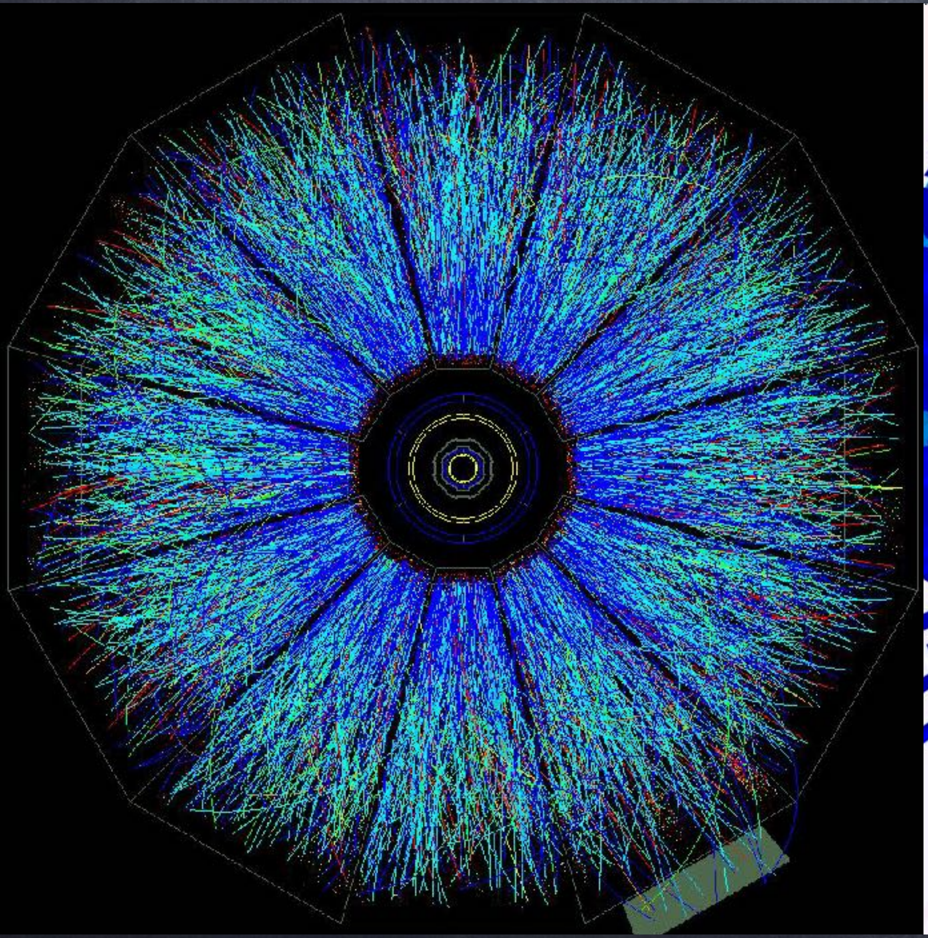
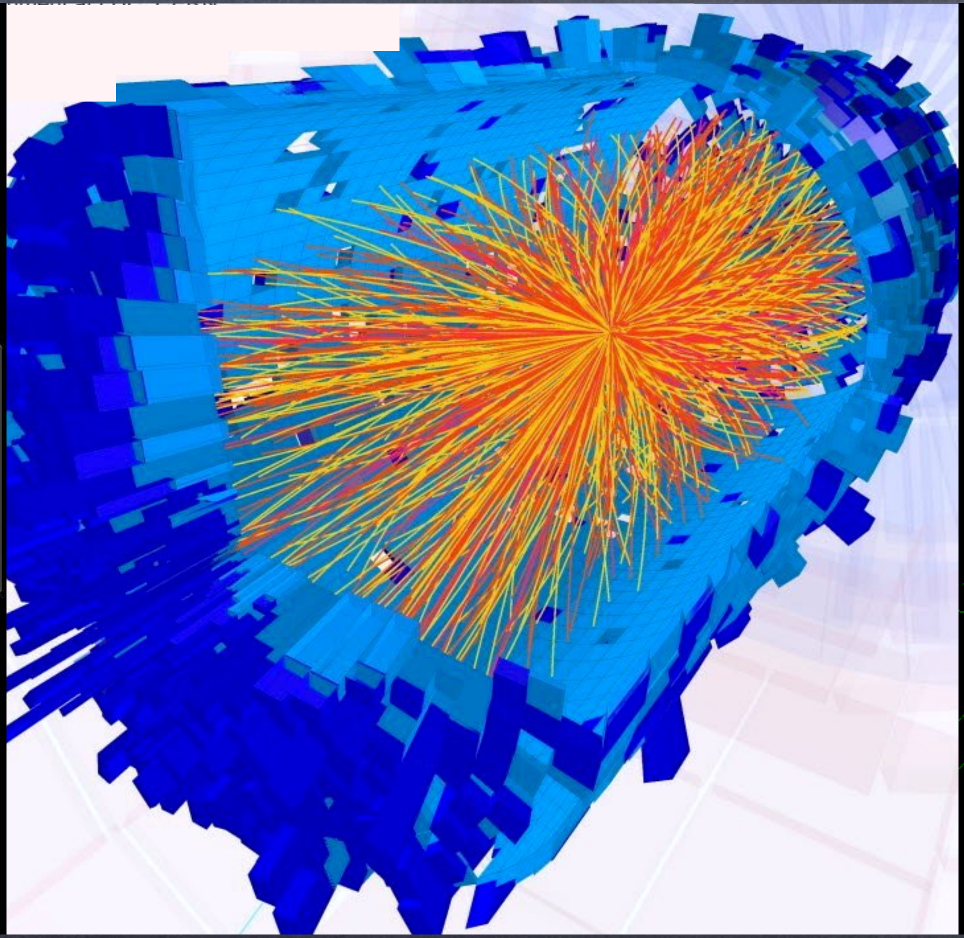
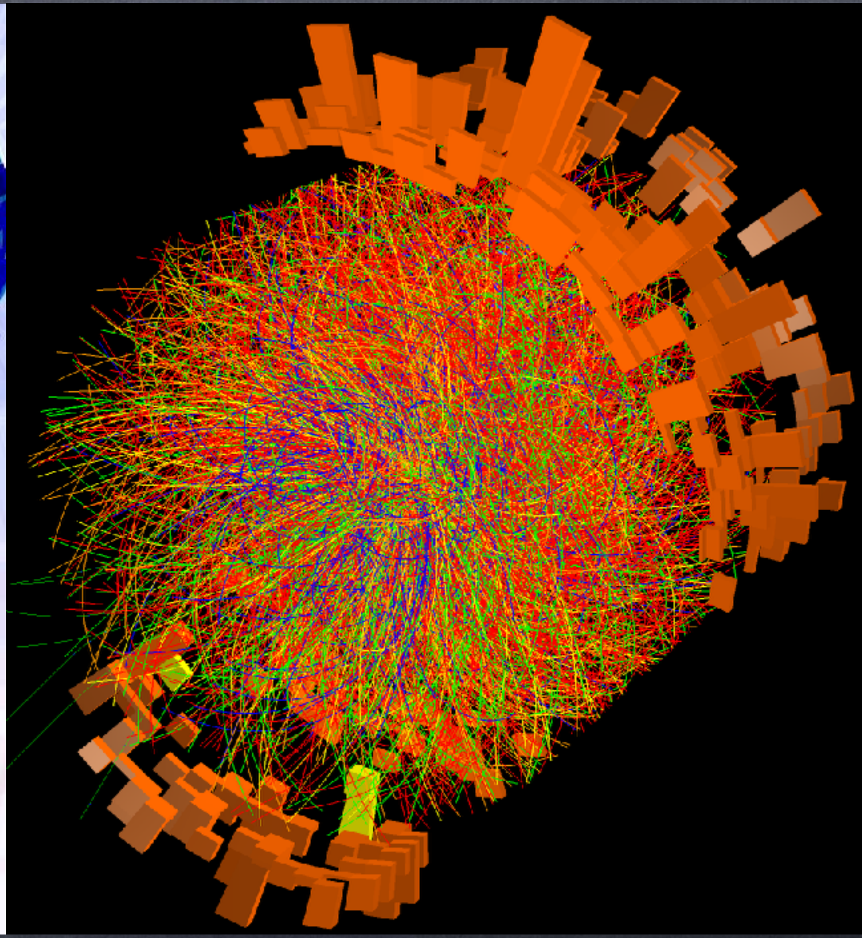
Secondo incontro sulla fisica con ioni pesanti a LHC, 9-10 Ottobre 2017, Torino

Introduction to soft probes: an experimental overview

Chiara Oppedisano, INFN Torino

QCD matter

"Ordinary" matter ➧ color confinement

Cabibbo, Parisi "Exponential hadronic spectrum and quark liberation" PLB 59 (1975) 67

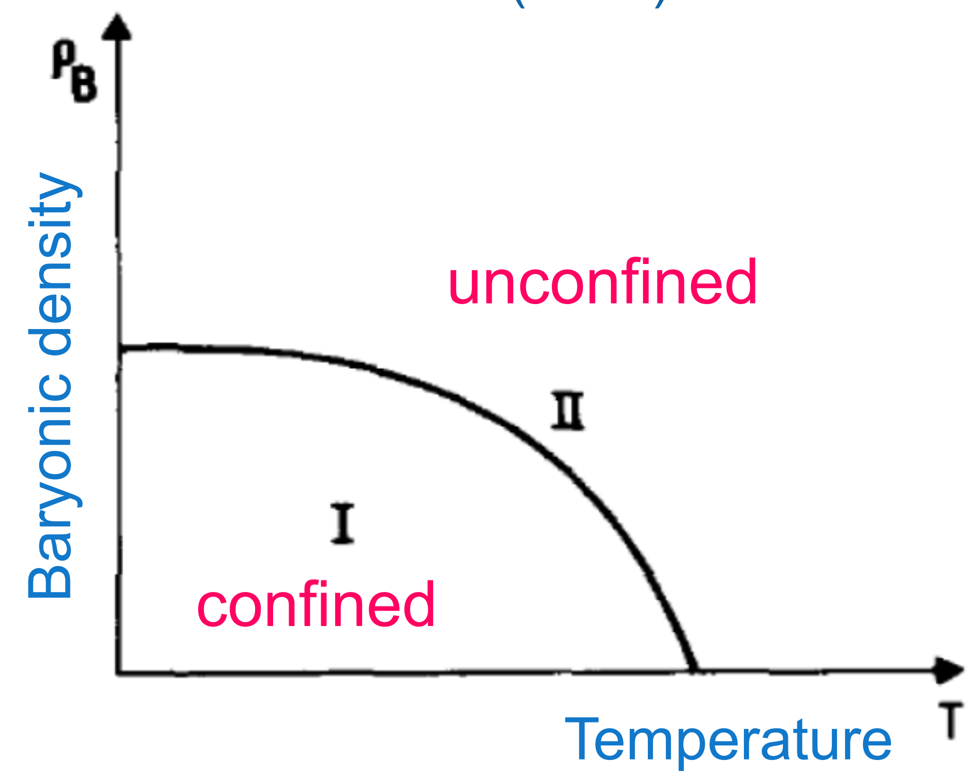


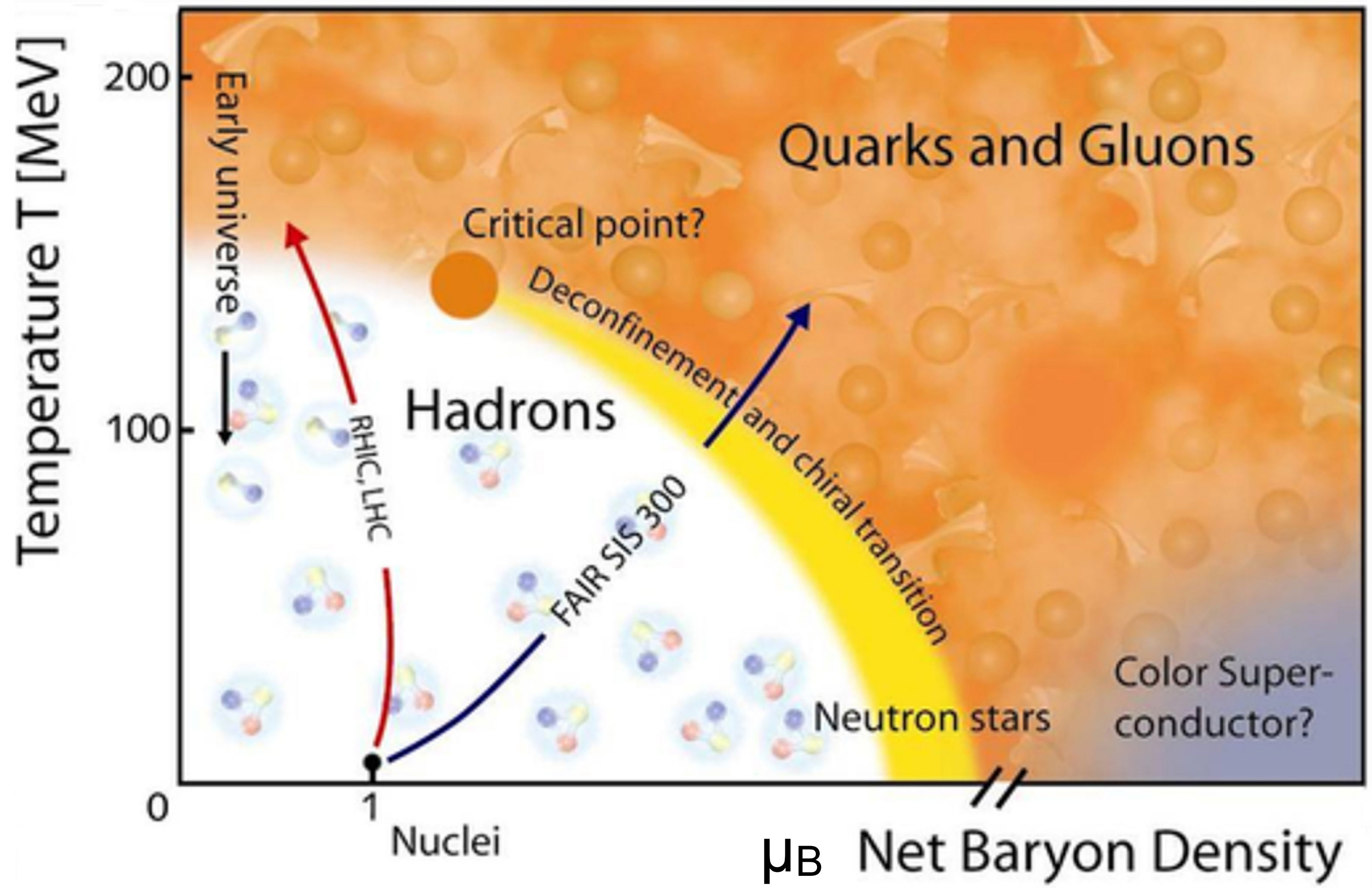
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

QCD matter

"Ordinary" matter ➧ color confinement

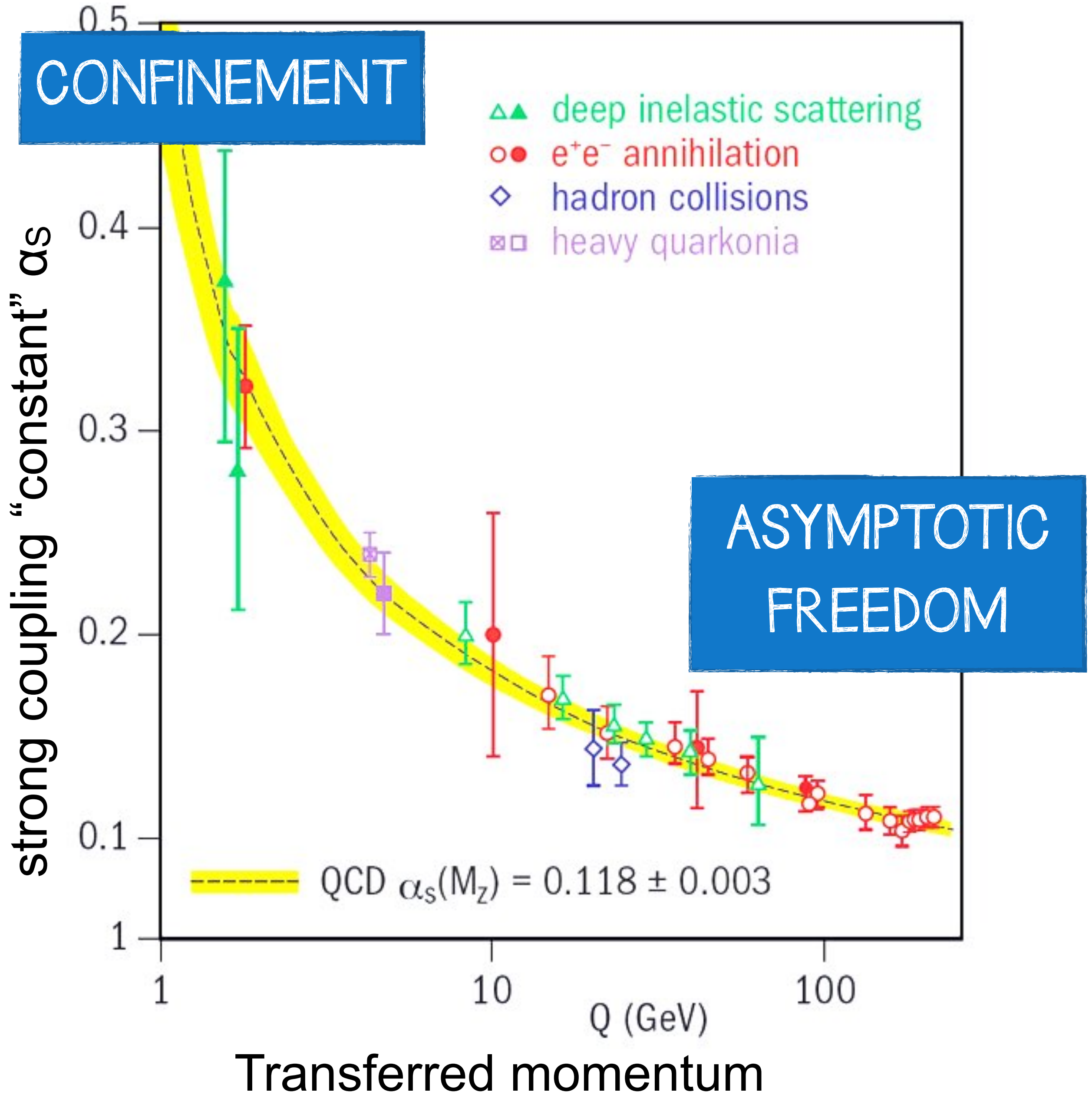
Phase transition from confined quark matter (hadron gas) to Quark-Gluon Plasma (QGP) ➧ DECONFINEMENT

Lattice QCD predictions for transition at μ_B~0:
- ➧ $T_C \sim 155 \pm 9$ MeV
- ➧ $\varepsilon_C \sim 0.2\text{-}0.7$ GeV/fm^3
- ➧ smooth crossover



Ultra-relativistic heavy-ion physics ➧ study QCD at high temperature and density (QCD thermodynamics)

Soft…

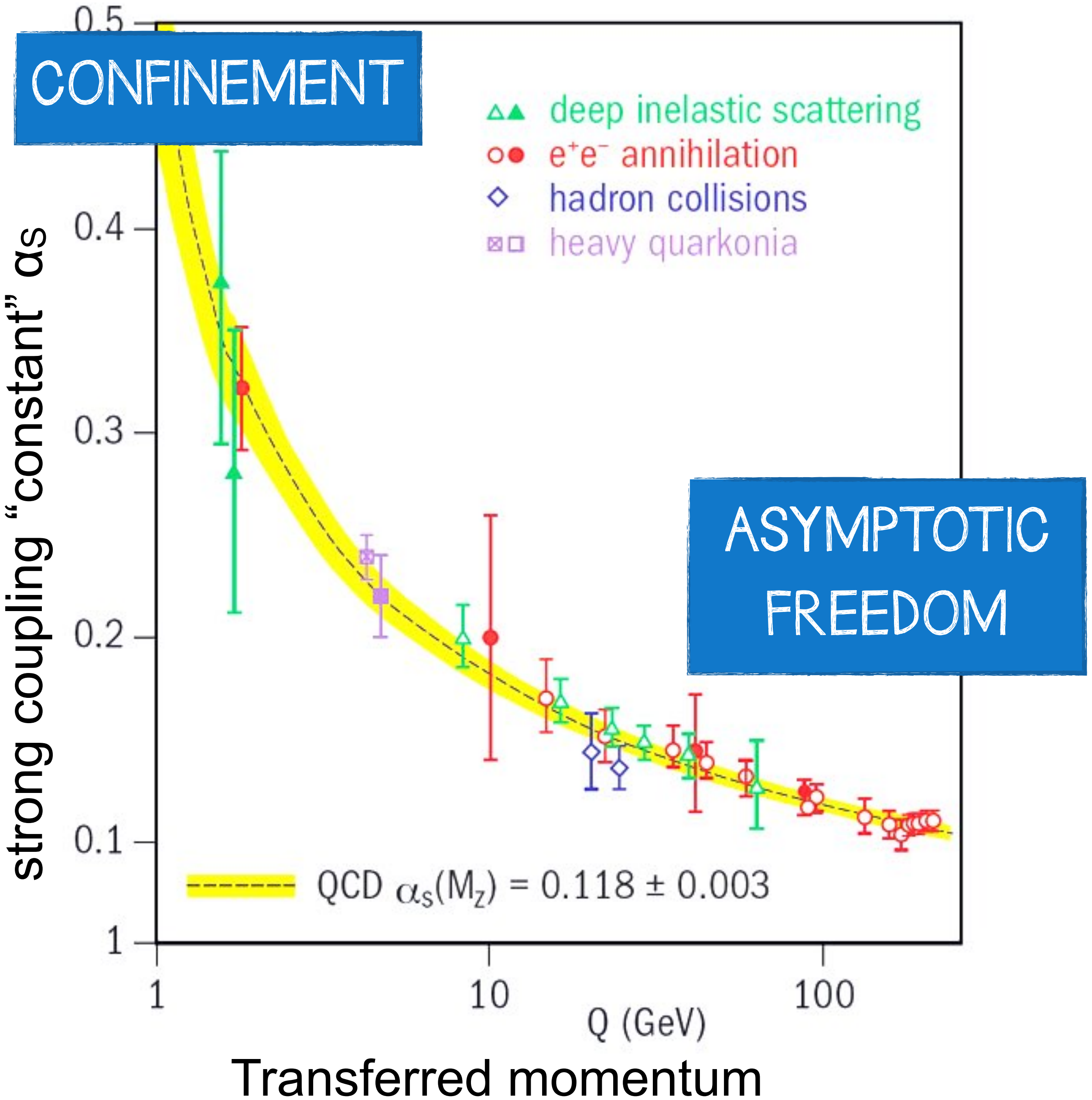


Gluons interact with quarks and with gluons, leading to antiscreening with increasing Q

high Q, low α_S ➧ ASYMPTOTIC FREEDOM
free quarks and gluons at high energies
high Q, small α_S
➧ perturbative QCD applicable

low Q, high α_S ➧ confinement

Soft…



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SOFT = not hard!

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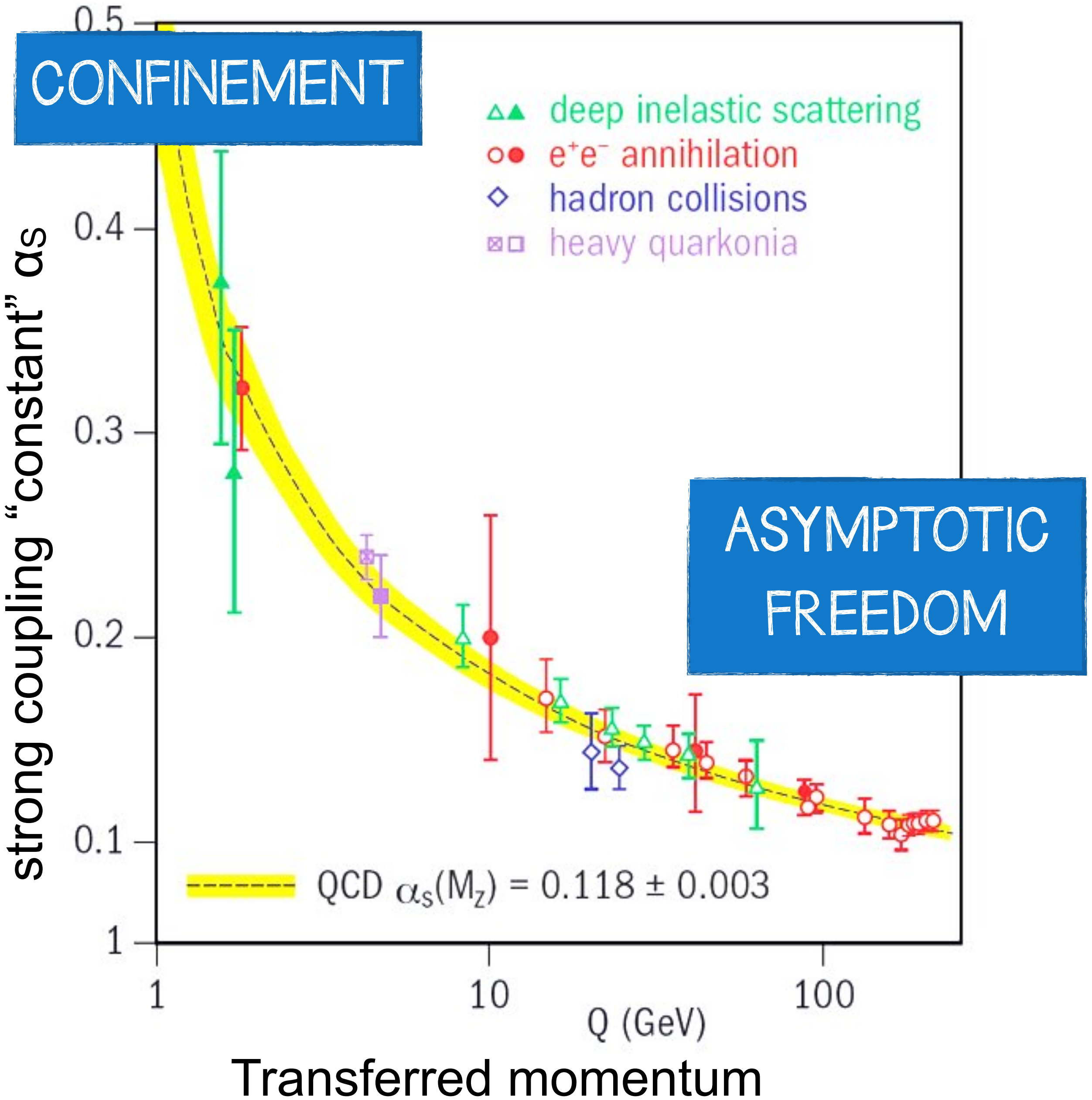

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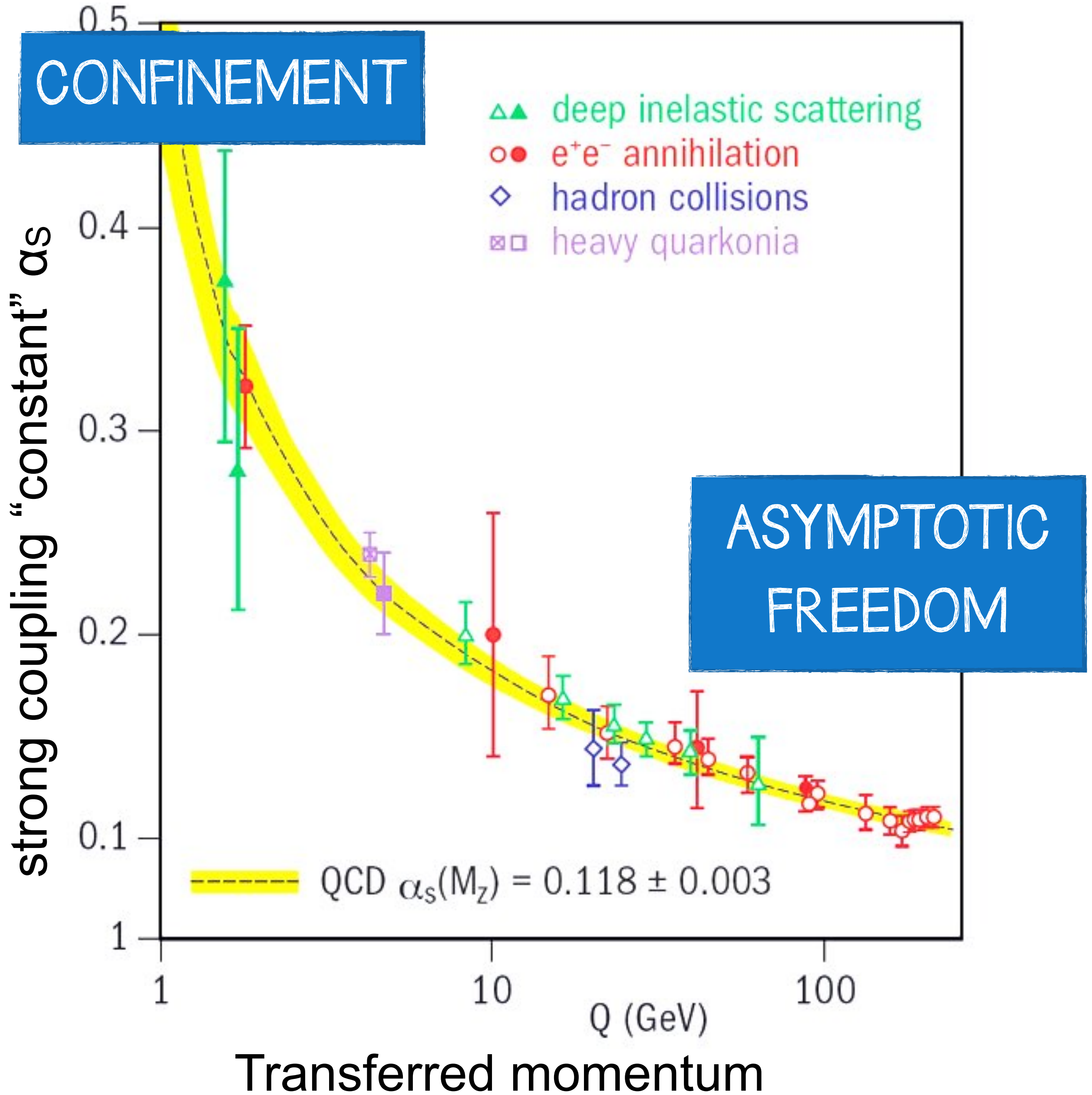
SOFT = not hard! ➧ small exchanged momentum Q ➧ pQCD not applicable
➧ effective theories, transport models, statistical models...

Soft...



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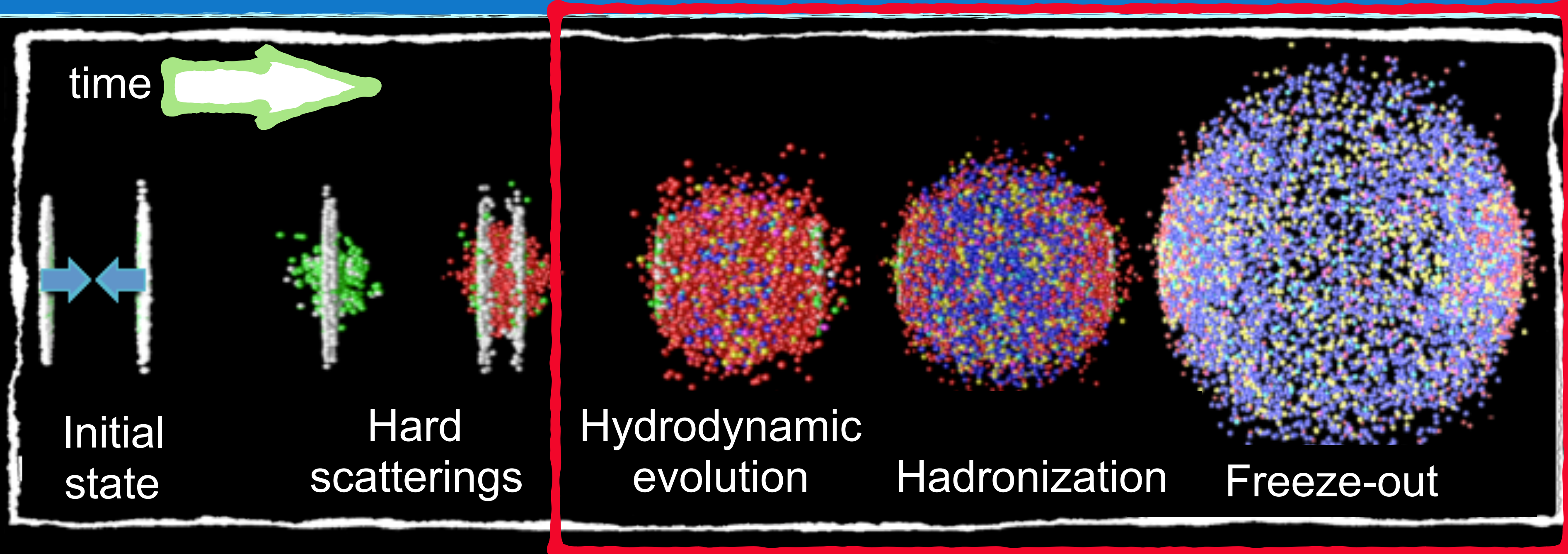
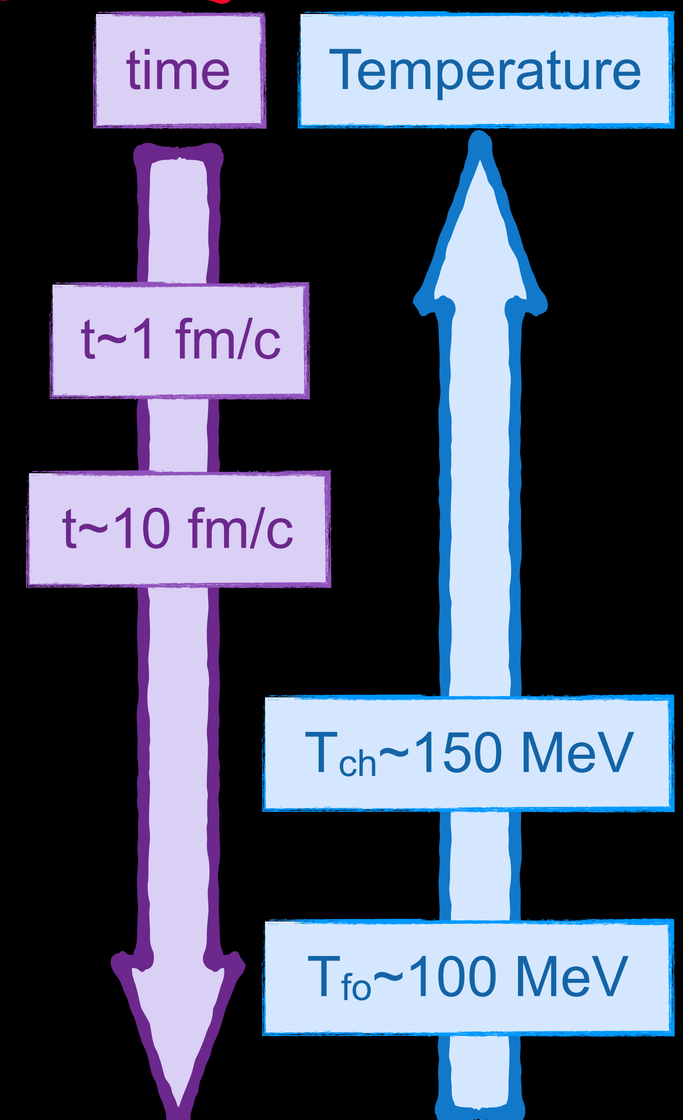
SOFT = harder!

