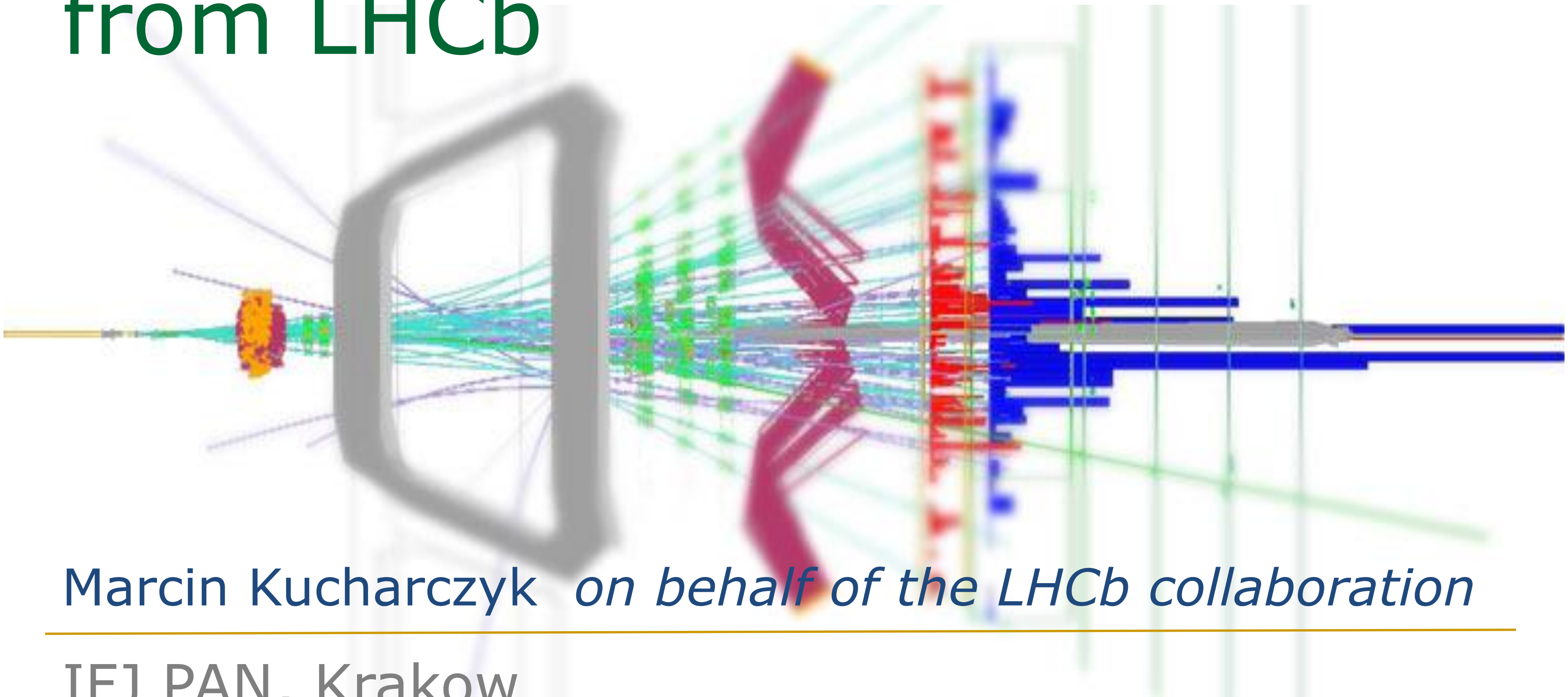
Precision QCD measurements from LHCb



Marcin Kucharczyk *on behalf of the LHCb collaboration*

IFJ PAN, Krakow

Large Hadron Collider Physics

Paris, 07-12 June 2021

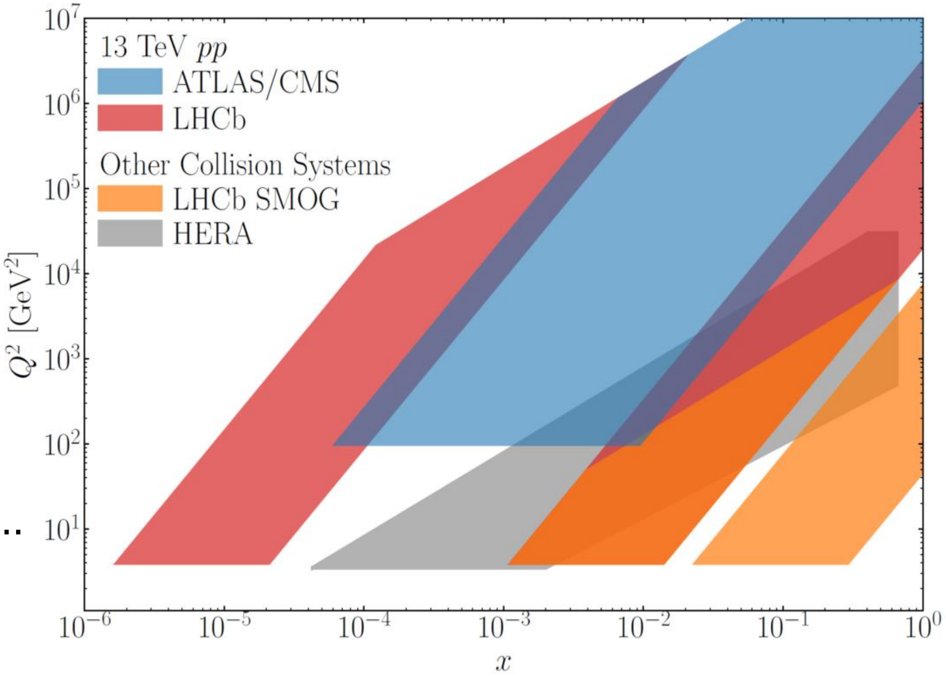
QCD at LHCb

LHCb - GPD in forward region

opportunity to study QCD processes in extended region of phase space

Probe QCD at many different scales

high energy jets, Drell-Yan, V+jets, fragmentation and hadronization, particle correlations, hadronic production x-sections, spectroscopy, …



Rich QCD physics program at LHCb

- jet production / jet fragmentation and hadronization
- particle correlations
- inelastic proton-proton cross section
- quarkonia and open heavy flavor production
- Central Exclusive Production (CEP)
- exotic QCD bound states

