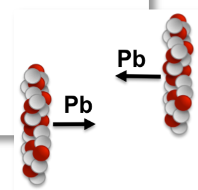
Strangeness in ALICE at LHC

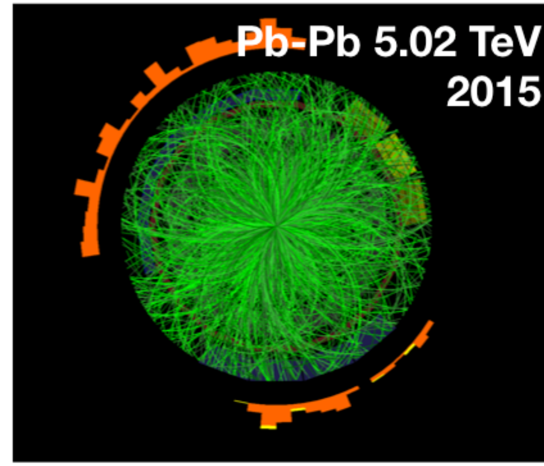
F. Bellini* on behalf of the ALICE Collaboration
*University of Bologna and INFN, Italy
SQM 2016 – Berkeley, 28th June 2016

Three collision systems compared

Pb-Pb collisions

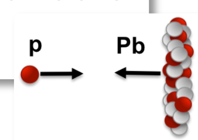
- Particle production mechanisms
- Strangeness enhancement
- In-medium energy loss
- Properties of the hadronic phase





p-Pb collisions

- Disentangle final from initial-state effects
- Collectivity in small systems?



A comprehensive set of measurements of identified particles production with ALICE in all collision systems, including

$\pi^{\pm}$, $K^{\pm}$, K^0_S, p, Λ, Ξ, Ω

ρ, K^{*0}, ϕ, $\Sigma^{*\pm}$, Ξ^{*0}

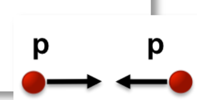
…plus light nuclei and exotica

(anti)d, (anti)^{3}H,

(anti)^{3}He, (anti)^{4}He, (anti)$^3_\Lambda$H

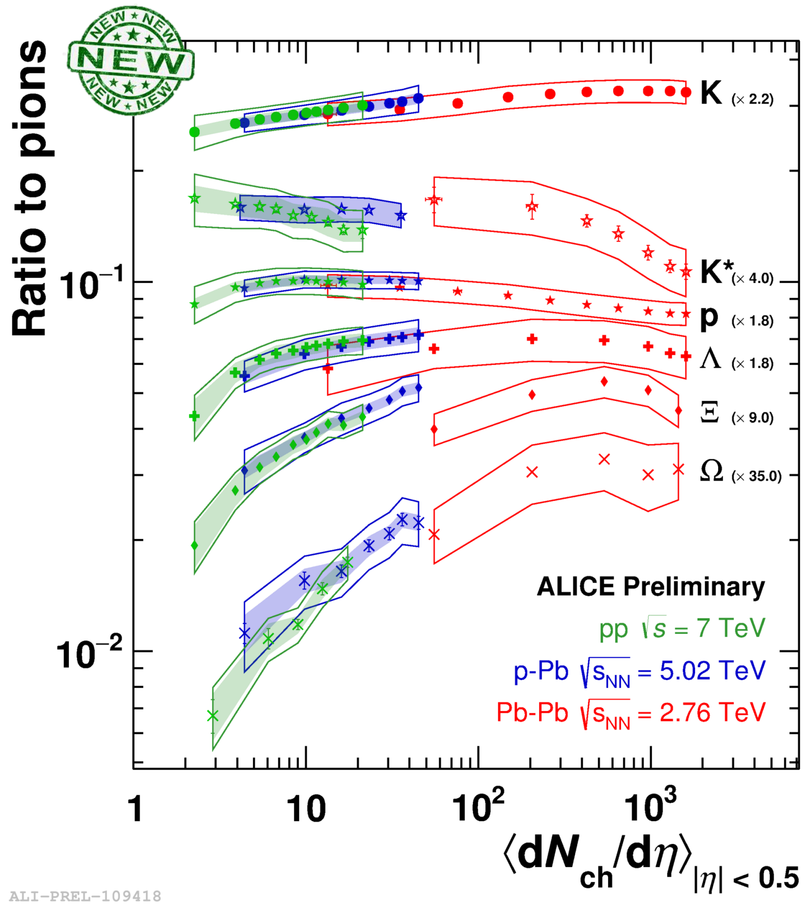
pp collisions

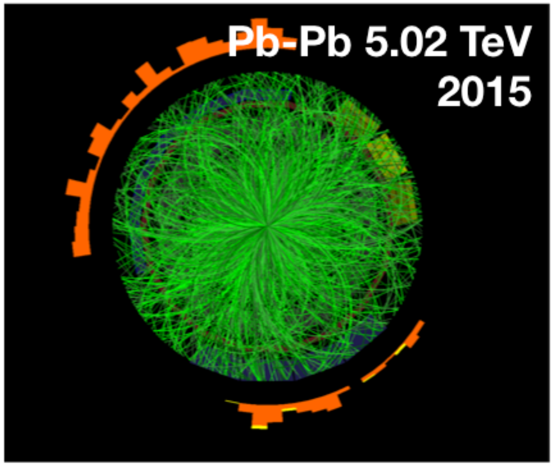
- No deconfinement expected
- No collectivity expected
- Reference for "larger" system



Three collision systems compared

Pb-Pb $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
pp $\sqrt{s}$ = 0.9, 2.76, 5.02, 8, 13 TeV
$\sqrt{s}$ = 7 TeV (multip. dep.)





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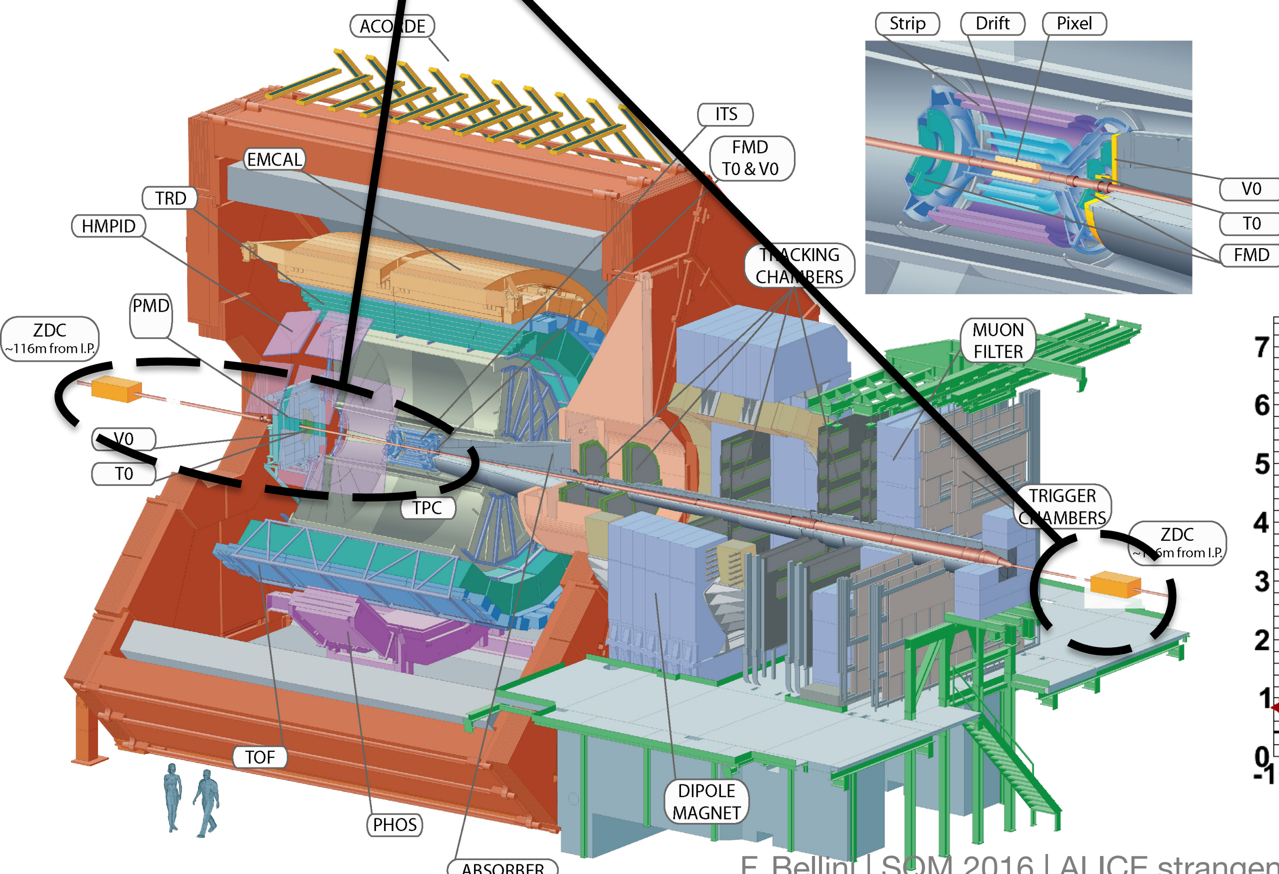
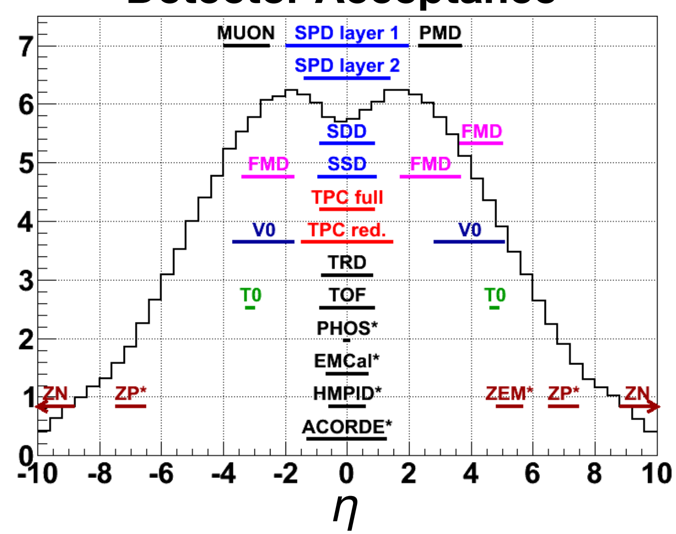
A Large Ion Collider Experiment at the LHC

Forward detectors
Multiplicity, centrality, trigger and timing

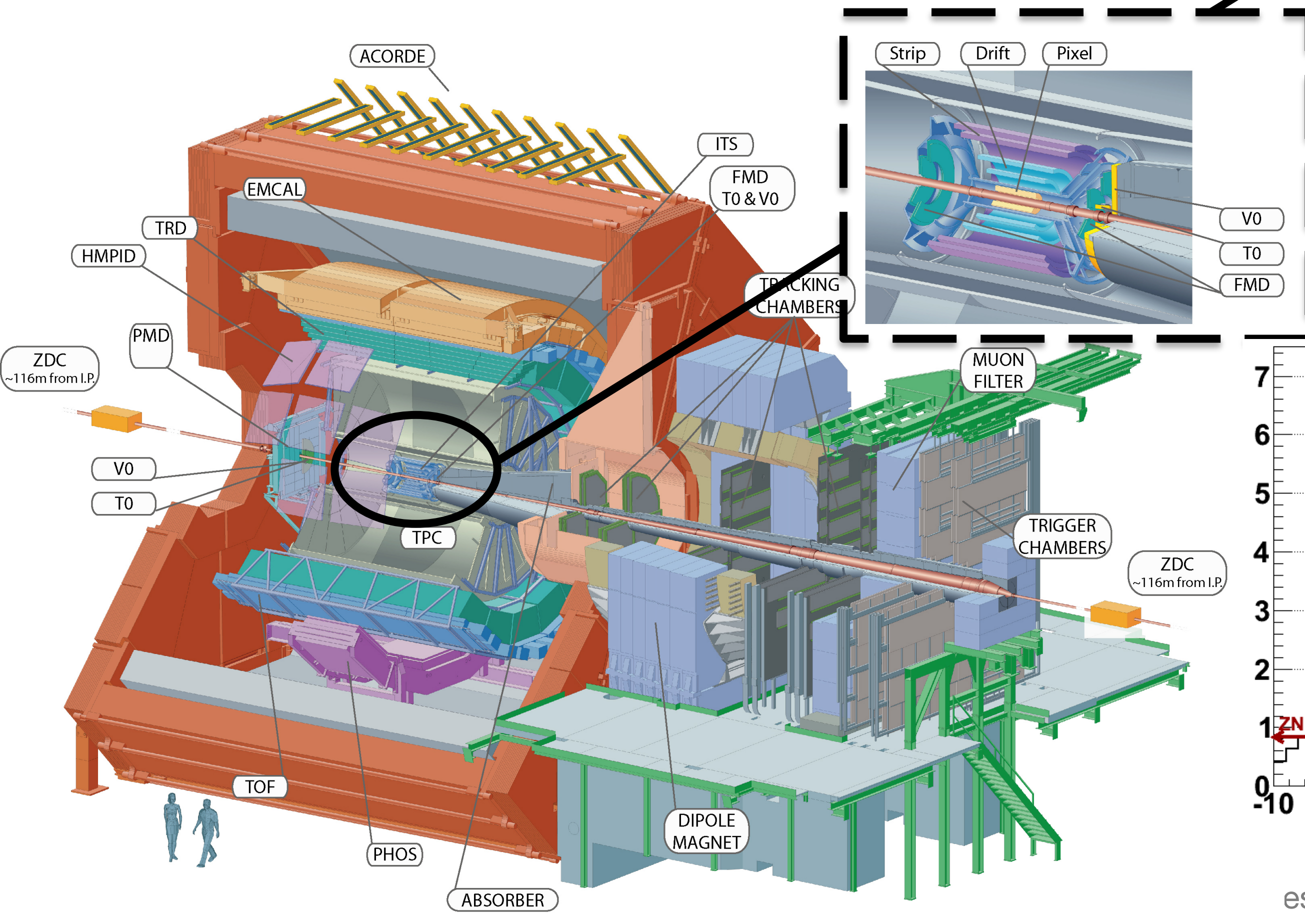


Detector Acceptance



A Large Ion Collider Experiment at the LHC

Inner Tracking System
Vertexing and tracking down to very low p_T



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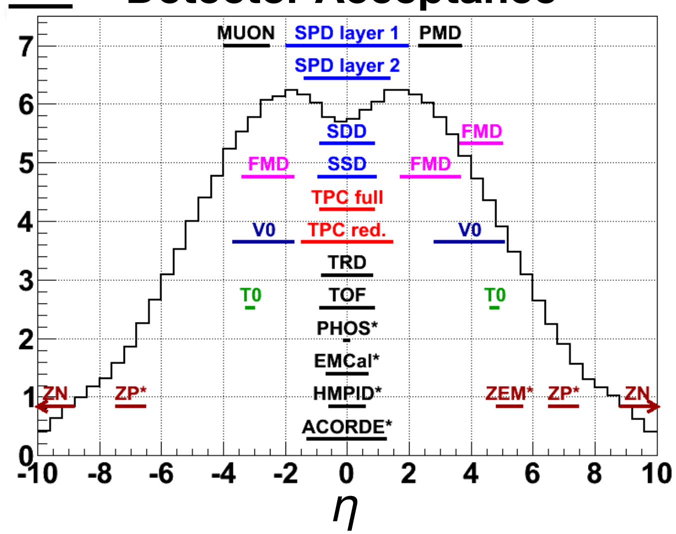
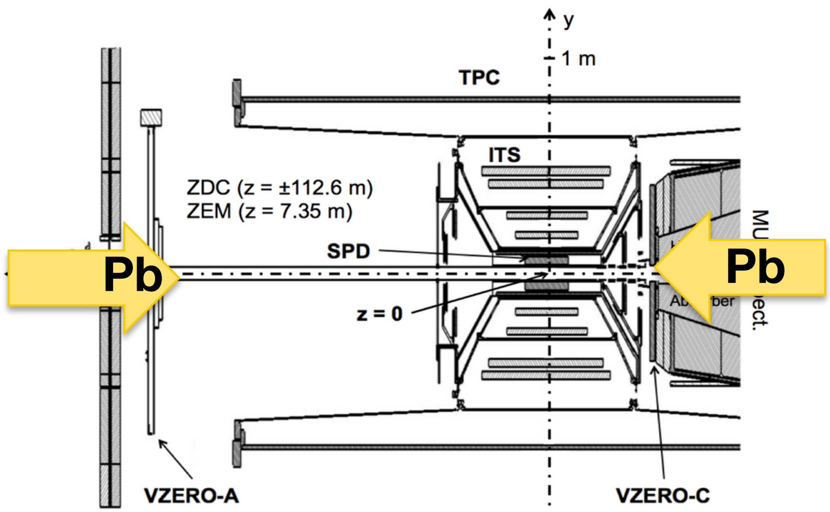


Event classes in Pb-Pb

ALICE, PRL 106 (2011) 032301
ALICE, PRC 88 (2013) 044909
ALICE, PRC 91 (2015) 064905

Event **multiplicity/centrality** classes are defined based on the amplitude measured in the **V0 scintillators**, placed at $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C)

