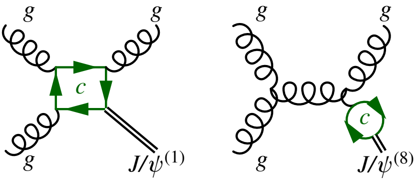
Jet fragmentation measurements at LHCb

colour singlet
low p_{T}
longitudinal pol.



colour octet
high p_{T}
transverse pol.

Naomi Cooke on behalf of the LHCb collaboration

University of Glasgow
ICHEP 2024

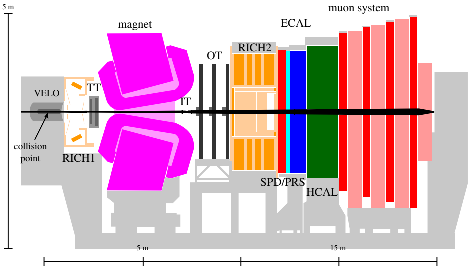
July 19, 2022

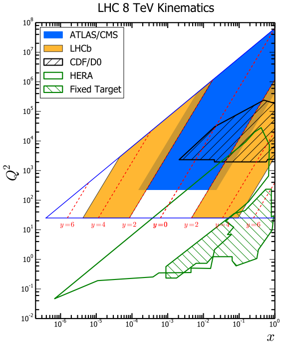
Today I will discuss:

- The first measurements of $\psi(2S)$ and $\chi_{c1}(3872)$ production in fully reconstructed jets. Presented for the first time at ICHEP.
- More jet fragmentation highlights: e.g. progression on $H \to b\bar{b}/c\bar{c}$.

Why LHCb?:

- Very good PID: Hadrons (RICH), di-muon masses (MUON).
- Probe unique phase space due to forward region.
- Trigger: probe low momentum particles.

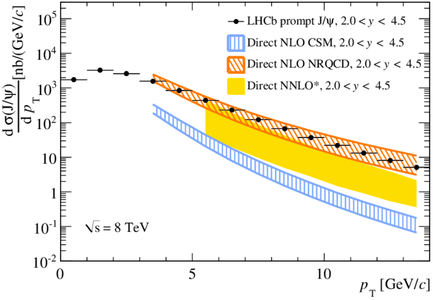


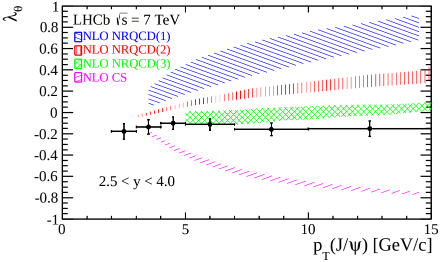


J/ψ production in jets

J/ψ production in jets

- Short-distance calculations from fixed order Non-Relativistic QCD (NRQCD) predicts:
  - Differential production cross section consistent with measurement.
  - J/ψ produced largely isolated [JHEP 10 (2015) 172].
  - Large transverse polarisation [Eur. Phys. J. C 73, 2631 (2013)].





colour singlet
low p_T
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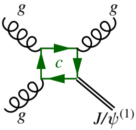
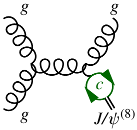
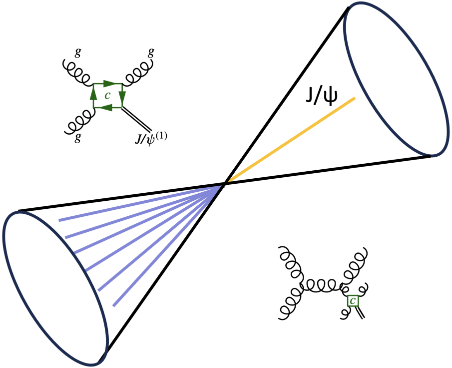




colour octet
high p_T
transverse pol.

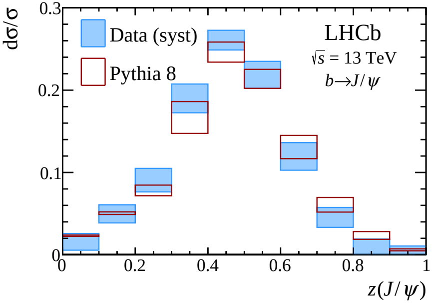
J/ψ production in jets

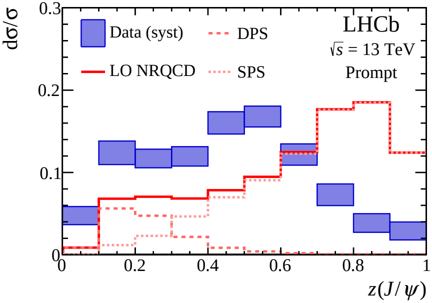
- Fragmentation calculations from NRQCD predicts:
  - Lack of polarisation.
  - J/ψ rarely produced in isolation.
- Two quarkonia production mechanisms distinguishable by studying radiation associated with them → jets.
- Instead of measuring cross section wrt $p_T(J/\psi)$, take into account surrounding radiation with $z(J/\psi) \equiv p_T(J/\psi)/p_T(\text{jet})$.

