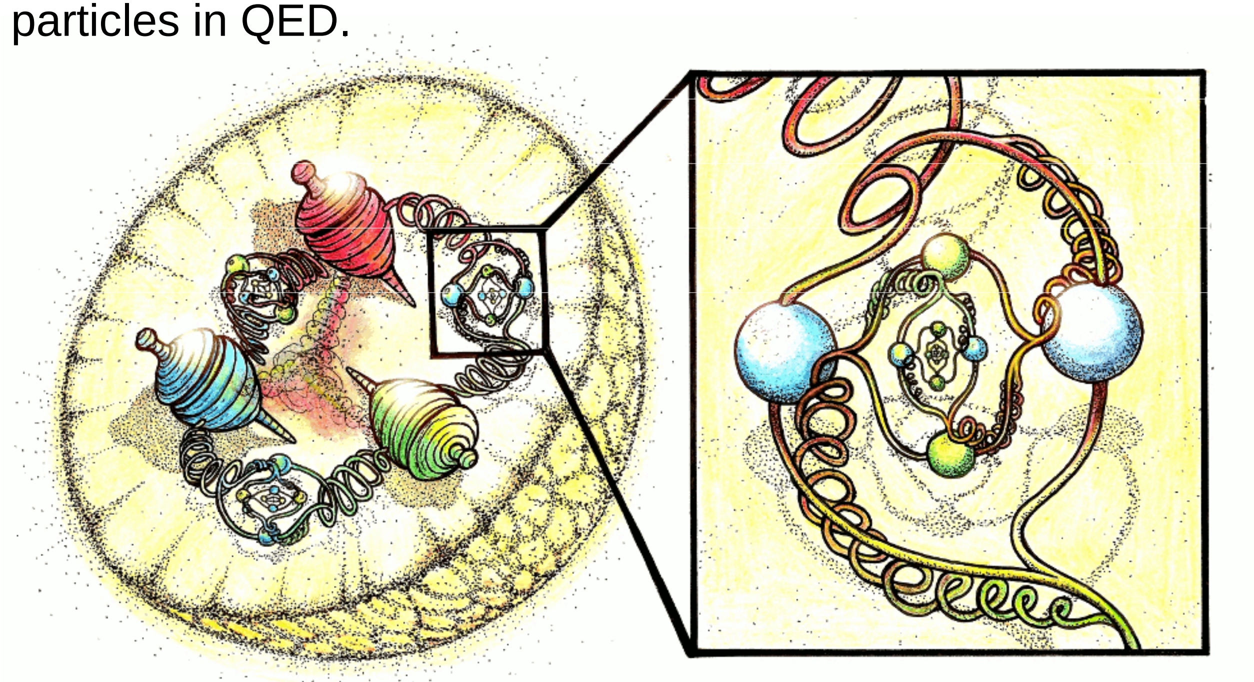
Recent ALICE Results

Astrid Morreale, SUBATECH/CNRS

CPPM Seminar– October 30 2017

Parton confinement

- QCD describes the strong interactions between spin 1/2 objects called quarks which possess color as an internal degree of freedom.
- Color is a quantum number that couples to a vector field whose quantas are the gluons.
- Gluons are the gauge bosons of QCD, they are massless and they mediate the interaction between the quarks , similar to photons mediating the interaction between charged particles in QED.



- When the distance between two quarks increases, the recoil interaction between these two quarks increases.
- It is not possible to observe isolated quarks or gluons under ordinary temperature and energy density conditions.

How can we liberate quarks?

Quark Gluon Plasma

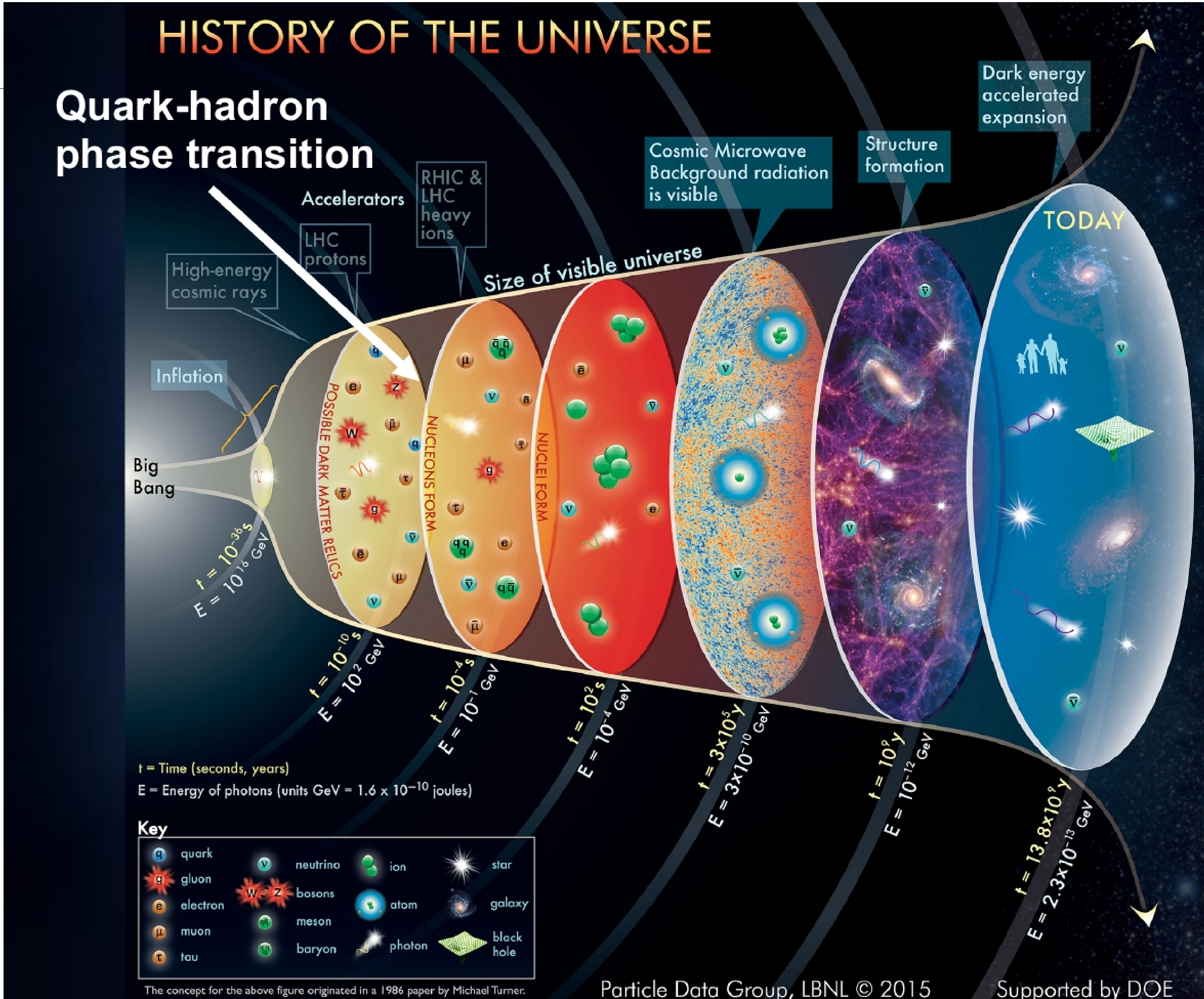
 → 

Heat and pressure leads to a phase transition:

collisions of heavy atomic nuclei Pb^{208}, Au ^{197}

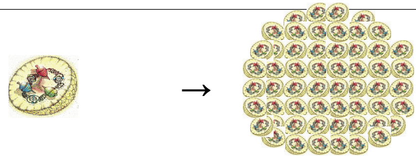
New state of matter: quarks and gluons are liberated. $T \sim 10^{12} K \sim 10^{5}$ sun's core

Evolution of the early universe, QGP may still exist in neutron stars



HISTORY OF THE UNIVERSE
Quark-hadron phase transition
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3\times10^{5}$ y
$E = 3\times10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\times10^{9}$ y
$E = 2.3\times10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

Quark Gluon Plasma



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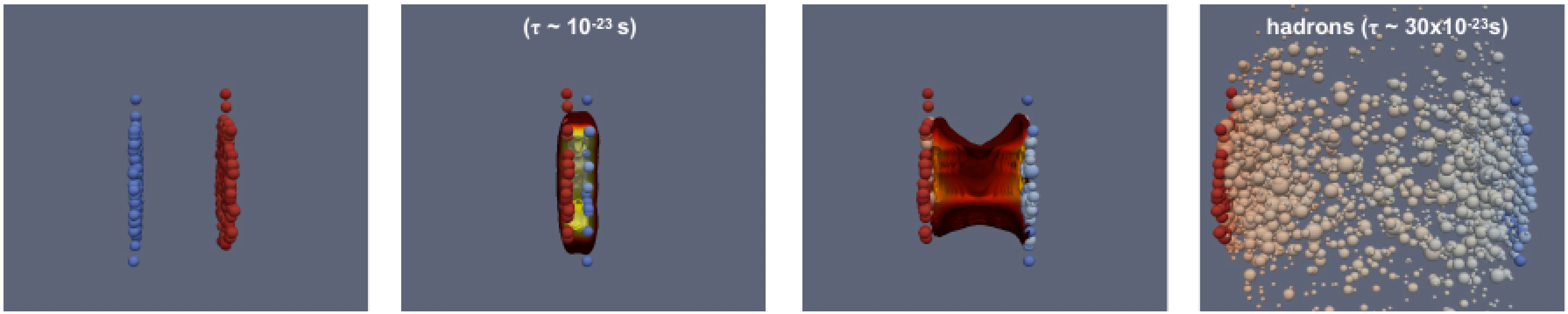

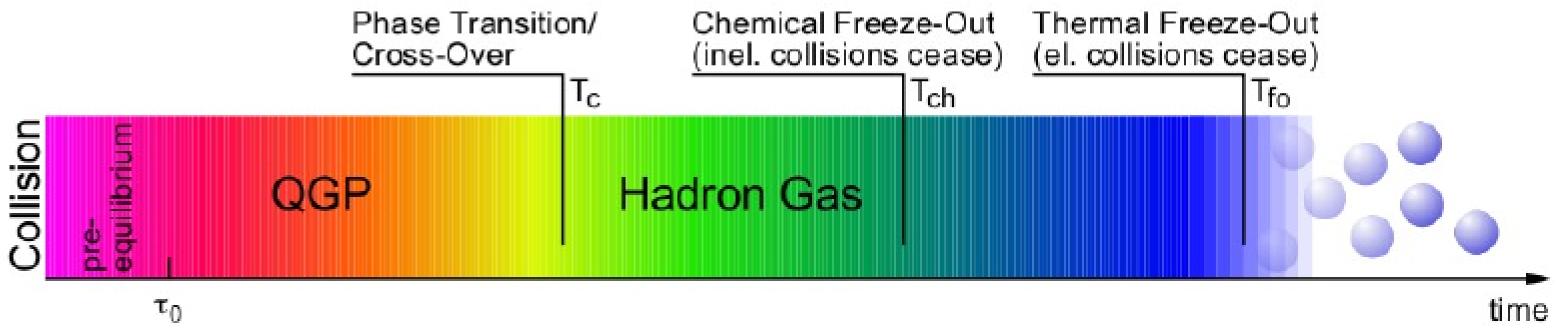

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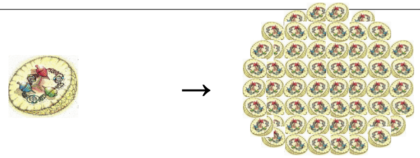

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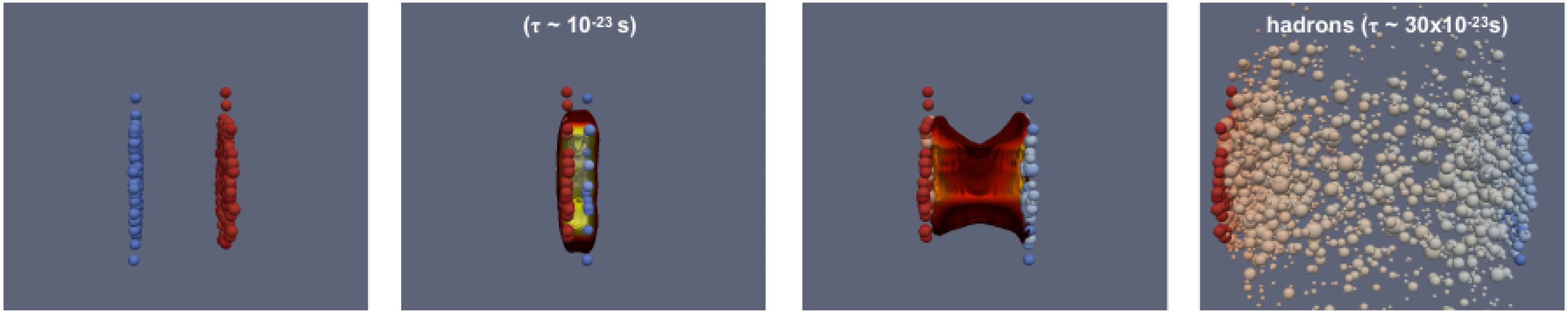
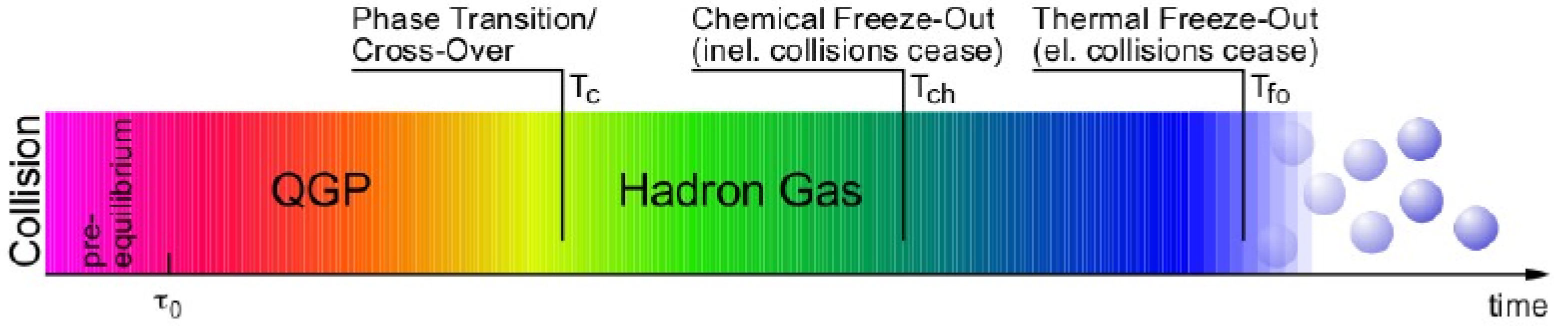
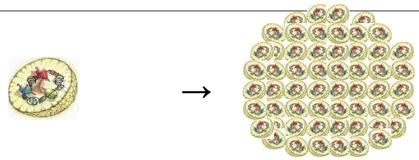




Time evolution of the QGP created in nucleus-nucleus collisions:

- Dynamical modeling of the different stages of the the collision
- Understand a significant fraction of the dynamics from hadron measurements
- Distinguish what can be related to the first and last stages

Quark Gluon Plasma



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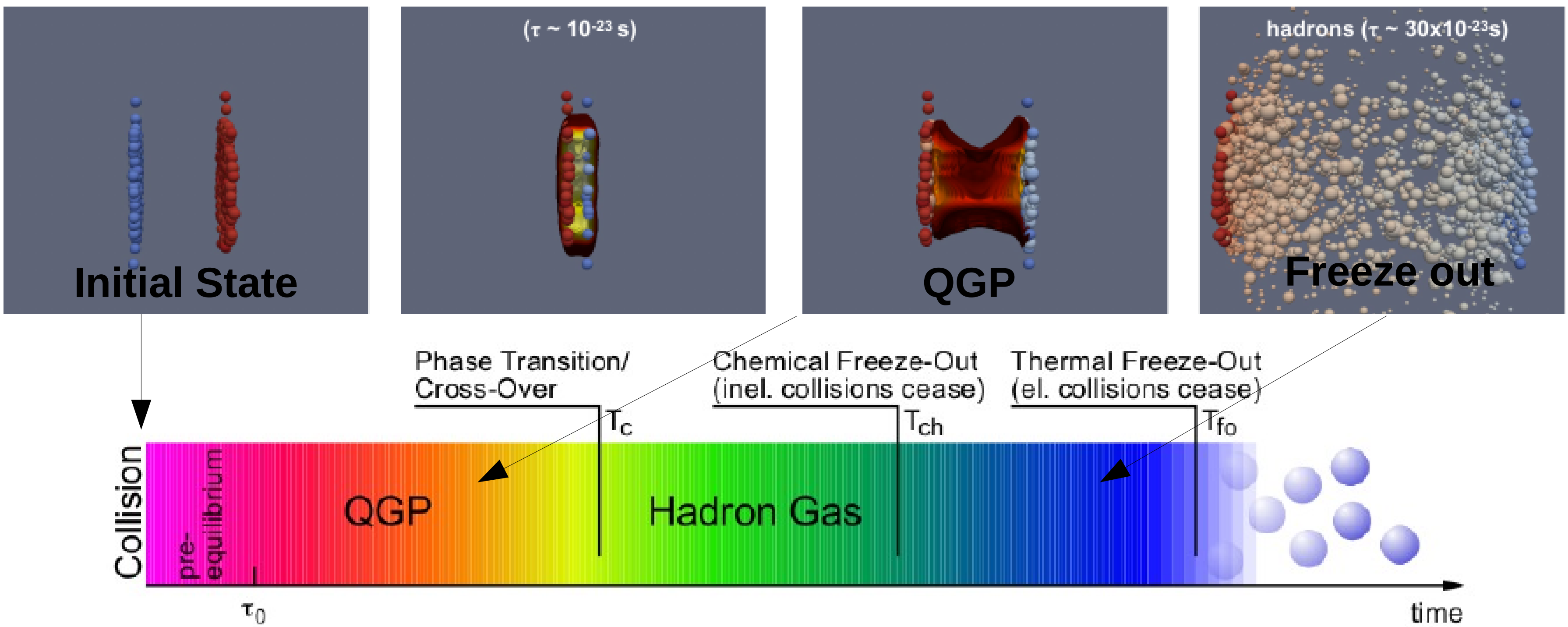

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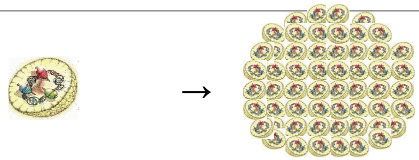

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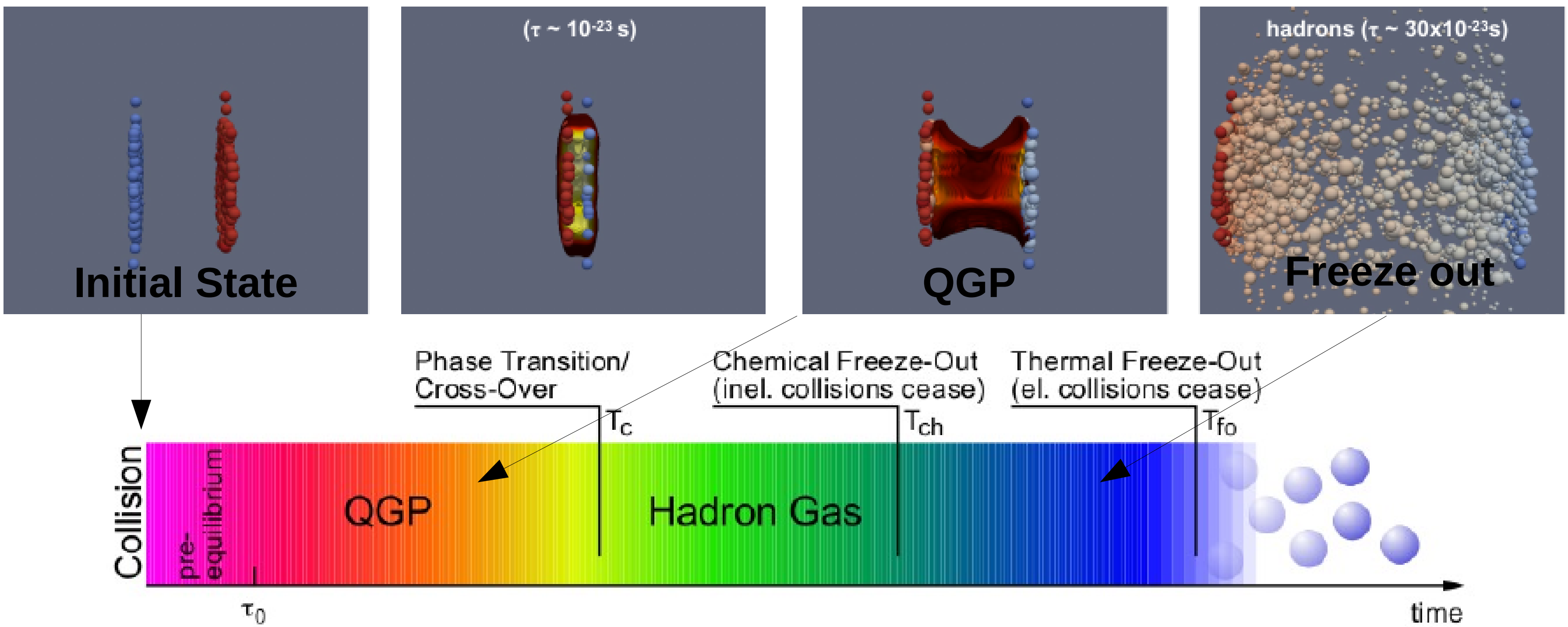


Collective expansion:

