

Recent results in Λ and K_S^0 production cross-sections at LHCb

QCD@LHC

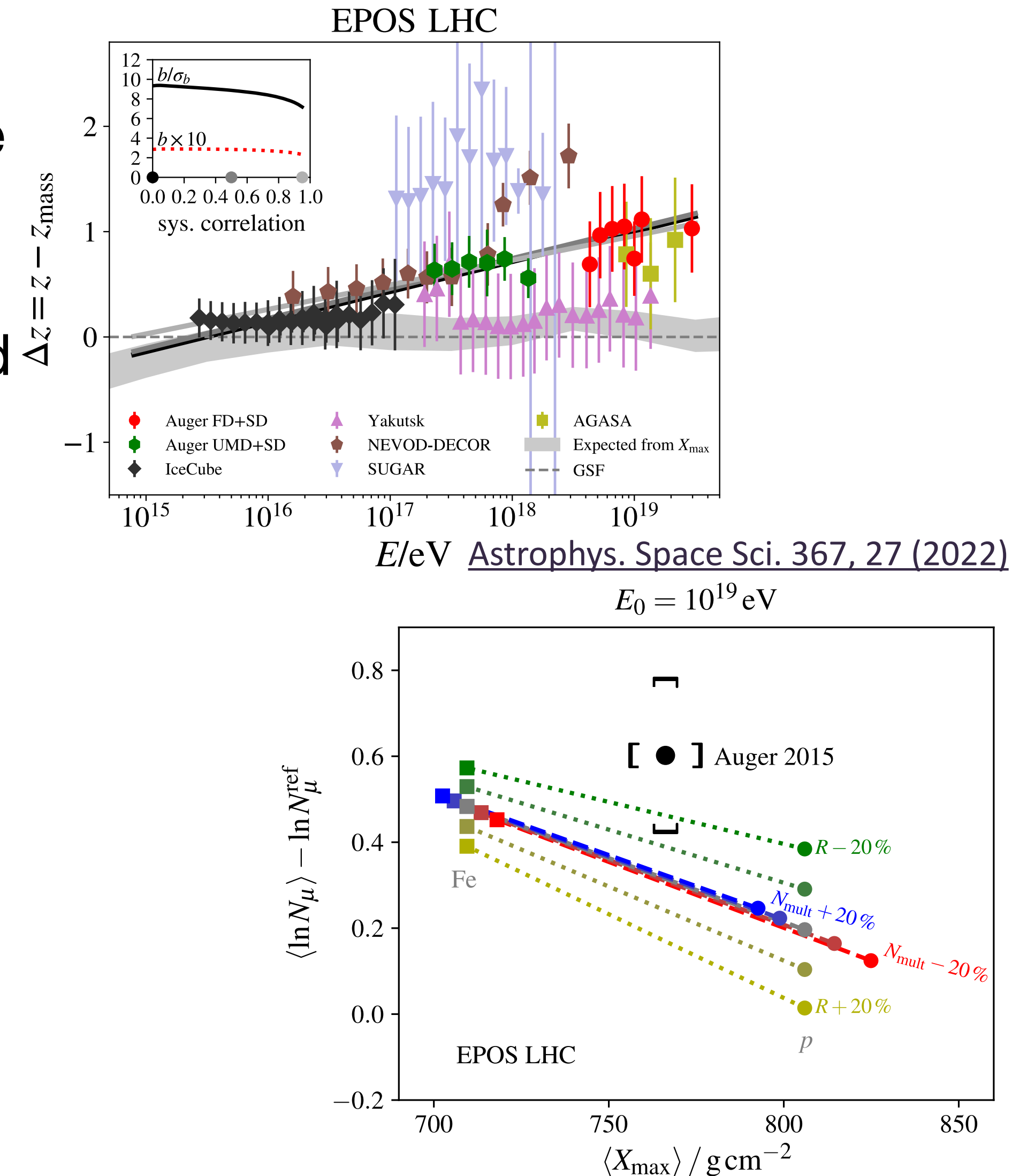
1st October 2026

Noah Behling on behalf of the LHCb collaboration

- Hard scattering processes well described in framework of perturbative QCD
- Calculations break down for soft processes with $q^2 \leq \Lambda_{\text{QCD}}$
 - Phenomenological models tuned to experimental data
- Accurate predictions not only crucial to understand underlying event in hadron colliders, but also limiting factor in interpretation of data collected by ground-based cosmic-ray observatories

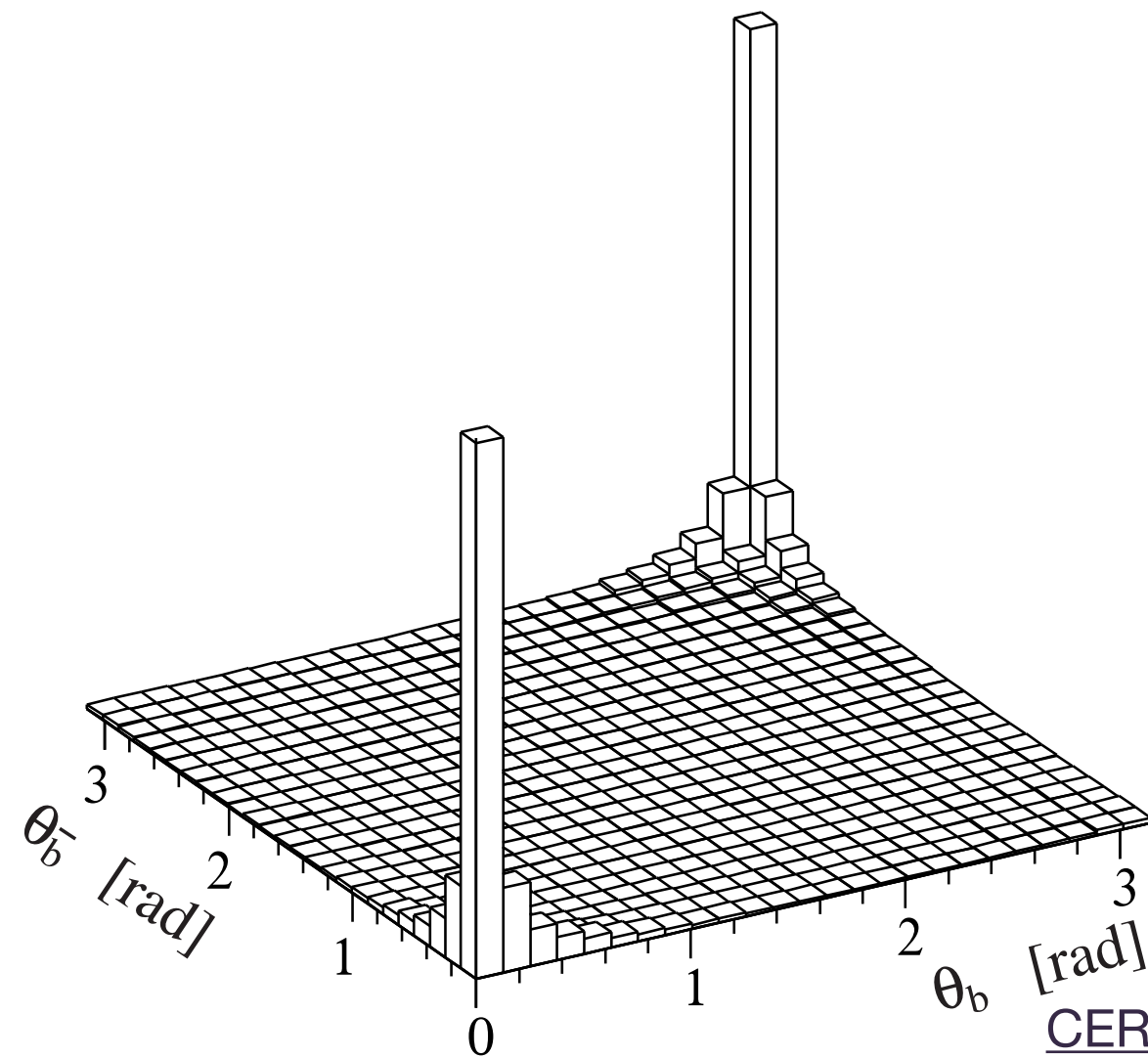
Atmospheric showers

- High energy cosmic rays reconstructed from hadronic and electromagnetic shower initiated by interaction with atmosphere
- Number of produced muons sensitive to primary nucleon mass
- MC event generators predict lower muon number than observed by experiments → Muon Puzzle
- **Promising solution:** Modification of ratio of energy carried by photons to that of long-lived hadrons
 - Achievable by increase of baryon and/or strangeness production
 - LHCb offers unique properties to probe these mechanisms in the forward region

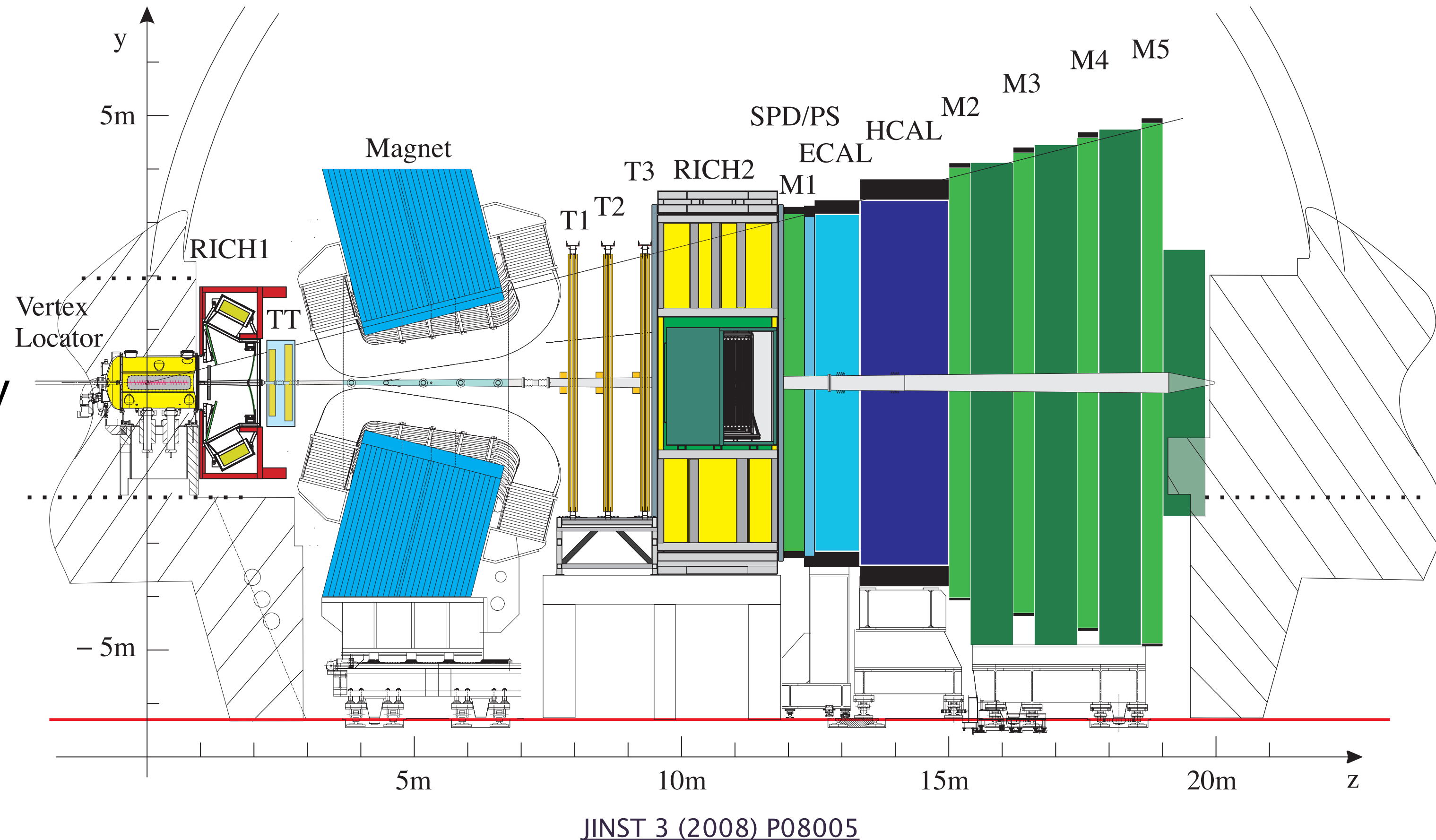


The LHCb detector

- Single-arm forward spectrometer covering $2 < \eta < 5$
- Designed to study CP violation and beauty hadron decays
- Fully upgraded prior to Run 3 to take data with $5 \times$ instantaneous luminosity



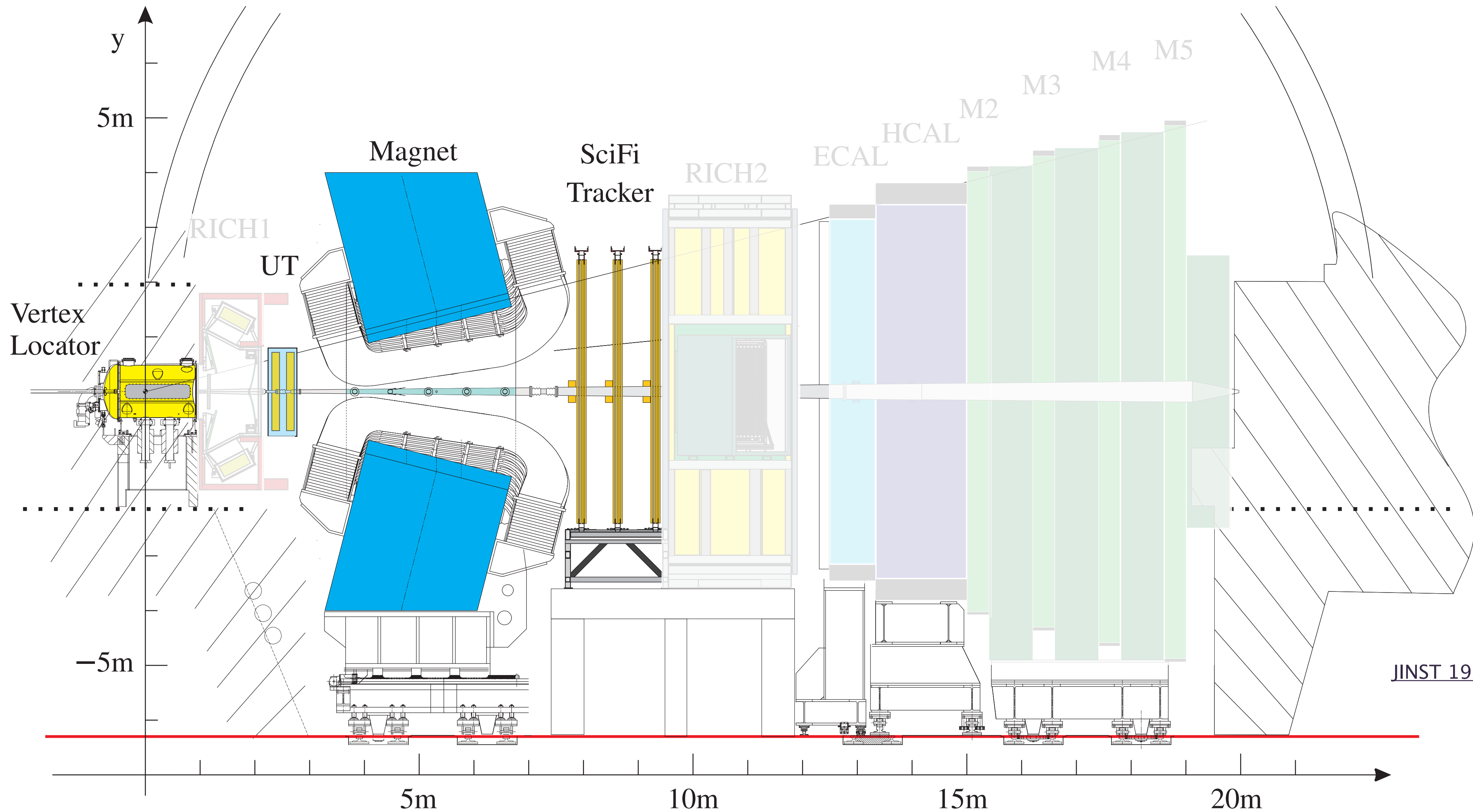
CERN-THESIS-2012-075



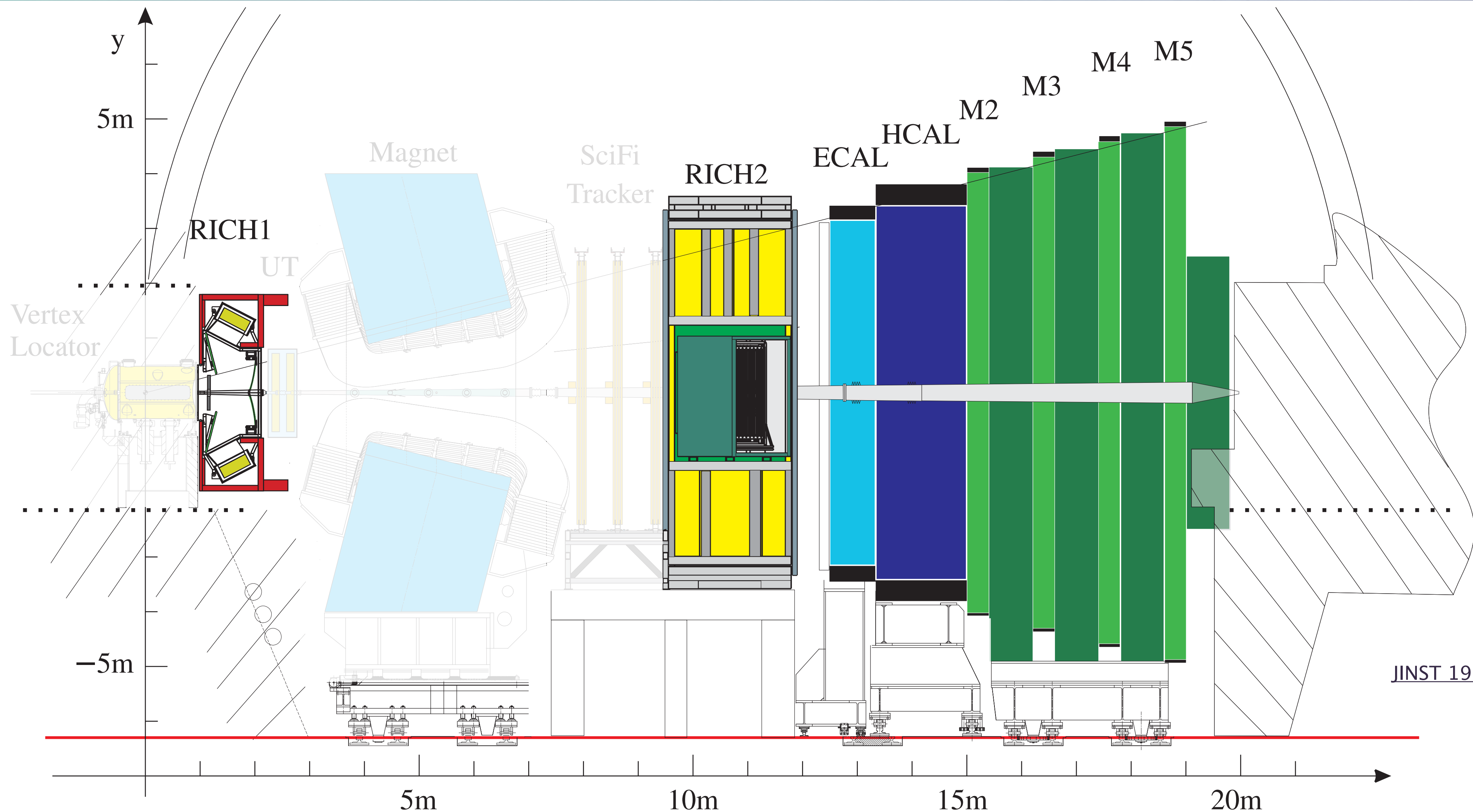
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The LHCb Upgrade I detector: Tracking system