QCD at LHCb → **covered in this talk**

LHCb - GPD in forward region

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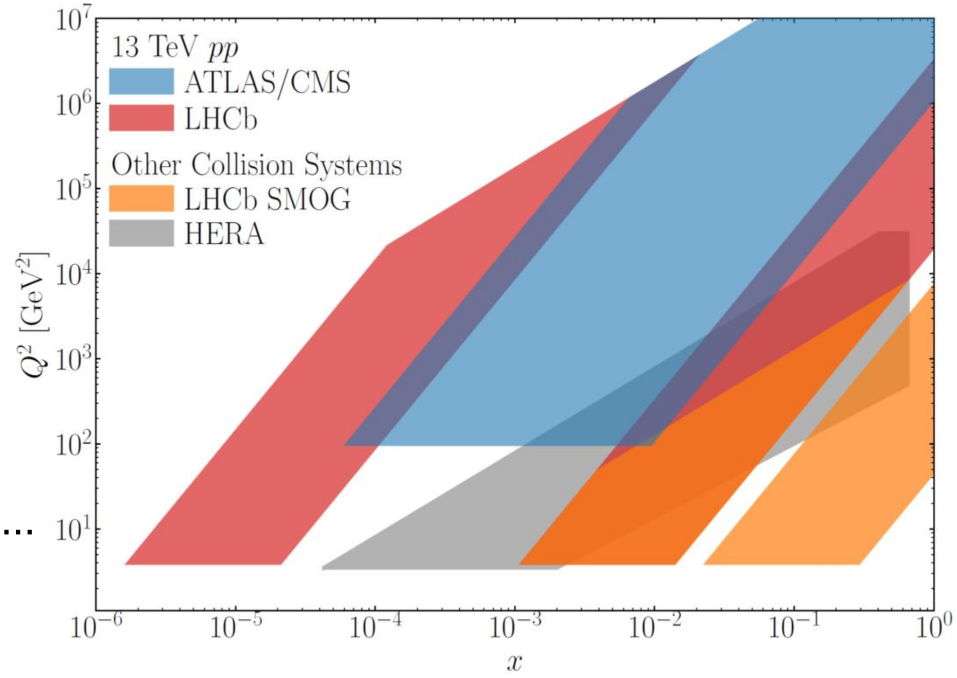

Rich QCD physics program at LHCb

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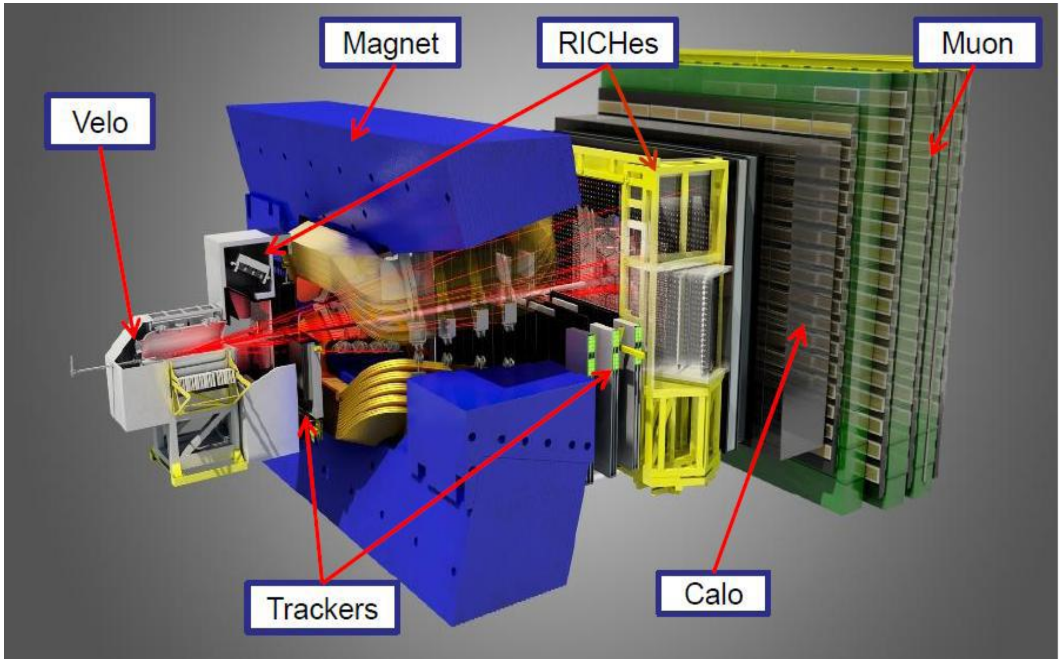
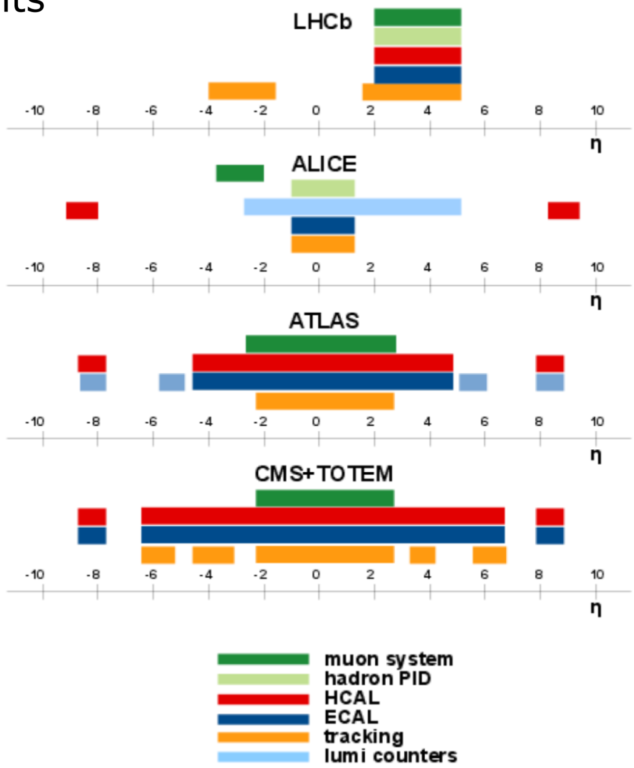
- **particle correlations**
- inelastic proton-proton cross section
- quarkonia and open heavy flavor production
- **Central Exclusive Production (CEP)**
- exotic QCD bound states

LHCb detector

[Int. J. Mod. Phys. A30 (2015) 1530022]

- single arm spectrometer fully instrumented in forward region → GPD in forward region
- designed to study CP violation in *B*, but also fixed target, heavy ion physics
- precision coverage unique for LHCb: $2 < \eta < 5$
- complementary results with respect to other LHC experiments





[IJMPA 30 (2015) 1530022]

- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of 20 μm for high-p_T tracks
- good PID separation up to 100 GeV *(misID ($\pi \to K$) ≈ 5% at 95% efficiency)*

Jet fragmentation and hadronization

[PRL 123 (2019) 232001]