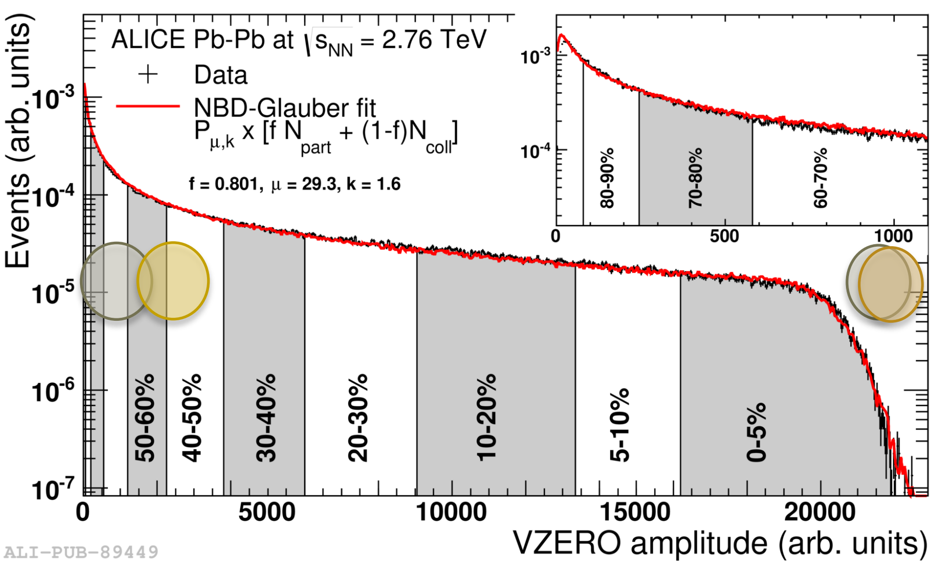


$\langle dN_{ch}/d\eta \rangle$ is measured in $|\eta|<0.5$
→ avoid “auto-biases” in multiplicity determination

In **Pb-Pb** the Glauber model is used to relate the V0A&V0C (“V0M”) amplitude* distribution to the geometry of the collision

0-5%: $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} = 1601 \pm 60$
$\langle N_{part} \rangle = 328.8 \pm 3.1$

70-80%: $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} = 35 \pm 2$
$\langle N_{part} \rangle = 15.8 \pm 0.6$



(*alternatively, multiplicity of spectators in the Zero Degree Calorimeters or number of tracks in the Silicon Pixel Detector or the Time Projection Chamber)

Event classes in Pb-Pb, p-Pb and pp

ALICE, PRL 106 (2011) 032301
ALICE, PRC 88 (2013) 044909
ALICE, PRC 91 (2015) 064905

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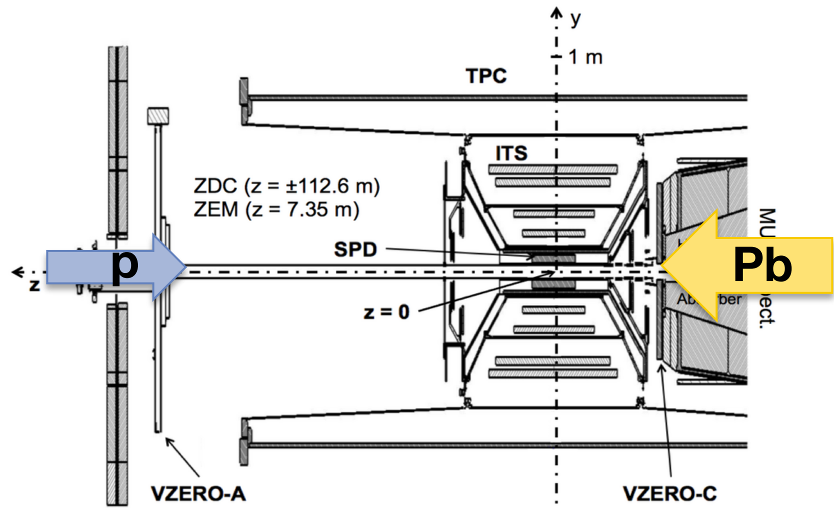

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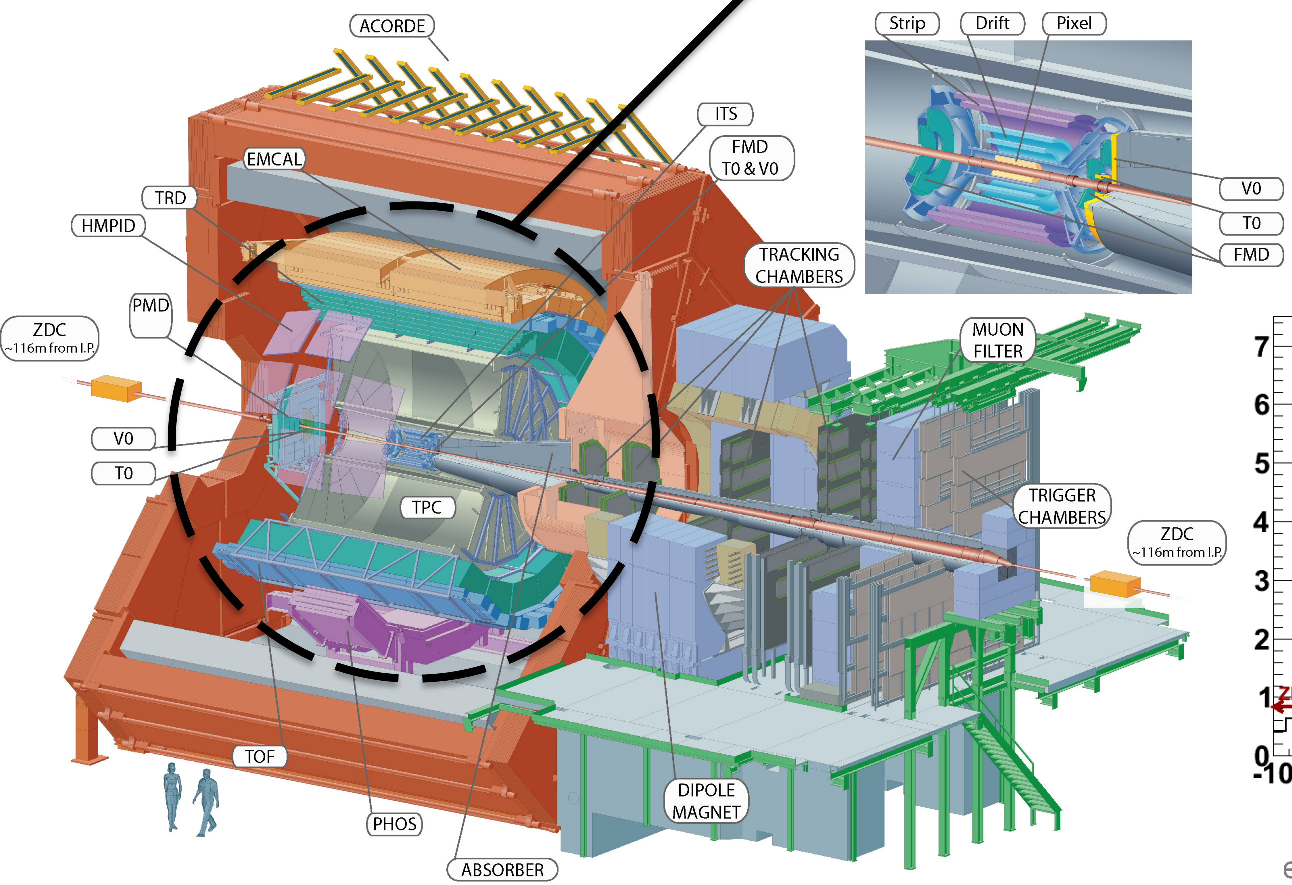
In **p-Pb** collisions, V0A (Pb side) is used:
0-5%: **$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} = 45 \pm 1$**
60-80%: **$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} = 9.8 \pm 0.2$**

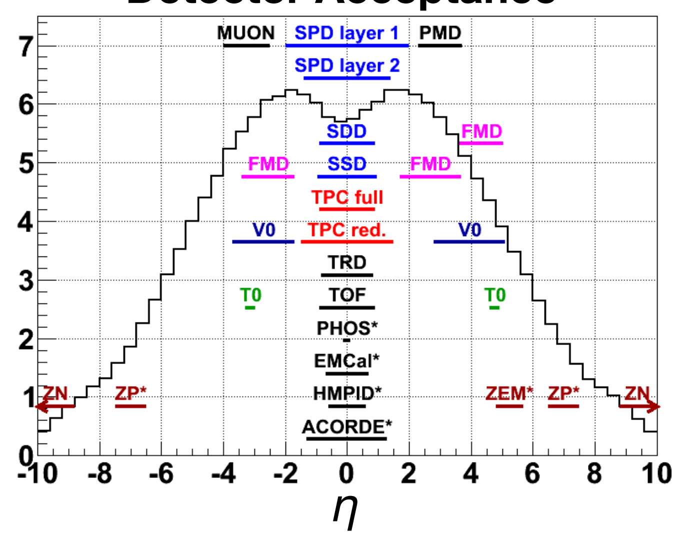
In **pp** collisions, V0A&V0C ("V0M") us used:
0-0.95%: **$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} = 21.3 \pm 0.6$**
48-68%: **$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} = 3.90 \pm 0.14$**

A Large Ion Collider Experiment at the LHC

ALICE Central Barrel
B = 0.5 T, |η|<0.9
2π tracking and PID

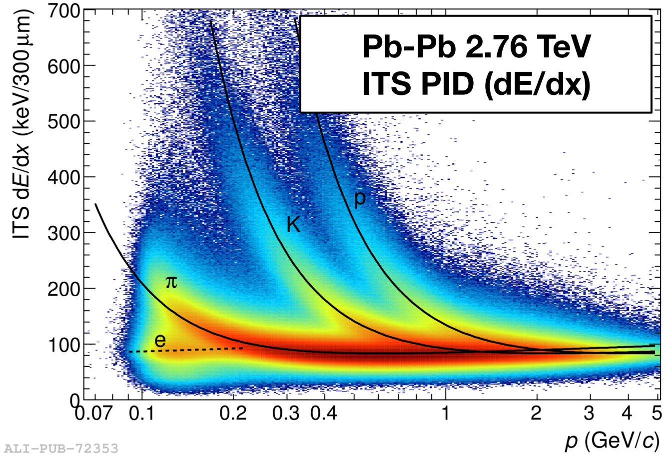


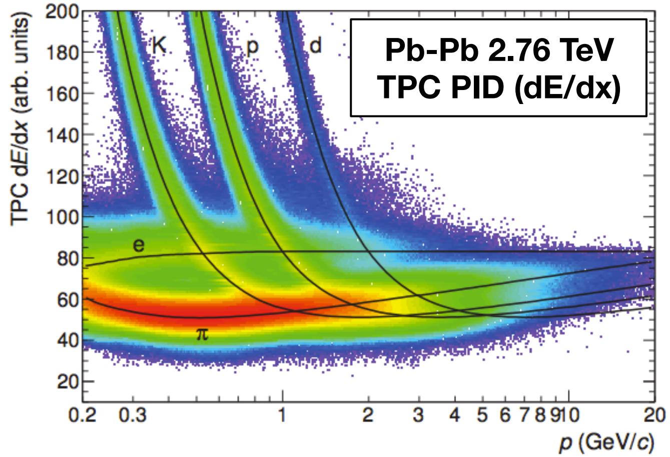
Detector Acceptance

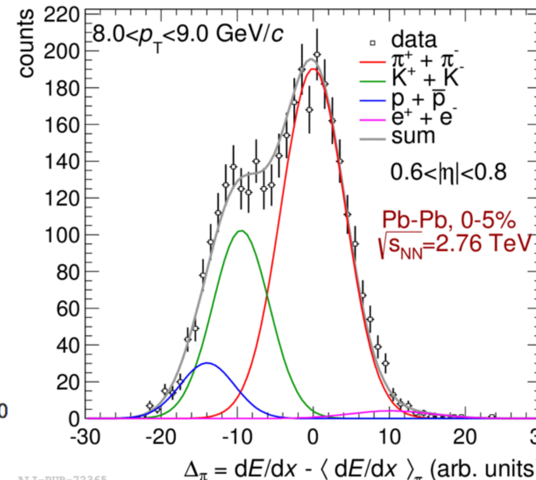


Particle identification

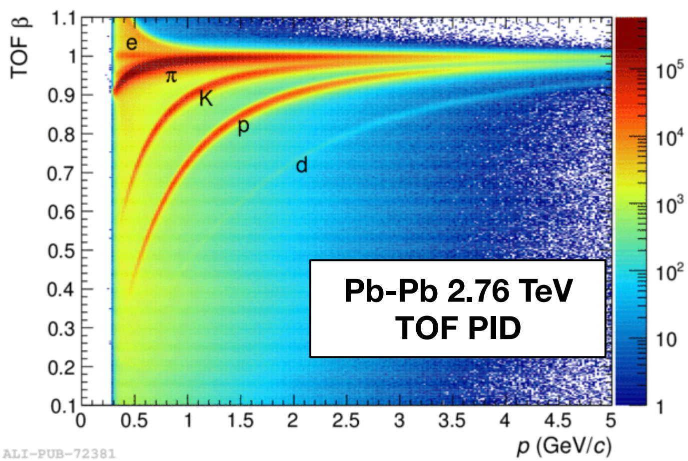
ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044

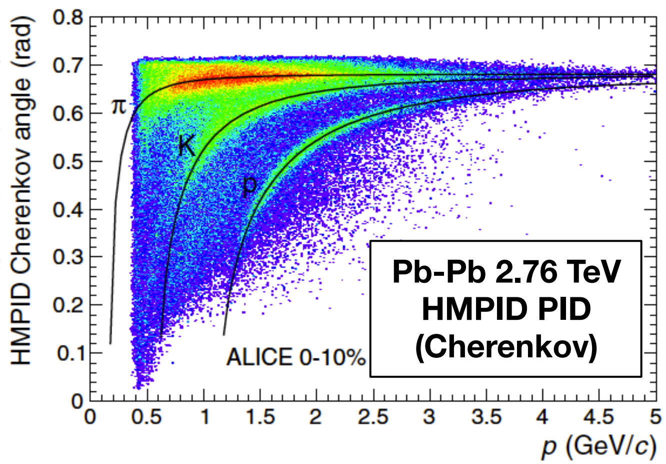




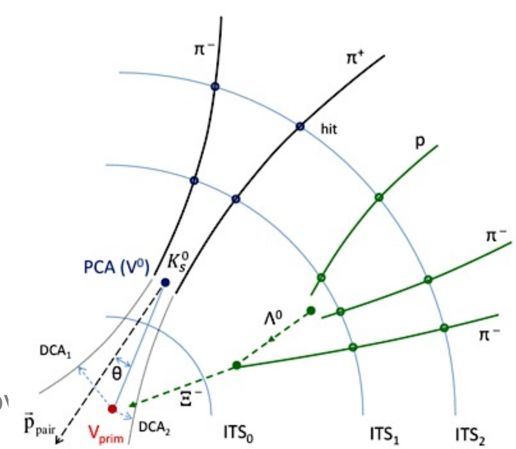


Pb-Pb 2.76 TeV
TPC PID (d*E*/d*x*, relativistic rise)
statistical PID via multi-Gaussian fits





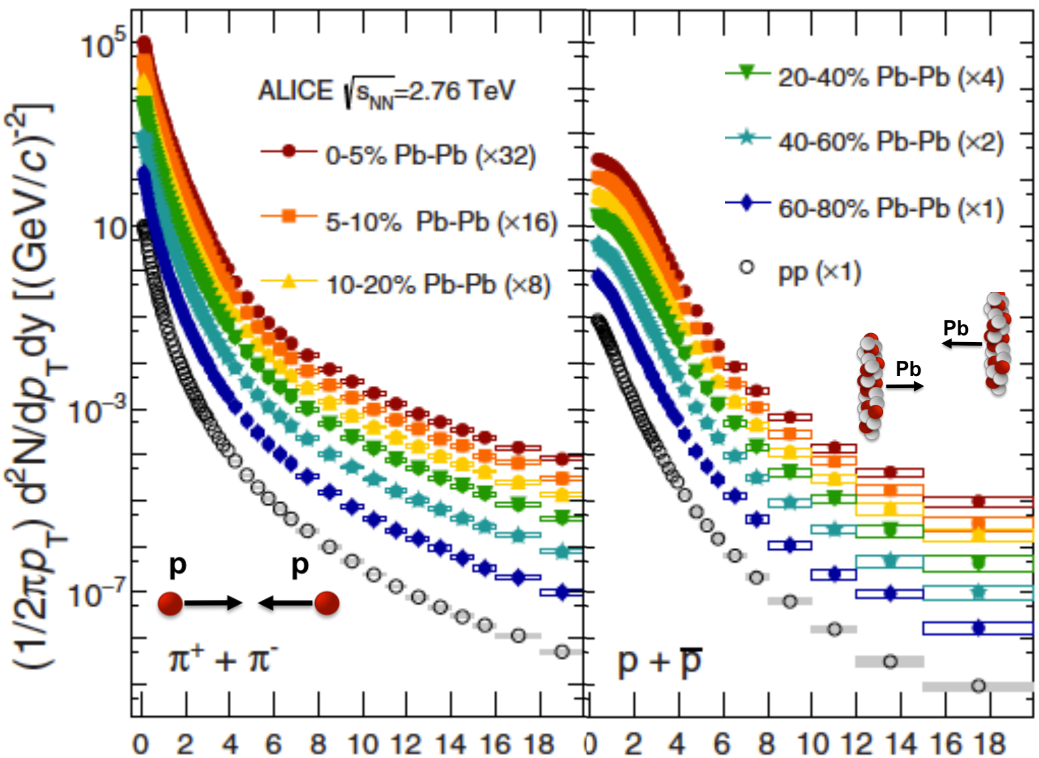
Decay topology
secondary vertex reconstruction +
invariant mass analysis



