WEEK 3:

SIGNATURES OF THE QUARK GLUON PLASMA

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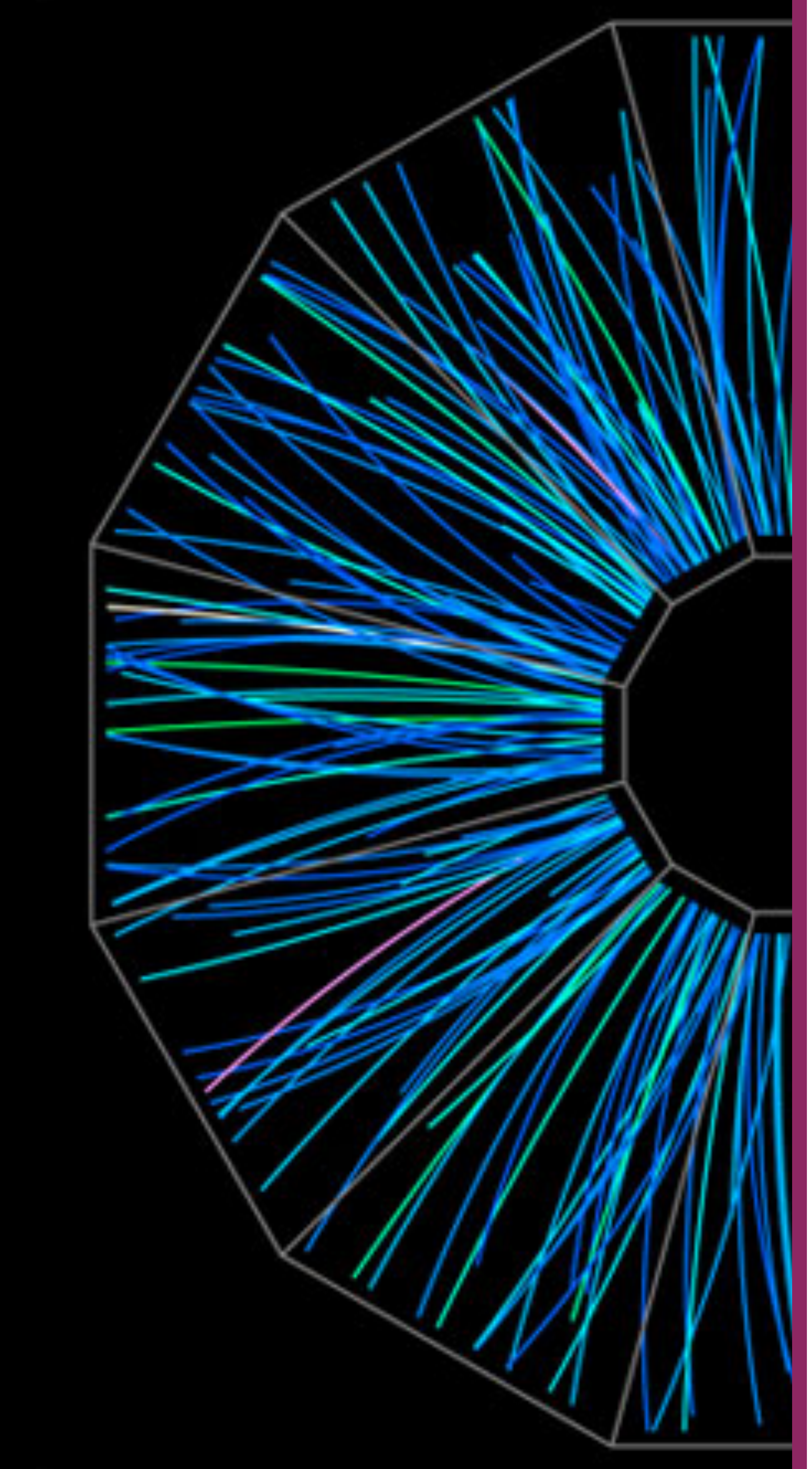

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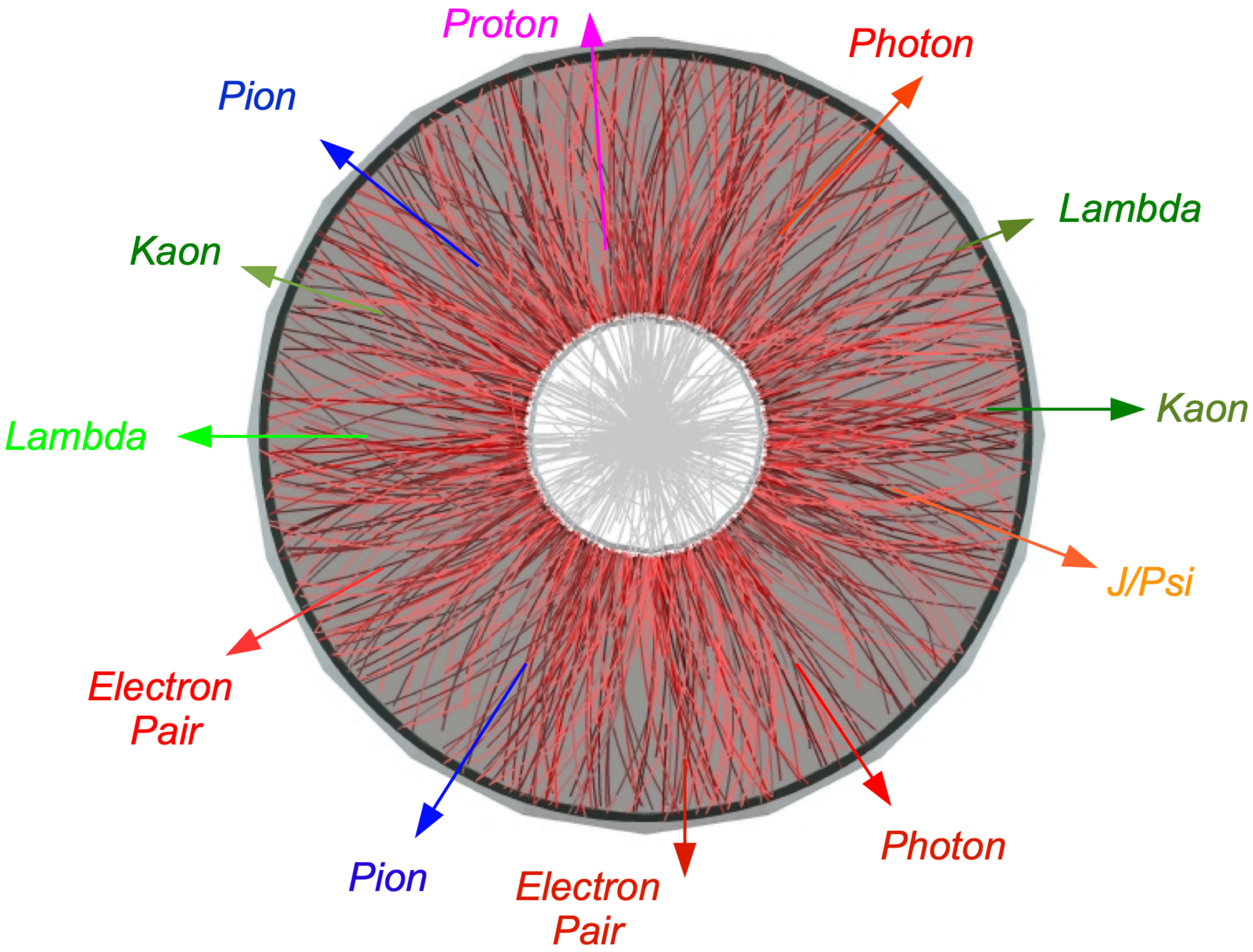
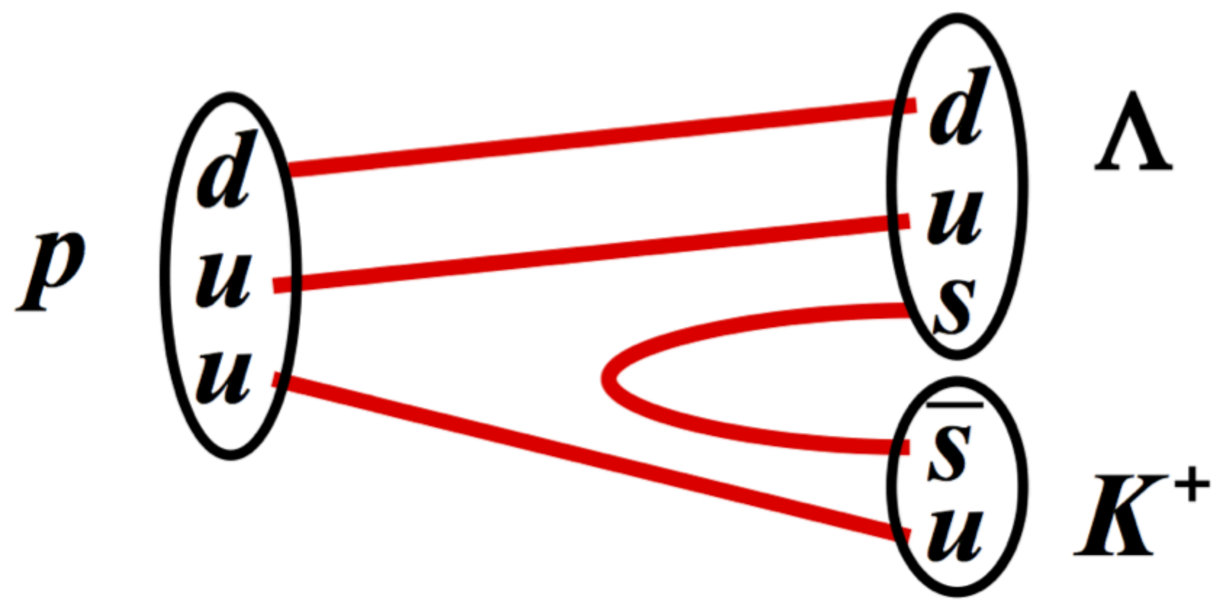
WHAT WE MEASURE



The process of measuring the particle and how to do it experimentally is not included in this lectures.