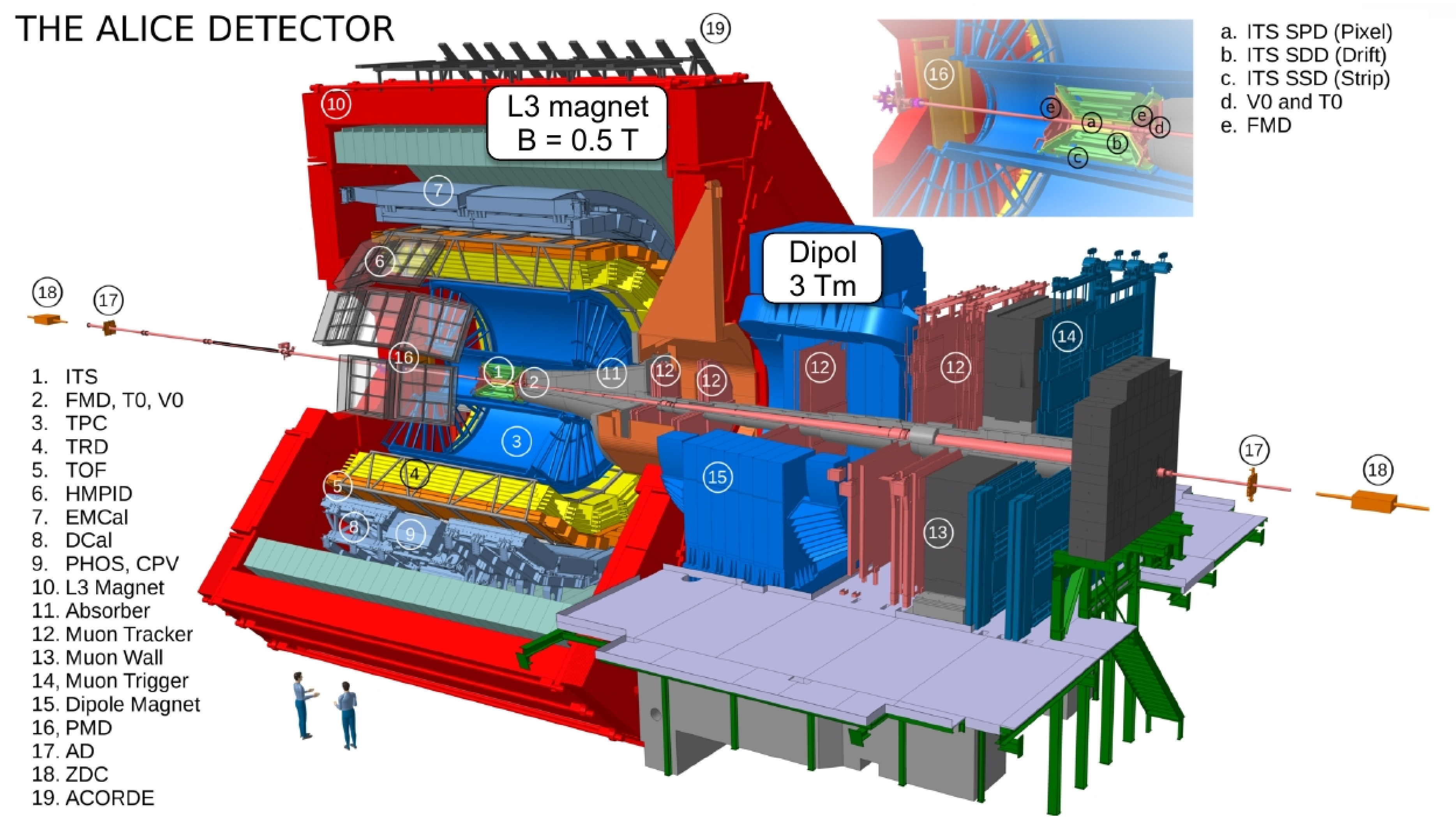
Hydrodynamical Flow

(How a liquid in motion flows)

Energy loss:

Particle abundances

ALICE



- PID over a very broad p_T range (> ~100 MeV/c mid-η and down to zero at fwd η)
- Full acceptance in azimuth
- Mid-rapidity coverage ($|\eta| < 0.9$) and $-4 < \eta < -2.5$ in forward region

Strategy

Large and dense → heavy ion physics

AA: Npdf, pQCD, FF, collectivity

Small and dilute → comparison measurement

pp: pdf, pQCD FF
pA Npdf, pQCD FF

Npdf: Modified parton distribution functions

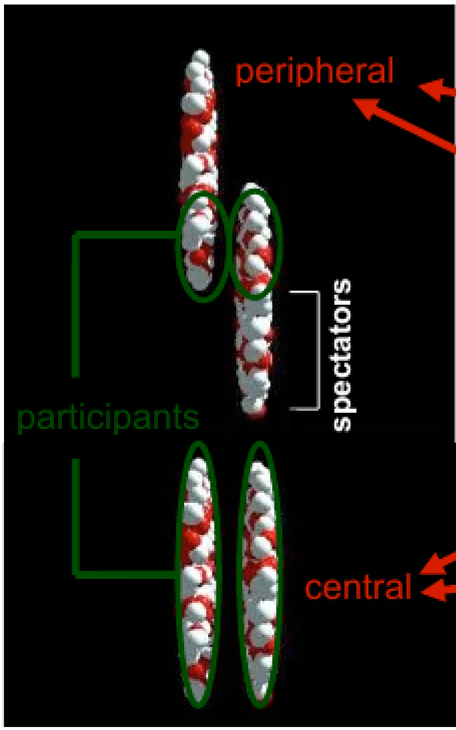
pQCD: perturbative QCD

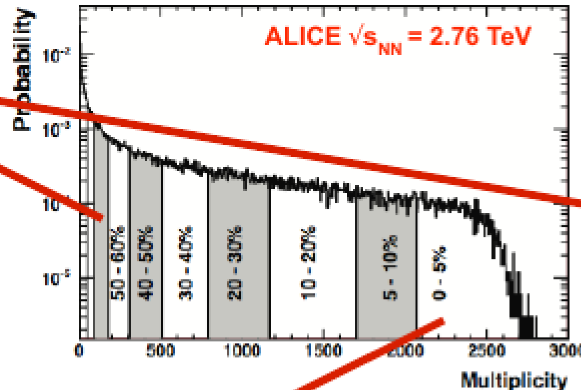
FF: Fragmentation functions

Collectivity: when a formed medium can be described as a locally equilibrated system evolving hydrodynamically as opposed to a group of individually interacting constituents.

Centrality determination in ALICE

- Correlate the multiplicity of produced particles with the geometry of the system i.e. impact parameter (not directly accessible), volume and (roughly) the shape...





ALICE, arXiv:1301.4361, Phys. Rev. C 88 (2013) 044909

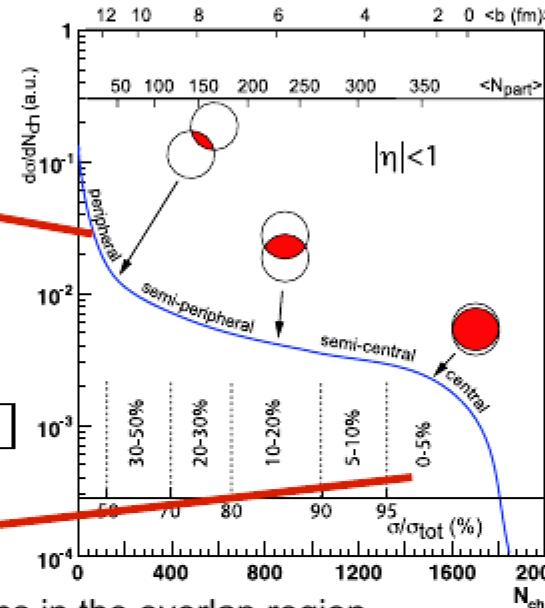


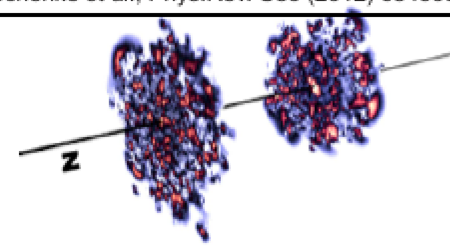
illustration: courtesy of T. Ullrich

Number of participants (N_{part}): nucleons in the overlap region

Number of binary collisions (N_{coll}): nucleon-nucleon inelastic collisions

B. Schenke *et al.*, Phys.Rev. C86 (2012) 034908

In the details, the situation is “slightly” more complicated:
→ after centrality, fluctuations play an important role



USIAS
University of Strasbourg
Institute for Advanced Study

Courtesy of B Hyppolyte

Outline

1. Hadronization, particle spectra and abundances

2. Collective Expansion

3. Hard Processes

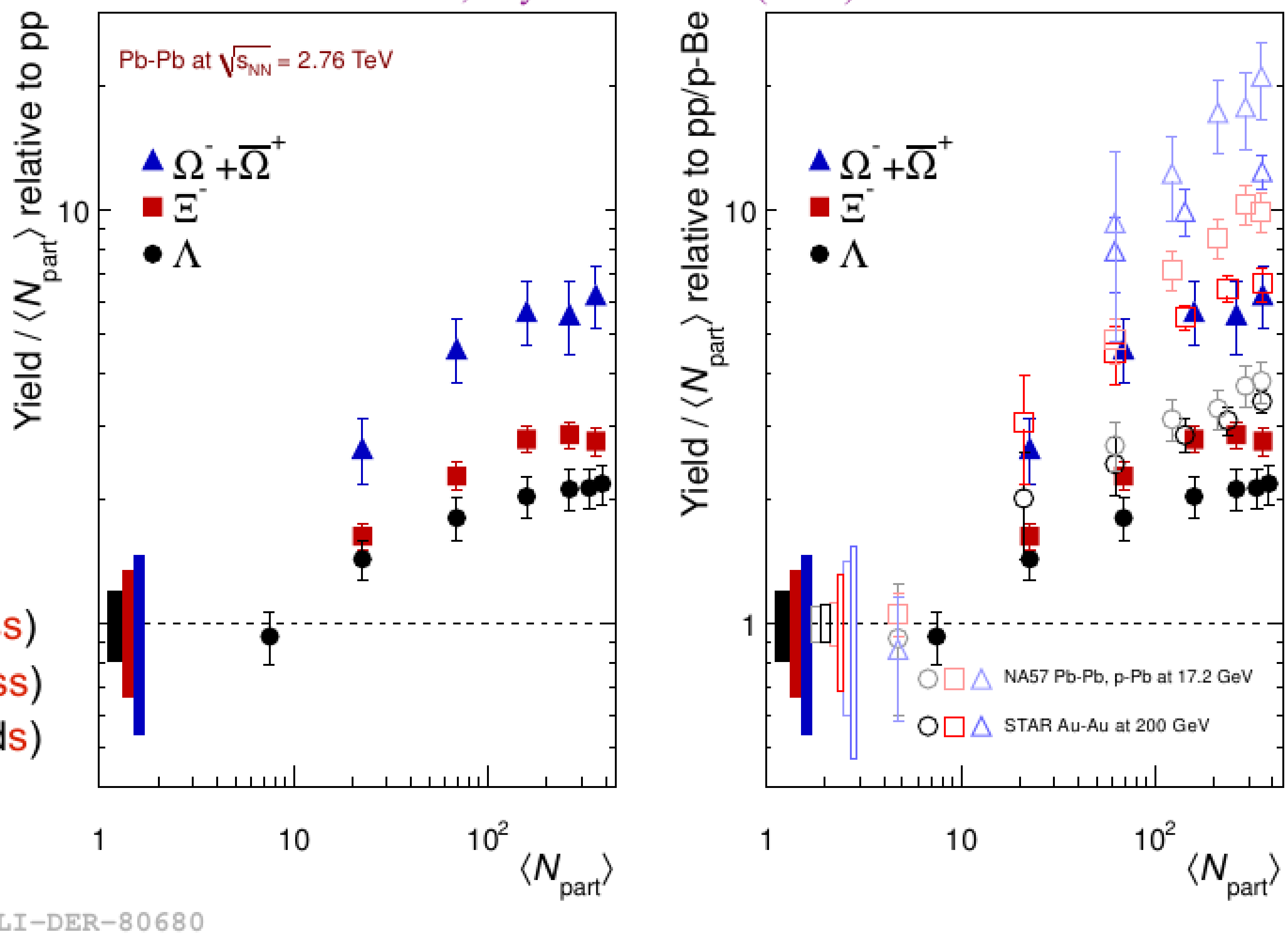
1. Hadronization, particle spectra and abundances

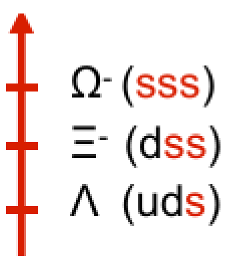
Strangeness enhancement

Among the first proposed signatures of the QGP PRL48(1982)1066

Observed in A-A at SPS, RHIC, LHC

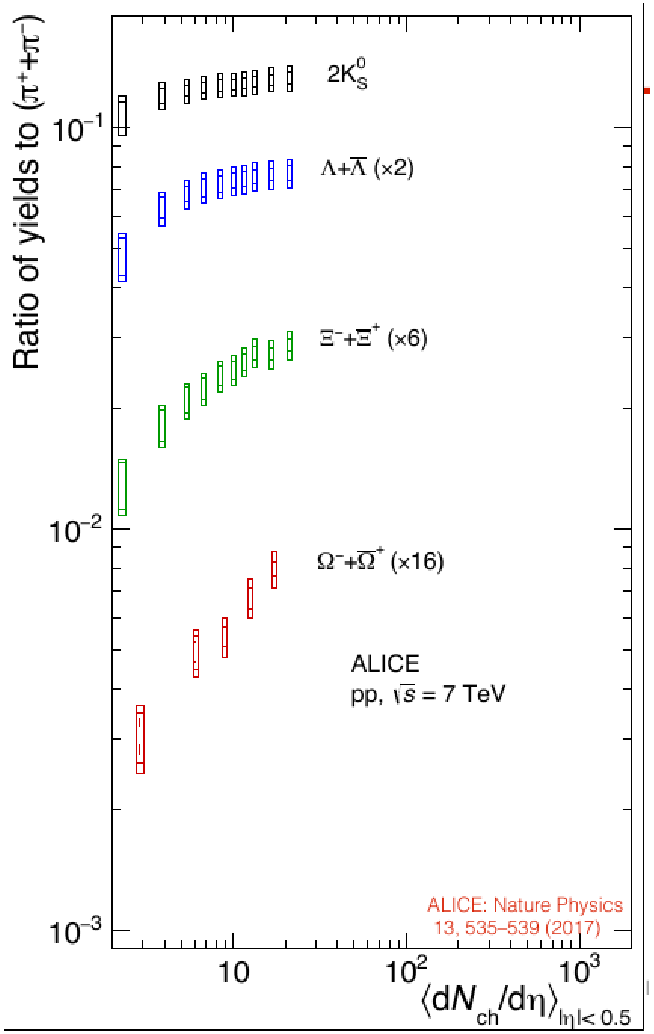
ALICE, Phys. Lett. B 728 (2014) 216





Strangeness enhancement

Enhancement of strange particles with respect to non-strange yield **is also observed** for high multiplicity **pp**



- Smooth evolution of particle ratios with multiplicity
- Challenges universality and factorization of fragmentation (Fischer, Sjostrand, JHEP01(2017)140)
- Study of hadronization mechanisms
- Multiple Parton Interactions? (MPI)

Nature Phys. 13 (2017) 535-539

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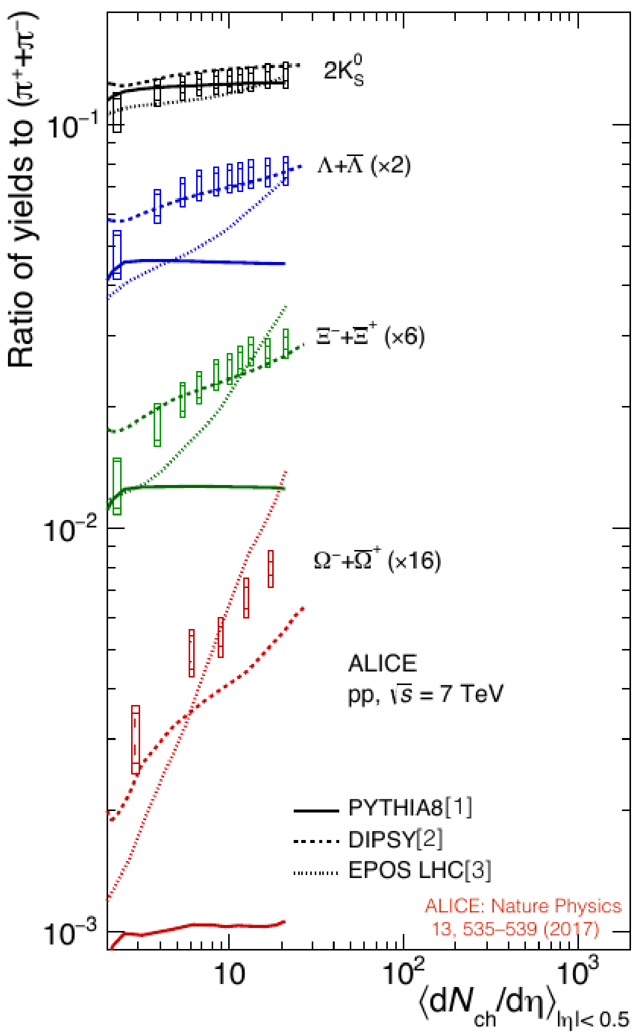

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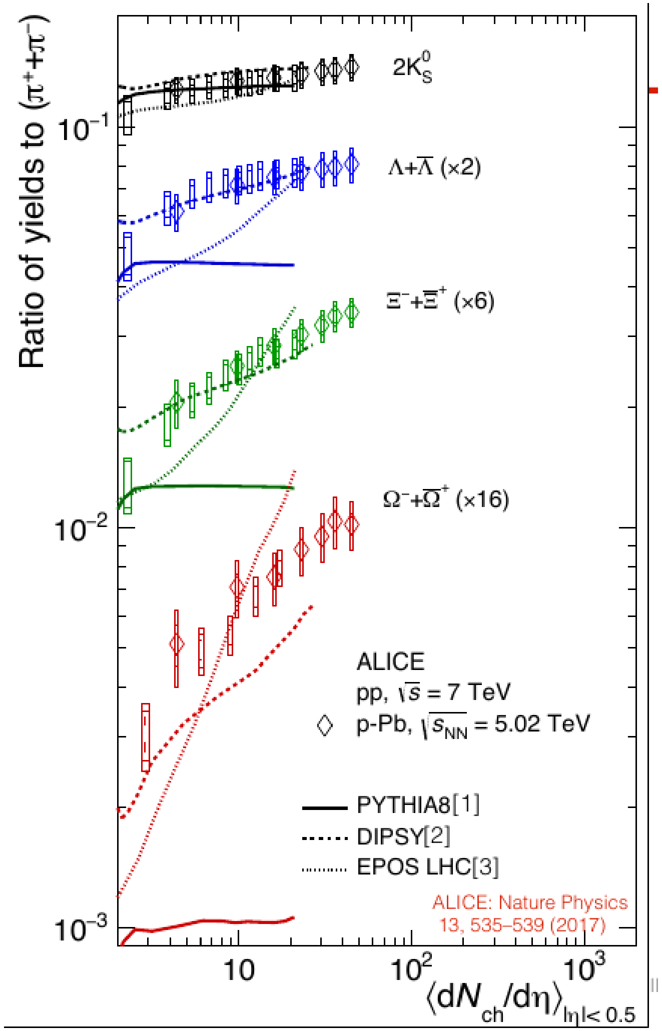

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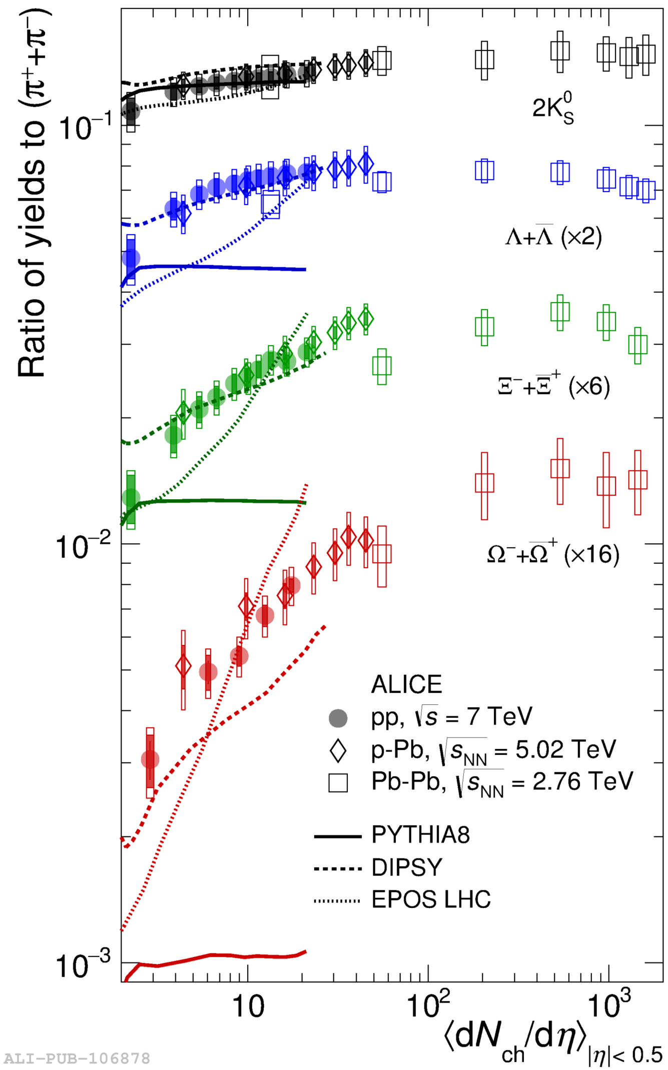