Jet fragmentation and hadronization

Hadron production in jets may probe many aspects of hadronization

- hadronization dynamics

  → *momentum and spatial distributions of hadrons*

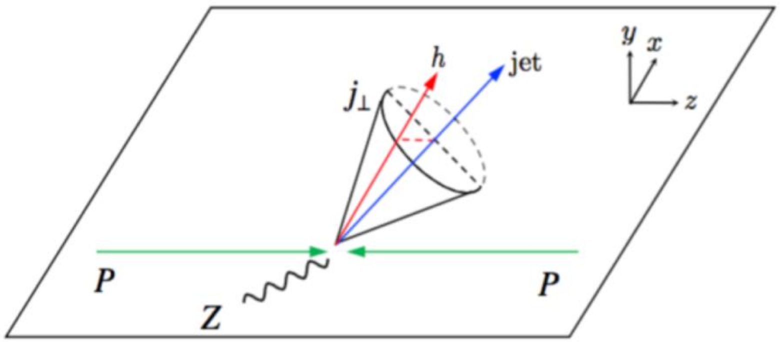
- flavor dependence

  → *hadron distributions in forward Z-tagged jets (light-quark dominated)*

  → *mid-rapidity inclusive jets (gluon-dominated)*

  → *heavy flavor jets*

- quarkonium formation mechanisms



Observables for charged hadrons in jets

- longitudinal momentum fraction z
- transverse momentum wrt jet axis j_T
- radial profile r

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

$$j_T = \frac{|p_{jet} \times p_h|}{|p_{jet}|}$$

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

Hadronization in quark-initiated jets

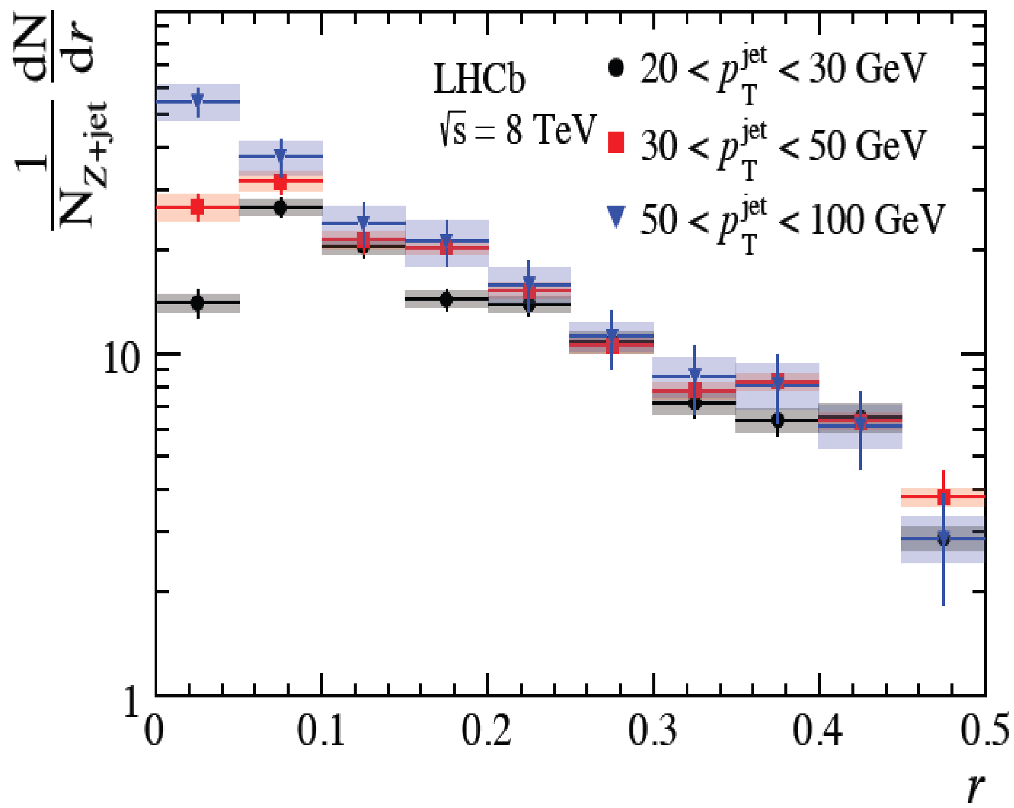
[PRL 123 (2019) 232001]

Measure production of charged hadrons within jets recoiling against a Z boson

LHCb sample dominated by light-quark jets

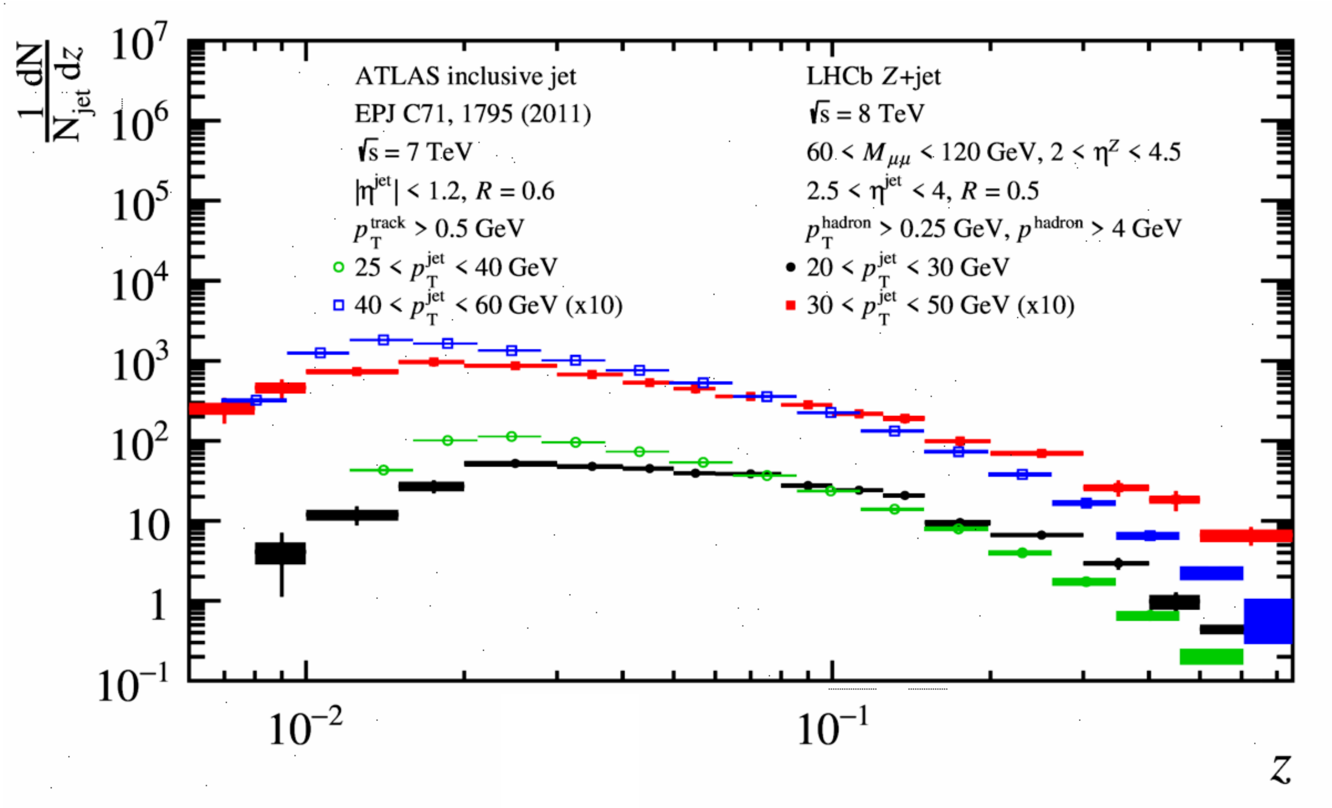
- larger energy in higher p_T jets leads to more hadrons, mainly close to jet axis
- reduced jet p_T dependence at larger r may indicate that nonperturbative contributions don't depend strongly on jet p_T

