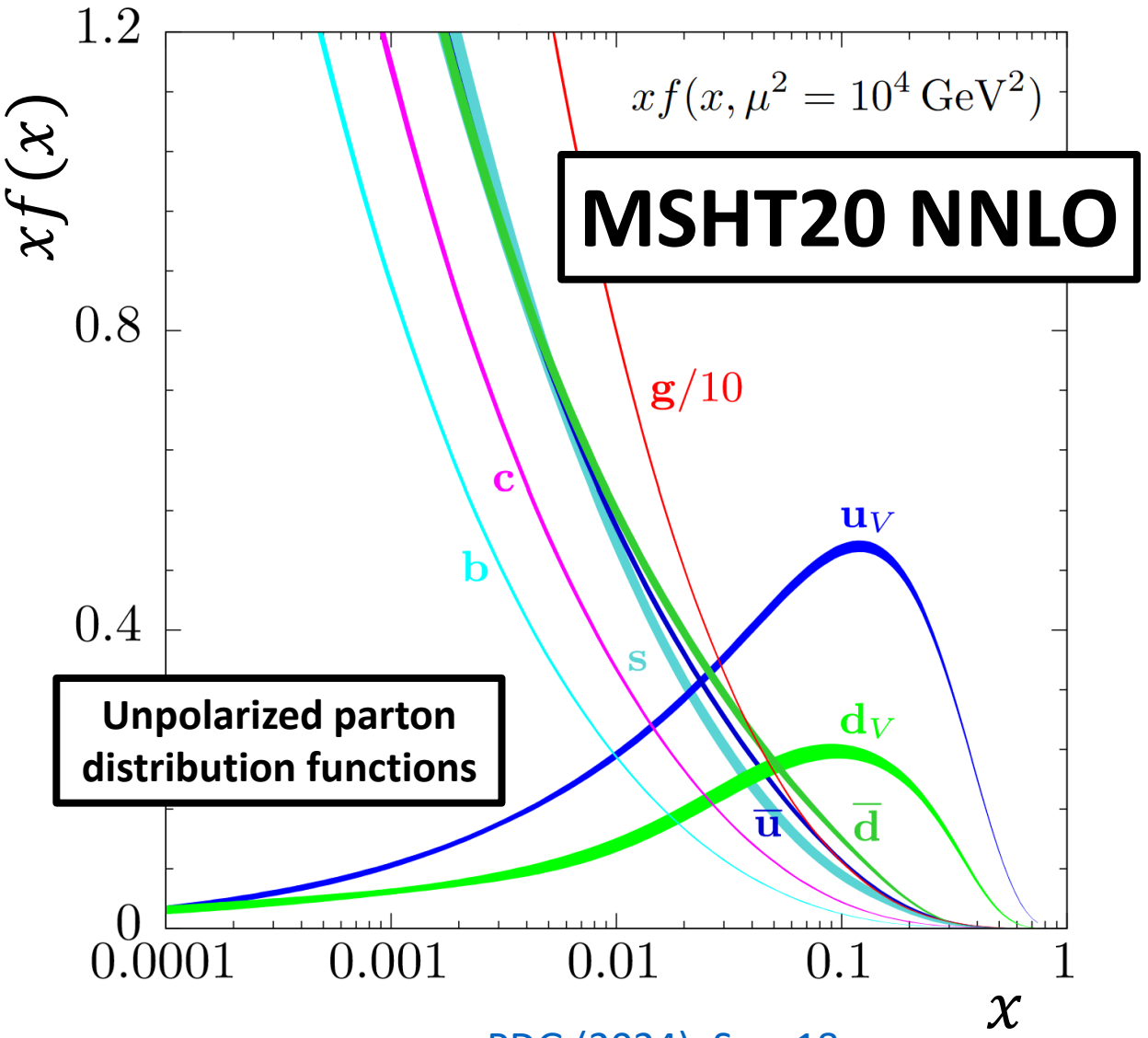
$$gg \to b\bar{b}, \qquad q\bar{q} \to b\bar{b}$$



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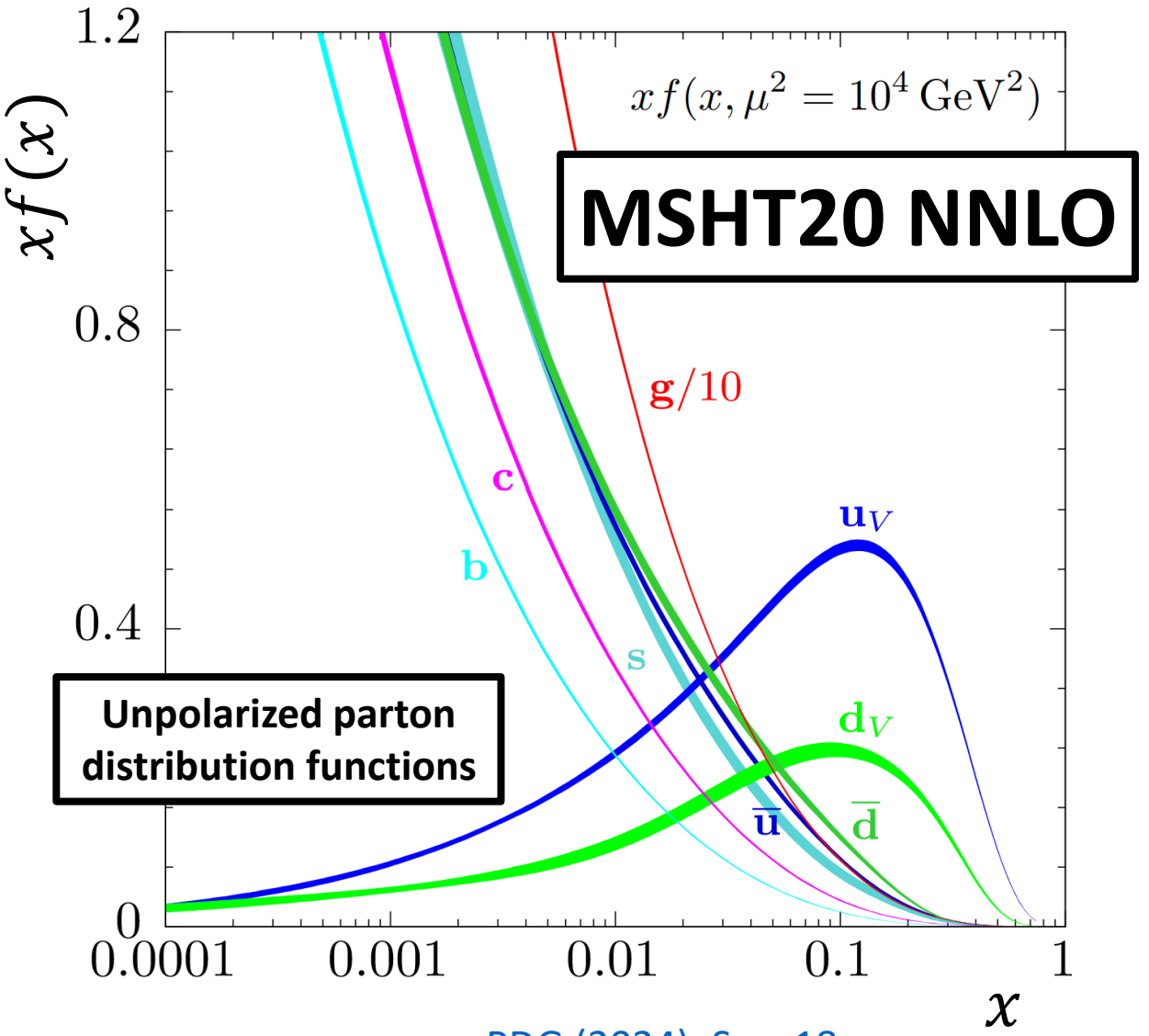

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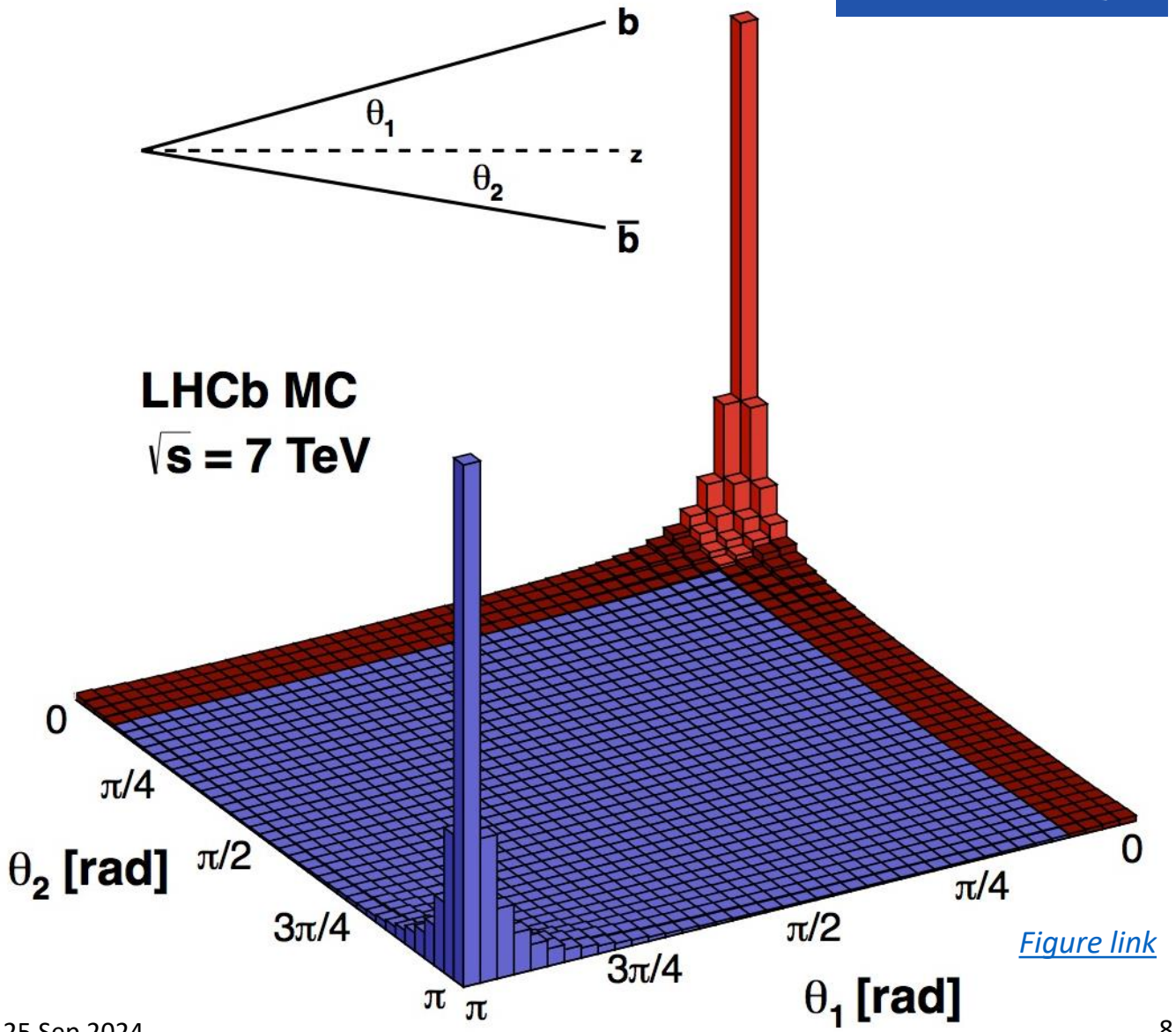
- **$b\bar{b}$ pairs are predominantly produced at small angles from the beam direction**



A different kind of jet detector…

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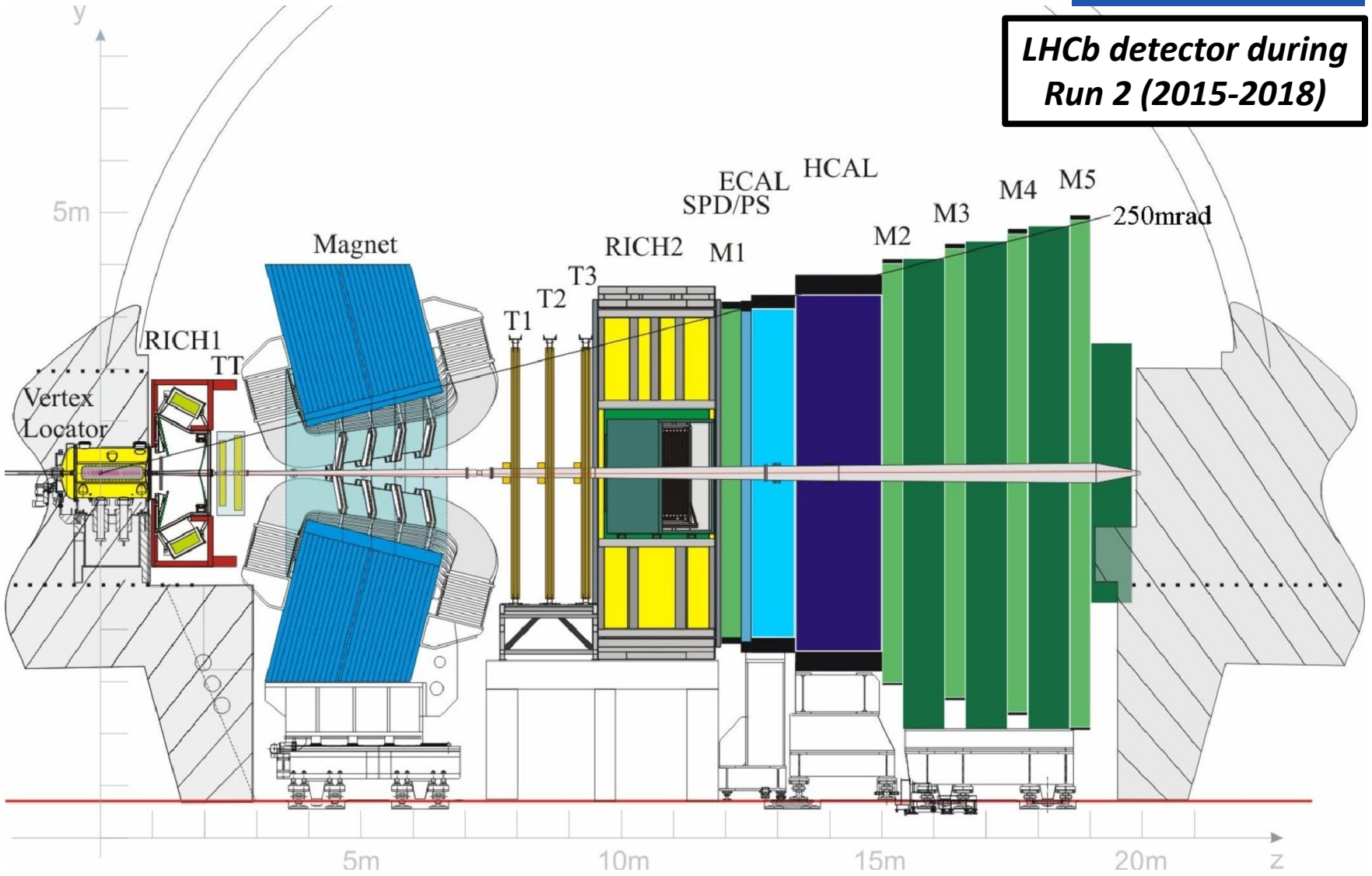
- LHCb is a completely forward detector ($2 < \eta < 5$)
- Low pileup ($\mu \approx 1$)



LHCb detector during Run 2 (2015-2018)

Int. J. Mod. Phys. A 30 (2015) 1530022

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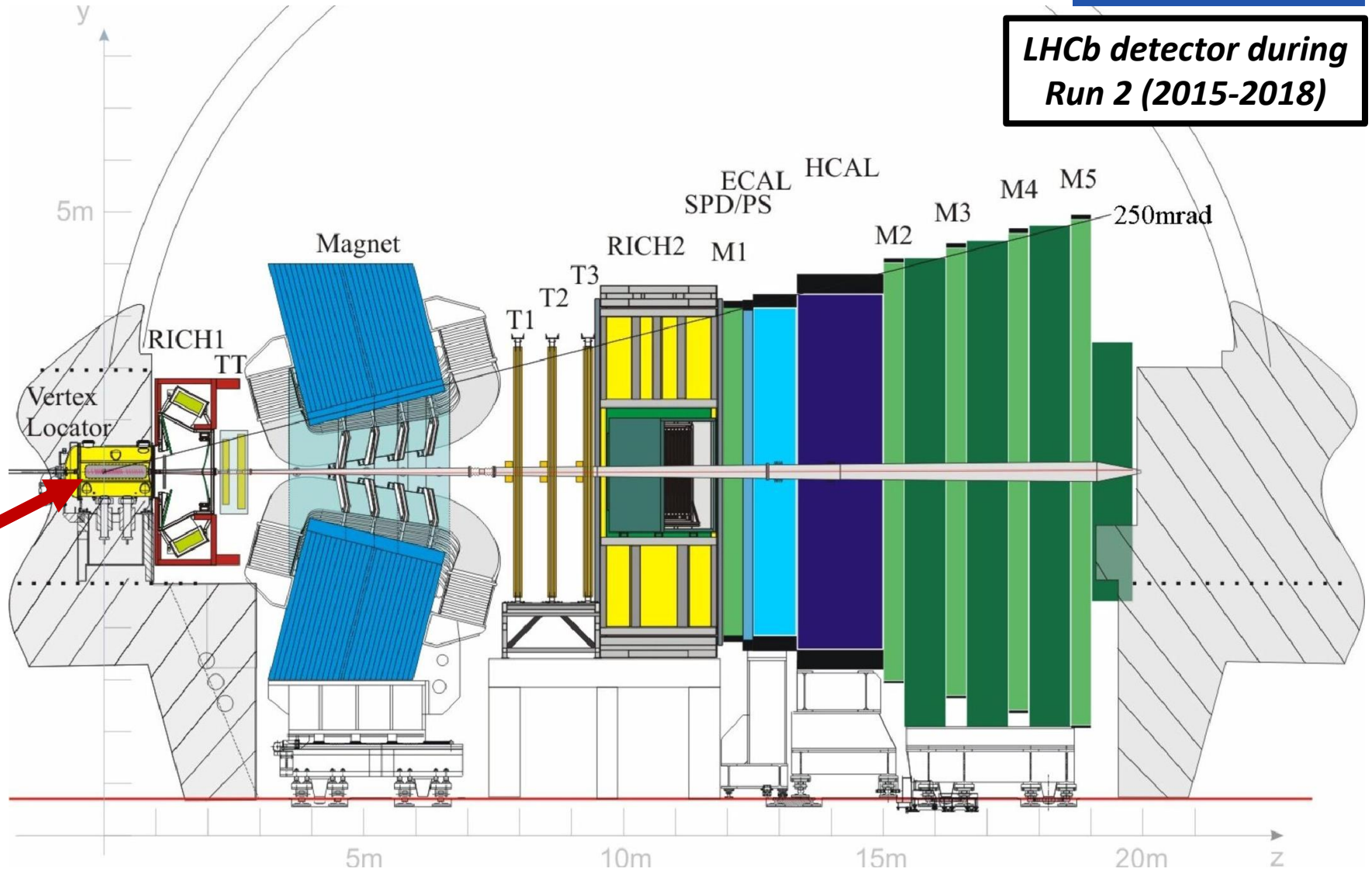

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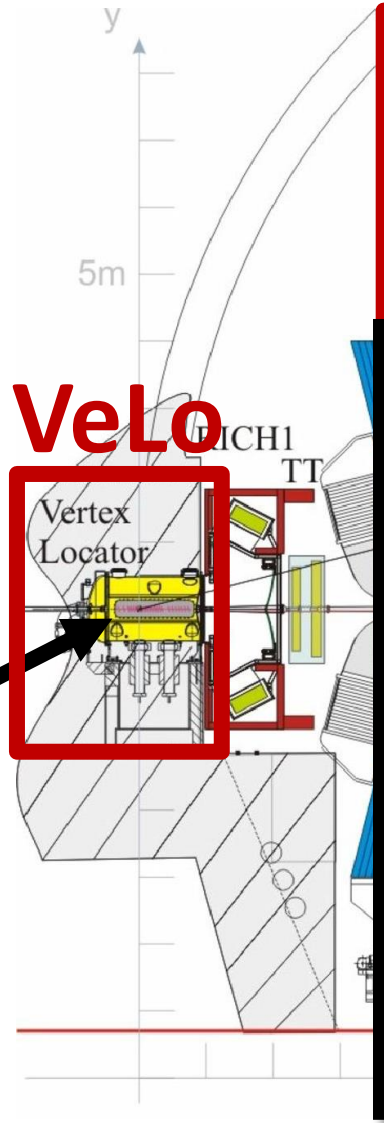
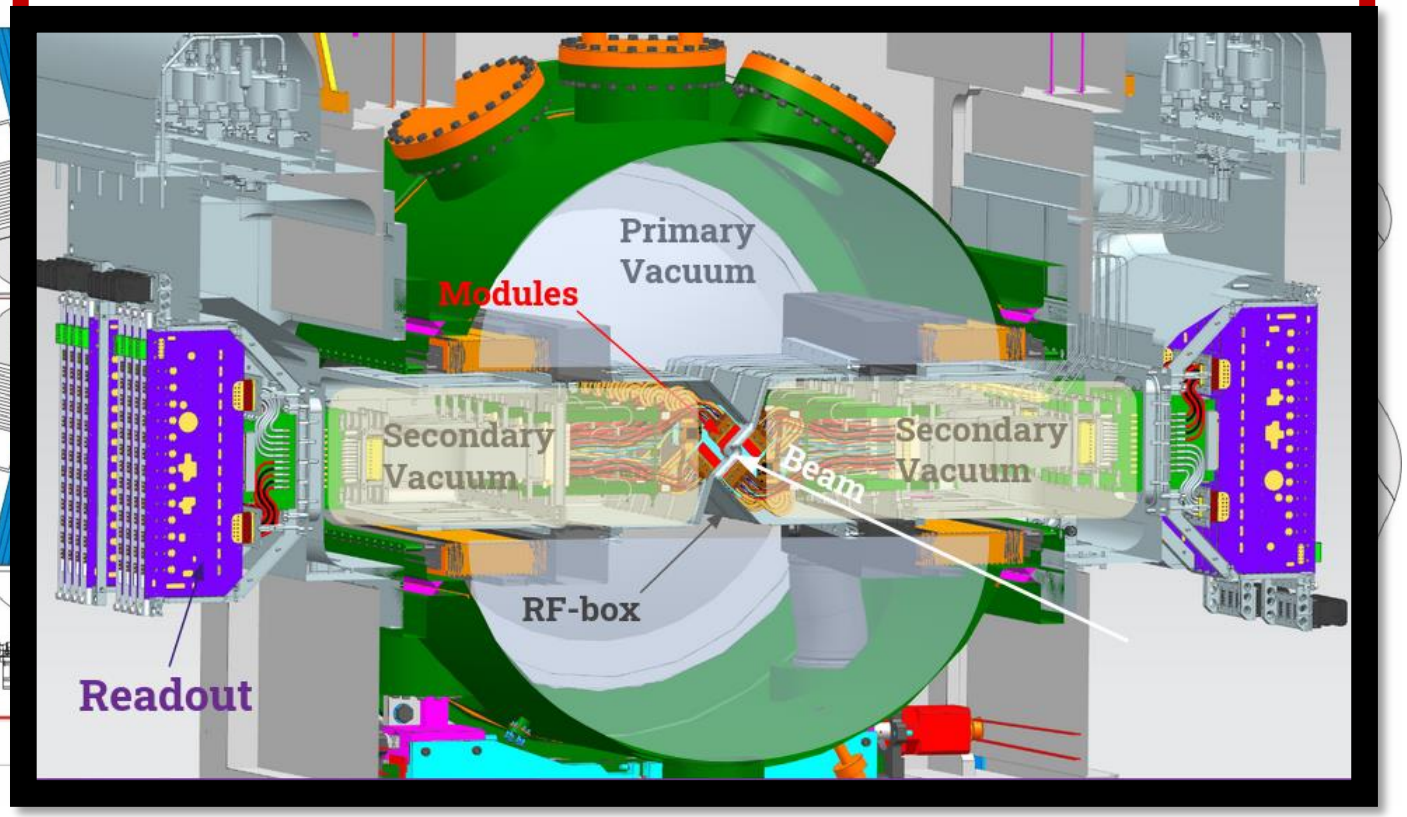


- LHC beampipe opened(!) for silicon tracking detectors to be placed closer to the beam
- Excellent primary vertex resolution of ~10 (transverse directions x, y) / ~40 (z) μm



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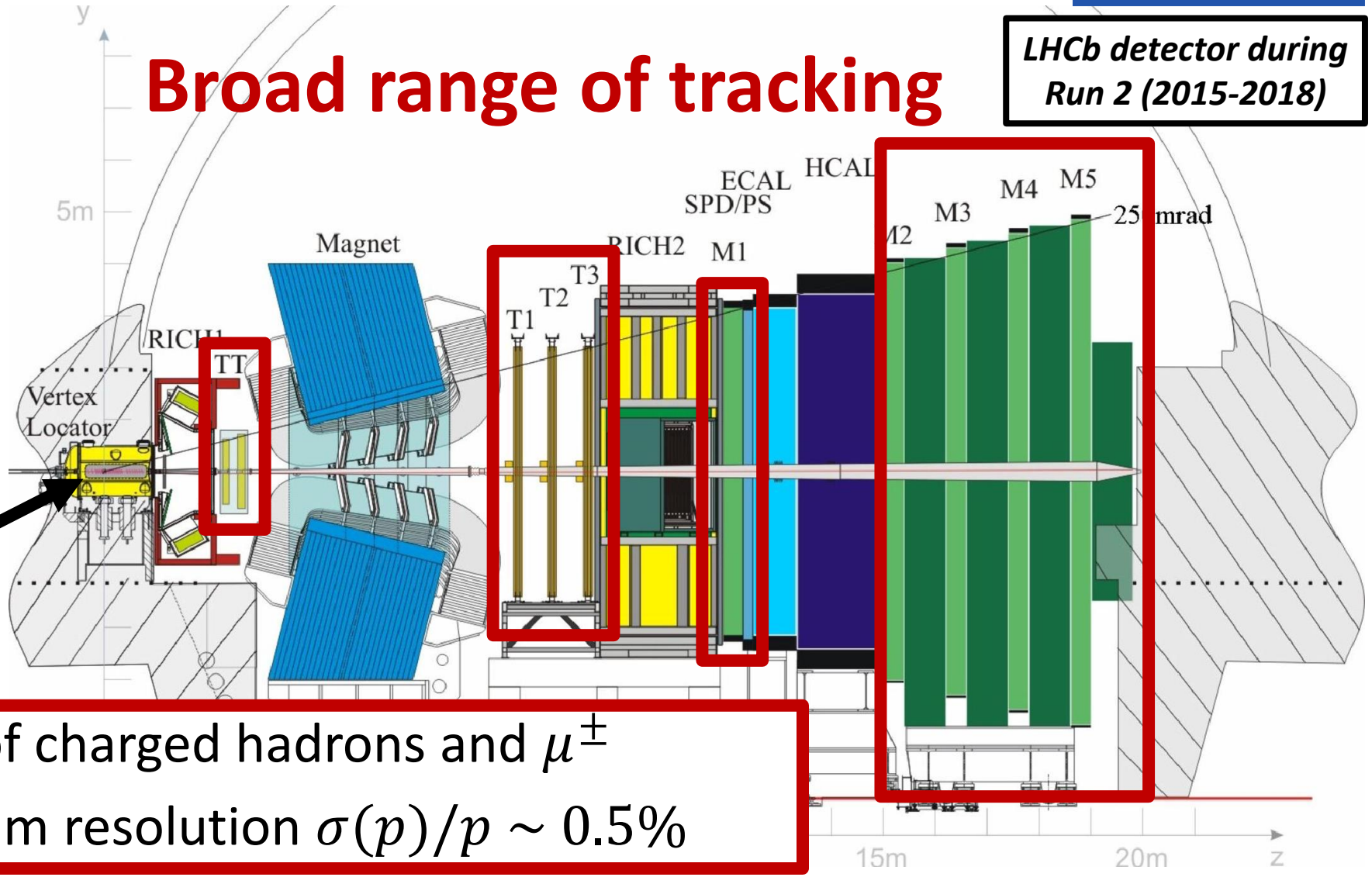
Broad range of tracking



LHCb detector during Run 2 (2015-2018)

- Measurement of charged hadrons and $\mu^{\pm}$
- Great momentum resolution $\sigma(p)/p \sim 0.5\%$

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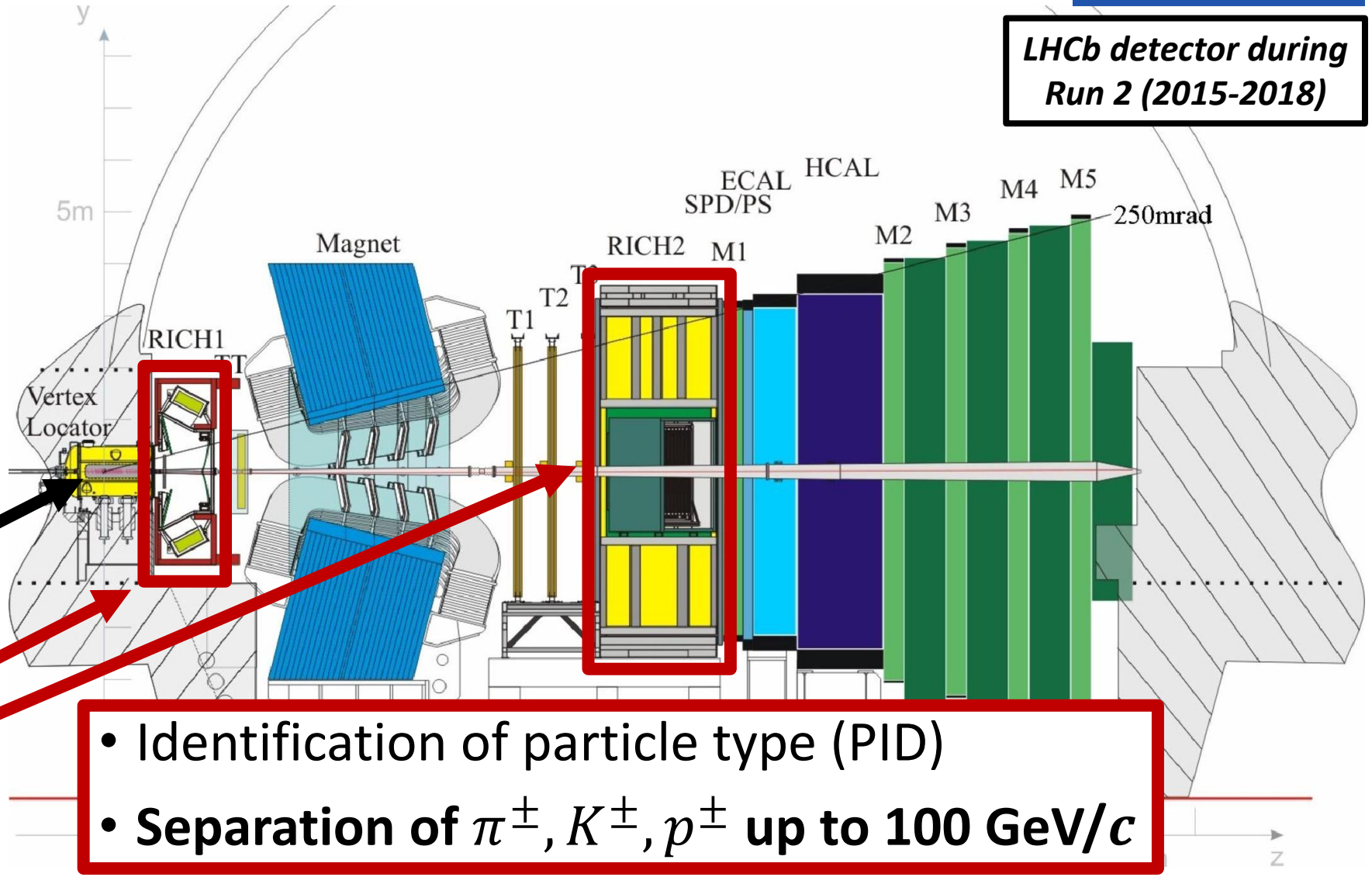

LHCb detector during Run 2 (2015-2018)

Cherenkov detectors

- Identification of particle type (PID)
- **Separation of $\pi^{\pm}, K^{\pm}, p^{\pm}$ up to 100 GeV/c**

A different kind of jet detector…

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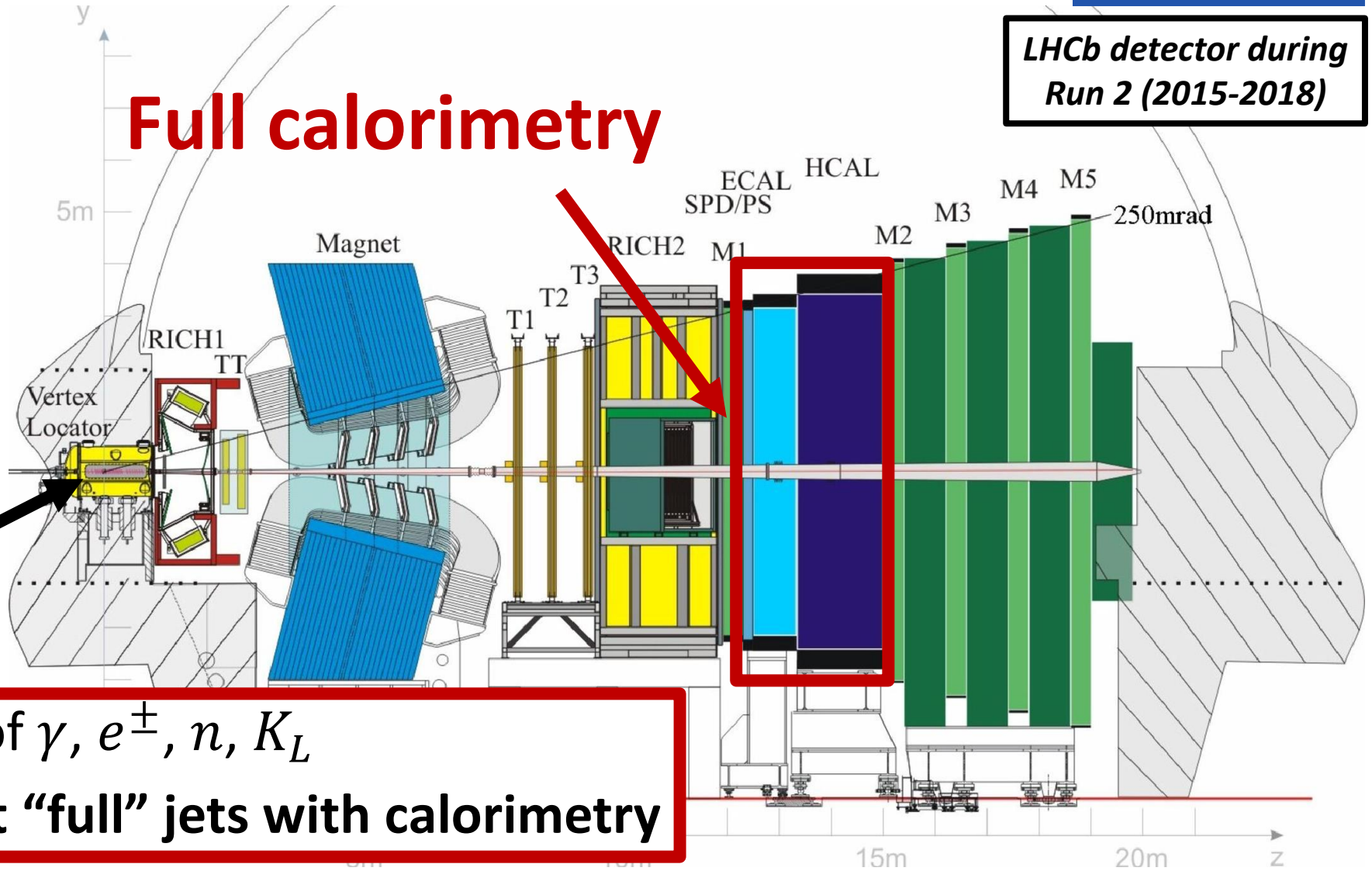
Interaction Point (IP)

Full calorimetry



LHCb detector during Run 2 (2015-2018)

- Measurement of γ, $e^{\pm}$, n, K_L
- **Can reconstruct "full" jets with calorimetry**

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A different kind of jet detector…

- LHCb is
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- **Can reconstruct "full" jets with calorimetry**

LHCb is an excellent detector for measuring heavy-flavor jets in LHC kinematics!

