A Large Ion Collider Experiment

ALICE

Heavy Ion Physics with ALICE

Grazia Luparello on behalf of the ALICE Collaboration

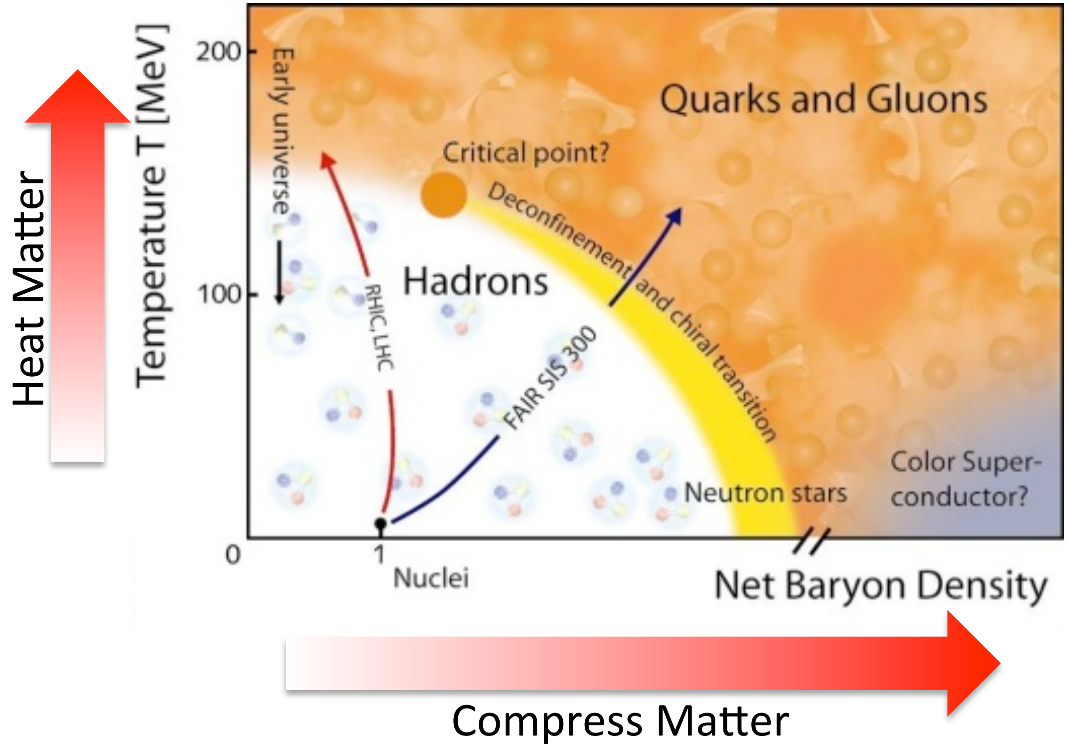
INFN – Sezione di Trieste

Les Rencontres de Physique de la Vallée d'Aoste

February 25th – March 3rd, 2018

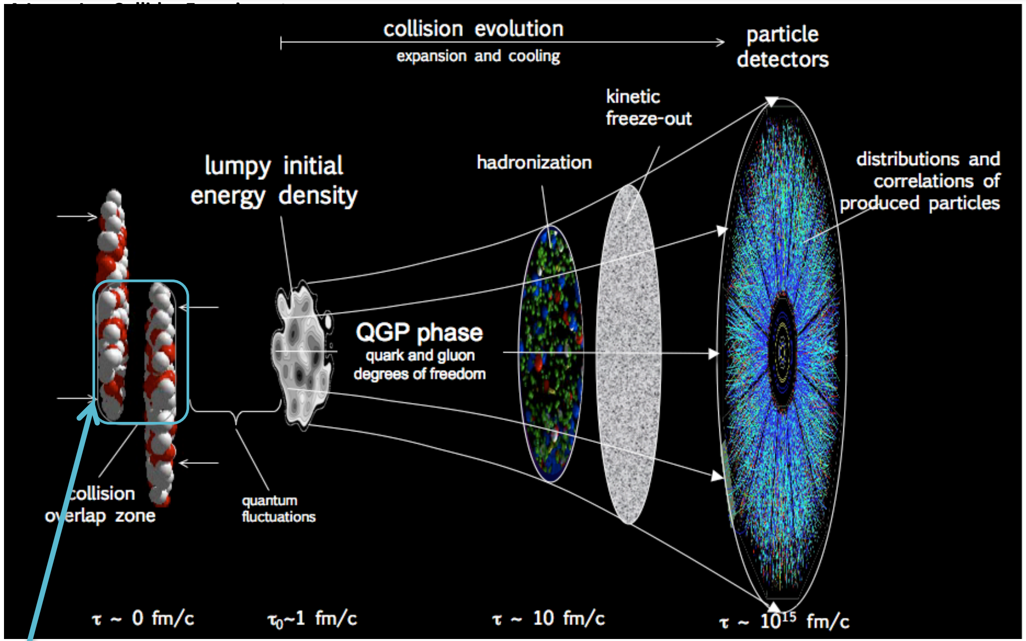
Istituto Nazionale di Fisica Nucleare

QCD Phase diagram



Collisions of relativistic heavy nuclei create the conditions for the phase transition from ordinary matter to the **Quark Gluon Plasma (QGP)**

Nuclear collision and QGP expansion



P. Sorensen, arXiv:0905.0174

- **Pre-thermal processes**: scattering of incoming quarks and gluons

Collision overlap zone:

Full overlap-> **“central”** collisions

Non-complete overlap -> **“peripheral”** collisions

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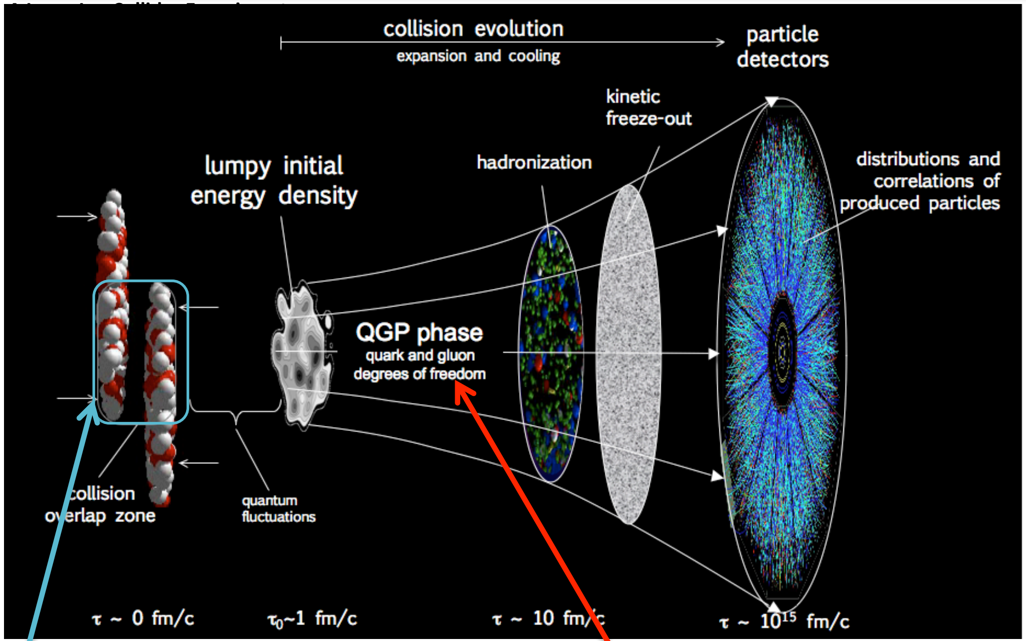

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Equilibrium is established (t~1 fm/c=3*10^{-24}s)

