Multiplicity-dependent heavy flavour production at the LHCb experiment

QCHSC XVI (2024)

Jake Lane on behalf of the LHCb collaboration

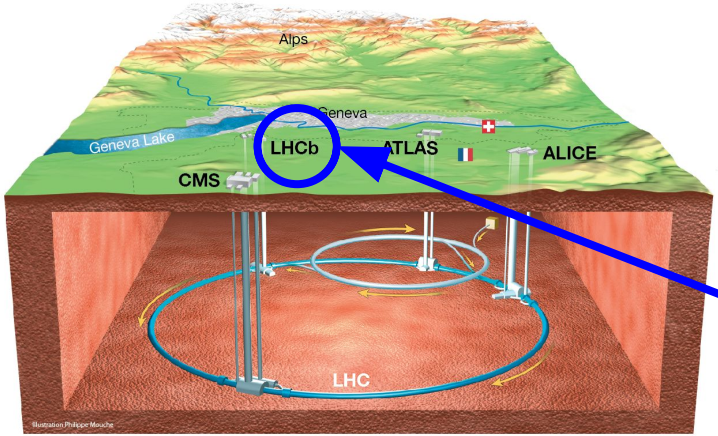
19-24 August 2024

Key points

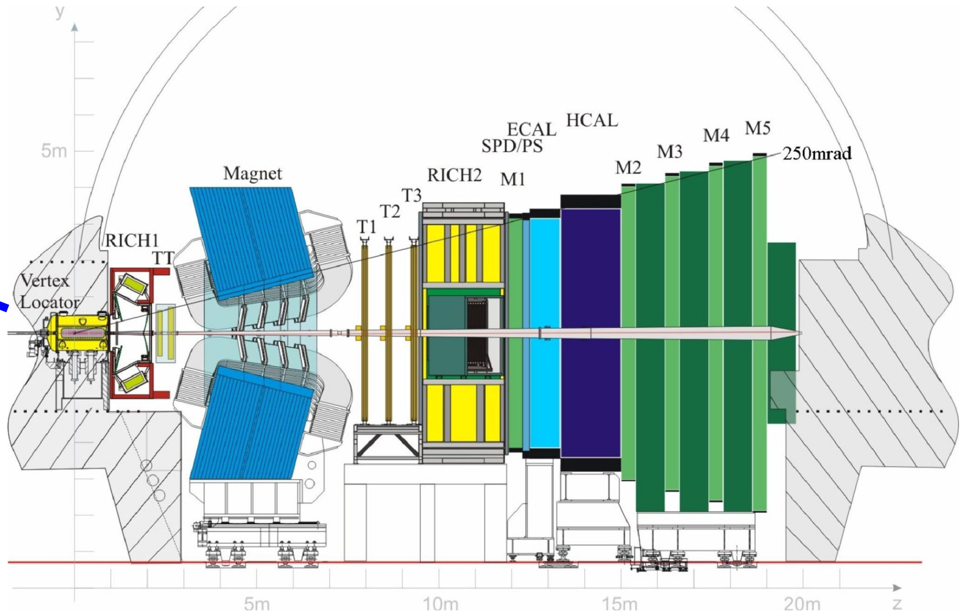
- LHCb studies heavy quark (b and c quark) physics from both proton and heavy ion collisions
- Heavy hadron physics at LHCb offers important insights into QCD
    - Co-mover effect in charmonia production
    - Strangeness enhancement in proton-lead collisions in the charm meson system
    - Modification of b quark hadronization
- Work is being done to produce RIVET plugins to connect experimental results to theorists to improve generators like Pythia

The LHCb Experiment

CERN-LHCC-98-004



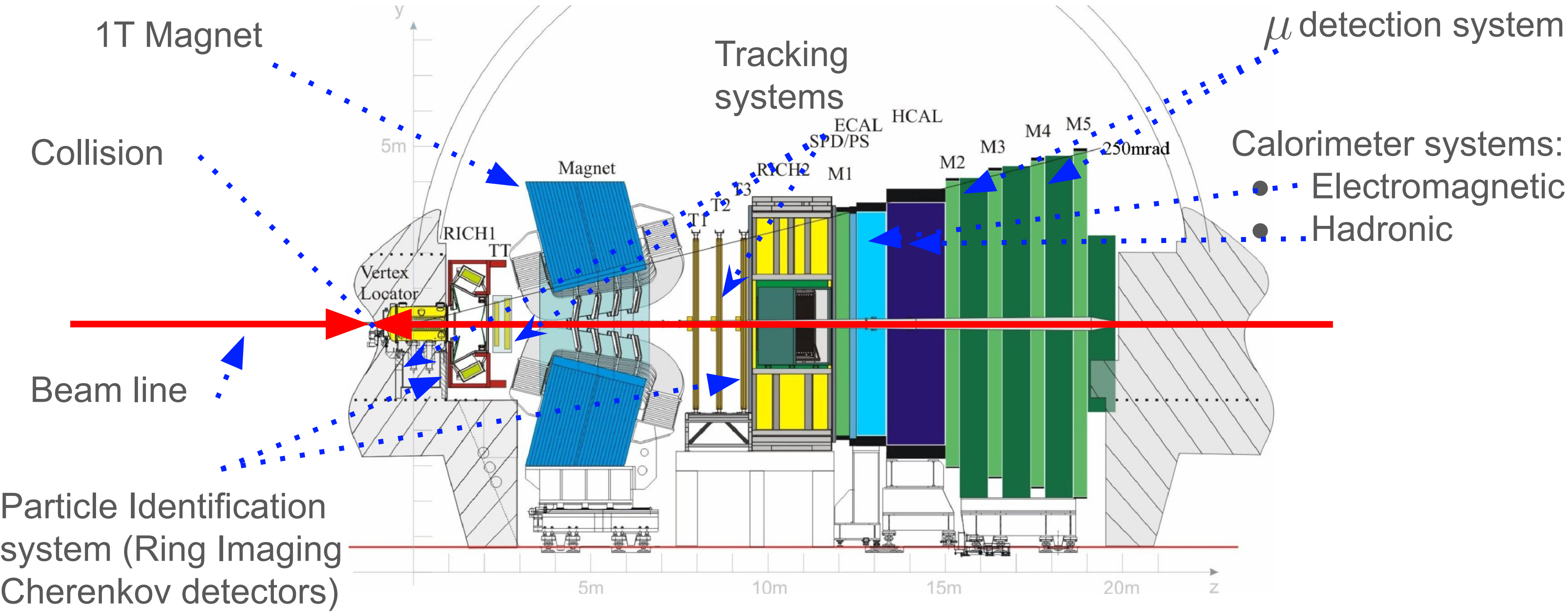
- LHC beauty experiment
- Point 8 of the LHC ring
- Forward arm spectrometer
- Has since been upgraded after Long Shutdown 2 (2018-2023)



Int.J.Mod.Phys.A 30 (2015) 07, 1530022 arxiv:1412.6352

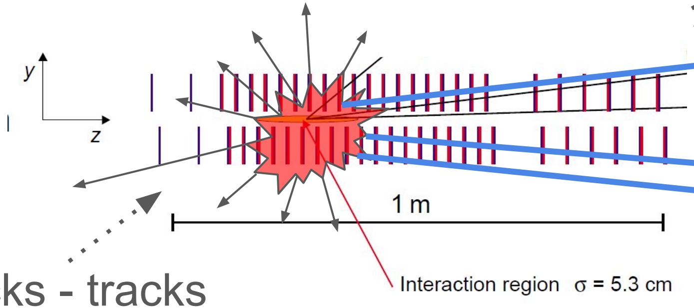
The LHCb Experiment

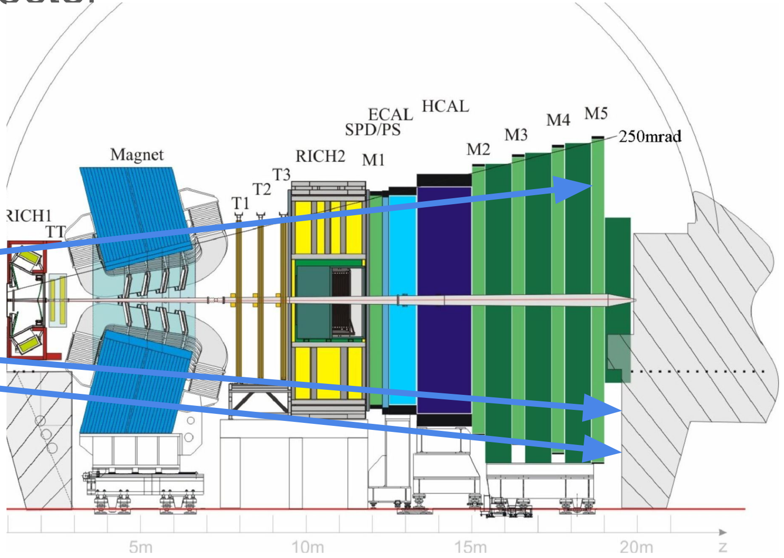
Int.J.Mod.Phys.A 30 (2015) 07, 1530022 arXiv:1412.6352



Event multiplicity in the VErtex LOcator (VELO)