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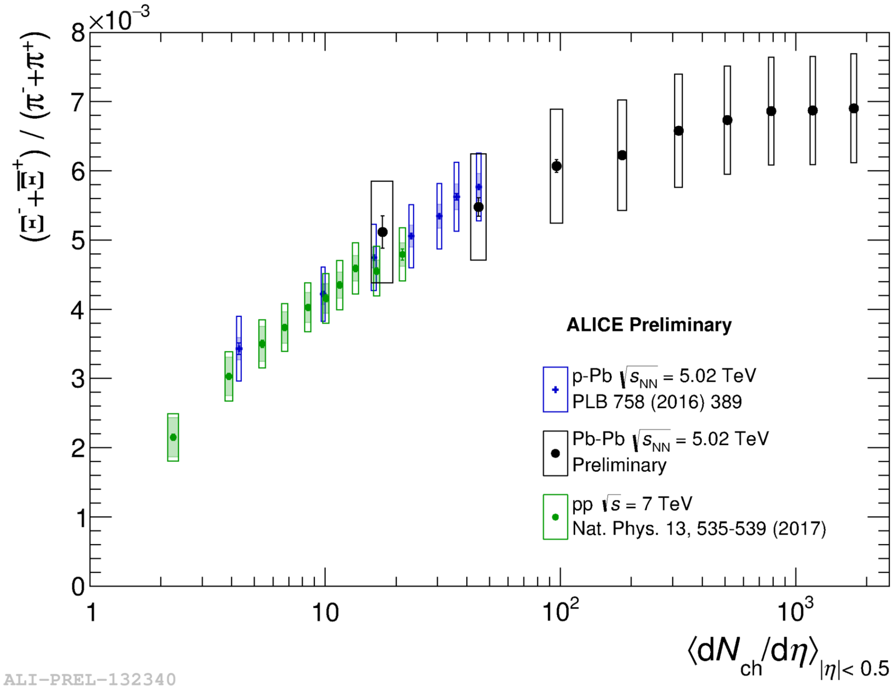
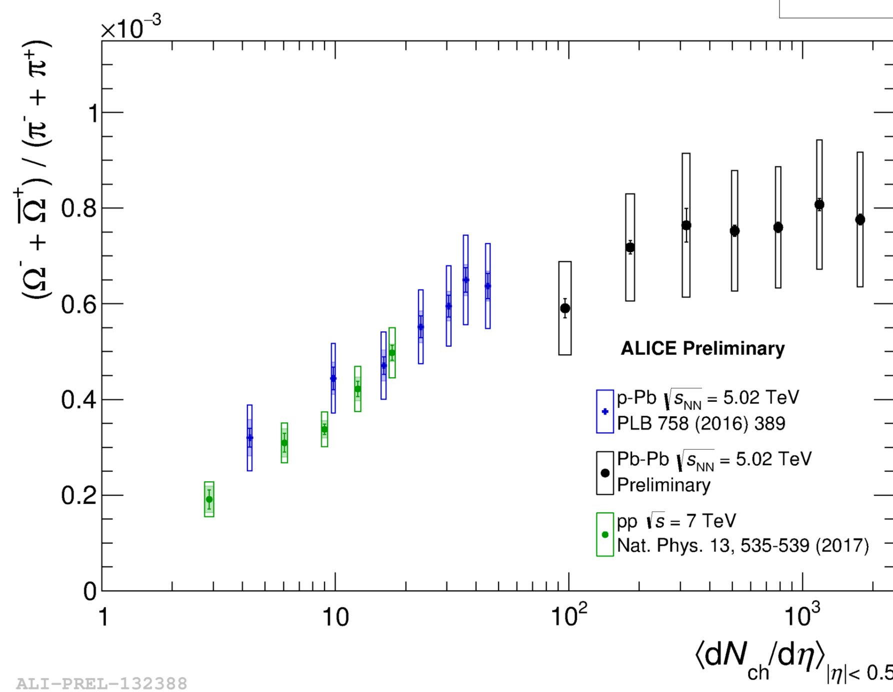
Strangeness Pb-Pb at √S_{NN} =5.02 TeV

Run 2





-Pb-Pb ratios follow the trend from pp and p-Pb

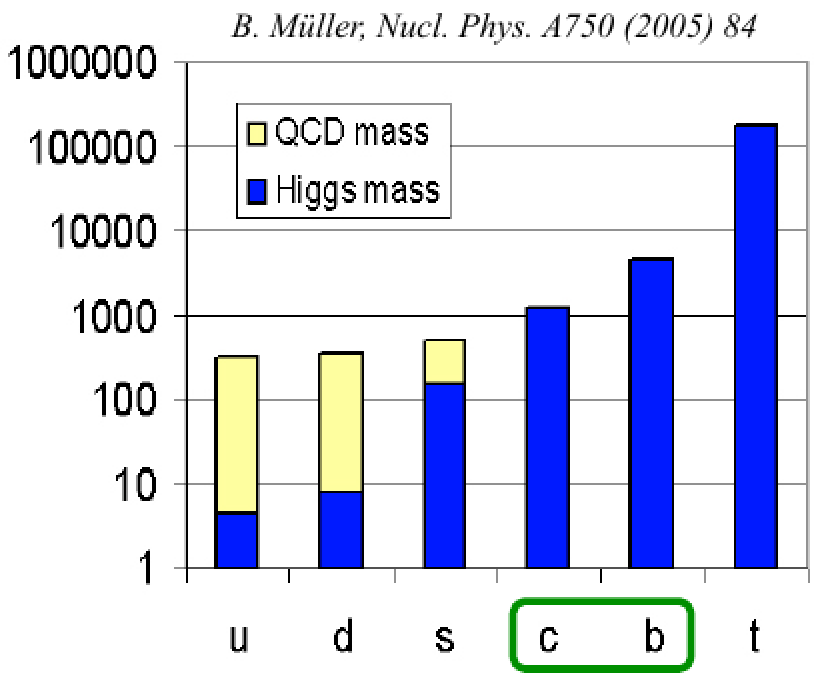
-The ratios of integrated yields seem to be saturating for higher values of $dN_{ch}/d\eta$.

-In Pb-Pb hadrons produced in apparent near thermal and chemical equilibrium

-Will pp and pPb also saturate?

EPS 2017 presentation

Heavy flavor vs multiplicity: quarkonia



The contribution of the QCD vacuum condensates to the masses for the three light quark flavours u, d, s considerably exceed the mass believed to be generated by the Higgs field.

Blue: masses generated by electroweak symmetry breaking (current quark mass)

Yellow: additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses)

- Charm and beauty quark masses are not affected by QCD vacuum (ideal probes to study QGP)
- Charm and beauty quarks provide hard scale for QCD calculations
- Charmonium production proceeds from hard initial processes and no strong correlations with event activity are expected

Heavy flavor vs multiplicity: quarkonia

Run 2

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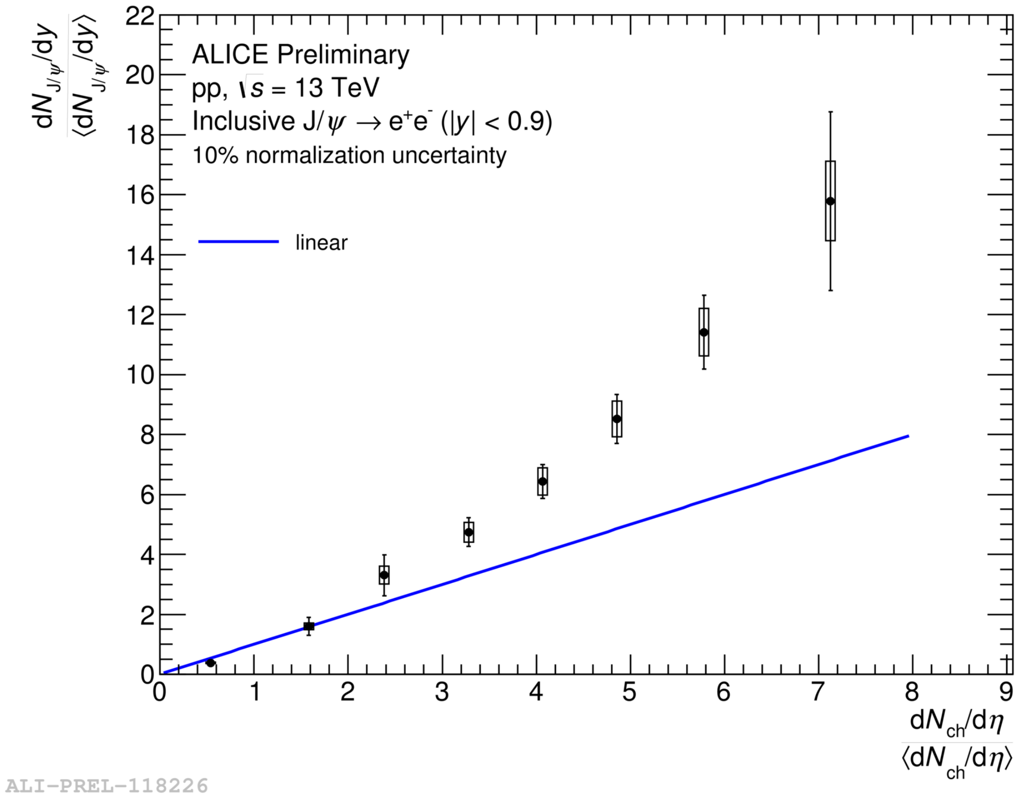

Initial stages 2017 Presentation

Heavy flavor vs multiplicity: quarkonia

Run 2

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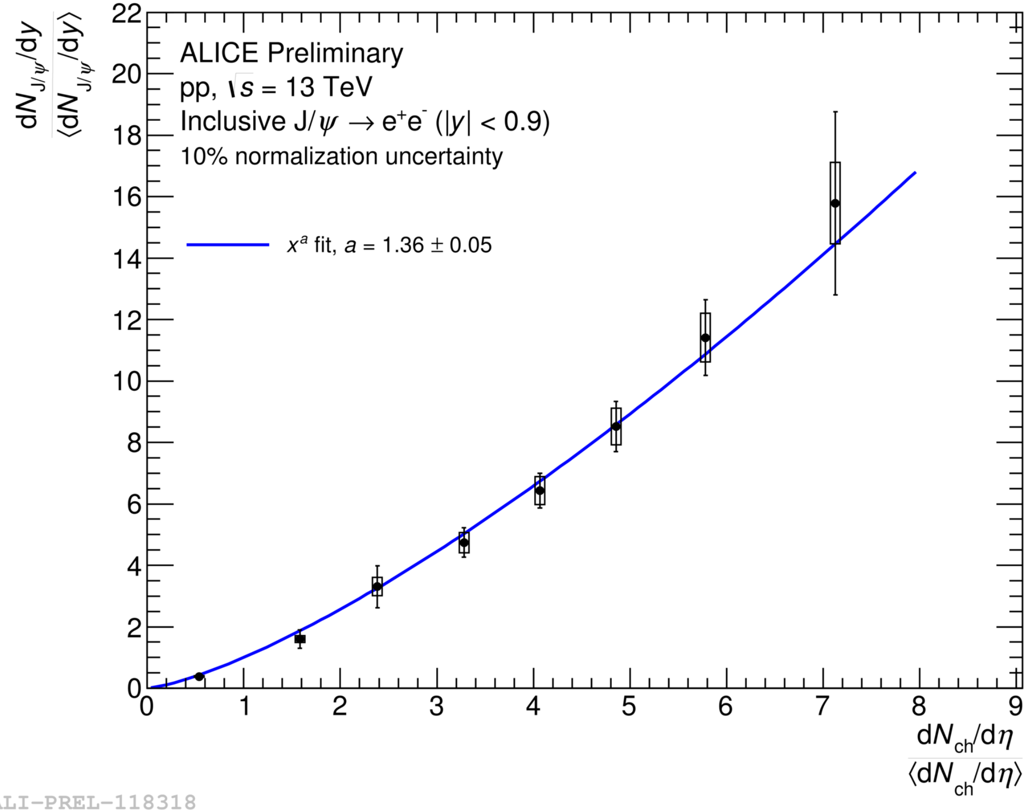


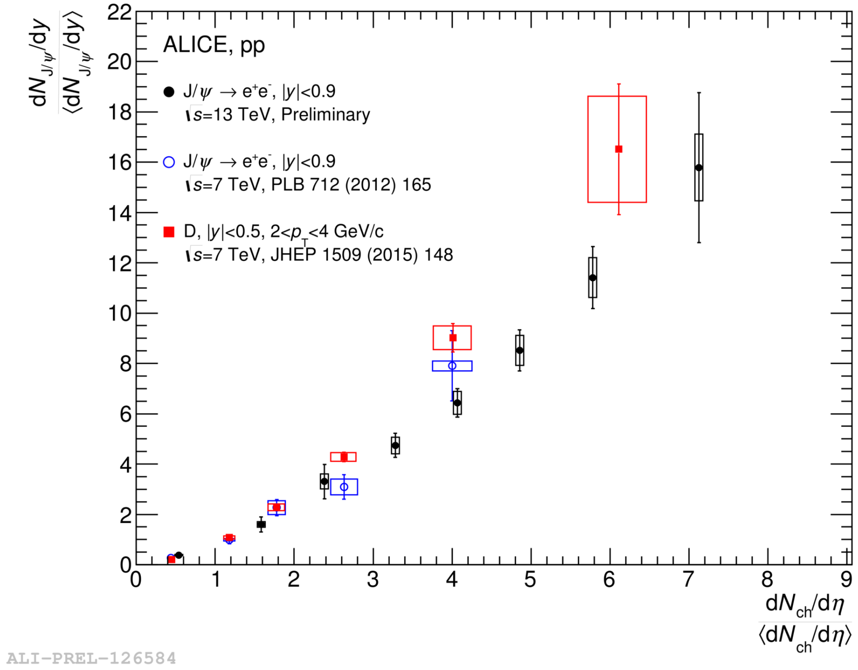
Increase is not linear: highlights importance of other physical processes: MPI, percolation effects, color re-connection

Initial stages 2017 Presentation

Heavy flavor vs multiplicity

Run 2

pp collisions

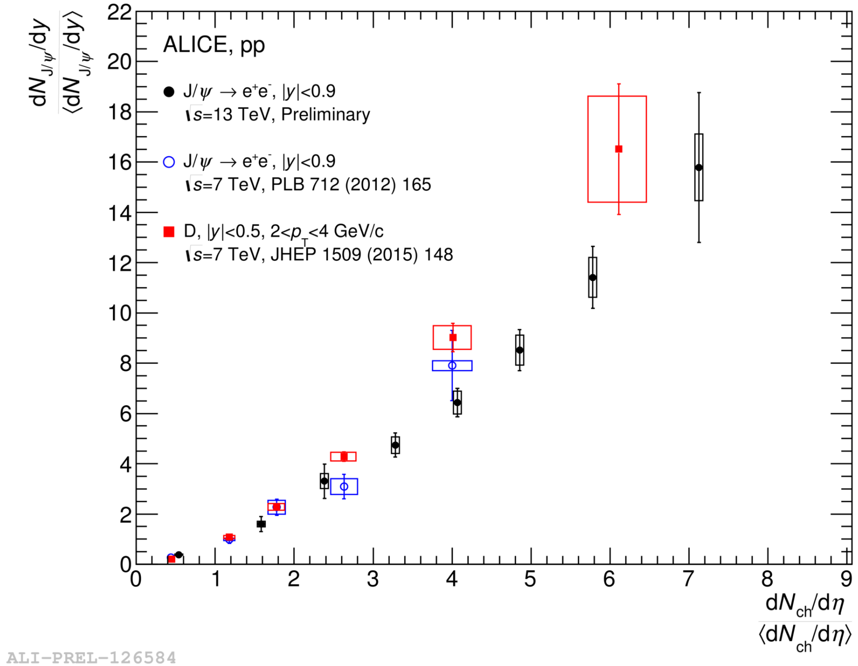


-Similar effects observed for D's

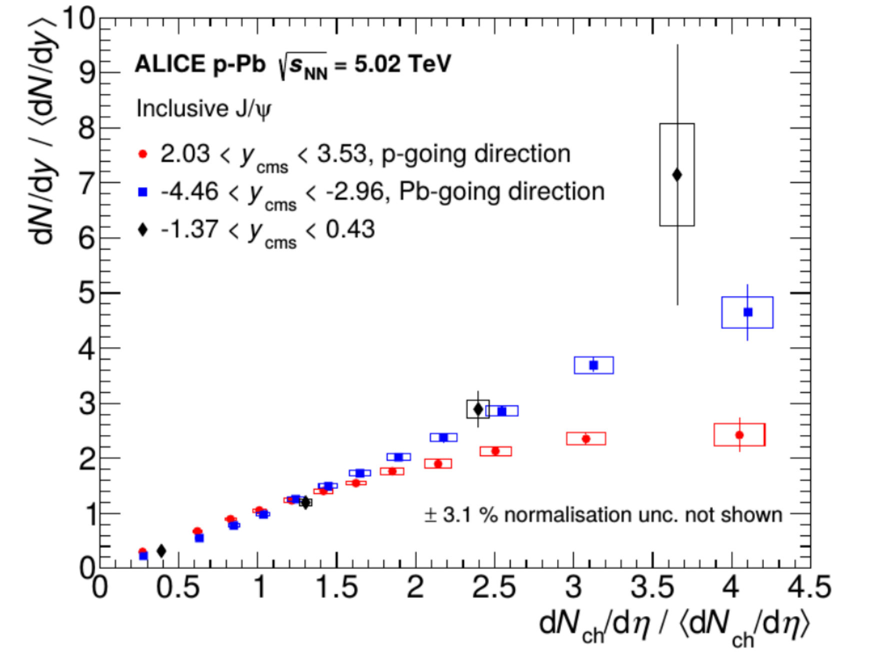
-Hadronization doesn't seem to play a role

Heavy flavor vs multiplicity

pp collisions



p-Pb arXiv 1704.00274



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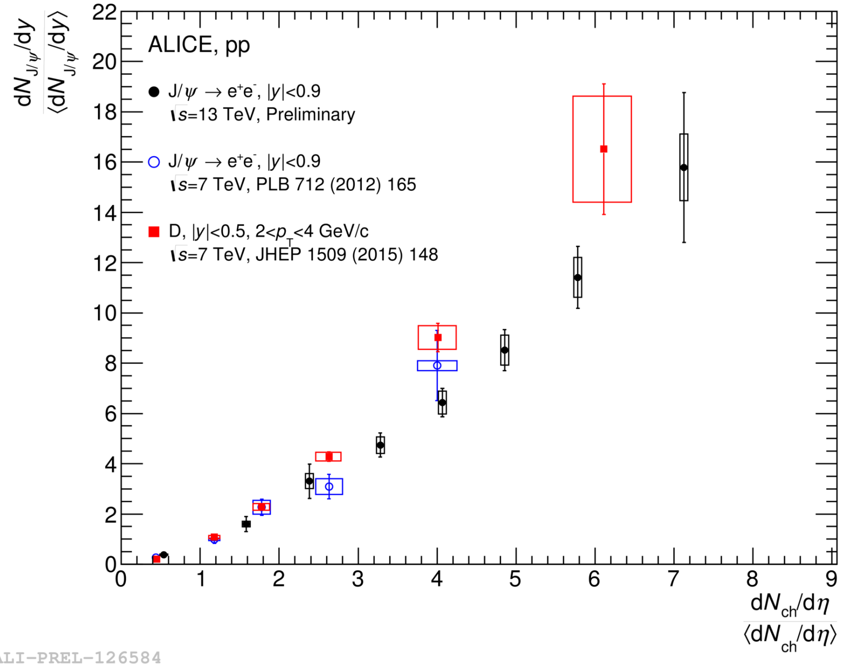

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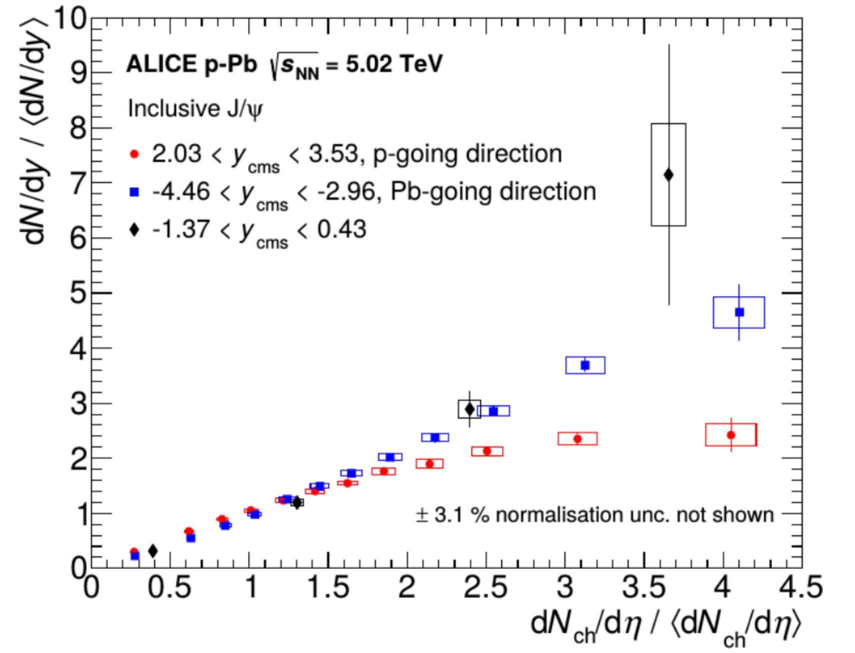


-Similar effects observed for D’s

-Hadronization doesn’t seem to play a role

Mid-and backward rapidity (Pb-going):

-Qualitatively similar behaviour as in pp collisions

Forward rapidity (p-going):

Saturation at high multiplicities (Bjorken-x range in the domain of shadowing / saturation)

2. Collective Expansion

Radial Flow:

Affects shape of low p_T particle spectra

Elliptic Flow:

Sensitive to initial geometry

Requires early thermalization of the medium

Identified particle spectra

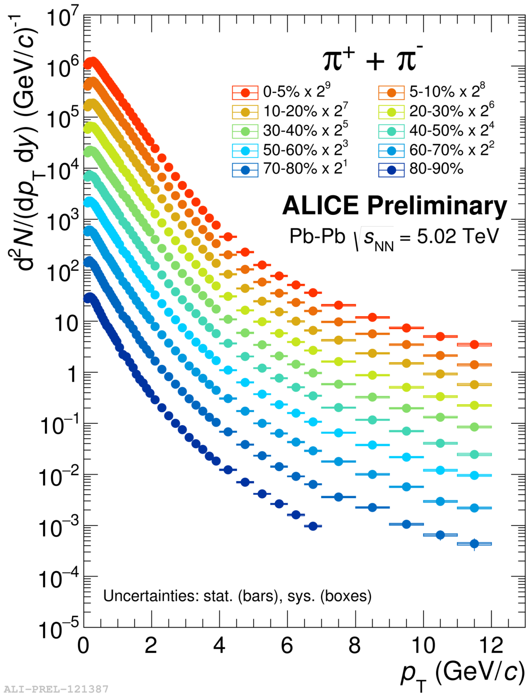
Thermalization: pressure drives the expansion

