[A selection of…]

Recent results from the ALICE experiment at the LHC

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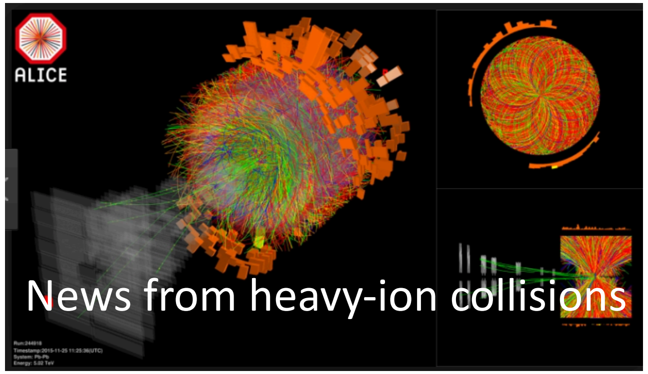
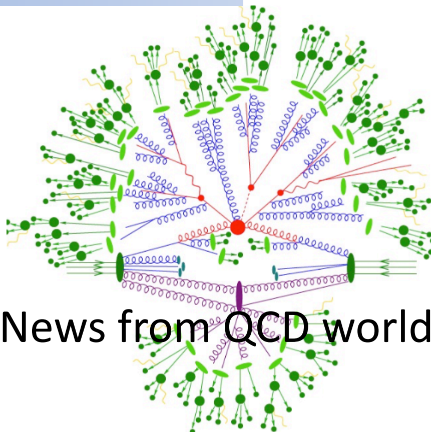
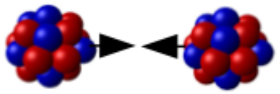
INFN - Bologna





The standard heavy-ion collisions movie

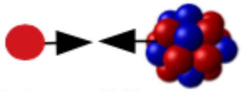


In heavy-ion collisions (HIC) we realize high density / energy conditions
→ Strongly interacting matter → study of a deconfined state of matter (QGP)

HIC as **door** to a wonderland of **collective** phenomena (a plasma!) and unseen QCD properties

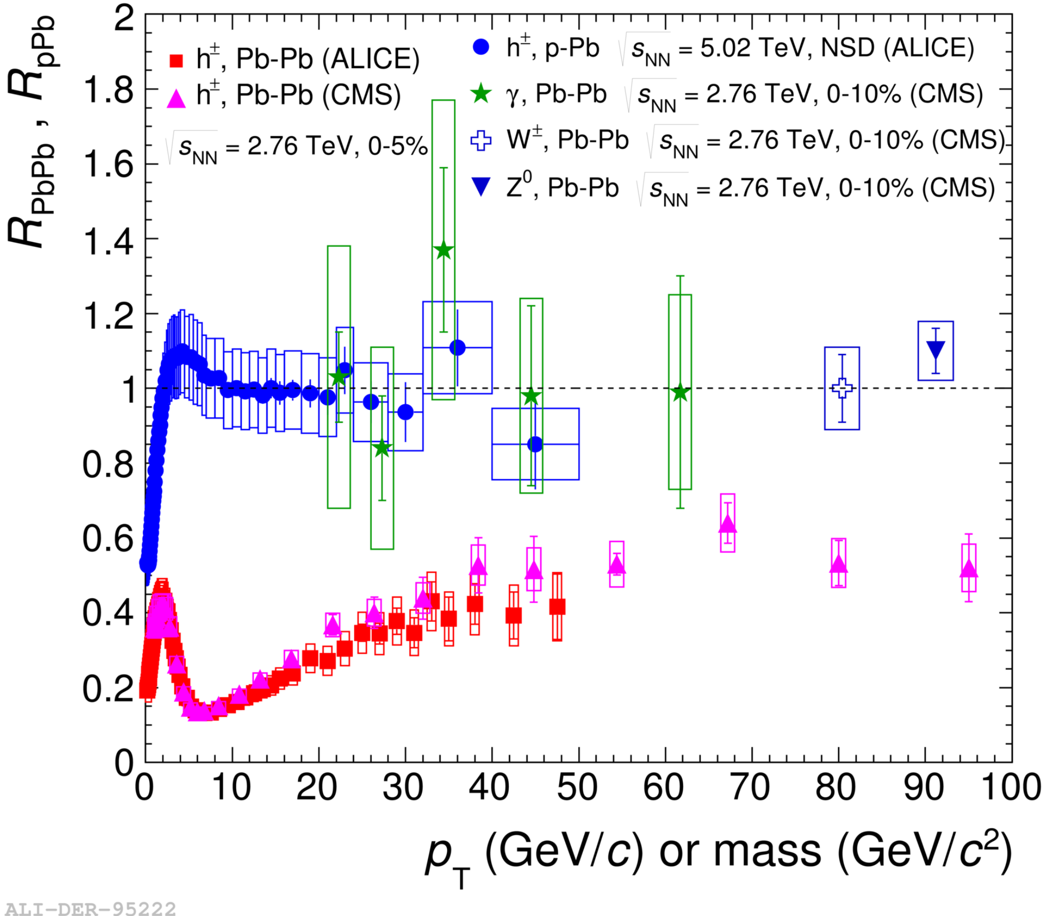
But…. We need a **"baseline reference"** to check differences…
→ pp collisions needed to study nuclear modification factor, particle production, tune MC…

$$R_{AA}(,p_T)=\frac{1}{N_{coll}}\times\frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

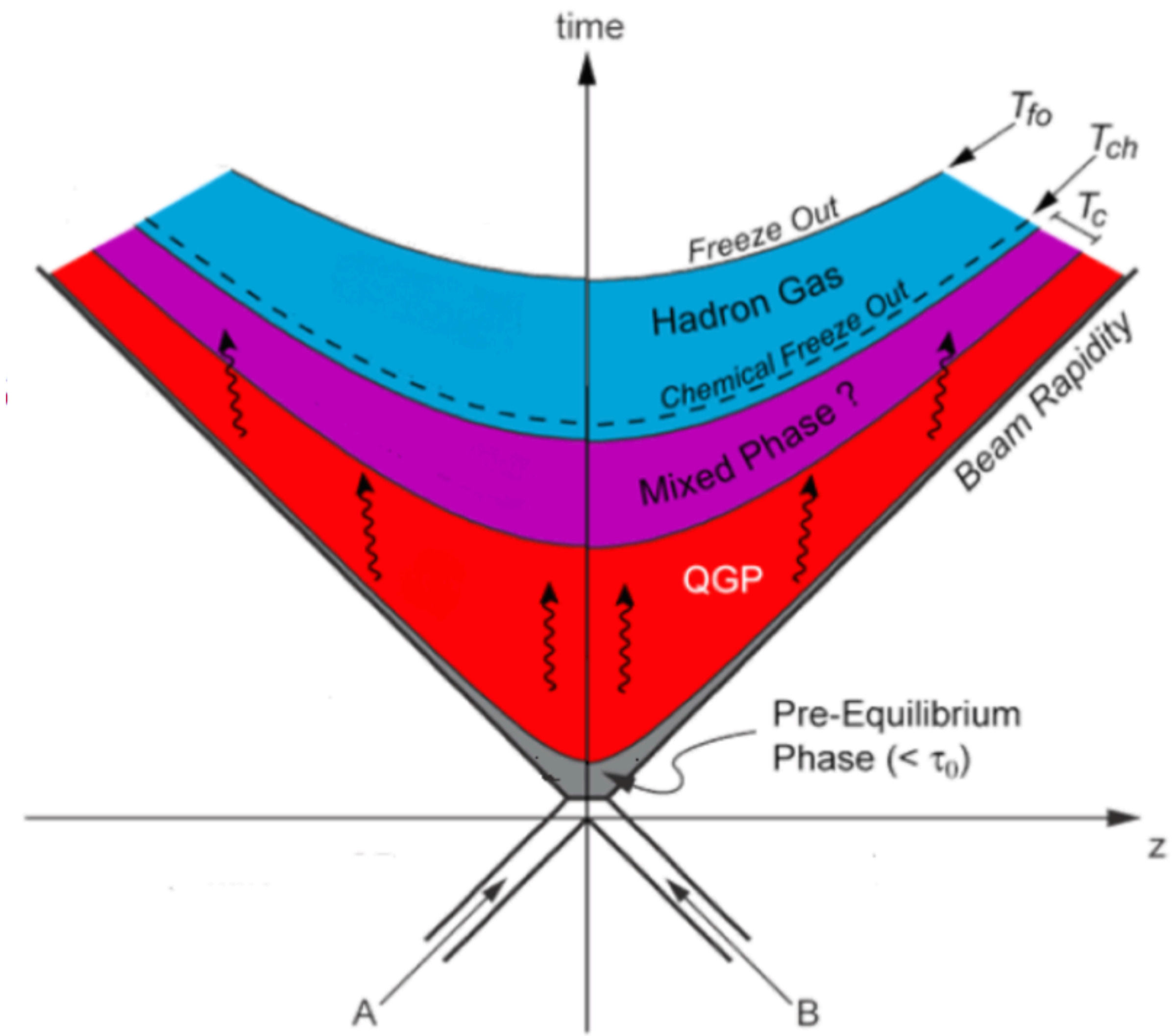


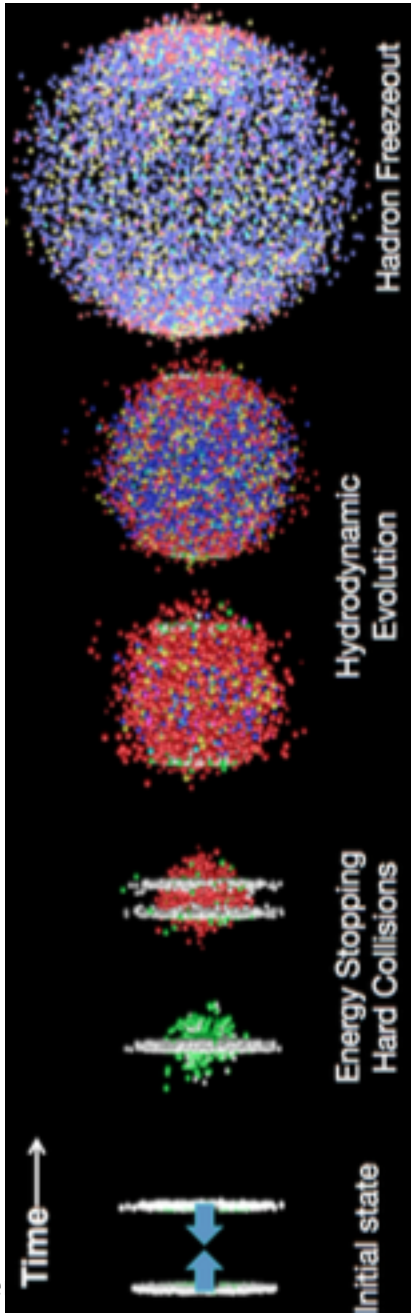
And…. we need to get rid of any "trivial nuclear effect" that could mud
→ p-A collisions needed to disentangle initial/final state effects
→ p-A collisions are our **control** experiment

EPJ C 74 (2014) 3054 (CMS (Z^0): JHEP 03 (2015) 022)



The movie plot: heavy ion collision





- Thermal freeze-out: no elastic interaction → momentum spectra "fixed"
- Chemical freeze-out → Particle abundances "fixed"
- Thermalization time

Bulk of matter produced in the collision can be described in terms of hydrodynamics:

- Strongly interacting matter
- Rapid expansion & cool down
- Collective flow develops

- Signatures:
  - particle correlations, anisotropic flow
  - p_T yields mass dependent
  - energy losses

This movie follows this empirical QGP script…

(script courtesy by M. Gyulassy famous paper **“The QGP discovered at RHIC”** arXiv:nucl-th/0403032)

2. The Empirical QGP

The discovery of the gedanken QGP phase of matter in the laboratory requires an empirical definition of the minimal number of necessary and sufficient conditions in terms of experimentally accessible observables. My empirical definition is summarized by the following symbolic equation

$$\mathrm{QGP} = \mathbf{P}_{\mathrm{QCD}} + \mathrm{pQCD} + \mathrm{dA}\ . \tag{1}$$

Why are three independent lines of evidence needed? The first term, $\mathbf{P}_{\mathrm{QCD}}$, stands for a class of observables that provide information about its bulk thermo-

study ‘bulk’ thermodynamic equation of state

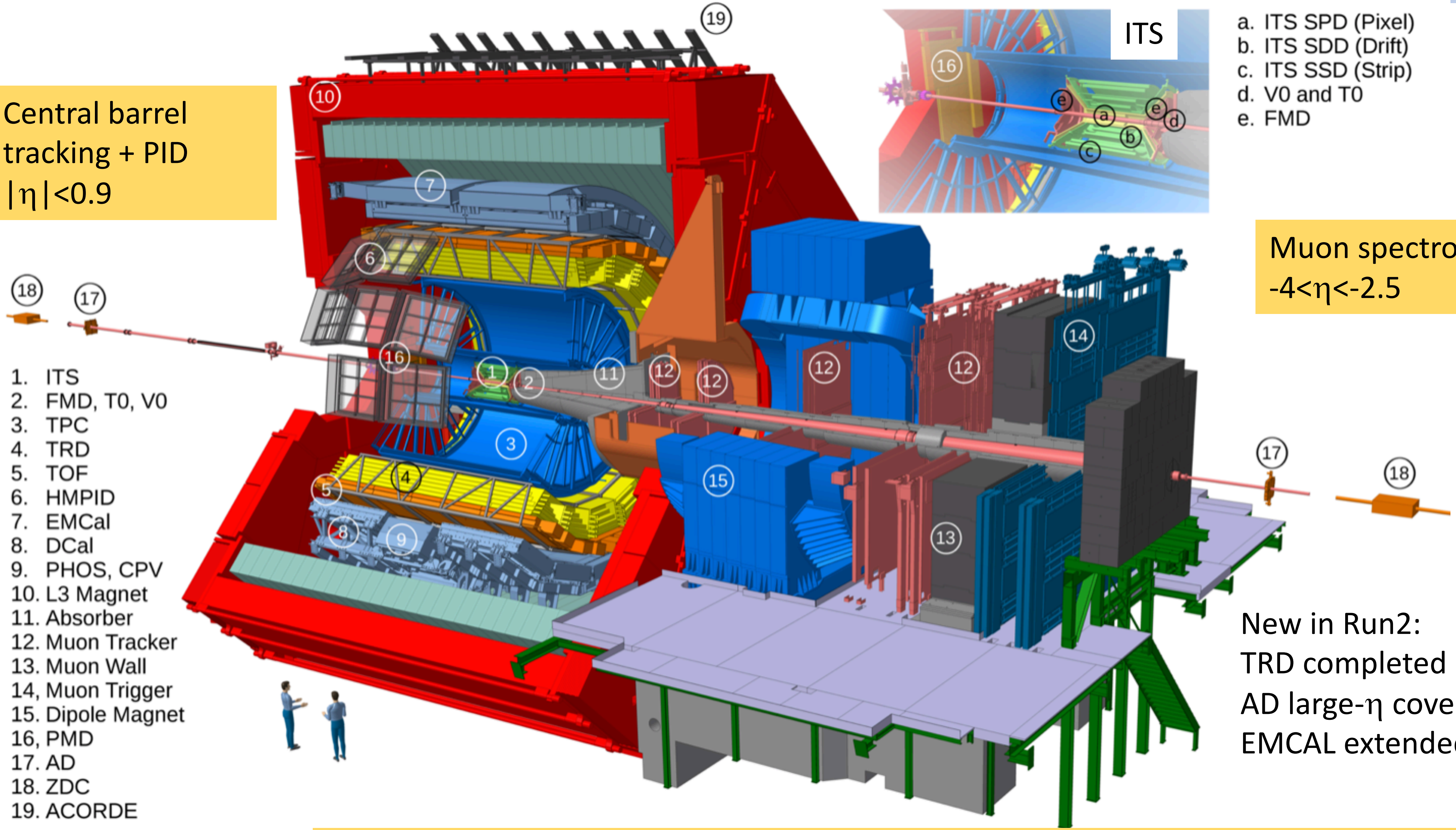
short wavelength dynamics predicted by pQCD: hard processes, jets, HF,...

control

With Run1 ended in 2013 with p-Pb run, LHC experiments (and ALICE) completed first round of data taking to go through this equation (and the script). We completed it with **confirmations**, **surprises** and **puzzles**, discovered also thanks to specific ALICE detector characteristics.

The ALICE detector

Central barrel tracking + PID
$|\eta|<0.9$



a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

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

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

New in Run2:
TRD completed
AD large-η coverage (diffraction)
EMCAL extended (DCal)

Low-momentum tracking and particle identification in a high multiplicity environment

ALICE data taking in Run I

System	Year	$\sqrt{s_{NN}}$(TeV)	L_{int}
pp	2009-2010	0.9	~ 0.15 nb^{-1}
pp	2011	2.76	~ 1.1 nb^{-1}
pp	2010-2011	7	~ 4.8 pb^{-1}
pp	2012	8	~ 9.7 pb^{-1}
p-Pb	2013	5.02	~ 30 nb^{-1}
Pb-Pb	2010-2011	2.76	~ 0.1 nb^{-1}

- All main characters to play our script gathered together to make our movie
- And note large bandwidth for this ALICE movie: 1.25 GB/s for Pb-Pb events

ALICE data taking in Run II so far

System	Year	$\sqrt{s_{NN}}$(TeV)	L_{int}
pp	2015-2016	13	~ 14 pb^{-1}
pp	2015 (4 days!)	5.02	~ 100 nb^{-1}
p-Pb	2016	5.02	~ 3 nb^{-1}
p-Pb	2016	8.16	~ 20 nb^{-1}
Pb-p	2016	8.16	~ 20 nb^{-1}
Pb-Pb	2015	5.02	~ 0.4 nb^{-1}

Targets for Run II:

- pp 13 TeV → reach 40 pb^{-1}
- Pb-Pb → 1 nb^{-1}
- high statistics pp 5 TeV sample (2017) “improve the reference”

More differential studies allowed in Run II (statistics)
Increased center-of-mass energies
Improved detector

A review of selected ALICE results

- Intriguing (and striking) similarities between pp/p-Pb/Pb-Pb collisions
- Traditional signatures of QGP formation (in HIC) seen now in smaller systems
- Collectivity in small systems?

Do we need to change our movie?

Paradigm shift for interpretation of all hadronic collisions?

- Strangeness enhancement
- Identified particle spectra
- Anisotropic flow and correlations
- Heavy flavour production
- Parton energy loss and jets

- The traditional script
- The movie twist (if present)
- The recent result

Strangeness enhancement (I)

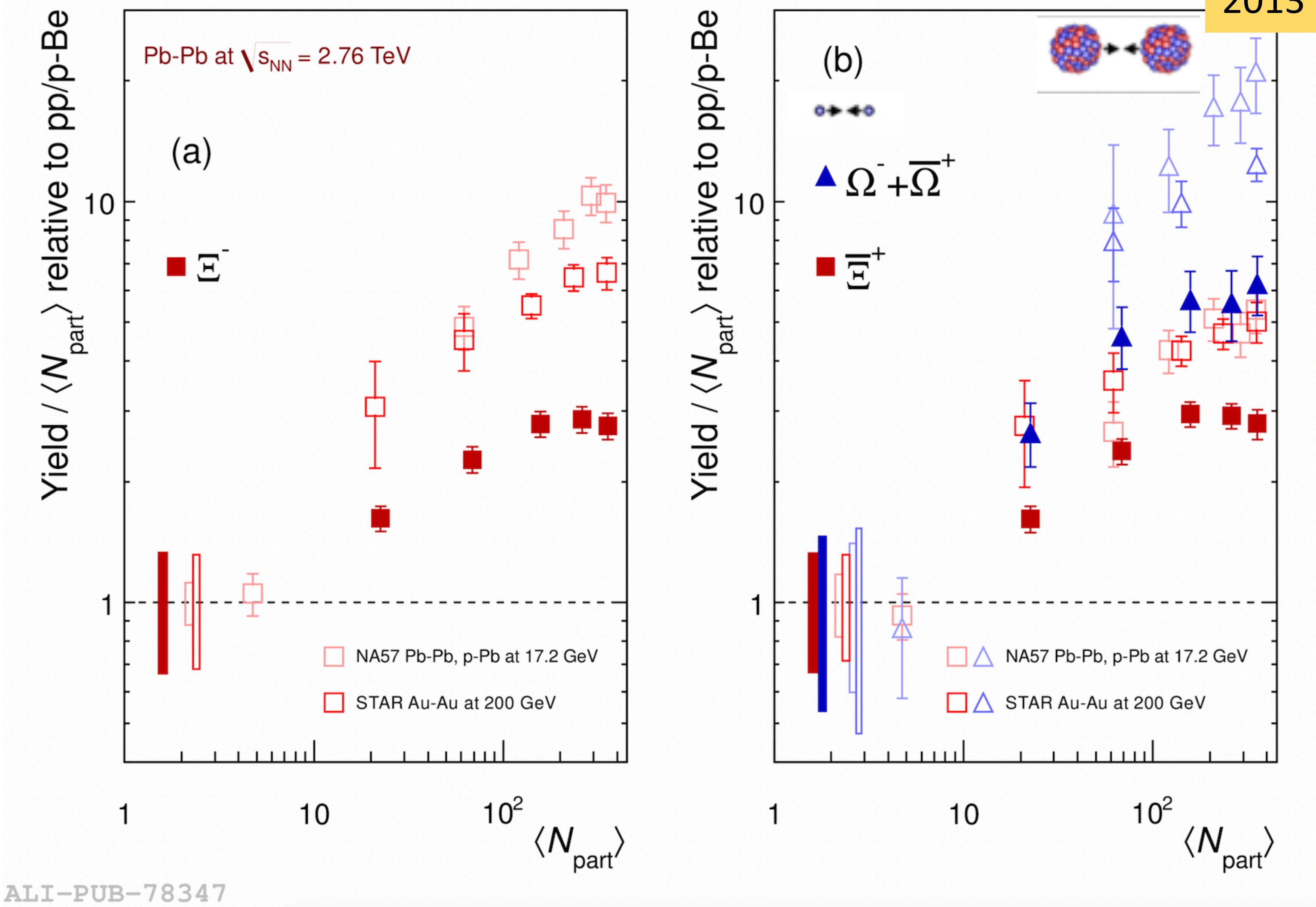
One of the first proposed smoking guns for QGP