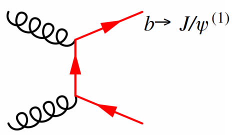


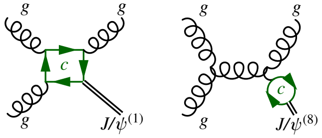
J/ψ production in jets

Measure $d\sigma/\sigma$ verses $z(J/\psi) \equiv p_T(J/\psi)/p_T(\text{jet})$. Prompt (direct from PV) and displaced (i.e. b decay) distributions, where $p_T(\text{jet}) > 20$ GeV [Phys. Rev. Lett. 118, 192001 (2017)].







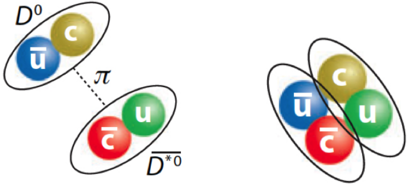


$\psi(2S)$ and $\chi_{c1}(3872)$ production in jets

$\psi(2S)$ and $\chi_{c1}(3872)$ production in jets

How do other quarkonia/mesons behave?

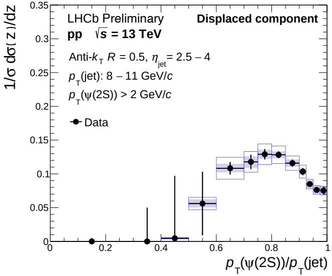
- Investigate $\psi(2S)$ & $\chi_{c1}(3872)$ production with $J/\psi\pi\pi$ decay channel.
- Will refer to $\psi(2S)$ or $\chi_{c1}(3872)$ as tags in this talk.
- Jets clustered by anti-k_t algorithm: $R = 0.5$, $2.5 < \eta(\text{jet}) < 4.0$ with $p_T(\text{jet}) > 5\text{GeV}/c$.
- Measure $z(\text{tag})$ in different $p_T(\text{jet})$ and $p_T(\text{tag})$ intervals.
- Use finer binning in $z(\text{tag})$ to see if we can probe unique structures.
- Perform cross-checks with di-muon channel [LHCb-PAPER-2024-021].

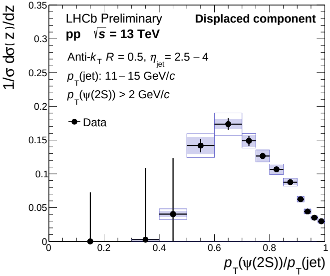


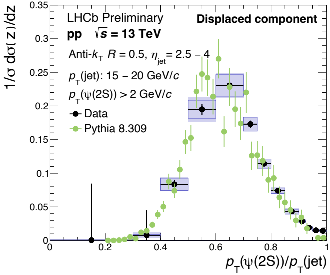
D^0–$\overline{D}^{*0}$ "molecule" **Diquark–diantiquark**

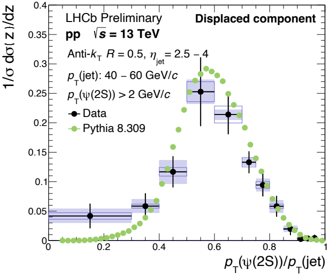
ψ(2S) distributions: displaced, p_T(jet)

[LHCb-PAPER-2024-021]



