
XIV International Workshop
on Hadron Physics
High energy
heavy-ion collisions
- hot QCD in a lab
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Berkeley Lab
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Florianópolis, SC, Brazil

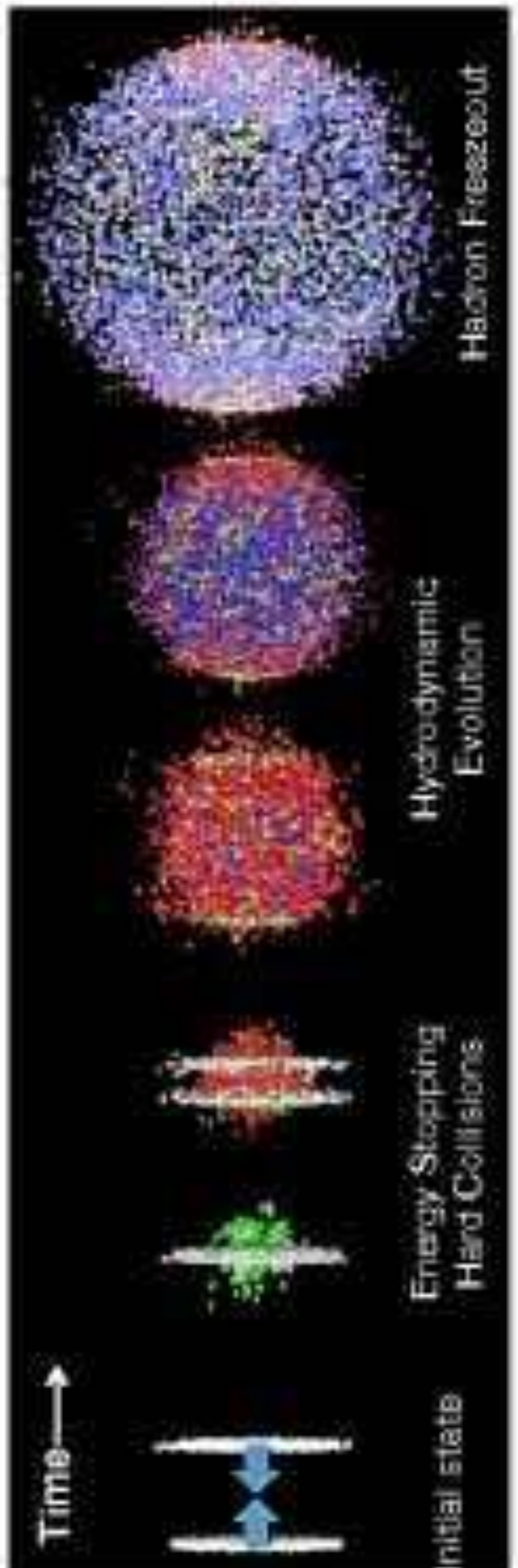
until now...

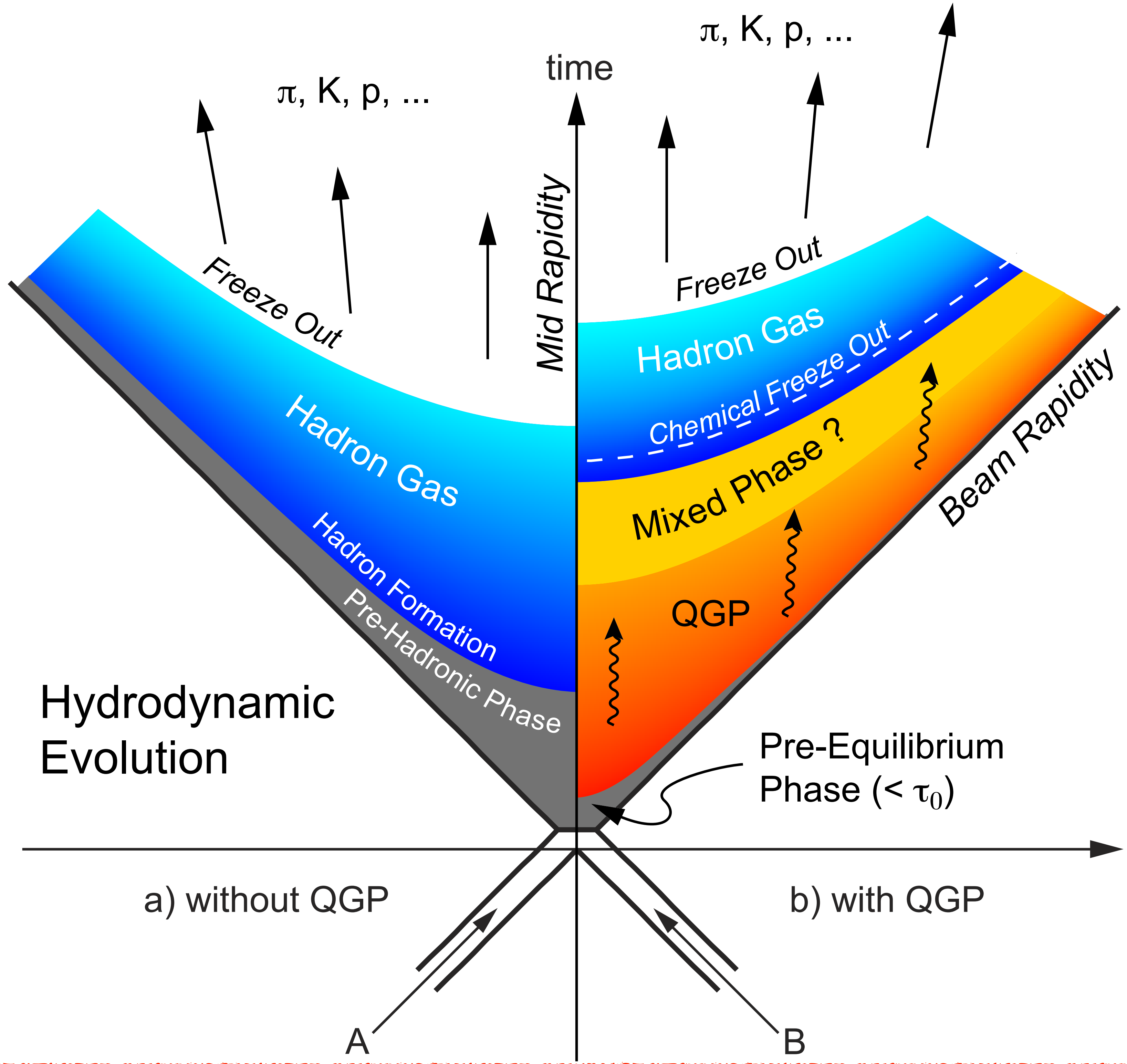
- phases of HI collision
- how to measure centrality of a collision
- ... energy density
- ... temperature
- ... freeze-out volume (and time)
- QGP: hot, short-lived system with rapid dynamical evolution

Today (2/3)

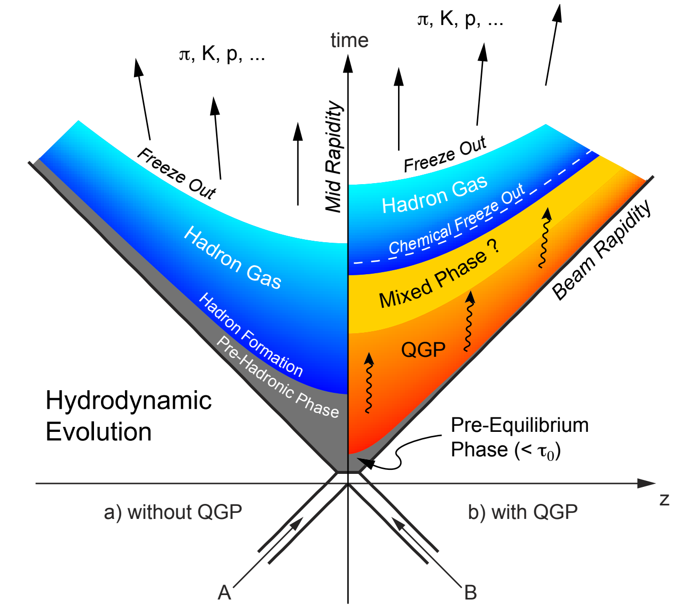
- particle abundance's at hadronization
- QGP properties / transport coefficients:
  - flow
  - jet-medium interactions

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:

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

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

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

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

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Hadron abundances

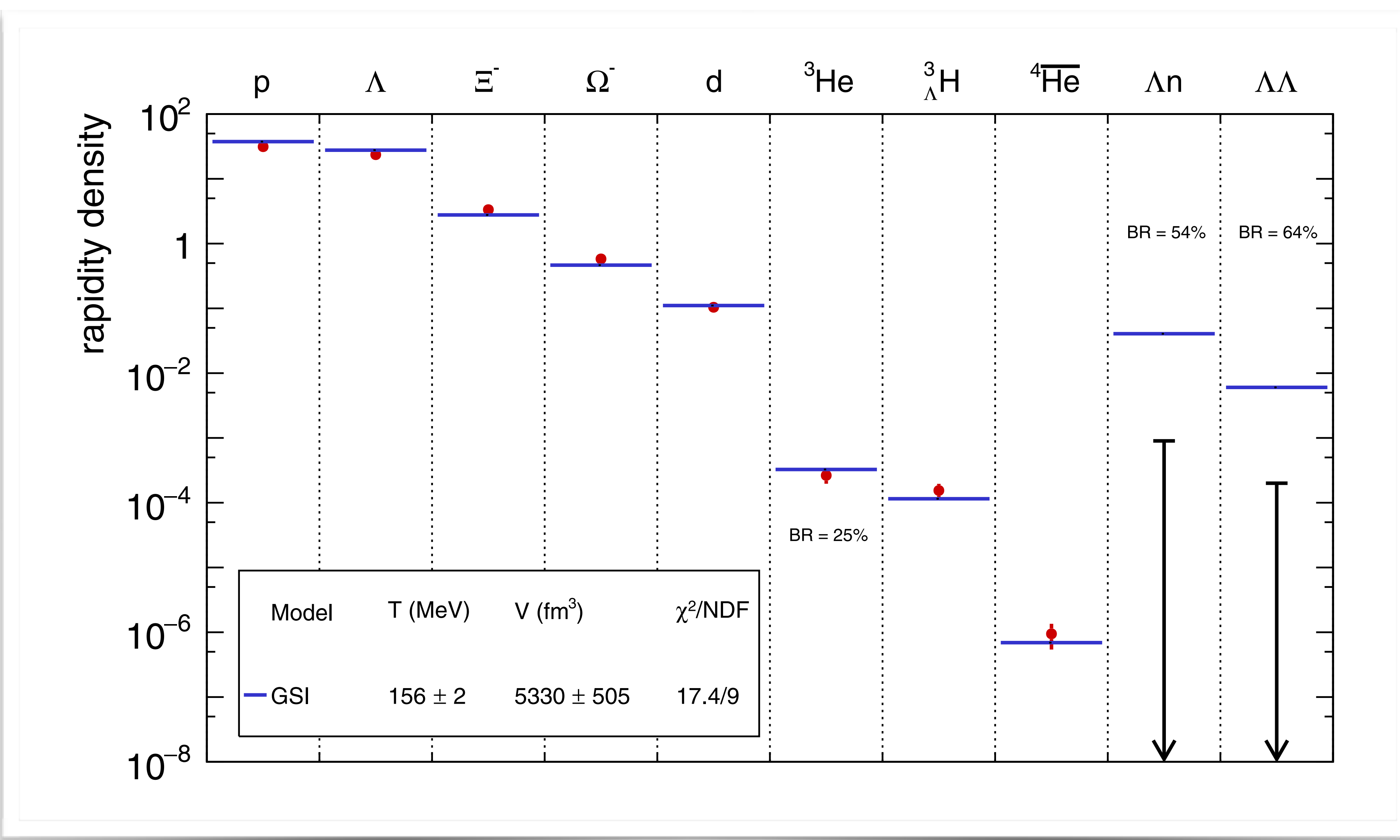
Assumption: Multiplicities are determined by statistical weights (chemical equilibrium)

Grand-canoniacal ensemble:

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

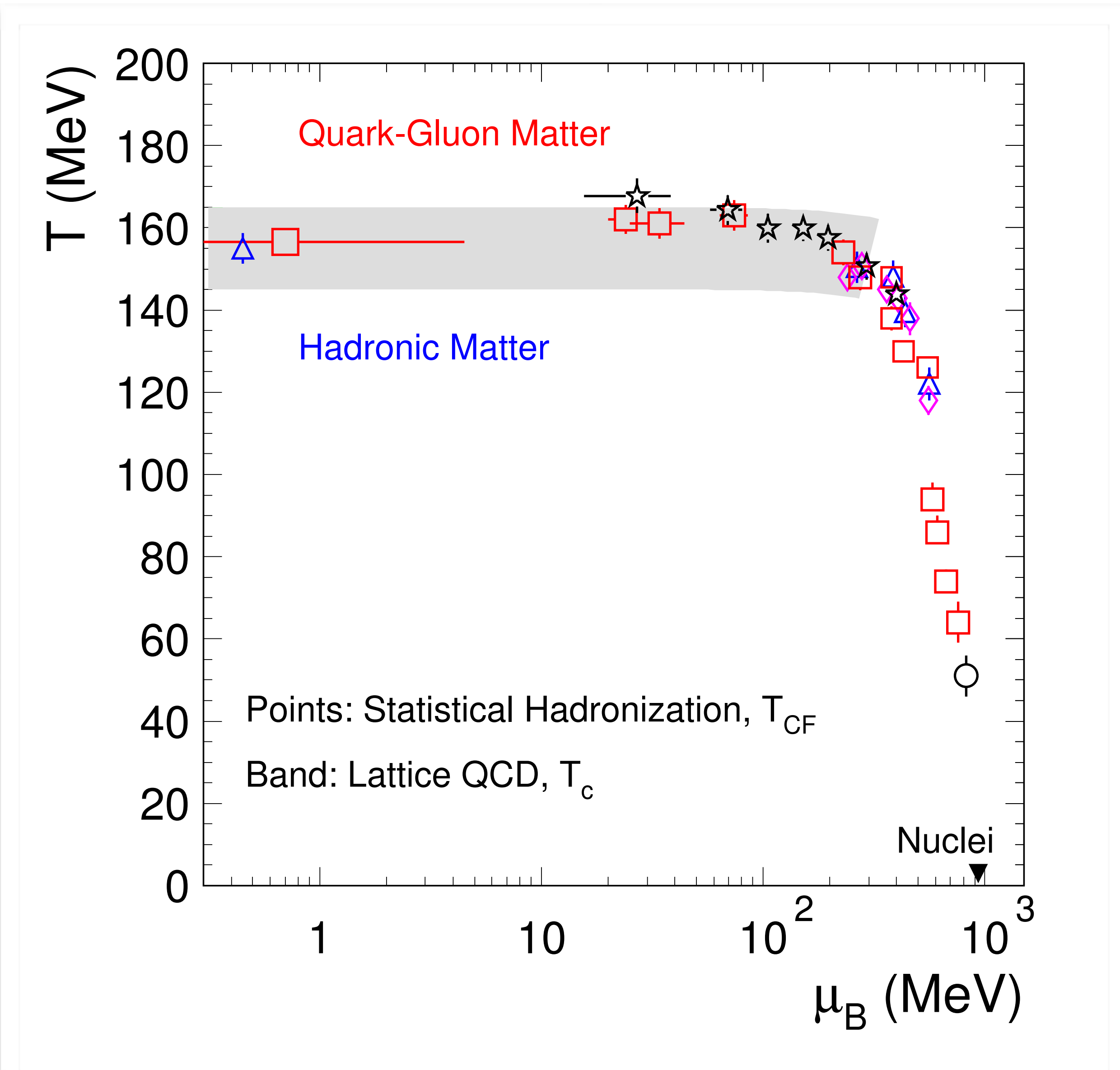
Parameters: V, T, μ_B, (γ_s)

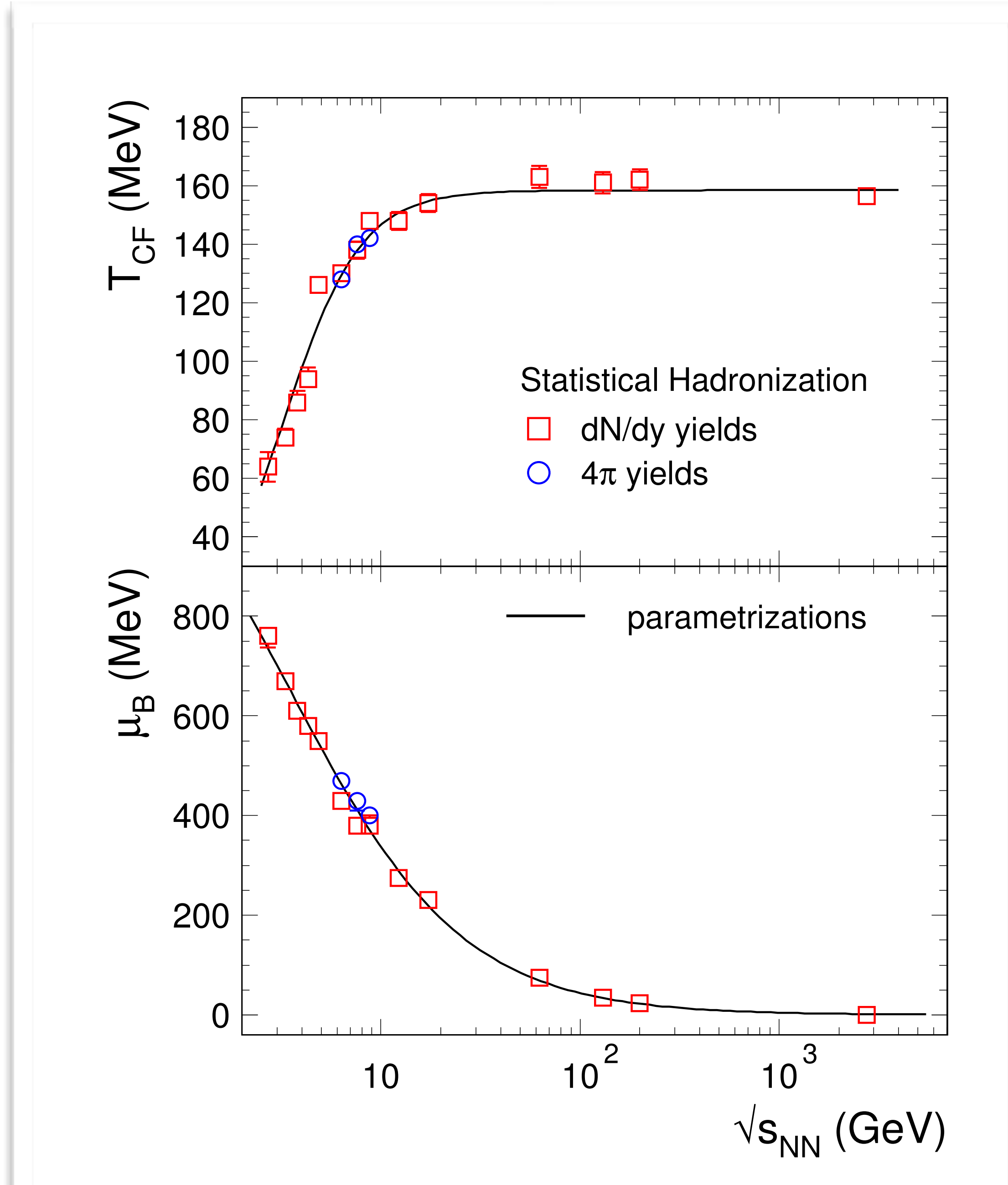
Results in excellent fits to measured multiplicities of hadron for ALL energies (even d, ^{3}He, $^3_\Lambda$He ...) - statistical harmonization of a thermal system...



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

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Chemical and kinetic freeze-out

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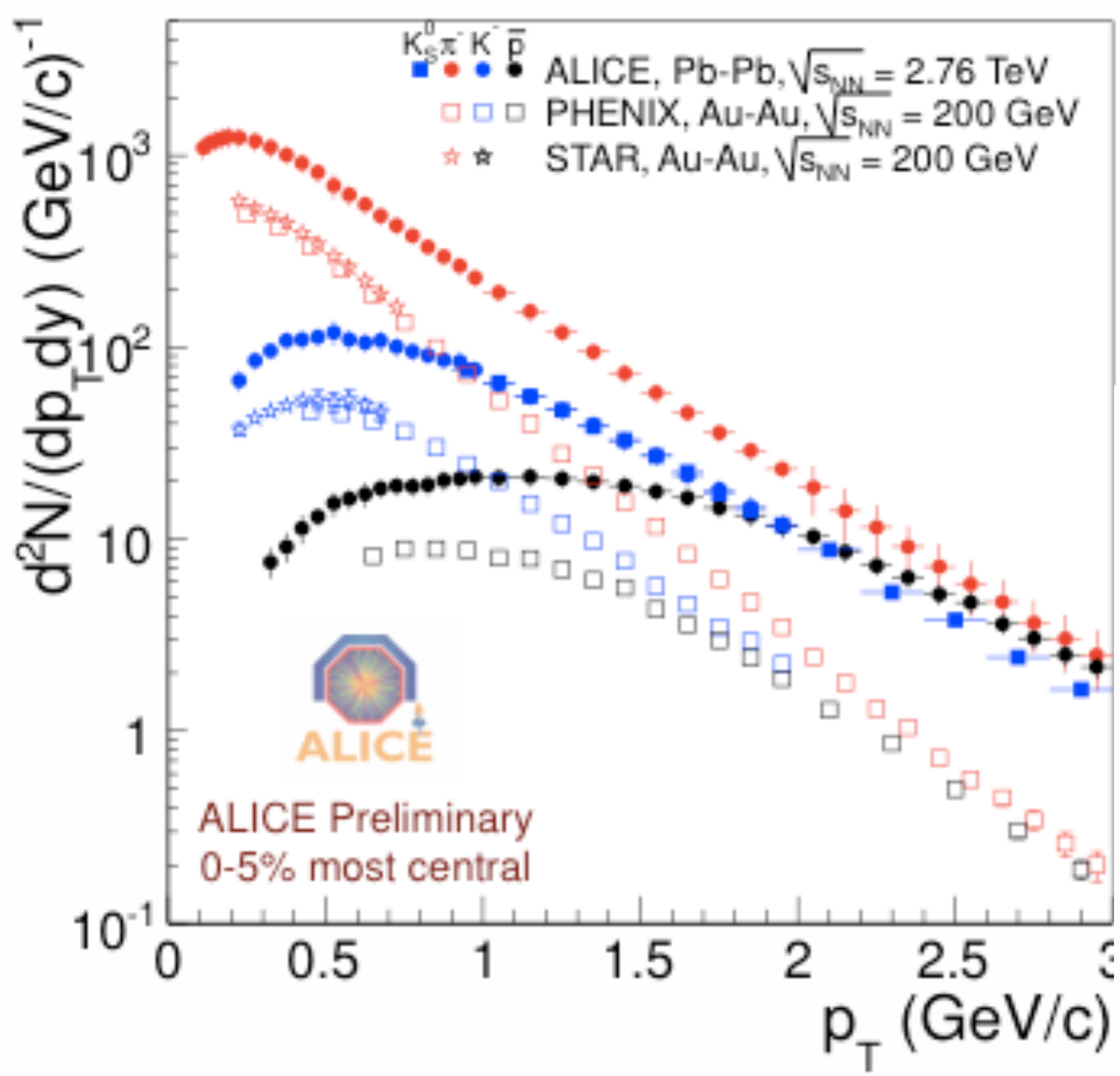
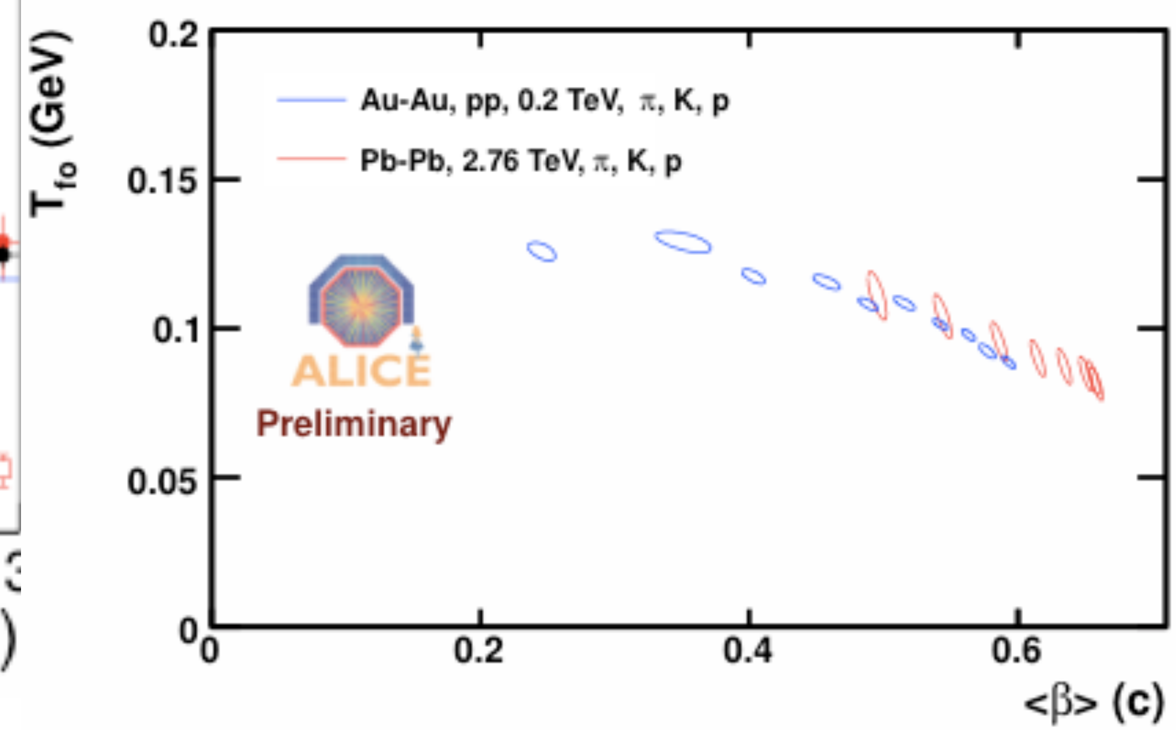
Blast Wave model => common T and β

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



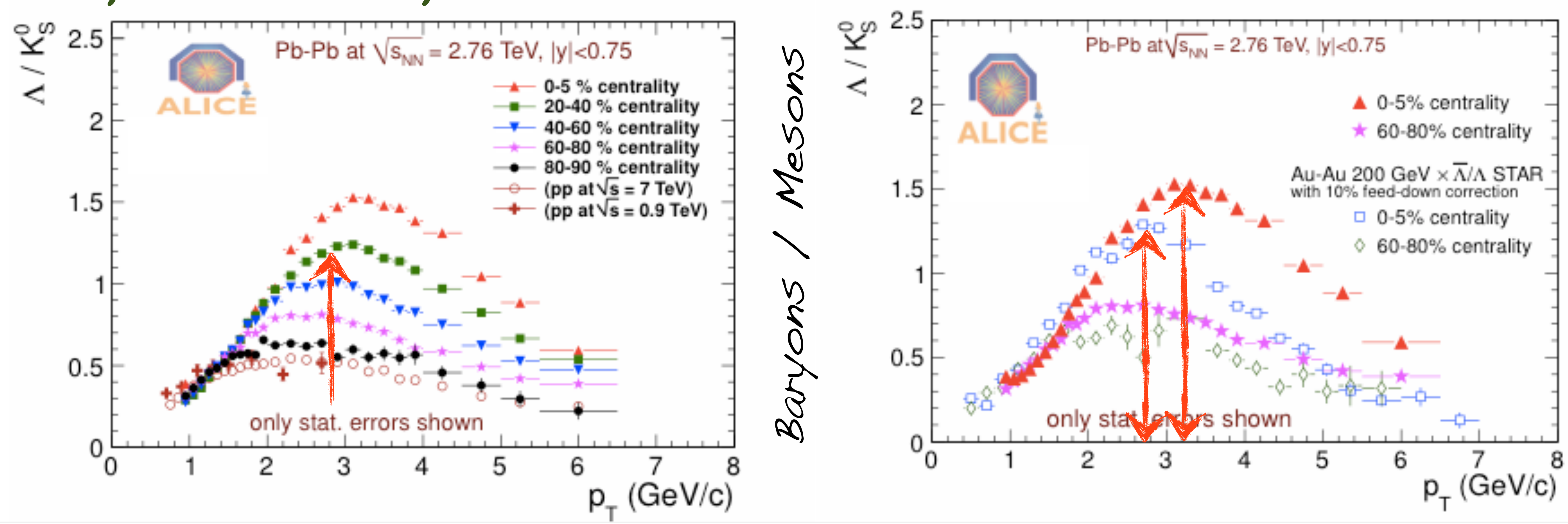
LHC: Large kinematic reach to explore

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 ...

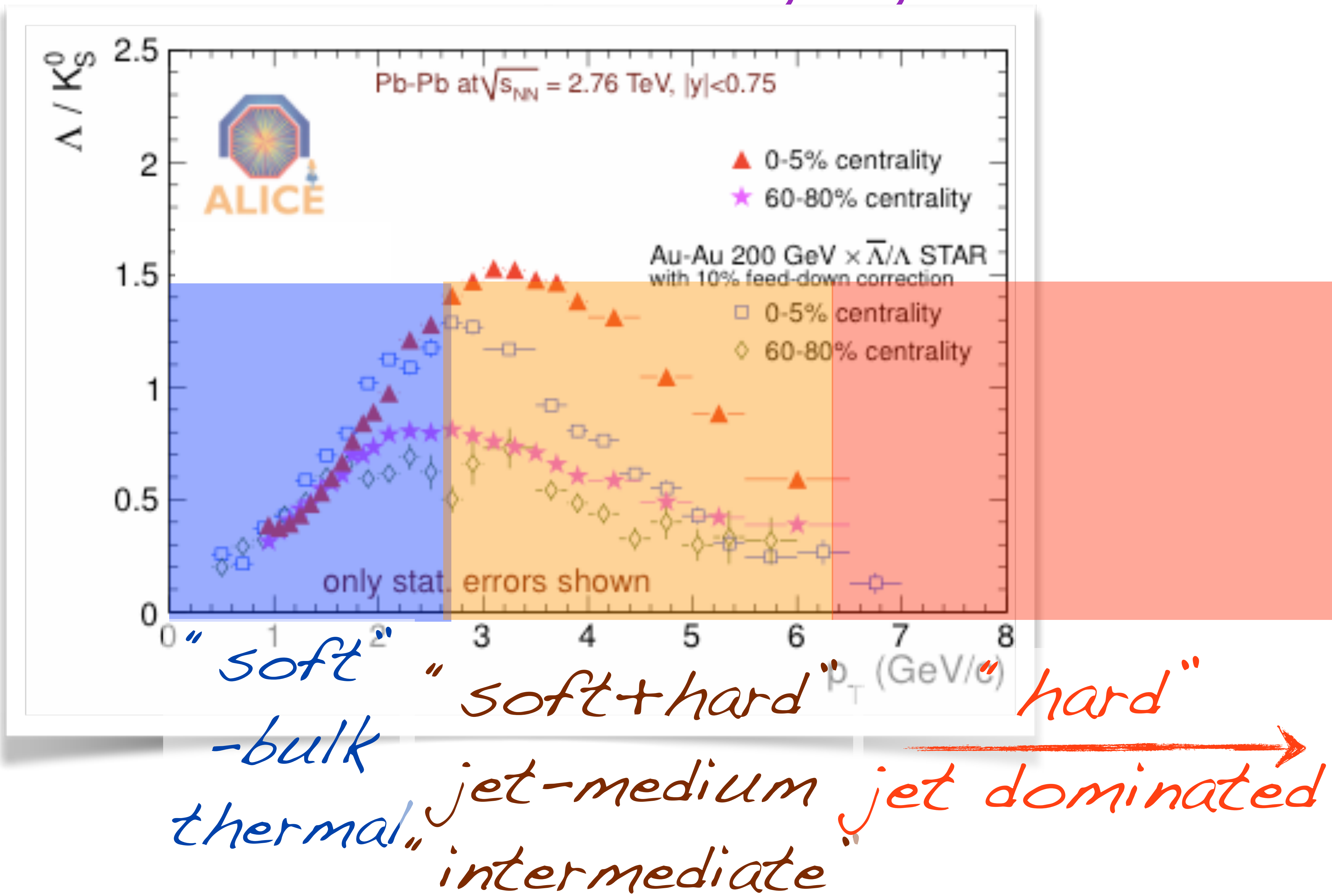
RHIC vs LHC
(LHC: higher mean pT - more flow)



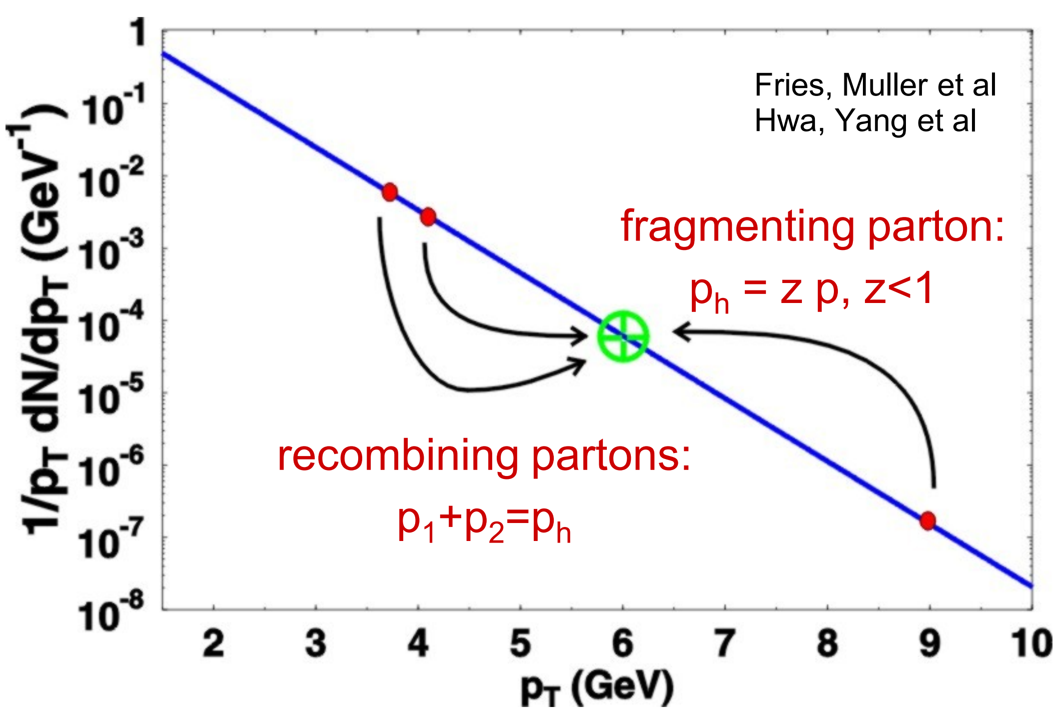
Much more baryons than mesons in central collisions as compared to proton-proton (coalescence/recombination? bulk+jet?)