LHCb detector during 2 (2015-2018)

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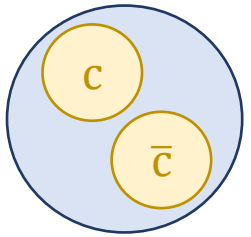
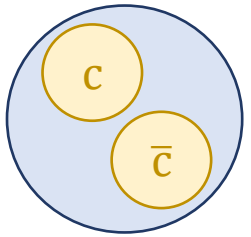
Heavy quarkonium in jets



J/ψ

- How are heavy $q\bar{q}$ pairs (e.g. J/ψ) produced according to QCD?

Heavy quarkonium in jets



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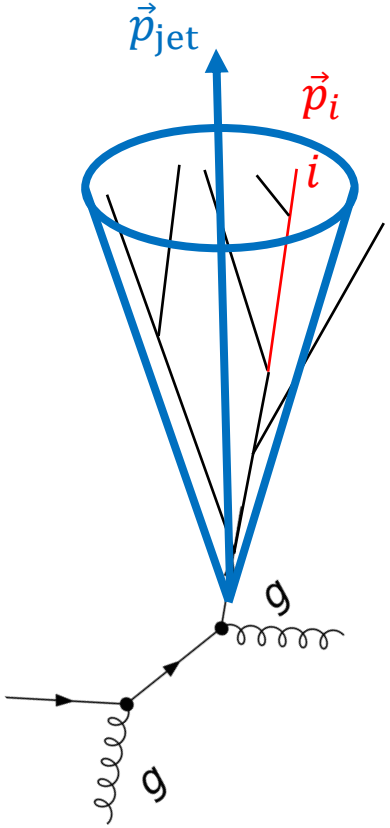
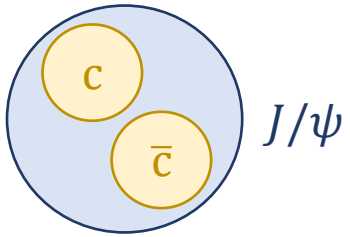


$$z = \frac{p_{\text{T},i}}{p_{\text{T,jet}}}$$

particle momentum fraction

Heavy quarkonium in jets



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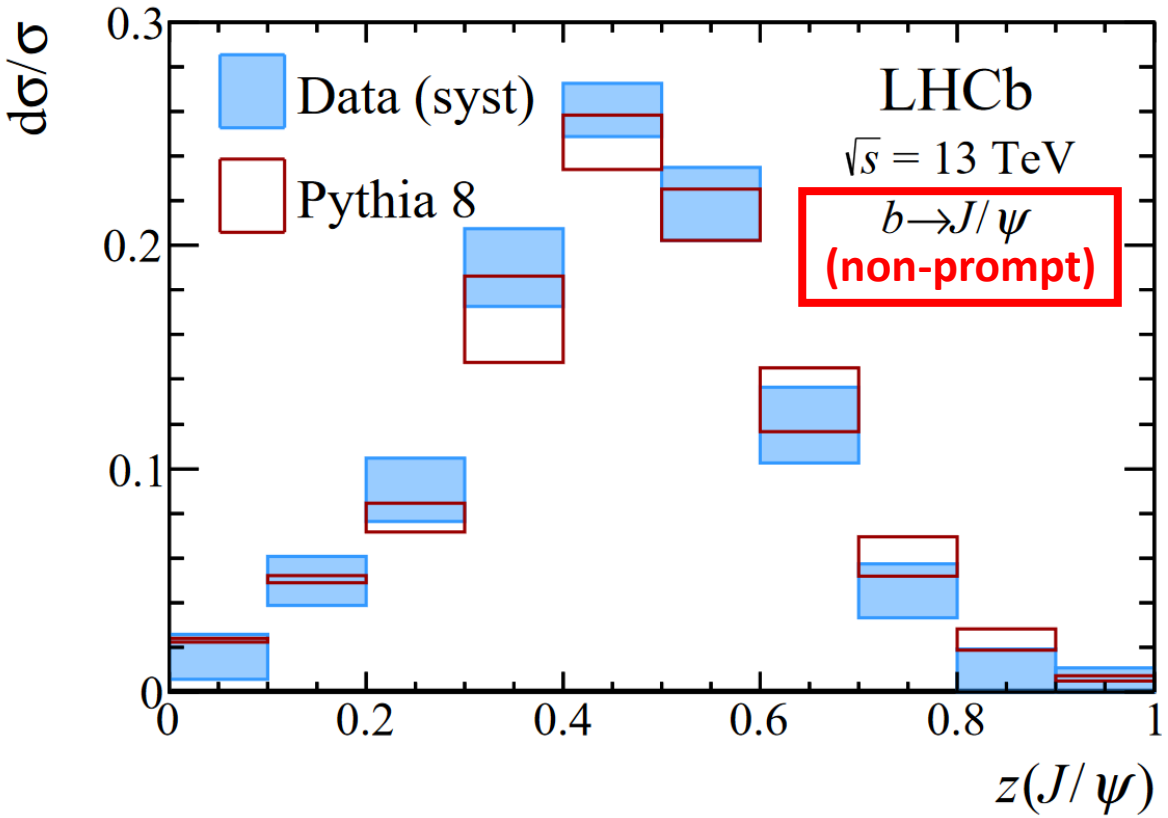
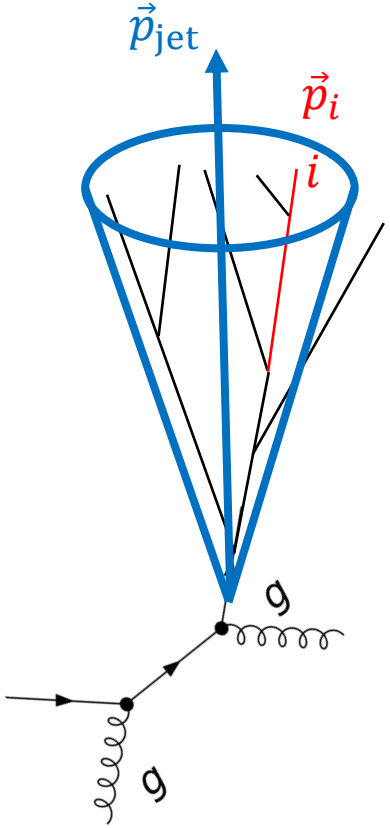


- Both **prompt** and **non-prompt (feed-down)** contributions



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

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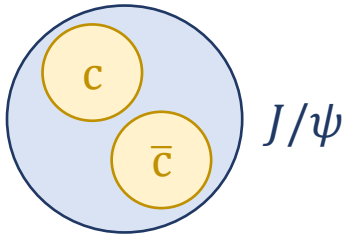

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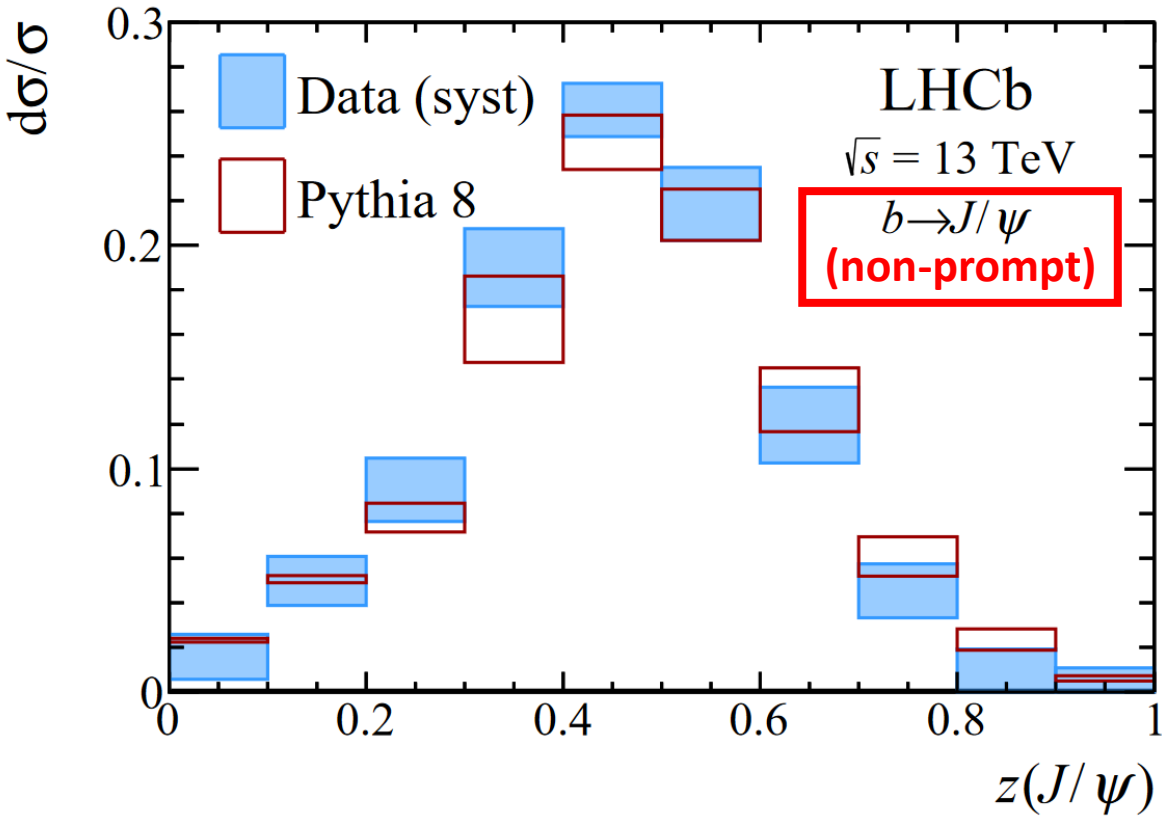
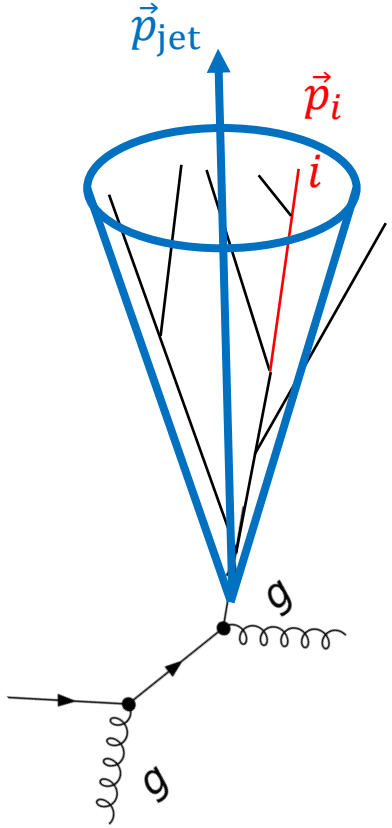


- Both **prompt** and **non-prompt (feed-down)** contributions

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



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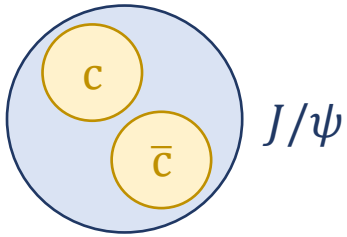

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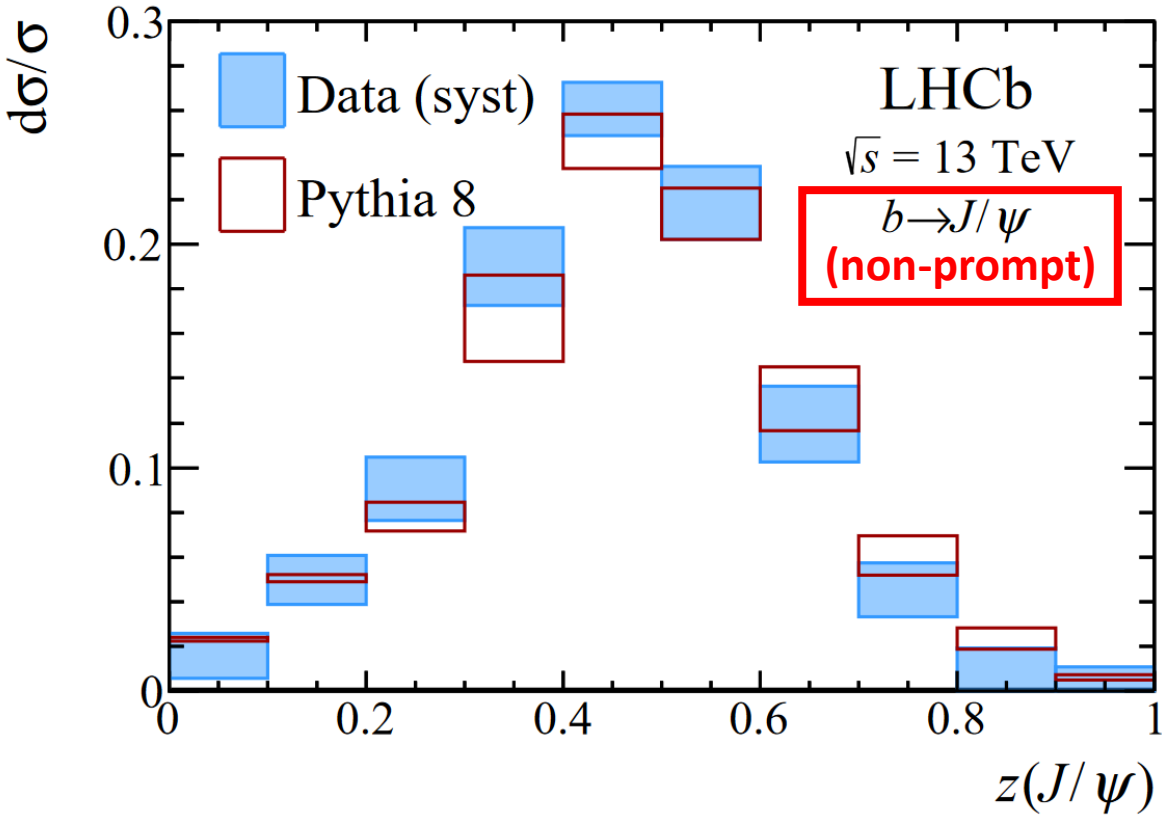

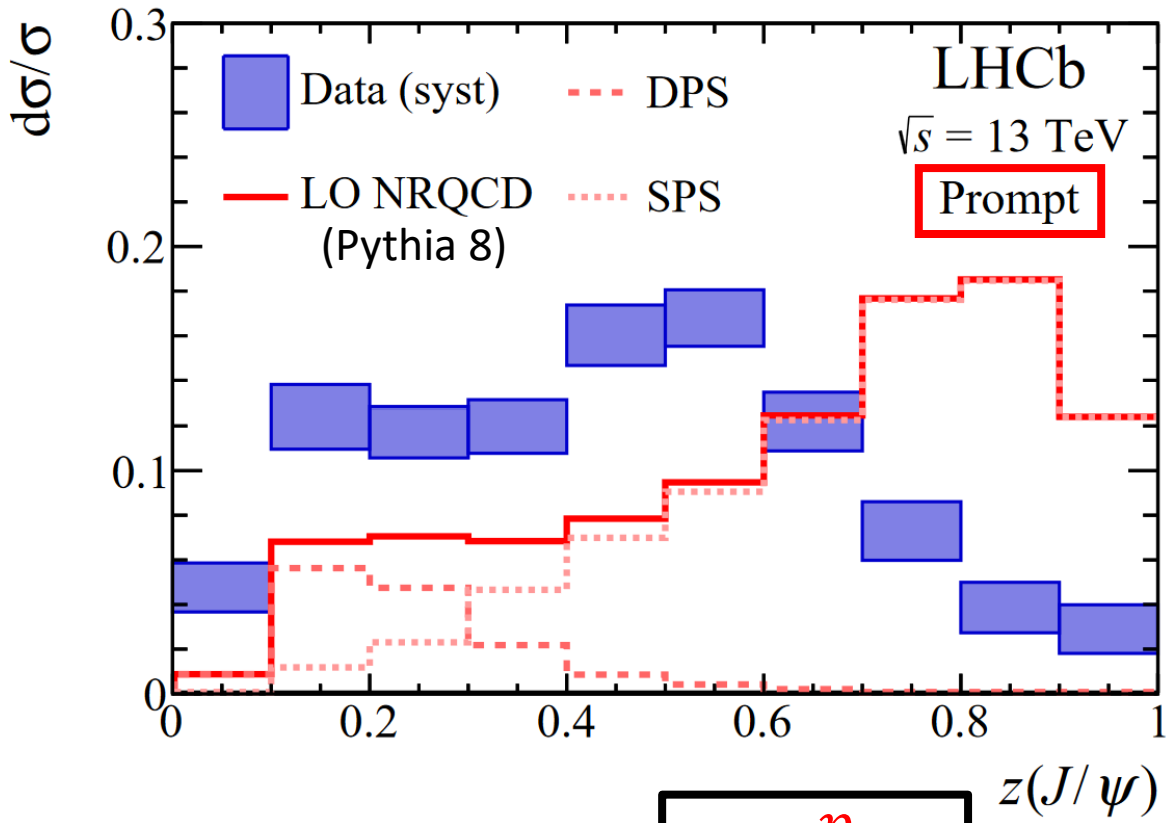

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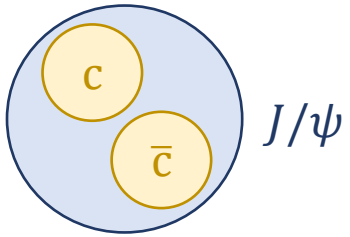

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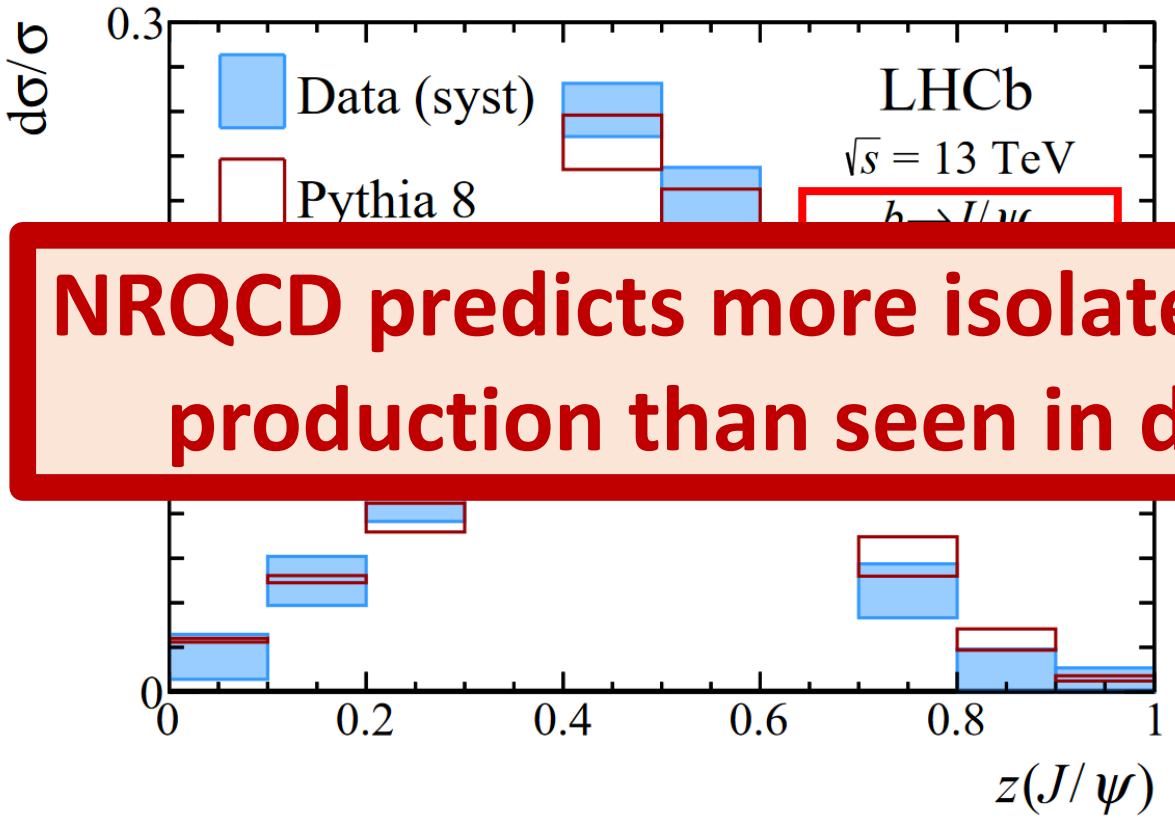

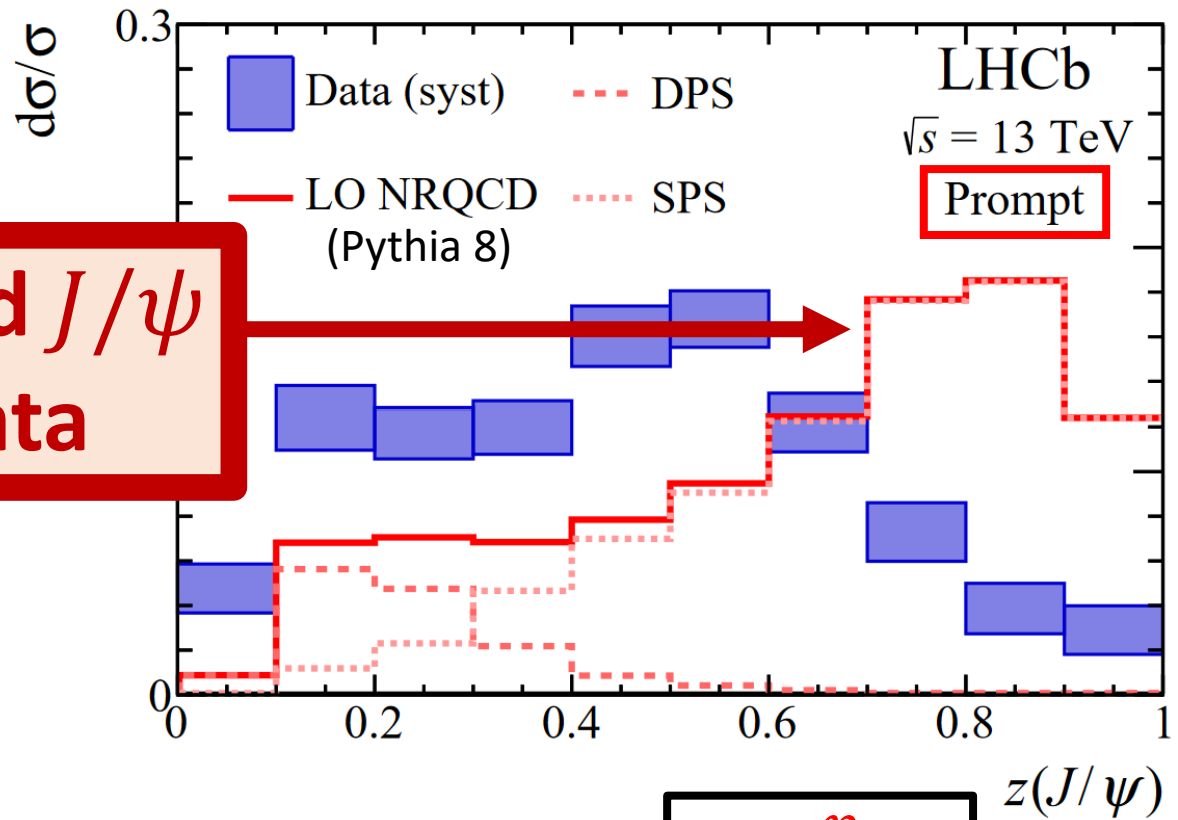

NRQCD predicts more isolated J/ψ production than seen in data

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

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This *same result* also observed by:

CMS: PLB 825 (2021) 136842

ATLAS: JHEP 12 (2021) 131

ALICE: preliminary

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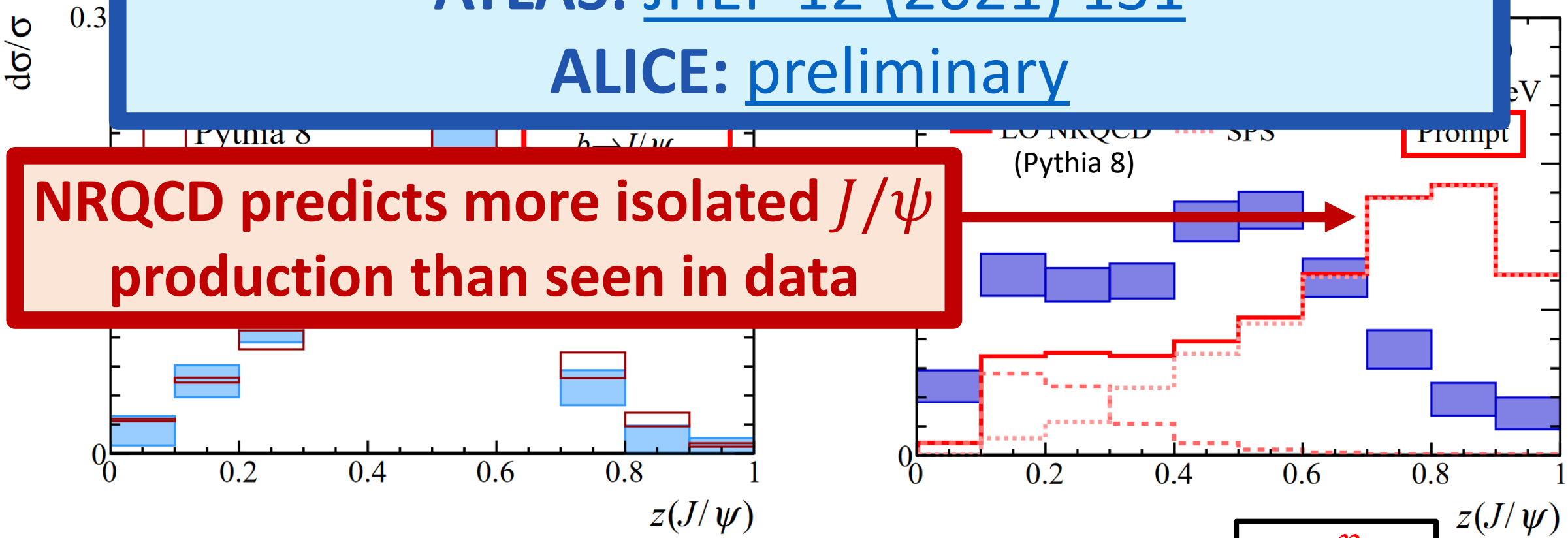

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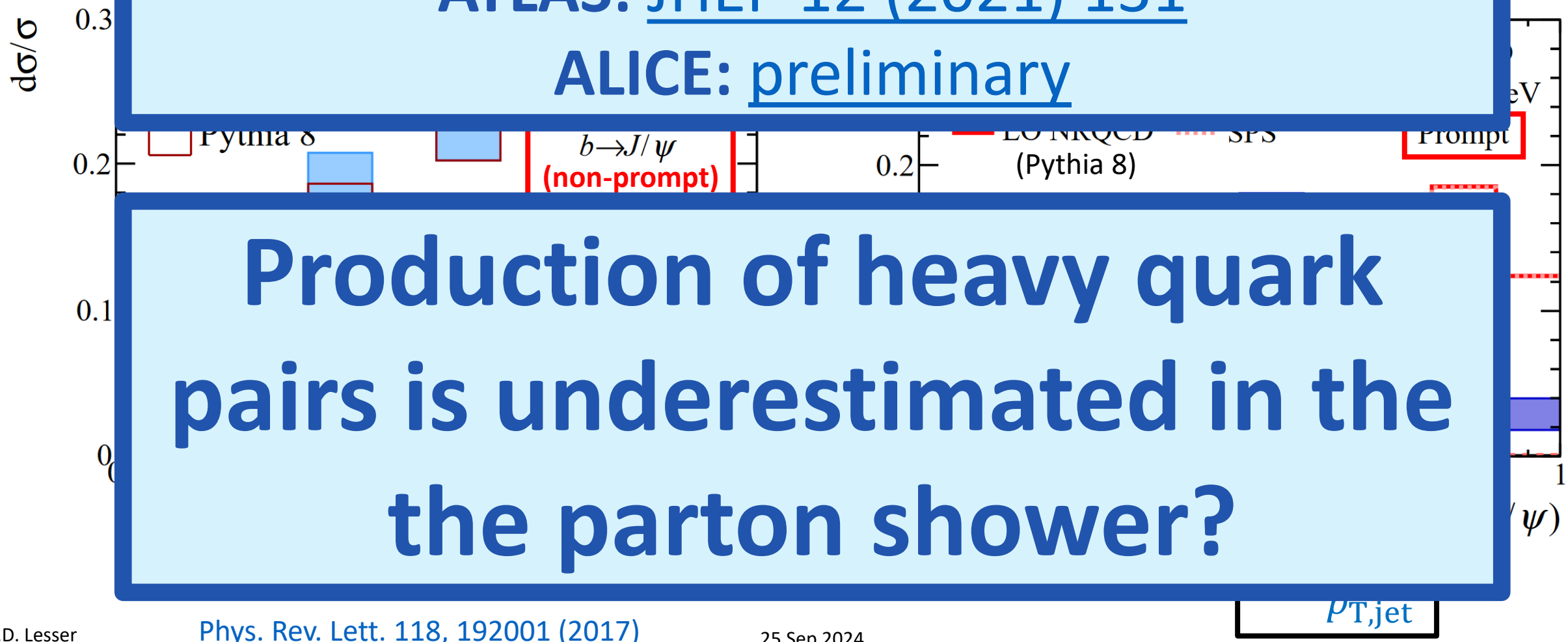
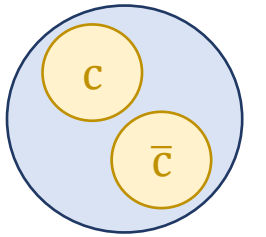


Production of heavy quark pairs is underestimated in the the parton shower?

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

Higher mass states



$\psi(2S)$

- What about heavier charmonium such as $\psi(2S)$ (less feed-down)?

NEW!