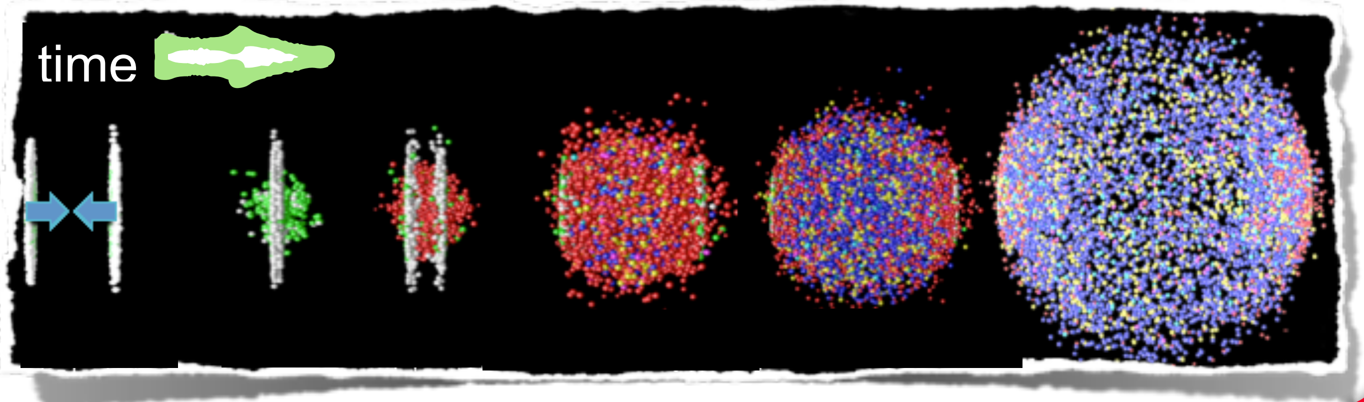
Evolution of the collision

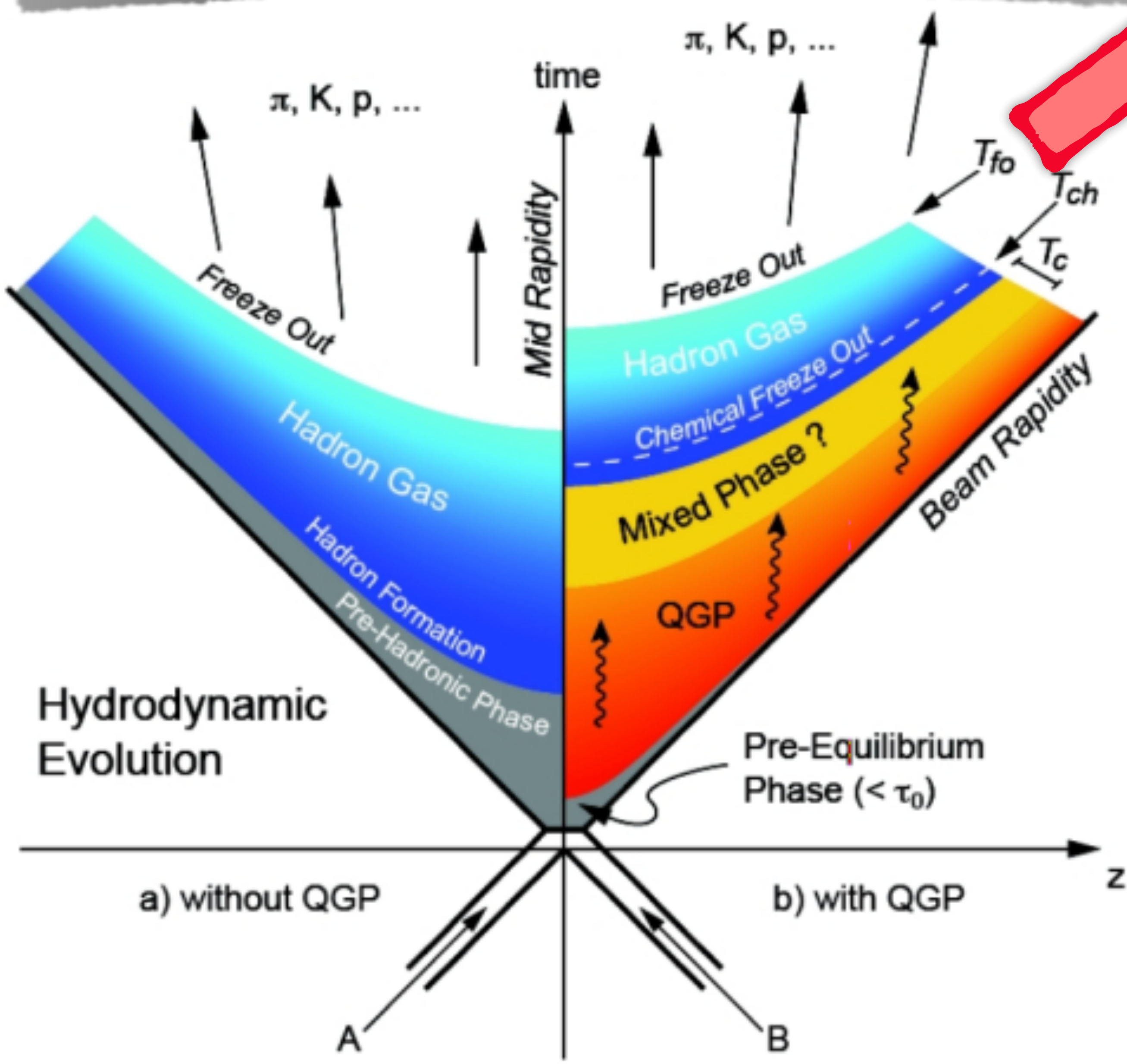


- INITIAL STATE ➧ saturated partonic system
- Local THERMAL EQUILIBRIUM rapidly (τ~1 fm/c) reached
- HYDRODYNAMICS ➧ system expansion and cooling described by almost ideal fluid dynamics
- HADRONIZATION ➧ transition from QGP to hadrons
- CHEMICAL FREEZE-OUT ➧ inelastic interactions cease, particle abundances frozen
- KINETIC FREEZE-OUT ➧ elastic interactions cease, particle dynamics (spectra) frozen



Observables



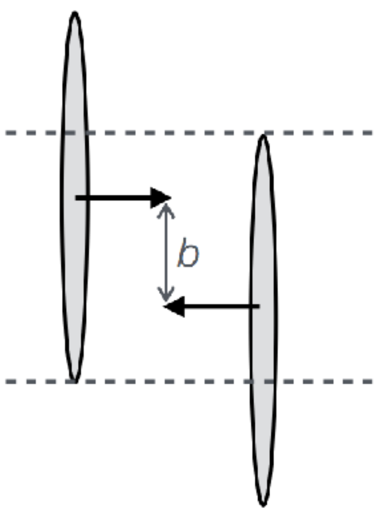


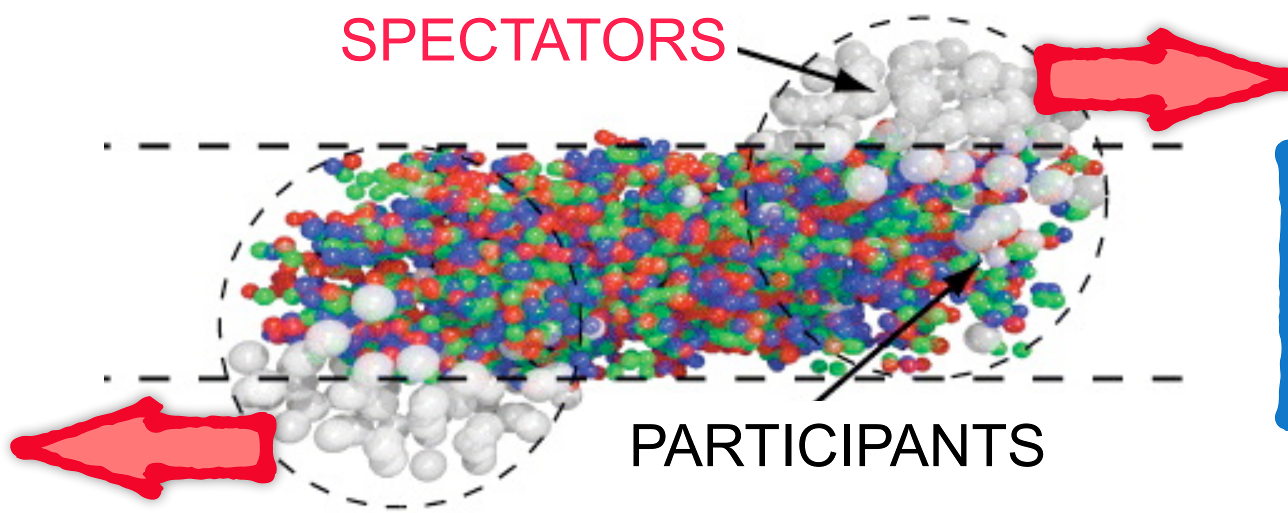
Soft probes produced at late stages with low transverse momentum, p_T, are a tool to characterize the produced medium

OBSERVABLES

- multiplicity
- transverse energy
- HBT femtoscopy
- direct photons
- fluctuations
- thermal photons
- particle yields
- particle spectra
- particle correlations
- flow
- strangeness production
- nuclei production

Global properties

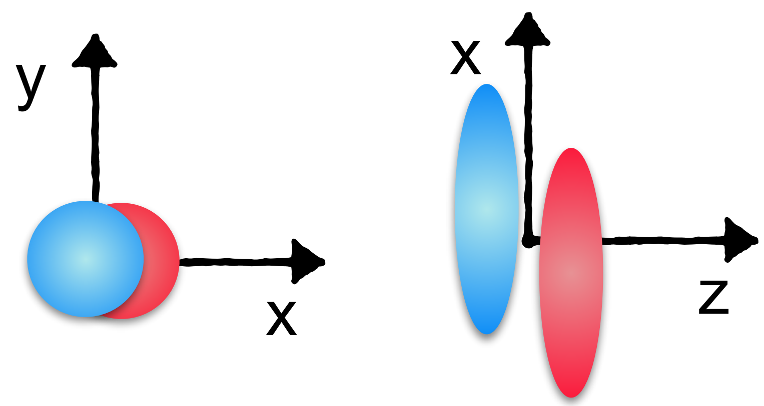


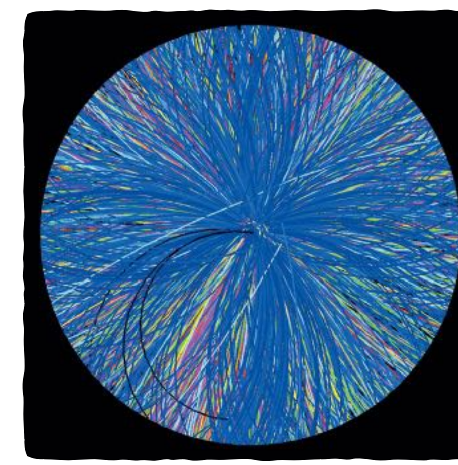


b ➧ impact parameter
N_{part} ➧ # participating nucleons
N_{coll} ➧ # of binary collisions

CENTRAL COLLISIONS

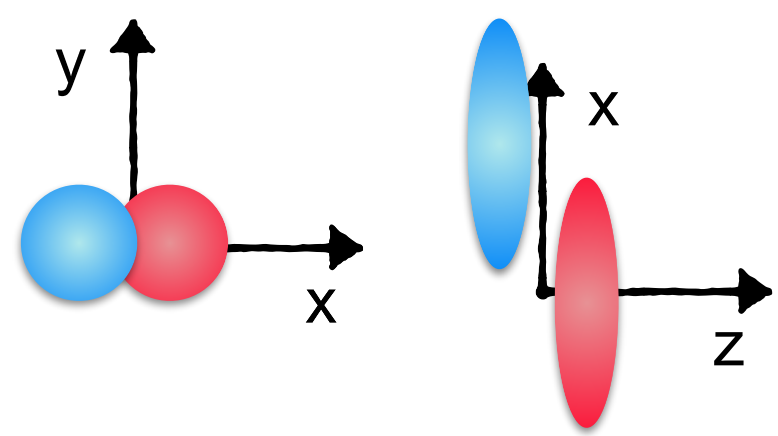
small b, large N_{part} N_{coll}
larger interaction volume
larger produced multiplicity

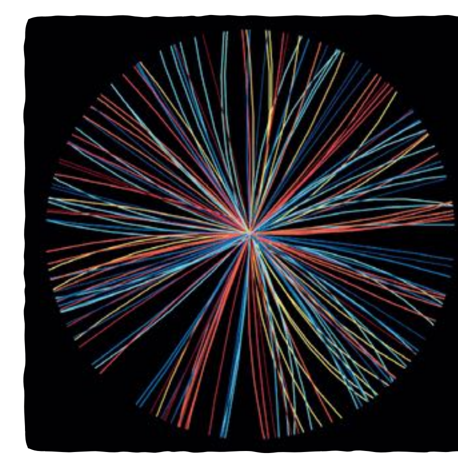




PERIPHERAL COLLISIONS

large b, small N_{part} N_{coll}
smaller interaction volume
smaller produced multiplicity



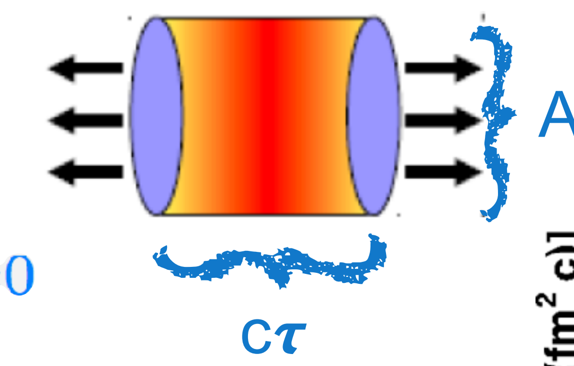


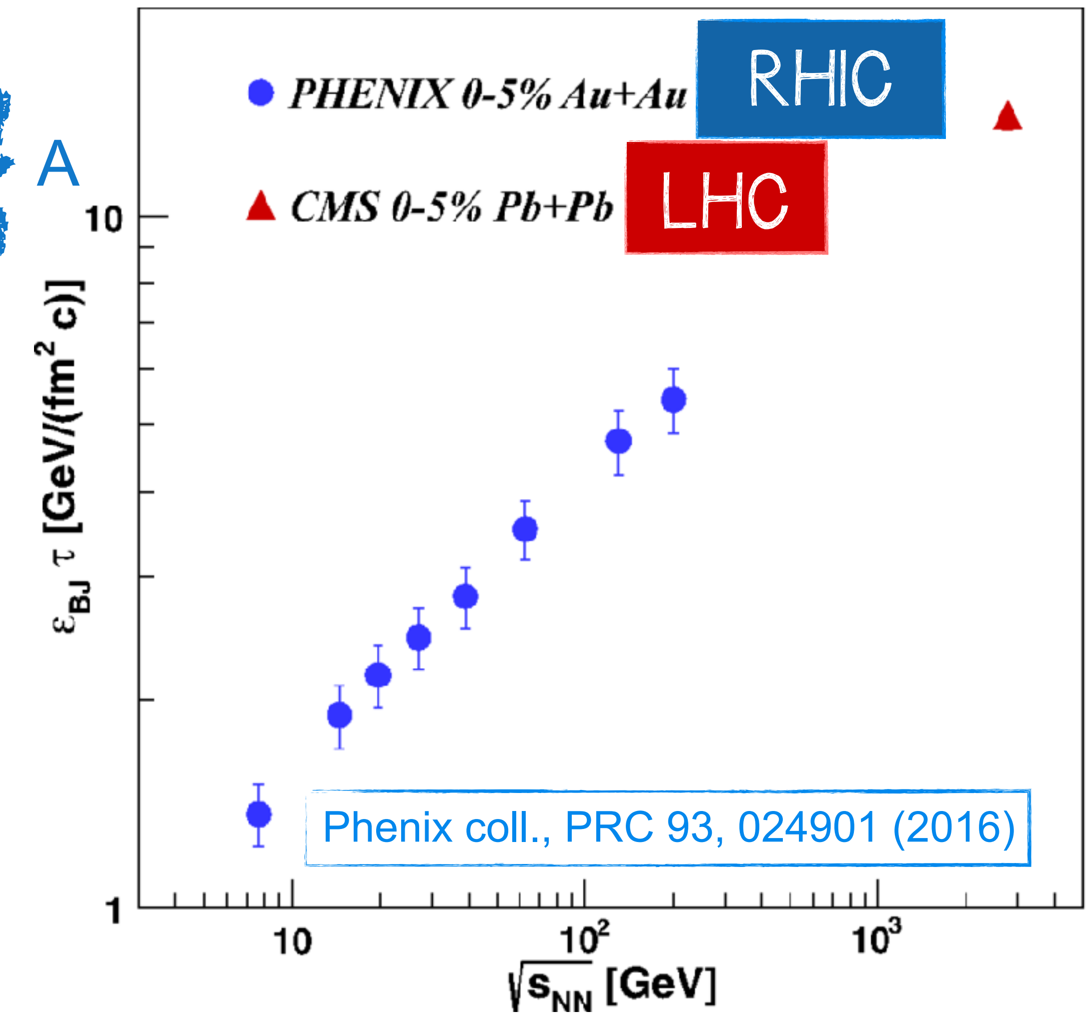
Global properties

Bjorken, PRD 27 (1983) 140

Bjorken estimate of initial energy density in central A-A collisions

$$\epsilon_{Bj} = \frac{\text{Energy}}{\text{Volume}} = \frac{1}{\tau A}\frac{dE_T}{dy}\bigg|_{y=0}$$





$\varepsilon_{LHC} \sim 14$ GeV/fm^3

Global properties

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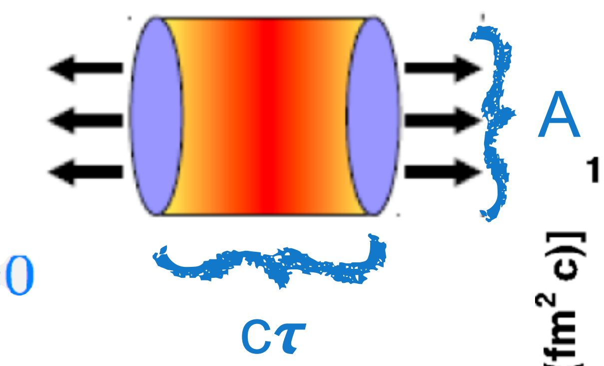
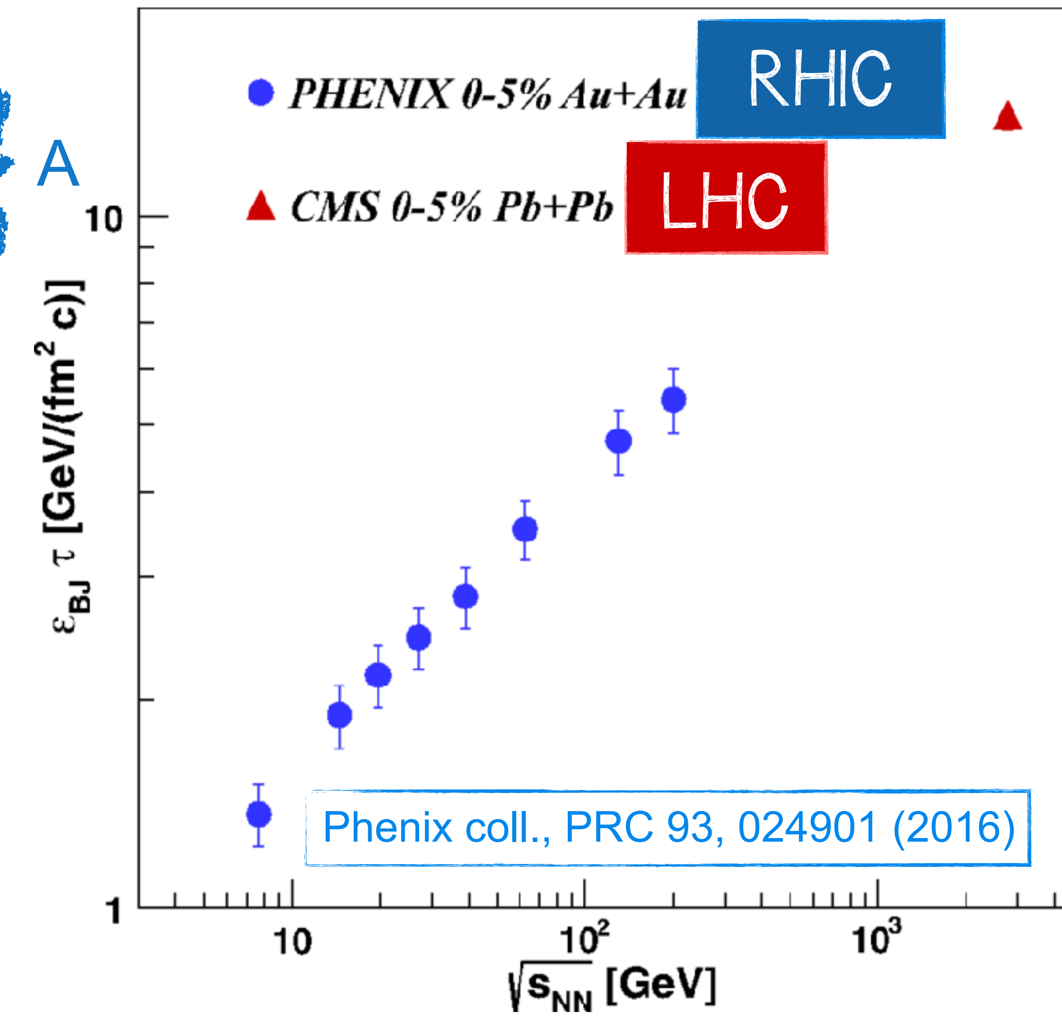
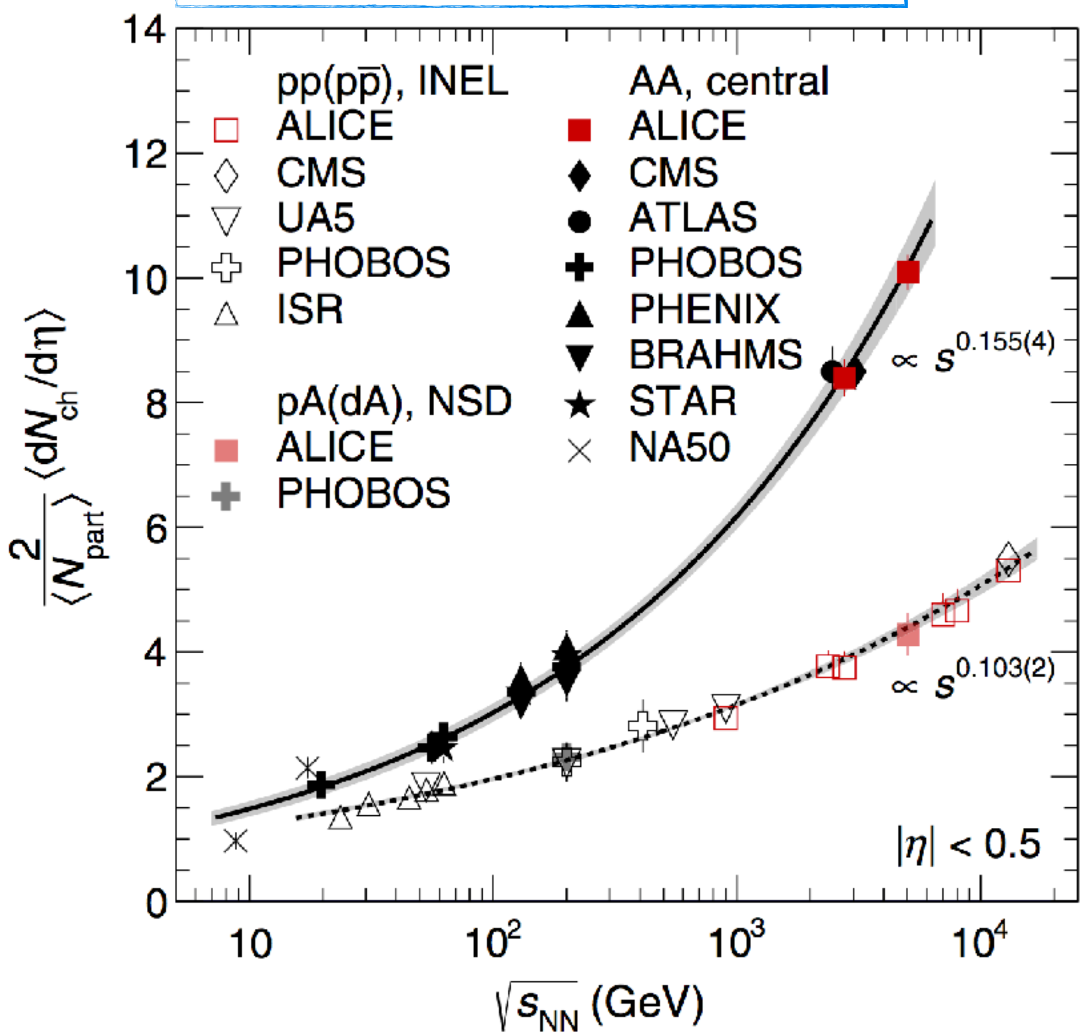


ε_{LHC} ~14 GeV/fm³



Phenix coll., PRC 93, 024901 (2016)

ALICE coll., PRL116, 222302 (2016)



Charged particle multiplicity densities

- scales with s^{α}
- increase in central A-A is stronger than in pp, p-A collisions

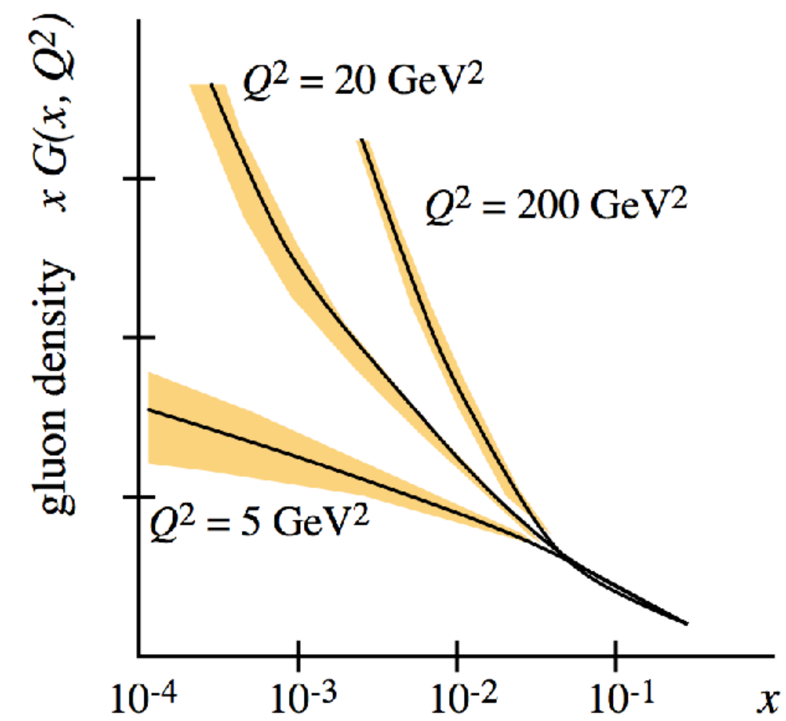
Density of gluons rises rapidly for decreasing x (increasing energy)

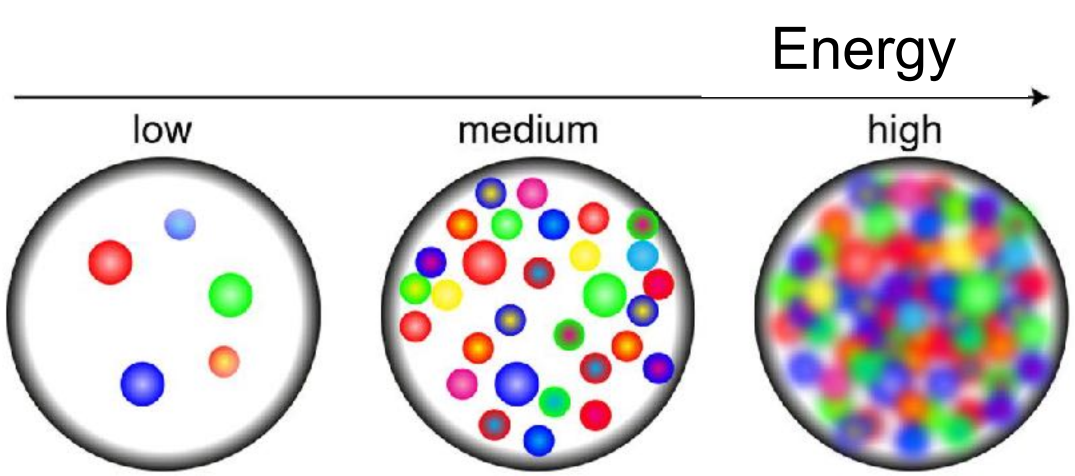
Cross-sections at high energies rise slowly

➧ gluon must "fit" inside hadron size

➧ gluon density limited ➧ SATURATION

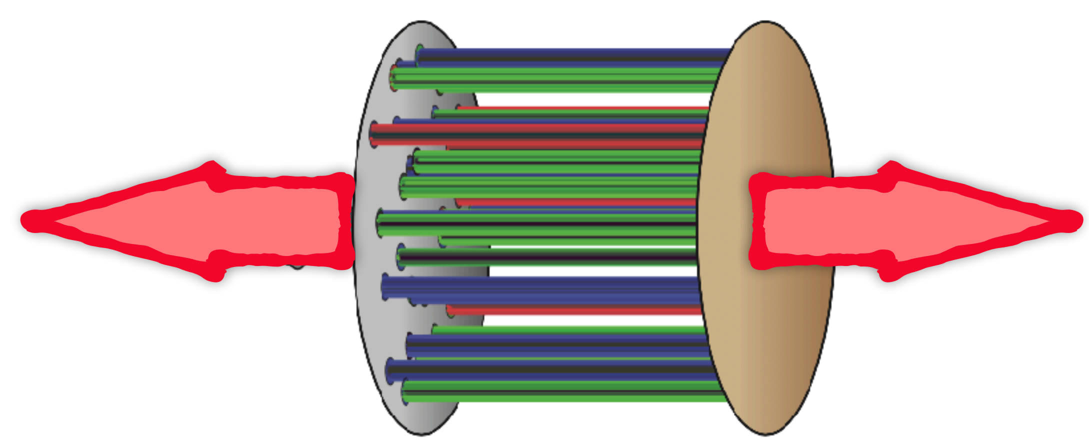
saturation scale ~ Q_s occupation number ~ α_s





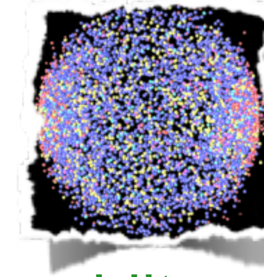
Weakly interacting tightly packed small-x gluons ➧ strong color fields between nuclei

Color Glass Condensate (CGC): effective field theory describing universal properties of saturated gluons in hadron wave functions



CGC dynamics produces GLASMA gluon field configurations at early time

Chemical freeze-out



Assuming thermal and chemical equilibrium

➧ STATISTICAL HADRONIZATION (THERMAL) MODEL

GRAND-CANONICAL ENSEMBLE: large number of produced particles (>10^4 full rapidity range at LHC) ➧ conservation on average of additive quantum numbers

Yield per species:

$$N_i = V \frac{g_i}{2\pi^2} \int \frac{p^2 dp}{e^{\frac{E_i - \mu_i}{T}} \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i}$$

Conservation laws to constrain V, μ_S, μ_{I3}

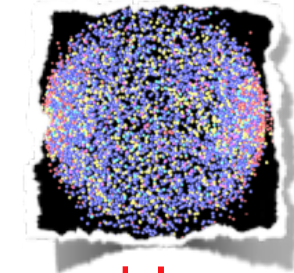
baryon number $V \sum_i n_i B_i = Z + N$

strangeness $V \sum_i n_i S_i = 0$

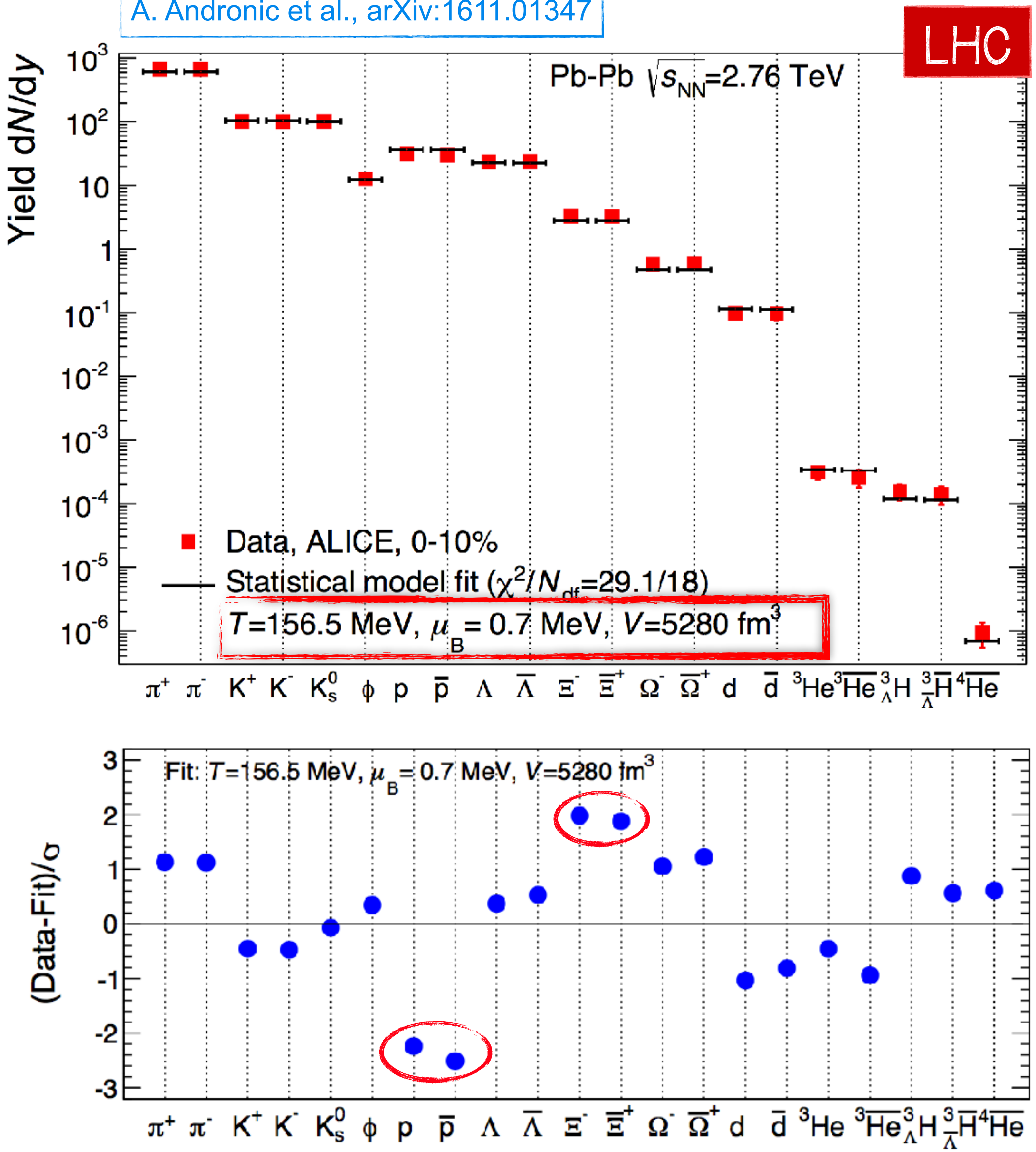
isospin charge $V \sum_i n_i I_{3,i} = \frac{Z-N}{2}$

- ➧ yields determined by 3 parameters: V, T, μ_B
- ➧ comparing particle ratios, V term cancels out
- ➧ fit experimental data to extract T, μ_B ➡ $\chi^2 = \sum_i \frac{N_i^{data} - N_i^{model}}{\sigma_i^2}$

Statistical model: yields



A. Andronic et al., arXiv:1611.01347



- hadron abundancies in reasonable agreement with a chemically-equilibrated system

what is the origin of equilibrium?

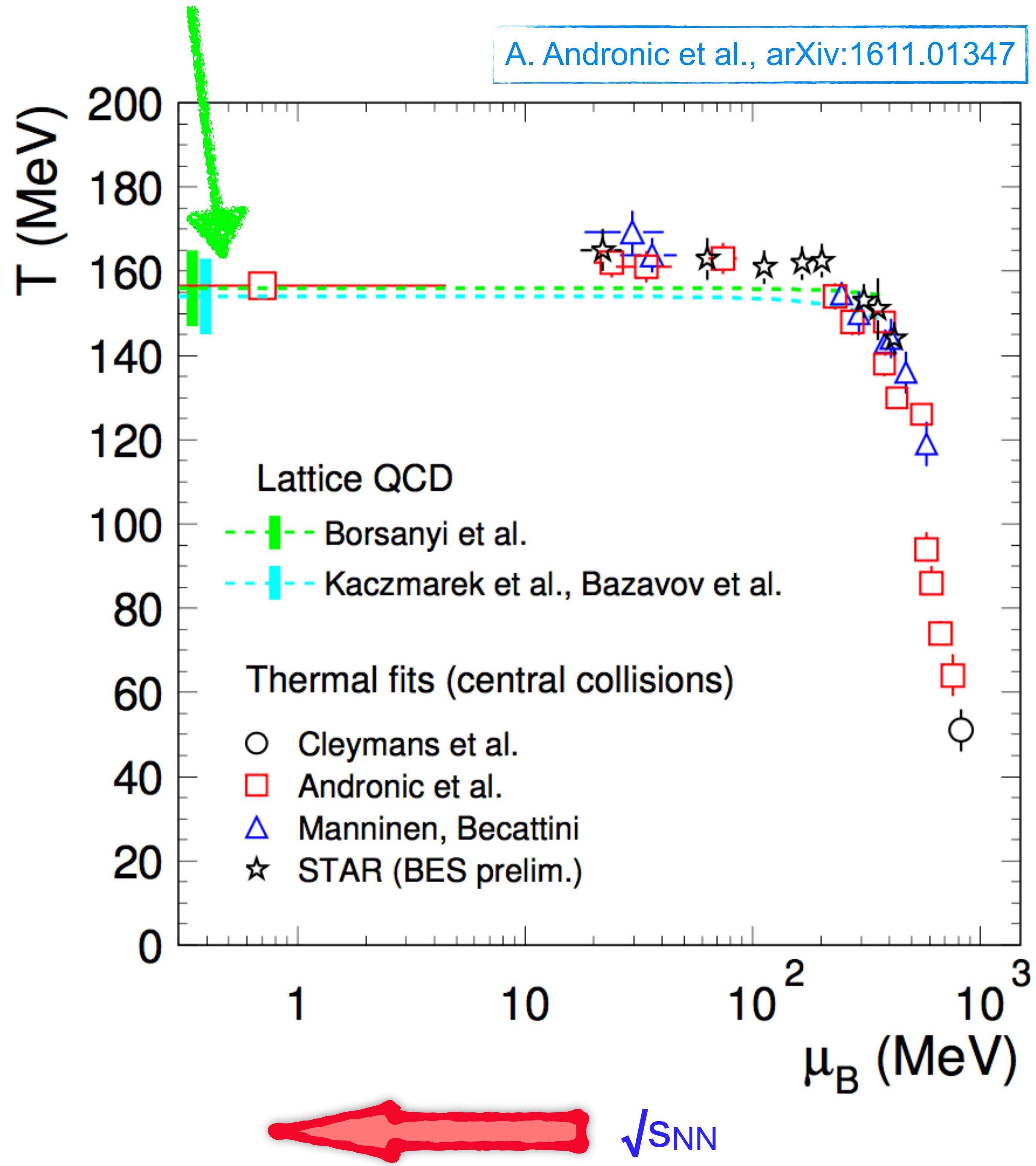
- general property of QCD hadronization process?
- hadron gas thermalizes through particle scattering in the high particle density environment?

Tensions for p[uud] (favour lower T_{ch})
Ξ[dss] (favour higher T_{ch})

- re-scattering in hadronic phase?
- flavor-dependent freeze-out?