LHC similar to RHIC
Maximum at slightly higher-pT

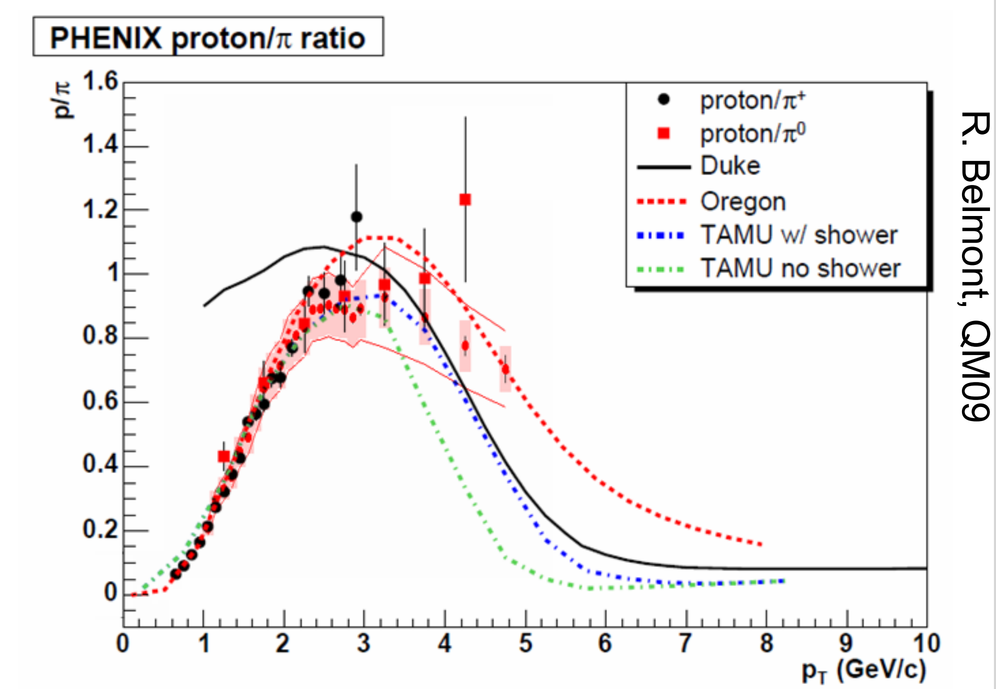
bulk, jets, medium and p_T: arbitrary regions and INFORMAL Language



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

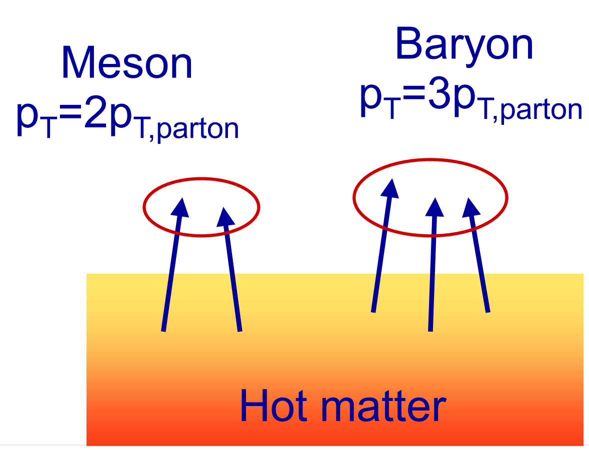


Recombination of thermal ('bulk') partons produces baryons at larger p_T



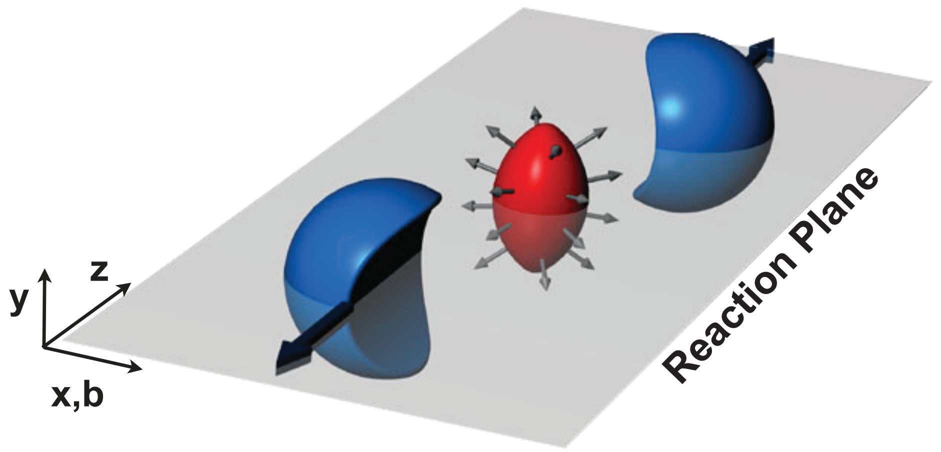
Recombination enhances baryon/meson ratio

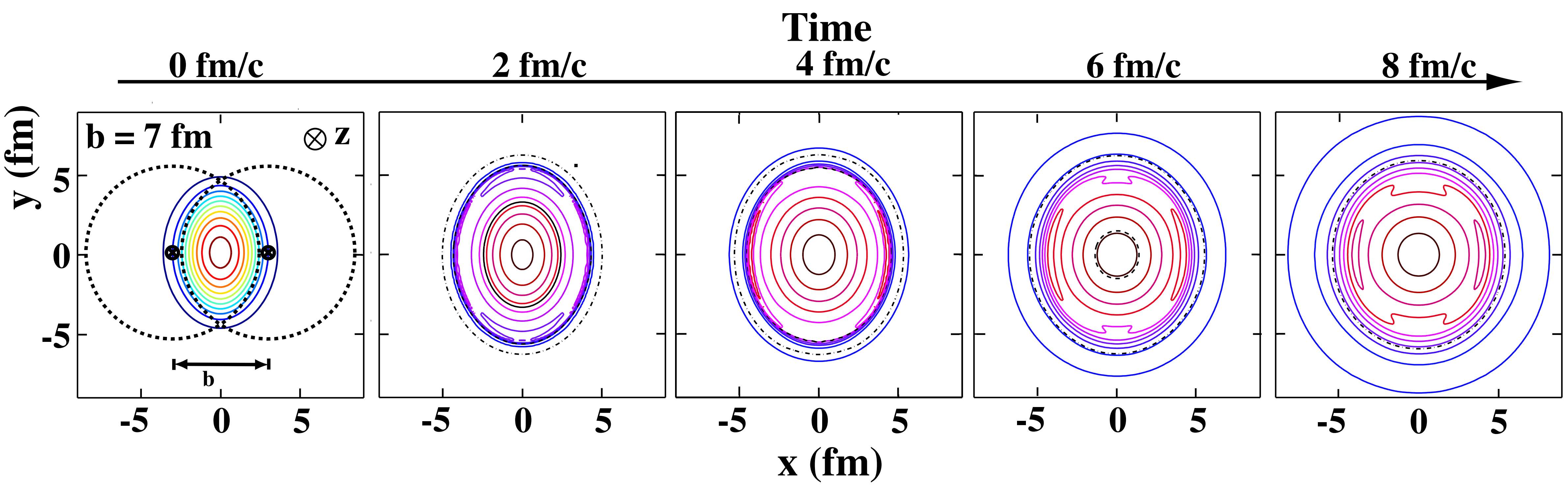
Note also: v_2 scaling



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.

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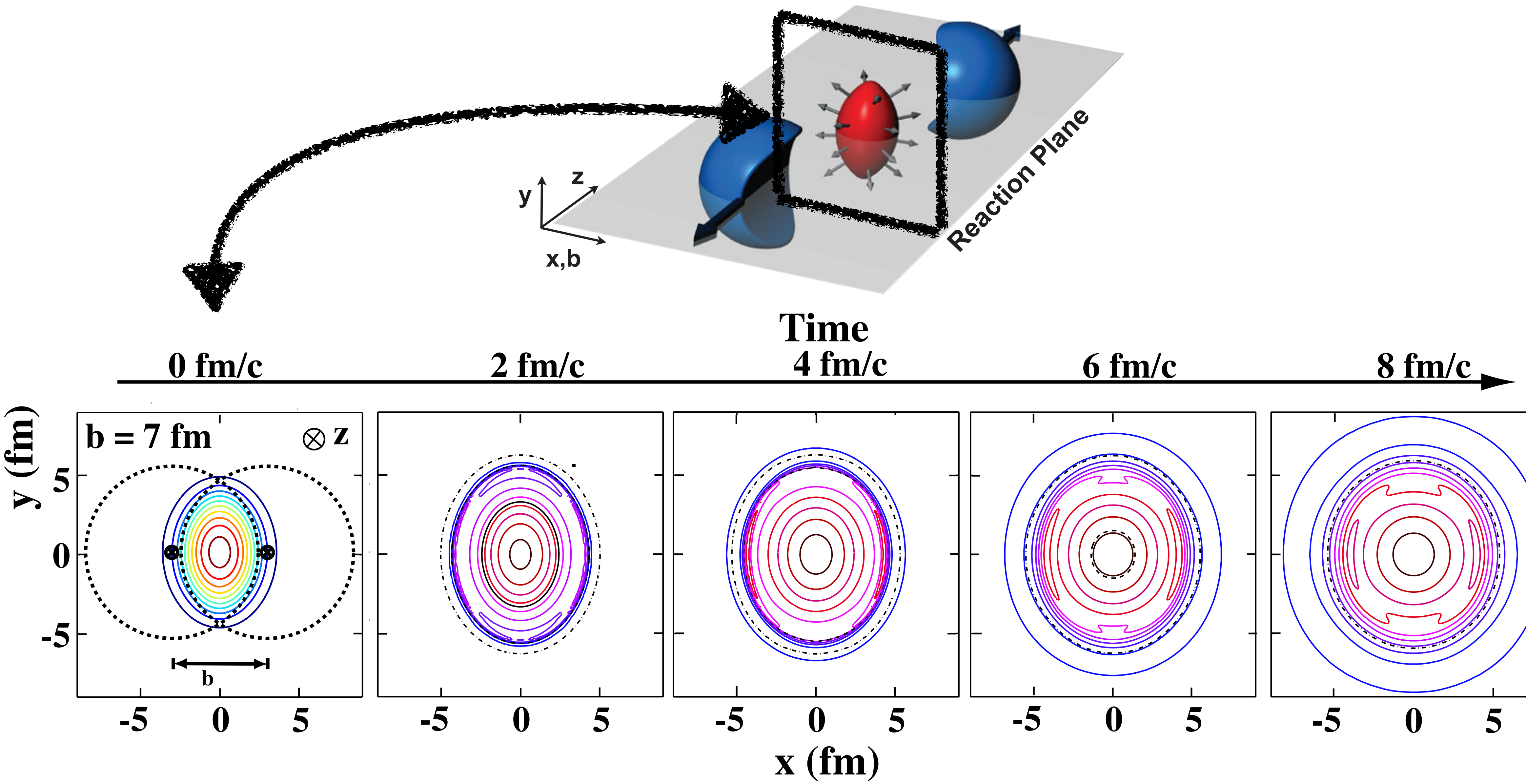

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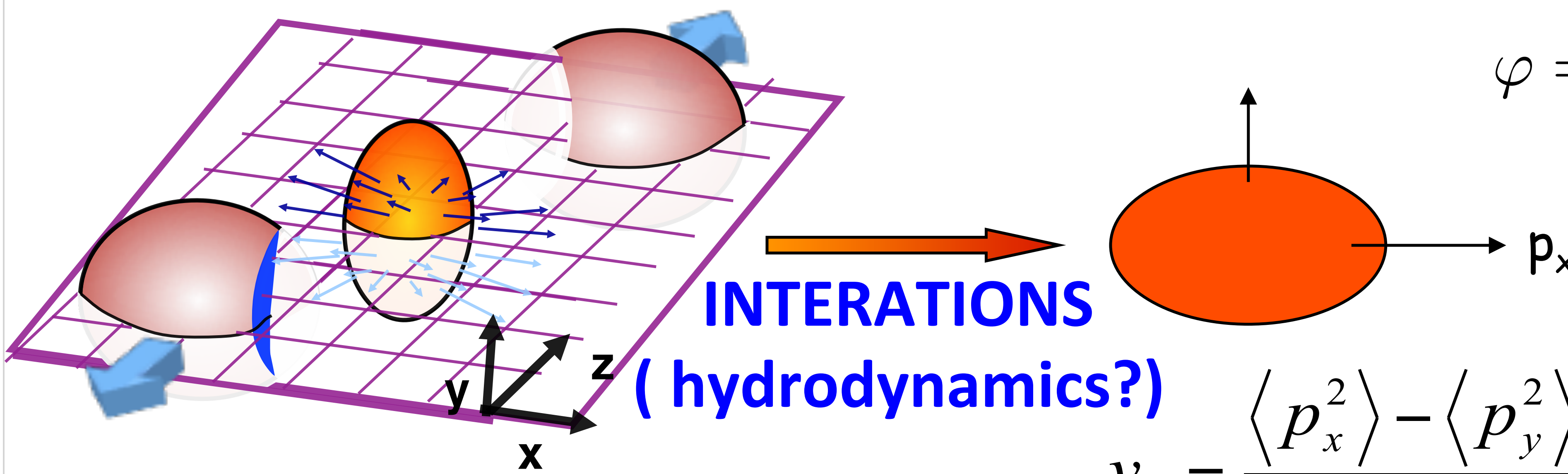
Azimuthal angular asymmetry in particle production

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



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

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

Initial spatial anisotropy

Final momentum anisotropy

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

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

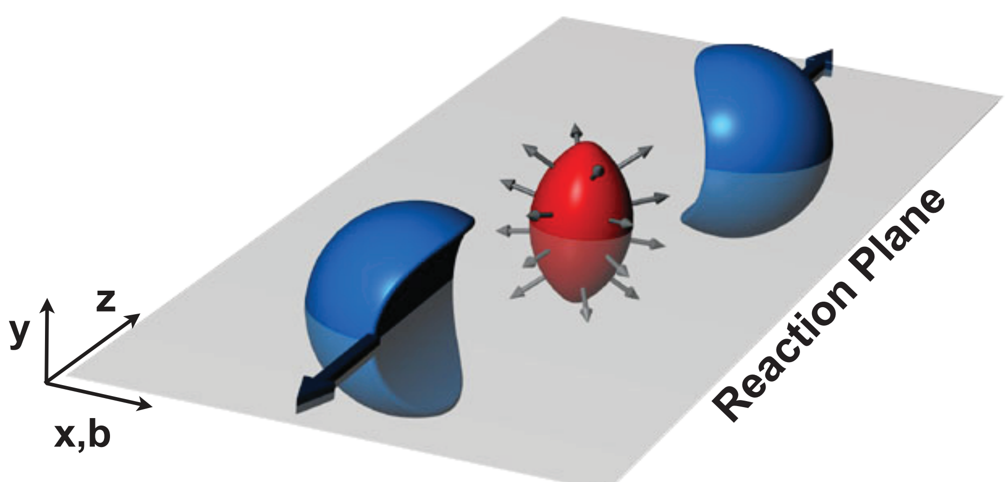
Elliptic flow

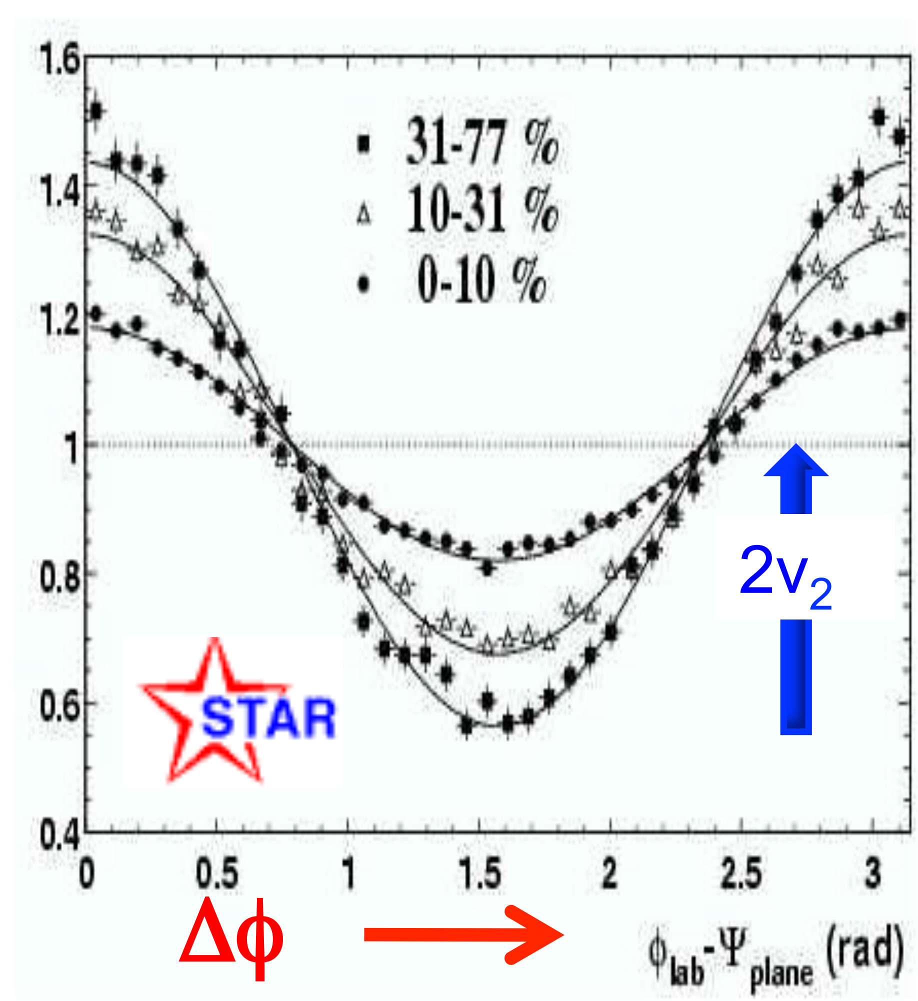
$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_2 \cos(2\Delta\varphi)$$

Experimental signature

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

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

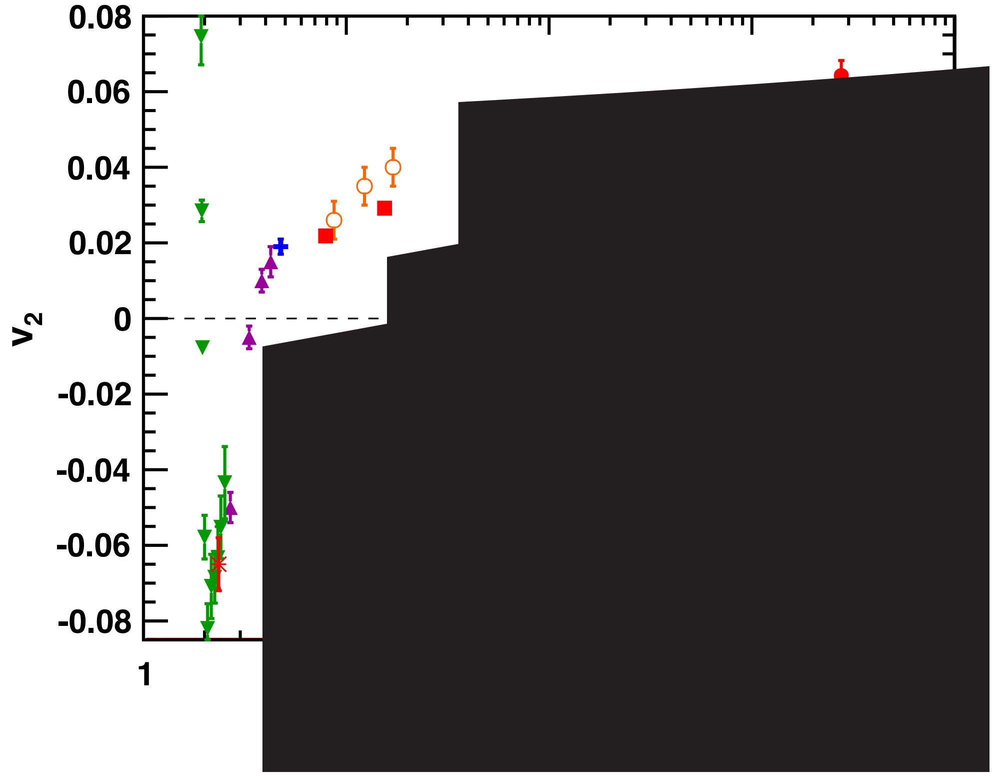


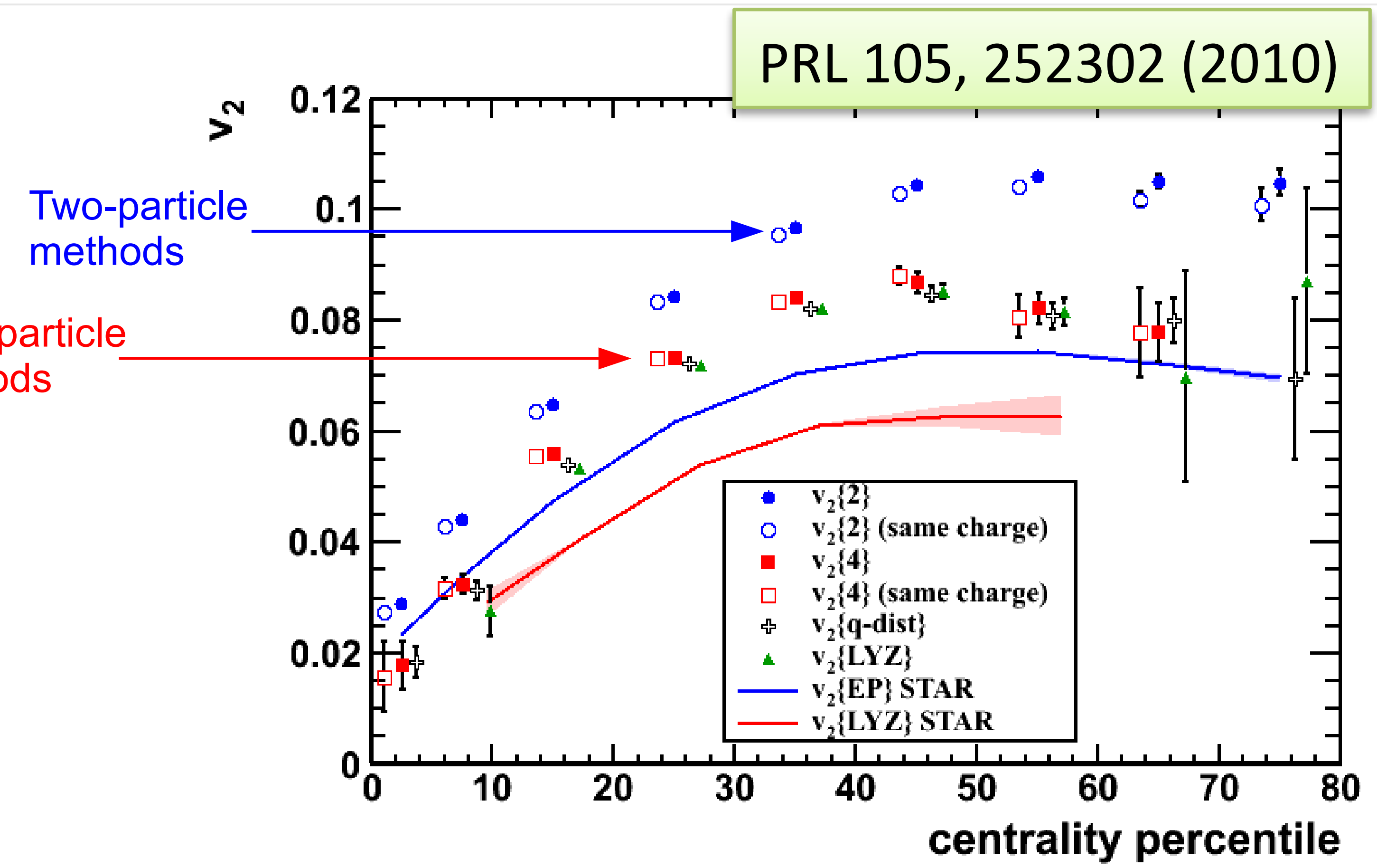


Sizeable effect!

Azimuthal anisotropy

Energy dependence of v2



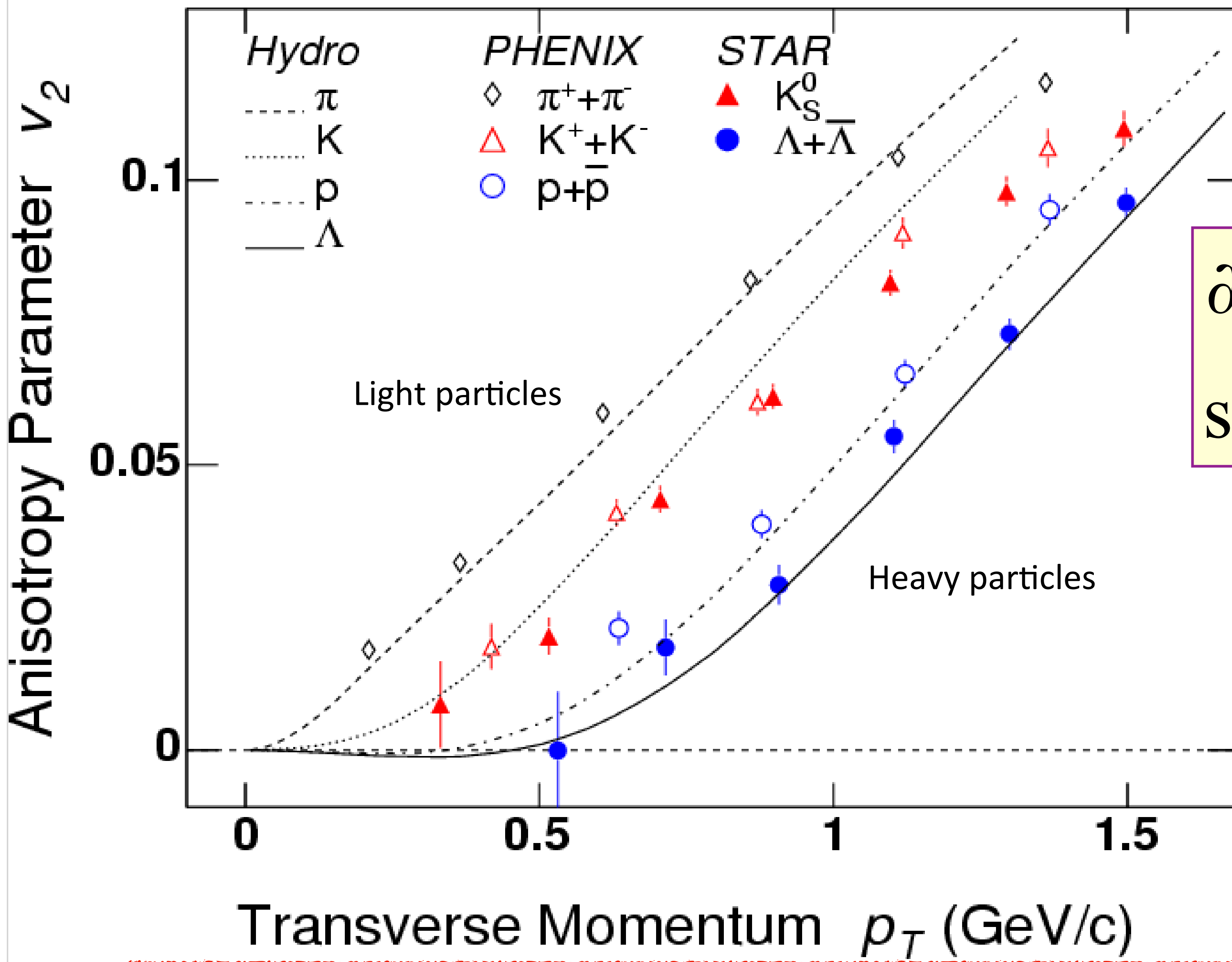


APS Viewpoint: A "Little Bang" arrives at the LHC (E. Shuryak)

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)

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

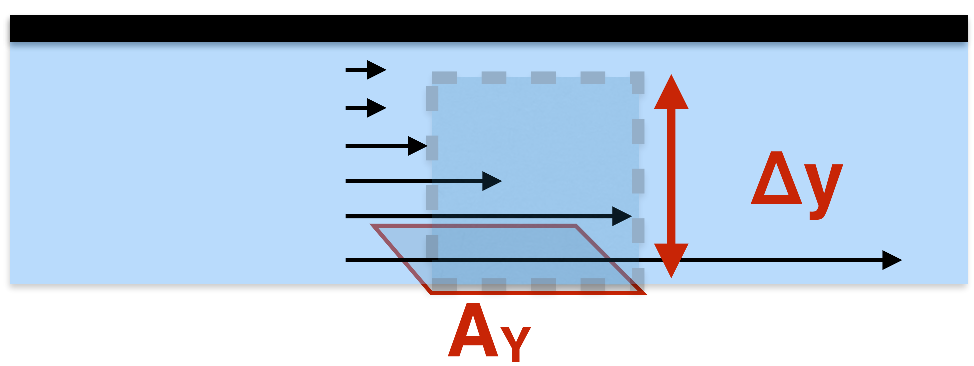
$$\partial_t T_{0x} = \partial_x T_{xx} + \partial_y T_{yx} + \partial_z T_{zx}$$

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

...motion of viscous fluids ...

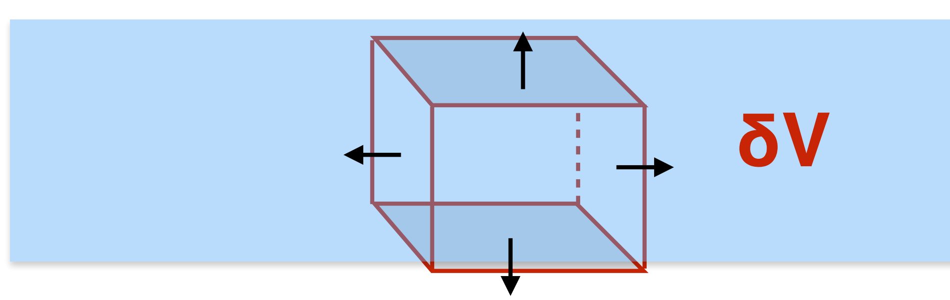
Navier-Stokes equation: $T_{ij} = P\delta_{ij} - \eta(\partial_i v_j + \partial_j v_i) - \zeta \nabla \cdot \vec{v}$

Where η is shear viscosity: friction between layers of fluid



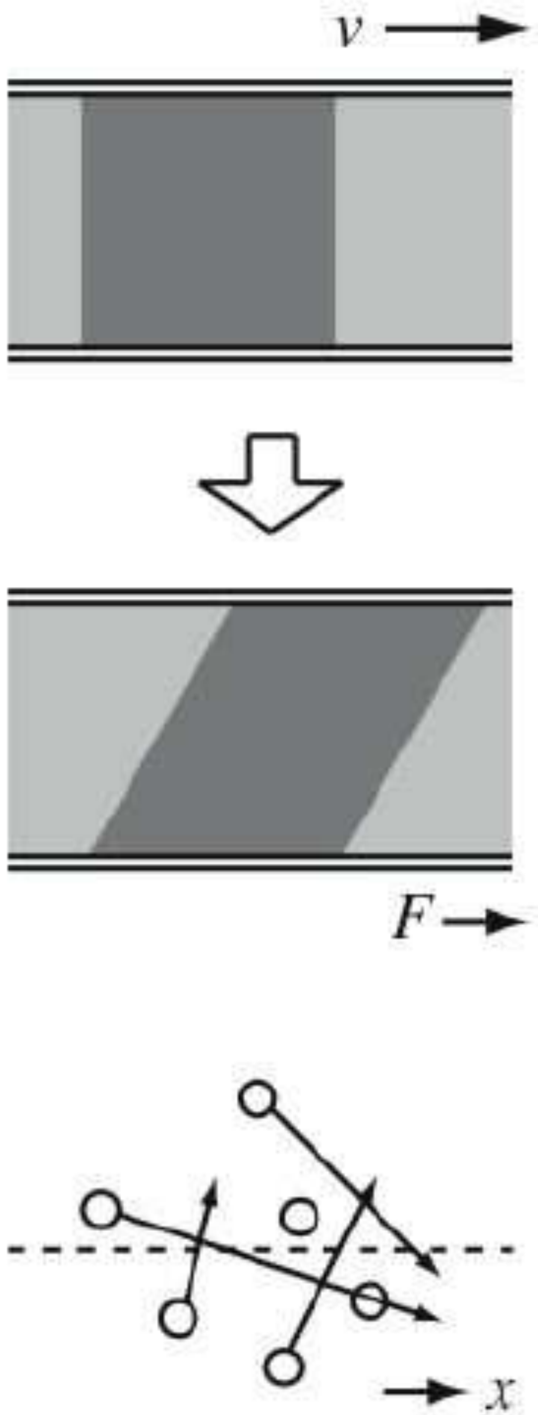
$$\frac{d}{dt} P_x = A_y \eta \partial_y v_x$$

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:

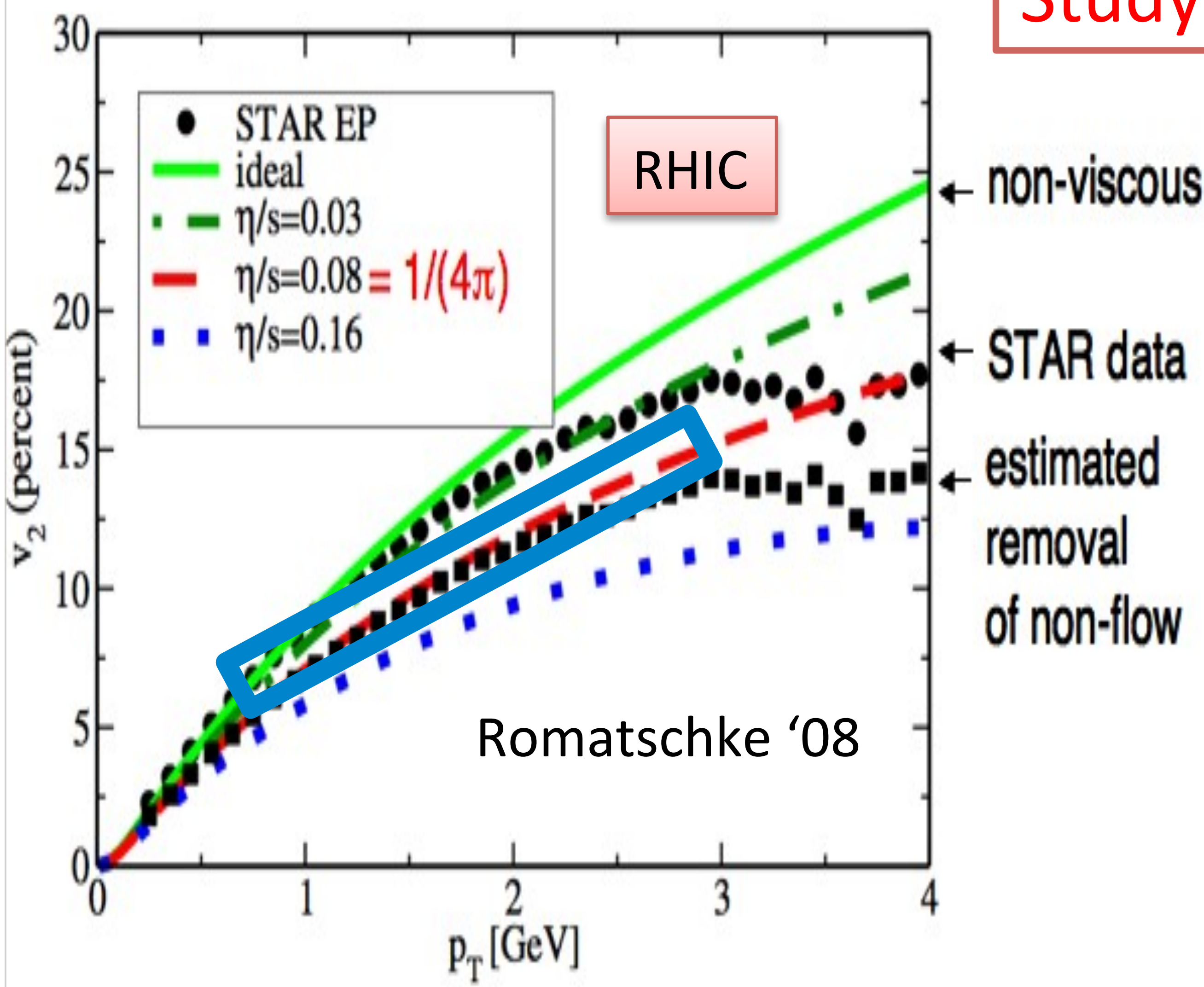
Weak coupling
• small cross section, long mean free path
⇒ large viscosity

