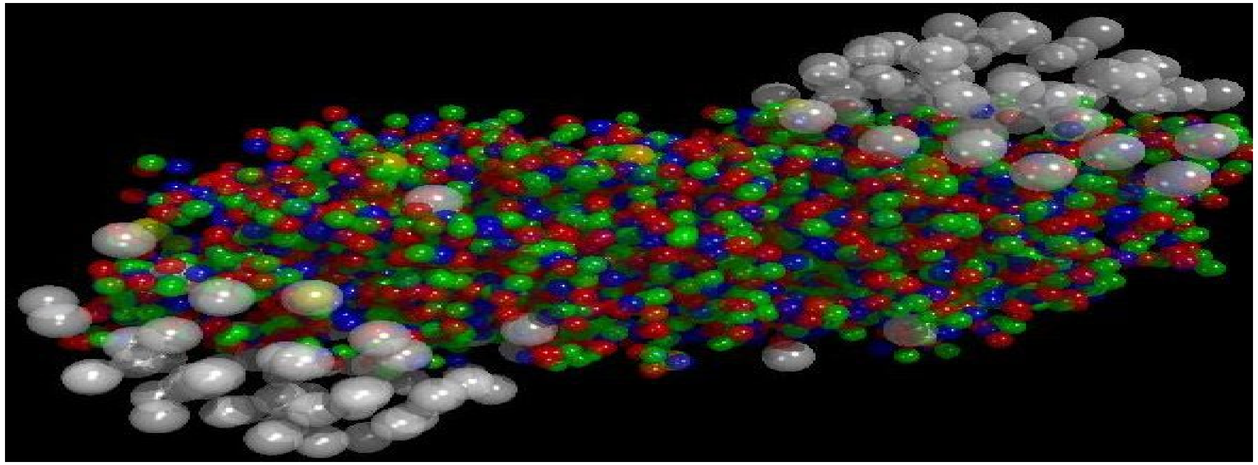
Heavy ions theory



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IGFAE, Universidad de Santiago de Compostela

LHC days in SPLIT, Oct 2022

---Conventional space-time evolution of a heavy ion collision

- Coherent effects. Multiplicities are not a sum of NN collsions.
- Ridge structure seen in PbPb and pp high multiplicity events (CMS 2011)
- Small systems present collective effects. How are they made?
- String interactions (color reconnection, color rope, string shoving, percolation, ……)
- dN/dy and energy density change behavior at high multiplicity. Transition from a strong interacting liquid to a free gas at T around 210 Mev?
- Entanglement of initial partons as origin of a fast thermalization
- Cumulative effect (QCD working as an accelerator)
- Quarkonium production as a function of the multiplicity

Goal of HIC experiments: Study hot and dense QCD matter

Starting point: Quantum Chromodynamics (QCD)

Fundamental question: How do collective phenomena and macroscopic properties emerge from the interactions of elementary particle physics?

Heavy Ion Physics addresses this question in the regime of the highest temperatures and densities accessible in laboratories: QGP search

Screening of long range confining potential at high T or density

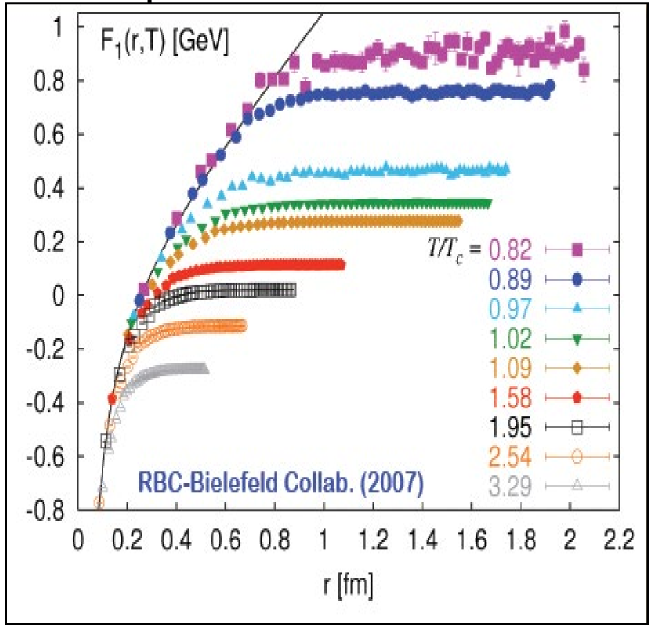
D.o.F. increases x10 reaching 80% of the non-interacting gas limit

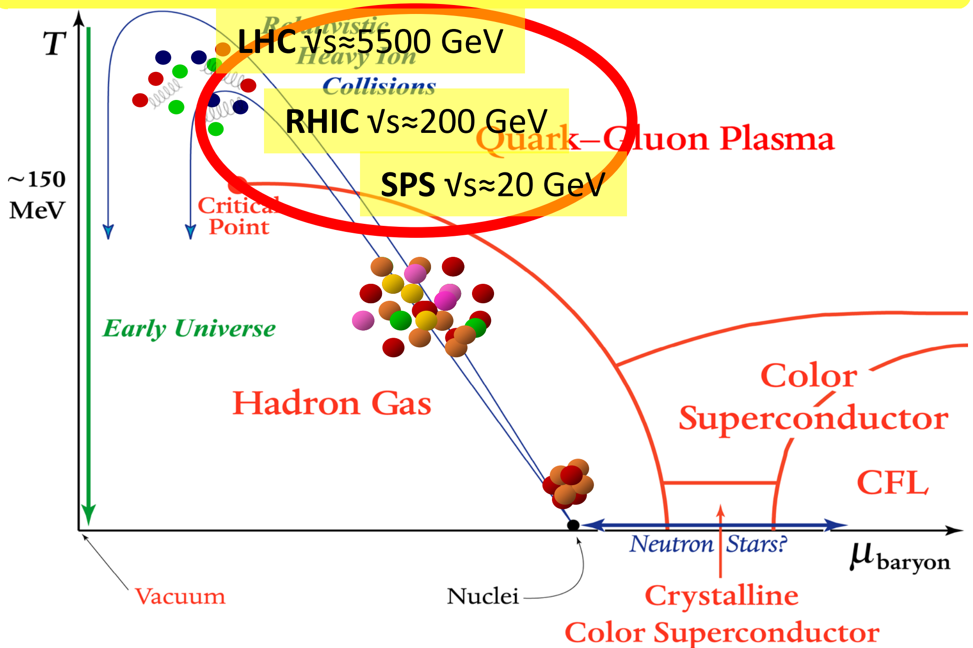
Where?:

in the Universe 10^{-5} s after the Big-Bang

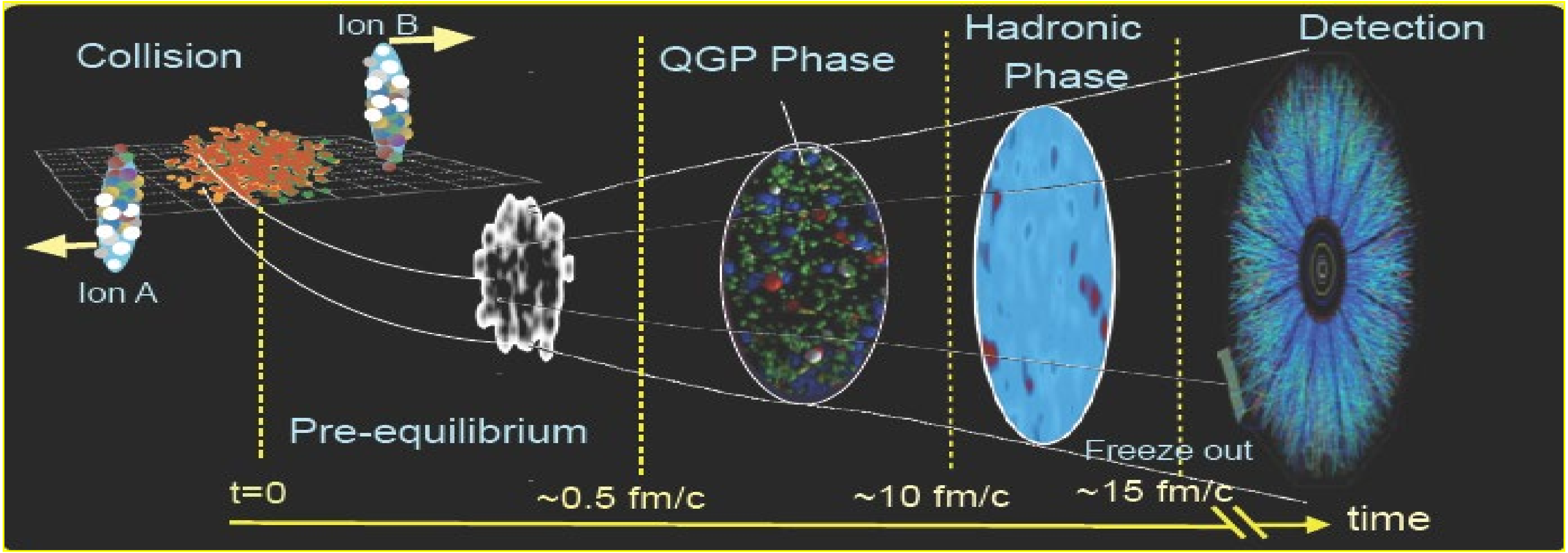
in the core of neutron stars

in ultra-relativistic heavy ion collisions





Space-time picture of heavy ion collisions: Observables



Bulk Observables: p ~ <pt>,T
~ 99% of detected particles
Multiplicities
Thermal dileptons & direct photons
Asymmetries, correlations, fluctuations

