K_S^0 and Λ hadrons production in proton-proton and proton-lead collisions at 5.02 TeV studied with the LHCb detector

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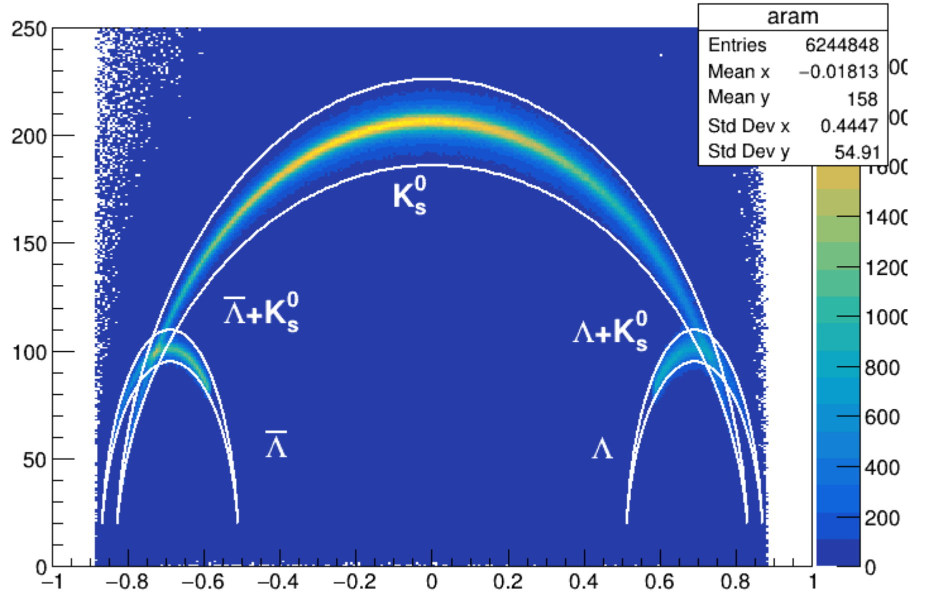
Sasha Okhrimenko on behalf of LHCb Kyiv Group

(Serhii Koliiev, Oleksandr Kot, Oleksandr Kshyvanskyi, Ievgenii Petrenko, Valery Pugatch)

Institute for Nuclear Research NAS of Ukraine, Kyiv, Ukraine

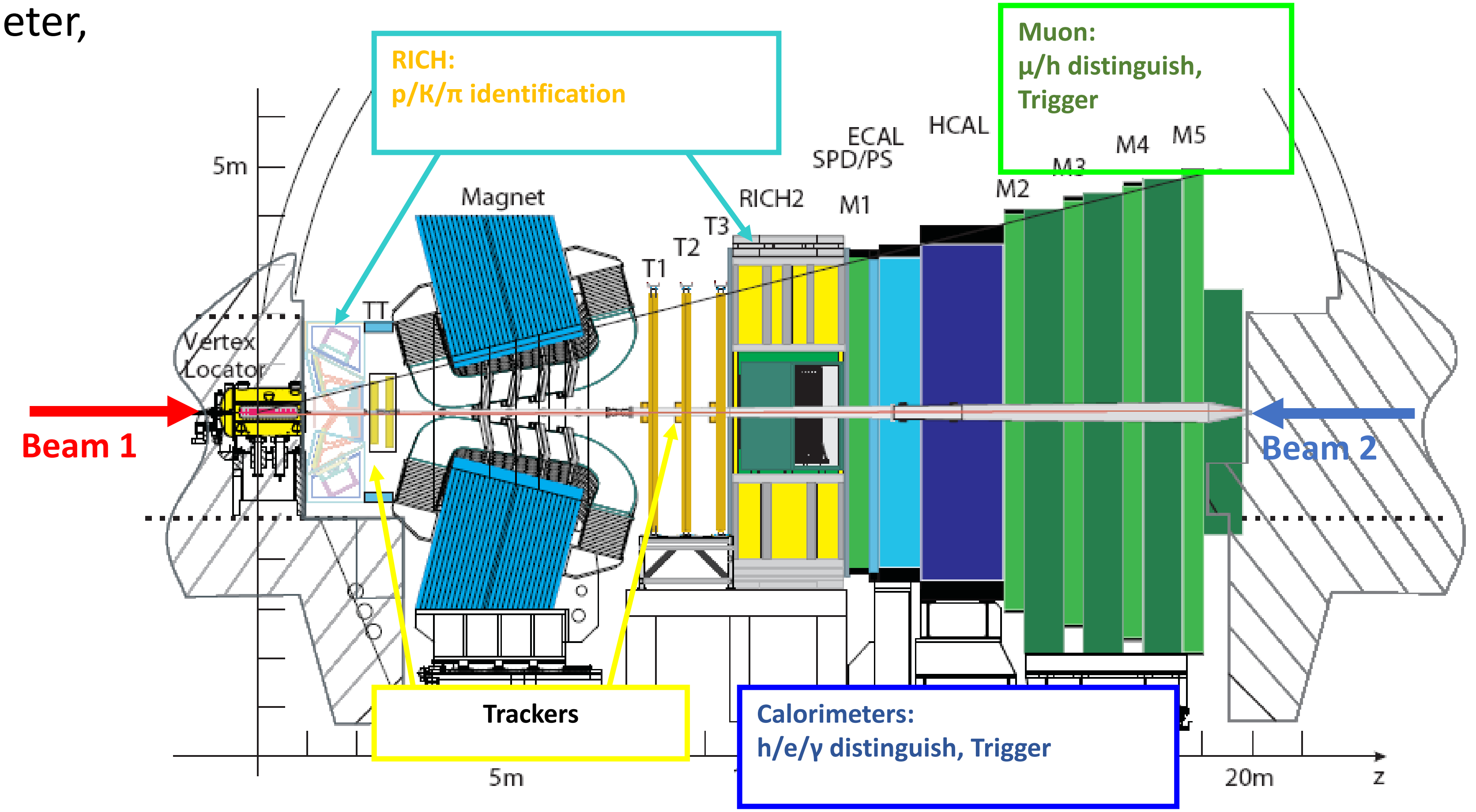
Motivation

- Differential production cross-sections — important input for QCD and MC tuning.
- Strange hadron production at LHCb — powerful tool to investigate hadronization processes:
  - Production cross-sections are higher than for heavier quarks
- Assuming that production cross-section for p-A collisions provide cold nuclear matter effects, one can take them into account searching signals from QGP in A-A collisions.
- Strangeness enhancement is one of the possible signal of QGP.
- NMF — a tool to study impact of nuclear environment
  - measurement of V^0 CS in p-p collisions
  - calculation of CS ratios (p-Pb)/(p-p)
- Λ-bar/Λ, Λ-bar/K_S, R_{FB} ratios:
  - Reduce systematic errors and avoid Luminosity uncertainties.
  - Baryon number transition and baryon/meson production.



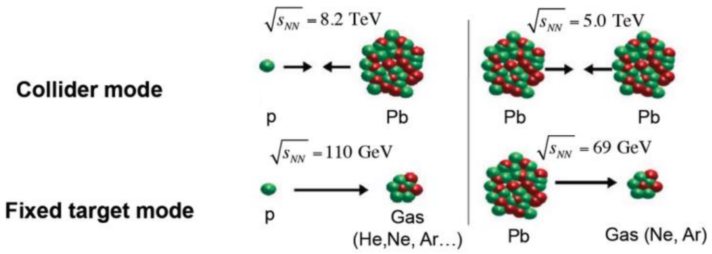
LHCb Experiment

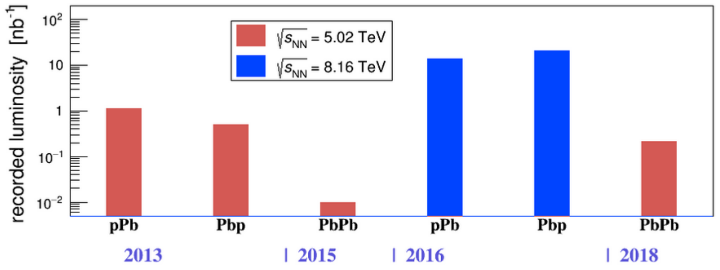
- **LHCb Run 2 [1]** – forward spectrometer, located at LHC.
- Acceptance **2 < *η* < 5**
- Proton-proton interaction at up to **$\sqrt{s}$ = 13 TeV,** **$\mathcal{L} = 4\cdot10^{32}$ cm^{-2}s^{-1}.**
- **Goal**: CP violation and rare decays of *B*-mesons.
- **Resolutions [2]:**
  - spatial (PV position): **~ 16 μm**;
  - decay time: **~ 50 fs**;
  - track's momentum: **0.5–0.4%**;
  - mass (FWHM): **~ 13 MeV (*J/ψ*)**;
  - particle identification: **~ 96%**.



