Jet Fragmentation and Central Exclusive Production at LHCb

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On behalf of the LHCb Collaboration

Standard Model at LHC 2021

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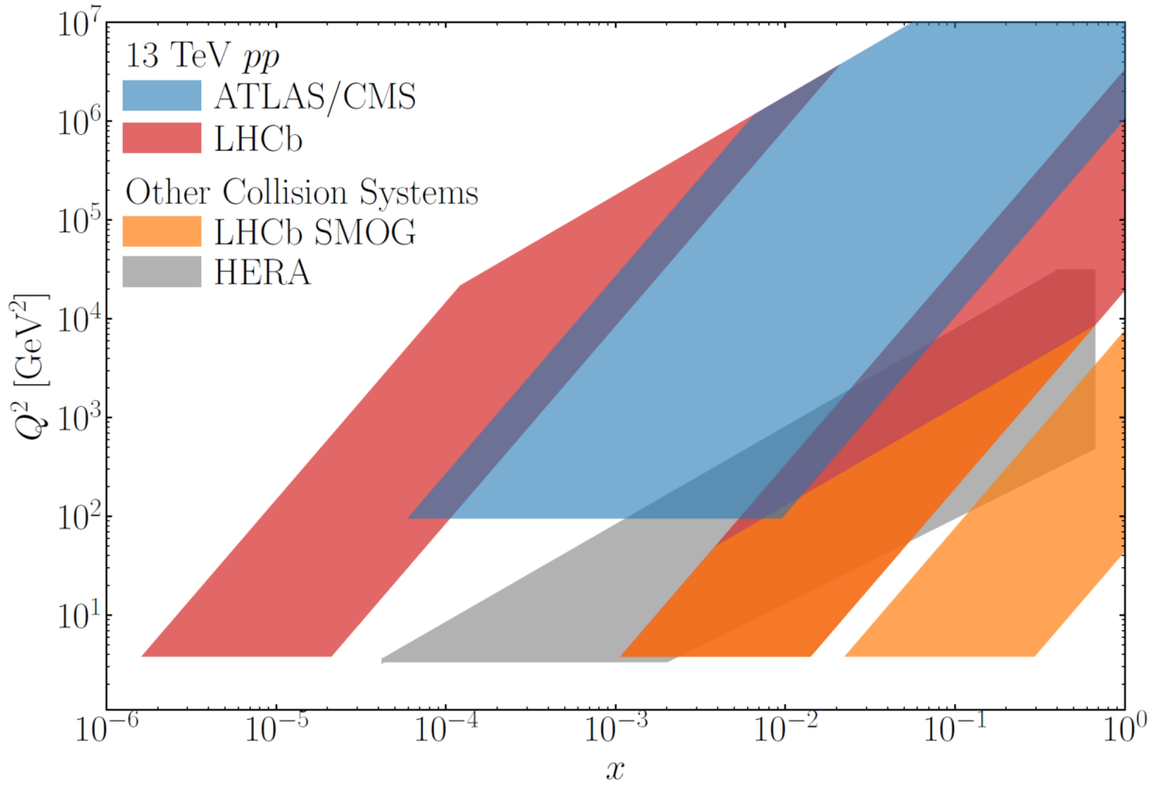
QCD at LHCb

The forward region accessible to LHCb offers an opportunity to study QCD processes in an extended region of phase space

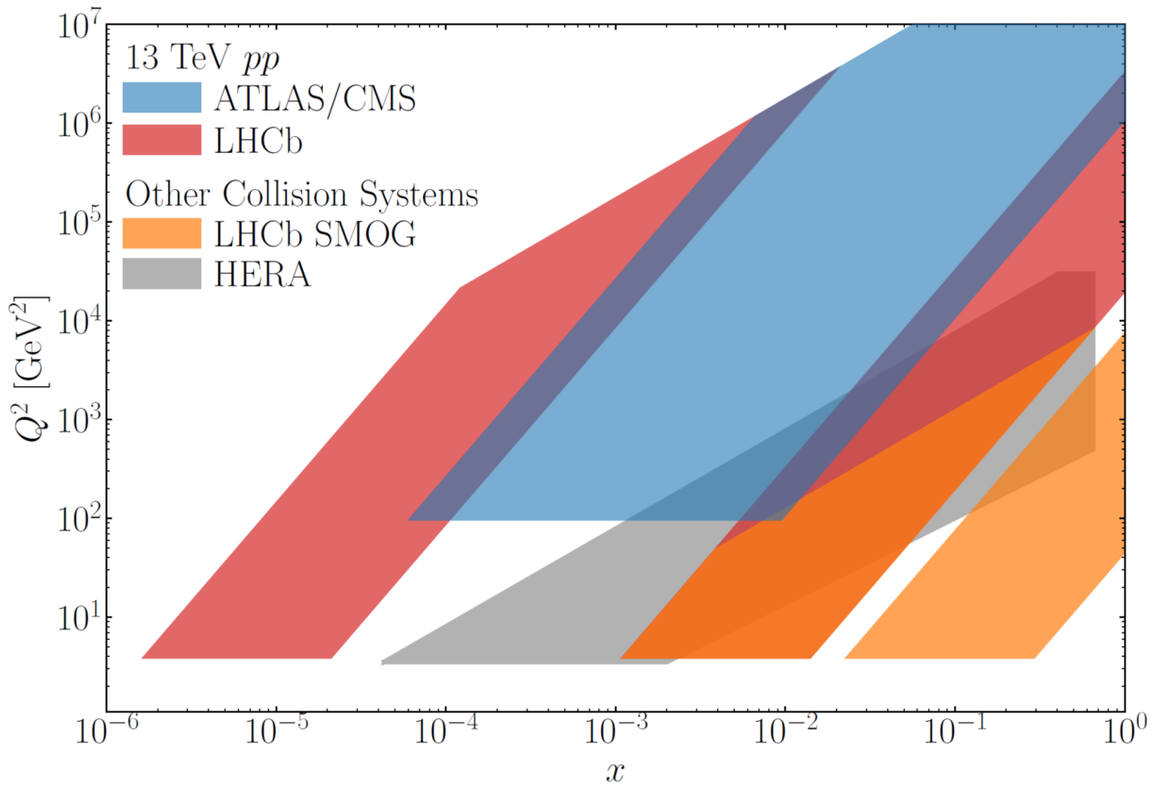


Wide range of QCD physics probed at LHCb:

- Jet production: W/Z-tagged, heavy flavor
- Jet fragmentation
- Quarkonia and open heavy flavor production
- Central Exclusive Production (CEP)
- Exotic QCD bound states

QCD at LHCb

The forward region accessible to LHCb offers an opportunity to study QCD processes in a less constrained region of phase space

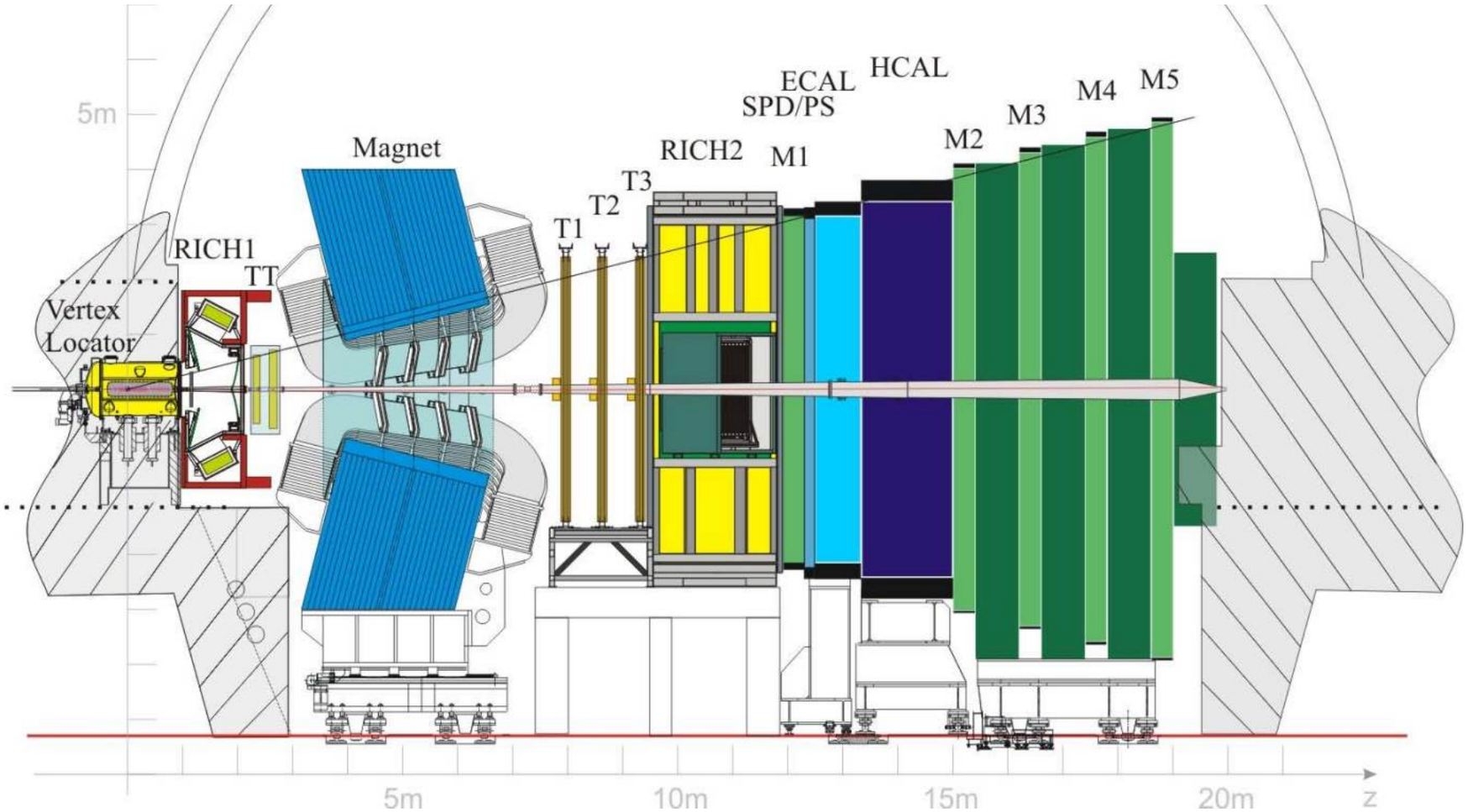


Wide range of QCD physics probed at LHCb:

- Jet production: W/Z-tagged, heavy flavor
- **Jet fragmentation**
- Quarkonia and open heavy flavor production **This talk!**
- **Central Exclusive Production (CEP)**
- Hadron spectroscopy, exotic QCD bound states

The Large Hadron Collider beauty (LHCb) Detector

Forward spectrometer designed to study the production and decays of heavy flavor hadrons

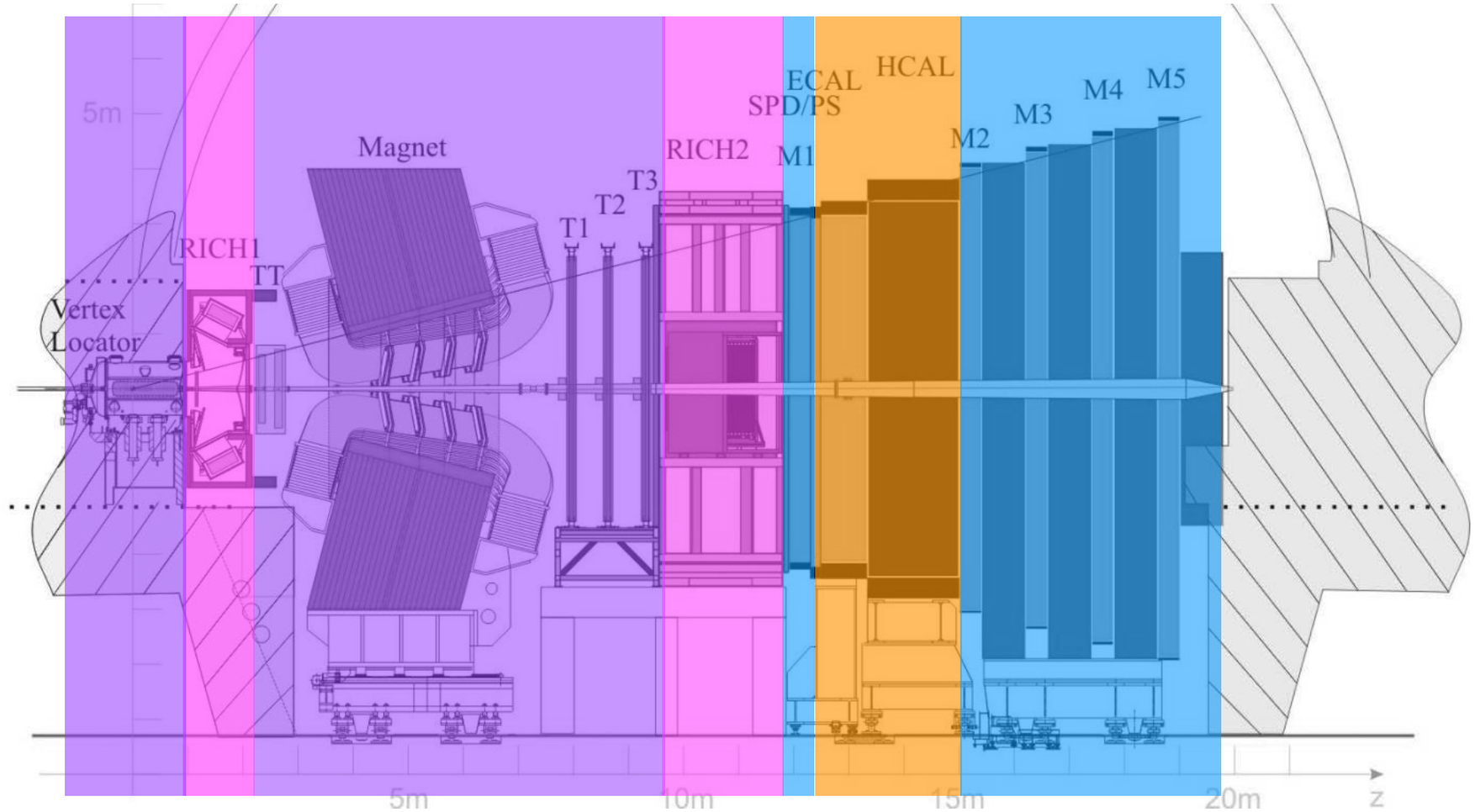


JINST **3**, S08005 (2010)