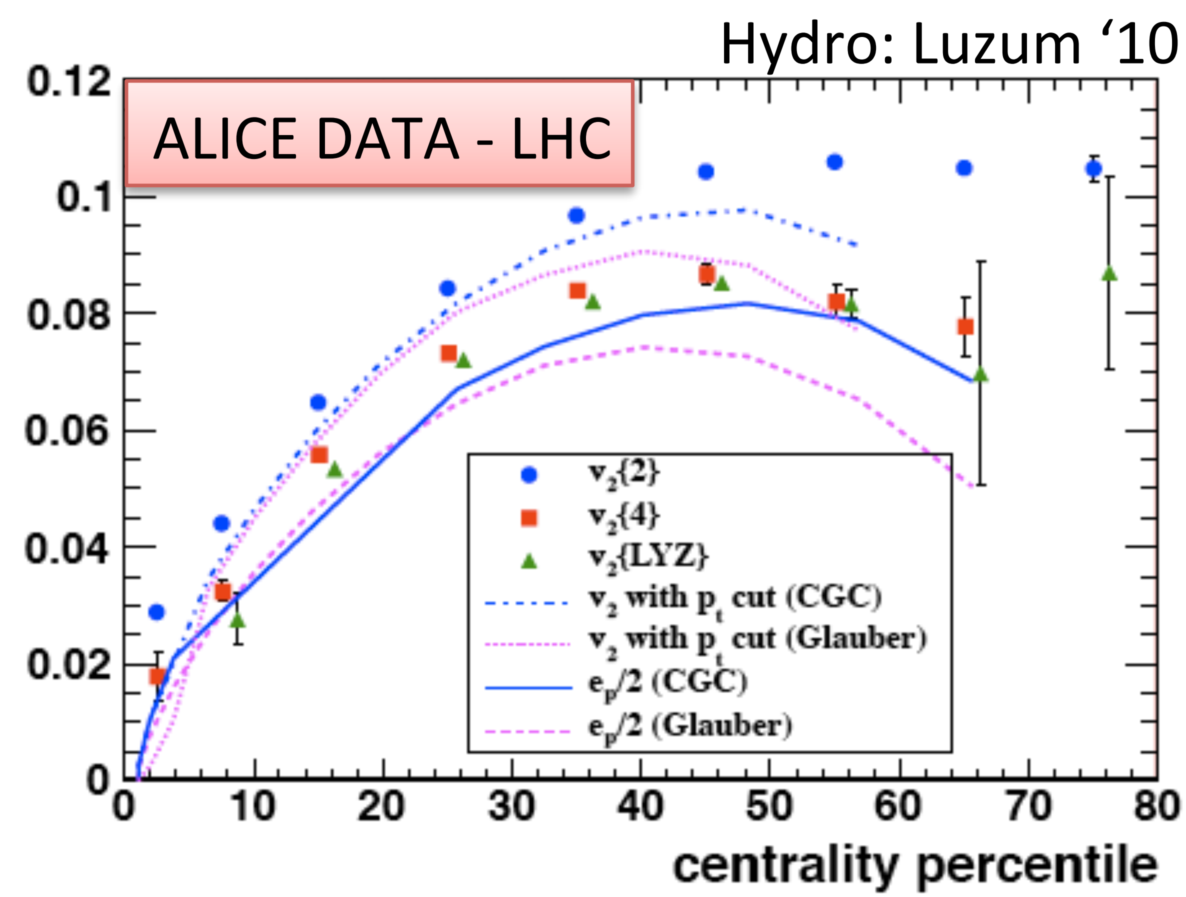
Strong coupling
• large cross section, small mean free path
⇒ small viscosity

$\eta \to 0$: strongly coupled (perfect) fluid
$\eta \to \infty$: 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)

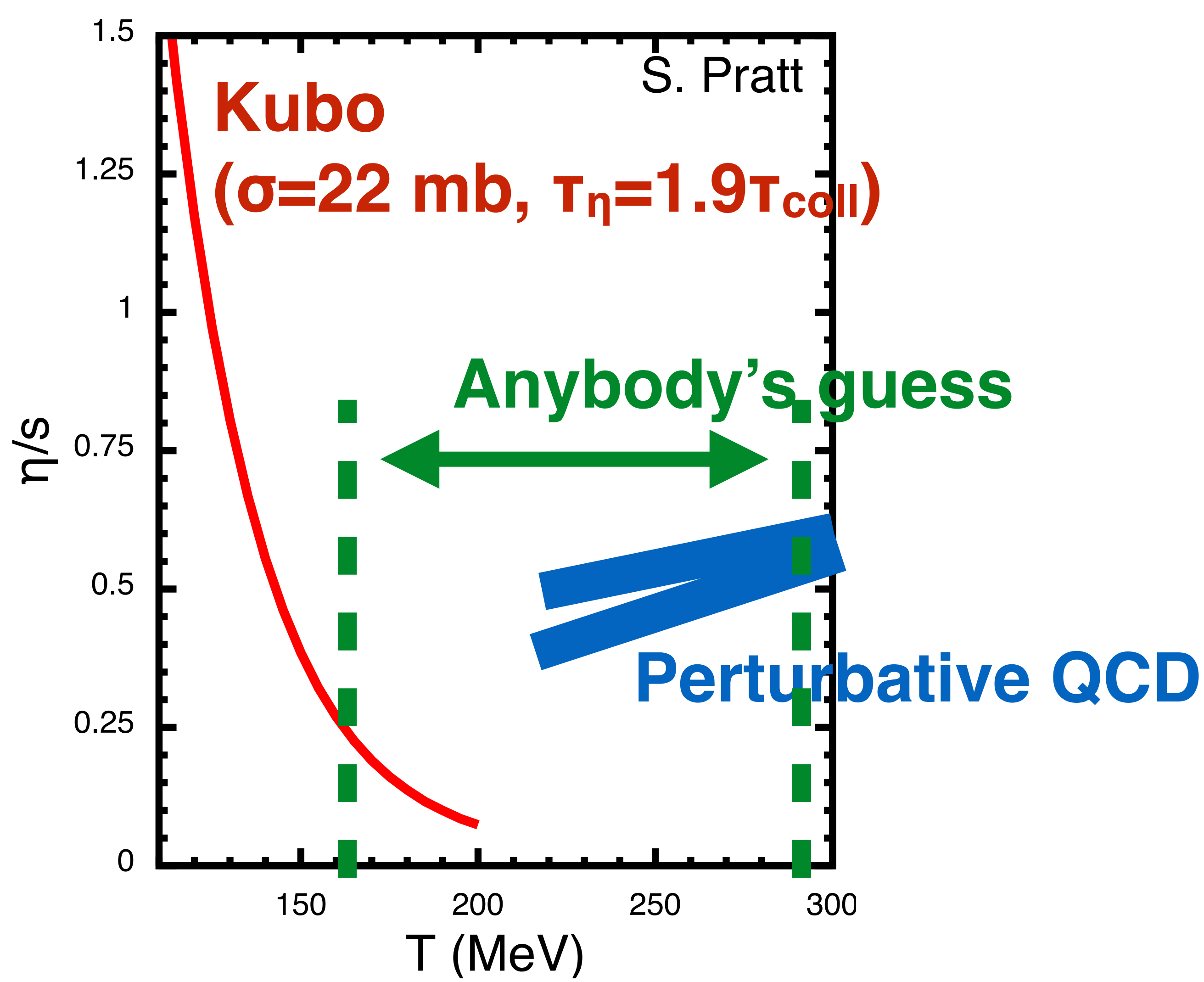
0.08 : λ_{therm} λ_{mfp} **(Danielewicz and Gyulassy)**

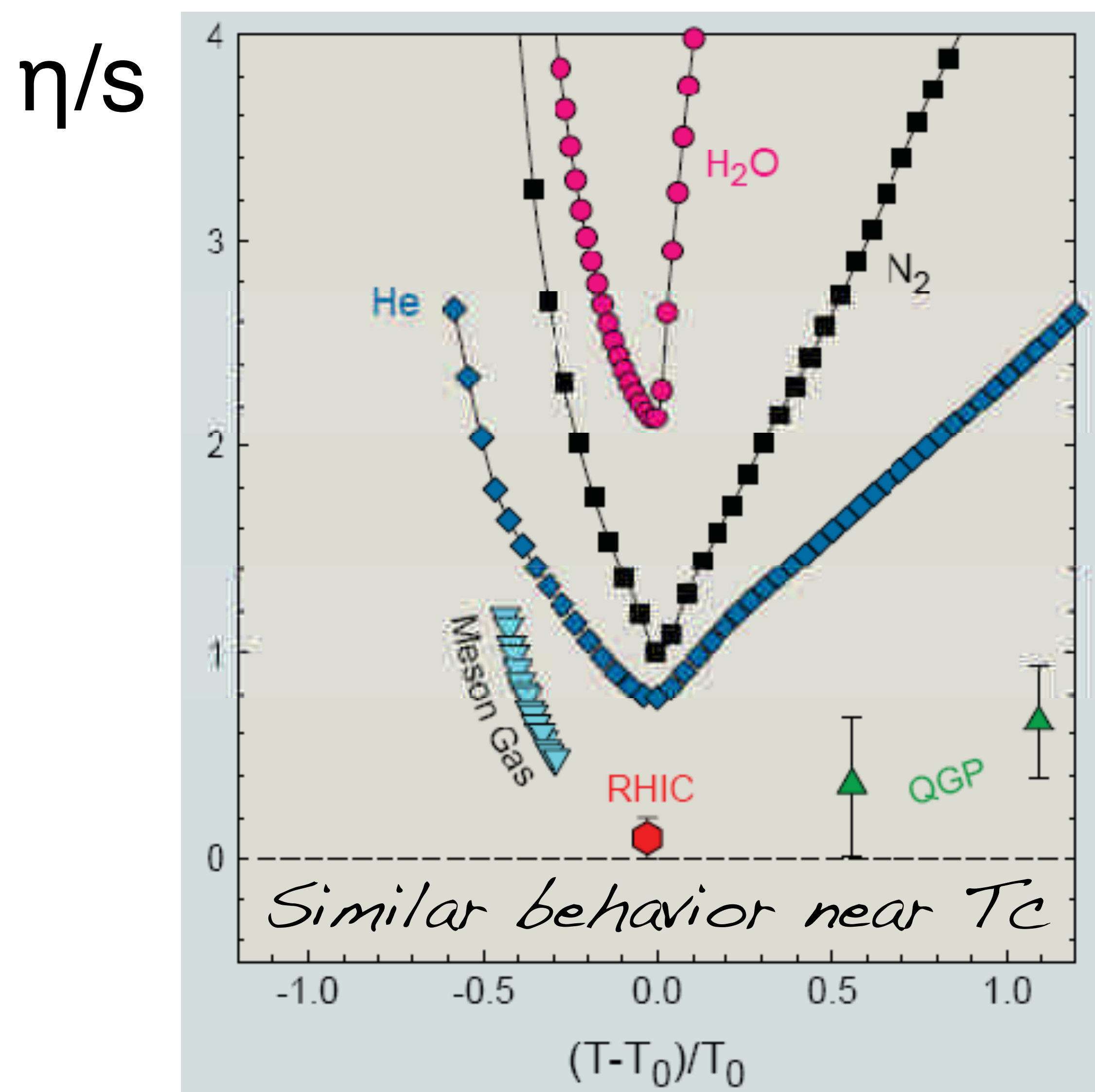
Hot, deconfined QCD matter flows as an almost perfect fluid

Comparison QGP to other fluids near Tc

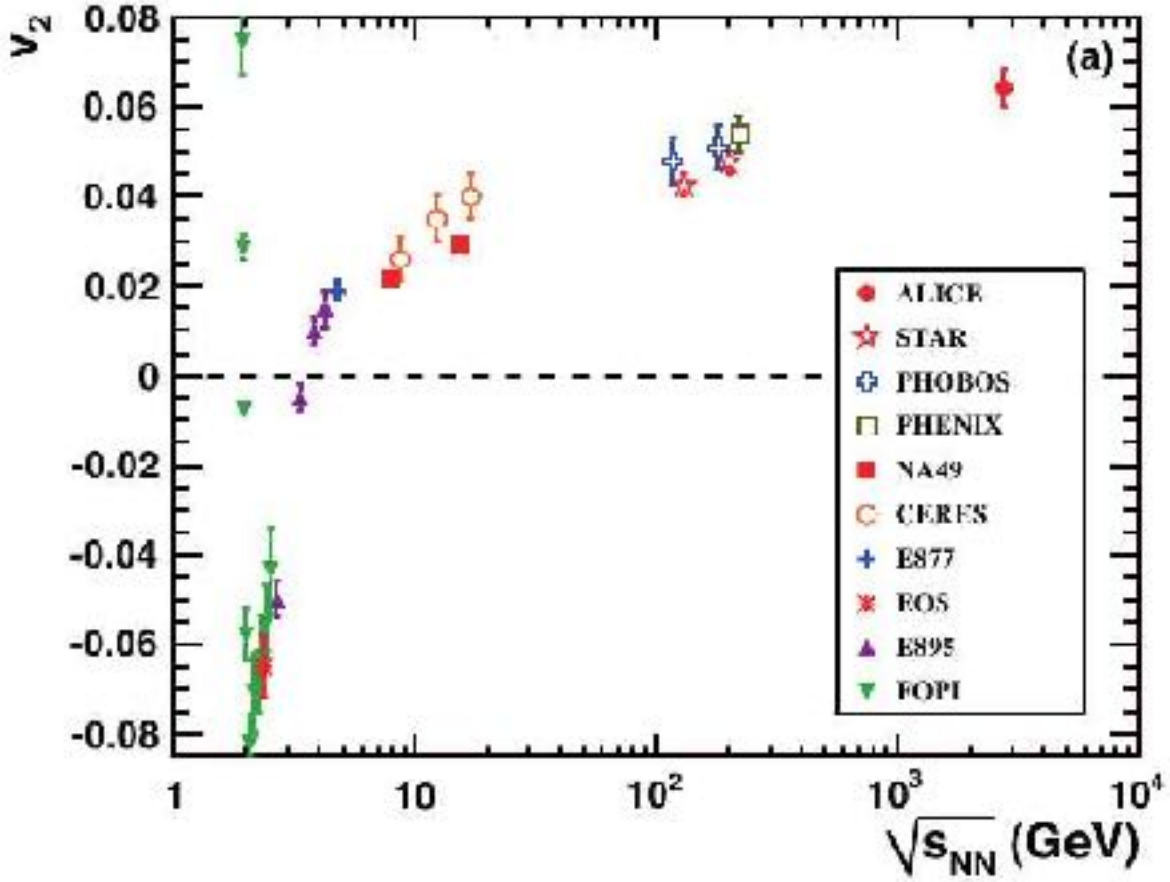
Green-Cubo relations:
transport coefficients in terms of integrals of time correlation functions
- correlations of particles x relaxation time

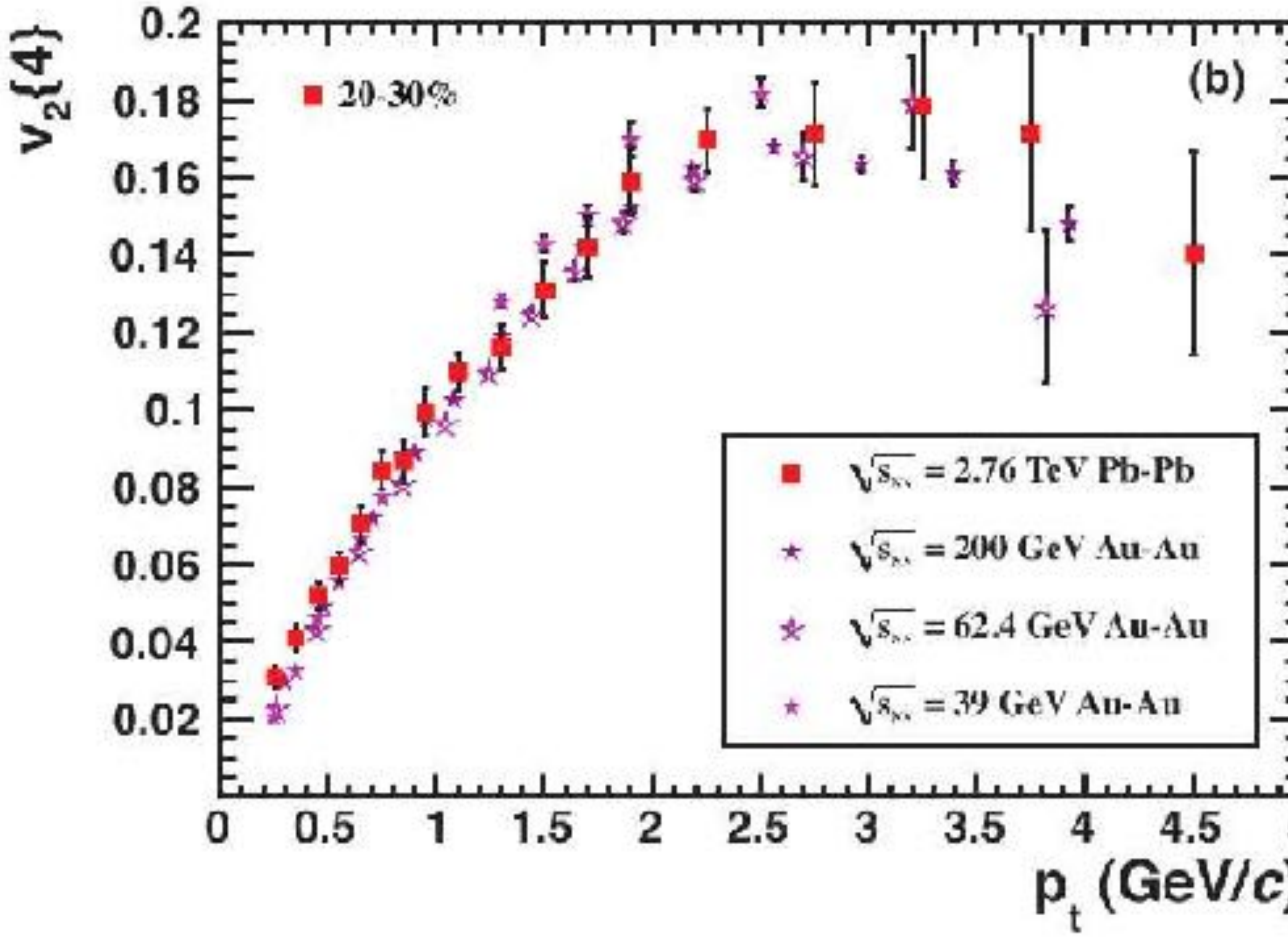
$$\eta = \frac{\tau_\eta}{T}\int d^3r \langle T_{xy}(0,0) T_{xy}(\vec{r}, t=0)\rangle$$
$$= \frac{\tau_\eta}{T}\sum_\alpha (2S_\alpha + 1)\int \frac{d^3p}{(2\pi)^3} e^{-E/T}\frac{p_x^2 p_y^2}{E^2}$$





Elliptic Flow – collision energy dependence

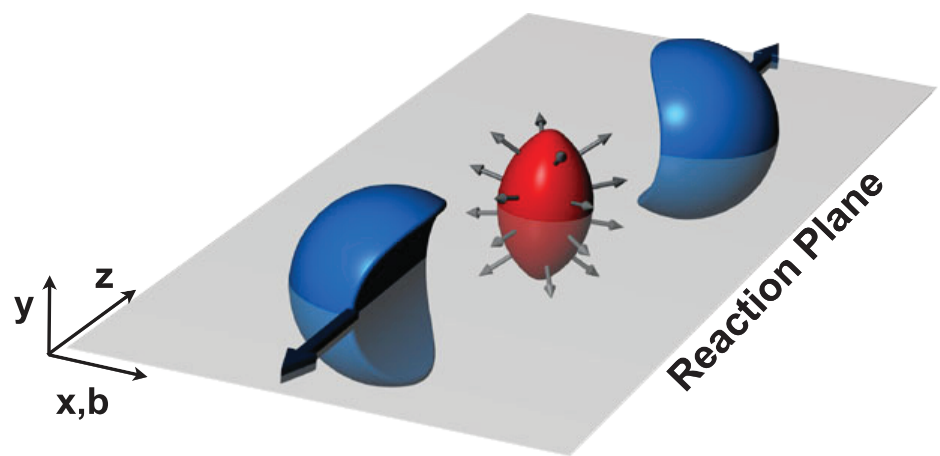




$$v_2 = \frac{\int dp_t \frac{dN}{dp_t} v_2(p_t)}{\int dp_t \frac{dN}{dp_t}}$$

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 !?

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



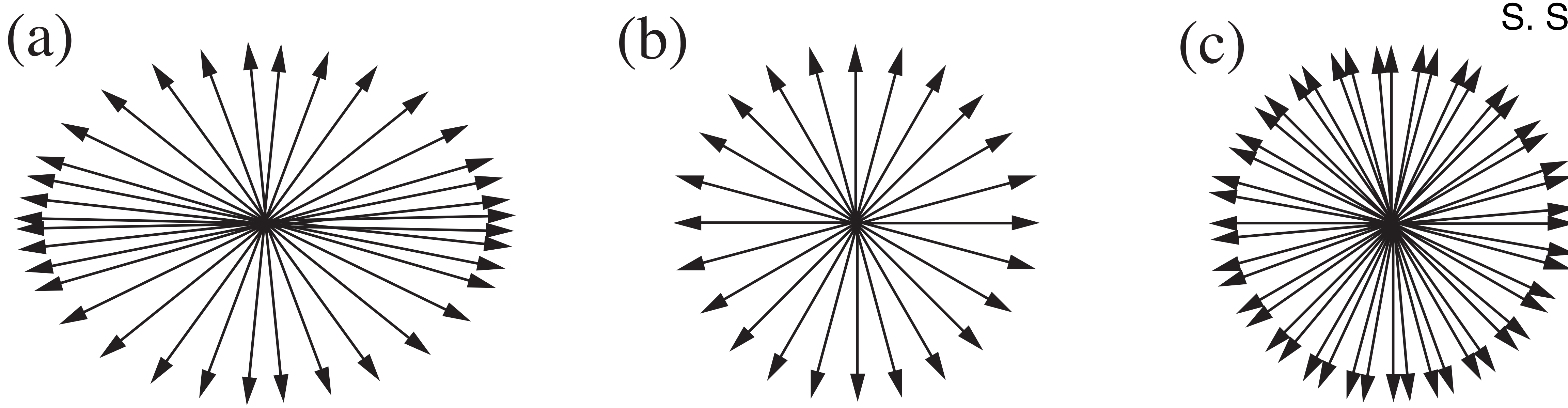
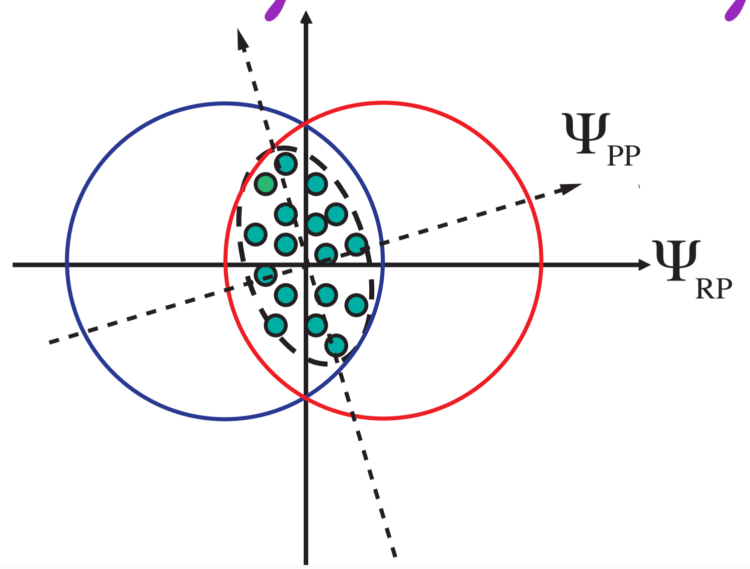


Figure 9. Examples of particle distributions in the transverse plane, where for a) $v_2 > 0$, $v_2\{2\} > 0$, b) $v_2 = 0$, $v_2\{2\} = 0$, and c) $v_2 = 0$, $v_2\{2\} > 0$.

Reaction plane (RP)
Participants plane (PP)

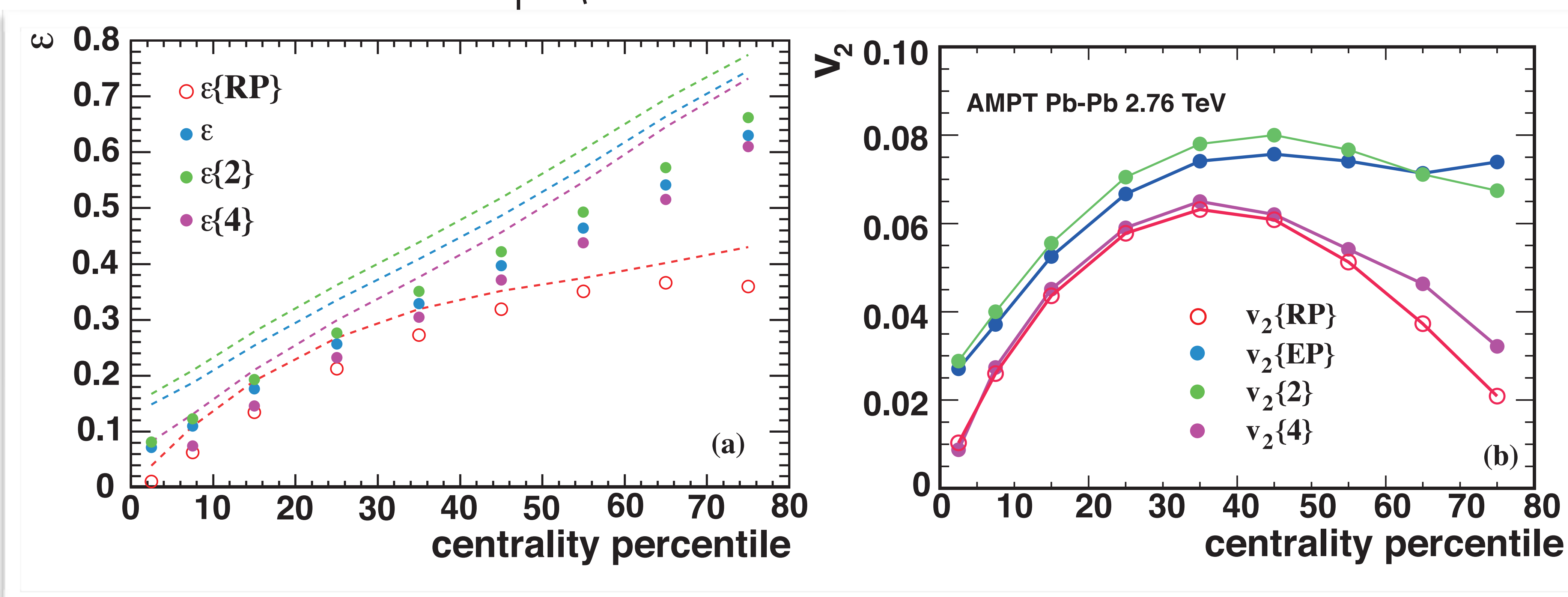


Genuine 2,4-particle correlations

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

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

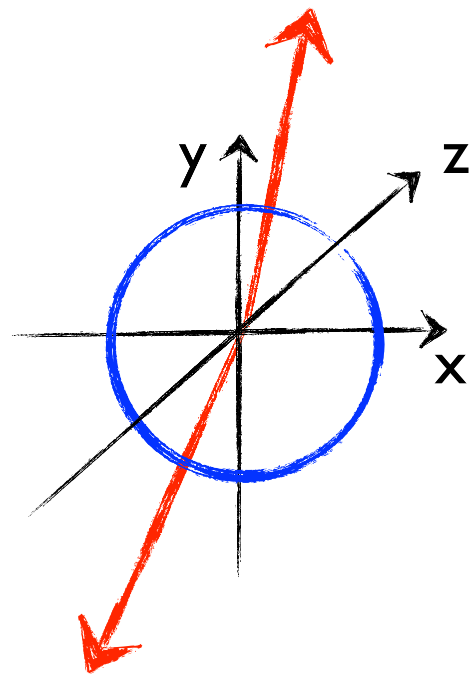
$\delta_2 \propto 1/M_c$ and $\delta_4 \propto 1/M_c^3$



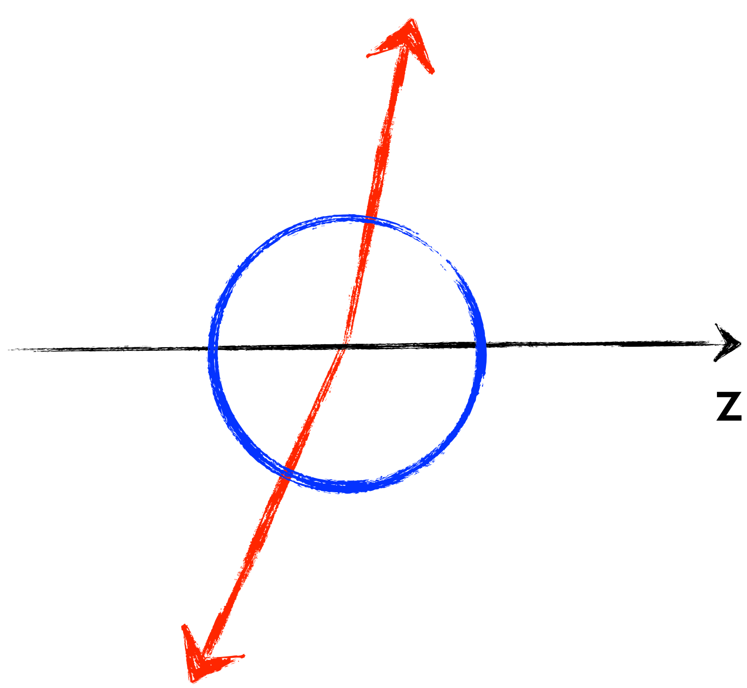
[AMPT] calculation using Glauber initial conditions

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

Two particle correlations



Δφ - azimuthal angle difference
angle in the transverse plane



Δη - longitudinal - pseudo-rapidity distance

Sensitivity of particle correlations to the underlying/initial conditions

Two-particle correlations

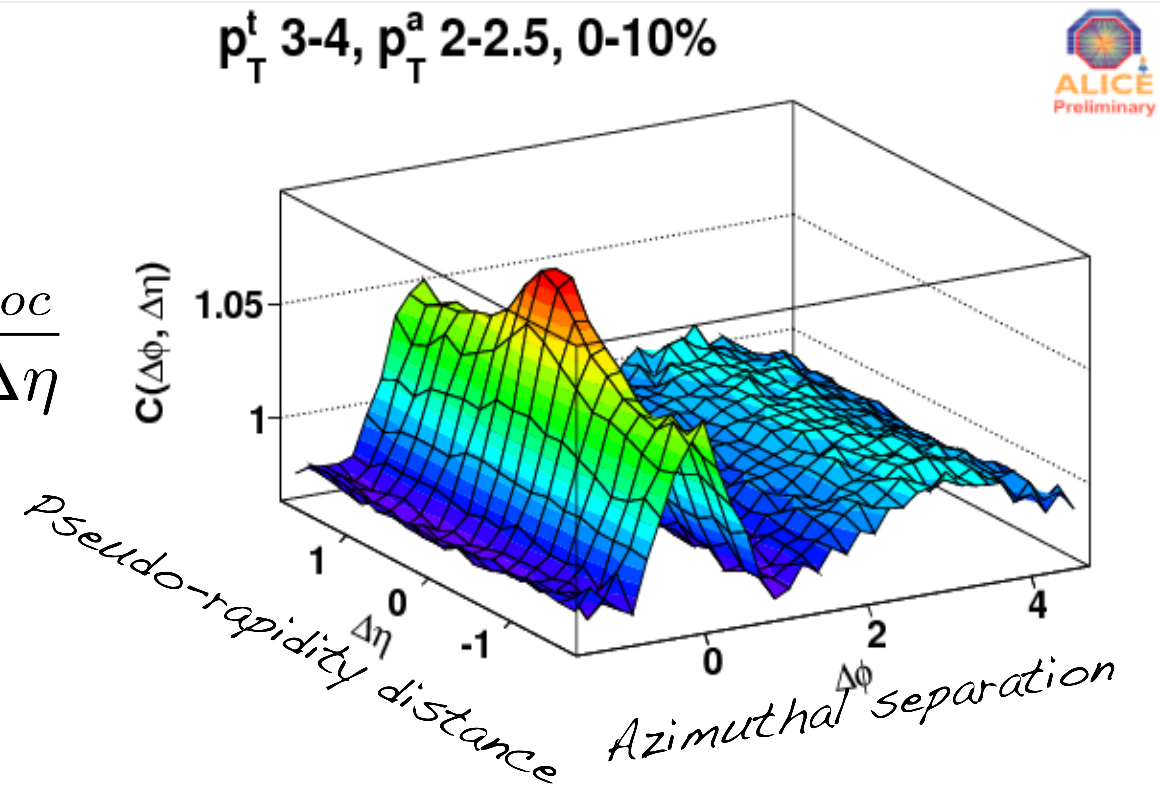
- conditional [per-trigger] yields

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

At Low-p_T :

Ridge

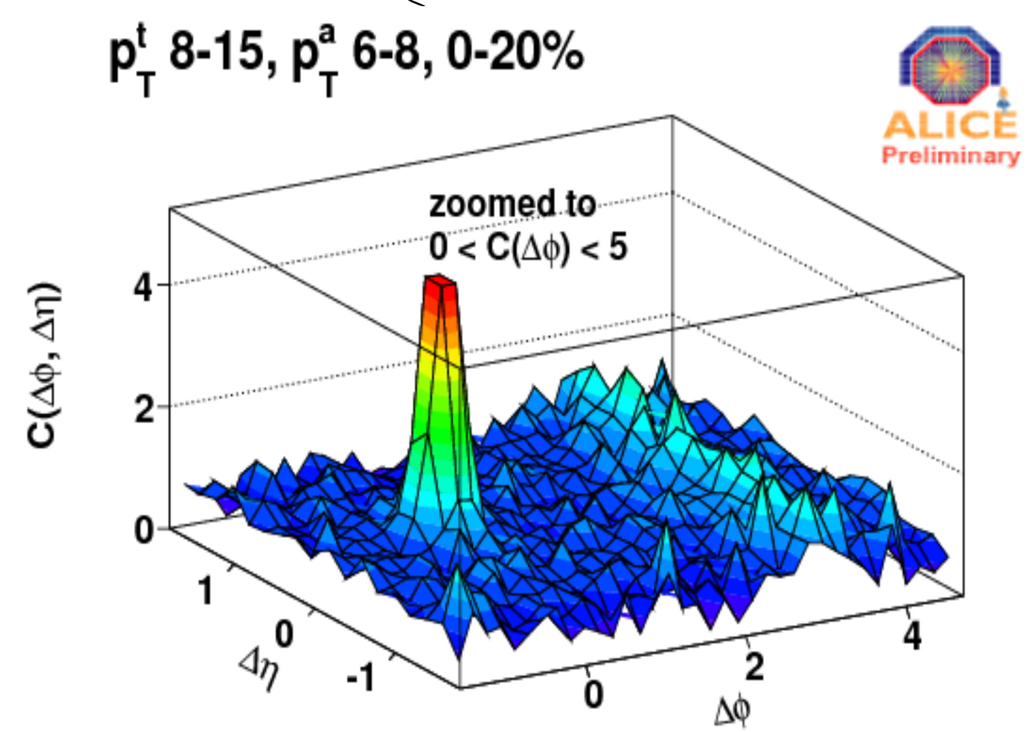
Hydrodynamics, flow



At High-p_T :