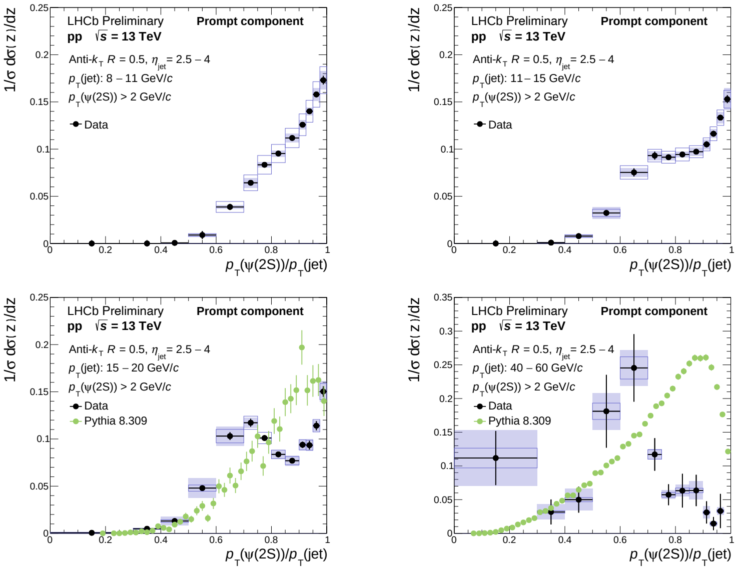






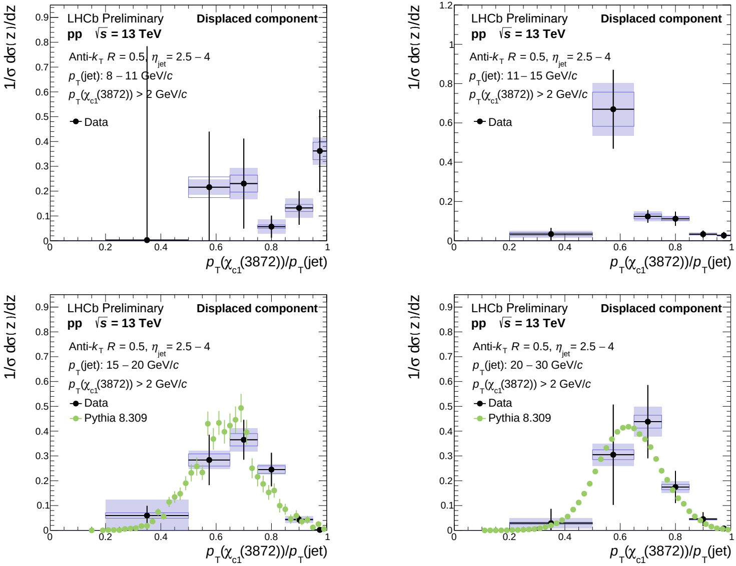
ψ(2S) distributions: prompt, p_T(jet)

[LHCb-PAPER-2024-021]



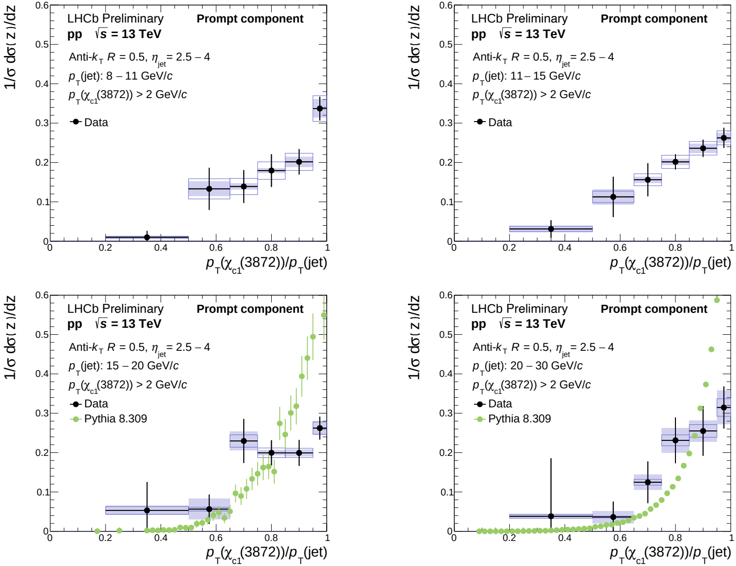
$\chi_{c1}(3872)$ distributions: displaced, p_T(jet)

[LHCb-PAPER-2024-021]



$\chi_{c1}(3872)$ distributions: prompt, p_T(jet)

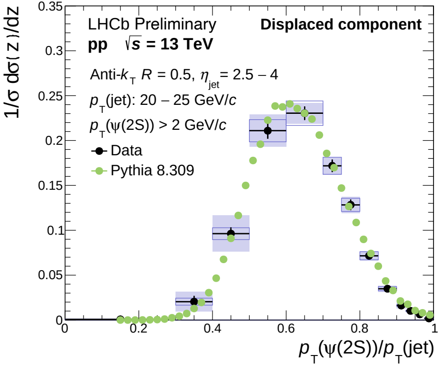
[LHCb-PAPER-2024-021]



Comparison prompt/displaced: $\psi(2S)$, p_T(jet)

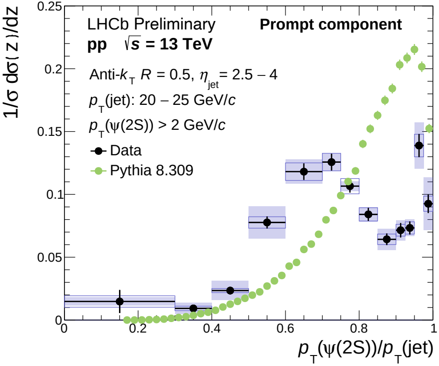
[LHCb-PAPER-2024-021]

$\psi(2S)$ - displaced



$20 < p_T\text{(jet)} < 25$ GeV/c

$\psi(2S)$ - prompt



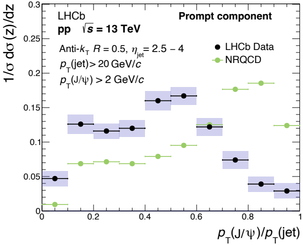
$20 < p_T\text{(jet)} < 25$ GeV/c

Two-prong structure appears in prompt $\psi(2S)$ (isolated + non-isolated component).