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller PRL 48(1982) 1066

PLB 11 (2013) 48

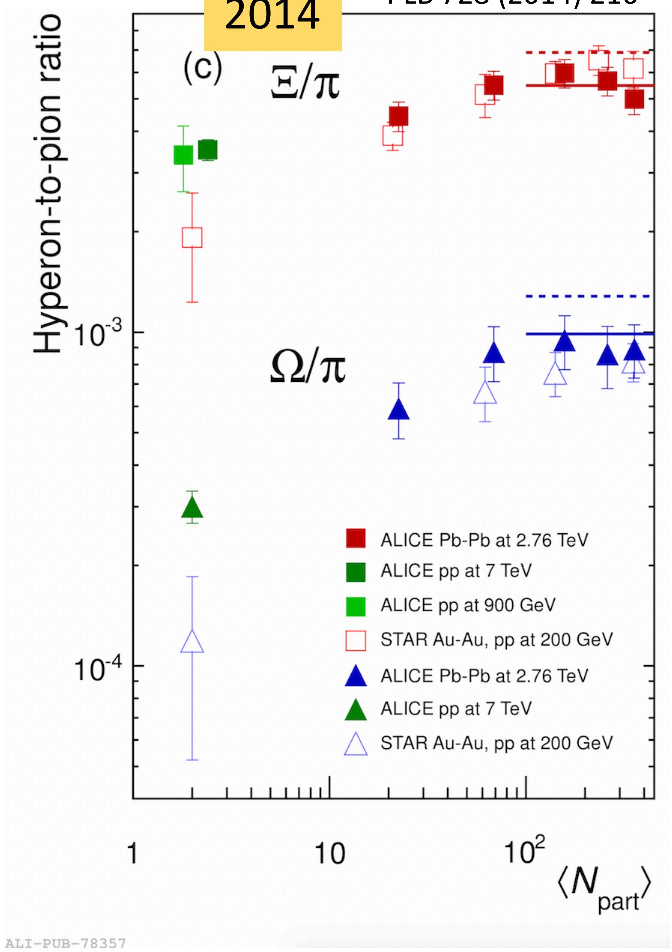
2013

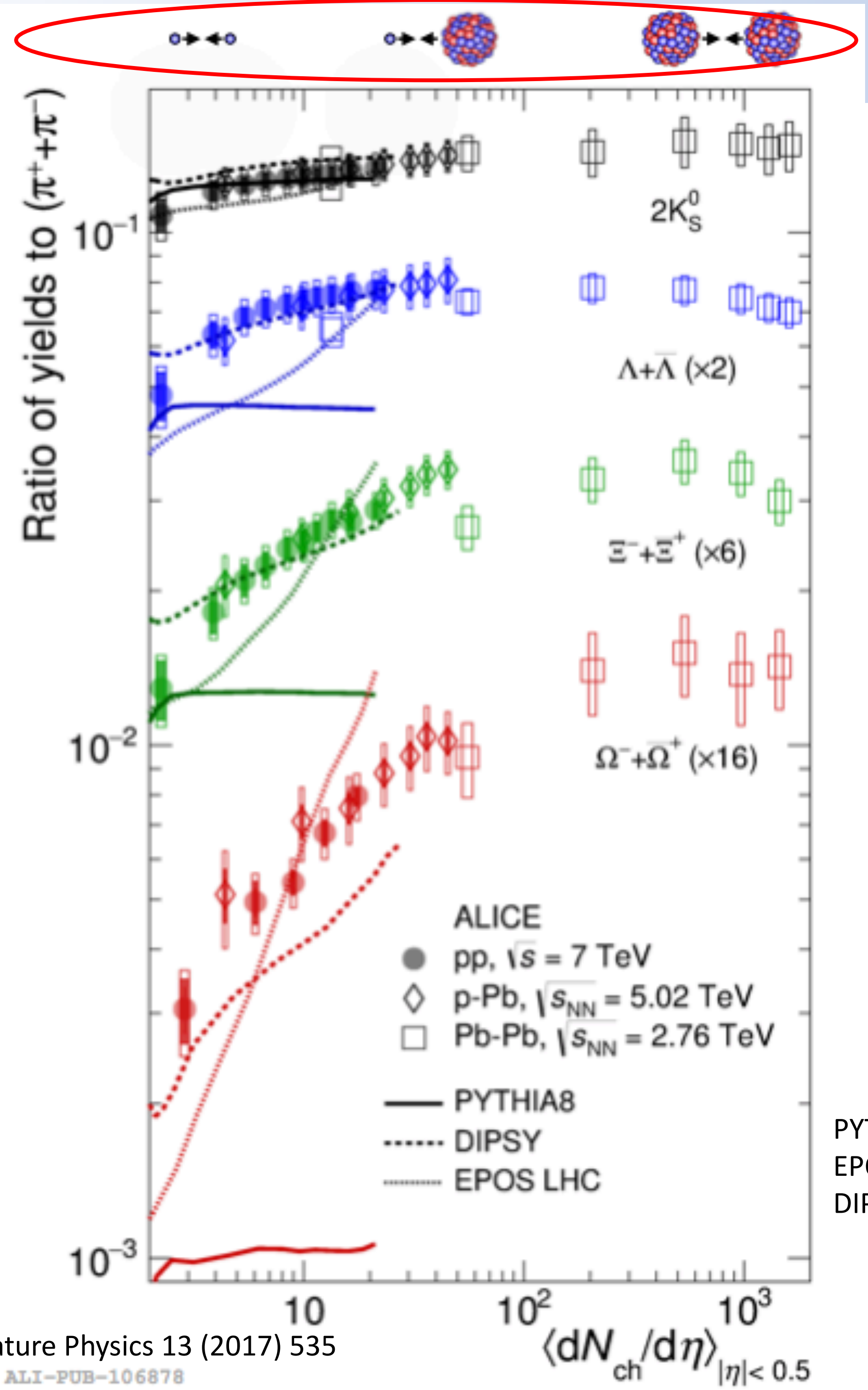


- enhancement confirmed with respect to pp as expected
- hyperon to pion ratio as expected from thermal models and larger at LHC w.r..t. RHIC

2014

PLB 728 (2014) 216





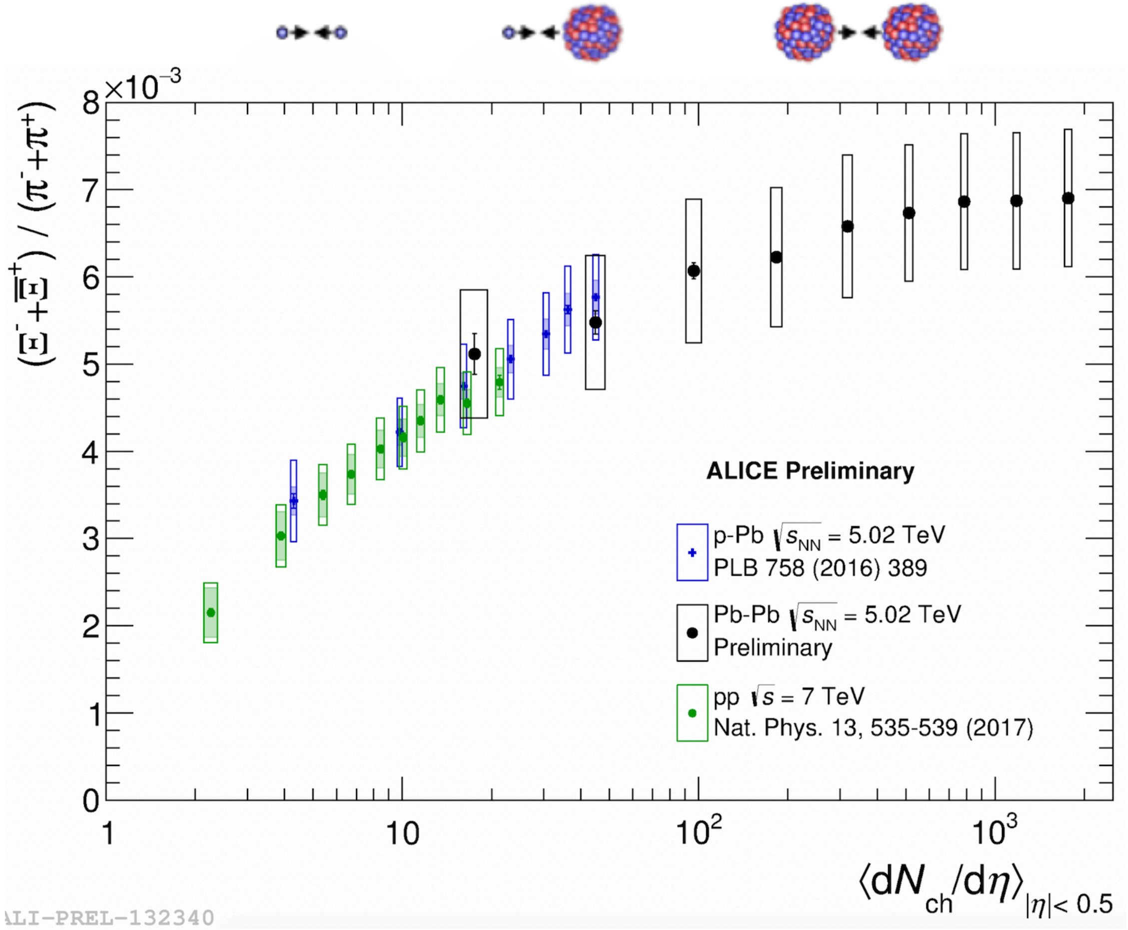
Nature Physics 13 (2017) 535

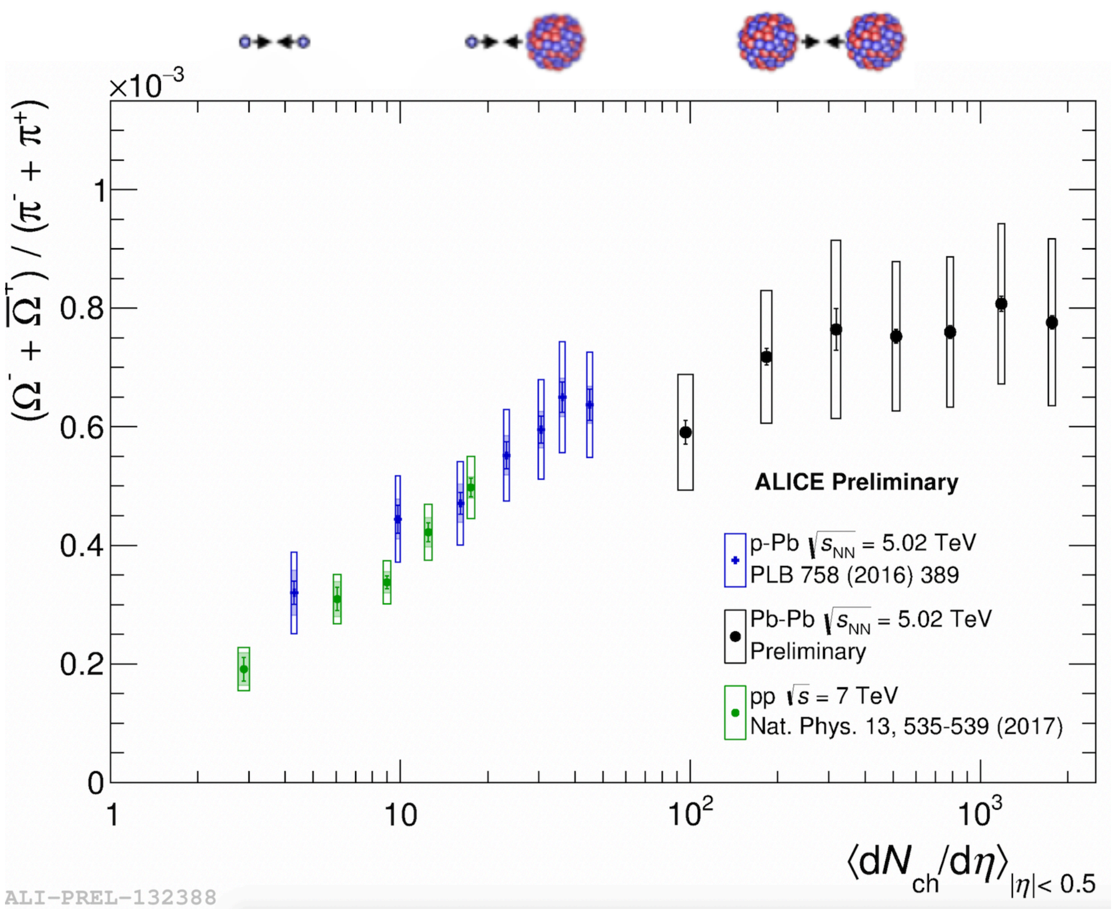
Strangeness enhancement (II)

- Studied via strange to non-strange integrated particle ratios vs <dN_{ch}/dη>
- Evolution of the enhancement driven by particle multiplicity, not by the collision system!
- MC predictions do not describe data
- Not reproduced by QCD inspired models as PYTHIA (note attempts to introduce thermodynamical model in string fragmentation model (Fischer and Sjostrand, JHEP 01 (2017) 140))
- DIPSY with color ropes (establish short range correlations) and EPOS LHC (QGP partially formed in pp) predict some trend similar to what seen in data. DIPSY (color ropes) gives qualitative description

PYTHIA8 Sjöstrand, T. et al, *Comput. Phys. Commun.* 178 (2008) 852
EPOS LHC Pierog T et al., PRC 92 (2015) 034906
DIPSY Bierlich C at al., PRD 92 (2015) 094010

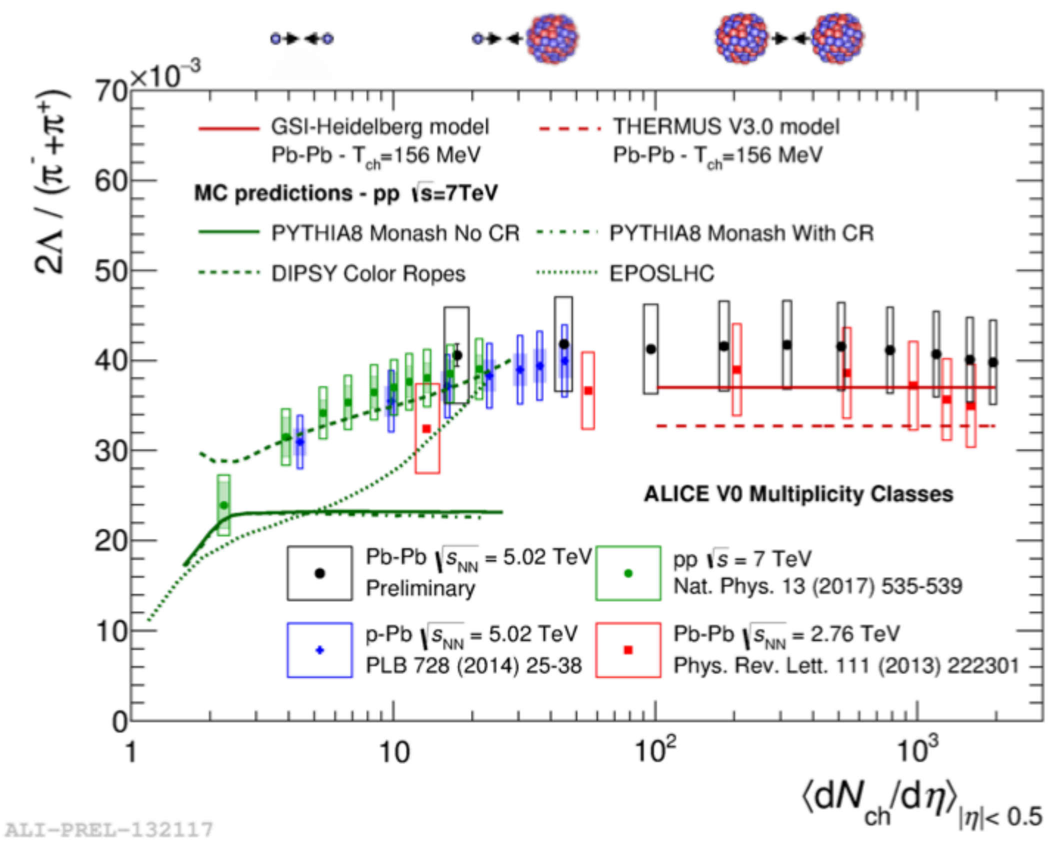
Strangeness enhancement (III)

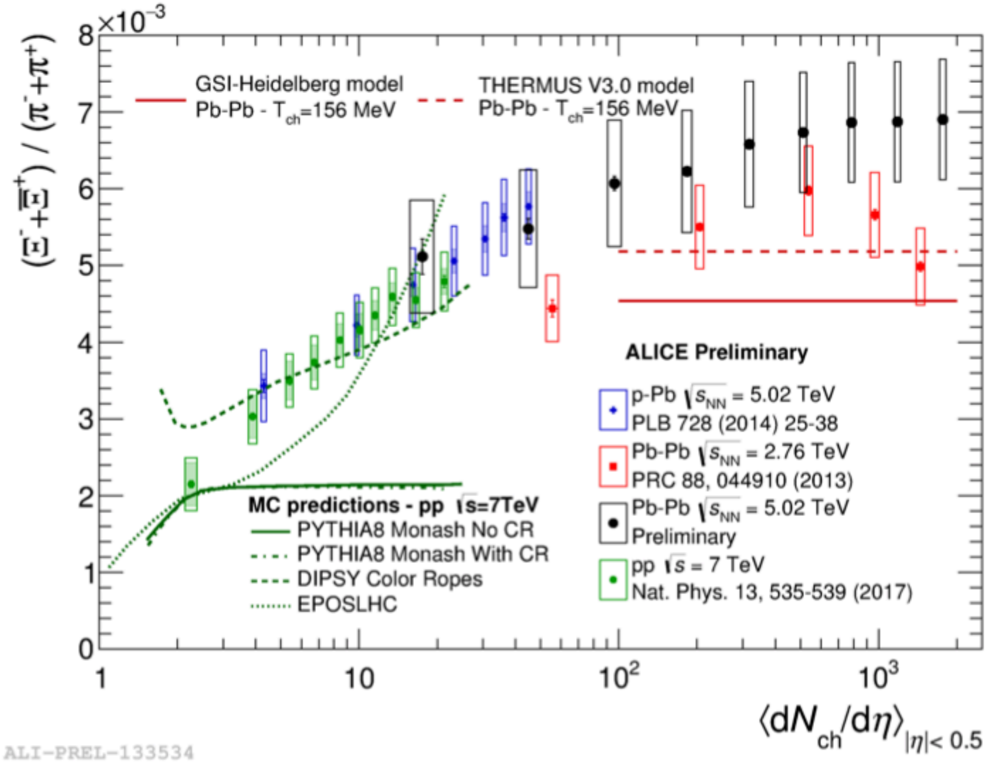




- New results with data from Pb-Pb at $\sqrt{s_{NN}}$=5.02 TeV
- pp ratios at very high pp multiplicity overlaps with peripheral Pb-Pb values…
- Thermal models successful to describe Pb-Pb production (production in thermally equilibrated regime)
  → concepts used now in some models in pp (EPOS)