Forward tracks - particles traverse towards rest of detector





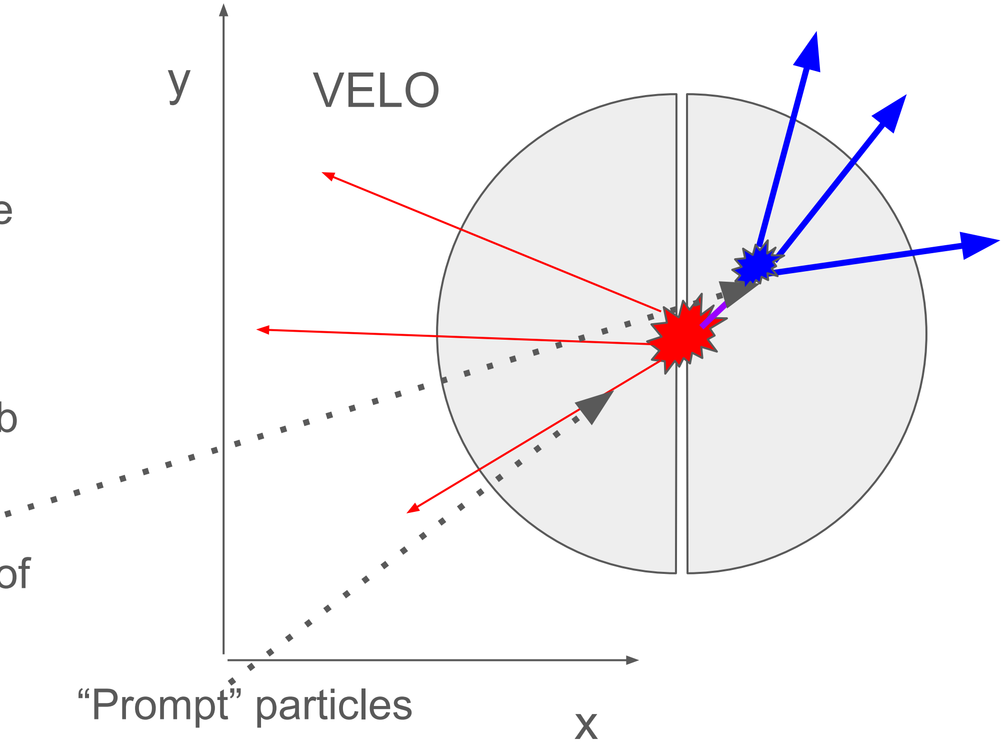
Backwards tracks - tracks are detected in the VELO but momentum/energy is not measured

Int.J.Mod.Phys.A 30 (2015) 07, 1530022 [arXiv:1412.6352]

Vertex reconstruction

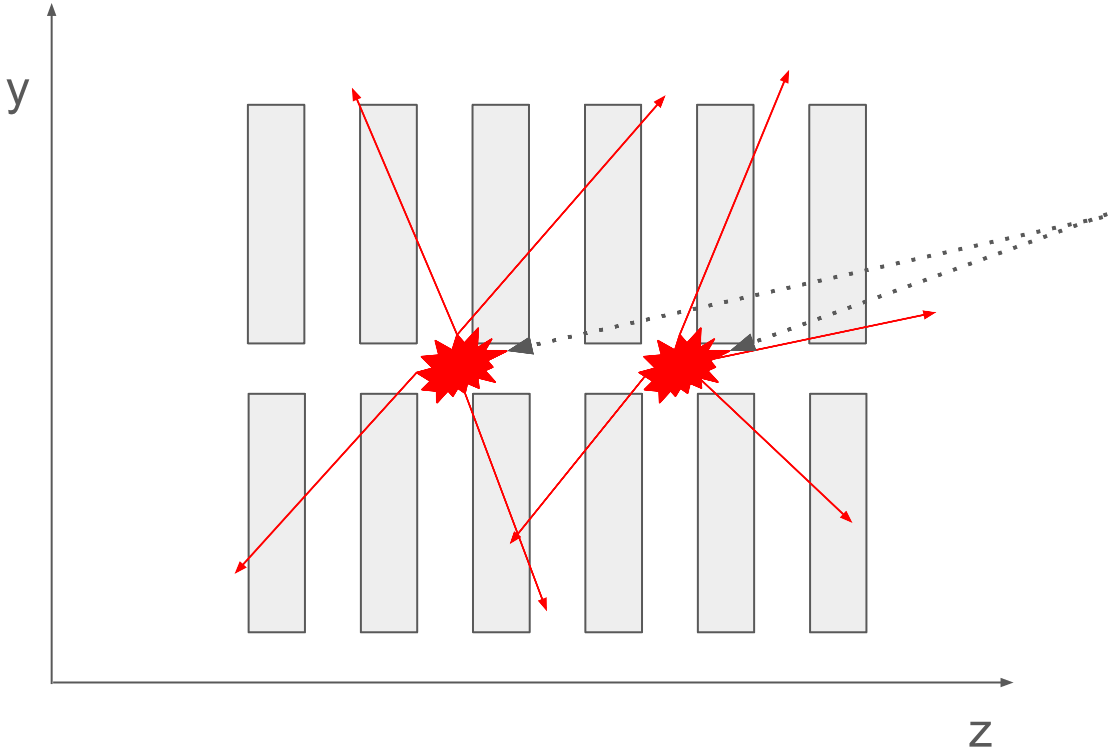
JINST 14 (2019) 04, P04013 arXiv:1812.10790

- Tracking and vertex reconstruction, 5 mm from the beam line.
- Reconstructs primary vertex (from initial hadron collisions) and secondary vertices from b (and c) hadrons.
- Distance between secondary and primary vertex ≈ lifetime of b (and c) hadron



Vertex reconstruction

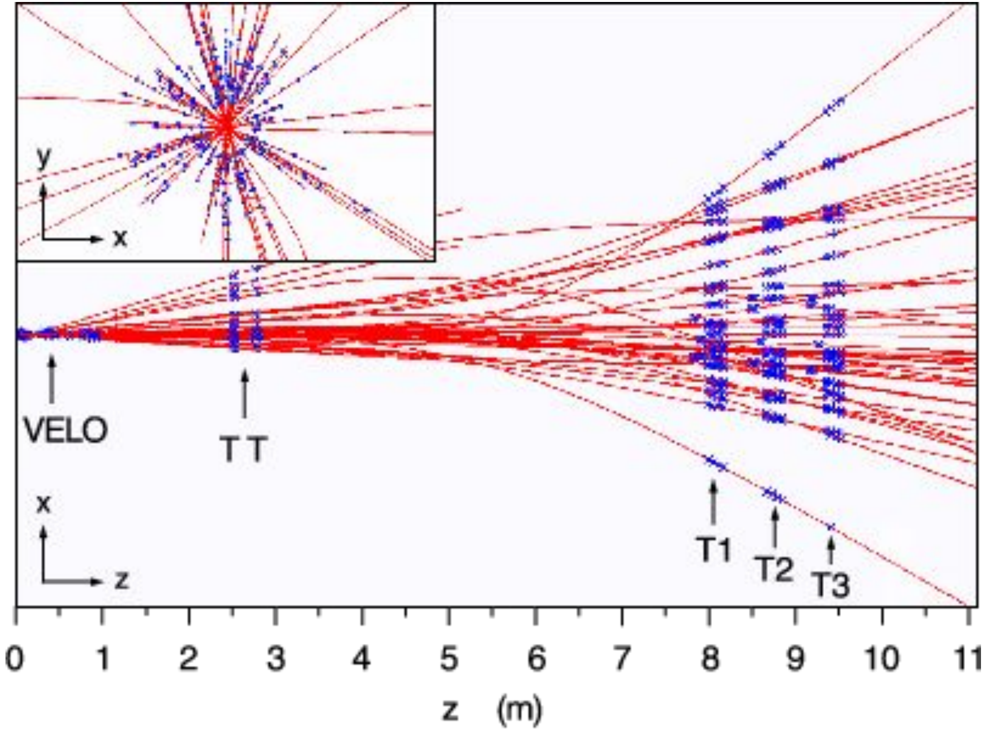
Int.J.Mod.Phys.A 30 (2015) 07, 1530022 [arXiv:1412.6352]

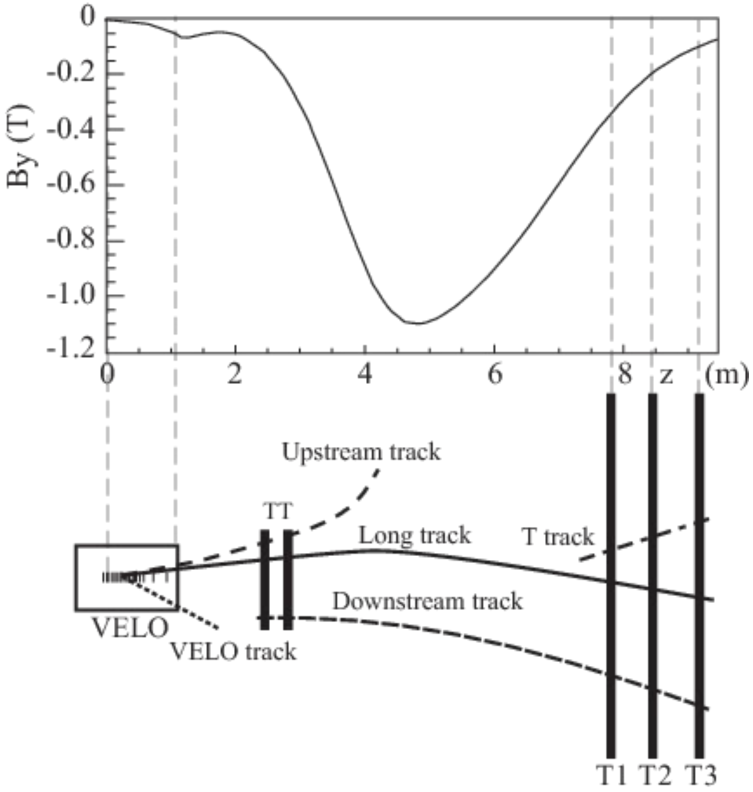


Able to distinguish multiple PVs from a collision.