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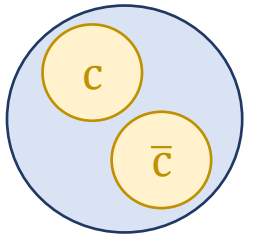

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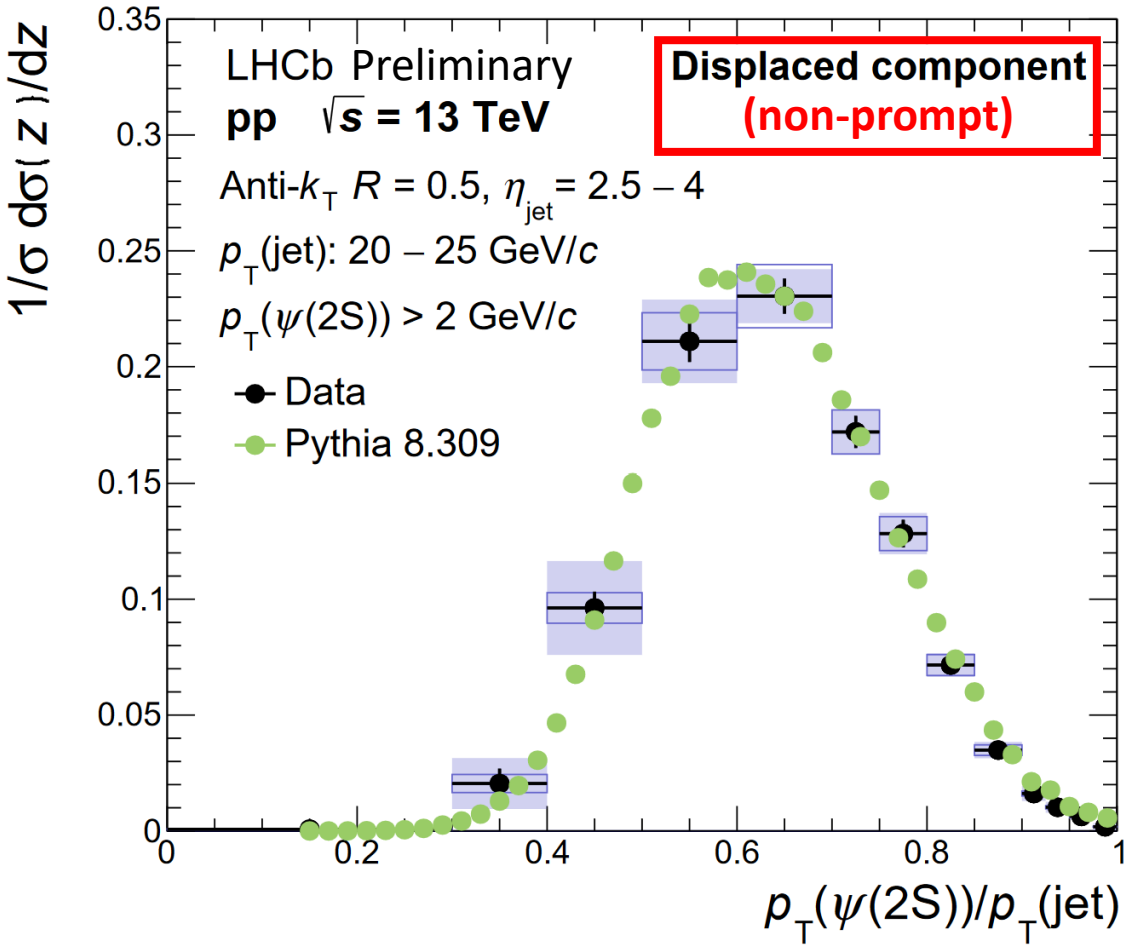

LHCb-PAPER-2024-021 *(in preparation)*

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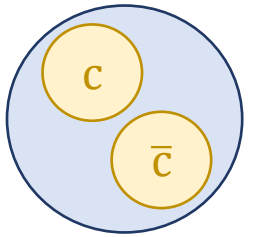

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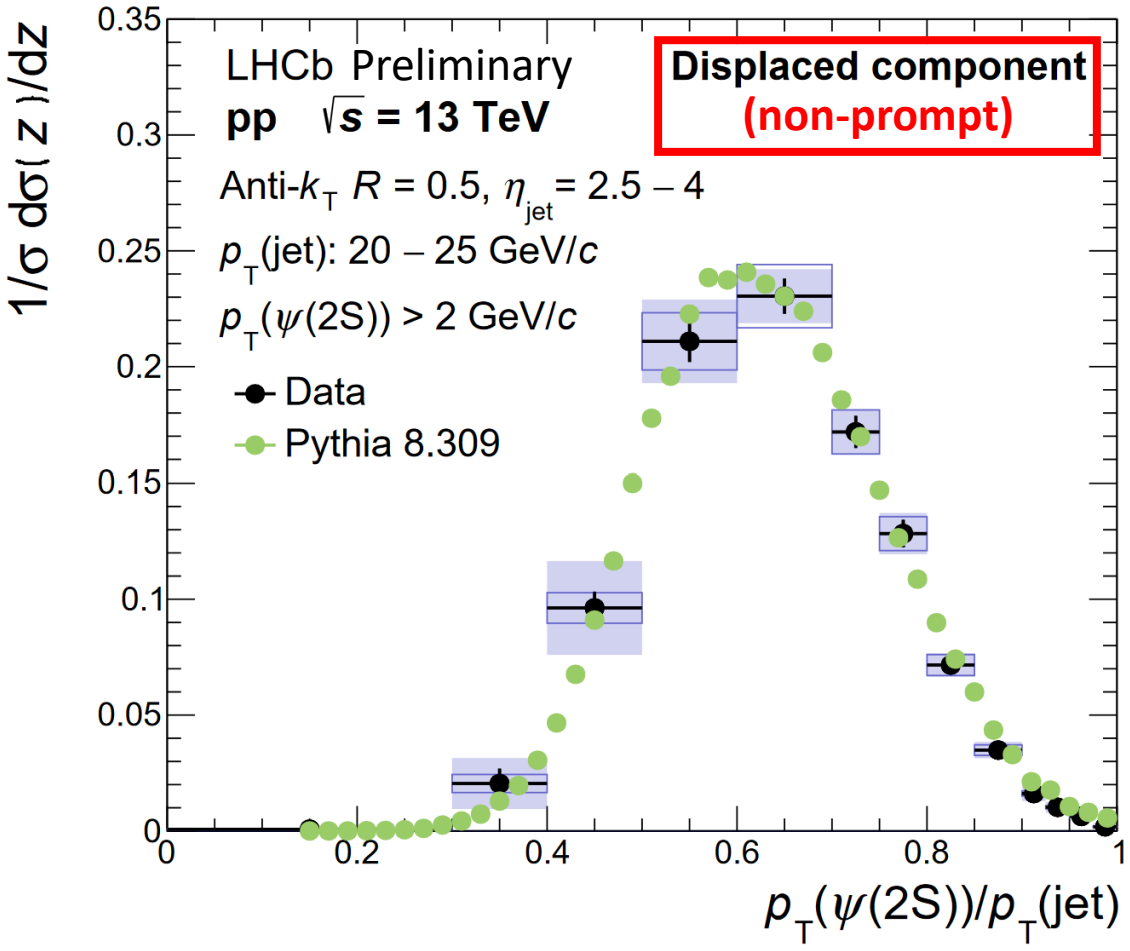

- **Good agreement** in non-prompt production (similar to J/ψ)

- Displaced $\psi(2S)$ carries ~60% of jet transverse momentum

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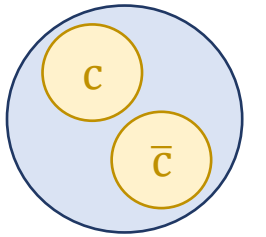

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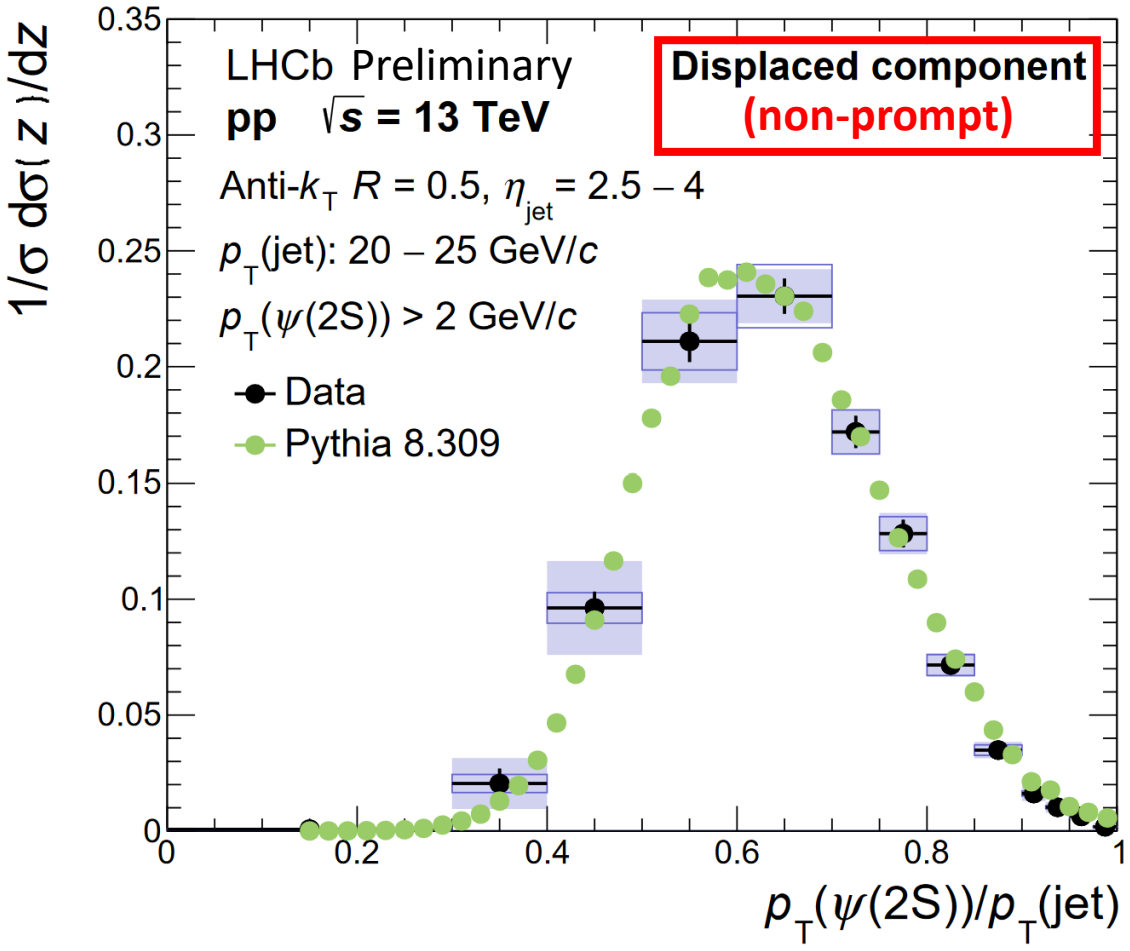

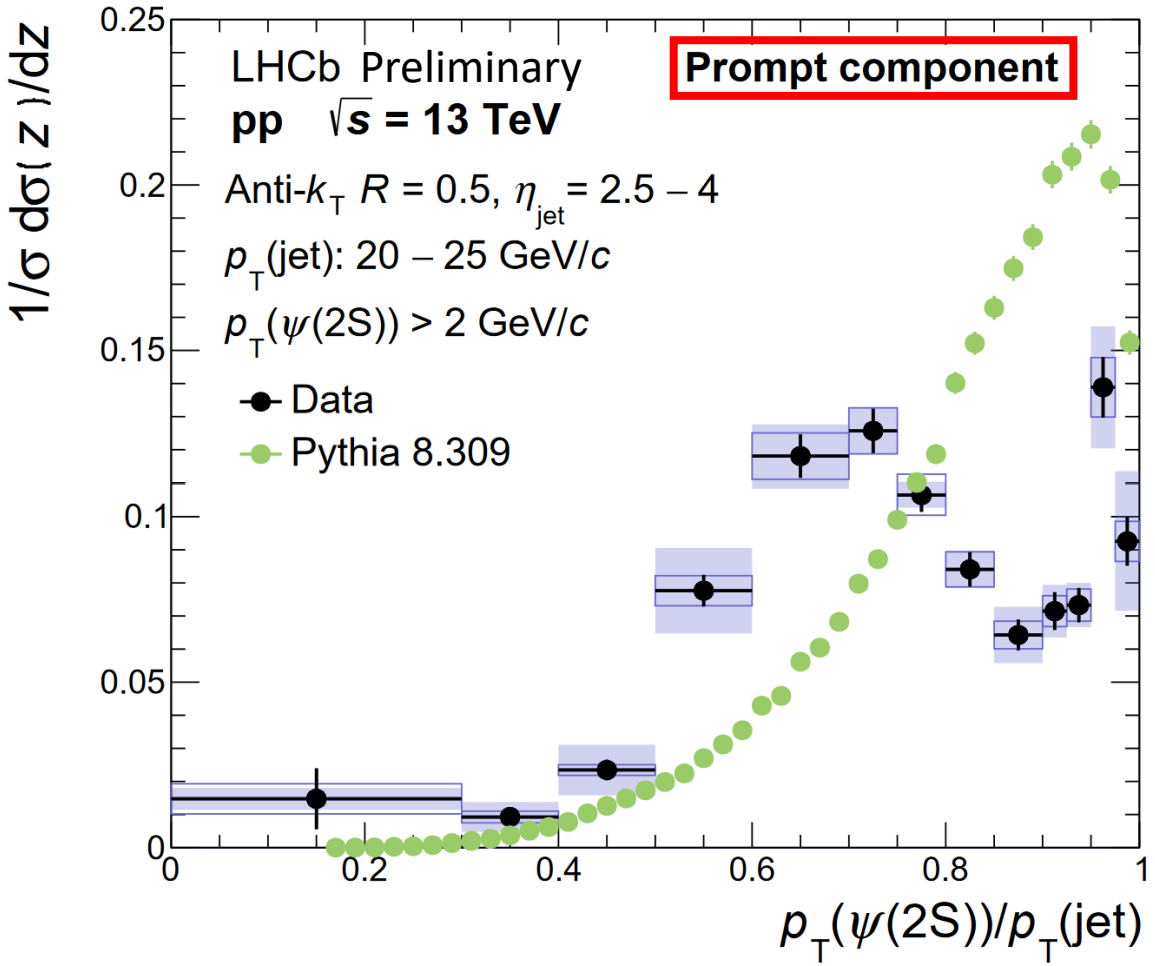

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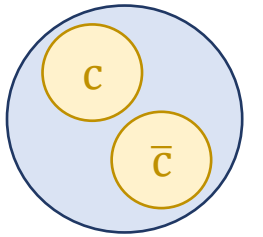

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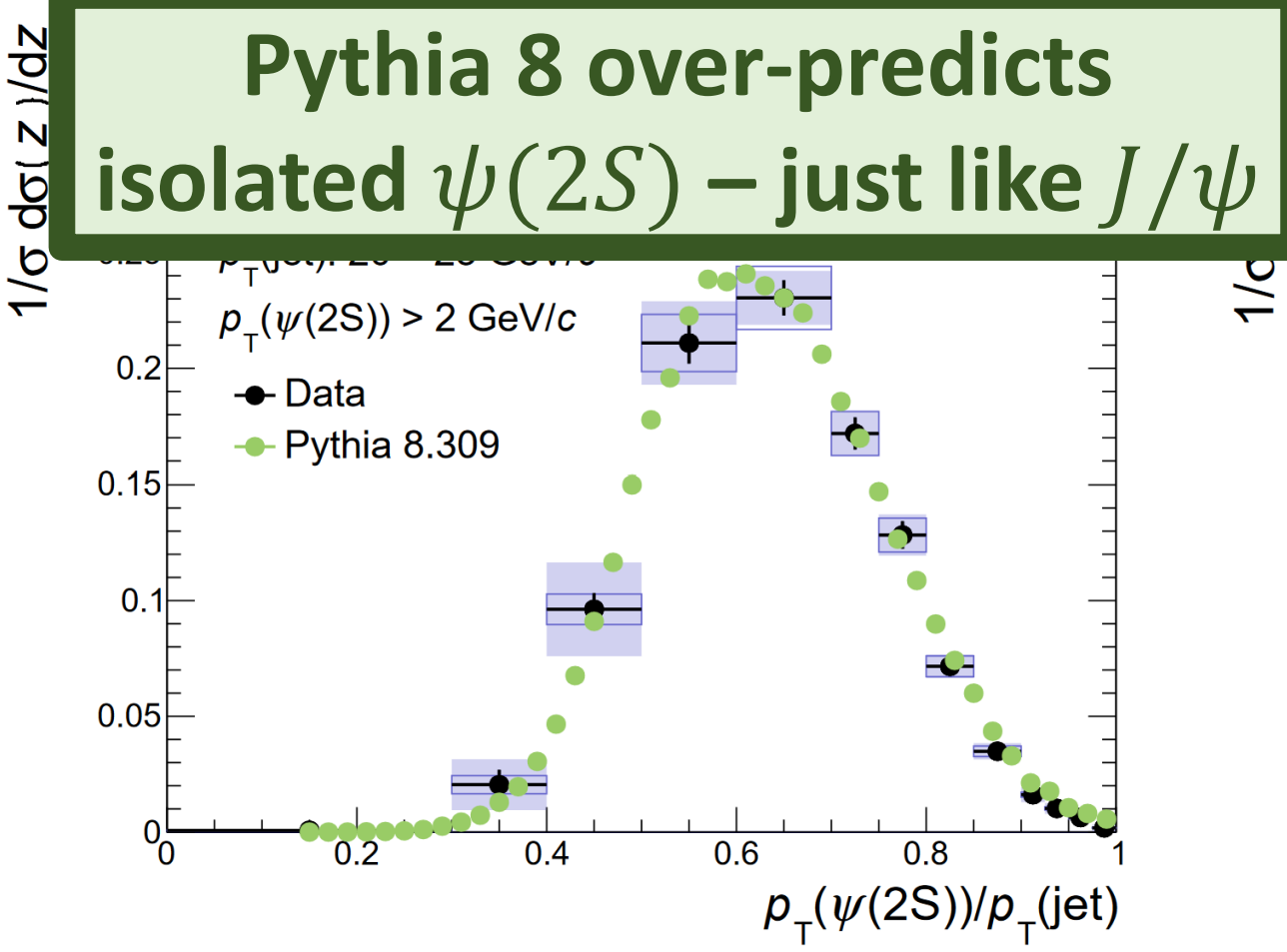
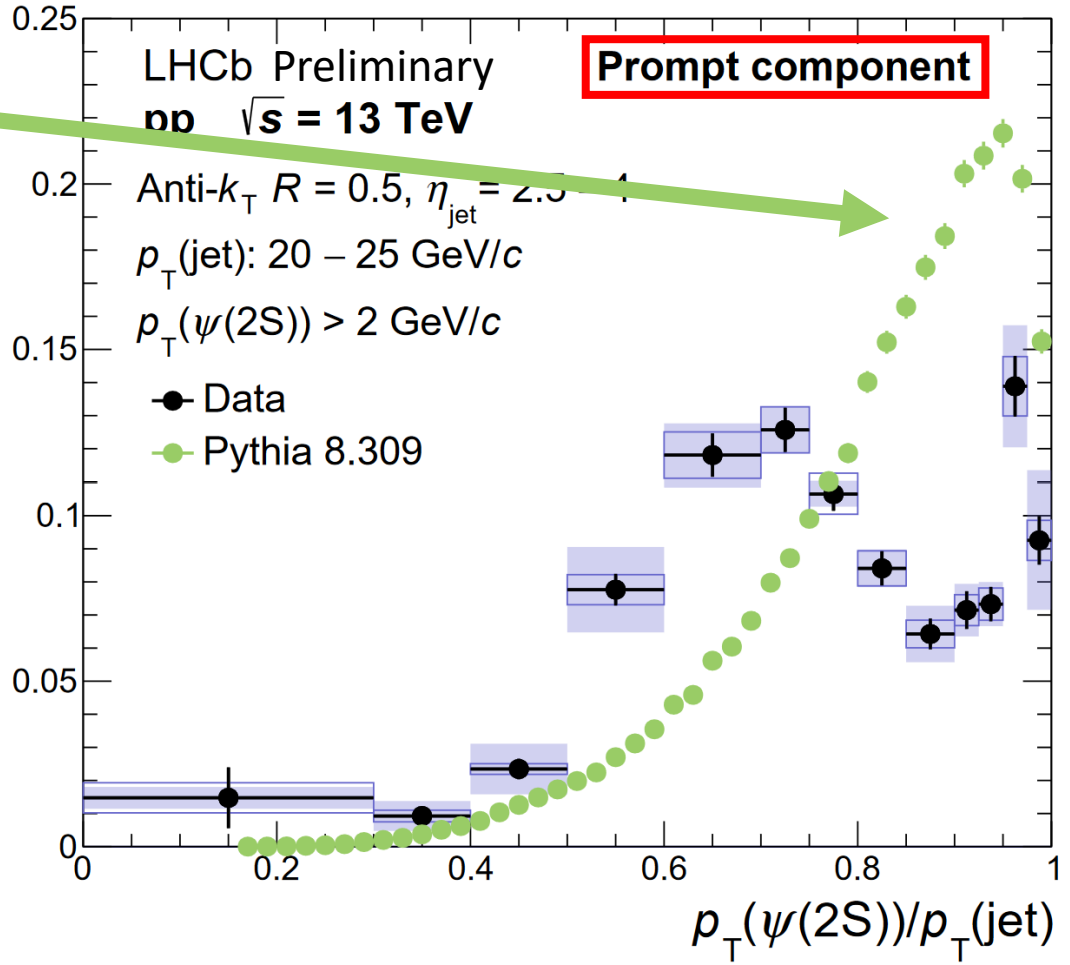
Pythia 8 over-predicts isolated $\psi(2S)$ – just like J/ψ





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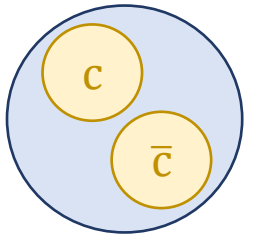

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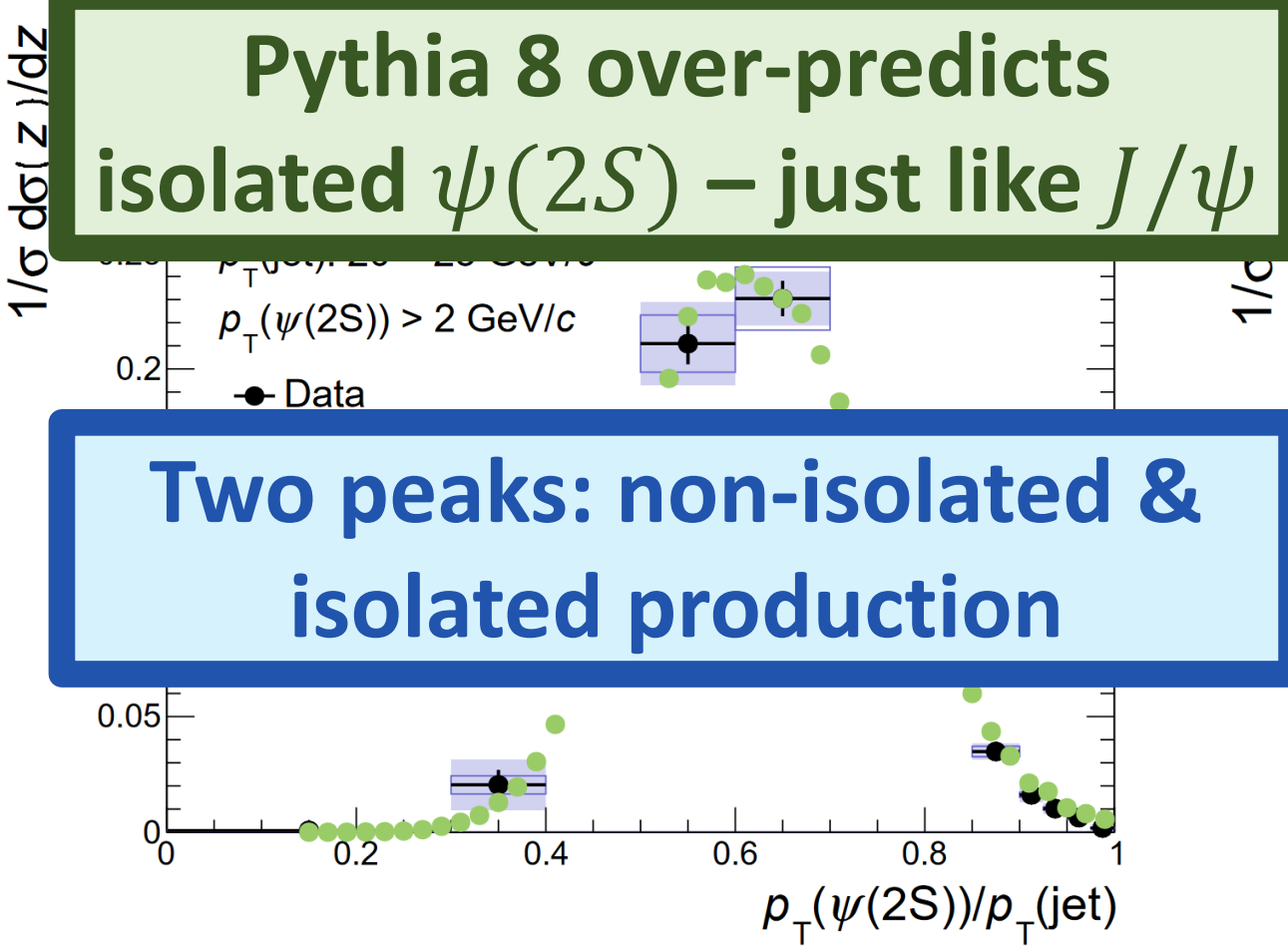
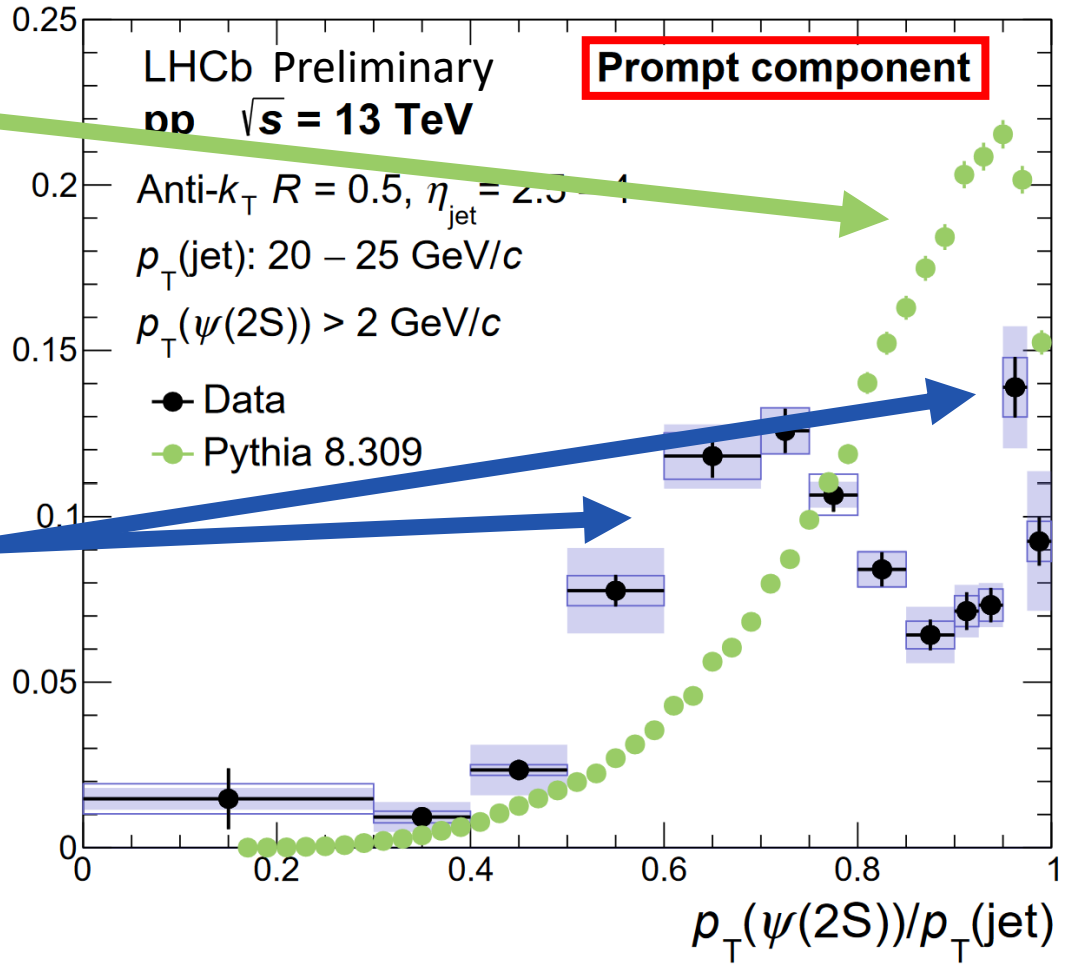
Two peaks: non-isolated & isolated production

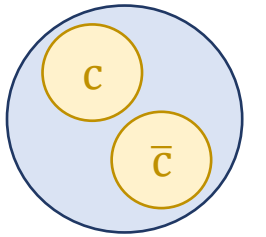




LHCb-PAPER-2024-021 *(in preparation)*

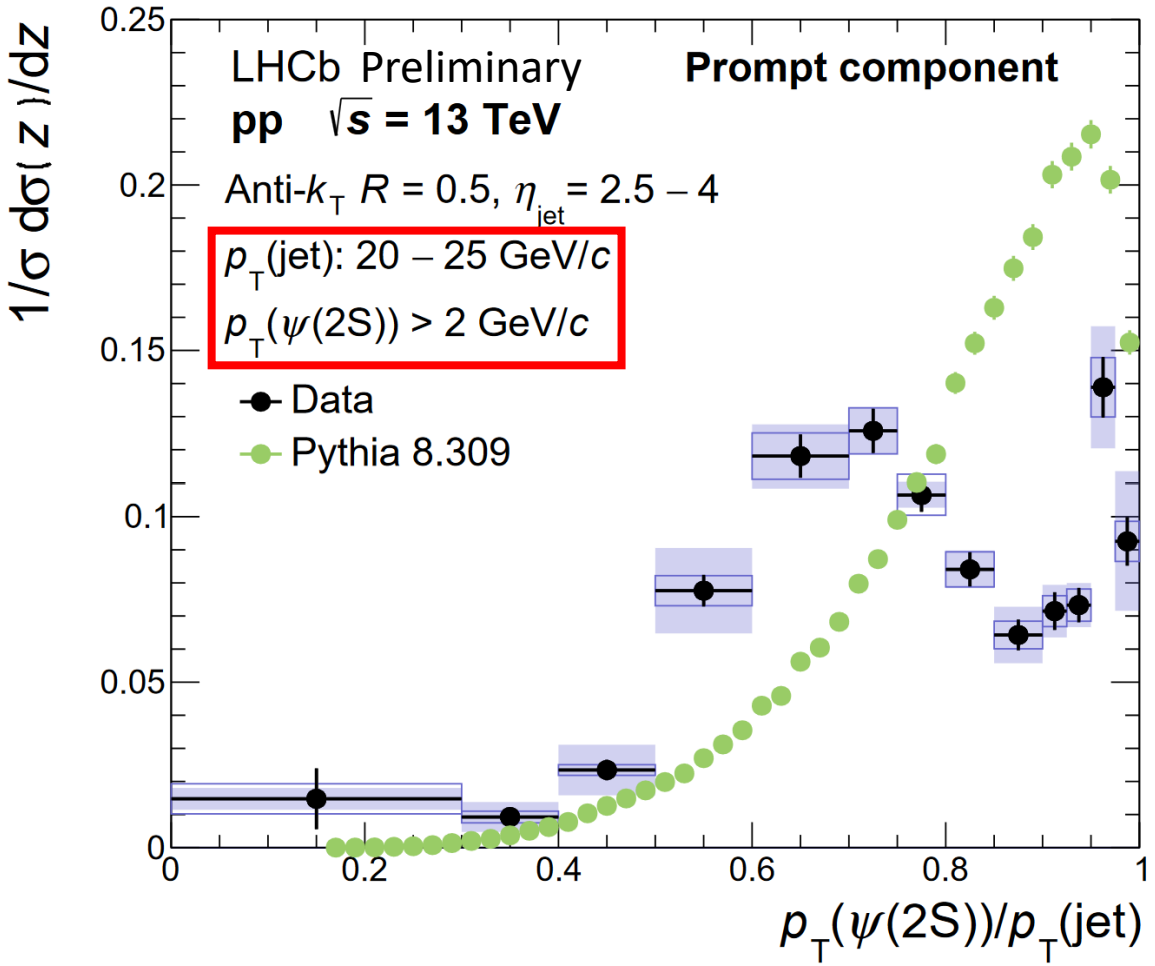
NEW!

Higher mass states



$\psi(2S)$

- What about heavier charmonium such as $\psi(2S)$ (less feed-down)?
- **Hard jets with mostly softer $\psi(2S)$**



LHCb-PAPER-2024-021 *(in preparation)*

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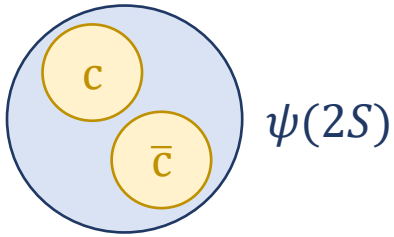
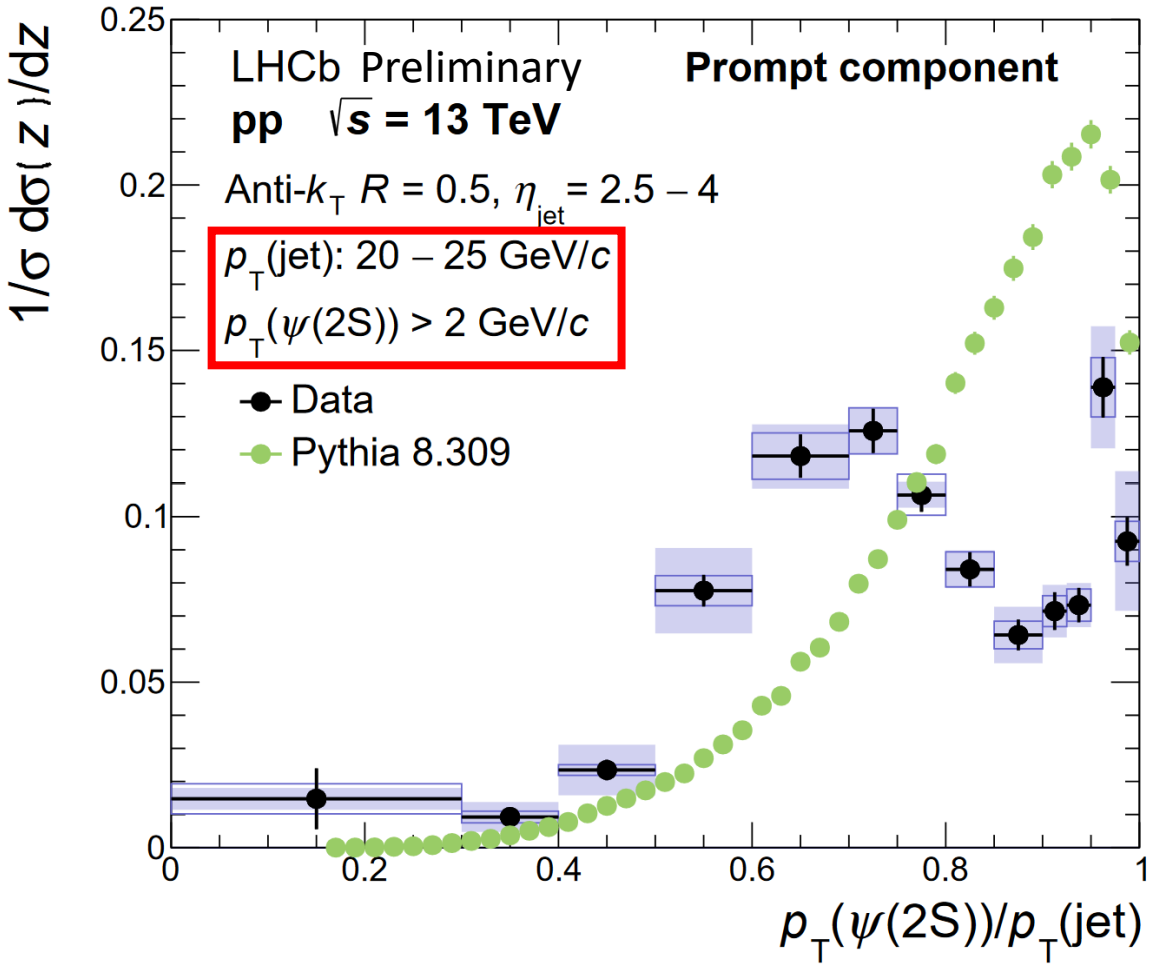


$\psi(2S)$

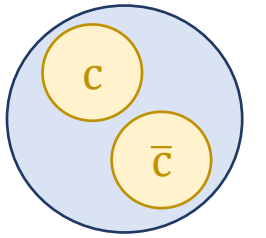
- What about heavier charmonium such as $\psi(2S)$ (less feed-down)?
- **Hard jets with mostly softer $\psi(2S)$**
- What about harder $\psi(2S)$ in any jet momentum range?



LHCb-PAPER-2024-021 *(in preparation)*

NEW!

