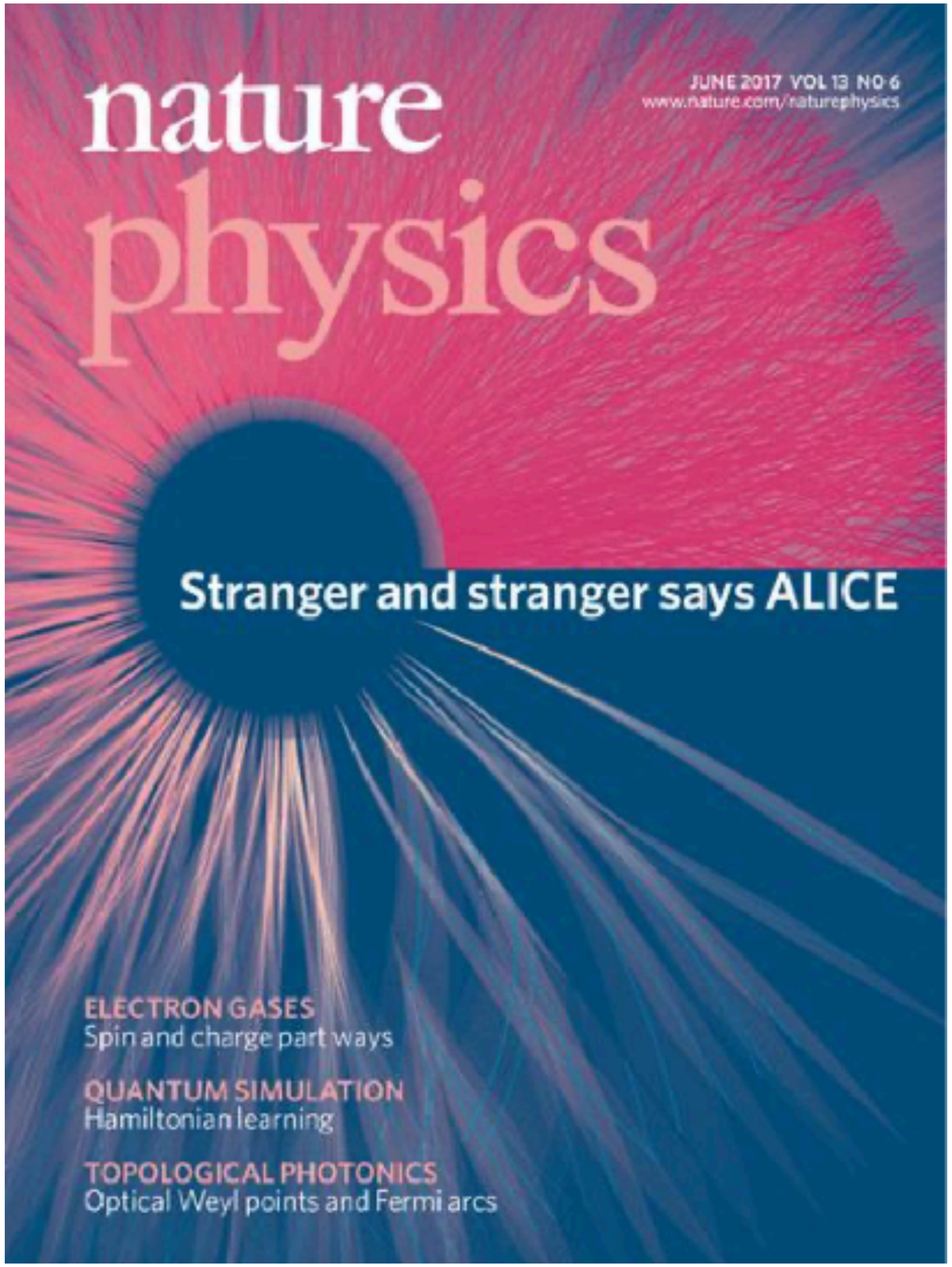
Congresso INFN 2021
Bari, 21-22 June 2021

Strangeness production in high energy collisions at LHC

Domenico Colella
Politecnico di Bari



nature physics

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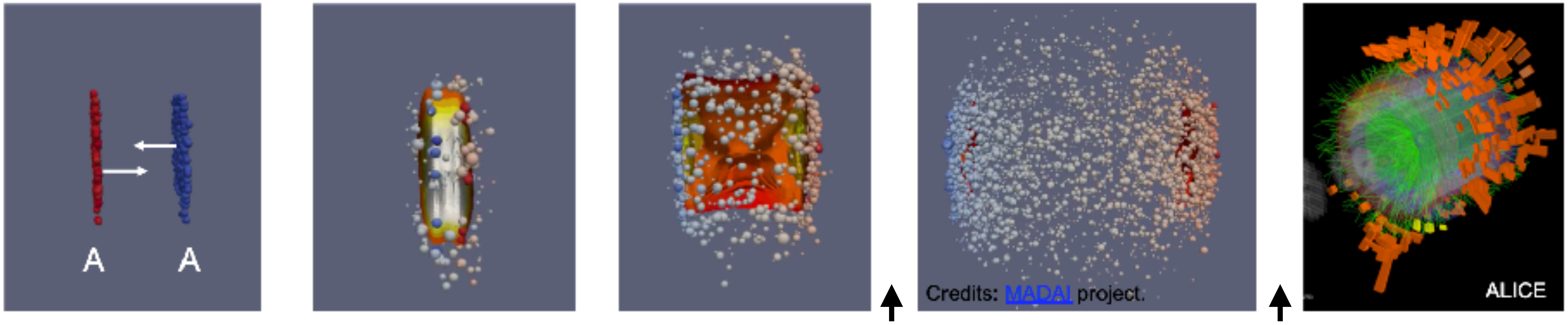
Stranger and stranger says ALICE

ELECTRON GASES
Spin and charge part ways

QUANTUM SIMULATION
Hamiltonian learning

TOPOLOGICAL PHOTONICS
Optical Weyl points and Fermi arcs

Fireball evolution and QGP formation



Credits: MADAI project.

Heavy-nuclei
$\tau \sim 0$

QGP
$\tau < 1$ fm/c

QGP
$\tau \sim 5$ fm/c

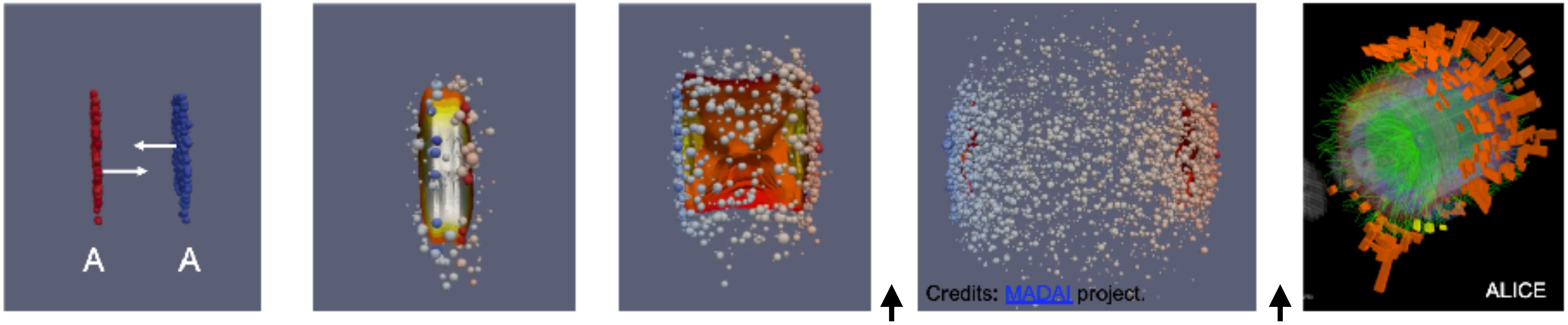
Hadronic phase
$\tau > 10$ fm/c

Detection
$\tau > 10$ pm/c

Chemical freeze-out
Relative particle abundances fixed

Kinematic freeze-out
p_T momentum distribution fixed

Small and large colliding systems



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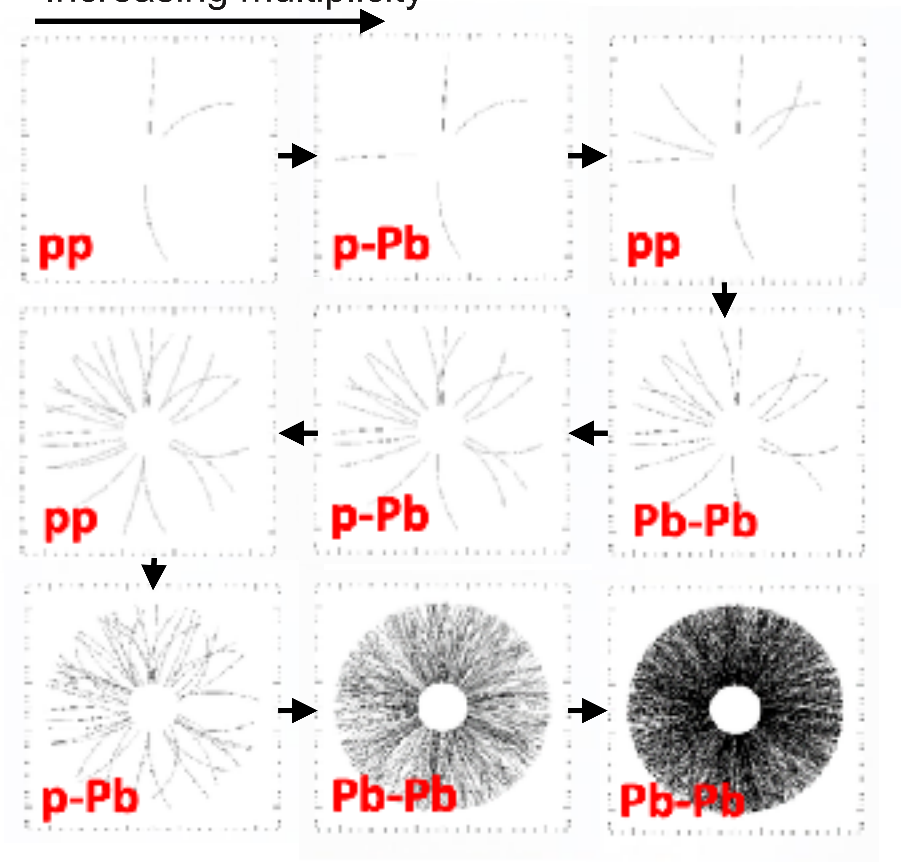
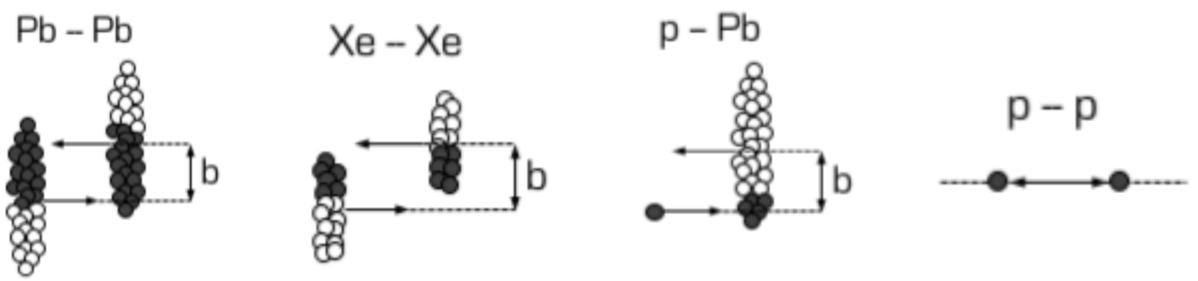
Chemical freeze-out
Relative particle abundances fixed

Kinematic freeze-out
p_T momentum distribution fixed

Increasing multiplicity





Centrality vs multiplicity

- Centrality definition not applicable for pp collisions
- Systems (of different size) can be compared looking at the charge particle multiplicity (initial energy density)

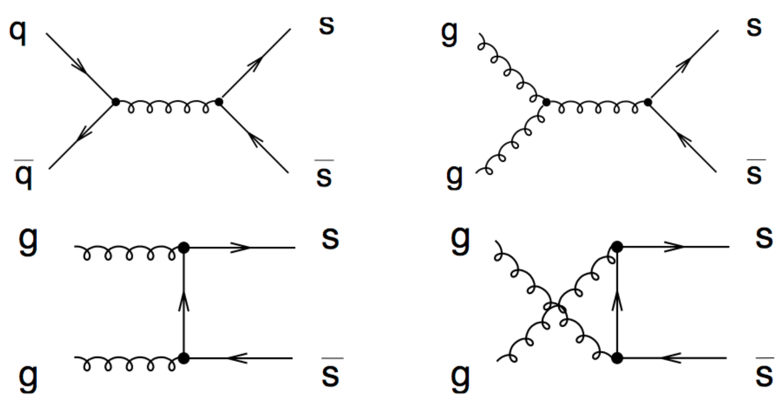
Strangeness as signature of QGP

In 1982 Rafelski-Muller suggested the strangeness would have been produced much easier in a Quark Gluon Plasma

- (i) lower threshold (Q)
- (ii) shorter equilibration time

QGP

$Q(s\bar{s}) = 200\, MeV$



Hadron Gas

Direct production: $\pi + \pi \rightarrow \pi + \pi + h(s) + \bar{h}(\bar{s})$

$Q(\Xi) = 2642\, MeV$ and $Q(\Omega) = 3344\, MeV$

Indirect production:

1 step: $\pi + N \rightarrow K + \Lambda$

2 step: $\pi + \Lambda \rightarrow K + \Xi$ or $\pi + \Xi \rightarrow K + \Omega$

$Q(\Xi) = 1100\, MeV$ and $Q(\Omega) = 1810\, MeV$

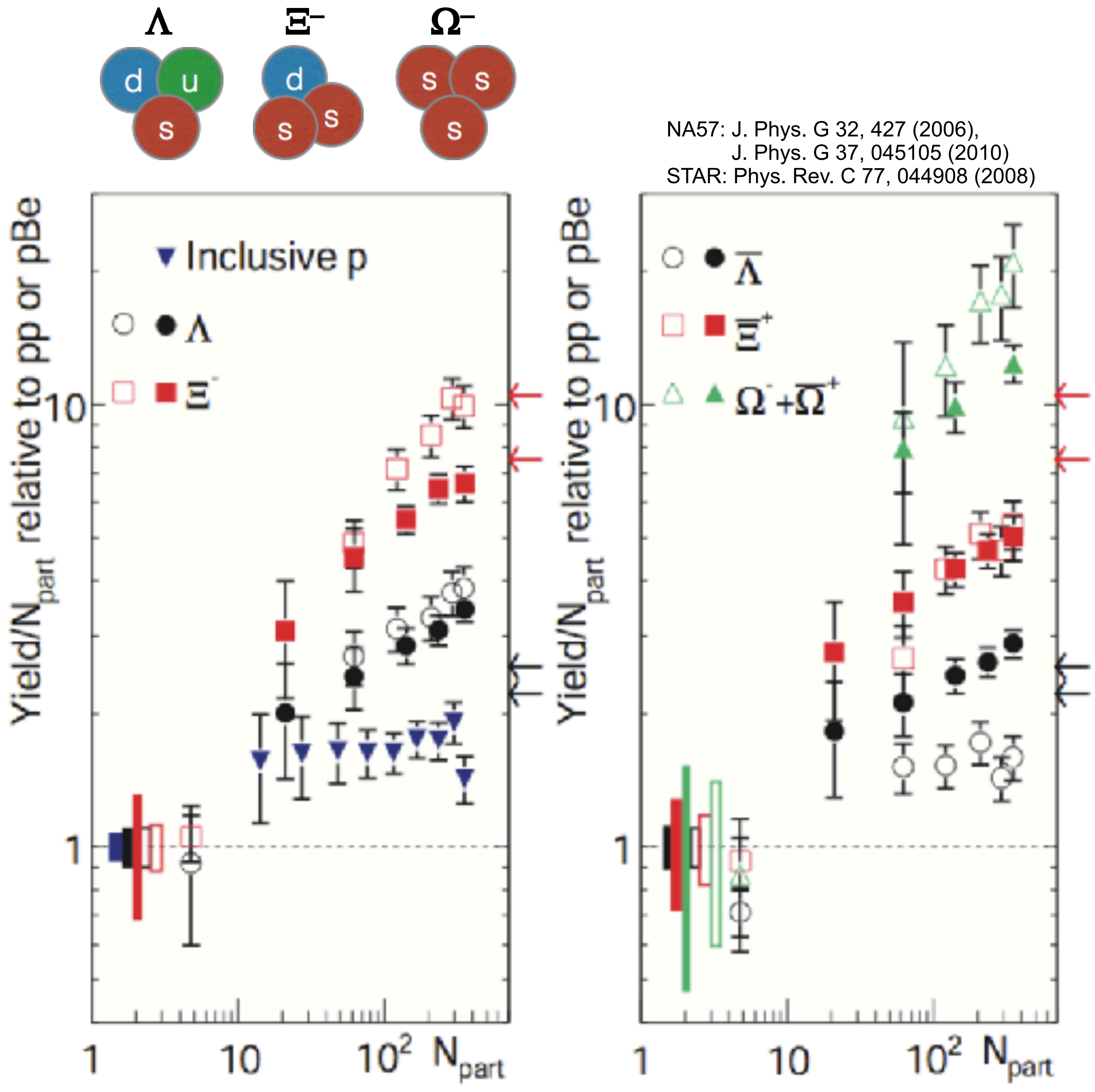
Study of (multi-)strange hadron production became pivotal signature of the QGP formation

J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066
P. Koch, J. Rafelski, W. Greiner, Phys. Lett. B 123 (1983) 151
P. Koch, B. Müller, J. Rafelski, Phys. Rep. 142 (1986) 167
P. Koch, B. Müller, J. Rafelski, arXiv:1708.08115 (2017)

Strangeness enhancement

Experimental observable measured at SPS and RHIC is the **strangeness enhancement**

$$E = \frac{Yield_{NN}/\langle N_{part}\rangle}{Yield_{pp}/2}$$



NA57: J. Phys. G 32, 427 (2006),
J. Phys. G 37, 045105 (2010)
STAR: Phys. Rev. C 77, 044908 (2008)

STAR [**RHIC**, Au-Au@**200 GeV**] (solid markers)
WA97, NA57 [**SPS**, Pb-Pb@**17.2 GeV**] (open markers)

Experimental observations:

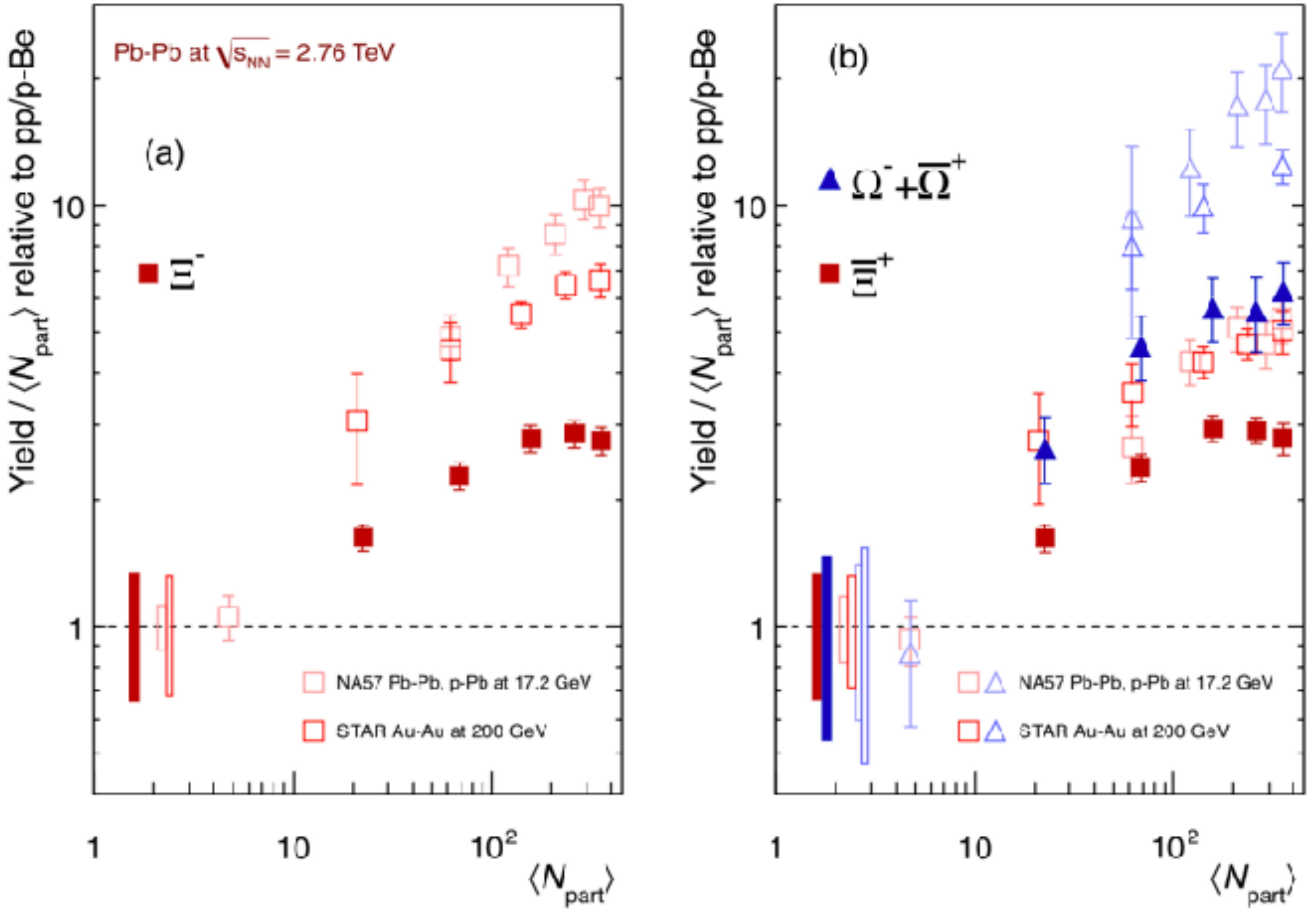
- E is above unity
- Hierarchy based on the strangeness content
- Decreasing trend with increasing energy (from SPS to RHIC)

Strangeness enhancement

Strangeness enhancement measured at LHC (very large jump in energy)

- Observations done at lower energies confirmed

PLB 728 (2014) 216-227

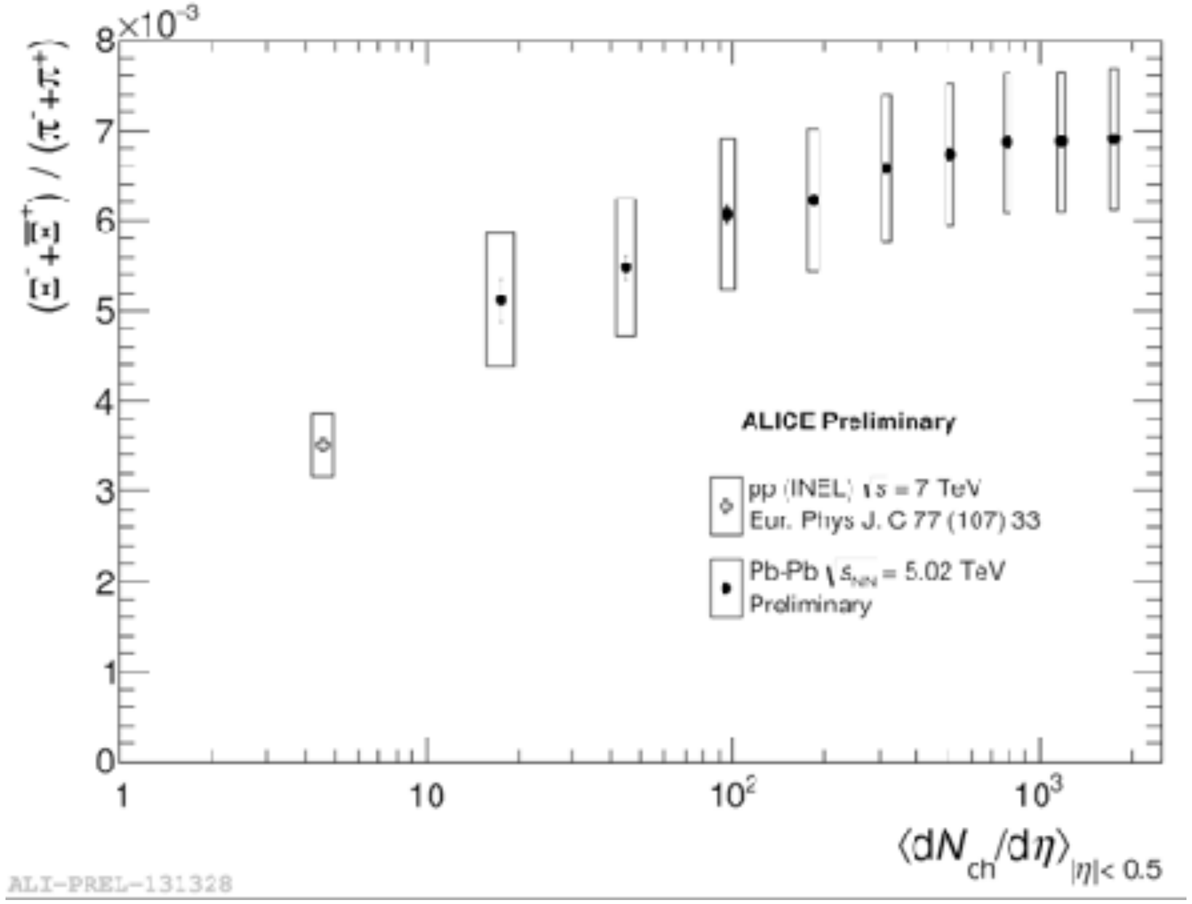


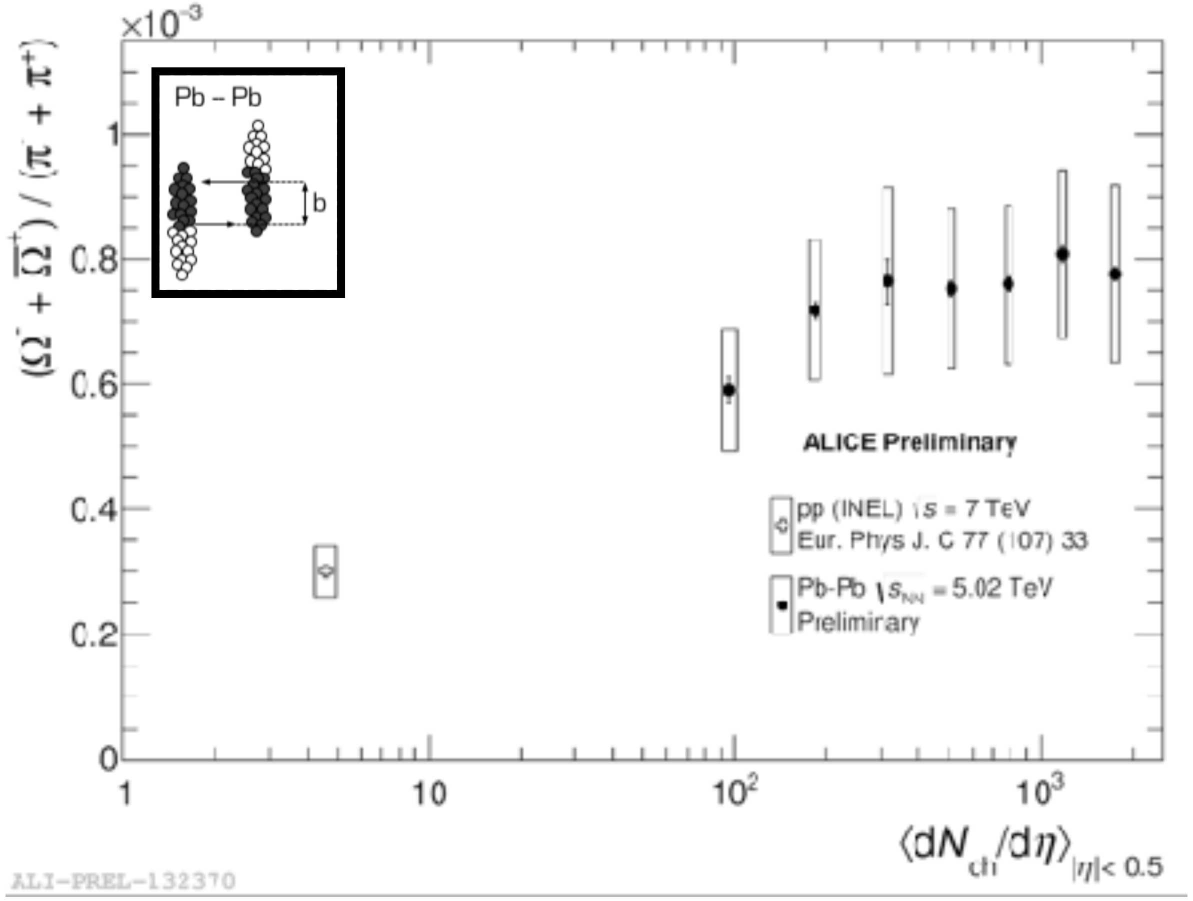
ALICE [**LHC**, Pb-Pb@**5500GeV**]
(solid markers)
STAR [**RHIC**, Au-Au@**200 GeV**]
(open markers)
WA97, NA57 [**SPS**, Pb-Pb@**17.2 GeV**]
(open light markers)

Strangeness enhancement

Strangeness enhancement through hyperon-to-pion yield ratio for easier colliding system comparison (get rid of $\langle N_{part} \rangle$ scaling)

- Increase of ratio-to-pion vs multiplicity from pp (min. bias) to Pb-Pb





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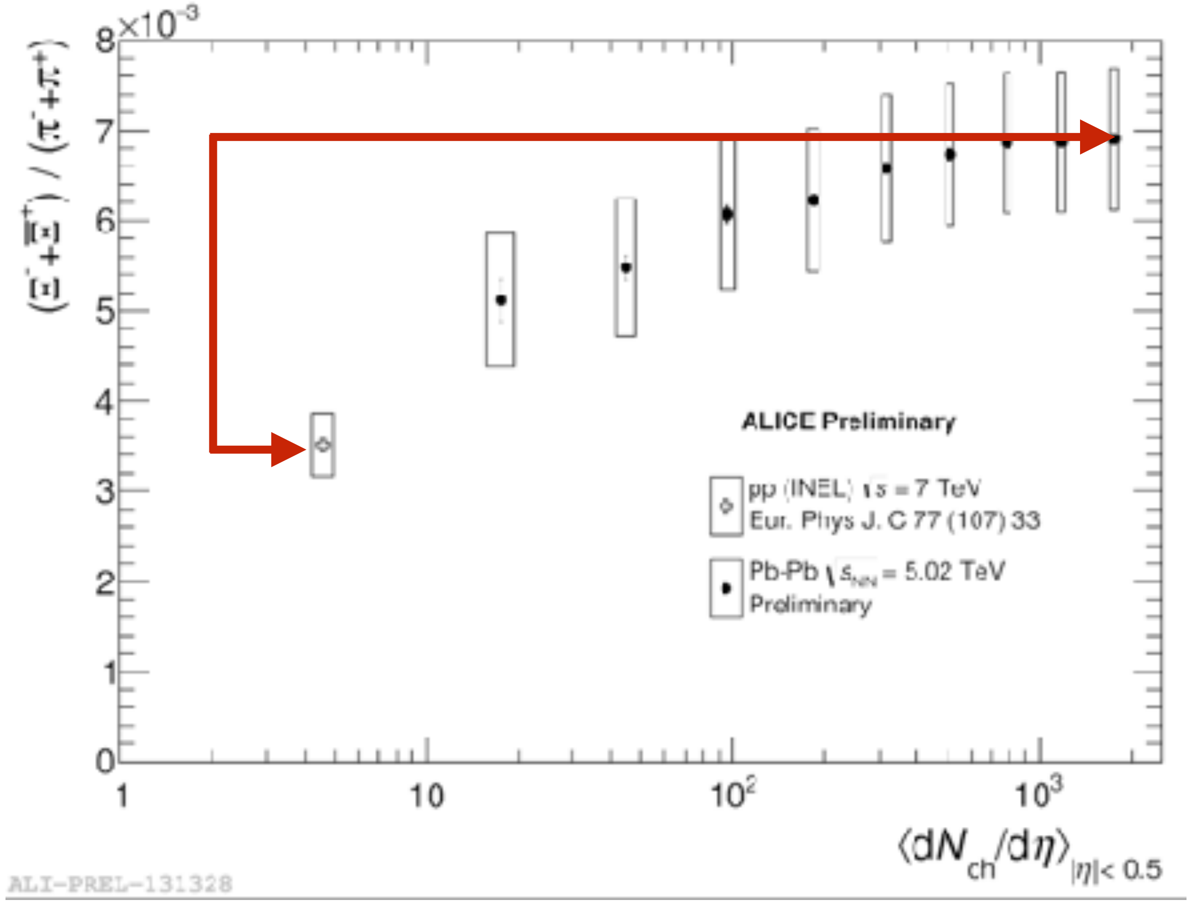

