Multiplicity-dependent resonances production in pp collisions in the EPOS4

Hyunji Lim*, Sanghoon Lim
Nuclear Physics Lab, Pusan National University
HIM 2024-3, 9th March 2024

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Outline

- Motivation
  - Probing the properties of hadronic phase
  - Rescattering in the small collision systems
- Analysis Method
  - Event and track selection
- Analysis Results
- Summary & Plan
  - EPOS4 study
  - $\rho(770)^0$ in pp 13 TeV with ALICE

Motivation

Probing the properties of hadronic phase:

Resonances are particles that are in unstable states and decay into stable particles with different short lifetimes **around hadronic phase lifetime**

Resonance	ρ^0	$K^{*\pm}$	K^{*0}	$\Sigma^{*\pm}$	Λ^*	Ξ^*	ϕ
Quark contents	$(u\bar{u} + d\bar{d})/\sqrt{2}$	$u\bar{s}$	$d\bar{s}$	uus, dds	uds	uss	$s\bar{s}$
Lifetime (fm/*c*)	1.3	3.6	**4.2**	5.0-5.5	12.6	21.7	**46.3**

Motivation

Probing the properties of hadronic phase:

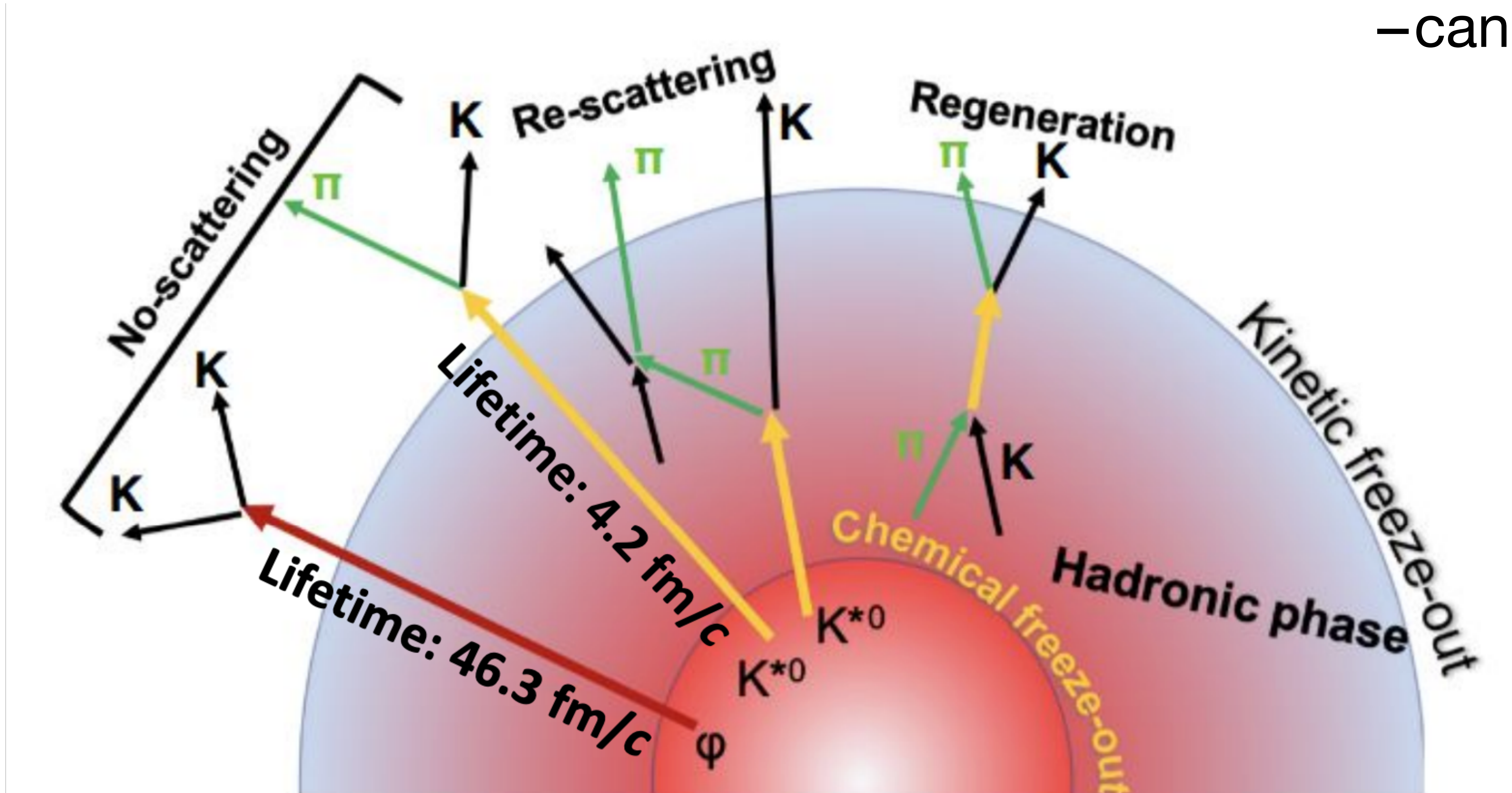
Long-lived resonances:

- mostly decay after the kinetic freeze-out
- less rescattering effect
- can have regeneration effect

Short-lived resonances:

- mostly decay before the kinetic freeze-out
- more rescattering effect

  (especially at low momentum particles, large system!)
- can have regeneration effect



Motivation

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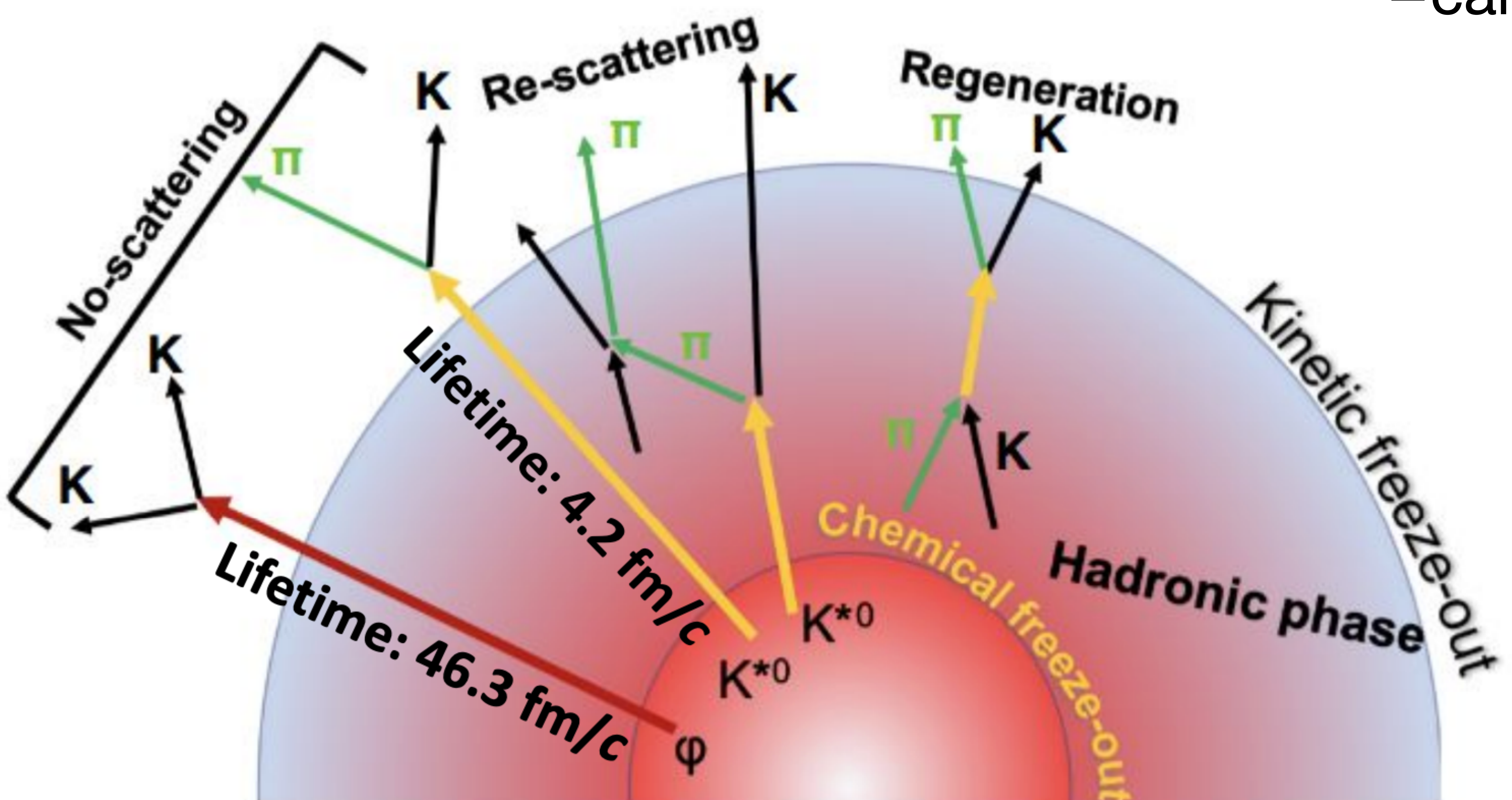
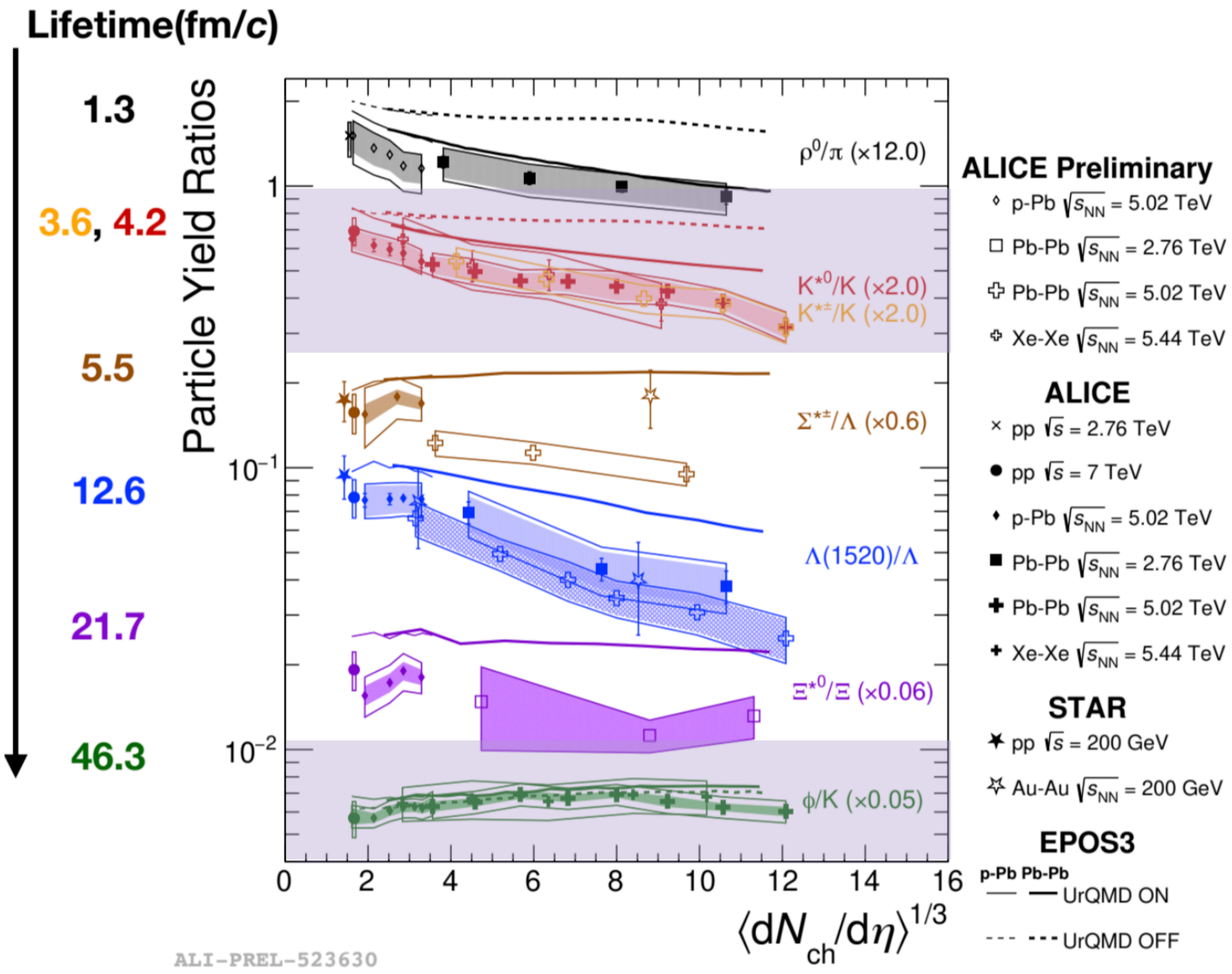


Momenta and Yields are modified!

Motivation

Probing the properties of hadronic phase:

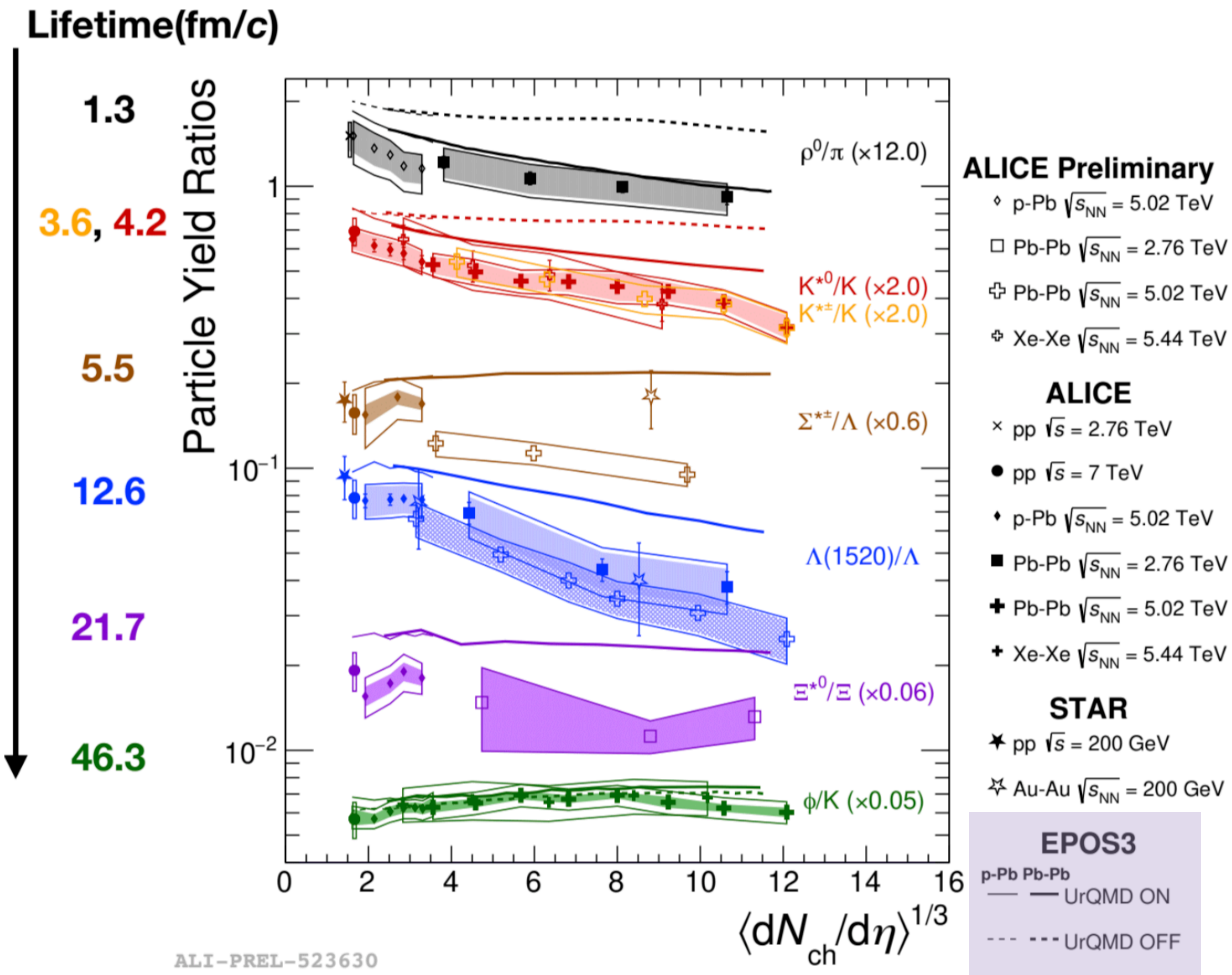


- The decreasing trend of the ratios of short-lived resonances indicates the **dominance of rescattering** over regeneration