Higher mass states



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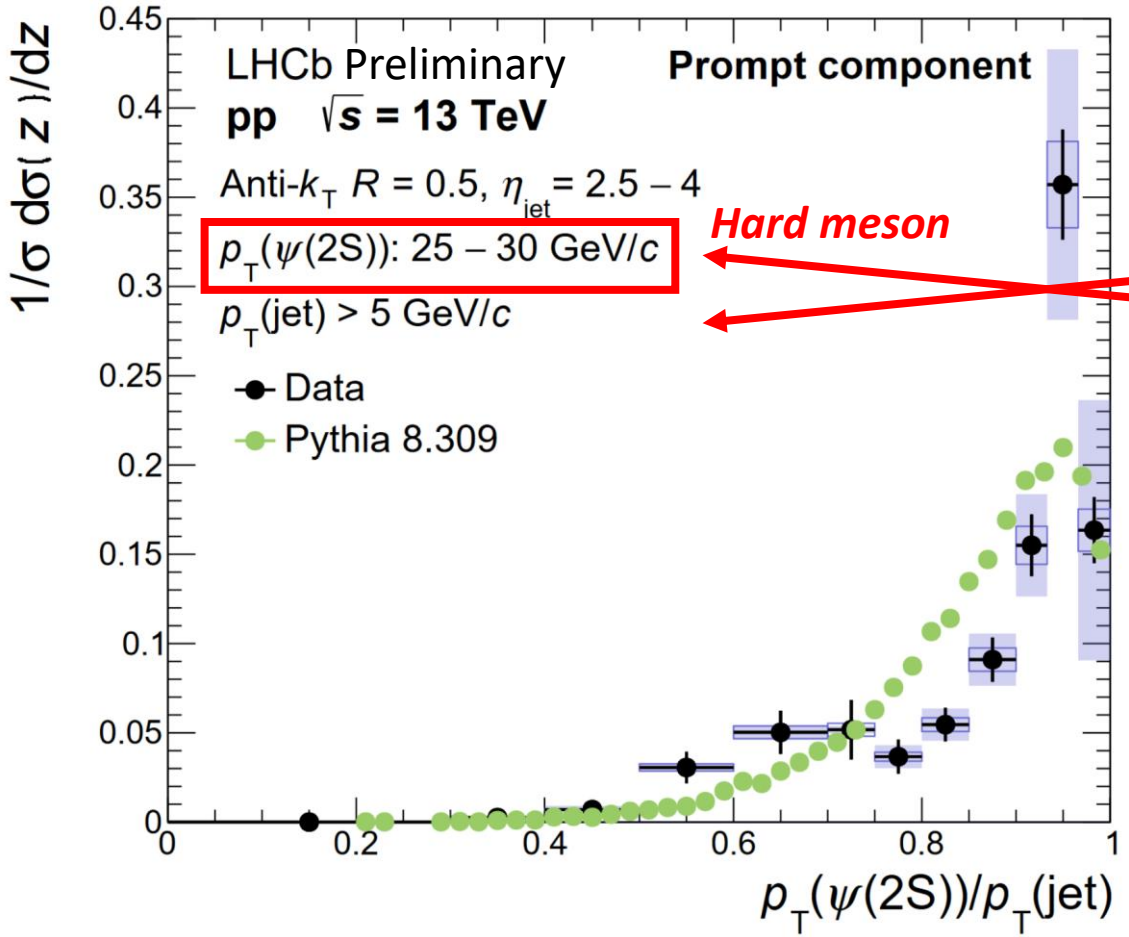
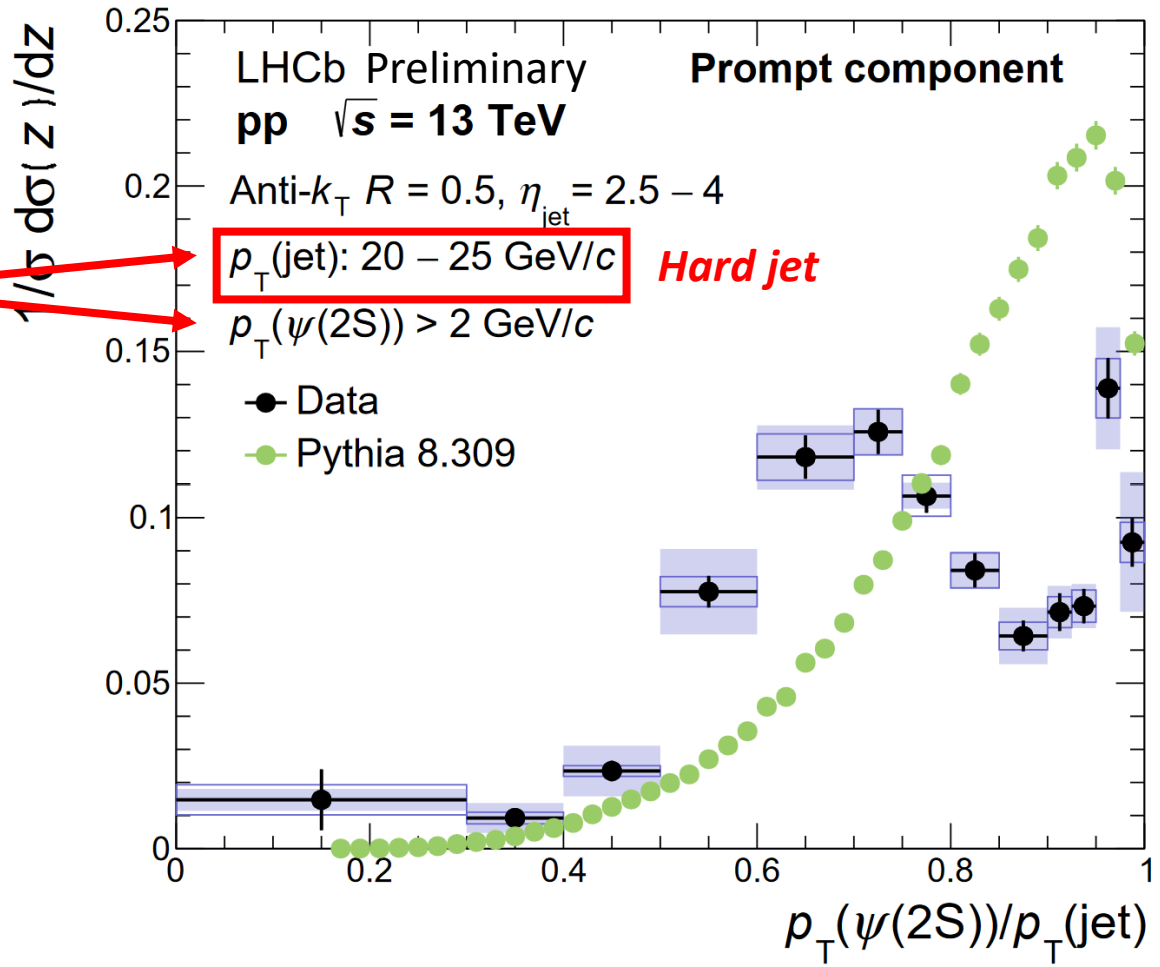


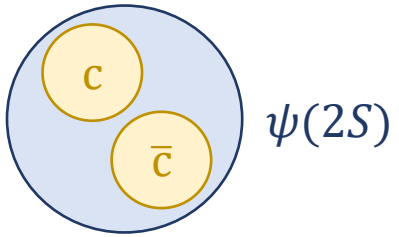
Hard meson

Hard jet



LHCb-PAPER-2024-021 *(in preparation)*

NEW! Higher mass states



$\psi(2S)$

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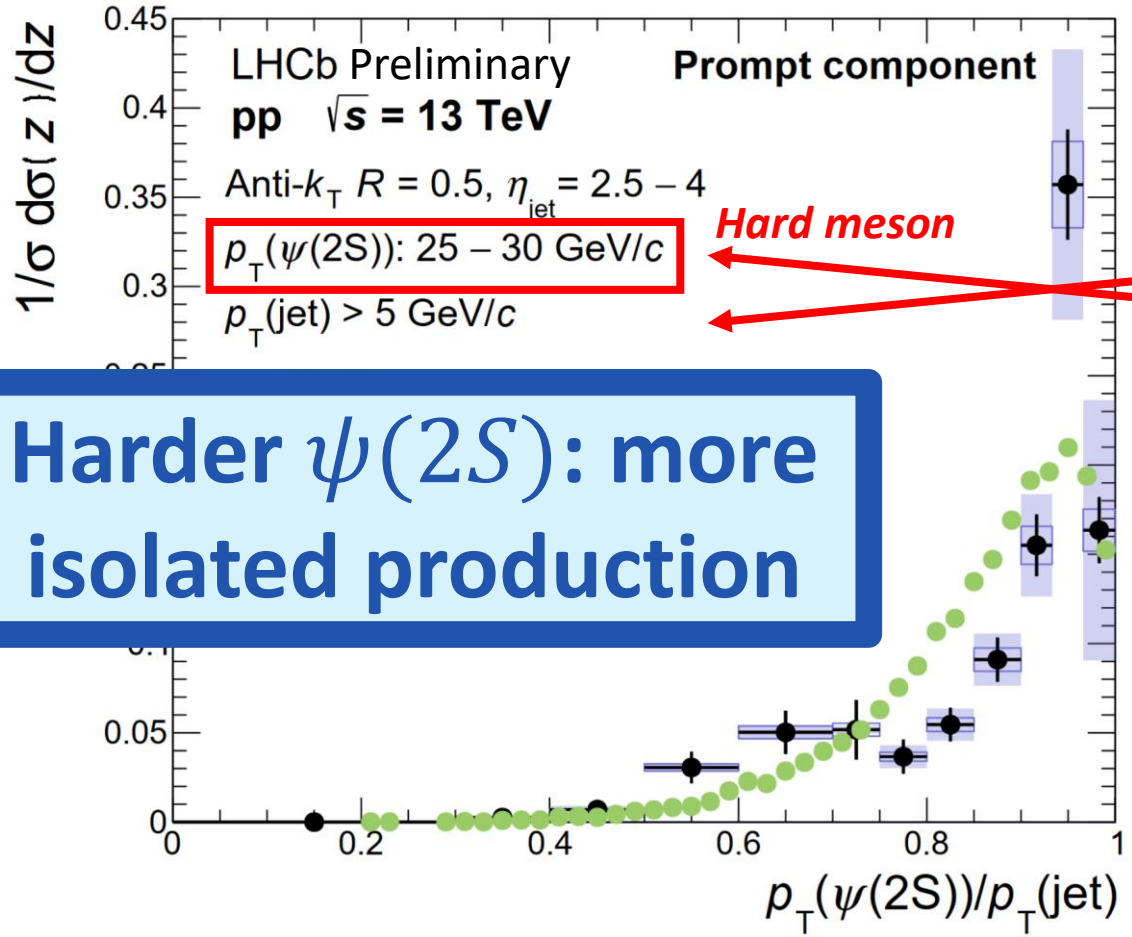
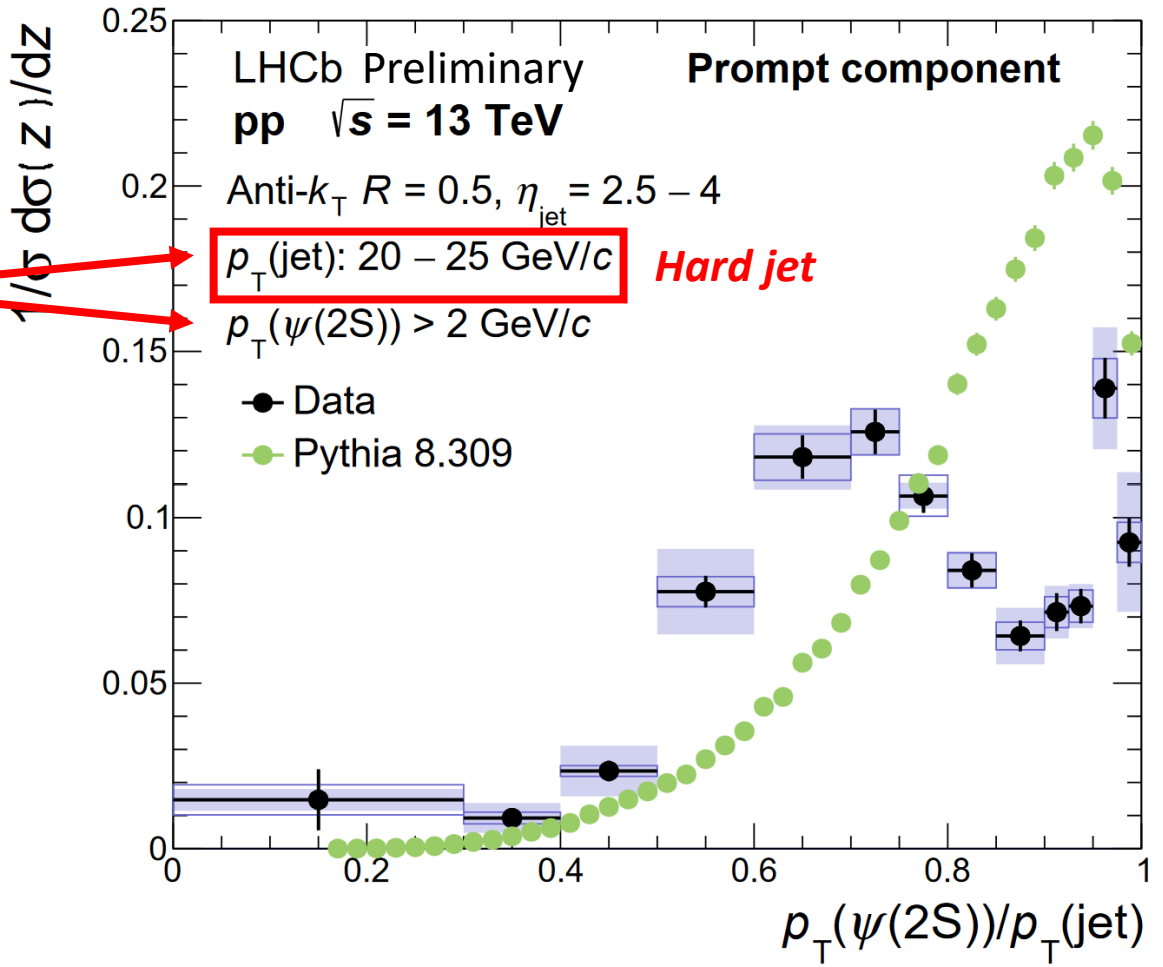


Hard meson

Hard jet

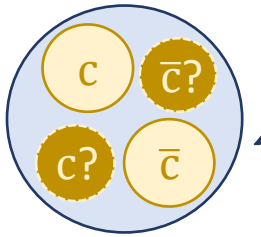


Harder $\psi(2S)$: more isolated production

LHCb-PAPER-2024-021 *(in preparation)*

NEW!

Higher mass states



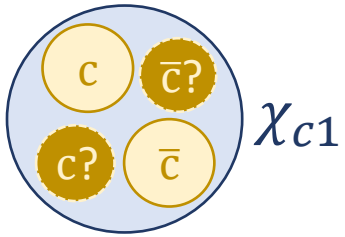
χ_{c1}

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

LHCb-PAPER-2024-021 *(in preparation)*

NEW!

Higher mass states



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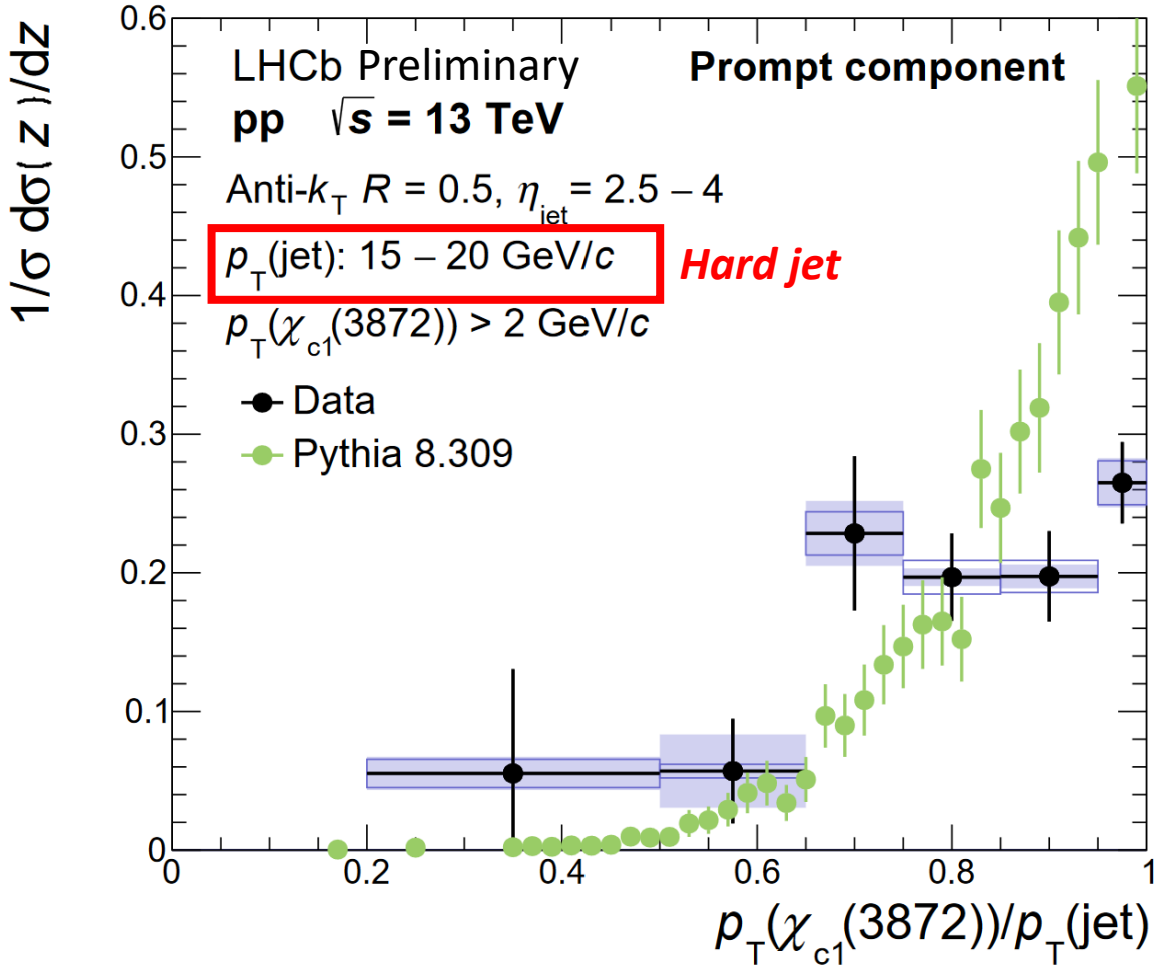
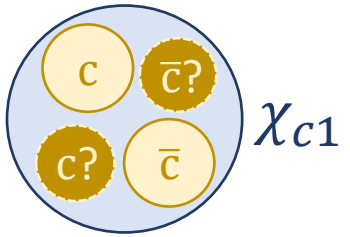


LHCb-PAPER-2024-021 *(in preparation)*

NEW!

Higher mass states



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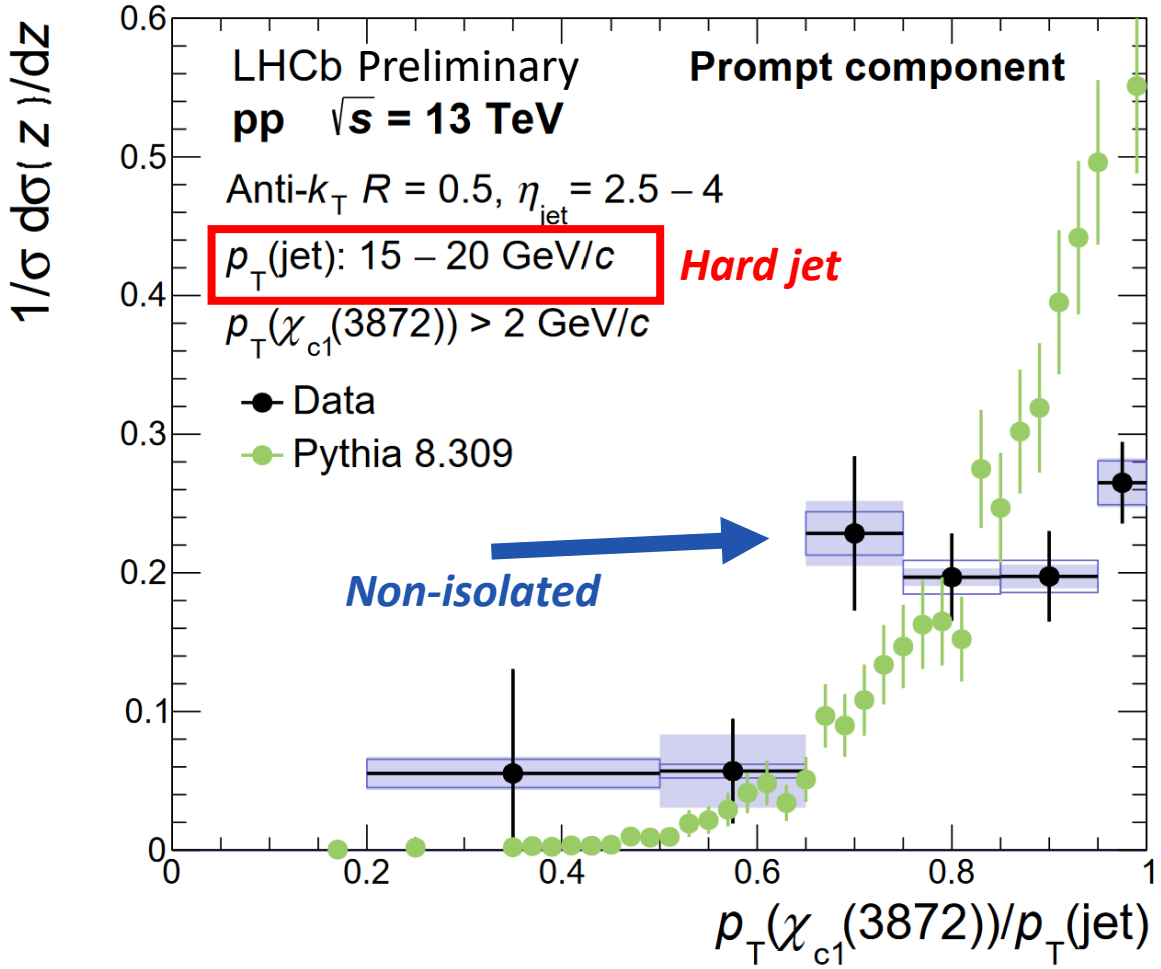

LHCb-PAPER-2024-021 *(in preparation)*

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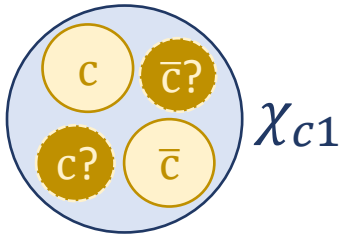
Higher mass states



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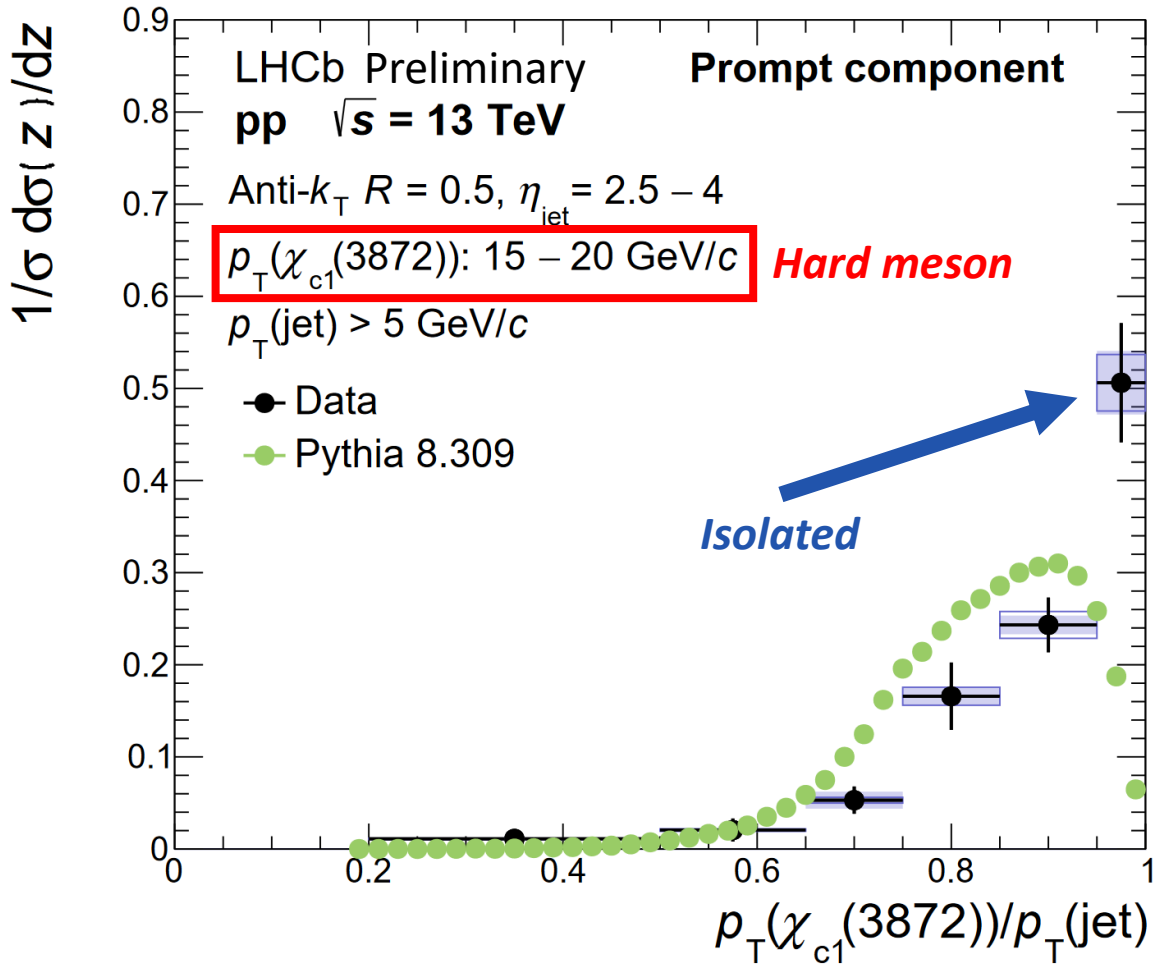
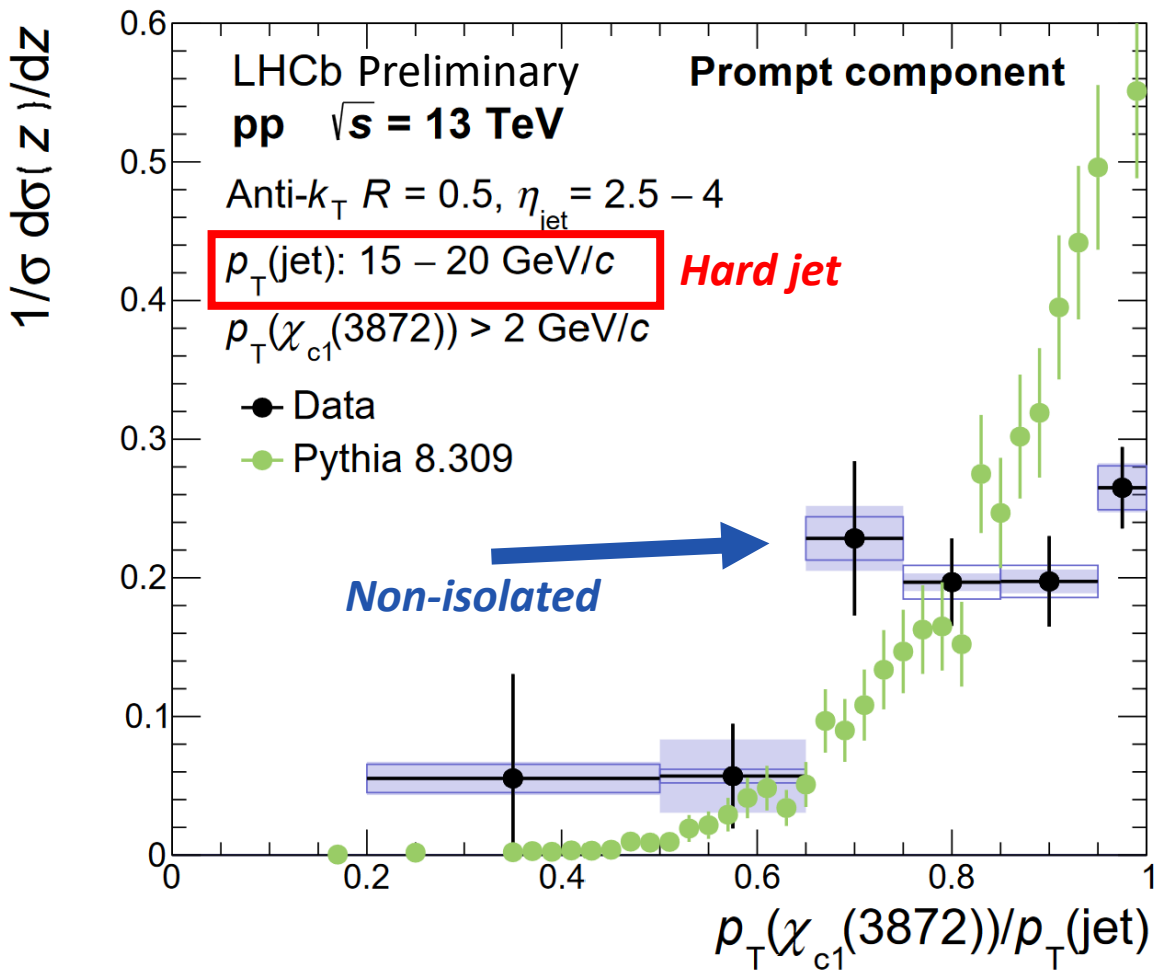
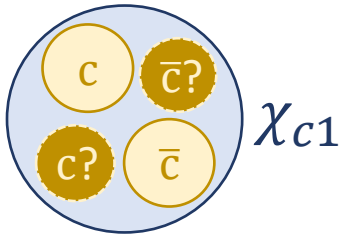




LHCb-PAPER-2024-021 *(in preparation)*

NEW!

Higher mass states



χ_{c1}

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

If charmonium is mostly produced in parton shower,

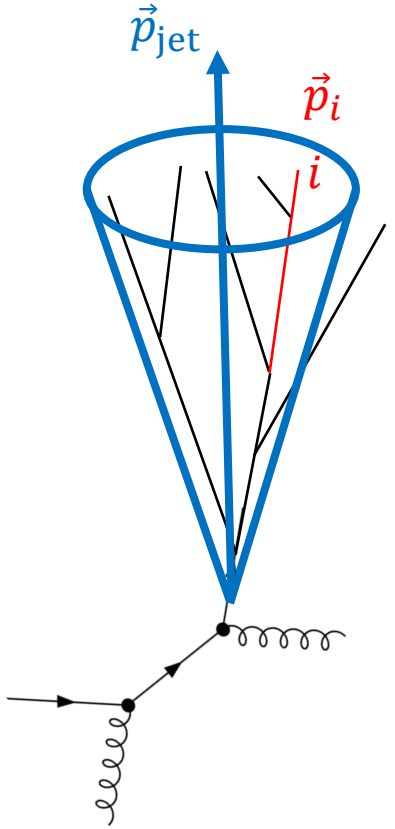
→ not a clean probe of QGP initial state?