Tracking at LHCb

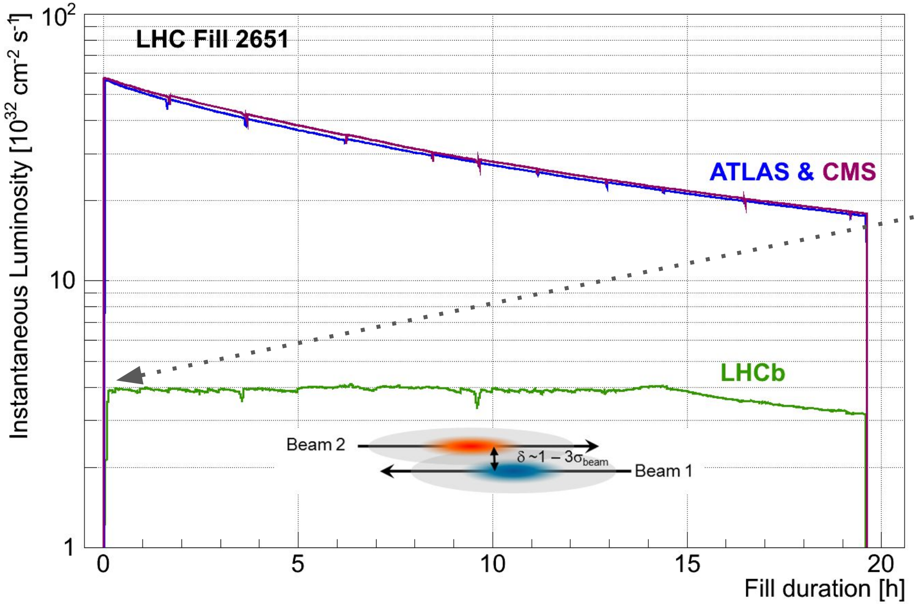
JINST 14 (2019) 04, P04013 arXiv:1812.10790





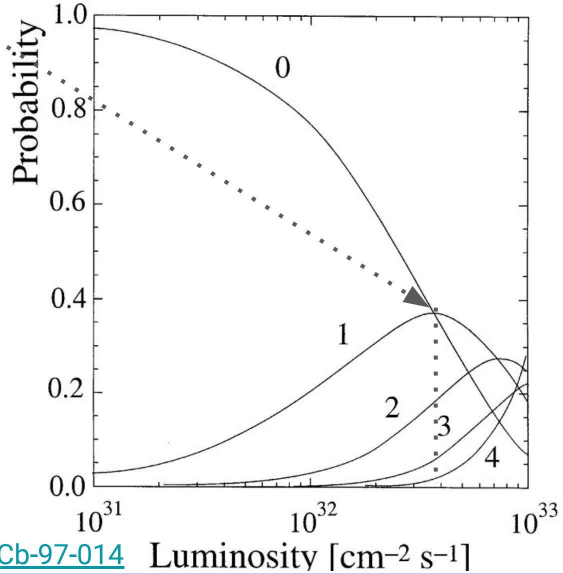
Int.J.Mod.Phys.A 30 (2015) 07, 1530022 arXiv:1412.6352

Luminosity at LHCb



Int.J.Mod.Phys.A 30 (2015) 07, 1530022 [arXiv:1412.6352]

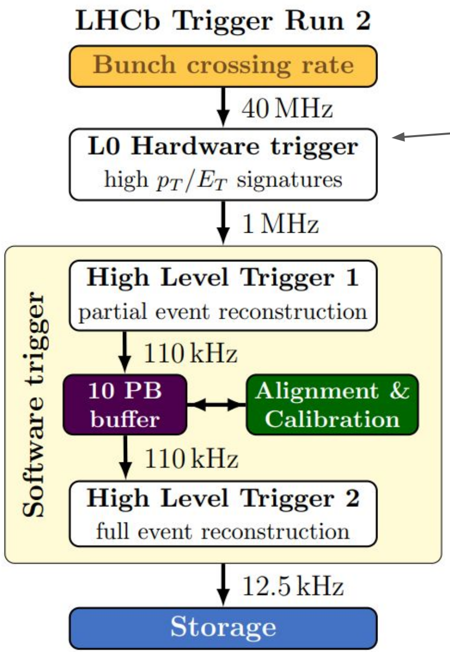
- Beams are less focused at the interaction point
- Luminosity set to maximise the probability of single pp collision



CERN-LHCb-97-014

Trigger system

JINST 14 (2019) 04, P04013 arXiv:1812.10790



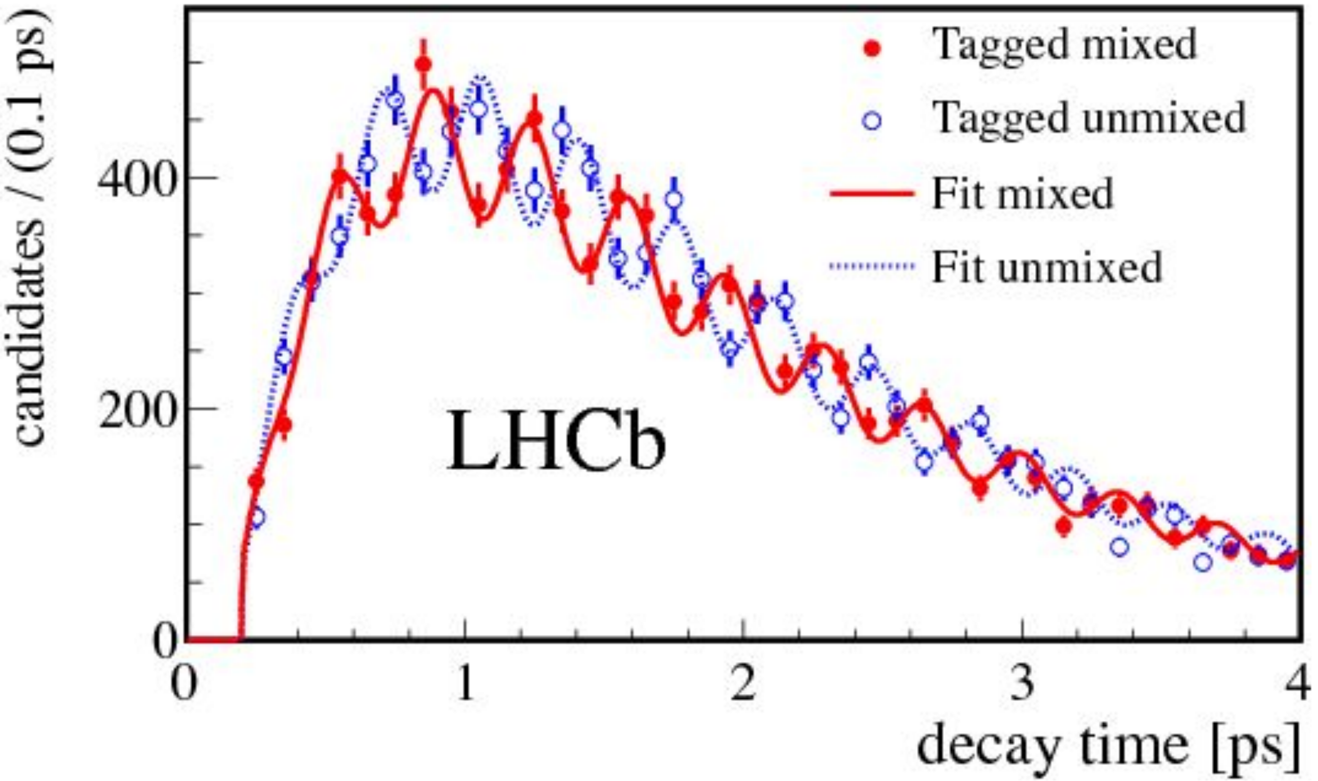
- From 40 MHz to 12.5 kHz, need to trigger for relevant physics
- L0 trigger : looks for hadron, muon (di-muon) and electromagnetic signals
- Two stages of software trigger (event building/buffering/calibration in HLT1, more sophisticated offline selection in HLT2)
- Analyses will start from a “trigger line” that filters events for relevant physics
- Minimum bias (or no bias) attempts to find events that show an “average” behaviour from collisions

LHCb precision

New J.Phys. 15 (2013) 053021 arXiv:1304.4741

B_s^0 - $\bar{B}_s^0$ mixing

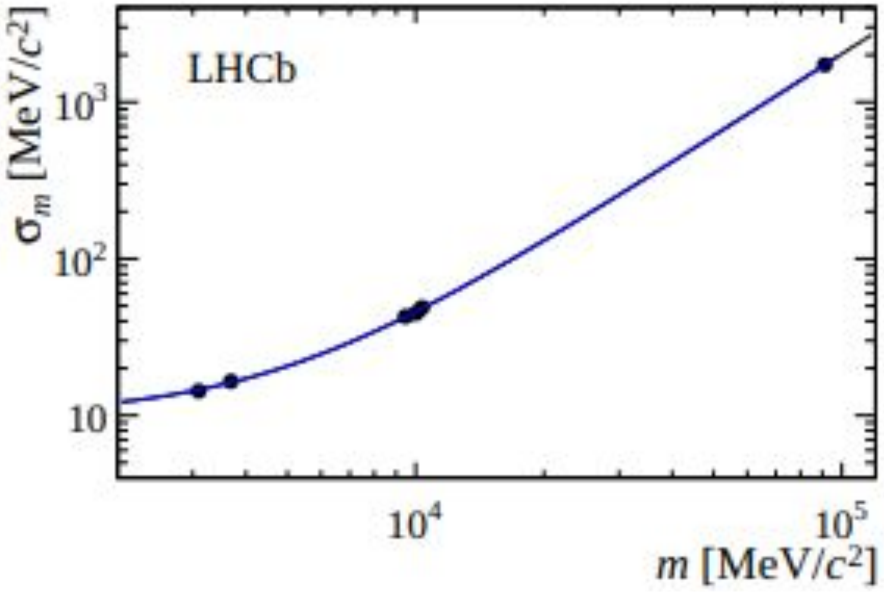
Excellent timing resolution due to excellent PV reconstruction