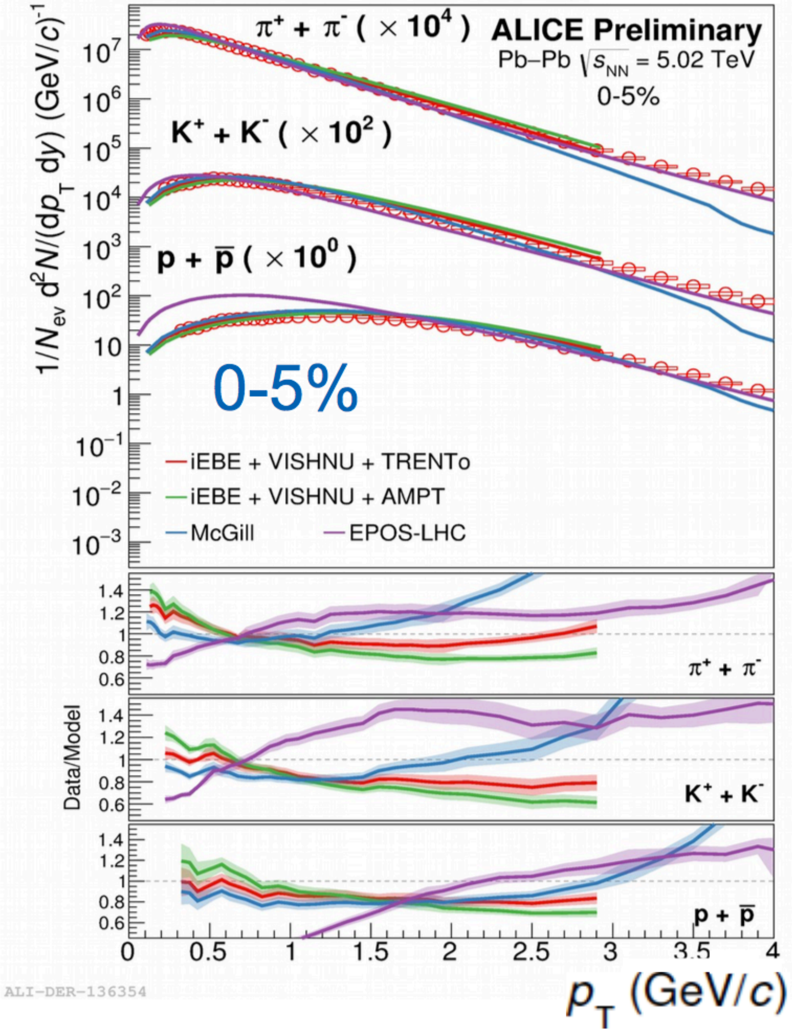
Hadrochemistry

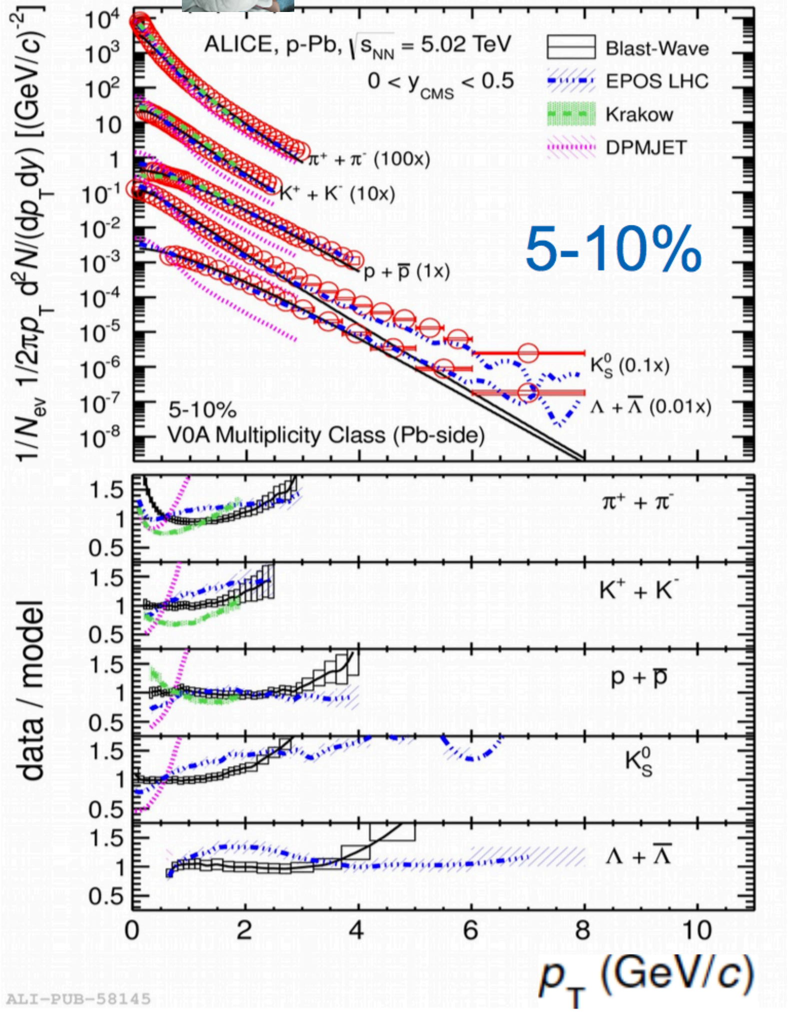


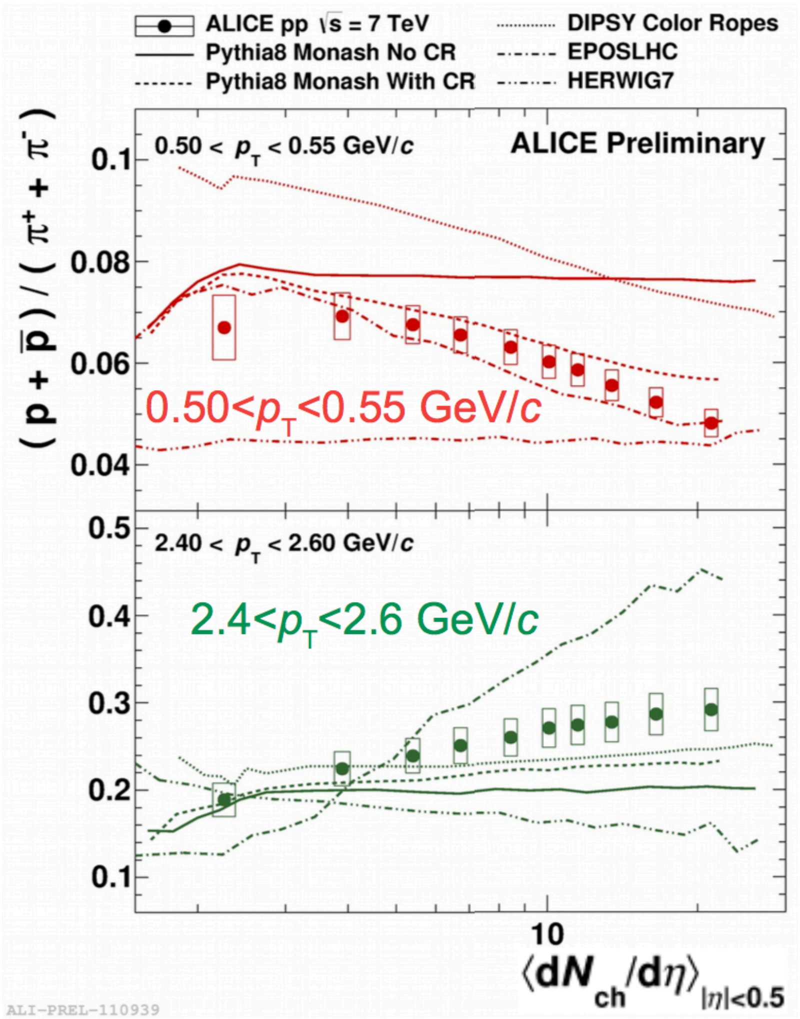


- Baryon-to-meson ratio sensitive to hadronization mechanisms and multiplicity dependent
- p_T integrated yield compatible at $\sqrt{s_{NN}}$=2.76 and $\sqrt{s_{NN}}$=5.02 in PbPb → no evident energy dependence
- Tension with thermal models (if present) to be investigated (note re-analysis of Pb 2.76 TeV for $\Xi^{\pm}$ on-going)
- Testing hydrodynamic and pQCD inspired models

Charged particle spectra





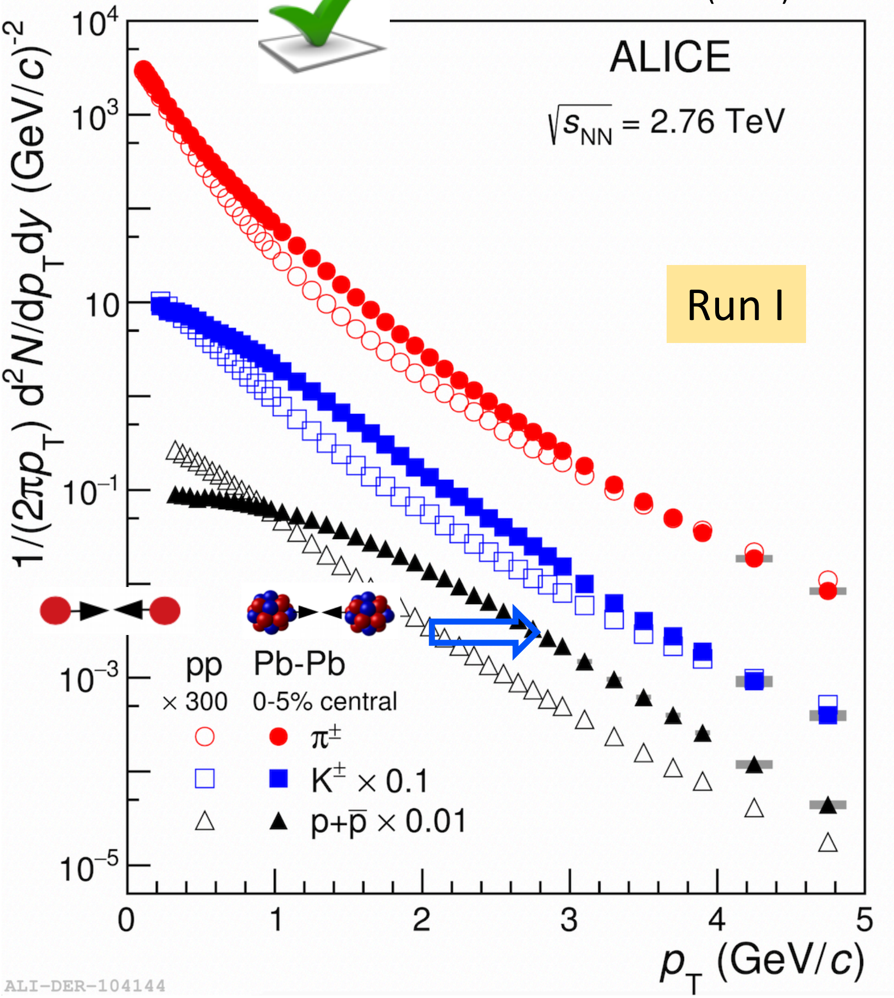


- Pb-Pb and p-Pb spectra reasonably described by hydrodynamic models. EPOS-LHC better on p-Pb
- For pp pQCD-inspired models need extra-mechanisms providing ‘coherence’ (CR, ropes)

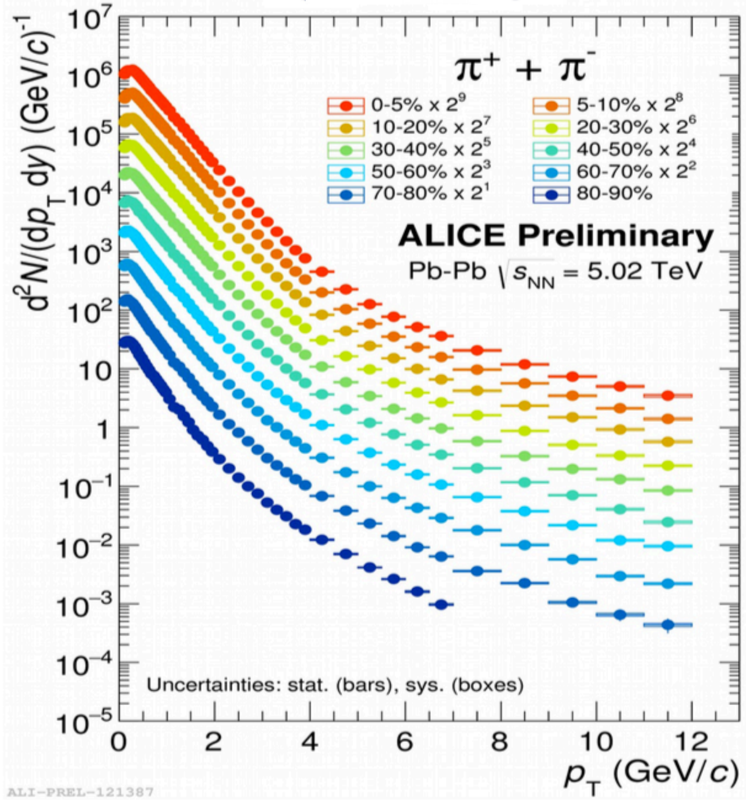
Identified Particle Spectra

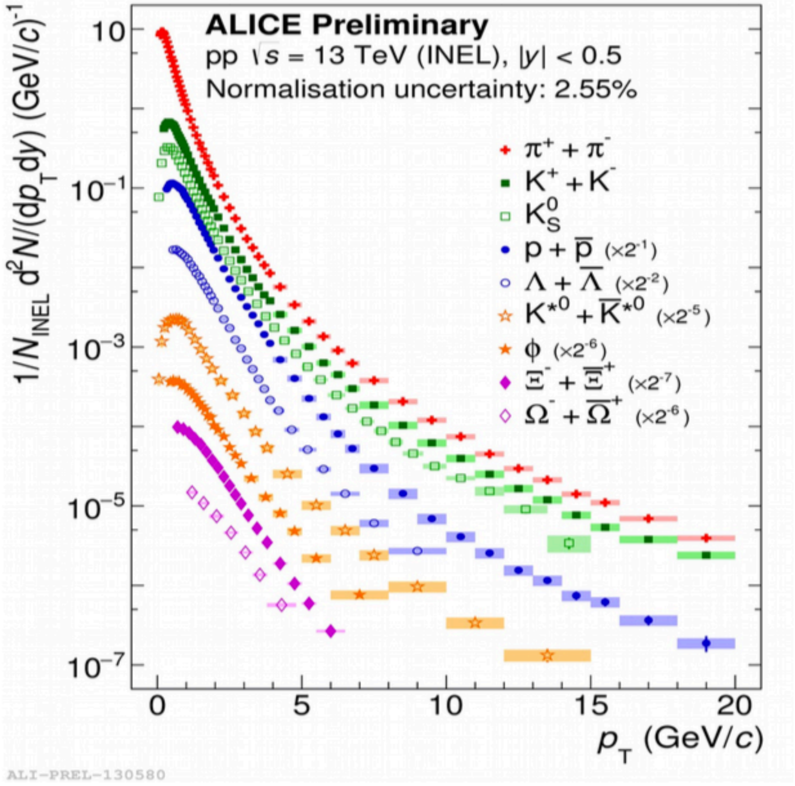
- In Pb-Pb collisions thermalization and fireball expansion process is standard interpretation mechanism
- Particles move in a common velocity field (“radial flow”)
- Expectation of blue-shifting w.r.t. pp and mass ordering

PLB 736 (2014) 196



Run II



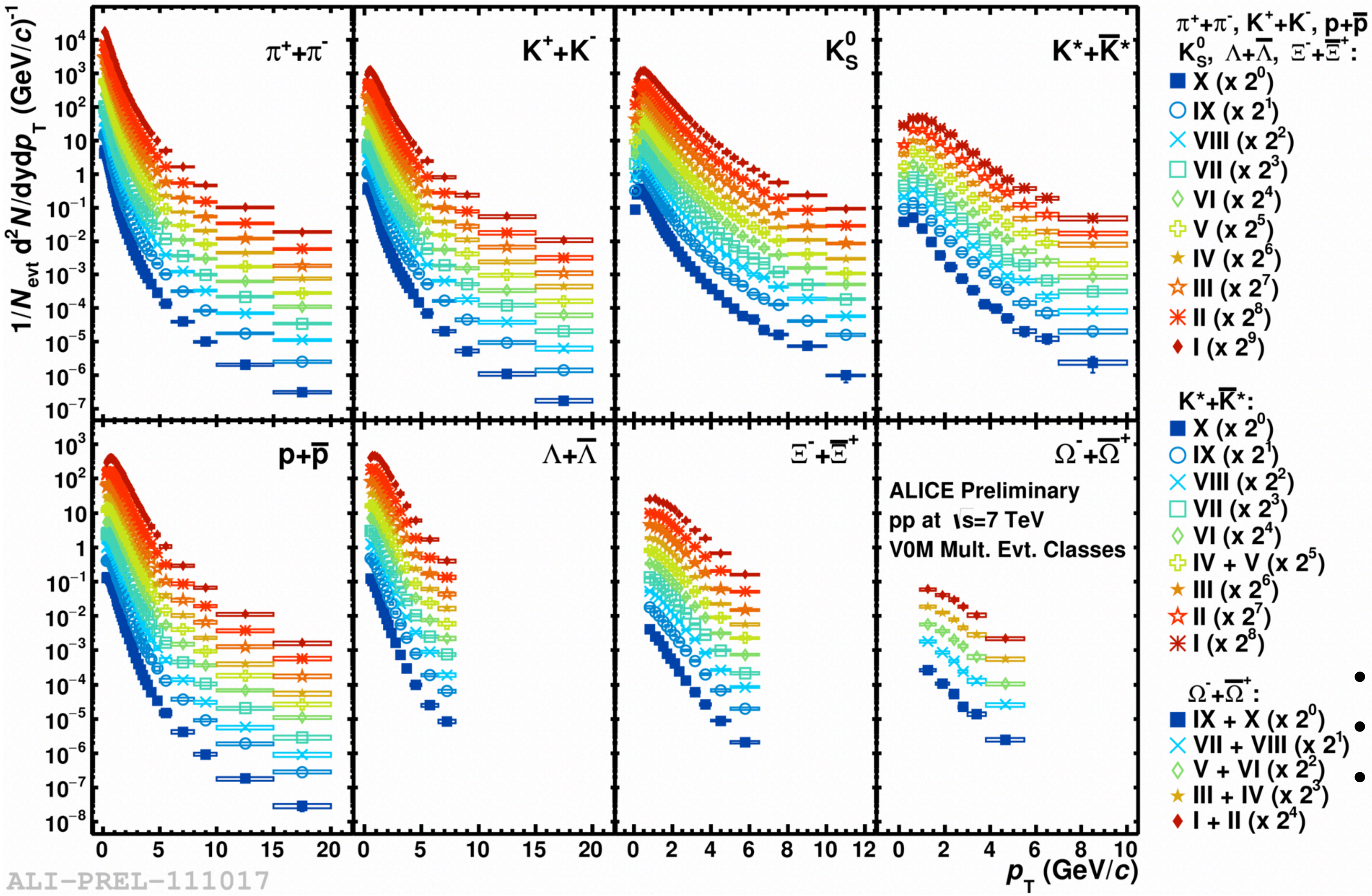


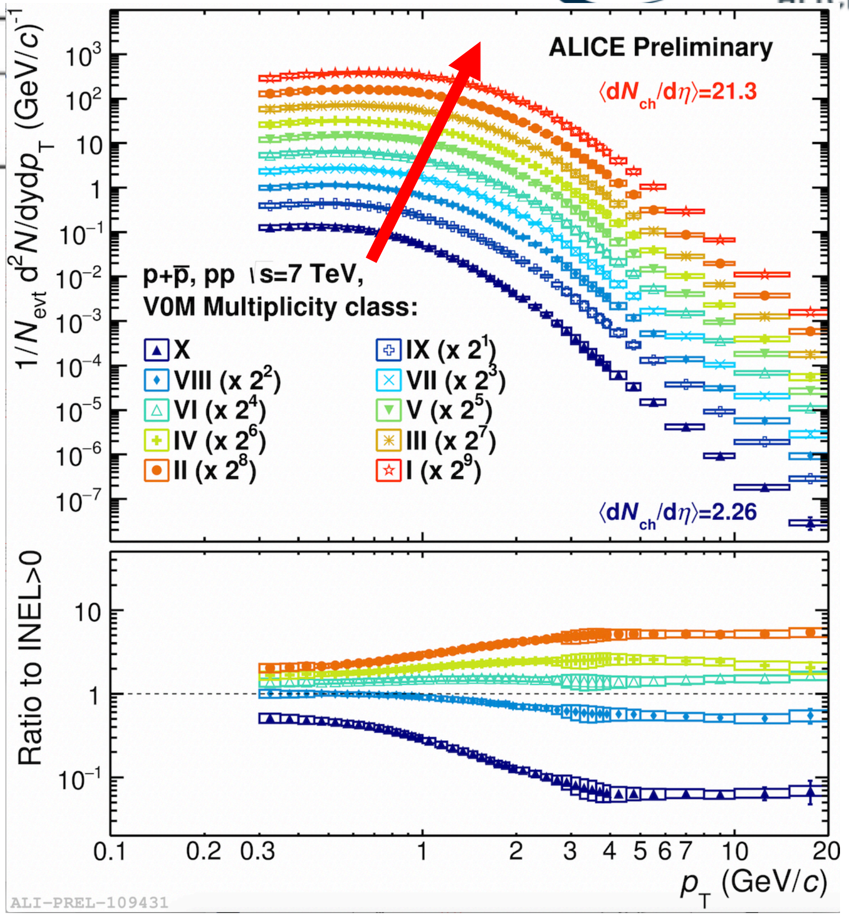
- High precision measurement in Run II (π, K, p in 10 centrality classes)
- PID one of ALICE specialities (five different PID techniques)

→ Test models!