$p_T(\chi_{c1}(3872))/p_T(\text{jet})$

$p_T(\chi_{c1}(3872))/p_T(\text{jet})$

LHCb-PAPER-2024-021 *(in preparation)*

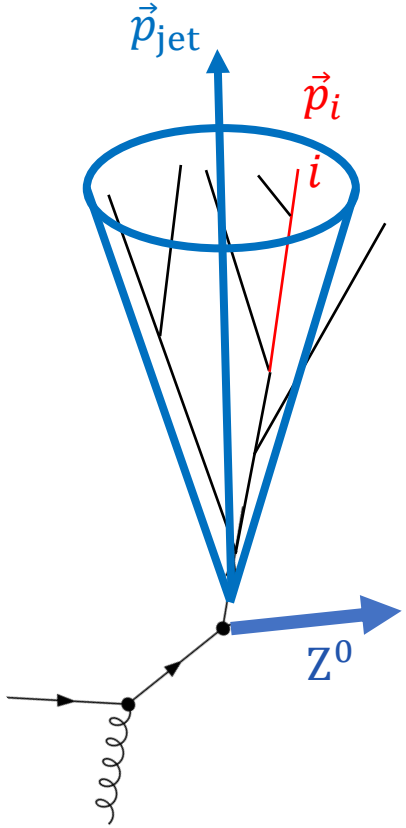
Jet fragmentation functions



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

Jet fragmentation functions

- Measurement for **inclusive Z^0+jets** (light quark enriched)



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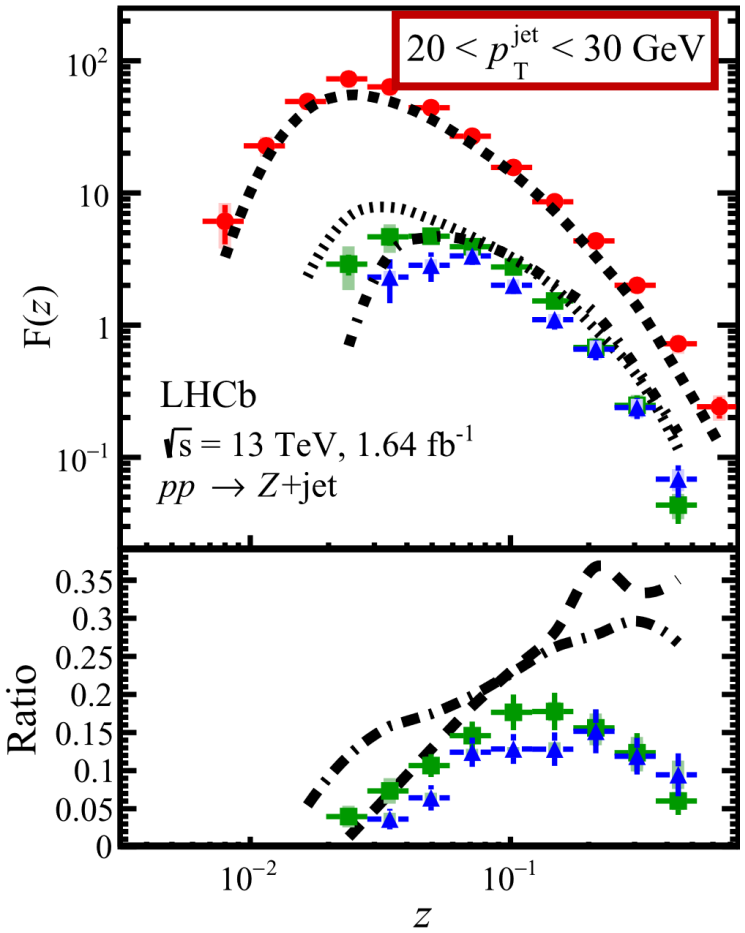
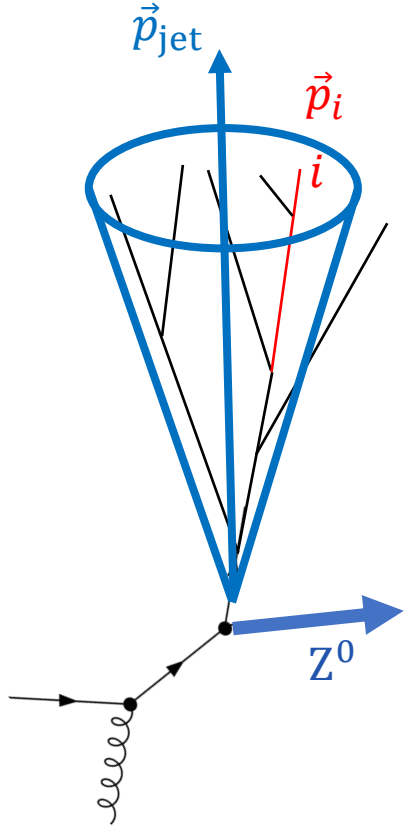
Jet fragmentation functions

- Measurement for **inclusive Z^0+jets** (light quark enriched)

$low \longleftarrow p_T^{jet} \longrightarrow high$





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

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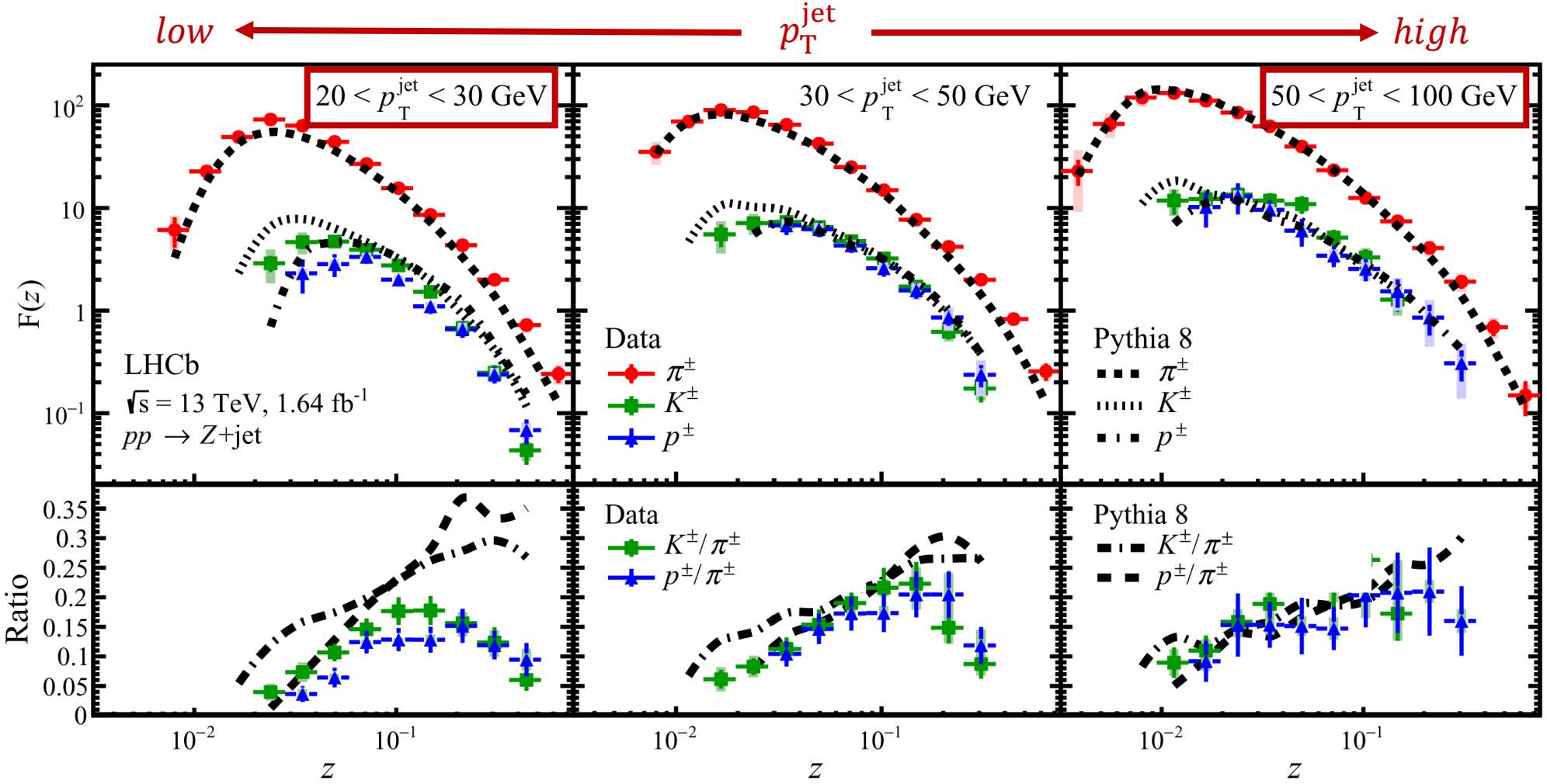

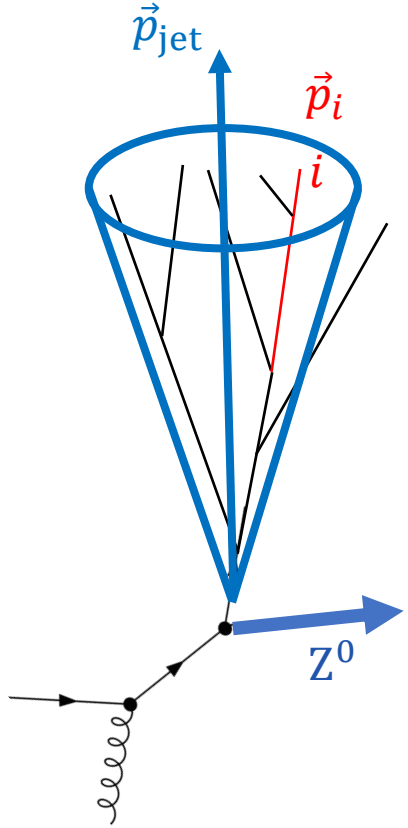

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Phys. Rev. D 108 (2023) L031103

Jet fragmentation functions

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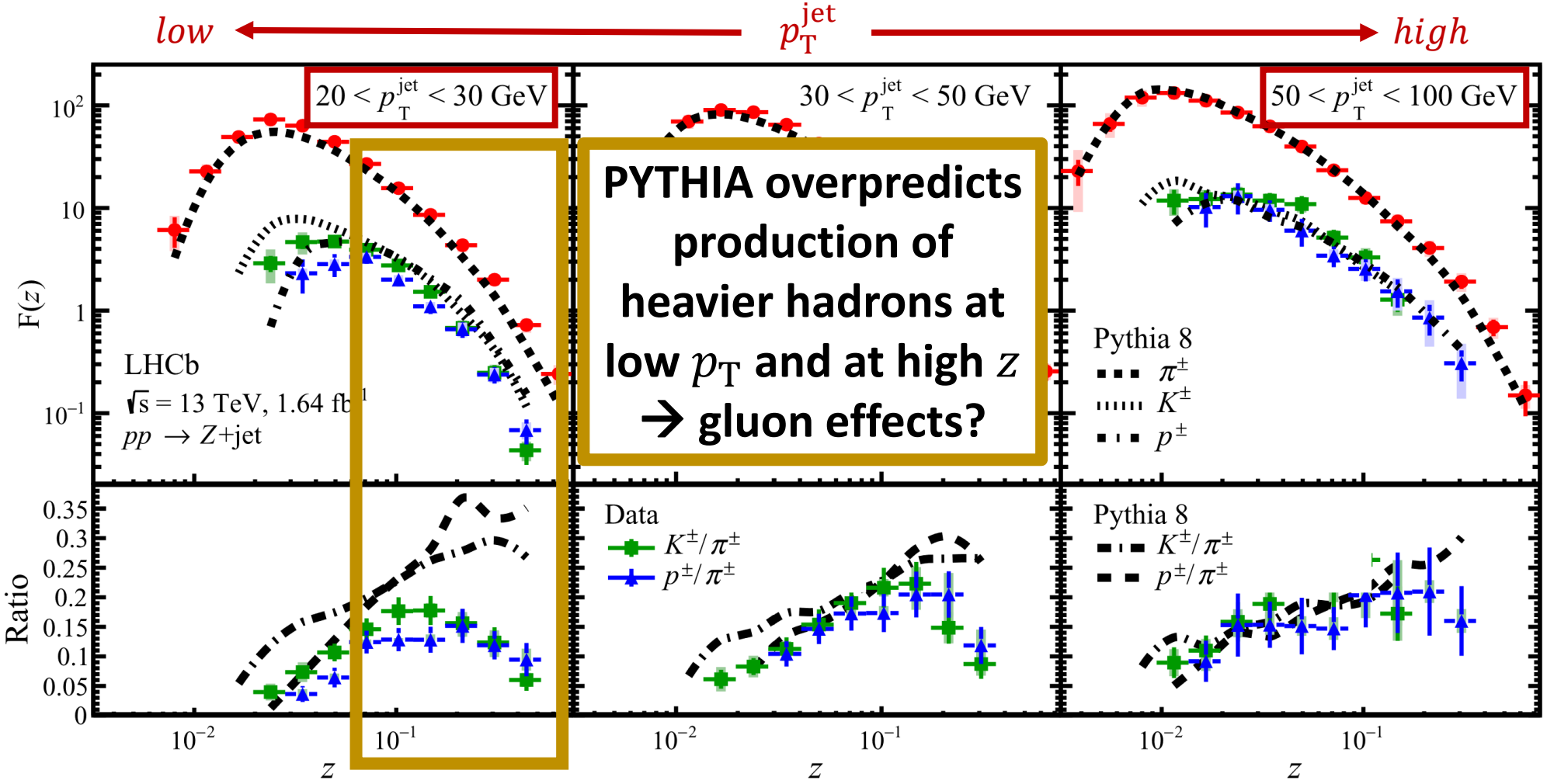
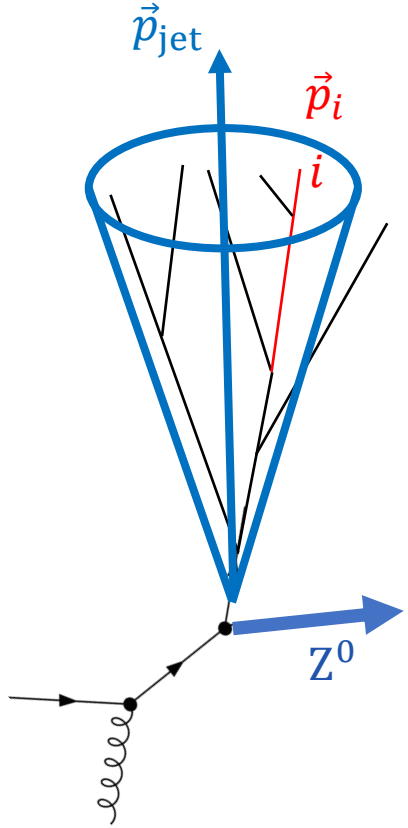


PYTHIA overpredicts production of heavier hadrons at low p_T and at high z → gluon effects?

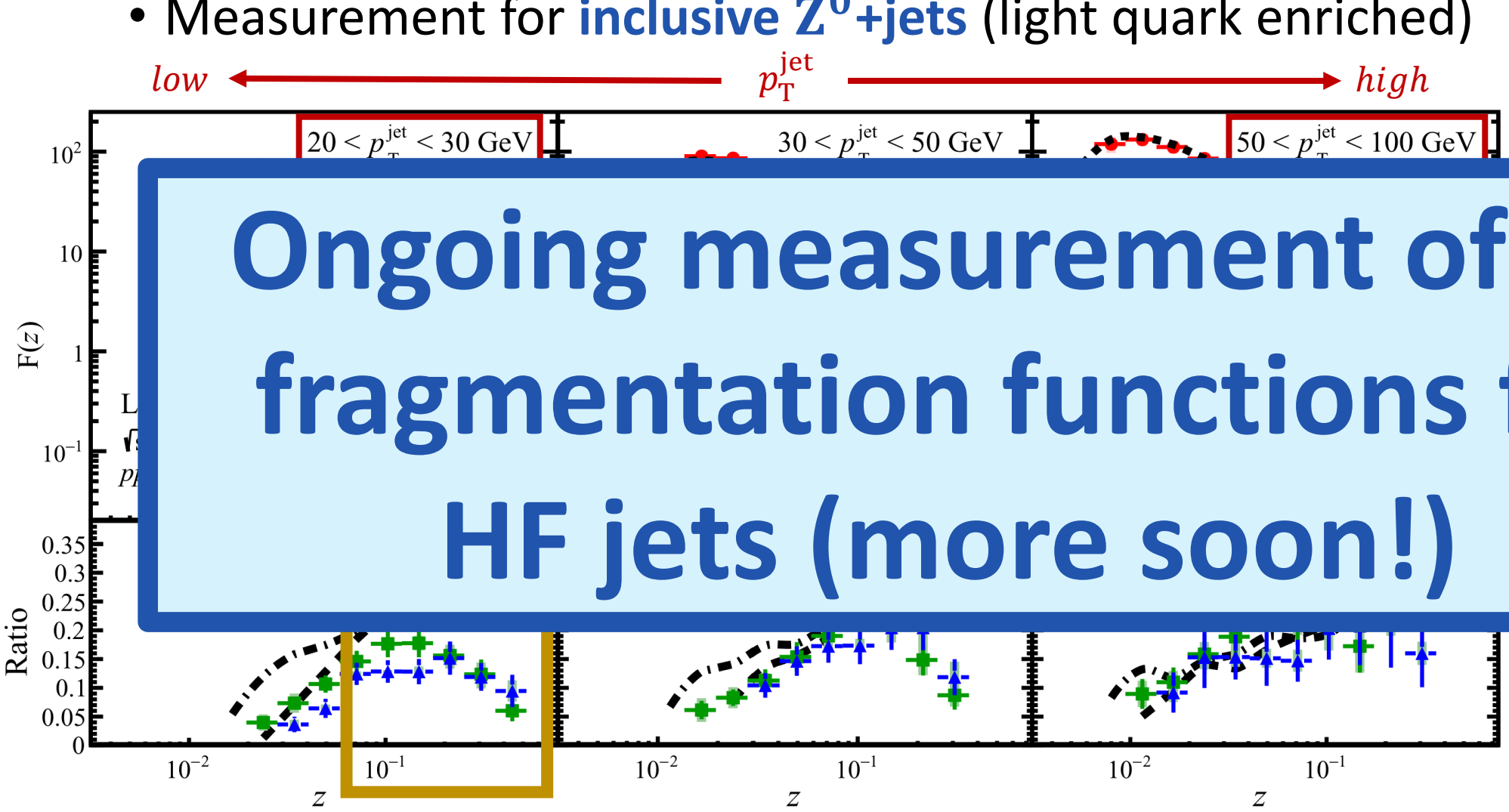


$$z = \frac{\vec{p}_{jet} \cdot \vec{p}_i}{|\vec{p}_{jet}|^2}$$

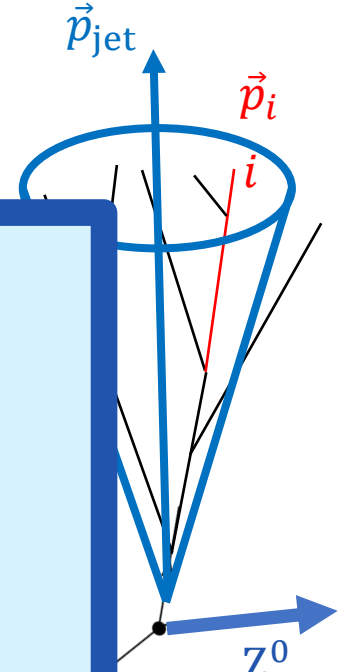
Phys. Rev. D 108 (2023) L031103

Jet fragmentation functions

- Measurement for **inclusive Z^0+jets** (light quark enriched)



Ongoing measurement of jet fragmentation functions for HF jets (more soon!)



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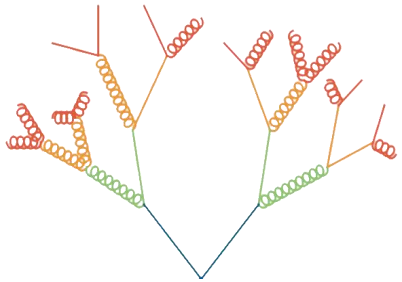
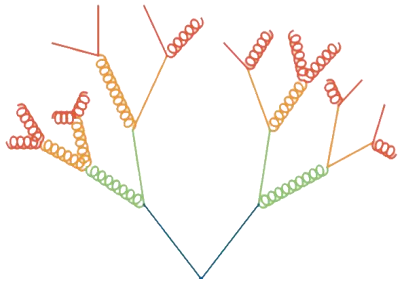
Probing parton emissions



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

Probing parton emissions



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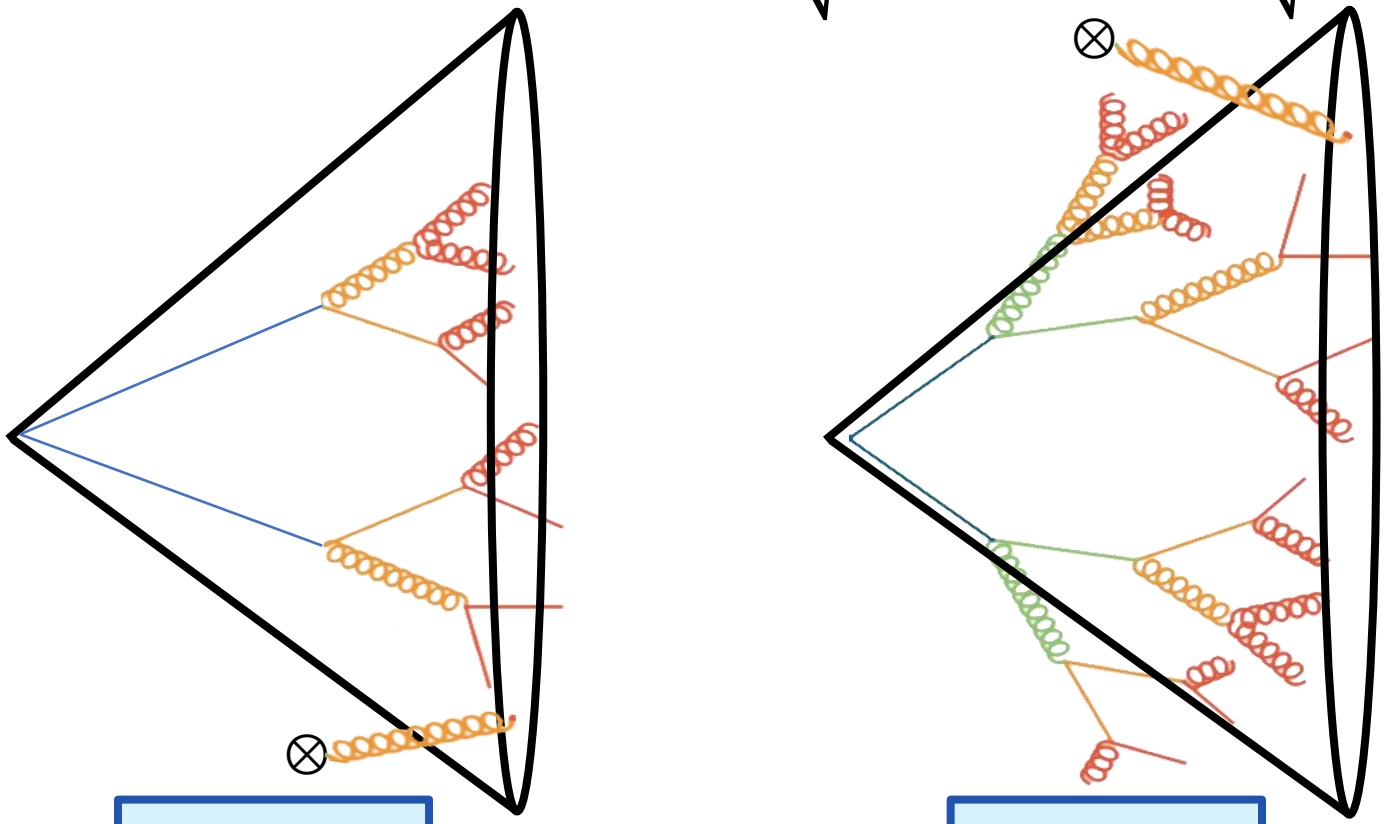
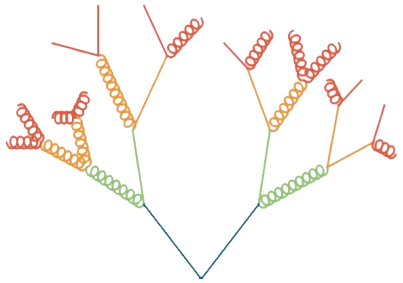


Small m_{jet} ⟷ Large m_{jet}

Probing parton emissions



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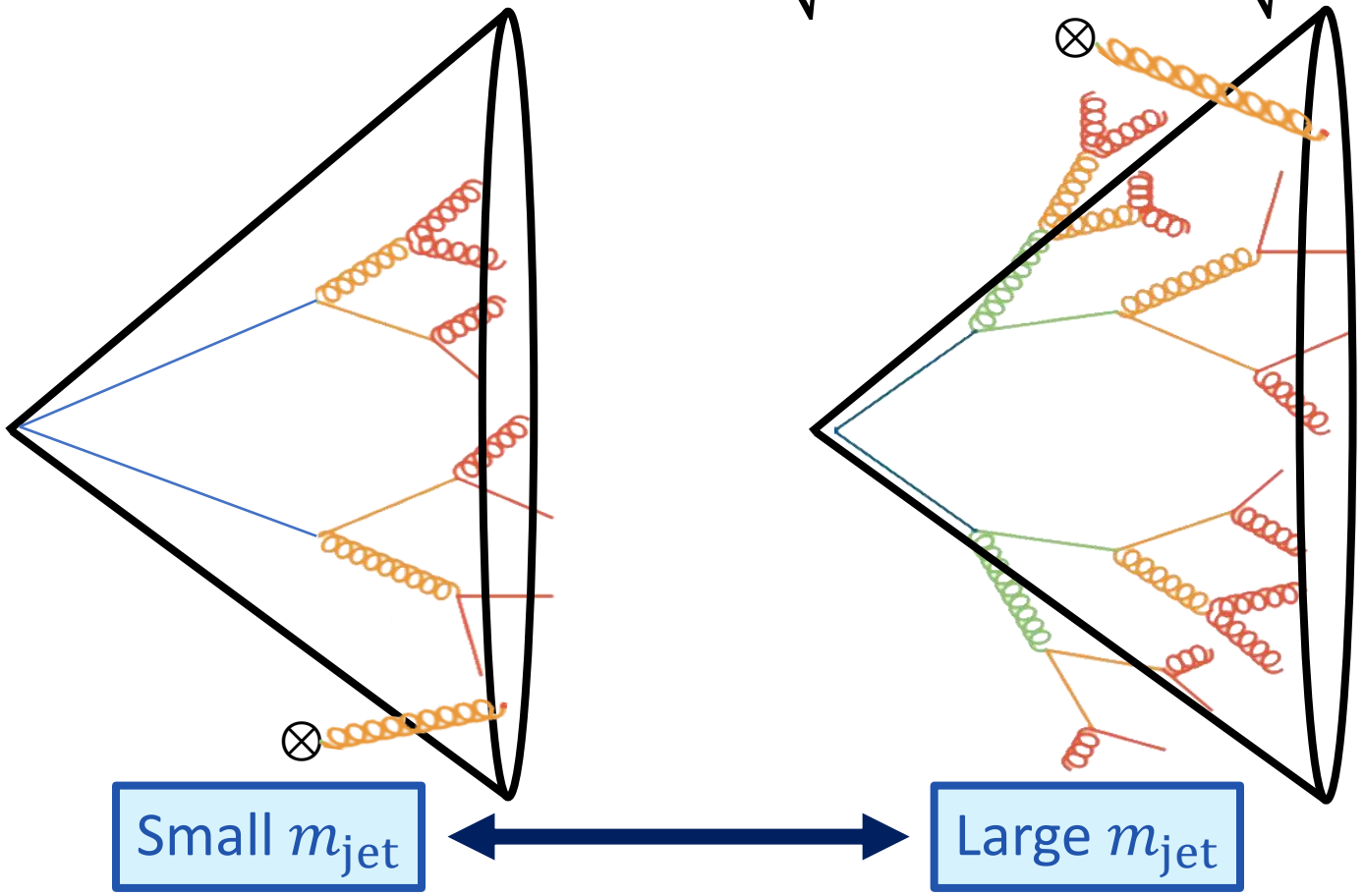
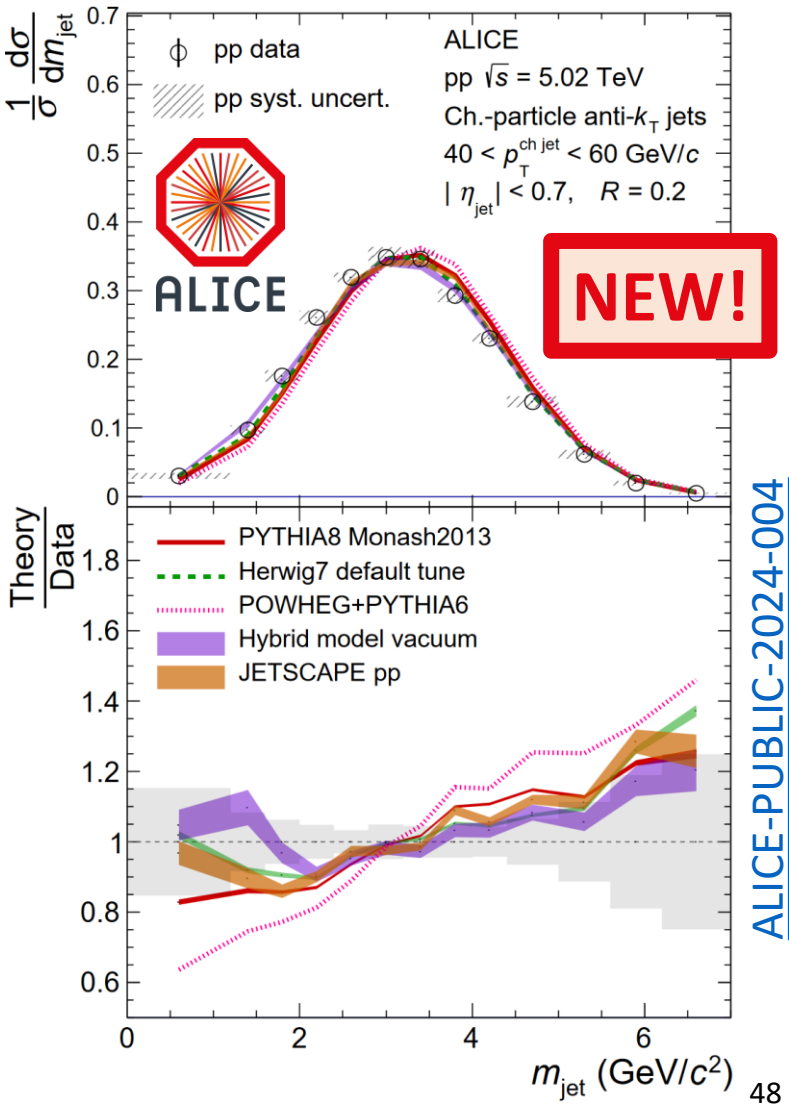
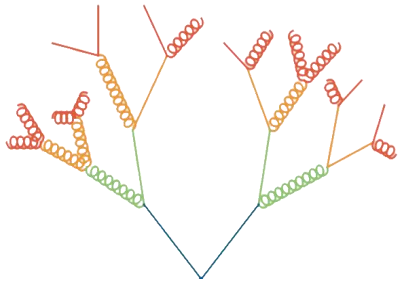




Probing parton emissions



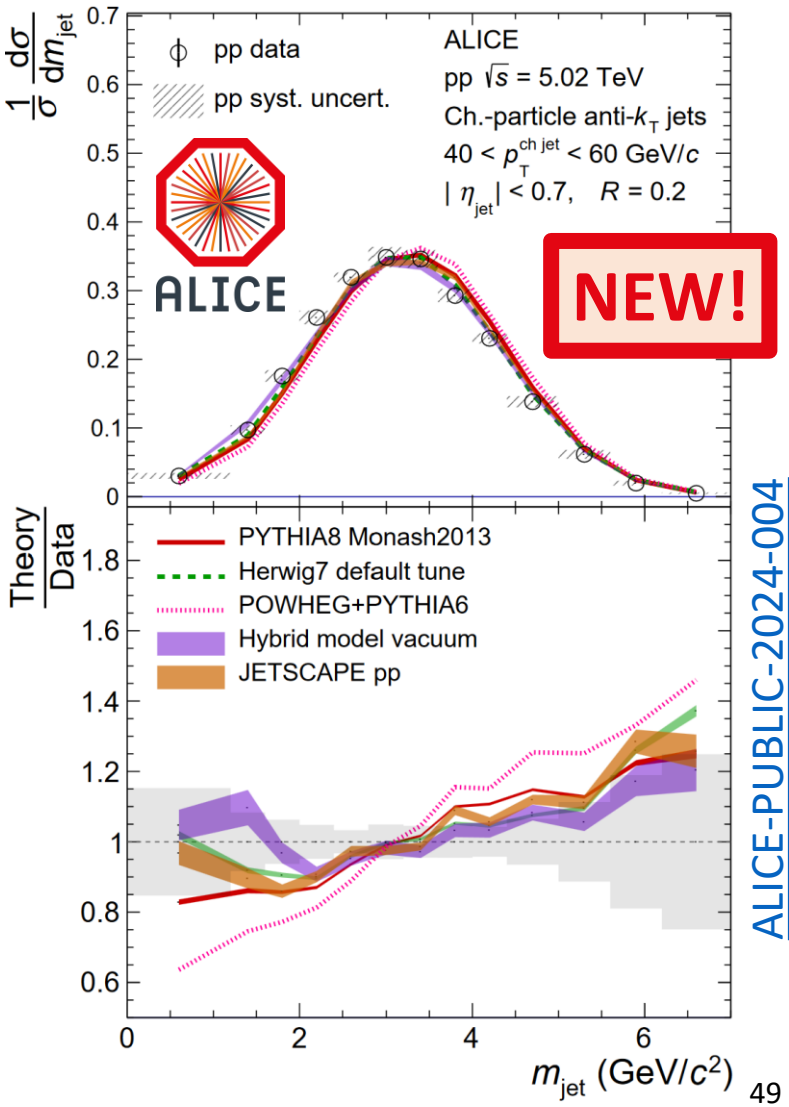
- **Invariant jet mass,** $m_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2} \approx \sqrt{Q_{\text{parton}}^2}$

Recently studied for inclusive jets

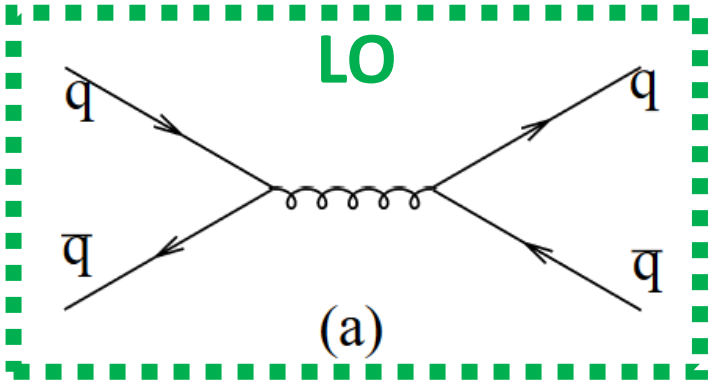
→ How is quark virtuality modified with larger quark mass?