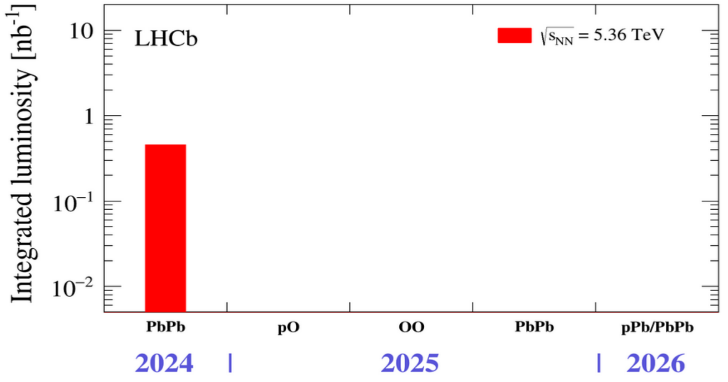
[1]. JINST 3 (2008) S08005.
[2]. Int. J. Mod. Phys. A 30 (2015) 15300227.

Proton-Ion setup at LHCb

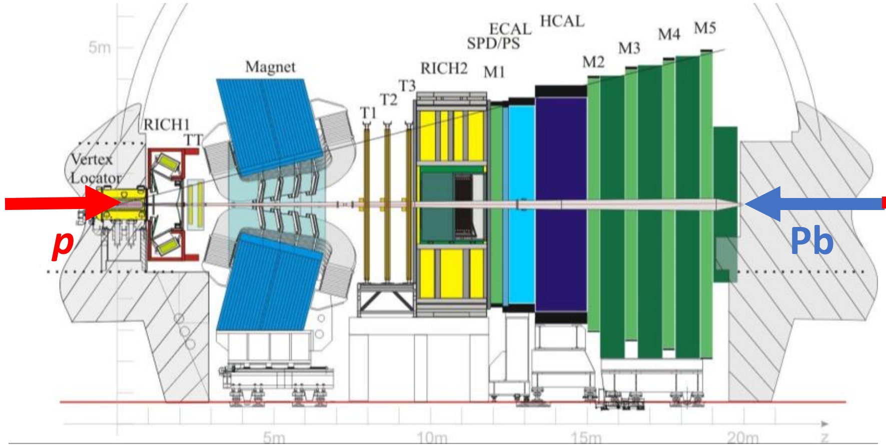




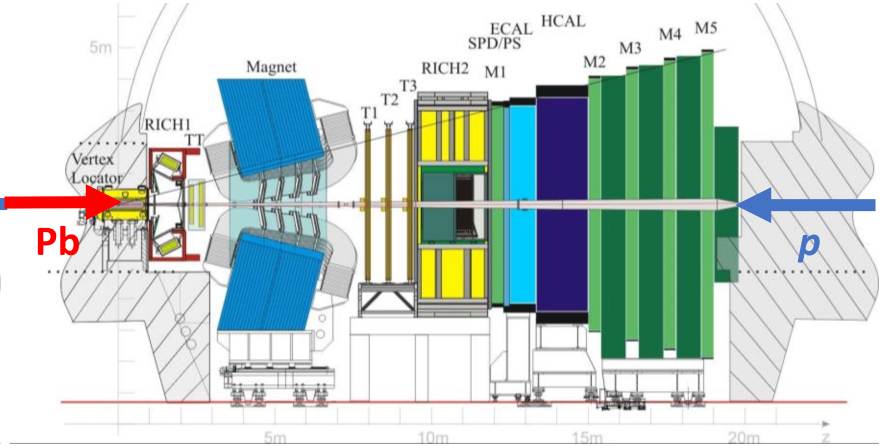
2013 heavy ion run:
Ion = ^{208}**Pb**, E_p = 4 TeV, E_{Pb} = 1.58 TeV →
$\sqrt{s_{NN}}$ = 5.02 TeV,
$\mathcal{L}_{int}$: **1.1** nb^{-1} (Fwd), **0.5** nb^{-1} (Bwd)

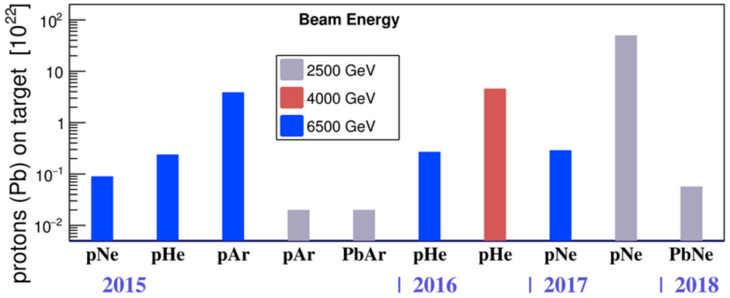


Forward (Fwd, p-Pb)



Backward (Bwd, Pb-p)





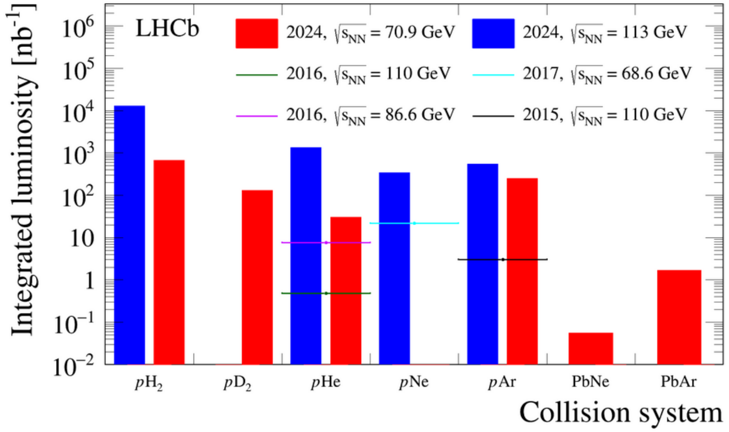
1.5 < y^* < 4.0

$y^* = y_{lab} - 0.465$

0.15 < p_T < 7.0 GeV/c

−5.0 < y^* < −2.5

$y^* = -(y_{lab} + 0.465)$

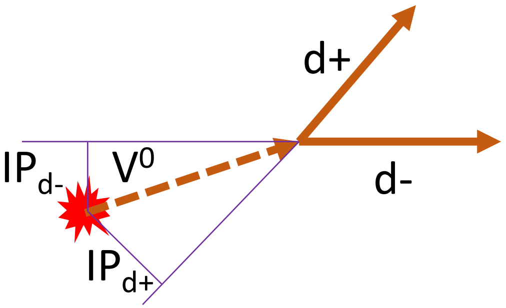


Monte Carlo samples:
20M Minimum Bias simulated events using **EPOS** generator under conditions similar to real ones. [1]

$$\varepsilon_{tot}(p_T, y^*) = \frac{N^{Rec}_{V^0 \to d + d^-}(p_T, y^*)}{N^{Gen}_{p+Pb \to V^0 X}(p_T, y^*)}$$

[1]. Phys. Rev. C92 (2015) 034906; arXiv:1306.0121.

