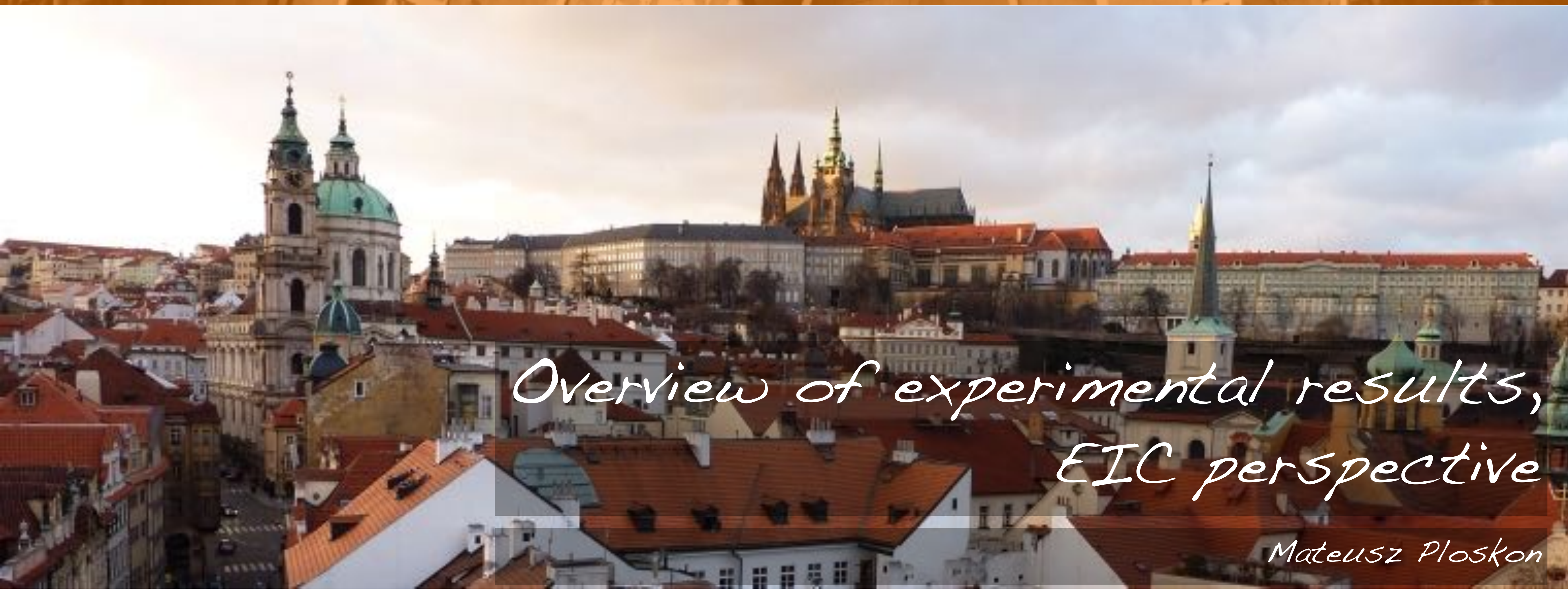
30th Indian-summer School of Physics

Phenomenology of Hot and Dense Matter for Future Accelerators

September 3–7, 2018, Prague, Czech Republic

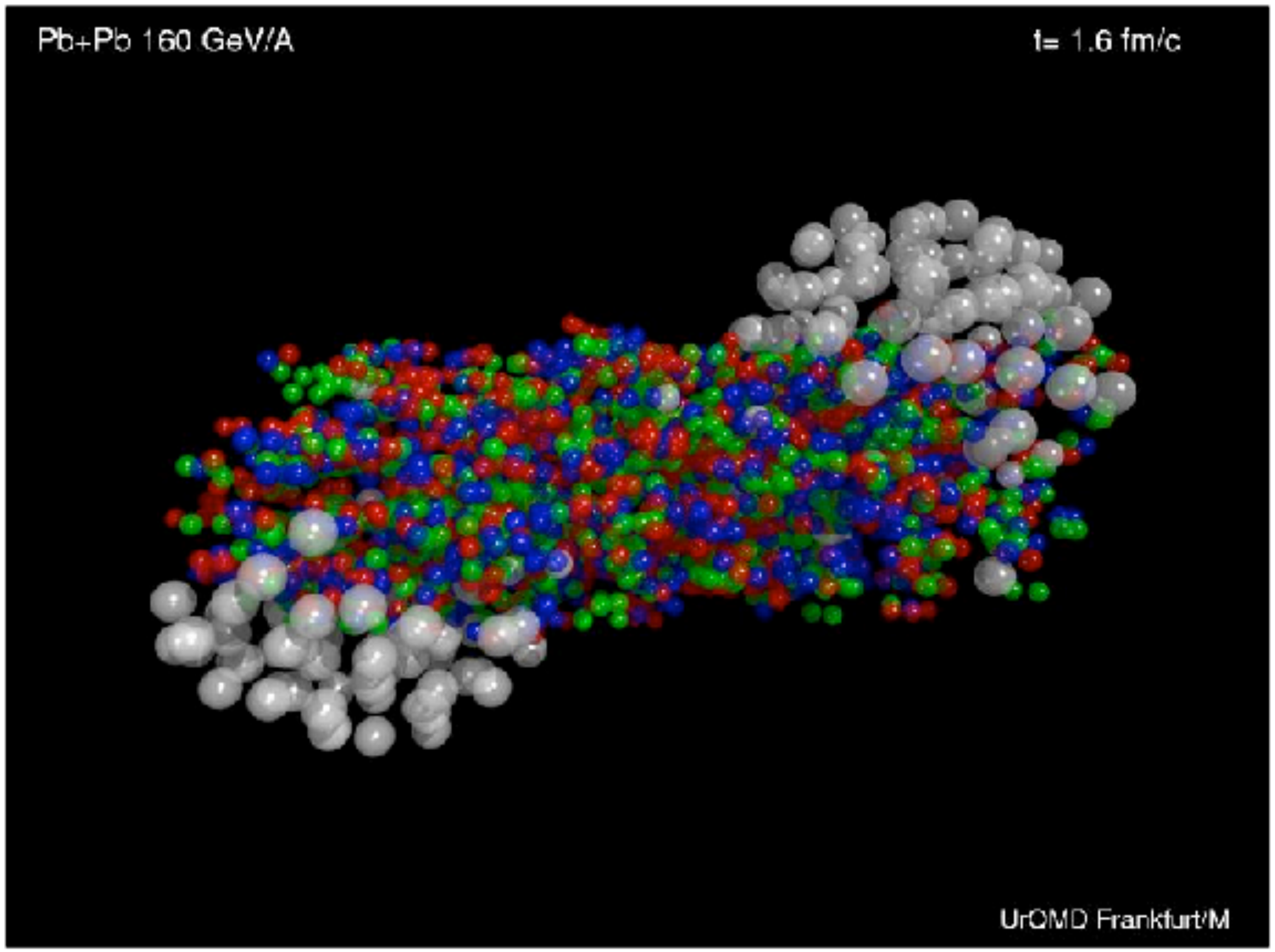


Overview of experimental results, EIC perspective

Mateusz Ploskon

#2

Glauber model - a description of heavy-ion collisions



central collisions:

small impact parameter b

- high number of participants
- high energy density
- large volume

-> large number of produced particles

peripheral collisions:

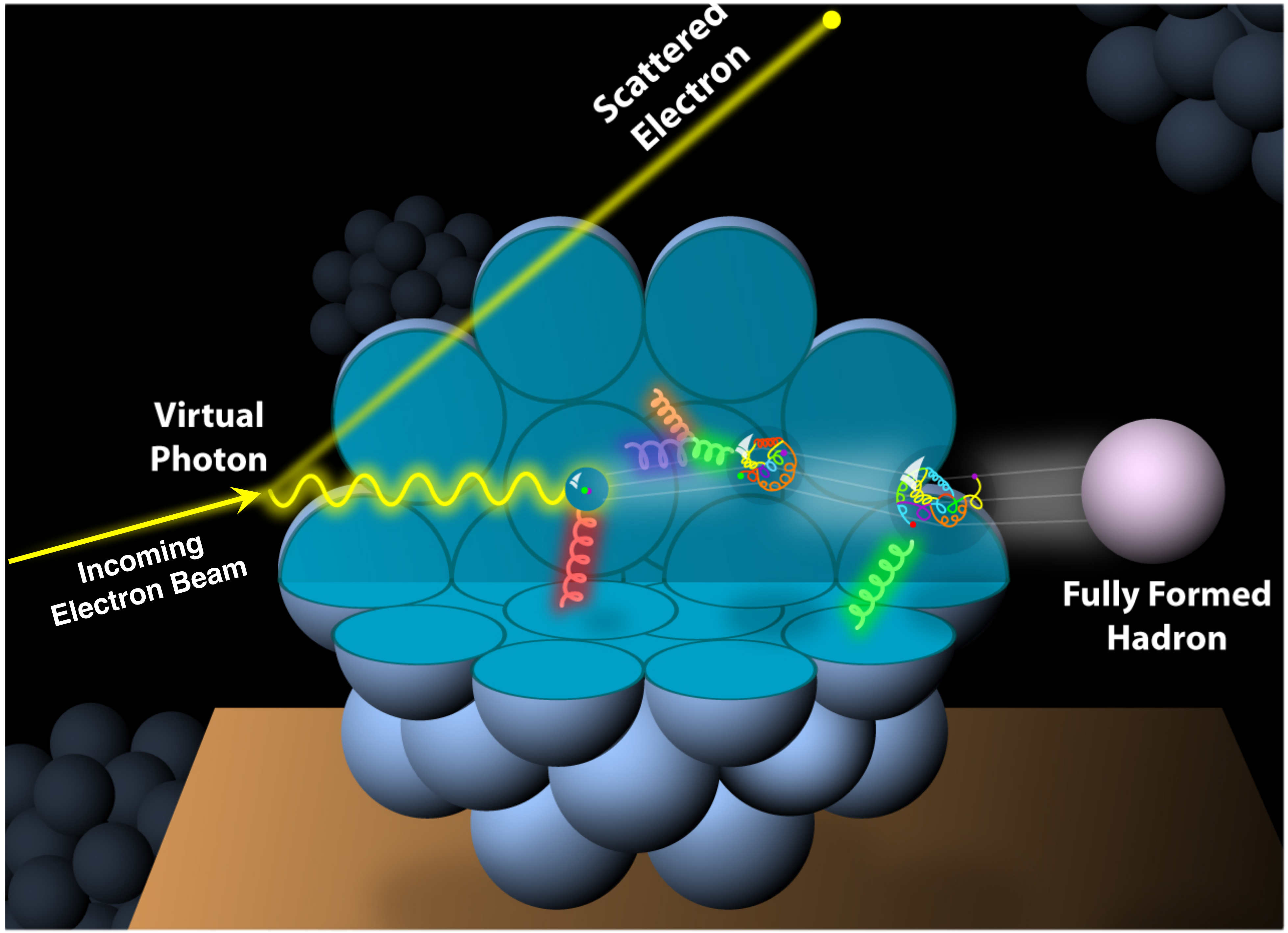
large impact parameter b

- low number of participants

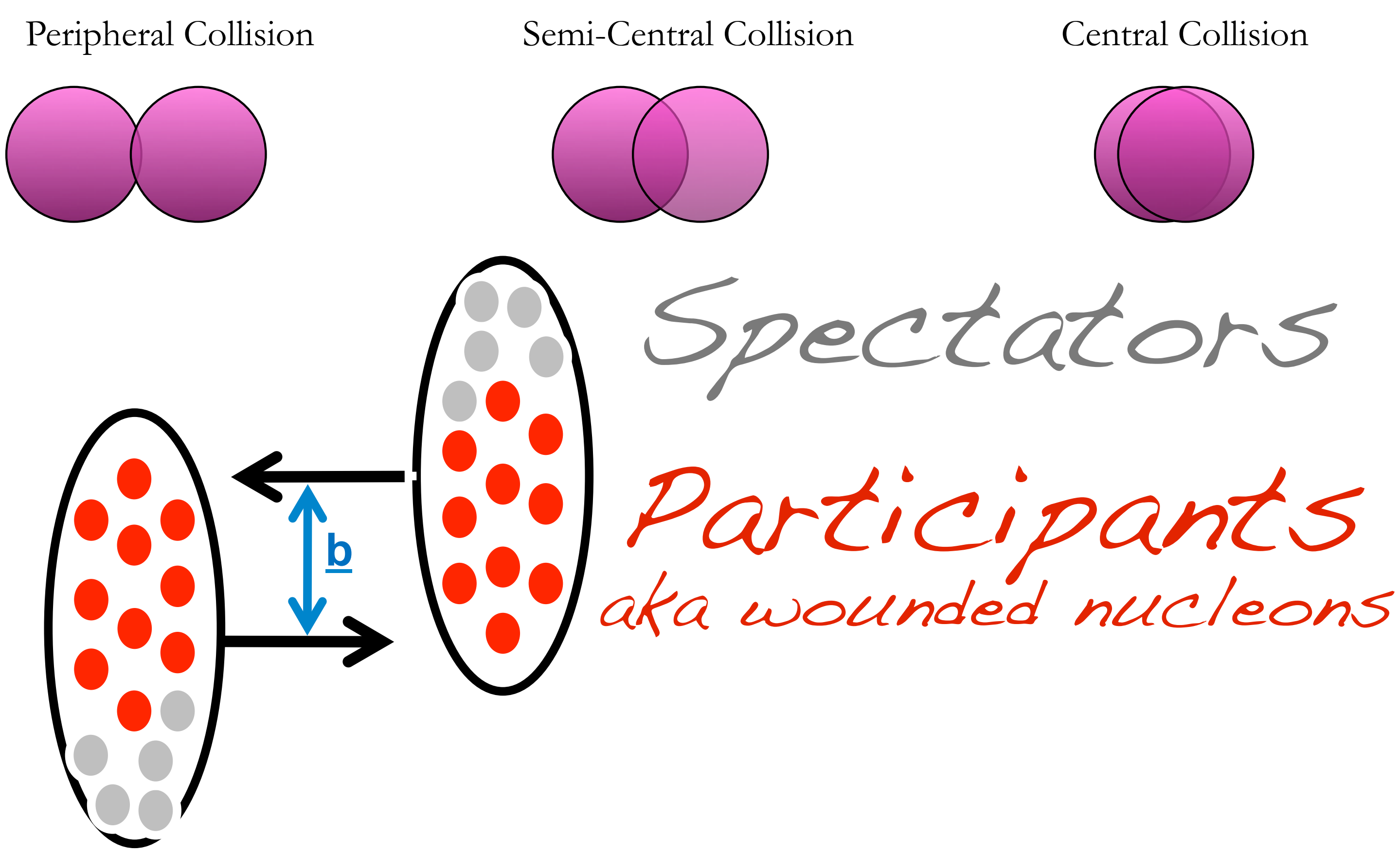
-> low multiplicity

... very different than electron-ion collisions...

- eIC coming later...



Glauber model - a description of heavy-ion collisions



central collisions:

small impact parameter b

- high number of participants
- high energy density
- large volume

-> large number of produced particles

peripheral collisions:

large impact parameter b

- low number of participants

-> low multiplicity

Impact parameter b is measured as:

Fraction of cross section "centrality"

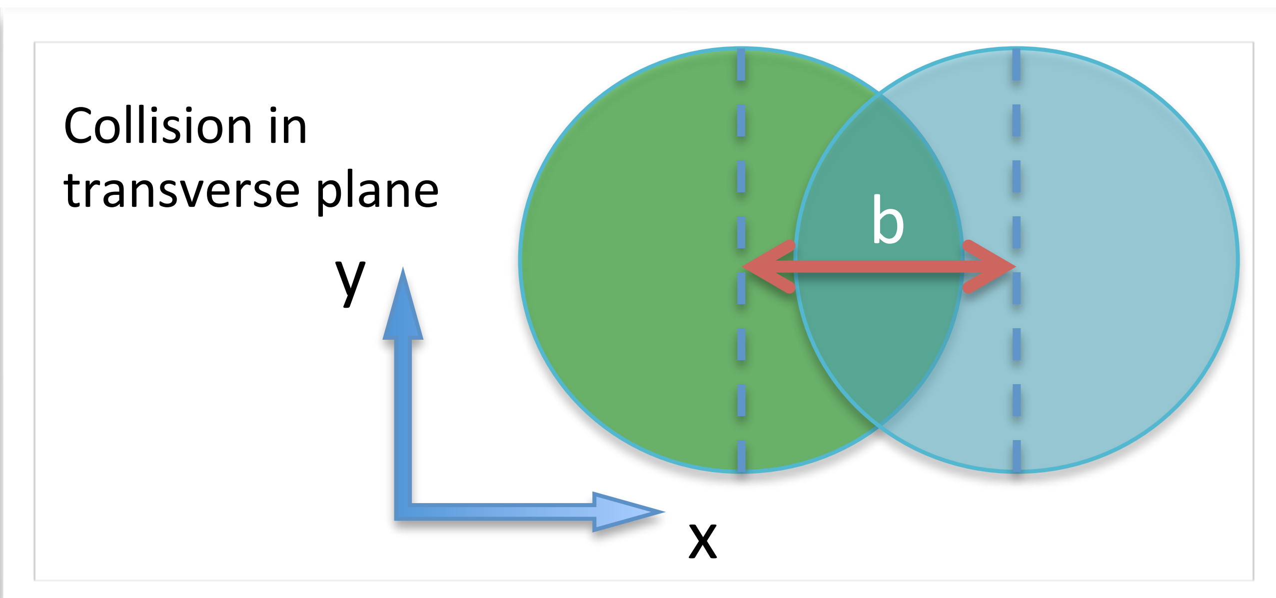
Number of participants

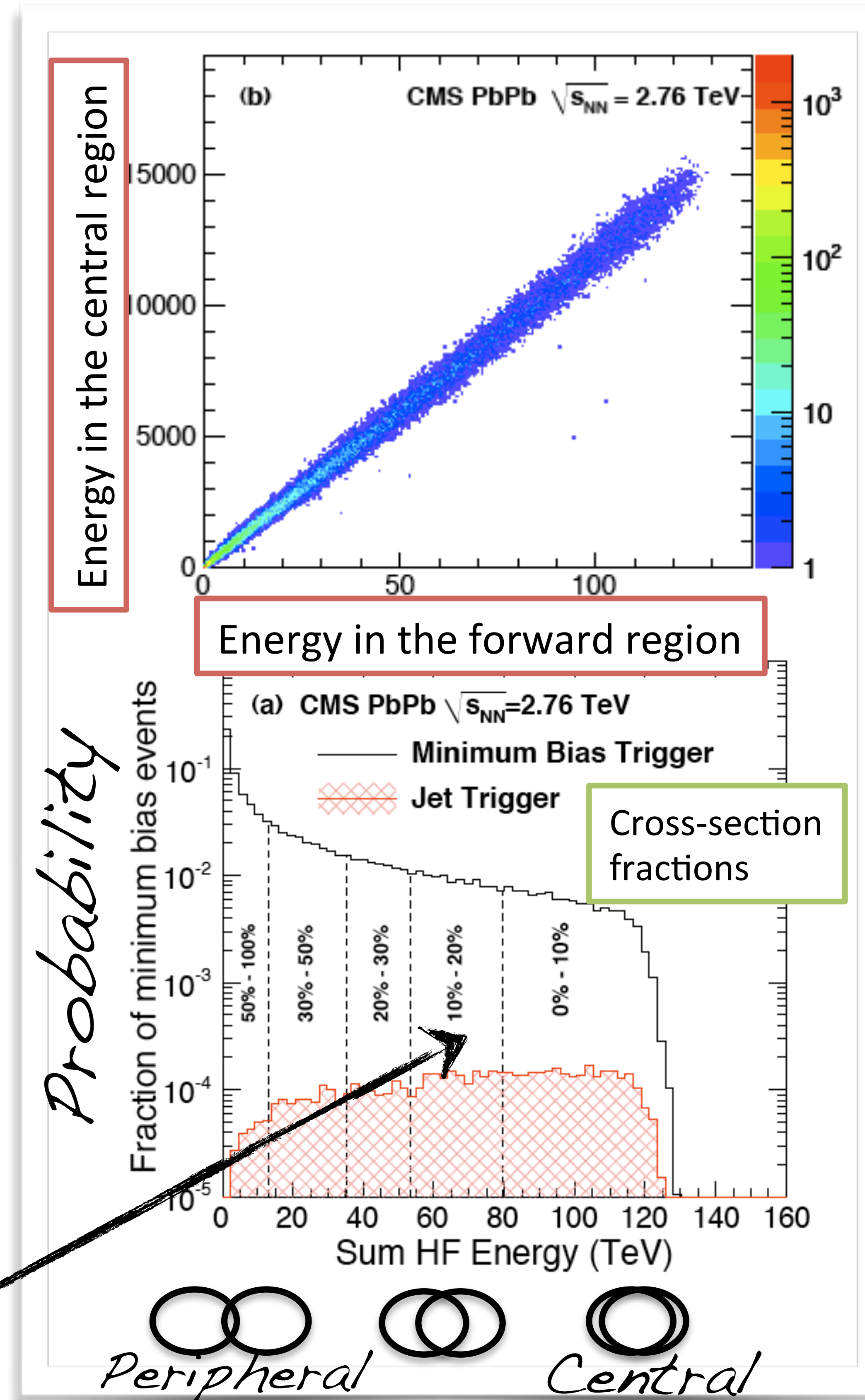
Number of nucleon-nucleon collisions

Experimental control of collision geometry

How can we measure impact parameter in heavy-ion collisions?

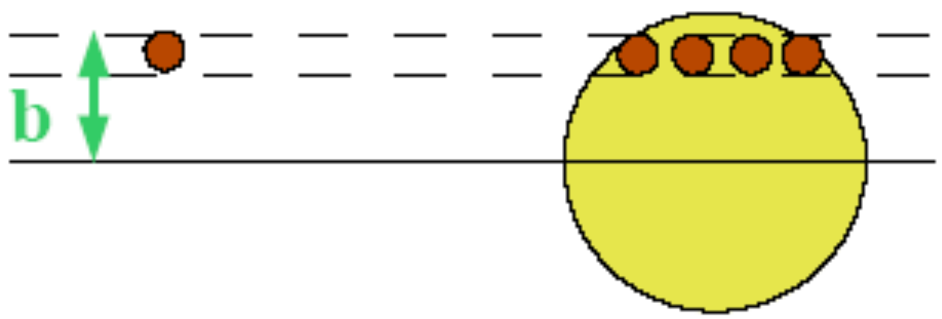
=> Correlate observables connected only by geometry





Characterize events via percentile (fraction) of inelastic cross section (jargon: "N% most central")

Nuclear geometry - Glauber model and hard (high-Q^2) processes



Normalized nuclear density r(*b*,*z*):

$$\int dz\, db\, \rho(b,z) = 1$$

Nuclear thickness function

$$T_A(b) = \int_{-\infty}^{\infty} dz\, \rho(b,z)$$

Inelastic cross section for p+A:

$$\sigma_{pA}^{inel} = \int d\vec{b} \left(1 - \left[1 - T_A(b)\sigma_{NN}^{inel}\right]^A\right)$$

Glauber scaling: hard processes with large momentum transfer

- short coherence length ⇒ successive NN collisions independent
- p+A is incoherent superposition of N+N collisions

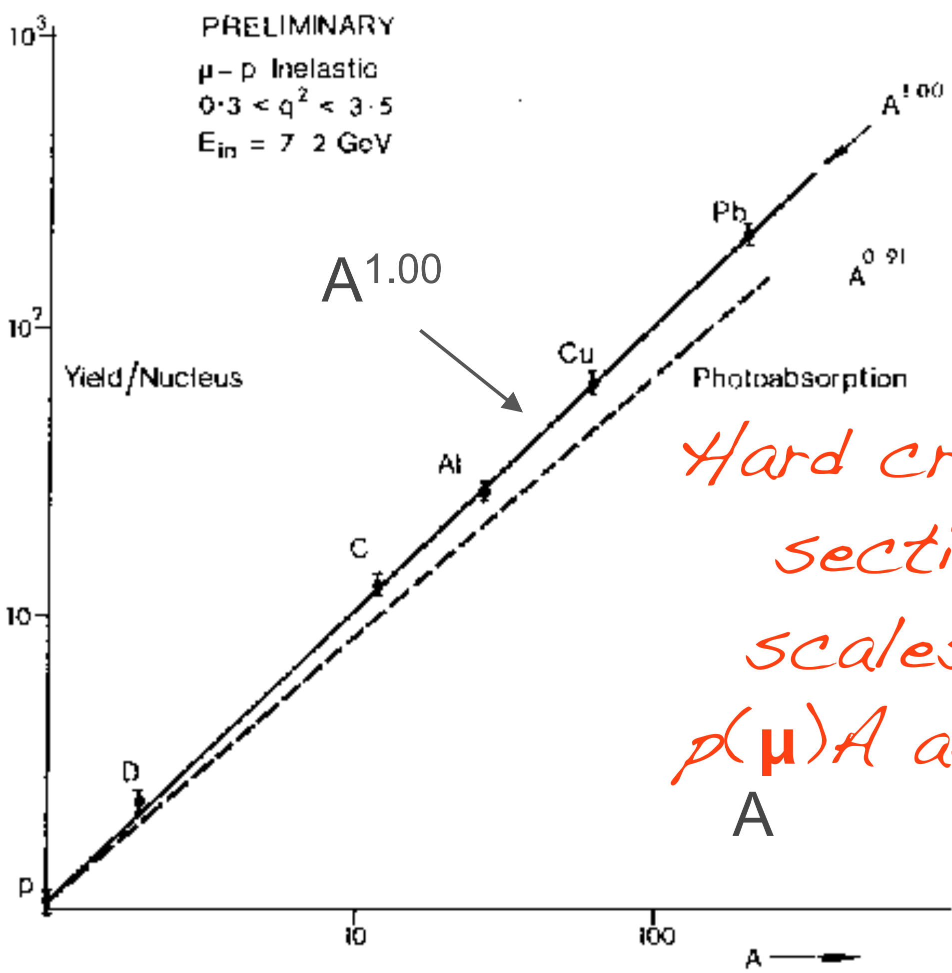
$$\sigma_{pA}^{hard} \approx A\sigma_{NN}^{hard} \int d\vec{b}\, T_A\left(\vec{b}\right) = A\sigma_{NN}^{hard}$$

Glauber scaling of hard processes

Glauber scaling: $\sigma_{pA}^{hard} = A\sigma_{NN}^{hard}$

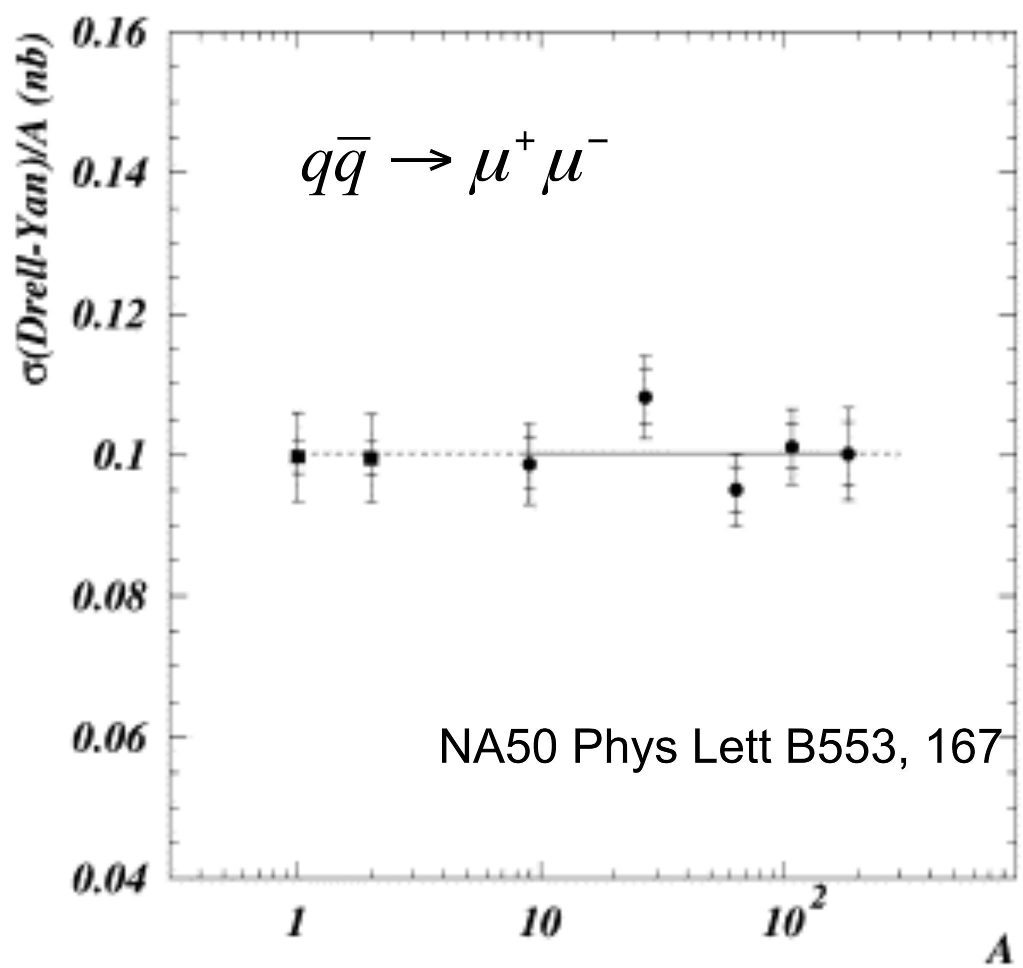
σ_{inel} for 7 GeV muons on nuclei

M.May et al, Phys Rev Lett 35, 407 (1975)



Hard cross-section scales in p(**μ**)A as $A^{1.0}$

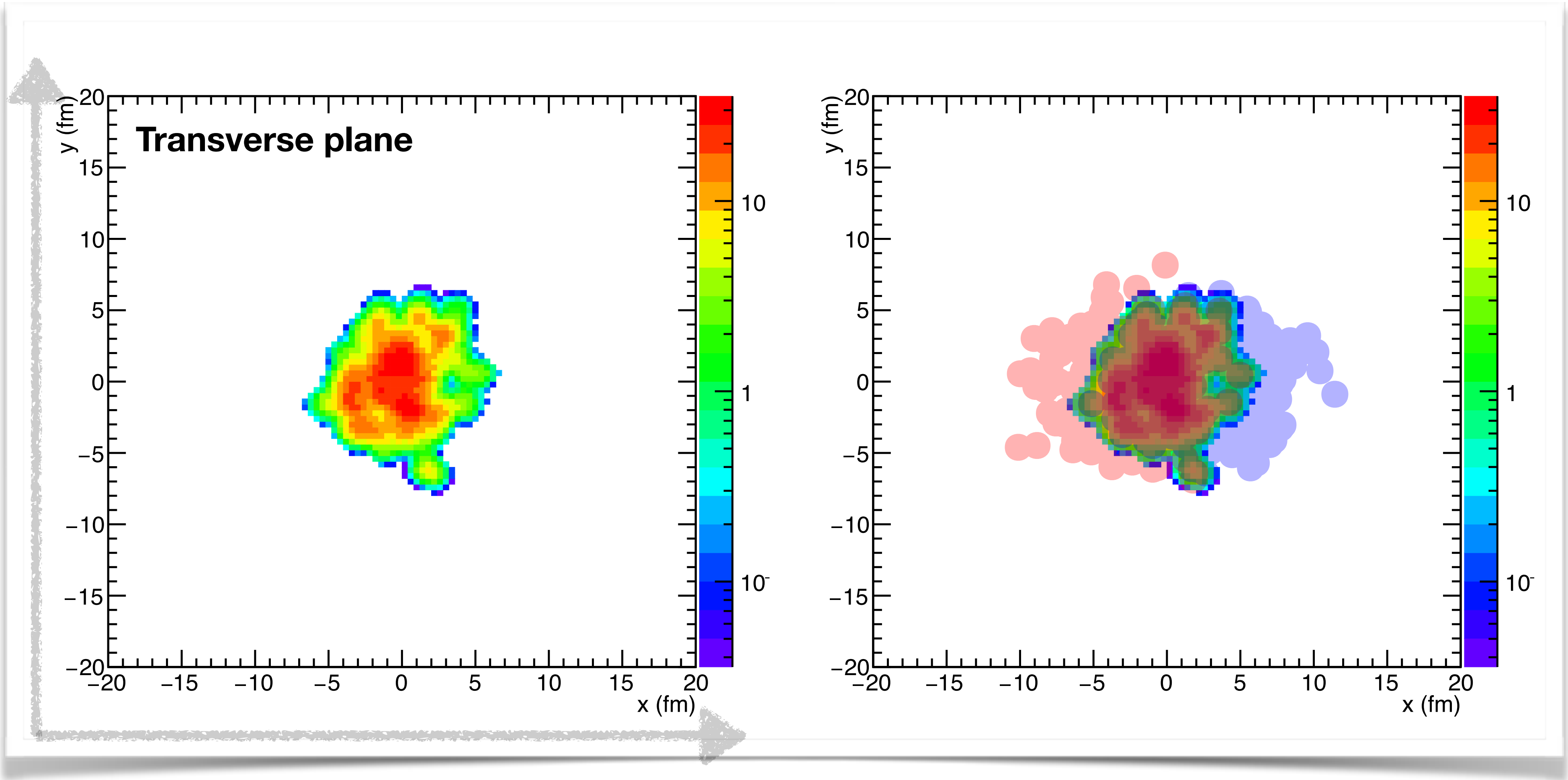
$\sigma_{Drell\text{-}Yan}/A$ in p+A at SPS



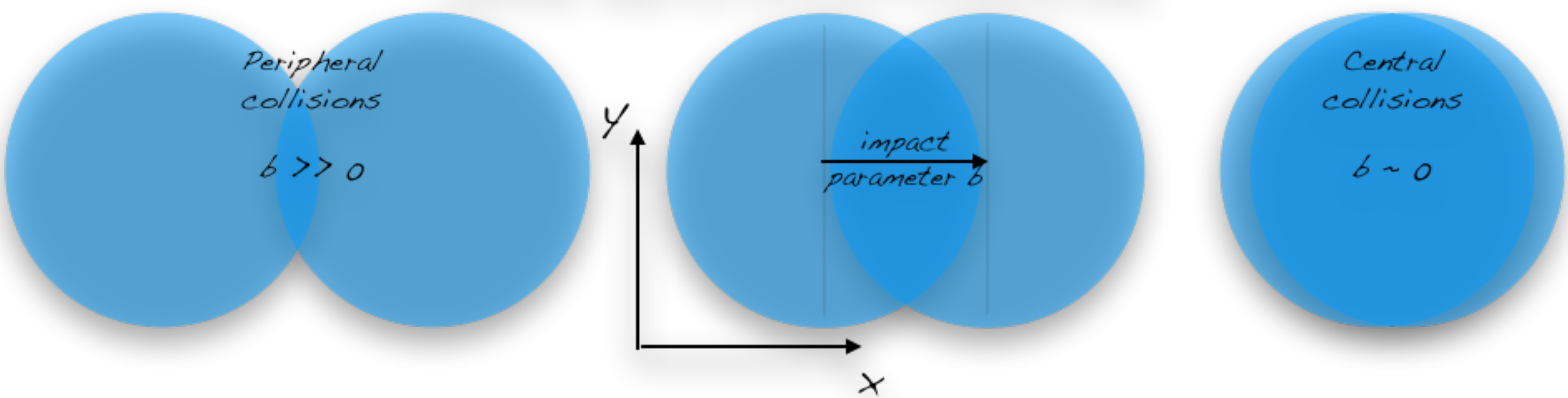
Experimental control in heavy-ion collisions?

=> direct photons, Z's, measure pA collisions (discussed later...)

Heavy-ion Collision Geometry



Centrality: heavy-ion collisions in transverse plane



Centrality measurement: use of the Glauber model in an experiment

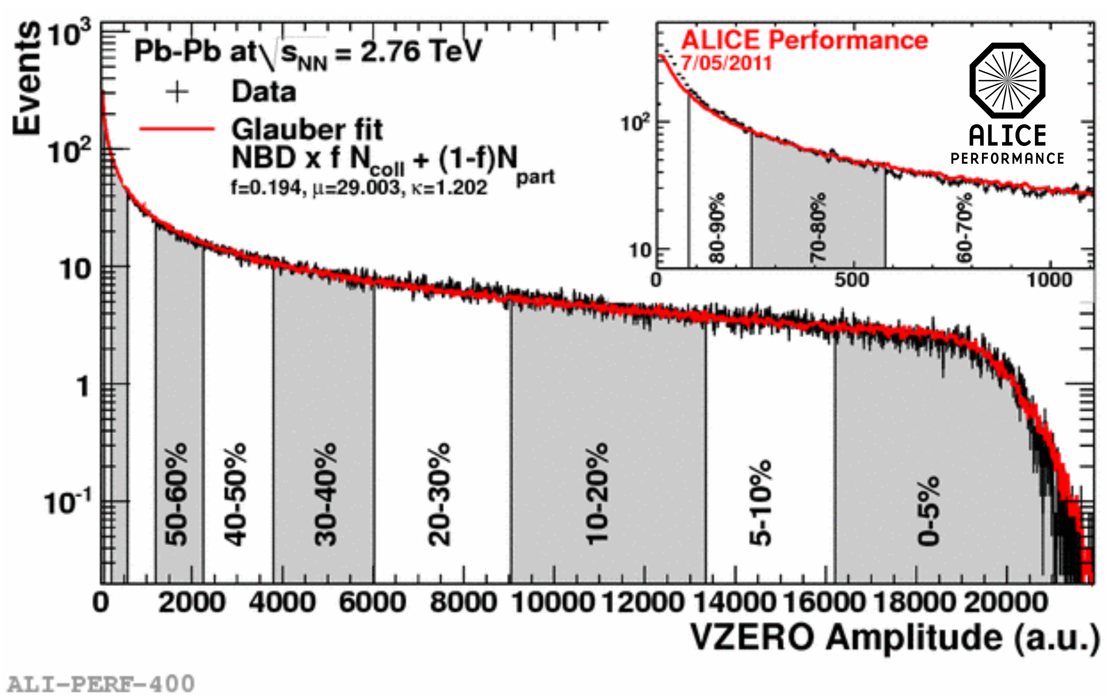
- Fraction of cross section, 2 approaches:
  - Fit with Glauber Monte Carlo
  - Correct: subtract BG, efficiency and integrate multiplicity distributions
- N_{part}, N_{coll}, N_{spect}: require Glauber fit (computed using cuts on impact parameter)
- Estimators:

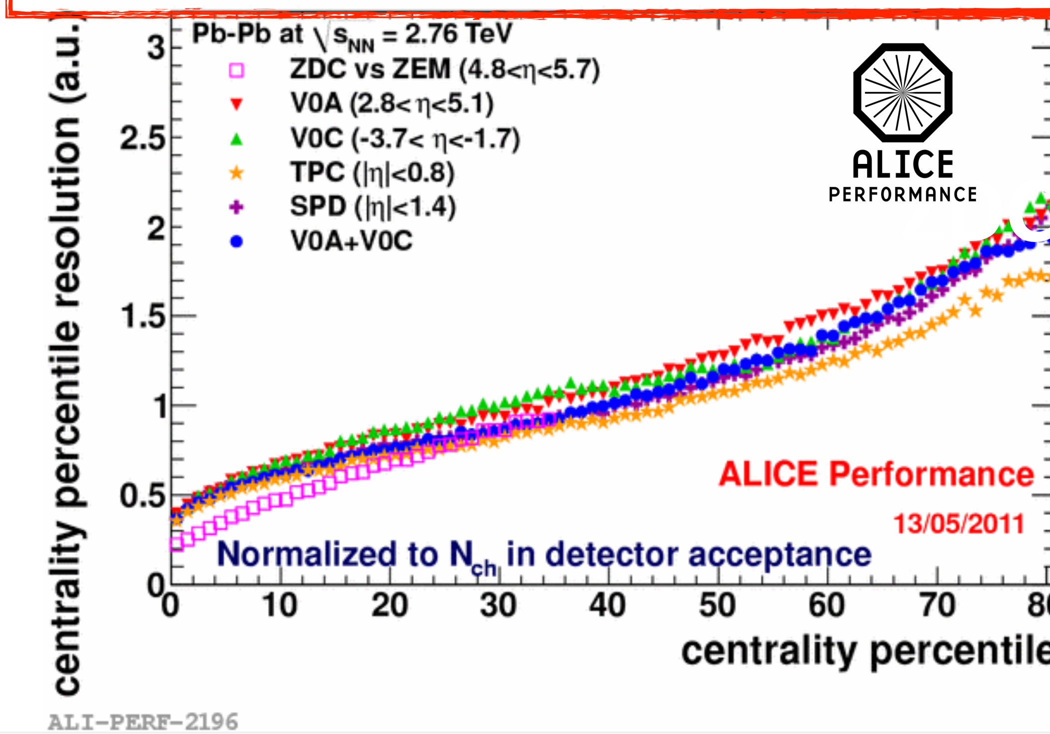
  V0, SPD clusters, TPC tracks, ZDCs, …
- ZDC measures N_{spect}: test of Glauber picture

- Glauber fit ingredients
  - Woods-Saxon (constrained by low energy electron-nucleus scattering)
  - Inelastic pp cross section (measured by ALICE)
  - Nucleons follow straight line trajectories, interact based on their distance
  - Compute (fit) observables assuming:

$$N_{ancestors} = \alpha \cdot N_{part} + (1-\alpha) \cdot N_{coll}$$

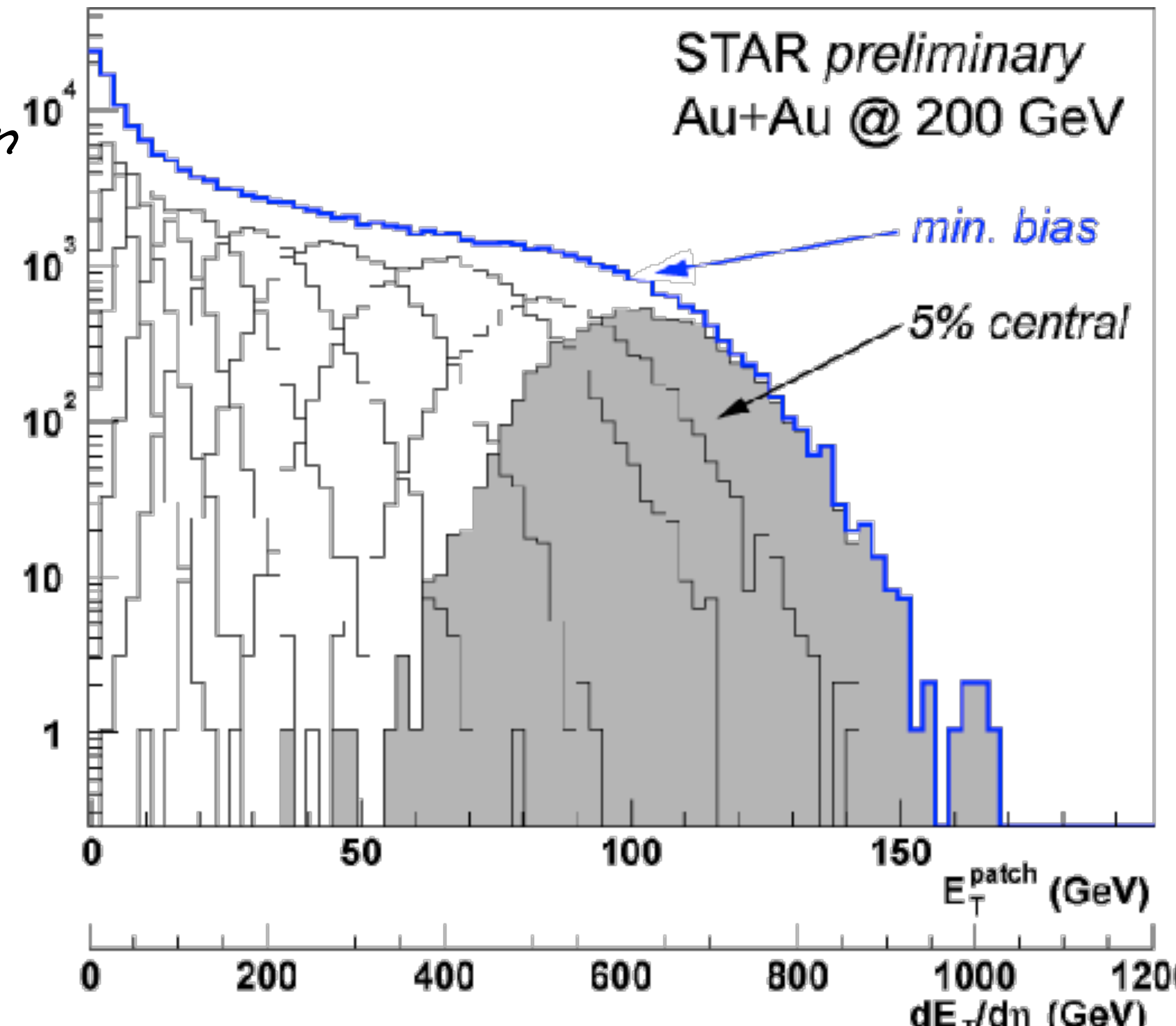
Several detectors – measure the correlation





Energy density in AA collisions
RHIC example

- (calorimeters) measure energy
- estimate volume of collision

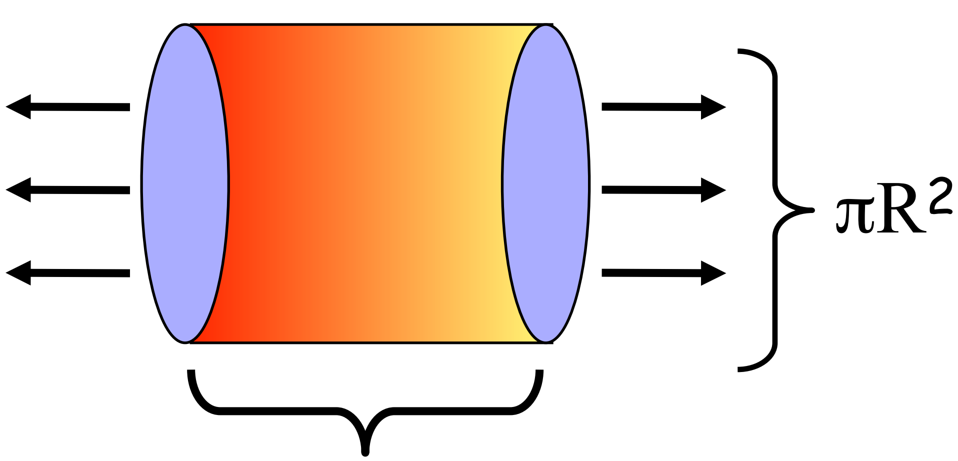


Bjorken energy density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system (t_0 ~ 1 fm/c)



$$dz = \tau_0 dy$$

$\varepsilon_{BJ} \approx$ 5.0 GeV/fm³ RHIC:

~30 times normal nuclear density

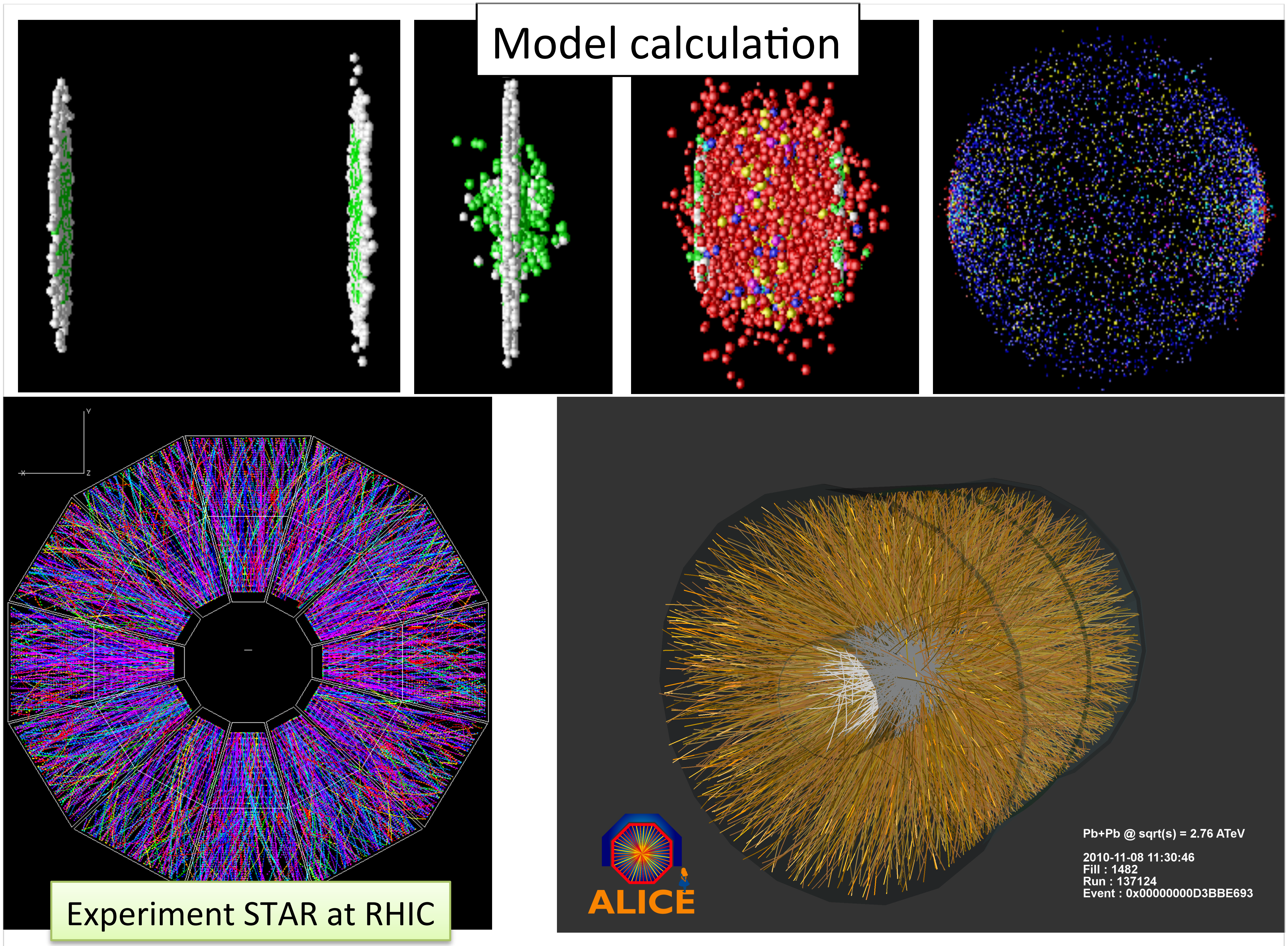
~ 5 times > $\varepsilon_{critical}$ (lattice QCD)

Will see later: LHC ~ 3 × RHIC

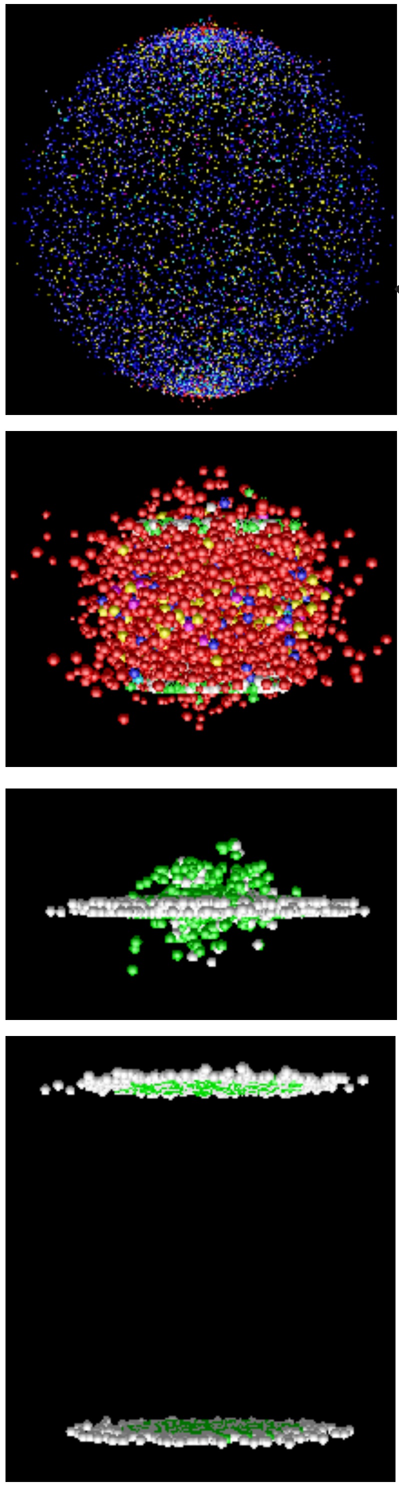
First: "control" understanding
- before further insight to QGP properties...