Same conditions of the Universe ~10μs after the Big Bang

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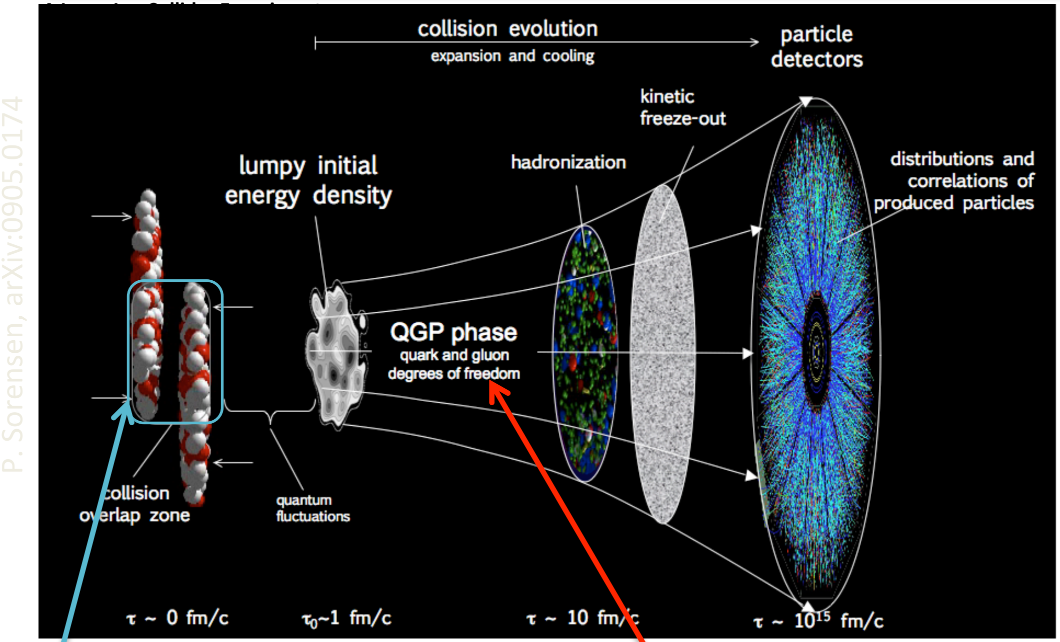

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Described by an almost perfect fluid dynamics

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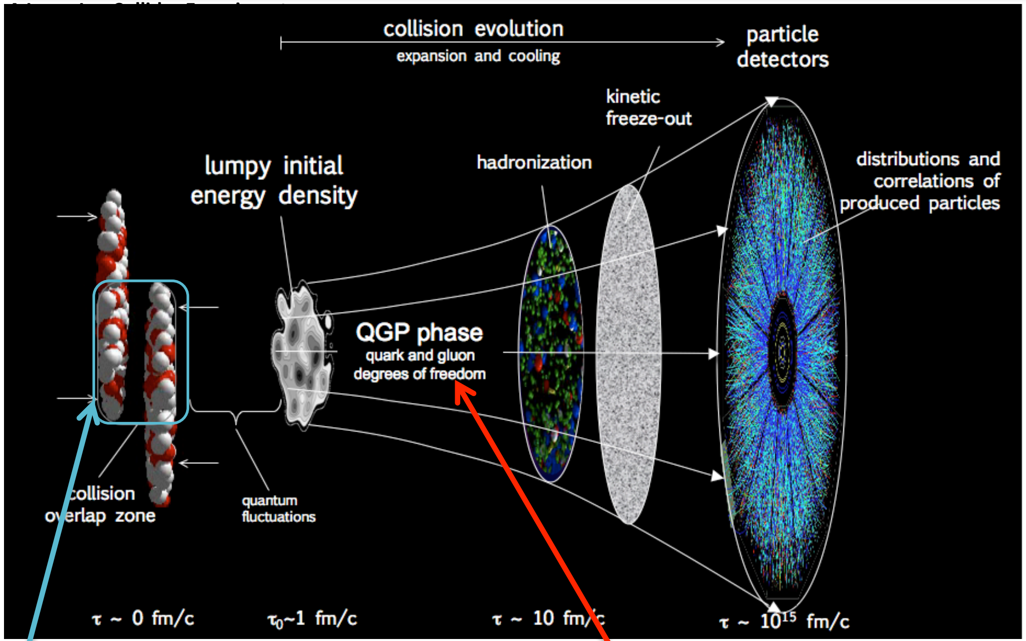

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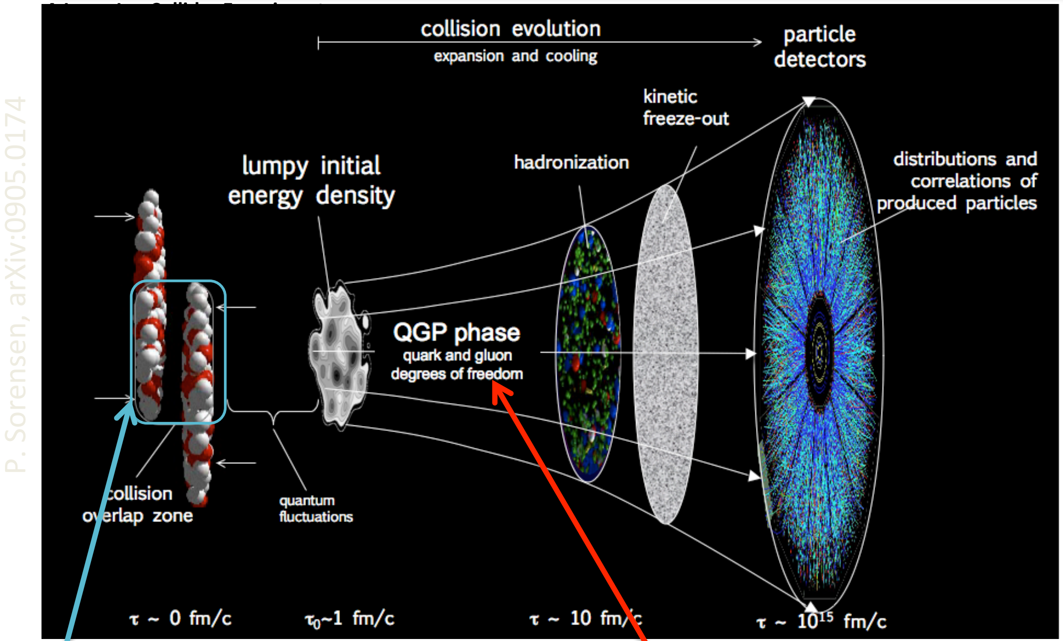

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- **Kinetic freeze-out**
Elastic interactions cease,
particle dynamics (spectra) frozen

Collision systems

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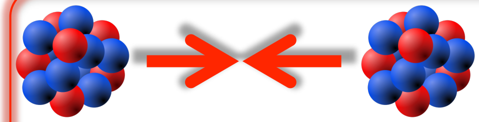

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  - Study the **QCD phase diagram** in the laboratory
  - Create and **characterize the Quark Gluon Plasma**

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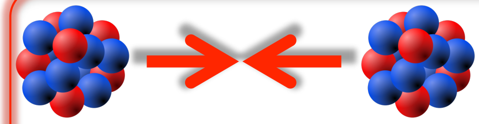

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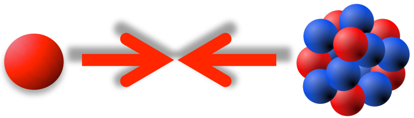
  - Provide **reference data** to check differences wrt to heavy-ion collisions



- **p-Pb collisions**
  - Control experiment, “Cold Nuclear Matter” effects

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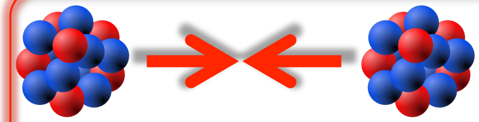

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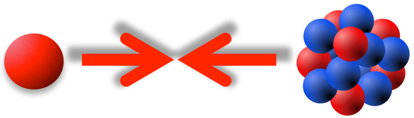

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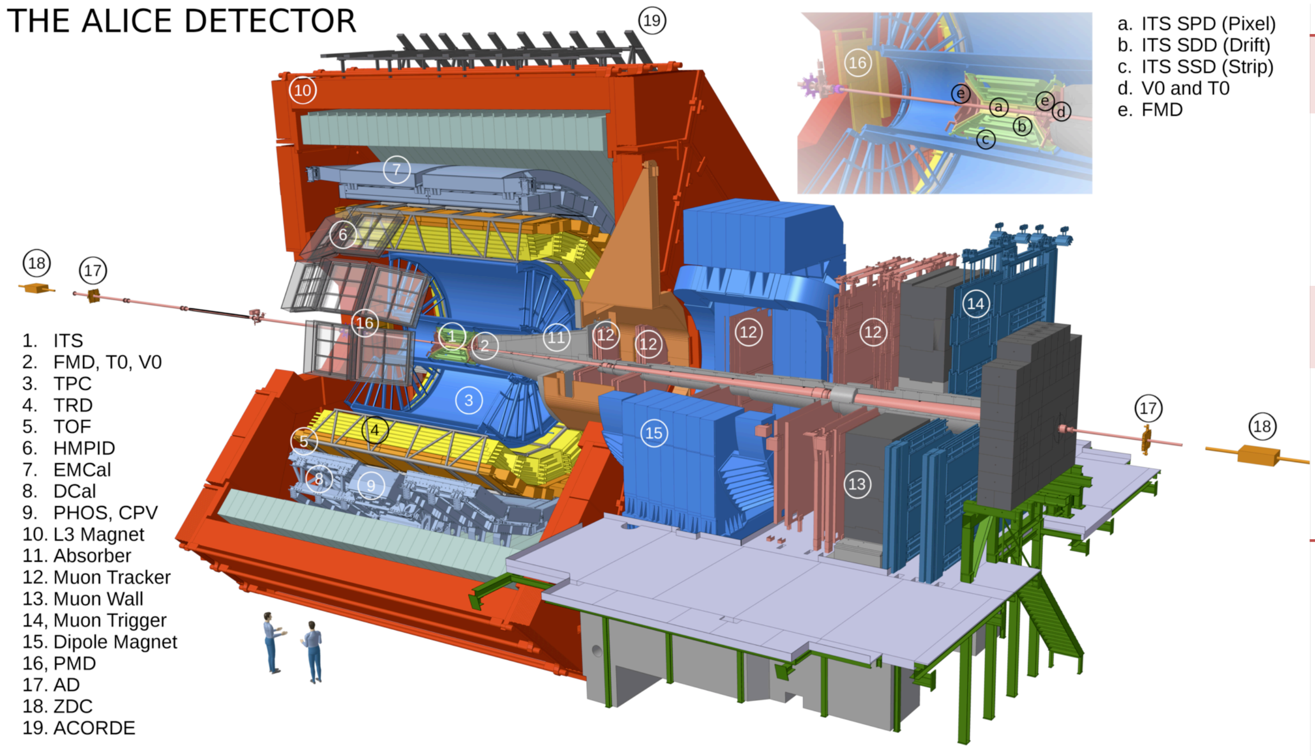
Intriguing similarities between pp /p-Pb/Pb-Pb collisions:
traditional signatures of Quark Gluon Plasma formation in heavy-ion collisions observed also in smaller systems (pp, and p-Pb)
Collectivity in small systems?