The LHCb Upgrade I detector: Particle Identification



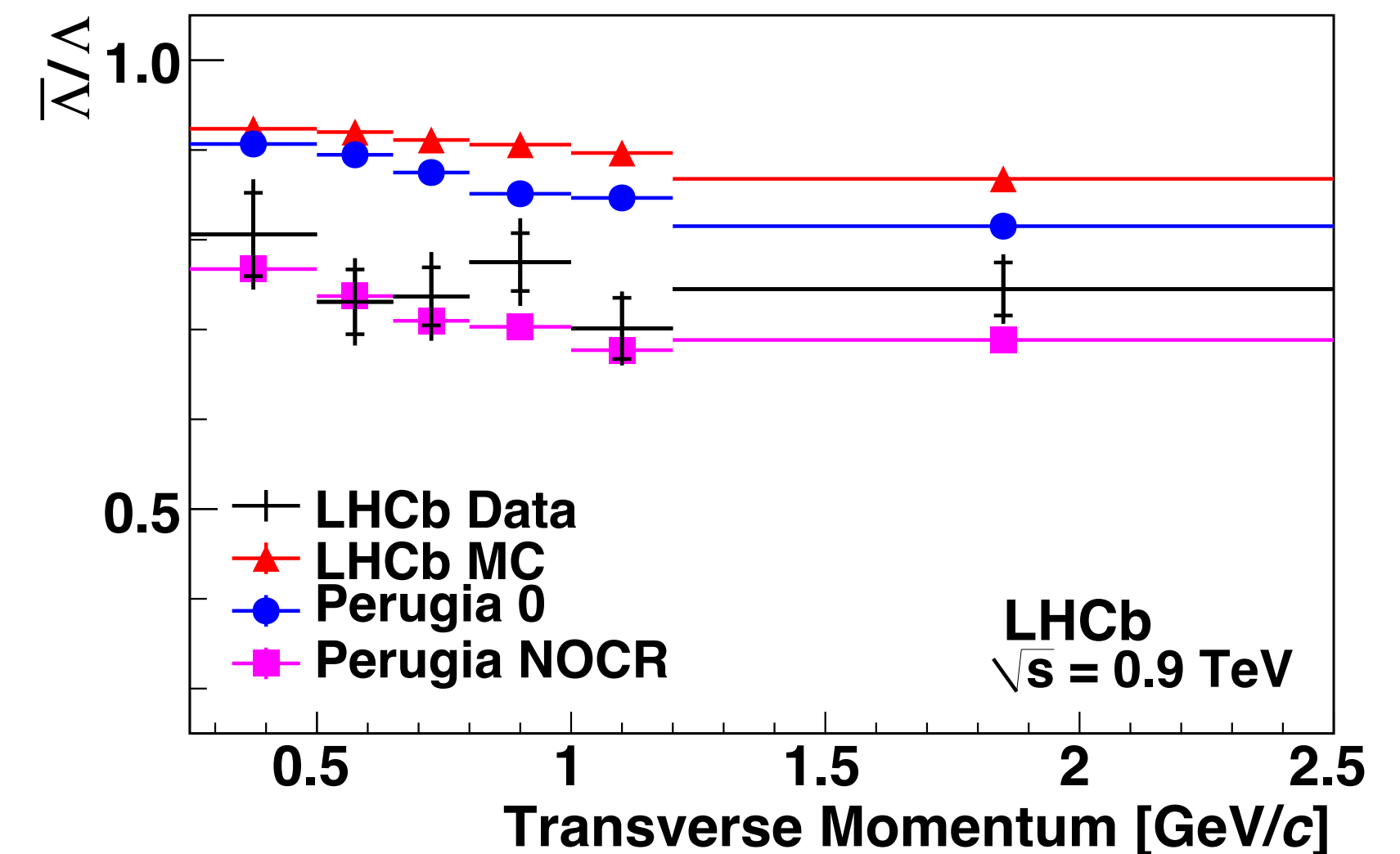
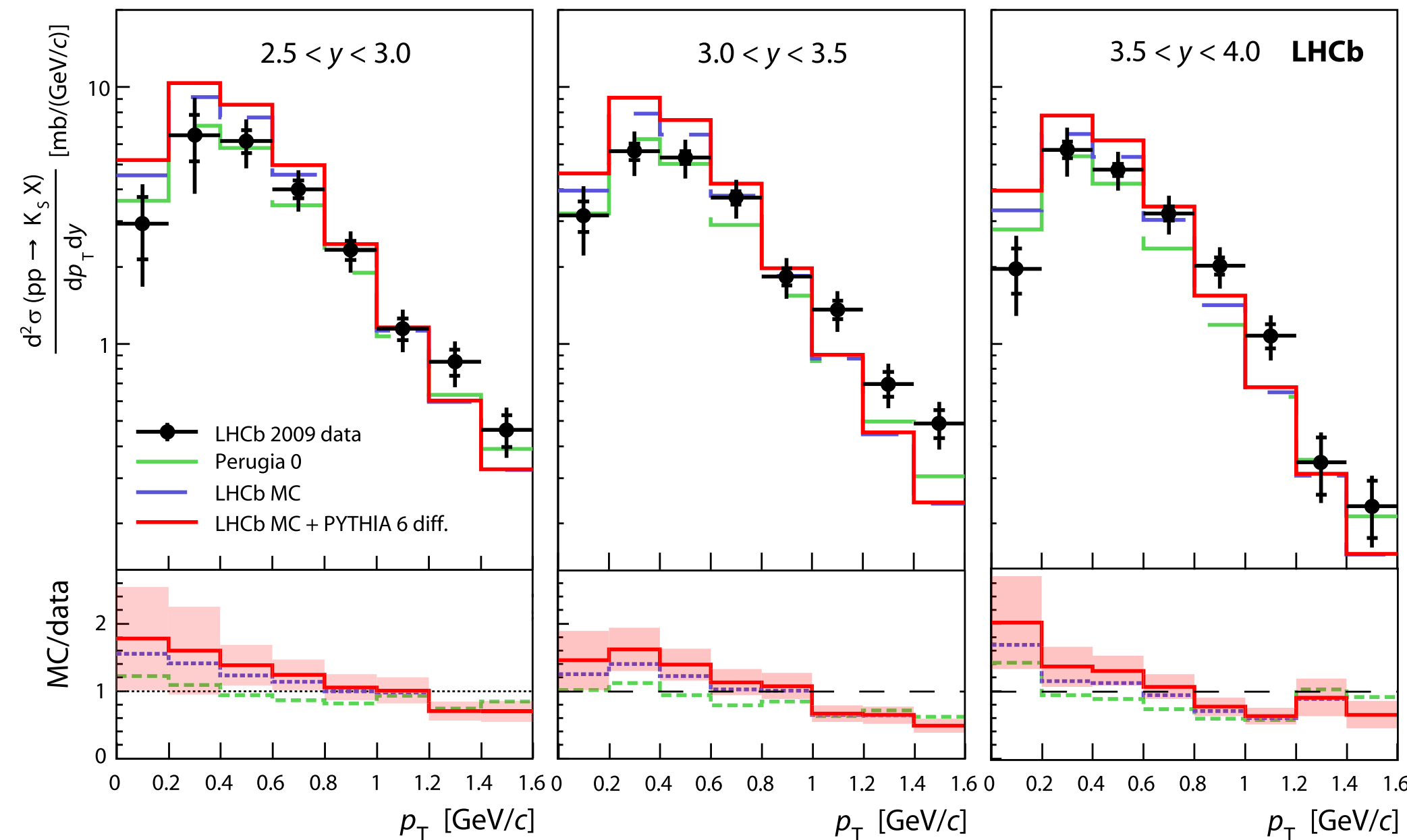
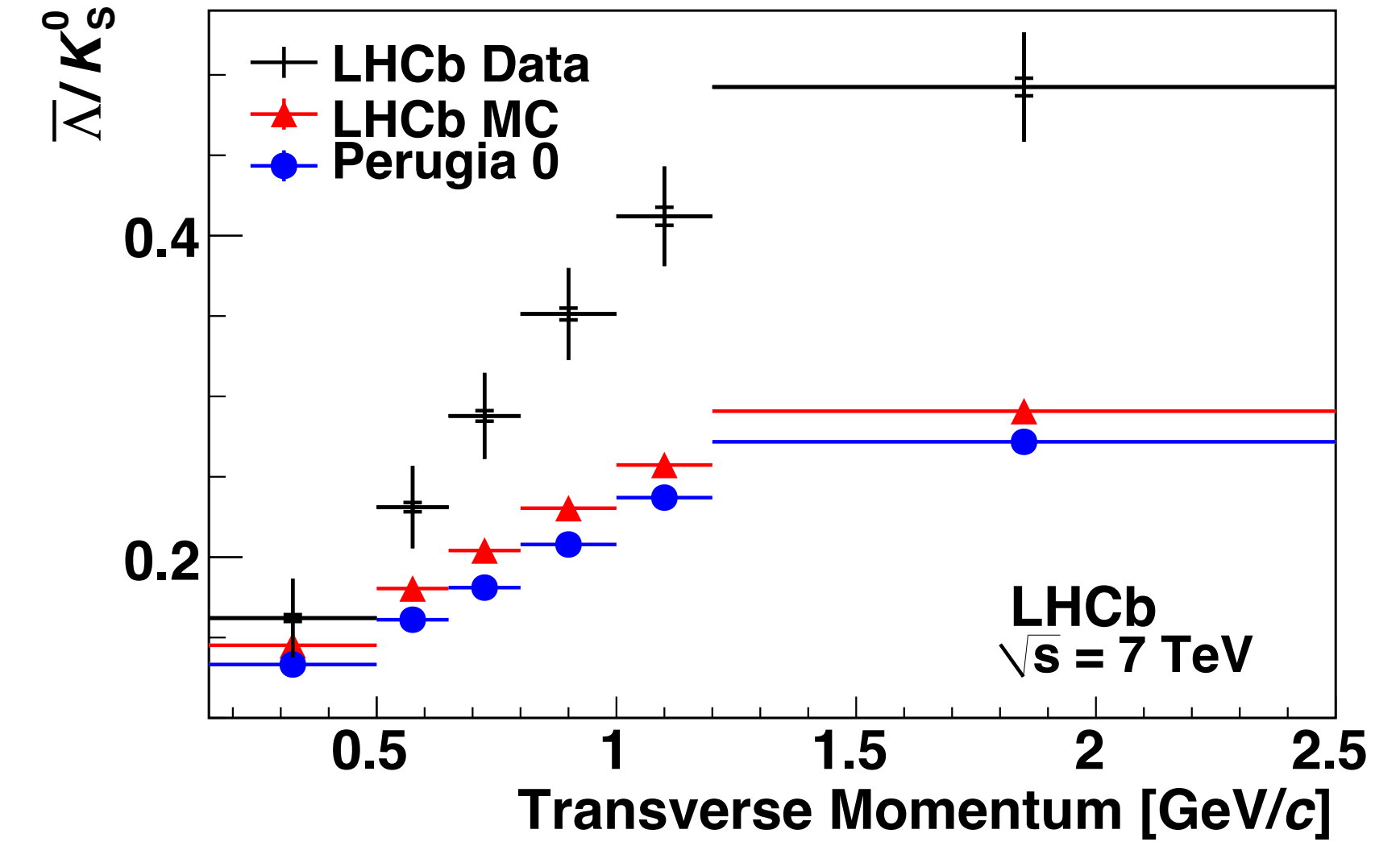
JINST 19 (2024) P05065

Previous measurements at LHCb

- Measurement of V^0 production ratios in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV [JHEP 08 \(2011\) 34](#)

$$V^0 = K_S^0, \Lambda, \bar{\Lambda}$$

- Prompt K_S^0 production in pp collisions at $\sqrt{s} = 0.9$ TeV [Phys. Lett. B 693 2 \(2010\) 69–80](#)



- Measurement of prompt K_S^0 and Λ production cross-sections and ratios in pp collisions at $\sqrt{s} = 13 \text{ TeV}$
→ Run 2 Legacy measurement
LHCb-PAPER-2026-031 (in preparation)
- $\bar{\Lambda}/K_S^0$ production cross-section ratio in pp collisions at 13.6 TeV
→ First measurement with partial Run 3 dataset
LHCb-PAPER-2026-045 (in preparation)

New

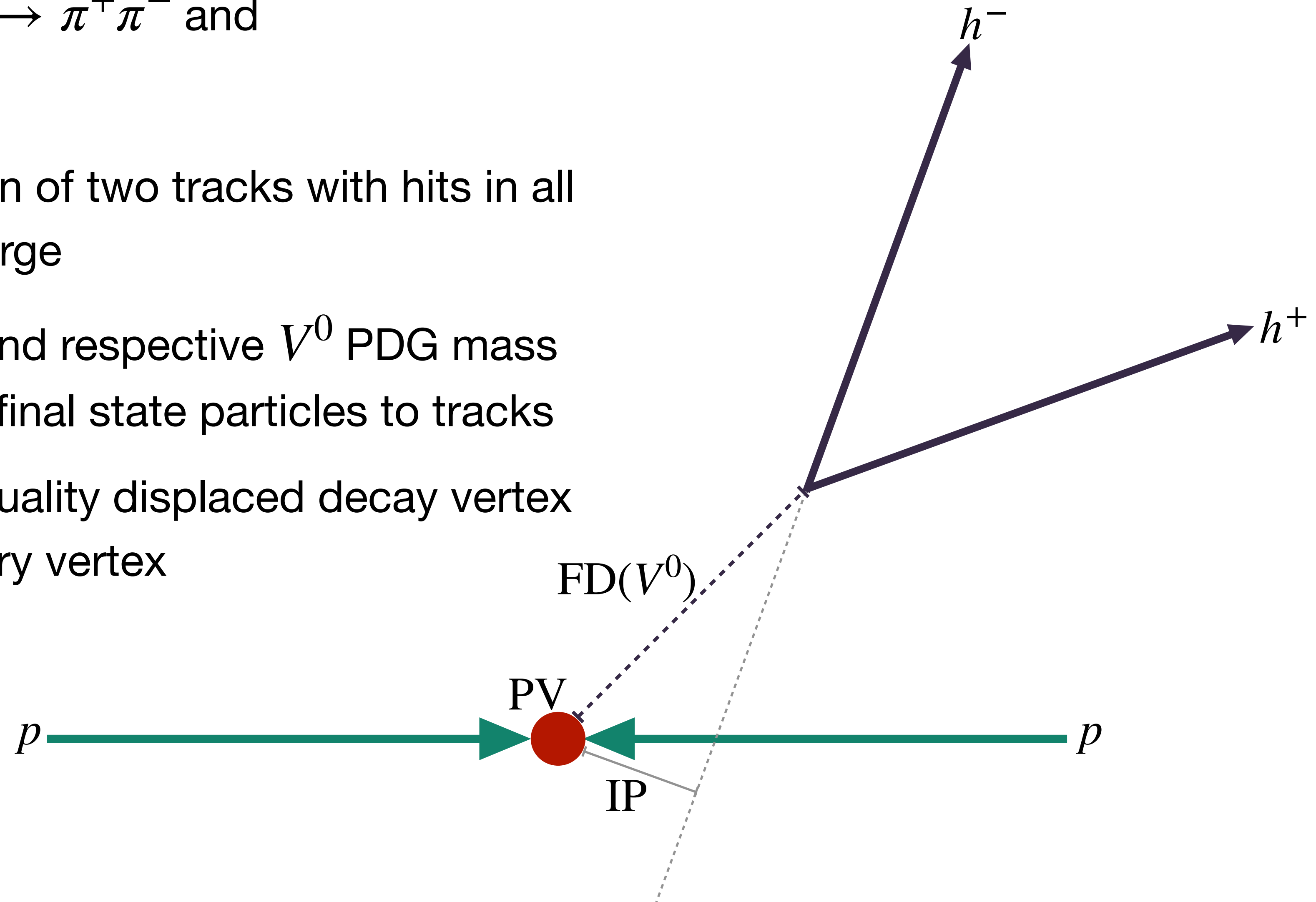
Measurement of prompt K_S^0 and Λ production
cross-sections and ratios in pp collisions at
 $\sqrt{s} = 13 \text{ TeV}$

LHCb-PAPER-2026-031 (in preparation)

- $3.61 \pm 0.07 \text{ nb}^{-1}$ of data recorded in 2015 at LHCb
- Unbiased trigger configuration
- Fiducial K_S^0 phase space $2 \leq y \leq 5$ and $10 \text{ MeV}/c \leq p_T \leq 10 \text{ GeV}/c$
- Fiducial regions reduced towards higher p_T for Λ due to detector acceptance and decay kinematics
- Double-differential measurement in 6×6 array of bins in y and $\log_{10}(p_T [\text{MeV}/c])$