Signal Extraction

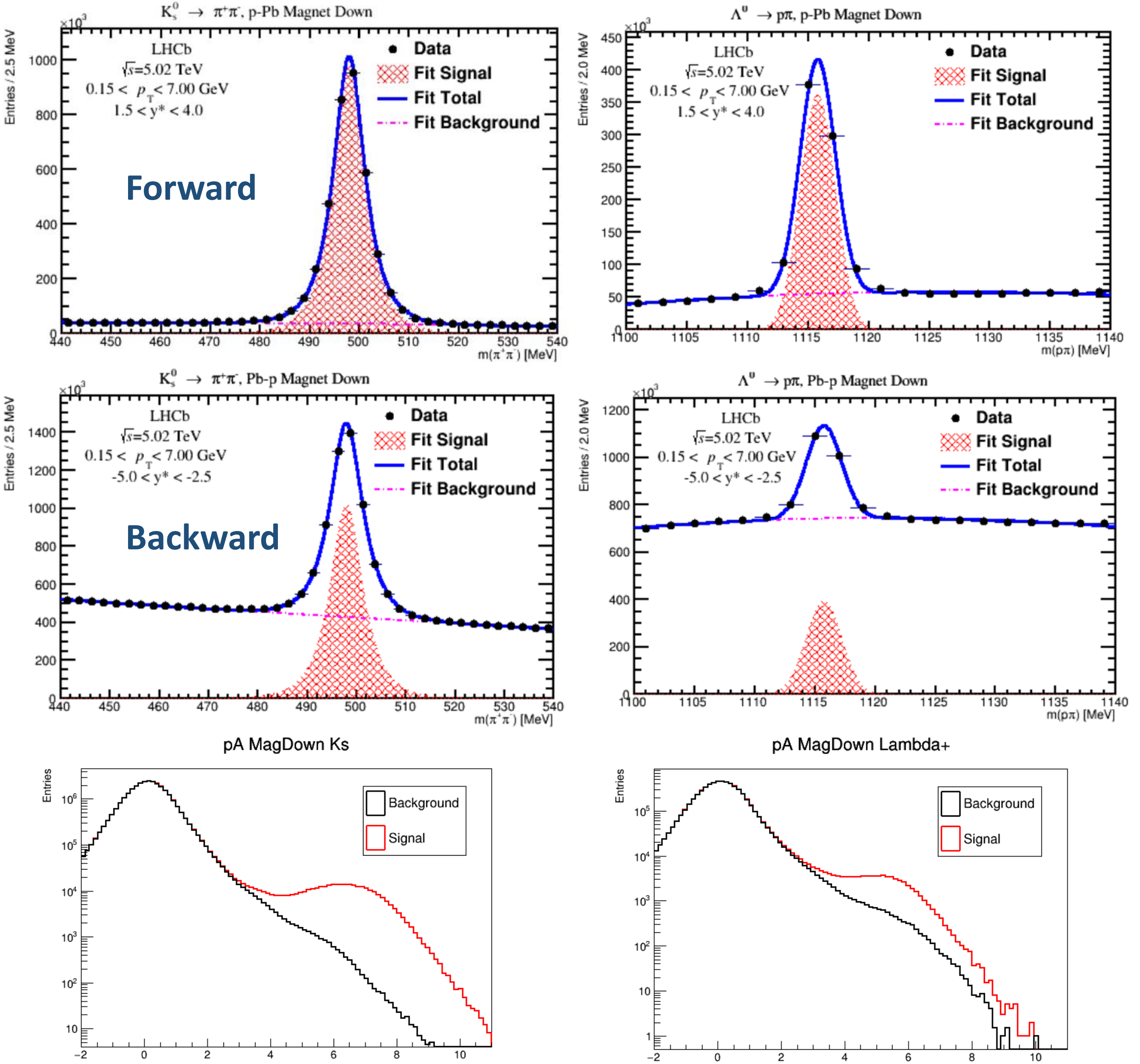


- ***$K_S^0 \to \pi^+\pi^-$ (BR: 0.692);***
- ***$\Lambda \to p\pi$ (BR: 0.639)***
- **Prompt V^0**
  Fisher's discriminant
  (variable related to impact parameters):
  $F_{IP} = \log_{10}(IP_{d+} * IP_{d-} / IP_{V0}) > 4$
- **Mass** distributions (fits):
  - K_S: Modified Gaussian (signal) + 2nd order Polynomial (*bkg*)

$$f(x\,;\,\mu,\sigma) \equiv \frac{A}{\sqrt{2\pi}\,\sigma}\exp\left(-\frac{1}{2}\left(\frac{|x-\mu|}{\sigma}\right)^{1+\frac{1}{1+\frac{|x-\mu|}{2\sigma}}}\right)$$

  - **Λ** : Sum of Gaussians (signal) + 3rd order Polynomial (bkg)
- **Total yields:**

	K_S	Λ
Forward:	~ 3.5·10^6;	~ 0.85·10^6
Backward:	~ 8.0·10^6;	~ 1.50·10^6
p-p :	~ 4.5·10^6;	~ 0.90·10^6



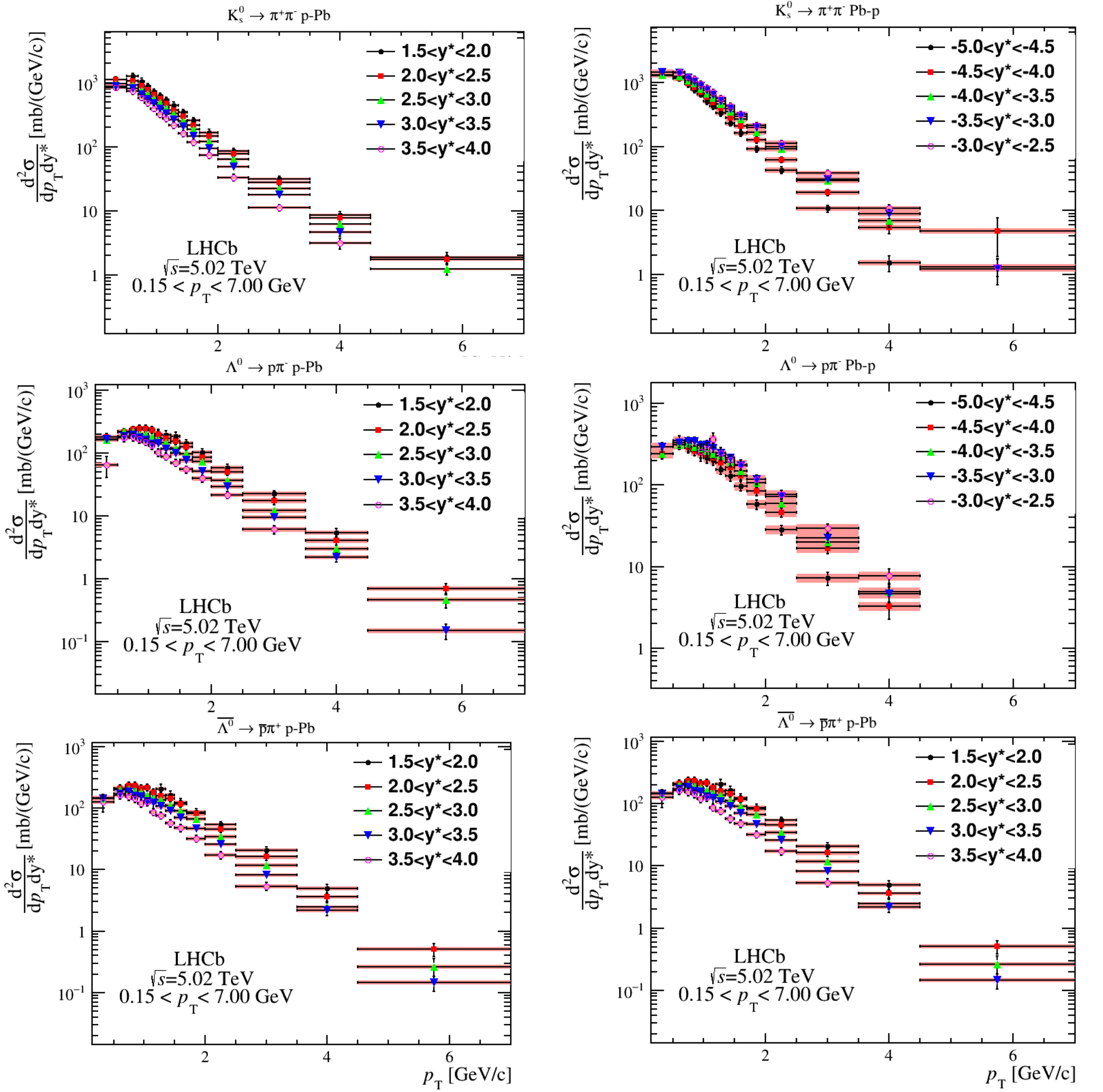
Results: Differential Production Cross-Sections

$$\frac{\mathbf{d}^2\boldsymbol{\sigma}}{\mathbf{d}\boldsymbol{p}_{\mathbf{T}}\,\mathbf{d}\boldsymbol{y}^*} = \frac{\boldsymbol{N}}{\Delta\boldsymbol{p}_{\mathbf{T}}\cdot\Delta\boldsymbol{y}^*\cdot\boldsymbol{\epsilon}\cdot\boldsymbol{\mathcal{B}}\cdot\boldsymbol{\mathcal{L}}}$$

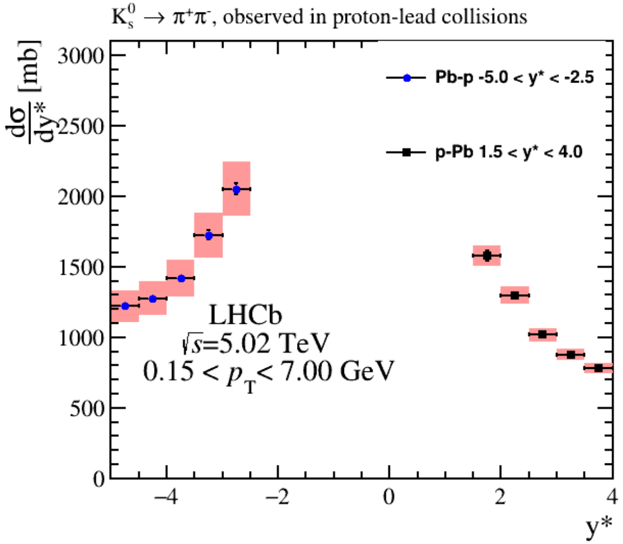
- $\boldsymbol{N}$ – number of reconstructed prompt V^0;
- $\Delta\boldsymbol{p}_{\mathbf{T}}$ – transverse momentum bins width;
- $\Delta\boldsymbol{y}$ – rapidity bins width;
- $\boldsymbol{\epsilon}$ – total efficiency (using MC);
- $\boldsymbol{\mathcal{B}}$ – branching fractions of $K_S^0 \rightarrow \pi^+\pi^-$ (0.692) and $\Lambda \rightarrow p\pi$ (0.639) decays [PDG];
- $\boldsymbol{\mathcal{L}}$ – integrated luminosity.

