# Overview of recent ALICE results

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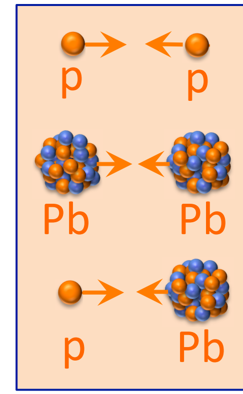
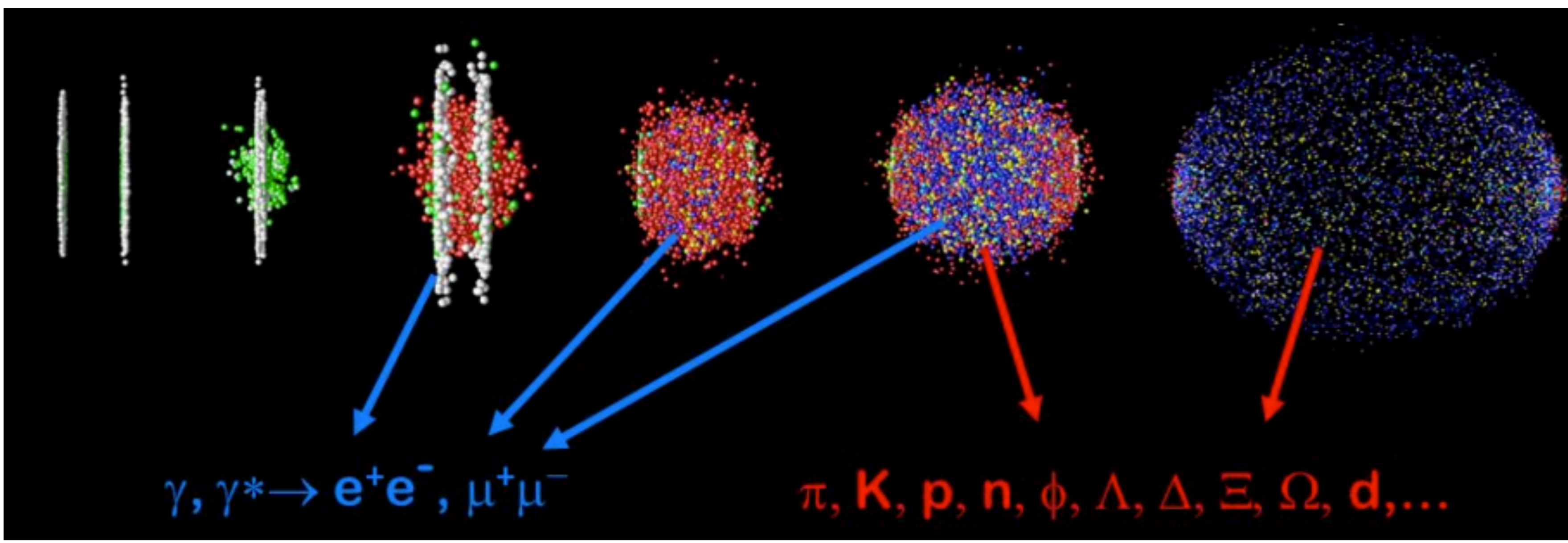
# Outline

ALICE is the only dedicated heavy-ion experiment at the LHC.

Highlights of recent results from the ALICE collaboration are presented.
The collision systems investigated are **pp**, **Pb–Pb** and **p–Pb**.

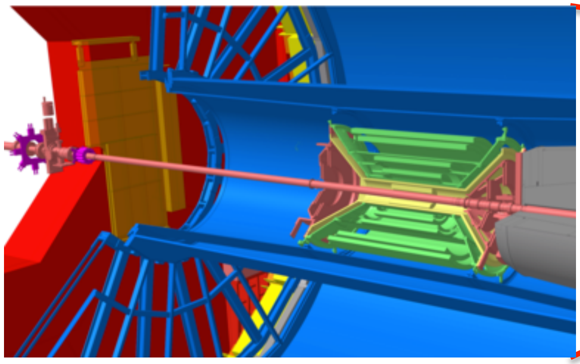


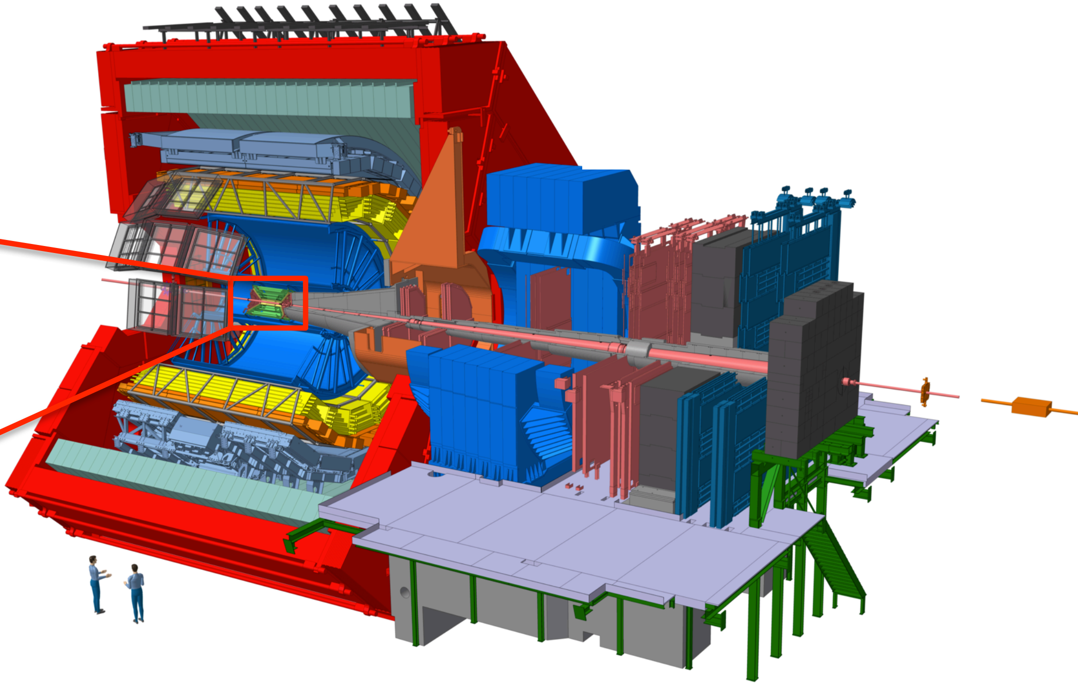

- bulk particle production
- azimuthal correlations
- collectivity in small systems?
- open and hidden heavy flavor



# ALICE detector

**Inner Tracking System (ITS)**
**$-0.9<\eta<0.9$**
tracking + triggering +
particle identification (PID)





# ALICE detector

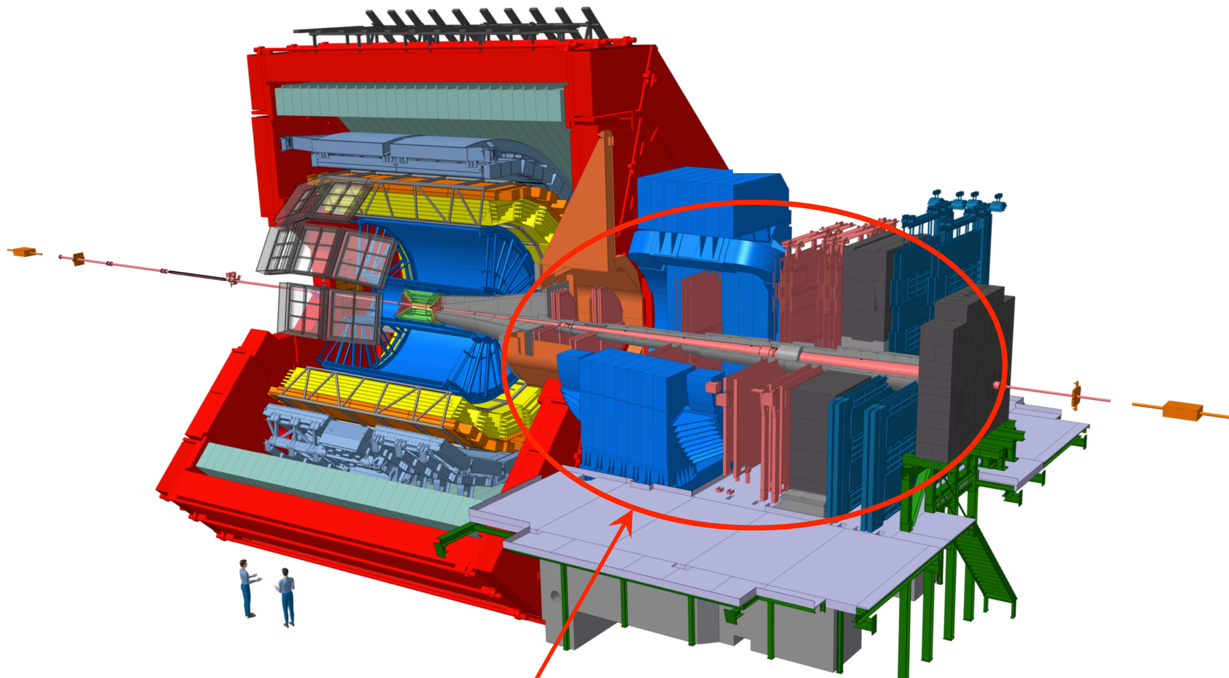
**Inner Tracking System (ITS)**
**$-0.9<\eta<0.9$**
tracking + triggering +
particle identification (PID)

**Time Projection Chamber (TPC)**
**$-0.8<\eta<0.8$**
tracking + PID

**Time Of Flight (TOF)**
**$-0.8<\eta<0.8$**
PID

**VZERO detector**
two forward scintillator arrays
**$-3.7<\eta<-1.7$,  $2.8<\eta<5.1$**
**centrality** + triggering

**Zero-Degree Calorimeters**
centrality + triggering



**Muon spectrometer**
**$-4<\eta<-2.5$**

# ALICE data harvest

**Run 1 (2009-2013)**

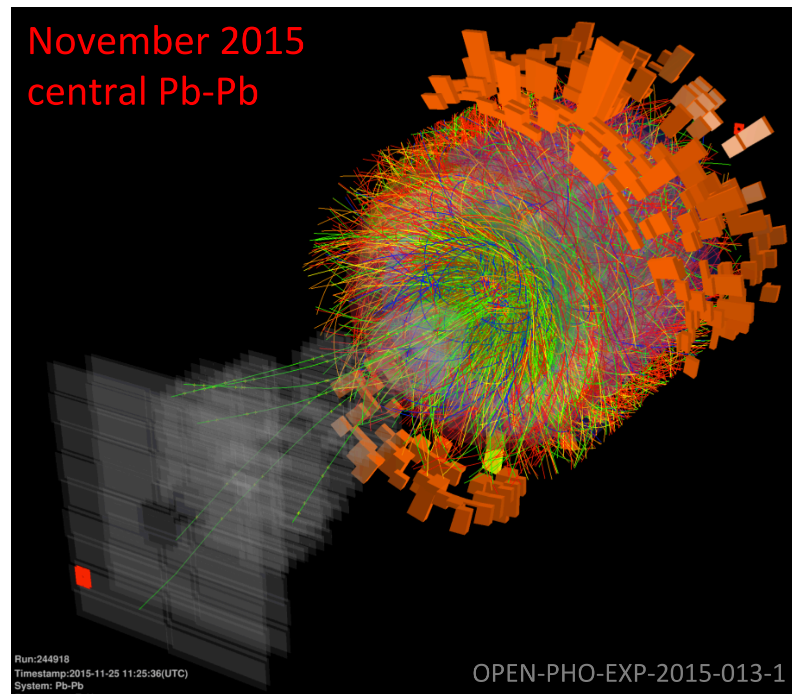
| System | Energy |
|---|---|
| **pp** | 0.9, 2.76, 7, 8 TeV |
| **p-Pb** | 5.02 TeV |
| **Pb-Pb** | 2.76 TeV |

**Run 2 (2015-now)**

| System | Energy |
|---|---|
| **pp** | 5.02, **13 TeV** |
| **p-Pb** | 5.02, **8.16 TeV** |
| **Pb-Pb** | **5.02 TeV** |

data taking at the end of 2015, ~130 million events

- minimum bias triggers
- rare triggers (muons, EMCAL, PHOS, etc.)

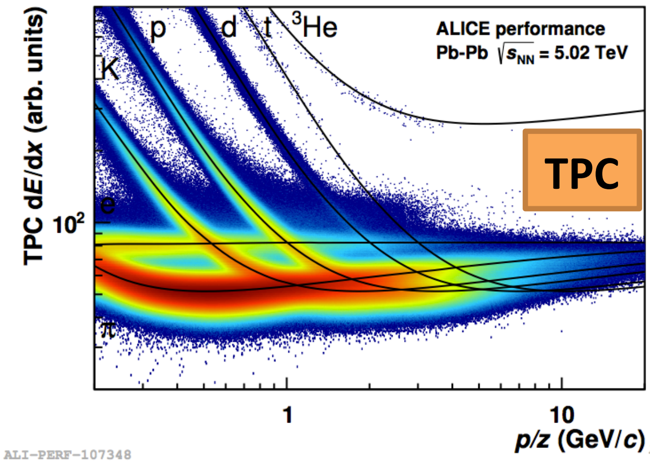


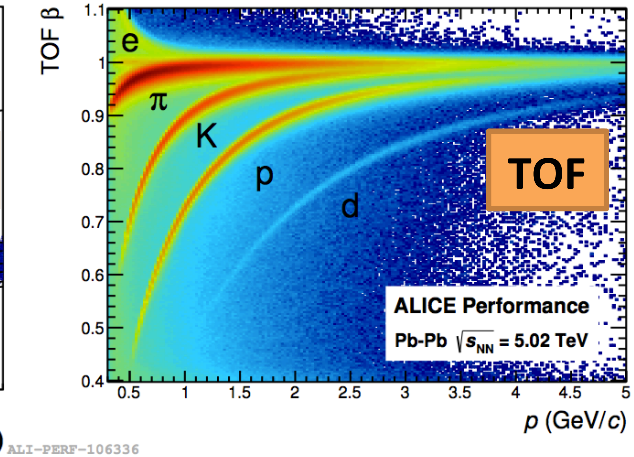
# Particle identification in ALICE

Multiple PID techniques

**TPC**
» d*E*/dx in gas ($Ar-CO_2$)

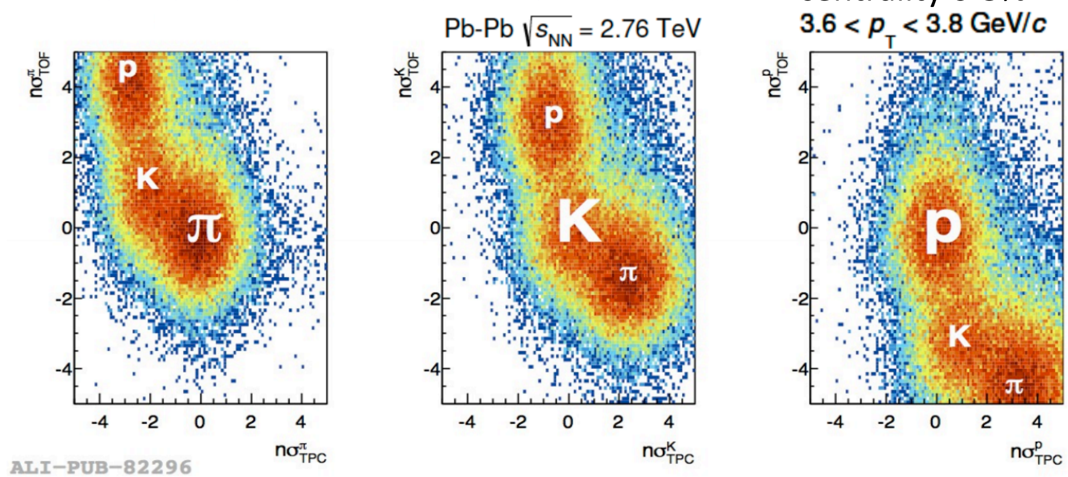
**TOF**
» time-of-flight ($\sigma_{TOF}$ ~ 80 ps)




**Combined TPC+TOF information:**

centrality 0-5%




**π** hypothesis **K** hypothesis **p** hypothesis

# Particle identification in ALICE

Multiple PID techniques

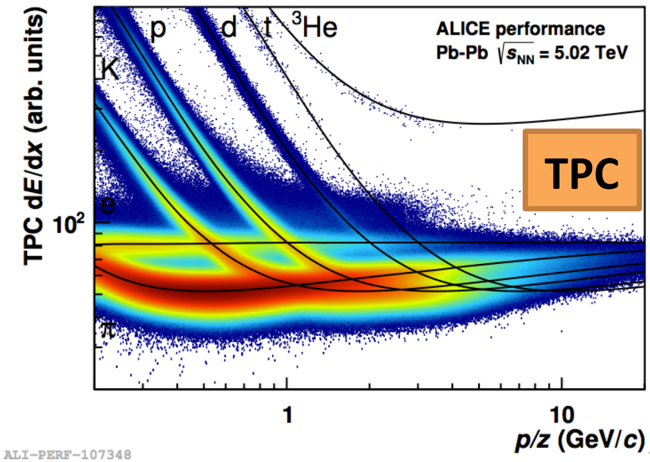
**TPC**
» d*E*/dx in gas ($Ar{-}CO_2$)

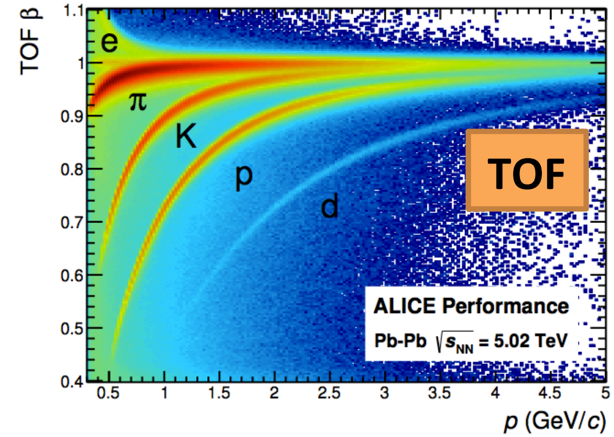
**TOF**
» time-of-flight ($\sigma_{TOF}$ ~ 80 ps)

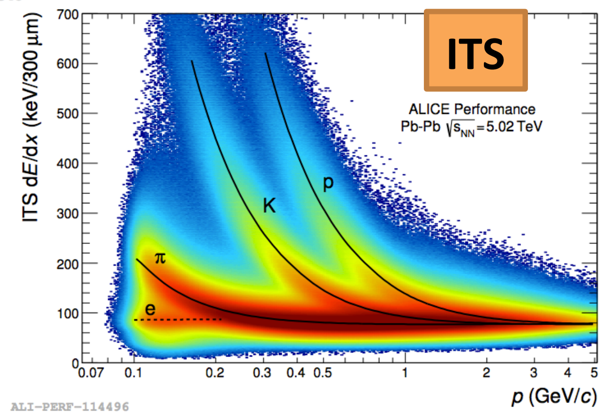
**ITS**
» d*E*/dx in 4 layers
with analogue readout
» low-mass tracker ~ 10% of $X_0$

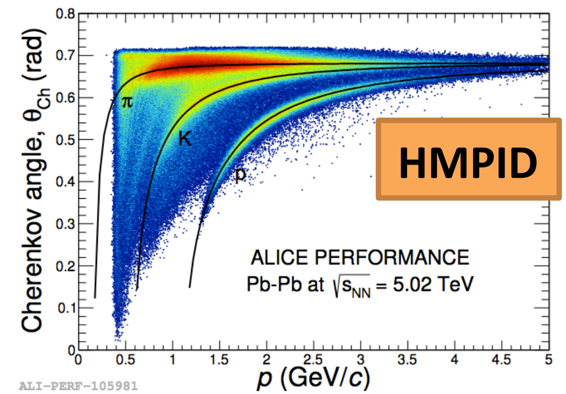
**TRD**
» transition radiation

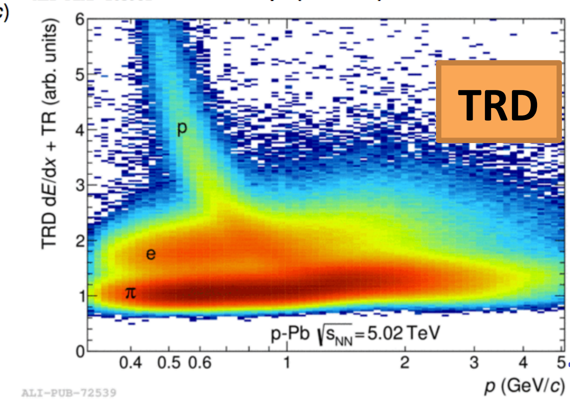
**HMPID**
» Cherenkov angle measurement



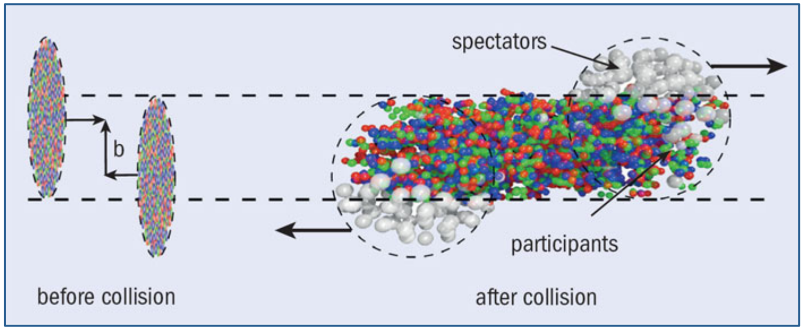




- efficient low-momentum tracking – down to ~ 100 MeV/*c*

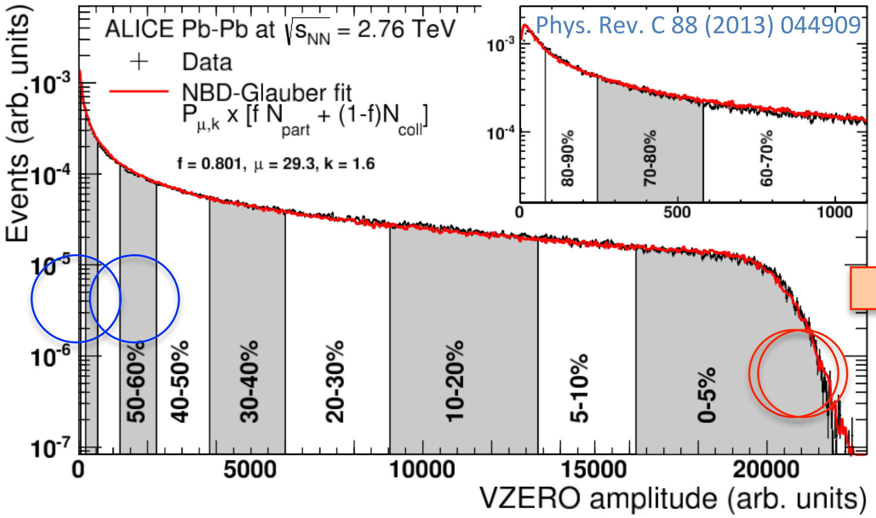
**Int.J.Mod.Phys. A29 (2014) 1430044**

Centrality – a key parameter in the study of QCD matter at extreme energy densities, directly related to the initial overlap region of the colliding nuclei.