Discussed later…

Quenching/suppression, broadening

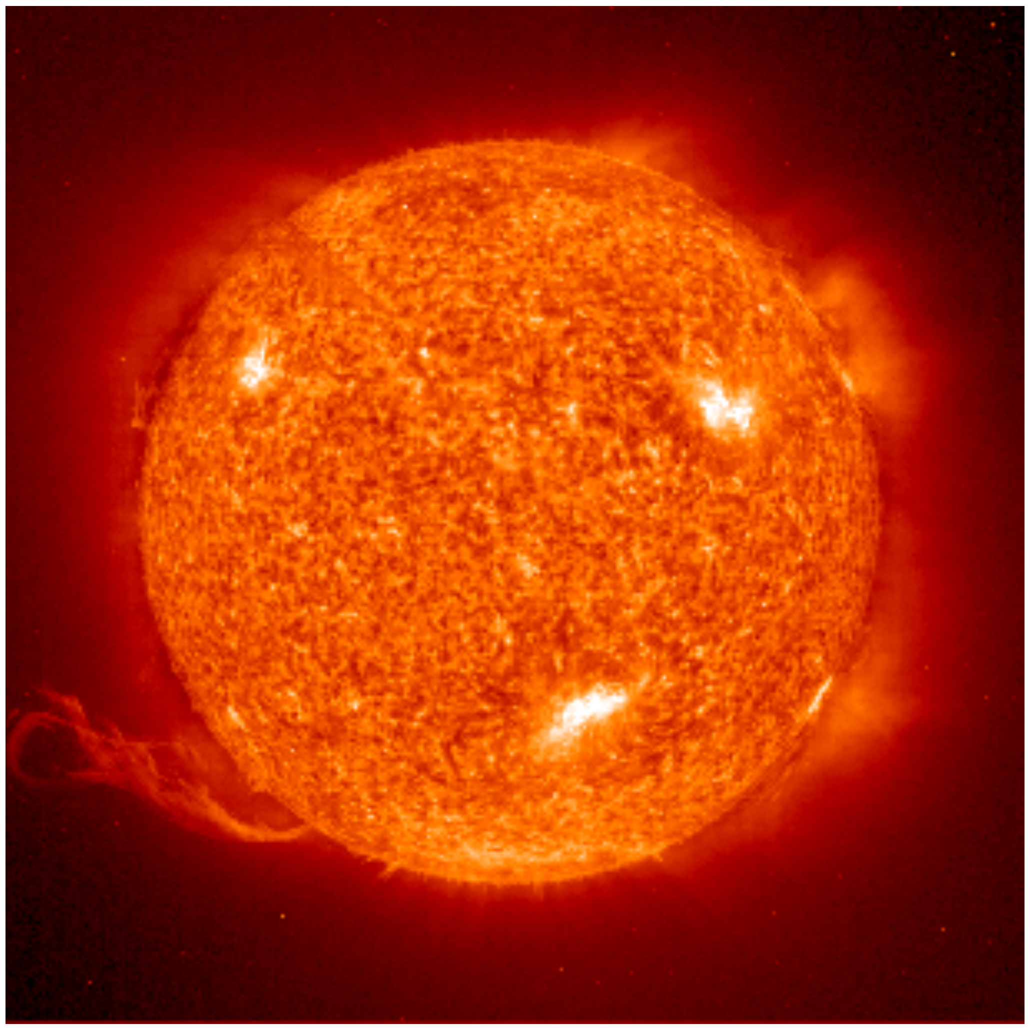


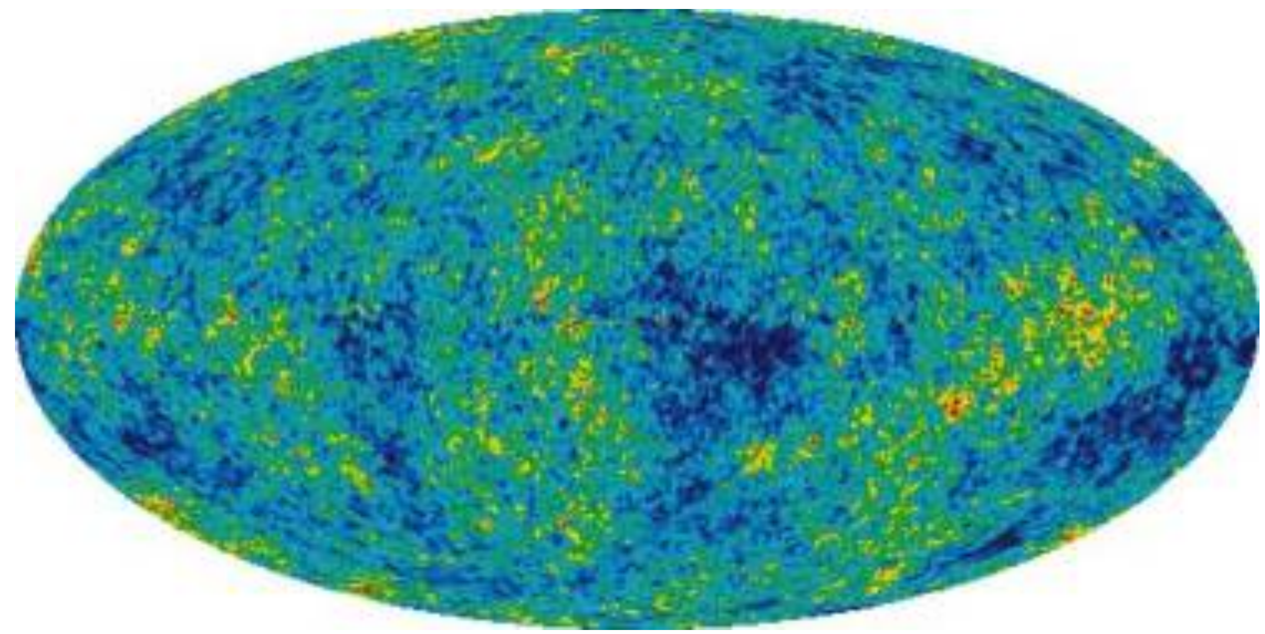
I_{CP}: Yields in central v.s. peripheral collisions

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

"Beyond" v2

higher moments -> fluctuations / hotspots



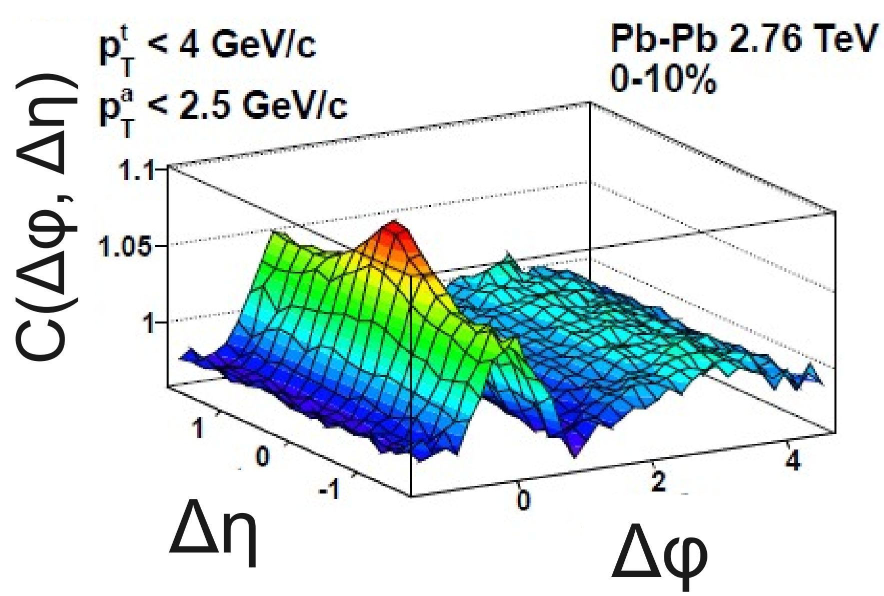


Single event!

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

Non-zero!

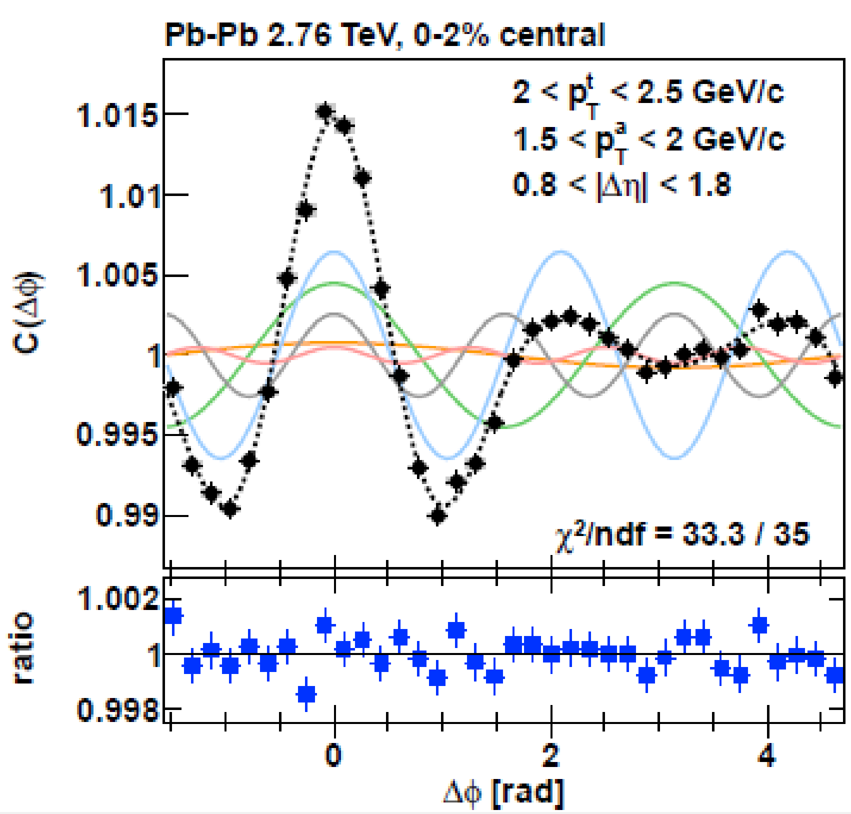
Two-particle correlations - Fourier decomposition

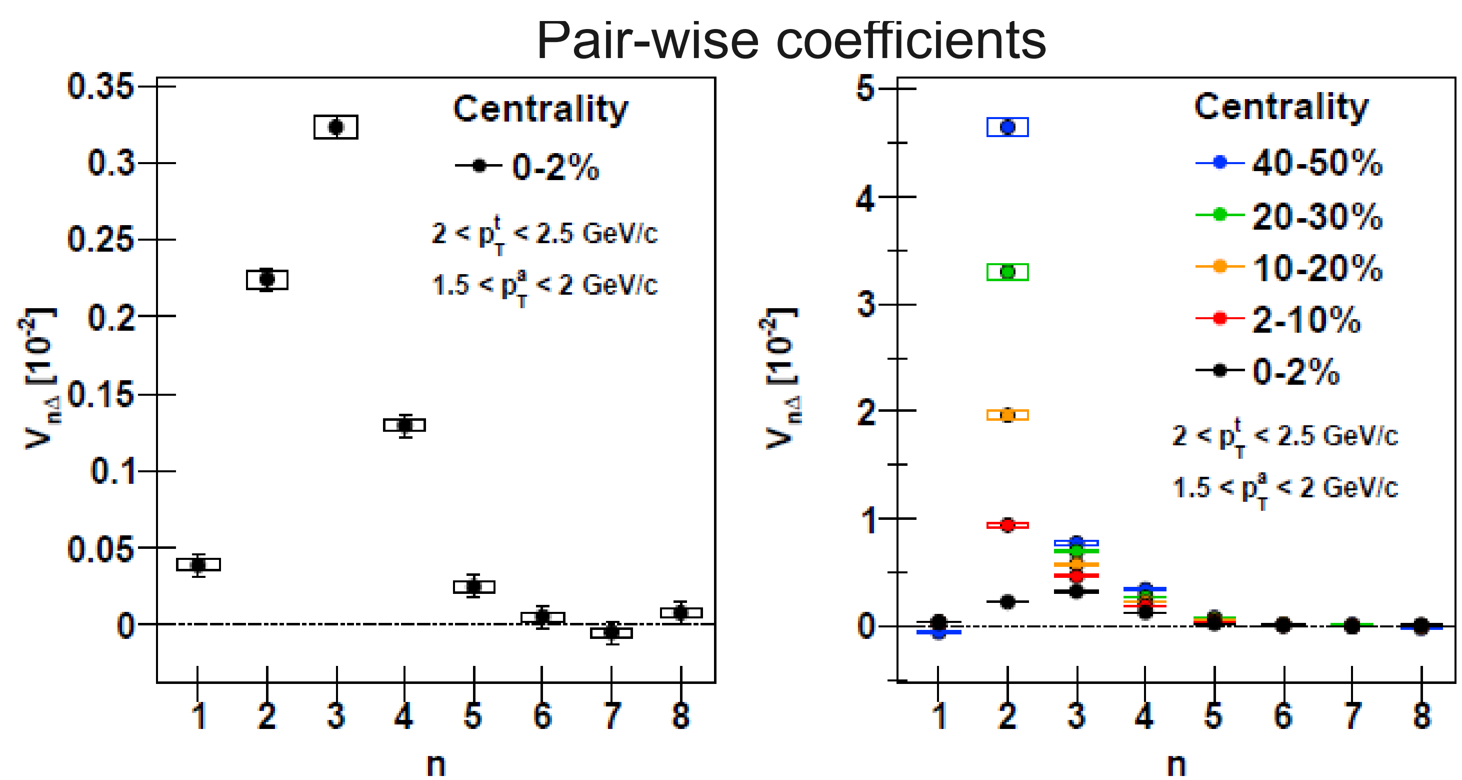


Integration of the correlation function in $0.8 < |\Delta\eta| < 1.8$ (long) and Fourier decomposition

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

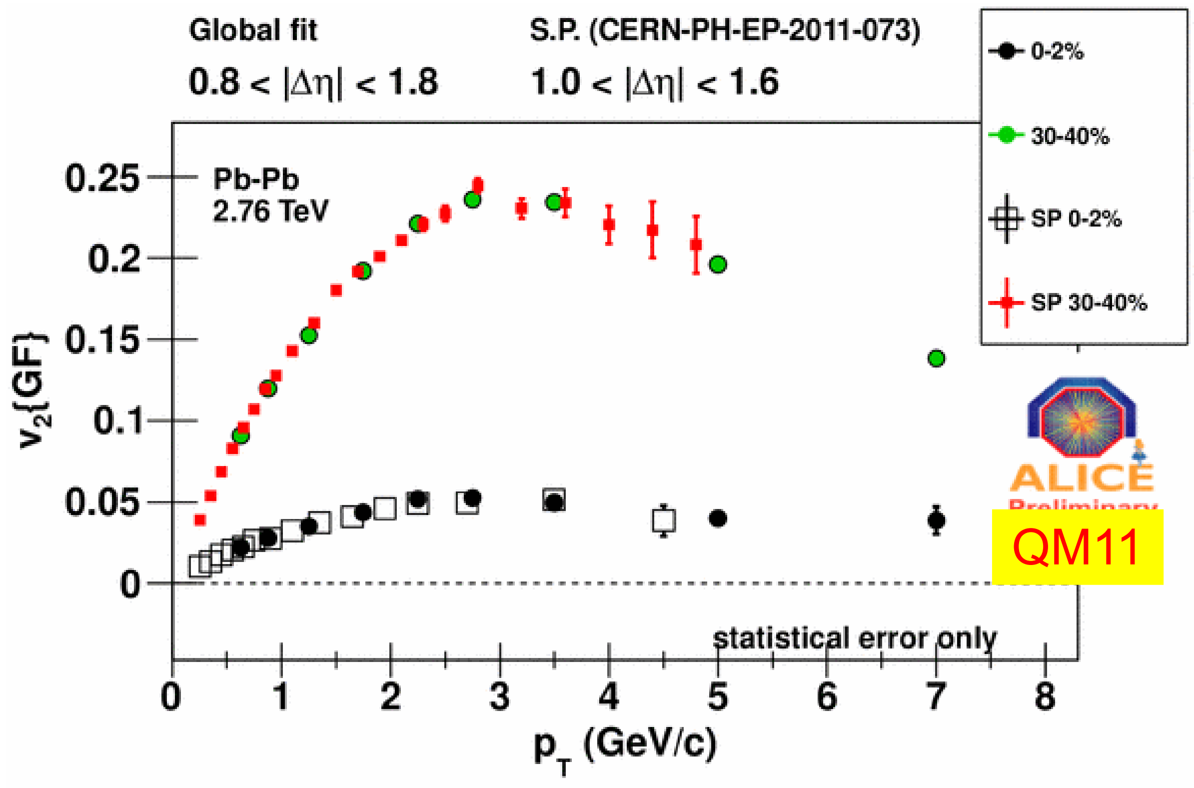
⇔ Also recoil jet up to p_T^{trig}>8 & p_T^{assoc} 6-8 in central

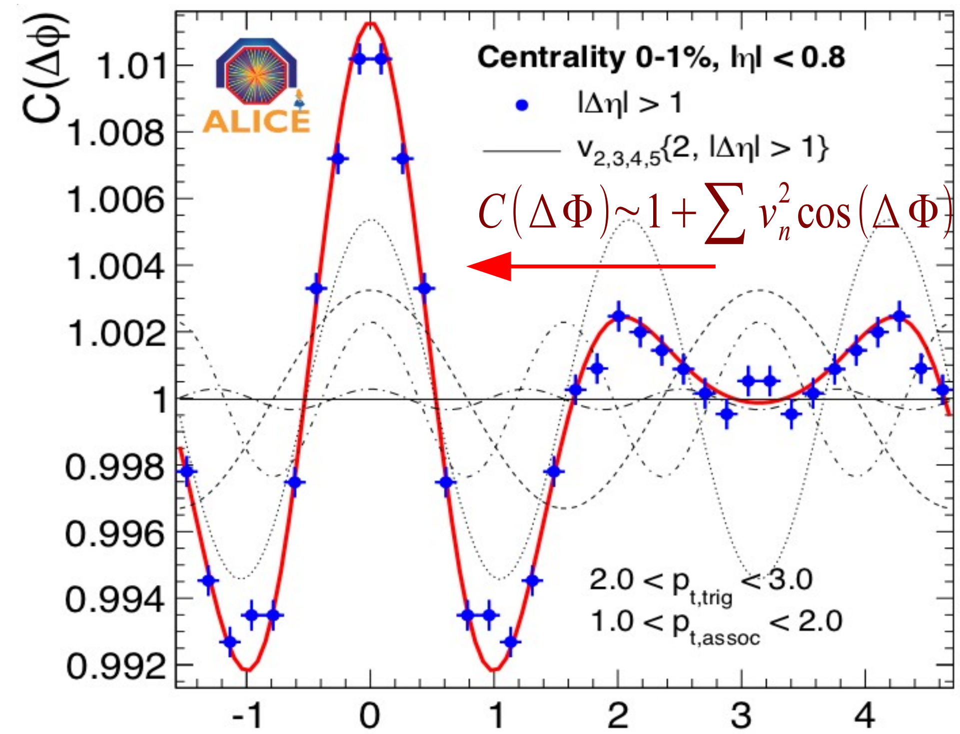
Correlations & hydrodynamics...

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



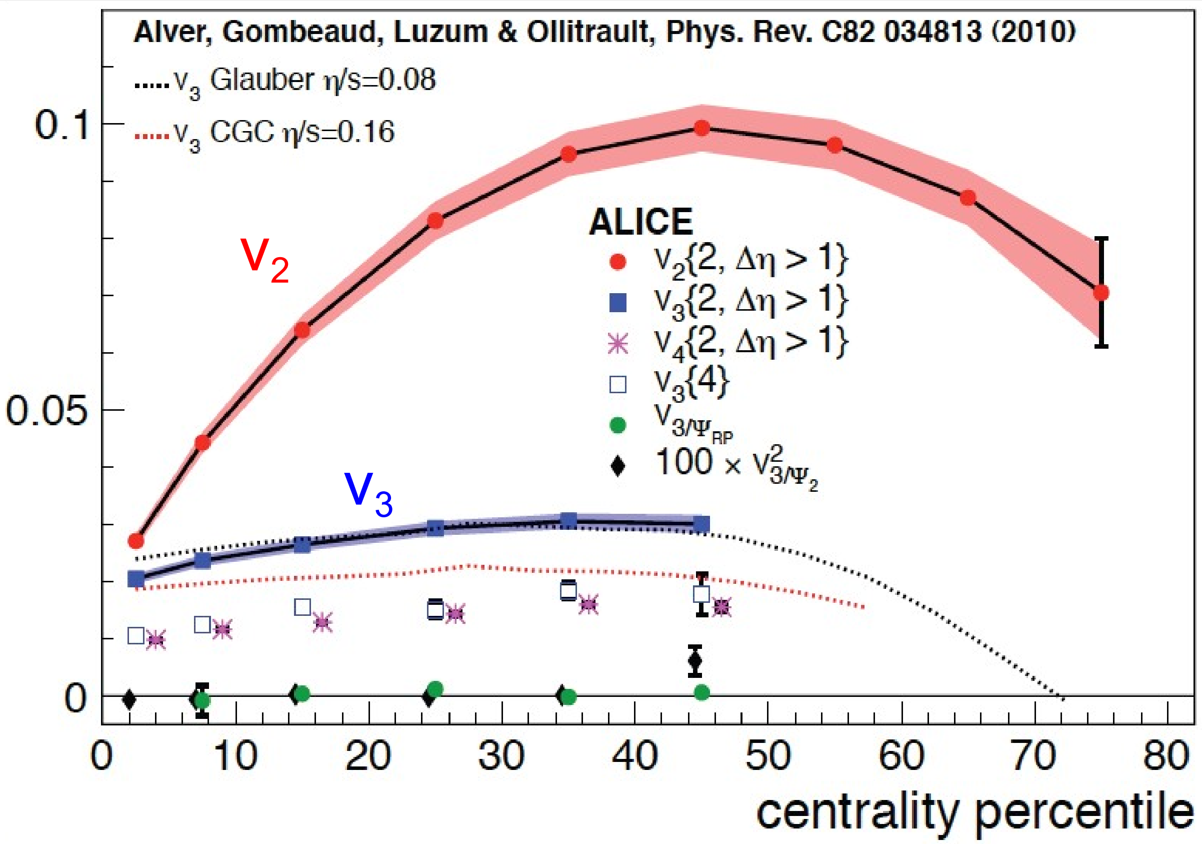


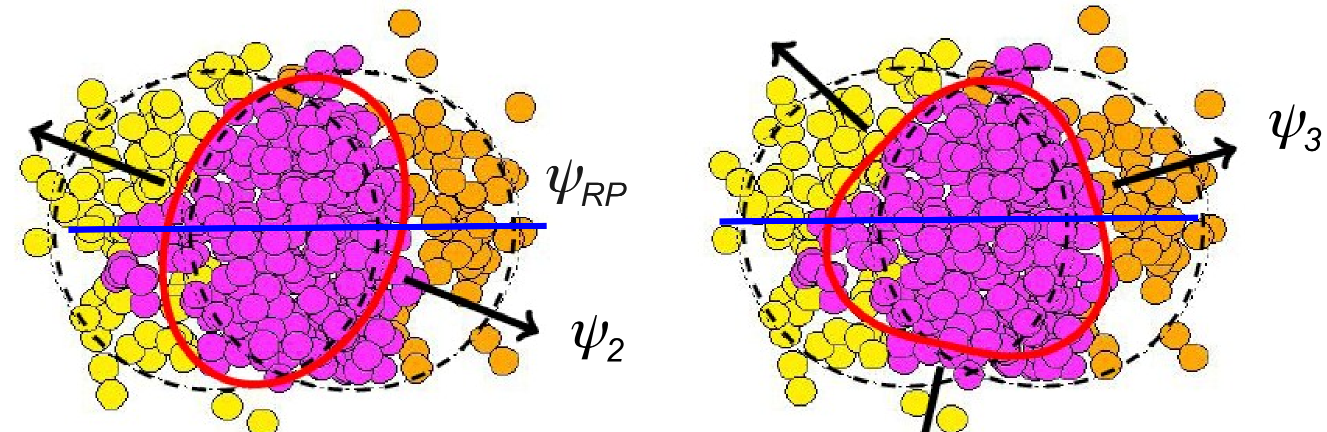
PRL, 107, 032301 (2011)

Global fits show:

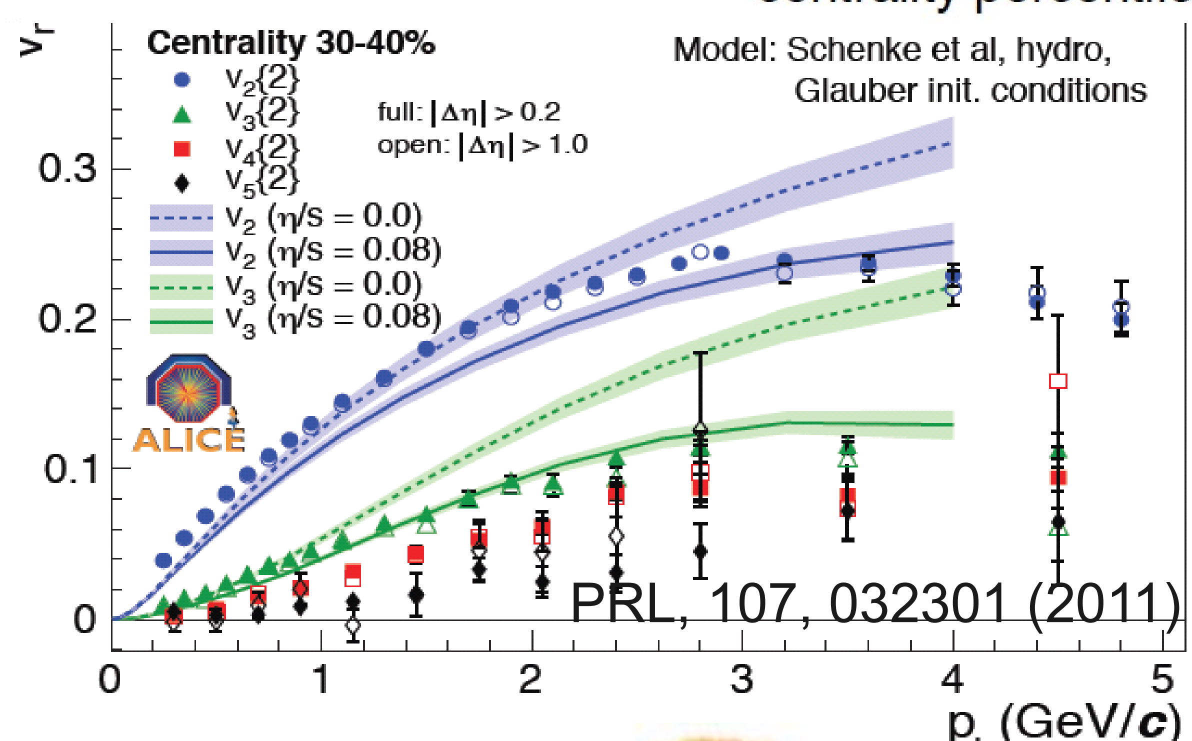
- Collective flow dominates to about 3-4 GeV/c for all n>1
- Description breaks for high pT or peripheral collisions
- For low pT: double peak and ridge structures seen in two particle correlations are naturally explained by measured anisotropic flow coefficients

Higher harmonics w.r.t. to event plane





Alver, Roland, 2010

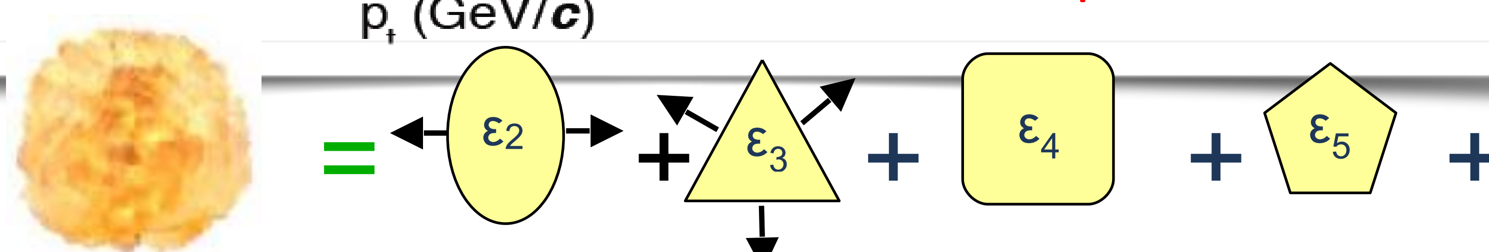


v_3 - triangular flow :
- weak centrality dependence
- vanishes as expected when measured w.r.t. reaction plane

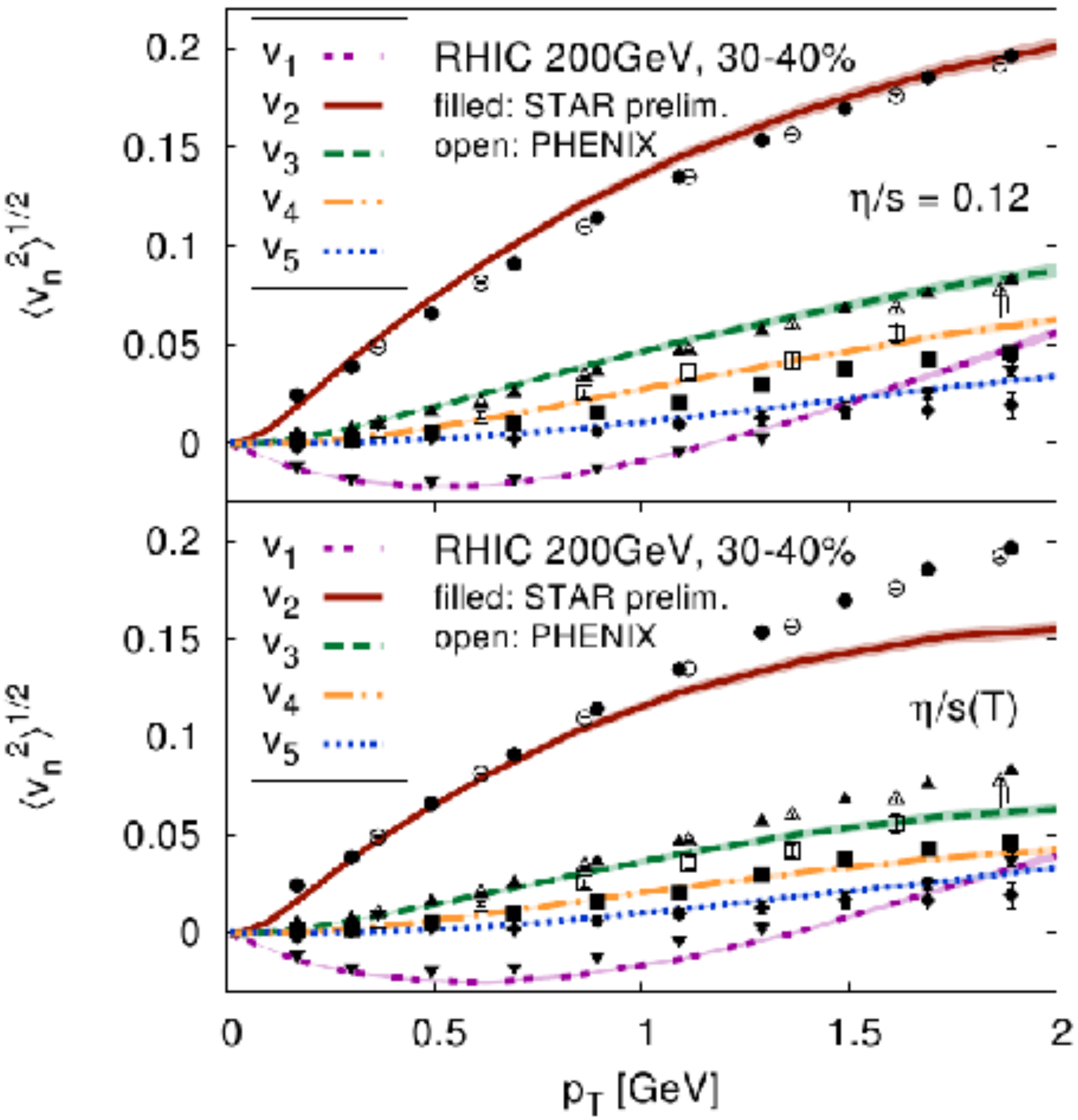
Similar pT dependence for all v_n

Higher harmonics - additional constraints on η/s

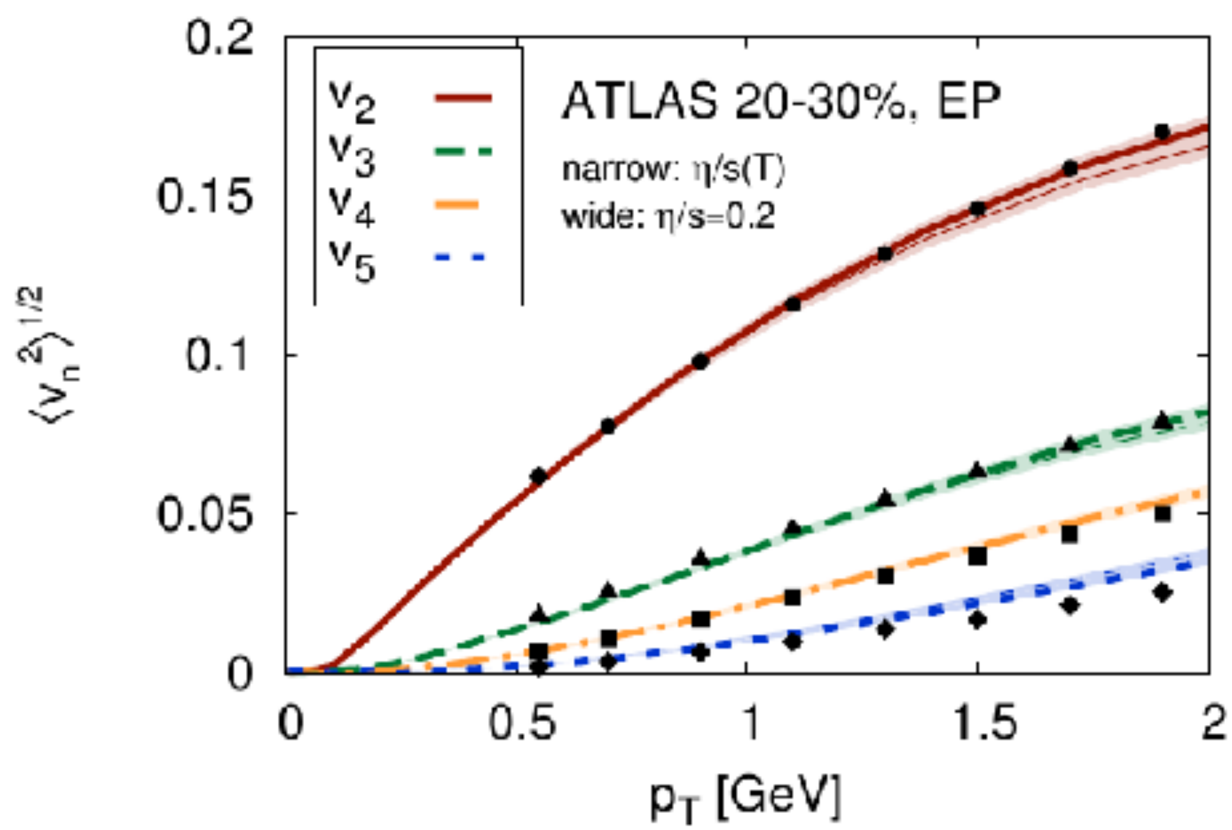
η/s small, similar as at RHIC



(viscous) fluid dynamics works!