→ Ongoing LHCb measurement with $B^{\pm}$-jets

Small m_{jet} ⟷ Large m_{jet}



Flavor definition problem



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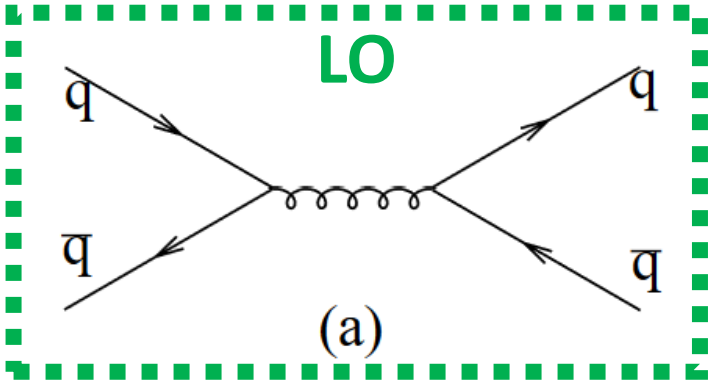
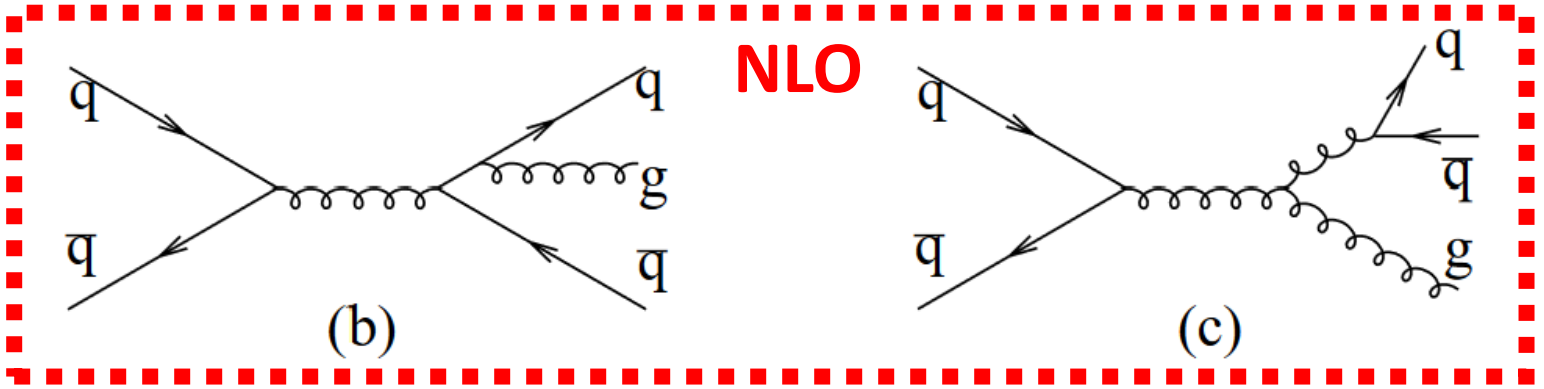
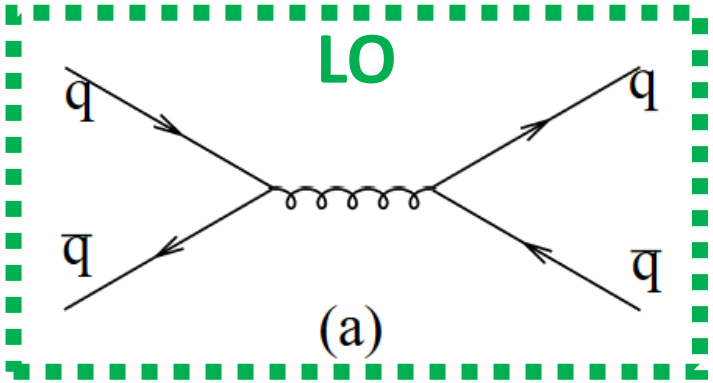


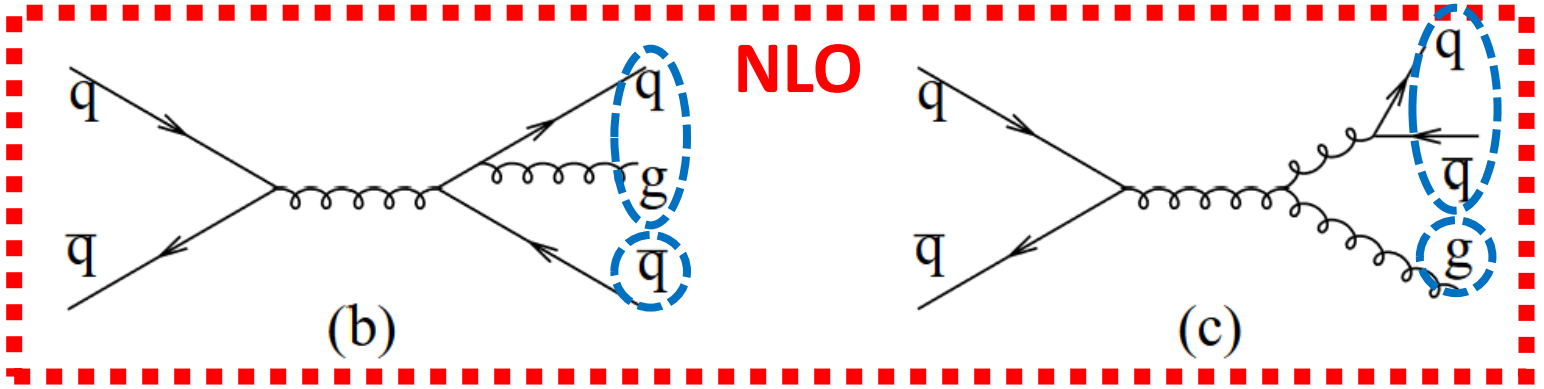


Banfi, Salam, Zanderighi, EPJC 47 (2006) 113-124

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

Flavor definition problem





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

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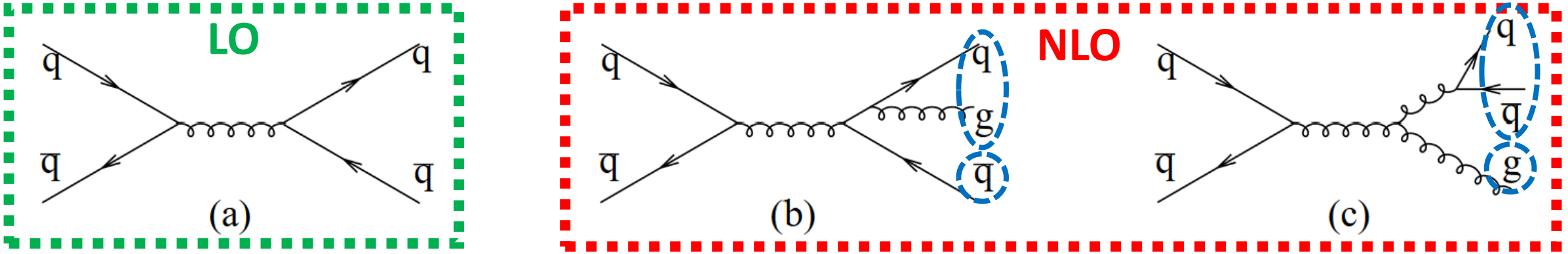
Flavor definition problem



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

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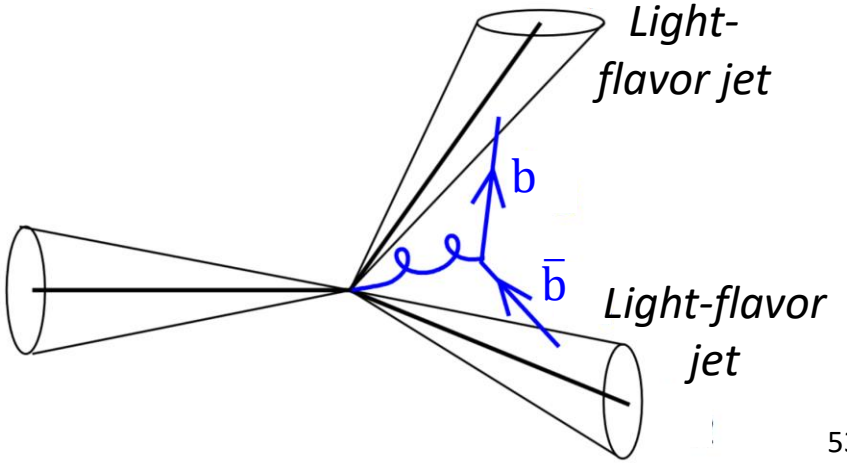
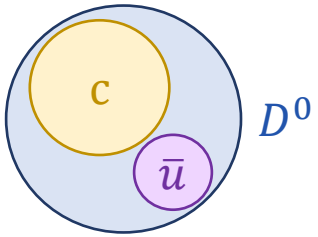
- **But soft gluons ruin this at NNLO**



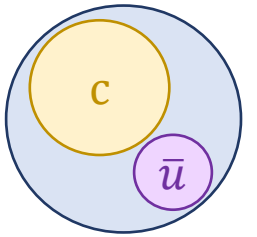
New flavor tagging algorithms

New flavor tagging algorithms



- Study D^0**-jet cross section**

New flavor tagging algorithms

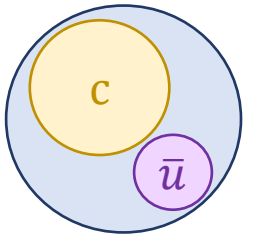


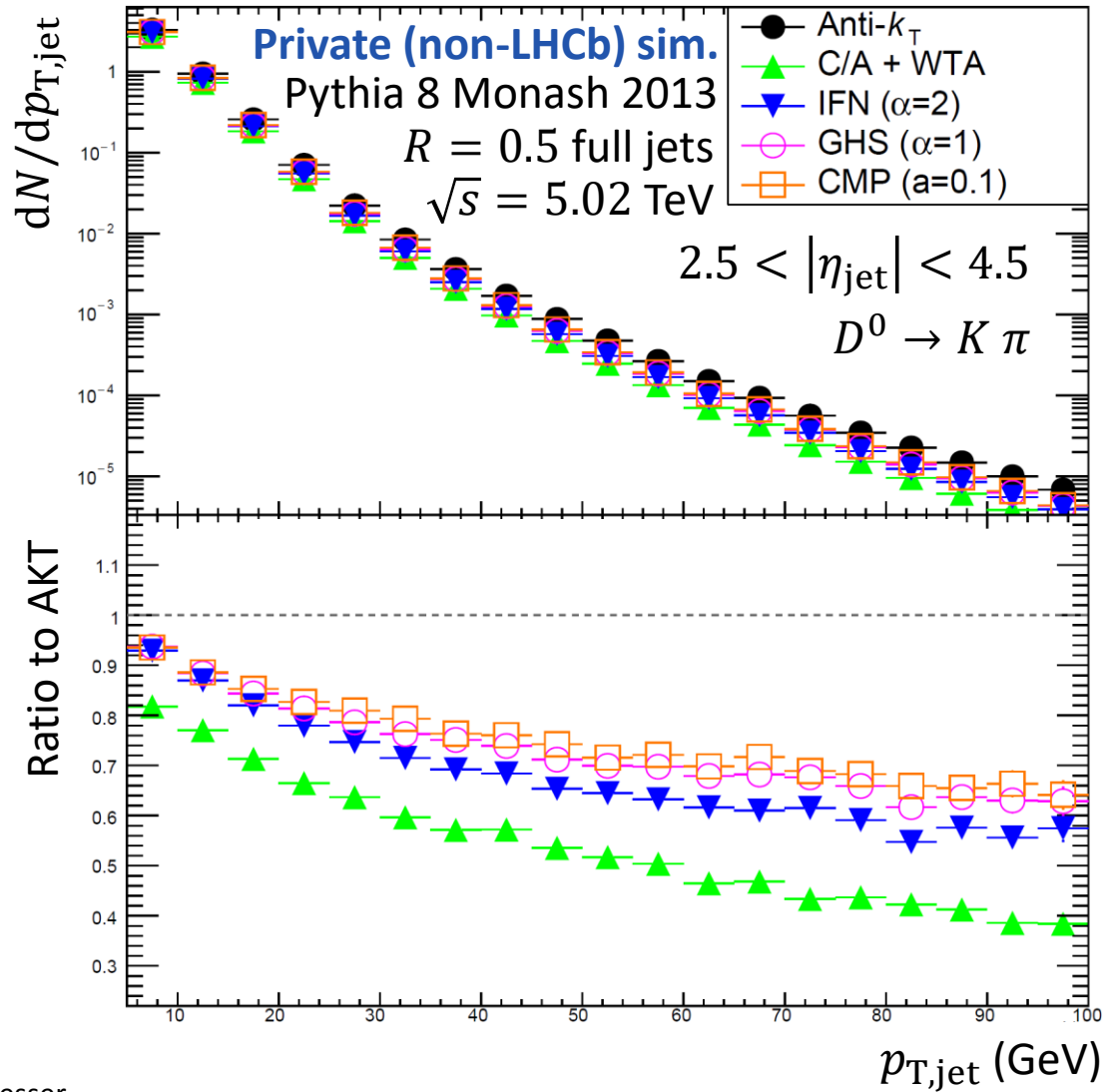
D^0

- Study D^0**-jet cross section** with new flavor-tagging algorithms:
  - **Winner-Take-All (WTA)** + C/A reclustering
    JHEP 10 (2022) 158
  - **Interleaved Flavor Neutralization (IFN)**
    arXiv:2306.07314 [hep-ph]
  - **Flavor dressing (GHS)**
    arXiv:2208.11138 [hep-ph]
  - **CMP (distance metric modification)**
    JHEP 04 (2023) 138

- New algorithms **calculable at NNLO(+)**

New flavor tagging algorithms





- Study D^0**-jet cross section** with new flavor-tagging algorithms:
  - **Winner-Take-All (WTA)** + C/A reclustering
    JHEP 10 (2022) 158
  - **Interleaved Flavor Neutralization (IFN)**
    arXiv:2306.07314 [hep-ph]
  - **Flavor dressing (GHS)**
    arXiv:2208.11138 [hep-ph]
  - **CMP (distance metric modification)**
    JHEP 04 (2023) 138

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Simulations privately produced by E. Lesser, R. Xu

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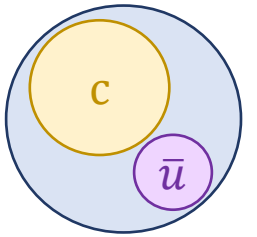

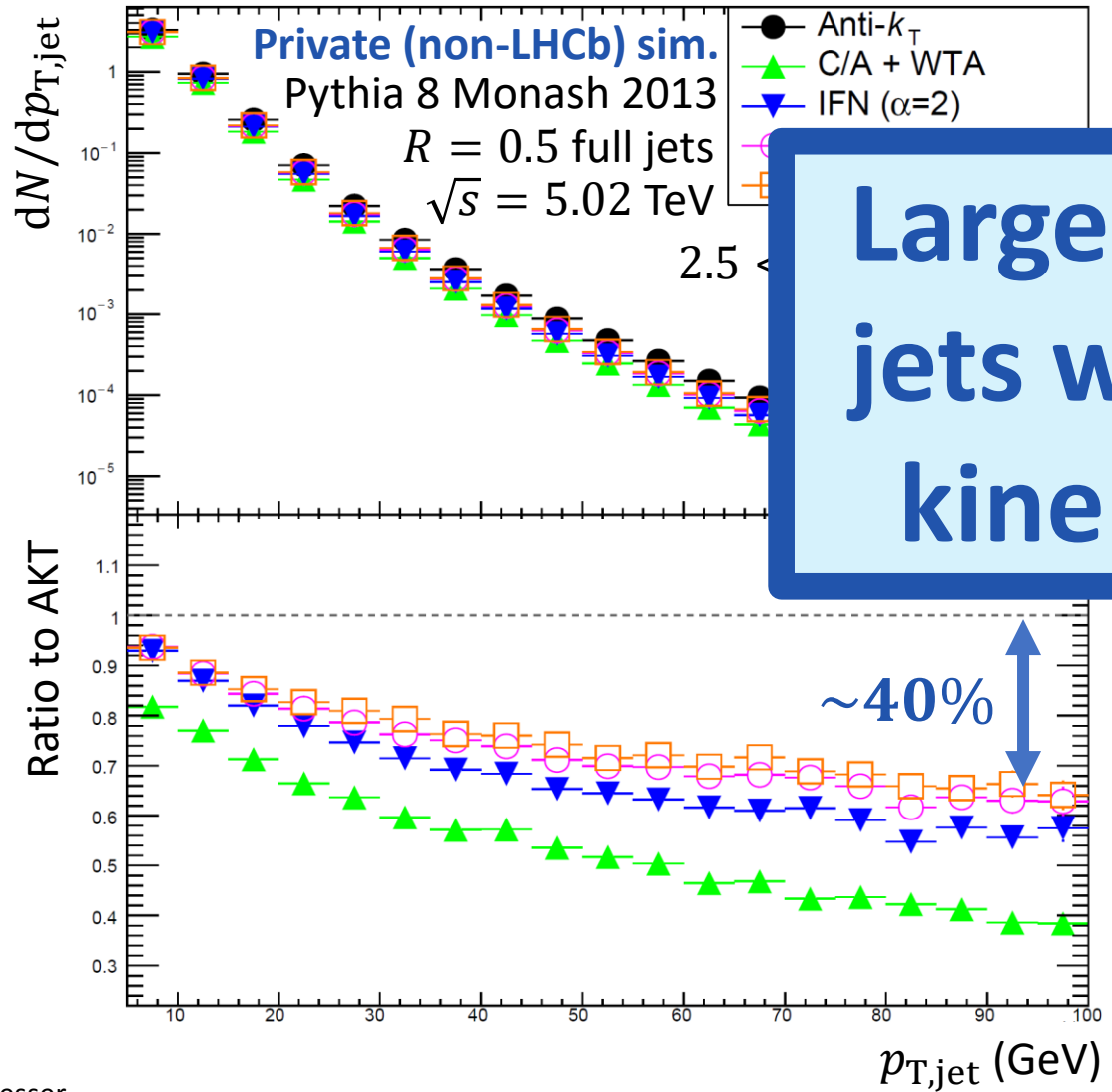

- Study D^0-**jet cross section** with new

Large contribution (10-40%) of jets with 2 HF hadrons in LHCb kinematics (*gluon splitting*?)

arXiv:2208.11138 [hep-ph]

- **CMP (distance metric modification)**

JHEP 04 (2023) 138

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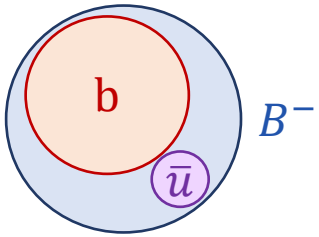

- Study $B^{\pm}$**-jet cross section**

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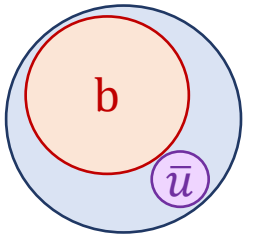

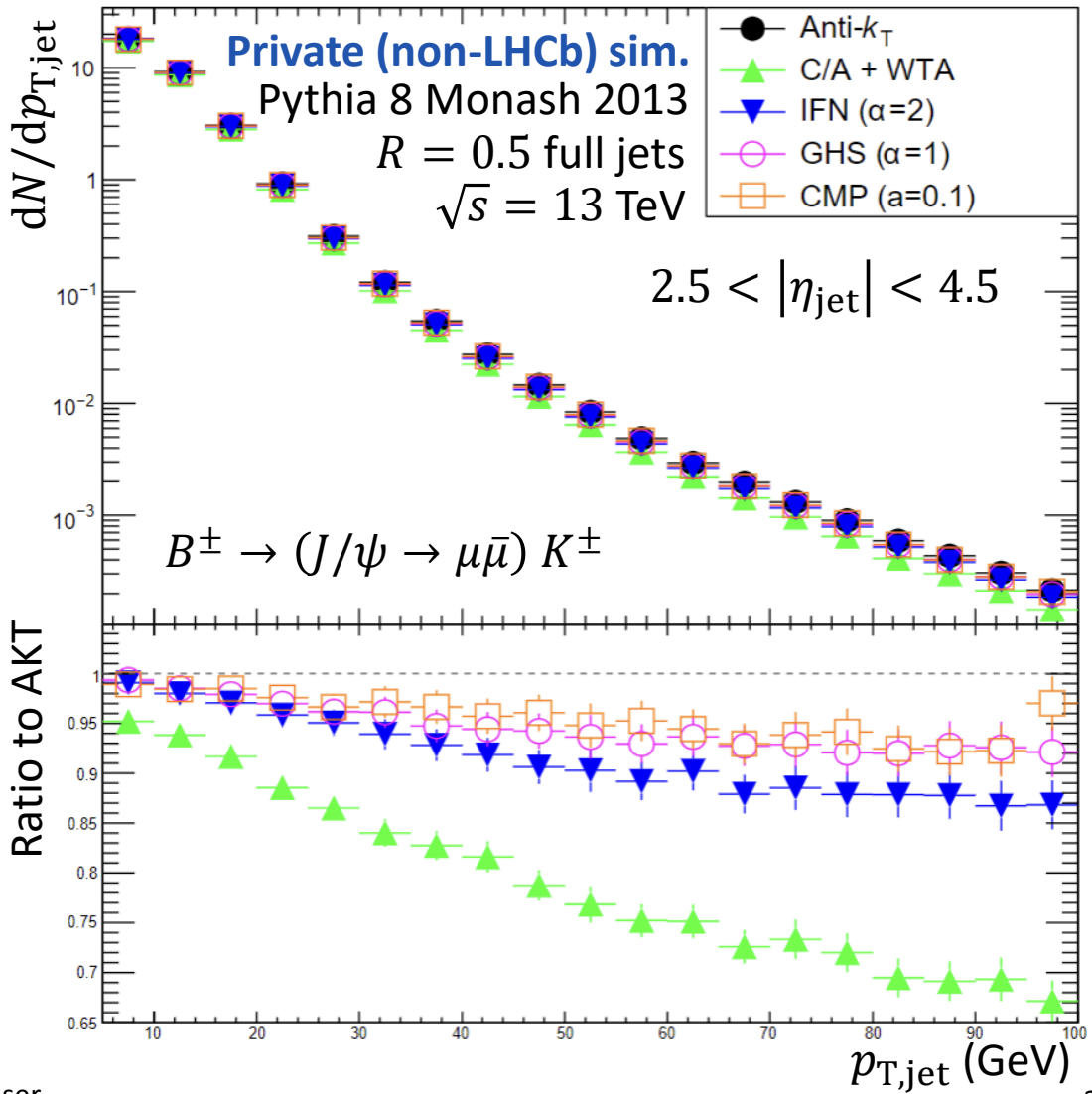

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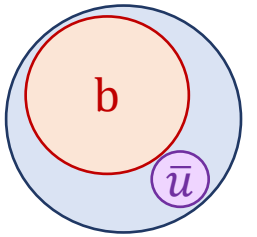

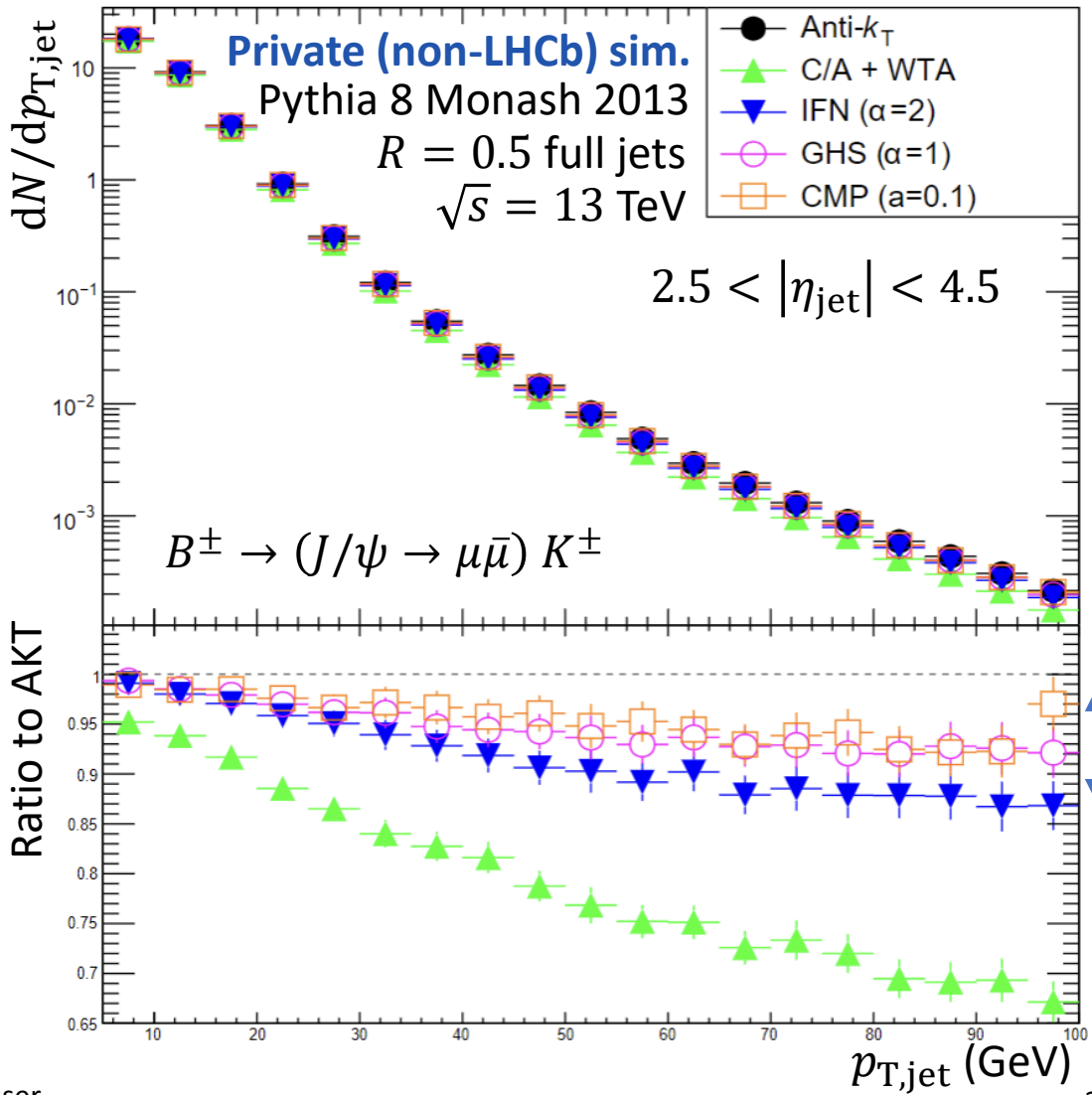

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- **Tagging fraction is much higher**

~10%

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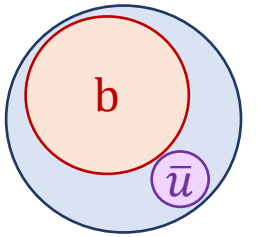

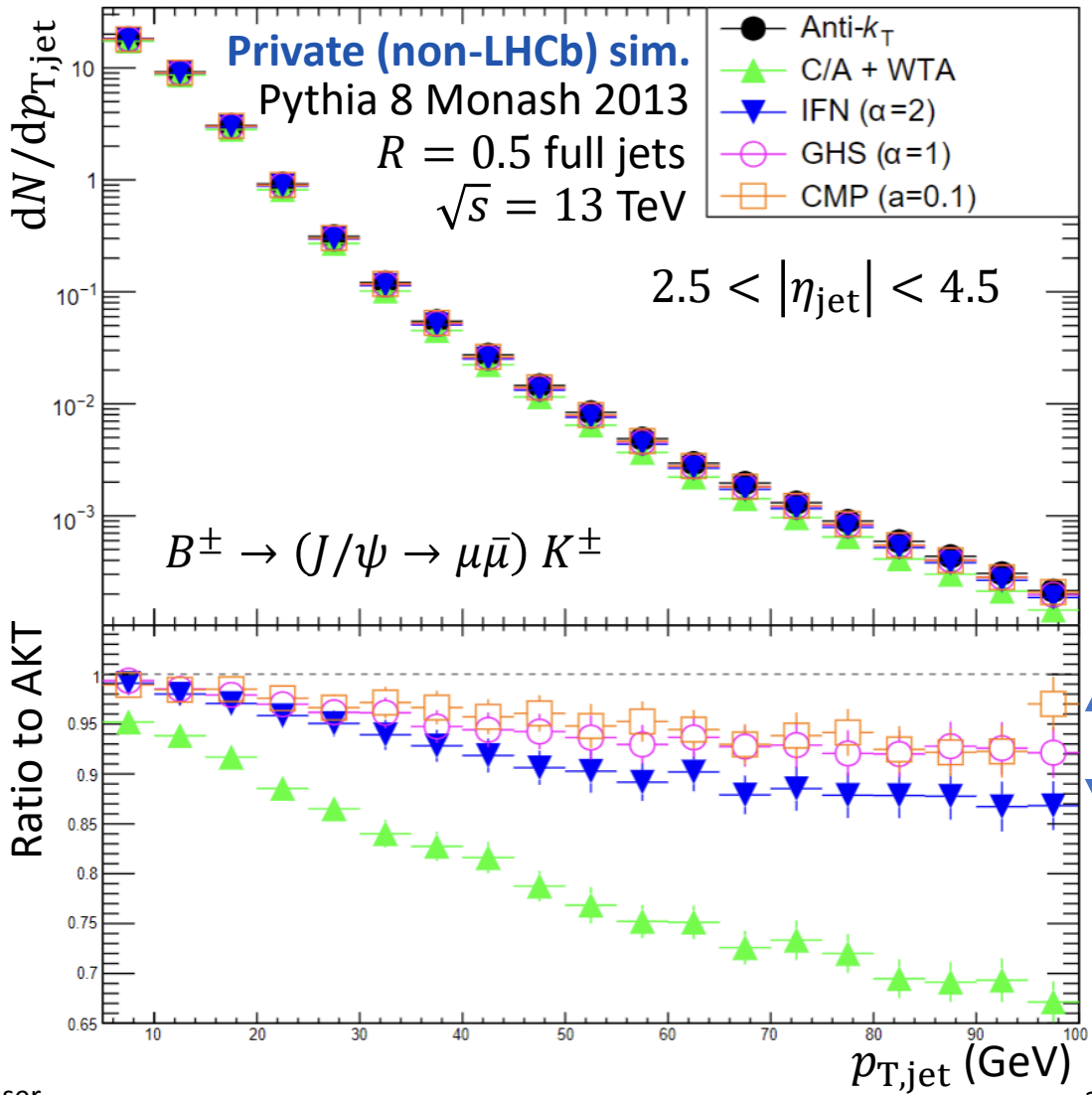

- Study $B^{\pm}$-jet cross section
- **Tagging fraction is much higher**
- **How is substructure affected?**

~10%

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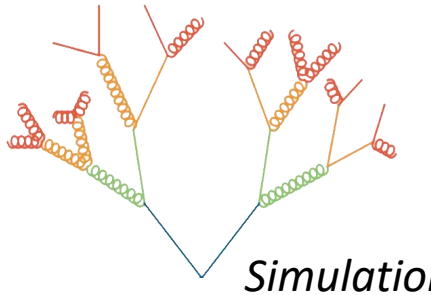
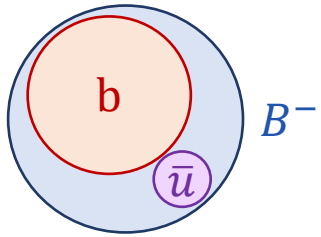
Heavy-flavor jet mass





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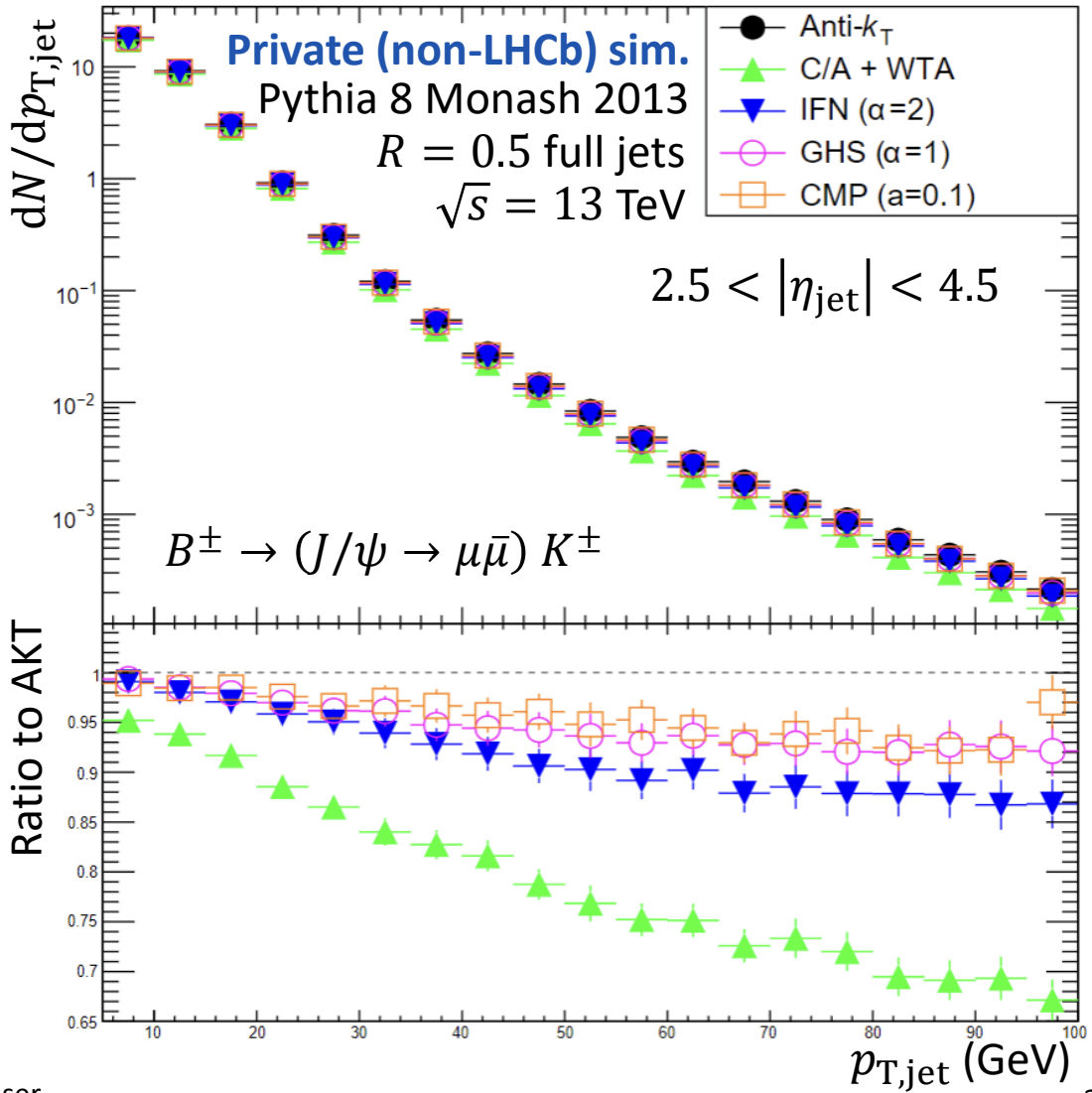

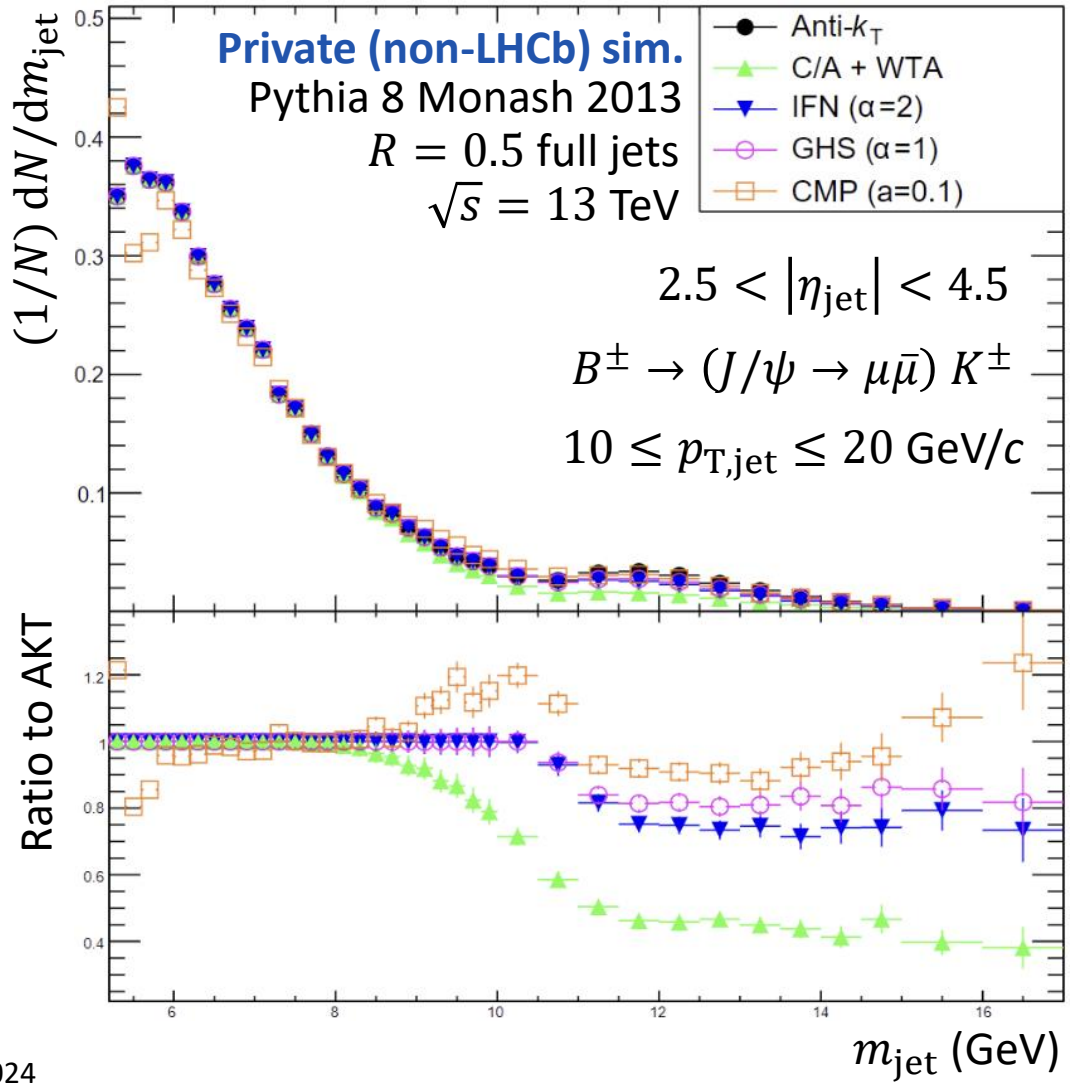

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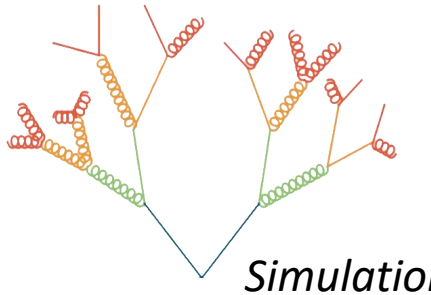

