Global analysis of heavy-ion collisions at the LHCb collaboration

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Outline

1. The LHCb collaboration at CERN
2. The LHCb detector and its particularities
3. Open questions on heavy-ion physics
4. Characterisation of heavy-ion collisions: centrality determination

   ➡ How-to at LHCb

5. Studying small systems at LHCb
6. A few illustrative results of global analyses

   - *trying my best to avoid those of topics already covered in future lectures*

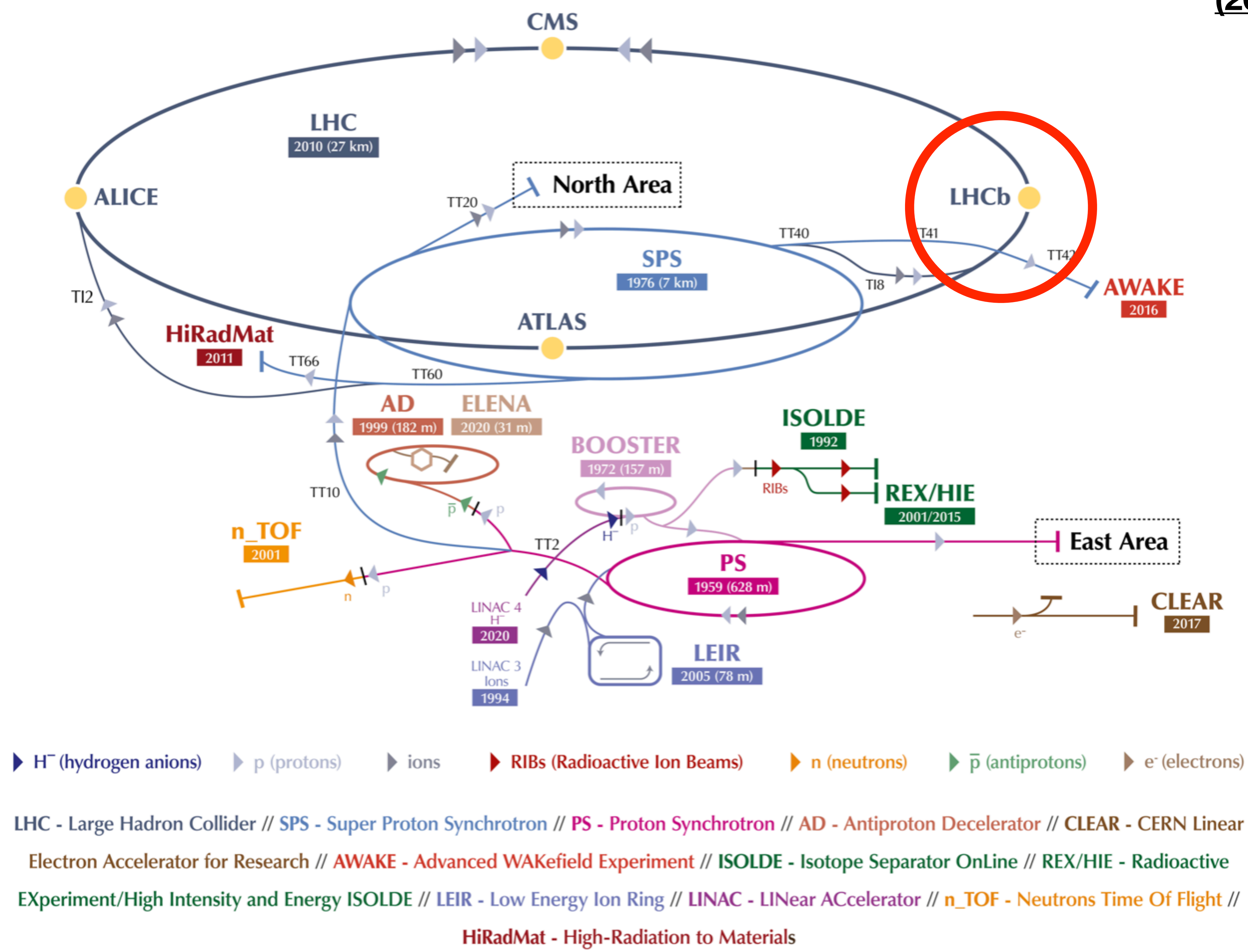
7. Outlook: a few words on the LHCb Upgrade

Please ask questions any time!

The LHCb collaboration at CERN

- One of the four main experiments at the Large Hadron Collider (LHC) at CERN
- Located at point 8

Figure from https://cds.cern.ch/record/2684277

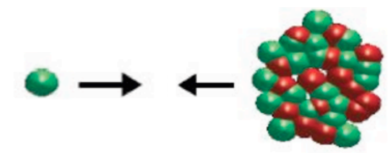


Beam configurations during Run 1 (2010-2013) and Run 2 (2015-2018)

p p

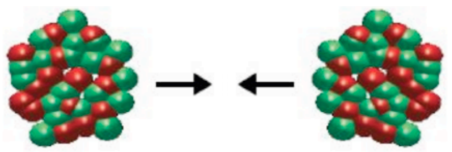
$$\sqrt{s} = 0.9, 2.76, 5, 7, 8, 13\ \text{TeV}$$

p Pb



$$\sqrt{s_{\text{NN}}} = 5, 8.16\ \text{TeV}$$

Pb Pb



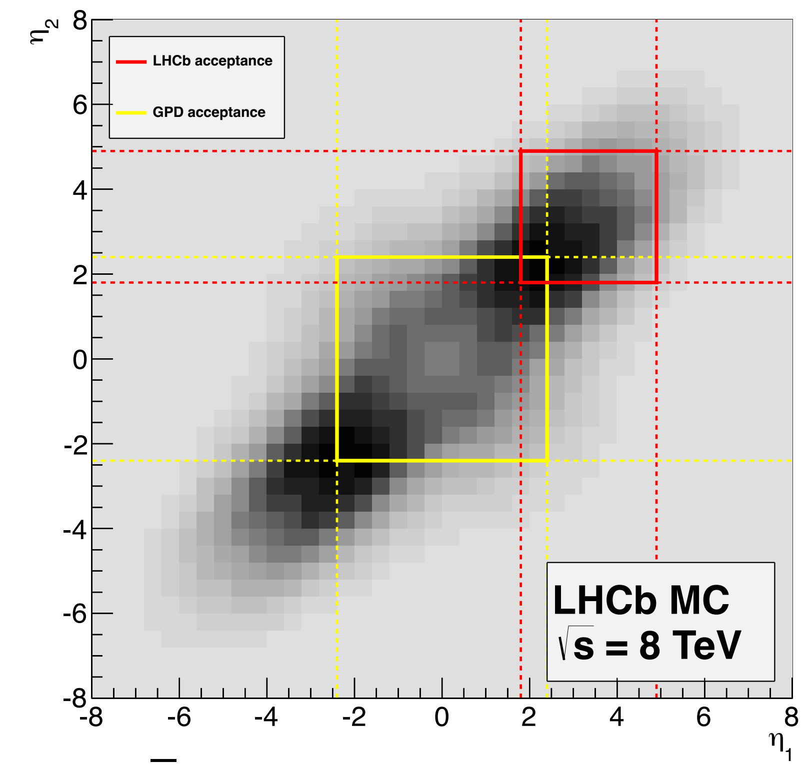
$$\sqrt{s_{\text{NN}}} = 2.76, 5\ \text{TeV}$$

The LHCb detector

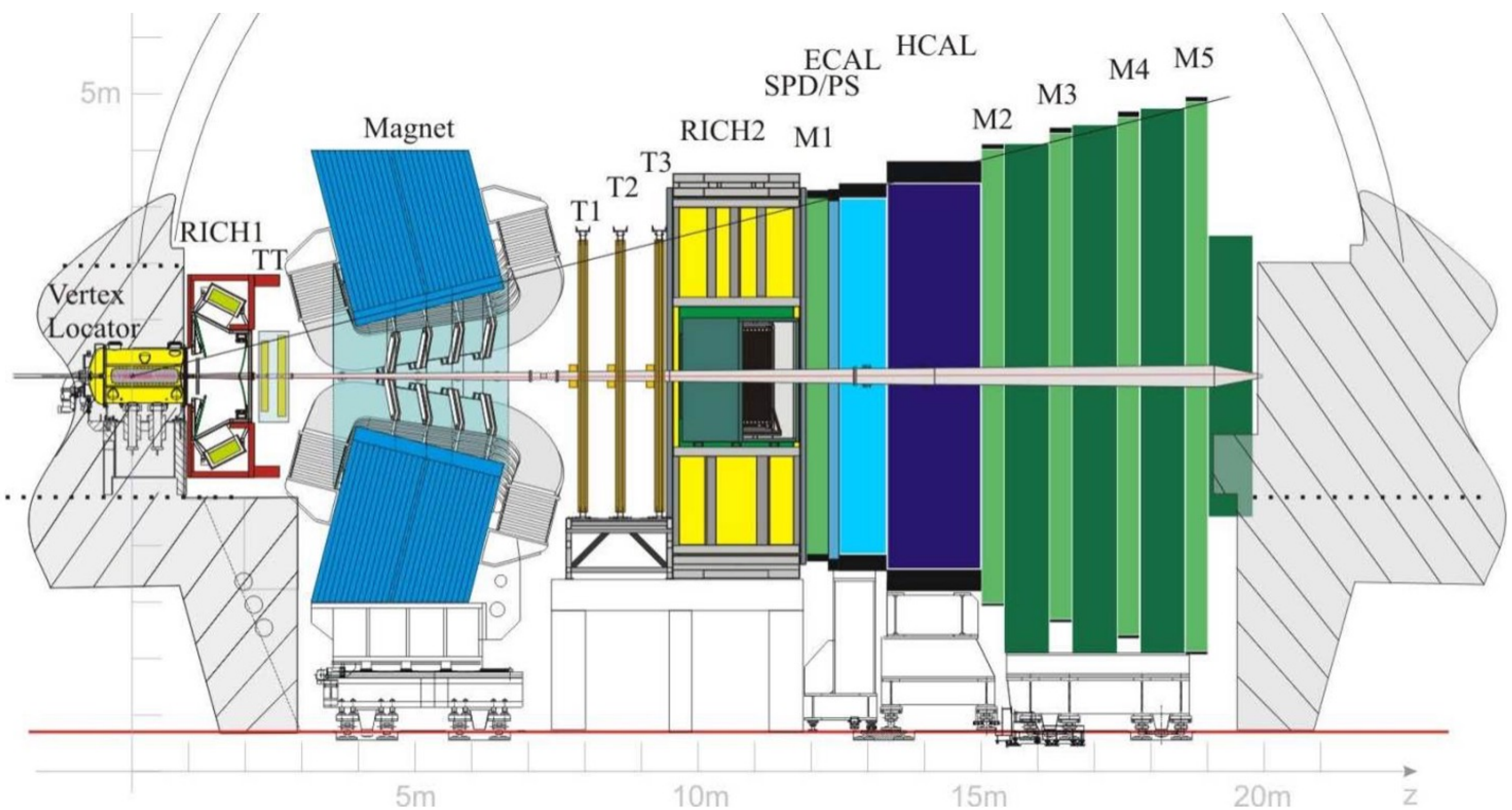
Forward spectrometer fully instrumented in $2 < \eta < 5$

- aimed to collect large statistics of b hadron production $\longrightarrow$

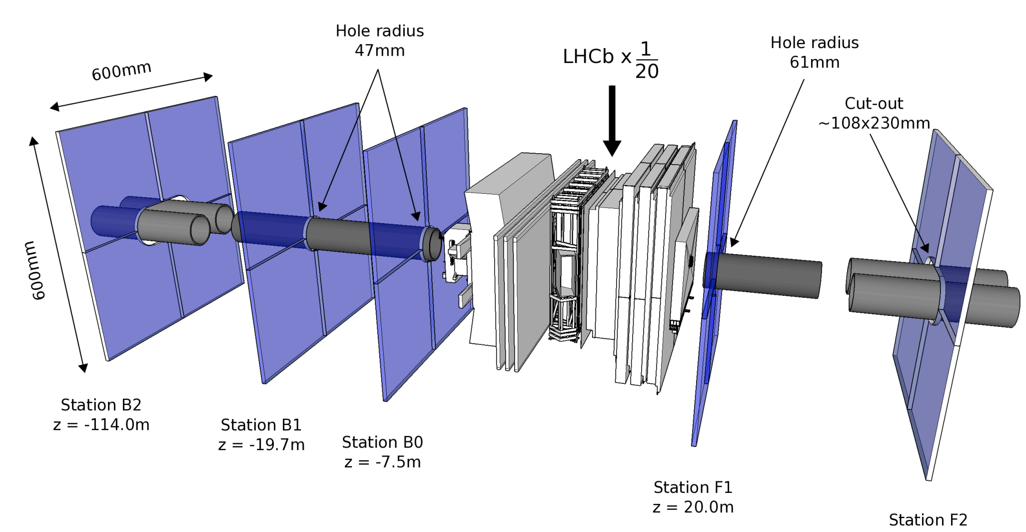
- **Tracking system** for charged particles
- **Particle Identification systems** (PID): hadrons (π, K, p), neutrals (γ, π^0), and leptons (μ, e)
- **Flexible trigger**, configured to measure down to low p_{T}



$b\overline{b}$ production cross-section
yellow: $|\eta| < 2.4$
red: LHCb acceptance

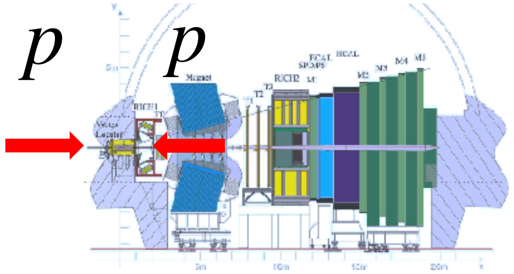


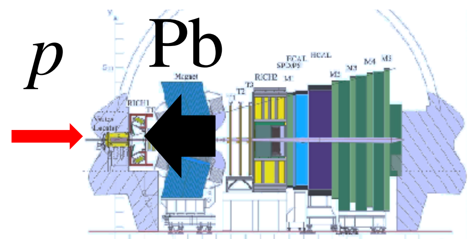
Hershel detector: JINST 13 (2018) no.04, P04017



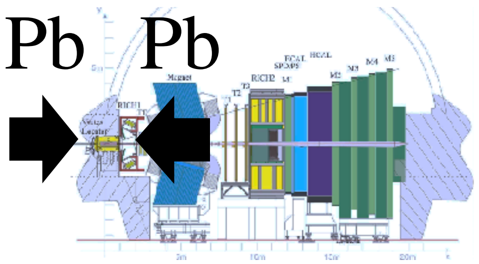
LHCb JINST 3 (2008) S08005
LHCb performance IJMPA 30 (2015) 1530022

Collider mode collisions at LHCb

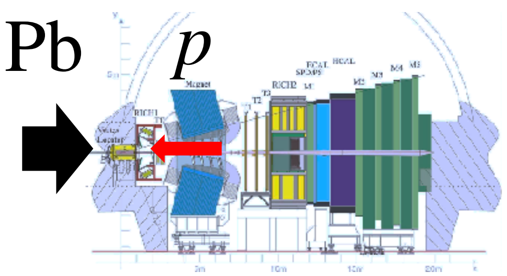




pPb: forward ($\eta > 0$)

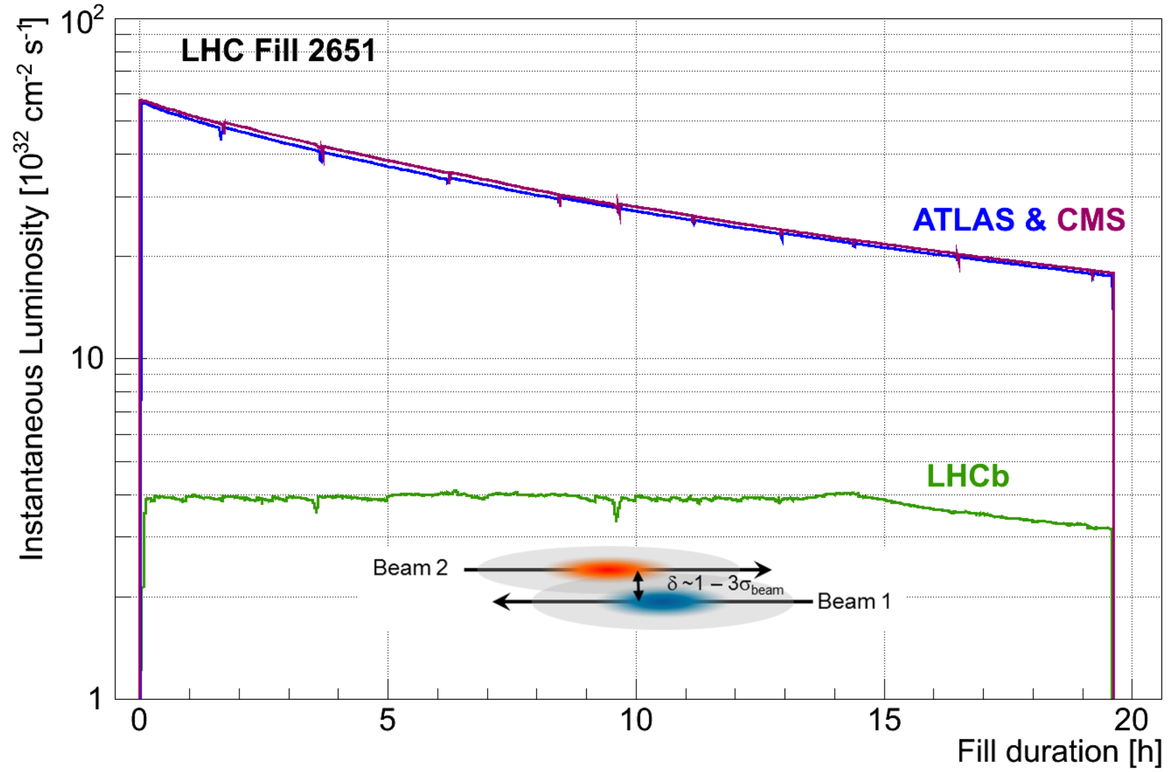


pp and Pb: $|\eta| = |-\eta|$



Pbp: backward ($\eta < 0$)

IJMPA 30 (2015) 1530022

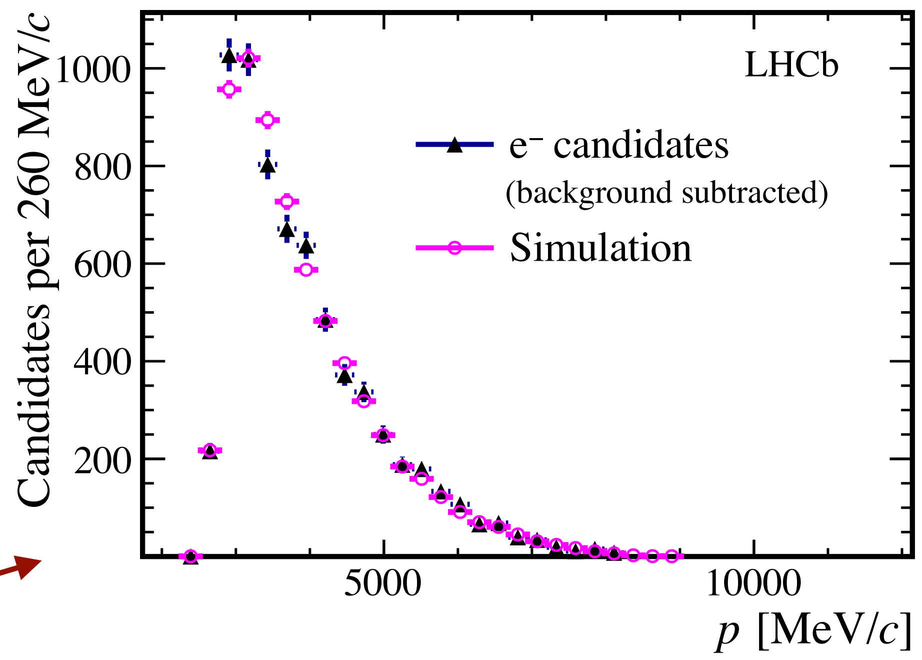


- Luminosity in pp levelled in LHCb, $\mu \sim 1$ (pile-up, average number of interactions/bunch crossing)
- Lower rate in pPb and PbPb, $\mu \ll 1$
- Different energy per nucleon of Pb and p beams: $E_{\text{Pb}} = (Z_{\text{Pb}}/A_{\text{Pb}})E_p \approx 0.39E_p$
  - Boost of nucleon-nucleon CMS system in proton-lead: $\eta = \eta_{lab} - 0.465$
- Larger detector occupancy with more particles per η unit: $pp < p\text{Pb} < \text{Pb}p < \text{PbPb}$

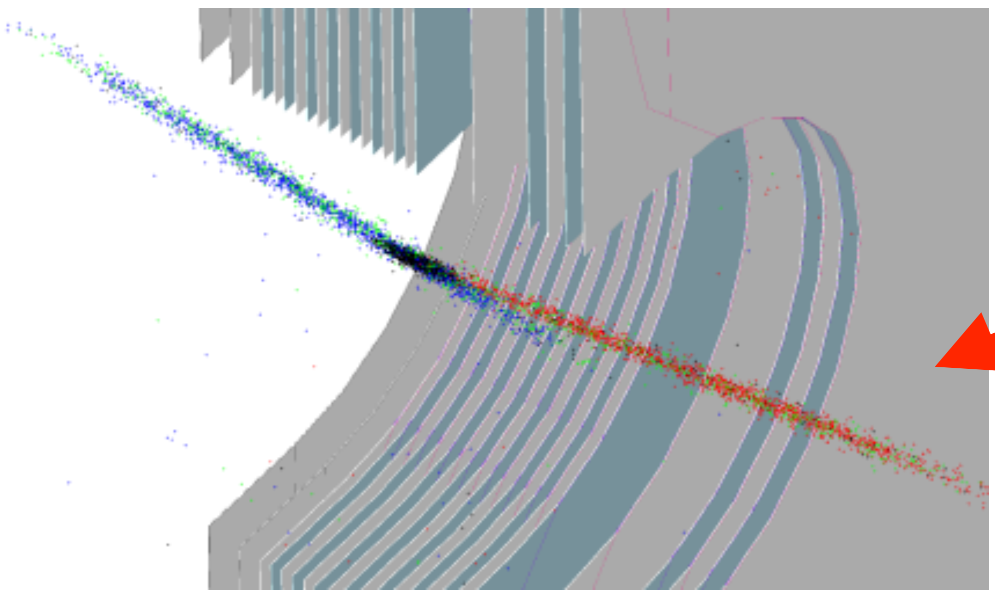
Fixed-target collisions at LHCb

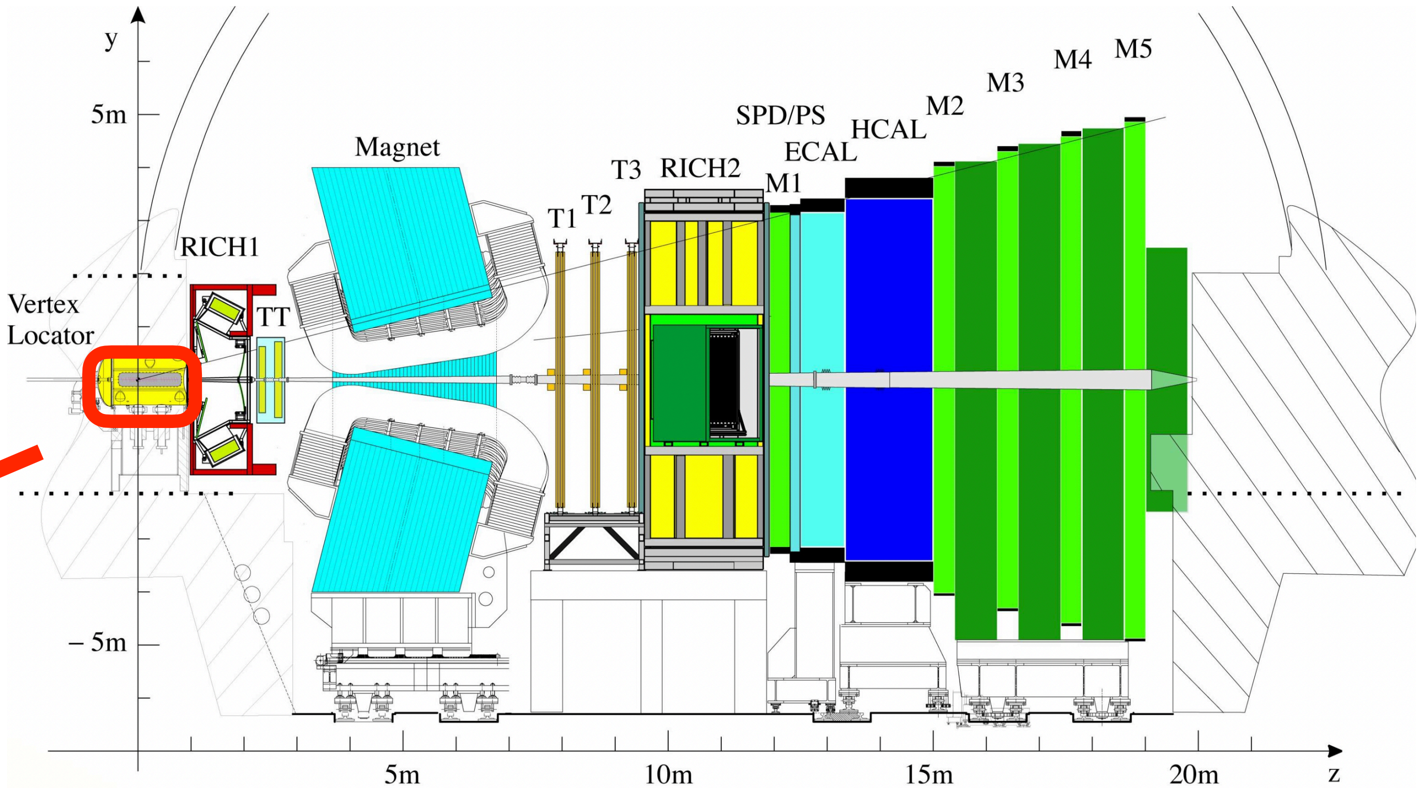
- SMOG system: inject gas inside LHC vacuum, measure collisions between beam and gas nuclei at rest
  - Used both for collider luminosity measurements 2014 JINST 9 P12005 and for physics measurements!
- Noble gas injection: He, Ne, Ar
- $\sqrt{s_{NN}} = \sqrt{2E_{beam}M_p} = 69$ to $110\,\text{GeV}$, energy gap between SPS&RHIC
- Rapidity in CMS system: $-3.0 < y^* < 0.0$
- Luminosity measured with pe elastic scattering events