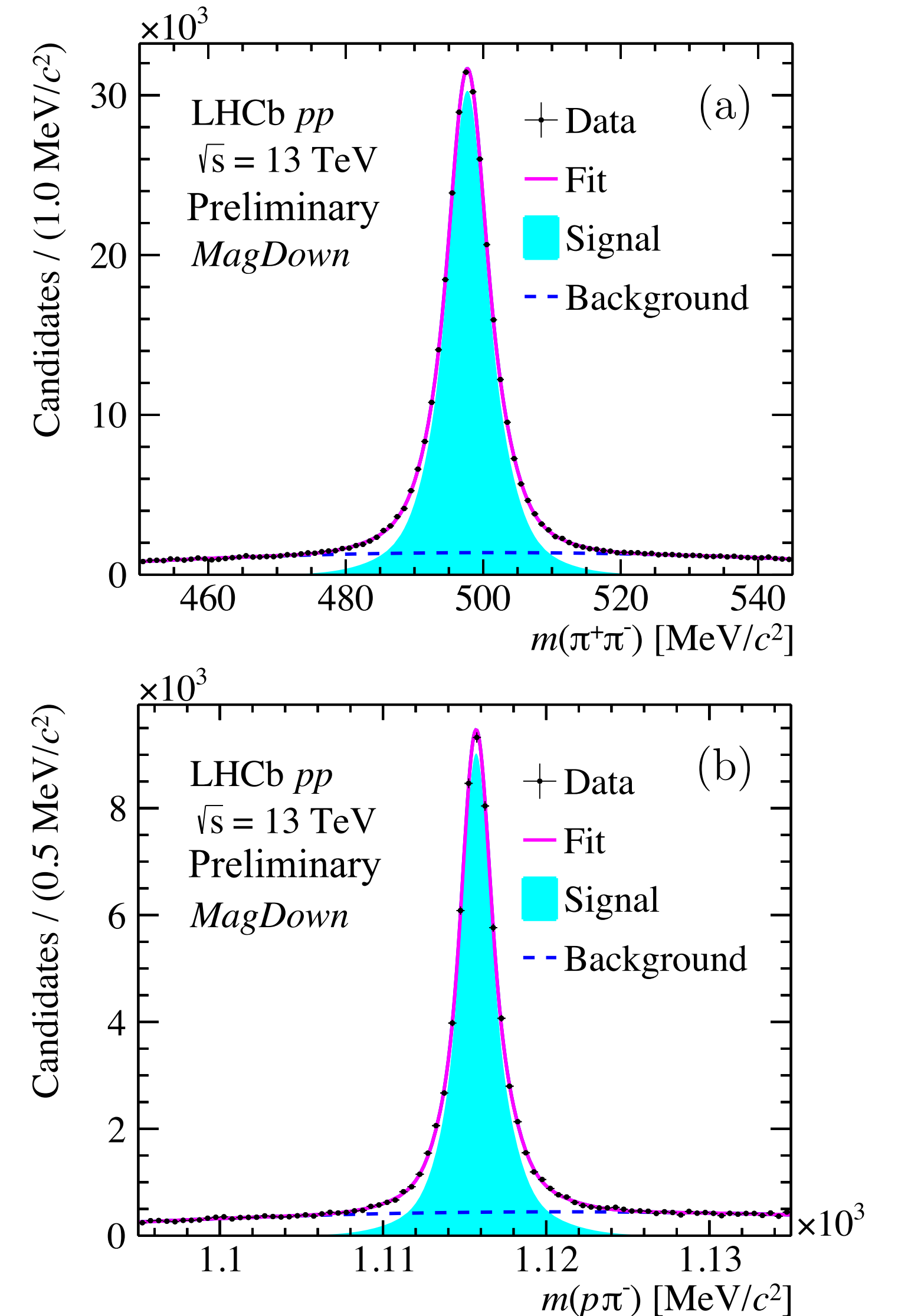
$$\sigma(pp \rightarrow V^0 X) = \frac{N_{\text{data}}^{\text{reco}}}{\varepsilon \cdot \mathcal{L}}$$

- Reconstruction in decay modes $K_S^0 \rightarrow \pi^+ \pi^-$ and $\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p})\pi^{-(+)}$
- Candidates formed from combination of two tracks with hits in all tracking detectors and opposite charge
- Mass window of $\pm 50 \text{ MeV}/c^2$ around respective V^0 PDG mass after assigning mass hypotheses of final state particles to tracks
- Candidates required to have good quality displaced decay vertex and originate from associated primary vertex



Efficiency determination and signal extraction

- Extraction of signal yield $N_{\text{data}}^{\text{reco}}$ via fit to invariant mass
- Efficiency factorises to $\varepsilon = \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{reco}} \cdot \varepsilon_{\text{sel}} \cdot \mathcal{B}(V^0 \rightarrow h^+ h^-)$
- Determined from simulation via $\varepsilon = N^{\text{reco}} / N_p^{\text{gen}}$
- Simulation calibrated to data in multiple steps
 - Event track multiplicity
 - Primary vertex position
 - Tracking calibration
 - Kinematics
 - Nonprompt contamination



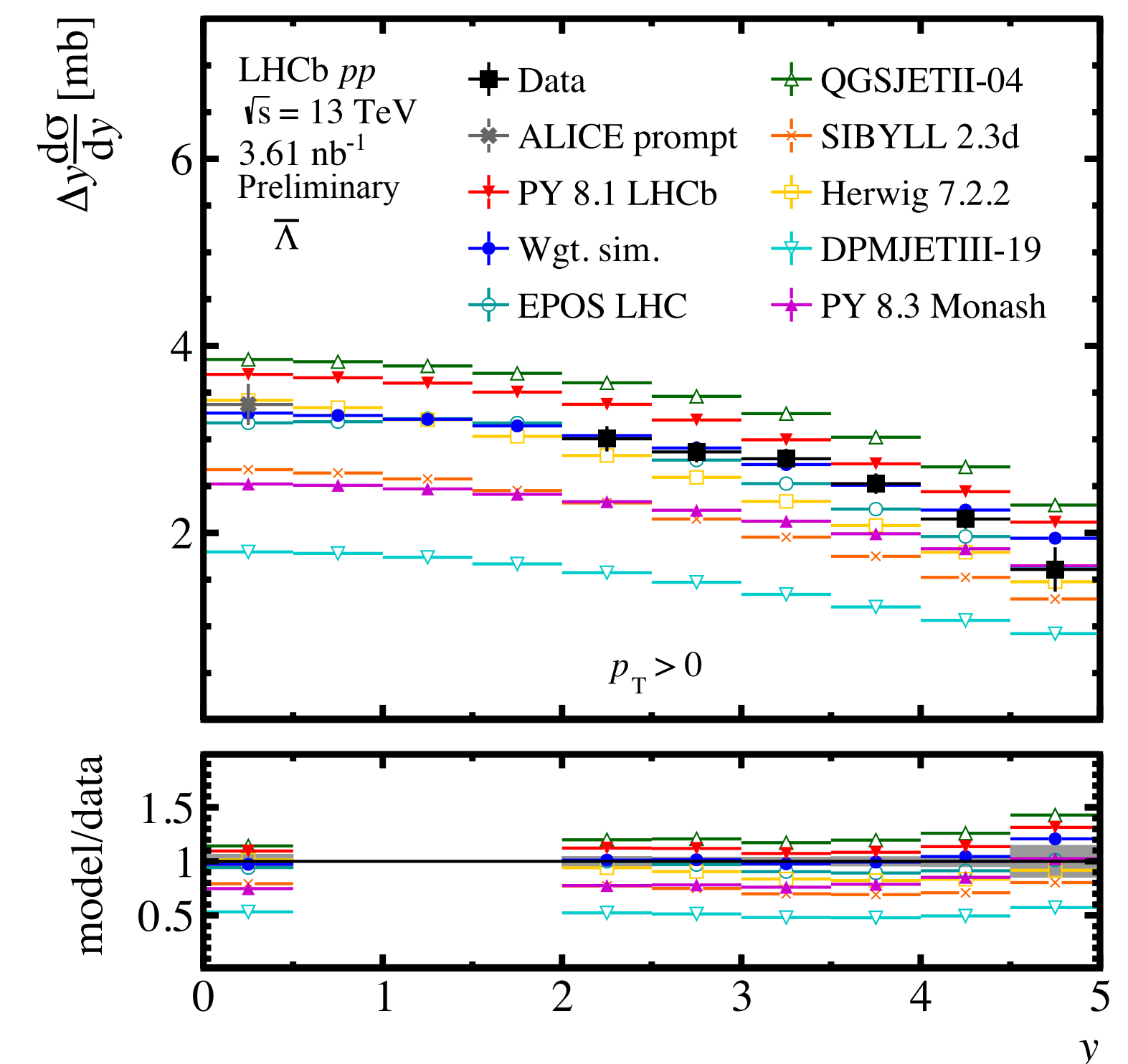
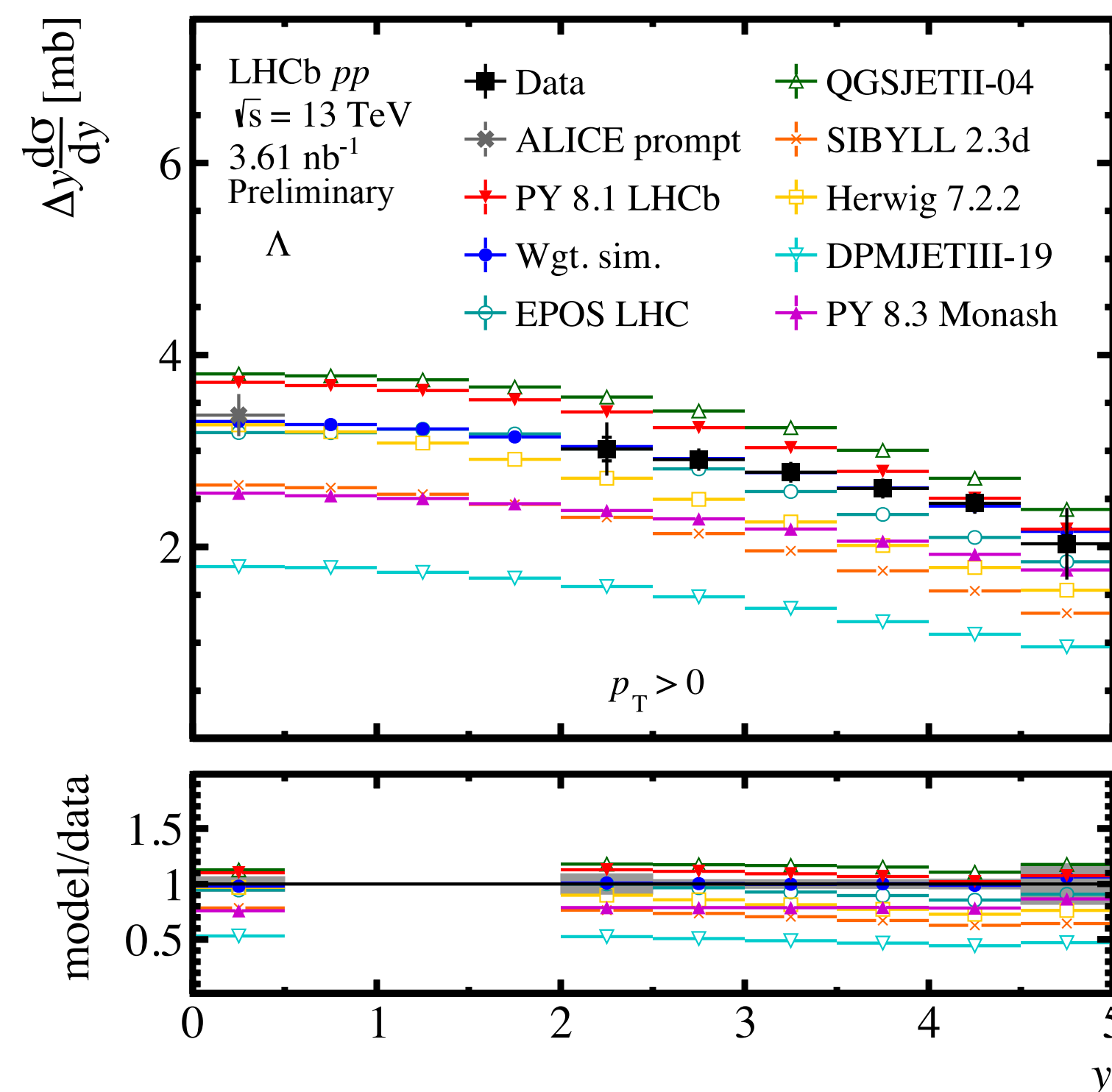
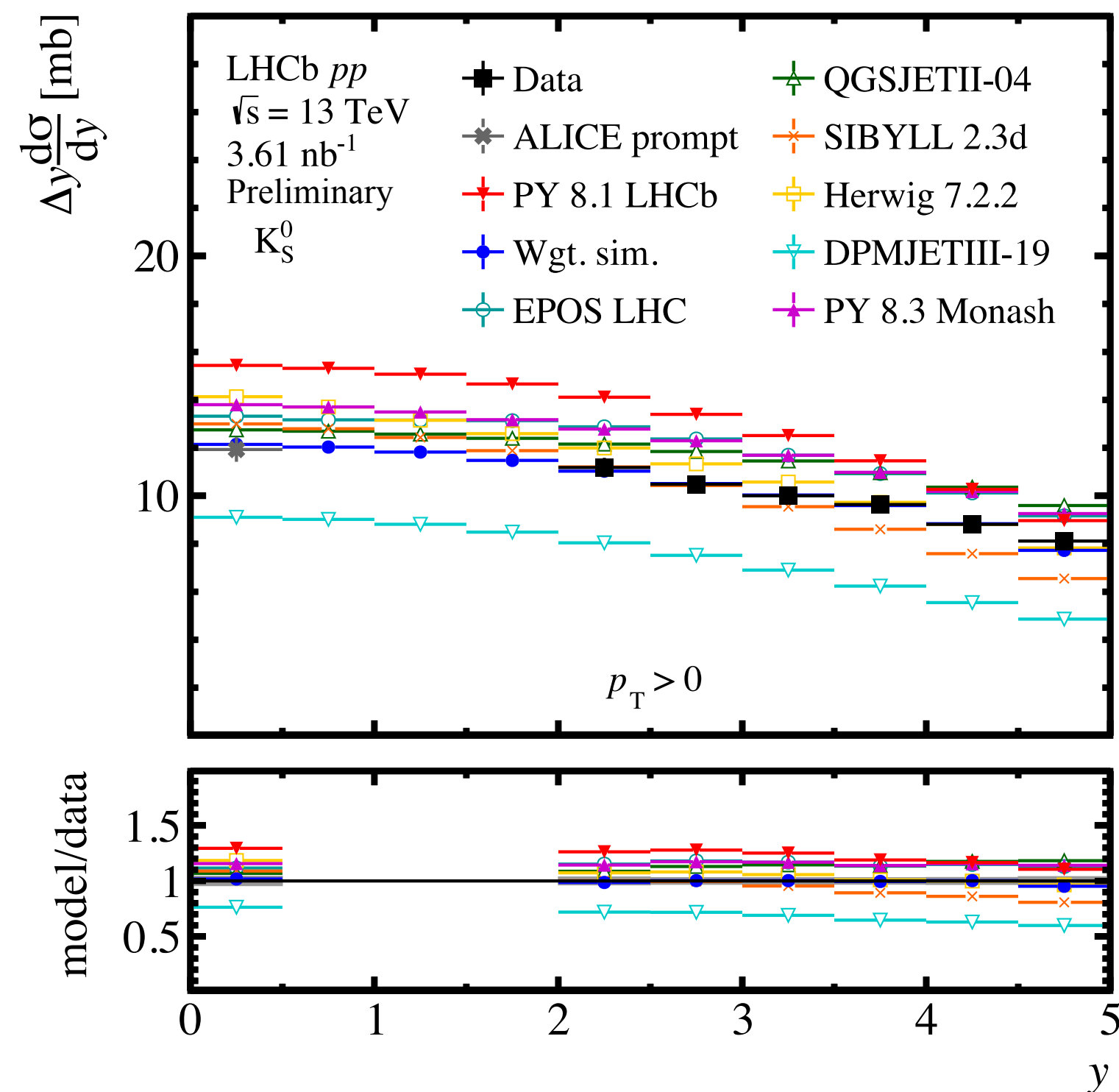
Systematic uncertainties

- Total uncertainties dominated by systematics
- Sizeable contributions from tracking correction and luminosity among whole measurement range
- Dominated by simulation sample size in peripheral bins

Source	Uncertainties [%]			Correlated between bins	Correlated between modes	
	K_S^0	Λ	$\bar{\Lambda}$		$\bar{\Lambda}, K_S^0$	$\bar{\Lambda}, \Lambda$
Statistical	0.2 – 35.3	0.4 – 43.1	0.5 – 21.7	no	no	no
Luminosity	2.0 – 2.2	2.0	2.0	yes	yes	yes
Simulation sample size	0.3 – 76.3	1.0 – 74.5	1.0 – 31.9	no	no	no
Branching fractions	0	0.8	0.8	yes	no	yes
Fit model	0.0 – 1.6	0.0 – 3.7	0.0 – 6.4	yes	yes	yes
Multiplicity correction	0.0 – 3.6	0.0 – 0.9	0.0 – 1.0	yes	yes	yes
Tracking						
Sample size	0.4 – 4.1	1.1 – 5.0	1.1 – 3.2	yes	no	no
Systematic	1.0 – 1.1	1.0	1.0	yes	yes	yes
Hadronic interactions	1.4 – 1.5	1.7	1.8	yes	yes	yes
Kinematic modelling	0.0 – 1.5	0.0 – 1.5	0.0 – 1.5	yes	yes	yes
Nonprompt contamination	0.0 – 2.1	0.0 – 5.8	0.0 – 5.8	yes	no	yes