STRANGENESS ENHANCEMENT



STRANGENESS ENHANCEMENT

Strangeness here corresponds to the total amount of particles measured which contain strange quarks.
For example,

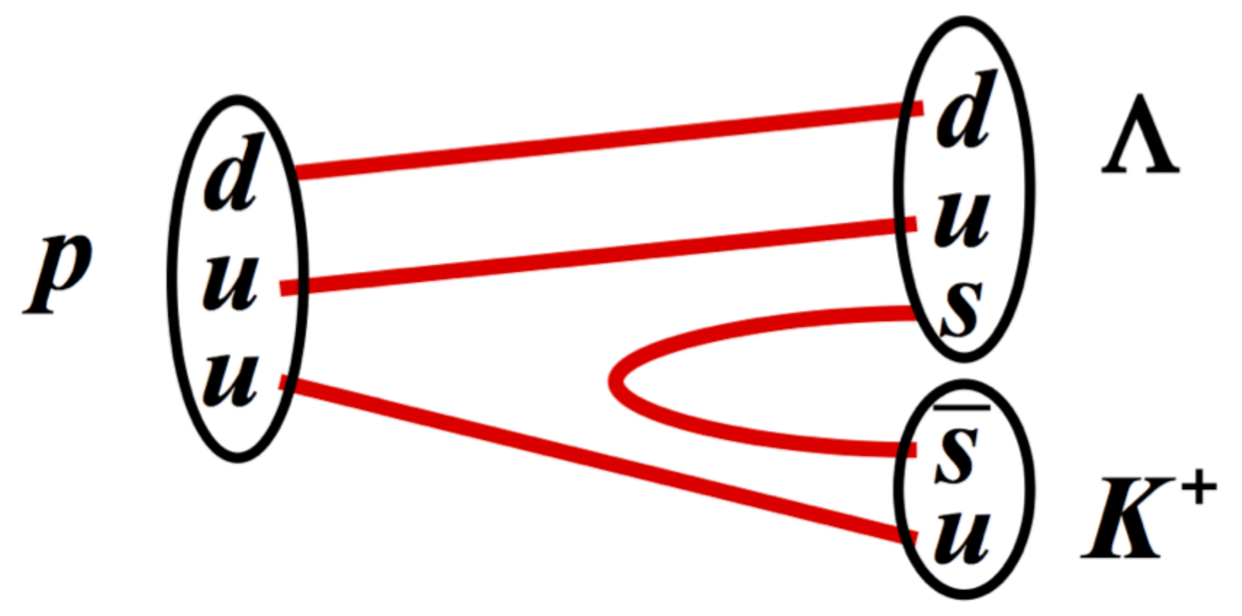
$$K^+ = (u\bar{s}),\ K^- = (\bar{u}s),\ K^0 = (d\bar{s}),\ \bar{K}^0 = (\bar{d}s),\ \phi = (s\bar{s}),$$

$$\Lambda = (uds),\ \Sigma = (qqs),\ \Xi = (qss),\ \Omega^- = (sss)$$

For example, they are created in collisions such as

$$p + p \to p + K^- + \Lambda \qquad Q = m_K + m_\Lambda - m_p \sim 0.67\,\mathrm{GeV}$$

$$p + p \to p + p + \Lambda + \bar{\Lambda} \qquad Q = 2m_\Lambda \sim 2.23\,\mathrm{GeV}$$



In what follows, remember that

$$m_u \sim m_d \sim 5 - 10\,\mathrm{MeV} \qquad m_s \sim 90 - 100\,\mathrm{MeV} \qquad m_c \sim 1.3\,\mathrm{GeV} \qquad m_b \sim 4.5\,\mathrm{GeV}$$

$$q_u = q_c = q_t = +\frac{2}{3} \qquad q_d = q_s = q_b = -\frac{1}{3}$$

STRANGENESS ENHANCEMENT

What do we mean enhancement? If there is an enhancement in the QGP, there must be a suppression first, no? Suppression wrt what?

$u - d$ baryons!

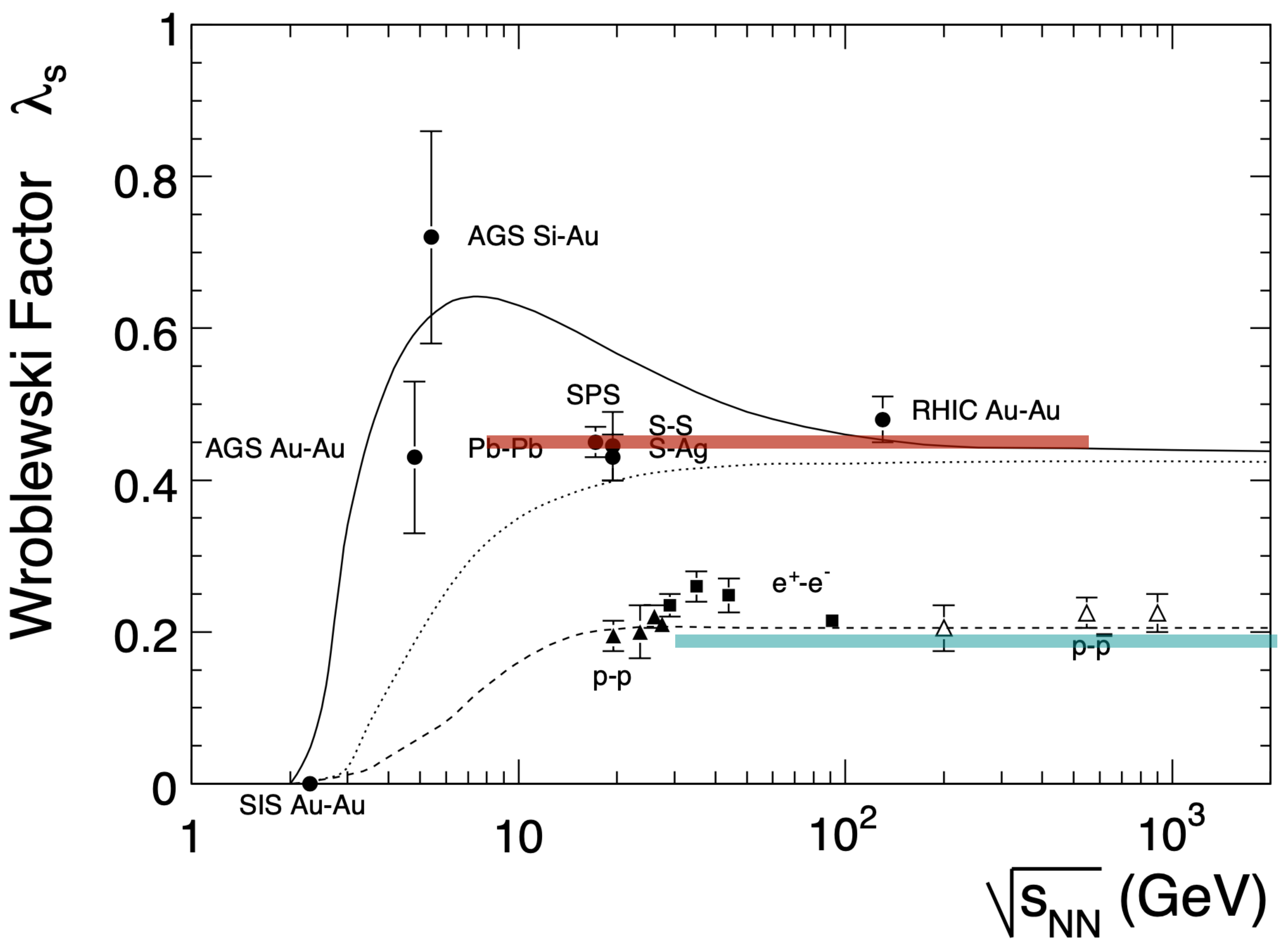
Let's define the Wroblenski factor: $$\lambda_s = \frac{2\langle \bar{s}s \rangle}{\langle \bar{u}u \rangle + \langle \bar{d}d \rangle}$$

Acta Phys.Polon.B 16 (1985) 379-392

Here, $\langle \bar{q}q \rangle$ stands for the total number of particles which contain at least one s quark as one of its of the valence quarks

In pp and e^+e^- collisions -small systems- we can find a very stable Wroblensky factor, $\lambda_s \sim 0.2$, strange quarks are indeed suppressed!

In AA collisions -large systems- we can easily see an increase in the relative Wroblensky factor, $\lambda_{s,AA} \sim 2\lambda_{s,pp}$. This is indeed what we call **strangeness enhancement.**



STRANGENESS ENHANCEMENT

An interpretation of what happens here is that there is the formation of a thermal QGP, in which strangeness is **canonically enhanced**

In the QGP, we saw that the number density is easily given by

$$n_q = \frac{g_q}{2\pi^2} m^2 T \sum_{k=1}^{\infty} \frac{(-1)^{k+1}}{k} z^k K_2\left(\frac{km}{T}\right)$$

In a QGP with $\mu_q = 0$ and $150 < T < 300\,\mathrm{MeV}$ the Wroblenski factor is given by

$$\lambda_{s,QGP} = \frac{2(n_s + n_{\bar{s}})}{n_u + n_{\bar{u}} + n_d + n_{\bar{d}}} \sim 0.92 - 0.98$$

Then, **canonically enhanced** only means here that the canonical ensamble increases the Wroblenski factor