ALICE Detector

A Large Ion Collider Experiment



Run-1 (2009-2013)

Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV
p-Pb @ $\sqrt{s_{NN}}$=5.02 TeV
pp @ $\sqrt{s}$=0.9, 2.76, 7, 8 TeV

Run-2 (2015-2018)

Pb-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV
p-Pb @ $\sqrt{s_{NN}}$=5.02, 8.16 TeV
pp @ $\sqrt{s}$= 5, 13 TeV

Light particle production

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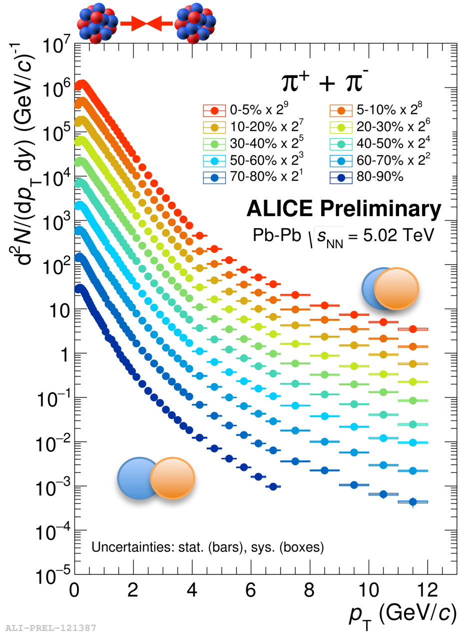
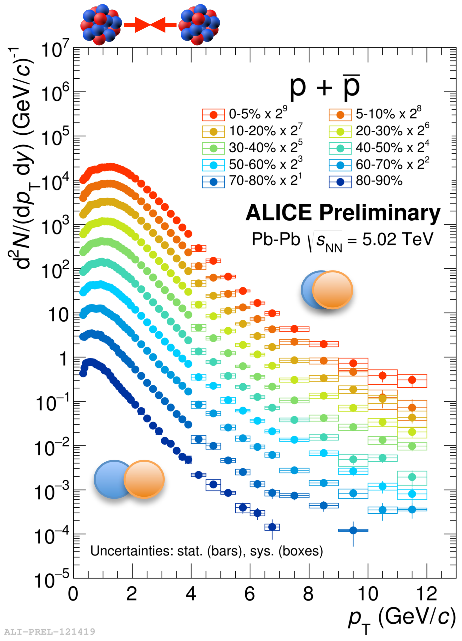
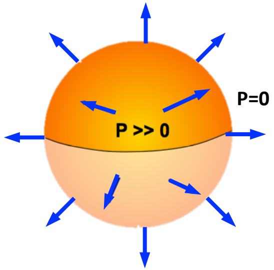
- **High precision p_T distributions of π, K, p**
  - ITS, TPC, TOF and HMPID for particle identification







- **Random thermal + collective motion driven by pressure gradient**
- Particles move in a **common velocity field**

Hardening of the spectra consistent with a radial collective flow: common velocity gives larger momentum boost to heavier particles p = γmβ

Collective expansion

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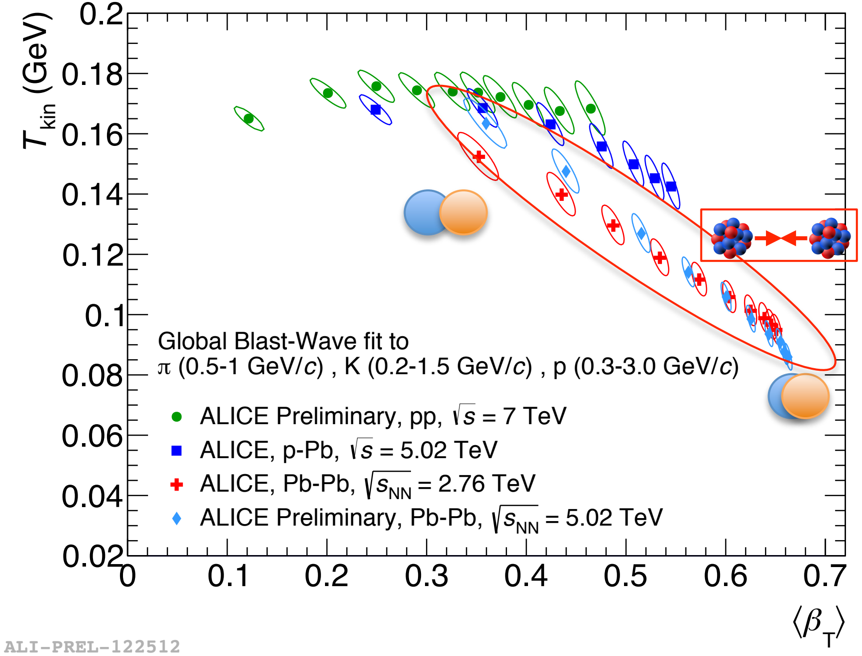
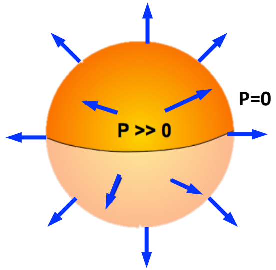


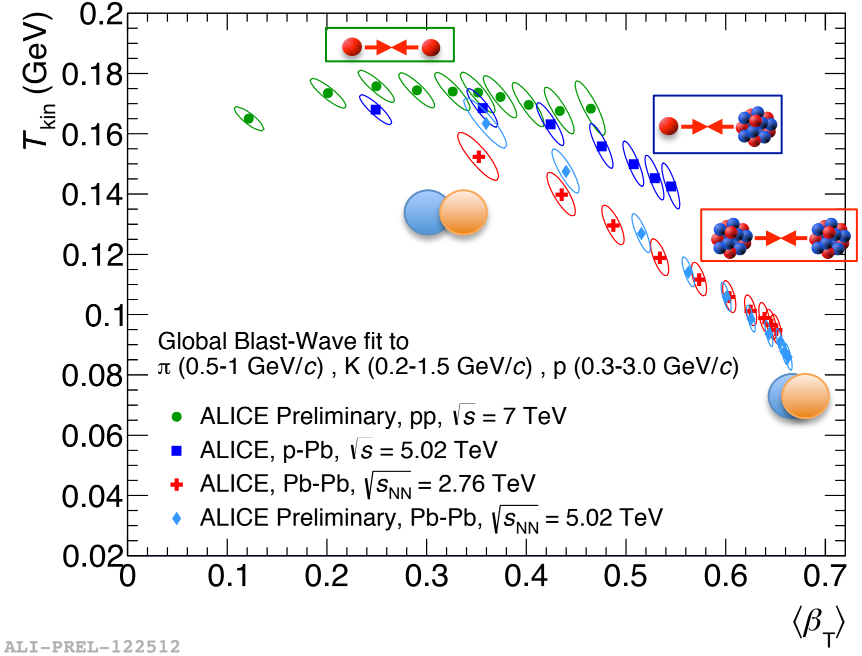


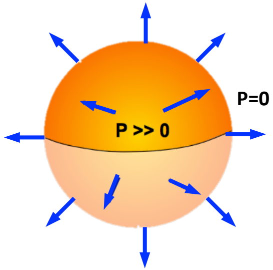
- **Random thermal + collective motion driven by pressure gradient**
- Particles move in a **common velocity field**