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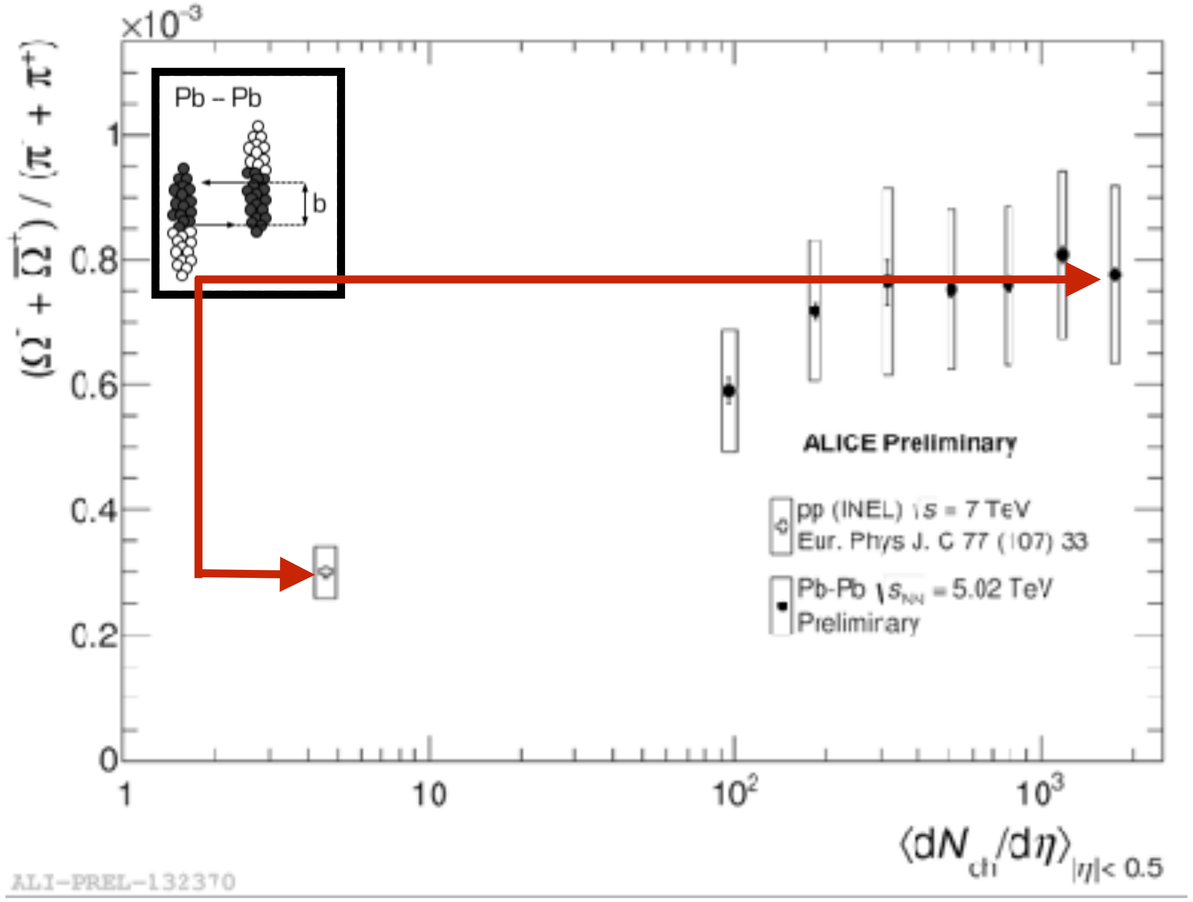
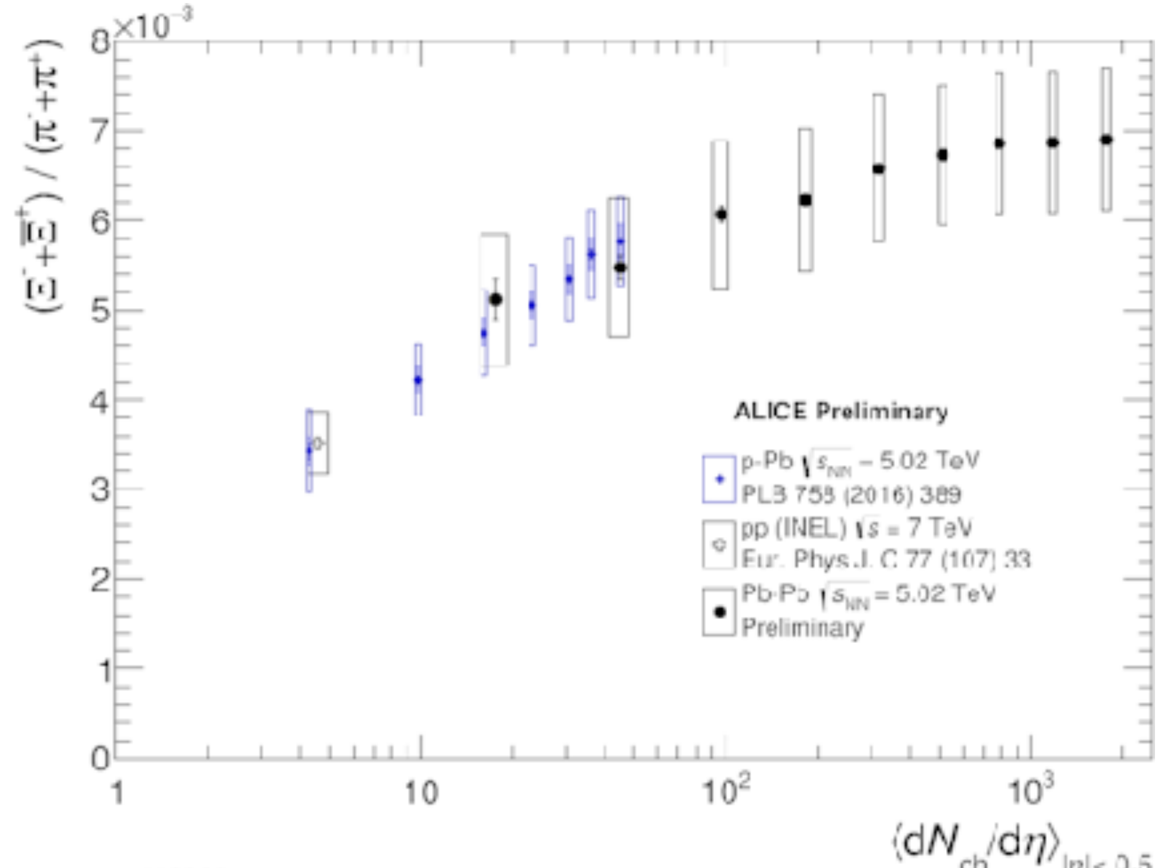


ALI-PREL-132370

Strangeness enhancement

Strangeness enhancement through hyperon-to-pion yield ratio for easier colliding system comparison (get rid of $\langle N_{part} \rangle$ scaling)

- Increase of ratio-to-pion vs multiplicity from pp (min. bias) to Pb-Pb
- Ratio-to-pion vs multiplicity in p-Pb bridge from pp to Pb-Pb



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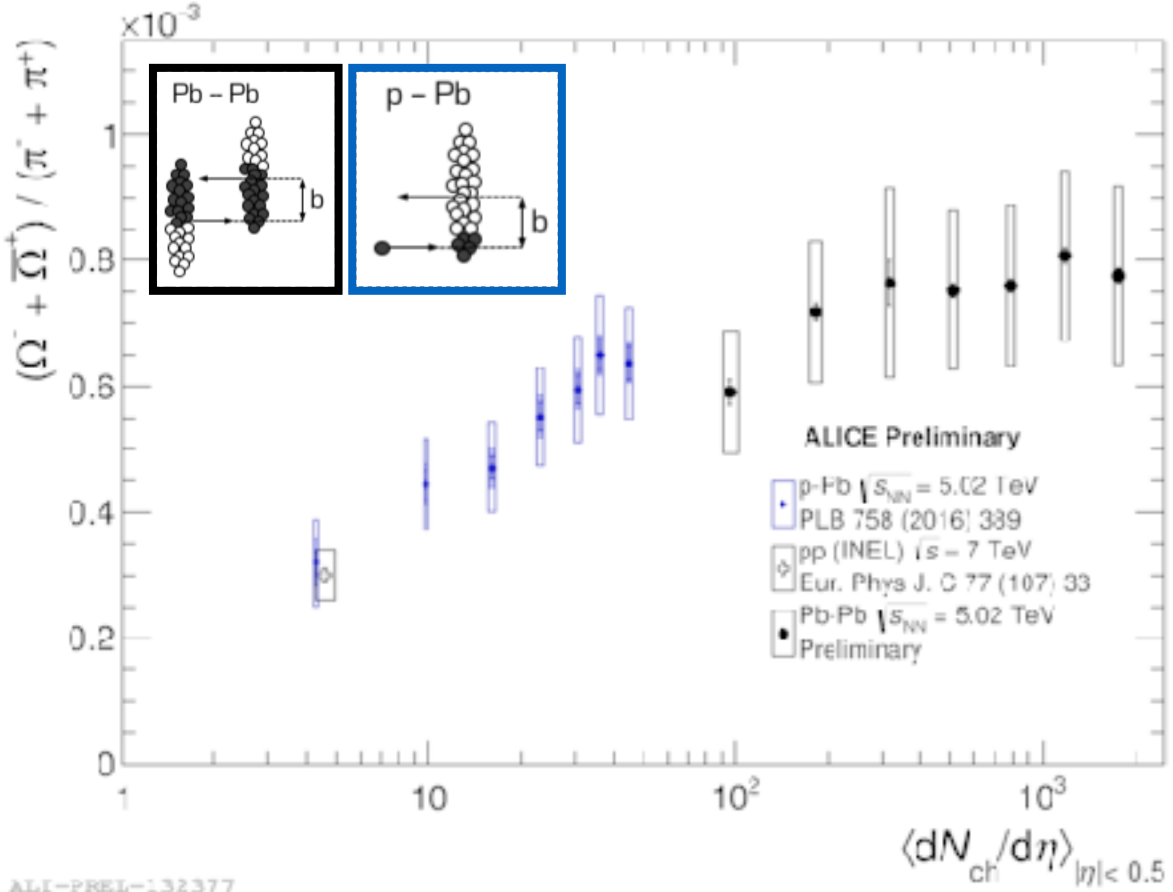
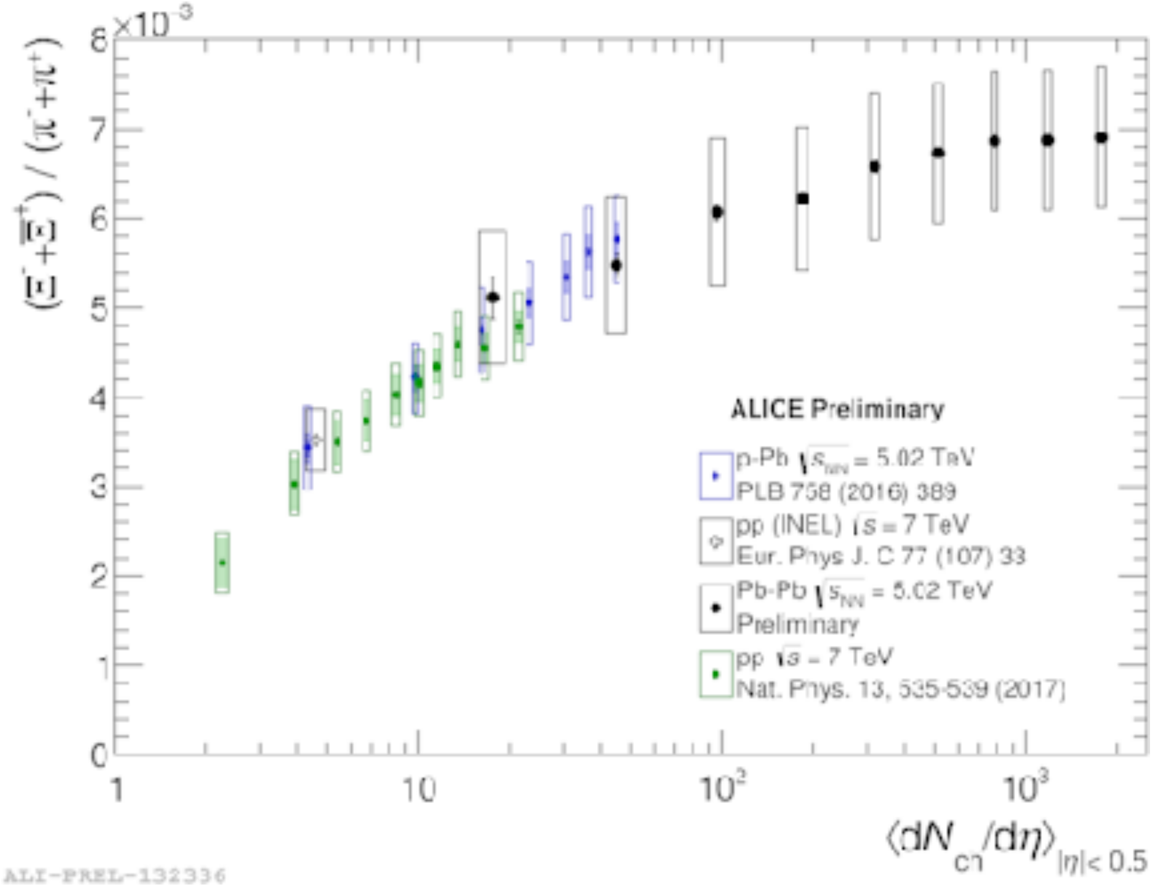


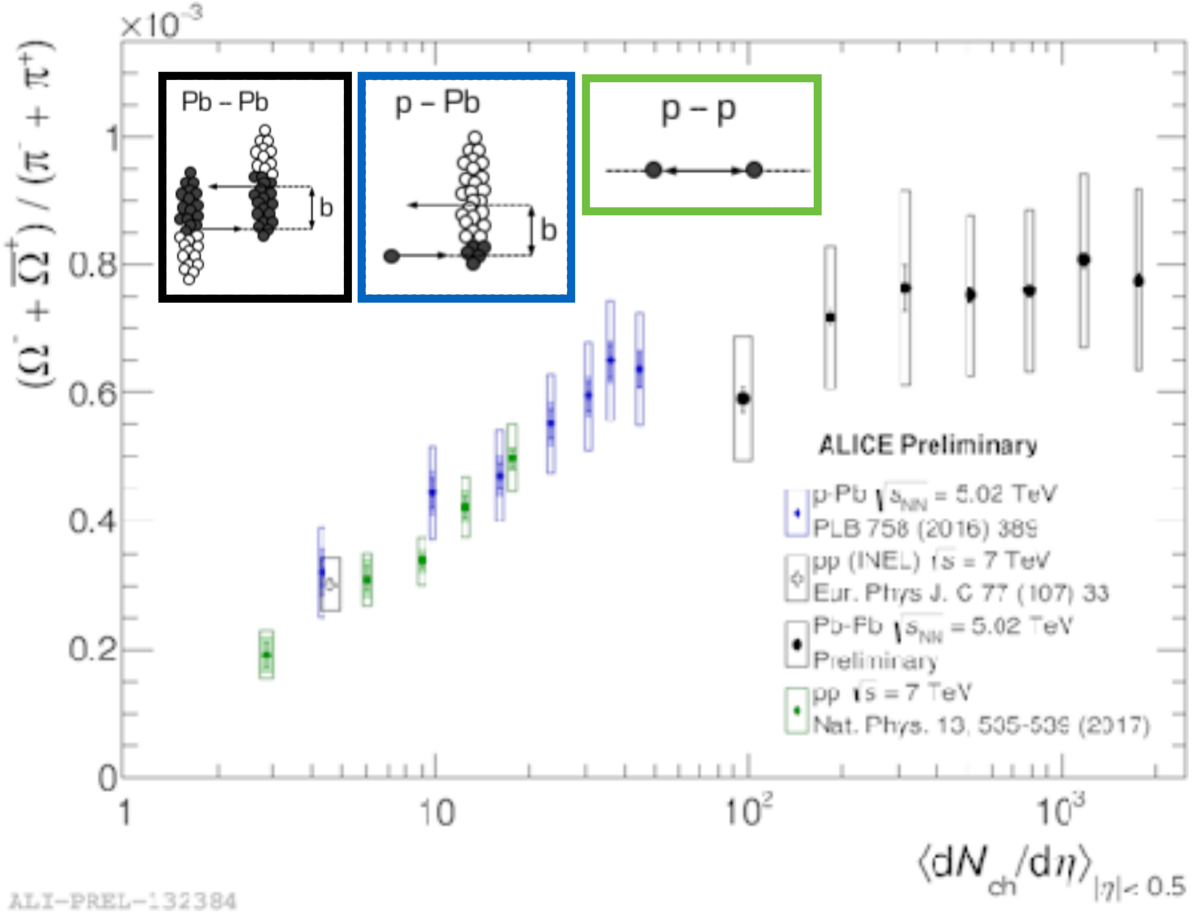
ALI-PREL-132377

Strangeness enhancement

Strangeness enhancement through hyperon-to-pion yield ratio for easier colliding system comparison (get rid of $\langle N_{part} \rangle$ scaling)

- Increase of ratio-to-pion vs multiplicity from pp (min. bias) to Pb-Pb
- Ratio-to-pion vs multiplicity in p-Pb bridge from pp to Pb-Pb
- Ratio-to-pion vs multiplicity in pp <u>surprisingly</u> increasing with multiplicity and overlapping with p-Pb measurements

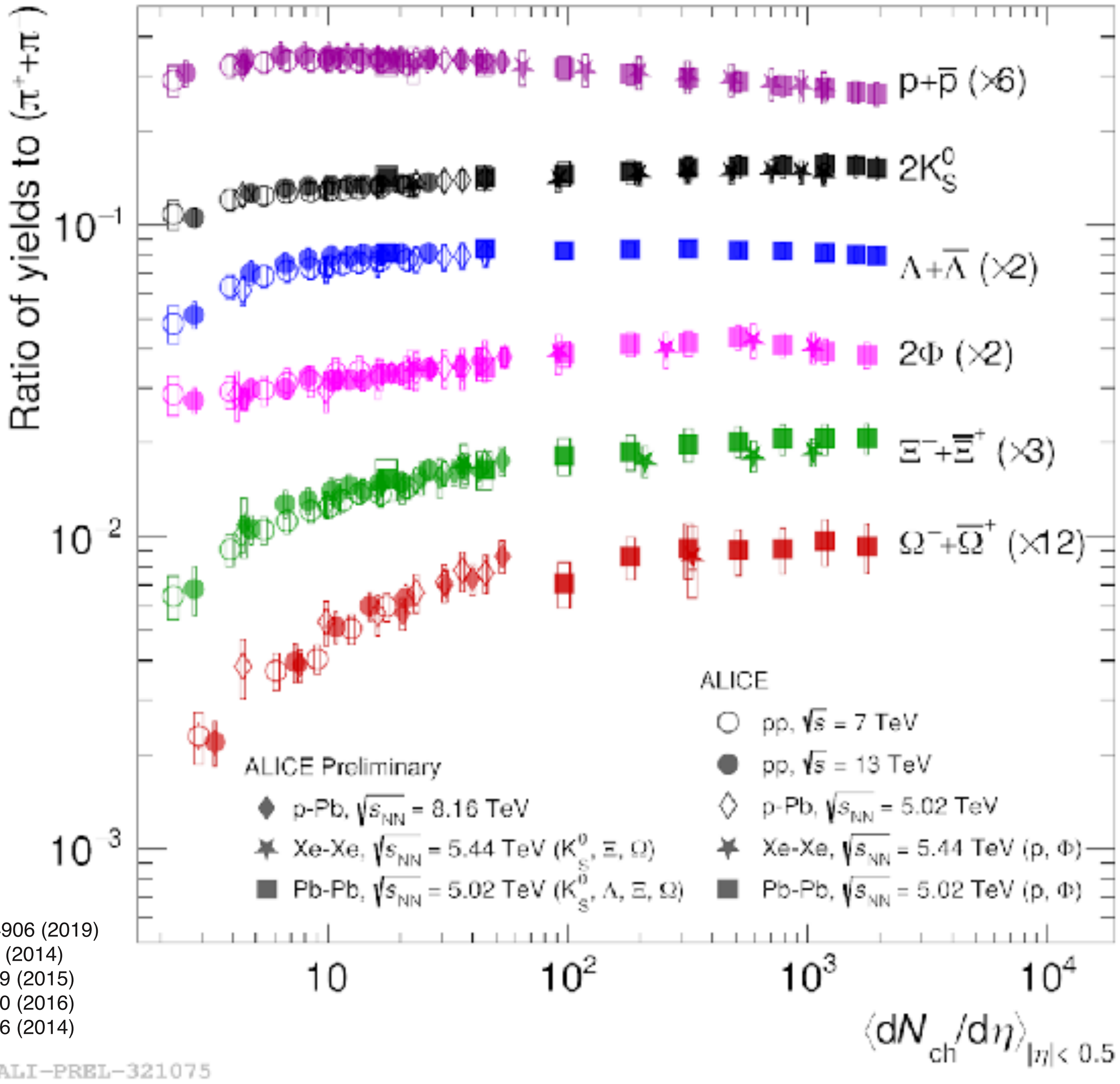




Strangeness enhancement

(1) Is strangeness enhancement a final state effect or is it related to initial colliding system characteristics?

- No colliding energy dependency
- No colliding system dependency
- Hadron chemistry is driven by the multiplicity



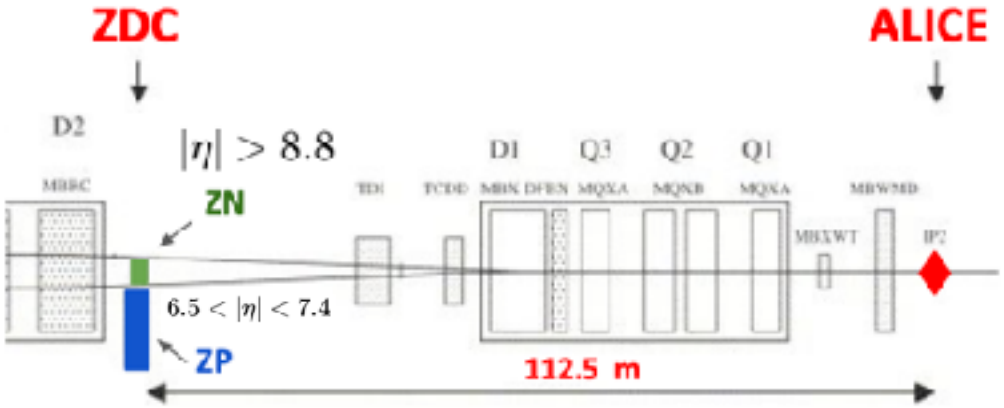
Phys. Rev. C 99, 024906 (2019)
Phys. Lett. B 728, 25 (2014)
Phys. Lett. B 758, 389 (2015)
Phys. Lett. B 760, 720 (2016)
Phys. Lett. B 736, 196 (2014)

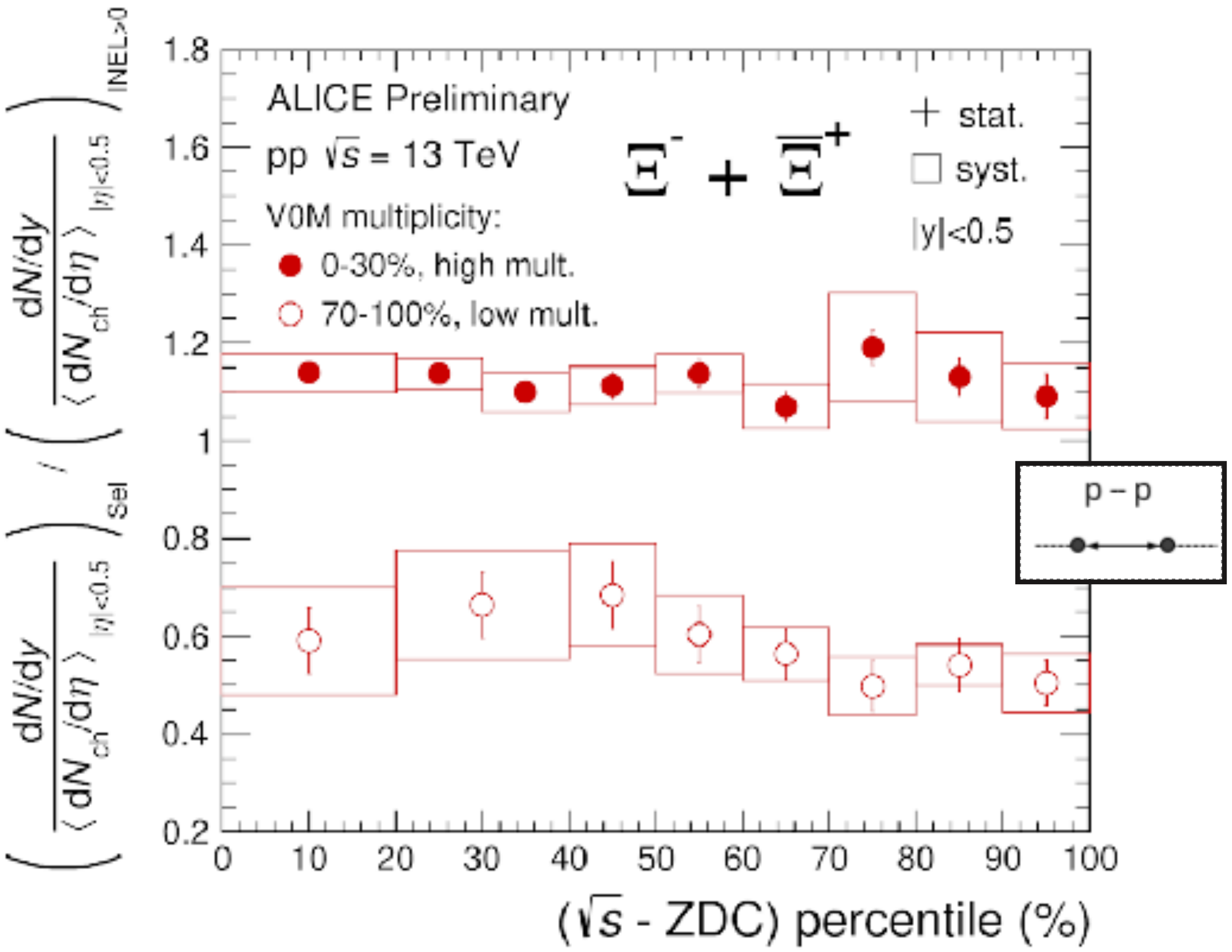
Strangeness enhancement

(1) Is strangeness enhancement a final state effect or is it related to initial colliding system characteristics?

Is strangeness enhancement related to effective energy?
Effective energy: energy available for particle production in the initial phase of a pp collision

$$E_{Eff} = \sqrt{s} - E_{|\eta|>8}$$





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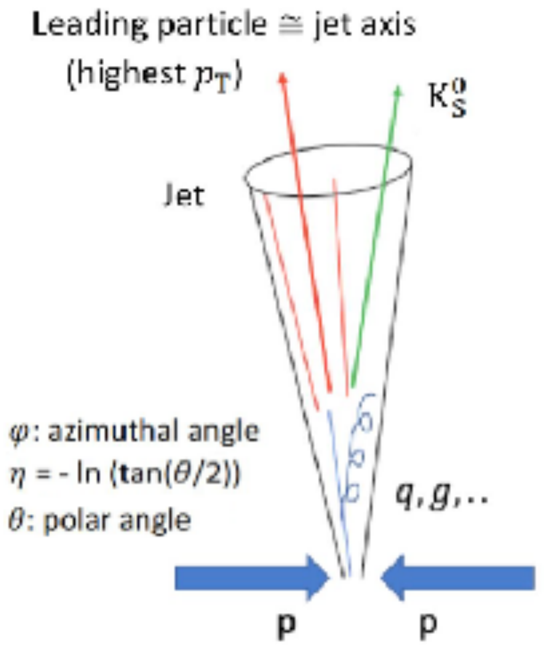
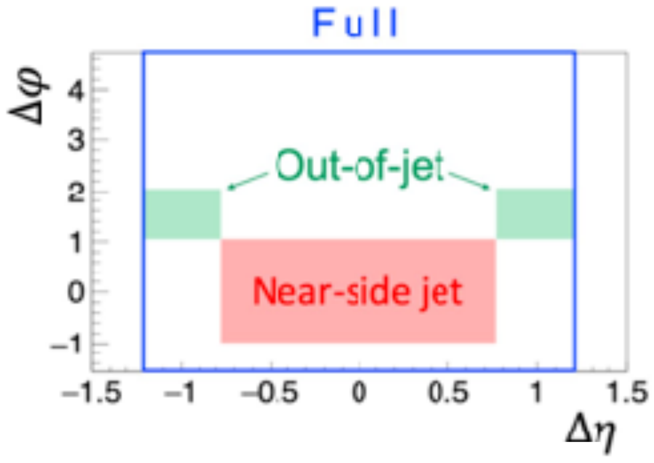
- No effective energy dependency

Strangeness enhancement

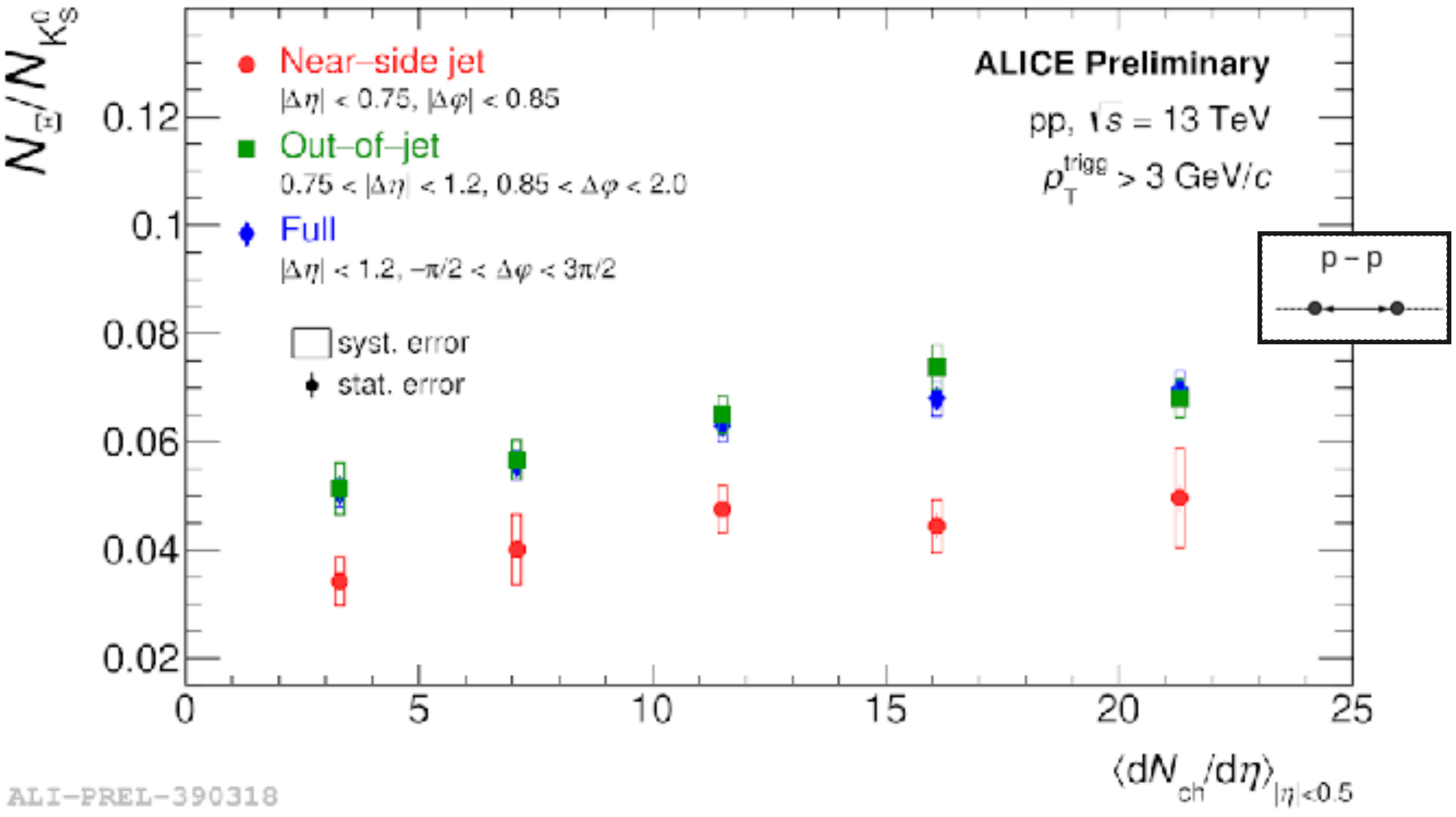
(2) Is strangeness enhancement related to soft particle production or to hard processes?





$$\Delta\varphi = \varphi_{Trigg} - \varphi_{Assoc}$$

$$\Delta\eta = \eta_{Trigg} - \eta_{Assoc}$$



ALI-PREL-390318

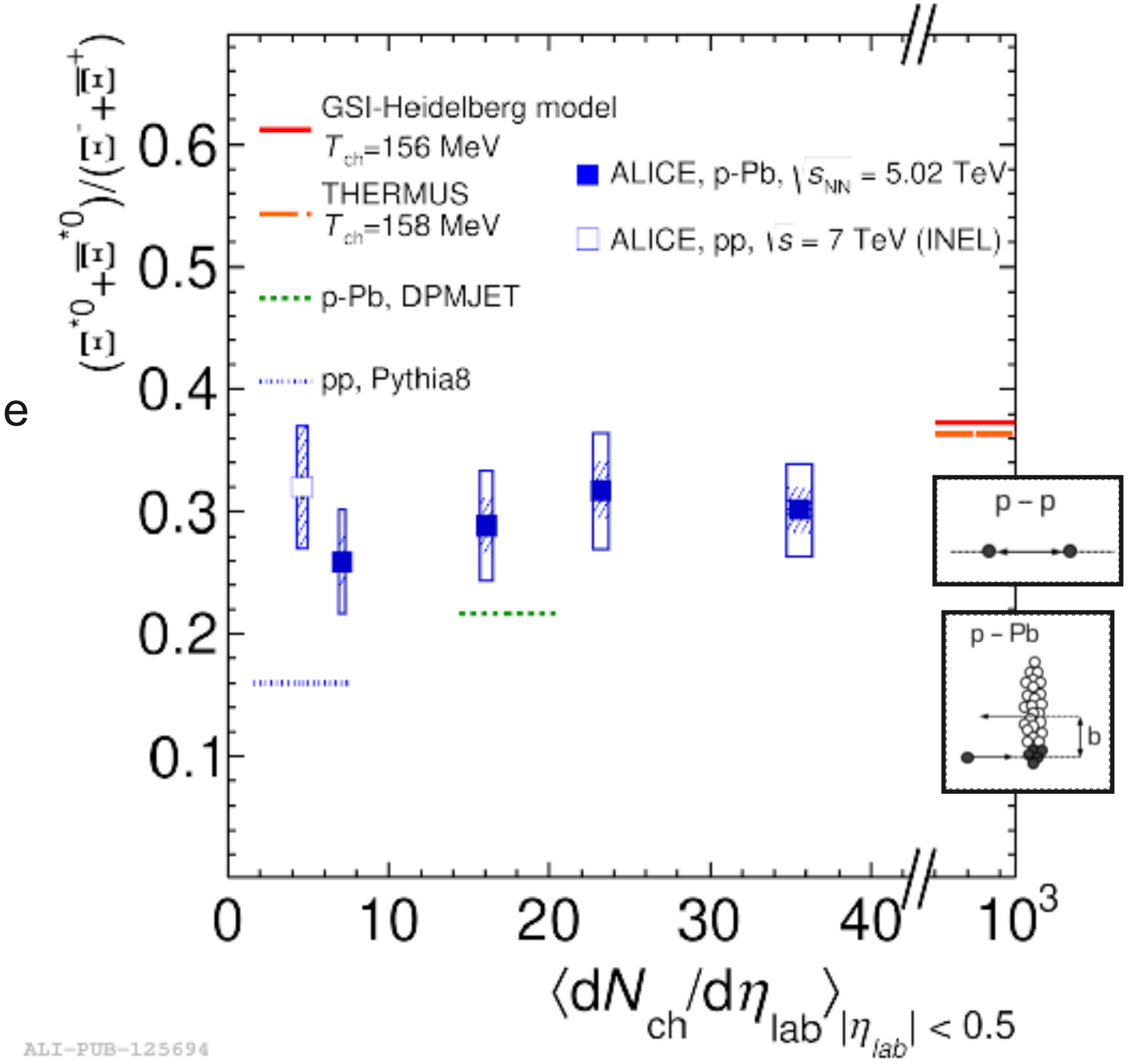
- The **out-of-jet** Ξ/K^0_S yield ratio increases with multiplicity
- The **near-side-jet** Ξ/K^0_S yield ratio shows hint of increase
- **Out-of-jet processes are the dominant contribution to the full yield ratio**

Strangeness enhancement

(3) Is strangeness enhancement due to mass difference?