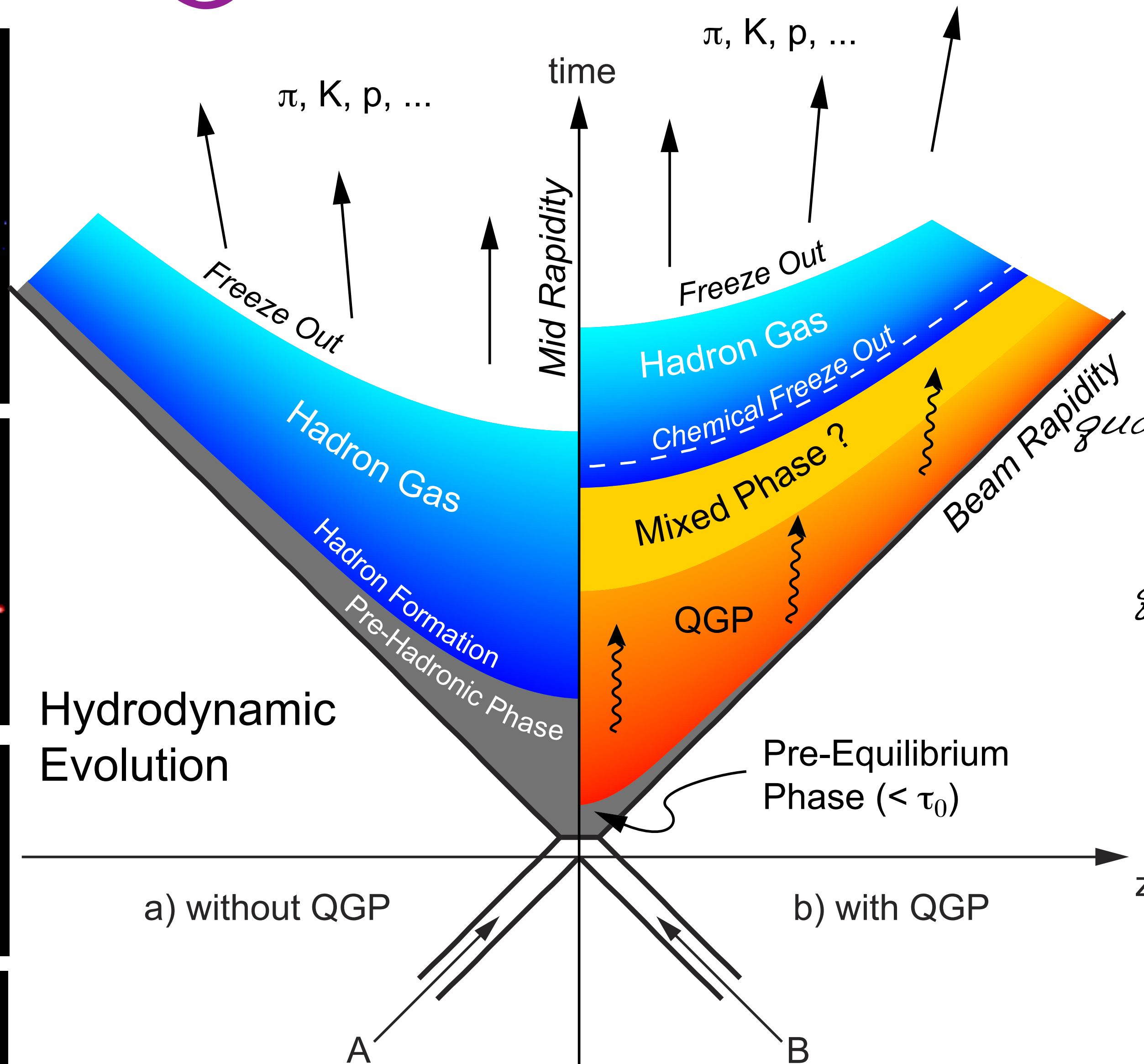
Warning: need to know what observations are "trivial" (we are colliding heavy-ions at hight energies) vs. what observations are sensitive to QGP properties (a thought experiment: what to expect when QGP is NOT formed - what is the baseline - when you know you created QGP - answer is suprisingly complex... more on that later...)

Heavy-ion collisions



Stages of HI collisions





hadrons - kinetic theory

quarks & gluons in equilibrium - hydrodynamics

q & g out-of-equilibrium - viscous hydro

strong-fields - saturation, CGC

"hard" objects - perturbative QCD

Note: hard scatterings occur early (at t~0)!

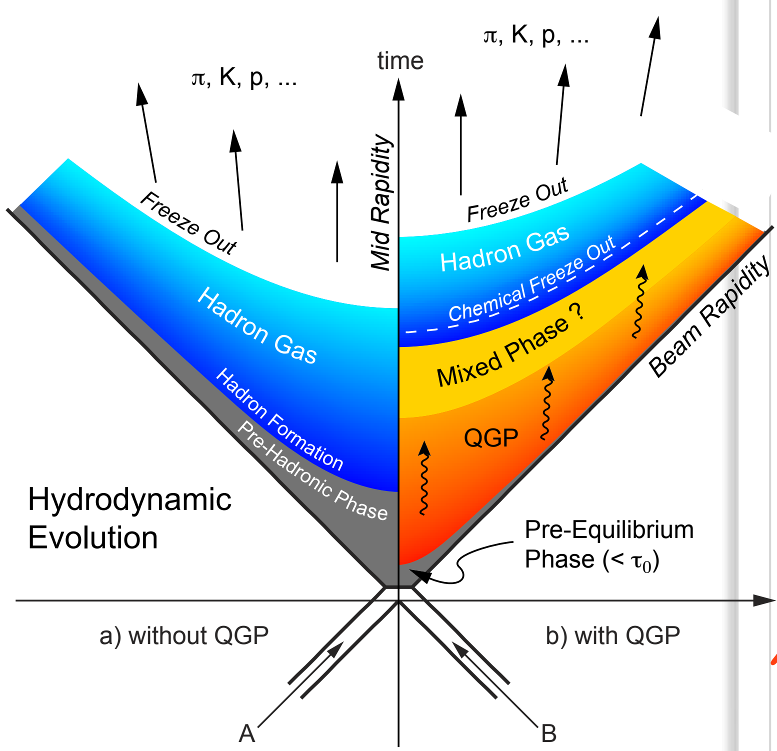
Flow & correlations - L#2

High energy partons - L#2 & L#3

Two key things to follow-up: Chemical freeze-out

Kinetic freeze-out

Collision evolution

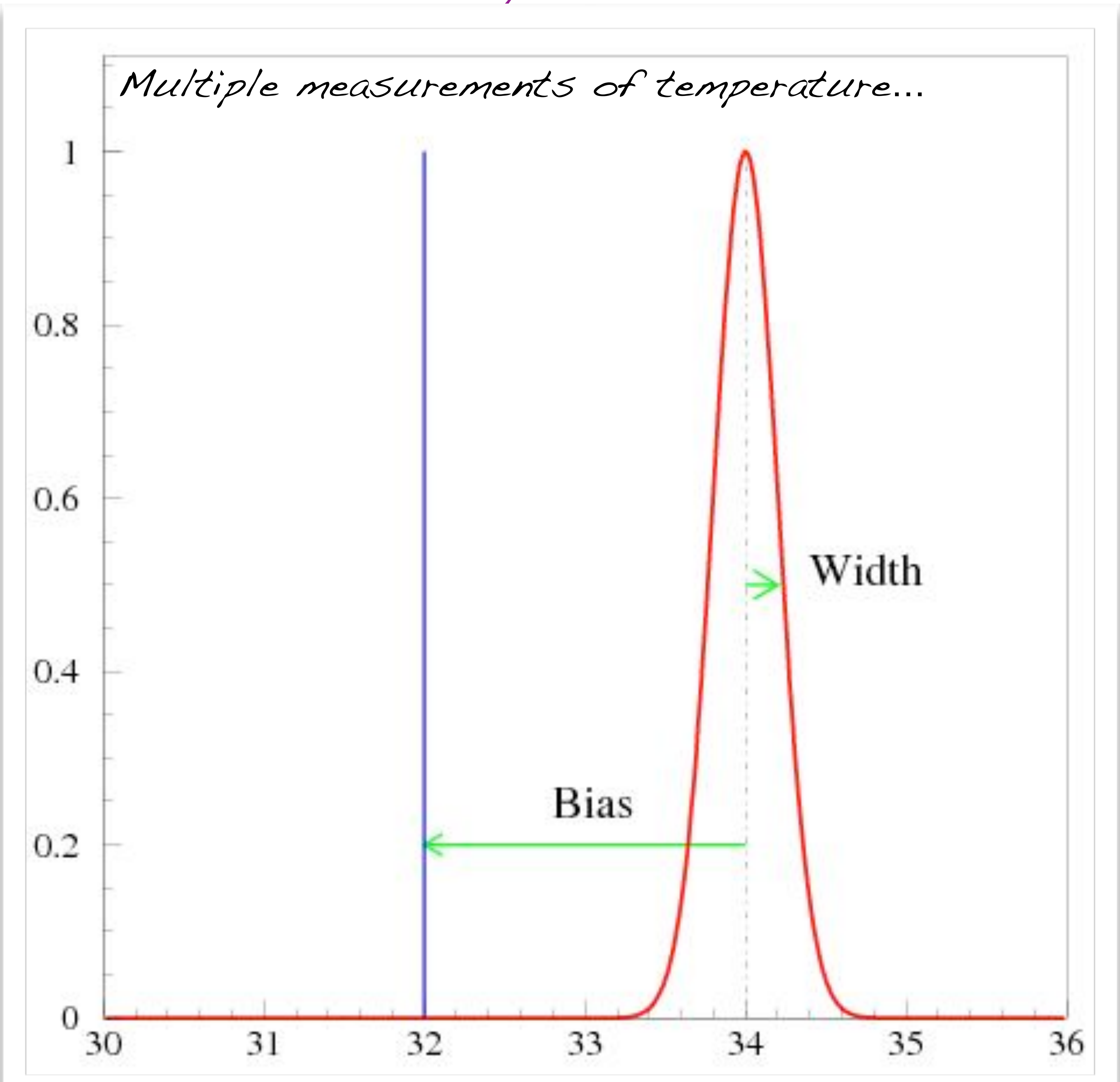


Notes:
We are interested in properties of QGP (lifetimes ~ few fm/c !)
Need to disentangle effects from different phases - not a simple problem by principle: detectors do NOT measure these time-periods/phases separately (detector: particles after hadronization!)
=> need for detail understanding of the physics processes, particle production, dynamics of the system in each phase(!)
=> modeling, various assumptions may play an important role in physics interpretation
Need for control of the initial conditions, geometry of the collision, the incoming parton distributions (nuclear-PDF vs nucleon-PDF) ...

Measurements…

estimating T

a remark...
valid for any measurement

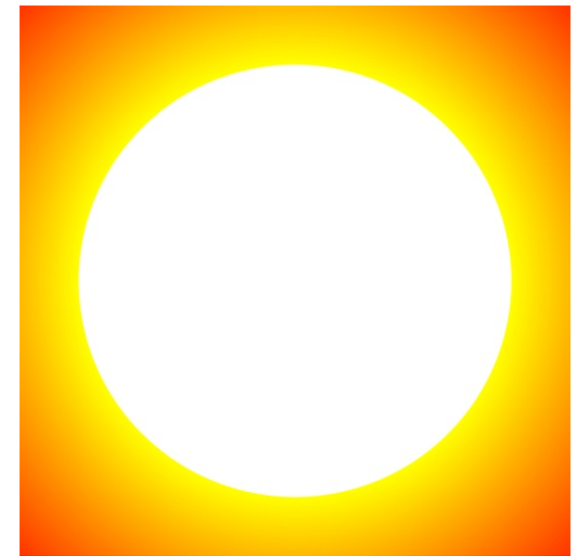


Bias == Scale

Width == Resolution

Remote Temperature Sensing

Red Hot



White Hot

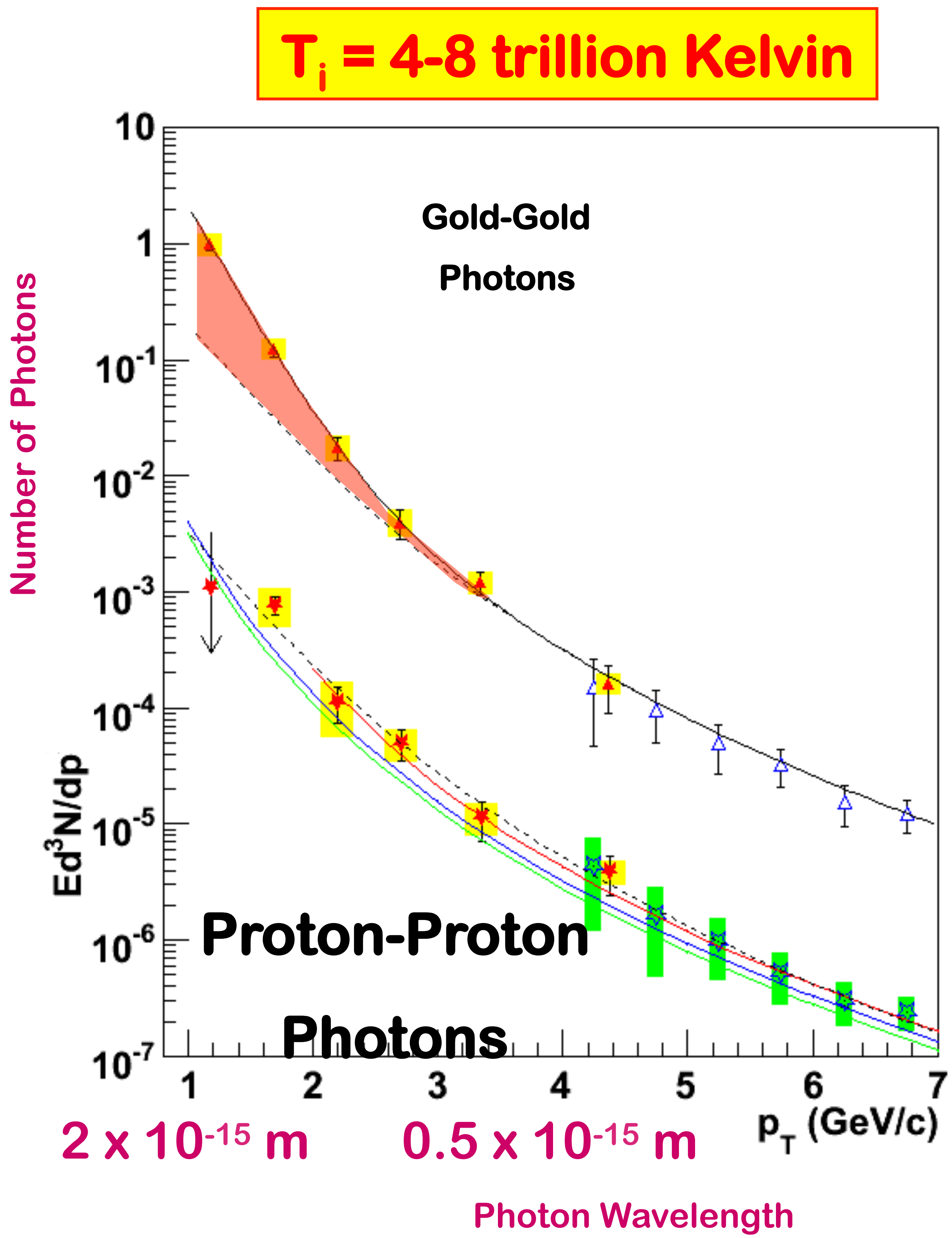
- **Hot Objects produce thermal spectrum of EM radiation.**
- **Red clothes are NOT red hot, reflected light is not thermal.**

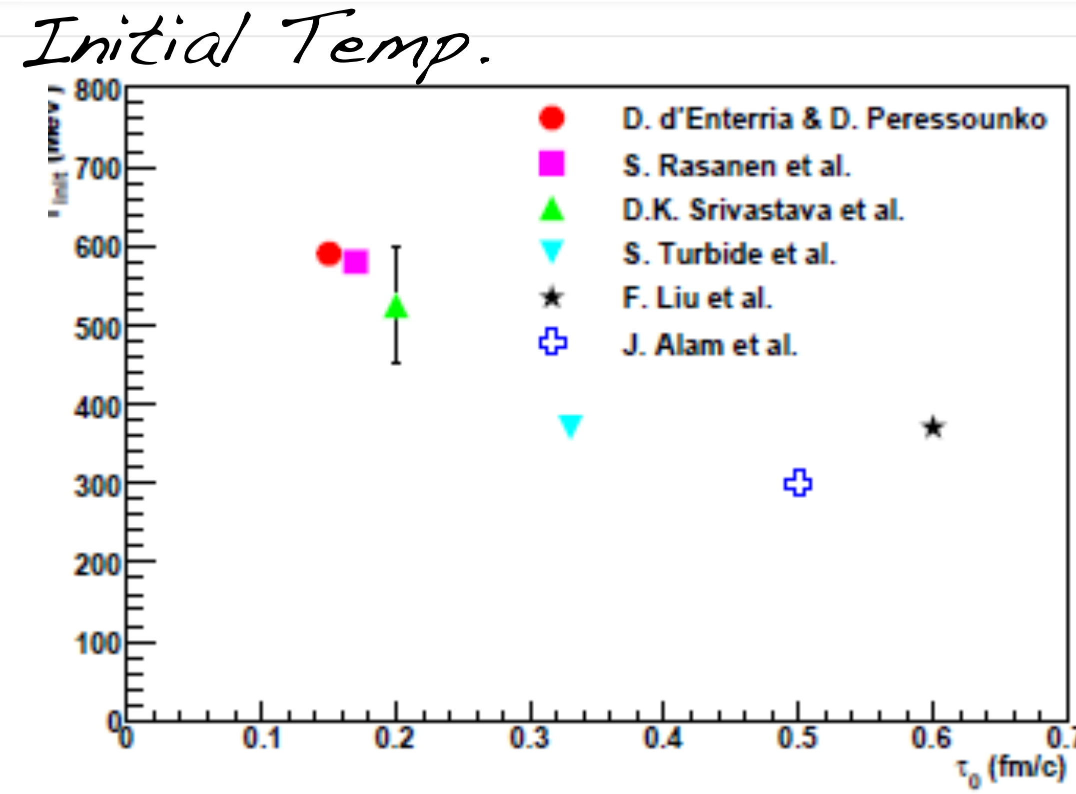
Photon measurements must distinguish thermal radiation from other sources: HADRONS!!!

Not Red Hot!

Thomas K Hemmick

Photons - RHIC



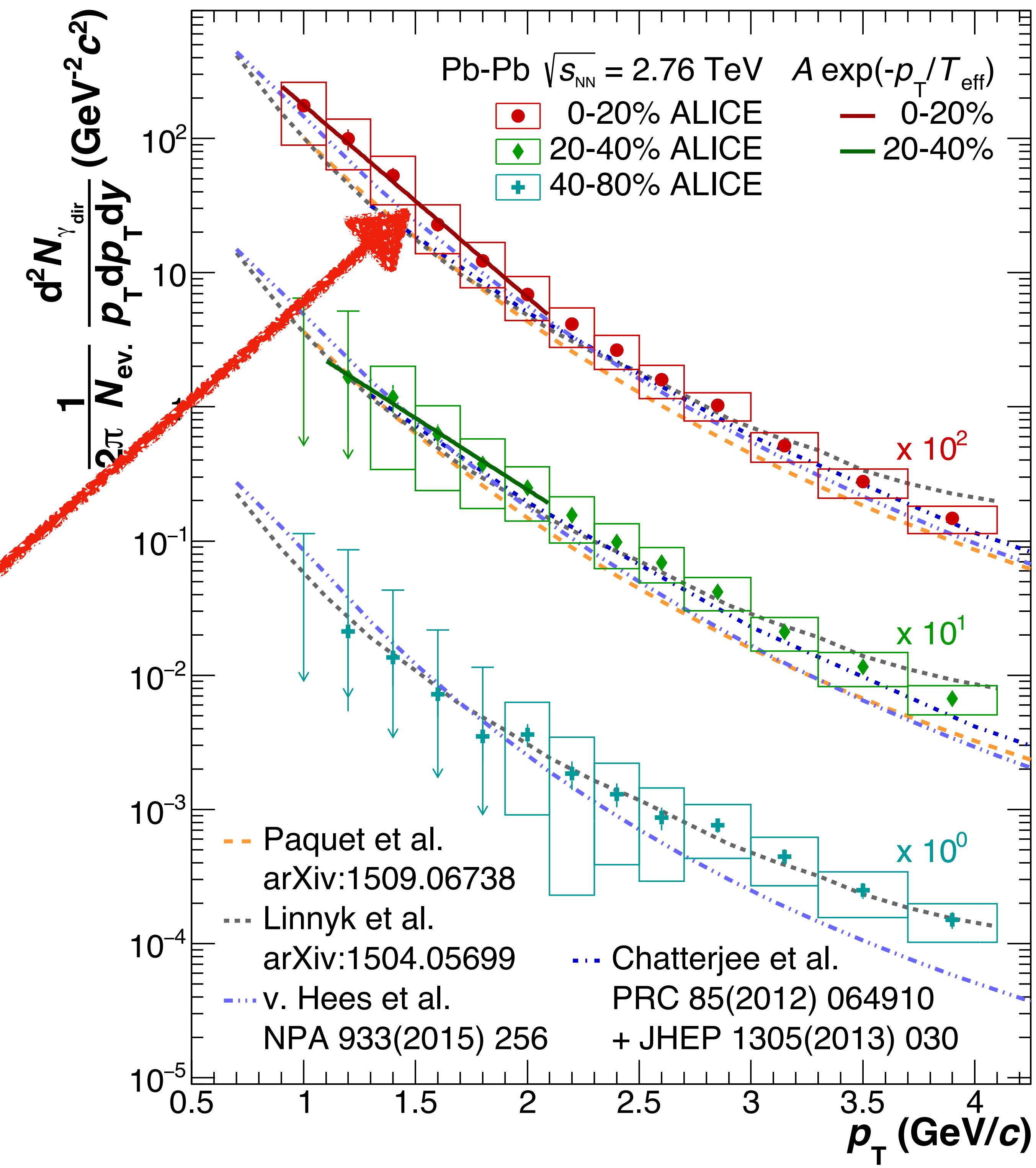


Emission rate and distribution consistent with equilibrated matter

T~300-600 MeV

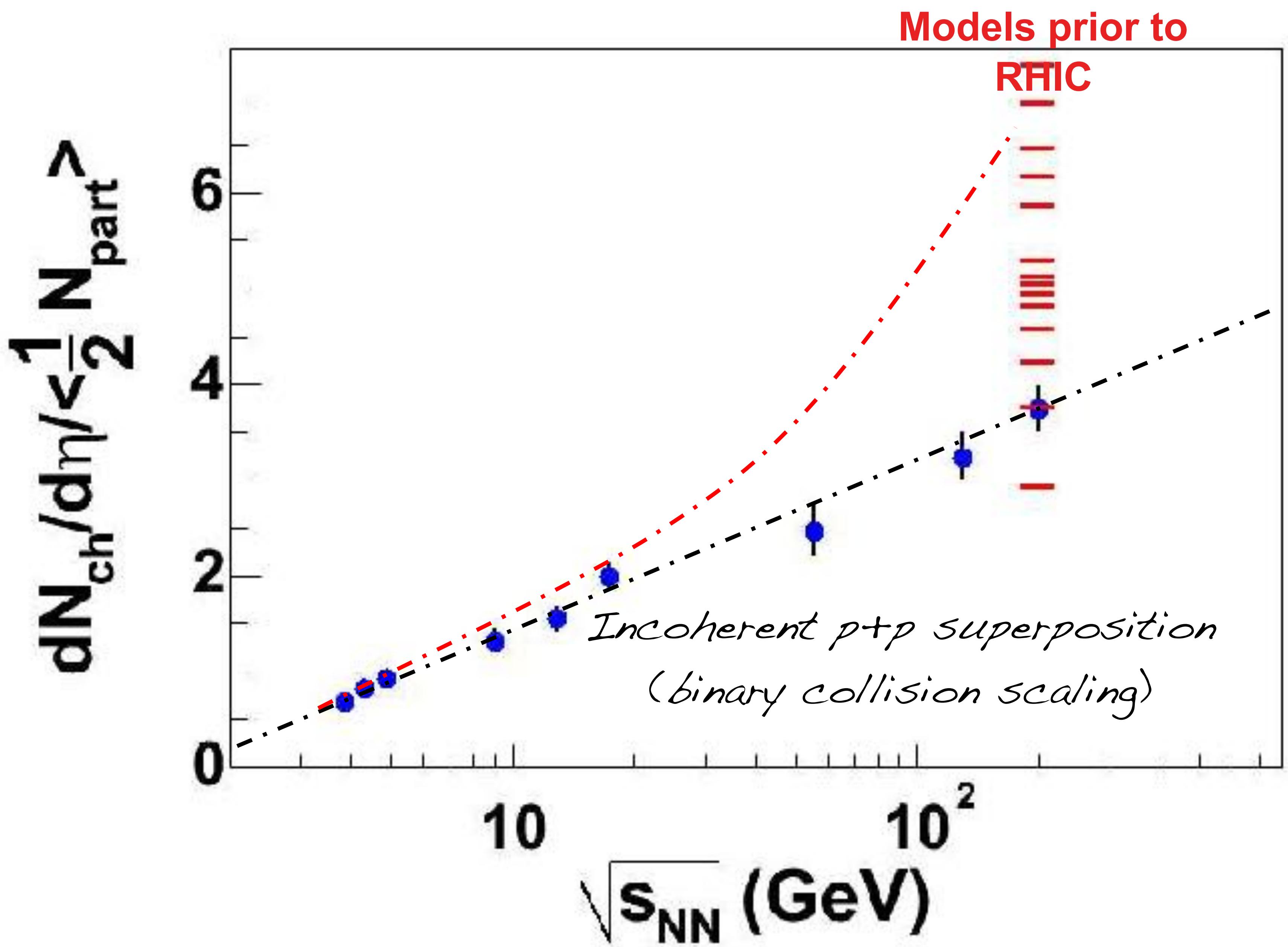
LHC-QGP Shines bright - thermal photons

- Production of photons in Pb-Pb collisions
- Thermal emission - photons shine from the plasma
  - Most central collisions: Inverse slope fits for low-p_T: T~300 MeV
- LHC QGP - hottest man-made matter



Calibration measurements...

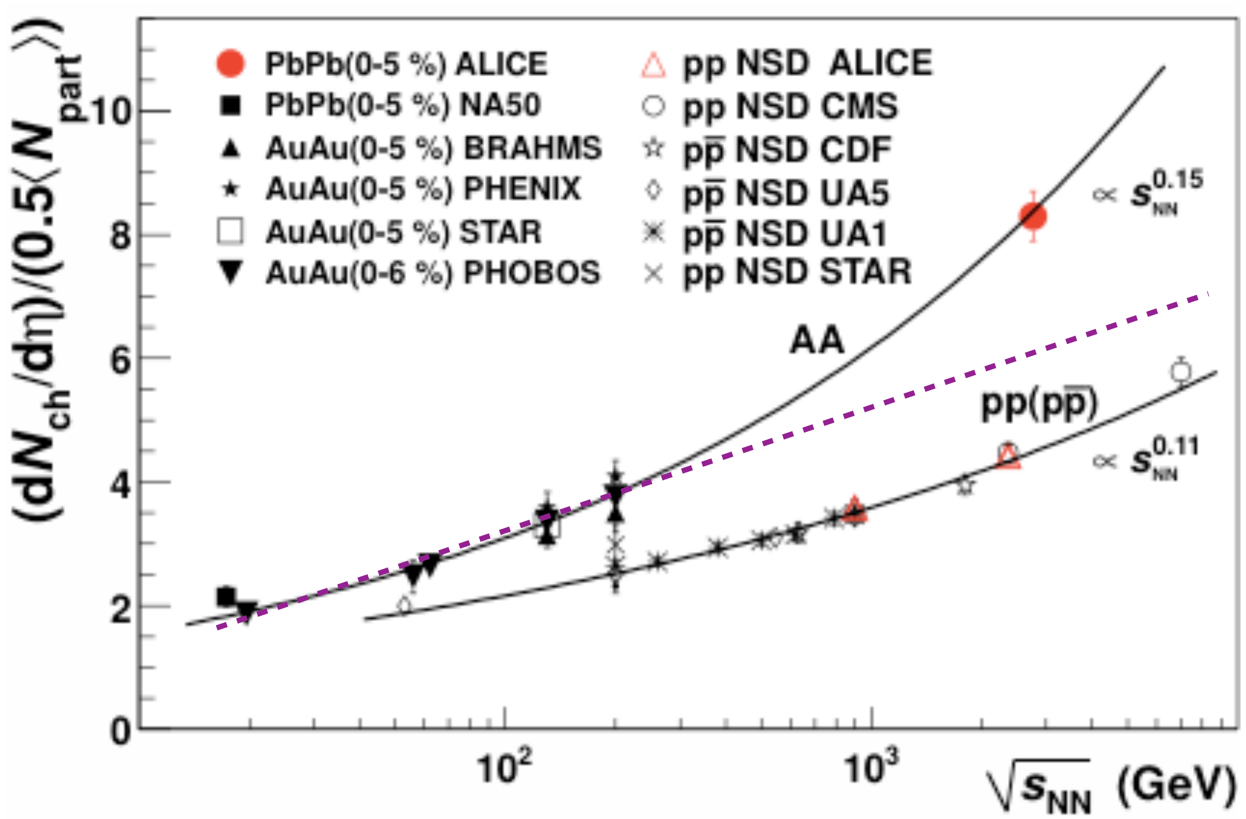
Multiplicity – energy dependence



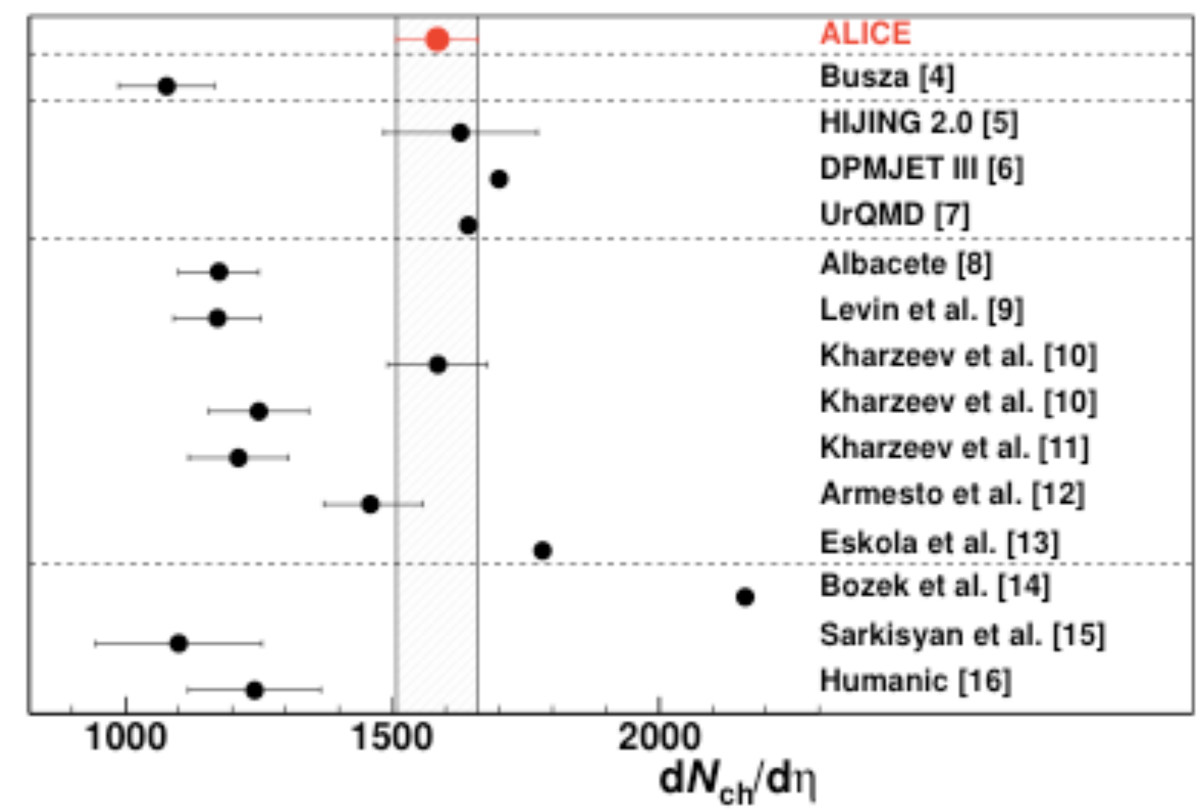
Scales just like pp; No evidence for (incoherent) multi-parton interactions at RHIC.

HI collisions: Particle production
Multiplicity - at high energies...

Energy dependence



Comparison to predictions



PRL 105, 252301 (2010)

Energy dependence

p-p ~ $s_{NN}^{0.11}$

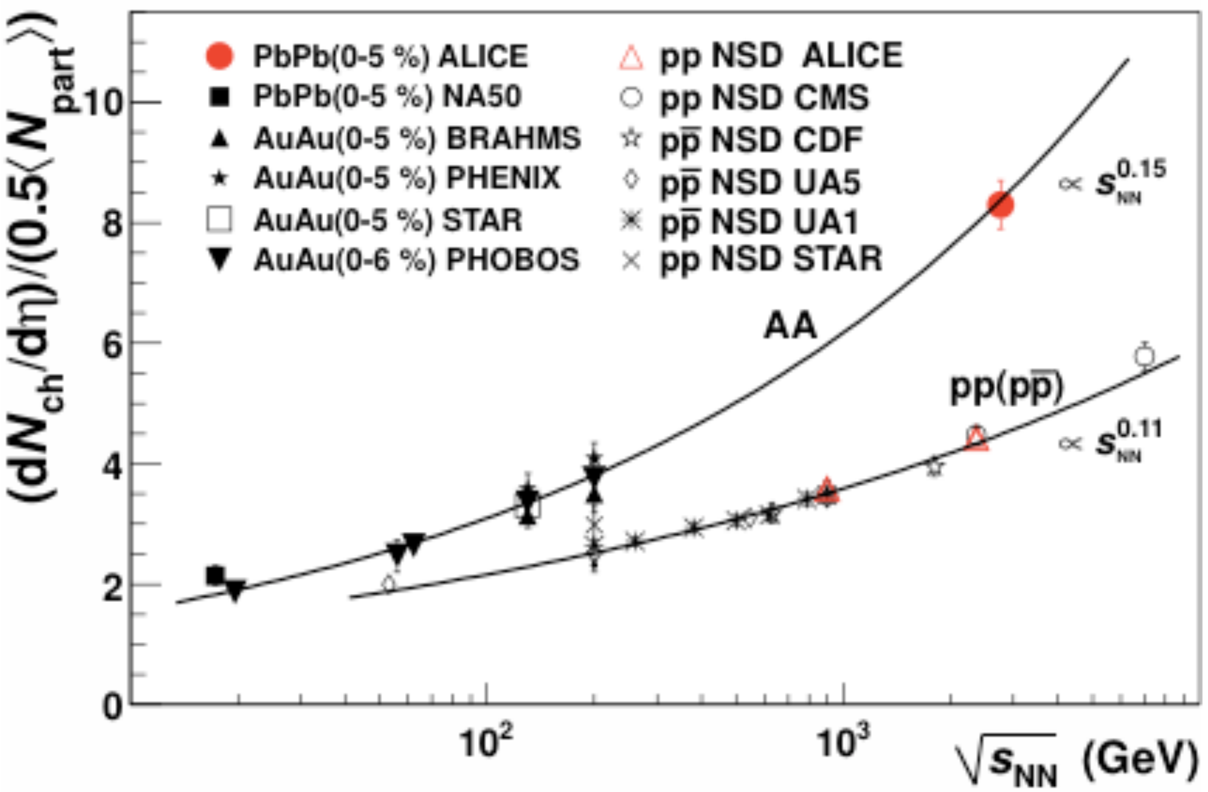
A-A ~ $s_{NN}^{0.15}$ (most central - 2x RHIC)

– stronger rise than log extrapolation

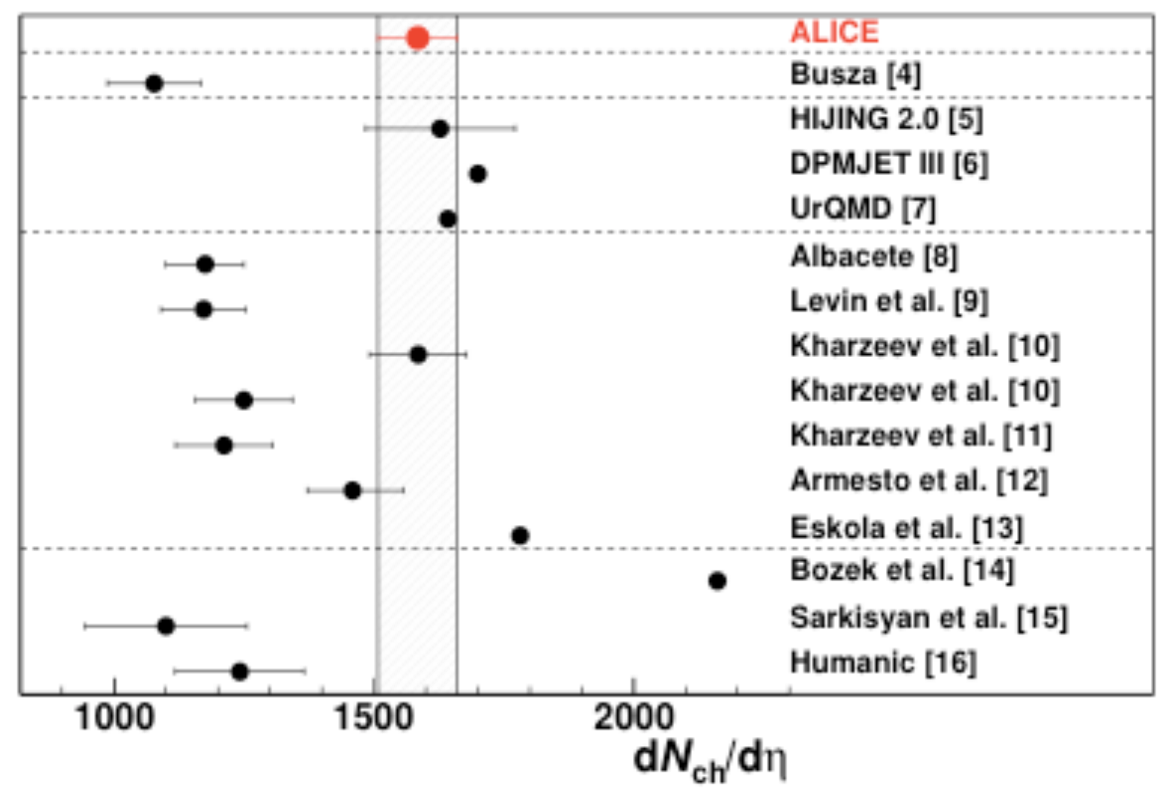
Higher energy
<->
Stronger growth
<->
more partons interacting...

HI collisions: Particle production

Energy dependence



Comparison to predictions



PRL 105, 252301 (2010)

Feedback within the heavy-ion community:

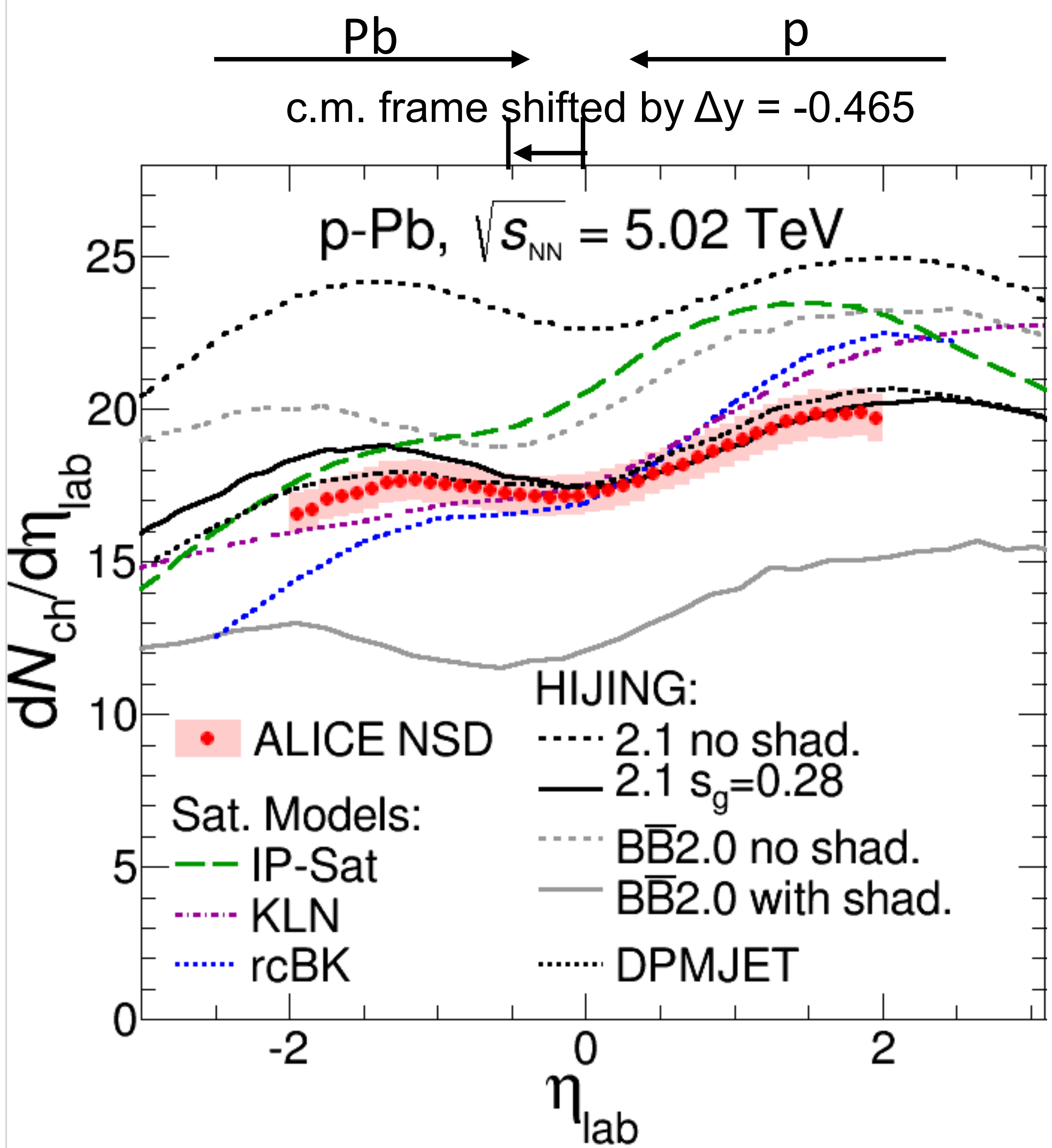
1. **Multiplicity is crucial [input] for modeling**
2. **Saturation models tend to predict lower multiplicity**
3. **Data driven extrapolations did not seem to anticipate the results**

Calibration: proton-A collisions

p-Pb – crucial tests at LHC & new phenomena

More during the next lectures…

ALICE: arXiv: 1210.3615



Basic measurement allows to discriminate between models

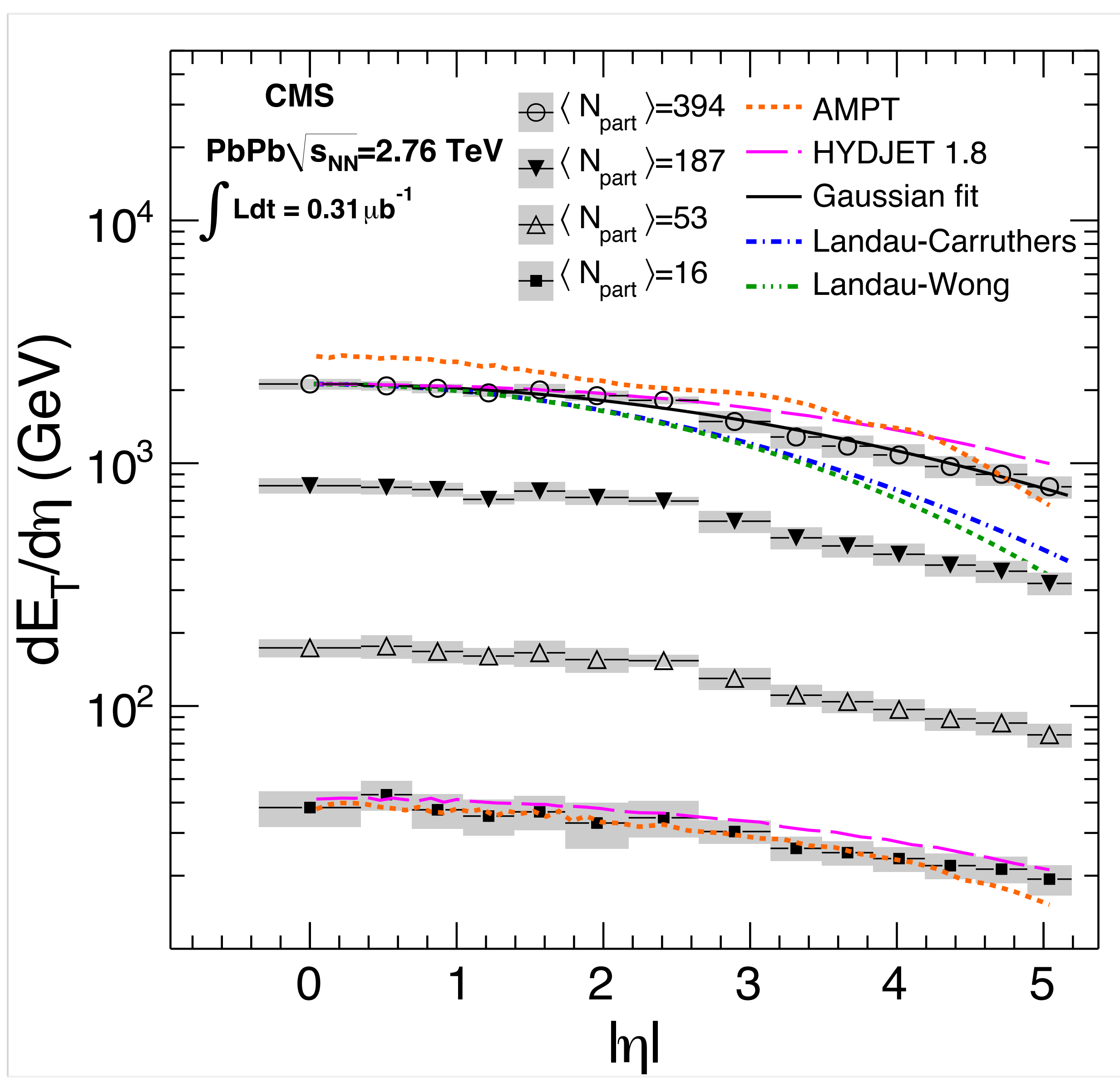
Data favors models that incorporate shadowing

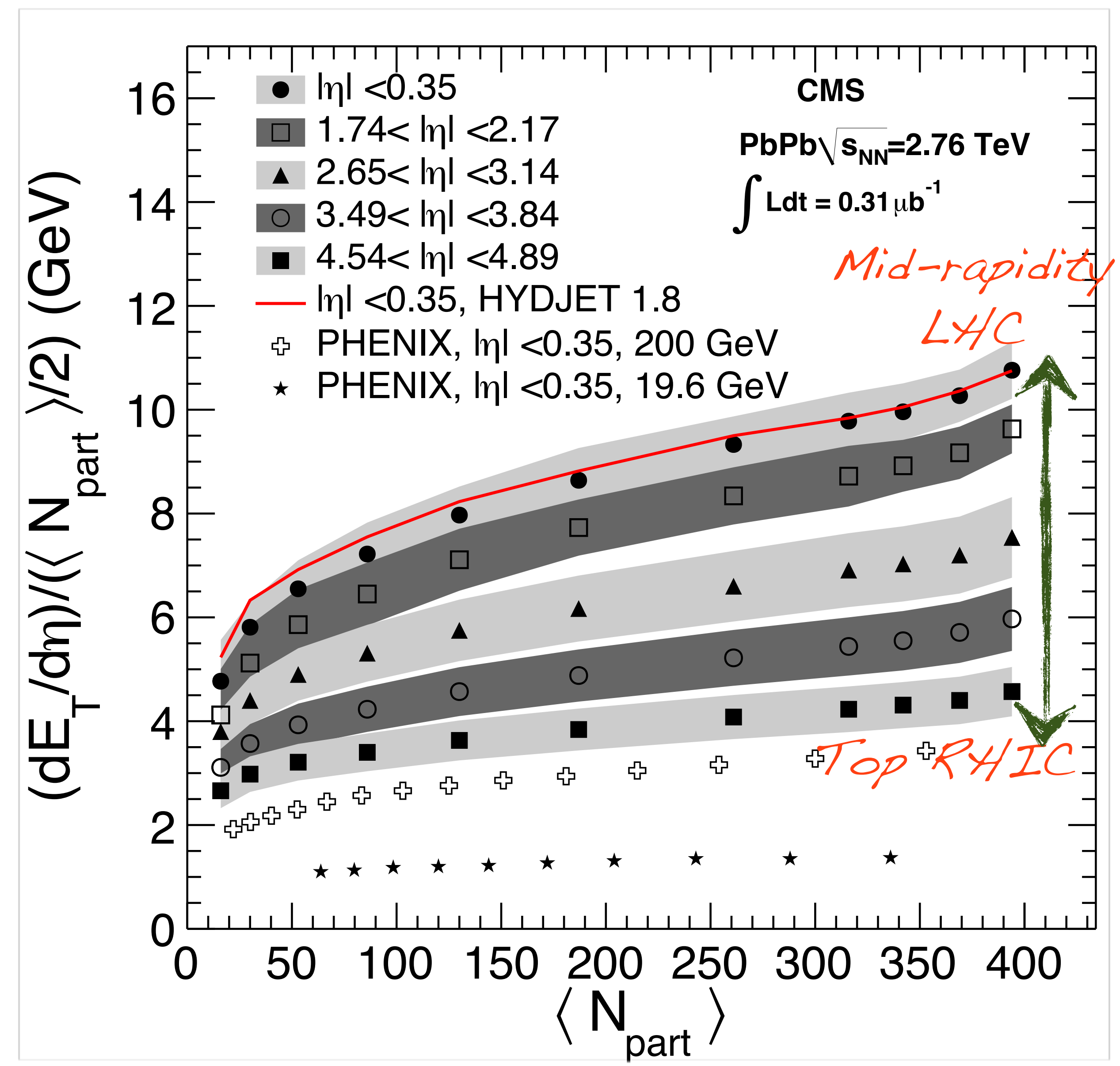
Saturation models predict much steeper η-dependence not seen in the data

Energy density: RHIC to LHC

LHC > 2.5 x RHIC

... within a volume (per nucleon)





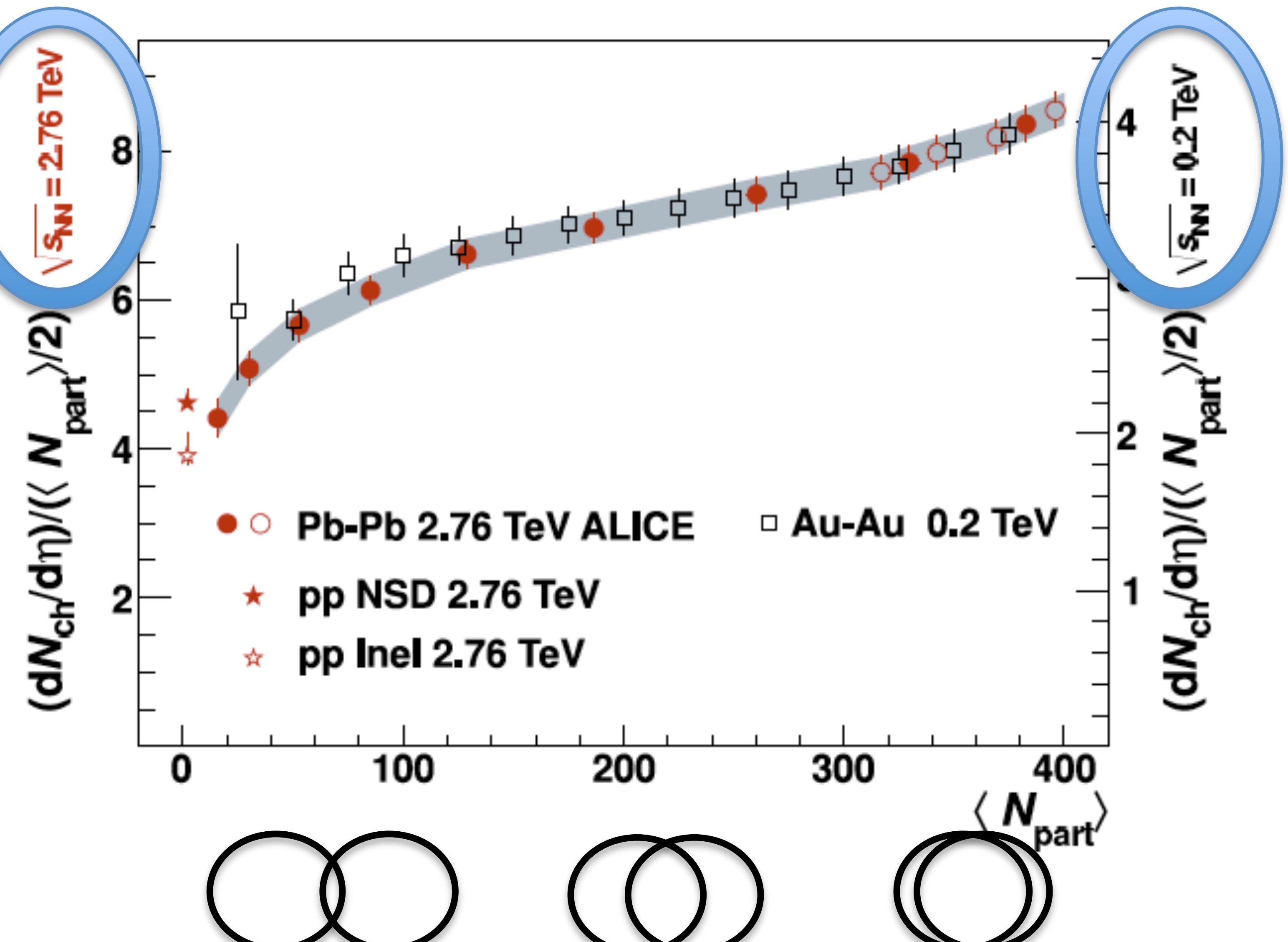
Very hot, super dense? -> what are its "transport" properties... fundamental QCD questions

Calibration measurements: what do we know about the source emitting particles?