Comparison $\psi(2S)/\chi_{c1}(3872)$: prompt, p_T(jet)

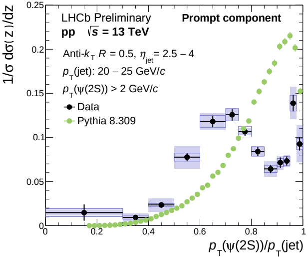
[Phys. Rev. Lett. 118, 192001 (2017), LHCb-PAPER-2024-021]

J/ψ - prompt



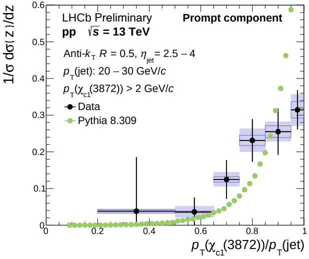
p_T(jet) > 20 GeV/c

$\psi(2S)$ - prompt



$20 < p_T$(jet) < 25 GeV/c

$\chi_{c1}(3872)$ - prompt

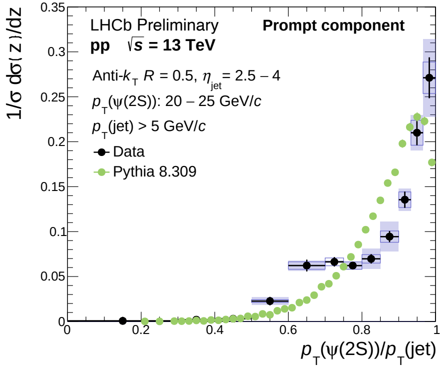


$20 < p_T$(jet) < 30 GeV/c

$\psi(2S)$ two-prong structure. X(3872) fairly isolated. All not described by hard process Pythia 8 predictions.

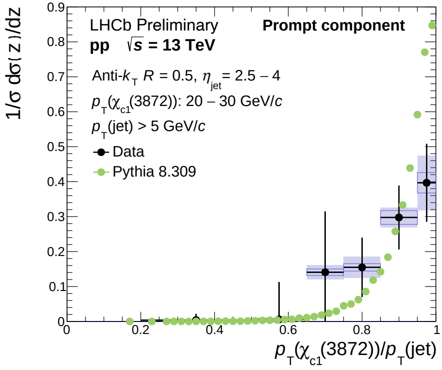
[LHCb-PAPER-2024-021]

$\psi(2S)$ - prompt



$20 < p_T(tag) < 25$ GeV

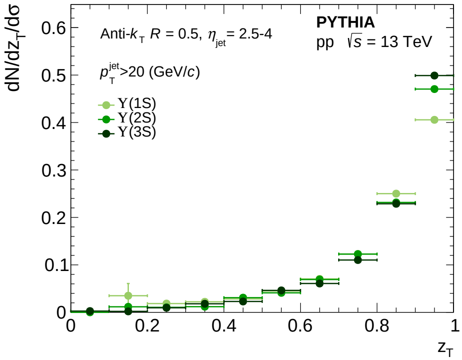
$\chi_{c1}(3872)$ - prompt



$20 < p_T(tag) < 30$ GeV

Differential distributions in $p_T(tag)$ exaggerates isolated structure in prompt $\psi(2S)$.

- Analyses for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ are in progress.
- Predictions for z distributions (without fragmentation) show Υ's are predicted to be isolated. (More so than $\psi(2S)$ and $\chi_{c1}(3872)$).
- New Pythia 8 developments include NRQCD fragmentation in the parton shower. This will significantly improve jet unfolding [Eur. Phys. J. C 84, 432 (2024)].

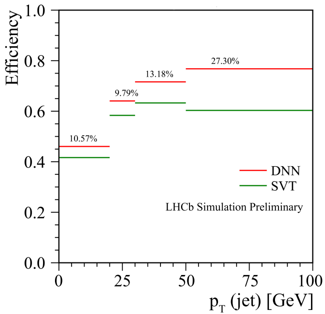


More LHCb jet fragmentation highlights!

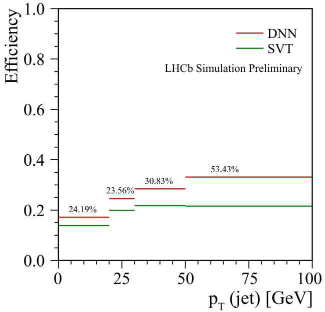
DNN to distinguish b, c and light jets gives better performance than current Secondary Vertex Tagger (SVT) [LHCb-FIGURE-2023-029]:

- Utilise in first inclusive search for $H \to b\bar{b}$ and $H \to c\bar{c}$ in the forward region. See D. Zuliani's talk for more details.

b-jets



c-jets



Identified charged hadron prod in Z+jet [Phys. Rev. D 108, L031103 (2023)]:

- Constrains transverse-momentum dependent fragmentation functions.
- Probes hadron-mass hierachy in hadronisation processes.

Conclusions

$\psi(2S)$ and $\chi_{c1}(3872)$ production in jets [LHCb-PAPER-2024-021]:

- Displaced z(tag) distributions are described well by Pythia 8.
- Prompt z(tag) distributions are less isolated than Pythia 8 predictions, $\psi(2S)$ even more so.
- Two-prong structure in $z(\psi(2S))$ could be explained by NRQCD short-distance + fragmentation mixture.
- Analyses for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ to be published soon.