Freeze-out and QCD phase diagram

crossover T value from lattice QCD



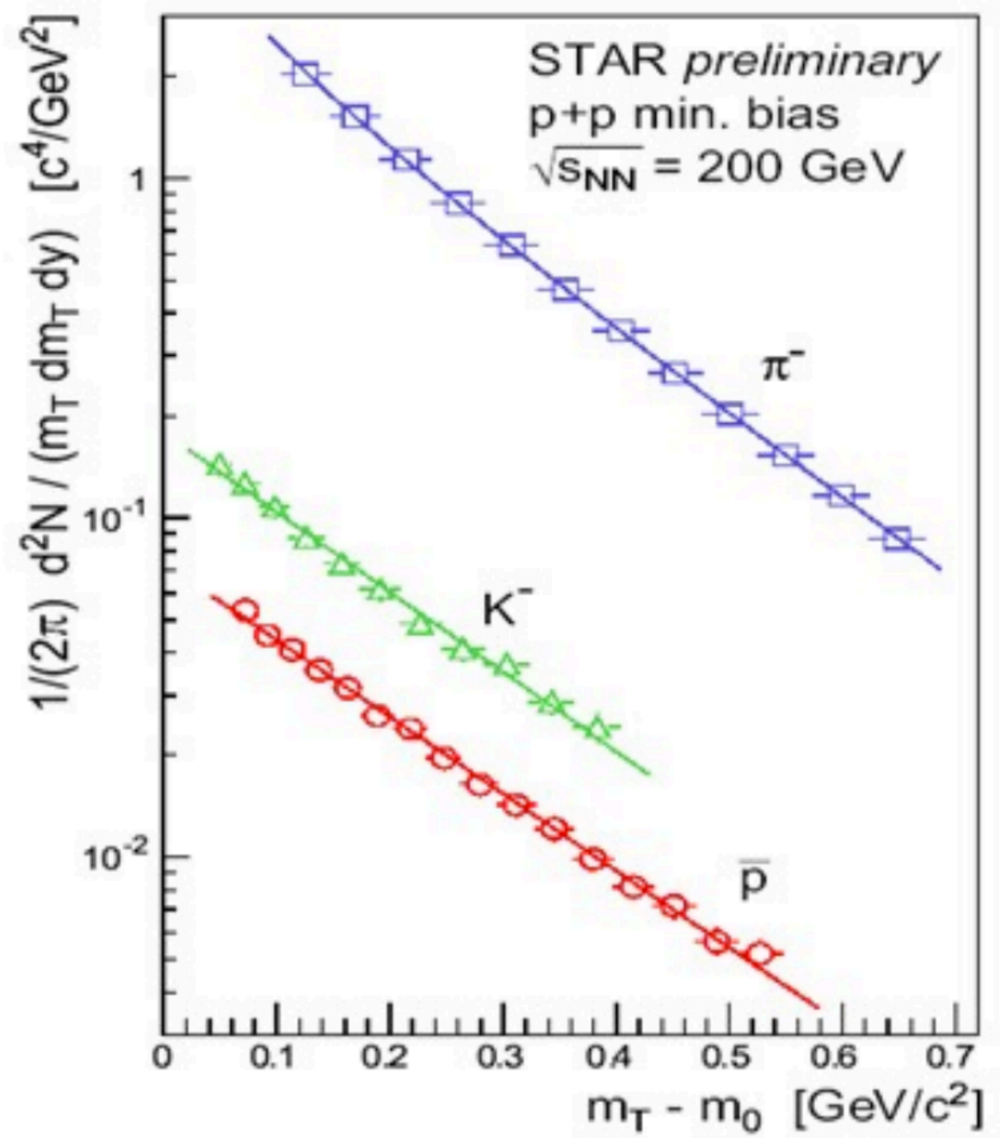
T, μ_B from thermal fits to hadron yields at different collision energies $\sqrt{s_{NN}}$

- hadron freeze-out curve

- at low μ_B chemical freeze-out T coincides with T_C
- hadron formation from deconfined matter

- at LHC μ_B ~0: (anti)matter production as in early Universe

Kinetic equilibrium



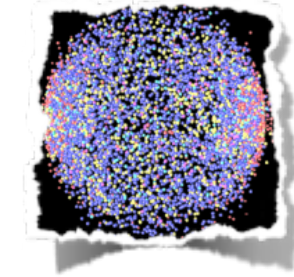
pp collisions at low p_T show transverse mass (m_T=m^2+p_T^2) scaling ➧ thermal spectra

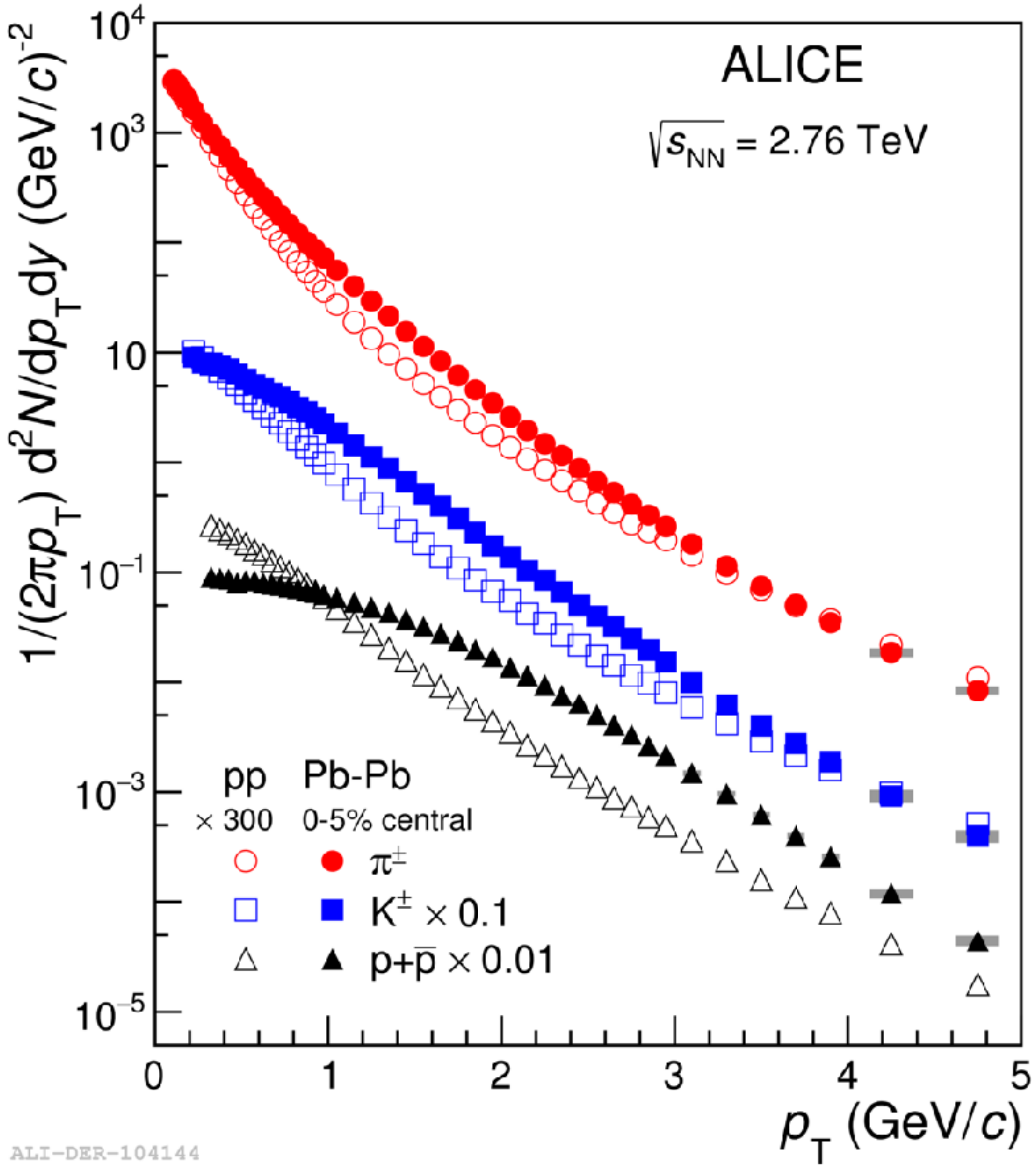
$$\frac{dN}{m_T dm_T} \propto e^{-\frac{m_T}{T_{slope}}}$$

➧ same inverse slope T_{slope} for all particles

➧ T_{slope} = T at kinetic freeze-out T_{fo}

Kinetic equilibrium





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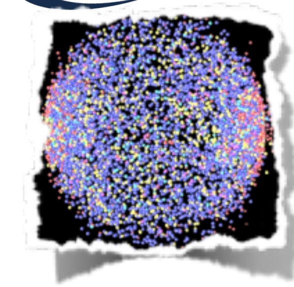
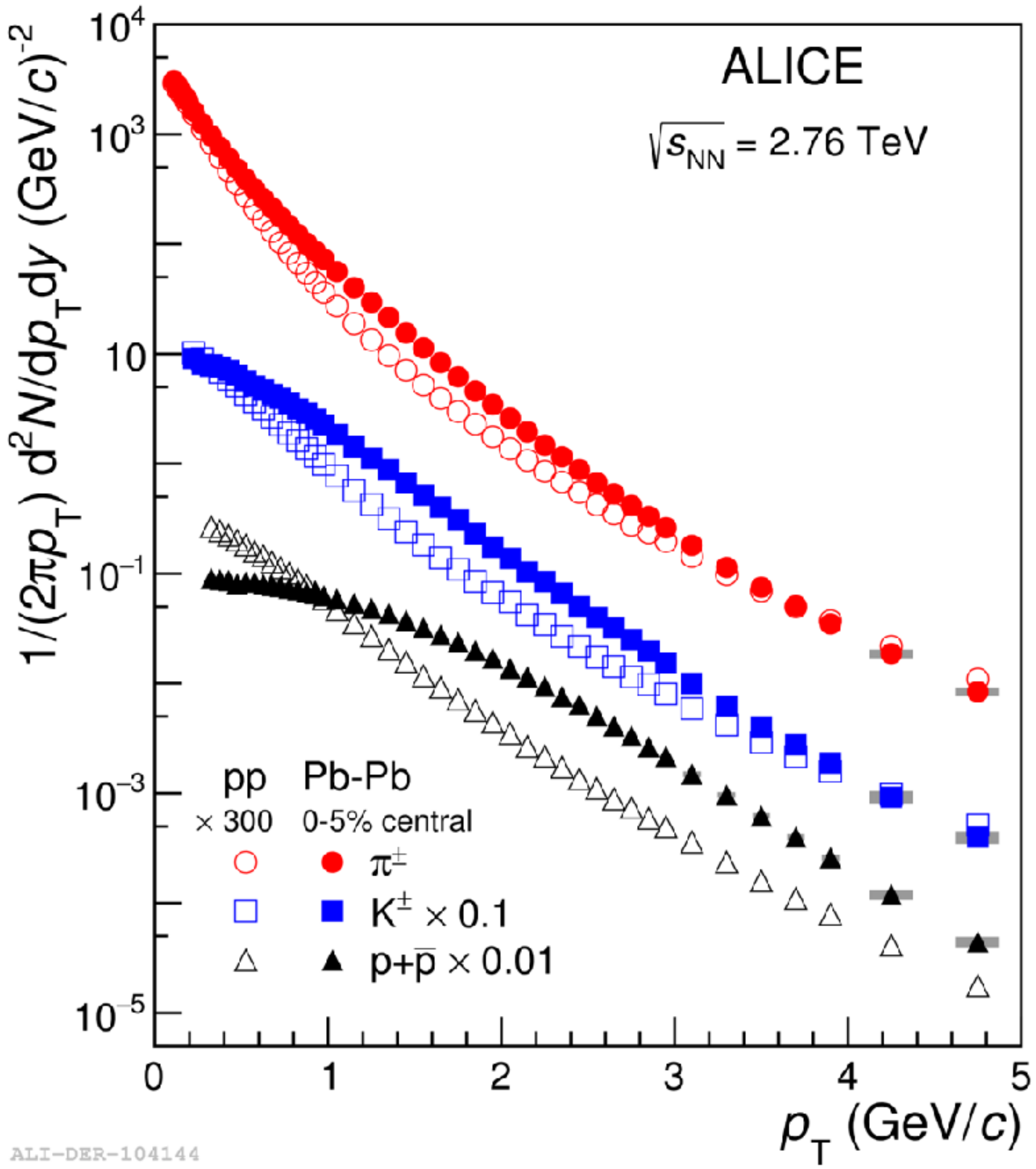
A-A collisions, low p_T: m_T scaling is broken

➧ harder spectra in A-A

➧ heavier particles are shifted to larger pT (harder spectra)

Kinetic equilibrium





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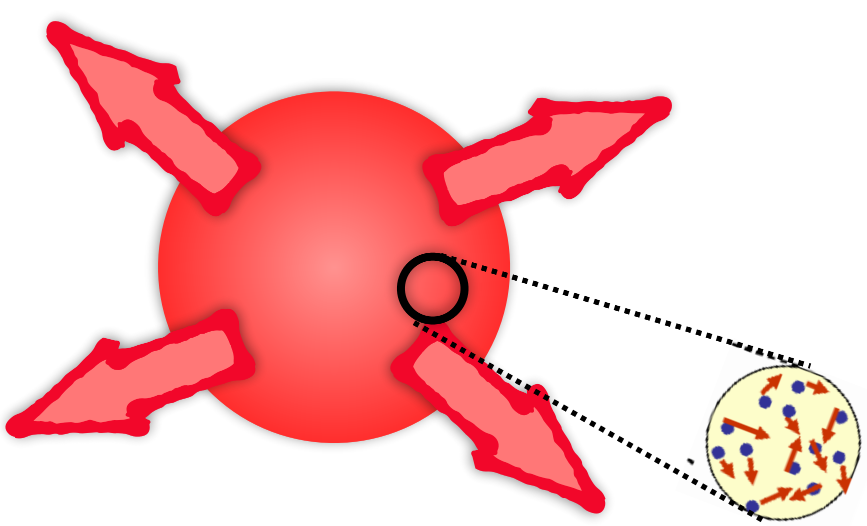


Random thermal motion + collective motion of expanding system driven by pressure gradient ➧ RADIAL FLOW

Particles moving in a common flow field

➧ blue-shift

$$T_{slope} = T_{fo}\sqrt{\frac{1+\beta_T}{1-\beta_T}}$$

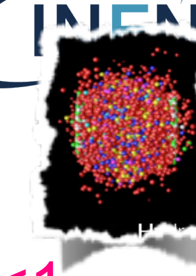
Hydrodynamic evolution

Hydrodynamic applicability ➧ medium in local thermodynamic equilibrium, with mean free path λ_{MFP} << size of the system L ➧ small Knudsen number Kn = λ_{MFP}/L <<1

Energy-momentum conservation $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{mu\nu}$$

Hydrodynamic evolution



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Equilibrium terms
energy density and pressure
related by EOS P=P(ϵ)
microscopic DOF

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Equilibrium terms
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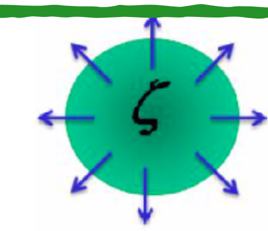
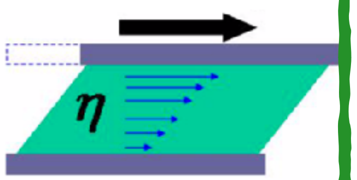
microscopic DOF

Dissipative terms
Bulk pressure $\Pi=\Pi(\zeta)$
ζ = bulk viscosity
Shear stress tensor
$\pi^{\mu\nu} = \pi^{\mu\nu}(\eta)$
η = shear viscosity

ζ = bulk viscosity
resistance to expansion



η = shear viscosity
resistance to flow gradients



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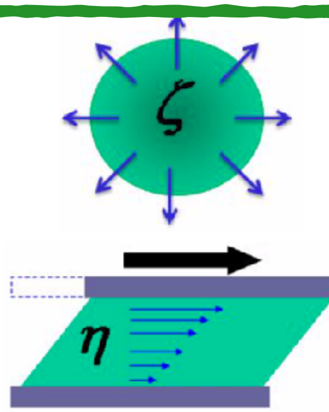
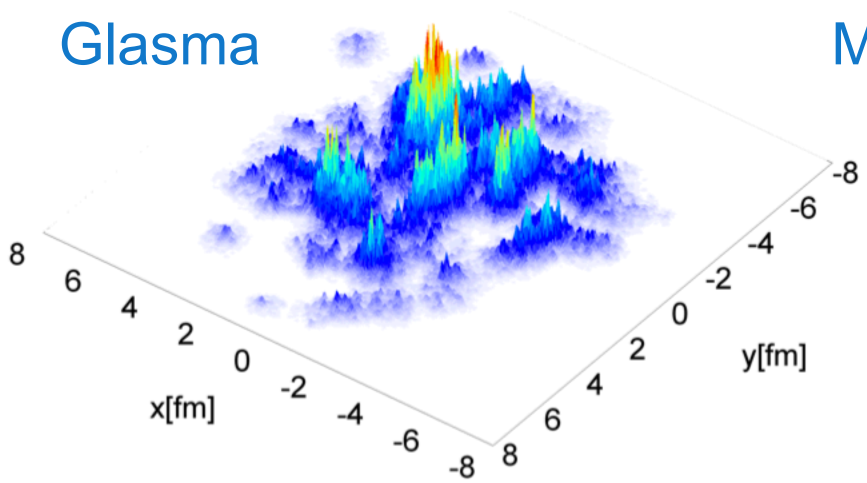


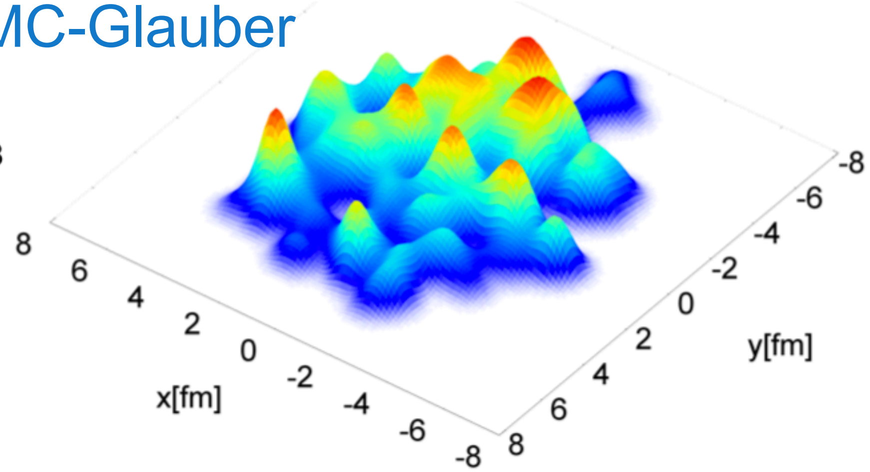
Event by event initial conditions fluctuations

Schenke et al., PRL 108 (2012) 252301

Glasma



MC-Glauber



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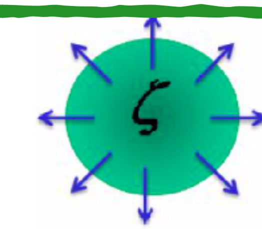
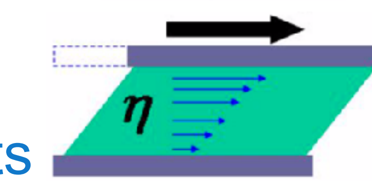


η = shear viscosity
resistance to flow gradients



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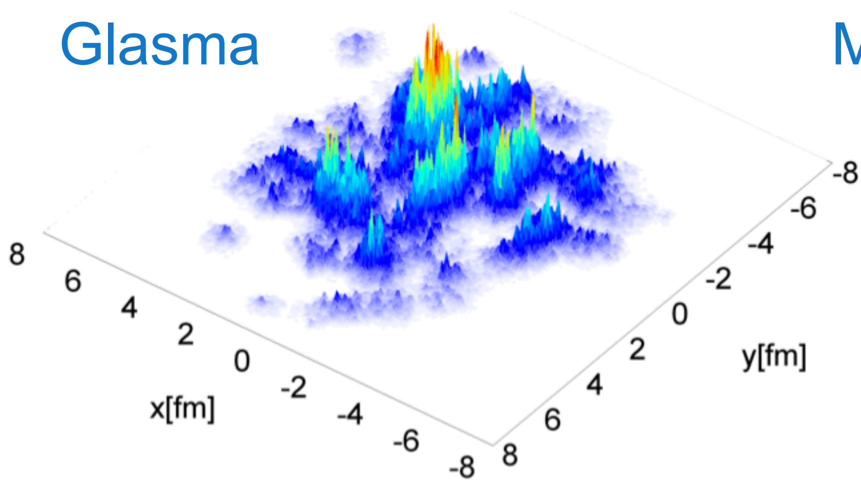
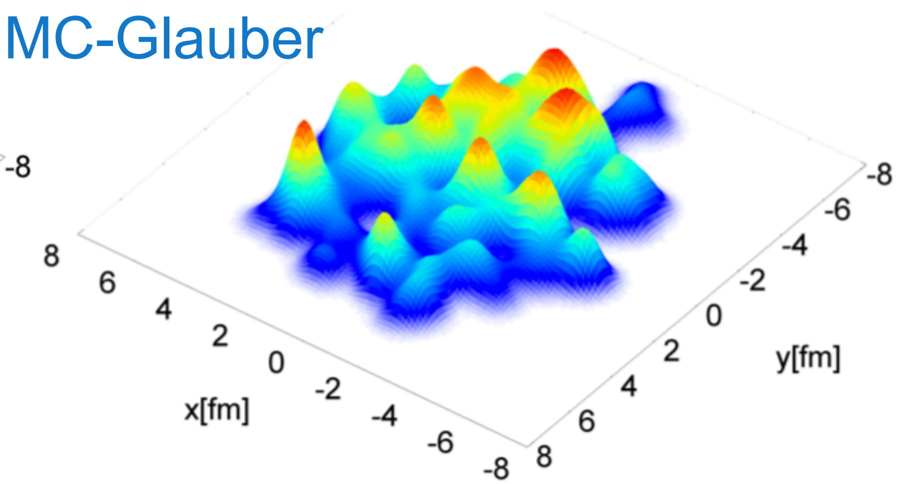
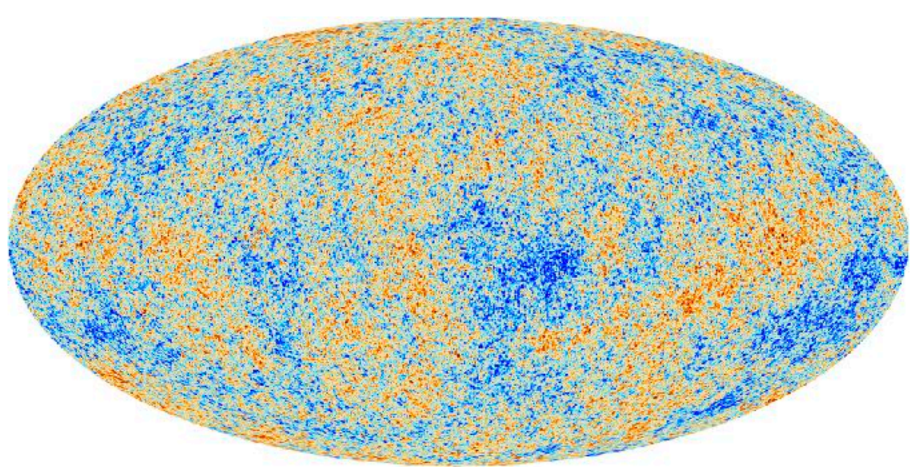
Schenke et al., PRL 108 (2012) 252301

Glasma

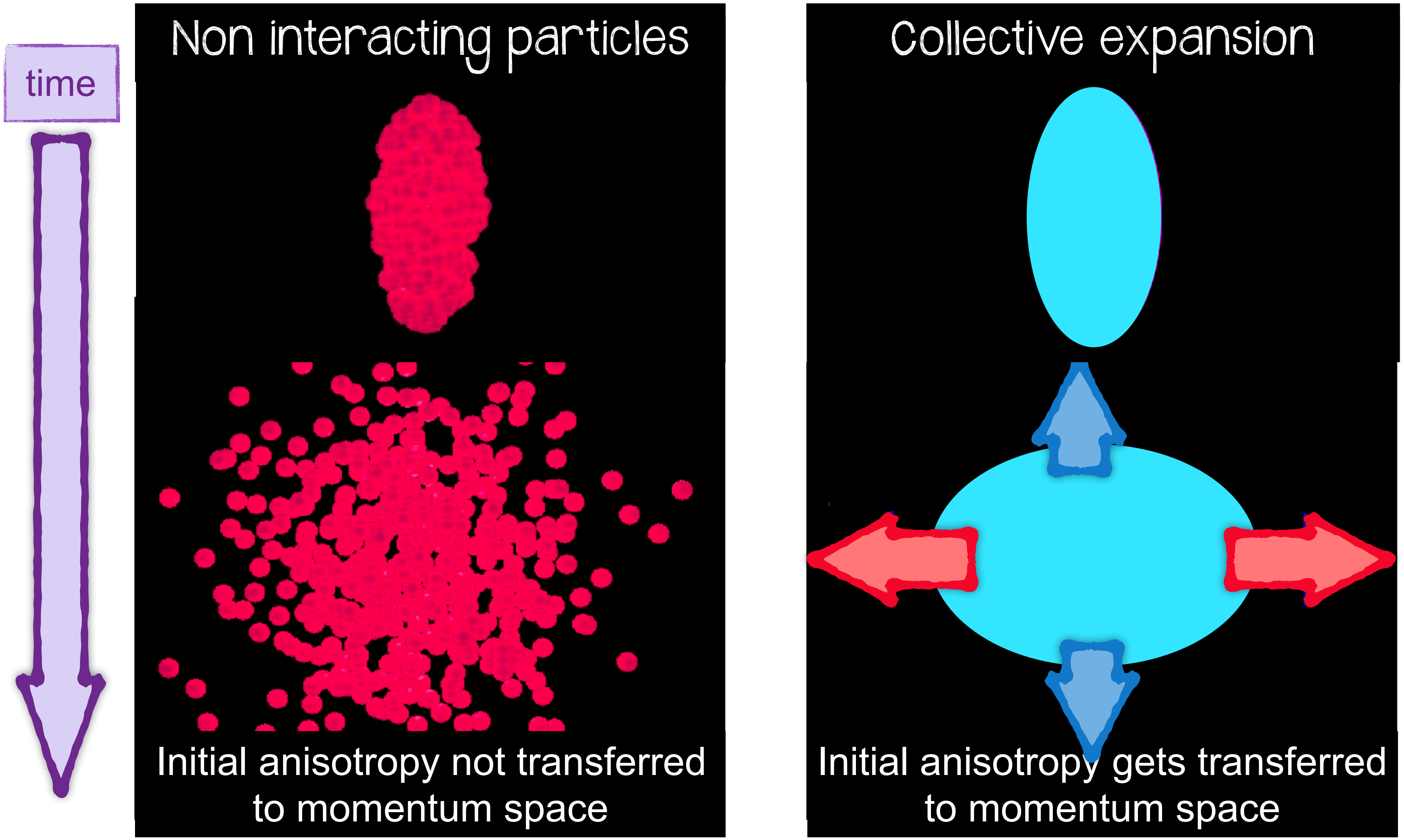


MC-Glauber

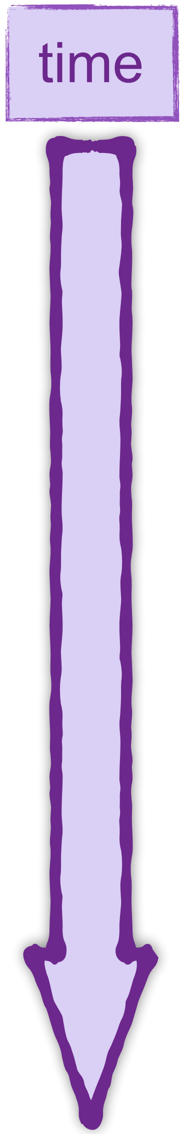




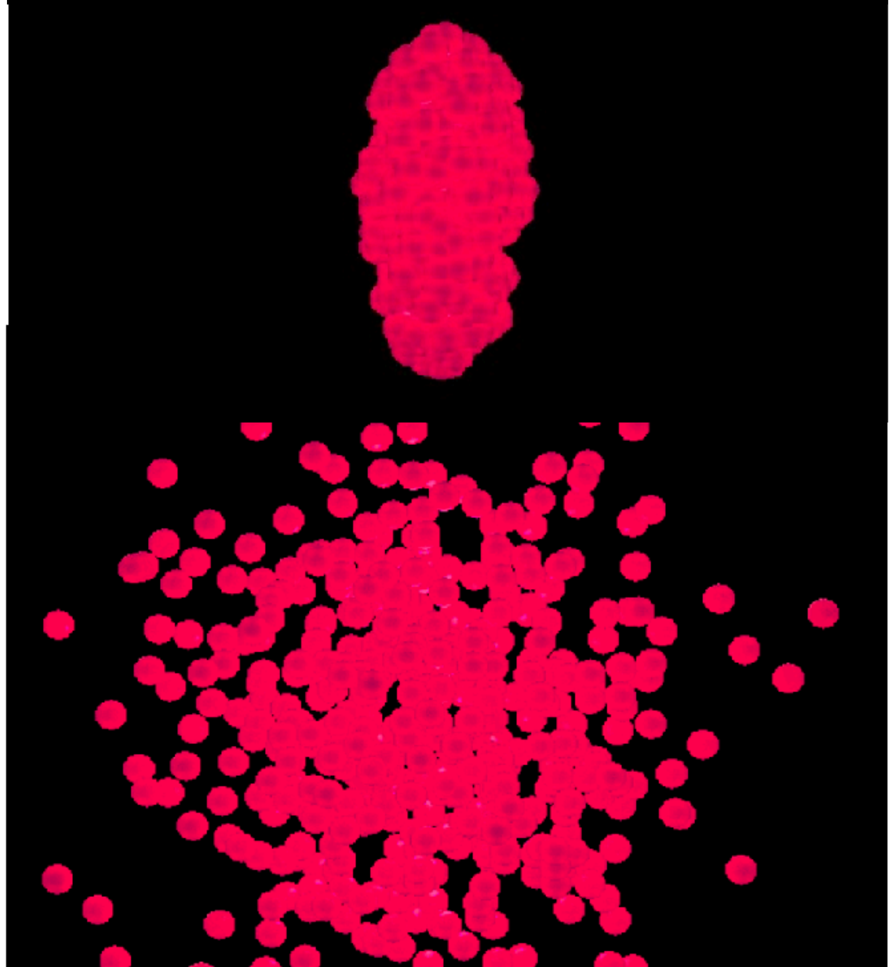
Hydrodynamic evolution



Hydrodynamic evolution

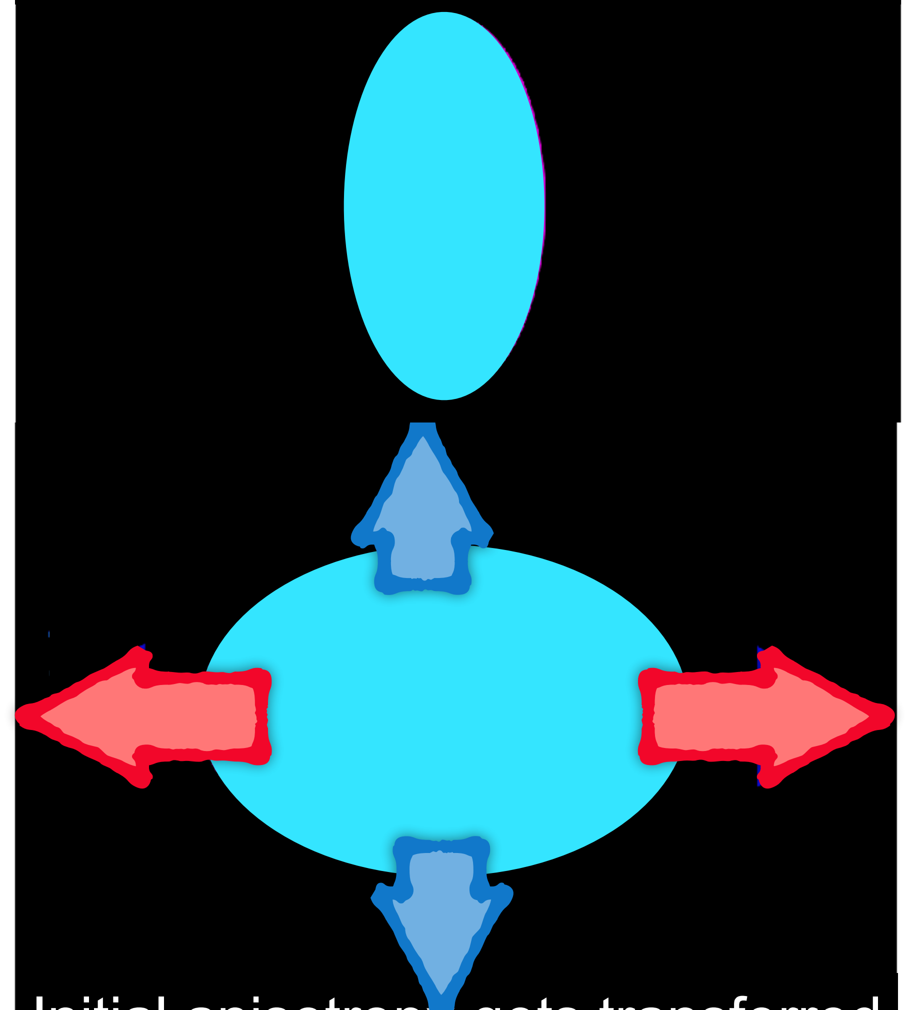


Non interacting particles

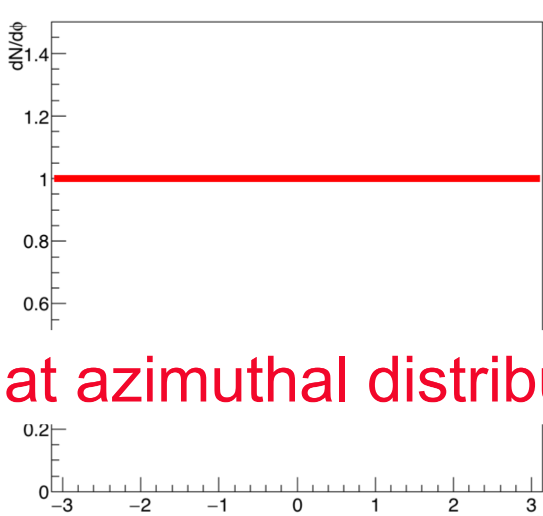


Initial anisotropy not transferred to momentum space

Collective expansion

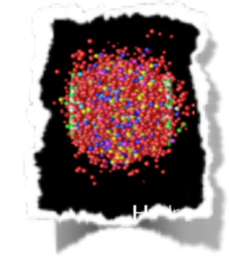


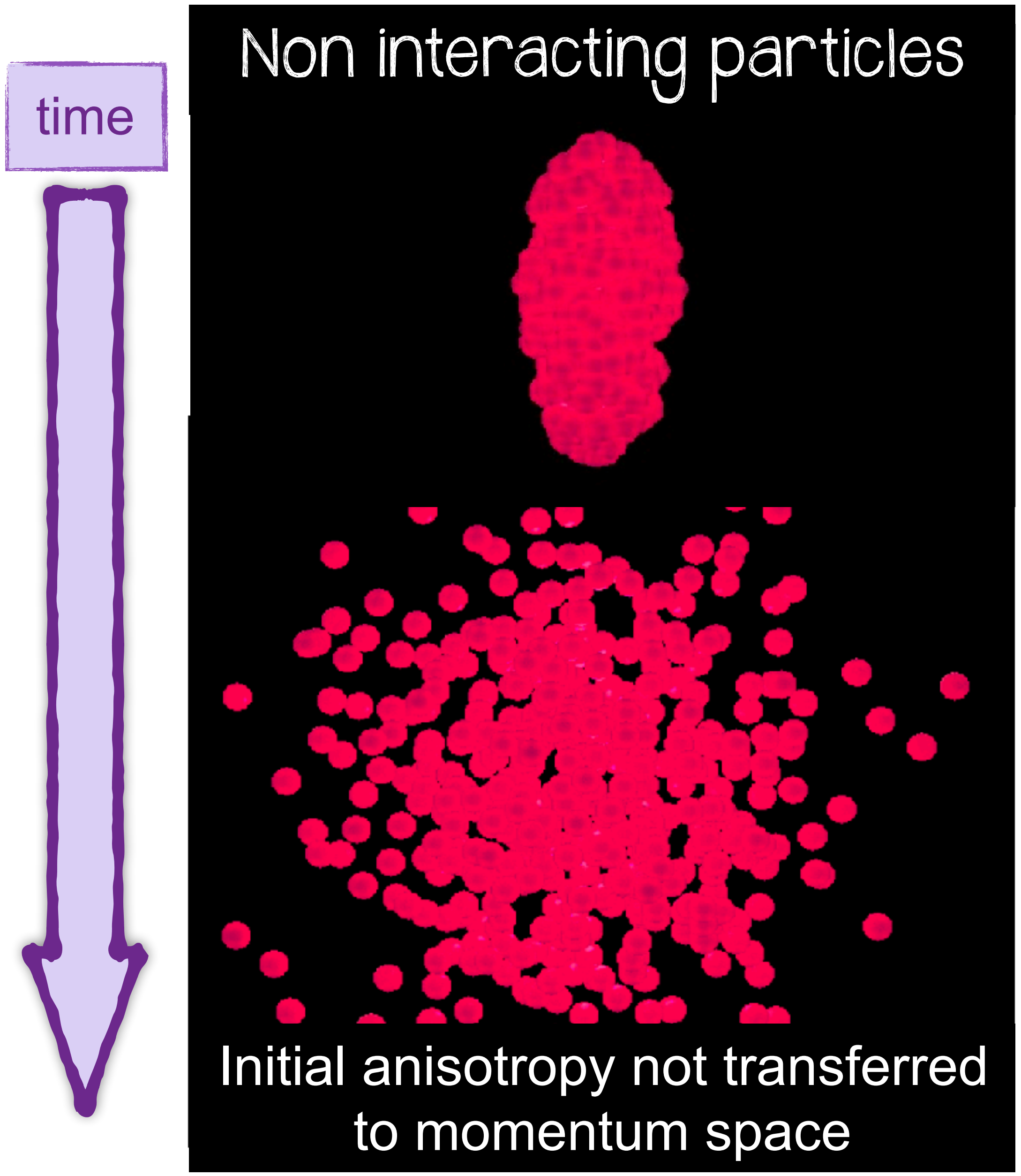
Initial anisotropy gets transferred to momentum space

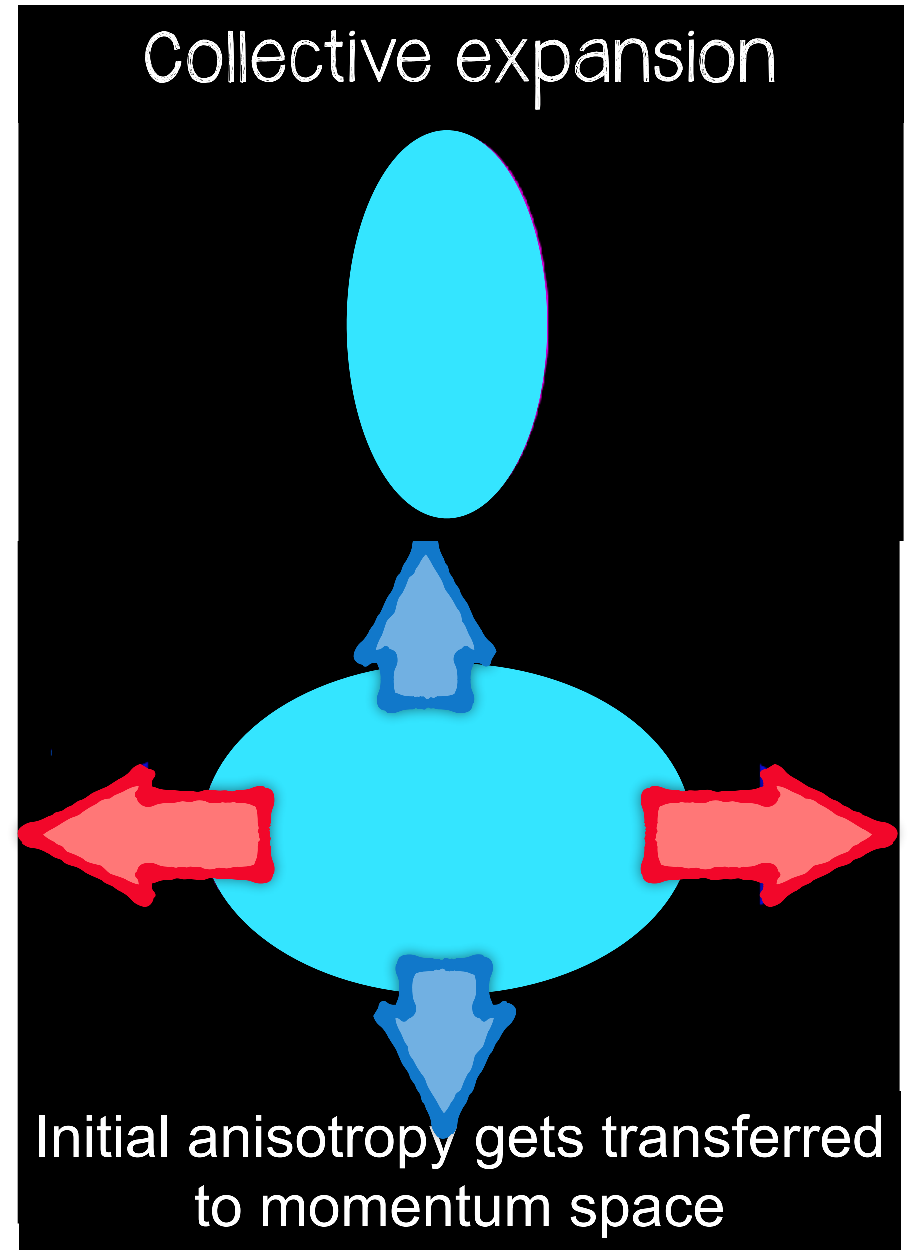


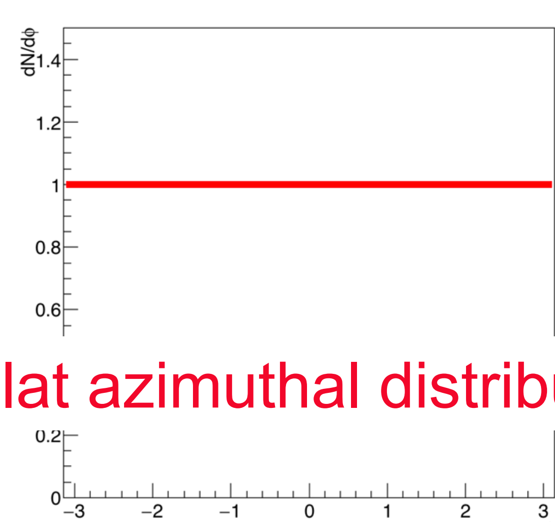
Flat azimuthal distribution

Hydrodynamic evolution

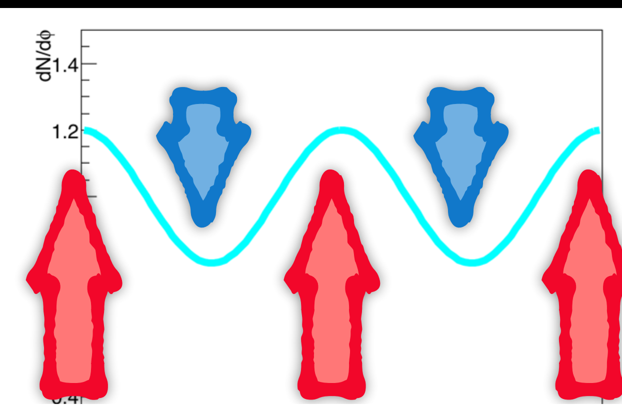






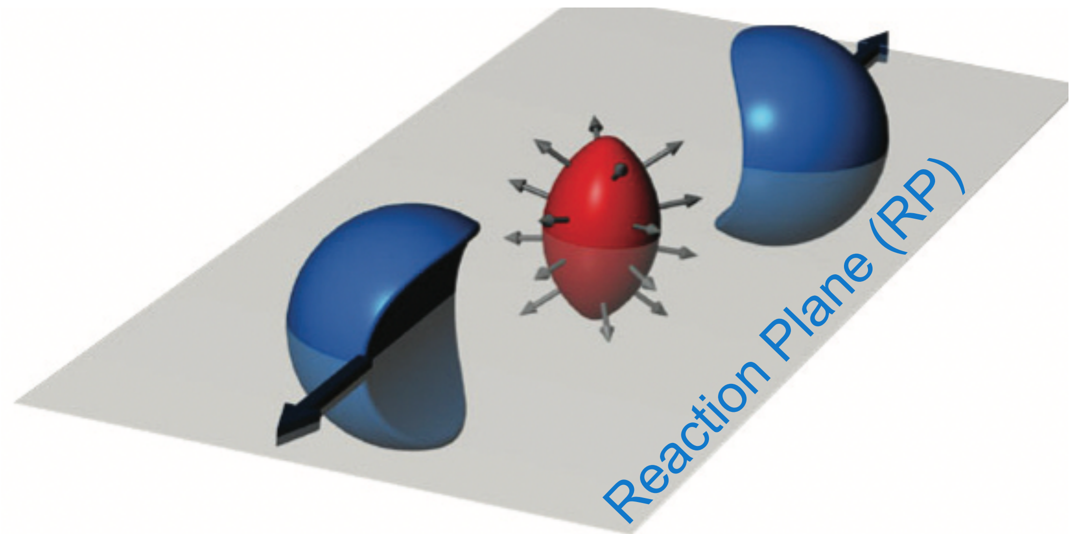


Flat azimuthal distribution



Modulated (cosϕ) azimuthal distribution

Hydrodynamic evolution

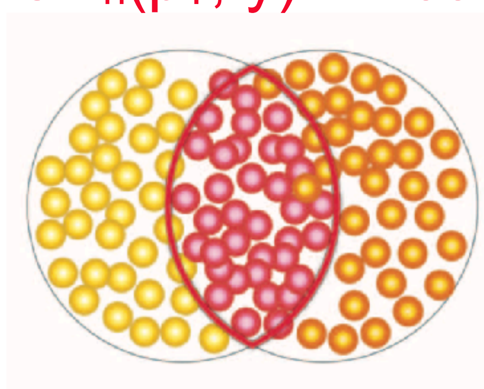


Initial anisotropies are mapped in final hadron spectra, can be quantified through a Fourier decomposition of azimuthal distributions relative to RP:

$$\frac{dN}{d\phi} \sim 1 + 2\sum_n v_n cos\left[n\left(\phi - \Psi_{RP}\right)\right]$$