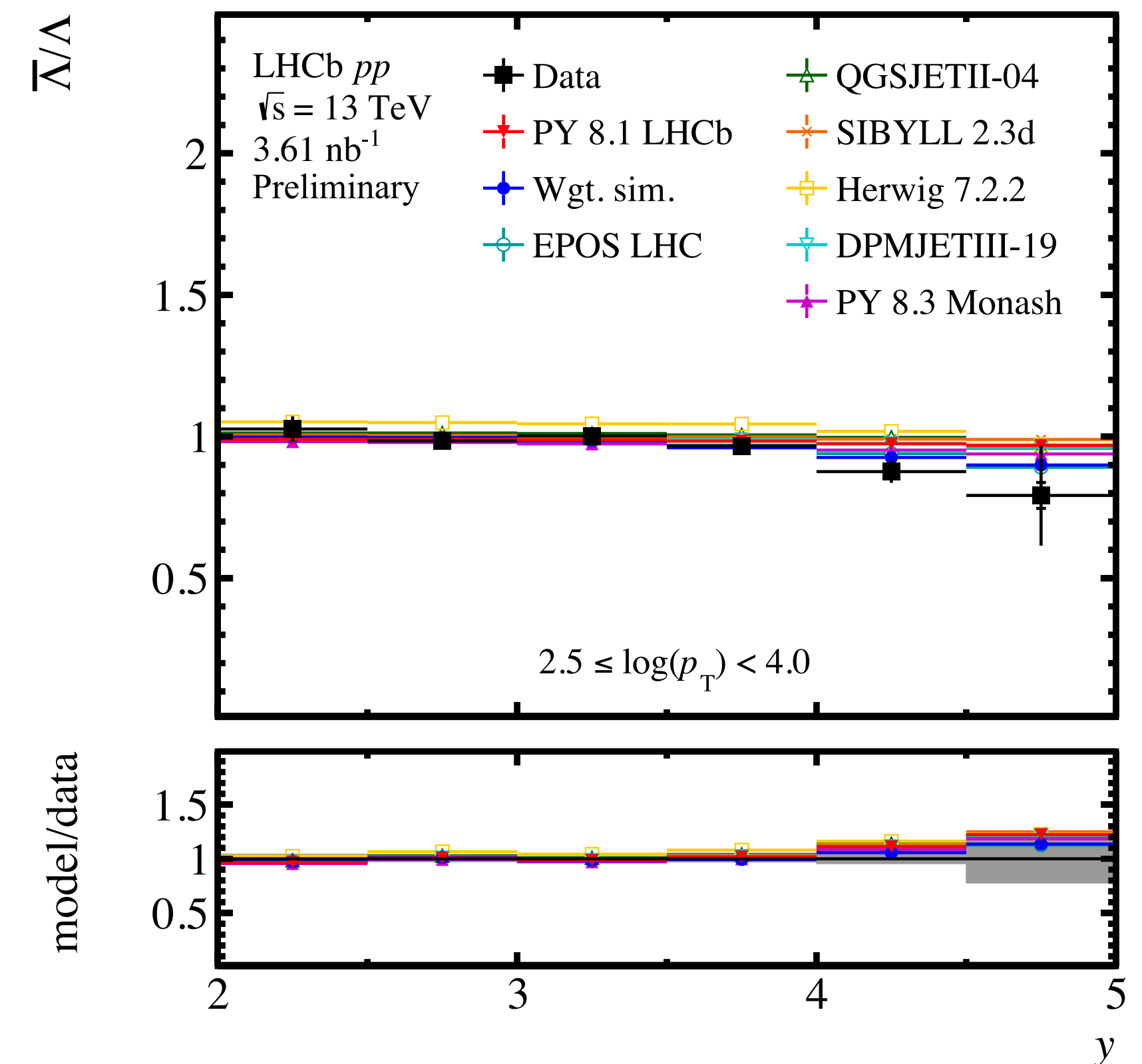
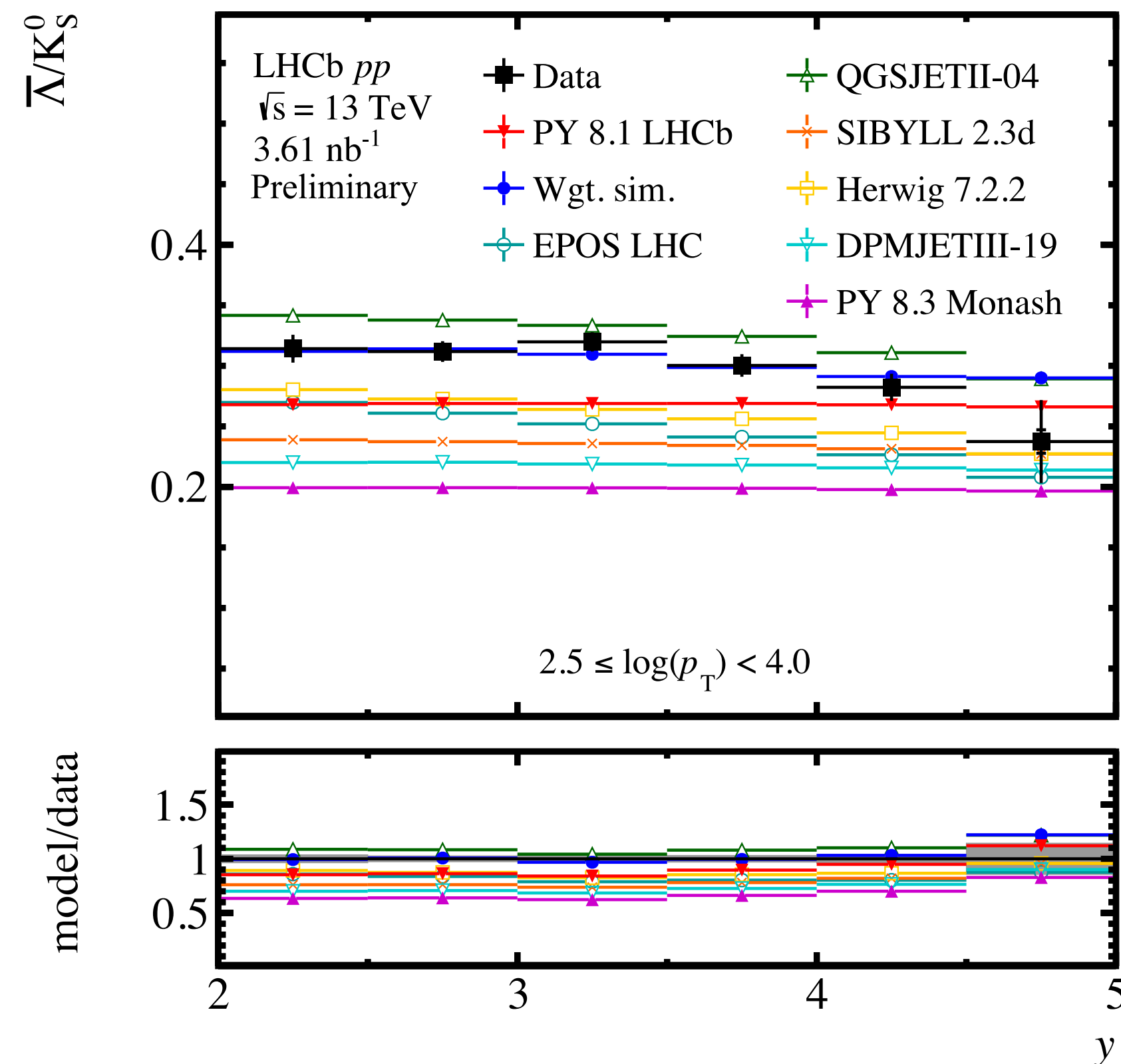
Cross-sections compared to event generators

- First LHCb measurement of Λ and $\bar{\Lambda}$ cross-section, first of K_S^0 cross-section at $\sqrt{s} = 13$ TeV
- Cross-sections extrapolated to full p_T spectrum
- Trends in rapidity well reproduced by all event generators, absolute numbers vary vastly



Ratios compared to event generators

- Relative baryon production underestimated by all probed event generators apart from QGSJet
- Stronger suppression of antibaryons towards high rapidity than predicted by generators



$\bar{\Lambda}/K_S^0$ production cross-section ratio in pp
collisions at 13.6 TeV

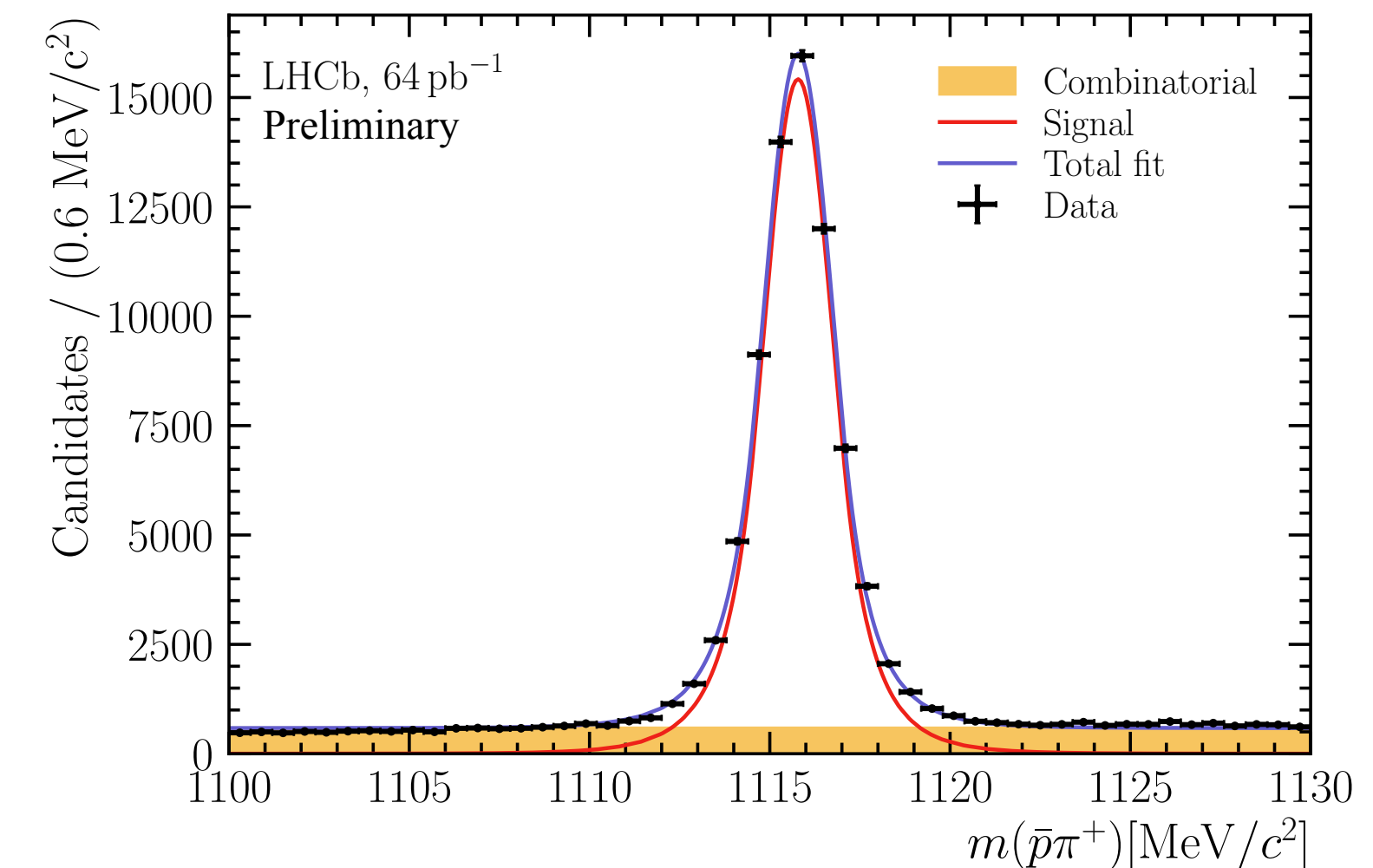
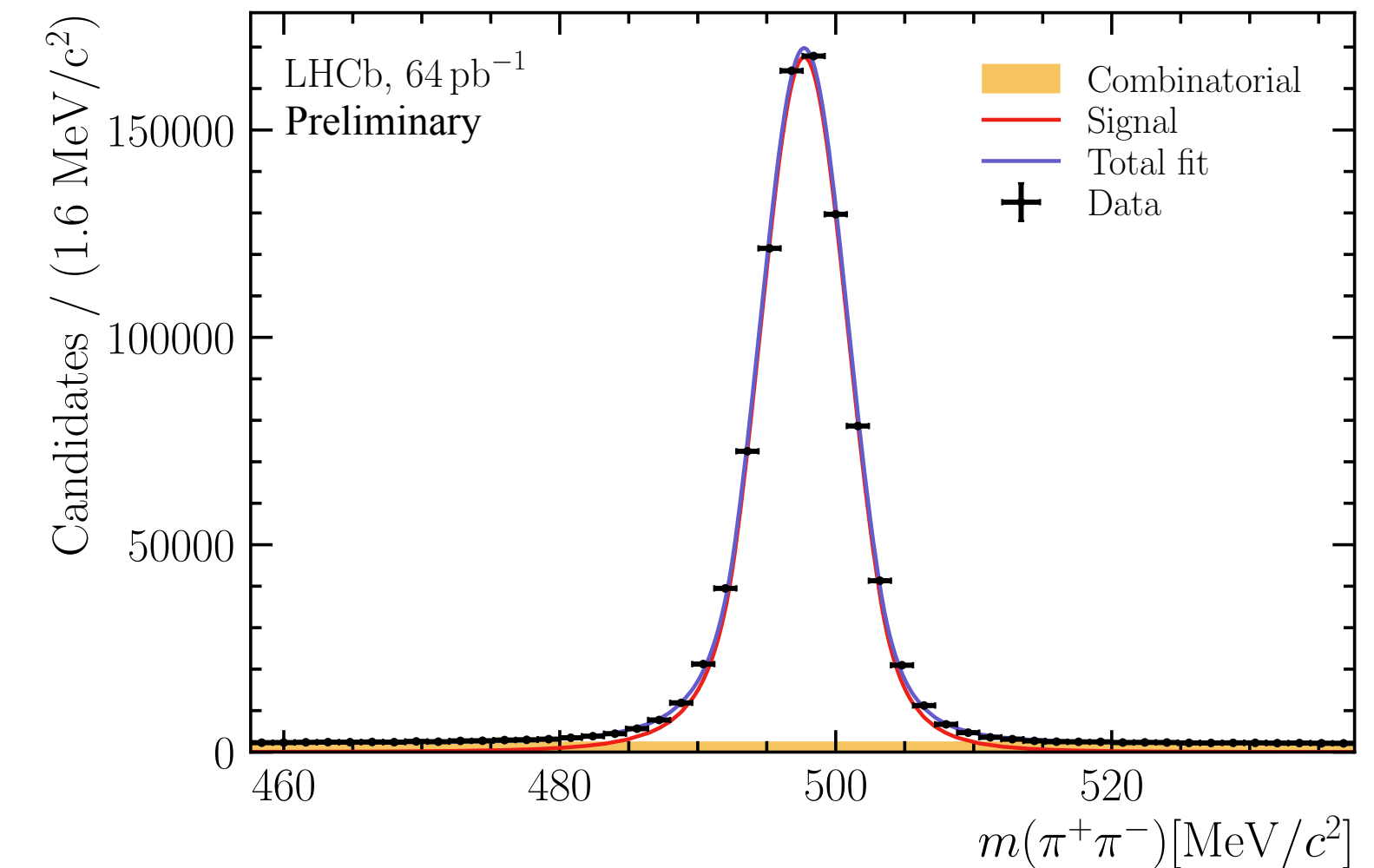
LHCb-PAPER-2026-045 (in preparation)

- 64 pb^{-1} of data recorded in 2024 at $\sqrt{s} = 13.6 \text{ TeV}$
- Unbiased trigger configuration
- Fiducial phase space $2 \leq y \leq 4.5$ and $150 \text{ MeV}/c \leq p_T \leq 2.5 \text{ GeV}/c$
- Differential measurement in y and p_T
- Binning adapted from Run 1 measurement with twice the number of bins

$$R(\bar{\Lambda}^0, K_S^0) = \frac{\sigma(pp \rightarrow \bar{\Lambda}^0 X)}{\sigma(pp \rightarrow K_S^0 X)} = \frac{N(\bar{\Lambda}^0 \rightarrow \bar{p}\pi^+) \varepsilon_{K_S^0 \rightarrow \pi^+\pi^-}}{N(K_S^0 \rightarrow \pi^+\pi^-) \varepsilon_{\bar{\Lambda}^0 \rightarrow \bar{p}\pi^+}}$$

Signal extraction and efficiency determination

- Candidates formed identically to Run 2 measurement
- Required to have good quality displaced decay vertex and originate from associated primary vertex
- Signal yields obtained via invariant mass fits
- Efficiencies estimated from simulation after multiple calibration step
 - Fake-track correction
 - Tracking calibration
 - Kinematics
 - Impact parameter calibration



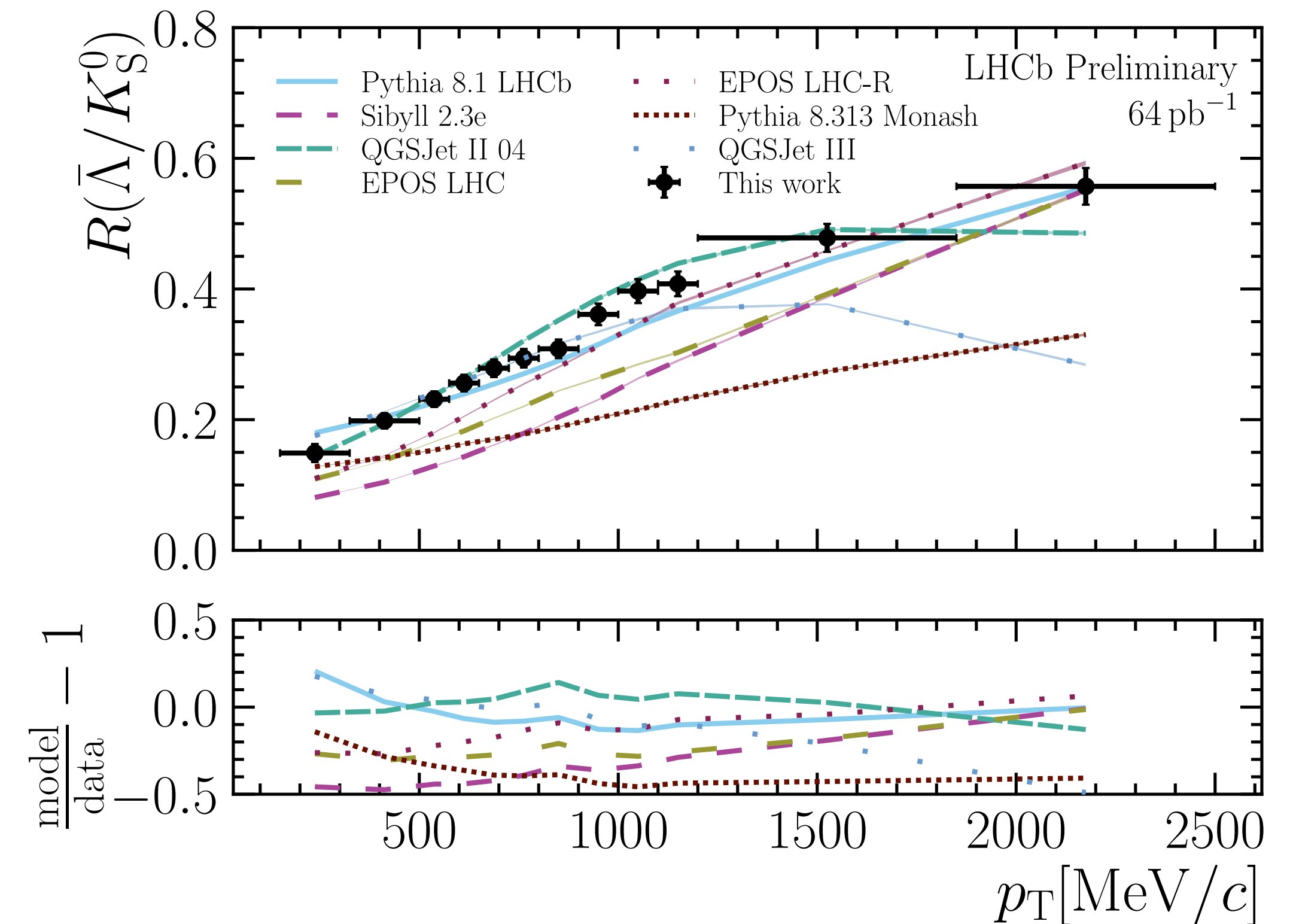
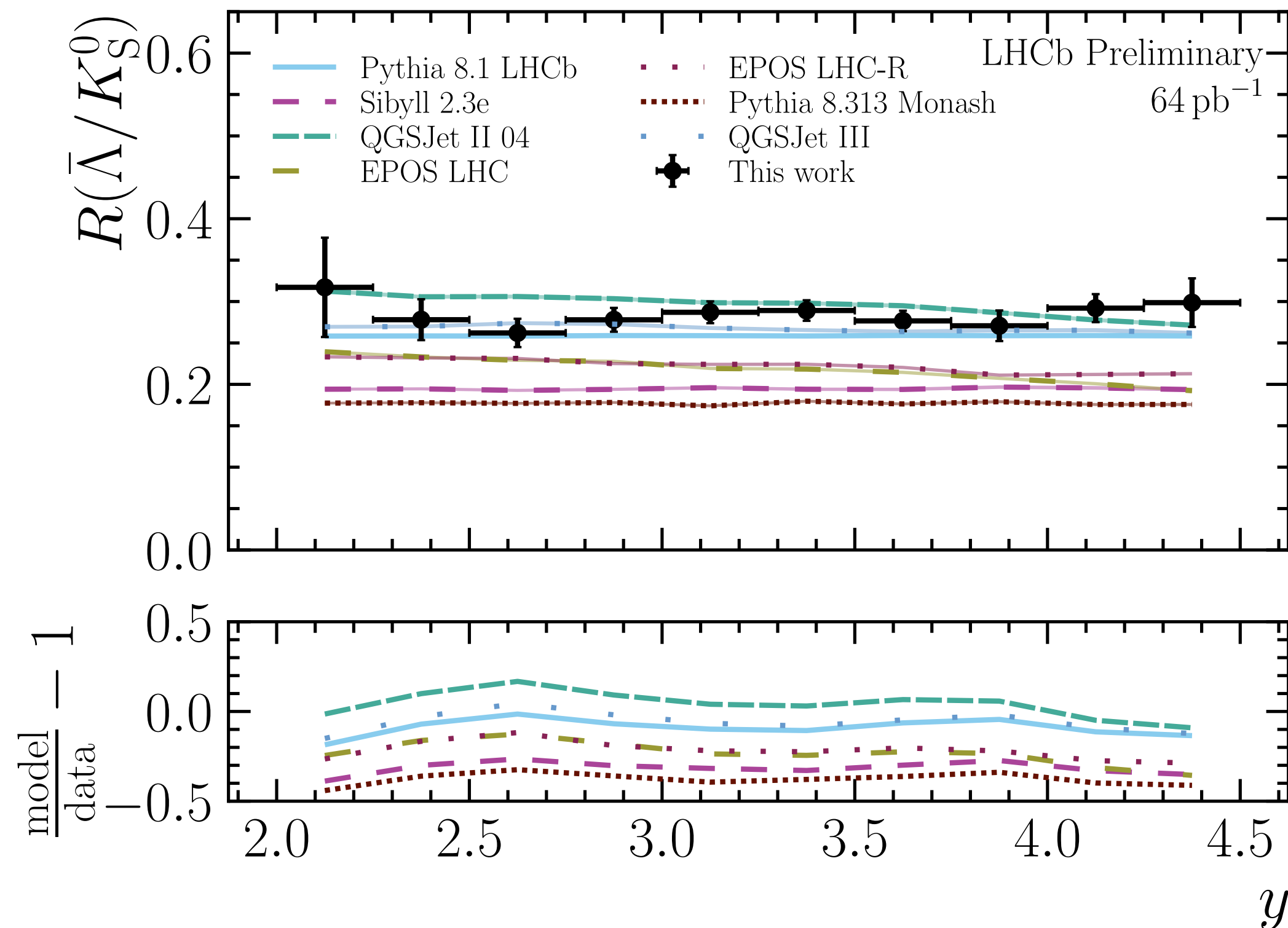
Systematic uncertainties