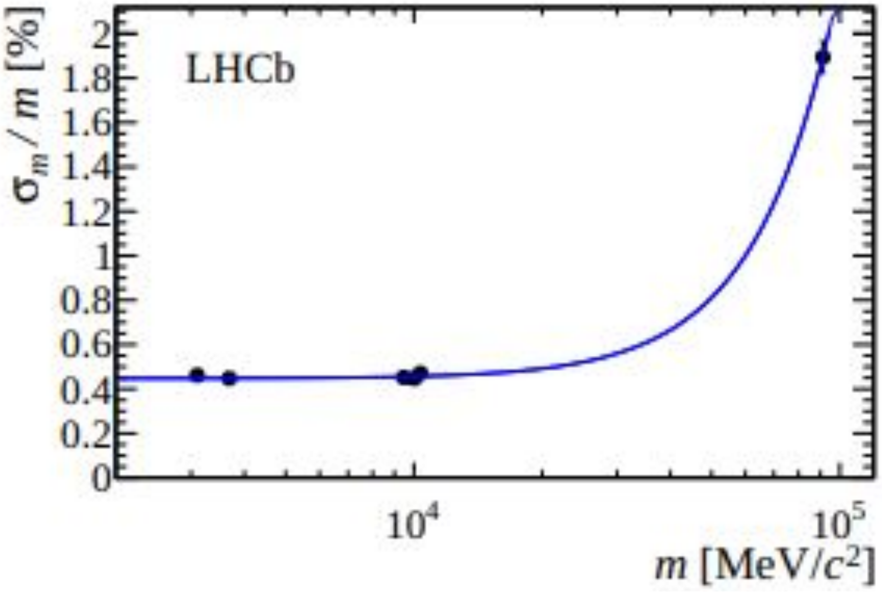


LHCb precision

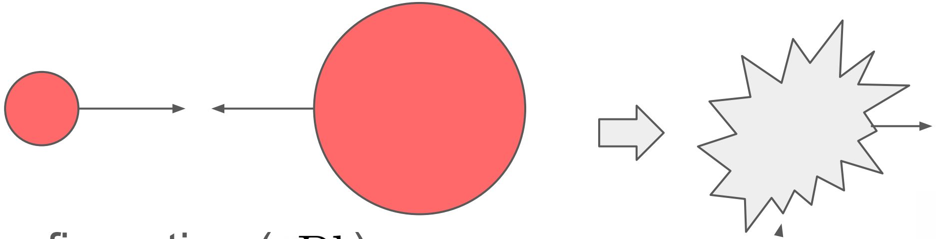
Int.J.Mod.Phys.A 30 (2015) 07, 1530022 arXiv:1412.6352

Excellent mass resolution at a wide range





Proton – Ion collisions at LHCb

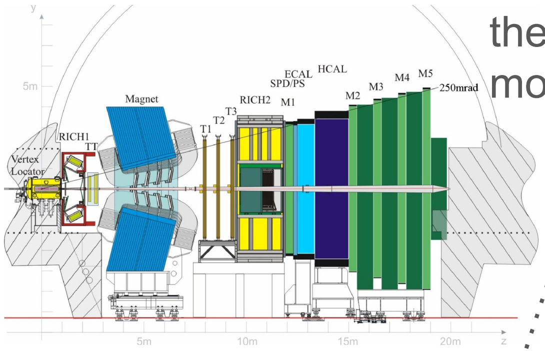


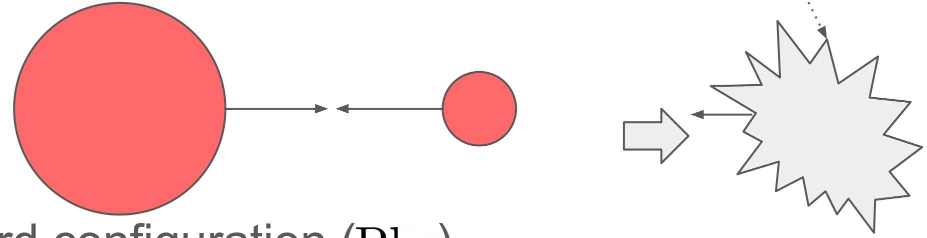
Forward configuration (pPb)

Boosted system ($\Delta y = 0.46$)

$1.5 < y^* < 4$

Rapidity is defined with respect to the proton momentum





$-5 < y^* < -2.5$

Backward configuration (Pbp)

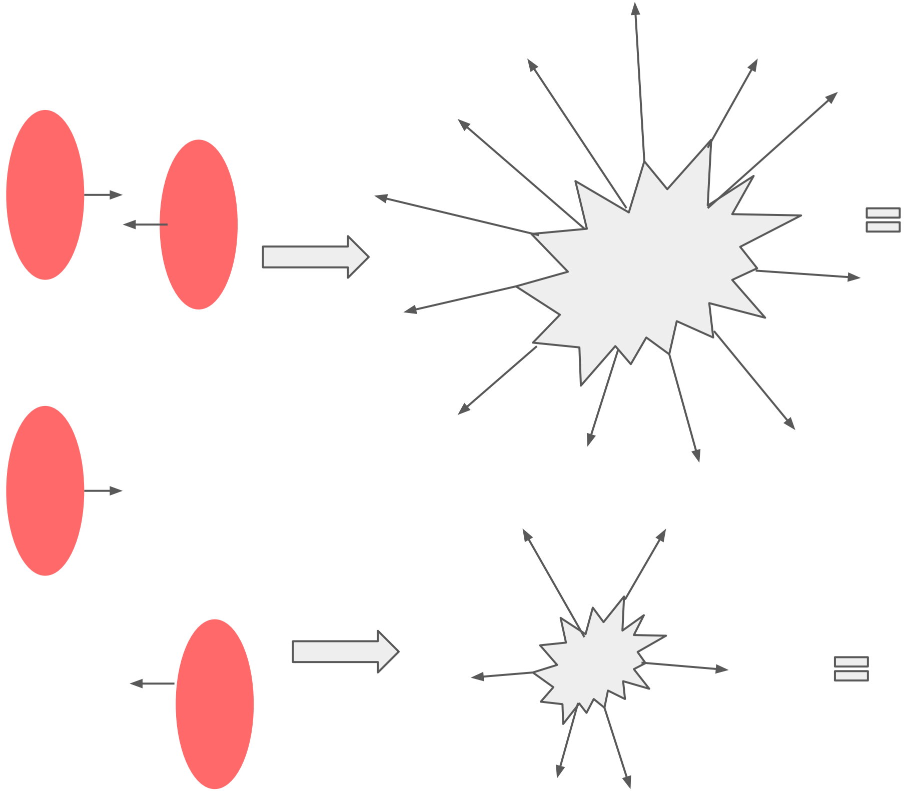
Density of hadronic medium (experimental view)

Central collision

- More overlap of partons
- Denser hadronic medium
- More likely to form QGP (in ion collisions)

Peripheral collision

- Sparser hadronic medium



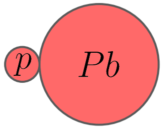
More tracks observed from the PV

Fewer tracks from the PV

Papers to cover

1. $\sigma_{\psi(2S)} : \sigma_{J/\psi}$ as a function of multiplicity from pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ JHEP 05 (2024) 243 arXiv:2312.15201
    - Charmonia suppression from fragmentation (affects all charmonia states equally) v.s. the co-moving effect

Papers to cover

2. $\sigma_{D_s^{\pm}} : \sigma_{D^{\pm}}$ as a function of multiplicity from 

collisions at $\sqrt{s_{NN}} = 8.16 \text{ TeV}$

Submitted to Phys. Rev. Lett. [arXiv:2311.084090]

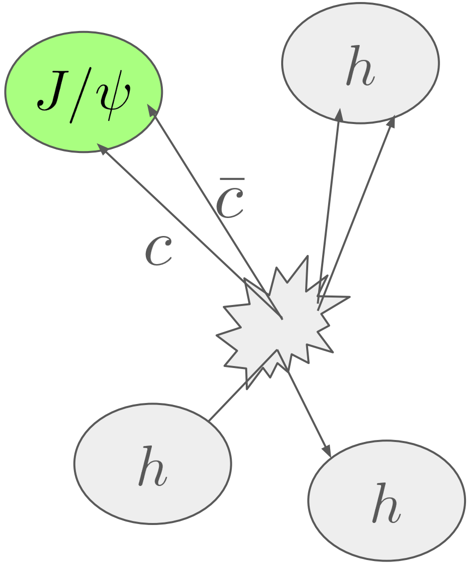
- Observation of strangeness enhancement in the charm meson system in collisions

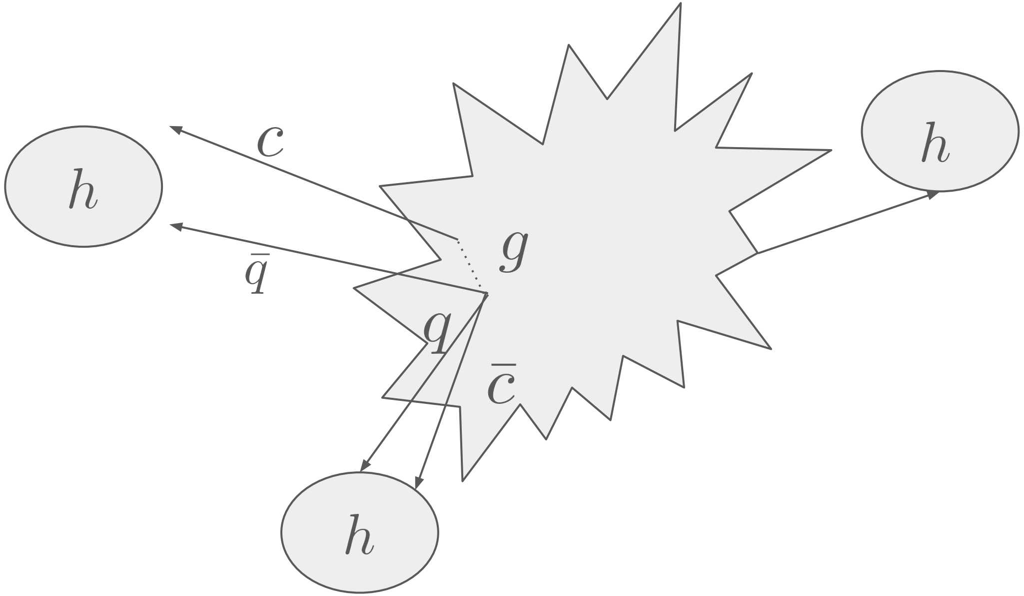
Papers to cover

3. $\sigma_{B_s^0} : \sigma_{B^0}$ as a function of multiplicity from pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$