Fourier coefficients $v_n(p_T, y) = \langle cos[n(\phi-\Psi_{RP})] \rangle$

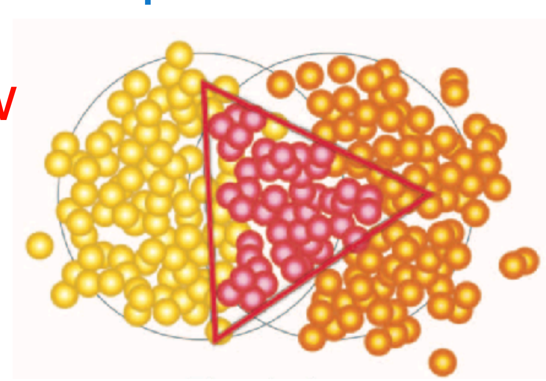
v_2 ➧ elliptic flow



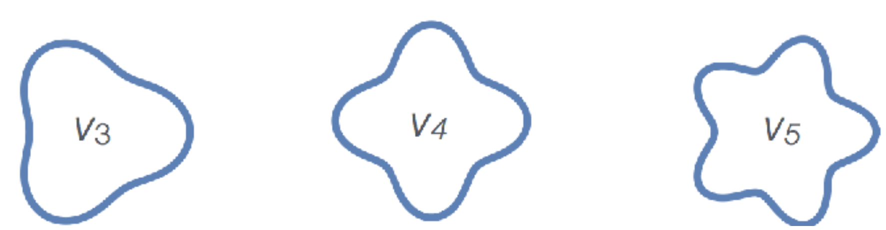
related to the geometry of the overlap zone
expansion tends to dilute initial space asymmetry (pressure gradients are stronger in the first stages)

Higher order coefficients due to fluctuations in the initial state
Odd coefficients are expected vanish on average for a symmetric system

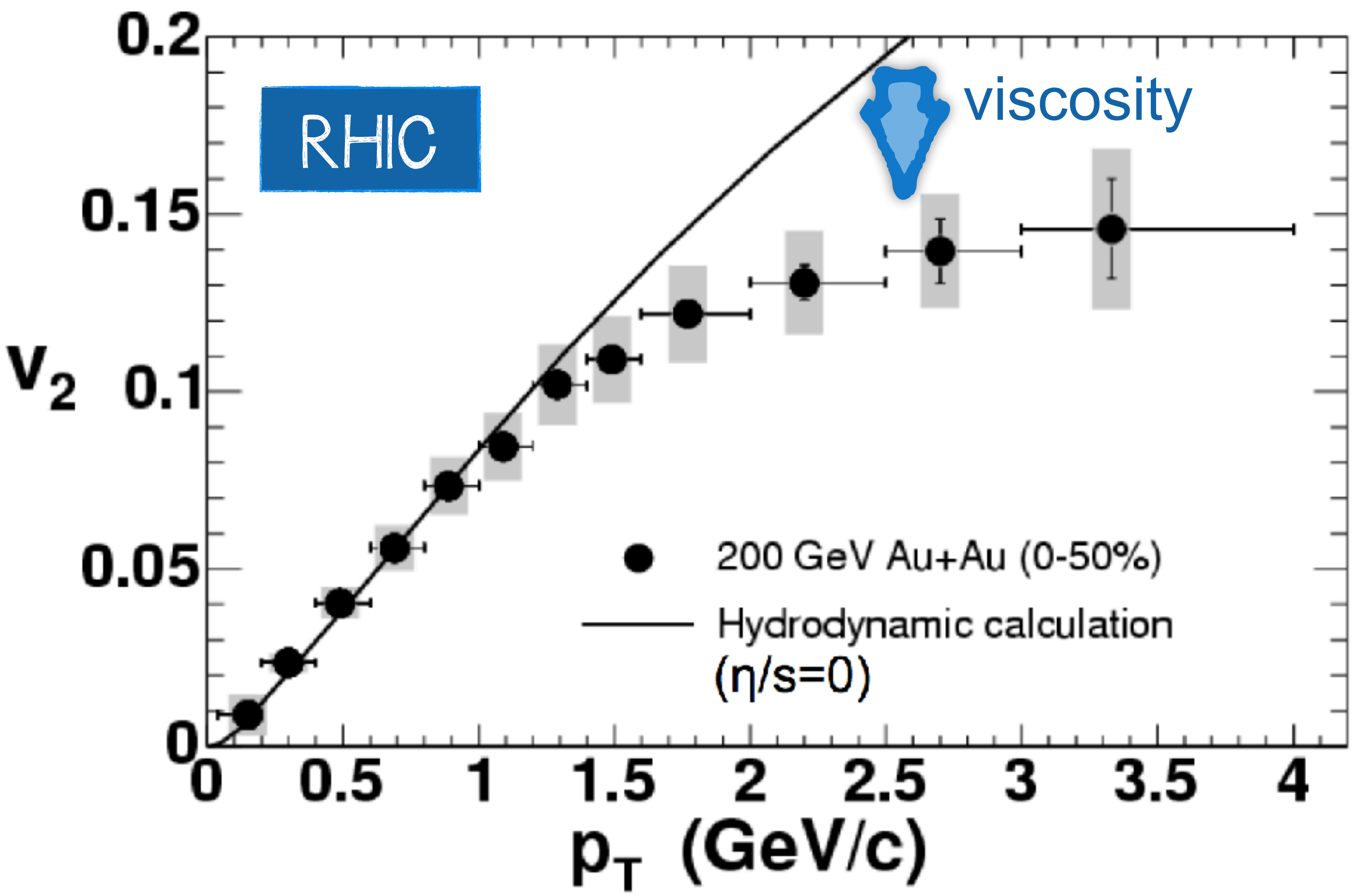
v_3 ➧ triangular flow



viscosity tends to suppress higher harmonics
➧ sensitivity to initial conditions and to η/s ratio



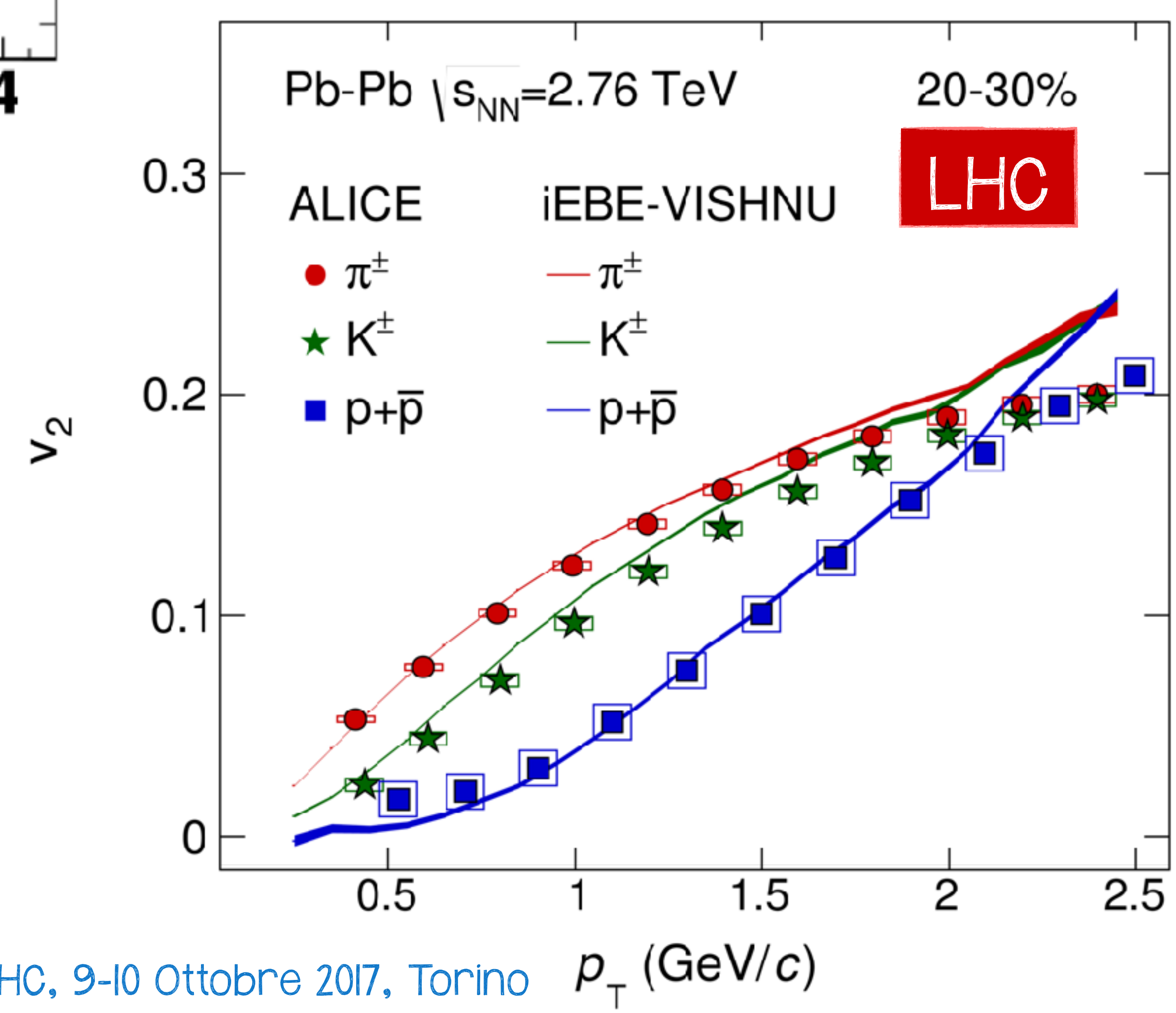
Elliptic flow v_2



Large p_T values measured at RHIC
➧ reproduced by hydrodynamic calculations with dissipative terms

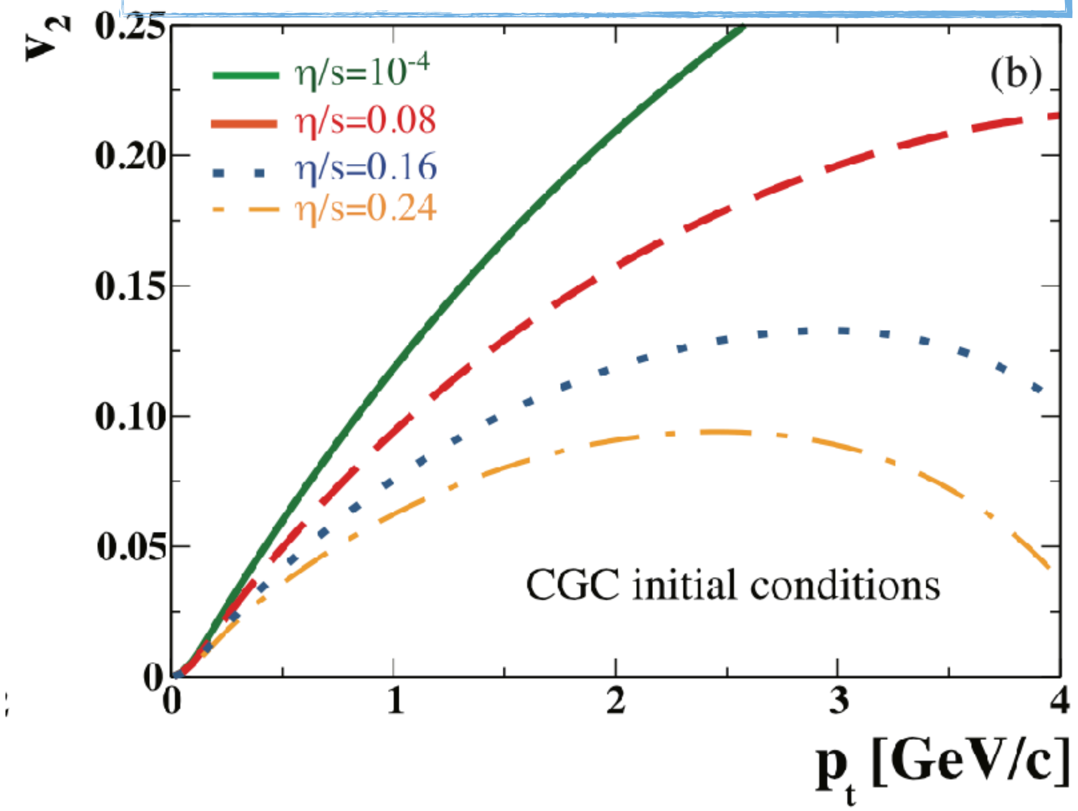
➧ point to early system thermalization fastly reached (τ~1 fm/c)

m dependence of v_2 at low p_T
➧ consistent with hydrodynamic predictions



Higher order harmonics

R.Snellings, 2011 New J. Phys. 13 055008



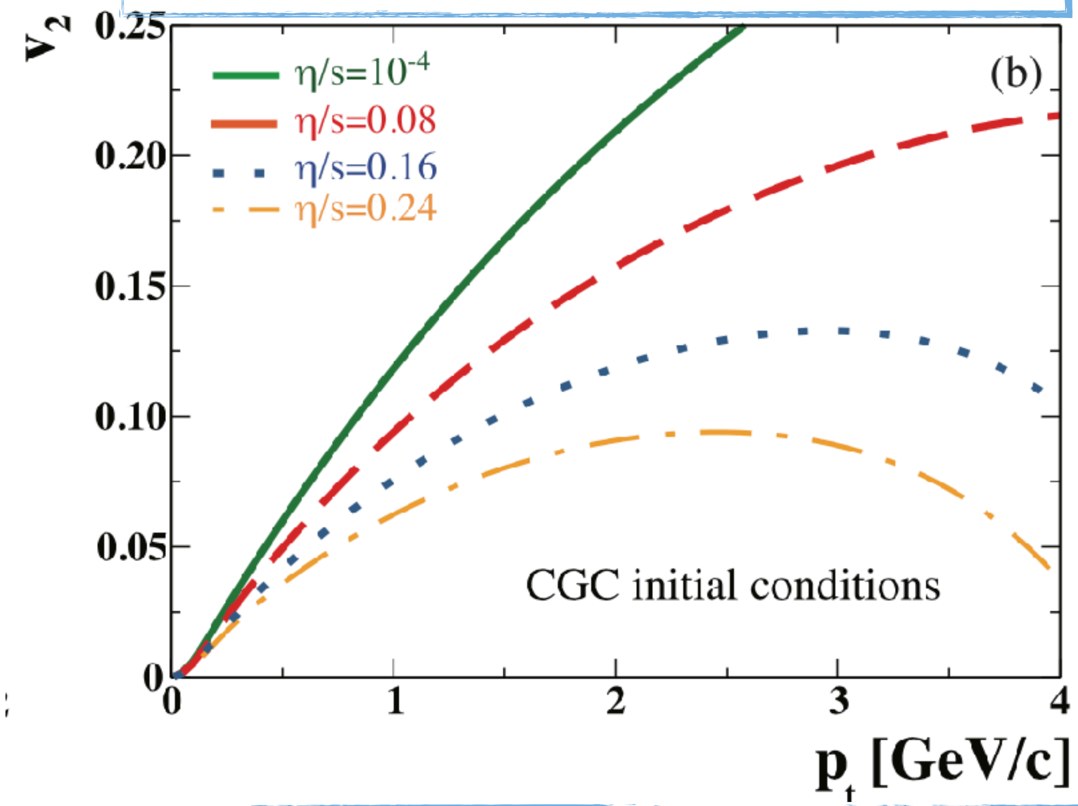
Viscosity tend to suppress higher order harmonics

v_n sensitive to transport in the medium

➧ $v_2(p_T)$ to constrain shear viscosity to entropy density ratio η/s

Higher order harmonics

R.Snellings, 2011 New J. Phys. 13 055008

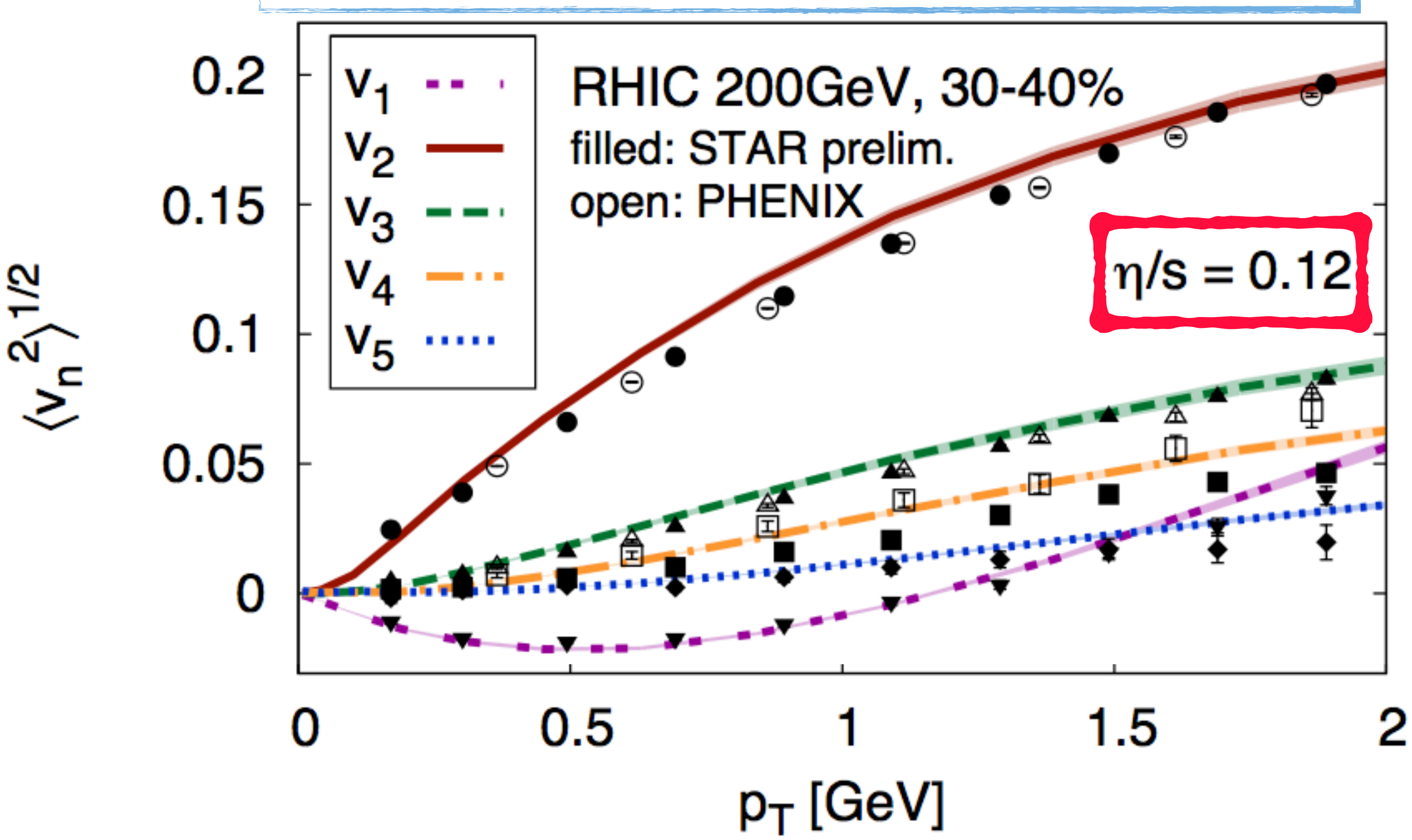


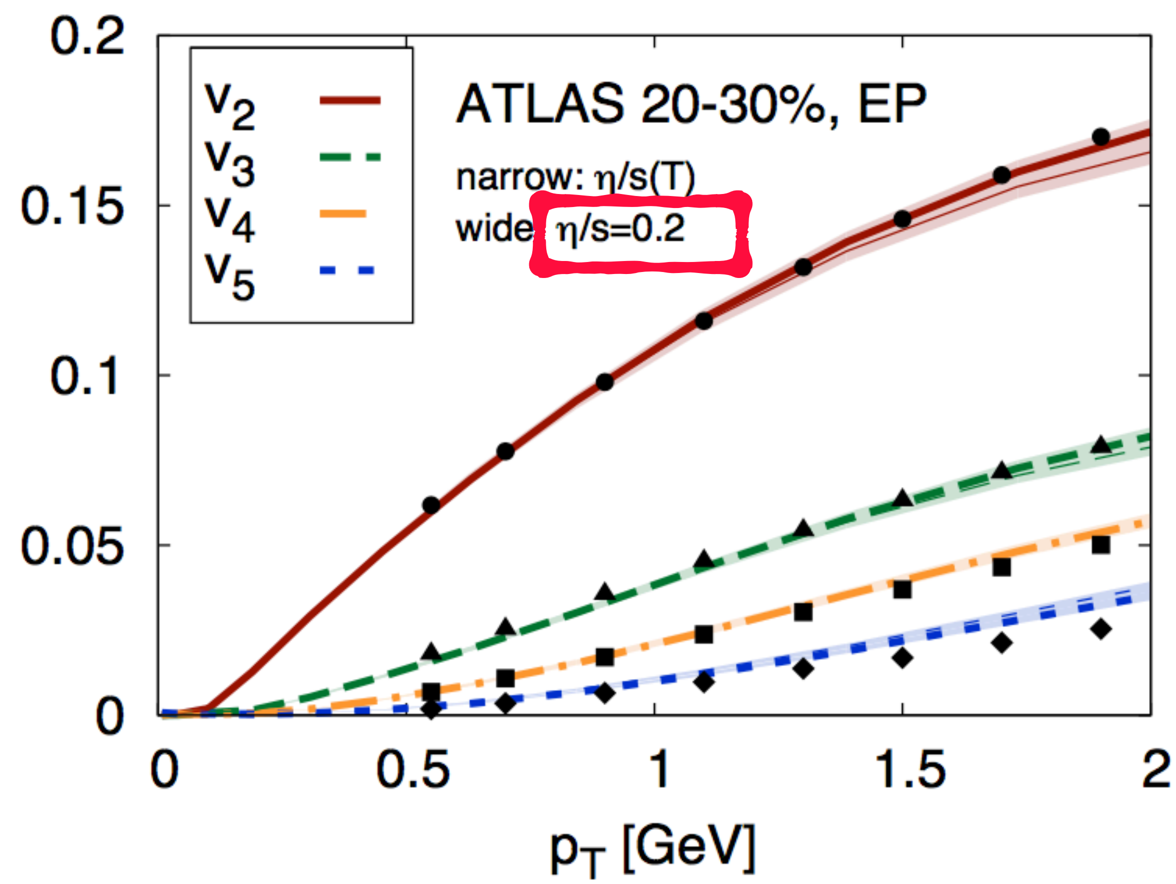
Viscosity tend to suppress higher order harmonics
v_n sensitive to transport in the medium
➧ $v_2(p_T)$ to constrain shear viscosity to entropy density ratio η/s

RHIC — LHC

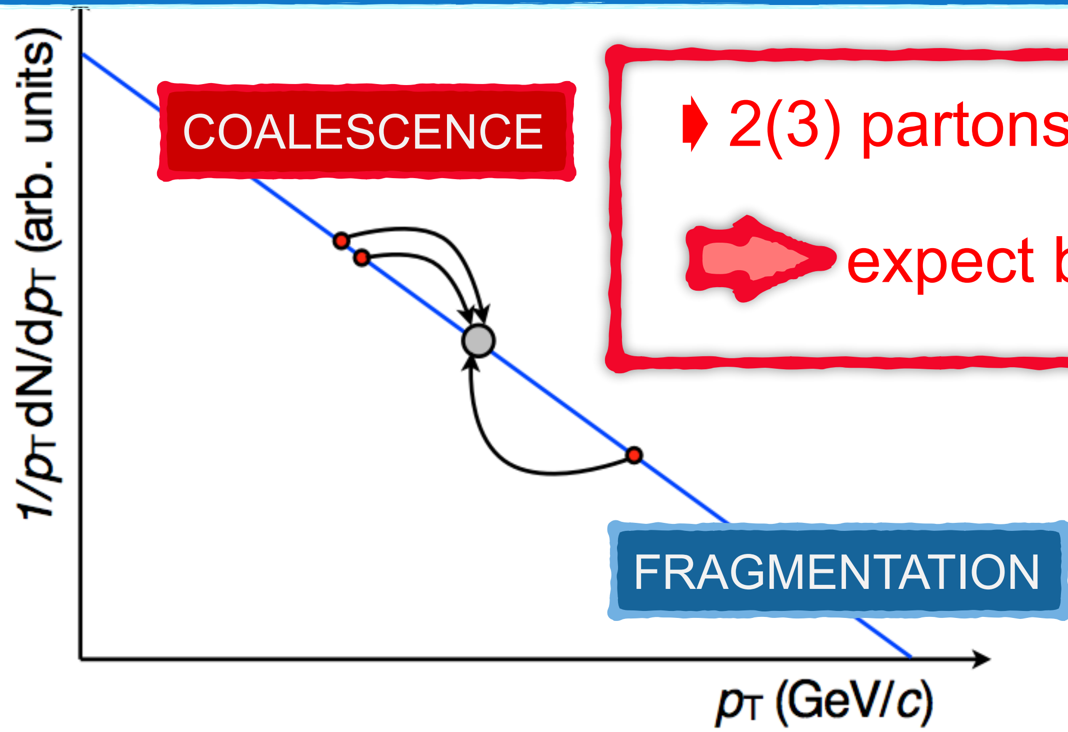
η/s = 0.12 — η/s = 0.2

C. Gale et al., Phys. Rev. Lett. 110 (2013) 012302





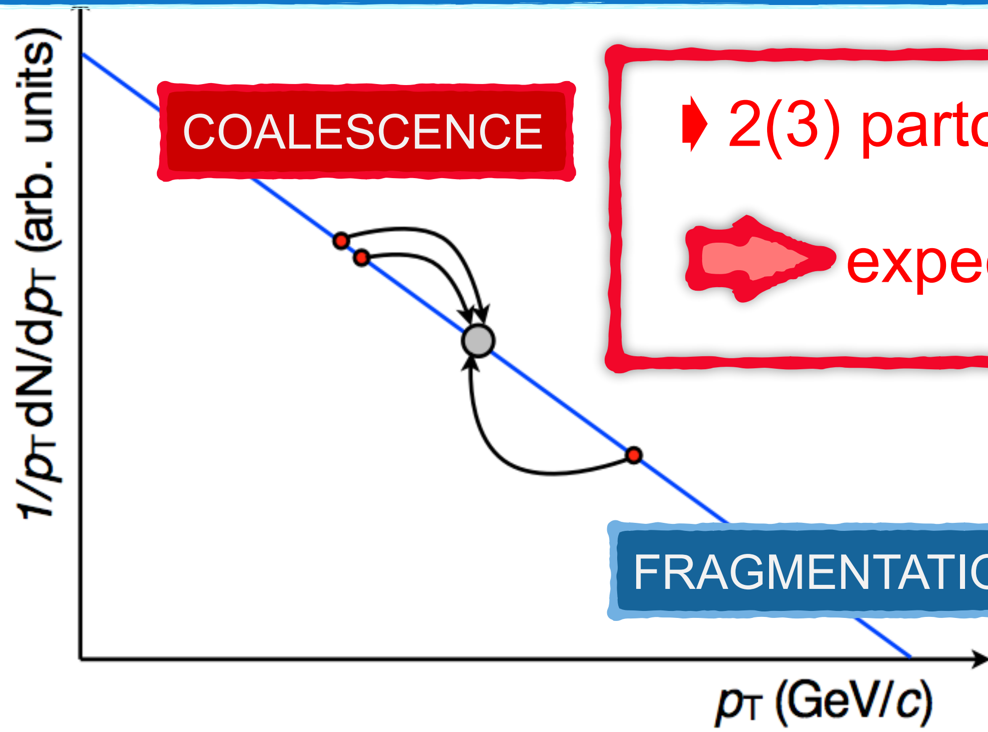
Hadronization



- 2(3) partons combine with p_T(hadron)~2(3)*p_T
- expect baryon(qqq)/meson(q-antiq) enhancement

- single parton fragments with p_T(hadron)<p_T

Hadronization



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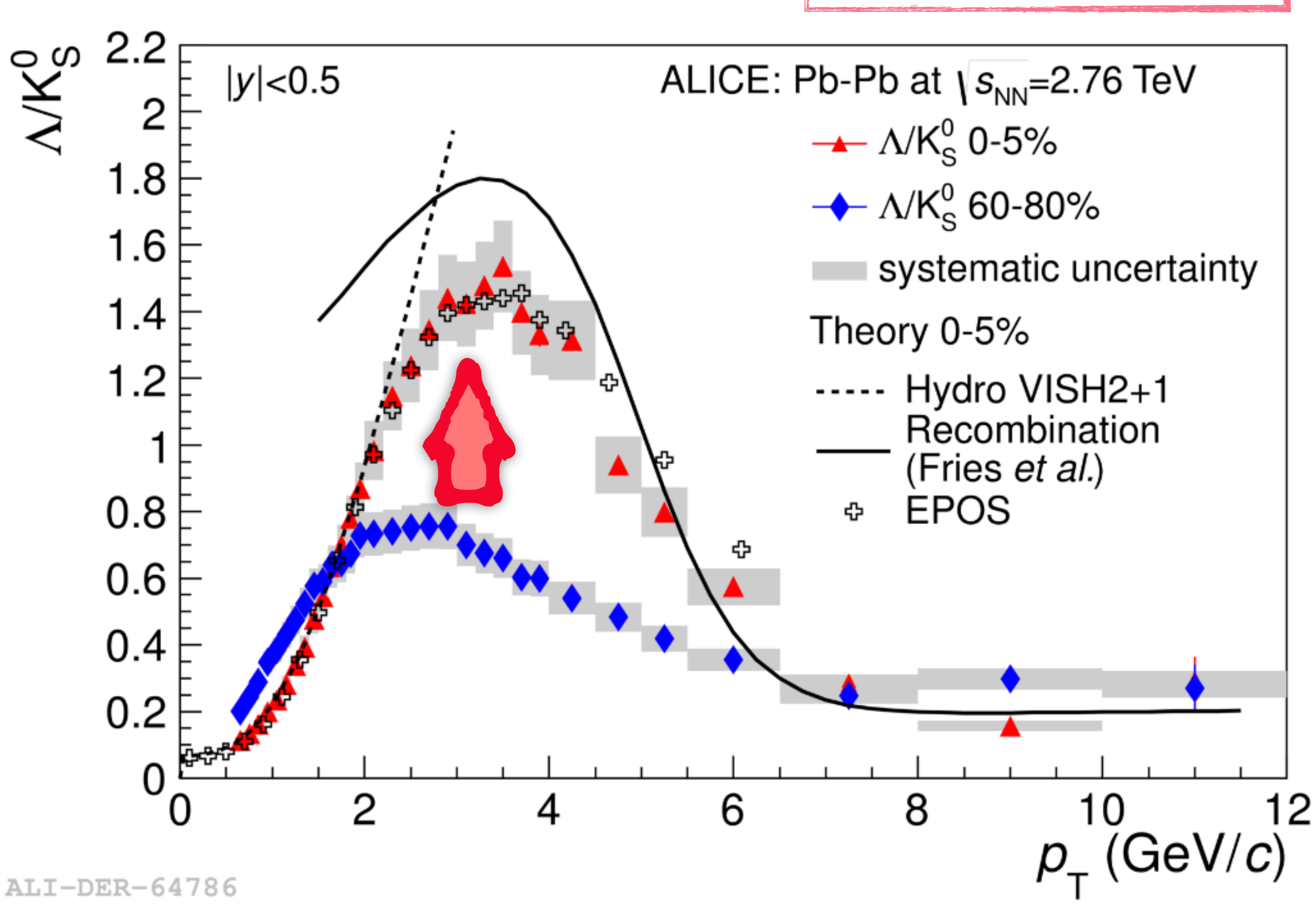
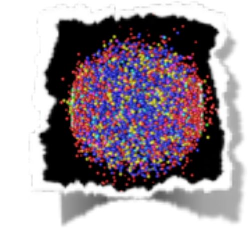
PRL 111(2013) 22301

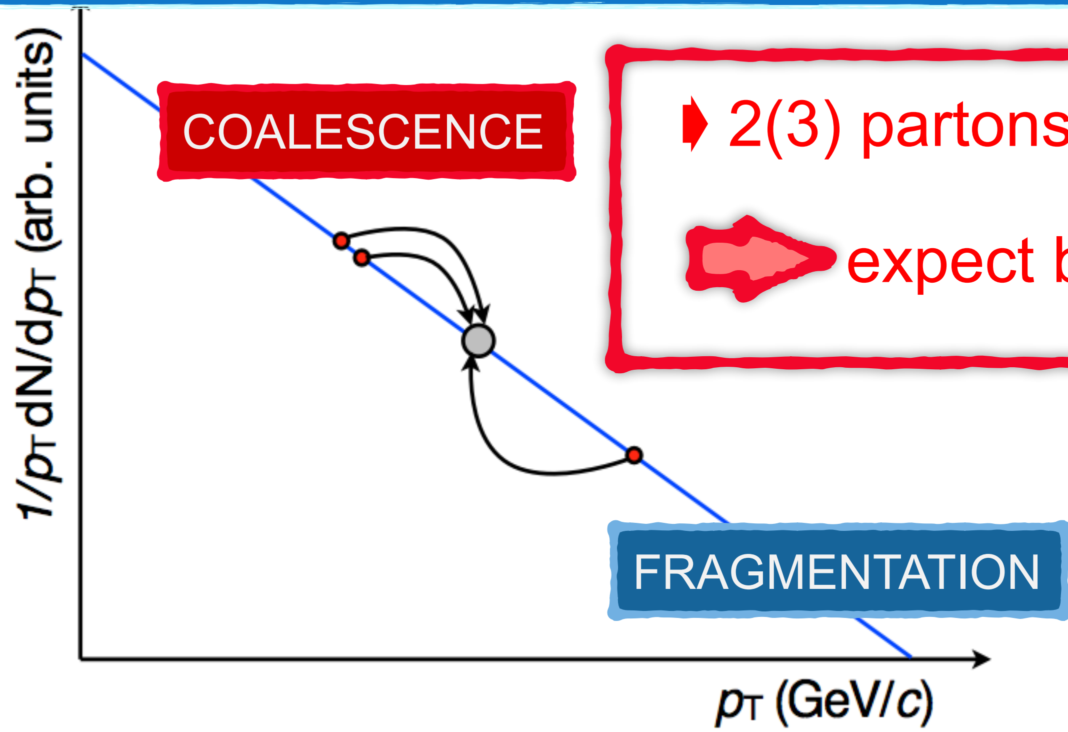


- baryon/meson enhanced in central A-A collisions at intermediate p_T
- hydrodynamics at low p_T
- coalescence+fragmentation or hydrodynamics+jets (EPOS) able to reproduce data

T.Pierog et al., Phys. Rev. C 92, 034906 (2015)