*In ALICE: use multiplicity distribution in*
**VZERO detector + Glauber model**

| VZERO-C | TPC | VZERO-A |
|---|---|---|
| $-3.7 < \eta < -1.7$ | $\lvert\eta\rvert < 0.8$ | $2.8 < \eta < 5.1$ |



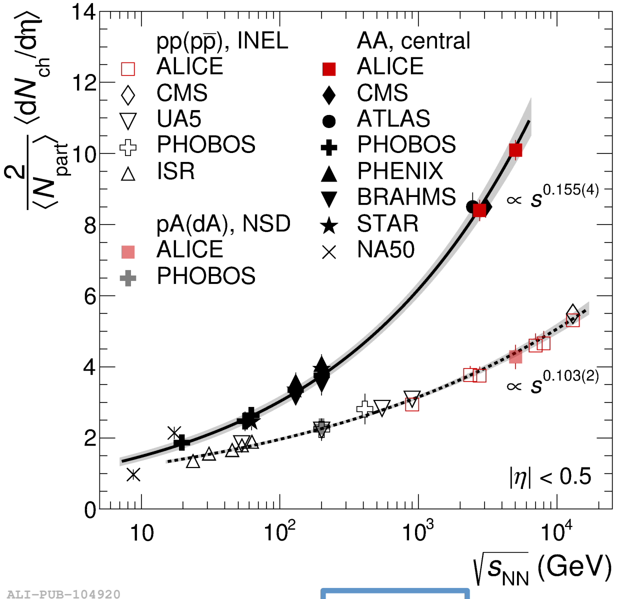

close to **0%** → most **central** events
closer to **100%** → **peripheral** events

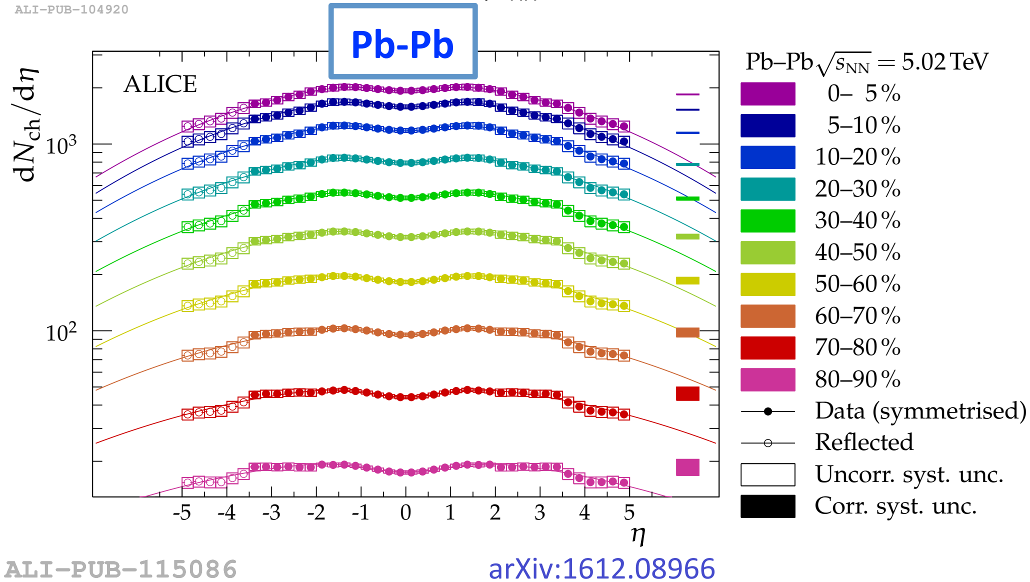
# Let's go to… bread and butter

# Charged particle density

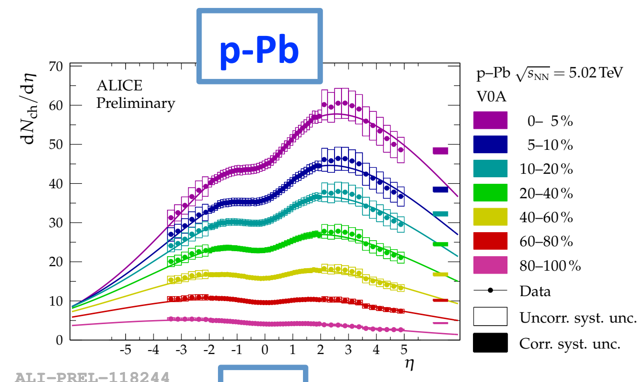
Phys. Rev. Lett. 116, (2016) 222302

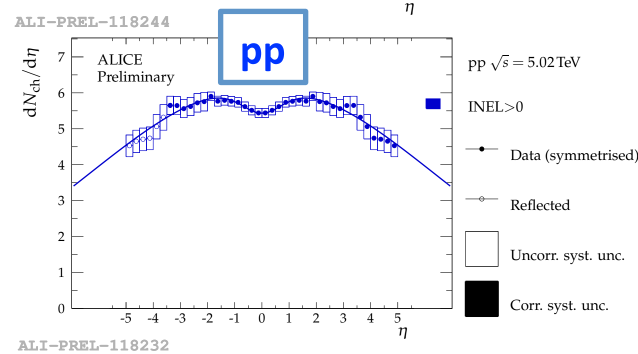
- ⟨$dN_{ch}/d\eta$⟩ at 5.02 TeV:
  increase of ~ 20% with respect to 2.76 TeV
- follows trends expected from lower energies
- pseudorapidity density is measured over a wide η range for 3 systems




arXiv:1612.08966



# Nuclear Modification Factors at $\sqrt{s_{NN}}$=5.02 TeV

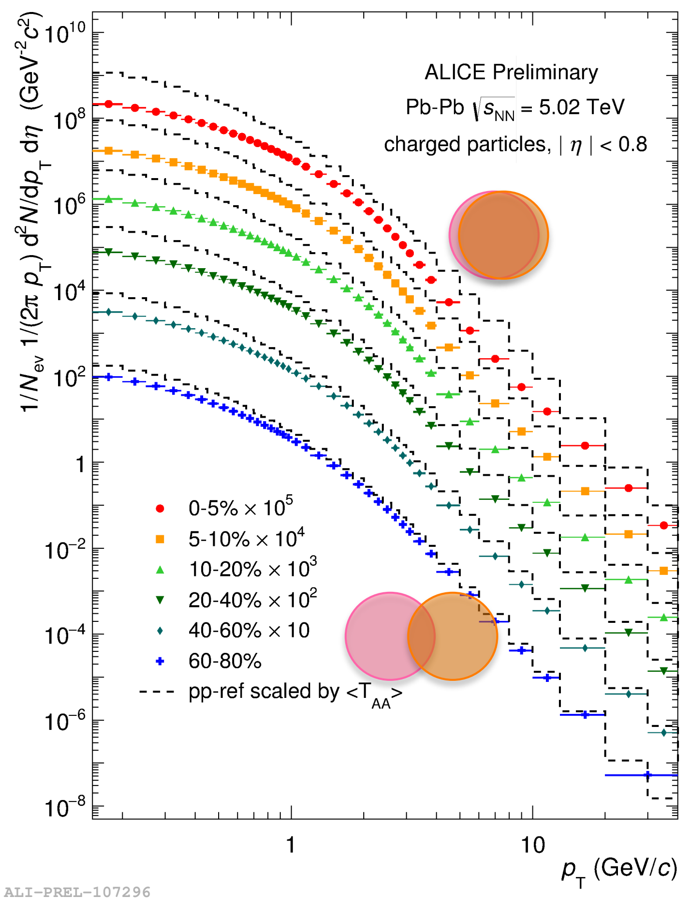
Pb Pb

ALICE

***Unidentified** particle spectra:*

*Nuclear modification factor:* $R_{AA}(p_T) = \frac{d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle T_{AA}\rangle d^2\sigma_{ch}^{pp}/d\eta\, dp_T}$

**$R_{AA}$ < 1 indicates parton energy loss**



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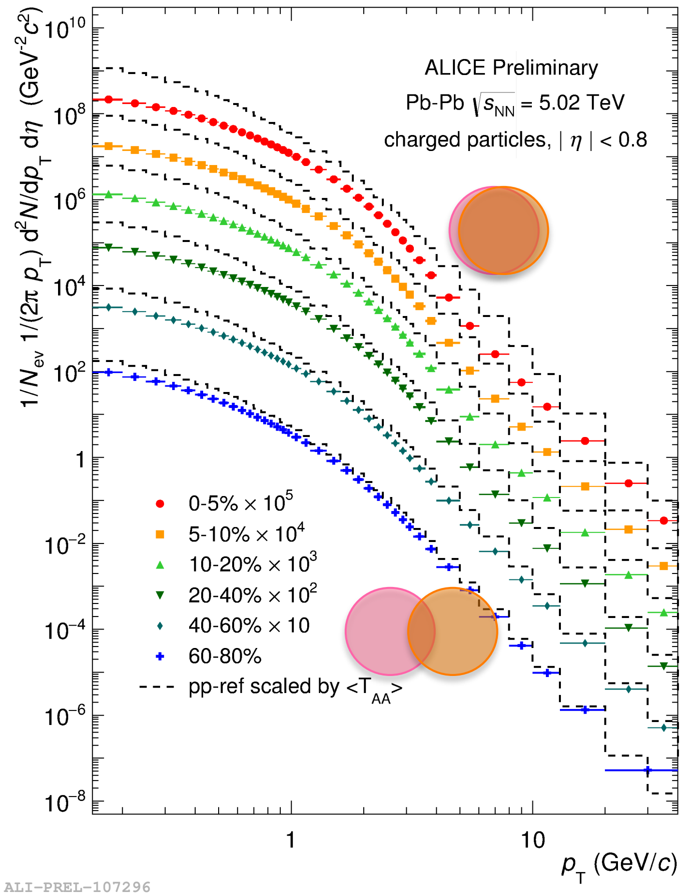
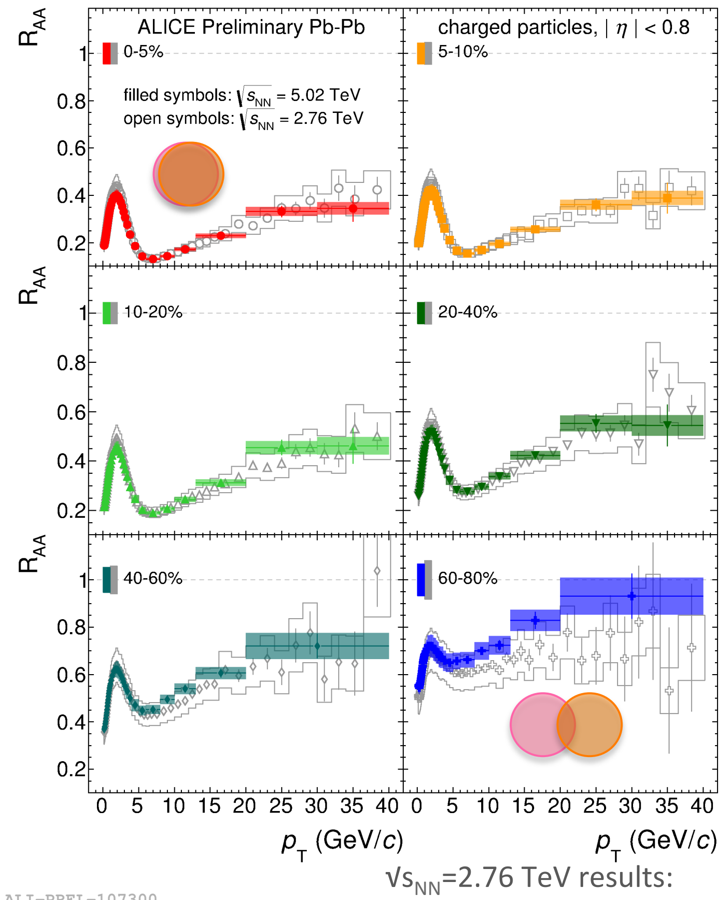
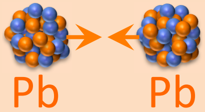



$\sqrt{s_{NN}}$=2.76 TeV results:
Phys.Lett. B720 (2013) 52-62

Compare values at 5.02 TeV with 2.76 TeV:

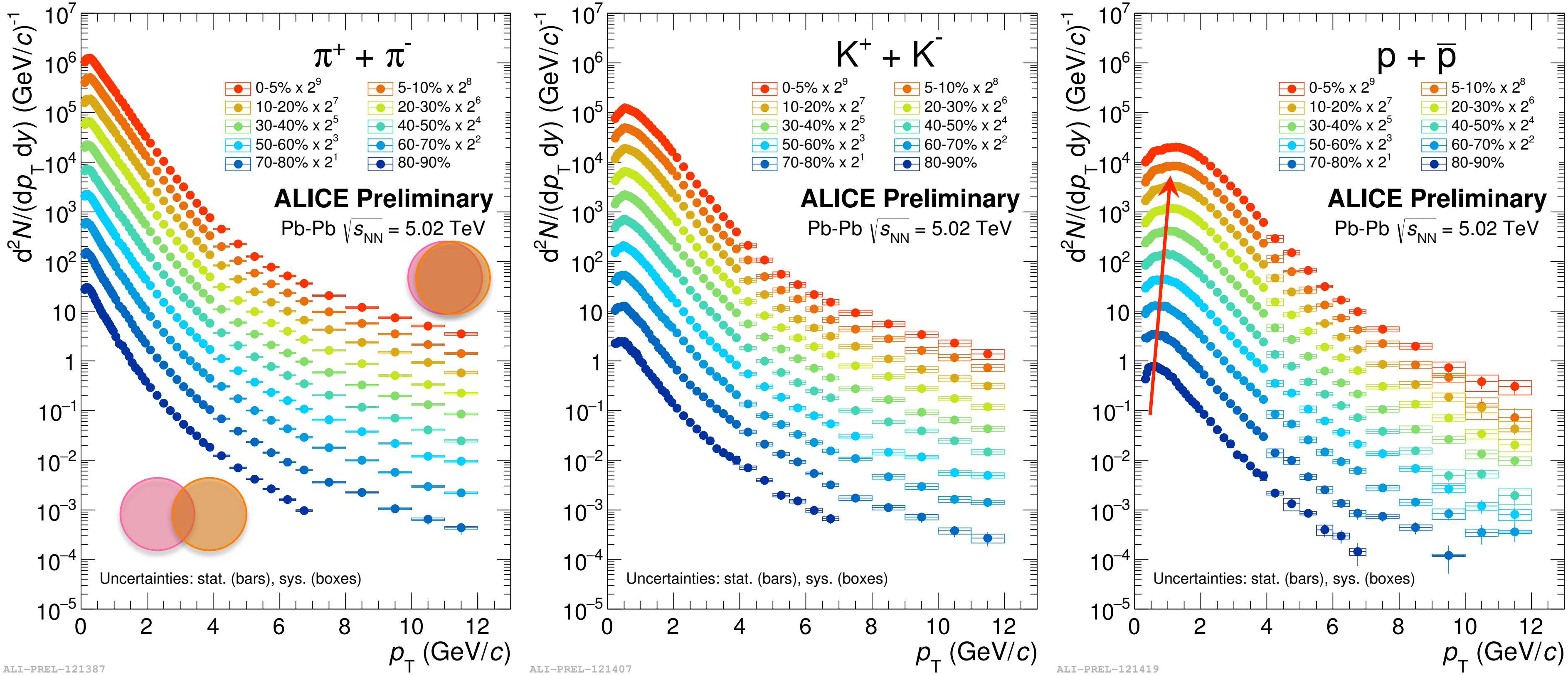
- No significant evolution with collision energy is found




# Identified particle spectra at $\sqrt{s_{NN}}$=5.02 TeV

***Reminder:***
**≈ 98%** of all particles are produced with **$p_T$ < 2 GeV/*c***
**≈ 80%** are pions, **≈ 13%** are kaons, **≈ 4%** are protons.

- ITS, TPC, TOF, HMPID were used for spectra

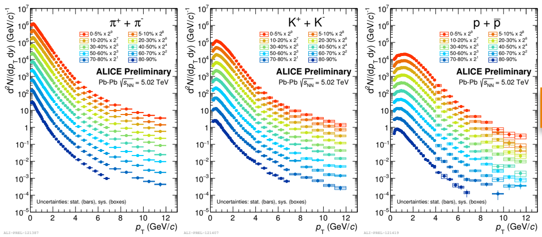


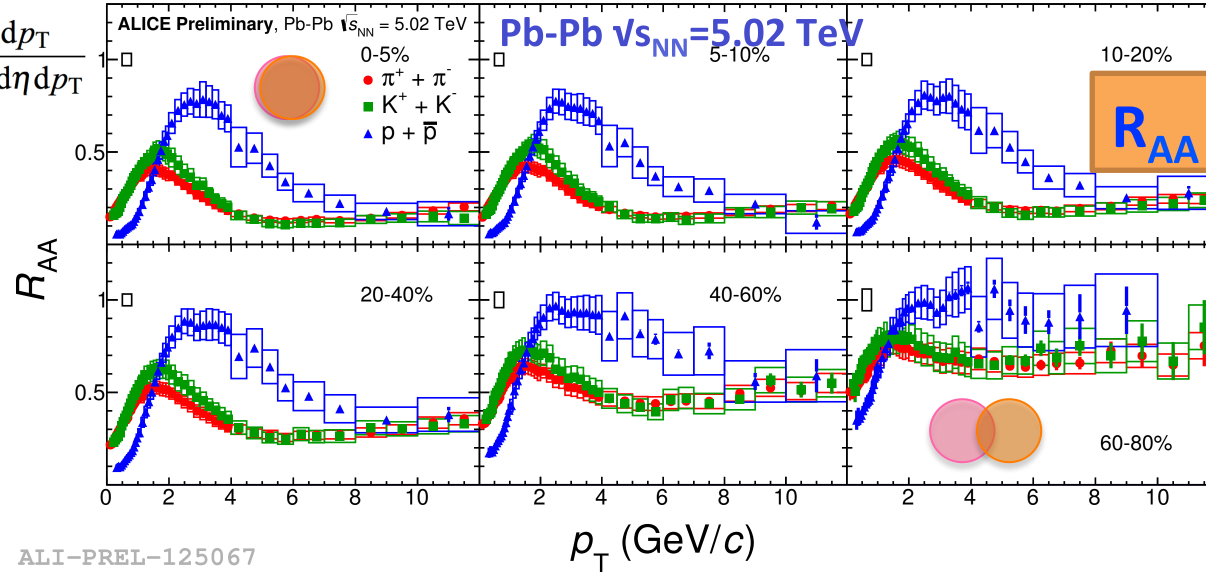

**maximum yield moves towards higher $p_T$** from peripheral to central collisions
(the effect is more pronounced *the heavier the hadron is*)

Pb Pb

# $\pi$, K, p: $R_{AA}$ and particle ratios

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




- all three species are equally suppressed at high $p_T$ (> 8 GeV/*c*)
  → **the energy loss is partonic in nature**

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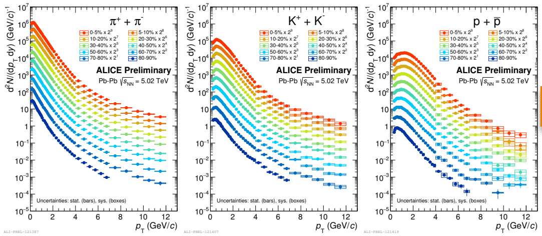