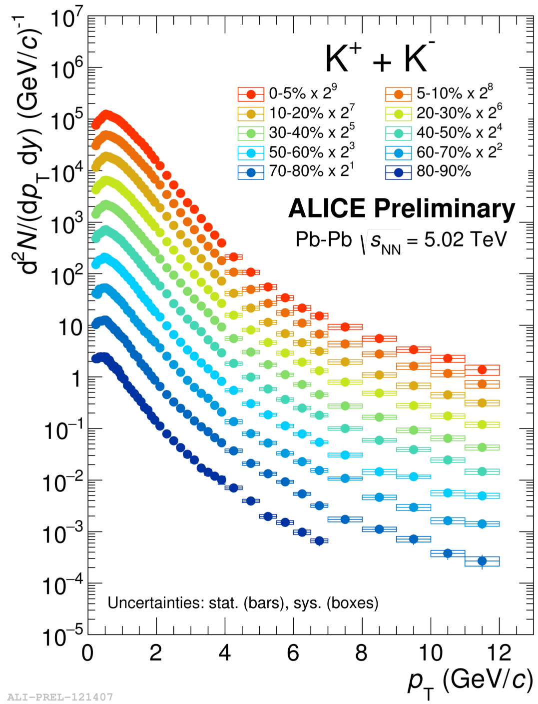
-Particles move in a common velocity field

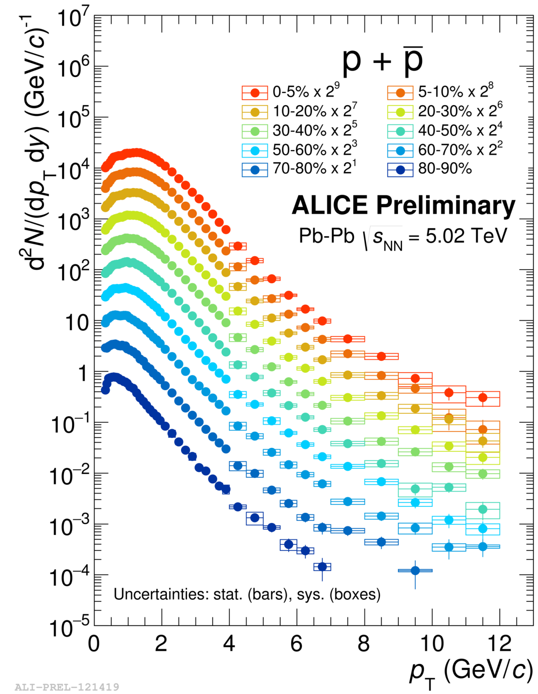
-Momentum distribution “blue-shifted”, mass ordering

Run 2

Pb-Pb $\sqrt{S_{NN}}$=5.02 TeV







Radial flow boosts hadrons:

- low p_T : mass dependent slope, high $p_{T:}$ common hardening of p_T spectra

-The spectra become harder for more central collisions

-The change is most pronounced for heavier particles: effect of radial flow

Baryon to meson ratio

Run 2

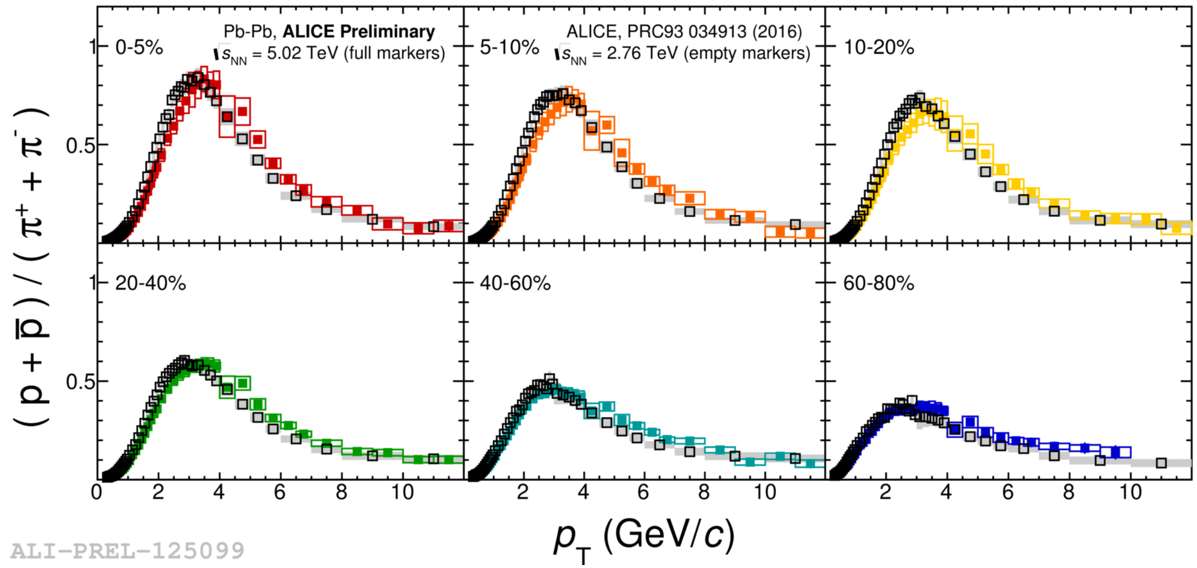
-Pb-Pb no significant energy dependence

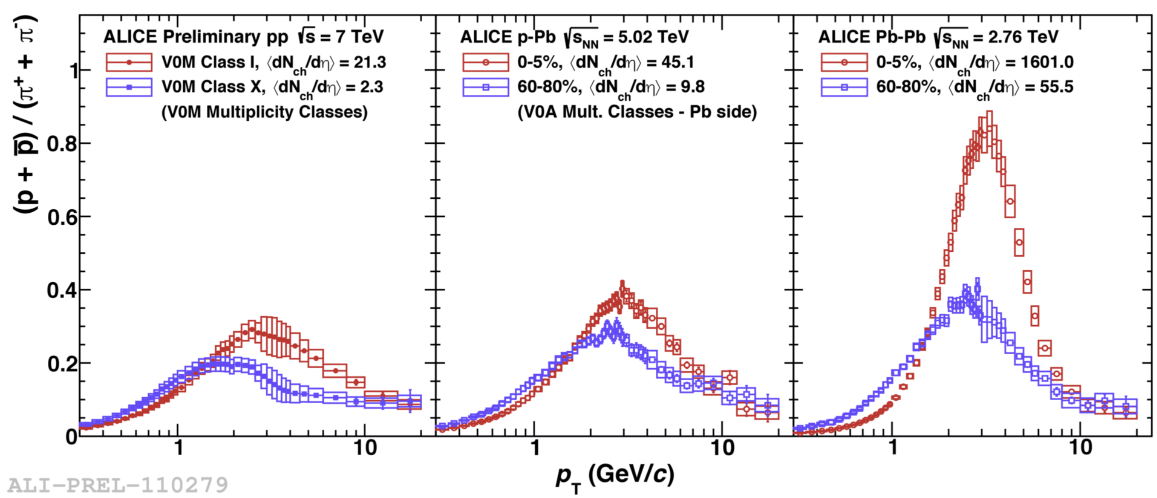
- Radial flow pushes protons to intermediate p_T and depletes low p_T

- Stronger radial flow in central Pb–Pb collisions

-Low to mid-p_T described by **hydrodynamic models**

- Similar effects observed in high-multiplicity pp and p–Pb collisions

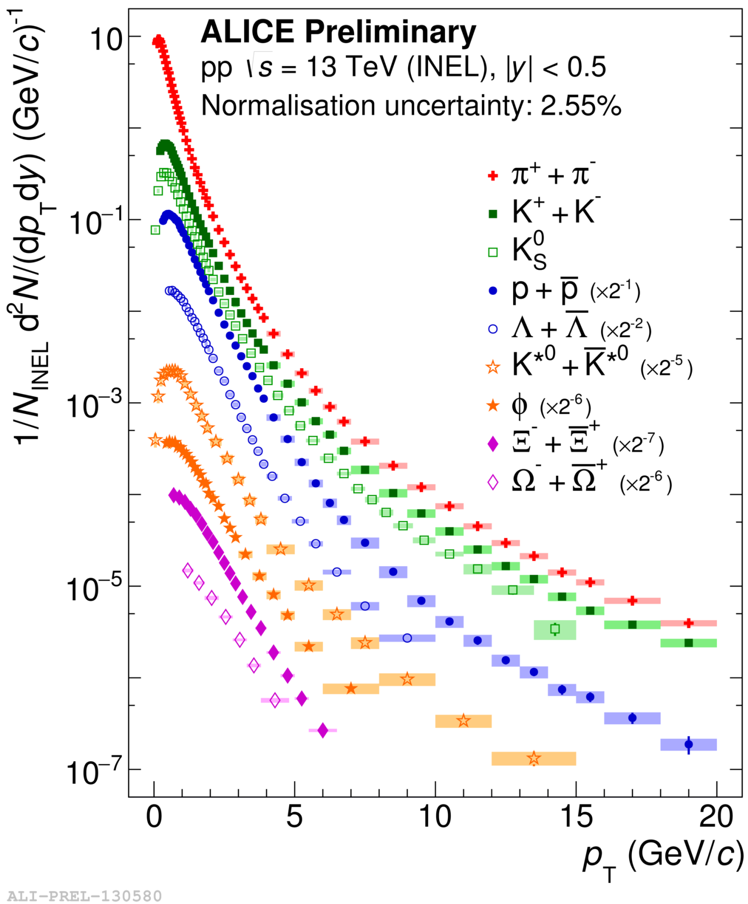




Initial Stages 2017 Presentation

Identified particles in pp

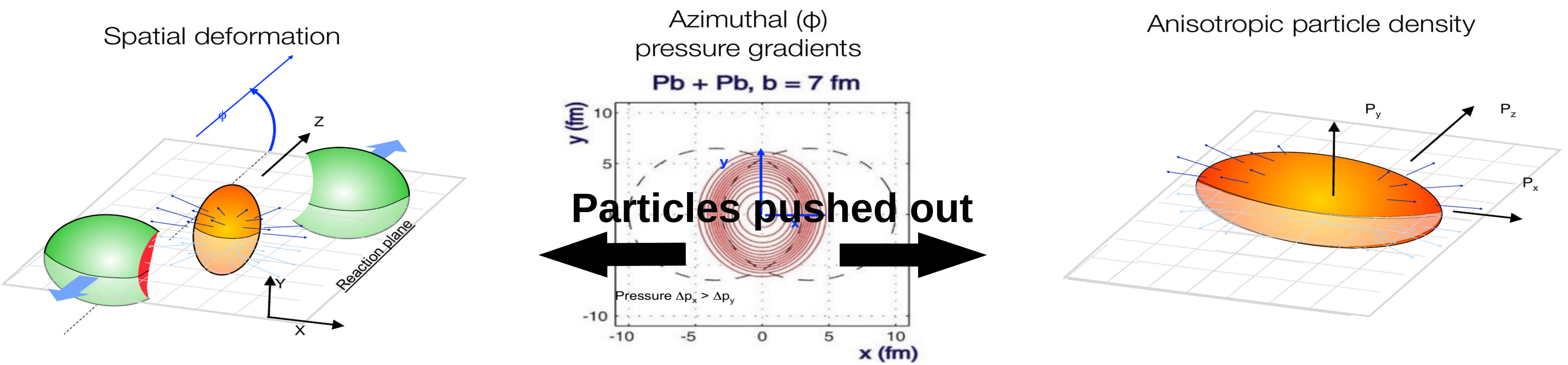
Run 2



Would be interesting to perform studies as a function of multiplicity of these same particles (possible hardening of particle spectra with increasing event multiplicity)

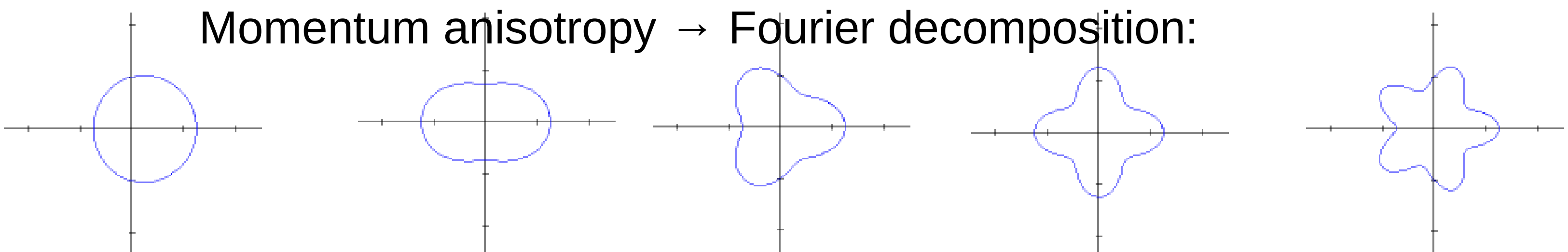
Initial Stages 2017 Presentation

Anisotropic flow



Initial overlap asymmetric → pressure gradients

Momentum anisotropy → Fourier decomposition:

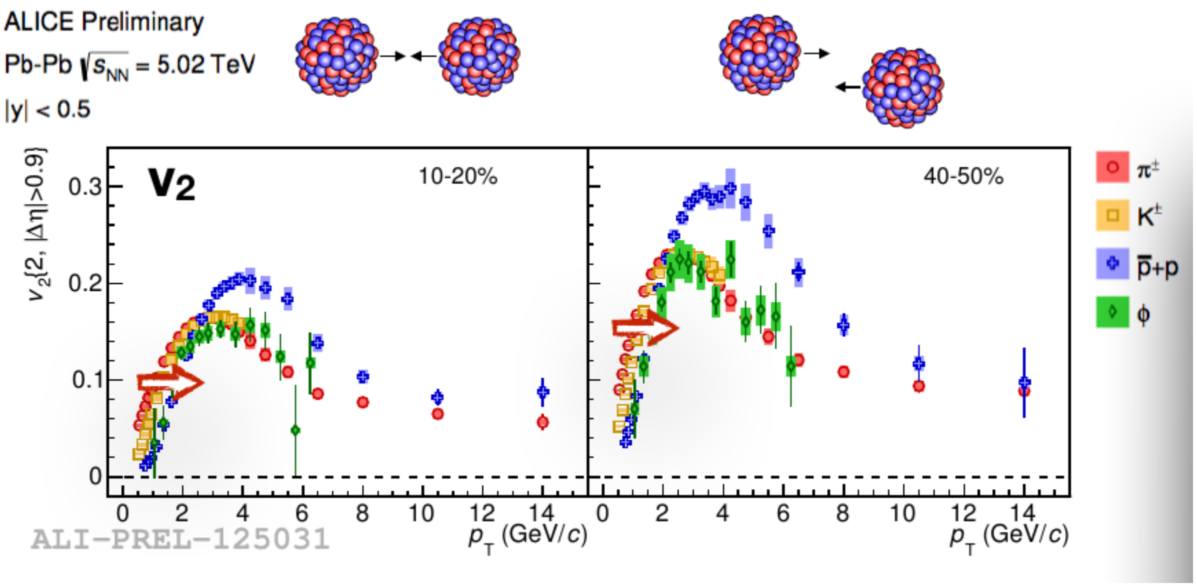


$$\frac{d^2N}{dp_T\,d\phi} \approx 1 + 2v_1\cos(d\phi) + 2v_2\cos(2d\phi) + 2v_3\cos(3d\phi) + 2v_4\cos(4d\phi) + 2v_5\cos(5d\phi) + \ldots$$

EPS 2017 presentation

Light meson flow

Run 2



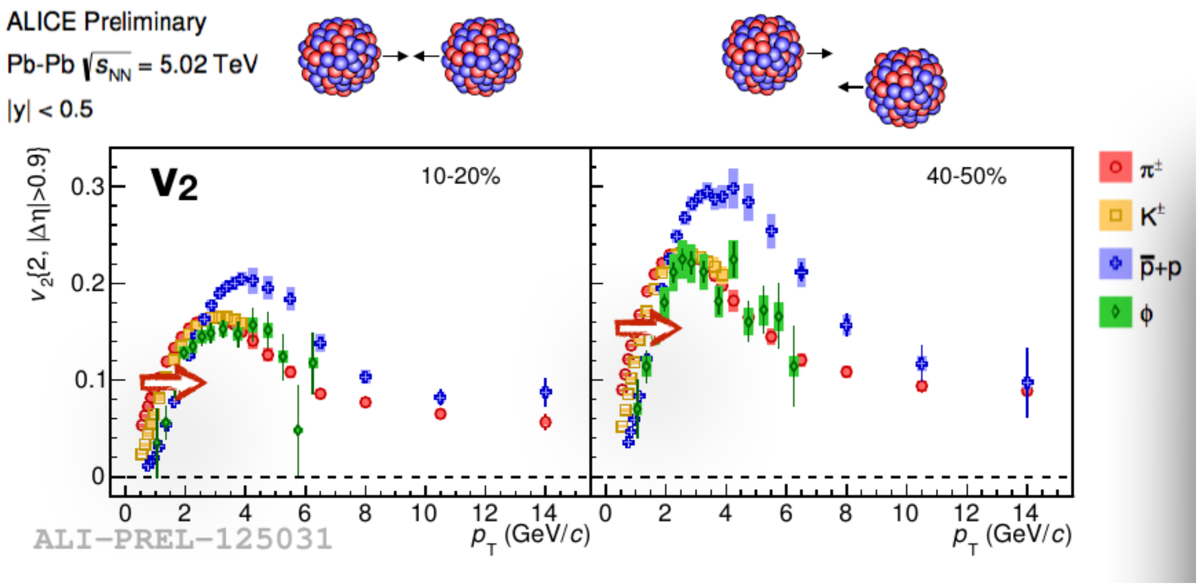
-Low p_T : Mass ordering expected in a collective expansion scenario.

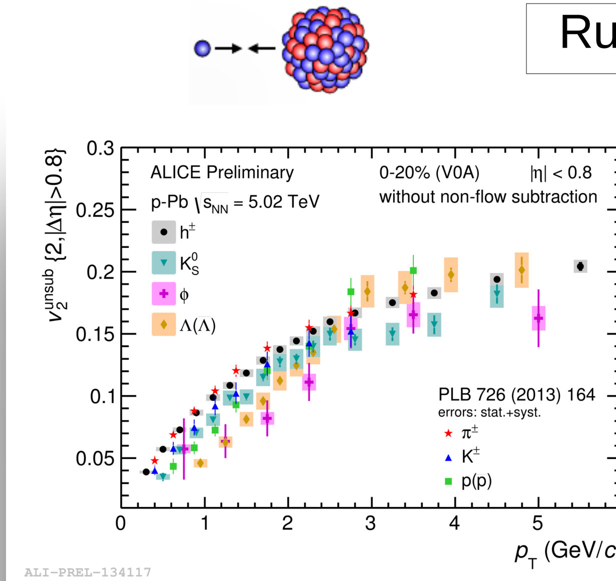
-Low-p_T : v_2 sensitive to hydrodynamic expansion and initial conditions (geometry).

SQM 2017 presentation

Light meson flow

Run 2





-Low p_T : Mass ordering expected in a collective expansion scenario.

-Low-p_T : v_2 sensitive to hydrodynamic expansion and initial conditions (geometry).

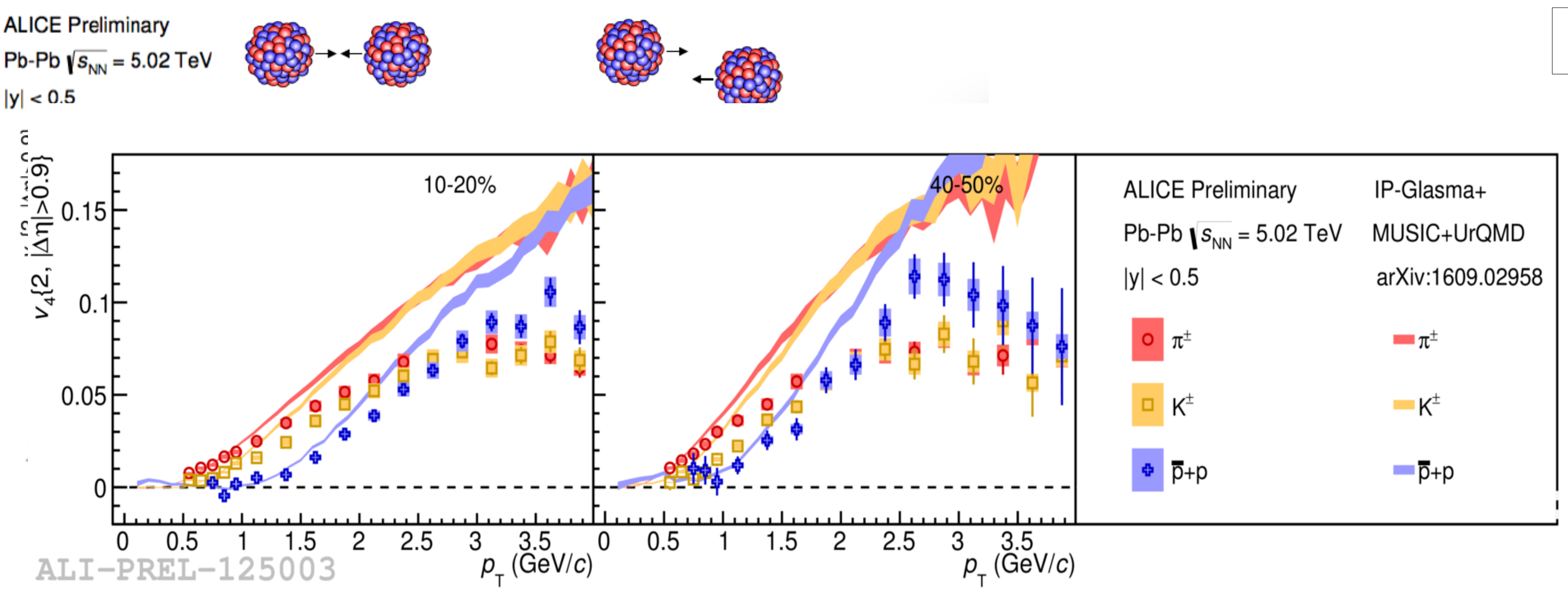
-Similar results observed in a high multiplicity p-Pb environment.

-Effect in these systems may be due to initial state (saturation?) or final state effects (expansion and/or thermal equilibrium ?)