Systematic control: RHIC vs LHC

The same experiment under vastly different conditions!

Centrality dependence of particle production



- **Identical variation of particle production with centrality (volume) at RHIC and LHC!**

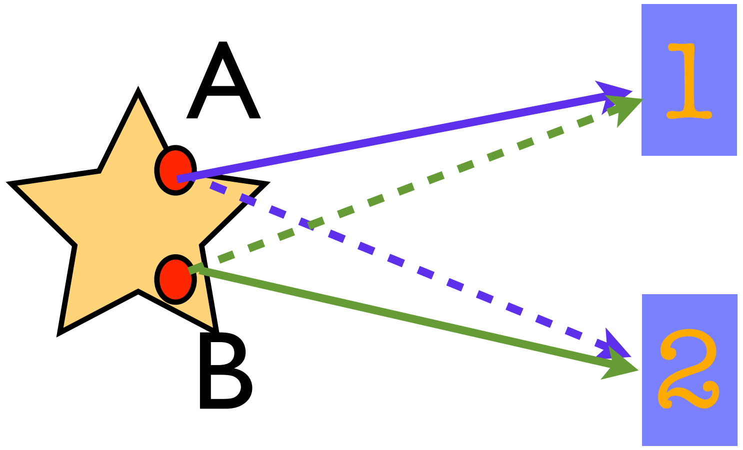
⇒ Global features of the system independent on energy

⇒ Initial conditions!

More on RHIC:
*Phobos (**Phys. Rev. Lett. 102, 142301 (2009)**)*

Centrality of the collisions: peripheral semi-central central

How to measure the dimensions of a source... interferometry



quantum phenomenon: enhancement of correlation function for identical bosons from Heisenberg's uncertainty principle

Two particles emitted from two locations (A,B) within a single source.
These two are detected by detector elements (1,2).

$$A = \frac{1}{\sqrt{2}}\left(e^{ik_1^\mu (r_1 - r_a)^\mu} e^{ik_2^\mu (r_2 - r_b)^\mu} + e^{ik_1^\mu (r_1 - r_b)^\mu} e^{ik_2^\mu (r_2 - r_a)^\mu}\right)$$

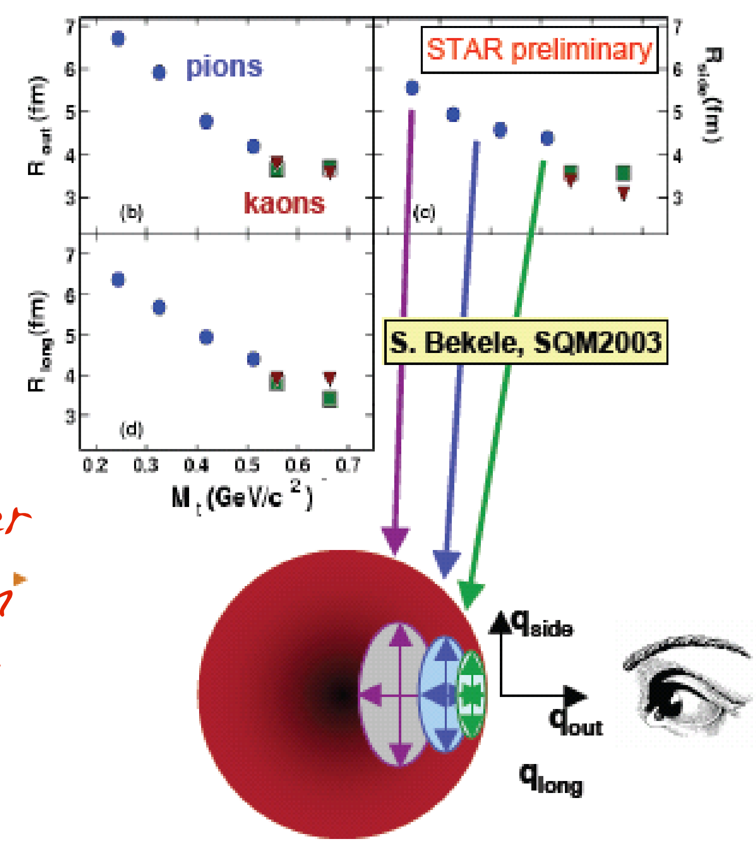
$$I = |A|^2 = 1 + \left\{ e^{i(k_2 - k_1)^\mu (r_a - r_b)^\mu} + c.c. \right\}$$

The intensity interference between the two point sources is an oscillator depending upon the relative momentum q=k2-k1, and the relative emission position!

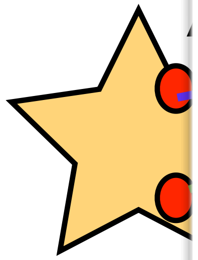
$$C(\mathbf{p}_1, \mathbf{p}_2) = \frac{E_1 E_2 dN/(d^3p_1 d^3p_2)}{(E_1 dN/d^3p_1)(E_2 dN/d^3p_2)}. \quad E_p\frac{dN}{d^3p} = \int d^4x\, S(x,p)$$

Correlation function summed incoherently (integration over all pairs of source points) in a function of 4-momentum sums and differences (q,K) – extract source dimensions:

$$C(q,K) = 1 \pm \lambda(K)\exp\left(-R_s^2(K)q_s^2 - R_o^2(K)q_o^2 - R_l^2(K)q_l^2\right)$$



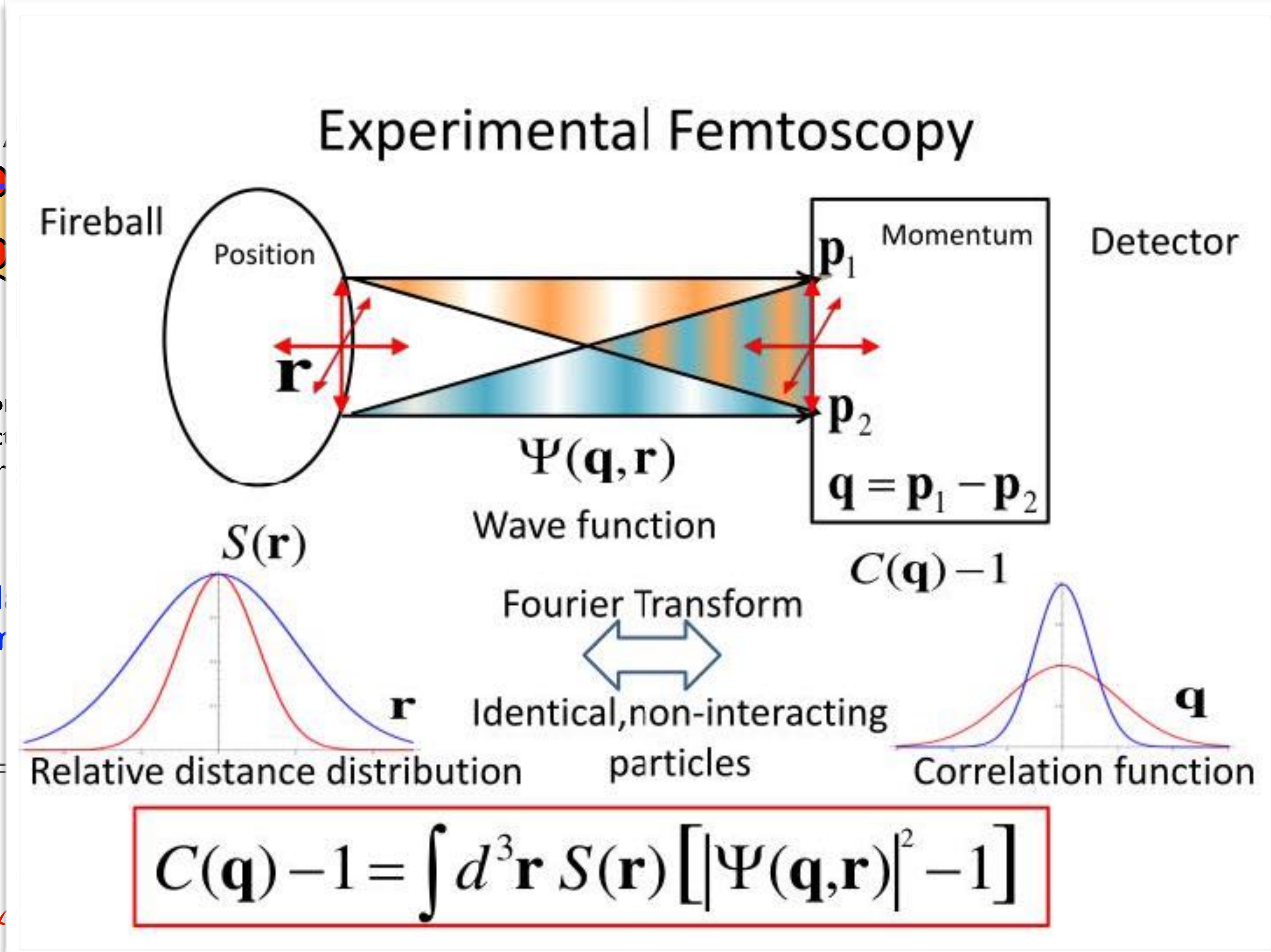
How to measure the dimensions of a source... interferometry



quantum pheno
correlation func
from Heisenber

The intensity is an oscill momentum position!

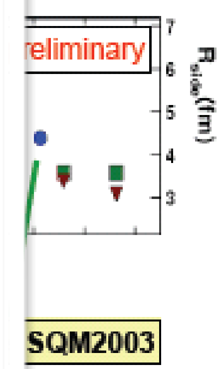
$C(p_1, p_2) =$



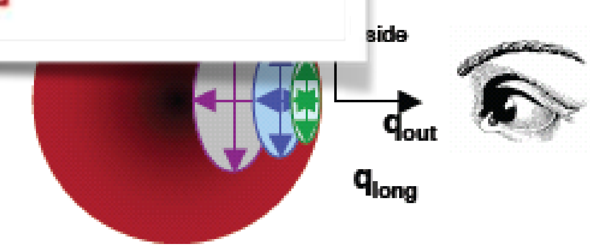
ions (A,B)

ements (1,2).

$k_2^\mu (r_2 - r_a)^\mu \Big)$

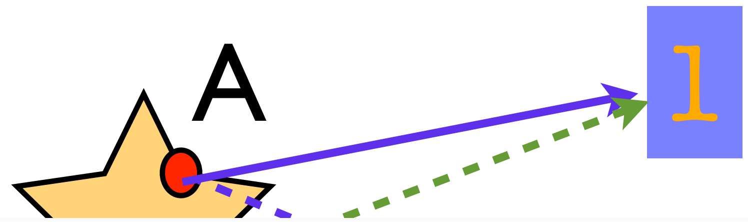


Correlation
all pairs of
sums and differences (q,K) - extract source dimensions:



$$C(q,K) = 1 \pm \lambda(K) \exp\left(- R_s^2(K) q_s^2 - R_o^2(K) q_o^2 - R_l^2(K) q_l^2 \right)$$

How to measure the dimensions of a source... interferometry

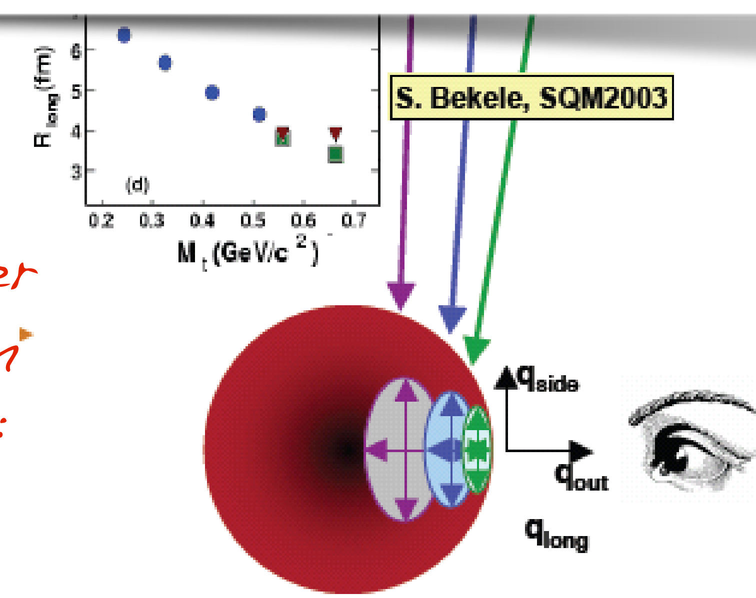


Two particles emitted from two locations (A,B) within a single source.
These two are detected by detector elements (1,2).

First used with photons in the 1950s by astronomers Hanbury Brown and Twiss - hence HBT measurements in heavy-ion collisions...
=> measured size of star Sirius by aiming at it two photomultipliers separated by a few meters

Th

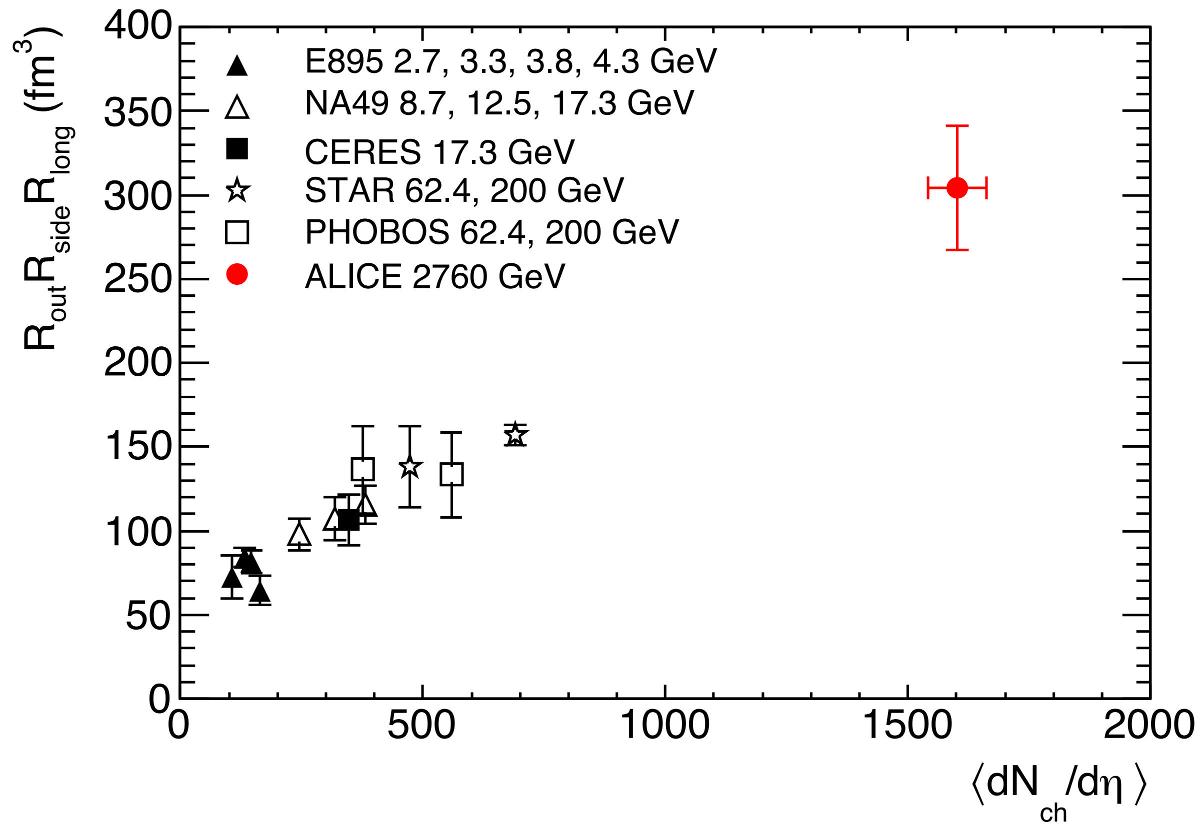
$$C(\mathbf{p}_1,\mathbf{p}_2) = \frac{E_1E_2dN/(d^3p_1d^3p_2)}{(E_1dN/d^3p_1)(E_2dN/d^3p_2)}. \qquad E_p\frac{dN}{d^3p} = \int d^4x\, S(x,p)$$

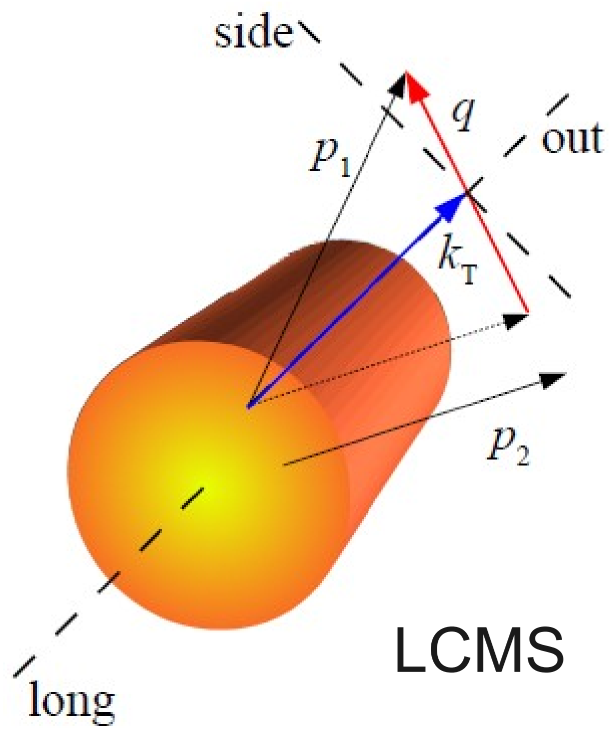


Correlation function summed incoherently (integration over all pairs of source points) in a function of 4-momentum sums and differences (q,K) - extract source dimensions:

$$C(q,K) = 1 \pm \lambda(K)\exp\left(-R_s^2(K)q_s^2 - R_o^2(K)q_o^2 - R_l^2(K)q_l^2\right)$$

Particle production: source dimensions

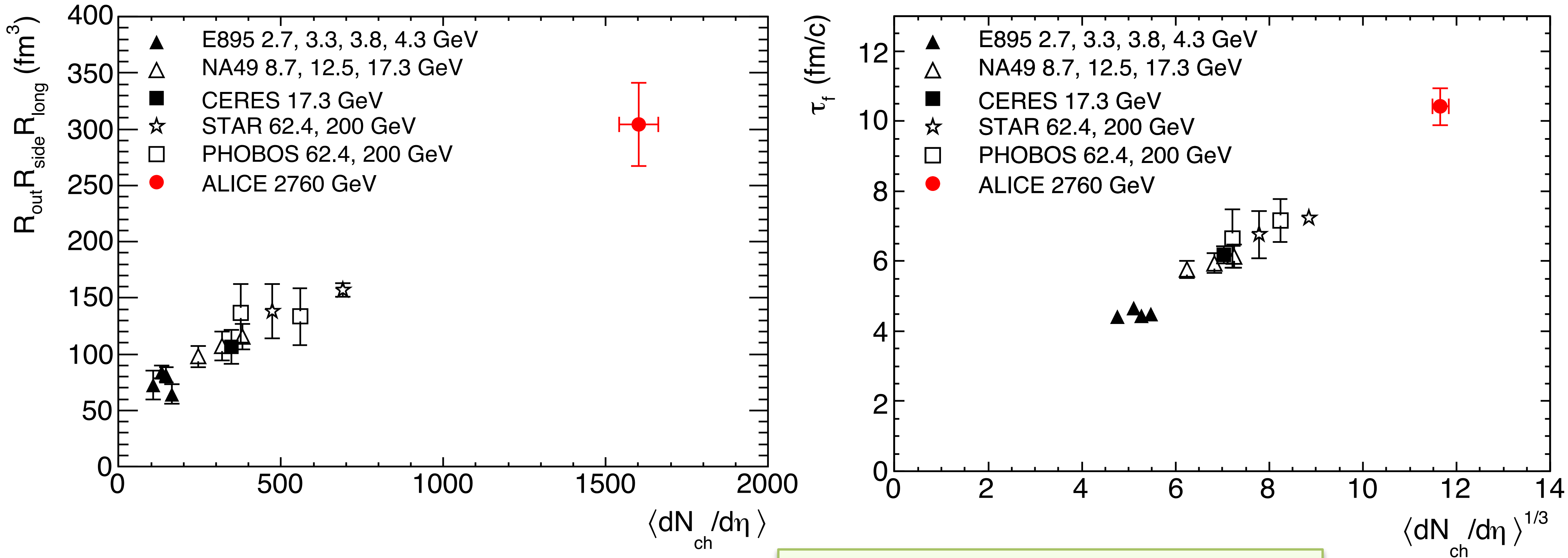




Phys.Lett.B 696:328-337,2011

1. **Energy dependence:**
   - **system with larger (2x) volume and (1.4x) lifetime (w.r.t RHIC); follows the trend of multiplicity; faster expansion <=> larger collective flow**
2. **Pair momentum dependence:**
   - **larger radii, strong dependence on kT; Rout/Rside smaller than at RHIC; overall agreement with extrapolations**
3. **Important constrains to [hydrodynamical] modelling**

Particle production: source dimensions



Phys.Lett.B 696:328-337,2011

1. Energy dependence:

- **system with larger (2x) volume and (1.4x) lifetime (w.r.t RHIC); follows the trend of multiplicity; faster expansion <=> larger collective flow**

2. Pair momentum dependence:

- **larger radii, strong dependence on kT; Rout/Rside smaller than at RHIC; overall agreement with extrapolations**

3. Important constrains to [hydrodynamical] modelling

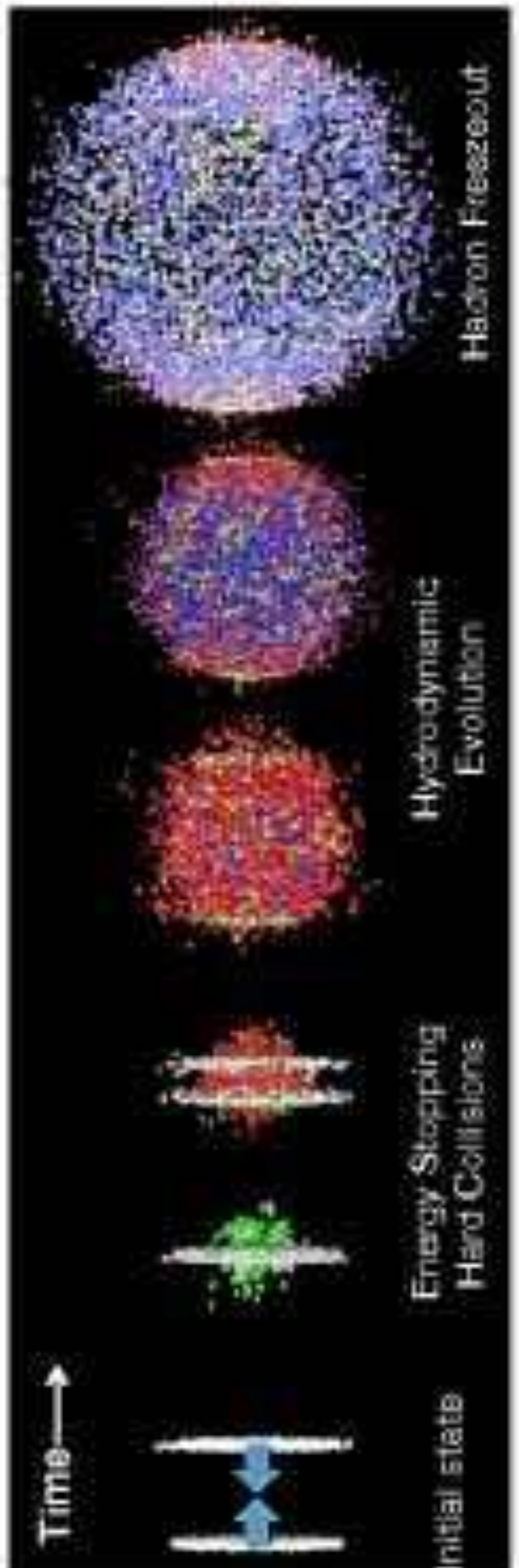
until now...

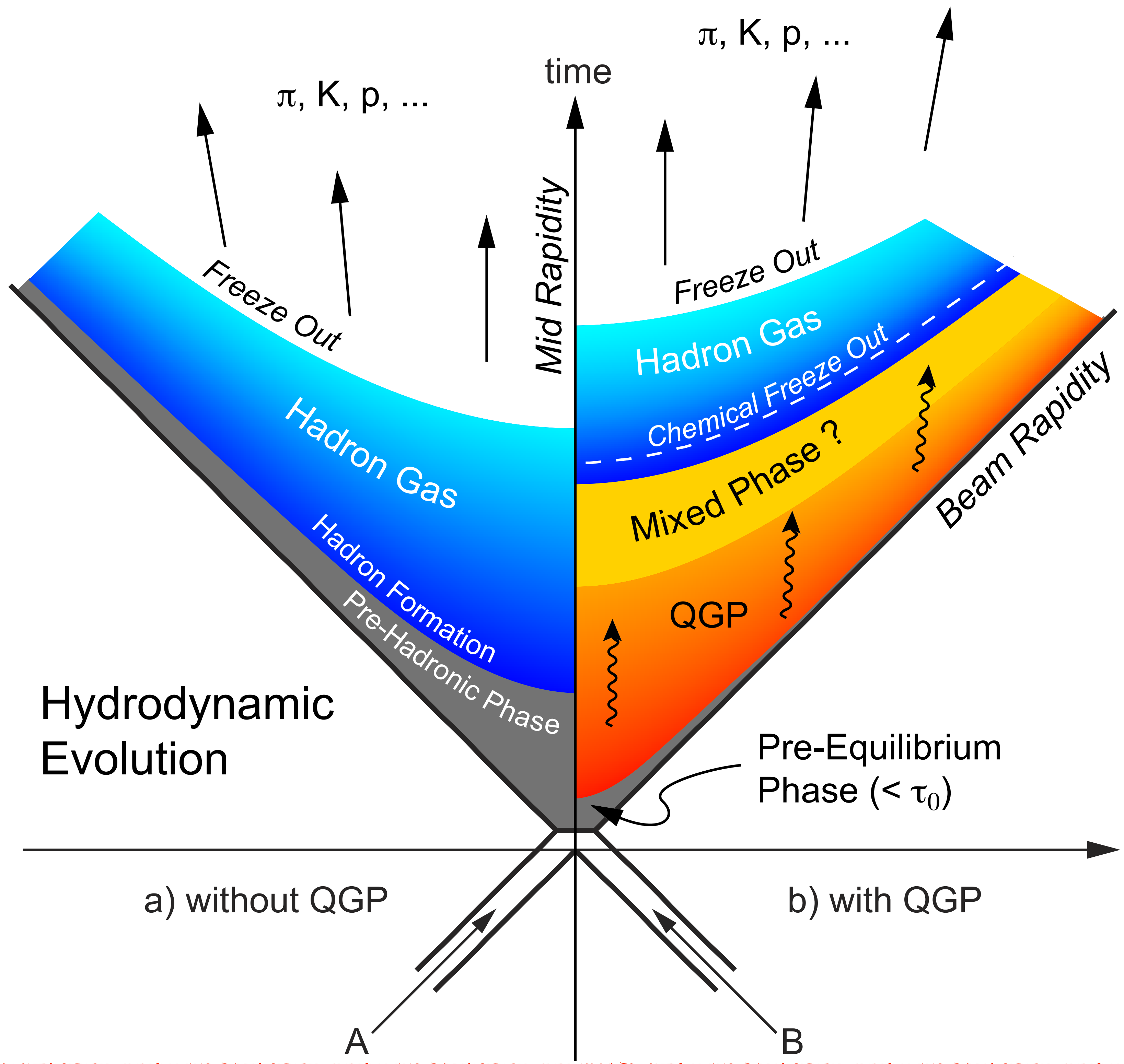
- phases of HI collision
- how to measure centrality of a collision
- ... energy density
- ... temperature
- ... freeze-out volume (and time)
- QGP: hot, short-lived system with rapid dynamical evolution

Next

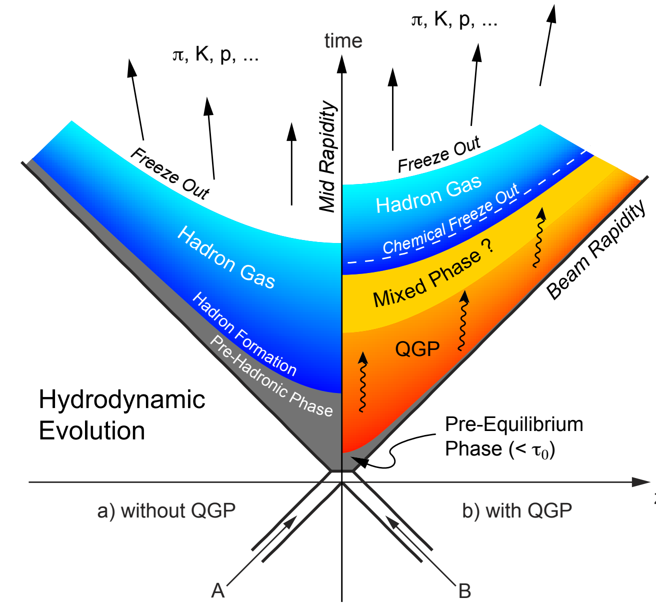
- particle abundance's at hadronization
- QGP properties / transport coefficients:
  - flow

Collision timeline





... to follow-up: chemical & kinetic freeze-out



Freeze-out:

- chemical freeze out <=> hadron composition fixed
- kinetic freeze-out <=> hadron momenta fixed (interactions stop)
- overall: $T_{ch} > T_{kin}$ (system cools down - follow the time axis)

Thermal equilibrium… Chemical and kinetic freeze-out

Chemical equilibrium:

- correct relative particle abundances?
- large system -> Grand Canonical ensemble: many particles; conservation laws on average - chemical potentials
- small system -> conservation laws E-by-E -> "canonical suppression" (strangeness)

$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\left(E-\mu_B B_i-\mu_s S_i-\mu_3 I^3\right)/T}\pm 1}$$

The ratios of produced particle yields between various species can be fitted to determine T, μ.

Kinetic equilibrium - radial flow:

- for any interacting system of particles expanding into vacuum, radial flow is a natural consequence.

During the cascade process, an ordering of particles with the highest common underlying velocity at the outer edge develops naturally

Hadrons are released in the final stage and therefore measure "FREEZE-OUT" Temp. - instructive simple parametrization - radially boosted source with velocity β and at y=0:

$$\frac{d^3N}{dp^3}\propto e^{-E/T};\ E\frac{d^3N}{dp^3}=\frac{d^3N}{m_T dm_T d\phi dy}\propto Ee^{-E/T}=m_T\cosh(y)e^{-m_T\cosh(y)/T}$$

$$\frac{1}{m_T}\frac{dN}{dm_T}\propto m_T I_0\left(\frac{p_T\sinh(\rho)}{T}\right)K_1\left(\frac{m_T\cosh(\rho)}{T}\right)$$

$$\rho=\tanh^{-1}\left(\beta_{boost}\right)$$

Simple assumption: uniform sphere of radius R and boost velocity varies linearly w/ r:

$$\frac{1}{m_T}\frac{dN}{dm_T}\propto\int_0^R r^2 dr\, m_T I_0\left(\frac{p_T\sinh(\rho)}{T}\right)K_1\left(\frac{m_T\cosh(\rho)}{T}\right)$$

$$\rho(r)=\tanh^{-1}\left(\beta_T^{MAX}\frac{r}{R}\right)$$

Blast Wave model => common T and β

Thermal equilibrium…
Chemical and kinetic freeze-out

Chemical equilibrium:

- correct relative particle abundances?
- large system -> Grand Canonical ensemble: many particles; conservation laws on average - chemical potentials
- small system -> conservation laws E-by-E -> "canonical suppression" (strangeness)

$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\left(E-\mu_B B_i-\mu_s S_i-\mu_3 I^3\right)/T} \pm 1}$$

The ratios of produced particle yields between various species can be fitted to determine T, μ.

Kinetic equilibrium - radial flow:

- for any interacting system of particles expanding into vacuum, radial flow is a natural consequence.

During the cascade process, an ordering of particles with the highest common underlying velocity at the outer edge develops naturally

Hadrons are released in the final stage and therefore measure "FREEZE-OUT" Temp. - instructive simple parametrization - radially boosted source with velocity β and at y=0:

$$\frac{d^3N}{dp^3} \propto e^{-E/T}; E\frac{d^3N}{dp^3} = \frac{d^3N}{m_T dm_T d\phi dy} \propto Ee^{-E/T} = m_T \cosh(y) e^{-m_T\cosh(y)/T}$$

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto m_T I_0\left(\frac{p_T\sinh(\rho)}{T}\right)K_1\left(\frac{m_T\cosh(\rho)}{T}\right)$$

$$\rho = \tanh^{-1}(\beta_{boost})$$

Simple assumption: uniform sphere of radius R and boost velocity varies linearly w/ r:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \int_0^R r^2 dr\, m_T I_0\left(\frac{p_T\sinh(\rho)}{T}\right)K_1\left(\frac{m_T\cosh(\rho)}{T}\right)$$

$$\rho(r) = \tanh^{-1}\left(\beta_T^{MAX}\frac{r}{R}\right)$$

Blast Wave model => common T and β

Hadron abundances

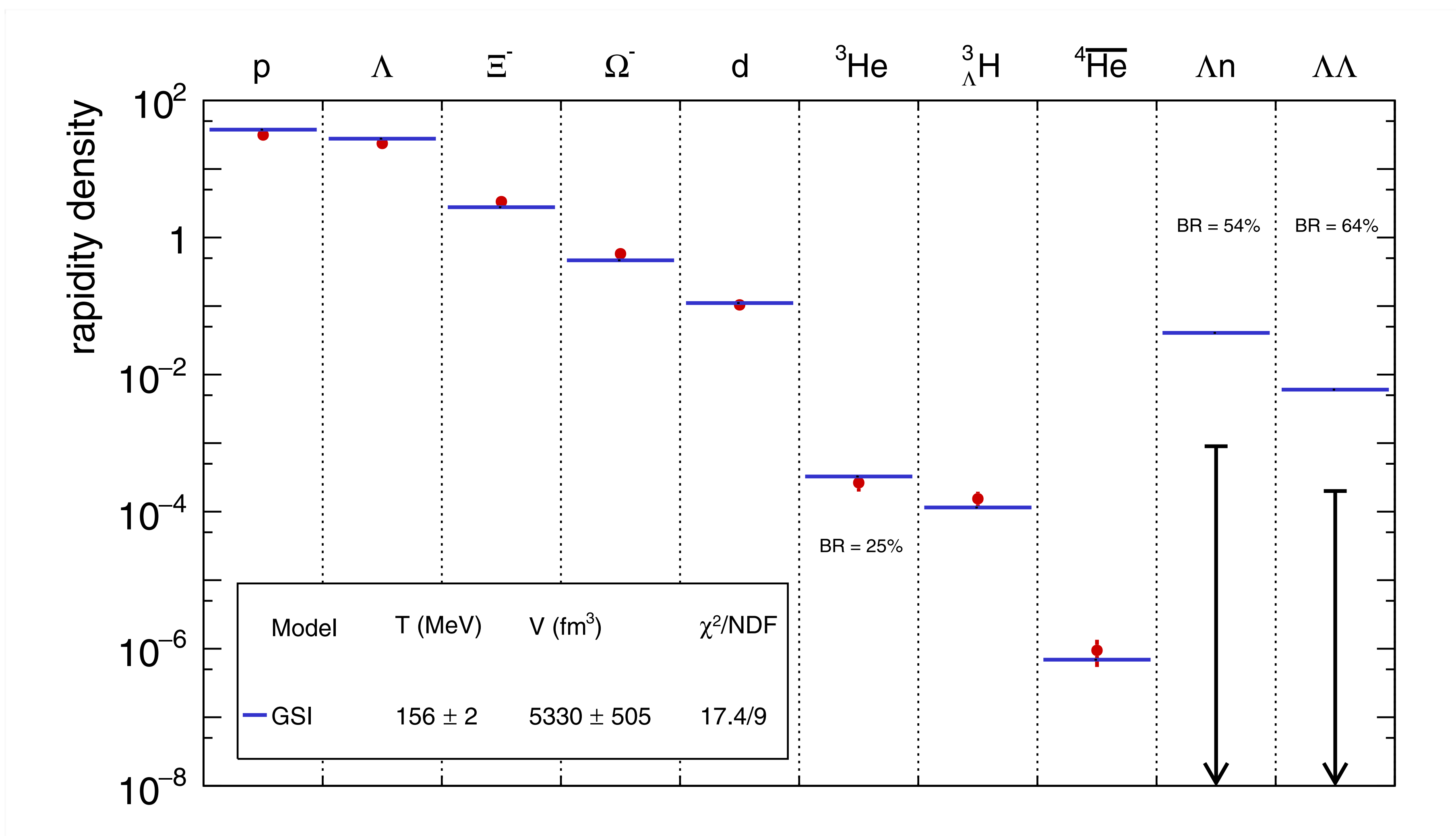
Assumption: Multiplicities are determined by statistical weights (chemical equilibrium)

Grand-canoniacal ensemble:

$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^2} \int d^3p \left[e^{\left(\sqrt{p^2+m_j^2}+\mu q_i\right)/T} \pm 1 \right]^{-1}$$

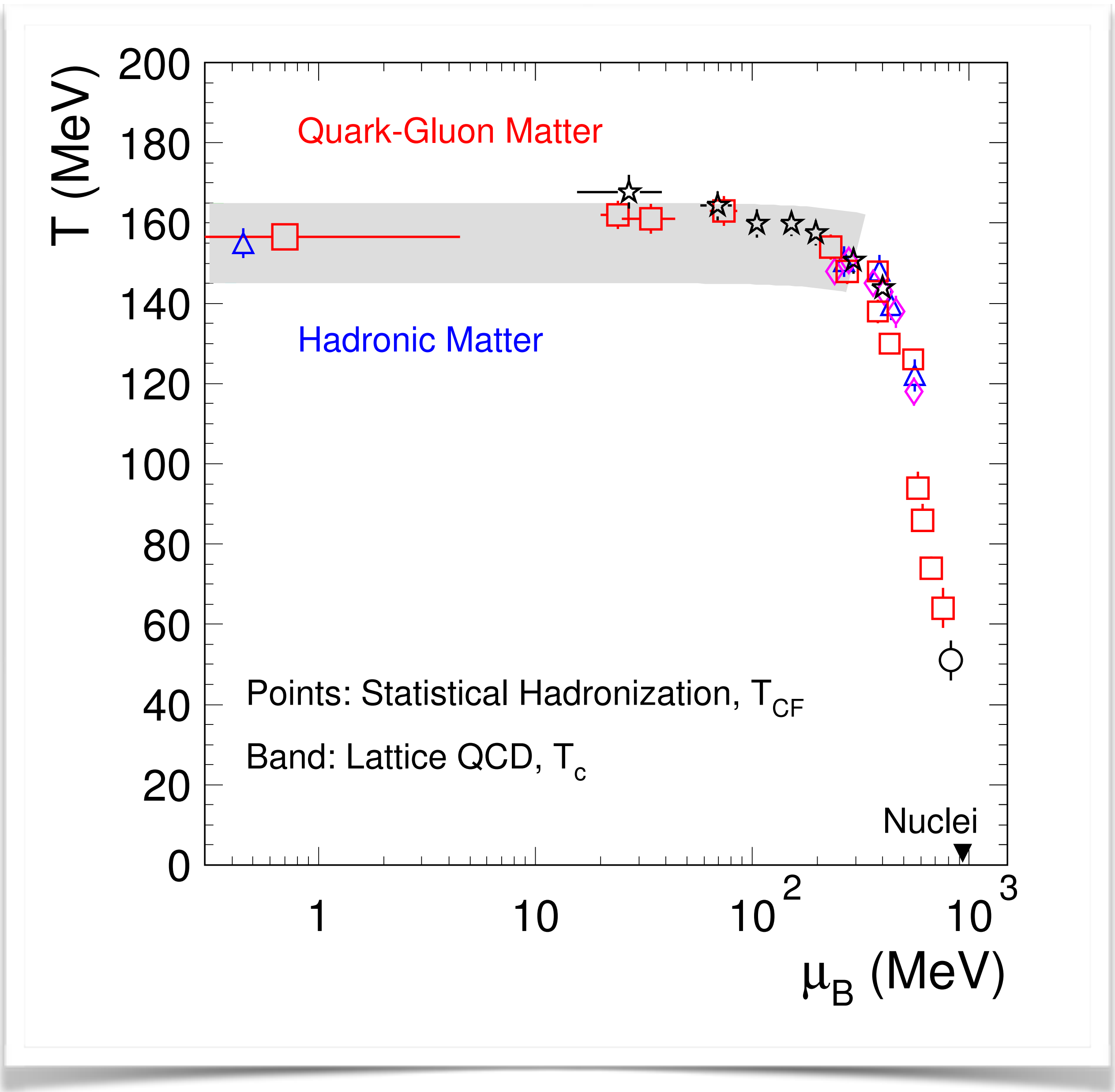
Parameters: V, T, μ_B, (γ_s)

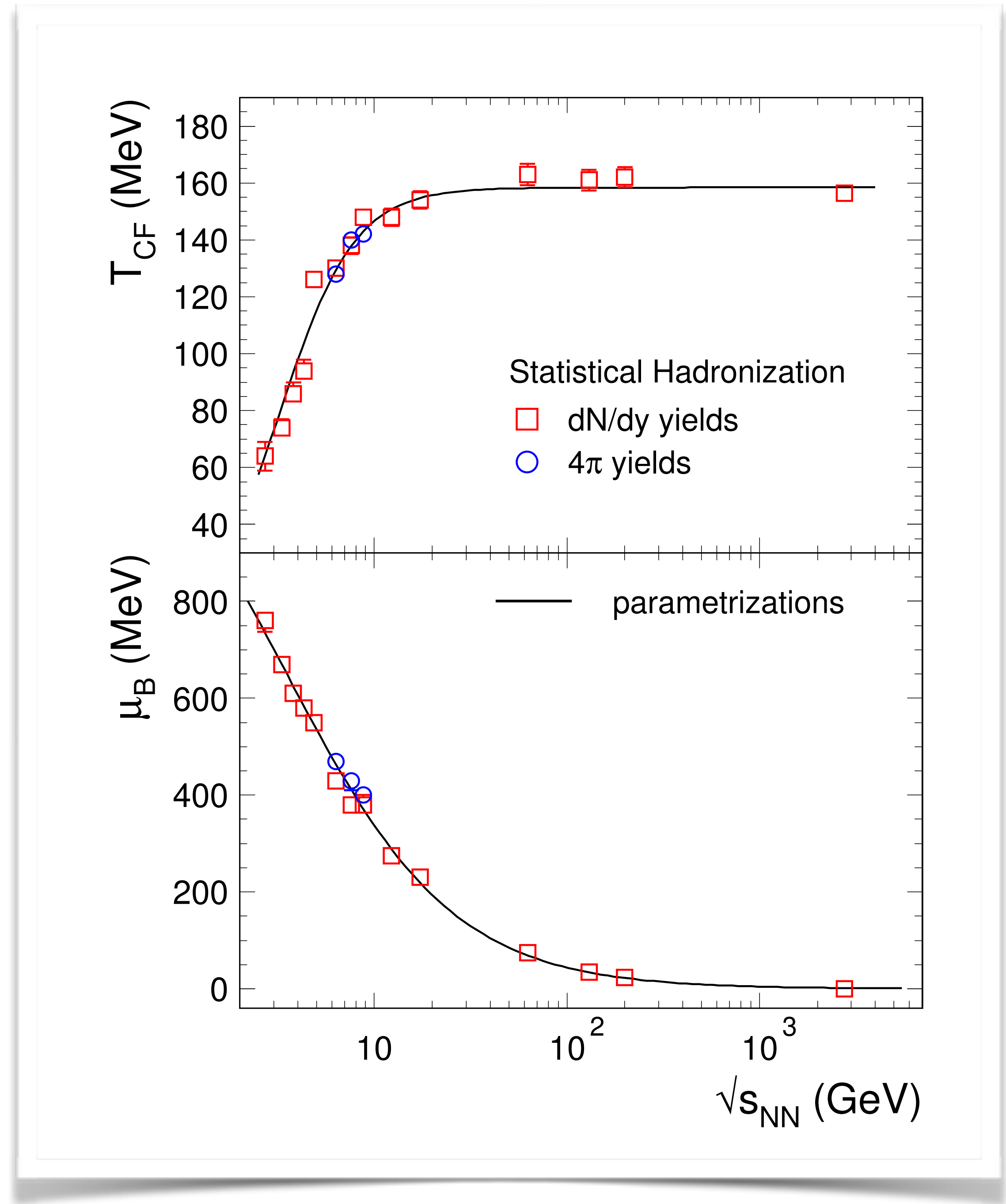
Results in excellent fits to measured multiplicities of hadron for ALL energies (even d, ^3He, $^3_\Lambda He$ ...) - statistical harmonization of a thermal system...



NB: works also for p+p (phase space dominance, Fermi 1950)

Chemical freeze out systematics





Provides rough idea which region in T, μ are probed

Thermal equilibrium...
Chemical and kinetic freeze-out

Chemical equilibrium:

- correct relative particle abundances?
- large system -> Grand Canonical ensemble: many particles; conservation laws on average - chemical potentials
- small system -> conservation laws E-by-E -> "canonical suppression" (strangeness)

$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\left(E-\mu_B B_i-\mu_s S_i-\mu_3 I^3\right)/T} \pm 1}$$

The ratios of produced particle yields between various species can be fitted to determine T, μ.

Kinetic equilibrium - radial flow:

- for any interacting system of particles expanding into vacuum, radial flow is a natural consequence.