- No significant multiplicity dependence for long-lived resonances

Motivation

Probing the properties of hadronic phase:



EPOS:

- Event generator based on 3+1D viscous hydrodynamical evolution
- Core and corona have different hadronization mechanism

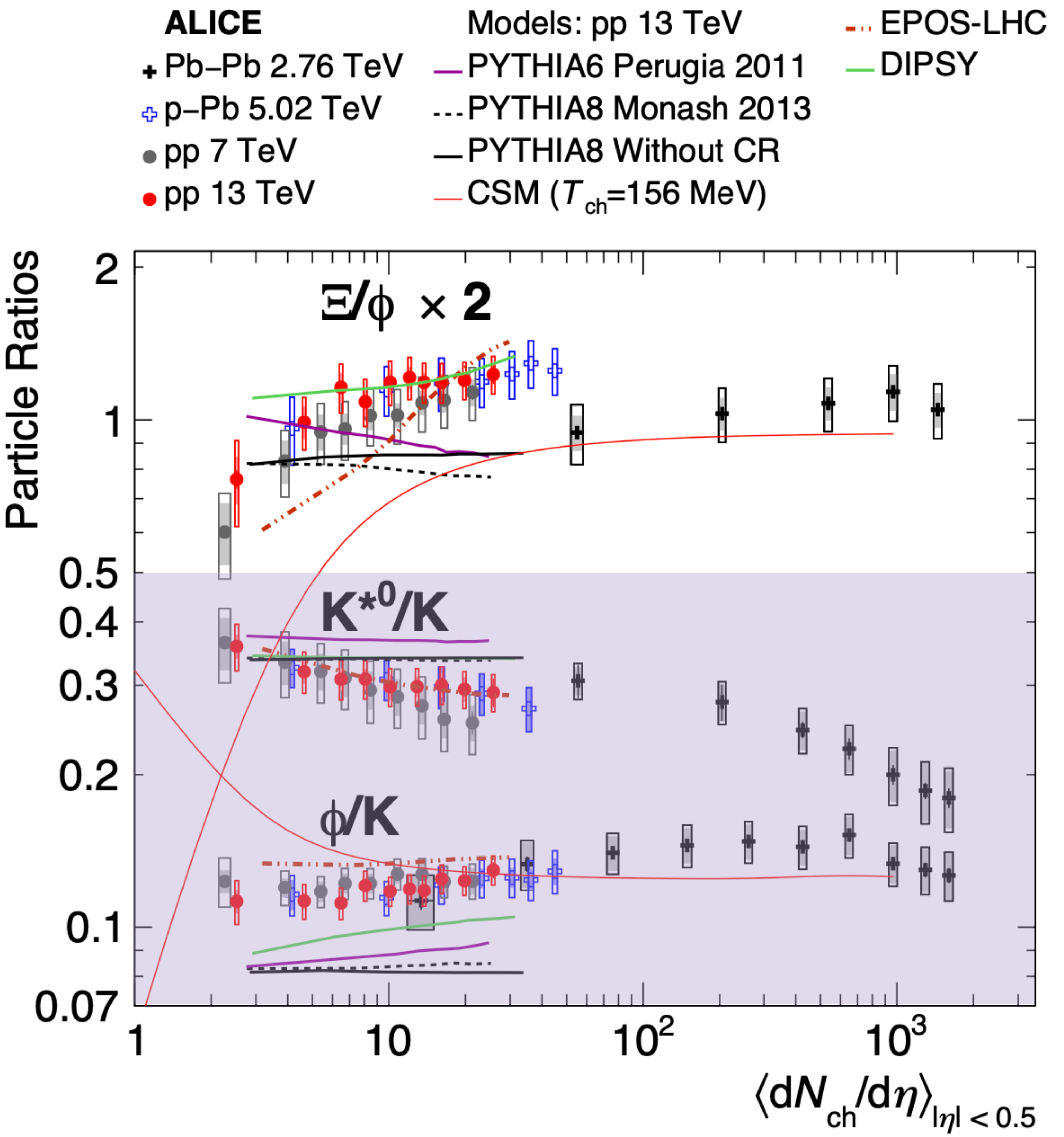
UrQMD:

- UrQMD describes the full phase-space evolution based on their hadronic interactions

Motivation

Rescattering in the small collision systems:

ALICE Collaboration. Physics Letters B Volume **807**, 135501 (2020)

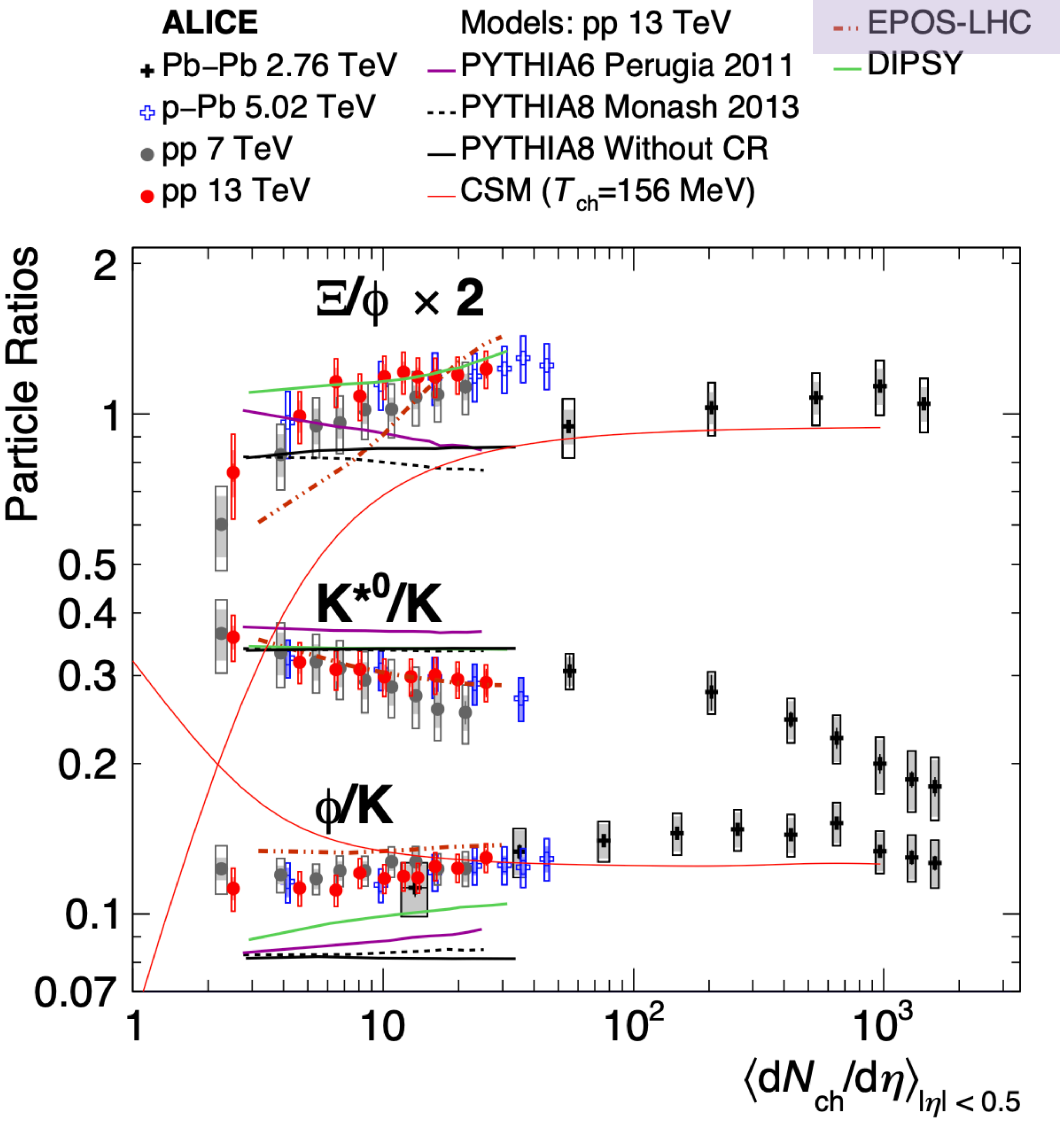


- Small systems show similar decrease or stable trend in small system such as pp and p-Pb
- Information about a possible **short-lived hadron gas phase**

Motivation

Rescattering in the small collision systems:

ALICE Collaboration. Physics Letters B Volume **807**, 135501 (2020)



EPOS - LHC:

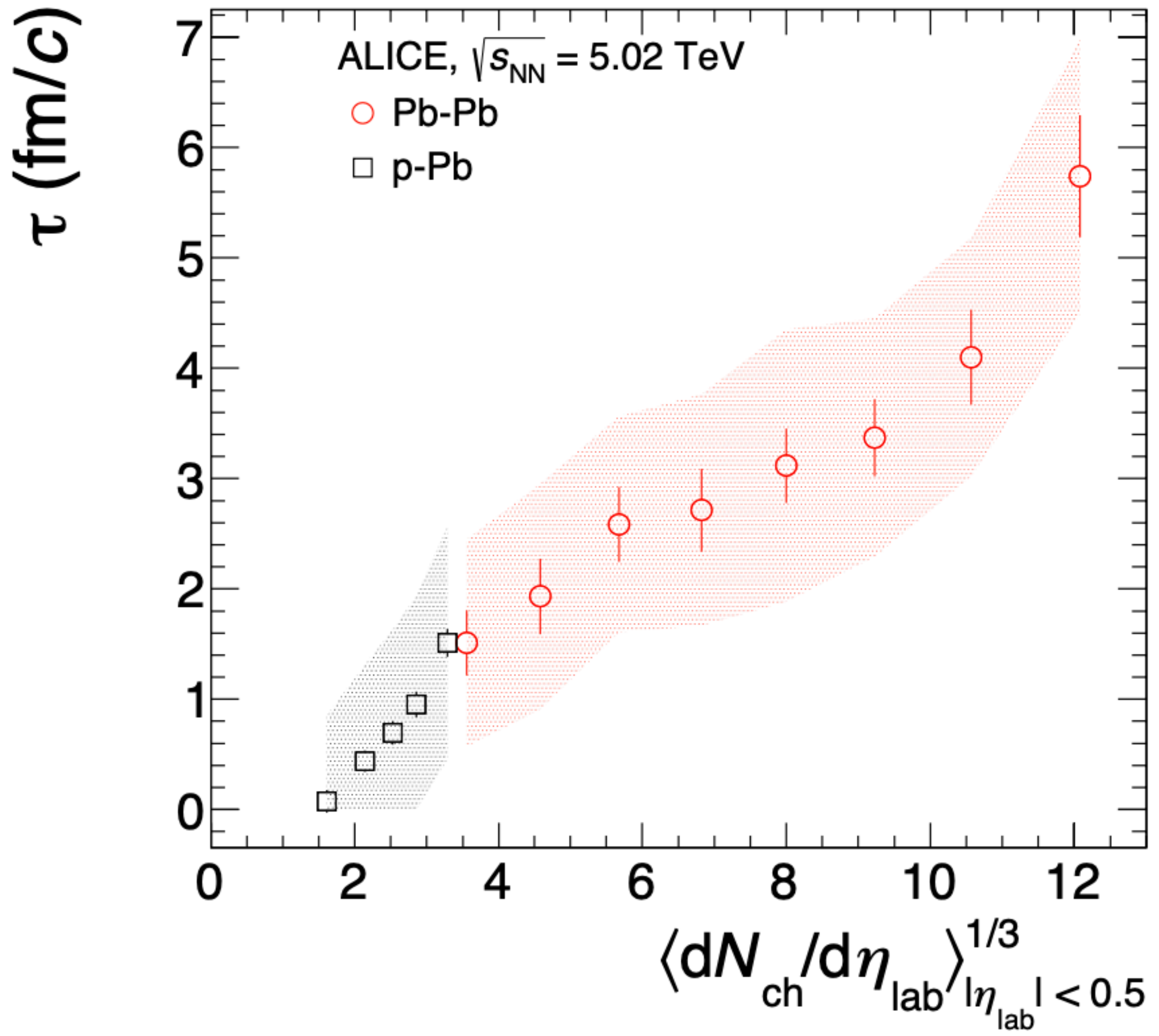
- The EPOS-LHC model describes the multiplicity dependence of the yields well for pp collisions
- No hadronization afterbuner
- **Cannot provide same physics with AA collisions**

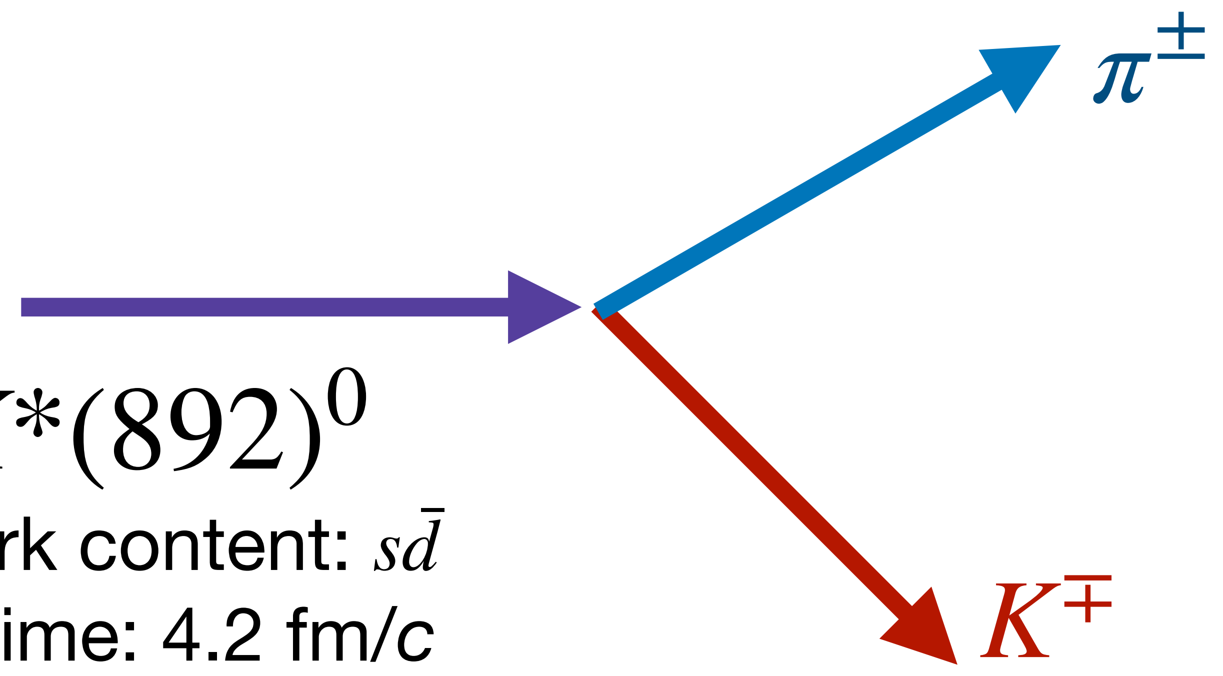
EPOS4+UrQMD model study in pp collisions