Radial profile



Quark- vs gluon-initiated jets

[PRL 123 (2019) 232001]

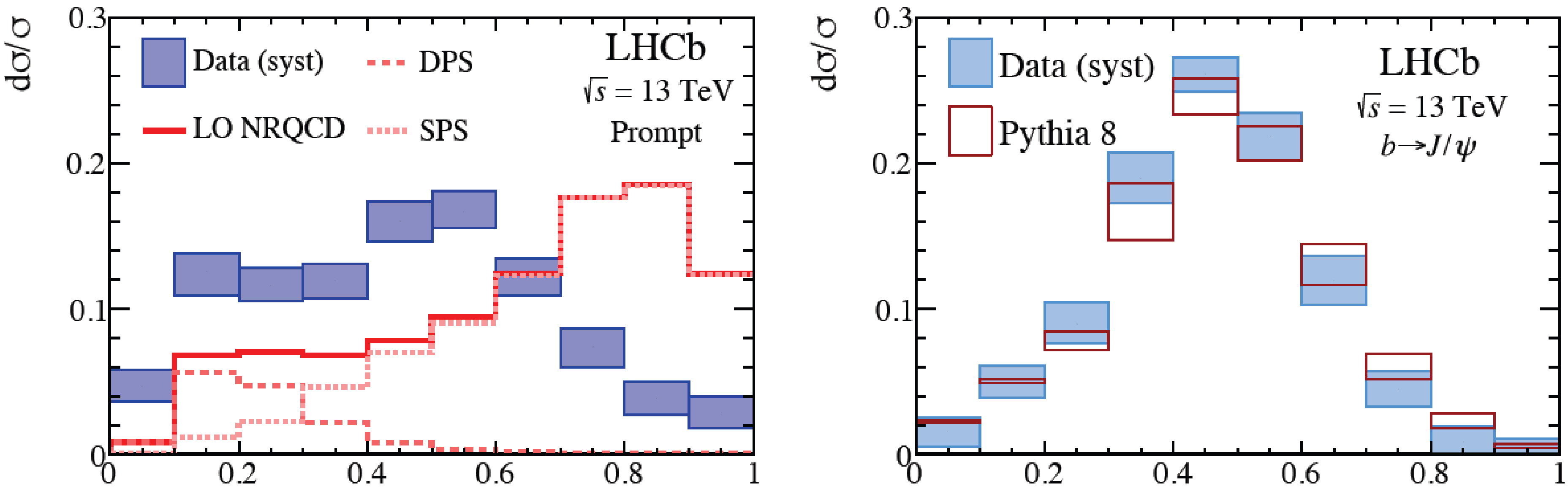


- quark-initiated jets (LHCb) narrower than gluon-initiated jets (ATLAS)
- quark-initiated jets with relatively more hadrons produced at higher longitudinal momentum fractions wrt gluon-initiated jets

Charmonium formation in jets

[PRL 118 (2017) 192001]

- looking at quarkonia inside jets
- collinear fragmentation along jet axis measured



PRL **118**, 192001 (2017)

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

- prompt J/ψ production in data differ from predictions with fixed-order non-relativistic QCD
- J/ψ production from *b*-hadron decays agrees well with Pythia 8

Bose-Einstein correlations

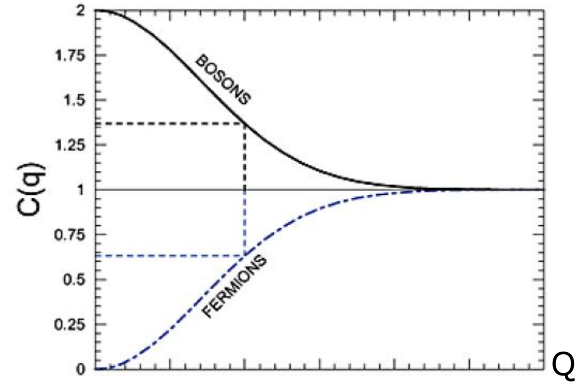
[JHEP 12 (2017) 025, Nucl. Phys. A982 (2019) 347–350]

Correlation function

[JHEP 12 (2017) 025]

- correlations exist between indistinguishable particles emitted from the same emitter volume
- useful tool to probe the spatial and temporal structure of the hadron emission volume

Experimentally: $C_2(Q) = \dfrac{N(Q)^{DATA}}{N(Q)^{REF}}$, $REF = mix, MC, unlike$



N(Q)^DATA - distribution for same-sign pairs in data *(BEC present)*

N(Q)^REF - distribution for reference sample with no BEC effect

$$Q = \sqrt{-(q_1 - q_2)^2} = \sqrt{M^2 - 4\mu^2}$$

Event-mixed reference sample used

- pions from different events from PVs with same VELO track multiplicity *(long-range correl.)*
- derived from data
- other correlations also removed → construct double ratio *(next slide)*

Parametrization of correlation function

- Levy parametrization with α =1 (Cauchy) + long-range correlations

$$C_2(Q) = N(1 + \lambda e^{-|RQ|^{\alpha}}) \times (1 + \delta \cdot Q)$$

- *R* - the radius of a spherical static source
- *λ* - chaoticity parameter
  (0 – coherent source, 1 – chaotic case)
- *N* - normalisation factor
- *δ* - long range correlations

Double ratio

[JHEP 12 (2017) 025]

Improved correlation function - double ratio *(DR)*

$$DR(Q) = \frac{C_2(Q)^{\text{data}}}{C_2(Q)^{\text{MC}}}$$

MC without BEC

- reduce possible imperfections in the construction of the reference sample
- eliminate second order effects to large extent
- correct for long range correlations *(if properly simulated)*

By construction the correlation function is largely independent of

- single particle acceptance and efficiency
- effects due to the detector occupancy, acceptance and material
- selection cuts
- two-track efficiency effects if properly simulated

Coulomb effect

Removed with Gamov penetration factor for *Q* distribution in data:

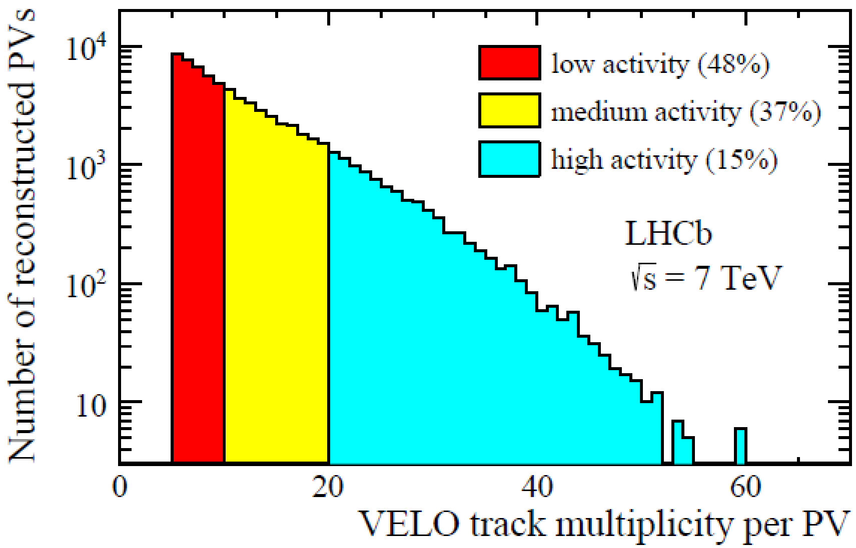
$$G_2(Q) = \frac{2\pi\zeta}{e^{2\pi\zeta} - 1}, \quad \text{where} \quad \zeta = \pm\frac{\alpha m}{Q}$$

$\rightarrow$ **systematics due to Coulomb correction found to be negligible**

Results

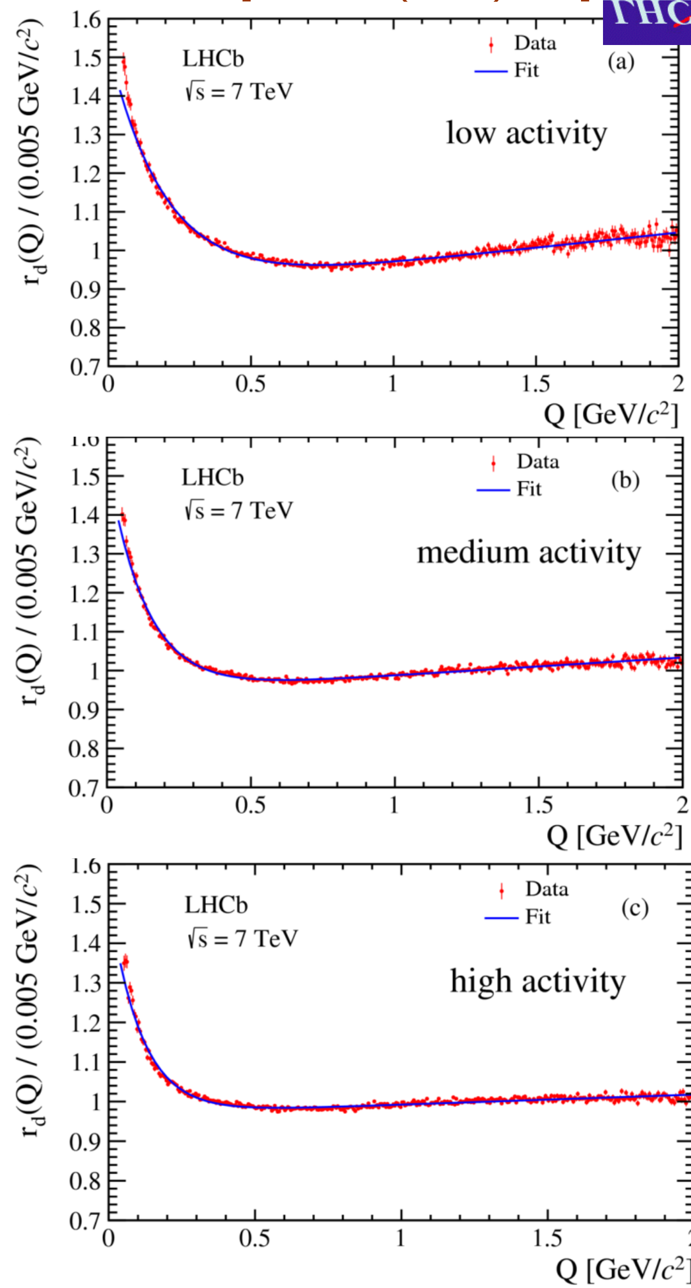
[JHEP 12 (2017) 025]

Fits to DR with Levy parametrization for 3 activity bins



Activity	R [fm]	λ
Low	**1.01 ± 0.01 ± 0.10**	**0.72 ± 0.01± 0.05**
Medium	**1.48 ± 0.02 ± 0.17**	**0.63 ± 0.01 ± 0.05**
High	**1.80 ± 0.03 ± 0.16**	**0.57 ± 0.01 ± 0.03**

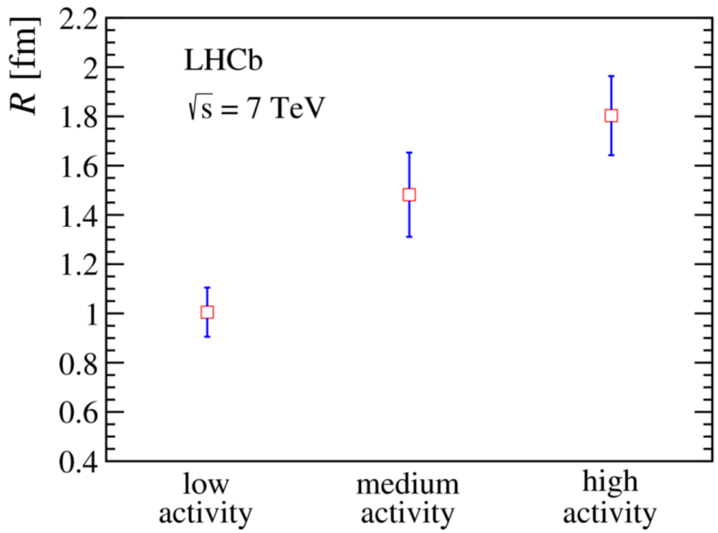
Systematic uncertainty (~10%) dominated by the generator tunings and pile-up effects