SQM 2017 presentation

Light meson flow

Run 2



V_4 more sensitive to interactions and less to initial state

– hydrodynamic models work at low p T (pT<1 GeV/c)

– only describes trend at intermediate pT (1<pT <2 GeV/c)

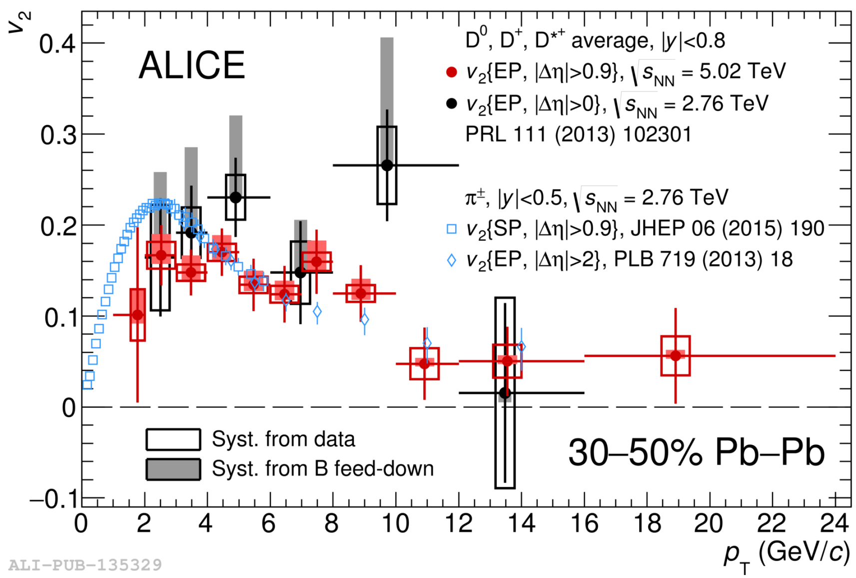
QCD@LHC Presentation

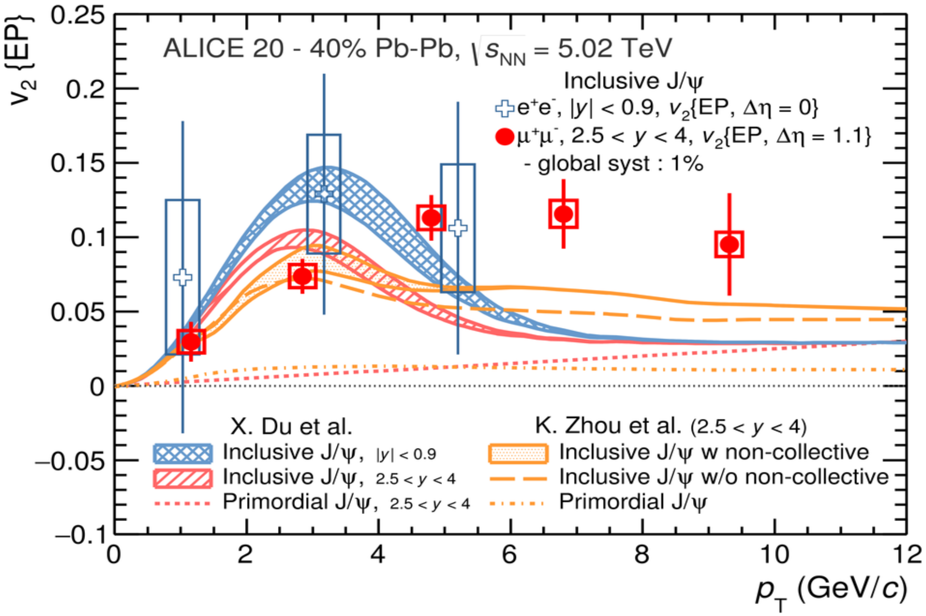
Charm flows

arXiv:1707.01005

arXiv:1709.05260

Run 2





Non zero v_2 for D-meson

Non zero v_2 for J/ψ's

Strong coupling of c-quark with the medium

Participation of low p_T charm to collective motion in the QGP

Additionally for the J/ψ this is interpreted as proof of recombination.

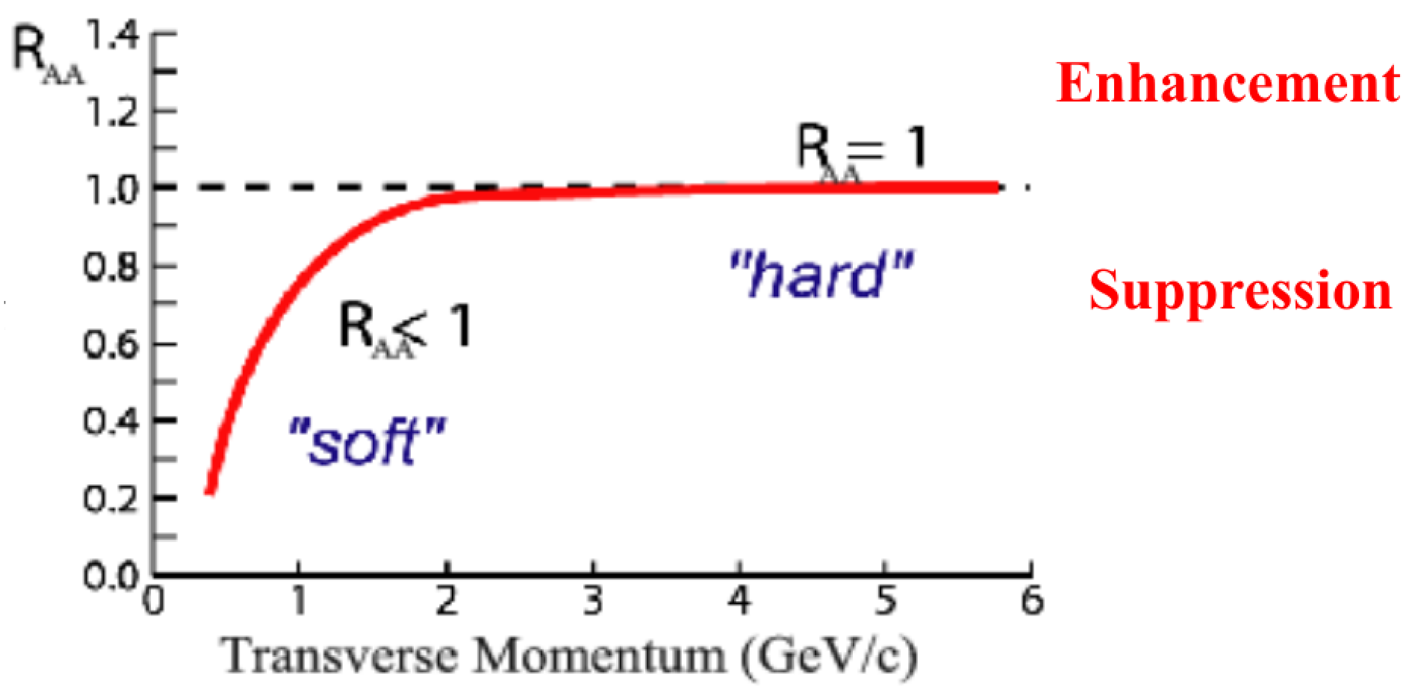
SQM 2017 presentation

3. Hard Processes

Nuclear modification factor

Measure spectra of probe and compare to those in pp collisions or A-A collisions

$$R_{\mathrm{AA}} = \frac{\mathrm{AA}}{\text{scaled pp}} = \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}^2 N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

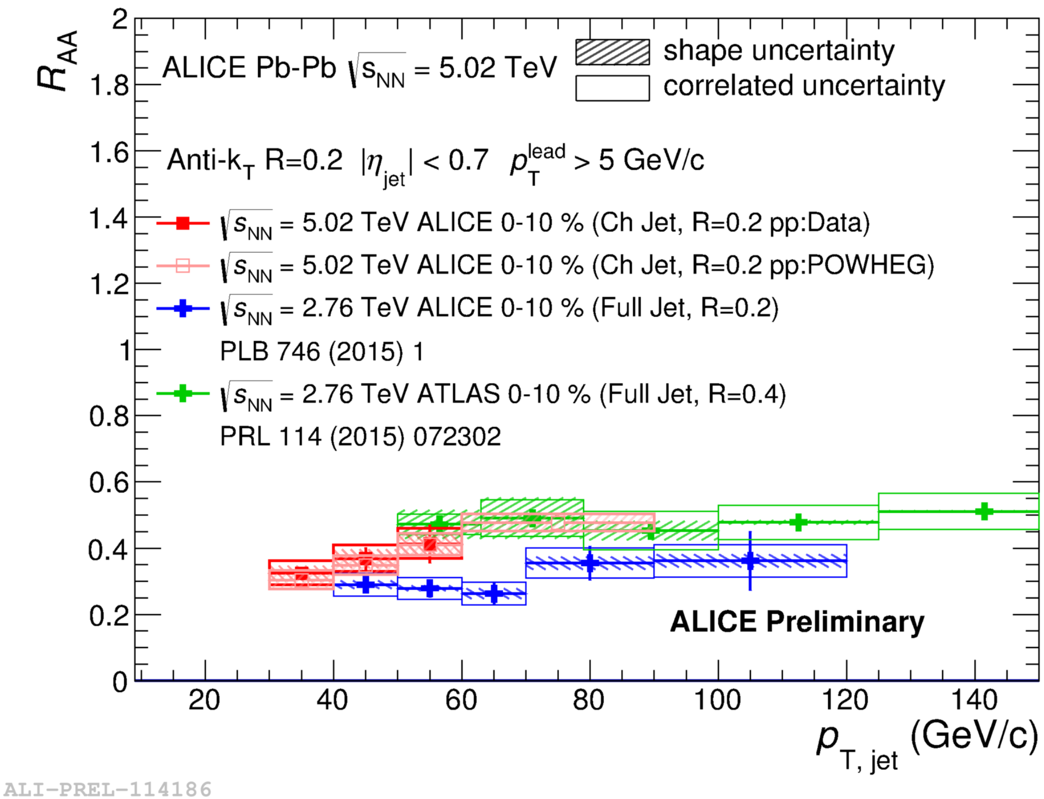


Energy loss in the medium

Run 2

-High momentum partons lose energy while propagating through the QGP
-Energy loss depends on parton type and properties of the medium.

$$R_{\mathrm{AA}} = \frac{\mathrm{AA}}{\text{scaled pp}} = \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}^2 N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$



Expectation:

Jet fragmentation is modified by the medium
- suppression of jet yield
- broadening of jet shape
- di-jet imbalance

Findings:

Strong suppression of jet yields in most central Pb-Pb collisions

Energy loss in the medium

Run 2

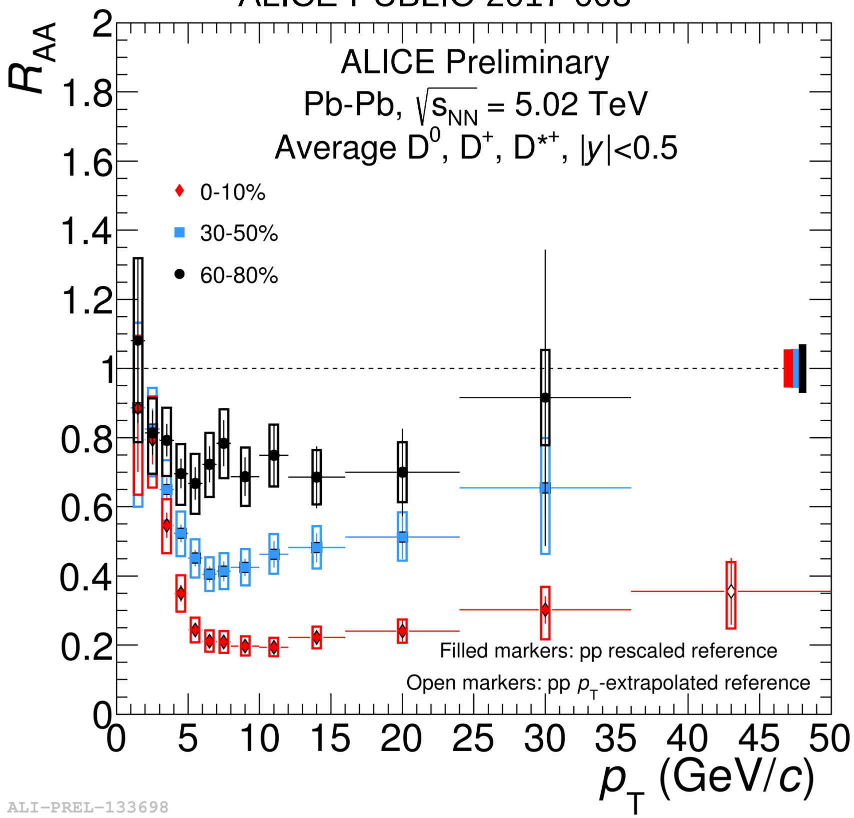
-High momentum partons lose energy while propagating through the QGP

-Energy loss depends on parton type properties of the medium.

-It can modify color flow

$$R_{\mathrm{AA}} = \frac{\mathrm{AA}}{\mathrm{scaled\ pp}} = \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}^2 N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

ALICE-PUBLIC-2017-003



Pb-Pb suppression:

- Increases with centrality

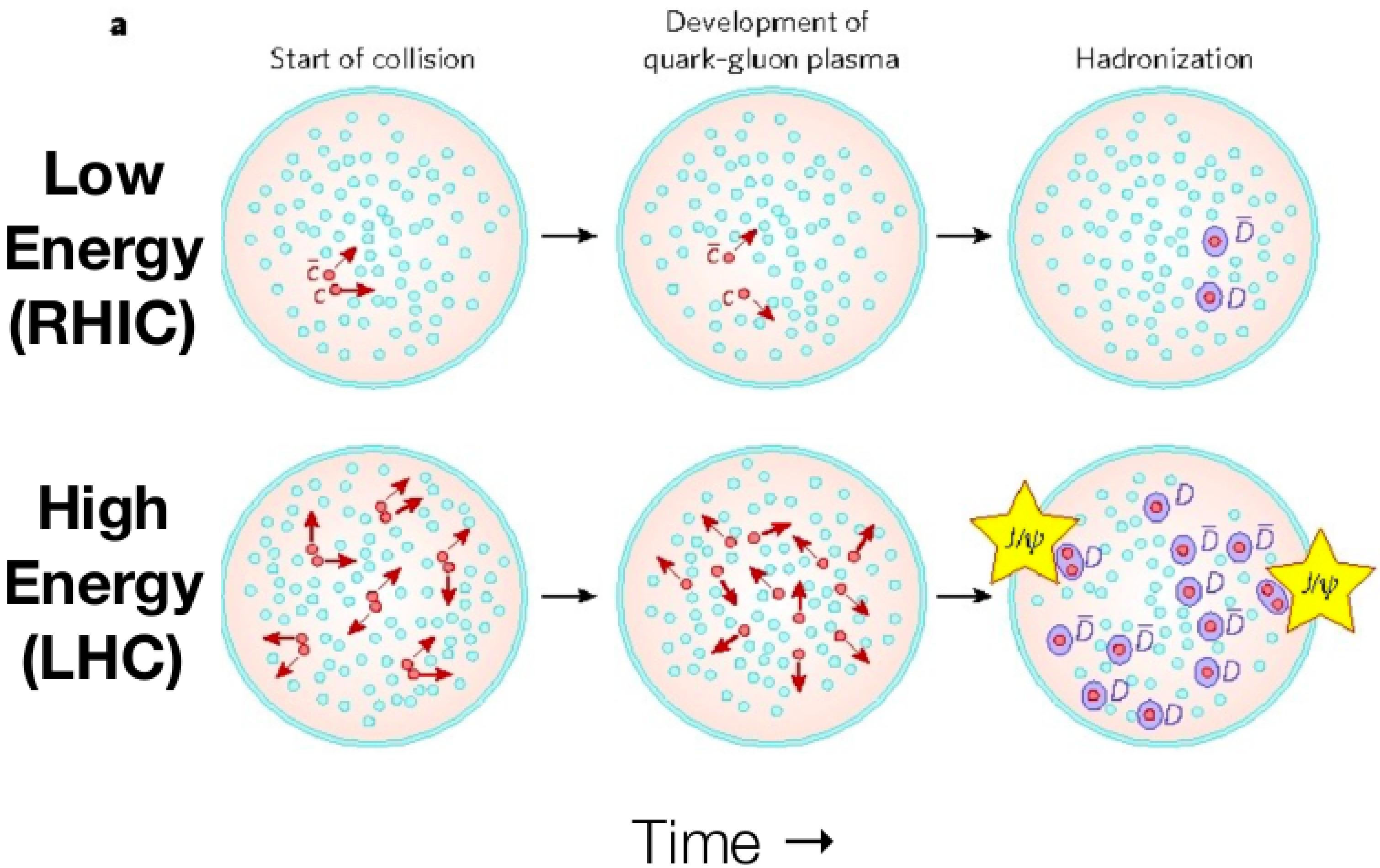
- Not initial state

- Final state effect; due to hot and dense QCD matter

- Similar to that of pions (at high enough p_T)

Quarkonia in Pb-Pb

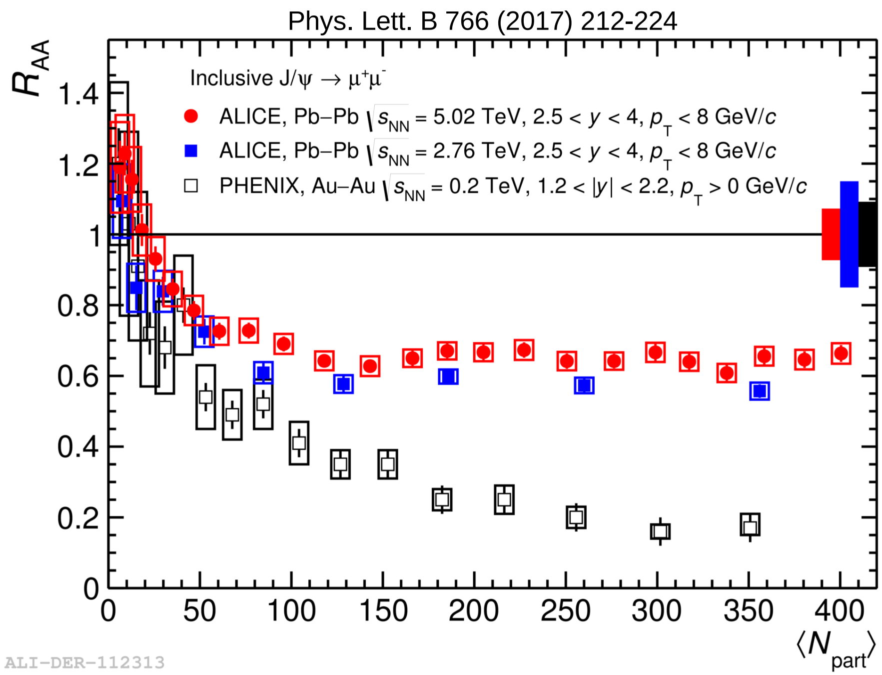
Bound states of ccbar or bbbar

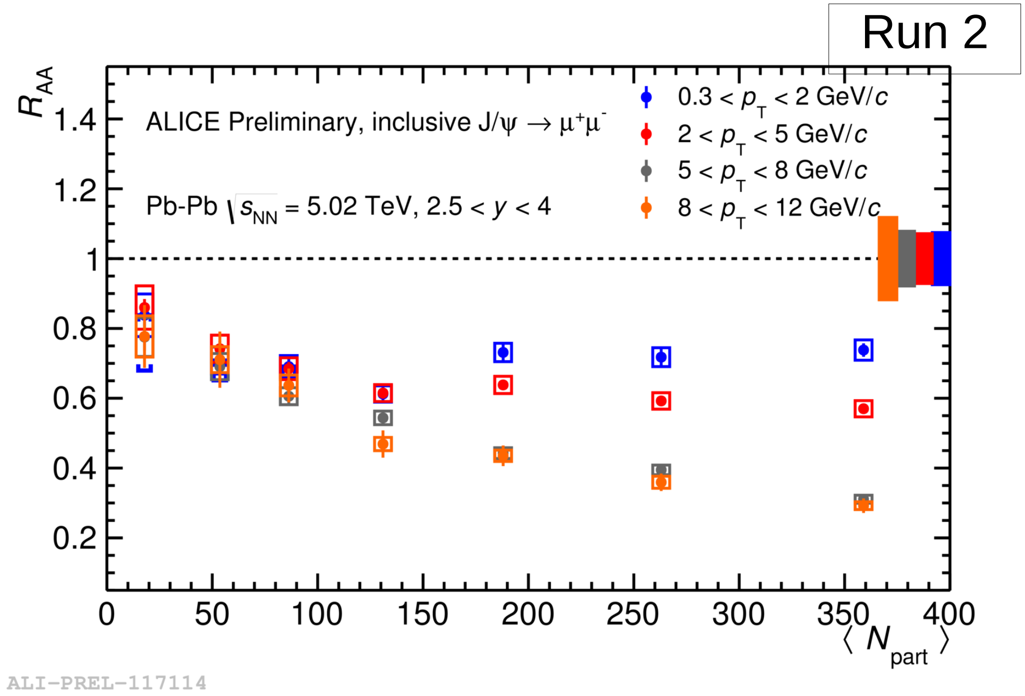


-QGP screens the $c\bar{c}$ interaction and quarkonia can be suppressed

-If many $c\bar{c}$ are created in the collision quarkonia on the other hand can form via quark recombination.