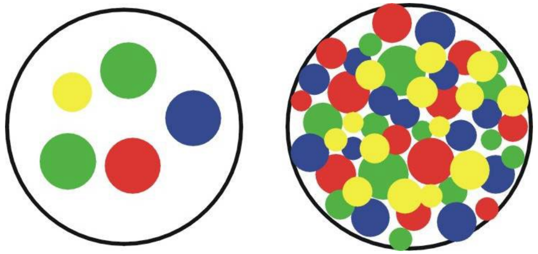
Collective behavior of the medium
Initial conditions: T, ε, μ
Thermalization and hydrodynamics

Hard Probes: p >> <pt>,T
~ 1% of detected particles
Fast quarks and gluons
Jet quenching
Quarkonia dissociation

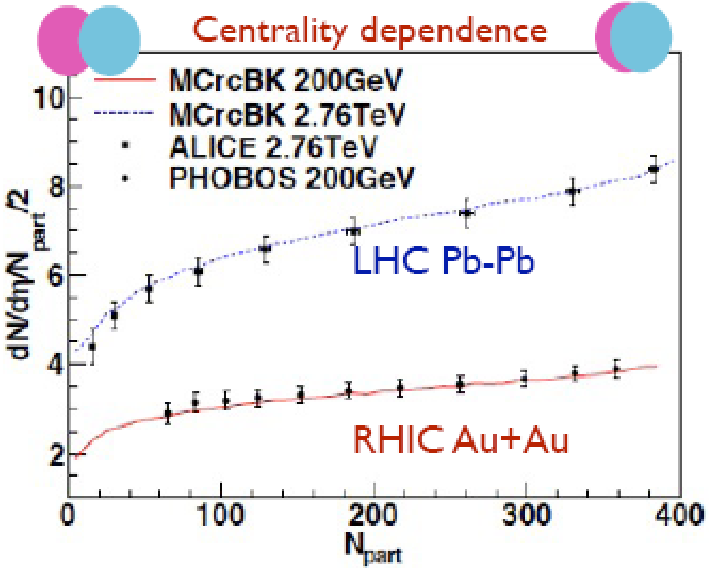
Medium tomography & diagnosis
Interpretation requires “vacuum” (p+p) and “cold nuclear” (p+Pb) data at the same energy

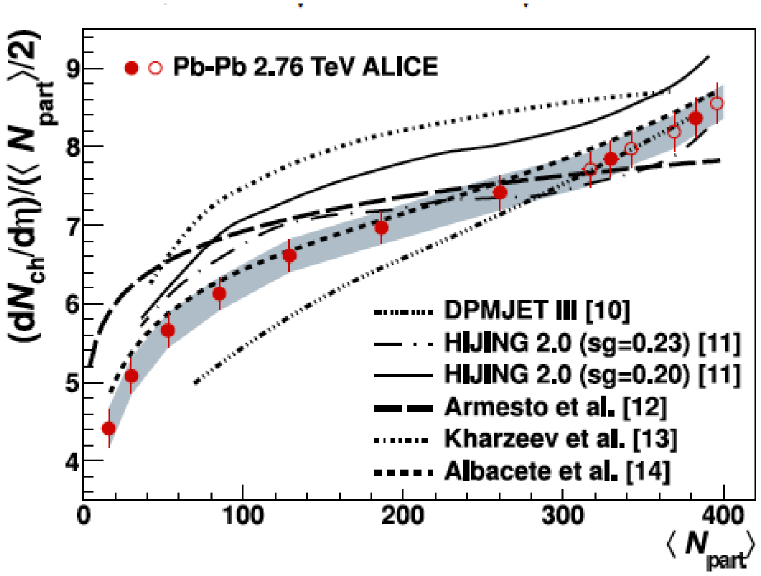
Multiplicities: Coherence effects

Both RHIC and LHC multiplicities are a lot smaller than predicted by simple superposition of proton+proton collisions: Coherence effects are important



Strong coherence in particle production:
CGC, percolation, strong gluon shadowing
=> Reduction in the effective number of colour sources



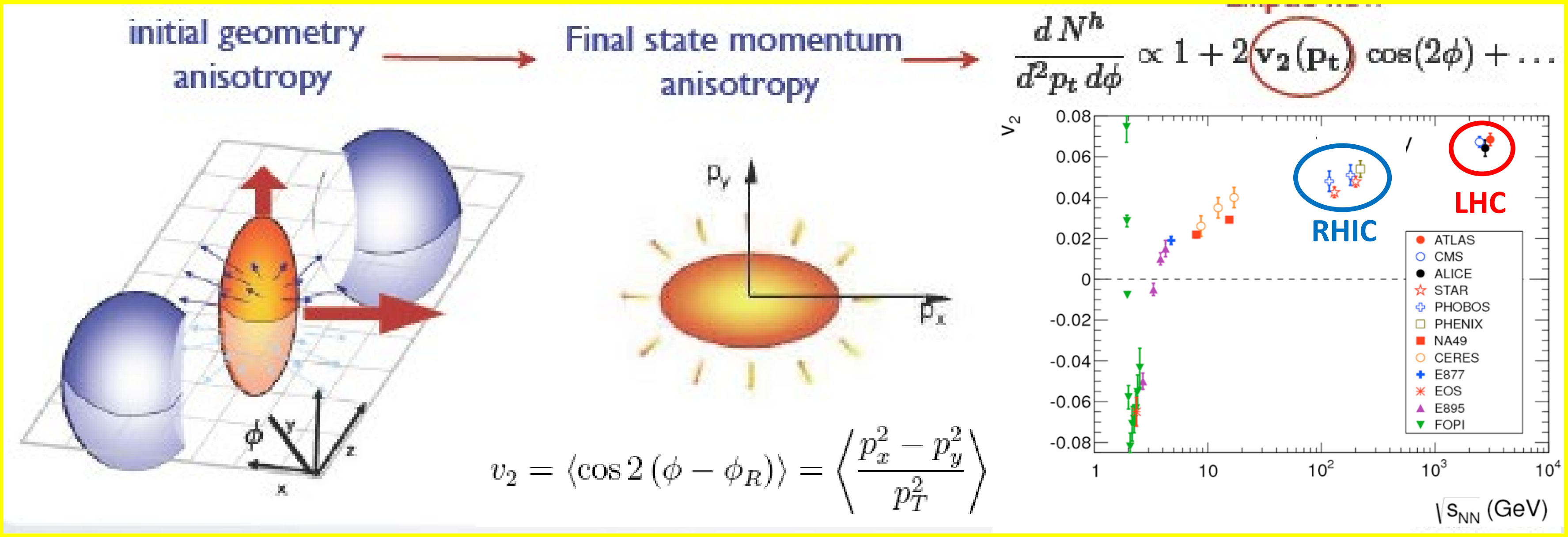


Behaviour compatible with factorization between energy and centrality dependences, as suggested by saturation, but….

$$\left.\frac{dN^{gluons}}{d\eta\, d^2b}\right|_{\eta=0} \propto Q_s^2(\sqrt{s}, b) \sim \sqrt{s}^{0.3} N_{part}$$

RHIC and LHC matter flow!

- **Matter behaves like a fluid whose expansion is driven by pressure gradients**

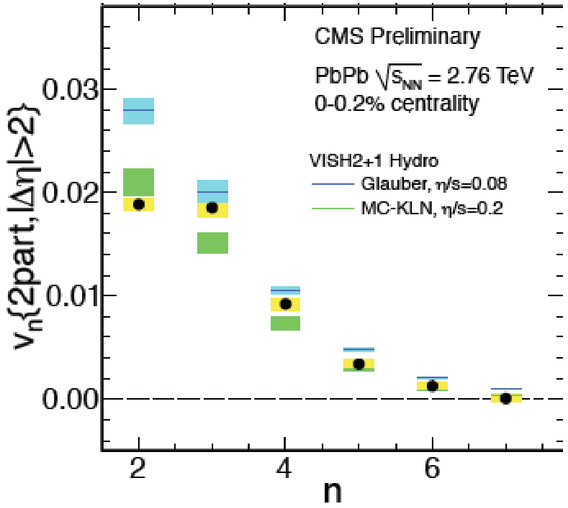


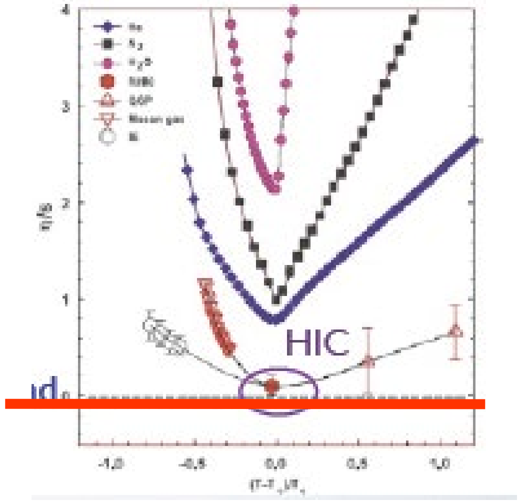
- **Perfect fluid: Smallest viscosity/entropy ever measured, close to ADS/CFT lower bound**