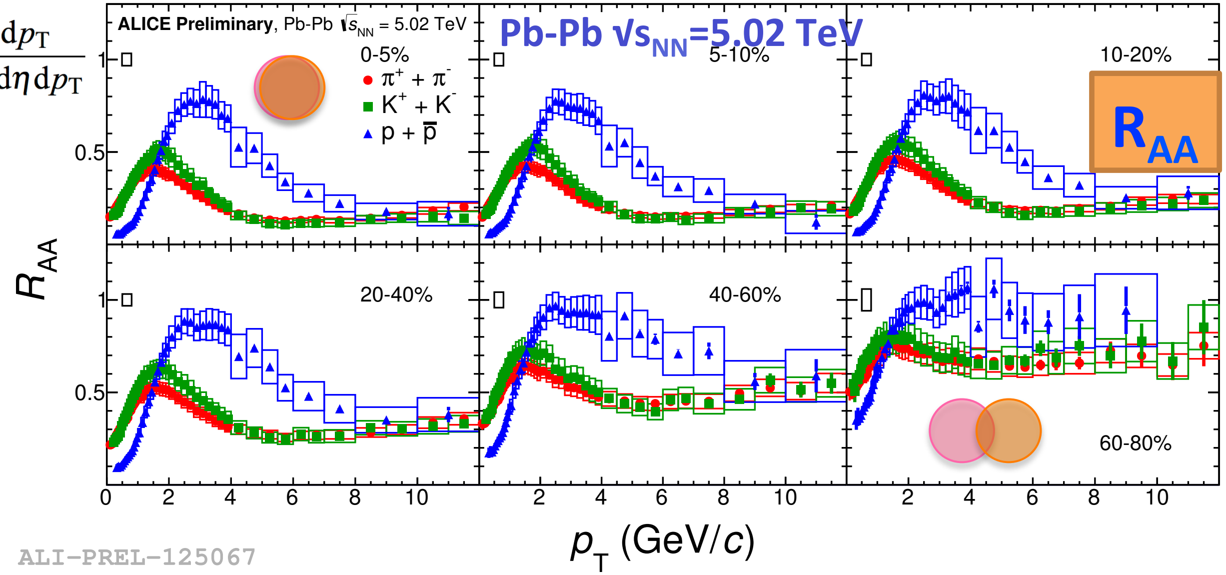


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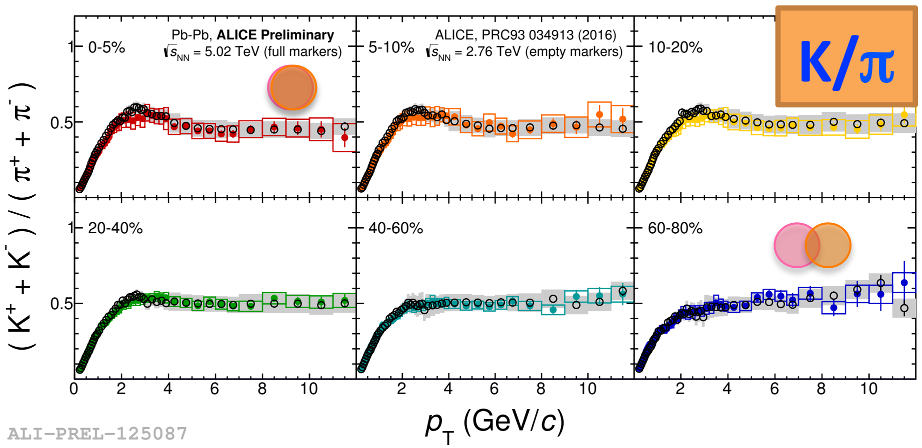
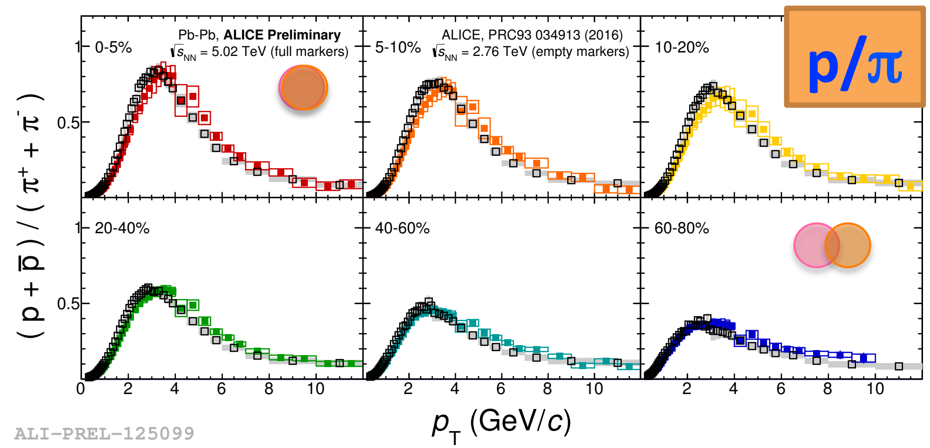
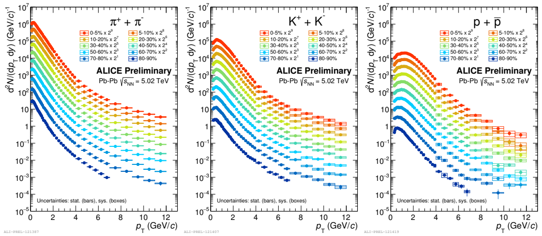


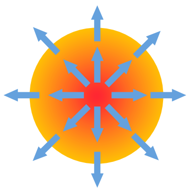

- No significant change between the two energies for K/π,
  small shift of the maximum of p/π to higher $p_T$ (larger radial flow)

# How does radial flow change from 2.76 to 5.02 TeV?




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

Phys. Rev. C 48, 2462 (1993)



*3 fit parameters:*

$\langle \beta_T \rangle$ – radial expansion velocity

$T_{kin}$ – kinetic freeze-out temperature

**n** – velocity profile

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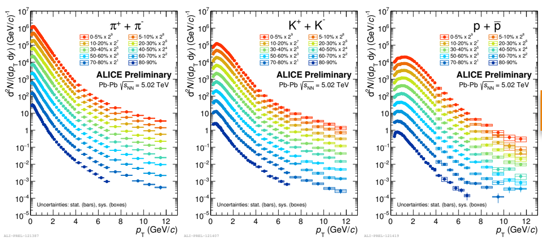


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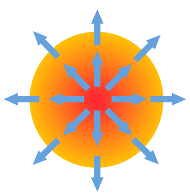

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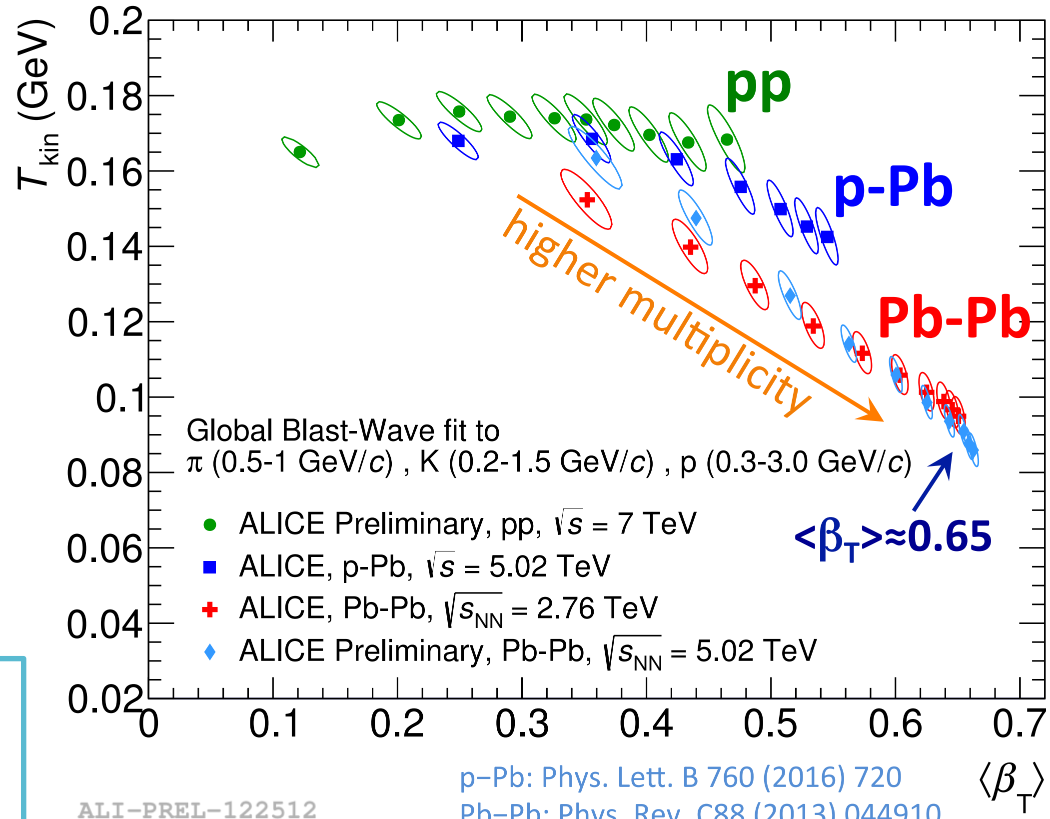
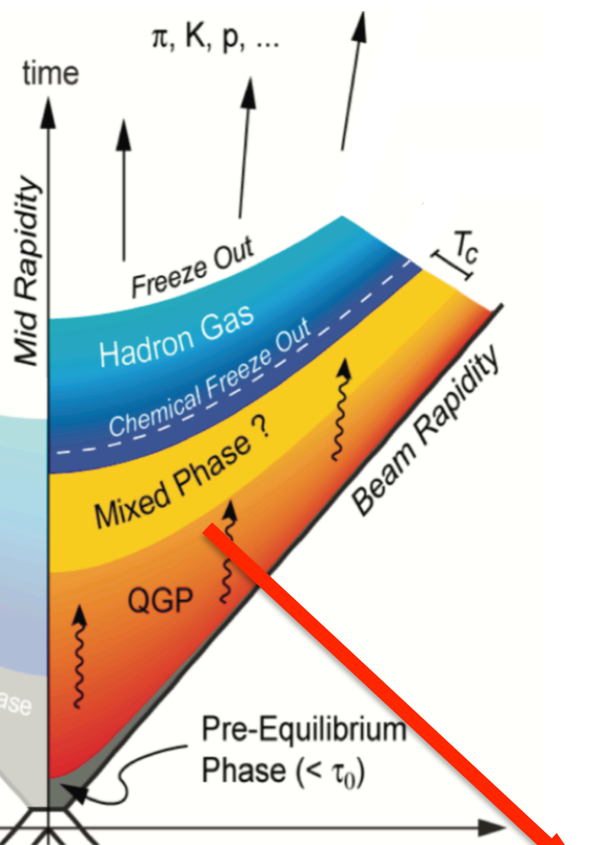



- Blast-Wave parameters for Pb-Pb at 5.02 TeV follow trends obtained at lower energy
- Larger expansion velocity for central Pb-Pb collisions
- Higher <$\beta_T$> for smaller collision systems at similar multiplicities

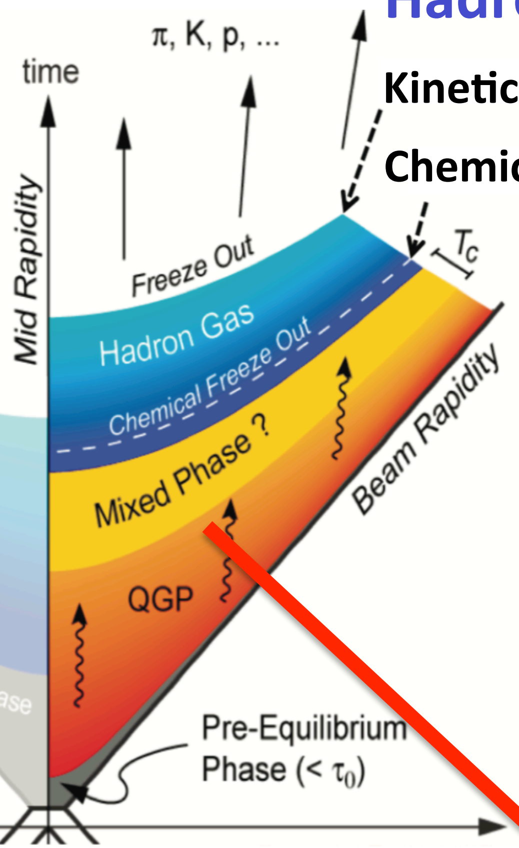



**Hydrodynamics**

**Recombination/coalescence** (quark content is important)

**In-medium energy loss**

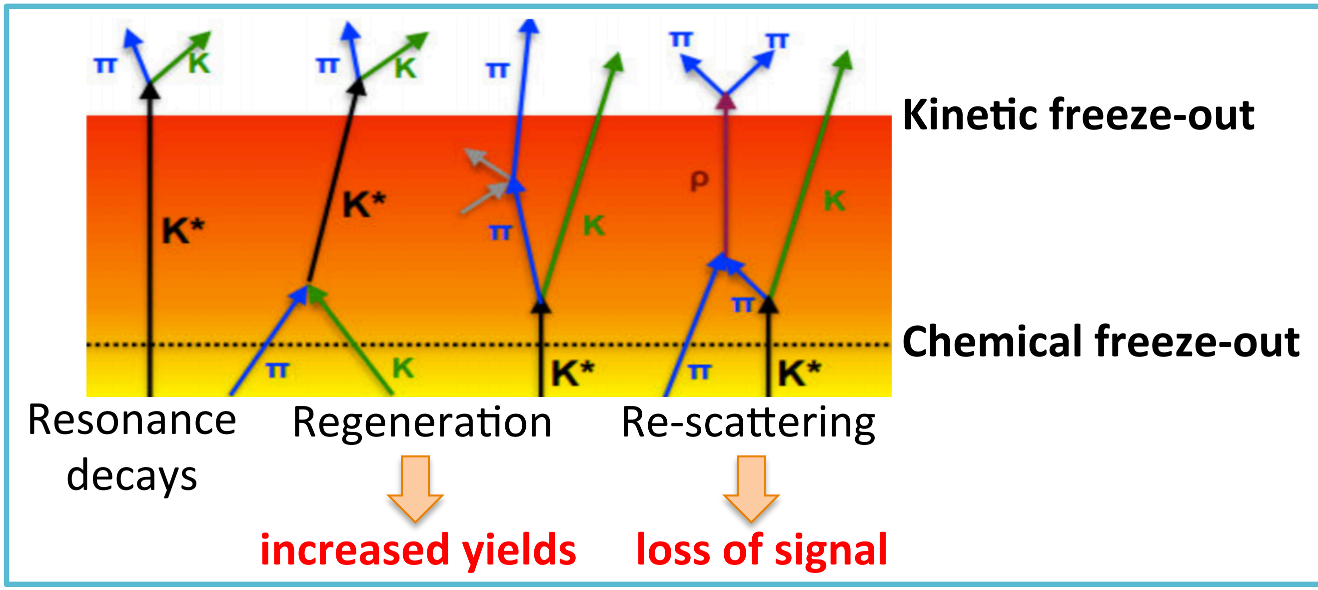
# Resonance production




## Hadronic phase *properties:* lifetime, density

**Kinetic freeze-out –** elastic processes cease, $p_T$ spectra are fixed

**Chemical freeze-out –** inelastic processes cease, particle yields are fixed

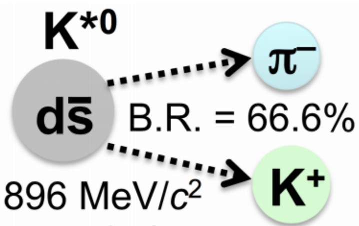



## Hydrodynamics

## Recombination/coalescence (quark content is important)

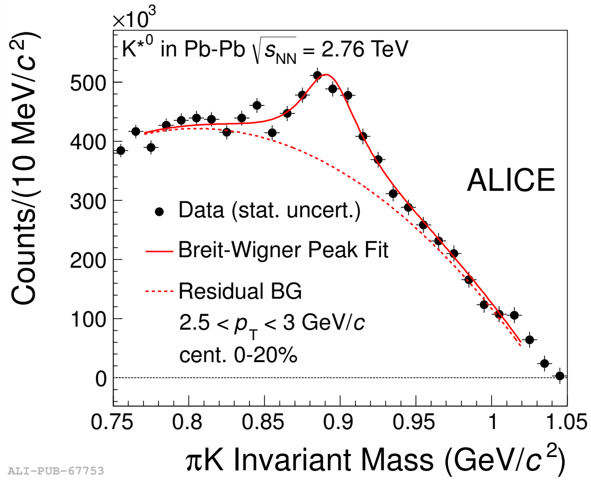
## In-medium energy loss

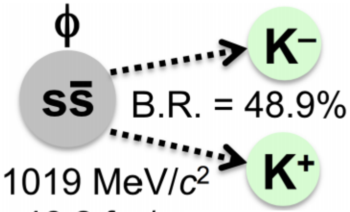
# Resonances: **invariant mass spectra**




$m$ = 896 MeV/$c^2$

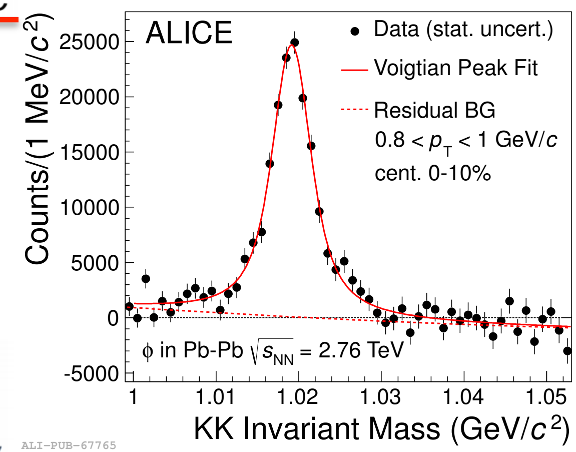
$\tau$ = 4.16 fm/$c$

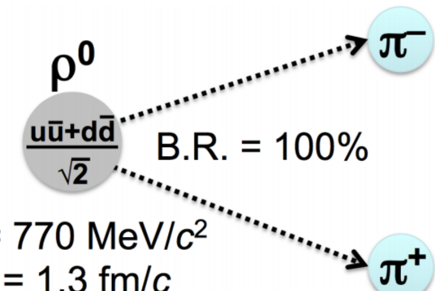



$m$ = 1019 MeV/$c^2$

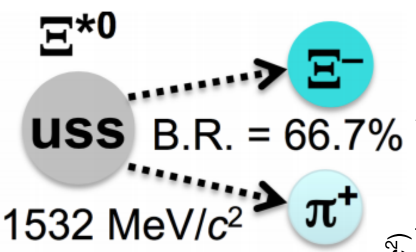
$\tau$ = 46.2 fm/$c$



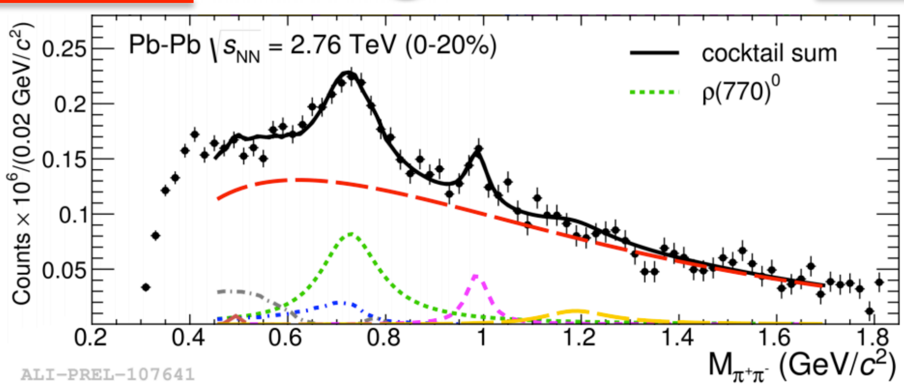

$m$ = 770 MeV/$c^2$

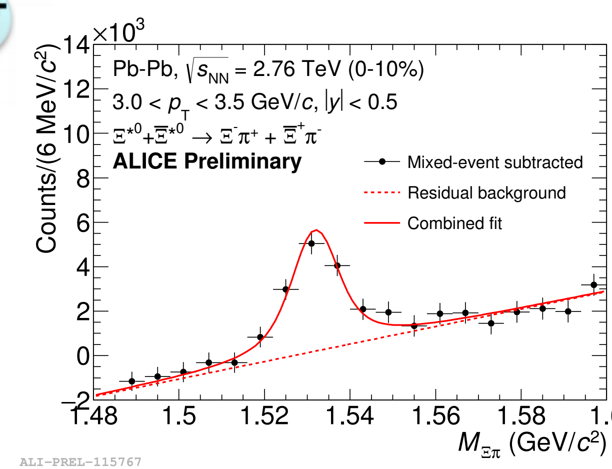
$\tau$ = 1.3 fm/$c$



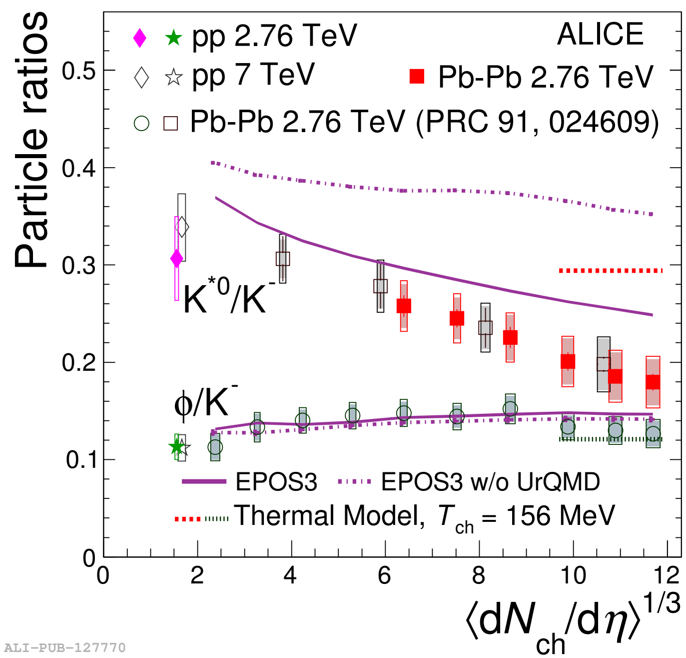

$m$ = 1532 MeV/$c^2$

$\tau$ = 21.7 fm/$c$

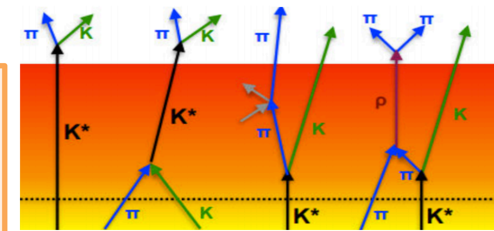


# Yield ratios with resonances




**K*/K: clear *suppression***
from pp and peripheral to central
Pb-Pb collisions
**not observed for ϕ/K**




$\tau(K^{*0}) \approx 4$ fm/c
$\tau(\phi) \approx 46$ fm/c

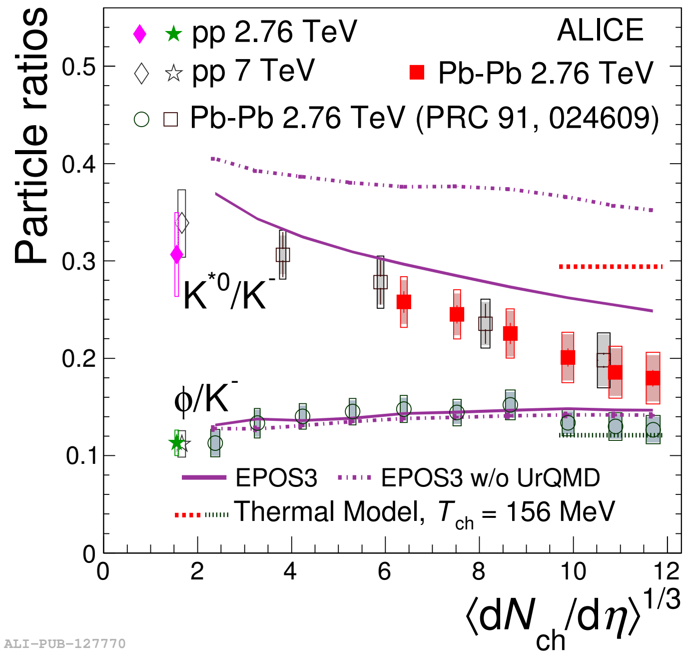
**Possible explanation:**

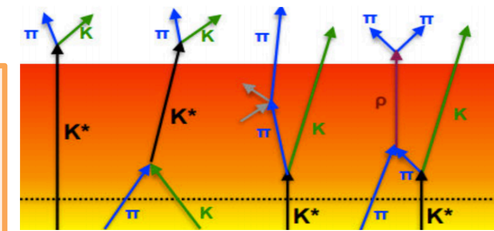
**K*/K:** rescattering of the decay daughters

**ϕ/K:** rescattering not significant due to *long lifetime*

Qualitatively described by EPOS3 with UrQMD.