Identified spectra in pp as a function of multiplicity

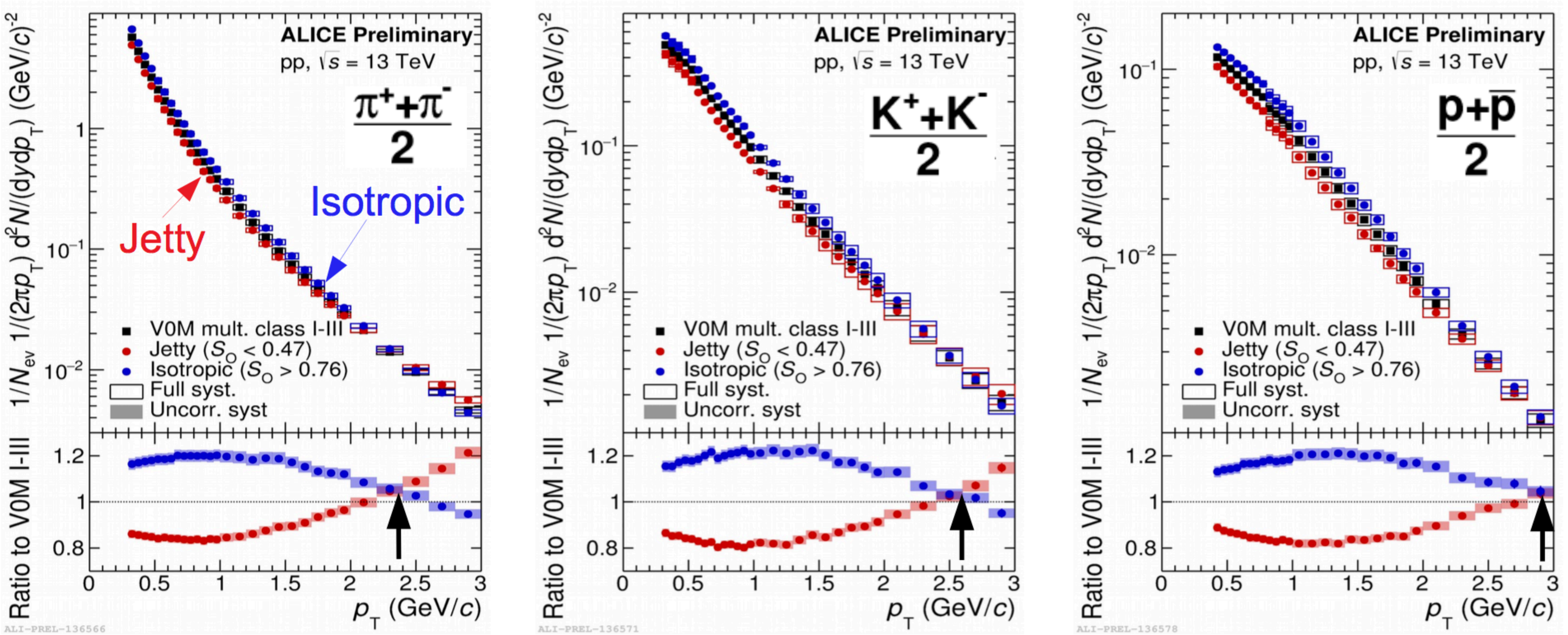
Class name	I	II	III	IV	V	VI	VII	VIII	IX	X
$\sigma/\sigma_{INEL>0}$	0–0.95%	0.95–4.7%	4.7–9.5%	9.5–14%	14–19%	19–28%	28–38%	38–48%	48–68%	68–100%
$\langle dN_{ch}/d\eta \rangle$	21.3±0.6	16.5±0.5	13.5±0.4	11.5±0.3	10.1±0.3	8.45±0.25	6.72±0.21	5.40±0.17	3.90±0.14	2.26±0.12

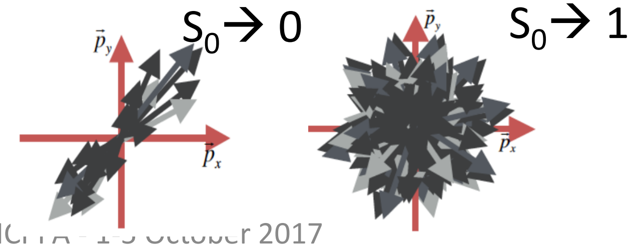




- Hardening with multiplicity + mass ordering!
- "collectivity hint" (radial flow) in pp?
- This would entail a hydrodynamic expansion of the system

Identified spectra in pp: multiplicity and spherocity





Selection of jetty or isotropic events in high multiplicity pp to further study differentially spectra modifications

- Spectral shape modified and it is mass dependent
- Hardening at low p_T larger in isotropic events (bulk production)

Hydrodynamic description: Blast-Wave model

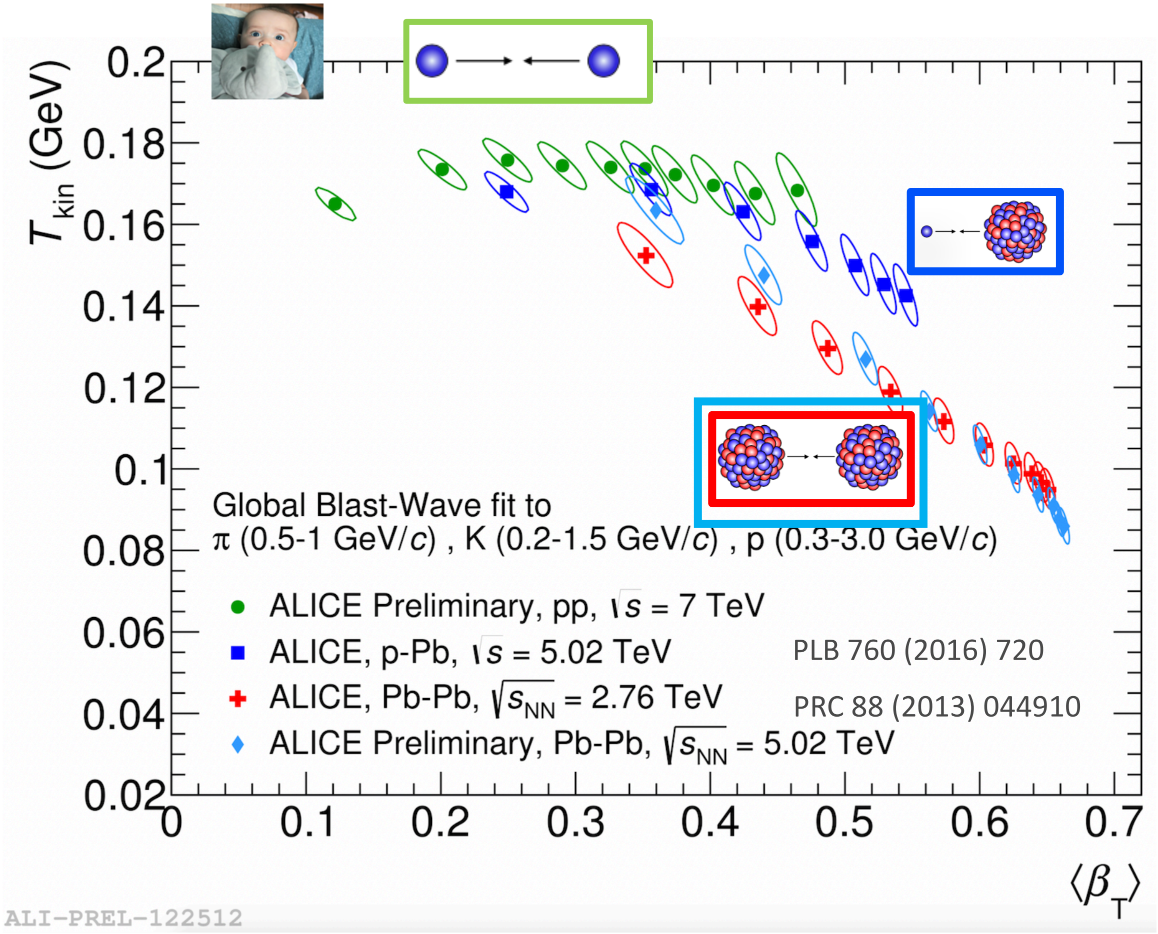
Simultaneous fit of p, K, p spectra
Extraction of:
- β_T radial expansion velocity
- T_{Kin} kinetic freeze-out
- n velocity profile

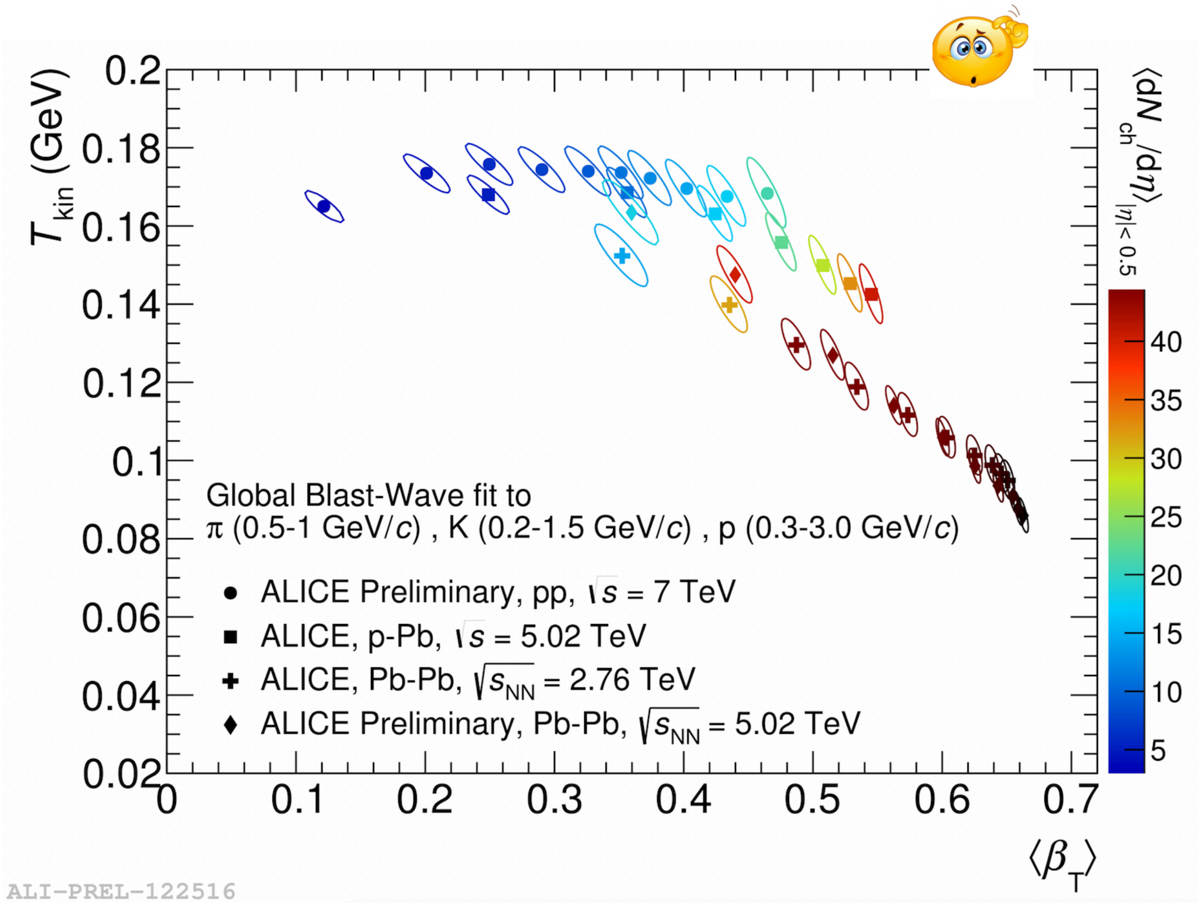
$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{Kin}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{Kin}}\right) r\,dr$$

$$m_T = \sqrt{m^2 + p_T^2} \qquad \rho = \tanh^{-1}(\beta_T) \qquad \beta_T = \beta_s\left(\frac{r}{R}\right)^n$$

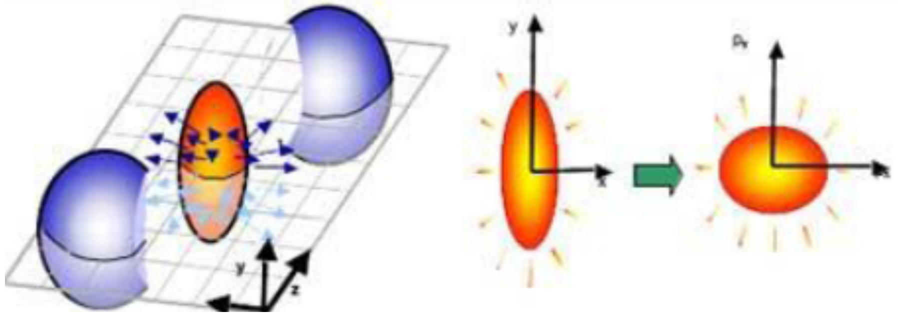
Schnedermann, Sollfrank and Heinz Phys. Rev. C 48, 2462

- Largest expansion velocity of Pb-Pb collisions
- Similar evolution for pp and p-Pb at highest multiplicity
- Higher β_T for smaller systems at similar multiplicity
- CAVEAT: QCD effects as color reconnection can mimic radial flow!



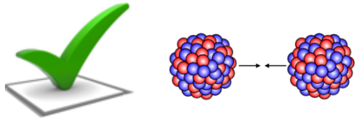


Collectivity: anisotropic flow



Geometrical asymmetry translates in momentum space (pressure gradients in a collective expanding medium)

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})]\right)$$



2010

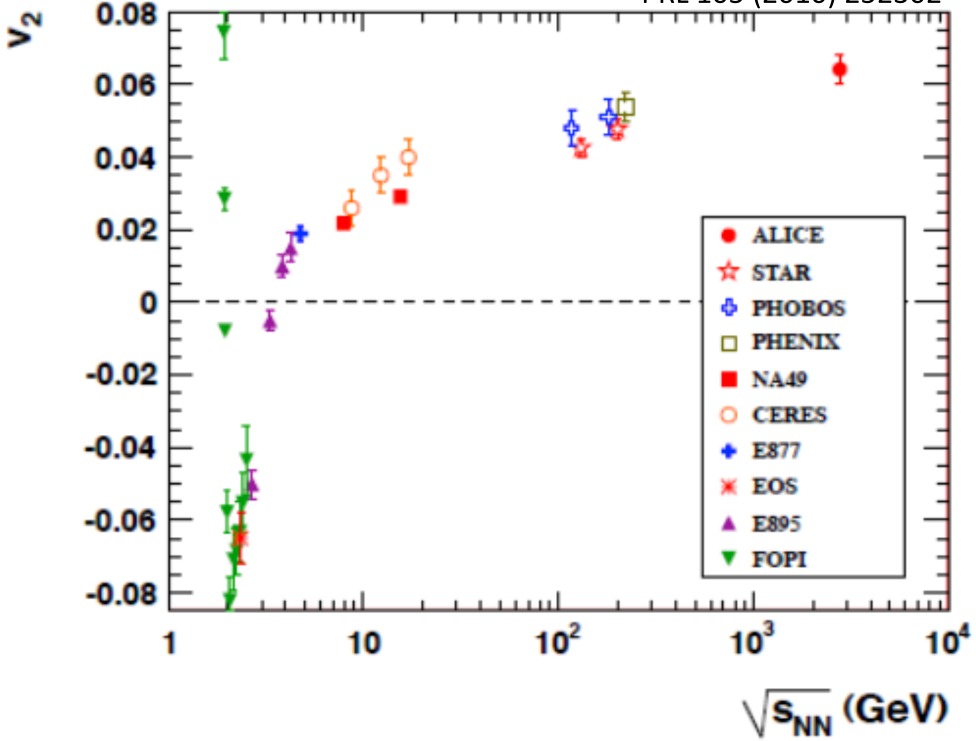
PRL 105 (2010) 252302

V_2: (elliptic flow) → thermalisation of the medium
Higher armonics: geometric fluctuations of the initial state

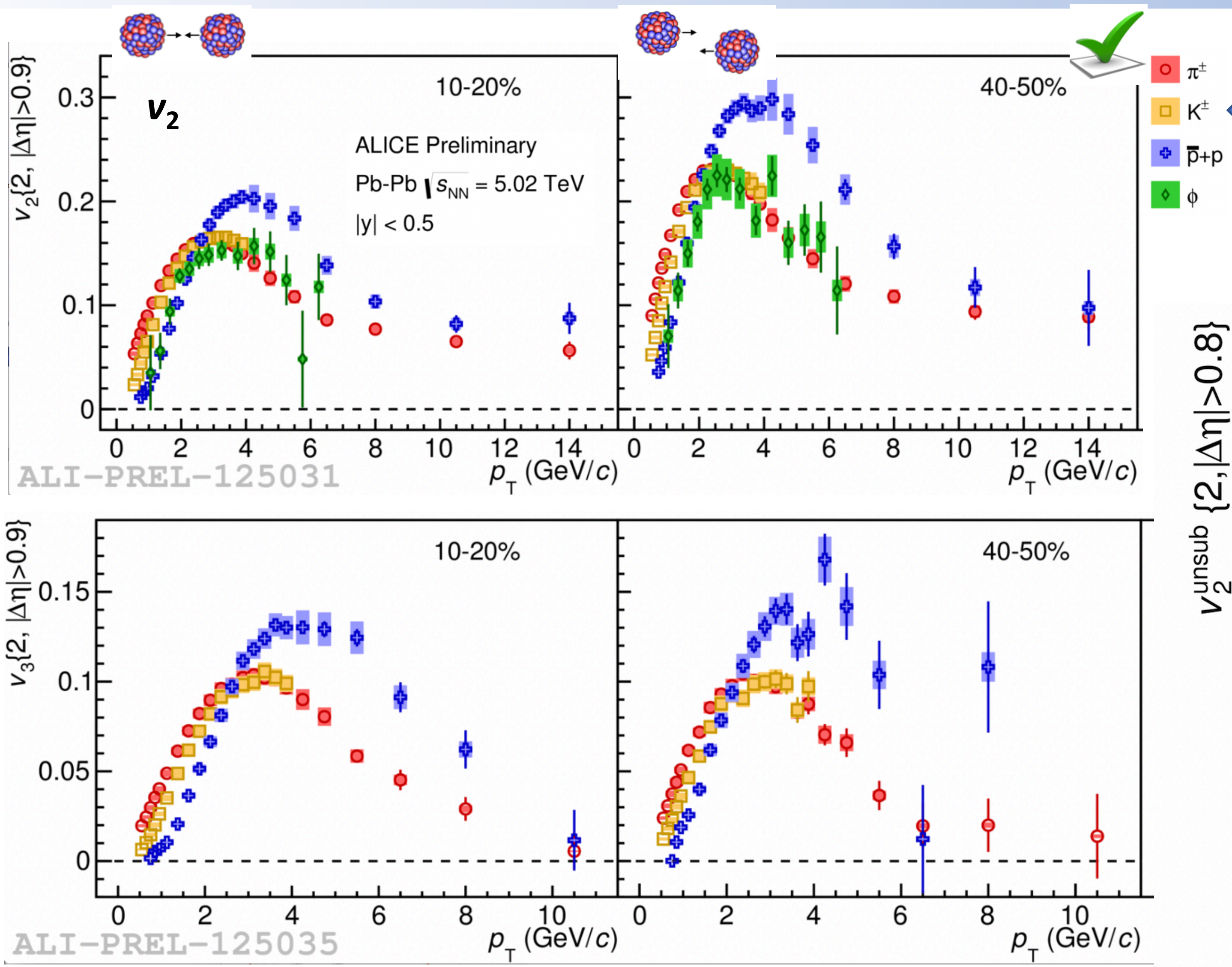
→ v_n sensitive to the evolution of the collision system and hydrodynamic properties of the medium (η/s)

RHIC legacy: QGP is a almost perfect fluid!

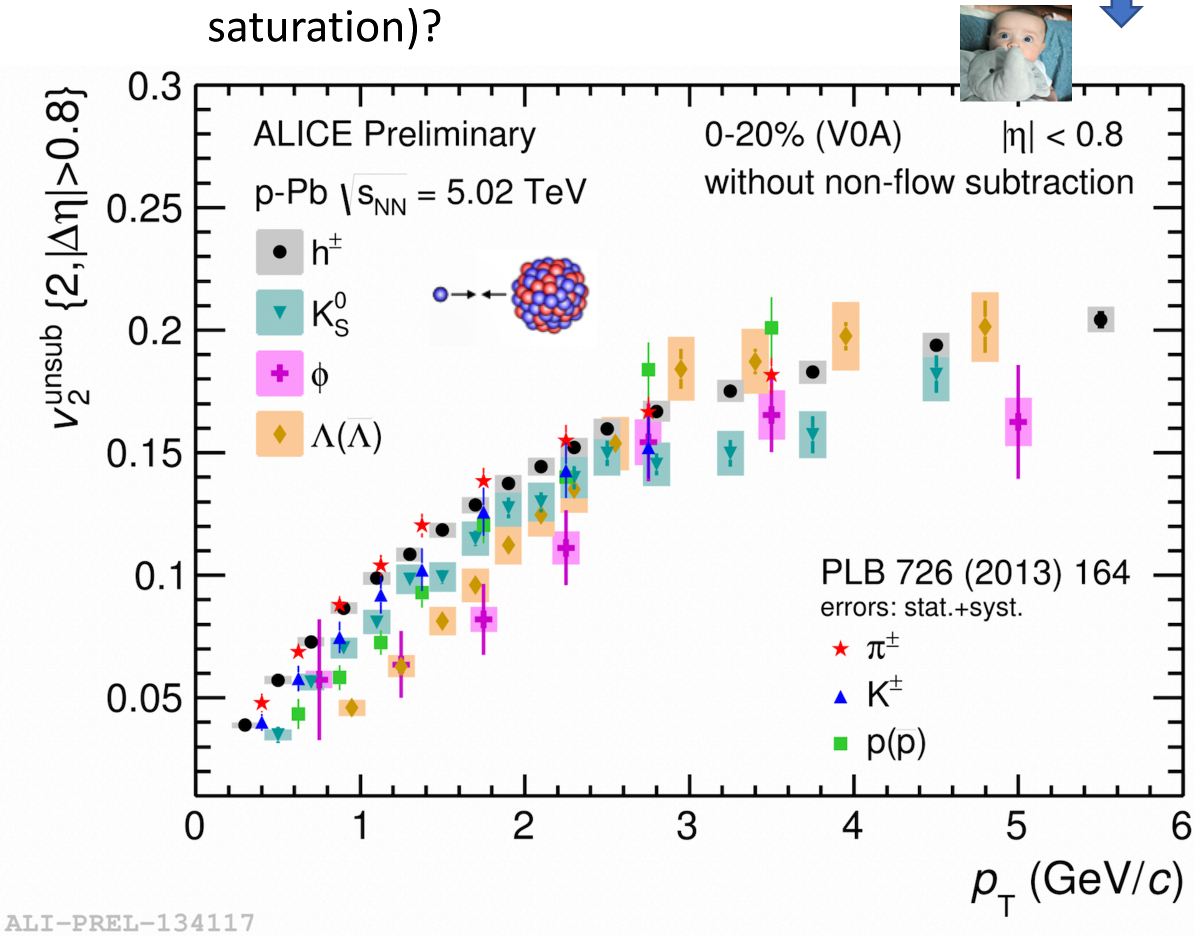
Higher integrated v_2 at LHC related to the p_T increase