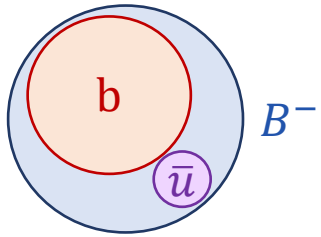

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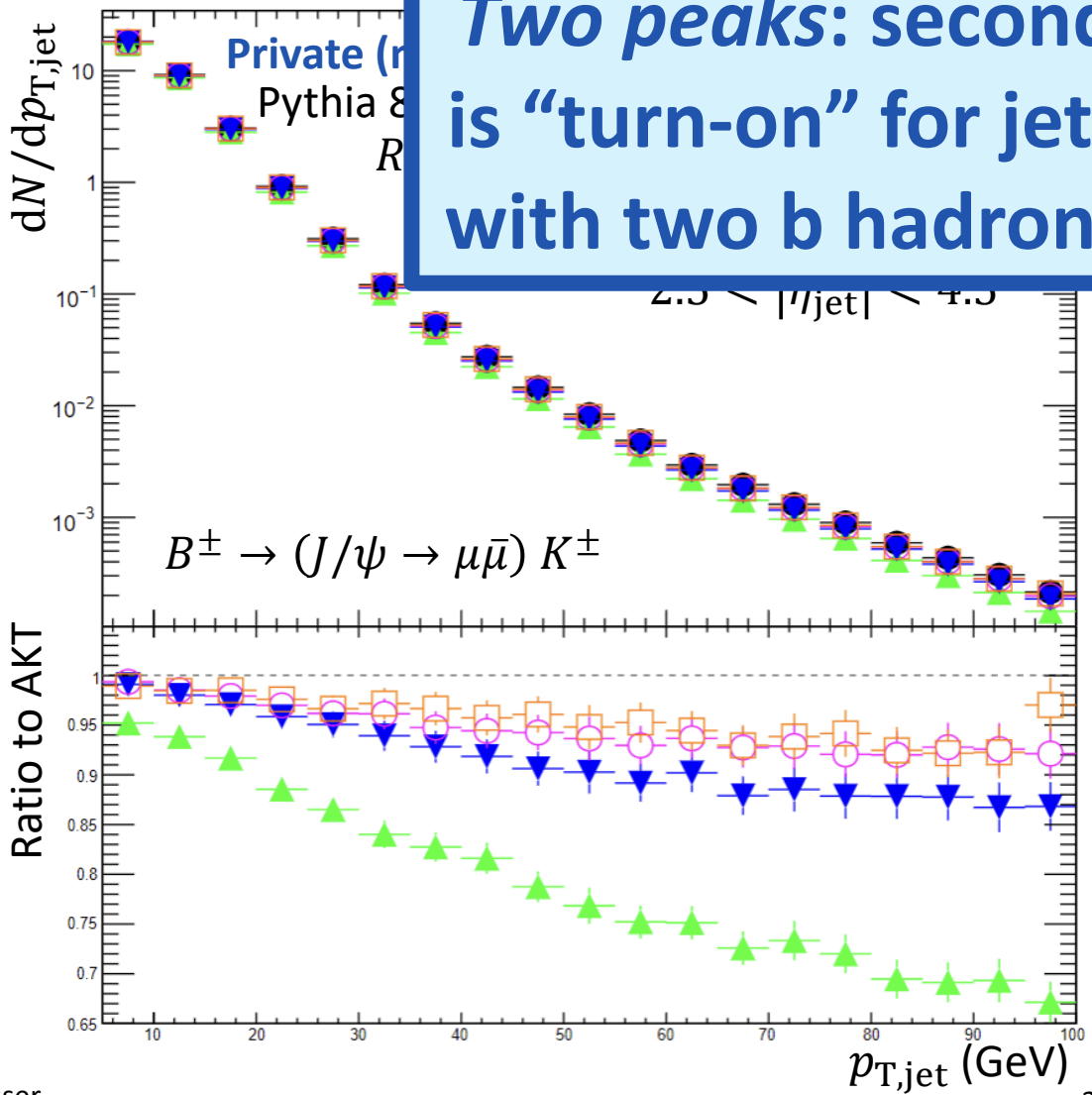

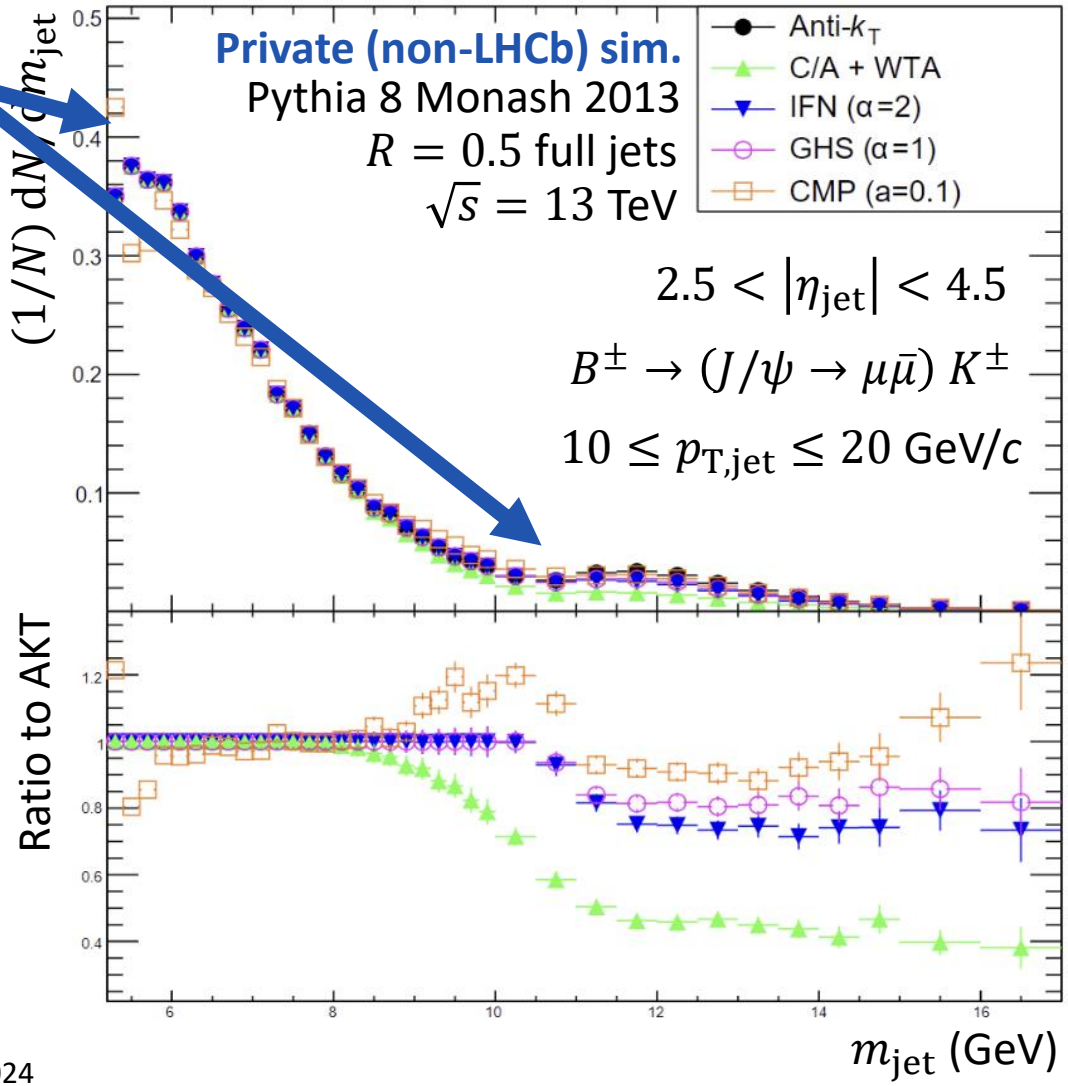

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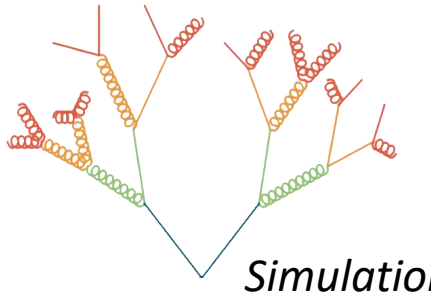

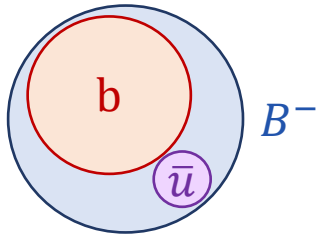

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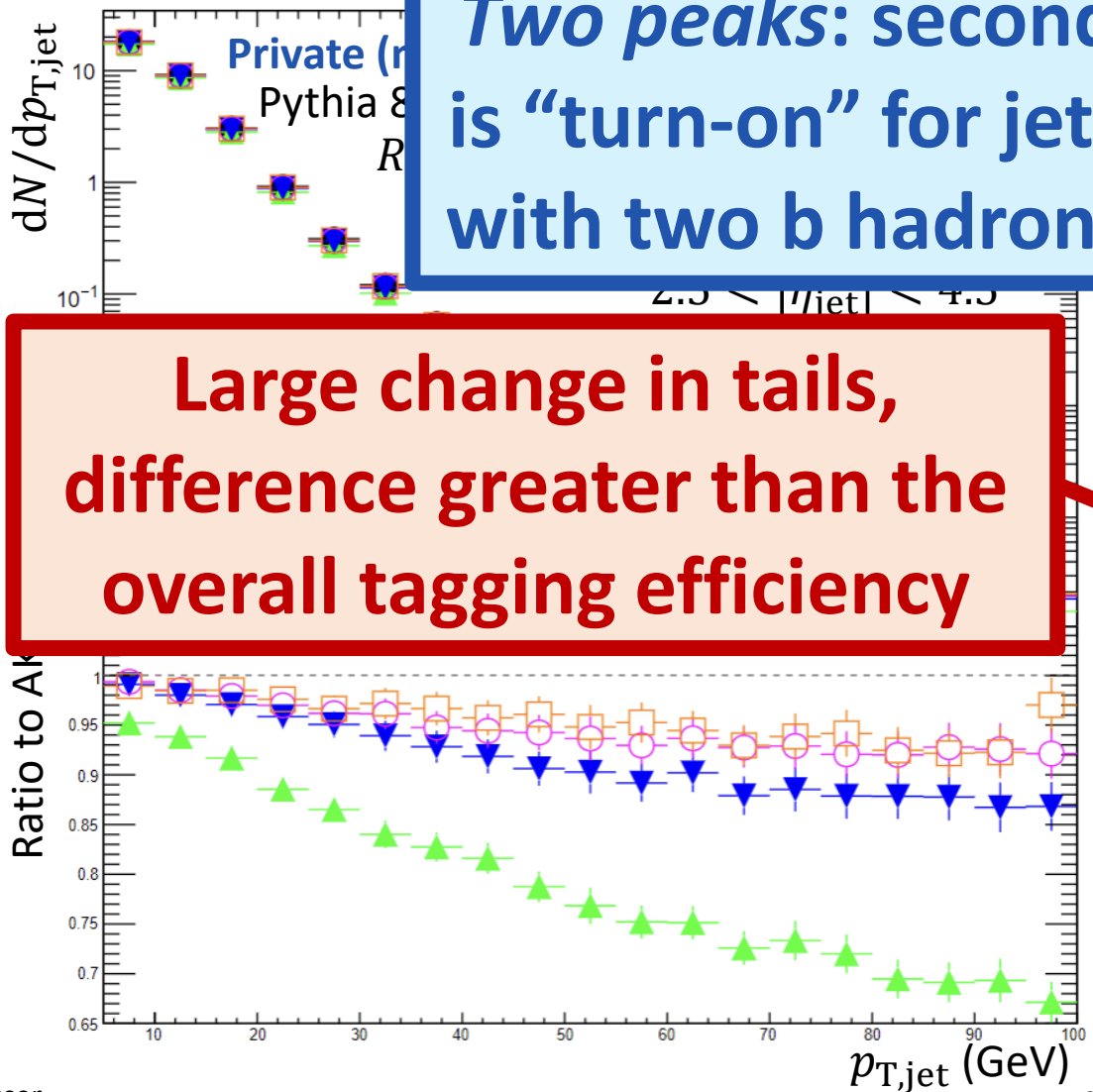

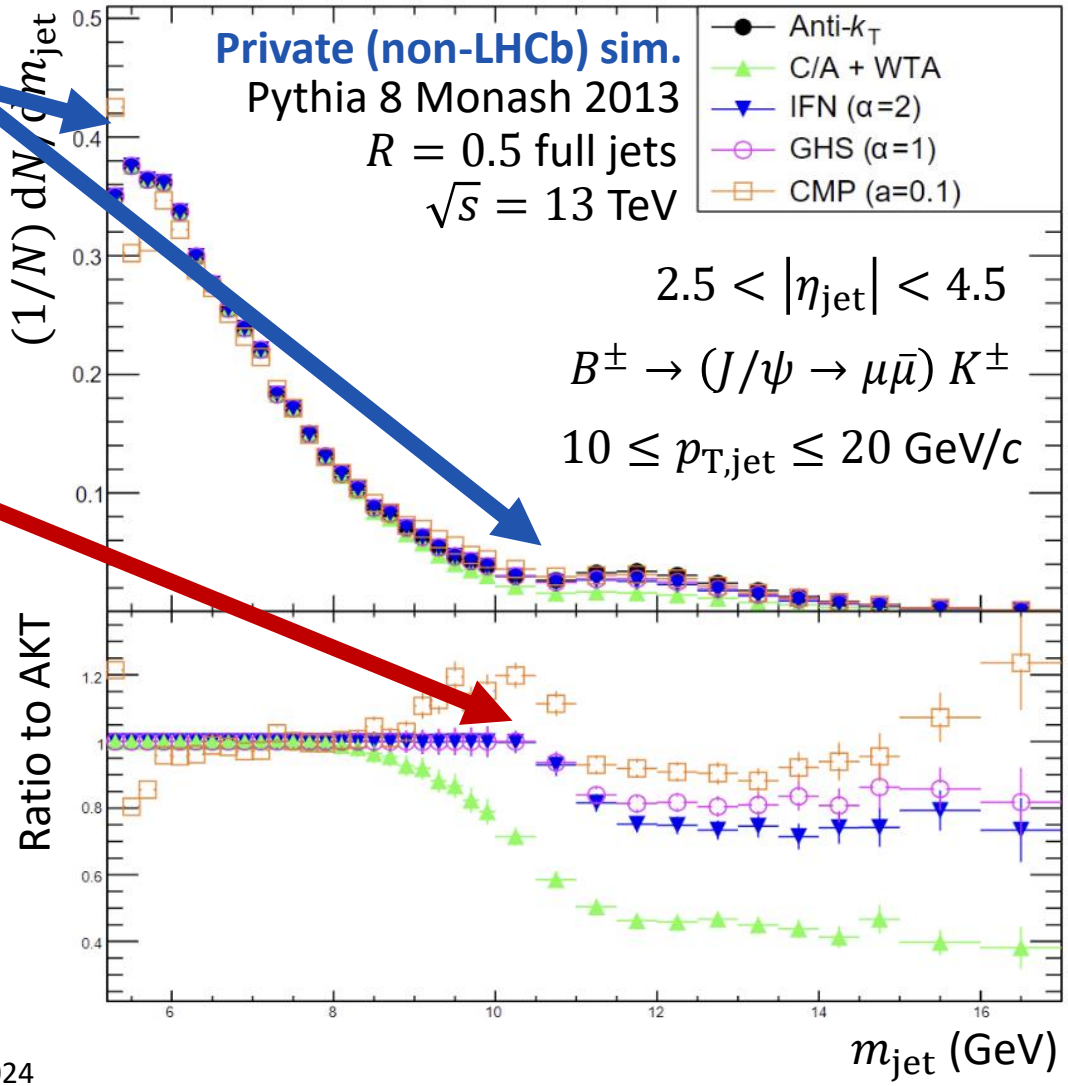

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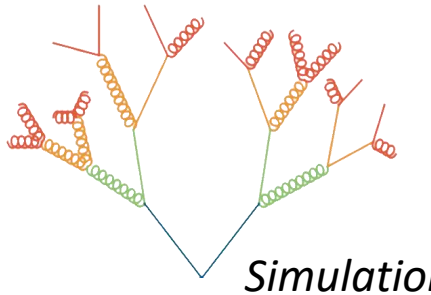

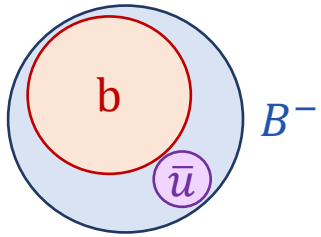

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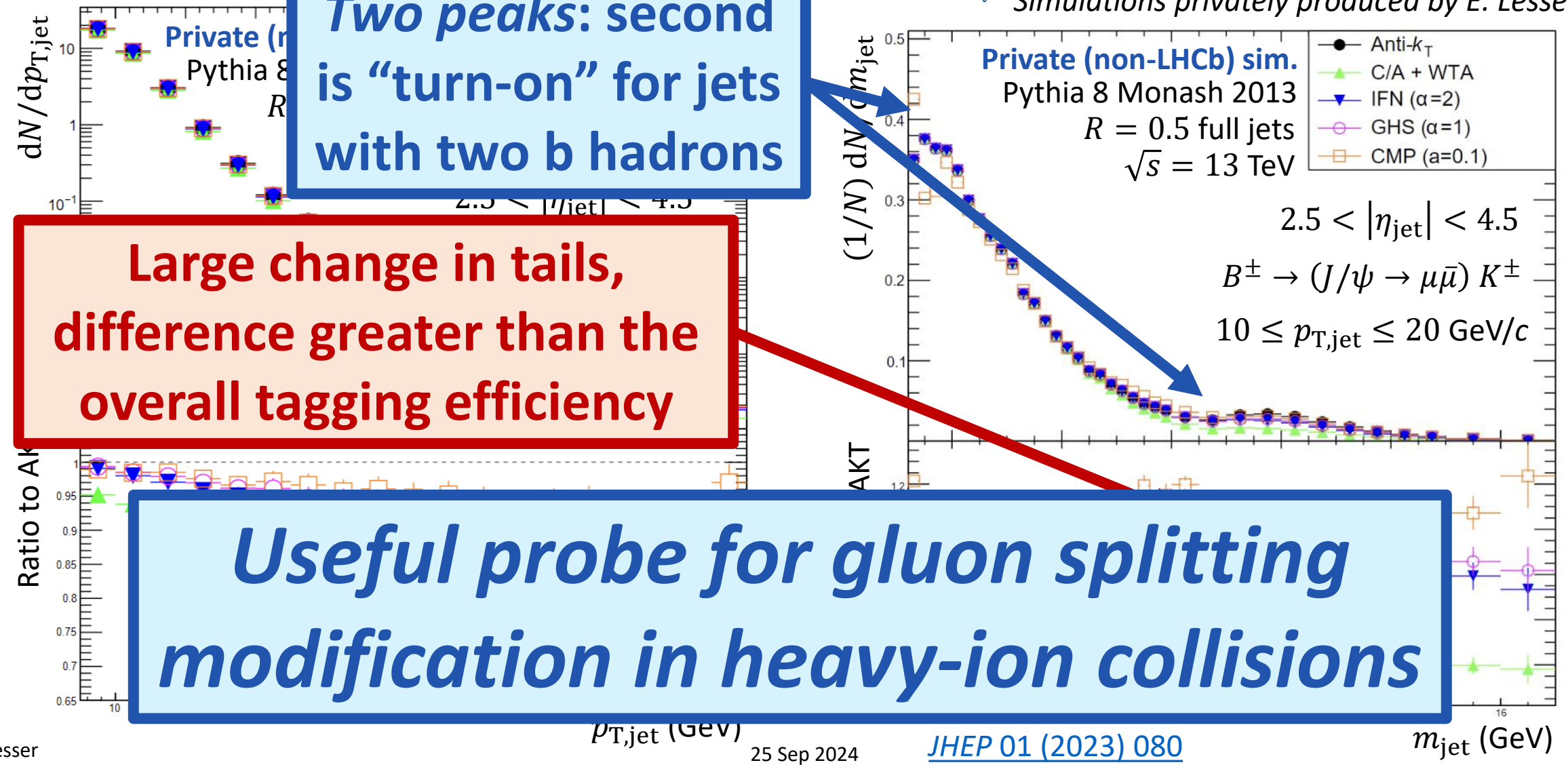

Useful probe for gluon splitting modification in heavy-ion collisions

Conclusions

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Cooke, Ilten, Lönnblad, Mrenna
arXiv:2312.05203 [hep-ph]

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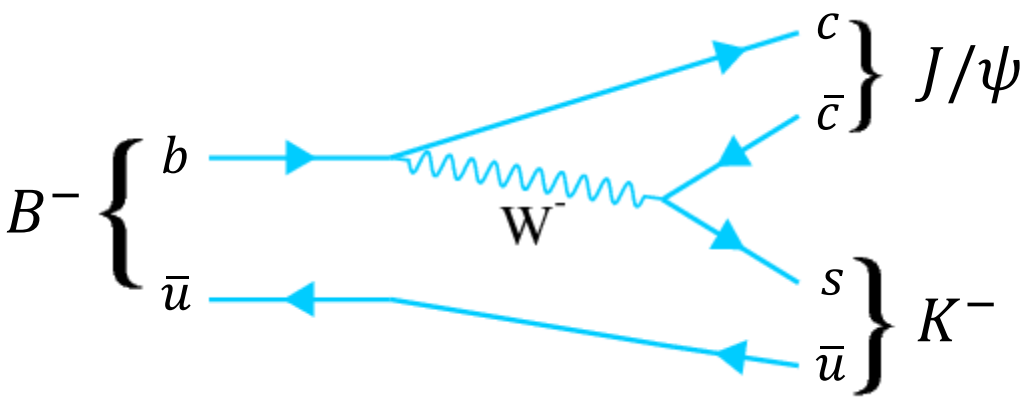
- Ongoing studies using **new flavor tagging algorithms** (including Lund jet plane, jet mass, groomed observables, EECs, and others)
  - *More exciting new results soon!*

Backup

Two paths to heavy flavor

1) Reconstructing **individual decay channels**
   - e.g., $B^{\pm} \to (J/\psi \to \mu^+\mu^-)\, K^{\pm}$
   - Minimal bias on the reconstructed HF-hadron candidates

2) Reconstructing **secondary vertices (SVs)**
   - Build SV from tracks which are displaced from the primary vertex (PV)



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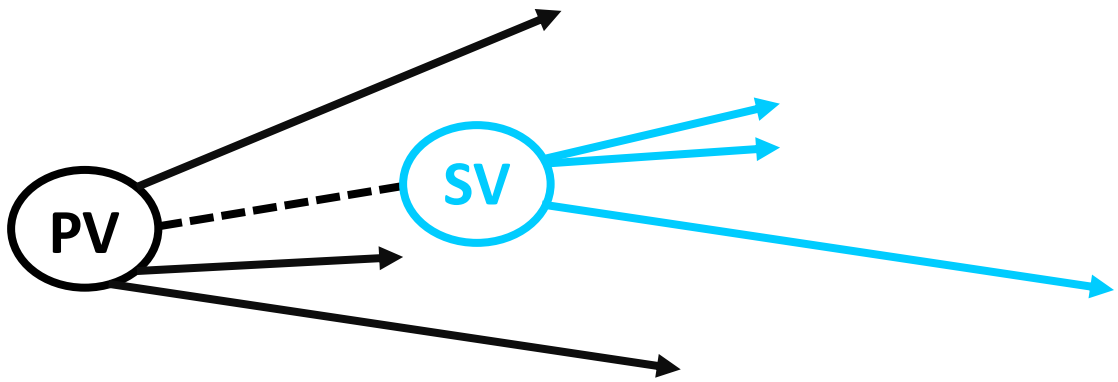

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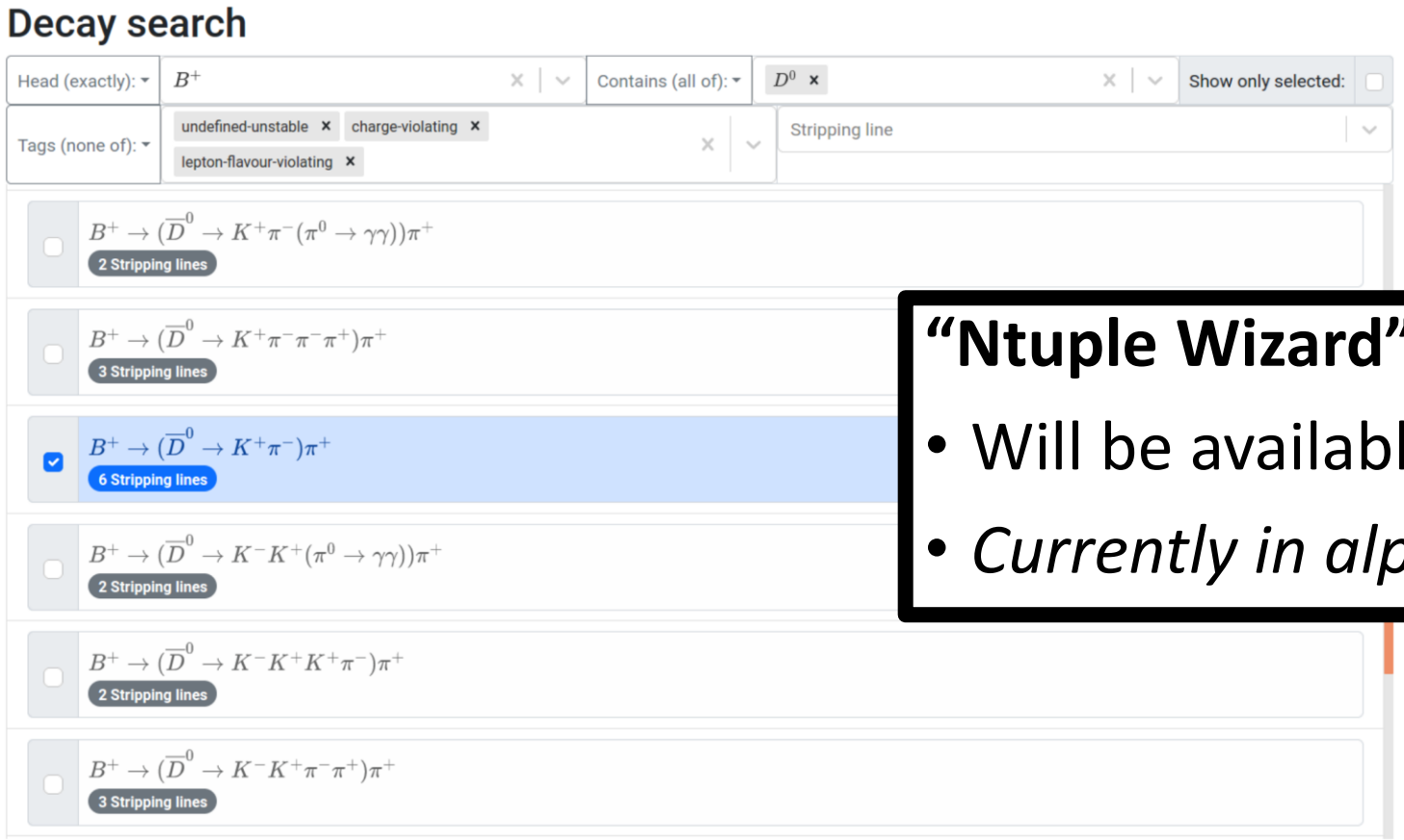

"Ntuple Wizard" for selecting decay(s)

- Will be available for **LHCb open data**
- *Currently in alpha testing (internal)*

Comput. Softw. Big Sci. 7 (2023), no. 6

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- Still impossible to reconstruct all HF hadrons through all decay channels
  - Must be taken into consideration when studying new jet flavor algorithms

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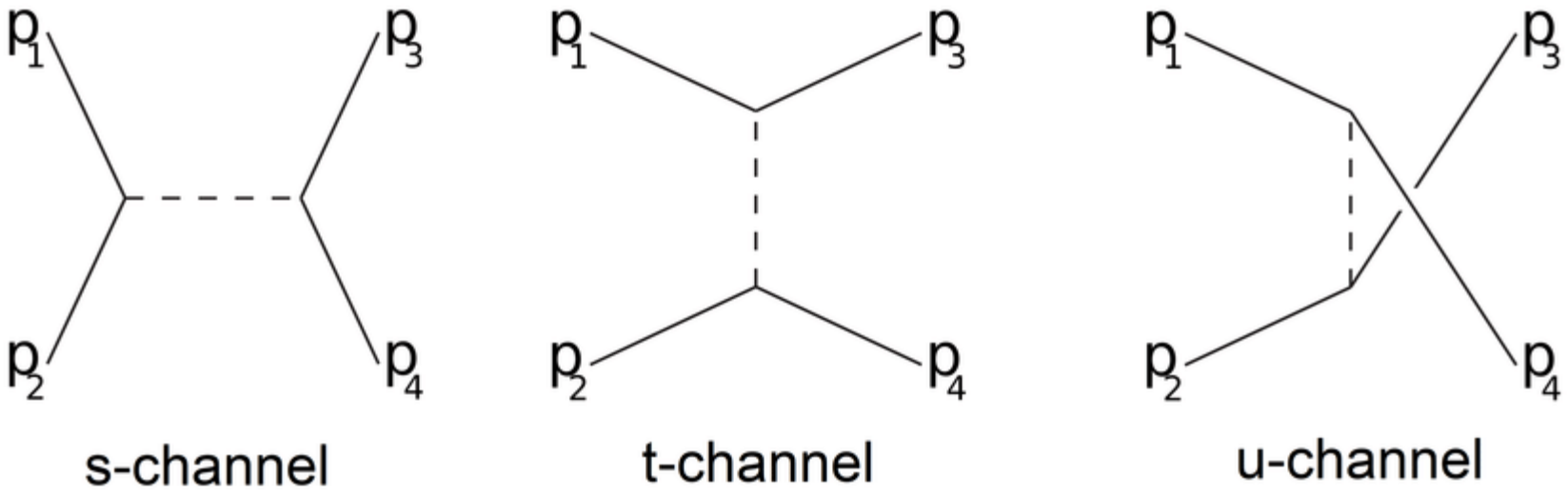
- Use Pythia 8 with **`HardQCD:all=on`** (enabling all 2 → 2 matrix elements)



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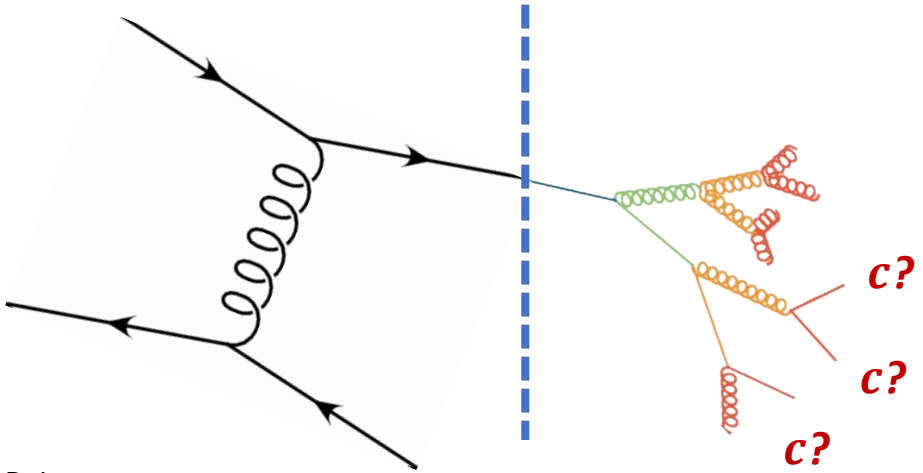

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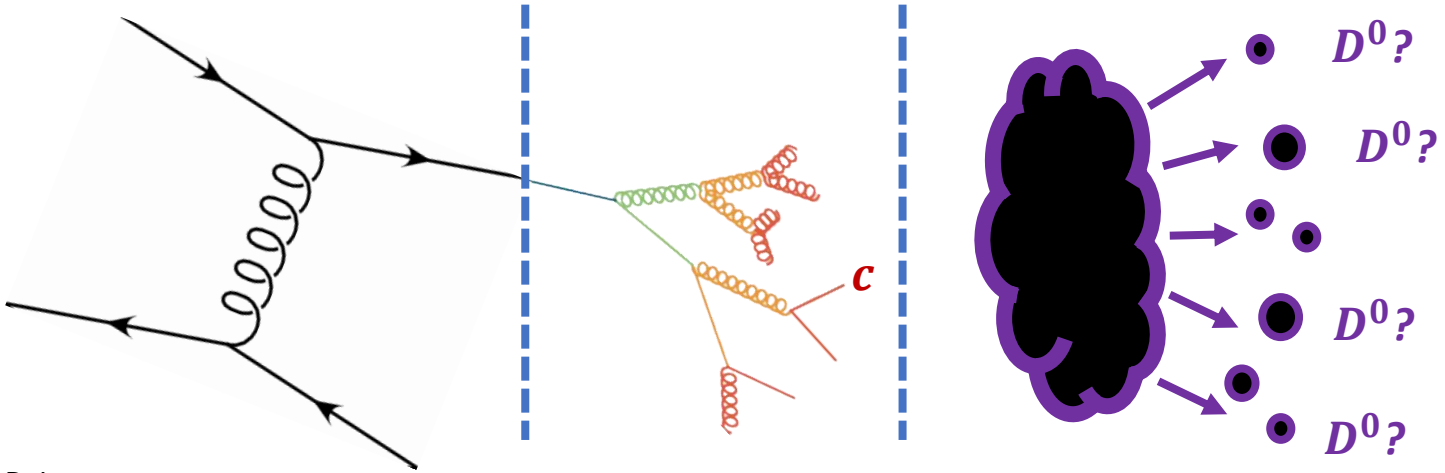

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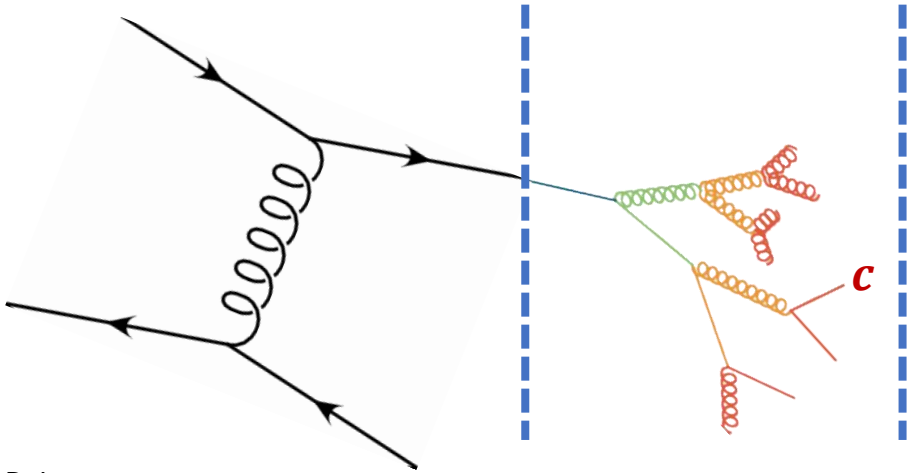
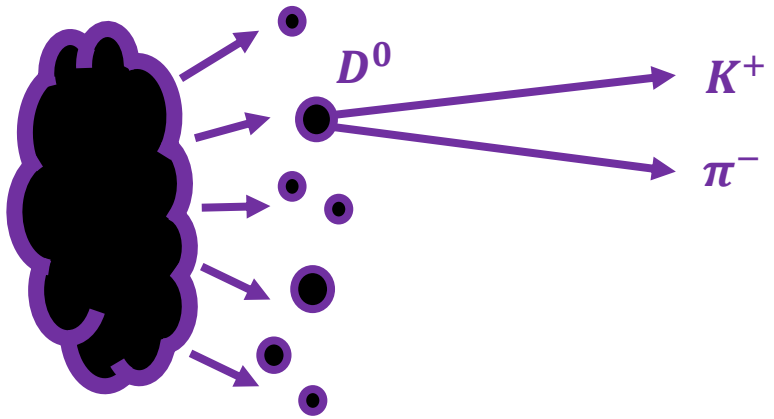
- Reconstruct jets and study those containing the HF hadron of interest





“Winner-Take-All” flavor tagging

*See **Andrew Larkoski’s talk** from public LHCb meeting on flavor algorithms:* https://indico.cern.ch/e/LHCb-jet-flavor

Caletti, Larkoski, Marzani, Reichelt
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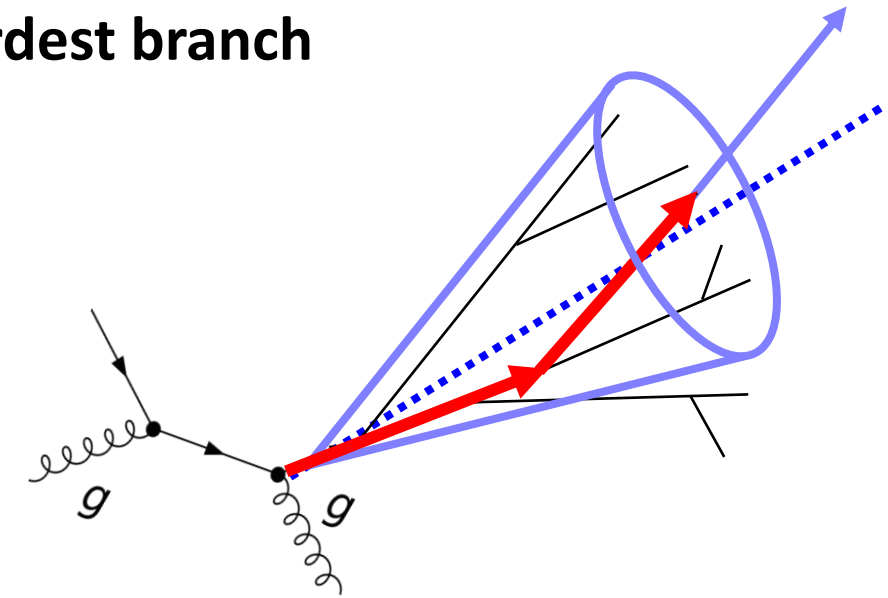

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- This WTA flavor definition is completely soft resilient → **IR-safe**
  - Not collinear safe, so introduce (perturbative) “flavor fragmentation function”

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Can compare experimental data to direct theoretical predictions up to NNLO!