# Yield ratios with resonances




τ($K^{*0}$) ≈ 4 fm/c
τ(ϕ) ≈ 46 fm/c

**K*/K: clear *suppression***
from pp and peripheral to central Pb-Pb collisions
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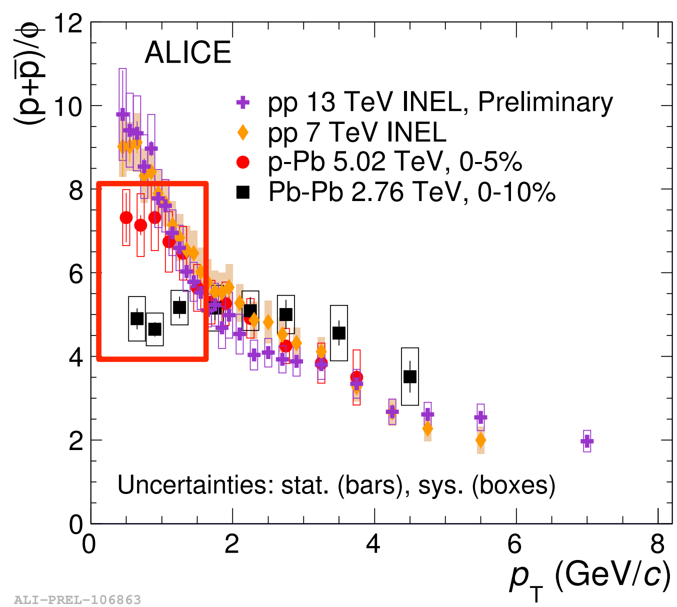



***p/ϕ vs $p_T$: flattens*** in most **central Pb-Pb**
and in **high-multiplicity p-Pb** collisions

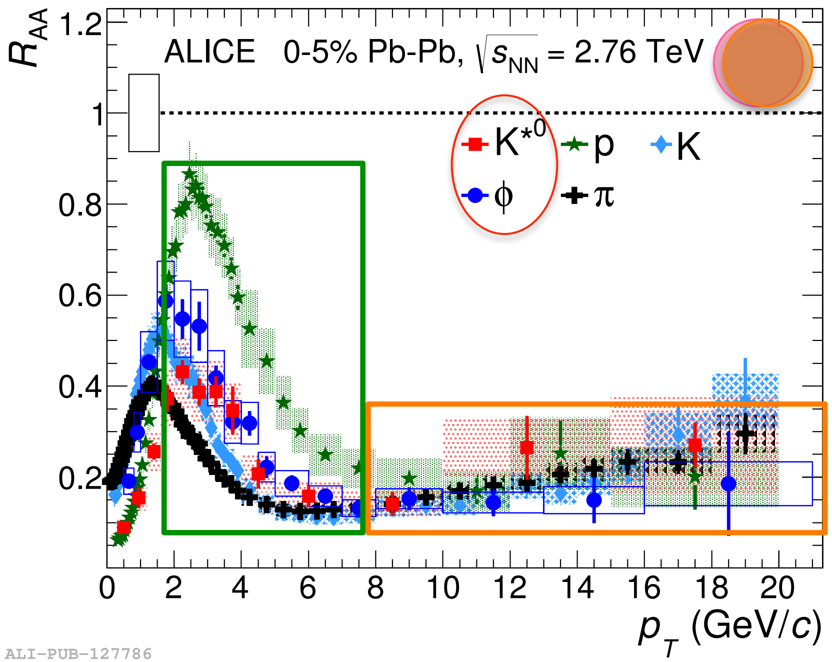
spectral shapes of p are ϕ similar
→ flow + **recombination**?
→ hint of the onset of collective behaviour in p-Pb?..

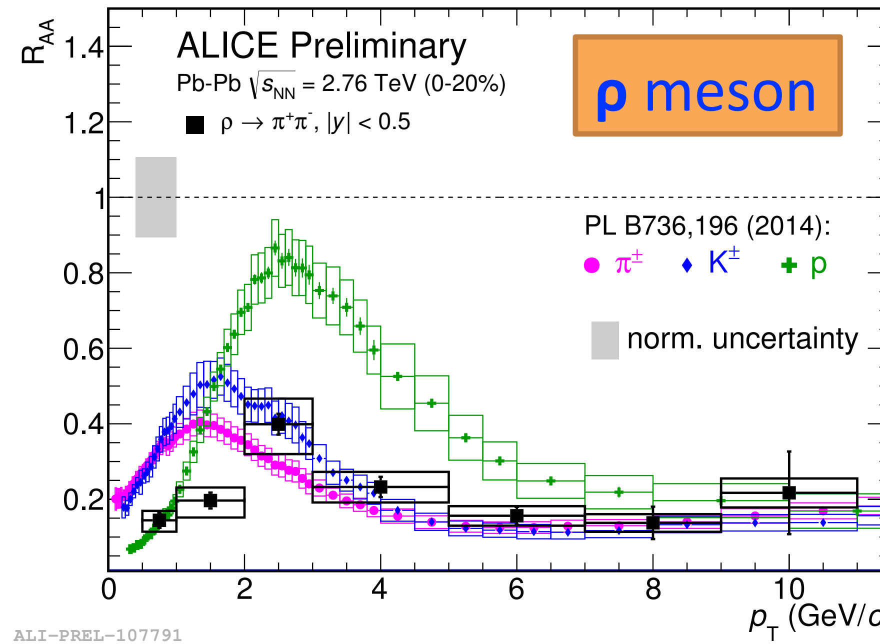
# $R_{AA}$ of resonances



**High $p_T$>8 GeV/*c*: same suppression for resonances as for long-lived particles**

- high-$p_T$ resonances can quickly escape the hadronic medium
- suppression not influenced by hadron properties (mass, baryon number, u/d/s quark content)
- rescattering is a low-$p_T$ effect



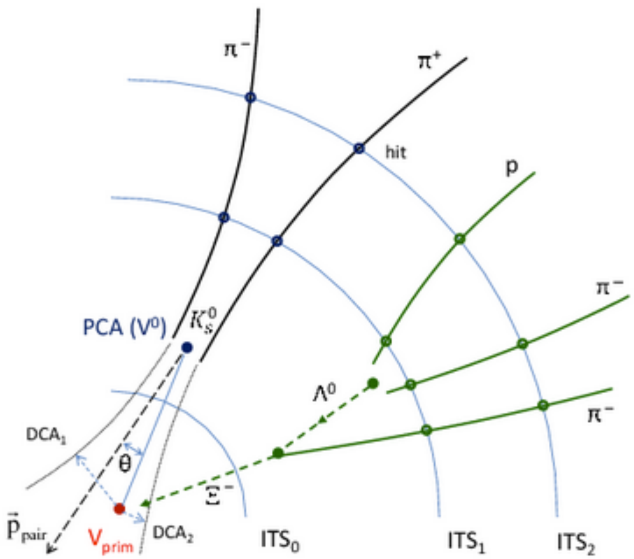




**Intermediate $p_T$ (2–8 GeV/*c*):**

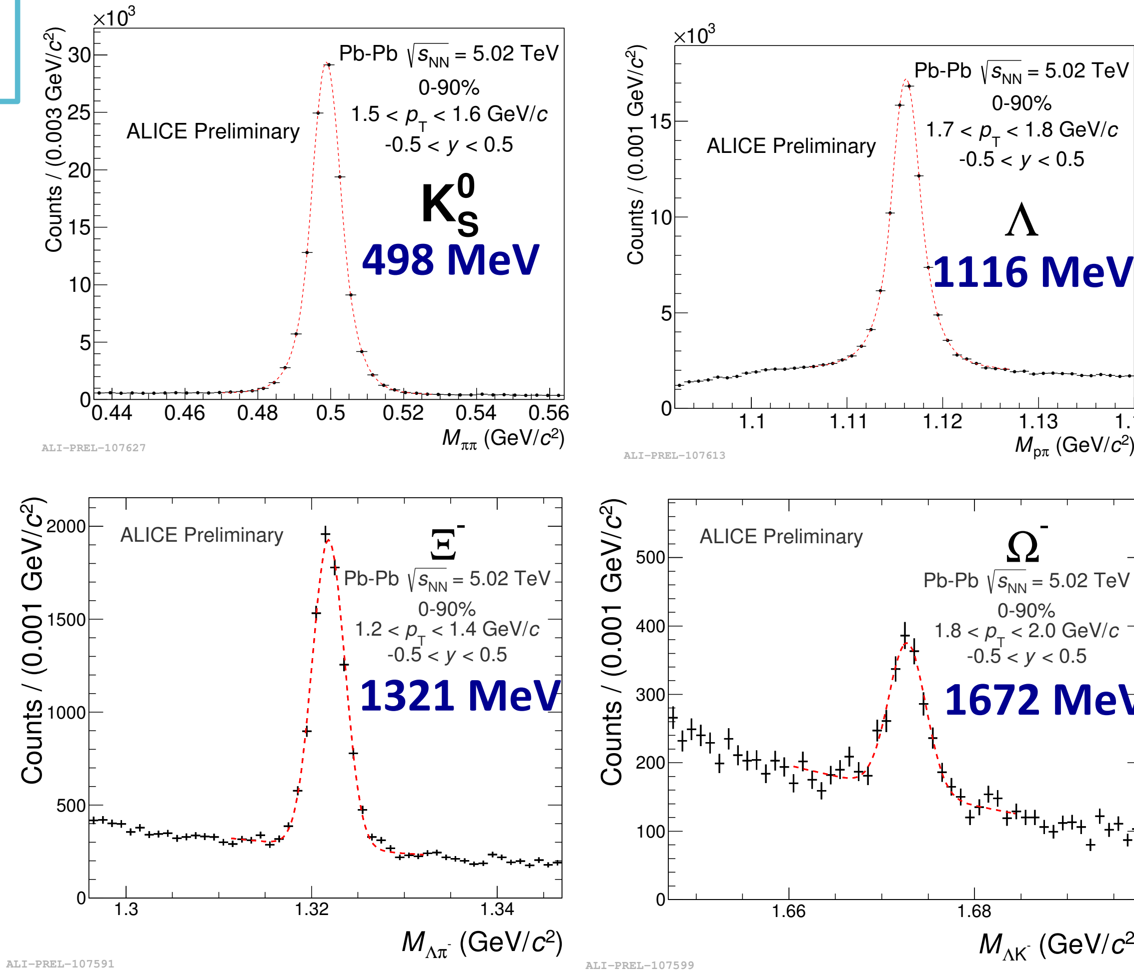
- $K^{*0}$ and ϕ are closer to other mesons than to protons
- mass ordering different for mesons and baryons?

# Reconstruction of strange particles

Long lifetime of strange particles
→ **reconstruction by weak-decay topology:**

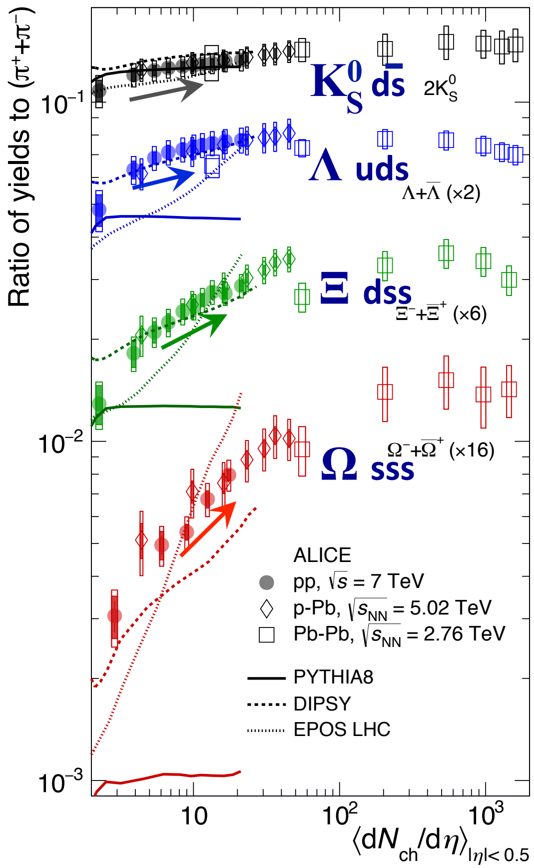



**… + invariant mass spectra:**



# Strangeness production in small systems

Nature Phys. 13 (2017) 535



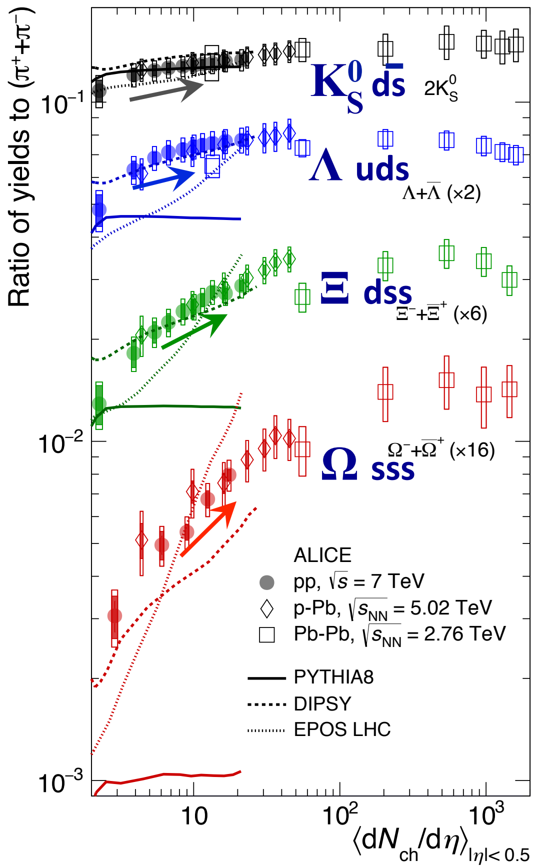

Enhanced production of strange and multi-strange hadrons now observed also **in high-multiplicity pp collisions**!

- **Remarkable agreement between pp and p-Pb at same dN/dη**
- PYTHIA doesn't reproduce the trend, while better agreement with EPOS and DIPSY (color ropes)

**Is the increase mass-related or strangeness-related?**

# Strangeness production in small systems

Nature Phys. 13 (2017) 535

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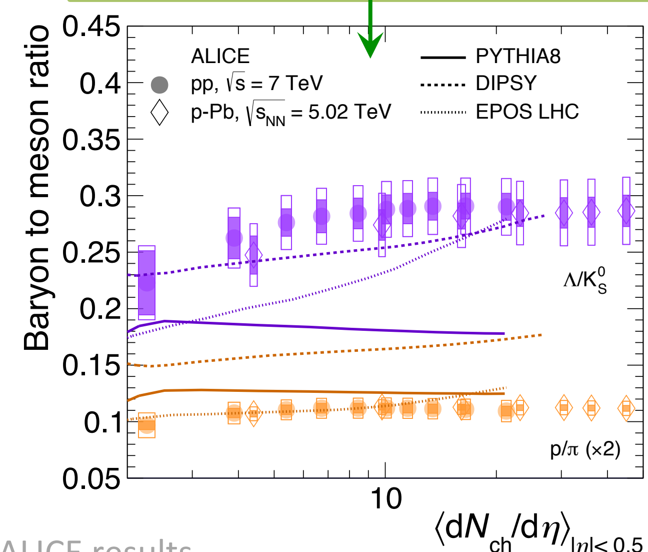
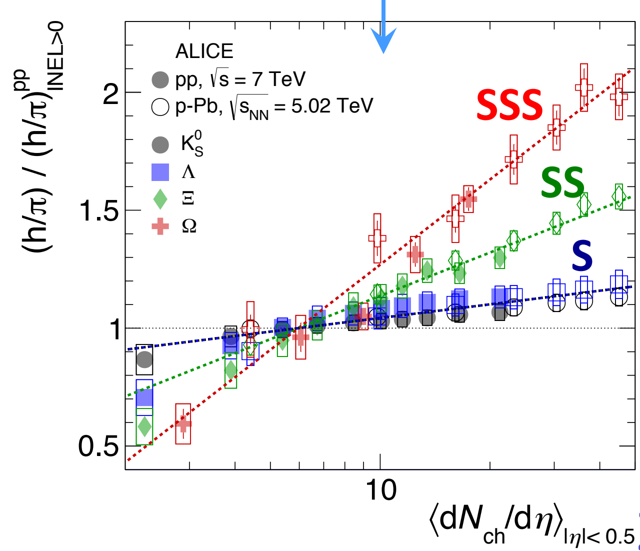
- PYTHIA doesn't reproduce the trend, while better agreement with EPOS and DIPSY (color ropes)

**Is the increase mass-related or strangeness-related?**

Baryon/meson ratios **do not** change significantly with multiplicity.

Relative increase is **more pronounced** for multi-strange hadrons.

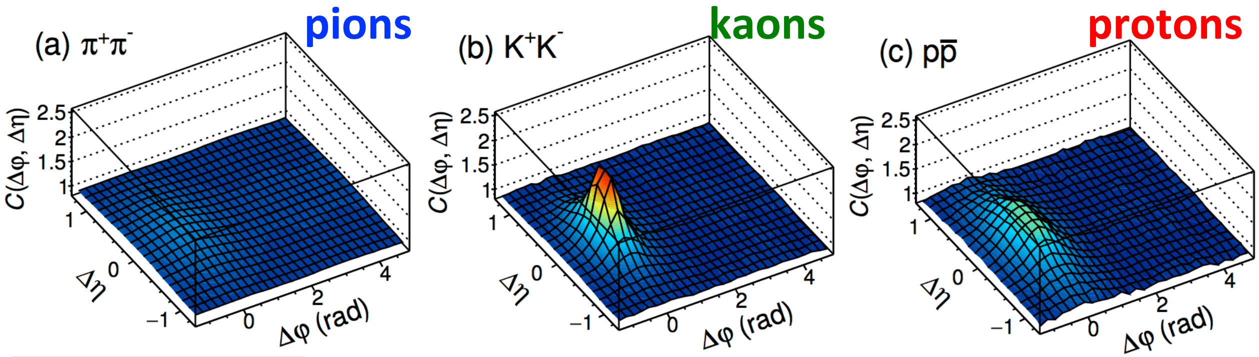


# Angular correlations of π, K, p in 7 TeV pp collisions

**arXiv:1612.08975**

**Unlike-sign pairs**



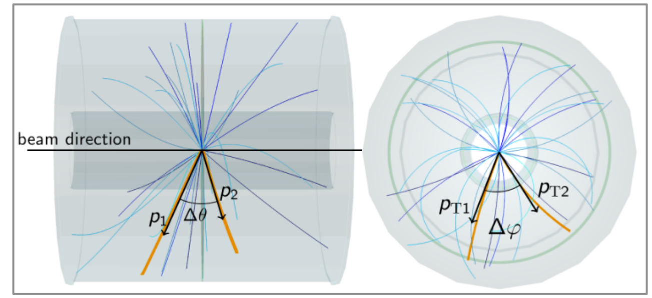
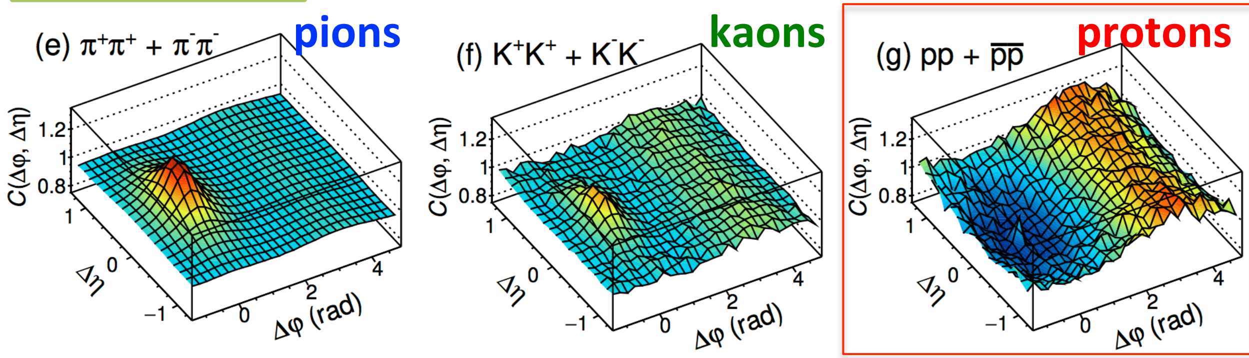