Look at the ratio between particles with same strangeness content but different mass ($m_{\Xi^-} = 1321\,GeV/c^2$, $m_{\Xi^{*0}} = 1530\,GeV/c^2$)

- No dependency from multiplicity
  - → **Not a mass effect**



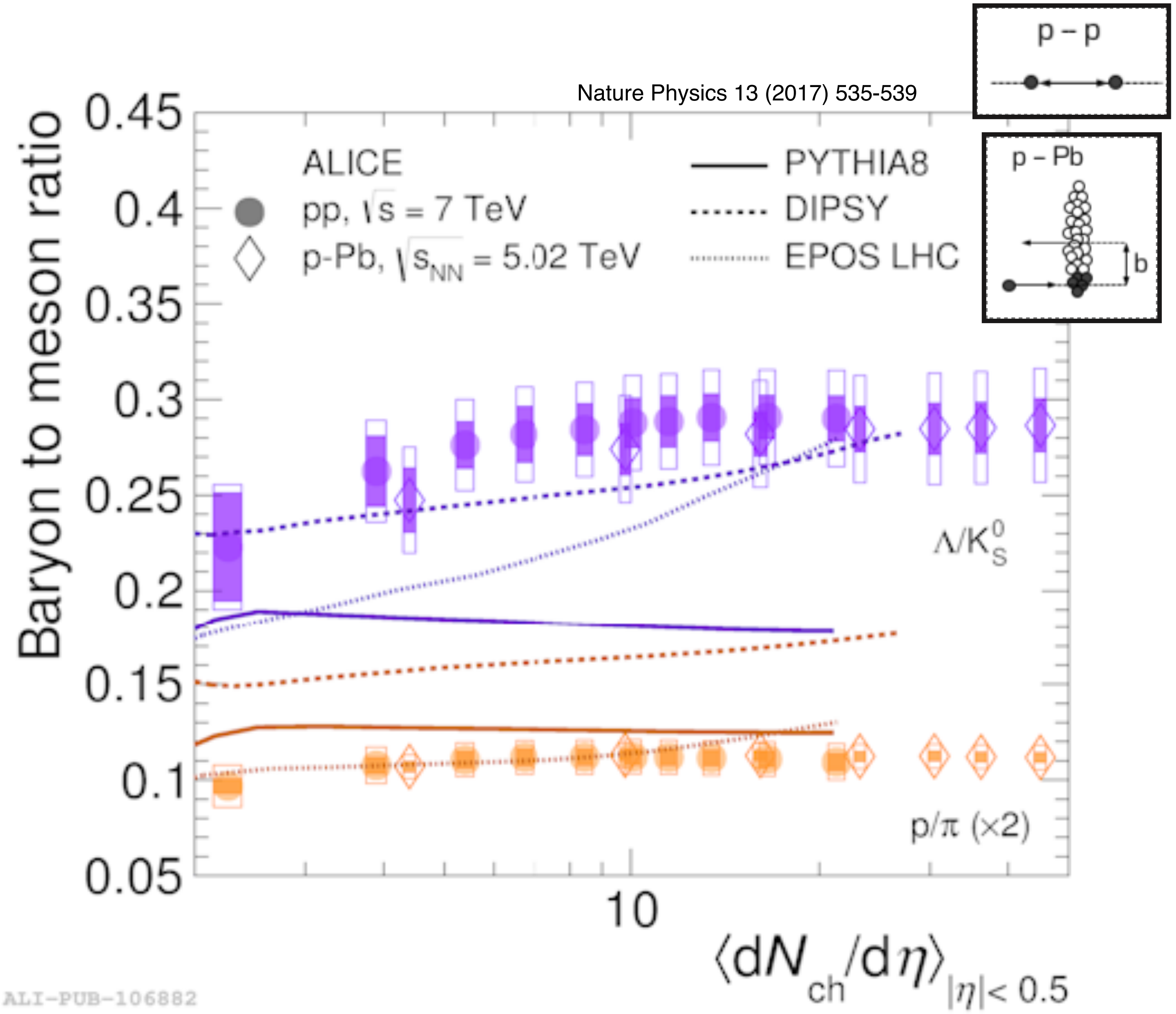
Strangeness enhancement

(4) Is strangeness enhancement related a baryon-meson effect?

Look at the ratio between baryon and meson having the same strangeness content

- No dependency from multiplicity

  → **Not a baryon-to-meson effect**



Nature Physics 13 (2017) 535-539

Strangeness enhancement

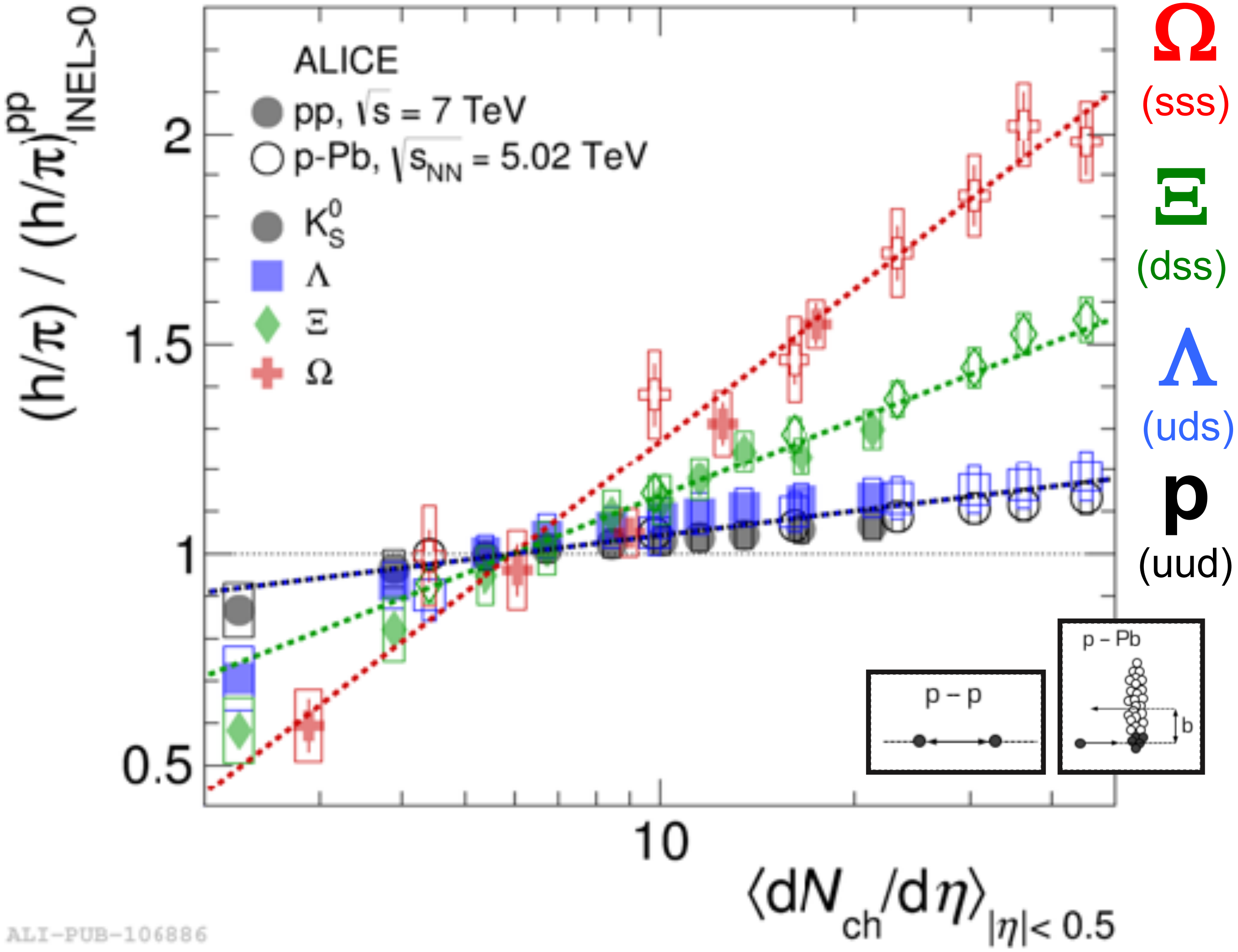
(5) Is strangeness enhancement hierarchy actually due to strangeness content?

Look at the double ratio $(h/\pi)/(h/\pi)^{pp}_{INEL}$

→ **Hierarchy with strangeness content confirmed**

→ **proton ($S = 0$) consistent with unity up to highest $\langle dN_{ch}/d\eta \rangle$**

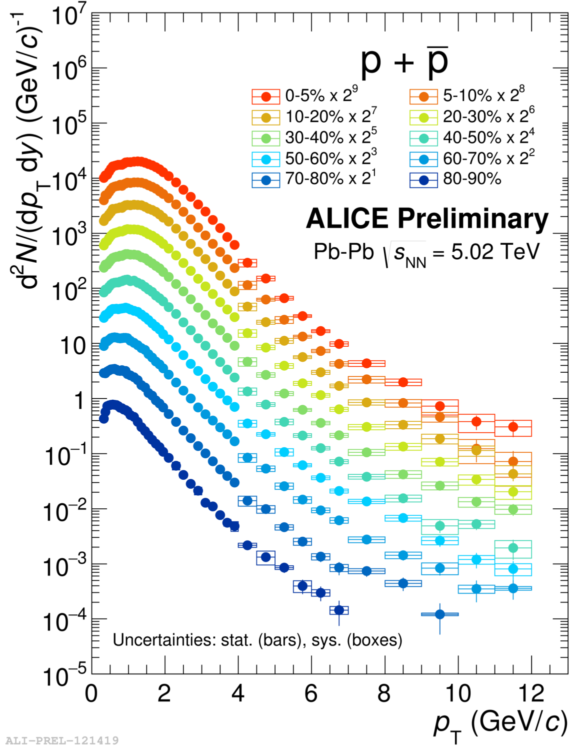
Nature Physics 13 (2017) 535-539



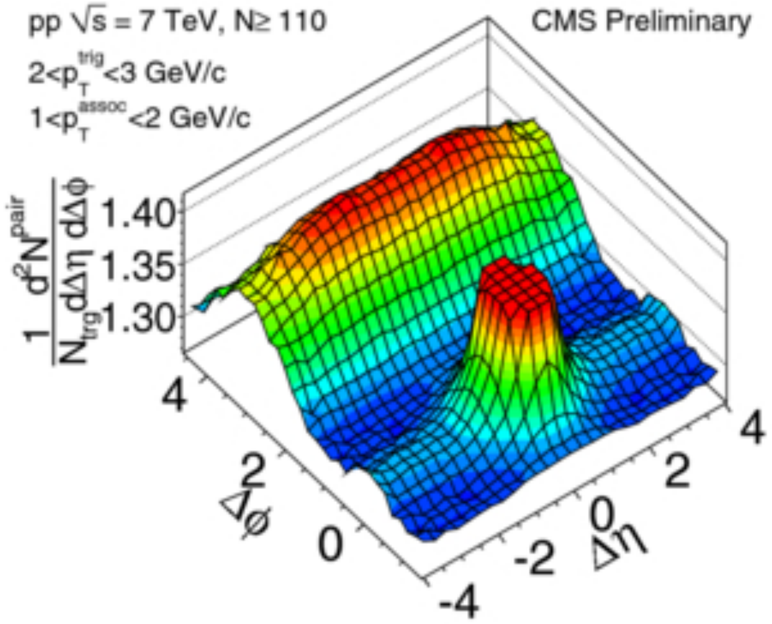
Strangeness enhancement

- Initial concept of strangeness enhancement as signature of QGP evolved and a lot of characteristics have been measured
  - No dependency from initial colliding system, energy and effective energy
  - Hadrochemistry driven by multiplicity
  - Property of the bulk ($p_T < 3\,GeV/c$) of particles
  - Due to strangeness content of the particles (not a mass or baryon-meson effect)
- Strangeness enhancement is another **collective phenomenon** (usually related to the properties of the QGP) observed **in small colliding systems high multiplicity events**

Hardening of the spectra with increasing multiplicity

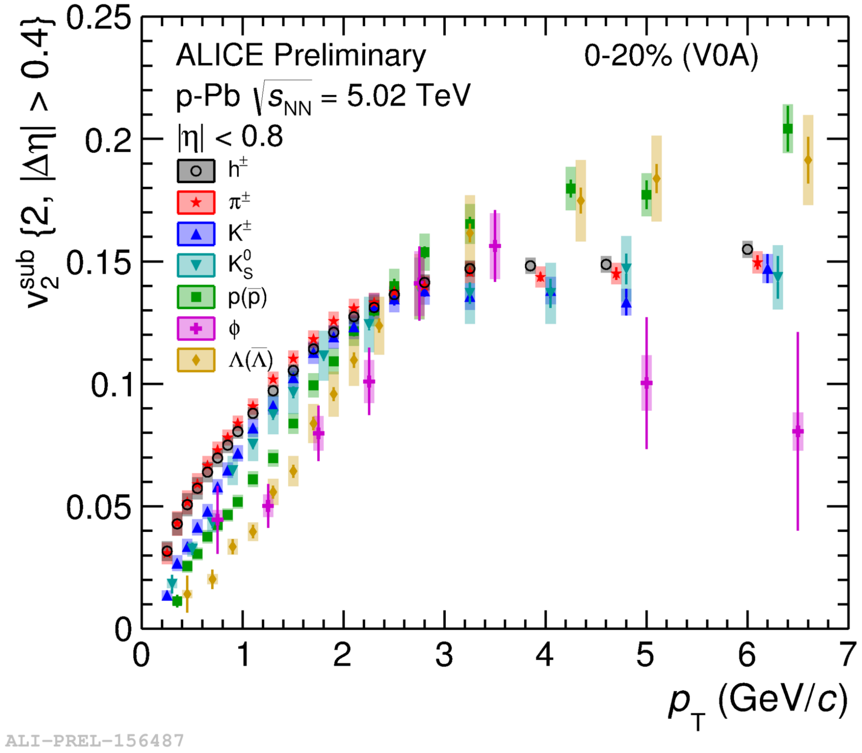


Ridge-like structure at $\Delta\phi \sim 0$

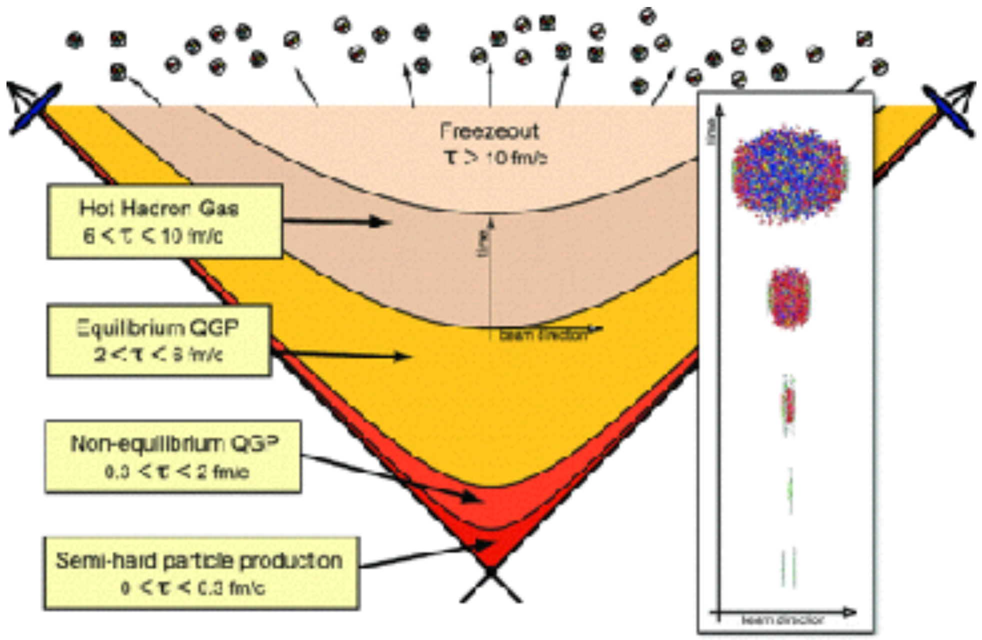


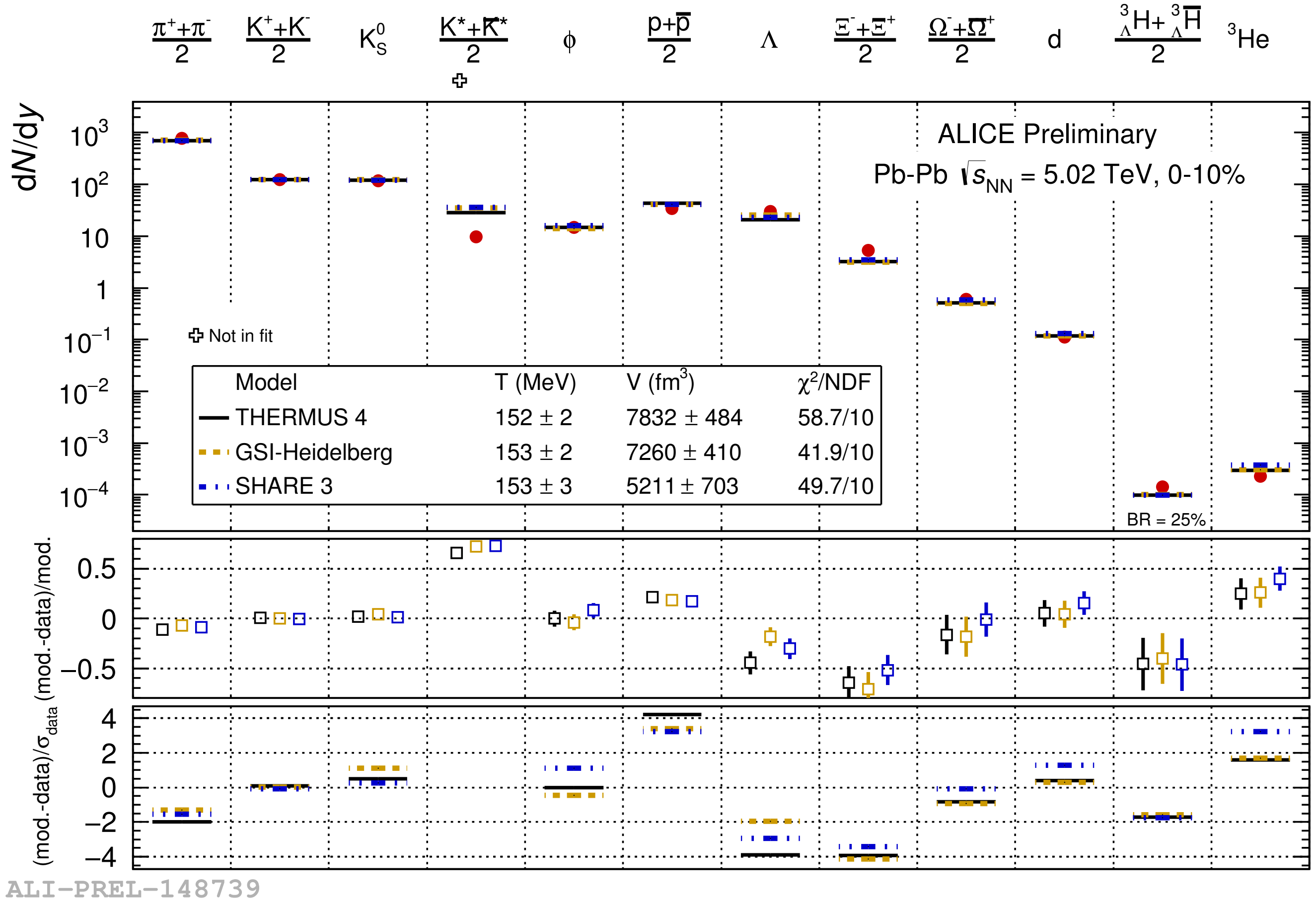
Phys. Lett. B 708, 249-264

Effect of anisotropic flow and mass ordering



Strangeness hadronisation process

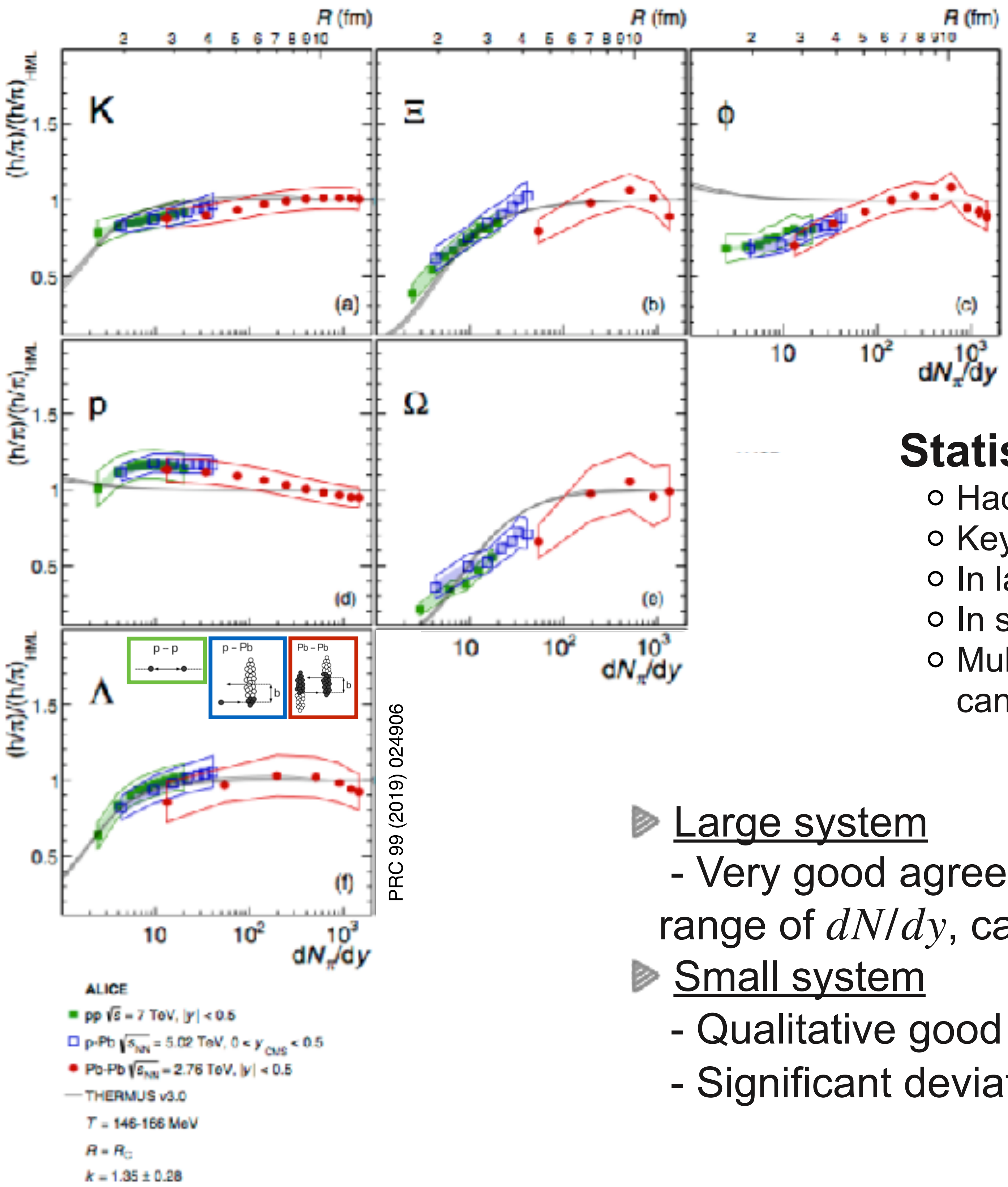




Statistical Hadronisation Model

- Hadrons emitted from a source in thermal equilibrium
- Key parameter: chemical freeze-out temperature T_{ch}
- In large systems: grand canonical approach
- In small systems: canonical approach
- Multiplicity dependency explained with removal of canonical suppression

Strangeness hadronisation process



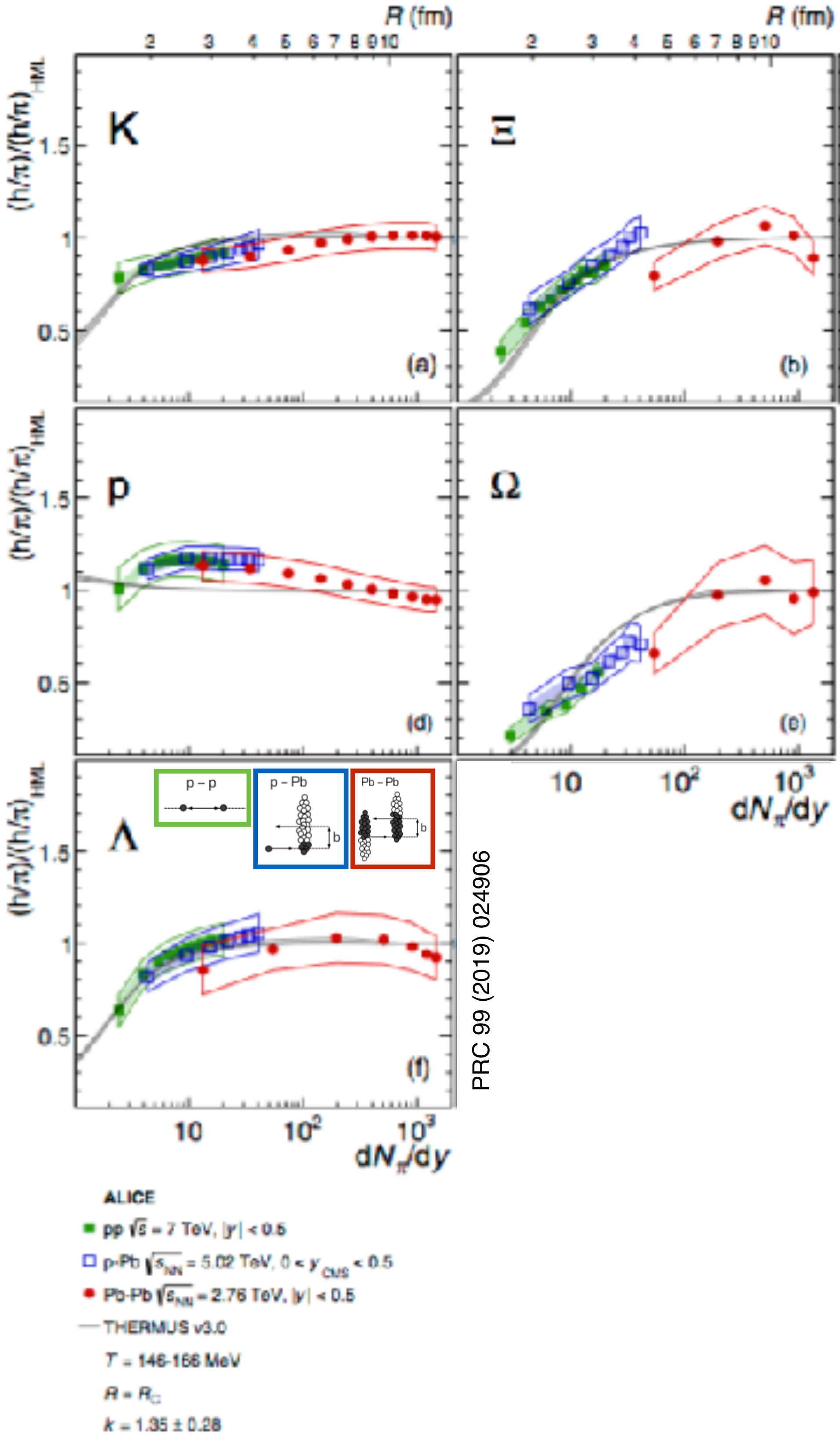
PRC 99 (2019) 024906

Statistical Hadronisation Model

- Hadrons emitted from a source in thermal equilibrium
- Key parameter: chemical freeze-out temperature T_{ch}
- In large systems: grand canonical approach
- In small systems: canonical approach
- Multiplicity dependency explained with removal of canonical suppression

- Large system
  - Very good agreement for yields over a wide range of dN/dy, catching also nuclei yield
- Small system
  - Qualitative good agreement for K, Λ, Ξ and Ω
  - Significant deviation for the ϕ

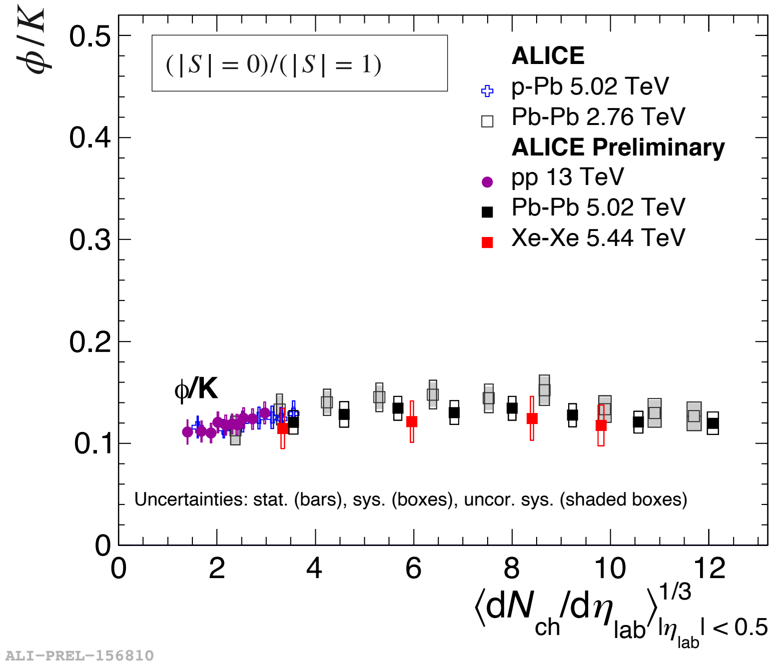
Strangeness hadronisation process

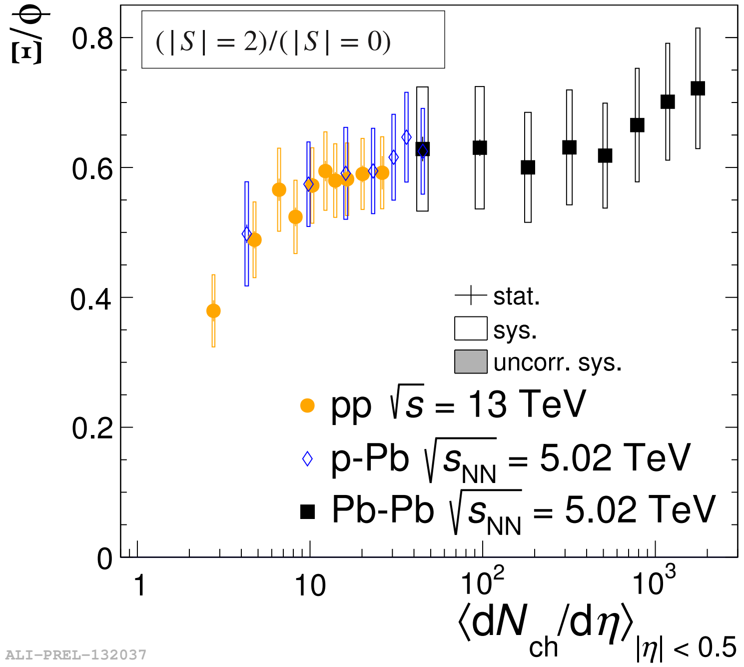


PRC 99 (2019) 024906

- The ϕ meson ($s\bar{s}$) has hidden strangeness and is a key probe in studying strangeness production
- Ratios ϕ/K and Ξ/ϕ fairly flat across wide multiplicity range