Common radial velocity <β_T> and **kinetic freeze-out temperature (T_{kin})** extracted via a simultaneous fit to the π, K, p spectra with the Blast-Wave model

Particle spectra consistent with collective expansion

Collective expansion





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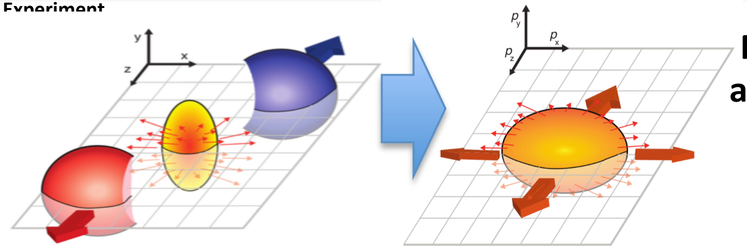
Particle spectra consistent with collective expansion

Elliptic flow

Initial spatial anisotropy



Momentum anisotropy of produced particles

Quantified via the Fourier expansion:

$$\frac{dN}{d\varphi} = \frac{N}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)\right]$$

- ***v*$_2$ elliptic flow**: related to the geometry of the overlap zone, sensitive to the thermalization of the system

Elliptic flow

A Large Ion Collider Experiment

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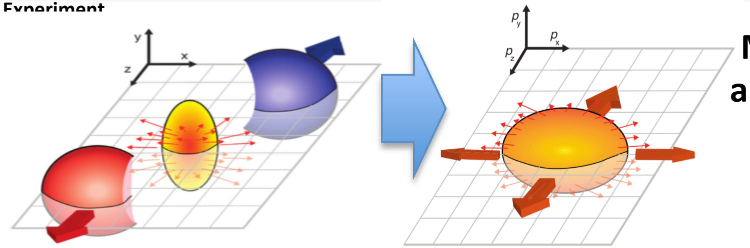

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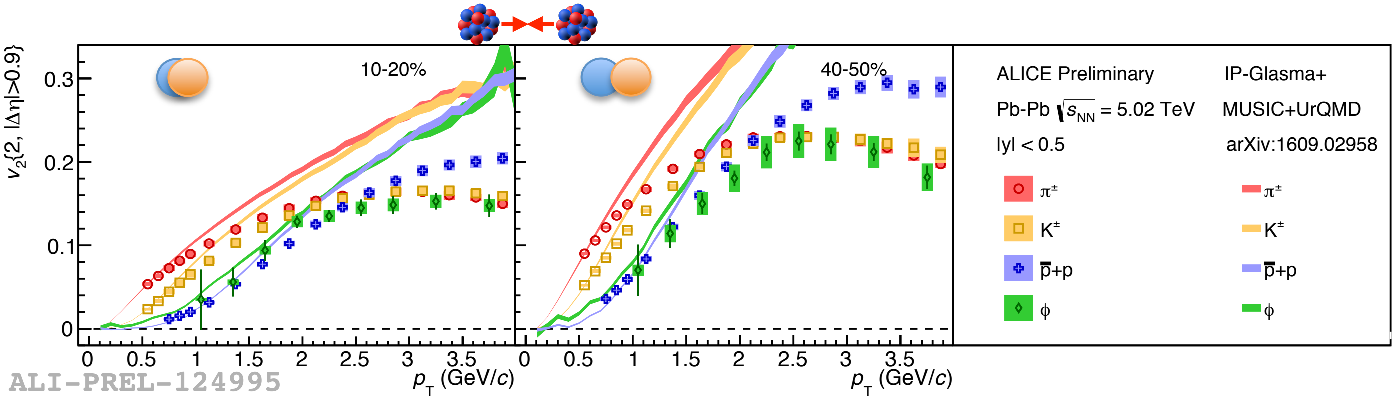
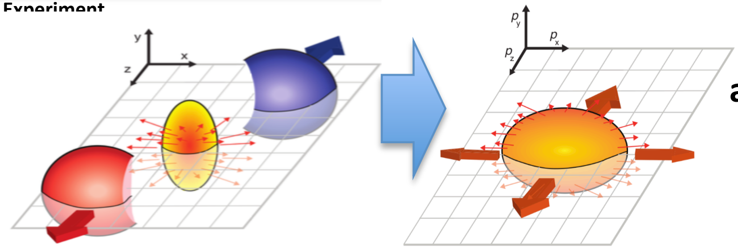


Mass ordering consistent with hydrodynamic expansion

Elliptic flow

A Large Ion Collider Experiment



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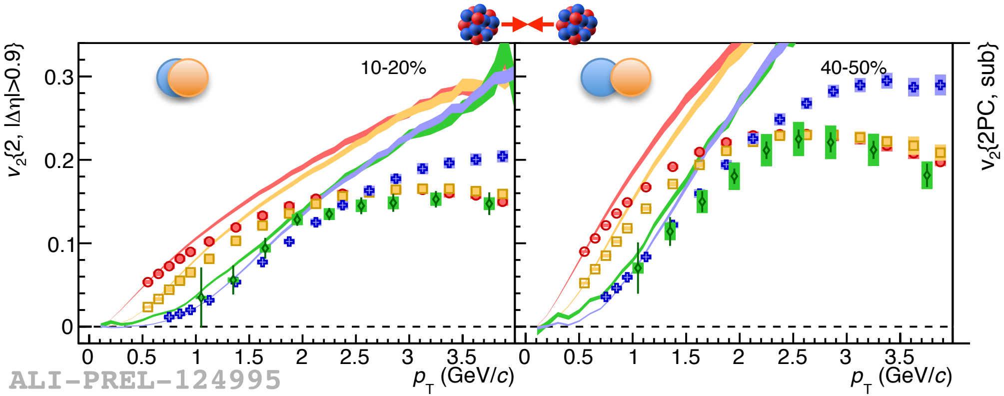
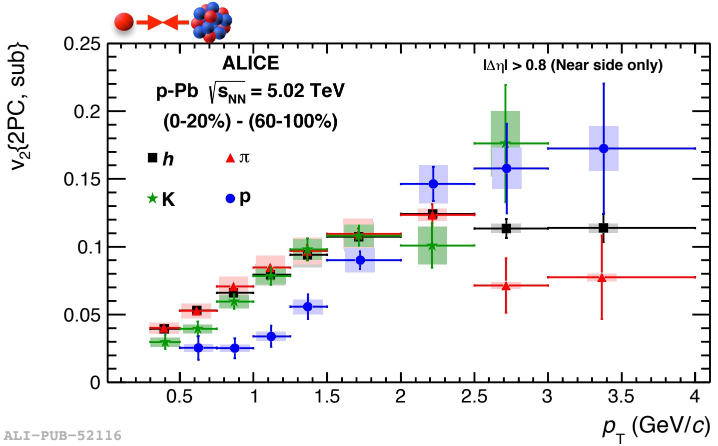




Significant v_2 in p–Pb collisions

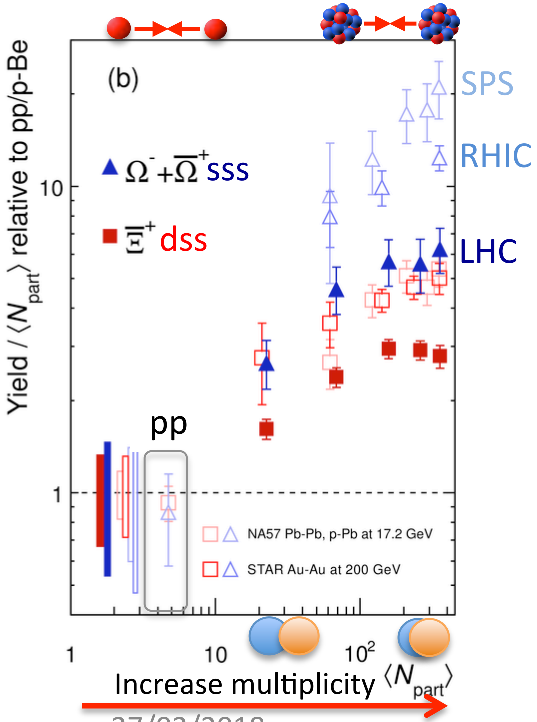
- Mass ordering just as in Pb–Pb
- Collectivity in high-multiplicity pp and p–Pb collisions?