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

The Large Hadron Collider beauty (LHCb) Detector

Full **hadronic and electromagnetic calorimetry**, **tracking**, **particle identification**, and **muon ID** in $2 < \eta < 5$

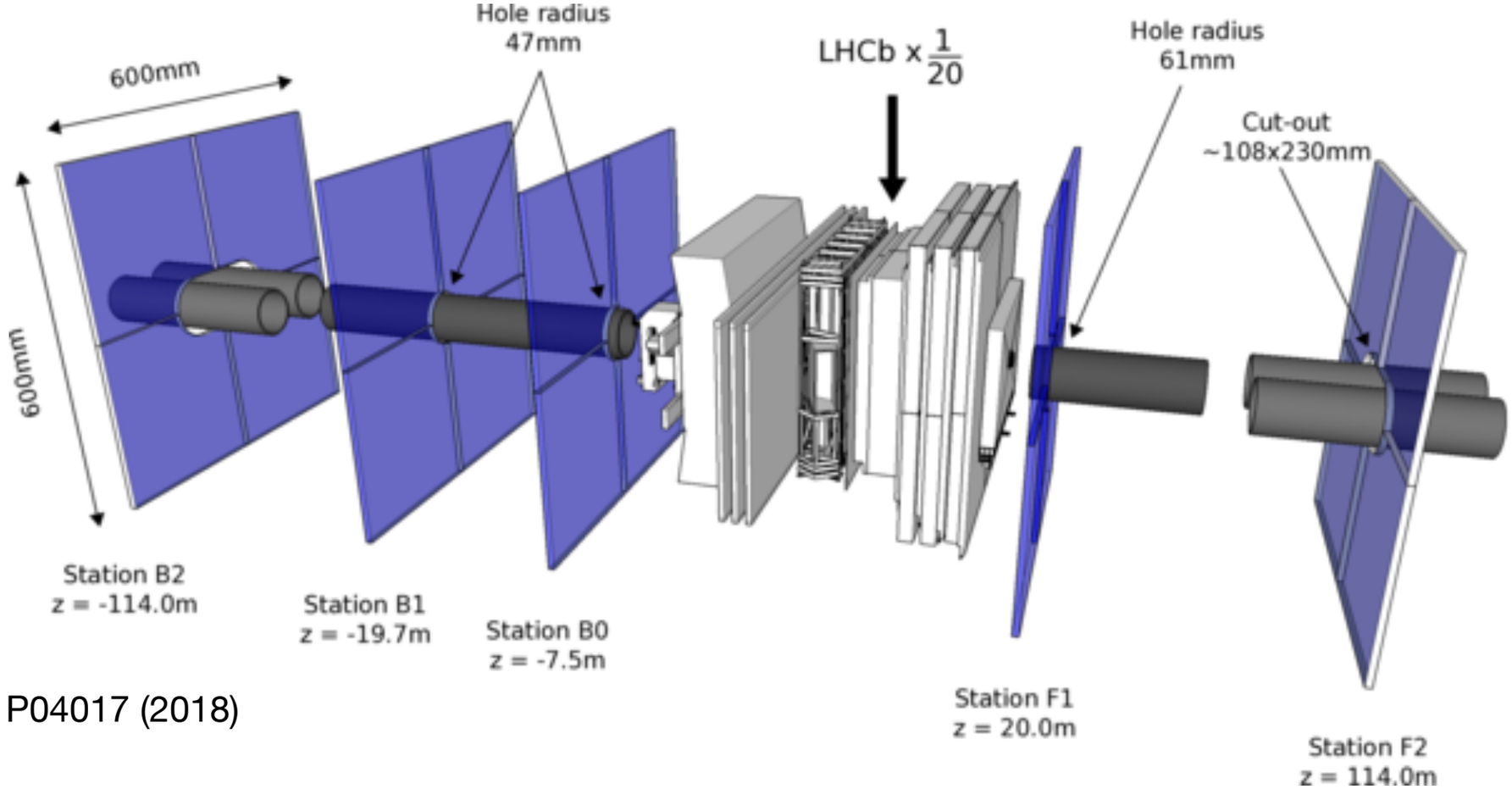


JINST **3**, S08005 (2010)

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

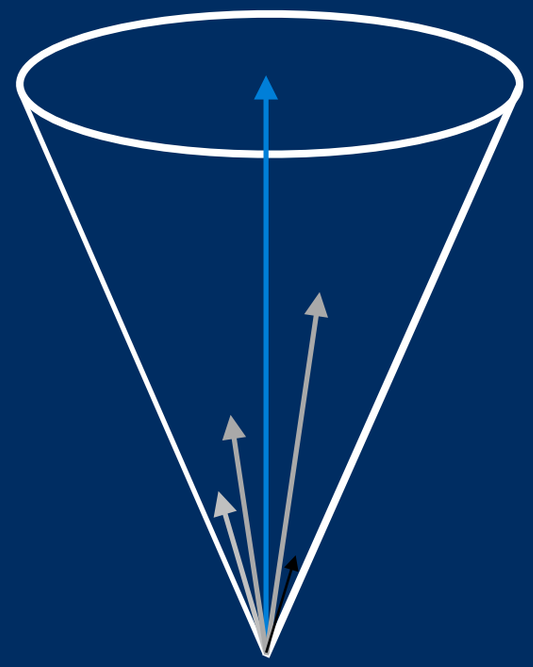
HeRSCheL: High-Rapidity Shower Counters for LHCb

- Five planes each consisting of four scintillator plates
- Extends pseudorapidity coverage for proton remnant detection to $-10 < \eta < -5$ and $5 < \eta < 10$



JINST **13**, P04017 (2018)

Jet Fragmentation

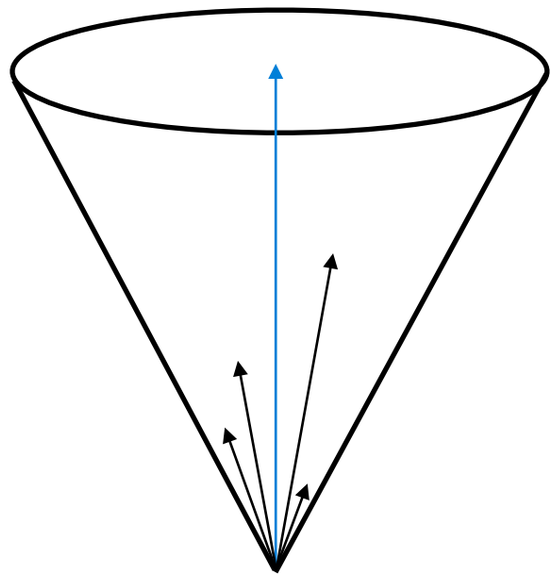


Jet fragmentation

- Jets are ideal systems in which to study hadronization, as they contain the hadrons produced during the high-energy hadronization of a quark or gluon

- Hadron distributions in jets can probe several aspects of hadronization:

Final states: produced hadrons



Initial state: fragmenting parton

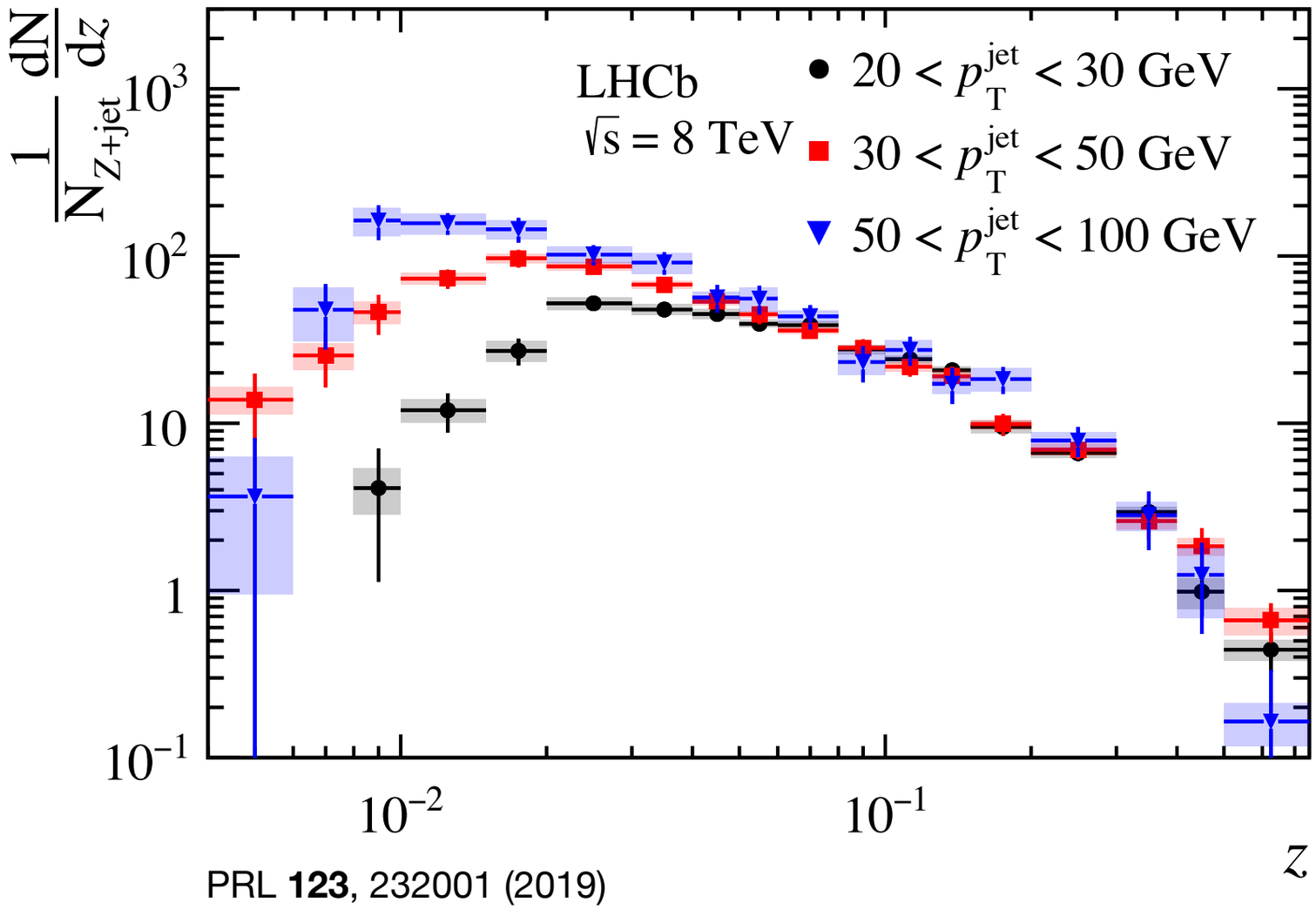
Hadronization dynamics - momentum and spatial distributions of hadrons

Flavor dependence of hadronization - hadron distributions in light-quark-dominated (forward Z-tagged jets), gluon-dominated (midrapidity inclusive jets), and heavy flavor jets

Colour neutralization mechanisms

Quarkonium formation mechanisms

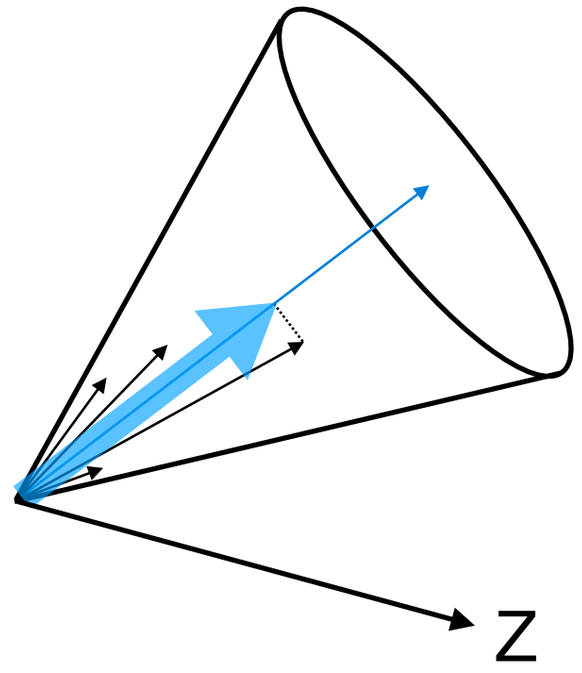
Results: Longitudinal Momentum Fraction z



PRL **123**, 232001 (2019)