Identification of light flavour hadrons and light (anti-)nuclei via practically all known PID techniques in **$0.1\ \mathrm{GeV}/c < p_T < 20\ \mathrm{GeV}/c$**

ALICE, PRC 88 (2013) 044910

π,K,p in Pb-Pb, pp at $\sqrt{s_{NN}}$ = 2.76 TeV



Phys. Rev. C 93 (2016) 034913

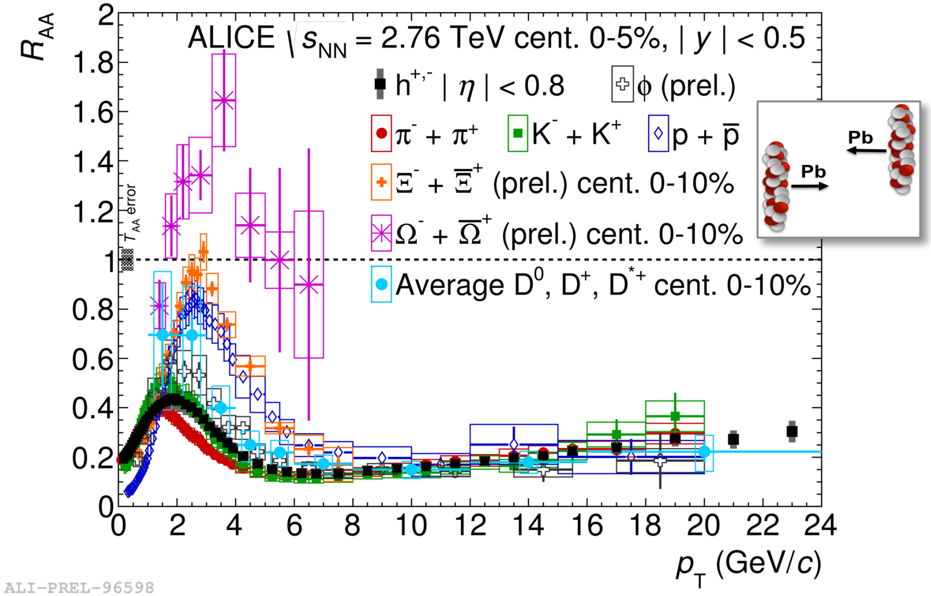
(High-p_T π,K,p and R_{AA})

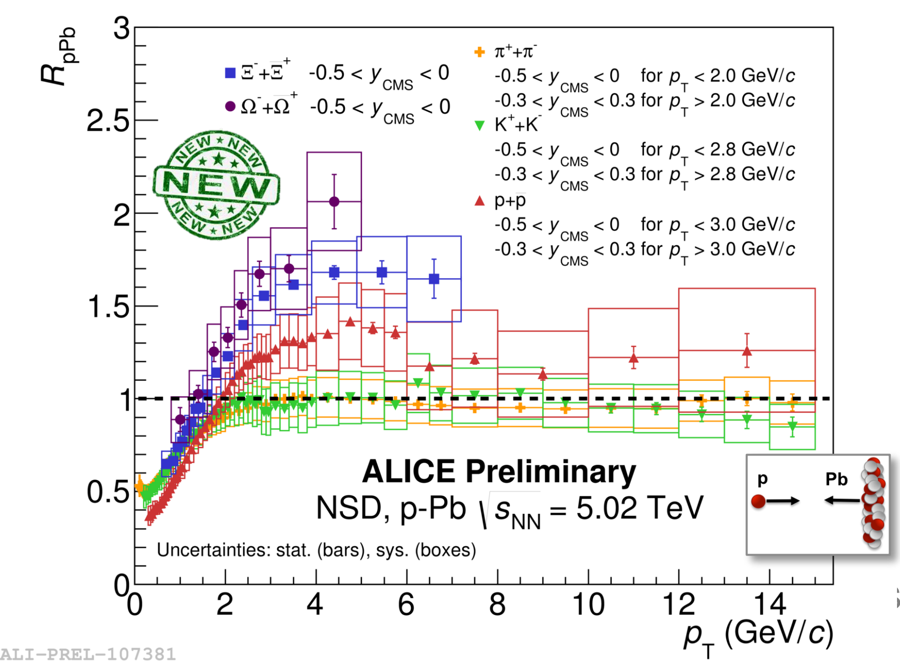
Low p_T (p_T < 3 GeV/c)
→ Study collective phenomena (radial flow)

Mid-p_T (3 < p_T < 8-10 GeV/c)
→ Study fragmentation vs recombination

High p_T (p_T > 8-10 GeV/c):
→ Study jet quenching and energy loss nuclear via nuclear modification factors

Nuclear modification of spectra





$$R_{xA}(p_T) = \frac{d^2 N_{ch}^{xA} / d\eta dp_T}{\langle T_{xA} \rangle d^2\sigma_{ch}^{pp} / d\eta dp_T}$$

At **high-p_T** (>8-10 GeV/c):

- strong **flavour-independent suppression** in **central Pb-Pb** with respect to pp
- **no suppression** observed **in p-Pb** for π,K,p above 6-8 GeV/c

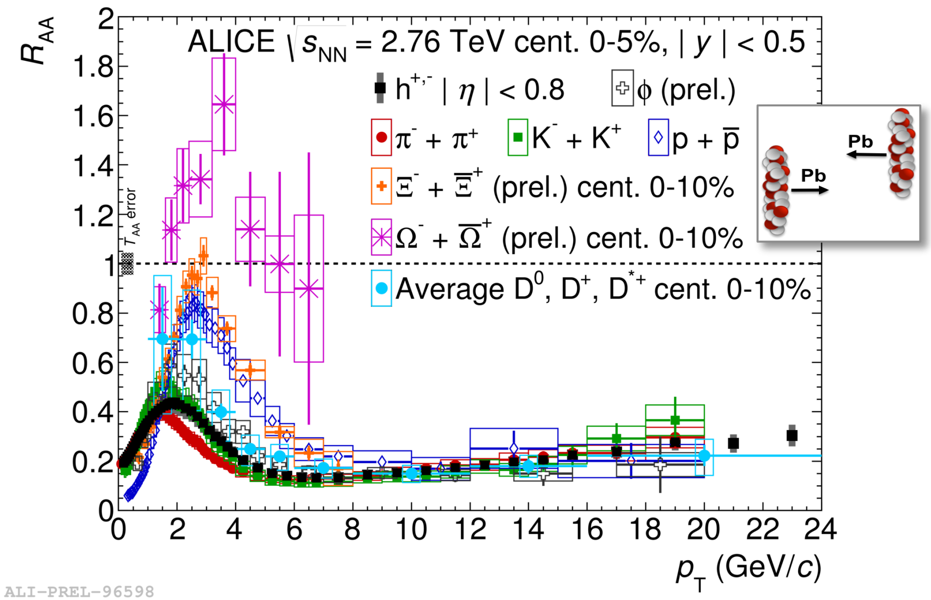
→ In Pb-Pb, due to **parton energy loss in the hot nuclear matter**

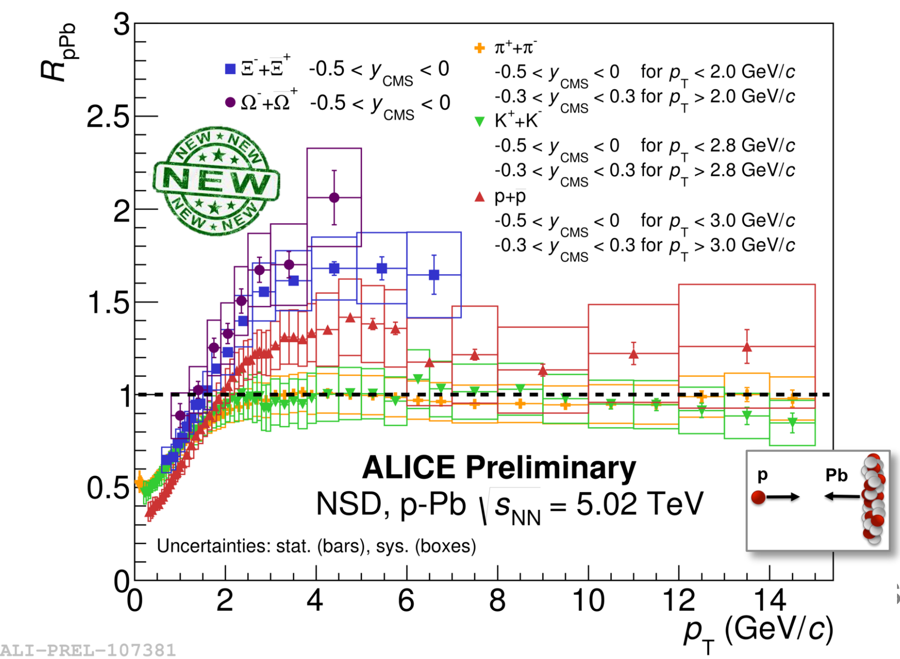
arXiv:1601.03658

(High-p_T π,K,p and R_{pPb})

Nuclear modification of spectra

ALICE, PLB 720 (2013) 52
ALICE, PLB 736 (2014) 196
ALICE, PRC 93 (2016) 034913





$$R_{xA}(p_T) = \frac{d^2N_{ch}^{xA} / d\eta dp_T}{\langle T_{xA} \rangle d^2\sigma_{ch}^{pp} / d\eta dp_T}$$

At **intermediate-p_T** ($3 < p_T < 6$ GeV/c):

- **Baryon/meson** difference in central **Pb-Pb**
- **Cronin peak** in **p-Pb** collisions

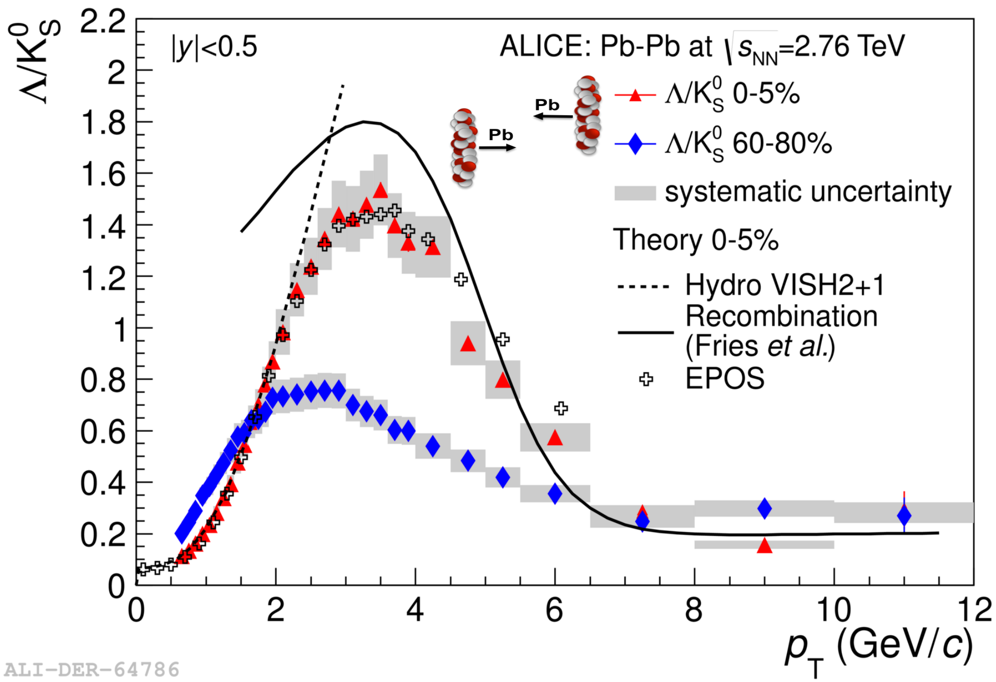
→ presence of **other final state effects or dynamics** (flow, recombination, …)?

arXiv:1601.03658

(High-p_T π,K,p and R_{pPb})

Baryon-to-meson ratio: Λ/K^0_s, p/π, p/ϕ

ALICE, PRL 111 (2013) 222301
ALICE, PRC 88 (2013) 044910
ALICE, PRC 91 (2015) 024609

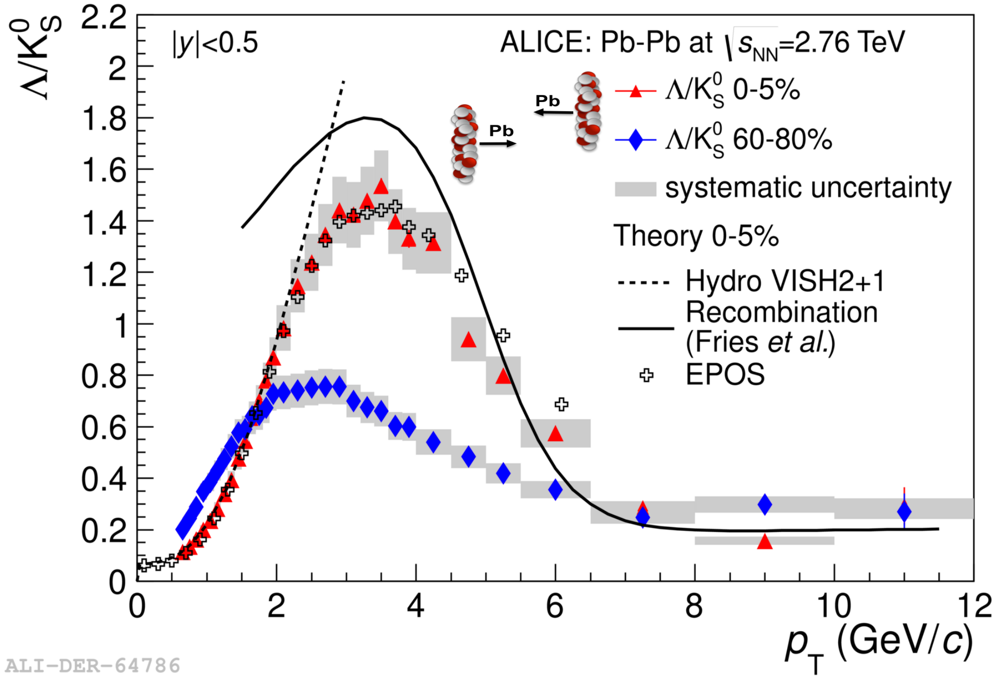


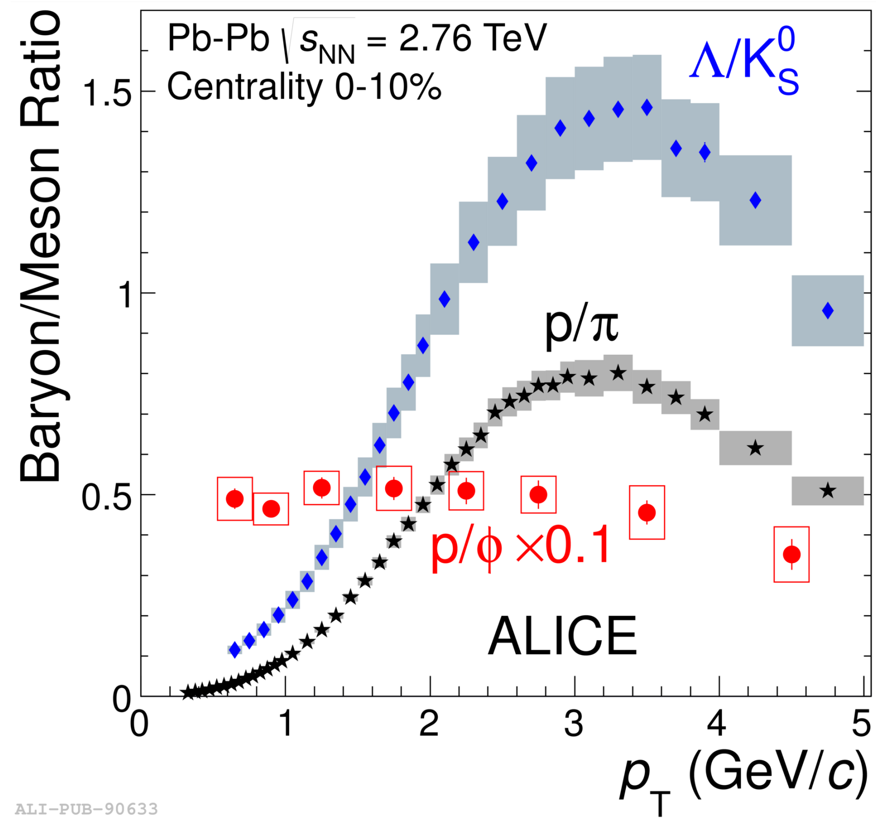
B/M enhancement at intermediate p_T

- **Hydrodynamics** describes only the rise < 2 GeV/*c*
- **Recombination** reproduces effect but overestimates
- **EPOS** gives good description of the data (with **flow**)