During the cascade process, an ordering of particles with the highest common underlying velocity at the outer edge develops naturally

Hadrons are released in the final stage and therefore measure "FREEZE-OUT" Temp. - instructive simple parametrization - radially boosted source with velocity β and at y=0:

$$\frac{d^3N}{dp^3} \propto e^{-E/T}; E\frac{d^3N}{dp^3} = \frac{d^3N}{m_T dm_T d\phi dy} \propto Ee^{-E/T} = m_T \cosh(y) e^{-m_T\cosh(y)/T}$$

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto m_T I_0\left(\frac{p_T\sinh(\rho)}{T}\right)K_1\left(\frac{m_T\cosh(\rho)}{T}\right)$$

$$\rho = \tanh^{-1}(\beta_{boost})$$

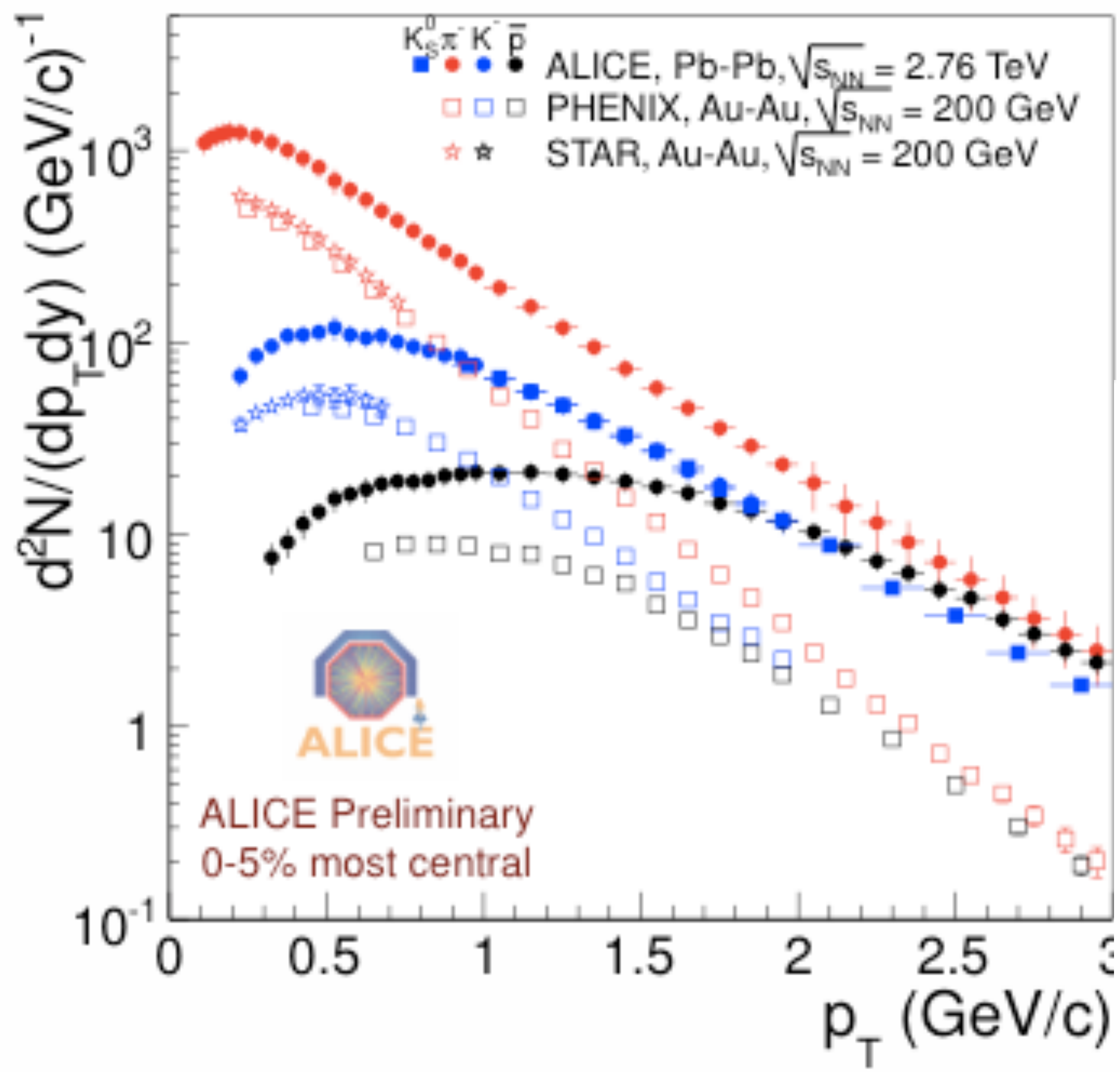
Simple assumption: uniform sphere of radius R and boost velocity varies linearly w/ r:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \int_0^R r^2 dr m_T I_0\left(\frac{p_T\sinh(\rho)}{T}\right)K_1\left(\frac{m_T\cosh(\rho)}{T}\right)$$

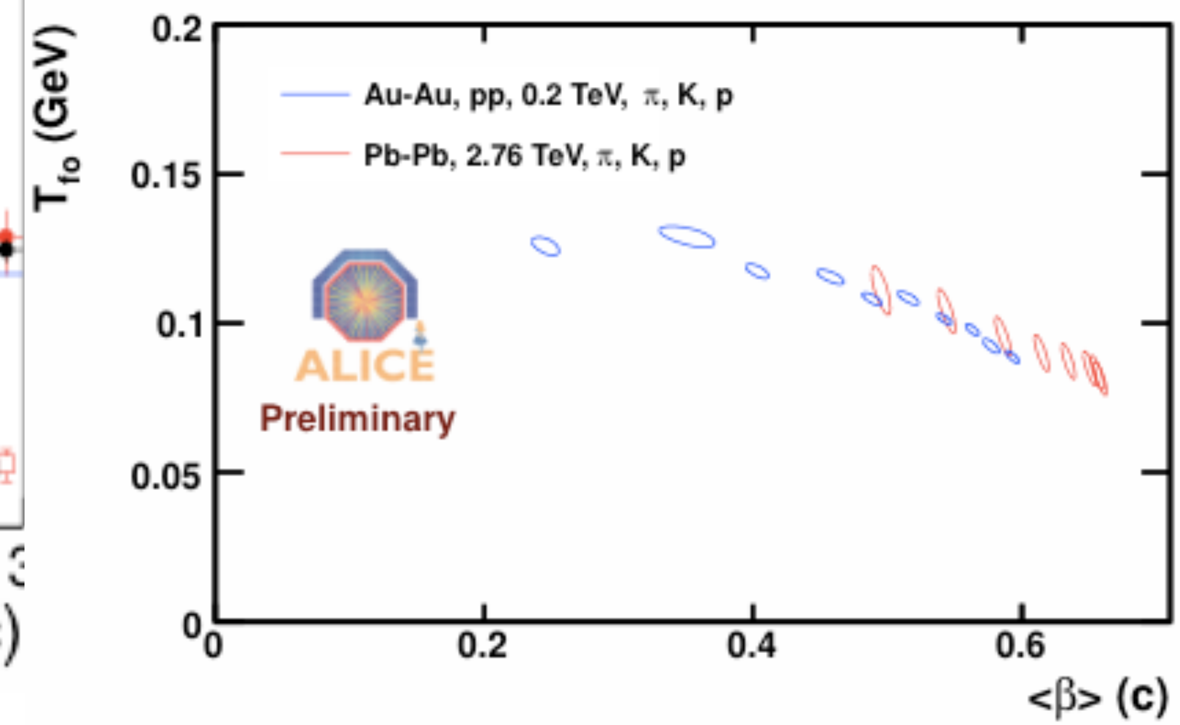
$$\rho(r) = \tanh^{-1}\left(\beta_T^{MAX}\frac{r}{R}\right)$$

Blast Wave model => common T and β

Identified particles & expansion of the system



Stronger radial flow at the LHC.
"Blast wave" fits to spectra indicate an **increase of the average radial boost velocity** up to (2/3)c and a decrease in the kinetic freezeout temperature to just below 100 MeV relative to RHIC



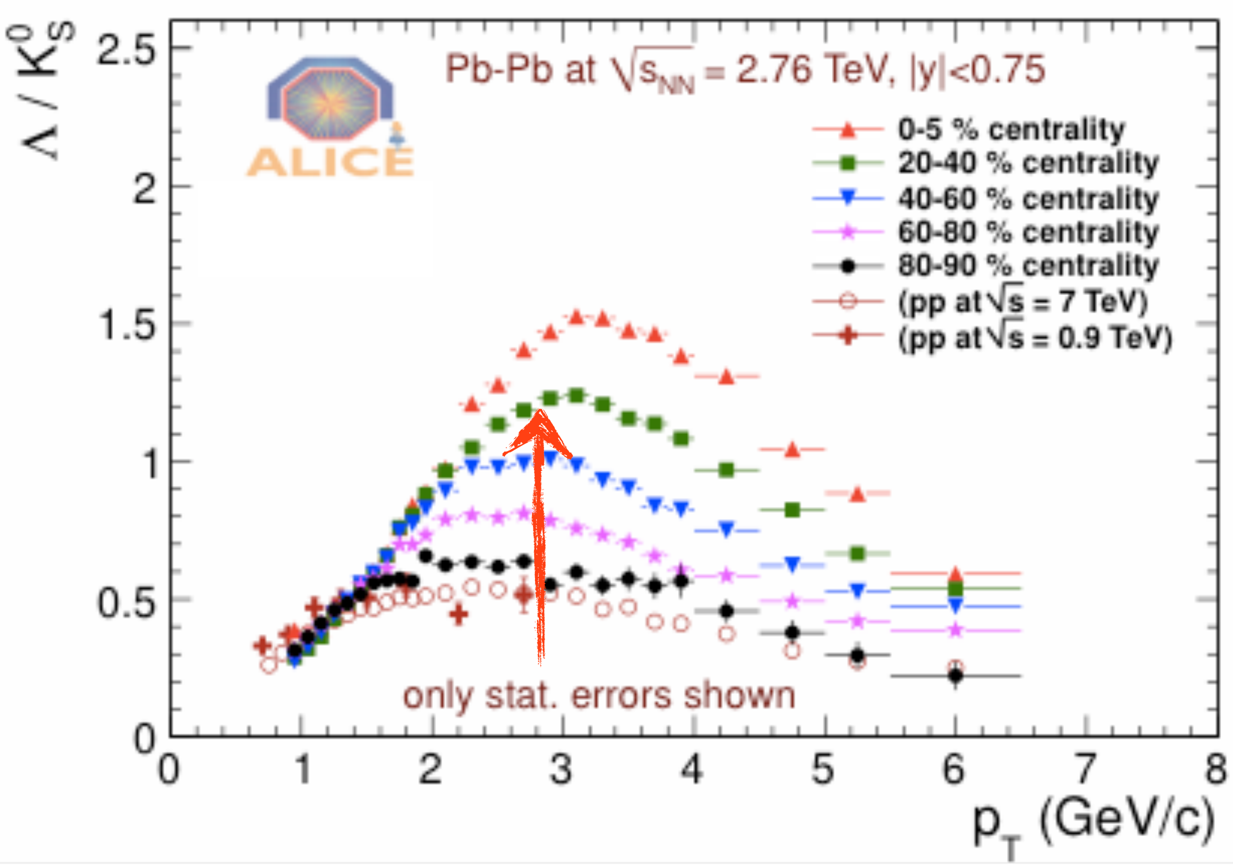
LHC: Large kinematic reach to explore

ALICE: excellent particle identification capabilities at the LHC

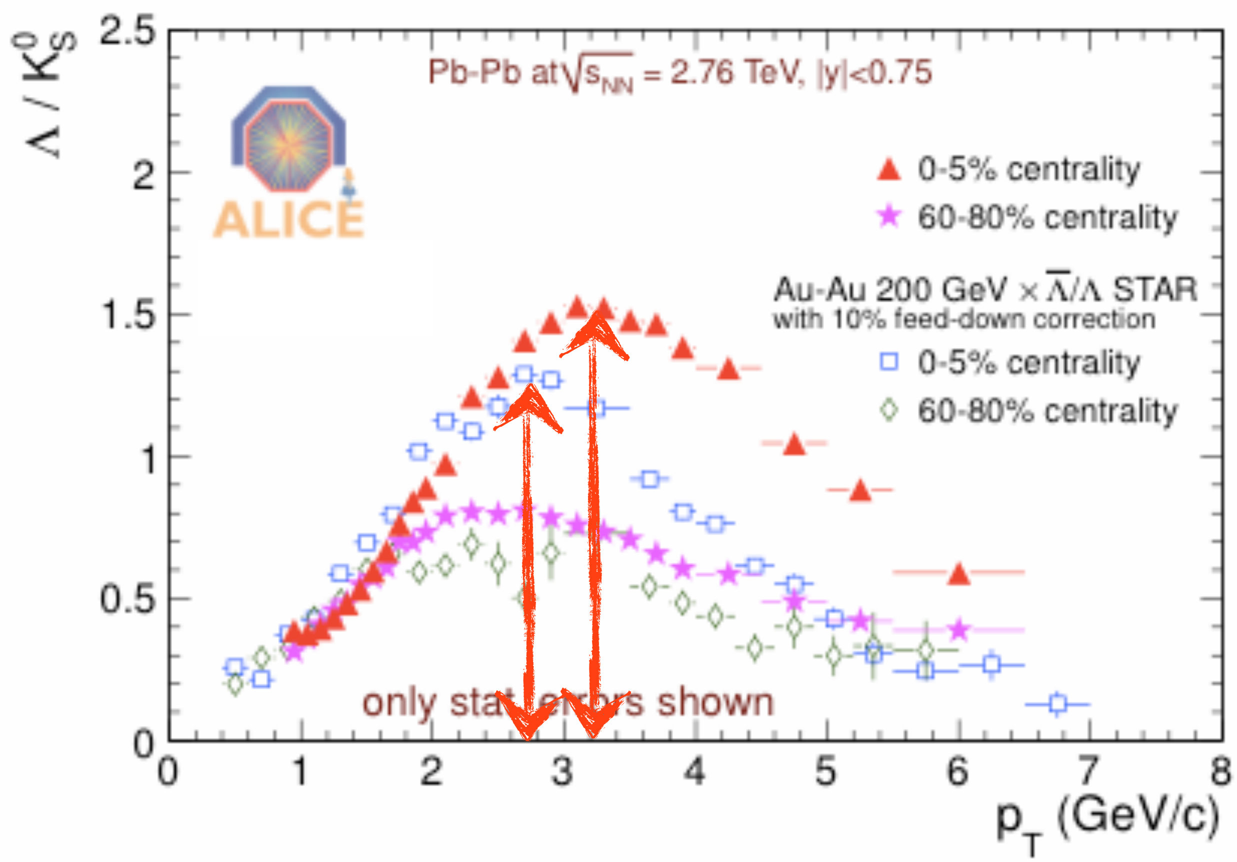
Impact of expansion on hadron p_T-spectra in heavy-ion collisions

A quick analysis of particle spectra ...

RHIC vs LHC
(LHC: higher mean pT - more flow)



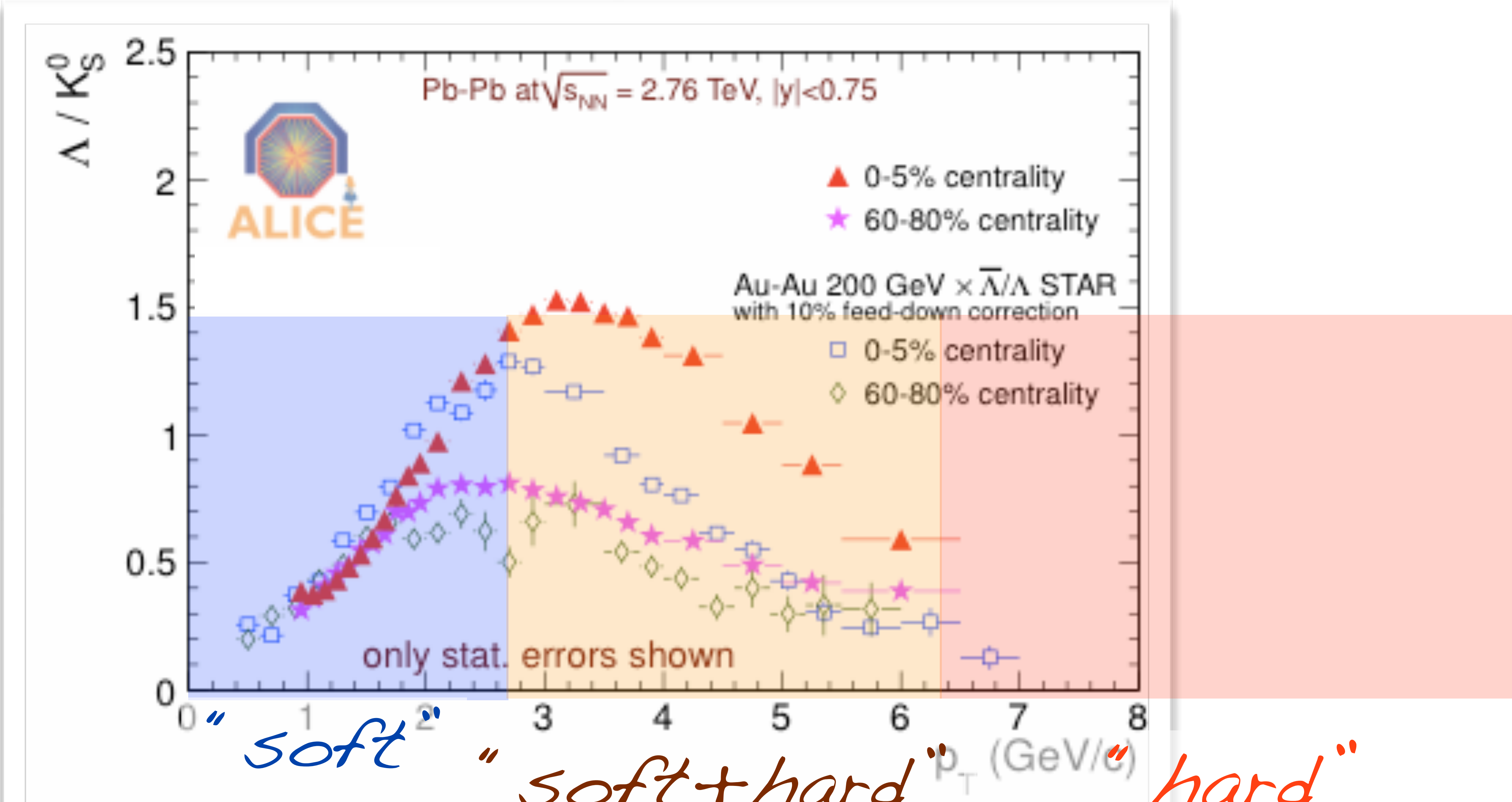
Baryons / Mesons



Much more baryons than mesons in central collisions as compared to proton-proton (coalescence/recombination? bulk+jet?)

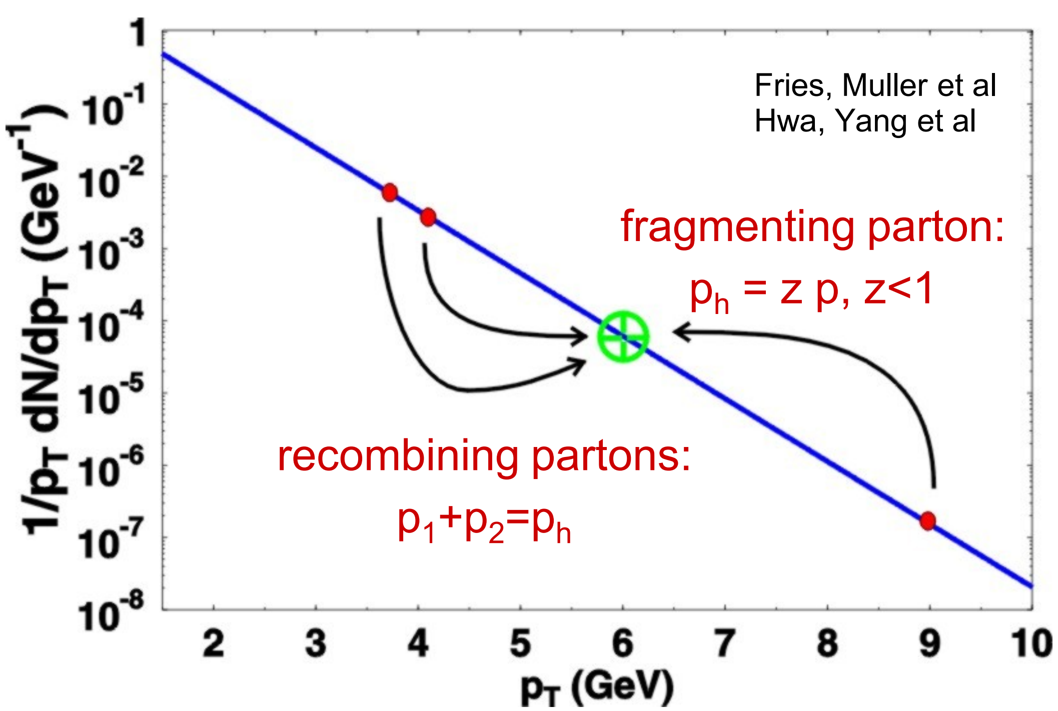
LHC similar to RHIC
Maximum at slightly higher-pT

bulk, jets, medium and p_T:
arbitrary regions
and INFORMAL Language

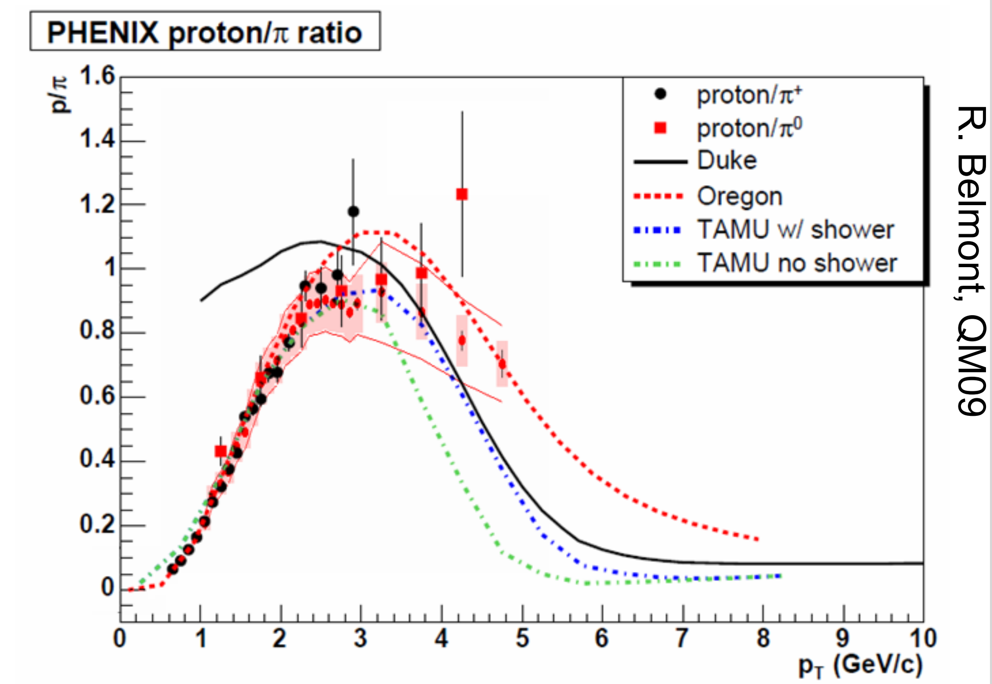


"soft" -bulk thermal"
"soft+hard" jet-medium "intermediate"
"hard" jet dominated

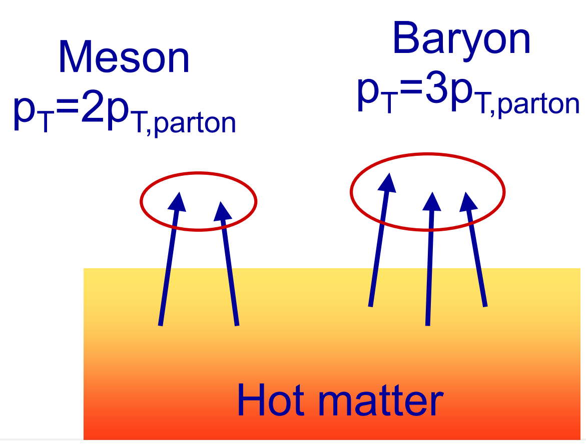
Novel effects: hadronization of a mix bulk & hard - parton coalescence



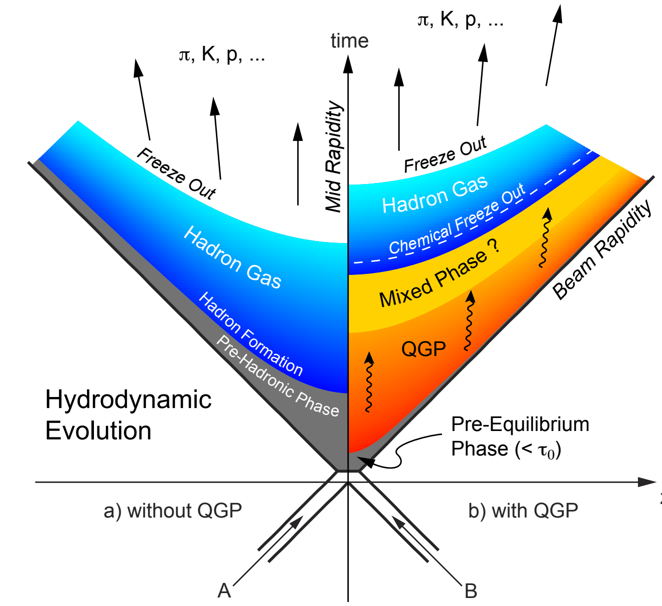
Recombination of thermal ('bulk') partons produces baryons at larger p_T



Recombination enhances baryon/meson ratio



Note also: v_2 scaling

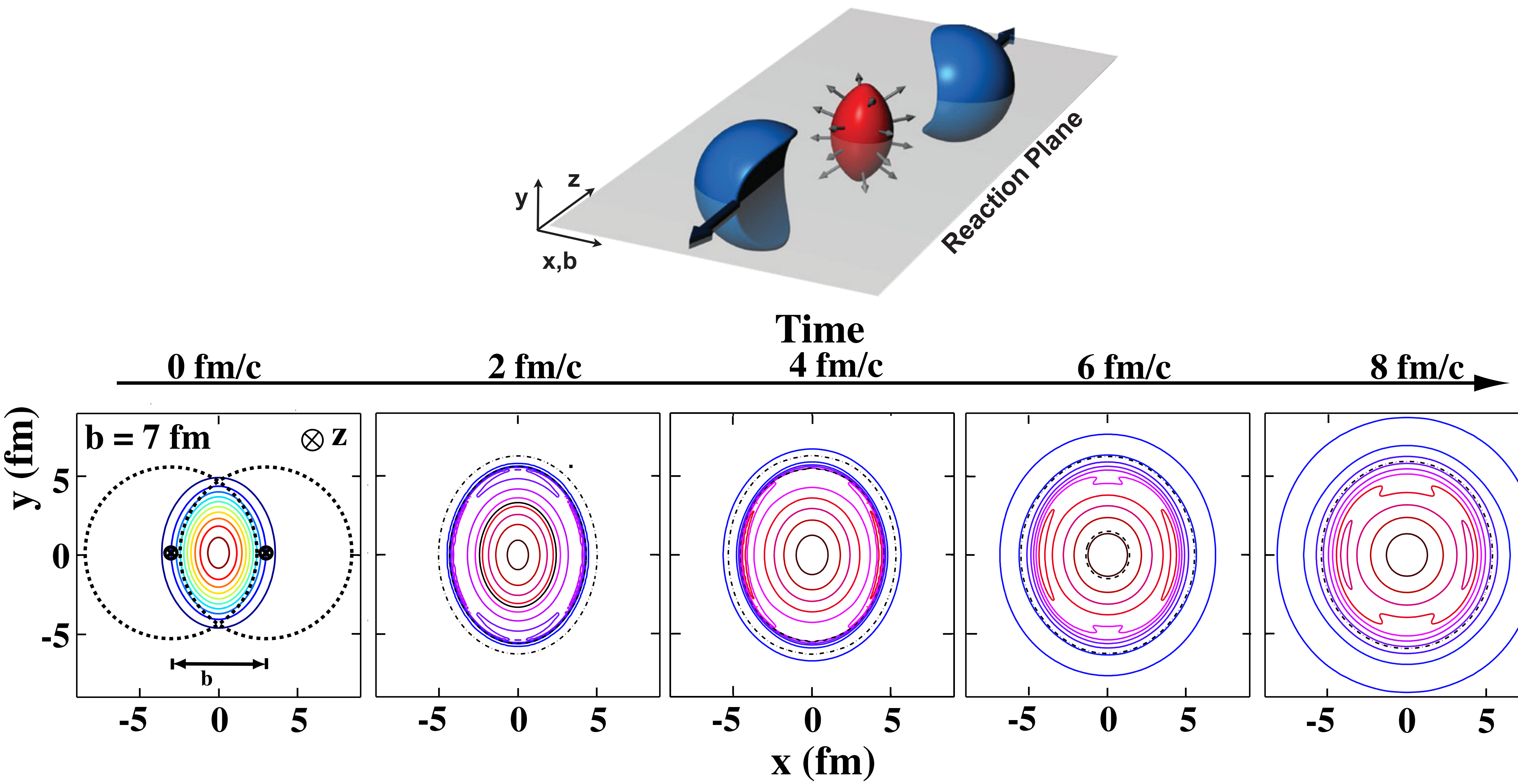


Freeze-out:

- chemical freeze out <=> hadron composition fixed
- kinetic freeze-out <=> hadron momenta fixed (interactions stop)
- overall: $T_{ch} > T_{kin}$ (system cools down - follow the time axis)

Properties of QGP with particle correlations

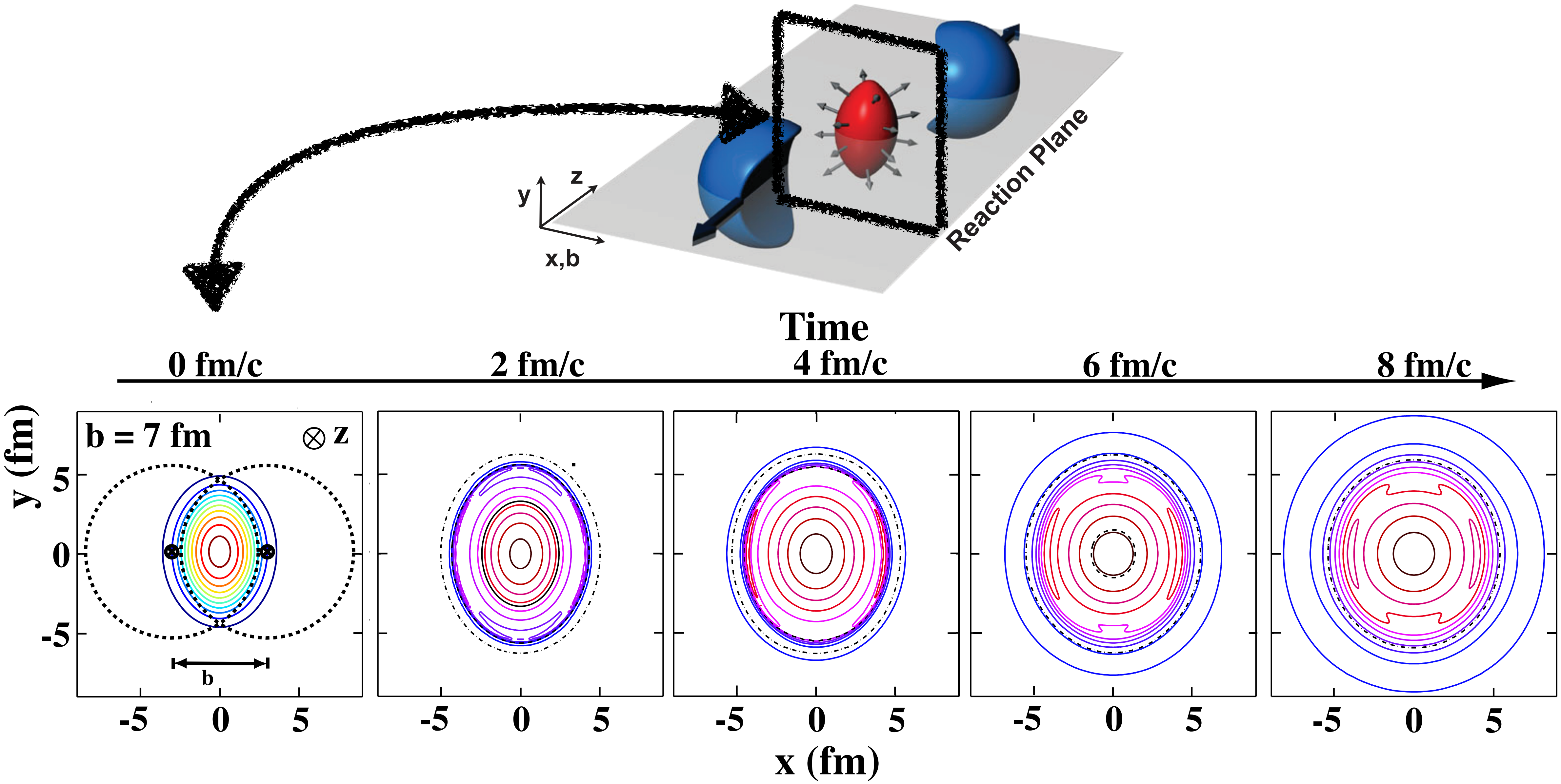
Expanding "fireball"



Initial transverse energy density profile and its time dependence in coordinate space for a non-central heavy-ion collision

Model calc.: P. F. Kolb, U. W. Heinz, In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 634-714.

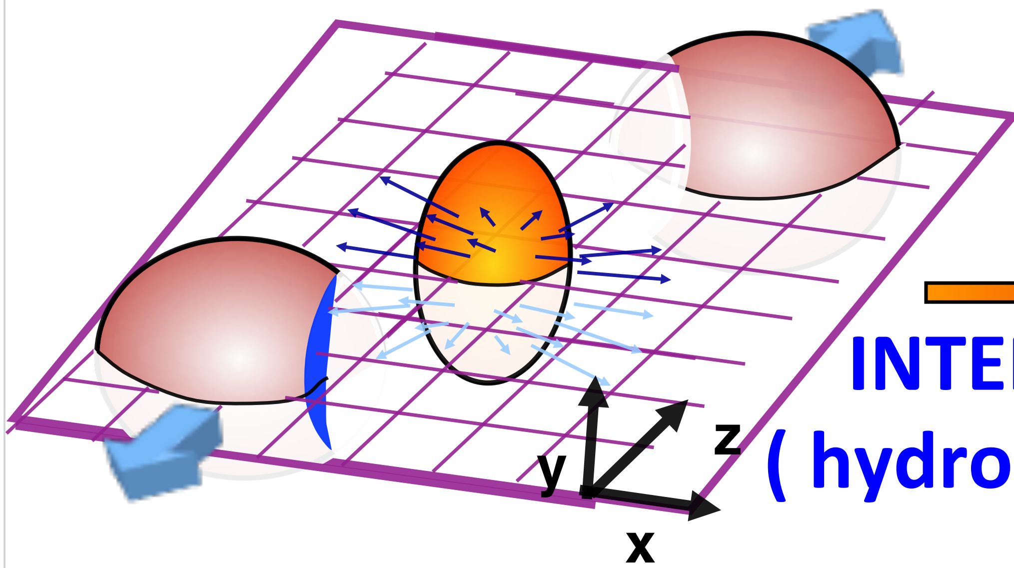
Expanding "fireball"



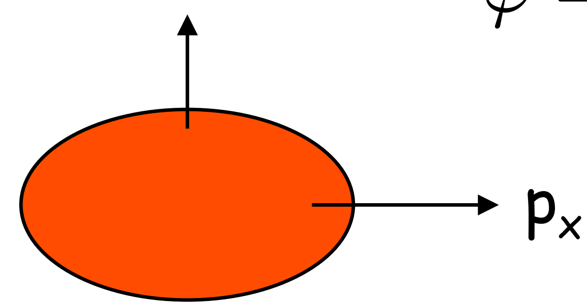
Initial transverse energy density profile and its time dependence in coordinate space for a non-central heavy-ion collision

Model calc.: P. F. Kolb, U. W. Heinz, In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 634-714.

Azimuthal angular asymmetry in particle production



INTERATIONS
(hydrodynamics?)



$$\varphi = \arctan \frac{p_y}{px}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial spatial anisotropy

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Final momentum anisotropy

Reaction plane defined by
"soft" (low p_T) particles

$$\Delta\varphi = \varphi - \varphi^{Reaction\ Plane}$$

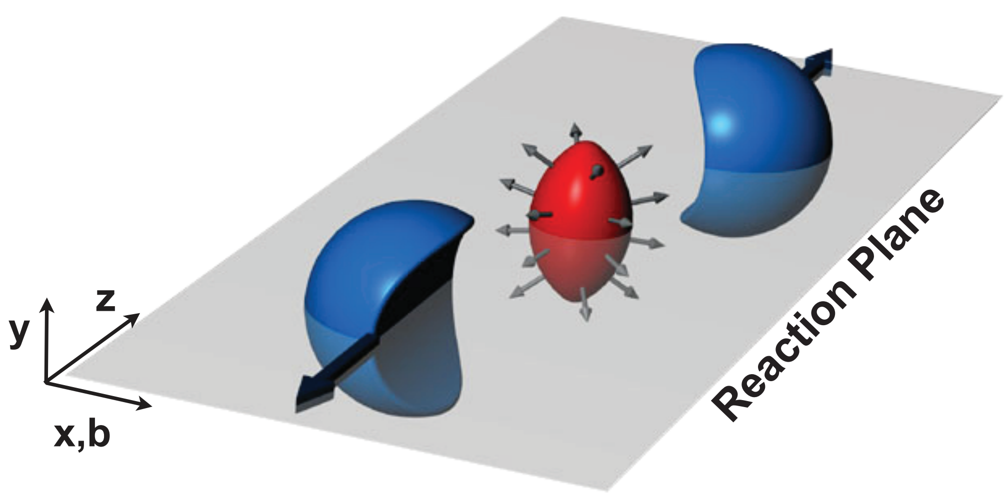
Elliptic flow

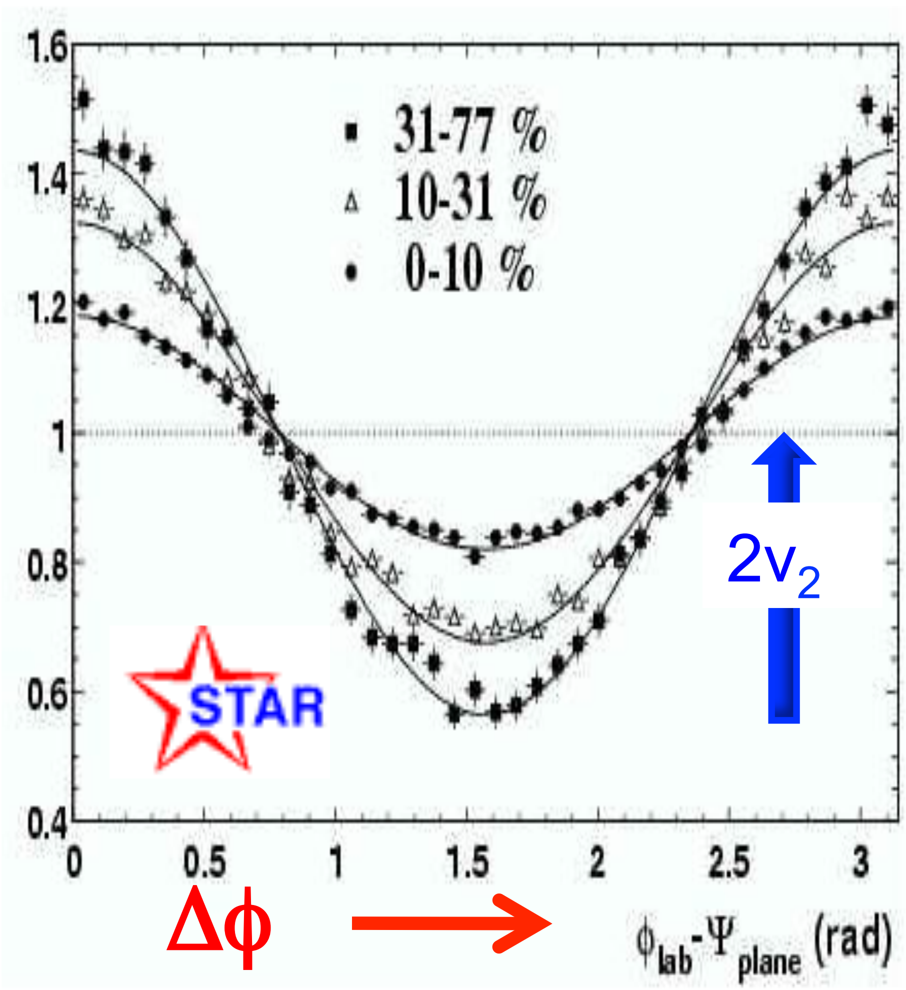
$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_2 \cos(2\Delta\varphi)$$

Experimental signature

measurement: azimuthal angular distribution of particles with respect to event plane

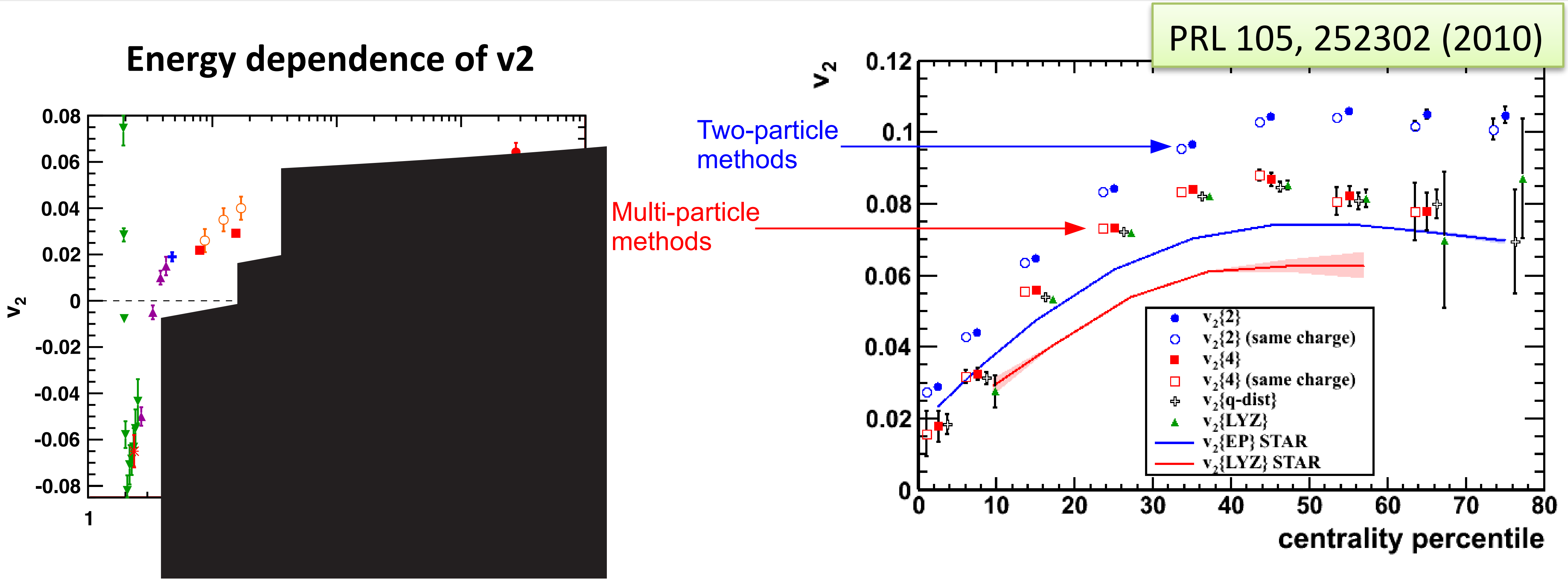
$$\frac{dN}{d\phi} \propto 1 + 2v_2 cos\left[2\left(\phi - \Psi_R\right)\right] + \ldots$$





Sizeable effect!

Azimuthal anisotropy

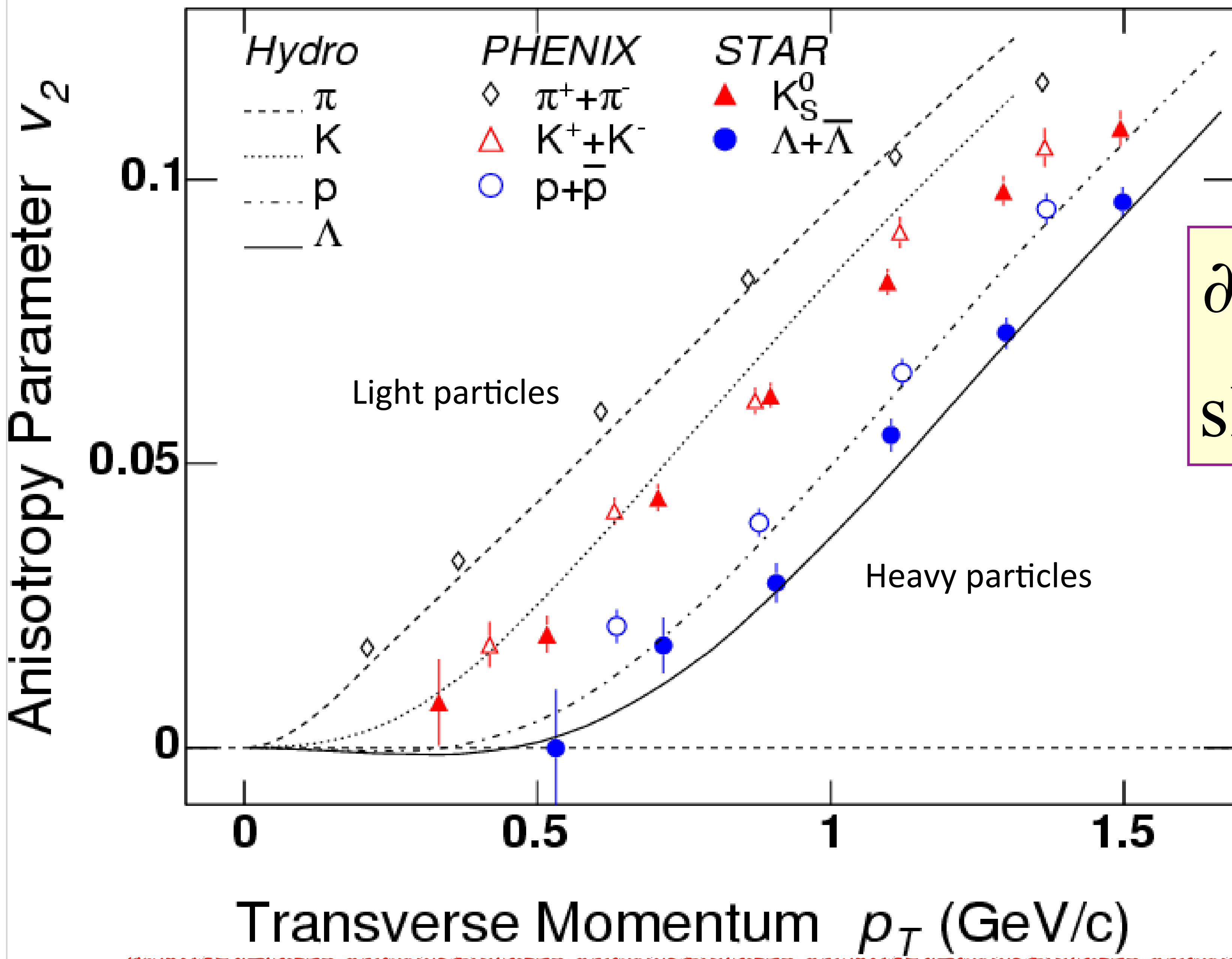


APS Viewpoint: A “Little Bang” arrives at the LHC (E. Shuryak)

1. **Collective behavior observed in Pb-Pb collisions at LHC (integrated: +0.3 v_2^{RHIC} – consequence of larger $<p_T>$) -> $v_2(p_T)$ similar to RHIC – almost ideal fluid at LHC ? Similar observation down to 39GeV!**
2. **New input to the energy dependence of collective flow**
3. **Additional constraints on Eq-Of-State and transport properties**

Relativistic (ideal) hydrodunamics

Heinz '04



$$\partial_\mu T^{\mu\nu} = 0$$

shear viscosity $\eta = 0$

Mass hierarchy vs *momentum* is characteristic of common *velocity* distribution

Ideal hydro: qualitative agreement but missing the details

Hydrodynamics crash course

Energy-momentum conservation (local)

$$\partial_t T_{00} = -\partial_x T_{0x} - \partial_y T_{0y} + \partial_z T_{0z}$$

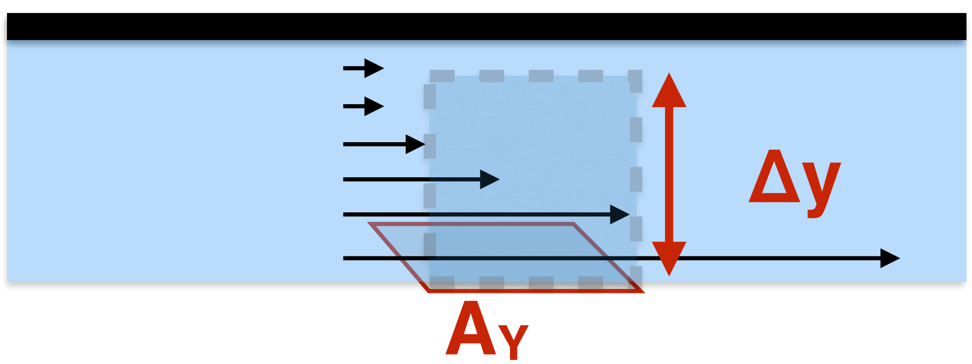
$$\partial_t T_{0x} = \partial_x T_{xx} + \partial_y T_{yx} + \partial_z T_{zx}$$

Ideal hydrodynamics: $T_{i \neq j} = 0$

...motion of viscous fluids ...