R = 0.5, anti-k_T jets

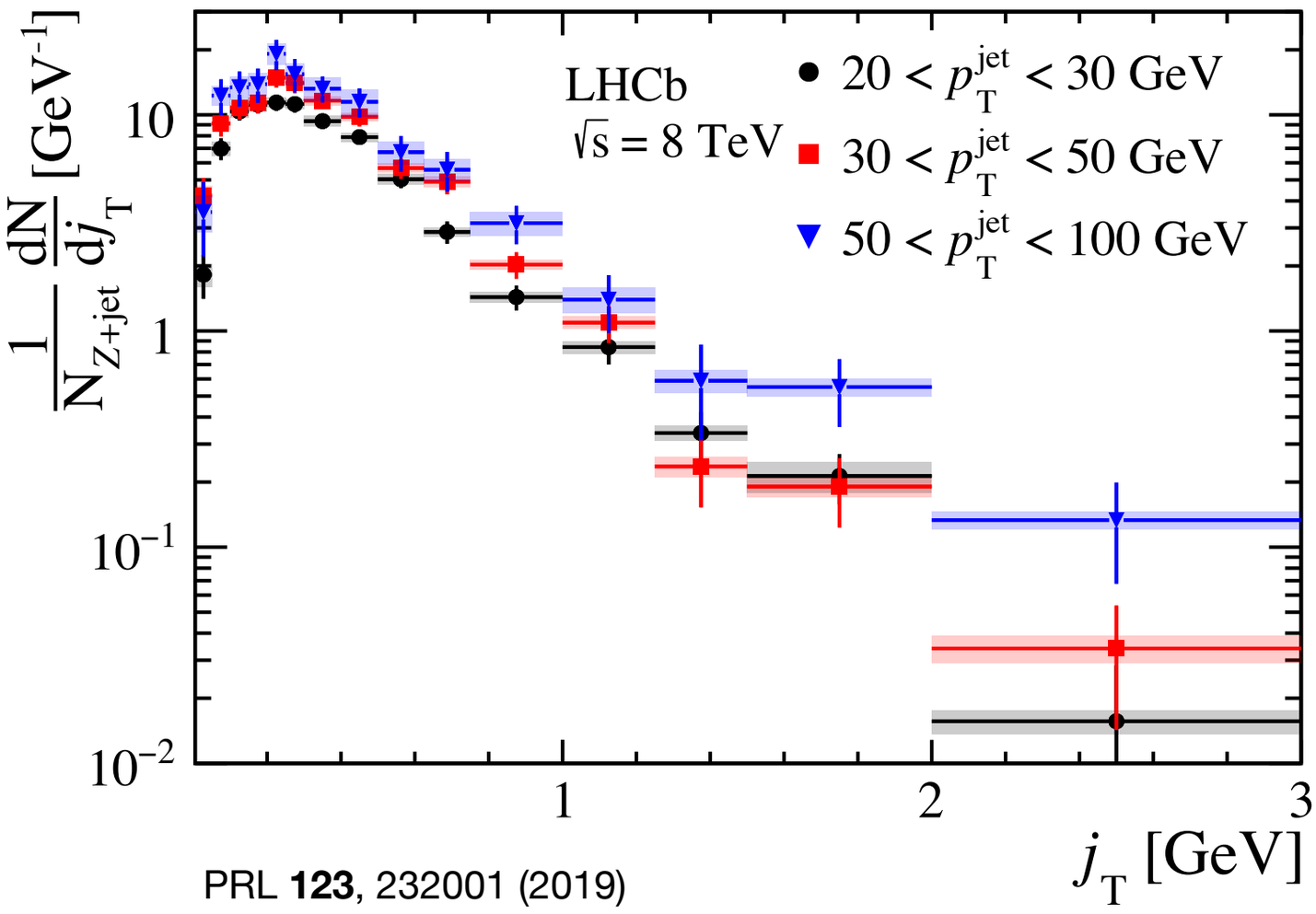
p_{hadron} > 4 GeV



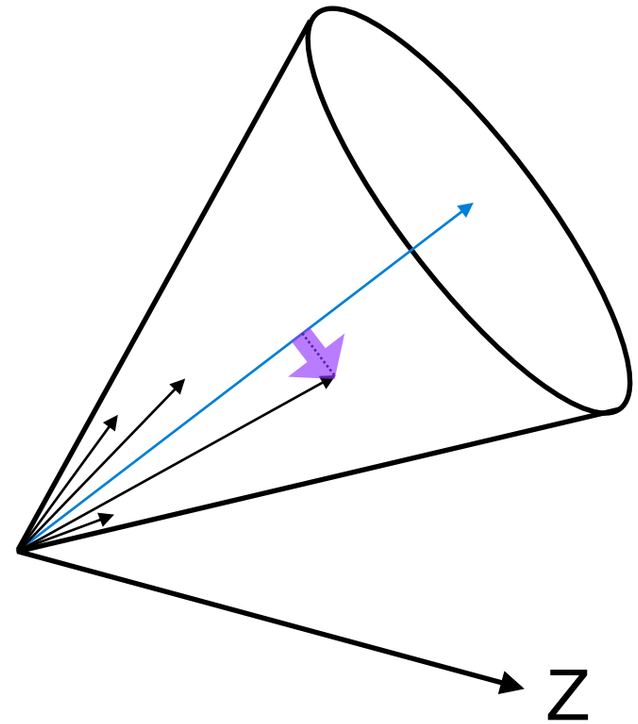
$$z = \frac{\mathbf{p_{jet}} \cdot \mathbf{p_{hadron}}}{|\mathbf{p_{jet}}|^2}$$

- Distributions are approximately constant as a function of jet p_T at high z
- Higher p_T jets probe lower z values

Results: Transverse Momentum j_T



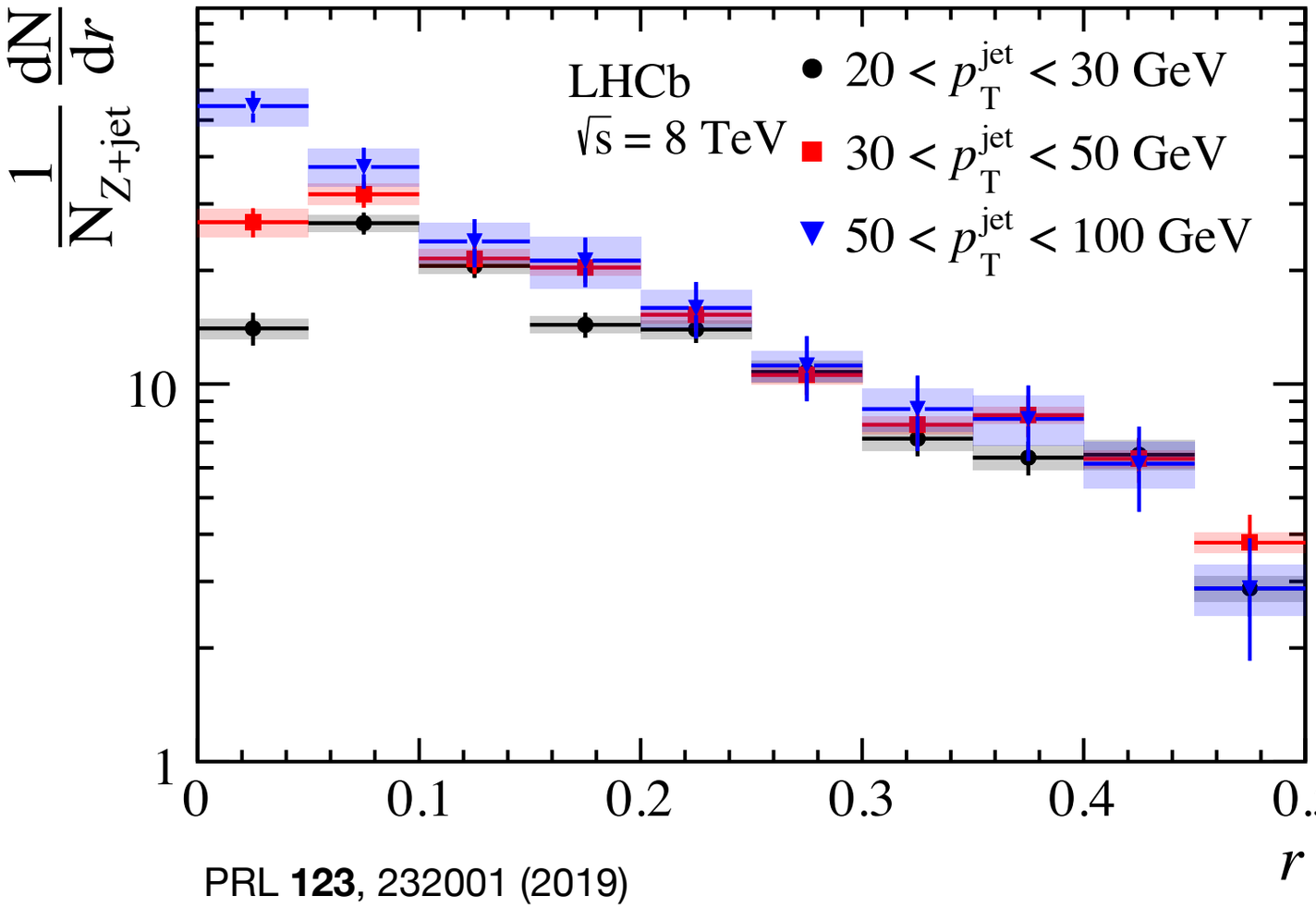
PRL **123**, 232001 (2019)



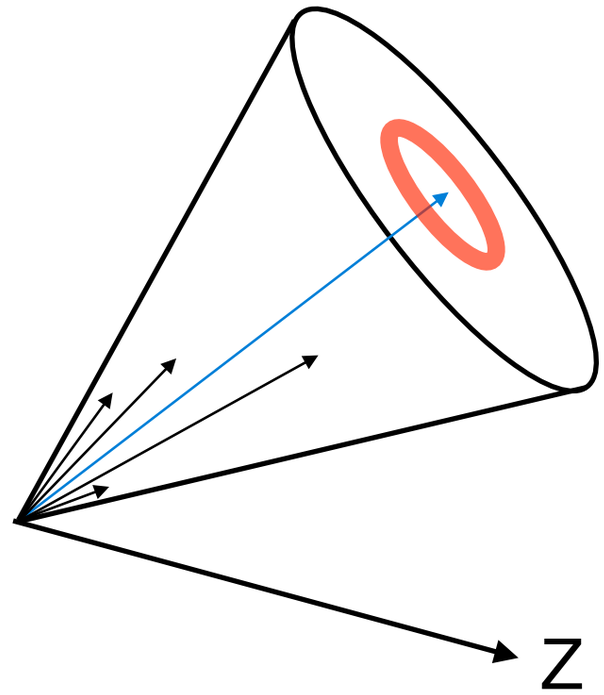
$$j_T = \frac{|\mathbf{p_{jet}} \times \mathbf{p_{hadron}}|}{|\mathbf{p_{jet}}|}$$

- Transition from nonperturbative shape at small j_T to a perturbative tail at large j_T indicates sensitivity to both small and large transverse momentum scales
- Needed to constrain transverse momentum dependent (TMD) jet fragmentation functions

Results: Radial distribution r



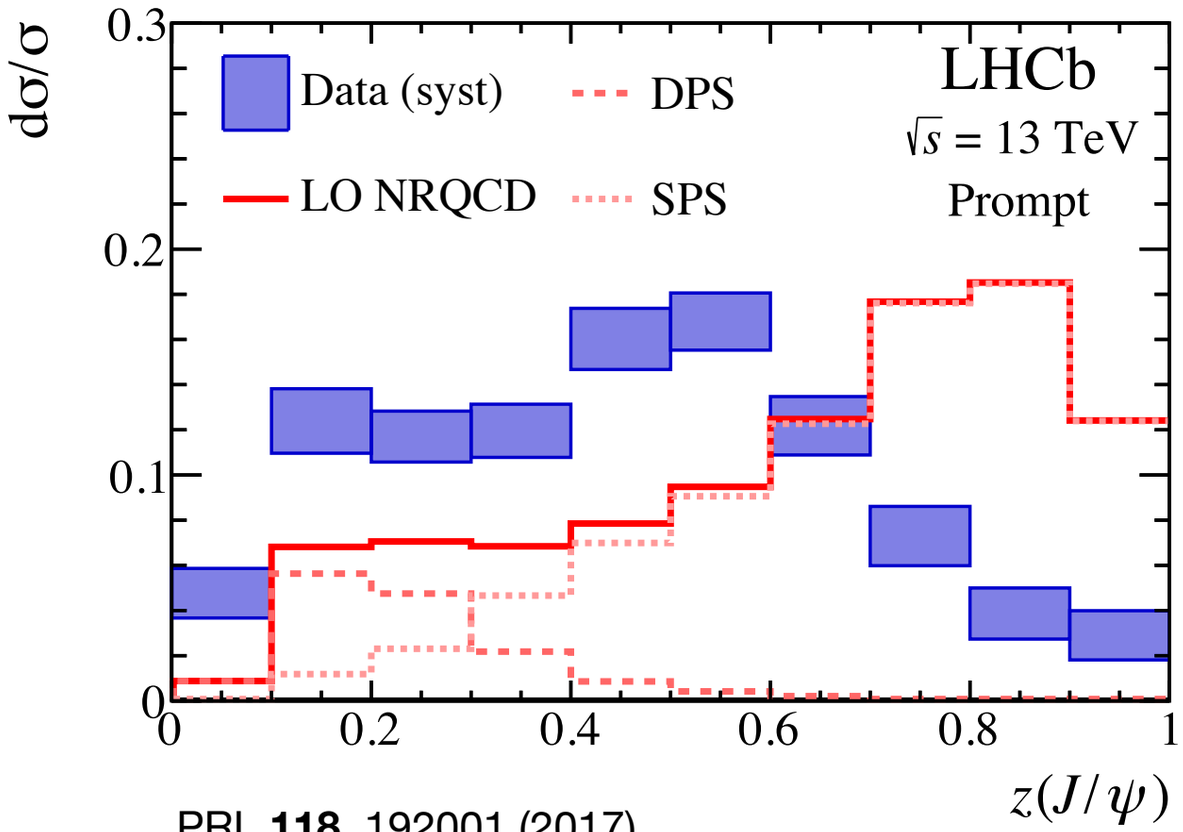
PRL **123**, 232001 (2019)