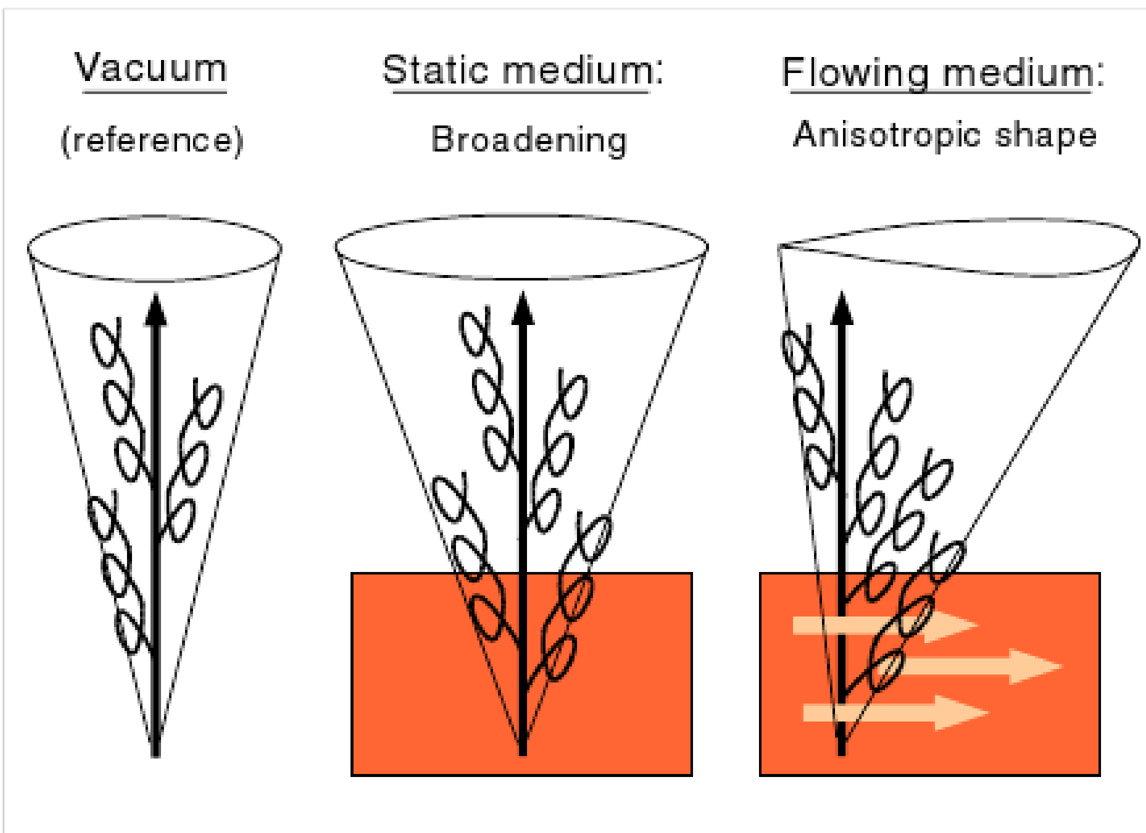


Good description of data for π+

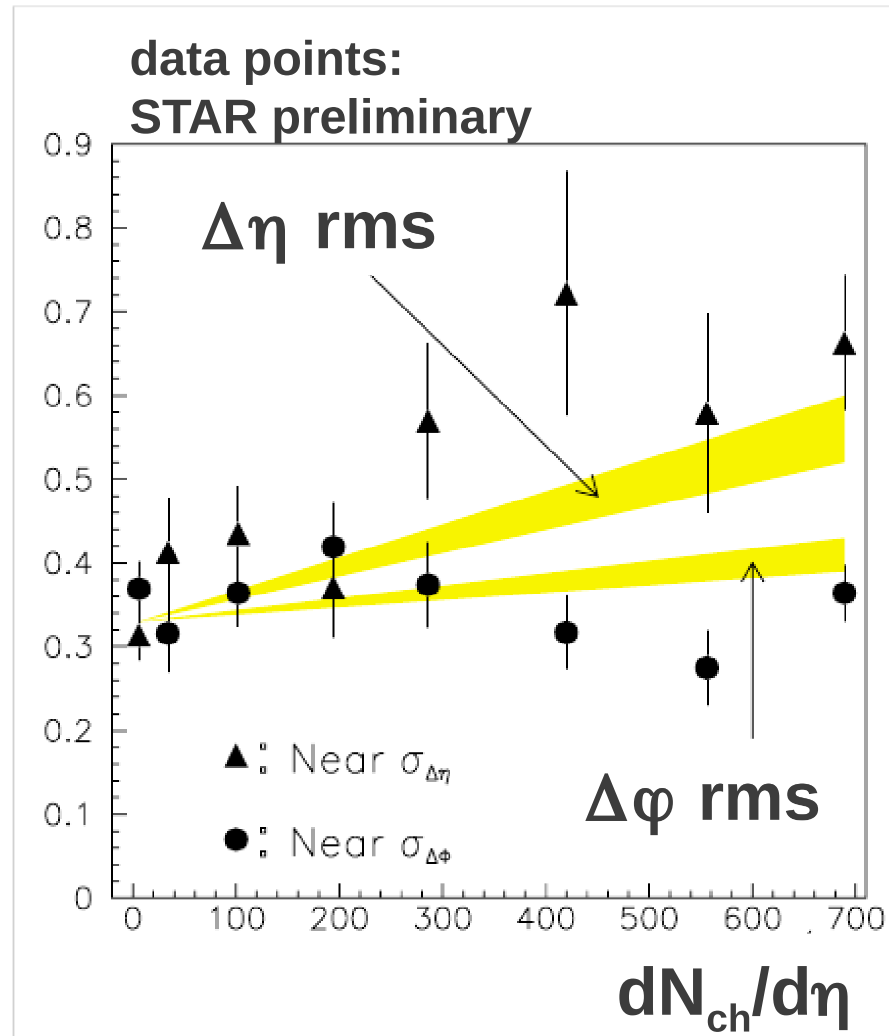


Small shear viscosity over entropy ratio: $$\frac{\eta}{s} \leq 0.25$$

Jet-medium-flow coupling via two particle correlations?



N. Armesto, C. Salgado, U. Wiedemann:
Measuring the Collective Flow with Jets
[PRL 93,242301 (2004)]

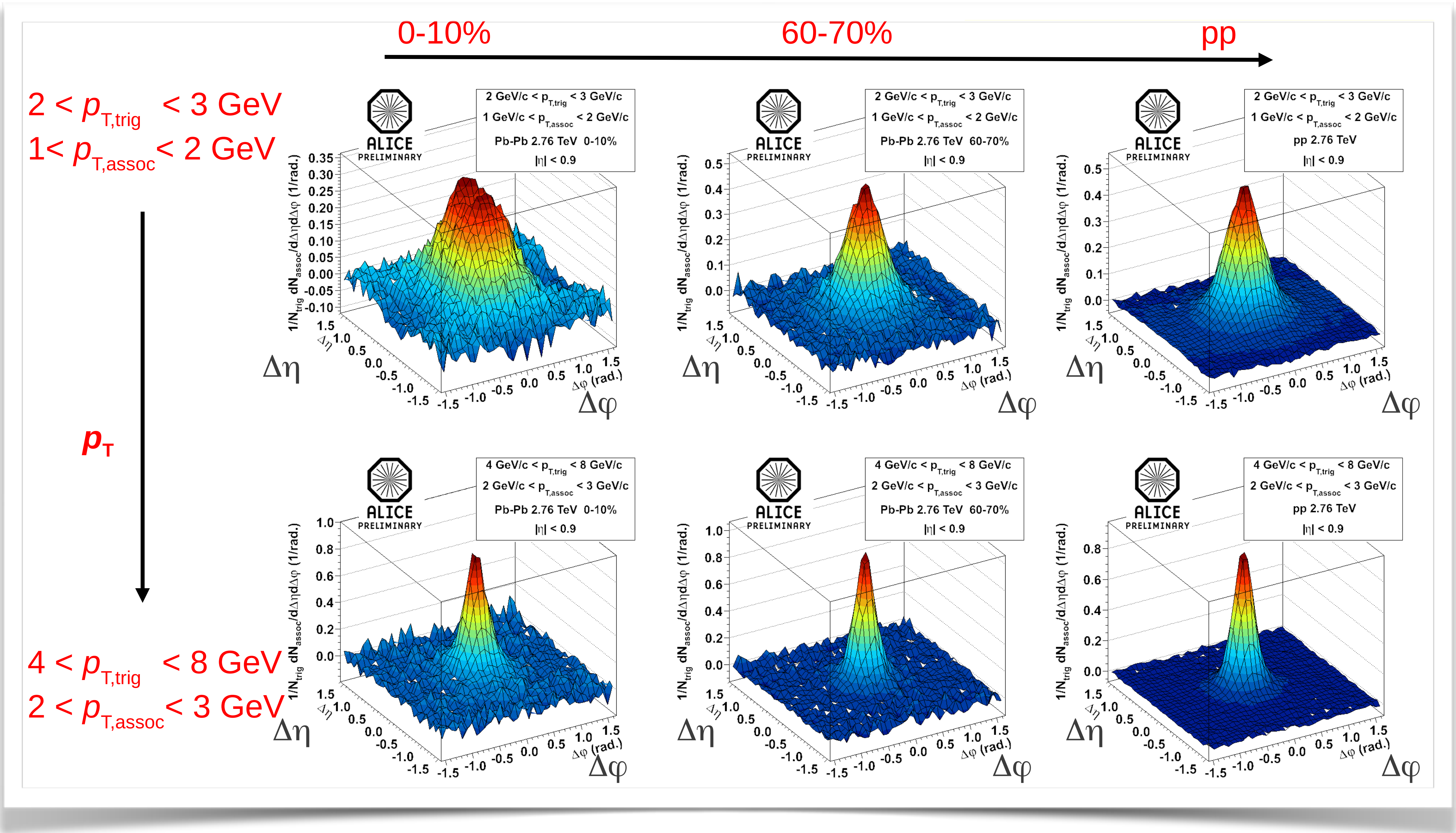


PRL 93,242301 (2004)

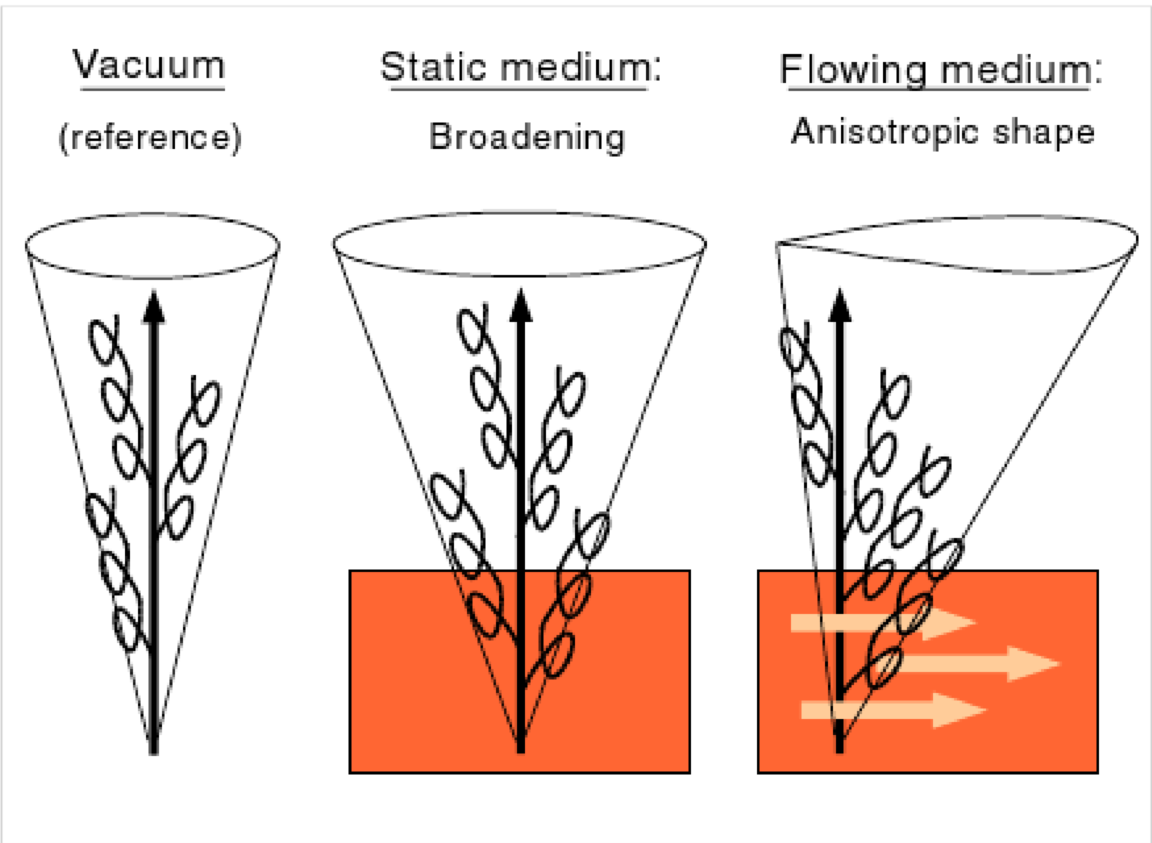
=> LHC? - more jets + somewhat more flow...

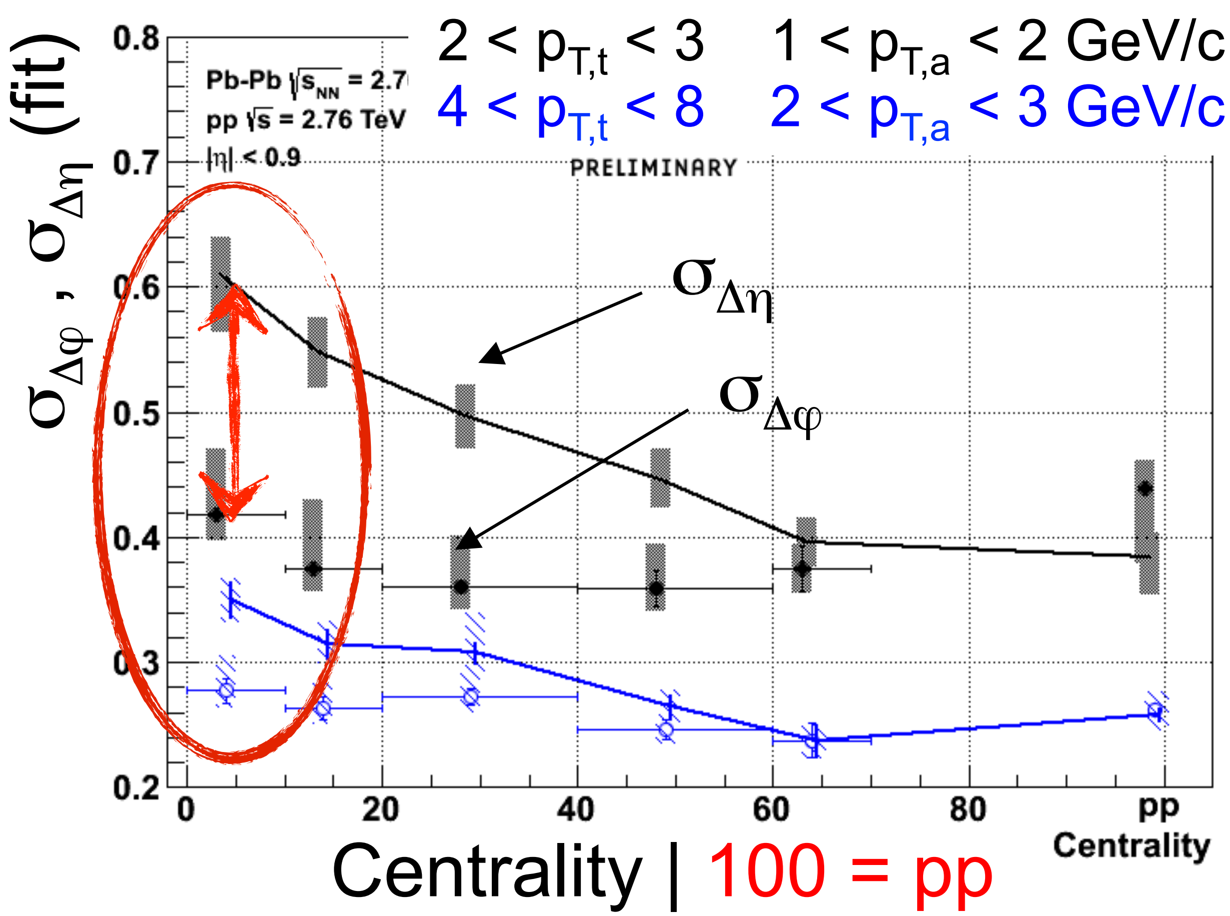
Jet-peak shape evolution - intermediate pT

Wider peak in central collisions
Peripheral and p-p similar shape
Strong pT dependence
=> Characterize the peak



Measuring widths of the correlations in azimuth and pseudo-rapidity



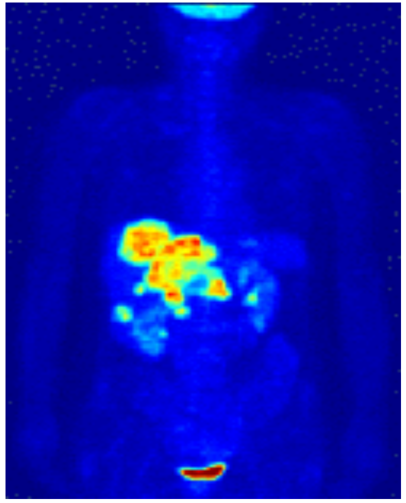


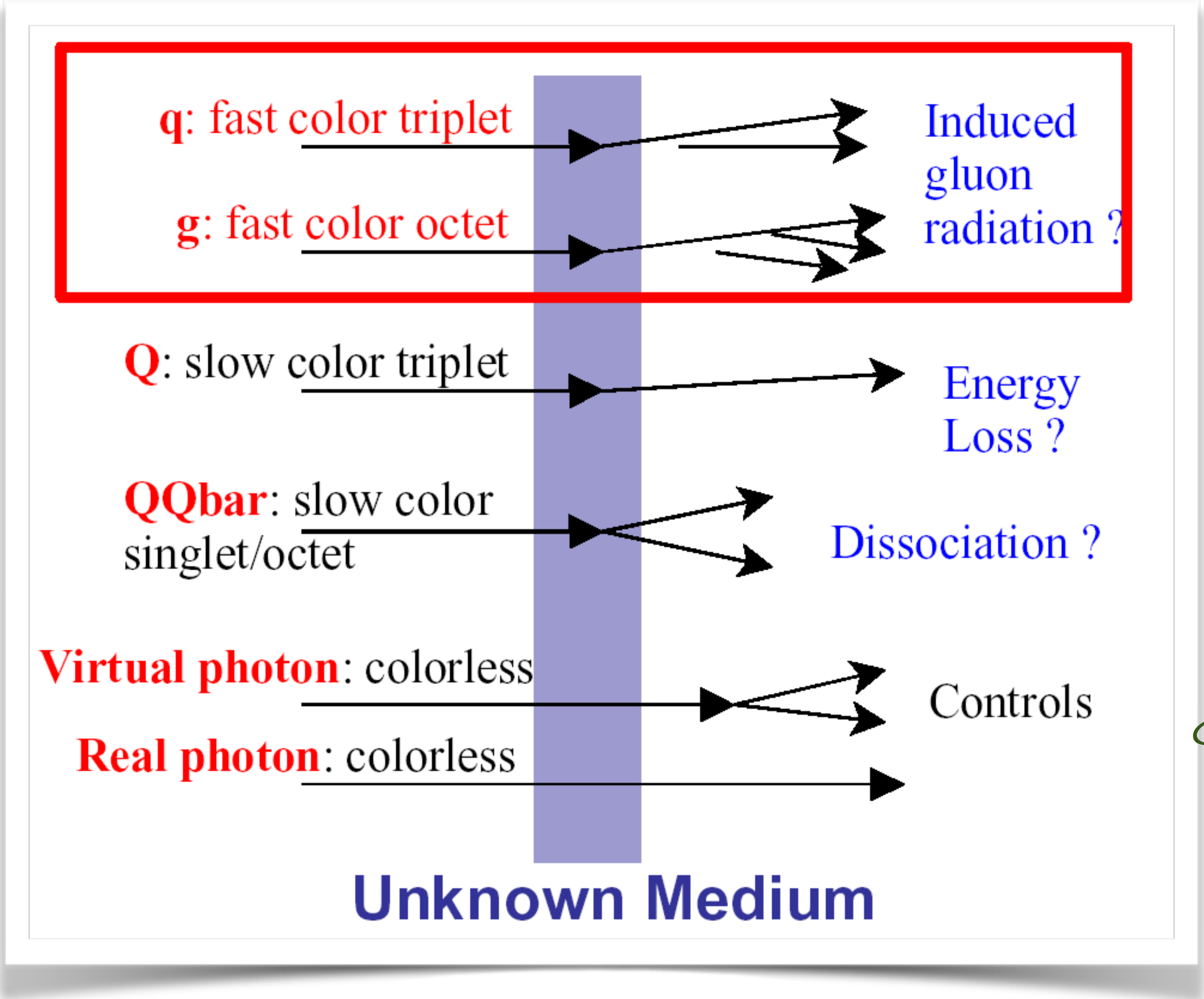
Measure of jets interactions with longitudinal flow (?)

- AMPT (**A** **M**ulti**P**hase **T**ransport Code)
  - Initial conditions simulated using HIJING
  - Parton scattering
  - Hadronization: Lund model + coalescence
  - Hadron scattering
- AMPT describes the main features of the near-side shape evolution observed in data

Probing an unknown medium...

Probing the unknown medium...





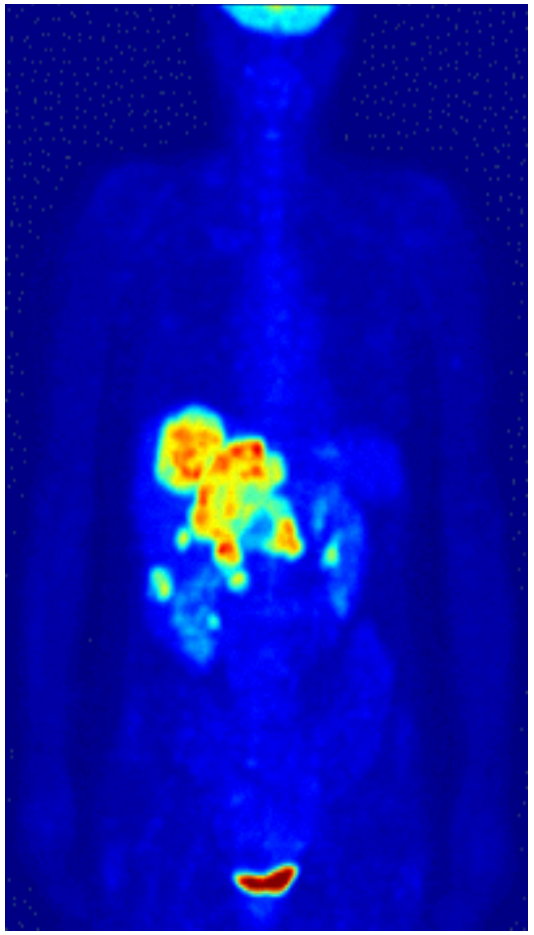
jet suppression (quenching)

charm/bottom dynamics

J/ψ & Υ

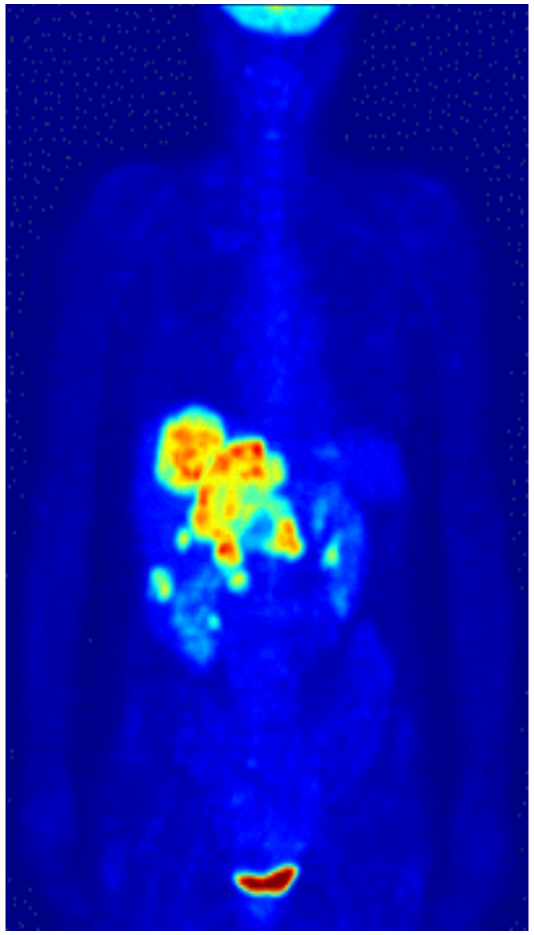
color-less particles

How to probe a patient that comes for only O(micro sec.)?



Human body

How to probe a medium that lasts only O(micro sec.)?

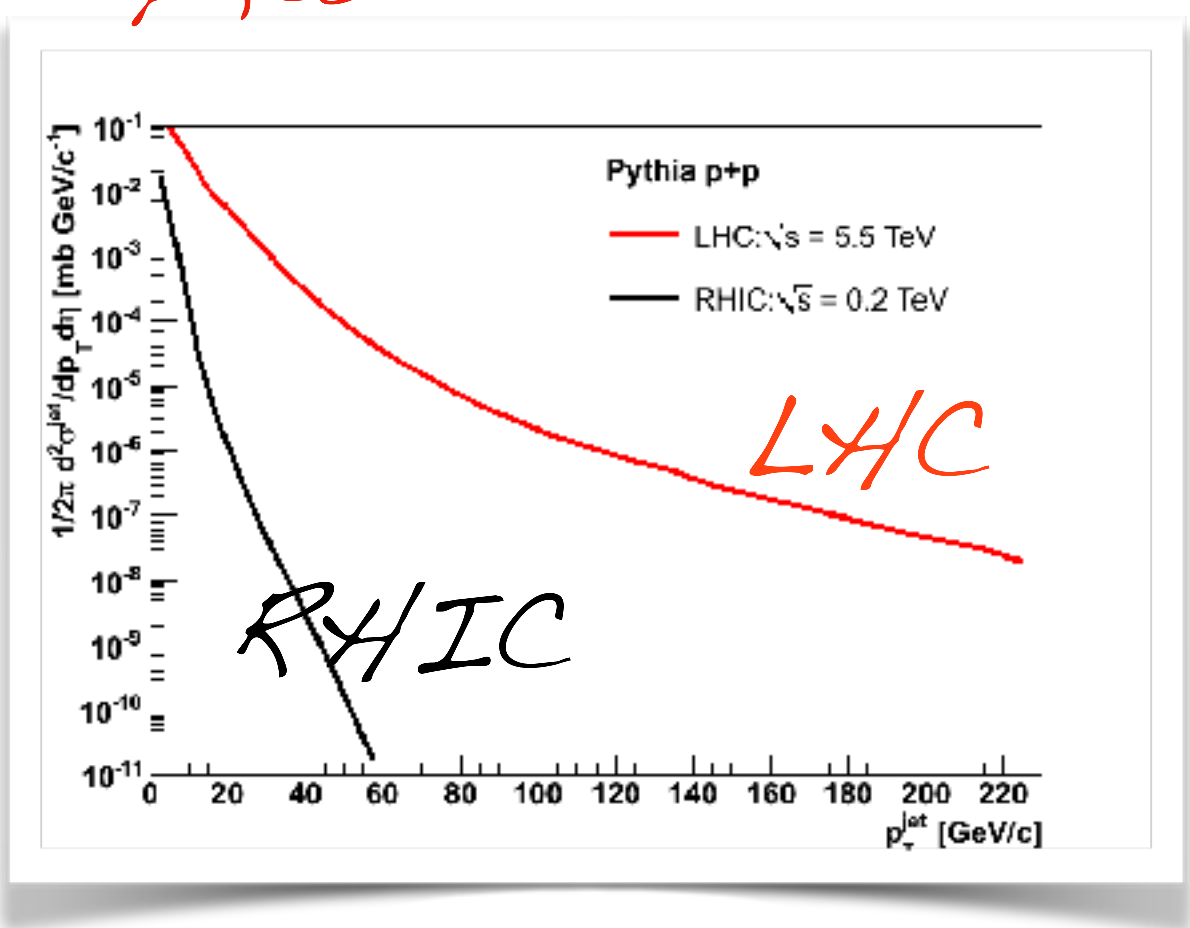


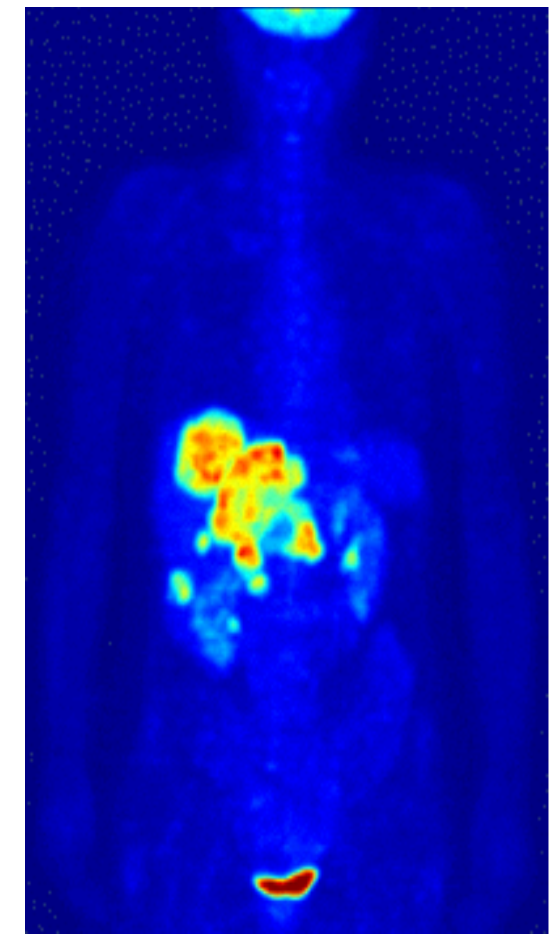
Human body

… 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)…

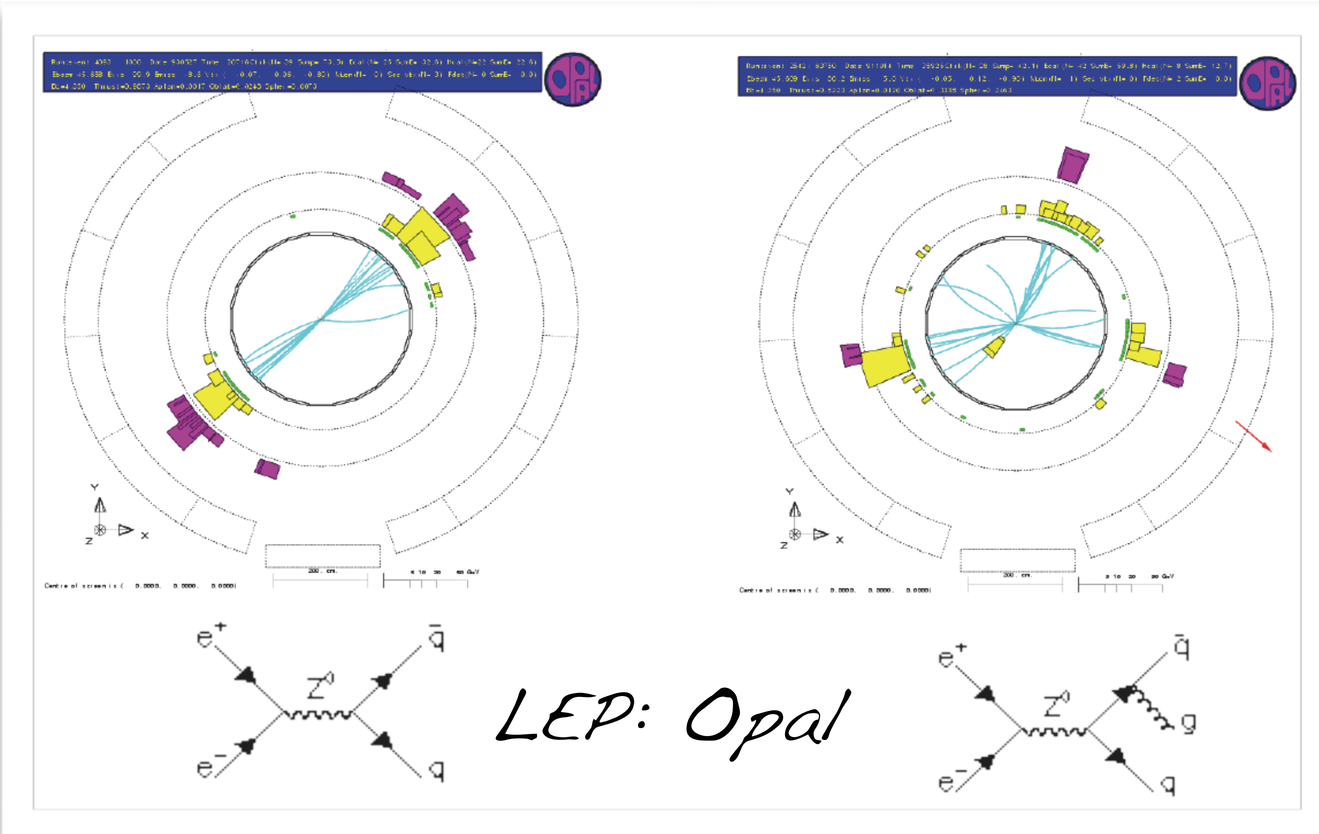
<=> critical input from pp (vacuum) measurements - pQCD