Usual exponential shape of $\boldsymbol{p_T}$ spectra which is in agreement with thermal evaporation model.

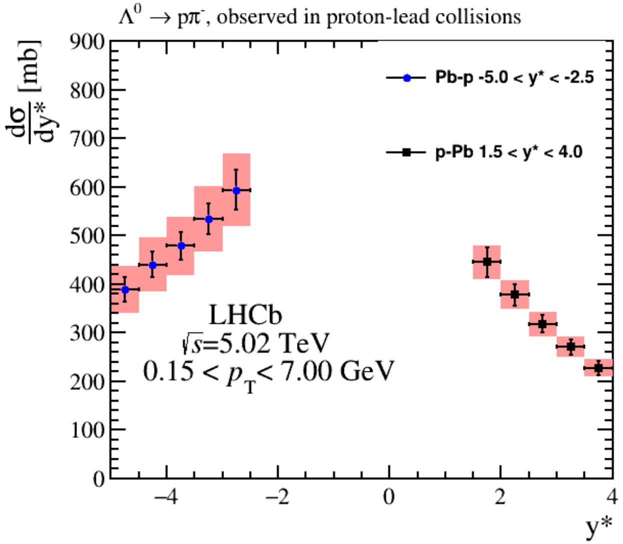
Cross-sections are higher for central rapidities.

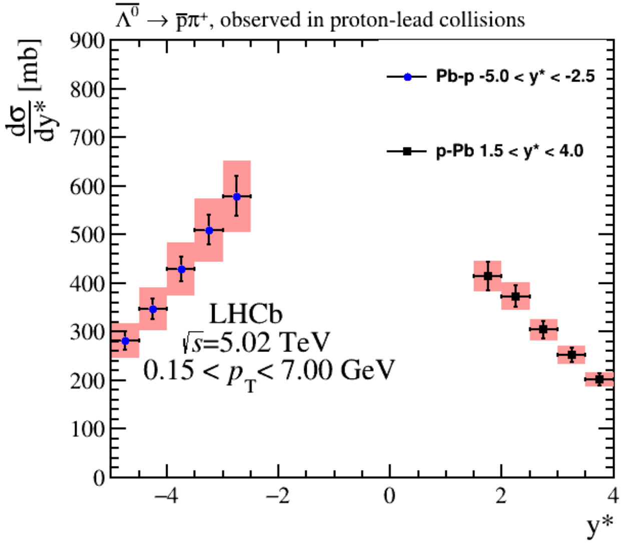


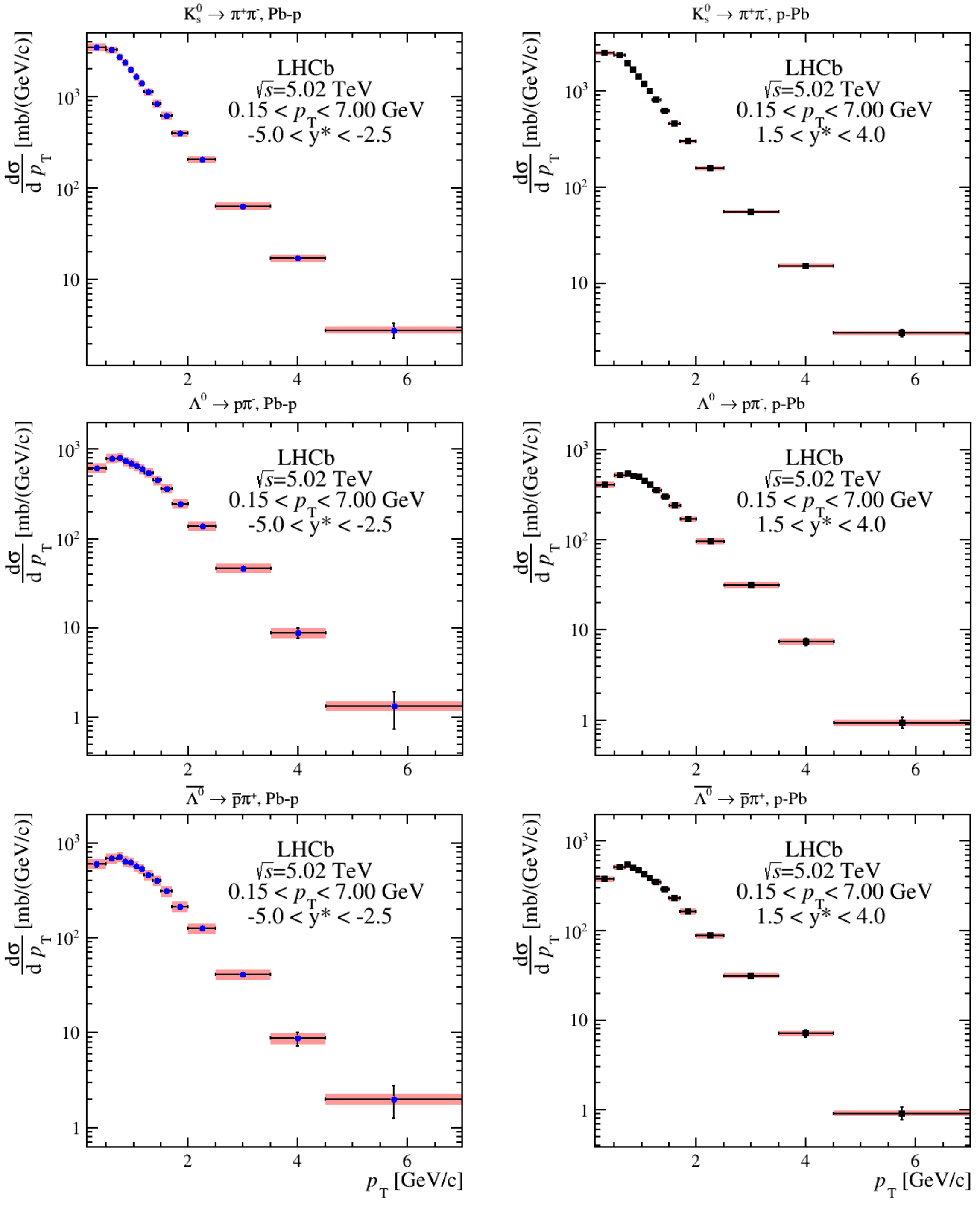
Results: Differential Production Cross-Sections



$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\,\mathrm{d}y^*} = \frac{N}{\Delta p_T \cdot \Delta y^* \cdot \epsilon \cdot \mathcal{B} \cdot \mathcal{L}}$$