Fig. A. Zaborowska

**Like-sign pairs**




**Strong anti-correlation!**

# Angular correlations of **π, K, p** in 7 TeV pp collisions

arXiv:1612.08975

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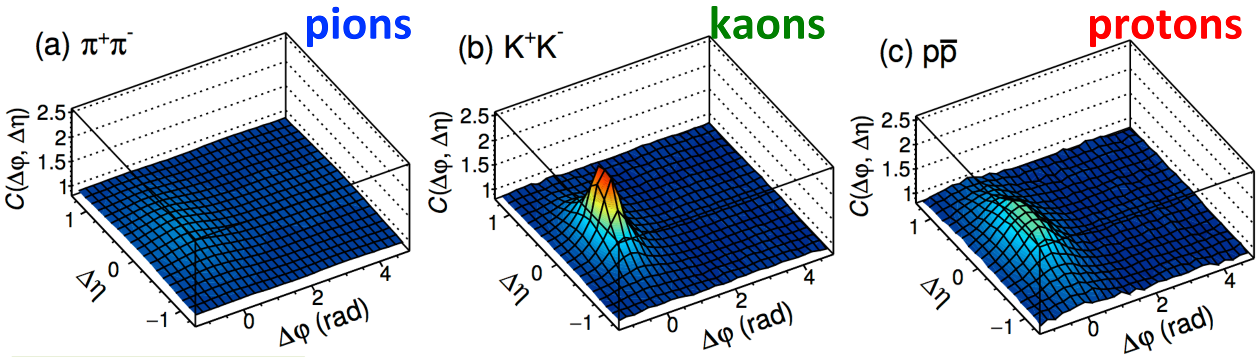


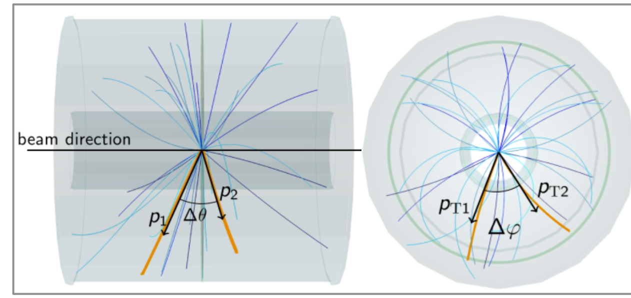
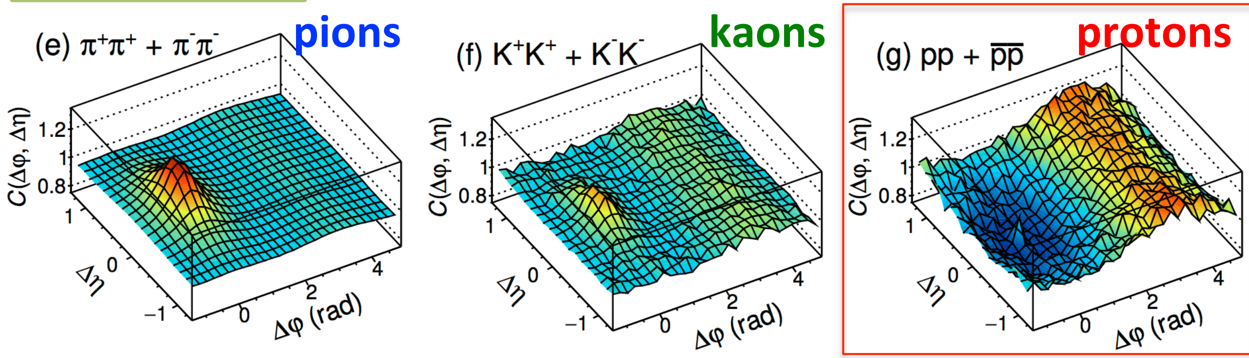
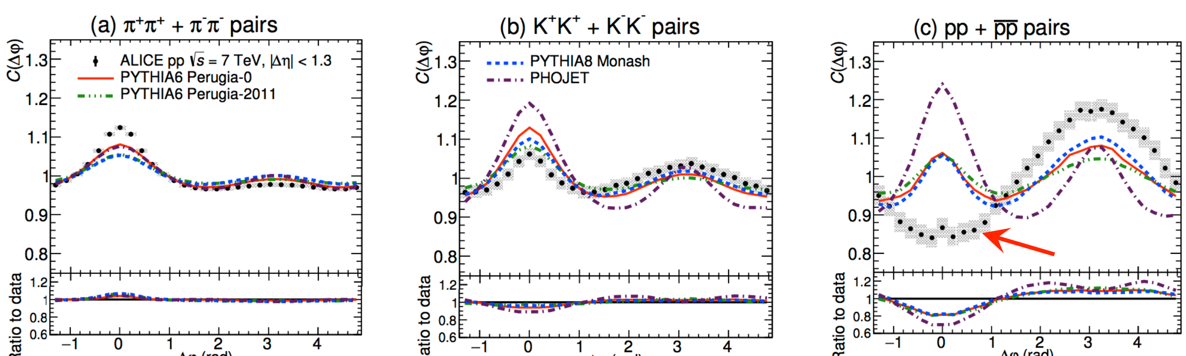




Fig. A. Zaborowska

**Like-sign pairs**

**Strong anti-correlation!**




**MC models:**

- reproduce mesons
- **but fail for baryons!**

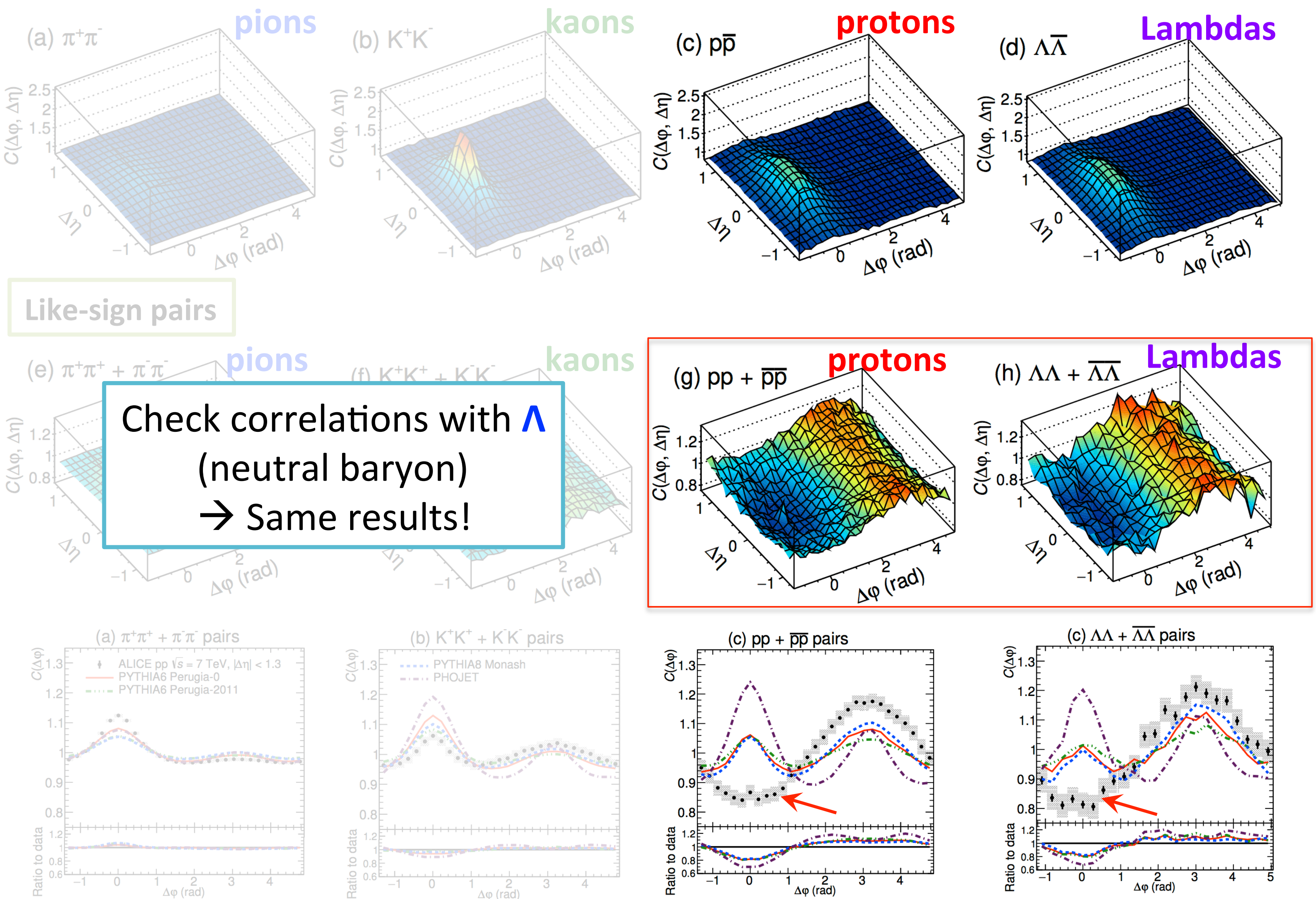
***Why?*** MC models contain conservation laws for E, p, baryon number.

***What else?***
Coulomb repulsion?
Fermi-Dirac Statistics?..

# Angular correlations of π, K, p and Λ in 7 TeV pp collisions

arXiv:1612.08975

Unlike-sign pairs



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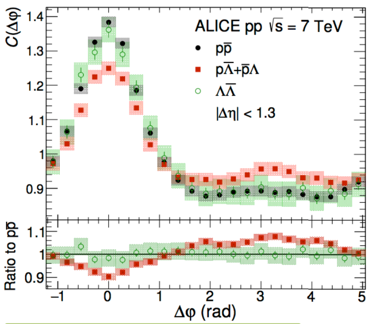
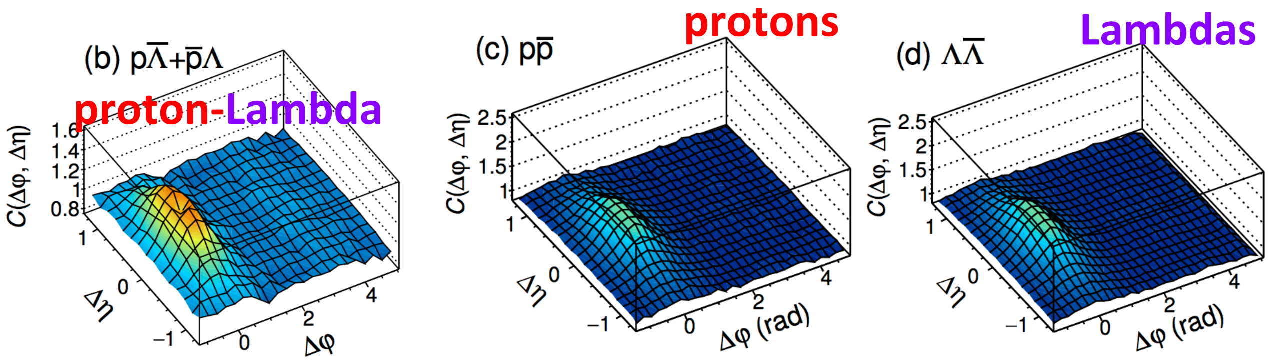
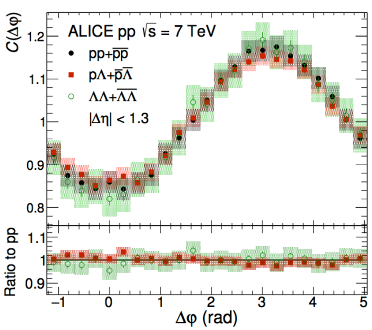
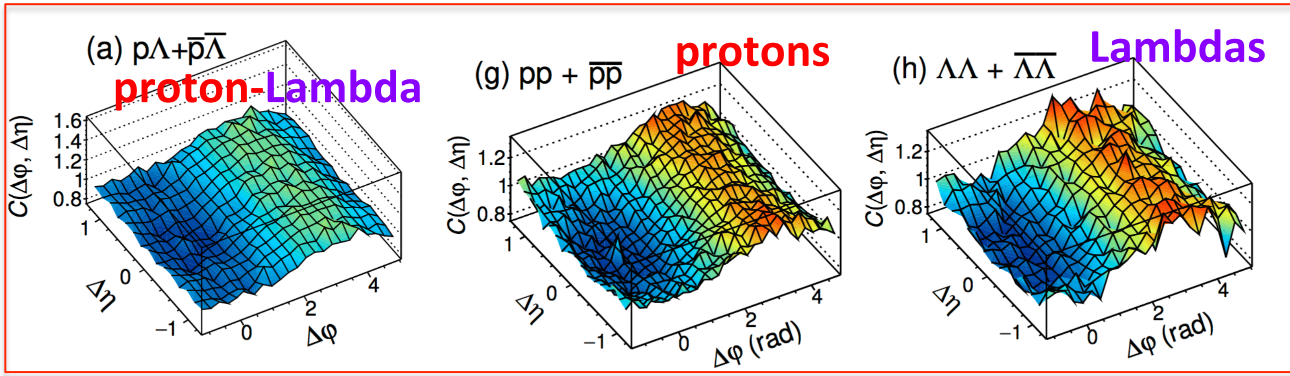



**Like-sign pairs**



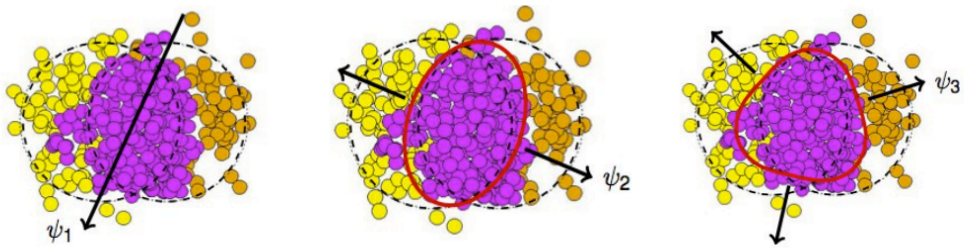




… even for **pΛ!**
(not identical baryons)

*Conclusion:*
observed baryon-baryon correlations are not reproduced by MC models.
**No explanation found so far.**

# Anisotropic flow at $\sqrt{s_{NN}}$=5.02 TeV





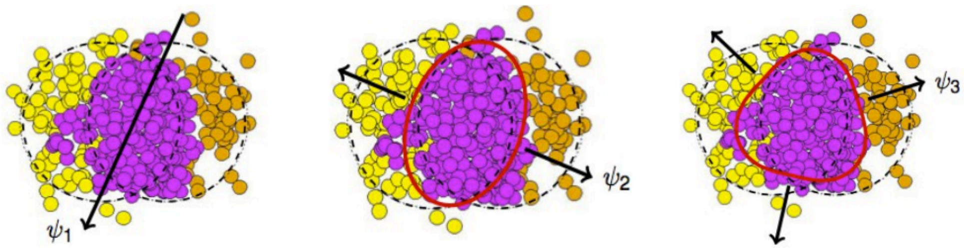

$$\frac{dN}{d\varphi} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\varphi - \Psi_n)$$

$$v_n = \langle \cos\left[n(\varphi - \Psi_n)\right] \rangle$$

$v_n$ quantify the event anisotropy
$v_2$ – elliptic flow, $v_3$ – triangular flow, …

# Anisotropic flow at $\sqrt{s_{NN}}$=5.02 TeV



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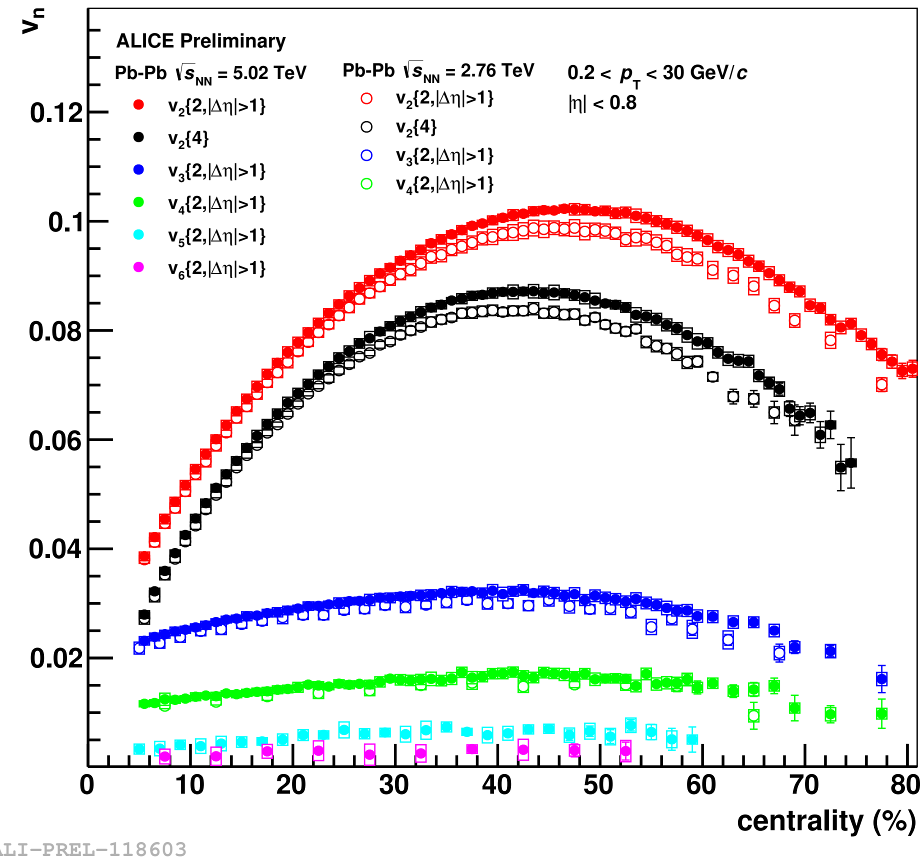
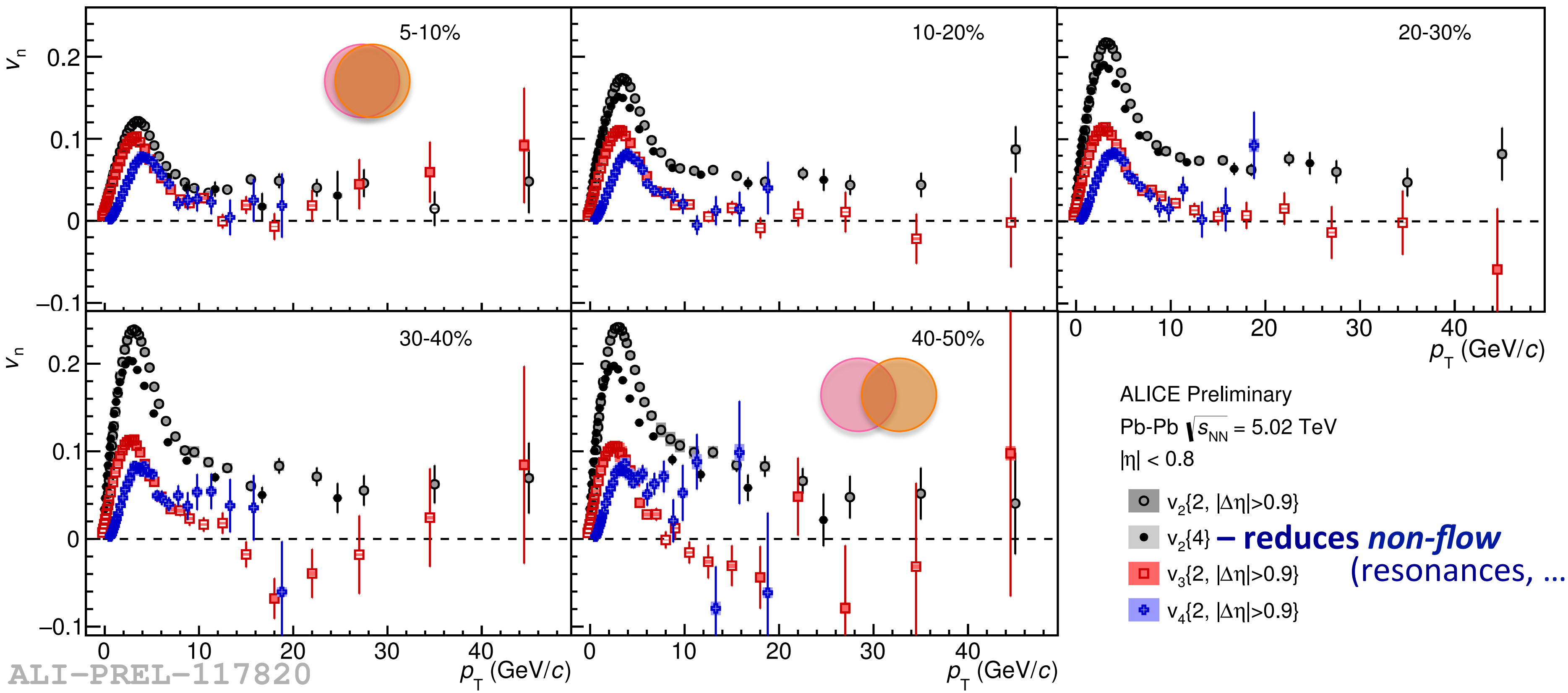



**Integrated $v_n$** measured **up to $v_6$** using cumulants.
Constrain initial conditions and temperature dependence of η/s.