Baryon-to-meson ratio: Λ/K^0_s, p/π, p/ϕ

ALICE, PRL 111 (2013) 222301
ALICE, PRC 88 (2013) 044910
ALICE, PRC 91 (2015) 024609





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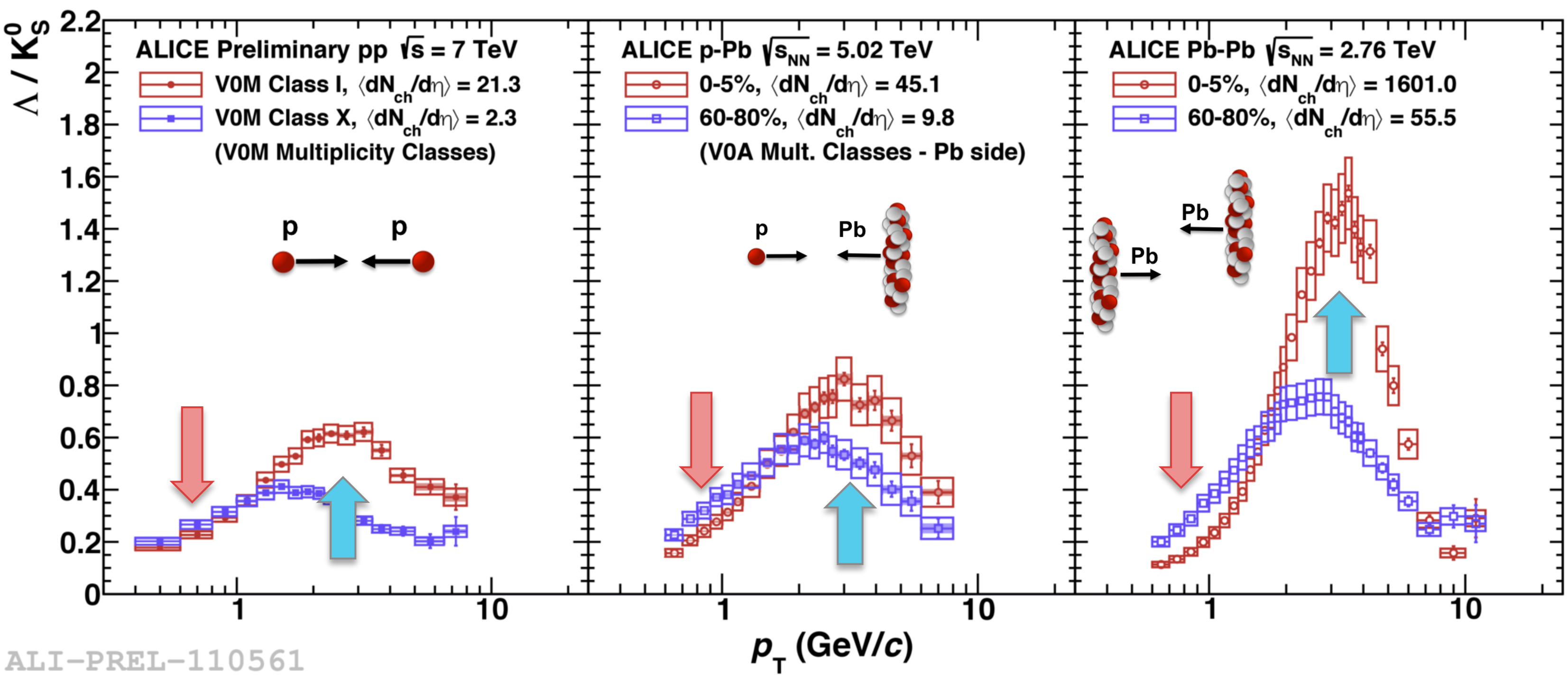
p/ϕ have similar mass
p/ϕ ratio is flat in central Pb-Pb
→ **Mass determines the spectral shapes** (as in hydrodynamics)

Baryon-to-meson ratio: Λ/K^0_s vs multiplicity

ALICE, PRL 111 (2013) 222301
ALICE, PLB 728 (2014) 25-38

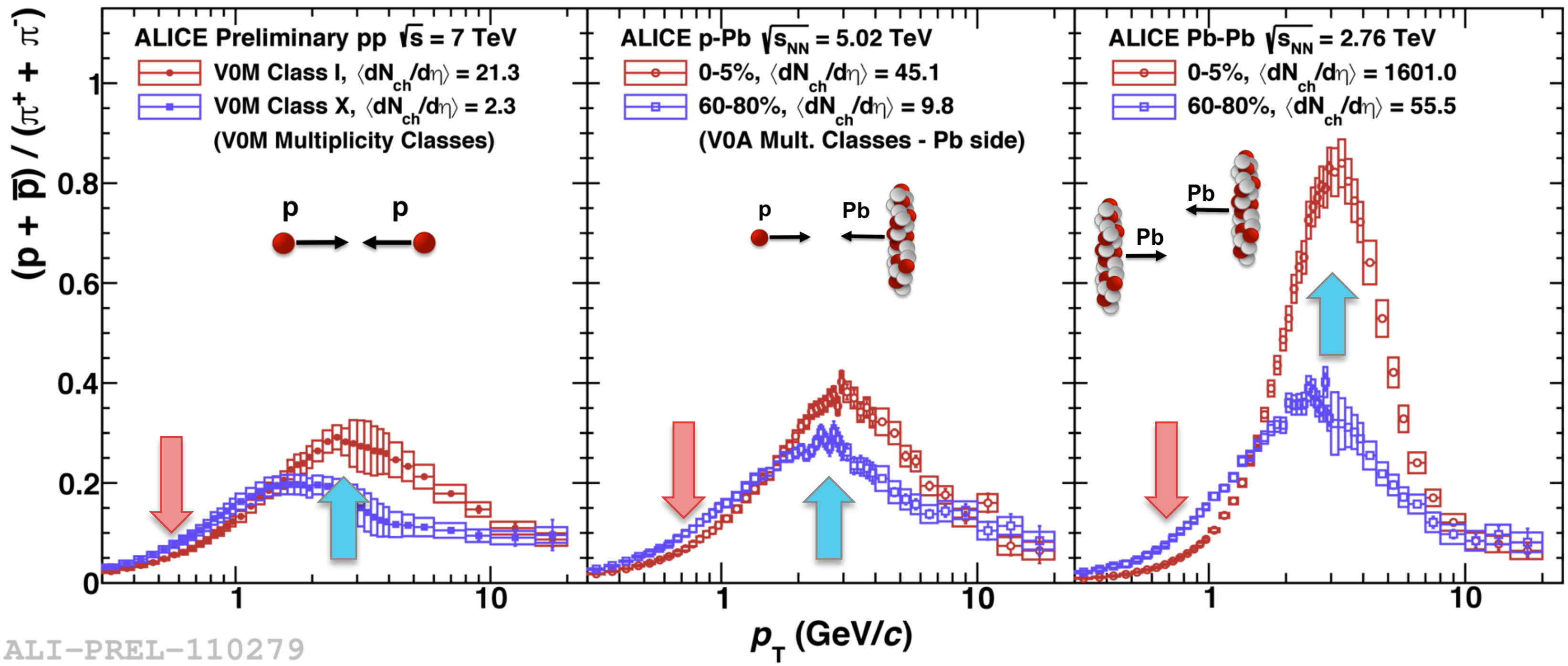


In pp, p-Pb and Pb-Pb collisions the B/M ratio as a function of multiplicity is

- qualitatively similar: **depletion** at low p_T, **enhancement** at intermediate p_T
- quantitatively different in the three systems

Baryon-to-meson ratio: p/π vs multiplicity

ALICE, PRC 93 (2016) 034913
ALICE, PLB 728 (2014) 25-38
ALICE, arXiv:1601.03658



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R. Derradi,
Today 28/6, 16:40

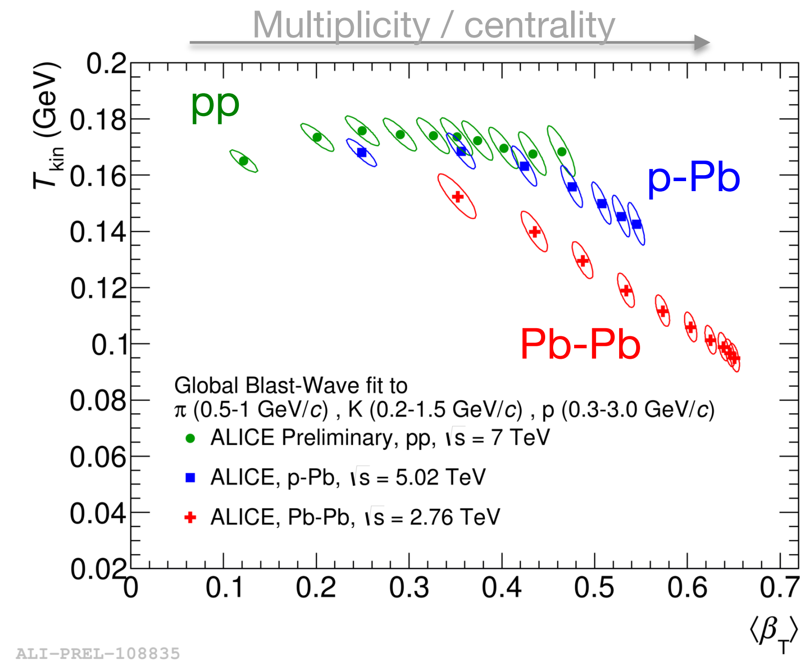
Blast-Wave model fit to π,K,p

E. Schnedermann et al., Phys. Rev. C48 (1993) 2462
ALICE, PRC 88 (2013) 044910
ALICE, PLB 728 (2014) 25-38

Simultaneous **Blast-Wave model** fit to the π, K, p spectra

- In **Pb-Pb**: increase of radial flow with centrality

- In **pp** and **p-Pb**, similar evolution of the parameters towards high multiplicity



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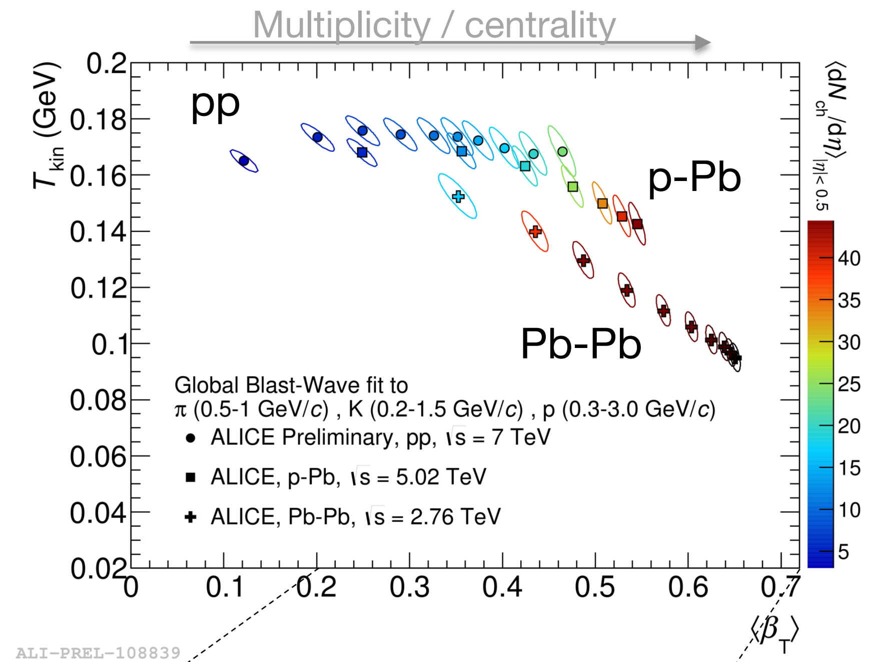
ALICE, PRC 88 (2013) 044910
ALICE, PLB 728 (2014) 25-38

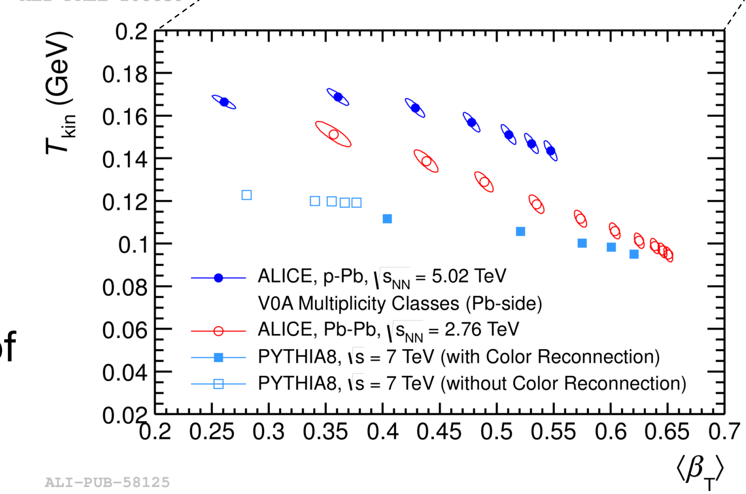
Simultaneous **Blast-Wave model** fit to the π, K, p spectra

- In Pb-Pb: increase of radial flow with centrality
- In pp and p-Pb, similar evolution of the parameters towards high multiplicity
- **Stronger $\langle\beta_T\rangle$ for smaller systems at similar multiplicity**

… but mind:

- Sensitivity to **fit range** and the set of **particles included in the fit**
- Mechanisms such as color reconnection in models of pp collisions can mimic the effects of radial flow





The deuteron

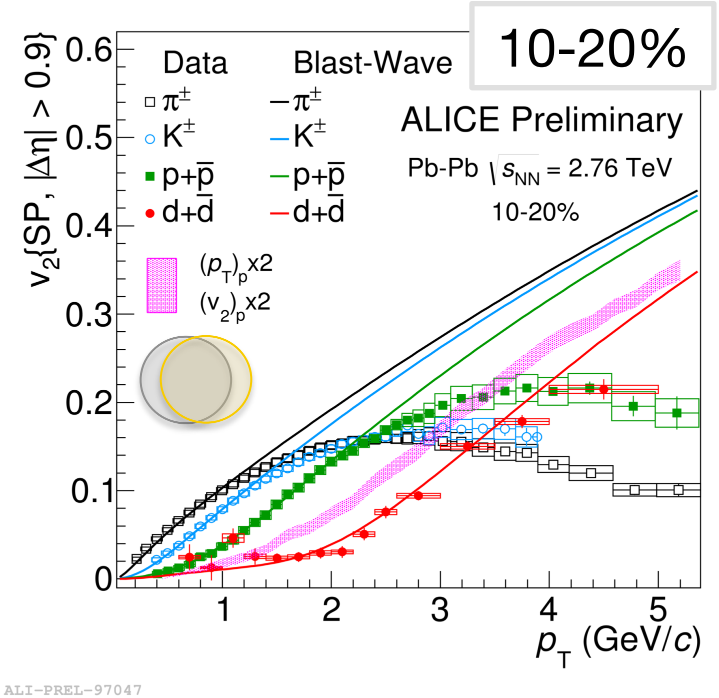
B. Doenigus,
Thu 30/6, 09:20

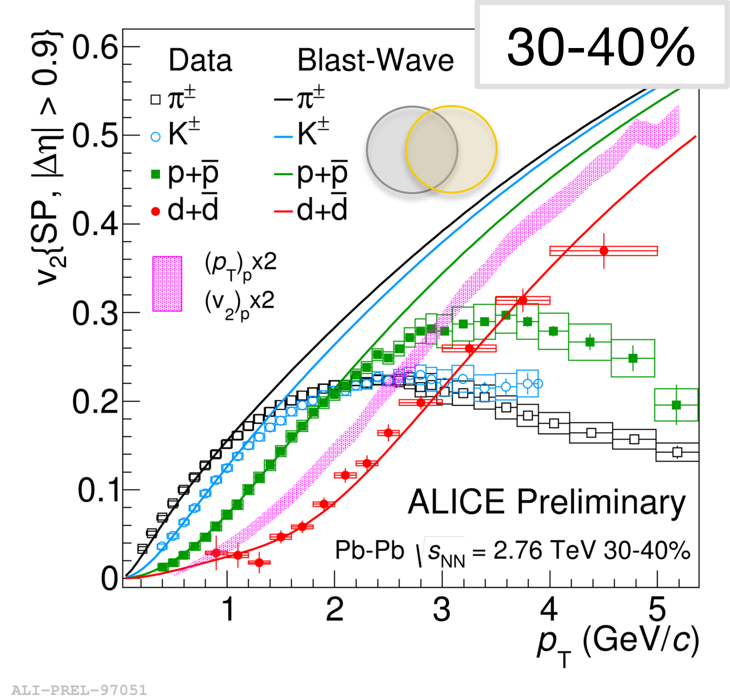
New measurement of **deuteron v_2** in comparison to

- Hydrodynamic (Blast-Wave) model from a simultaneous fit of π,K,p spectra and v_2
- simple coalescence model, from measured proton as $2v_{2,p}(2p_{T,p})$

