A Large Ion Collider Experiment

Observation of enhanced production of strange and multi-strange hadrons in high-multiplicity pp and p-Pb collisions with the ALICE detector

Lee Barnby
University of Birmingham and CERN
on behalf of the ALICE Collaboration

Outline

- Brief review of strangeness enhancement measurements
- ALICE Experiment
- The p-Pb analysis
- Extension to proton-proton collisions
- Investigating collectivity
- Conclusions

Heavy-ion collisions and QGP

- Examine hadron yields
  - so-called chemical composition
- Information on conditions in ‘fireball’

Why study strangeness?

- Long-standing ideas
  - J. Rafelski and B. Müller PRL, 48, 106-1069 (1982)
  - J. Rafelski and R. Hagedorn, in *Statistical Mechanics of Quark and Hadrons*
- Gluon fusion, $gg \rightarrow s\bar{s}$, most efficient means to produce strangeness
- Partons $\rightarrow$ hadrons, plenty of strange quarks for producing strange and multi-strange hadrons
- More efficient than multi-step hadronic interactions

CERN SPS Announcement (2000)

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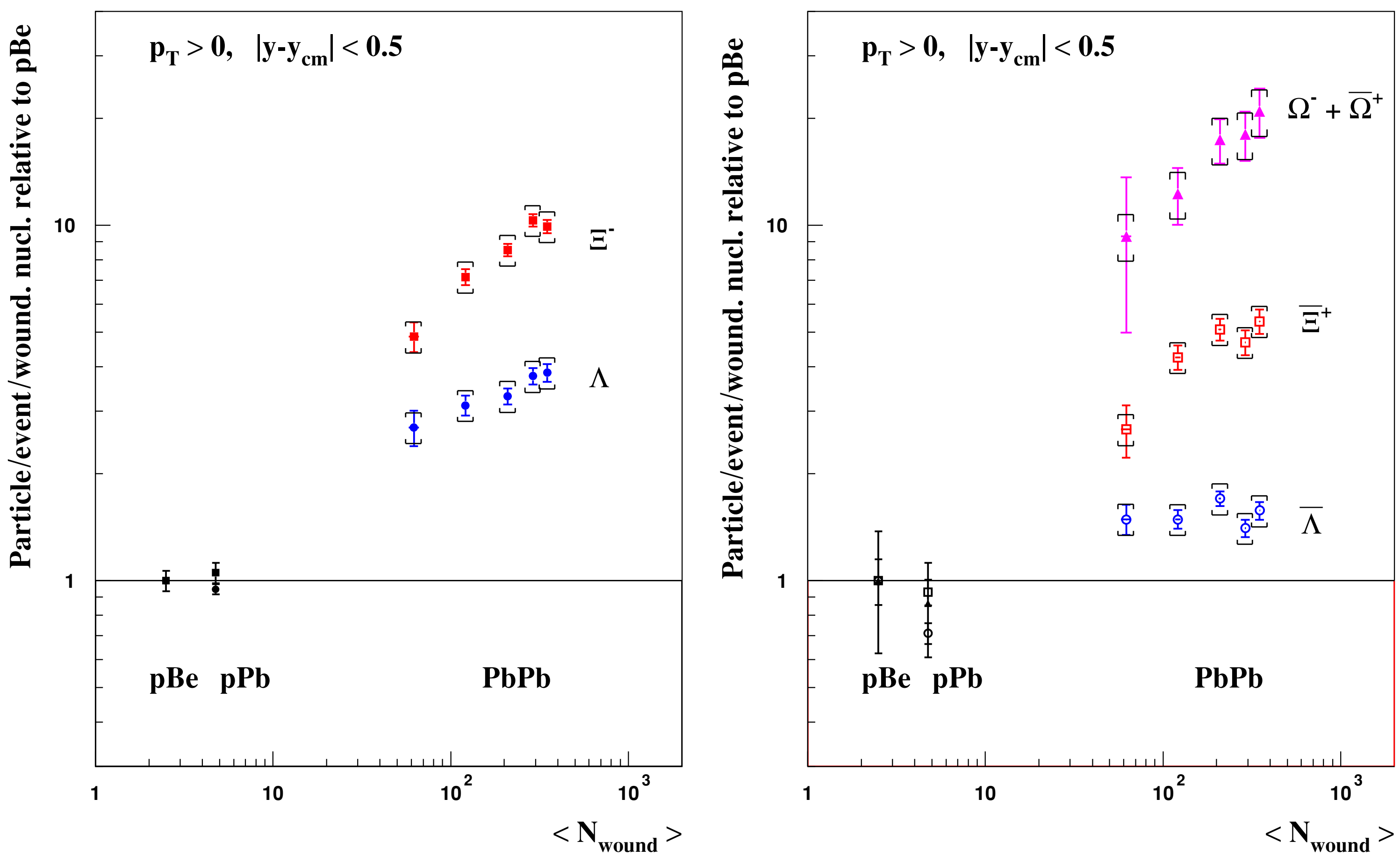
- A particularly striking aspect of this apparent "chemical equilibrium" at the quark-hadron transition temperature is the observed enhancement, relative to proton-induced collisions, of hadrons containing **strange** quarks. Globally, when normalised to the number of participating nucleons, this enhancement corresponds to a factor 2 (NA49), but hadrons containing more than one **strange** quark are enhanced much more strongly (WA97, NA49, NA50), up to a factor 15 for the Omega (Ω) hyperon and its antiparticle (WA97)! Lead-lead collisions are thus qualitatively different from a superposition of independent nucleon-nucleon collisions. That the relative enhancement is found to increase with the **strange** quark content of the produced hadrons contradicts predictions from hadronic re-scattering models where secondary production of multi-**strange** (anti)baryons is hindered by high mass thresholds and low cross sections.

SPS Results

- Detailed final publication from NA57
- Centrality-selected p_T-integrated yields of Λ, Ξ, Ω (and anti-particles) in $\sqrt{s_{NN}}$ = 17 GeV Pb-Pb collisions



- Divided by number of ‘wounded nucleons’ and normalised to same quantity in p-Be collisions
  - p-Be is a proxy for pp since N_{wound} is close to 2 (as in pp)

NA57, J. Phys. G: Nucl. Part. Phys. 32 (2006) 427-441

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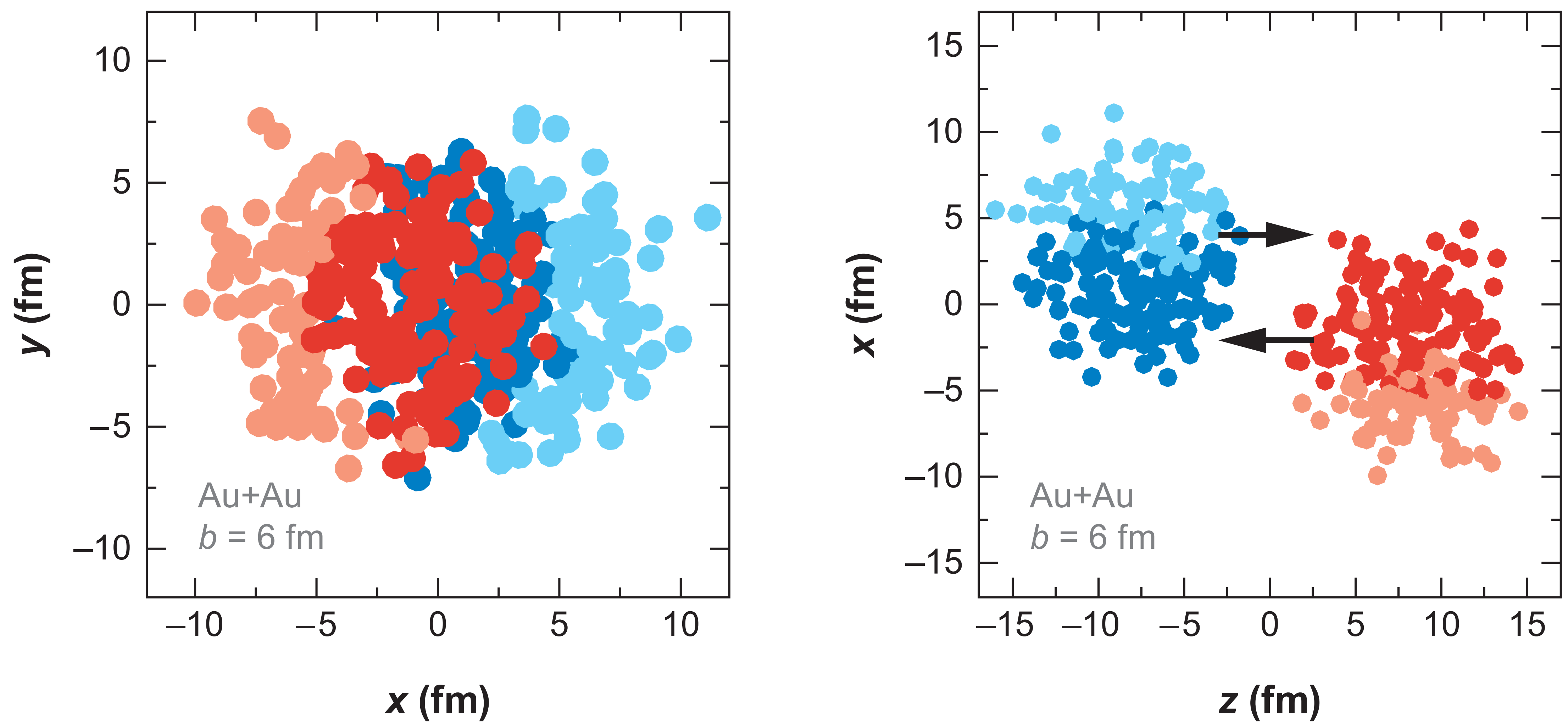
Monte Carlo Glauber calculations

- Use N-N cross-section and knowledge of nuclear density profile
- Calculate number of participant nucleons as a function of impact parameter, b
- Can map onto centrality interval expressed as a percentage of the cross section
- Participants are denoted N_{part} or, sometimes N_{wound} (for wounded nucleons)



Annu. Rev. Nucl. Part. Sci. 2007. 57:205–43

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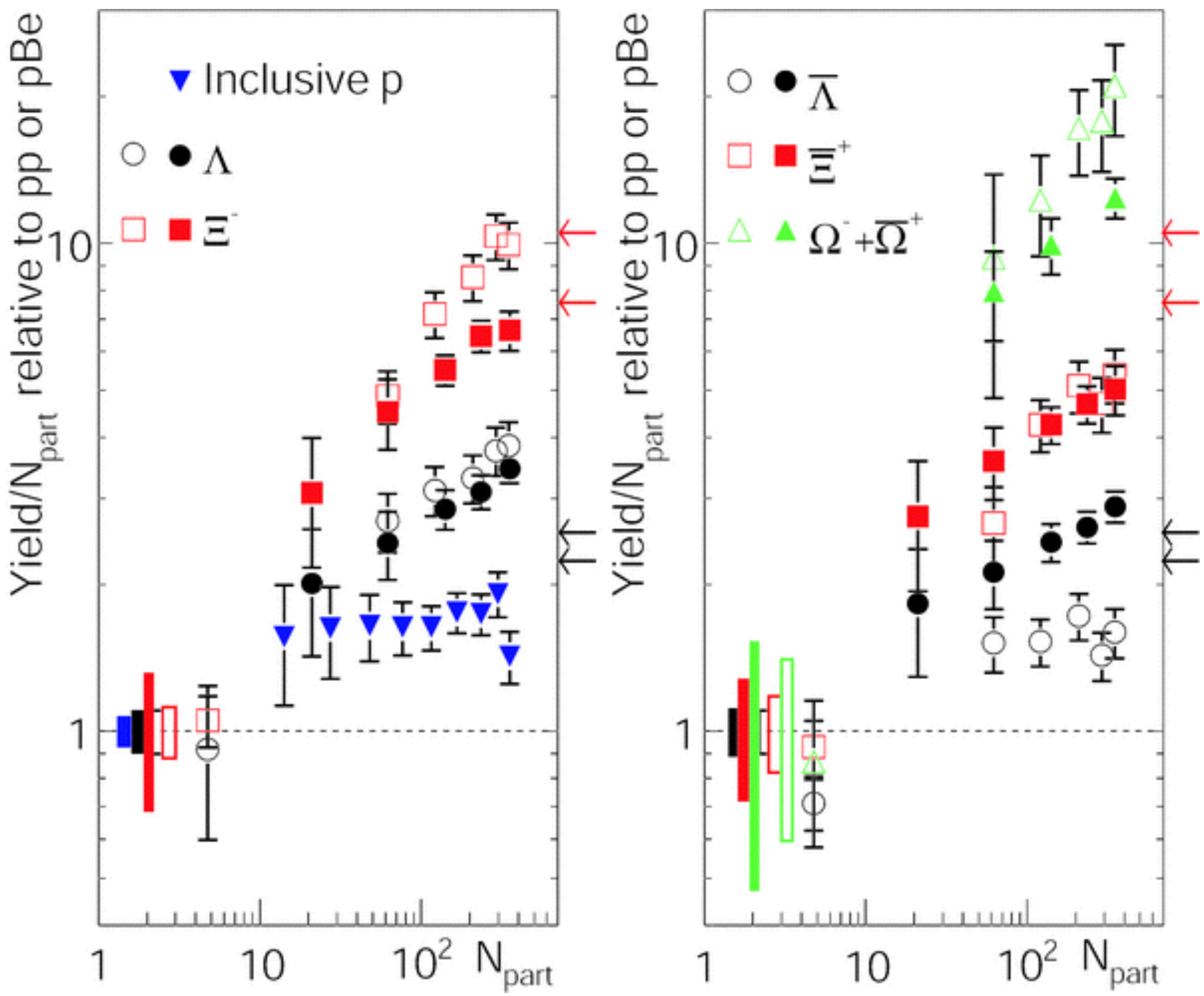
RHIC Era

STAR Collaboration
Phys. Rev. C 77, 044908 (2008)



- dN/dy normalised to N_{part}, as fn. of N_{part}
- Solid symbols STAR: Au-Au $\sqrt{s_{NN}}$ = 200 GeV
- Open symbols NA57: Pb-Pb $\sqrt{s_{NN}}$ = 17 GeV

NB Nomenclature: $N_{part} \equiv N_{wound}$

Theoretical description of enhancement

K. Redlich, A. Tounsi
Eur. Phys. J. C 24, 589–594 (2002)

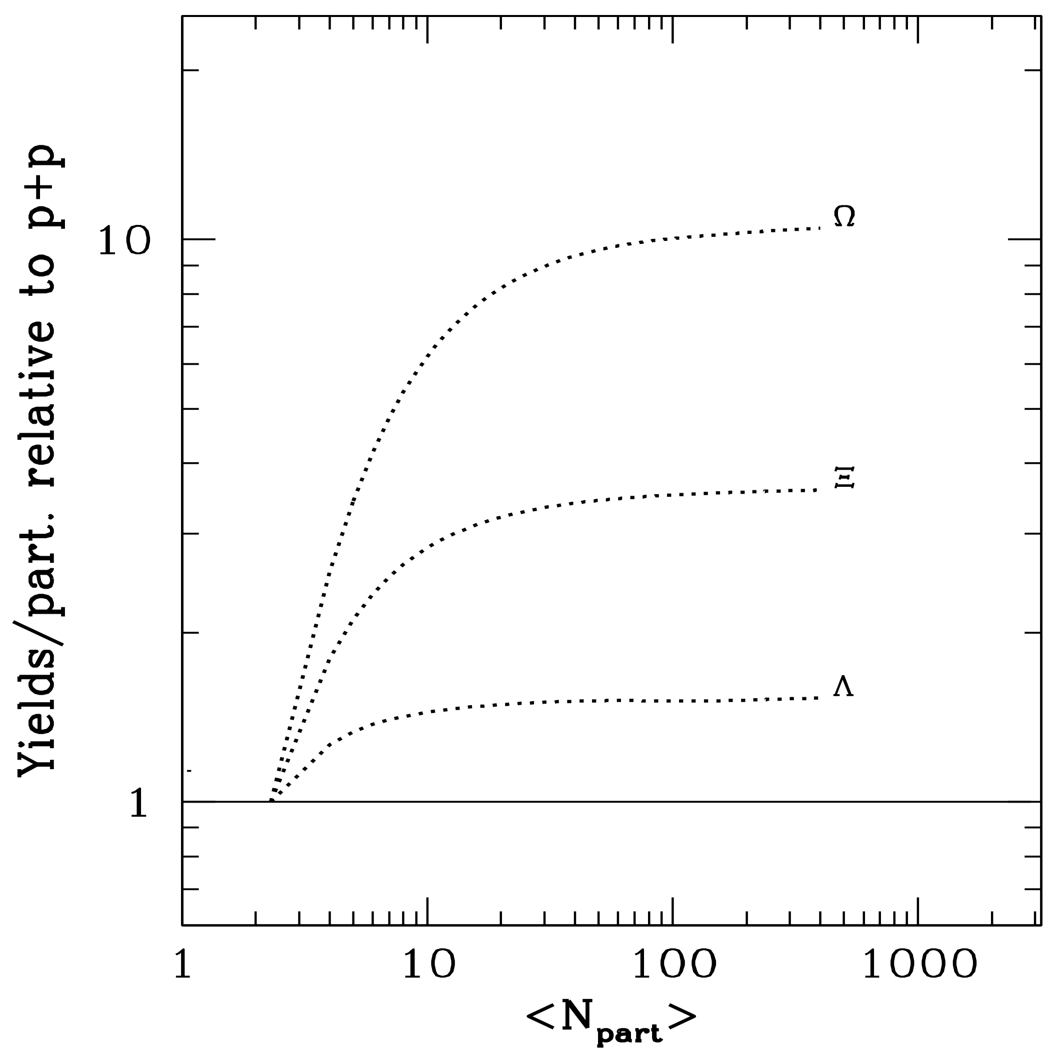


Fig. 4. Centrality dependence of the relative enhancement of particle yields/participant in central Pb–Pb to p–p collisions at fixed energy $\sqrt{s} = 130\,\mathrm{GeV}$

- Statistical model calculation
- Suppression of particle yields in small systems due to conservation laws
  – strangeness quantum number

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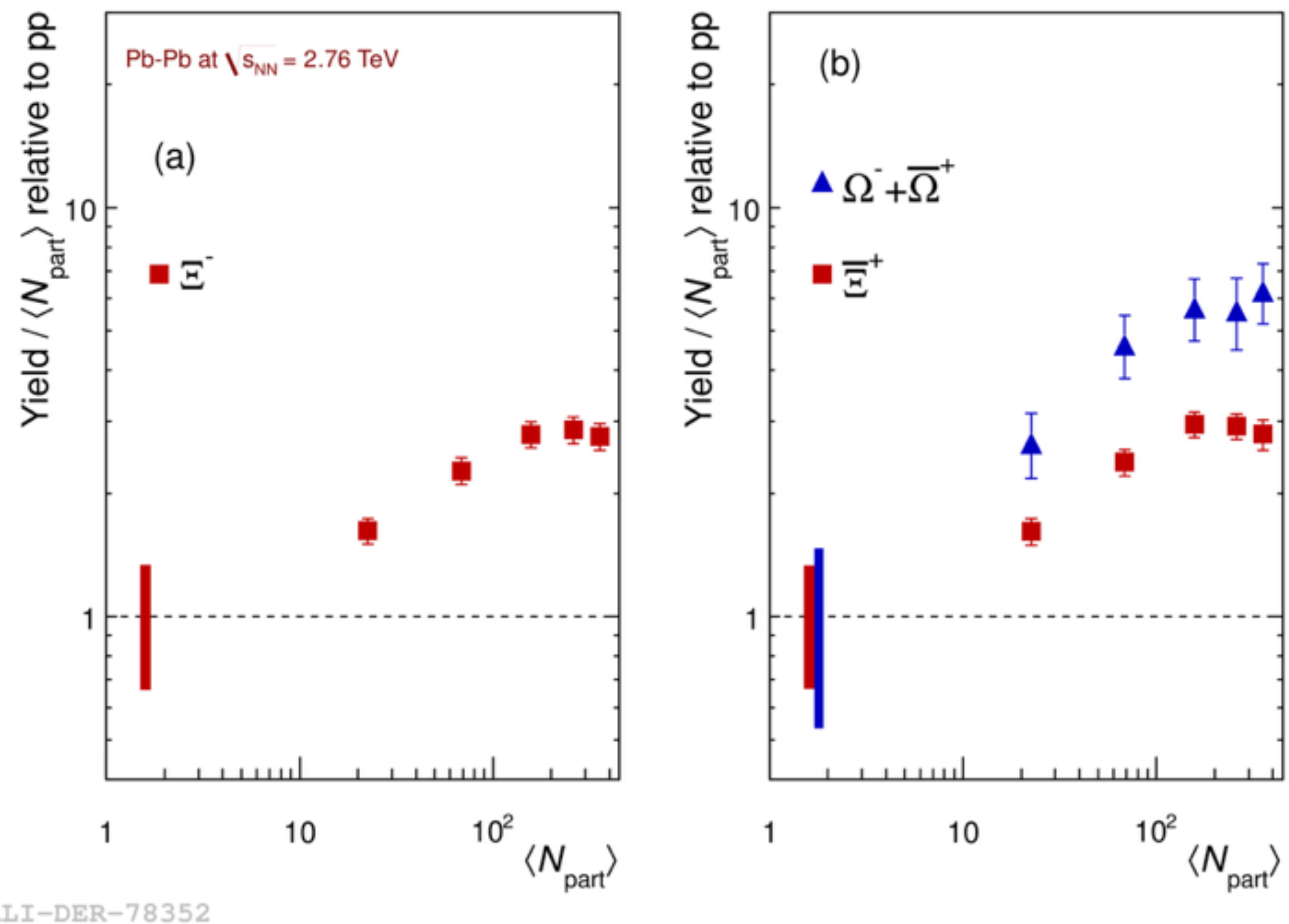
ALICE Results

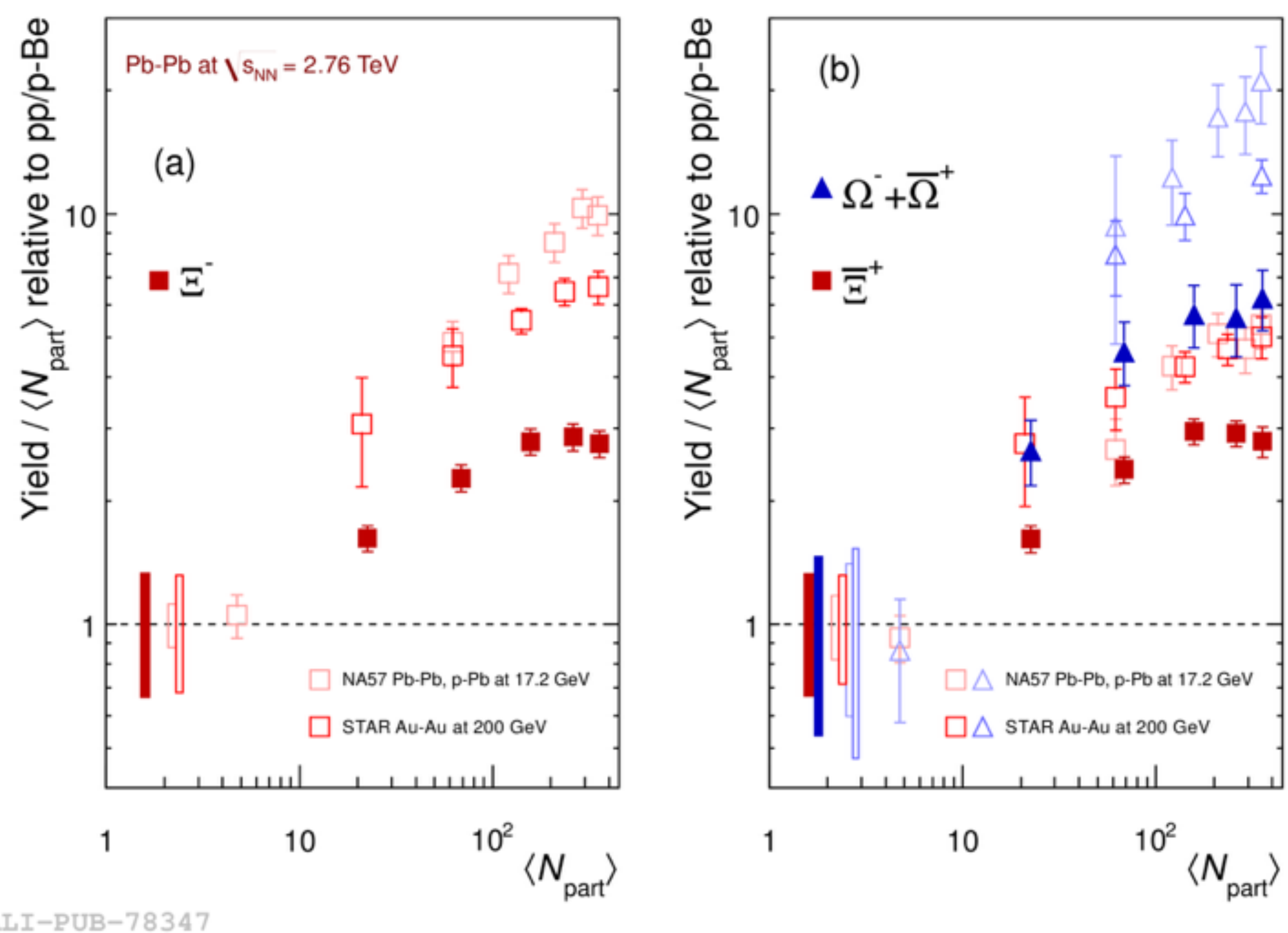
- Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV



Phys. Lett. B 728 (2014) 216

ALICE Results

- Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV



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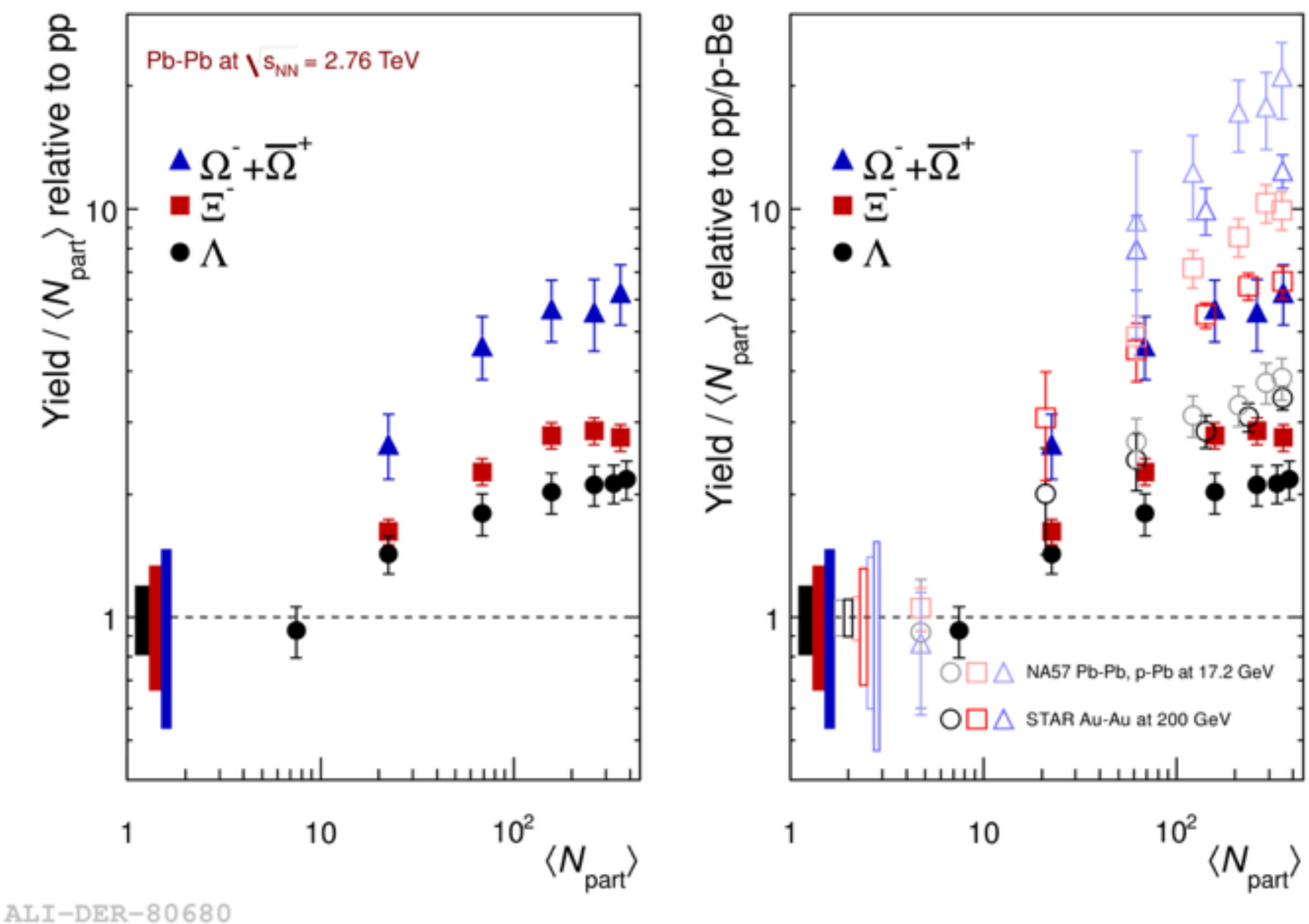
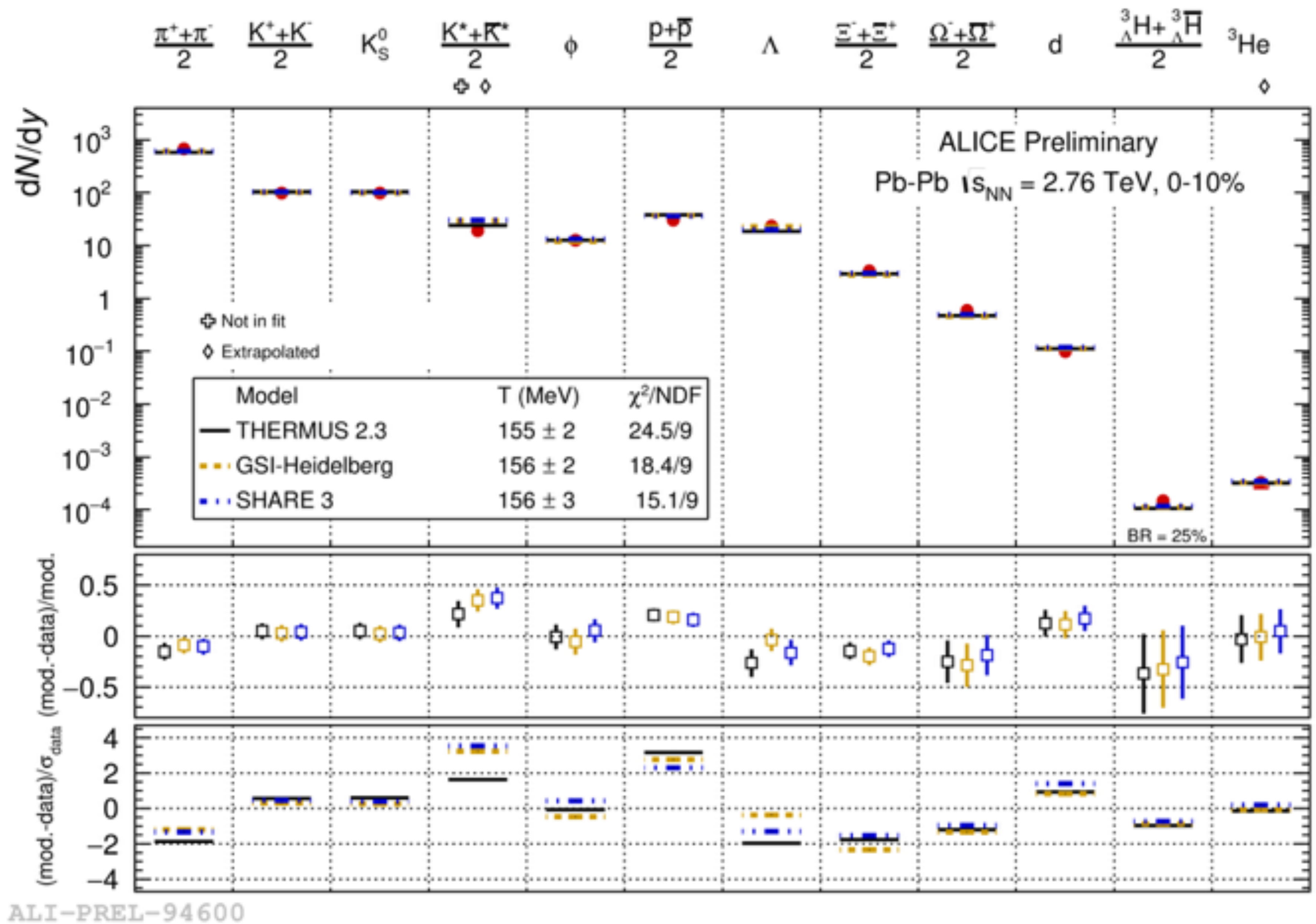
Complete picture



- Hierarchy with
  - strangeness, S
  - centre-of-mass energy

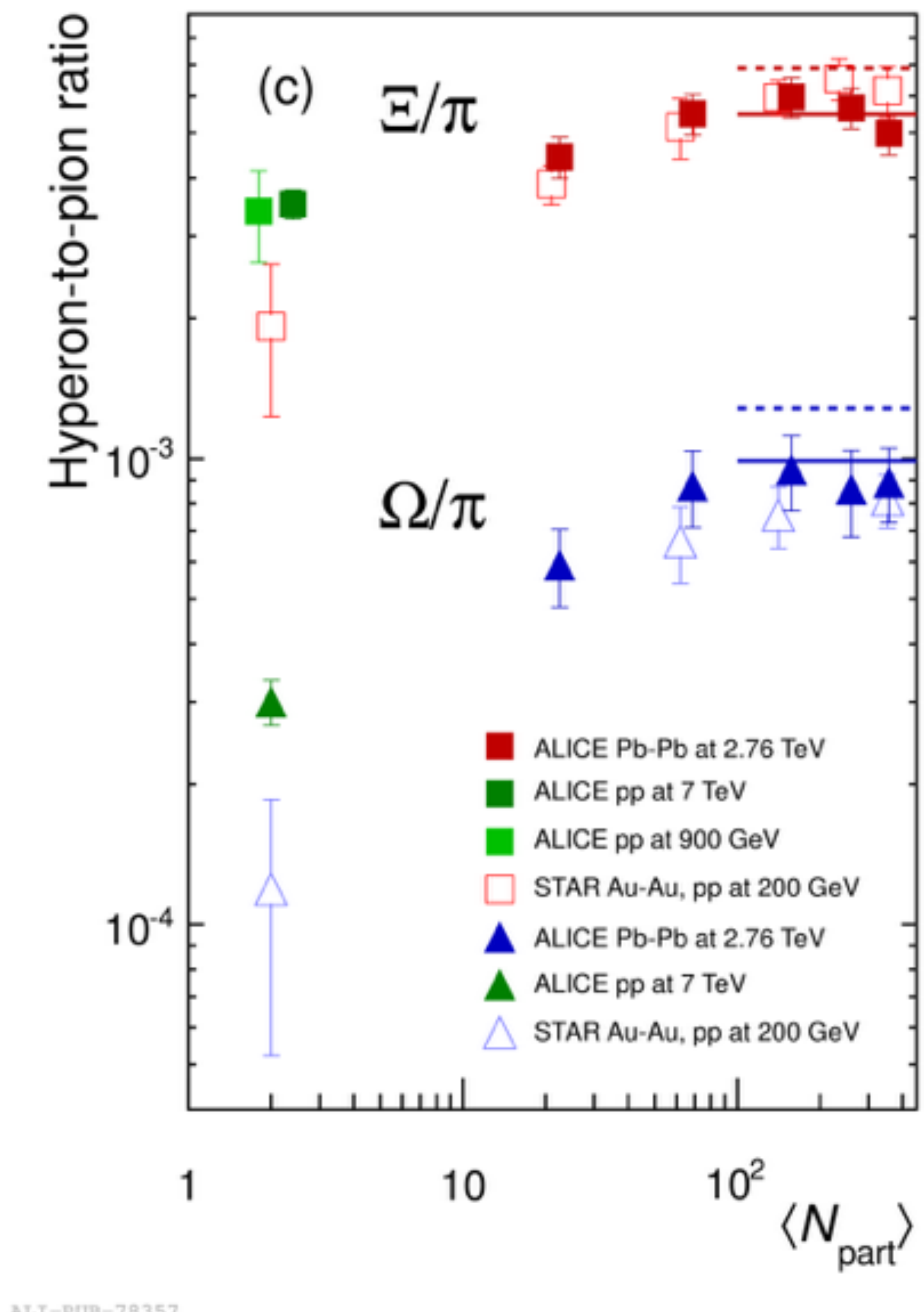
Thermal Equilibrium



- Several models fit the hadron yields in central Pb-Pb collisions with a temperature 156±2 MeV

THERMUS: Comp. Phys. Comm. **180** (2009) 84-106
GSI-Heidelberg: PLB **673** (2009) 142-145
SHARE: Phys. Rev. C **88** (2013) 034907

ALICE Pb-Pb



- Remove N_{part} normalisation
- Make ratio to π yields instead
- Most of the difference in enhancement is due to lower yields in pp reference

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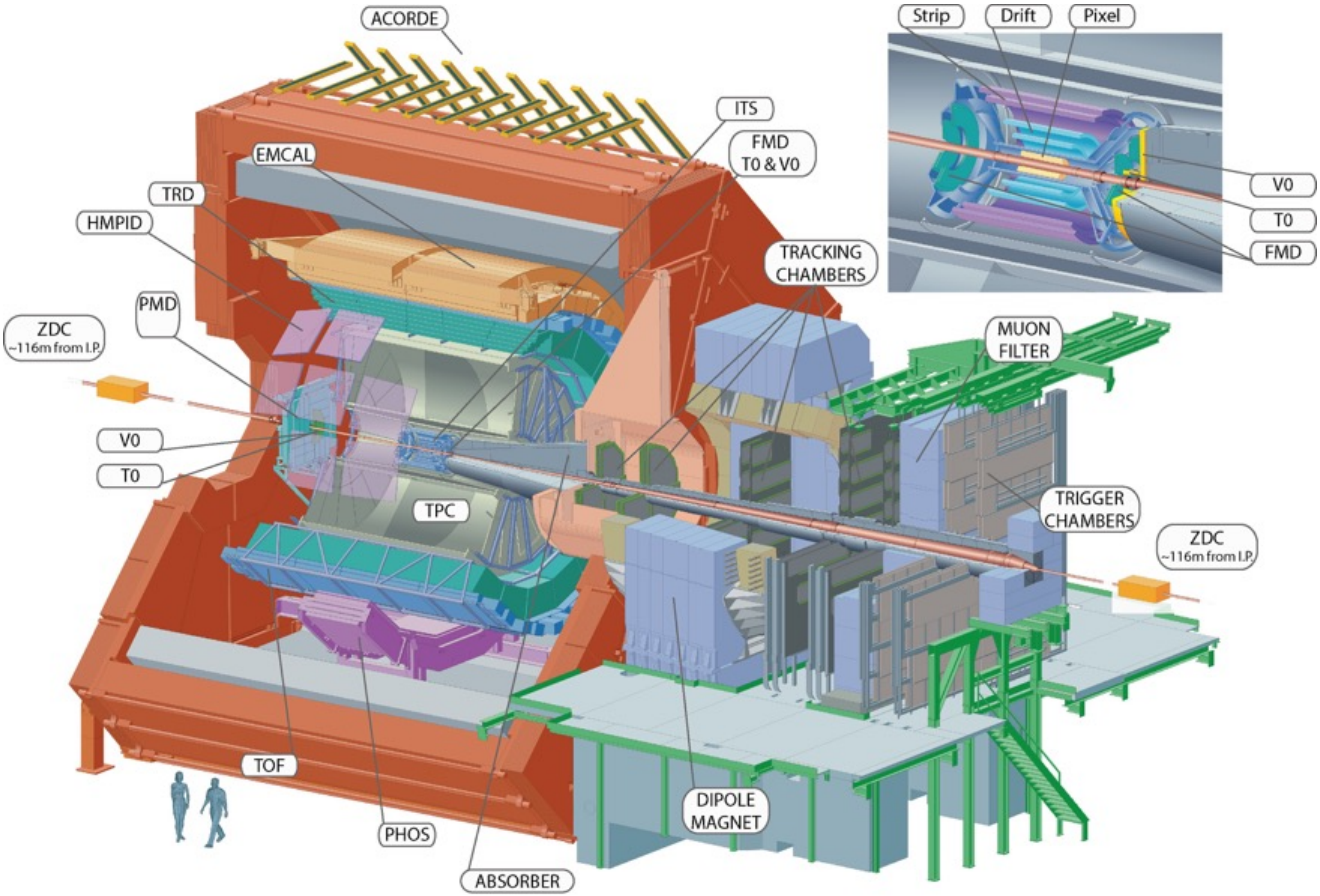
ALICE Experiment

Experiment


ACORDE
ITS
FMD
T0 & V0
EMCAL
TRD
HMPID
PMD
ZDC
~116m from I.P.
V0
T0
TPC
TRACKING
CHAMBERS
MUON
FILTER
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
TOF
PHOS
ABSORBER
DIPOLE
MAGNET
Strip
Drift
Pixel
V0
T0
FMD

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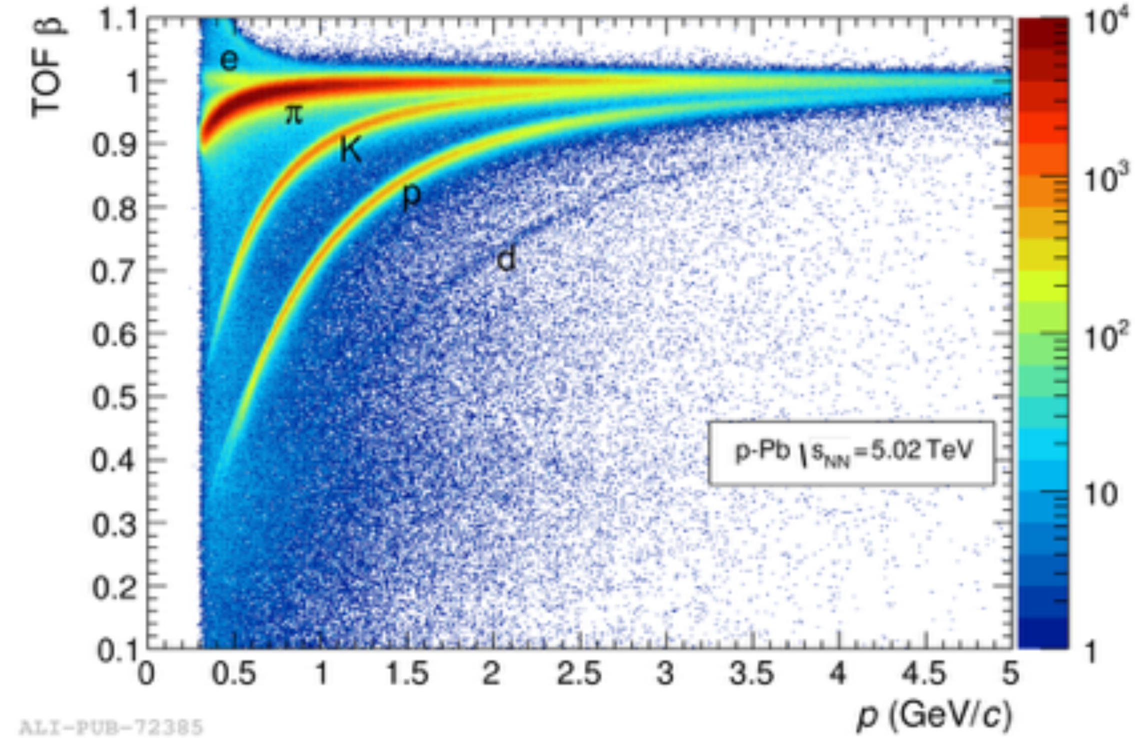
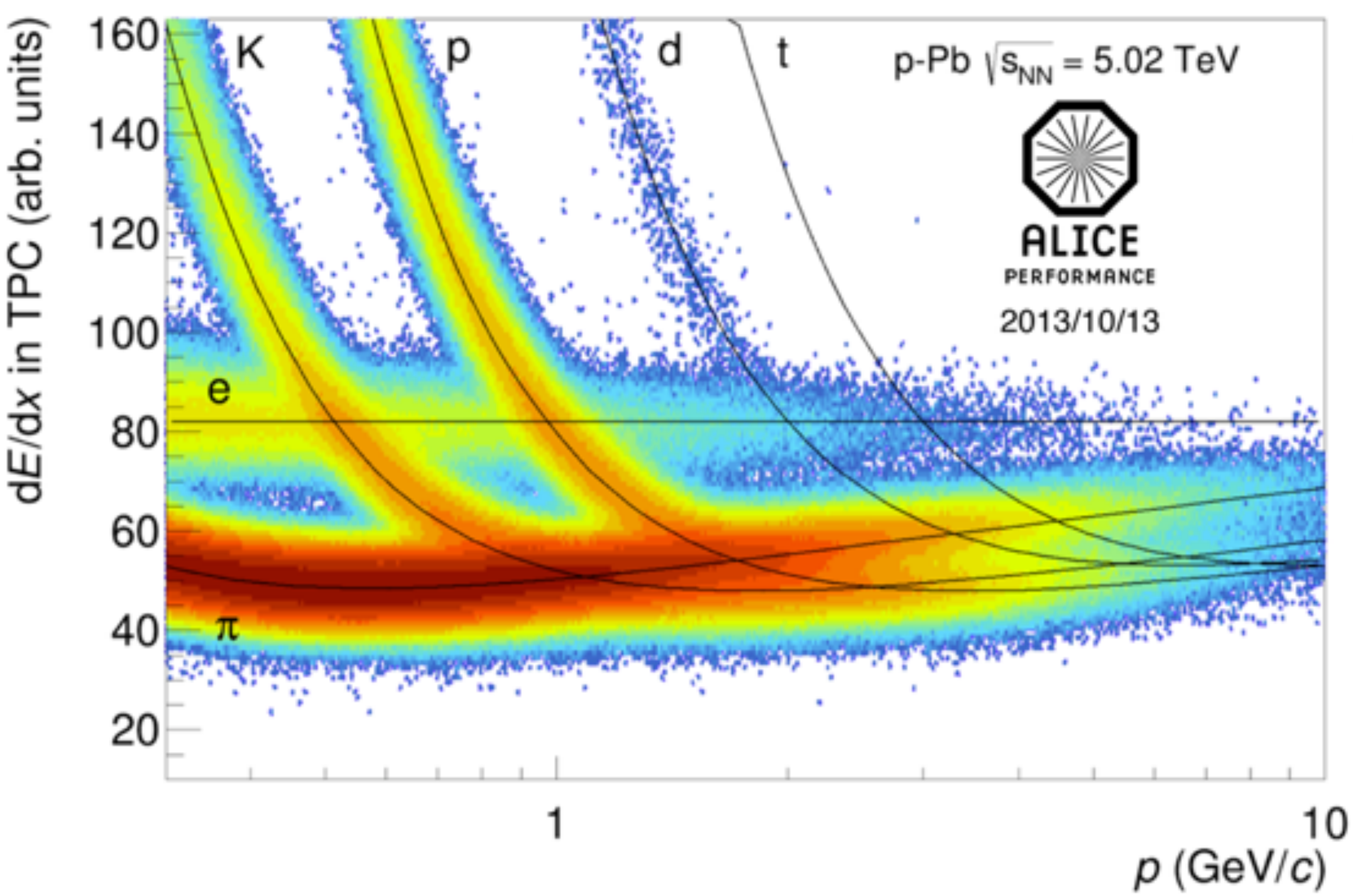
Particle Identification in ALICE

- Identify particles
- In particular weak decay daughters
  - E.g. K from Ω→ΛK

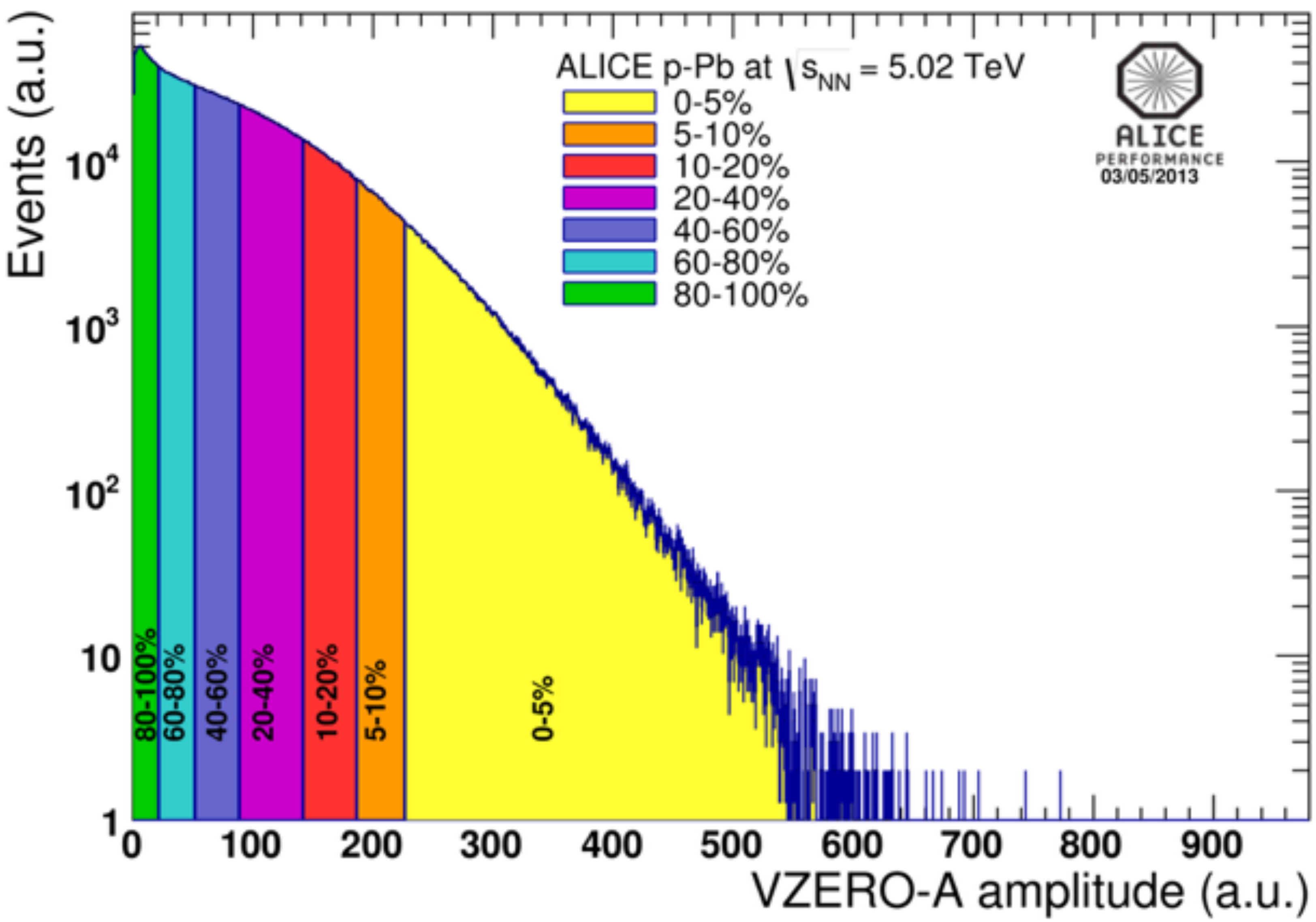




p-Pb analysis

p-Pb Event Classification

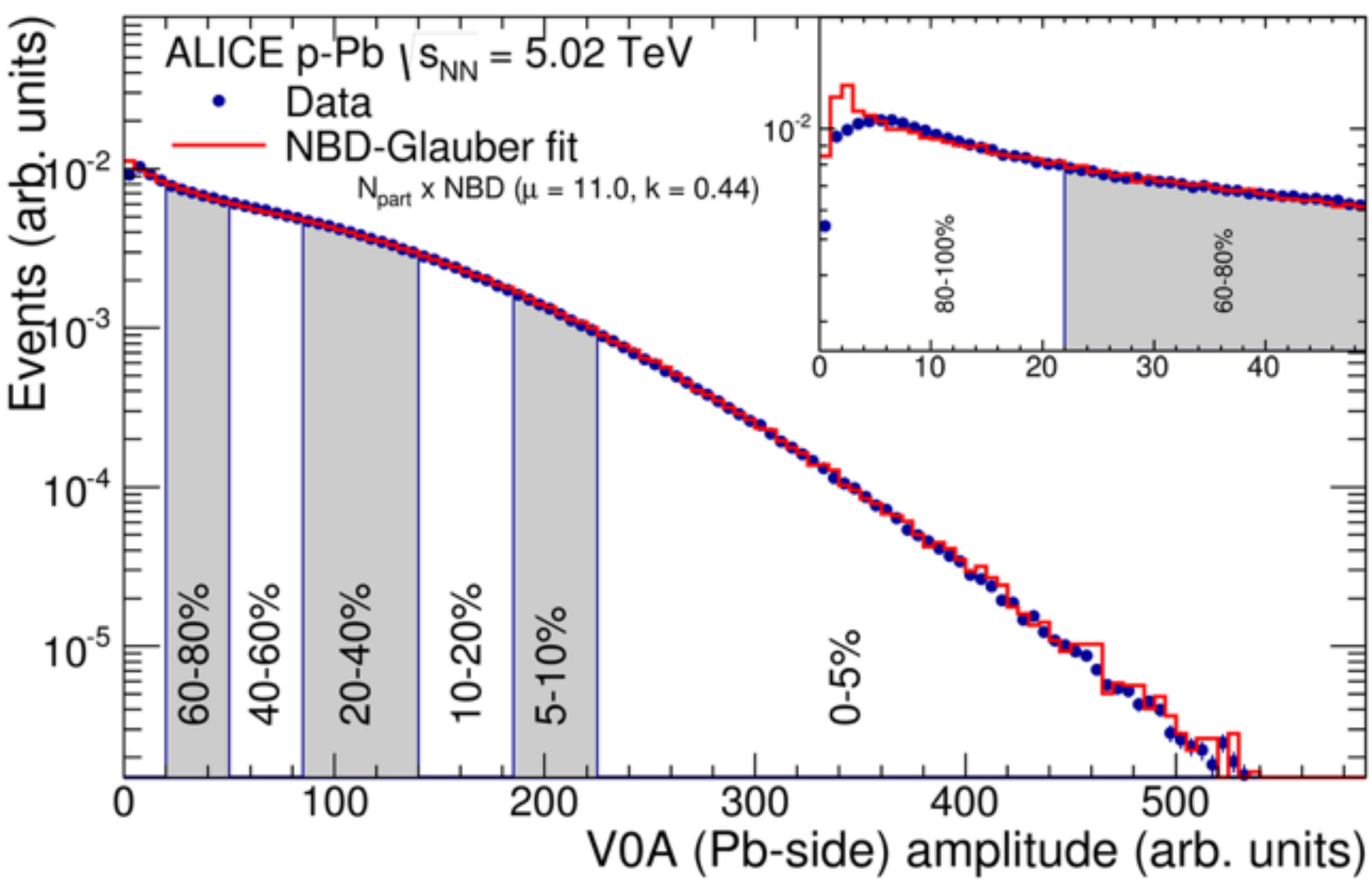
- Event sample divided into classes based on signal in forward V0 detector