Hadronization





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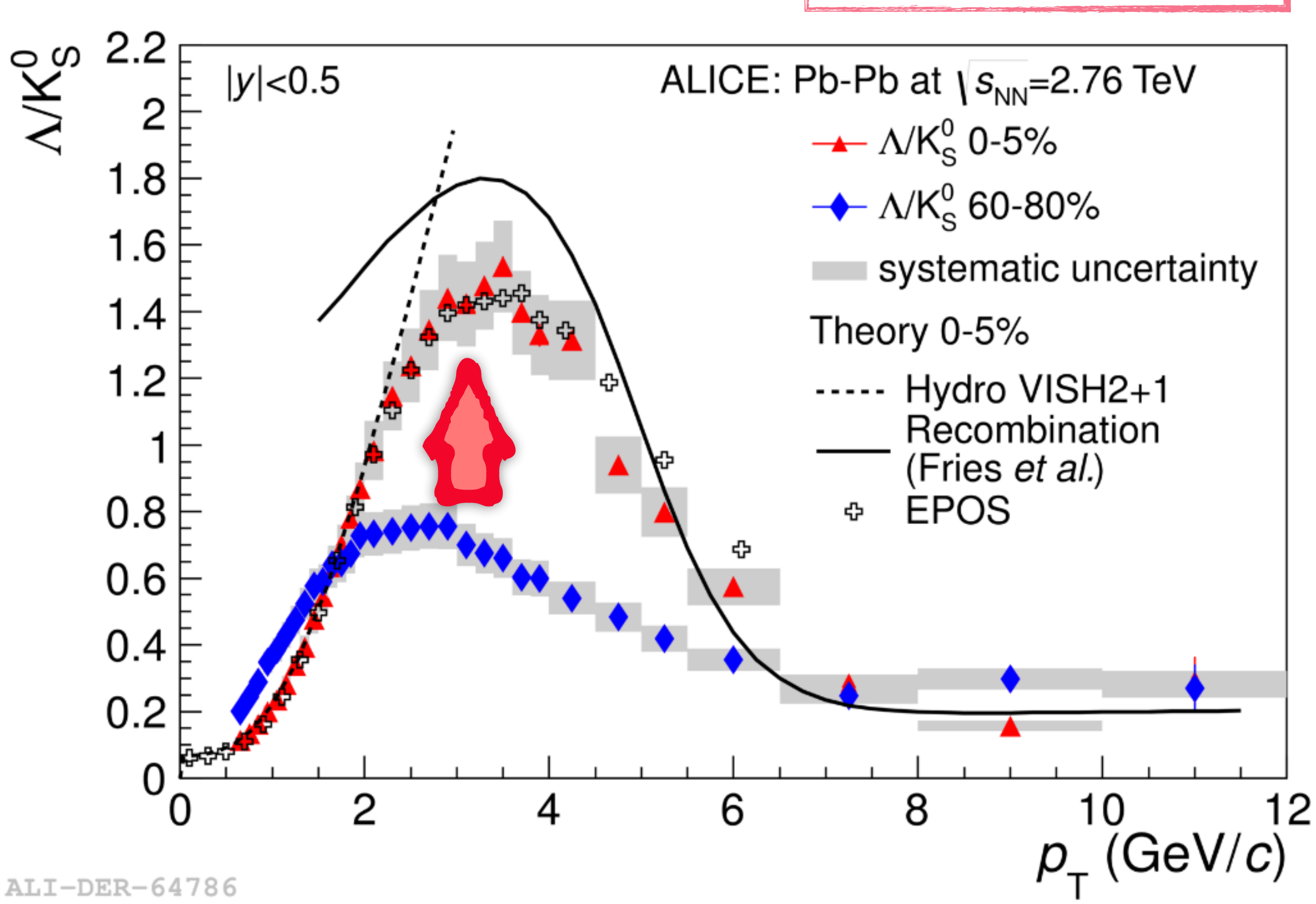
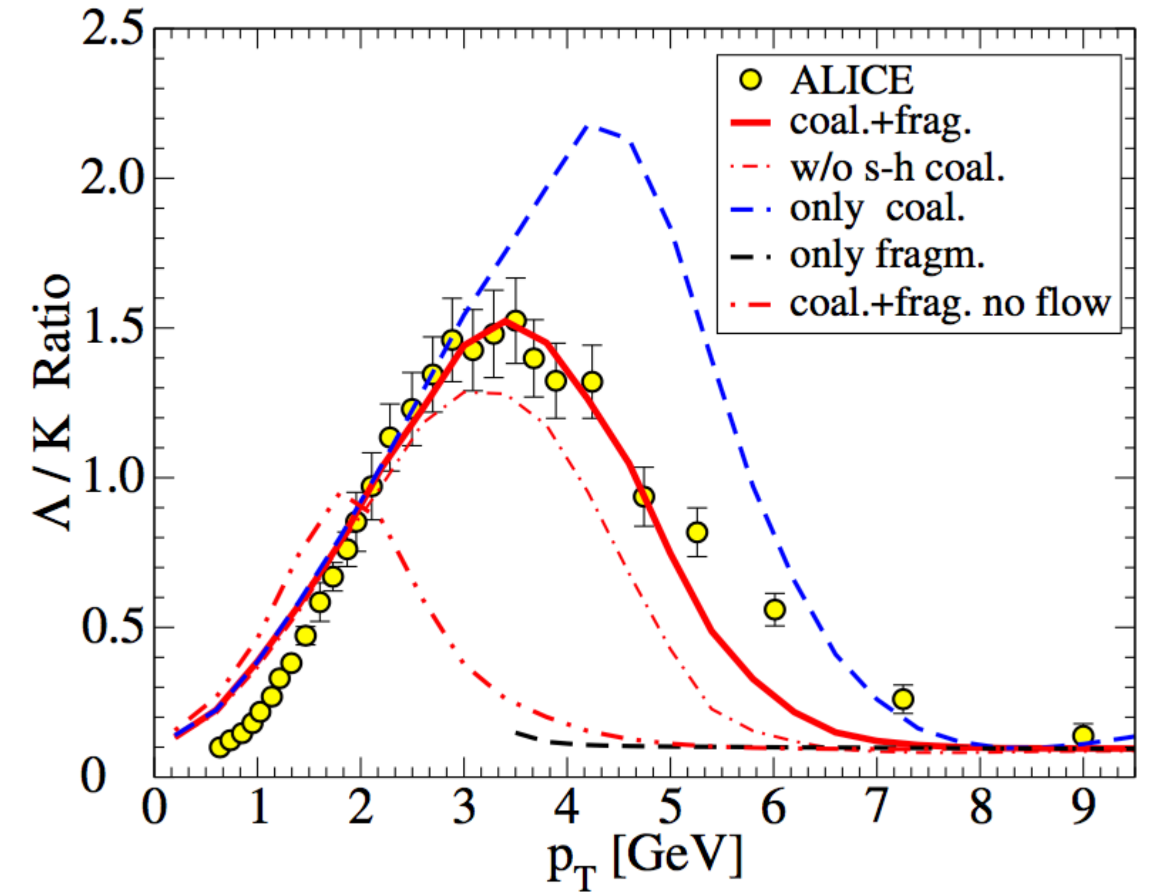
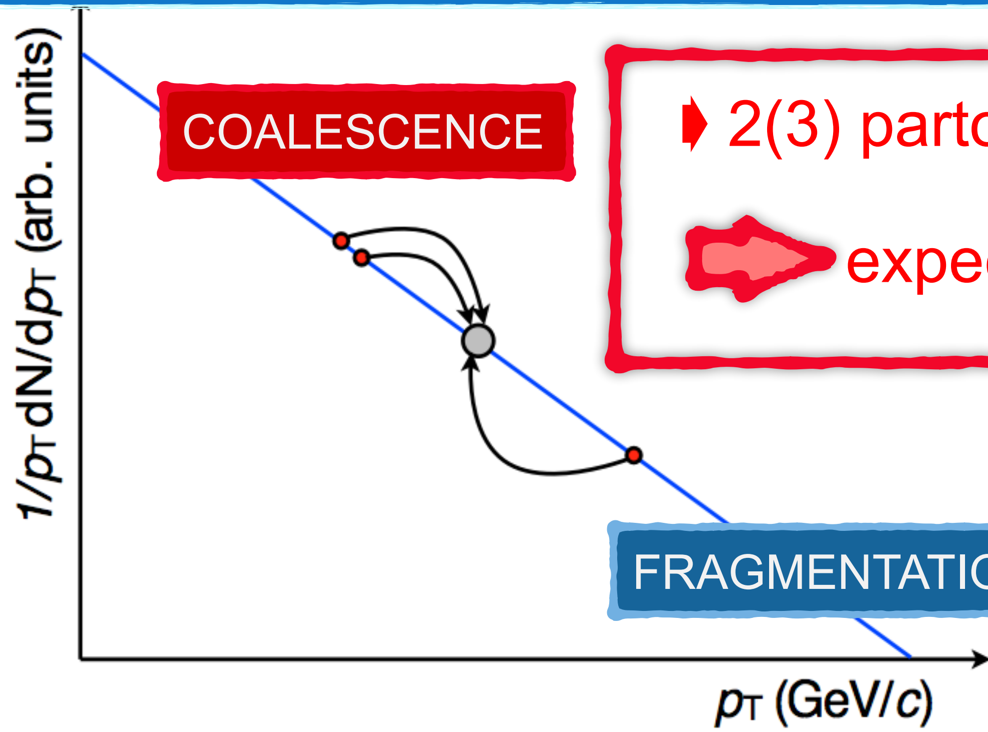




V.Minissale et al., Phys.Rev. C92 (2015) no.5, 054904

Hadronization



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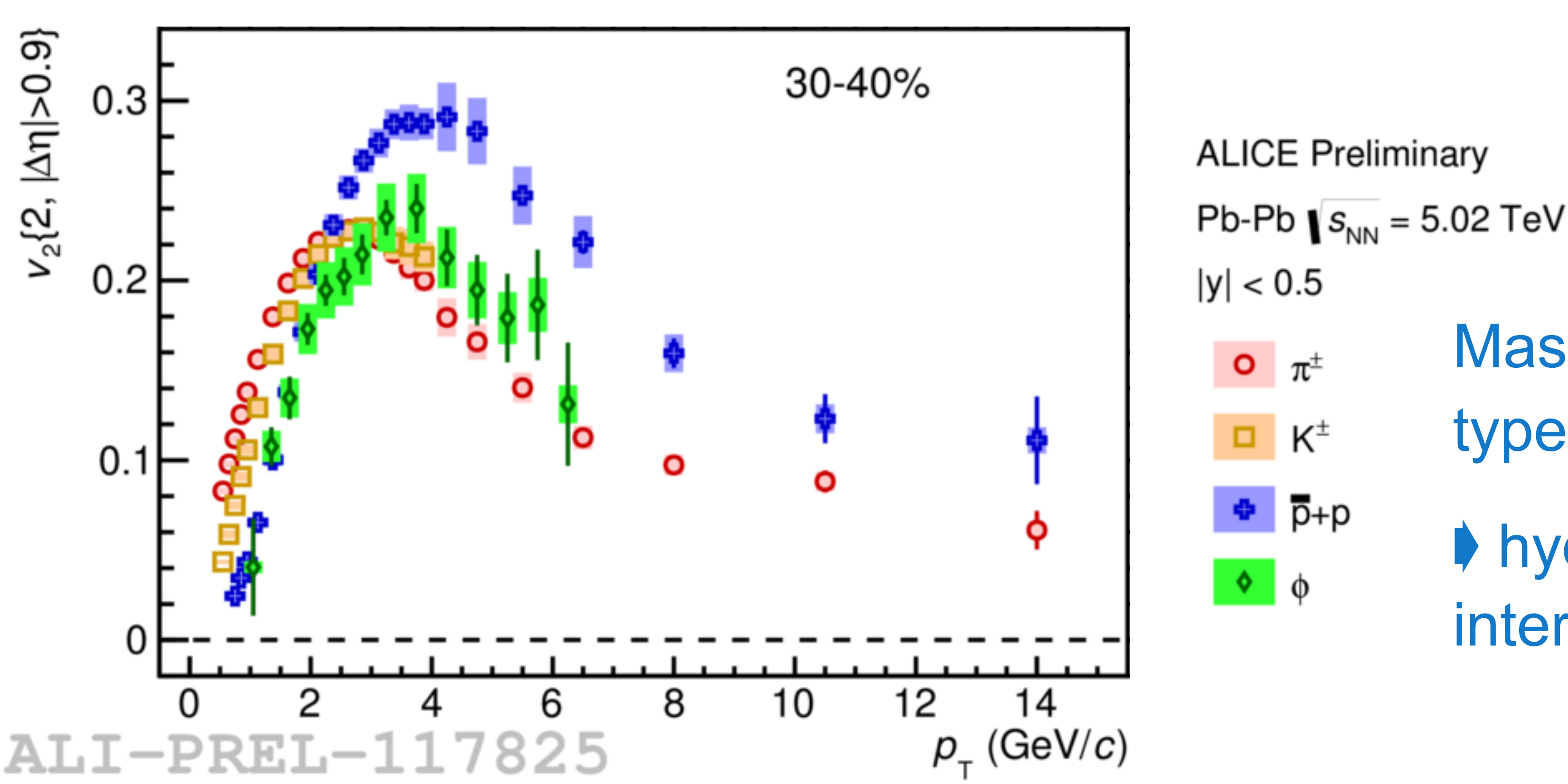


Mass ordering for p_T<2 GeV/c, particle type dependence for p_T>3 GeV/c

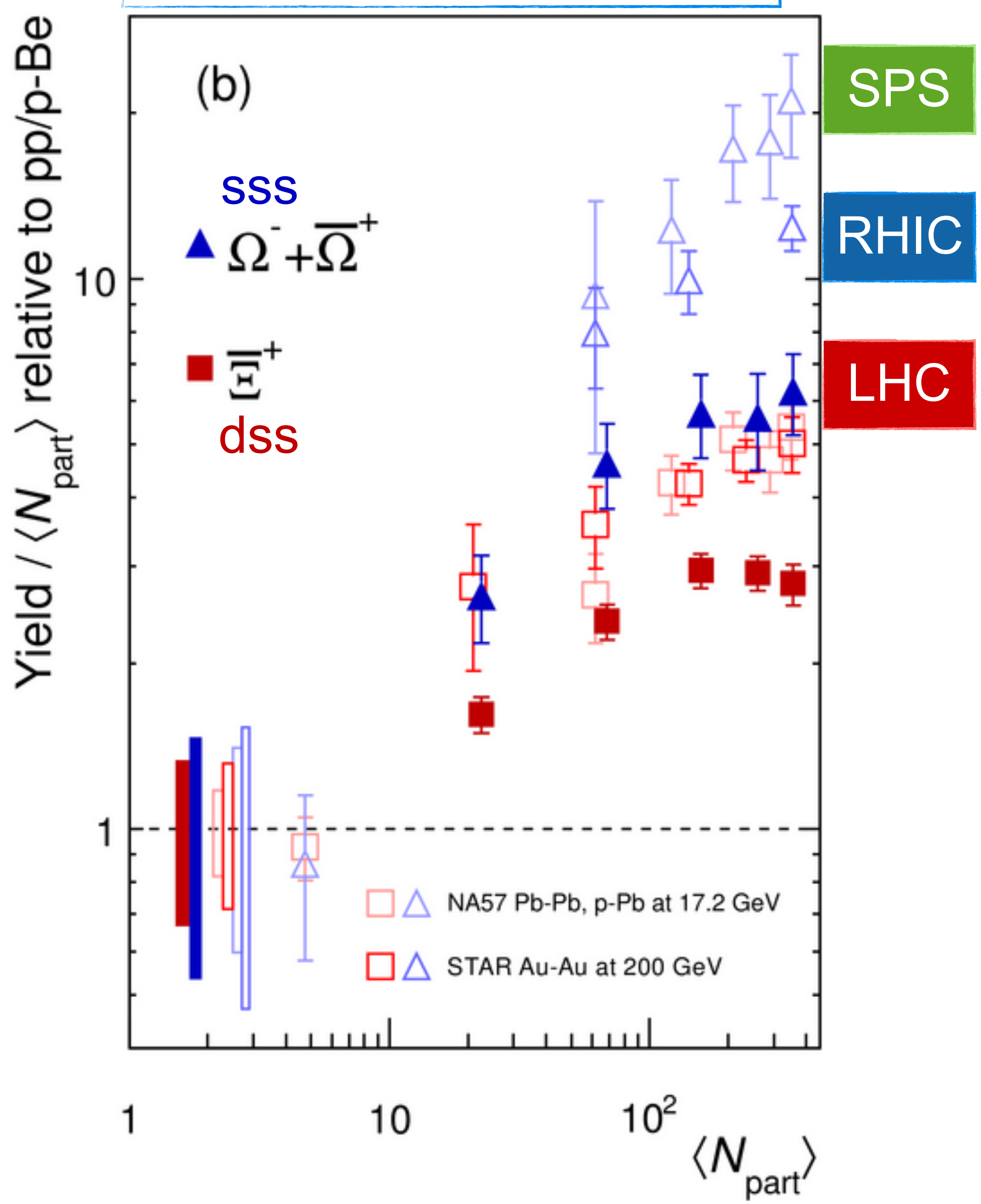
- hydro at low-p_T and coalescence at intermediate p_T

Strangeness

Rafelski, Muller, PRL 48 (1982) 1066

Enhancement of strangeness production in QGP w.r.t. hadron gas

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



Enhancement of strange baryons production in A-A relative to pp (p-A) collisions

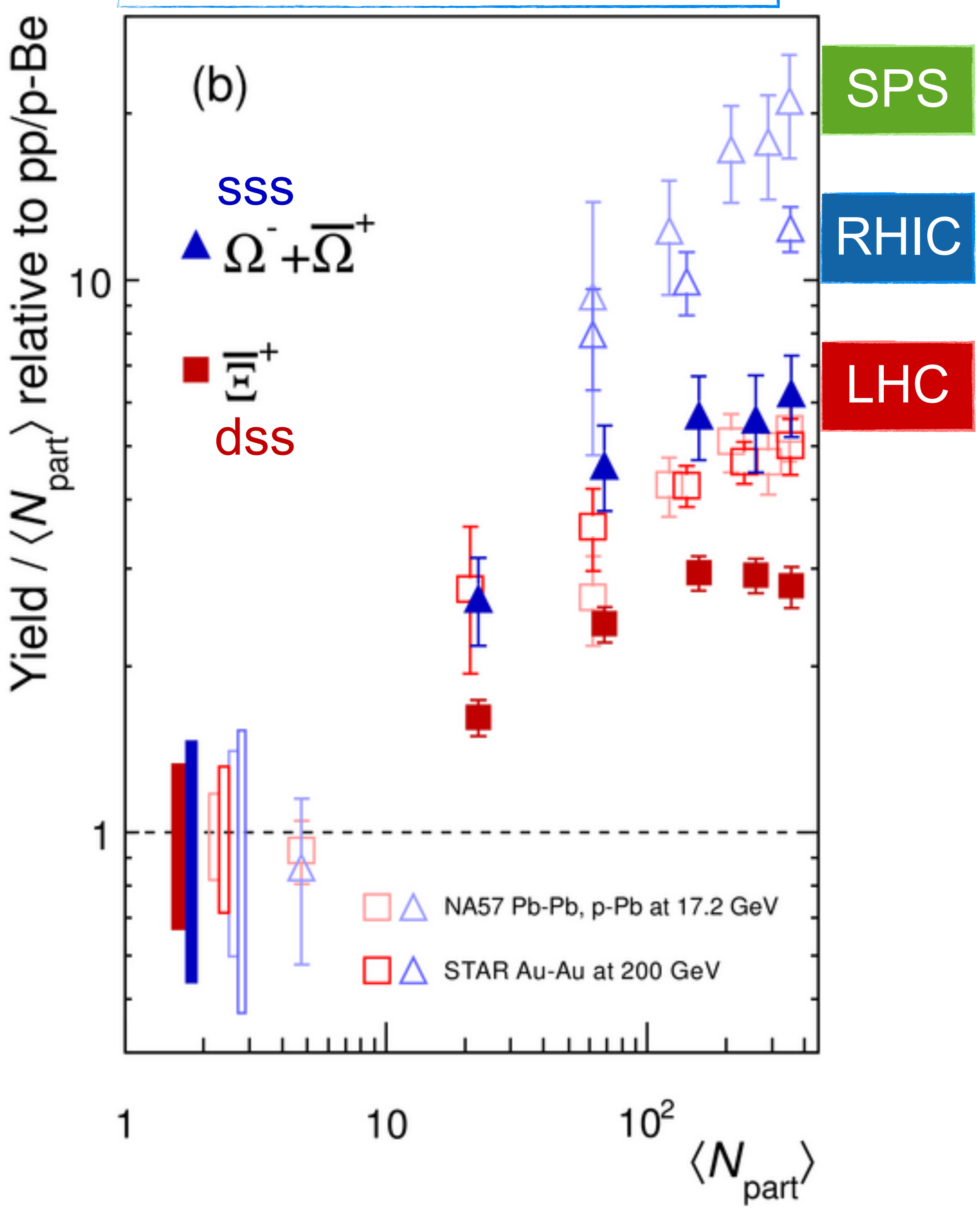
- reduced with increasing $\sqrt{s}$
- increased with s quark content

Strangeness

Rafelski, Muller, PRL 48 (1982) 1066

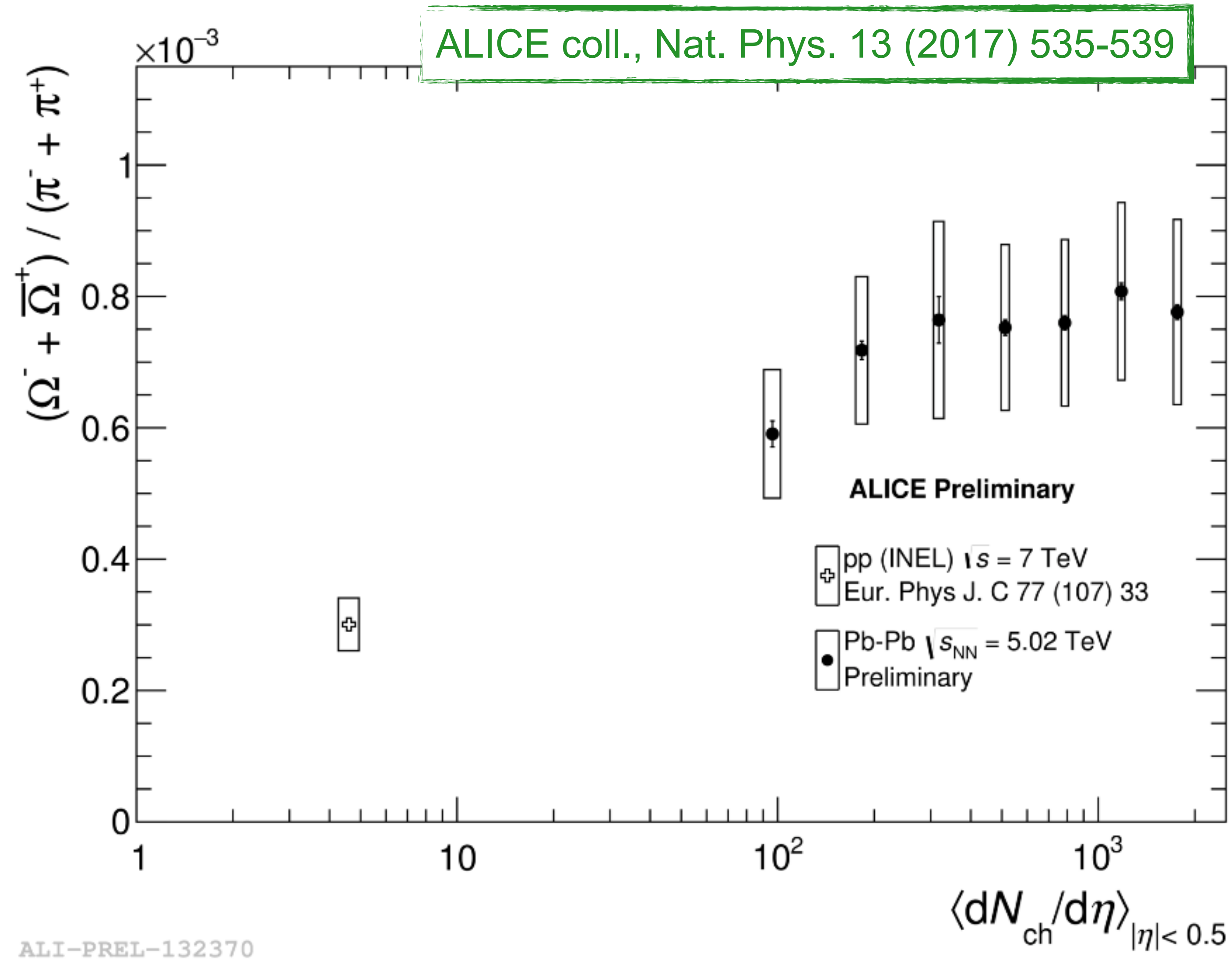
Enhancement of strangeness production in QGP w.r.t. hadron gas

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



Enhancement of strange baryons production in A-A relative to pp (p-A) collisions

ALICE coll., Nat. Phys. 13 (2017) 535-539



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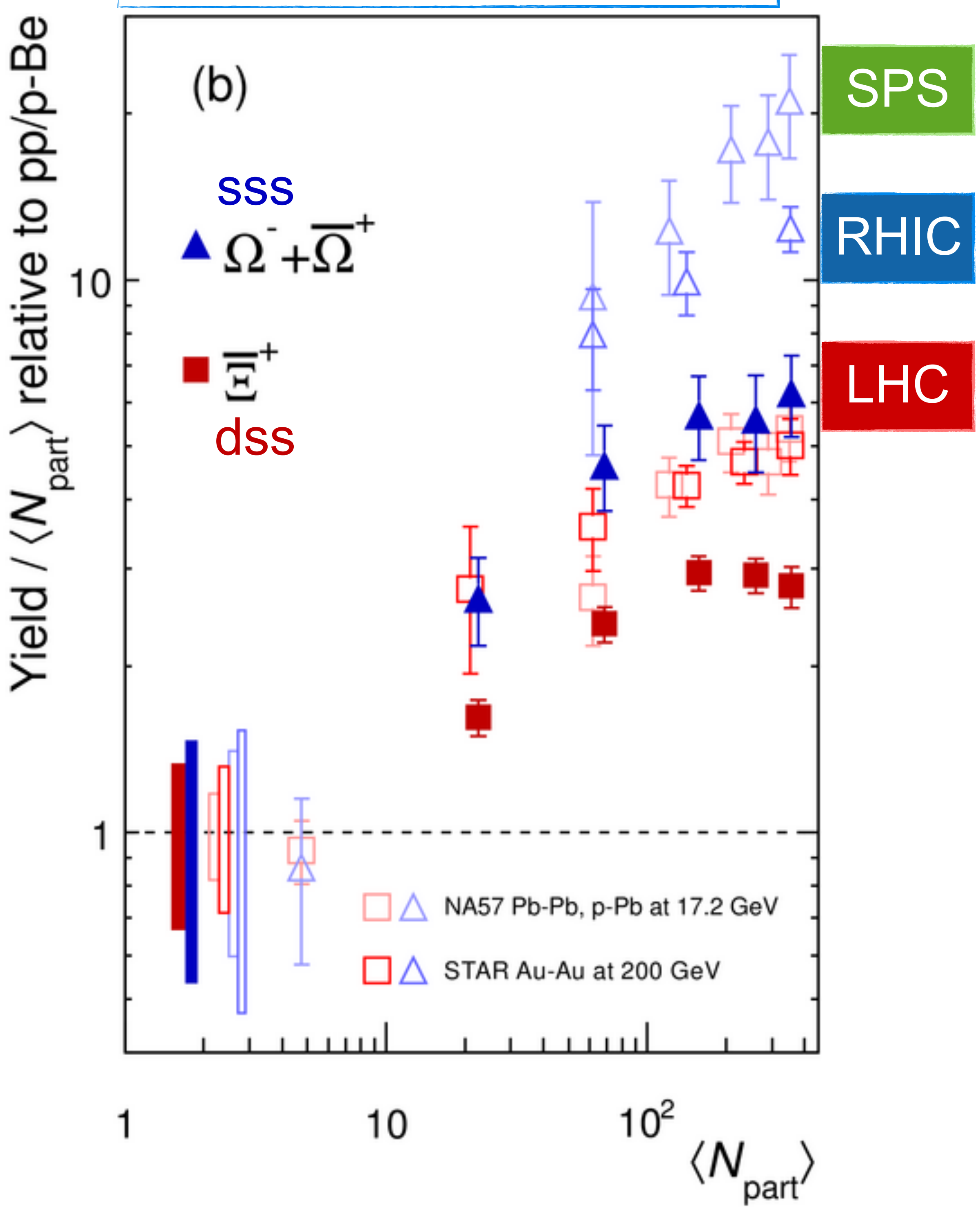

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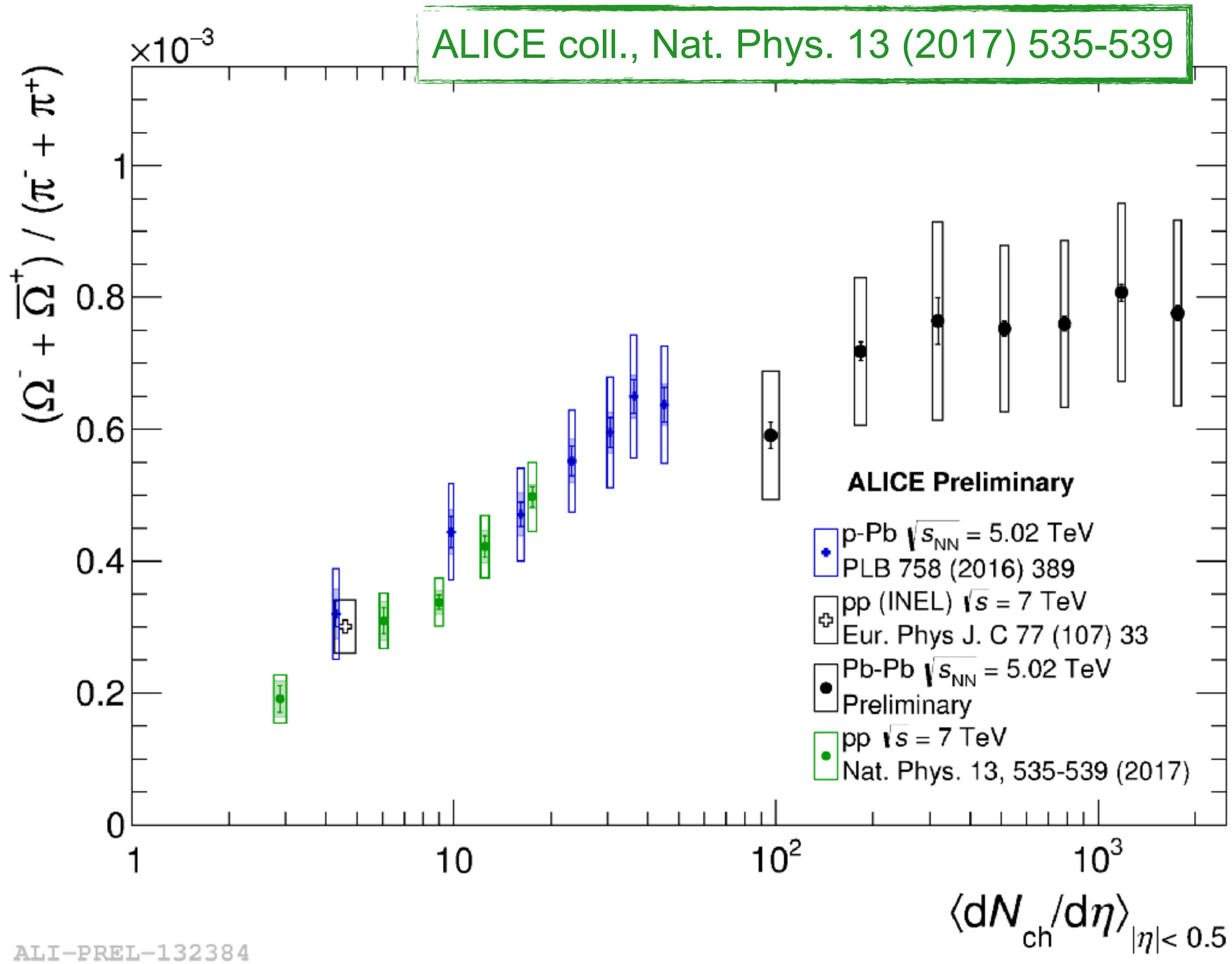
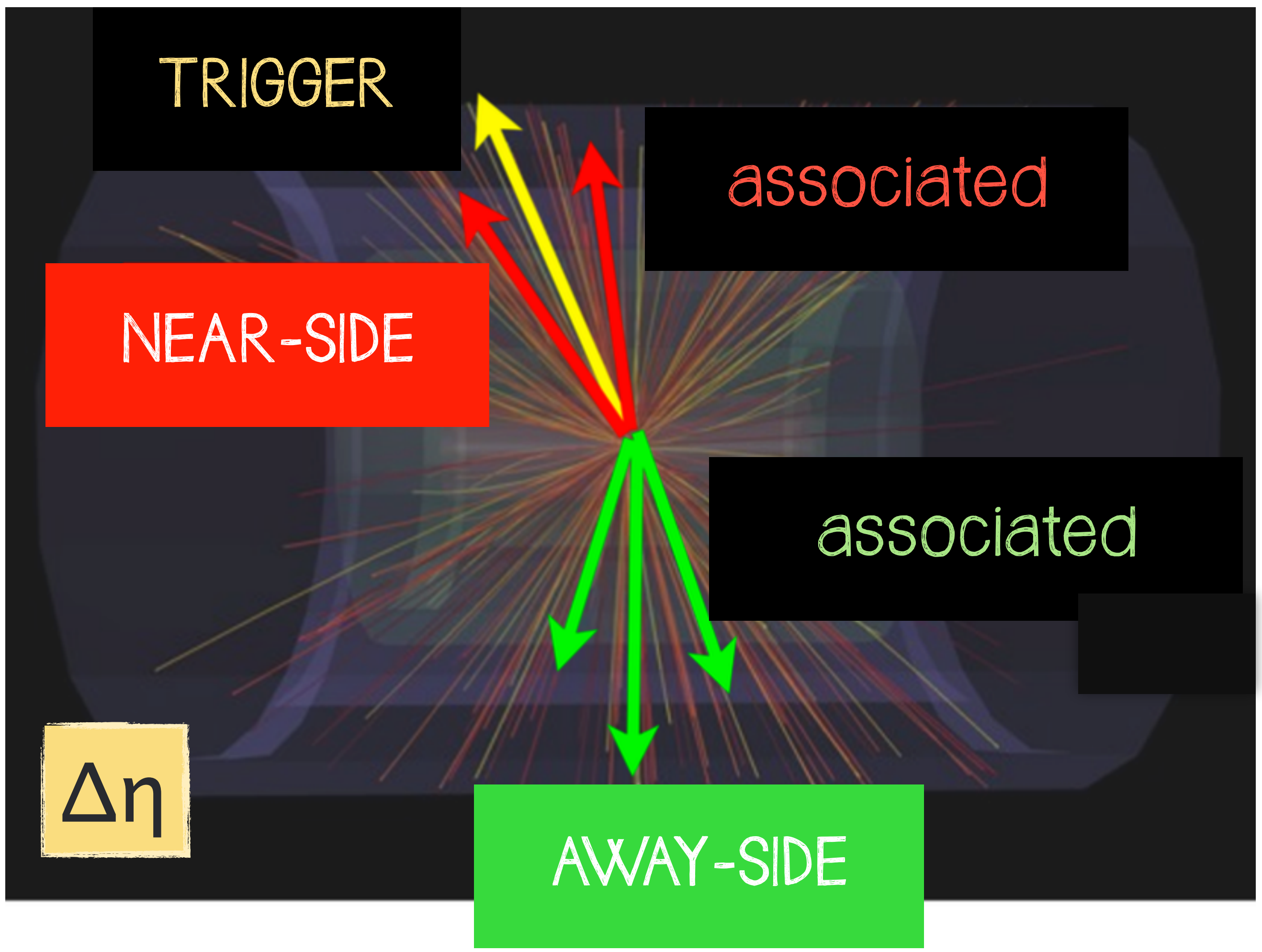
ALICE coll., Nat. Phys. 13 (2017) 535-539

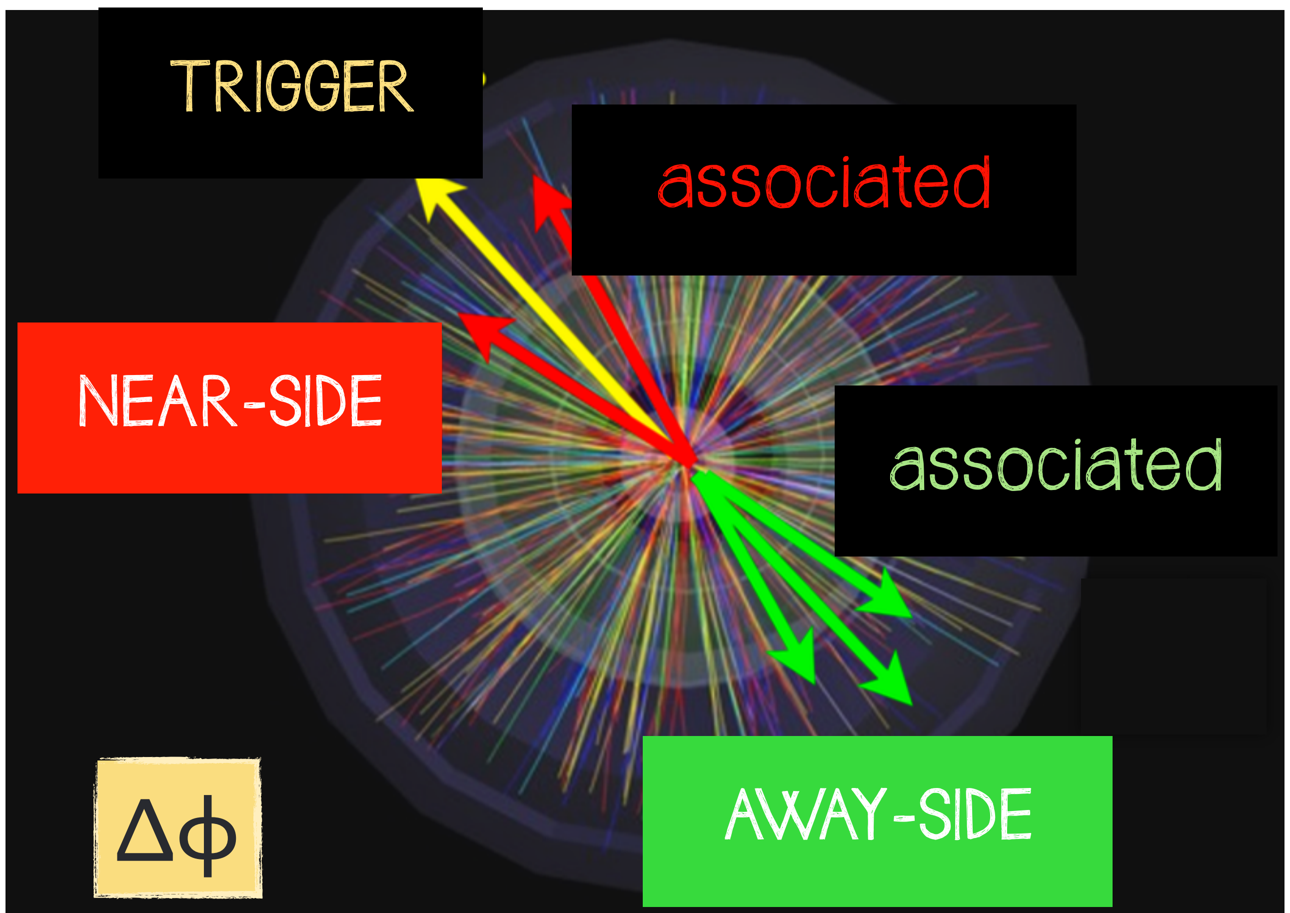


smooth "transition" from pp to p-Pb to Pb-Pb
➧ driven by multiplicity?