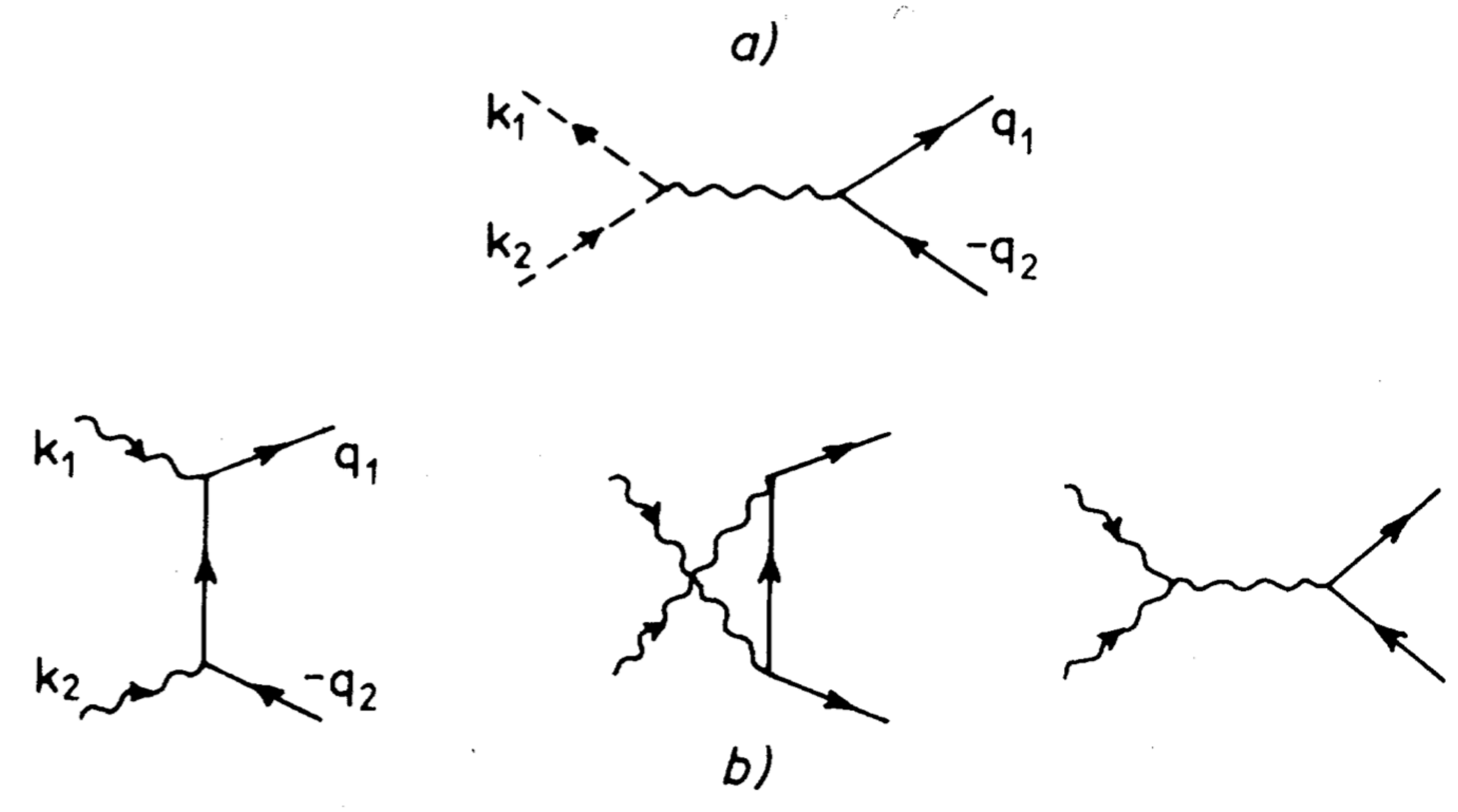
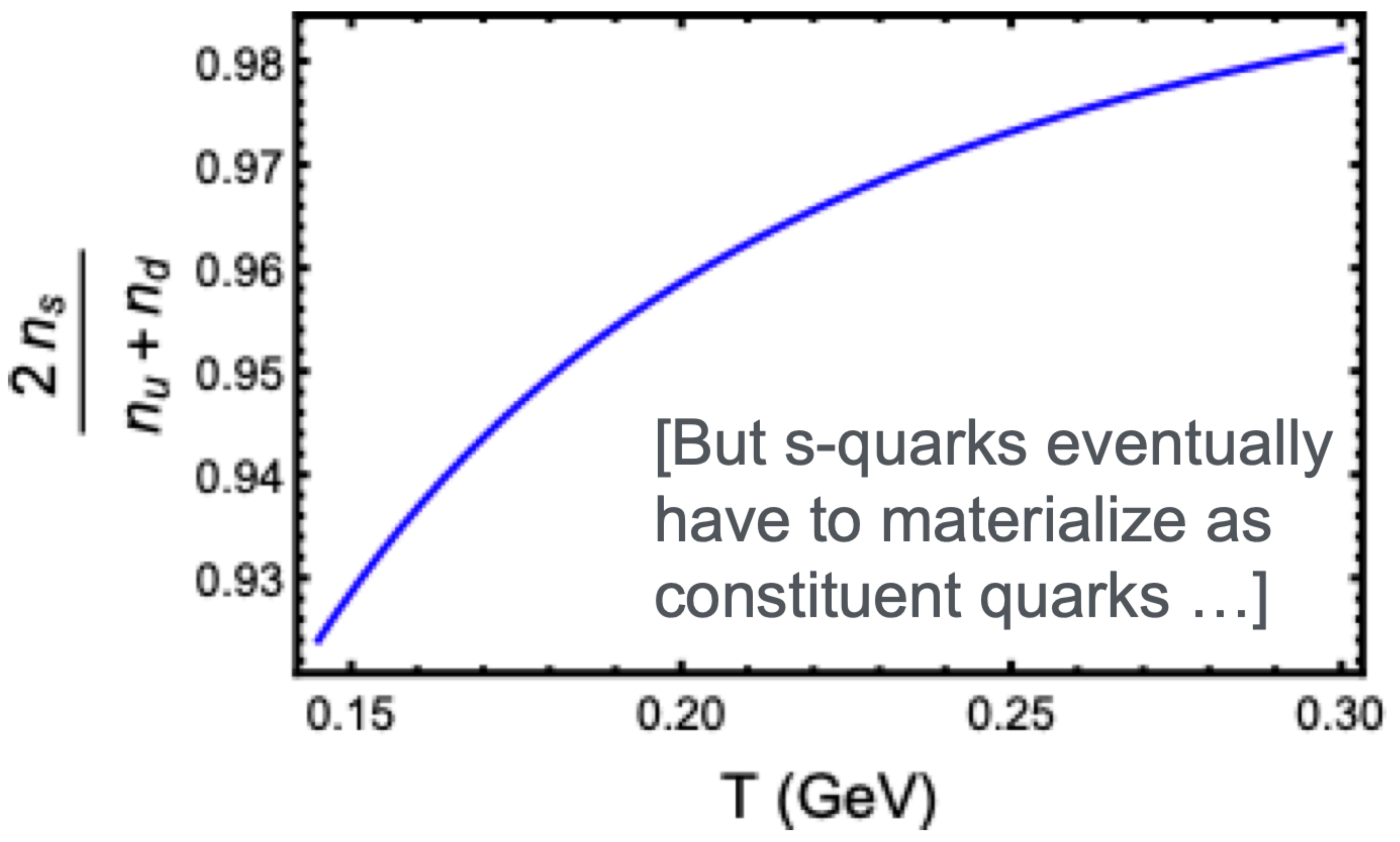


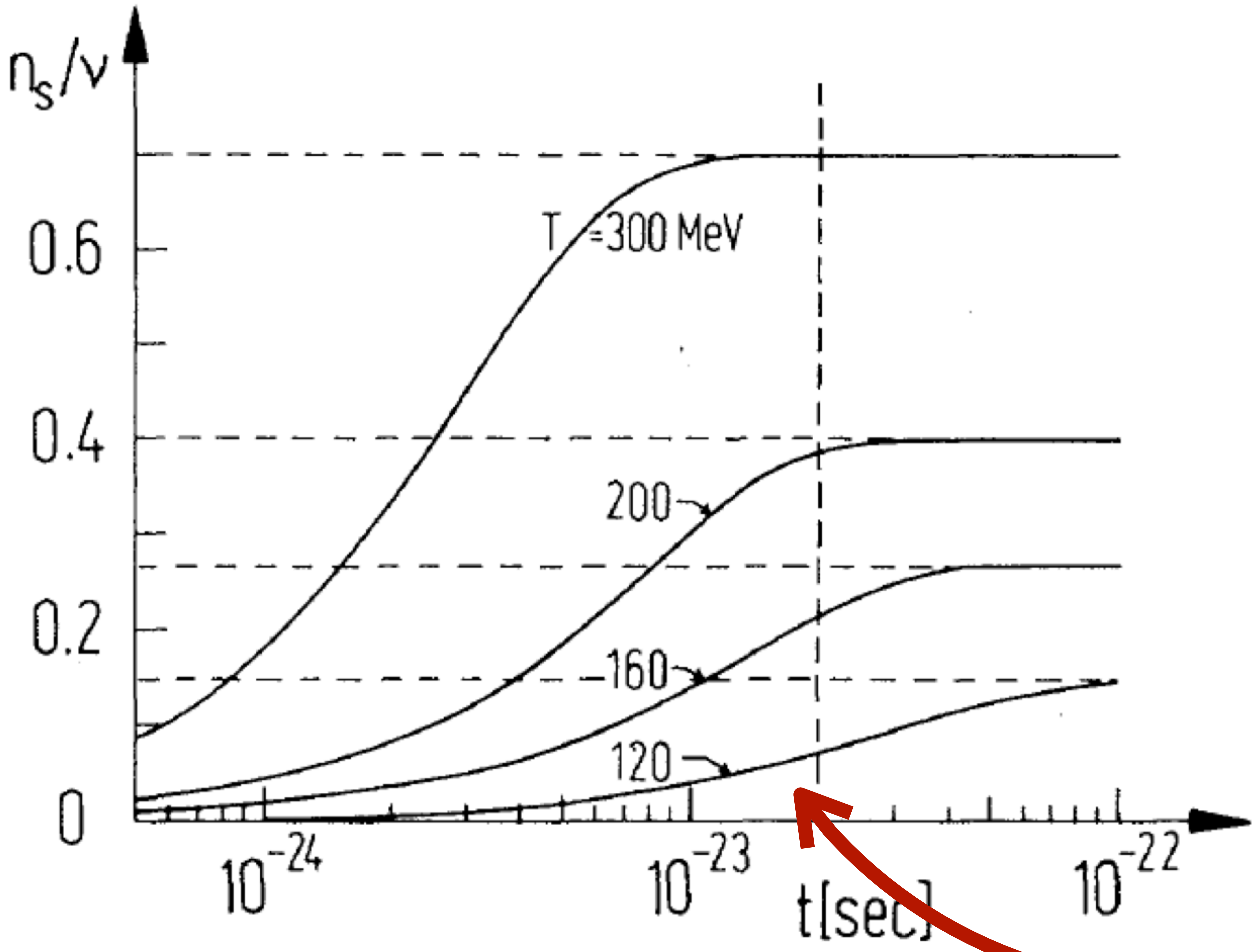
FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q} \to s\bar{s}$, (b) $gg \to s\bar{s}$.



STRANGENESS ENHANCEMENT

canonically enhanced only means here that

If there is a QGP, then why don't we see a $\lambda_s > 0.9$??



Phys. Rev. Lett. 48 (1982) 1066

Things tend to be complicated in reality.

- QGP needs to thermalize.
- There is zero strangeness at initial time (it needs to build up)
- Fluctuations of temperature may give fluctuating yields.

But one can see that in any case, in ideal situations strangeness thermalises pretty fast.

Here, rate equation (from kinetic theory) assuming an ideal QGP initialised with $n_s = n_{\bar{s}} = 0$ and thermal u, ddistributions as background

STRANGENESS ENHANCEMENT

canonically enhanced only means here that

If there is a QGP, then why don't we see a $\lambda_s > 0.9$??