ALI-PERF-51387

p-Pb multiplicity classes

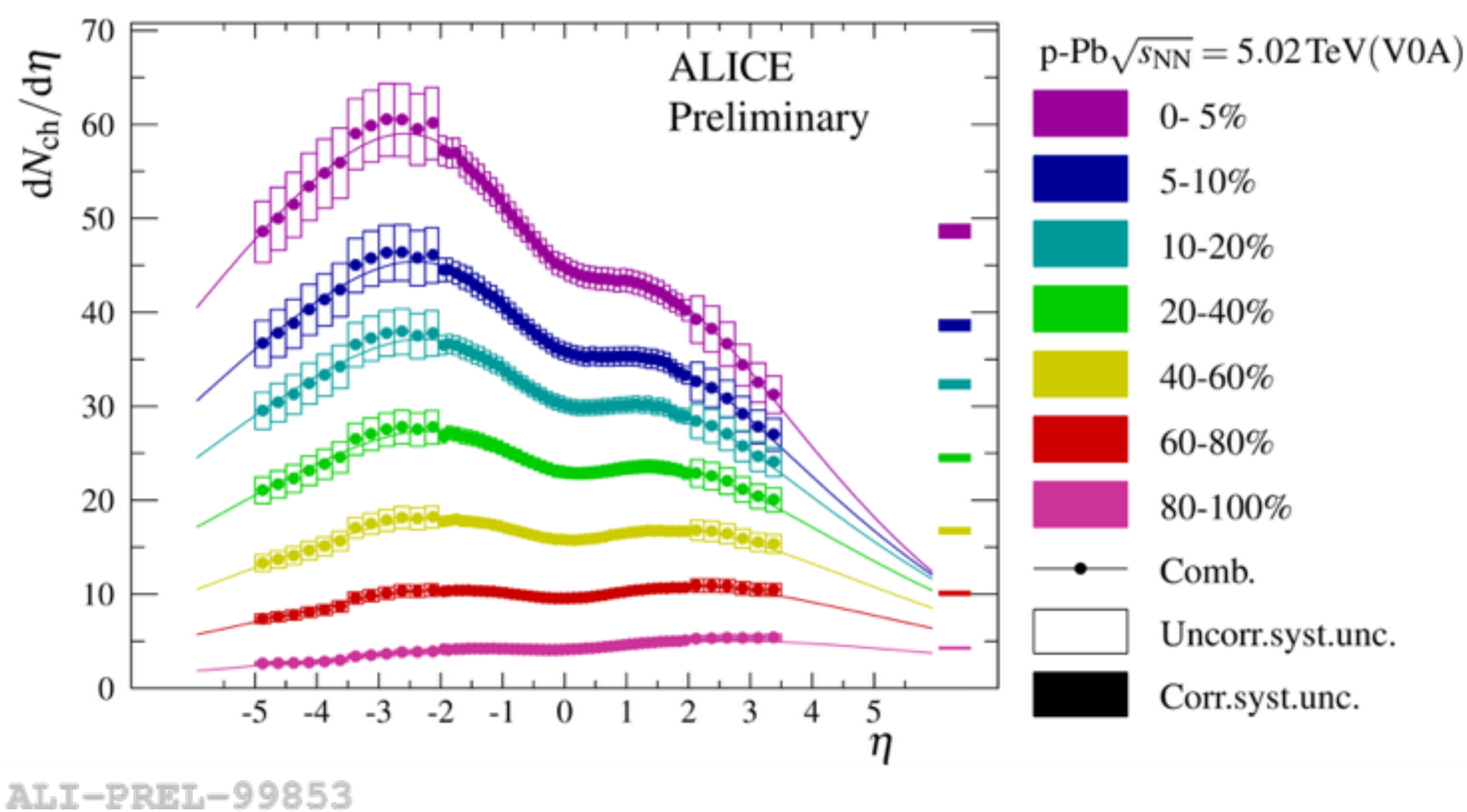
- Event sample divided into classes based on signal in forward V0 detector
- Connection to N_{part} explored further in publication



ALICE, Phys. Rev. C 91, 064905 (2015)

p-Pb dN/dη distribution

- $dN_{ch}/d\eta$ for multiplicity classes selected with the V0A scintillator ($-5.1 < \eta < -2.8$)
- measured with FMD and SPD



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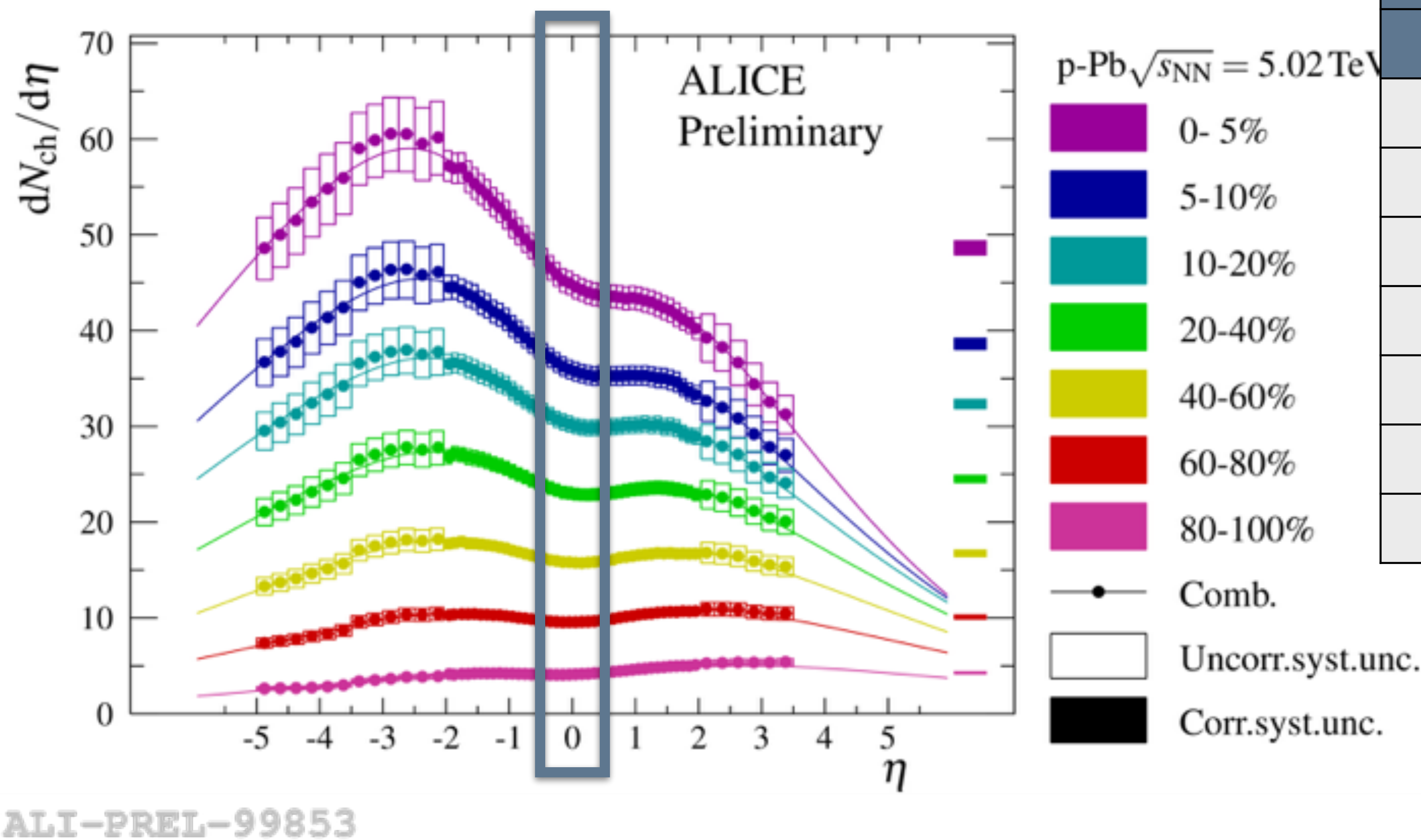
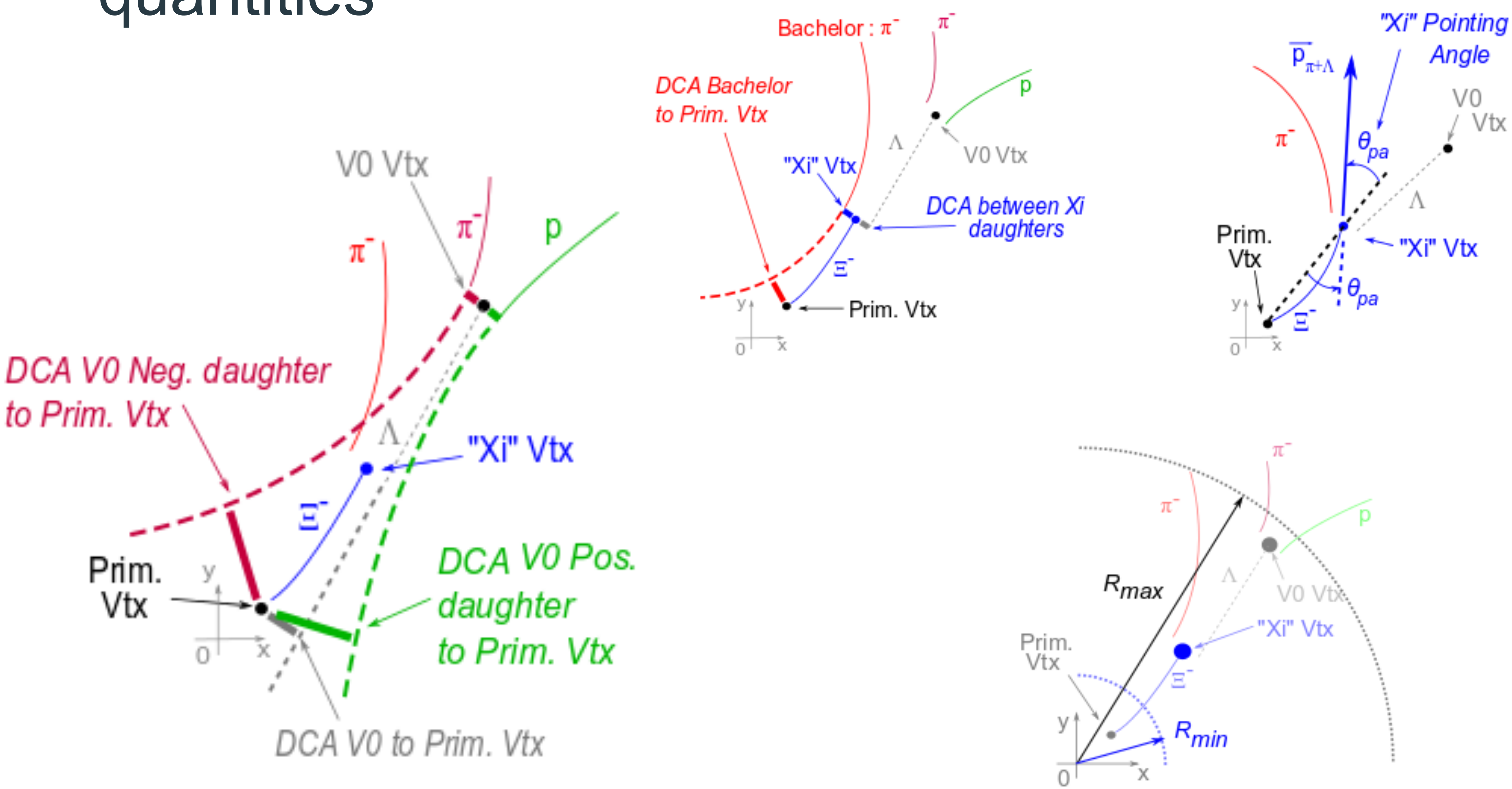


$dN_{ch}/d\eta$
$\lvert\eta_{lab}\rvert < 0.5$
45±1
36.2±0.8
30.5±0.7
23.2±0.5
16.1±0.4
9.8±0.2
4.4±0.1

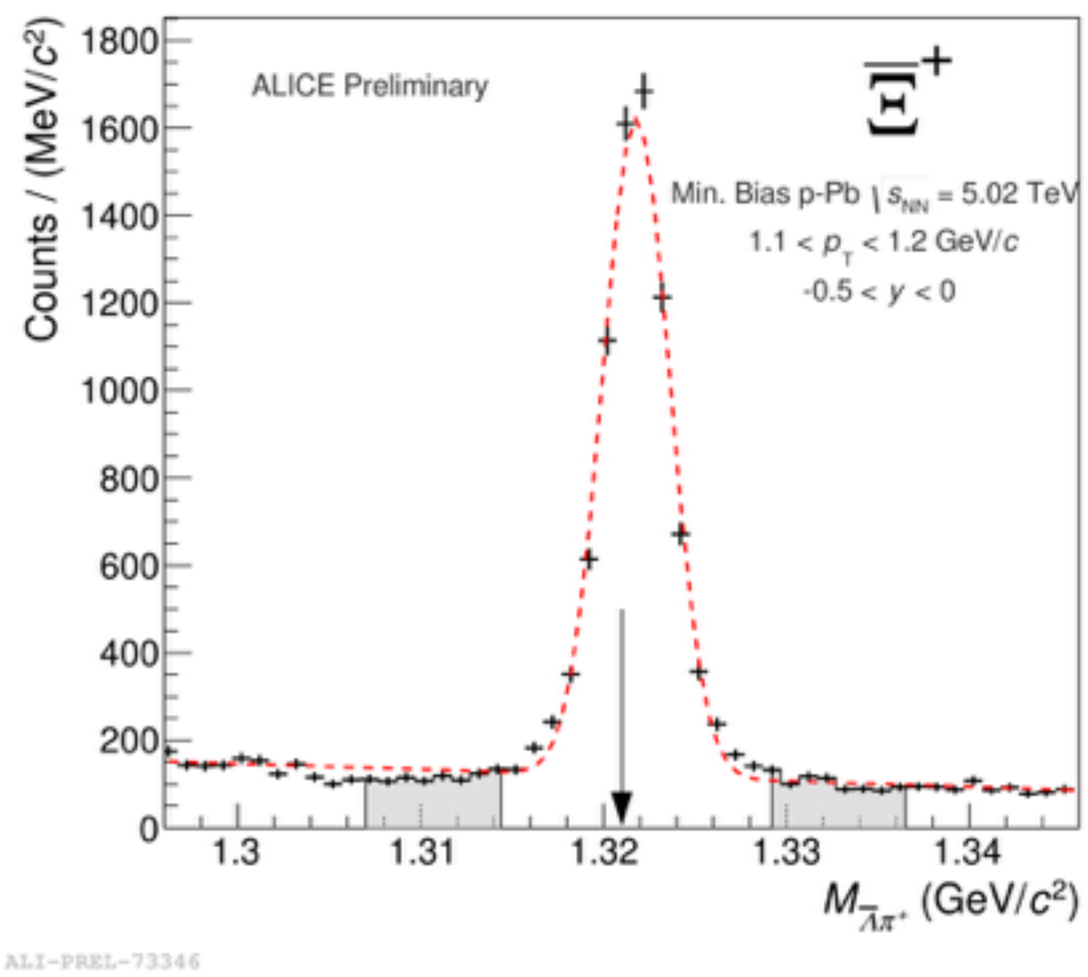
Multi-strange

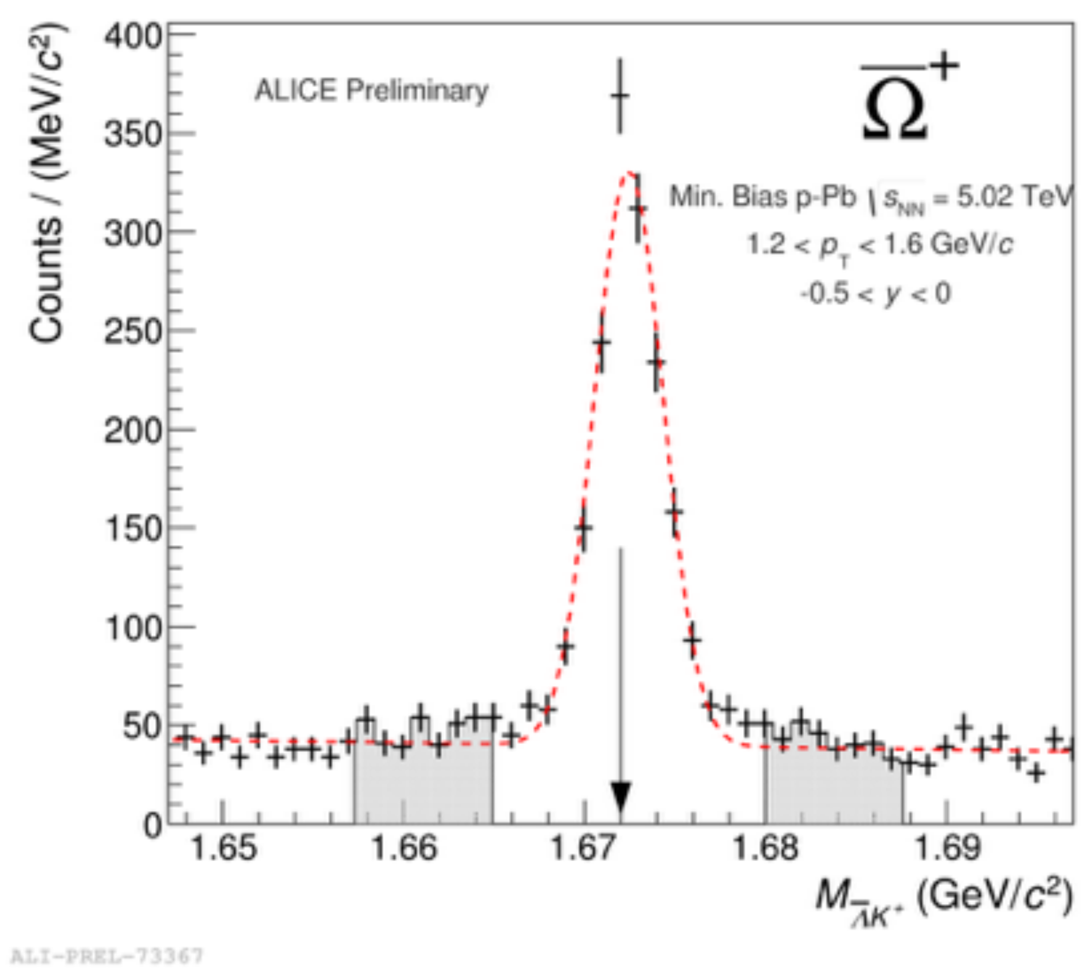
- Decay channels, reconstruction via geometrical quantities



Signal extraction

- Example peaks for $\overline{\Xi}^{+}$ and $\overline{\Omega}^{+}$ (minimum bias data) in their respective lowest p_T bins





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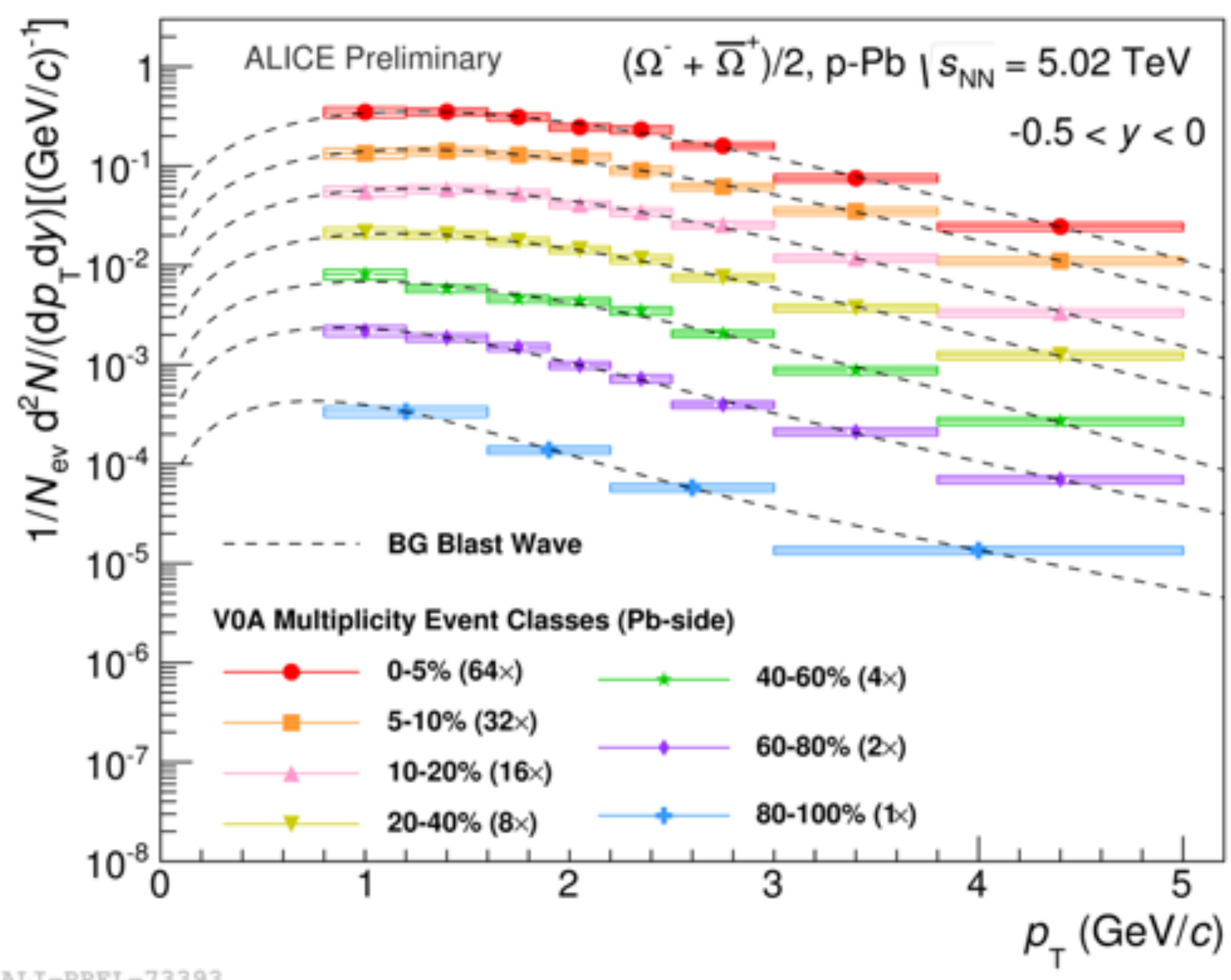
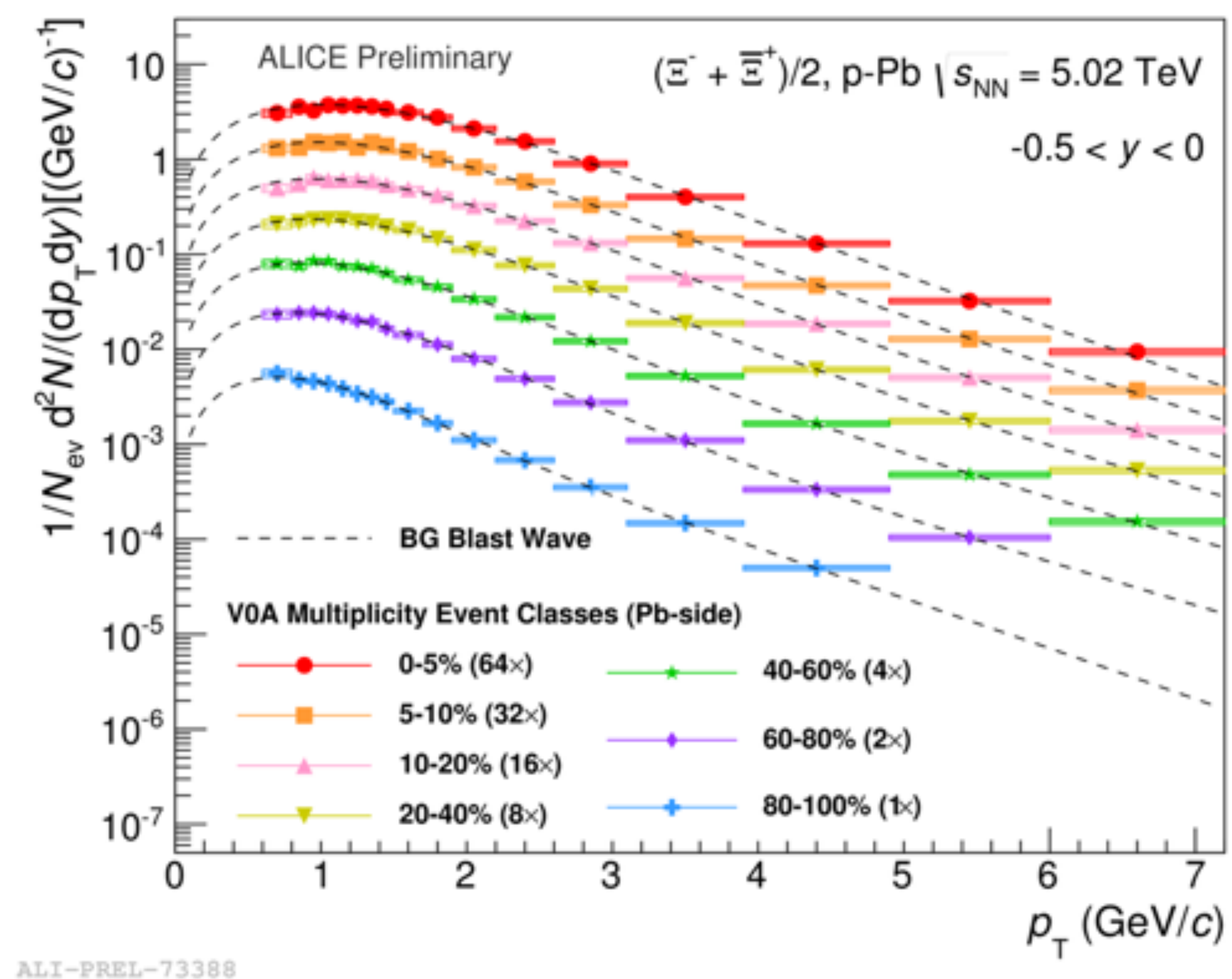
Transverse momentum spectra