Blast-wave model describes the d v_2

Deuteron follows mass-scaling, simple coalescence model doesn't work





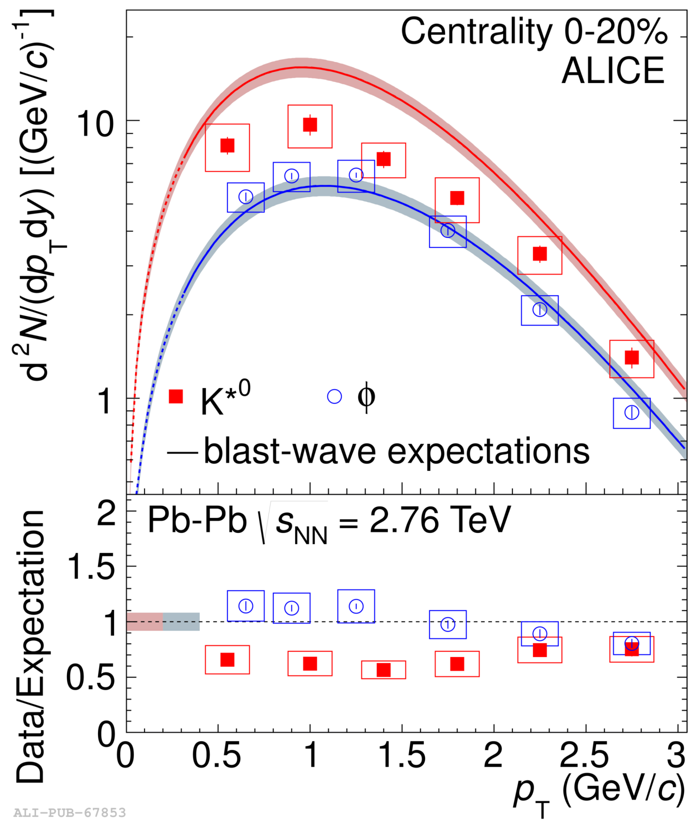
Resonances

K^{*0} resonance not described by the Blast-Wave model (also in p-Pb, pp)

- On the right: Blast wave model from a fit to π,K,p in 0-20% Pb-Pb and normalization to thermal model prediction for Rsn/K scaled to the measured K yield

Better agreement for ϕ in Pb-Pb, p-Pb

Suppression of K^{*0}/K in central Pb-Pb consistent with **re-scattering of the decay products during the late hadronic phase**



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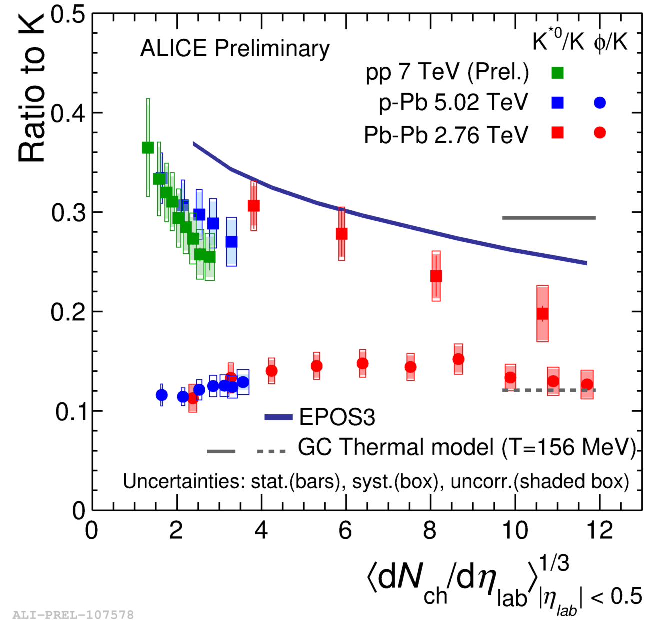


Suppression of K^{*0}/K in central Pb-Pb consistent with **re-scattering of the decay products during the late hadronic phase**

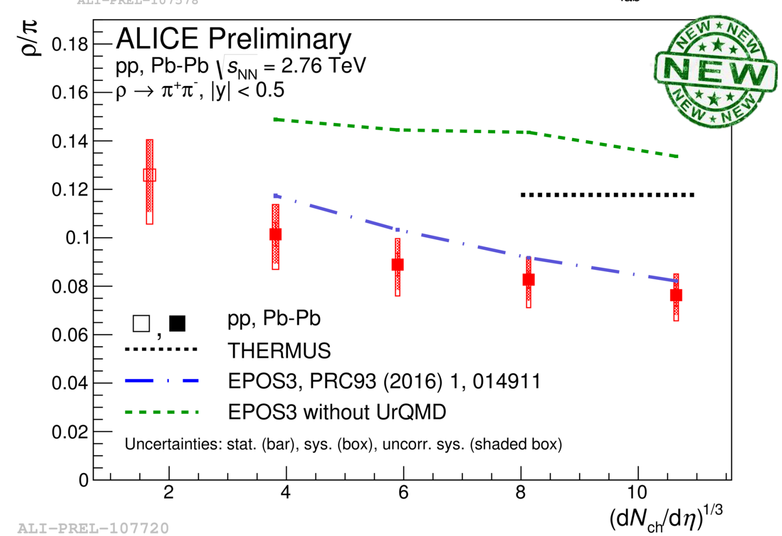
New results for **ρ/π in Pb-Pb collisions show similar behaviour**

[τ_ρ ~ 1.3 fm/c < τ_{K^*}~ 4 fm/c << τ_ϕ ~ 45 fm/c]

→ Suppression qualitatively described by EPOS3 (with UrQMD)

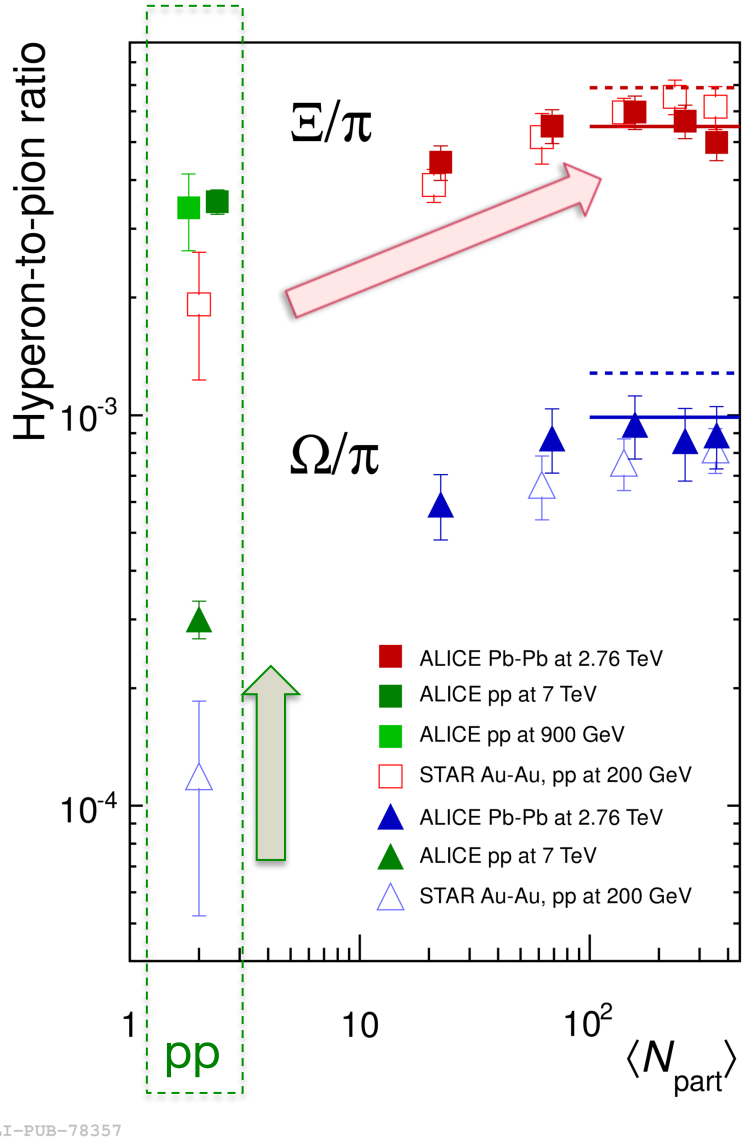
ALICE, EPJC 76 (2016) 245
(resonances in p-Pb)

A. Knospe,
Today 28/6, 16:00



Strangeness enhancement in AA

ALICE, PLB 728 (2014) 216-227
Andronic et al, PLB 673 (2009) 142
Cleymans et al, PRC 74 (2006) 034903



One of the first proposed QGP signatures

J. Rafelski and B. Muller, PRL 48 (1982) 1066

In **pp collisions** the production of strangeness relative to π at LHC is larger than at RHIC

From **pp to Pb-Pb** strangeness production increases

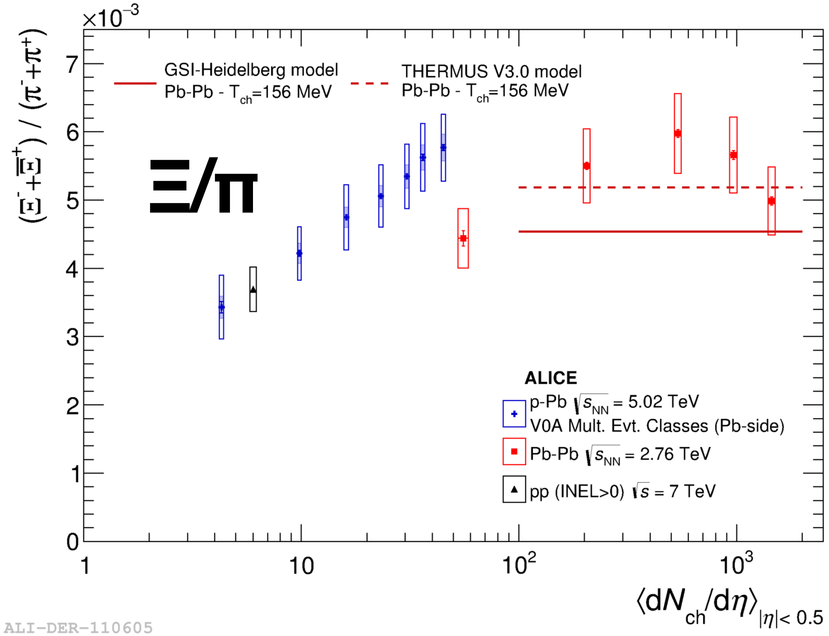
For N_{part} >150 the ratios saturate and match predictions from the grand-canonical thermal models. For instance, models at equilibrium

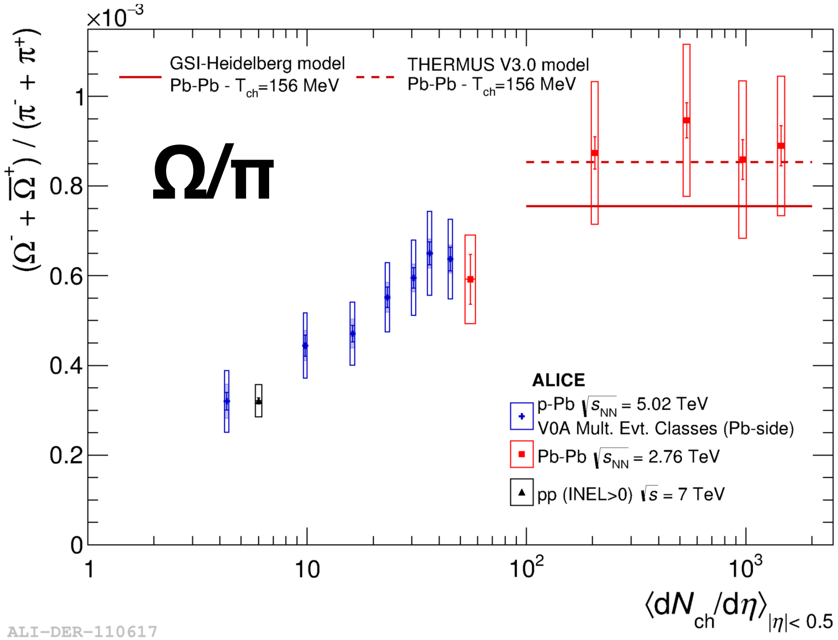
—— GSI-Heidelberg: T_{ch} = 164 MeV

- - - - THERMUS: T_{ch} = 170 MeV

Strangeness production in p-Pb

ALICE, PLB 728 (2014) 216
Andronic et al, PLB 673 (2009) 142
Cleymans et al, PRC 74 (2006) 034903





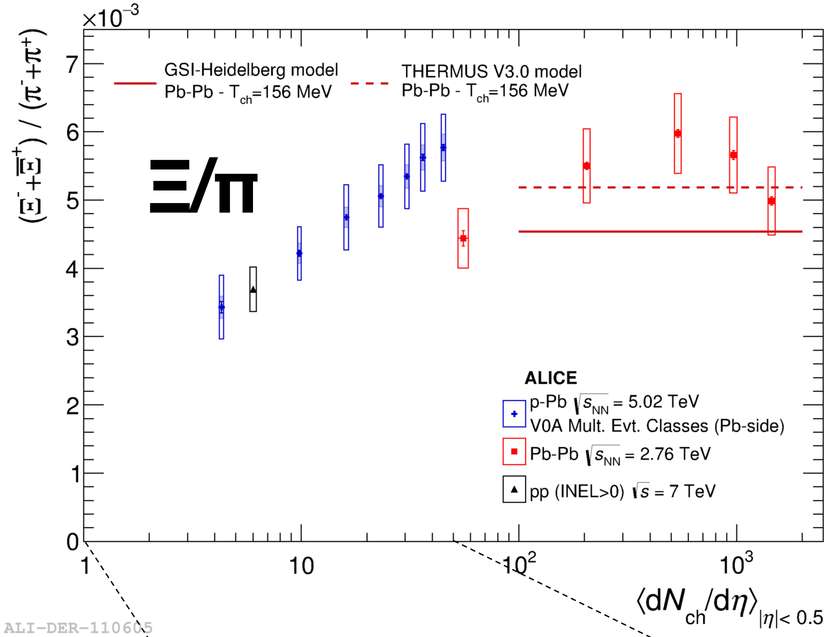
Phys. Lett. B 759 (2016) 389-401
(Ξ and Ω in p-Pb)

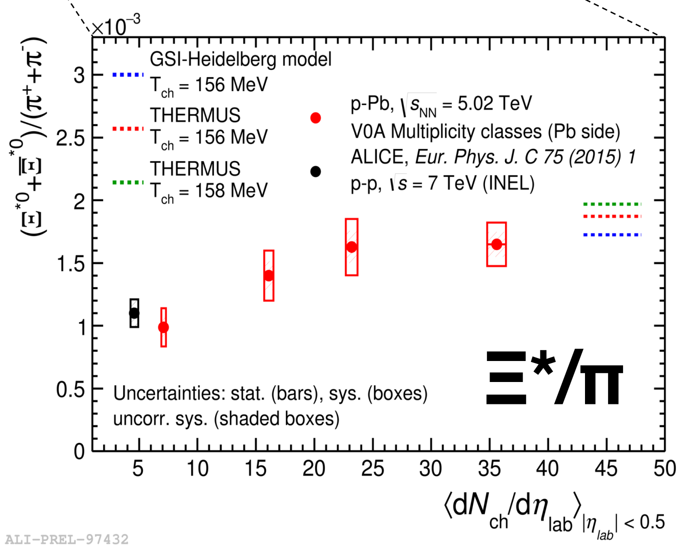
In **p-Pb** collisions

- Ξ/π reaches values seen in Pb-Pb
- Ω/π exhibits a strong rise (~2x) and reaches 60-80% Pb-Pb

Strangeness production in p-Pb

ALICE, PLB 728 (2014) 216
Andronic et al, PLB 673 (2009) 142
Cleymans et al, PRC 74 (2006) 034903





Phys. Lett. B 759 (2016) 389-401
(Ξ and Ω in p-Pb)

In **p-Pb** collisions

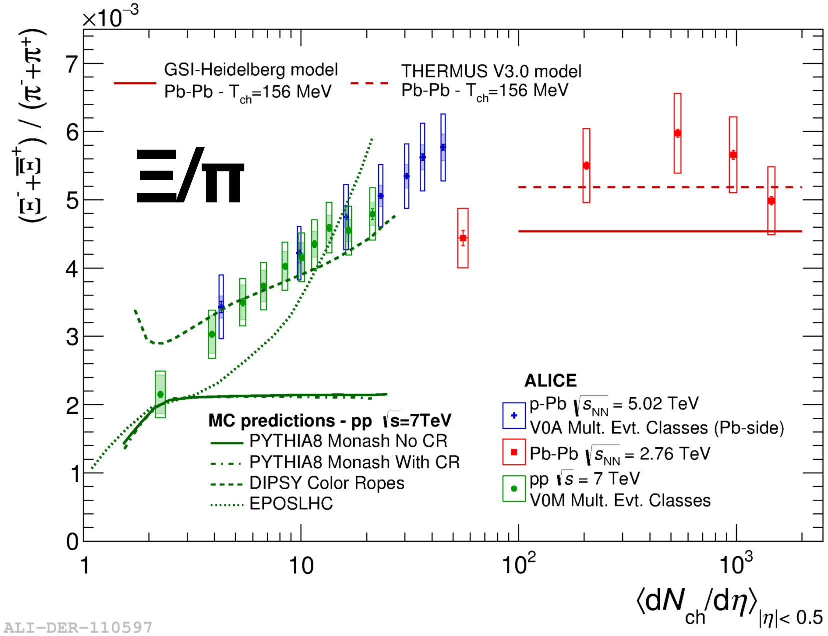
- Ξ/π reaches values seen in Pb-Pb
- Ω/π exhibits a strong rise (~2x) and reaches 60-80% Pb-Pb