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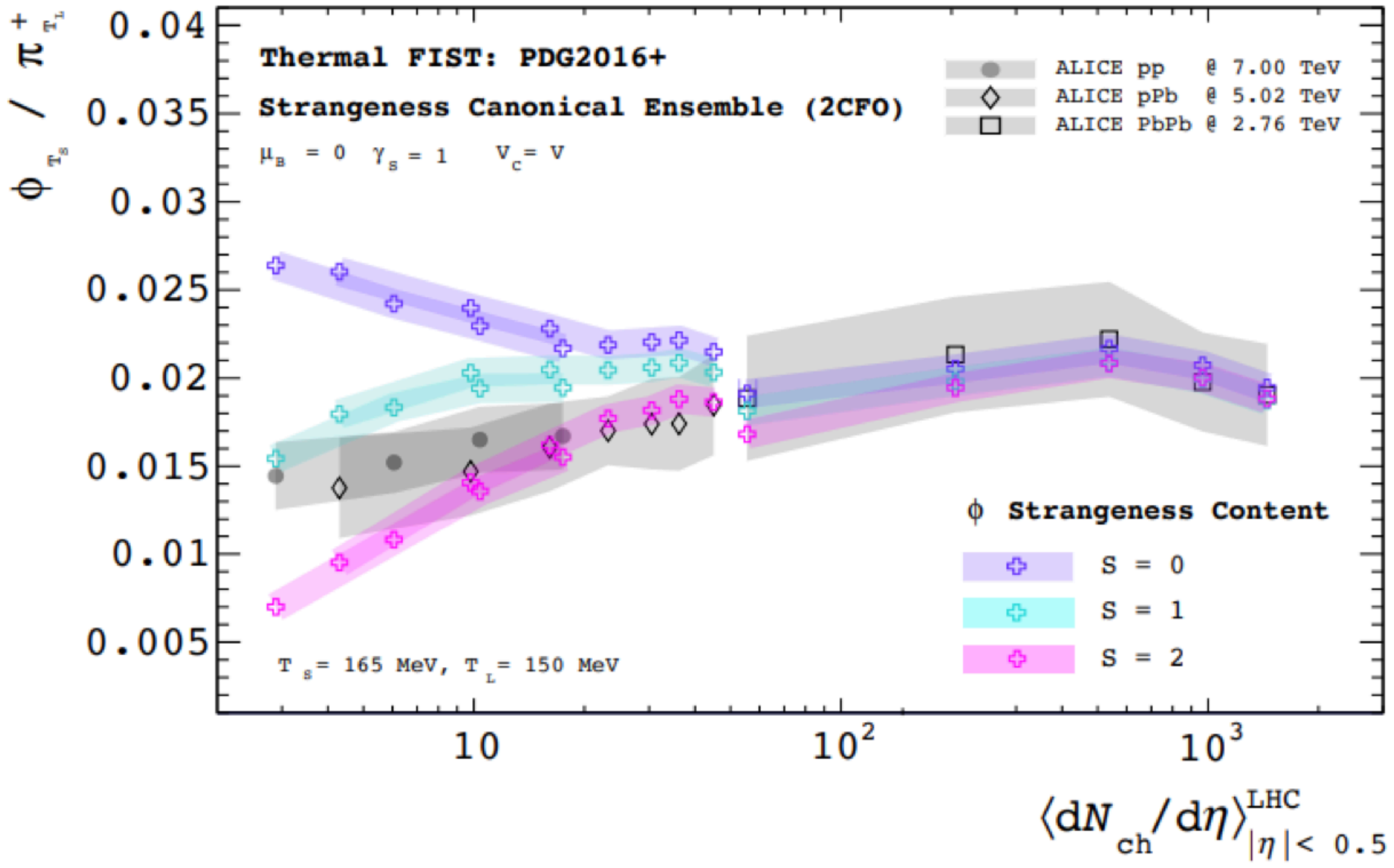
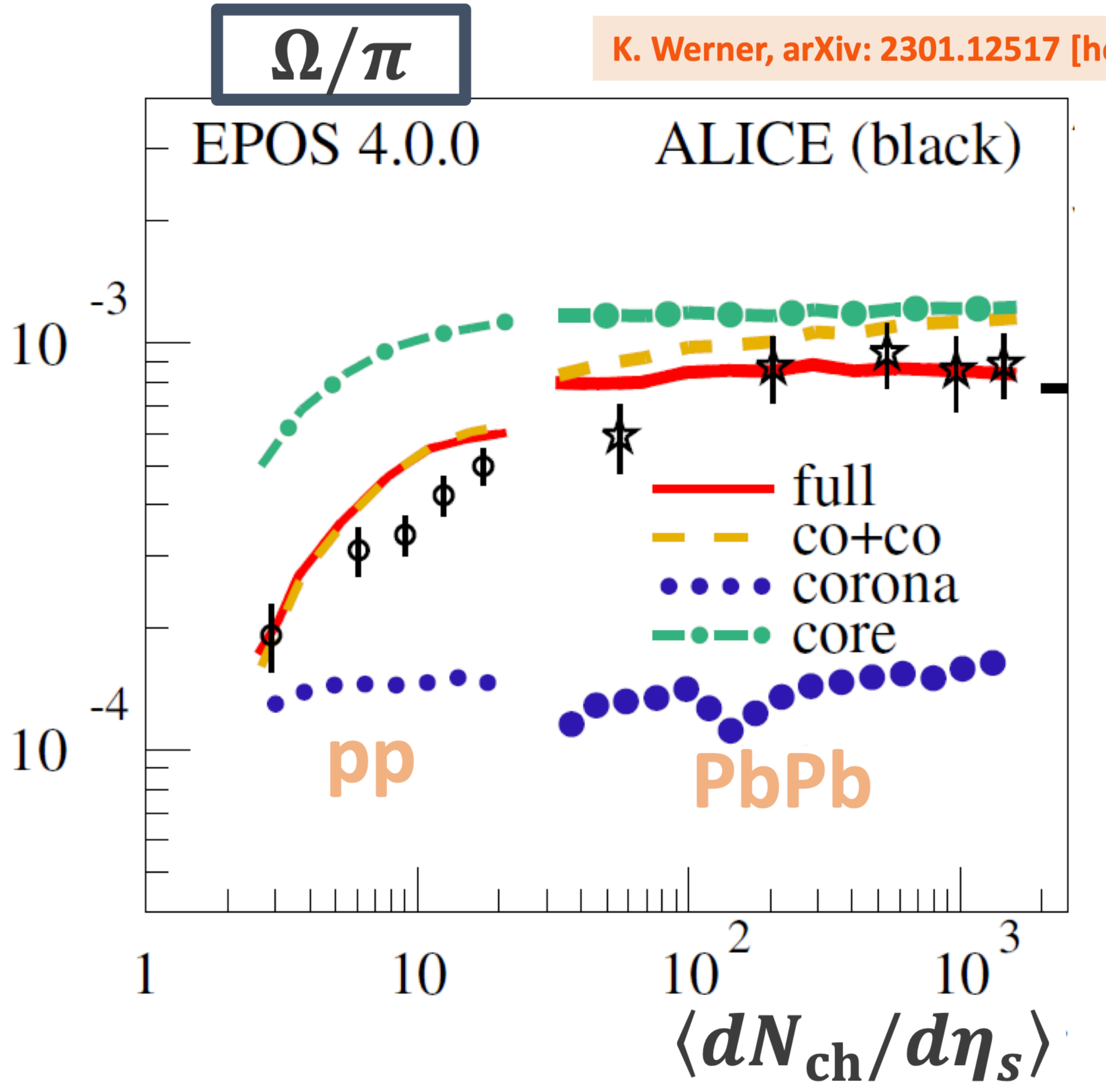
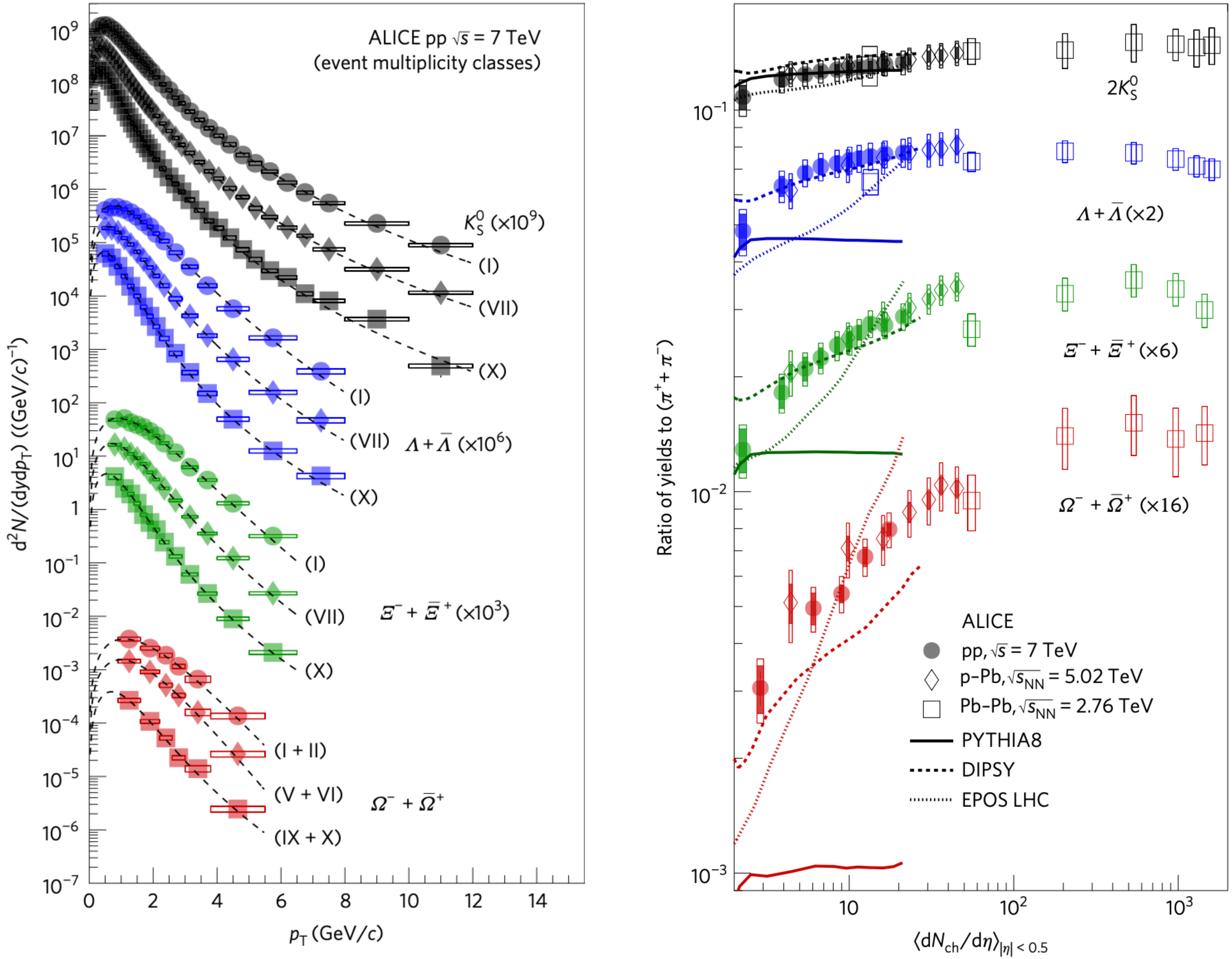