→ **The ϕ has “effective strangeness” of 1–2 units**



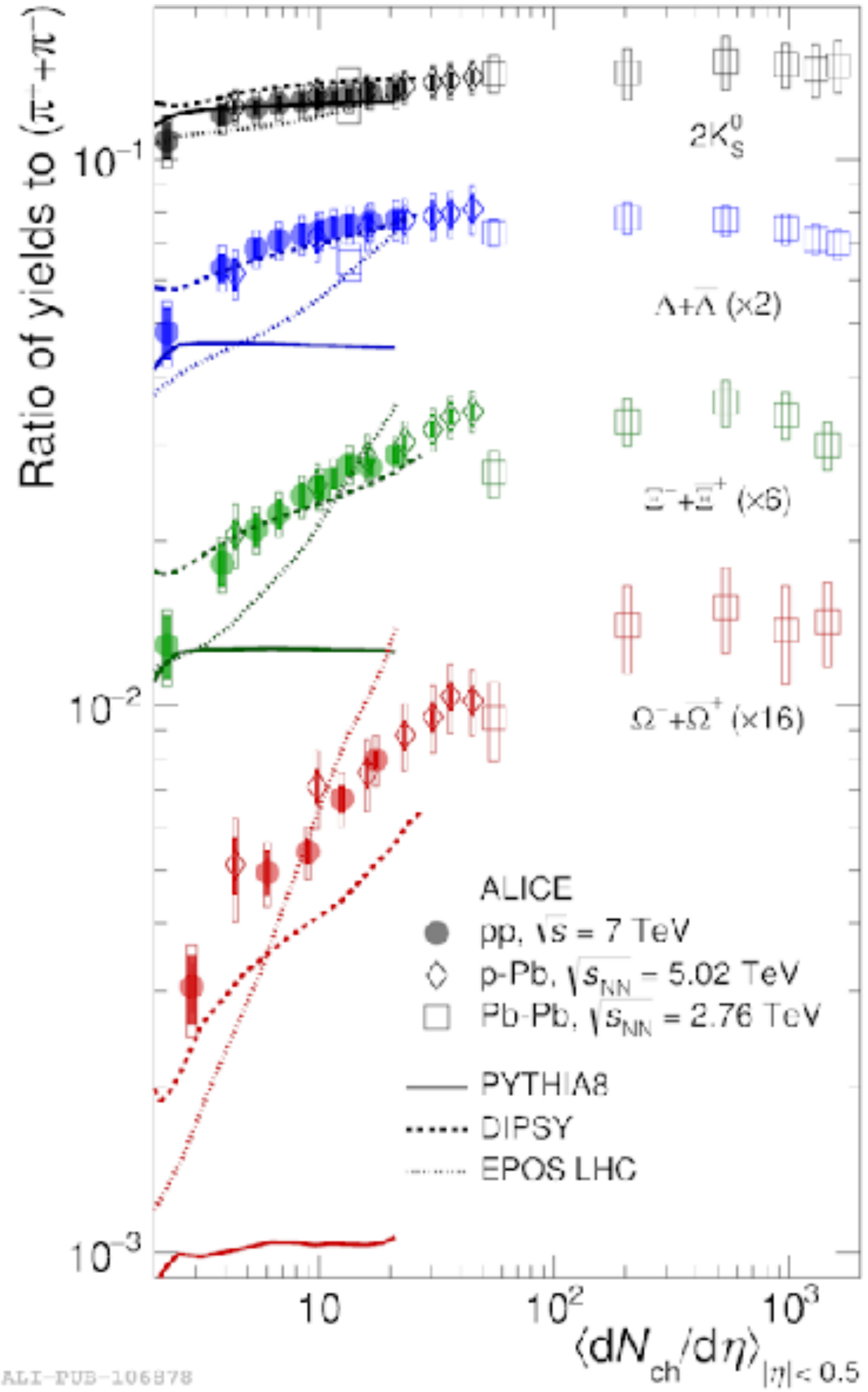


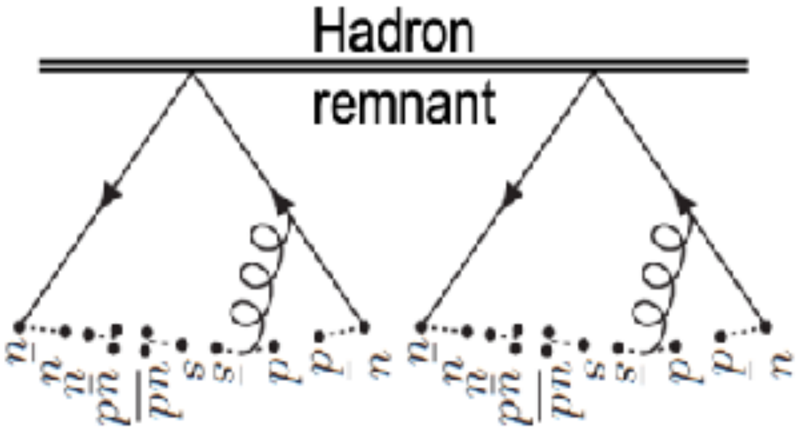
Strangeness hadronisation process

Microscopic models from pp collisions

- Traditional soft-QCD models based on Multiple Parton Interactions (MPI), e.g. **PYTHIA**, are not able to reproduce the observed trends
  - Breaks concept of universality and factorization of fragmentation [JHEP01(2017)140]
- MPI based models that embed also effects from densely packed strings (**DIPSY**) or core-corona hadronization mechanisms (**EPOS**) reproduce qualitatively the observed increasing trends for strange particle
  - Further tuning needed to reproduce all ratios simultaneously

Nature Physics 13 (2017) 535-539

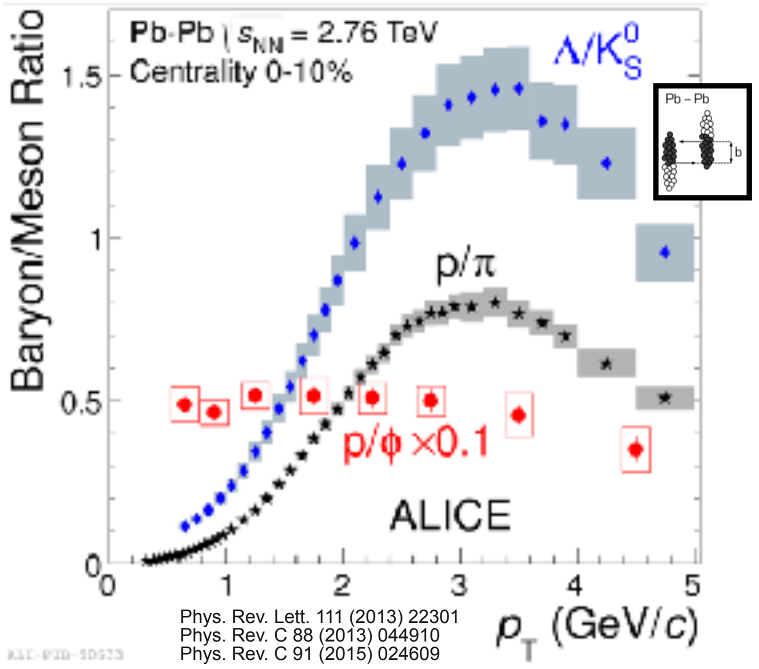




Strangeness hadronisation process

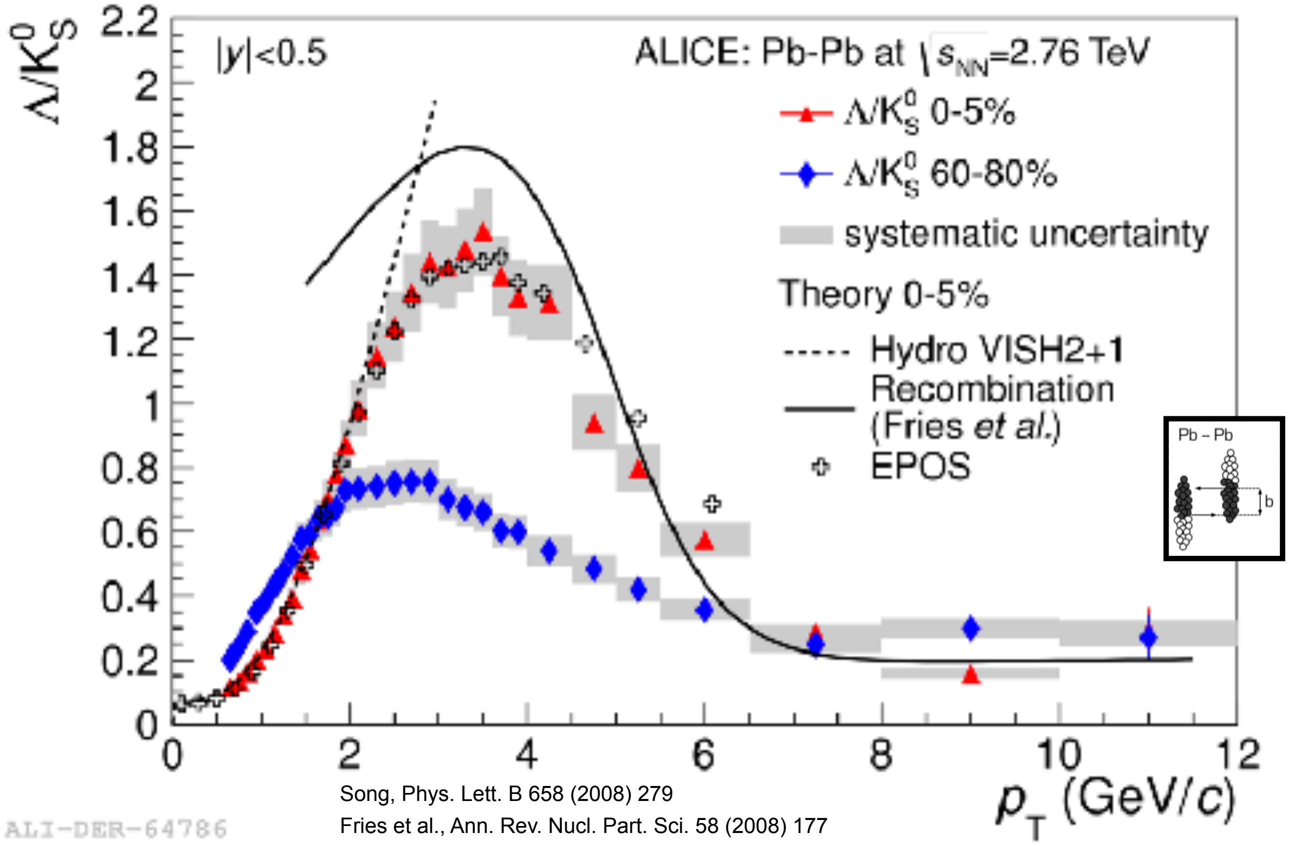
Baryon anomaly

- Interplay between **hydrodynamics** and **recombination**
- In central Pb-Pb collisions
  - p/π, Λ/K^0 enhancement at intermediate p_T
  - Hydro models: effect consistent with a flow boost pushing particles from low to high p_T (describes only the rise < 2 GeV/c)
  - Recombination reproduces the effect at intermediate p_T but overestimates towards lower p_T
  - EPOS (with flow) gives good description
- p/ϕ independent of p_T → Similar mass drives similar spectral shape
  - Can be explained by models with recombination



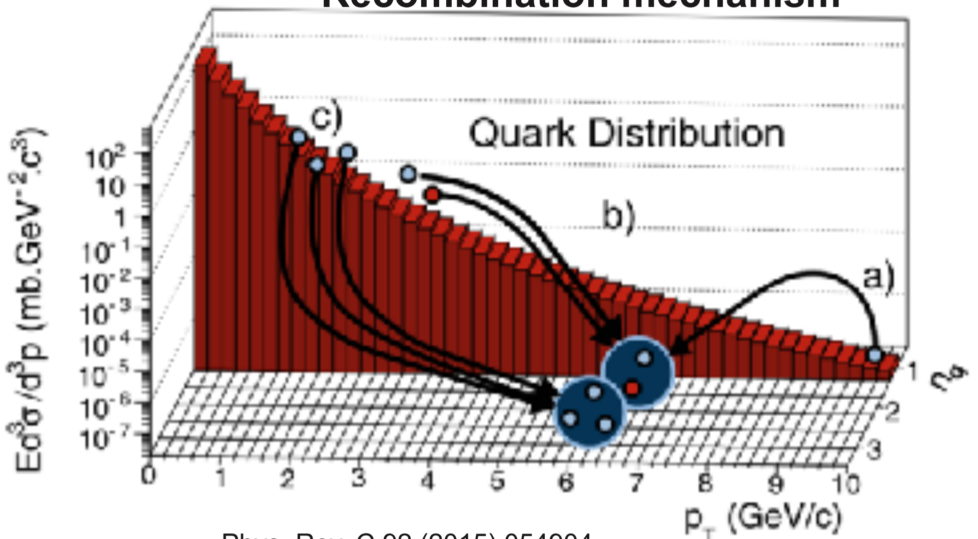
Phys. Rev. Lett. 111 (2013) 22301
Phys. Rev. C 88 (2013) 044910
Phys. Rev. C 91 (2015) 024609

PRL 111 (2013) 222301



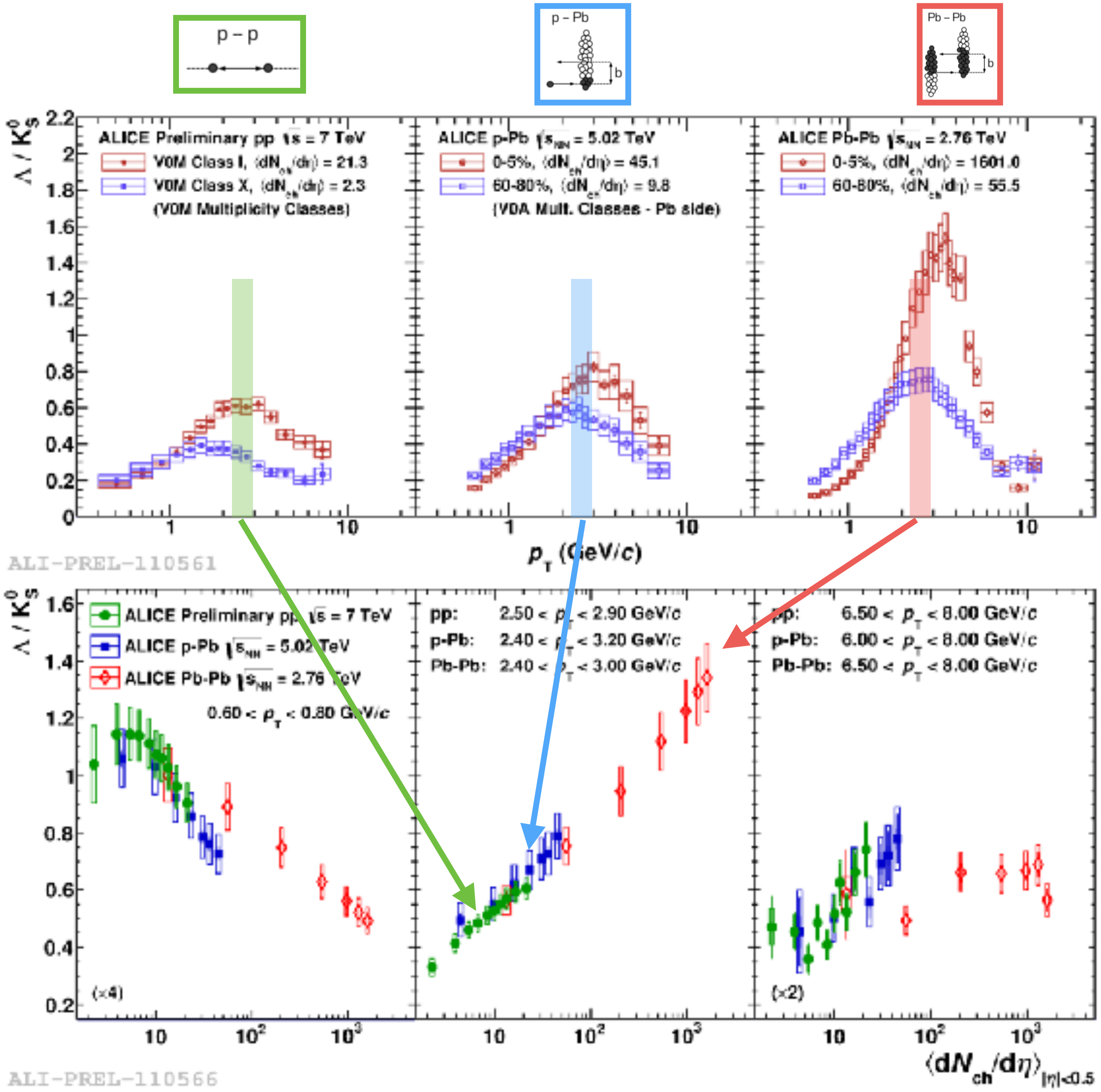
Song, Phys. Lett. B 658 (2008) 279
Fries et al., Ann. Rev. Nucl. Part. Sci. 58 (2008) 177
Werner, Phys. Rev. Lett. 109 (2012) 102301

Recombination mechanism



Phys. Rev. C 92 (2015) 054904

Strangeness hadronisation process

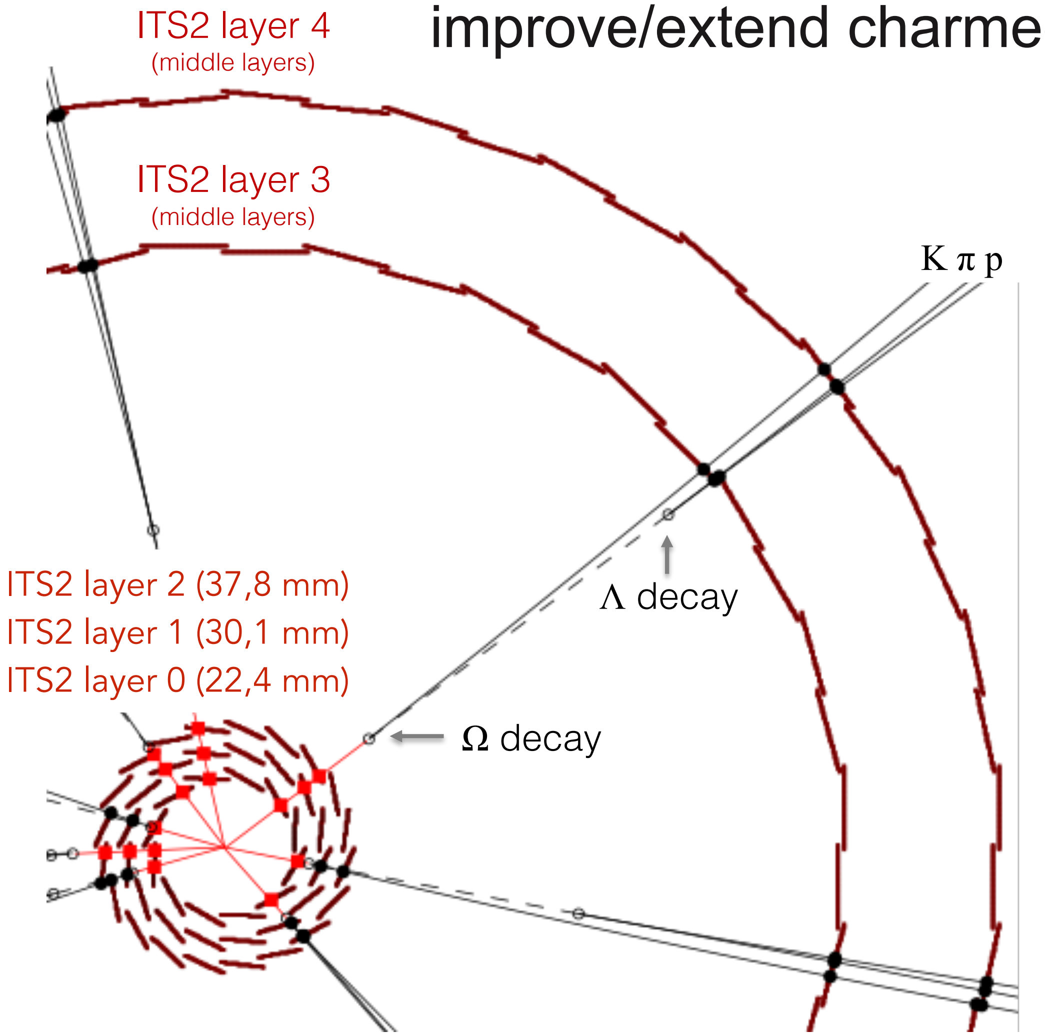


- Similar pattern observed also in smaller systems
- Clear continuity among different systems
  → **Points toward one common driving mechanism in all systems**

Future strangeness tracking

- **Open question for the future:** is the trend with multiplicity going to saturate at the thermal limit as observed in Pb-Pb collisions or is it going to keep growing?

- Using the new ALICE inner tracker (ITS) as **strangeness tracker**, expected to largely improve/extend charmed baryon reconstruction



$$\Omega^- \rightarrow \Lambda + K^-$$

Direct detection — Topological reconstruction

$$(c\tau = 2{,}46\,cm)$$

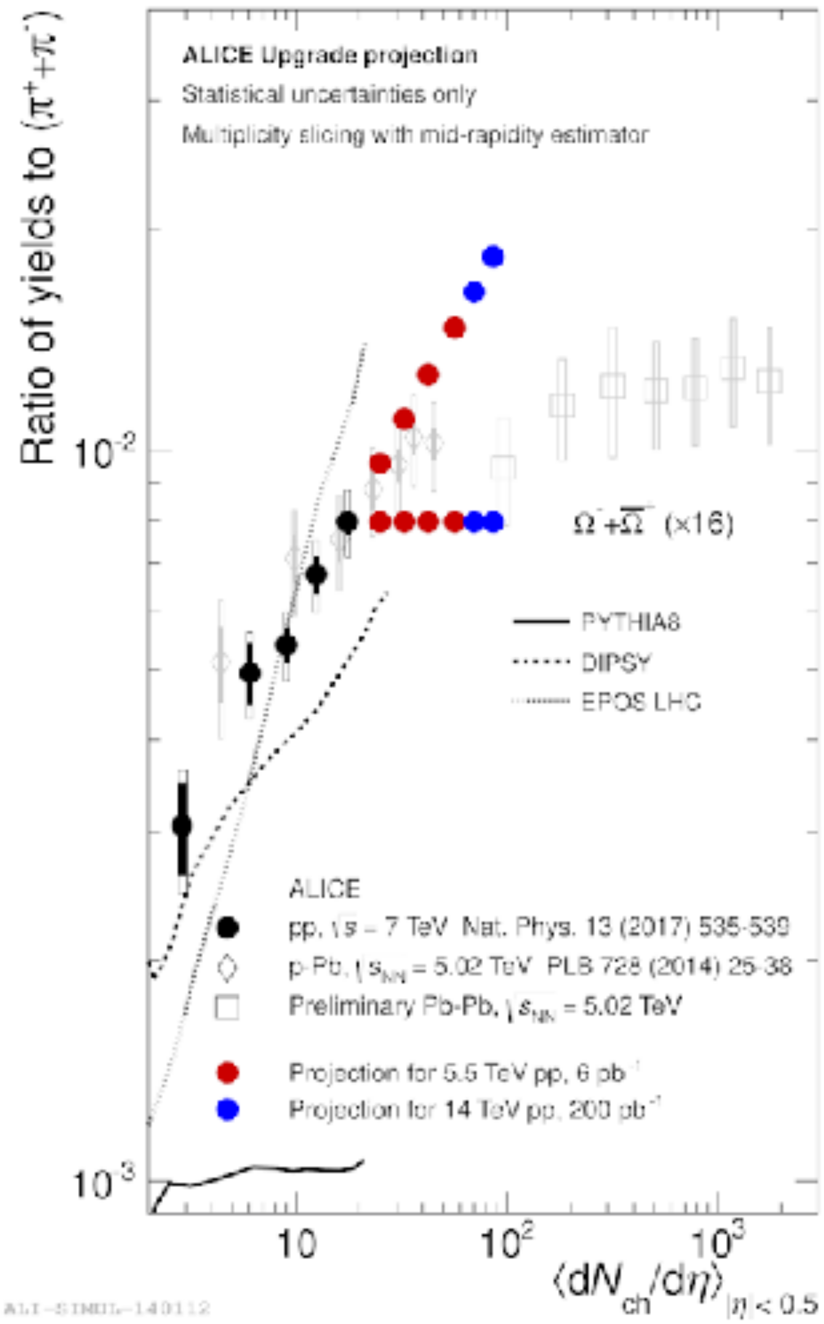
$$\downarrow$$

$$\Xi_C^+ \rightarrow \Xi^- + 2\pi^+$$

$$(c\tau = 132\,\mu m)$$

$$\Omega_C^0 \rightarrow \Omega^- + \pi^+$$

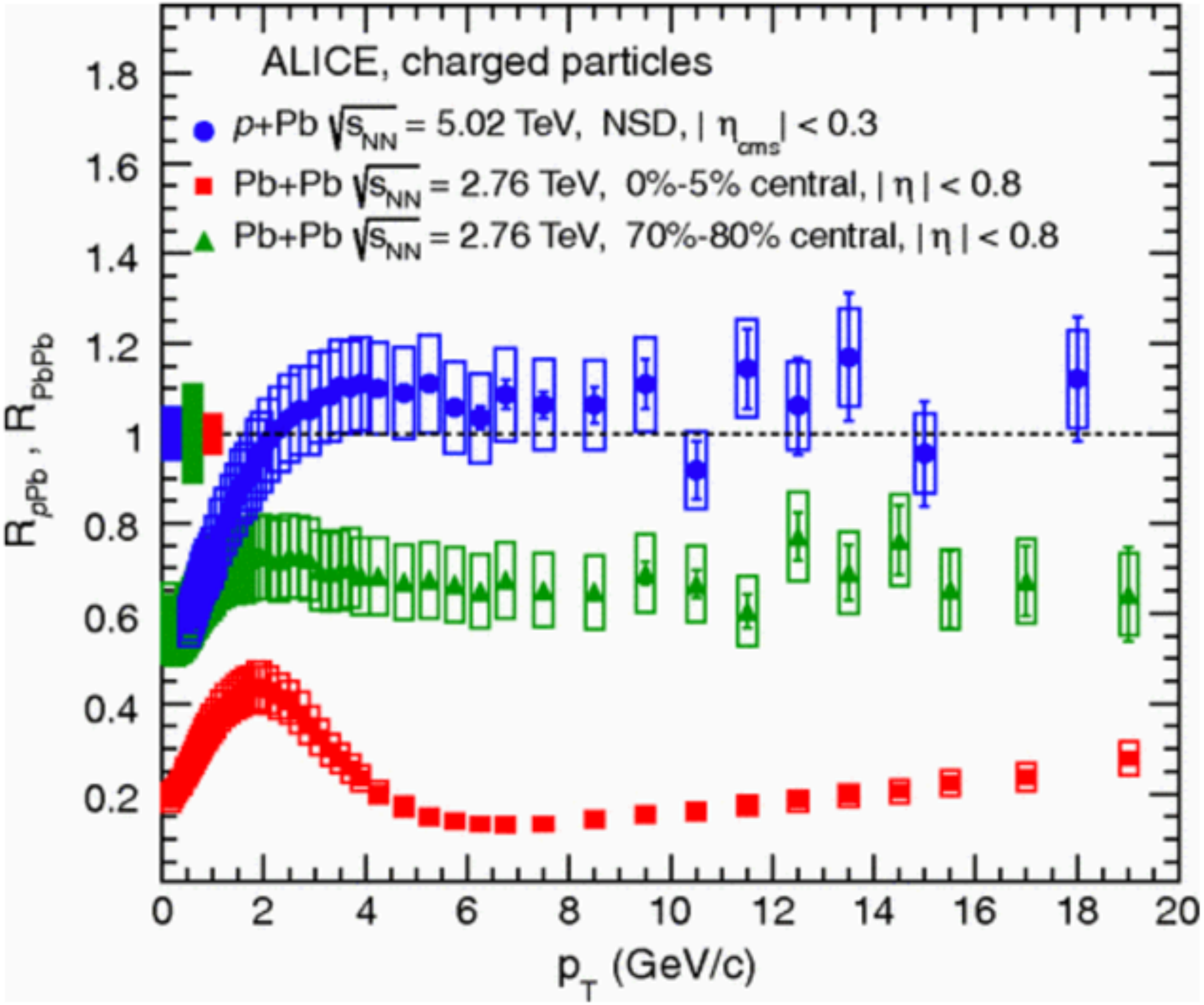
$$(c\tau = 80\,\mu m)$$



Backup

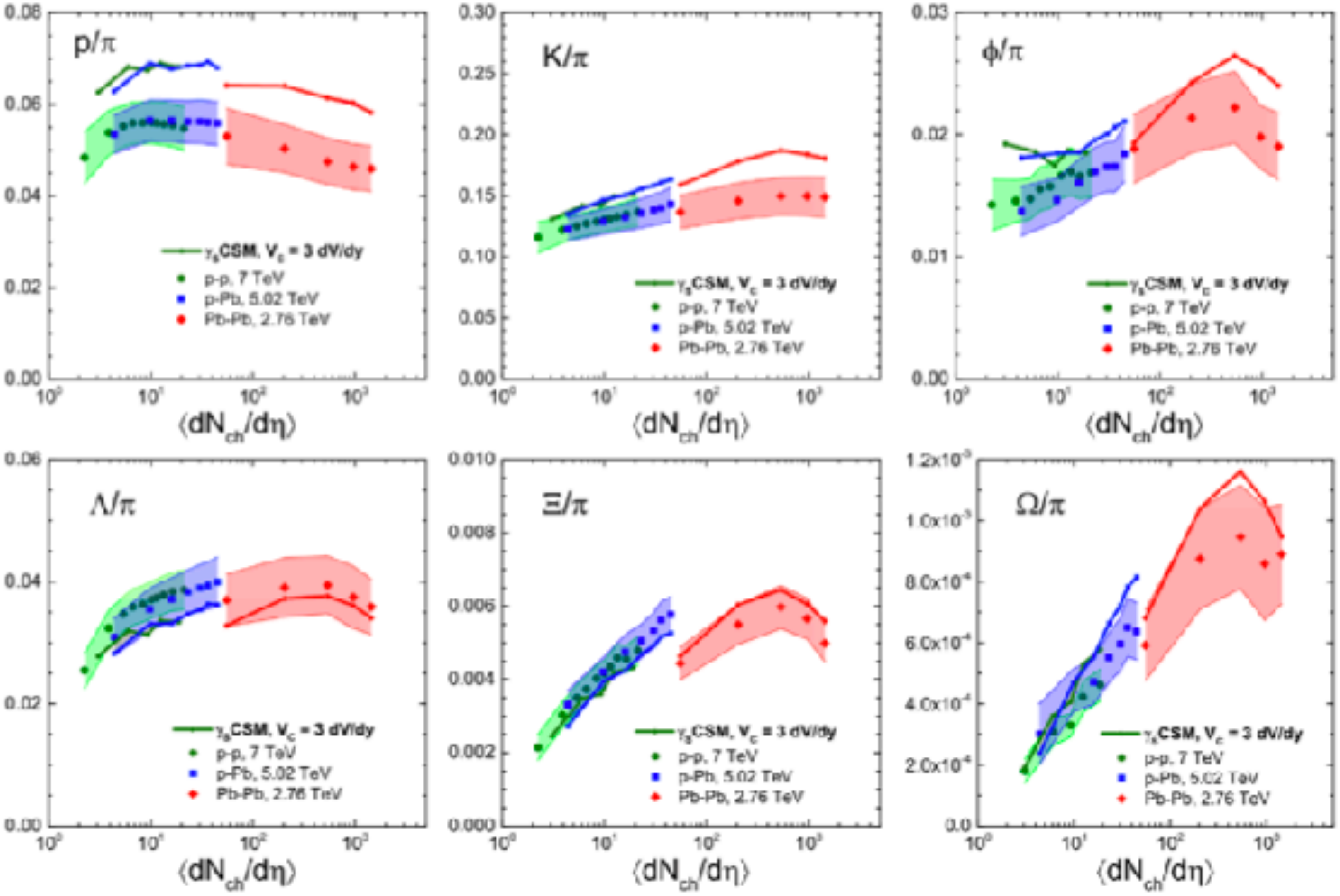
Backup

Nuclear Modification Factor in pPb collisions



Backup

Canonical statistical model with incomplete chemical equilibration



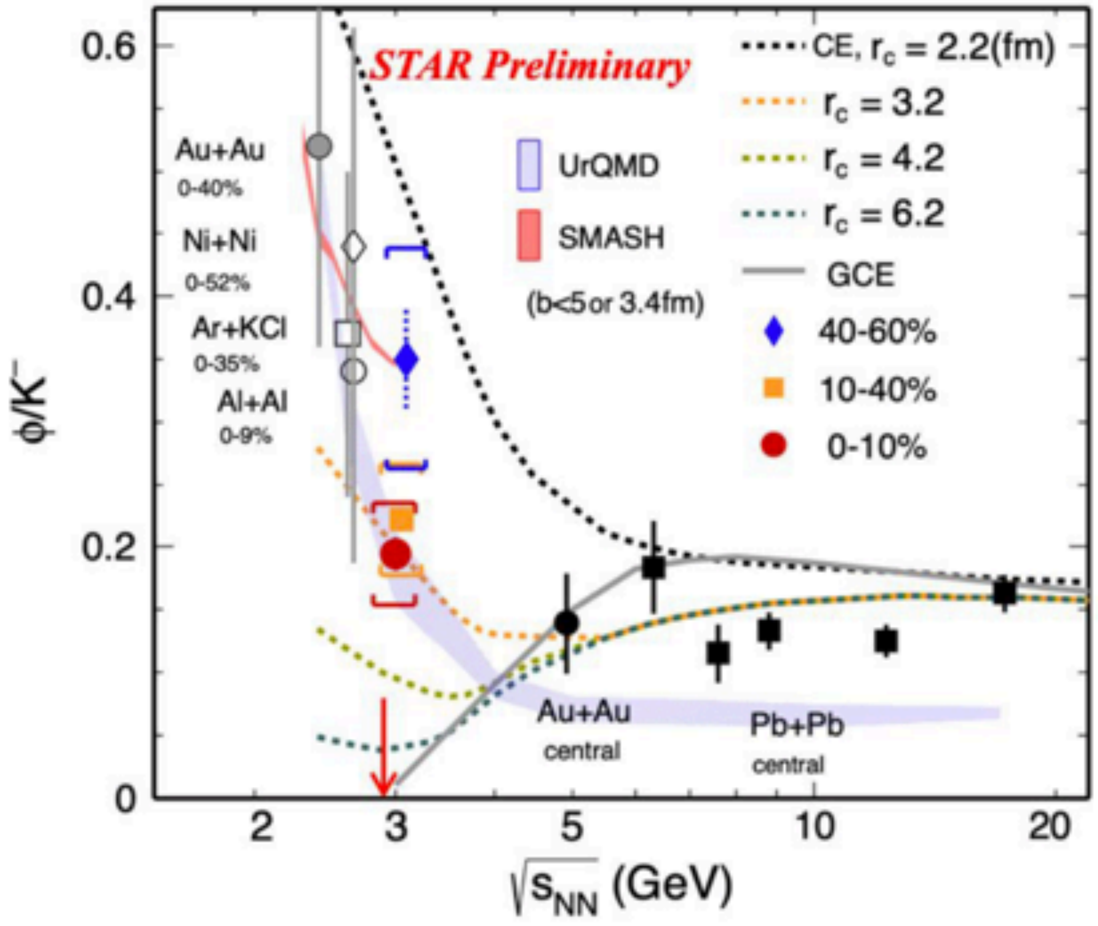
Recent developments (γ_S canonical statistical model) include:

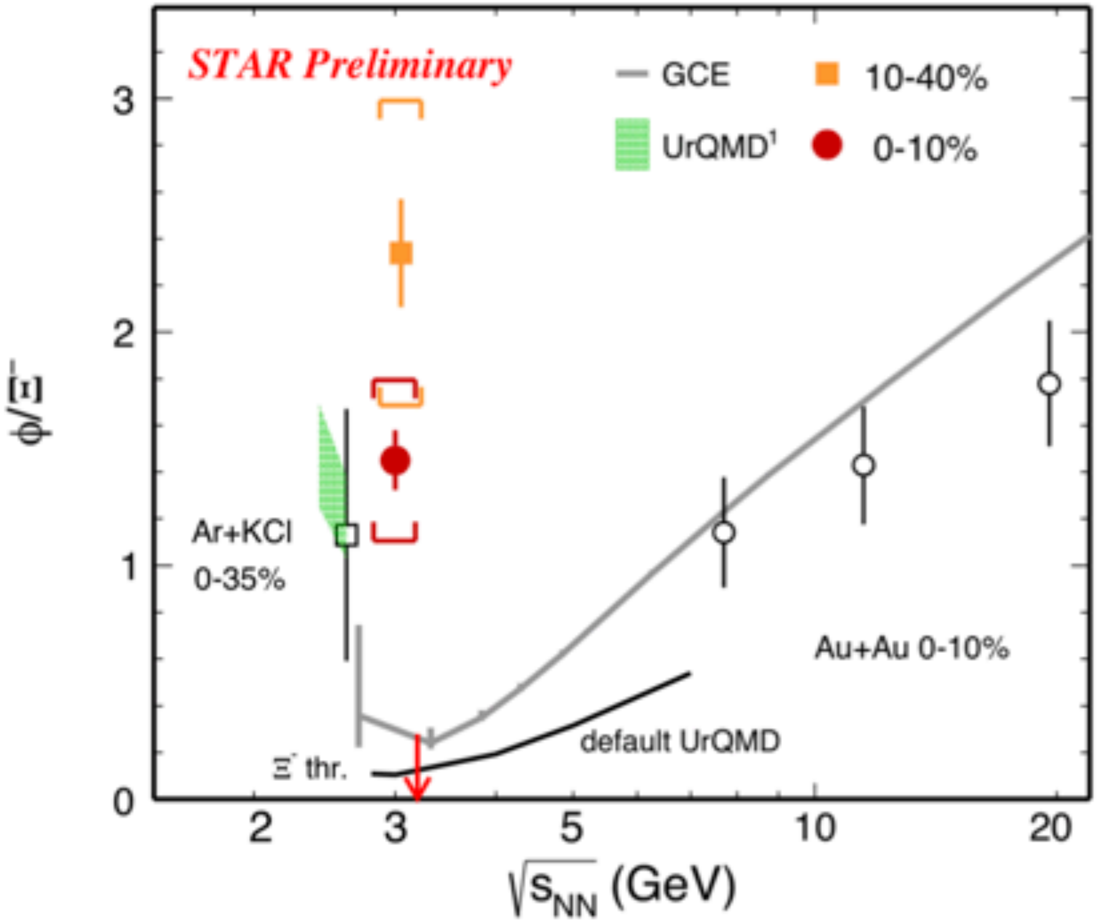
- Multiplicity-dependent T_{Ch}
- Incomplete chemical equilibration described by a multiplicity-dependent strangeness saturation parameter γ_S
- Good description of the available data except for p/π ratio (2σ at all multiplicities)

Backup

Canonical statistical model at RIHC

Statistical models:
A. Andronic et al, Nucl. Phys. A 772, 167;
J. Cleymans et al, Phys. Lett. B 603, 146

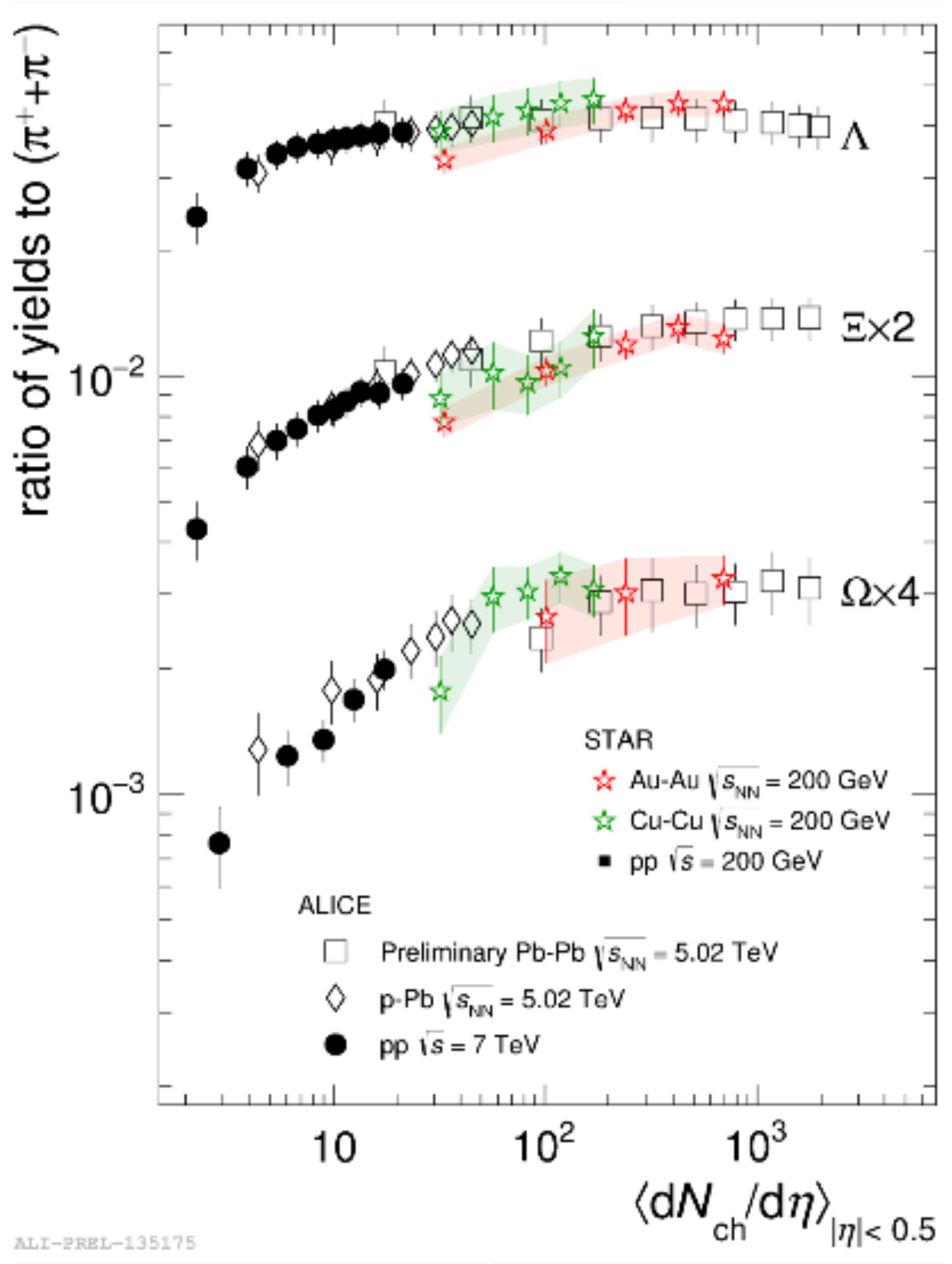




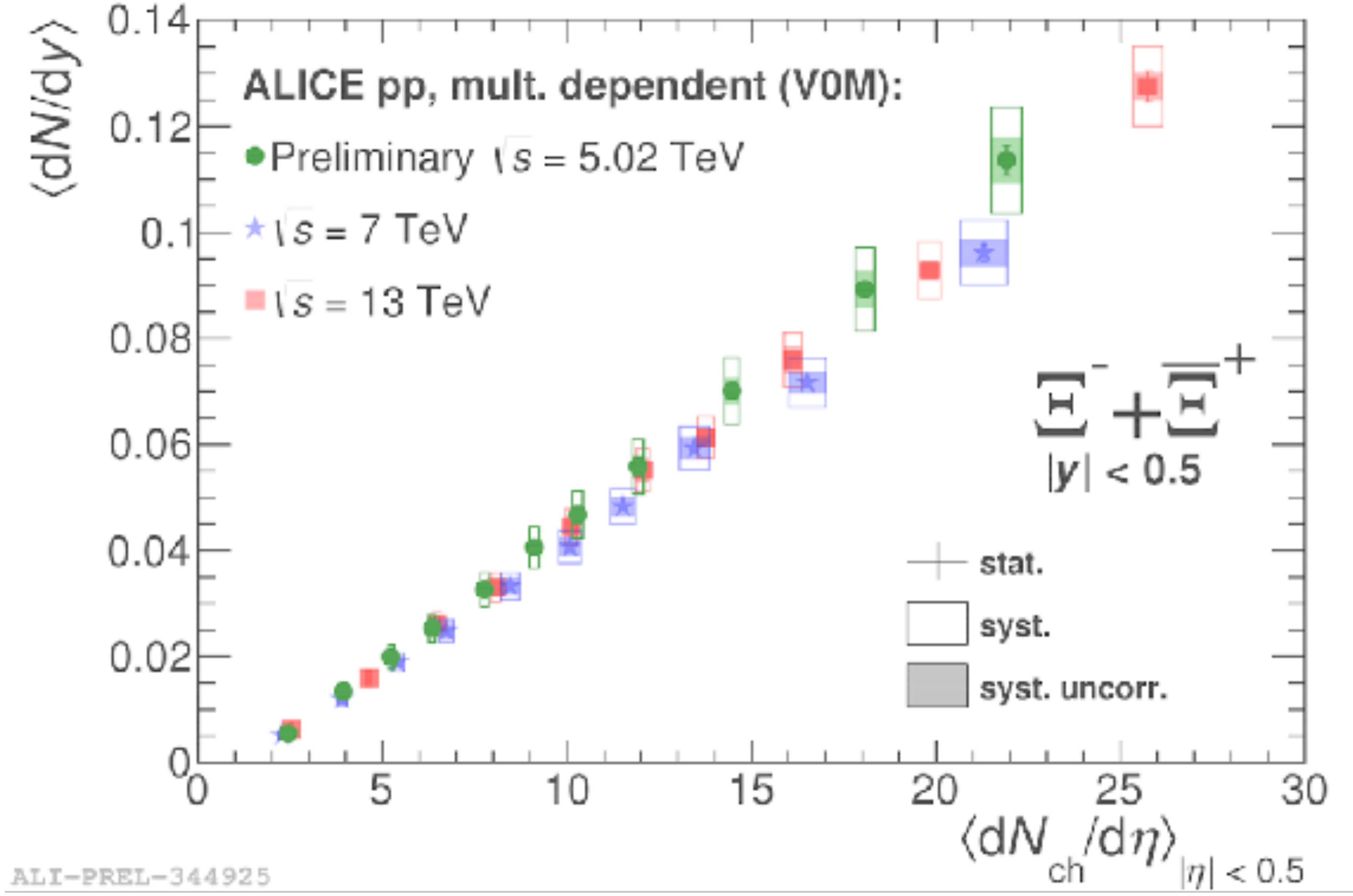
r_c : correlation length, radius of the volume inside which the production of particles with open strangeness is canonically conserved.

- Low energies, strangeness production is rare, local strangeness conservation may be required
- ~5σ deviation from zero (GCE) for 0-10% central collisions. Data favors the CE with r_c~ 3.2 fm
- Transport models with high mass resonance can reasonably describe data at low energies
  - Transport models with high mass resonance decay to ϕ and Ξ^- can reasonably describe previous measurement from SIS energies
  - NPA772: GCE + I_0/I_S+V_C=1500 fm³ describes data well at > 5 GeV, but underestimate our measurement at 3 GeV. Canonical suppression is important at low energies

Backup



pp 7 TeV: Nat. Phys. 13 (2017) 535-539
p-Pb 5 TeV: PLB 728 (2014) 25-38, PLB 758 (2016) 389-401
Au-Au 200 GeV: PRL 98 (2007) 62301
Cu-Cu 200 GeV: PRL 108, 072301



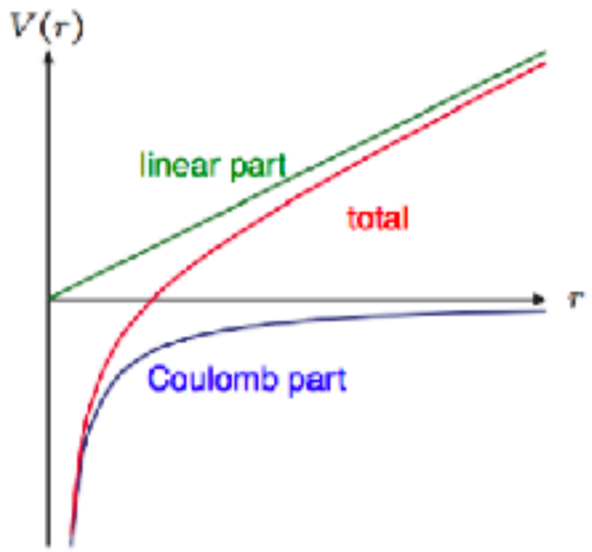
Backup

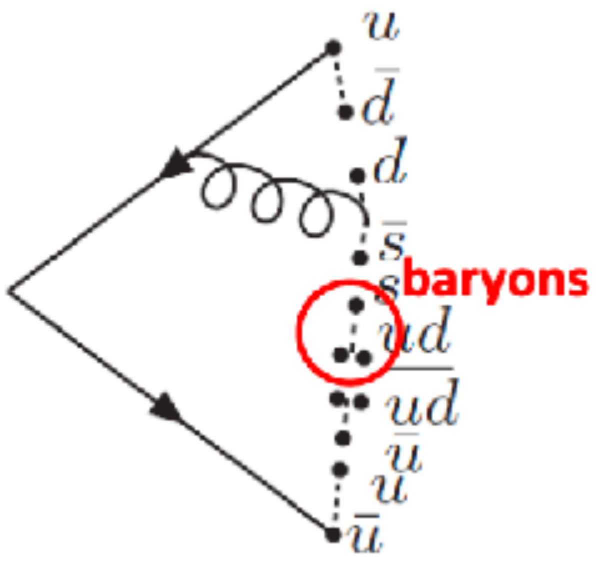
PYTHIA model
The Lund string model

- Linear confinement potential for large distances (confirmed by lattice QCD). For short distances perturbation theory holds
- Confined colour fields described as strings with tension $\kappa = 1\,GeV/fm$
- Breaking strings (tunnelling) give hadrons

$$P \propto e^{-\frac{\pi m_T^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} \cdot e^{-\frac{\pi p_{T_q}^2}{\kappa}}$$

- Flavour of hadrons determined by Gaussian mass suppression term.
  Which mass to put?
    - current mass → less suppression than observed
    - constituent mass → too much suppression
    - s/u empirical number to be tuned on data



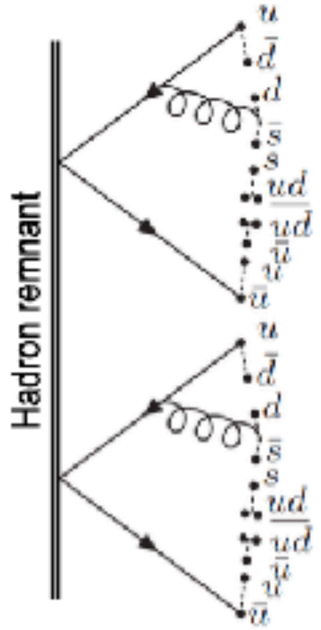


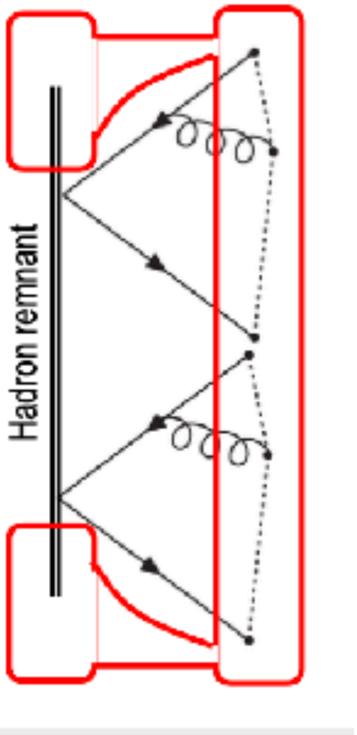
Fisher & Sjostrand arXiv:1610.09818 (2017)

Backup

PYTHIA model
The Lund string model

- In hadronic collisions multiple strings are needed to describe multiplicity distribution (**MPI**)
- In the LC Lund model each string is hadronizing separately with respect to the others
- The multiplicity increases, but not the $\langle p_T \rangle$ nor the relative flavour abundances





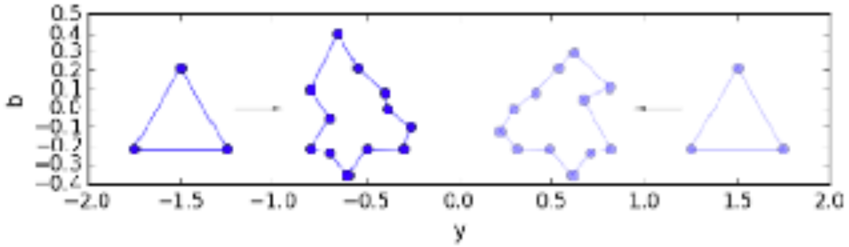
- Multiple strings are close in space-time. Dynamical interaction is not implemented in this model, but color re-arrangement can happen: **Color Reconnection** (CR)
- Takes place after parton shower and takes into account all SU(3) permitted configurations. Selection parameter: minimum total string length
- After re-arrangement of the strings, hadronization takes place
- Correctly take into account the colour re-arrangement in the remnant

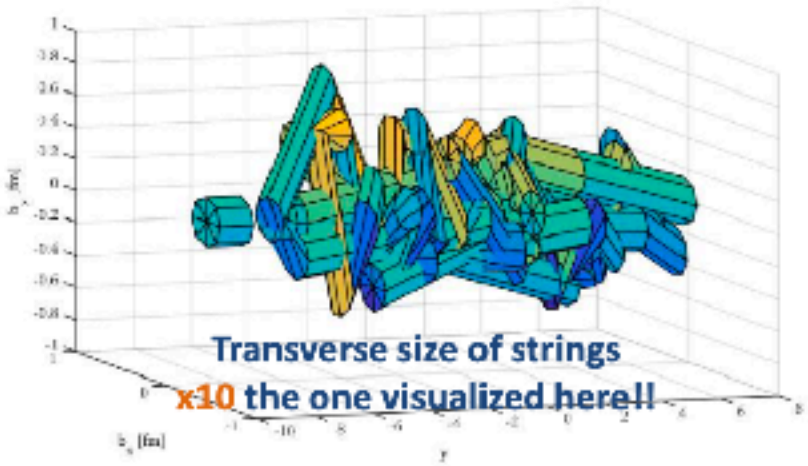
Christiansen & Skands arXiv:1505.01681 (2015)

Backup

DIPSY model

- Partonic model in impact parameter space and rapidity (**D**ipole evolution in **I**mpact **P**arameter **S**pace and rapidit**Y**)
- Mueller dipole model (LL-BFKL)
- Proton/Nucleus structure built up dynamically from dipole splittings
- Builds-up initial state + collision in impact parameter space. Naturally treats saturation and MPI
- The model follows the evolution of colour strings during the whole parton shower



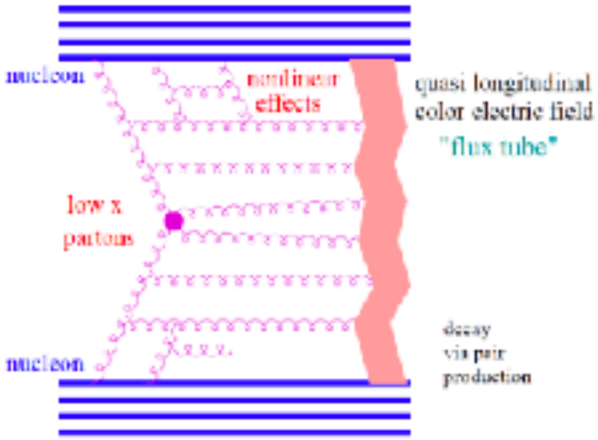


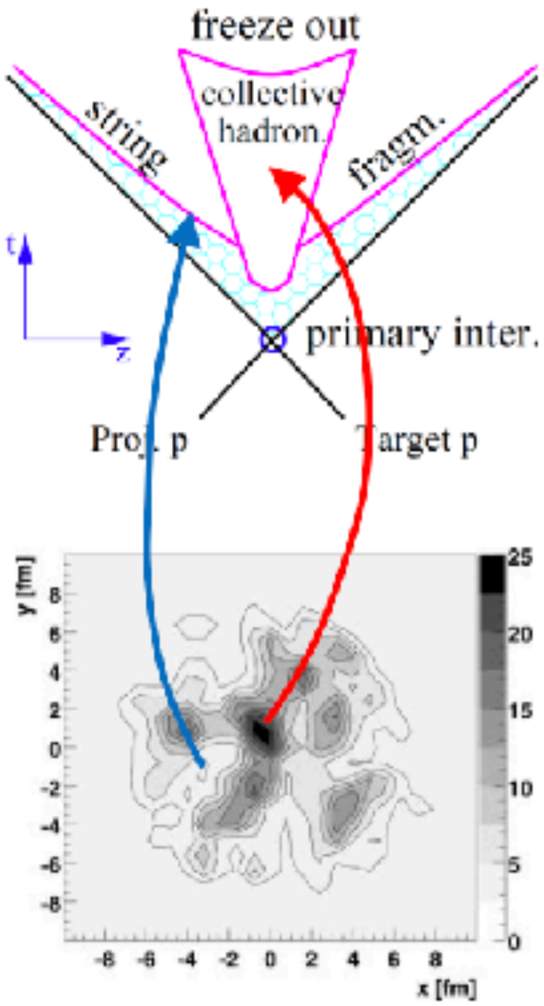
Transverse size of strings x10 the one visualized here!!

- Stack of colour strings close in the IP-y space can form colour singlets or multiplets (**ROPES**) according to the summing rules of SU(3)
- Hadronizing a rope means fragmenting string-by-string with an effective string tension $\kappa > \kappa_0 \rightarrow$ Higher tension means more baryons and more flavour different from (u, d)
- Before hadronizing a string swing mechanism further allow colour re-arrangement (in analogy with colour reconnection)

Backup

EPOS

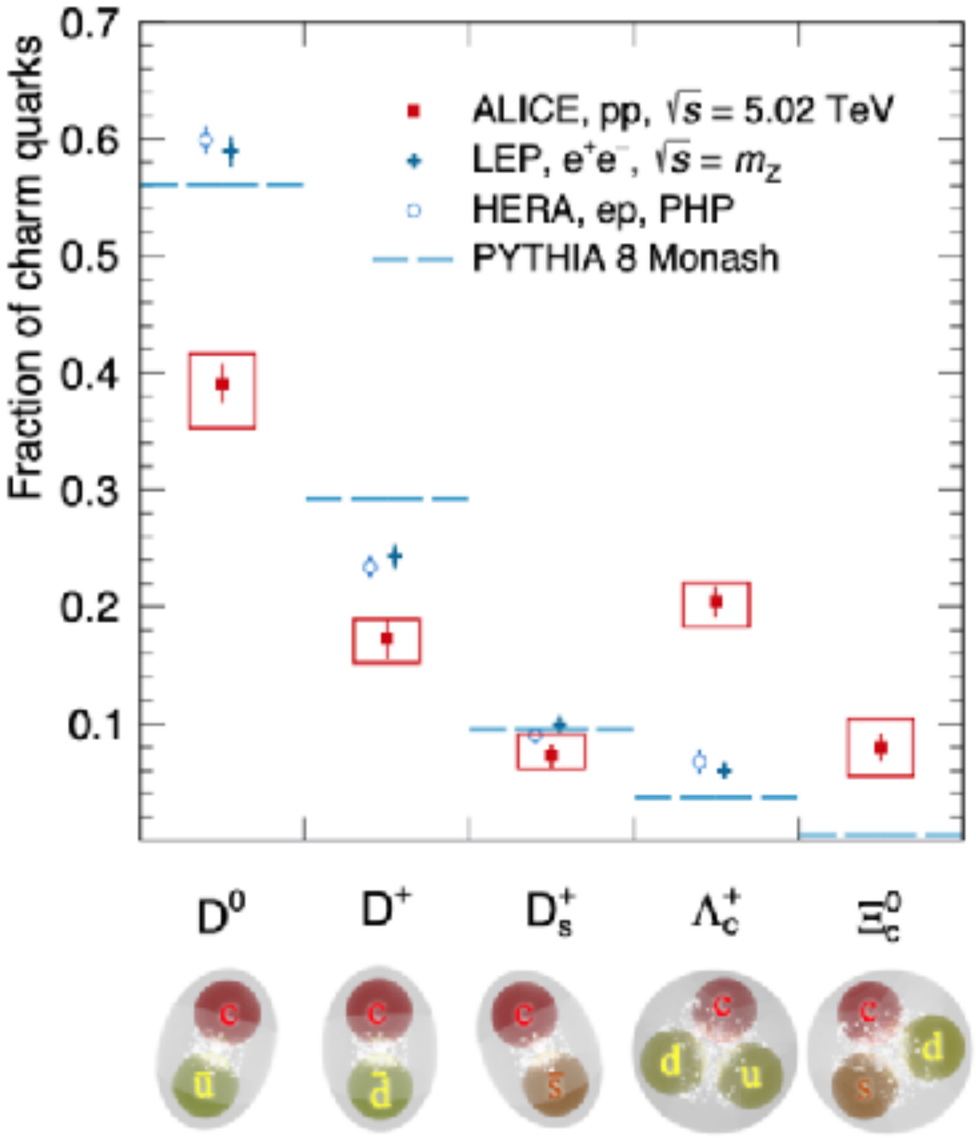




- Hard scattering treated with the addition of several DGLAP parton "ladders" (pomerons) + a CGC-inspired saturation scale
- Parton ladders are then considered as relativistic strings, conveniently treated in a string fragmentation approach (a-la Lund)
- At time τ_0 (well before hadronization) strings are divided into: fluid (CORE) and escaping (CORONA) according to their momenta density of the string segments:
  - **CORONA**: strings can hadronize as in Lund approach
  - **CORE**: from the time τ_0 evolves as a viscous hydrodynamic system that hadronize statistically at a common T_H
- After hadronization hadron-hadron rescattering can be considered, making use of an afterburner (like UrQMD)

Backup

New measurements by the ALICE collaboration show that the way charm quarks form hadrons in proton-proton collisions differs significantly from expectations based on electron collider measurements.



Hadronisation of charm quarks into mesons (D_0, D^+, D_S) or baryons (Λ_C, Ξ_C, …) occurs on a long space-time scale and was considered to be universal - that is, independent of the species of the colliding particles - until the recent findings by the ALICE collaboration.

The charm quarks were found to form baryons almost 40% of the time, which is four times more often than what was expected based on measurements previously made at colliders with electron beams (e_+e_- and ep in the figure below).