$\Xi(1530)^0$ resonance:
- Same strangeness content as Ξ
- Intermediate in mass between Ξ and Ω

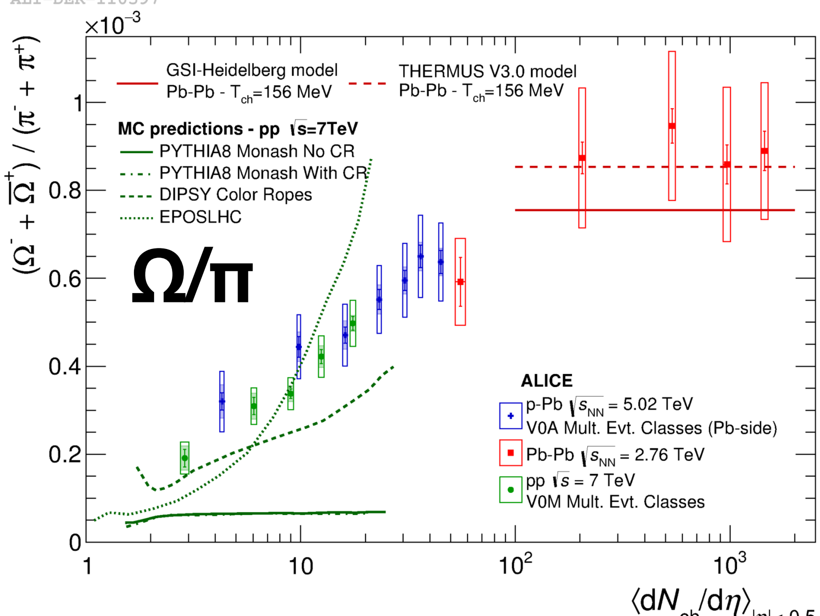
→ Ξ*/π shows an increase compatible with that of Ξ/π
→ Strangeness content more relevant than mass

New results in pp vs multiplicity

C. Bierlich et al., PRD 92 (2015) 094010
T. Pierog et al., arXiv:1306.0121



ALI-DER-110597



ALI-DER-110609

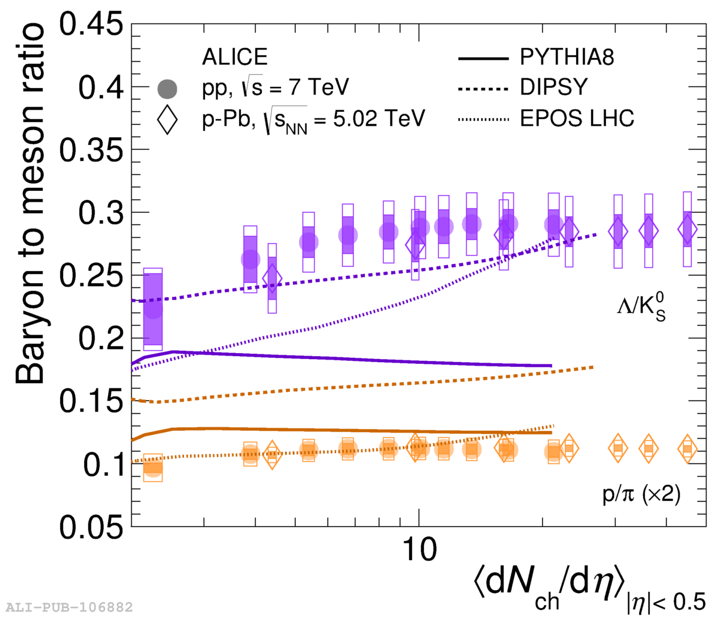
arXiv:1606.07424

Increase of (multi)strange production to non-strange with multiplicity in pp

- Λ/K^0_s and p/π do not increase significantly

→ **Increase** is not mass related but **strangeness related**

- **MC models** as DIPSY (color ropes) and EPOS LHC exhibit a trend with multiplicity but may still need tuning…



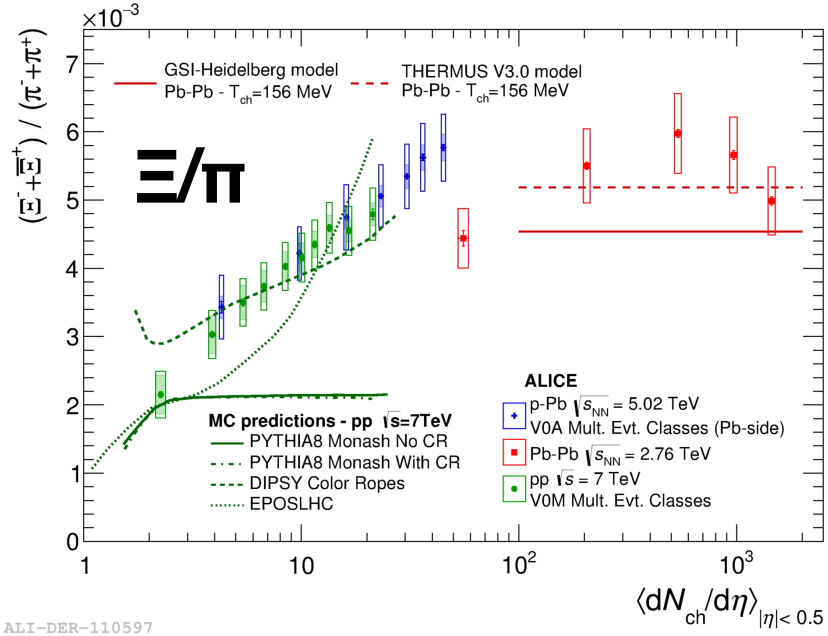
ALI-PUB-106882

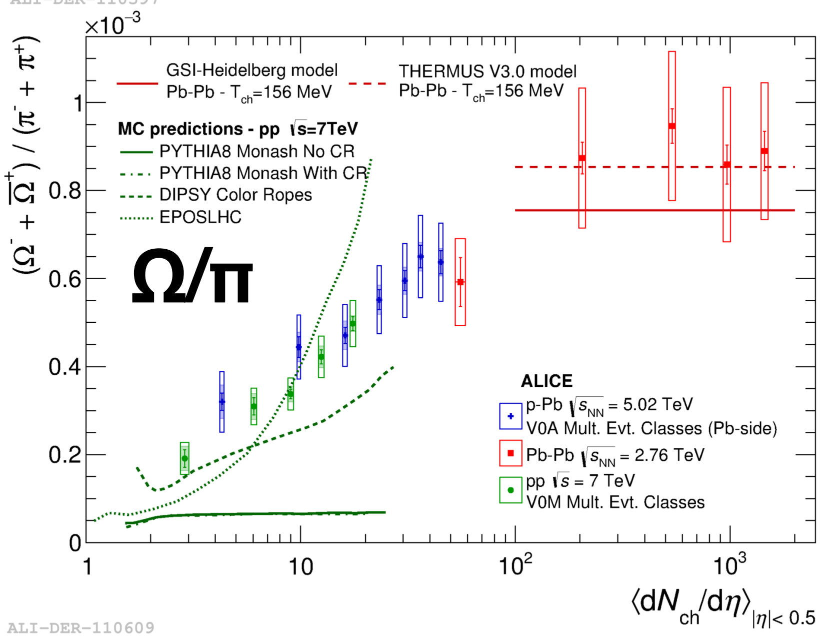
Λ/K^0_s

p/π

New results in pp vs multiplicity

C. Bierlich et al., PRD 92 (2015) 094010
T. Pierog et al., arXiv:1306.0121

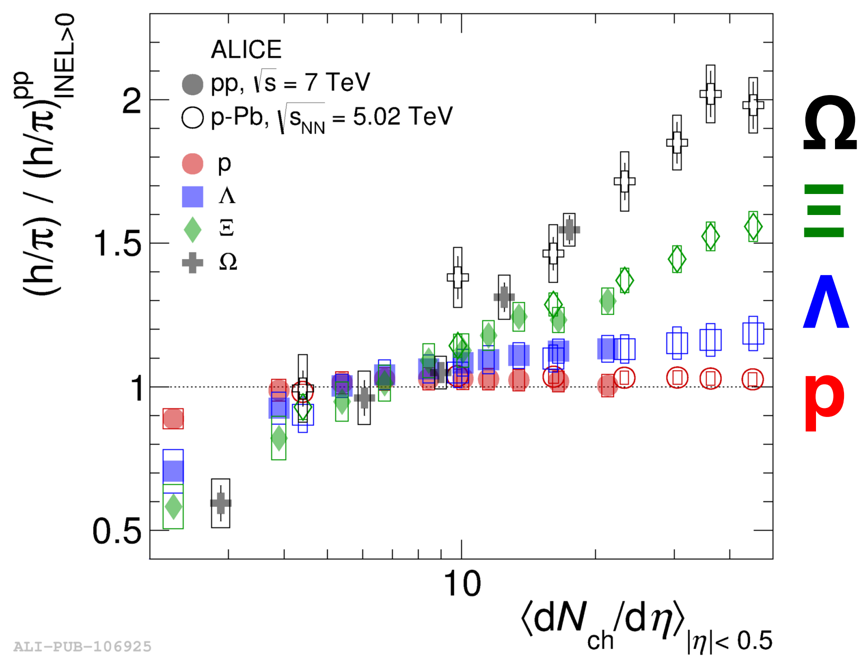




arXiv:1606.07424

Normalised values to INEL>0 show

- No increase for p/π
- **Hierarchy** of the increase clearly associated with the strangeness content



Outlook: pp at $\sqrt{s}$ = 13 TeV

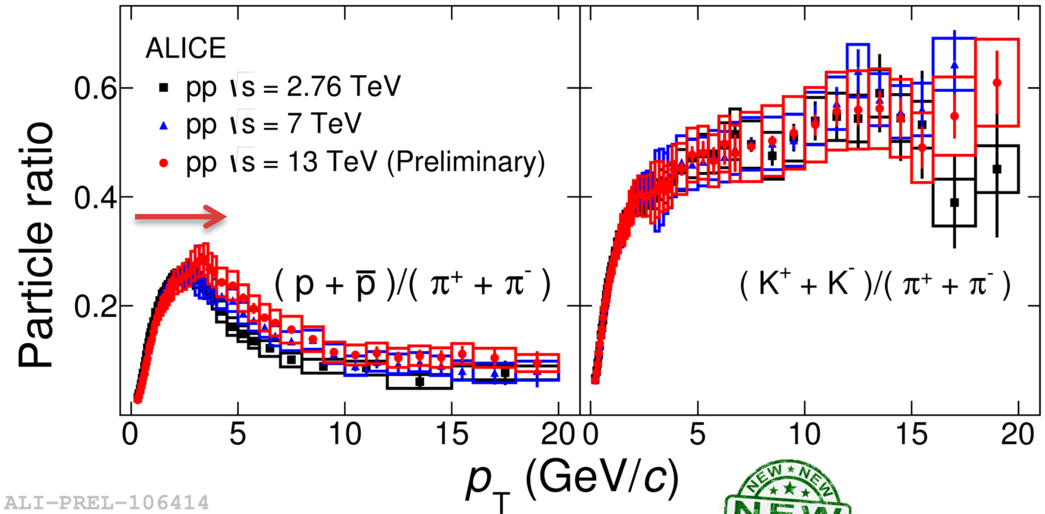
Recent measurements in pp at 13 TeV

$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ increases by ~15% from 7 to 13 TeV

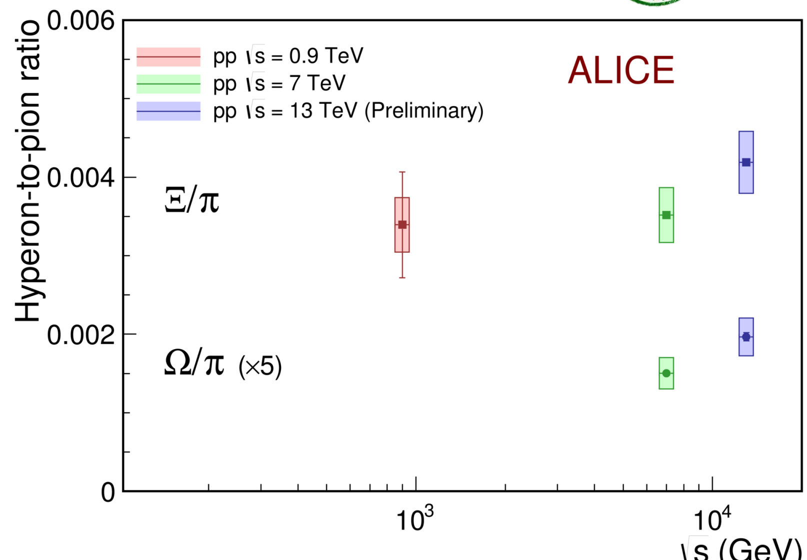
Identified hadron production:

- shift of the maximum of **p/π** ratio towards higher p_T with energy
- No significant evolution with energy for K/π and integrated K*/K, ϕ/K
- hint for increase of **hyperon-to-pion** ratios in min. bias collisions

→ disentangle multiplicity and energy dependence of spectral shapes and hard-scattering contribution