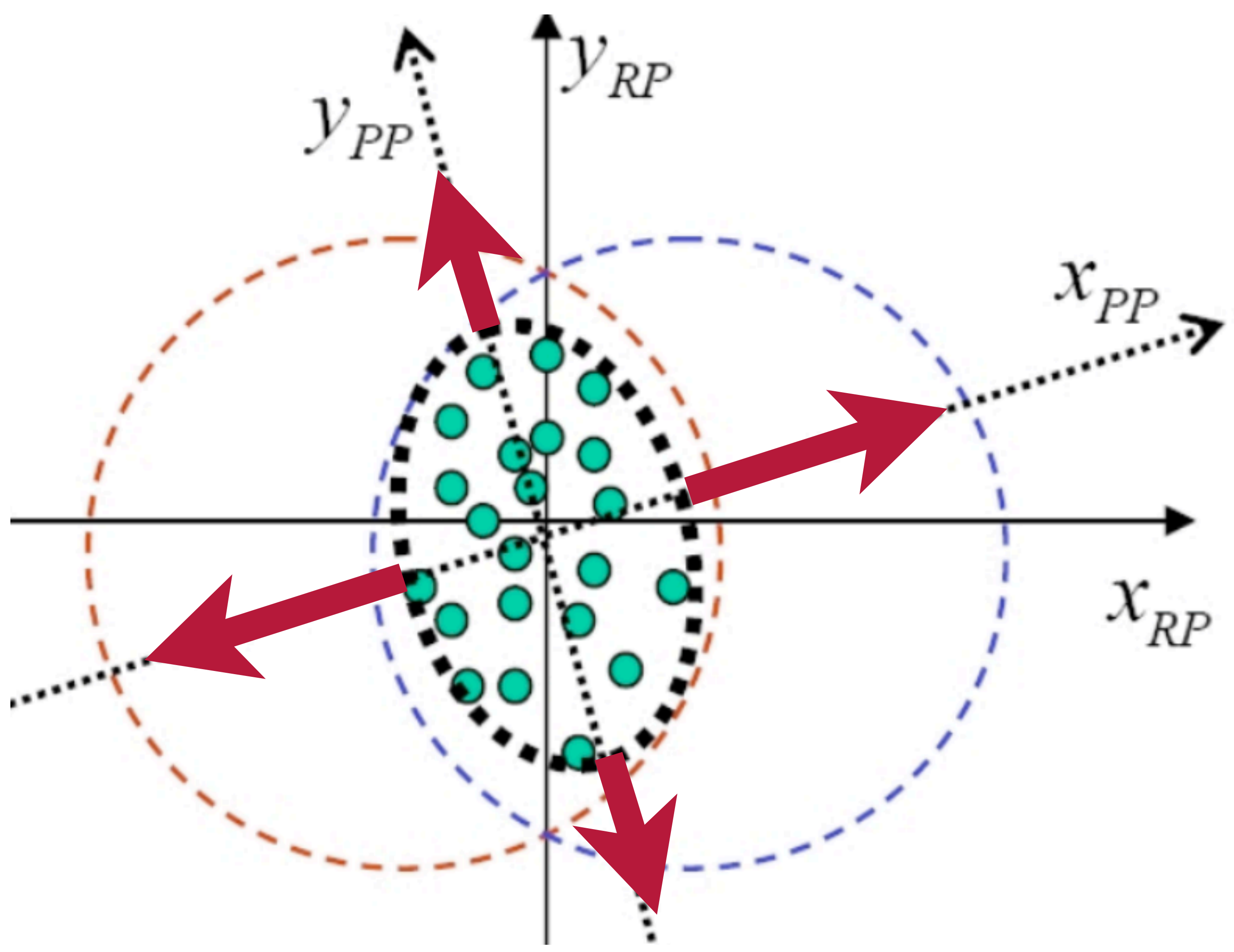
K. Werner, arXiv: 2301.12517 [hep-ph]





ALICE pp $\sqrt{s}$ = 7 TeV
(event multiplicity classes)
K^0_S (×10^9)
(I)
(VII)
(X)
$\Lambda+\bar{\Lambda}$ (×10^6)
$\Xi^- + \bar{\Xi}^+$ (×10^3)
$\Omega^- + \bar{\Omega}^+$
(I + II)
(V + VI)
(IX + X)
$d^2N/(dydp_T)$ ((GeV/c)$^{-1}$)
p_T (GeV/c)
$2K^0_S$
$\Lambda+\bar{\Lambda}$ (×2)
$\Xi^- + \bar{\Xi}^+$ (×6)
$\Omega^- + \bar{\Omega}^+$ (×16)
Ratio of yields to ($\pi^+ + \pi^-$)
$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$
ALICE
pp, $\sqrt{s}$ = 7 TeV
p–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Pb–Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
PYTHIA8
DIPSY
EPOS LHC

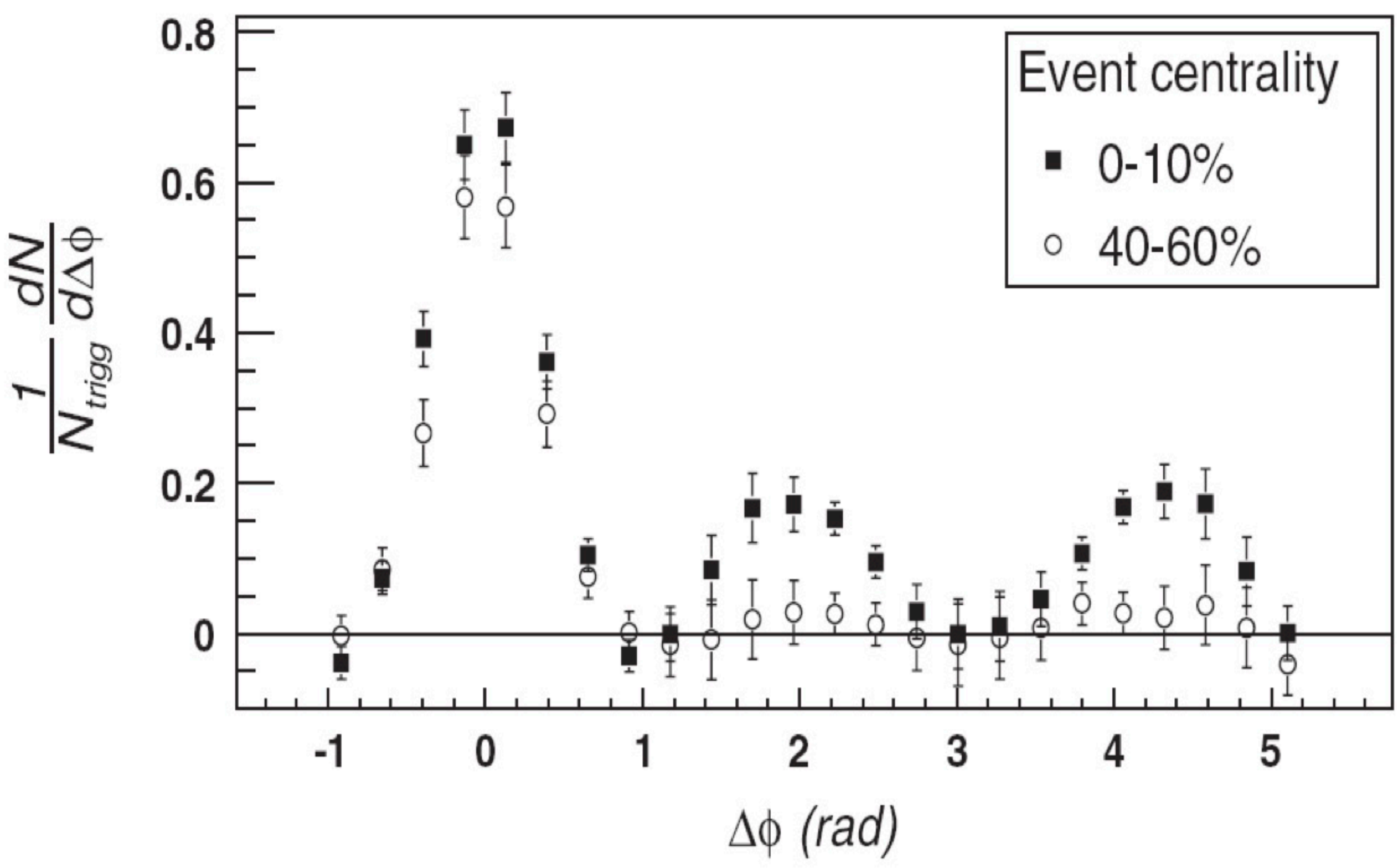
COLLECTIVE FLOW

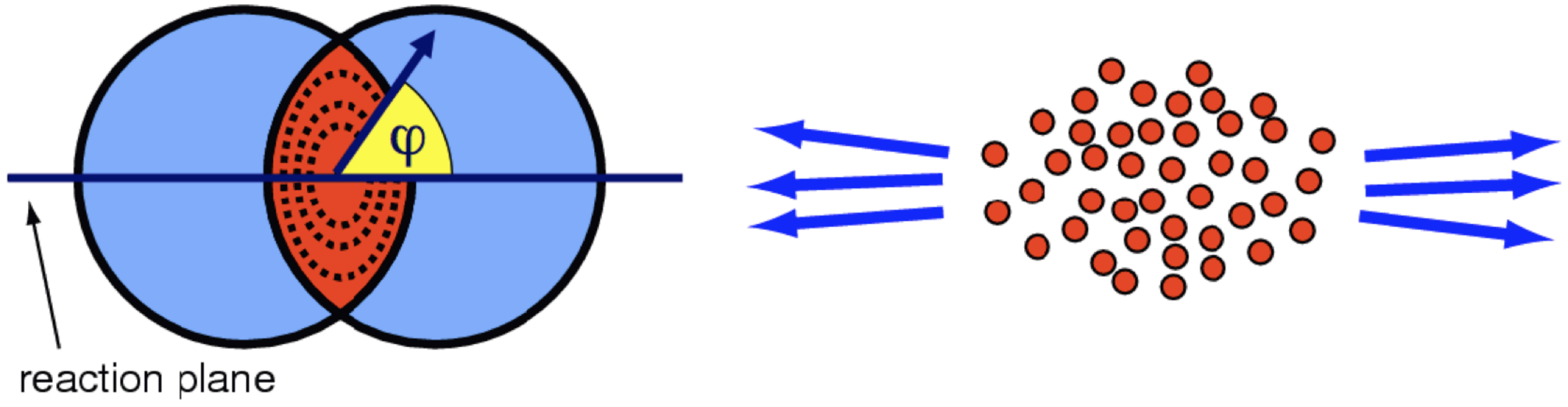


COLLECTIVE FLOW

Angular anisotropies found in particle spectra produced in A-A collisions

AA collisions are **not** a collection of incoherent p-p collisions!