Phys.Rev.Lett. 131 (2023) 061901 [arXiv:2204.13042]

- B_s^0 production via fragmentation of quarks v.s. coalescence of b and s quark wave-functions in the hadronic medium



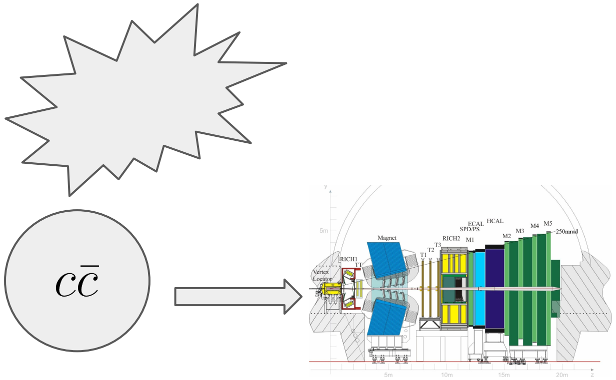


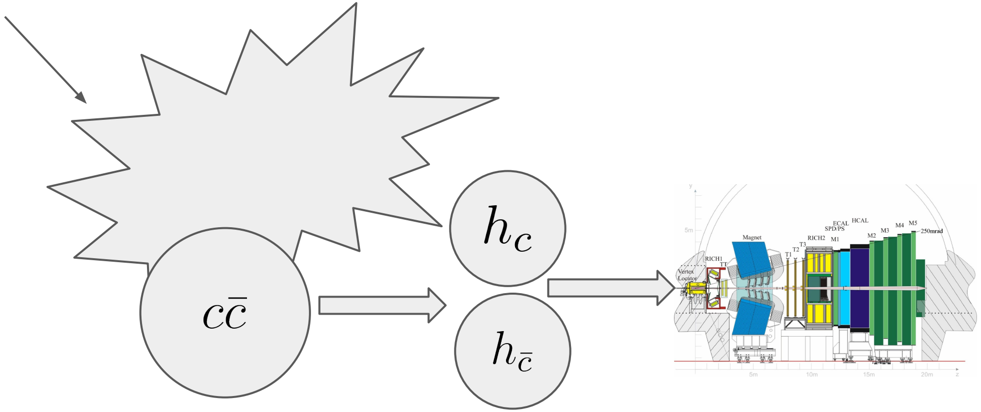
More dense hadronic medium - quarkonia production is suppressed due to screening

$\sigma_{\psi(2S)} : \sigma_{J/\psi}$ JHEP 05 (2024) 243 arXiv:2312.15201

pp

More dense hadronic medium = larger overlap between charmonia and hadronic medium wave functions

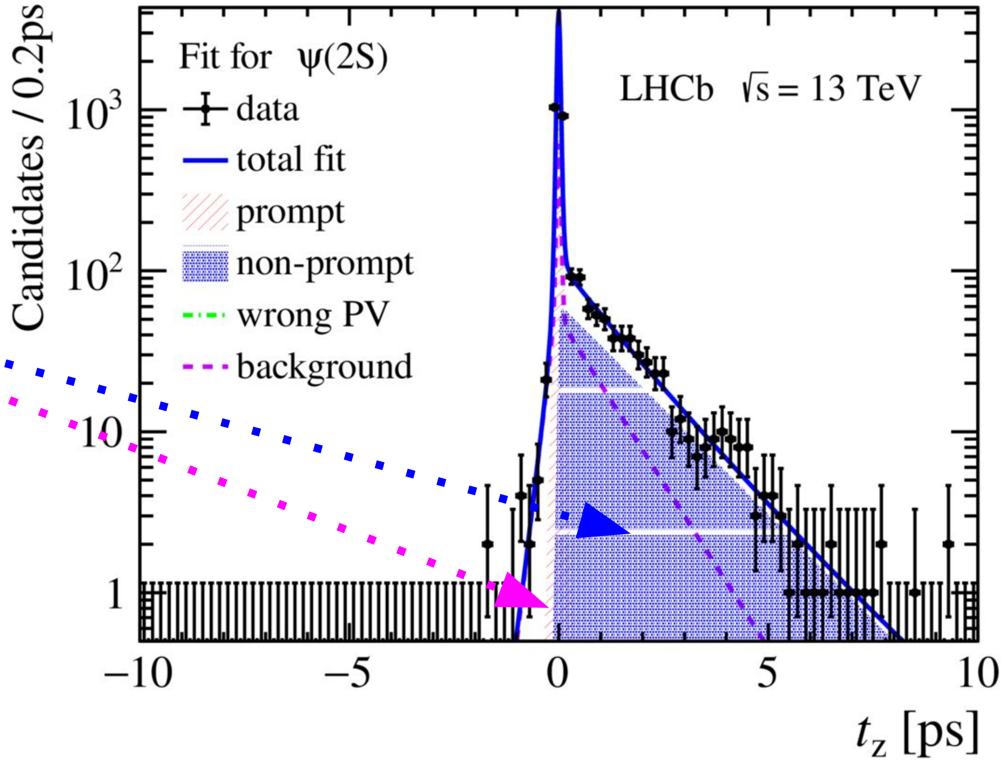




Charmonia with larger radii more likely to interact with hadronic medium to split into open charm hadrons

Prompt and non-prompt events are distinguished using the pseudo decay time from the VELO

$$t_z \equiv (z - z_{\mathrm{PV}})\frac{m}{p_z}$$

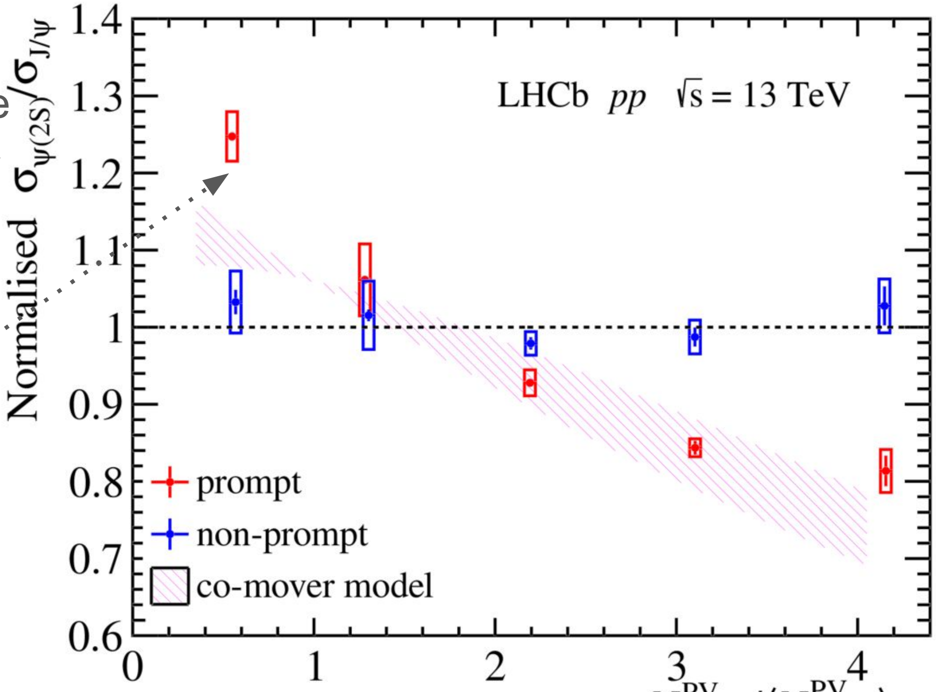


$\sigma_{\psi(2S)} : \sigma_{J/\psi}$ JHEP 05 (2024) 243 arXiv:2312.15201

y-axis : the ratio with detector effects, integrated over the kinematic phase-space

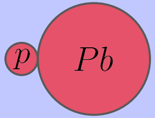
$$\frac{\sigma_{\psi(2S)}(p_{\mathrm{T}},y)}{\sigma_{J/\psi}(p_{\mathrm{T}},y)} = \frac{N_{\psi(2S)}(p_{\mathrm{T}},y)}{N_{J/\psi}(p_{\mathrm{T}},y)} \times \frac{\epsilon_{\mathrm{tot},J/\psi}(p_{\mathrm{T}},y)}{\epsilon_{\mathrm{tot},\psi(2S)}(p_{\mathrm{T}},y)} \times \frac{\mathcal{B}_{J/\psi\to\mu^+\mu^-}}{\mathcal{B}_{\psi(2S)\to e^+e^-}}$$

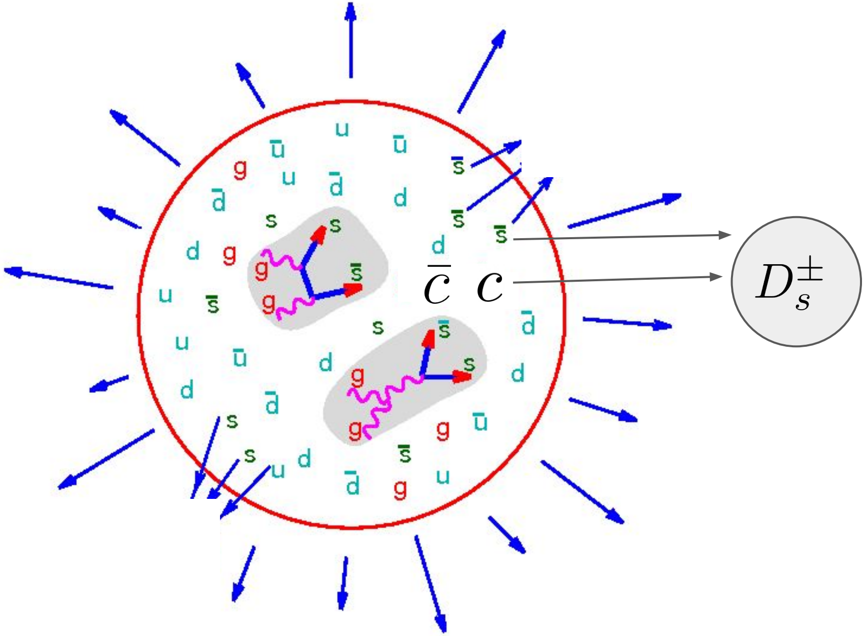
- Clear decline in prompt events
- Non-prompt (from B mesons) are unaffected by the hadronic medium



x-axis : relative number of tracks compared to $\langle N^{\mathrm{PV}}_{\mathrm{tracks}} \rangle_{\mathrm{NB}} \approx 27$ $N^{\mathrm{PV}}_{\mathrm{tracks}}/\langle N^{\mathrm{PV}}_{\mathrm{tracks}}\rangle_{\mathrm{NB}}$