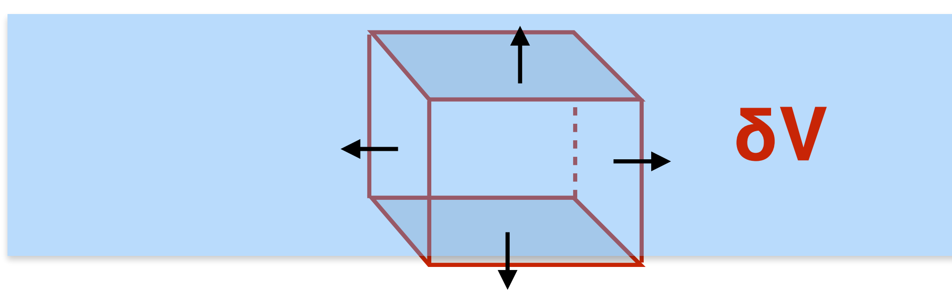
Navier-Stokes equation: $T_{ij} = P\delta_{ij} - \eta(\partial_i v_j + \partial_j v_i) - \zeta \nabla \cdot \vec{v}$

Where η is shear viscosity: friction between layers of fluid



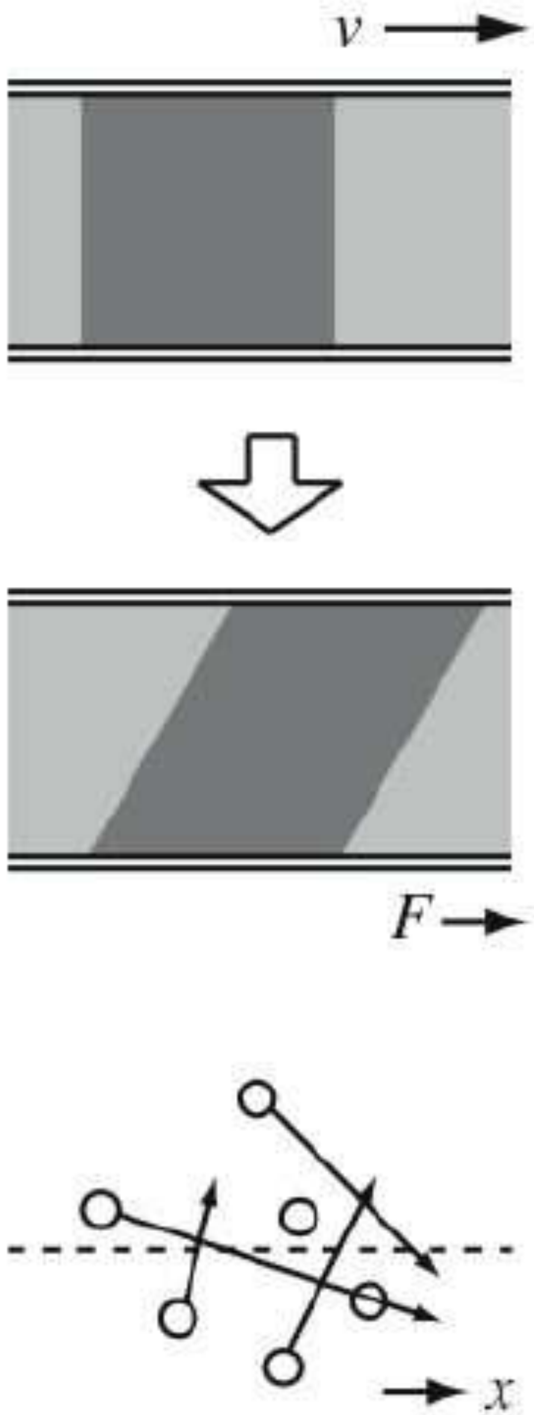
$$\frac{d}{dt} P_x = A_y \eta \partial_y v_x$$

and ζ is bulk viscosity: dissipation of divergent flow



$$\delta E = -P\delta V + \zeta \nabla \cdot \vec{v} \delta V$$

Shear viscosity in fluids...



$$\frac{F}{A} = \eta \frac{\mathrm{v}}{L}; \quad \eta \sim \rho \langle \mathrm{v} \rangle \lambda_{mfp}$$

Properties are counter-intuitive:

Weak coupling
- small cross section, long mean free path

$\Rightarrow$ large viscosity

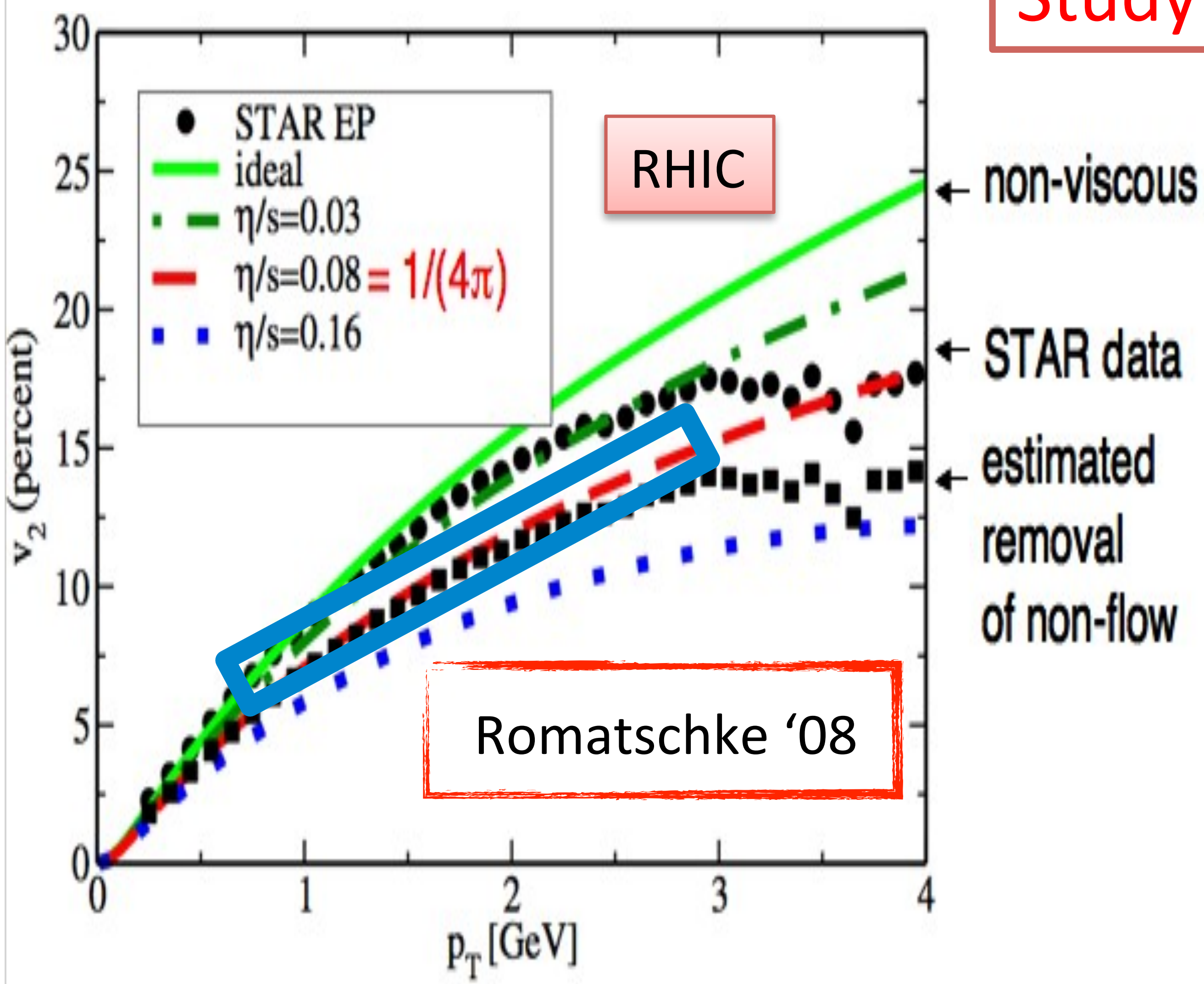
Strong coupling
- large cross section, small mean free path

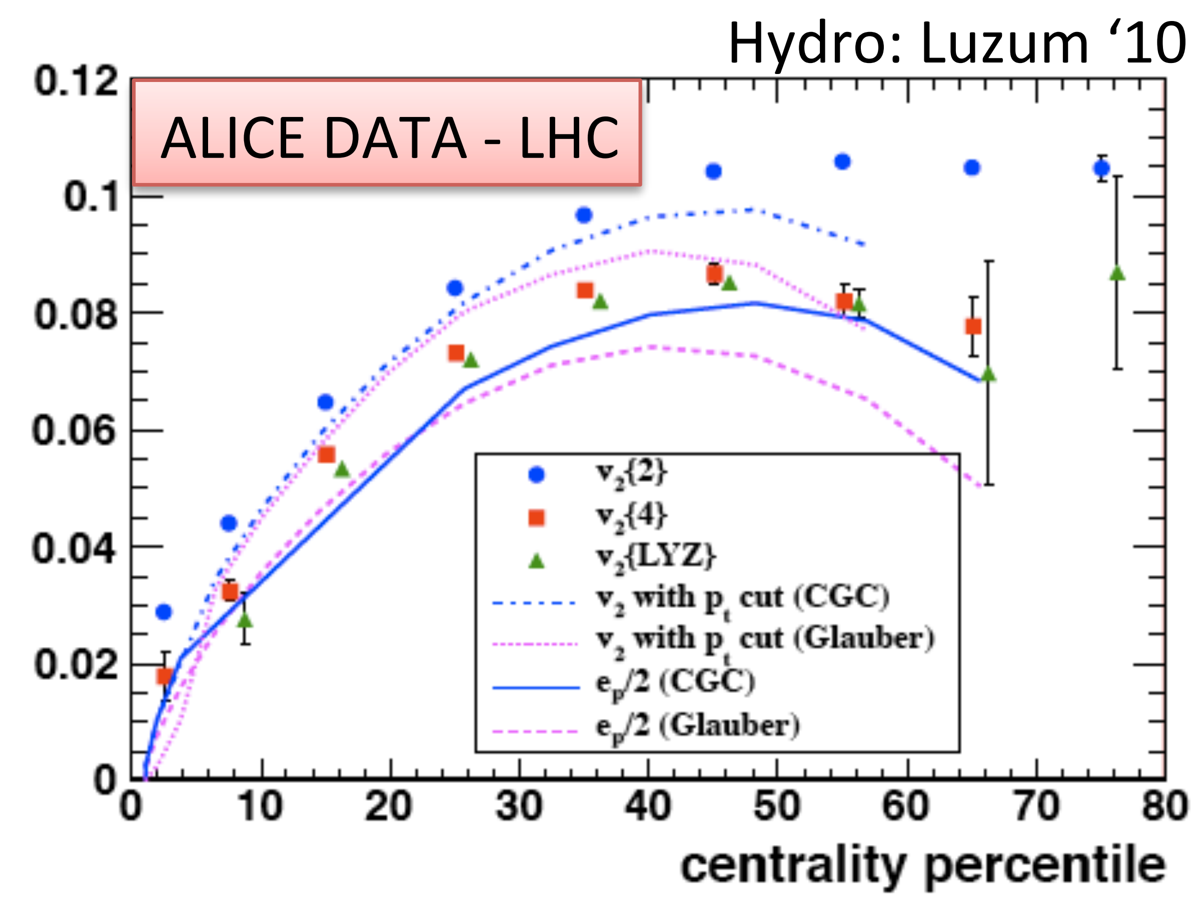
$\Rightarrow$ small viscosity

$\eta \rightarrow 0$: strongly coupled (perfect) fluid
$\eta \rightarrow \infty$: weakly coupled (ideal) gas

QGP liquid- how perfect is perfect?

Study elliptic flow of matter





Shear viscosity – lower limit: $$\frac{\eta}{s} > \frac{1}{4\pi}$$

rather recent: in principle can go to zero

KSS (string theory); Gyullassy-Danielewicz (quantum mechanics + ballistic theory)

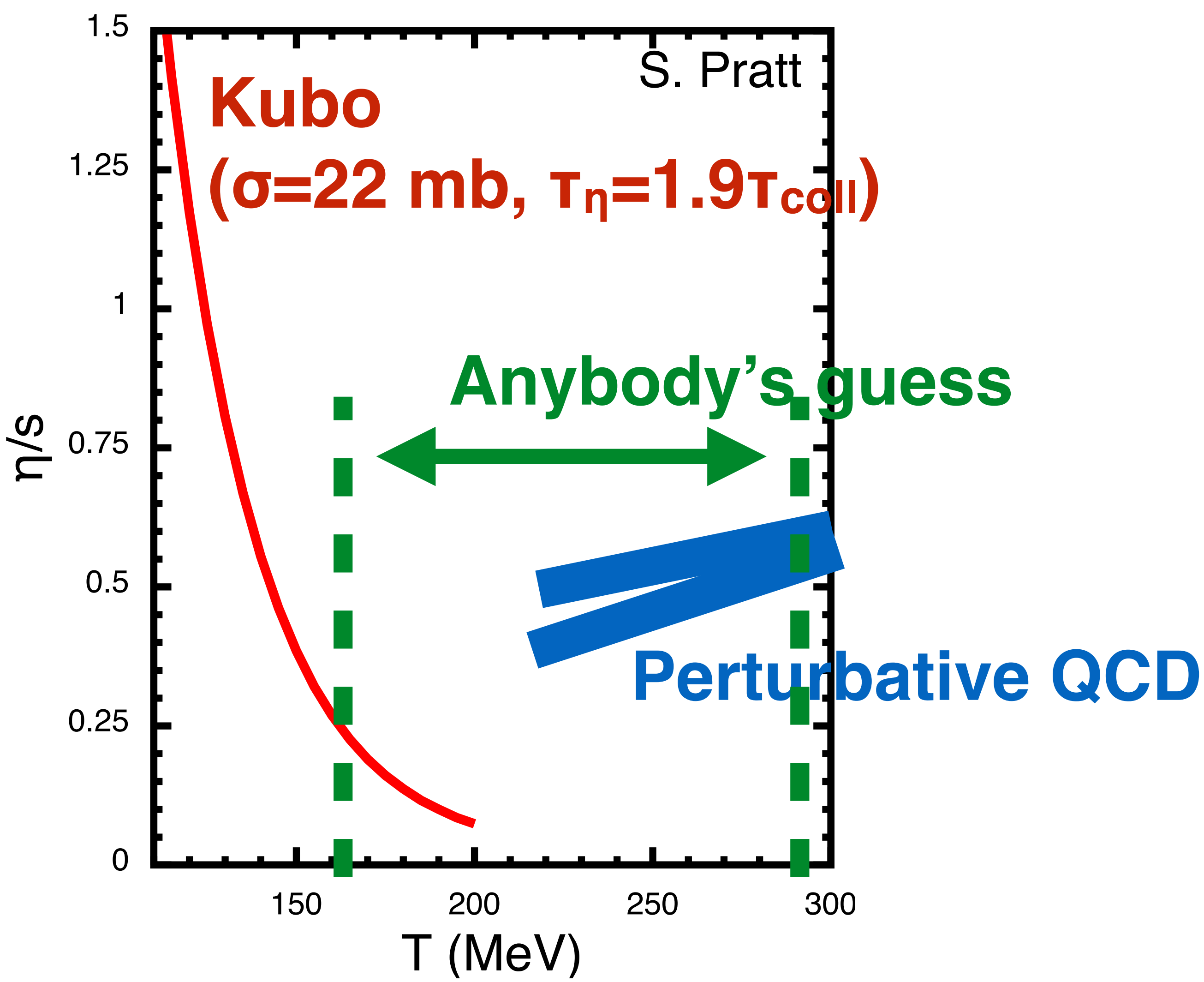
0.08 : λ_{therm} λ_{mfp} **(Danielewicz and Gyulassy)**

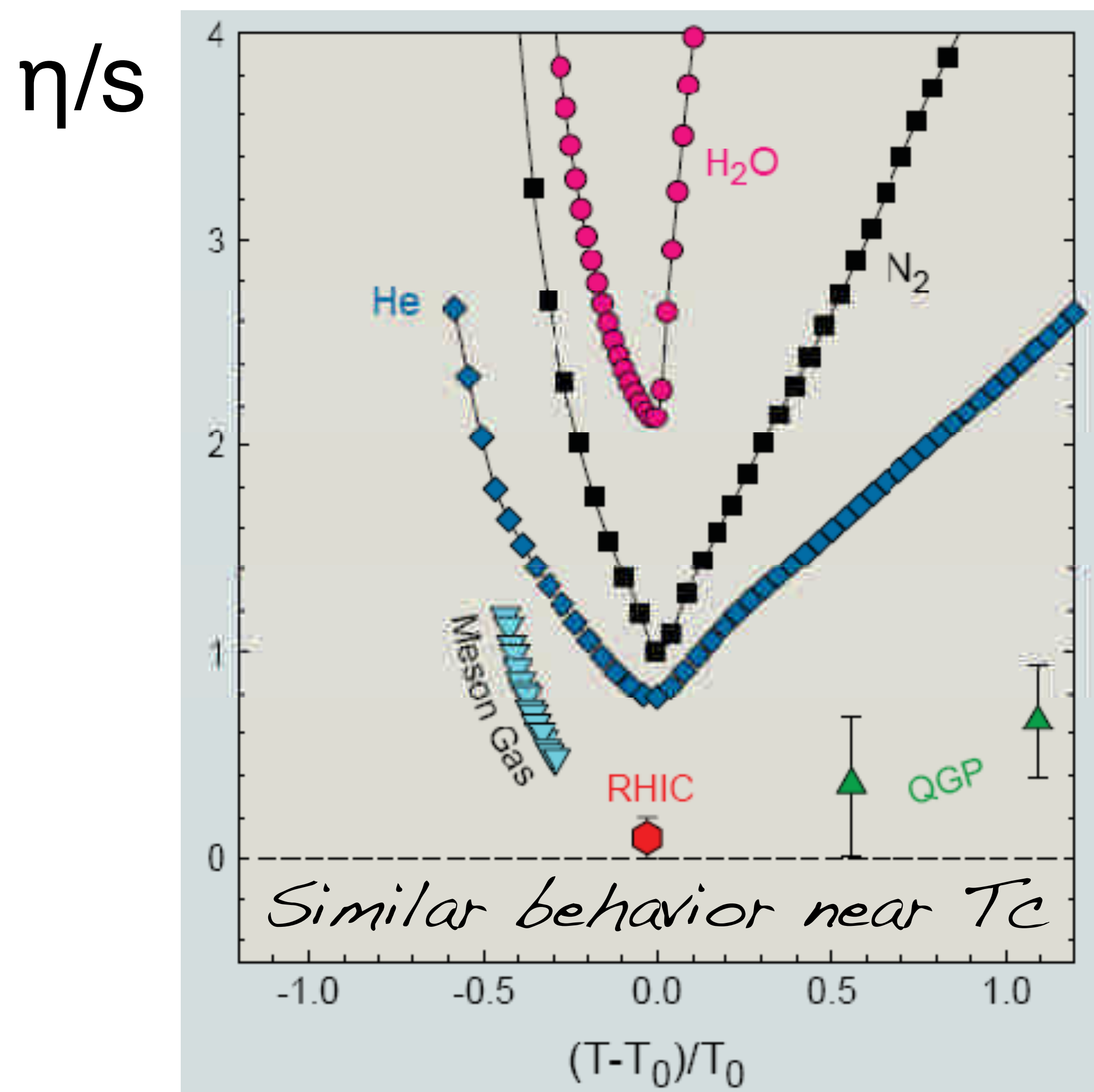
Hot, deconfined QCD matter flows as an almost perfect fluid

Comparison QGP to other fluids near Tc .

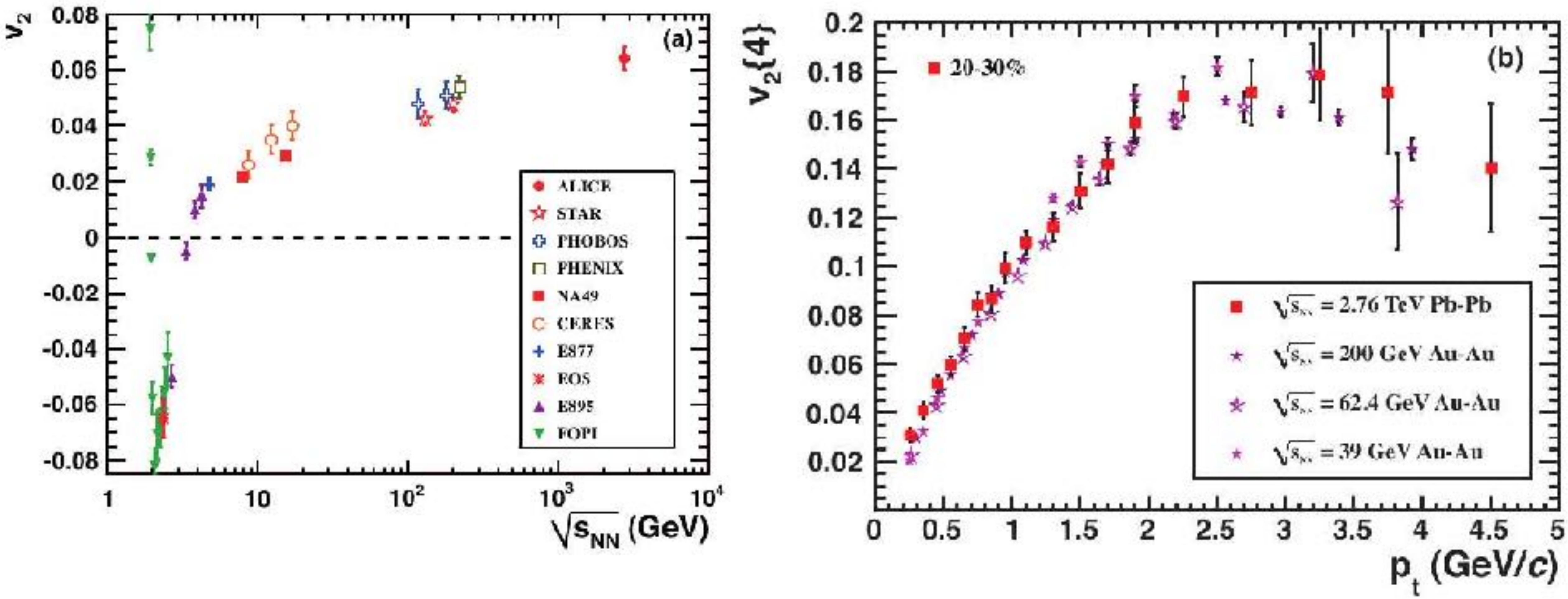
Green-Cubo relations:
transport coefficients in terms of integrals of time correlation functions
- correlations of particles x relaxation time

$$\eta = \frac{\tau_\eta}{T}\int d^3r \langle T_{xy}(0,0)T_{xy}(\vec{r},t=0)\rangle$$
$$= \frac{\tau_\eta}{T}\sum_\alpha (2S_\alpha+1)\int\frac{d^3p}{(2\pi)^3}e^{-E/T}\frac{p_x^2p_y^2}{E^2}$$





Elliptic Flow
– collision energy dependence



$$v_2 = \frac{\int dp_t \frac{dN}{dp_t} v_2(p_t)}{\int dp_t \frac{dN}{dp_t}}$$

Improved (multiparticle) v2{4} :
very weak energy dependence of $v_2(p_t)$ –
from 2.76 TeV down to 39 GeV (!)
Same phase for different initial
collision energies !?

$$\Delta\varphi = \varphi - \varphi^{Reaction\ \ Plane}$$

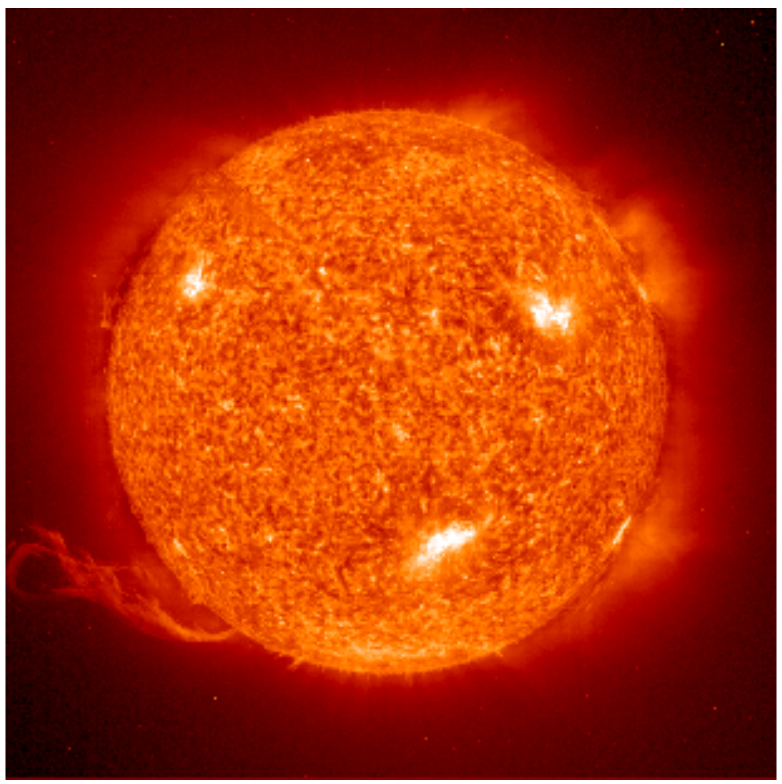
Elliptic flow

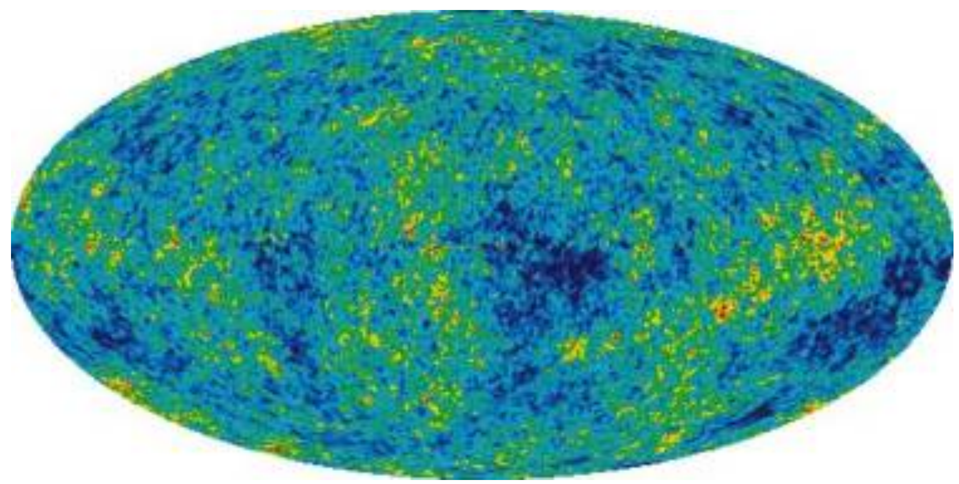
$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_2\cos(2\Delta\varphi)$$

?

"Beyond" v2

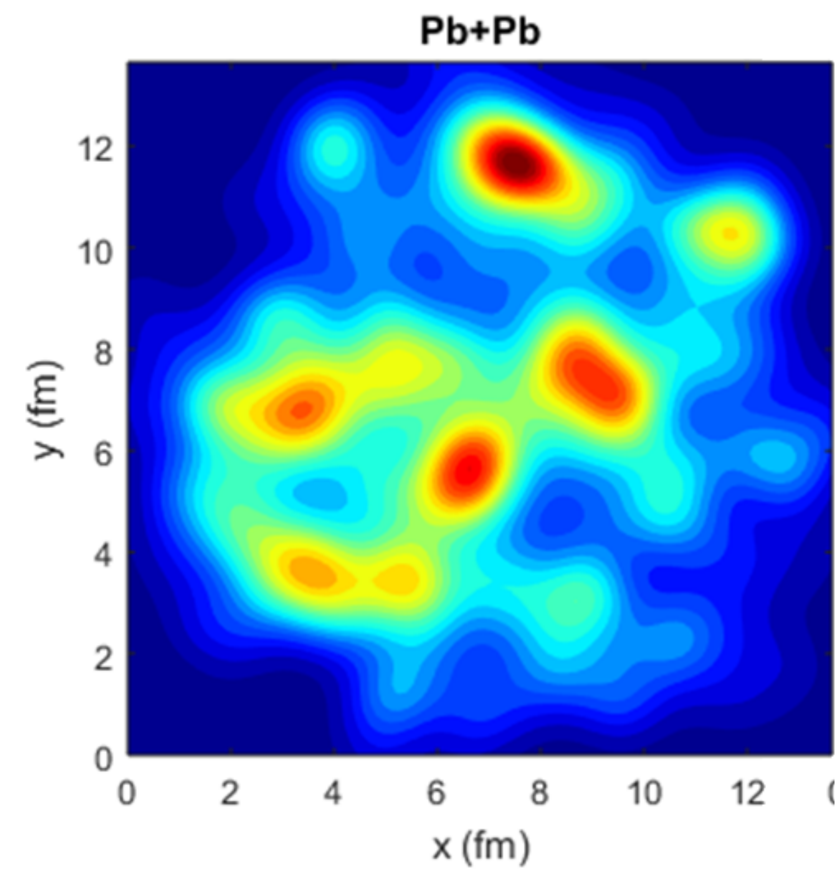
higher moments -> fluctuations / hotspots





Single event!

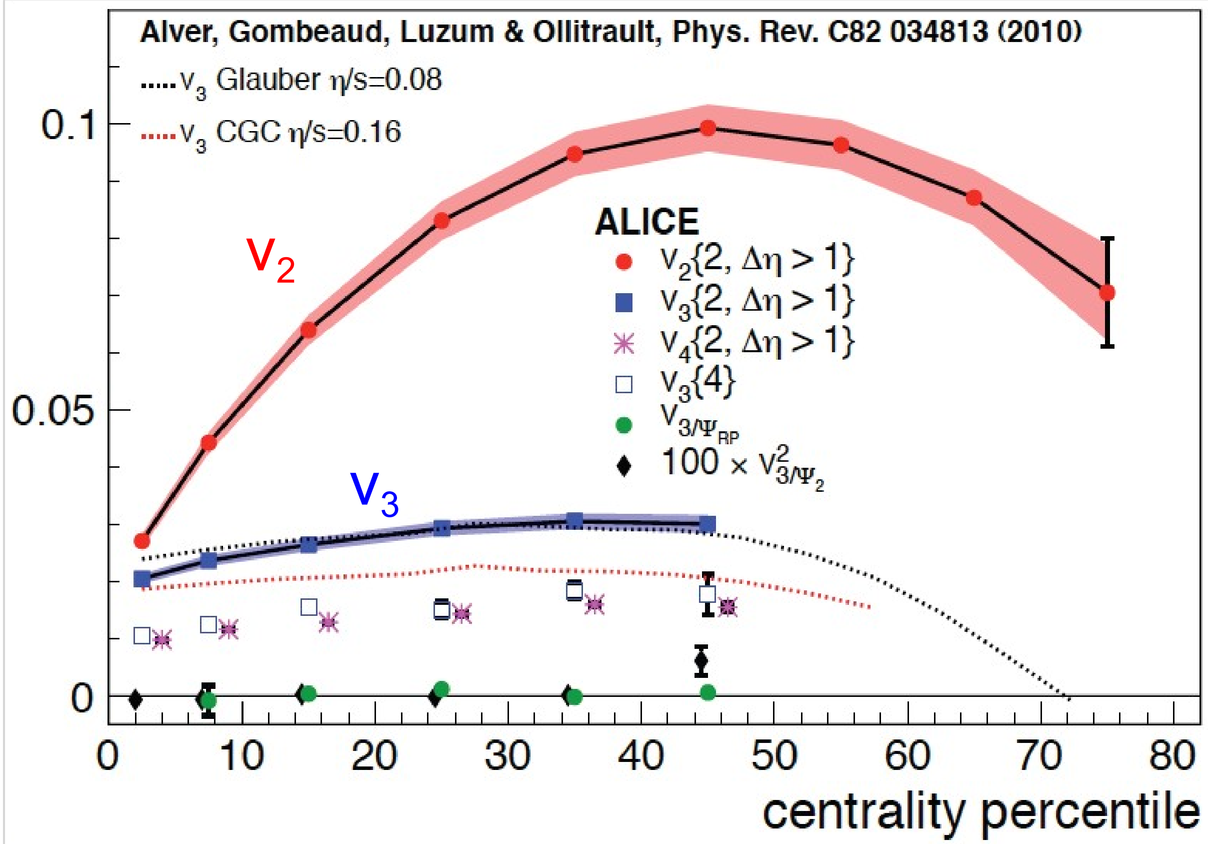
Ryan D. Weller[1] and Paul Romatschke[1,2]

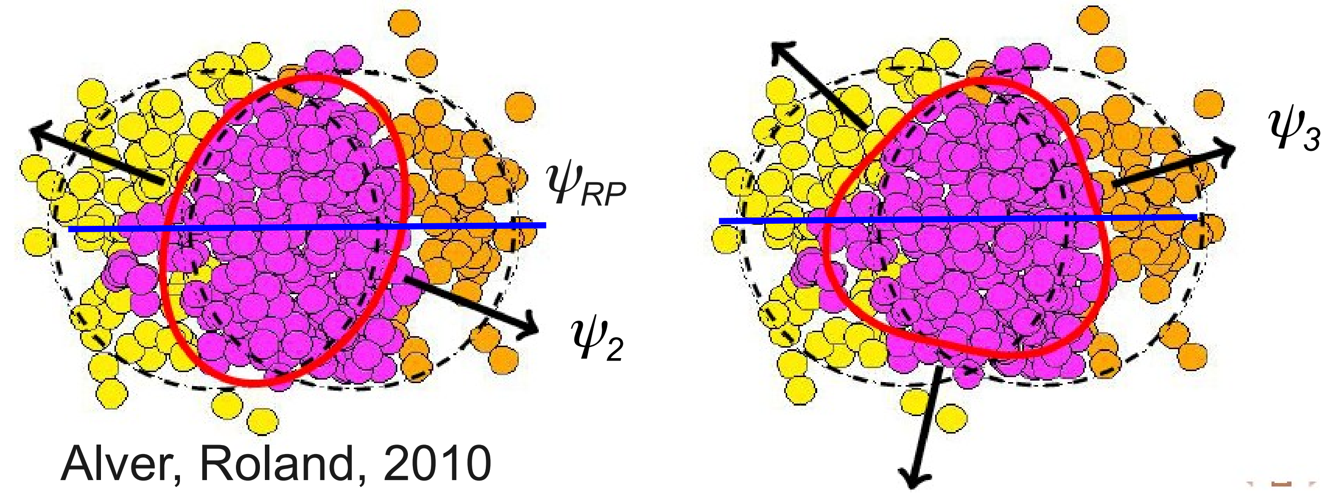


$$\frac{dN}{d\varphi} \sim 1 + 2v_2 \cos(2\Delta\varphi) + \ldots$$

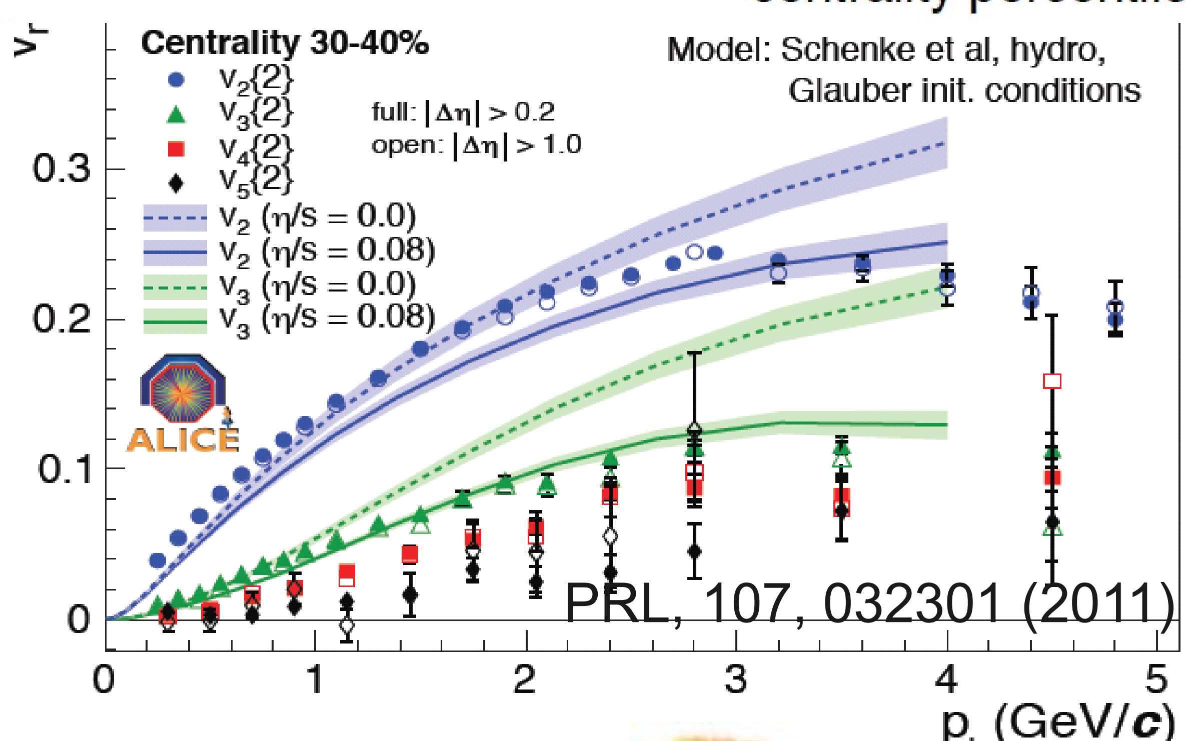
Non-zero!

Higher harmonics w.r.t. to event plane





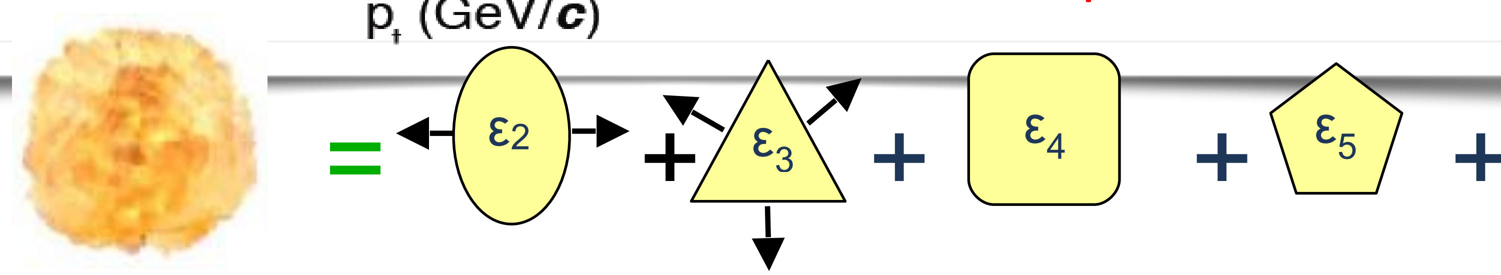
v_3 - triangular flow :
- weak centrality dependence
- vanishes as expected when measured w.r.t. reaction plane



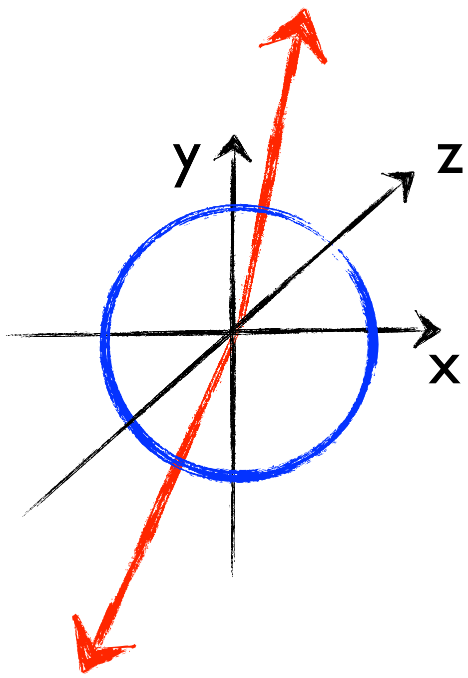
Similar pT dependence for all v_n

Higher harmonics - additional constraints on η/s

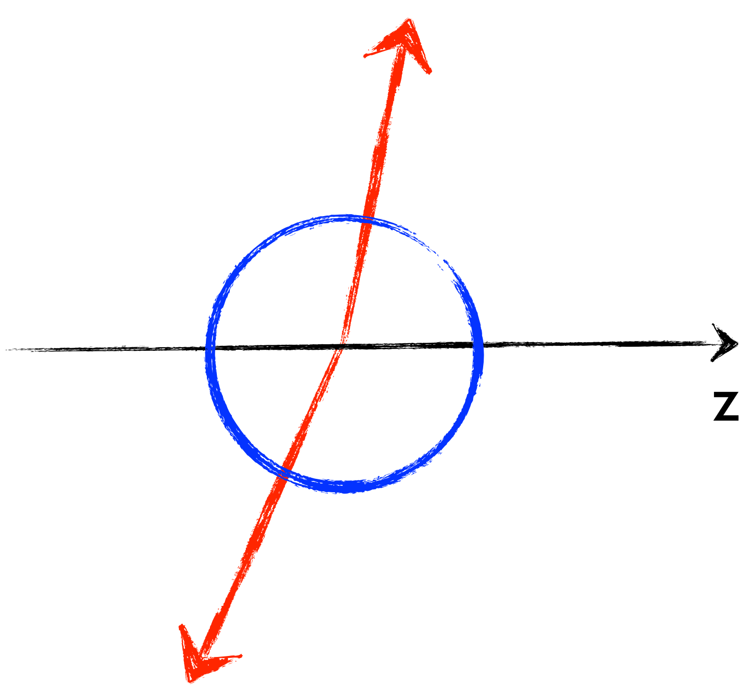
η/s small, similar as at RHIC



Two particle correlations



$\Delta\varphi$ - azimuthal angle difference
angle in the transverse plane



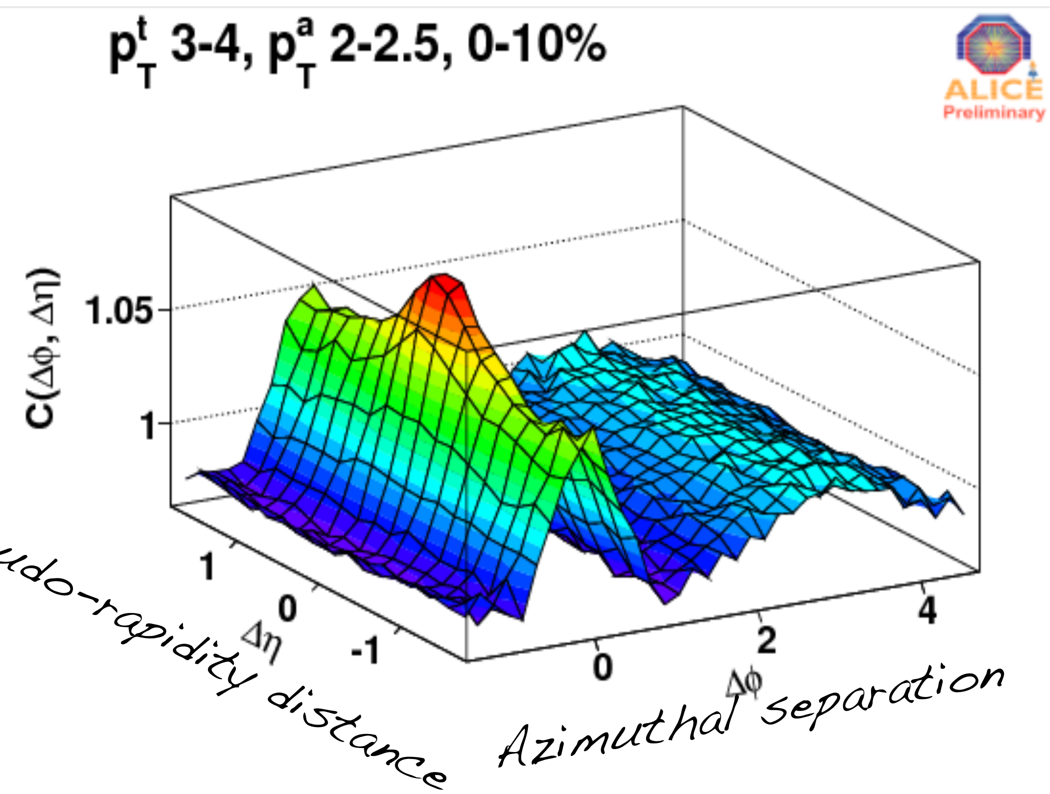
$\Delta\eta$ - longitudinal - pseudo-rapidity distance

Sensitivity of particle correlations to the underlying/initial conditions

Two-particle correlations

- conditional [per-trigger] yields

$$\frac{1}{N_{trig}}\frac{dN_{assoc}}{d\Delta\varphi} \quad \text{and} \quad \frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\varphi d\Delta\eta}$$



At Low-p_T :

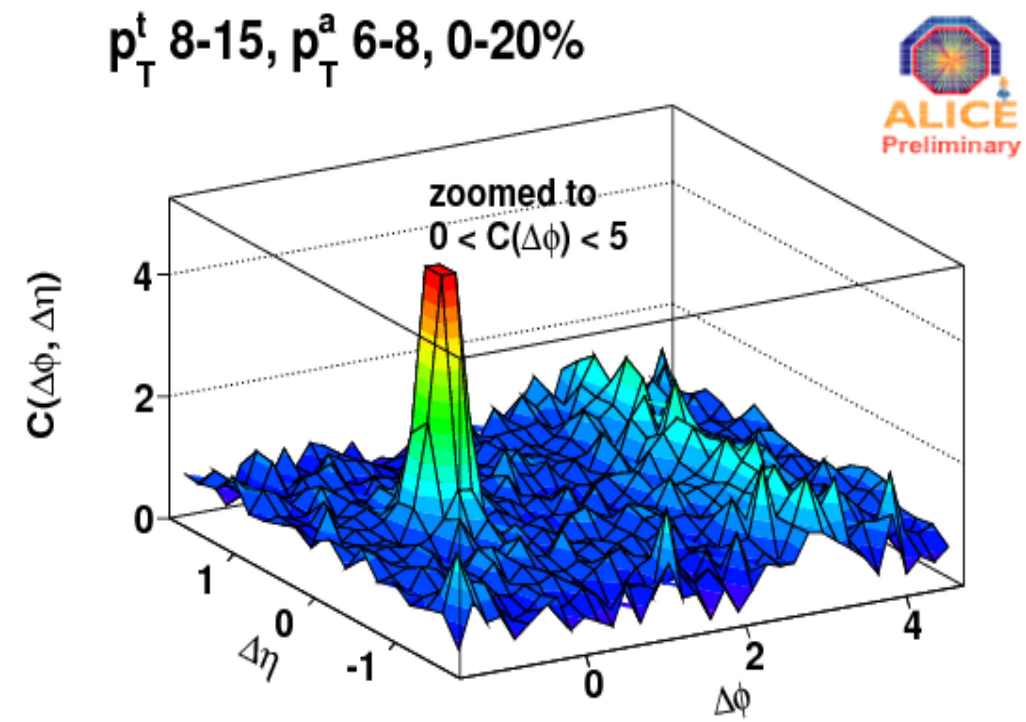
Ridge

Hydrodynamics, flow

At High-p_T :

Discussed later…

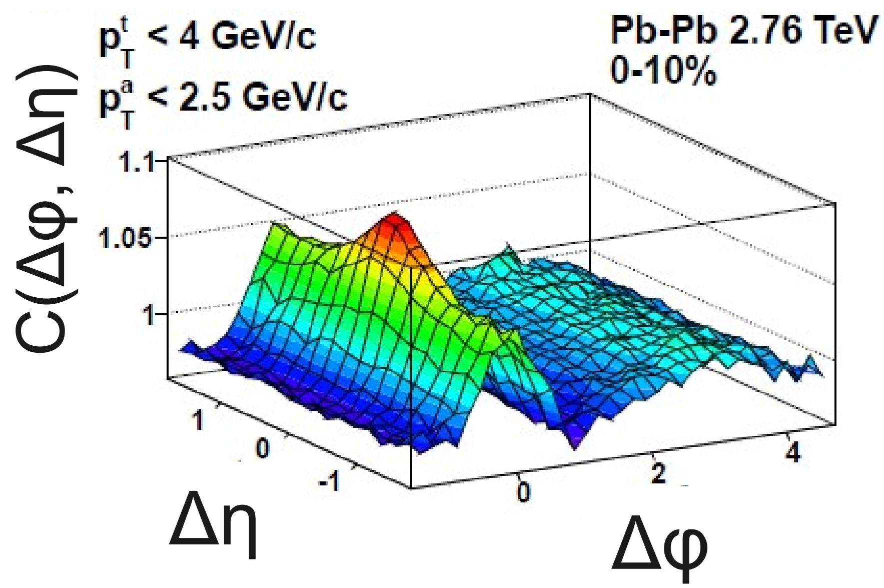
Quenching/suppression, broadening



I_{CP}: Yields in central v.s. peripheral collisions

I_{AA}: Yields in A-A compared to p-p

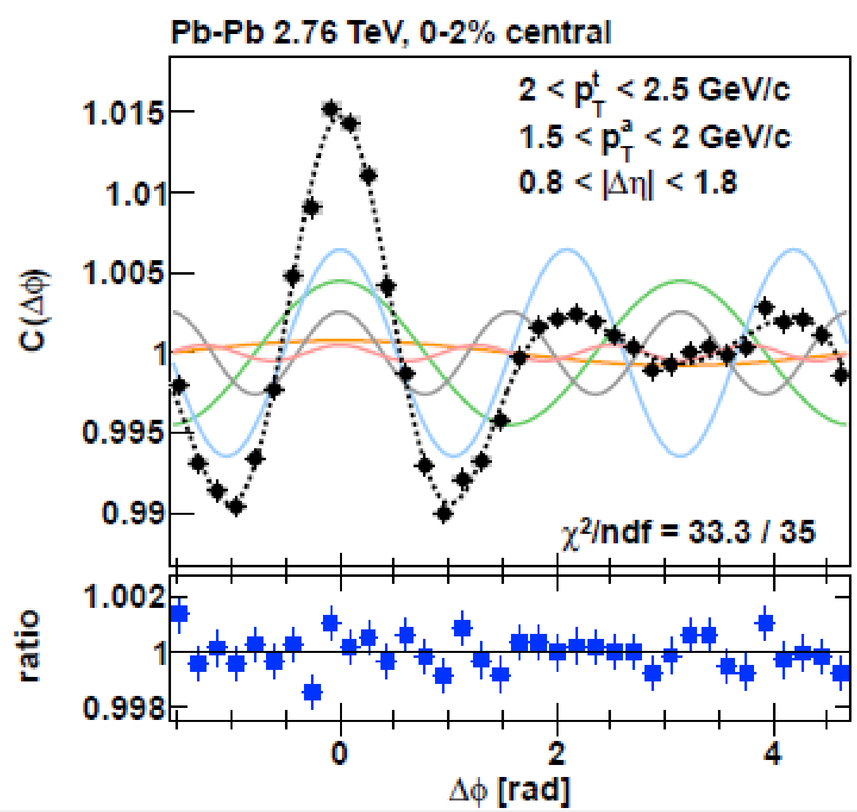
Two-particle correlations – Fourier decomposition

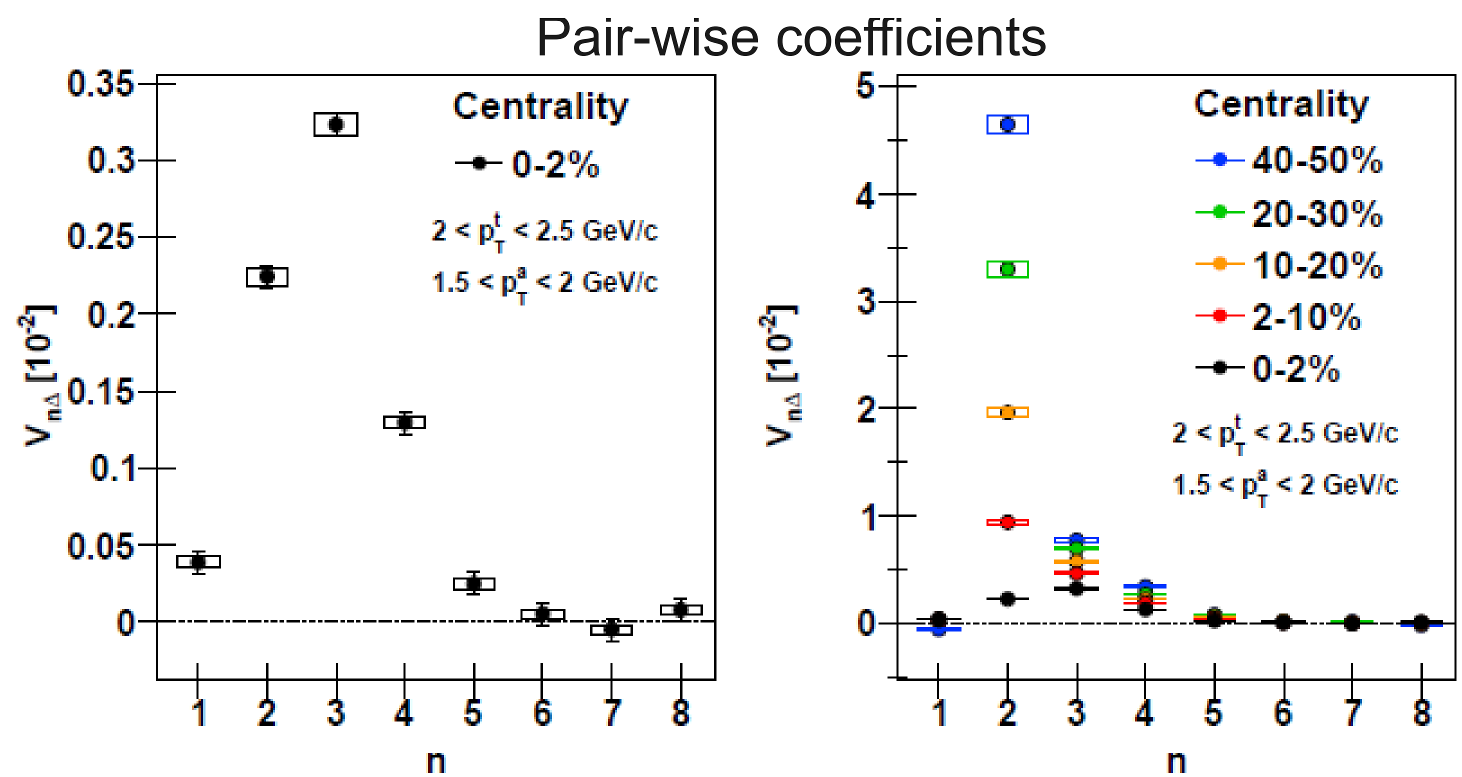


Integration of the correlation function in 0.8 < |Δη| < 1.8 (long) and Fourier decomposition

Collective flow: the coefficients factorize $V_{n\Delta} = v_n(p_T^T) v_n(p_T^A)$

$$C(\Delta\phi) = \frac{1}{\Delta\eta_{max} - \Delta\eta_{min}} \int_{\Delta\eta_{min}}^{\Delta\eta_{max}} C(\Delta\eta, \Delta\phi) \sim 1 + 2\sum_{n=1} V_{n\Delta} \cos(n\Delta\phi)$$





Few components describe the low-pT correlations

⇔ Strong near side ridge and double-peak on the away

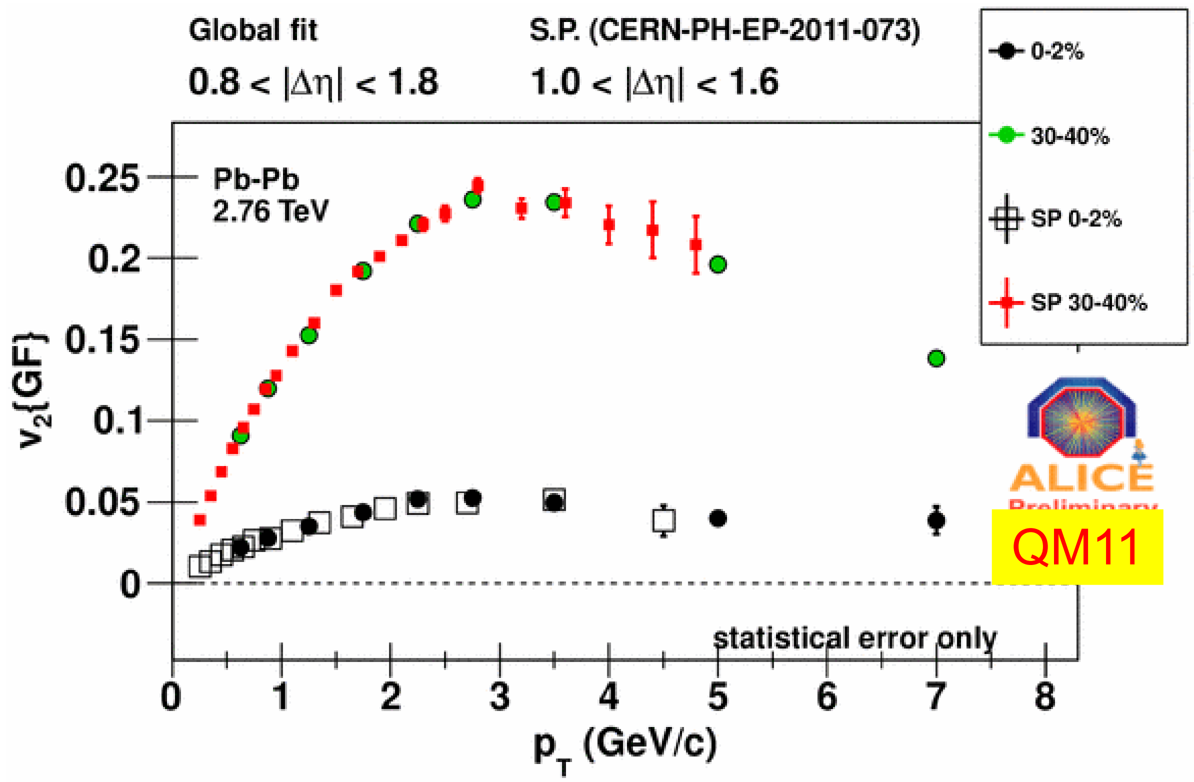
⇔ Also recoil jet up to p_T^{trig}>8 & p_T^{assoc} 6-8 in central

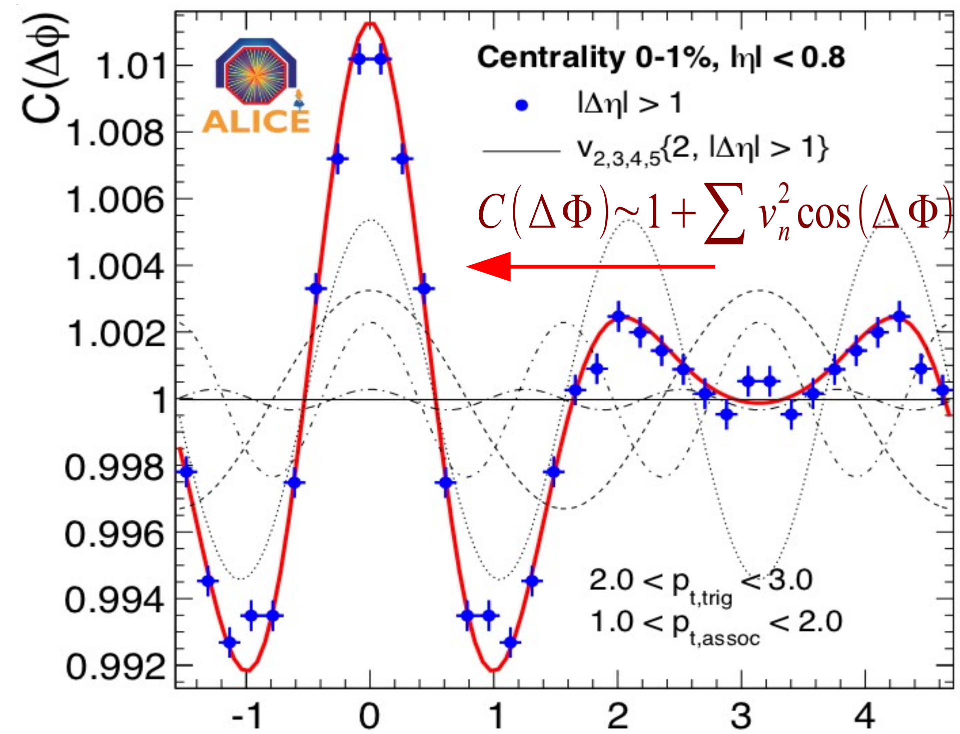
Correlations & hydrodynamics...