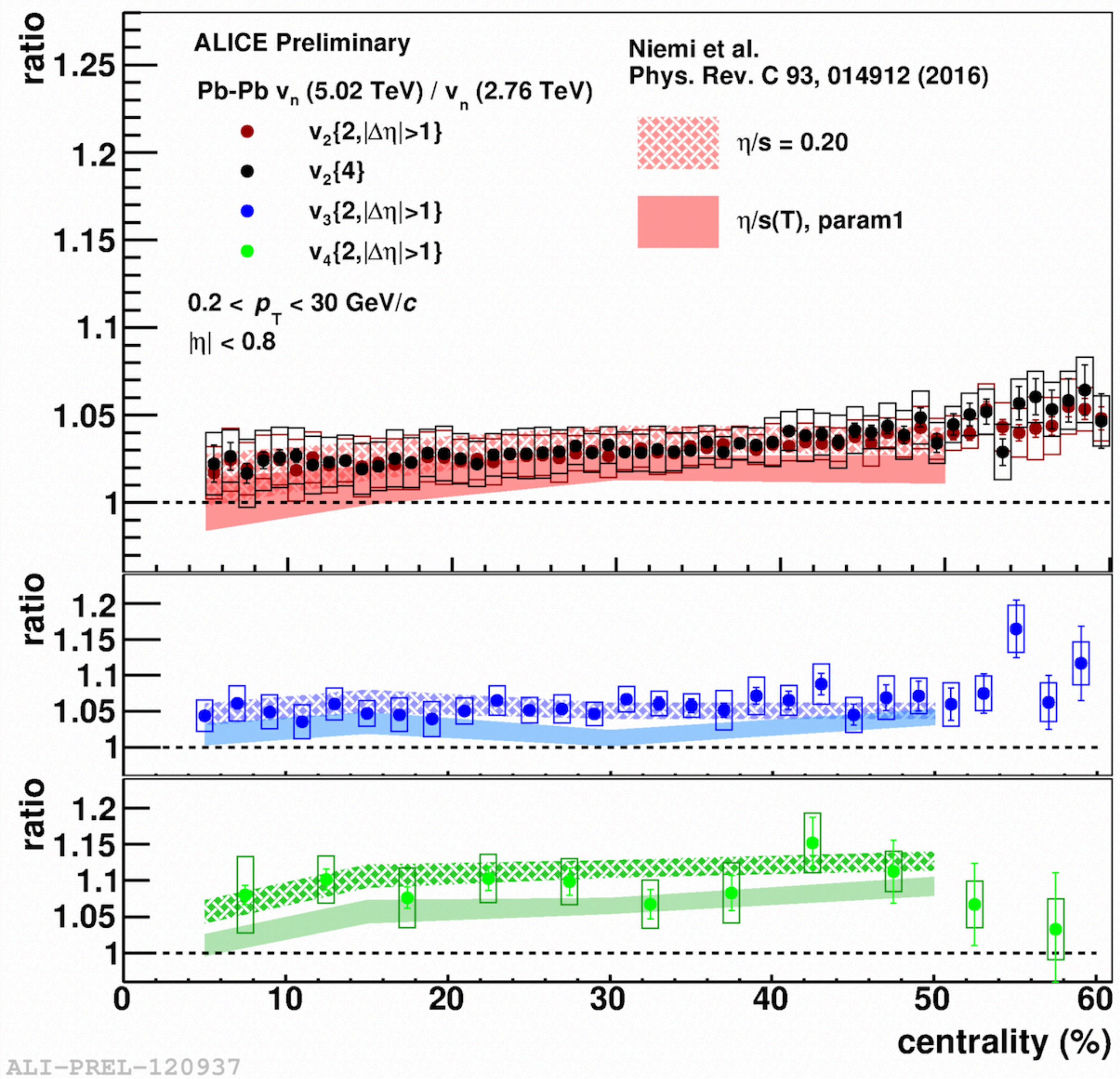
Anisotropic flow: identified particles



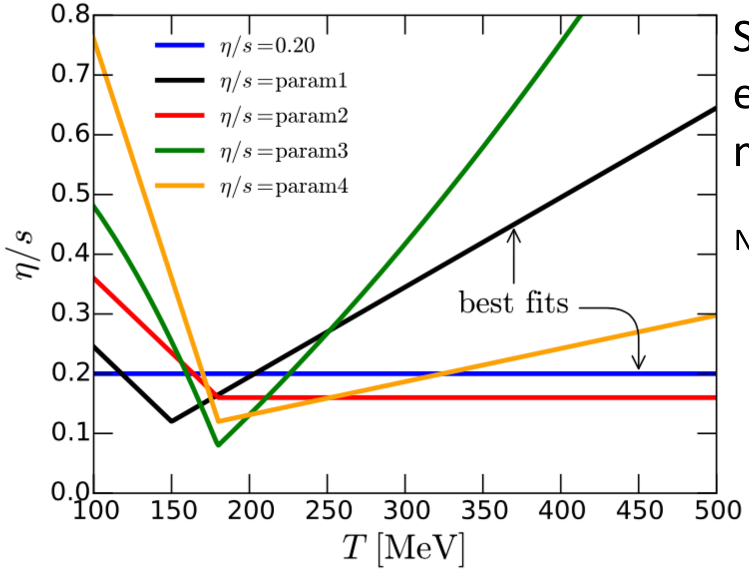
- Mass ordering pattern as expected due to collective expansion in Pb-Pb
- Seen also in p-Pb! (high multiplicity)
  → Final or initial effect here (expansion or saturation)?



Mapping plasma properties with higher order flow harmonics

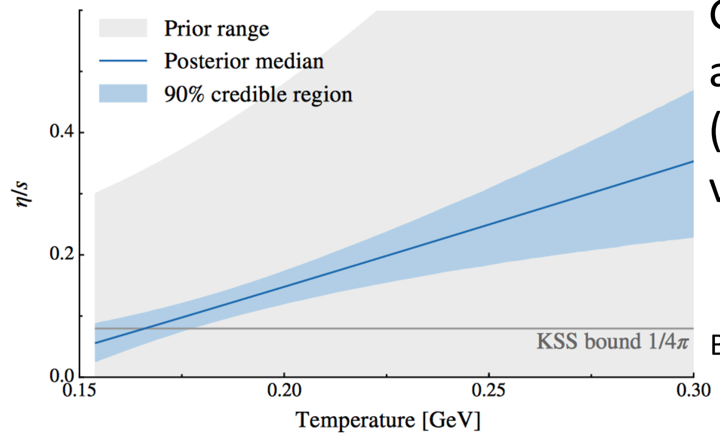


- v_n obtained up to 6th order
- Ratio of v_n at different $\sqrt{s_{NN}}$ sensitive to models (Run I+II)
- Constrain initial conditions and η/s(T)
- Data favor fixed η/s=0.2



Shear viscosity-to-entropy ratio (EKRT model)

Niemi et al., PRC 93 (2016) 014912



Global Bayesian analysis (mean p_T, v_2, dN_{ch}/dy vs centrality as input)

Bass et al., arxiv:1704.07671

And heavy flavours?

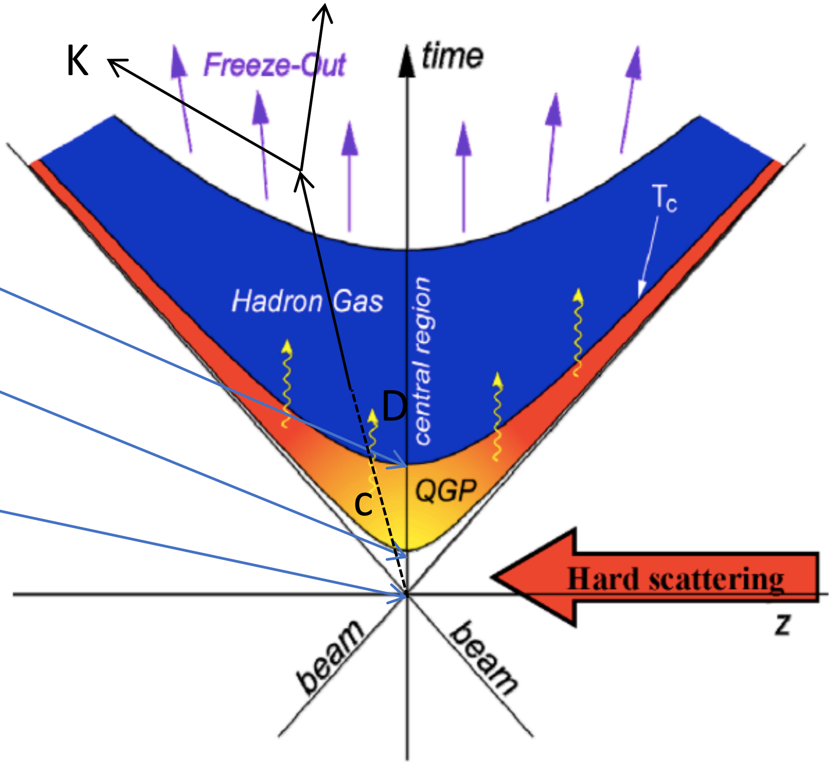
a probe of the medium from production to observation that gives a unique access to HF interactions in the QGP.

t

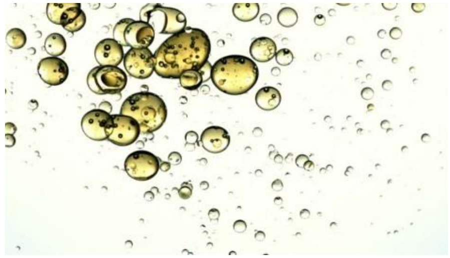
Lifetime of QGP ≈ 10 fm/c

Formation time of the QGP ≤ 0.1 fm/c

heavy-flavor (HF) early production during the collision: $1/2m_c = 0.08$ fm/c

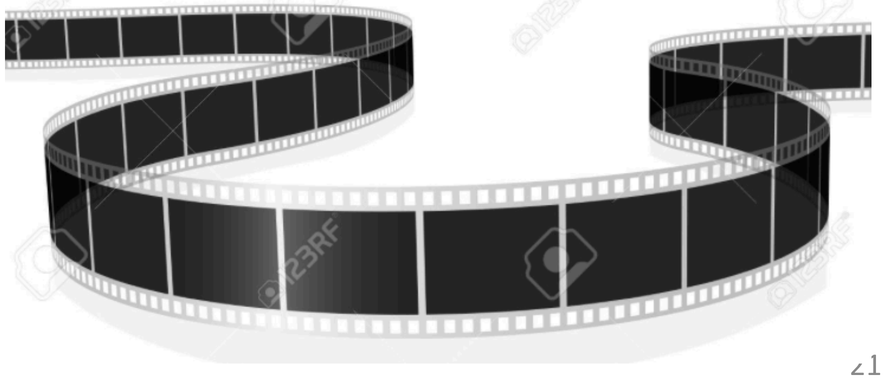


Heavy probes easily tagged in a liquid….



production cross sections (hard scattering) calculable with perturbative QCD
pp reference critical to test pQCD

Standard movie here?



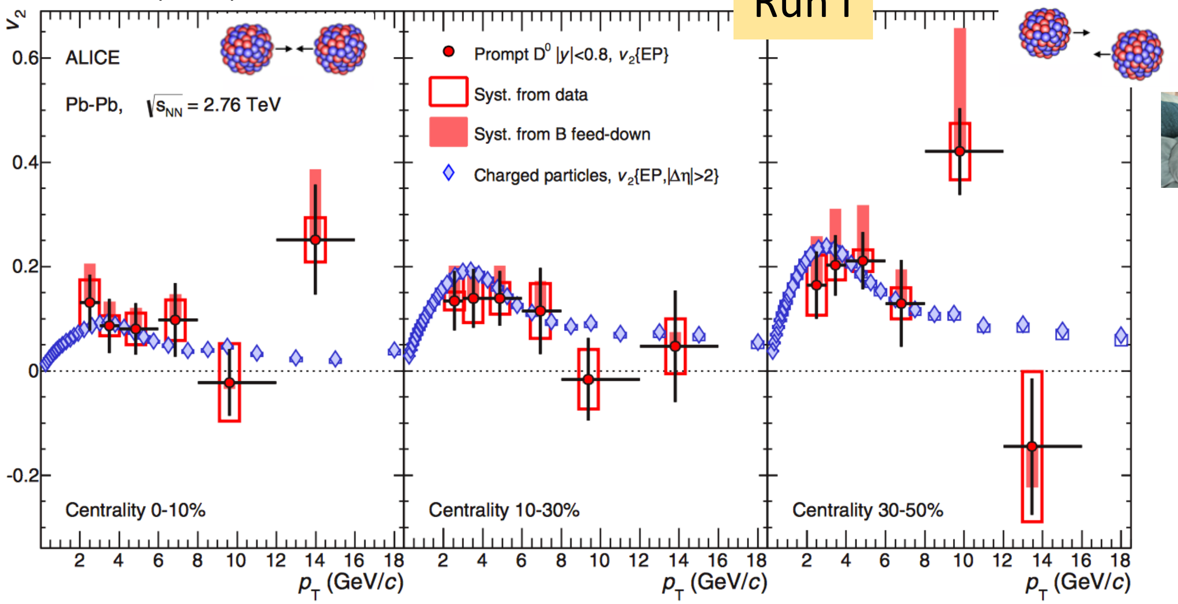
We can investigate:

1. Parton **energy loss** in the QGP
2. Participation of heavy quarks in the **collective expansion** of the medium

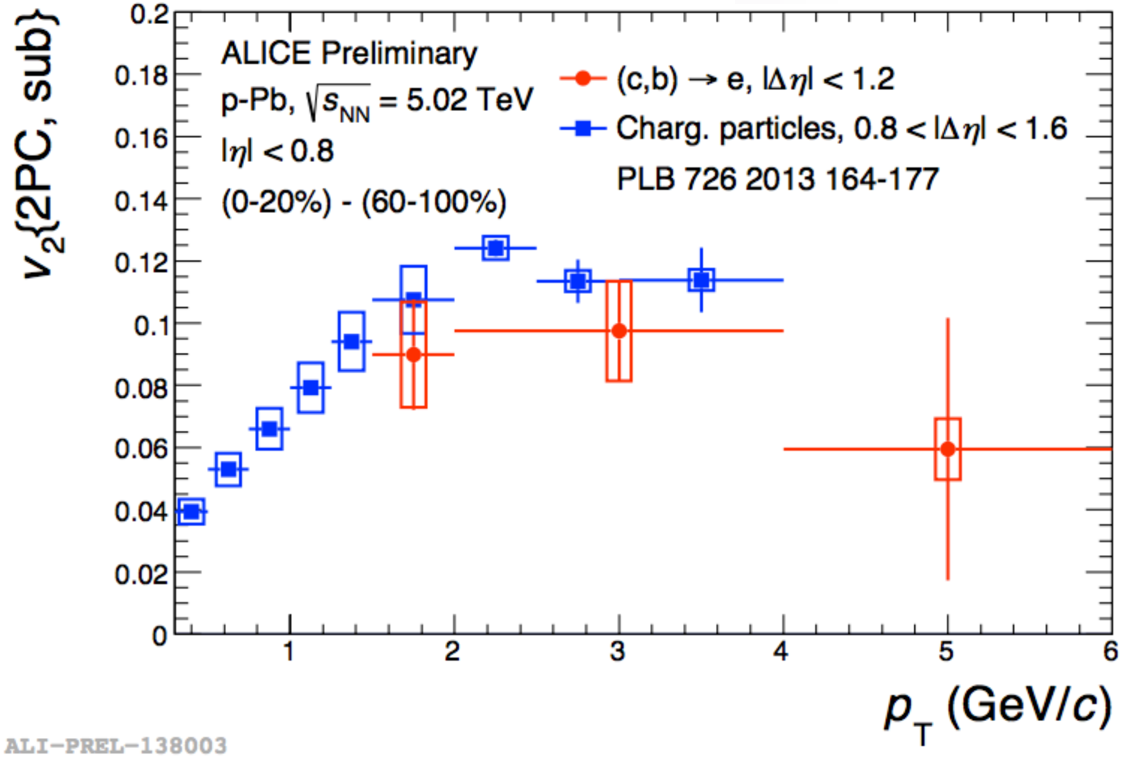
Charm takes part in collective expansion! (I)

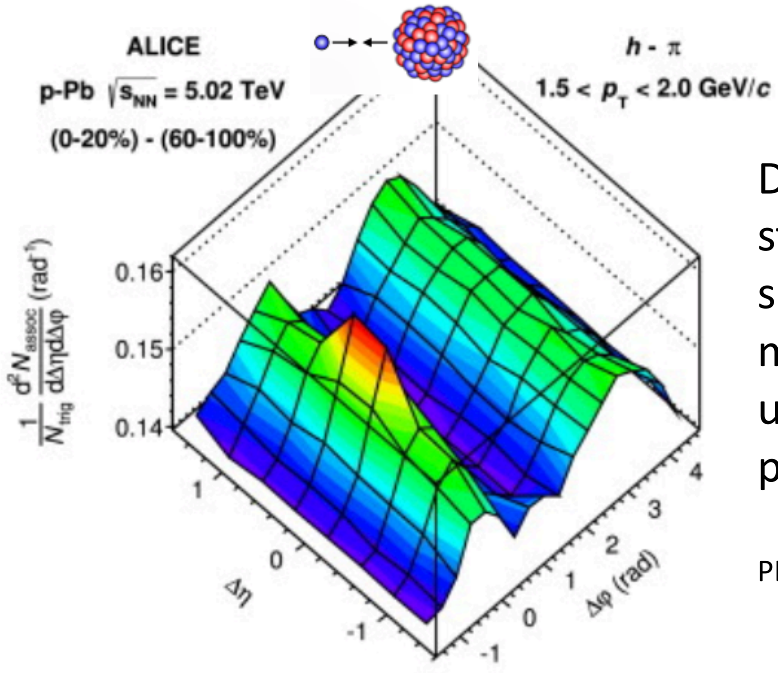
PRC 90 (2014) 034904

Run I



Recent result: now positive flow seen in p-Pb via **HF-electron** in the charm sector



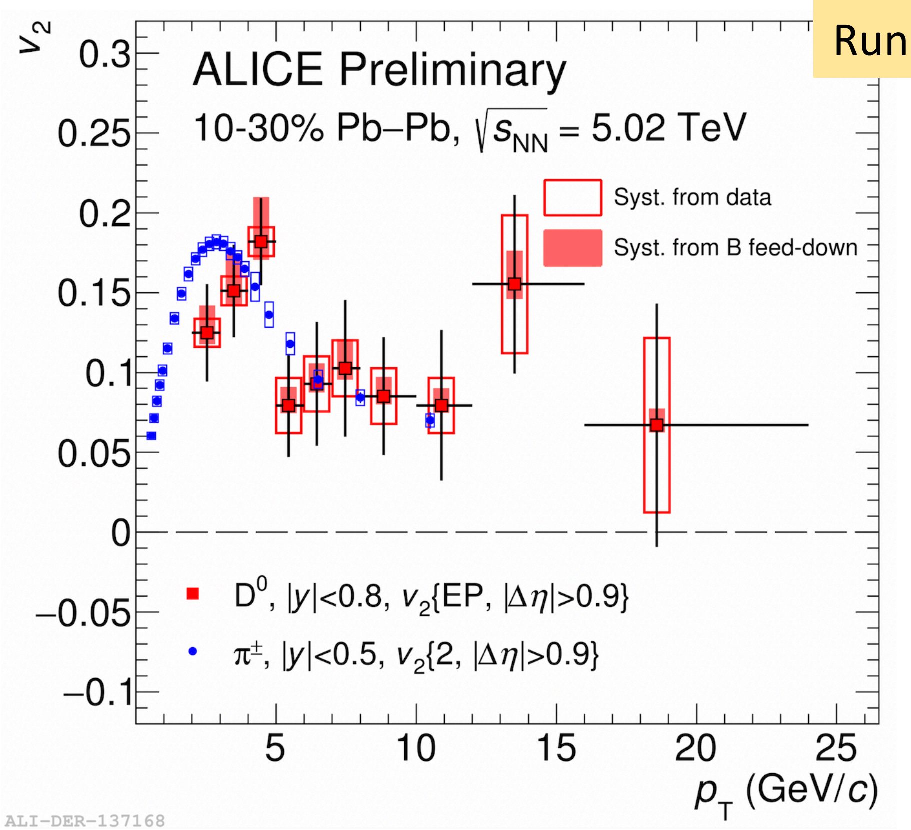


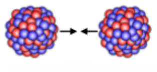
Don't forget double ridge structure emerging via subtraction of high/low multiplicity for unidentified and identified particles

PLB 726 (2013) 164-177

Similar to charged particles within uncertainties
Collective expanding system in p-Pb?