Hydro+EoS+initial conditions+hadronization works

$\eta/s = h/4\pi k_B$

Further constraint on initial conditions and η/s:
Higher harmonics v_n



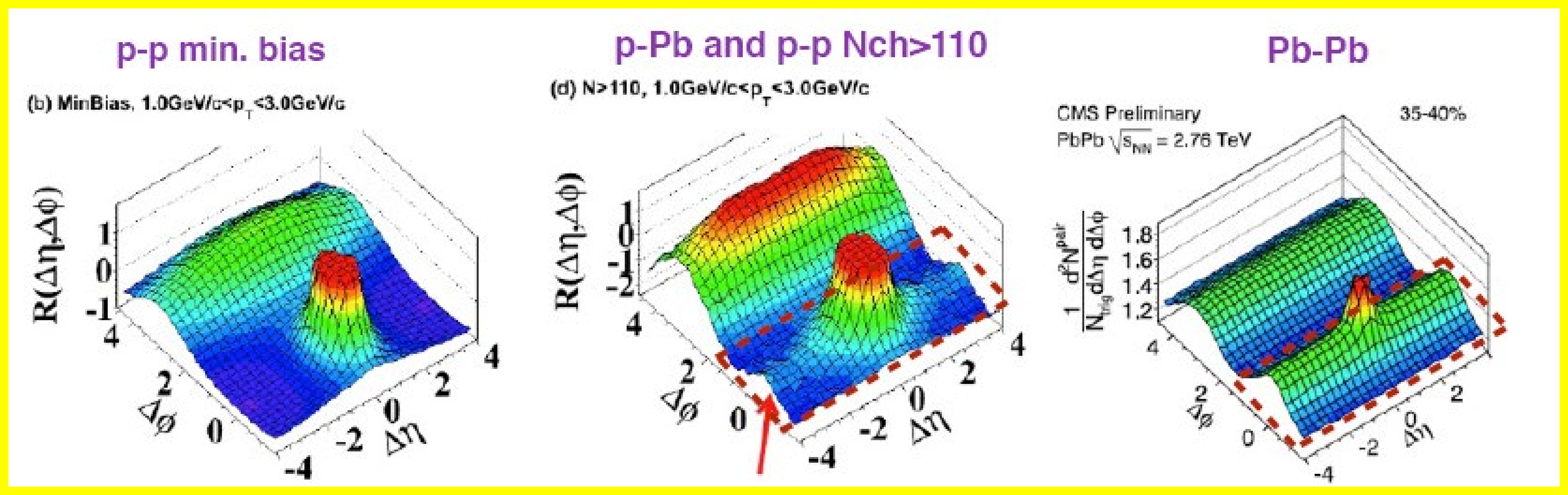


Long range rapidity correlations: The ridge

Ridge structure in $\Delta\varphi$ - $\Delta\eta$ angular correlations, where $\Delta\varphi$ and $\Delta\eta$ are the azimuthal angle and pseudorapidity differences of two produced hadrons

Ridge structures along $\Delta\eta$ appear on the same side (near side, $\Delta\varphi \sim 0$) and on the away side ($\Delta\varphi \sim \pi$), with or without a high p_T trigger.

Observed in Au+Au @ RHIC, and in Pb+Pb, high mult. p+Pb & p+p collisions @ LHC



Different theoretical models of the ridge: hydrodynamic flows, local hot spots, initial-state fluctuations, parton cascades, glasma flux tubes, glasma turbulence fields, the momentum kick model, pQCD modeling, etc..

Long range y-correlations natural in string models, CGC,..

Most of the effects seen in AA, as ridge structure, rapidity long range correlations, strangeness enhancement, elliptic flow are seen in pp high multiplicity collisions. (not jet quenching)

How is made the coherent collective fluid behavior ? The thermalization is due to final state interactions?

String interactions in models

-EPOS(Venus, Core with fusión and Hydrodynamic evolution plus corone)
-AMPT (with string melting and transport)
-HIJING (Fritiof + string fusión)
-Pythia (color reconnection,color rope formation, string shoving)
-String percolation +final parton interactions
-Glasma picture of CGC +(Hydro evolution)

Color rope formation

p coherent triplet and q coherent anti-triplet colours by $\{p, q\}$, this gives

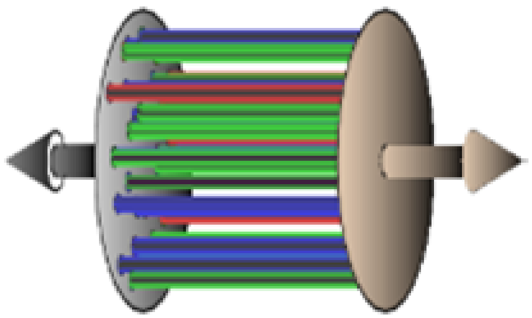
$$\kappa^{\{p,q\}}/\kappa^{\{1,0\}} = C_2^{\{p,q\}}/C_2^{\{1,0\}} = \frac{1}{4}\left(p^2 + pq + q^2 + 3p + 3q\right),$$

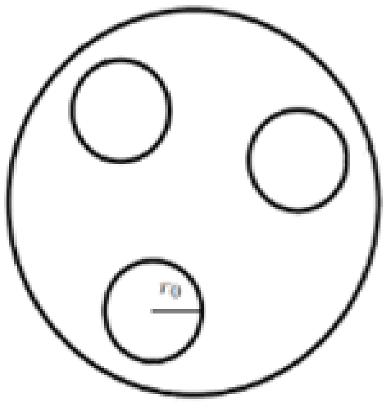
Applied to the dependence on multiplicity of the strangeness enhancement the results are in agreement with data on pp collisions but overcome PbPb collisions. May be including the string shoving could improve the agreement.

Some modification of the propagating jet in the médium is seen with string interactions

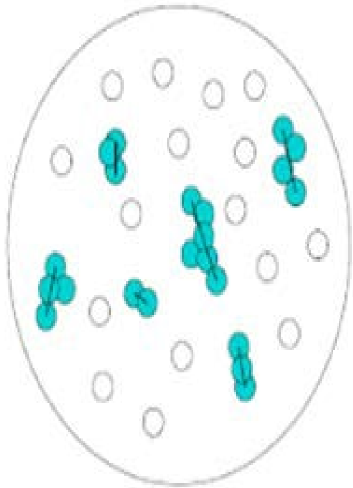
C.Bierlich,S.Chakraborty, G.Gustafson,L.Lönnblad arXiv: 2205.11170

String percolation





$r_0 = 0.2 - 0.25\ fm$



- Projectile and target interact via color field created by the constituent partons of the nuclei.
- Color field is confined in a region with transverse size $r_0 \sim$ **0.2 fm**.
- We can see them as small areas in transverse plane.
- These color "strings" break producing $q\bar{q}$ pairs (Schwinger mechanism) that subsequently lead to the observed hadrons.

- With growing energy and/or atomic number of colliding particles, the number of **sources** grows → The **number of strings** grows with energy and/or atomic number.
- The **number of strings** also increases with increasing centrality.
- Strings are **randomly distributed** in transverse plane so they can overlap forming clusters.

- A cluster of n strings **behaves like a single string with a color field**

$$\vec{Q}_n = \sum_1^n \vec{Q}_1$$

.

- The field is **randomly oriented** so

$$\left\langle \vec{Q}_n^2 \right\rangle = n \left\langle \vec{Q}_1^2 \right\rangle$$

- Using the Schwinger formula

$$\mu_n = \sqrt{\frac{nS_n}{S_1}}\mu_1 , \quad \langle p_T^2 \rangle_n = \sqrt{\frac{nS_1}{S_n}} \langle p_T^2 \rangle_1$$

where μ_n and $\langle p_T^2 \rangle_n$ are, respectively, the multiplicity and the mean p_T^2 of the particles created by the fragmentation of a cluster of n strings ocupping an area S_n.

- At a certain critical density 1.2-1.5 a macroscopic cluster appears which marks the percolation transition.