Two-particle correlations

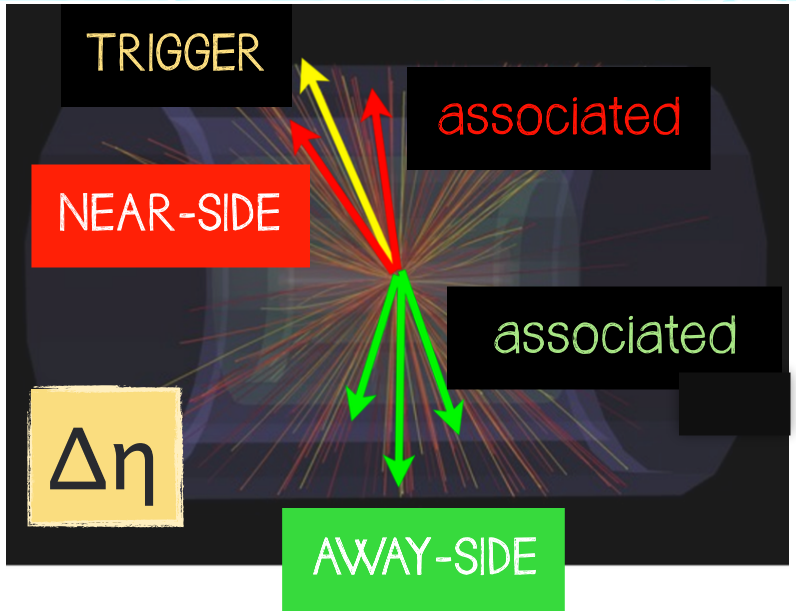
Distributions of relative angles $\Delta\phi$ and $\Delta\eta$ between pairs of particles: TRIGGER particle in a certain $p_{T,trig}$ interval and ASSOCIATED particles in a $p_{T,assoc}$ range

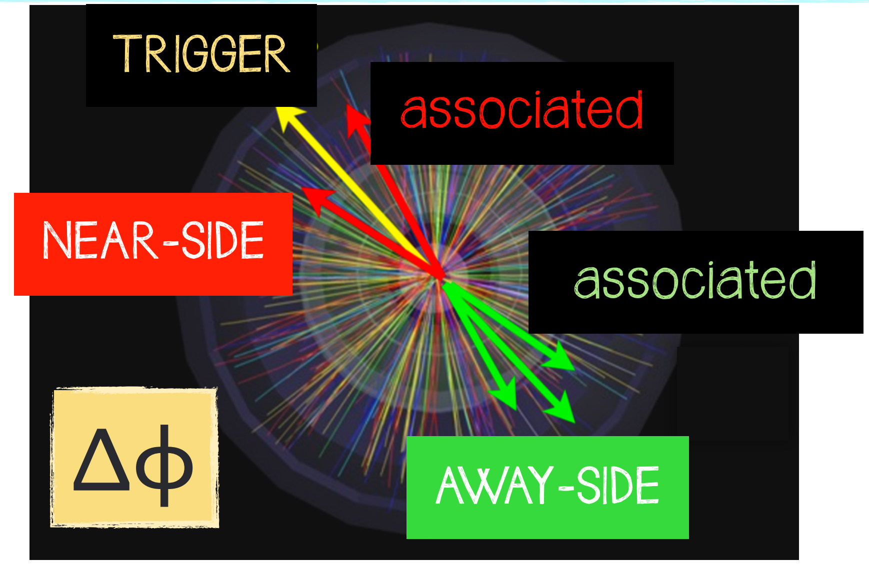


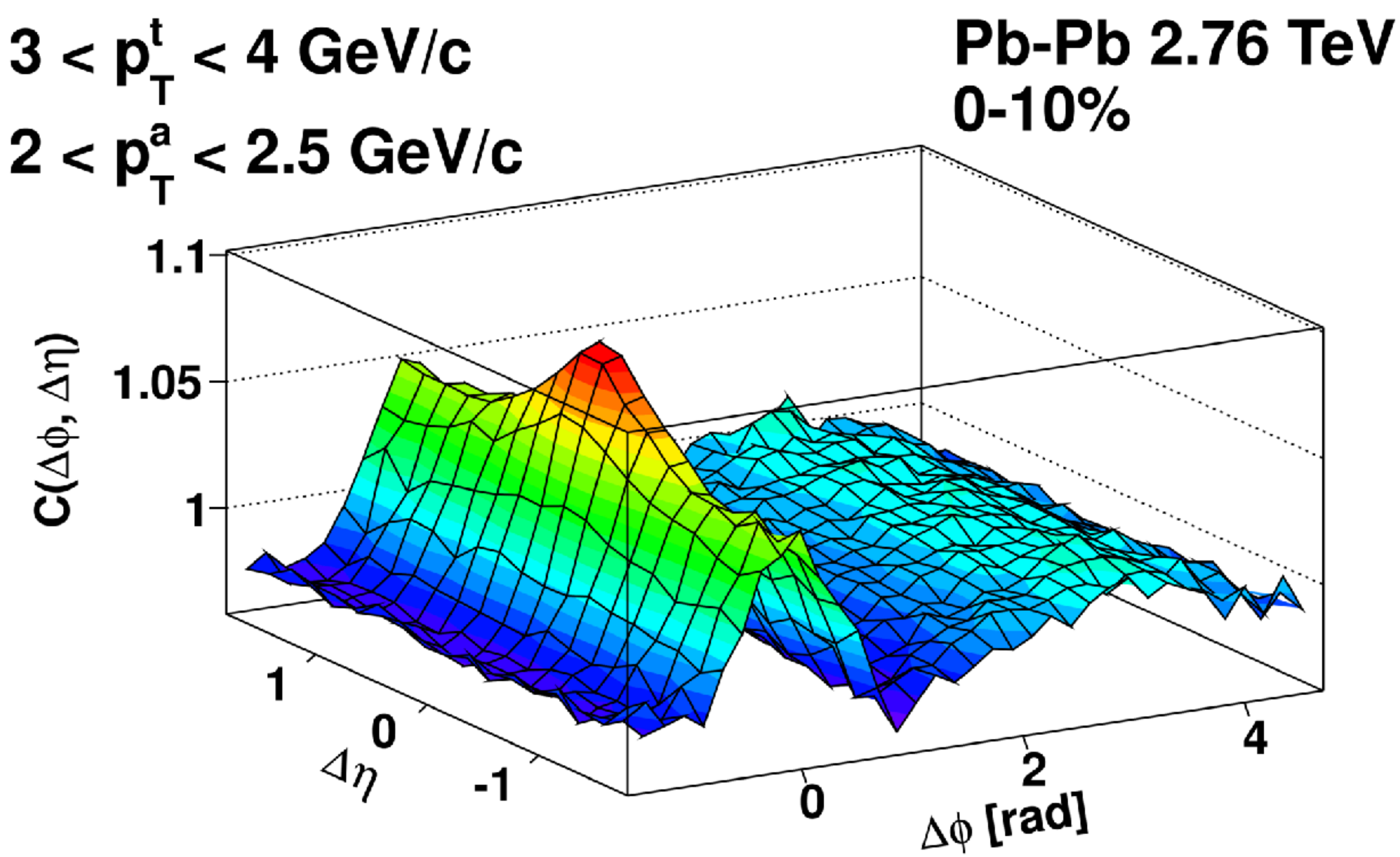


- test long range correlations between particles

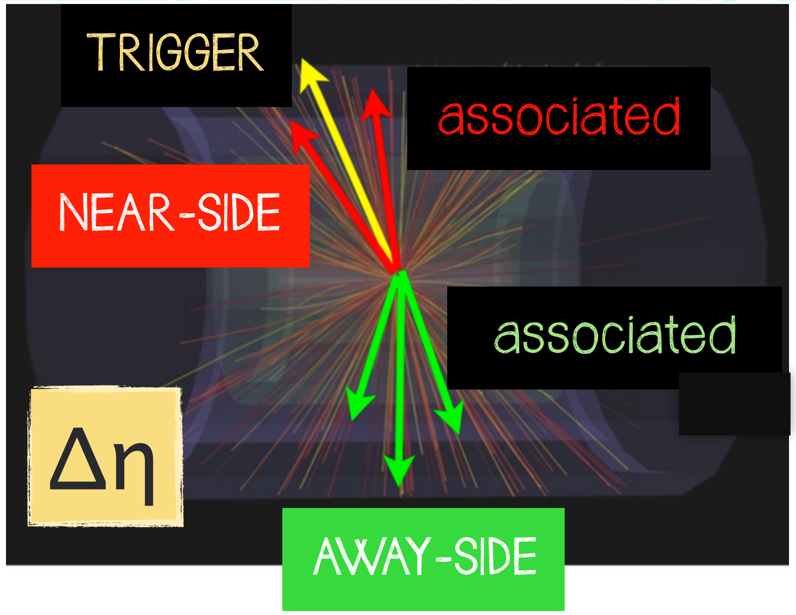
Two-particle correlations

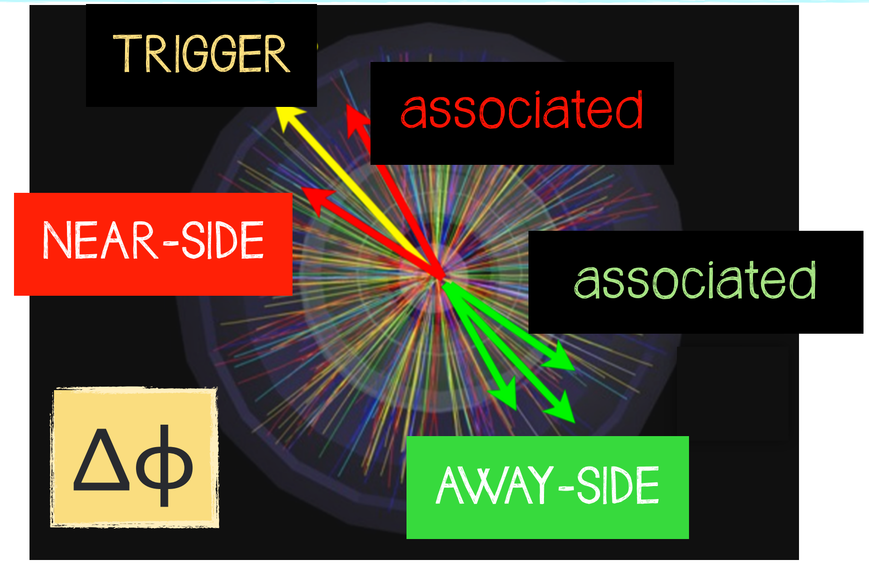


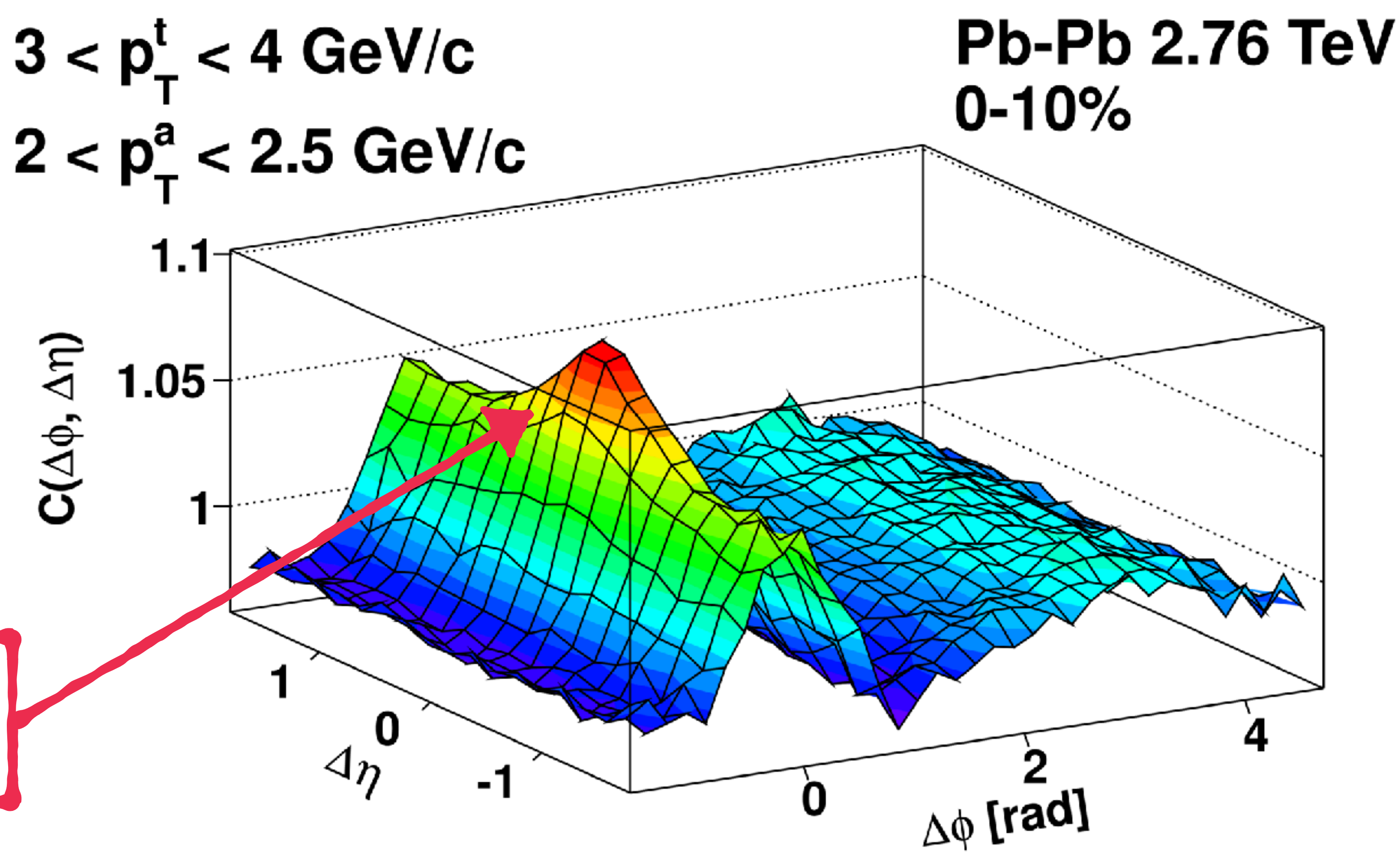




Two-particle correlations

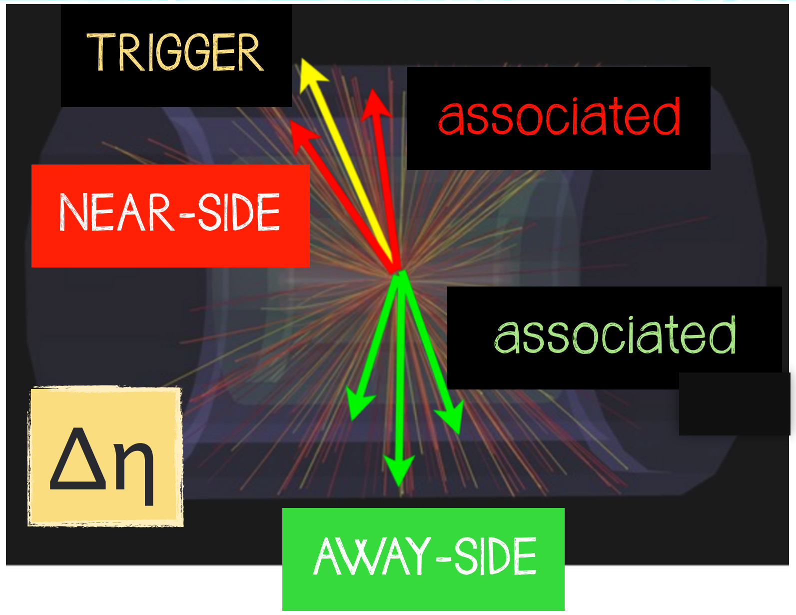


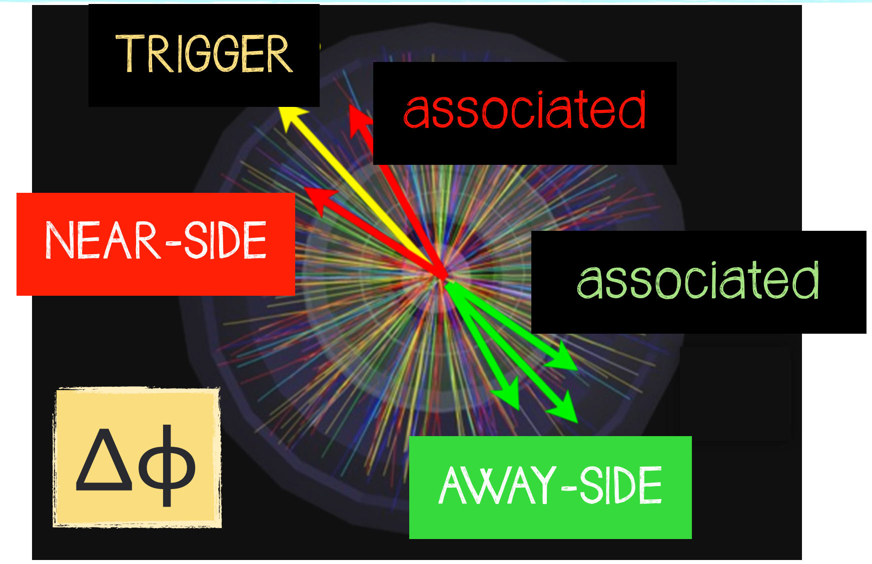




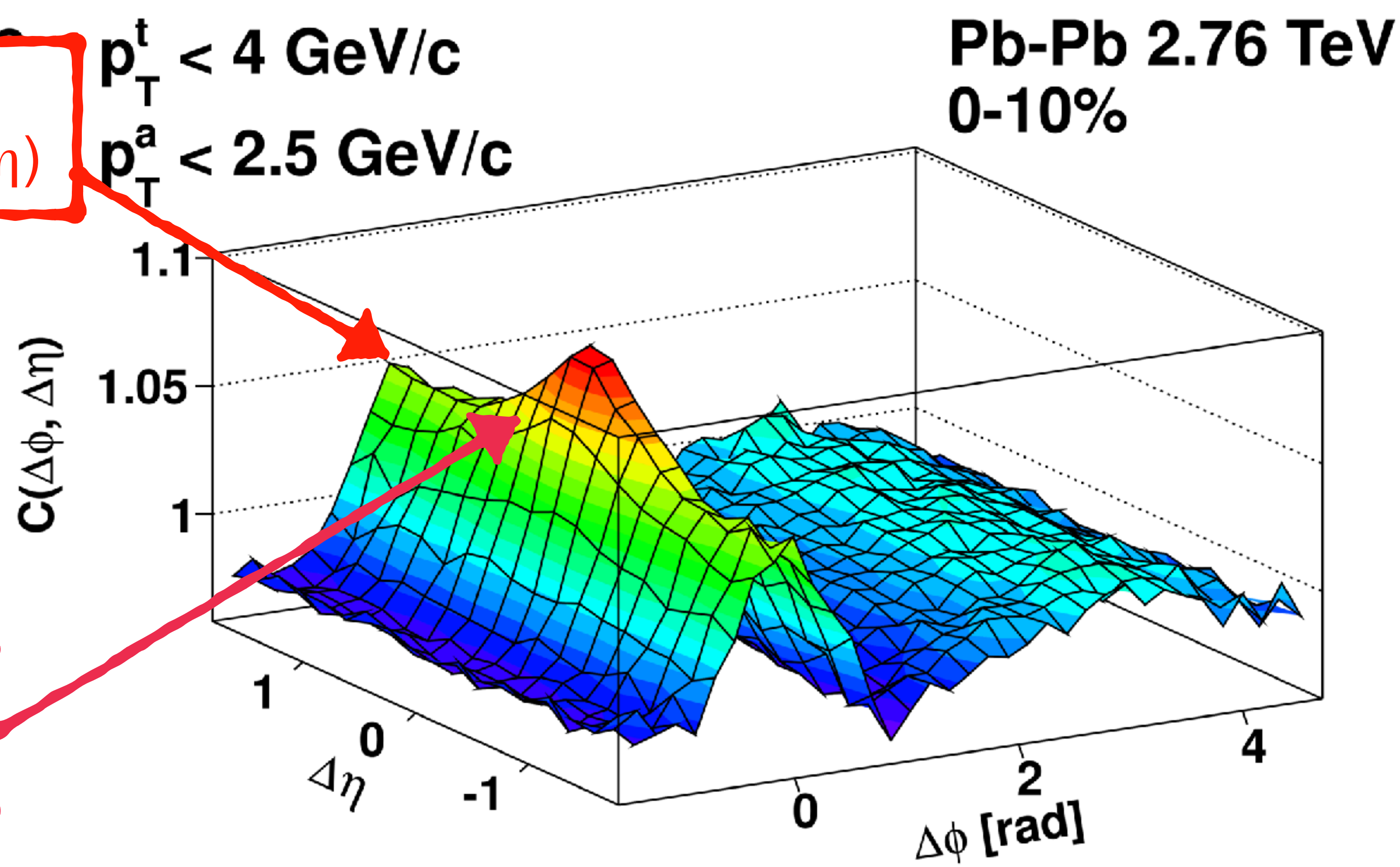
Near-side jet peak
(Δφ ~ 0, Δη ~ 0)

Two-particle correlations



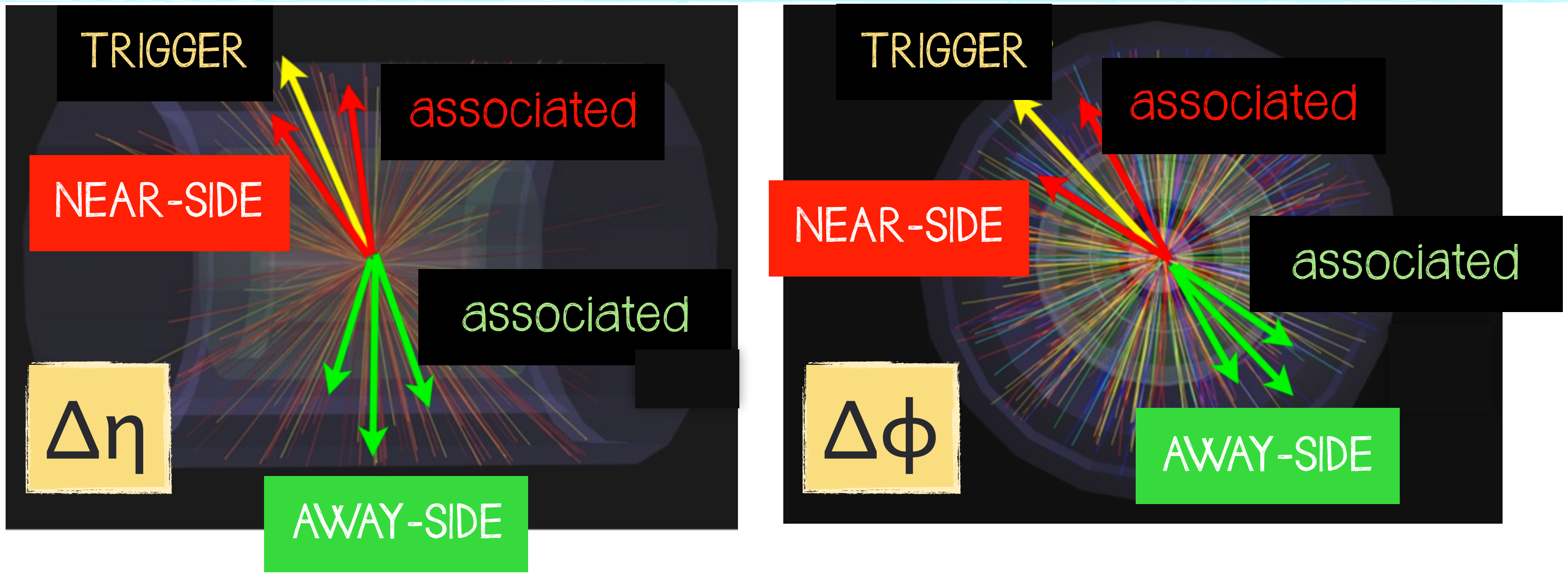


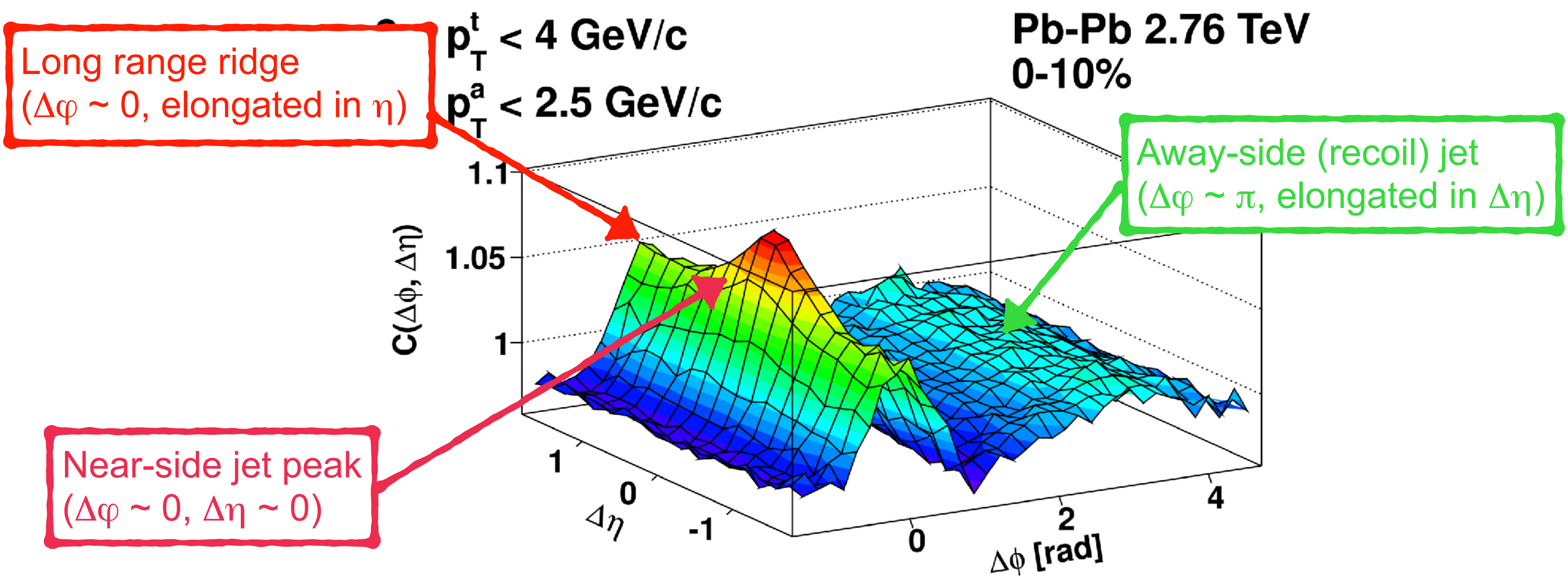
Long range ridge
($\Delta\varphi \sim 0$, elongated in η)



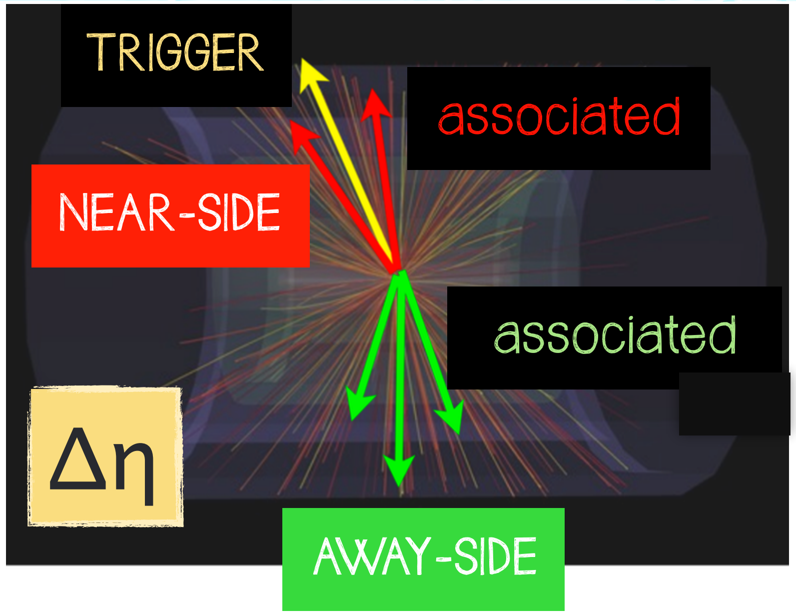
Near-side jet peak
($\Delta\varphi \sim 0$, $\Delta\eta \sim 0$)

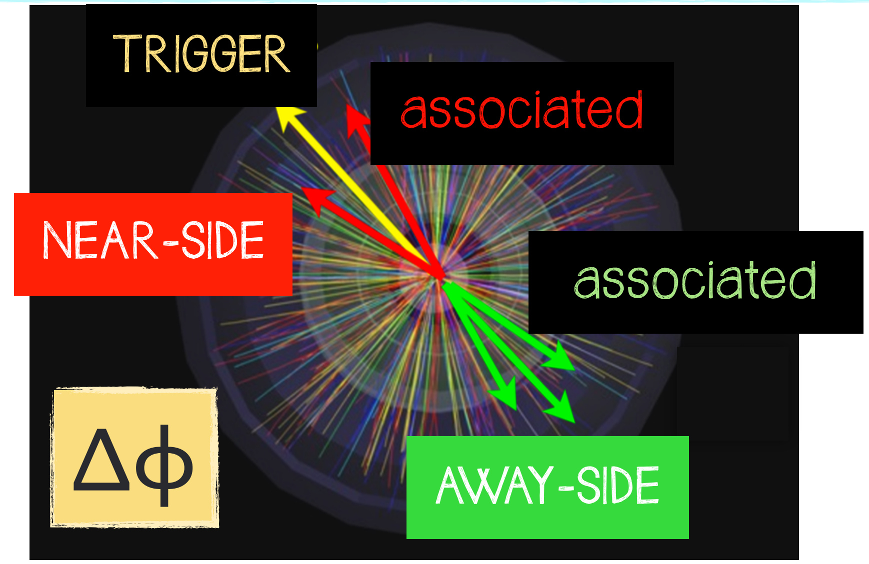
Two-particle correlations

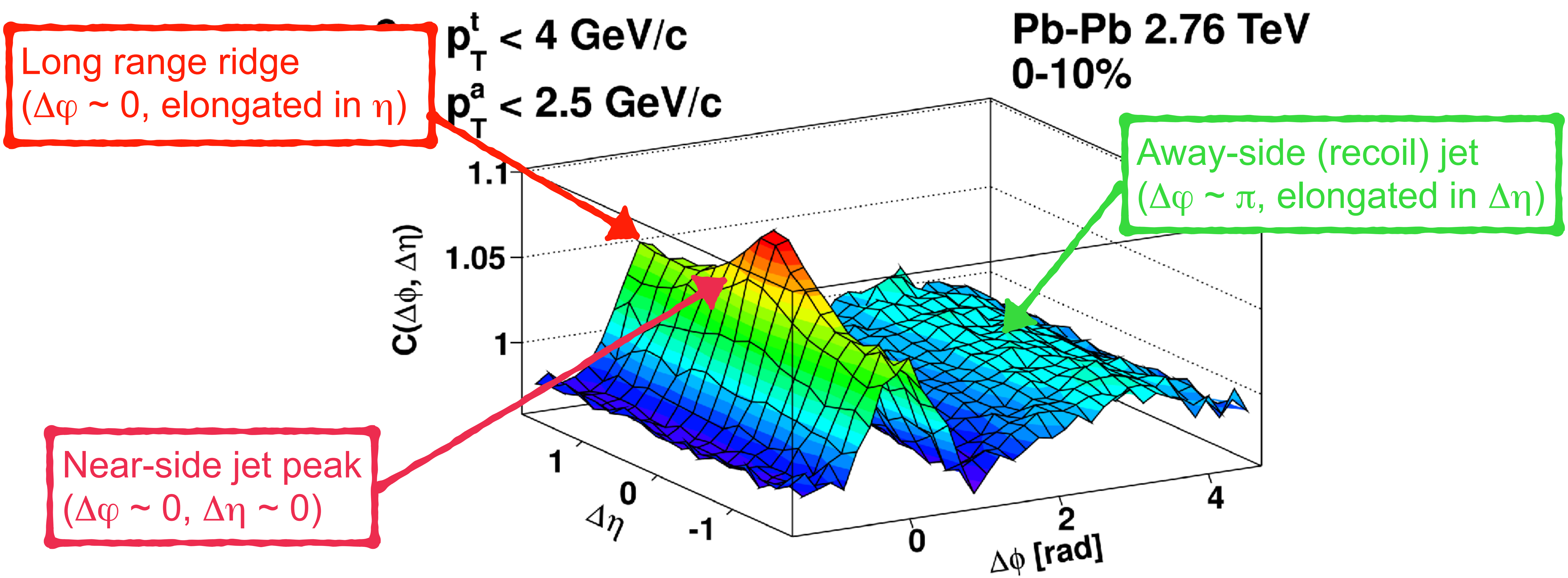




Two-particle correlations



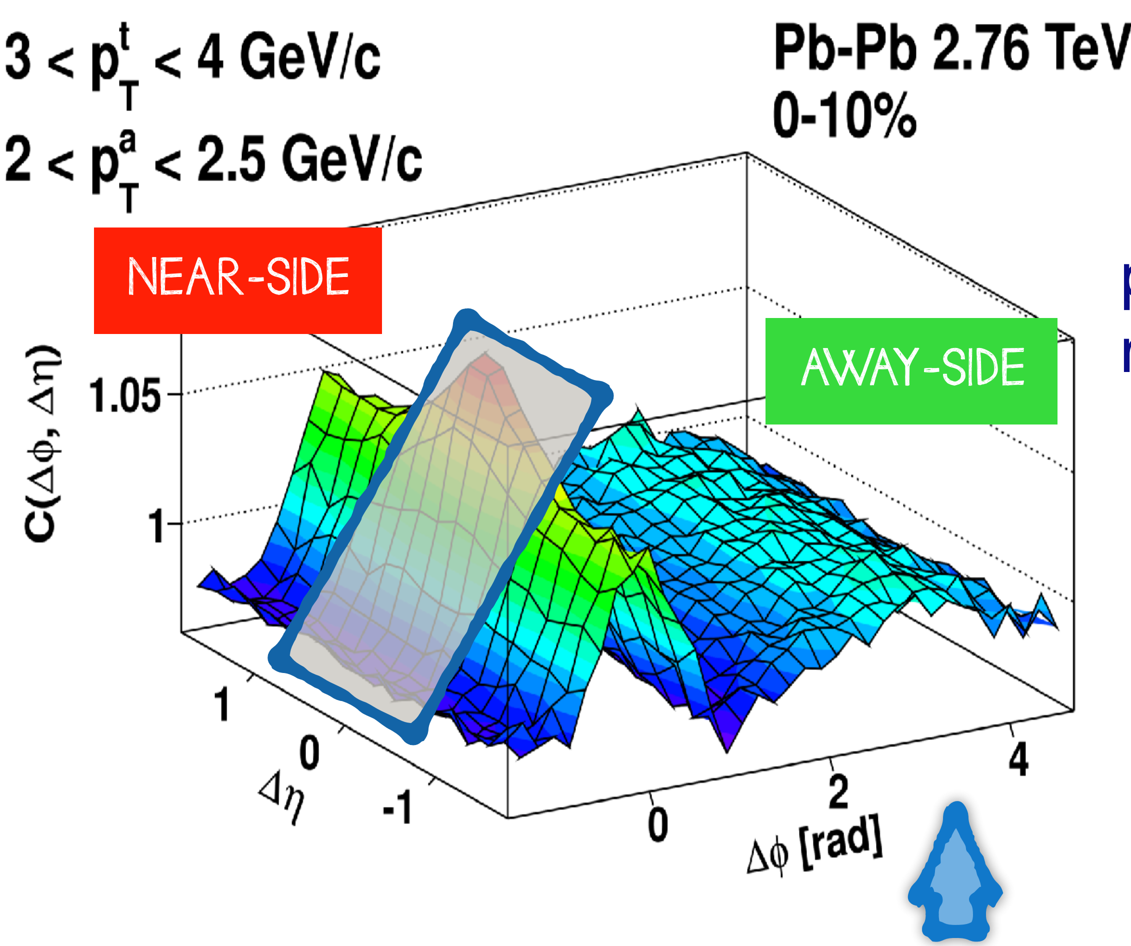




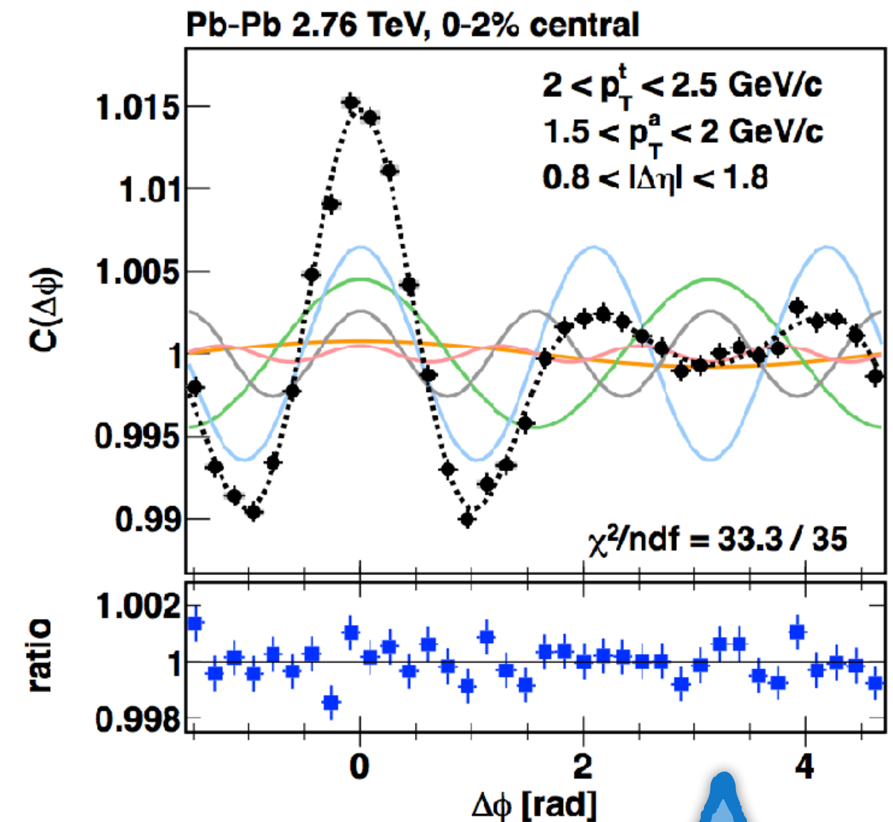
long range "ridges" in Δη ➧ evidence of collective behavior in the dense medium

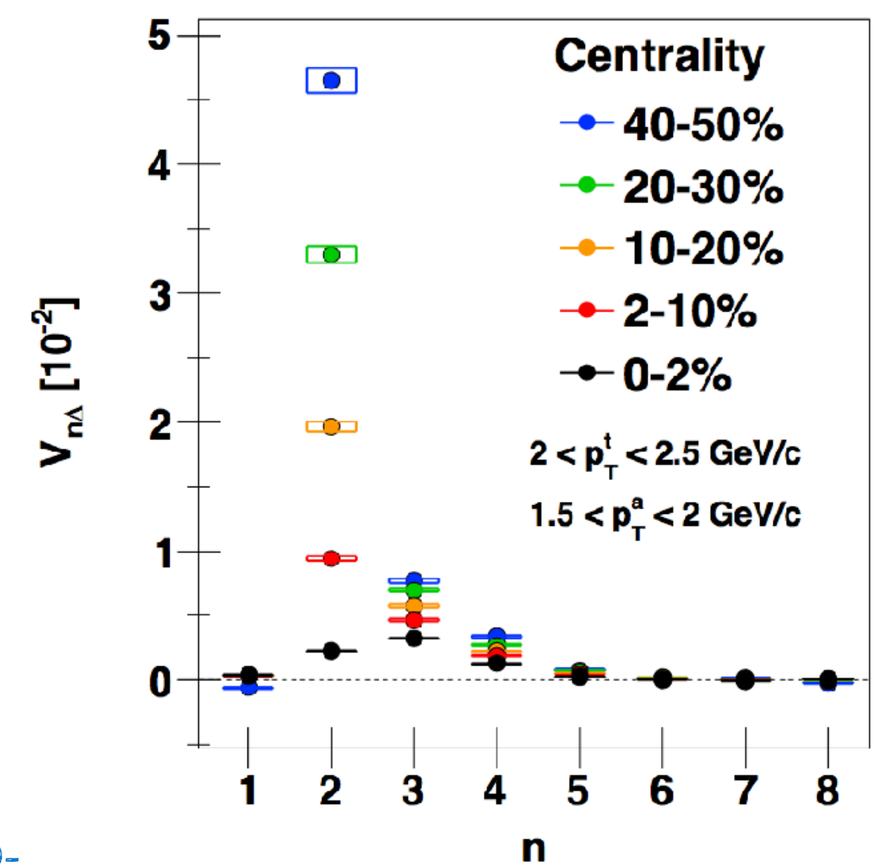
Long range correlations

ALICE coll., Phys. Lett. B 708 (2012) 249



project along ϕ
removing jet peak





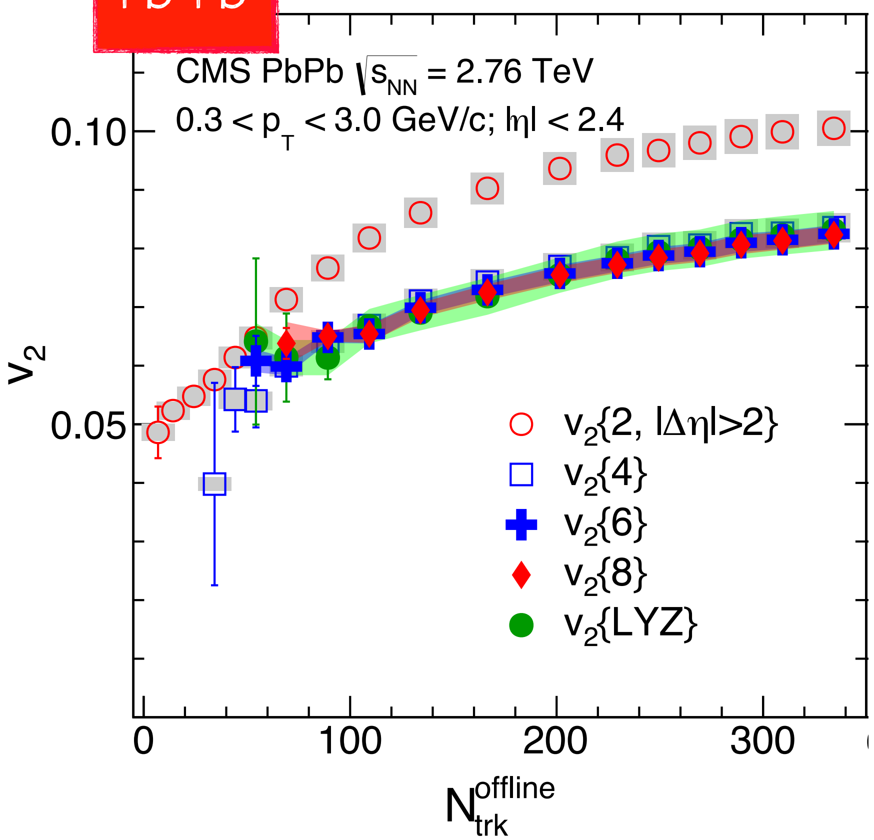
Decomposition of correlations (after jet peak subtraction) in Fourier harmonics
➧ extract $v_n(p_T)$ from 2-particle correlations

Multi-particle correlations

Multi-particle correlations ➧ contribution from jet fragmentation strongly suppressed

CMS coll., PRL 115, 012301 (2015)

Pb-Pb



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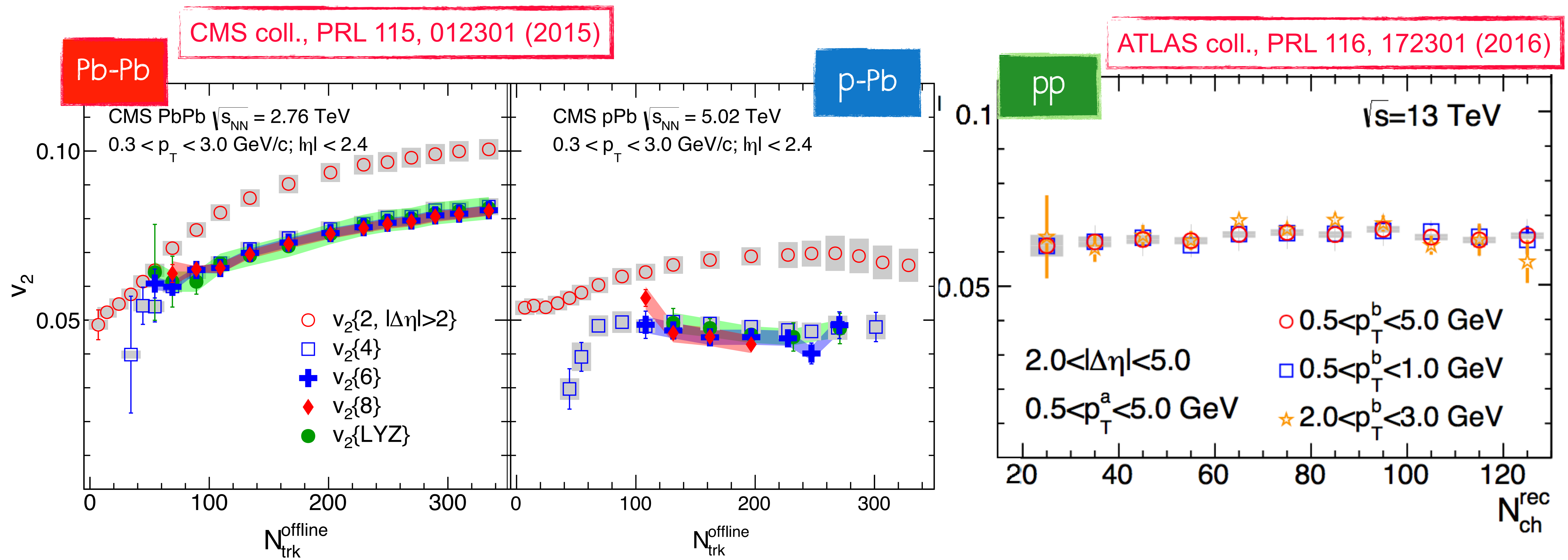


Large elliptic flow already in small system as p-Pb and high multiplicity pp collision

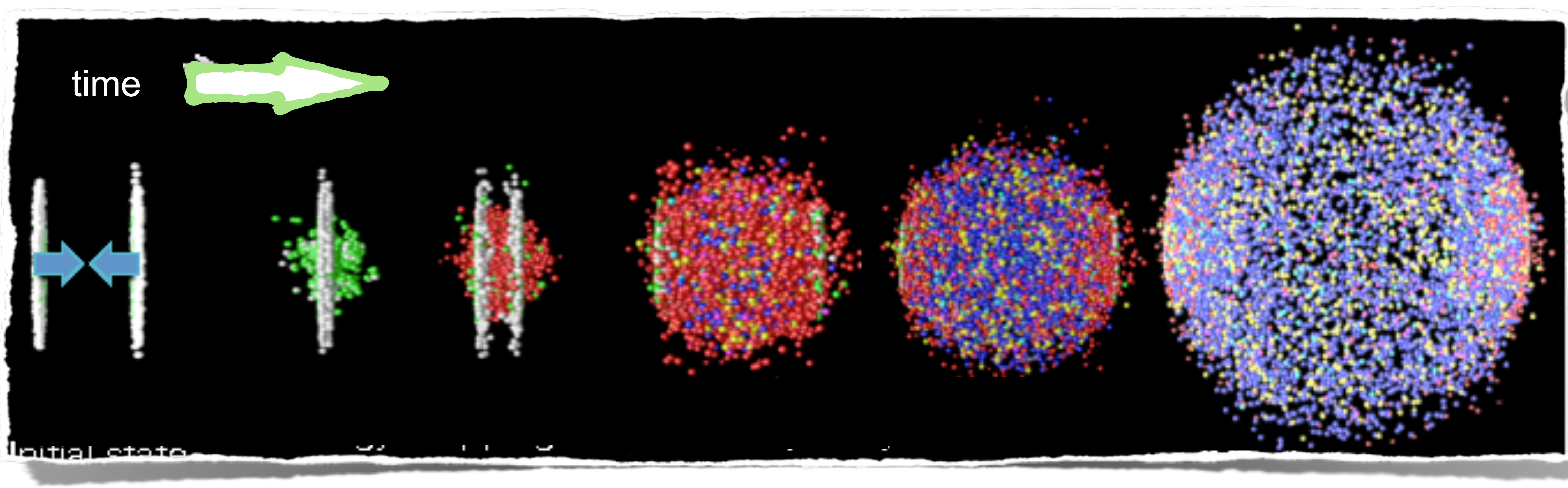
➧ hydrodynamics at work or partonic interactions?