Long range correlations – collective flow: the coefficients must factorize such that:

$$V_{n\Delta} = \langle \cos[n(\phi_{trig} - \phi_{assoc})] \rangle = \langle \cos[n(\phi_{trig} - \Psi_n)] \rangle \langle \cos[n(\phi_{assoc} - \Psi_n)] \rangle = v_n(p_t^{trig}) \cdot v_n(p_t^{assoc})$$

arXiv:1109.2501



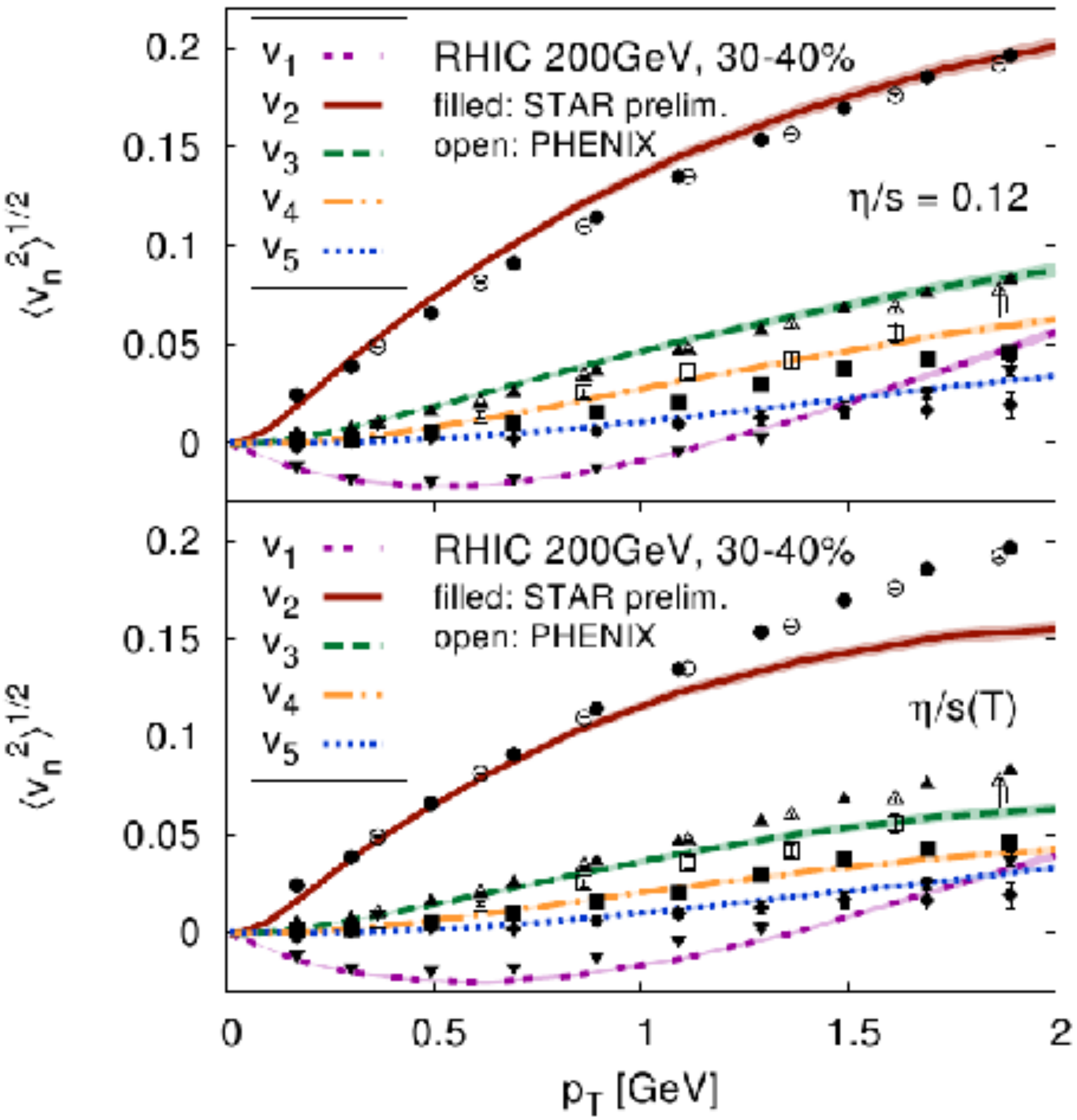


PRL, 107, 032301 (2011)

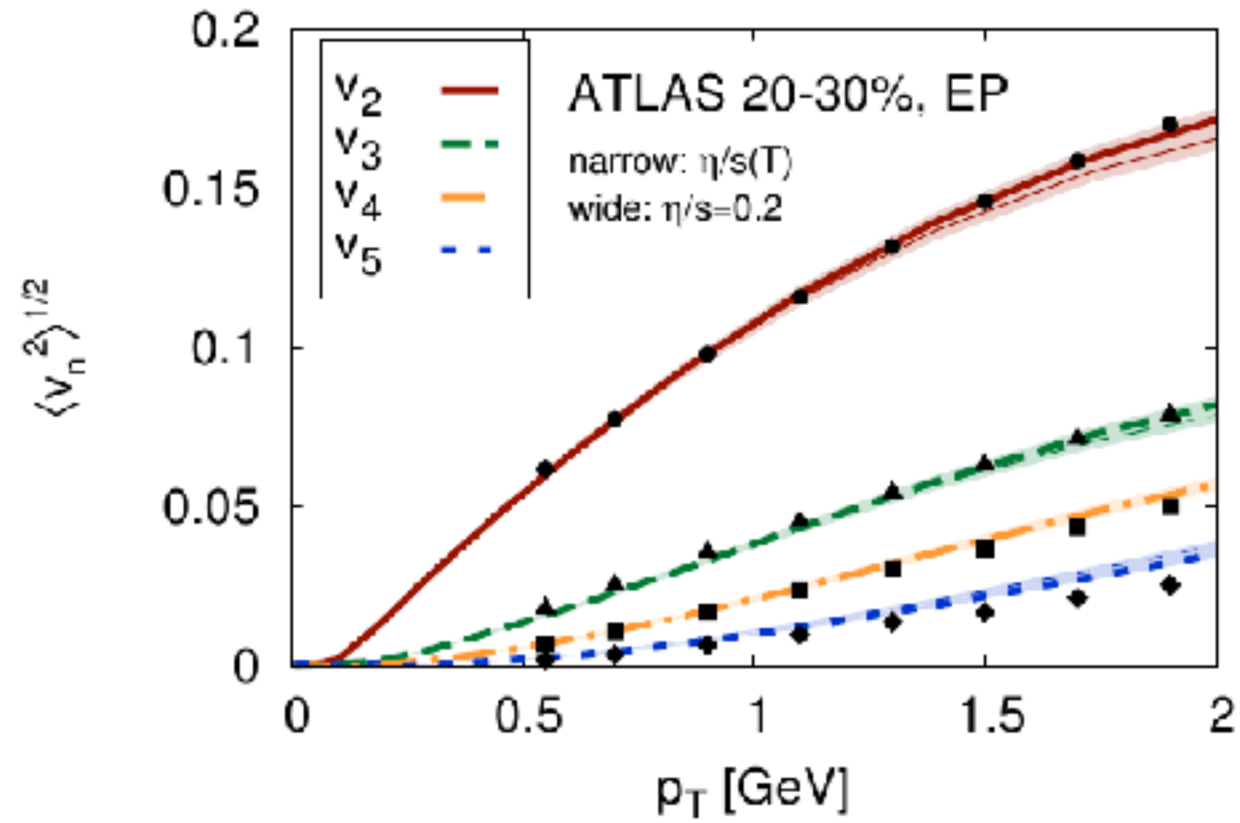
Global fits show:

- **Collective flow dominates to about 3-4 GeV/c for all n>1**
- **Description breaks for high pT or peripheral collisions**
- **For low pT: double peak and ridge structures seen in two particle correlations are naturally explained by measured anisotropic flow coefficients**

(viscous) fluid dynamics works!



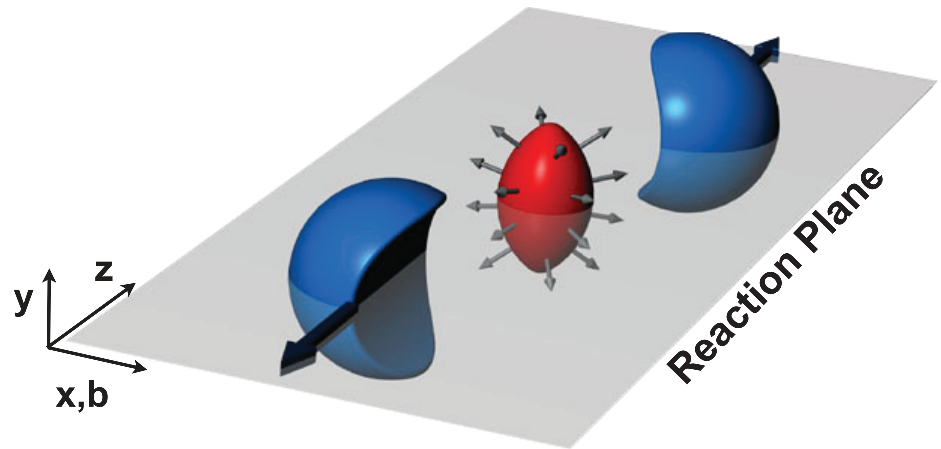
Good description of data for π++



Small shear viscosity over entropy ratio: $\frac{\eta}{s} \leq 0.25$

Understanding correlations & v2 – the so-called non-flow

For completeness...



S. Snellings

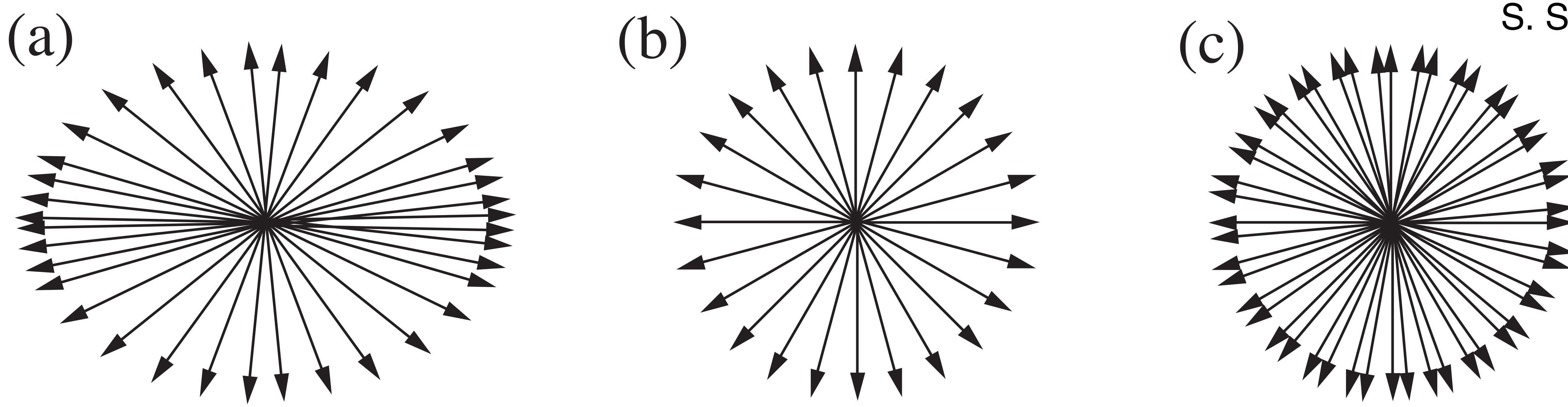
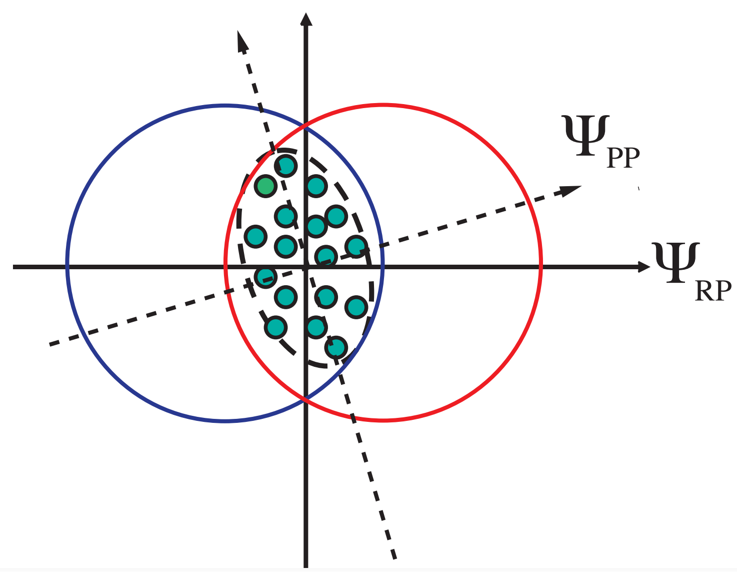


Figure 9. Examples of particle distributions in the transverse plane, where for a) $v_2 > 0$, $v_2\{2\} > 0$, b) $v_2 = 0$, $v_2\{2\} = 0$, and c) $v_2 = 0$, $v_2\{2\} > 0$.

Reaction plane (RP)
Participants plane (PP)

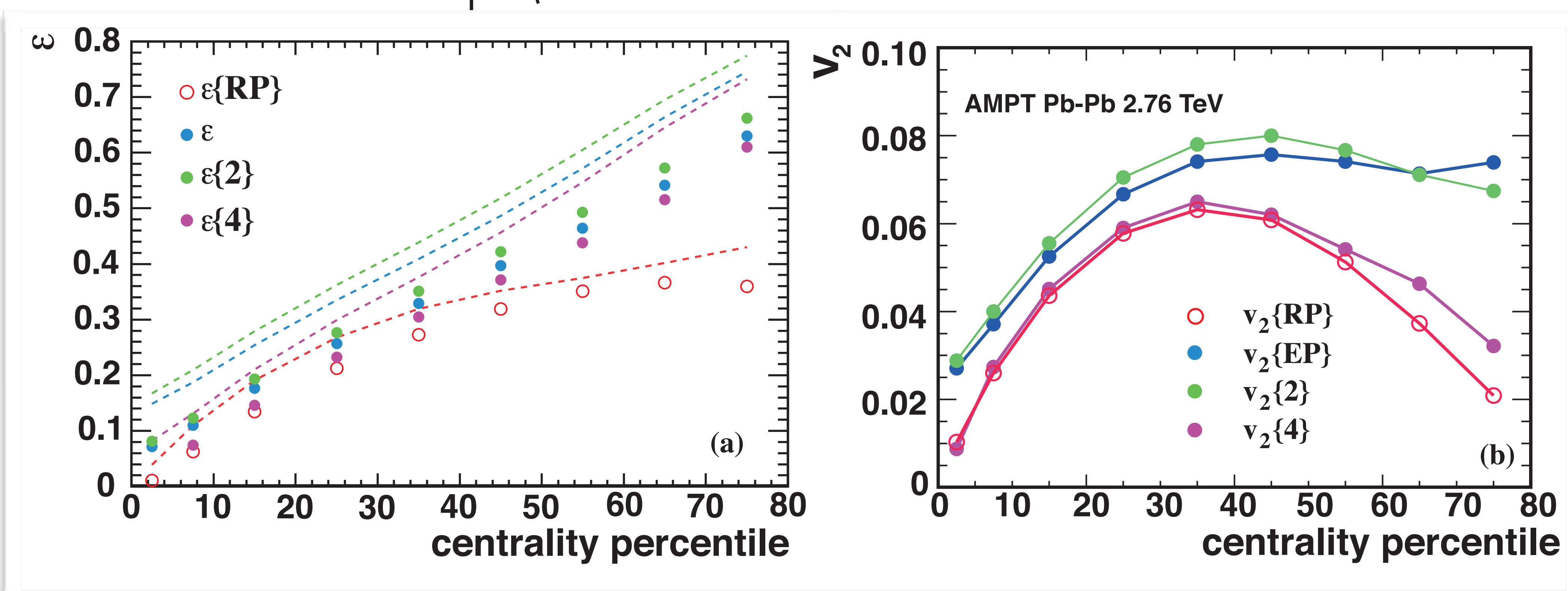


Genuine 2,4-particle correlations

$$c_2\{2\} \equiv \left\langle\left\langle e^{i2(\varphi_1-\varphi_2)}\right\rangle\right\rangle = \left\langle v_2^2+\delta_2\right\rangle .$$

$$\begin{aligned} c_2\{4\} &\equiv \left\langle\left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\right\rangle\right\rangle - 2\left\langle\left\langle e^{i2(\varphi_1-\varphi_2)}\right\rangle\right\rangle^2 , \\ &= \left\langle v_2^4+\delta_4+4v_2^2\delta_2+2\delta_2^2\right\rangle - 2\left\langle v_2^2+\delta_2\right\rangle^2 , \\ &= \left\langle -v_2^4+\delta_4\right\rangle . \end{aligned}$$

$\delta_2 \propto 1/M_c$ and $\delta_4 \propto 1/M_c^3$

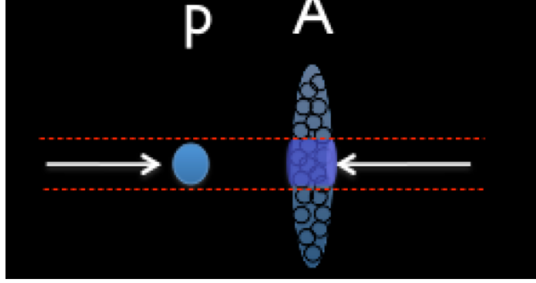


[AMPT] calculation using Glauber initial conditions

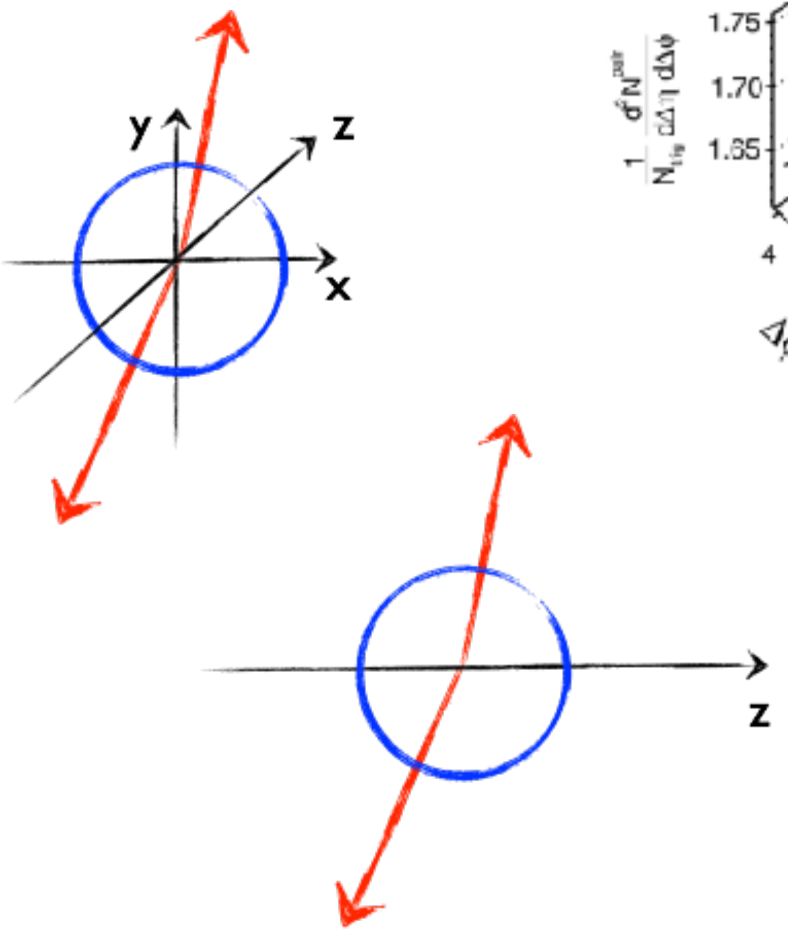
v2: RP, EP v2{2} v2{4}

An LHC surprise!

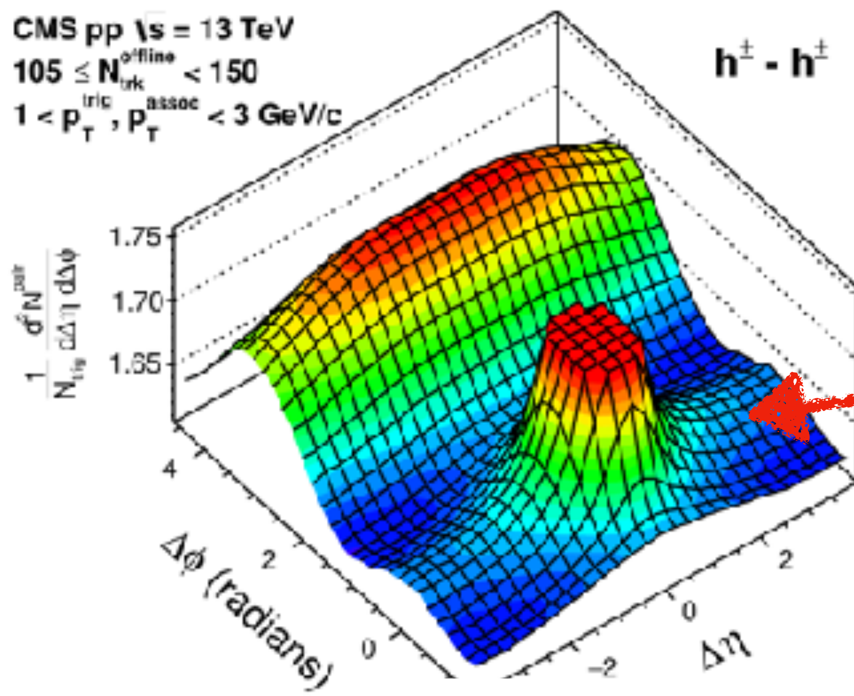
Not seen before LHC



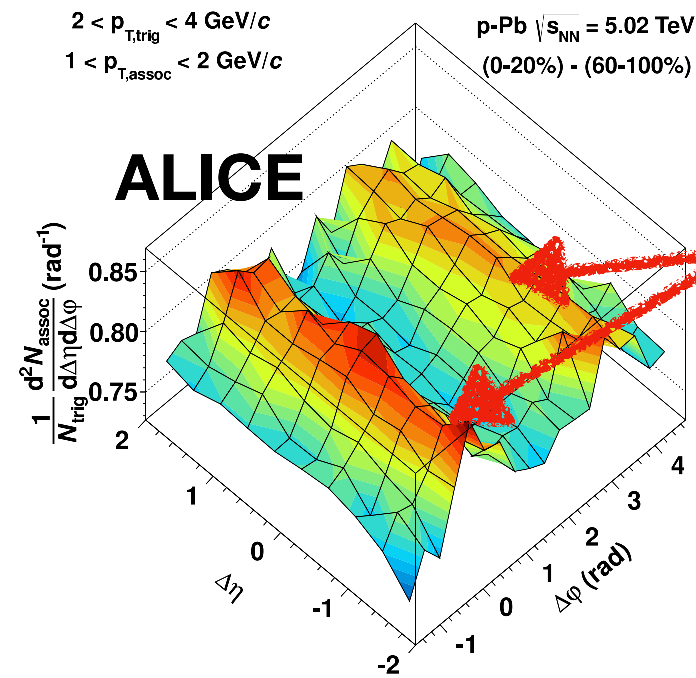
Δφ azimuthal angle difference
- angle in the transverse plane



Δη - longitudinal - pseudo-rapidity distance



Long-range correlation structure in high-multiplicity pp collisions



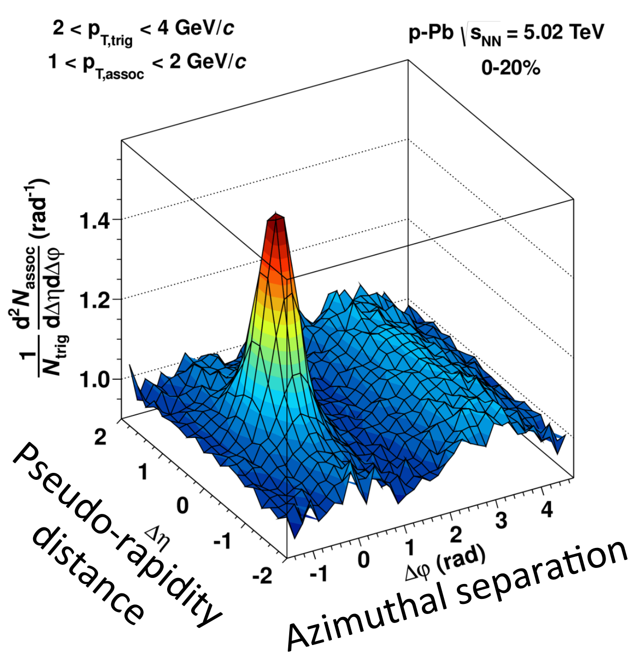
Long-range correlation double structure in high-multiplicity pPb collisions

Similar observations made by ATLAS & LHCb

Long range correlations are intimately related to initial stages - early times - ~10^{-24}s.
Do we fully understand initial stages of nuclear collisions? - No (!).
ALICE: + (not shown) indication of v_2>HF (?) in p-Pb collisions (muon-hadron correlations)

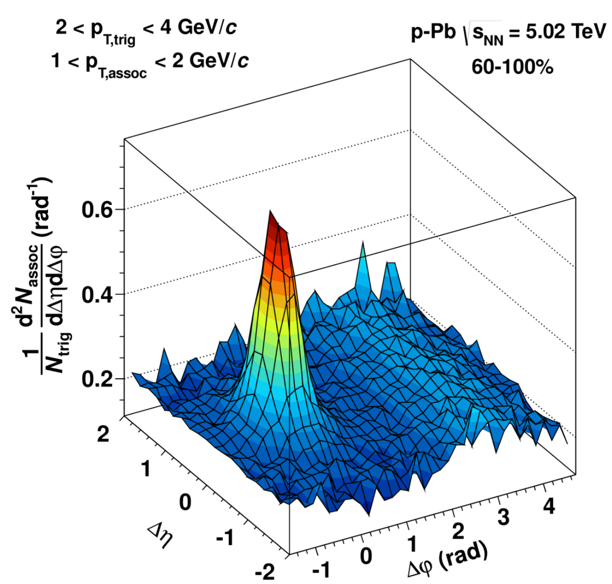
Extraction of the ridge properties

The method: from the high-multiplicity yield subtract the jet yield in low-multiplicity events (no ridge)



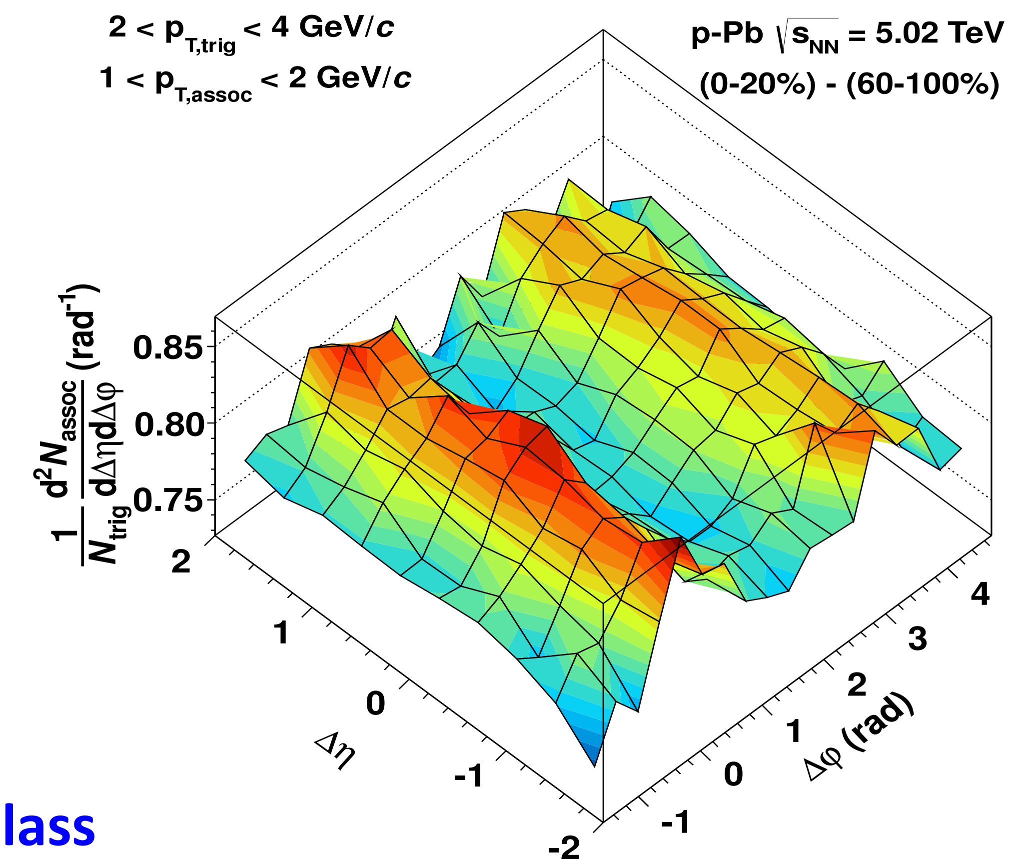
High multiplicity event class

$\langle dN_{ch}/d\eta \rangle \sim 35$



Low multiplicity event class

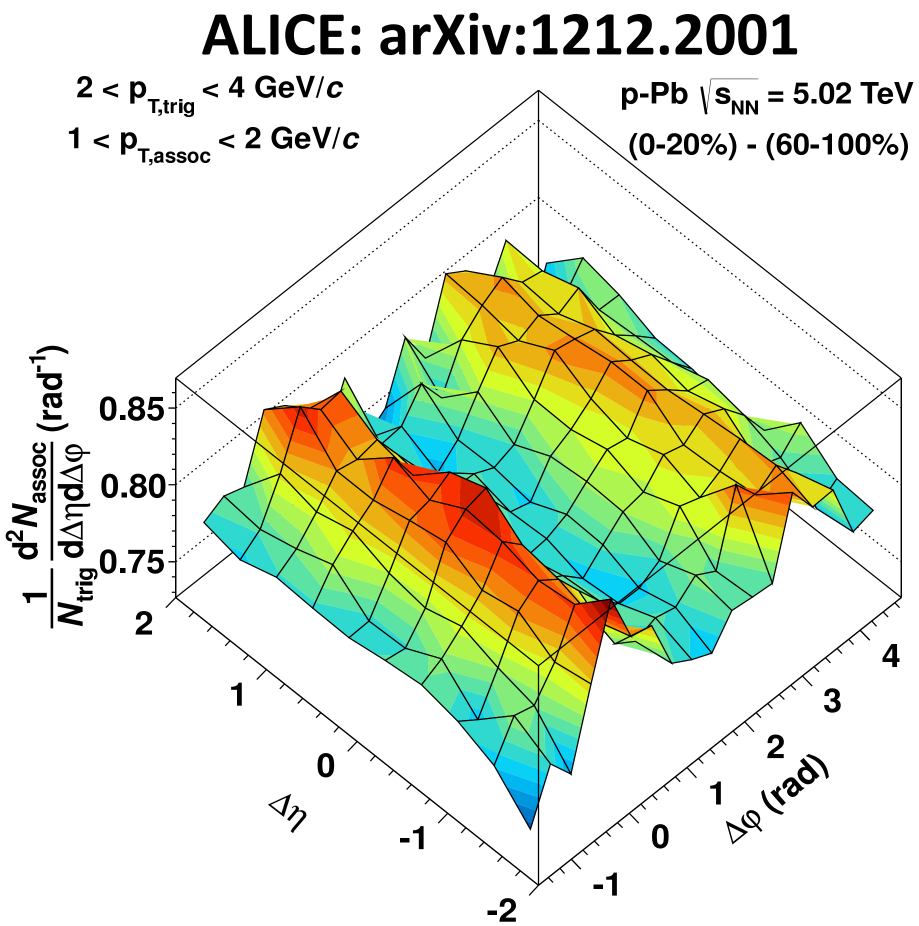
$\langle dN_{ch}/d\eta \rangle \sim 7$



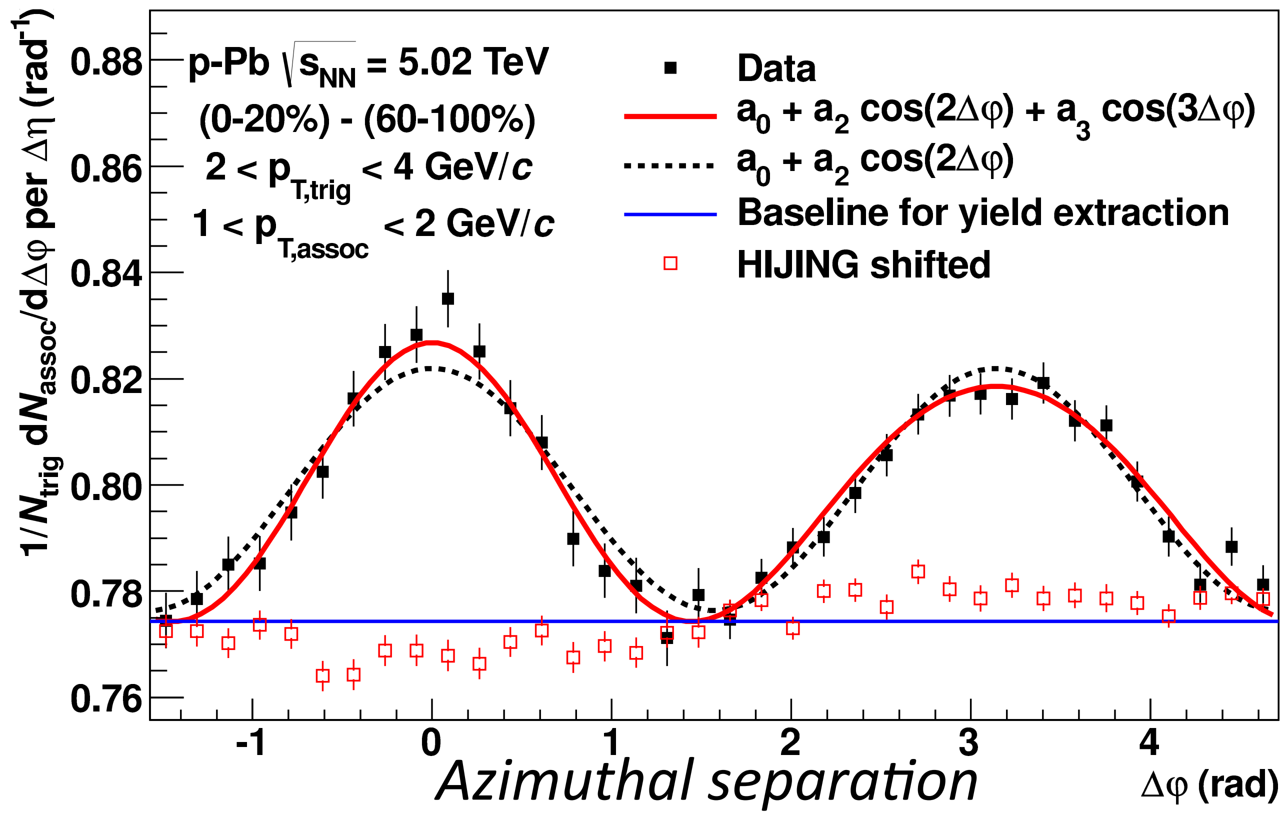
Remaining correlation: two twin long range structures

Analysis in multiplicity classes defined by the total charge in VZERO detector (away from the central region)

Twin ridge structure – in AA but also in pA collisions



Remaining correlation described by finite amplitudes of Fourier terms



Further investigations reveal:

- **the full modulation is (1) di-jets and (2) the double-ridge structure – nothing more**
- **Same yield near and away side for all classes of p_T and multiplicity suggest a common underlying process**

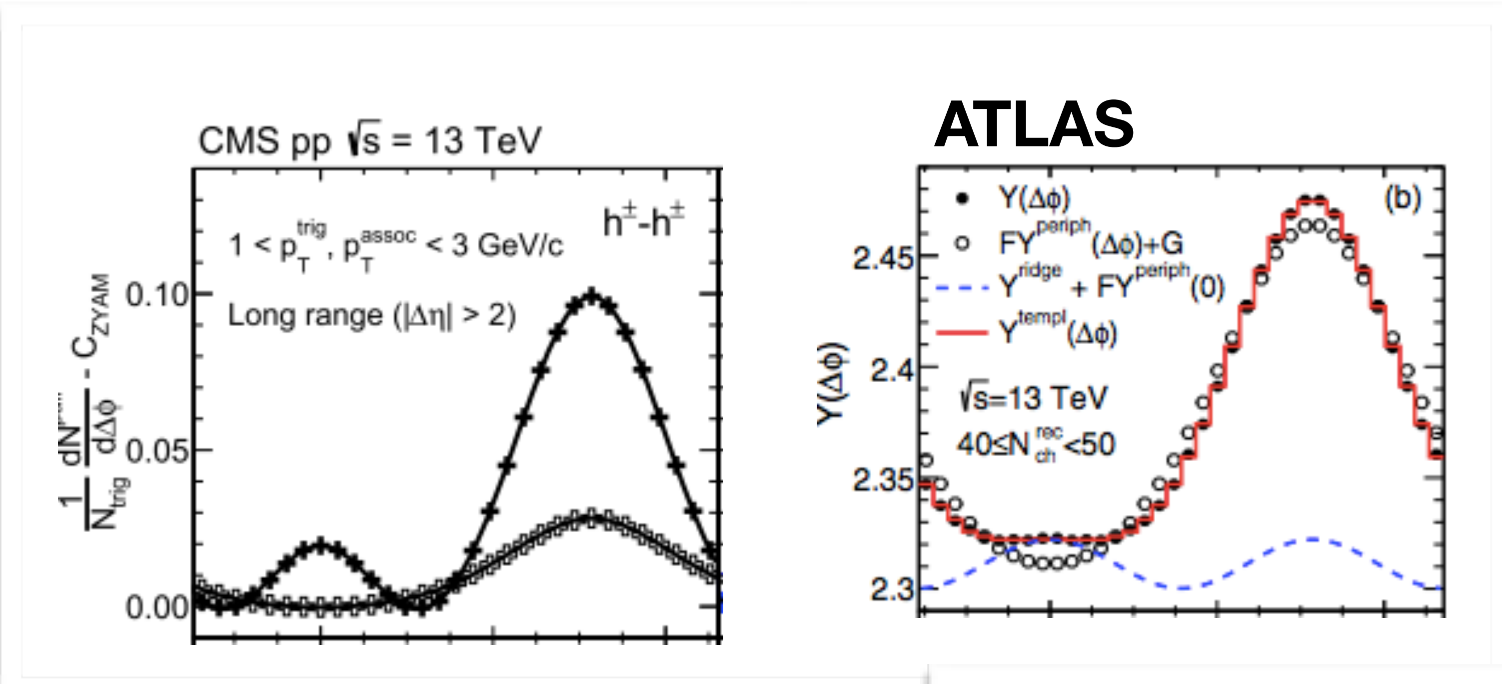
Similar observations in Pb-Pb are ascribed to collective effects!

Early explanations

First explanations are being put forward:

- Hydrodynamics – arXiv: 1112.0915
- Colour Glass Condensate – arXiv:1211.3701

v2>0 down to low-multiplicities



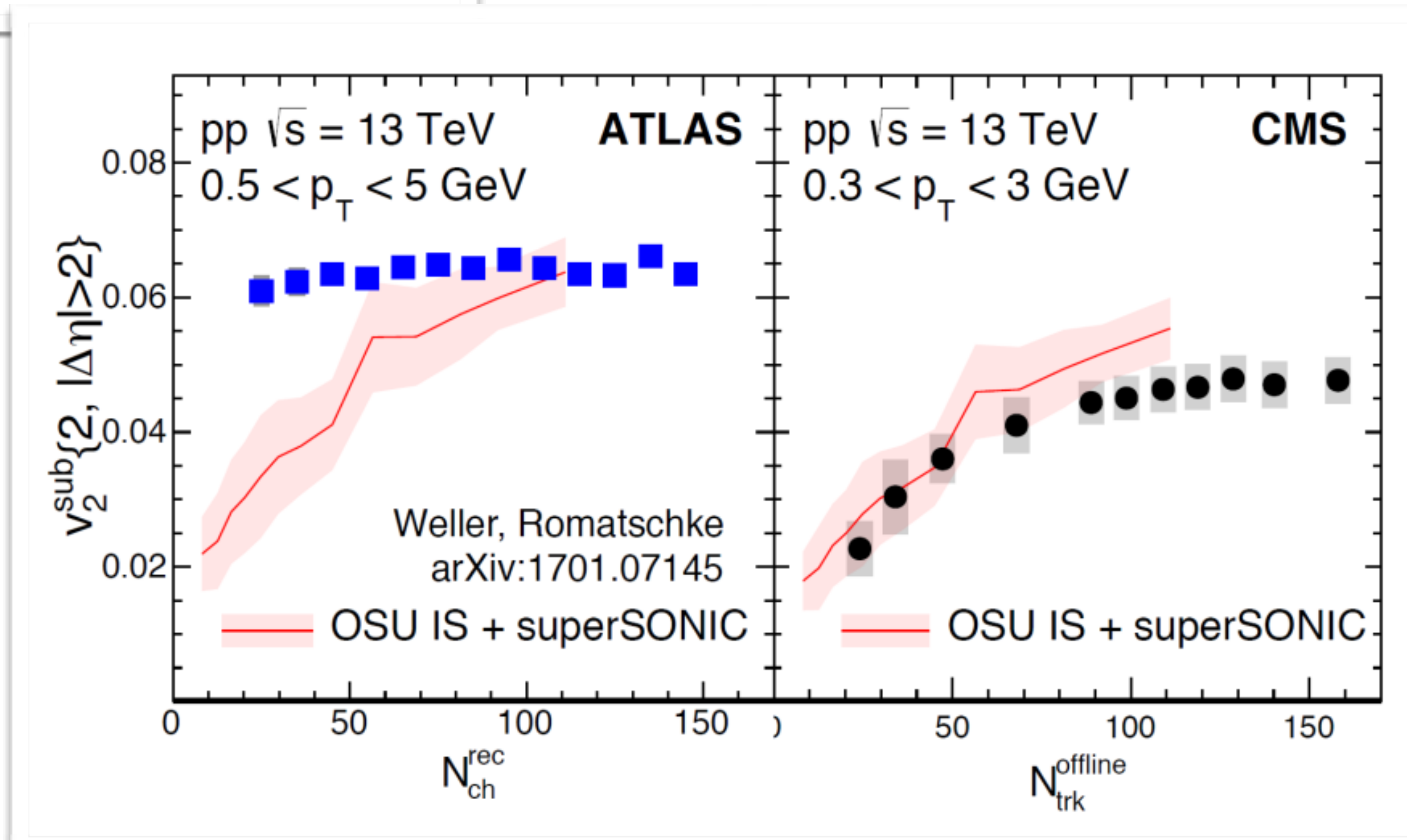
Note: experiments extract the signal in different way:
ALICE, CMS: high-mult. minus low-mult.
ATLAS: template fit

proton-proton collisions!