Motivation

Rescattering in the small collision systems:

ALICE Collaboration. Physics Letters B Volume 802, 135225 (2020)



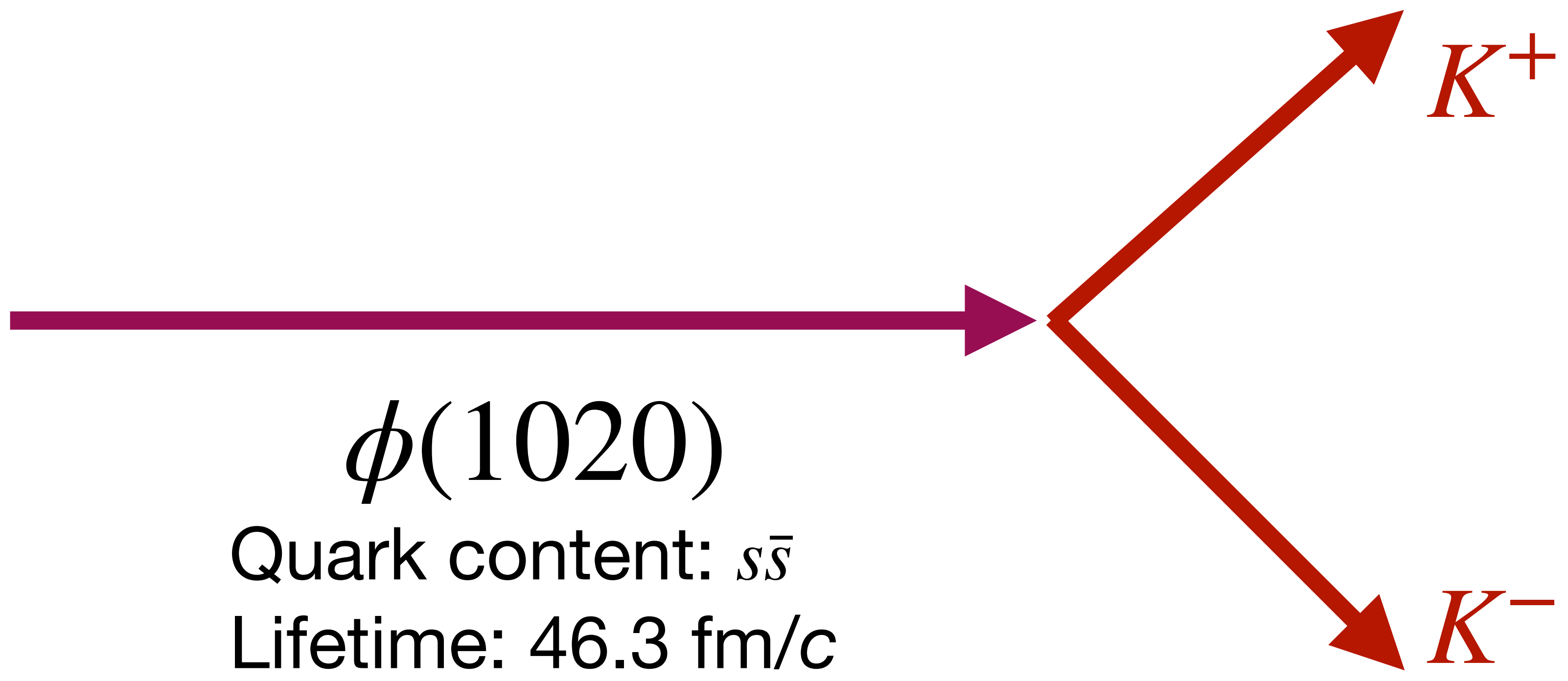


$K^*(892)^0$

Quark content: $s\bar{d}$

Lifetime: 4.2 fm/c

B.R: 66.6%



$\phi(1020)$

Quark content: $s\bar{s}$

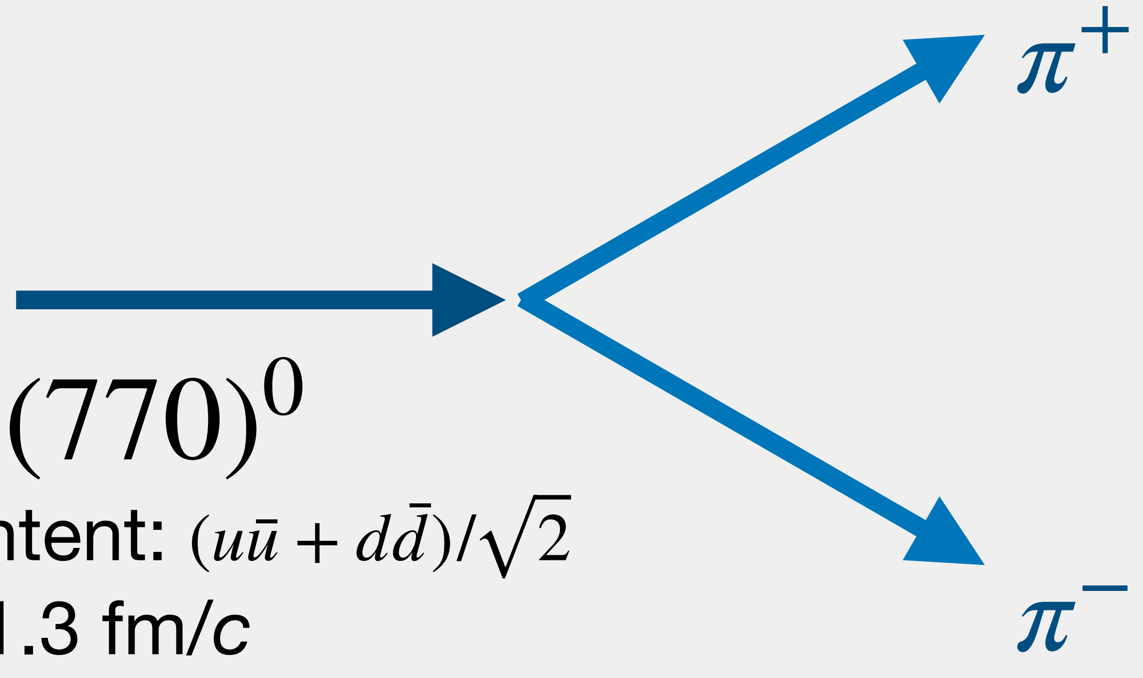
Lifetime: 46.3 fm/c

B.R: 49.1%

Different lifetime → **Rescattering effect**

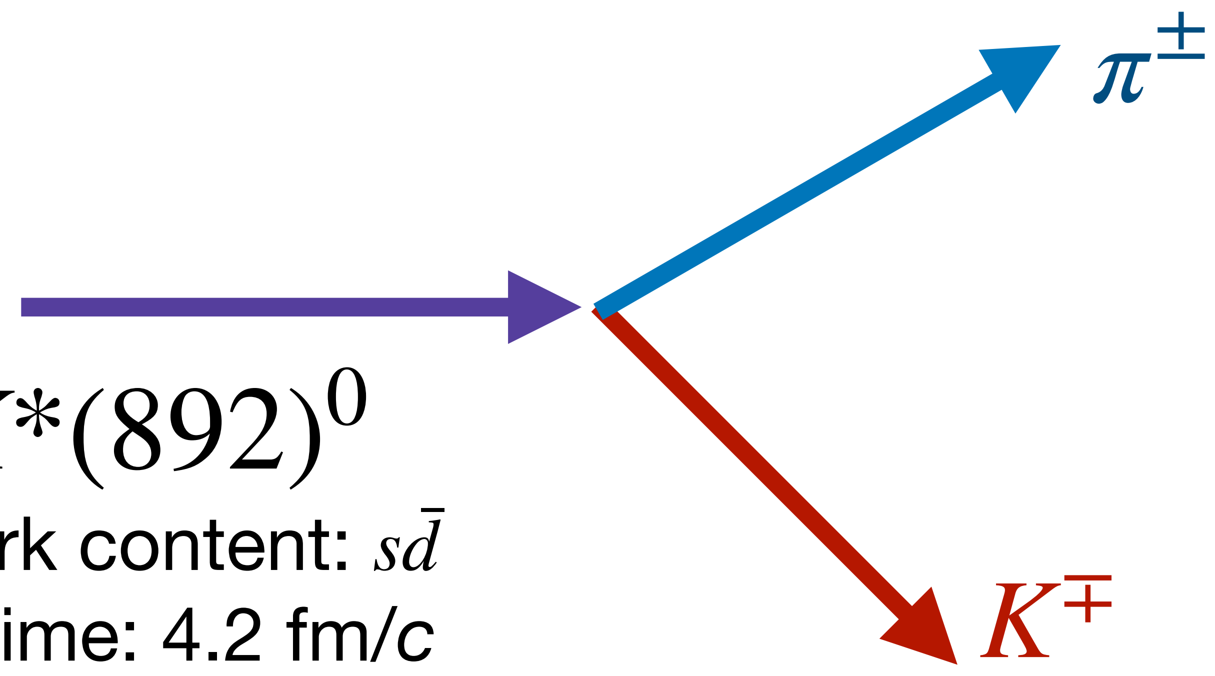
Motivation

Rescattering in the small collision systems:



$\rho(770)^0$

Quark content: $(u\bar{u} + d\bar{d})/\sqrt{2}$
Lifetime: 1.3 fm/c
B.R: 100%



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Quark content: $s\bar{d}$
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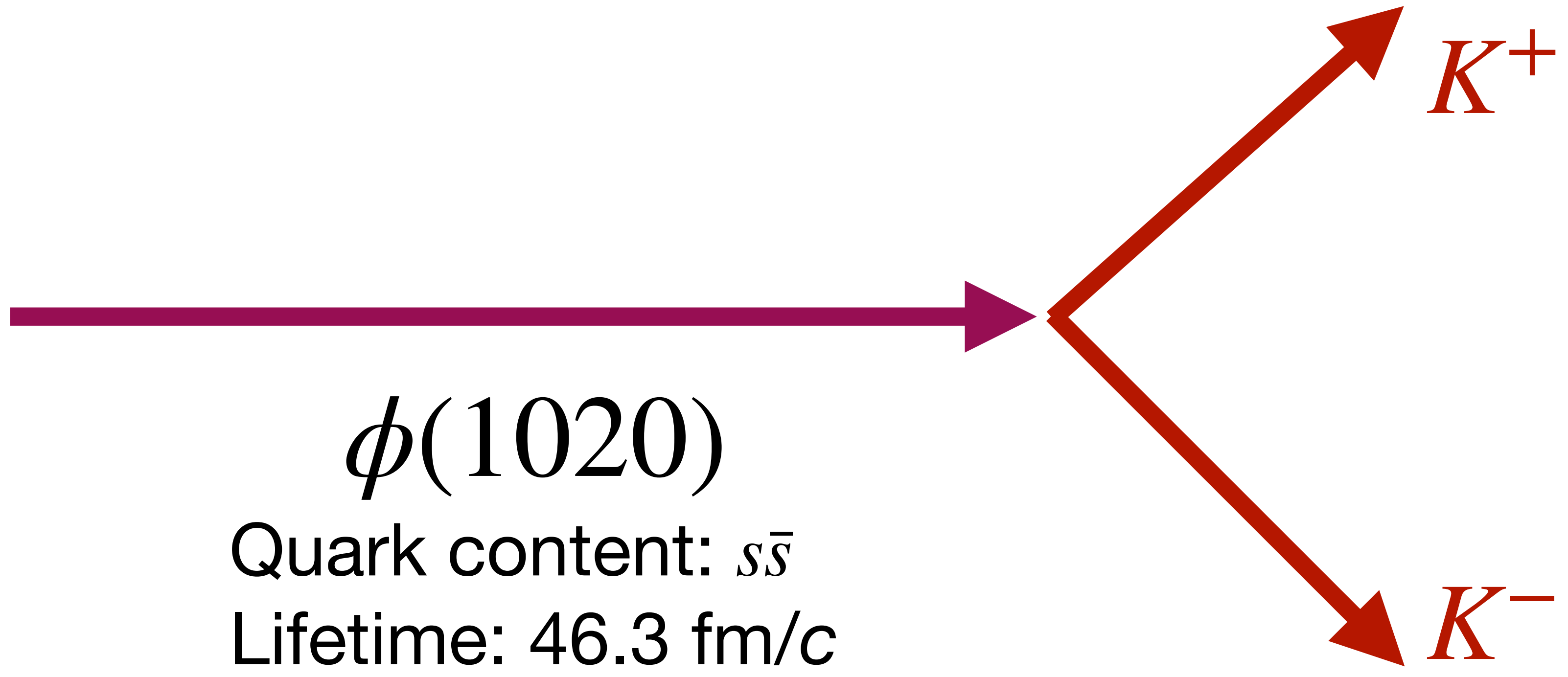


$\phi(1020)$

Quark content: $s\bar{s}$
Lifetime: 46.3 fm/c
B.R: 49.1%

Shorter lifetime: Good probe to study short-lived hadronic phase

Analysis Method

Event and Track Selection:

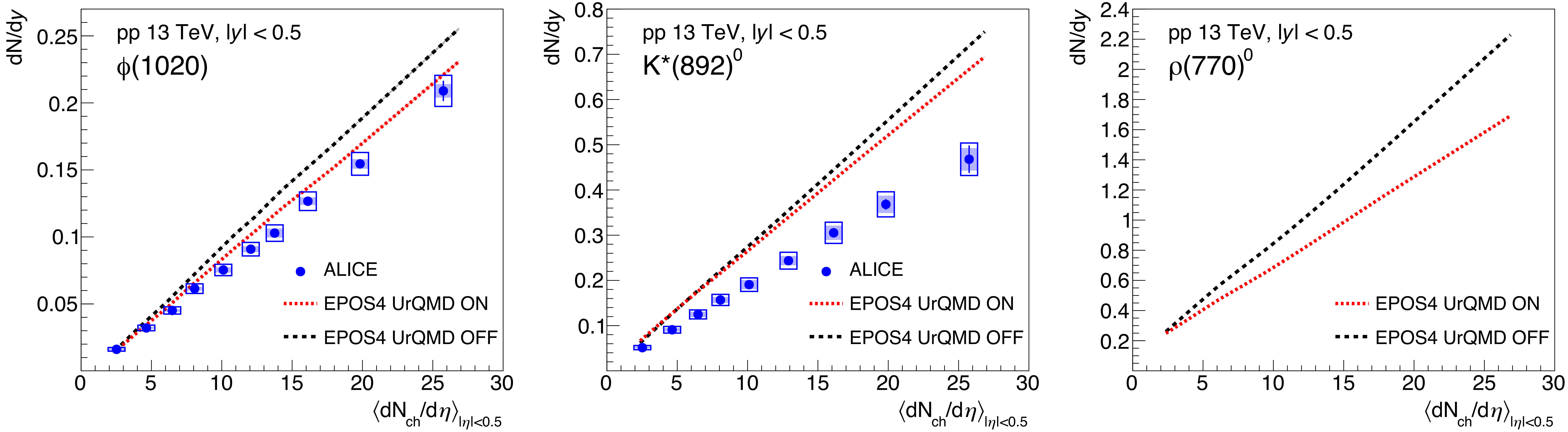
- **Target:** Multiplicity-dependent ϕ, K^{*0}, ρ^0 production in EPOS4+UrQMD
- **Collision system & Data:** pp at $\sqrt{s}$ = 13 TeV & Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
- **Event selection:** INEL > 0 events (least charged π, K, p in the $|\eta| < 1.0$)
- **Multiplicity:** # of charged π, K, p in the V0M range ($-3.7 < \eta < -1.7$ & $2.8 < \eta < 5.1$)
- **Track selection:** ϕ, K^{*0}, ρ^0, K^{+-}, π^{+-} in the $|y| < 0.5$