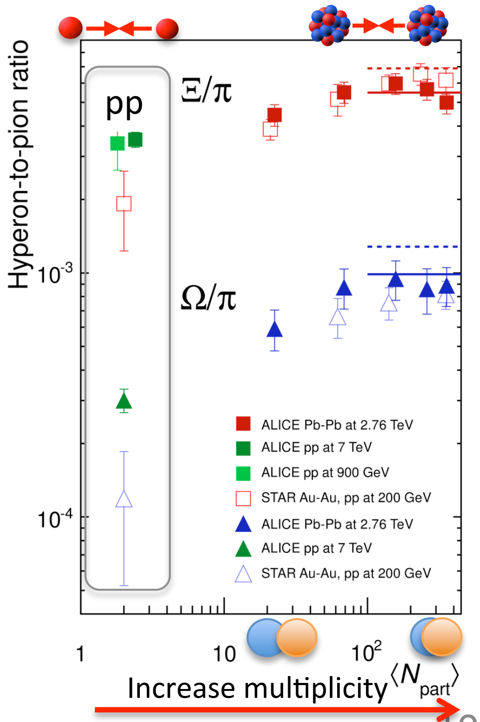
Strangeness production in Pb-Pb collisions

- Strangeness enhancement **originally proposed as a signature of QGP formation in nuclear collisions**
  Rafelski & Muller, PRL 48 (1982) 1066

- Hyperon-to-pion ratio larger in Pb-Pb than in pp collisions and in agreement with thermal model expectations

- Enhancement increases with strangeness content





PLB 11 (2013) 48

Strangeness production: new results @ 5 TeV

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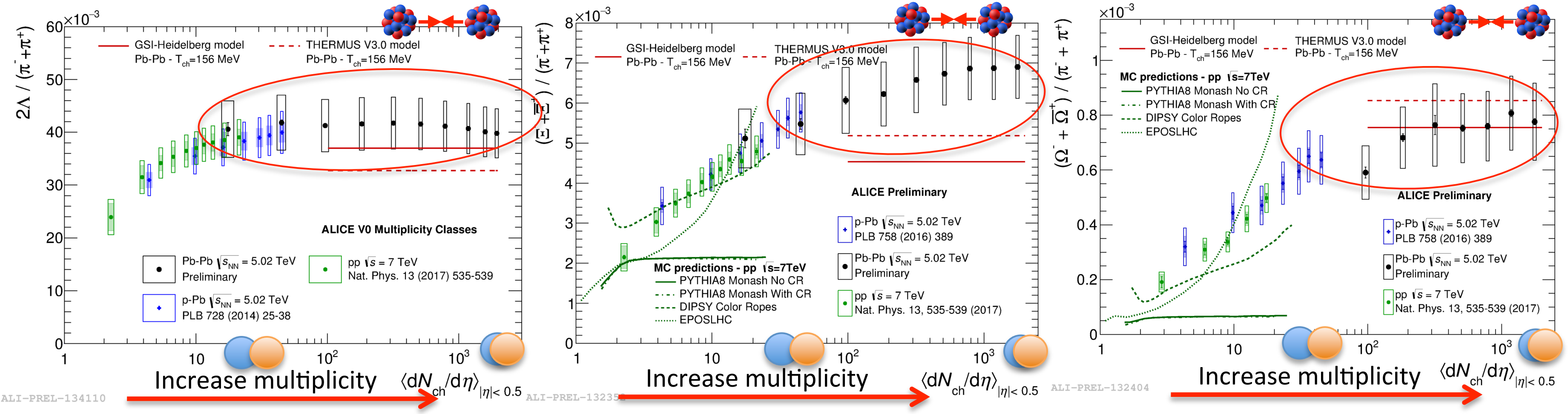
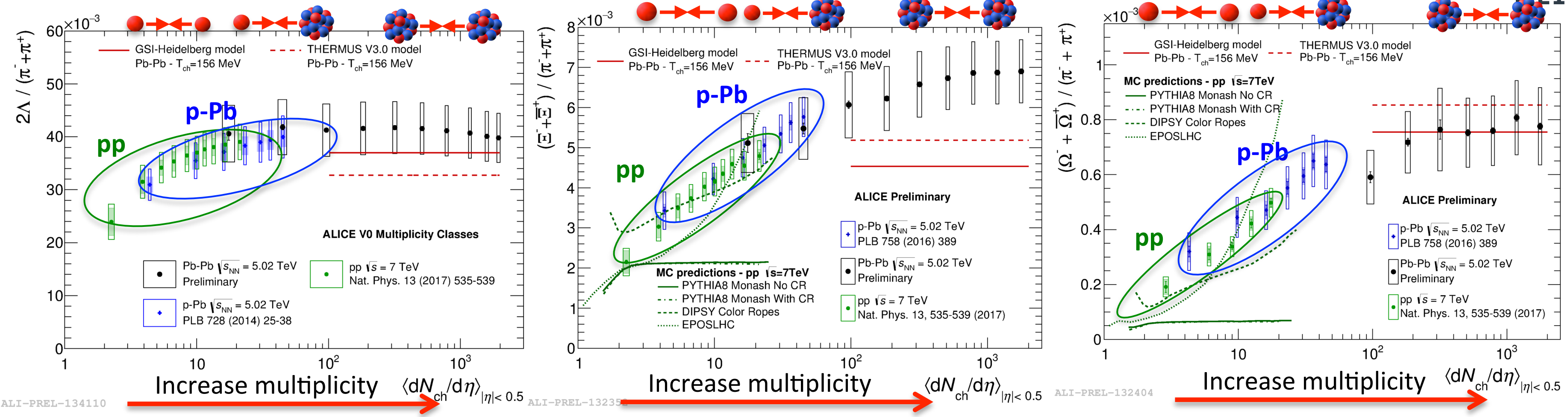


- Ratio of p_T-integrated yields to pions measured at both 2.76 TeV (not shown) and 5.02 TeV
- Strangeness increase compatible at the two energies
  - Apparently produced near thermal and chemical equilibrium

Strangeness production

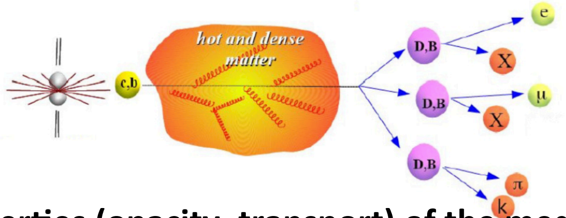
A Large Ion Collider Experiment



- **Increase of strangeness observed also in high multiplicity pp/p-Pb events:**
  - At high multiplicity pp events the ratio reaches values similar to the ones in Pb-Pb
- **No evident dependence on center-of-mass energy**
  - Driven by final state rather than collision system or energy
- **Traditional models (e.g. Pythia) fail to reproduce the data**
  - Qualitative description only by models that introduce extra-mechanism providing 'coherence' (e.g DIPSY)

See also ***Nature Phys. 13 (2017) 535-539***

Heavy-flavor production: D mesons



- Heavy quarks are produced in parton hard scatterings in the initial phases of the heavy-ion collision
- Flavor is conserved in strong interactions
  - Transported through the full system evolution -> **Probe properties (opacity, transport) of the medium**

Nuclear modification factor:
(if R_{AA}=1 no medium effects)

$$R_{\mathrm{AA}} = \frac{1}{N_{\mathrm{coll}}} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_T}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_T}$$

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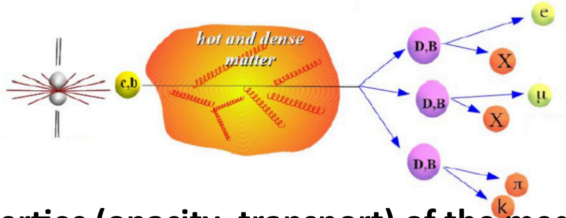

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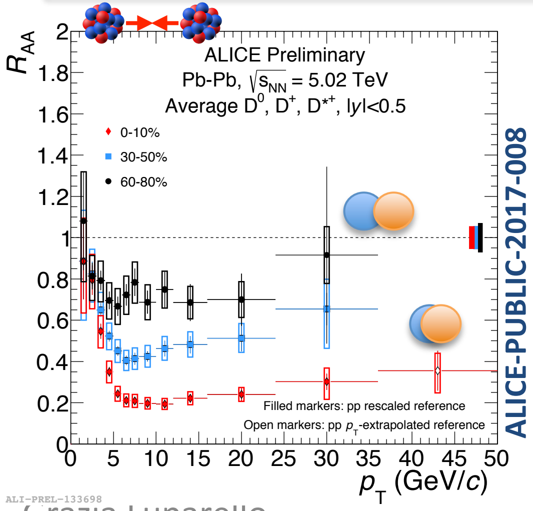