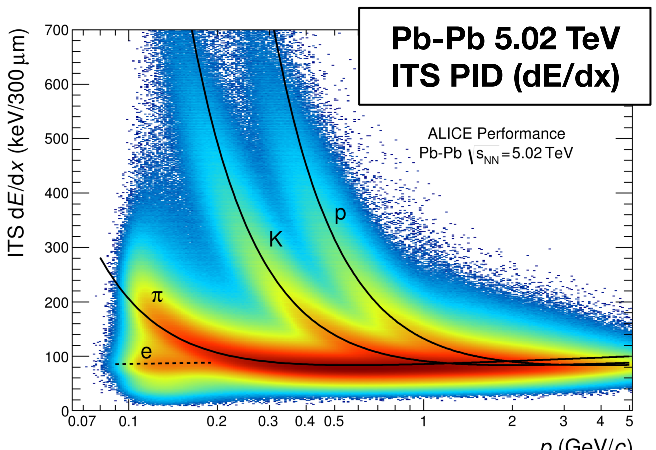


ALI-PREL-106414

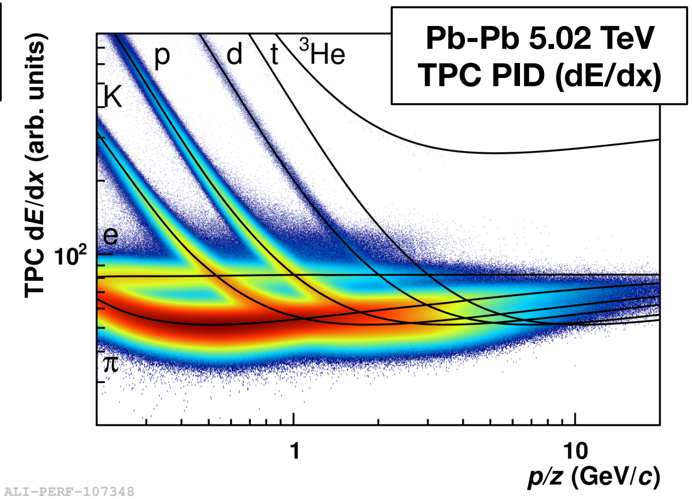


ALI-PREL-107393

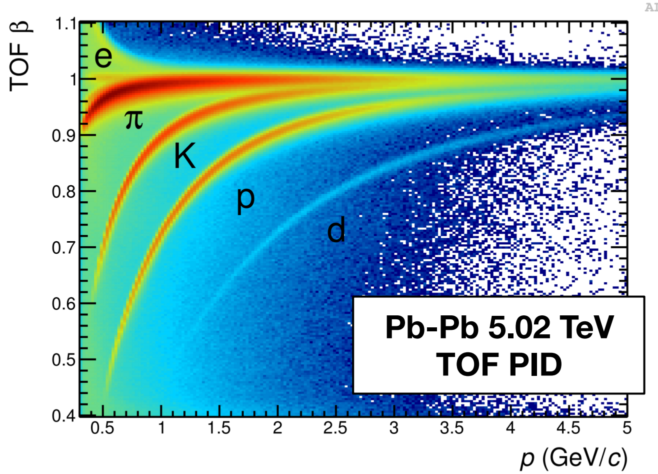
Outlook: PID in Pb-Pb at 5.02 TeV



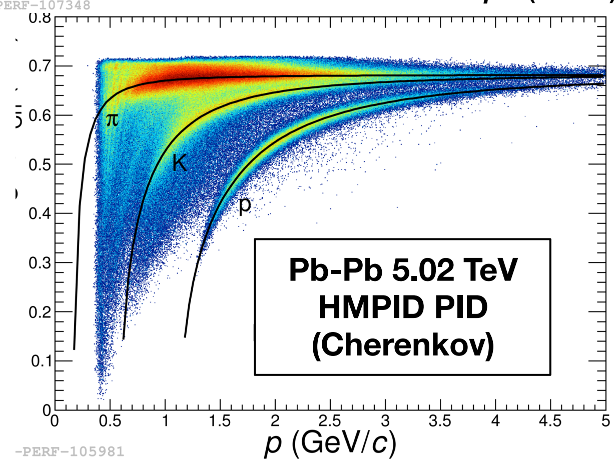
ALI-PERF-107385



ALI-PERF-107348



ALI-PERF-106336

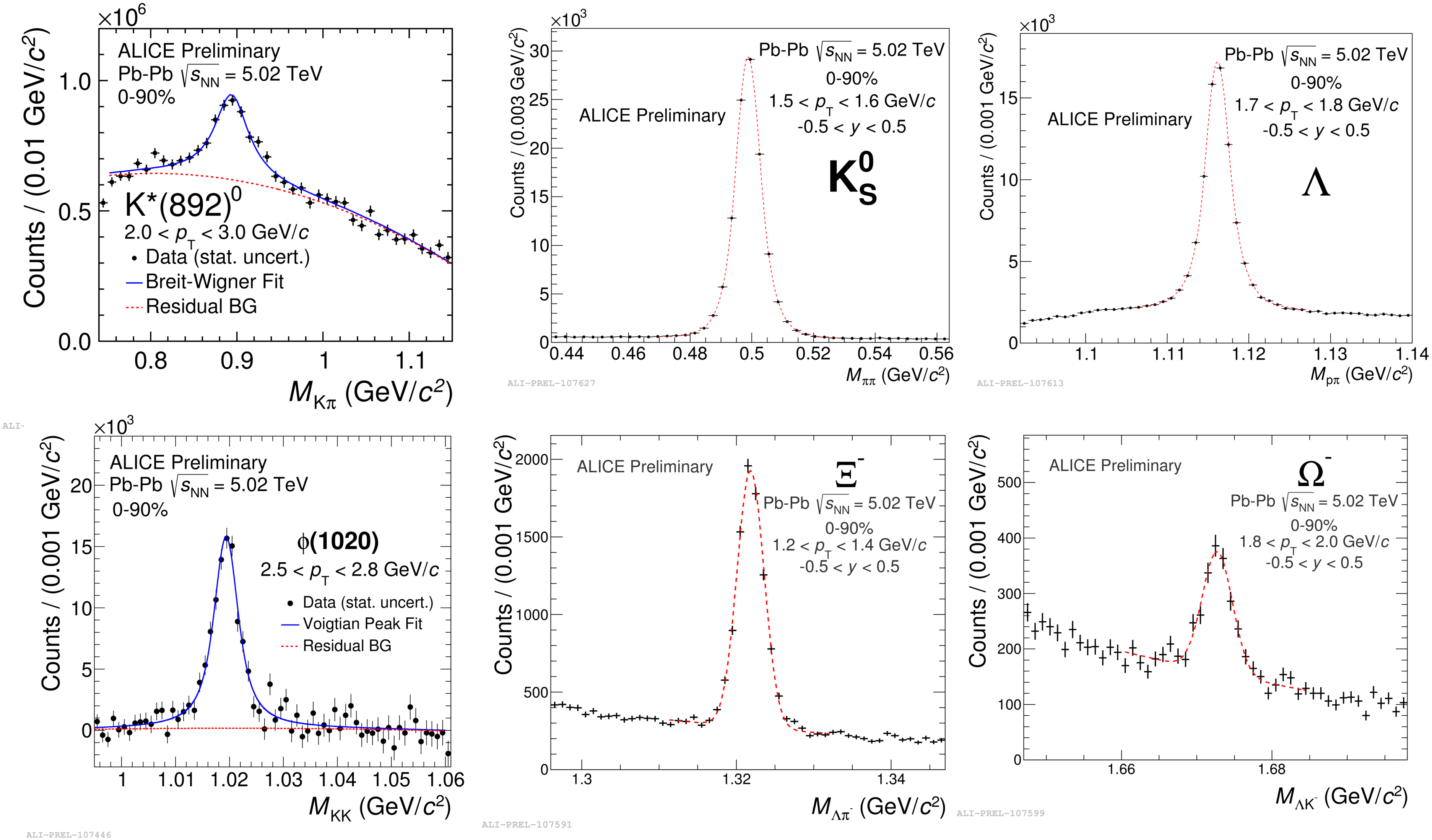


-PERF-105981

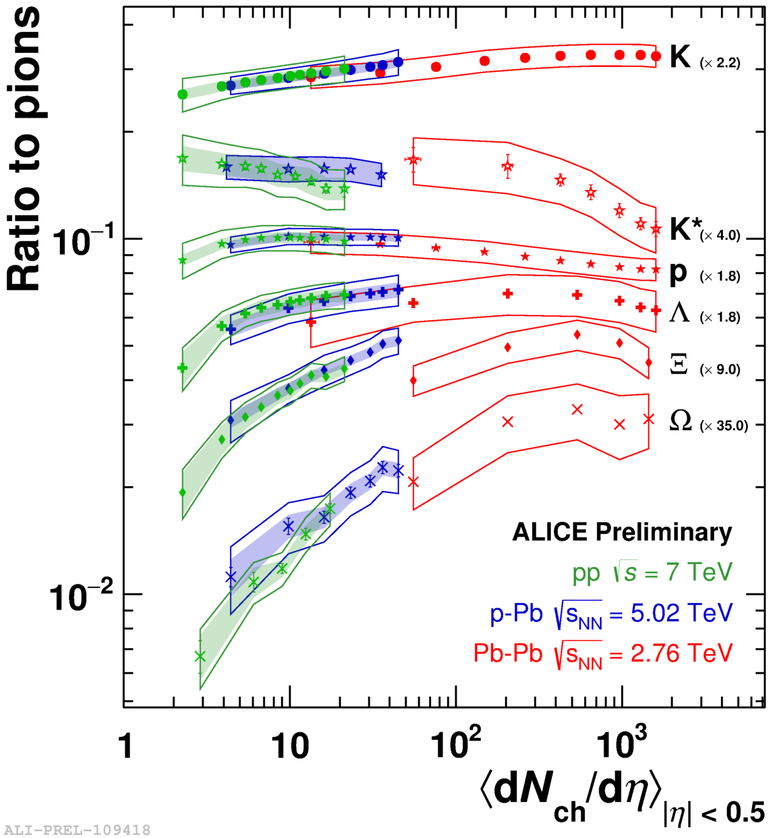
Analysis shown corresponding to ~3M Pb-Pb events at $\sqrt{s_{NN}}$ = 5.02 TeV, about 3% of the recorded statistics

Very **promising PID performance** in Run II

Outlook: (multi)strange particles in Pb-Pb at 5.02 TeV



Summary



ALICE measurements of identified particle production in pp, p-Pb, Pb-Pb collisions have revealed interesting and **similar features across different systems**

- Collectivity in small systems? What origin (radial flow, color reconnection, …)?

Enhancement of strangeness production observed towards **high-multiplicity pp** events at $\sqrt{s}$ = 7 TeV

- not described by the currently available QCD inspired MC generators
- What will happen at higher multiplicities

More details in the parallel talks…

...and yet more to come from the Run II data!