➧ hydrodynamics assumptions at the edge of validity: $\lambda_{MFP}/L \sim 1$

Soft probes: what have we learnt?

- matter formed in the collision has very low η/s ratio, close to minimum value $1/4\pi$
- early thermalization
- multi-particle anisotropic flow ➧ soft particles flow
- long-range correlation in anisotropic flow ➧ system collective response to initial fluctuations

A strongly coupled nearly perfect liquid ➧ sQGP



Soft probes: what can we learn?

- ❑ pre-equilibrium: weakly or strongly coupled system?
- ❑ mechanism driving fast thermalization?
- ❑ QCD medium transport properties
- ❑ deviations from perfect fluid to understand underlying physics
- ❑ perfect fluid for all probes? Hard probes flow
- ❑ origin of strangeness enhancement? Flavor-dependent freeze-out?
- ❑ QGP in small systems? Same physic origin or only similar appearance? Do we need different models or different physics?

…what else?

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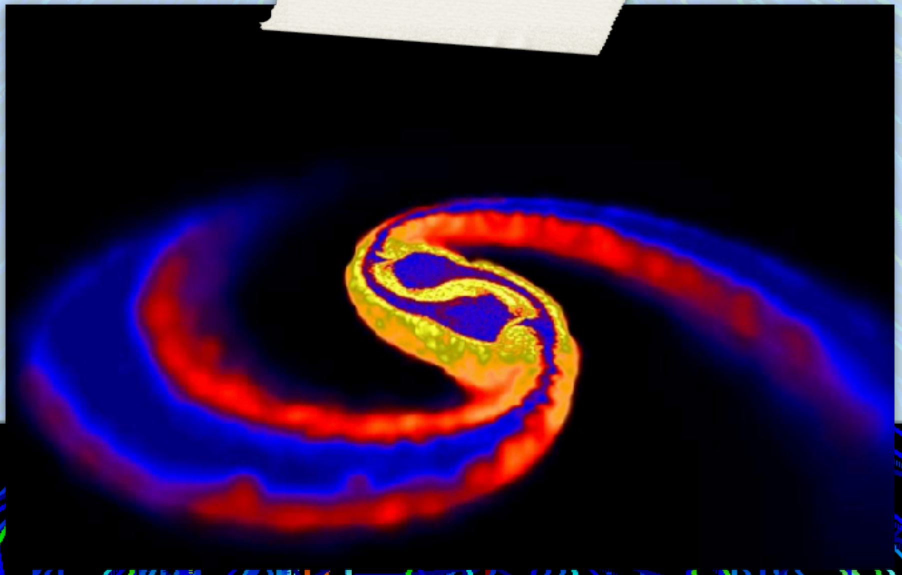
- QGP in small systems? Same physic origin or only similar appearance? Do we need different models or different physics?

...what else?

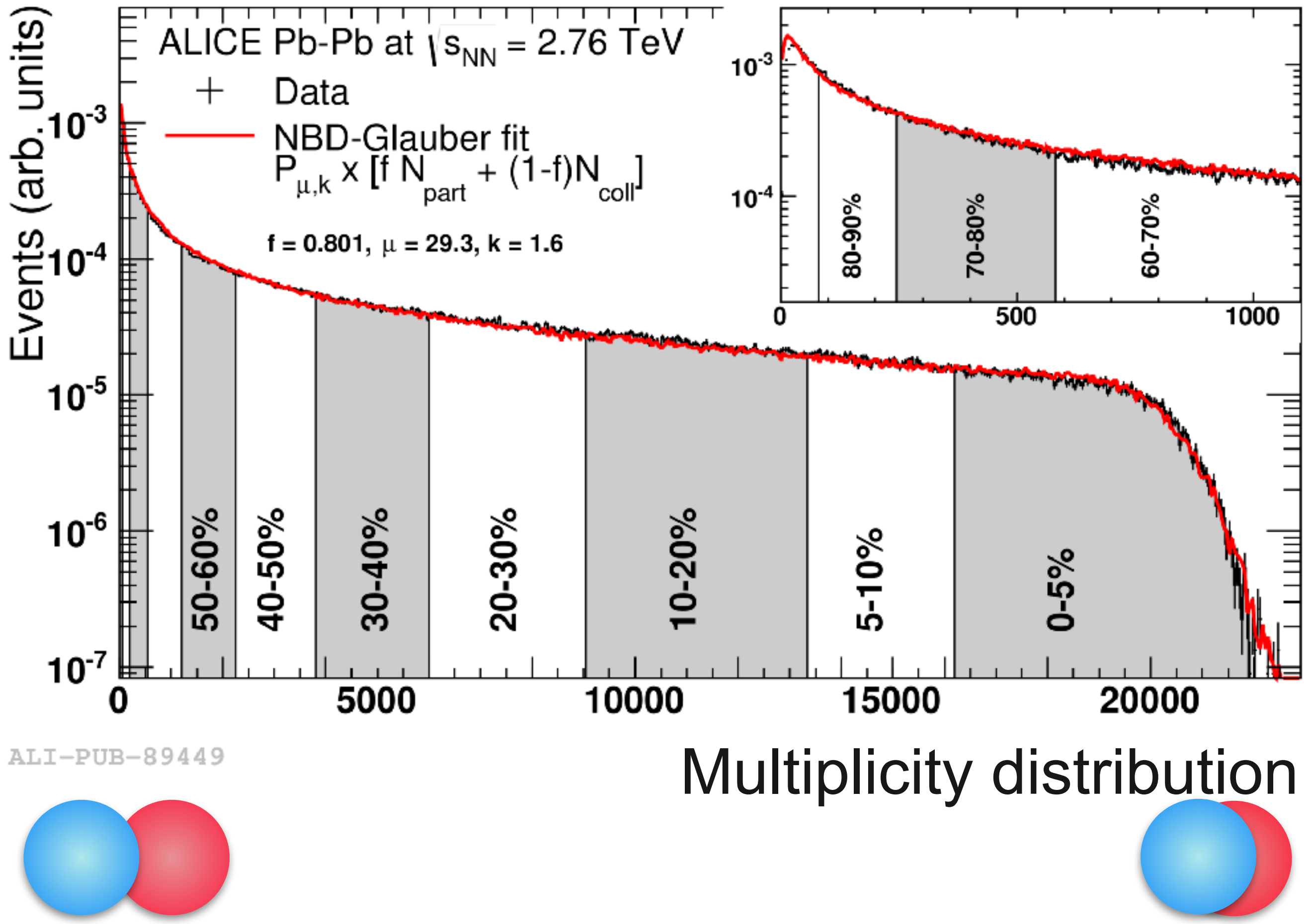


The end…

Centrality determination

Centrality determination

ALICE coll., Phys. Rev. C 88, 044909

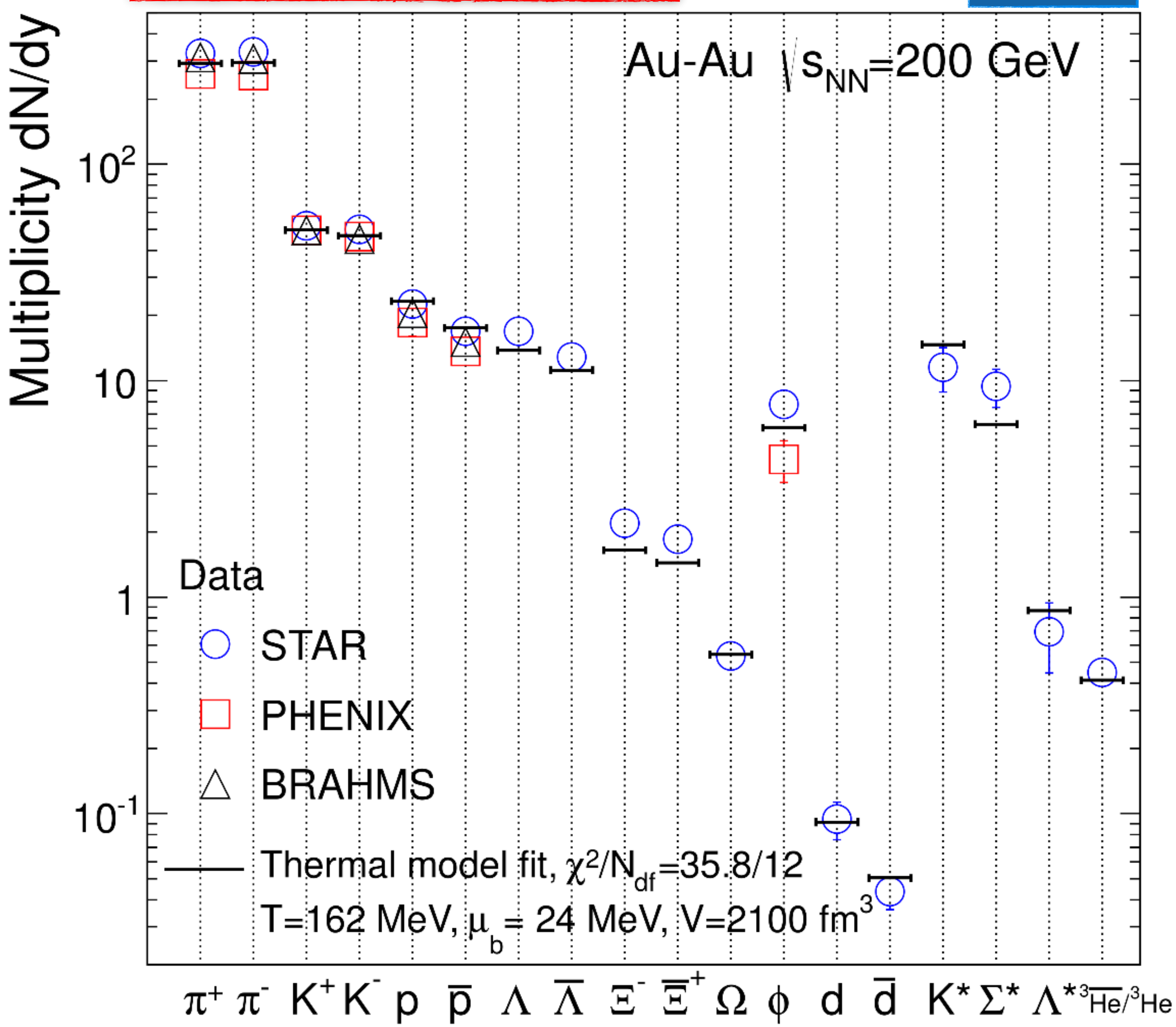


Measured charged particle multiplicity N_{ch}
assuming $\langle N_{ch} \rangle(b)$ increases monotonically with decreasing b
Glauber fit model
Define centrality classes selecting percentile of the measured distribution

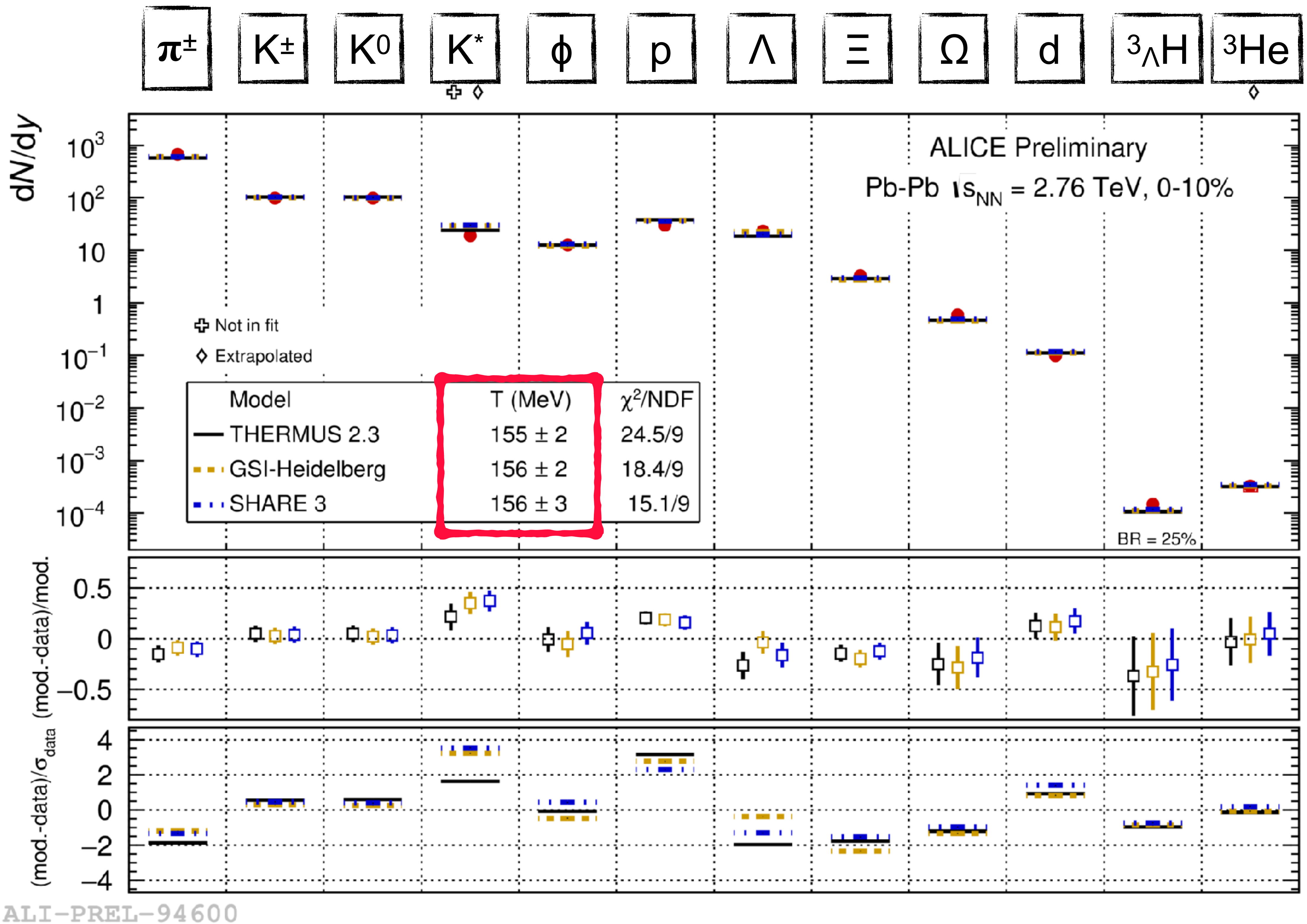
Statistical models

Nucl. Phys. A 904 (2013) 535-538

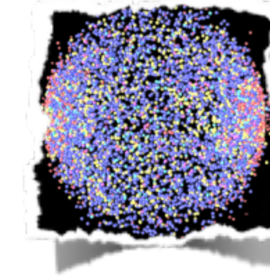
RHIC



Statistical models

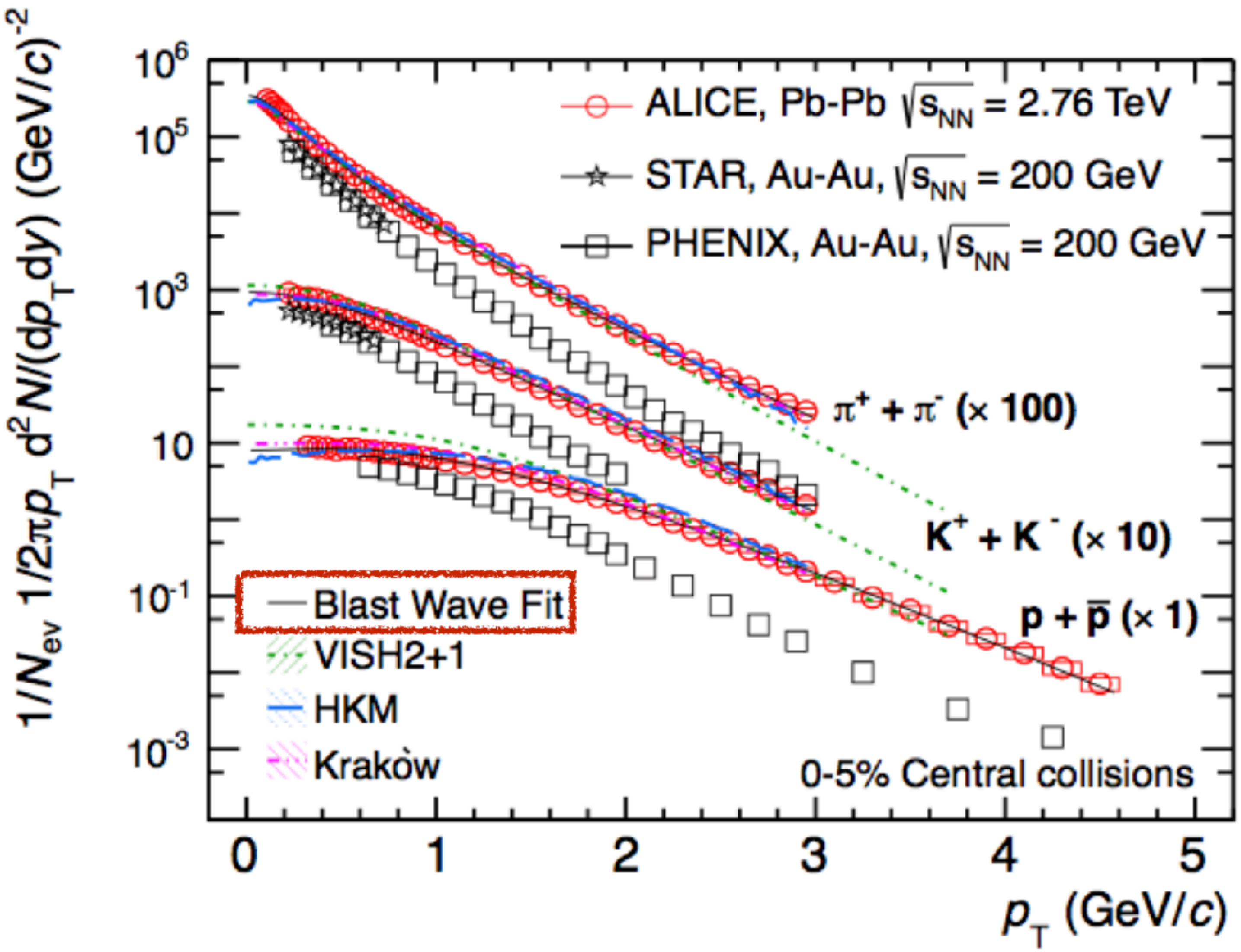


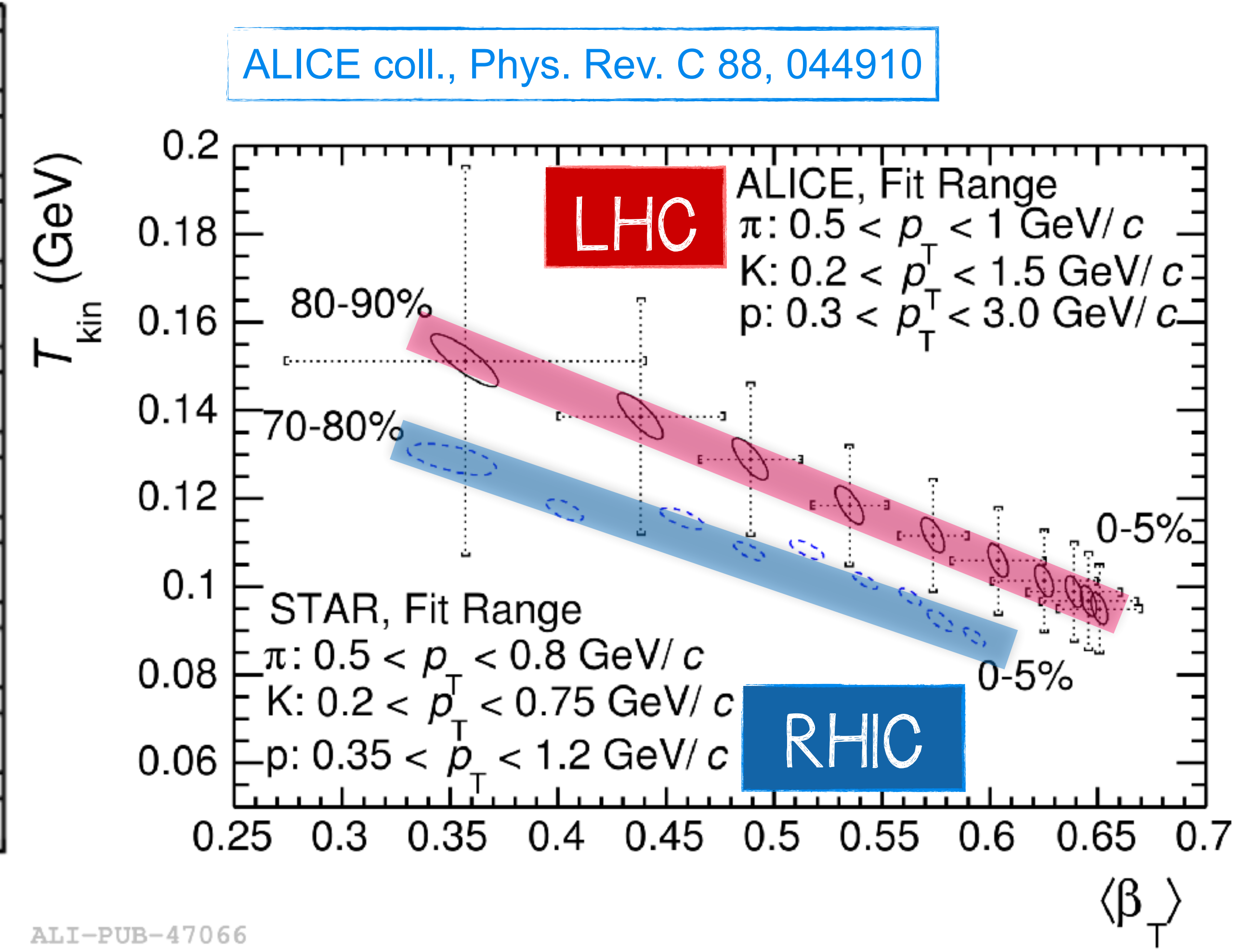
Kinetic freeze-out



Fit particle spectra to disentangle thermal component from collective motion

- T_{fo}, β_T from simultaneous fit to p, K, π





➡ average radial flow velocity $<\beta_T>$ ~ 0.65 (10% larger than at RHIC)

➡ kinetic freeze-out temperature T_{fo}~100 MeV (compatible with RHIC within errors)

Blast wave description

- Consider a thermal Boltzman source

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} \propto E\, e^{-E/T} \qquad E = m_\mathrm{T}\cosh(y)$$

- Boost source radially with velocity β and evaluate at midrapidity

$$\frac{1}{m_\mathrm{T}}\frac{\mathrm{d}N}{\mathrm{d}m_\mathrm{T}} \propto m_\mathrm{T}\, I_0\left(\frac{p_\mathrm{T}\sinh(\rho)}{T}\right) K_1\left(\frac{m_\mathrm{T}\cosh(\rho)}{T}\right)$$

with $\rho = \tanh^{-1}(\beta)$

- Consider a uniform sphere of radius R

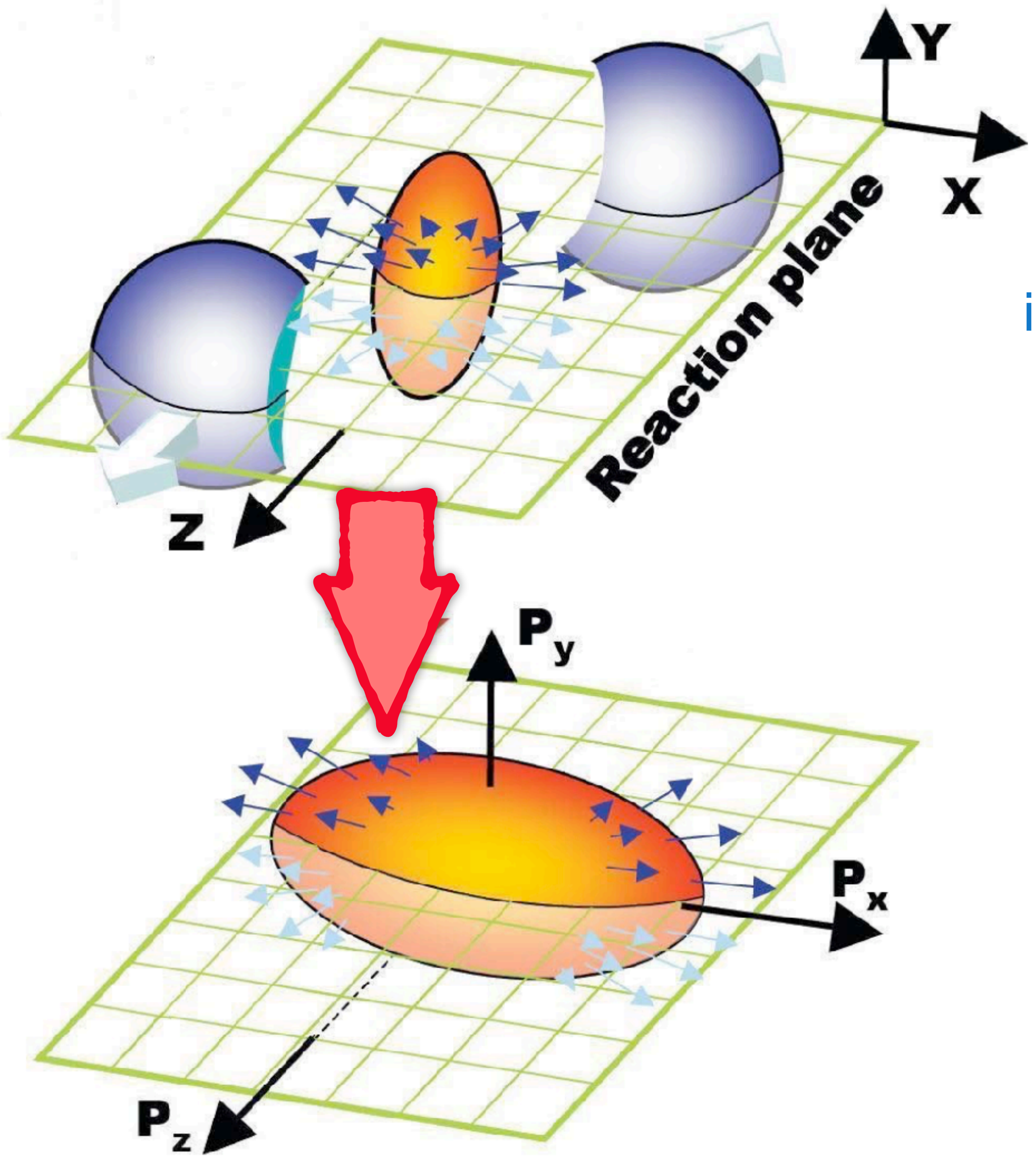
$$\frac{1}{m_\mathrm{T}}\frac{\mathrm{d}N}{\mathrm{d}m_\mathrm{T}} \propto \int_0^R \mathrm{d}r\, m_\mathrm{T}\, I_0\left(\frac{p_\mathrm{T}\sinh(\rho(r))}{T}\right) K_1\left(\frac{m_\mathrm{T}\cosh(\rho(r))}{T}\right)$$

parametrize surface velocity with

$$\beta(r) = \beta_\mathrm{s}\,(r/R)^n$$

➧ 3 parameters: T, β_S and n

Hydrodynamics



initial spatial anisotropy

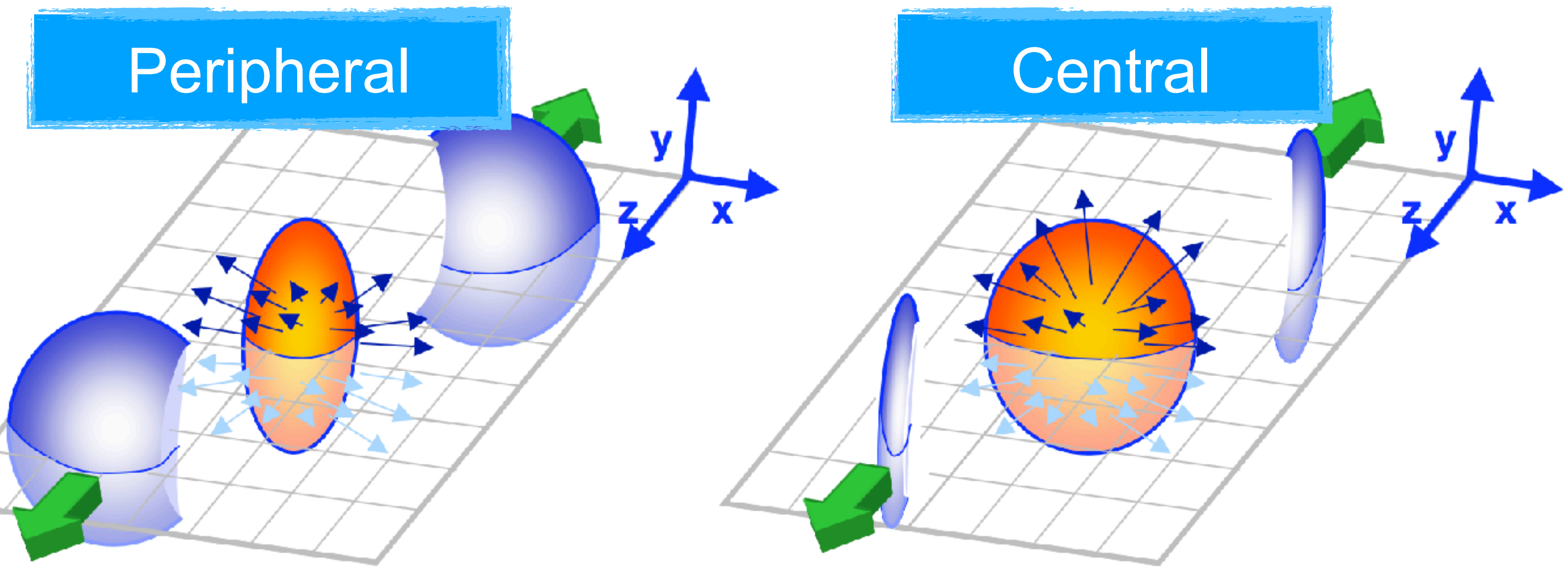
momentum anisotropy

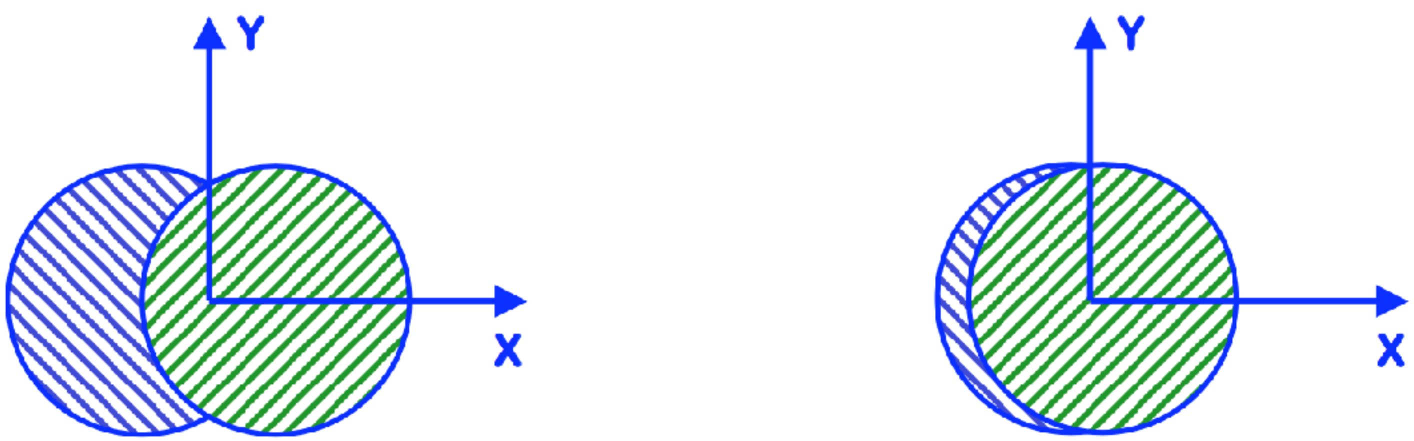
eccentricity

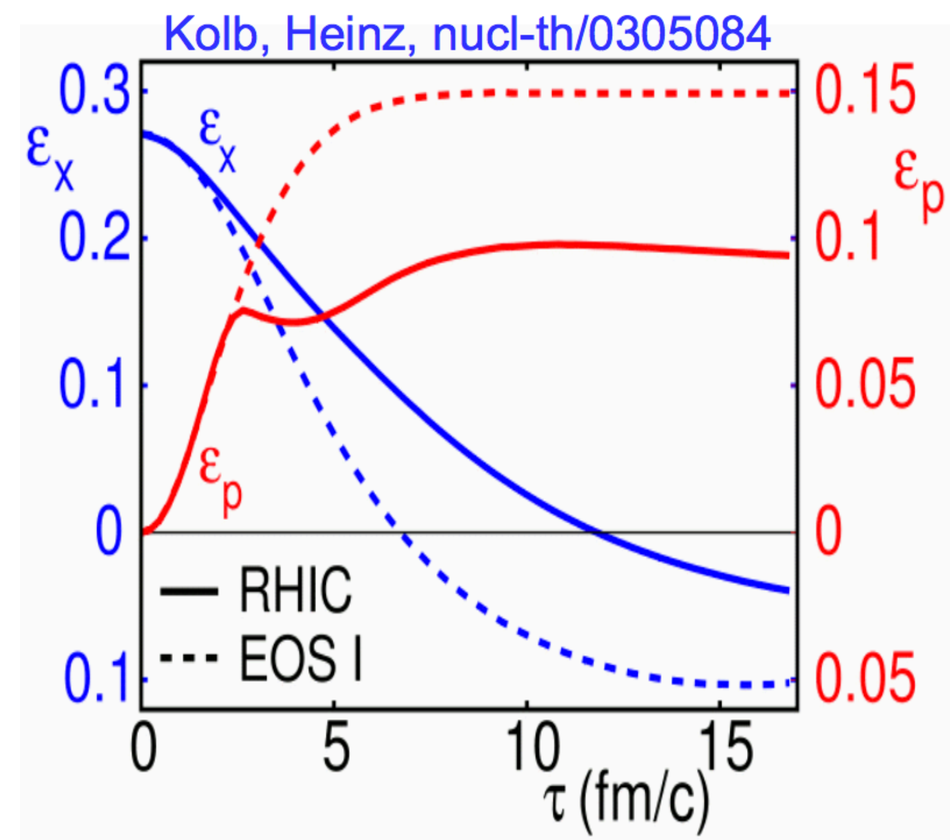
$$\epsilon = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