$\sigma_{D_s^{\pm}} : \sigma_{D^{\pm}}$ Phys. Rev. Lett. arXiv:2311.084090



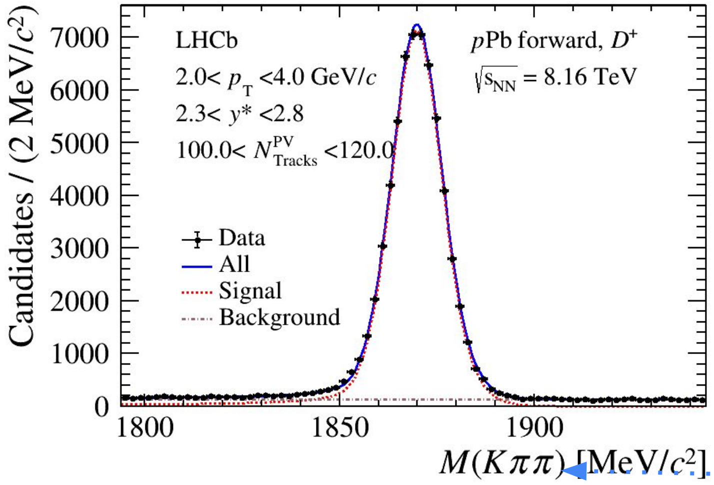


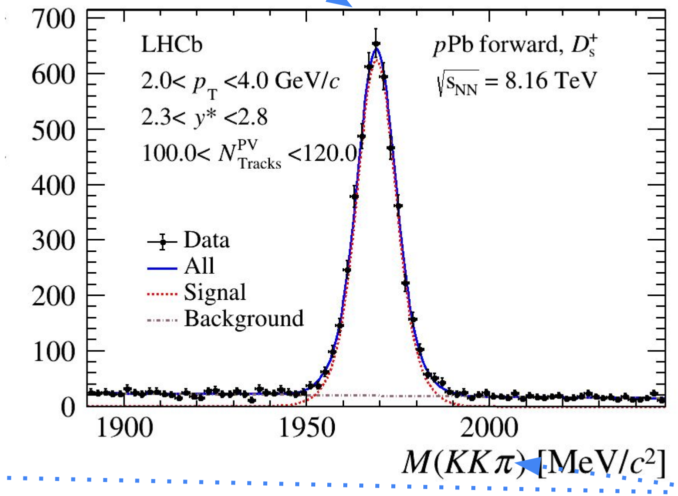
- If QGP like effects occur in collisions, strangeness enhancement (higher density of strange quarks due to partial restoration of chiral symmetry) could occur.
- Increasing the relative number of strange charmed mesons to charmed mesons