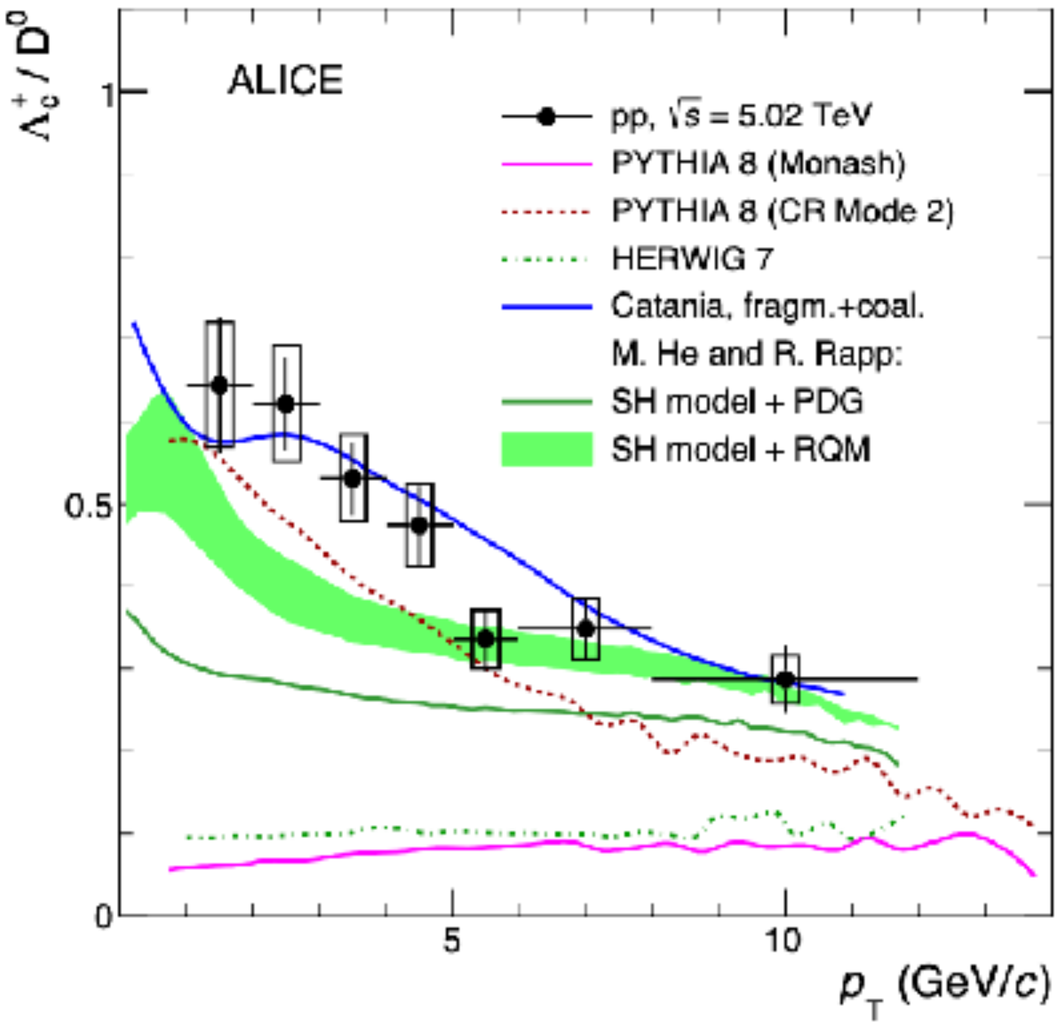
These measurements show that the process of colour-charge confinement and hadron formation is still a poorly understood aspect of the strong interaction.

https://home.cern/news/news/physics/alice-finds-charm-hadronisation-differs-lhc

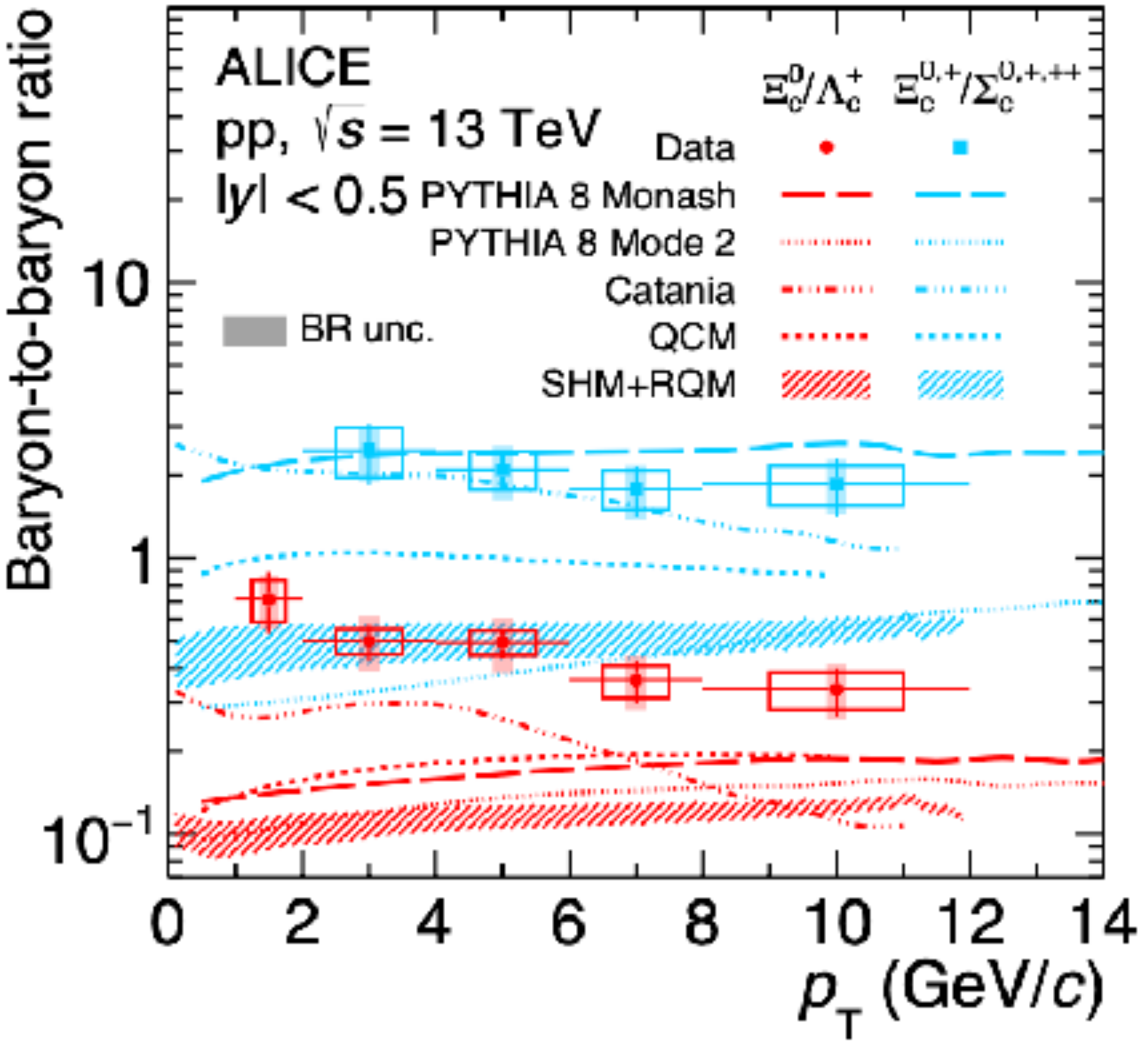
Backup

New measurements by the ALICE collaboration show that the way charm quarks form hadrons in proton-proton collisions differs significantly from expectations based on electron collider measurements.

arXiv:2011.06078



arXiv:2105.0518



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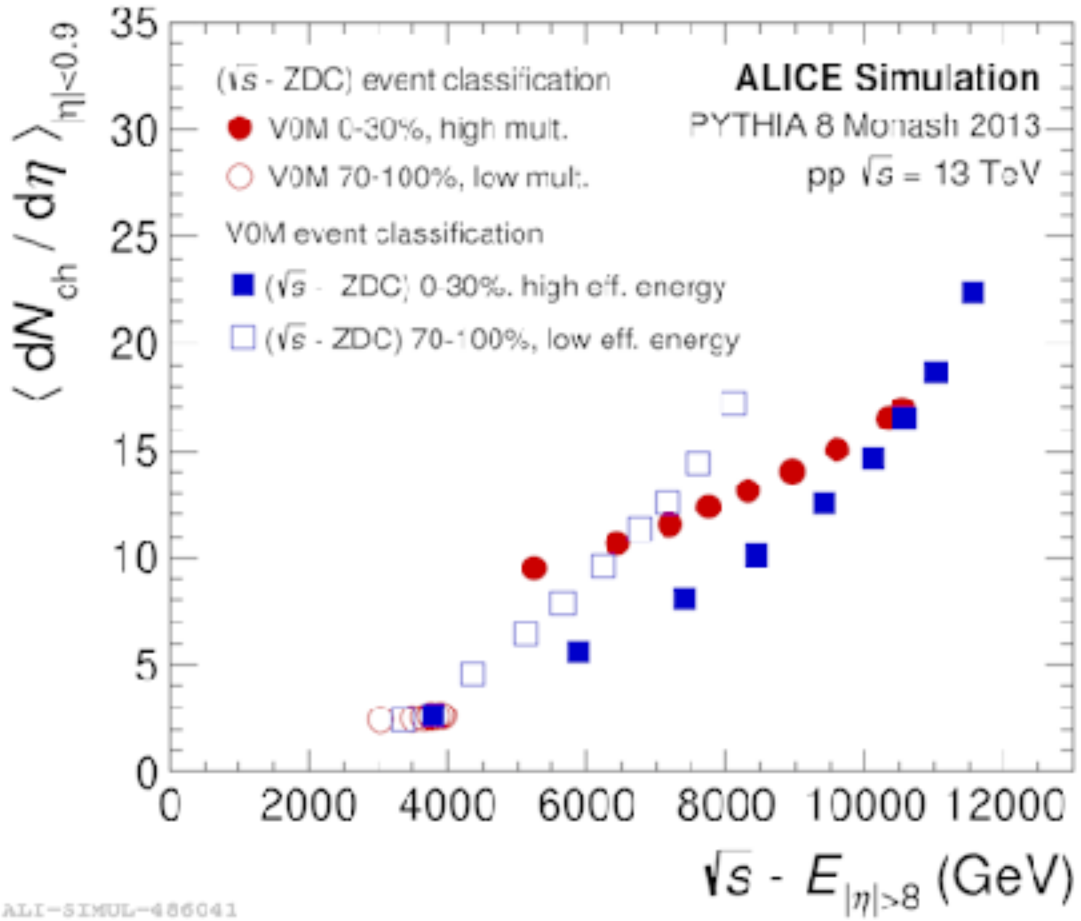
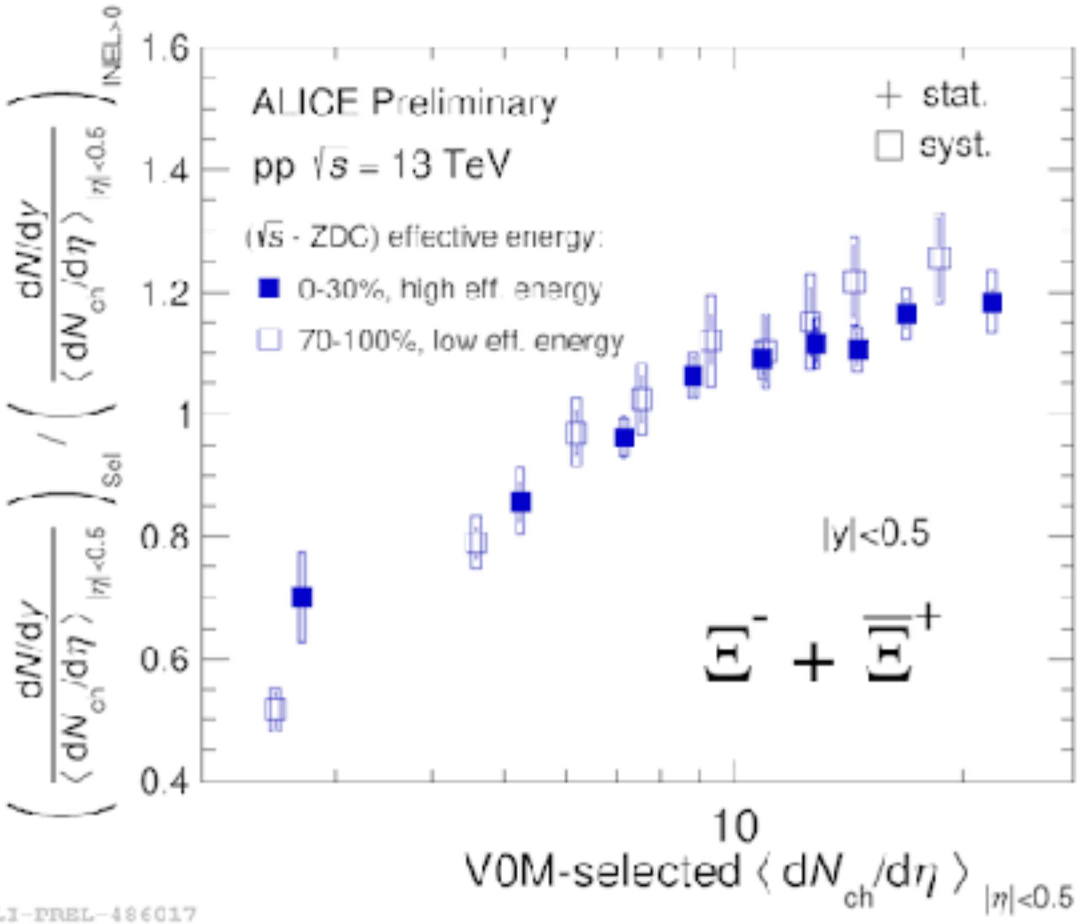
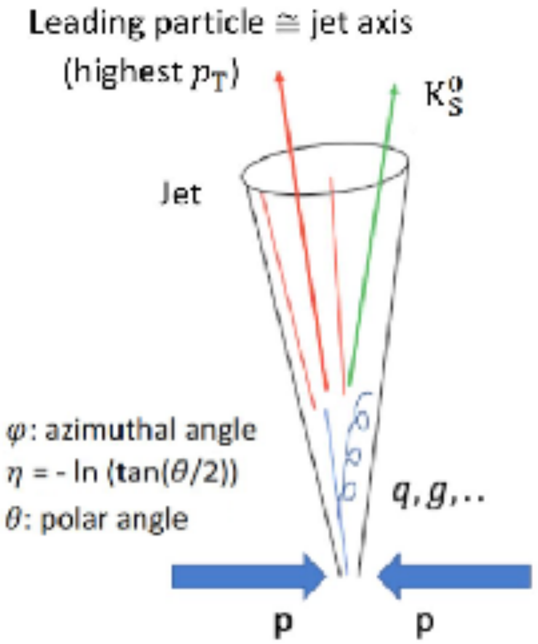


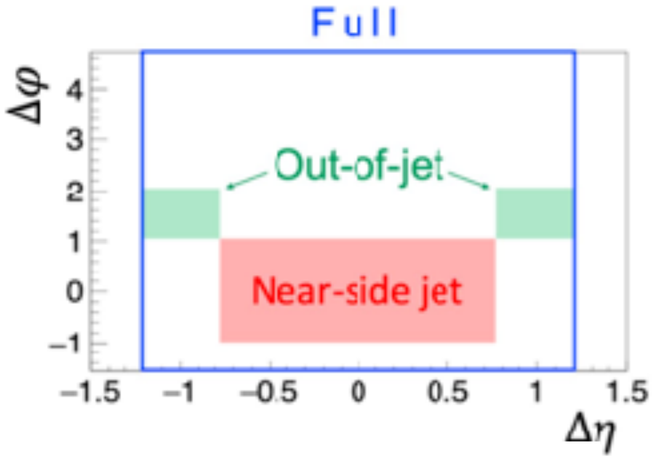
ALI-SIMUL-486041



ALI-PREL-486017

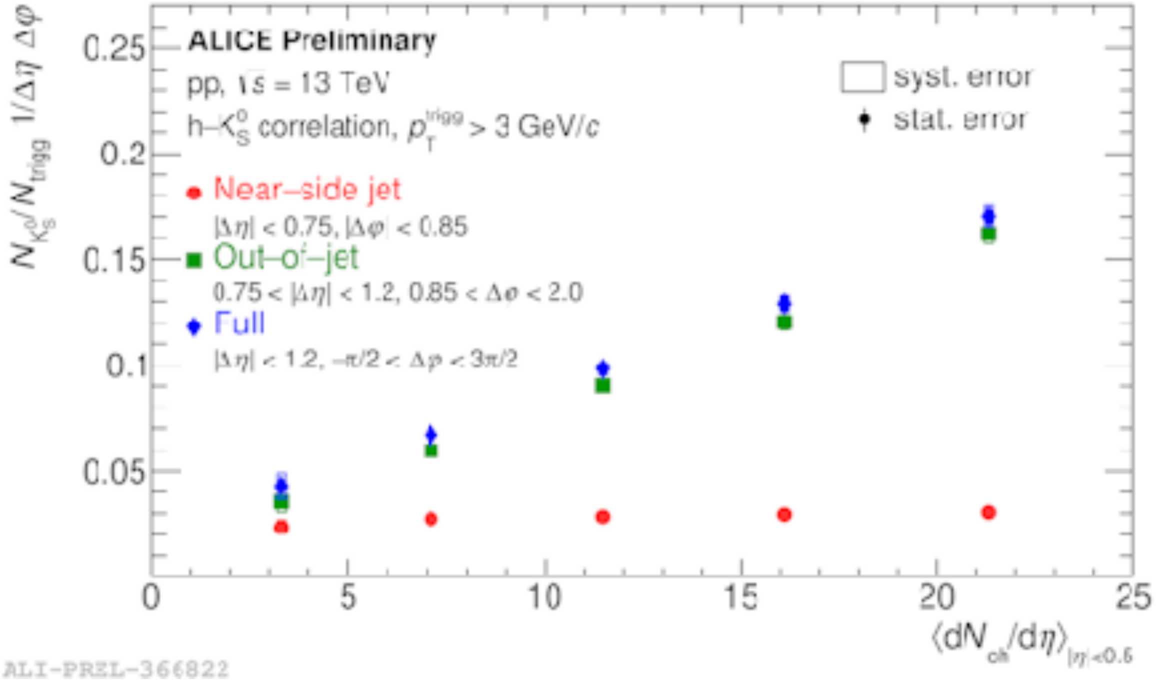
Backup

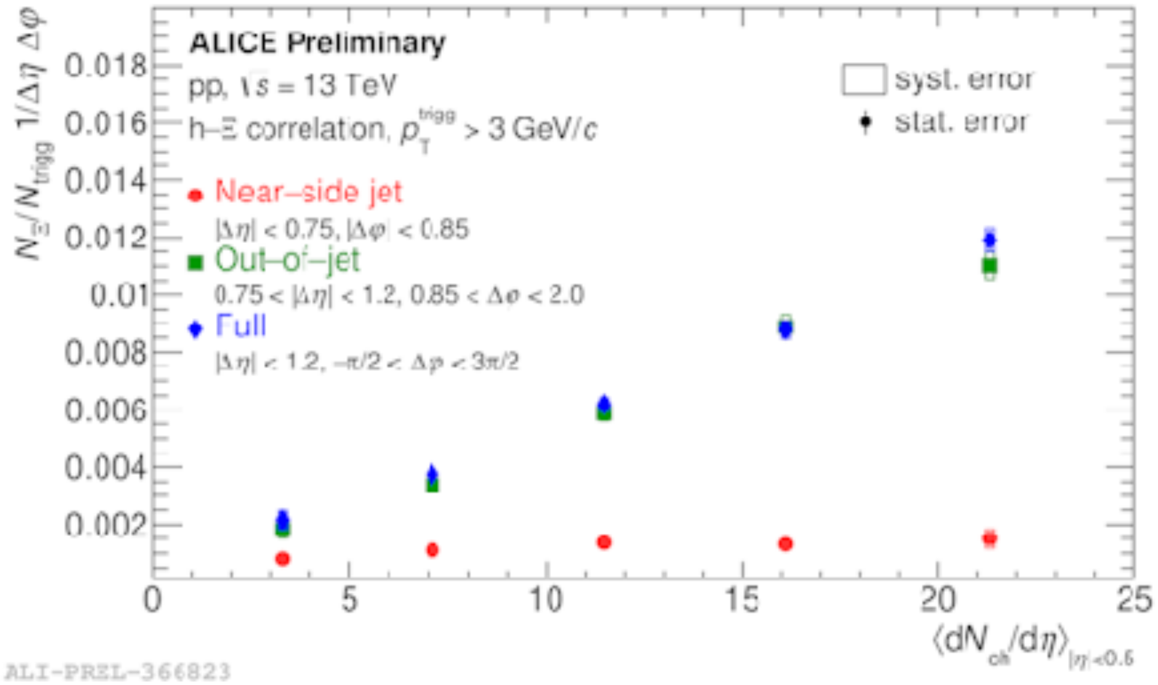




$$\Delta\varphi = \varphi_{Trigg} - \varphi_{Assoc}$$

$$\Delta\eta = \eta_{Trigg} - \eta_{Assoc}$$





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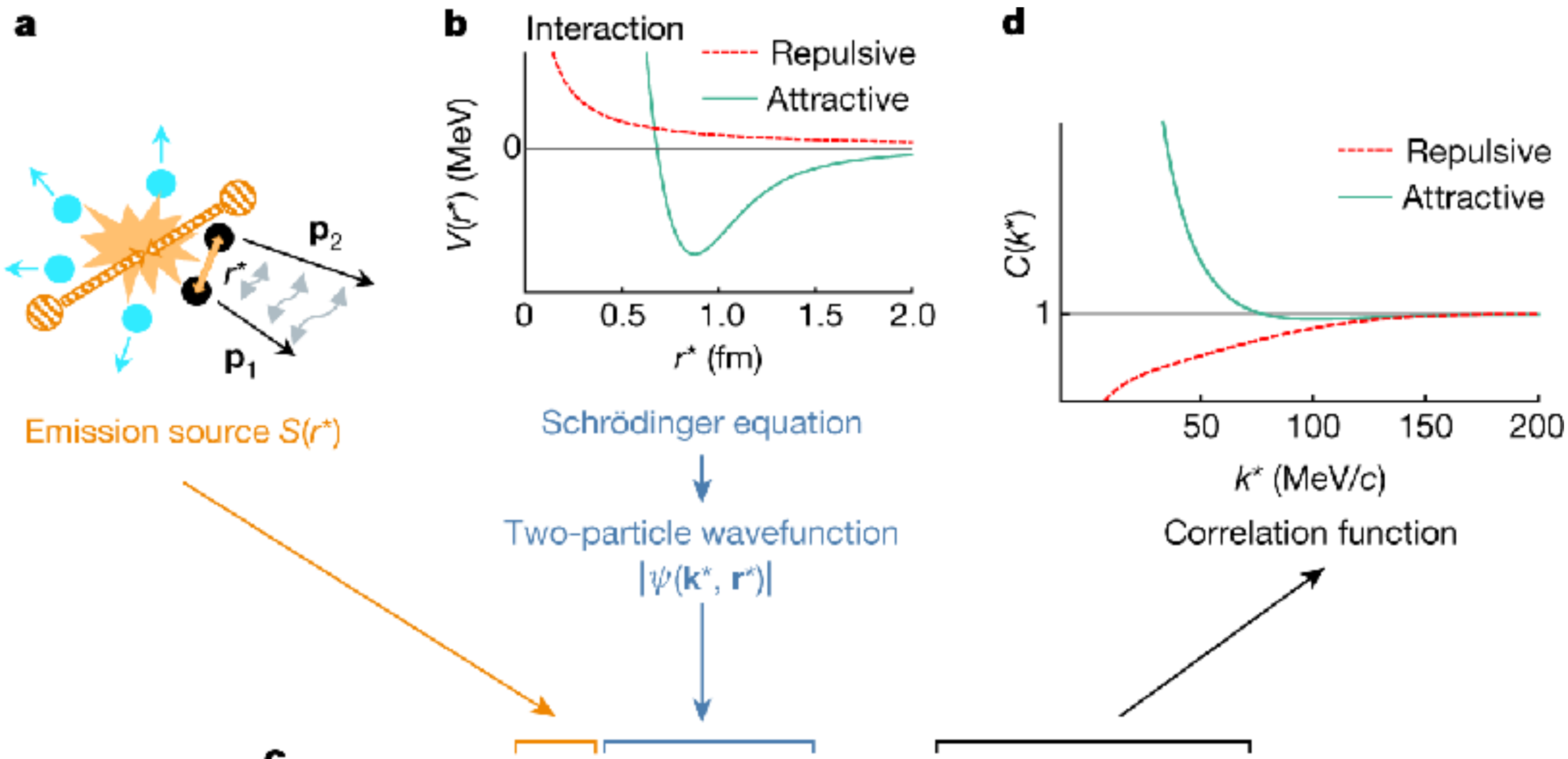
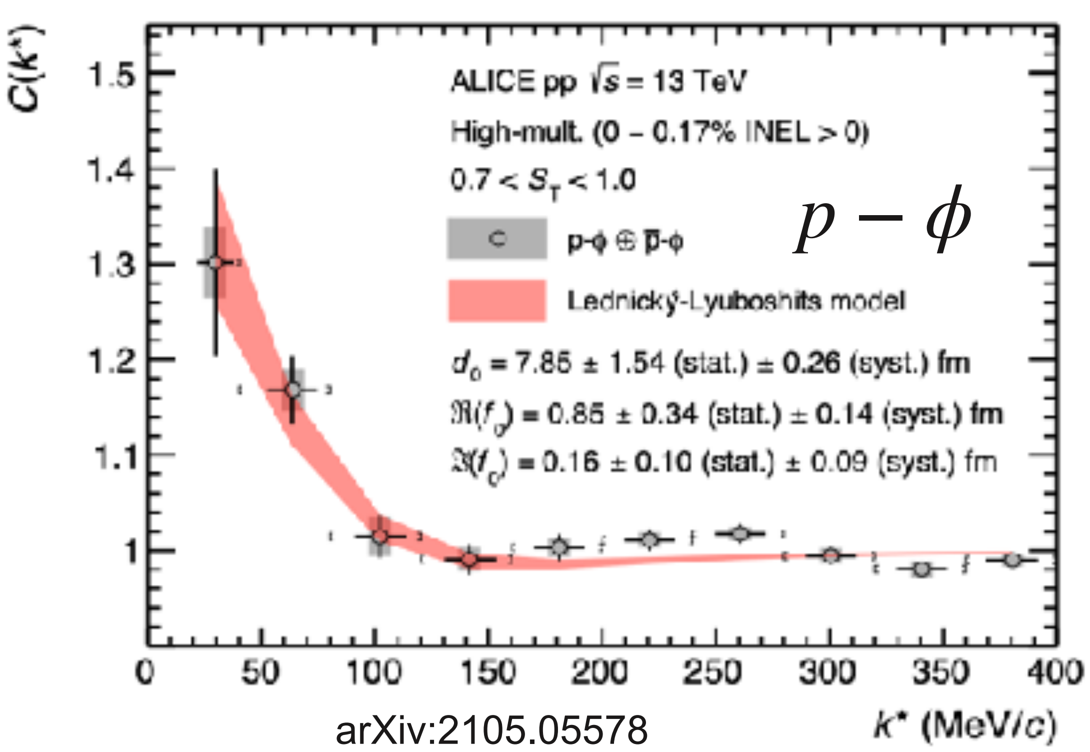


c

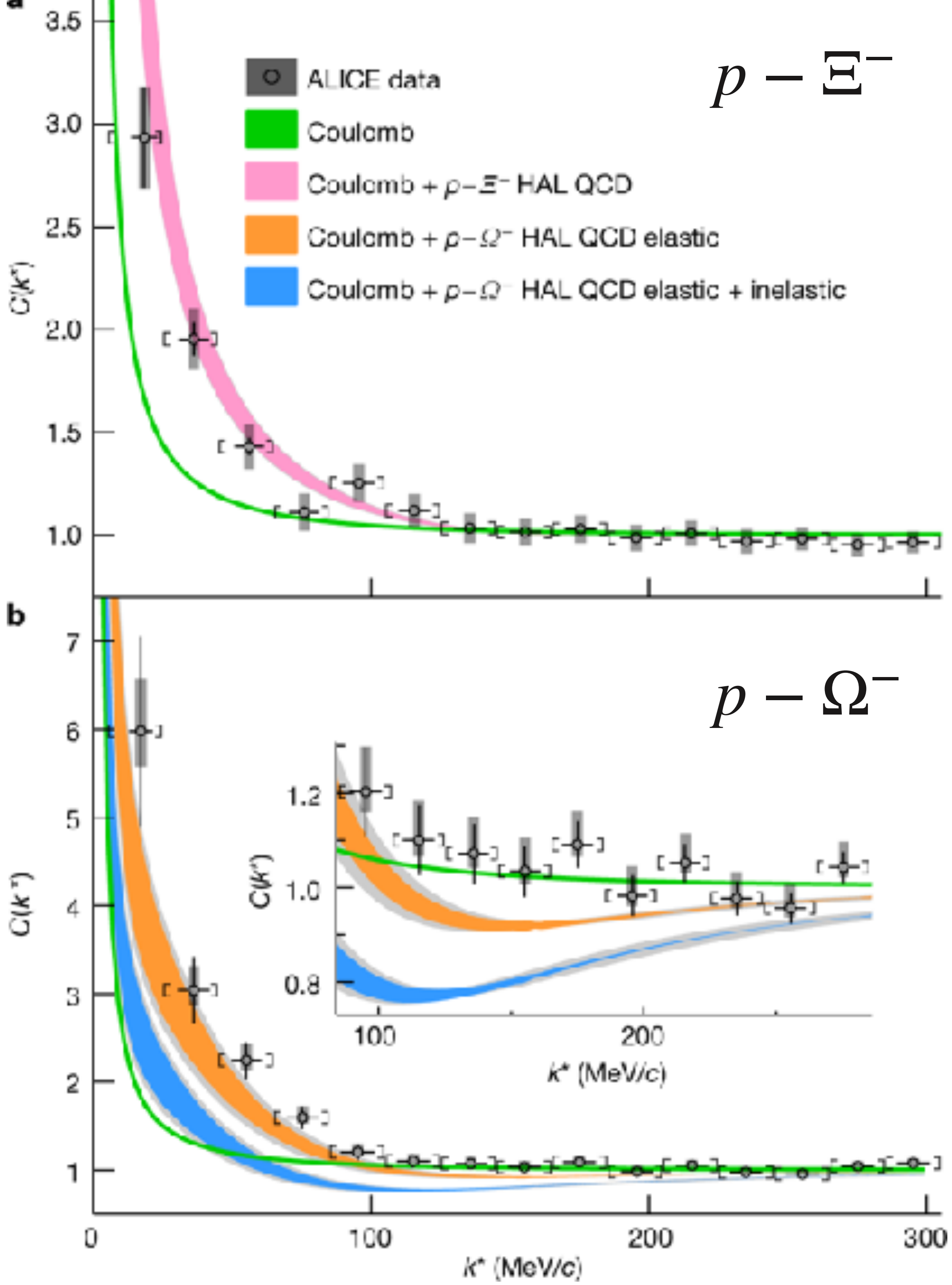
$$C(k^*) = \int S(r^*)\,|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2\, d^3r^* = \xi(k^*)\,\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

Backup



arXiv:2105.05578

Nature 588 232 (2020)



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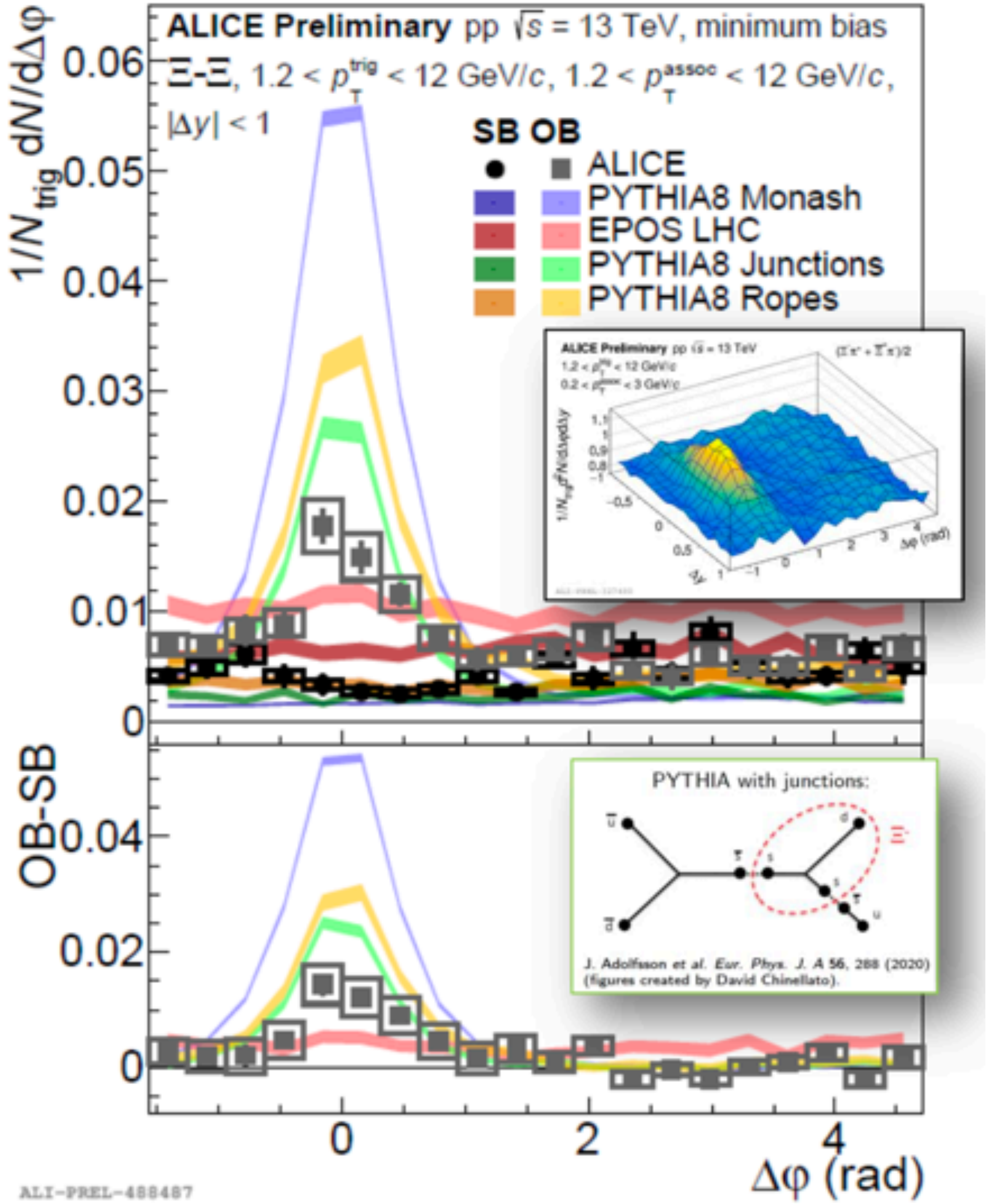


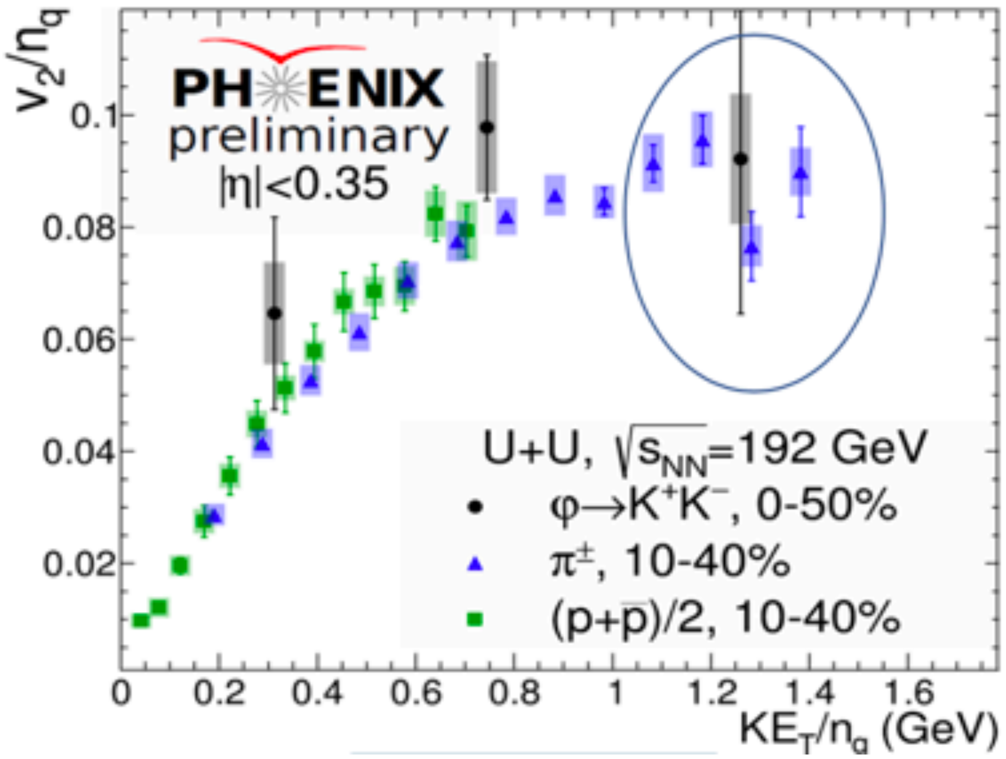
Measurements of Ξ-hadron angular correlations in pp collisions used to constrain formation mechanism in event generators and investigate multiplicity dependence

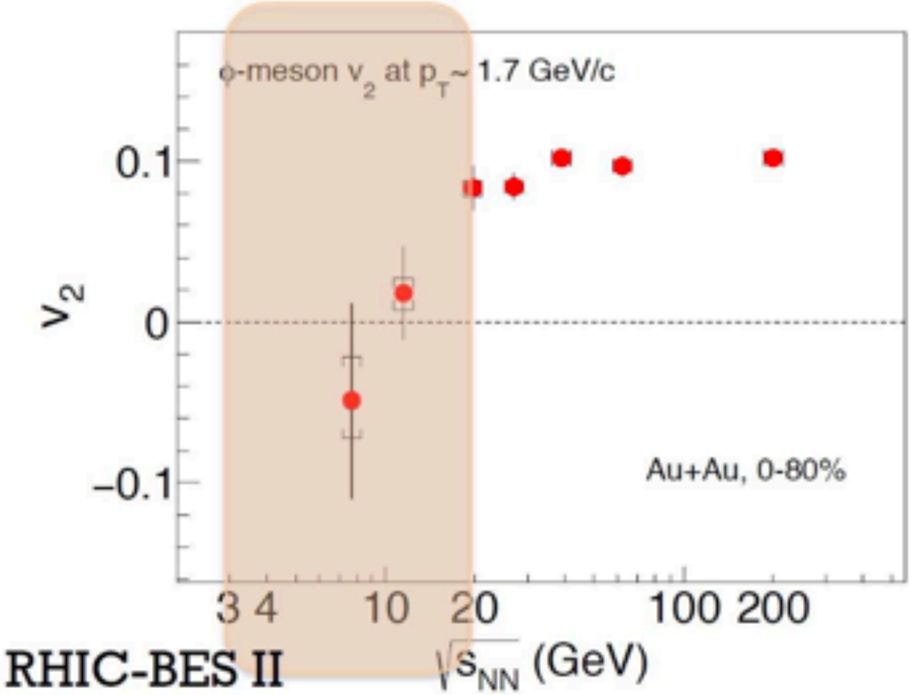
→ challenge the Lund string fragmentation for strangeness (favours junction model)

→ investigate the conservation of quantum numbers

→ extend to ϕ-hadron having in mind that ϕ/π is not described by CSHM?