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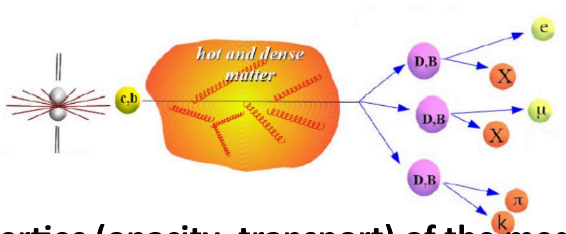

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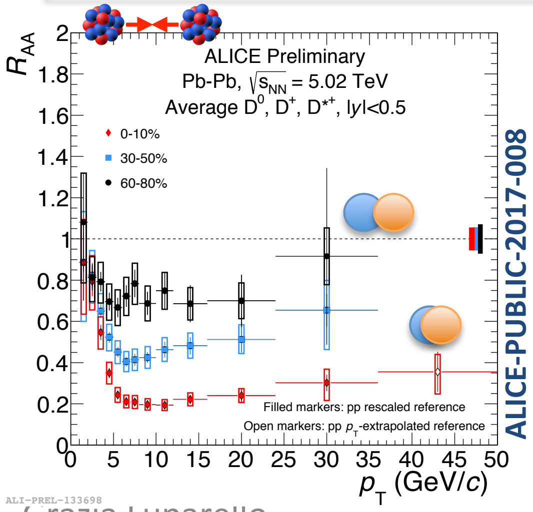
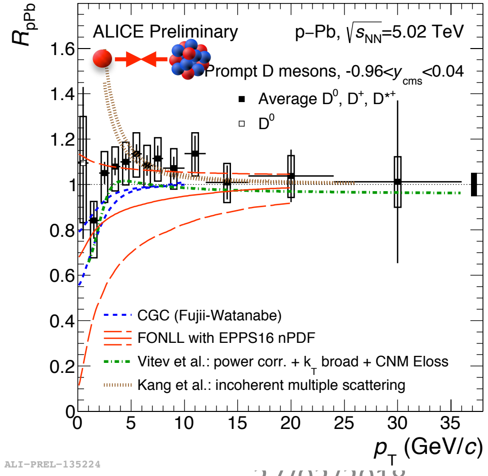


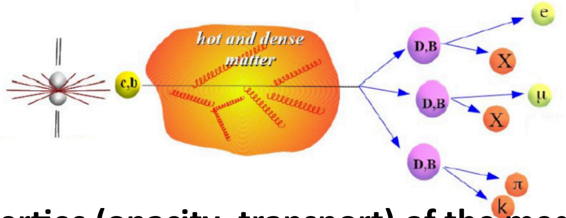


- **Strong suppression of D mesons in Pb–Pb collisions**
- **No modification in p-Pb collisions**

Strong energy loss of charm quarks in the medium

Heavy-flavor production: D mesons

A Large Ion Collider Experiment



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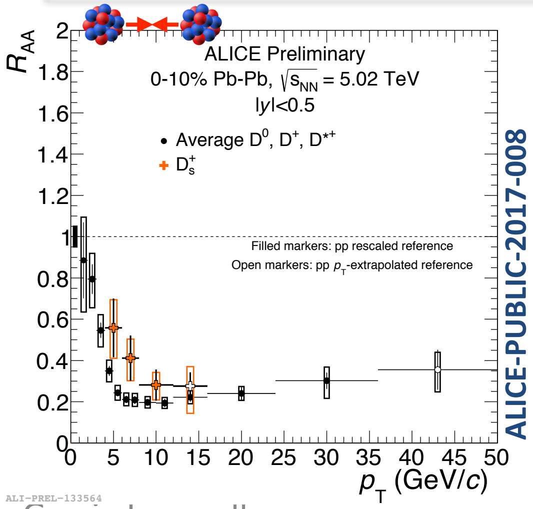
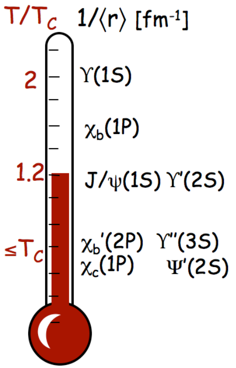


- Comparison of D_s^+ with non-strange D mesons hints a lower D_s^+ suppression
- **Coalescence + strangeness enhancement?**

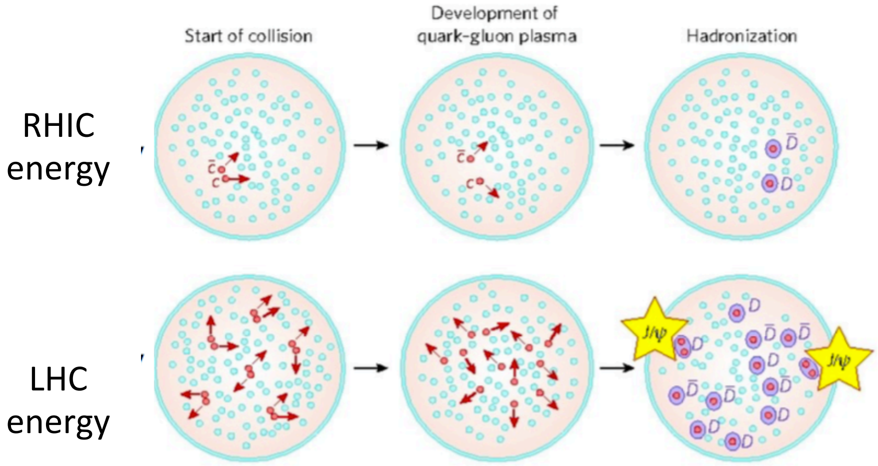
Strong energy loss of charm quarks in the medium

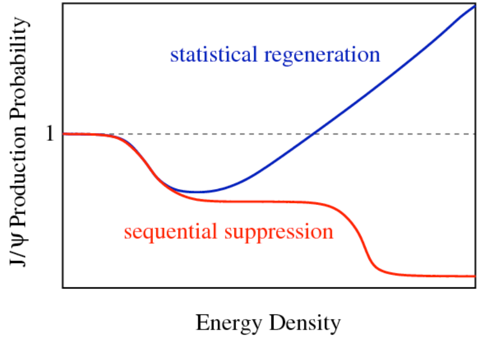
Heavy-flavor production: quarkonia



- Binding energy dependent quarkonium **suppression** -> QGP thermometer
  Matzui and Satz, PLB 178 (1986) 416

- Enhancement via **(re)generation** due to large c quark multiplicity at LHC





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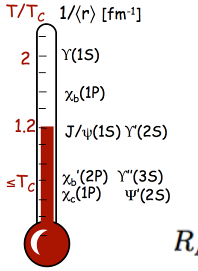

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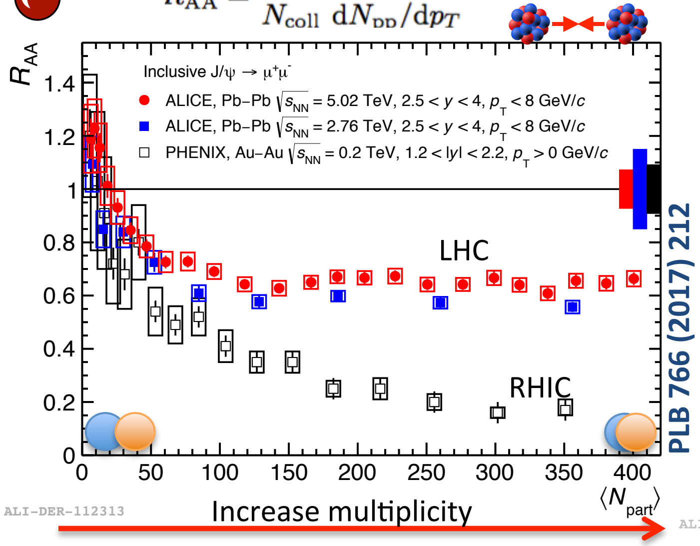
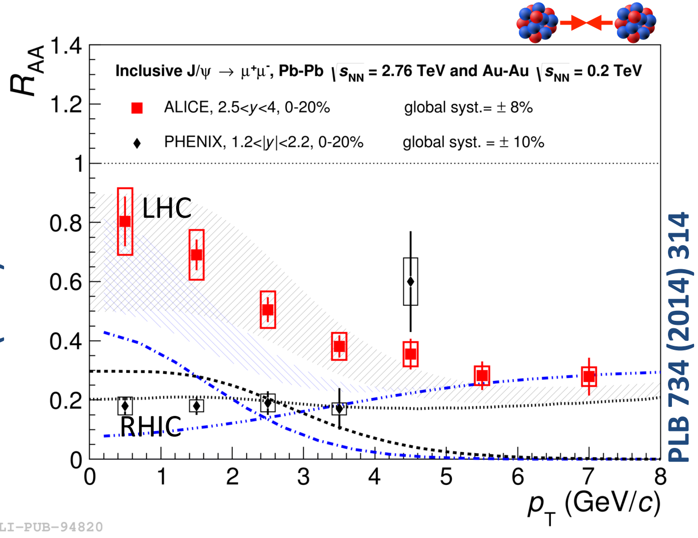
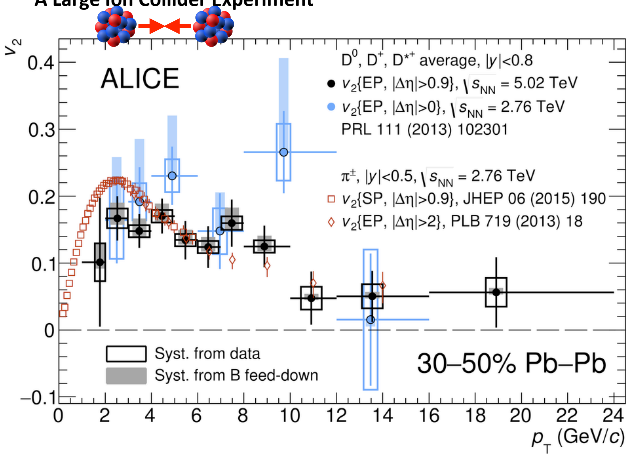