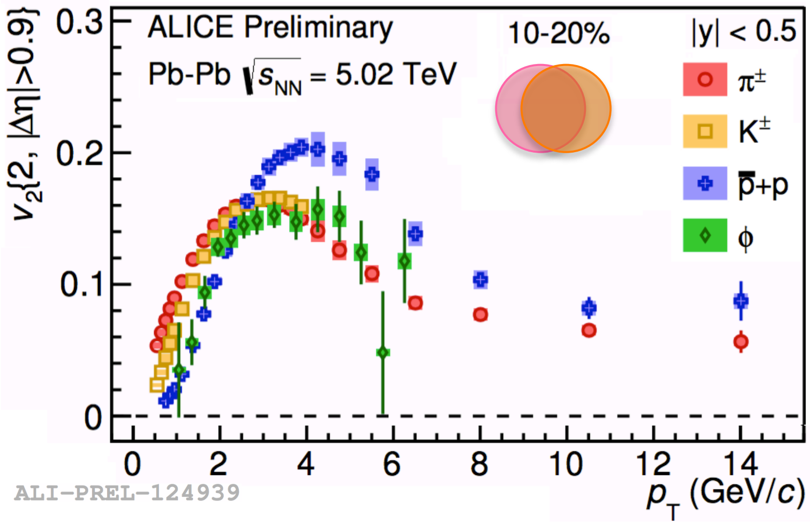
- use η gap between particles for 2-particle correlations to suppress *non-flow* (decays, …)
- $v_2\{4\}$ uses 4-particle correlations → reduced non-flow
- difference between $v_2\{2\}$ and $v_2\{4\}$ is sensitive to event-by-event fluctuations of $v_2$

# Unidentified particle $v_n$ at $\sqrt{s_{NN}}$=5.02 TeV




- **$v_2 > v_3 > v_4$** for $p_T$ < 5 GeV/c for all centralities
- **$v_2 > 0$** up to $p_T$ = 50 GeV/c
- **$v_2\{4\} < v_2\{2\}$** for $p_T$ < 10 GeV/c

# Identified particle $v_2$ at $\sqrt{s_{NN}}$=5.02 TeV




- For $p_T$ < 2 GeV/$c$: mass ordering indicative of radial flow
- For $p_T$ > 3 GeV/$c$: particle type dependence

- $\phi$ follows mass ordering at low $p_T$ and pion $v_2$ at intermediate $p_T$

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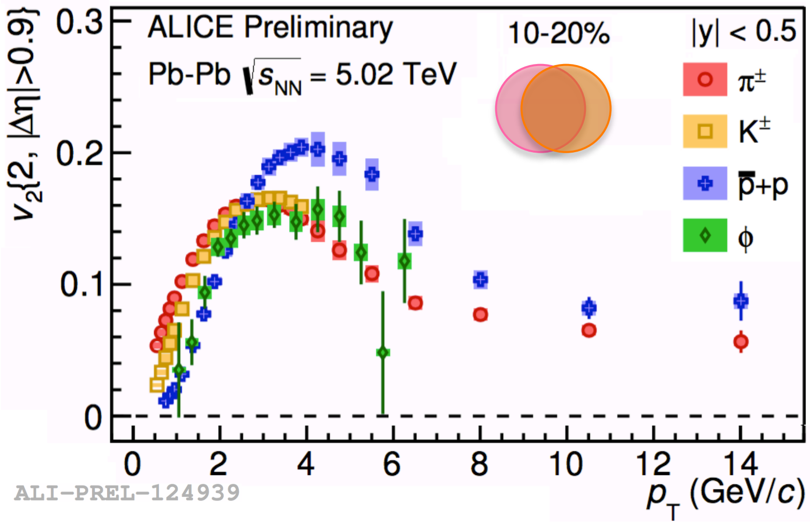


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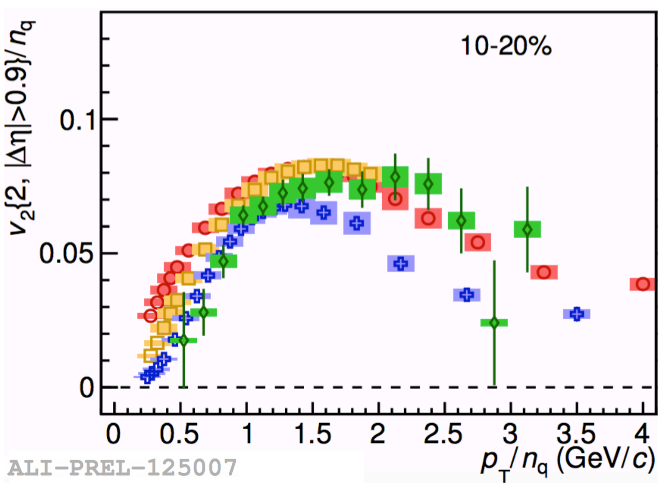
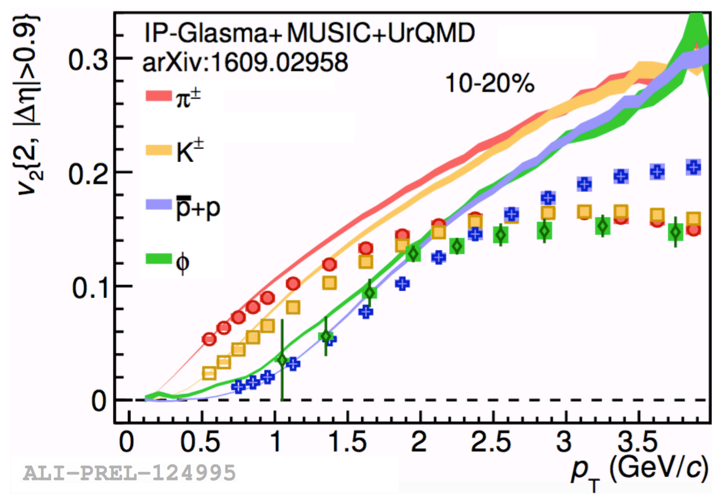


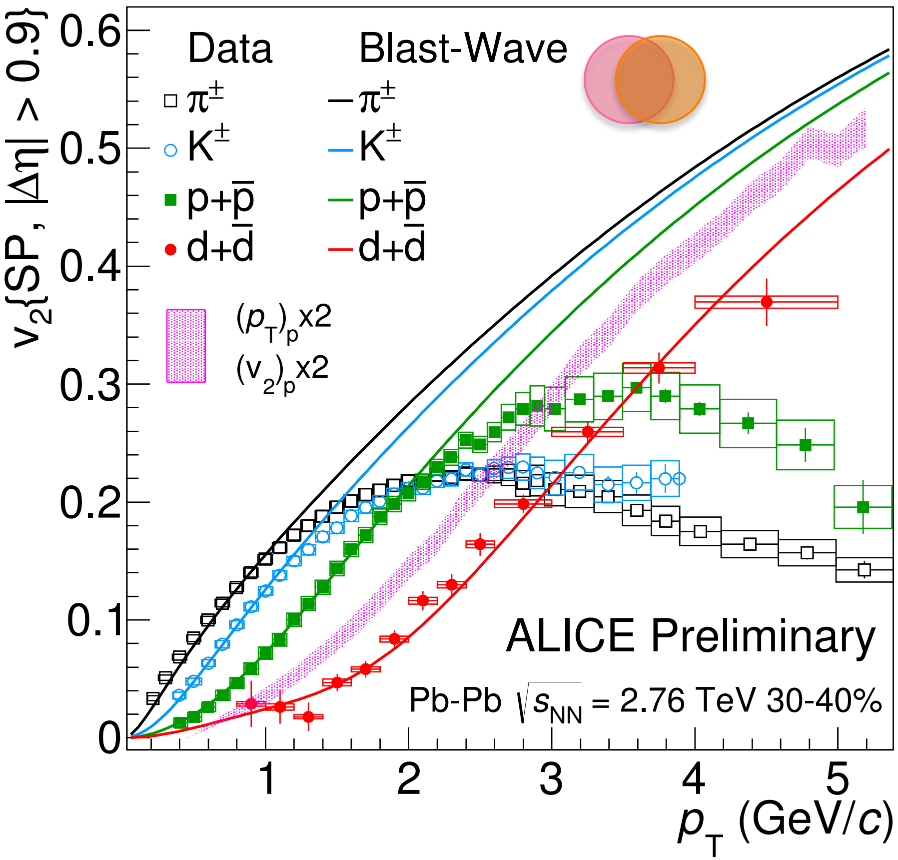

particle production via **quark coalescence**?
– scaling is only approximate




**Hydrodynamical calculations**
(IP-Glasma) + hadronic cascade model (UrQMD):
reproduce the main features of $v_2$ for $p_T$ < 2 GeV/$c$

# Elliptic flow of **deuterons**






ALI-PREL-97051

**Simple nucleon coalescence?**

**– does not describe deuteron $v_2$**

**"Blast-wave" prediction**

– ~ hydrodynamics parametrisation

– parameters from fit to π/K/p

**→ nicely describes deuteron trend!**

→ Similar production mechanism for **strongly-coupled** hadrons like π/K/p and **very weakly-bound deuteron**?

# Event-by-event correlations of flow harmonics

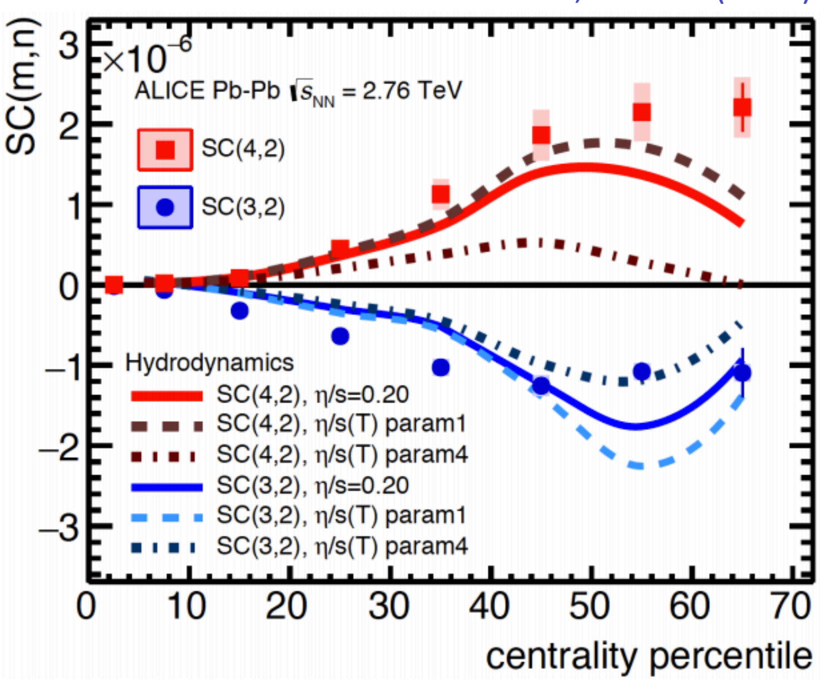


Symmetric Cumulants, **SC(m,n)** – measures the correlations of $v_n$ and $v_m$. PRC 89, 064904 (2014)

$$SC(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

- not sensitive to non-flow effects and inter-correlations of various symmetry planes

PRL 117, 182301 (2016)

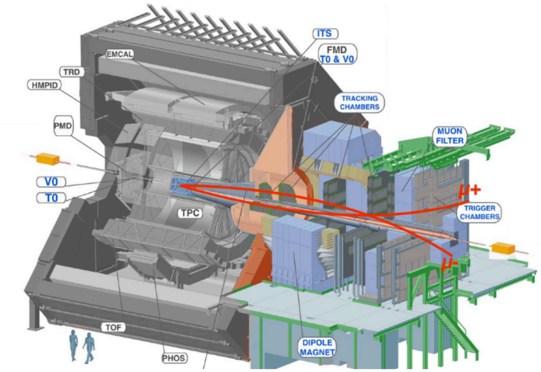


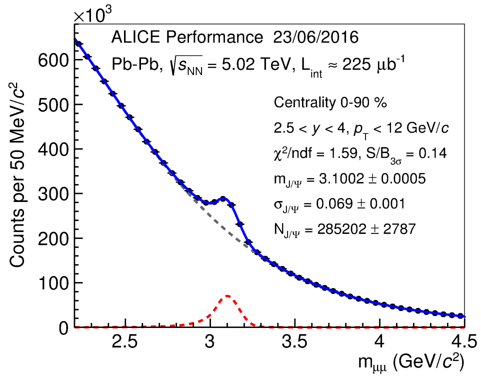

Stronger constraints on the initial conditions and η/s in hydrodynamic calculations than $v_n$ alone.

Pb Pb

# J/ψ suppression at $\sqrt{s_{NN}}$=5.02 TeV

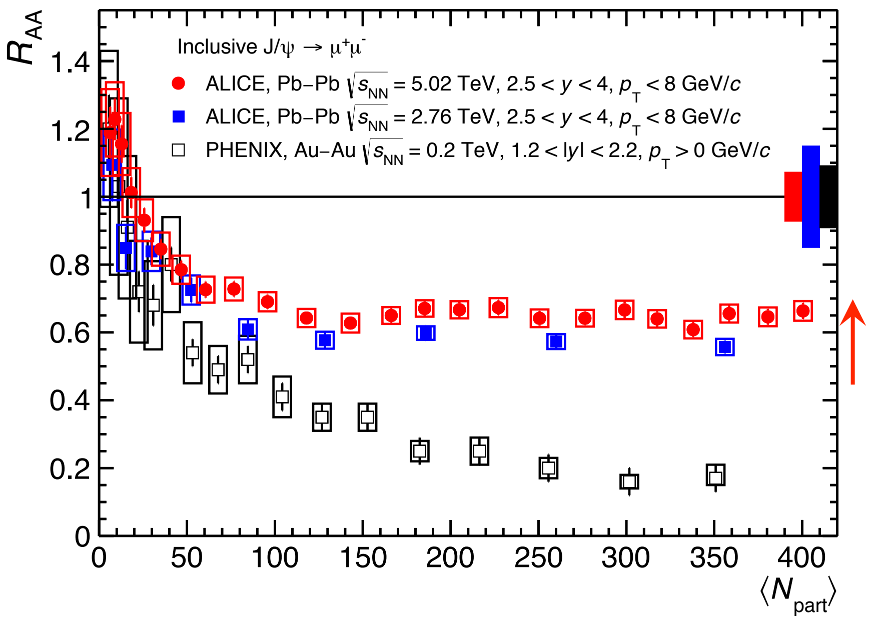
Phys. Lett. B 766 (2017) 212-224




$$R_{AA} = \frac{N(J/\psi)_{AA}}{\langle N_{bin}\rangle N(J/\psi)_{pp}}$$

→ =1 if yield scales as number of binary pp collisions in AA

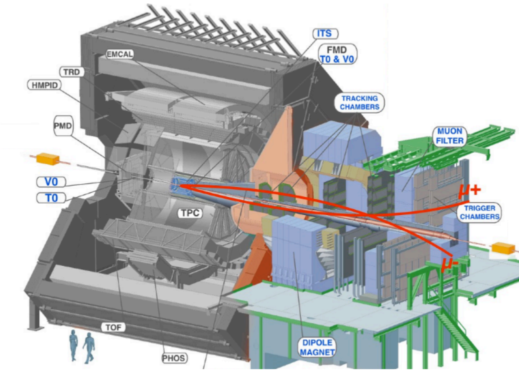


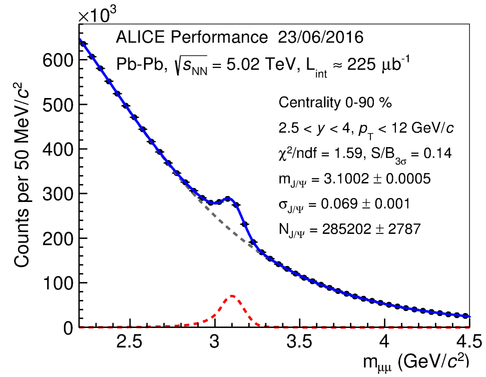

- Very different behaviour between LHC and RHIC (*vs* both centrality and $p_T$)
  →most straightforward explanation: **c-cbar recombination at LHC**!
- Results at 5.02 TeV → small further increase?

# J/ψ suppression at $\sqrt{s_{NN}}$=5.02 TeV

Pb Pb

Phys. Lett. B 766 (2017) 212-224

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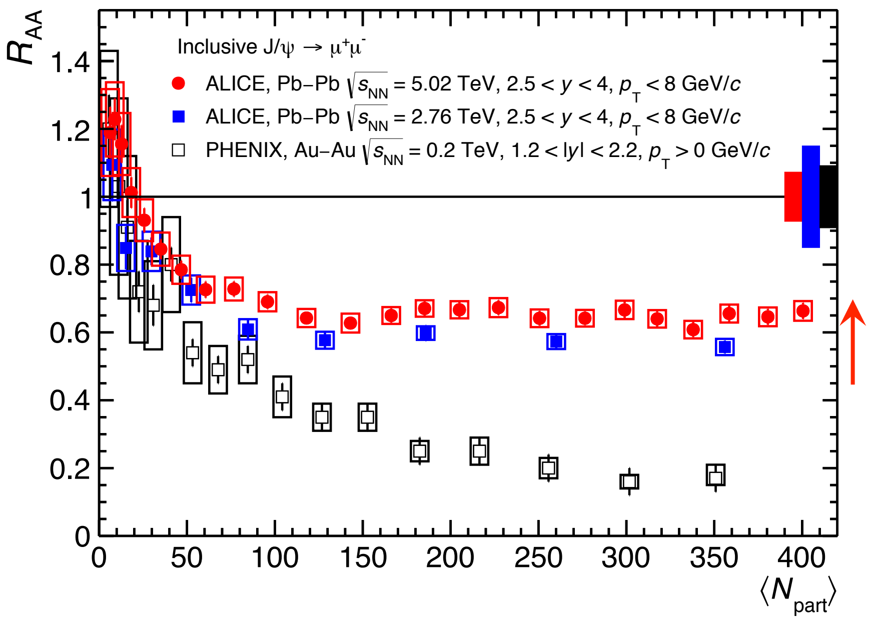
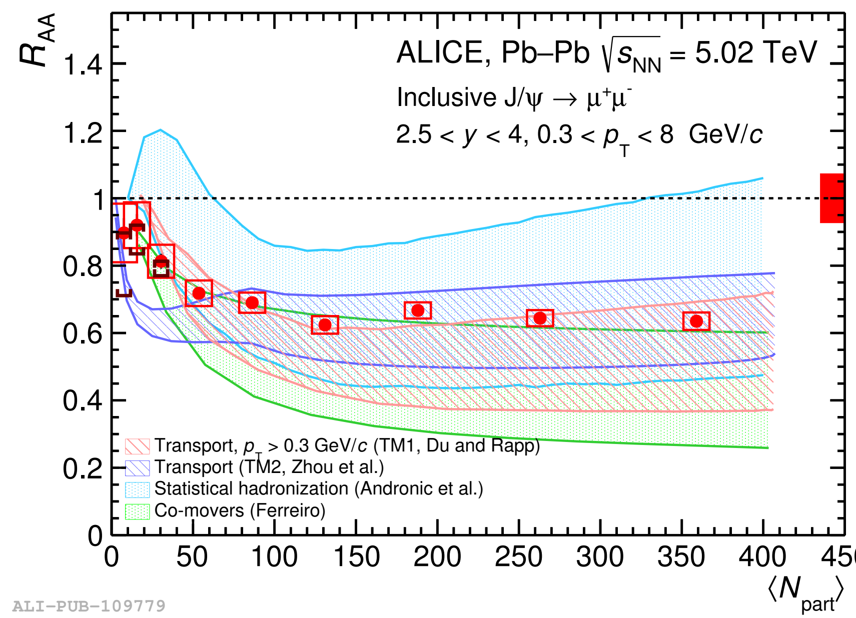
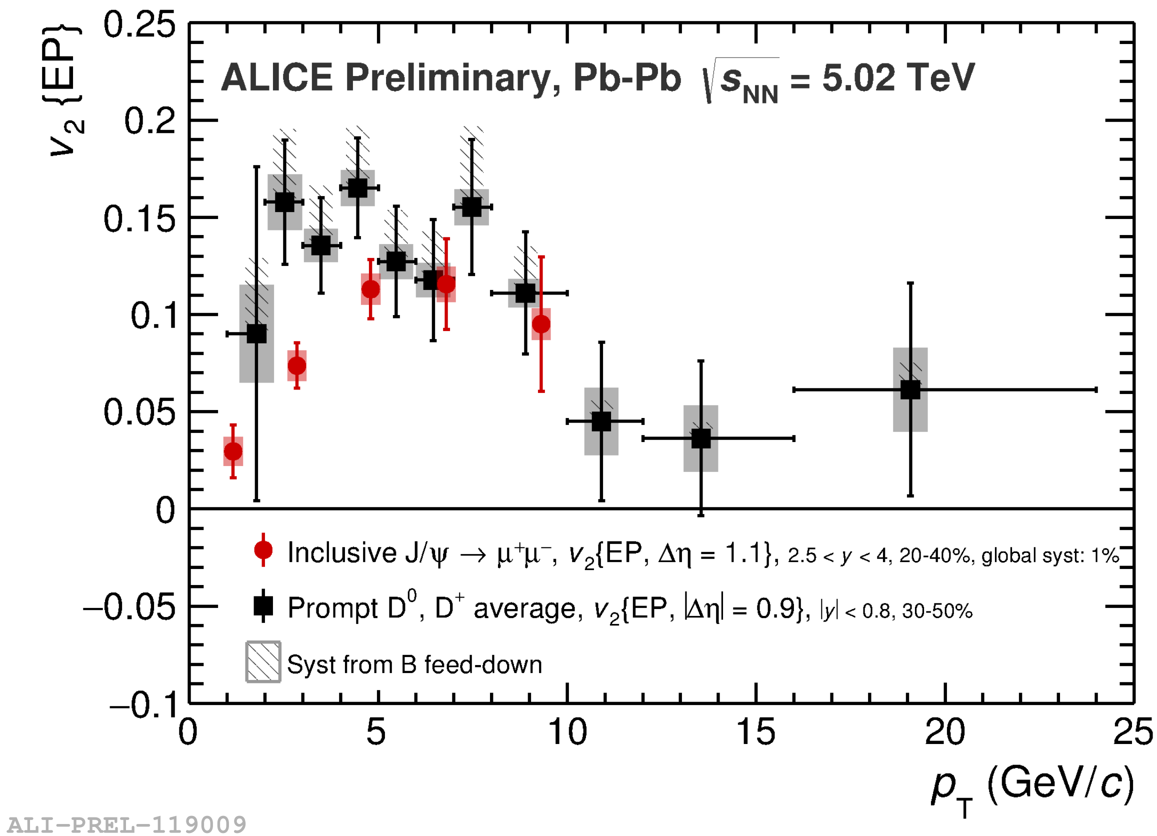



- Very different behaviour between LHC and RHIC (*vs* both centrality and $p_T$)
  →most straightforward explanation: **c-cbar recombination at LHC**!
- Results at 5.02 TeV → small further increase?