DNN to distinguish b, c and light jets gives better performance than current Secondary Vertex Tagger (SVT). Utilise in search for $H \to b\bar{b}$ and $H \to c\bar{c}$ [LHCb-FIGURE-2023-029].

Identified charged hadron production in Z+jet will help constrain transverse-momentum dependent fragmentation functions [Phys. Rev. D 108, L031103 (2023)].

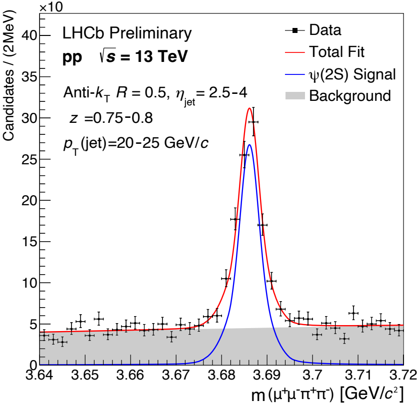
Appendix

$\psi(2S)$ and $\chi_{c1}(3872)$ production in jets

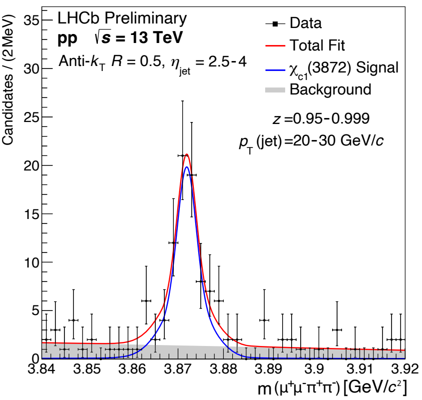
Procedure in [LHCb-PAPER-2024-021]:

- Build $\psi(2S)/\chi_{c1}(3872) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ candidates in jets.
- Determine $\psi(2S)/\chi_{c1}(3872)$ signal yield with mass fits.

$\psi(2S)$



$\chi_{c1}(3872)$

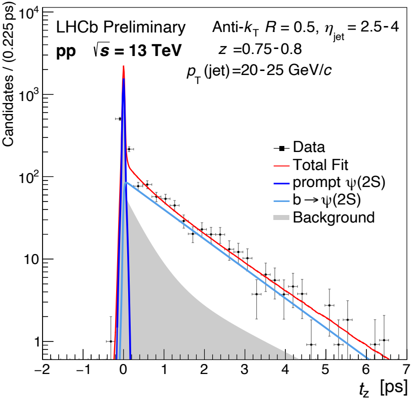


Lifetime distributions: $\psi(2S)/\chi_{c1}(3872)$

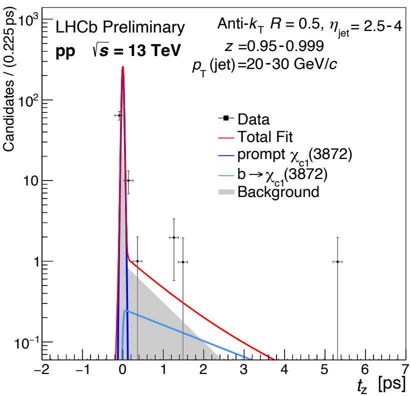
Procedure in [LHCb-PAPER-2024-021]:

- Separate prompt (direct) from displaced (i.e. b decay) yields with pseudo-lifetime fits, $t \equiv x_z - x_z(PV) m_{tag}/p_z$.

$\psi(2S)$



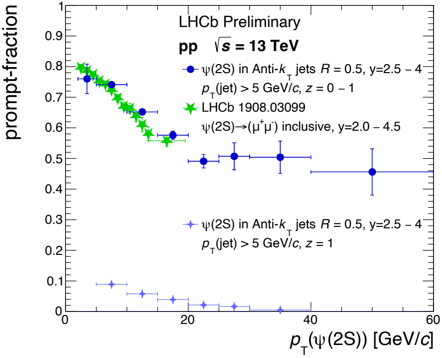
$\chi_{c1}(3872)$



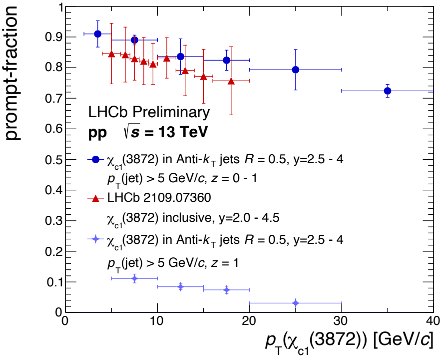
Prompt production fractions: $\psi(2S)/\chi_{c1}(3872)$

- Prompt production fractions for $\psi(2S)$ & $\chi_{c1}(3872)$ are consistent with previous LHCb measurements [LHCb-PAPER-2024-021].