$\sigma_{D_s^\pm} : \sigma_{D^\pm}$ Phys. Rev. Lett. arXiv:2311.084090

p Pb

Mass resolution enables distinction between $D_s^\pm$ and $D^\pm$

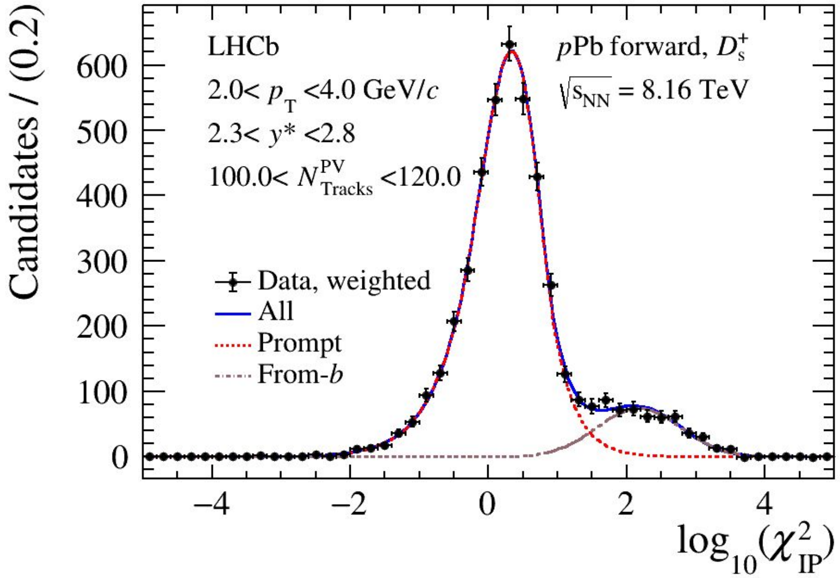


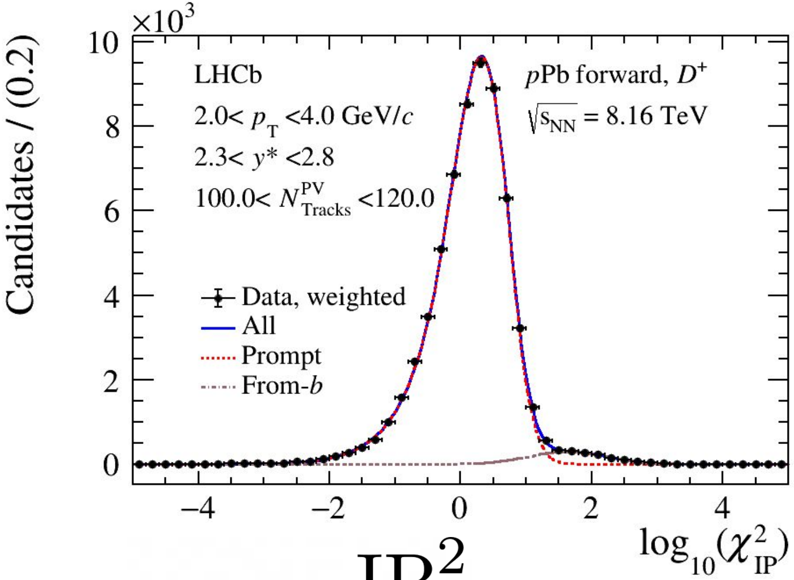


Cabibbo favoured final states

$\sigma_{D_s^\pm} : \sigma_{D^\pm}$ Phys. Rev. Lett. arXiv:2311.084090

p Pb



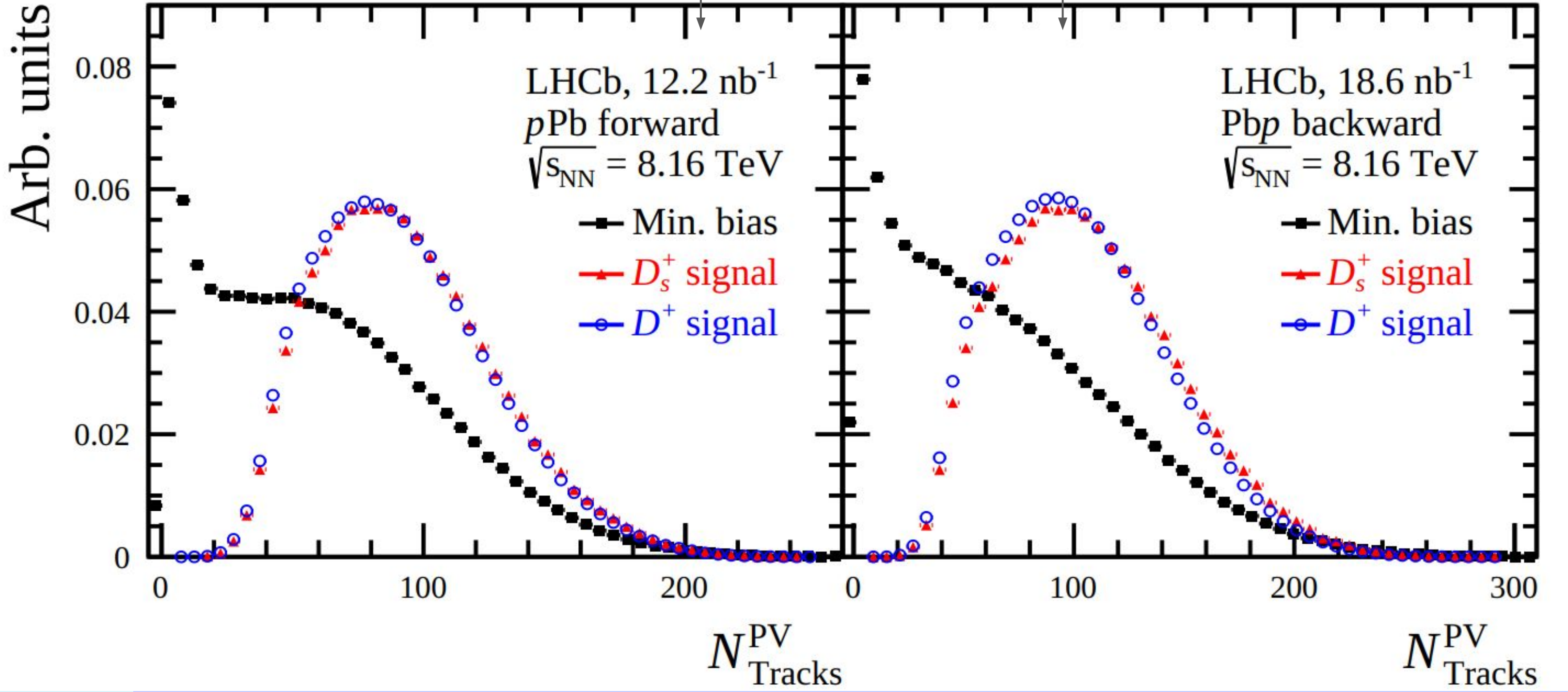


Can distinguish prompt $D_s^\pm$ and from B decays

$$\chi^2_{IP} \equiv \frac{IP^2}{\sigma^2_{IP}}$$

$\sigma_{D_s^\pm} : \sigma_{D^\pm}$ Phys. Rev. Lett. arXiv:2311.084090

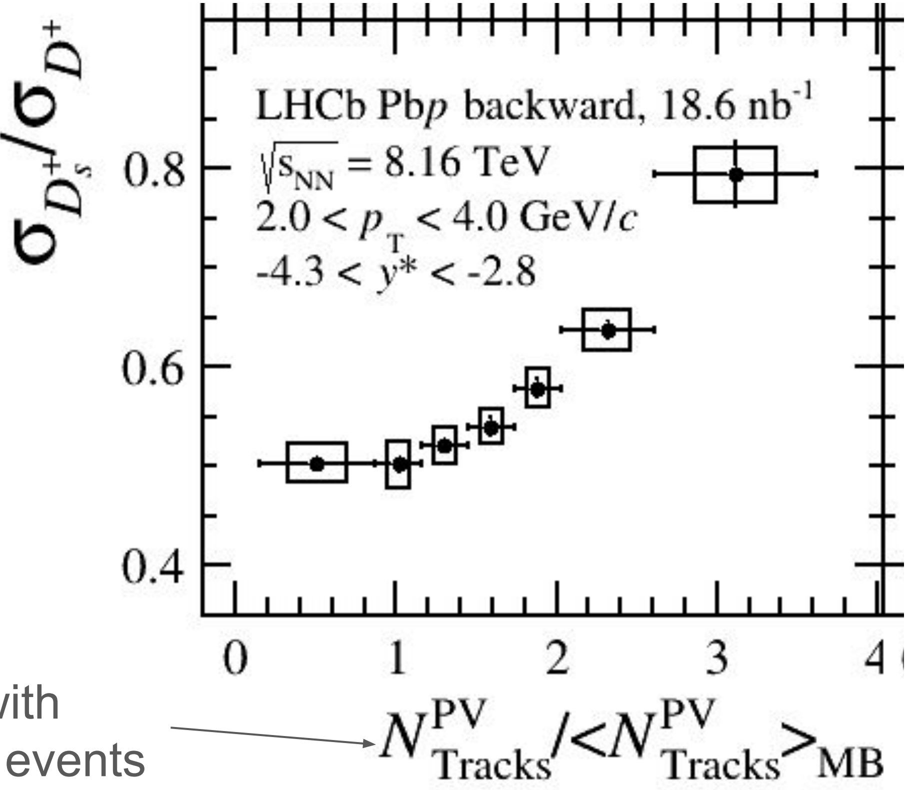
$\langle N^{\rm PV}_{\rm tracks} \rangle_{\rm MB} \approx$ 60 69



$\sigma_{D_s^\pm} : \sigma_{D^\pm}$ Phys. Rev. Lett. arXiv:2311.084090

y-axis - ratio of cross-sections between $D_s^\pm$ and $D^\pm$ production

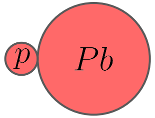
$$\frac{\sigma_{D_s^+}}{\sigma_{D^+}} = \frac{N_{D_s^+}}{N_{D^+}} \times \frac{\mathcal{B}_{D^+}}{\mathcal{B}_{D_s^+}} \times \frac{\epsilon^{\mathrm{acc}}_{D^+}}{\epsilon^{\mathrm{acc}}_{D_s^+}}$$

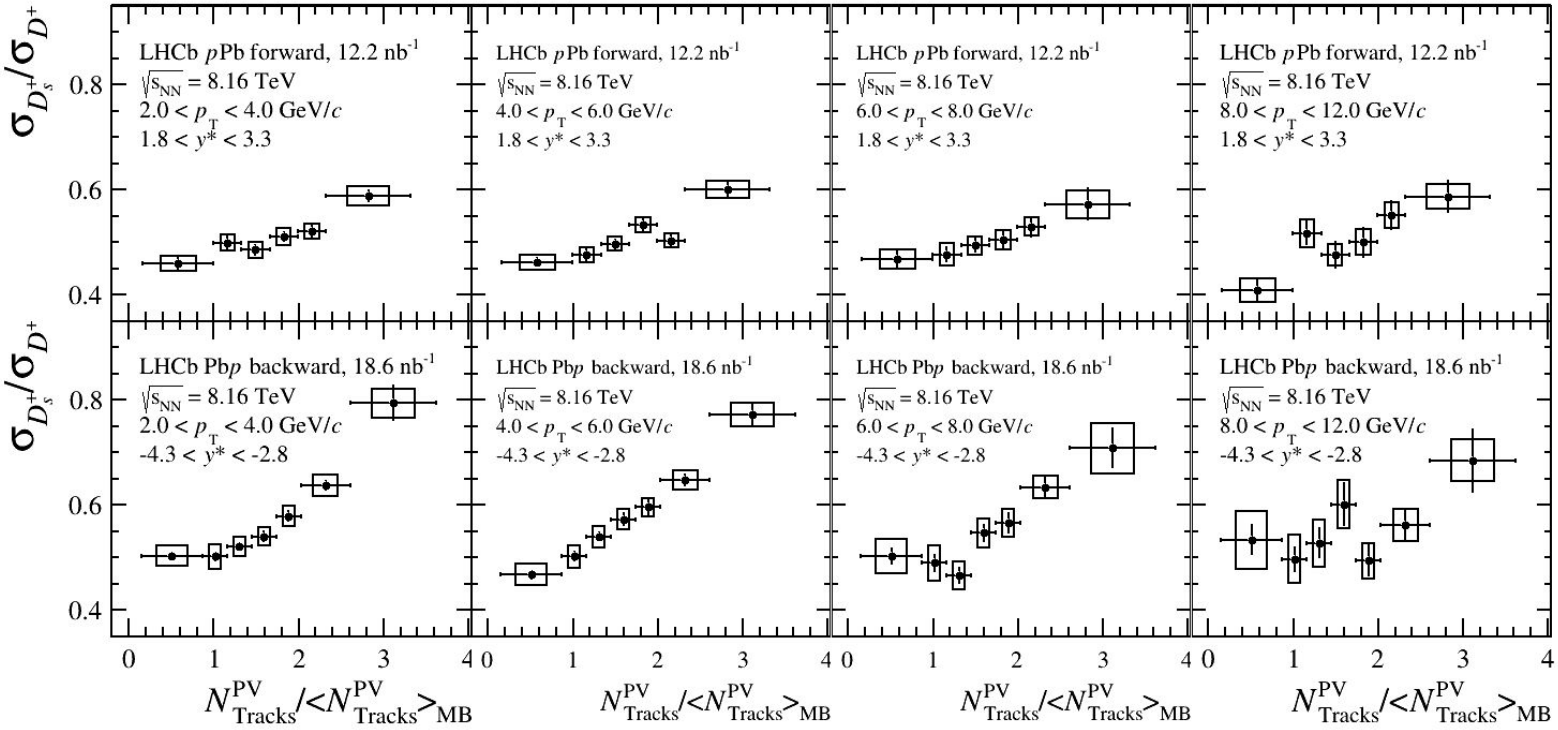


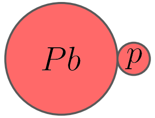
Density of the collision, with respect to minimum bias events

$\sigma_{D_s^\pm} : \sigma_{D^\pm}$ Phys. Rev. Lett. arXiv:2311.084090

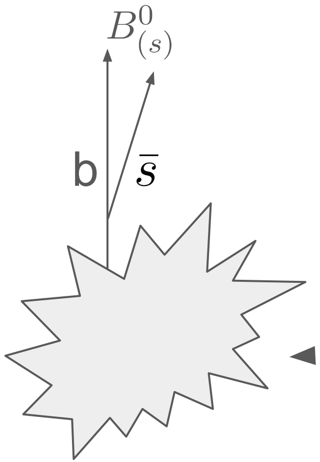
Strangeness enhancement in all kinematic regions



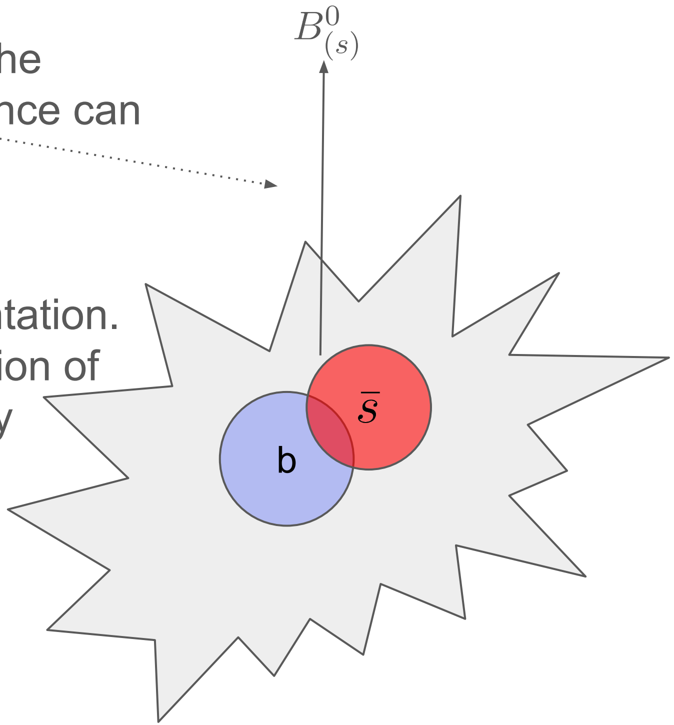




$\sigma_{B_s^0} : \sigma_{B^0}$ Phys.Rev.Lett. 131 (2023) 061901 arXiv:2204.13042