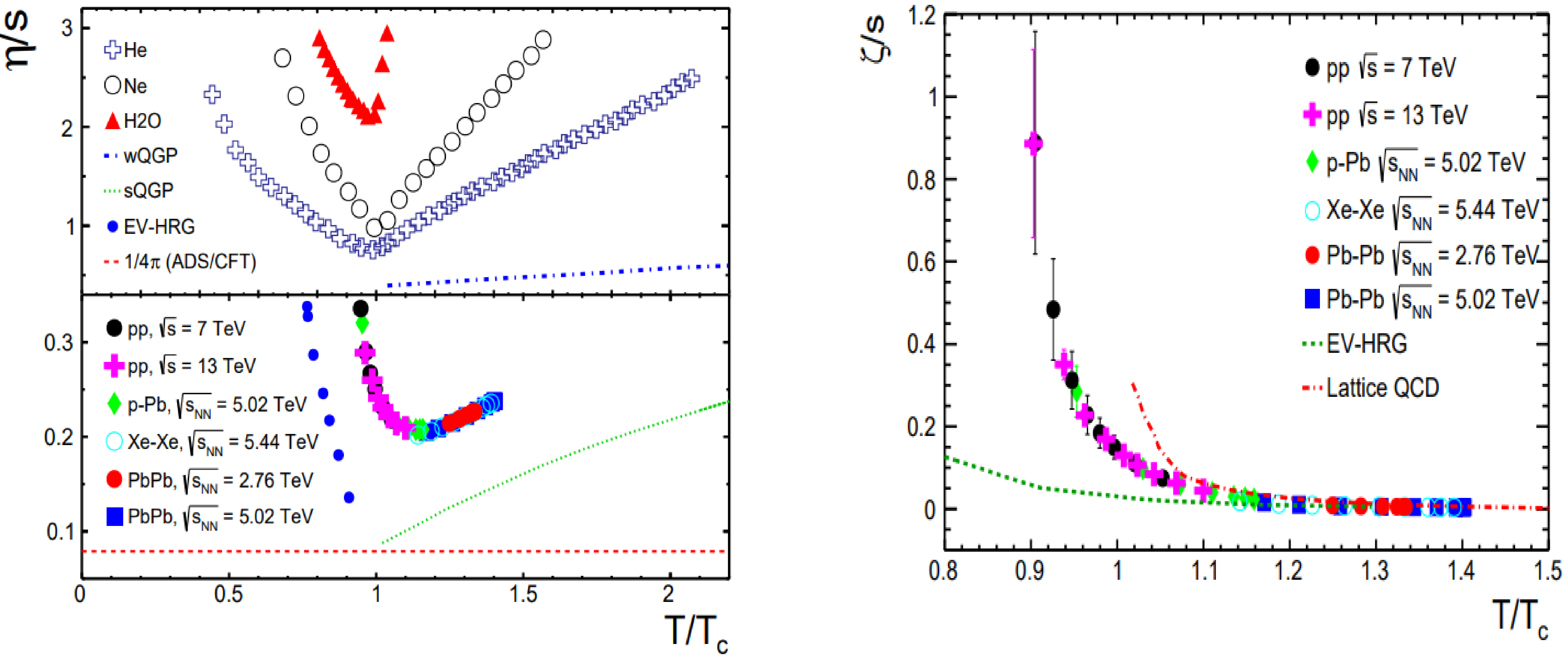
$$\mu_n = nF(\xi)\mu_1; \qquad \langle p_t^2 \rangle_n = \langle p_t^2 \rangle_1 / F(\xi).$$

$$F(\xi) = \sqrt{\frac{1 - e^{-\xi}}{\xi}}.$$

$$\xi = \frac{N_s S_1}{S_N} \qquad T(\xi) = \sqrt{\frac{\langle p_t^2 \rangle_1}{2F(\xi)}}.$$

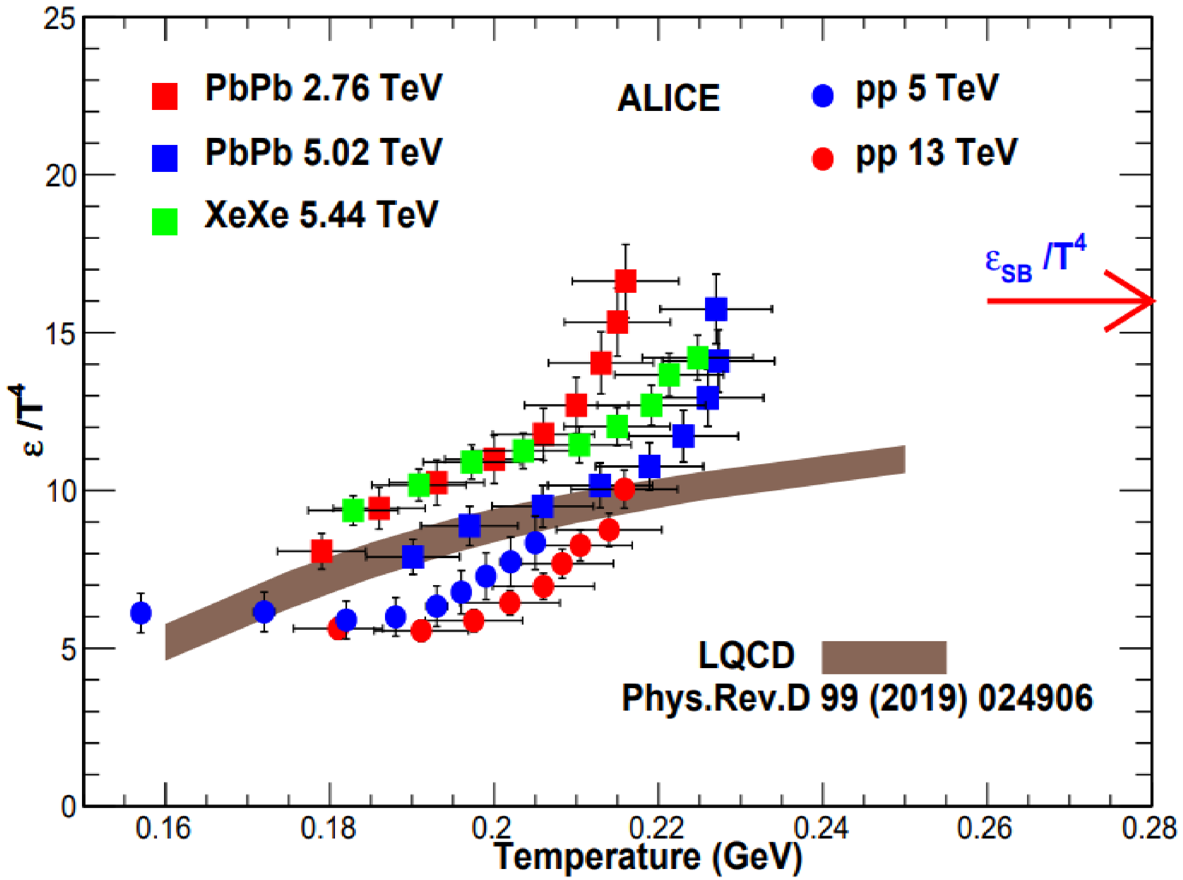
$$\frac{\eta}{s} = \frac{TL}{5(1 - e^{-\xi})}$$

$$\frac{\eta}{s} \approx \frac{3}{2}\frac{T^3}{\hat{q}}$$



η/s
He
Ne
H2O
wQGP
sQGP
EV-HRG
1/4π (ADS/CFT)
pp, √s = 7 TeV
pp, √s = 13 TeV
p-Pb, √sNN = 5.02 TeV
Xe-Xe, √sNN = 5.44 TeV
PbPb, √sNN = 2.76 TeV
PbPb, √sNN = 5.02 TeV
T/Tc
ζ/s
pp √s = 7 TeV
pp √s = 13 TeV
p-Pb √sNN = 5.02 TeV
Xe-Xe √sNN = 5.44 TeV
Pb-Pb √sNN = 2.76 TeV
Pb-Pb √sNN = 5.02 TeV
EV-HRG
Lattice QCD
T/Tc

$$\varepsilon = \frac{3}{2}\frac{\frac{dN_c}{dy}\langle m_t\rangle}{S_n\tau_{pro}}$$



In addition to the confinement-deconfinent temperatura at T=Tc around 160 Mev (not shown) appears a second change around T=210-220 Mev, see centrality experimental data on dN/dy. The sQGP liquid starts the transition to a gas free at that temperature?

Entanglement between soft and hard partons Origin of fast thermalizations?

$$|\Psi\rangle = \sum_n \alpha_n |\Psi_n^H\rangle \otimes |\Psi_n^S\rangle,$$

$$\rho_H = \mathrm{Tr}_S\, \rho = \sum_n \langle\Psi_n^S|\Psi\rangle\langle\Psi|\Psi_n^S\rangle = \sum_n |\alpha_n|^2 |\Psi_n^H\rangle\langle\Psi_n^H|$$

(

$$S = -\,\mathrm{Tr}(\rho_H \log \rho_H) = -\sum_n p_n \log p_n,$$

$$\frac{1}{N_{ev}}\frac{1}{2\pi p_t}\frac{d^2N_{ev}}{d\eta dp_t} = A_{th}\exp\left(-\frac{m_t}{T_{\mathrm{th}}}\right) \quad A_h \frac{1}{\left(1+\frac{m_t^2}{nT_{\mathrm{h}}^2}\right)^n},$$

$$\frac{dN}{dp_T^2} \sim \int_0^\infty \exp\left(-\frac{\pi p_T^2}{x^2}\right) N_q(x,\sigma)dx.$$

$$N_q(x,\sigma) = \frac{\sqrt{q-1}\,\Gamma\left(\frac{1}{q-1}\right)}{\sigma\sqrt{2\pi}\,\Gamma\left(\frac{q-3}{2(1-q)}\right)}\left(1+\frac{(q-1)x^2}{2\sigma^2}\right)^{\frac{-1}{q-1}}$$

$$\frac{dN}{dp_T^2} \sim \frac{1}{\sqrt{\pi}}\Gamma\left(\frac{1}{q-1}\right) U\left(\frac{1}{q-1}-\frac{1}{2},\frac{1}{2},\pi p_T^2\frac{q-1}{2\sigma^2}\right).$$

$$\frac{dN}{dp_T^2} \sim \exp\left(-\frac{\sqrt{2\pi(q-1)}\,\Gamma\left(\frac{1}{q-1}\right) p_T}{\Gamma\left(\frac{1}{q-1}-\frac{1}{2}\right)\sigma}\right).$$