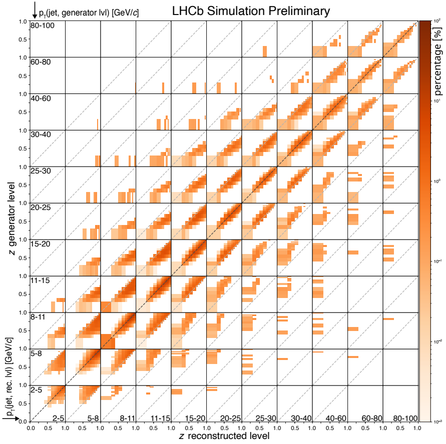
$\psi(2S)$



$\chi_{c1}(3872)$



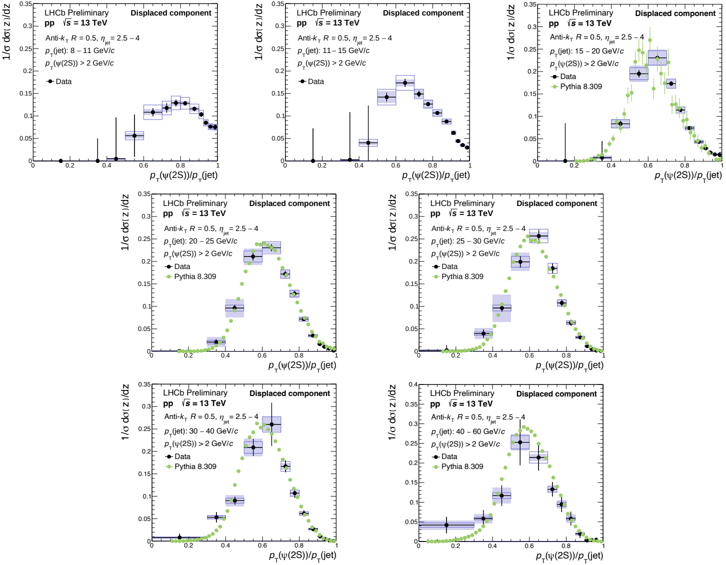
- Distributions are efficiency corrected.
- Unfolding p_T(jet) from reconstruction to truth level is used to correct for jet energy resolution effects [LHCb-PAPER-2024-021].
- Response matrix for ψ(2S) with 28% of events containing V^0's.



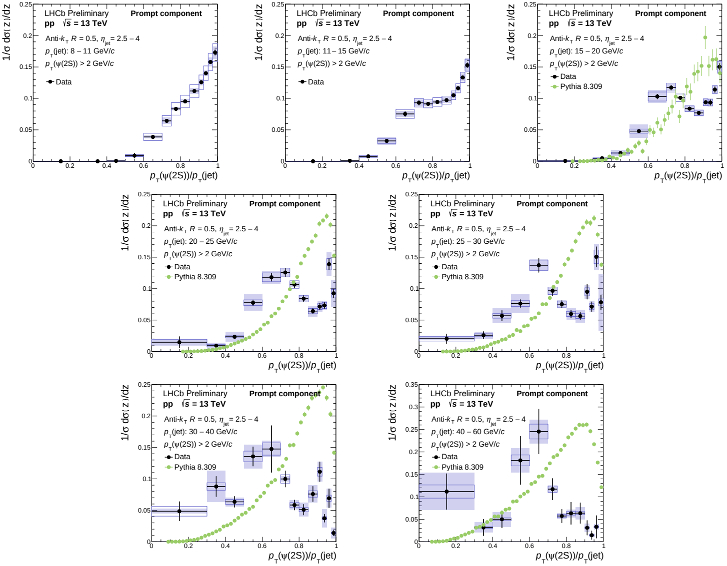
$\psi(2S)$ and $\chi_{c1}(3872)$ production in jets: $z(\text{tag})$ in $p_T(\text{jet})$ intervals

ψ(2S) distributions: displaced, p_T(jet)

[LHCb-PAPER-2024-021]

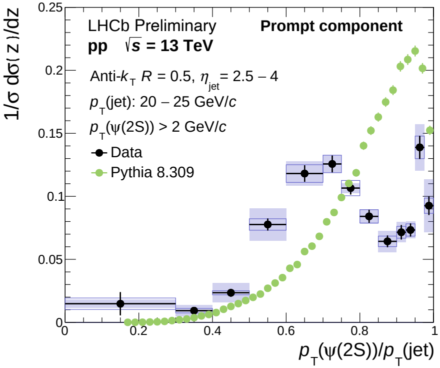


[LHCb-PAPER-2024-021]



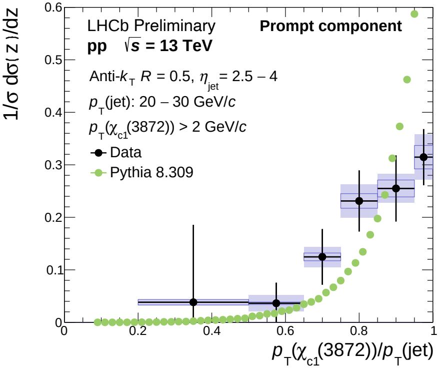
[LHCb-PAPER-2024-021]