Phys. Rev. Lett. 121 (2018) 222001

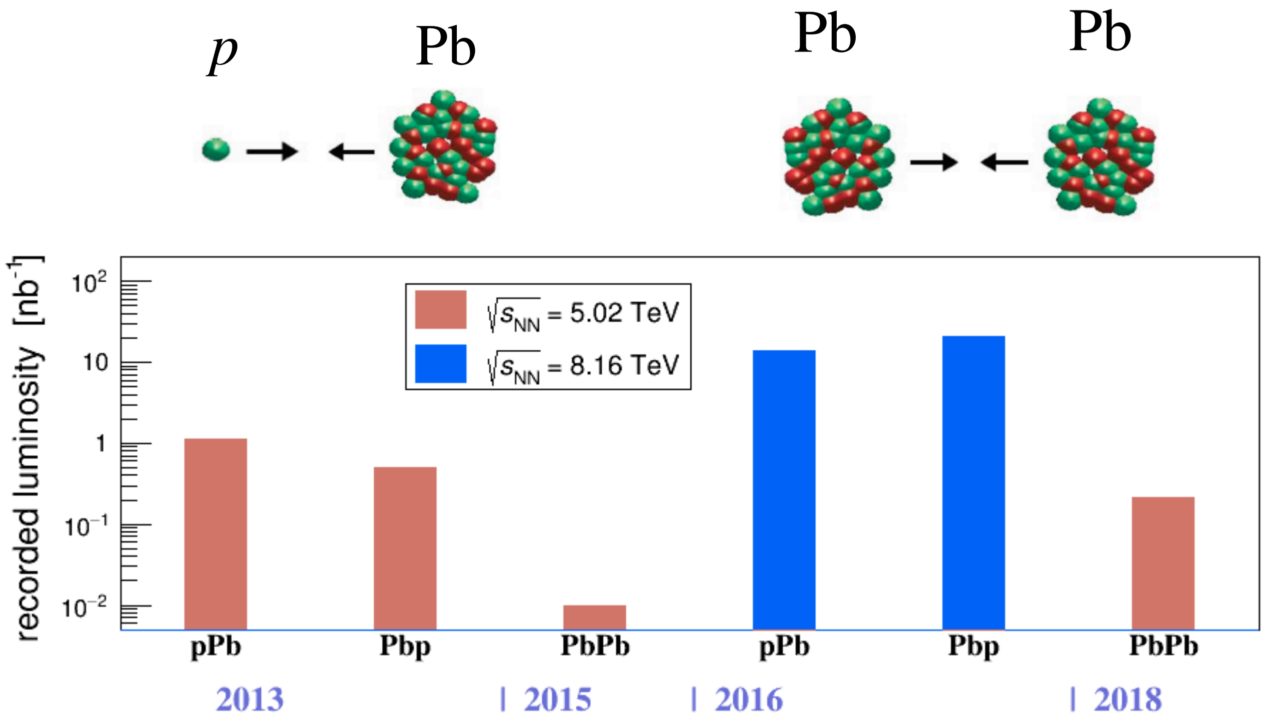


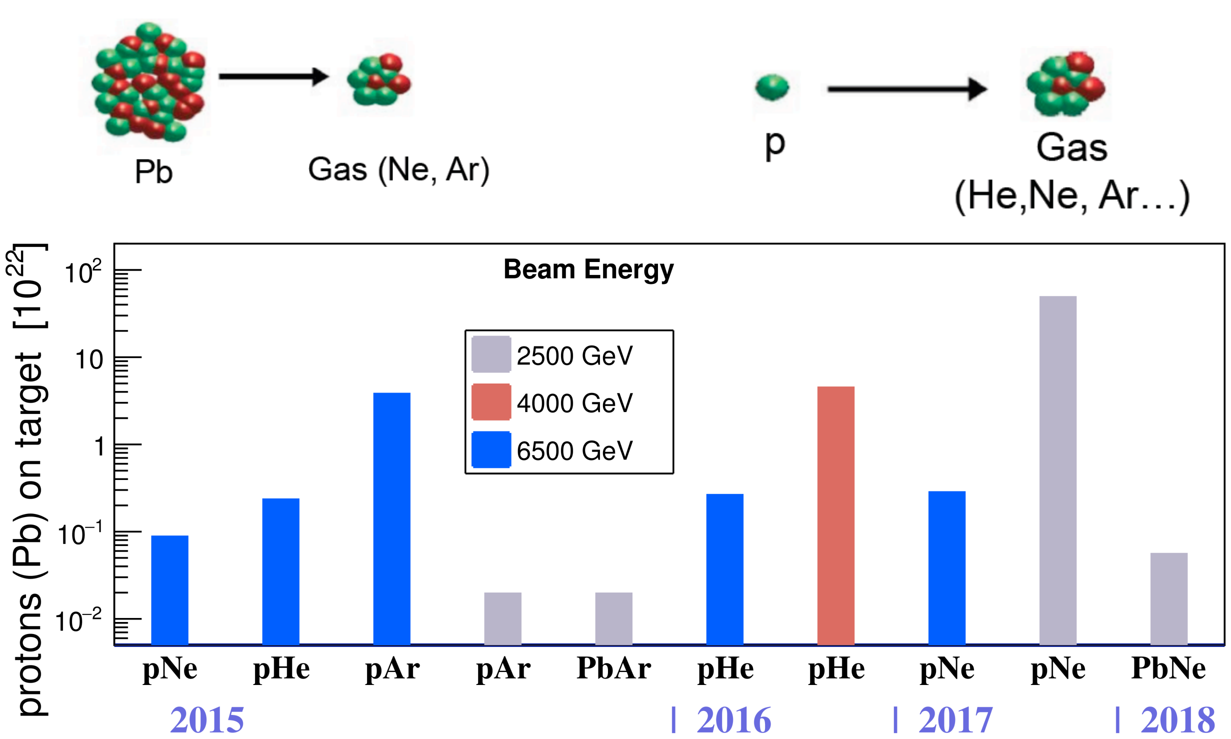
Nominal LHCb vacuum pressure: 10^{-8} to 10^{-9} mbar
Typical pressure with injection: $\sim 2 \times 10^{-7}$mbar

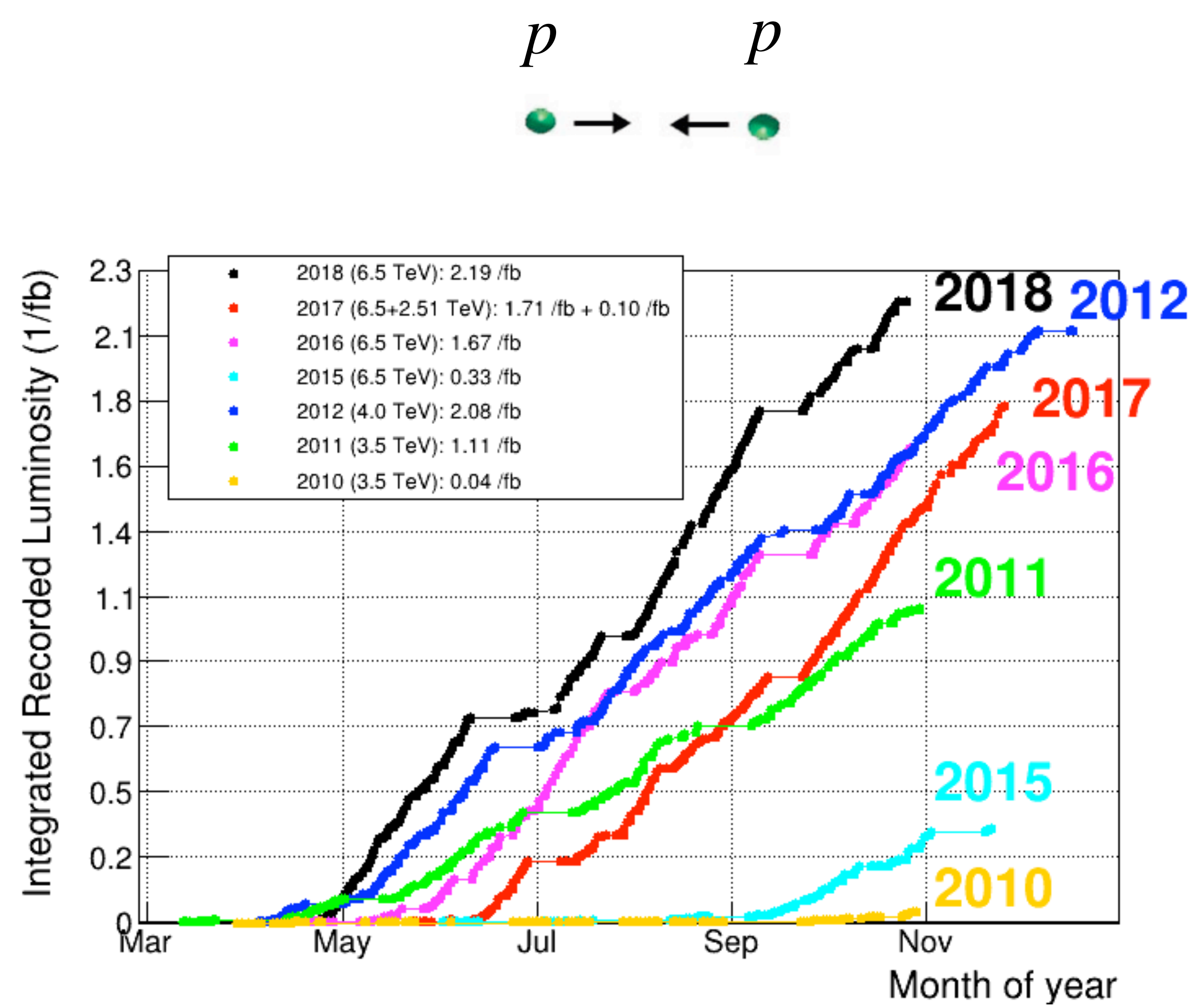




Summary of available datasets

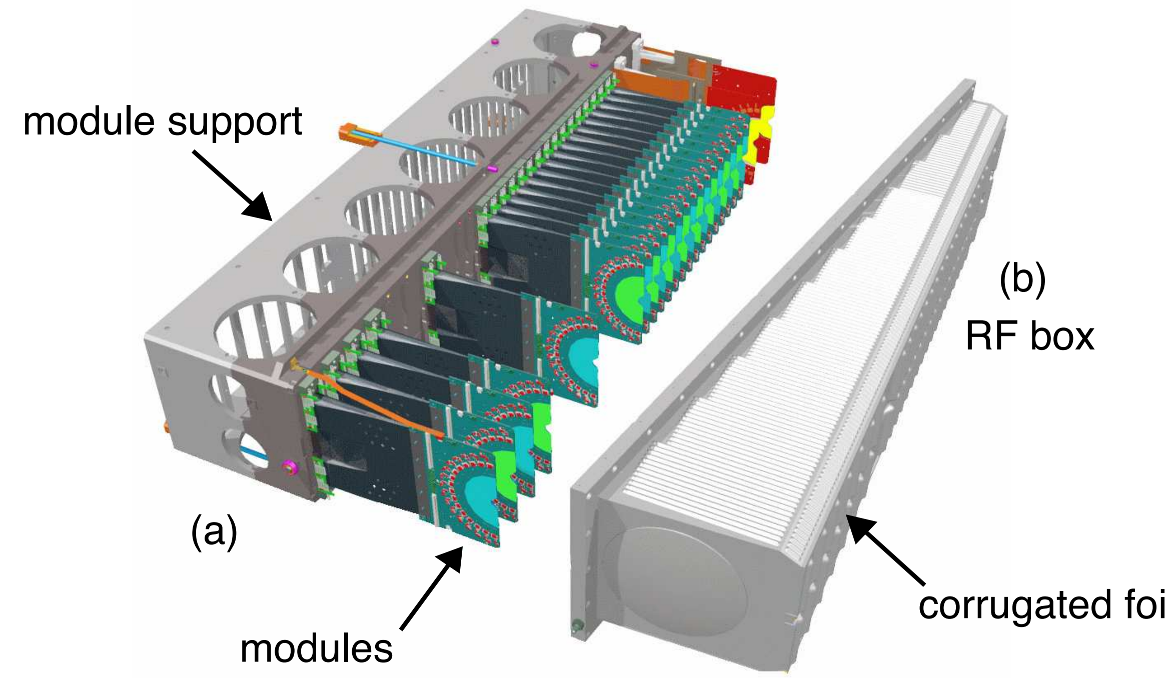


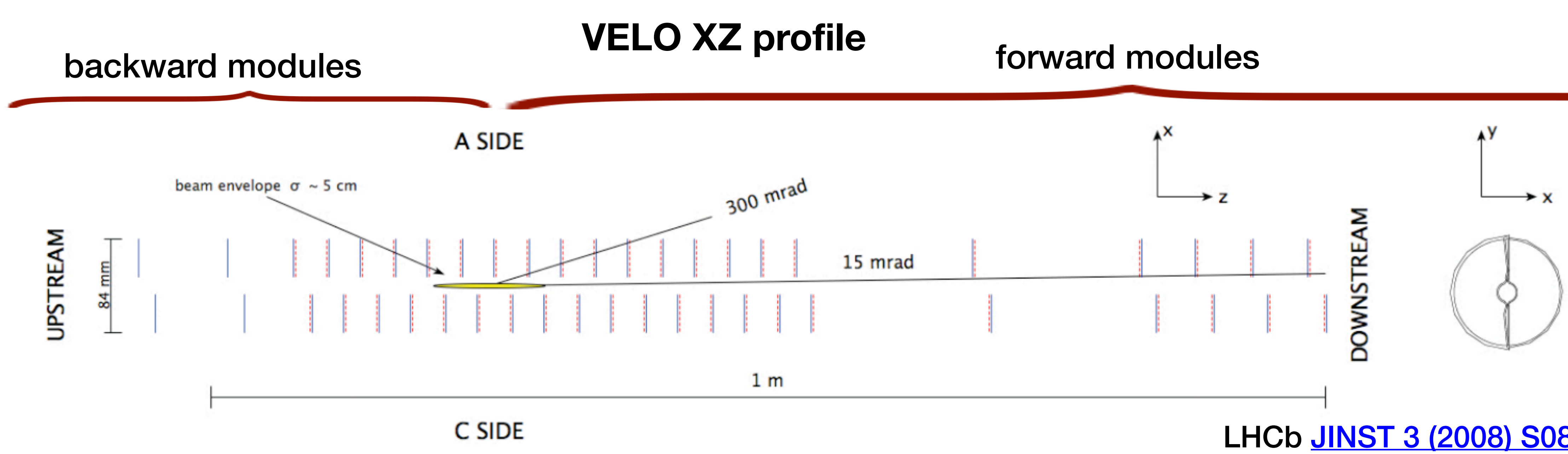




The Vertex Locator (VELO)

- **VErtex LOcator:** silicon micro-strip tracking detector around the interaction point
  - Primary Vertex (PV) reconstruction
  - Secondary Vertex (SV) reconstruction → high vertex resolution needed to resolve D, B vertex
  - Provides first seed for track reconstruction
- Coverage of $2.0 < \eta < 5.0$ (forward region) and around $-3.0 < \eta < -2.0$ (backward region)
- High efficiency and low fake track rate



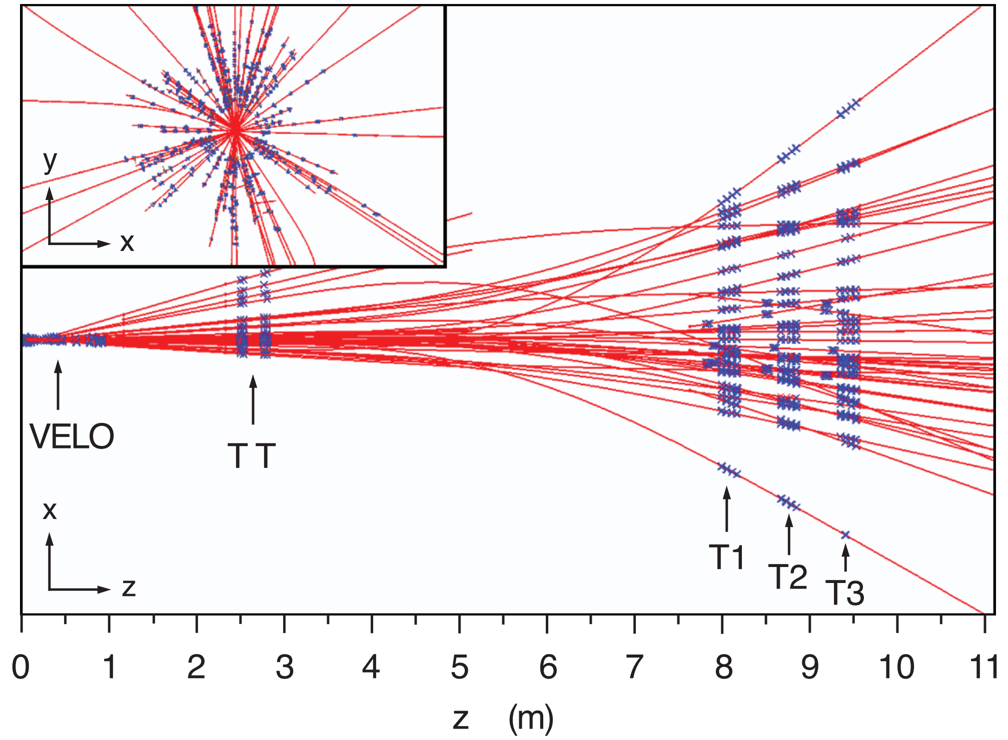


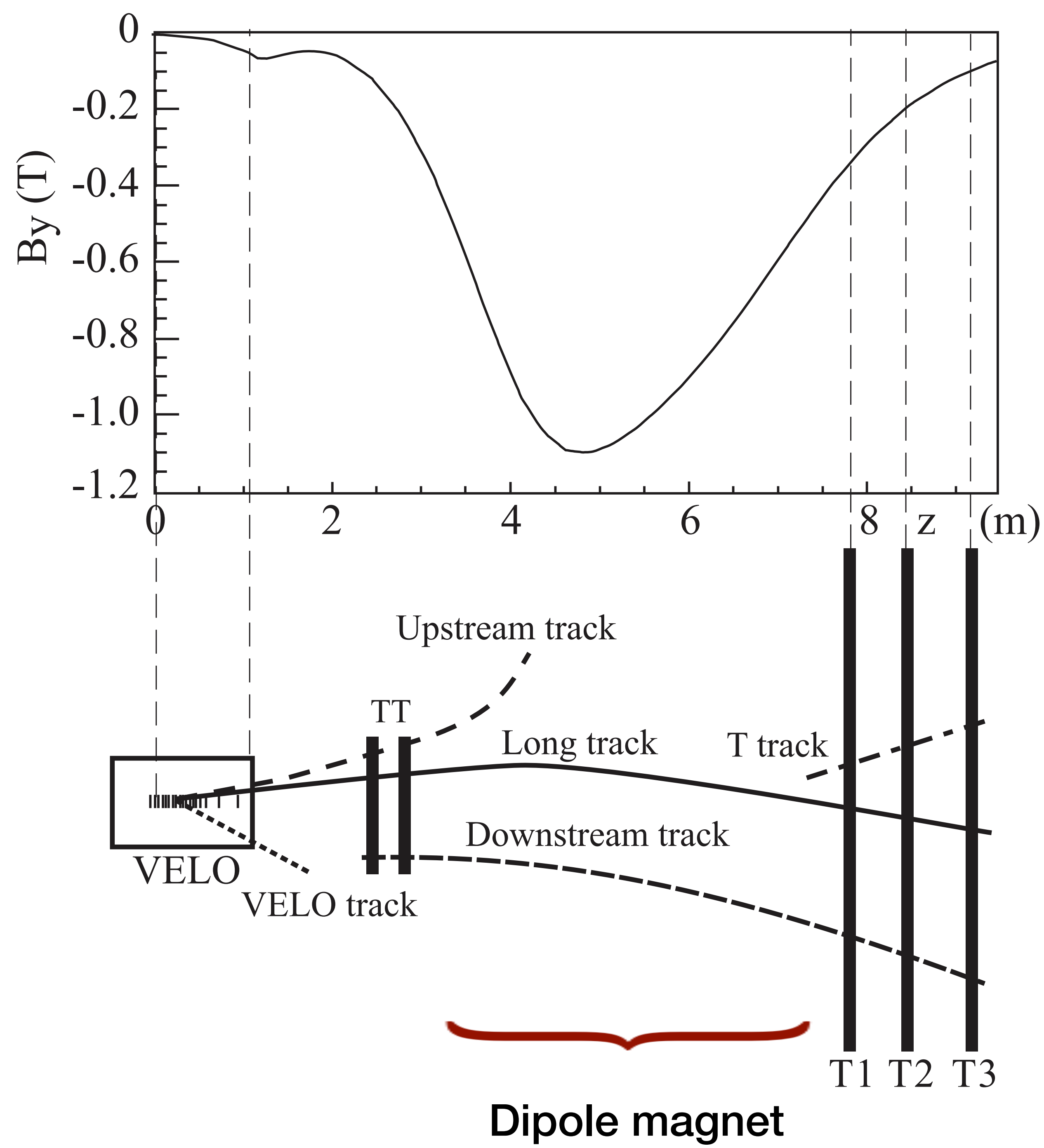
LHCb JINST 3 (2008) S08005

VELO performance JINST 9 (2014) P09007

Tracking at LHCb

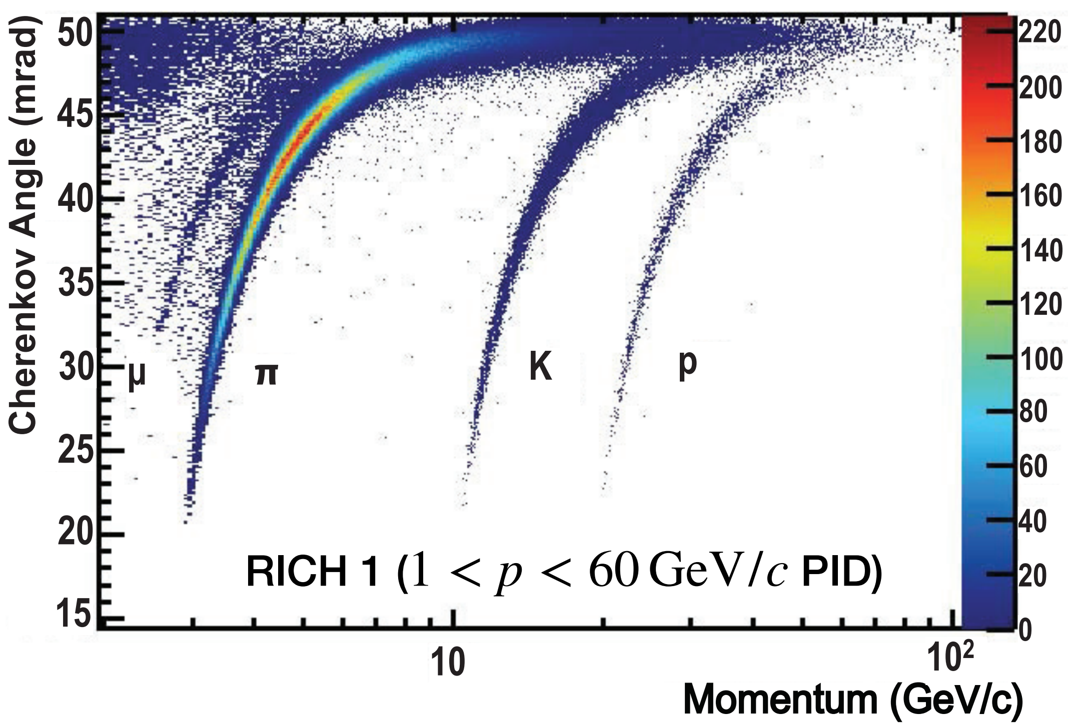
- **TT** (upstream magnet) + **T1/2/3** (downstream magnet)
  - high resolution p measurement, specially for long tracks
  - Kinematic constrain: long tracks need $p > 2\,\mathrm{GeV}/c$ to reach T1/2/3
- Tracking optimised for low-occupancy (pp collisions with $\mu \sim 1$)
  - VELO saturation in $60\,\%$ most central PbPb events