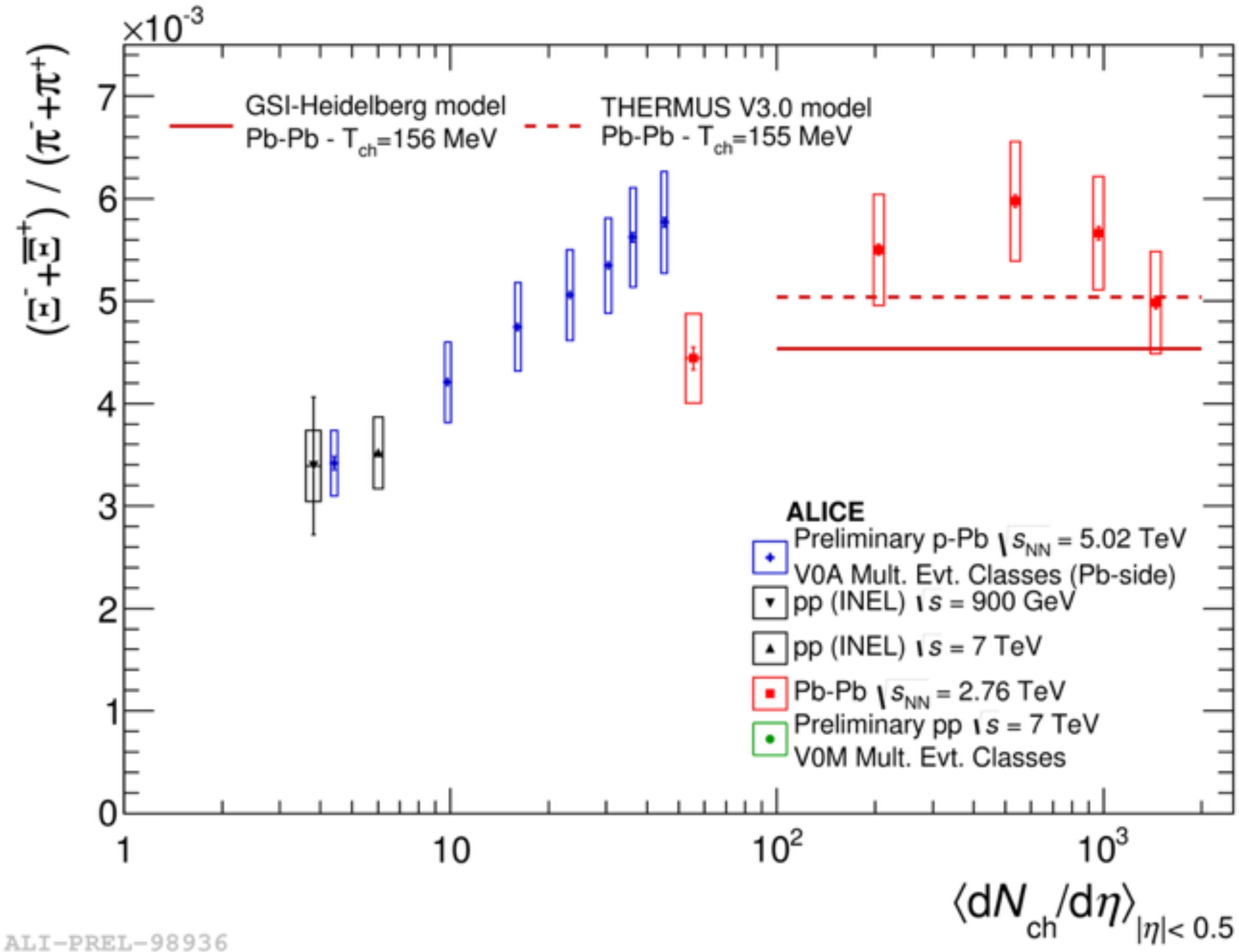
- Spectra in V0A multiplicity classes
- dN/dy extracted by extrapolating spectra to $p_T = 0$





Ξ/π

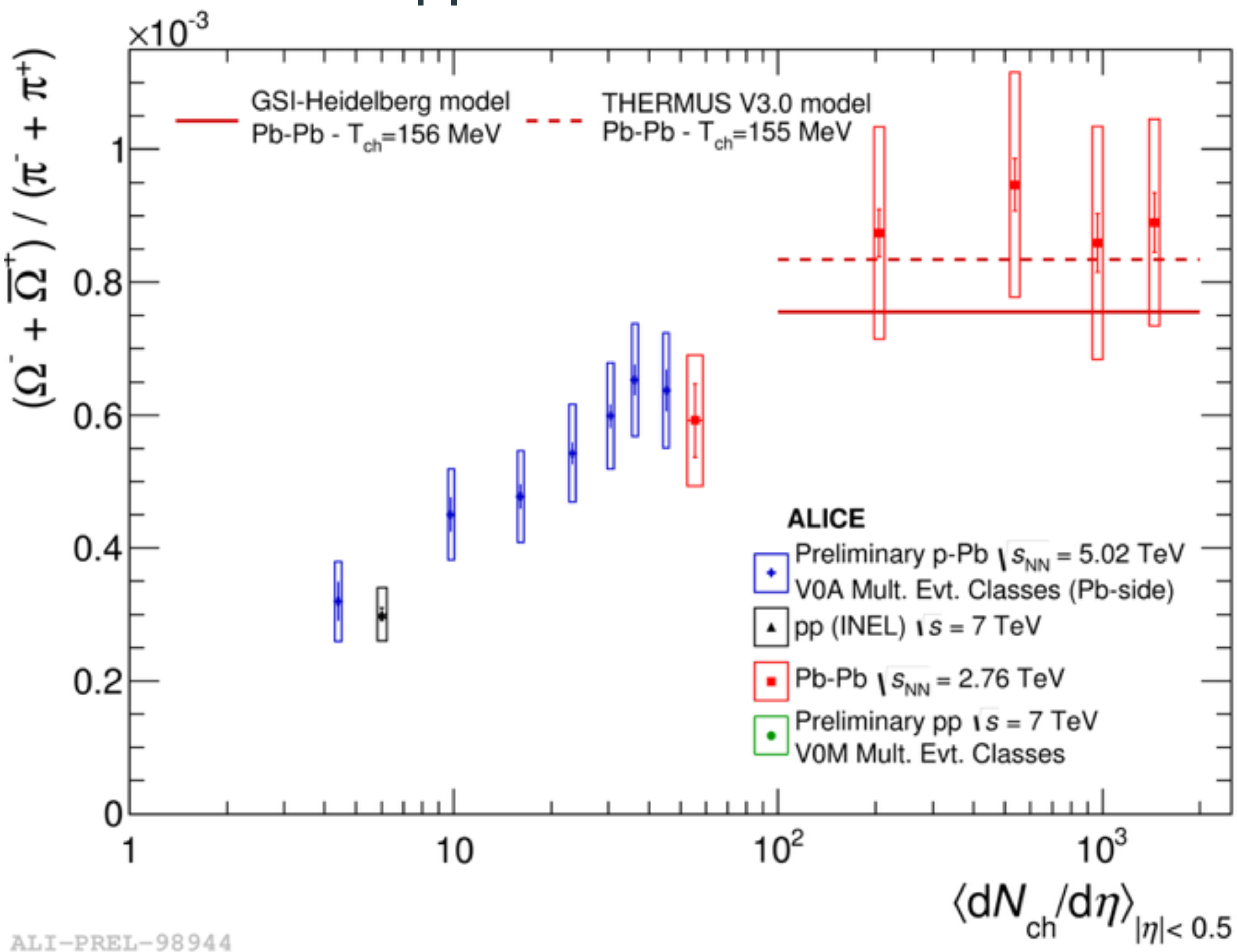
- Ratio to π
- Shown with pp and Pb-Pb data



- Rise of around 60% within p-Pb dN/dη range
- Reaches values seen in Pb-Pb

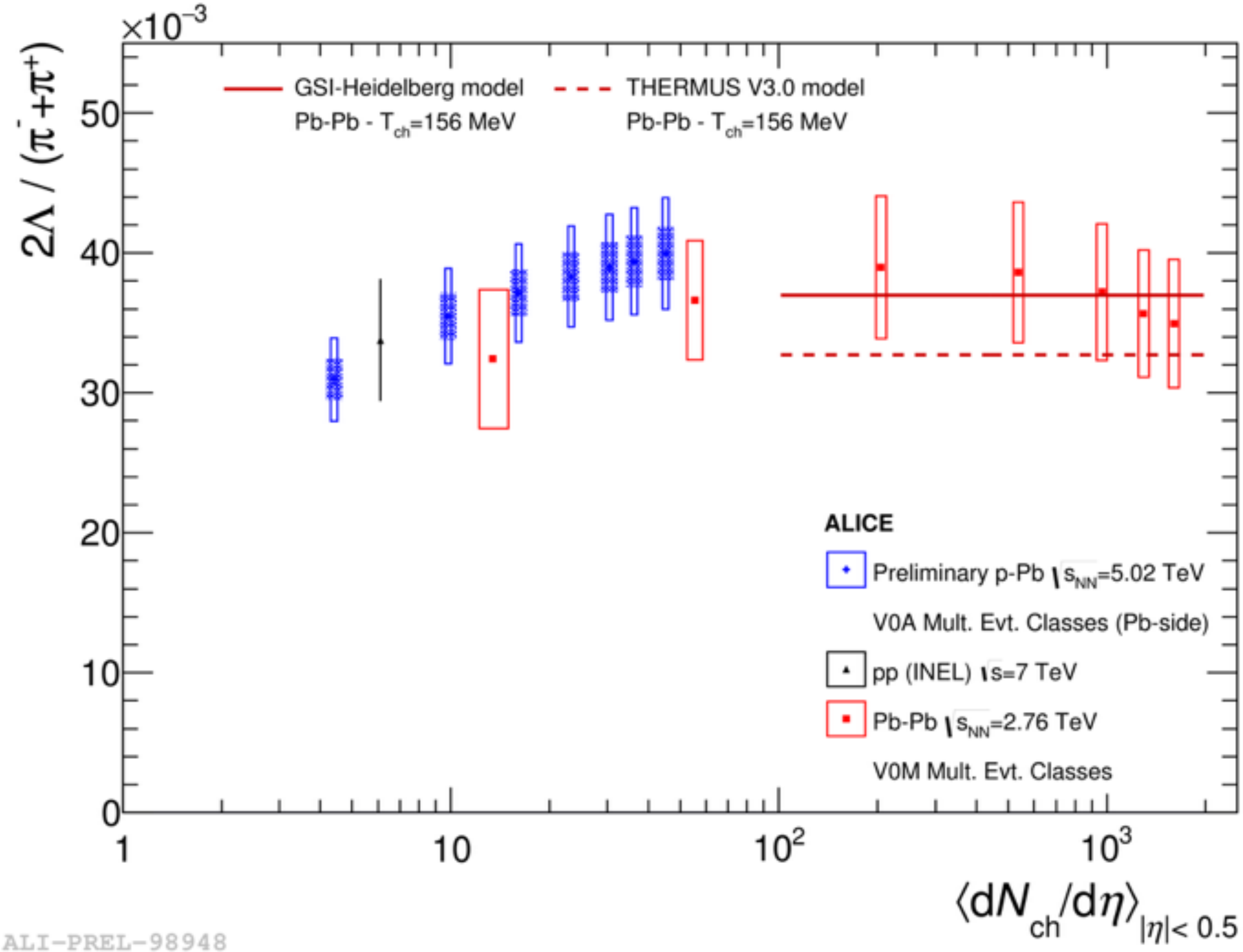
Ω/π

- Ratio to π
- Shown with pp and Pb-Pb data



- Strong rise of factor ~2 within p-Pb dN/dη range
- Does not reach highest Pb-Pb values

Λ/π ratio



- Modest, ~30%, rise also visible in Λ/π

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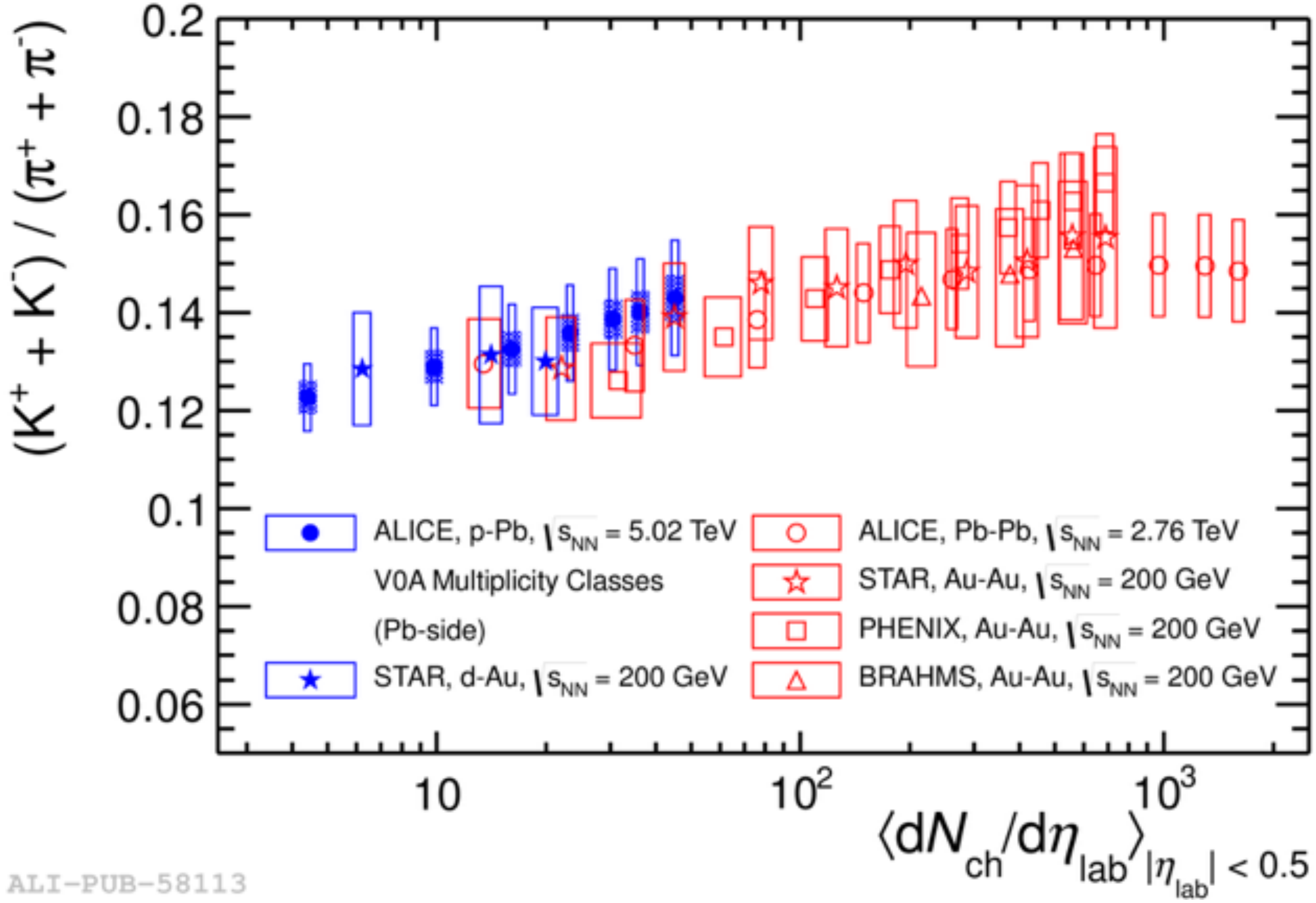
K/π



- Rise in p-Pb comparable with Λ/π
  - ie Λ/K ratio is flat

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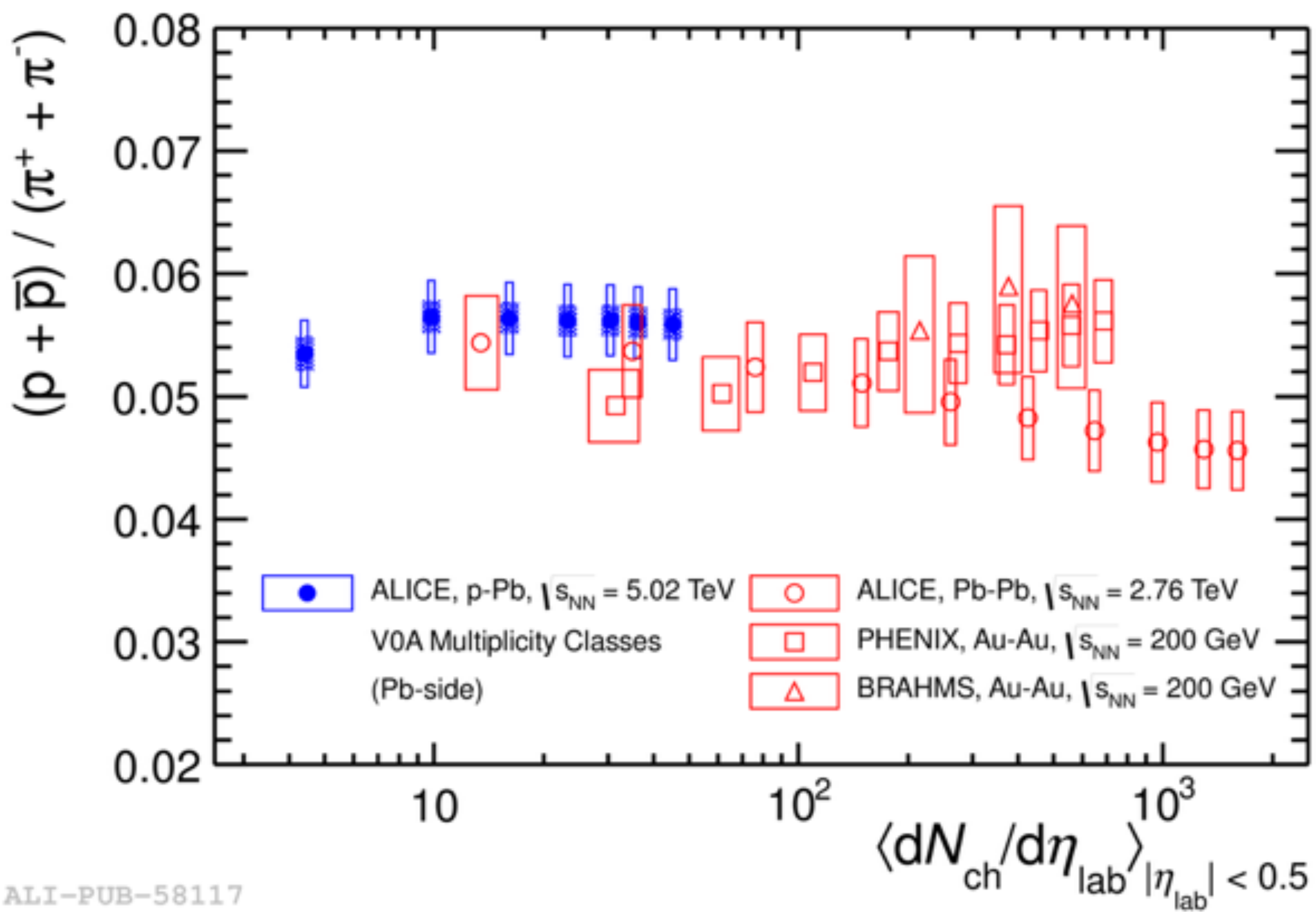
p/π



- Does not change with dN/dη in p-Pb but falling trend in Pb-Pb
  - is it significant
  - not discussed further in this talk

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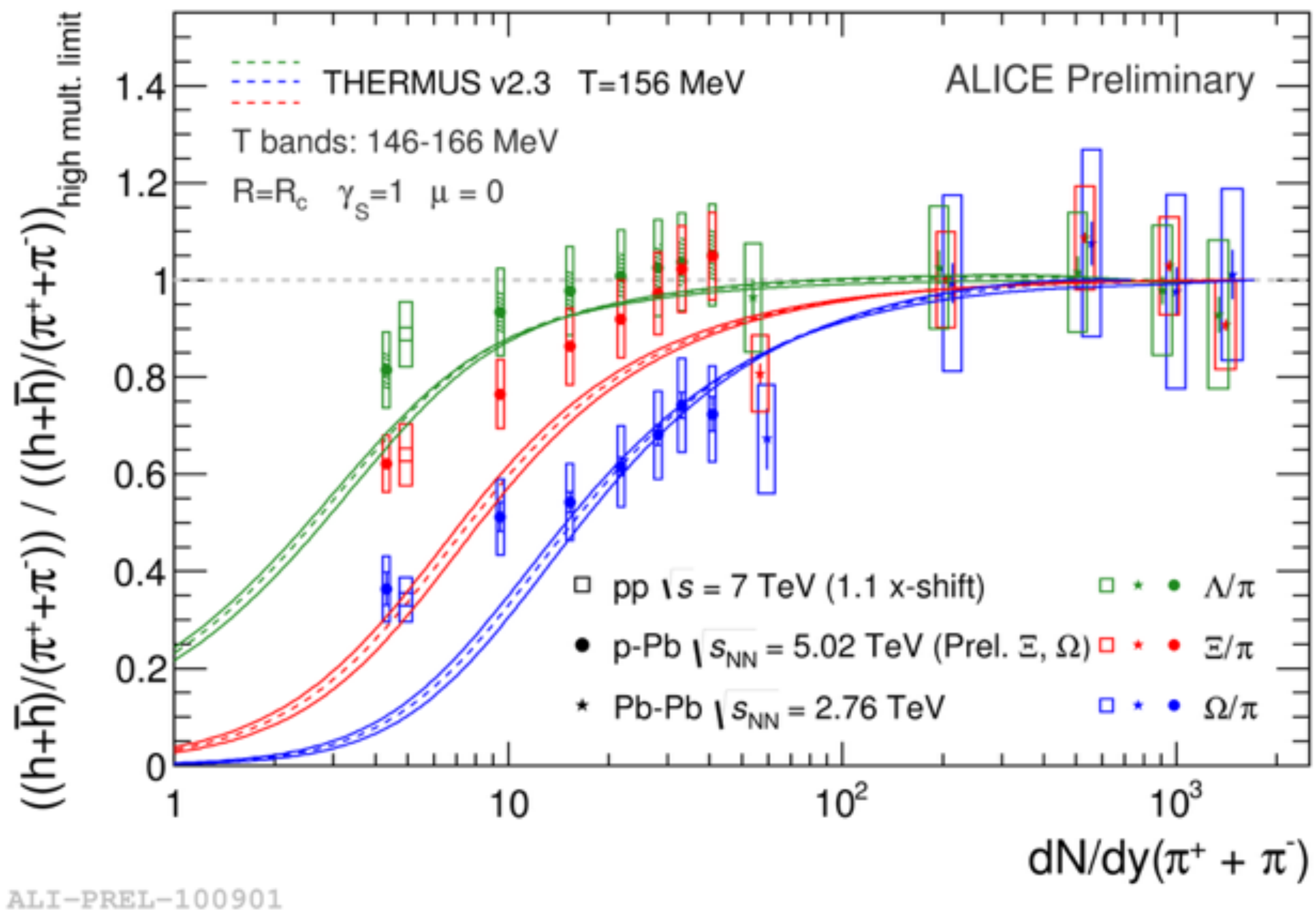
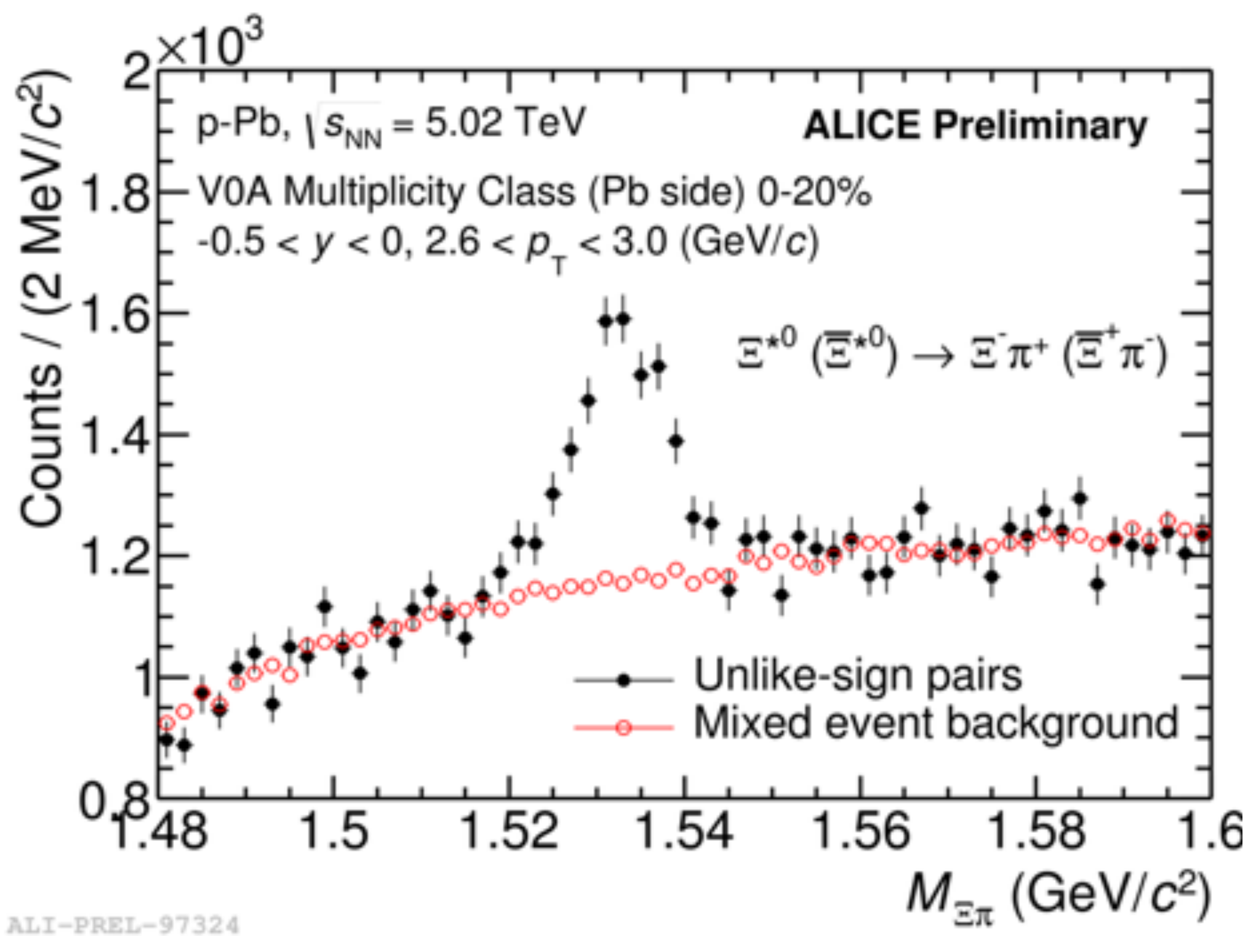
Canonical suppression

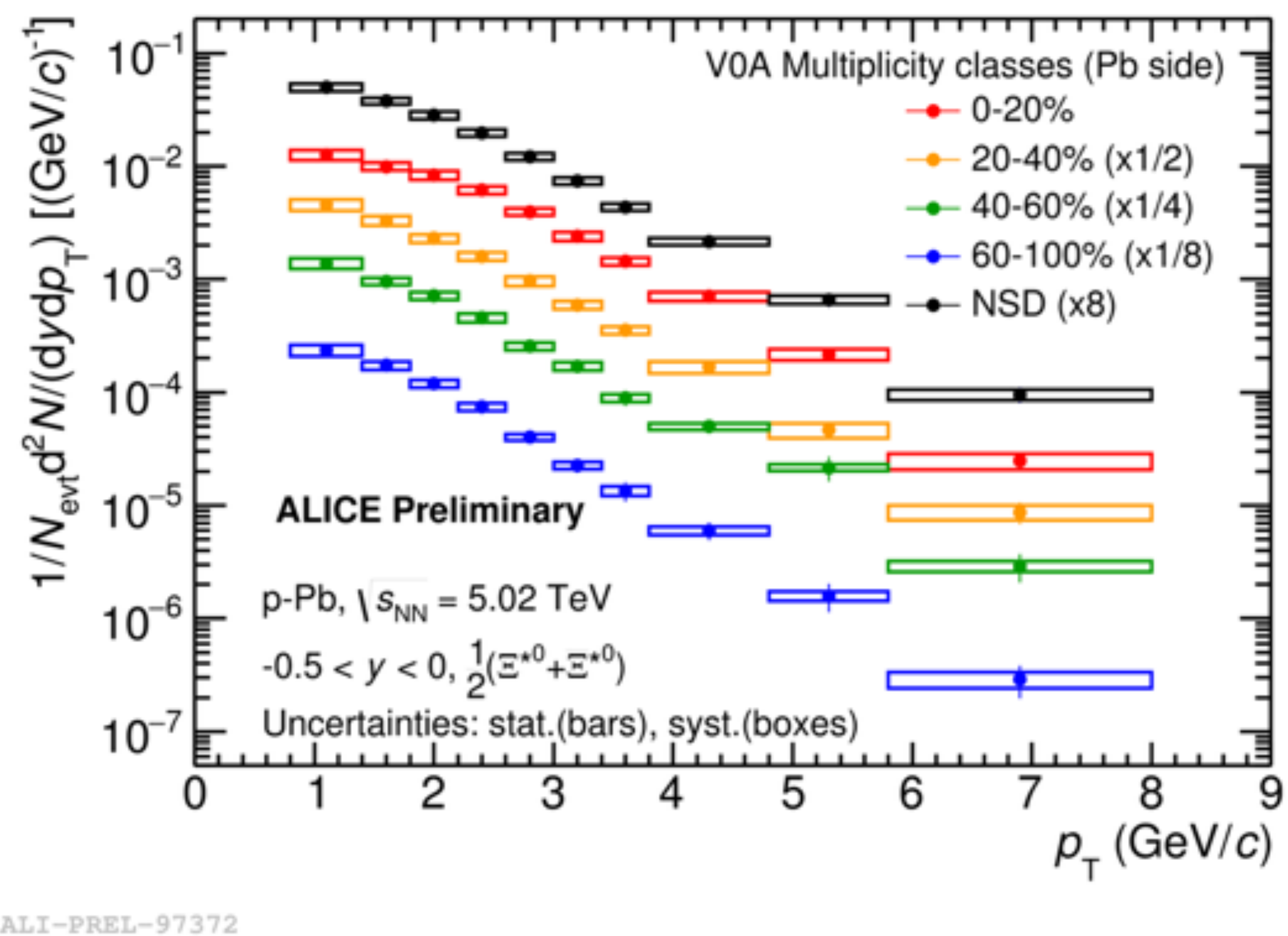


- Calculated with THERMUS
- Ratios normalised to 'large volume' values
  - fit to Pb-Pb data
  - large volume limit in model