“Winner-Take-All” flavor tagging

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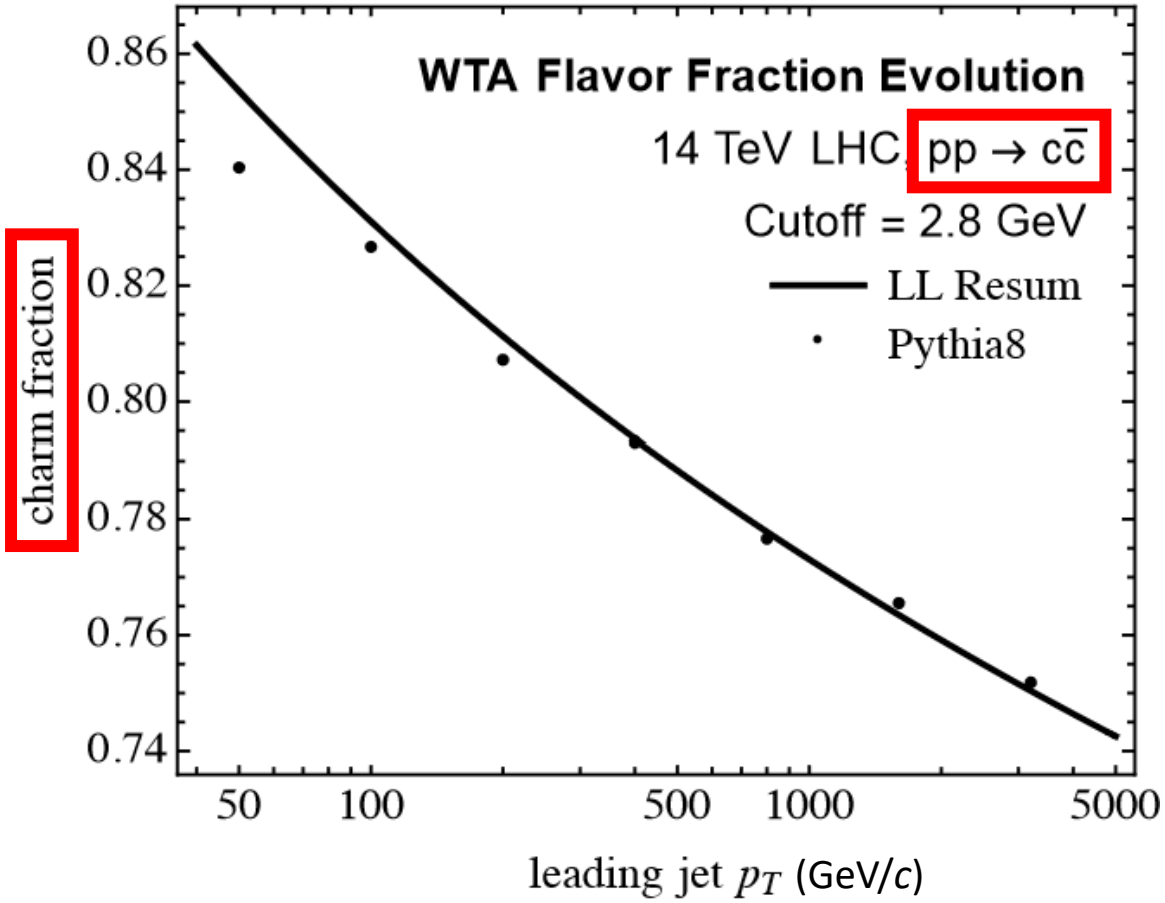

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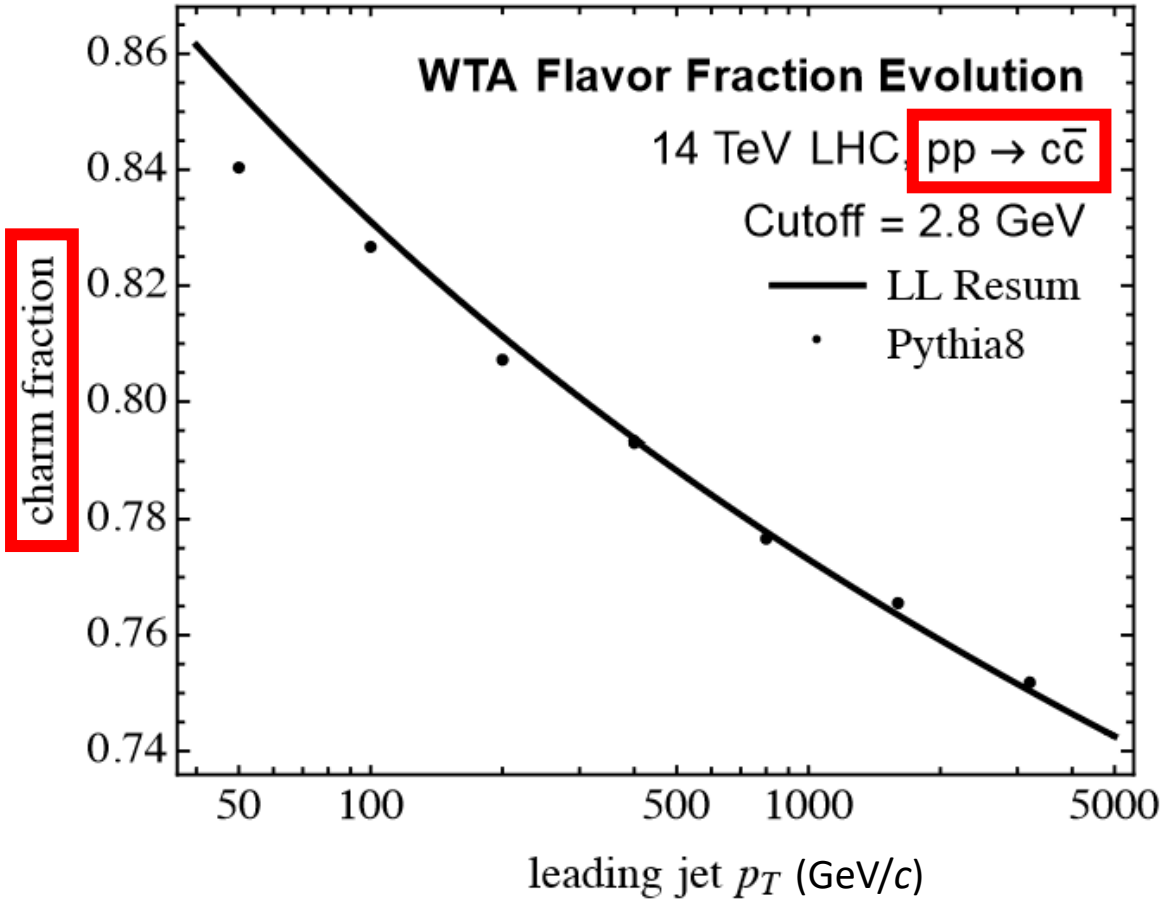

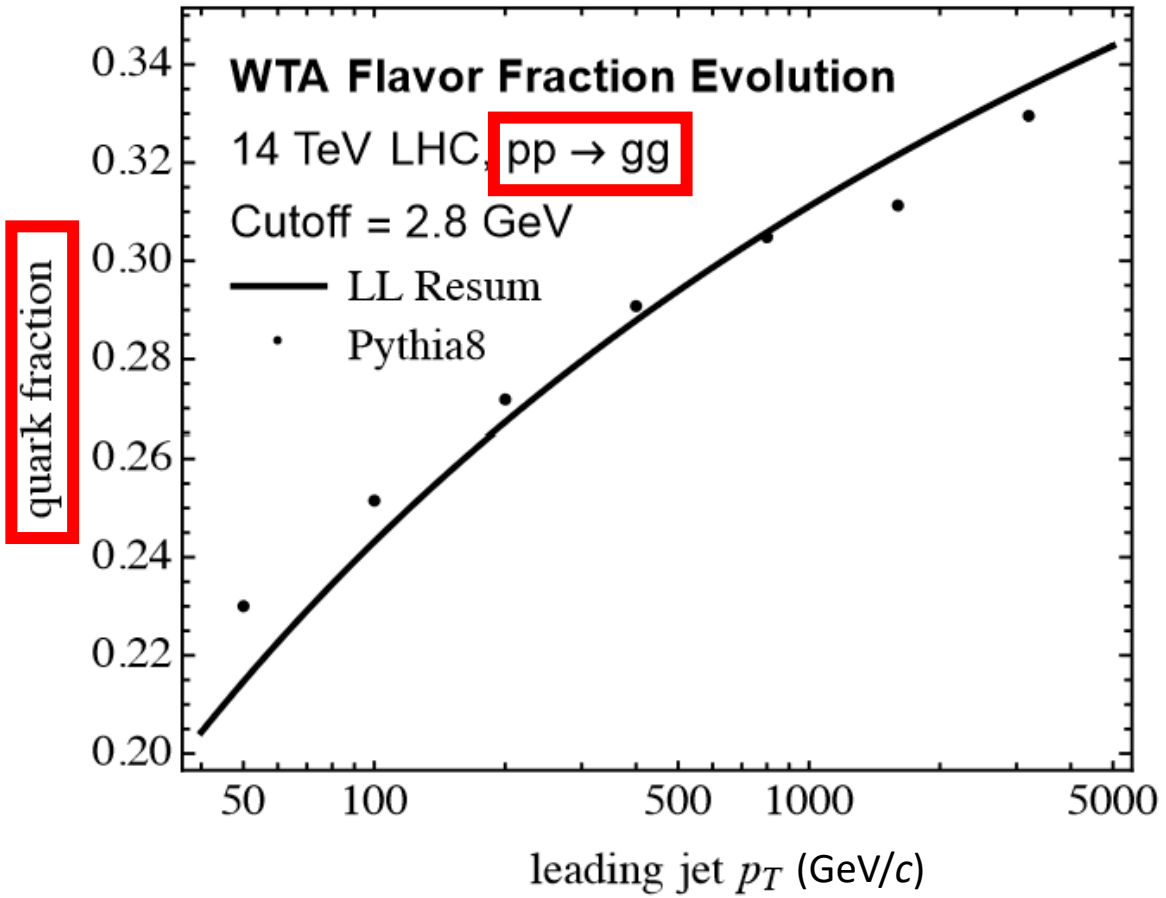

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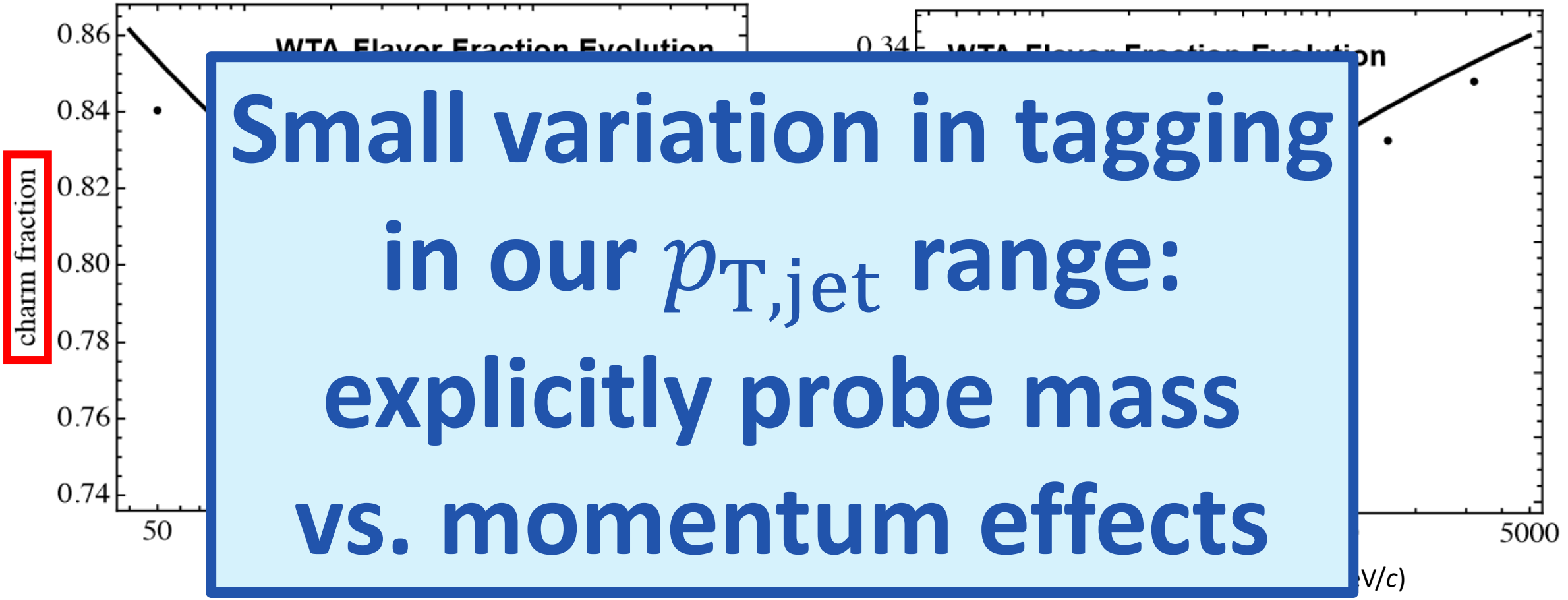
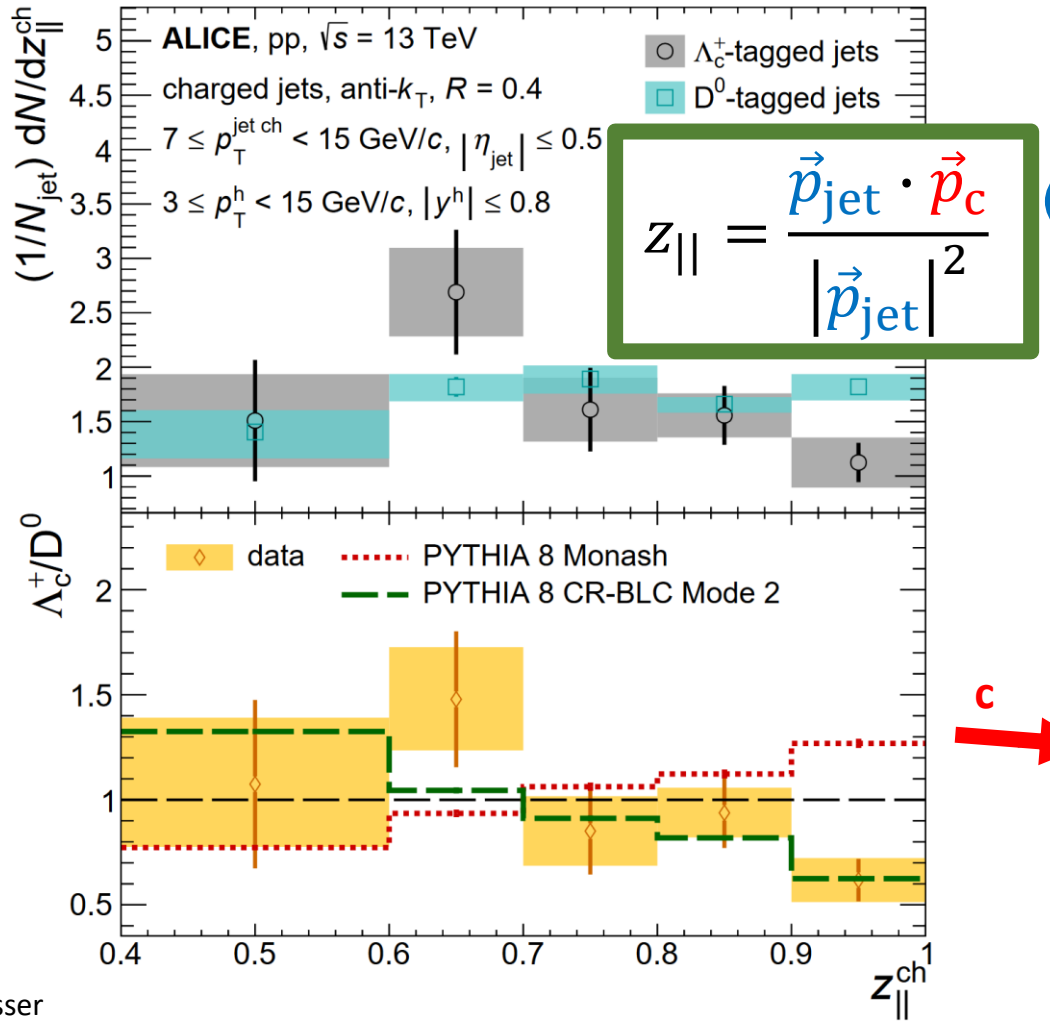


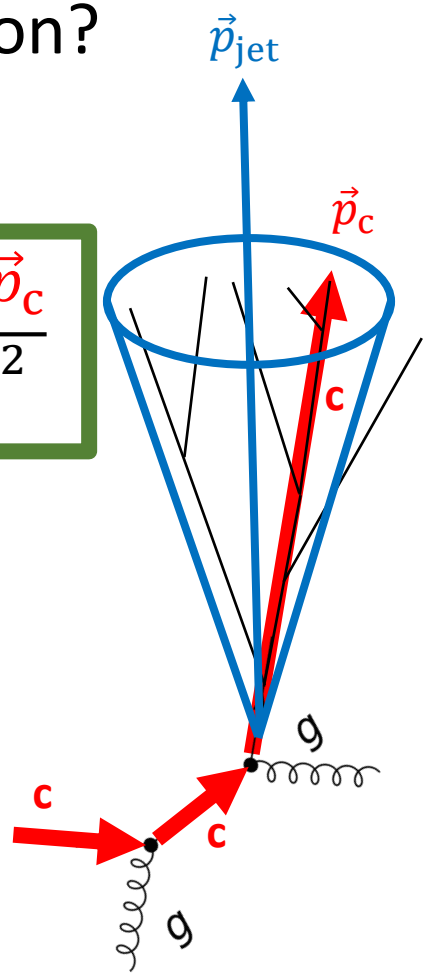
Small variation in tagging in our $p_{\mathrm{T,jet}}$ range: explicitly probe mass vs. momentum effects

Charm quark fragmentation

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



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



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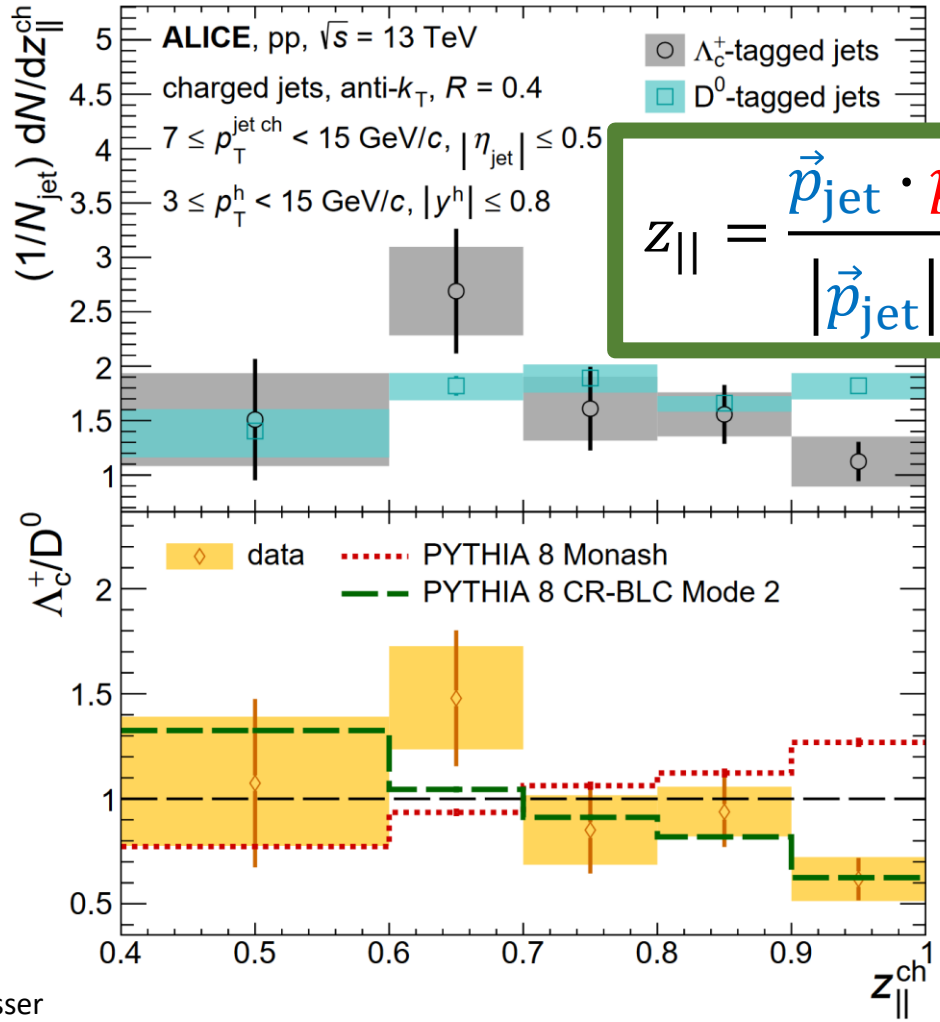

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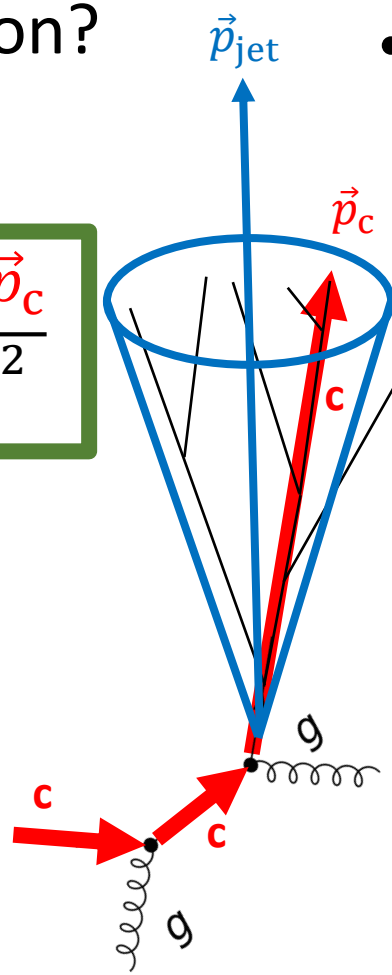
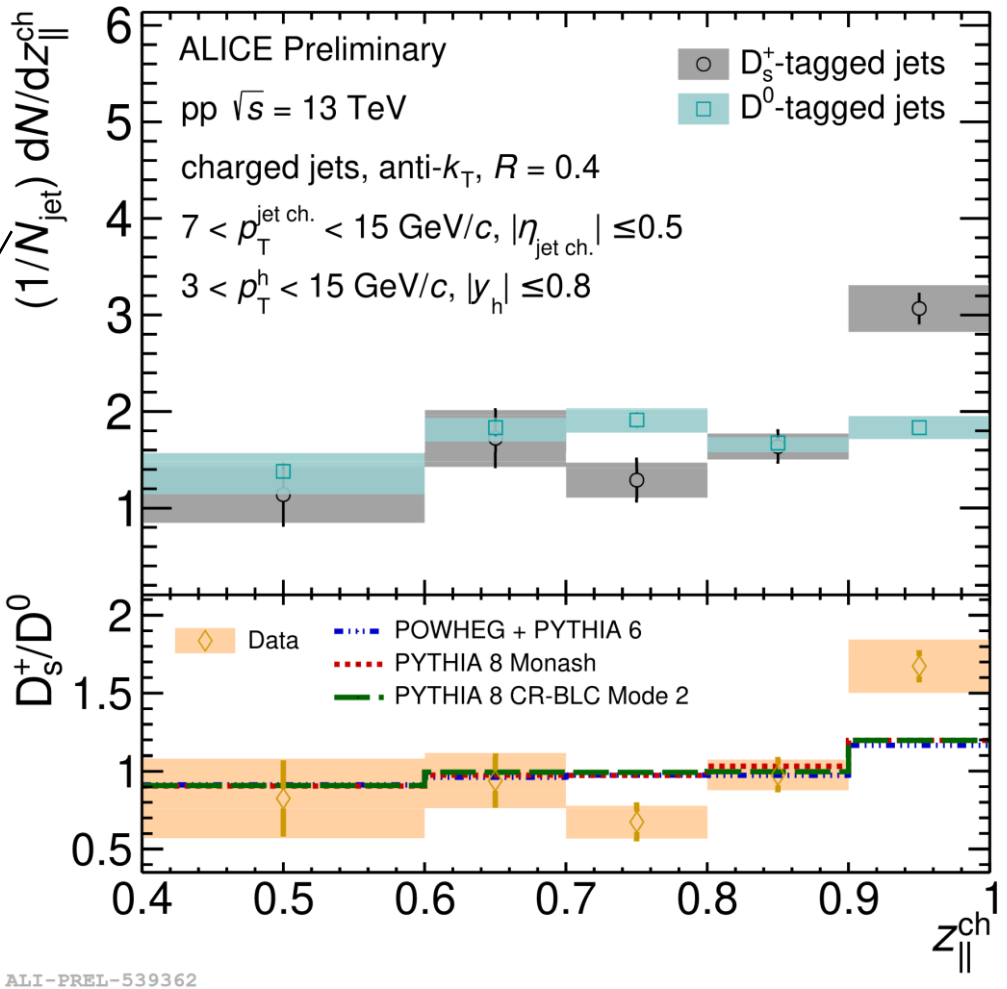


- D_s^+ meson **harder** than D^0 meson?



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

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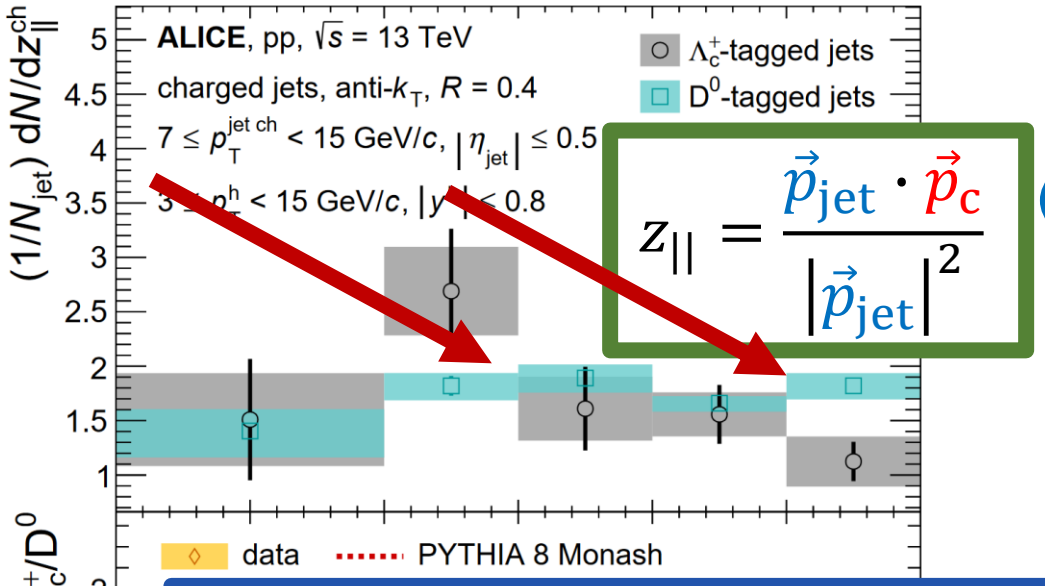

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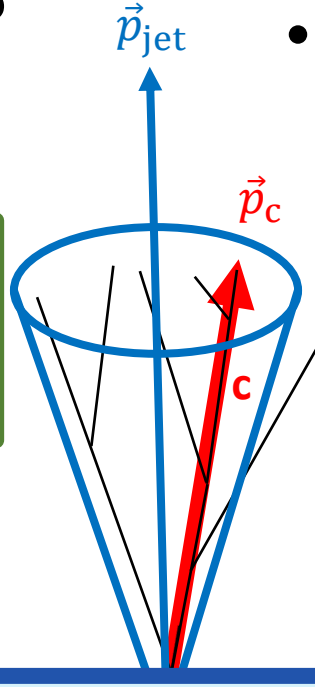

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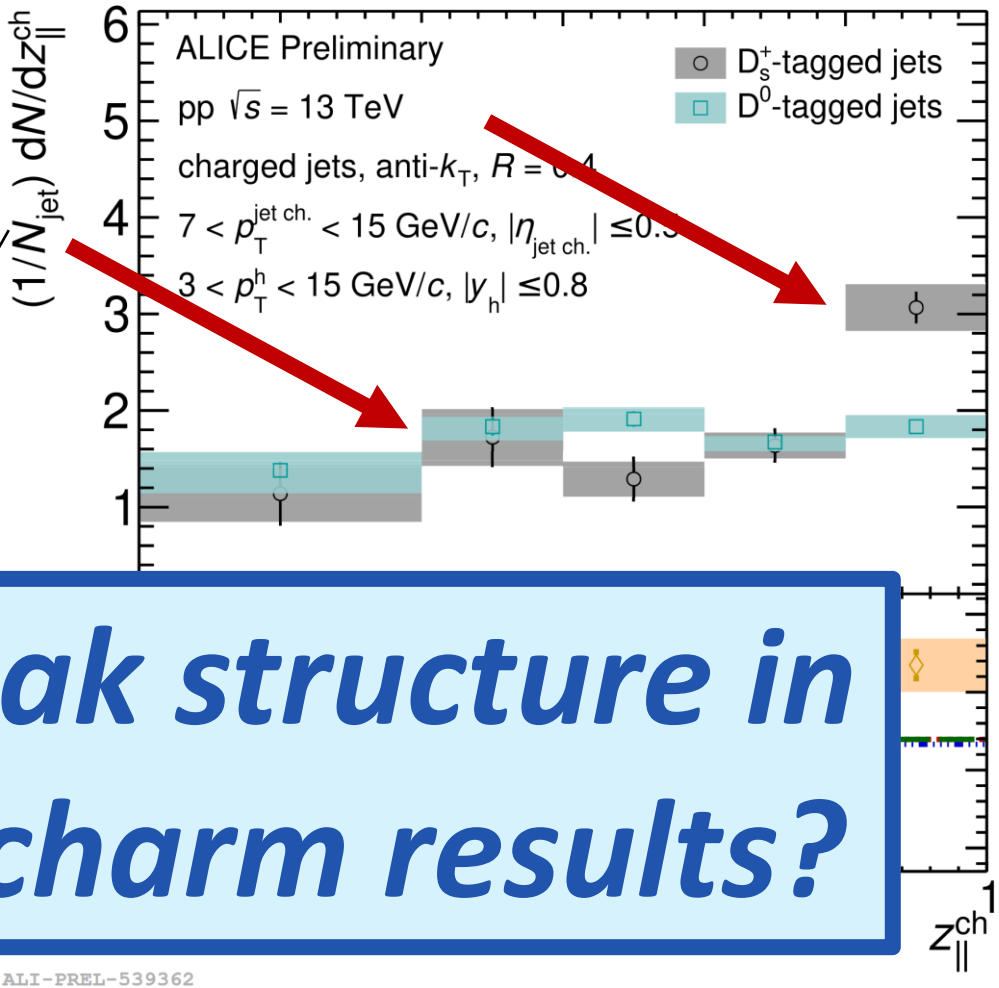

Hint of similar 2-peak structure in recent ALICE open charm results?

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