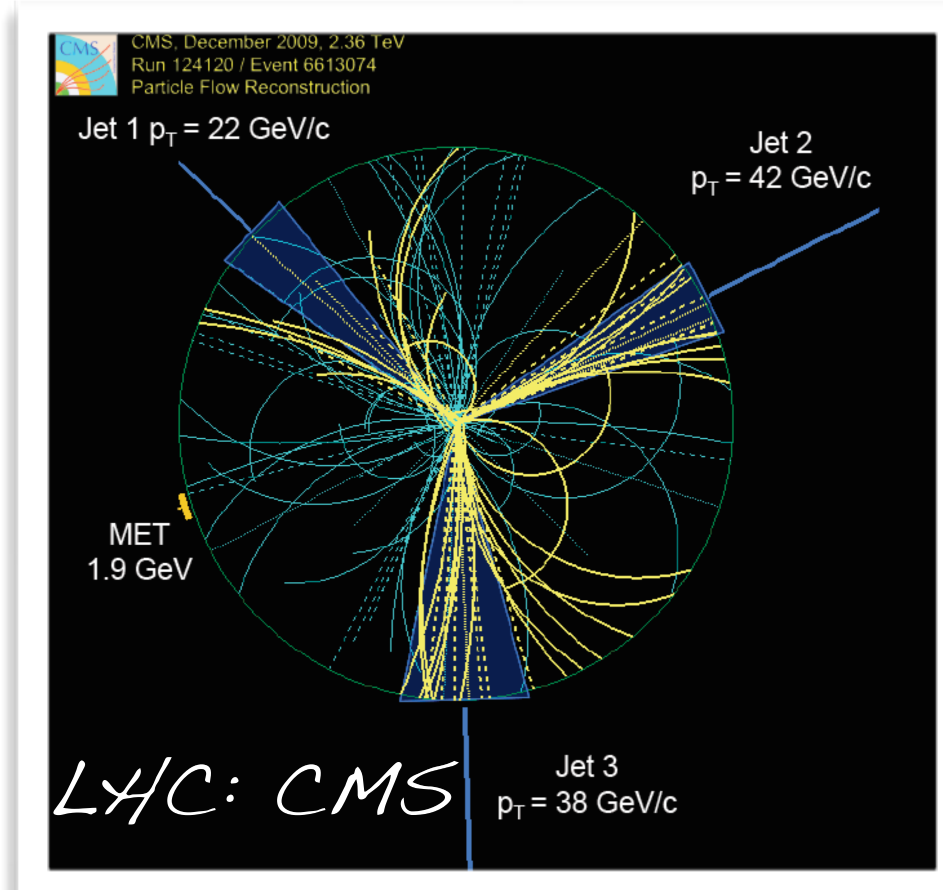


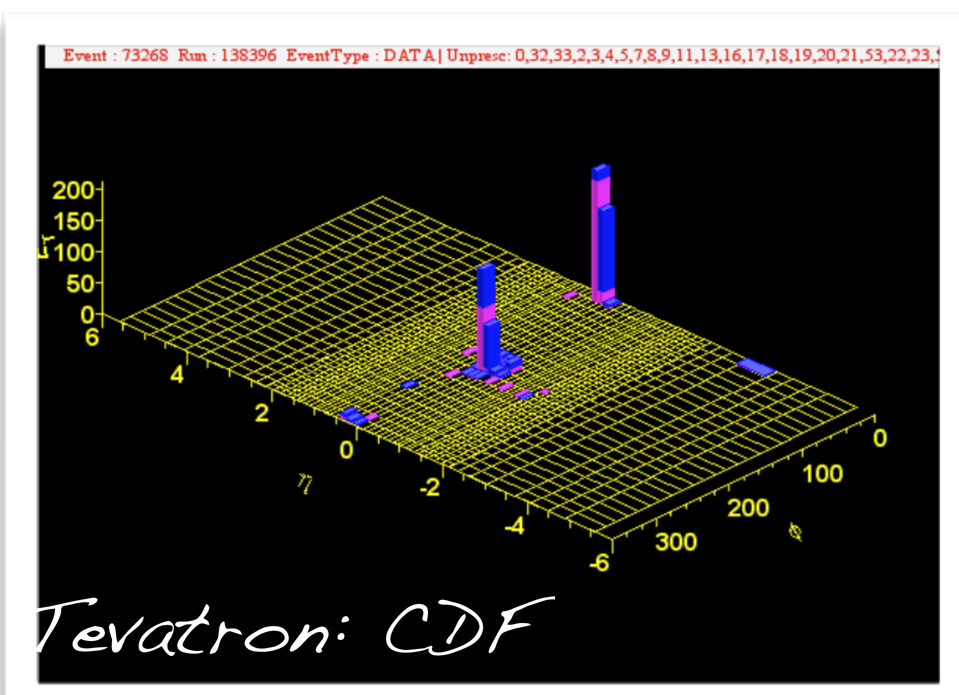


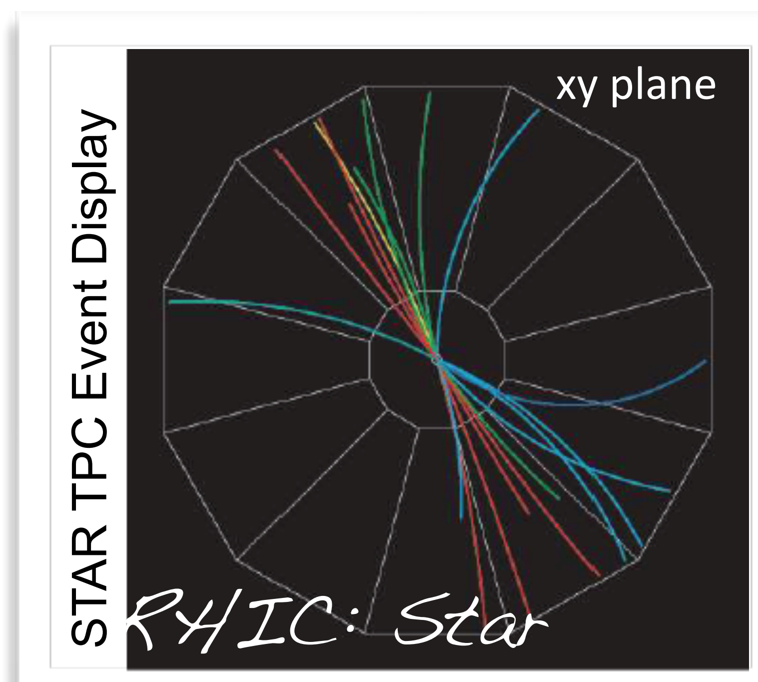
Human body

Jets in collider experiments









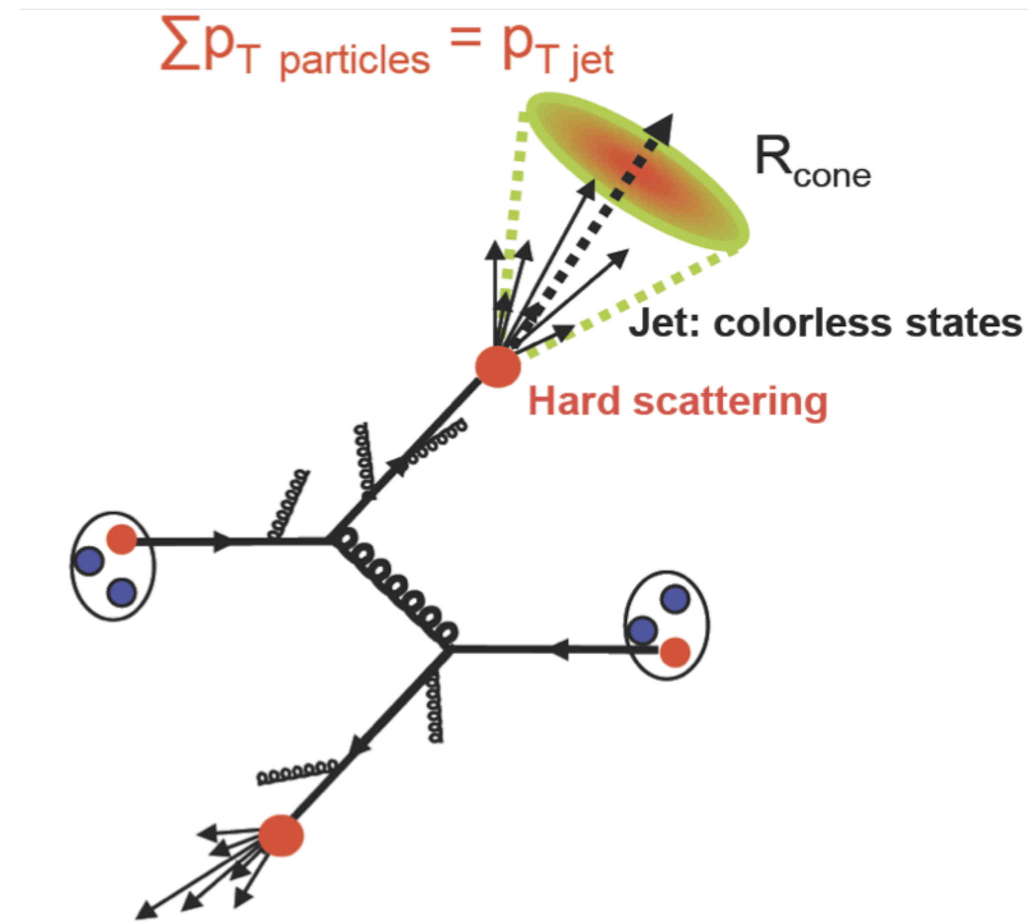
What is a jet?

A spray of collimated showers/particles
- Hardly ever better defined...

Jet = Parton AND its radiation

Note: experiment measures spray of particles (~hadrons)

Jets (unlike single hadrons) are objects which are "better" understood/ calculable within pQCD

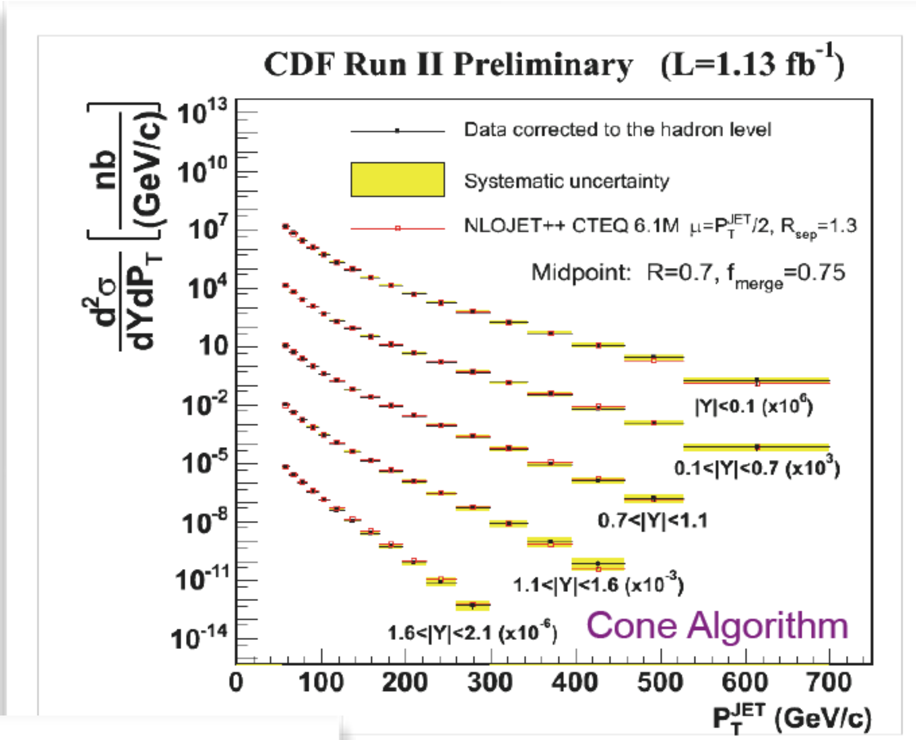


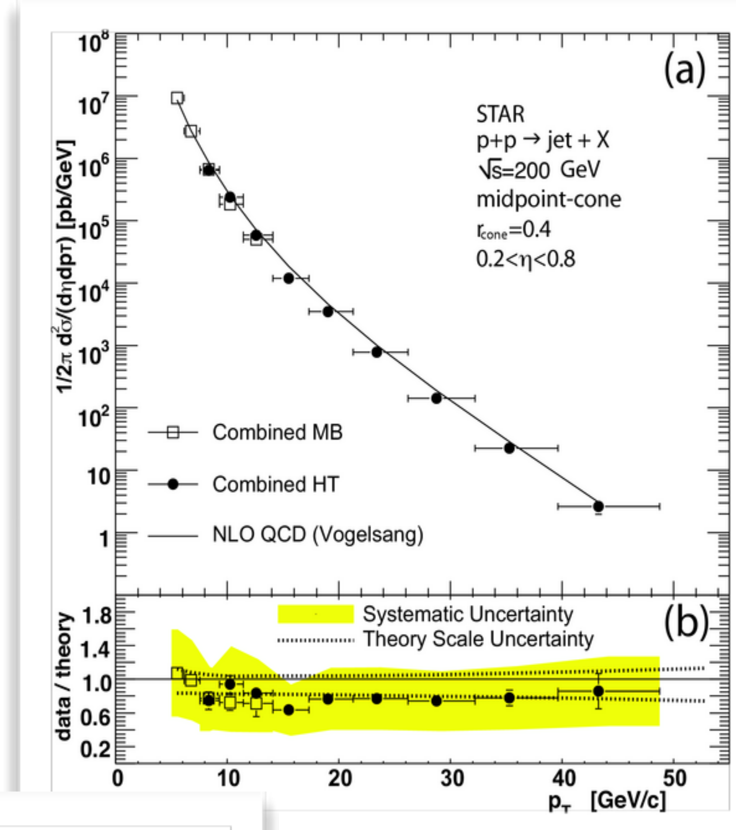
S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) ...

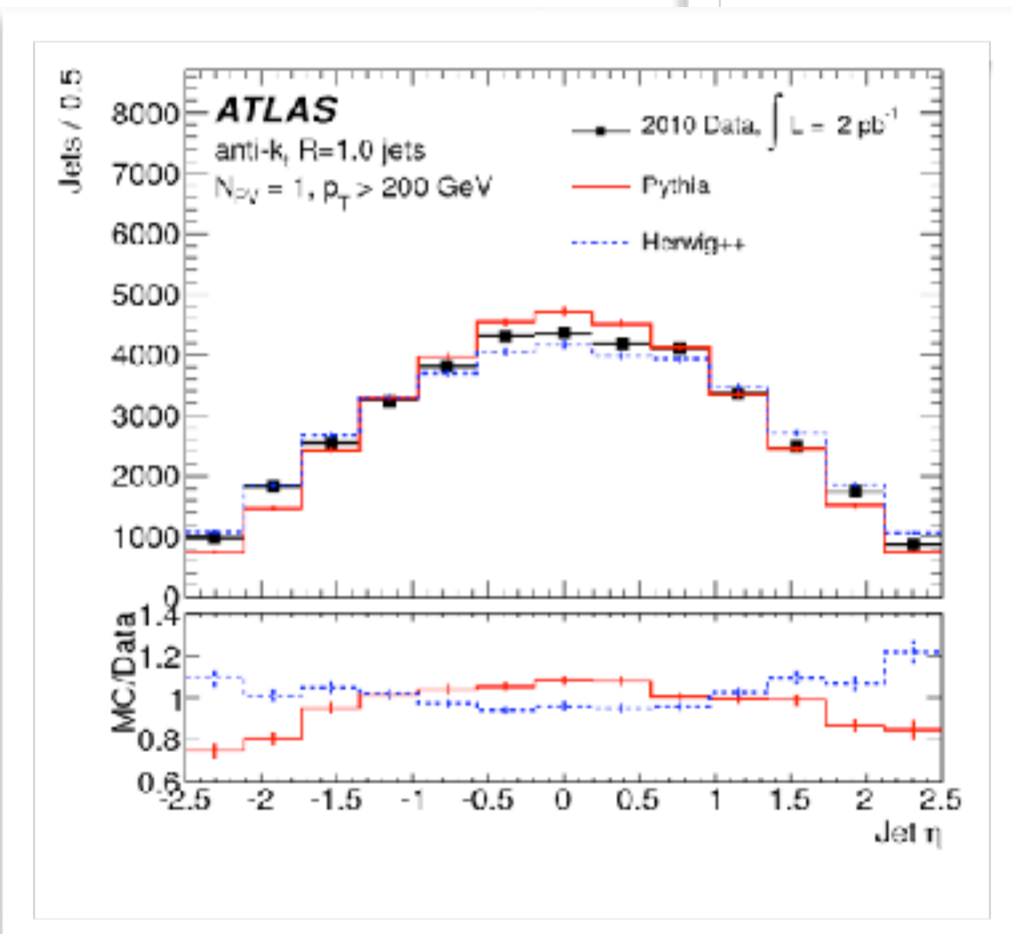
Jets in collider experiments

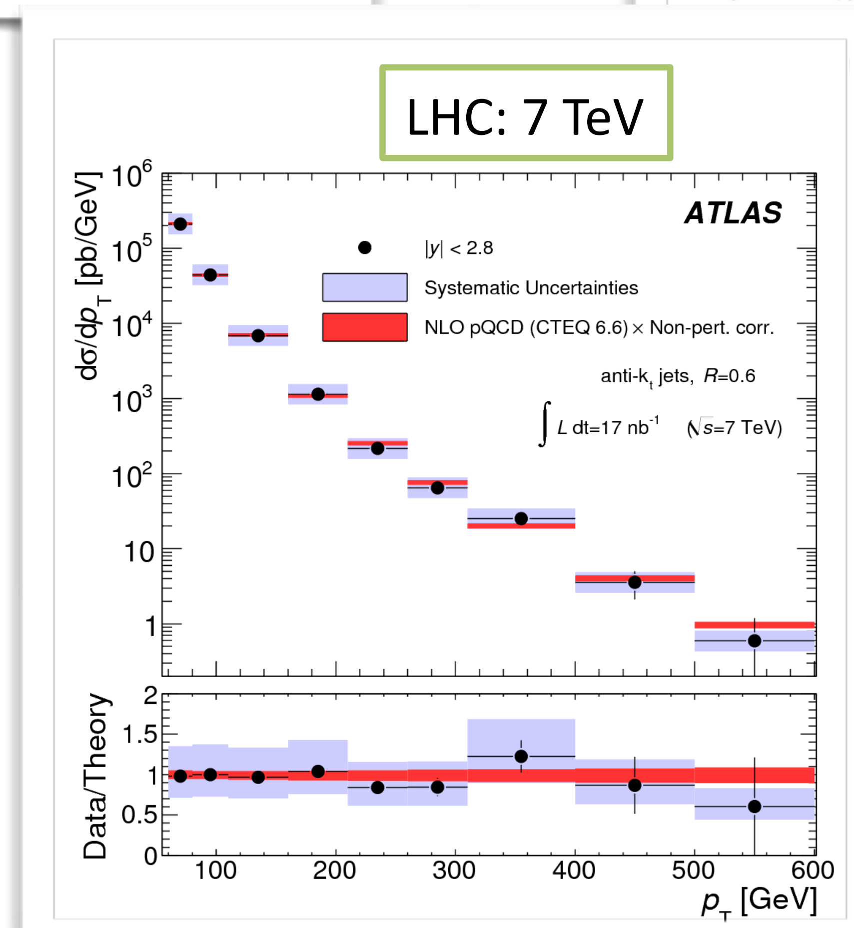
Jets are fairly well known by now... and well described by theory and MC

=> attractive tool for heavy-ions









Hadronic collisions: pQCD and jets

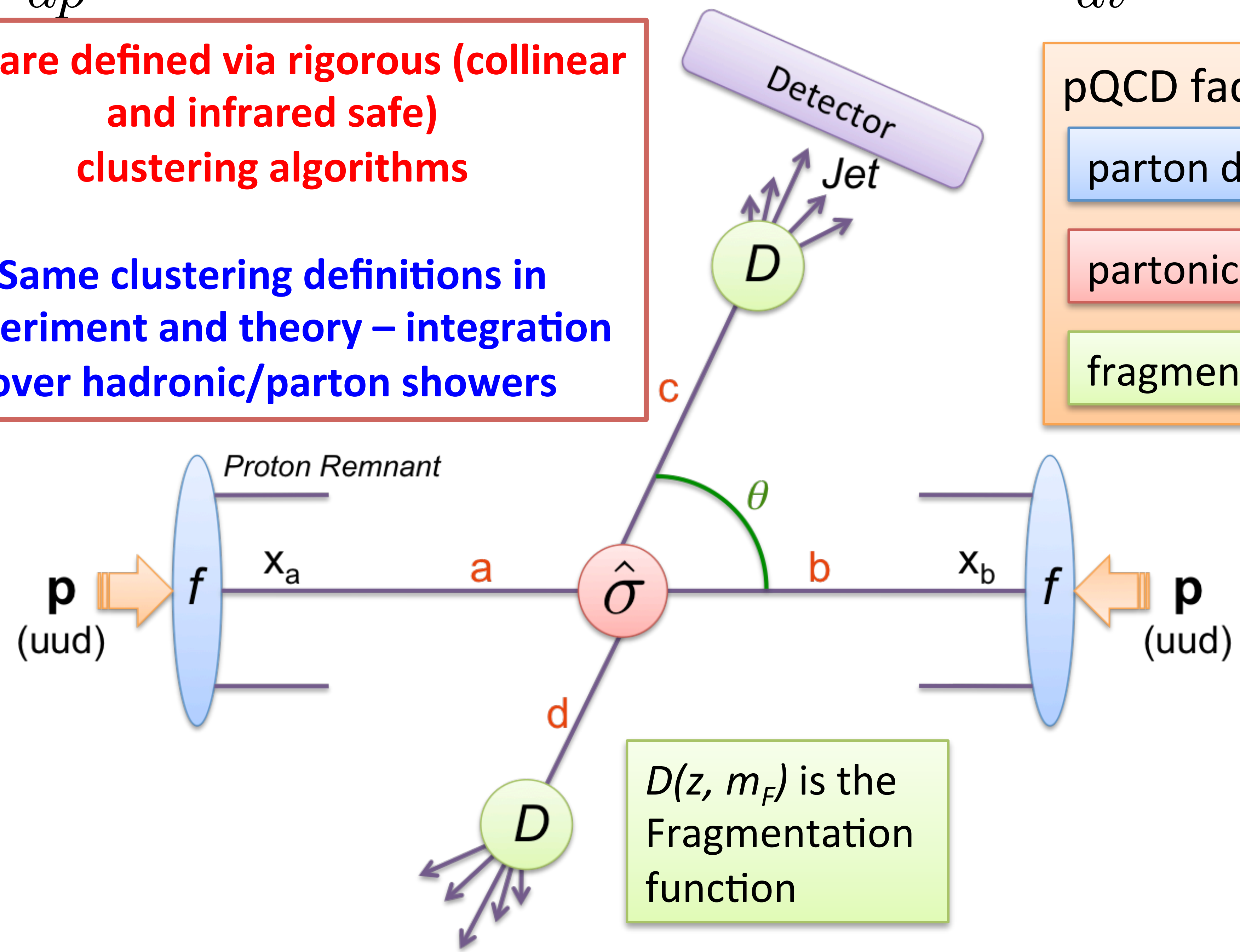
$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}(z_c, Q^2)$$

Jets are defined via rigorous (collinear and infrared safe) clustering algorithms

Same clustering definitions in experiment and theory – integration over hadronic/parton showers

pQCD factorization:

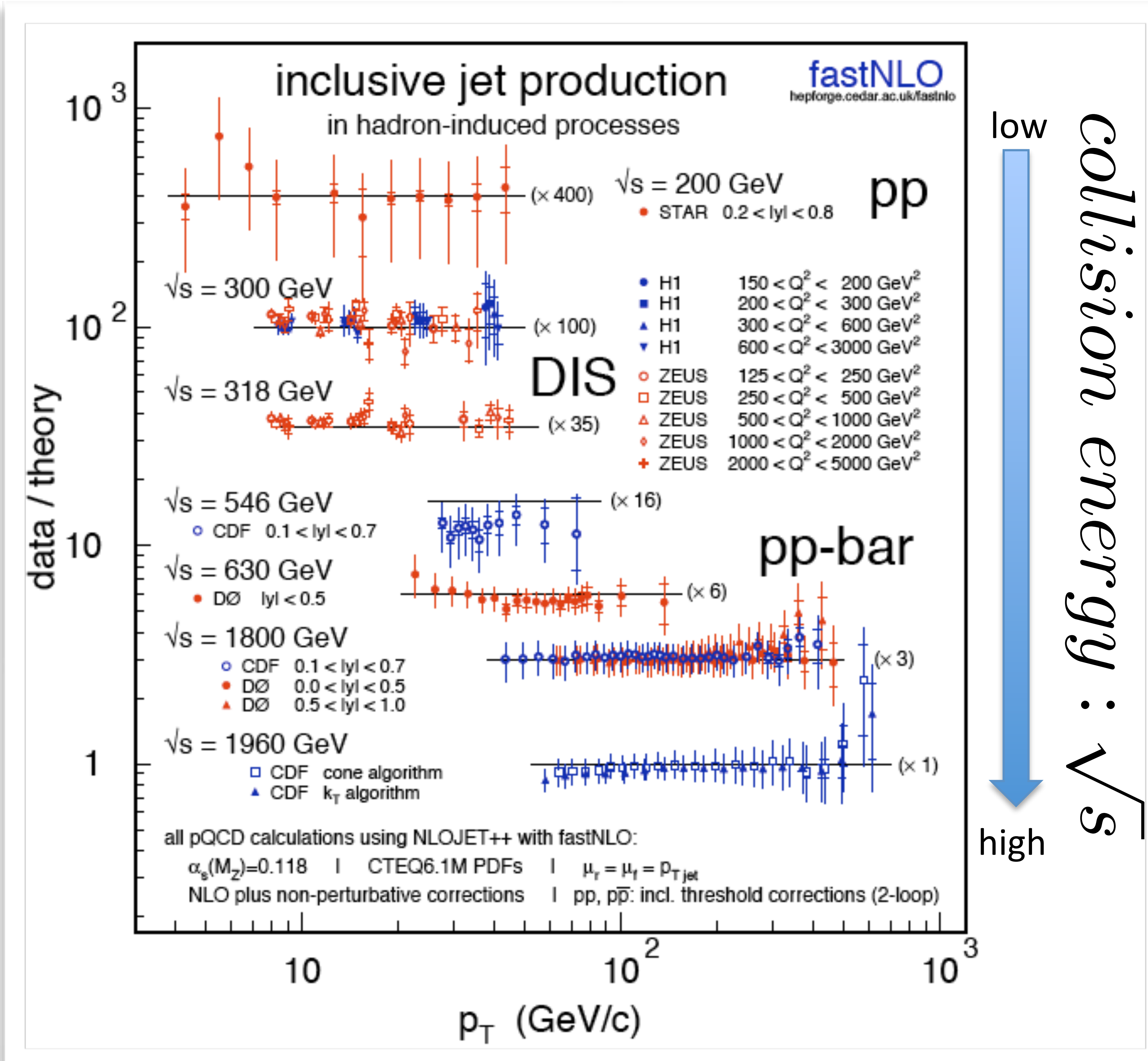
- parton distribution fn $f_{a/A}$
- partonic cross section
- fragmentation fn $D_{h/c}$

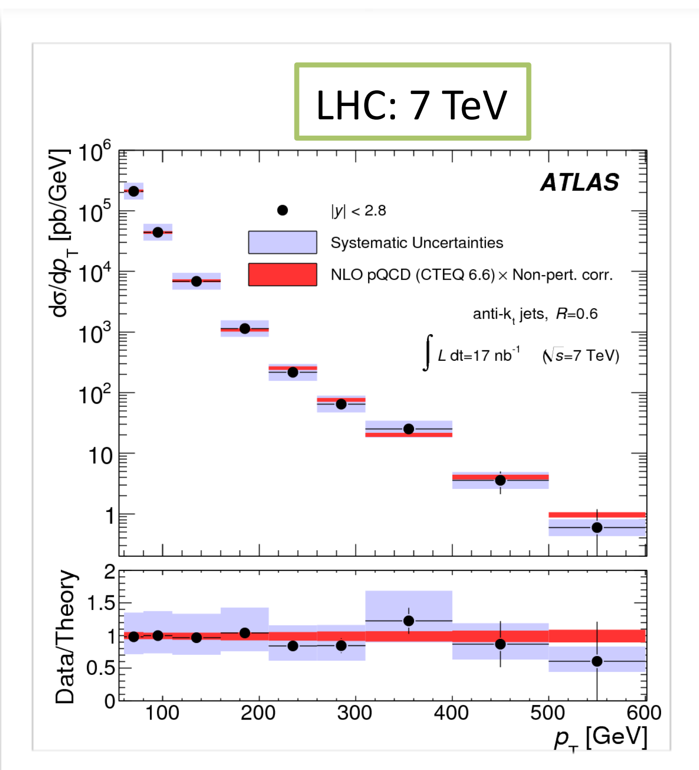


Inclusive jet production: pQCD & data

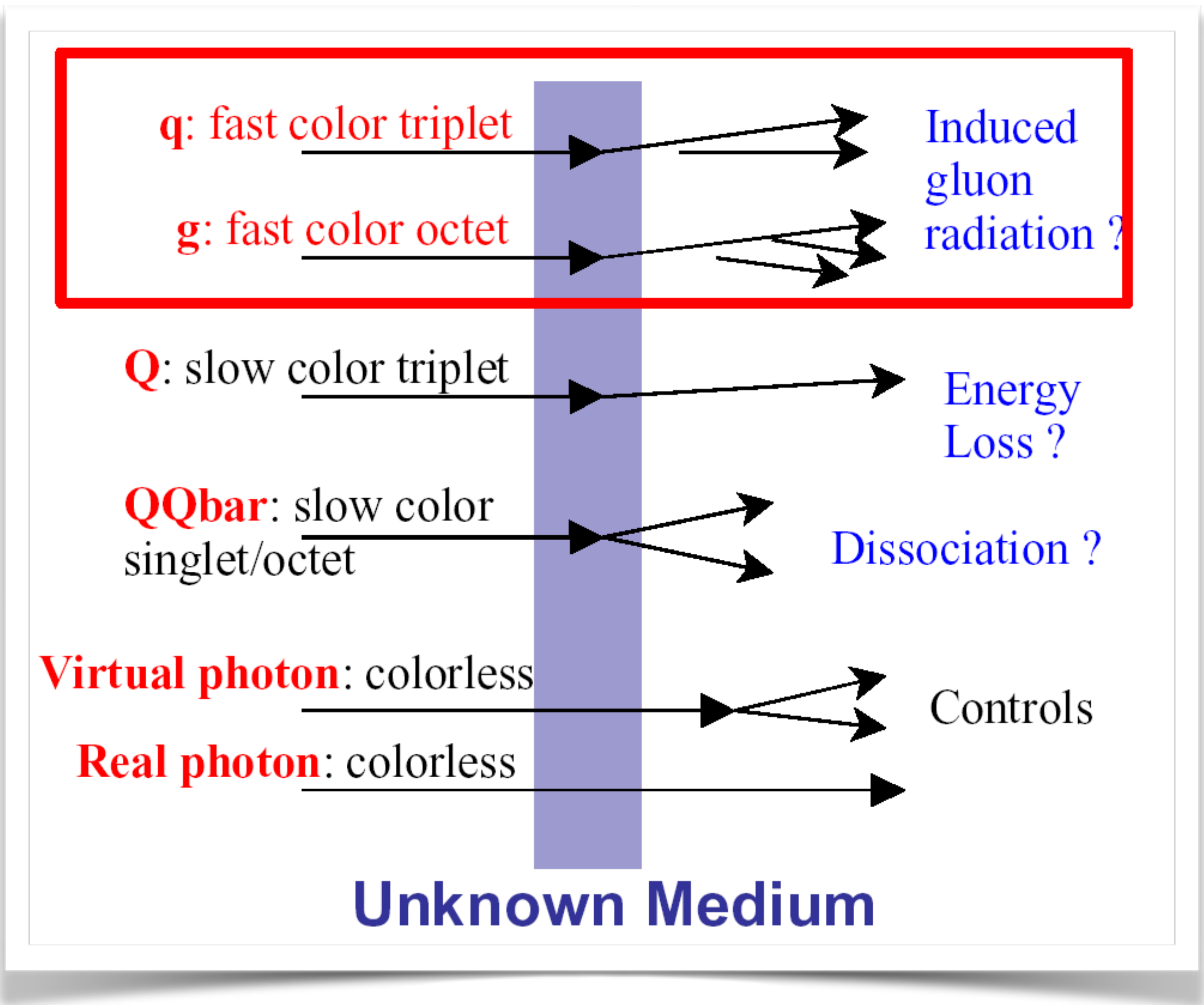
Jets are fairly well known by now... and well described by theory and MC

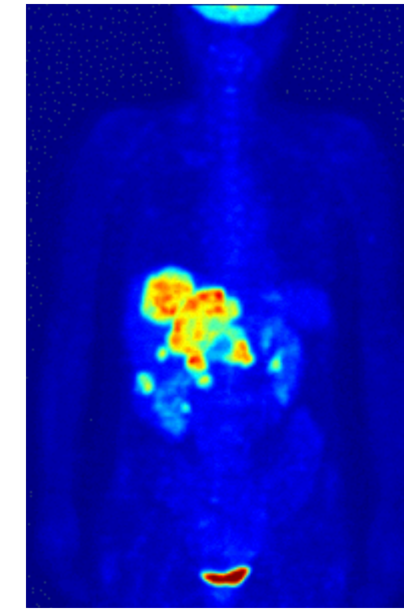
=> attractive tool for heavy-ions





Probing the unknown medium...