Transport models can describe suppression for central collisions

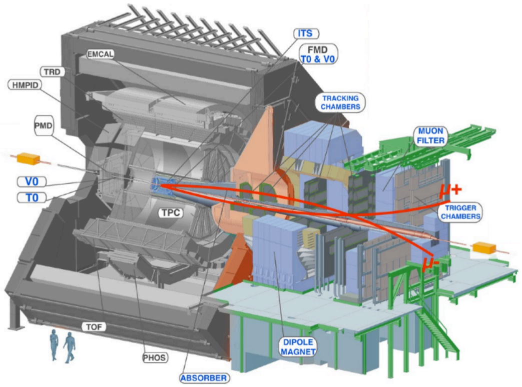
# Elliptic flow of J/ψ and D mesons

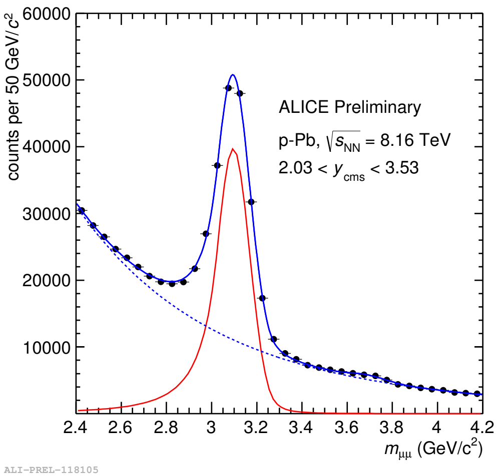


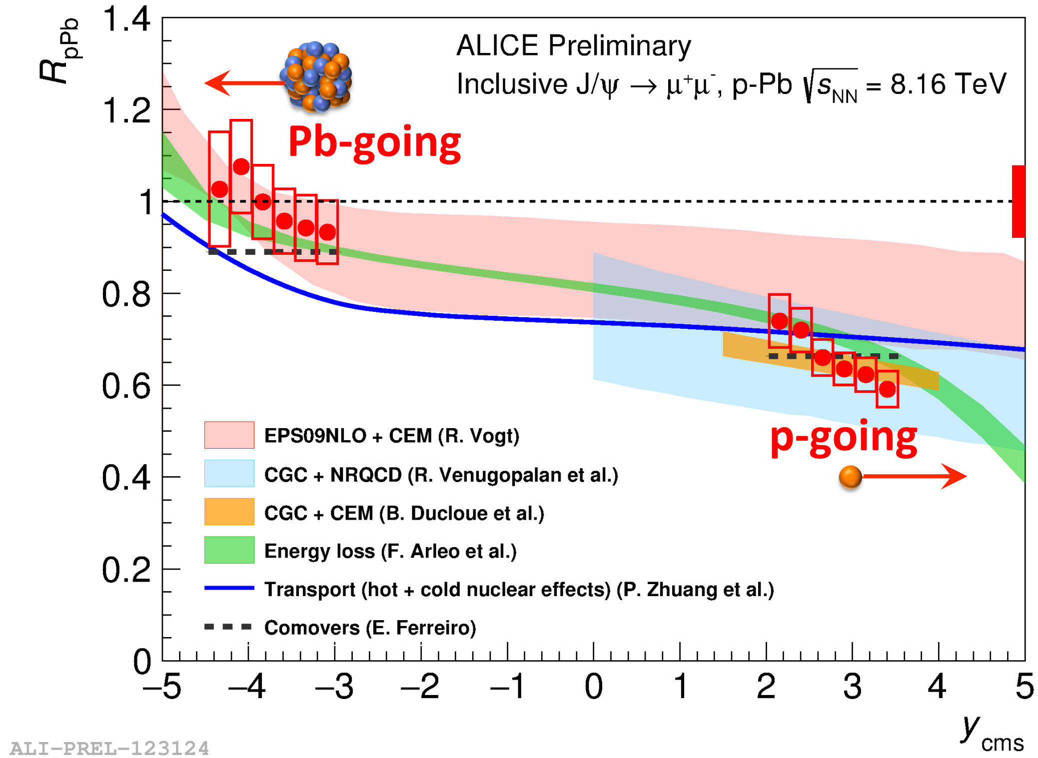

- **charm quark flow at the LHC energies!**
  - seen for J/ψ and open heavy-flavor D mesons
- should help constrain the hadronization mechanisms with the c-quark

# J/ψ production *vs* rapidity in **p-Pb at $\sqrt{s_{NN}}$=8 TeV**

ALICE-PUBLIC-2017-001



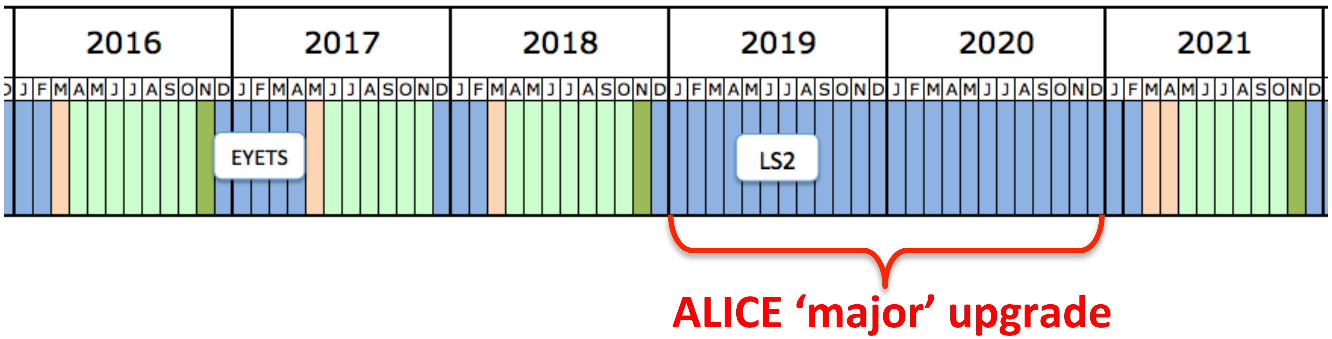




- suppression in p-going direction
- $R_{pPb}$≈1 in Pb-going direction

- models (shadowing, energy loss, CGC) describe the $y_{cms}$ dependence

# Upgrade of the ALICE detector


**Main physics goals:**

- dynamics of heavy flavour and quarkonia at very low-$p_T$
  thermalisation, recombination
- vector mesons and low-mass di-leptons
  chiral symmetry restoration, virtual thermal photons
- precise measurement of light nuclei and hypernuclei

**Main detector requirements:**

- high tracking efficiency and resolution at low $p_T$
  increase granularity, reduce material thickness
- high-statistics, untriggered data sample
  increase read-out rate, reduce data size (online data reduction)
- preserve excellent particle ID capabilities
  consolidate and "speed-up" PID detectors

# Upgrade of the ALICE detector


**New Inner Tracking System (ITS)**
- improved pointing precision
- less material → thinnest tracker at the LHC

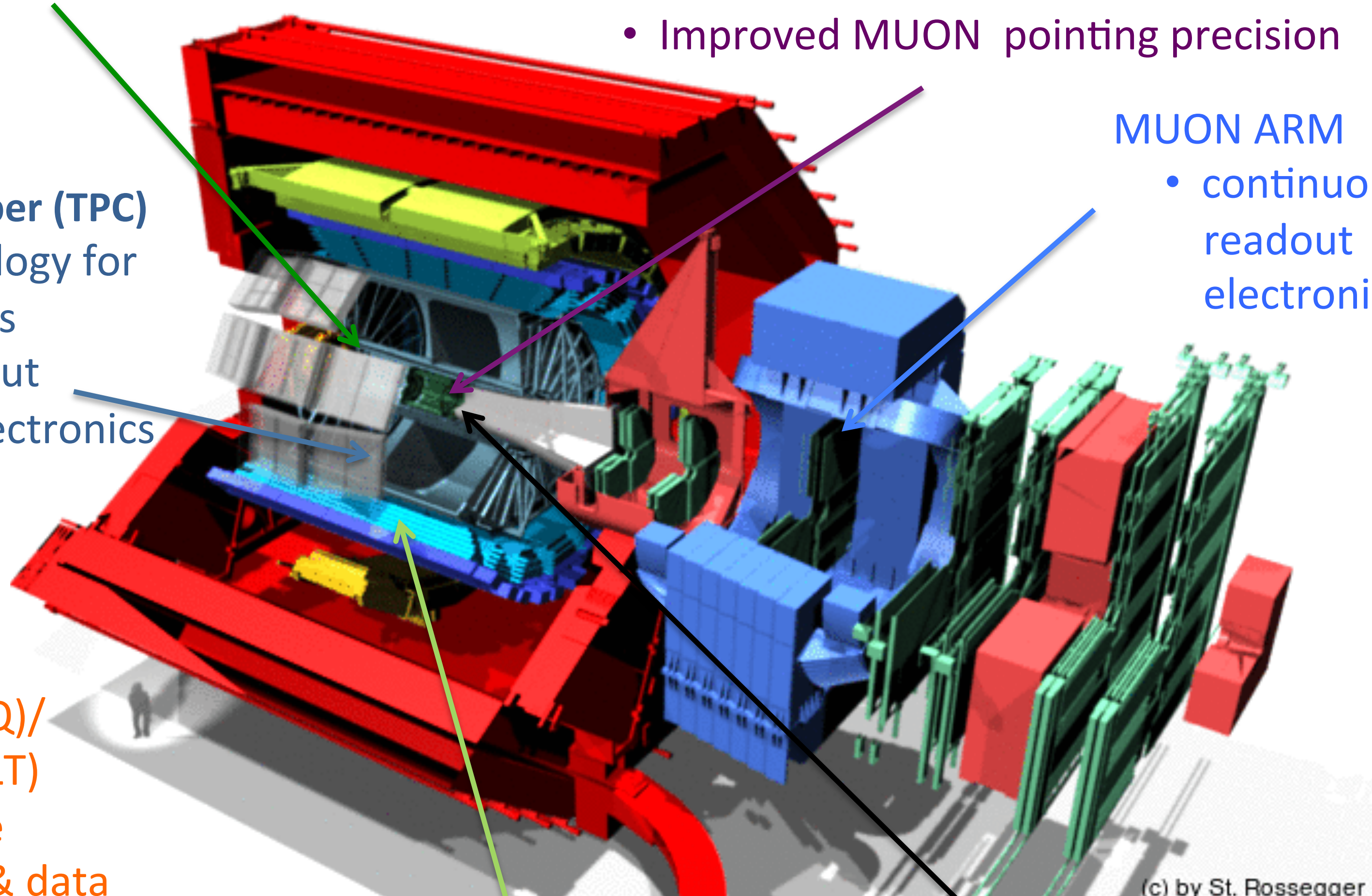
**Muon Forward Tracker (MFT)**
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

**Time Projection Chamber (TPC)**
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

New Central Trigger Processor

Data Acquisition (DAQ)/
High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pb-Pb event rate




(c) by F.Antinori

TOF, TRD, ZDC
- Faster readout

New Trigger Detectors (FIT)

# Summary

- Hadron yields in Pb-Pb are probably affected by **rescatterings after chemical freeze-out**
- **Strong suppression at high-$p_T$** with no dependence on mass, baryon number, quark content

- **Enhanced production of strange and multi-strange hadrons in high-multiplicity pp collisions**
- **Baryon-baryon anti-correlations in pp are observed**, not reproduced by MC models
- More hints on collective phenomena in p-Pb

- Azimuthal flow is described by hydrodynamics at low-$p_T$, **$v_2$ is observed for deuterons**
- Measurements of **e-by-e flow harmonics correlations** – stronger constraints on IS models

- **J/ψ regeneration in Pb-Pb**, increased at 5.02 TeV
- **First direct evidence of charm $v_2$ at LHC energies**

… a lot of interesting results didn't fit into this talk.

**Upgrade programme: installation of upgraded detectors in 2019-2020**

*Thank you for attention!*

# Backup slides

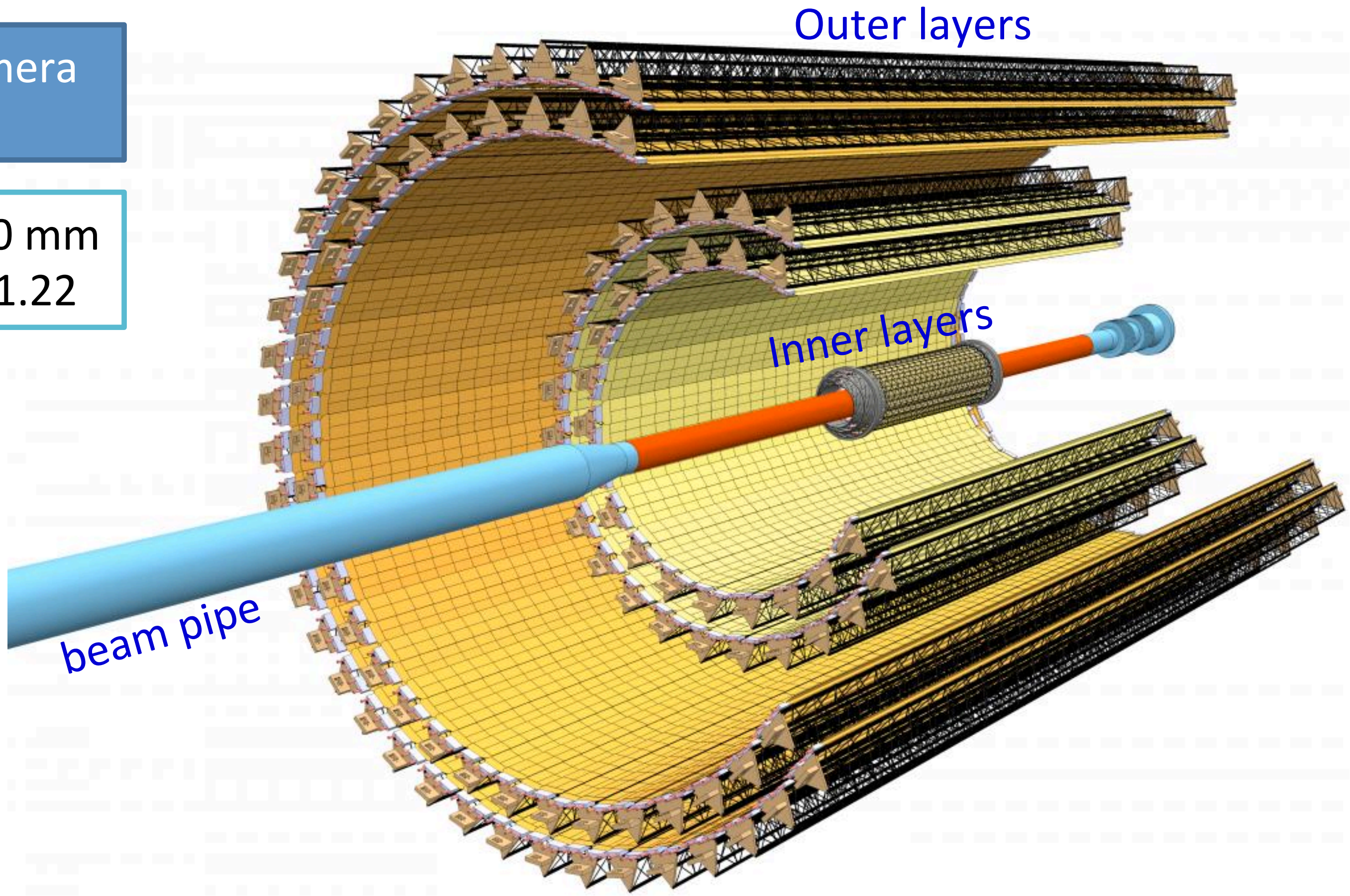
# New ALICE Inner Tracker System

ALICE-TDR-017

7-layer barrel geometry based on CMOS sensors

12.5 G-pixel camera
(~10m²)

r coverage 23-400 mm
η coverage: |η|≤1.22

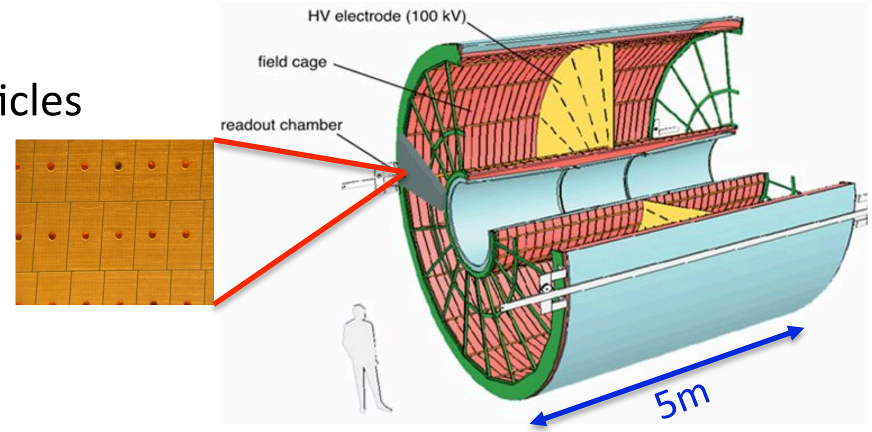



3 Inner Barrel layers (**IB**)
4 Inner Barrel layers (**OB**)
Material / layer: 0.3% $X_0$ (IB), 1% $X_0$ (OB)

# Upgrade of TPC readout system

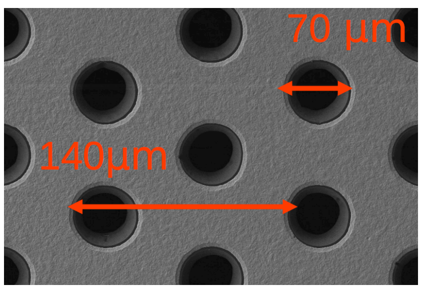
***Current TPC:***

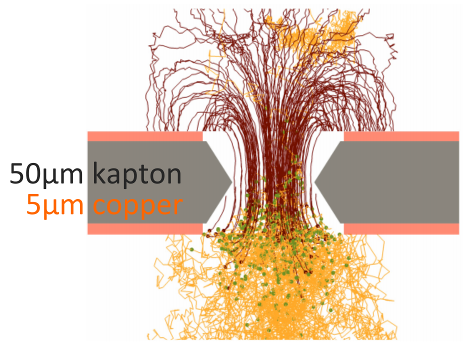
- designed to measure up to 20000 charged particles in a central Pb-Pb collision
- **MWPC** readout
- Limitation from ion backflow:
  max. readout rate is **~3.5kHz**

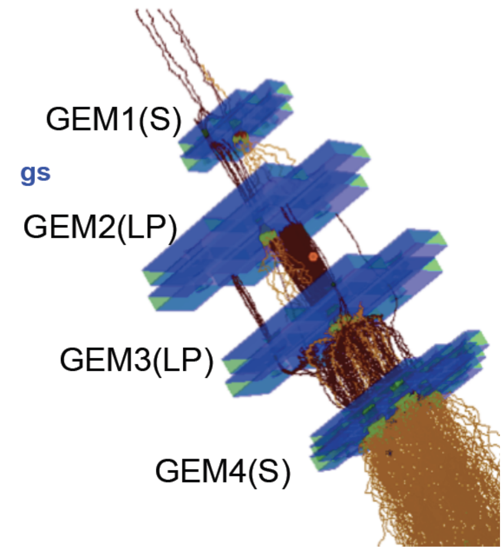



***Upgrade:*** readout chambers with Gas Electron Multipliers (**GEMs**)

ALICE-TDR-016



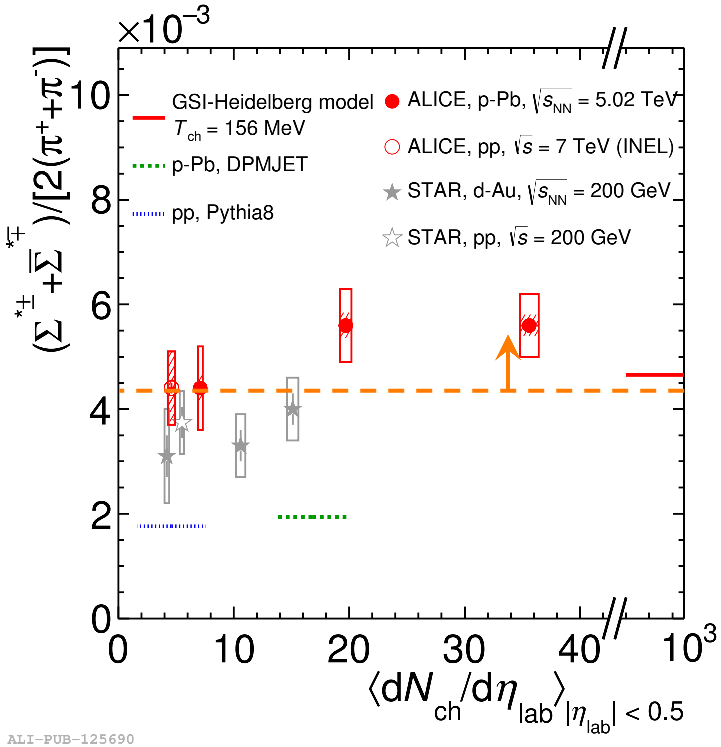

- continuous readout
- collision rates of 50 kHz in Pb-Pb beyond 2019
  - expected average pileup of 5 events
  - online reconstruction and data compression by a factor of 20
- *Drawback*: higher ion backflow (~1%)