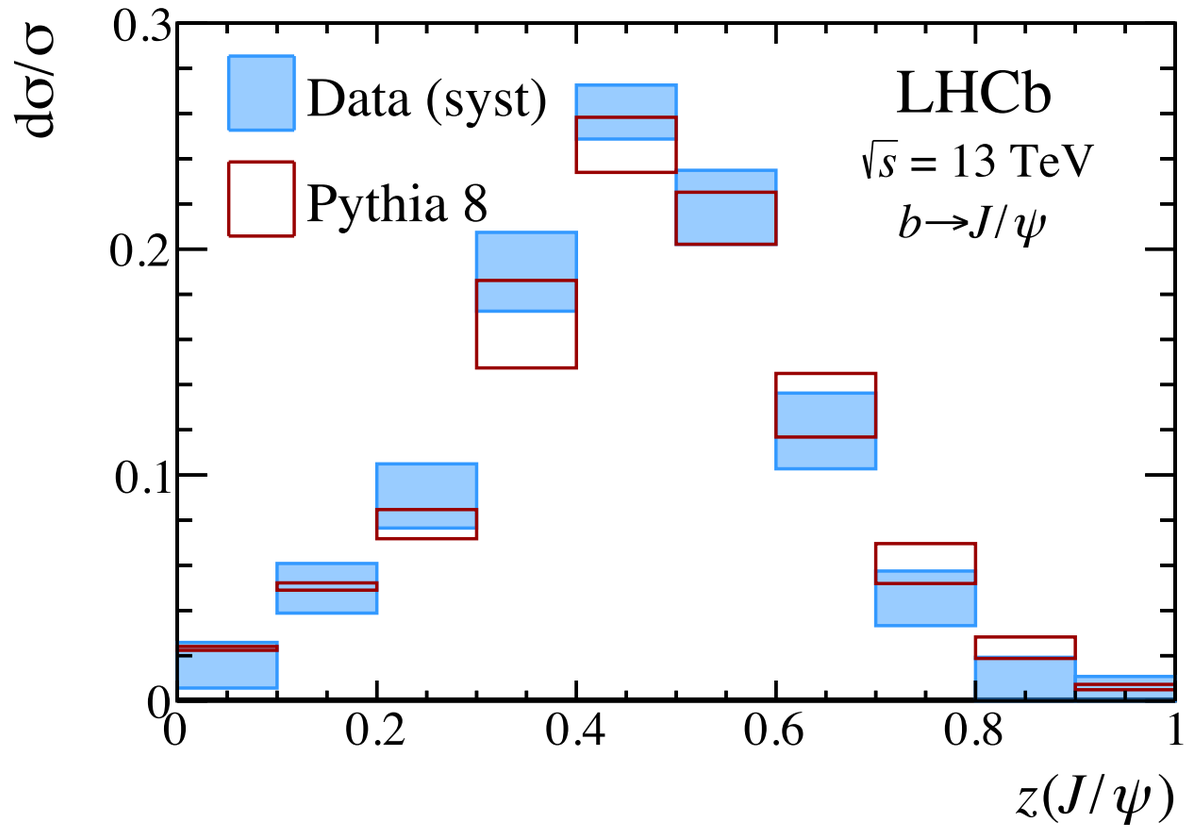
$$r = \sqrt{(\phi_{jet} - \phi_{hadron})^2 + (y_{jet} - y_{hadron})^2}$$

- Strong dependence on jet p_T at very small r, with more hadrons produced close to the jet axis in high-p_T jets
- Reduced jet p_T dependence at larger values of r could indicate that nonperturbative contributions away from the jet axis do not depend strongly on jet p_T

Results: J/ψ production in jets



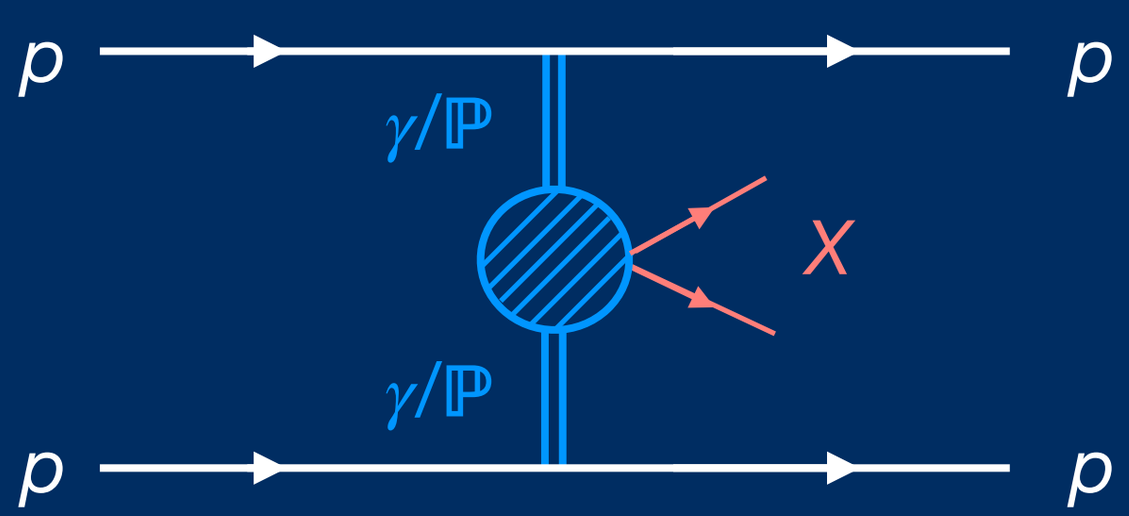
PRL **118**, 192001 (2017)



- Prompt J/ψ production in data disagrees with predictions from fixed-order non-relativistic QCD
- J/ψ production from beauty hadron decays is well described by Pythia 8

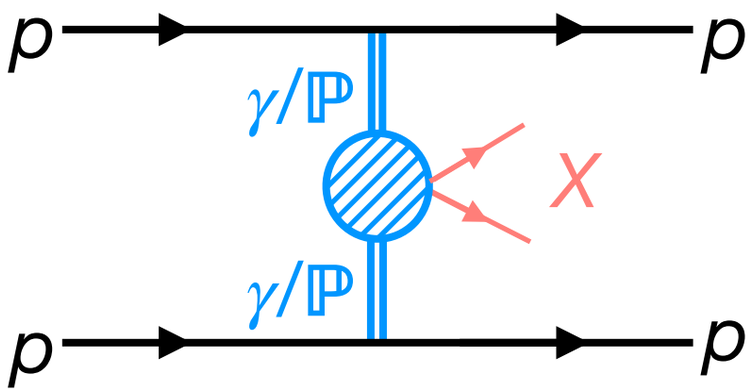
$$z(J/\psi) = \frac{p_{\mathrm{T}}(J/\psi)}{p_{\mathrm{T}}(\mathrm{jet})}$$

Central Exclusive Production



Central Exclusive Production (CEP)

Diffractive process *pp* -> *pXp* in which X is produced in the exchange of colourless objects (photons, pomerons) and the protons remain intact:



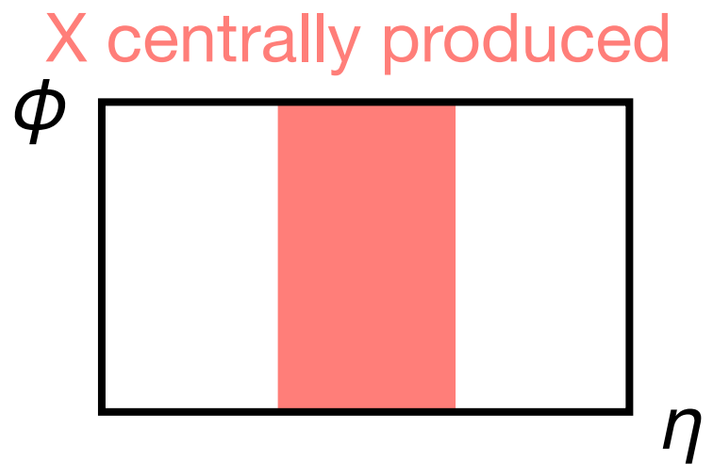
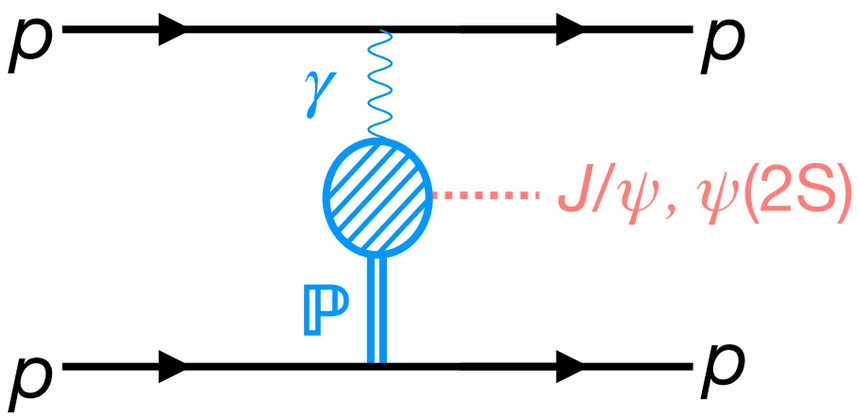


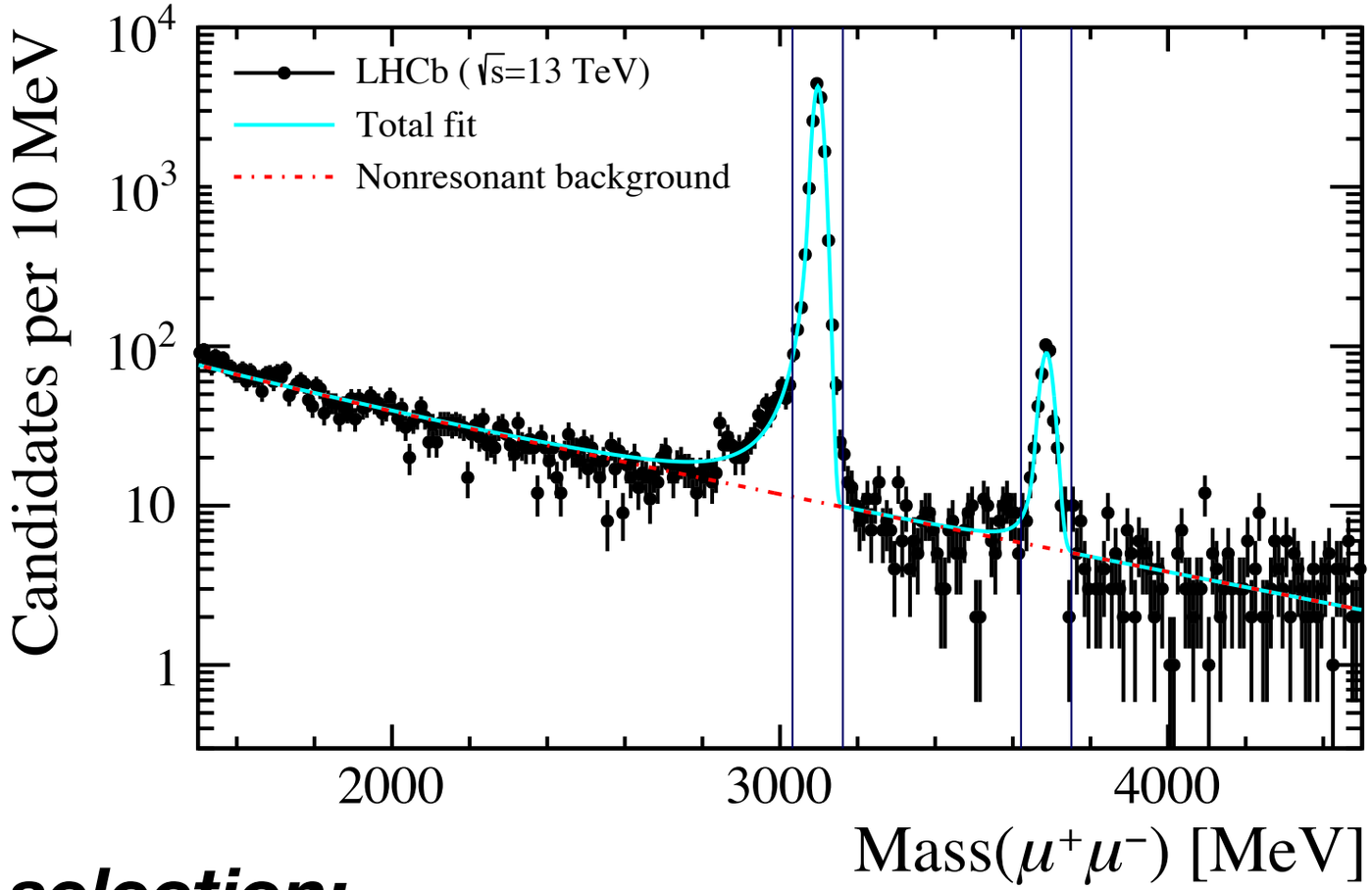
Figure based on arXiv: 0806.0883

CEP production of J/ψ and ψ(2S) occurs through photon-pomeron fusion:



Cross section at leading order in QCD is proportional to the **gluon PDF - can constrain down to x ≈ 2 x 10^{-6} at LHCb**