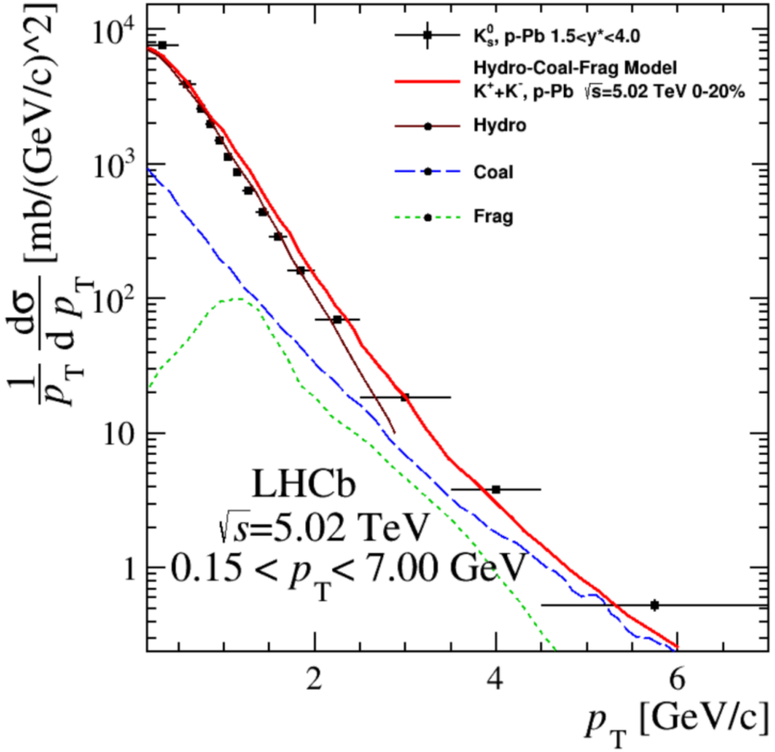


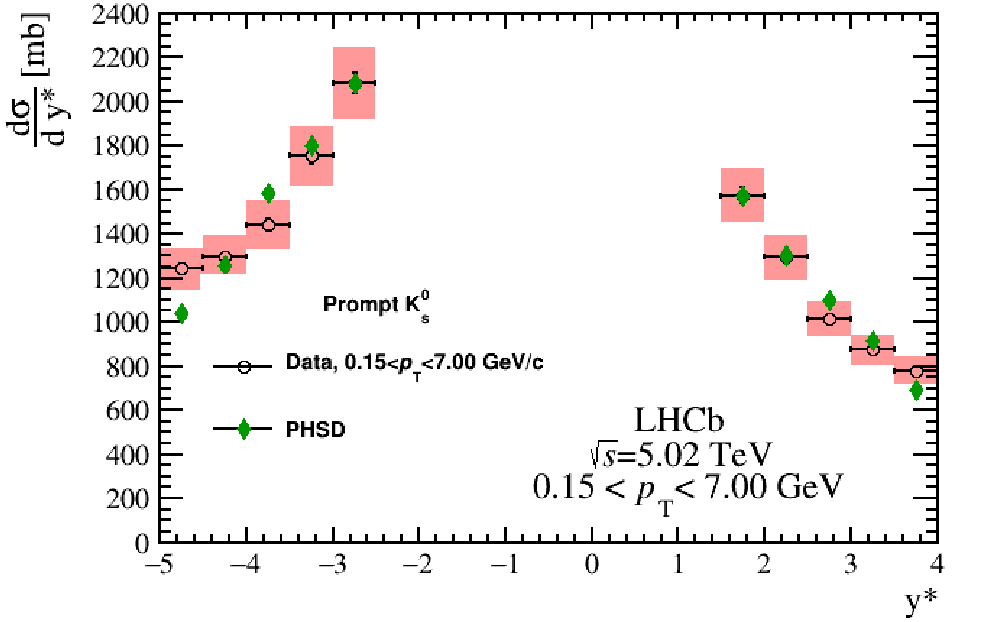
Results: Differential Production Cross-Sections

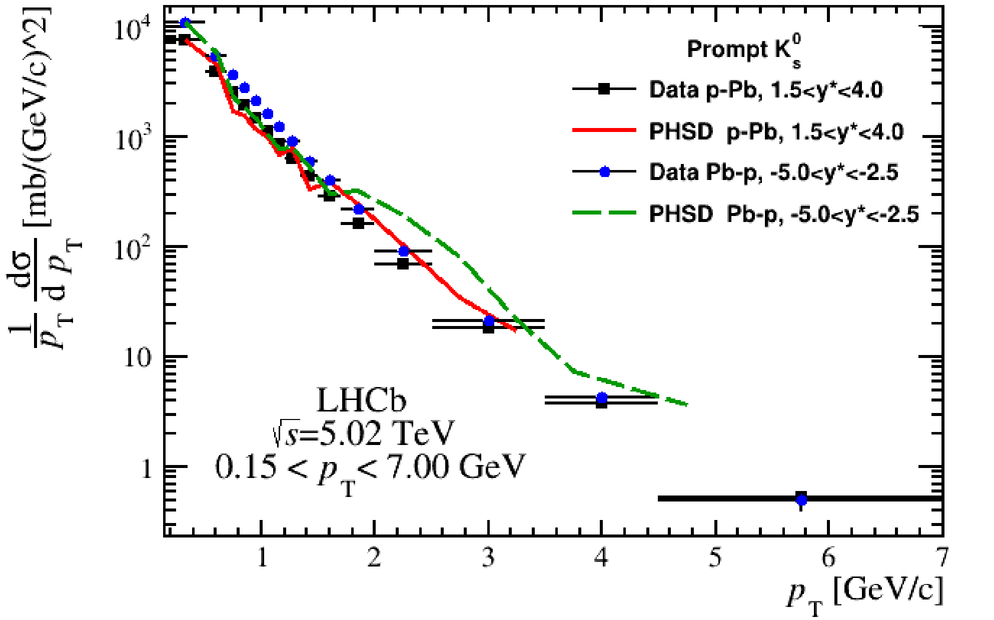
p_T and ***y**** specta shapes of ***K_S*** comparison.

Reasonable agreement with:

- **Hydrodynamics-Coalescence-Jet Fragmentation (Hybrid)** model [1]
- **Parton Hadron String Dynamic (PHSD)** model designed at GSI [2]







[1]. Phys. Rev. Lett. 125 (2020) 072301, arXiv:1911.00826.
[2]. Nucl. Phys. A831 (2009) 215, arXiv:0907.5331; Nucl. Phys. A856 (2011) 162, arXiv:1101.5793.

Results: Differential Production Cross-Sections

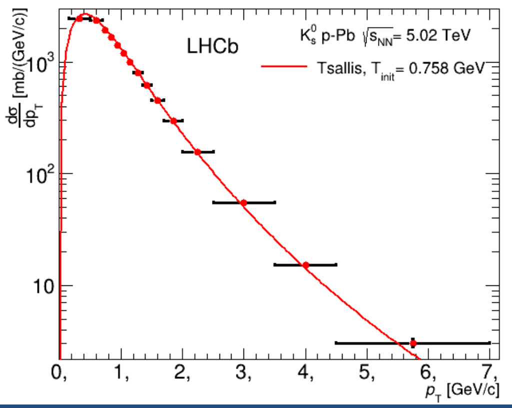
- To characterize those differences in cross-section slopes quantitatively we have approximated the measured p_T spectra with the Tsallis function [1] to extract initial temperature of the emission source (T_{init})

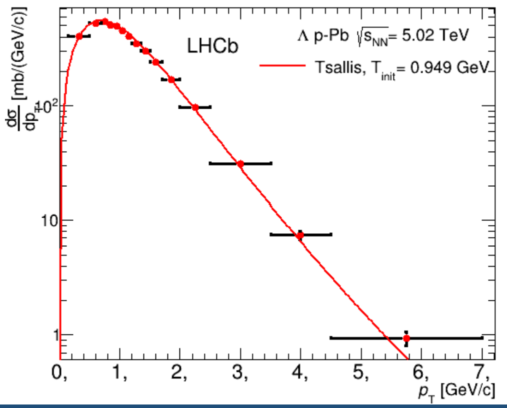
$$F_{Ts} = A \cdot p_{\mathrm{T}} \cdot \left(1 + (q-1)\frac{\sqrt{p_{\mathrm{T}}^2 + m_0^2} - m_0}{T}\right)^{-\frac{1}{q-1}} \qquad \langle p_{\mathrm{T}}^2 \rangle = \frac{\int_0^\infty p_{\mathrm{T}}^2 F_{Ts}(p_{\mathrm{T}}) \mathrm{d}p_{\mathrm{T}}}{\int_0^\infty F_{Ts}(p_{\mathrm{T}}) \mathrm{d}p_{\mathrm{T}}}$$

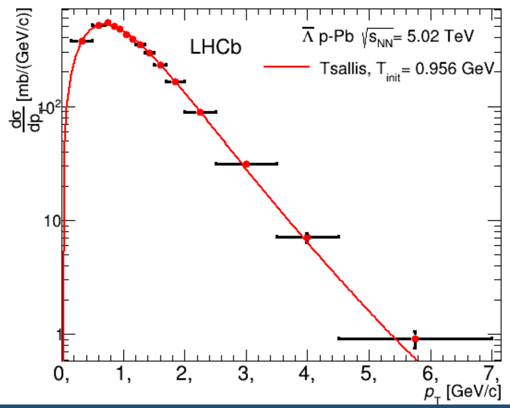
$$T_{init} = \sqrt{\frac{\langle p_{\mathrm{T}}^2 \rangle}{2}}$$

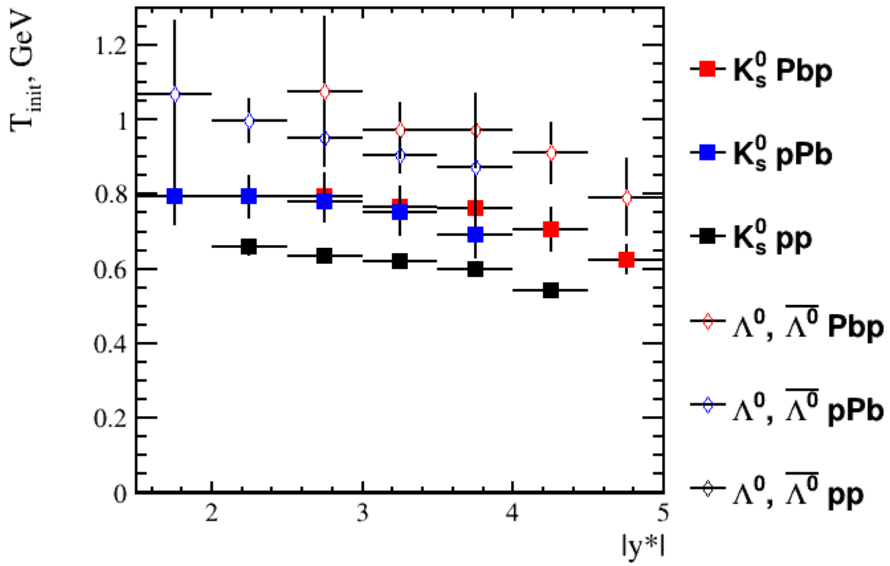
T_{init} increases:

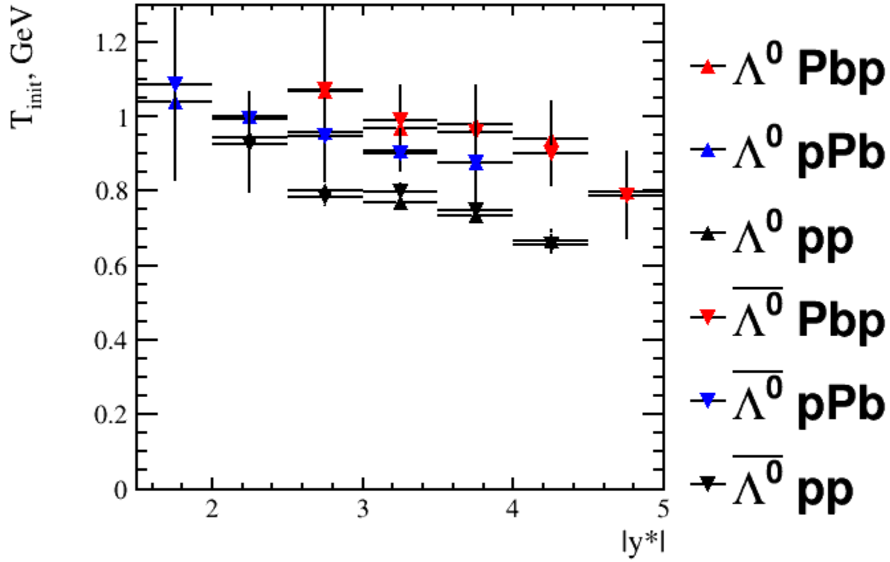
- with the mass of produced hadron
- in p-Pb/Pb-p configurations compared to p-p one, what is in agreement with other experimental observations.
- for bins that are closer to $y^*=0$









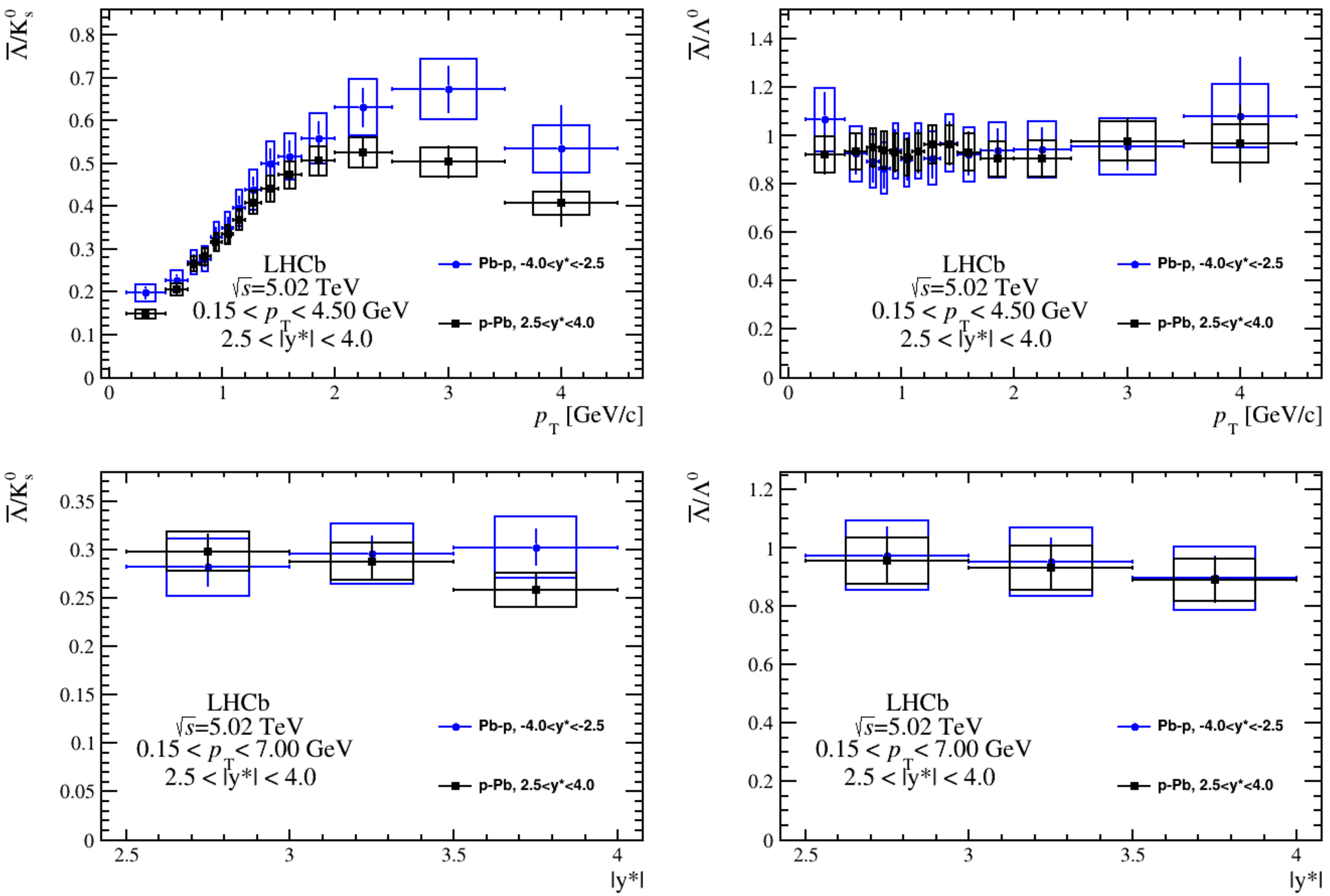


[1]. J. Stat. Phys. 52 (1988) 479.

Baryon/Meson ratio:

$$\bar{\Lambda}/\Lambda(K_S) = \frac{\frac{d^2\sigma_{\bar{\Lambda}}}{dp_T\, dy}}{\frac{d^2\sigma_{\Lambda(K_S)}}{dp_T\, dy}} \cong \frac{N_{\bar{\Lambda}}}{N_{\Lambda(K_S)}} \frac{\mathcal{B}_{\Lambda(K_S)}}{\mathcal{B}_{\bar{\Lambda}}} \frac{\epsilon_{\Lambda(K_S)}}{\epsilon_{\bar{\Lambda}}}.$$

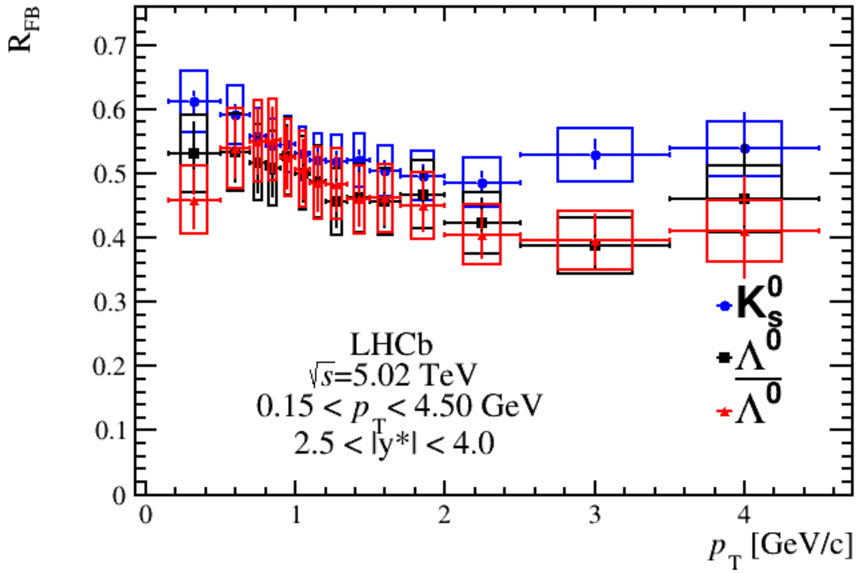
- Λ-bar/K ratio goes up with respect to p_T increases -> strange quarks are hadronized into baryons easier than into mesons with energy increase
- Λ-bar/Λ ratio does not demonstrate significant deviations from the unity

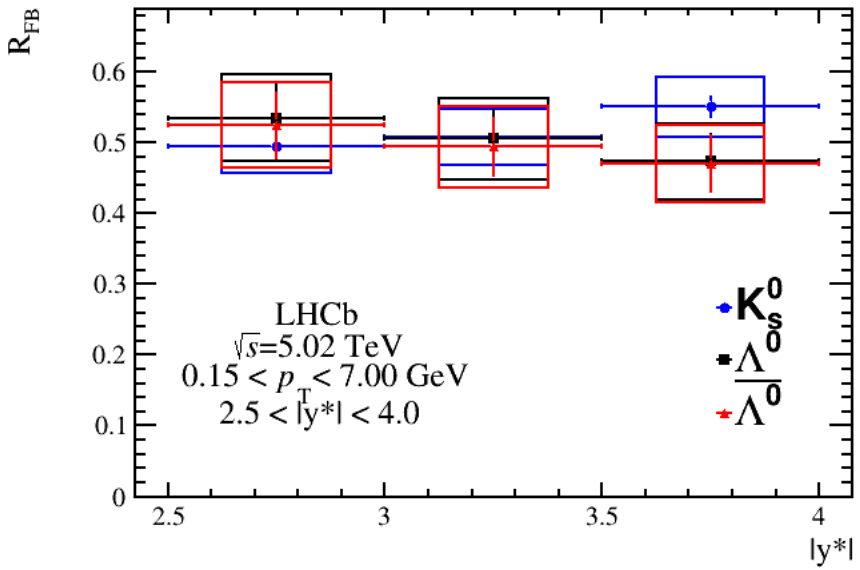


Results: Forward-Backward Asymmetry

$$R_{FB}(p_T,|y^*|) = \frac{\frac{d^2\sigma}{dp_T\,dy^*}(p_T,y^*)}{\frac{d^2\sigma}{dp_T\,dy^*}(p_T,-y^*)}$$