$\psi(2S)$ - prompt



$20 < p_T(\text{jet}) < 25$ GeV/c

$\chi_{c1}(3872)$ - prompt



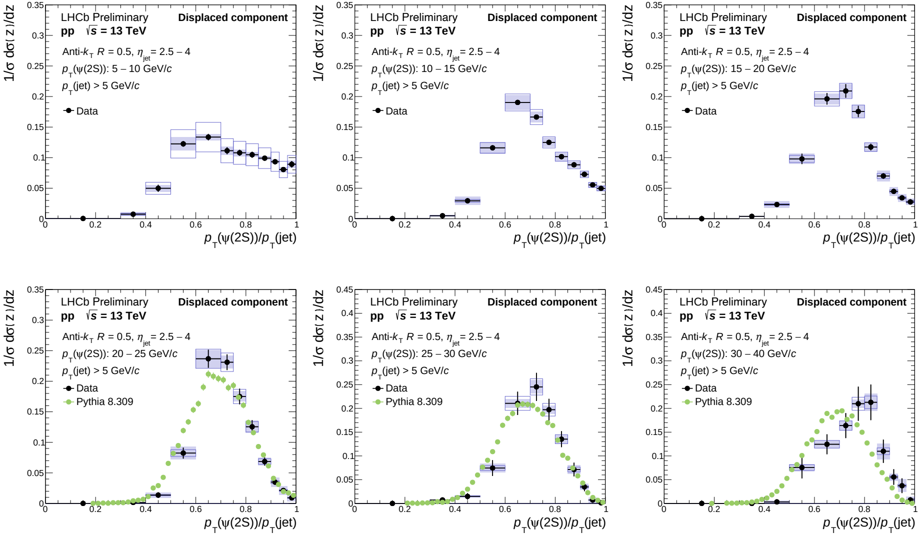
$20 < p_T(\text{jet}) < 30$ GeV/c

Two-prong structure appears in $\psi(2S)$ in comparison to X(3872) which is more isolated.

$\psi(2S)$ and $\chi_{c1}(3872)$ production in jets: $z(\text{tag})$ in $p_T(\text{tag})$ intervals

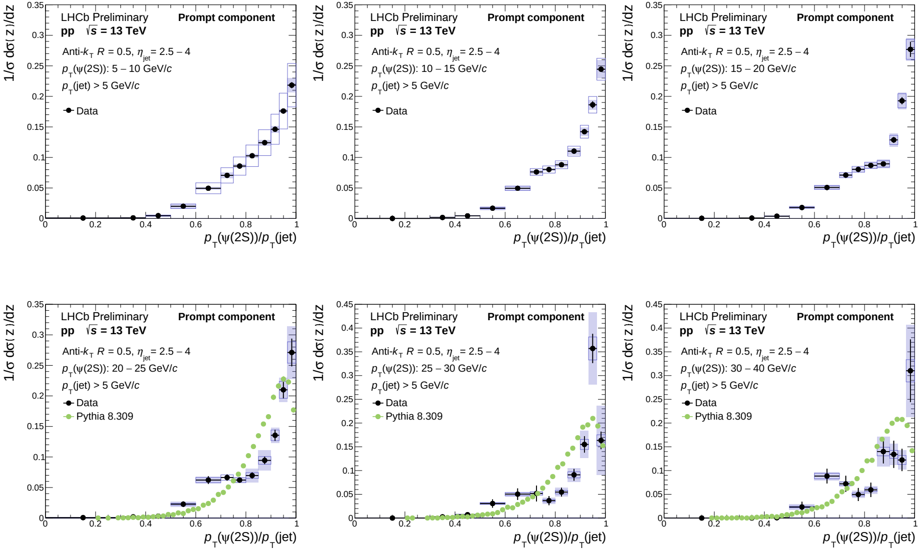
$\psi(2S)$ distributions: displaced, p_T(tag)

[LHCb-PAPER-2024-021]



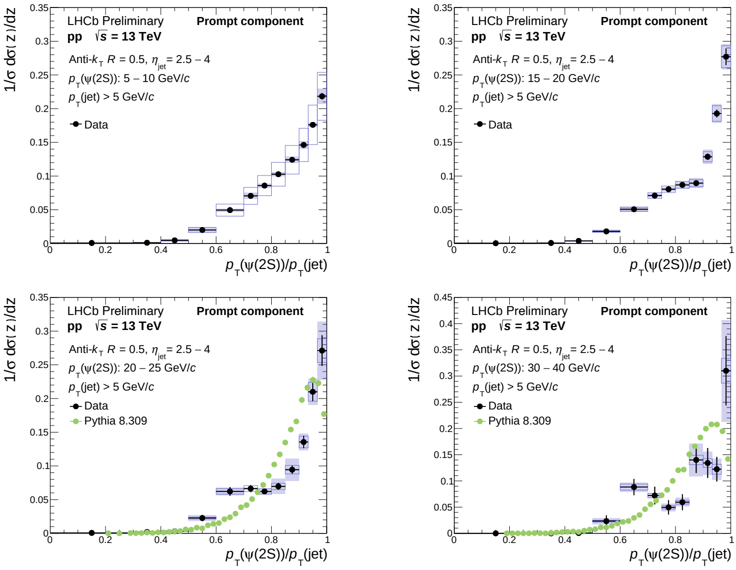
ψ(2S) distributions: prompt, p_T(tag)