Quarkonia in Pb-Pb

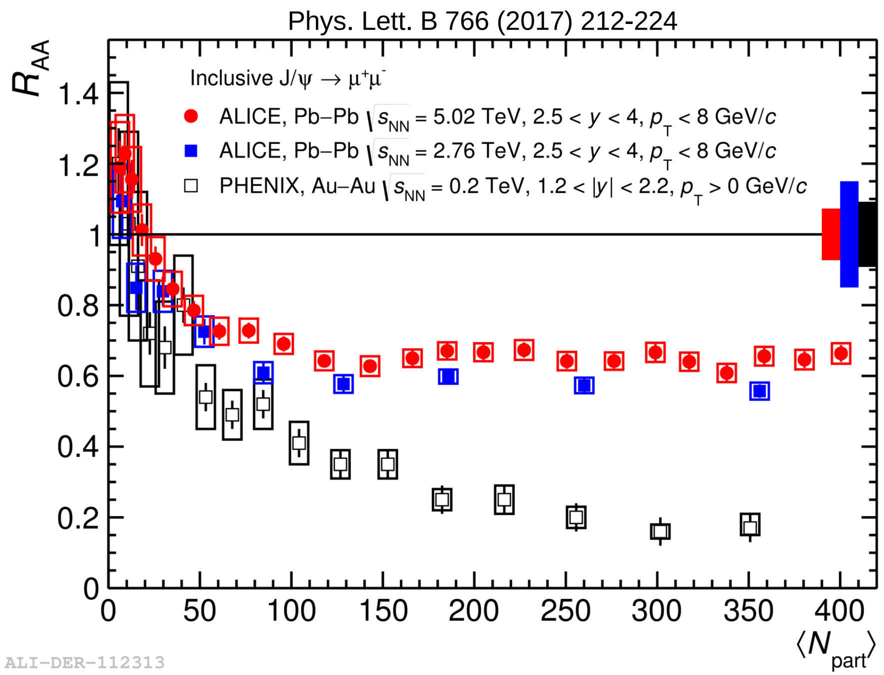


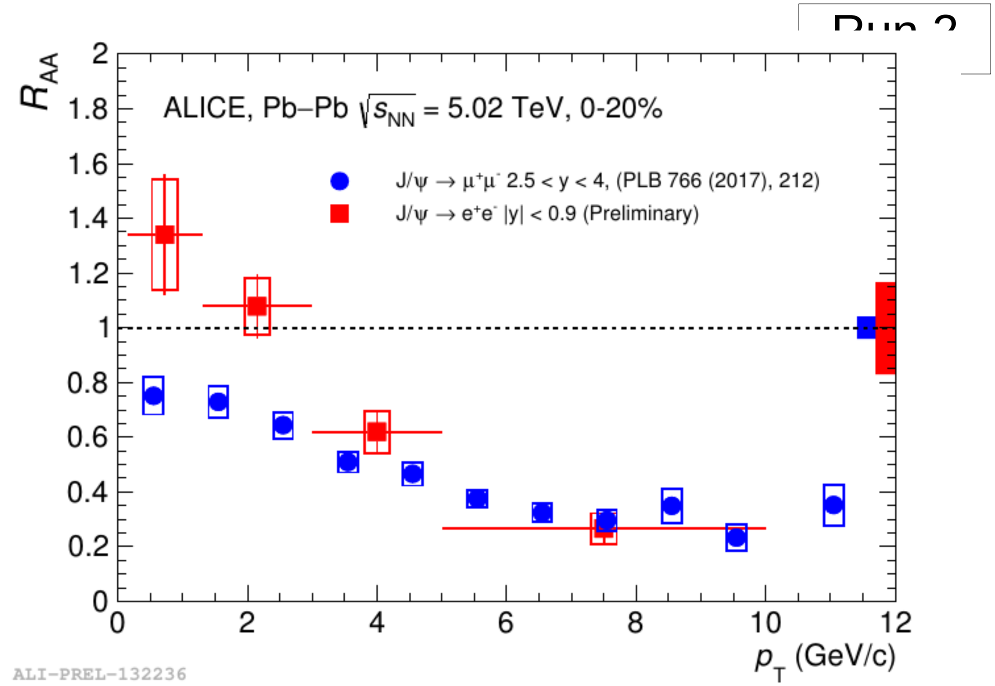


Stronger suppresion at RHIC than at LHC despite larger energy densities at LHC: regeneration?

In central collisions, larger suppression for higher p_T

Quarkonia in Pb-Pb





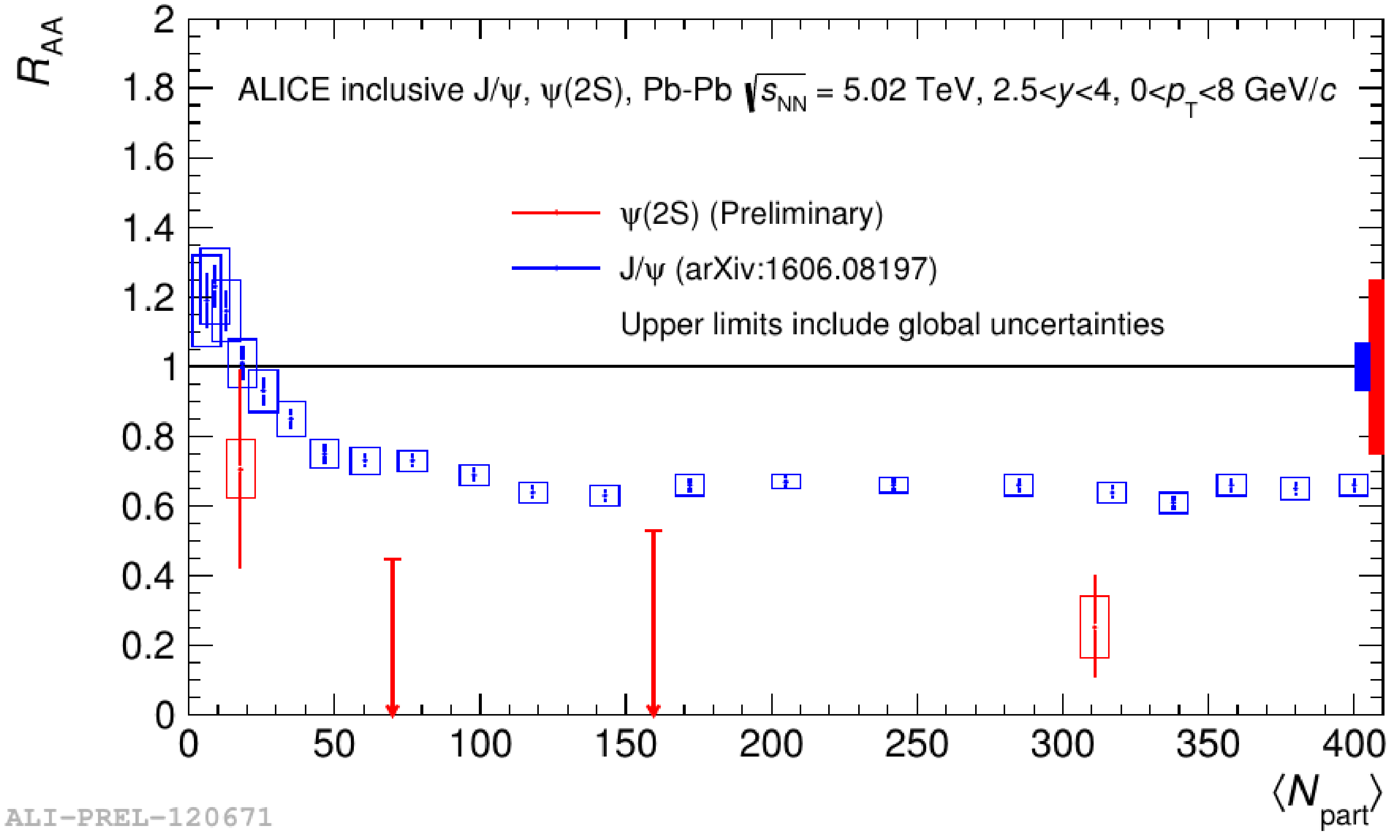
Stronger suppresion at RHIC despite larger LHC densities: regeneration?

Larger suppression for higher p_T, similar to that of pions

Smaller suppression at mid-rapidity (recombination?)

Quarkonia in Pb-Pb

Run 2



ψ(2S) indicates larger suppression than J/ψ (BE)

Summary

Interesting new emerging phenomena for high multiplicity events in pp and pPb
→ Lack of a consistent picture yet.

Collective flow is observed also for massive particles (charm).

→ This requires strong interaction with the QGP.

→ High p_T v_2 is a challenge to models.

Charm meson R_{AA} (high p_T) similar to that of light mesons.

→ Precise measurements of J/ψ R_{AA} now available.

→ ψ(2S) will need more statistics and detector upgrades.

Extras

Run 2 Publications

1. Search for collectivity with azimuthal J/ψ-hadron correlations in high-multiplicity p-Pb collisions at $\sqrt{s}$ = 5.02 and 8.16 TeV
PLB https://arxiv.org/abs/1709.06807

2. J/ψ elliptic flow in Pb-Pb Collisions at 5.02 TeV
PRL https://arxiv.org/abs/1709.05260

3. $\Dzero$, $\Dplus$, $\Dstar$ and $\Ds$ azimuthal anisotropy in mid-central Pb-Pb collisions at $\mathbf{\sqrtsNN=5.02}$ TeV
PRL https://arxiv.org/abs/1707.01005

4. Energy dependence of forward-rapidity j/psi and psi (2S) production in pp collisions at the LHC
EPJC https://arxiv.org/abs/1702.00557

5. Centrality dependence of the pseudorapidity density distribution for charged particles in Pb-Pb collisions at $\sqrt{s_{\rm NN}}=5.0
PLB http://arxiv.org/abs/1612.08966

6.J/ψ suppression at forward rapidity in Pb-Pb collisions at sqrt(sNN) = 5.02 TeV
PLB https://arxiv.org/abs/1606.08197

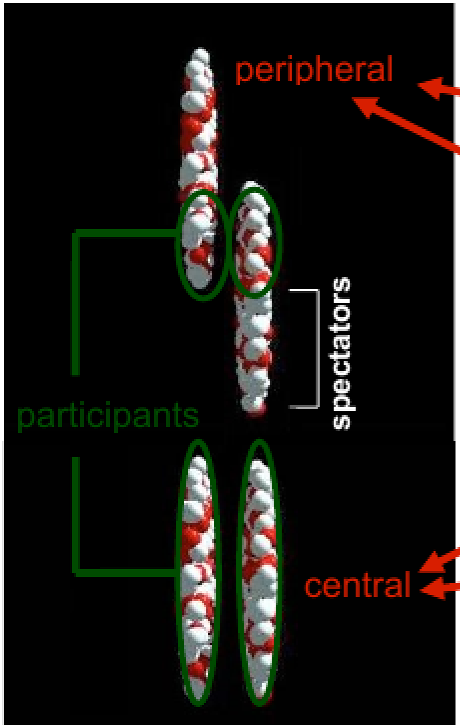
7. Anisotropic flow of charged particles in Pb-Pb collisions at √sNN = 5.02 TeV
PRL http://arxiv.org/abs/1602.01119

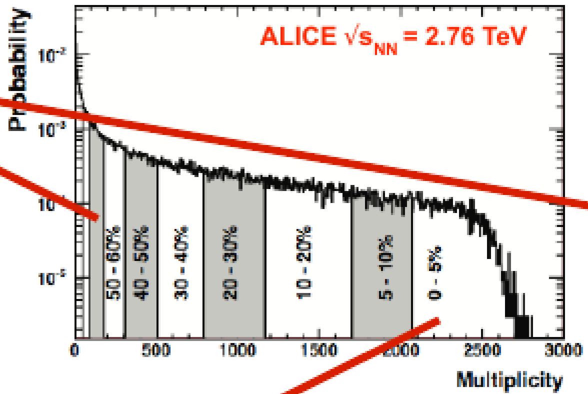
8. Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 T
PRL http://arxiv.org/abs/1512.06104

9. Pseudorapidity and transverse-momentum distribution of charged particles in proton-proton collisions at √s = 13 TeV
PLB http://arxiv.org/abs/1512.06104

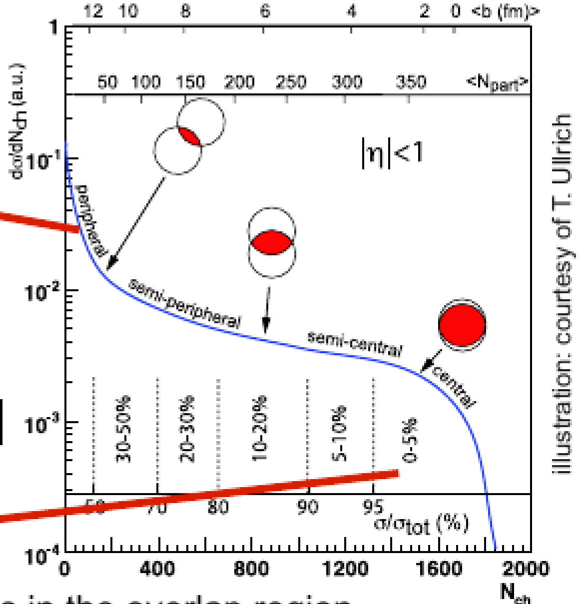
Centrality determination in ALICE

- Correlate the multiplicity of produced particles with the geometry of the system i.e. impact parameter (not directly accessible), volume and (roughly) the shape...





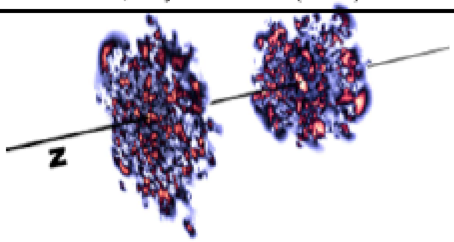
ALICE, arXiv:1301.4361, Phys. Rev. C 88 (2013) 044909



Number of participants (N_{part}): nucleons in the overlap region

Number of binary collisions (N_{coll}): nucleon-nucleon inelastic collisions

B. Schenke *et al.*, Phys.Rev. C86 (2012) 034908



In the details, the situation is “slightly” more complicated:
→ after centrality, fluctuations play an important role

USIAS University of Strasbourg Institute for Advanced Study

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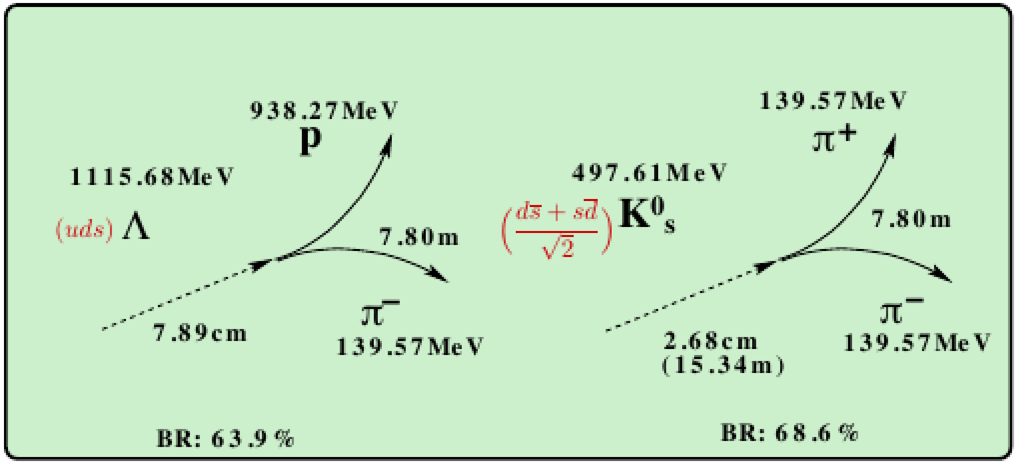
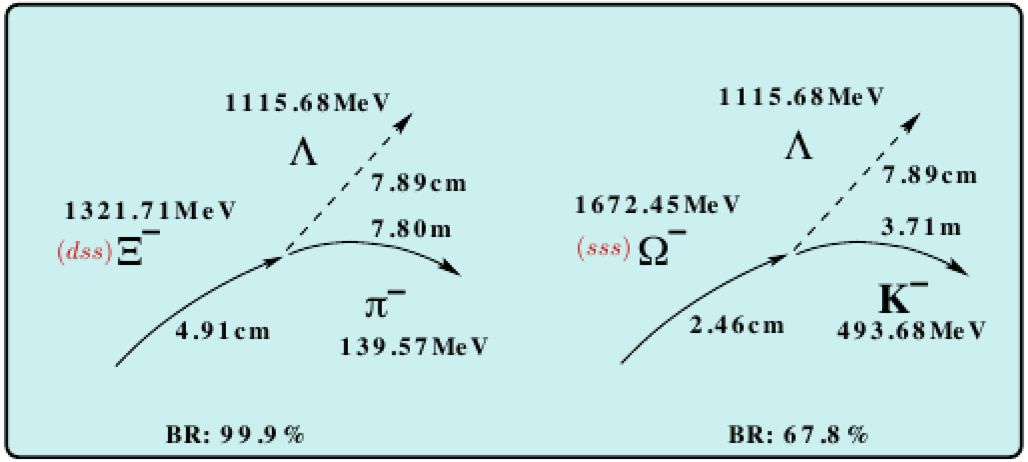
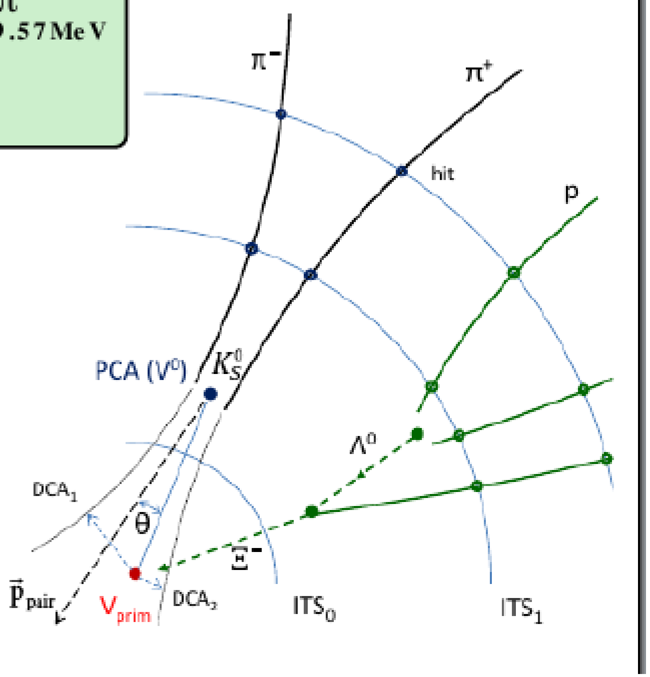
Slide from B Hyppolyte

Weak Decay Topologies

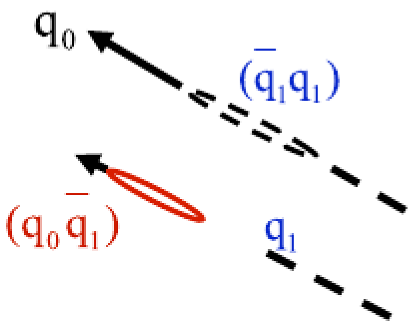






Courtesy of B. Hyppolyte

Hadron production from framentation in PYTHIA



In vacuum production of meson via string break-up

Probability to produce $(q_i \bar{q}_i)$
Probability to form $(q_{i-1} \bar{q}_i)$
Factorization: production of $(q_i \bar{q}_i)$ independent of q_{i-1} but the pair mass quark (flavour) is relevant.
⇨ Fragmentation in $(q_{i-1} \bar{q}_i)$ ≡ meson

probability: $e^{-\frac{\pi m_T^2}{\kappa}} = e^{-\frac{\pi m^2}{\kappa}} \times e^{-\frac{\pi p_T^2}{\kappa}}$

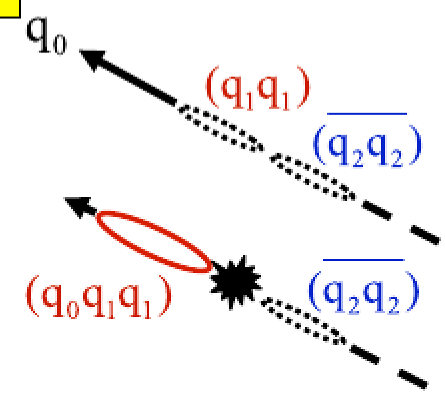
κ (string tension) ≈ 1 GeV/fm ≈ 0.2 GeV²

mass suppression: u:d:s:c≈1:1:0.3:10⁻¹¹

Production of $(q_i \bar{q}_i)$ via quantum mechanical tunneling:
- Classically, the pair is pulled apart by the field (no annihilation);
- Quantum mechanically, the pair is created at one point then tunnels out with a non zero probability (mass and flavor dependence).