CEP of J/ψ and ψ(2S) in *pp* collisions

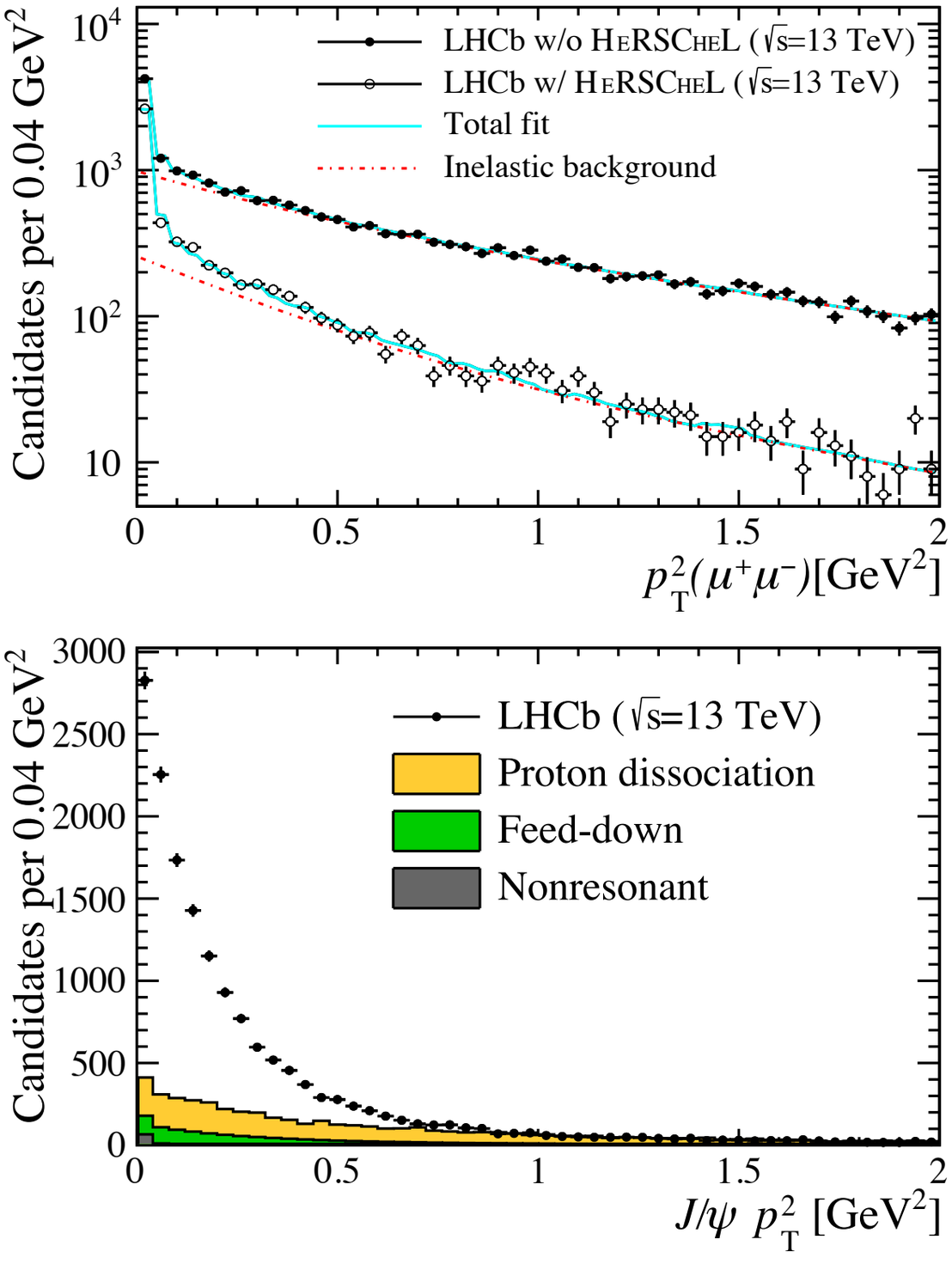


JHEP **10**, 167 (2018)

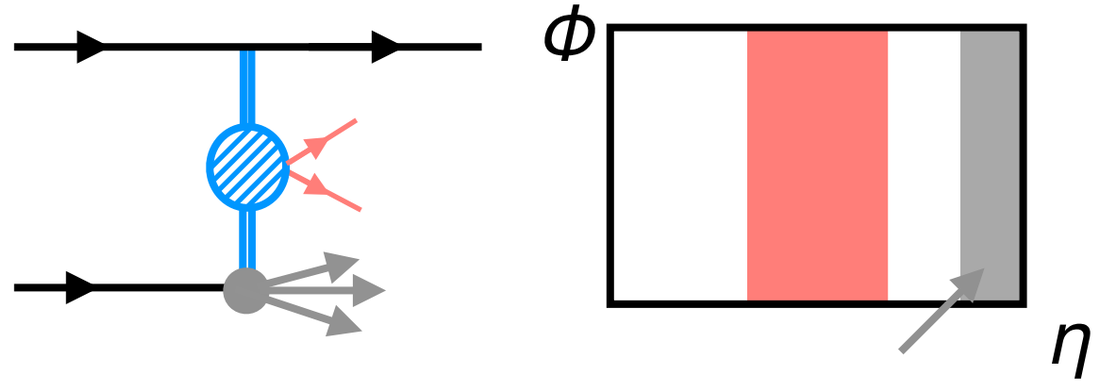
CEP event selection:

- Two reconstructed muons in $2 < \eta < 4.5$
- Dimuon invariant mass within 65 MeV of the known J/ψ or ψ(2S) mass
- $p_T^2(\mu^+\mu^-) < 0.8$ GeV ^{2}
- Additional event activity veto with HeRSCheL

Effect of HeRSCheL



- Background reduced with additional HeRSCheL vetoes of far-forward proton remnants:



proton dissociation remnants

- HeRSCheL allows for data-driven determination of the shape of the proton dissociation background

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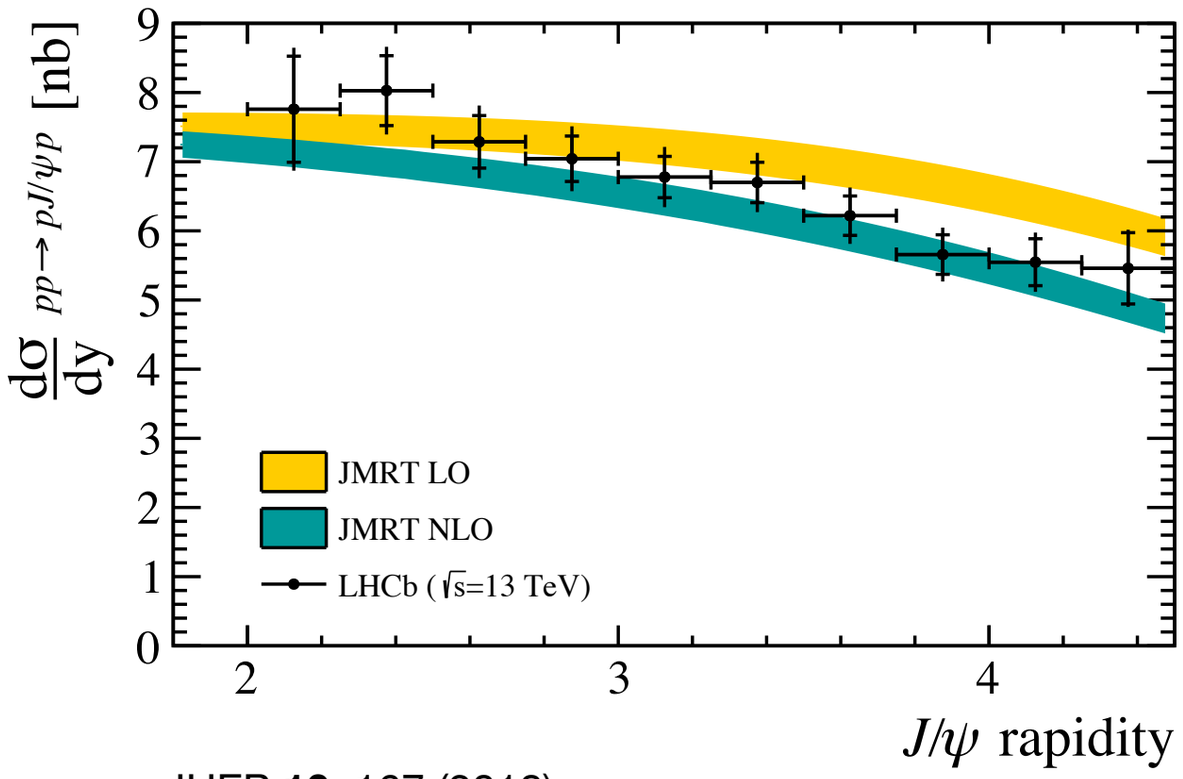
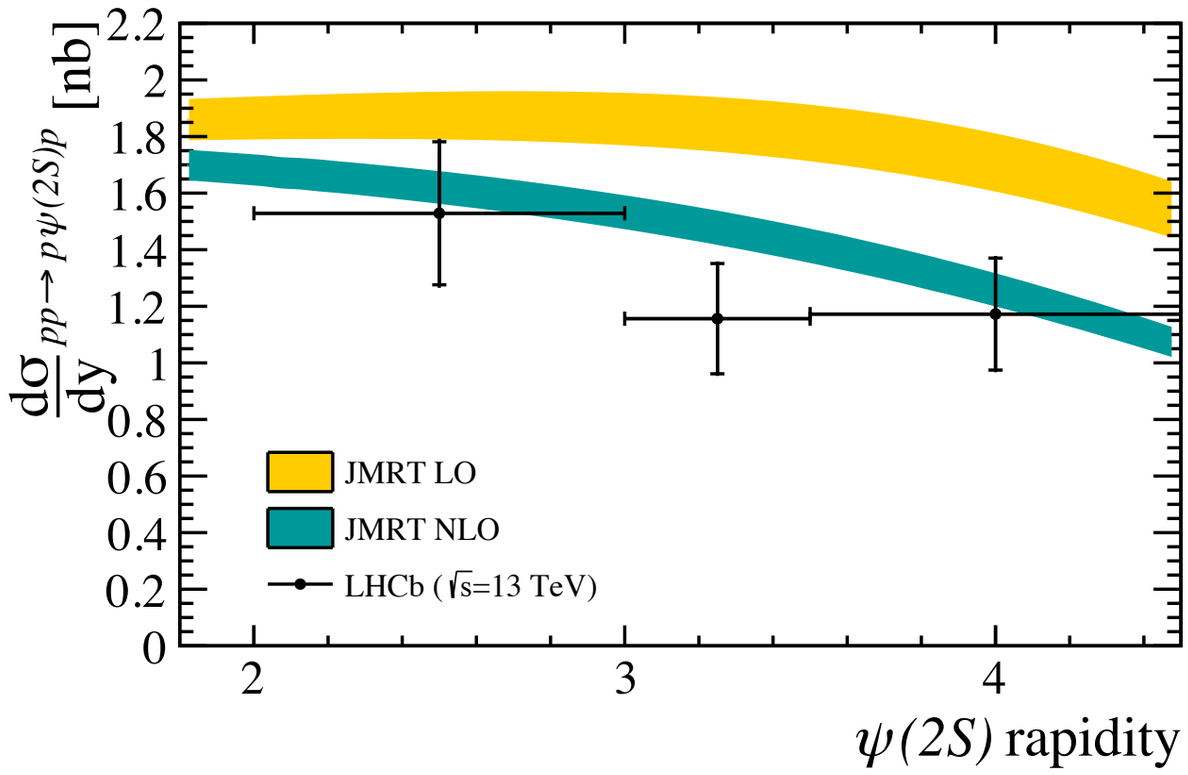
Results: CEP of J/ψ and ψ(2S) in pp collisions at $\sqrt{s}$ =13 TeV

pp -> p J/ψ *p*



pp -> p ψ(2S) *p*



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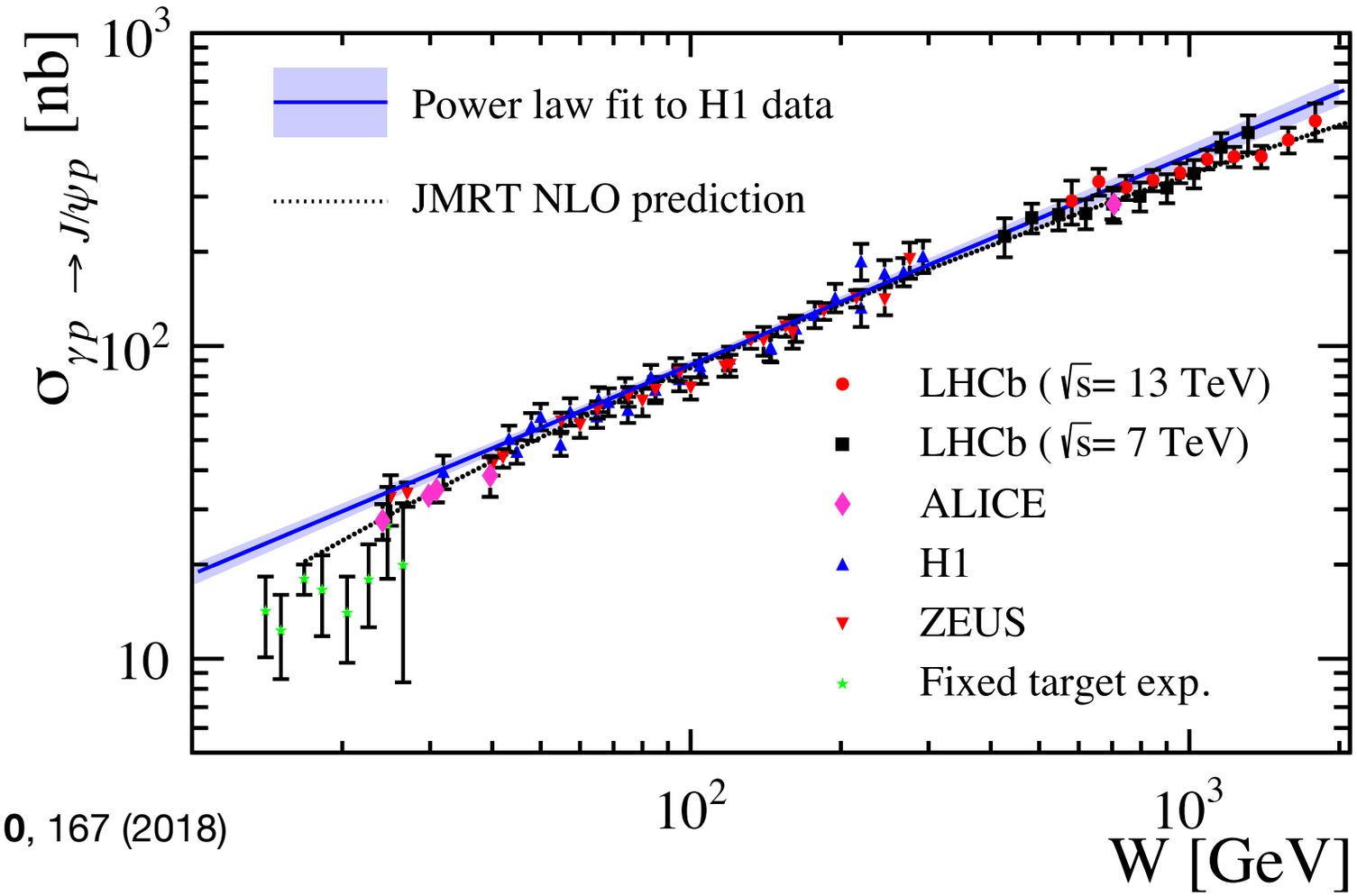
- Theory comparisons show the importance of NLO perturbative QCD calculations