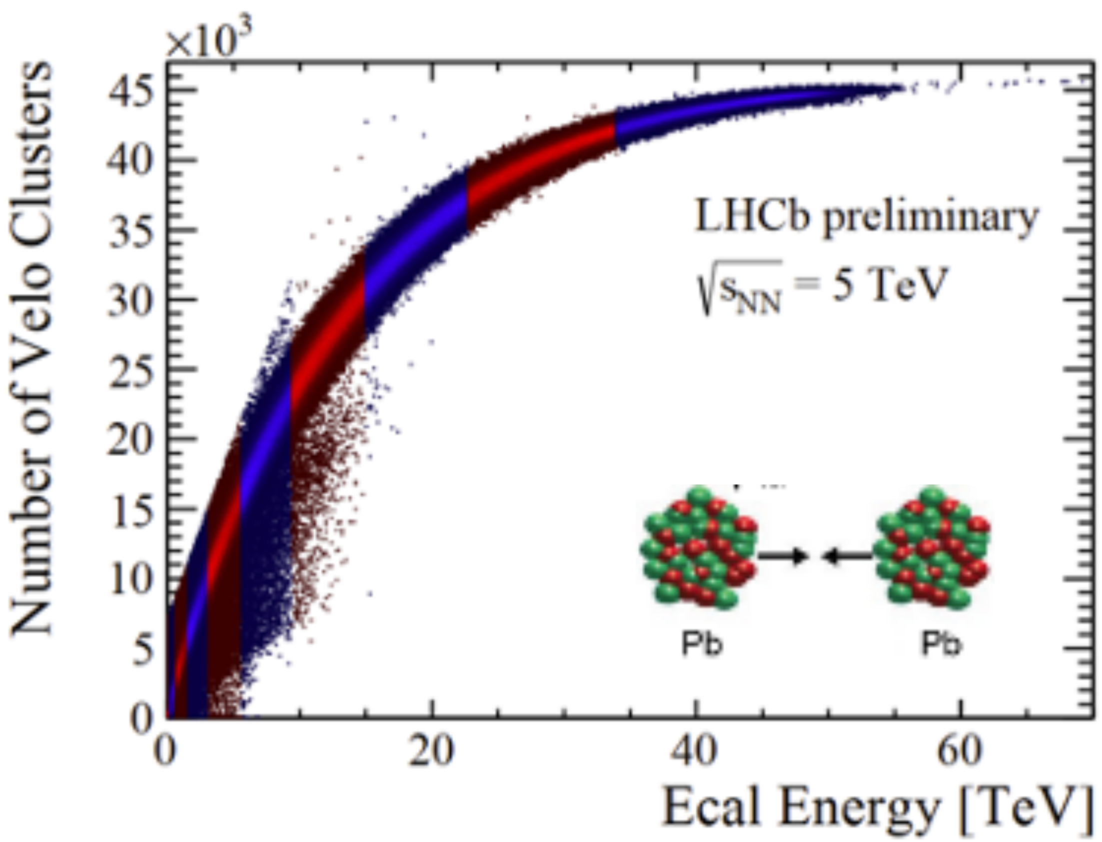


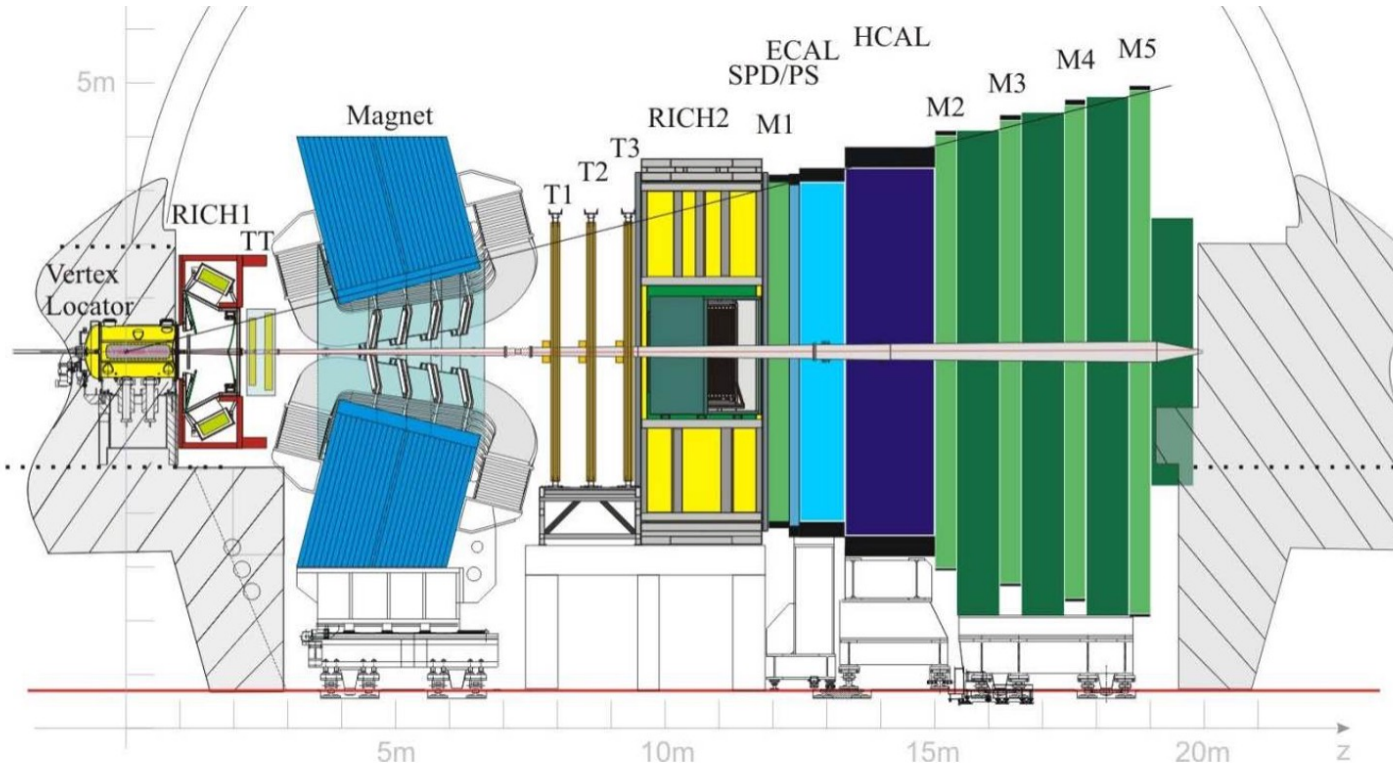


Particle identification systems

- Already discussed in previous lecture
  - RICH1/2: π, K, p separation
  - Calorimetry:
    - SPD, PRS: hardware trigger
    - ECAL: γ (and $\pi^0 \to \gamma\gamma$) and e ID
    - HCAL: contribute to hadron ID
    - **no saturation down to very central collisions**
      $\to$ crucial detector for centrality determination
  - Muon system: μ ID







LHCb JINST 3 (2008) S08005

LHCb performance IJMPA 30 (2015) 1530022

Heavy-ion (HI) collisions

Heavy-ion collision and open questions

- Understanding of the evolution of a AA collision:
  1. Initial state
  2. Hard scattering
  3. QGP formation
  4. Hydrodynamic expansion
  5. Hadronization and freeze-out
- Characterisation of the Quark Gluon Plasma (QGP)
- Evolution of physics phenomena from small to large systems. Explanation for QGP-like signatures in small systems ($pp \rightarrow p\mathrm{A} \rightarrow \mathrm{AA}$)

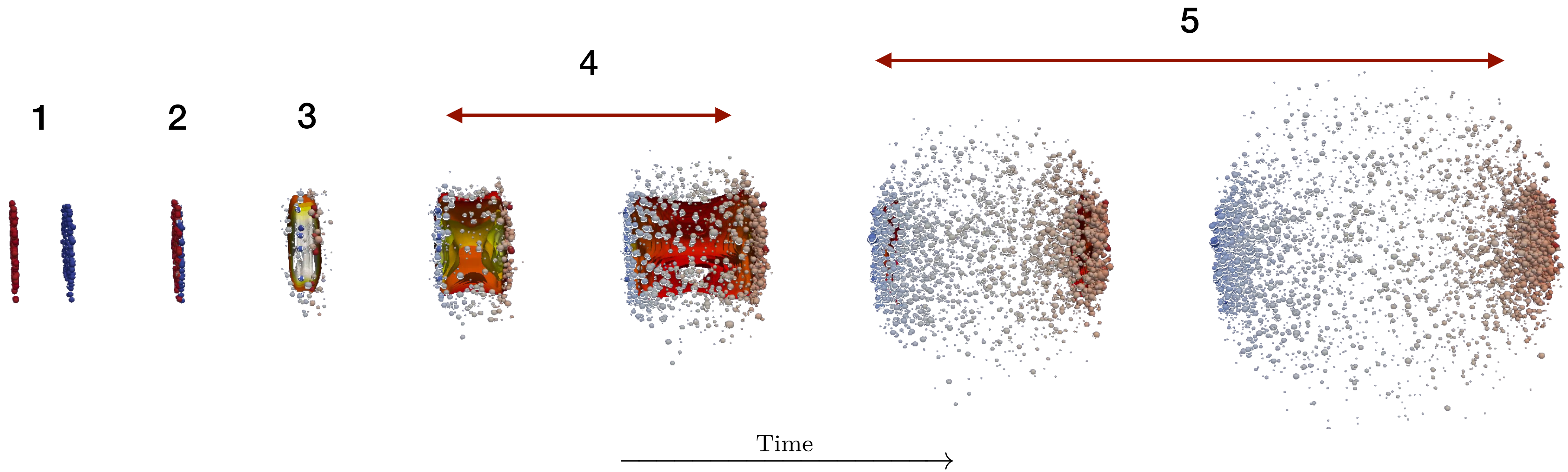
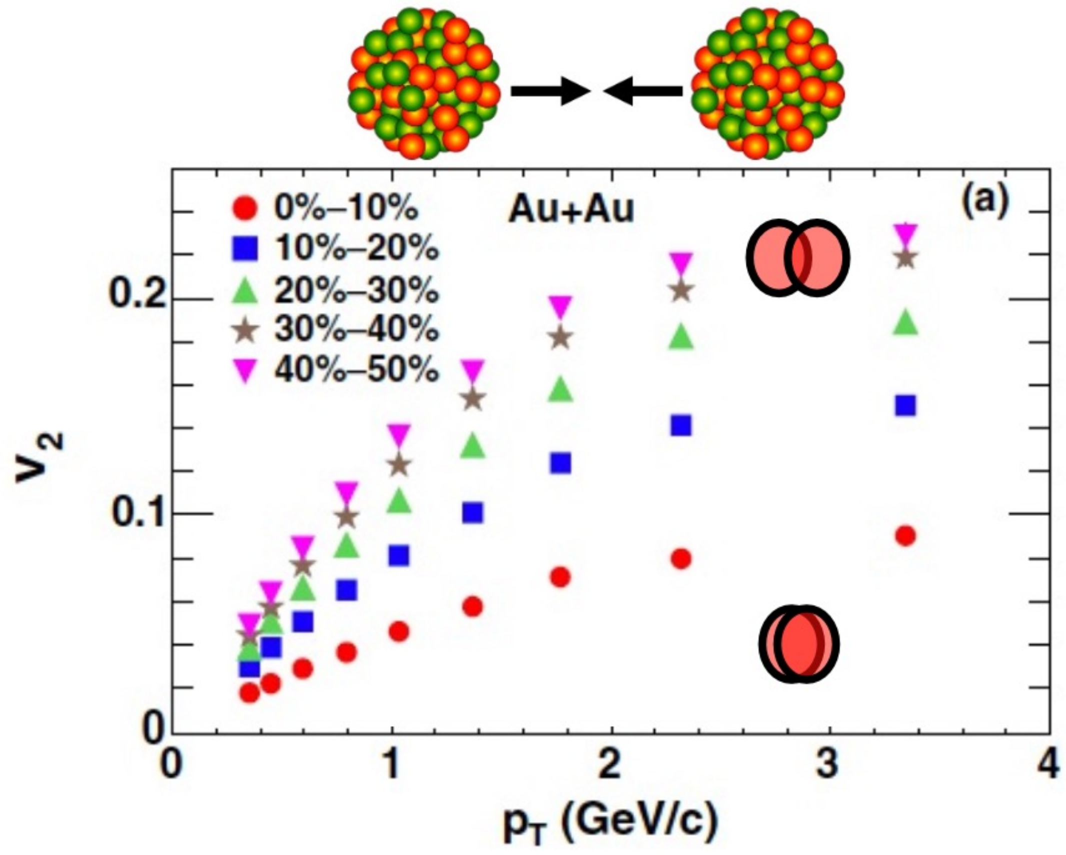
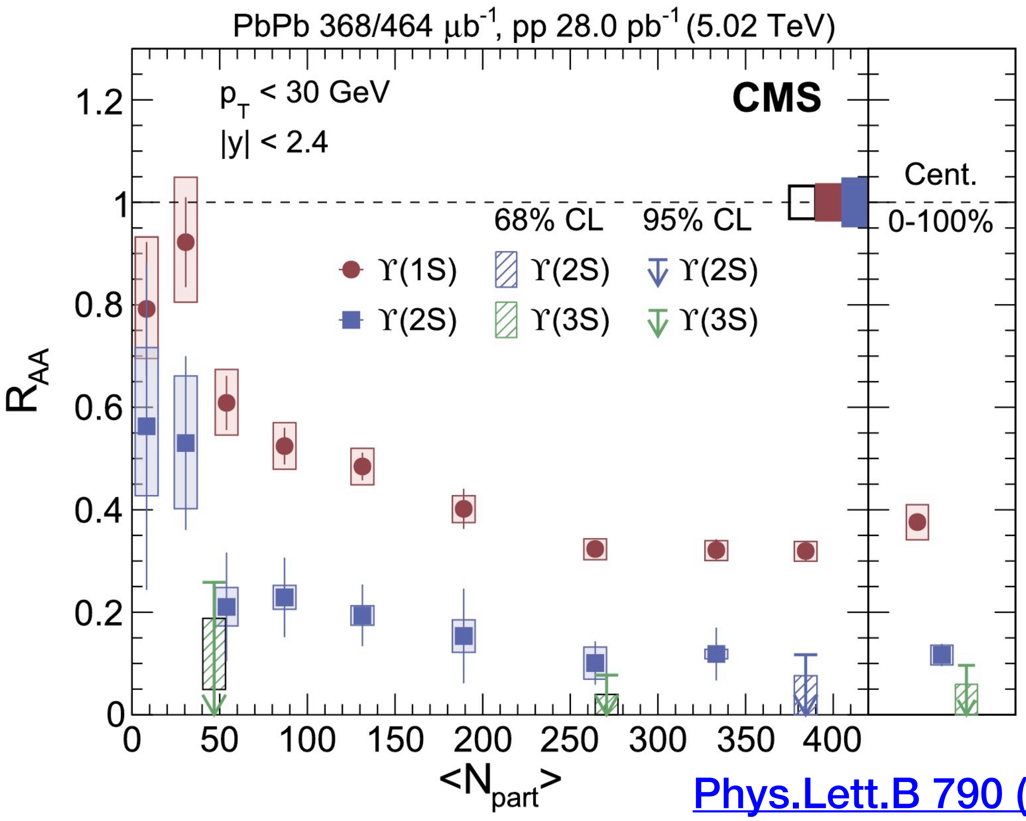


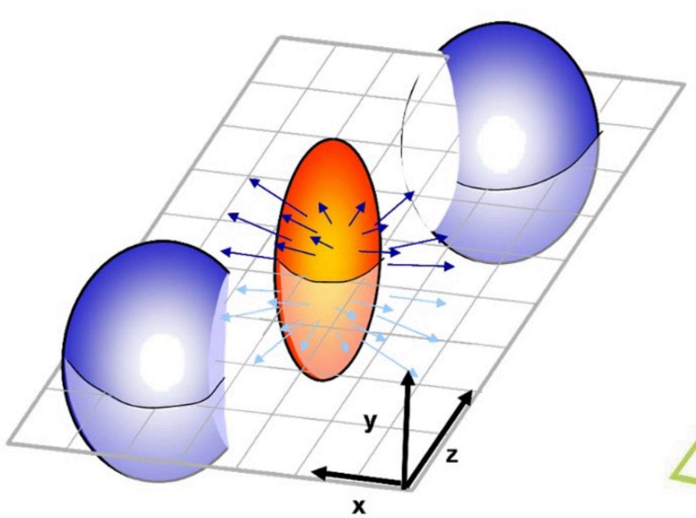
Figure of J. E. Bernhard from arXiv:1804.06469

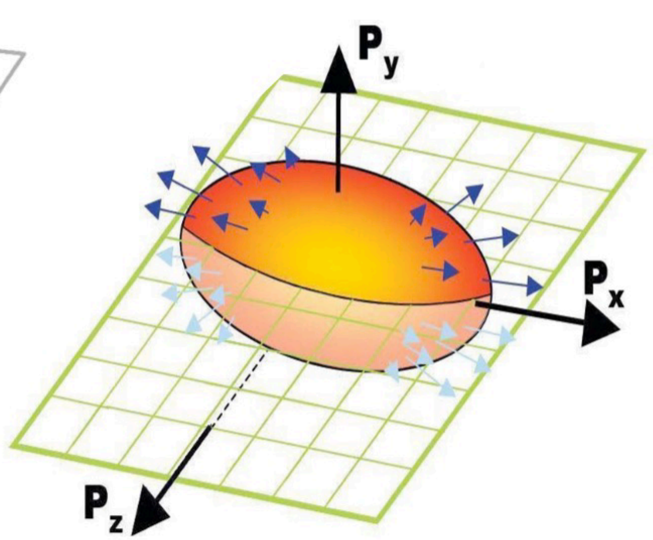
Characterisation of heavy-ion collision

- Not all AA collisions are the same…
- Collision geometry affects QGP evolution and measured observables
- The medium created after the collision is heavily influenced by the impact parameter between colliding nuclei (centrality)
  - QGP fluid subject to pressures gradients in peripheral collisions
- Other QGP-signatures (quarkonia suppression) are also affected









[Phys.Lett.B 790 (2019) 270-293]

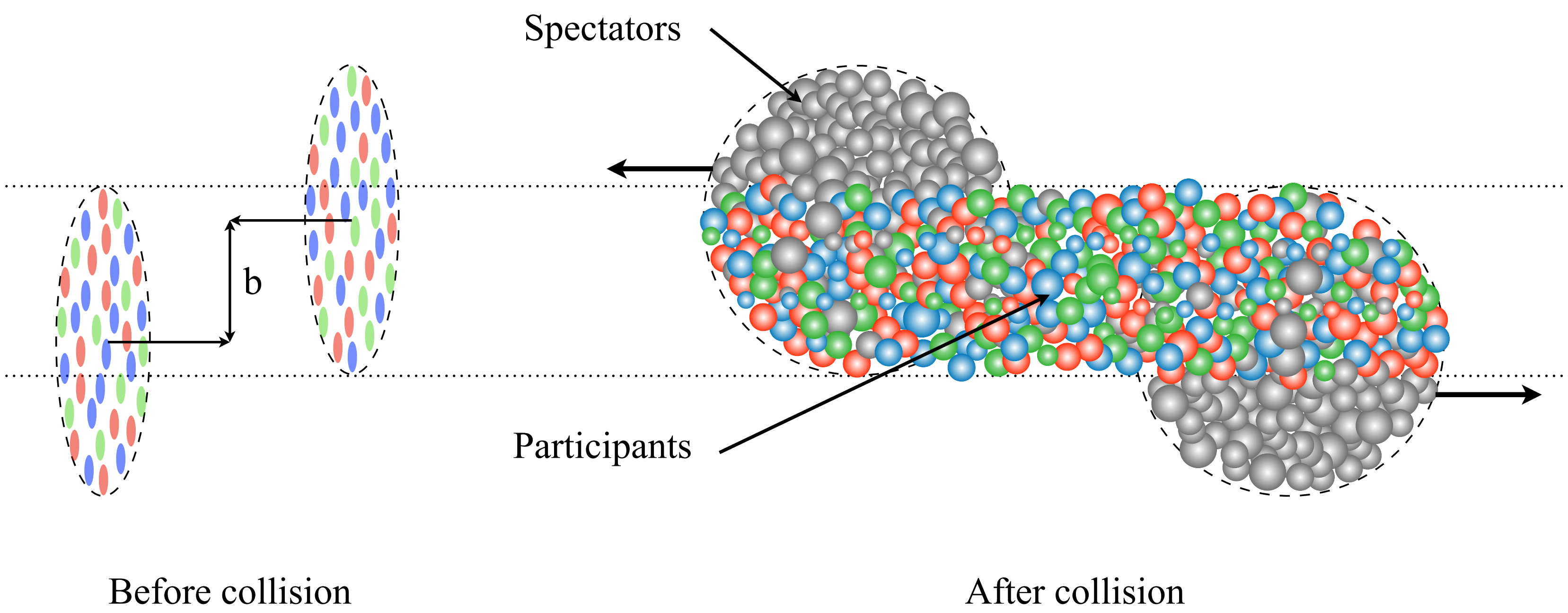
Centrality determination at LHCb

- Geometrical quantities of interest:
  - b: impact parameter (transverse distance between nuclei centre)
  - N_{part}: number of participant nucleons
  - N_{coll}: number of binary nucleon-nucleon collisions
- No direct way to determine experimentally this quantities
  - Model-dependent analysis, using the well-established MC Glauber model
  - works well specially in central collisions
  - in peripheral collisions, electromagnetic interactions are important

Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243

Phys.Rev. C97 (2018) 054910

Ann.Rev.Nucl.Part.Sci. 71 (2021) 315-344



JINST 17 (2022) 05, P05009

The MC Glauber Model

- Nucleons from nuclei A and B generated as hard spheres, simulate nucleus-nucleus collisions as:
  - superposition of individual nucleon-nucleon interactions
  - nucleons move in straight lines (even if they collide)
  - nucleons collide if $d < \sqrt{\sigma_{\mathrm{inel}}^{\mathrm{NN}}/\pi}$
- Two key ingredients:
  - Nuclear transverse density profile $\rho(r)$
  - Nucleon-nucleon cross-section $\sigma_{\mathrm{inel}}^{\mathrm{NN}}$ → extracted from measurements

Wood-Saxon distribution:

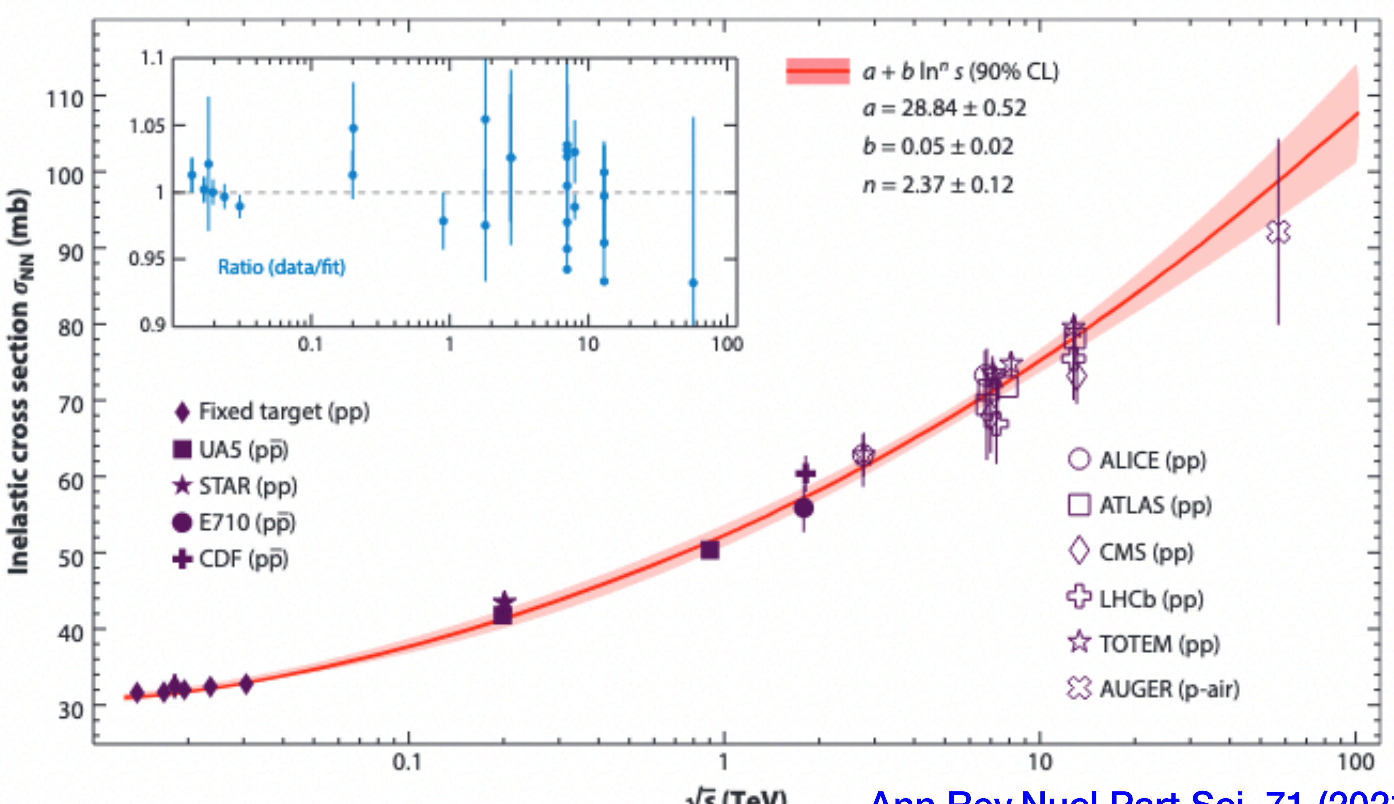
$$\rho(r)\mathrm{d}r = \rho_0 \frac{1 + w\frac{r^2}{R^2}}{1 + \exp(\frac{r-R}{a})}\mathrm{d}r;$$