$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

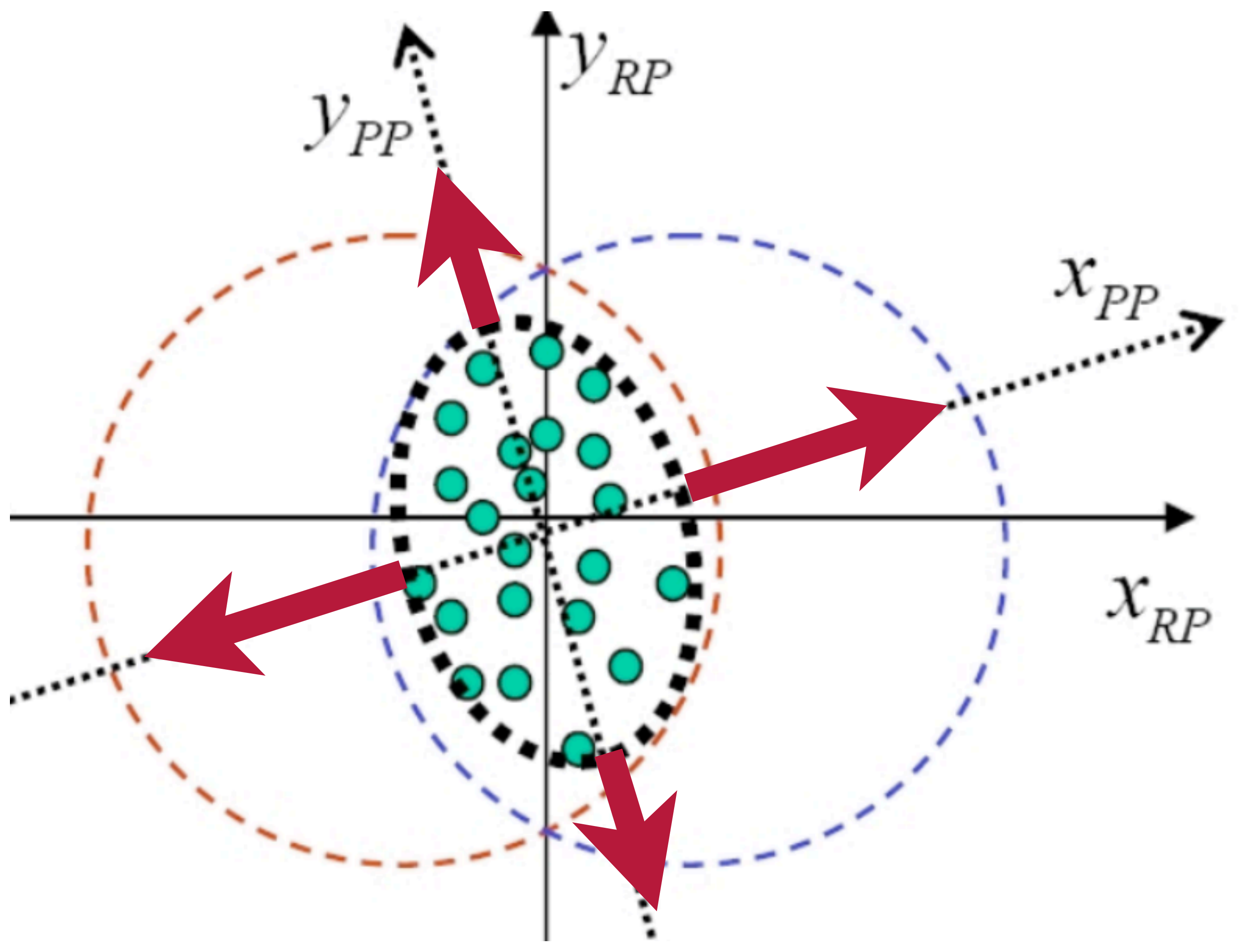
Initial idea: geometry of the collisions + hydrodynamical expansion triggers the

Πάντα ῥεῖ - Everything Flows

- Angular anisotropies found in particle spectra produced in Nucleus-Nucleus collisions

$$\frac{dN}{d^2p_\perp dy} = \frac{1}{2\pi p_\perp}\frac{dN}{dp_\perp dy}\left\{1 + 2\sum_i v_i(p_\perp)\cos\left[n(\phi - \Phi_{ev})\right]\right\}$$

(Nothing but a Fourier expansion...)



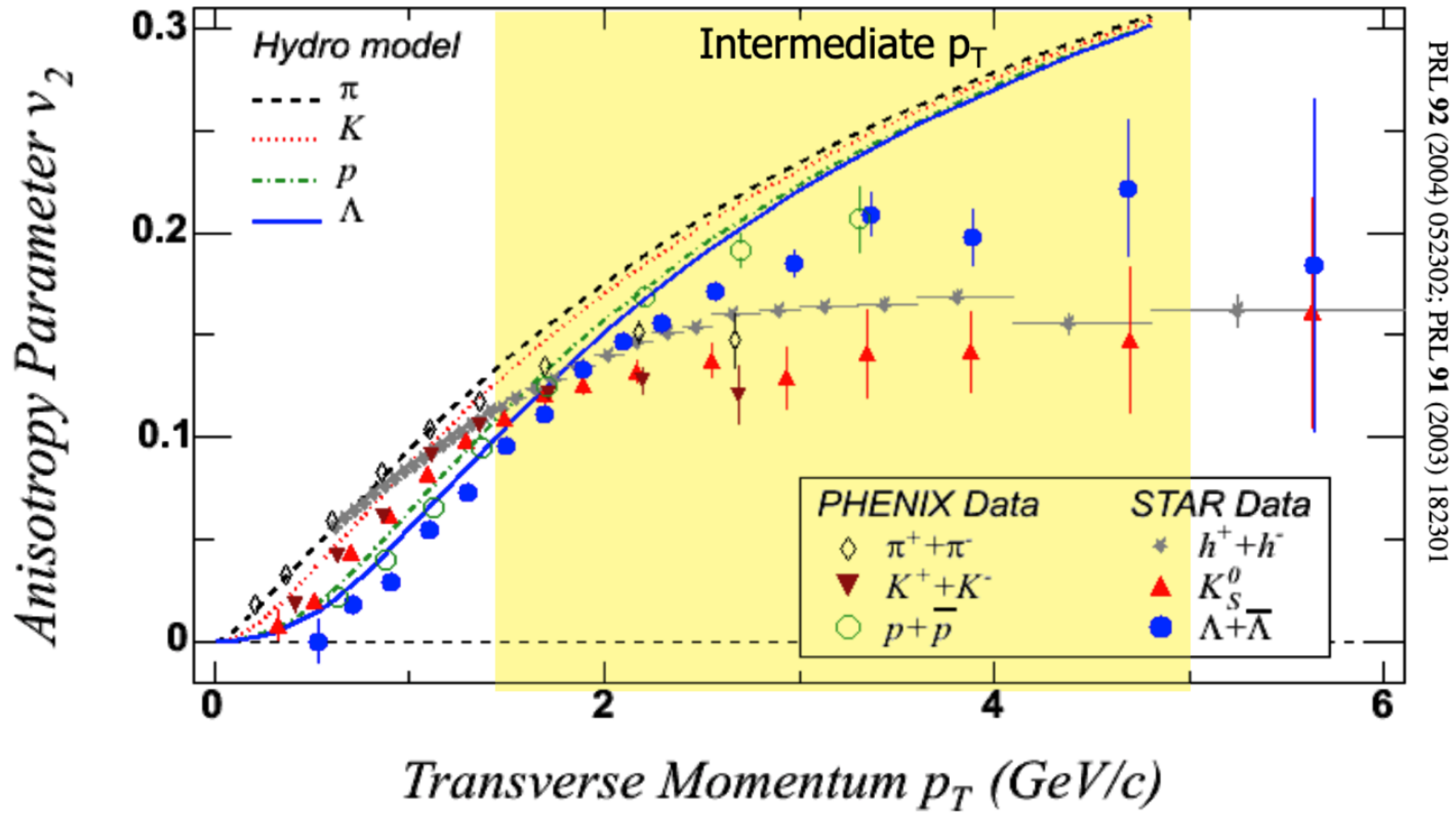
- Flow dynamics said to signal collectivity, medium creation

- Why is does this mean collective dynamics?

$$\varepsilon = \frac{\langle y^2 - x^2\rangle}{\langle y^2 - x^2\rangle} \xrightarrow{\text{Interactions}} v_2 = \frac{\langle p_y^2 - p_x^2\rangle}{\langle p_y^2 - p_x^2\rangle}$$

Spatial anisotropy (eccentricity)