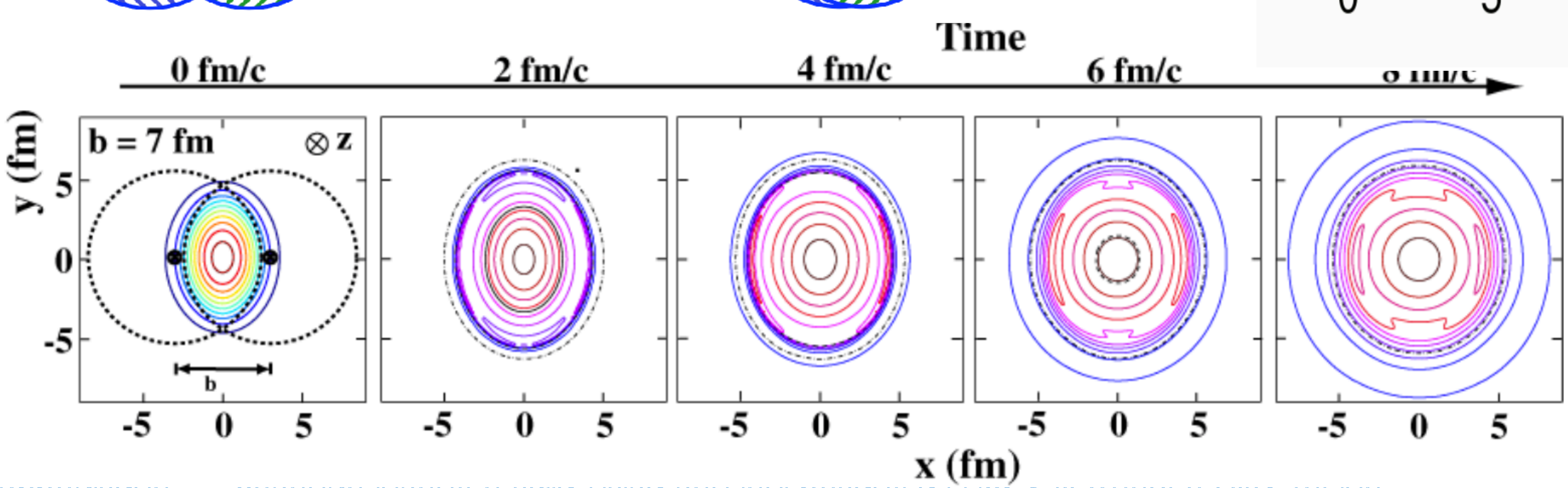
elliptic flow
v_2

Hydrodynamics

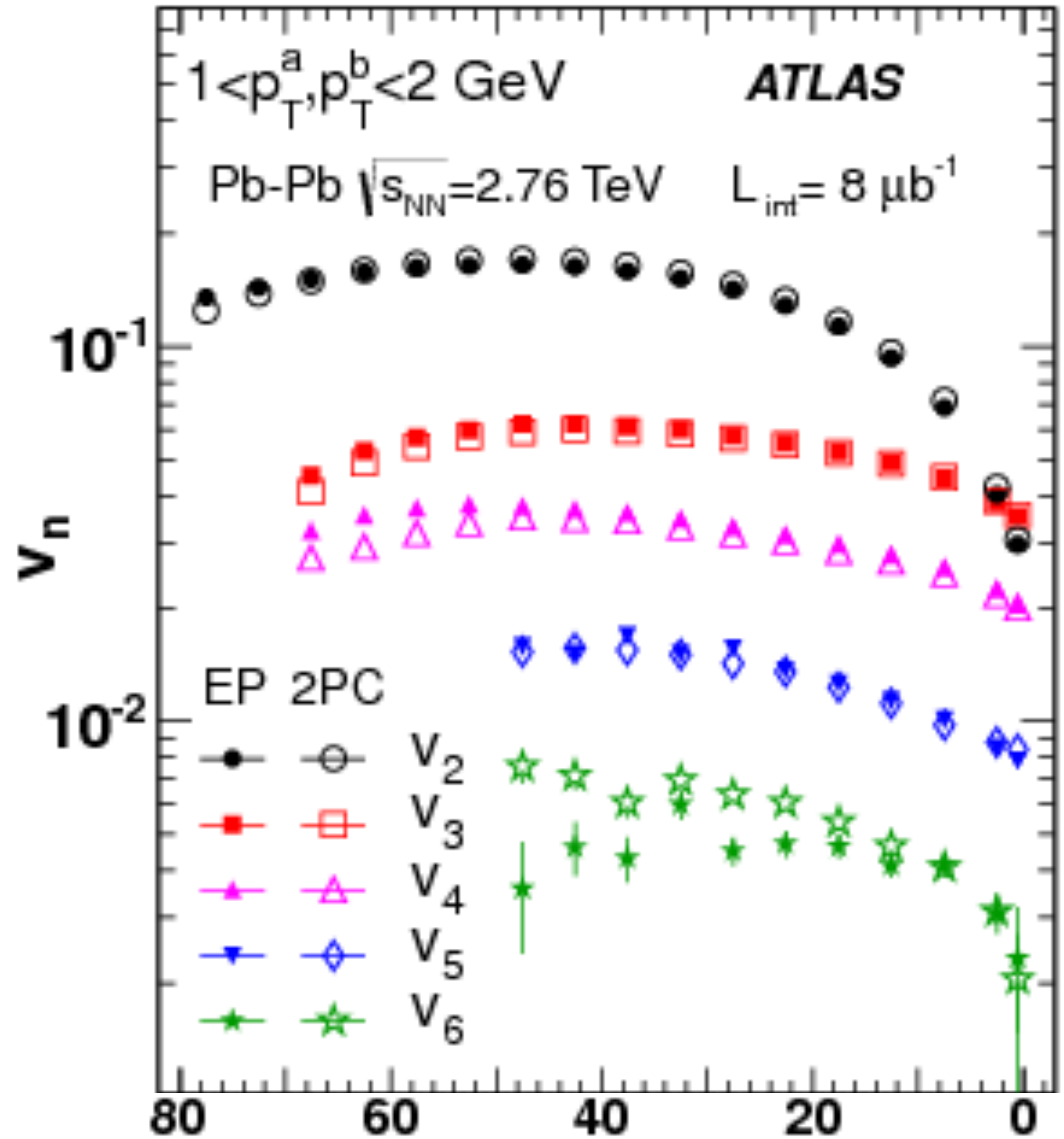




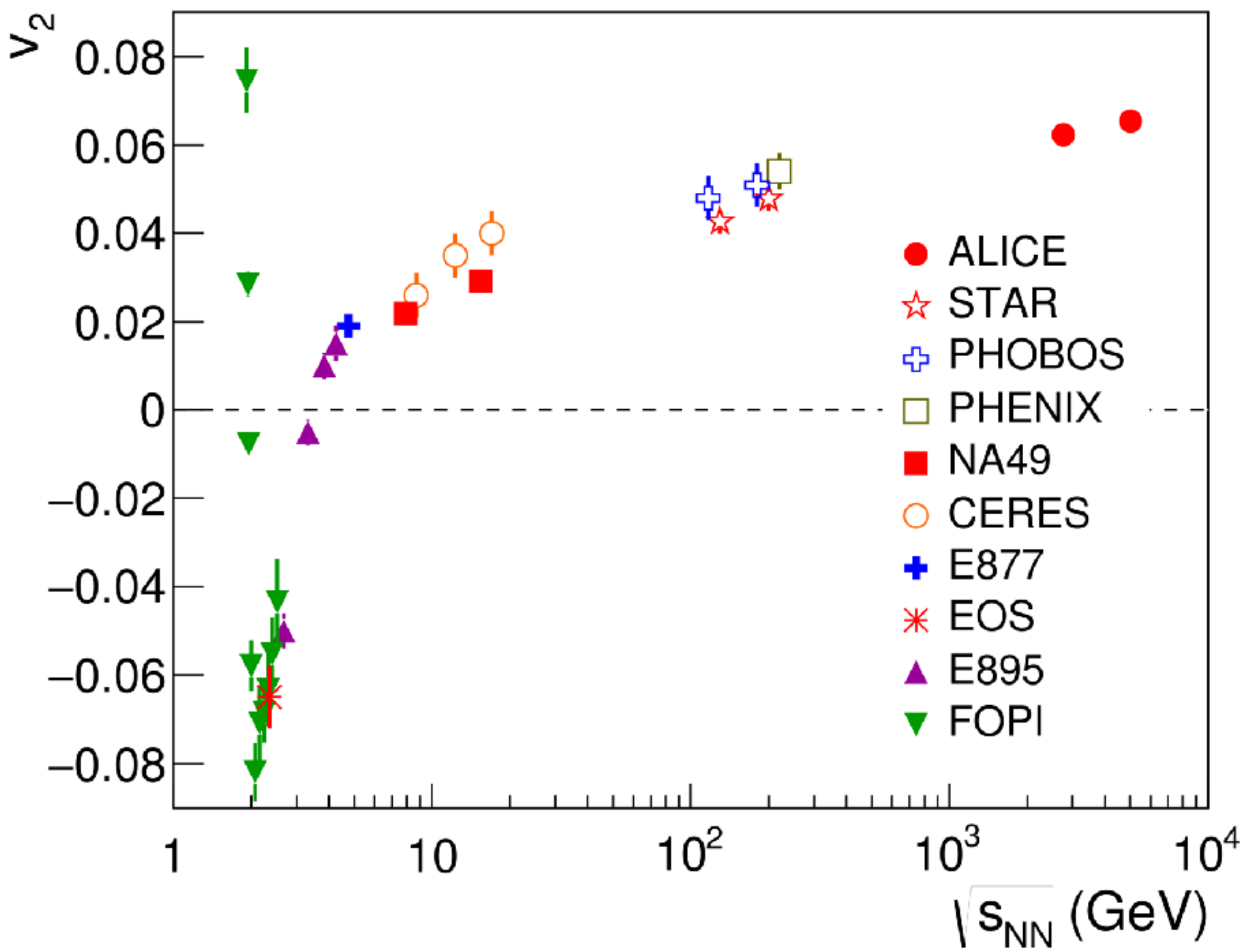




Hydrodynamics



Hydrodynamics



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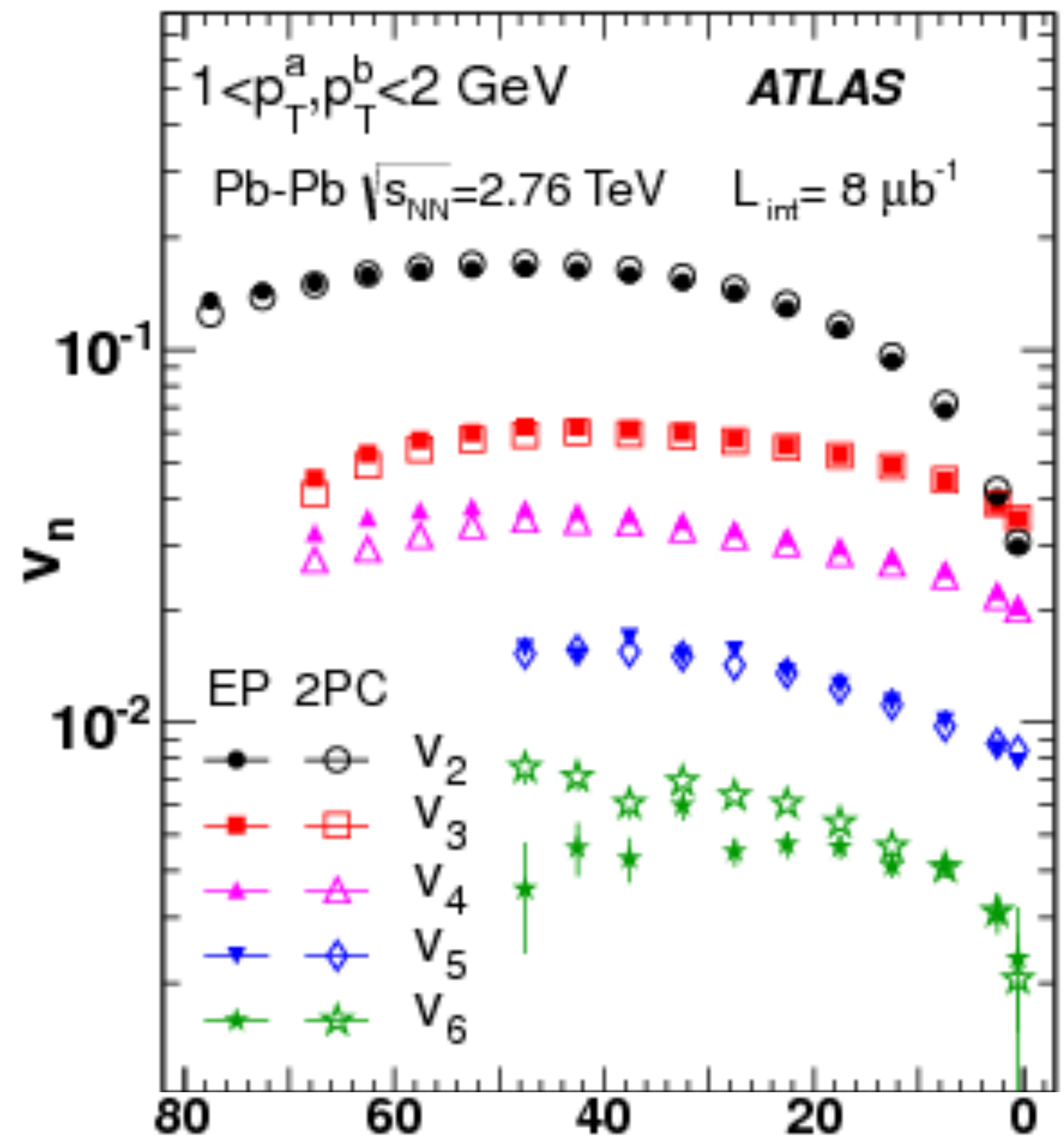
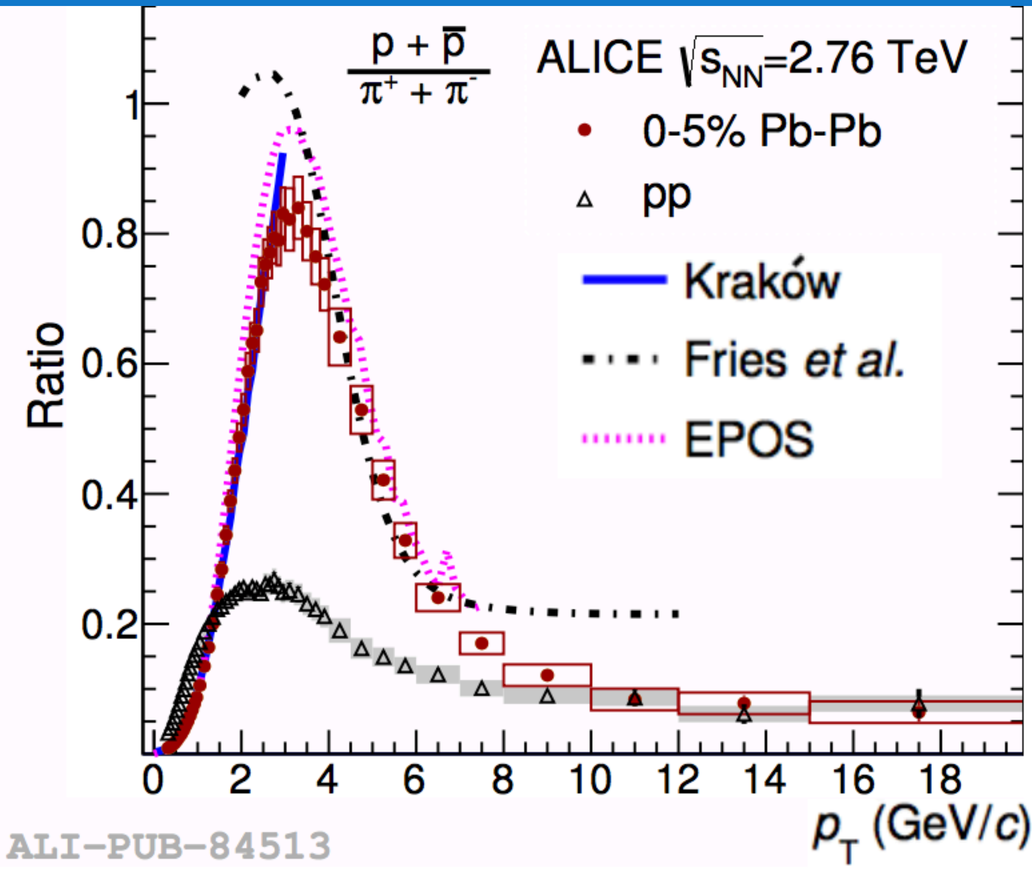
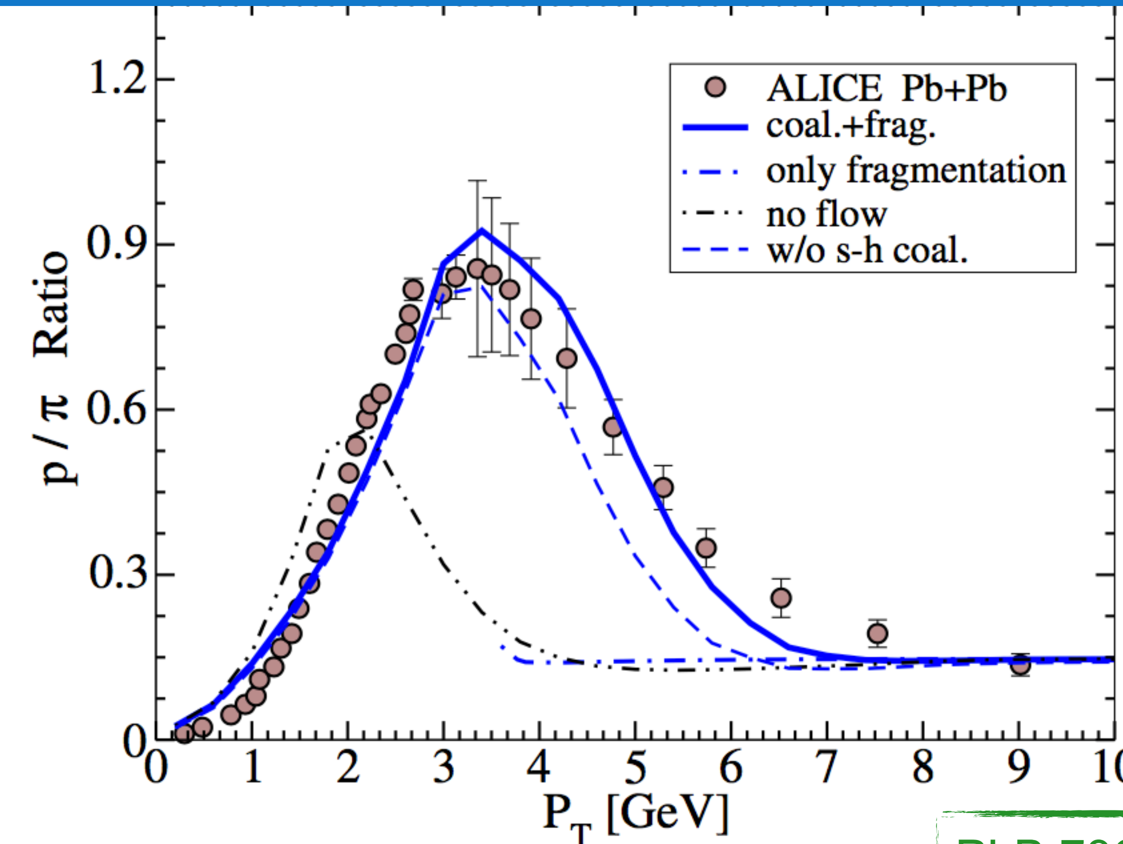


Hadronization





PLB 736 (2014) 196

p_T dependent baryon/meson enhancement in central Pb-Pb collisions

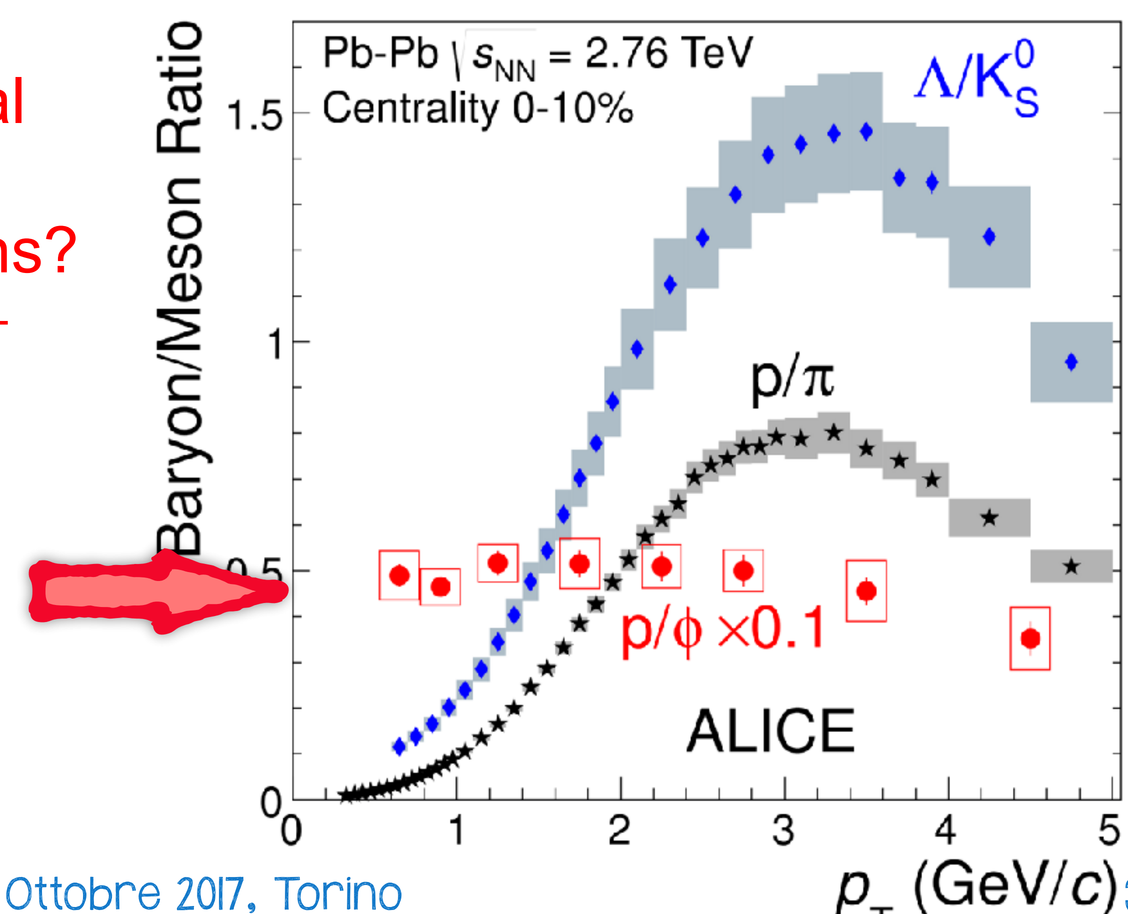
- q coalescence: different p_T for baryons and mesons?
- hydrodinamic flow: mass-dependent (blue-shift) p_T spectra

p (uud) 938 MeV

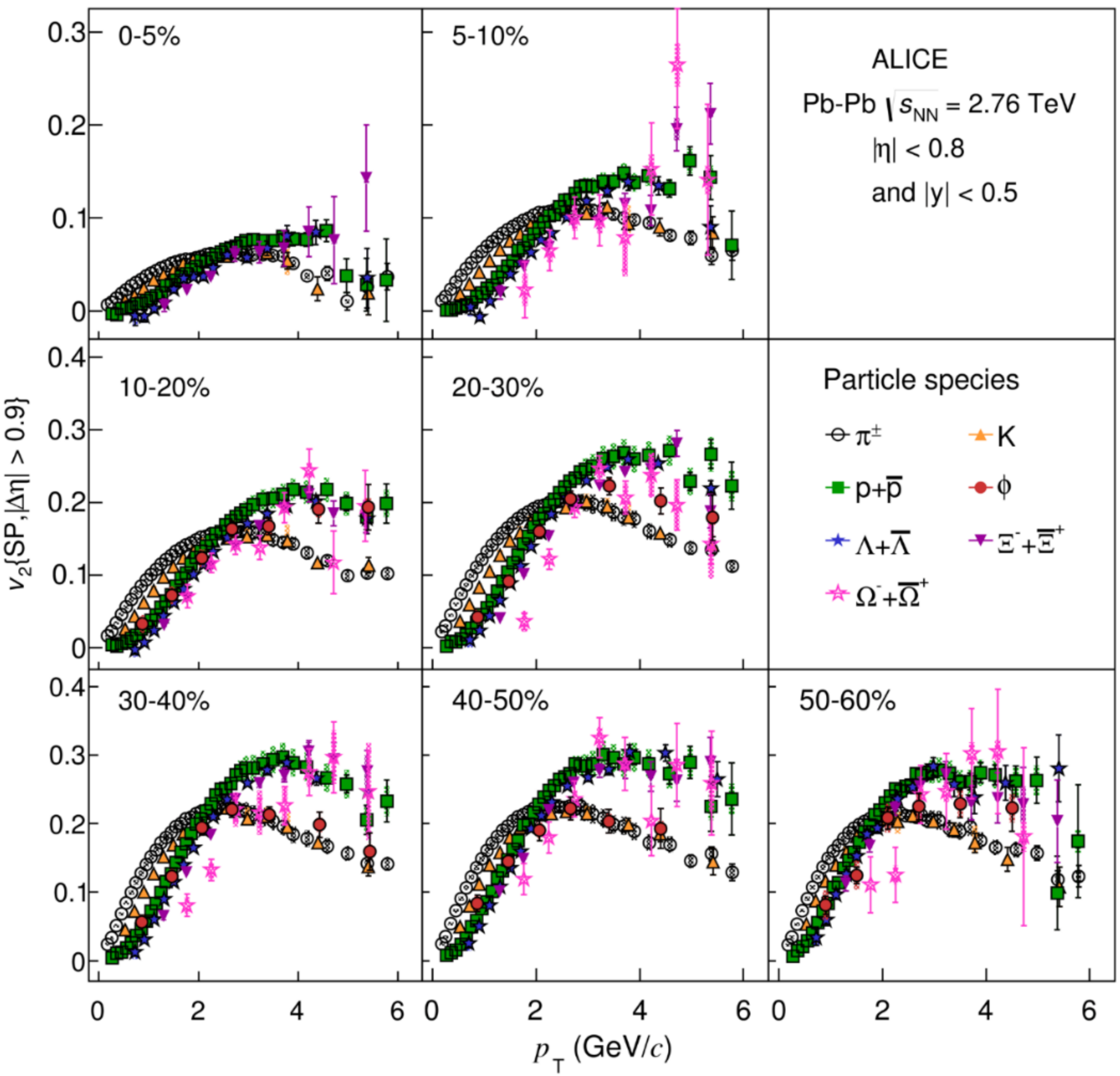
ϕ (s anti-s) 1020 MeV

Coalescence production ➧ different p_T spectra

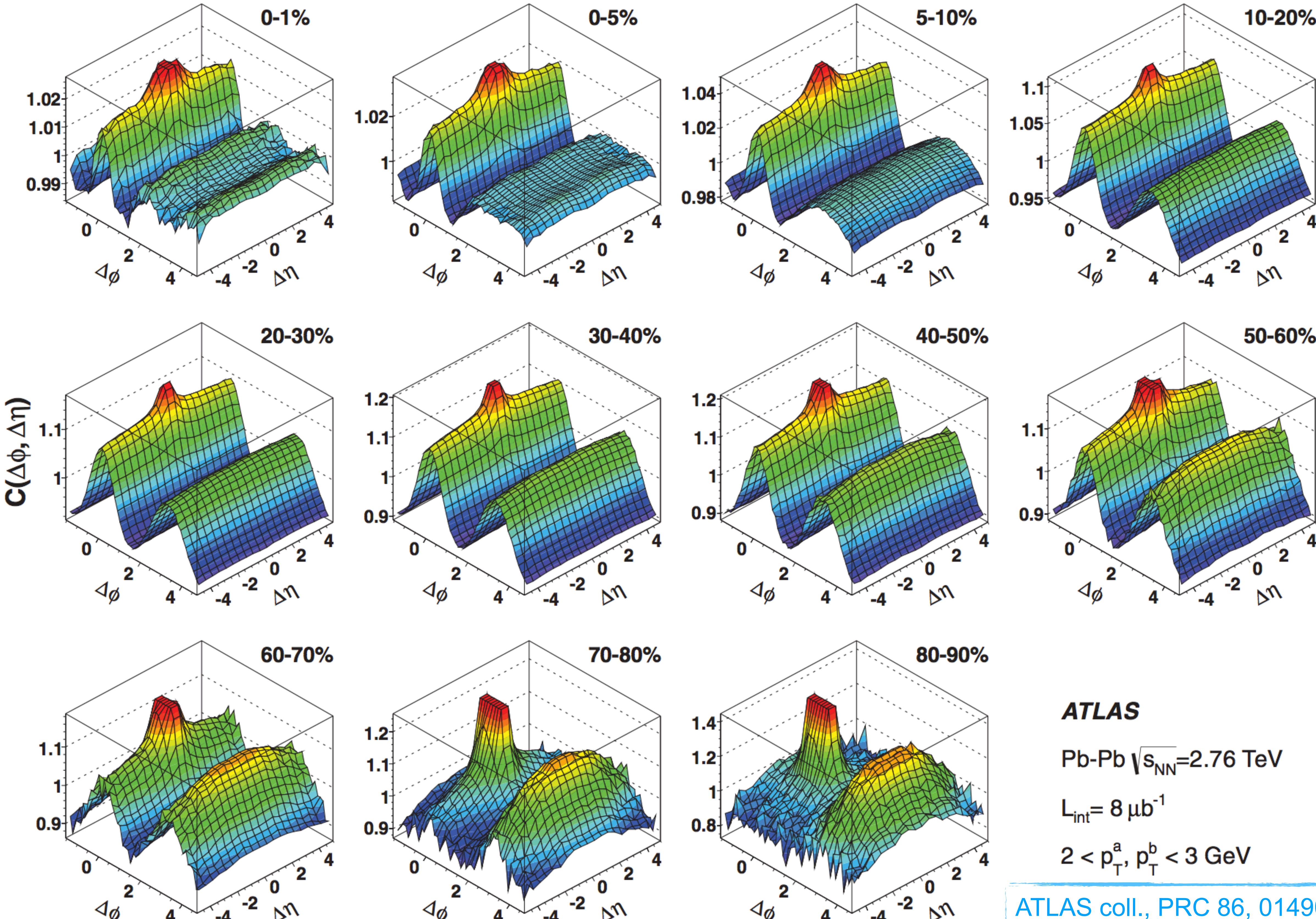
Hydrodynamics ➧ similar p_T spectra



Hadronization



Hadronization



ATLAS

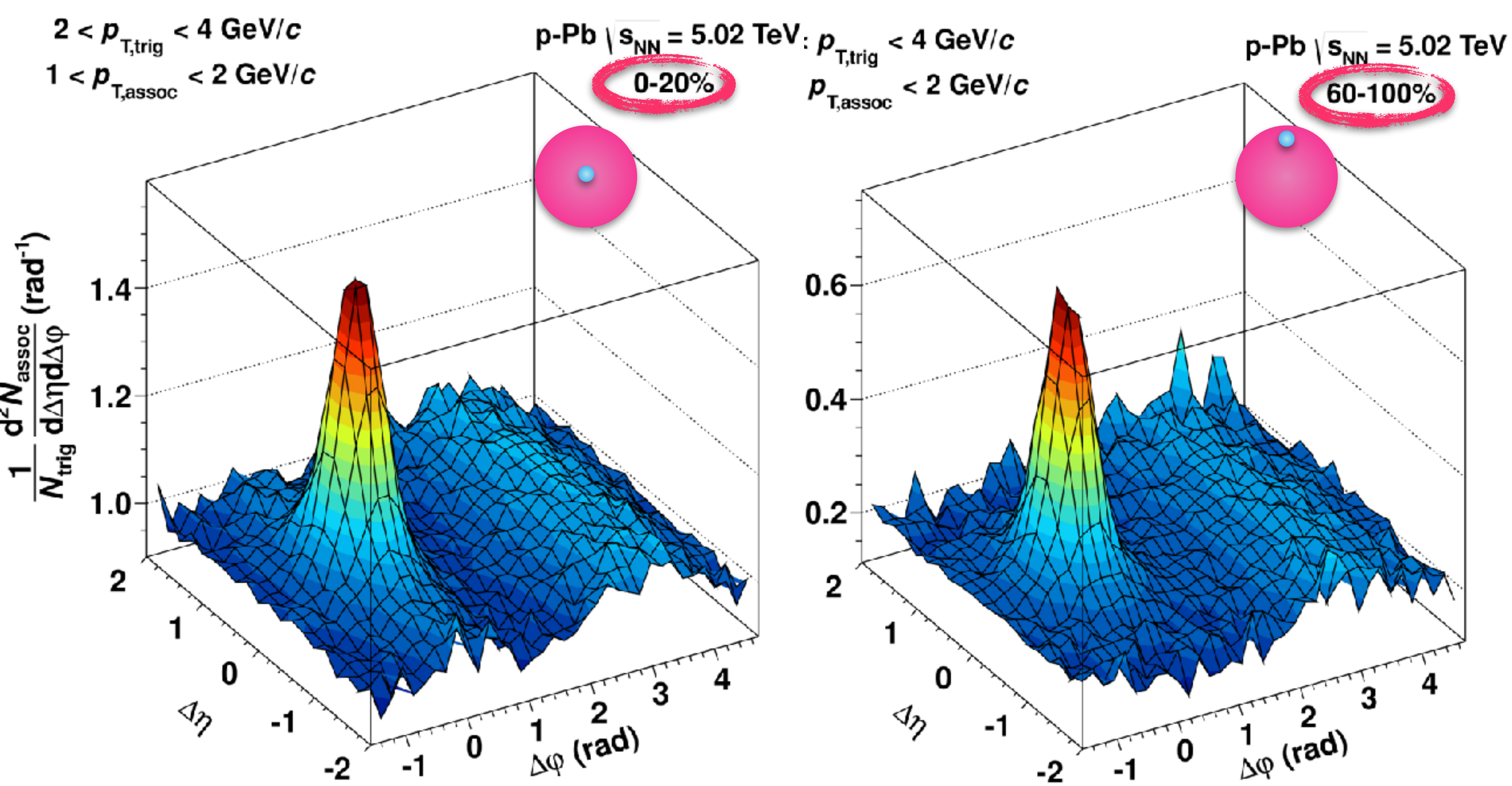
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV

L_{int}= 8 μb^{-1}

2 < p_T^a, p_T^b < 3 GeV

ATLAS coll., PRC 86, 014907 (2012)

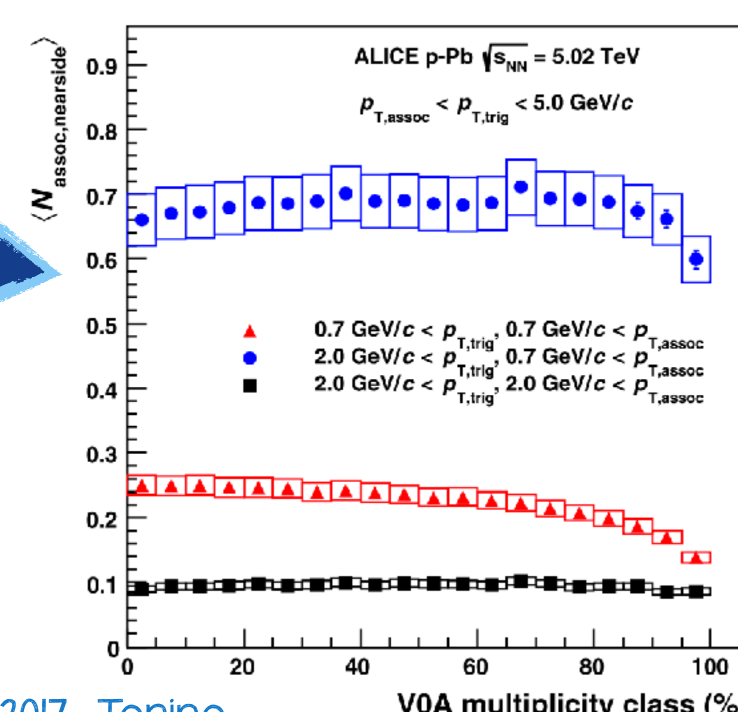
Two-particle correlations in p-Pb



Subtraction of the contribution from jet fragmentation:

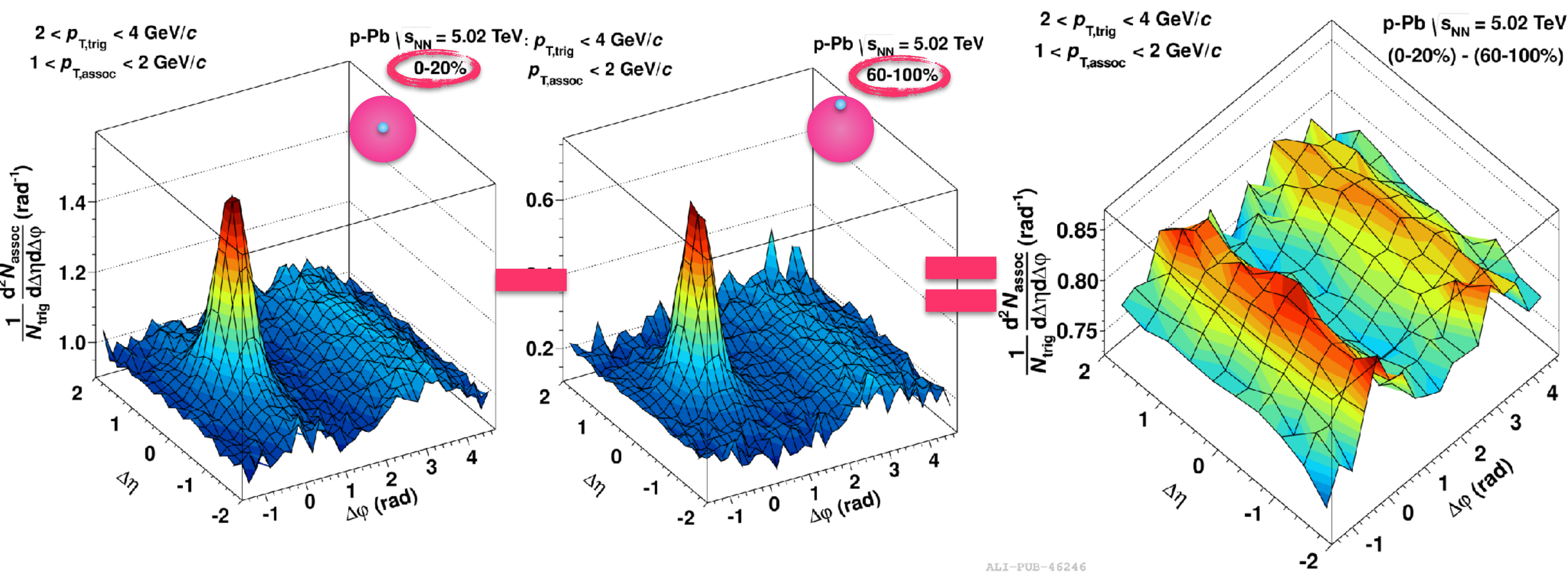
0-20% - 60-100%

➧ justified by the observation that the near side peak yield does not depend on particle multiplicity



ALICE Coll., PLB 741 (2015) 38

Two-particle correlations in p-Pb



- symmetric double ridge observed in p-Pb collisions where collective behaviors were not expected (no flowing medium formed)!

Shear viscosity

Analytic: Csernai, Kapusta and McClerran PRL 97, 152303 (2006)
Lattice: H. Meyer, PR D76, 101701R (2007)