UrQMD OFF: Tagging from daughter particles

UrQMD ON: Tagging from daughter particles are not scattered

Analysis Results

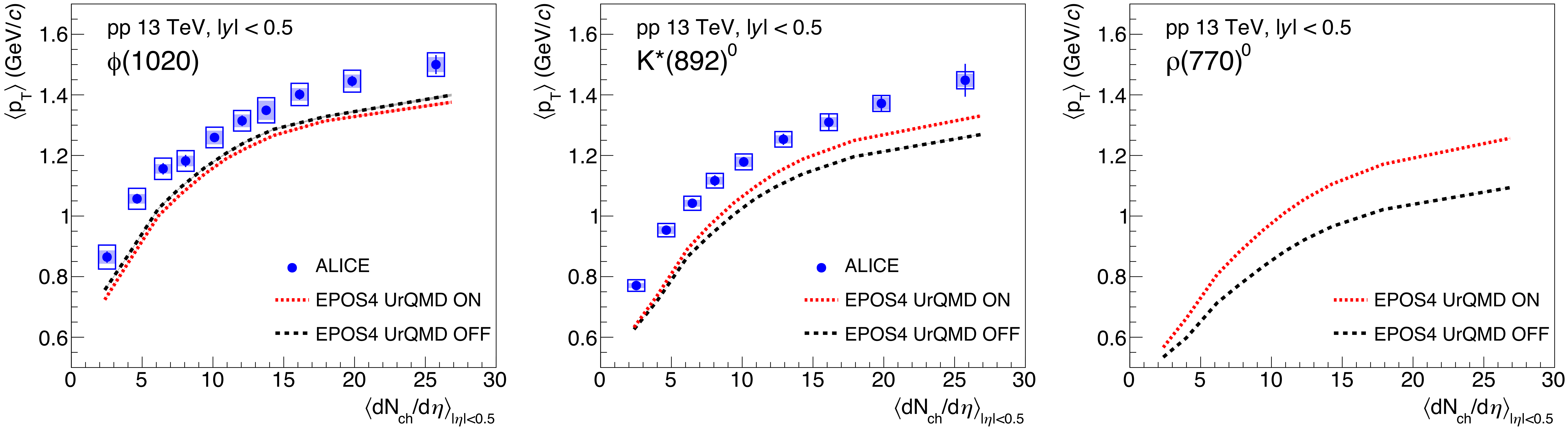
dN/dy vs <dN/dη>:



- EPOS4 UrQMD ON measured less on all particles than UrQMD OFF
- EPOS4 results of K*(892)⁰ overestimates ALICE Data

Analysis Results

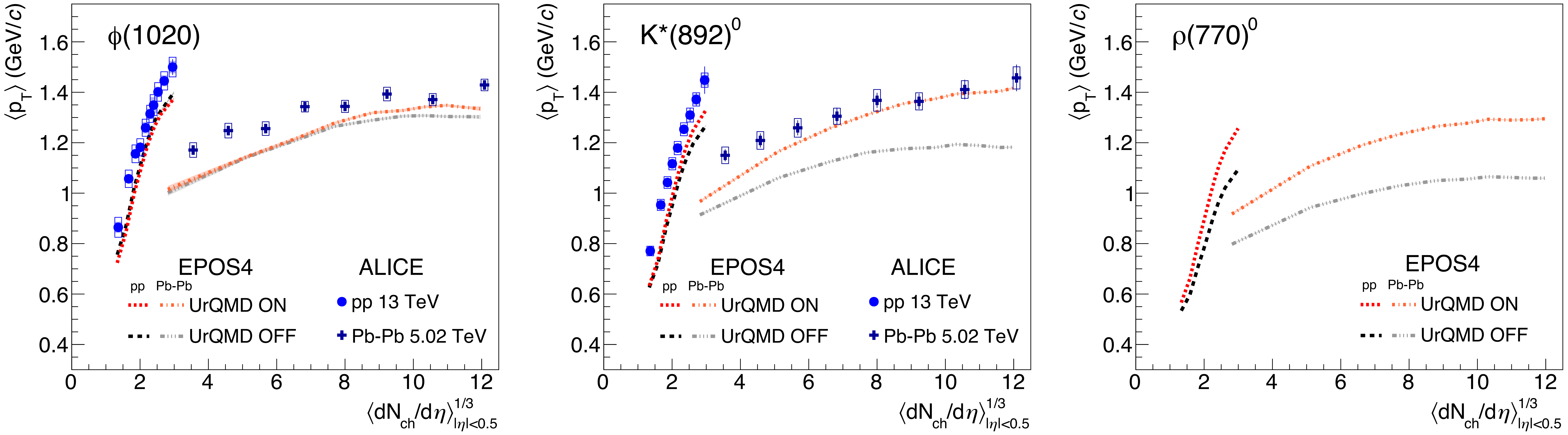
$\langle p_T \rangle$ vs $\langle dN/d\eta \rangle$:



- EPOS4 reproduces the trends seen in the ALICE data
- The gaps between UrQMD ON and OFF for the short-lived resonances show rescattering

Analysis Results

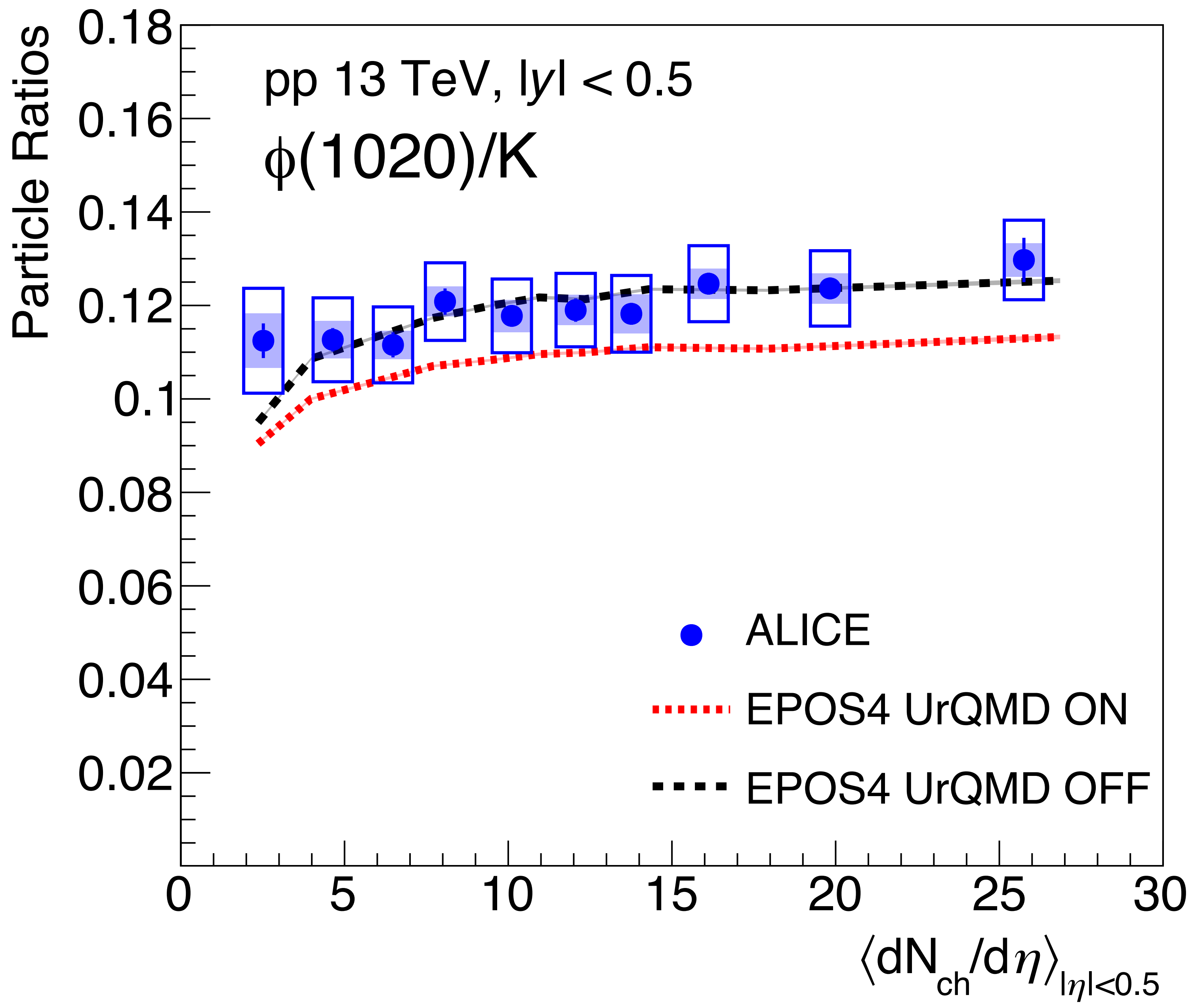
$<p_T>$ vs $<dN/d\eta>$:

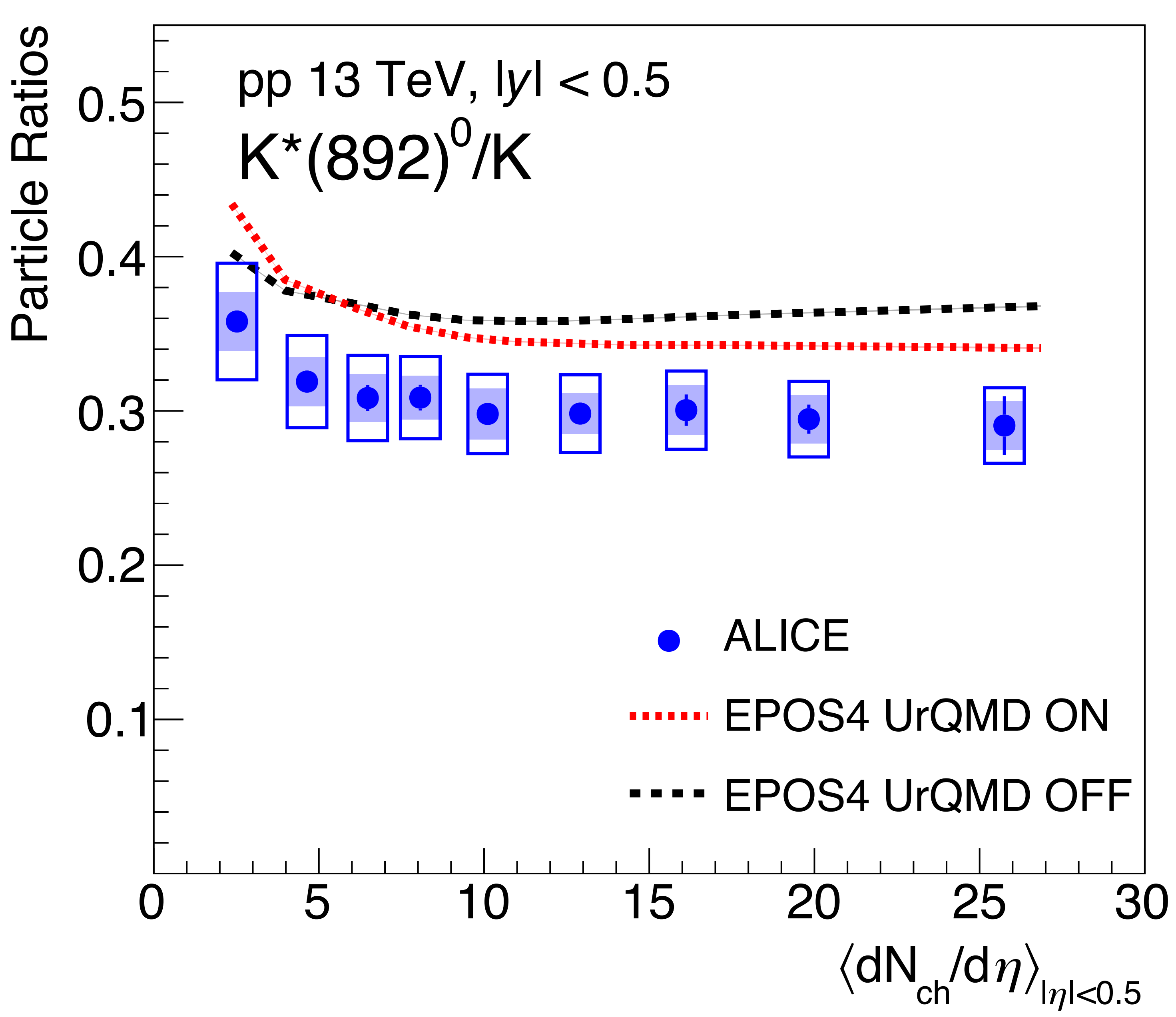


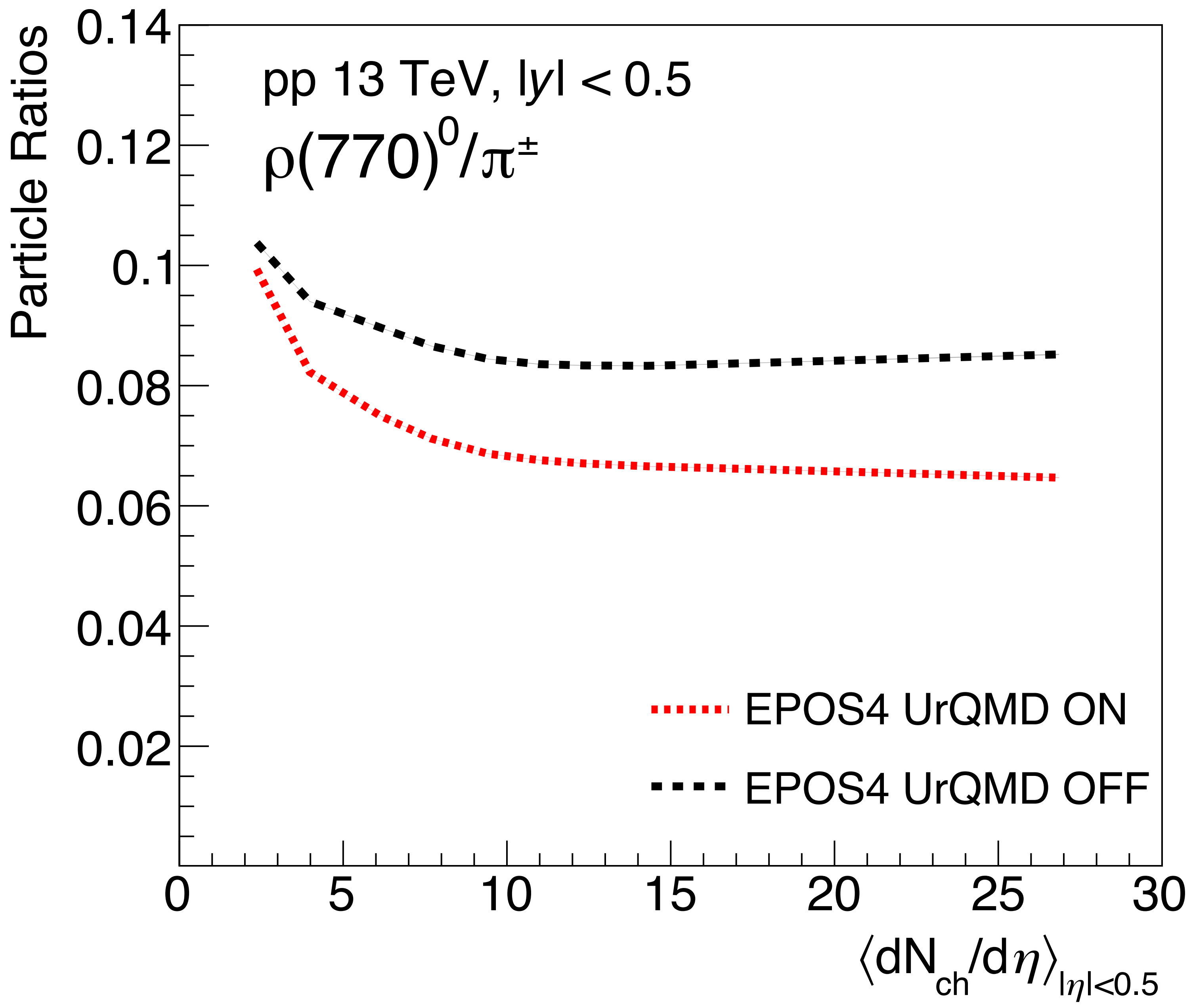
- EPOS4 reproduces the trends seen in the ALICE data
- The gaps between UrQMD ON and OFF for the short-lived resonances show rescattering
- The discontinuous part between the two systems shows system effects