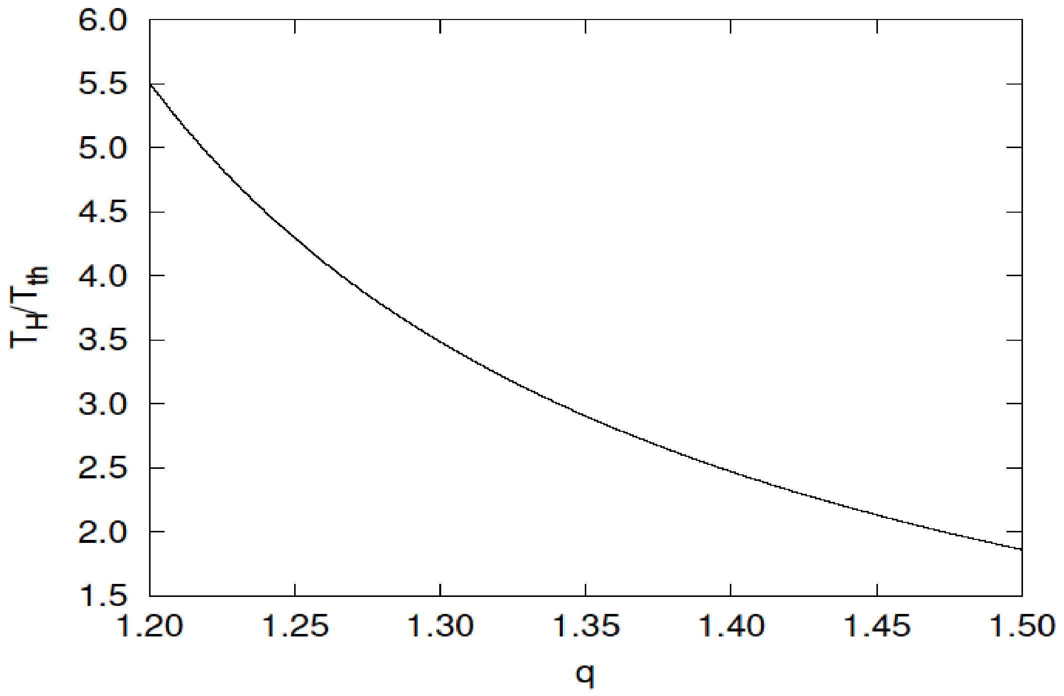
$$\frac{dN}{dp_T^2} \sim \frac{\Gamma\left(\frac{1}{q-1}\right)}{\sqrt{\pi}} \left(\frac{\pi p_T^2 (q-1)}{2\sigma^2}\right)^{\frac{1}{2}-\frac{1}{q-1}}$$

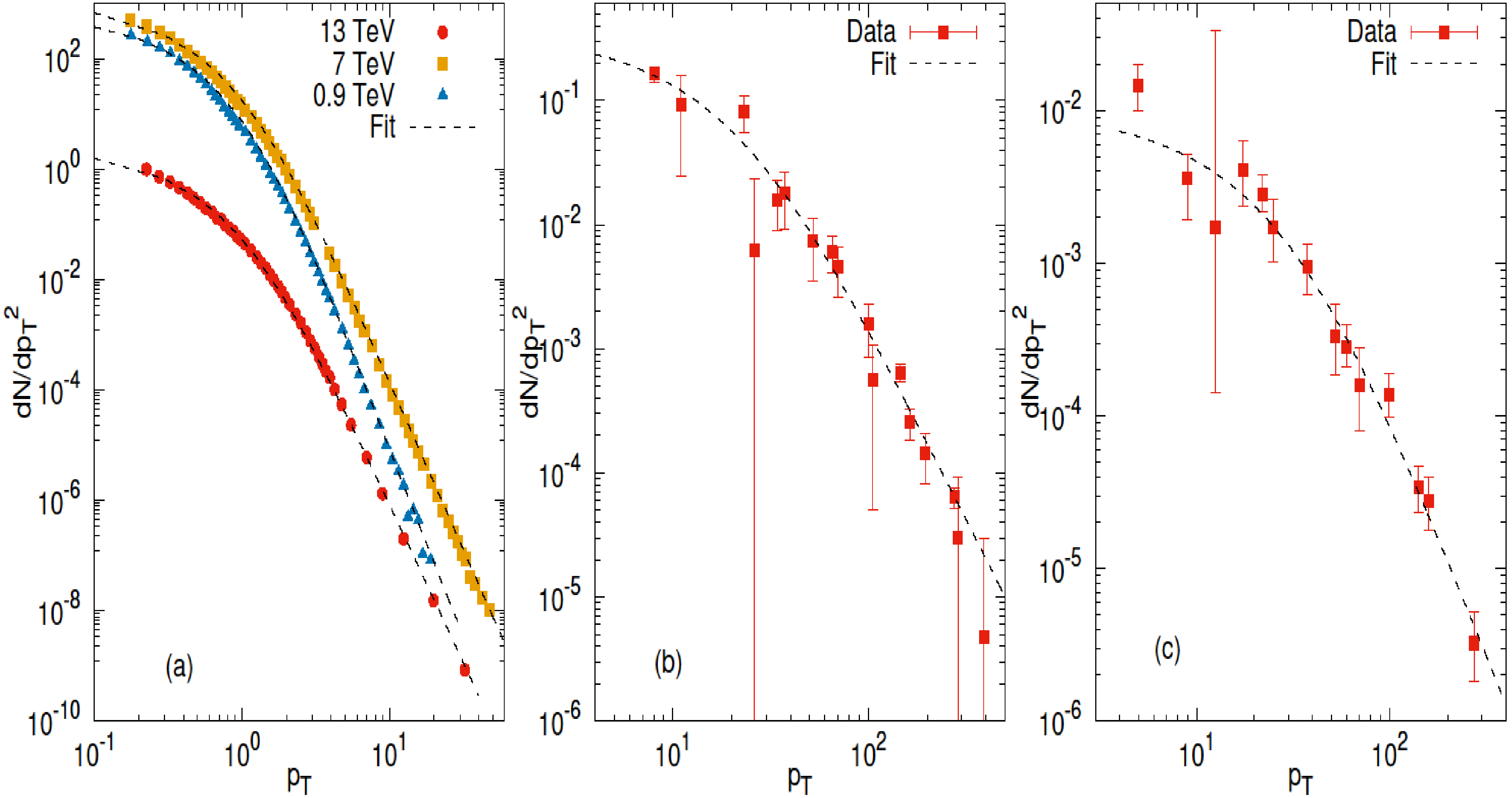
$$\frac{T_H}{T_{th}} = 2\left(\frac{\sqrt{\pi}}{\Gamma\left(\frac{1}{q-1}\right)}\right)^{\frac{q-1}{q-3}} \frac{\Gamma\left(\frac{1}{q-1}\right)}{\Gamma\left(\frac{1}{q-1}-\frac{1}{2}\right)}.$$

q-1 marks the power like behavior at high pt as well as the fluctuations (and the departure from the thermal behavior)

The thermal scale Tth is determined by the hard scale TH and its fluctuations (determined by q-1)

. The thermal behavior can be obtained without final state interactions





13 TeV
7 TeV
0.9 TeV
Fit
Data
Fit
Data
Fit
dN/dp$_T^2$
p$_T$
(a)
(b)
(c)

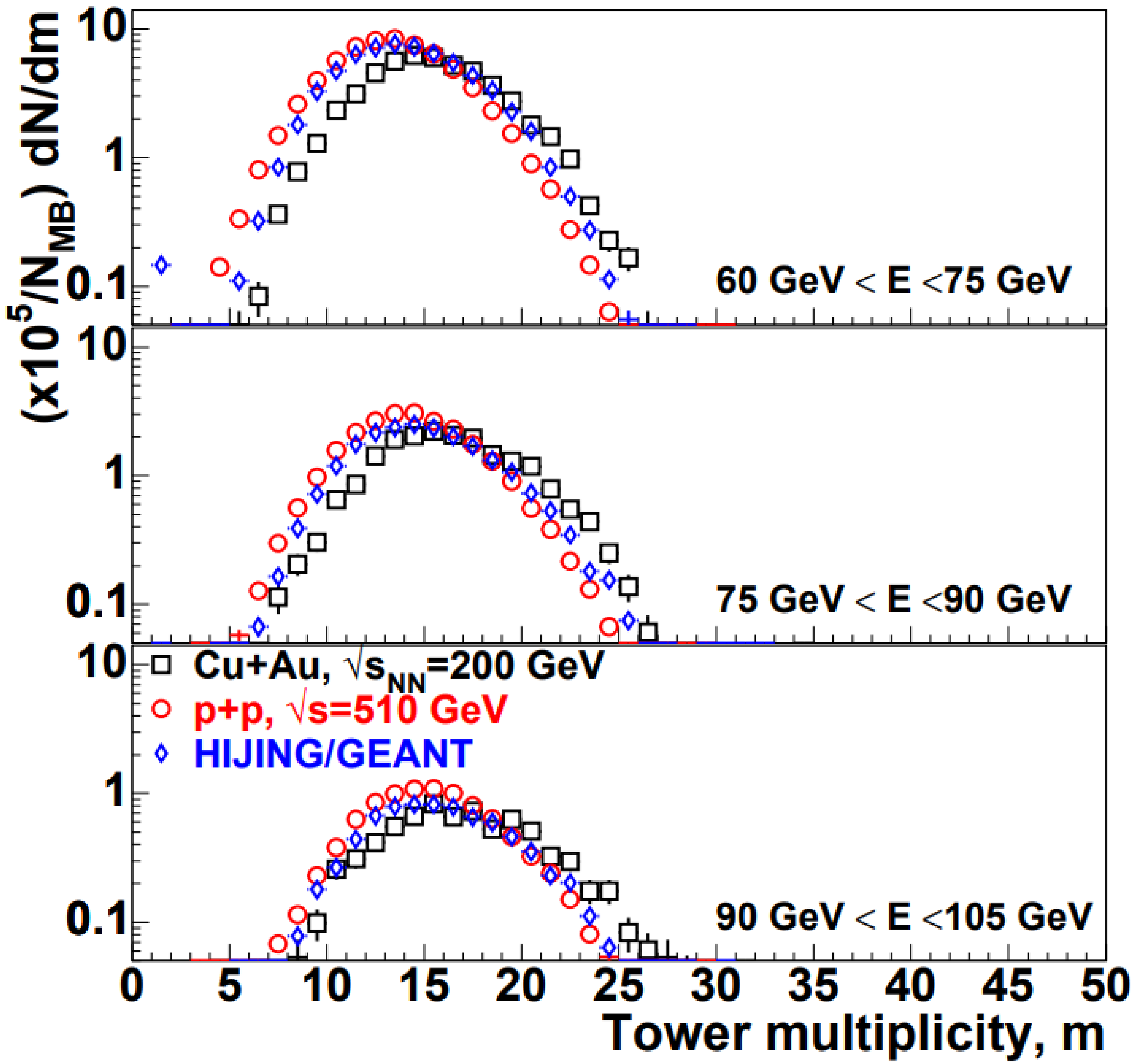
Cumulative effect. (particles with higher energy than the original NN energy)