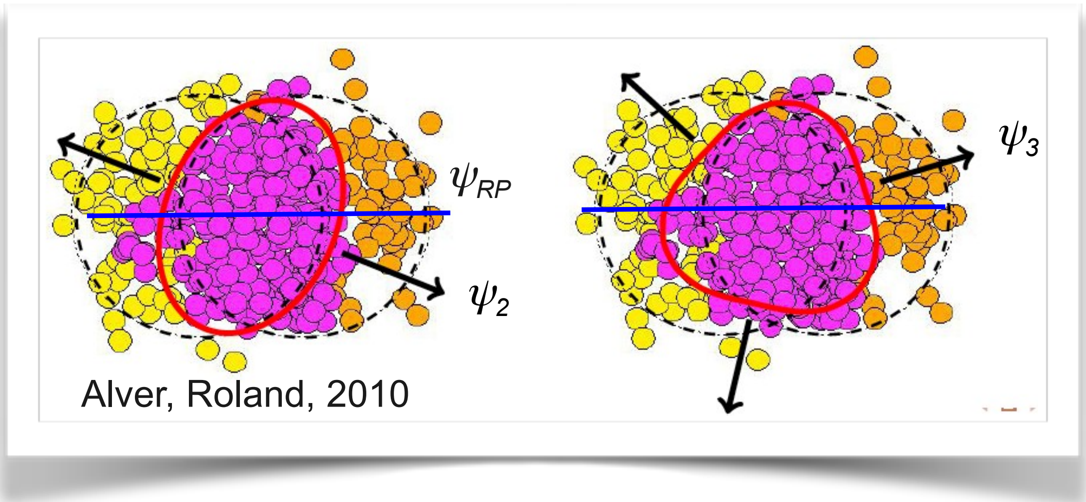
scaling of background => impact on the measurement

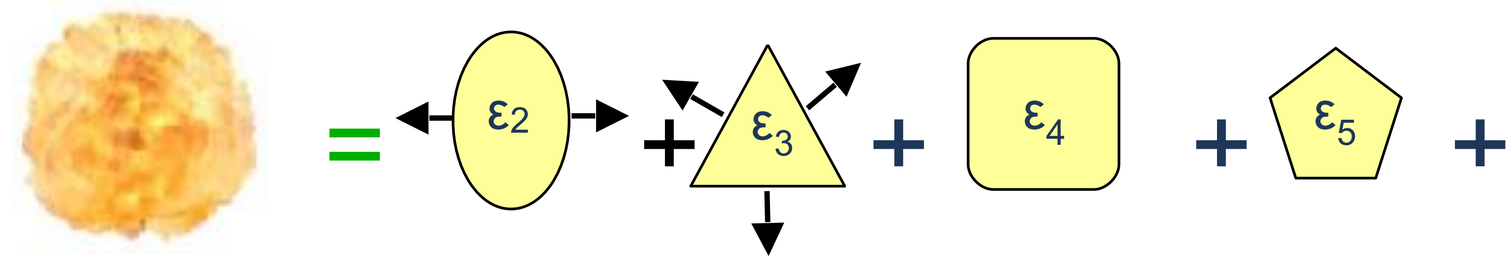
Hydro code claims signal down to lowest multiplicities

<=> even a smallest number of colored quanta "can flow"



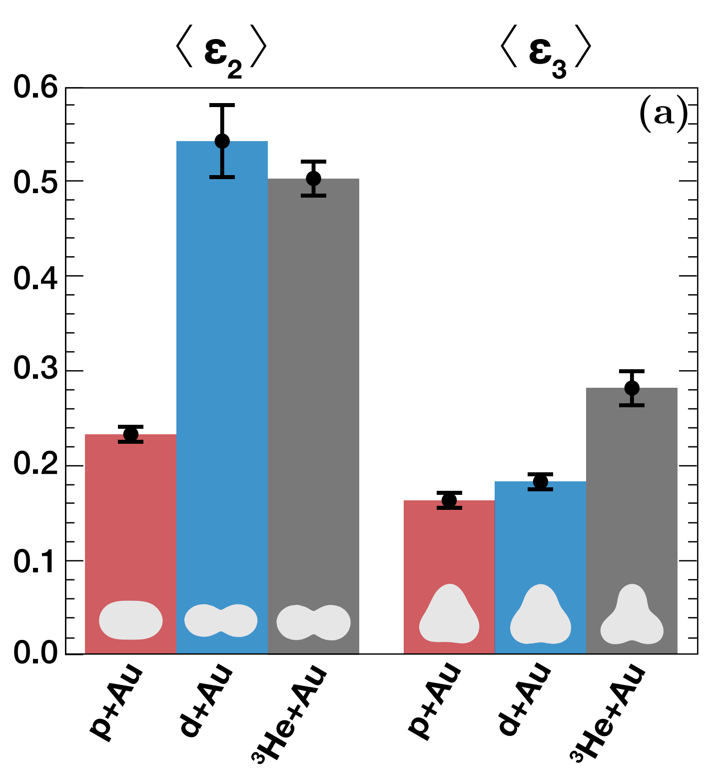
Studying different collision shapes

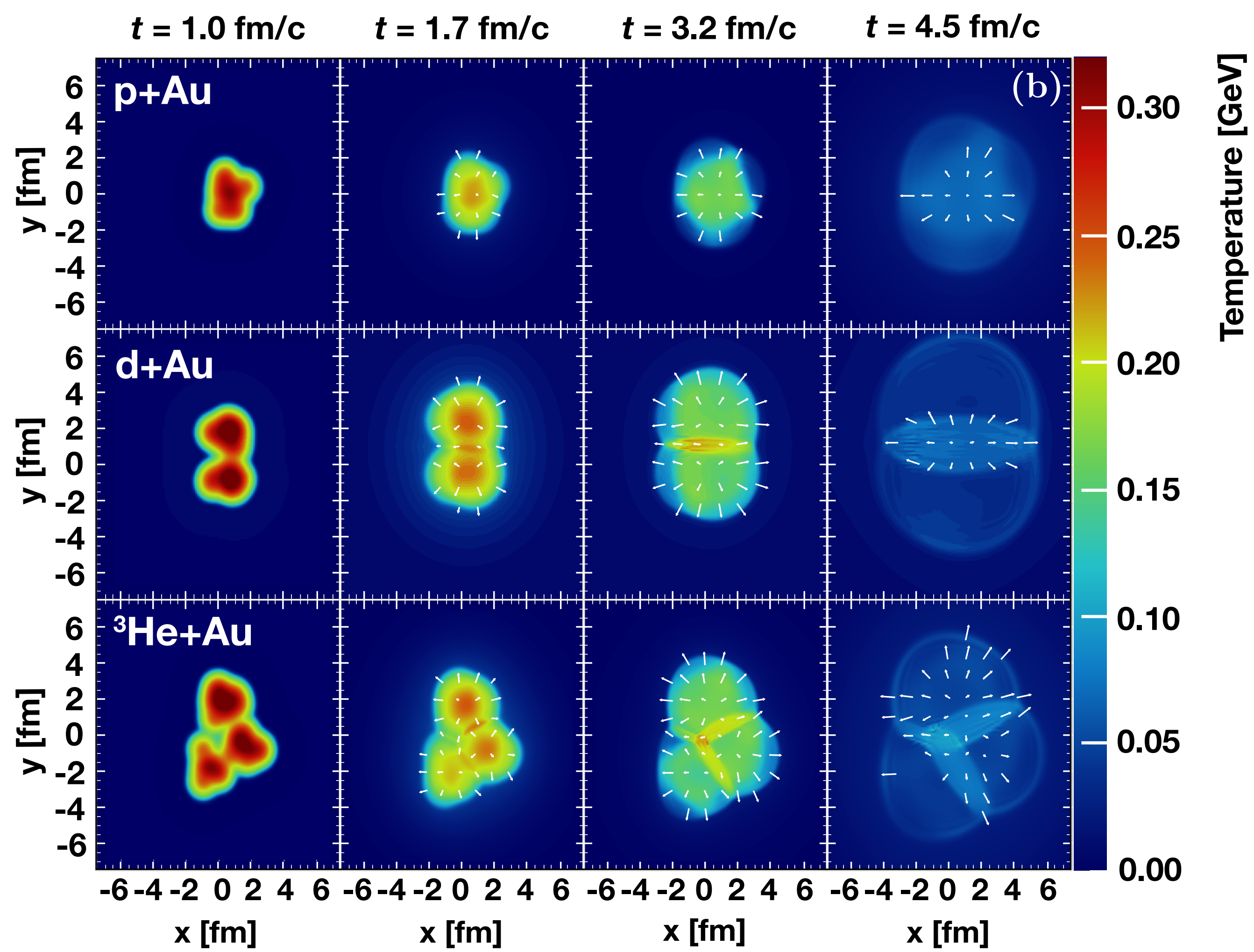




Creating small circular, elliptical, and triangular droplets of quark-gluon plasma - PHENIX https://arxiv.org/abs/1805.02973

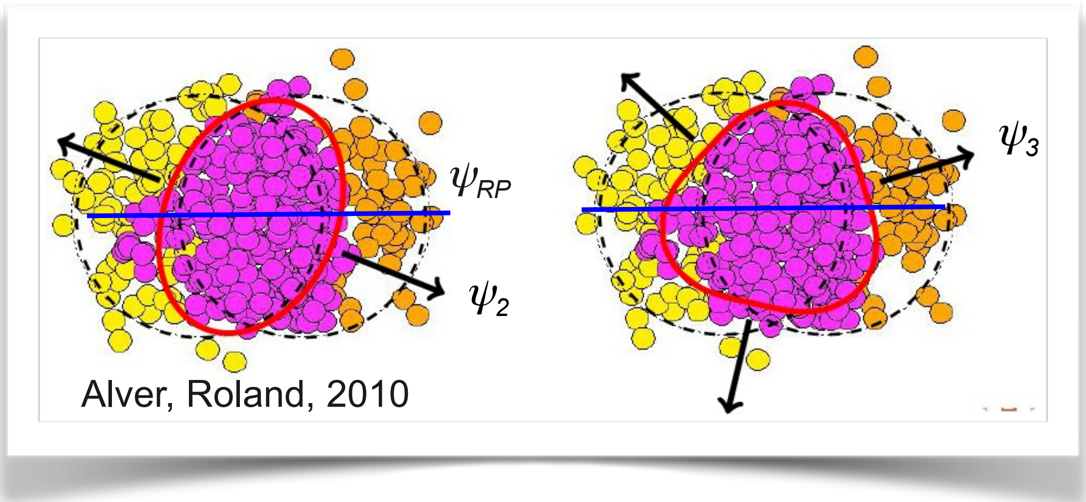
Study different collision systems: pA, dA, HeA

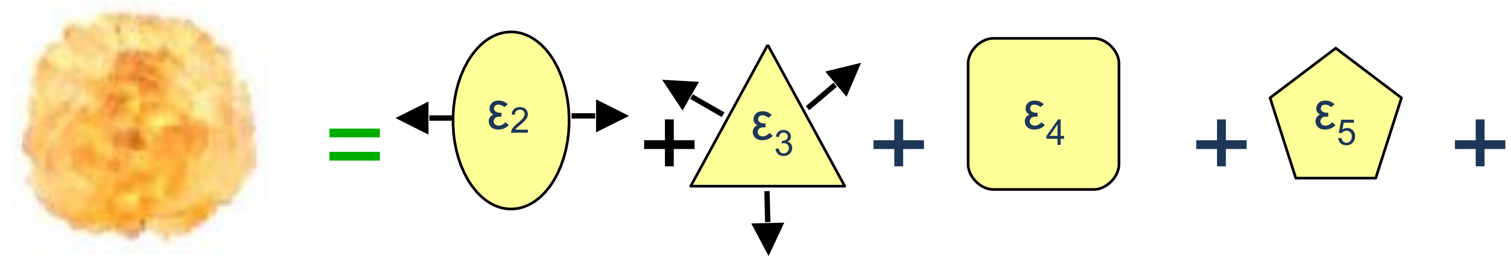




A calculation: MC Glauber + Hydrodynamical evolution

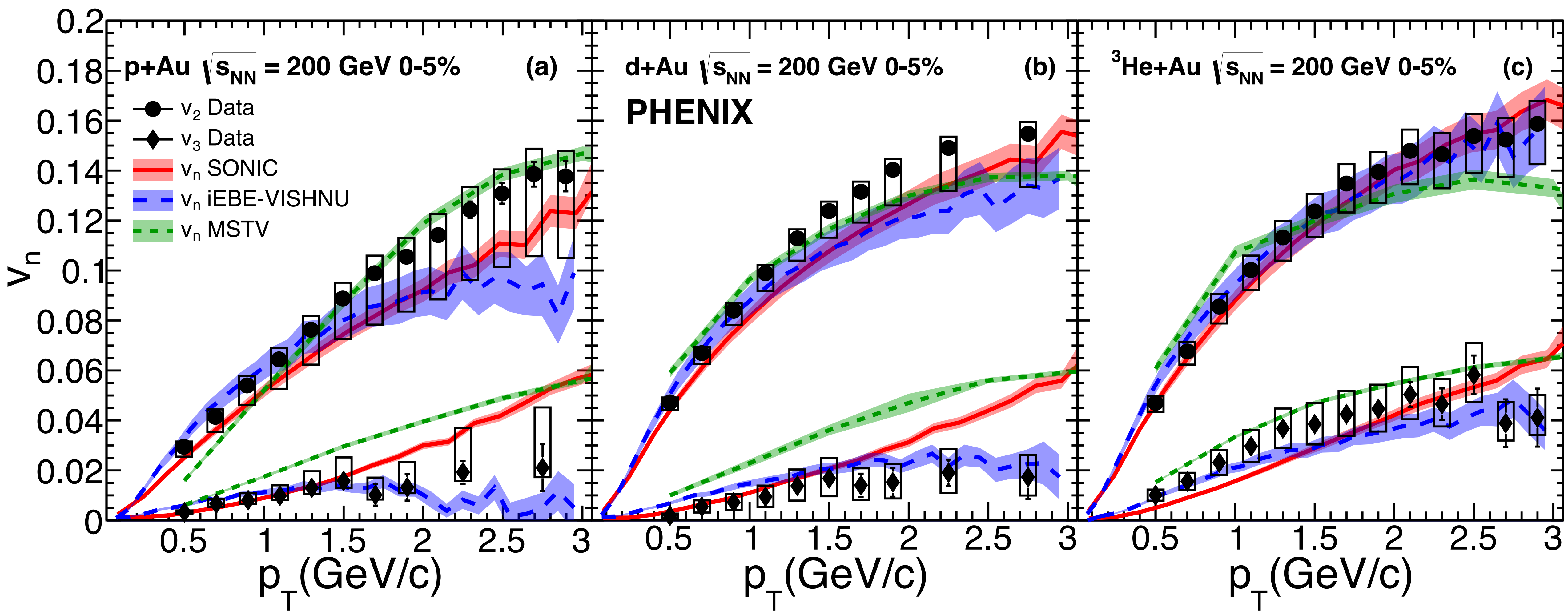
Studying different collision shapes



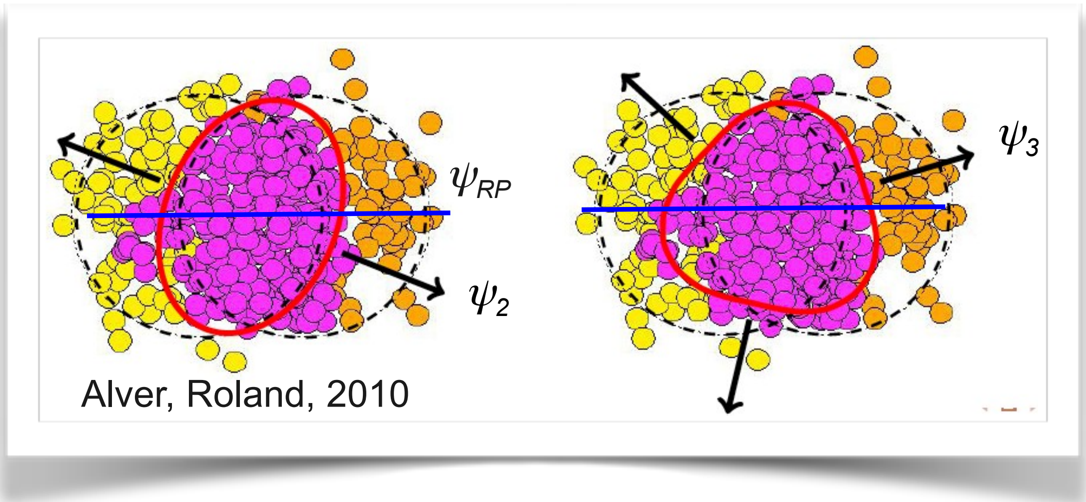


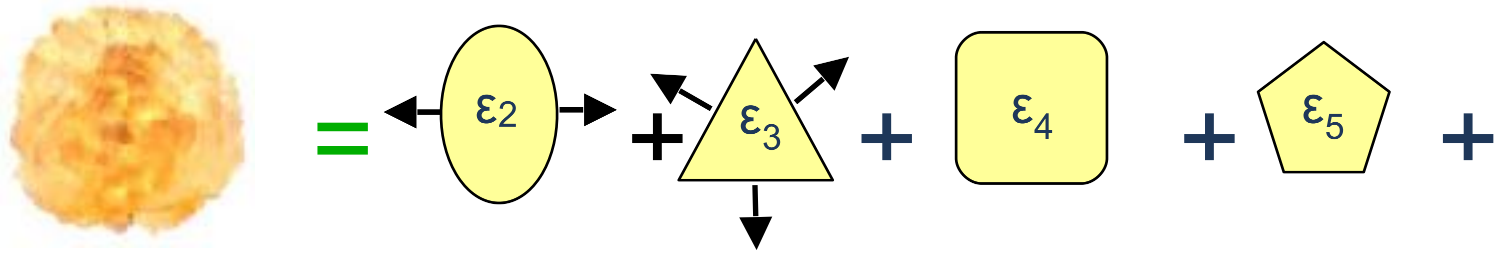
Study different collision systems: pA, dA, HeA

Creating small circular, elliptical, and triangular droplets of quark-gluon plasma - PHENIX https://arxiv.org/abs/1805.02973



Studying different collision shapes





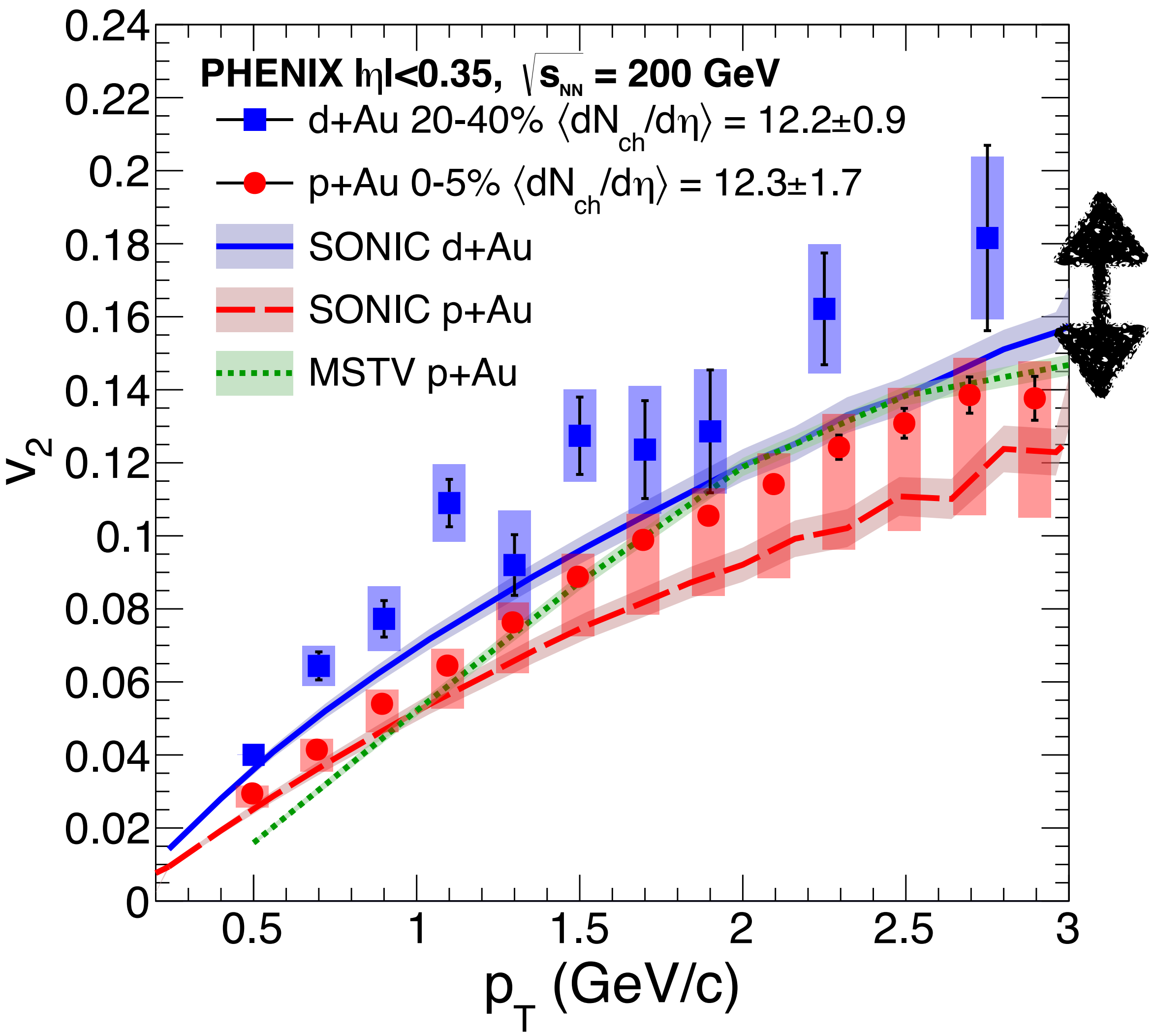
Study different collision systems: pA, dA, HeA

Creating small circular, elliptical, and triangular droplets of quark-gluon plasma - PHENIX <u>https://arxiv.org/abs/1805.02973</u>

Same charged particle density BUT Different % centrality

Systematically larger v_2 in larger system

Problem! pPb, pp collisions do not show jet quenching (while v2>0)! - something is not right?



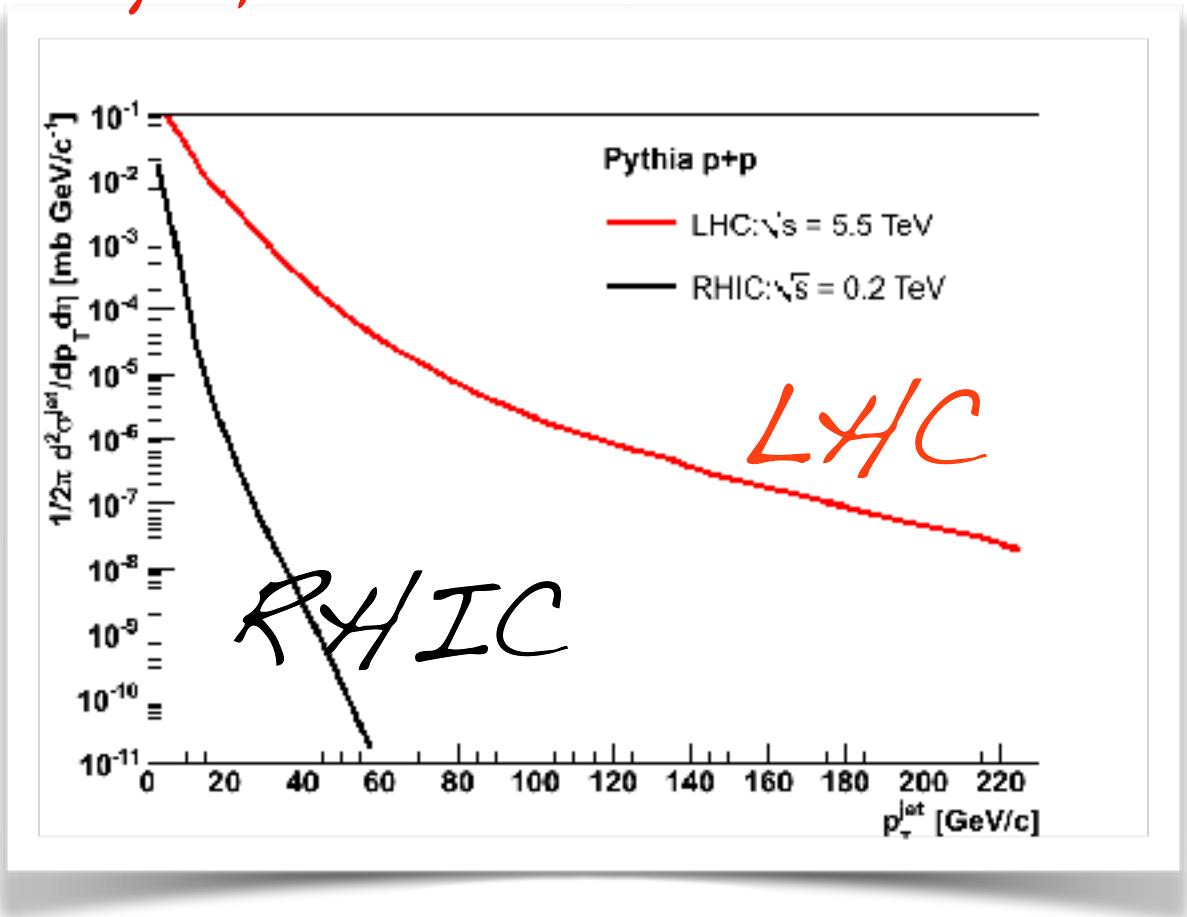
end of 2/4 (?)

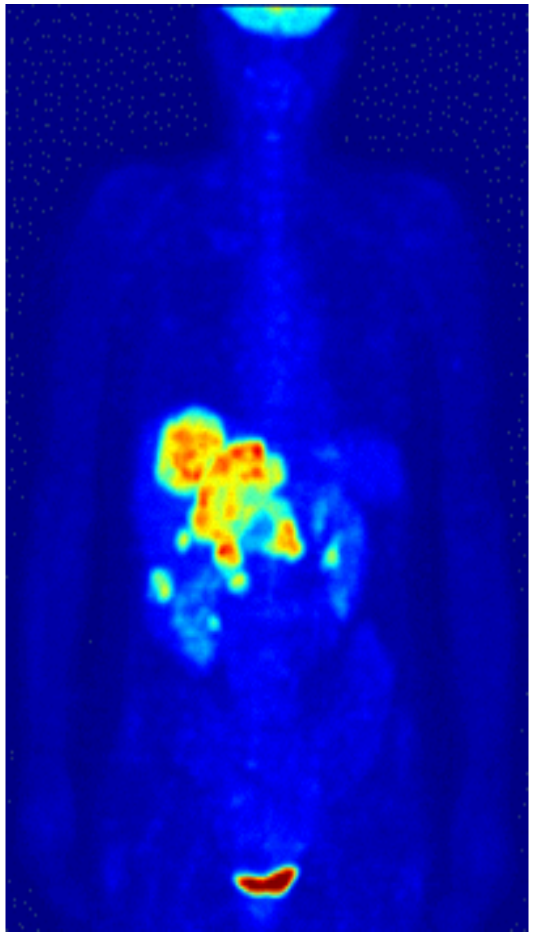
Probing an unknown medium...

... to probe the short lived medium

=> use "auto-generated probes" - heavy-ion collisions at high-energies produce internally high-energy partons (fragment into jets of particles)...

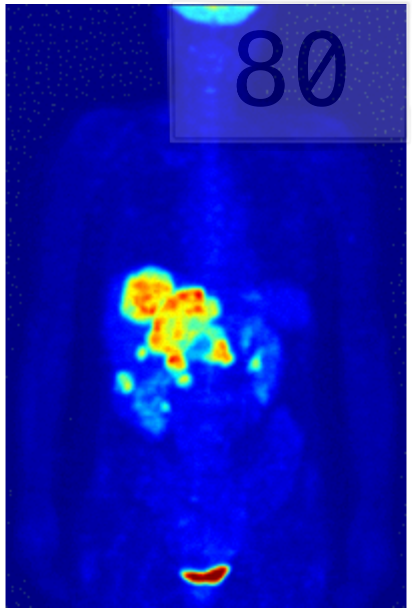
<=> critical input from pp (vacuum) measurements - pQCD



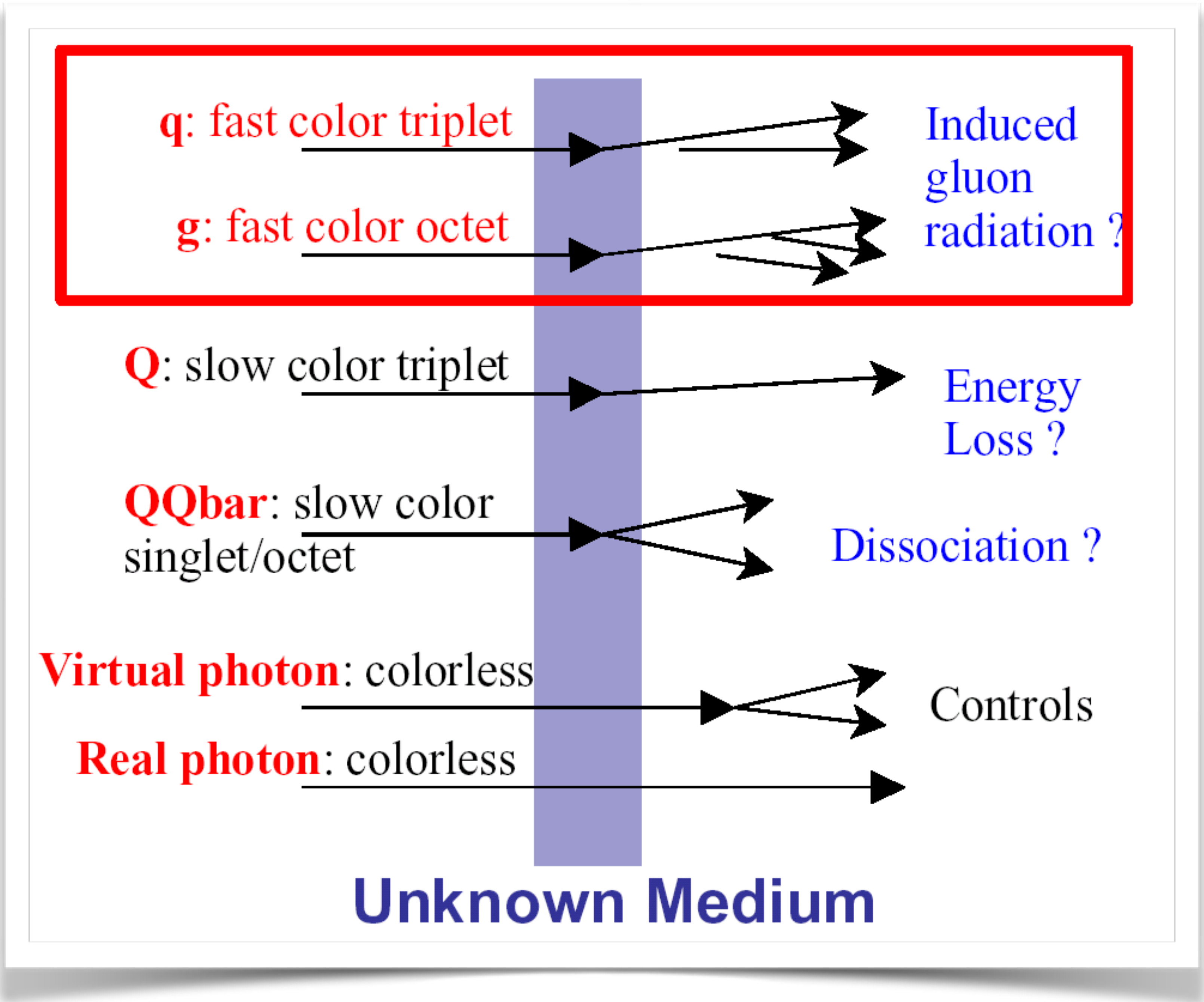


Human body

Probing the unknown medium...



Human body



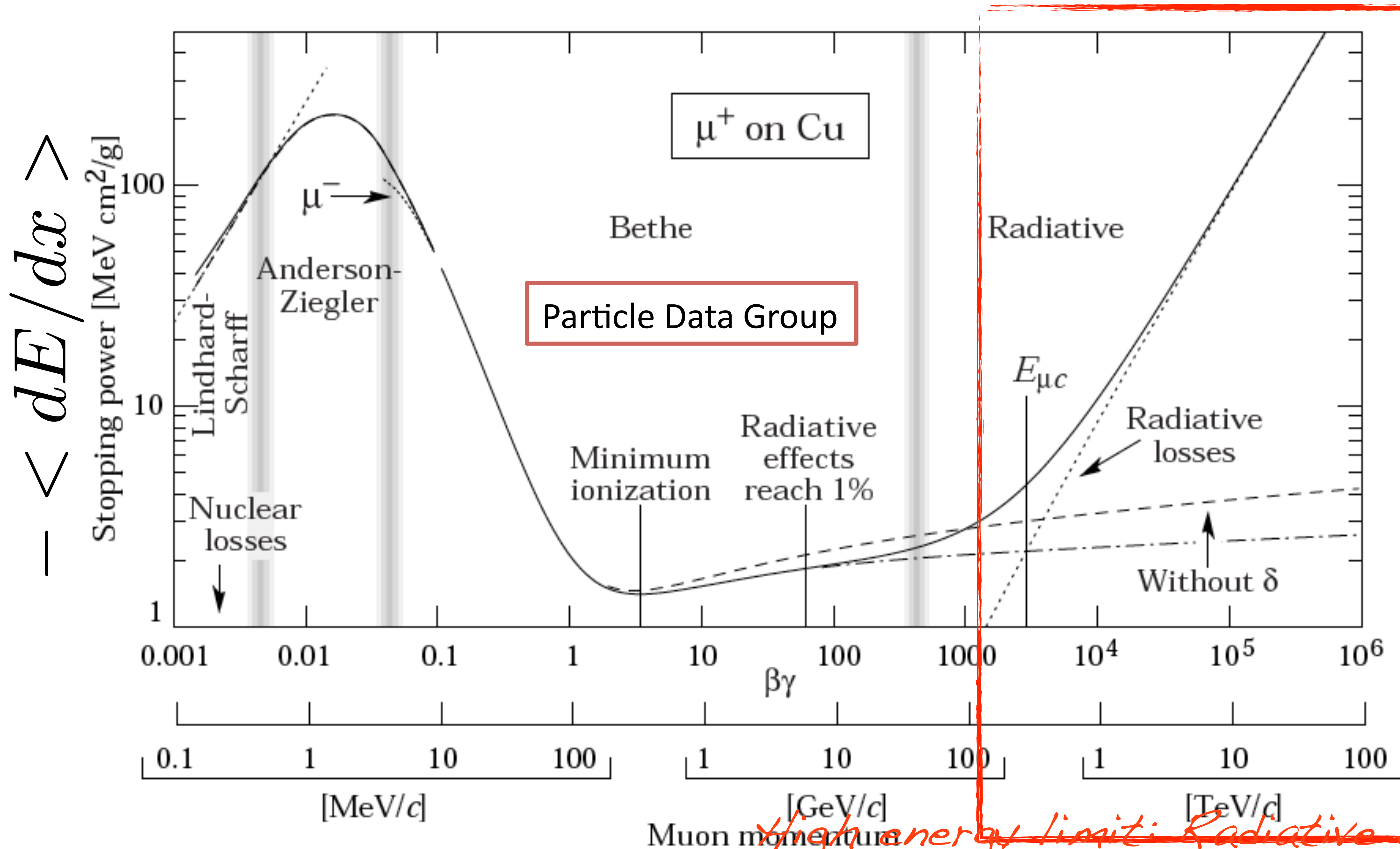
jet suppression (quenching)

charm/bottom dynamics

J/ψ & Υ

color-less particles

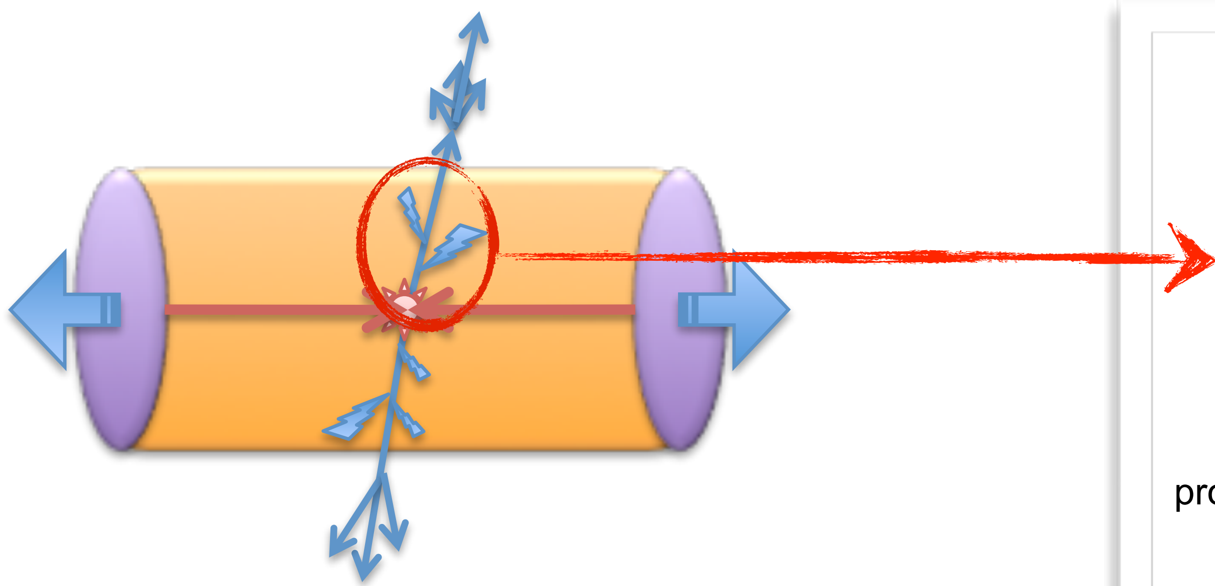
QED: Passage of electrically charged particle through matter

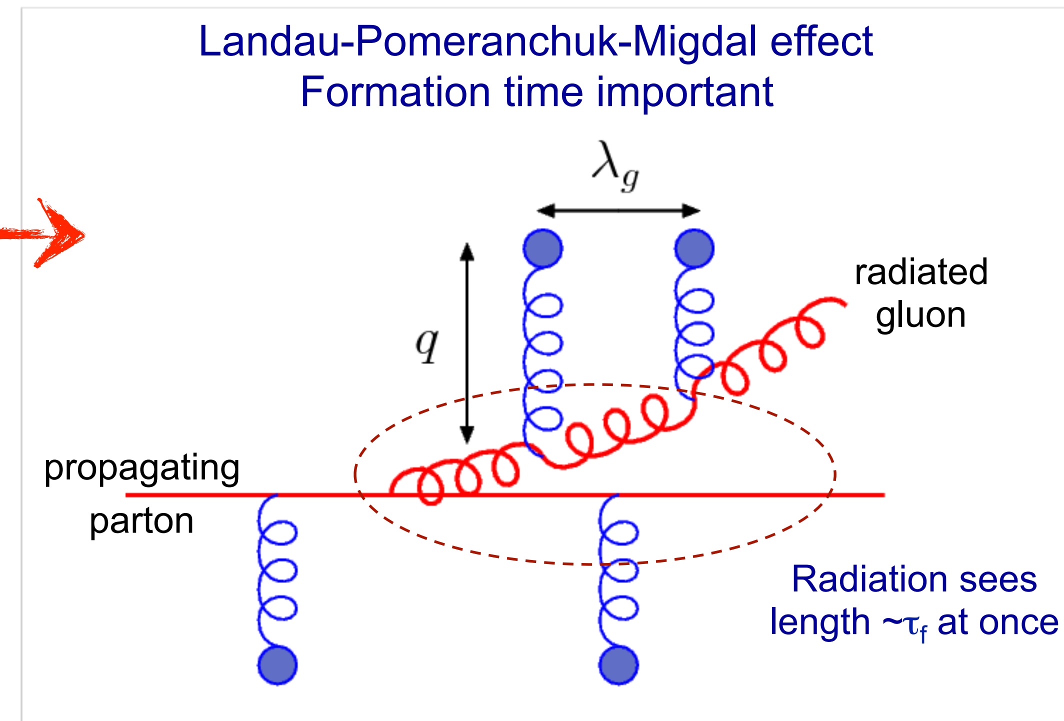


High energy limit: Radiative energy loss

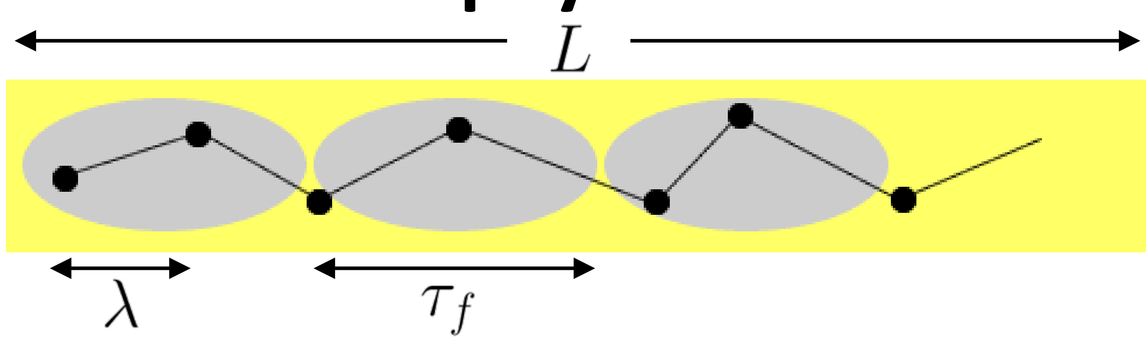
What is the equivalent in QCD?

Bremsstrahlung in QCD: Formation time -> coherence effects





Formation time physics

- 

$\tau_f \sim \frac{2\omega}{k_\perp^2}$ $\quad q \to qg$

  - $\tau_f < \lambda < L$ Incoherent multiple collisions
  - $\lambda < \tau_f < L$ LPM effect (radiation suppressed by multiple scatterings within one coherence length)
  - $\lambda < L < \tau_f$ Factorization limit (acts as one single scatterer)

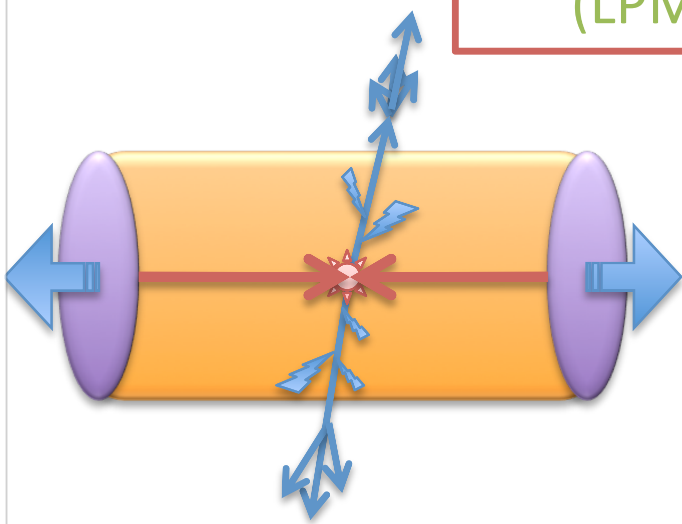
Bremsstrahlung in QCD

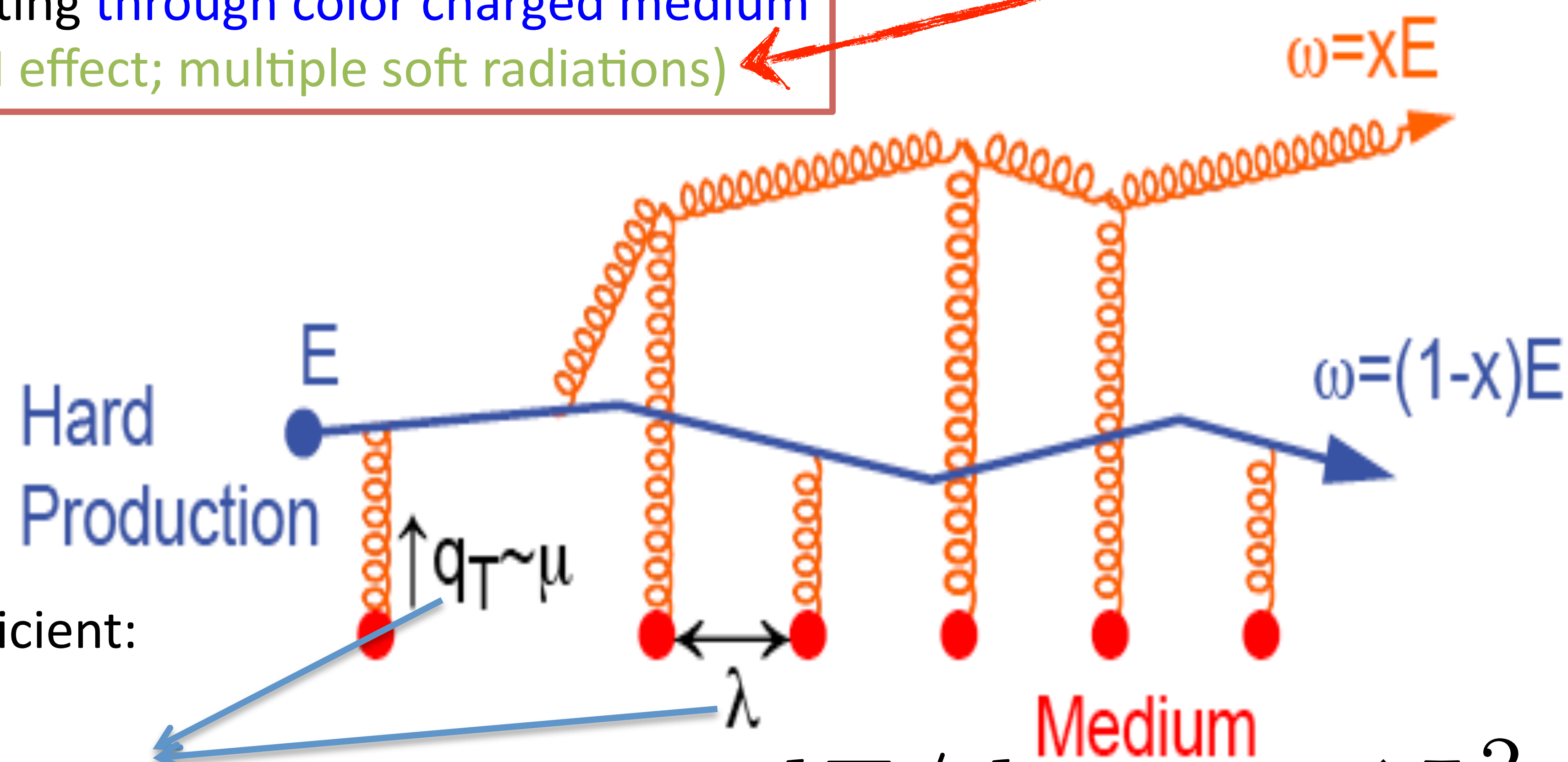
$q \to qg \quad \tau_{form} = 2\omega/k_T^2$

$\lambda < \tau$: multiple scatterings add coherently

$t_{formation} < L \Leftrightarrow \omega < \omega_c$

High energy **color charged probe**
propagating **through color charged medium**
(LPM effect; multiple soft radiations)





Define a transport coefficient:

$$\hat{q} \sim \mu^2/\lambda$$

$$-dE/dx \sim \alpha_s \hat{q} L^2$$

Partonic energy loss in QCD medium is proportional:

- to squared average path length (Note: QED ~ linear)
- to density of the medium

$$\lambda \propto \frac{1}{\rho}$$

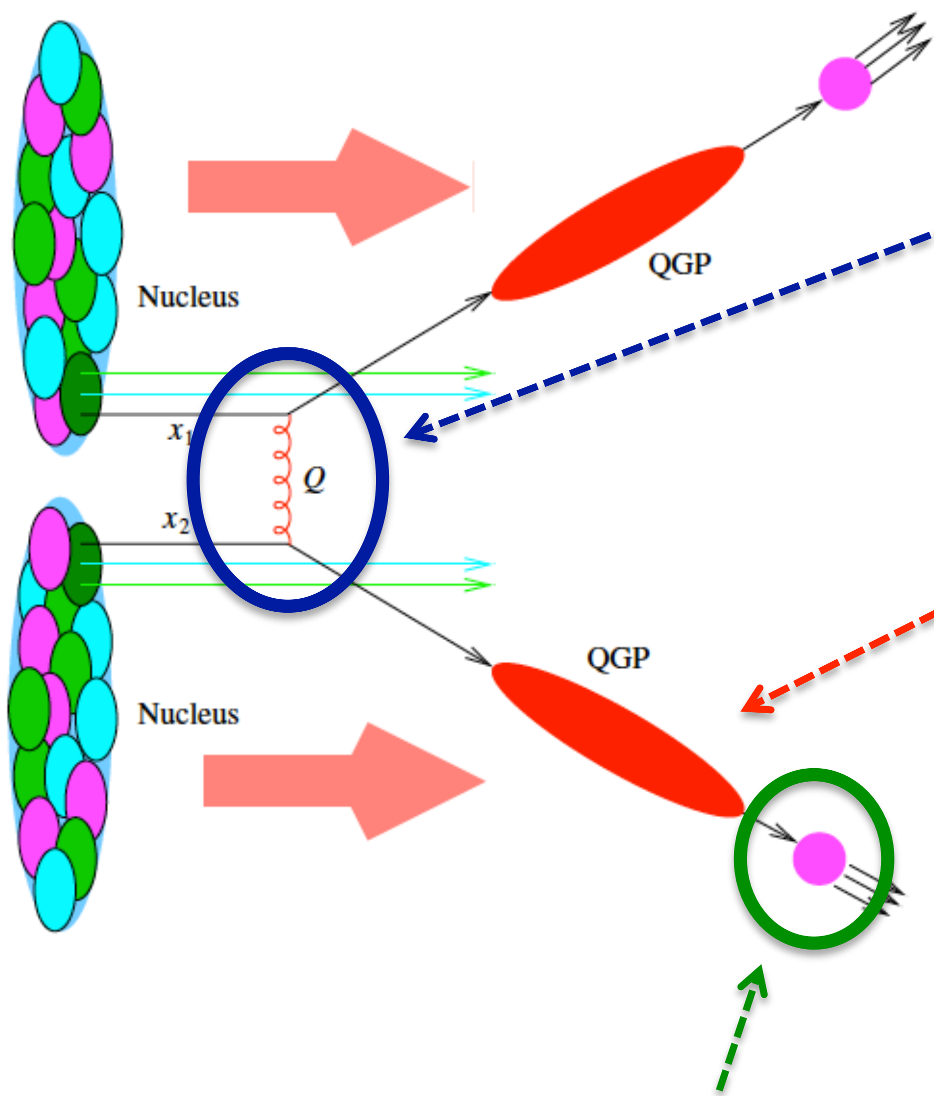
⇒ **energy flow (parton+radiation) modified as compared to jet in vacuum**

⇒ **jet “quenched” (“softened” fragmentation)**

Jets in heavy-ion collisions – an idealization

=> Factorized picture.

$$\sigma \propto f_a^{PDF} \otimes f_b^{PDF} \otimes \sigma^{hard}$$



production vertex: high Q^2

➔pQCD

Propagation in strongly coupled Quark Gluon Plasma

➔pQCD-based jet quenching

➔hydrodynamics

➔AdS/CFT

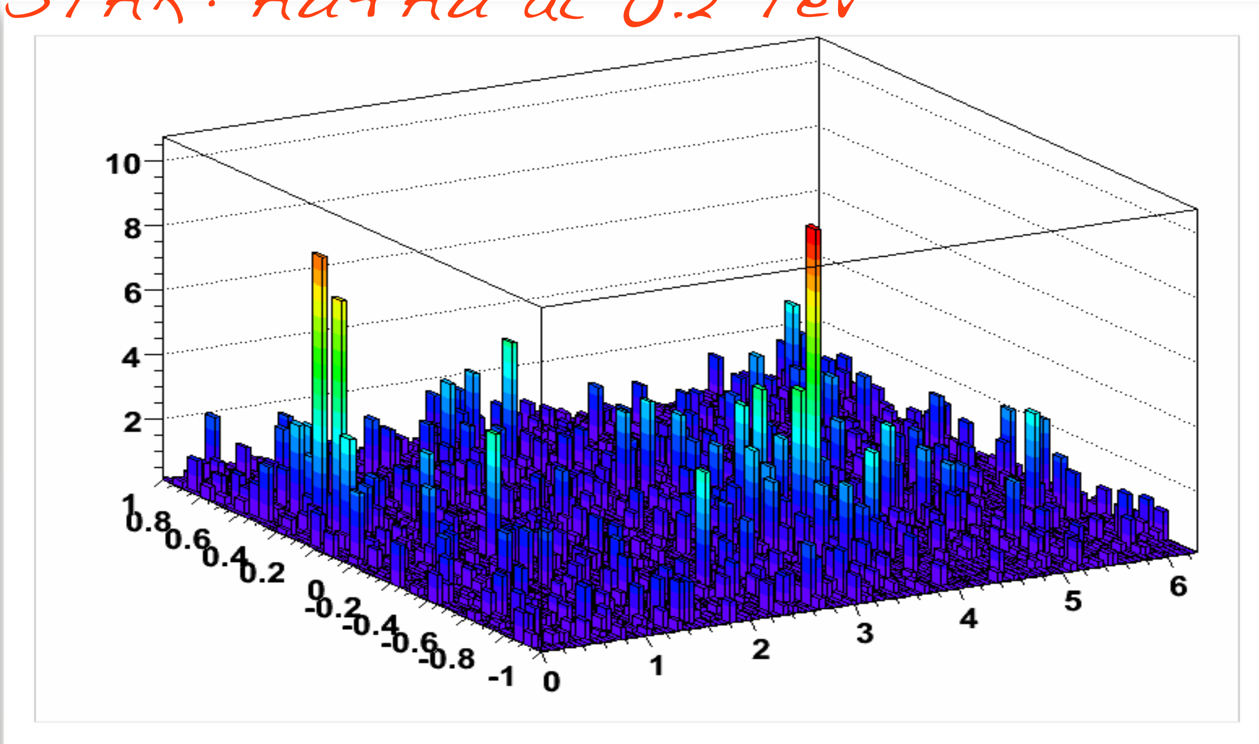
➔...

Vacuum fragmentation into hadrons

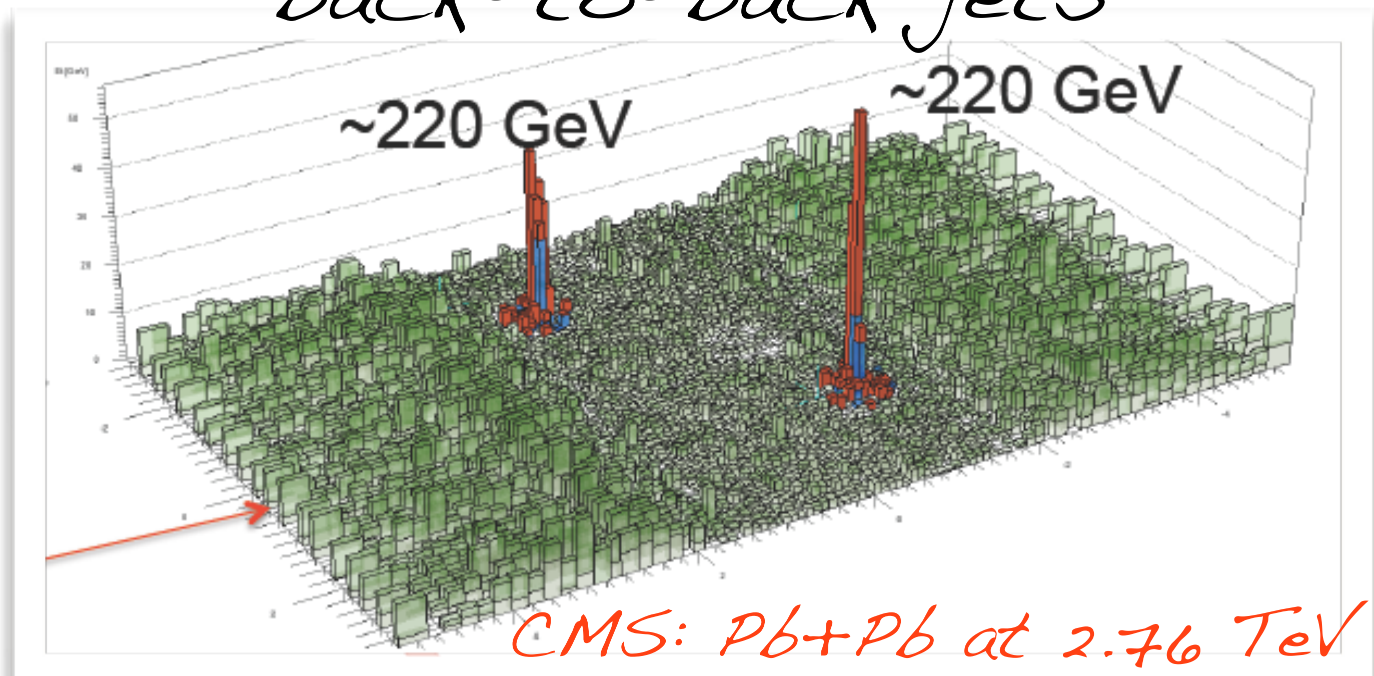
➔non-pert. QCD

Jets in heavy-ion collisions RHIC & LHC

STAR: Au+Au at 0.2 TeV



back-to-back jets



CMS: Pb+Pb at 2.76 TeV

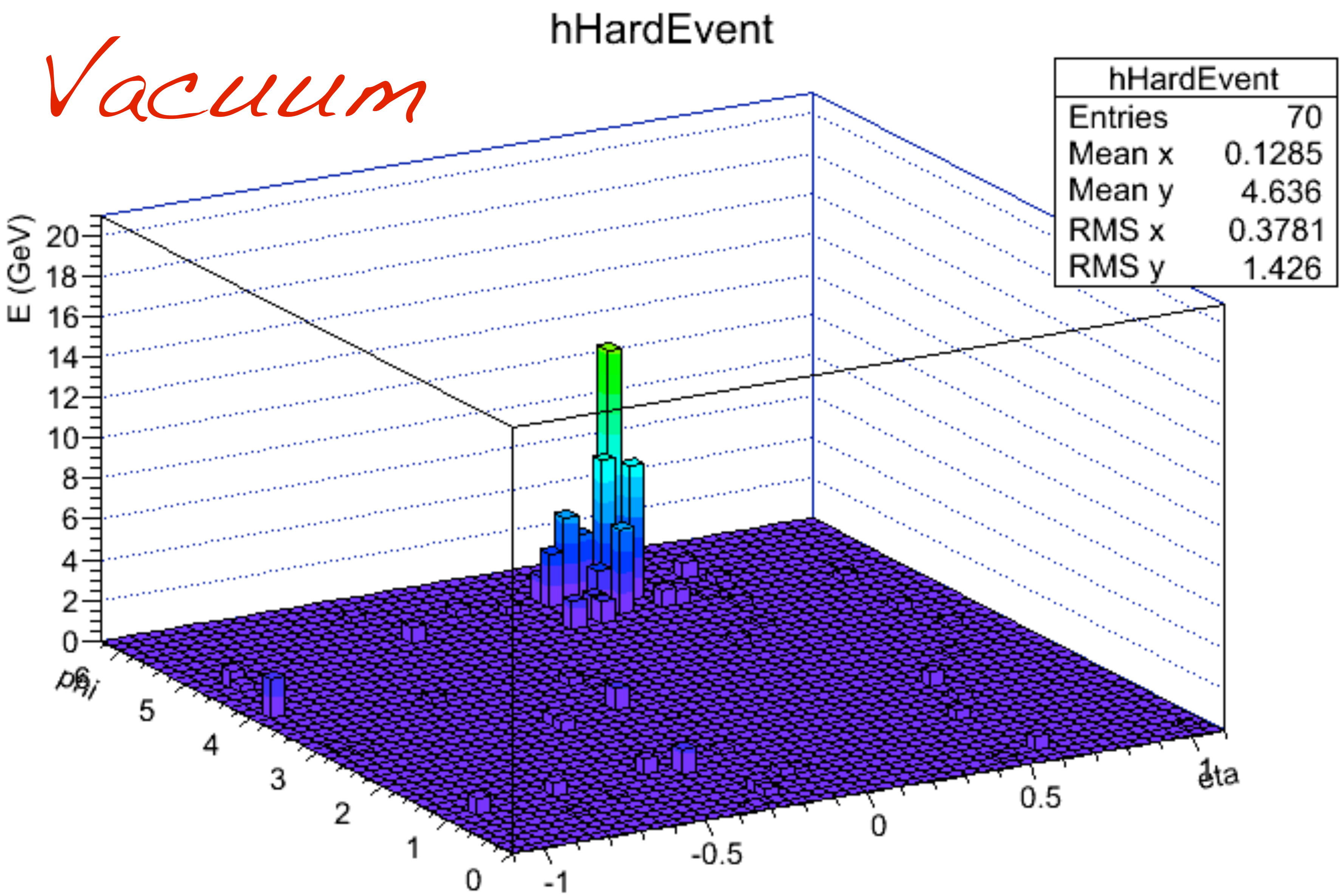
LHC + RHIC: QCD evolution of jet quenching ?