Ξ*(1530)

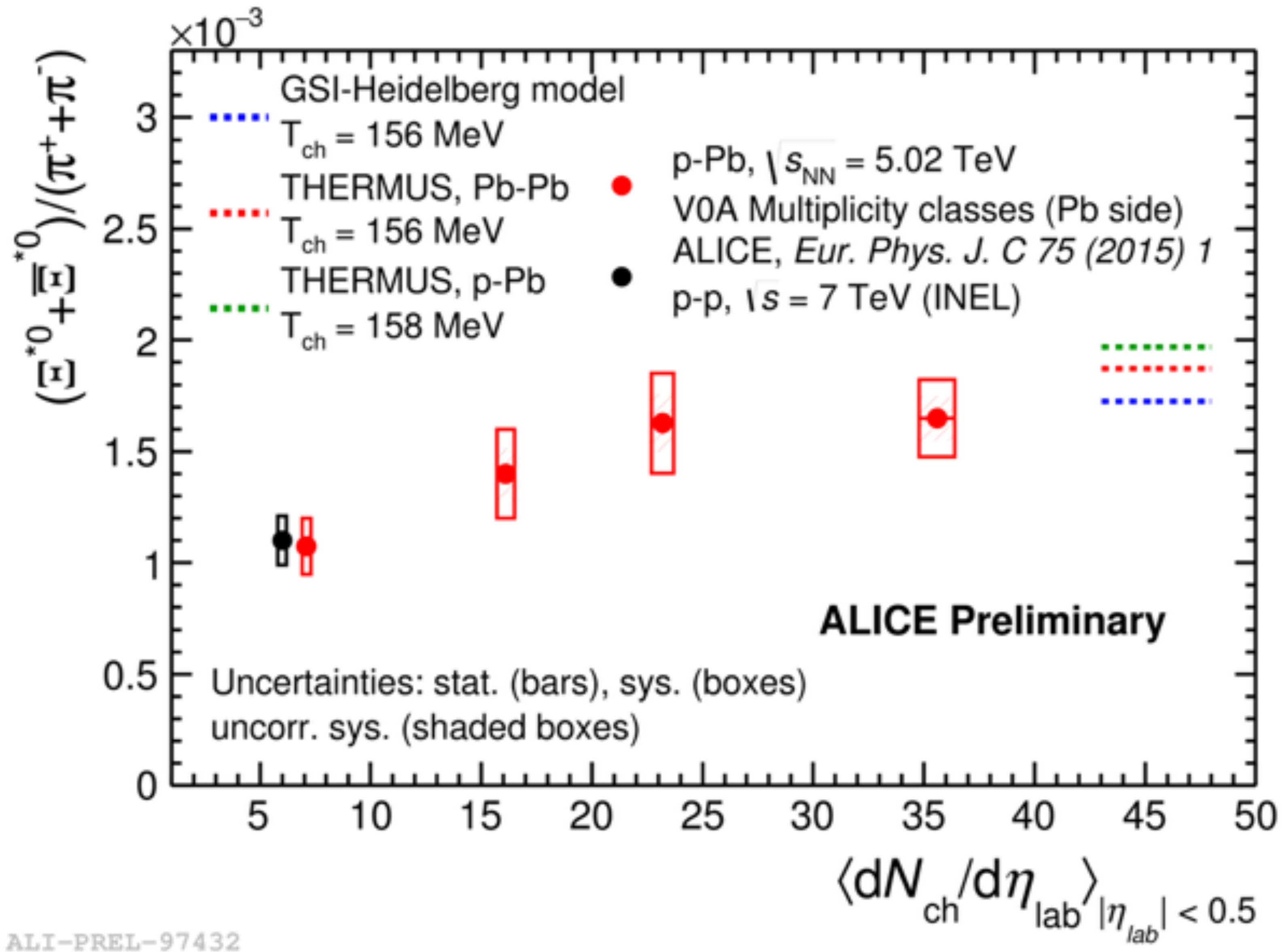
- Heavy resonance intermediate in mass Ξ*→Ξπ
- Closer to Ω(1672) than Ξ(1322), S = -2





Ξ*(1530) part 2

- Ξ*/π ratio shows rise compatible with that of Ξ/π
  - i.e. ratio Ξ */Ξ is flat as a function of multiplicity
  - strangeness content more important than mass



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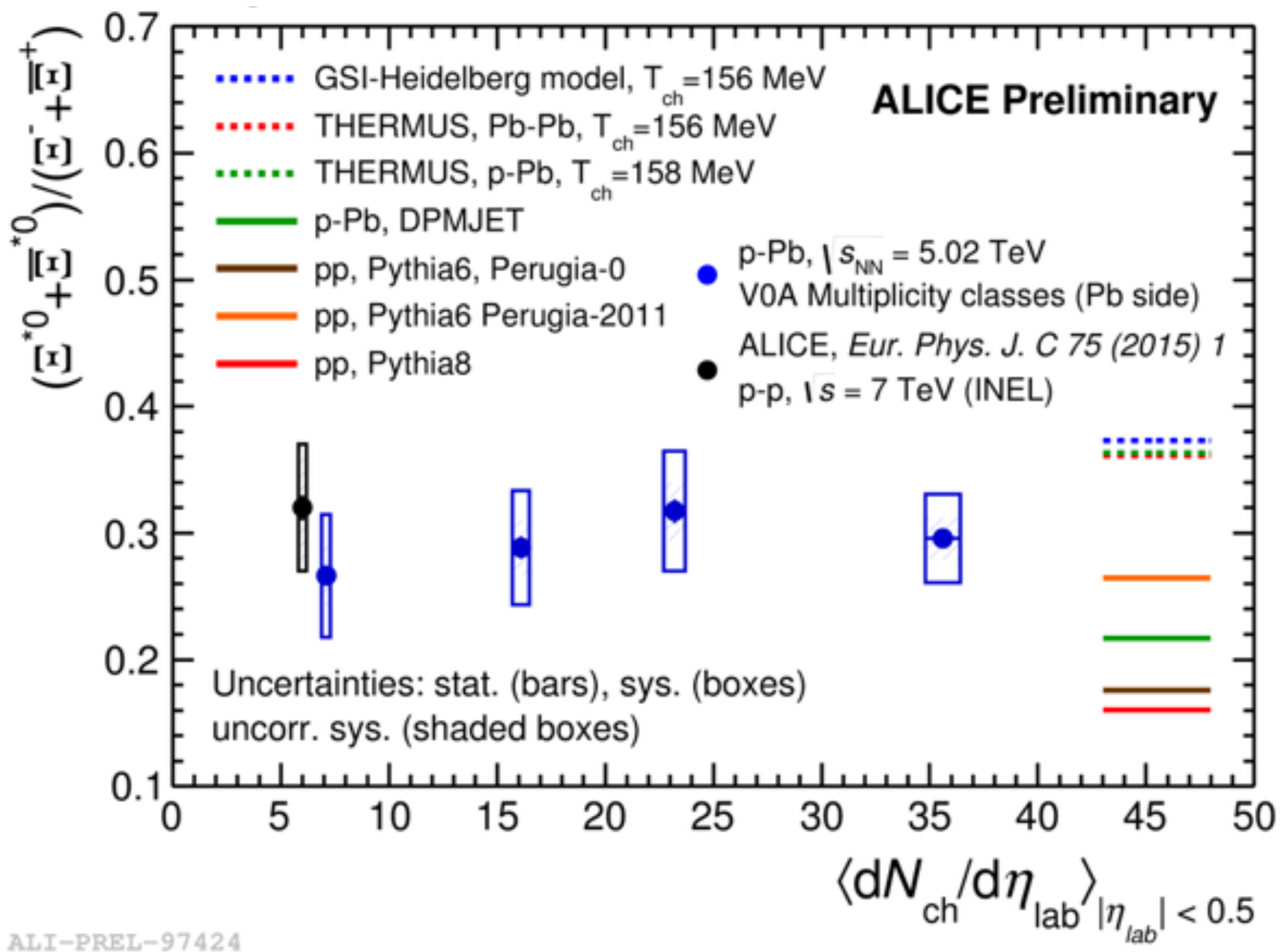
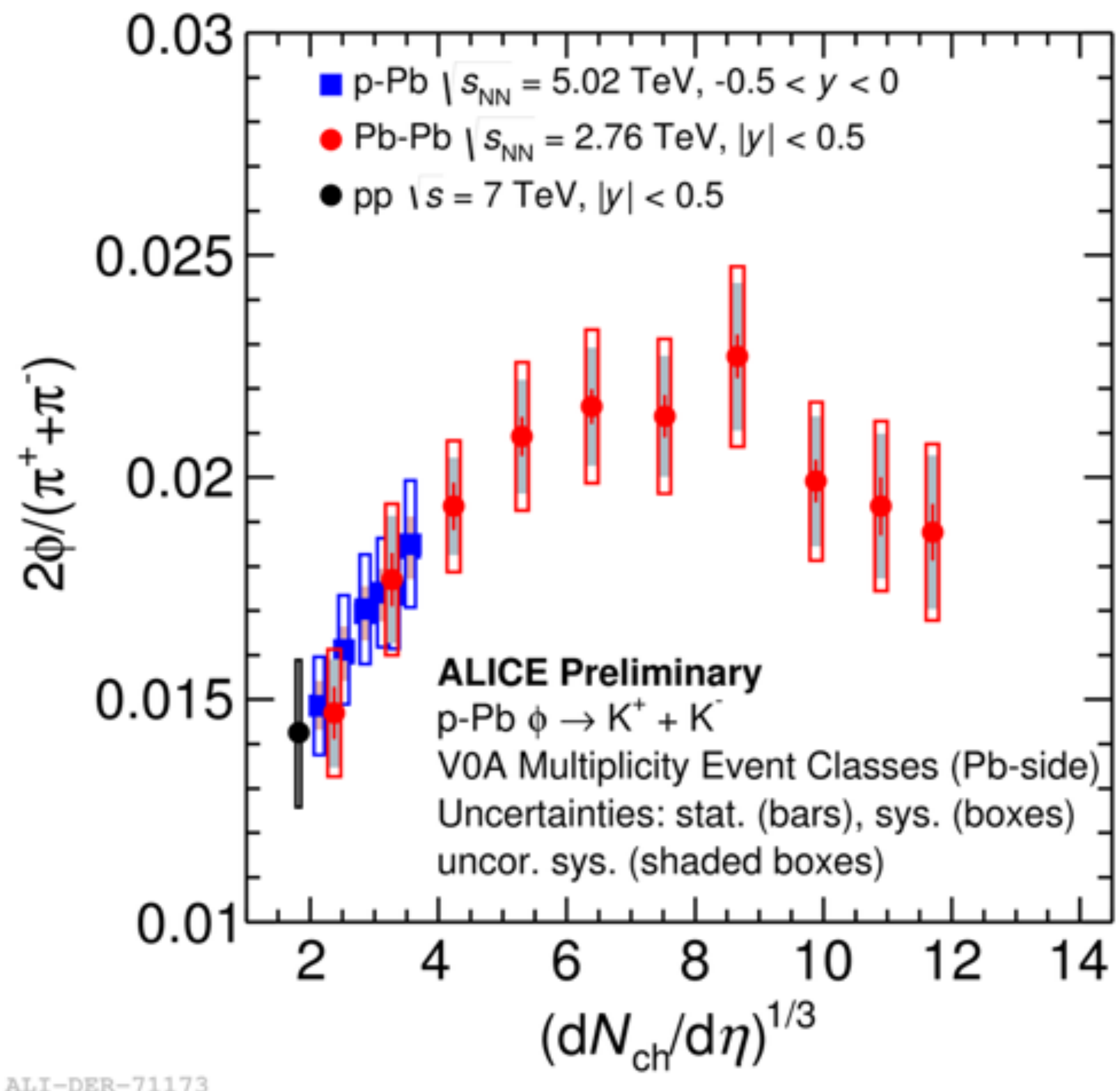


More resonances

- ϕ meson



- Rise in p-Pb dN/dη range
- Would not fit into canonical suppression picture
  - net S=0

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proton-proton analysis

pp analysis

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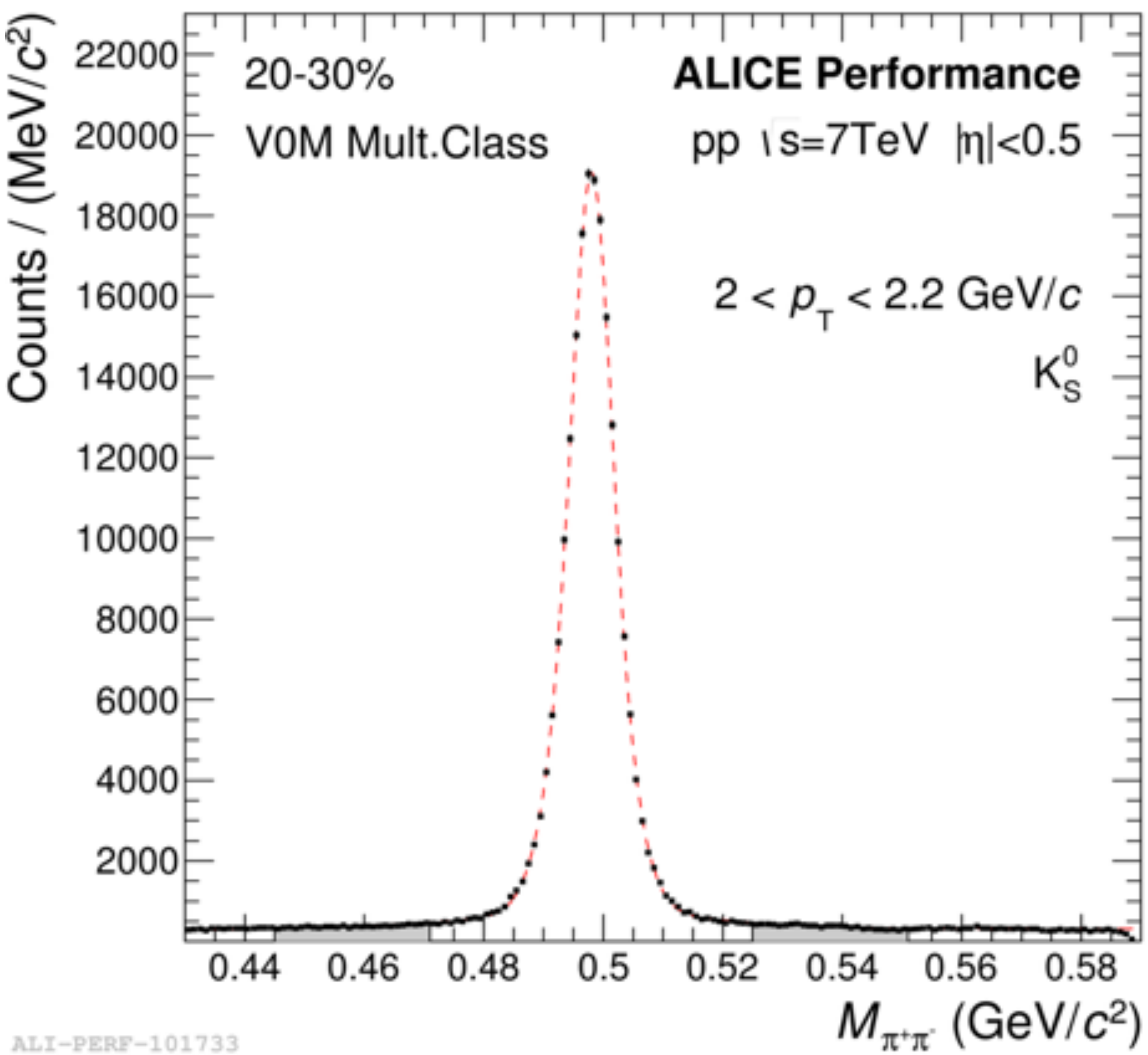
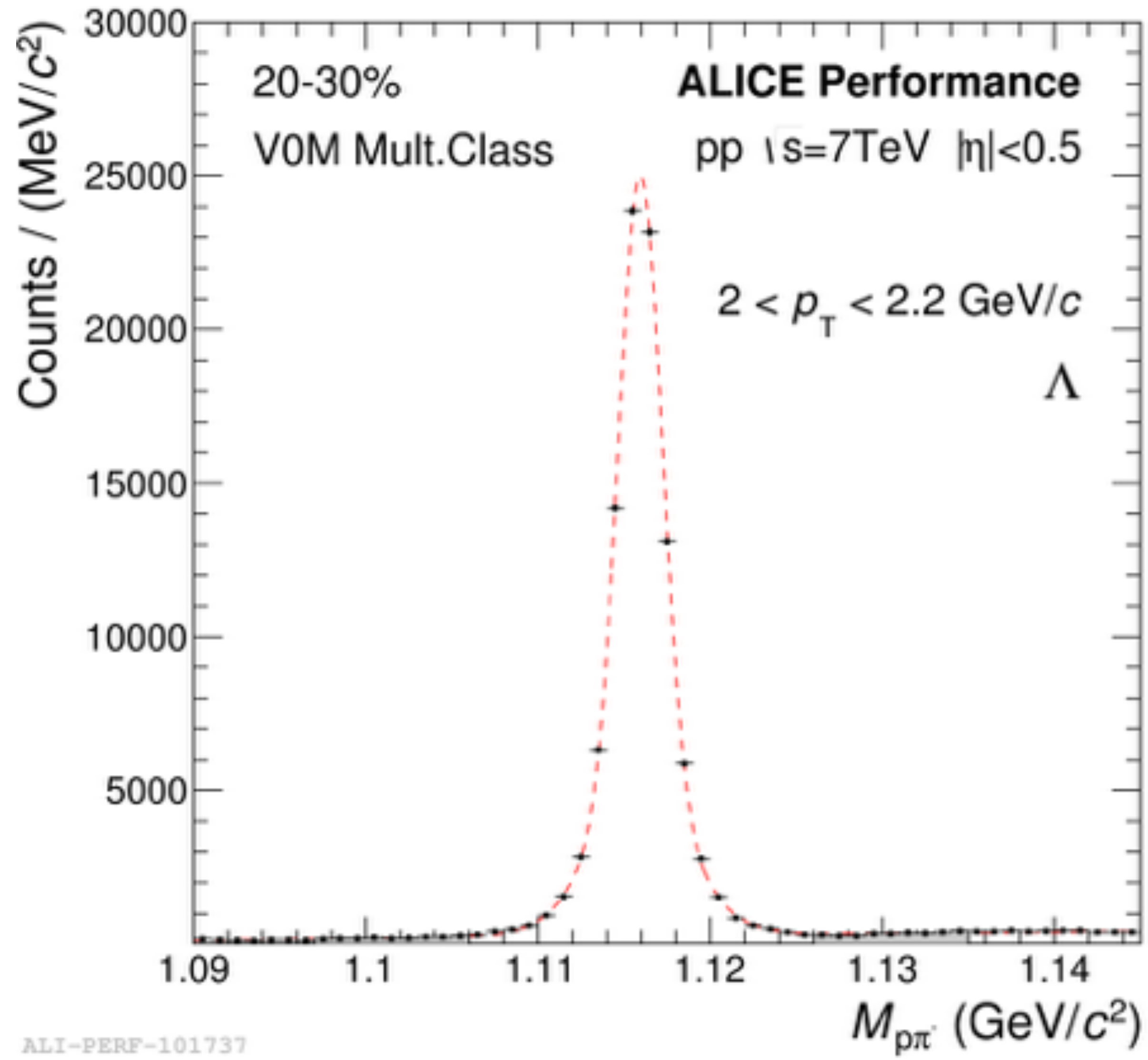
- 7 TeV minimum bias dataset (2010)
- Divide into multiplicity classes based on sum of signals in V0A and V0C detectors
  - V0M = **V0** su**M**
  - Recall V0A alone was used in p-Pb because that is the Pb-going side
  - In symmetric pp system the sum, covering $-5.1 < \eta < -2.8$ and $1.7 < \eta < 3.7$ is preferred to reduce influence of fluctuations

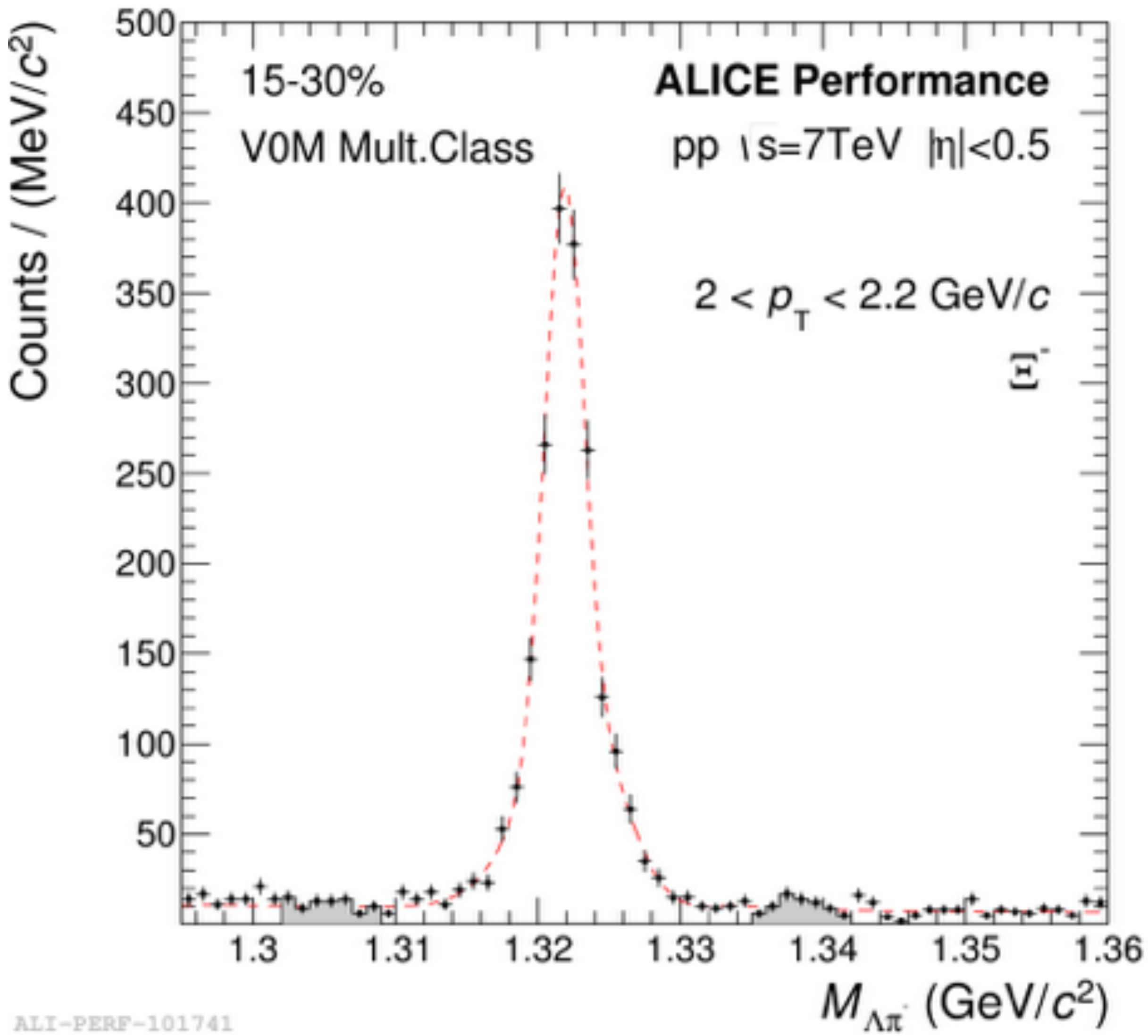
V^0 signal extraction pp

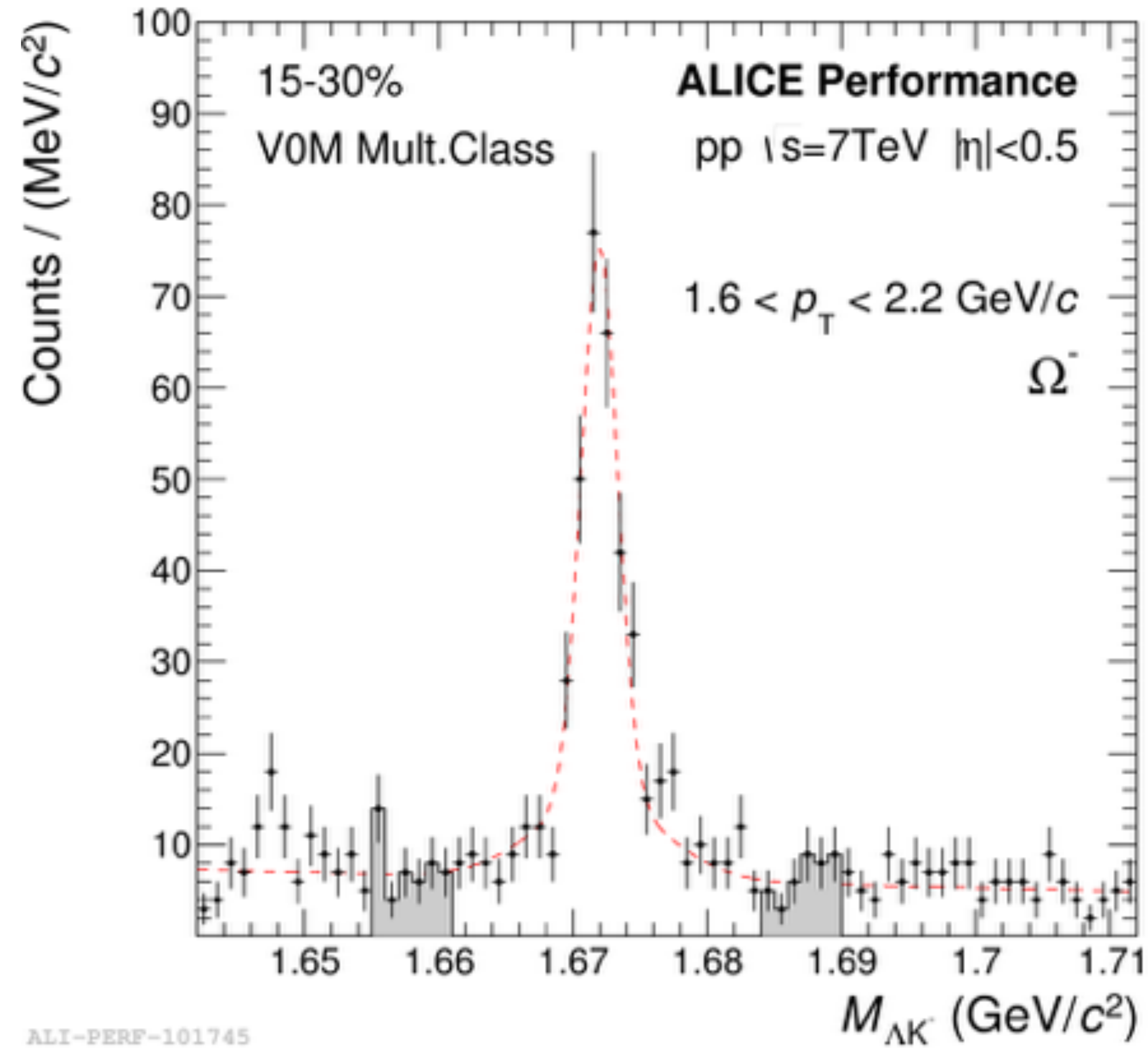
- Divided into several multiplicity classes
  - granularity depends on particle species