---The overlapping strings concentrate the individual color field. The energy of the cluster is the sum of the energy of each string. In the case of strings originated from different Nucleon-Nucleon collisions , the energy of the cluster can be larger than the original NN energy and thus also the particles produced from the fragmentation of the cluster.

---(Hijing, string percolation are some models predict such effect. The overlapping of strings work as a QCD accelerator)

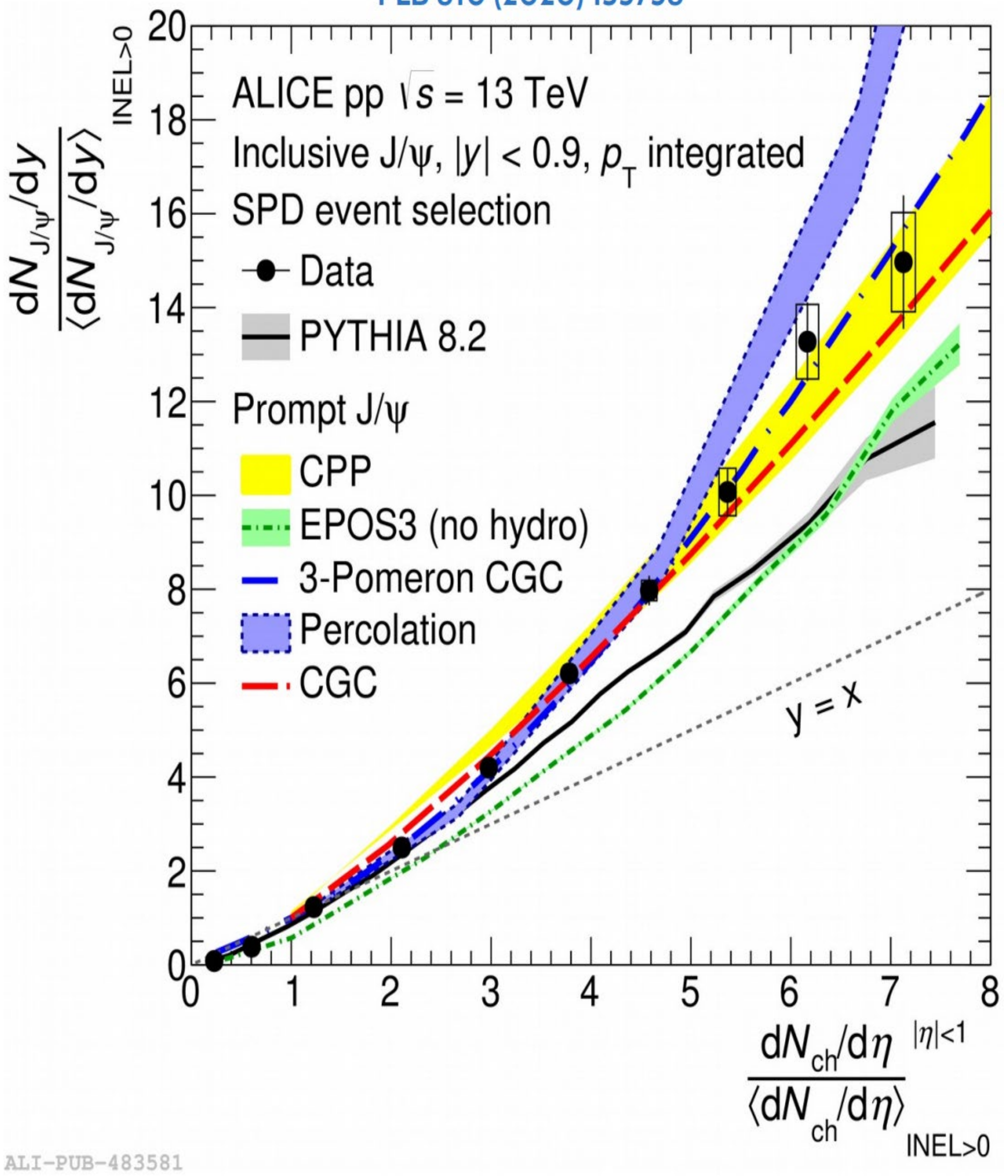
---L.C.Bland et al arXiv: 2110.09432 (nucl-exp) Phys Rev C106 34902 (2022) found in Cu-Au at 200 Gev forward jets violating Feynman scaling. To recover scaling the NN energy should be larger in a factor 1.5- 2

The tower multiplicity of these jets are similar to the jets produced in pp at much higher energy


(x10^5/N_MB) dN/dm
60 GeV < E <75 GeV
75 GeV < E <90 GeV
90 GeV < E <105 GeV
Cu+Au, √s_NN=200 GeV
p+p, √s=510 GeV
HIJING/GEANT
Tower multiplicity, m
0.1
1
10
0
5
10
15
20
25
30
35
40
45
50

Quarkonium dependence on multiplicity

PLB 810 (2020) 135758



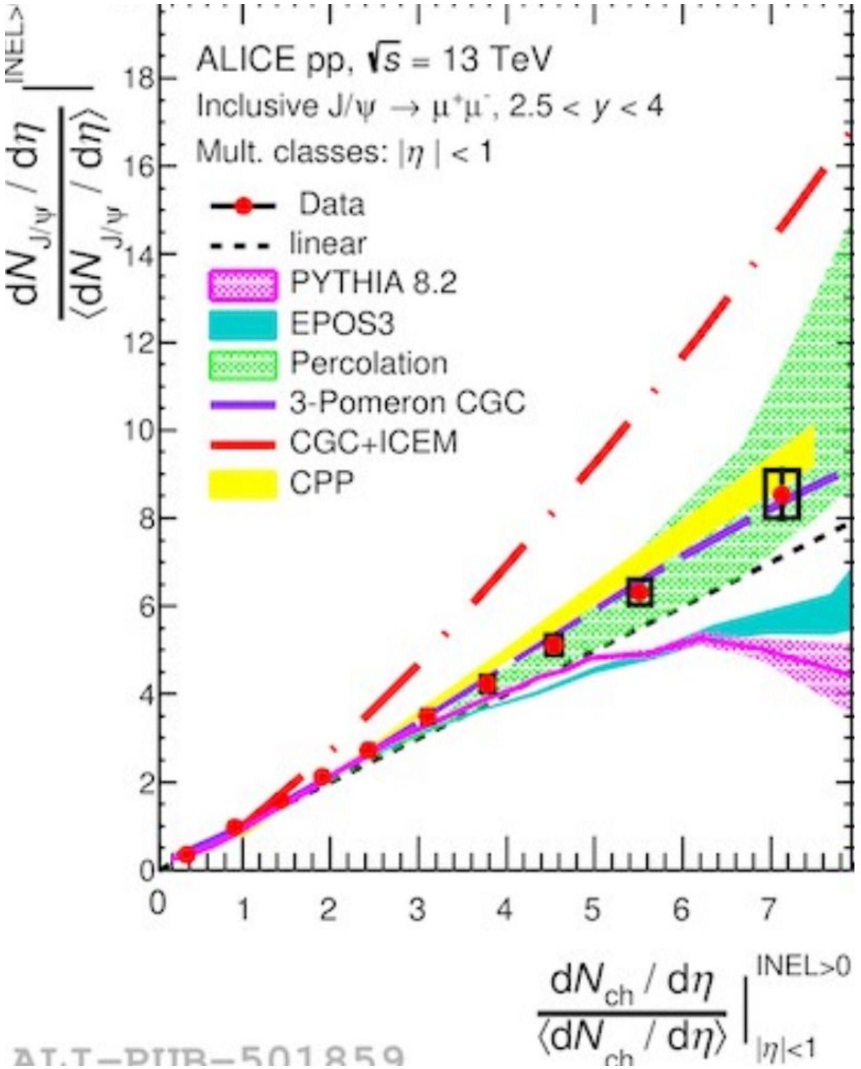
Self normalized J/ψ yields at midrapidity vs multiplicity at midrapidity.

Faster than linear increase of J/ψ yields vs multiplicity .