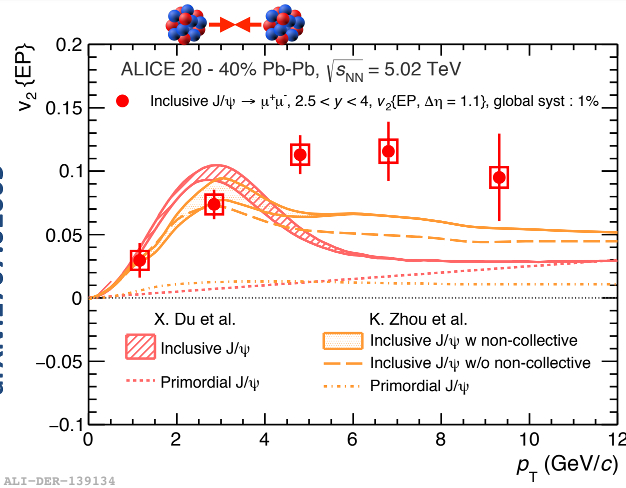
- Larger suppression at RHIC than at LHC
- **Compatible with regeneration scenario**

Heavy-flavor elliptic flow v_2

A Large Ion Collider Experiment



arXiv:1707.01005



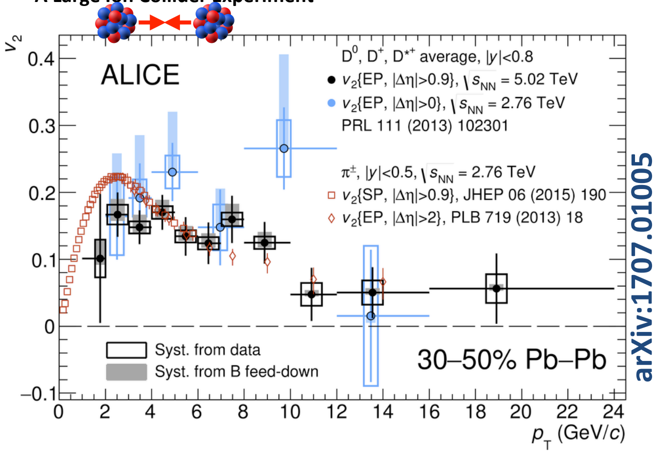
PRL 119 (2017) 242301

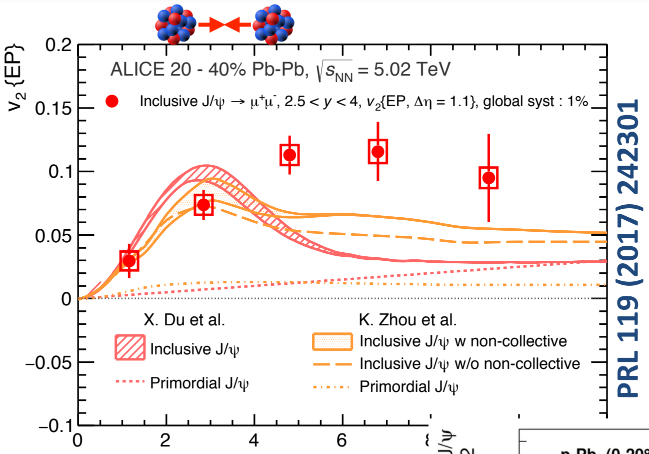
- Non-zero v_2 for D mesons and J/ψ, and comparable with that for π

Further signs of charm thermalization and recombination

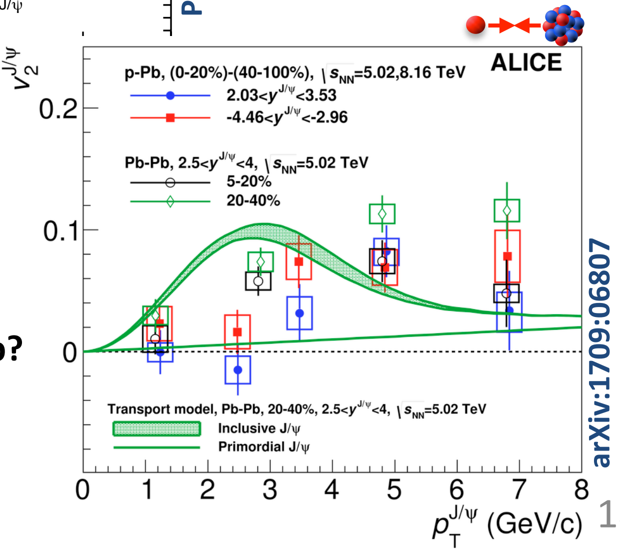
Heavy-flavor elliptic flow v_2

A Large Ion Collider Experiment





- **Non-zero v_2 for D mesons and J/ψ, and comparable with that for π**



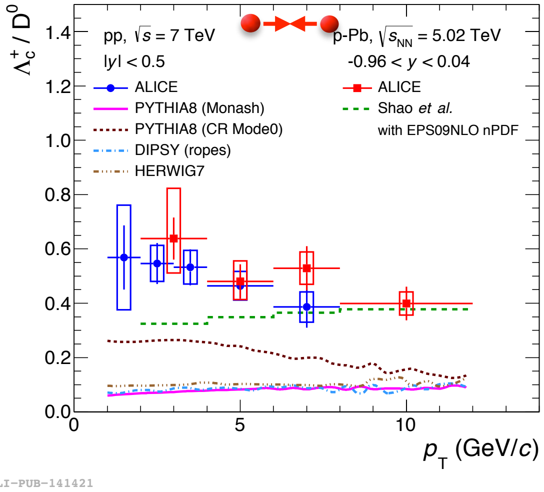
In p-Pb collisions:

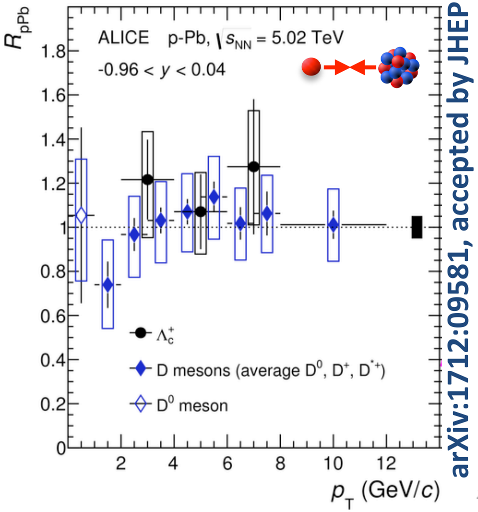
- At p_T<3 GeV/c v_2 compatible with 0 (No recombination expected)
- At p_T>3 GeV/c v_2>0
- Values compatible with J/ψ v_2 in central Pb-Pb collisions

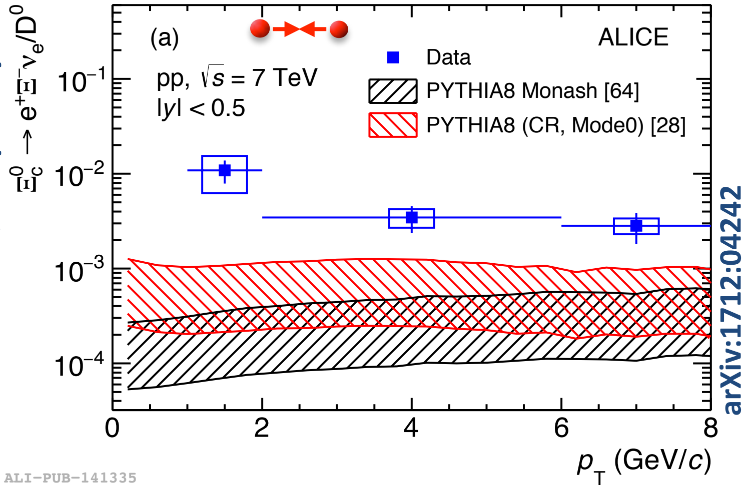
Suggest that charm quarks participate in collective effects also in p-Pb? other mechanism?