Multi-strange signal extraction pp





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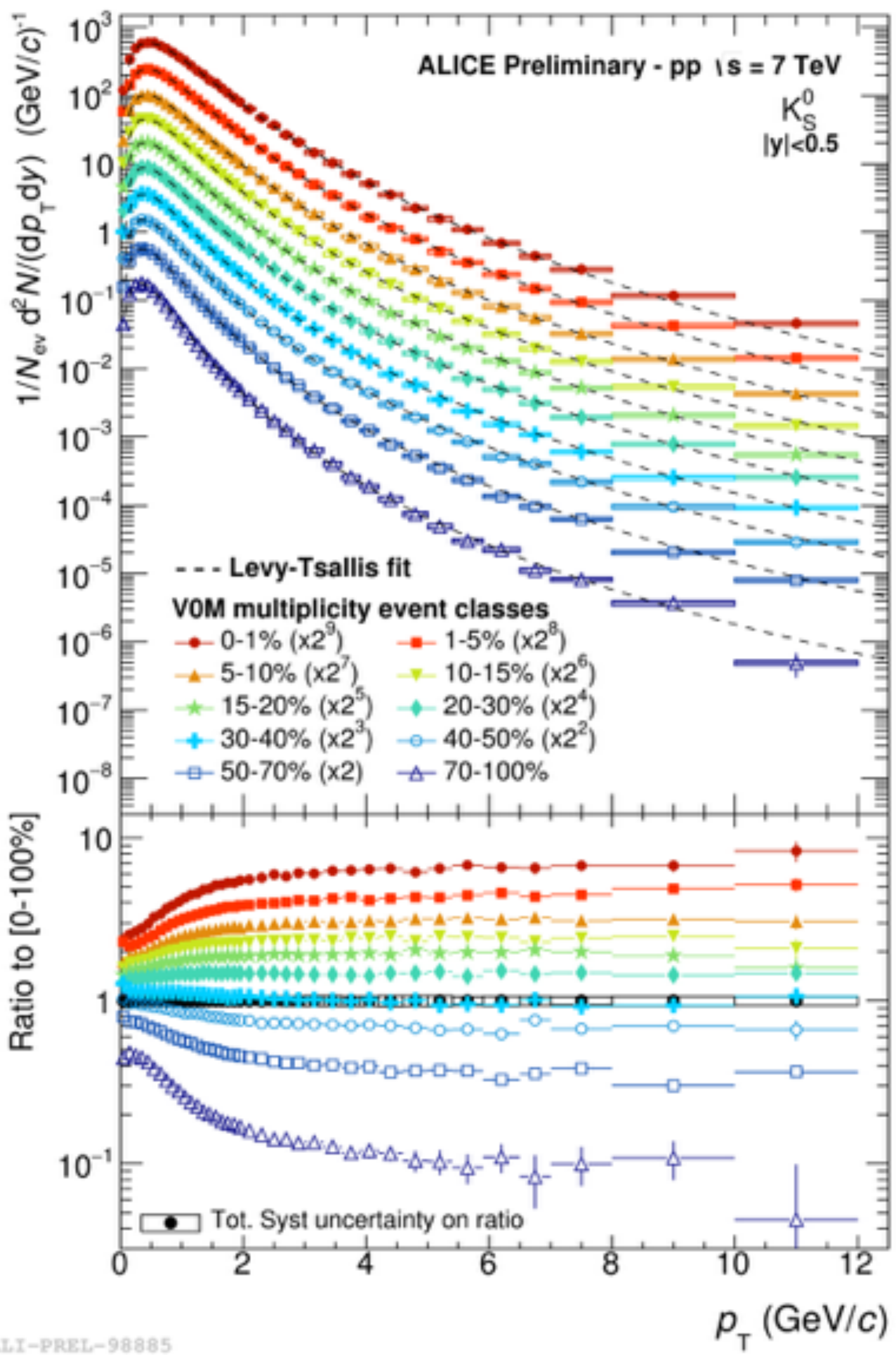
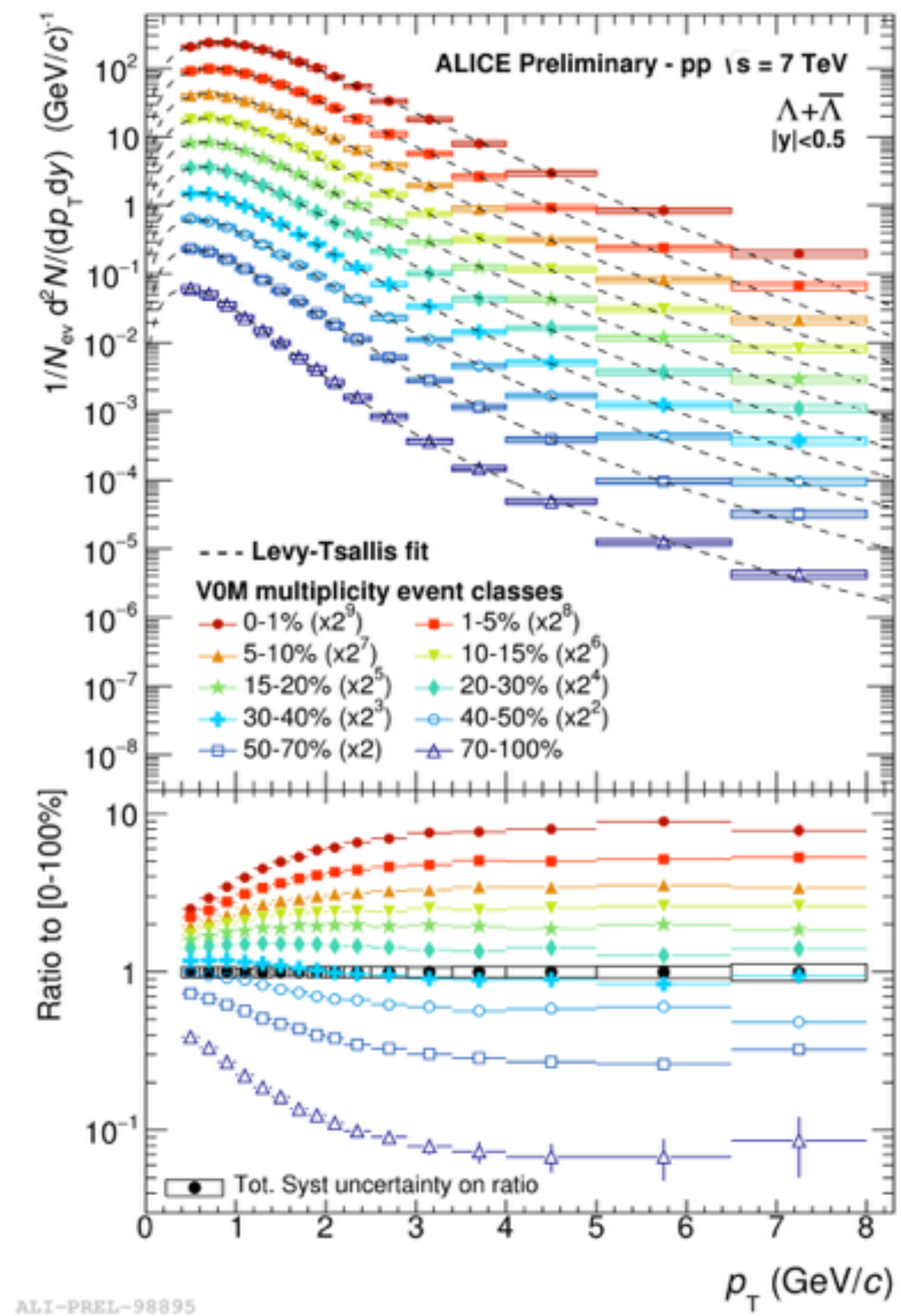
Multiplicity-dependent spectra: 7 TeV pp collisions





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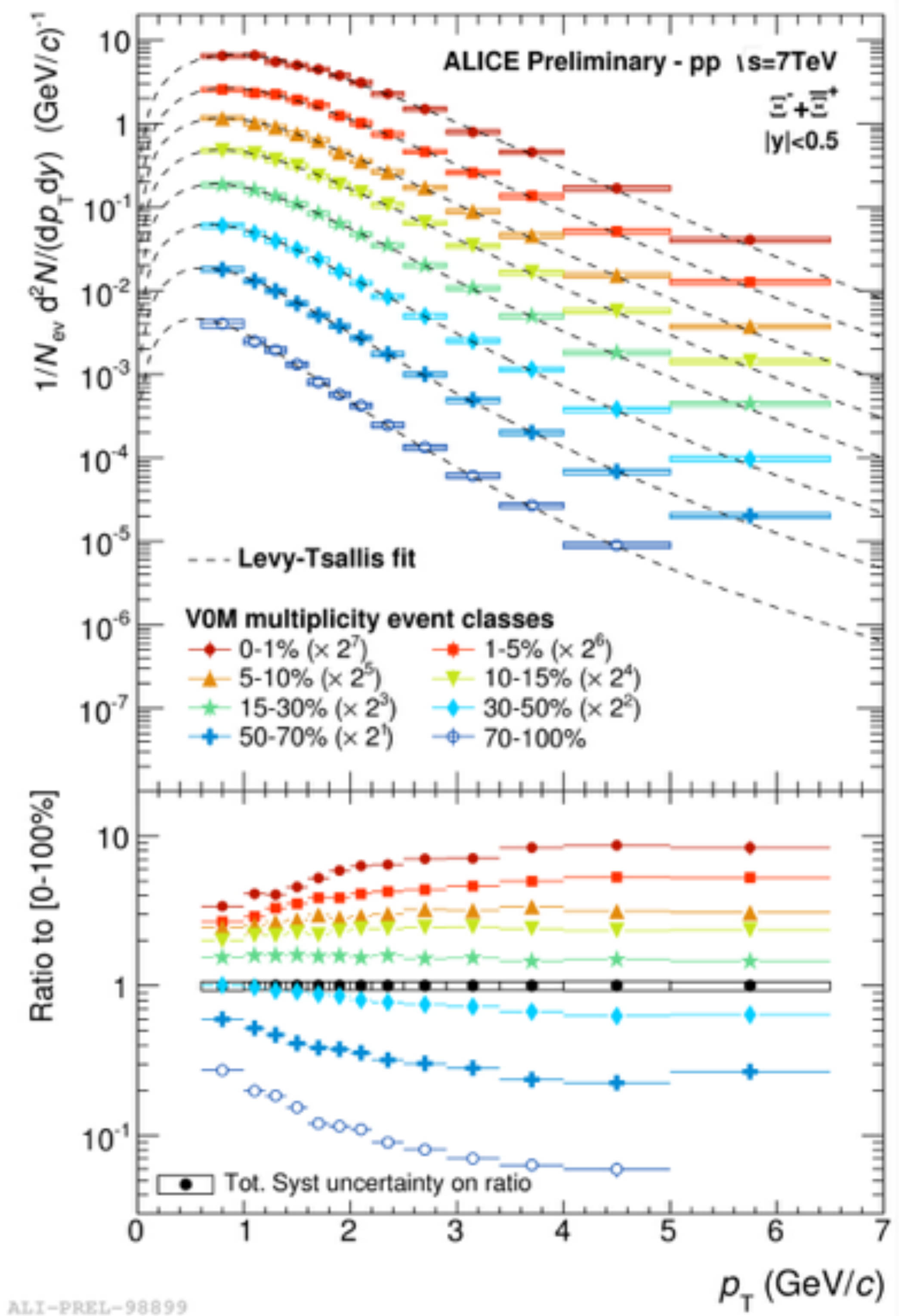
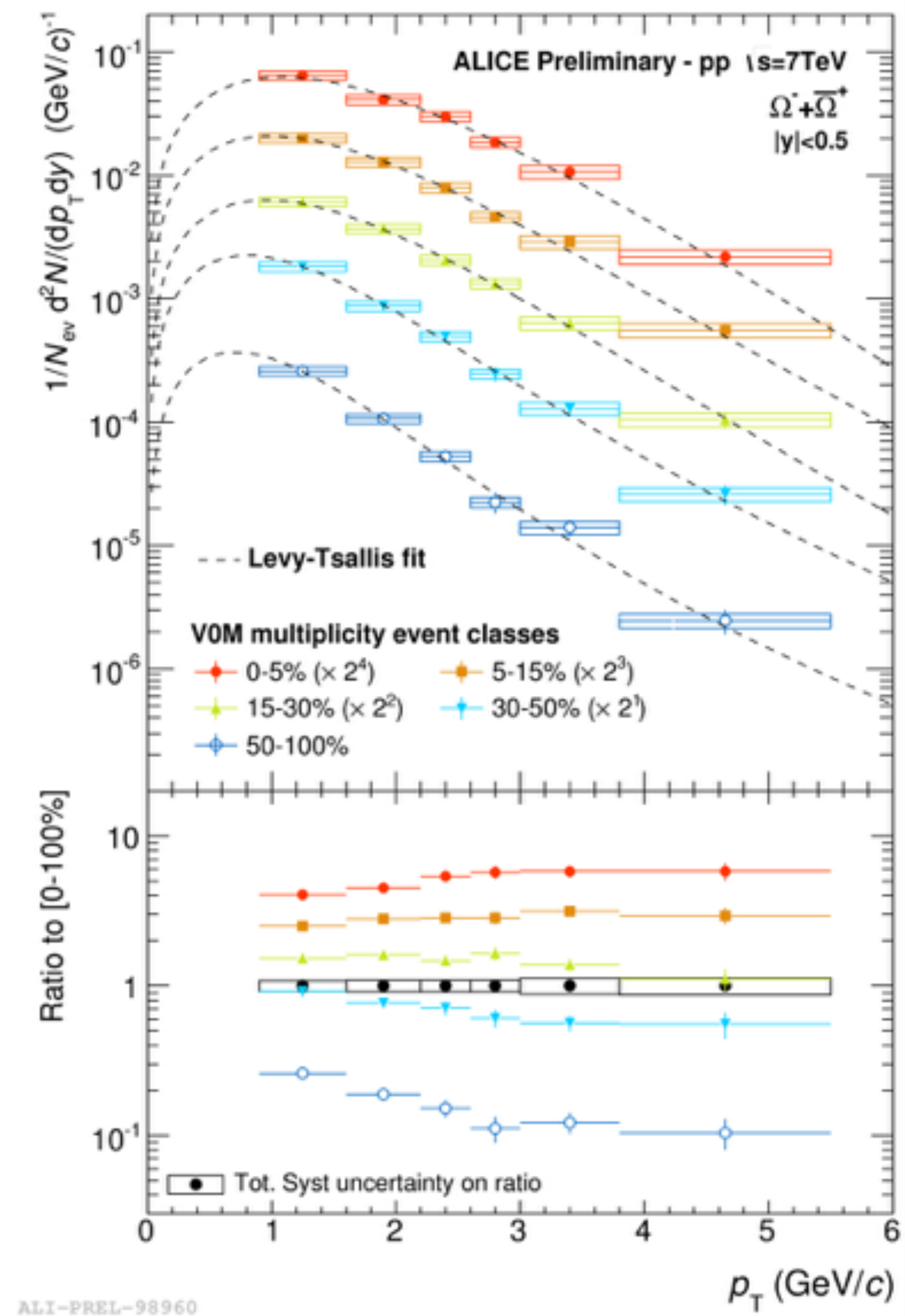
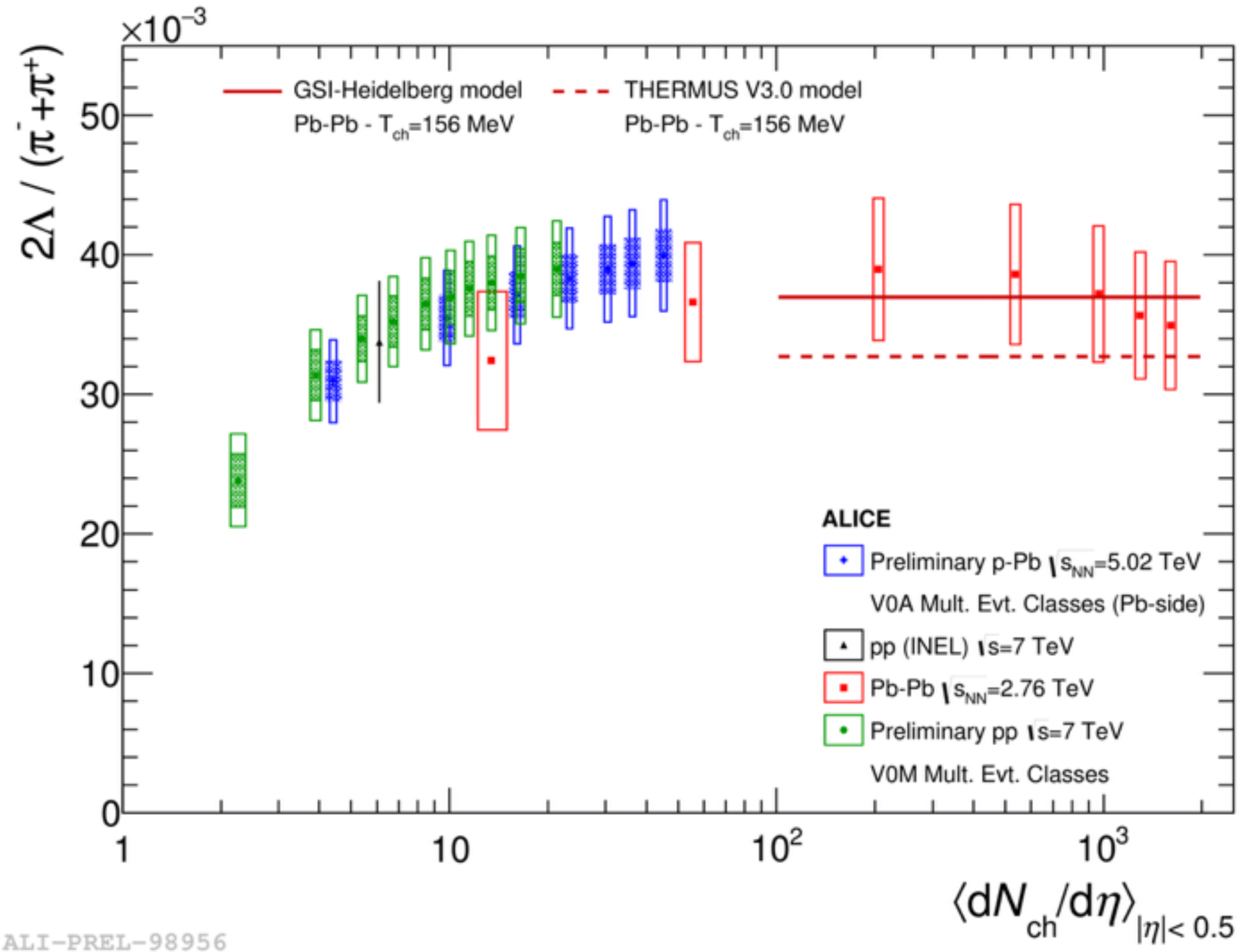