The trend is described by models include either initial and/or final state effects.

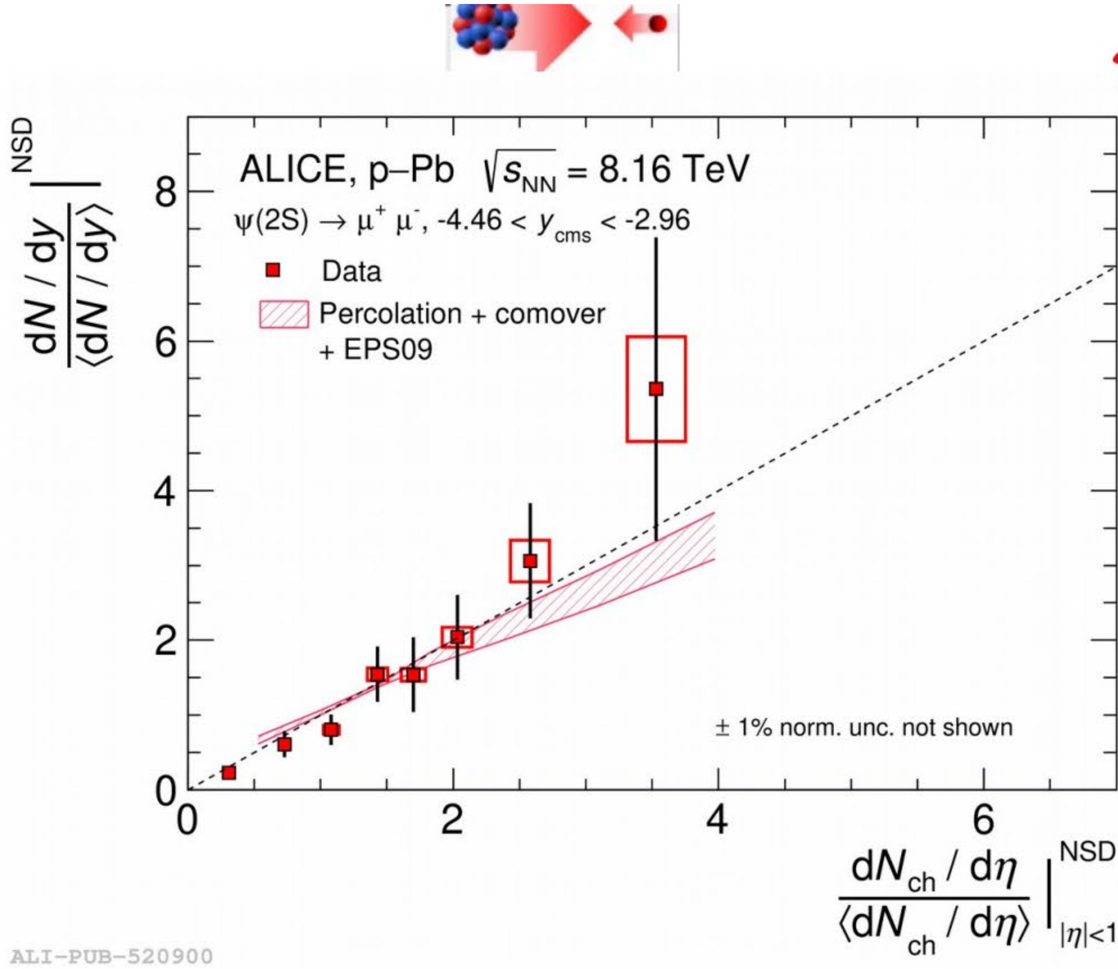
EPOS 3 and PYTHIA 8.2 event generators do not reproduce the behavior of the data.

Forward production dependence on multiplicity

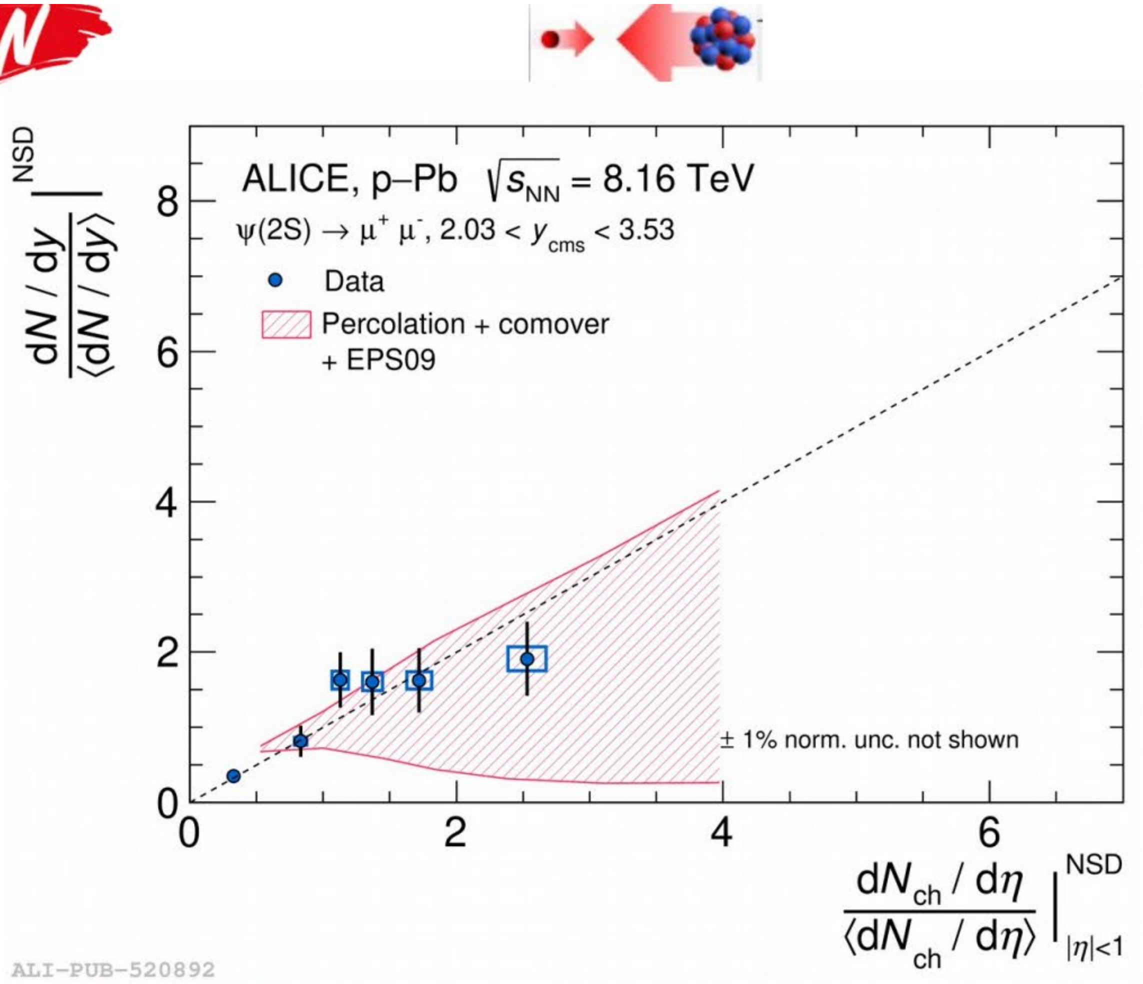


J/ψ yields at forward rapidity vs multiplicity measured at midrapidity:

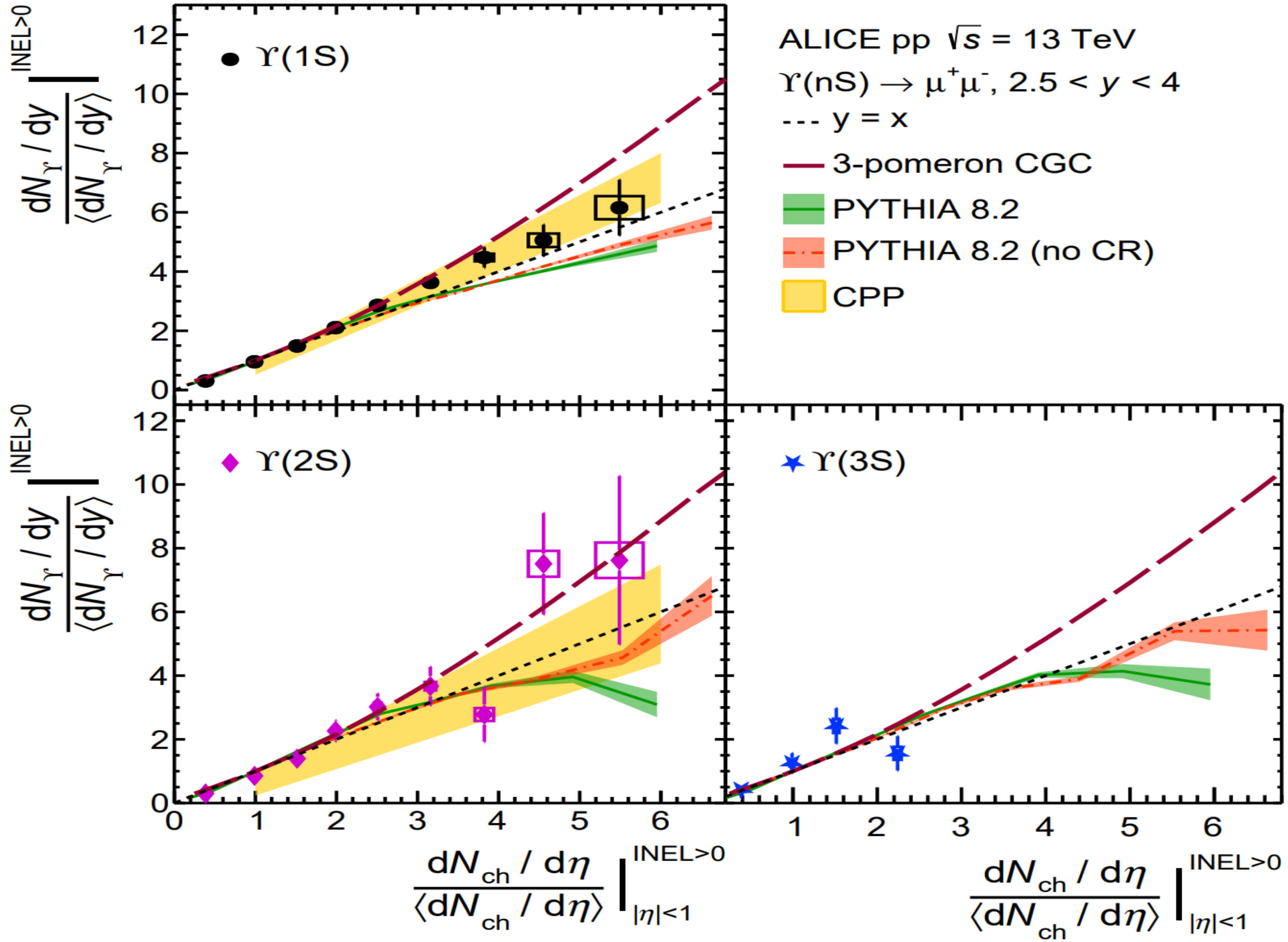
- Compatible with a linear increase within uncertainty.
- Models includes initial and/or final state effects reproduce the measurements
- EPOS 3 and PYTHIA 8.2 event generators do not reproduce the behavior of the data.