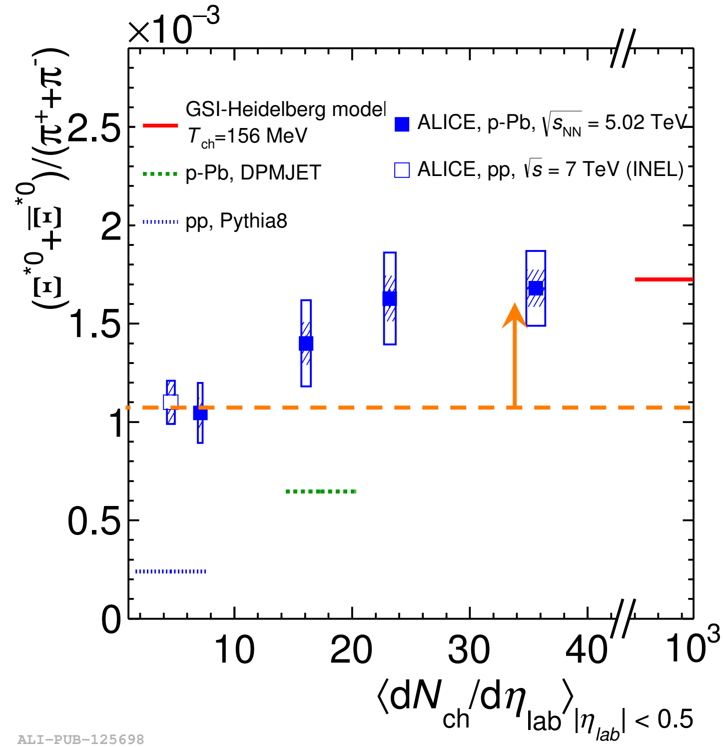
- preserve momentum resolution for ITS+TPC tracks
- preserve particle identification via d*E*/dx

Main components of the existing TPC will be reused

# Hyperon resonances in p-Pb

arXiv:1701.07797

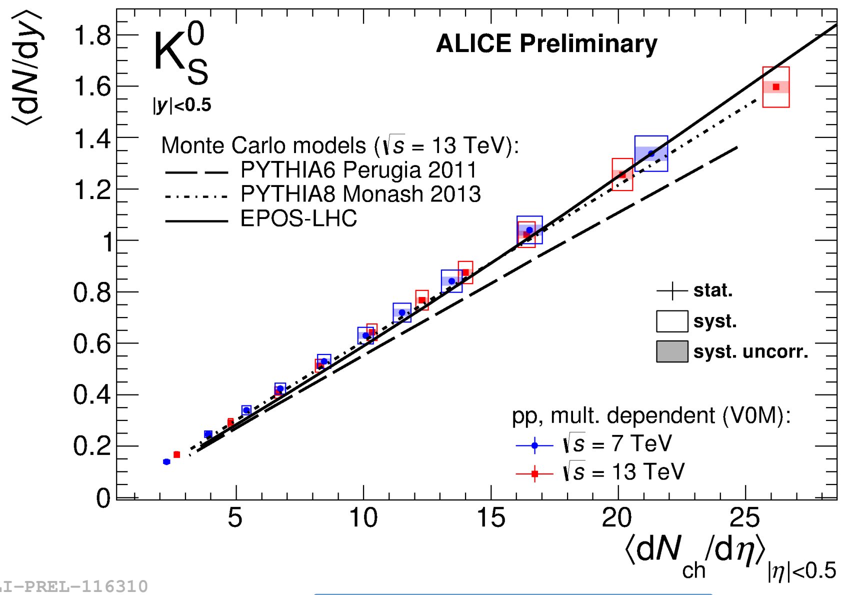


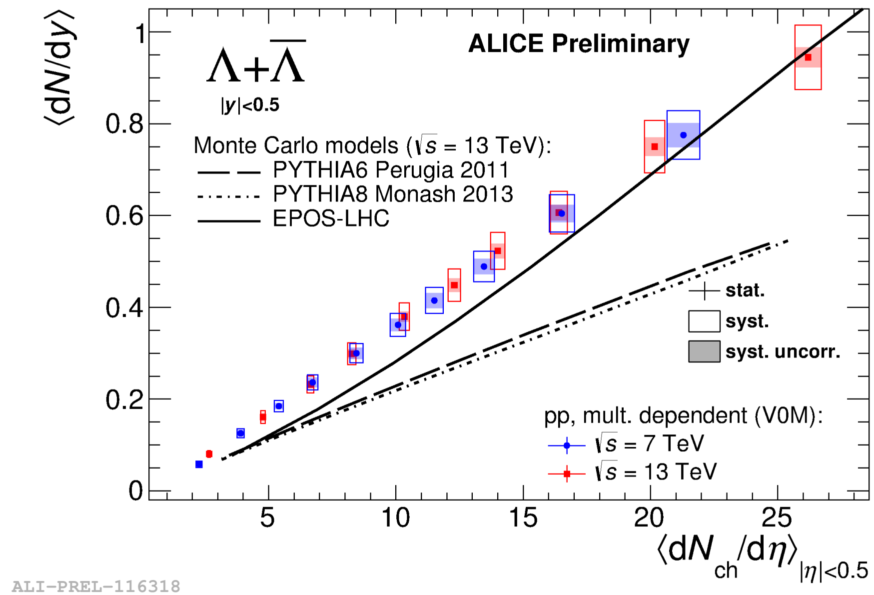




Results for $\Sigma^{*\pm}$ (strangeness S=1) and $\Xi^{*0}$ (strangeness S=2) in p-Pb collisions at 5.02 TeV **confirm findings of a strangeness-related increase of yields in small systems.**

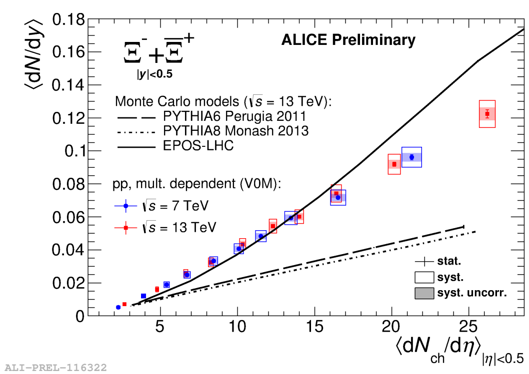
# Multiplicity dependence of strangeness production vs √s

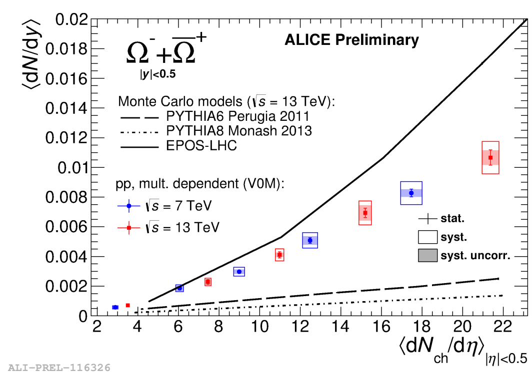
Strange hadron production with ‹$dN_{ch}/d\eta$›: **same scaling at different √s**




Same for Ξ and Ω!

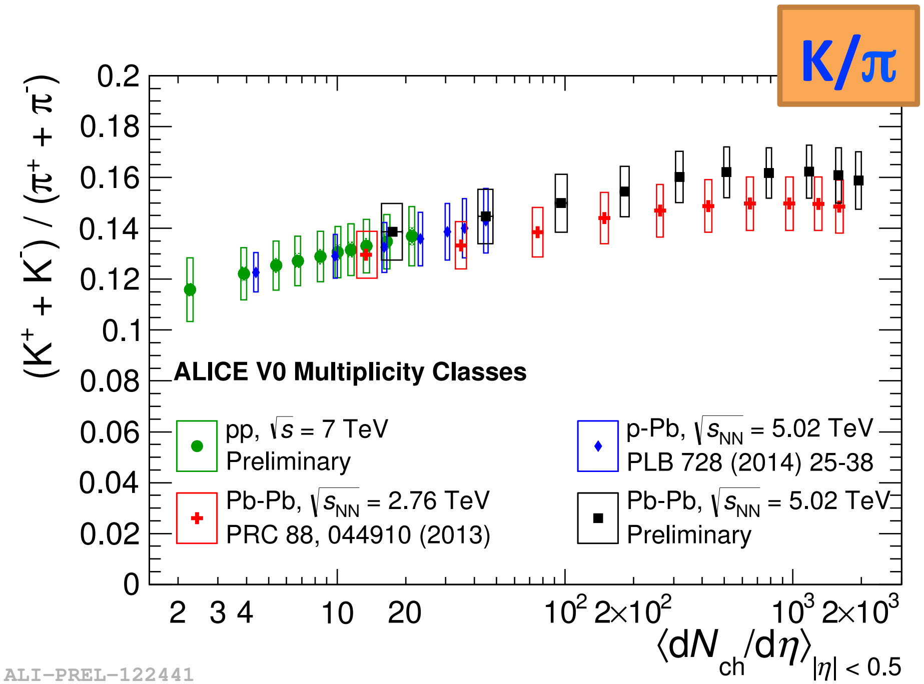


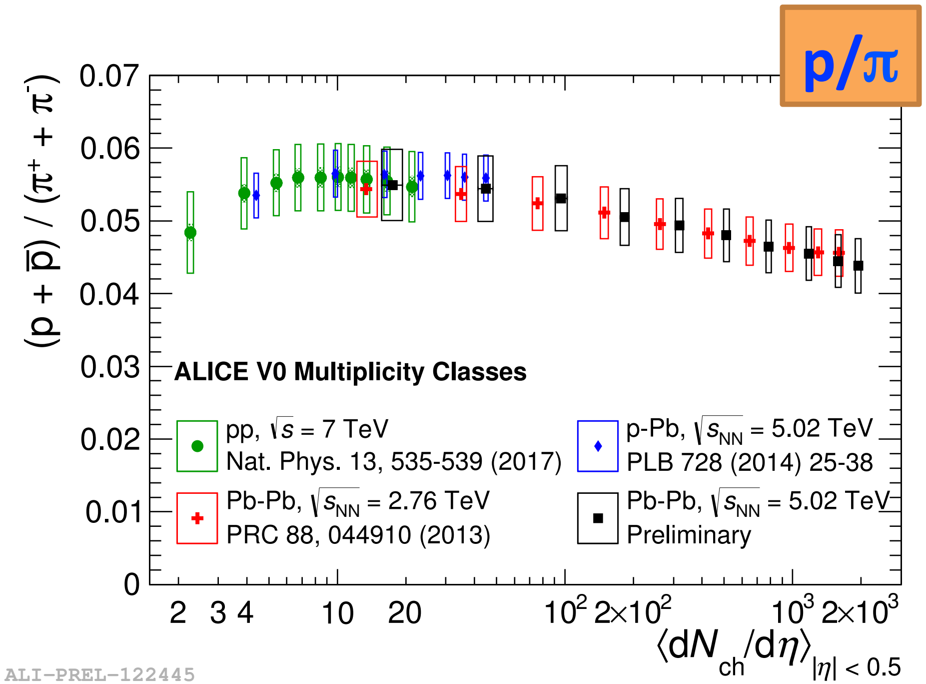




Hadronic chemistry is driven by event activity, irrespective of the collision energy!

MC models poorly describe ratios of integrated yields

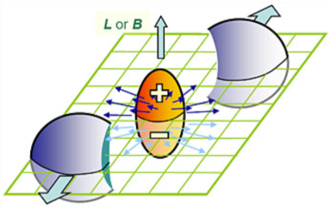
# Ratios of integrated yields: multiplicity dependence




- **Smooth evolution** of K/π and p/π ratios across different systems
- Same values for high multiplicity pp, p-Pb and peripheral Pb-Pb
- No significant evolution in Pb-Pb collisions from 2.76 to 5.02 TeV

# Study of Chiral Magnetic Effect with Event Shape Engineering




Interaction of quarks with QCD domains and magnetic field B
→ spin alignment and induced electric field
→ In experiment: charge separation perpendicular to the reaction plane

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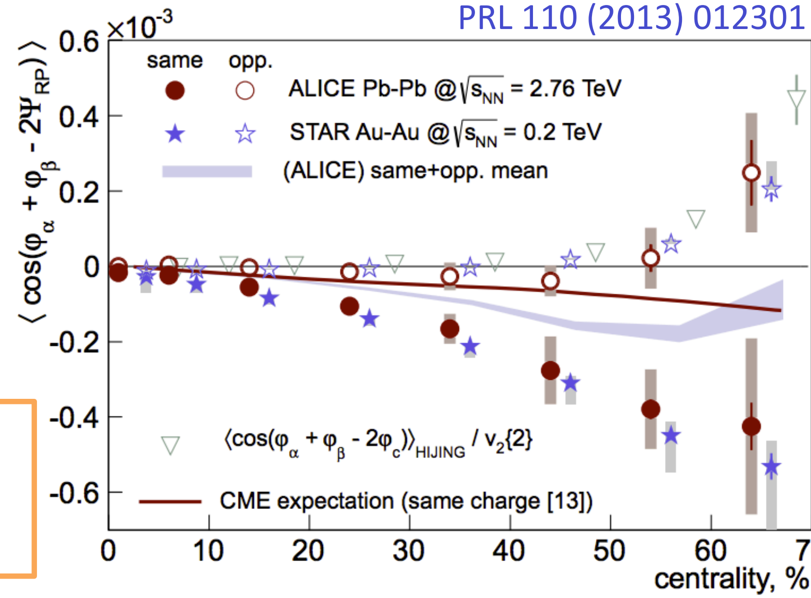


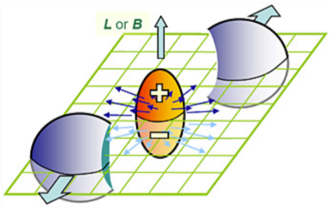

3-particle correlator:

$$\gamma_{ab}=\langle\cos(\varphi_a+\varphi_b-2\Psi_2)\rangle\approx-\langle a_{1,a}a_{1,b}\rangle+B_{in-plane}-B_{out-plane}$$

Interpretation is complicated by **background contributions**
→ use **Event Shape Engineering** technique to disentangle them from potential CME signal

# Study of Chiral Magnetic Effect with Event Shape Engineering



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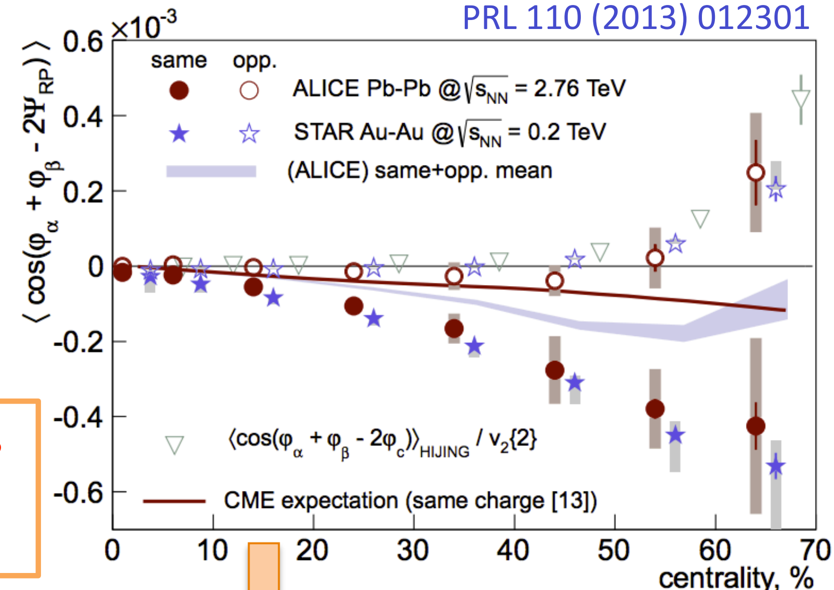
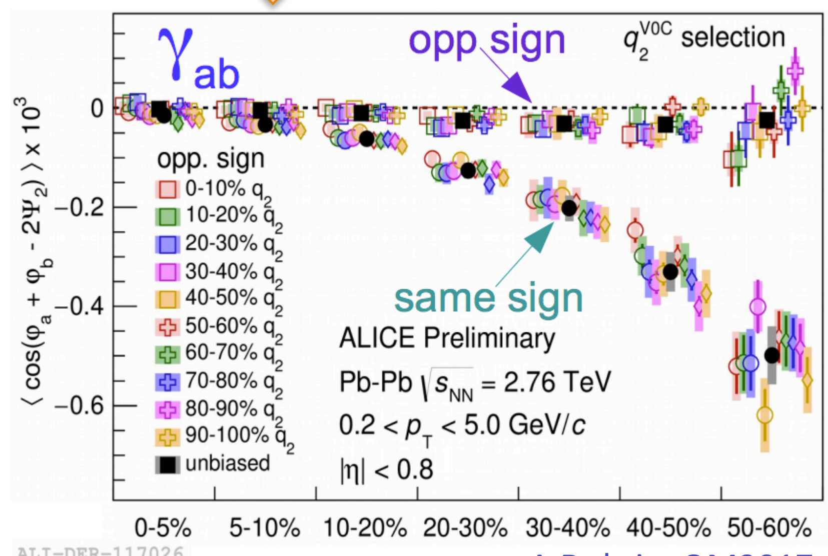



Event Shape Engineering:

use classification by $q_2^{V0C}$ to select with **larger or smaller $v_2$ within each centrality class**

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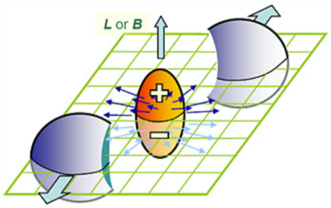
# Study of Chiral Magnetic Effect with Event Shape Engineering

Pb Pb

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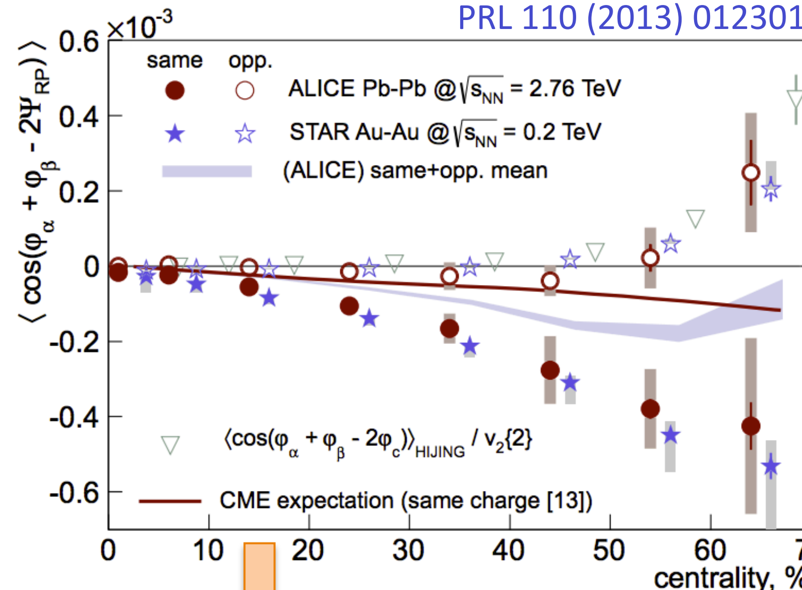
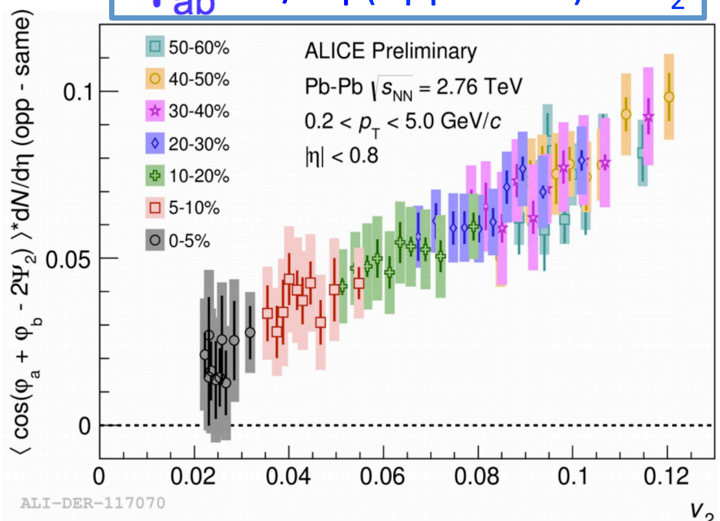
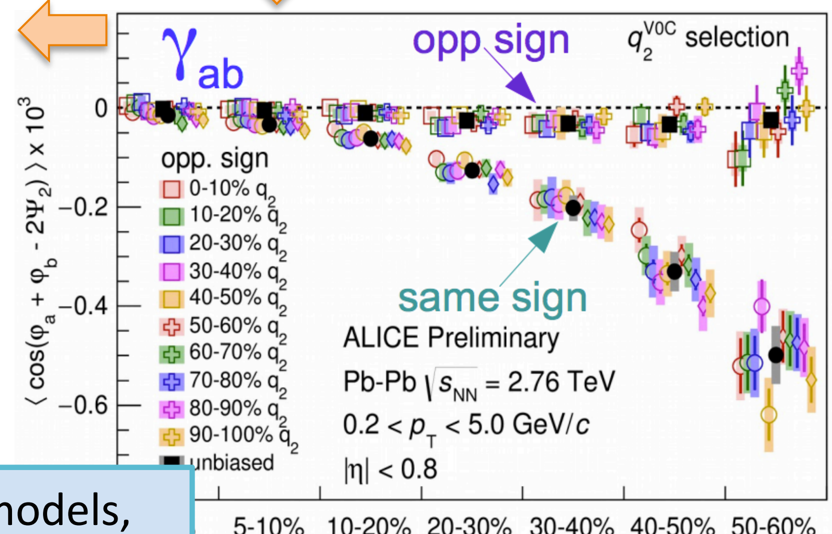



$\gamma_{ab}$*dN/dη (opp-same) *vs* $v_2$




Difference is positive and ~scales with $v_2$ and multiplicity → mostly background contribution

After studies of magnetic field *vs* $v_2$ in initial state models,
upper limit for CME fraction is <30% in centrality class 10-50%

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