Results: Photoproduction cross section

- Can calculate photoproduction cross section γp -> J/ψp from CEP cross section pp-> pJ/ψp



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W = center of mass energy of γp system

- J/ψ results deviate from the pure power-law extrapolation of H1 data

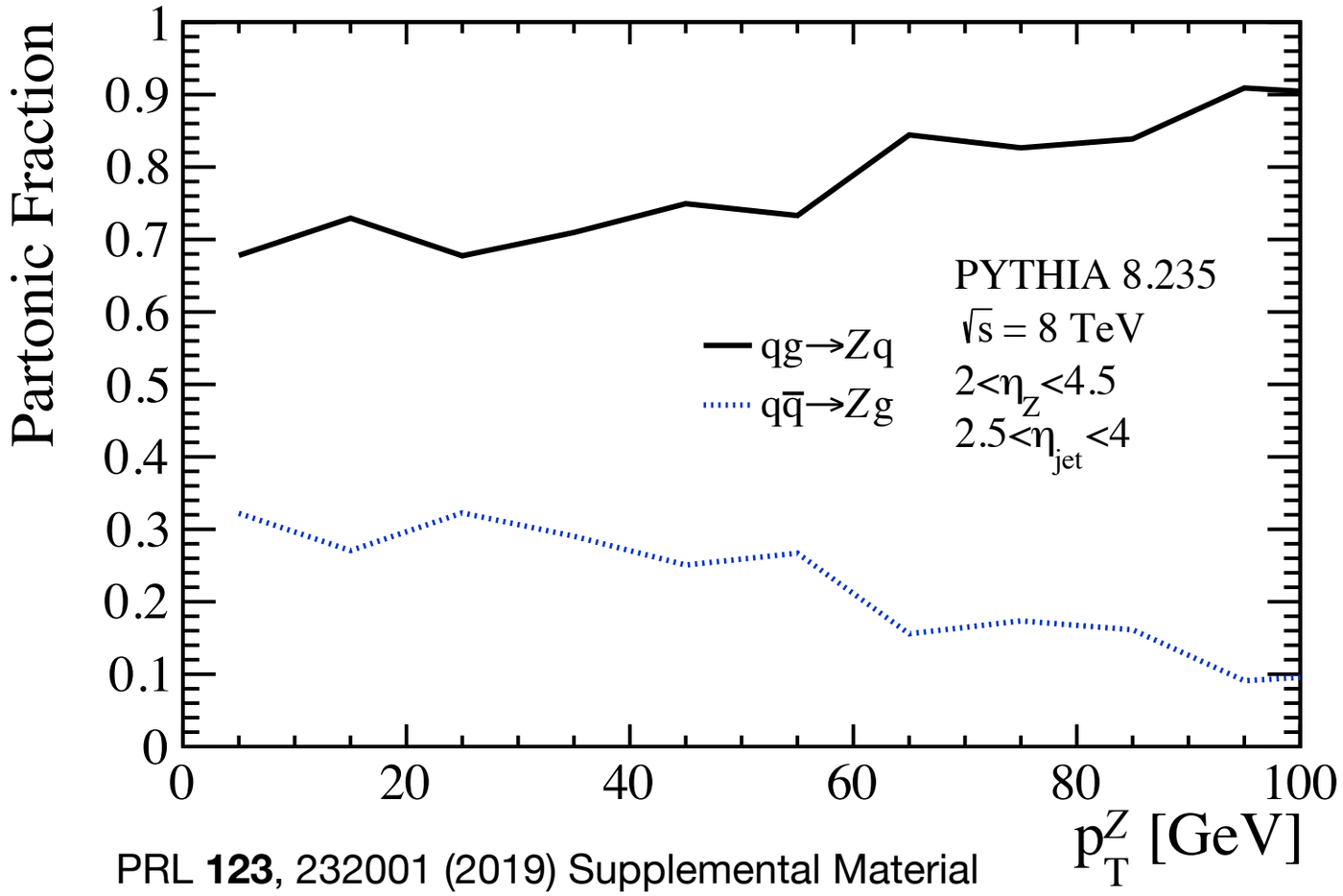
Summary

- Jet fragmentation measurements can be used to probe several different aspects of hadronization
- Charged hadron distributions in Z-tagged jets at LHCb probe hadronization in predominantly light-quark-initiated jets
- The HeRSCheL detector significantly reduces the background for CEP measurements at LHCb
- CEP measurements of J/ψ and ψ(2S) mesons at LHCb can constrain the gluon PDF down to $x \approx 2 \times 10^{-6}$
- More jet fragmentation and CEP measurements to come from LHCb!

Thank you for your attention!

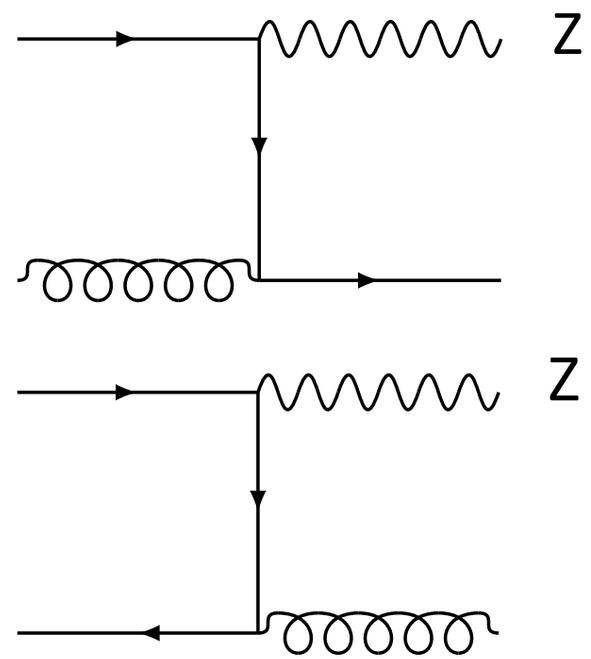
backup

Light-quark-jet tagging with Z bosons



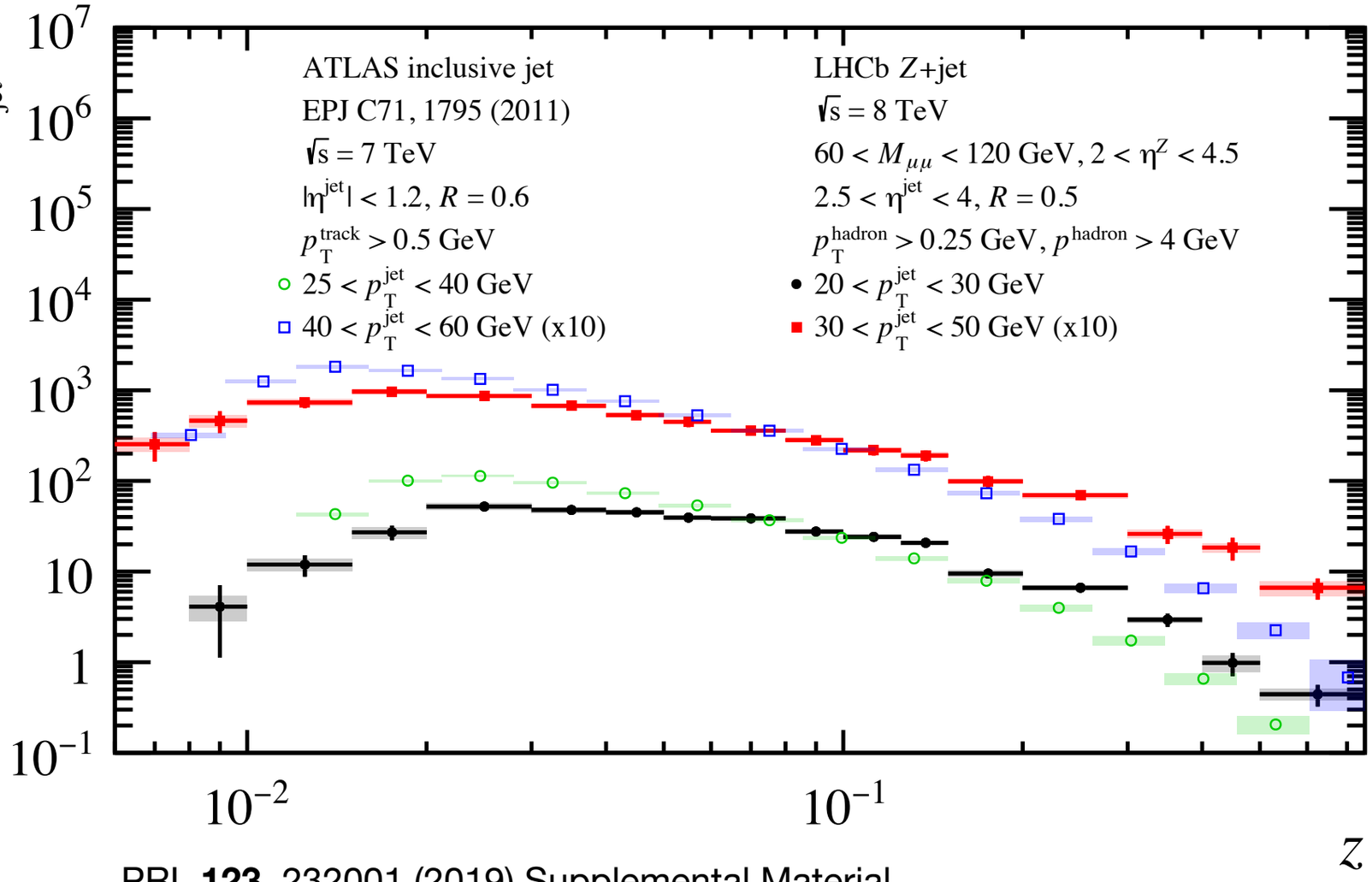
PRL **123**, 232001 (2019) Supplemental Material

LO Z+jet processes:



- Quark-gluon LO process dominates at LHC energies, selecting quark-initiated Z-tagged jets
- Most forward Z-tagged jets are quark-initiated, with the majority being light-quark-initiated due to the large-x quark needed for forward production

Comparison to gluon-dominated jets: z



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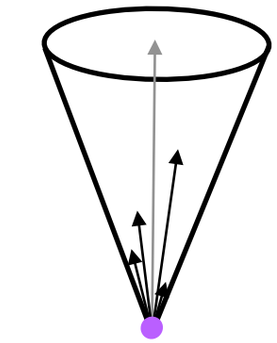
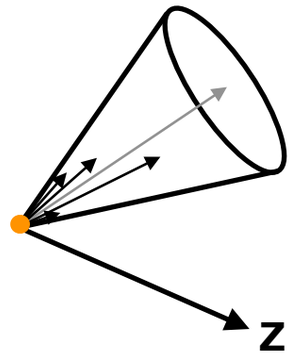