Analysis Results

Ratios vs <dN/dη>:



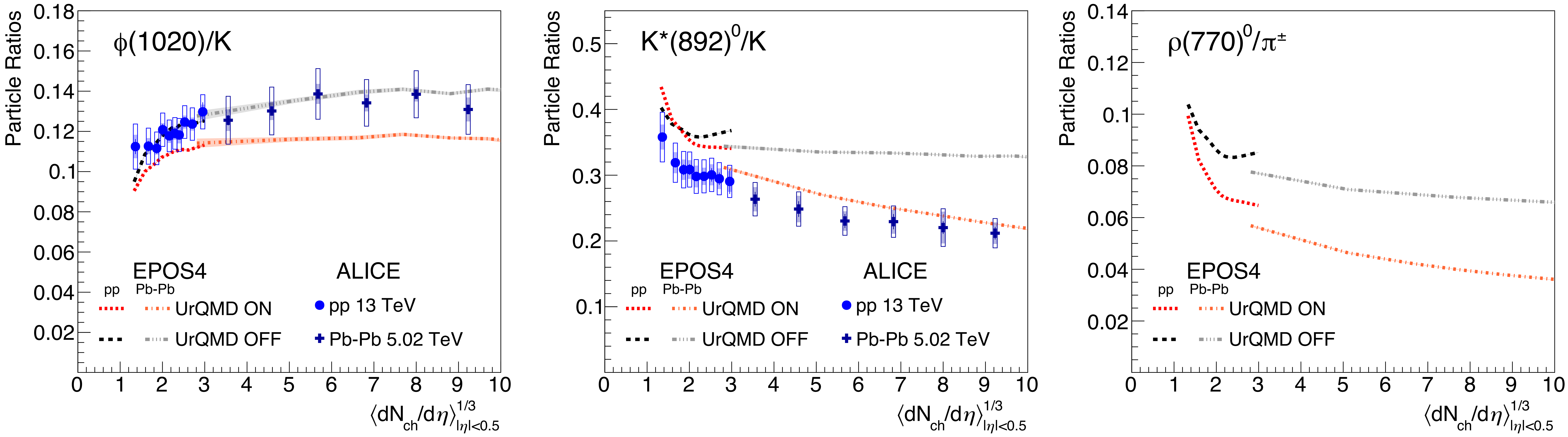




- The difference between UrQMD ON and OFF is multiplicity-dependent in the short-lived resonances
- Larger ON/OFF difference and a decreasing trend in $\rho(770)^0$, which may be due to the short lifetime of the hadron gas phase of pp system

Analysis Results

Ratios vs <dN/dη>:

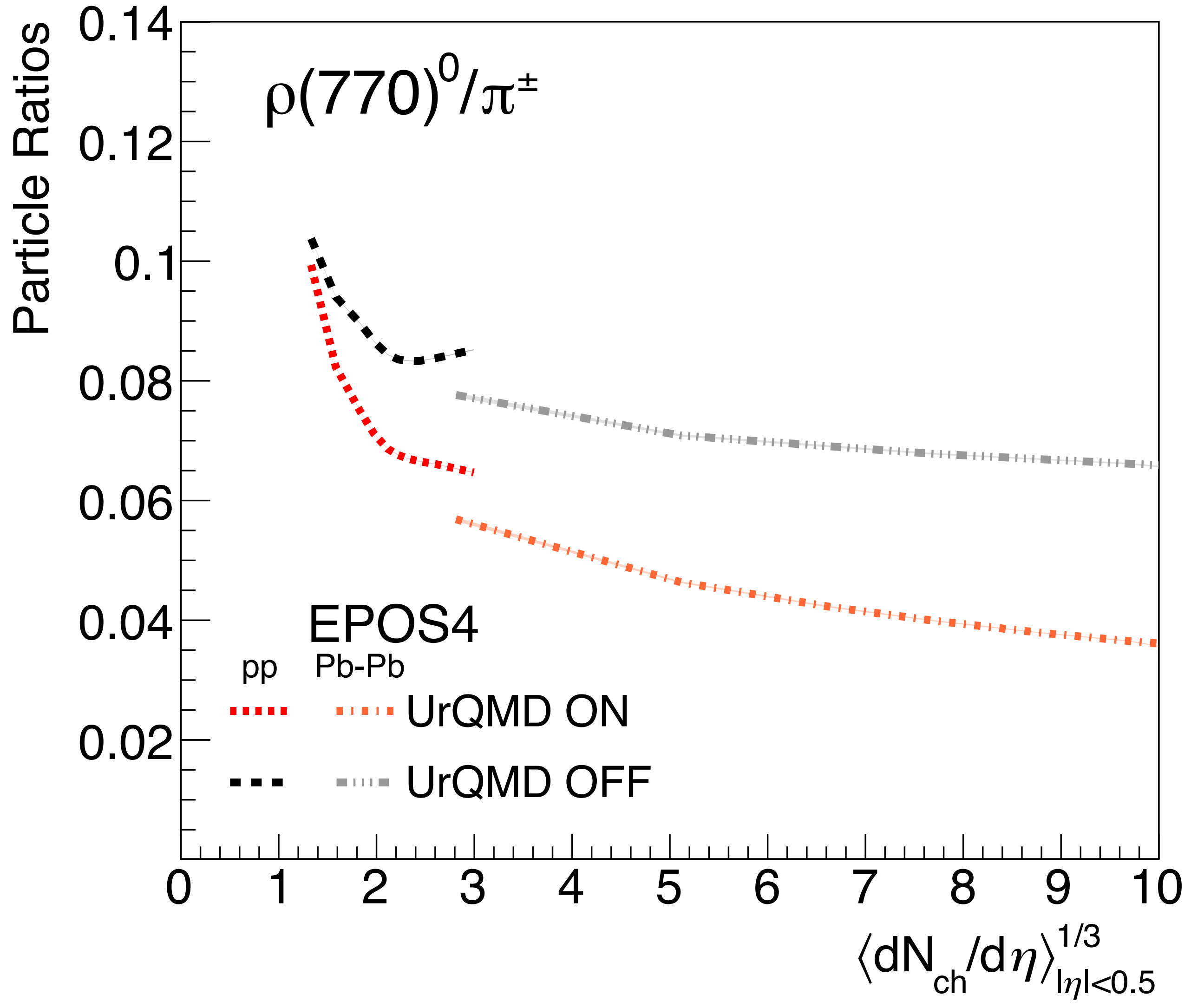


- EPOS4 UrQMD ON can reproduce the trend of resonance productions in small systems with the same physics in AA
- In the EPOS4 UrQMD ON/OFF, $\rho(770)^0$ shows largest effect of hadronic interaction

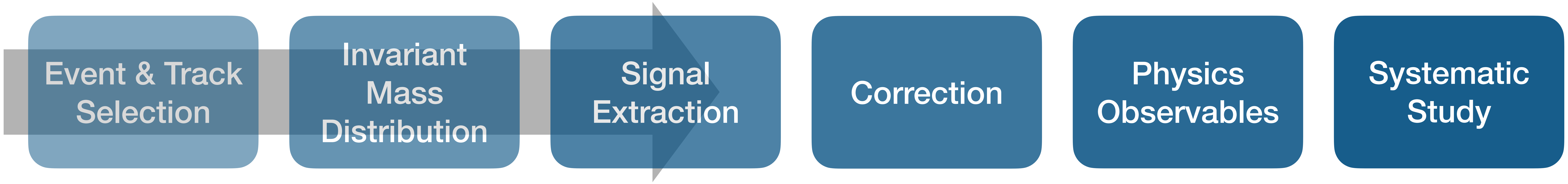
Summary & Plan

EPOS4 study:

- EPOS4 and UrQMD described the trend of resonance productions well in pp and Pb-Pb using the same physics
- Suggested that shorter-lived $\rho(770)^0$ will undergo greater change due to hadronic interaction

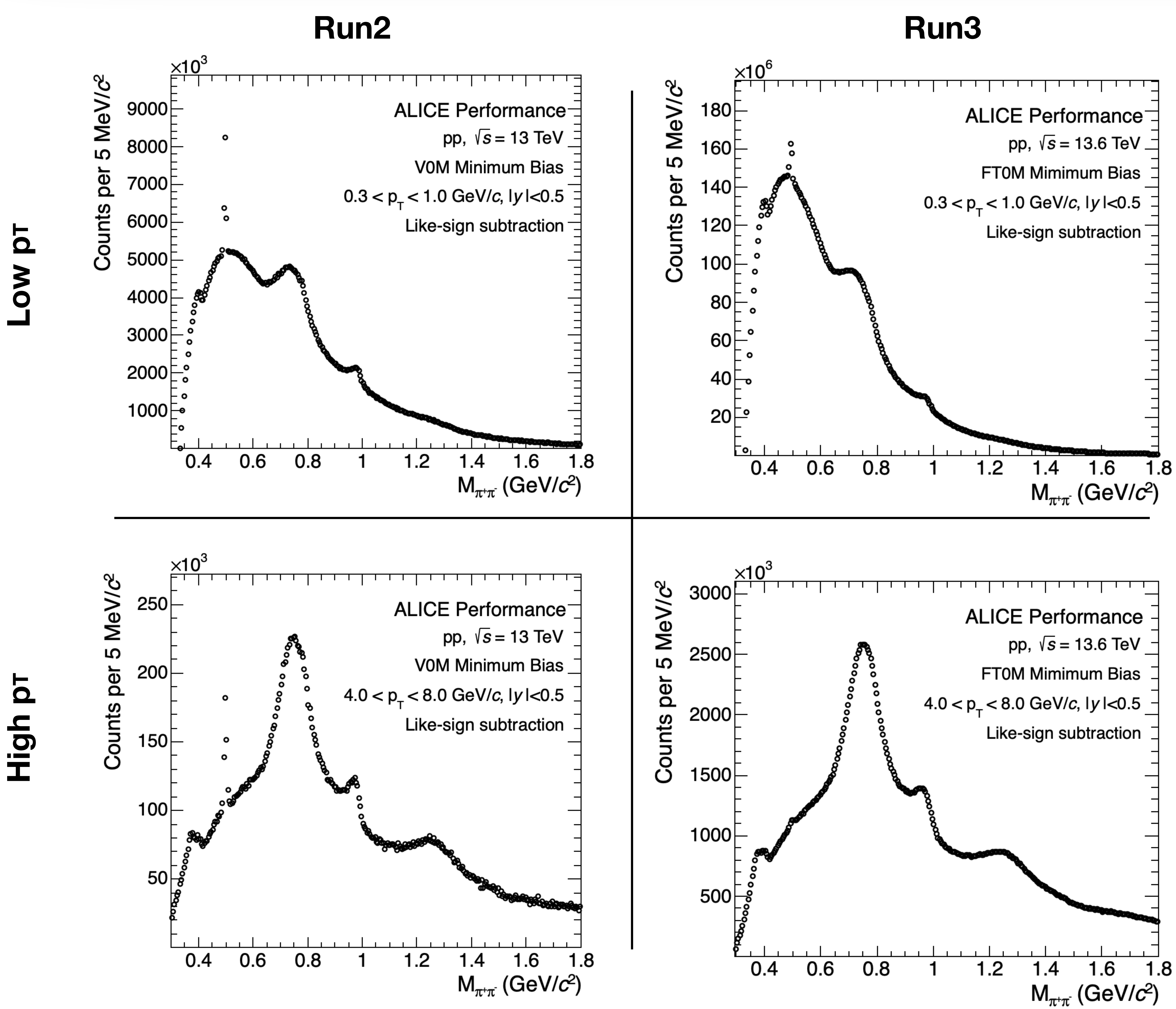


$\rho(770)^0$ in pp 13 TeV with ALICE:



- Analyze Multiplicity-dependent $\rho^0(770)$ production in pp at $\sqrt{s}$ = 13 TeV & $\sqrt{s}$ = 13.6 TeV

Summary & Plan



- In invariant mass distributions with like-sign subtraction, peaks from various hadronic decays are recognized
- Similar performance between Run 2 and Run 3
- Currently, about x10 more statistics of data from Run 3 are available

Analysis in progress!

Back-up

Mutiplicity & Event

Class	$\langle dN/d\eta \rangle_{\|\eta\|<0.5}$	
	EPOS4	ALICE
INEL > 0	6.292	6.89
0~1%	26.858	25.75
1~5%	17.897	19.83
5~10%	14.285	16.12
10~15%	12.334	13.76
15~20%	10.950	12.06
20~30%	9.417	10.11
30~40%	7.694	8.07
40~50%	6.153	6.48
50~70%	3.979	4.64
70~100%	2.360	2.52

```
root [0]
Processing Draw_Yield.C...
Number of pp INEL>0 event: 44226486
mult: 100~70%    Nch: 0~15     <dN/deta>: 2.360     <dN/deta>1/3: 1.331     event #: 12224412
mult: 70~50%     Nch: 16~25    <dN/deta>: 3.979     <dN/deta>1/3: 1.585     event #: 9672101
mult: 50~40%     Nch: 26~31    <dN/deta>: 6.153     <dN/deta>1/3: 1.832     event #: 4025861
mult: 40~30%     Nch: 32~39    <dN/deta>: 7.694     <dN/deta>1/3: 1.974     event #: 5005819
mult: 30~20%     Nch: 40~47    <dN/deta>: 9.417     <dN/deta>1/3: 2.112     event #: 4257675
mult: 20~15%     Nch: 48~52    <dN/deta>: 10.950     <dN/deta>1/3: 2.221     event #: 2160748
mult: 15~10%     Nch: 53~59    <dN/deta>: 12.334     <dN/deta>1/3: 2.311     event #: 2376855
mult: 10~5%     Nch: 60~69    <dN/deta>: 14.285     <dN/deta>1/3: 2.426     event #: 2212032
mult: 5~1%     Nch: 70~91    <dN/deta>: 17.897     <dN/deta>1/3: 2.616     event #: 1831281
mult: 1~0%     Nch: 92~219    <dN/deta>: 26.858     <dN/deta>1/3: 2.995     event #: 459702
```

```
mult: 100~90%    Nch: 0~40     <dN/deta>: 4.899     <dN/deta>1/3: 1.698     event #: 8486
mult: 90~80%     Nch: 41~106     <dN/deta>: 17.711     <dN/deta>1/3: 2.607     event #: 8596
mult: 80~70%     Nch: 107~235     <dN/deta>: 43.853     <dN/deta>1/3: 3.526     event #: 8620
mult: 70~60%     Nch: 236~449     <dN/deta>: 93.399     <dN/deta>1/3: 4.537     event #: 8548
mult: 60~50%     Nch: 450~770     <dN/deta>: 173.971     <dN/deta>1/3: 5.582     event #: 8577
mult: 50~40%     Nch: 771~1237     <dN/deta>: 291.866     <dN/deta>1/3: 6.633     event #: 8573
mult: 40~30%     Nch: 1238~1853     <dN/deta>: 454.342     <dN/deta>1/3: 7.688     event #: 8558
mult: 30~20%     Nch: 1854~2763     <dN/deta>: 683.667     <dN/deta>1/3: 8.809     event #: 8573
mult: 20~10%     Nch: 2764~3979     <dN/deta>: 1004.949     <dN/deta>1/3: 10.016     event #: 8575
mult: 10~0%     Nch: 3980~5936     <dN/deta>: 1458.492     <dN/deta>1/3: 11.341     event #: 8569
```