R: nuclear radius

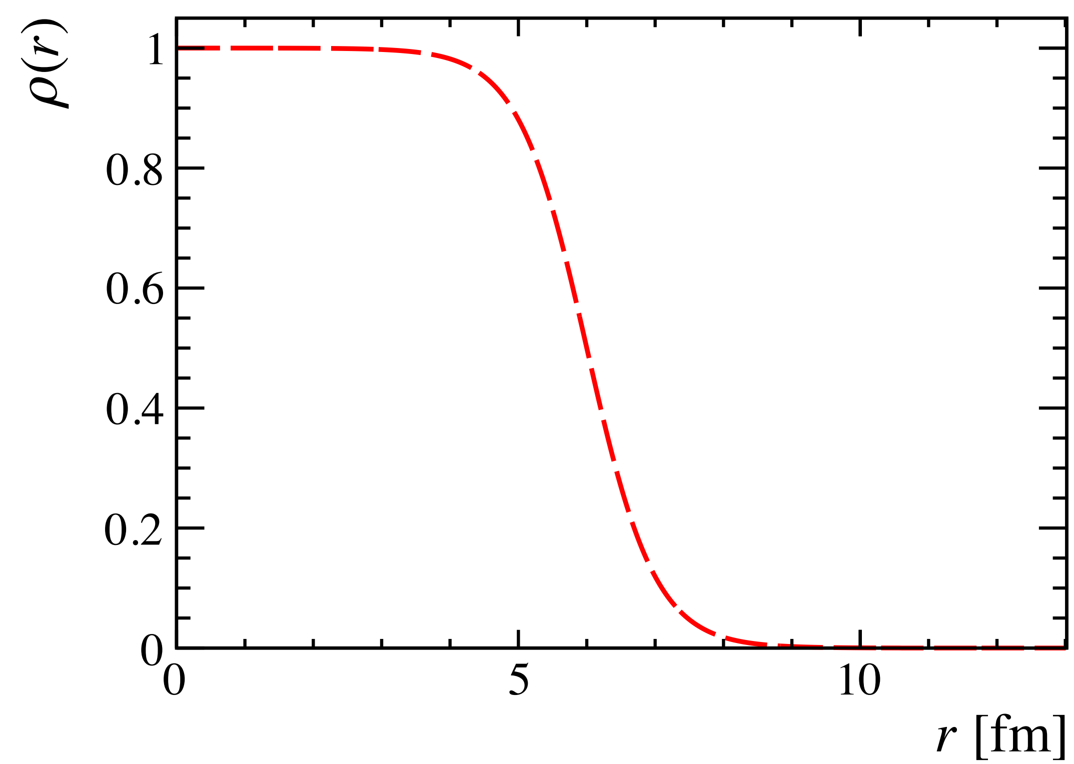
w: spherical shape deviations

a: diffusivity (skin depth)

ρ_0: density at nucleus centre



Ann.Rev.Nucl.Part.Sci. 71 (2021) 315-344

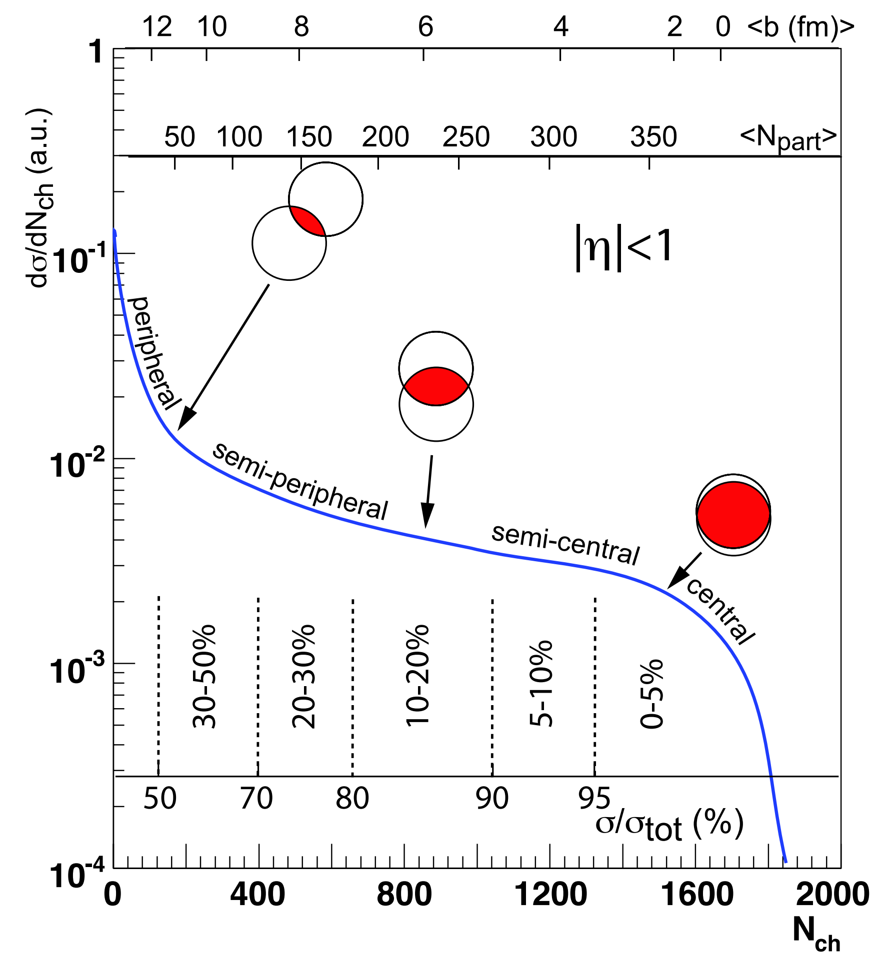


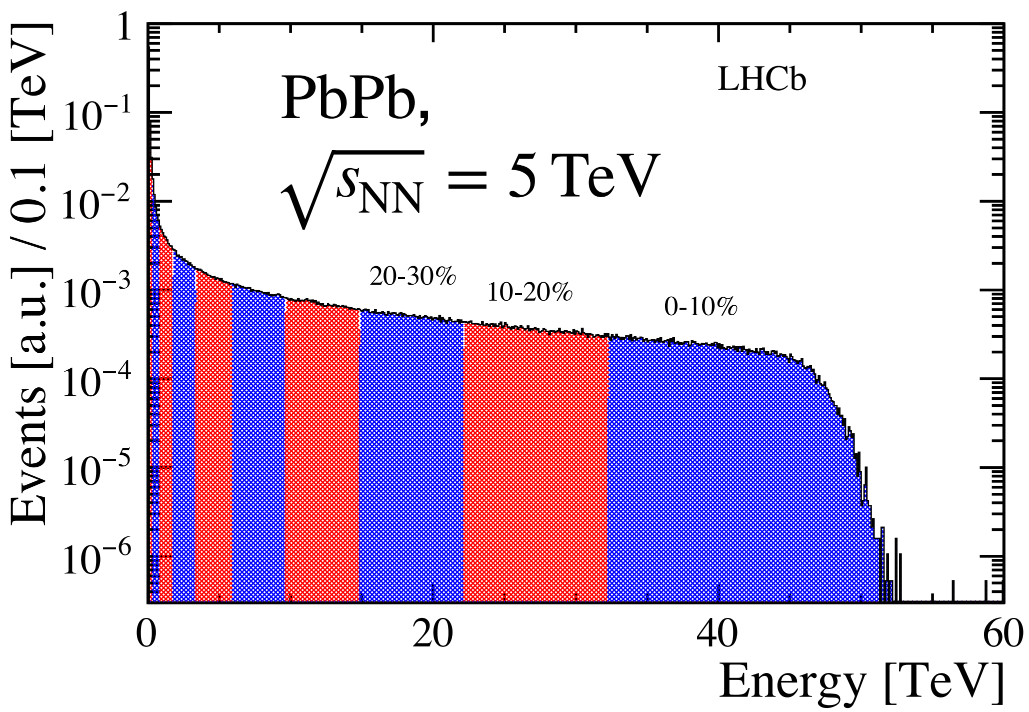
JINST 17 (2022) 05, P05009

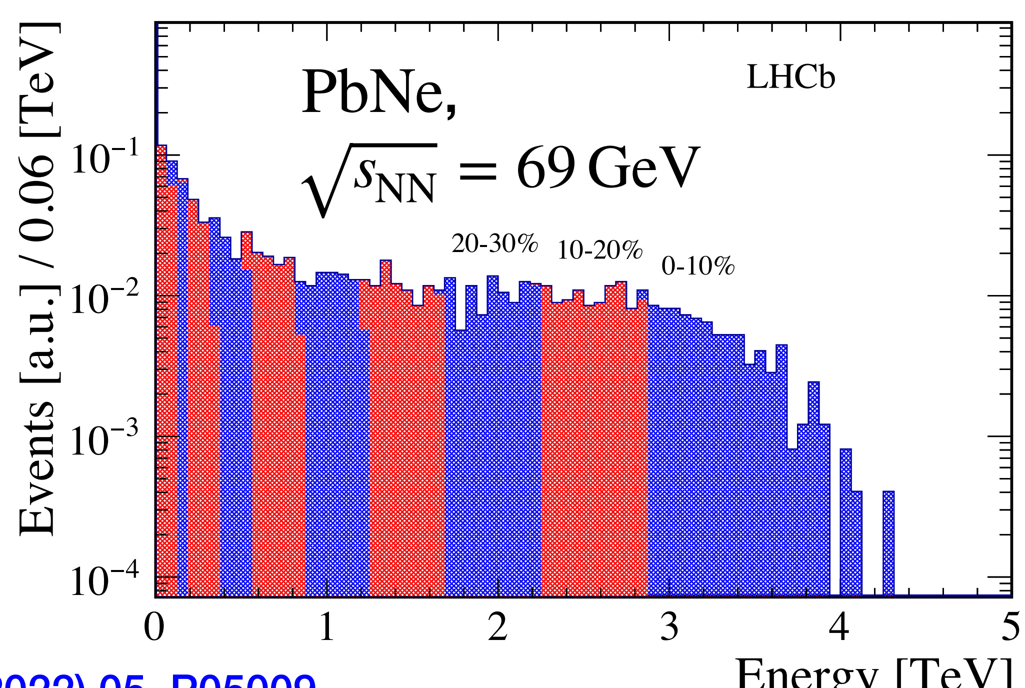
Centrality determination at LHCb

- Relate Glauber parameters with experimentally measured quantity (dN_{ch}/dN_{evt}, dE/dN_{evt}…) with a mapping procedure
  - Assume that b is monotonically related with particle multiplicity
- In LHCb, best option for experimental quantity is total energy collected in the ECAL
  - No ECAL saturation down to $0\,\%$ centrality in PbPb
  - ECAL energy does not depend on vertex position of PbNe collision
- ECAL energy proportional to π^0 production, mean energy deposited per particle: $\langle E^{\mathrm{PbPb}} \rangle = 10.4\,\mathrm{GeV}$; $\langle E^{\mathrm{PbNe}} \rangle = 10.4\,\mathrm{GeV}$

Ann.Rev.Nucl.Part.Sci.57:205-243,2007





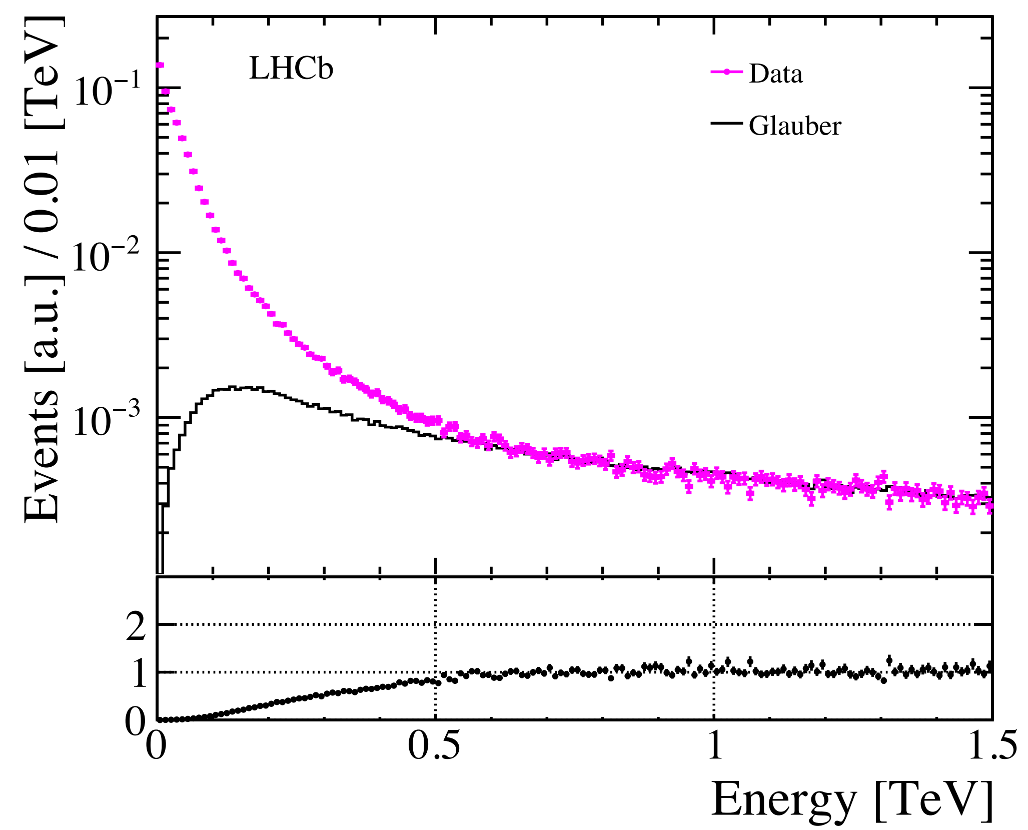


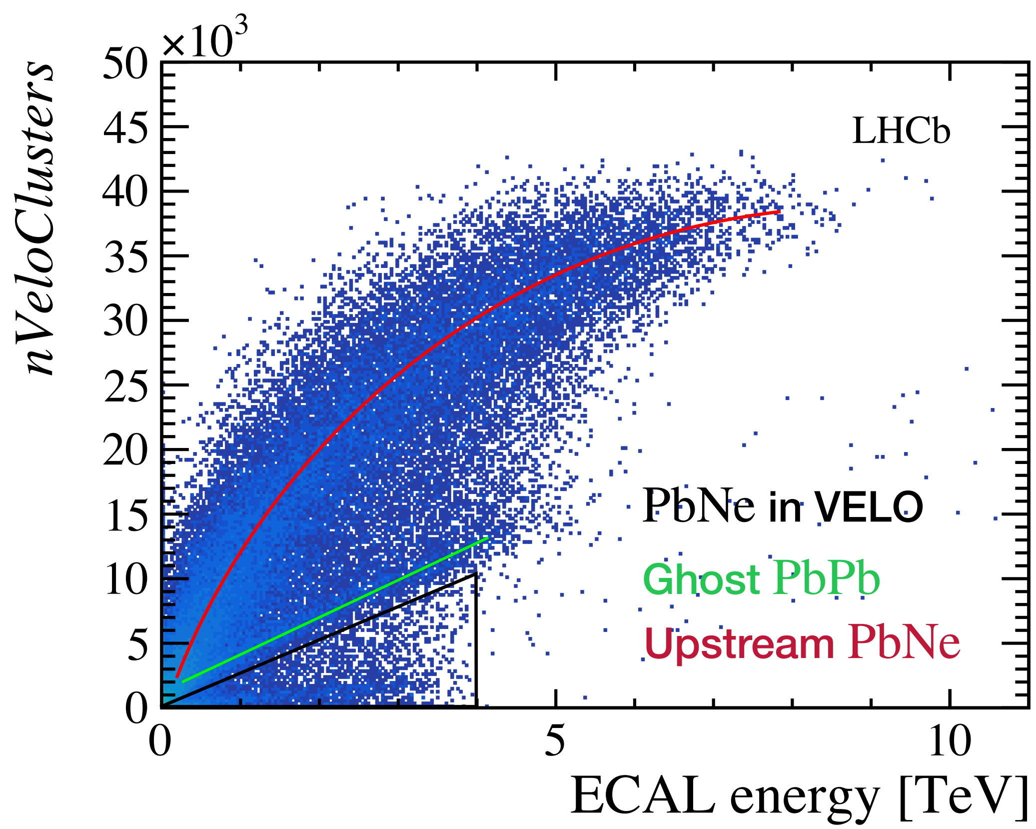
JINST 17 (2022) 05, P05009

Data selection

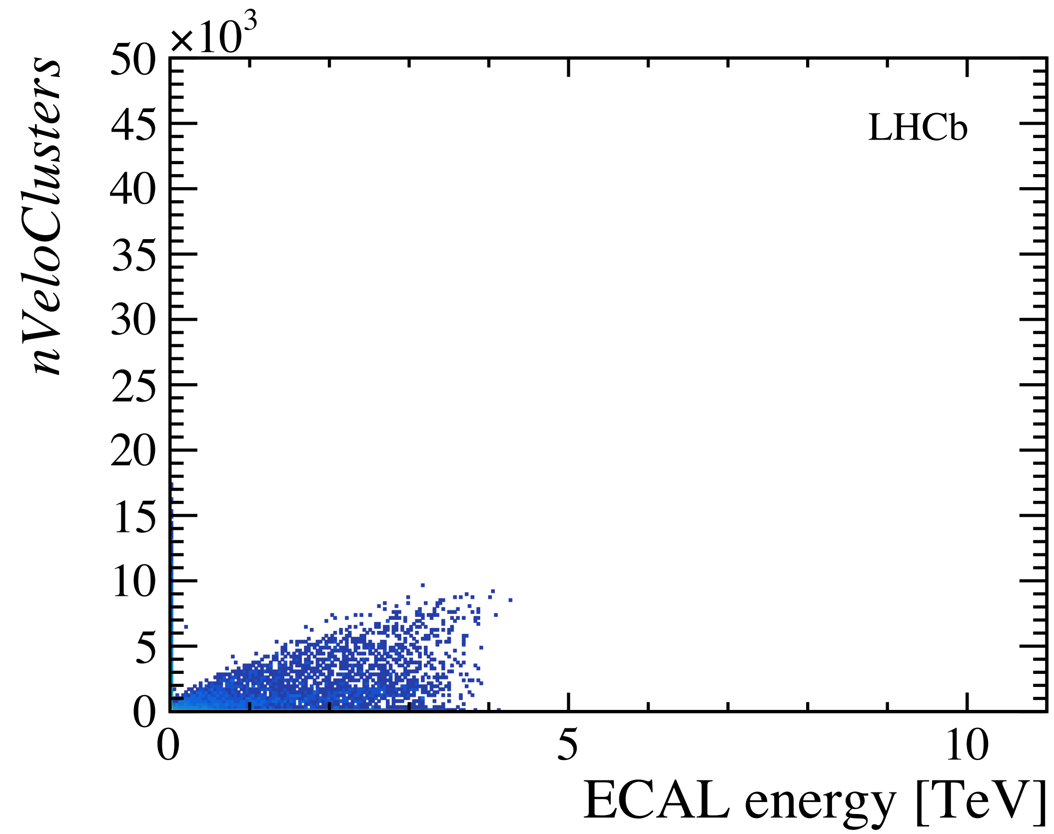
[JINST 17 (2022) 05, P05009](https://doi.org/10.1088/1748-0221/17/05/P05009)

- Low-energy events dominated by electromagnetic interactions
  - Restrict fit to $E_{\rm tot}^{\rm ECAL}|_{\rm PbPb} > 2\,{\rm TeV};\ E_{\rm tot}^{\rm ECAL}|_{\rm PbNe} > 0.5\,{\rm TeV}$
- Background interactions in PbNe collisions
  - Simultaneous PbPb and PbNe data-taking in 2018
  - Need to disentangle both contributions
    - ✳ Fixed-target collisions do not leave backward VELO activity
    - ✳ Remove SMOG interactions upstream the VELO and ghost PbPb interactions





No activity in backward VELO →



Fitting the model parameters

[JINST 17 (2022) 05, P05009](#)

- We construct a model from the output of the MC Glauber to reproduce data distribution:

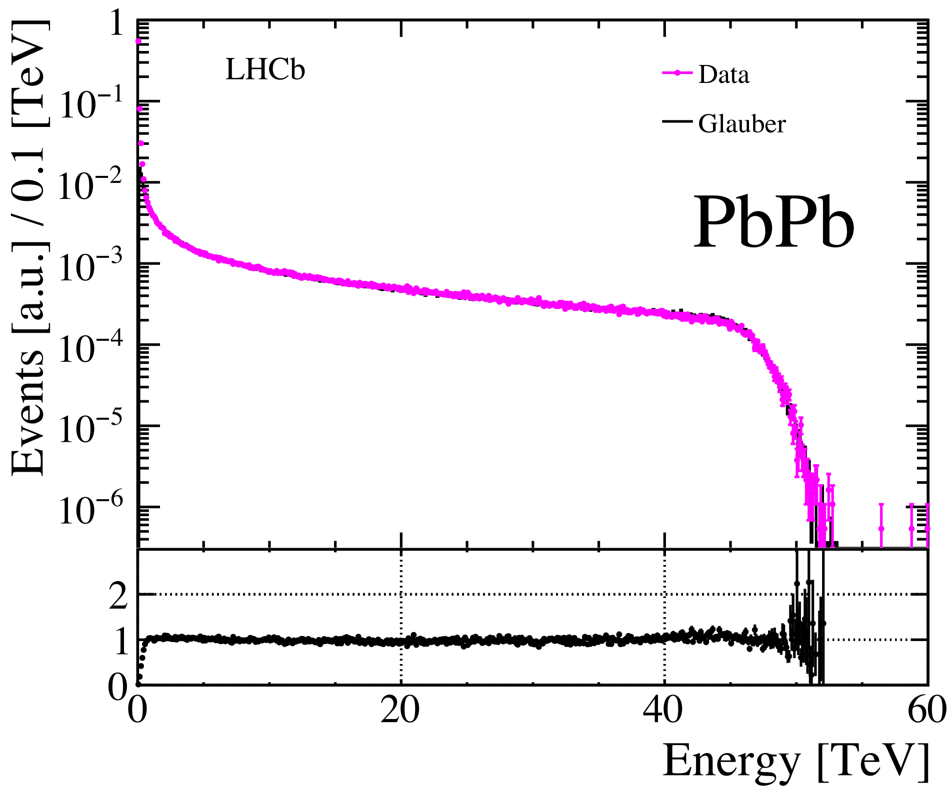
$$N_{\text{anc}} = f \times N_{\text{part}} + (1 - f) \times N_{\text{coll}}$$

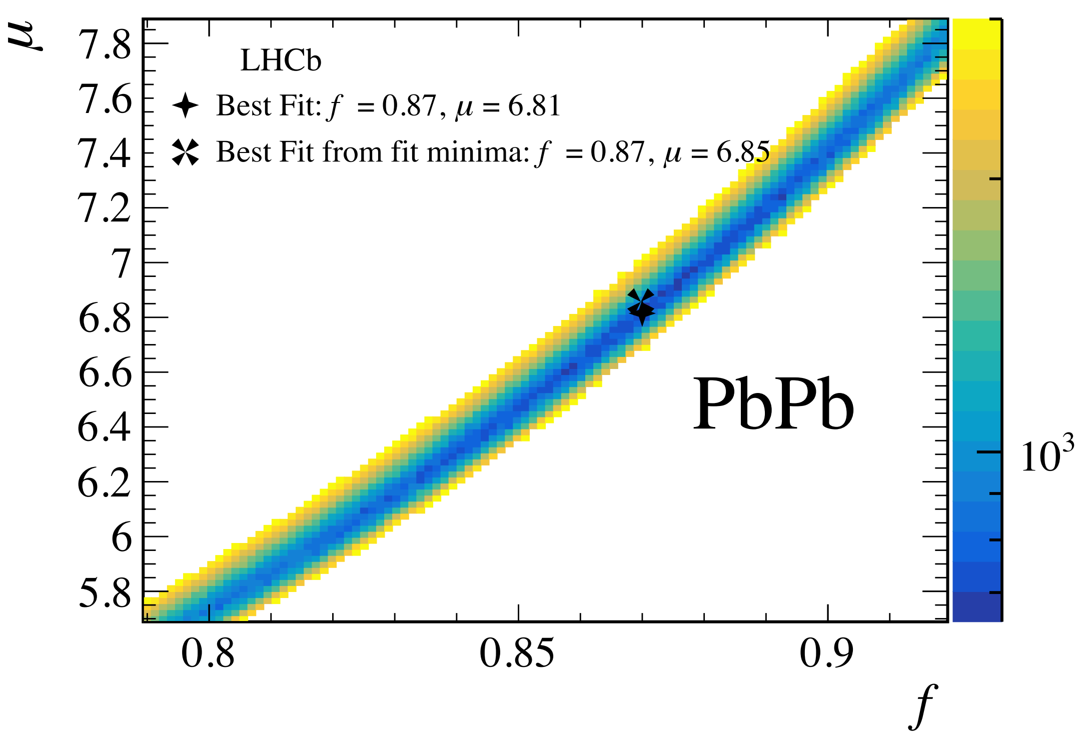
f: fraction of soft processes contributing to particle production

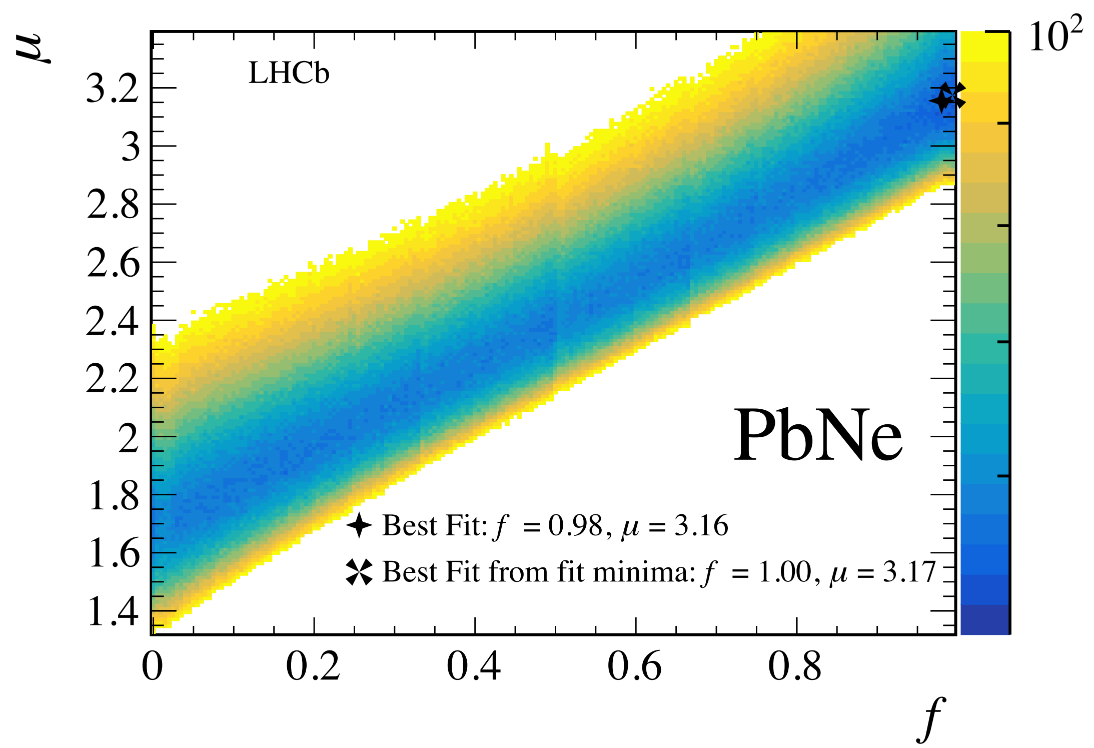
- N_{anc} → proportional to particle emitting sources. We sample a negative binomial distribution (NBD) N_{anc} times:

$$P_{p,k}(n) = \frac{(n+k-1)!}{n!(k-1)} p^k (1-p)^n; \quad p = (\mu/k + 1)^{-1}$$