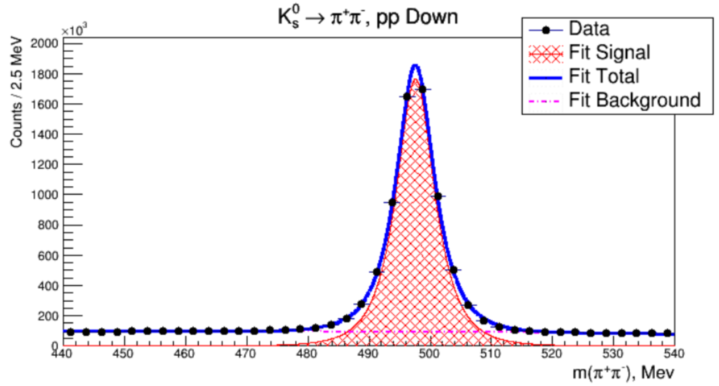
- Clear forward-backward asymmetry (suppression) for all prompt V^0 .
- Suppression in forward direction up to 60%
- Does not depend on p_T and y* within uncertainties.

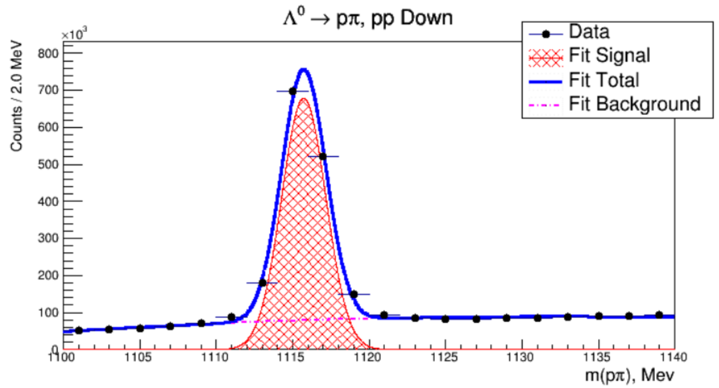


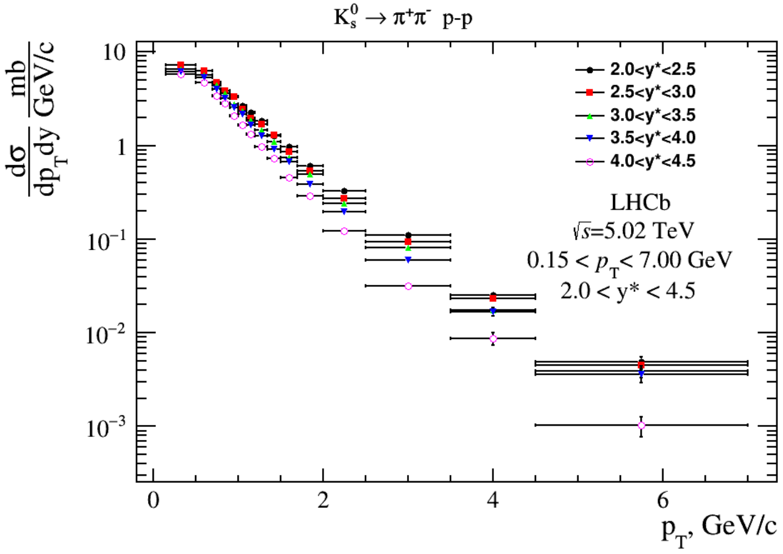


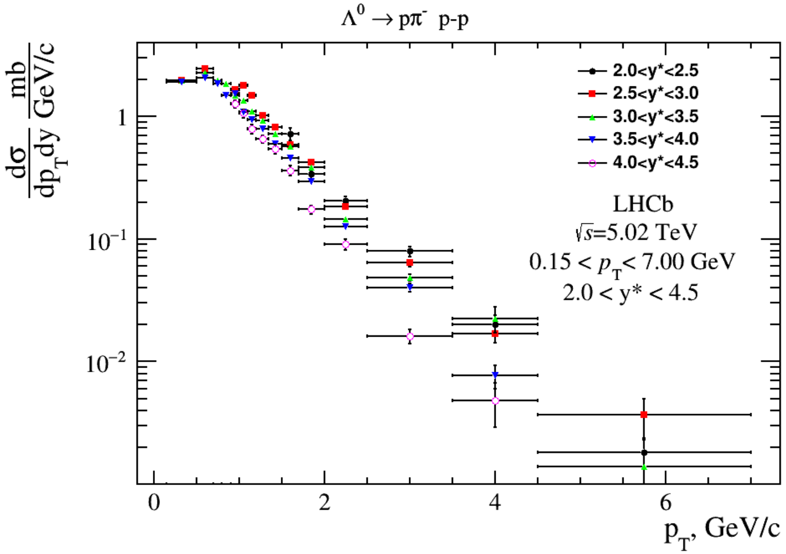
Results: pp@5.02 TeV reference

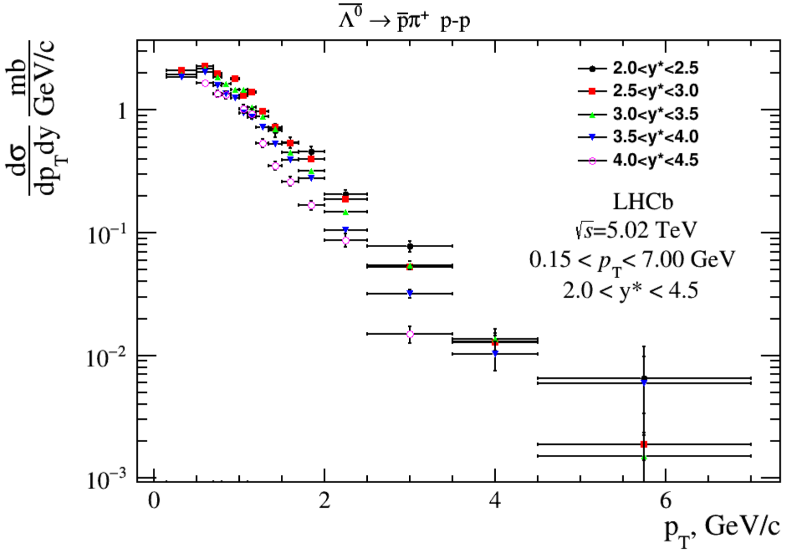
- NoBias sample collected in 2015 in p-p collisions at 5.02 TeV.
- Total luminosity of the sample is **3.8 ± 0.14/nb** **(K_S ~ 4.5·10^6; Λ ~ 0.9·10^6)**
- **10M MC** simulated events using Pythia 8.1 generator under the similar conditions.
- Same to p-Pb reconstruction and selection procedure.
- Rapidity ranges to calculate NMF:
  - 2.0 < y* < 4.0 (correspond to p-Pb) and
  - 2.5 < y* < 4.5 (correspond to Pb-p)