- Measurement dominated by systematic uncertainties
- Systematic accounting for tracking correction leading at low p_T and y edges
- Uncertainty on V^0 hadrons absorbed by detector material leading at mid to high p_T and mid y

V^0 branching fraction	0.8 %
Alternative mass-fit models	0.4 – 5.7 %
Nonprompt backgrounds	0.8 – 1.6 %
Reconstruction efficiency	0.8 – 17.6 %
Selection efficiency, global	2.2 %
Selection efficiency, local	1.2 %
Material interactions	3 %
Fake-track correction	0.2 – 3.3 %
Total systematic uncertainty	4.2 – 18.2 %
Statistical uncertainty	0.8 – 5.4 %

Ratios compared to event generators

- Ratio underestimated by all probed generators but QGSJet II 04
- Trend in rapidity described well by generators, absolute values vary depending on model
- Transverse momentum dependence either at low or high p_T mismodelled



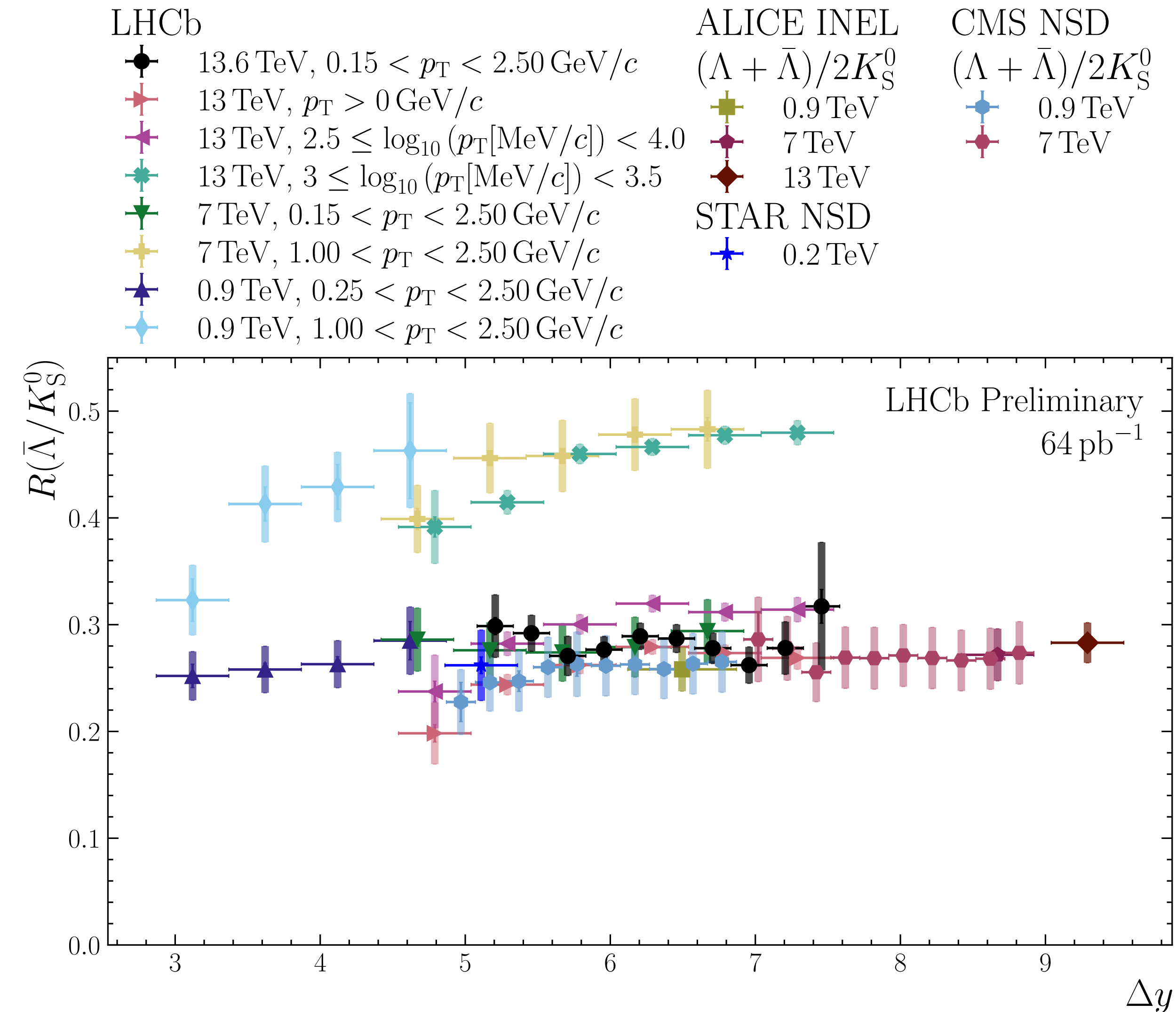
Ratios compared to previous measurements

- Results of different experiments not comparable out of the box due to different centre-of-mass energy and rapidity coverage

→ Compare in Lorentz invariant rapidity loss

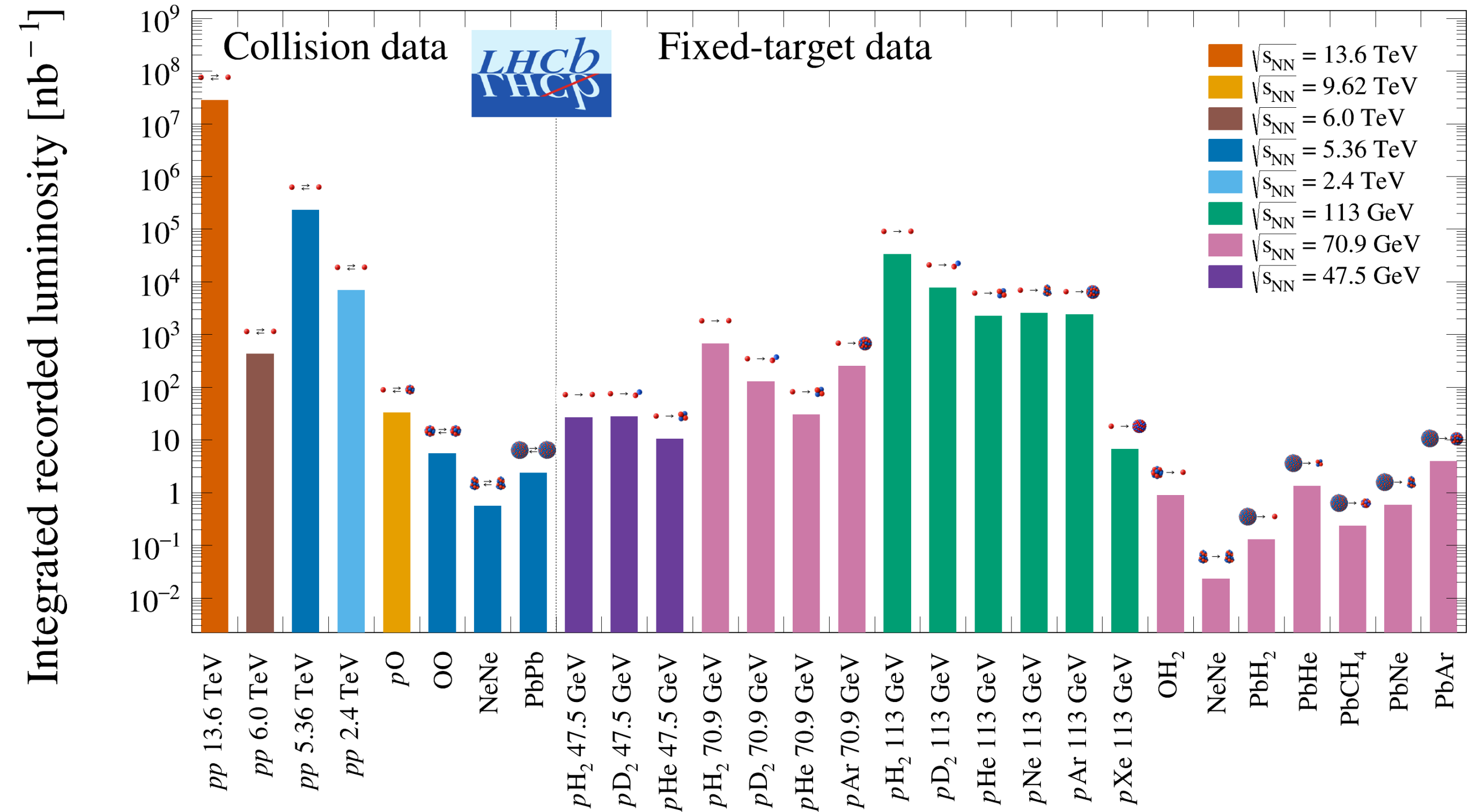
$$\Delta y = y_{\text{beam}} - y_{V^0}$$

- Universal ratio of $\bar{\Lambda}$ to K_S^0 production among wide range of Δy
- Variations due to different fiducial phase spaces



Future Prospects

- Significant uncertainty in event generators originating from extrapolation from pp to other collision systems
 - Analyse SMOG2 and oxygen collision data
- Multiplicity-dependent strangeness enhancement observed by ALICE collaboration [Nature Phys. 13 \(2017\) 535–539](#)
 - Probe multiplicity dependence of cross-sections in forward region

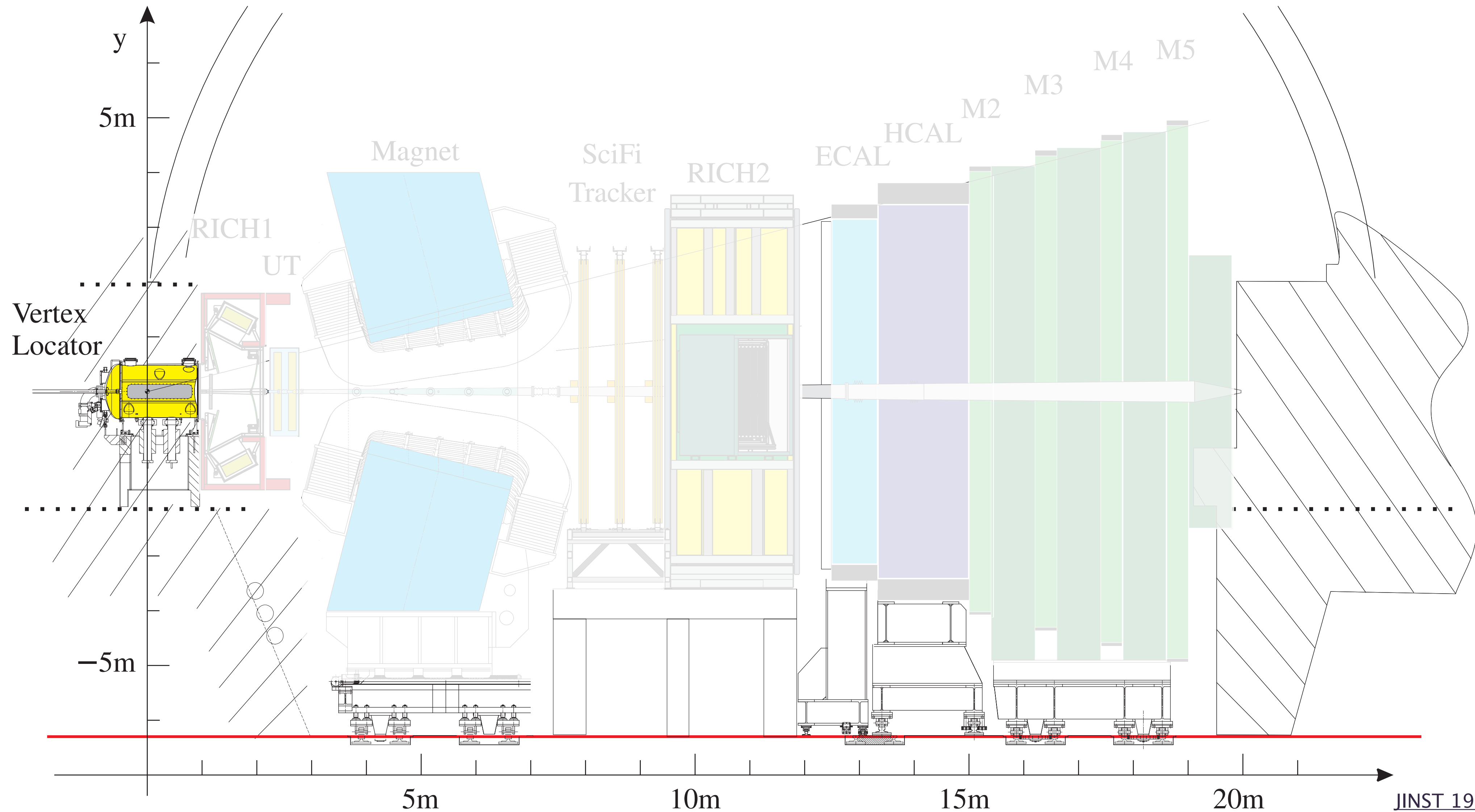


Run 3 Collision system

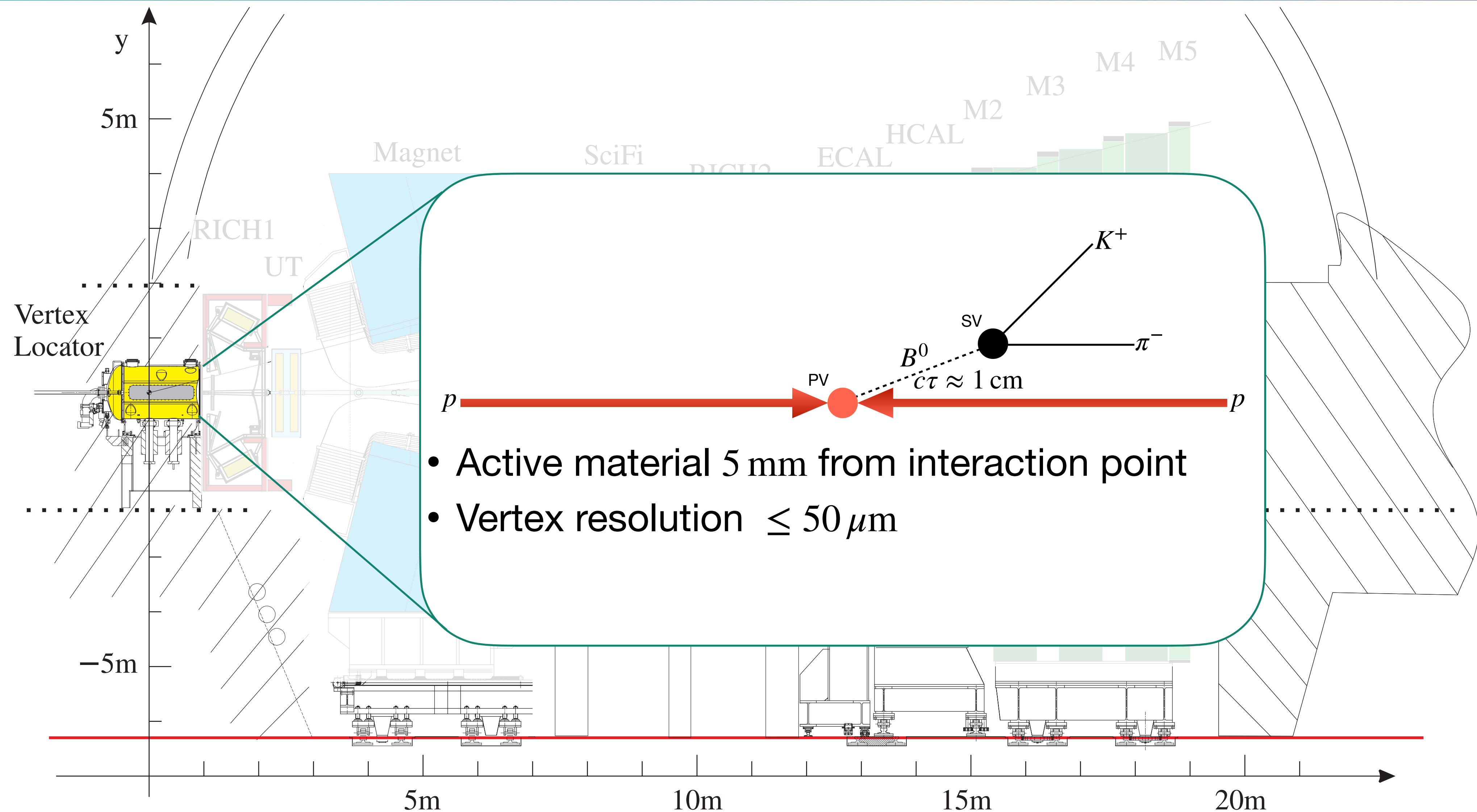
- LHCb offers unique environment to probe soft QCD processes relevant to model environment in collider experiments and interactions of cosmic rays with atmosphere
- First LHCb measurement of $\sigma(pp \rightarrow K_S^0 X)$, $\sigma(pp \rightarrow \bar{\Lambda} X)/\sigma(pp \rightarrow K_S^0 X)$, and $\sigma(pp \rightarrow \bar{\Lambda} X)/\sigma(pp \rightarrow \Lambda X)$ at $\sqrt{s} = 13$ TeV
- First LHCb measurement of $\sigma(pp \rightarrow \bar{\Lambda} X)$ and $\sigma(pp \rightarrow \Lambda X)$
- First measurement of $\sigma(pp \rightarrow \bar{\Lambda} X)/\sigma(pp \rightarrow K_S^0 X)$ at $\sqrt{s} = 13.6$ TeV
- Run 3 measurement proves successful upgrade of LHCb detector
- Baryon-to-meson production ratio underestimated by most common event generators
- Future measurements in different collision systems and as function of multiplicity will reduce extrapolation uncertainties of hadronic interaction models and probe strangeness enhancement in forward direction