D. Colella, Today 28/6, 14:40

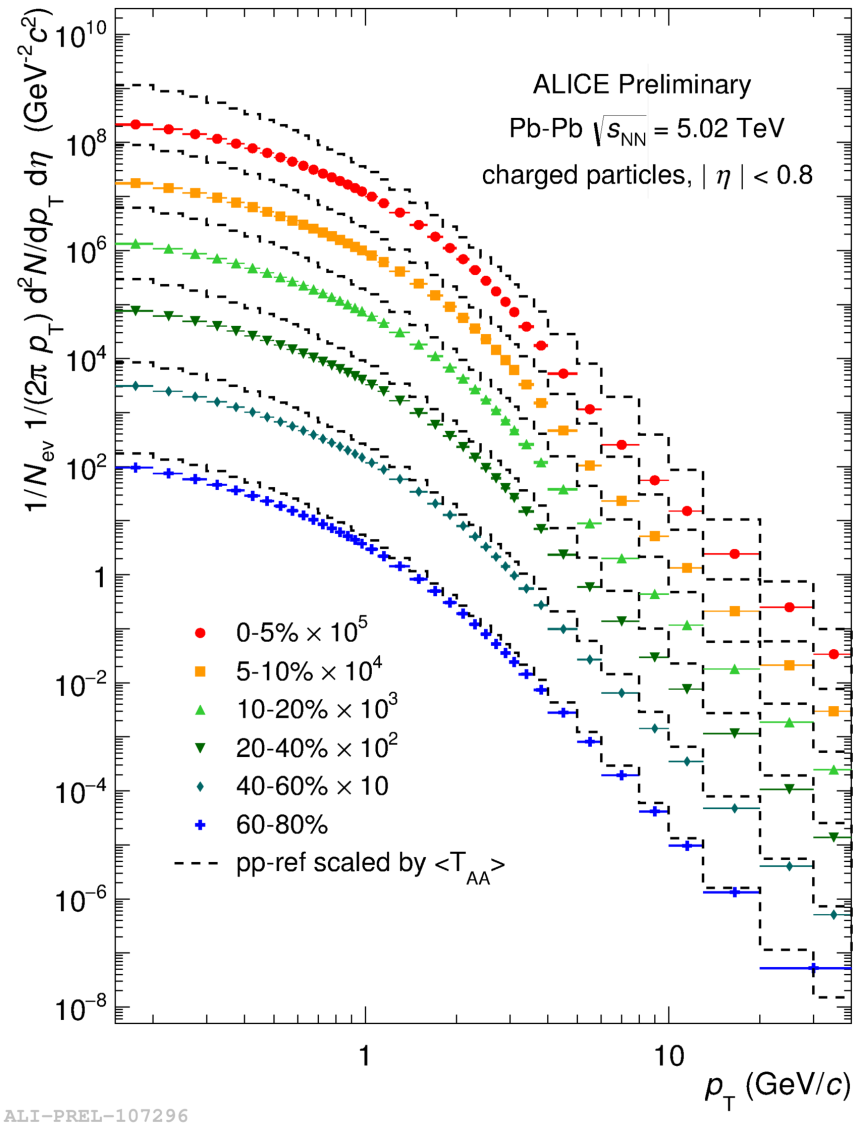
A. Knospe, Today 28/6, 16:00

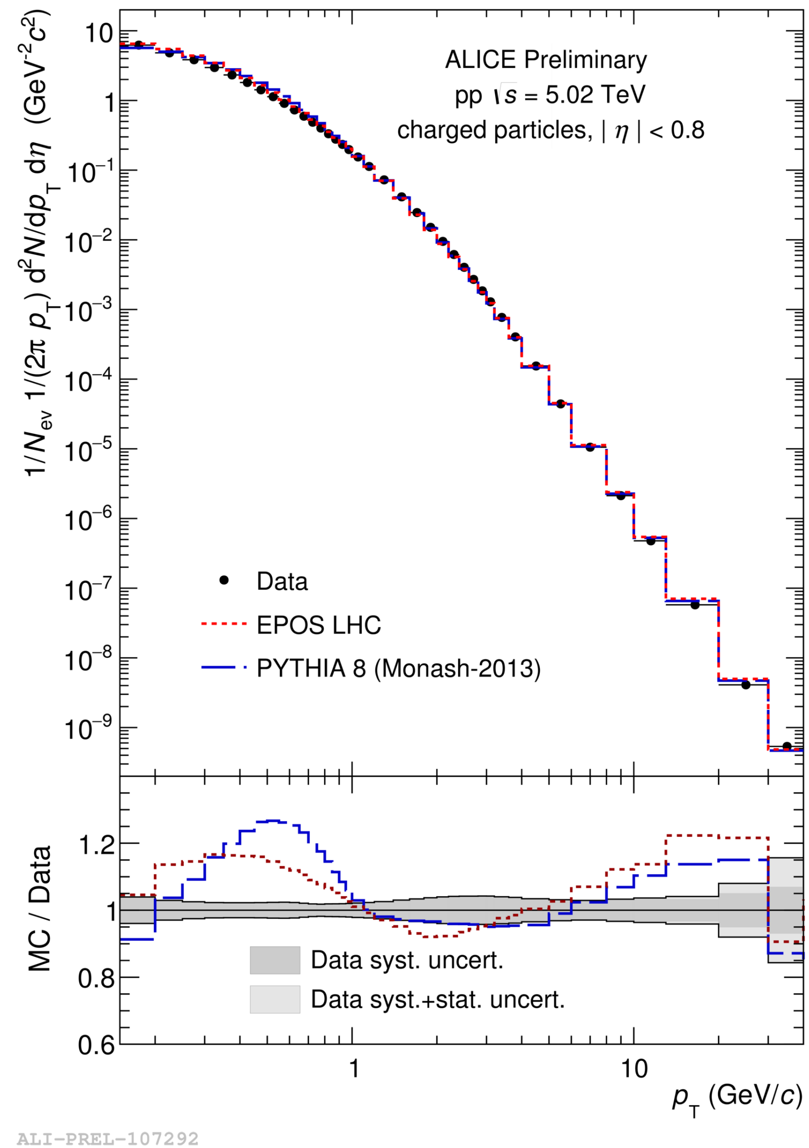
R. Derradi, Today 28/6, 16:40

B. Doenigus, Thu. 30/6, 09:20

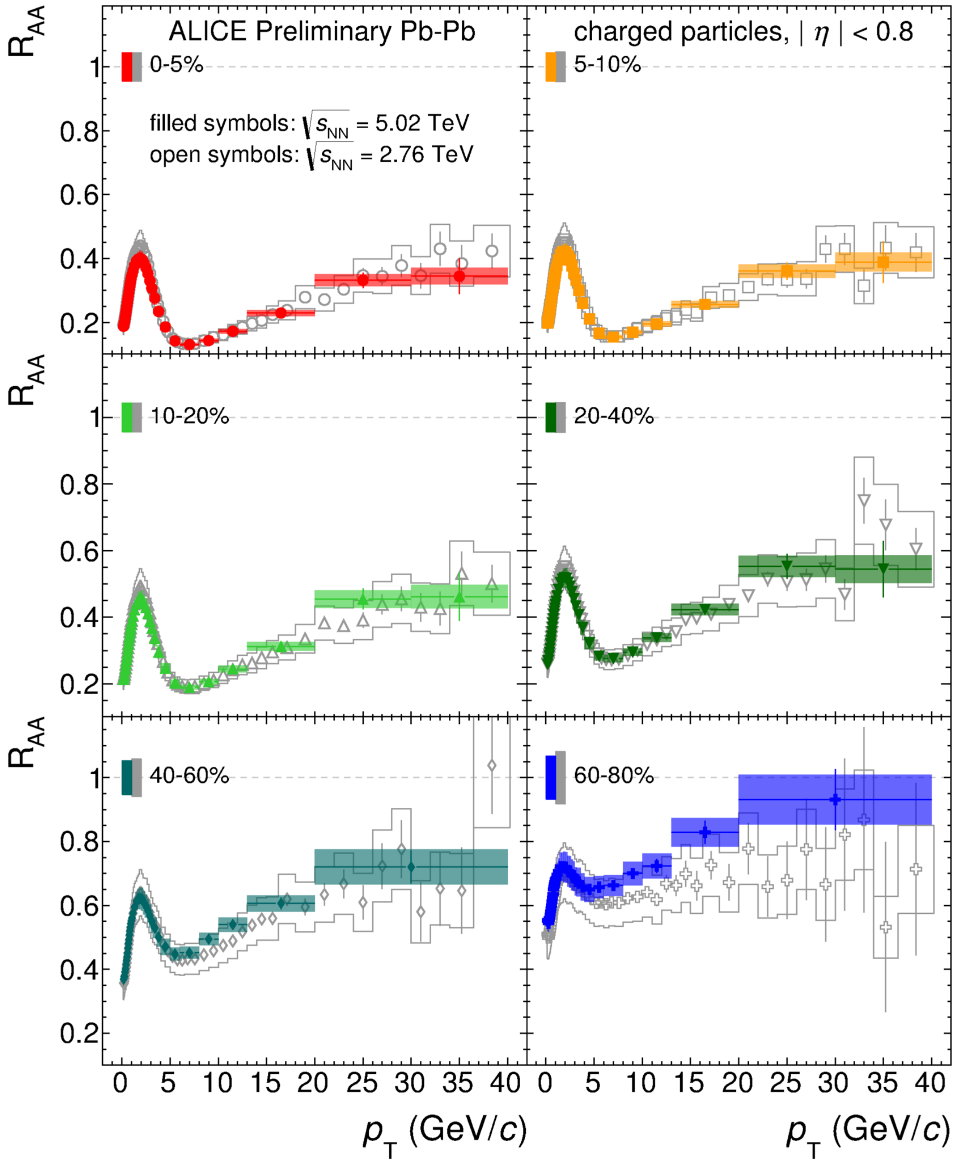
Additional slides

Charged particles spectra in Pb-Pb, pp at 5.02 TeV





R_{AA} in Pb-Pb at 5.02 TeV



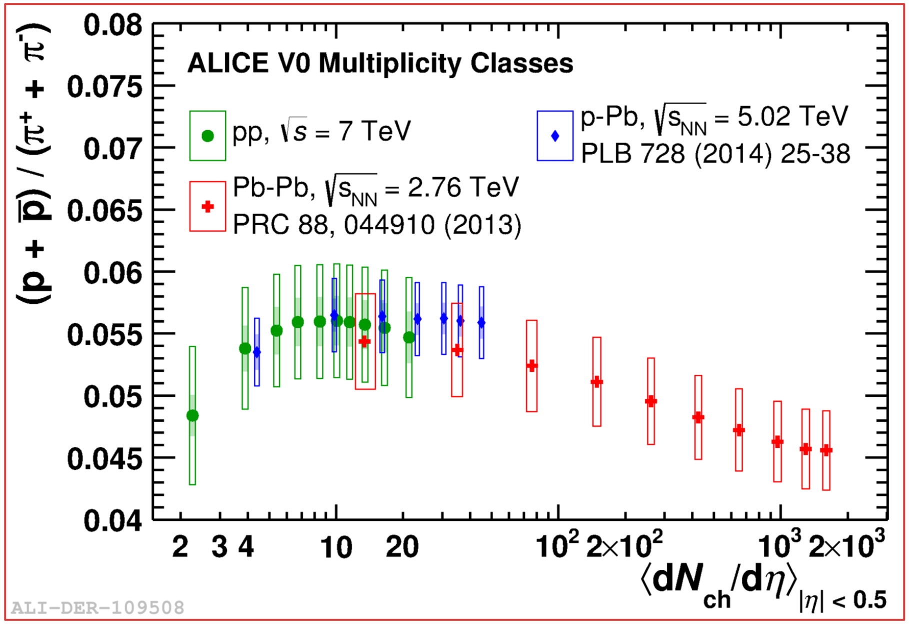
ALI-PREL-107300

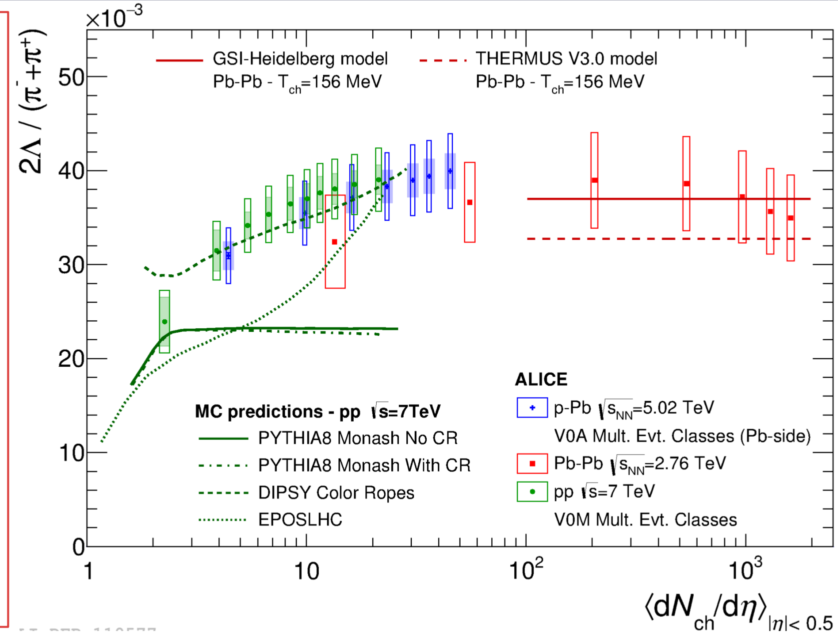
New measurement of nuclear modification factor of inclusive charged particles as a function of centrality

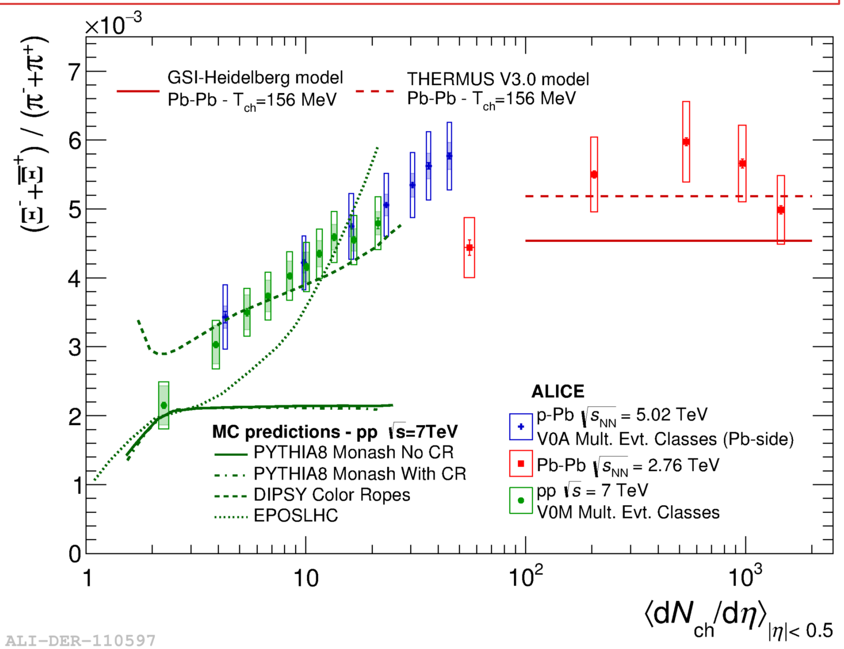
- Improved systematics wrt previous 2.76 TeV measurement

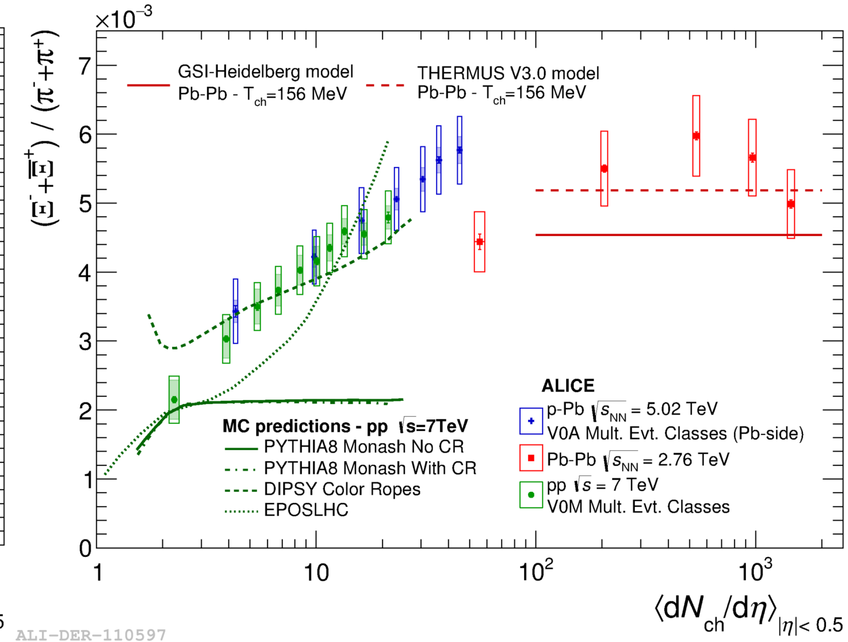
- R_{AA} compatible with 2.76 TeV
- hotter/denser medium?

Strange and multi-strange vs multiplicity

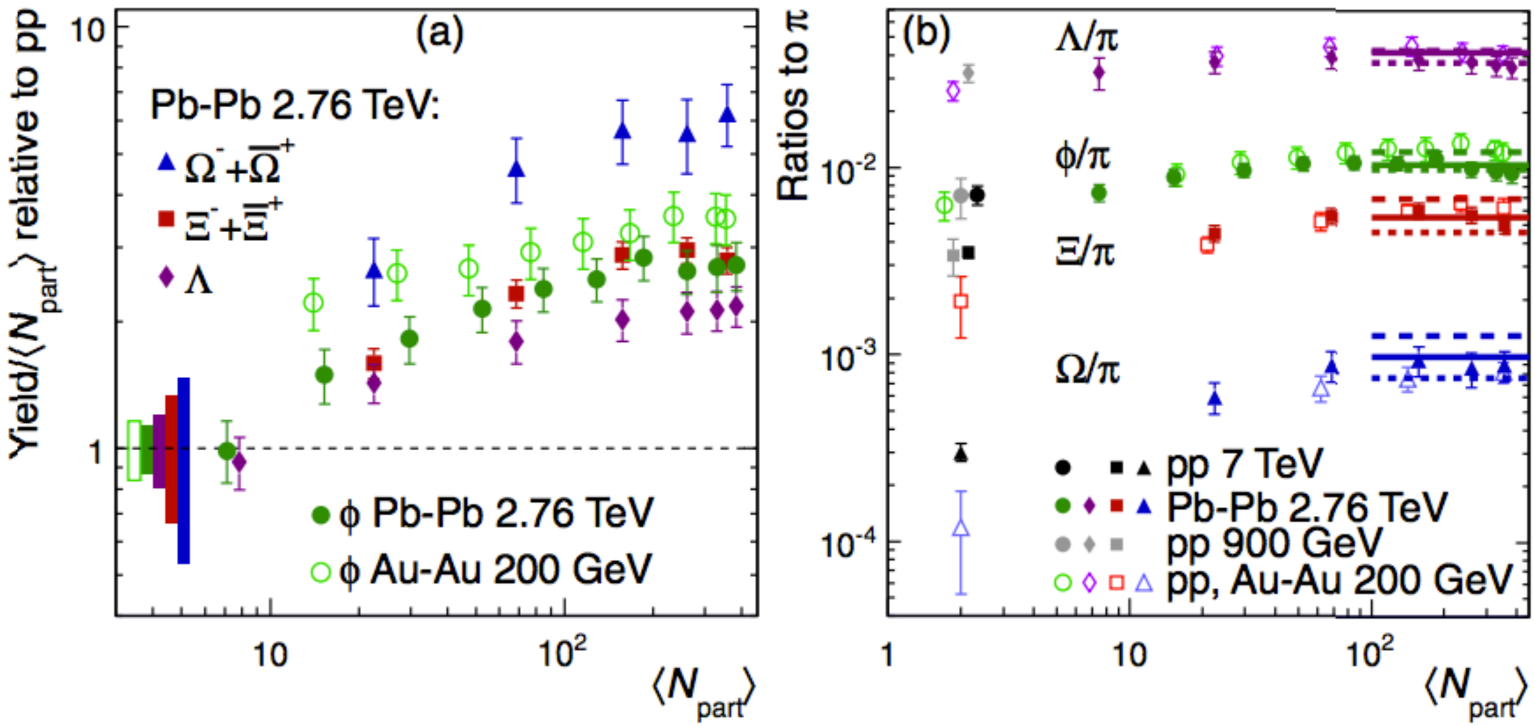








Strangeness enhancement in Pb-Pb: ϕ/π



E(S=1) <
E(S=0)~
E(S=2) <
E(S=3)

Charged particle multiplicity in Pb-Pb, p-Pb

Definition of the event classes as fractions of the analyzed event sample and their corresponding $\langle dN_{ch}/d\eta \rangle$ within $|\eta_{lab}| < 0.5$ (systematic uncertainties only, statistical uncertainties are negligible).

p-Pb

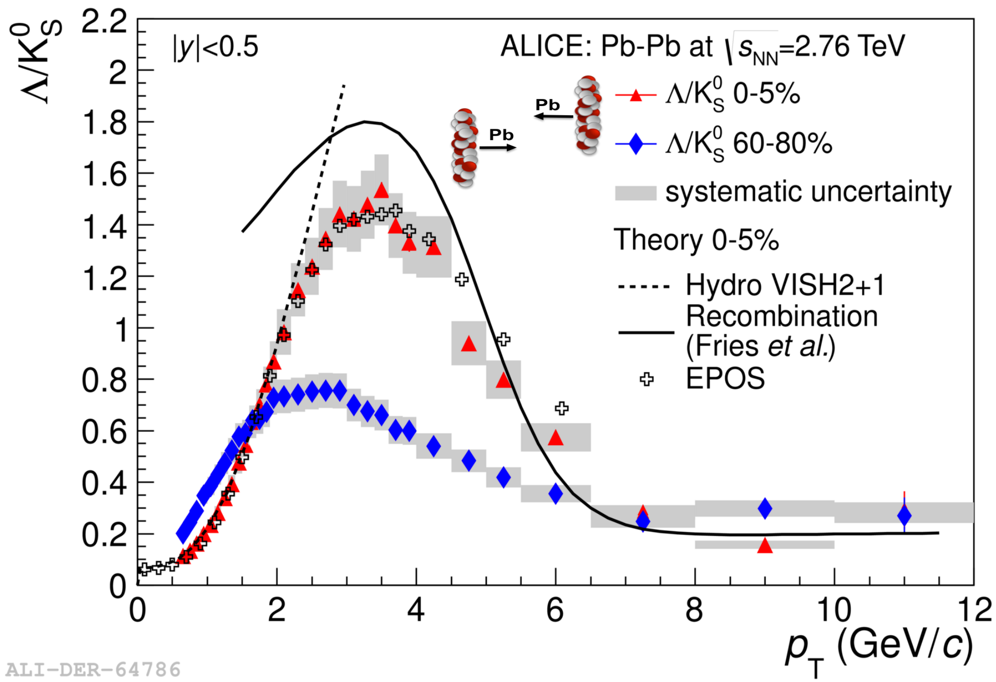
Event class	V0A range (arb. unit)	$\langle dN_{ch}/d\eta \rangle$ $|\eta_{lab}| < 0.5$
0–5%	>227	45 ± 1
5–10%	187–227	36.2 ± 0.8
10–20%	142–187	30.5 ± 0.7
20–40%	89–142	23.2 ± 0.5
40–60%	52–89	16.1 ± 0.4
60–80%	22–52	9.8 ± 0.2
80–100%	<22	4.4 ± 0.1

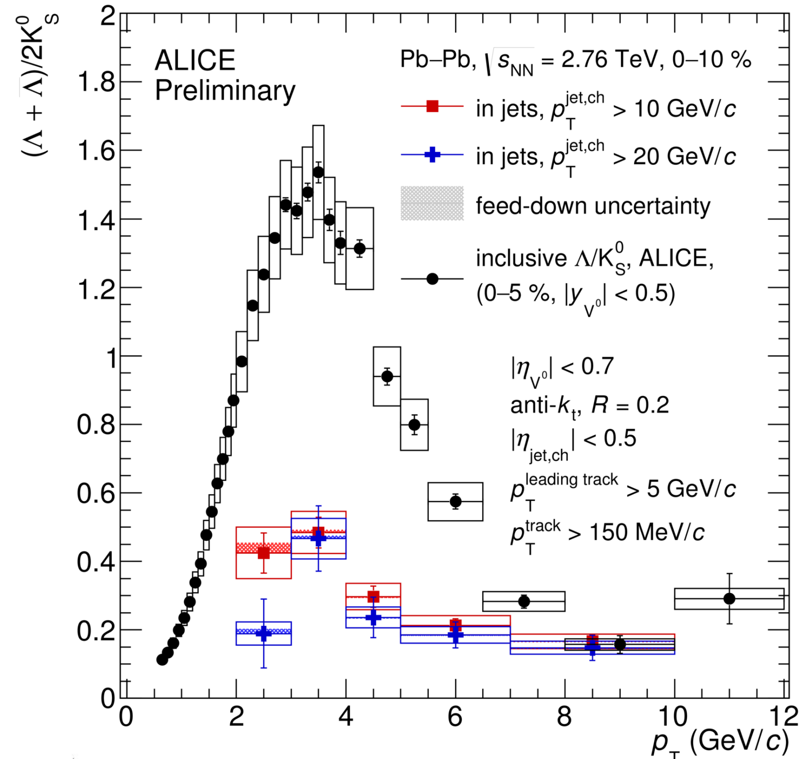
TABLE I. $dN_{ch}/d\eta$ and $(dN_{ch}/d\eta)/(\langle N_{part}\rangle/2)$ values measured in $|\eta| < 0.5$ for nine centrality classes. The $\langle N_{part}\rangle$ obtained with the Glauber model are given.

Pb-Pb

Centrality	$dN_{ch}/d\eta$	$\langle N_{part}\rangle$	$(dN_{ch}/d\eta)/(\langle N_{part}\rangle/2)$
0%–5%	1601 ± 60	382.8 ± 3.1	8.4 ± 0.3
5%–10%	1294 ± 49	329.7 ± 4.6	7.9 ± 0.3
10%–20%	966 ± 37	260.5 ± 4.4	7.4 ± 0.3
20%–30%	649 ± 23	186.4 ± 3.9	7.0 ± 0.3
30%–40%	426 ± 15	128.9 ± 3.3	6.6 ± 0.3
40%–50%	261 ± 9	85.0 ± 2.6	6.1 ± 0.3
50%–60%	149 ± 6	52.8 ± 2.0	5.7 ± 0.3
60%–70%	76 ± 4	30.0 ± 1.3	5.1 ± 0.3
70%–80%	35 ± 2	15.8 ± 0.6	4.4 ± 0.4

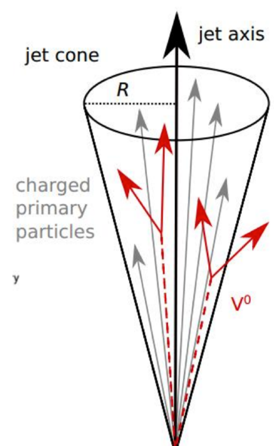
Baryon-to-meson ratio: Λ/K^0_s





B/M enhancement at intermediate p_T

- **Hydrodynamics** describes only the rise < 2 GeV/*c*
- **Recombination** reproduces effect but overestimates
- **EPOS** gives good description of the data (with **flow**)



B/M in jets significantly lower than inclusive ratio
→ **baryon anomaly is not a jet effect**, but arises from the bulk