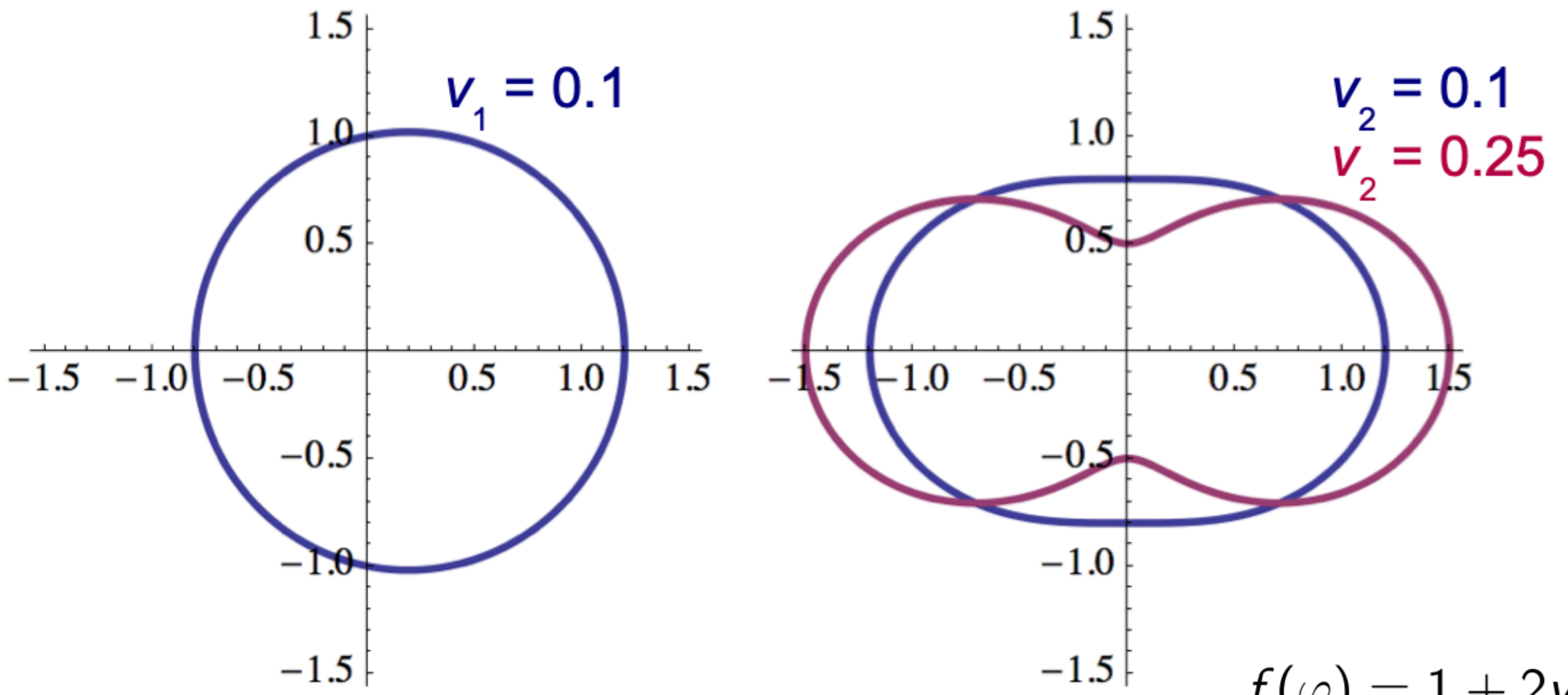
Momentum anisotropy



A CLOSER LOOK: MASS ORDERING

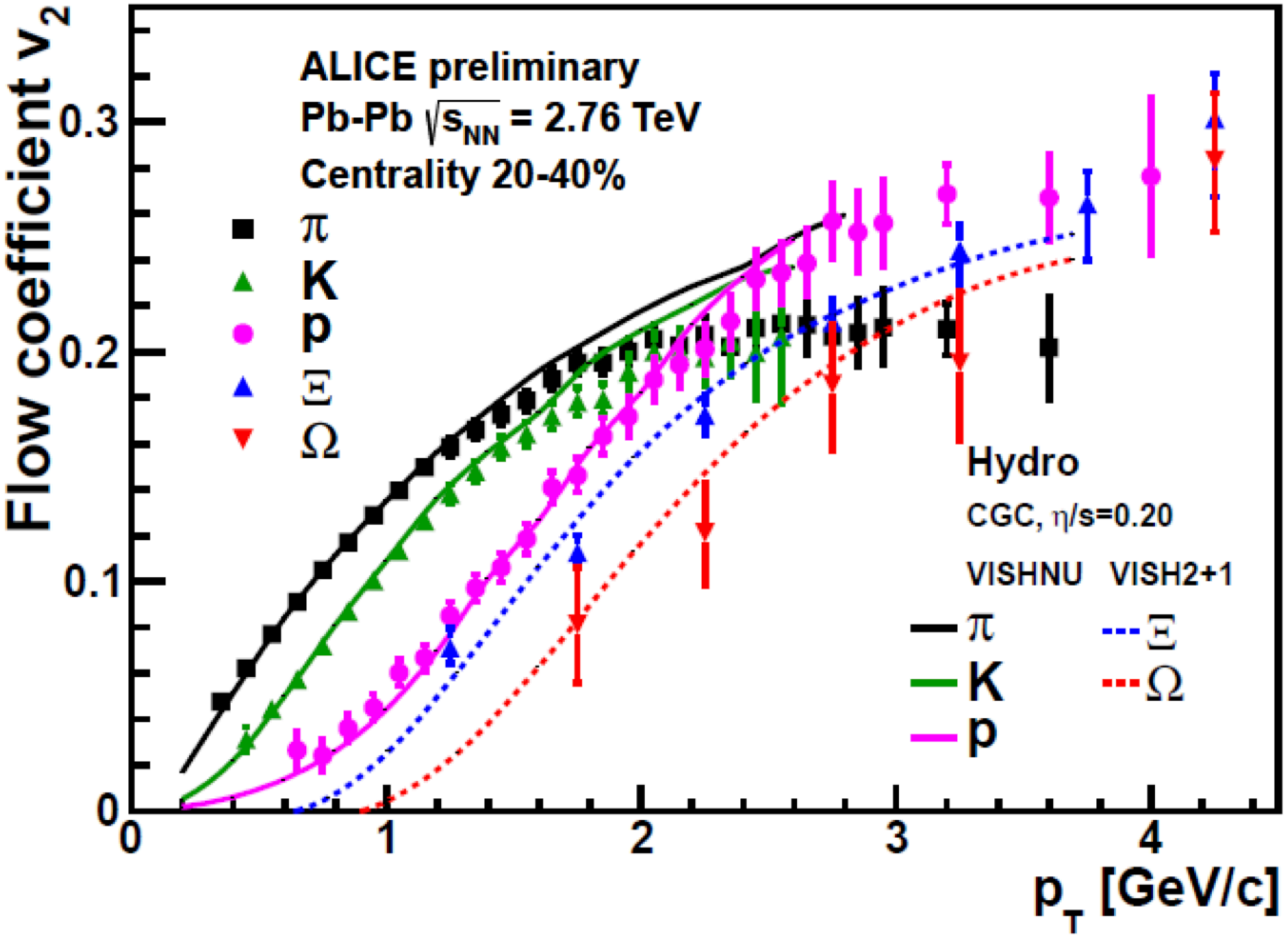
Mass ordering: v_2 of hadrons with higher masses exhibit slower increase with higher masses.

- Curves are "ordered" by mass.
- In the hydrodynamical picture, this is caused by the boost particles feel from the movement of the fluid cell



$f(\varphi) = 1 + 2v_n \cos(n\varphi)$

final results: arXiv:1405.4632



MASS ORDERING

Mass ordering: v_2 of hadrons with higher masses exhibit slower increase with higher masses. But… why?

- Recall $\frac{dn}{d^3p} \sim e^{-u \cdot p/T}$ where $u \cdot p = m_\perp u_0 - u_\perp p_\perp$ and $\begin{aligned} u_0 &= \cosh \rho_\perp \\ u_\perp &= \sinh \rho_\perp \end{aligned}$ Transverse Rapidity

- Assume that the radial velocity is modulated $u(\phi) = u + 2\alpha \cos(2\phi)$

- Expanding to first order in α, we get $u(\phi) = u_0 + 2\beta\alpha \cos(2\phi)$ where $\beta = u/u_0$

- Expanding the yield to first order in α, we find

$$\frac{dn}{d^3p} \sim e^{-(m_\perp u_0 - u_\perp p_\perp)/T} \left[1 + 2\frac{\alpha}{T}(p_\perp - \beta m_\perp)\cos(2\phi)\right]$$

MASS ORDERING

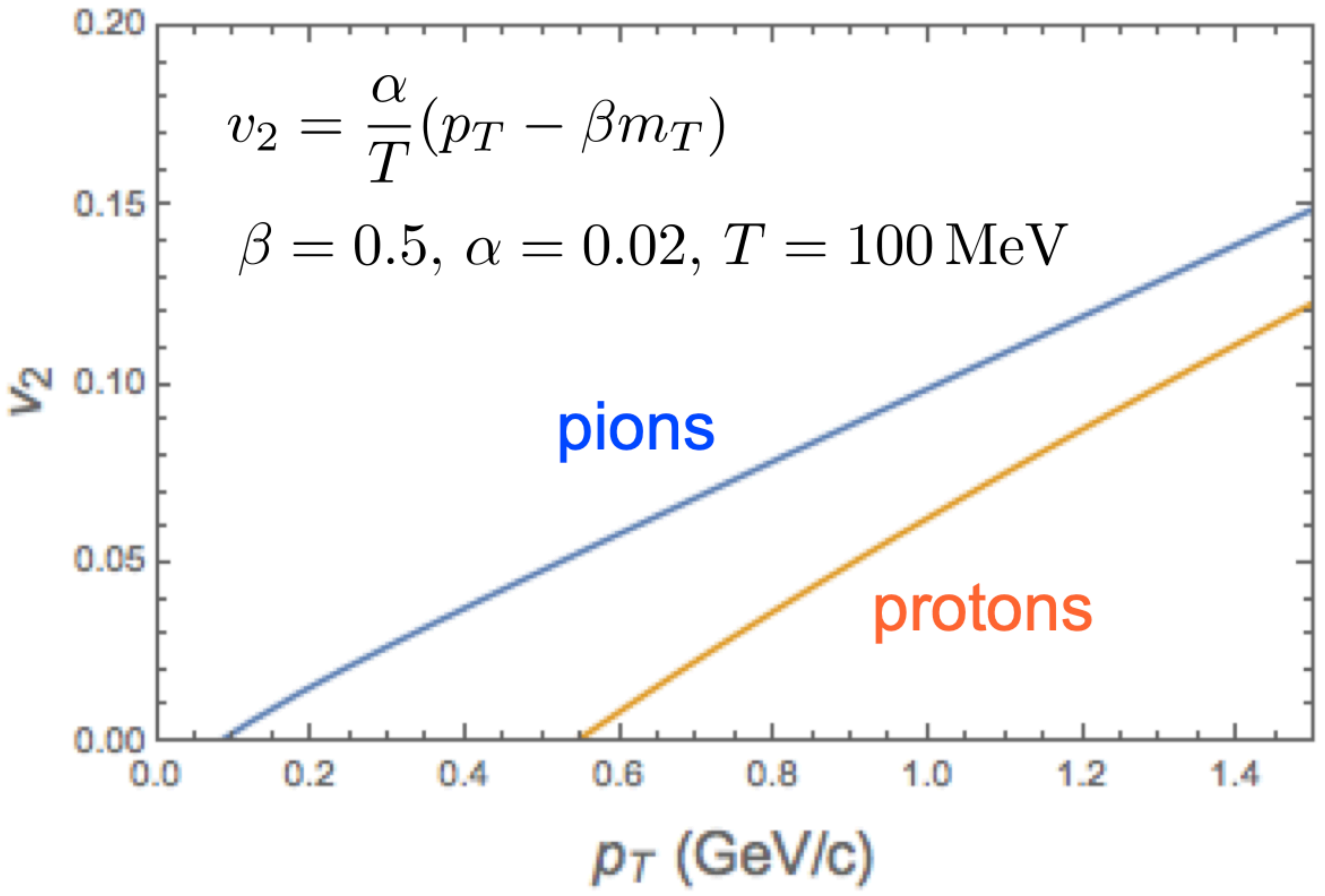
- Expanding the yield to first order in α, we find

$$\frac{dn}{d^3p} \sim e^{-(m_\perp u_0 - u_\perp p_\perp)/T}\left[1 + 2\frac{\alpha}{T}(p_\perp - \beta m_\perp)\cos(2\phi)\right]$$

- We can define from this, the flow coefficient

$$v_2(p_\perp) = \frac{\alpha}{T}(p_\perp - \beta m_\perp)$$

- Higher mass particles will have a higher $m_\perp$ for same $p_\perp$, leading to a higher shift!