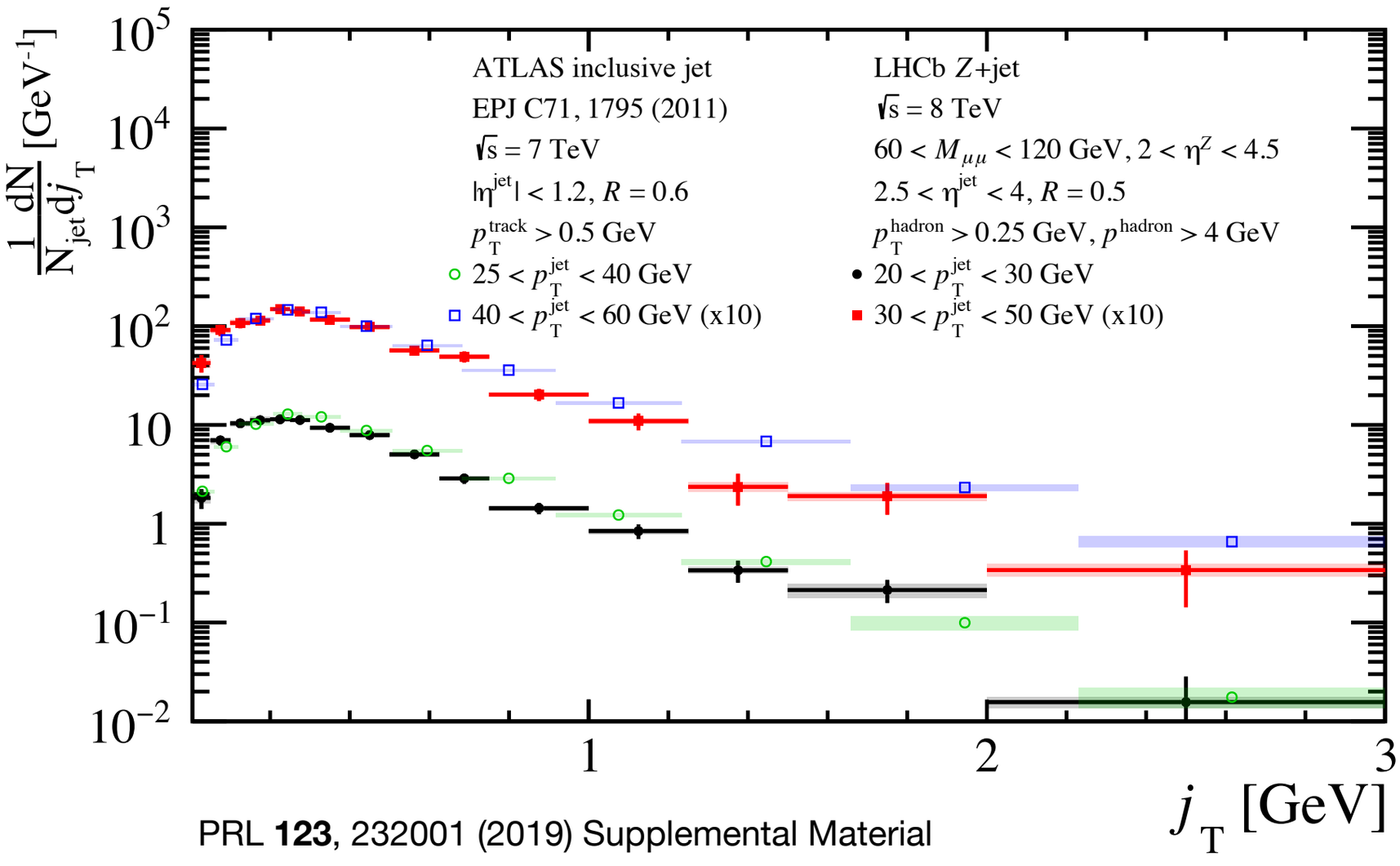
ATLAS inclusive jets: gluon-dominated



LHCb Z-tagged jets: light-quark dominated

- Gluon-initiated jets have a more steeply falling z distribution than light-quark-initiated jets
- Light-quark-initiated jets have slightly more hadrons produced at higher z values

Comparison to gluon-dominated jets: j_T



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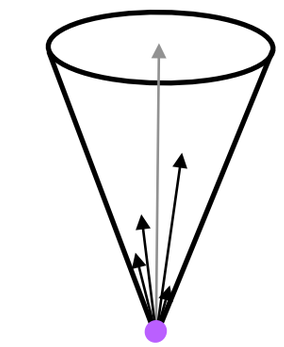
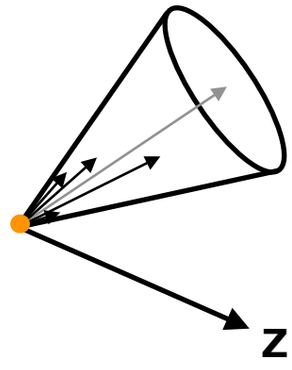


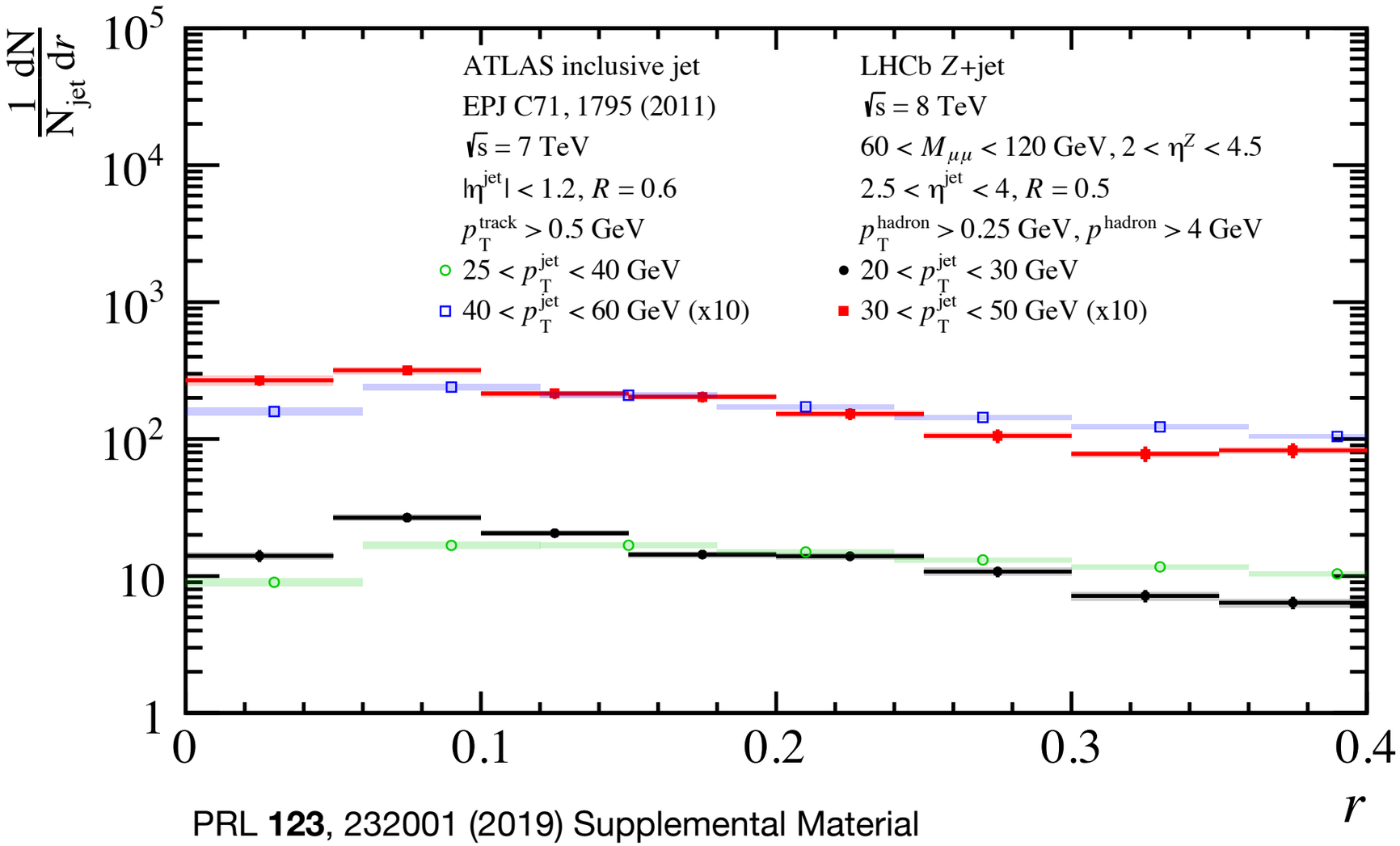
ATLAS inclusive jets: gluon-dominated



LHCb Z-tagged jets: light-quark dominated

- Light-quark-initiated jets and gluon-initiated jets have similar j_T distributions

Comparison to gluon-dominated jets: r



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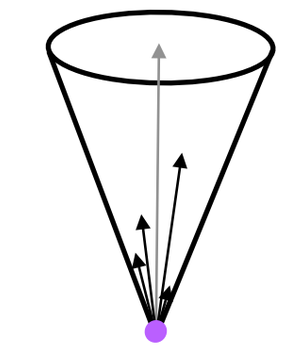
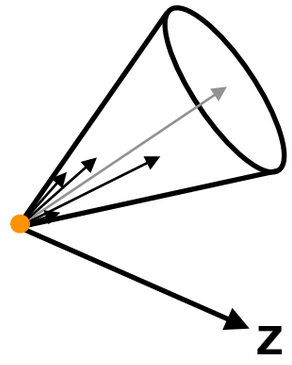


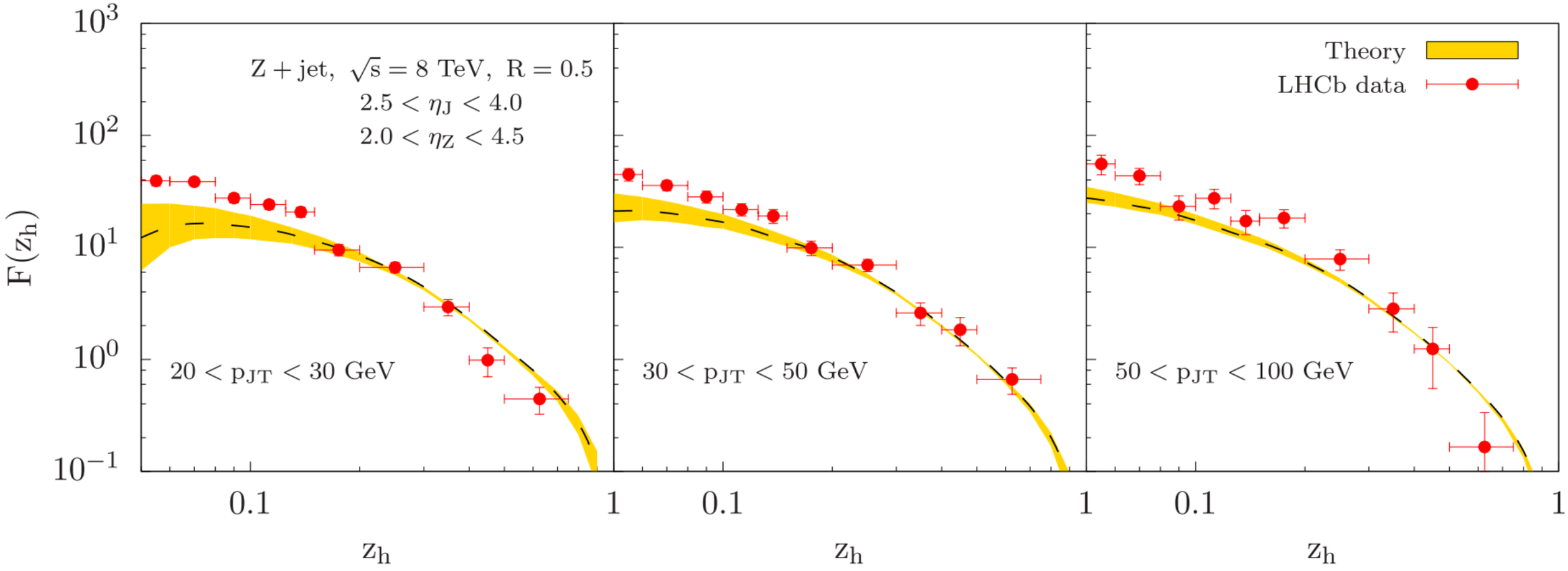
ATLAS inclusive jets: gluon-dominated



LHCb Z-tagged jets: light-quark dominated

- Light-quark-initiated jets are more collimated than gluon-initiated jets

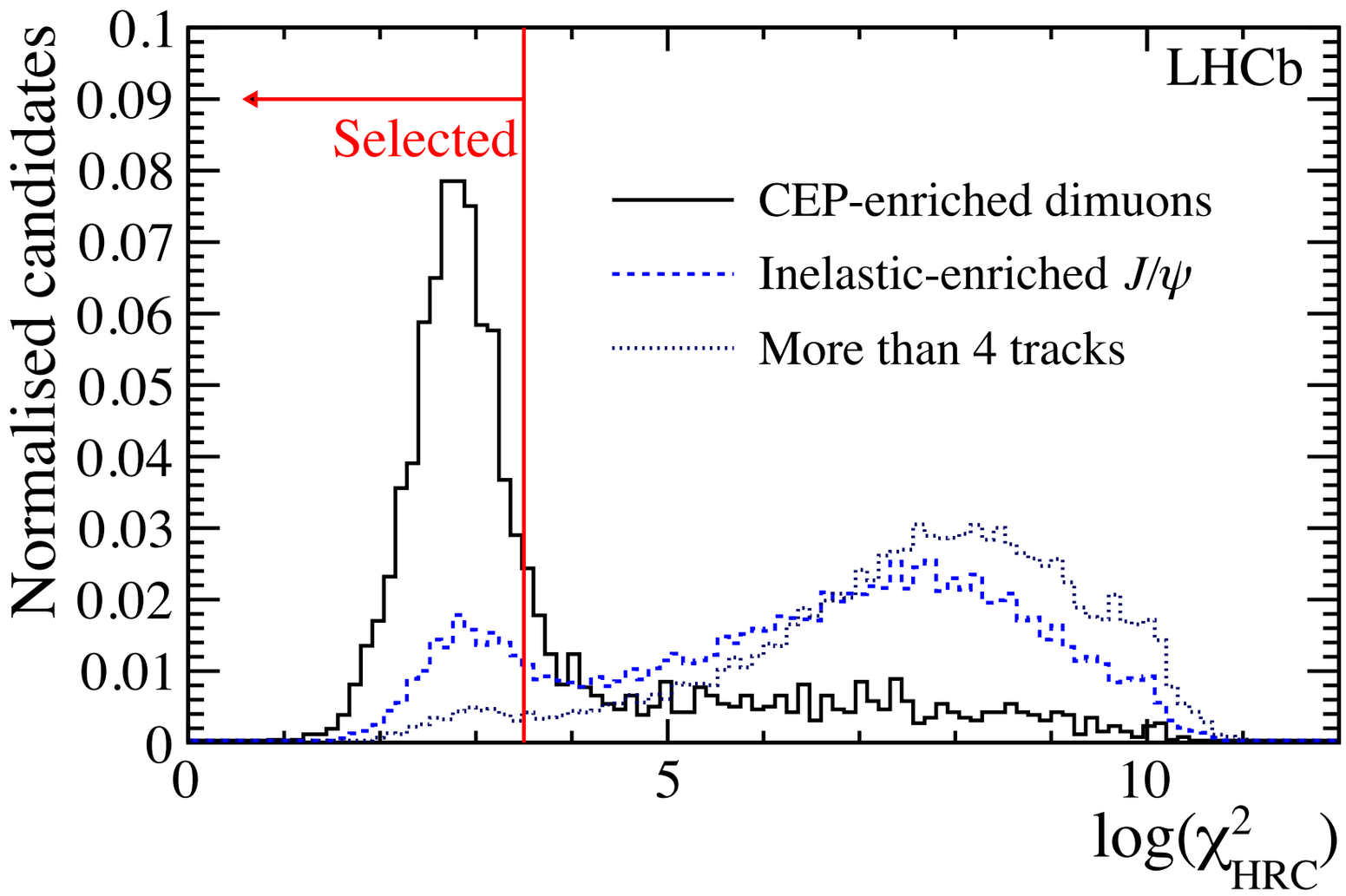
Theoretical comparisons: z



Kang, Lee, Terry, Xing PLB **798**, 134978 (2019)