Backup



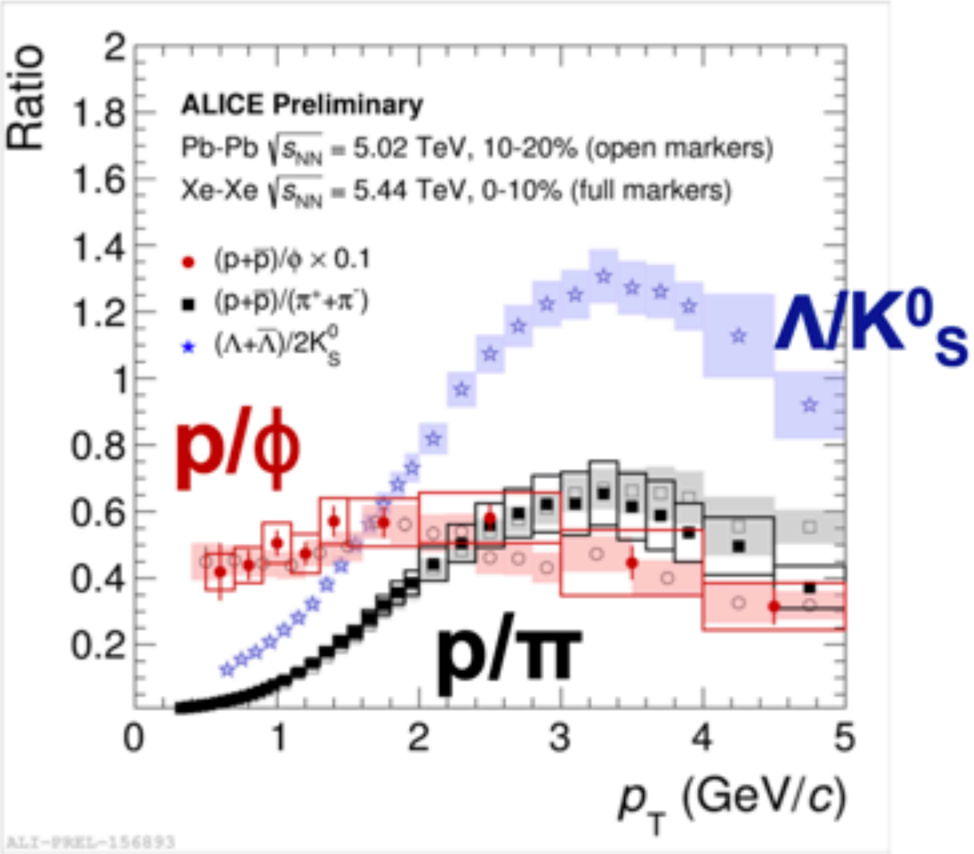


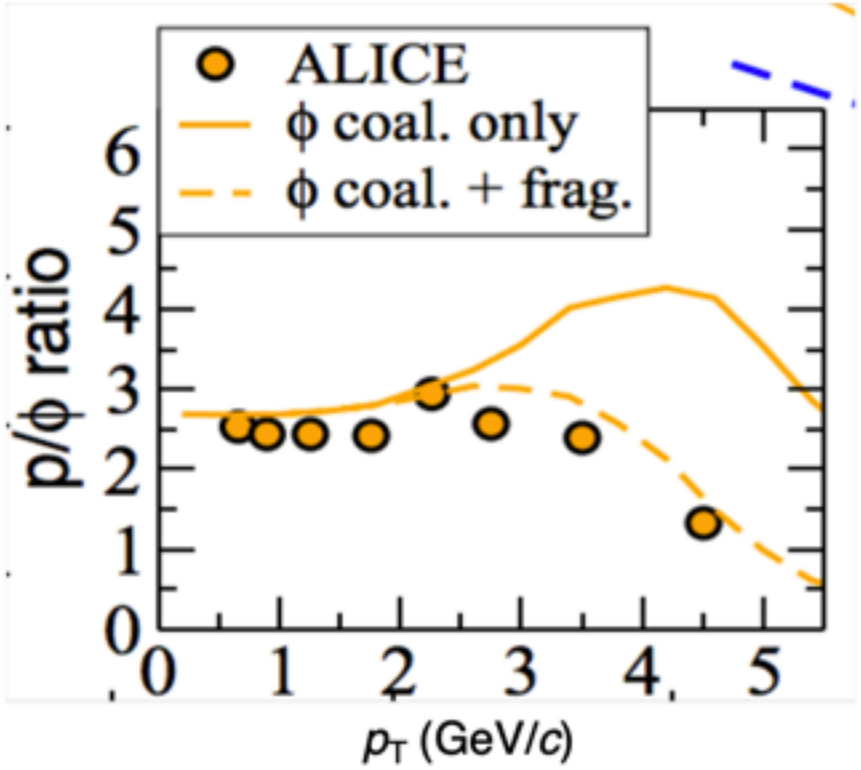
RHIC-BES II
+ FXT Program

φ-meson confirms as crucial to understand strangeness production, hadronization mechanisms, collectivity

New measurement of v_2 of φ in U-U might suggest relevance of coalescence mechanism

Backup



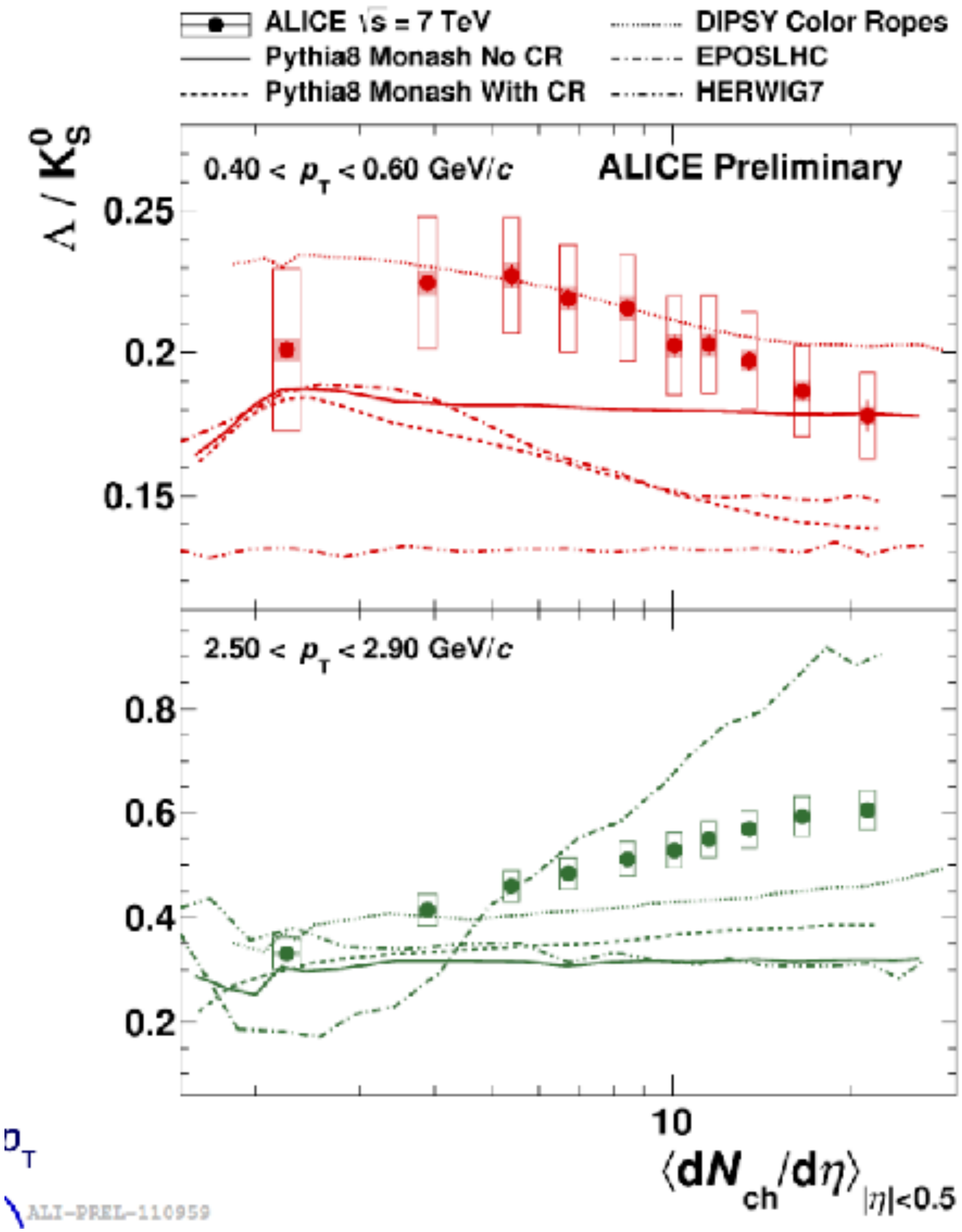


V. Greco at al, PRC 92 (2015) 054904

Having similar mass as the proton, the ϕ meson can be used to investigate the interplay of flow and recombination / fragmentation.

⟶ Still an open point on whether recombination or flow determine the spectral shape at intermediate p_{T}

Backup


ALICE $\sqrt{s}$ = 7 TeV
Pythia8 Monash No CR
Pythia8 Monash With CR
DIPSY Color Ropes
EPOSLHC
HERWIG7
Λ / K^0_S
0.40 < p_T < 0.60 GeV/c
ALICE Preliminary
0.25
0.2
0.15
2.50 < p_T < 2.90 GeV/c
0.8
0.6
0.4
0.2
10
$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$
p_T
ALI-PREL-110959

Light flavour particle production in ALICE

ALICE is designed to study the physics of strongly interacting matter under extreme temperature and energy densities to investigate the properties of the **quark-gluon plasma**

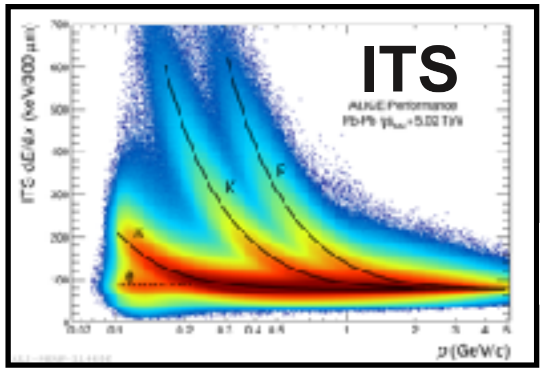
LHC Run1 and Run2 data taking

Colliding System	Year(s)	$\sqrt{s_{NN}}$ (TeV)
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13
p-Pb	2013 2016	5.02 5.02, 8.16
Xe-Xe	2017	5,44
Pb-Pb	2010-2011 2015-2018	2.76 5.02

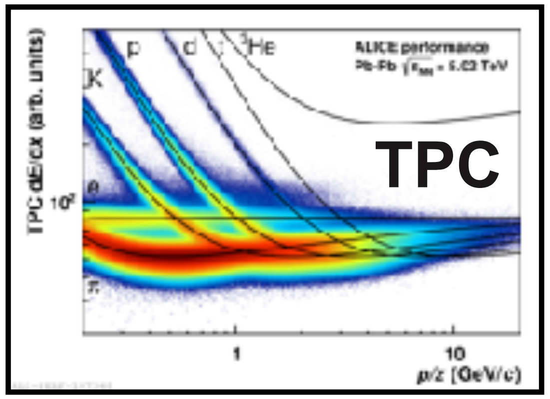
Published and Preliminary results available for most light-flavour and strange hadron species in all the colliding systems provided by LHC: π, $K^{\pm}$, p, K^{*0}, ϕ, Ξ^{*0}, $\Sigma^{*\pm}$, K^0, Λ, Ξ, Ω, d, t, ^{3}He, $^3_\Lambda$H.

The ALICE detector in LHC Run 1 and Run 2

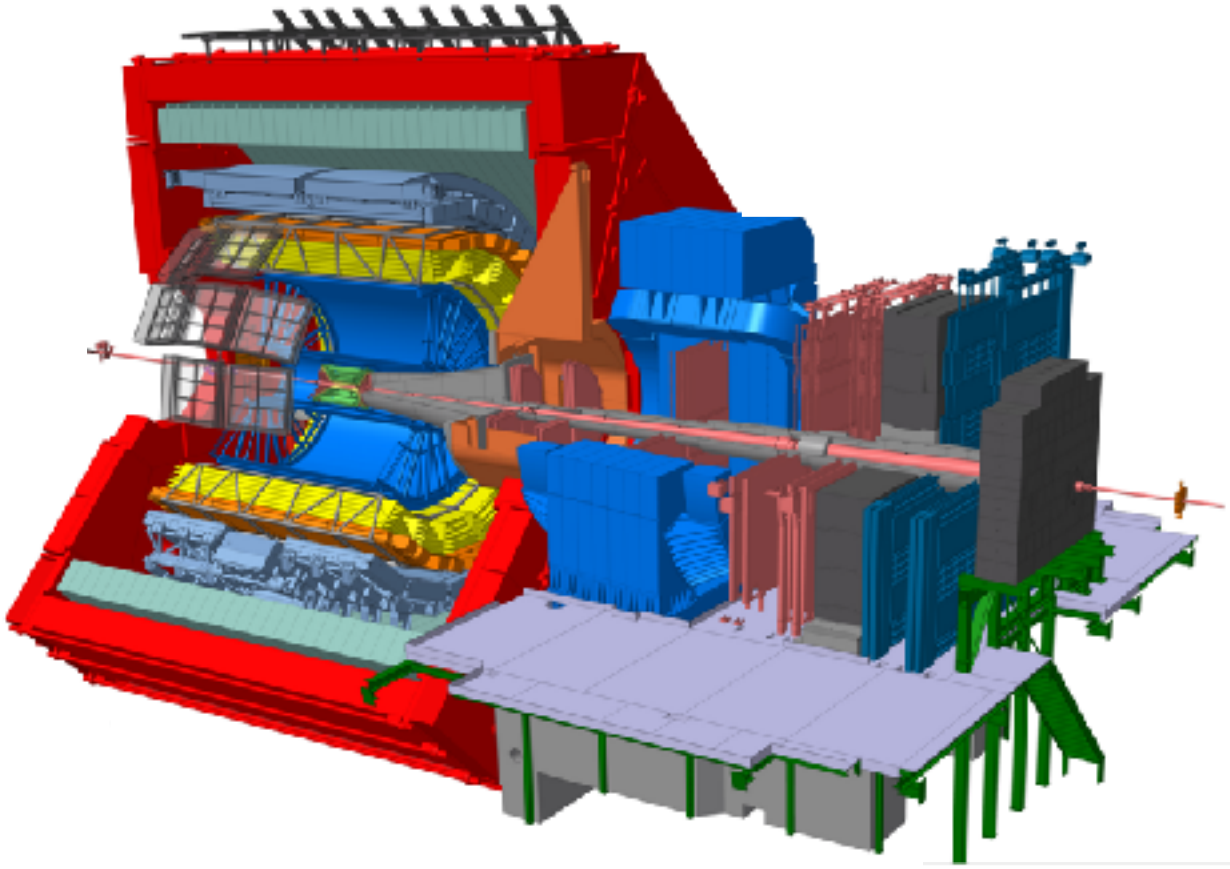
Multi-purpose detector at the LHC with unique particle identification capabilities and tracking down to very low momenta



ITS $\sigma_{dE/dx}$ ~ 10-15%



TPC $\sigma_{dE/dx}$ ~ 5%



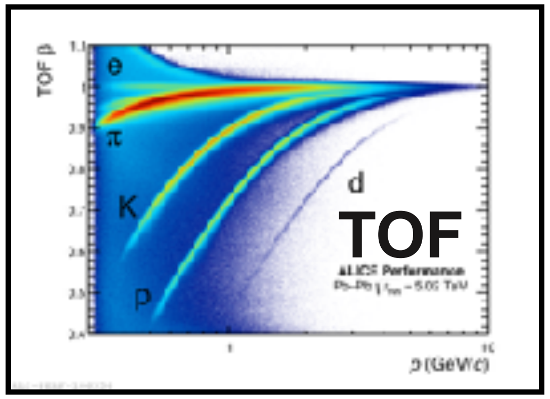
<u>Central Barrel Detectors ($|\eta| < 1$)</u>

Inner Tracking System (**ITS**)
- » Tracking, Vertexing, Triggering, Low momentum PID (dE/dx)

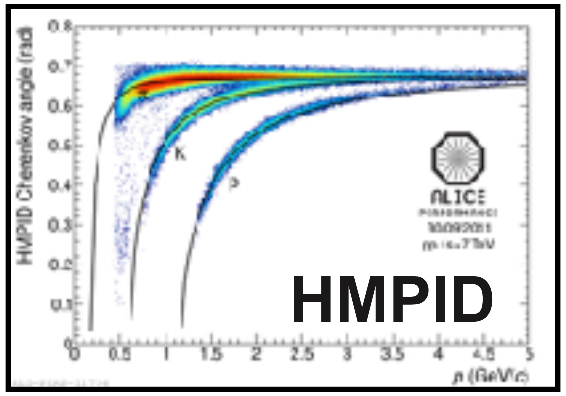
Time-Projection Chamber (**TPC**)
- » Tracking, PID (dE/dx)

Time-of-flight detector (**TOF**)
- » PID (time-of-flight)

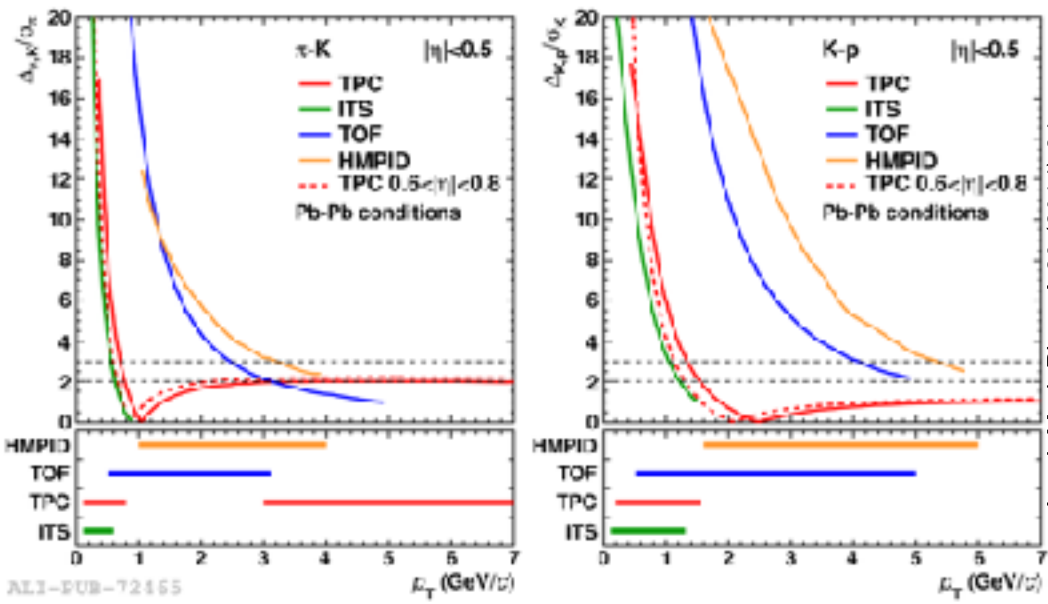
High Momentum PID (**HMPID**)
- » PID (Cherenkov)



TOF $\sigma_{Time\ Of\ Flight}$ ~ 56 ps



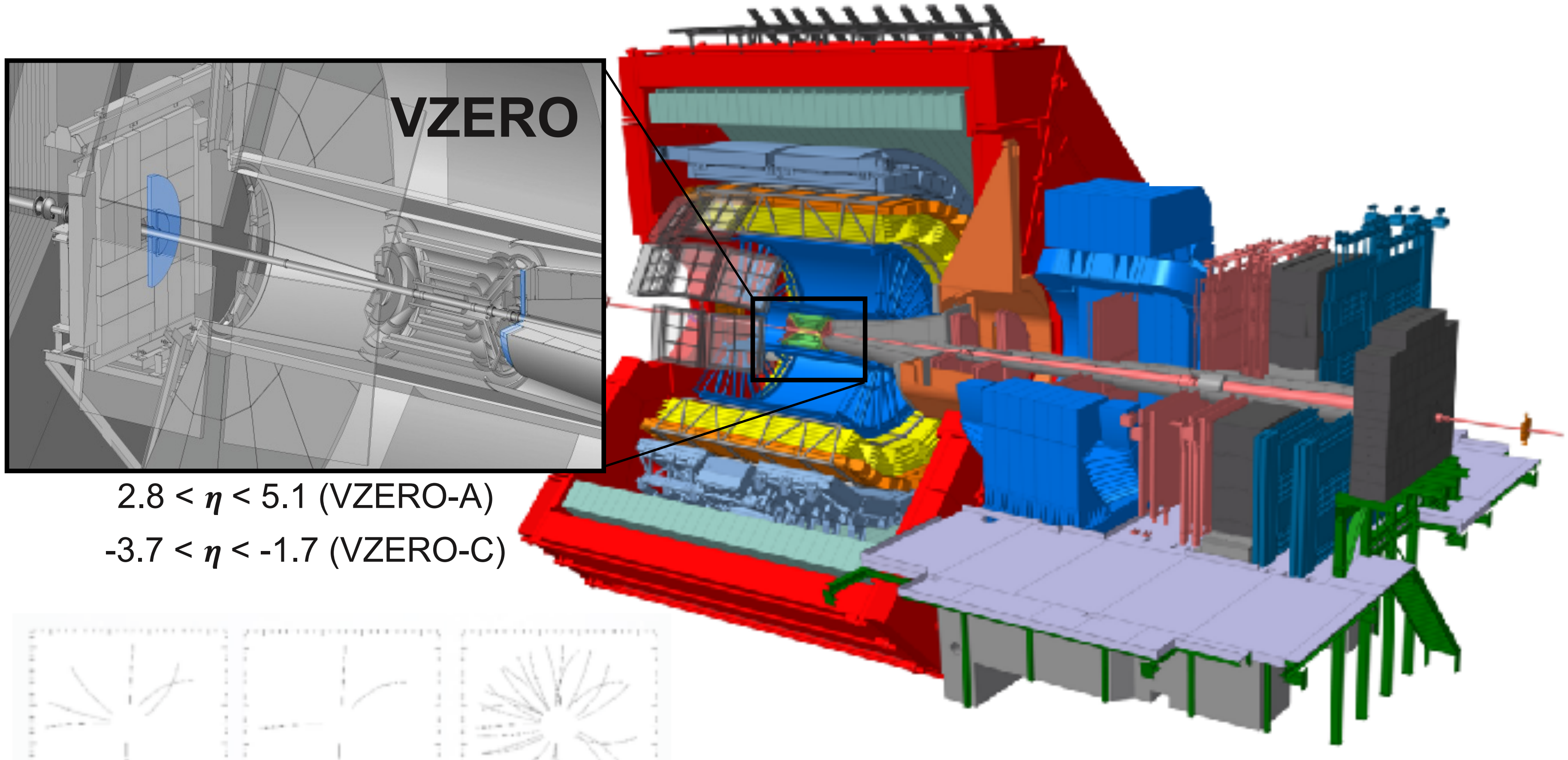
HMPID $\sigma_{Cherenkov\ Angle}$ ~ 3 mrad



Int. J. Mod. Phys. A 29 (2014) 24

The ALICE detector in LHC Run 1 and Run 2

Multi-purpose detector at the LHC with unique particle identification capabilities and tracking down to very low momenta



2.8 < η < 5.1 (VZERO-A)
-3.7 < η < -1.7 (VZERO-C)

Central Barrel Detectors (|η| < 1)

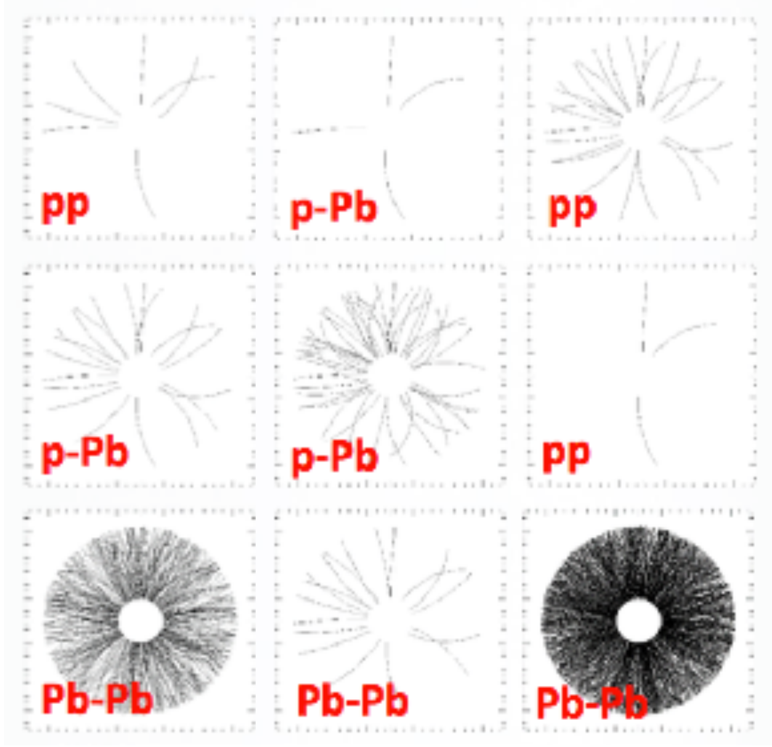
Inner Tracking System (**ITS**)
- » Tracking, Vertexing, Triggering, Low momentum PID (dE/dx)

Time-Projection Chamber (**TPC**)
- » Tracking, PID (dE/dx)

Time-of-flight detector (**TOF**)
- » PID (time-of-flight)

High Momentum PID (**HMPID**)
- » PID (Cherenkov)

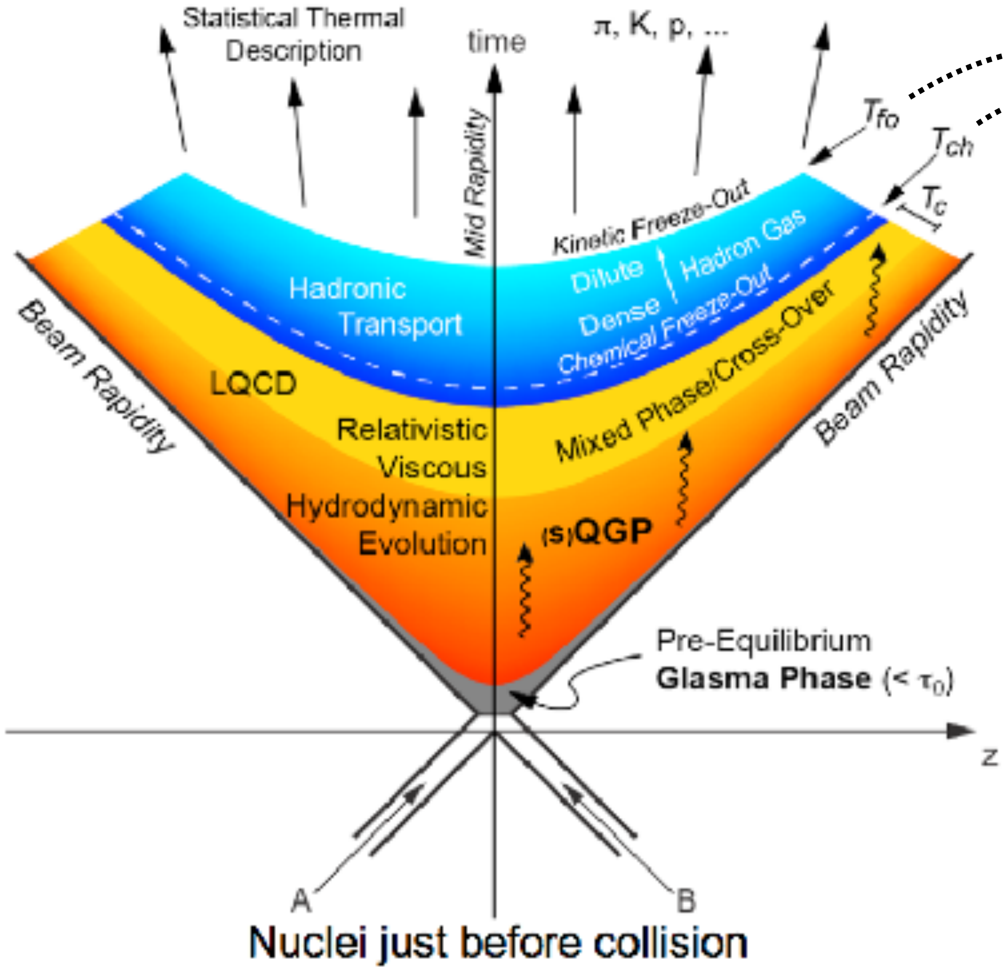
VZERO
- » Triggering, Event multiplicity determination

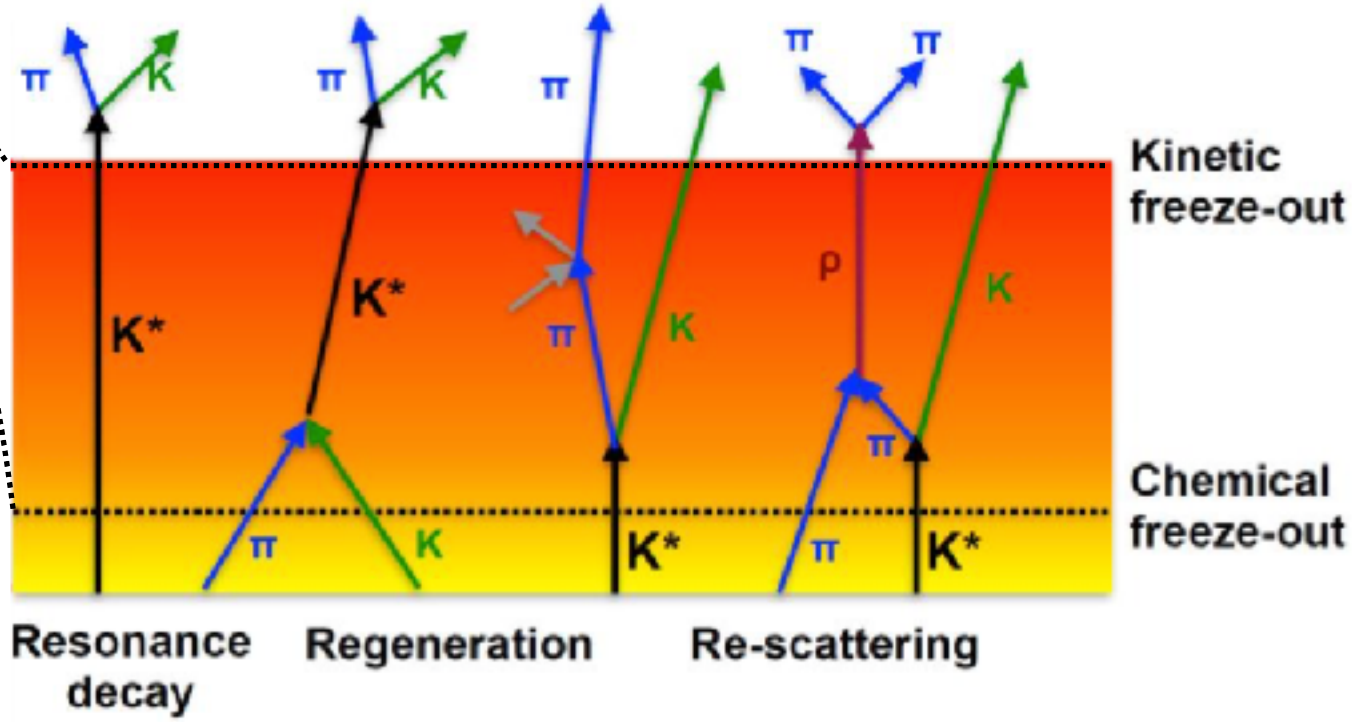


Small and large system definition

- » Commonly referred to the colliding system size (ee < pp < p-A < A-A)
- » In the following referred to the created medium size
  - ✓ Defined in terms of charge particle multiplicity
  - ✓ Correspondence to the previous true only on average
  - ✓ Multiplicity estimator used to categorise event according to its multiplicity (best if unbiased from particle under study)