- No large effect from k, fixed to $k = 1.5$
- f and μ parameters obtained by fitting the obtained Glauber distribution to data



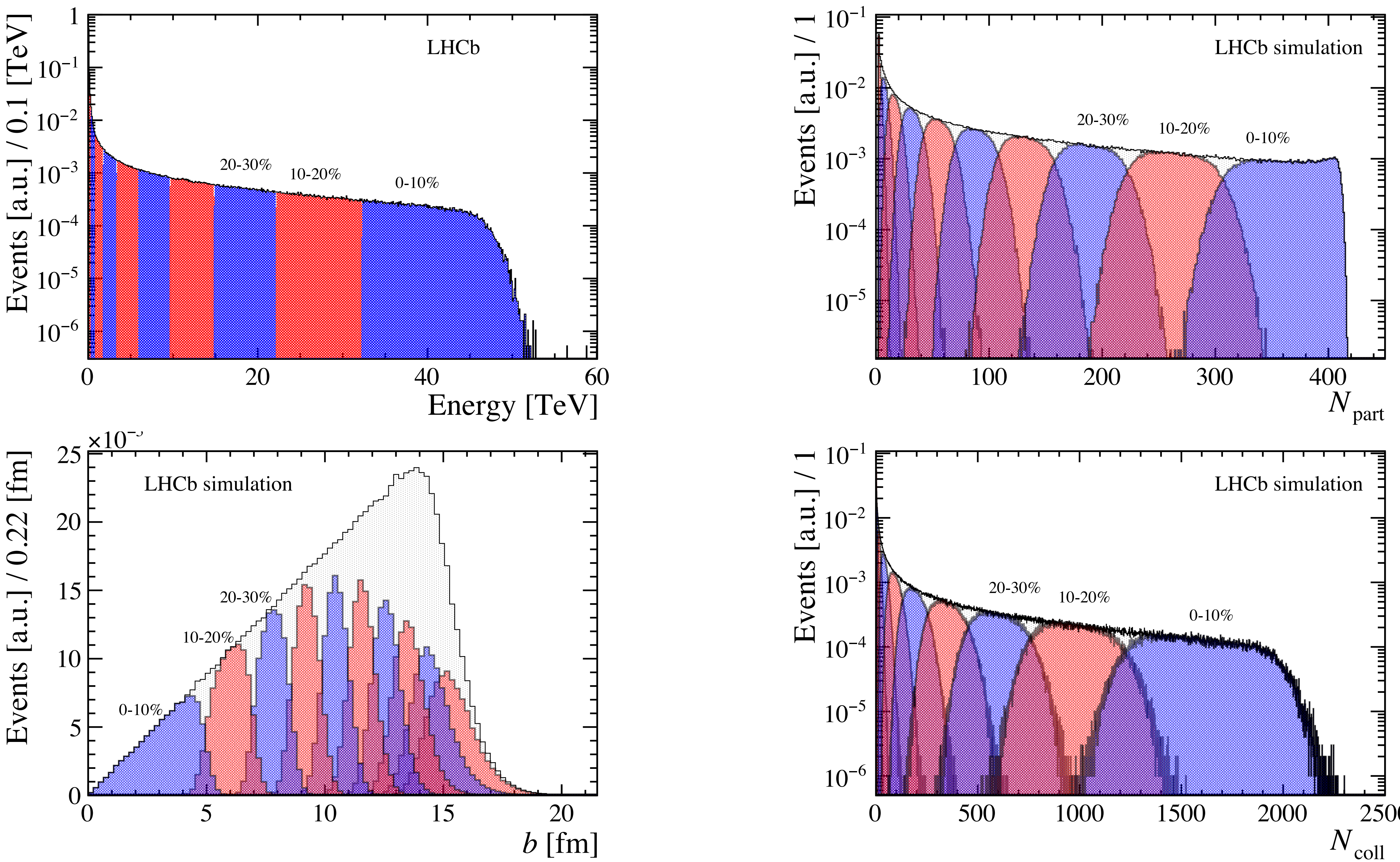




Results: Glauber parameters in PbPb

JINST 17 (2022) 05, P05009

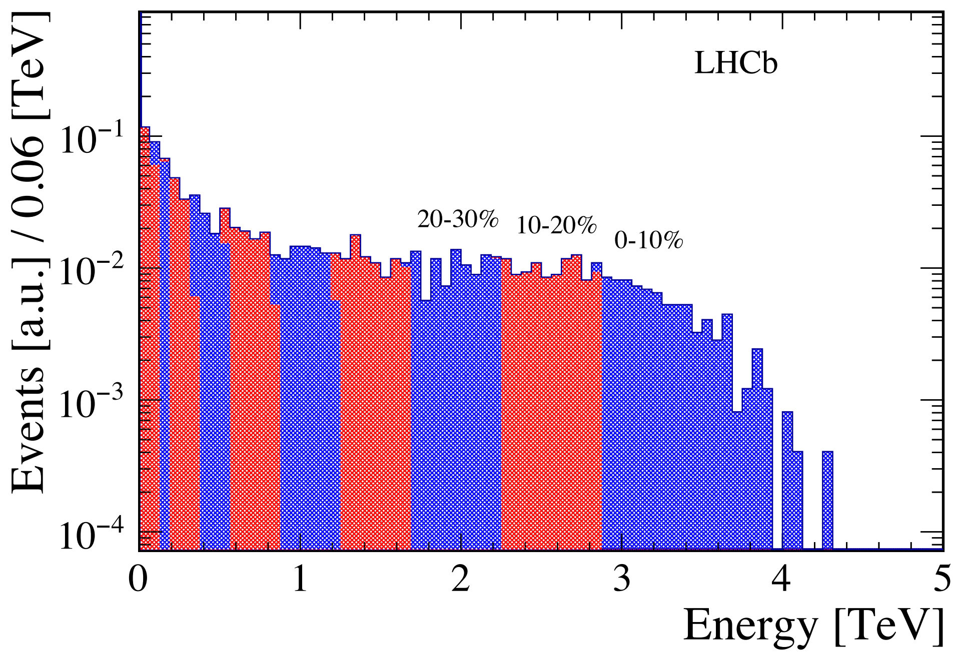
- PbPb; $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$
- Centrality class definition ($p\,\%$): $(p \times 0.01)\, I_{\mathrm{T}} = \int_{E_p}^{\infty} \frac{\mathrm{d}N}{\mathrm{d}E} \mathrm{d}E$

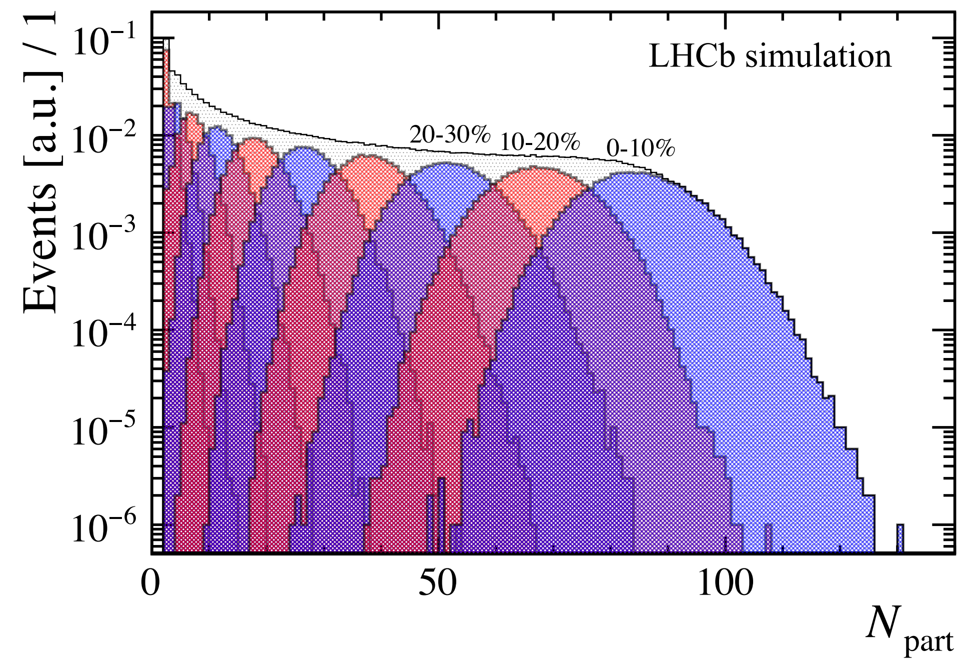


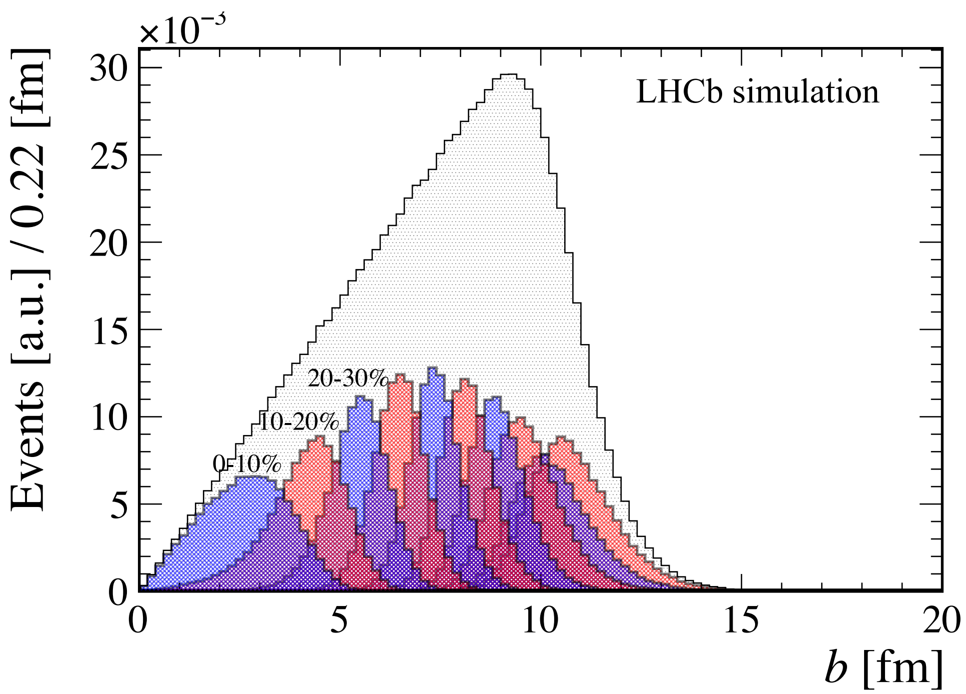
Results: Glauber parameters in PbNe

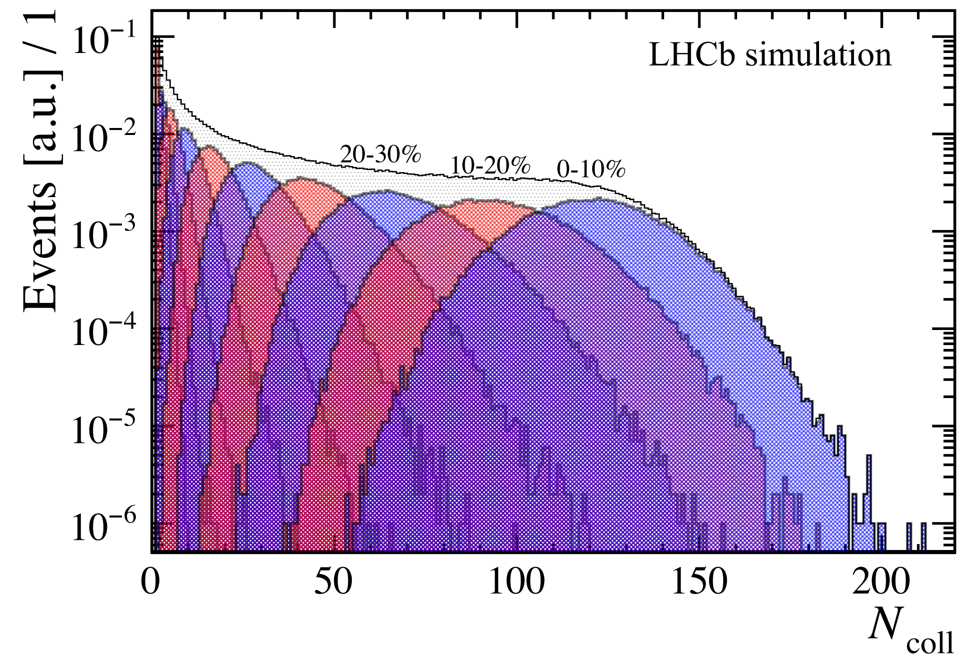
[JINST 17 (2022) 05, P05009](#)

- PbNe; $\sqrt{s_{NN}} = 69\,\text{GeV}$









Systematic uncertainties

JINST 17 (2022) 05, P05009

- Considered systematics:
  - Bin-width dependence → from boundary E_{ECAL} values to sample percentiles
  - Hadronic cross-section $\sigma_{\mathrm{inel}}^{\mathrm{NN}}$ uncertainty
  - Fit uncertainty: alternative (f, μ) best fit results
  - NBD sampling
- Additionally, contamination from electromagnetic events below $5\,\%$ for $> 84\,\%$ central events in PbPb ($> 89\,\%$ central events in PbNe)
- Smaller than RMS from Glauber Model

	Centrality class	Bin-width	Hadronic cross-section	Fit	NBD
PbPb	80–70%	3.96%	0.44%	0.38%	0.25%
	10– 0%	0.46%	0.08%	0.06%	0.03%
PbNe	80–70%	3.53%	0.74%	0.29%	0.29%
	10– 0%	0.54%	1.01%	0.12%	0.06%

Summary of systematic uncertainties

PbPb

Centrality %	E [GeV]	N_{part}	$\sigma_{N_{\mathrm{part}}}$	N_{coll}	$\sigma_{N_{\mathrm{coll}}}$	b	σ_b
100–90	0–310	2.9	1.2	1.8	1.2	15.4	1.0
90–80	310–800	7.0	2.9	5.8	3.1	14.6	0.9
80–70	800–1750	15.9	4.8	16.4	7.0	13.6	0.7
70–60	1750–3360	31.3	7.1	41.3	14.7	12.6	0.6
60–50	3360–5900	54.7	10.0	92.6	27.7	11.6	0.5
50–40	5900–9630	87.5	13.3	187.5	46.7	10.5	0.5
40–30	9630–14860	131.2	16.9	345.5	71.6	9.2	0.5
30–20	14860–22150	188.0	21.5	593.9	105.2	7.8	0.6
20–10	22150–32280	261.8	27.1	972.5	151.9	6.0	0.7
10–0	32280–∞	357.2	32.2	1570.3	236.8	3.3	1.2

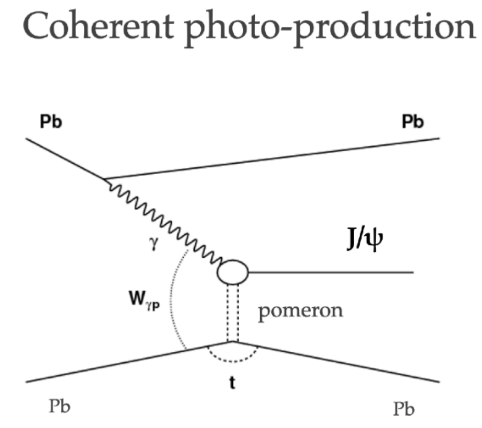
PbNe

Centrality %	E [GeV]	N_{part}	$\sigma_{N_{\mathrm{part}}}$	N_{coll}	$\sigma_{N_{\mathrm{coll}}}$	b	σ_b
100–90	0–94	2.5	0.8	1.4	0.7	10.9	1.1
90–80	94–184	3.9	1.6	2.7	1.5	10.4	1.0
80–70	184–324	6.8	2.4	5.2	2.4	9.7	0.9
70–60	324–533	11.3	3.2	9.7	3.8	9.0	0.8
60–50	532–828	17.9	4.2	17.3	5.9	8.2	0.7
50–40	828–1213	26.7	5.2	29.0	8.7	7.4	0.6
40–30	1213–1690	38.0	6.3	45.6	12.3	6.5	0.7
30–20	1690–2250	51.7	7.5	67.8	16.1	5.4	0.8
20–10	2250–2879	67.3	8.3	94.1	18.9	4.1	1.0
10–0	2879–∞	84.8	9.5	120.4	18.6	2.7	1.1

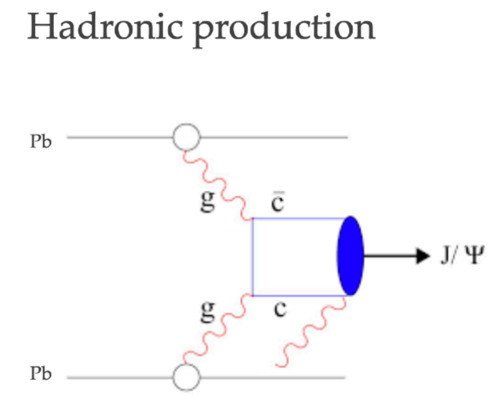
Example 1: photo-produced J/ψ in PbPb

Phys. Rev. C105 (2022) L032201

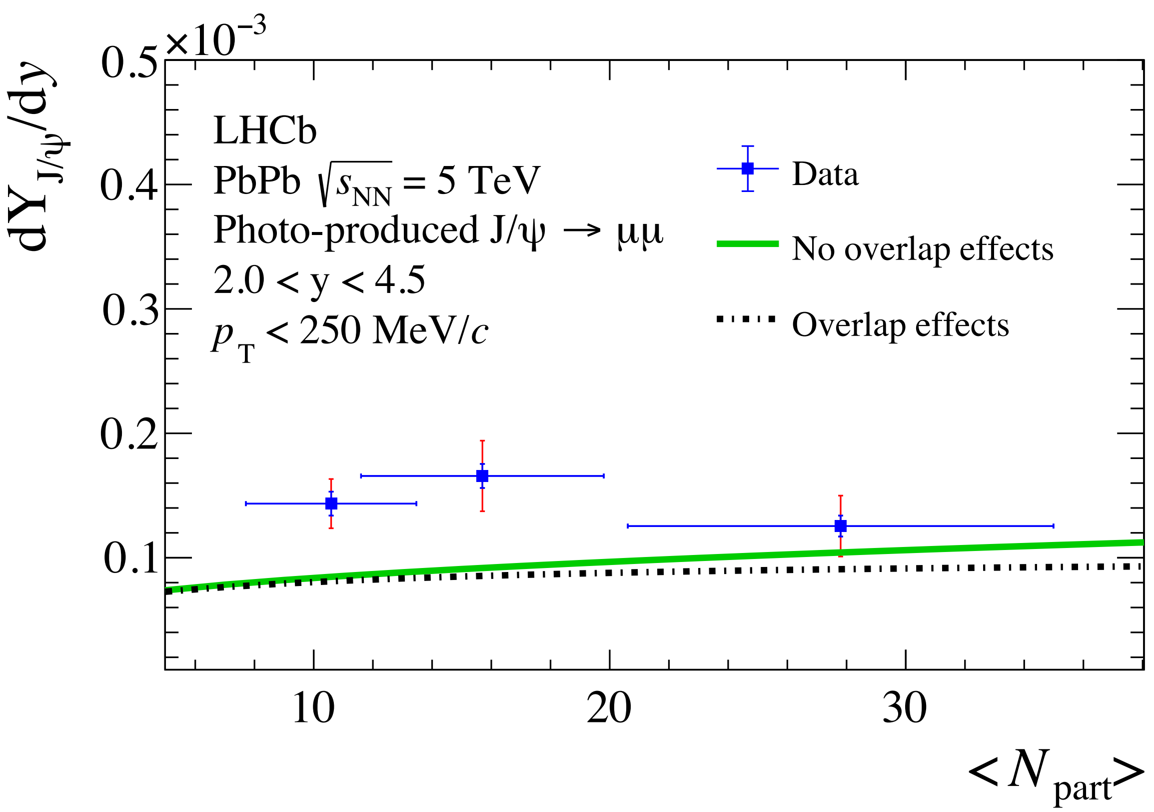
- In PbPb collisions, J/ψ can be produced both in electromagnetic and hadronic interactions between nuclei
- Measurement to quantify photo-production
- Ratio between hadro-produced and photo-produced J/ψ depends on centrality