Charmed baryons

- **First mid-rapidity measurement of Λ_c in pp and p-Pb collisions at the LHC**
  - Charmed baryon-to-meson ratio not reproduced by event generators
- **Measurement of Ξ_c in pp collisions**
- Constrains charm hadronization
- Benchmark for measurements in heavy-ion collisions







Toward LHC Run 3

A Large Ion Collider Experiment

Major upgrade of ALICE apparatus during Long Shutdown 2 (2019-2020)

Goals: study **rare low *p_T*** probes (heavy flavour and quarkonia, low mass dielectrons, nuclei)

- Non triggerable probes -> Need continuous readout at 50 kHz (x50 faster)
- Improve tracking resolutions at low p_T and vertexing -> increase granularity and reduce material thickness
- Secondary vertex for measurements in the forward region

- **Data taking during Run 3-4** (2021-2029) : aim at 10 nb^{-1}

CERN-LHCC-2013-024

CERN-LHCC-2012-012

CERN-LHCC-2015-021

CERN-LHCC-2013-019

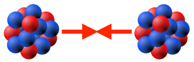
CERN-LHCC-2015-006

Conclusions

A Large Ion Collider Experiment

Progress in the **characterization of the QGP** created in **heavy-ion collisions**

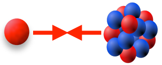
Run 2 (Pb–Pb at 5 TeV): similar trends, more data ⇒ **precise** characterization



Early thermalization and strong collective behavior consistently described by hydrodynamic models

Strangeness enhancement as predicted in a QGP medium

Suppression of heavy flavor and high p_T particle production wrt to binary scaled pp collisions



Evidence of collective behaviour in p-Pb and high-multiplicity pp collisions

Smooth strangeness enhancement from pp to p-Pb driven by event multiplicity

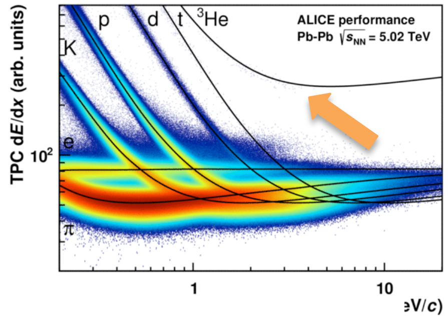
Heavy flavors are NOT suppressed

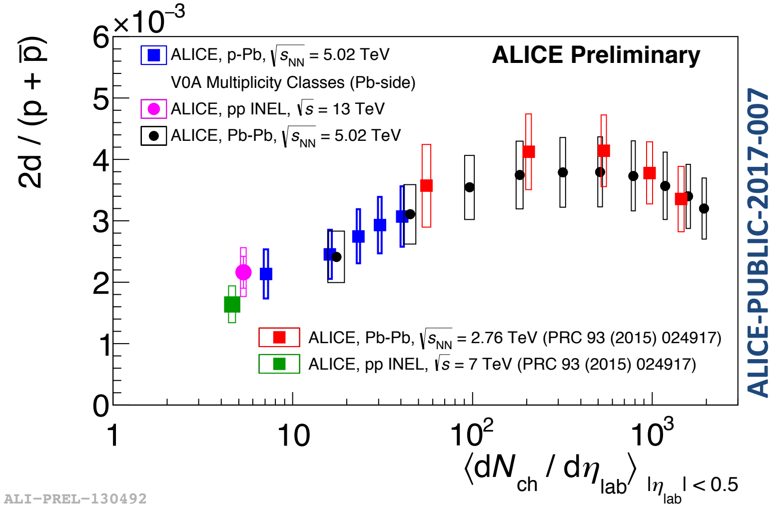
More to come with the **upgrade**: high Pb-Pb luminosity and improved tracking

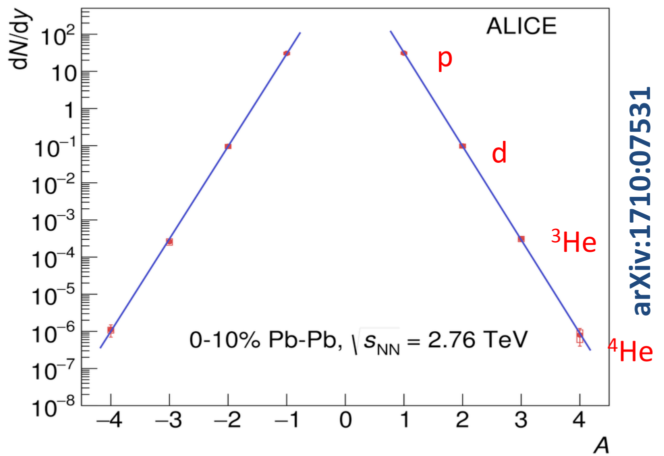
Nuclei production

A Large Ion Collider Experiment

- **Heavy-ion collisions are also factory for nuclei**
- Production mechanism of compound objects inside the fireball
  - Coalescence or thermal production?







- **Increase of d/p ratio with multiplicity expected from coalescence model**
- **Saturation at high multiplicities expected for thermal production**

- **Yield compatible with exponential fall predicted by the thermal model with T_{chem} ~156 MeV**

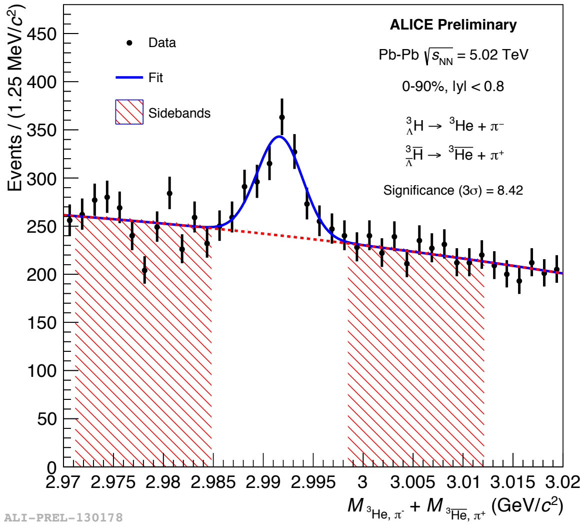
Mechanism of nuclei production not yet fully understood

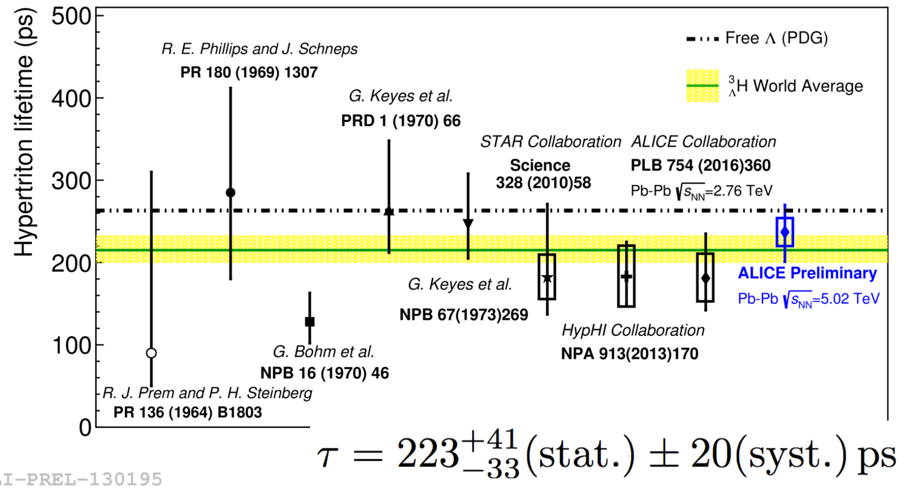
Hyper-Nuclei production

A Large Ion Collider Experiment

- **Heavy-ion collisions are also factory for hyper-nuclei**
- Hypernucleus: nucleus containing at least an hyperon
- **Hypertriton ($^3_\Lambda$He)** is the lightest hypernuclus formed by (p,n, Λ)

$$^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$$





$$\tau = 223^{+41}_{-33}(\mathrm{stat.}) \pm 20(\mathrm{syst.})\ \mathrm{ps}$$

Most precise measurement of hypertriton lifetime