Backup

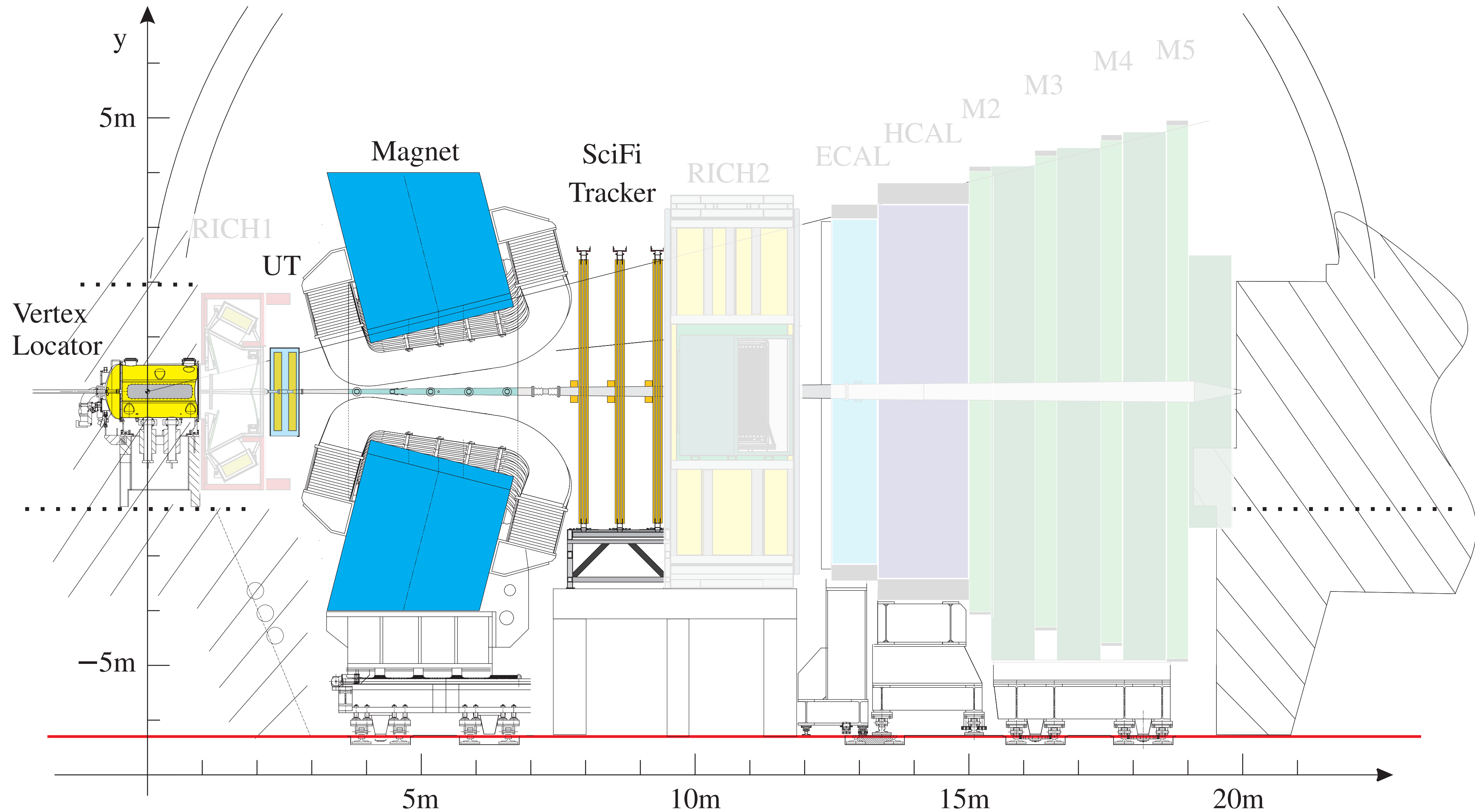
The LHCb detector: Vertex locator



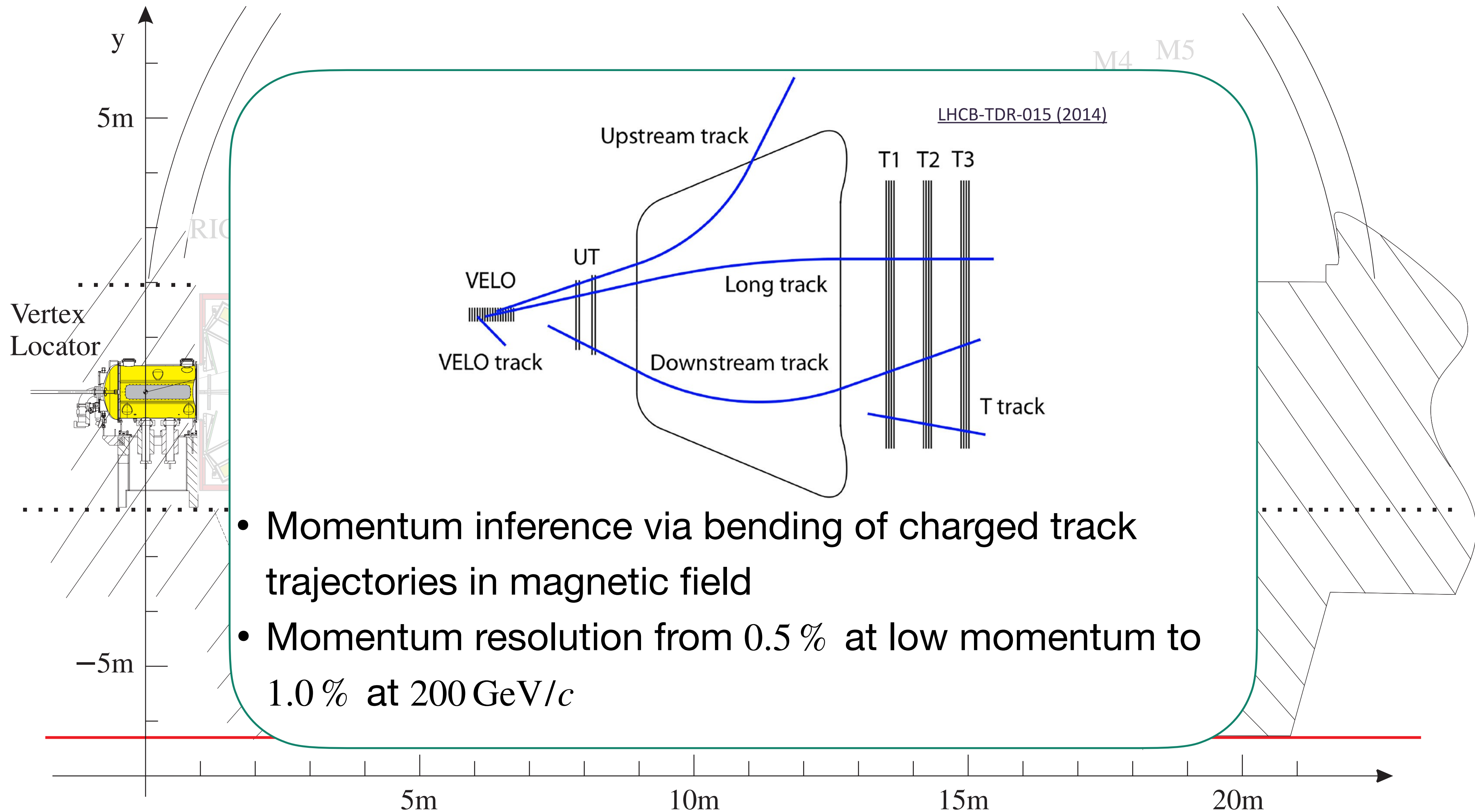
The LHCb detector: Vertex locator



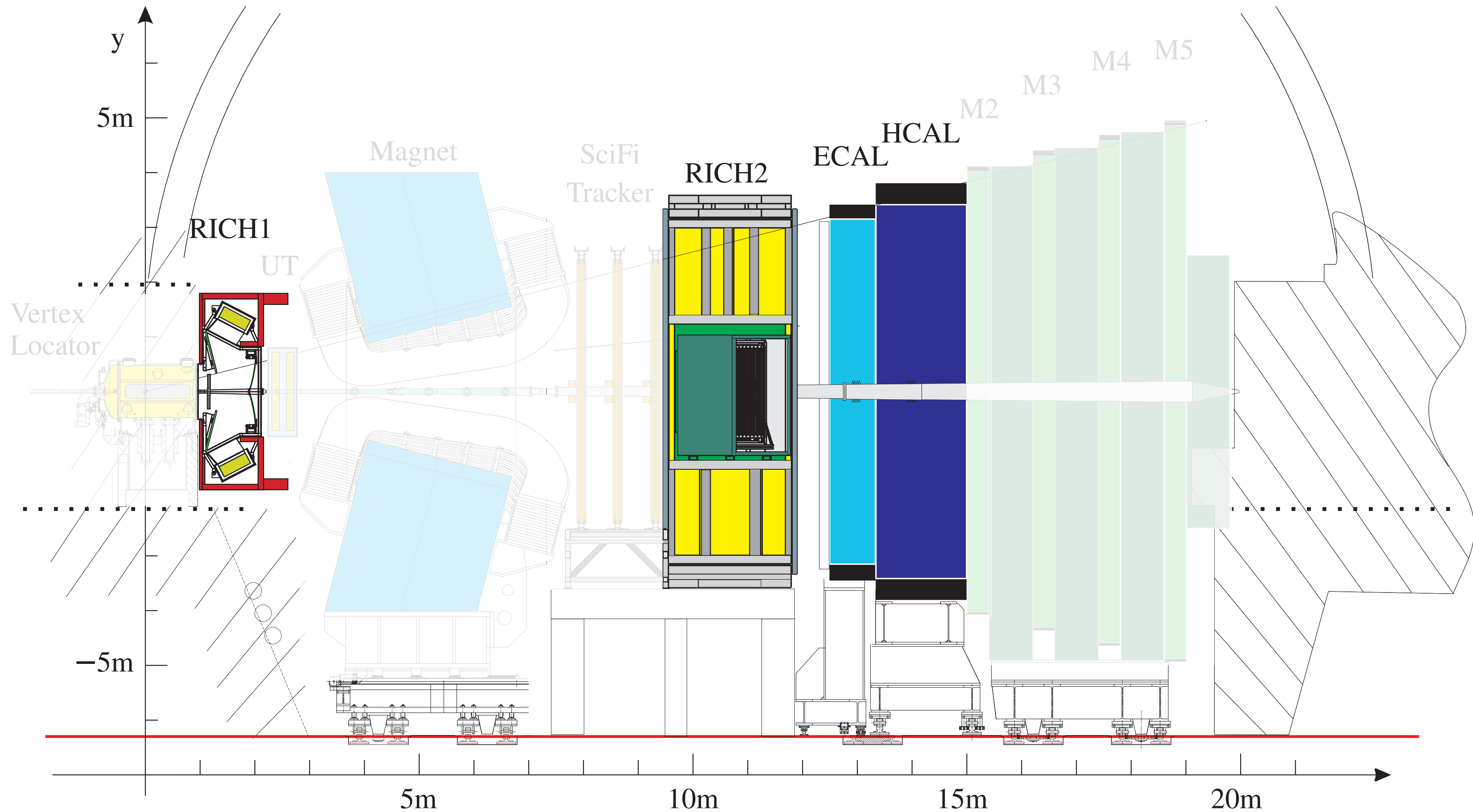
The LHCb detector: Tracking system



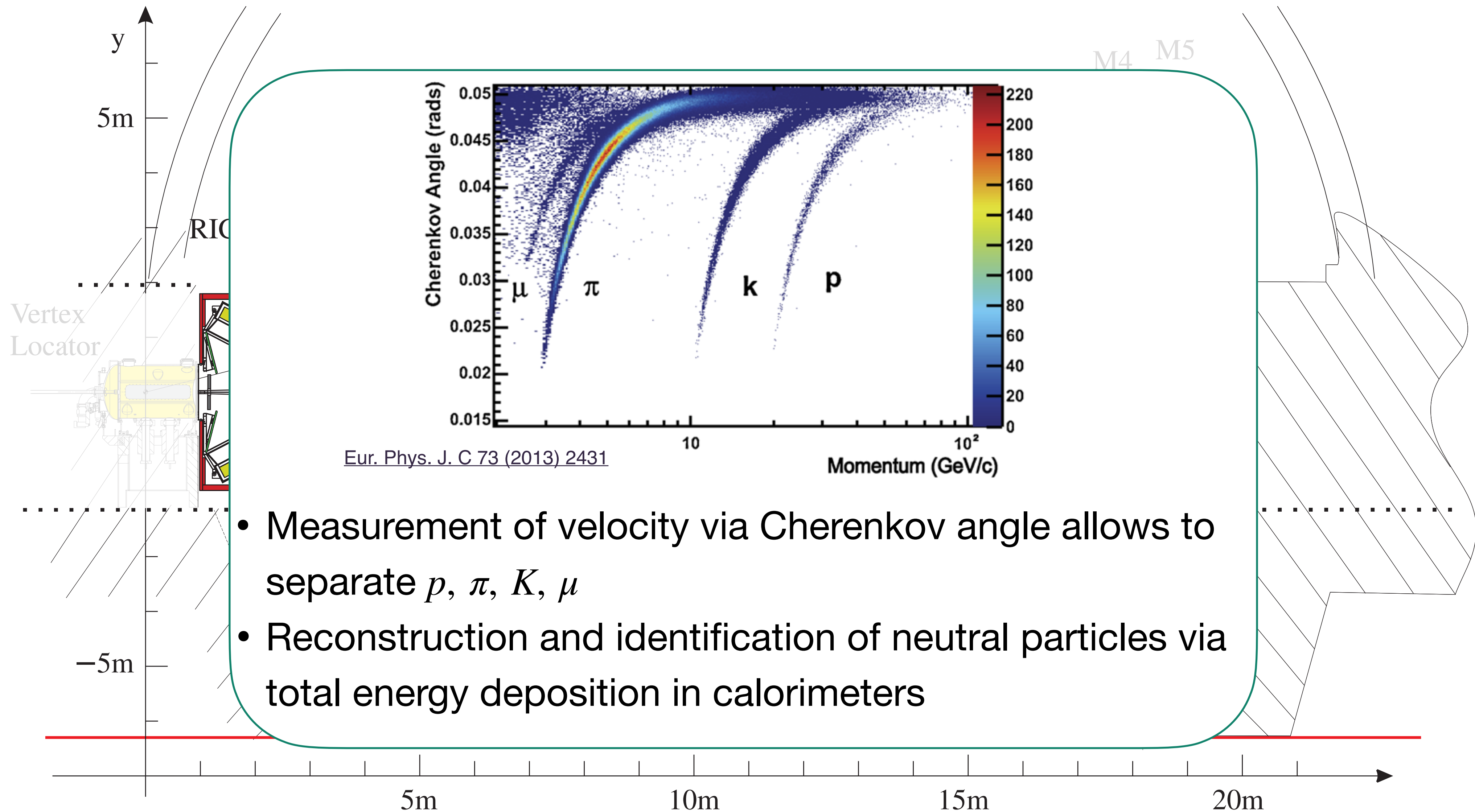
The LHCb detector: Tracking system



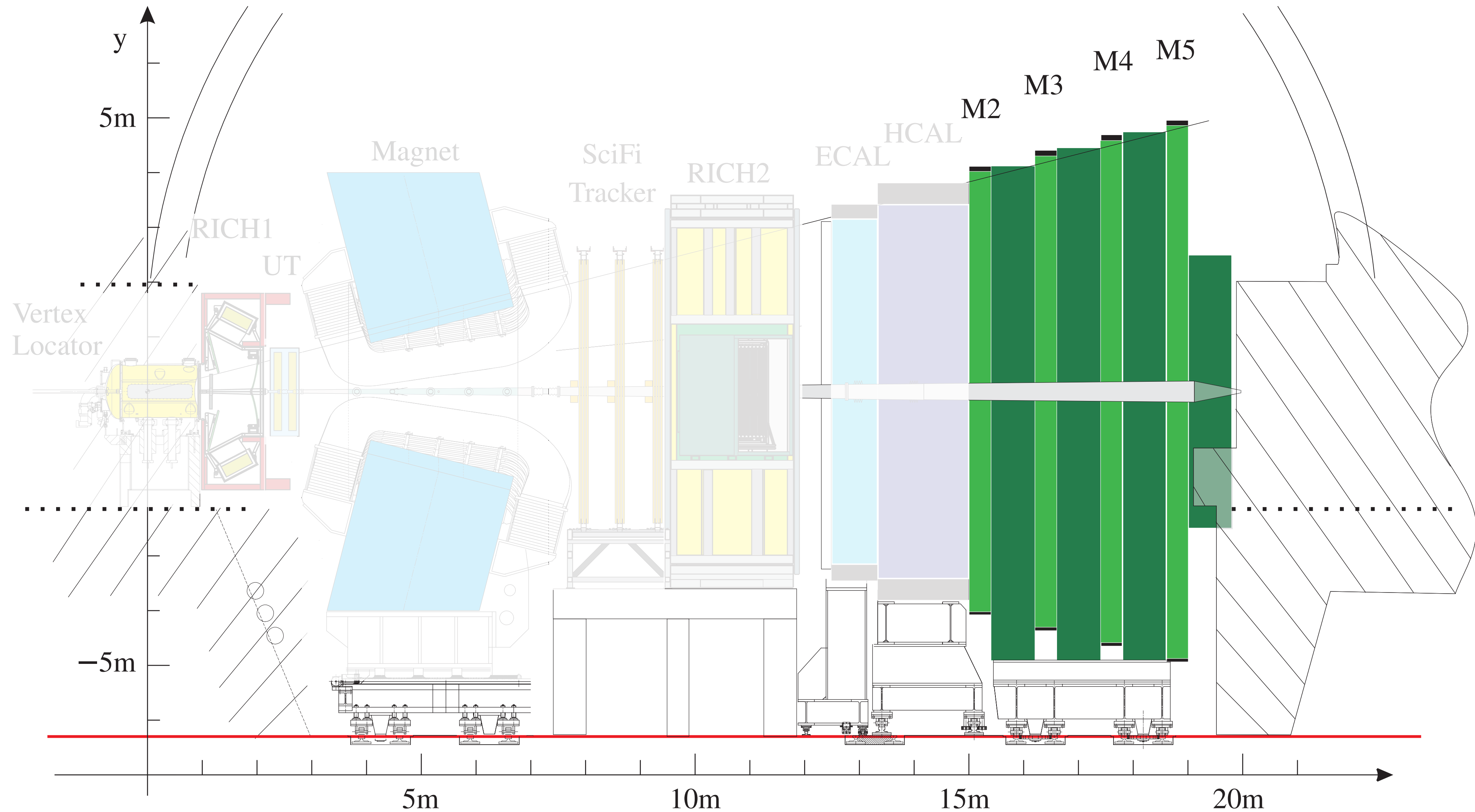
The LHCb detector: Particle identification (PID)