Motivation

Rescattering in the small collision systems:

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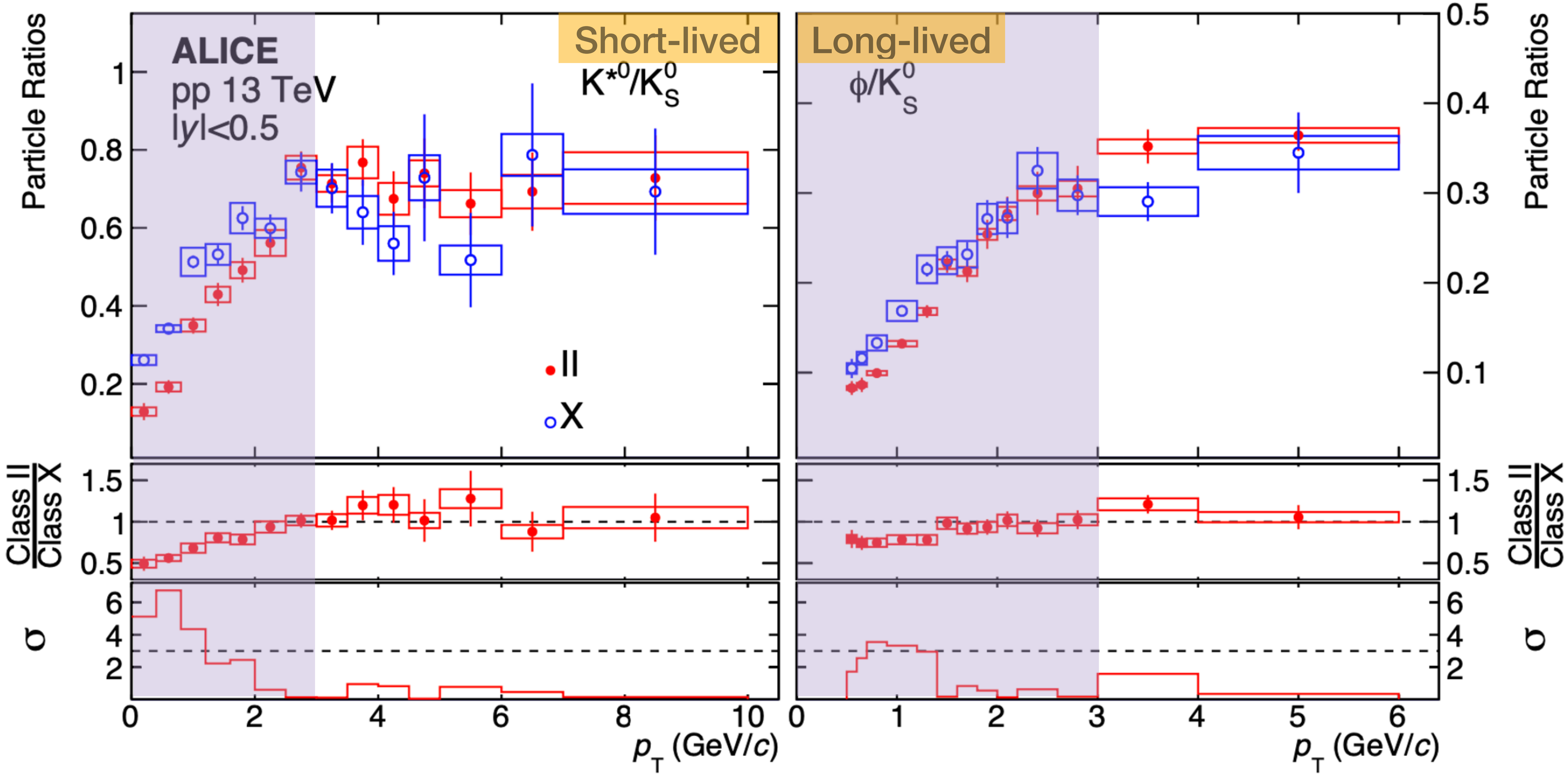
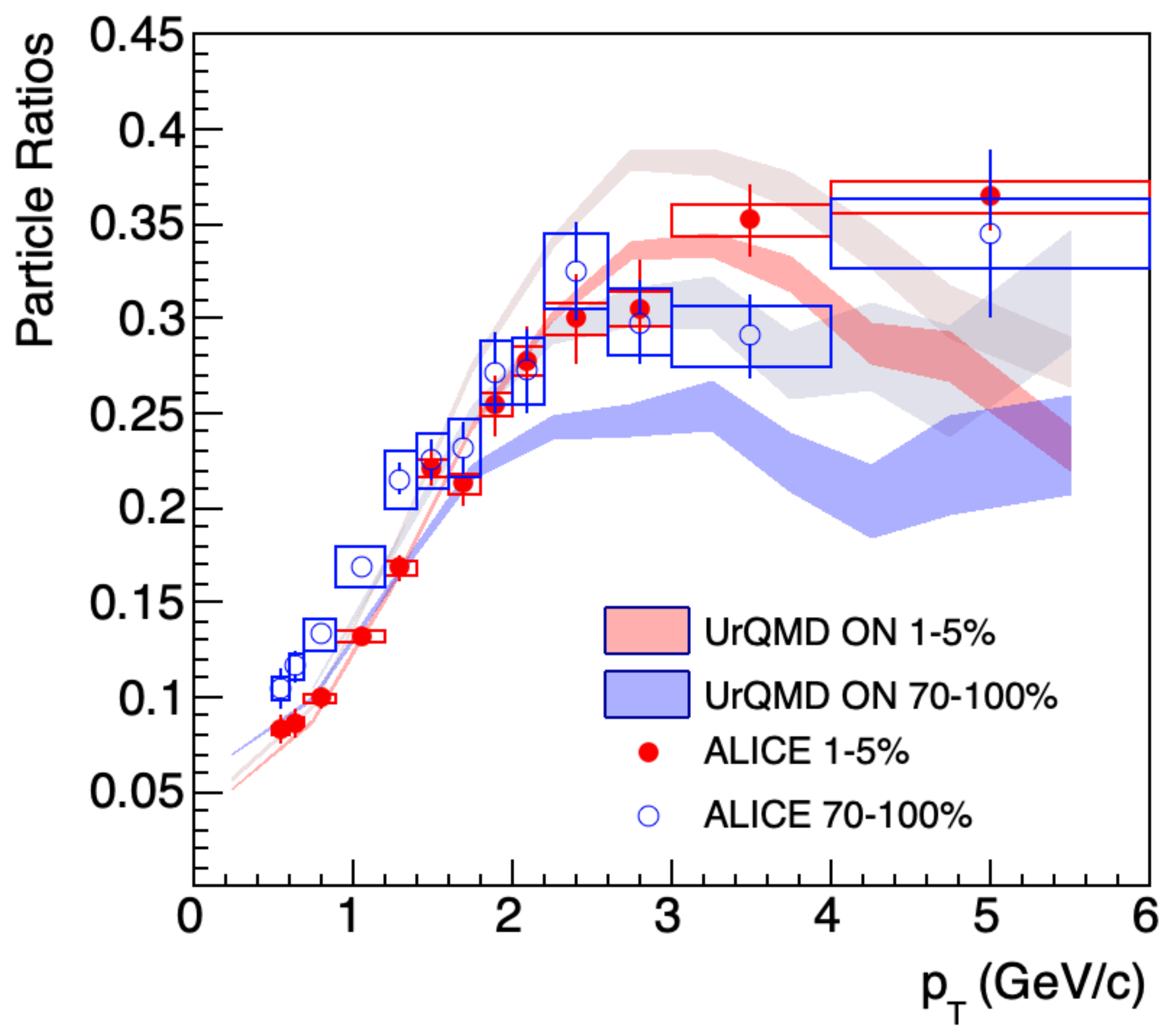


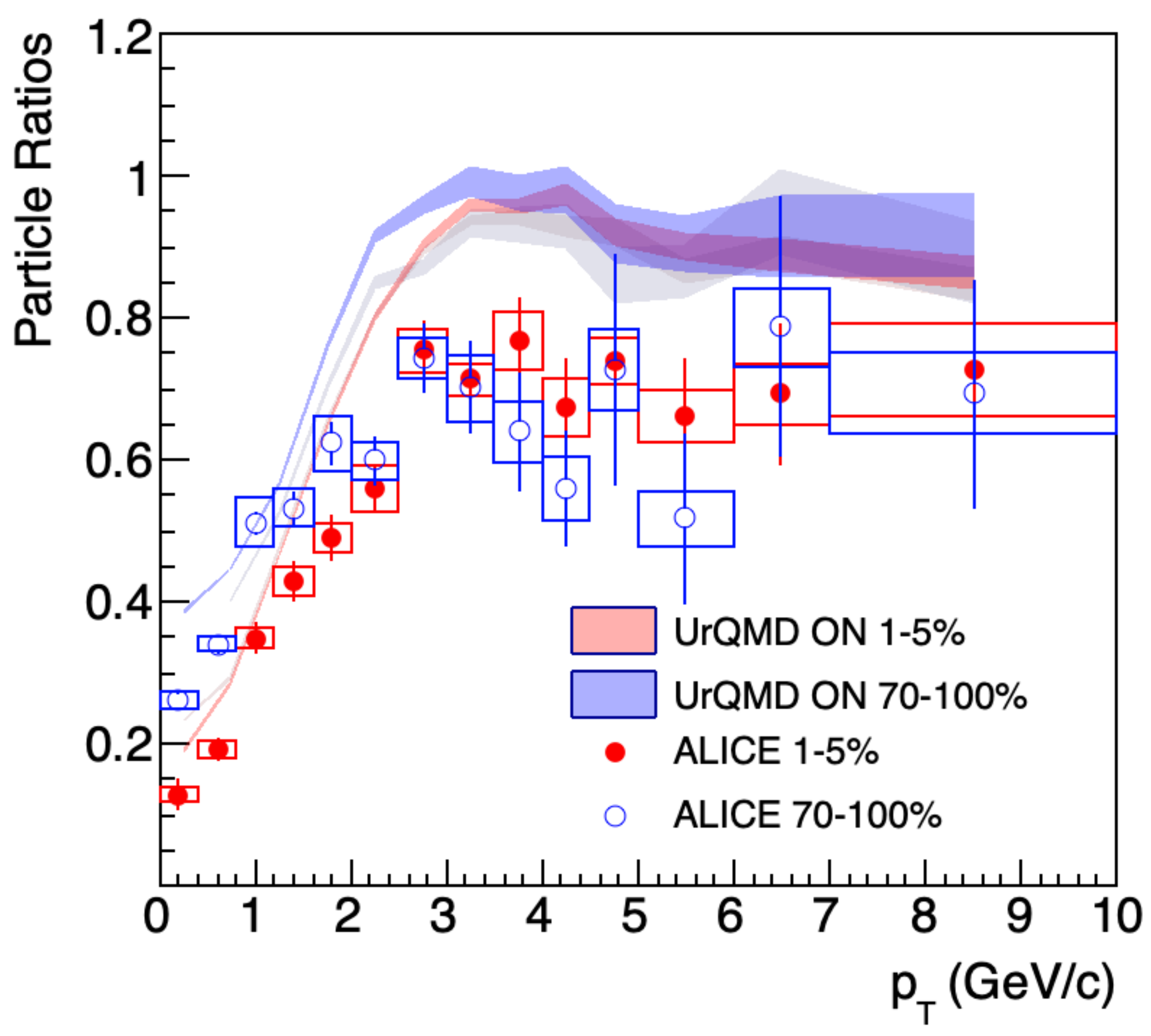
Class	$\langle dN_{ch}/d\eta \rangle_{\lvert\eta\rvert<0.5}$
INEL>0	6.89±0.11
I	25.75±0.40
II	19.83±0.30
III	16.12±0.24
IV	13.76±0.21
V	12.06±0.18
VI	10.11±0.15
VII	8.07±0.12
VIII	6.48±0.10
IX	4.64±0.07
X	2.52±0.04

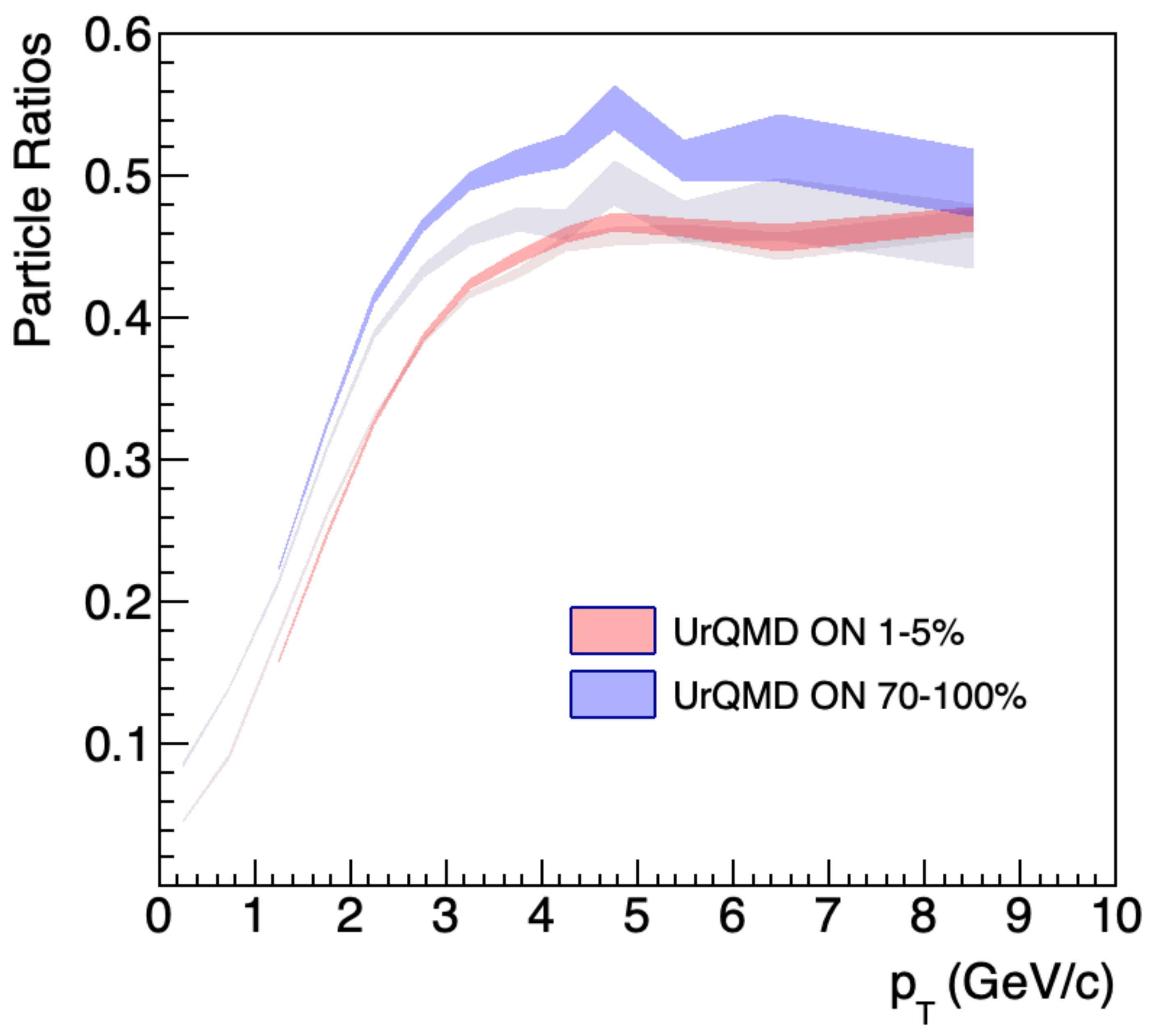
Information about a possible **short-lived hadron gas phase**