Human body

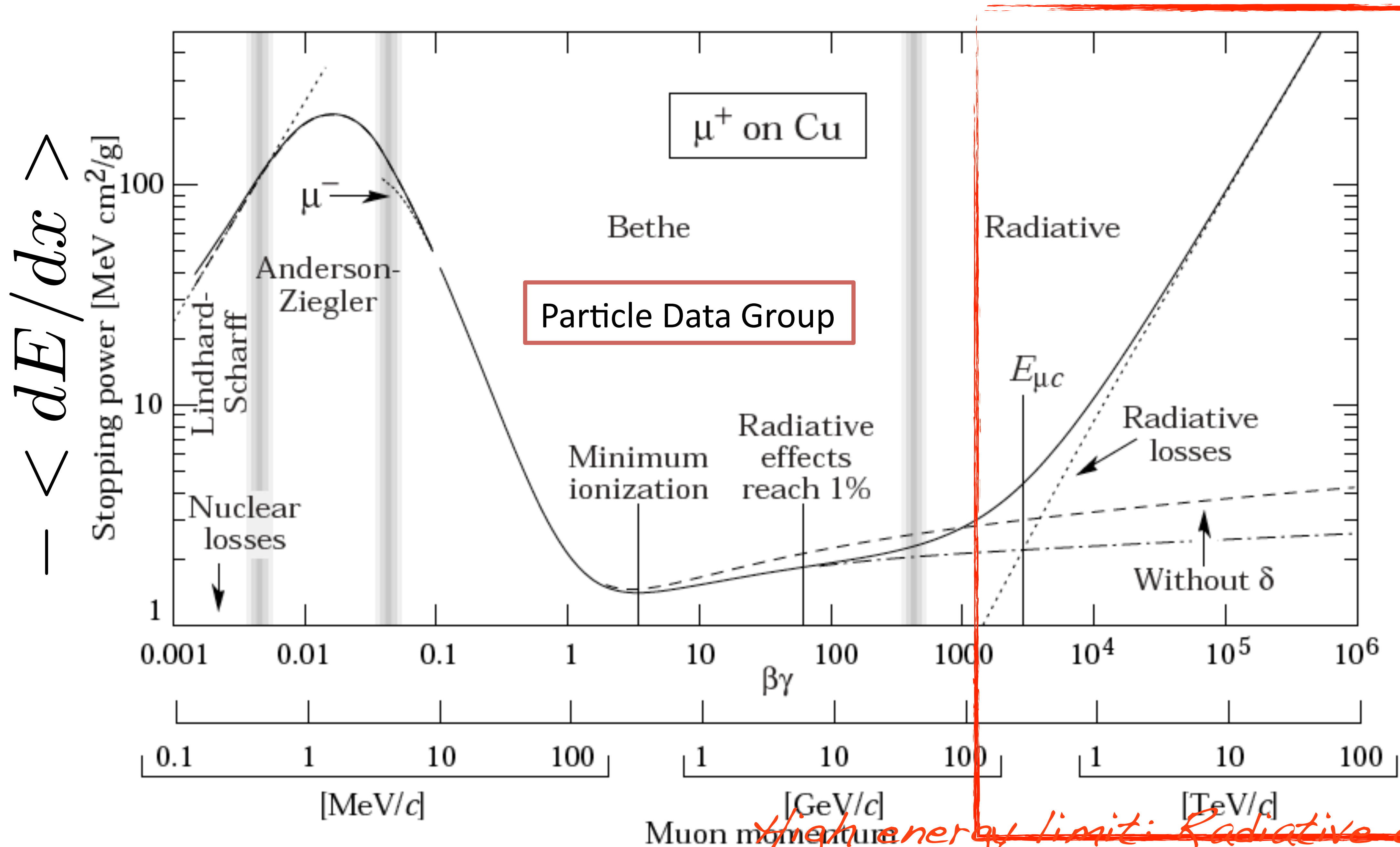
jet suppression (quenching)

charm/bottom dynamics

J/ψ & ϒ

color-less particles

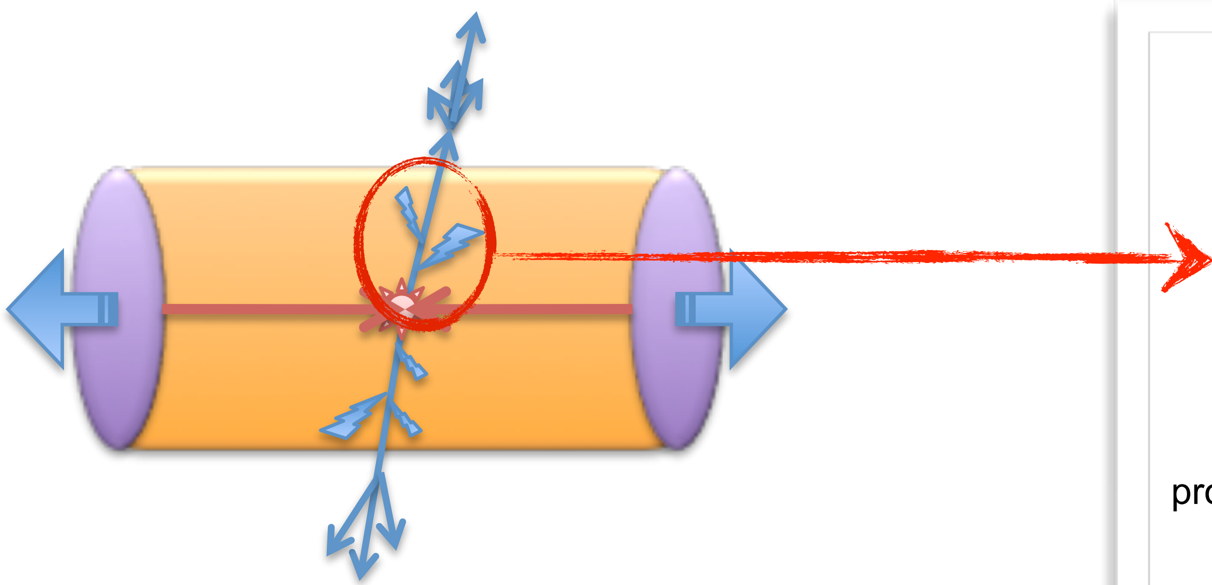
QED: Passage of electrically charged particle through

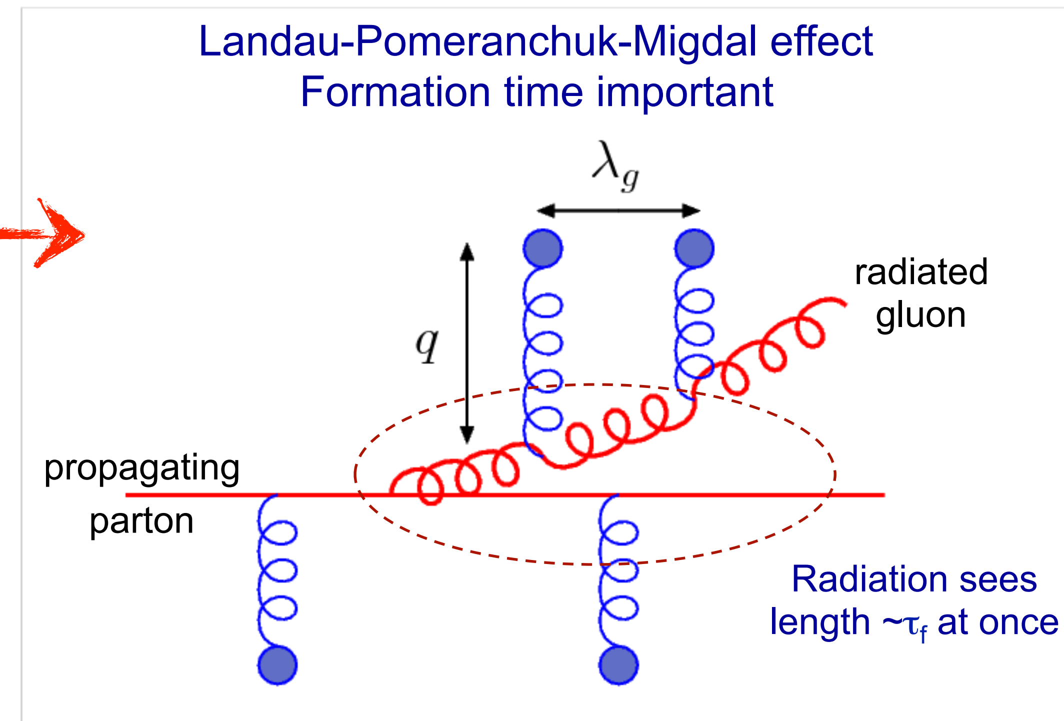


High energy limit: Radiative energy loss

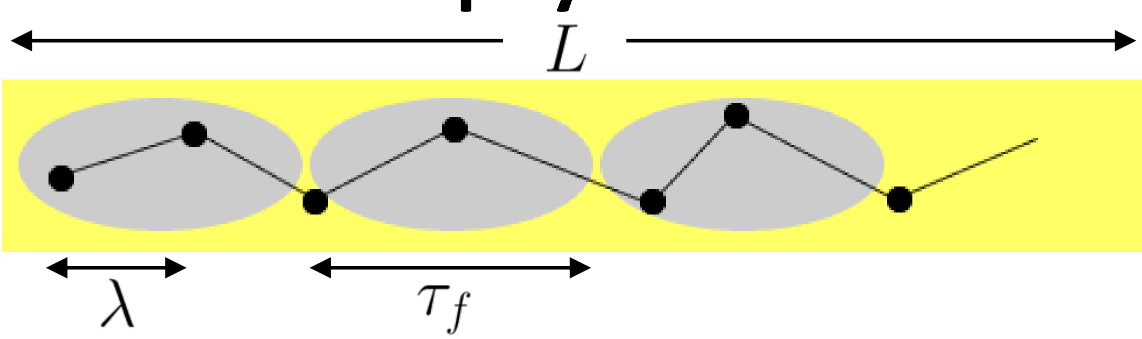
What is the equivalent in QCD?

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)

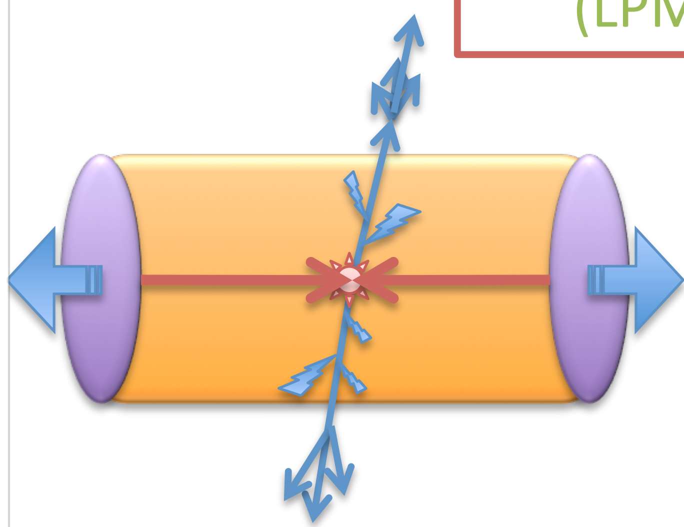
Bremsstrahlung in QCD

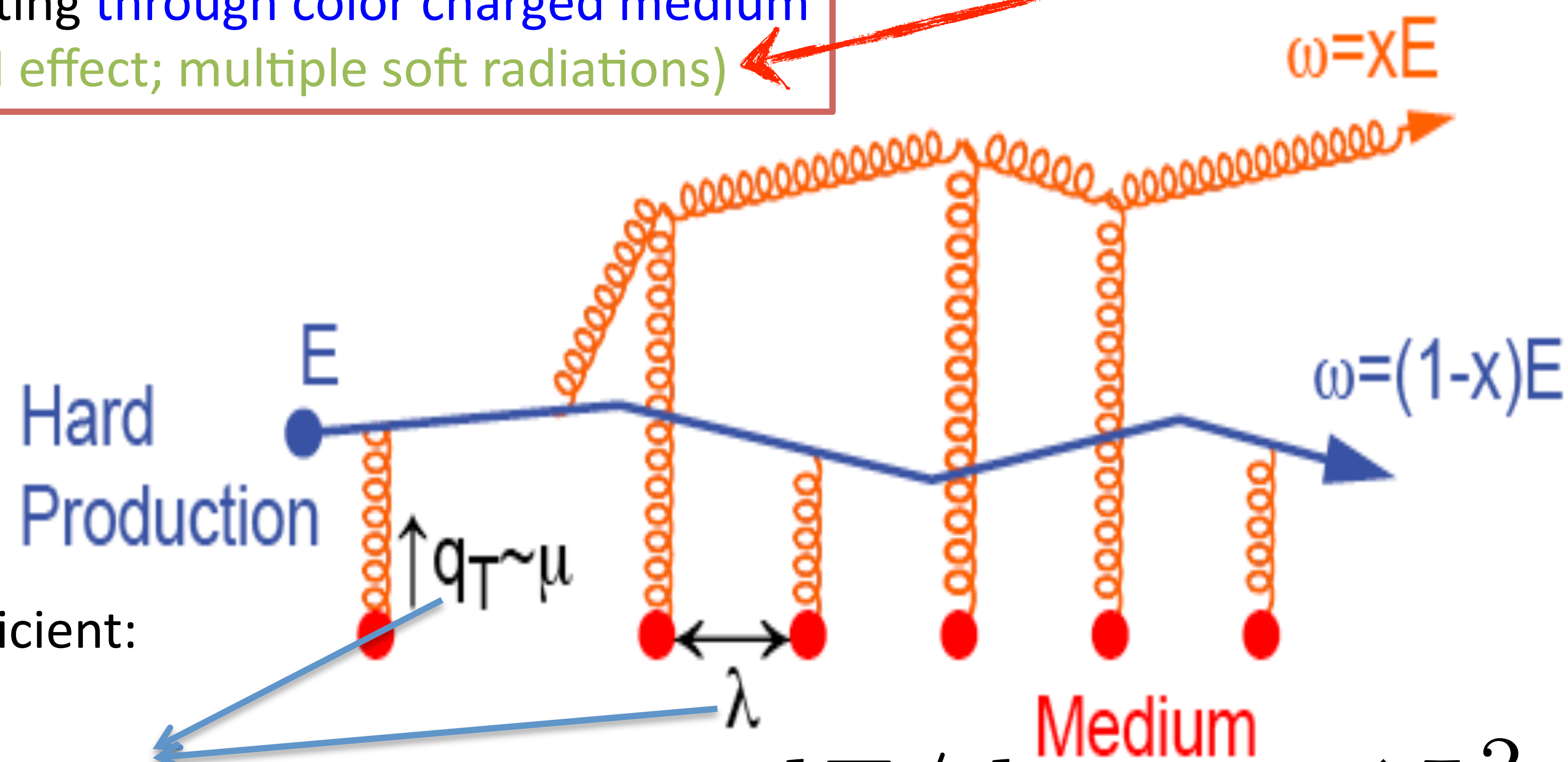
$q \to qg \quad \tau_{form} = 2\omega/k_T^2$

λ<τ : 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

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

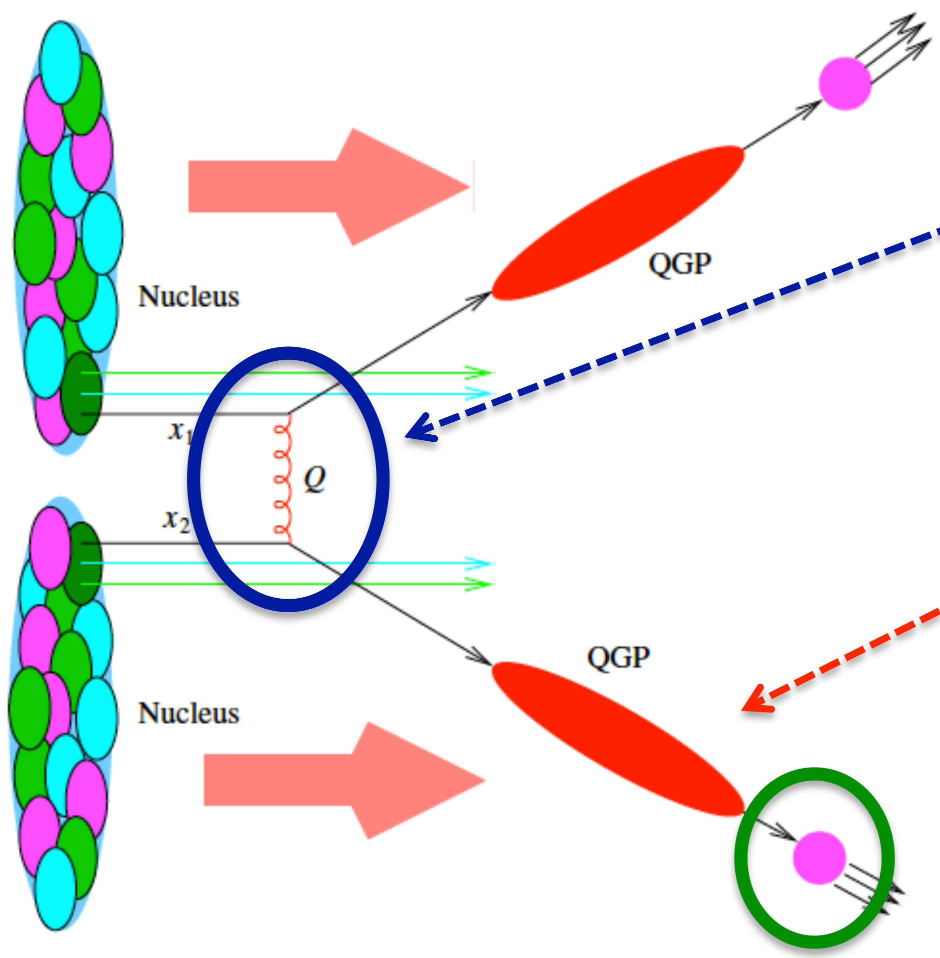
⇒ **energy flow (parton+radiation) modified as compared to jet in vacuum**

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

Jets in heavy-ion collisions - an idealization

=> Factorized picture.

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



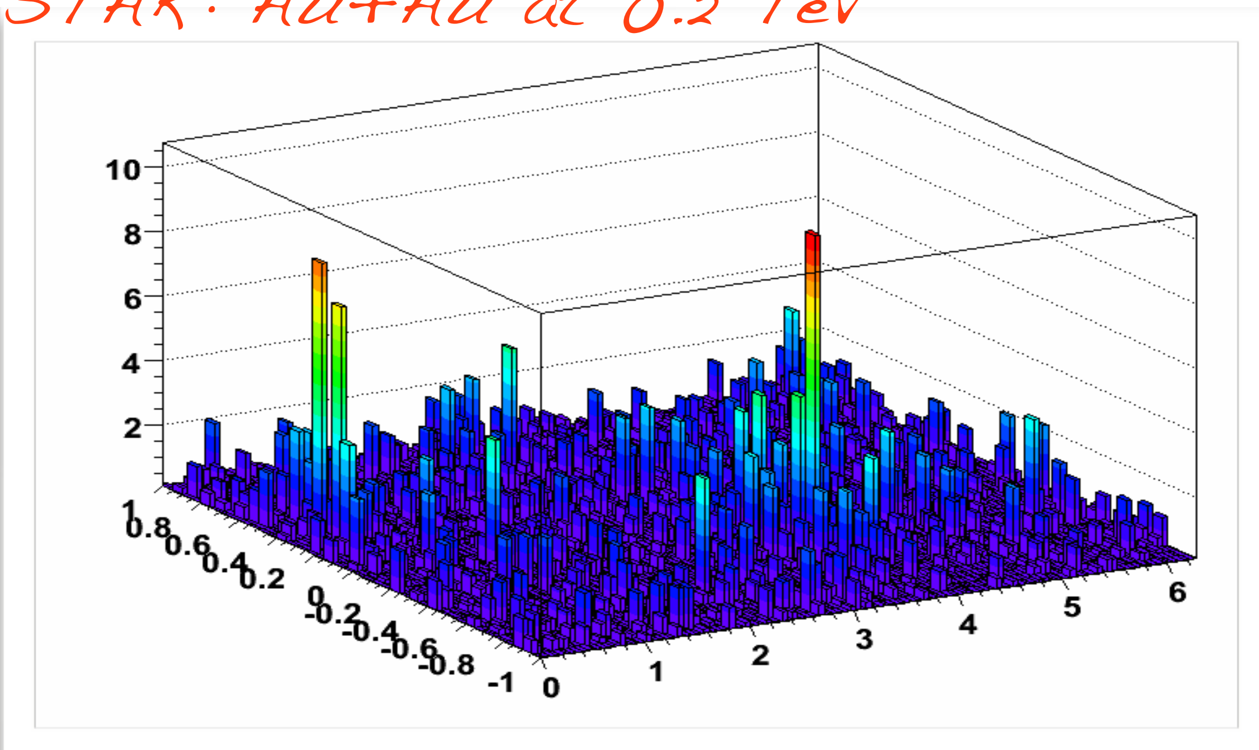
production vertex: high Q^2
➔pQCD

Propagation in strongly coupled Quark Gluon Plasma
➔pQCD-based jet quenching
➔hydrodynamics
➔AdS/CFT
➔...

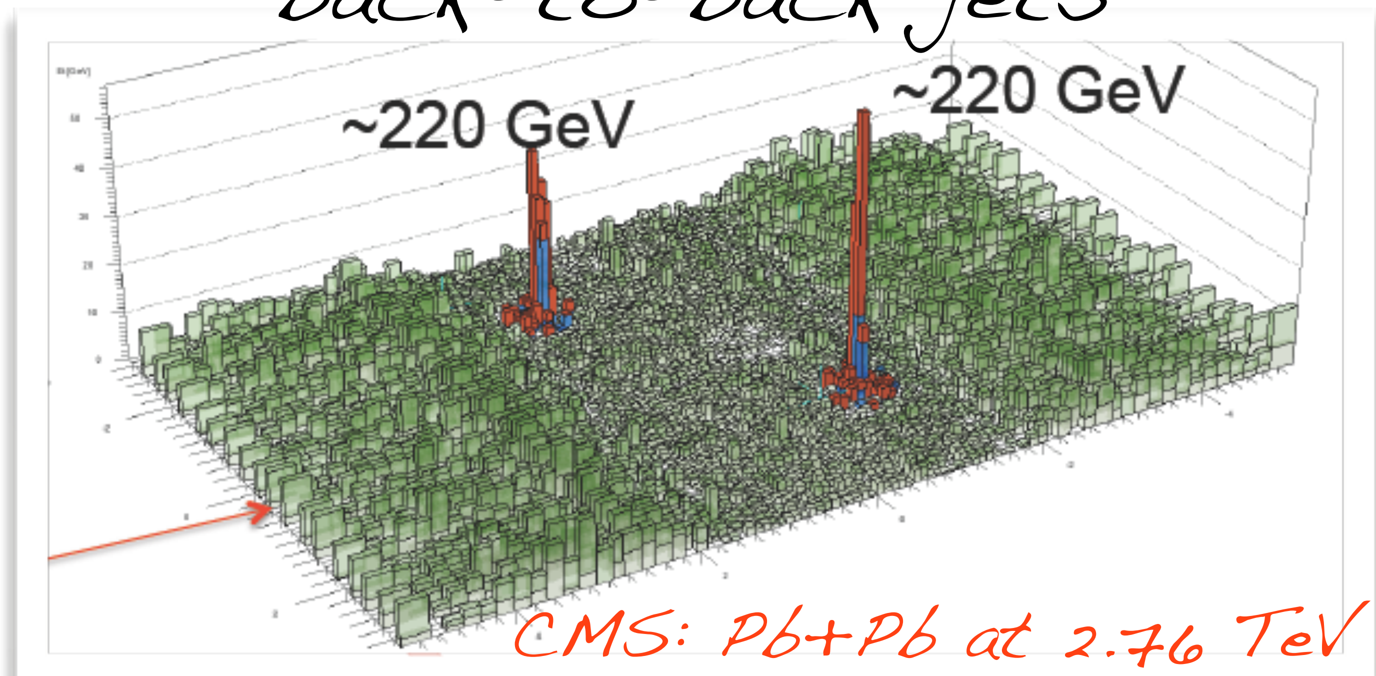
Vacuum fragmentation into hadrons
➔non-pert. QCD

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 ?

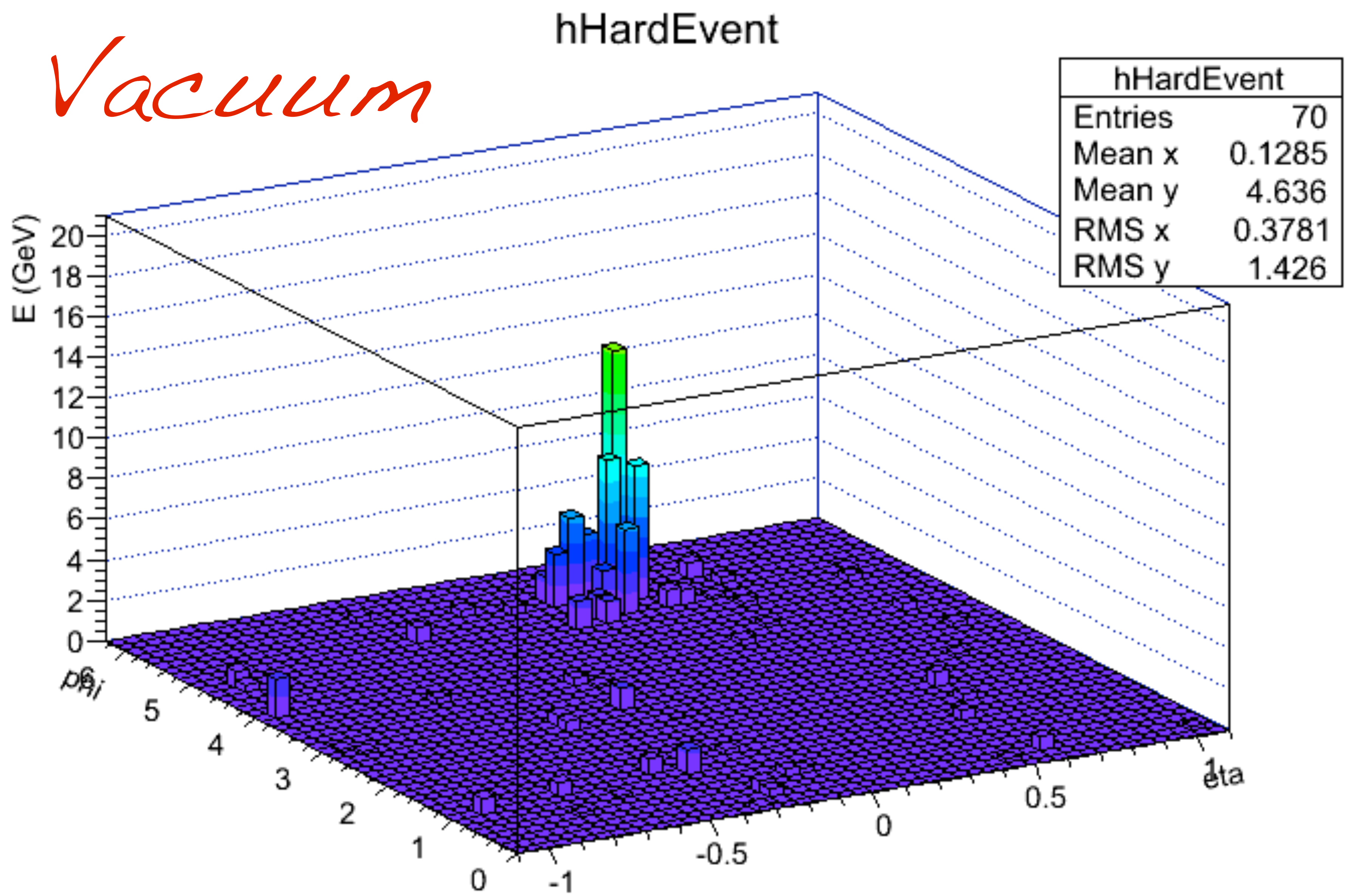
Vary energy of the jet:

LHC: Vary the scale with which QGP is probed (a la DIS)

Compare and contrast RHIC and LHC

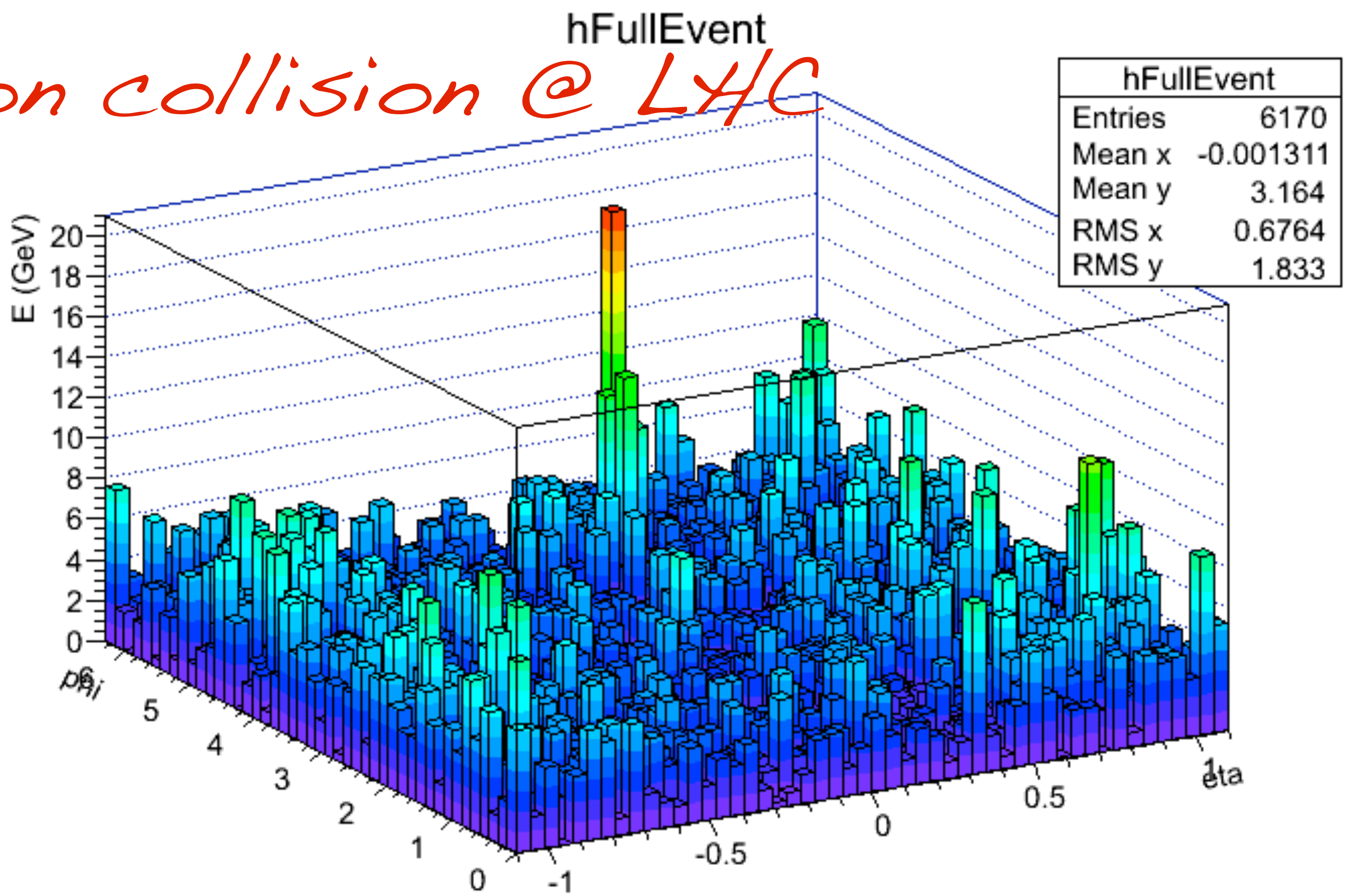
Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

Vacuum

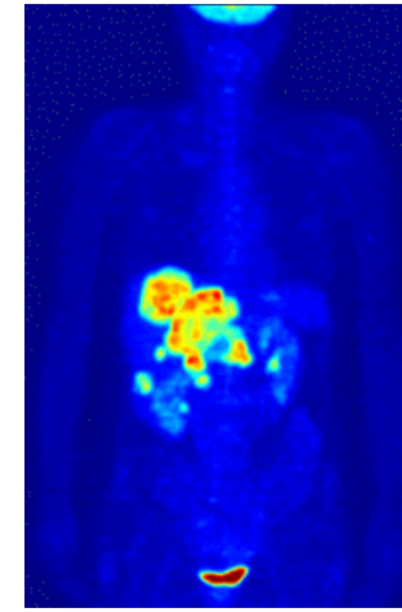


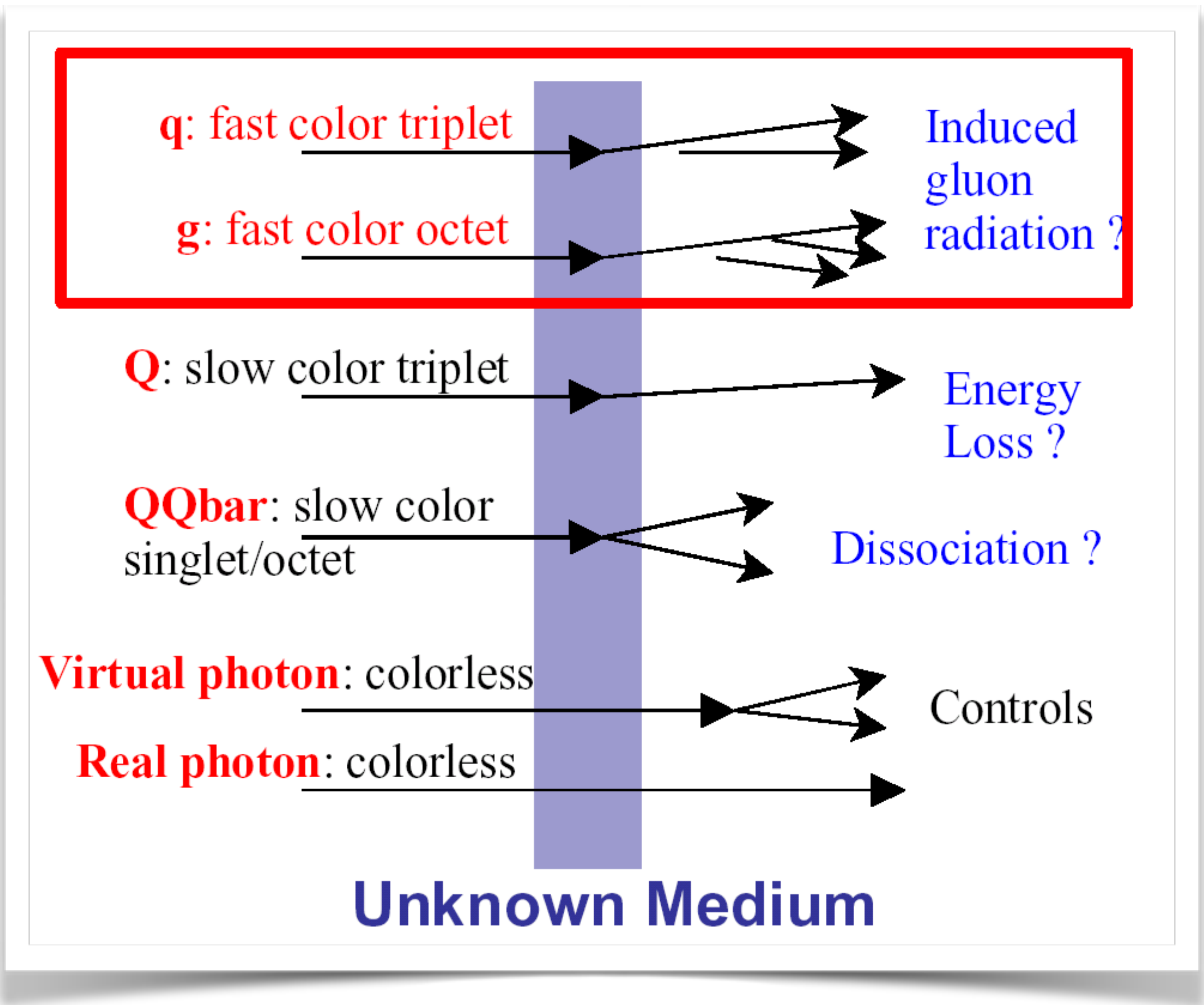
Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

Heavy-ion collision @ LHC



Probing the unknown medium...