In vacuum production of baryon with the diquark model

Relative probability to produce a <u>diquark</u> <u>pair</u> wrt quark pair
Extra suppression associated to s content
Spin suppression (spin 1 diquarks wrt spin 0 diquarks)
Weighted probability relative to 3-q state symmetry
⇨ Fragmentation in $(q_{i-1} q_i q_i)$≡ baryon



Courtesy of B. Hyppolyte

Multiplicity selection in pp collisions

- Multiplicity event class… with minimising auto-correlation bias
  - using V0 detectors in the forward region
    - V0A ($2.8 < \eta < 5.1$)
    - V0C ($-3.7 < \eta < -1.7$)

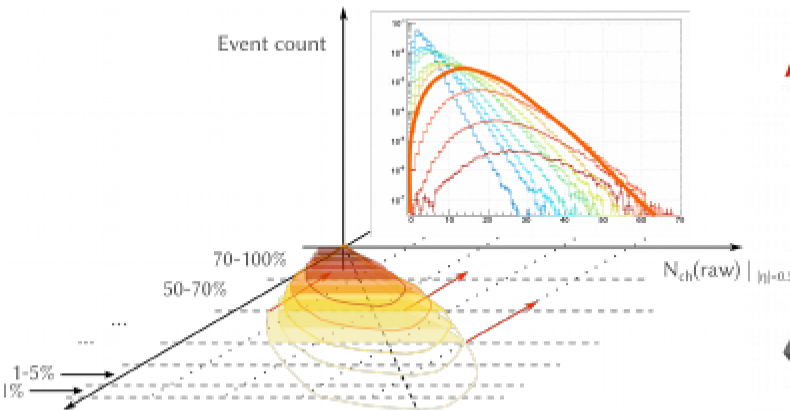
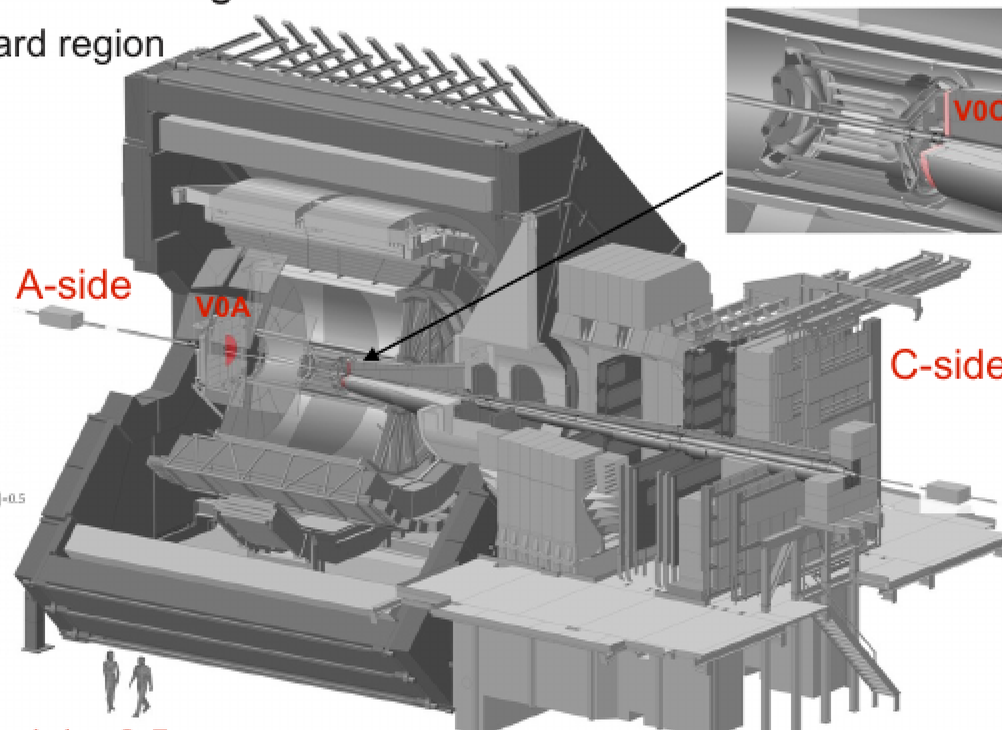


illustration: courtesy of A. Maire



1) select events with INEL>0 measured in $|\eta| < 0.5$
2) compute V0M = sum (V0A+V0C signals)
3) for each V0M percentile interval, extract the $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ corresponding to a corrected distribution of charged tracks in the central region $|\eta| < 0.5$

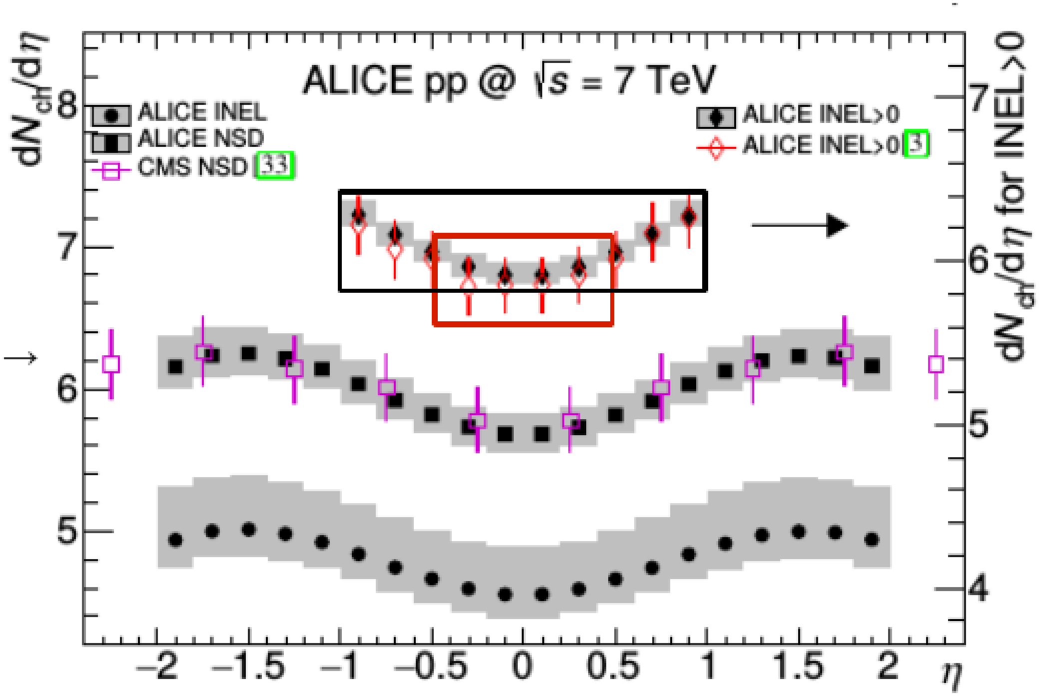
Courtesy of B. Hyppolyte

Multiplicity selection in pp collisions

- Global event class… several possibilities to select events
  - relevant for consistency checks between experiment and model comparisons

non single diffractive ? inelastic ? (with one charged track in a selected η interval ?)

NSD (ALICE and CMS) →



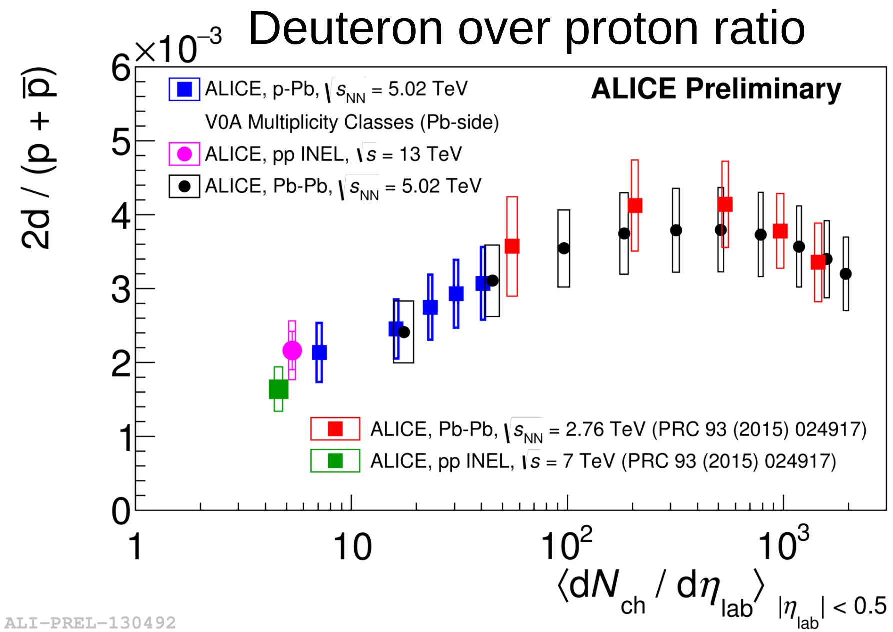
← INEL>0 measured in $|\eta|<1$

➡ choice: INEL>0 measured in $|\eta| < 0.5$

ALICE Collaboration, arXiv:1509.07541
Eur. Phys. J. C 77 (2017) 33

Courtesy of B. Hyppolyte

Anti and Hyper nuclei measurements



Run 2

Thermal model:

- Ratio is fixed by the temperature of the source → constant with the charged particle multiplicity

Coalescence model:

-Ratio should increase with the multiplicity of nucleons produced in the collision

- Smooth transition from pp to Pb-Pb is observed, peripheral Pb-Pb at 5 TeV is consistent with p-Pb
- The increase of the d/p ratio with charged particle multiplicity from pp to Pb-Pb is consistent with the coalescence picture at low multiplicity

• low multiplicity: corona effects can lead to a depletion of the d/p ratio going to the pp values

• high multiplicity: possible different rescattering of protons and deuterons after chemical freeze-out leads to a depletion

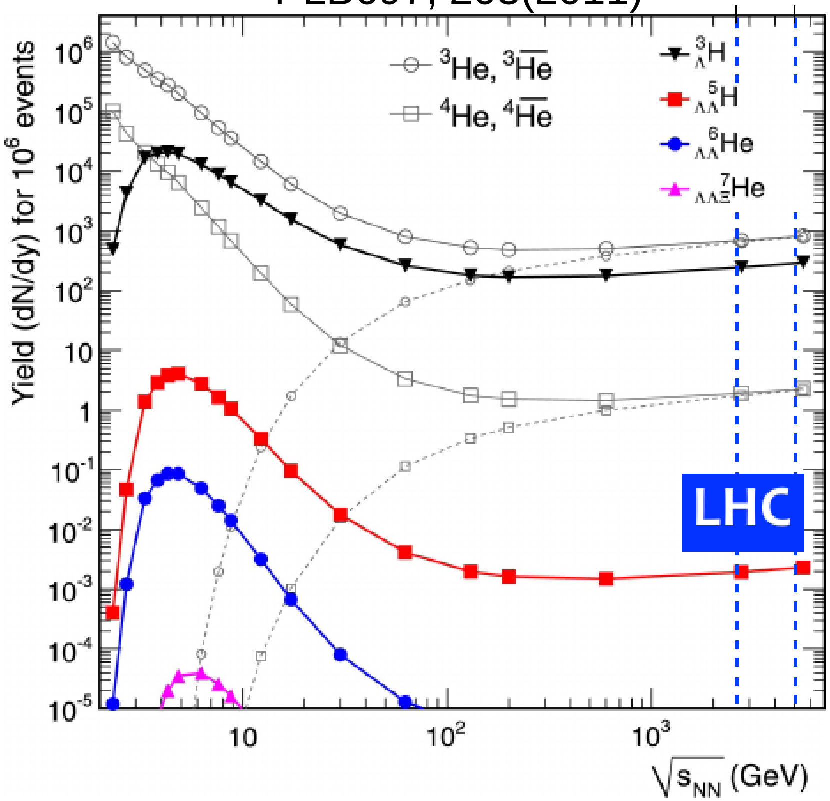
NB:Trend at high multiplicities currently under investigation (determination of the uncorrelated systematics)

Nuclei and hyper nuclei measurements

Production mechanism of compound objects

PRC21,1301 (1980)

PLB697, 203(2011)



Thermal Model:

-Hadrons emitted from the interaction region in statistical equilibrium once the chemical freeze-out temperature is reached.

-Abundance of a species proportional to $e^{-m/T_{chem}}$

-The large mass of Hyper nuclei gives a strong dependence on T_{chem}

Coalescence Model:

-Anti-baryons close in phase space at the kinetic freeze-out stage can form anti-hypernuclei

- These newly formed nuclei can **break** or **regenerate** in the time interval between chemical and kinetic freeze-out

NB: Hyper nuclei, nuclei in which one or several p/n is replaced by a strange baryon

EPS Presentation

Probing pQCD and hot QCD with hard probes

What can we learn from measuring hard processes

“Simplest way” to establish the properties of a system calibrated probe and calibrated interaction suppression pattern tells about density profile

Hard processes serve as calibrated probe (pQCD)

•pp: understand production mechanisms, probe PDFs, (particularly gluon’s PDF’s down to low x: gluon saturation) , provide a reference to p-Pb and Pb-Pb measurements

In Heavy-ion collisions:

- p-Pb: probe cold nuclear matter effects (i.e. modification of the PDFs, saturation, Cronin enhancement…)
- Pb-Pb: probe the formation and properties of the QGP
  - Traverse through the medium and interact strongly
  - Suppression pattern provides density measurement
  - General picture: parton energy loss through medium-induced gluon radiation and collisions with medium constituents

Radiative energy loss

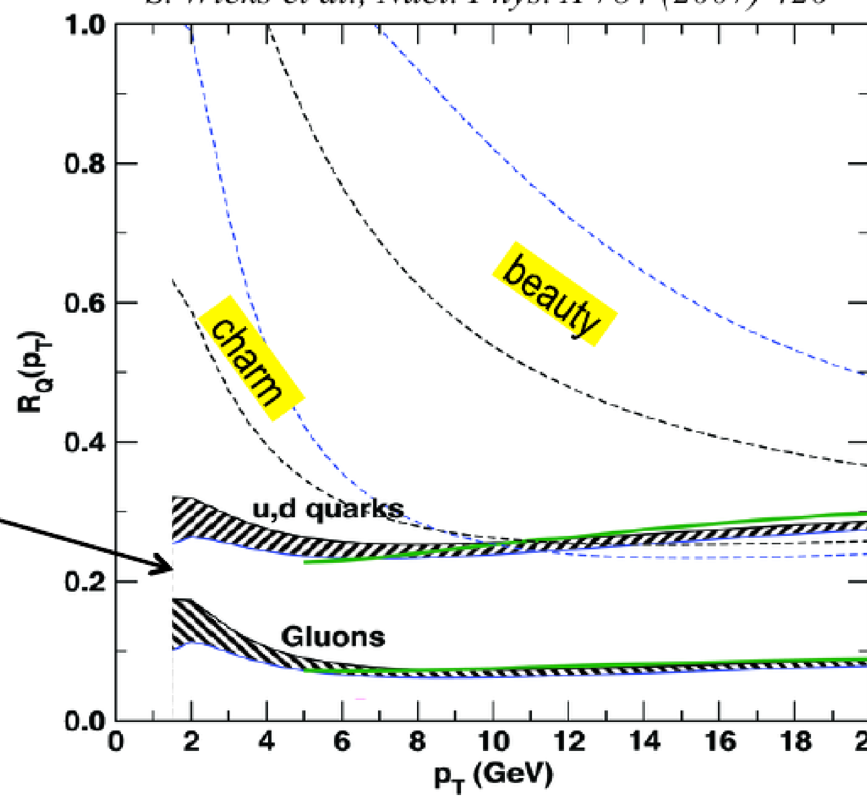
- …depends on
  - Medium properties (e.g. density, temperature, mean free path)
    → transport coefficients $(\hat{q})$
  - Path length in the medium (L)
  - Parton properties (colour charge and mass) traversing the medium → Casimir coupling factor (C_R):
    C_R = 4/3 for quarks and 3 for gluons
    R. Baier et al., Nucl. Phys. B483 (1997) 291 (BDMPS)

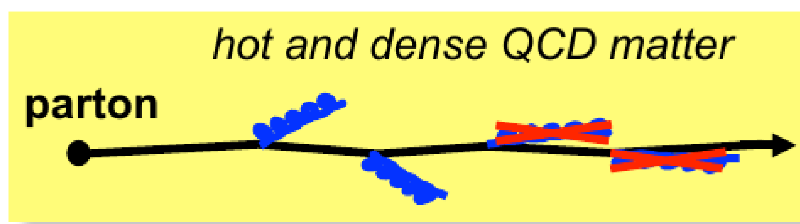
$$\langle \Delta E_{medium} \rangle \propto \alpha_S C_R \hat{q} L^2$$

- Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)
  Y. Dokshitzer, D. Kharzeev, PLB 519 (2001) 199, hep-ph/0106202

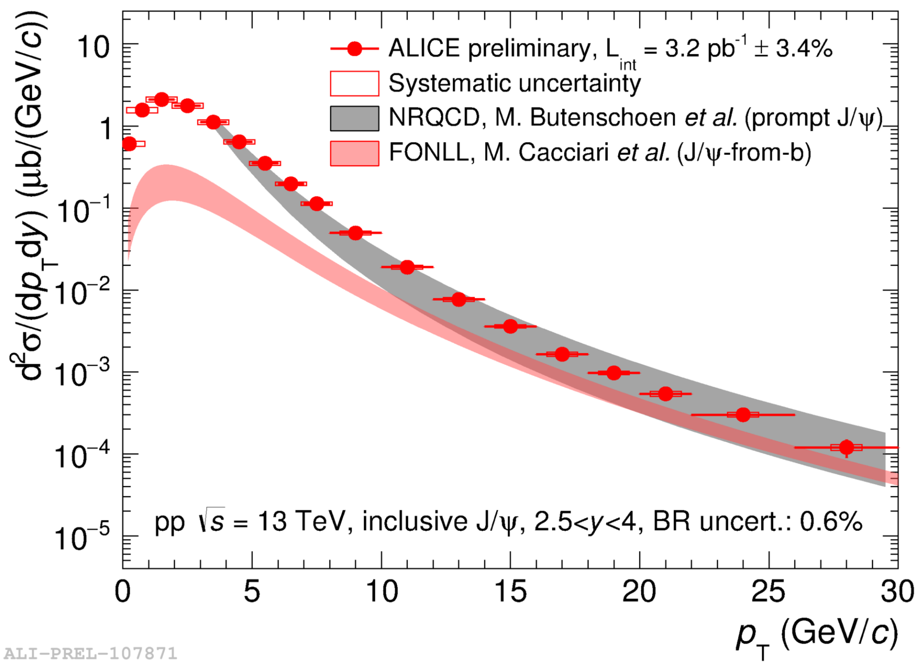
- *Expectation:* $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
  $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

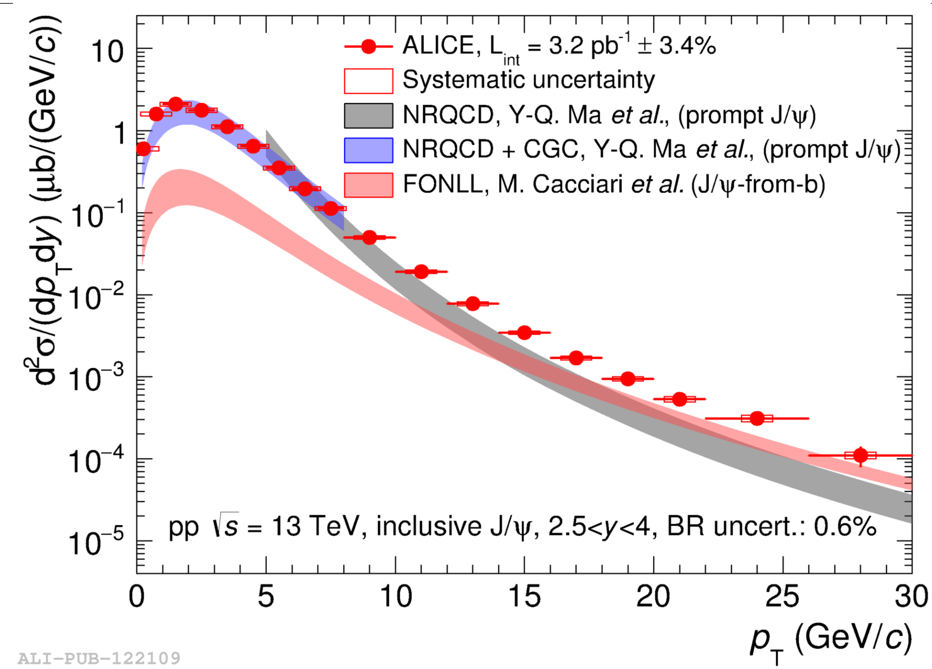
S. Wicks et al., Nucl. Phys. A 784 (2007) 426





Inclusive results compared to NRQCD





J/ψ vs p_T @13 TeV

NRQCD (left)	Butenschoen and Kniehl, PRL 106 (2011) 022003
NRQCD (right)	Ma, Wang and Chao, PRL 106 (2011) 042002
NRQCD+CGC	Ma and Venugopalan, PRL 113 (2014) 192301
FONLL	Cacciari *et al.*, JHEP 1210 (2012) 137

All models properly account for higher mass resonance decays

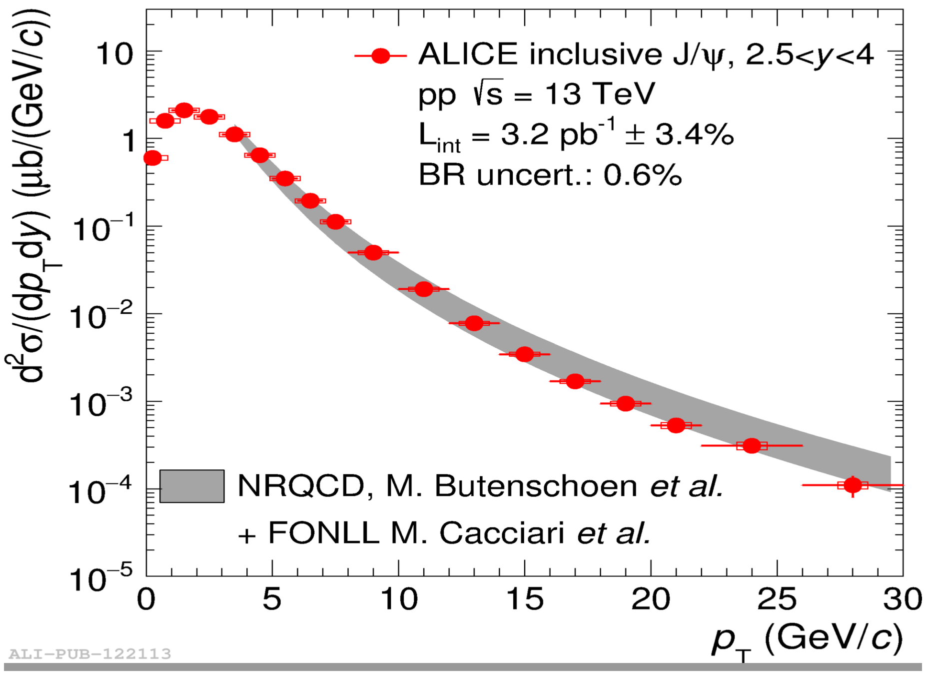
NRQCD models differ in the set of LRME that is used, the p_T at which fits are performed and the datasets considered.

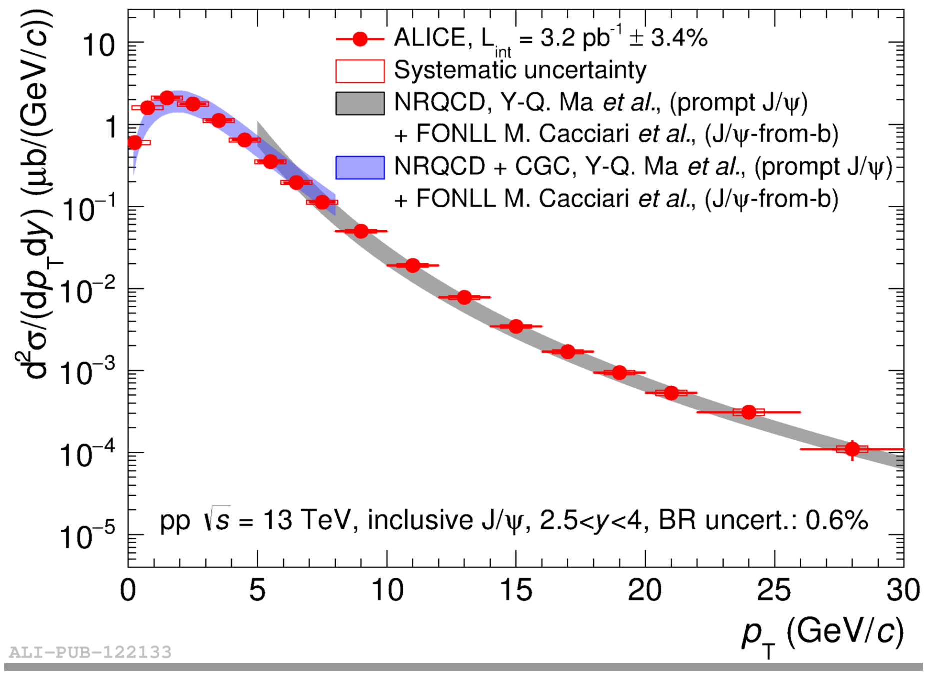
At low p_T (right), NRQCD is coupled to a CGC description of the proton

Predictions are quite different at high p_T, but in both cases, non-prompt J/ψ constitute a sizable contribution to the inclusive cross section

Inclusive results compared to NRQCD

Summed NRQCD and FONLL calculations assuming fully uncorrelated uncertainties.