NEW



- The ψ(2S) yield increases with increasing $dN_{ch}/d\eta$ in p–Pb collisions.
- Percolation+ comovers+EPS09 calculation predicts the trend of the measurements
  - Large uncertainty at forward rapidity due to EPS09 nPDF uncertainty.


ALICE pp √s = 13 TeV
ϒ(nS) → μ⁺μ⁻, 2.5 < y < 4
y = x
3-pomeron CGC
PYTHIA 8.2
PYTHIA 8.2 (no CR)
CPP
ϒ(1S)
ϒ(2S)
ϒ(3S)
dNϒ / dy / ⟨dNϒ / dy⟩ |INEL>0
dNch / dη / ⟨dNch / dη⟩ |INEL>0 |η|<1

Conclusions

-- Collective effects seen in small systems. How are made such effects? Initial state interactions or final state interactions or both?

-- How do interact color field configurations (strings)? Is there repulsión between strings?

-- Attention to the trend of the very central multiplicity data implying a fast increasing of the energy density as a function of temperatura. Change from strong interacting QGP to a free QGP gas at T 210 Mev?

-- Fast thermalization can take place due to parton entanglement. The hard scale plus its fluctuations determines the thermal spectrum

-- The string interactions work as a QCD Accelerator in heavy ion collisions. A large cumulative effect seen at RHIC, need confirmation, Pb-Ar fixed target at LHCb or Au-Au at NICA?

-- Most models describe quarkonium dependence on multiplicity (not EPOS 3 and Pythia 8.2 with CR and without CR)

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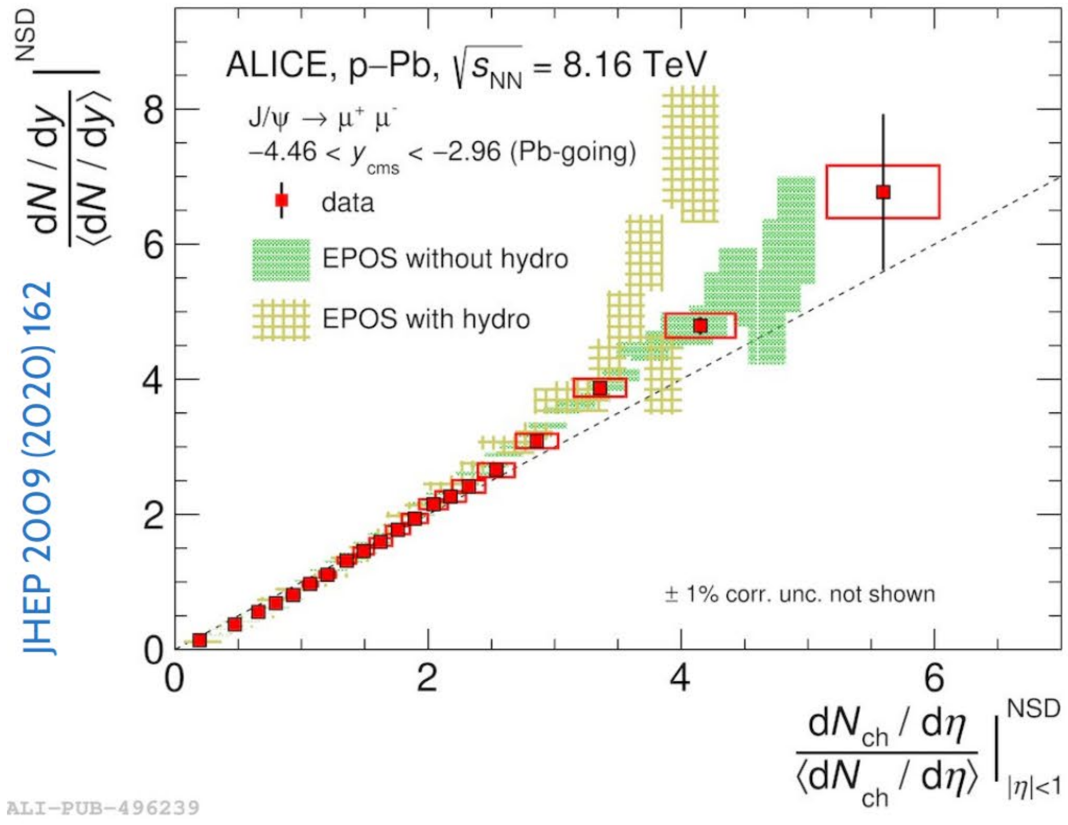

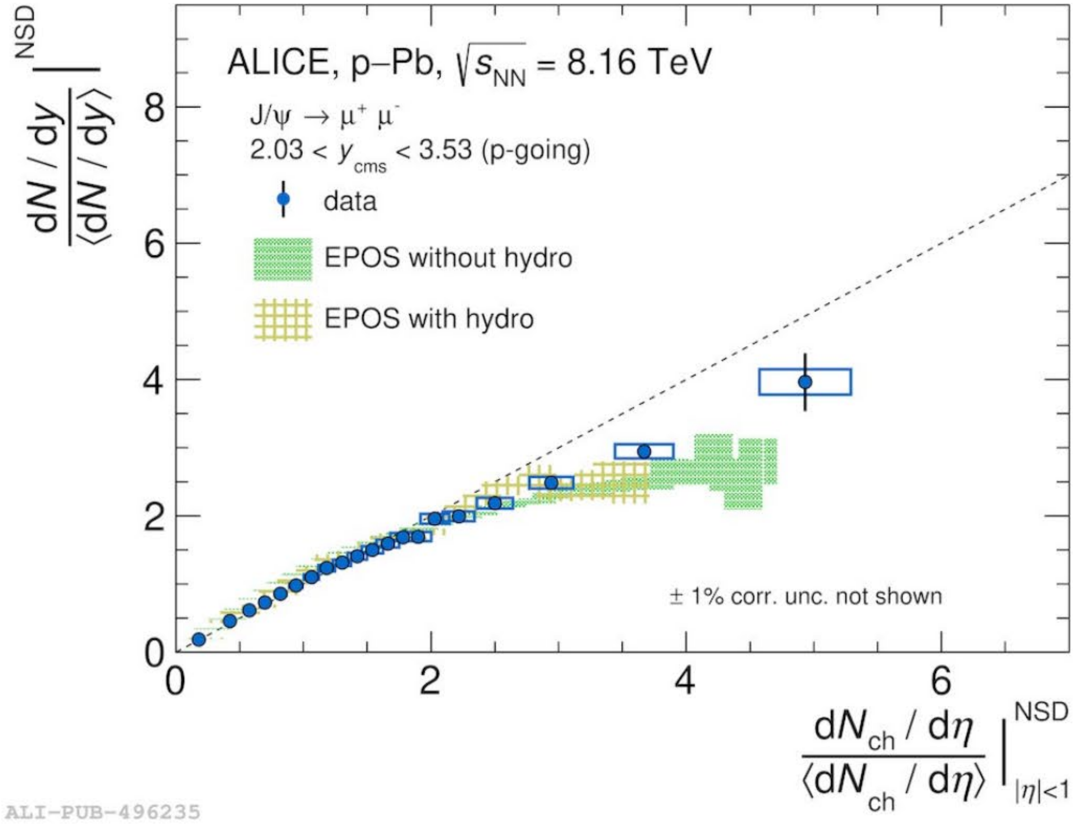

EPOS describes the behavior of J/ψ vs multiplicity in both rapidity regions.