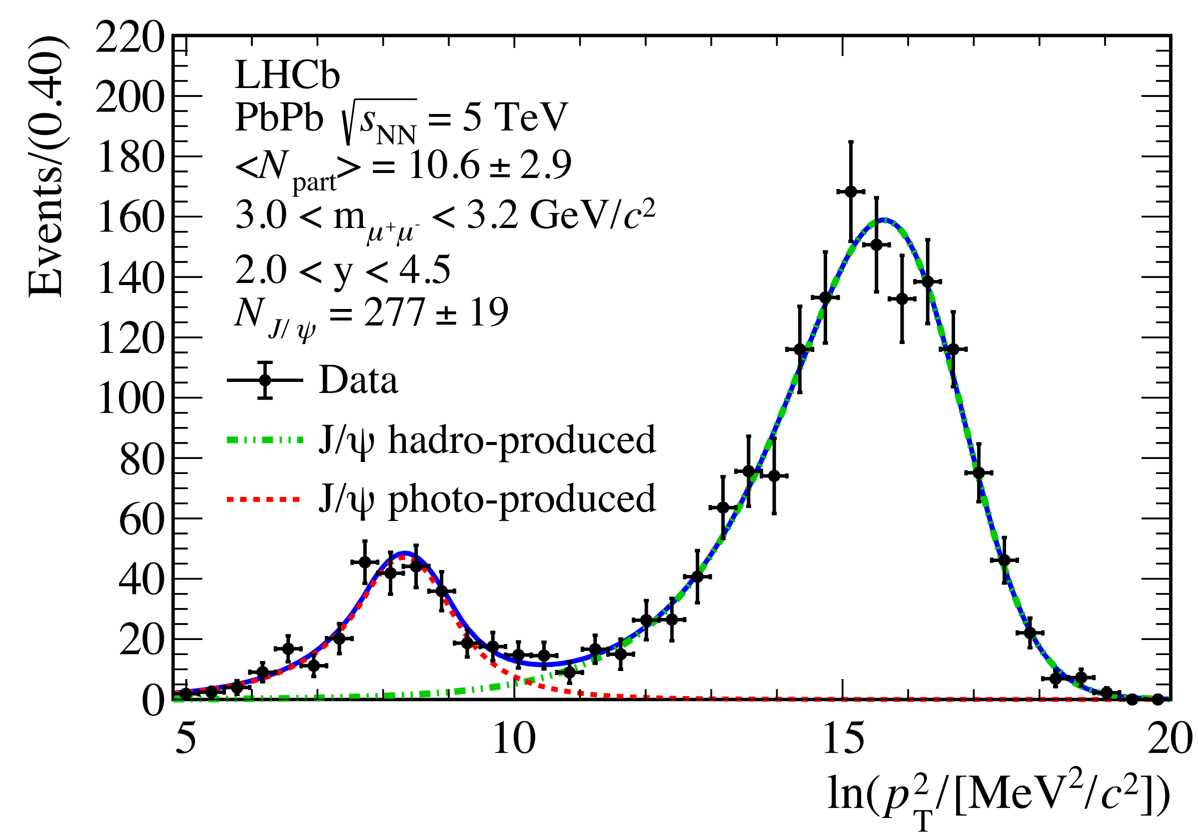


$\gamma(pomeron) \rightarrow J/\psi$



$gg \rightarrow J/\psi$

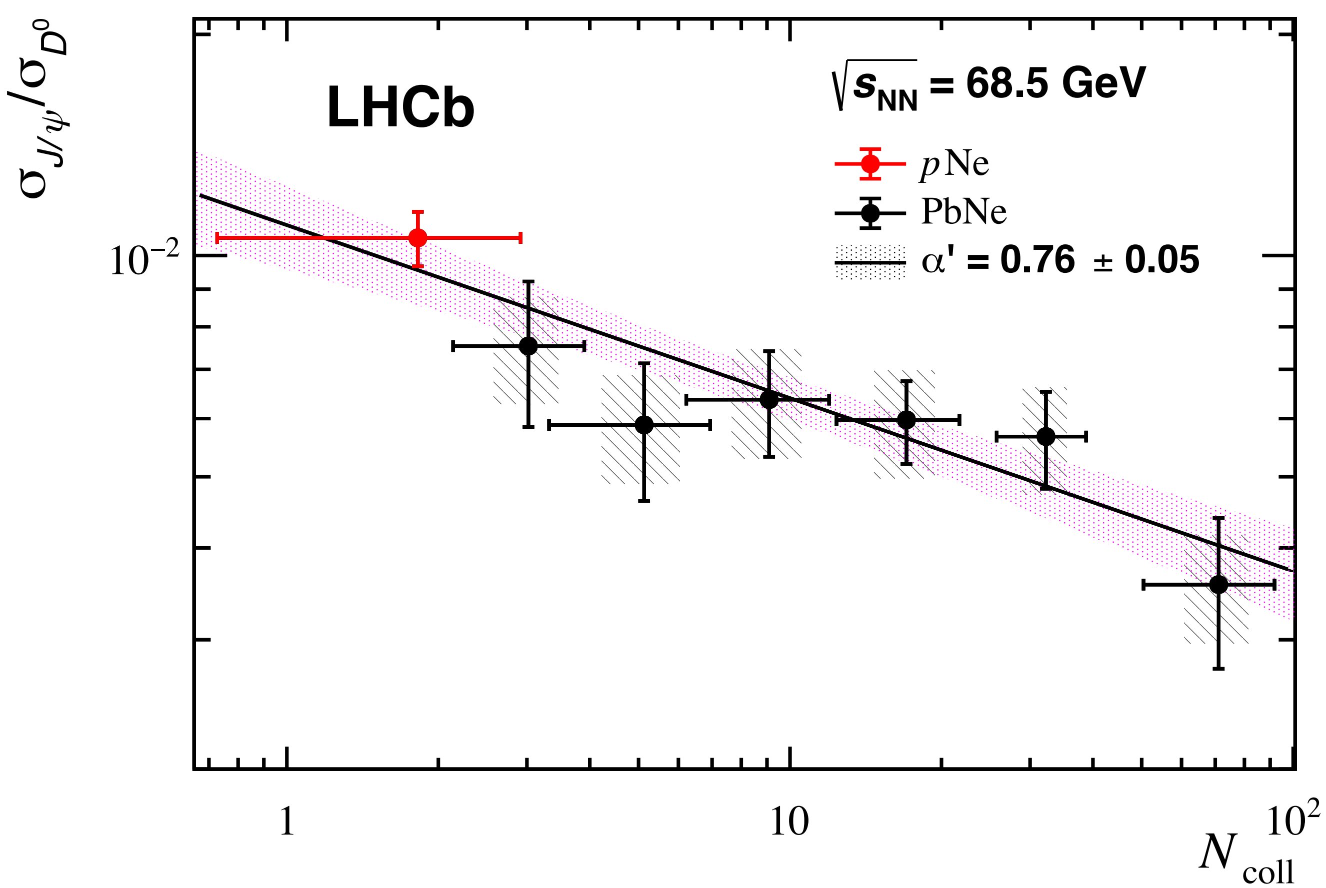


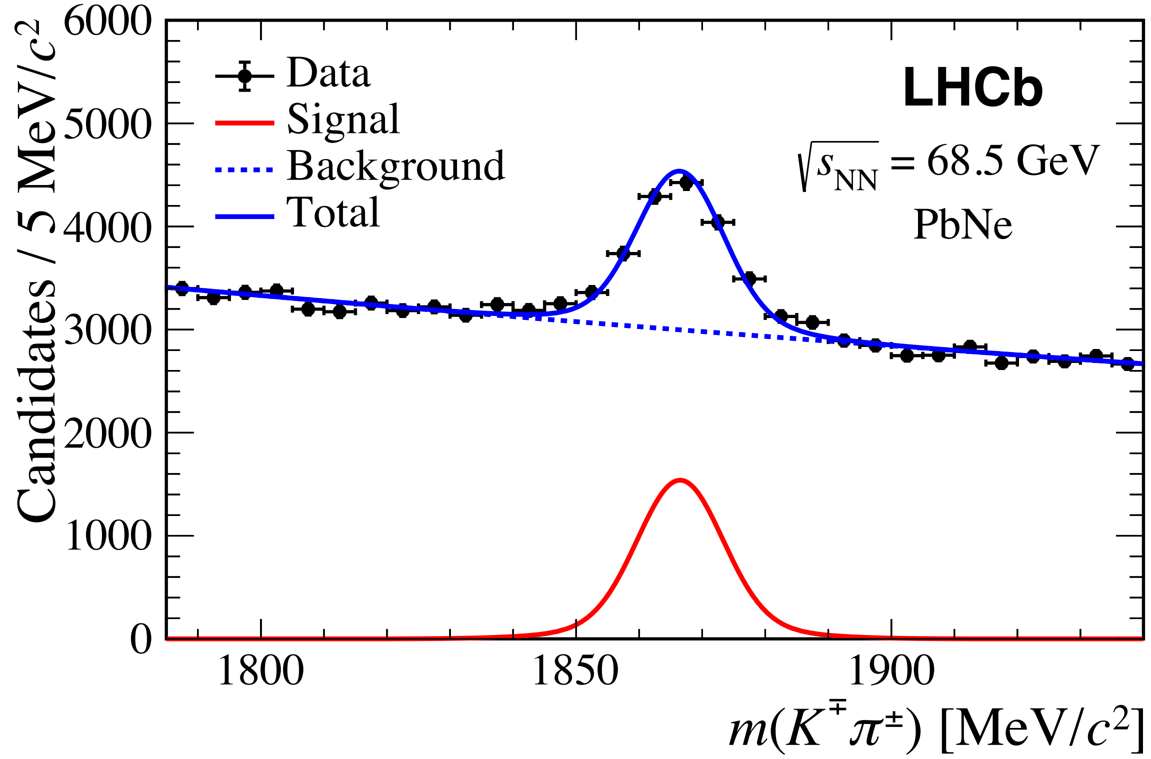


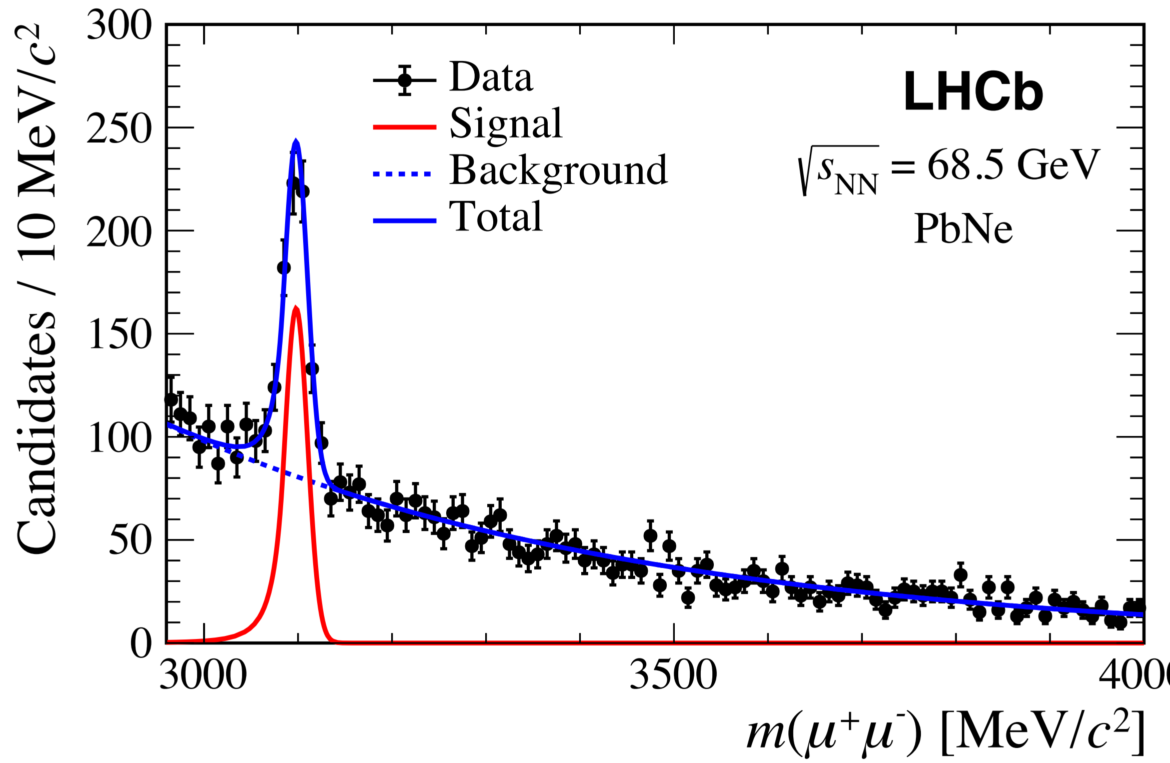
Example 2: $J/\psi/D^0$ ration in PbNe

arXiv:2211.11652

- J/ψ is suppressed in low energy nuclear collisions due to nuclear absorption with respect to D^0
  - Expecting an additional "anomalous" suppression if QGP forms in PbNe collisions
- Trend fitted to $N_{\rm col}^{\alpha'-1}$, $\alpha' = 0.76 \pm 0.05$, compatible with values fitted with pA collisions
- no anomalous J/ψ suppression is observed







Small systems: pPb, pp, pHe, pNe, pAr...

Studying collectivity in small systems: multiplicity

- Small systems are the core program of heavy-ion physics at LHCb
  - no centrality limitations such in PbPb, optimal performance of all subsystems

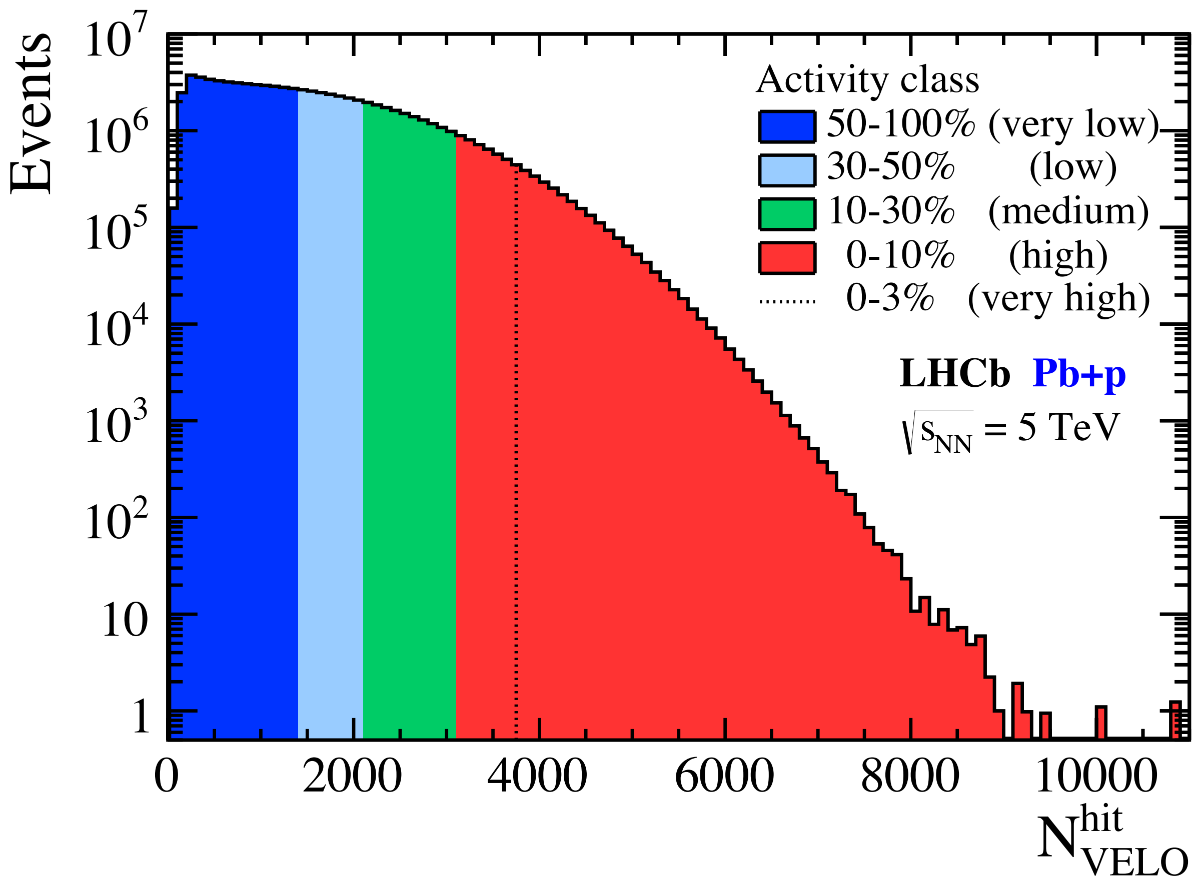
- Transition between small to large systems
  - is there a connection between high multiplicity and low multiplicity?
- Centrality determination is challenging in small systems:
  - low multiplicities subject to fluctuations in $p\mathrm{A}$
  - no centrality analogue in pp

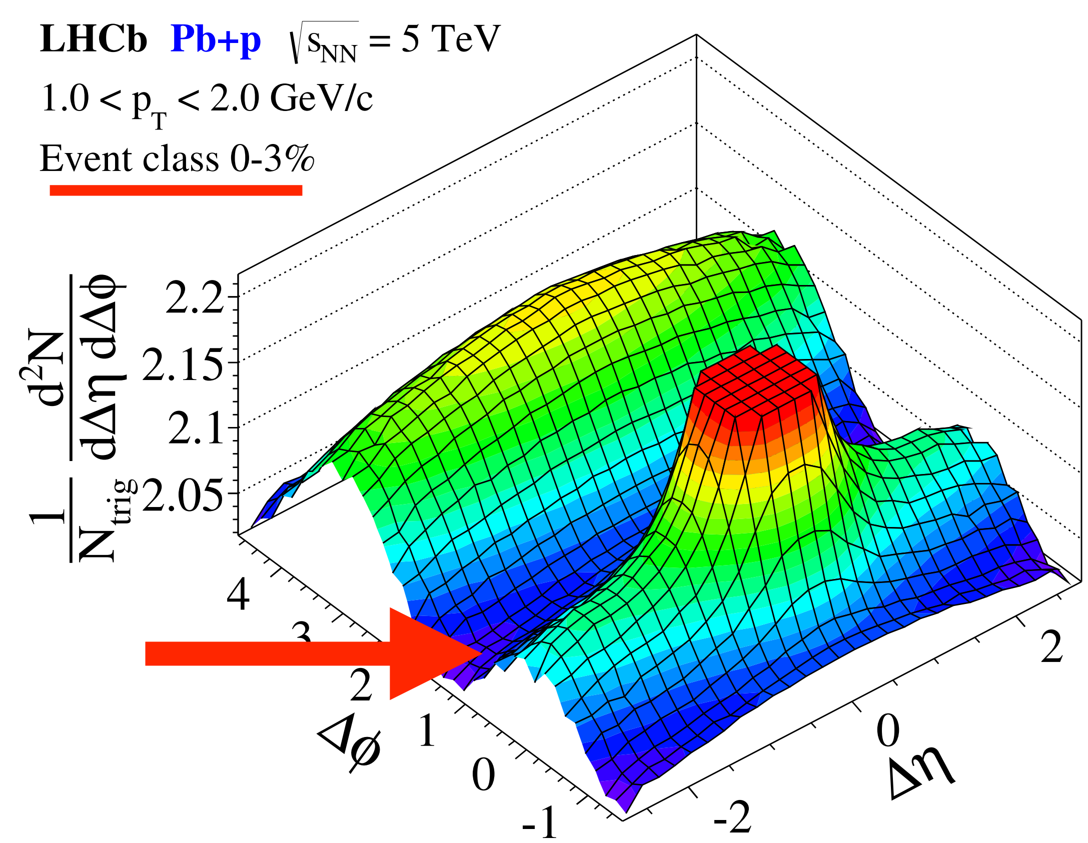
- Generally, event multiplicity (i. e. N_{ch} per event) is used directly as a metric
- Some complications:
  - which η region is used to determine the multiplicity, effect in result?
  - N_{ch} without detector effects not always available
- At LHCb, we generally use VELO information:
  - Very good performance (high efficiency, low fake track rate)
  - best η coverage ($2.0 < \eta < 5.0$ and around $-3.0 < \eta < -2.0$)

Di-hadron correlations in pPb

Phys. Lett. B762 (2016) 473

- Search for ridge-like structures in high multiplicity pPb collisions
  - Sign of collectivity, considered a QGP signature
- Using **hit (cluster)-multiplicity** in the VELO detector as activity estimator
- Measure two charged particle correlations in (η, ϕ): $\frac{1}{N_{trigg}} \frac{d^2 N_{pair}}{d\Delta\eta d\Delta\phi}$ $\quad \Delta\eta = \eta_{trigg} - \eta_{assoc}$, $\Delta\phi = \phi_{trigg} - \phi_{assoc}$
- Ridge observed both in forward and backward detector configurations



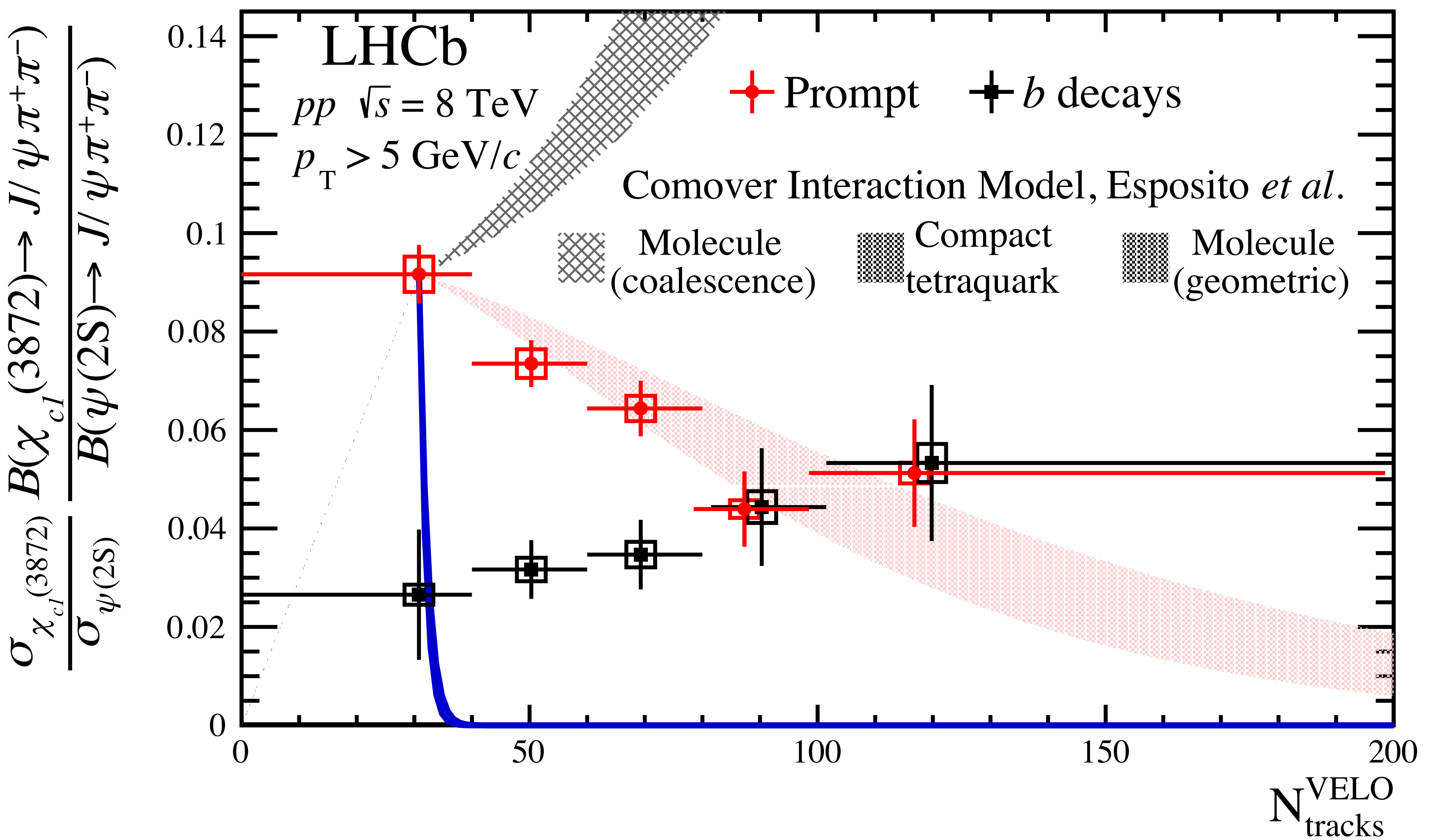


Other studies with multiplicity

- Study of exotic particle production with event multiplicity → Information
- Observed dependency of $\chi_{c1}(3872)/\psi(2S)$ ratio with event activity
- Estimator: number of VELO tracks in the event $N_{\text{tracks}}^{\text{VELO}}$

- Different models of comover interaction provide different conclusions (tetraquark vs molecule)

Phys. Rev. Lett. 126 (2021) 092001



Study of cold nuclear matter

- Cold Nuclear Matter (CNM) effects: modifications of particle production yields in ion collisions with respect to pp that are not due to formation of a deconfined medium, including:
  - Final state effects
  - Initial state effects
- Initial state effects can be treated with global analyses that parametrise modifications with respect to pp in nuclear PDFs
  - Need of experimental data as input!
- Experimental data is also needed to characterise other CNM effects

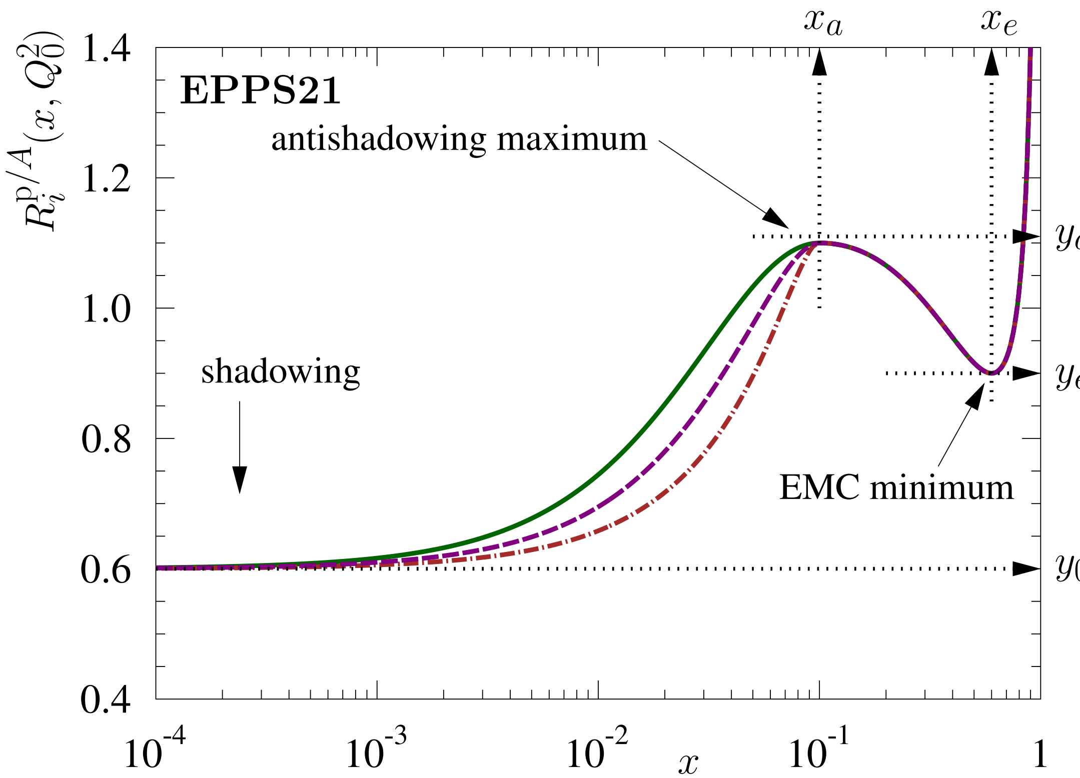


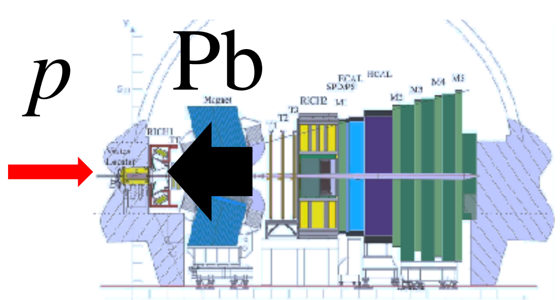
Figure from Eur.Phys.J.C 82 (2022) 5, 413