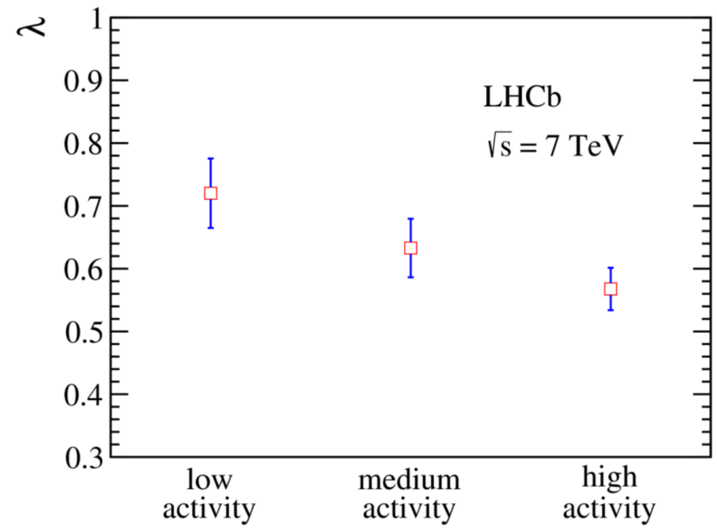
Results

[JHEP 12 (2017) 025]

Source size increases with activity



Chaoticity decreases with activity



Direct comparison between experiments not straightforward *(different η ranges)*

A trend compatible with previous observations at LEP and the other LHC experiments and with some theoretical models

- *R* and λ parameters measured in the forward region are slightly lower wrt ATLAS
- Need to measure the BEC parameters using a full three-dimensional analysis to perform a more detailed comparison

Central Exclusive Production

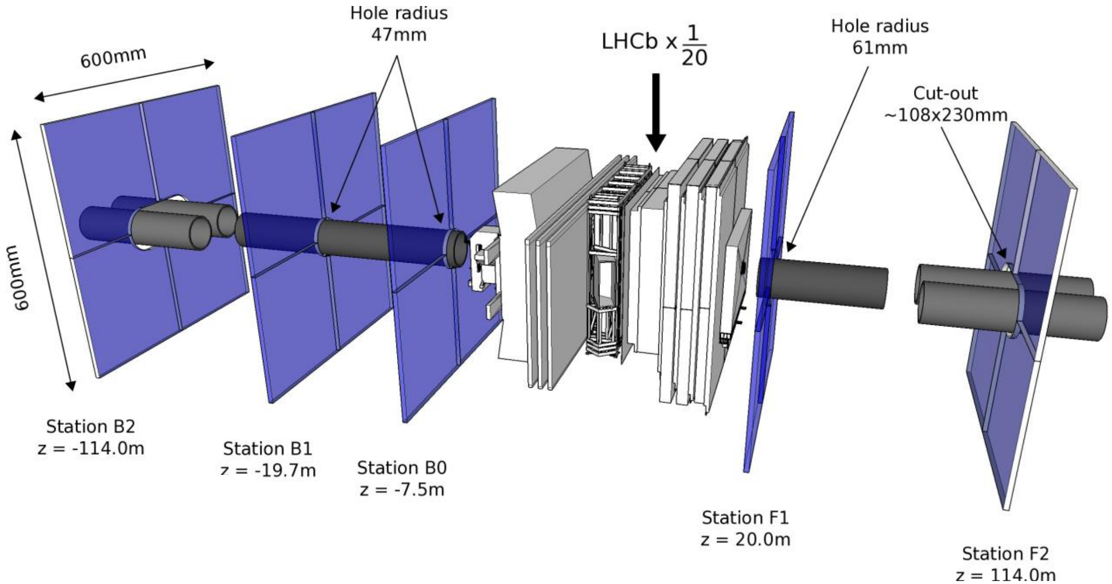
[JHEP 1810 (2018) 167]

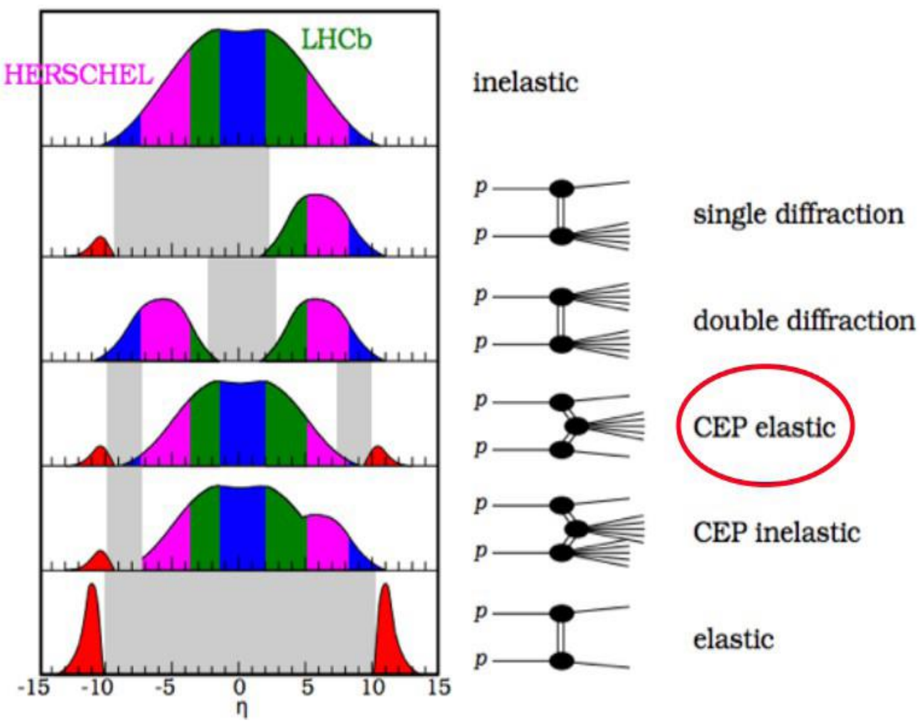
HeRSCheL

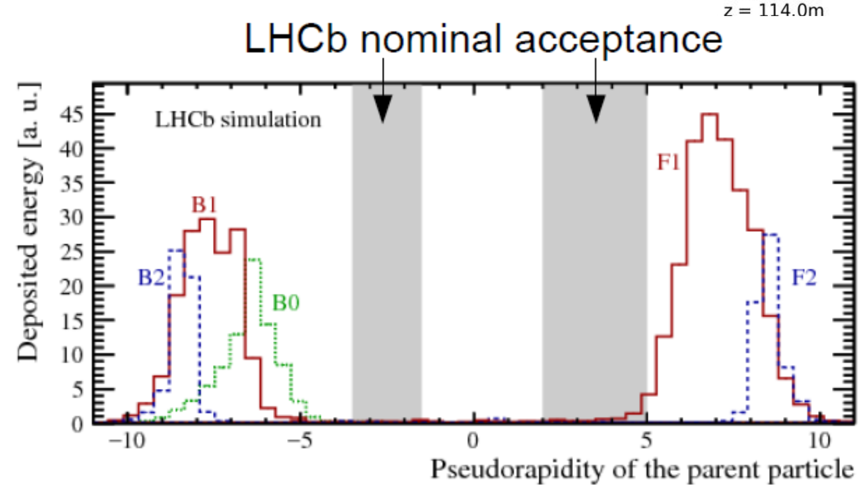
[JINST 13 (2018) 04, P04017]