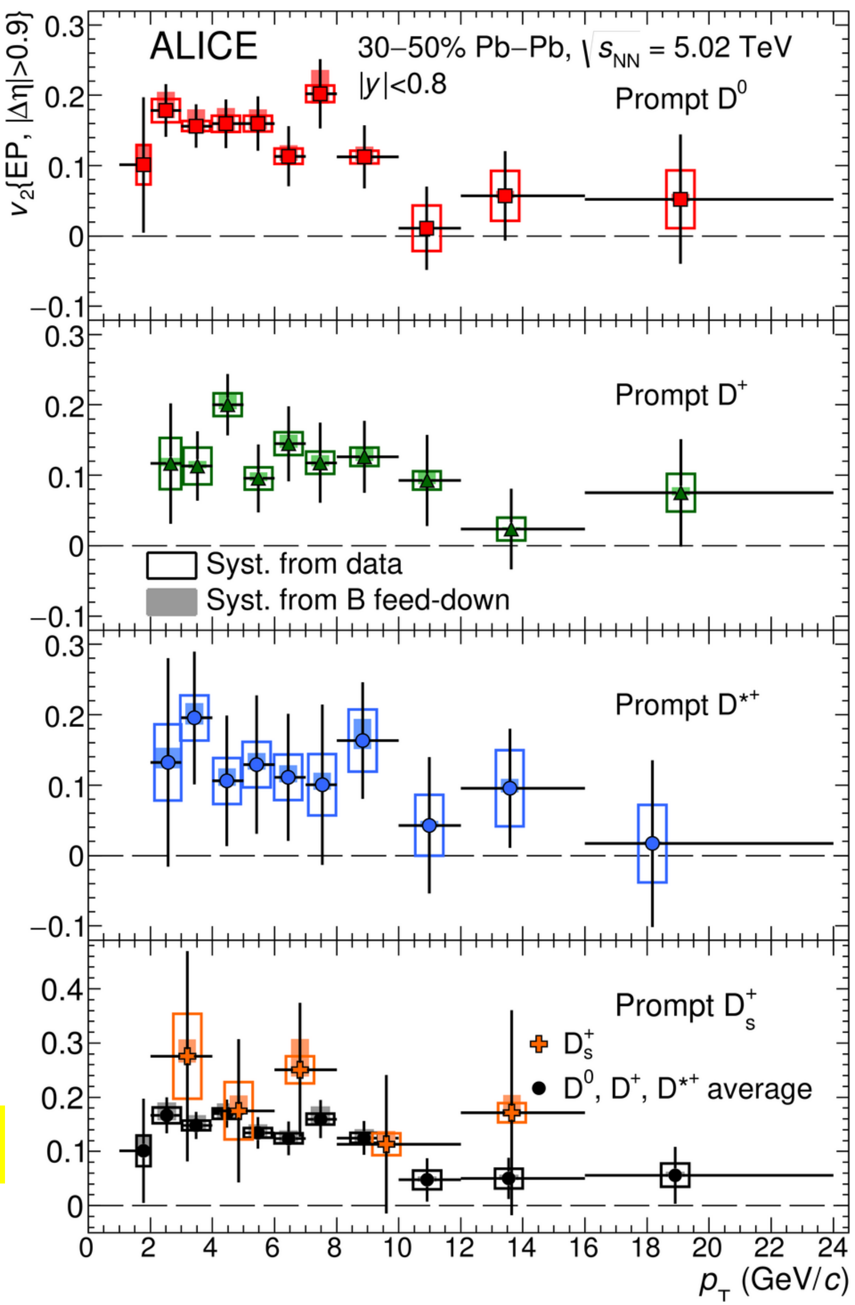
Charm takes part in collective expansion! (II)





More statistics
More precision

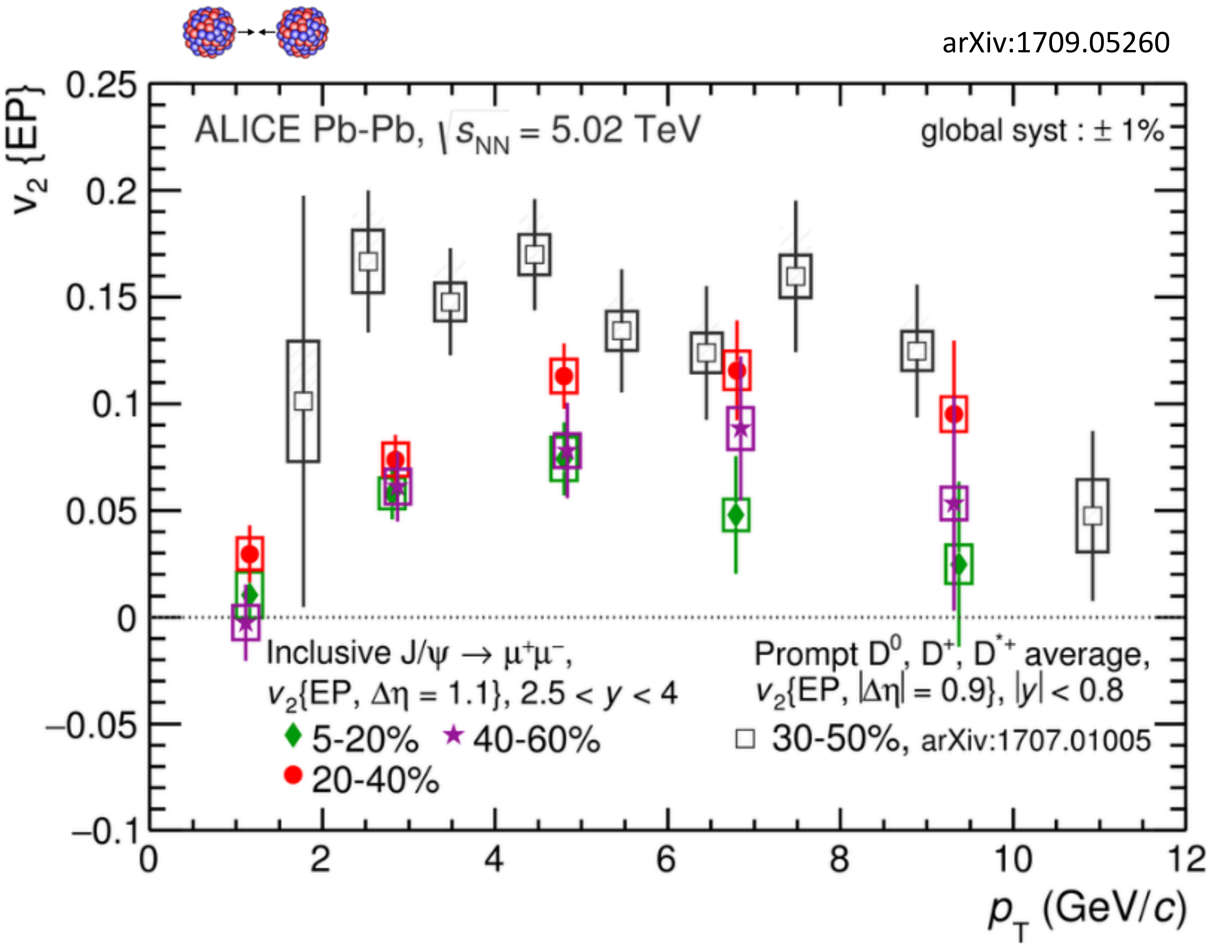
arXiv:1707.01005



- D-meson v_2 similar to pions
- Difference for p_T<4 GeV/c ?
- First D_s v_2 measurement at LHC

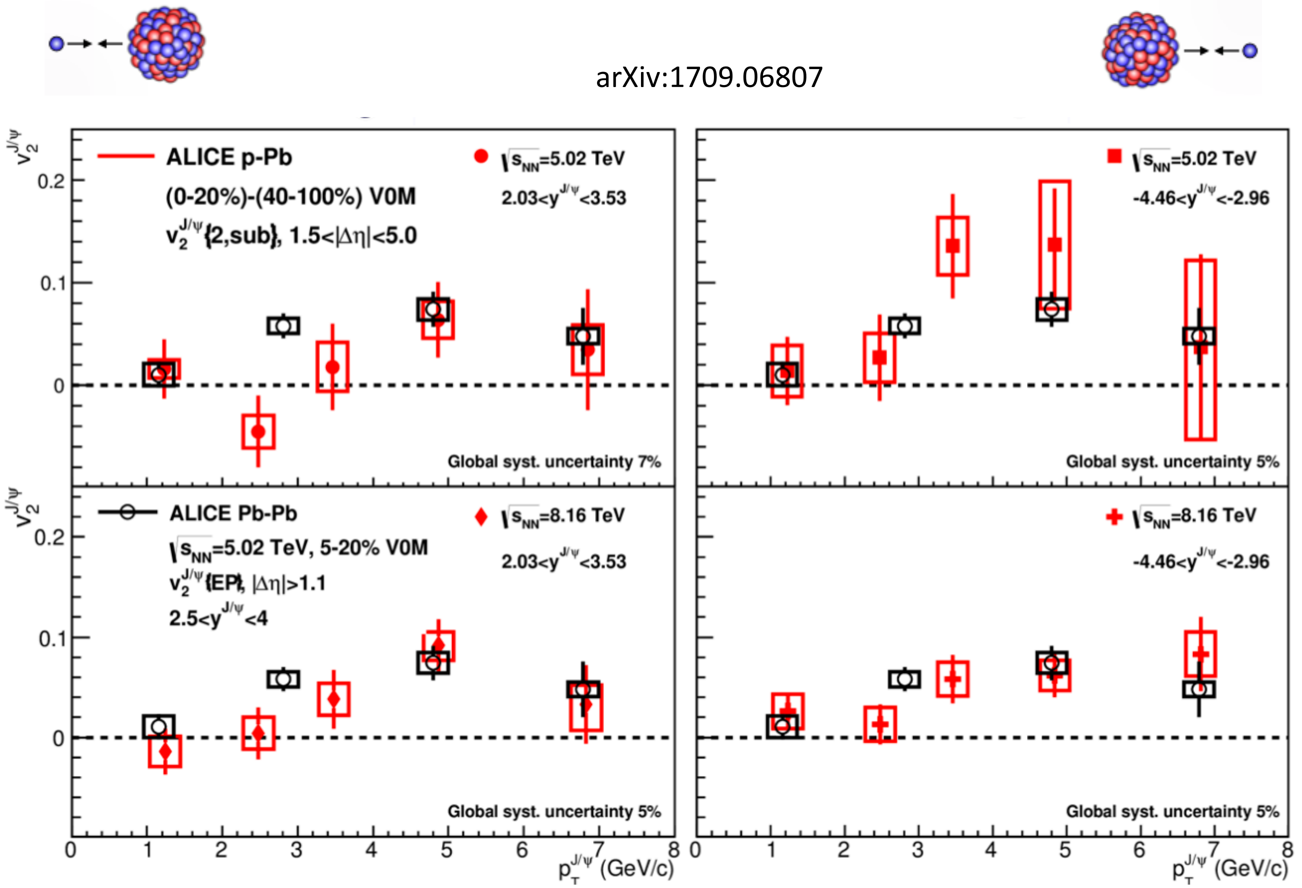
All together robust evidence of strong coupling of c-quark with the medium

J/Ψ v_2: Pb-Pb and p-Pb

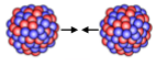


- Significant v_2 observed for J/Ψ in different p_T and centrality ranges
- 6.6σ in 4<p_T<6 GeV/c for 20-40%
- Comparison to transport and recombination models tend to show tensions at high p_T (> 4 GeV/c)

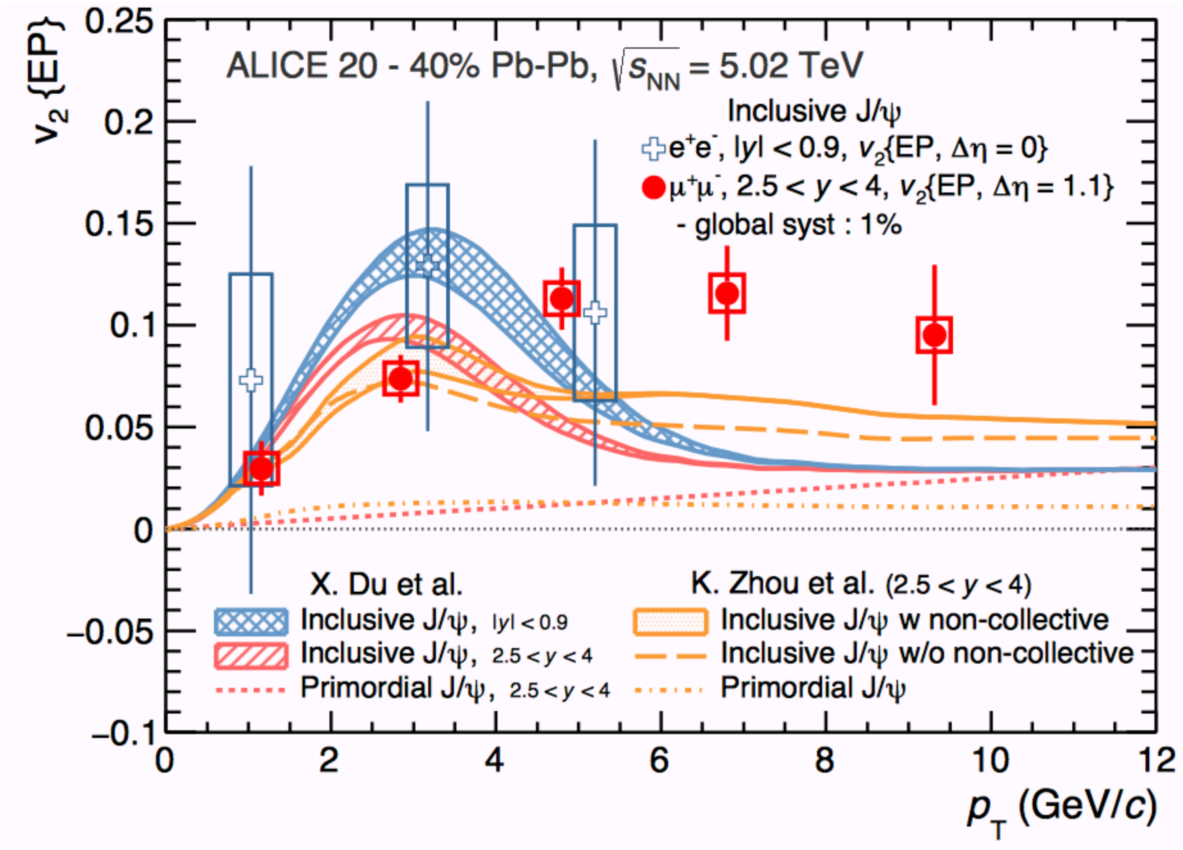
- v_2 for p_T<3 GeV/c is compatible with zero
- v_2 in 3<p_T<6 GeV/c is positive with a total significance of 5σ and similar to Pb-Pb!
- Recombination expected to be negligible in p-Pb, but measured values imply J/Ψ participates in the collective behaviour



J/Ψ v_2: Pb-Pb and p-Pb



arXiv:1709.05260



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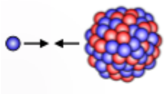
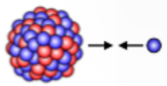
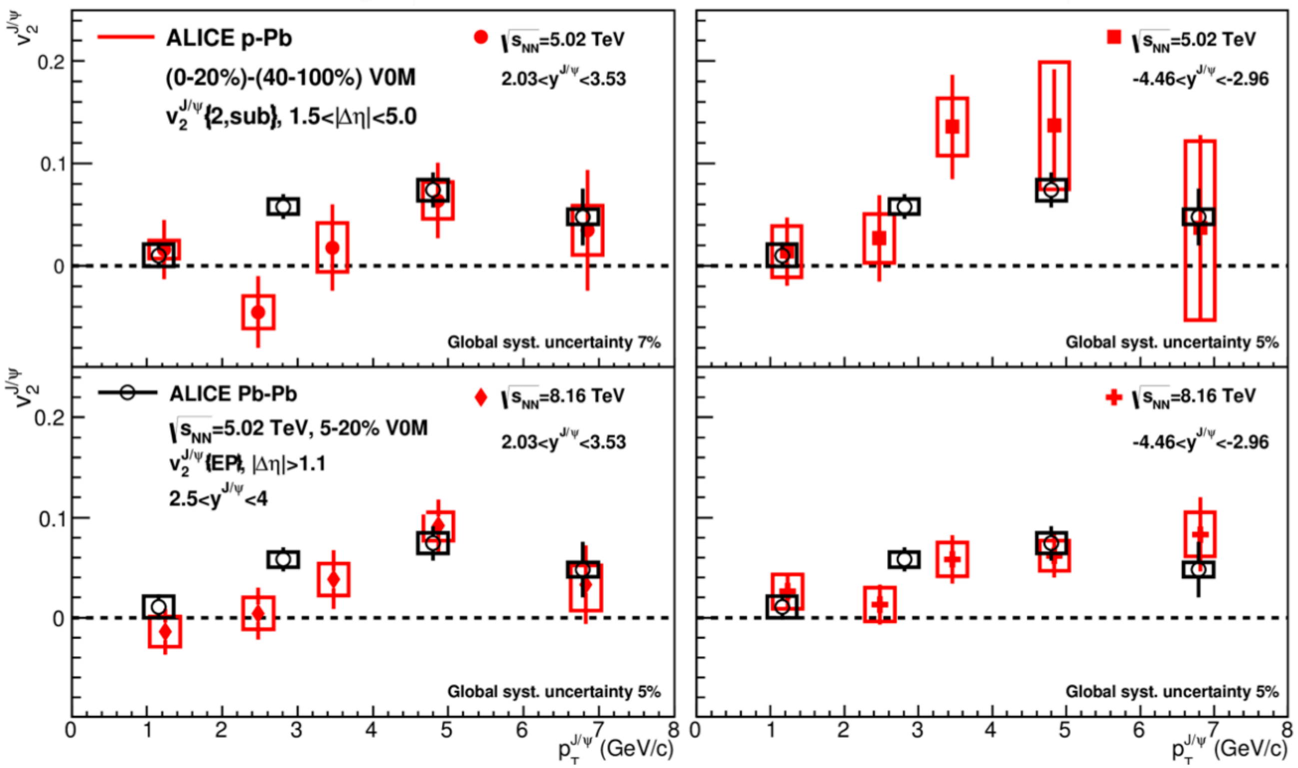




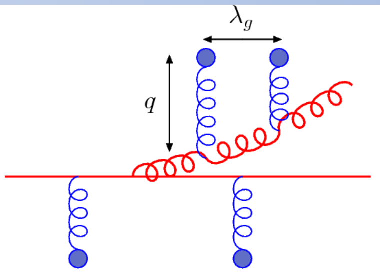
arXiv:1709.06807



Heavy flavour energy loss

heavy flavour: testing our understanding of QCD energy loss in the medium

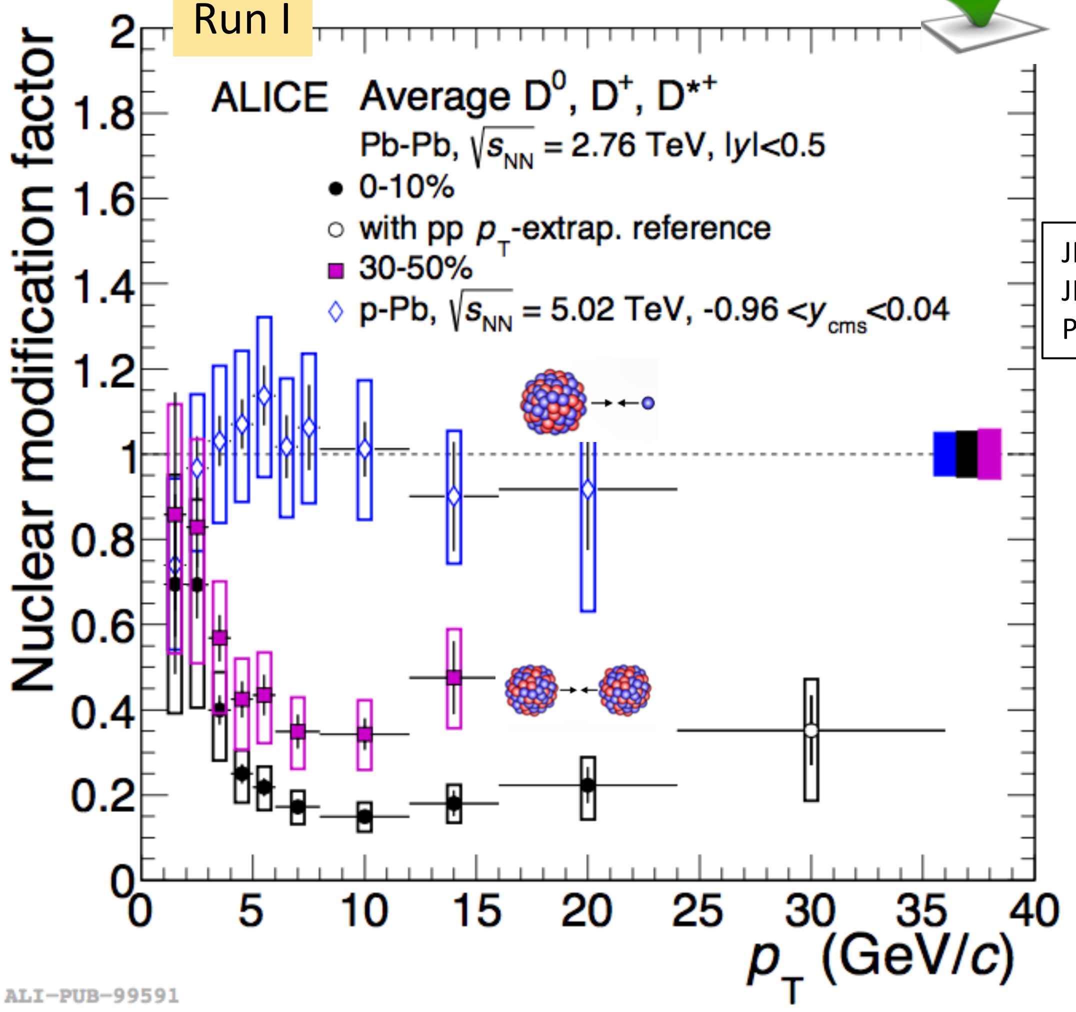
Casimir factors and dead-cone effect: **gluon/quark hierarchy** and **mass hierarchy**



$$\Delta E \propto \alpha_S C_R \bar{q} L^2$$

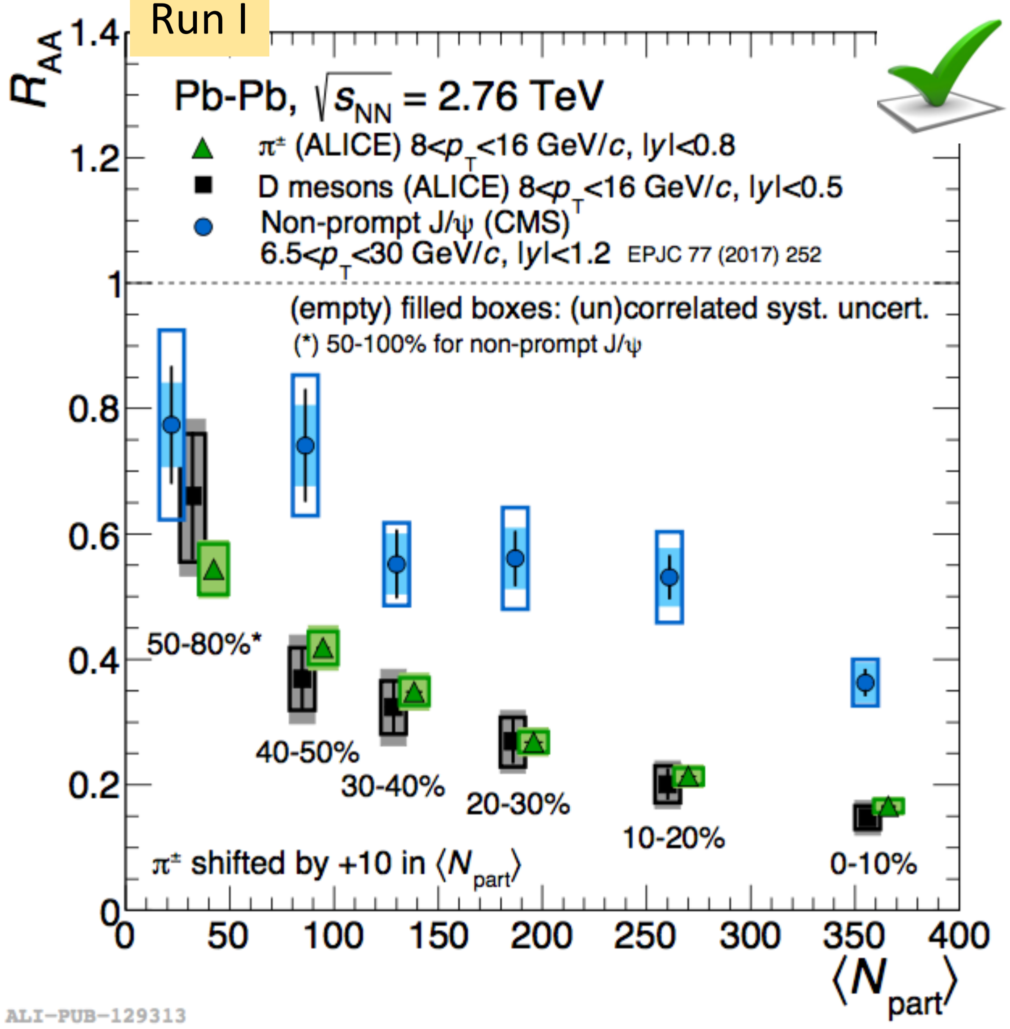
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