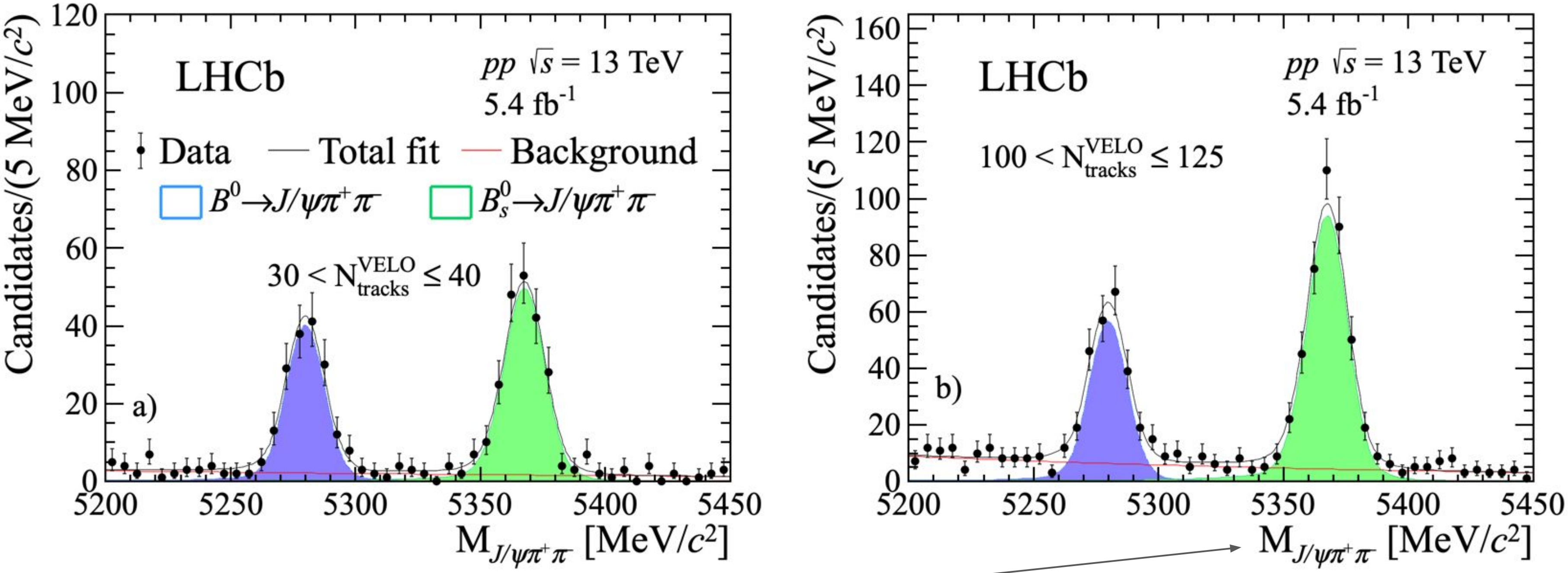


- If b and s quarks overlap in the hadronic medium - coalescence can occur,
- More likely with more dense hadronic medium
- This is in addition to fragmentation.
- Coalescence increases fraction of B_s^0 to B^0 with higher density



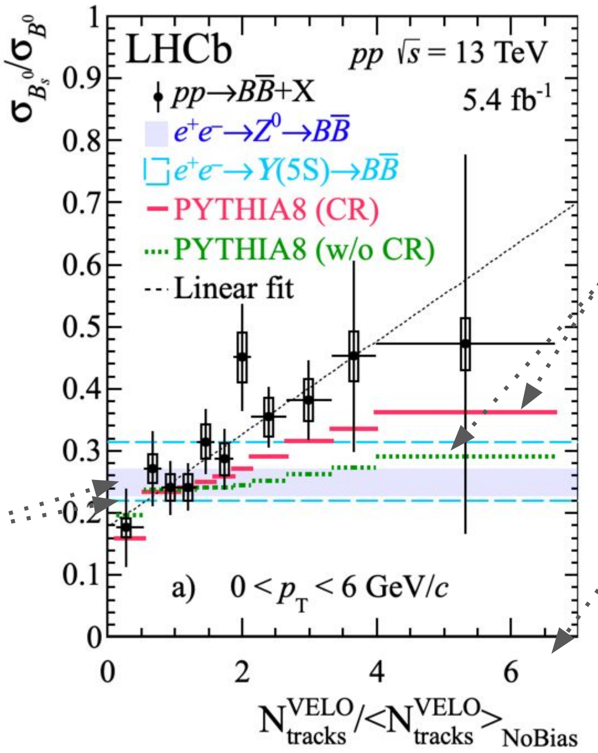
$B^0_{(s)}$ is formed from fragmentation of b quark emerging from hadronic medium

$\sigma_{B_s^0} : \sigma_{B^0}$ Phys.Rev.Lett. 131 (2023) 061901 arXiv:2204.13042



Same final state

$$\frac{\sigma_{B_s^0}}{\sigma_{B^0}} = \frac{N_{B_s^0}}{N_{B^0}} \times \frac{\mathcal{B}_{B^0}}{\mathcal{B}_{B_s^0}} \times \frac{\varepsilon_{B^0}}{\varepsilon_{B_s^0}}$$



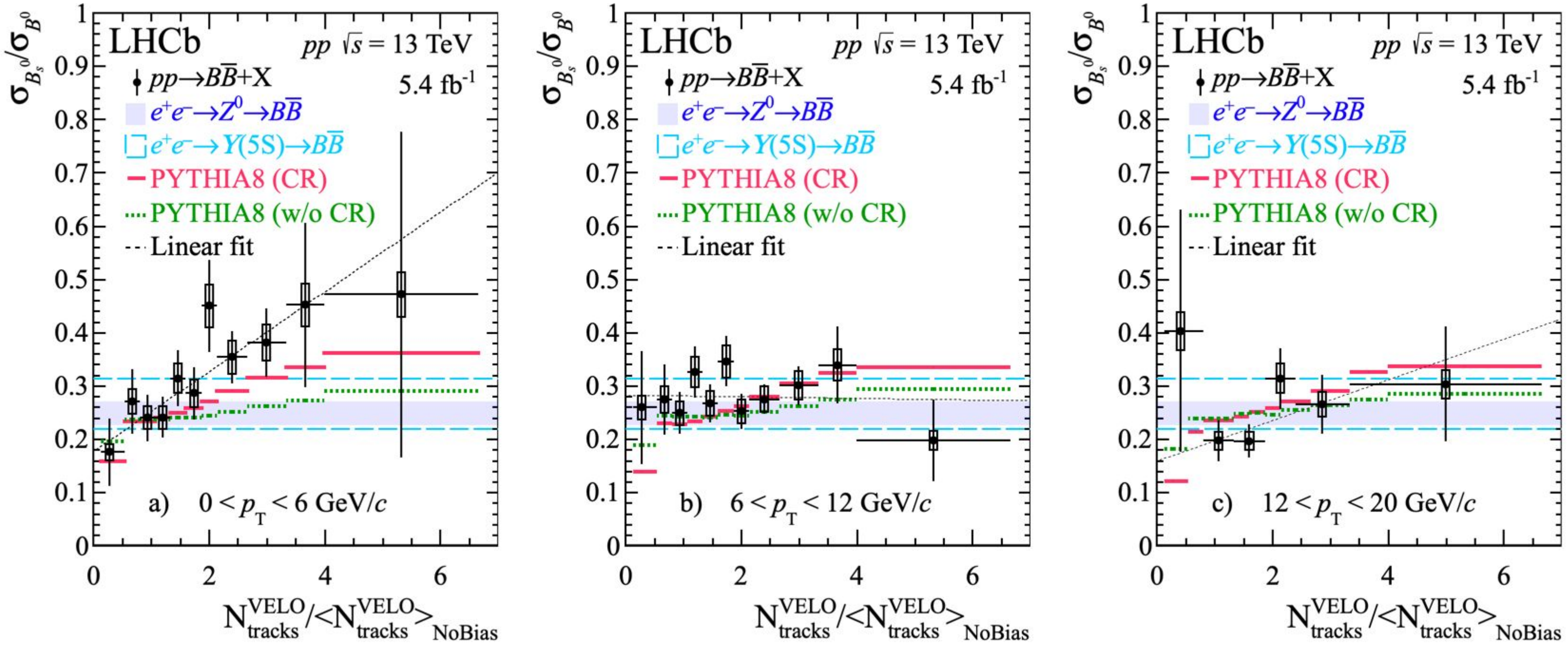
Pythia considers only hadronisation through fragmentation.
The simulation uses an infinite

Number of tracks that produced the $B^0_{(s)}$ is compared to the number produced in collisions with no bias (i.e. random trigger decisions)

$$\langle N_{\rm tracks}^{\rm PV} \rangle_{\rm NoBias} \approx 38$$

Results are compared to the e^+e^- experiments, which are single points

$\sigma_{B_s^0} : \sigma_{B^0}$ Phys.Rev.Lett. 131 (2023) 061901 arXiv:2204.13042



Increasing transverse momentum, weaker enhancement with multiplicity

Conclusion

- The hadronic medium affects the production of heavy hadrons
- Evidence of the co-mover effect in suppressing charmonia in high multiplicity collisions
- Evidence of different contributions to the heavy hadron production other than fragmentation
- Strangeness enhancement observed in the charm systems in proton-lead collisions
- Results will be useful for QCD theory calculations/tuning event generators
  - We are working on more RIVET plugins to connect theory to experimental results

Thank you for listening