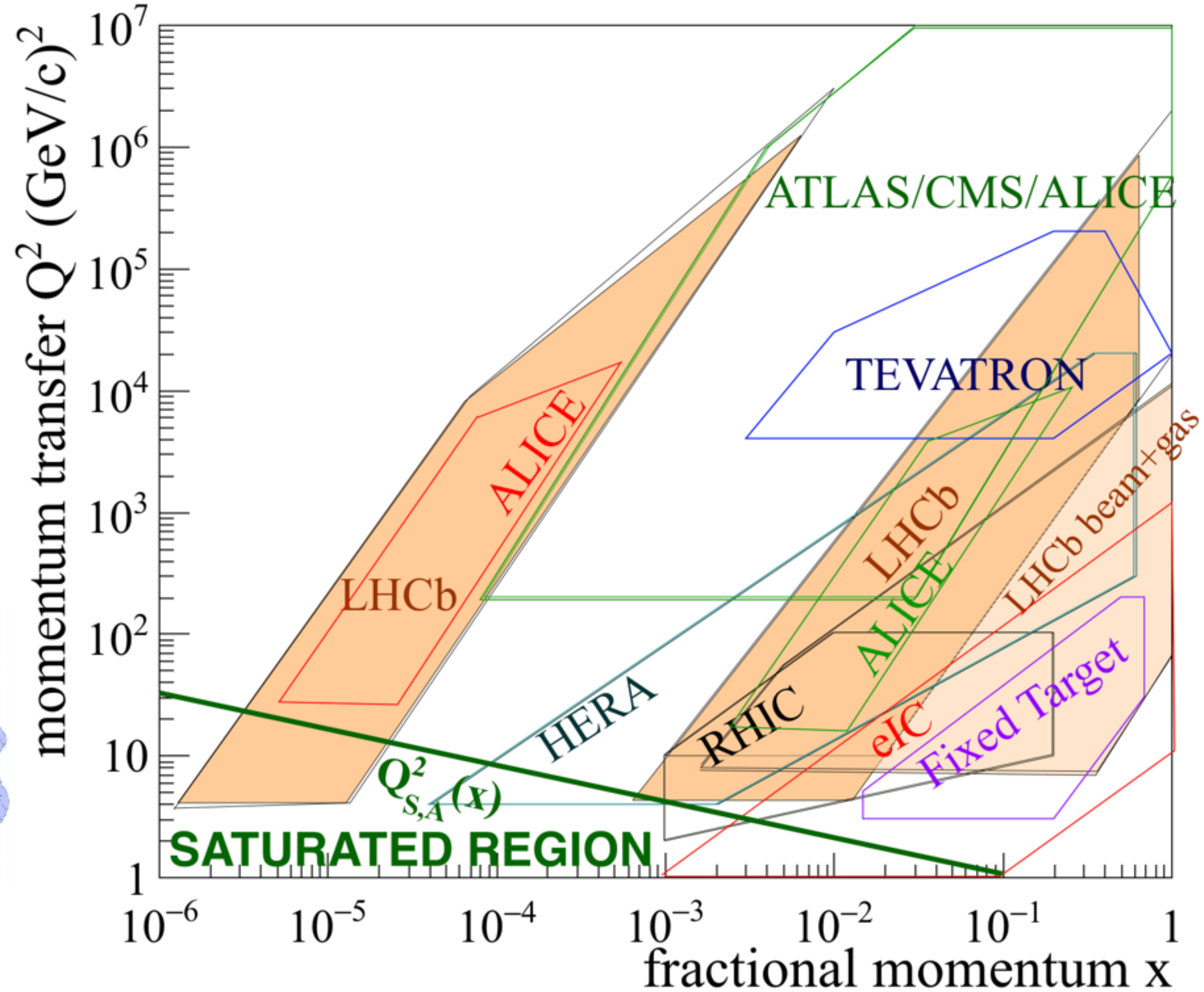
- Main observable: **nuclear modification factor:**

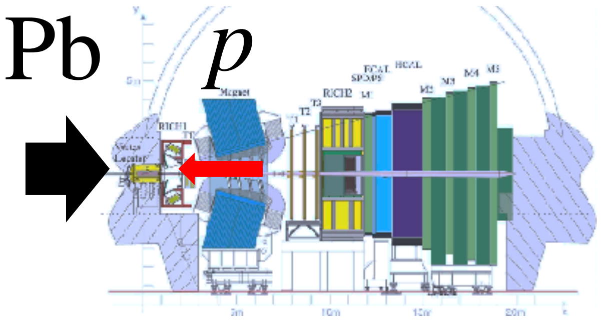
$$R_{p\mathrm{Pb}}(\eta, p_\mathrm{T}) = \frac{1}{A}\frac{d^2\sigma_{p\mathrm{Pb}}(\eta, p_\mathrm{T})/dp_\mathrm{T}d\eta}{d^2\sigma_{pp}(\eta, p_\mathrm{T})/dp_\mathrm{T}d\eta}, \quad A = 208$$

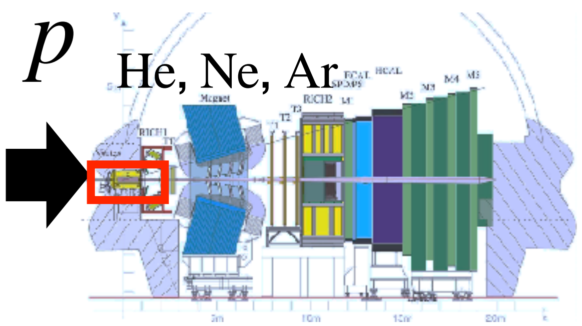
Exploring (x, Q^2) diagram

- LHCb probes the frontier regions of the (x, Q^2) diagram
  - set additional constrains to nPDFs and other CNM models
  - analyses generally aim to provide production cross-sections and $R_{p\mathrm{Pb}}$ with respect to (η, p_T)
    - ✳ Two examples with light probes: light hadrons and π^0 production in pPb and pp









Prompt charged particles production in pPb and pp

Phys. Rev. Lett. 128, 142004

Nuclear modification factor $\rightarrow$ $R_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}}) = \frac{1}{A} \frac{d^2\sigma_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}{d^2\sigma_{pp}(\eta, p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}$, $A = 208$

$$\left.\frac{d^2\sigma}{dp_{\mathrm{T}}d\eta}\right|_{p\mathrm{Pb},\,pp} = \frac{1}{\mathscr{L}} \cdot \frac{N^{ch}(\eta, p_{\mathrm{T}})}{\Delta p_{\mathrm{T}} \Delta\eta}$$

N^{ch}: **prompt charged particle yield**

$\Delta\eta$, Δp_{T}: **bin size**

$\mathscr{L}$: **integrated luminosity of the dataset**

- Prompt charged particles:
  - long-lived particles (lifetime $< 30\,\mathrm{ps}$)
  - produced in primary interaction or without long-lived ancestors
- Long-lived charged particles: π^-, K^-, p, e^-, μ^-, Ξ^-, Σ^+, Σ^-, Ω^- $(+cc.)$

- Datasets at $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$ →
- Measure $R_{p\mathrm{Pb}}$ in common η range

Beam	Acceptance	Luminosity
pp	$2 < \eta < 4.8$	$3.49 \pm 0.07\,\mathrm{nb}^{-1}$
pPb	$1.6 < \eta < 4.3$	$42.73 \pm 0.98\,\mu\mathrm{b}^{-1}$
Pbp	$-5.2 < \eta < -2.5$	$38.71 \pm 0.97\,\mu\mathrm{b}^{-1}$

Prompt charged particles production in pPb and pp

Phys. Rev. Lett. 128, 142004

- N^{ch} measured with long tracks, covering $p > 2\,\text{GeV}/c,\ 0.2 < p_{\text{T}} < 8\,\text{GeV}/c$
- $N^{\text{ch}} = N^{\text{candidates}} \dfrac{P}{\varepsilon_{\text{reco}}\varepsilon_{\text{sel}}}$
  - $N^{\text{candidates}}$: selected long tracks
  - P: signal purity
  - $\varepsilon_{\text{reco}}$: reconstruction efficiency
  - ε_{sel}: selection efficiency

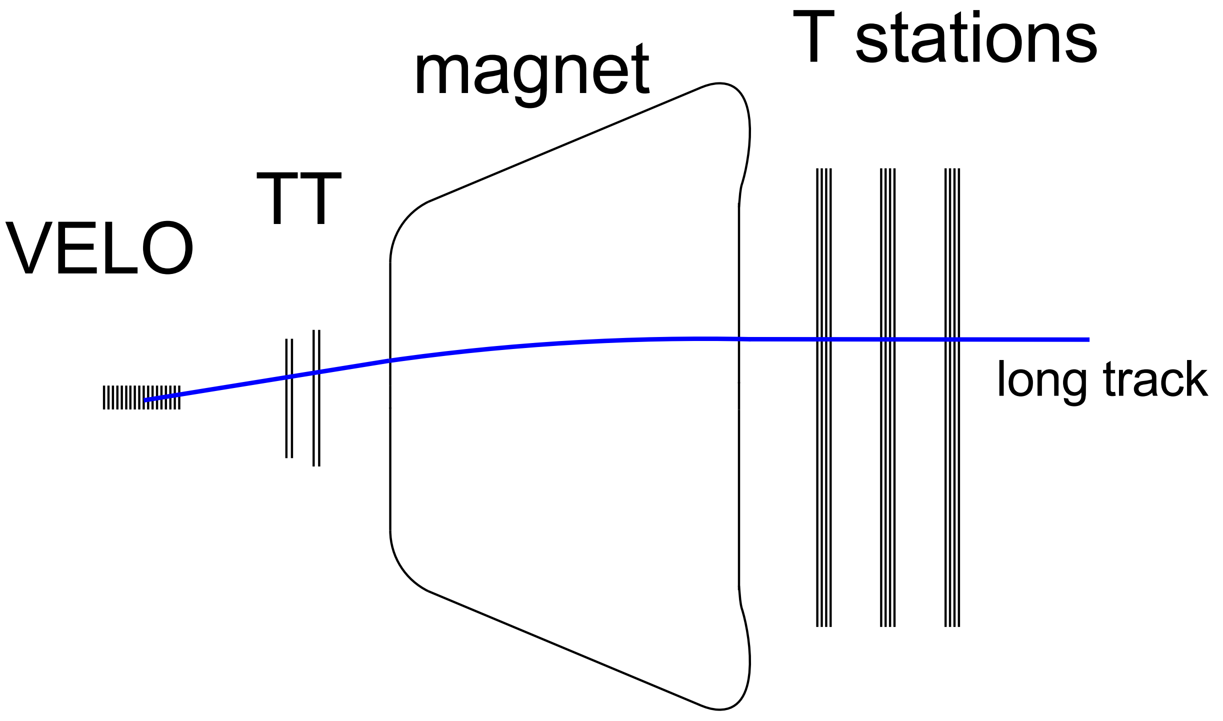


Figure from JINST 10 (2015) 02, P02007

- **Background contributions**:
  - Fake tracks, reconstruction artefacts not produced by charged particles
  - Secondary particles: particles from
    - ✳ interactions with the detector material (e^- from γ conversions and hadrons from hadronic interactions)
    - ✳ daughters of long-lived particles ($\Lambda^0, K_S^0, \Sigma^+ \ldots$)

Prompt charged particles production in pPb and pp

Background description

Phys. Rev. Lett. 128, 142004

- Background from fake tracks specially important
  - Increases with event occupancy, large contribution in Pbp
  - Contribution rises strongly with p_{T}
- Remove most background with a tight track selection
- Selection efficiency measured on data using a calibration sample of $\phi(1020) \to K^+K^-$ decays
- Remaining background estimated with simulation and corrected with data
  - use background-enriched proxy samples

Relative particle composition

- Reconstruction efficiency depends on relative particle composition
- Charged particle composition not yet measured in LHCb acceptance for pPb $\to$ use EPOS-LHC simulation validated with ALICE data (Phys. Lett. B760 (2016) 720)

Prompt charged particles production in pPb and pp

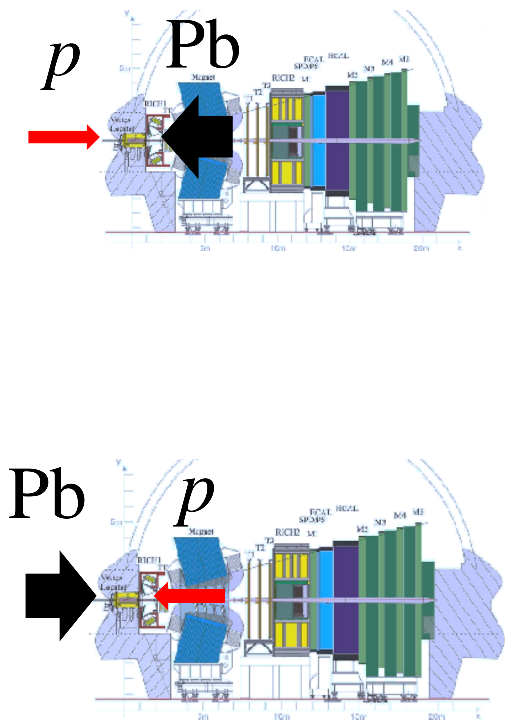
Phys. Rev. Lett. 128, 142004

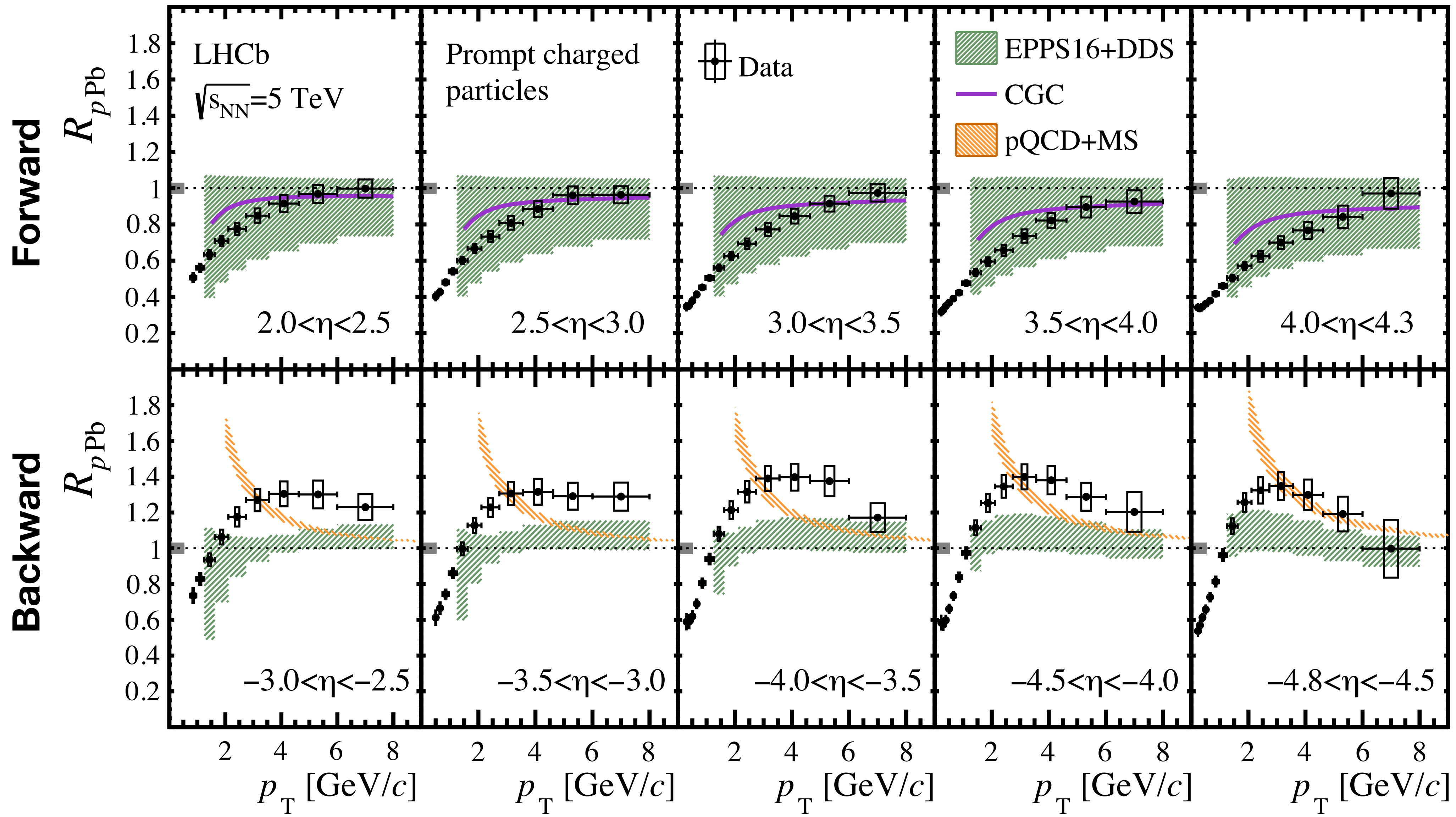
- Measurement dominated by systematic uncertainties:
  - particle composition in pPb for most bins
  - tracking efficiency and signal purity in boundary (η, p_{T}) bins
- How to improve the precision?
  - Measuring abundance of π, K and p using PID information, greatly reducing particle composition systematic

Uncertainty source	pPb [%] (forward)	pPb [%] (backward)	pp [%]
Track-finding efficiency	1.5 – 5.0	1.5 – 5.0	1.6 – 5.3
Detector occupancy	0.0 – 2.8	0.6 – 2.9	0.1 – 1.6
Particle composition	0.4 – 4.1	0.4 – 4.6	0.3 – 2.4
Selection efficiency	0.7 – 2.2	0.7 – 3.0	1.0 – 1.7
Signal purity	0.1 – 1.8	0.1 – 11.7	0.1 – 5.8
Luminosity	2.3	2.5	2.0
Statistical uncertainty	0.0 – 0.6	0.0 – 1.0	0.0 – 1.1
Total (in $\mathrm{d}^2\sigma/\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}$)	3.0 – 6.7	3.3 – 14.5	2.8 – 8.7
Total (in $R_{p\mathrm{Pb}}$)	4.2 – 9.2	4.4 – 16.9	–

- **Strong suppression** at forward η (saturation region)
- **Enhancement** at backward for $p_T > 1.5\,\mathrm{GeV}/c$, not reproduced by nPDF predictions →additional CNM effects there?

Phys. Rev. Lett. 128, 142004



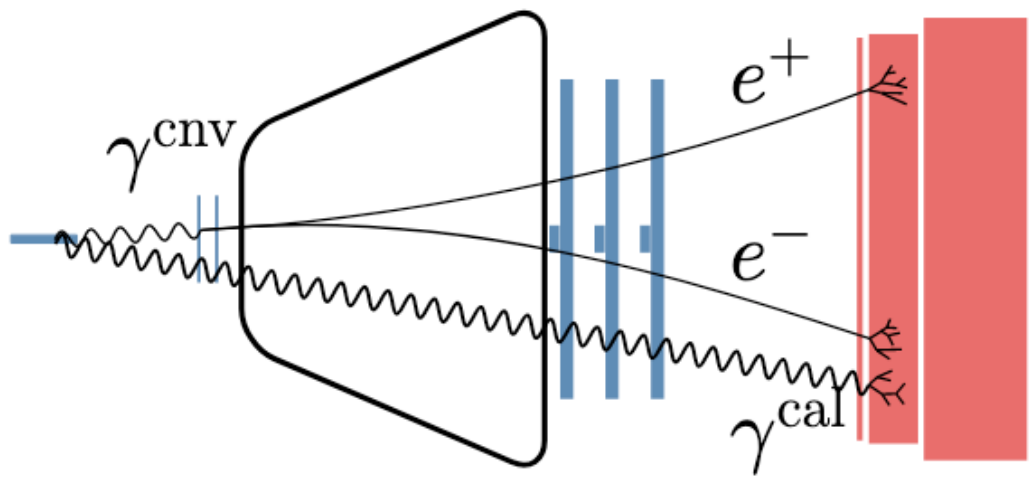


Neutral pion production in pPb and pp

arXiv:2204.10608

- Measurement of π^0 production cross-section:
  - Disentangle effects from different hadrons → better understand enhancement in backward

- Detection technique fully independent from charged particle analysis:
  - Measure $\pi^0 \to \gamma^{\text{cnv}}\gamma^{\text{cal}}$
    - ✳ use $\pi^0 \to \gamma^{\text{cal}}\gamma^{\text{cal}}$ as cross-check and efficiency calibration



- Datasets:
  - pPb and Pbp data at $8.16\,\text{TeV}$
  - pp reference constructed with 5 and $13\,\text{TeV}$ datasets

Kinematic coverage:

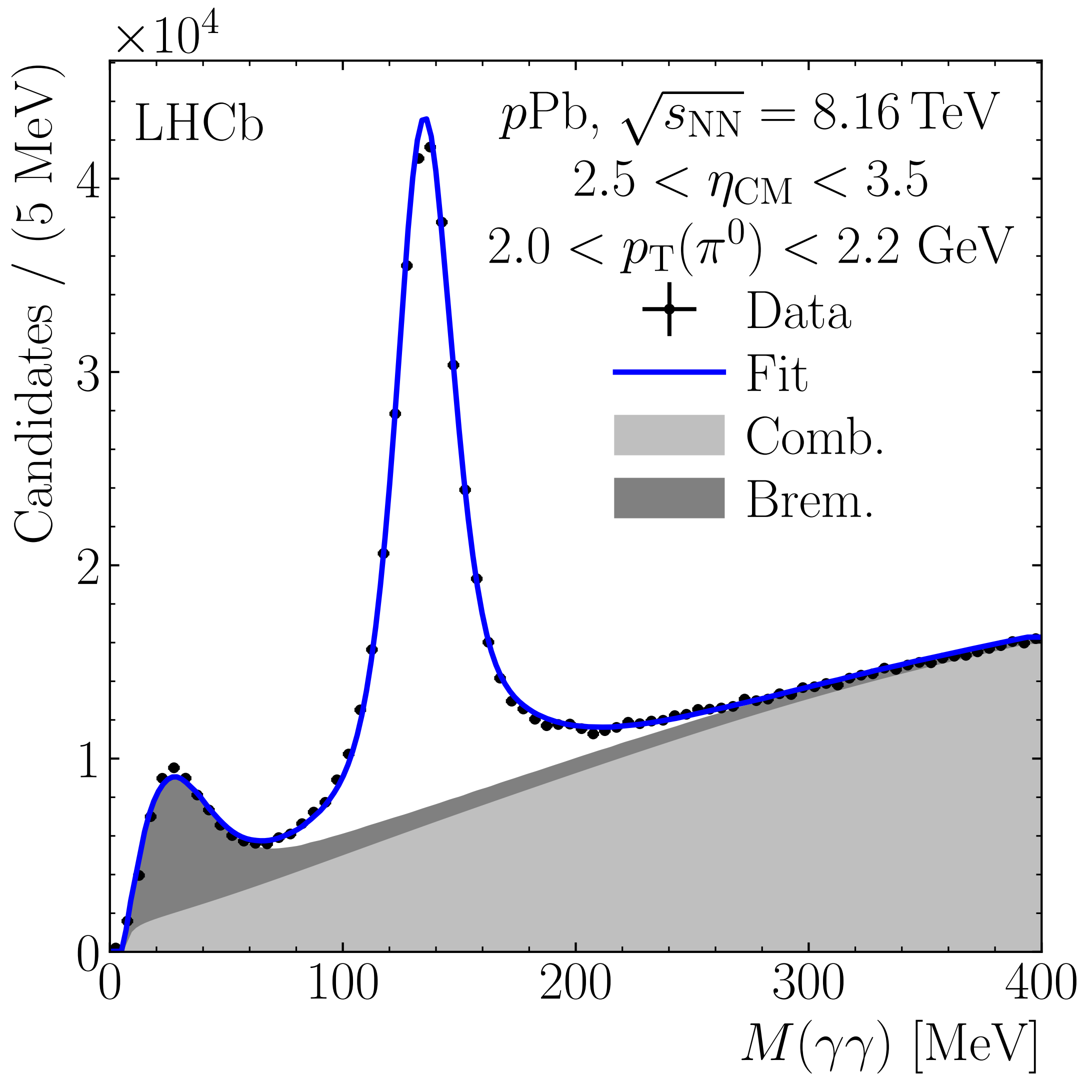
$$1.5 < p_{\text{T}} < 10.0\,\text{GeV}/c$$

$$\begin{cases} 2.5 < \eta_{\text{CM}} < 3.5 \\ -4.0 < \eta_{\text{CM}} < -3.0 \end{cases}$$

Neutral pion production in pPb and pp

arXiv:2204.10608

- Yields of π^0 extracted from fit to mass spectrum for each kinematic bin
  - Signal: two-sided Crystal Ball function
  - Combinatorial background: constructed with proxy sample of charged tracks
  - Bremsstrahlung: combination of the converted photon and its own brem. radiation
- Yields of π^0 corrected by detector effects using simulation:
  - Calibration to correct data-simulation differences (JINST 14 (2019) P11023)
  - Iterative unfolding technique used to correct efficiency and resolution effects

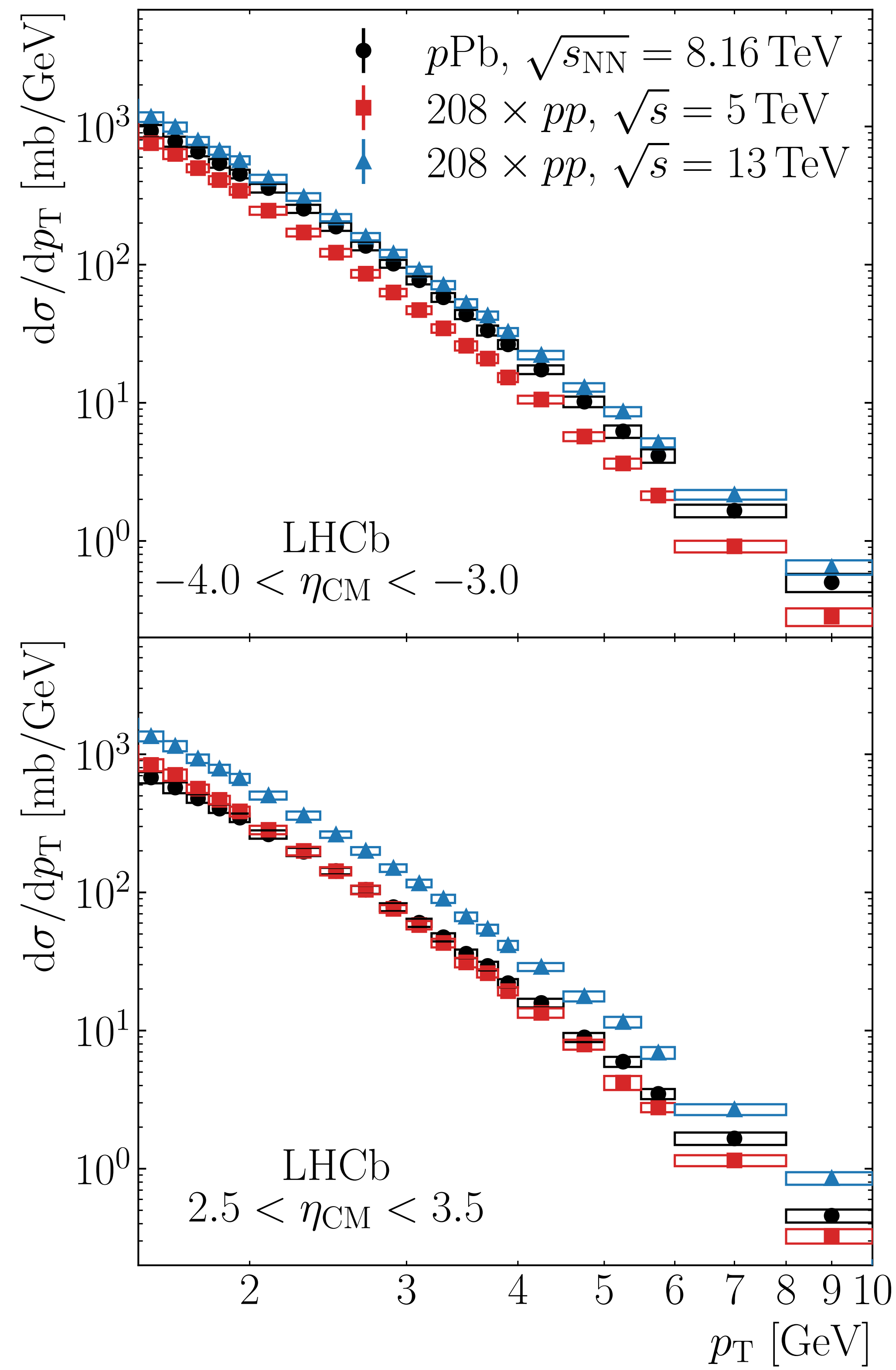


Neutral pion production in pPb and pp

arXiv:2204.10608

- Result for $d\sigma/dp_{\mathrm{T}}$ cross-section
- Interpolation of $5\,\mathrm{TeV}$ and $13\,\mathrm{TeV}$ cross-section to construct the reference for $R_{p\mathrm{Pb}}$
- Correlated uncertainties across datasets cancel in $R_{p\mathrm{Pb}}$:
  - total uncertainty less than $6\,\%$ in most p_{T} intervals