Run I

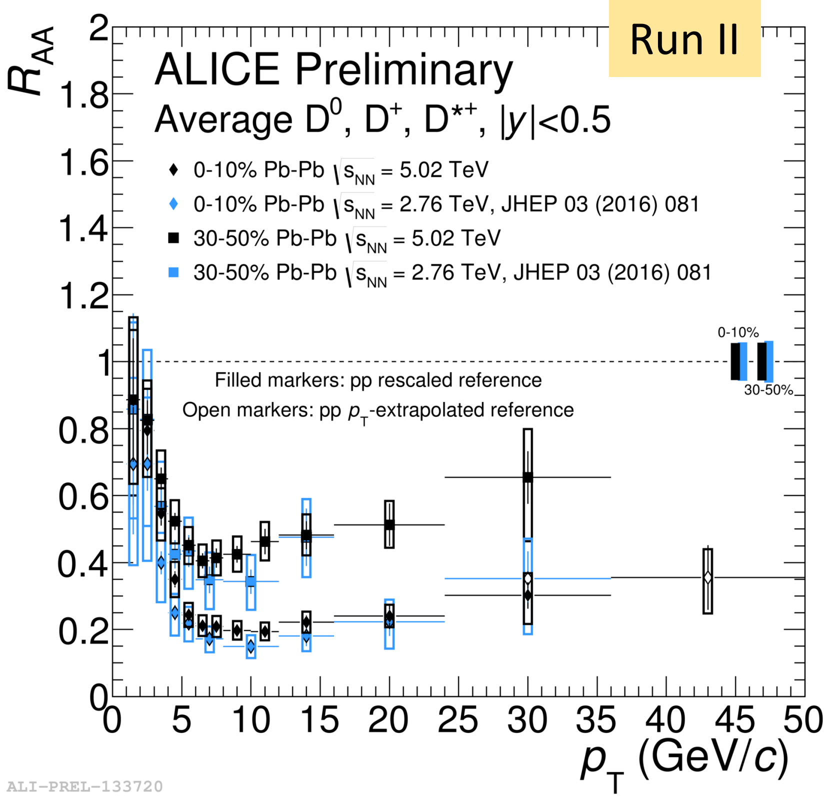


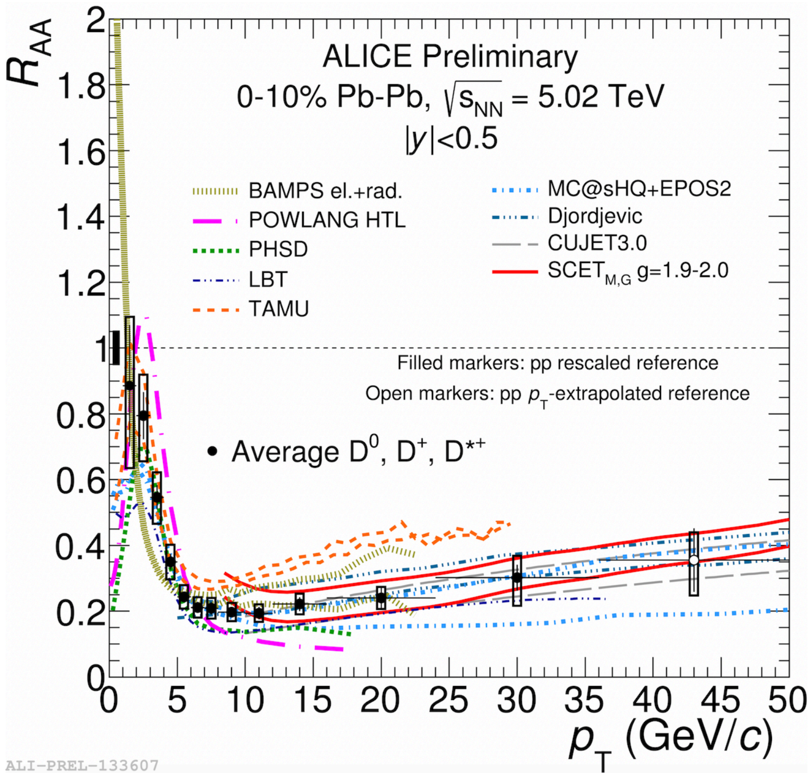
JHEP 03 (2016) 081
JHEP 11 (2015) 205
PRC 90 (2014) 034904

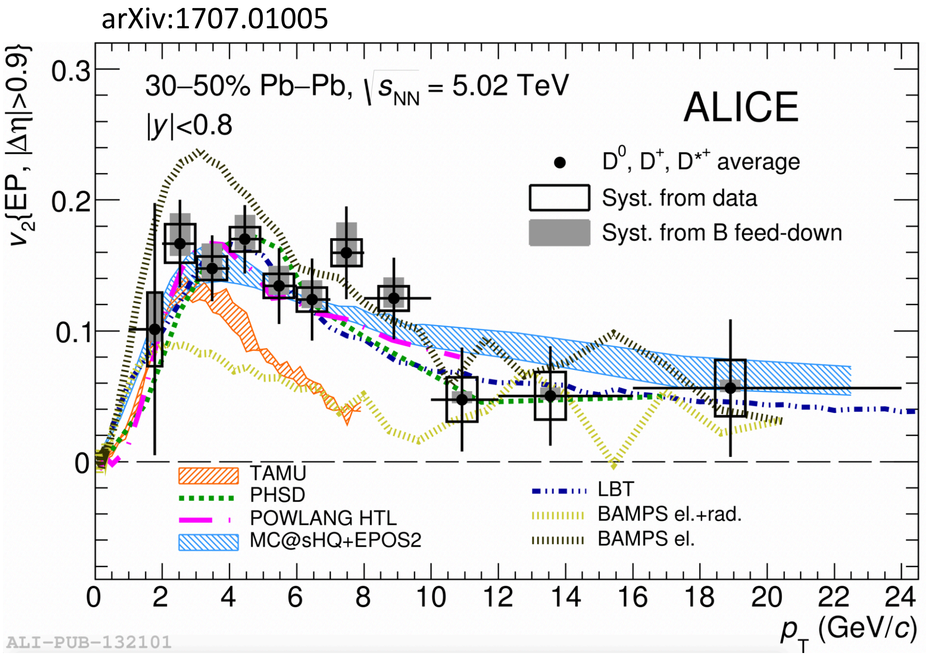
Run I



R_{AA} and v_2: now potential to constrain models





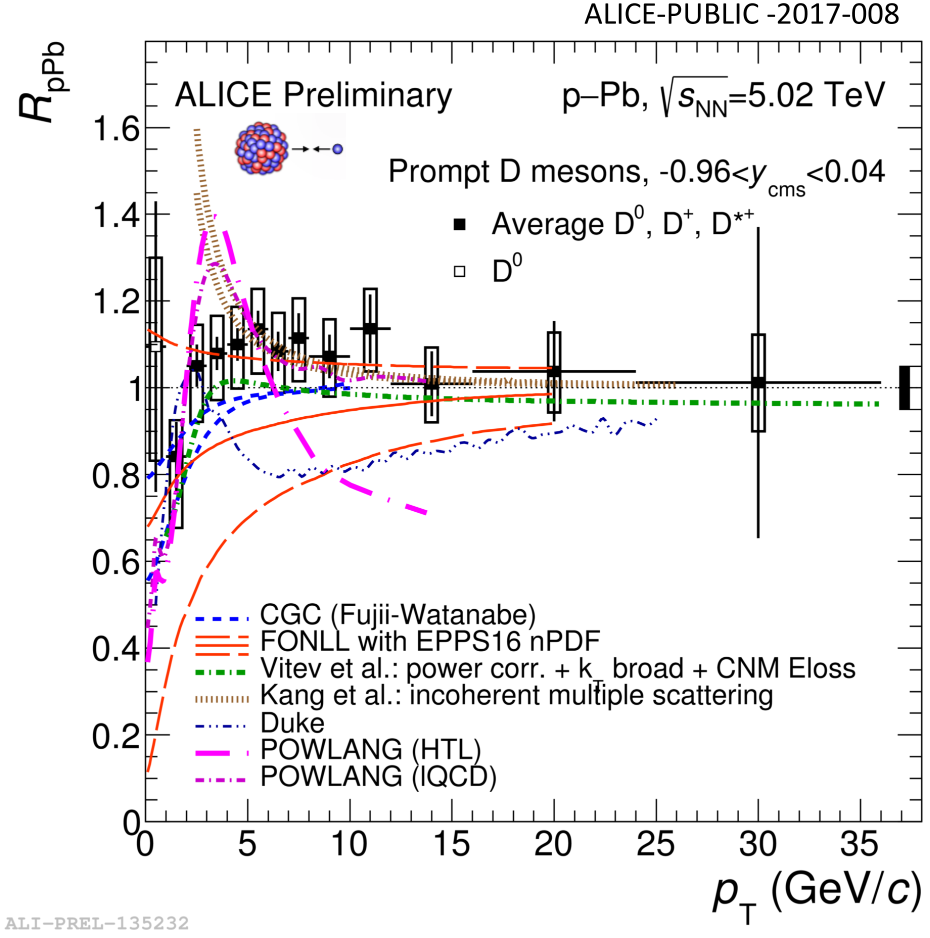


- Better precision in Run II and higher p_T reach: similar values at $\sqrt{s_{NN}}$=2.76 and 5.02 TeV → harder spectra vs denser medium
- Models that describe better R_{AA} tend to underestimate v_2 and viceversa (especially at high p_T)!
- From v_2 LBT, MC@sHQ, PHSD and POWLANG models have $\chi2/ndf < 1$, the TAMU, BAMPS-el+rad and BAMPS-el models have larger values.

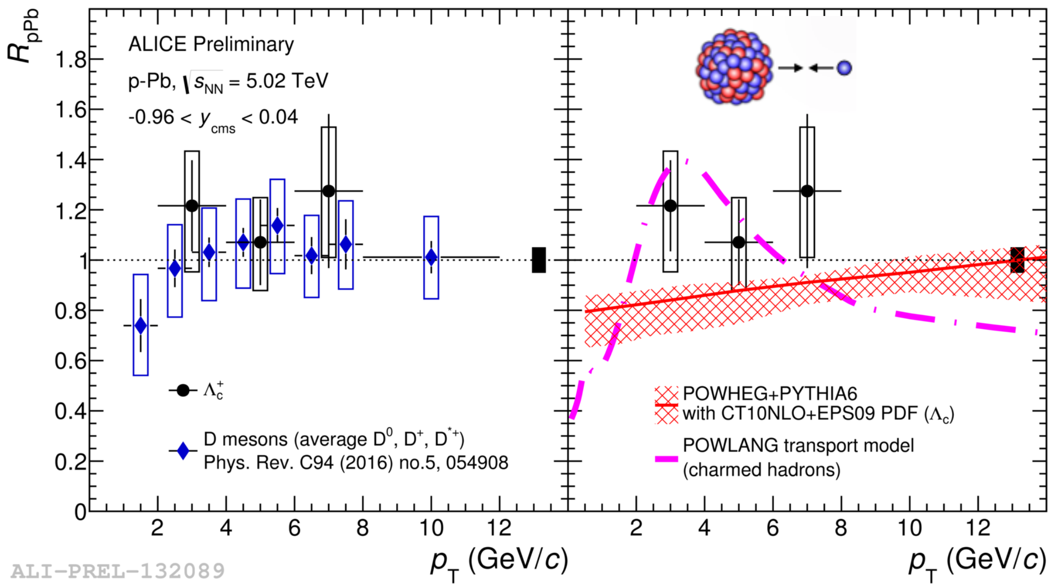
Data precision starts to constrain models and extract medium parameters!

(references for models in backup)

R_{pPb}: charmed mesons and baryons



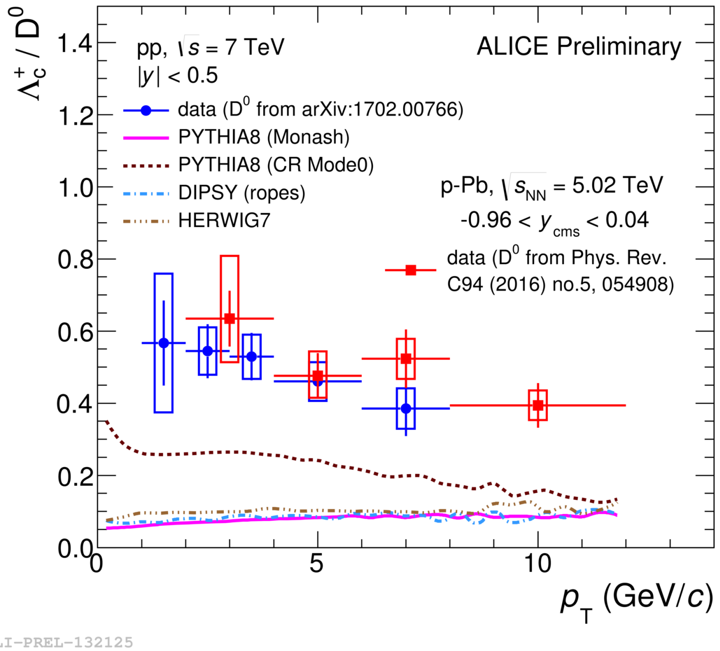
- R_{pPb} compatible with unity. No energy loss?
- CNM effects expected negligible at high p_T
- Models including nPDFs, incoherent mult. scattering describe data



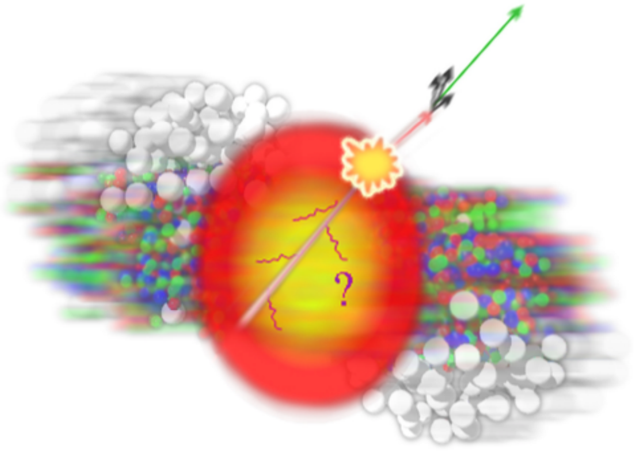
R_{pPb} for Λ_c!

Large uncertainties but compatible with unity

- In pp Λ_c measurement underestimated by NLO calculations
- Λ_c/D^0 baryon-to-meson ratio sensitive to hadronization mechanisms
- Larger than model predictions

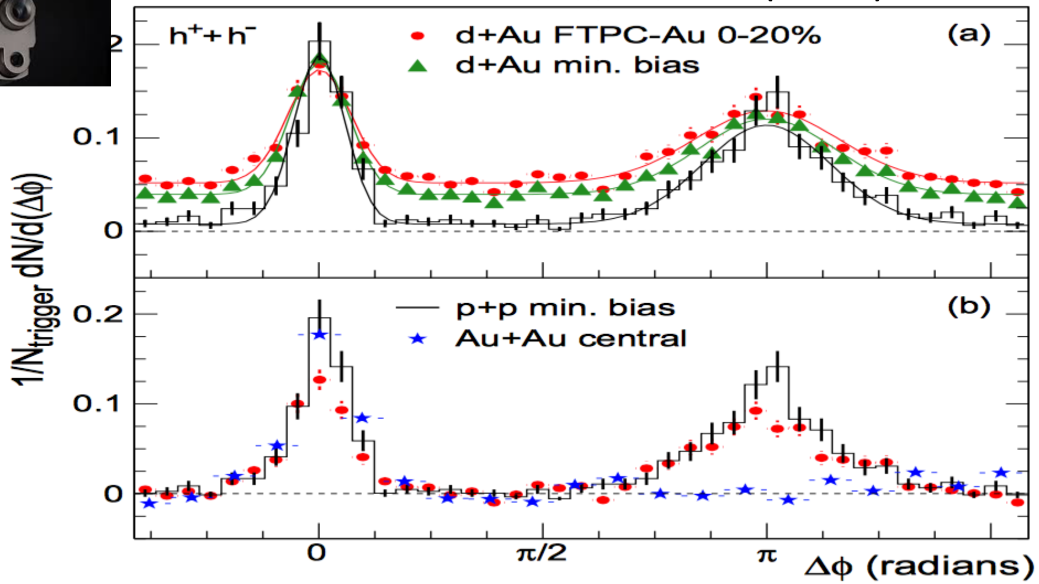


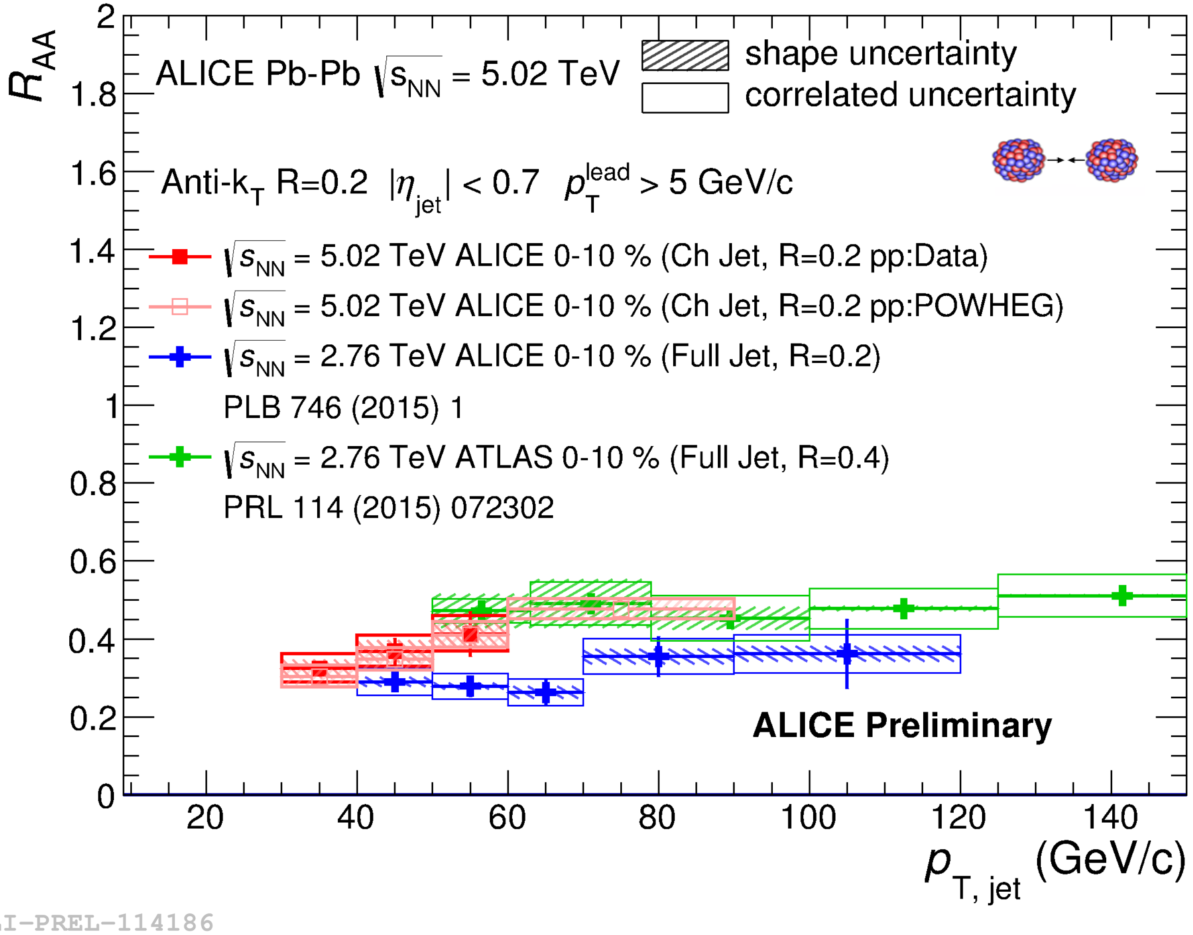
Energy loss: jet quenching



One of the smoking guns at RHIC (Au-Au and d-Au)
Strong energy loss confirmed at LHC