③ Resonances suppression

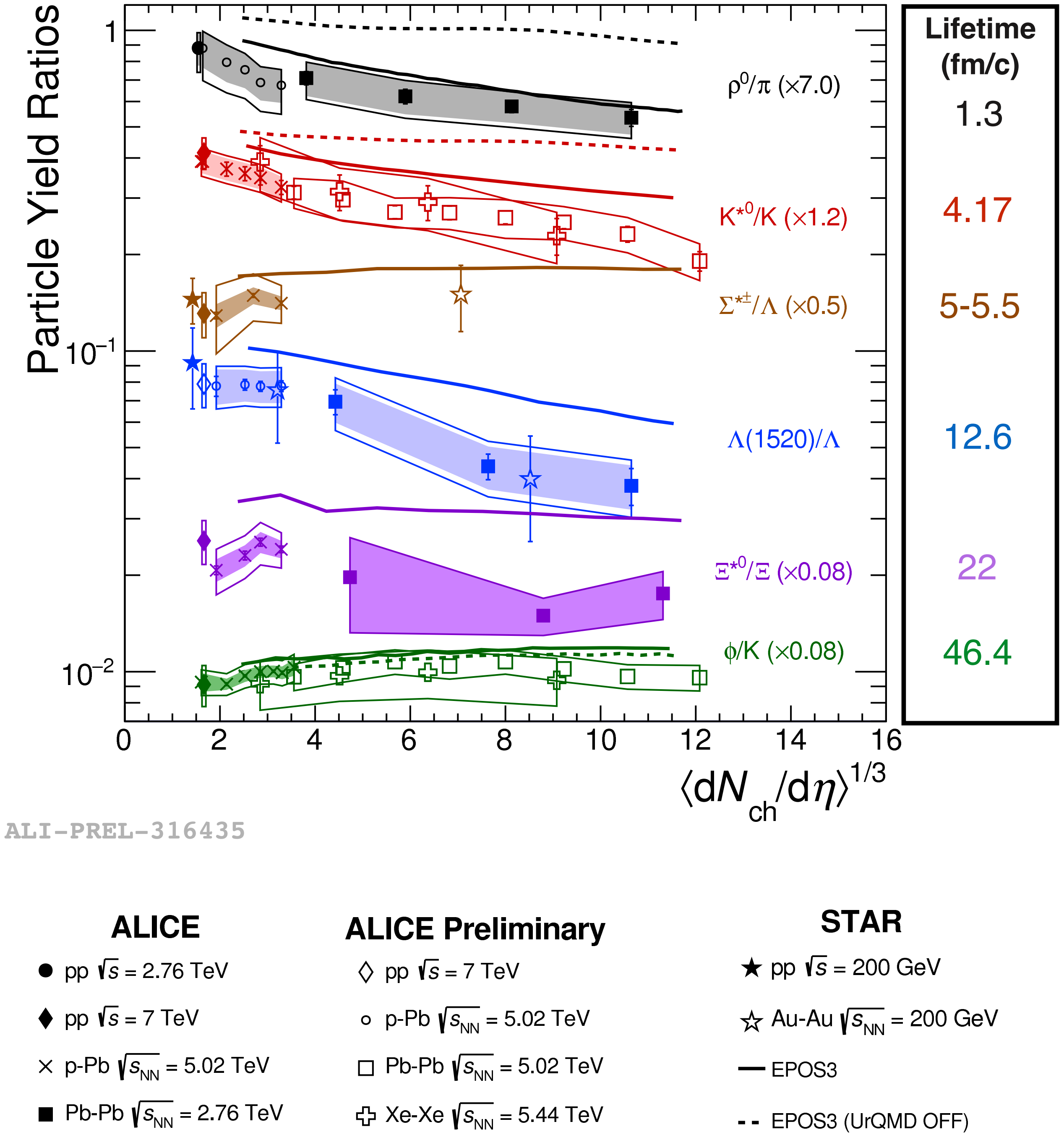




- »Resonances are powerful tools to probe the hadronic phase after chemical freeze-out
- »Final resonance yields depend on:
  - ✓ Chemical freeze-out temperature
  - ✓ Lifetime of hadronic phase
  - ✓ Resonance lifetimes
  - ✓ Scattering cross-section of decay products

③ Resonances suppression

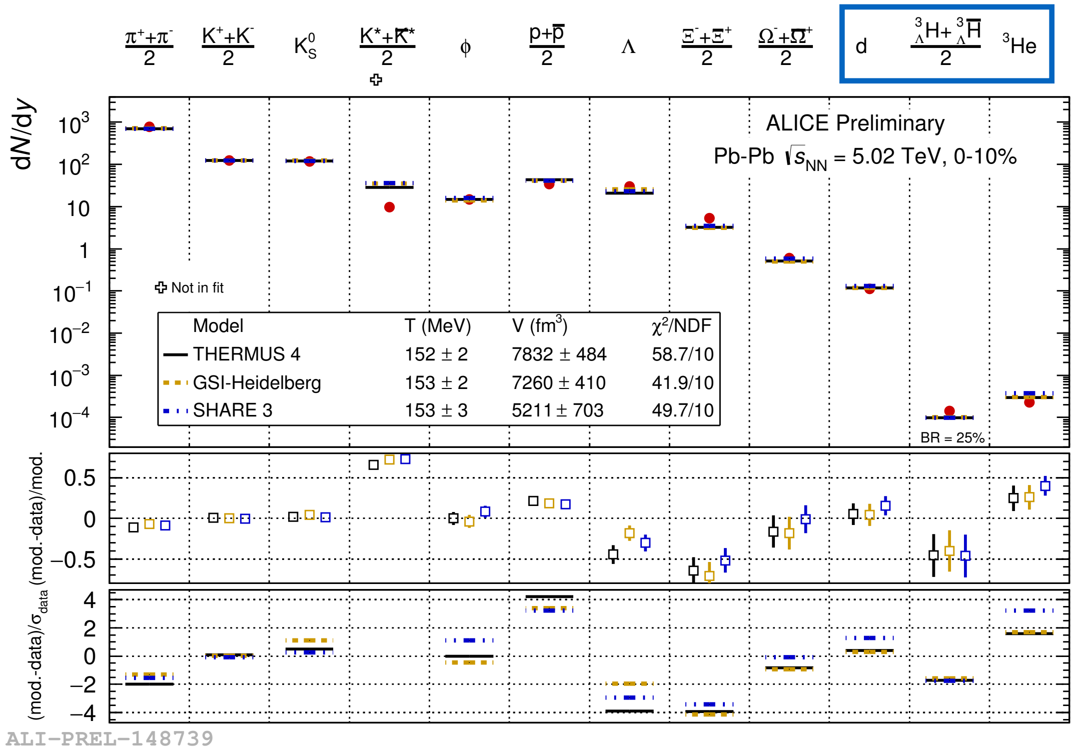
- Suppression of K^{0*} in high multiplicity events
  - ✓ K^{0*}/K reduction from low to high multiplicity
  - ✓ Central Pb-Pb values below thermal model prediction
  - ✓ Re-scattering of decay products in hadronic medium
  - ✓ Hint of K^{0*} suppression in high-multiplicity pp and p-Pb
- Similar suppression of ρ^0 and $\Lambda(1520)$
- No ϕ suppression: lives longer, decay outside fireball
- Possible weak suppression of Ξ^{*0} w.r.t. pp collisions
- No measurement of $\Sigma^{*\pm}/\Lambda$ in Pb-Pb yet, but STAR point
- Ratios do not depend on energy (RHIC → LHC) or collision system (same for p-Pb and Xe-Xe)
- Trends qualitatively described by EPOS
  - ✓ Includes scattering effects modelled with UrQMD



Eur. Phys. J. C (2012) 72:2183
Eur. Phys. J. C (2015) 75:1
Eur. Phys. J. C (2016) 76:245
Eur. Phys. J. C (2017) 77:389
Physical Review C 91, 024609 (2015)
Physical Review C 95, 064606 (2017)
Physical Review C 99, 024905 (2019)
Physical Review C 93, 014911 (2016)

⑤ Light nuclei production

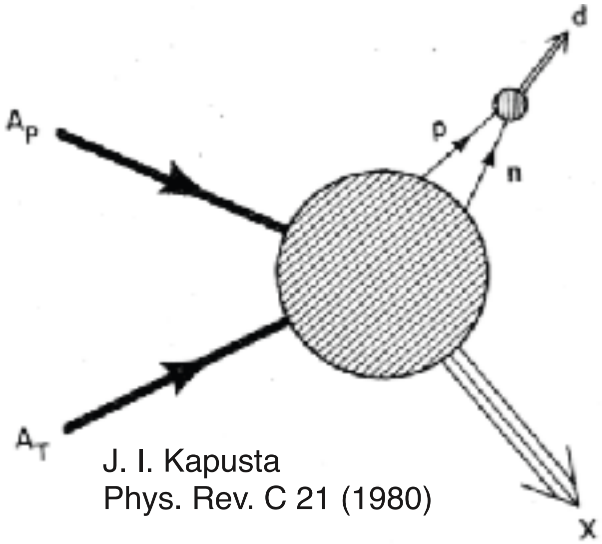
- » Light (anti-)nuclei significantly produced at the LHC in pp, p-Pb and Pb-Pb collisions
- » The production mechanisms in high-energy physics still not completely understood
  - ✓ Low binding energy (E_B ~ 1 MeV) w.r.t. the kinetic freeze-out temperature (T_{fo} ~ 100 MeV)



- » Two classes of models are available:
  - ✓ The **statistical-thermal model**
    - Predicted yield dN/dy ∝exp(-m/T_{ch}) strongly dependent on T_{ch} for nuclei given large m
    - Yield well predicted for d, ^{3}He and $^3_\Lambda$H
  - ✓ The **coalescence model**
    - Nucleons that are close in phase-space at the freeze-out can form a nucleus via coalescence
    - Main parameter is B_A, related to the probability to form a nucleus :

$$B_A = \frac{E_A \frac{d^3N_A}{dp_A^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^A}$$

- A is the mass number of the nucleus
- $p_p = p_A/A$

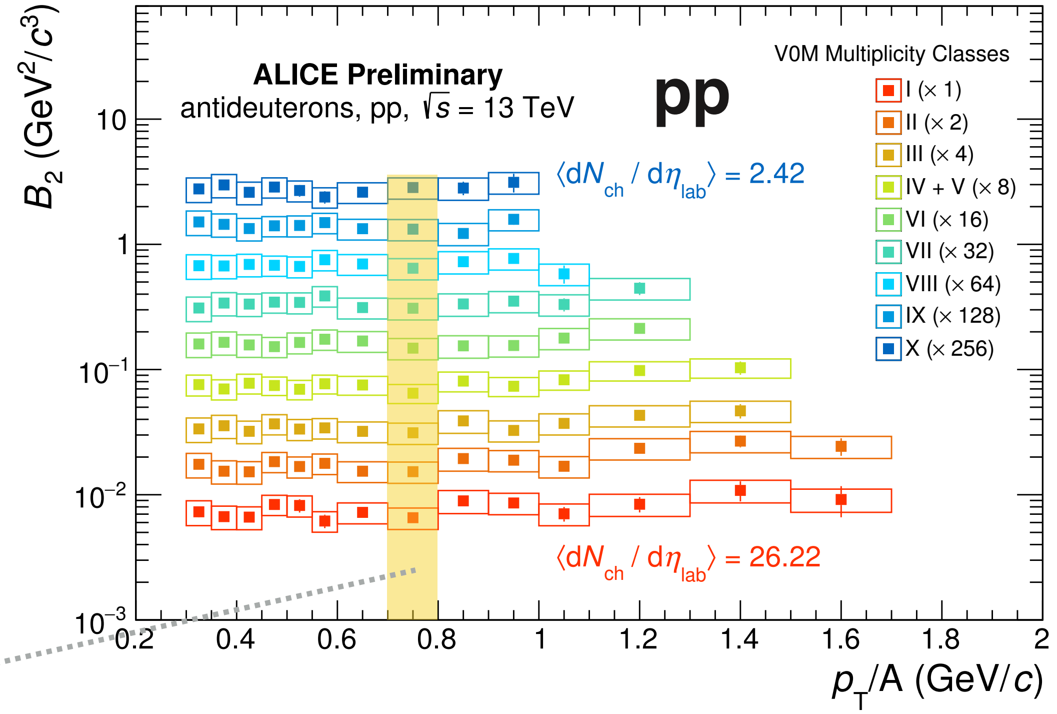


J. I. Kapusta
Phys. Rev. C 21 (1980)

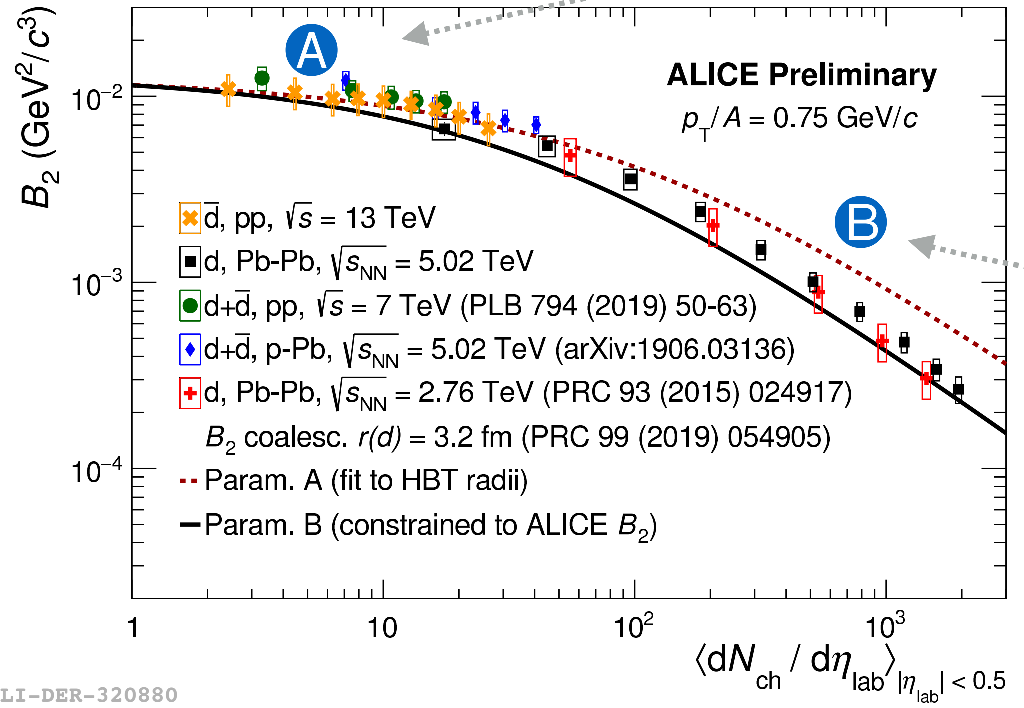
⑤ Light nuclei production

- Simple coalescence → B_A flat in p_T
  - ✓ Behaviour in Pb-Pb → NOT described
  - ✓ From high to low multiplicity → rise in p_T becomes milder
  - ✓ In pp collisions B_2 flat in p_T

- B_2 does not show discontinuity between different colliding systems and different energies
  - ✓ Unique production mechanism depending on the system size
  - ✓ Two regimes observed
    1. ***flat***: system size smaller than deuteron size
    2. **decreasing**: system size larger than deuteron size



ALI-PREL-146141



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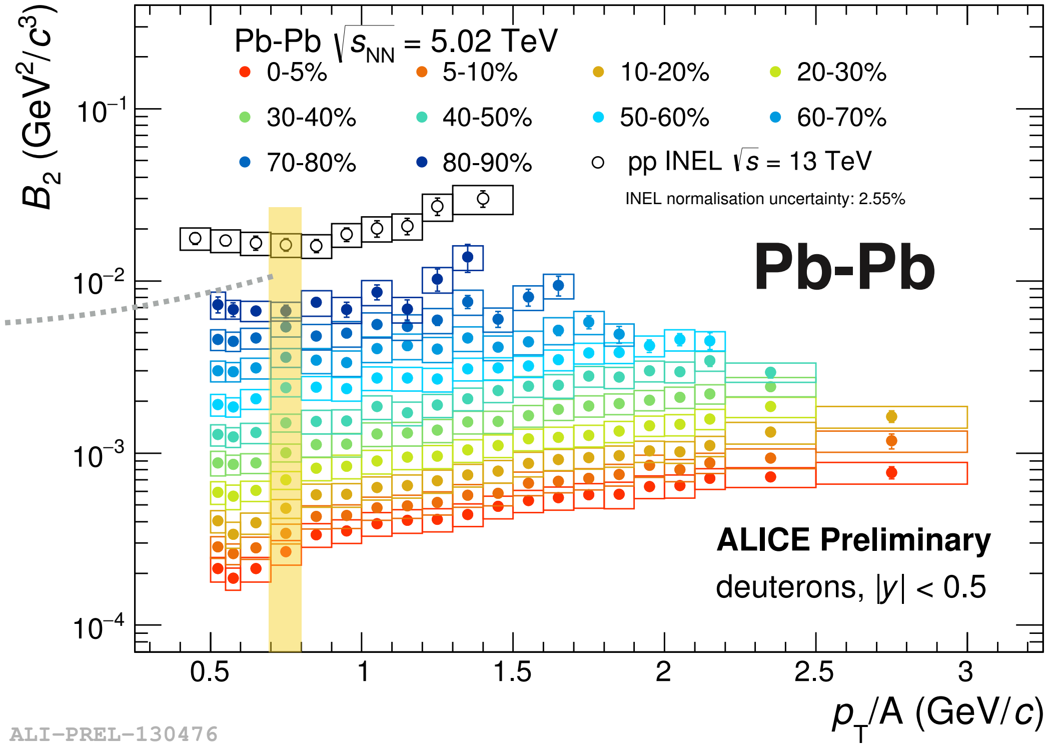
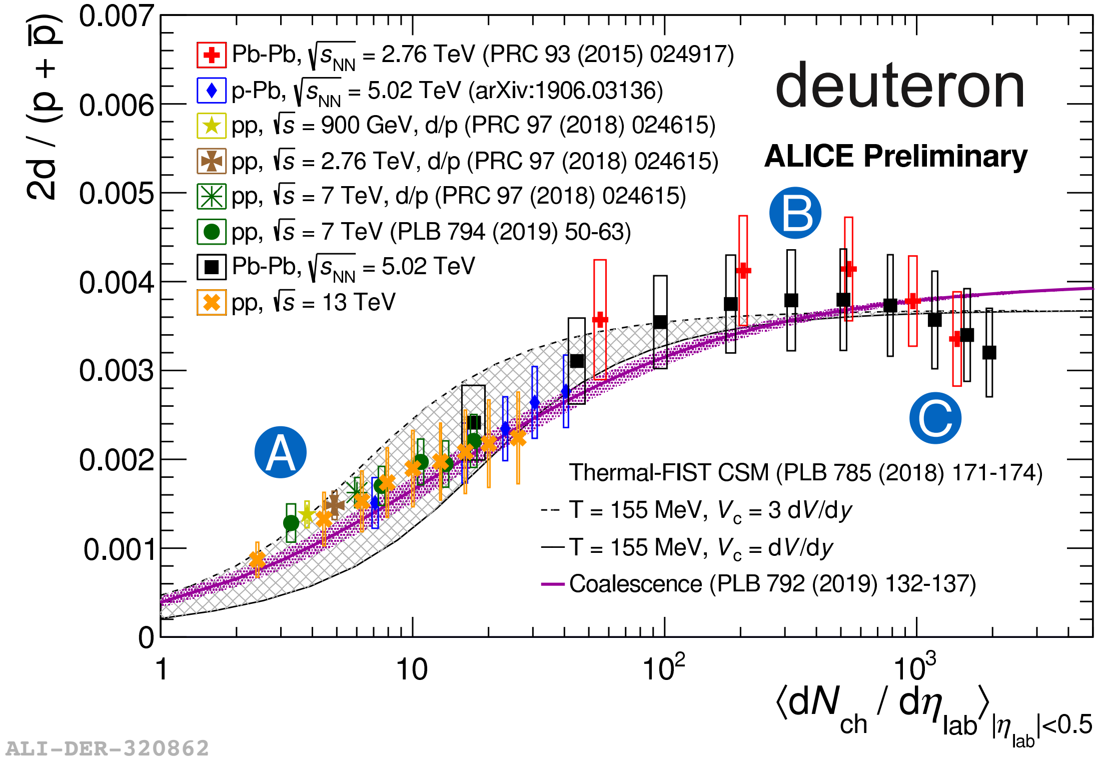


ALI-PREL-130476

⑤ Light nuclei production

- Deuteron/proton ratio does not show discontinuity between different colliding systems and different energies
  - ✓ Unique production mechanism depending only on the system size
  - ✓ Two different regimes (or three)
    - A. **increasing**: thermal model → canonical suppression, coalescence → small phase space
    - B. **flat**: no dependence multiplicity, in agreement withe thermal model and coalescence
    - C. **suppression (?)**: too large uncertainties for a conclusion
- Similar smooth transition vs multiplicity and regimes observed also for ^{3}He → More data needed to cover the multiplicity gap



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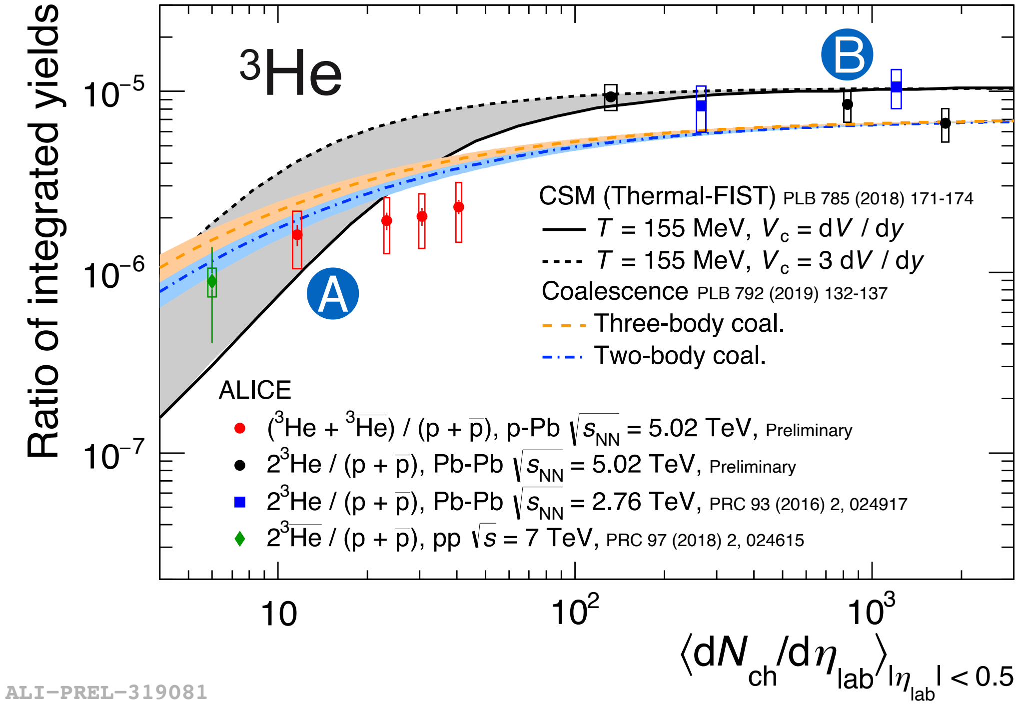

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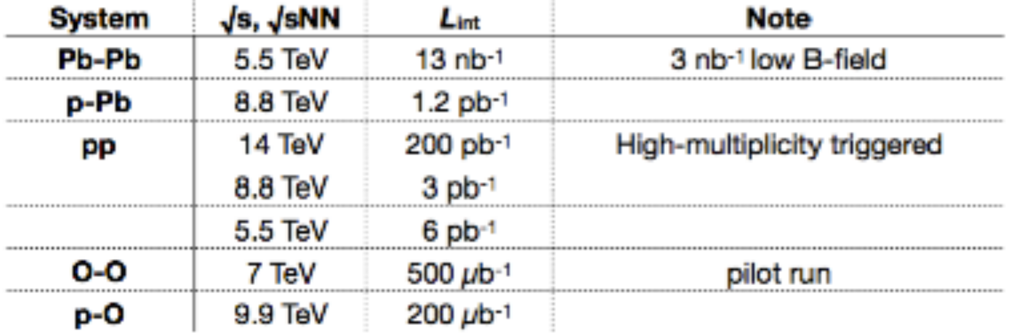
Backup

LHC Run3/4 program and ALICE Upgrade strategy

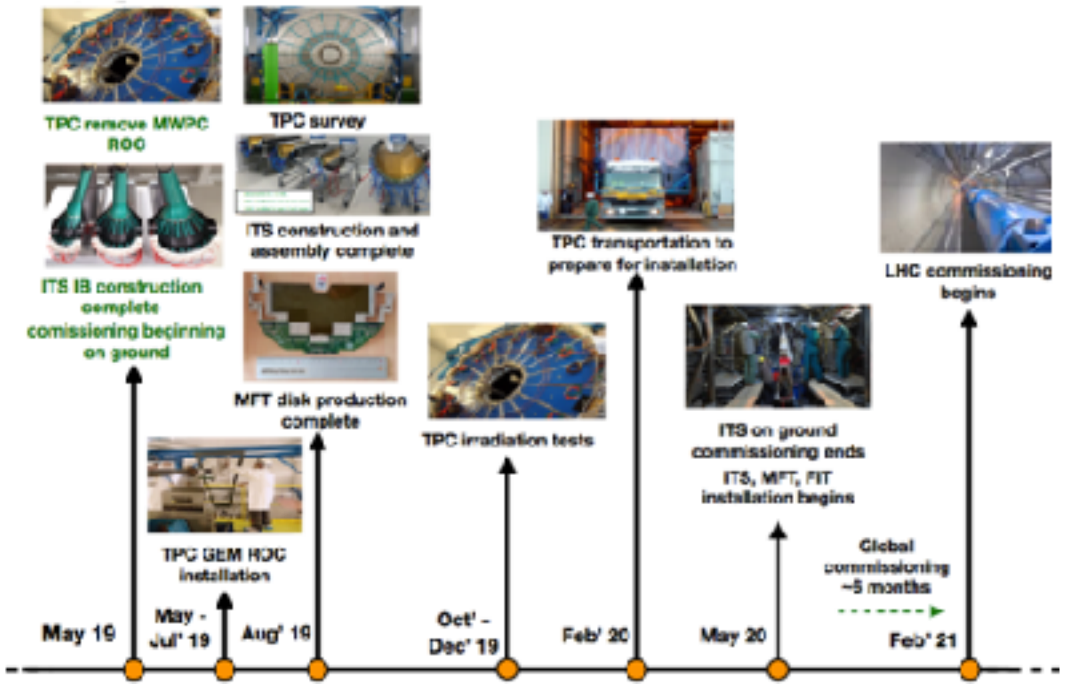
4 key objectives identified by HL/HE-LHC working group 5 for high-density QCD at LHC after LS2

1. Characterising the microscopic long-wavelength QGP properties with unprecedented precision
2. Accessing the microscopic parton dynamics underlying QGP properties
3. Developing a unified picture of partial production from small (pp) to larger (p-A and A-A) systems
4. Probing parton densities in nuclei in a broad (x, Q2) kinematic range and searching for possible onset of parton saturation

Proposed run schedule for Run 3/4

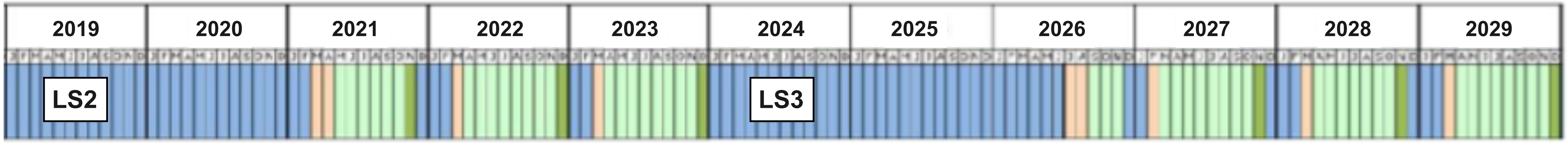


System	$\sqrt{s}$, $\sqrt{s_{NN}}$	L_{int}	Note
Pb-Pb	5.5 TeV	13 nb^{-1}	3 nb^{-1} low B-field
p-Pb	8.8 TeV	1.2 pb^{-1}	
pp	14 TeV	200 pb^{-1}	High-multiplicity triggered
	8.8 TeV	3 pb^{-1}	
	5.5 TeV	6 pb^{-1}	
O-O	7 TeV	500 μb^{-1}	pilot run
p-O	9.9 TeV	200 μb^{-1}	



ALICE Upgrade strategy

- » New silicon trackers: ITS (mid-rapidity), MFT (forward rapidity)
- » New TPC read-out chambers (GEMs) and electronics
- » New Fast Interaction Trigger (FIT)
- » New Read-out of other detectors (TOF, TRD, Muon arm, ZDC,…)
- » Upgrade of Online and Offline systems (O^2 project)



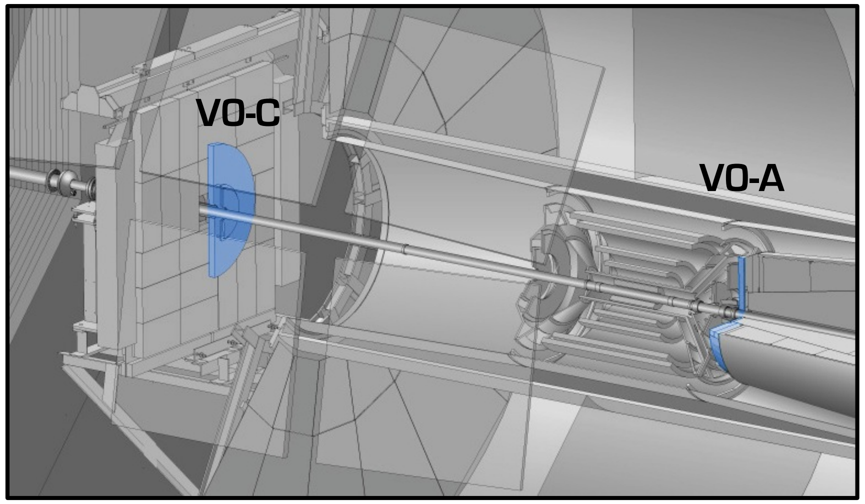
Run 3: $L_{Pb\text{-}Pb}$ = 6.0 nb^{-1}

Run 4: $L_{Pb\text{-}Pb}$ = 7.0 nb^{-1}

Backup

Centrality/Multiplicity determination

- » The centrality/multiplicity classes requires the following steps:
  - ✓ the V0 amplitude distribution is fitted with Glauber MC
  - ✓ absolute scale is defined, through the definition of anchor point, as the amplitude of the V0 equivalent to 90% of hadronic cross-section
  - ✓ data are divided into several percentiles selecting on signal amplitude measured in the V0
- » V0 amplitude distribution
  - ✓ **Pb—Pb and pp:** sum of amplitudes in the two V0 scintillators, V0-A&V0-C (“V0M”)
  - ✓ **p--Pb:** amplitude by V0-A (placed on the outgoing Pb side)
- » $\langle dN_{ch}/dh \rangle$ is measured in $|h| < 0.5$ to avoid “auto-biases” in multiplicity determination



The V0 detector is composed of a pair of forward scintillator hodoscopes placed at $2.8 < \eta < 5.1$ (V0-A) and $-3.7 < \eta < -1.7$ (V0-C)

$\langle dN_{ch}/d\eta \rangle$			
Centrality/Multiplicity class (Pb—Pb/p—Pb/pp)	Colliding system		
	Pb—Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)	p—Pb ($\sqrt{s_{NN}}$ = 5.02 TeV)	pp ($\sqrt{s}$ = 7 TeV)
0-5%/0-5%/0-0.95%	1601±60	45±1	21.3±0.6
70-80%/60-80%/48-68%	35±2	9.8±0.2	3.90±0.14

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