Human body



jet suppression (quenching)

charm/bottom dynamics

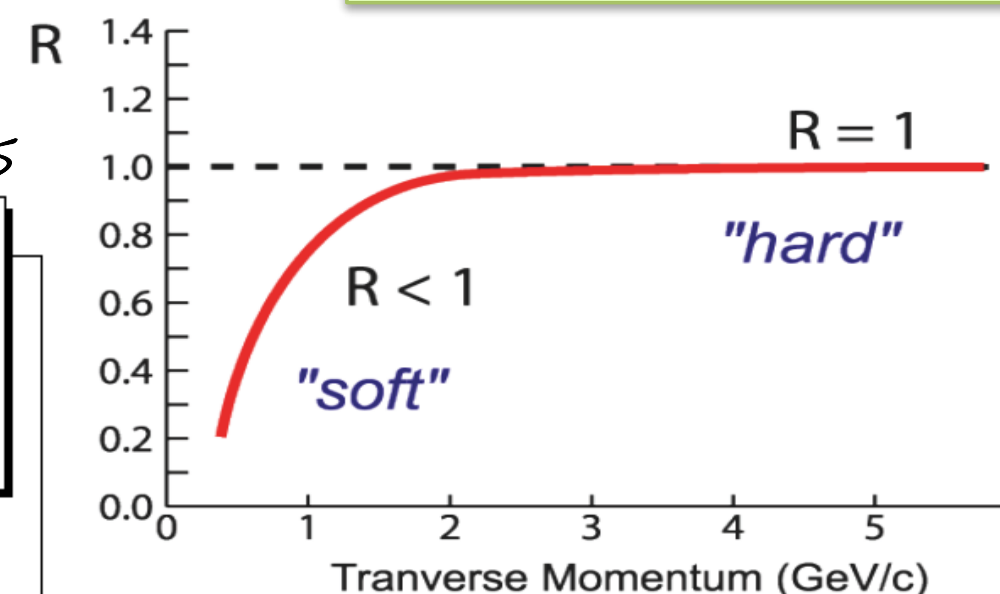
J/ψ & ϒ

color-less particles

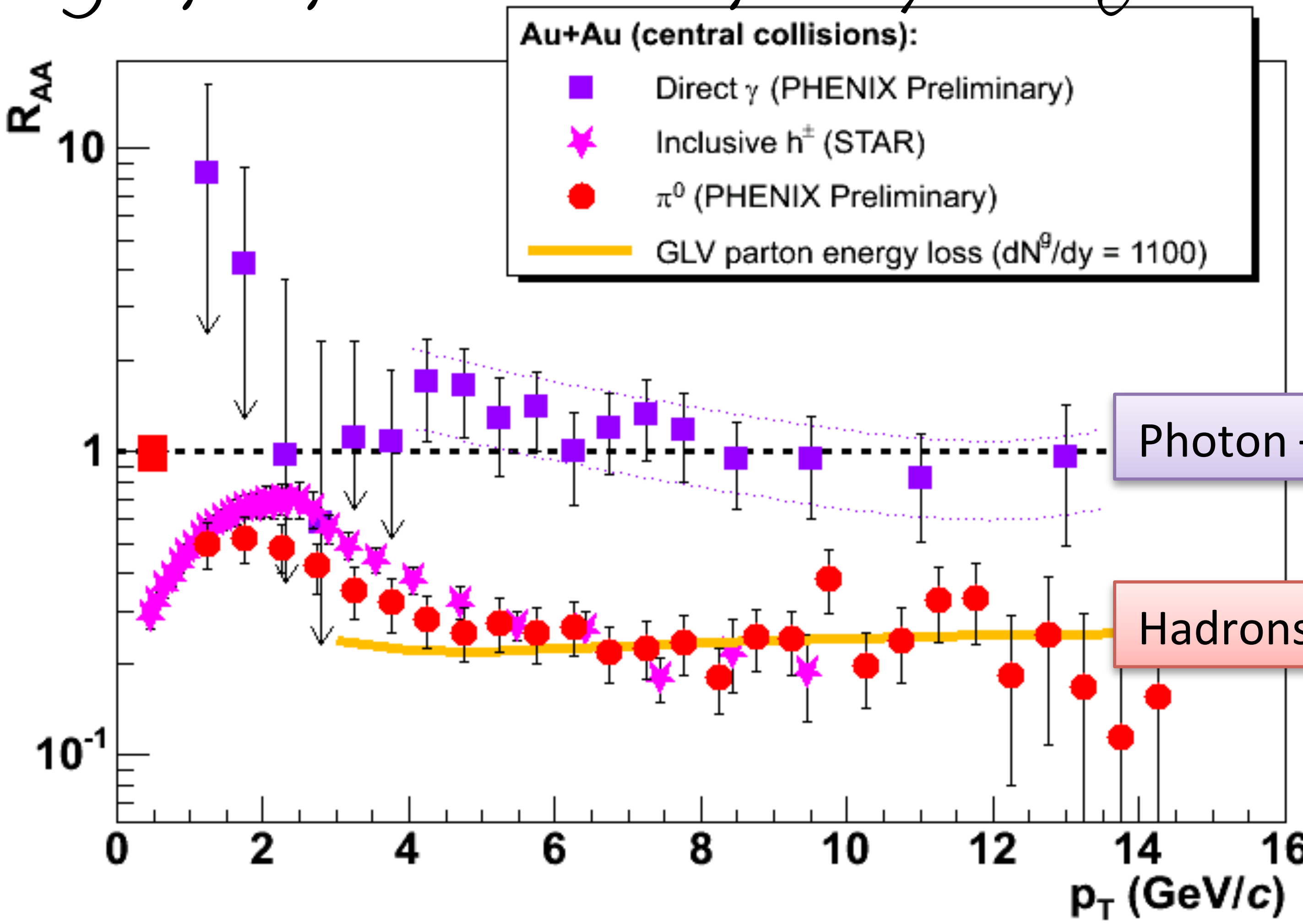
Jet quenching - RHIC

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

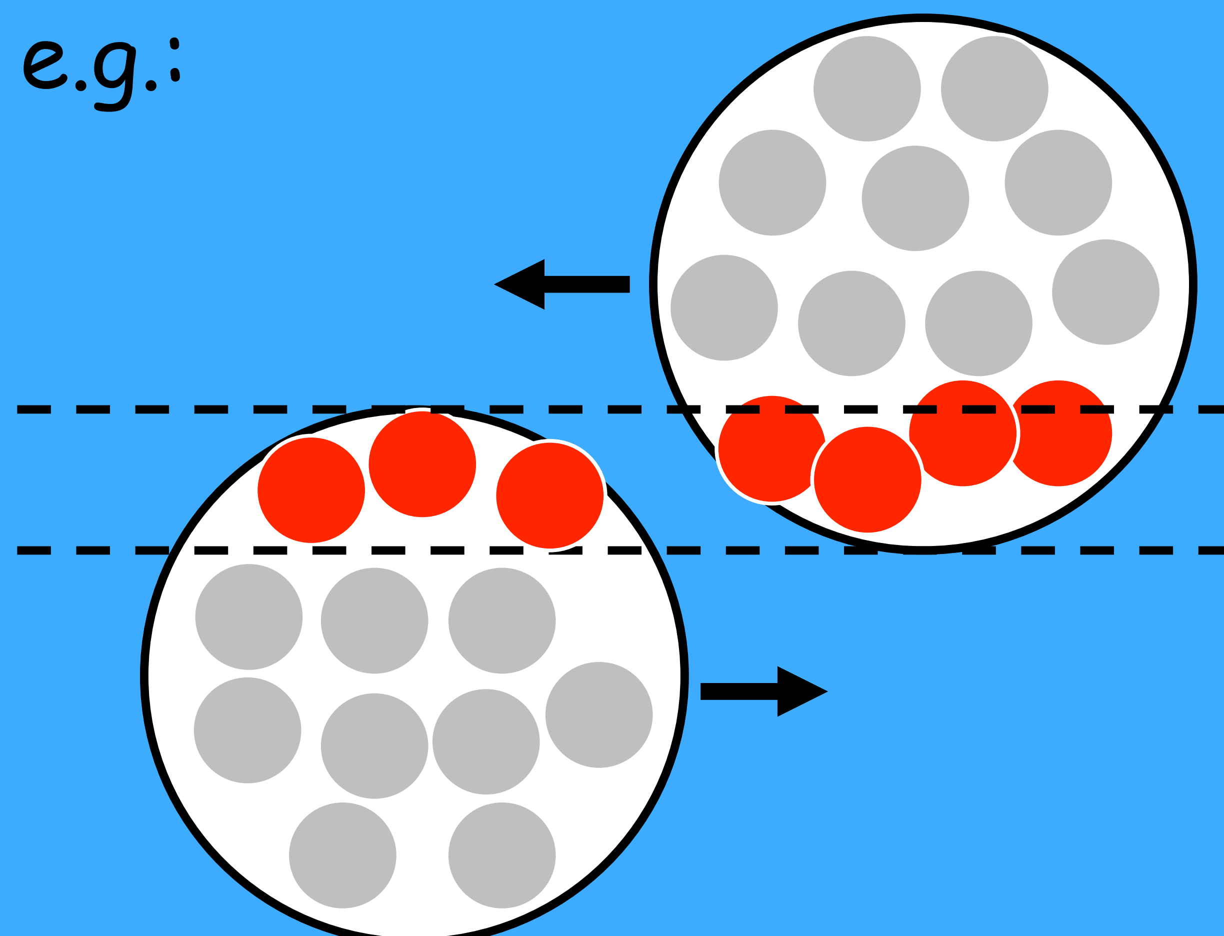
Hadrons from color charged jets => Suppression

Reminder...

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

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

e.g.:



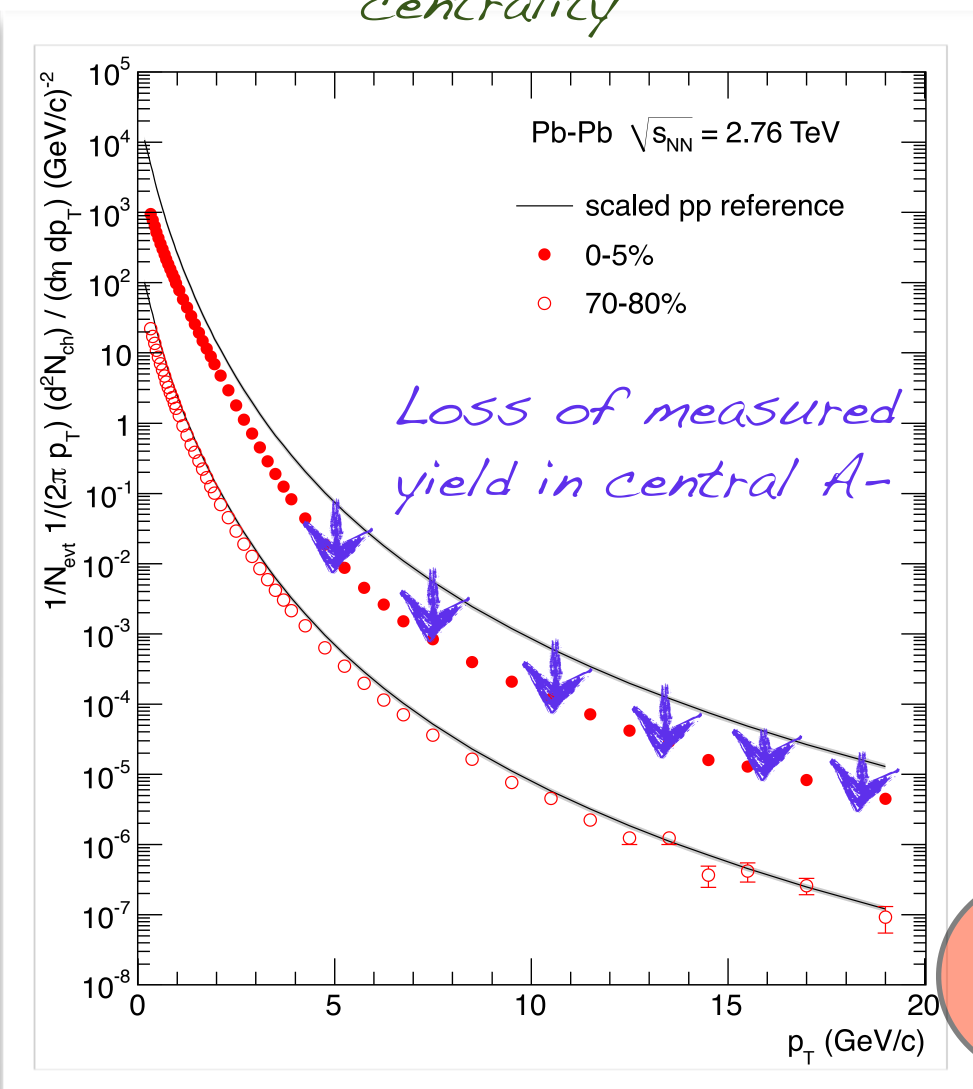
N_{part} (or N_{wound}) = 7 "participants"

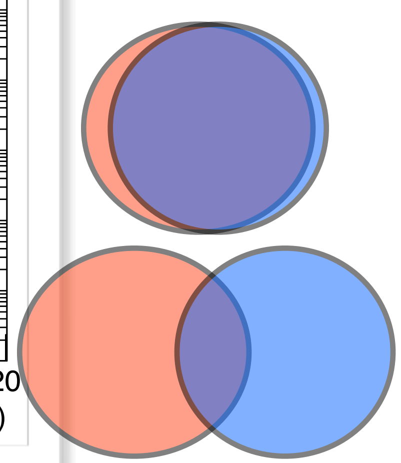
N_{bin} (or N_{coll}) = 12 "binary collisions"

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

Inclusive hadron production

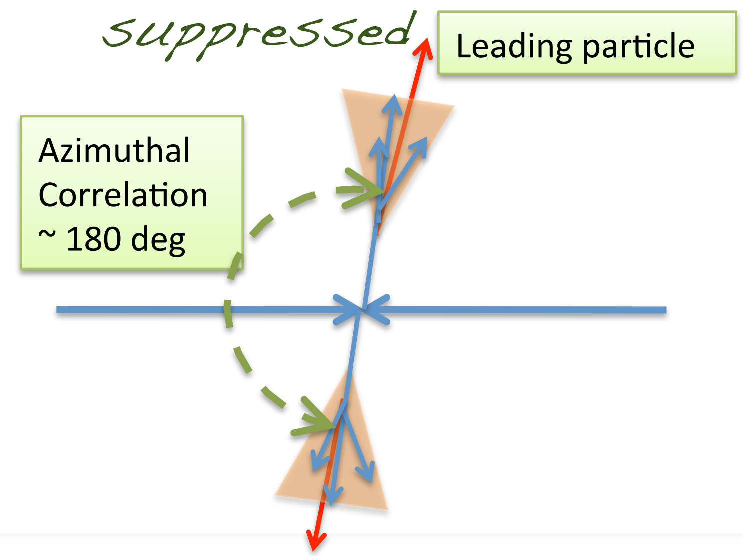
Measured as a function of collision centrality

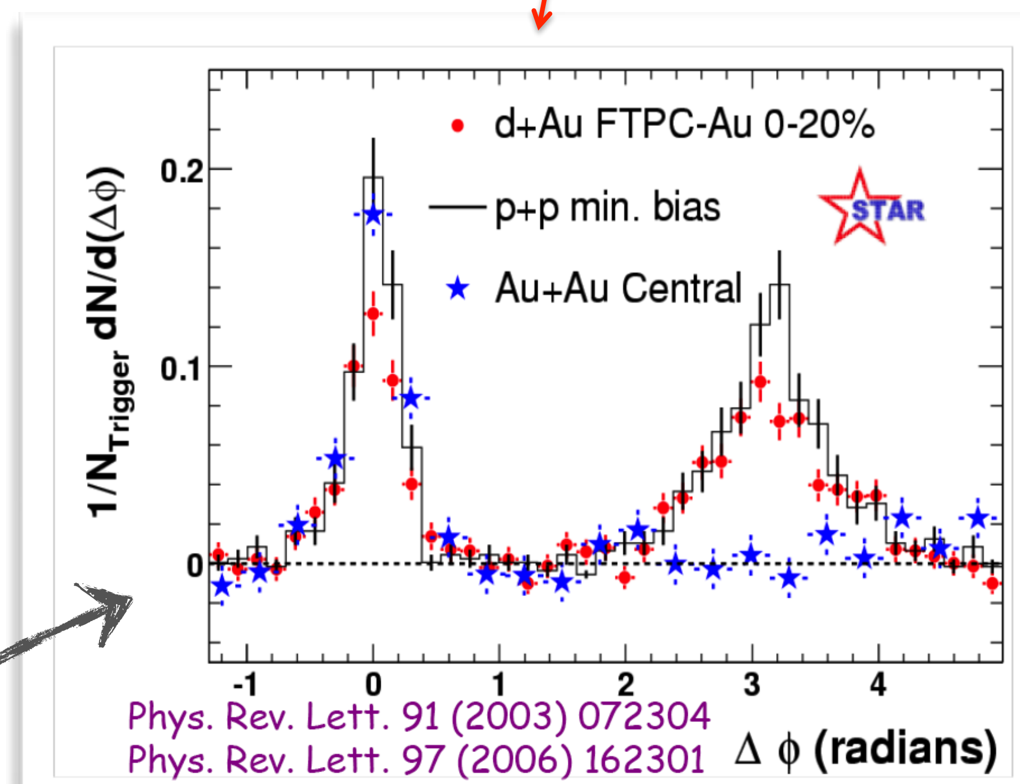




Di-hadron correlations

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





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

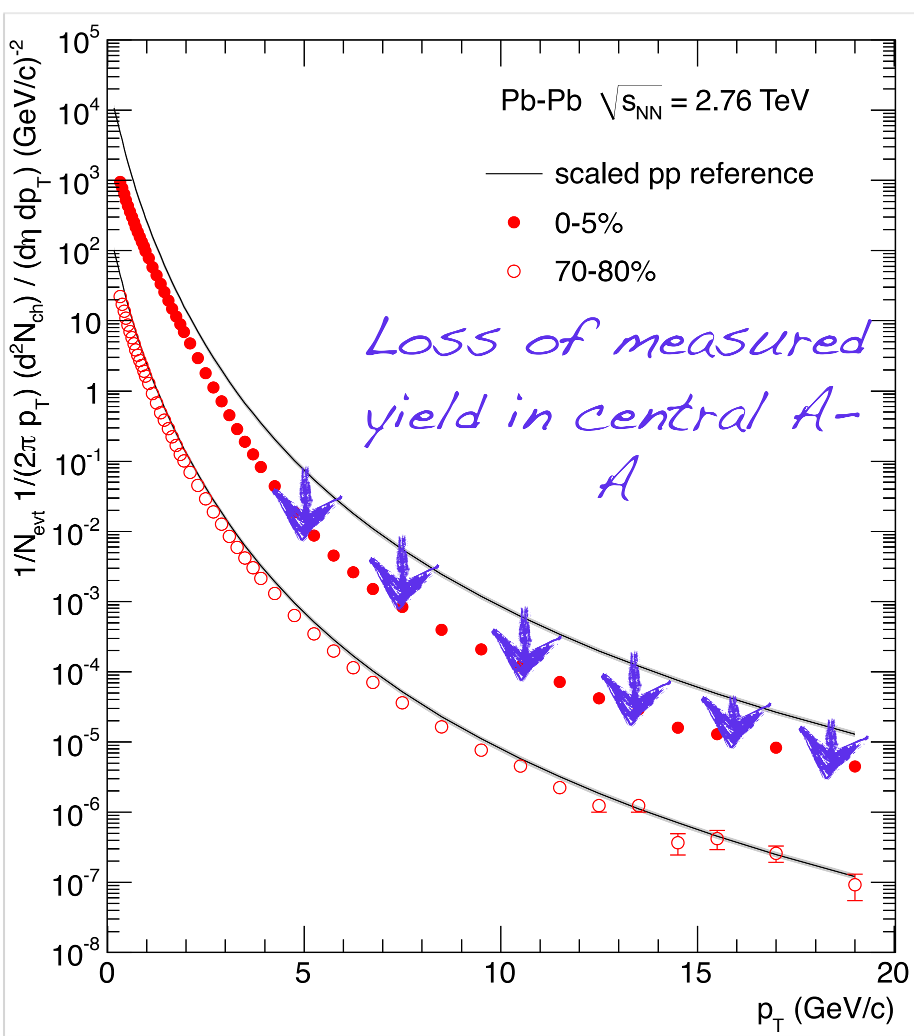
Hadron suppression

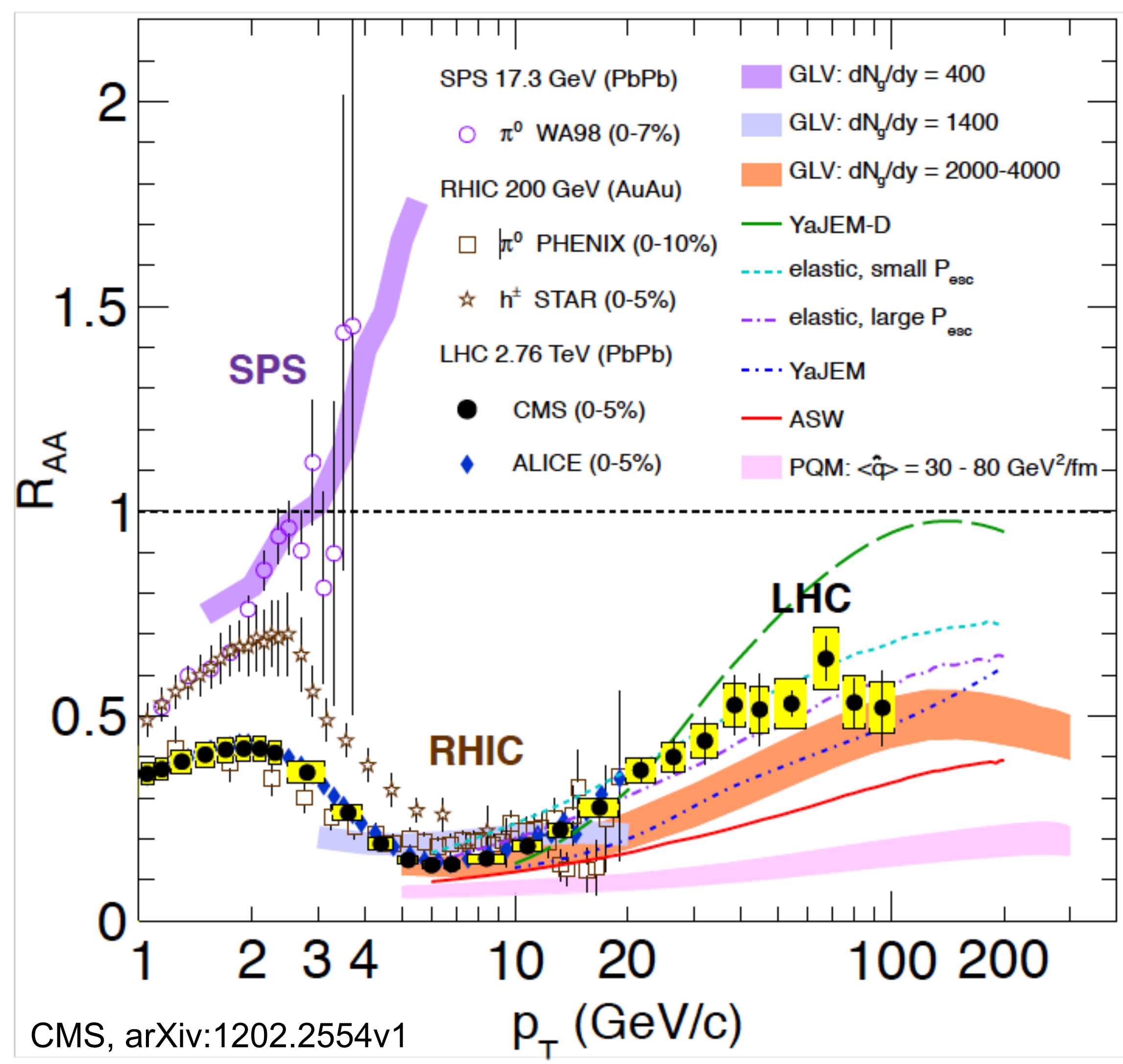
$$R_{AB} = \frac{d^2N/dp_t d\eta}{T_{AB} d^2\sigma^{pp}/dp_t d_\eta}$$

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

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

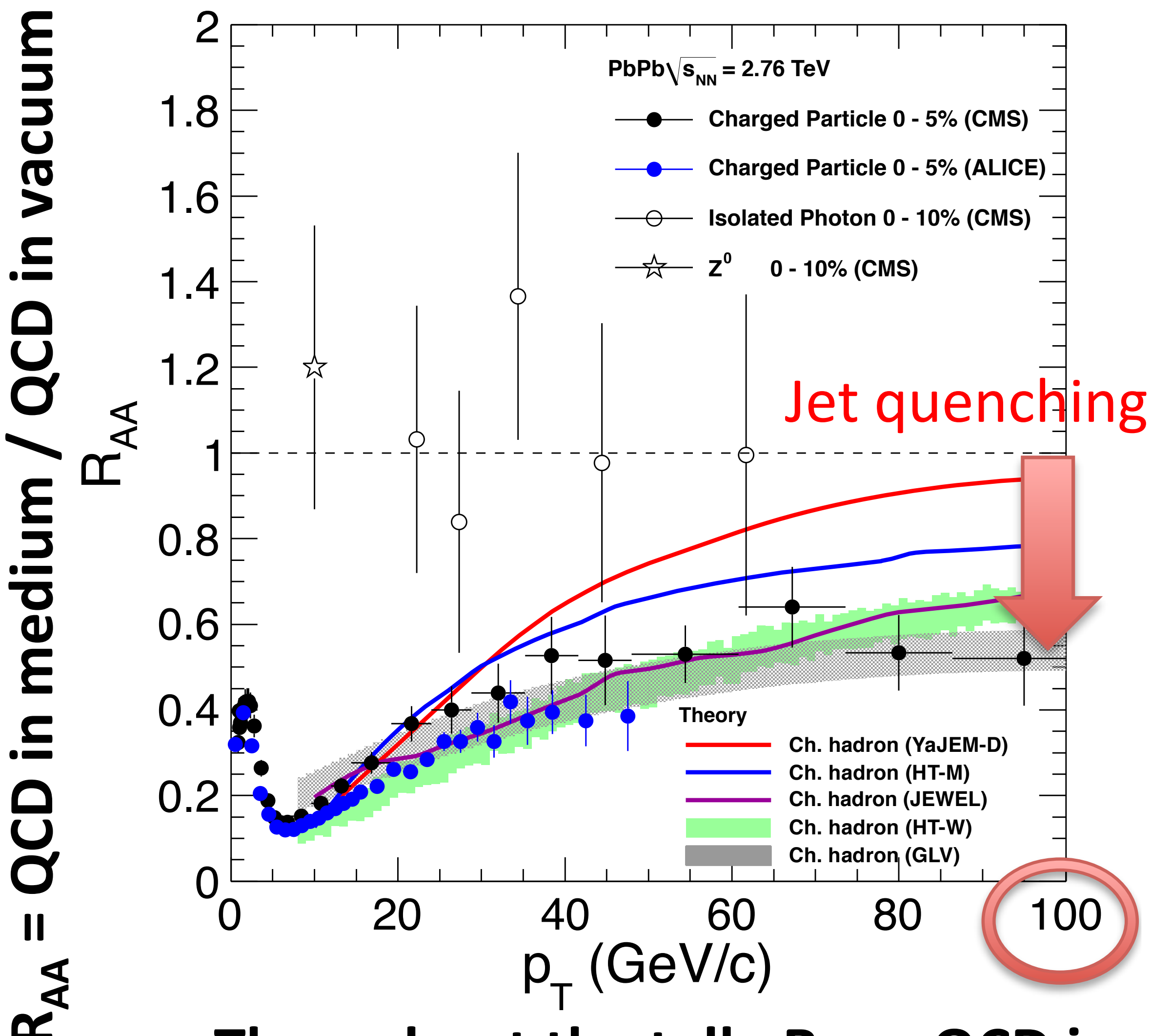
Energy-loss - QGP state effect!

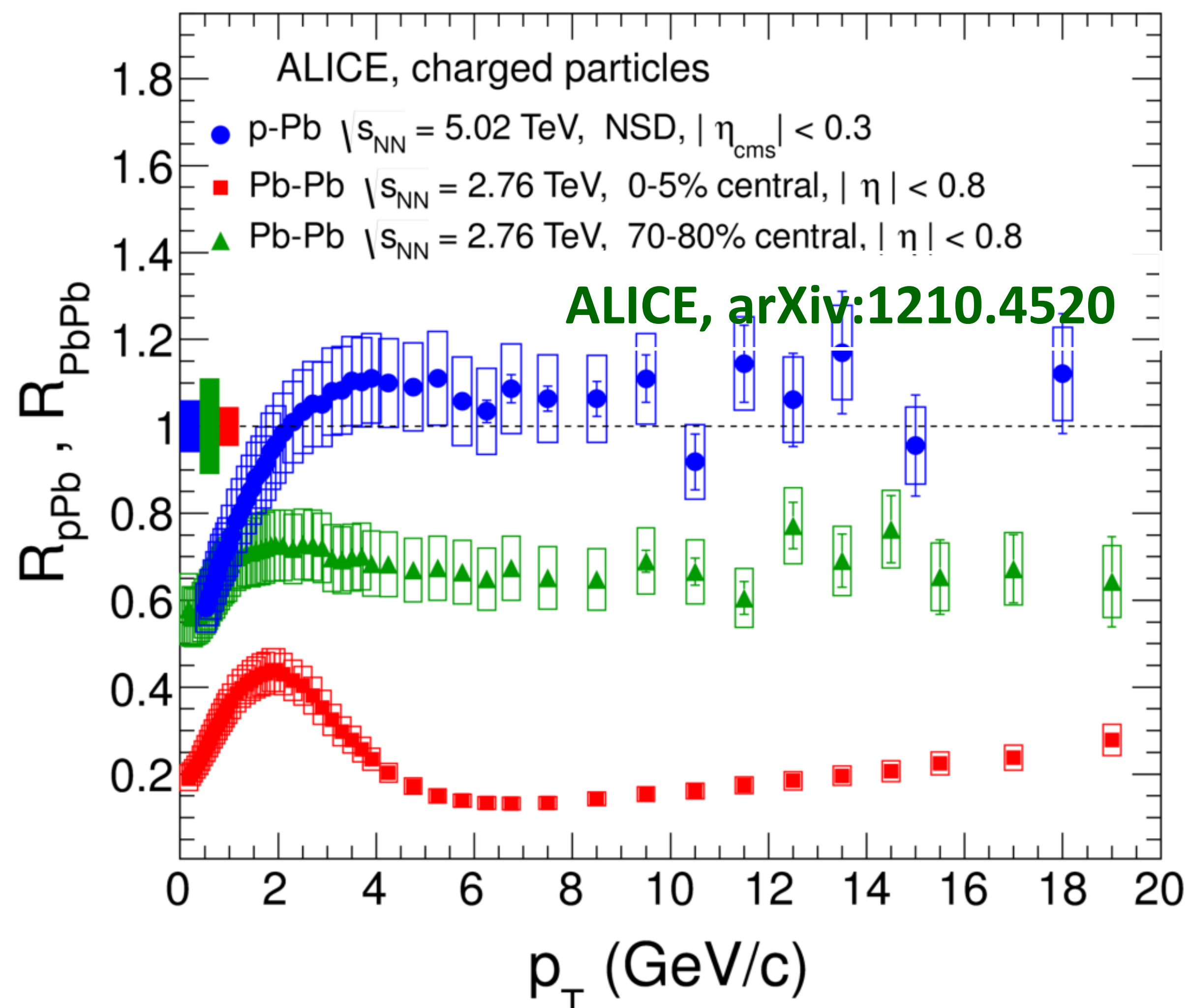
Color charged probes suppressed

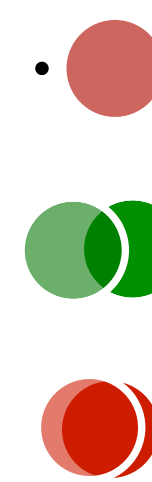
Color neutral probe production scales with Nbin collisions

pA collisions: suppression is an effect of QGP

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





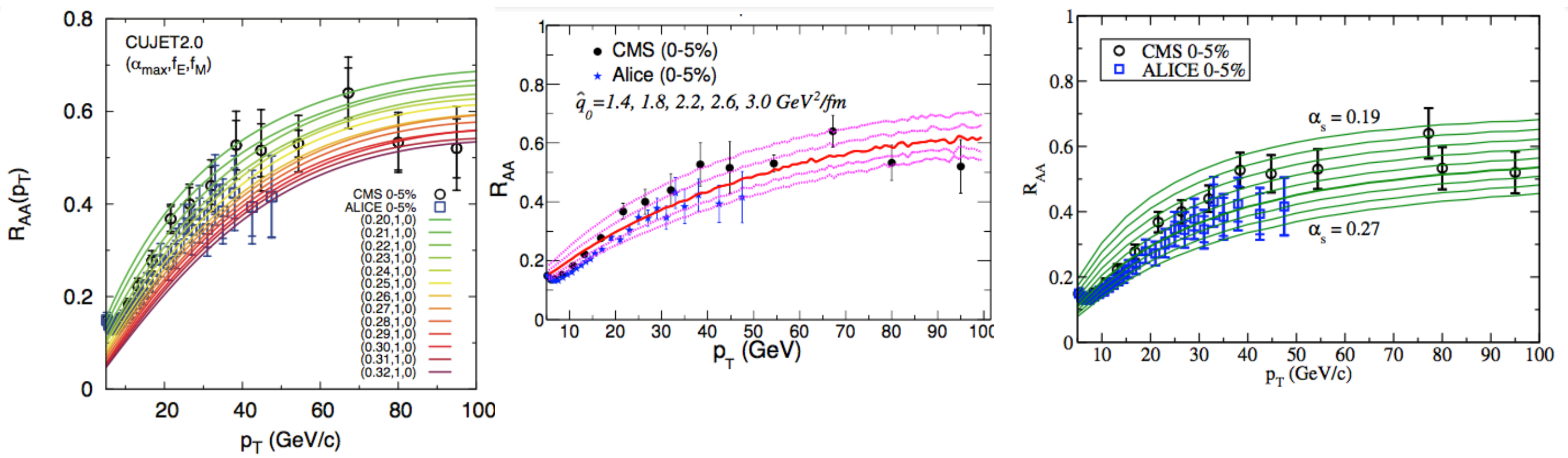


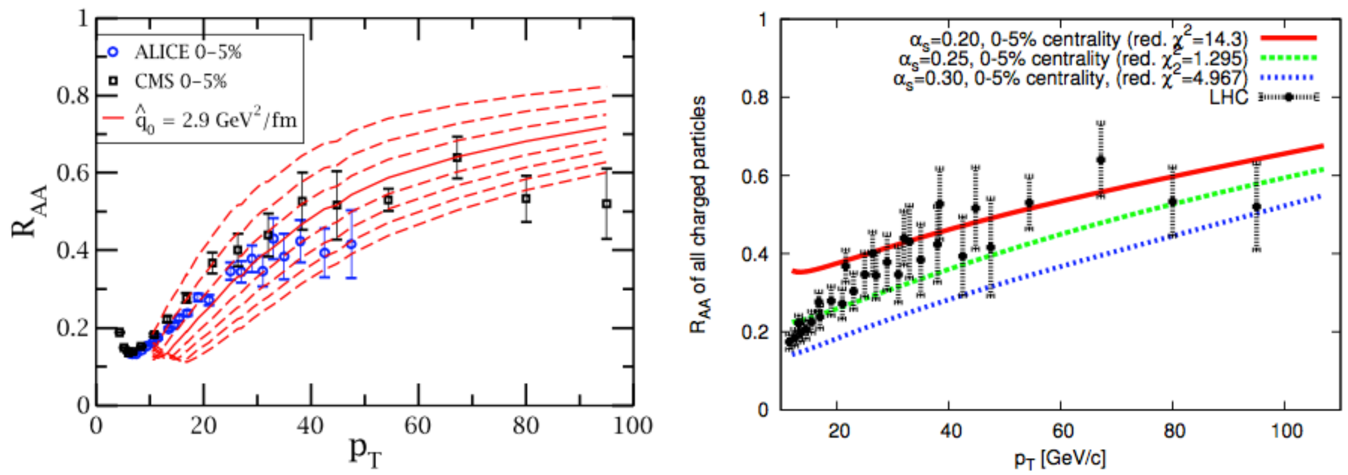
Throughout the talk: R_{AA} = QCD in medium / QCD in vacuum

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

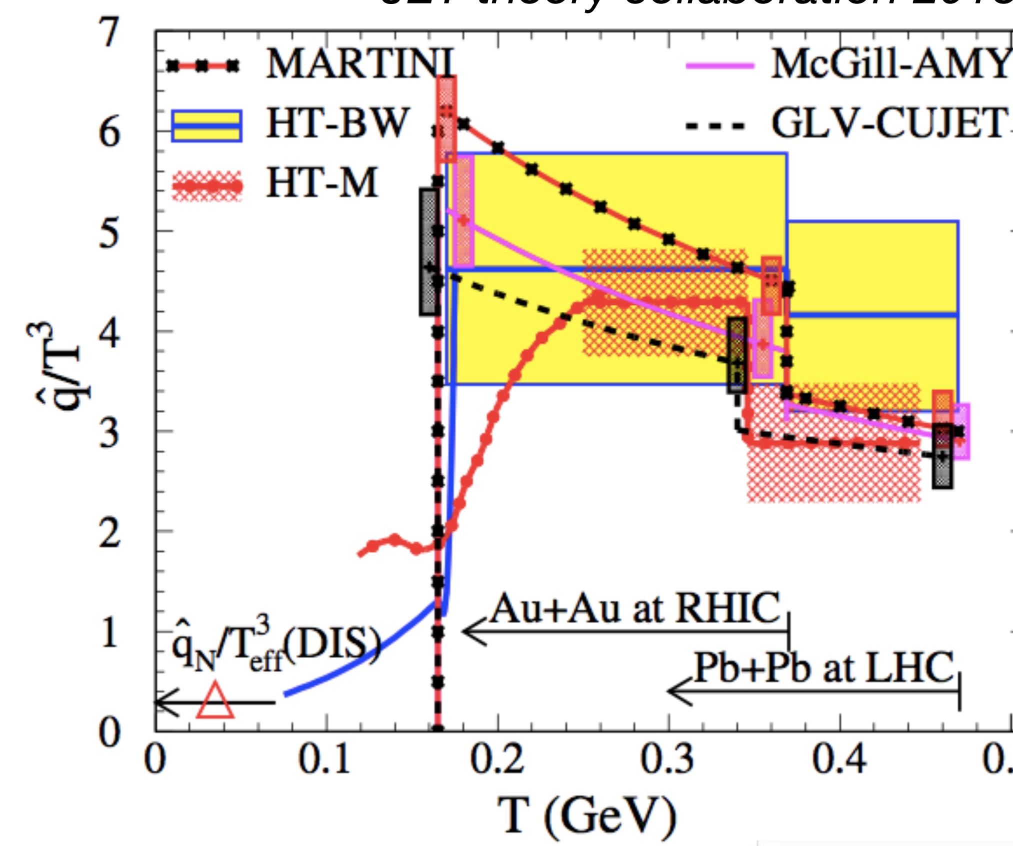
Extraction of QGP transport coefficients

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





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 (?)

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

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

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

so far...

- High energy heavy-ion collisions:
  - hot medium; thermal [statistical hadronization] particle emission
  - QGP flows as almost perfect fluid - well described by viscous hydrodynamics - transport coefficient constrained
    - slow evolution with energy - similar medium over large span of energies (?) - role of mean free path vs. medium size...
  - QGP is opaque to high energy jets (dense medium) - transport coefficient constrained (first syst. results)