Vary energy of the jet:

- LHC: Vary the scale with which QGP is probed (a la DIS)
- Compare and contrast RHIC and LHC

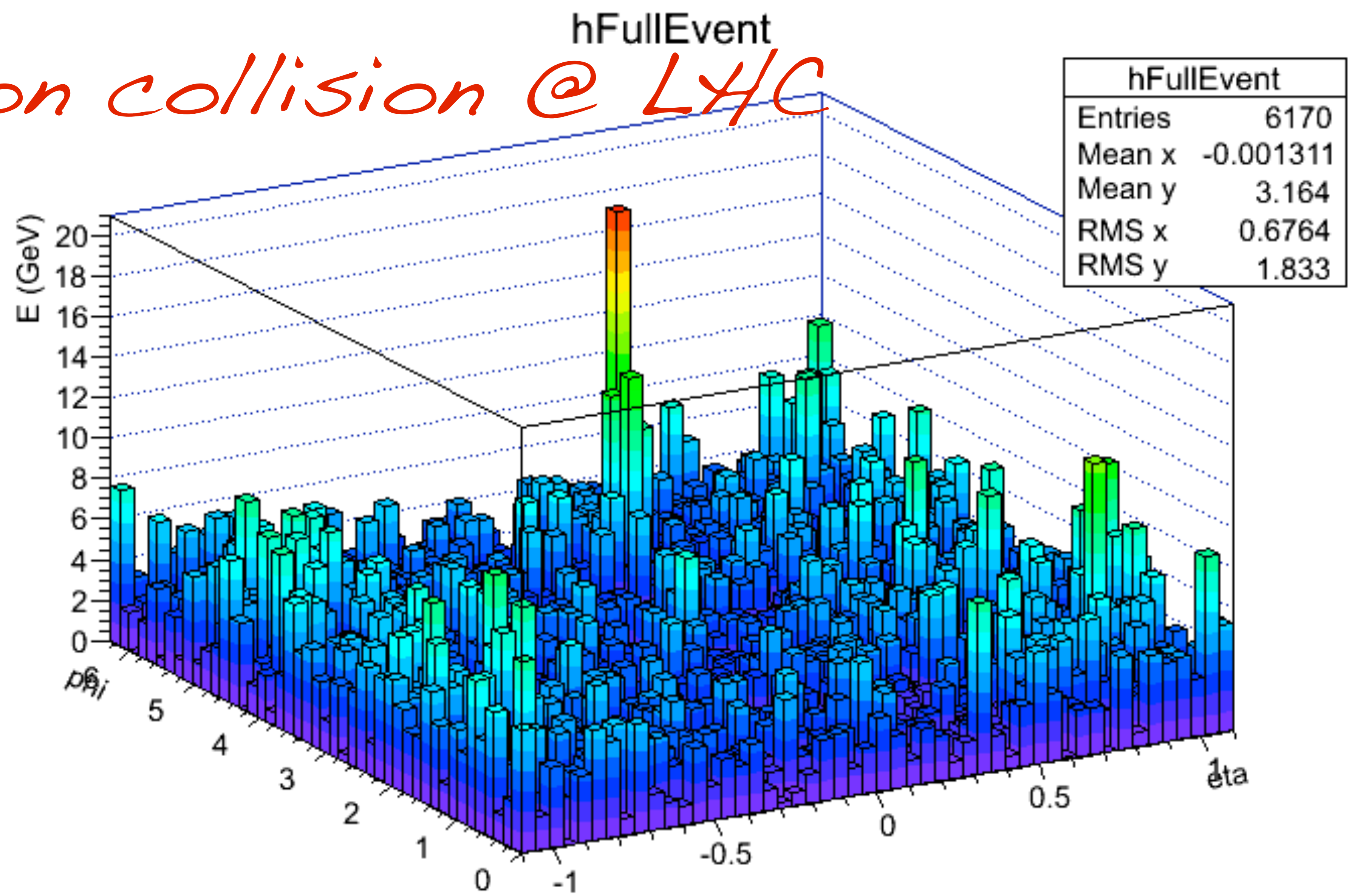
Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

Vacuum

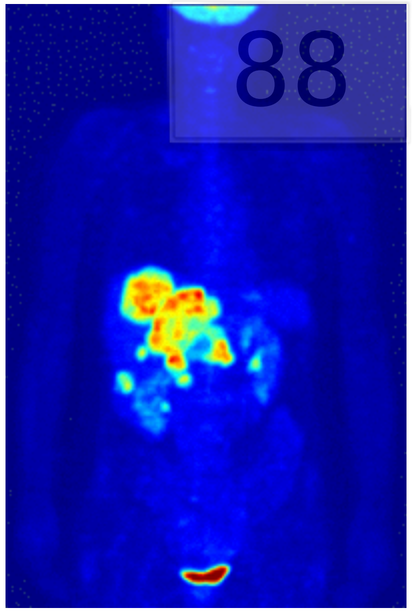


Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

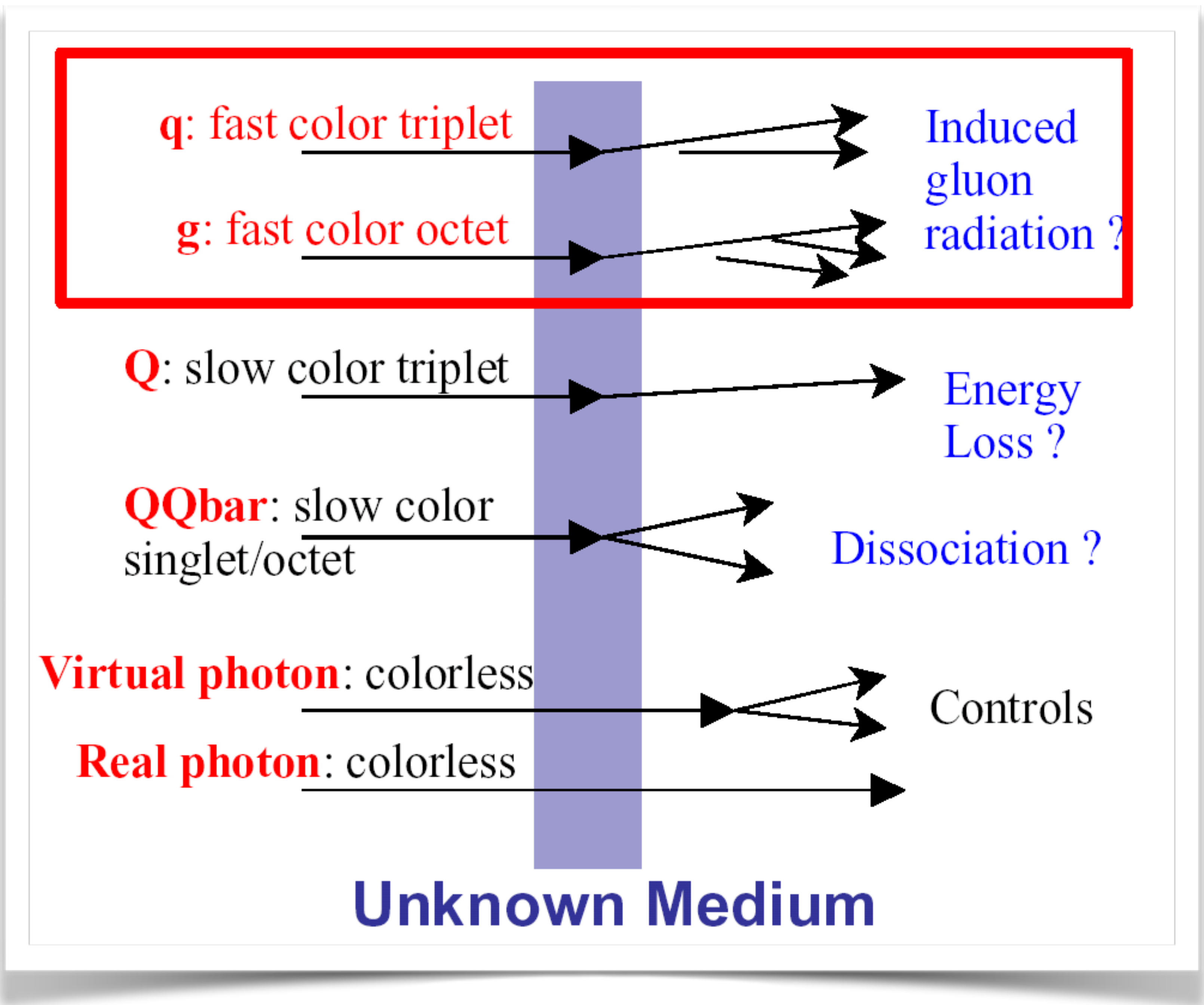
Heavy-ion collision @ LHC



Probing the unknown medium…



Human body



jet suppression (quenching)

charm/bottom dynamics

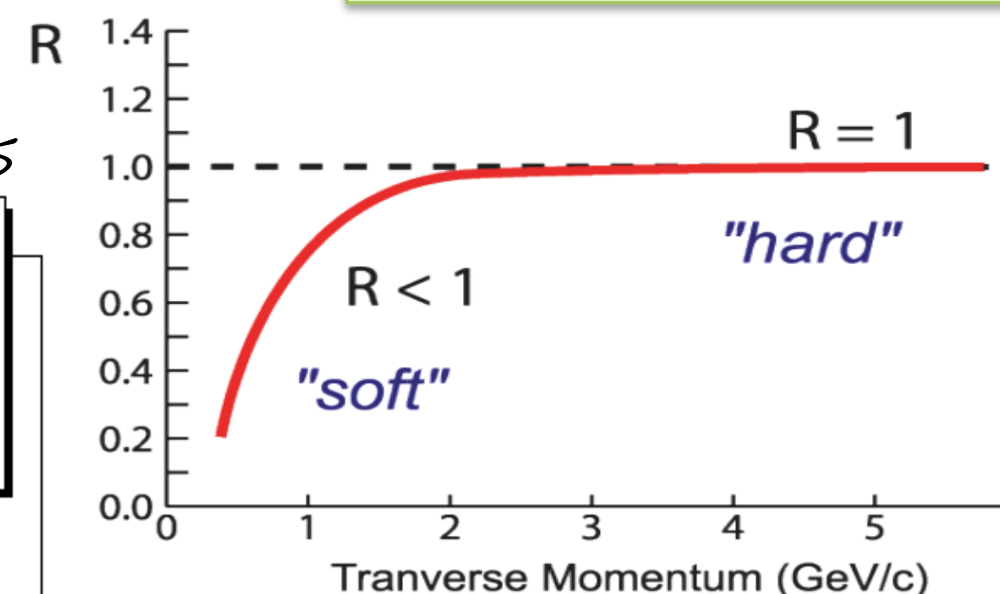
J/ψ & Υ

color-less particles

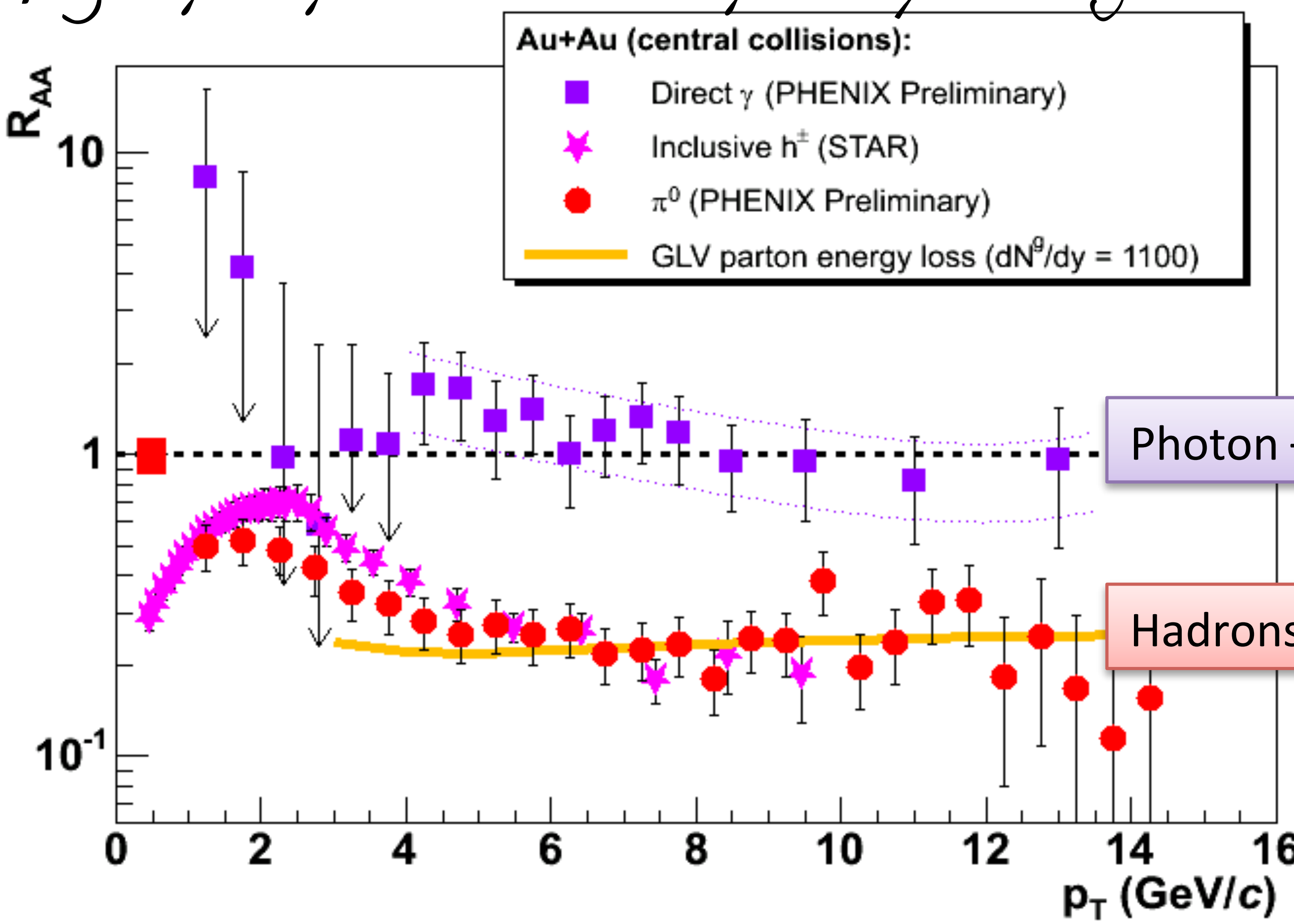
Jet quenching - RHIC

$$\text{Ratio} = \frac{\#(\text{particles observed in AA collision per binary collision})}{\#(\text{particles observed per p-p collision})}$$

No "effect":
R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate



High-pT particles - proxy for jets

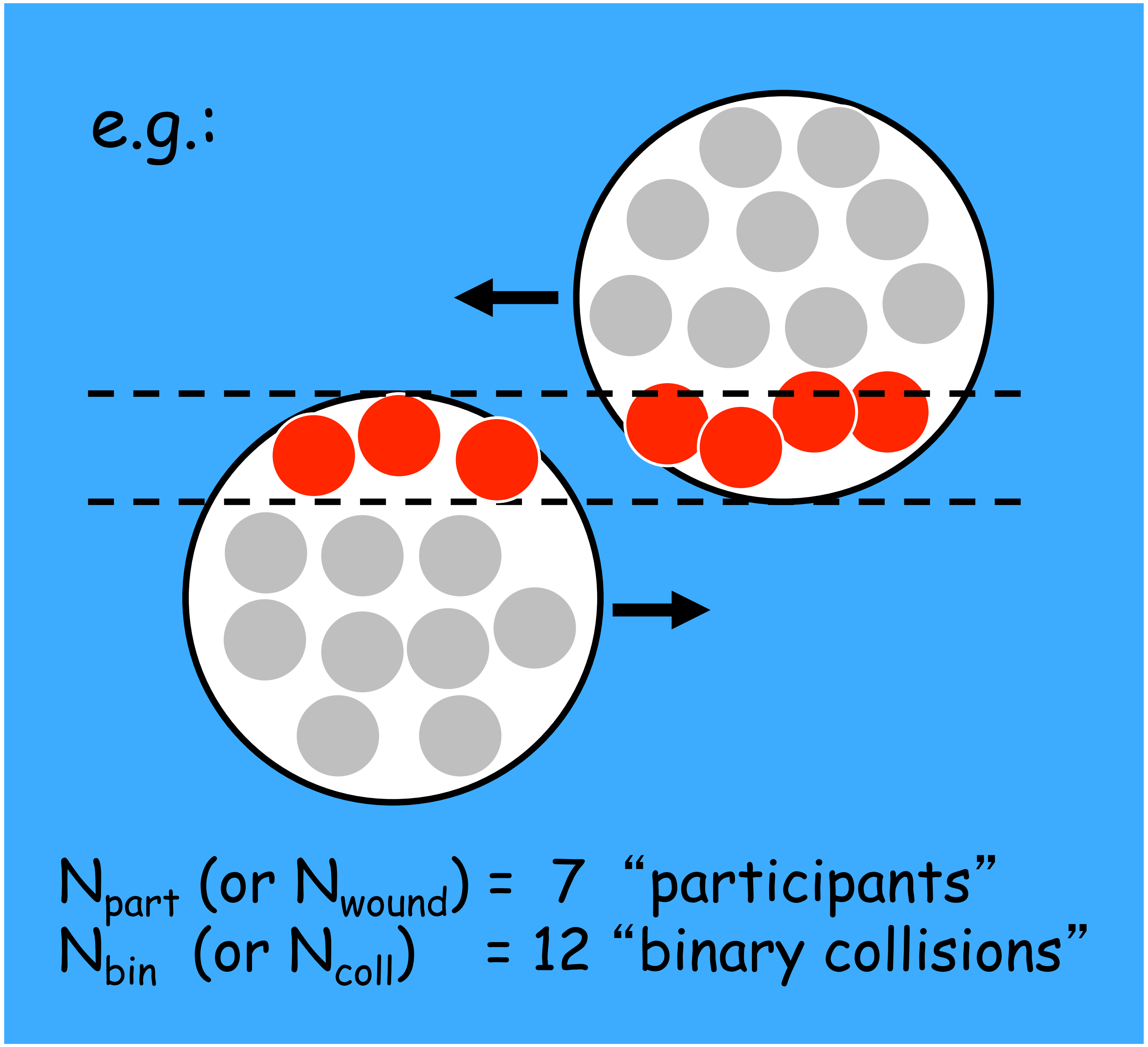


Photon – color neutral probe => No suppresion

Hadrons from color charged jets => Suppression

Reminder...

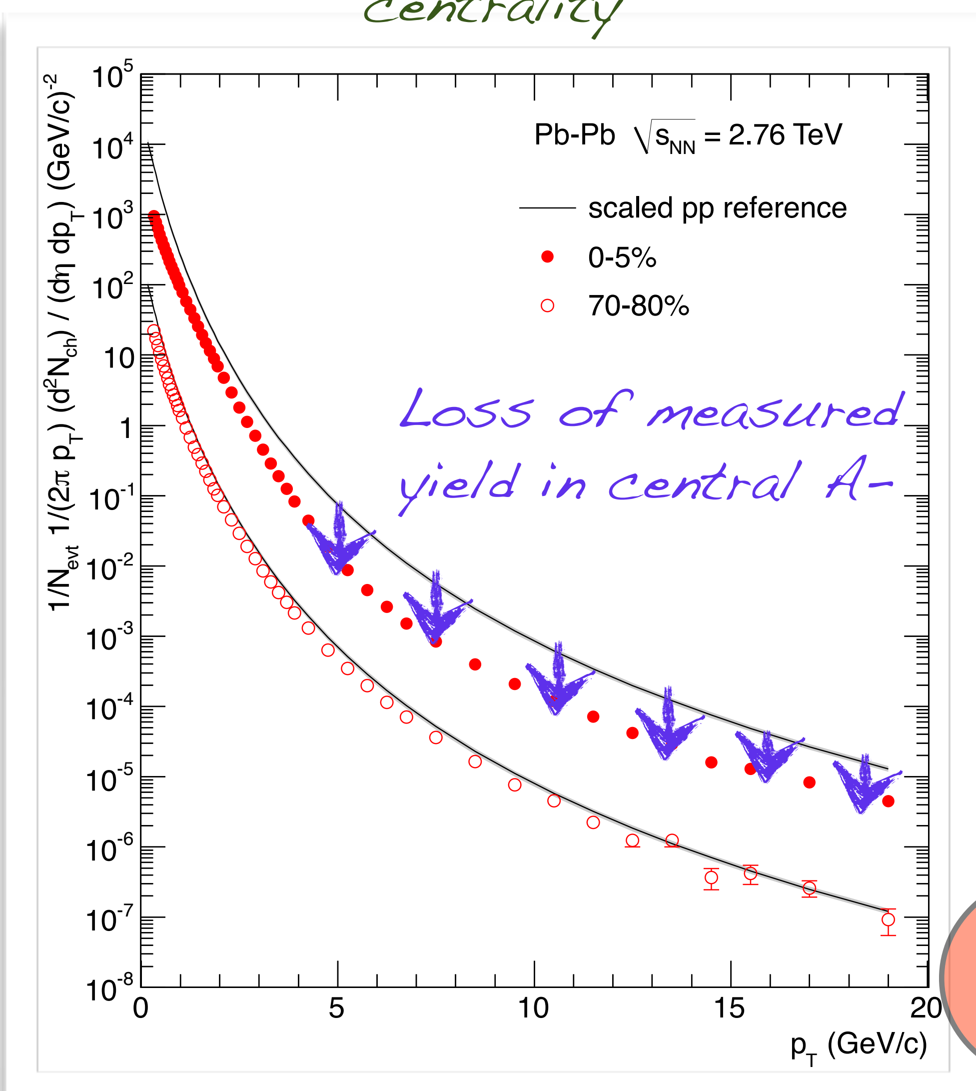
"Soft", large cross-section processes expected to scale with N_{part}
"Hard", low cross-section processes expected to scale with N_{bin}

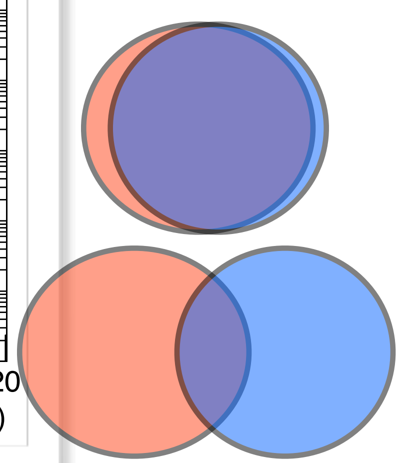


"Easier" (than full jet reconstruction) exercise: Jet-quenching via leading hadrons

Inclusive hadron production

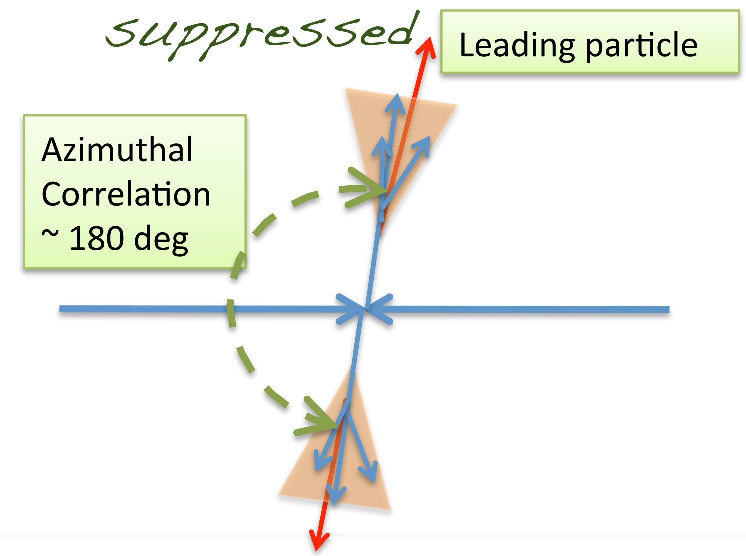
Measured as a function of collision centrality

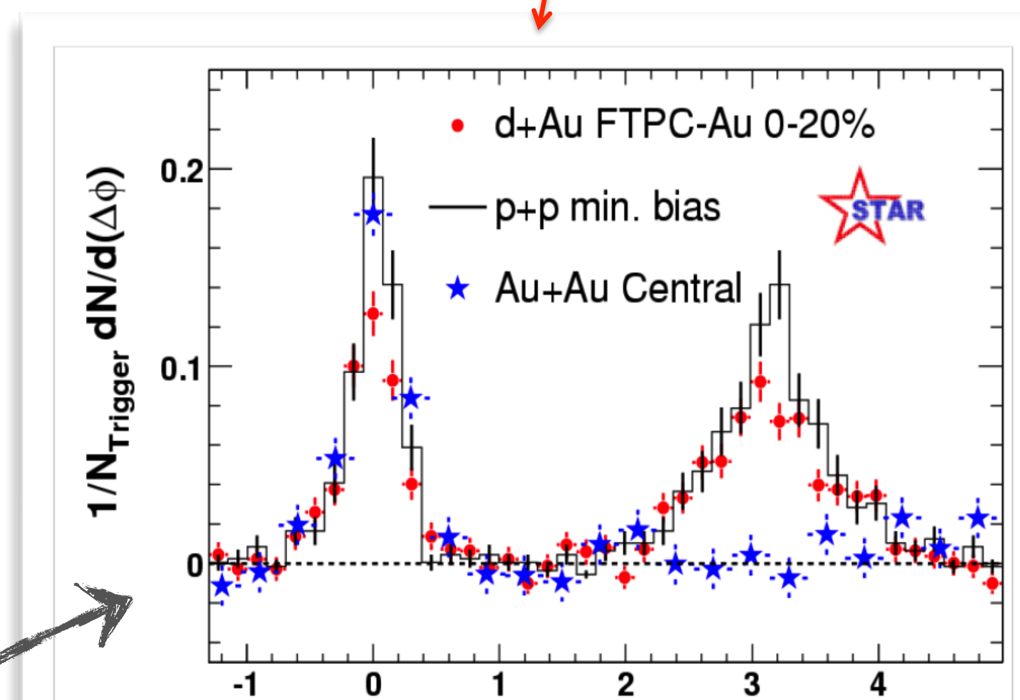




Di-hadron correlations

Rates of recoil ("away-side") hadrons suppressed





Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

Note on correlations: interesting tool to study the "intermediate"-p_T region - jets vs flow and recombination

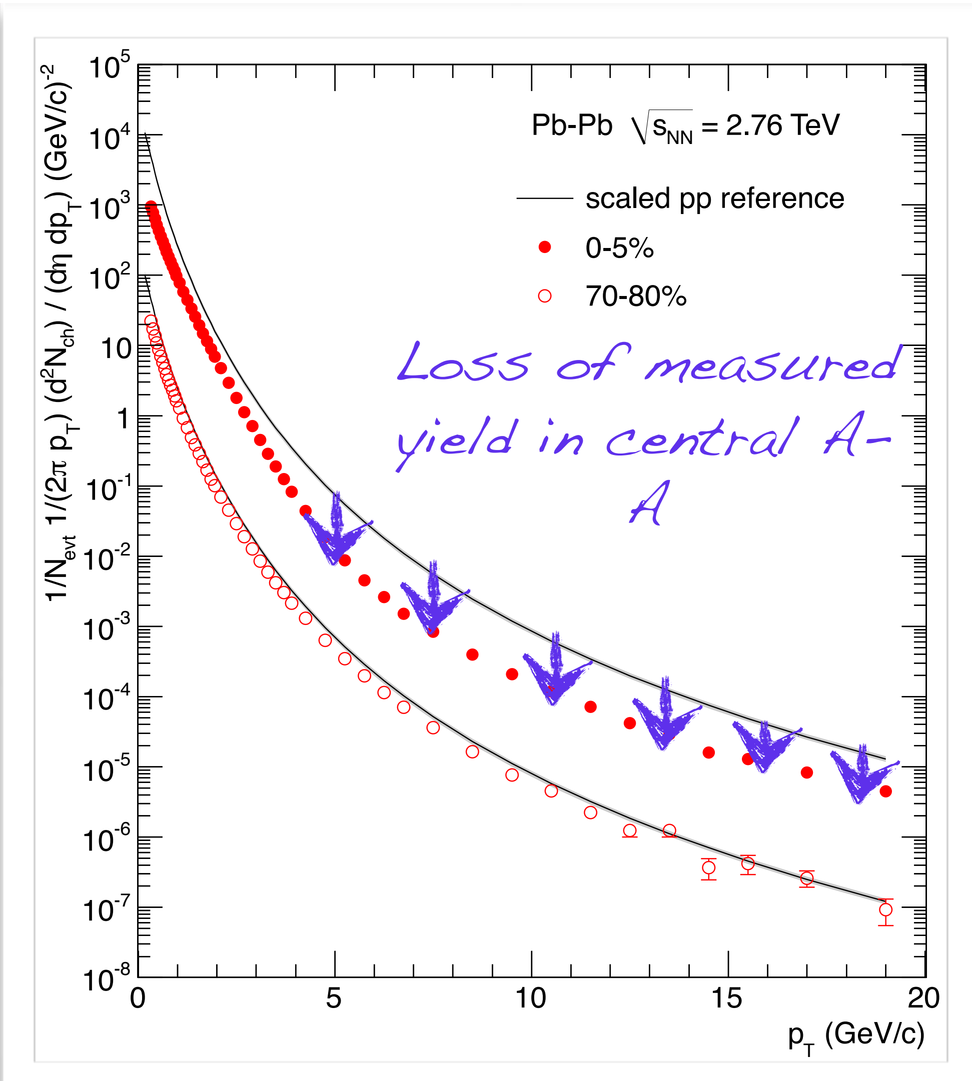
$$R_{AB} = \frac{d^2N/dp_t d\eta}{T_{AB} d^2\sigma^{pp}/dp_t d_\eta}$$

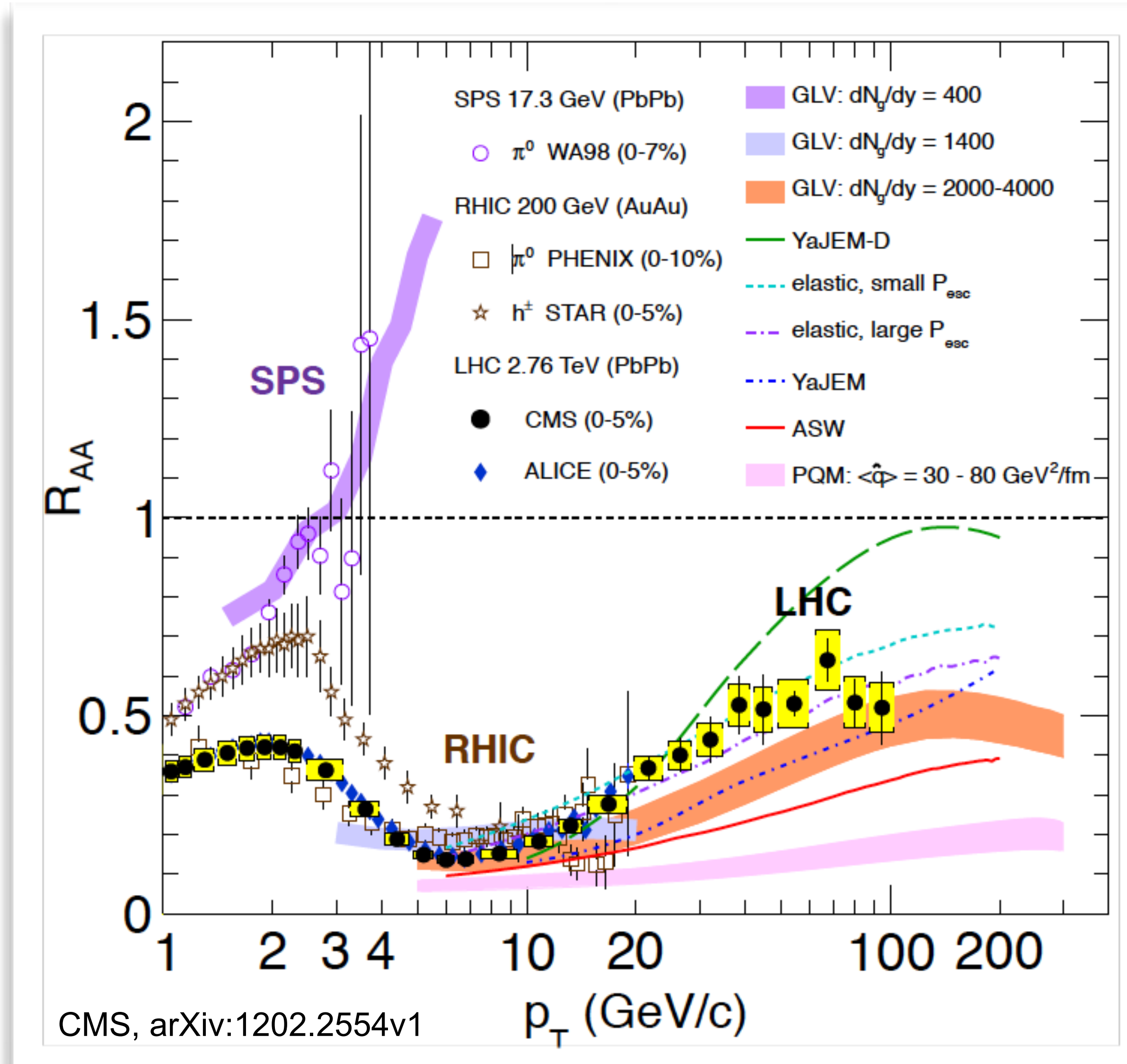
$$T_{AB} = < N_{bin} > / \sigma^{pp}_{inel}$$

Hadron suppression

Nuclear modification factor:

$$R_{AA} = \frac{\#(\text{particles observed in AA collision per N-N (binary) collision})}{\#(\text{particles observed per p-p collision})}$$





"No effect" case is for $R_{AA} = 1$ at high pT where hard processes

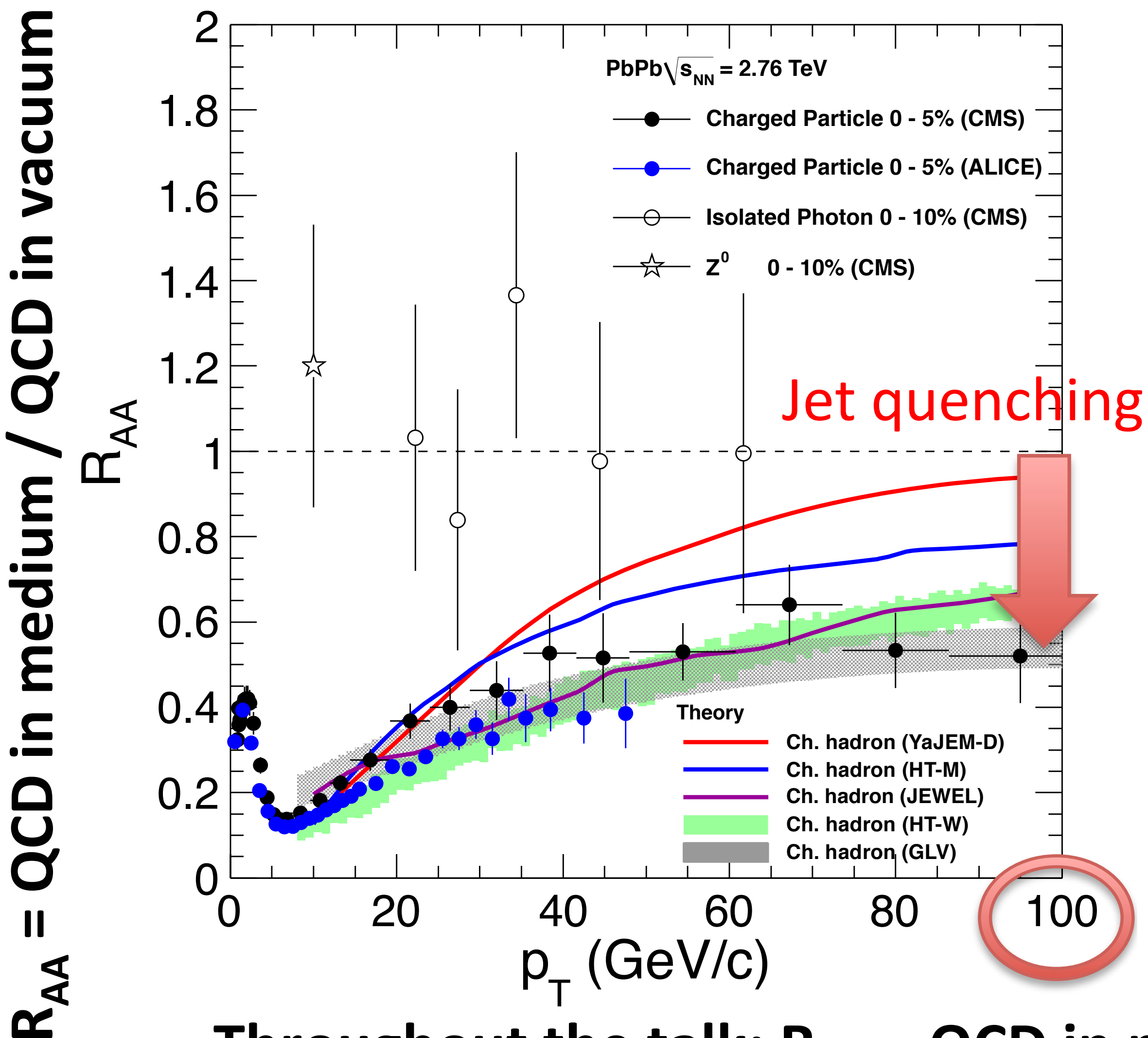
Energy-loss - QGP state effect

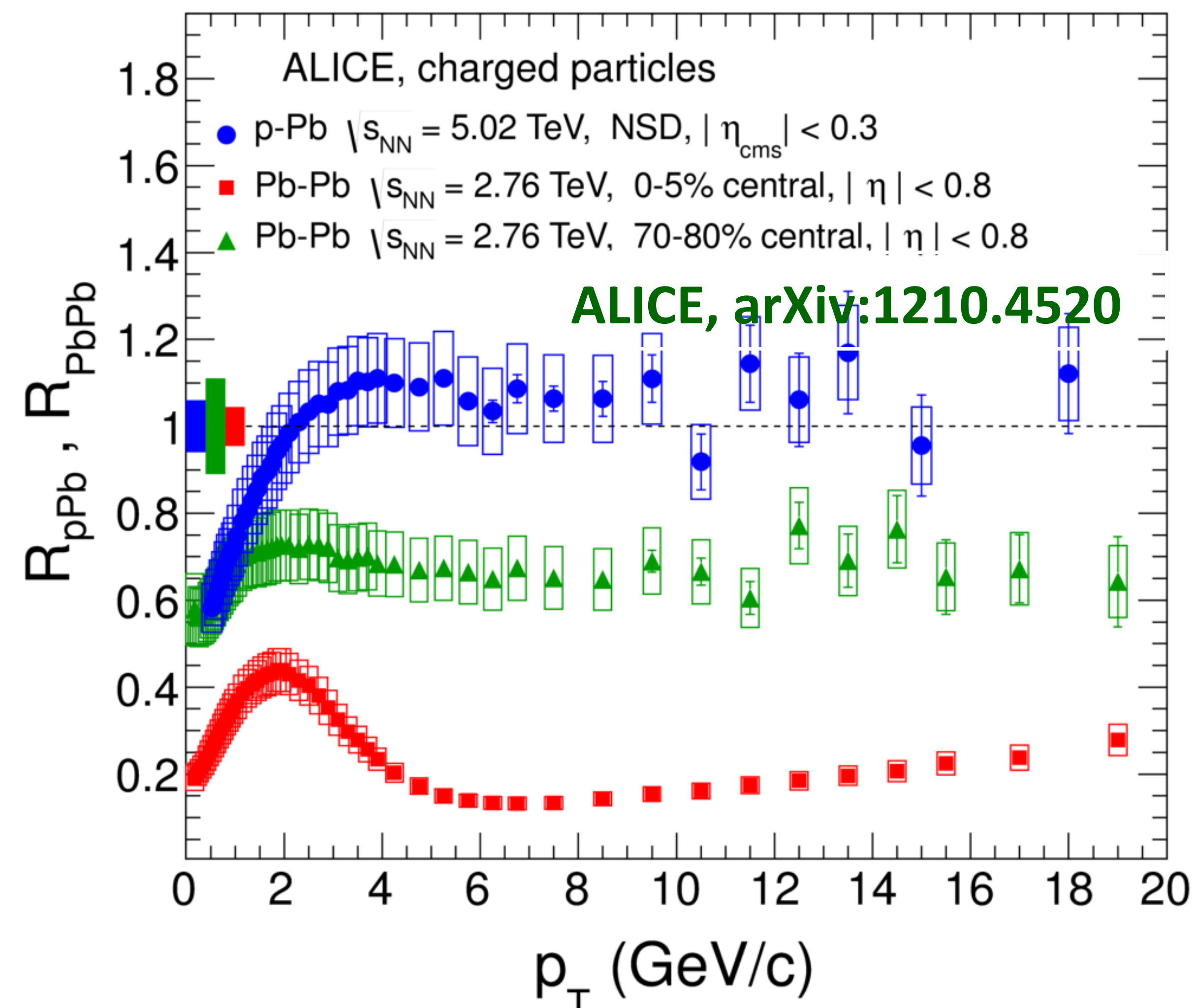
Color charged probes suppressed

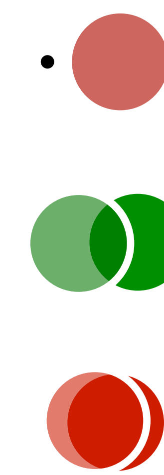
Color neutral probe production scales with Nbin collisions

pA collisions: suppression is an effect of QGP

$$R_{AA} = \frac{1}{< N_{\rm coll} >} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$





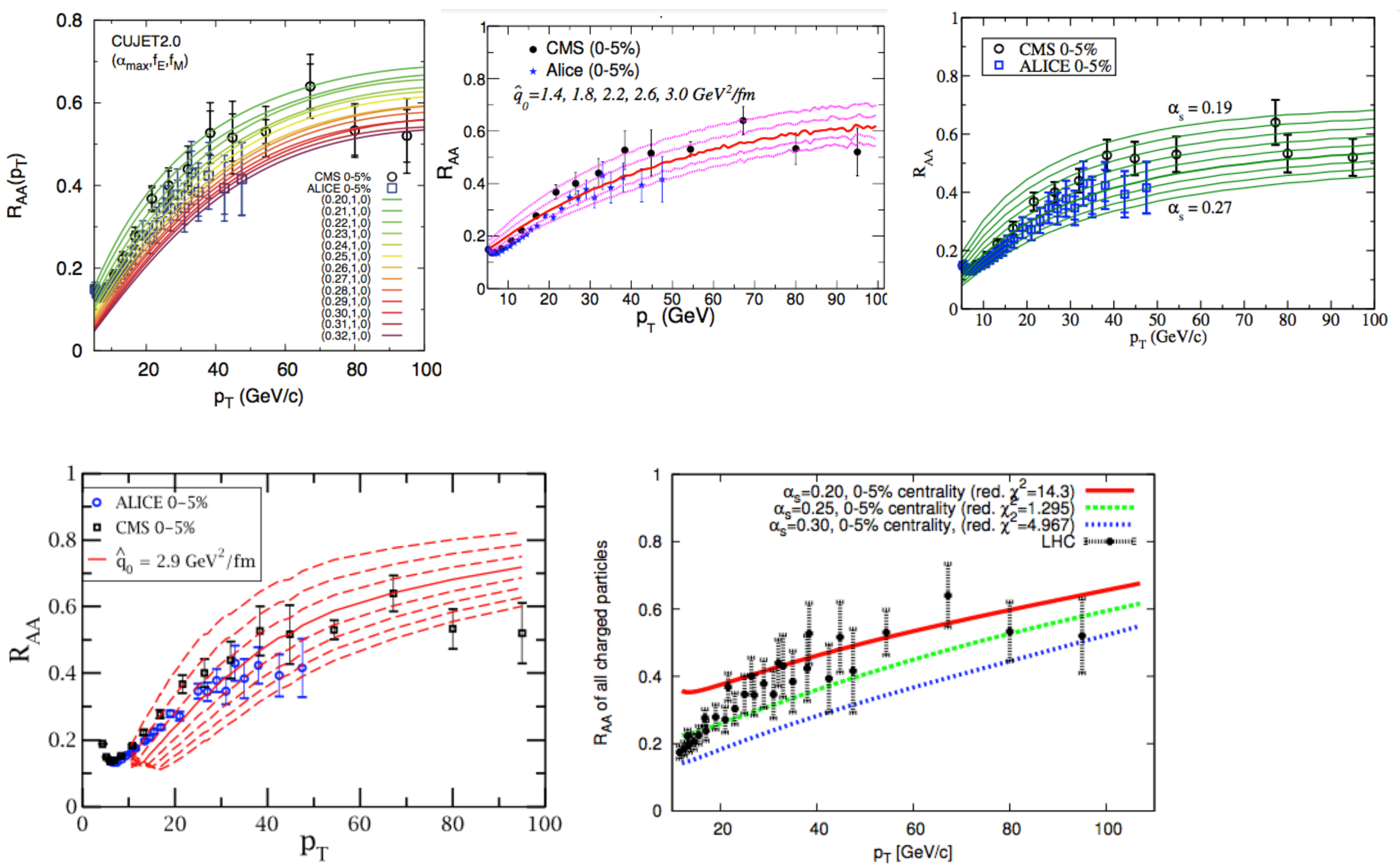


Throughout the talk: R_{AA} = QCD in medium / QCD in vacuum

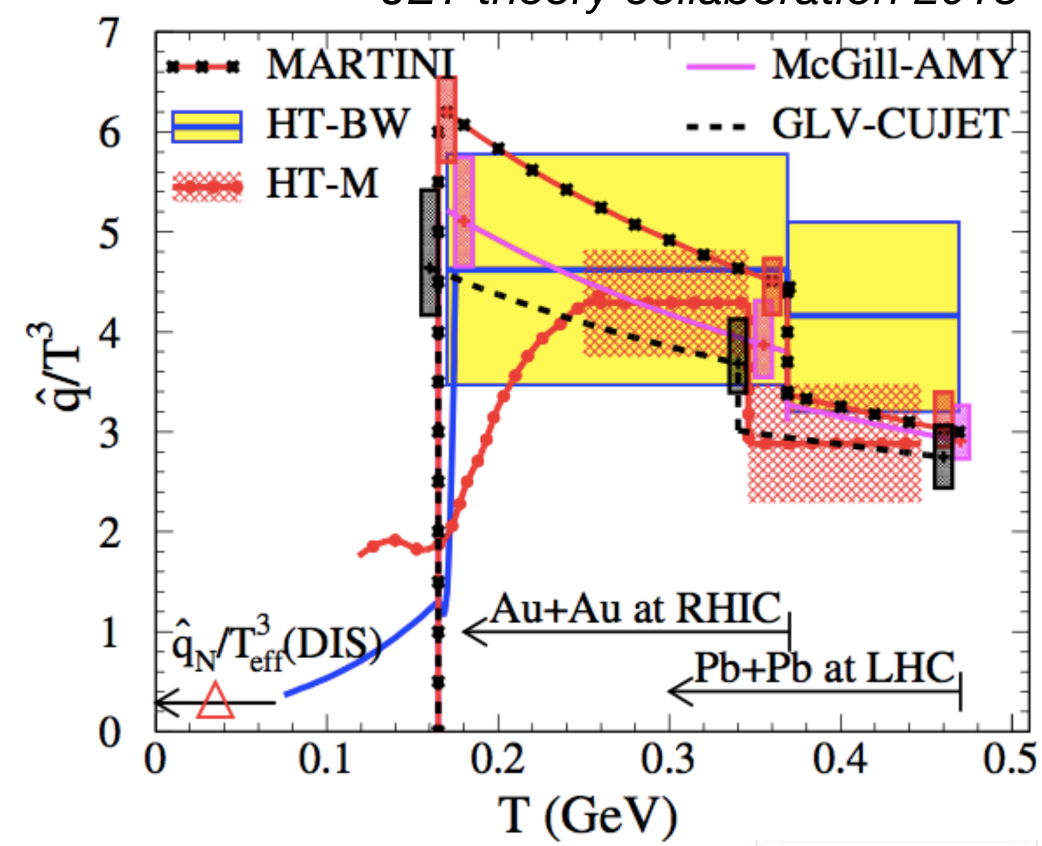
Note: only colored probes quenched; pA: jet quenching is a in-medium effect

Extraction of QGP transport coefficients

$$-dE/dx \sim \alpha_s \hat{q} L^2$$



JET theory collaboration 2013



$$\hat{q} \sim \mu^2/\lambda$$

$$\lambda \propto \frac{1}{\rho}$$

Systematic data-model(s) study

=> extract transport coefficient

Use of RHIC & LHC data

Temperature dependence (?)

$$\text{RHIC}: \ \hat{q} \approx 1.2 \pm 0.3 \ \text{GeV}^2/\text{fm}$$

$$\text{LHC}: \ \hat{q} \approx 1.9 \pm 0.7 \ \text{GeV}^2/\text{fm}$$

Cold matter (HERMES DIS) : $\hat{q} \approx 0.02$ GeV^2/fm