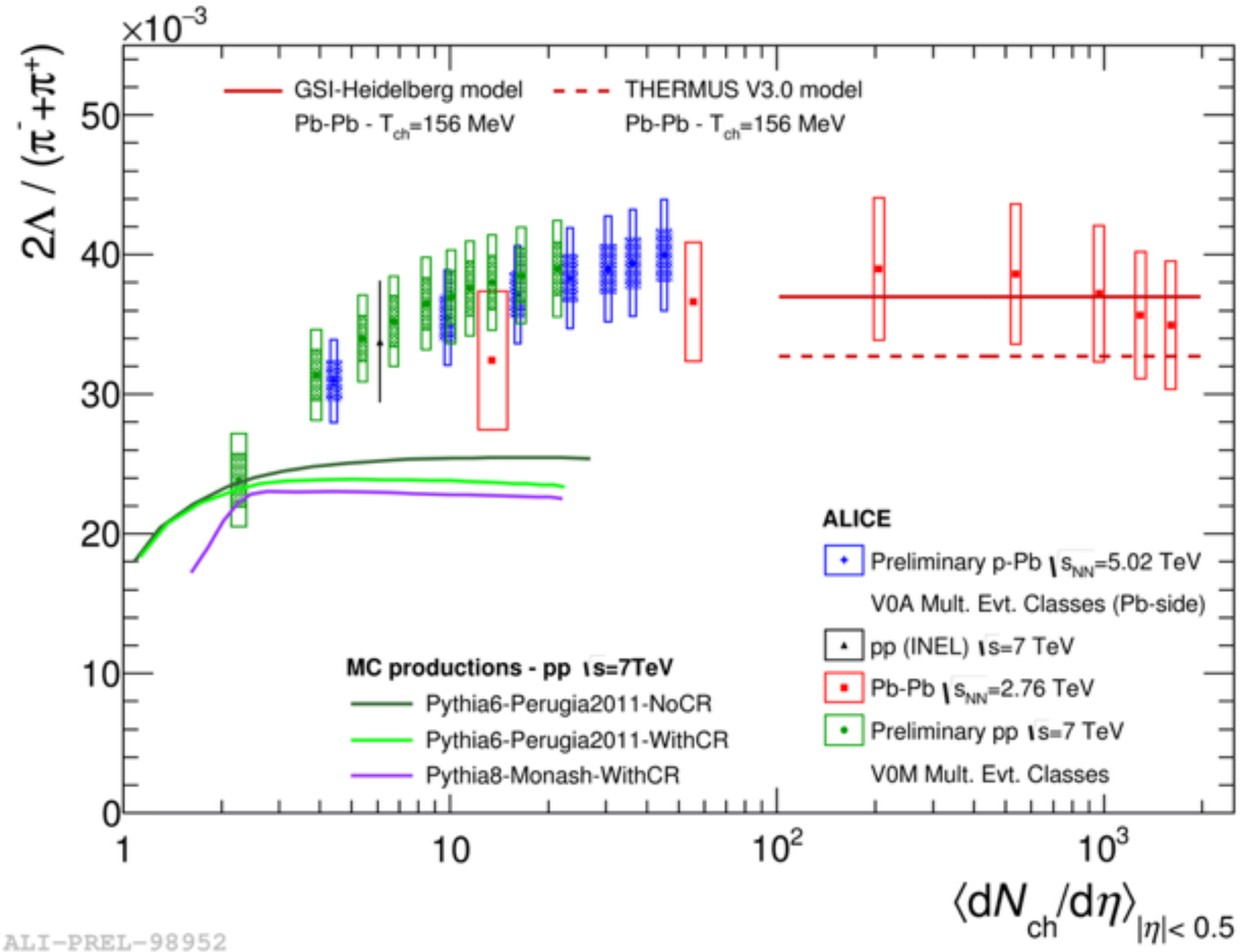
Λ/π

- Clear rise with multiplicity



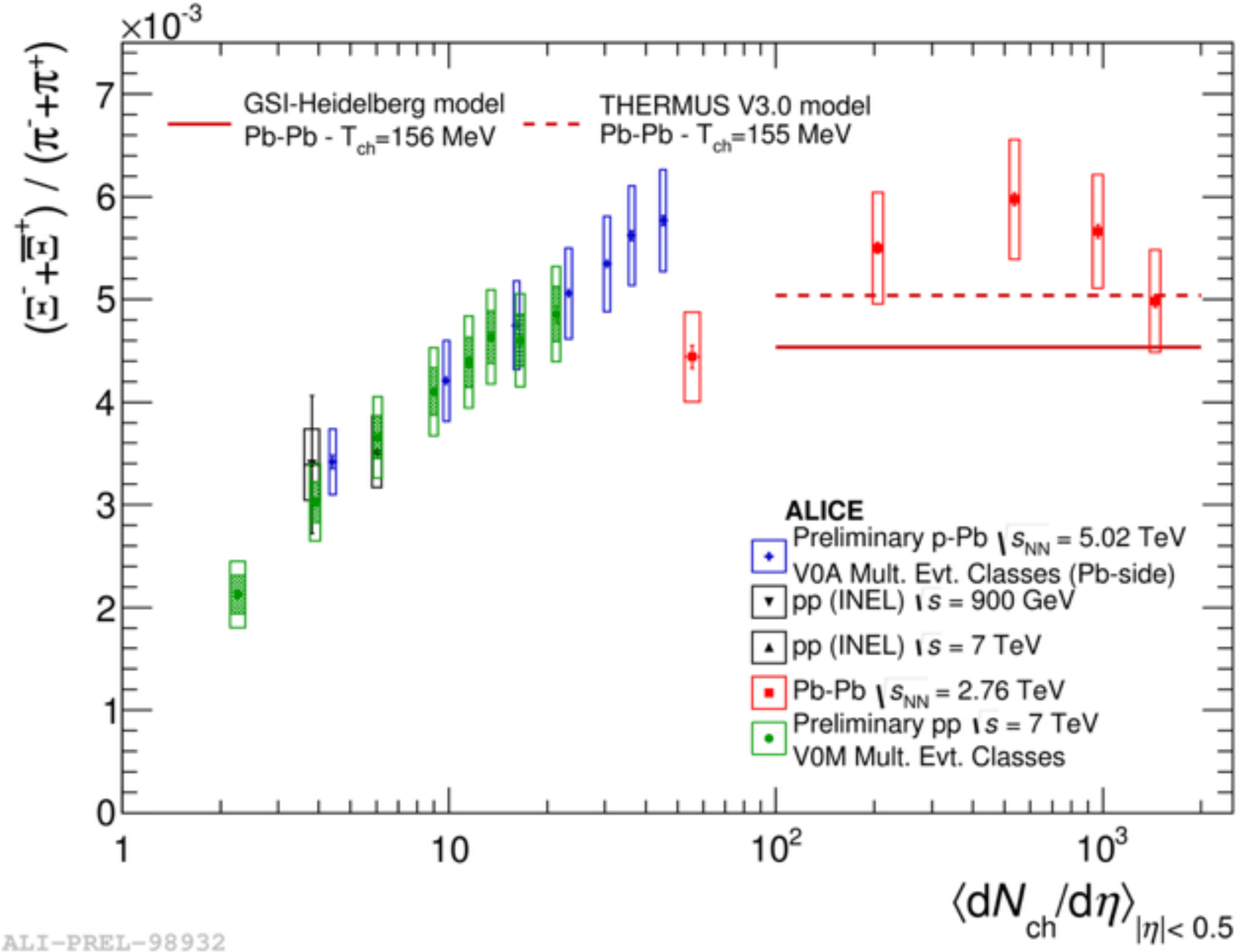
Λ/π

- Rise with multiplicity **not** reproduced with PYTHIA Monte Carlo



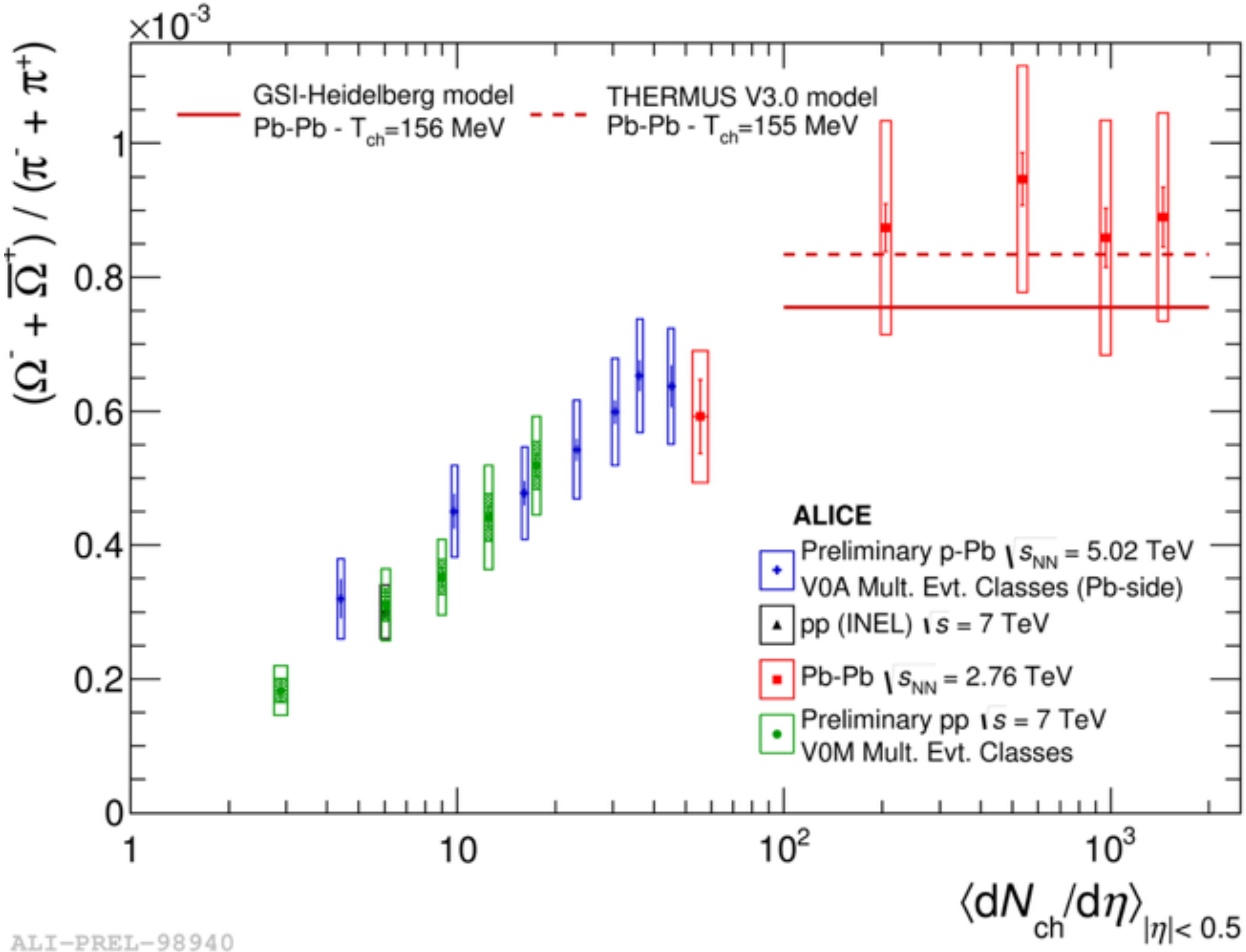
Ξ/π

- Excellent agreement between pp (green) and p-Pb (blue) data points

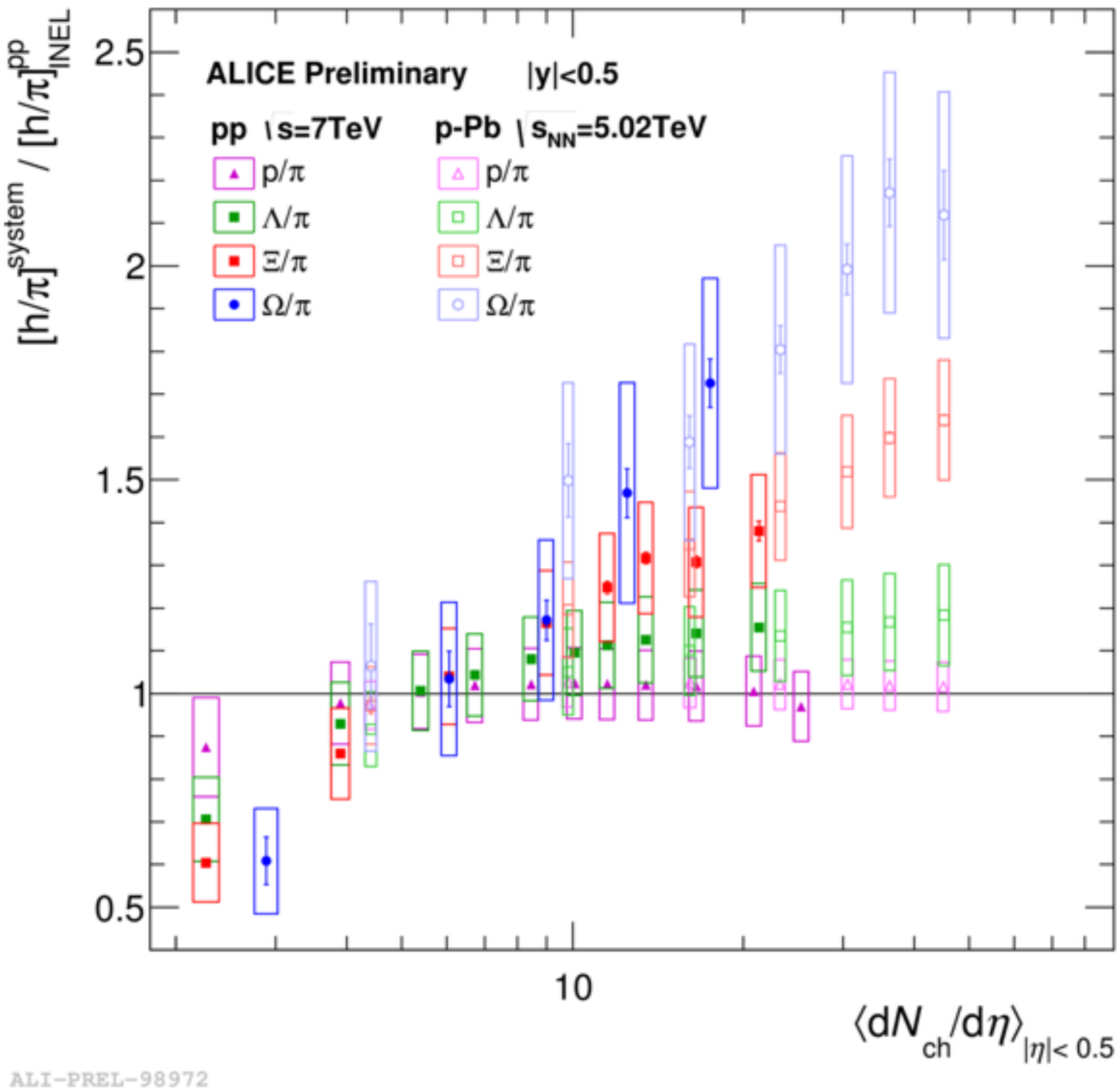


Ω/π

- Good agreement between pp (green) and p-Pb (blue) data points



Baryon/π ratio compilation



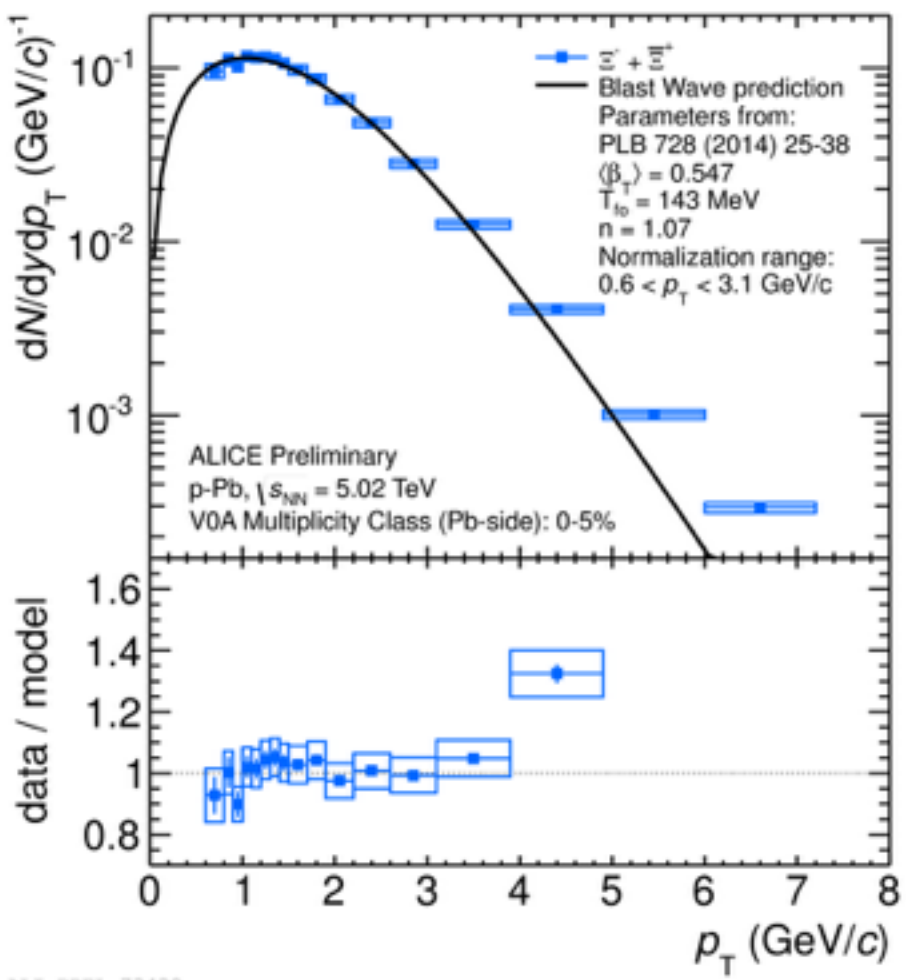
- Normalised to values in min. bias
- Shows rate of increase with dN/dη is larger for greater |S|

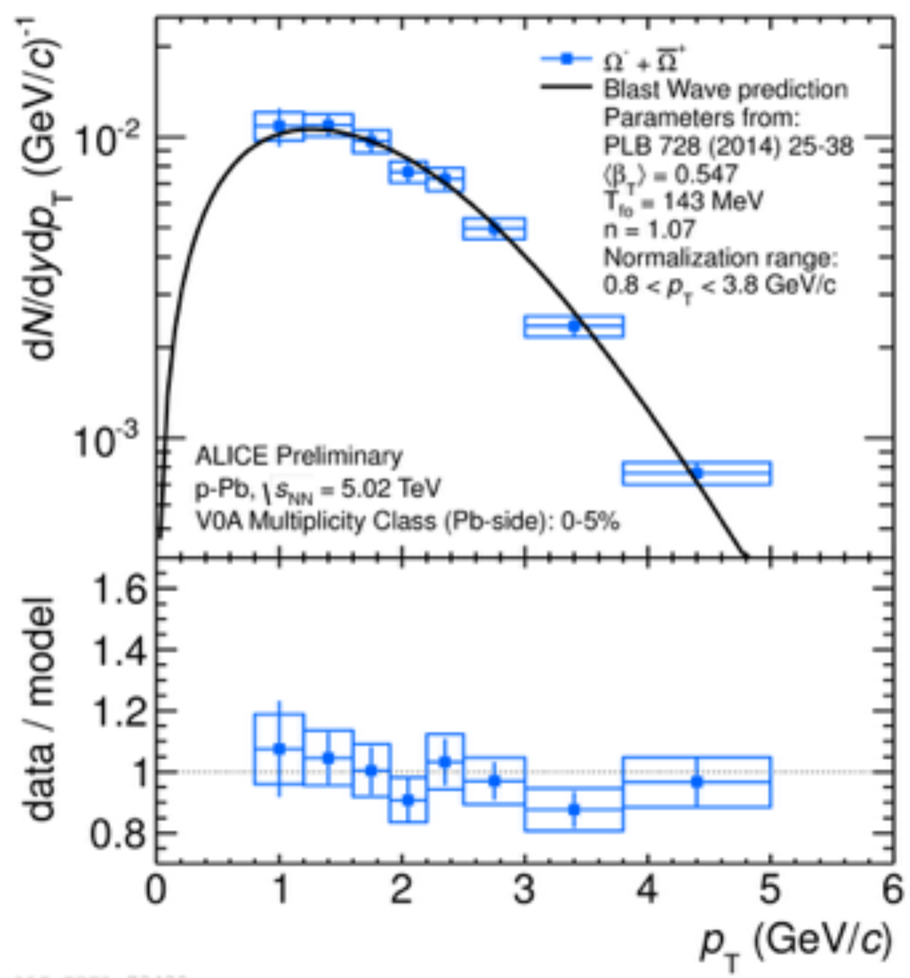
Conclusion on yields

- Ratios of baryons to pions show rise with multiplicity in both pp and p-Pb collisions
- $dN_{ch}/d\eta$ is a good scaling variable
  - to be checked with 13 TeV collisions
- A statistical model calculation, including extensive system properties (volume/ number of particles), reproduces qualitative features of the data
  - further details can be extracted from upcoming large minimum bias Pb-Pb data

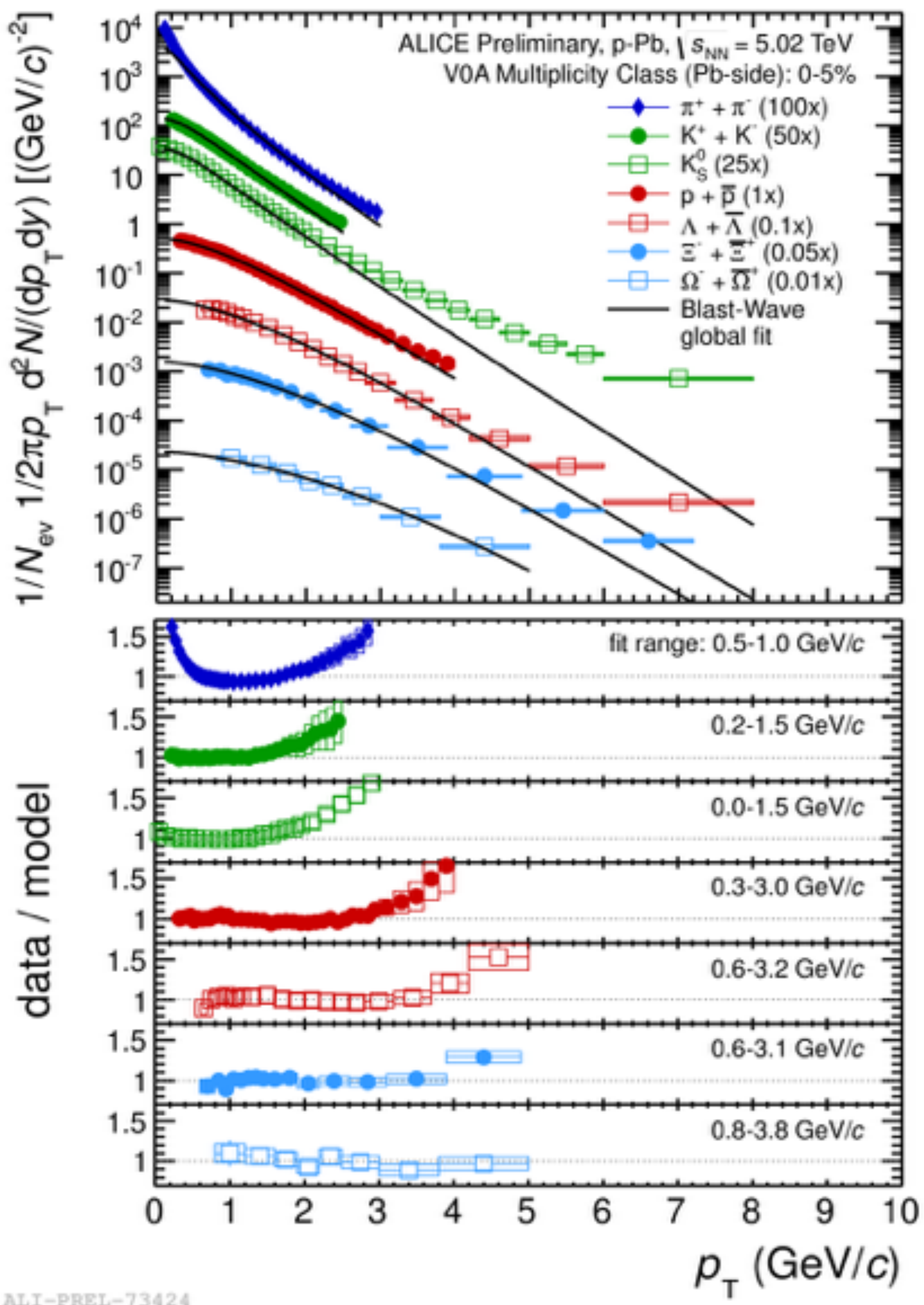
Investigating collectivity in p-Pb

- High multiplicity p-Pb collisions blast-wave fit
- Parameters for π, K, p and Λ fit describe the multi-strange baryons spectra well





Addendum on collectivity



- Blast-wave fit describes several species
  - different p_T-ranges because of different masses
- Parameters indicate freezeout conditions

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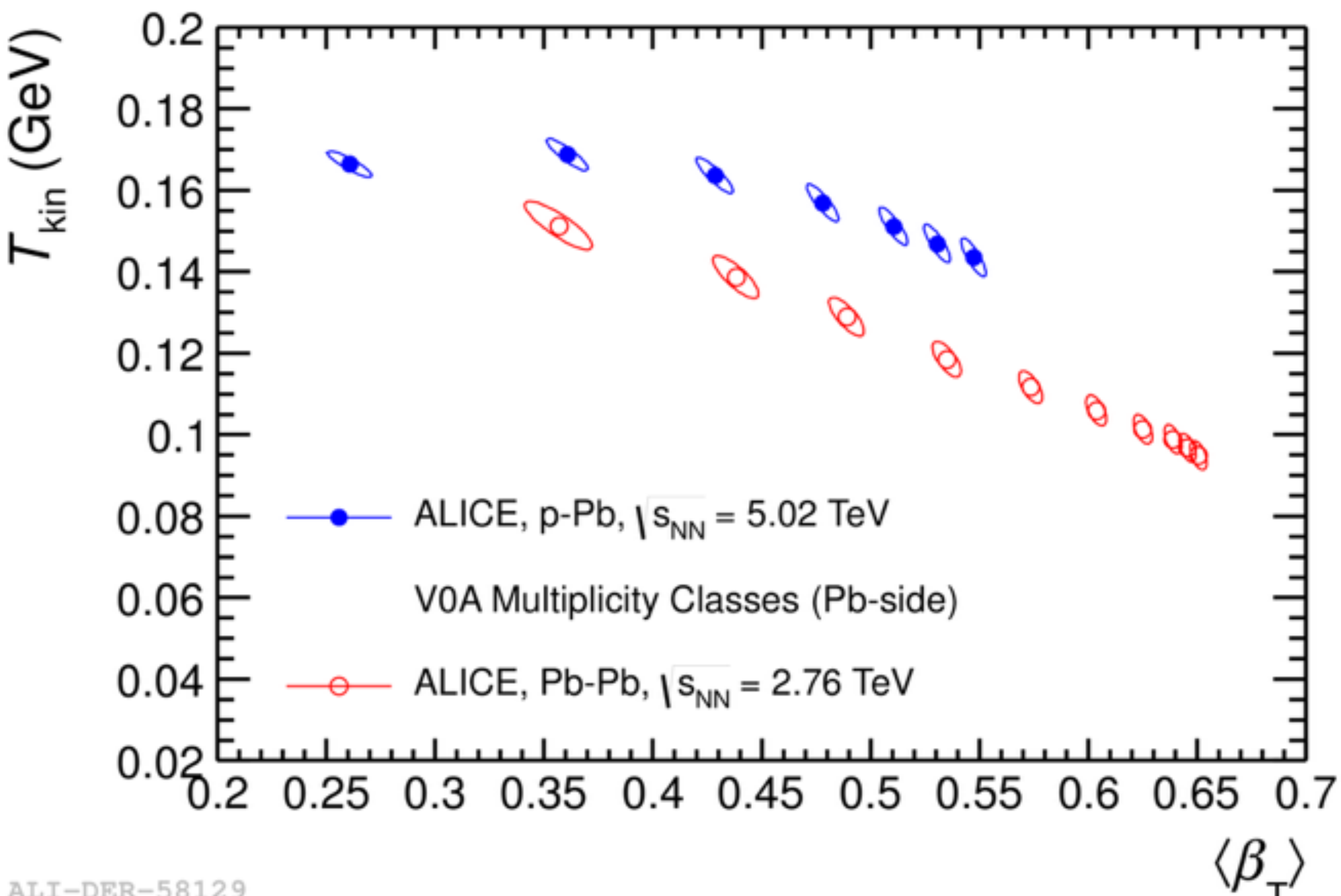
Blast-wave fit

- Extract freeze-out temperature and velocity
- Similar $dN_{ch}/d\eta$ have *different* parameters



Blast-wave fit

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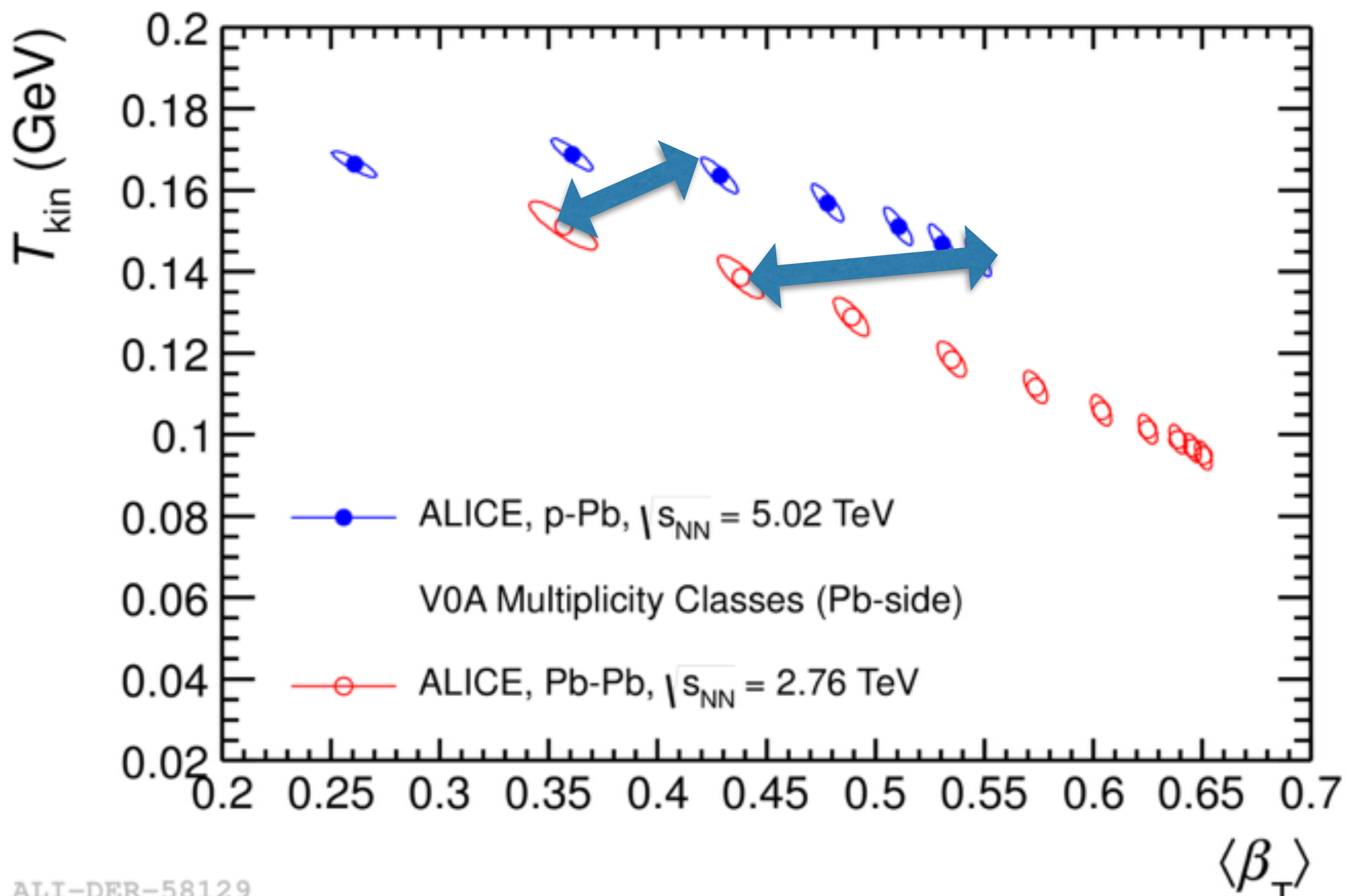
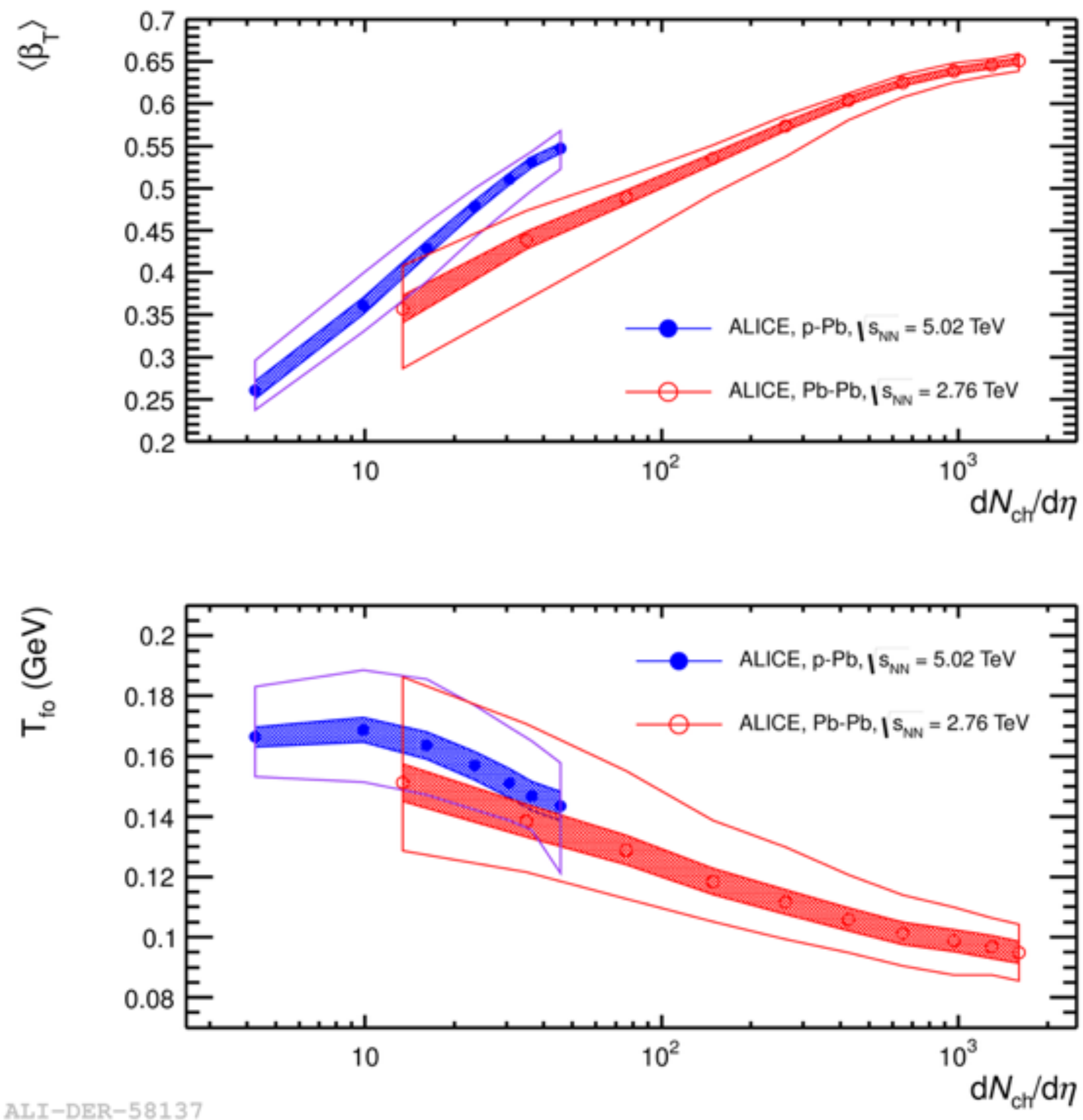