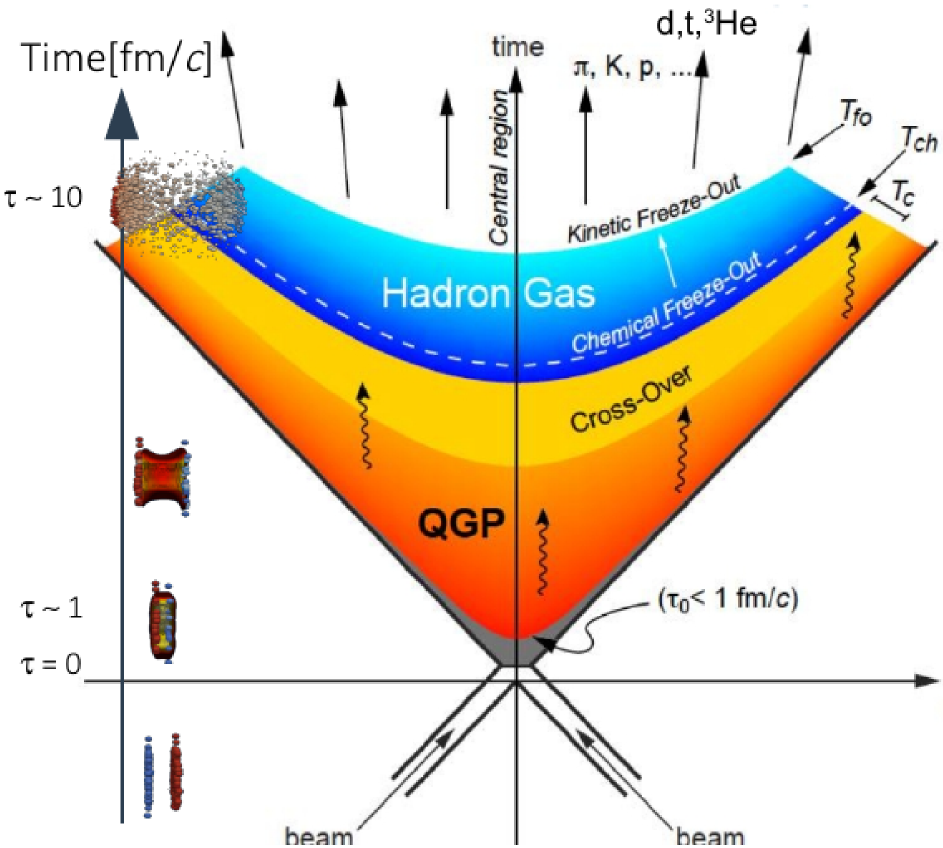




Agreement to the data is much improved, already at intermediate p_T and especially for the calculation from Ma *et al.*

Note that the calculations are completely independent, and that there was no data at this energy, this rapidity and at such high p_T before

Evolution if the heavy ion collision



- Kinetic freeze-out (T_{kin} ~ 100 MeV)
  - elastic reactions cease: spectra and correlations are frozen (free streaming of hadrons)
- Chemical freeze-out (T_{chem}~156 MeV):
  - inelastic reactions cease: the chemical composition of the system is fixed (particle yields and fluctuations)
- Phase transition from QGP to hadron gas ($T_C \approx 160$ MeV)
- Formation of Quark-Gluon Plasma phase (if $T > T_c$)
- "Pre-equilibrium"
- Two Lorentz contracted nuclei approach and collide

Evolution if the heavy ion collision

Coalescence

- If baryons at freeze-out are close enough in phase space (i.e. geometrically and in momentum) and match spin state a (anti-)nucleus can be formed
- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space
- The yield of any nucleus can be determined as:

$$\gamma_A \frac{d^3 N_A}{dp_A^3} = \left(\frac{2s_A + 1}{2^A}\right) \left(\frac{4\pi}{3} p_0^3\right)^{A-1} \left(\gamma_p \frac{d^3 N_p}{(dp_A^3/A)}\right)^Z \left(\gamma_n \frac{d^3 N_n}{(dp_A^3/A)}\right)^N$$

- Assuming that p an n have the same mass and have the same p_T spectra

$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3}\right)^A$$

$$\boxed{\begin{array}{r} d \propto p^2 \\ {}^3He \propto p^3 \end{array}}$$

Statistical thermal model

- Thermodynamic approach to particle production in heavy-ion collision: all the particles are produced at chemical freeze-out
- Starting point: Grand Canonical partition function (Z) for an relativistic ideal quantum gas of hadrons of particle type i (i = pion, proton,... → full PDG)
- For each hadron i : Z depends on the temperature T, the volume V and the chemical potentials μ_B, μ_S, μ_Q : $Z(T, V, \mu_B, \mu_S, \mu_Q) = \sum_i Z_i$
- The mean particle number can be calculated as:

$$\langle N_i \rangle = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \ln\left(1 \pm \lambda_i \exp(-\beta \epsilon_i)\right) dp$$

Spin degeneracy factor

$\beta = \frac{1}{kT}$

Total Energy
$\varepsilon_i = \sqrt{p^2 + m_i^2}$

+ fermion
- bosons

Fugacity:
$$\lambda_i(T, \mu) = \exp\left(\frac{B_i \mu_b + S_i \mu_s + Q_i \mu_Q}{T}\right)$$
Chemical potential representing each conserved quantity

Statistical thermal model

- Particle density n_i can then be calculated as: $$n_i = \frac{\langle N_i \rangle}{V} = \frac{T g_i}{2\pi^2} \lambda_1 K_2 \left(\frac{m_i}{T} \right)$$
- If ratios are considered (n_i/n_j) Volume (V) cancels –> ratio depends only on T, μ and m
- Thermal model can predict also the yields of (anti-)nuclei → The binding energy of light nuclei is not taken into account: nuclei are considered as not compound objects

  ➔ Exponential dependence of the yield: $$\frac{dN}{dy} \propto e^{\left(-\frac{m}{T_{chem}}\right)}$$

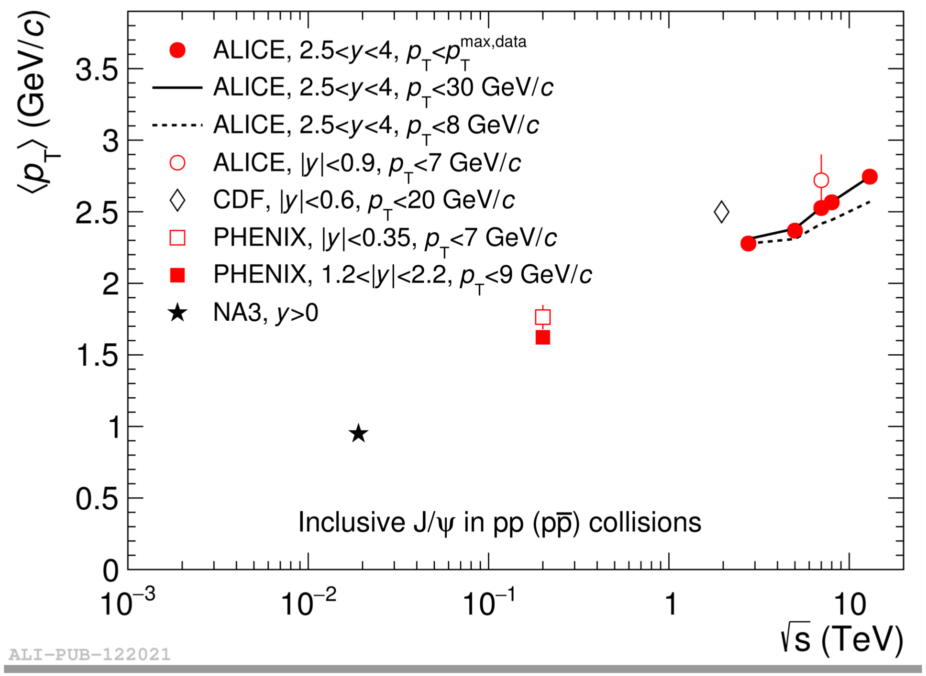
  Nuclei can be use as a precise thermometer of the chemical freeze-out temperature

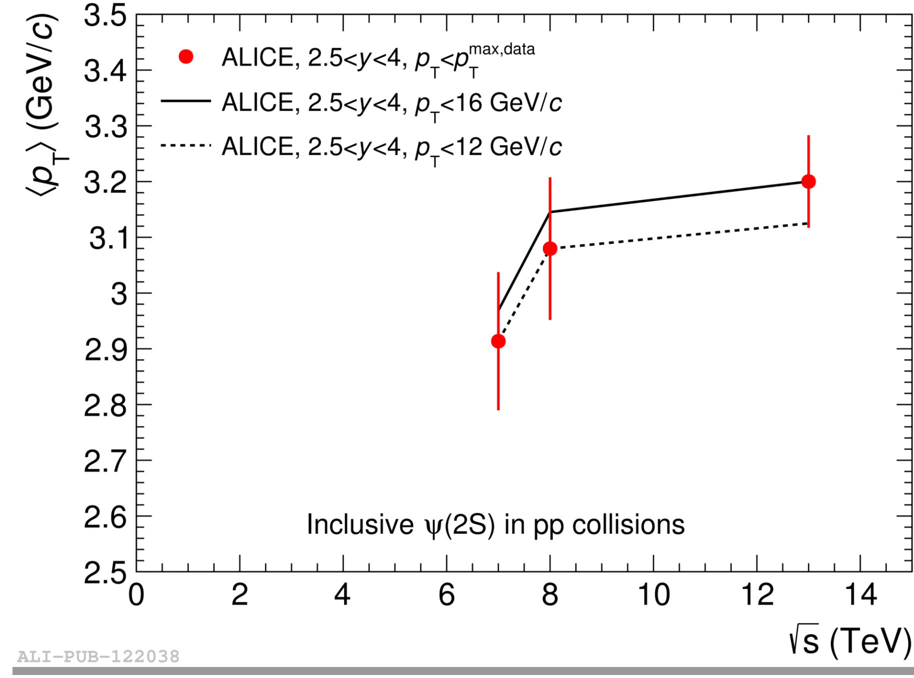
- The density ratio of a particle with the next heavier one: $$\frac{n_i}{n_{i+1}} \approx \exp\left(-\frac{\Delta m}{T}\right)$$

  ➔ The thermal model predicts an exponential decrease of particle yields with increasing mass at a given temperature

$(m_p - m_d) \sim 938$ MeV
$p/d \sim \exp(938/160) \sim 350$

Mean p_T energy dependence





$<p_T>$ is measured using fits to the p_T distributions.

A steady increase of $<p_T>$ with increasing $\sqrt{s}$.

Consistent with the expected hardening of the of the J/ψ and ψ(2S) p_T distributions.

Values at mid- are systematically larger than at forward-rapidity.

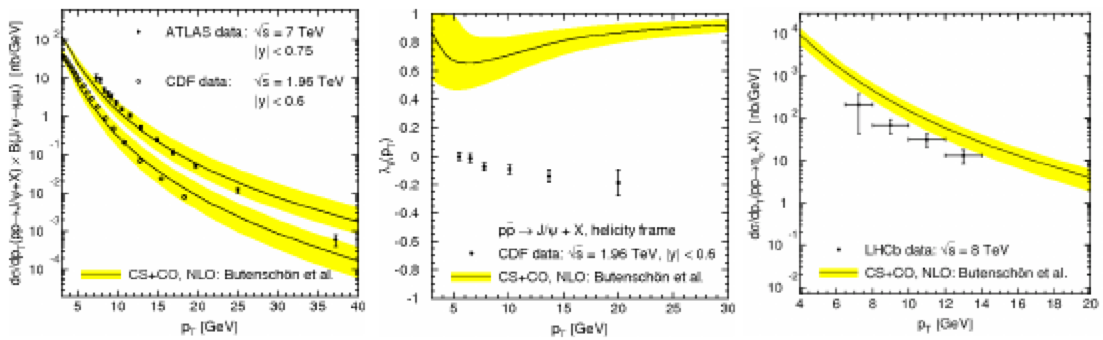
Could be attributed to an increase in the longitudinal momentum at forward-rapidity leaving less energy available in the transverse plane.

What about model comparisons?

***pp* yield:** ***pp* polarization:** ***ηc* production:**

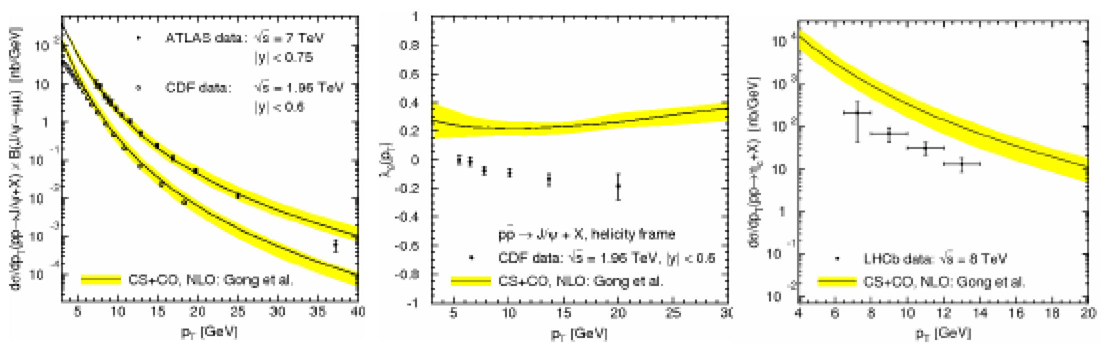
Butenschön, Kniehl:

$\langle O_8^{J/\psi}(^1S_0)\rangle = 0.0497\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3S_1)\rangle = 0.0022\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3P_0)\rangle = -0.0161\ \mathrm{GeV}^5$



Gong, Wan, J.-X. Wang, H.-F. Zhang:

$\langle O_8^{J/\psi}(^1S_0)\rangle = 0.097\ \mathrm{GeV}^3$ $\langle O_8^{\psi'}(^1S_0)\rangle = -0.0001\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3S_1)\rangle = -0.0046\ \mathrm{GeV}^3$ $\langle O_8^{\psi'}(^3S_1)\rangle = 0.0034\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3P_0)\rangle = -0.0214\ \mathrm{GeV}^5$ $\langle O_8^{\psi'}(^3P_0)\rangle = 0.0095\ \mathrm{GeV}^5$
$\langle O_8^{\chi_0}(^3S_1)\rangle = 0.0022\ \mathrm{GeV}^3$



Chao, Ma, Shao, K. Wang, Y.-J. Zhang:

$\langle O_8^{J/\psi}(^1S_0)\rangle = 0.089\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3S_1)\rangle = 0.003\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3P_0)\rangle = 0.0126\ \mathrm{GeV}^5$

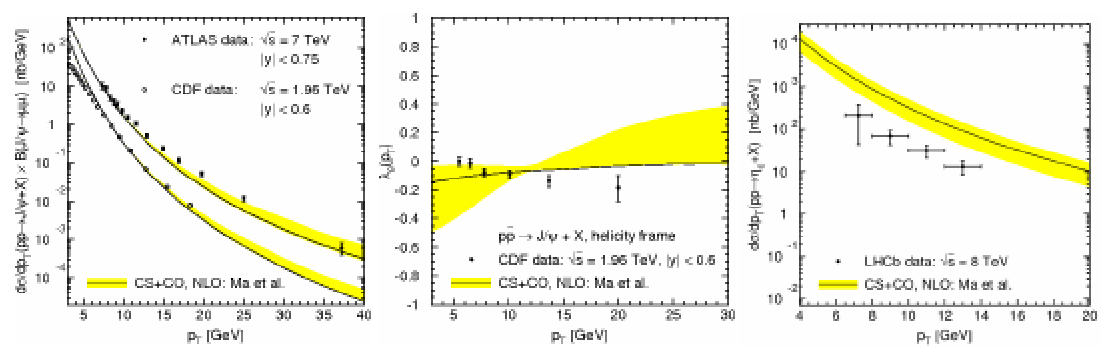


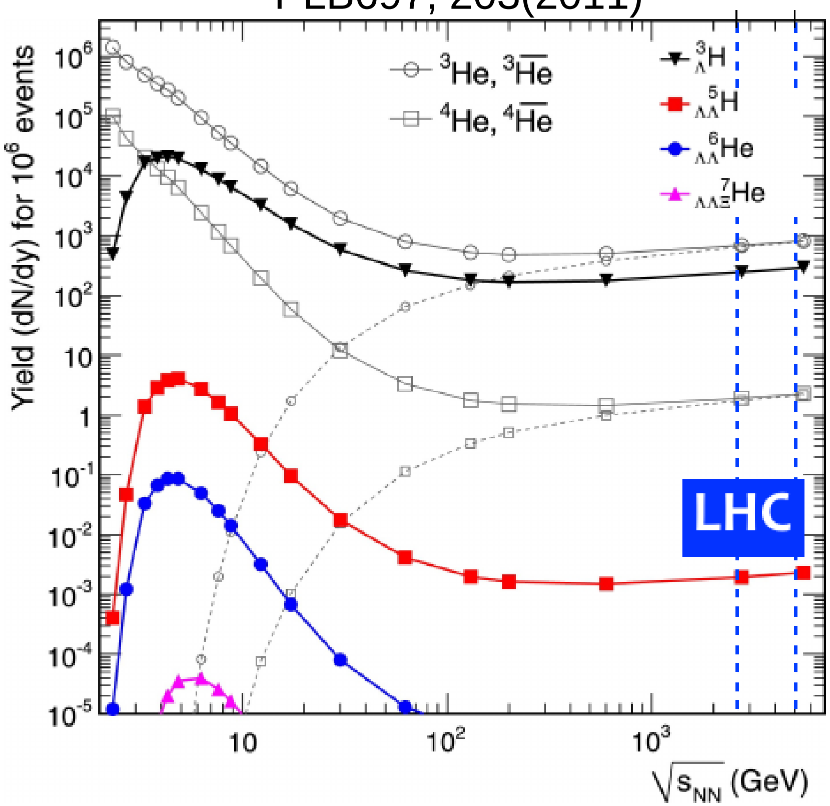
Figure from **KNIEHL B.** Quarkonium 2016 VA, USA

Nuclei and hyper nuclei measurements

Production mechanism of compound objects

PRC21,1301 (1980)

PLB697, 203(2011)



Thermal Model:

-Hadrons are emitted from the interaction region in statistical equilibrium once the chemical freeze-out temperature is reached.

-Abundance of a species proportional to $e^{-m/Tchem}$

-The large mass of Hyper nuclei gives a strong dependence on T_{chem}

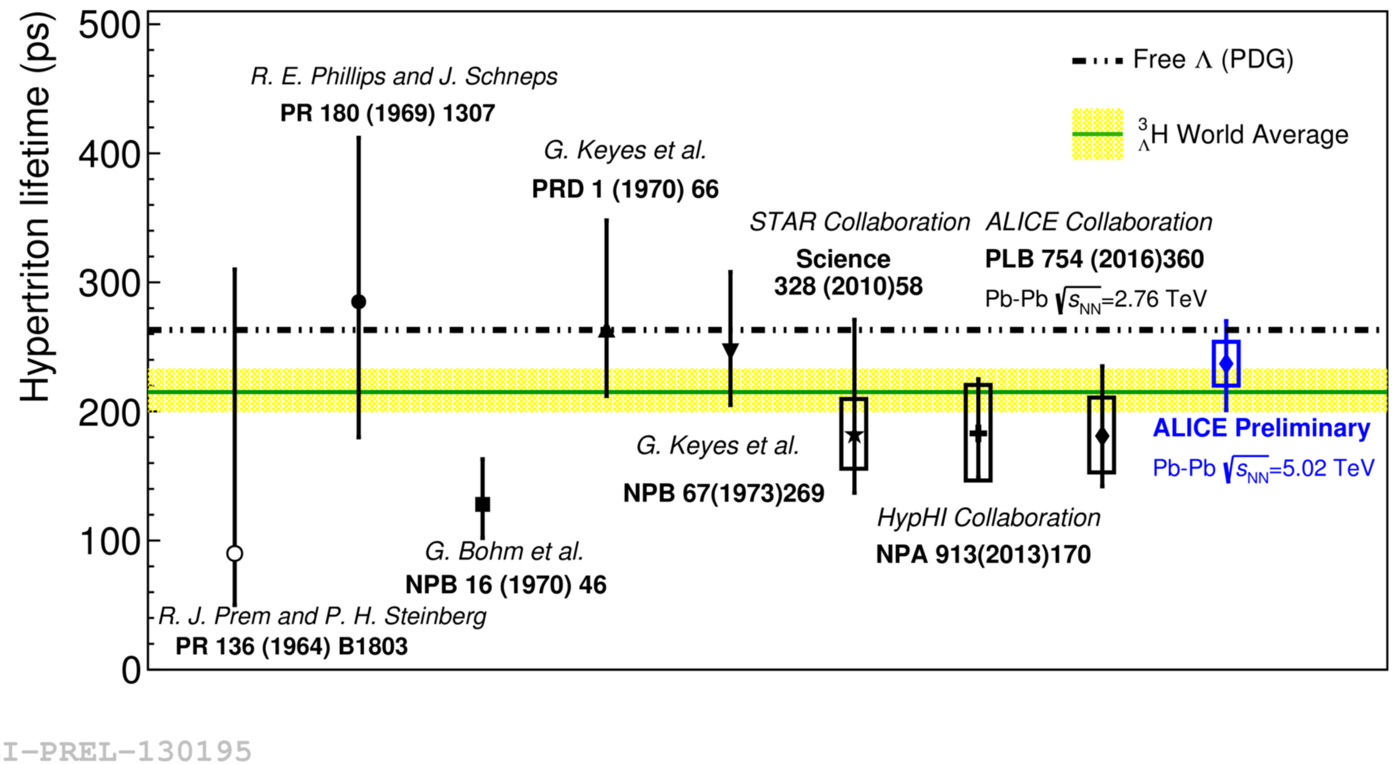
NB: Hyper nuclei, nuclei in which one or several p/n is replaced by a strange baryon

EPS Presentation

Hyper nuclei measurements

Hypertriton lifetime expected to be slightly below free Λ lifetime

Run 2



New ALICE result from Pb-Pb at 5.02 TeV is consistent to the free Λ prediction

This is one of the most precise measurements of hypertriton lifetime