HeRSChel - High Rapidity Shower Counters

- installed at the end of 2014
  → *increase η coverage (5 < |η| < 10)*
- read-out synchronic LHCb
  → *5 stations with 4 scintillators with PMT*
- able to detect forward particle showers and veto events







B0 – high-rapidity collisions

F1, B1- high-rapidity collisions

F2, B2 – showers from high rapidity neutral particles

Production of J/ψ and $\psi(2S)$ at 13 TeV

[JHEP 1810 (2018) 167]

Selection

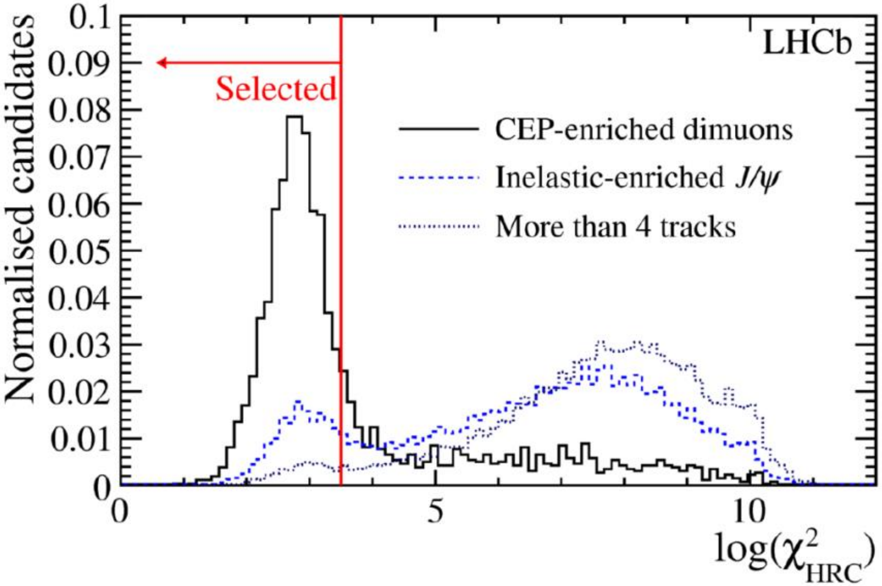
- 2 muons within $2 < \eta < 4.5$
- no additional tracks or energy
- J/ψ $p_T^2 < 0.8$ GeV^2
- within 65 MeV of the $M_{J/\psi}$

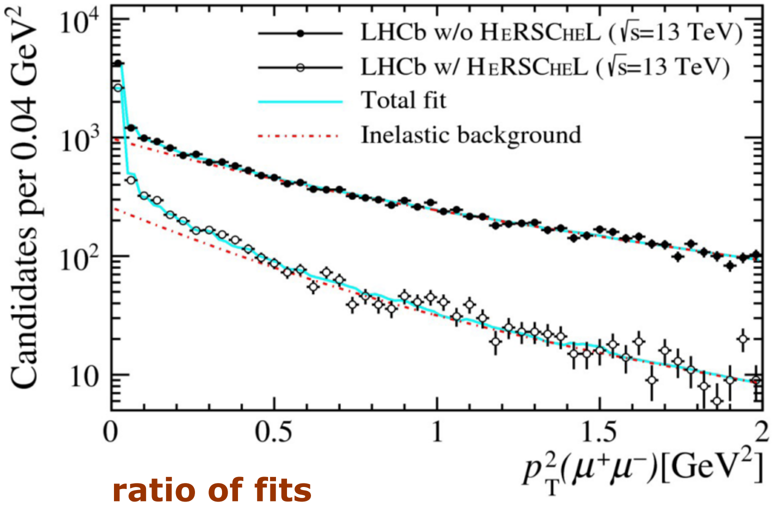
$L = 204$ pb^{-1} (2015)

14753 J/ψ candidates

440 $\psi(2S)$ candidates

HeRSCheL activity requirement





ratio of fits

→ *efficiency of the veto = 0.723±0.008*

χ^2_{HRC} quantifies the activity above noise, including correlations between counters

CEP-enriched dimuons

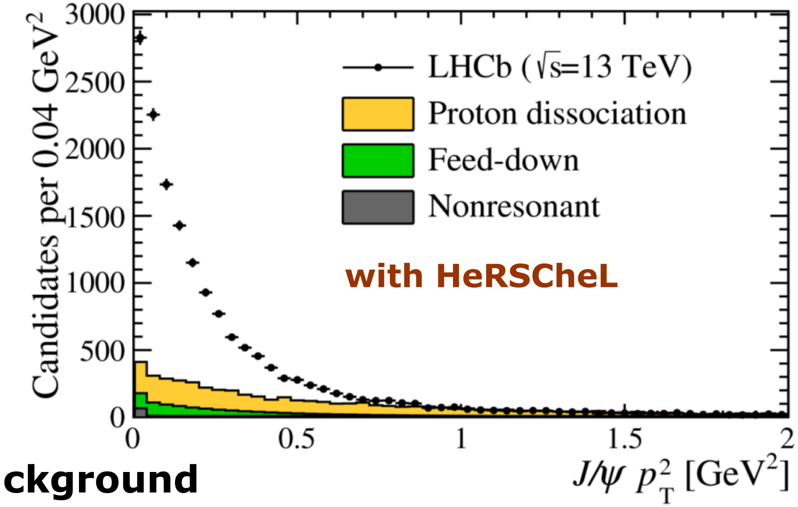
→ non-resonant dimuon events with $p^2_T < 0.01$ GeV^2 *(97% purity)*

Inelastic-enriched J/ψ

→ additional cut on J/ψ $p^2_T > 2$ GeV^2

Cross sections

[JHEP 1810 (2018) 167]

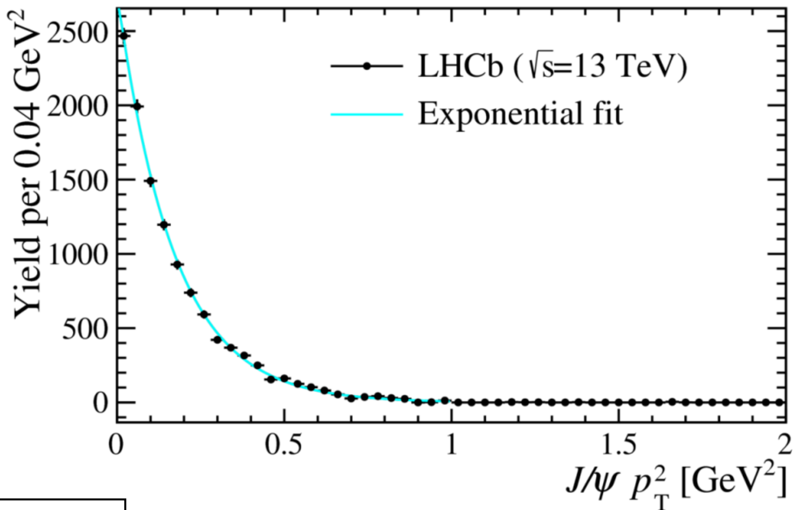


Efficiencies

- reconstruction and selection
  → *data driven methods*
- fraction of 1 interaction beam xings
  → *0.3662 ± 0.0003*