Analysis Results

Ratios vs p_T:

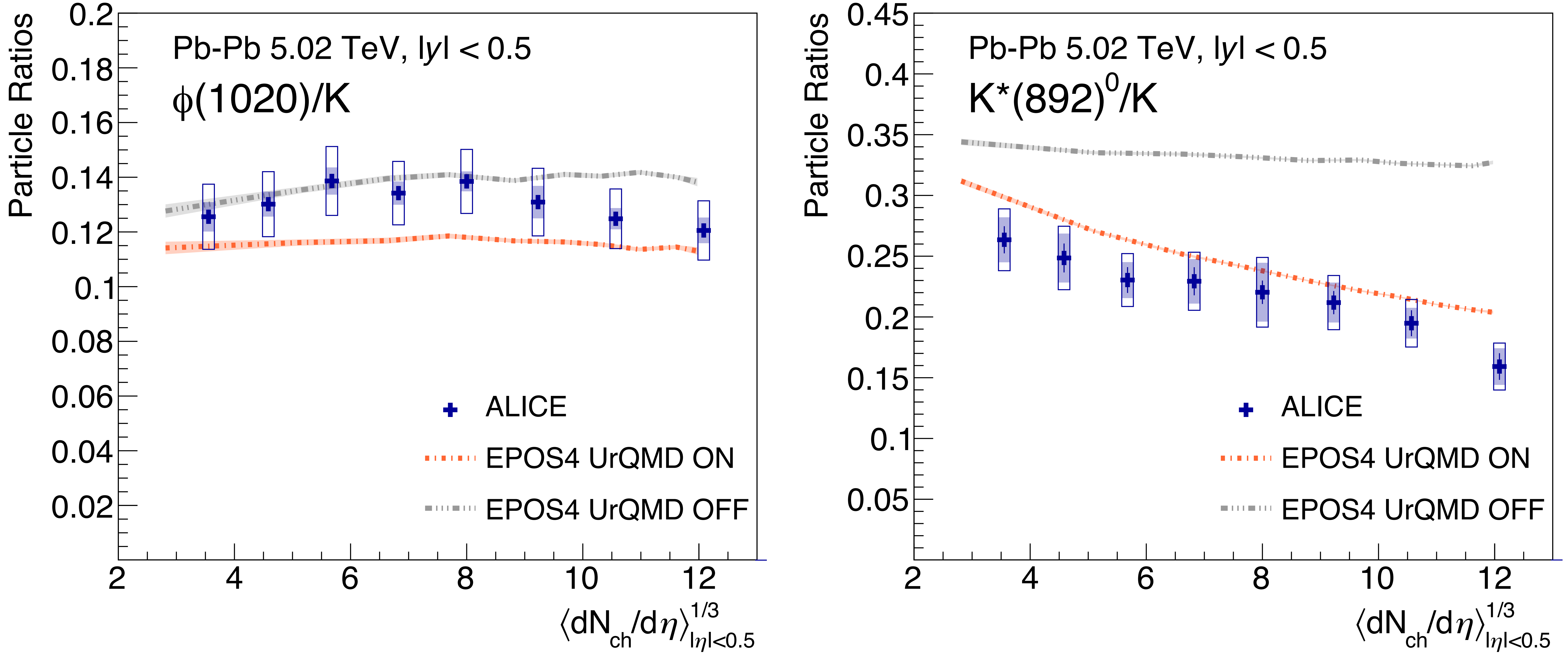






Analysis Method

EPOS4 in Pb-Pb:



- EPOS4 and UrQMD reproduce the trend observed in the ALICE Pb-Pb 5.02 TeV results

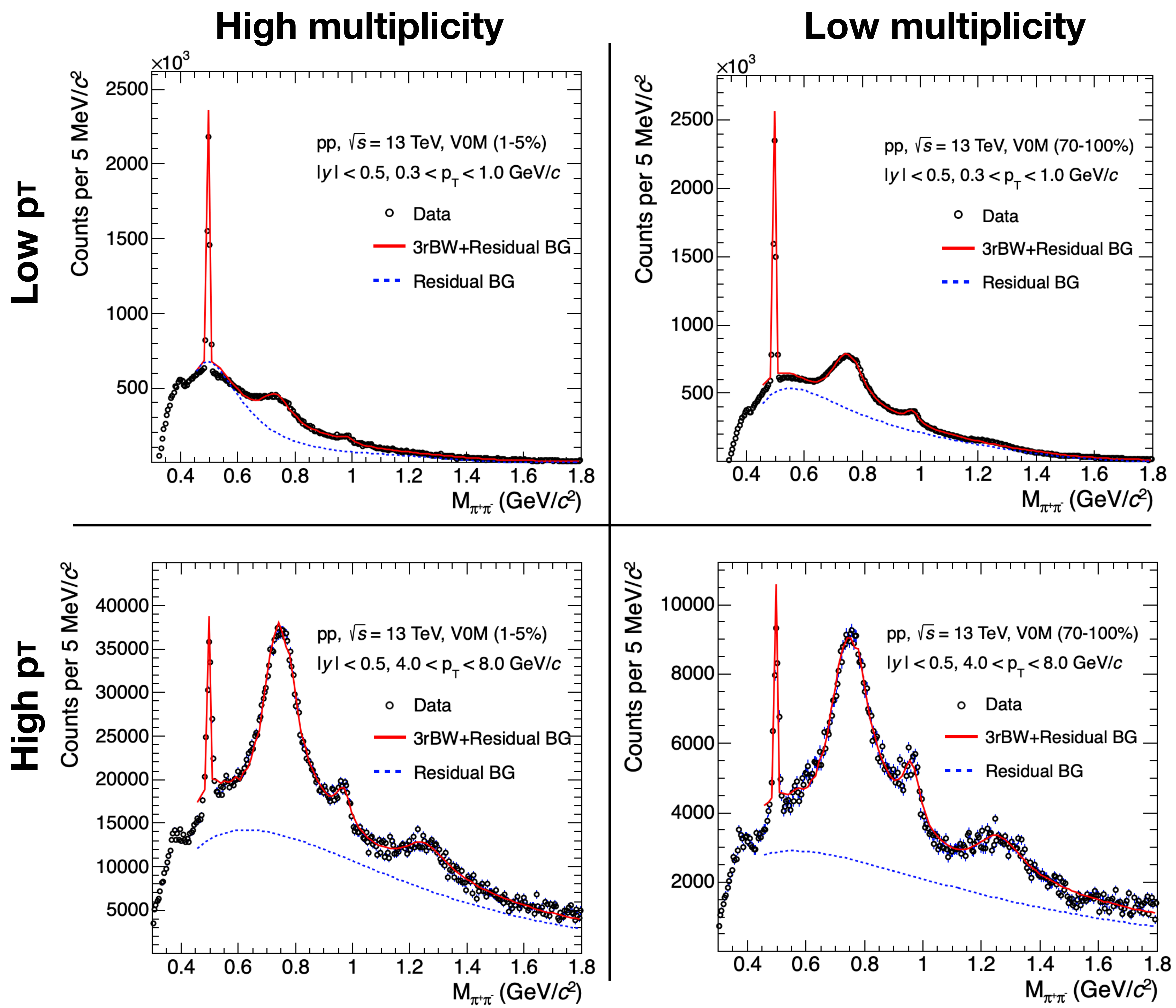
Analysis Method

Event & Track Selection → Invariant Mass Distribution → Signal Extraction → Correction → Physics Observables → Systematic Study

- **Target:** Multiplicity-dependent $\rho^0(770)$ production
- **Collision system & Data:** pp at $\sqrt{s}$ = 13 TeV from Run 2 & $\sqrt{s}$ = 13.6 TeV from Run 3
- **Event selection & Multiplicity:** V0M(Run 2) & FT0M(Run 3) minimum bias events
- **Track selection:** $\pi^{\pm}$ candidate with $p_T > 0.15$ GeV/c, $|\eta| < 0.8$
- **Background estimation:** Like-sign pair

Summary & Plan

ρ(770)⁰ in pp 13 TeV with ALICE

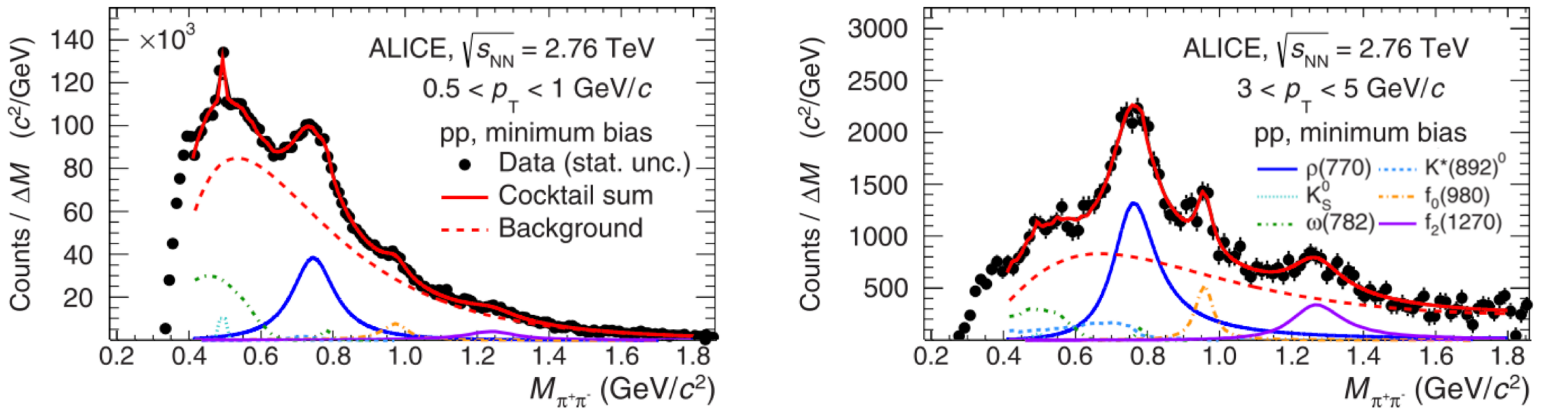


- Minimize the contribution from η, η', ϕ by limiting the lower bound to 0.45 GeV/c^2
- ω and K*; not applied in the fitting
- K_S; get template by GP MC, not normalized
- ρ^0, f_0 and f_2; rBW (IF, PS term not included)
- BG: $F_{BG}(m) = (m - 2\cdot m_\pi)^{par0} \cdot \exp(par1 + par2\cdot m)$

Analysis in progress!

Plan for Signal Extraction

ALICE Collaboration. PHYSICAL REVIEW C **99**, 064901 (2019)



- Peak model based on relativistic Breit-Wigner function: ρ^0, f_0, f_2

$$\mathrm{rBW}(M_{\pi\pi}) = \frac{AM_{\pi\pi}M_0\Gamma(M_{\pi\pi})}{\left(M_0^2 - M_{\pi\pi}^2\right)^2 + M_0^2\Gamma^2(M_{\pi\pi})}, \qquad \Gamma(M_{\pi\pi}) = \left(\frac{M_{\pi\pi}^2 - 4m_\pi^2}{M_0^2 - 4m_\pi^2}\right)^{(2J+1)/2} \times \Gamma_0 \times M_0/M_{\pi\pi},$$

- Background shape function:

$$F_{BG}(m) = (m - 2\cdot m_\pi)^{par0} \cdot \exp(par1 + par2\cdot m + par3\cdot m^2)$$

- Minimize the contribution from other hadron by limiting the lower bound
- Ignore other hadron's contribution at fitting and put it to systematic error: systematic study needed!

Event & Track selection

Run2:

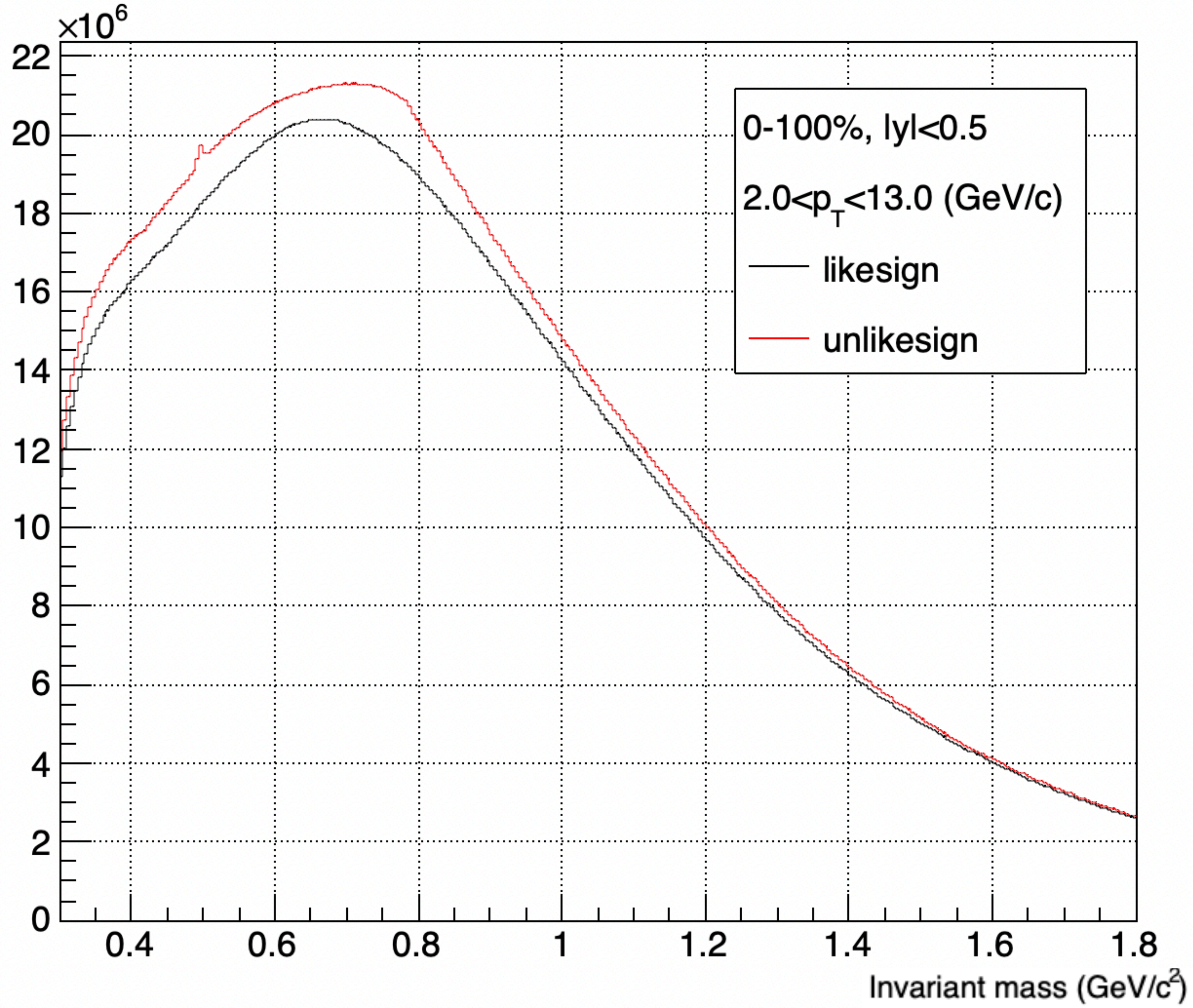
- **Dataset:** LHC16, 17, 18
- **Event selection cut:**
  Minimum Bias Trigger (kINT7)
  Pileup rejection using the SPD
  NContributors > 0.5
  $|z_{vertex}| < 10$ cm
  Standard selection from AliMultSelection
  Percentile of V0M multiplicity should be between 0% and 100%
- **Multiplicity:** V0M
- **Track selection cut:**
  Global tracking (TestFilterMask(0x20))
  $|DCA_z| < 2$ cm, $|DCA_r| < 0.15$ cm
  $p_T > 0.15$ GeV/c , $|\eta| < 0.8$
  $|\sigma_{TPC}| < 5$ and $|\sigma_{TOF}| < 3$ if TOF is available
  $|\sigma_{TPC}| < 2$ if TOF is not available
- **Pair selection**: $|y| < 0.5$