- Perturbative QCD calculations agree well with measured z distributions for intermediate z values
- 2D j_T vs. z distribution measurements in progress - will allow for jet TMD FF extraction

HeRSCheL performance



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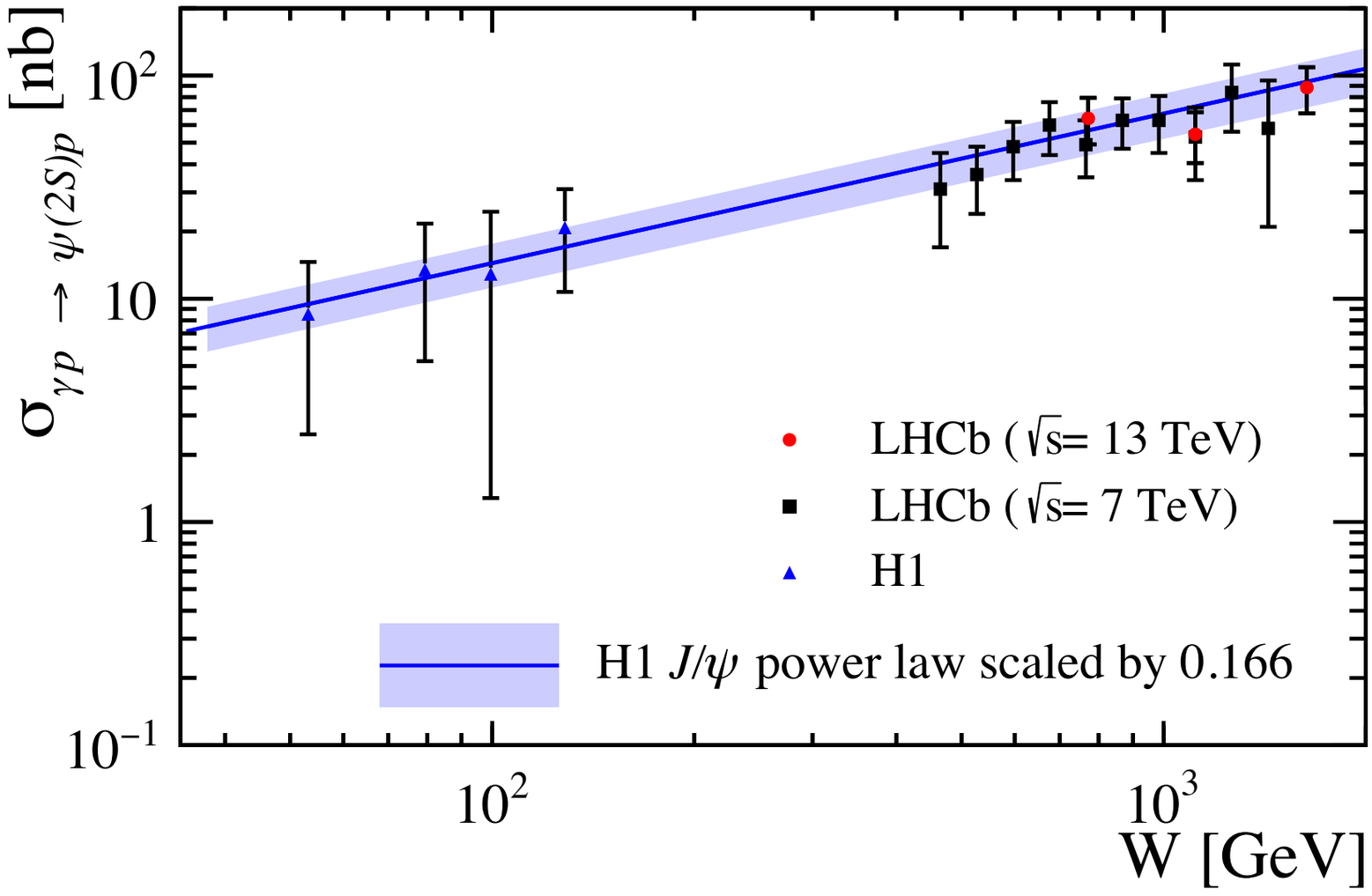
- χ^2_{HRC} is a discriminating variable related to event activity in HeRSCheL

Results: ψ(2S) Photoproduction cross section



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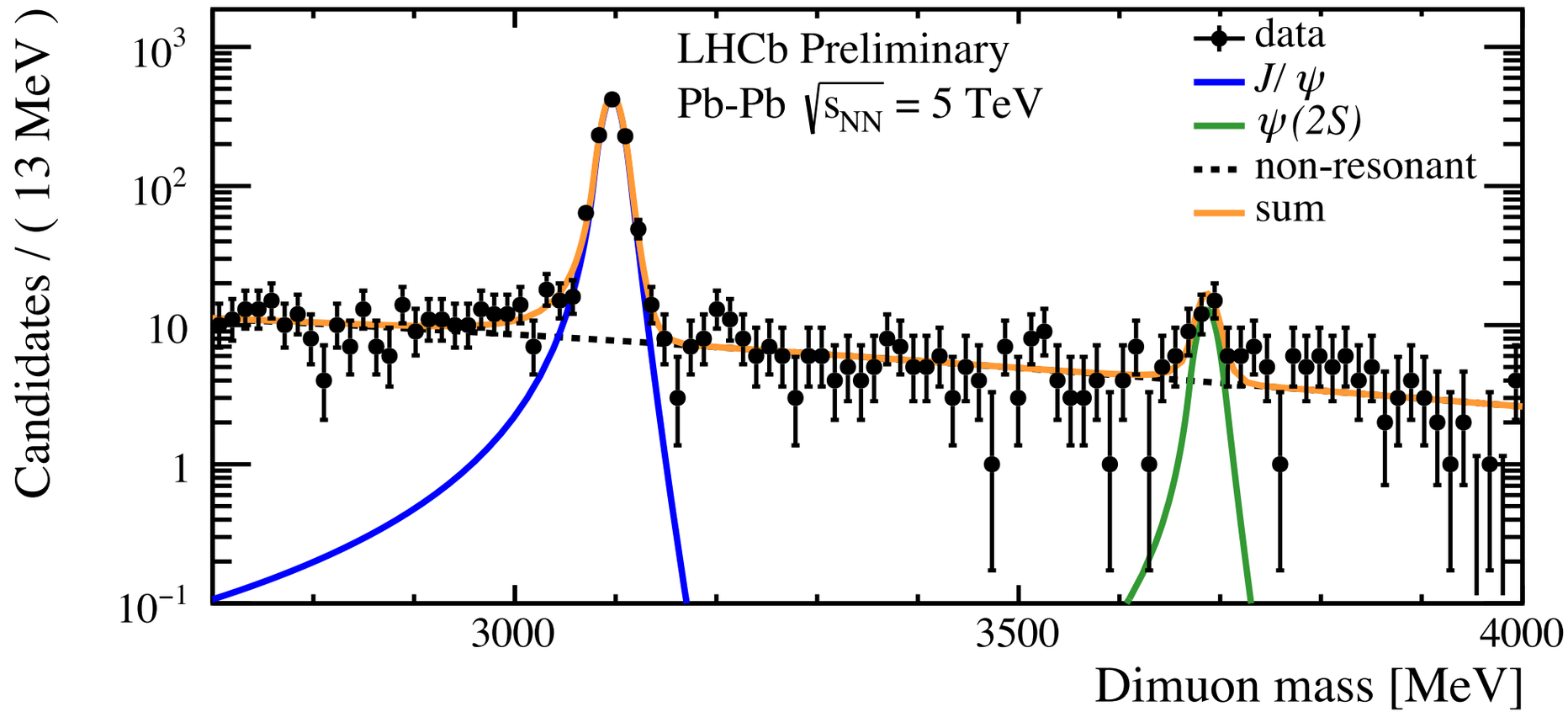
- ψ(2S) results are consistent with the pure power law extrapolation of H1 data

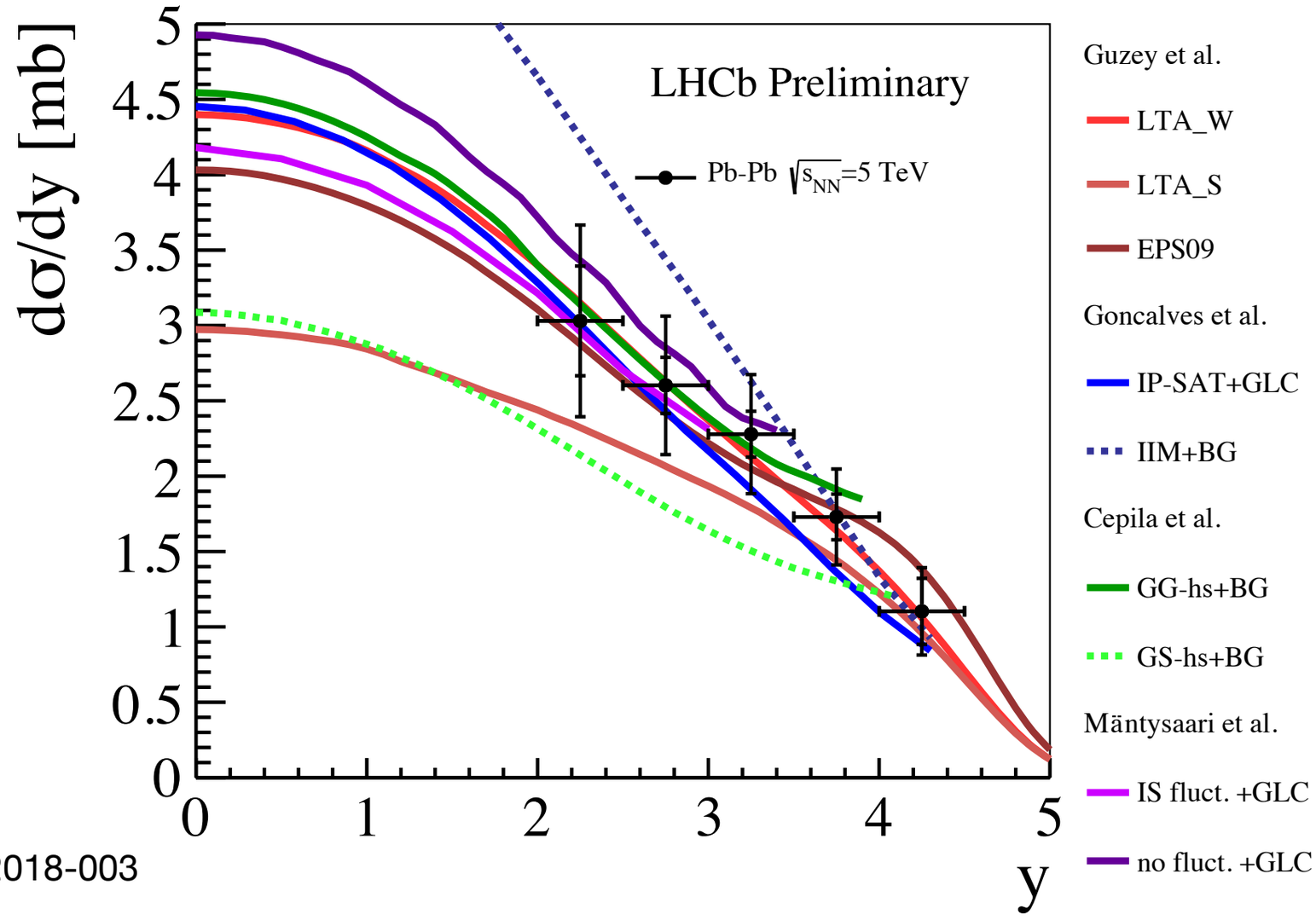
CEP of J/ψ in *PbPb* collisions at $\sqrt{s_{NN}} = 5$ TeV



LHCb-CONF-2018-003

- CEP of J/ψ in *PbPb* collisions probes the nuclear gluon PDF, can probe down to x ≈ 10^{-5} at LHCb

Preliminary results: CEP of J/ψ in *PbPb* collisions at $\sqrt{s_{NN}} = 5$ TeV



LHCb-CONF-2018-003

- Preliminary results compared to several phenomenological predictions