The LHCb detector: Particle identification (PID)

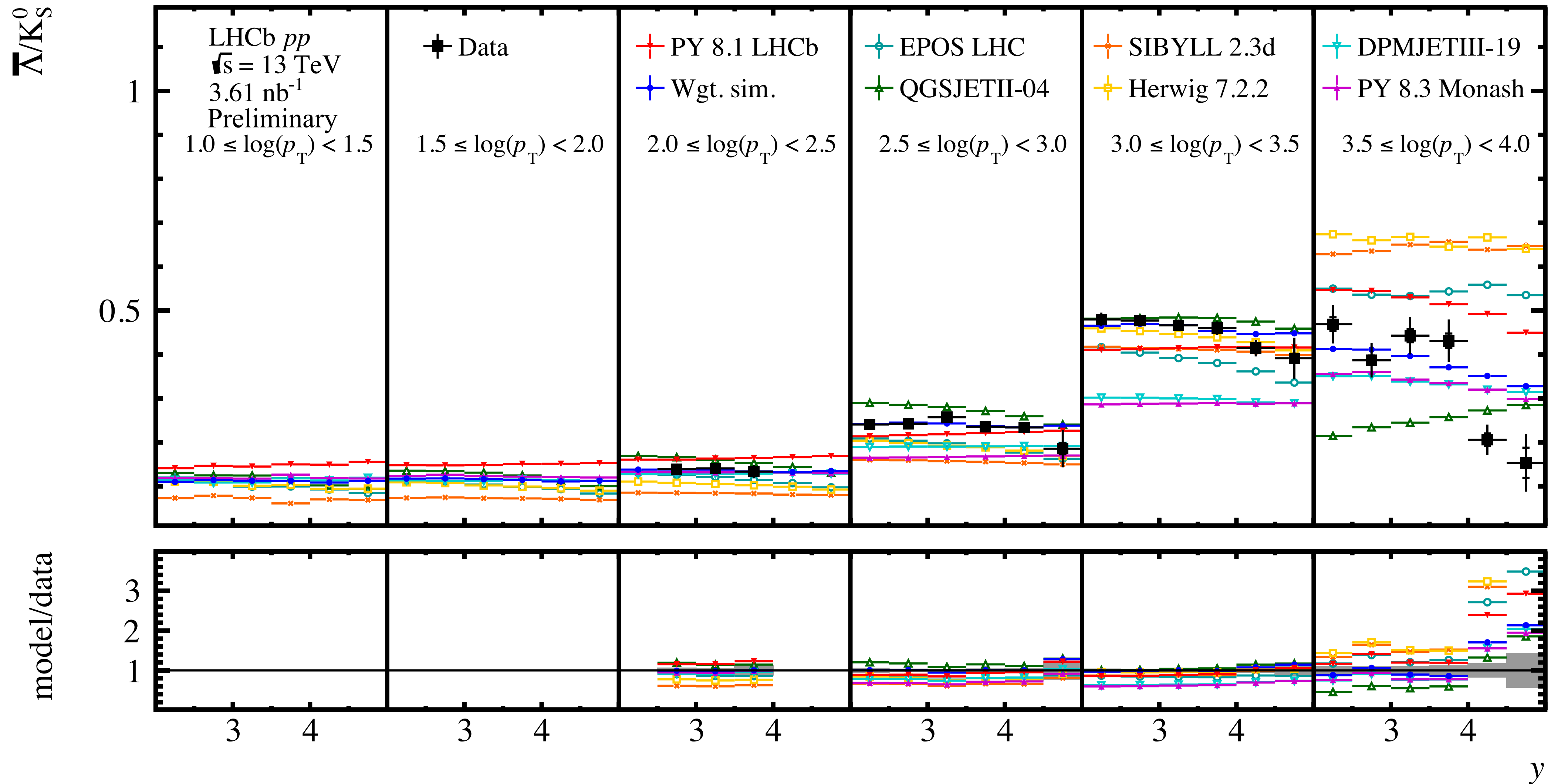


The LHCb detector: Muon chambers

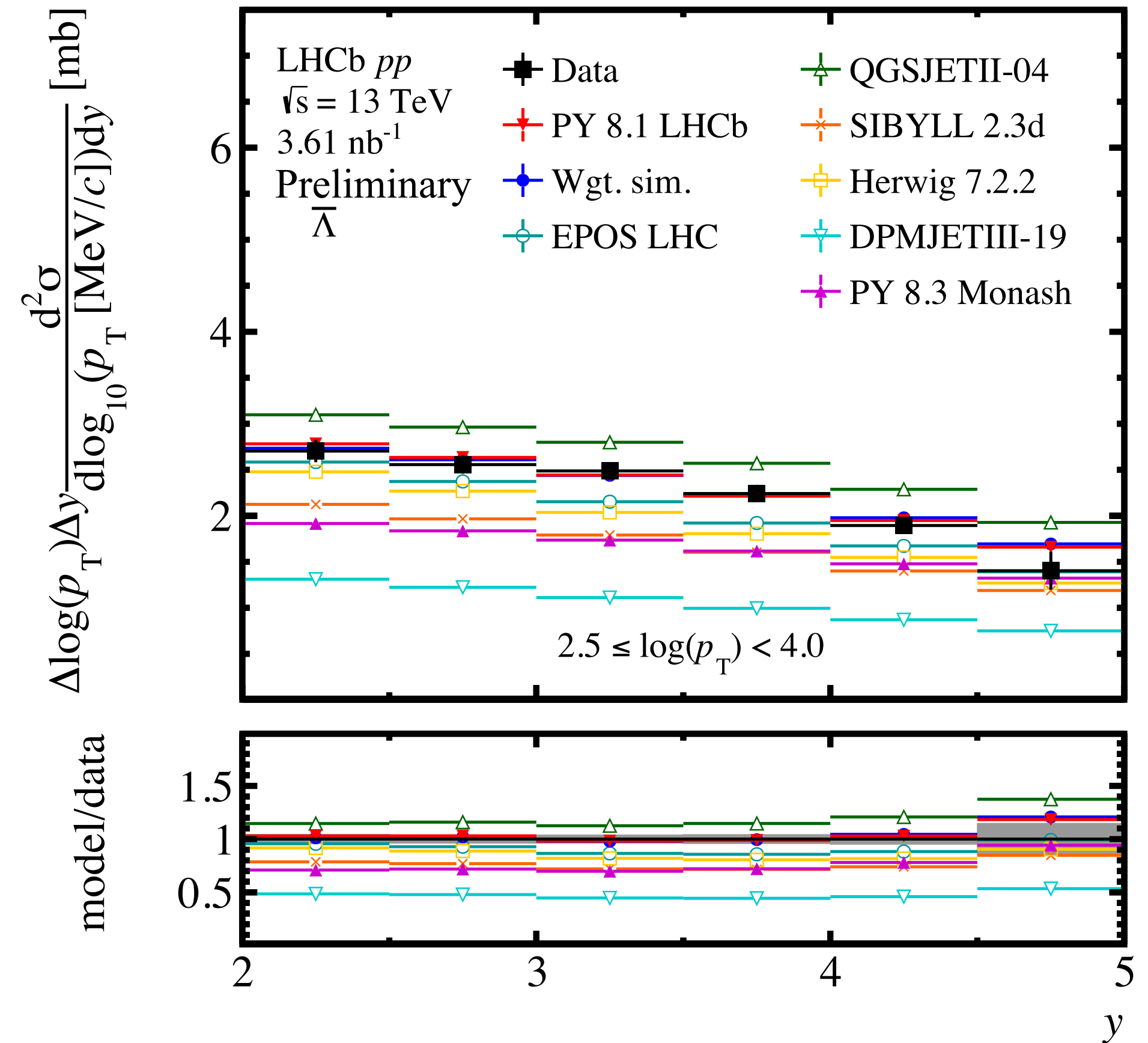
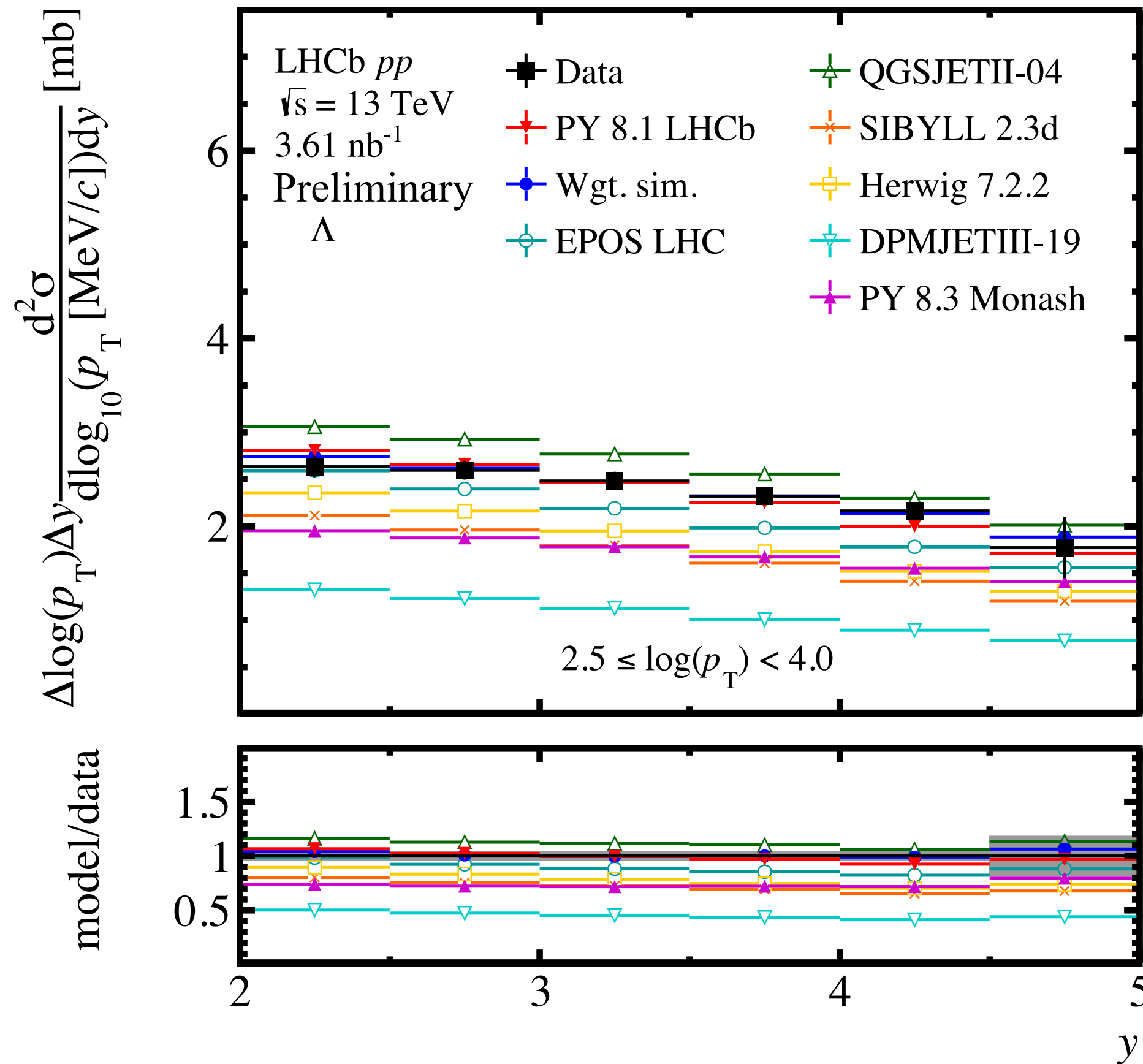


Double differential cross-section ratio $\bar{\Lambda}/K_S^0$

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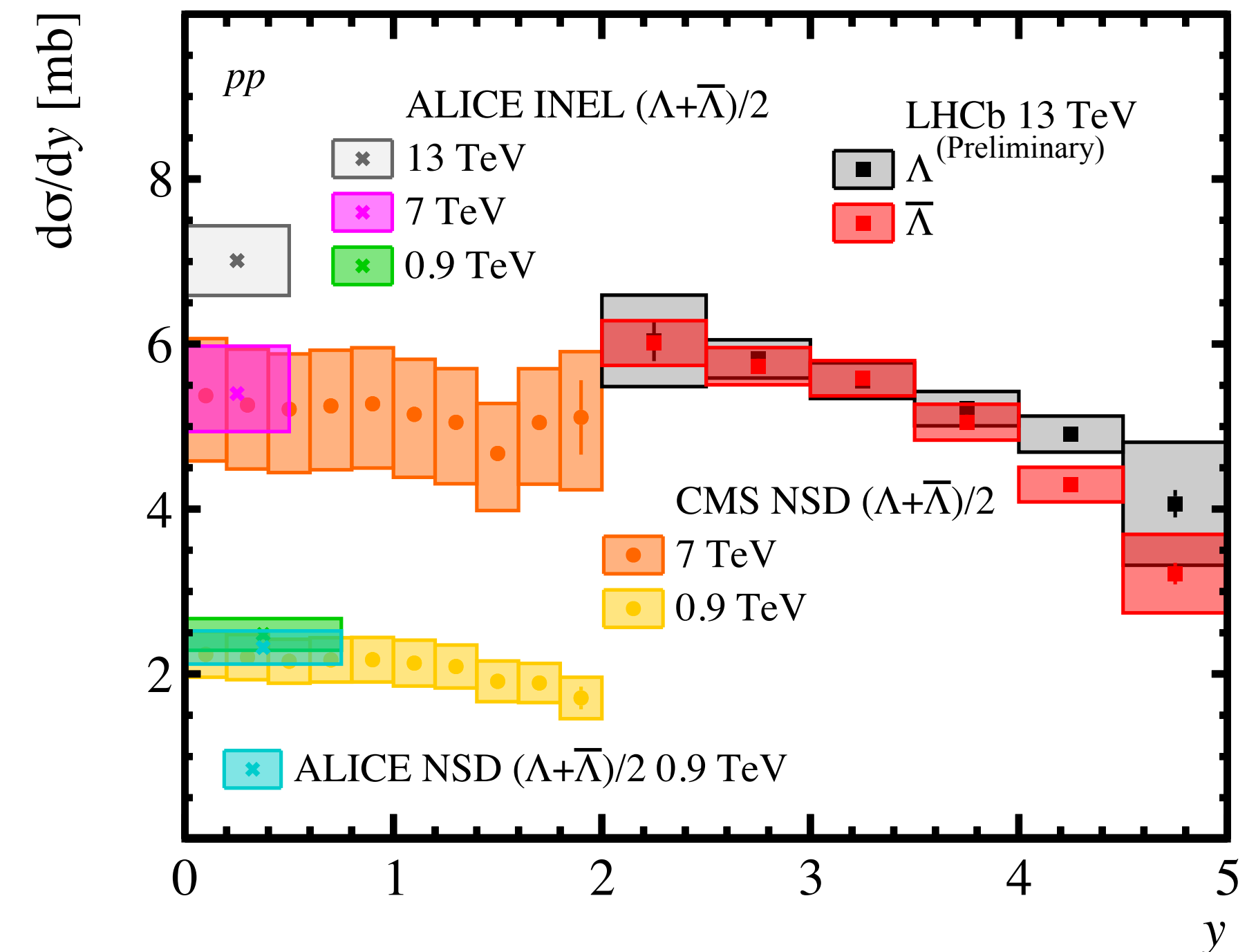
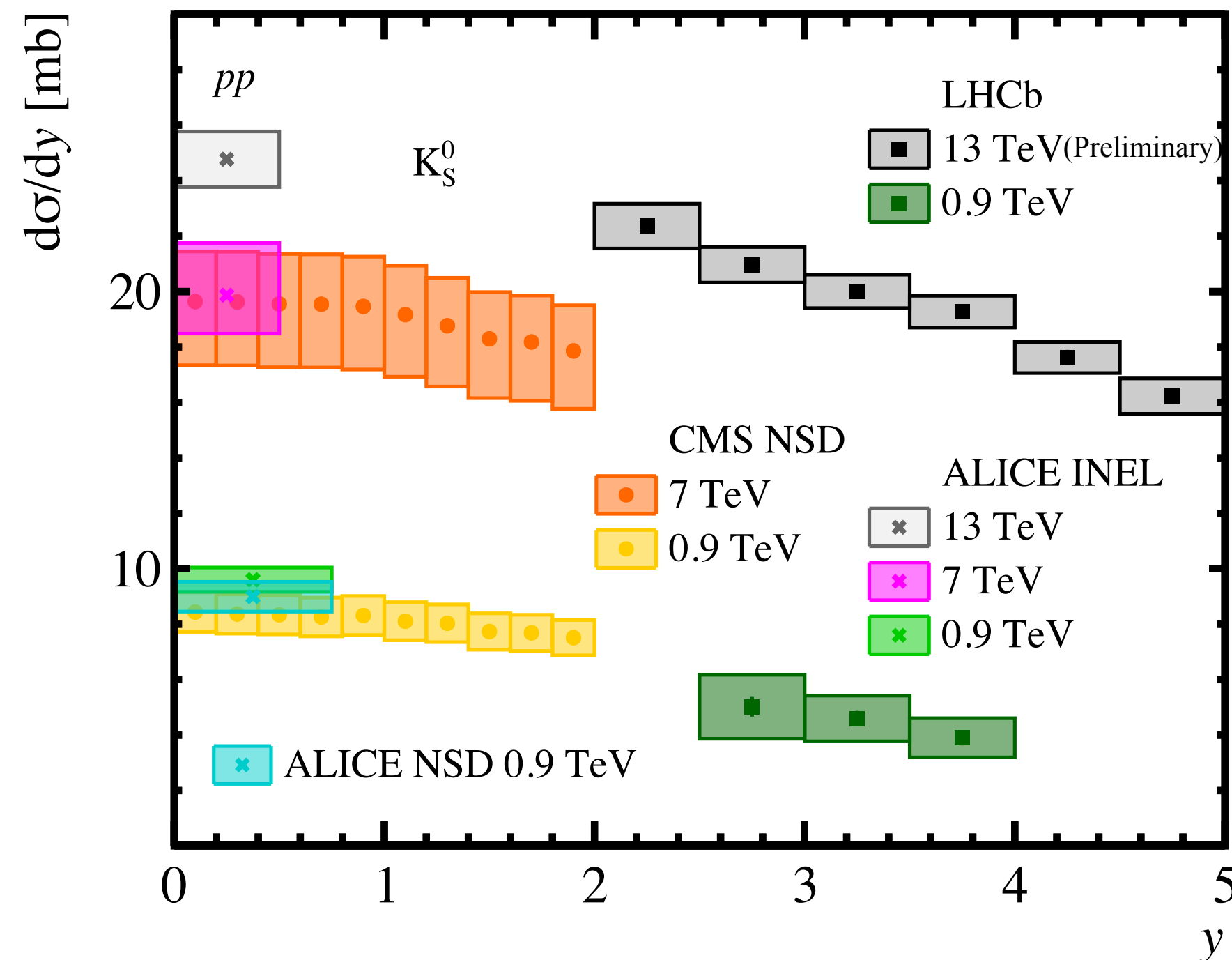