Background

- non-resonant dimuon
  → *from the invariant mass fit*
- feed-downs from $\chi_{cJ}(1P)$, $\psi(2S)$, …
  → *from data-calibrated simulation*
- proton dissociation → *fit to the p^2_T distribution*



$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy}(2.0 < \eta_\mu < 4.5) = \frac{\mathcal{P}N}{\epsilon_{rec}\epsilon_{sel}\Delta y \epsilon_{single}\mathcal{L}_{tot}},$$

Signal purity

0.755 ± 0.015 for *J/ψ*

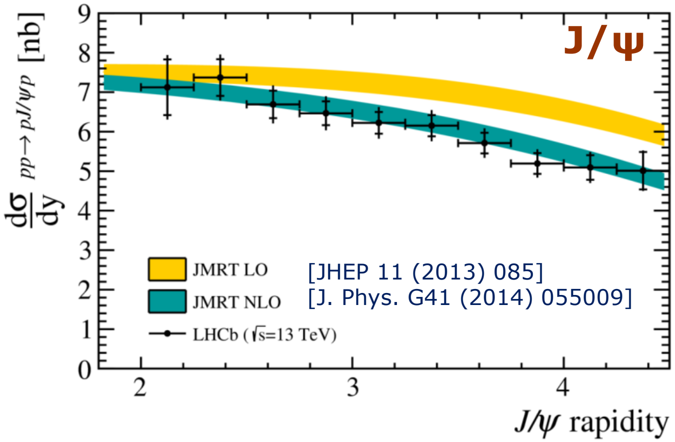
0.726 ± 0.061 for *ψ(2S)*

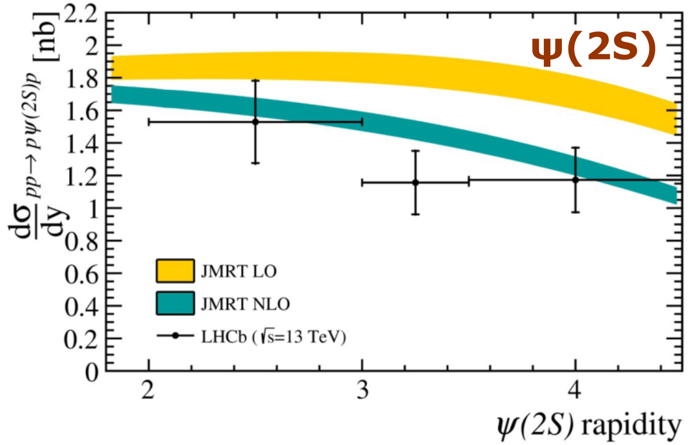
$$\sigma_{J/\psi\to\mu^+\mu^-}(2 < \eta < 4.5) = 435 \pm 18 \pm 11 \pm 17 \text{ pb}$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2 < \eta < 4.5) = 11.1 \pm 1.1 \pm 0.3 \pm 0.4 \text{ pb}.$$

Results

[JHEP 1810 (2018) 167]

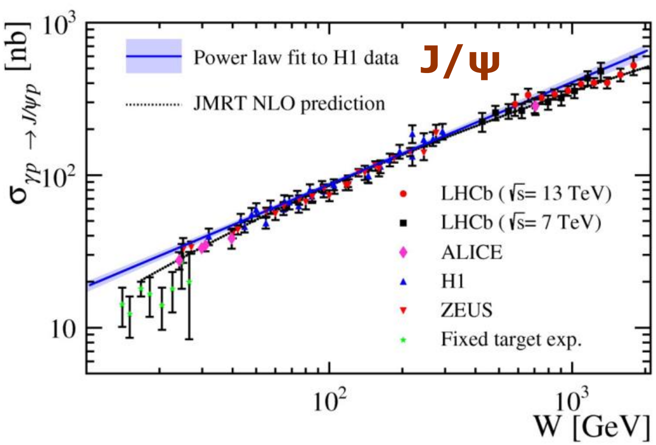
Results corrected by $J/\psi \rightarrow \mu\mu$ branching fractions and detector geometry

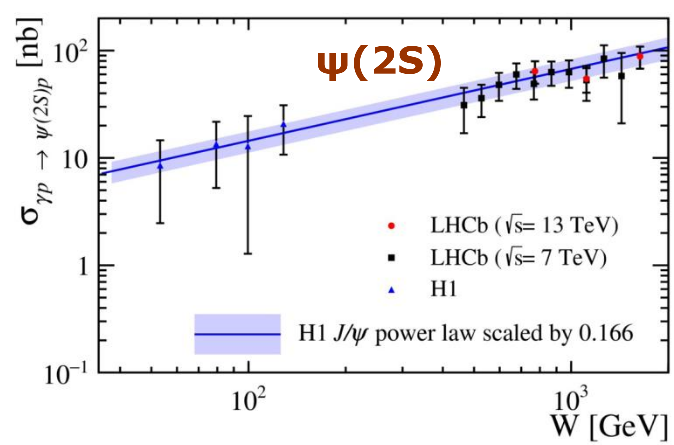




$$\sigma_{pp\rightarrow p\psi p} = r(W_+)k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\sigma_{\gamma p\rightarrow\psi p}(W_+) + r(W_-)k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\sigma_{\gamma p\rightarrow\psi p}(W_-).$$

r - gap survival factor, $\boldsymbol{k_\pm}$ - photon energy, $\boldsymbol{dn/dk_\pm}$ - photon flux, $\boldsymbol{W_\pm}$ - inv. mass of photon-proton system





- measured cross sections for J/ψ and $\psi(2S)$ in better agreement with JMRT NLO
- derived cross section for J/ψ photoproduction differs from power-law extrapolation of H1 data

Conclusions

Jet fragmentation can probe different aspects of hadronization

- heavy flavor tagged jets can probe quark mass effects if compared to light-quark jet results
- charmonium production mechanisms can be studied with collinear fragmentation within jets

First measurement of BEC in the forward region $2 < \eta < 5$

- measured correlation parameters slightly lower compared to results in central η region
- LHCb shows a potential to perform a set of further quantum correlations analyses with different hadrons, collision energies, collision types etc.

Central exclusive production of J/ψ and $\psi(2S)$

- measured cross-section for J/ψ photoproduction differs from a power-law extrapolation of H1 data