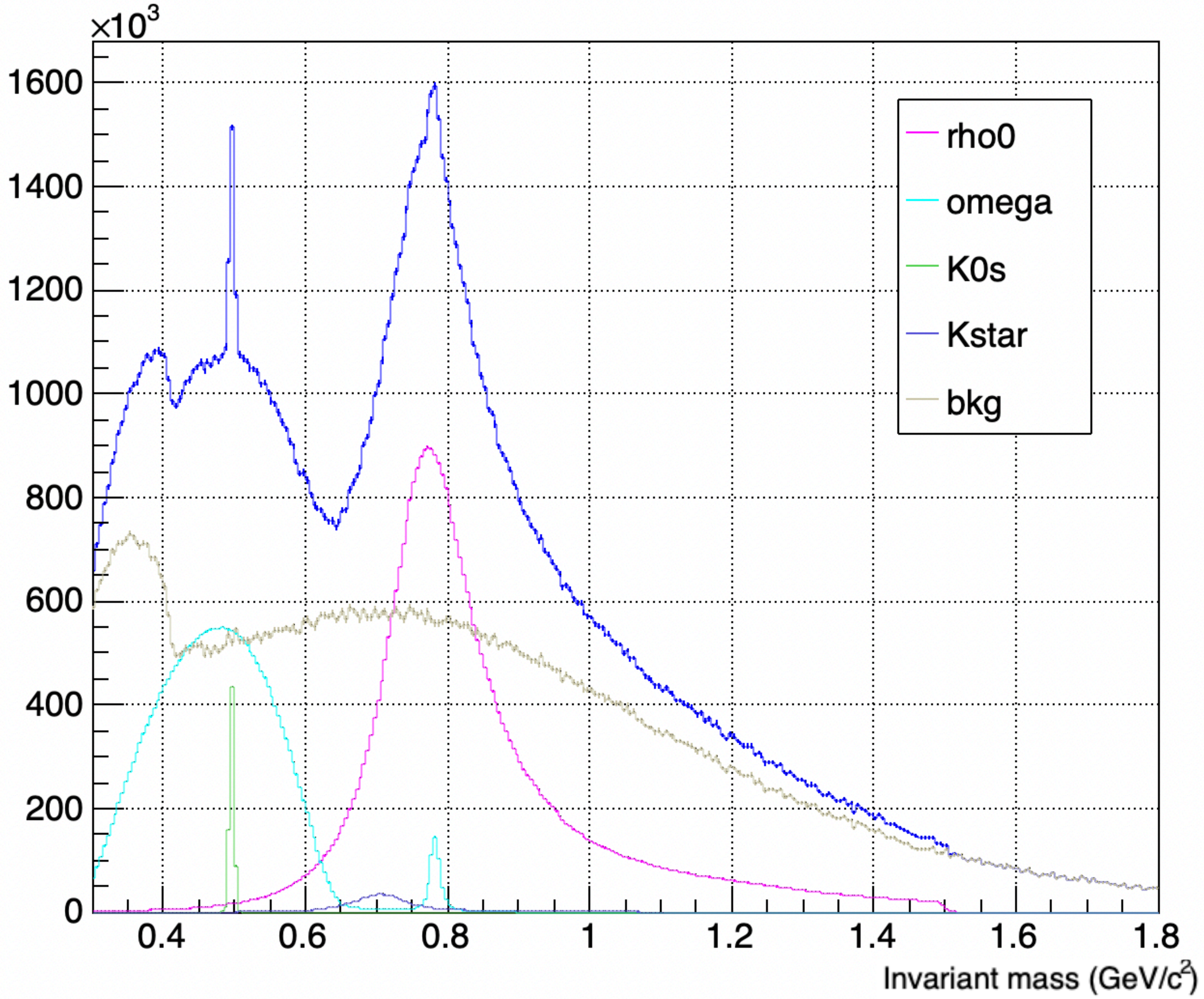
Run3:

- **Dataset:** LHC22o_pass4
- **Event selection cut:** sel8
- **Multiplicity:** FT0M
- **Track selection cut:**
  $|DCA_z| < 2$ cm, $DCA_r| < 0.15$ cm, $N_{clus} > 70$
  $p_T > 0.15$ GeV/c , $|\eta| < 0.8$
  $|\sigma_{TPC}| < 5$ and $|\sigma_{TOF}| < 3$ if TOF is available
  $|\sigma_{TPC}| < 2$ if TOF is not available
- **Pair selection**: $|y| < 0.5$

Fitting method

Monte Carlo:





– GP MC to get template shape and initial parameter

– LHC17, 18 (pass2)

Fitting method of previous analysis

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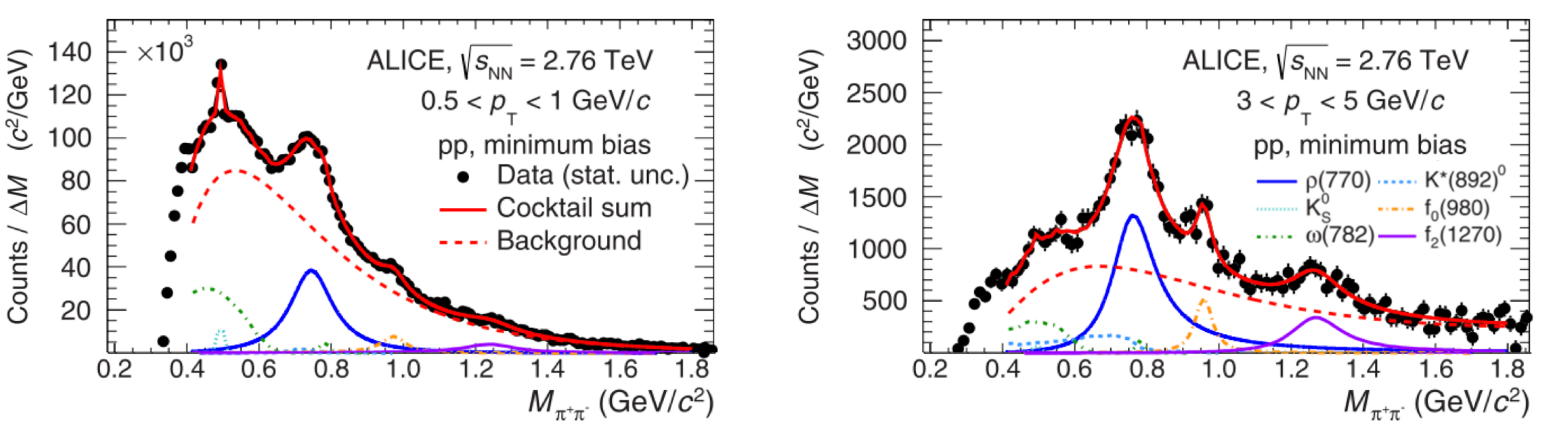


- Peak model based on relativistic Breit-Wigner function: ρ^0, f_0, f_2

$$\mathrm{rBW}(M_{\pi\pi}) = \frac{A M_{\pi\pi} M_0 \Gamma(M_{\pi\pi})}{\left(M_0^2 - M_{\pi\pi}^2\right)^2 + M_0^2 \Gamma^2(M_{\pi\pi})}, \qquad \Gamma(M_{\pi\pi}) = \left(\frac{M_{\pi\pi}^2 - 4m_\pi^2}{M_0^2 - 4m_\pi^2}\right)^{(2J+1)/2} \times \Gamma_0 \times M_0/M_{\pi\pi},$$

- Get templates from MC, normalized to known yield: K^{*0}, $K^0{}_s$, ω
- Background shape function:

$$F_{BG}(m) = (m - 2\cdot m_\pi)^{par0} \cdot \exp(par1 + par2\cdot m + par3\cdot m^2)$$

Fitting method of previous analysis

Fitting (Previous paper):

Contribution	Term	Parameters
ρ	rBW(m) * G(m) * BE(m) * PS(m) * RecEff(m)	Free: Yield, Mass, C Fixed: Γ_0 to values extracted from Monte-Carlo; estimated equal to Γ_0(PDG, 147.8 MeV/c^2) + 1.5 MeV/c^2 from mass resolution
f0	rBW(m) * G(m) * PS(m) * RecEff(m)	Free: Yield, Mass Limited: Width to PDG limits 40-100 MeV/c^2
f2	rBW(m) * G(m) * PS(m) * RecEff(m)	Free: Yield, Mass Fixed: Width to PDG value (184.2 MeV/c^2)
K^*	Template * Amplitude	Fixed: Amplitude to expected value
K_s	Template * Amplitude	Fixed: Amplitude to expected value
ω	Template * Amplitude	Fixed: Amplitude to expected value
BG	F_{FG}(m)	Free: par0, par1, par2, par3

https://alice-notes.web.cern.ch/system/files/notes/analysis/374/2018-May-11-analysis_note-Rho_11A_pp276_TPCPID_v4.pdf

- PHYSICAL REVIEW C **99**, 064901 (2019)

background shape: $F_{BG}(m) = (m - 2 \cdot m_\pi)^{par0} \cdot \exp(par1 + par2 \cdot m + par3 \cdot m^2)$

Fitting method

Peak model for ρ^0, f_0 and f_2:

- Basic shape (rBW):

$$\mathrm{rBW}(M_{\pi\pi}) = \frac{A M_{\pi\pi} M_0 \Gamma(M_{\pi\pi})}{\left(M_0^2 - M_{\pi\pi}^2\right)^2 + M_0^2 \Gamma^2(M_{\pi\pi})}, \qquad \Gamma(M_{\pi\pi}) = \left(\frac{M_{\pi\pi}^2 - 4m_\pi^2}{M_0^2 - 4m_\pi^2}\right)^{(2J+1)/2} \times \Gamma_0 \times M_0 / M_{\pi\pi},$$

- Phase space (PS) correction:

$$\mathrm{PS}(M_{\pi\pi}) = \frac{M_{\pi\pi}}{\sqrt{M_{\pi\pi}^2 + p_T^2}} \times \exp\left(-\sqrt{M_{\pi\pi}^2 + p_T^2}/T\right),$$

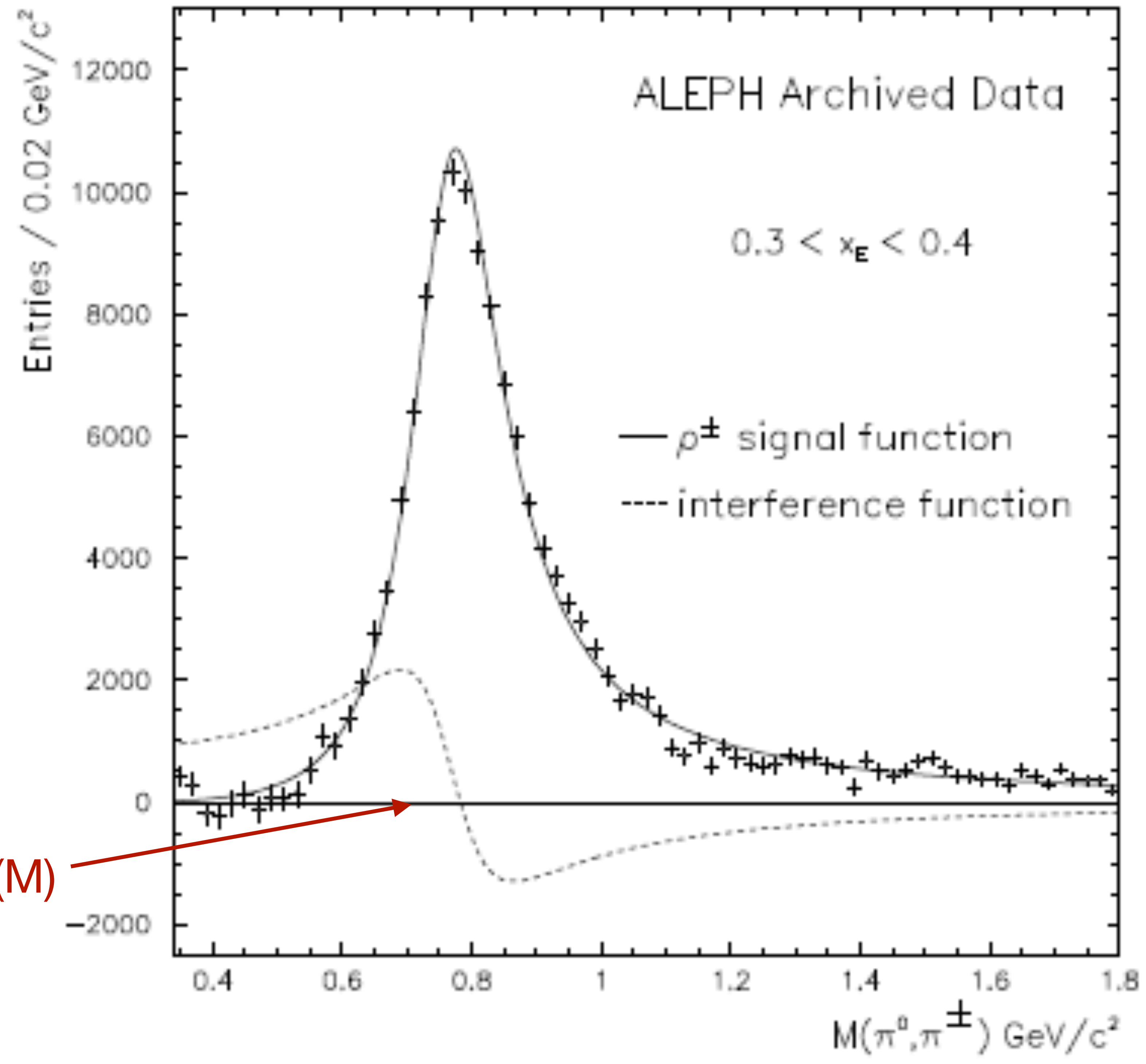
- Mass dependence of reconstruction efficiency: RecEff(M)

- Interference term (Söding parameterization):

  only needed to ρ_0

$$f_i(M_{\pi\pi}) = C\left[\frac{M_0^2 - M_{\pi\pi}^2}{M_{\pi\pi}\Gamma(M_{\pi\pi})}\right] f_s(M_{\pi\pi}),$$

rBW



Interference term: f_i(M)

Fitting method

Template normalization:

- K*: https://alice-notes.web.cern.ch/system/files/notes/analysis/469/2020-03-04-Analysis_note-kstar_pp13TeV_MB_v3.pdf
  - Phys. Rev. C 95 (2017) 064606
- K_S: https://alice-notes.web.cern.ch/system/files/notes/analysis/478/2019-08-03-ALICE_analysis_note_CRupdate.pdf
  - Eur. Phys. J. C 80 (2020) 167
- ω: https://alice-notes.web.cern.ch/system/files/notes/analysis/1313/2022-08-30-OmegaAnalysisNote_pp13TeV_v2_0.pdf