Fiducial differential cross-sections in y

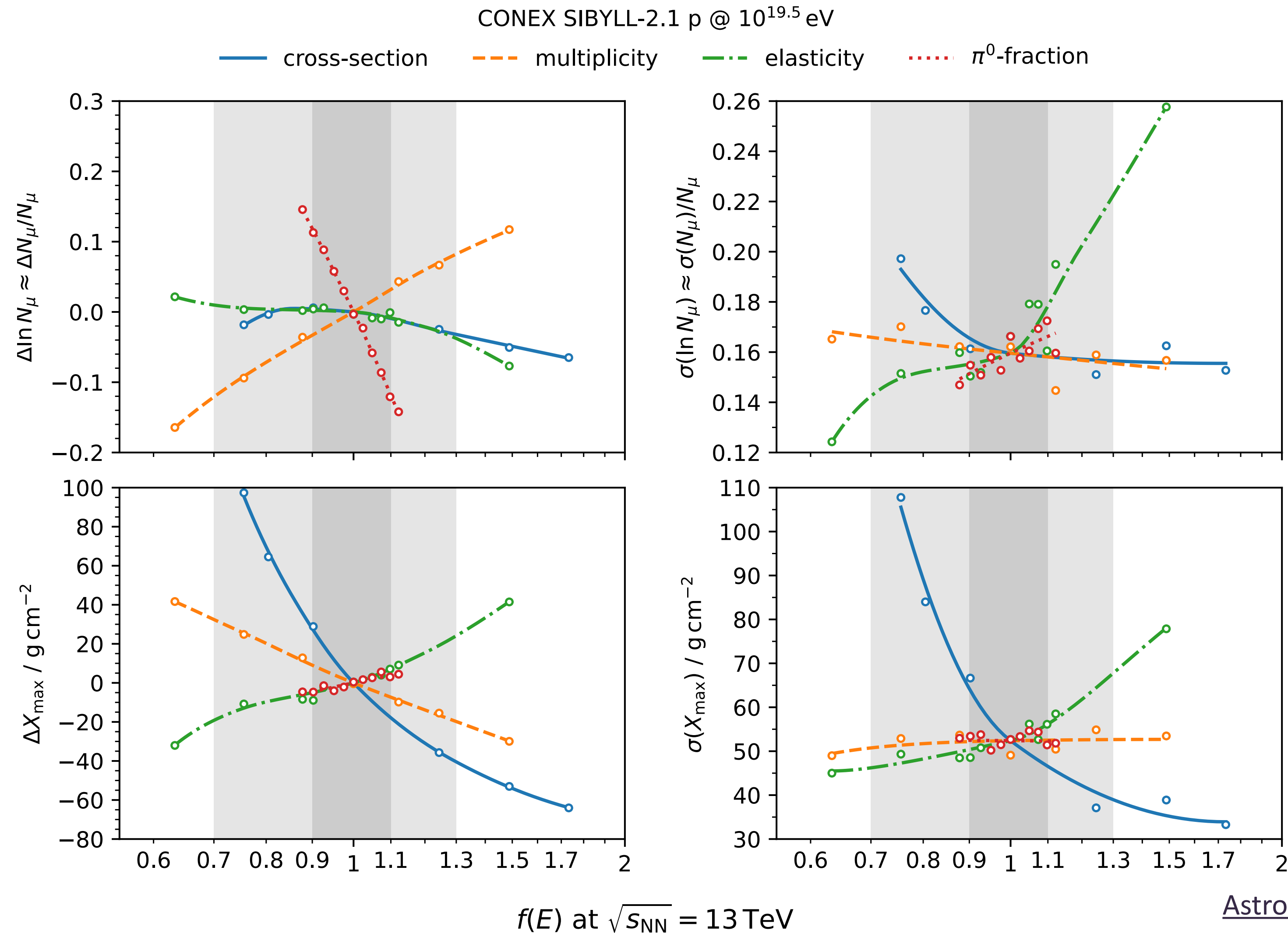


Cross-sections compared to other experiments

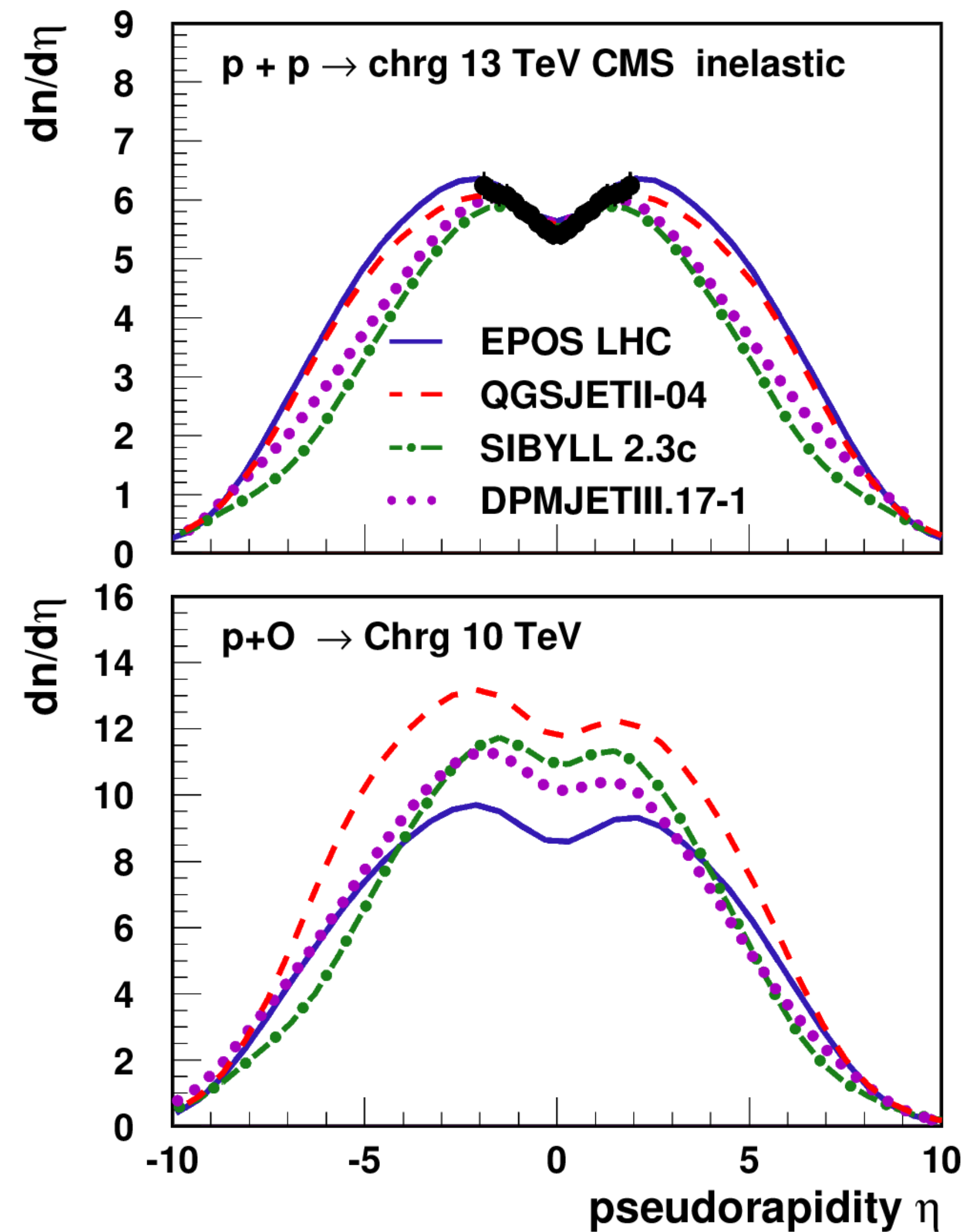
- Consistent increase of K_S^0 cross-section with centre-of-mass energy observed
- Continuation of decreasing trend towards higher rapidity



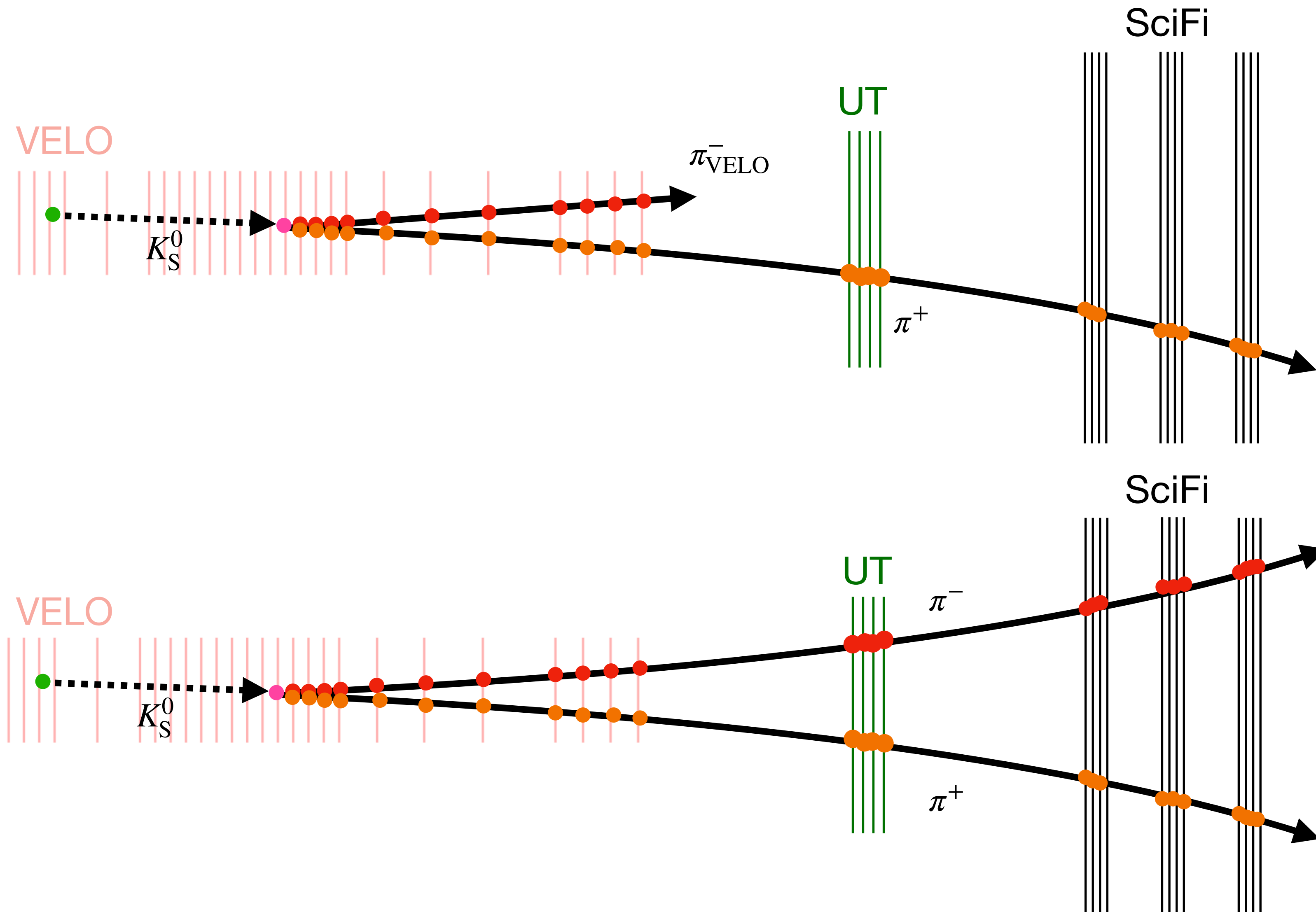
Impact of change in basic parameters on muon number tu



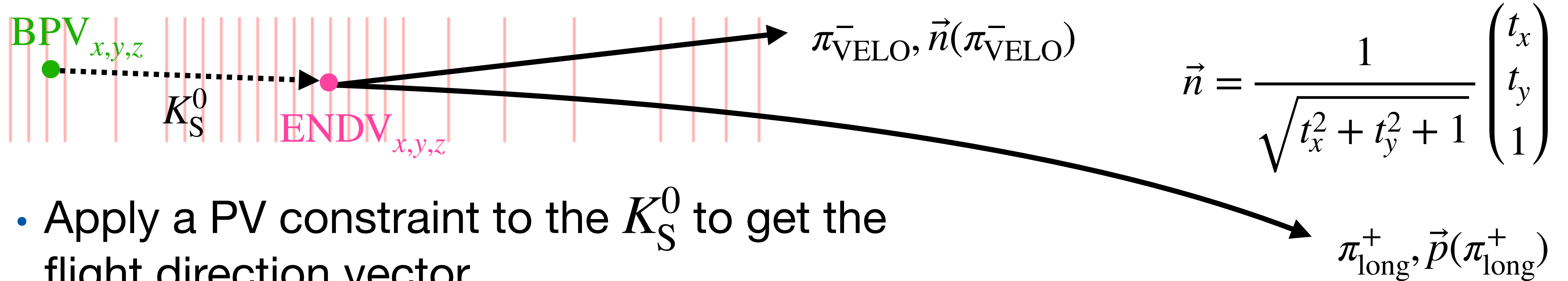
Predictions of charged-particle spectra in η



Tag-and-Probe approach



Least-squares method



- Apply a PV constraint to the K_S^0 to get the flight direction vector

$$t_{x,y}^{K_S^0} = \frac{\text{ENDV}_{x,y} - \text{BPV}_{x,y}}{\text{ENDV}_z - \text{BPV}_z} \rightarrow \vec{n}(K_S^0)$$

- This leaves an overdetermined system of **2 unknowns** and 3 equations

$$|\vec{p}(K_S^0)| \vec{n}(K_S^0) = \vec{p}(\pi_{\text{long}}^+) + |\vec{p}(\pi_{\text{VELO}}^-)| \vec{n}(\pi_{\text{VELO}}^-)$$

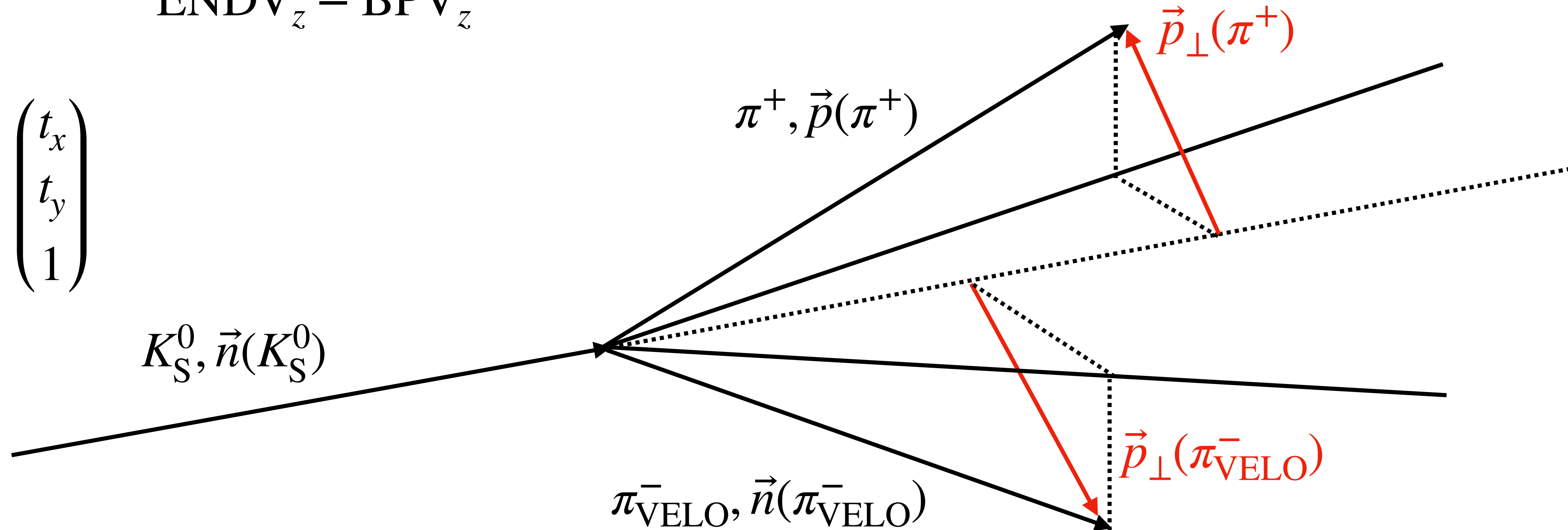
- Solve with a least-square-fit by finding minimum of

$$\left| \begin{pmatrix} p_x(\pi_{\text{long}}^+) \\ p_y(\pi_{\text{long}}^+) \\ p_z(\pi_{\text{long}}^+) \end{pmatrix} - \begin{pmatrix} n_x(K_S^0) & -n_x(\pi_{\text{VELO}}^-) \\ n_y(K_S^0) & -n_y(\pi_{\text{VELO}}^-) \\ n_z(K_S^0) & -n_z(\pi_{\text{VELO}}^-) \end{pmatrix} \cdot \begin{pmatrix} |p(K_S^0)| & |p(\pi_{\text{VELO}}^-)| \end{pmatrix} \right|$$

Perpetual-momentum method

$$t_{x,y}^{K_S^0} = \frac{\text{ENDV}_{x,y} - \text{BPV}_{x,y}}{\text{ENDV}_z - \text{BPV}_z} \rightarrow \vec{n}(K_S^0)$$

$$\vec{n} = \frac{1}{\sqrt{t_x^2 + t_y^2 + 1}} \begin{pmatrix} t_x \\ t_y \\ 1 \end{pmatrix}$$



$$|\vec{p}_{\perp}(\pi_{\text{VELO}}^-)| = |\vec{p}_{\perp}(\pi^+)| \rightarrow |\vec{p}(\pi_{\text{VELO}}^-)| = |\vec{p}(\pi^+)| \frac{|\vec{n}(\pi^+) - \vec{n}(K_S^0)(\vec{n}(\pi^+)\vec{n}(K_S^0))|}{|\vec{n}(\pi_{\text{VELO}}^-) - \vec{n}(K_S^0)(\vec{n}(\pi_{\text{VELO}}^-)\vec{n}(K_S^0))|}$$