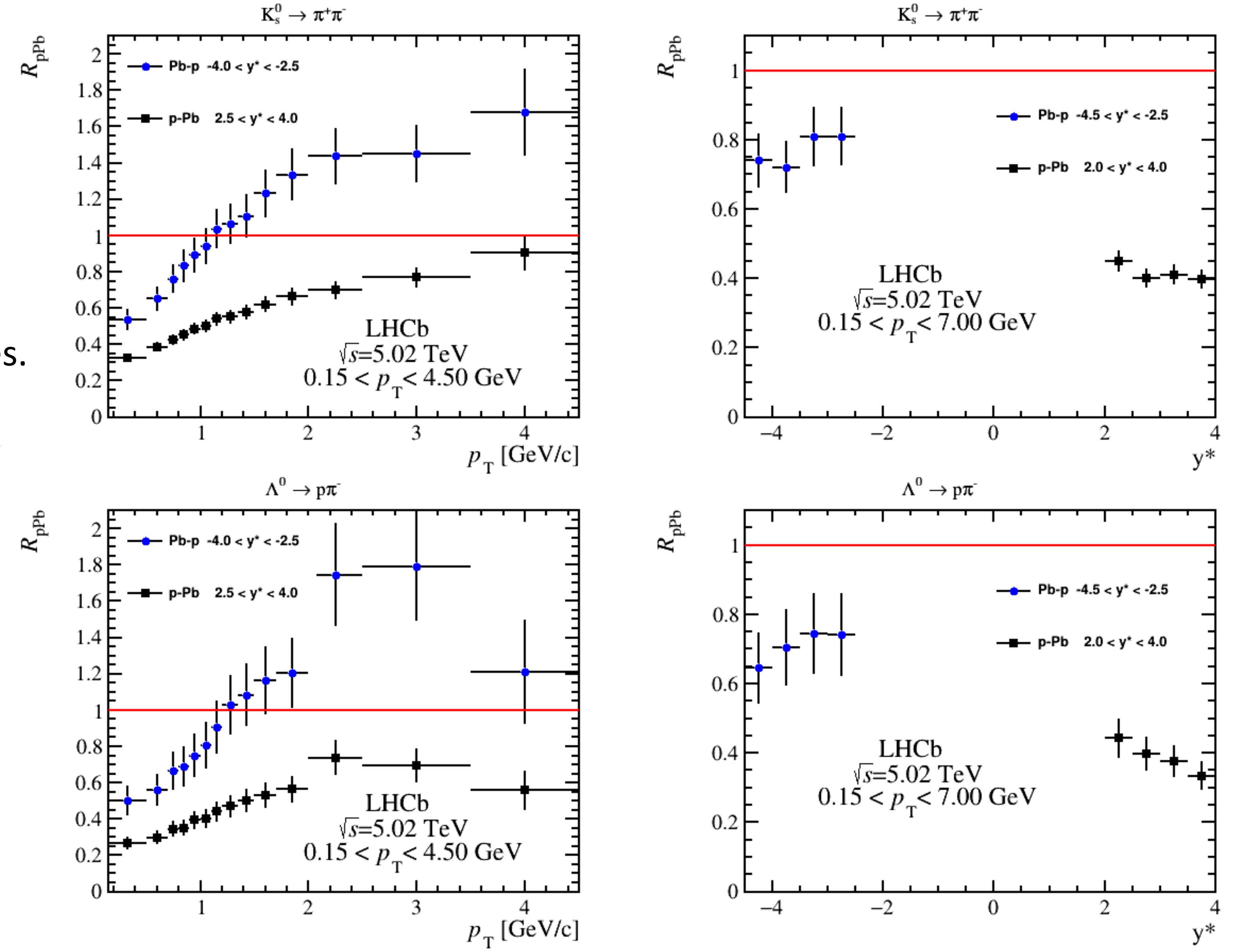




Results: Nuclear Modification Factors

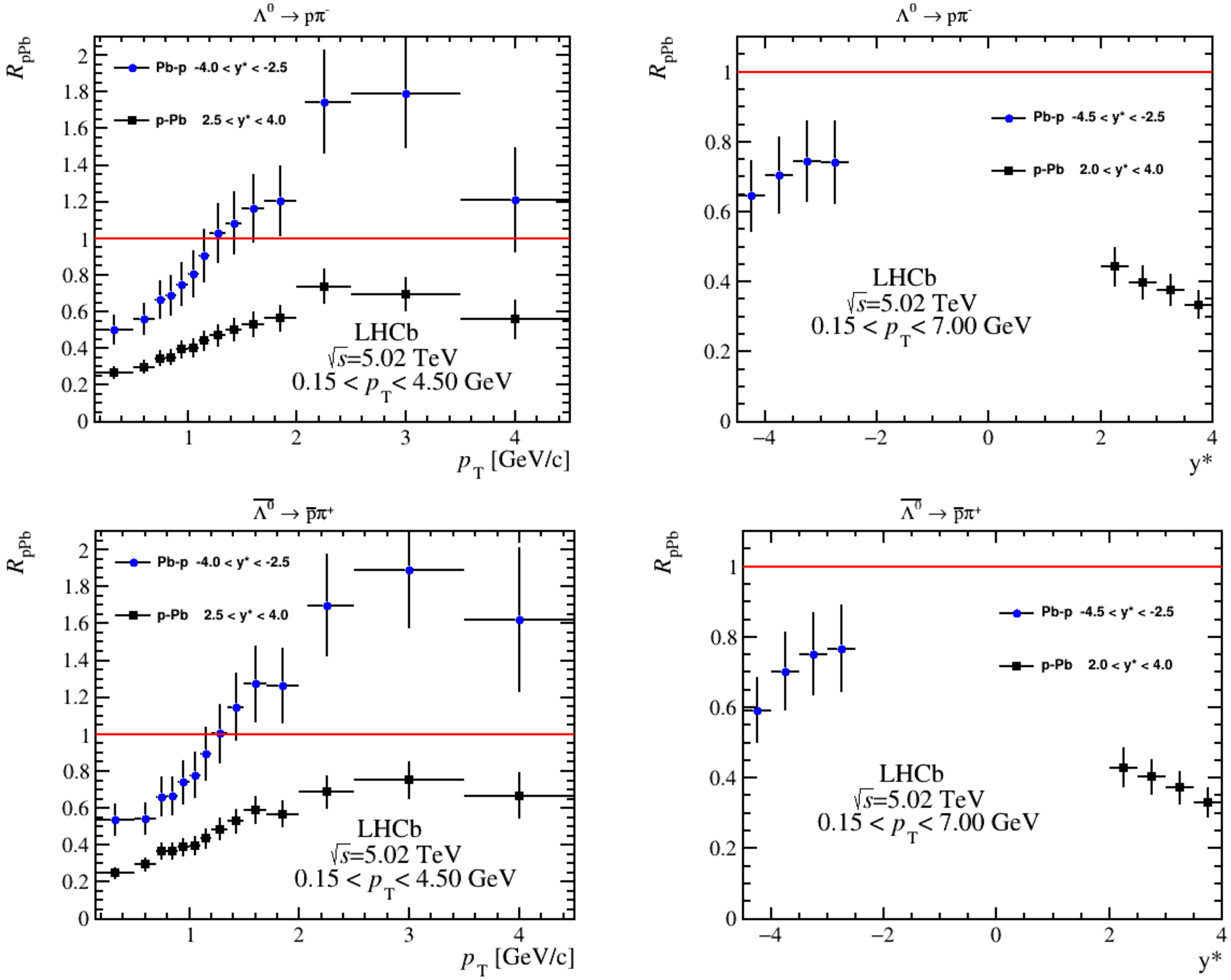
$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) = \frac{\left[\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y^*}\right]_{p\mathrm{Pb}}}{208\cdot\left[\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y^*}\right]_{pp}}$$

- Significant suppression at p_T < 2 GeV/c
- NMF Grows up from nearly 0.3 for p-Pb and 0.5 for Pb-p in the first p_T bin for all V^0 species.
- The maximum NMF values for Kaons is reached in the last bins of the measurement, so no peak structure observed.
- The peaks for both Lambdas are located between p_T > 2 and p_T < 3 GeV/c.
- The NMF values are below the unity for the whole p_T-range for p-Pb and exceeds unity near p_T =1 GeV/c for Pb-p.
- NMF as function of y^* decreases as rapidity moves away from 0
- NMF suppression is more pronounced in the forward region compared to the backward.
- Error bars represent sum of statistical and systematic component



Results: Nuclear Modification Factors

Just to show NMF for Λ-bar in comparison with Λ ones.



Conclusions

- **V^0** hadrons production was studied in LHCb experiment in proton-proton and proton-lead collisions at N-N cms energy of 5.02 TeV.
- Absolute values of Double and Single Differential cross-sections were measured for K_S mesons and Λ baryons distributed over transverse momentum of $0 < \boldsymbol{p_T} < 7$ GeV/c as well as over rapidity ranges of $-5.0 < \boldsymbol{y^*} < -2.5$ and $1.5 < \boldsymbol{y^*} < 4.0$.
- Shape of $\boldsymbol{p_T}$ distribution differs slightly between K_S mesons and Λ baryons.
- It does not depend strongly on rapidity, demonstrating unique production mechanism.
- Approximation of the data by Tsallis thermal model shows that $\boldsymbol{T_{init}}$ increases with the mass of produced hadron as well as in the backward beam configuration, in agreement with other experimental observations.
- ***Λ-bar/K_S*** goes up with respect to $\boldsymbol{p_T}$ increasing → strange quarks are hadronized easily into baryons than into mesons with energy increasing.
- ***Λ-bar/Λ*** is constant with respect to $\boldsymbol{p_T}$ increasing and ~ 1 .
- $\boldsymbol{R_{FB}}$: suppression in forward direction up to 60%. Does not depend on $\boldsymbol{p_T}$ within uncertainties.
- **Nuclear Modification factors** calculated as function of $\boldsymbol{p_T}$ and $\boldsymbol{y^*}$ demonstrate significant suppression for all three hadrons at $\boldsymbol{p_T} < 3$ GeV/c.
- **NMF** grows up (nearly linearly) from 0.4 for K_S and 0.2 for Λ at $\boldsymbol{p_T} = 0.3$ GeV/c to 1.0 and 1.2 (correspondingly) at $\boldsymbol{p_T} = 4.0$ GeV/c.
- Good agreement with PHDS and Hydro-Coal-Frag hybrid model

Acknowledgments

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Thank You for Your Attention!