[LHCb-PAPER-2024-021]



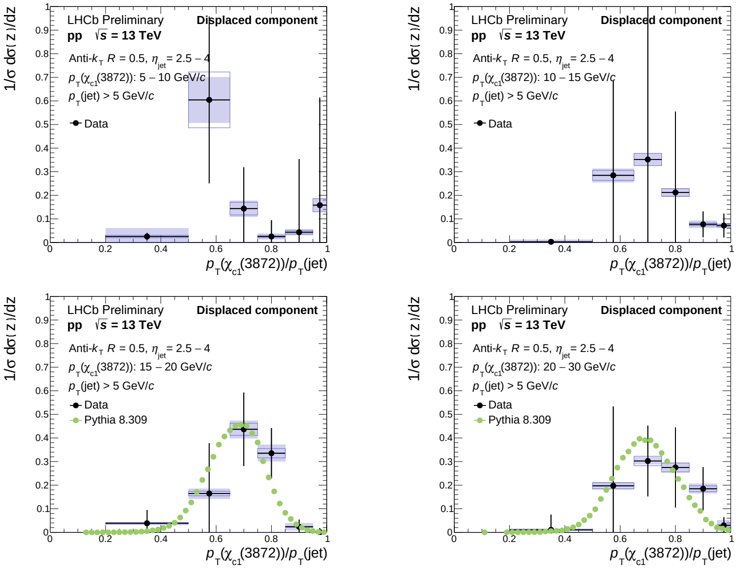
ψ(2S) distributions: prompt, p_T(tag)

[LHCb-PAPER-2024-021]



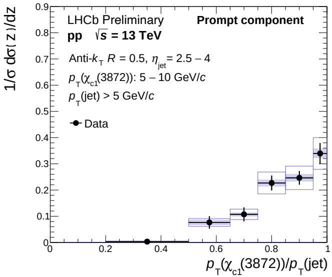
$\chi_{c1}(3872)$ distributions: displaced, p_T(tag)

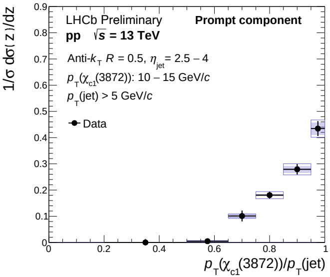
[LHCb-PAPER-2024-021]

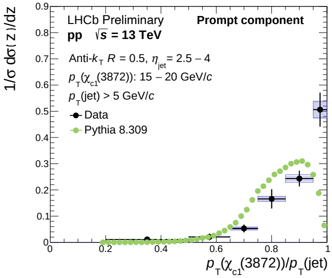


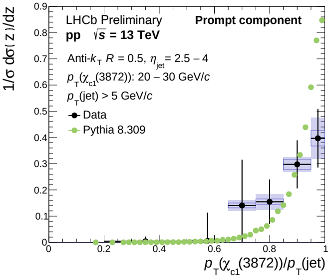
$\chi_{c1}(3872)$ distributions: prompt, p_T(tag)

[LHCb-PAPER-2024-021]





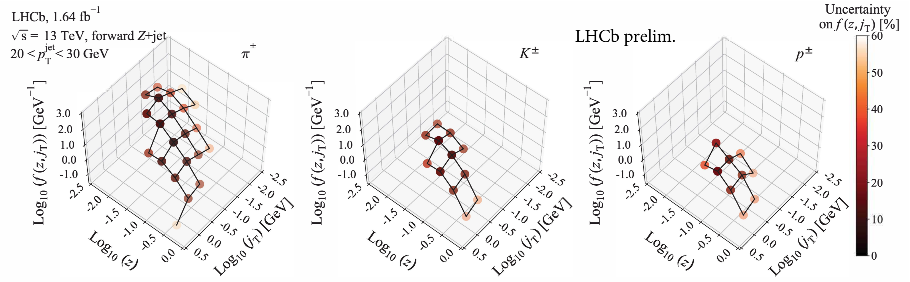




Identified charged hadron production in Z-tagged jets (π,K,p)

Identified charged hadrons in Z-tagged jets (i)

- Triple differential distributions in j_T, z and p_T(jet) for three hadron species.
- Centre of distribution: higher mass $\rightarrow$ larger z and j_T.
- Heavier hadrons produced from heavier partons.
- Comparison to PYTHIA8: number of charged pions (kaons & protons) largely underestimated (overestimated) [Phys. Rev. D 108, L031103 (2023)].



- z ratios for heavier identified hadrons wrt pions.
- Heavier mass hadrons require larger z threshold for formation.
- Suppression: $K^{\pm}$ $\rightarrow$ content of proton, $p^{\pm}$ $\rightarrow$ baryon formation [Phys. Rev. D 108, L031103 (2023)].