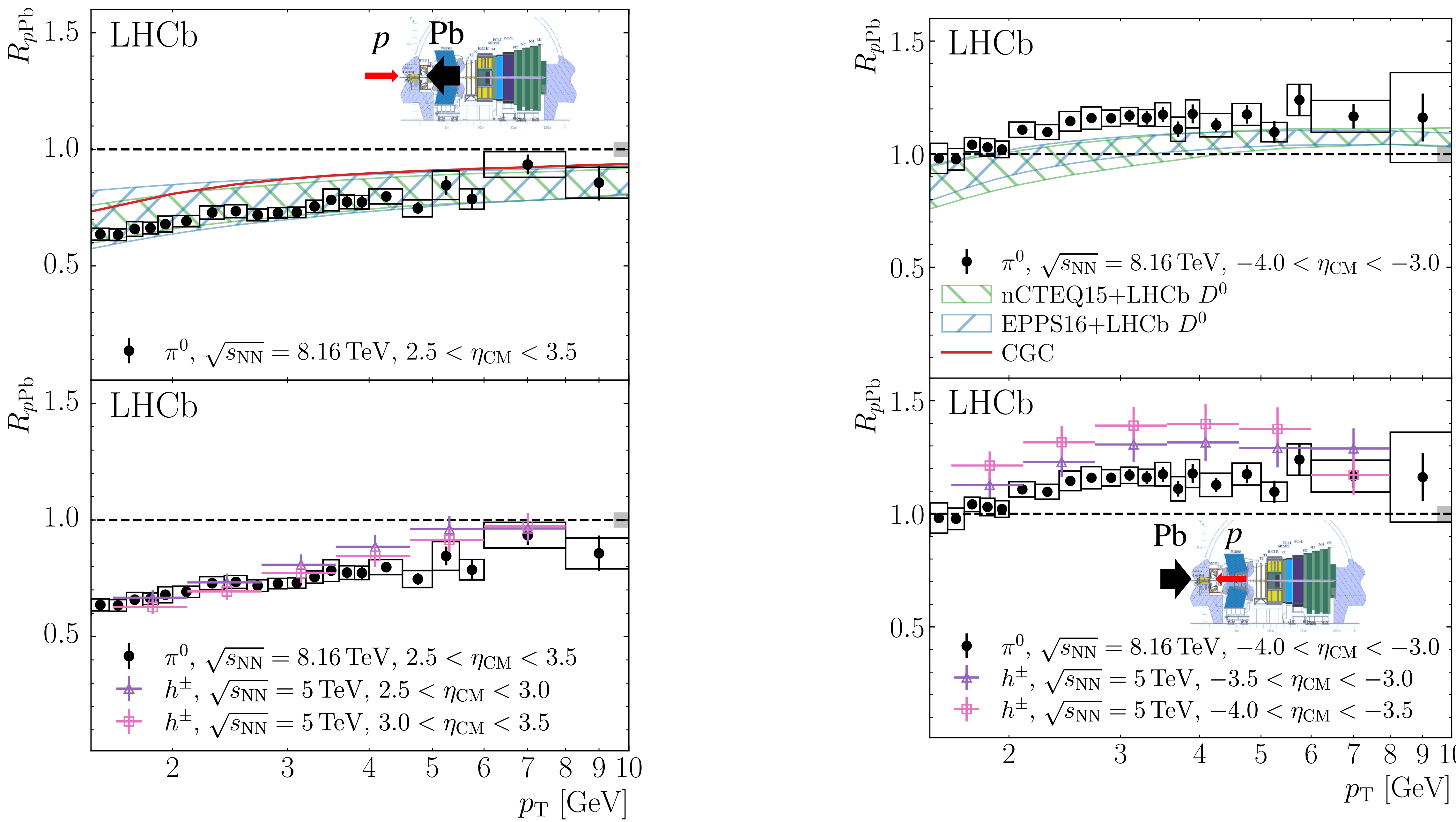
Source	$\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$ [%]	$R_{p\mathrm{Pb}}$ [%]
Fit model	2.0–12.6	0.9–15.8
Unfolding	0.3–6.4	0.4–6.4
Interpolation	–	0.9–4.5
Material	4.0	–
Efficiency	1.3–1.9	1.9–2.1
Luminosity	2.0–2.6	2.2–2.3
Total systematic	5.4–15.0	4.3–17.4
Statistical	1.0–9.6	1.4–9.1



Neutral pion production in pPb and pp

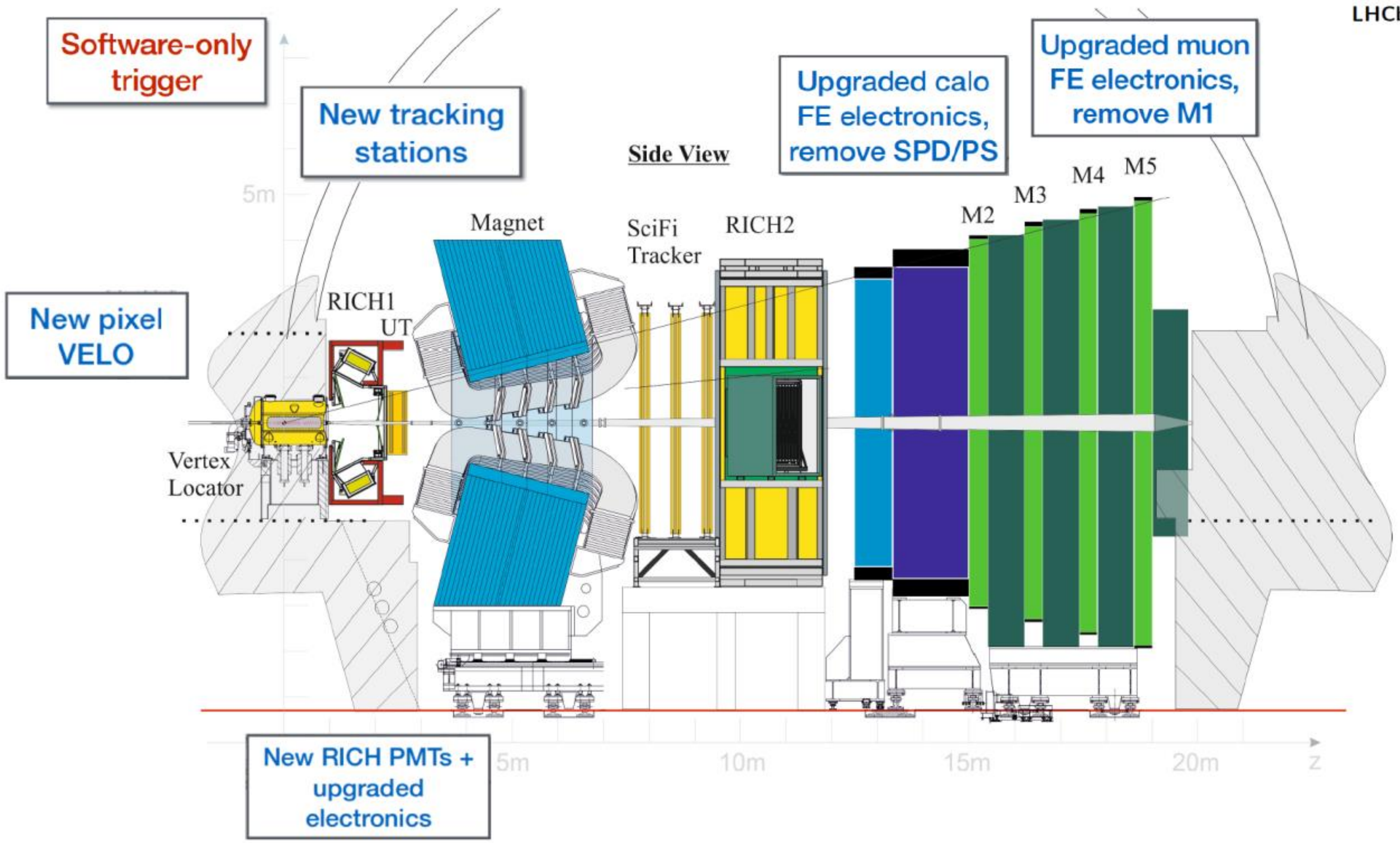
arXiv:2204.10608

- Forward region: similar suppression as charged hadrons, compatible with predictions
- Backward region: less enhancement than charged hadrons → effect stronger for p, K?

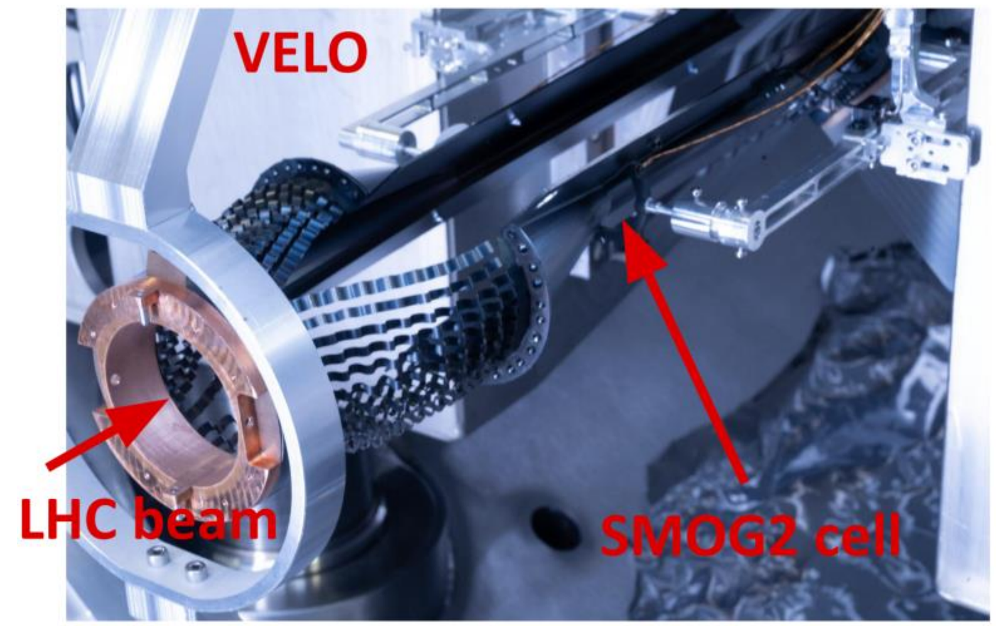


Outlook:

The LHCb Upgrade I



LHCb-TDR-12

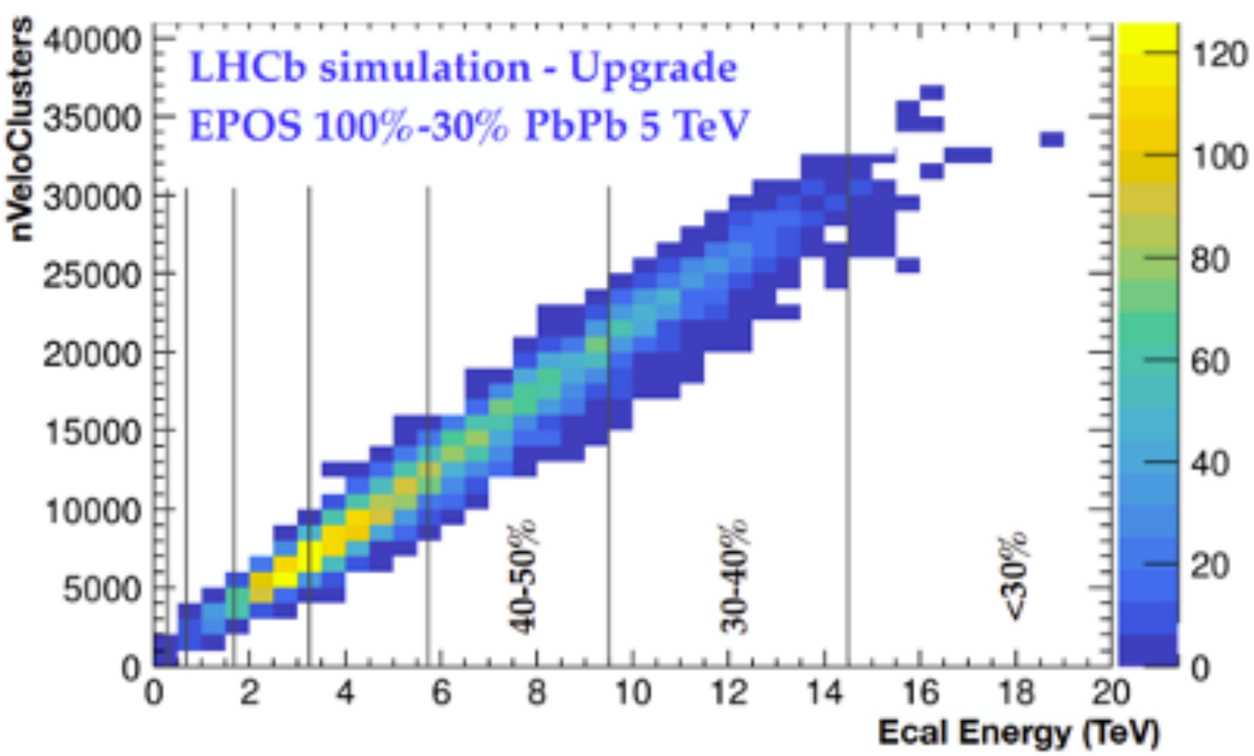


- Major upgrade: replacement of tracking and particle identification detectors
- New SMOG2 system → confinement gas cell upstream VELO
  - up to $\times 100$ gas pressure ($\times 100$ increase in luminosity)
  - non-noble gases $(H_2, O_2, D_2, \ldots)$
  - precise luminosity determination

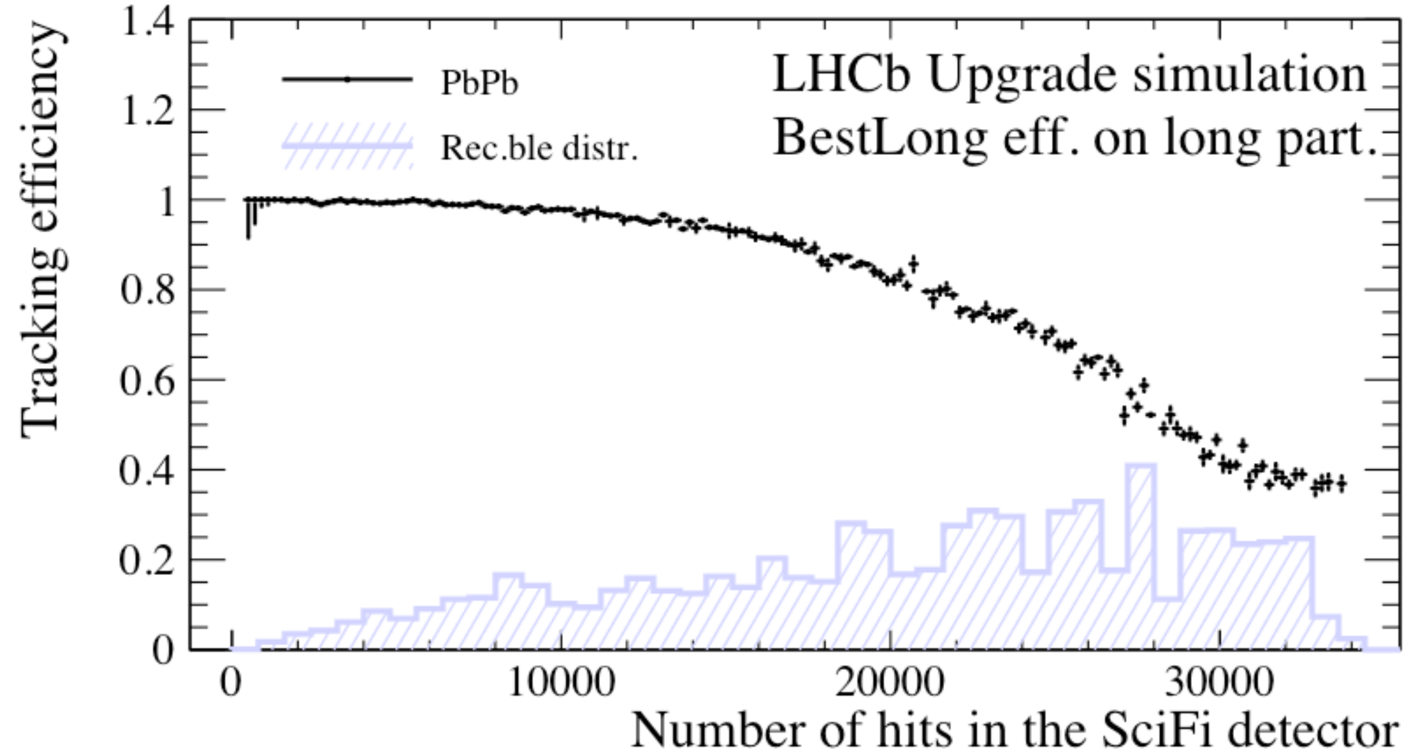
Expected improvements in AA collisions

- Expecting to be able to reconstruct down to 30 % centrality in PbPb
  - new VELO is a pixel silicon detector →larger granularity→ no saturation
  - limitation expected to come from downstream tracker (SciFi)
- Also expecting to reach full coverage with heavier gases → PbAr

LHCb-FIGURE-2019-021



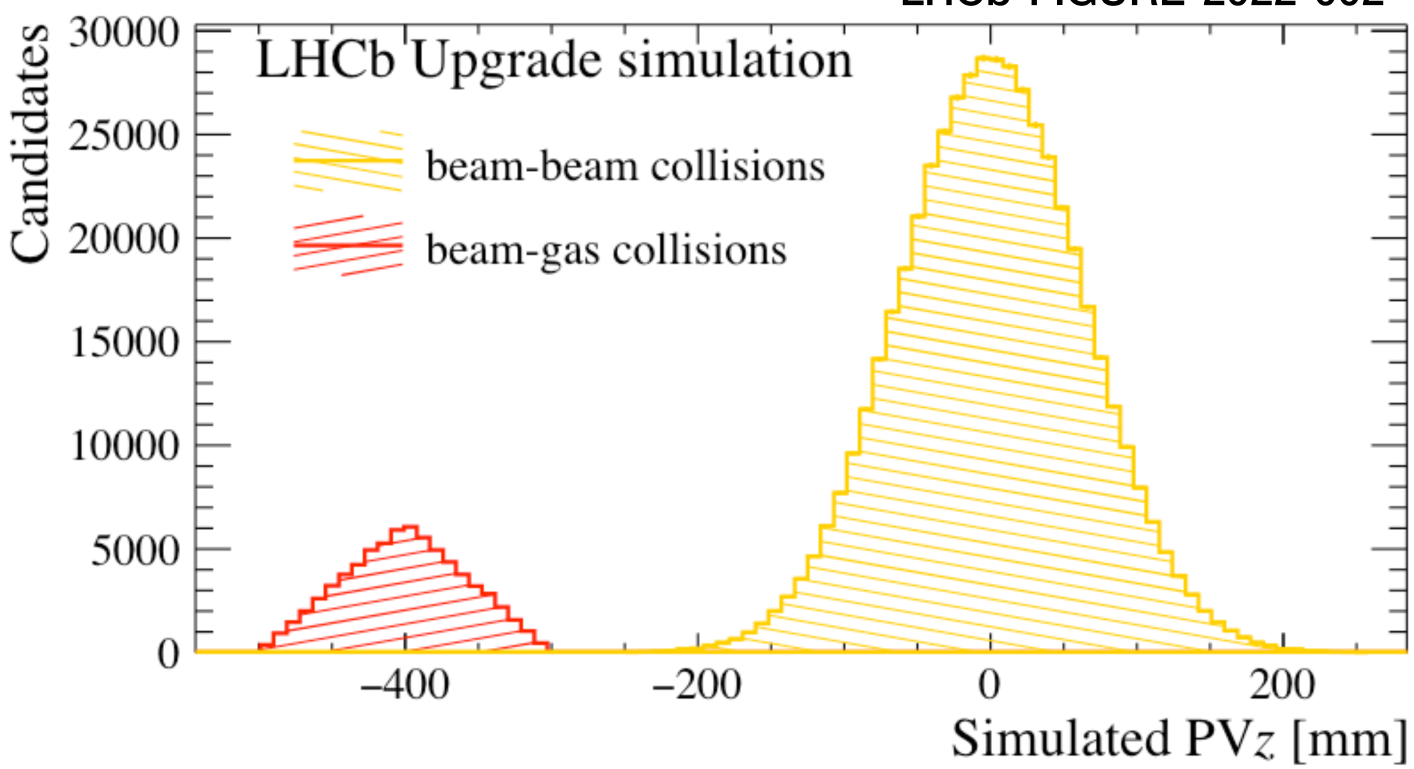
LHCb-FIGURE-2022-002

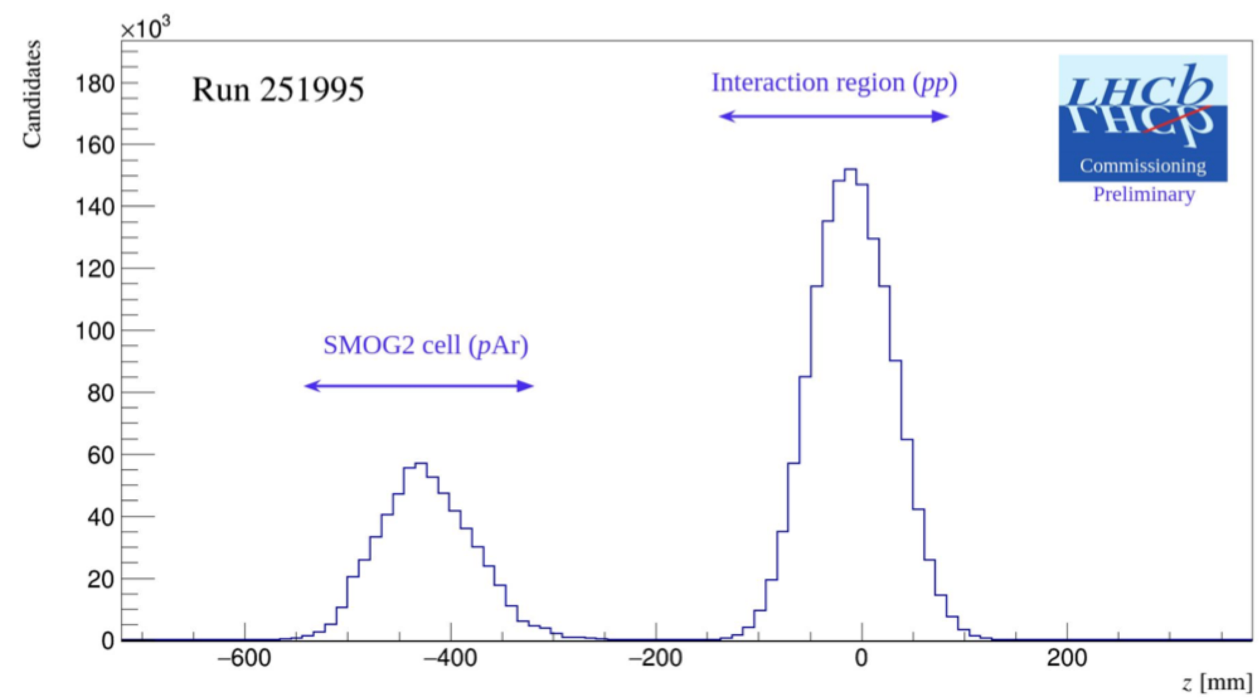


The LHCb Upgrade I: SMOG system

- Left plot: primary vertex z position in simulation
- Right plot: firsts plot from commissioning run (data!)
  - Two independent interaction regions, separation of both types of collisions possible even with simultaneous data-taking
  - much better control of systematic uncertainties

LHCb-FIGURE-2022-002





Summary

- The LHCb detector:
  - collider mode: pp, pPb, PbPb
  - fixed-target mode: pHe, pNe, pAr, PbAr
- Centrality in PbPb and PbNe collisions at LHCb
  - The Glauber Model and ECAL
- Studying small systems at LHCb:
  - Strategies to measure with respect to charged particle multiplicity
  - Analysing data: measurements of (η, p_{T}) spectra of charged particles and neutral pions
- Outlook: the LHCb Upgrade
  - will increase our centrality reach in AA collisions
  - new SMOG2 gas storage cell:
    - ∗ more luminosity
    - ∗ more gases
    - ∗ simultaneous data-taking with pp