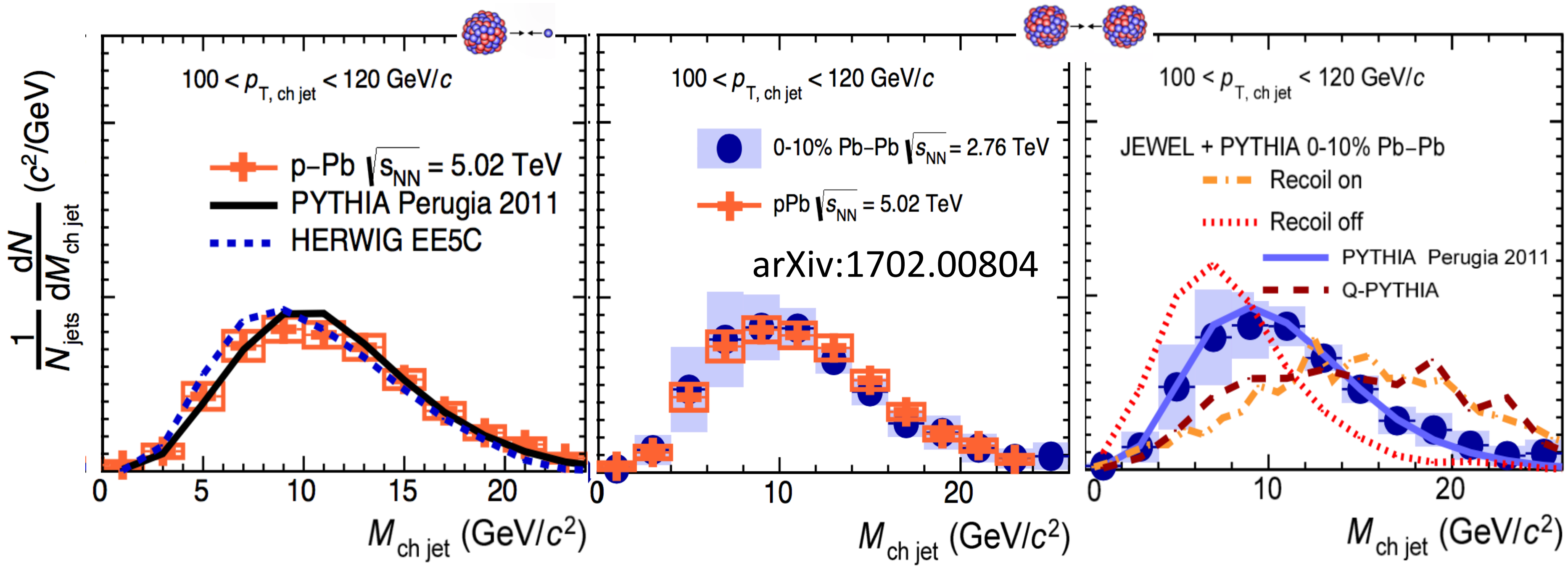
STAR, PRL 91 (2003) 072304





With increasing $\sqrt{s_{NN}}$ → increasing density → increasing quenching?
Comparable R_{AA} → harder spectrum compensates higher density

Energy loss: jets



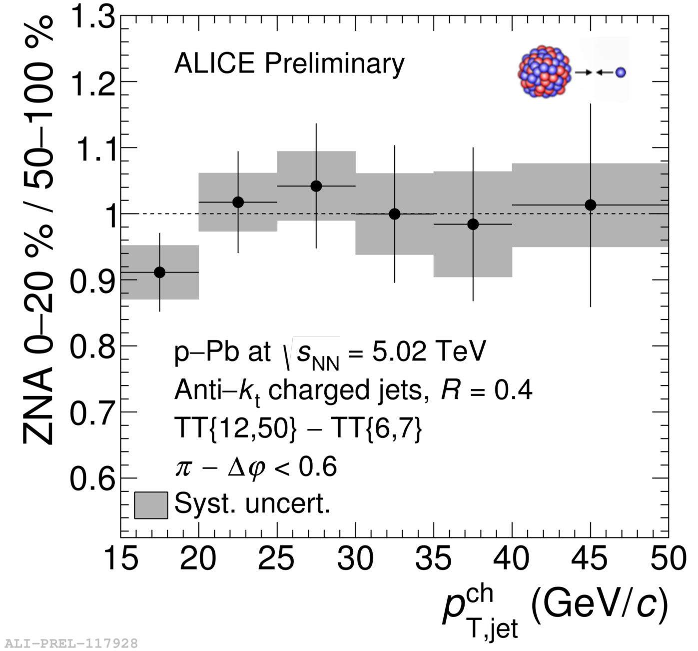
$$M = \sqrt{p^2 - p_T^2 - p_z^2}.$$

$$p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i, \quad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i$$

$\langle M_q \rangle_{jet} < \langle M_g \rangle_{jet}$

- First measurement of M_{jet} in Pb-Pb (and p-Pb)
- Jet mass sensitive to virtuality of the parton
- Interaction with hot medium may increase virtuality
  - → larger gluon radiation
- p-Pb baseline described by PYTHIA and HERWIG
- Data are best described by vacuum expectations (PYTHIA) without quenching mechanisms

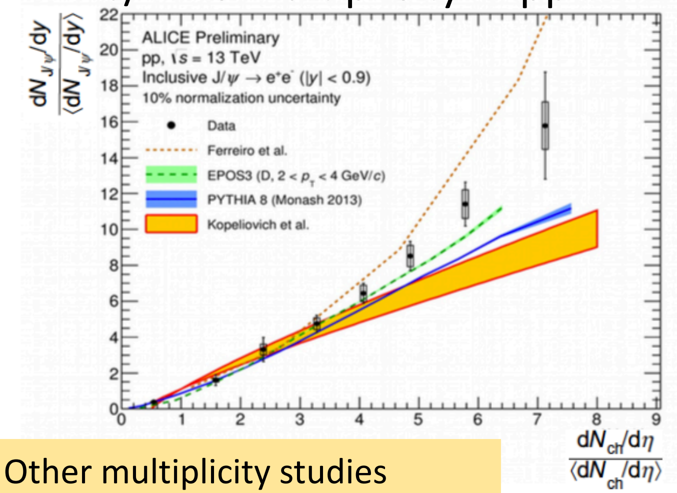
And p-Pb data jets at different multiplicity class don't show any quenching
No "hard" smoking gun in p-Pb: "collective-like medium but not dense enough"?



A further final disclaimer notice + some advertisement

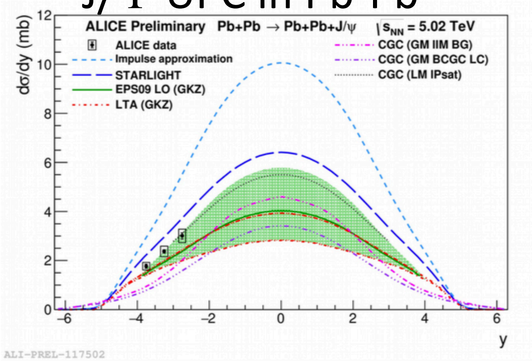
A lot of ALICE recent results **not** included in this presentation!

J/Ψ vs multiplicity in pp



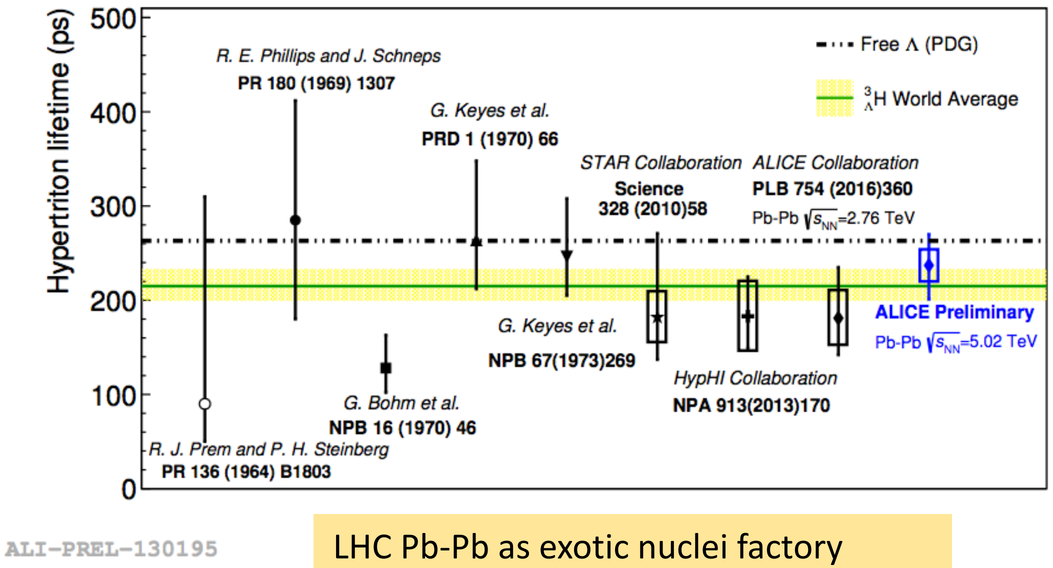
Other multiplicity studies

J/Ψ UPC in Pb-Pb



LHC Pb-Pb as large photon-nucleon collider

One of moste precise ${}^{3}_{\Lambda}H$ lifetime measurement



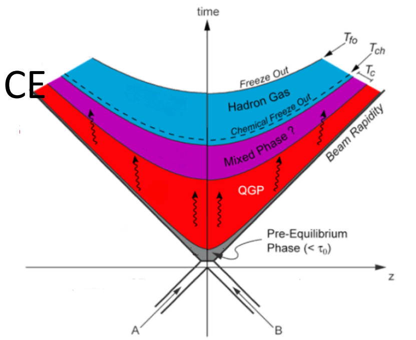
[....]

LHC Pb-Pb as exotic nuclei factory

And excellent opportunities **at this conference** to know better some of them:

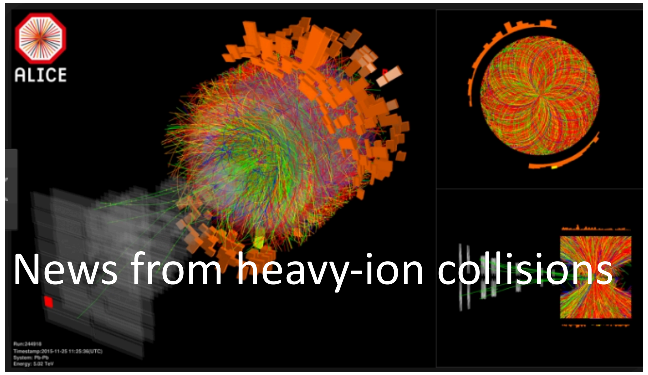
- Viktor Riabov, Measurement of **hadronic resonances** with ALICE at the LHC
- Igor Altsybeev, **Forward-backward correlations** between event-mean transverse momentum in Pb-Pb collisions with ALICE
- Ludmilla Malinina, **Femtoscopy** with ALICE at the LHC [arXiv:1709.01731]
- Dmitri Peresunko, Measurement of neutral mesons and **direct photons** with ALICE at the LHC [arXiv:1708.08745]

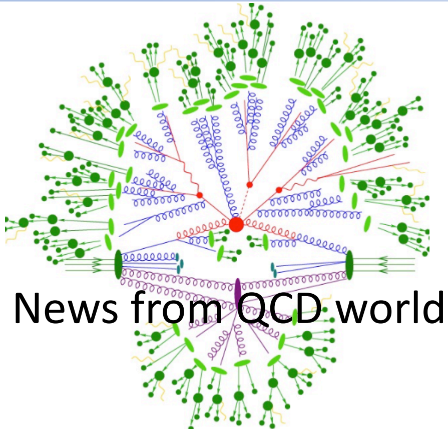
- Evgeny Kondratyuk, **Charge Particle Veto** at the LHC ALICE experiment
- Grigory Feofilov, **Upgraded ITS** for ALICE at the LHC: status and plans



+ You Zhou, Overview on HIC results

Conclusions and outlook





Standard script for a movie to explore QGP in HIC showed surprises at LHC energies:

- **traditional QGP signatures** started to show up **in pp and p-Pb collisions** (strangeness, flow-like effects, J/Ψ and Ψ(2S) yield, baryon/meson increase…)
- **multiplicity-dependent studies** show approximation of superposition of isolated scattering is not enough to describe hadronic collisions (extra final-state, multiple interactions mechanisms connected with high density of color charges?)

At ALICE, LHC Run II is providing more differential results in many observables:

- better **extracting properties of the hot medium** created in Pb-Pb collisions
- **exploring unexpected properties of pp and p-Pb** collisions

Backup: the ALICE upgrade programme

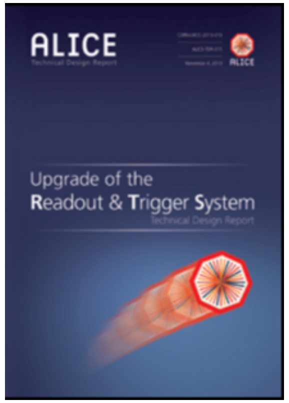
- Major upgrade of detector system during Long Shutdown 2 (2019-2020)
  - Study the thermalization of partons in the QGP, with focus on charm and beauty quarks
    → secondary vertices → improve inner tracker
  - Low-momentum charmonia dissociation (and regeneration?) to study deconfinement and medium temperature
  - Production of thermal photons and low-mass dileptons emitted by QGP to study initial temperature and equation of state of the medium
    → exploit low p_T reach & PID
  - Precision study of light nuclei and hyper-nuclei

All this… difficult to trigger...
→ read everything and reconstruct/compress online!
(rate capabilities)
→ TPC with GEM readout + improved readout

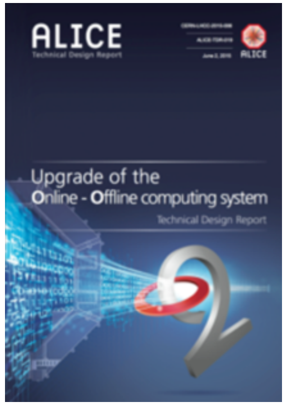
CERN-LHCC-2013-024

CERN-LHCC-2012-012

CERN-LHCC-2015-021



CERN-LHCC-2013-019



CERN-LHCC-2015-006

All results with $\mathcal{L}_{int}$=10 nb^{-1} achievable only via the five joint ALICE upgrade projects

Backup (references)

EPOS LHC

Werner et al., Phys. Rev. C 85, 064907 (2012)
Pierog T. et al., arXiv:1306.0121

- minimum bias MC
- break up parameterization of flux tubes created by initial hard scattering
- flow parameterization as a function of volume

Krakow

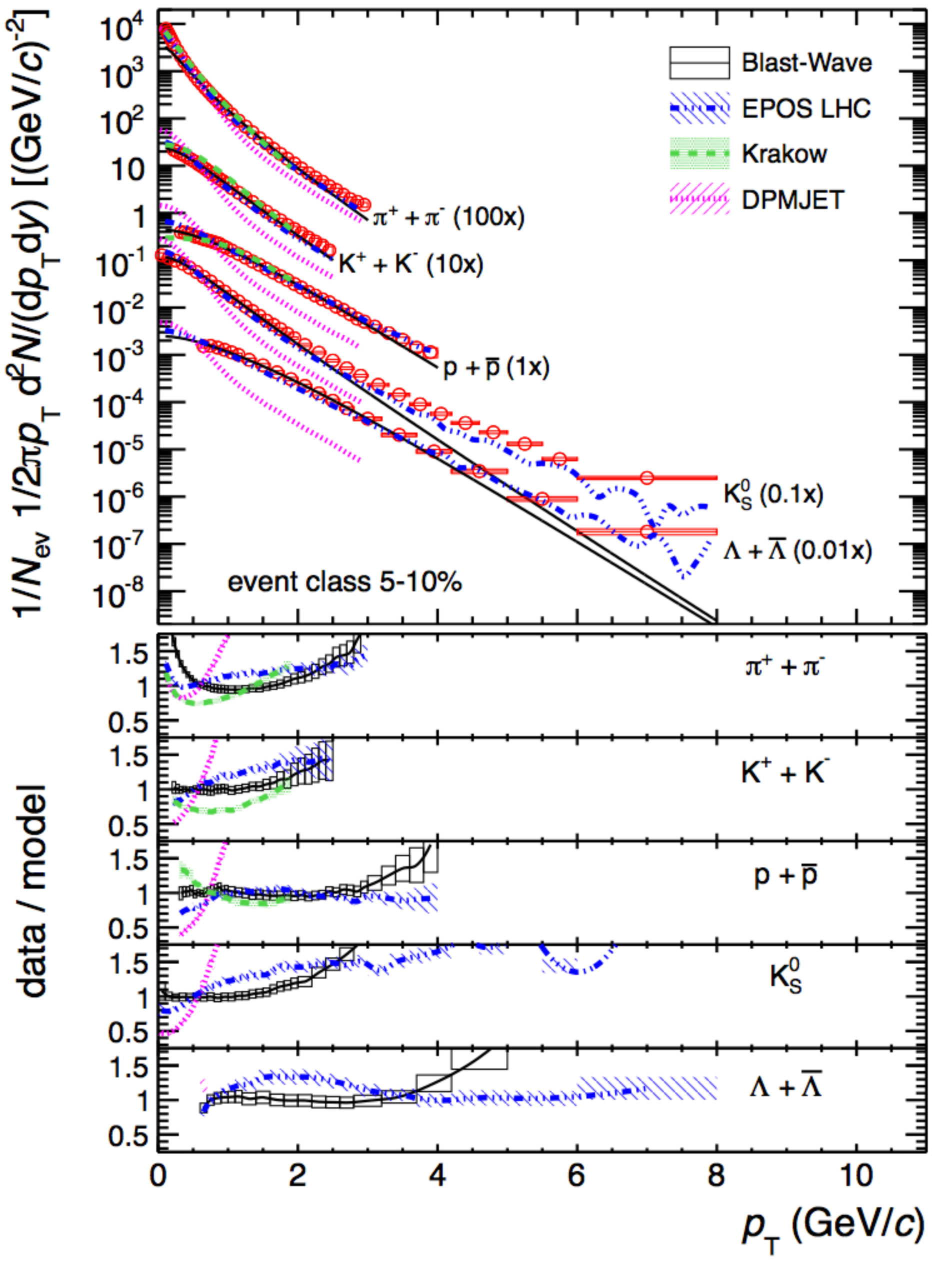
Bozek P., Phys. Rev. C 85, 014911 (2012)

- collective flow in pp and p-Pb
- hydro + non equilibrium corrections due to bulk viscosity
- statistical hadronization at freeze-out

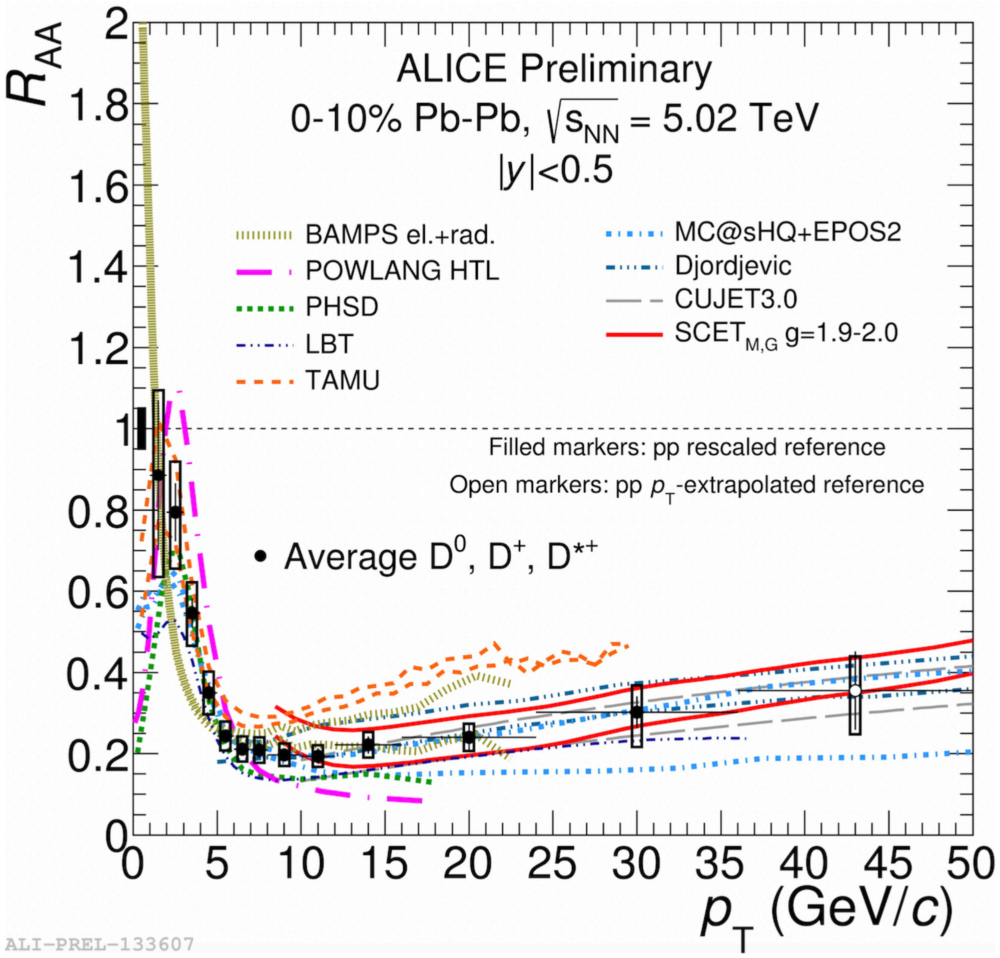
DPMJET-III

Roesler S. et al., hep-ph/0012252 (SLAC-PUB-8740)

- QCD inspired: soft/hard components treated in a unified way
- percolation of hadronic strings
- doesn't reproduce identified spectra, but it reproduce $dN_{ch}/d\eta$ in pp



Backup (references)



BAMPS: JP G 38 (2011) 124152; PL B 717 (2012) 430
Boltzmann transport, Coll. Eloss, expansion

POWLANG HTL: EPJ C71 (2011) 1666; JP G38 (2011) 124144
Langevin transport, Coll Eloss, recombination, hydrodynamics

PHSD: PR C92 (2015) 1, 014910, PR C93 (2016) 3, 034906
Parton-Hadron-String Dynamics transport, coalescence

LBT Cao, et al. PR C94 (2016) 014909
Boltzmann transport, radiation + coll.

TAMU: PL B735 (2014) 445-450
Transport, Coll. Eloss, resonant scatt. and coalescence+hydro

MC@sHQ+EPOS2: PR C89 (2014) 014905
Coll+Rad Eloss, recombination, EPOS-expansion

Djorkevic: PR C92 (2015) 024918
Coll+Rad Eloss, recombination, finite-size hydro

CUJET 3.0 Xu et al., JHEP 02 (2016) 169
Eloss+hydro + sQGMP

SCETM,G NLO: arXiv: 1610.02043
Soft Collinear Effective Theory, Bjorken expansion