Blast-wave fit parameters

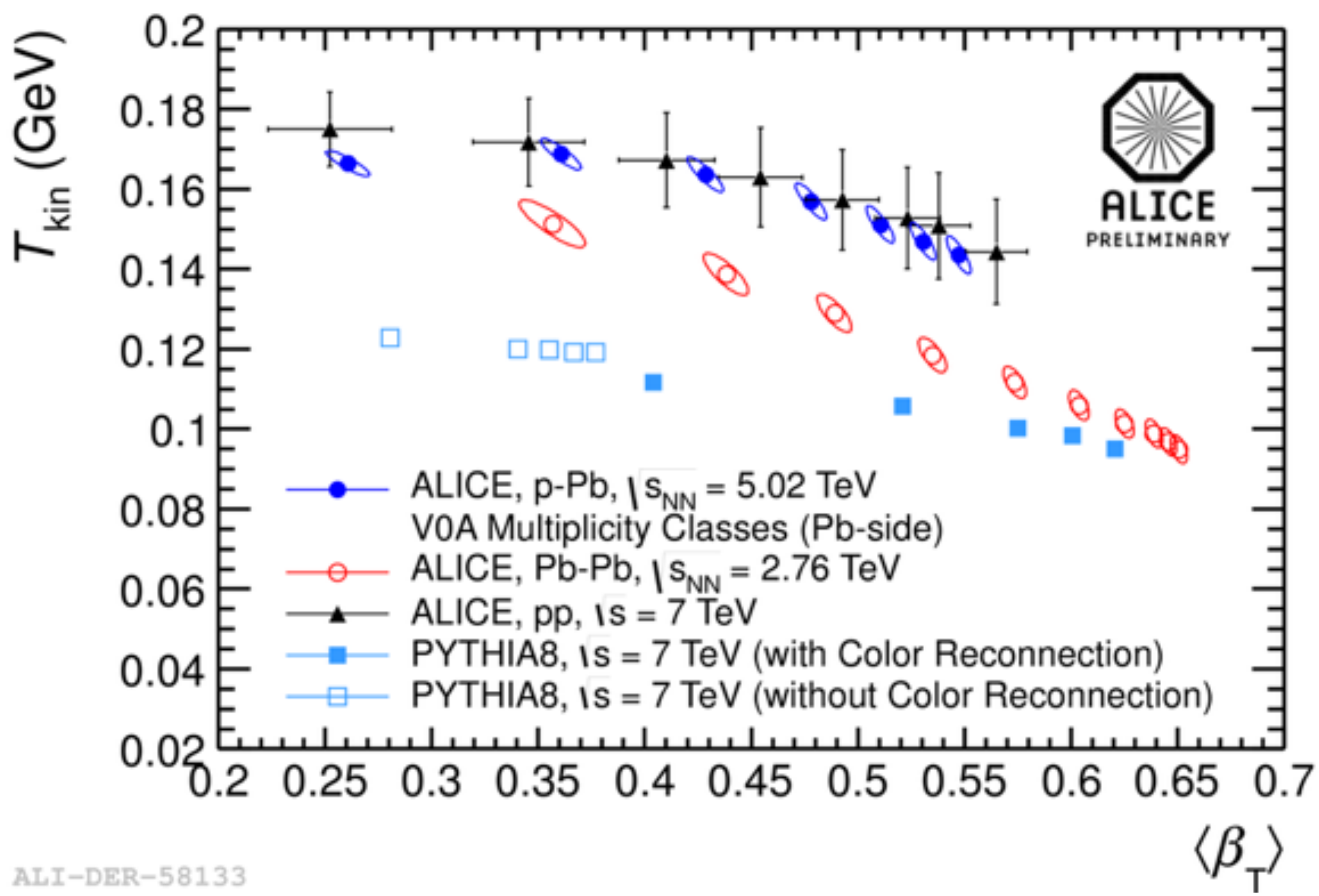


- different $\langle \beta_T \rangle$ in p-Pb and Pb-Pb at same dN/dη

ALICE

Other explanations

- It may be possible for other processes to mimic expansion
- E.g. colour reconnection mechanisms
  - –implemented in PYTHIA (it is *not* a hydrodynamic model)



Conclusions on collectivity

- Transverse momentum spectra in p-Pb collisions show similar features to Pb-Pb
- *Necessary* but not *sufficient* to demonstrate collective behaviour seen in heavy-ion collisions and used as evidence for de-confinement

Final conclusions

ALICE

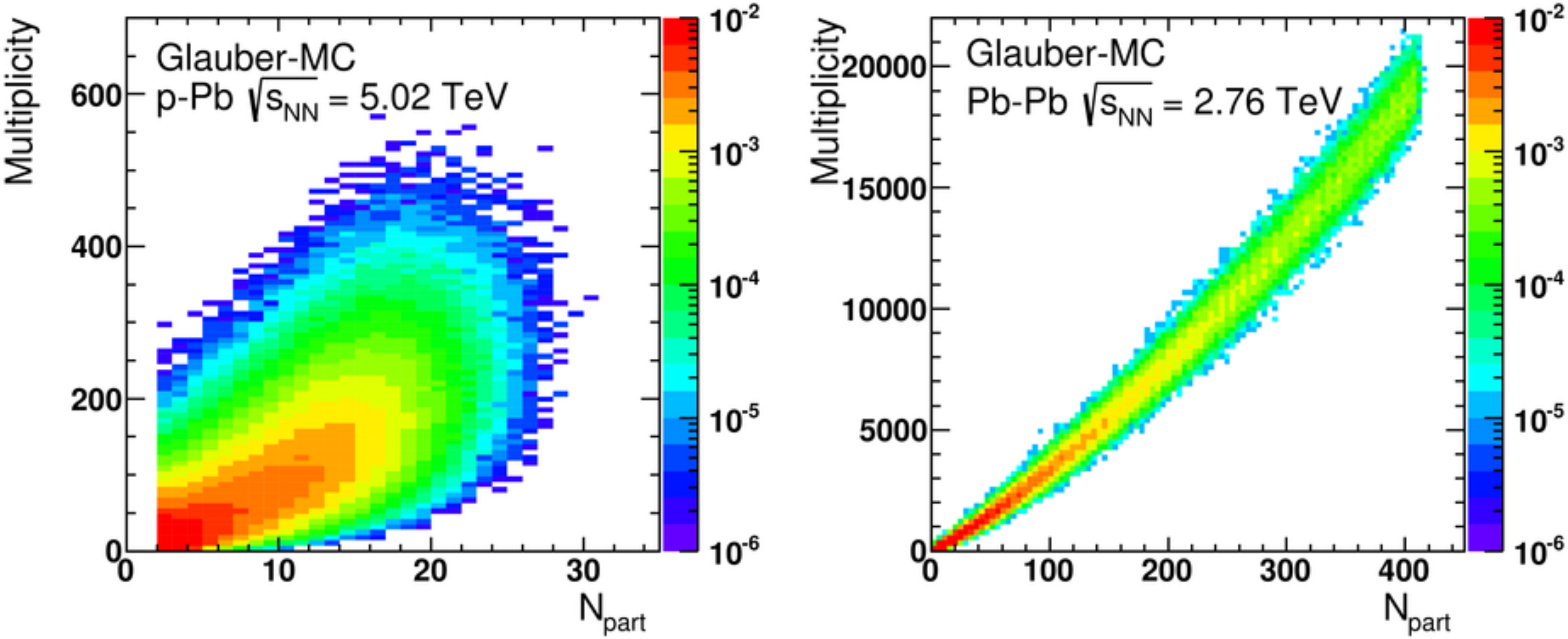
- Features of the production of hadron species relative to one another — chemistry — show close connection to number of particles produced by the system
- The momentum spectra are less closely tied to this number and suggest that the density play a role in any expansion, or other physics mechanism
- Studying smaller systems is a rich source of information to connect the thermodynamic and microscopic pictures
- Were able to trace the development of strangeness enhancement with system size

BACKUP SLIDES

ALICE

Npart to multiplicity relationship

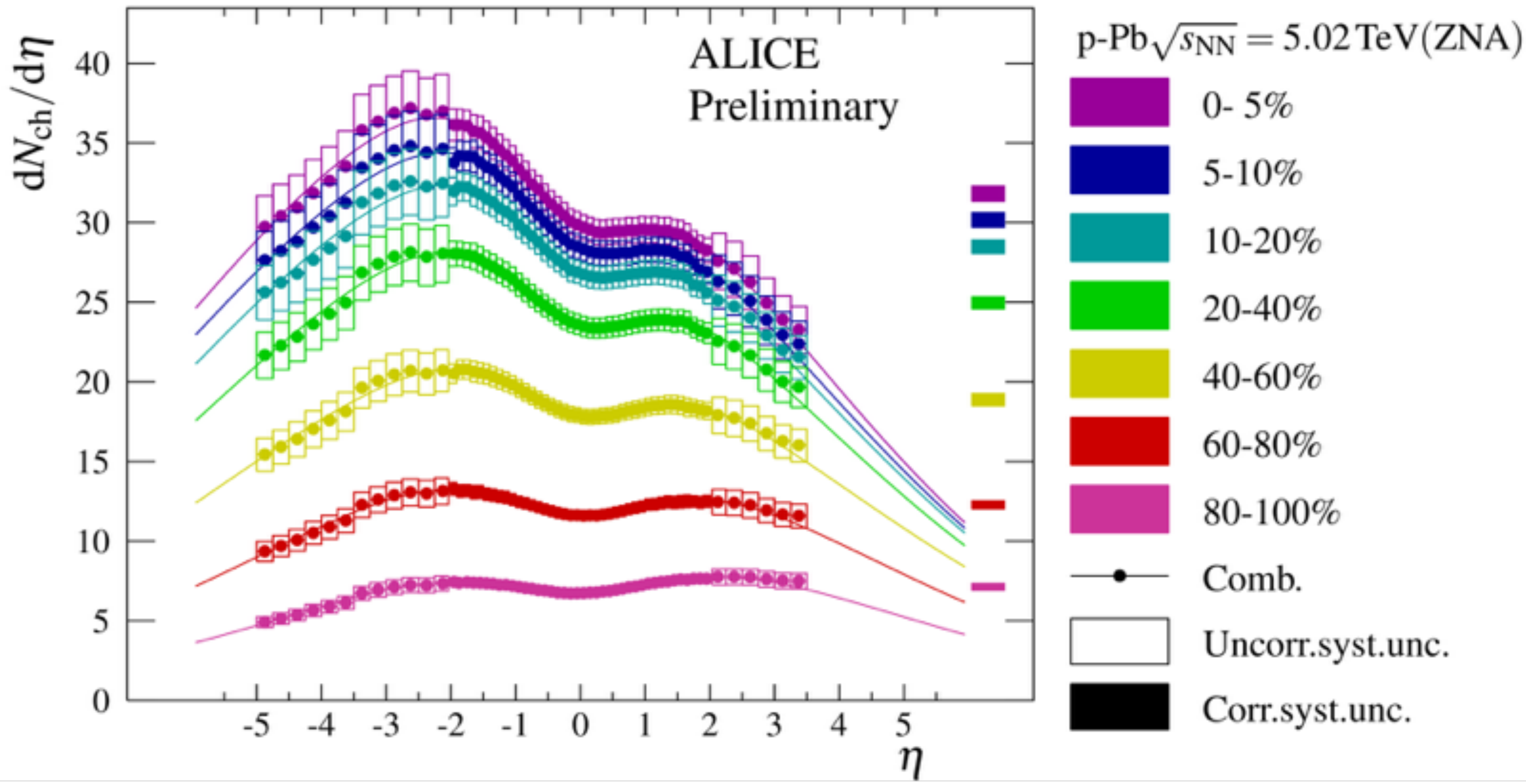
- p-Pb left and Pb-Pb right



ALICE

p-Pb dN/dη distribution

- $dN_{ch}/d\eta$ for multiplicity classes selected with the zero degree (neutral) calorimeter |η|>8.8



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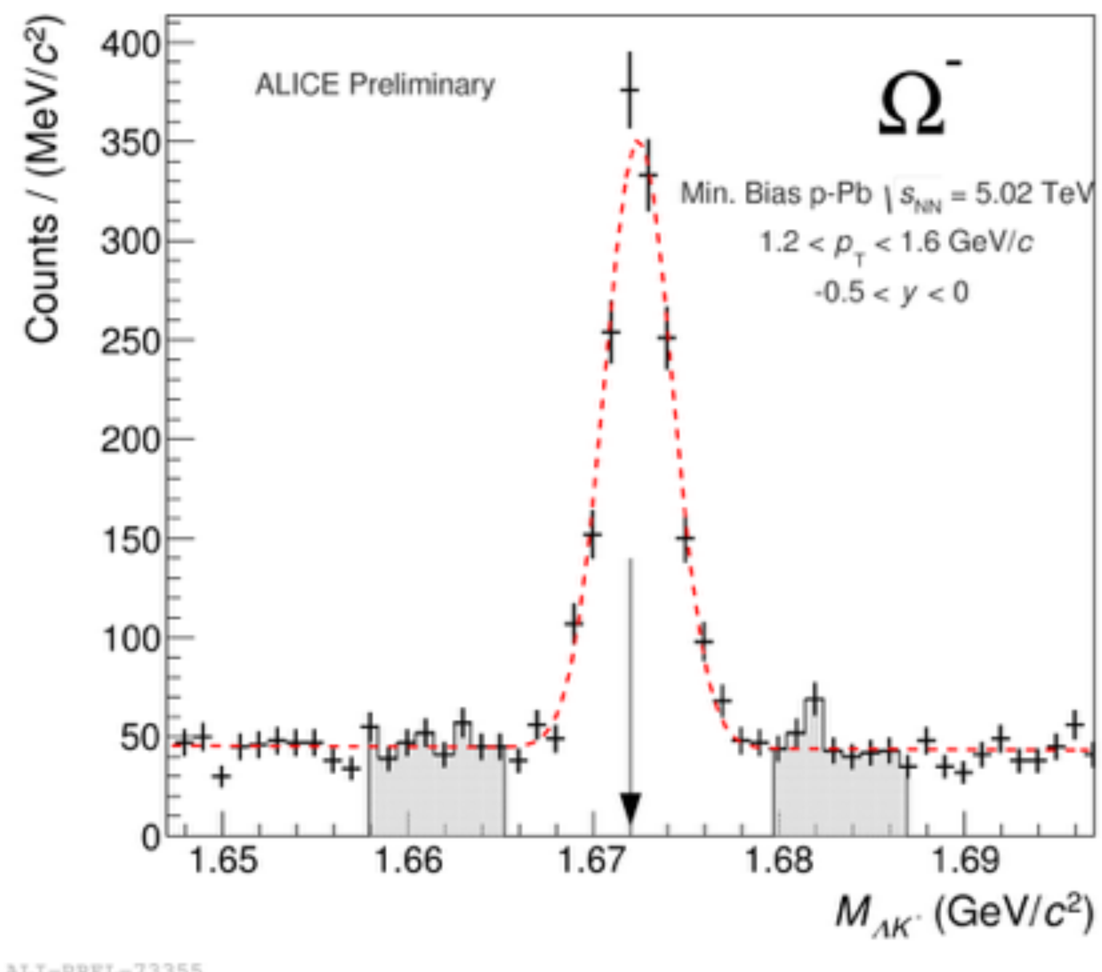
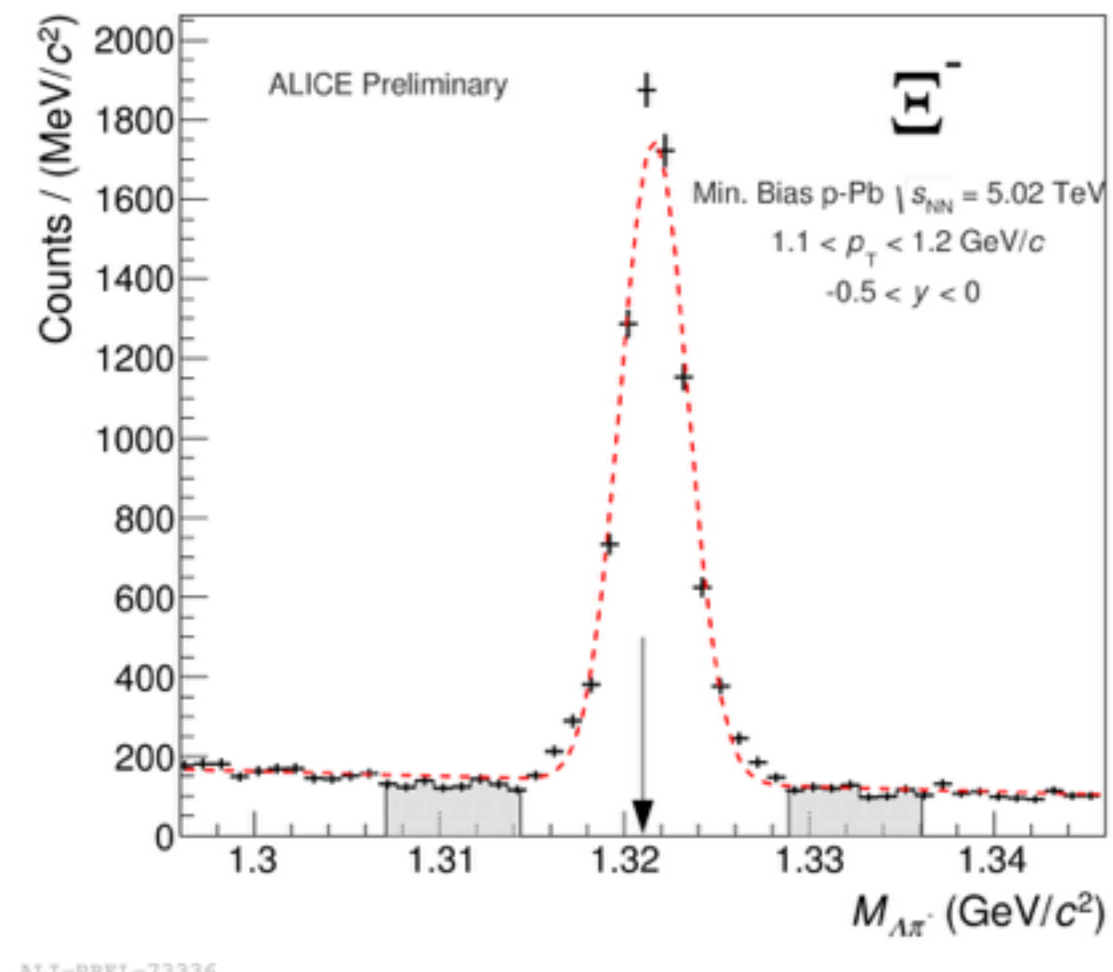
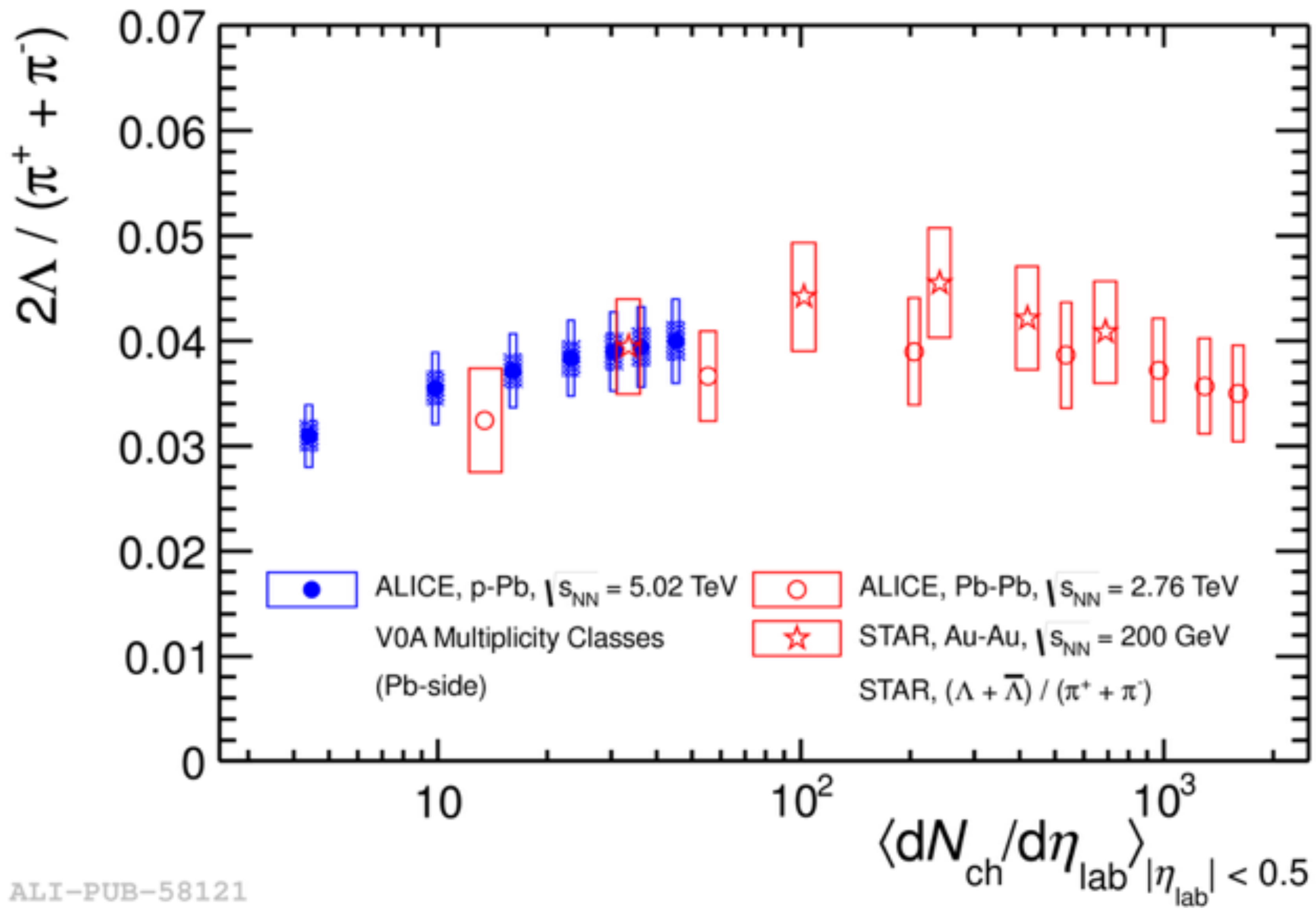
Multi-strange mass plots for p-PN

- Particles to go with anti-particles shown



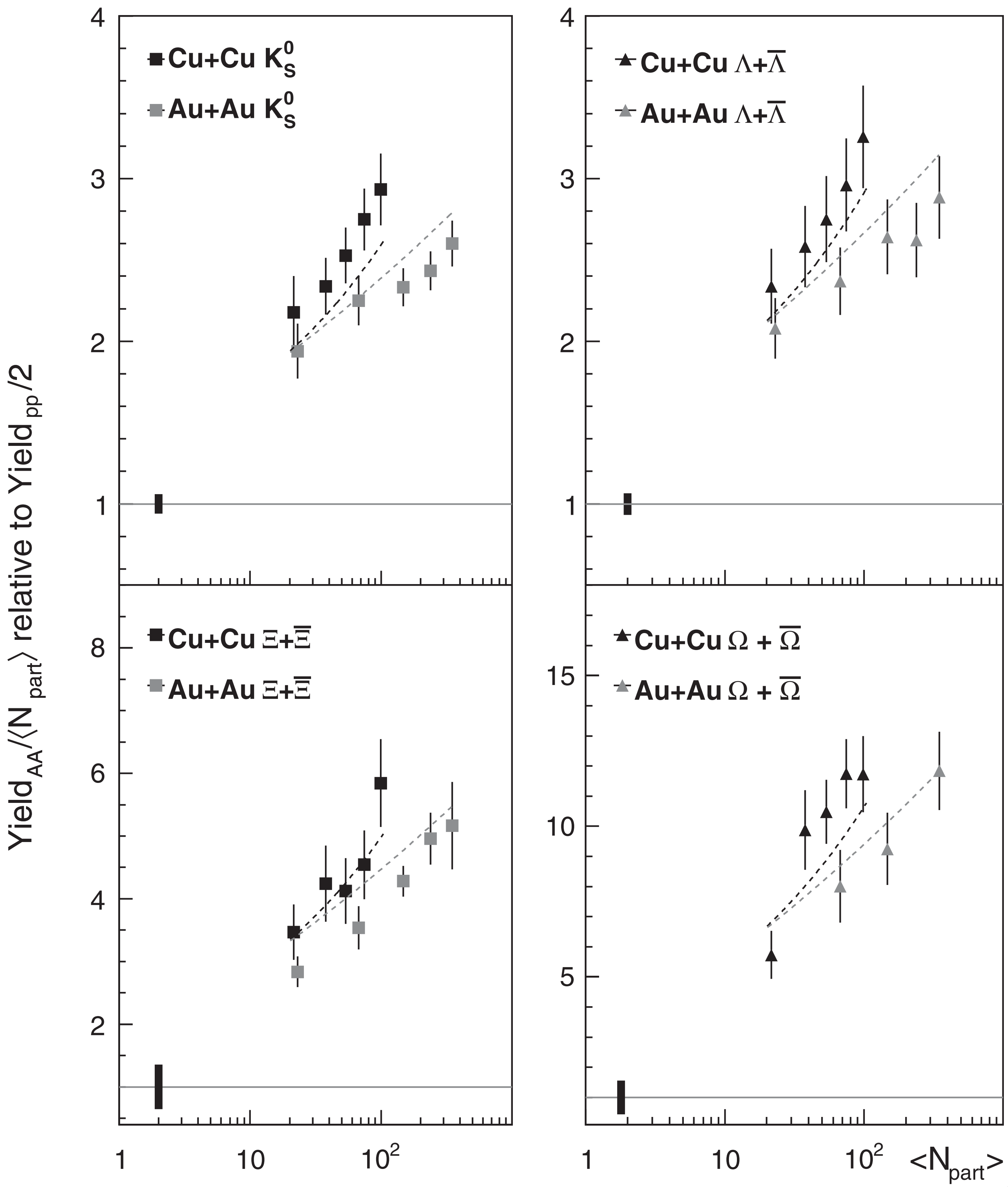


Λ/π with RHIC



2Λ / (π⁺ + π⁻)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
10
10²
10³
⟨dN_ch/dη_lab⟩ |η_lab| < 0.5
ALICE, p-Pb, √s_NN = 5.02 TeV
V0A Multiplicity Classes
(Pb-side)
ALICE, Pb-Pb, √s_NN = 2.76 TeV
STAR, Au-Au, √s_NN = 200 GeV
STAR, (Λ + Λ̄) / (π⁺ + π⁻)
ALI-PUB-58121

Core-corona effects



- STAR data Au-Au and Cu-Cu scaled by N_{part}

STAR, PRL 108, 072301 (2012)