V2: COLLISION ENERGY DEPENDENCE

- $\sqrt{s_{\mathrm{NN}}} < 2\,\mathrm{GeV}$

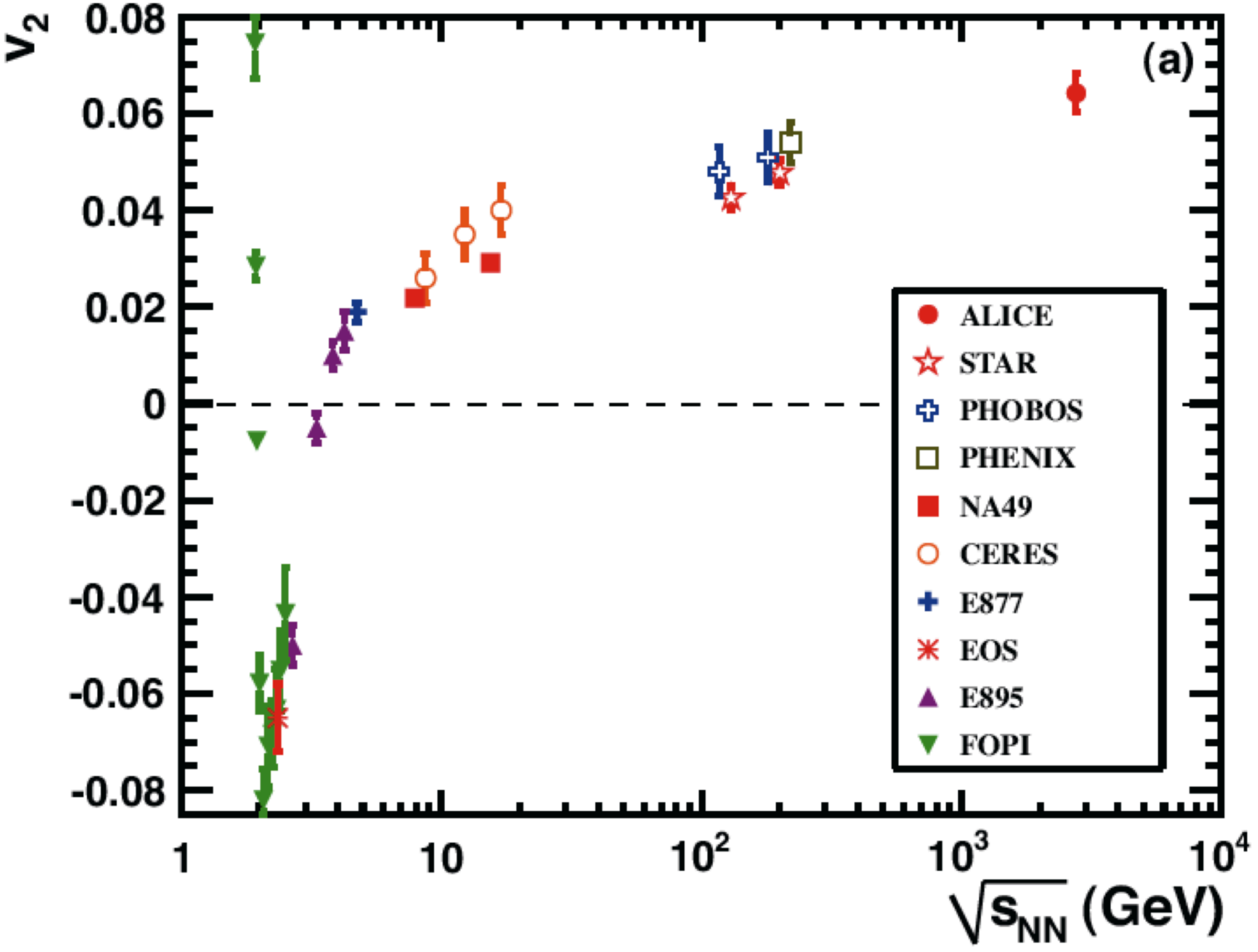
  Mechanical rotation of the collision system leads to fragments being emitted in-plane

- $2 > \sqrt{s_{\mathrm{NN}}} > 5\,\mathrm{GeV}$

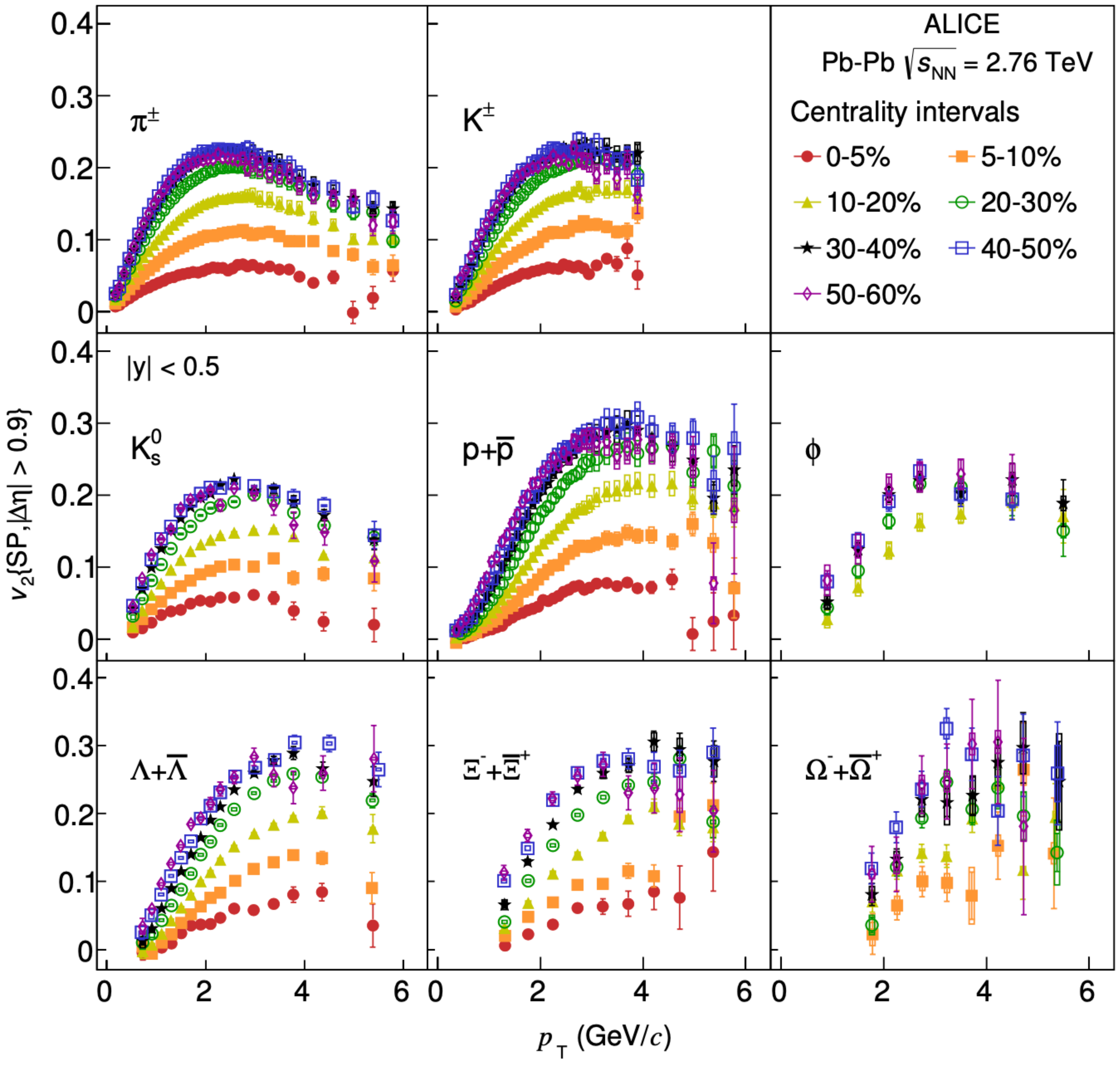
  The velocity of the nuclei is small so that presence of spectator matter inhibits in-plane particle emission ("squeeze-out")

- $\sqrt{s_{\mathrm{NN}}} > 5\,\mathrm{GeV}$

  Pressure gradients (collective flow) translates initial geometry to momentum anisotropies



V2: CENTRALITY DEPENDENCE

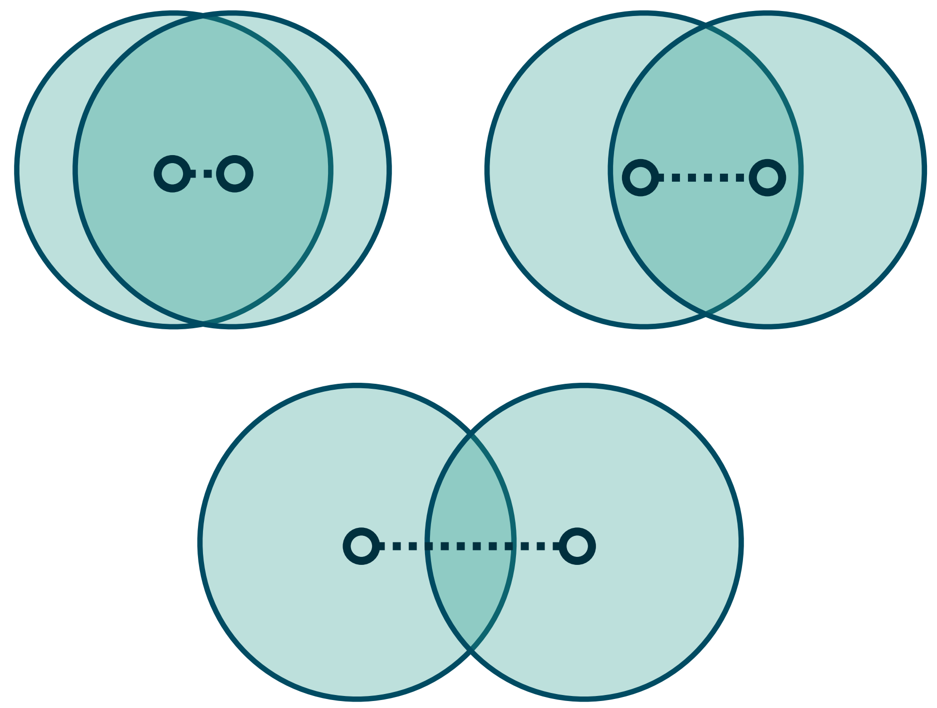


We are back at the high energy cases

The flow coefficient v_2 increases with decreasing centrality.

Inflection point around 50-60%.

This supports the geometric picture



COLLECTIVE FLOW: MEDIUM RESPONSE TO GEOMETRY

It has been shown that the hydrodynamical expansion acts as a medium response on the initial geometry, quantified by the initial eccentricity

The initial eccentricity can be computed

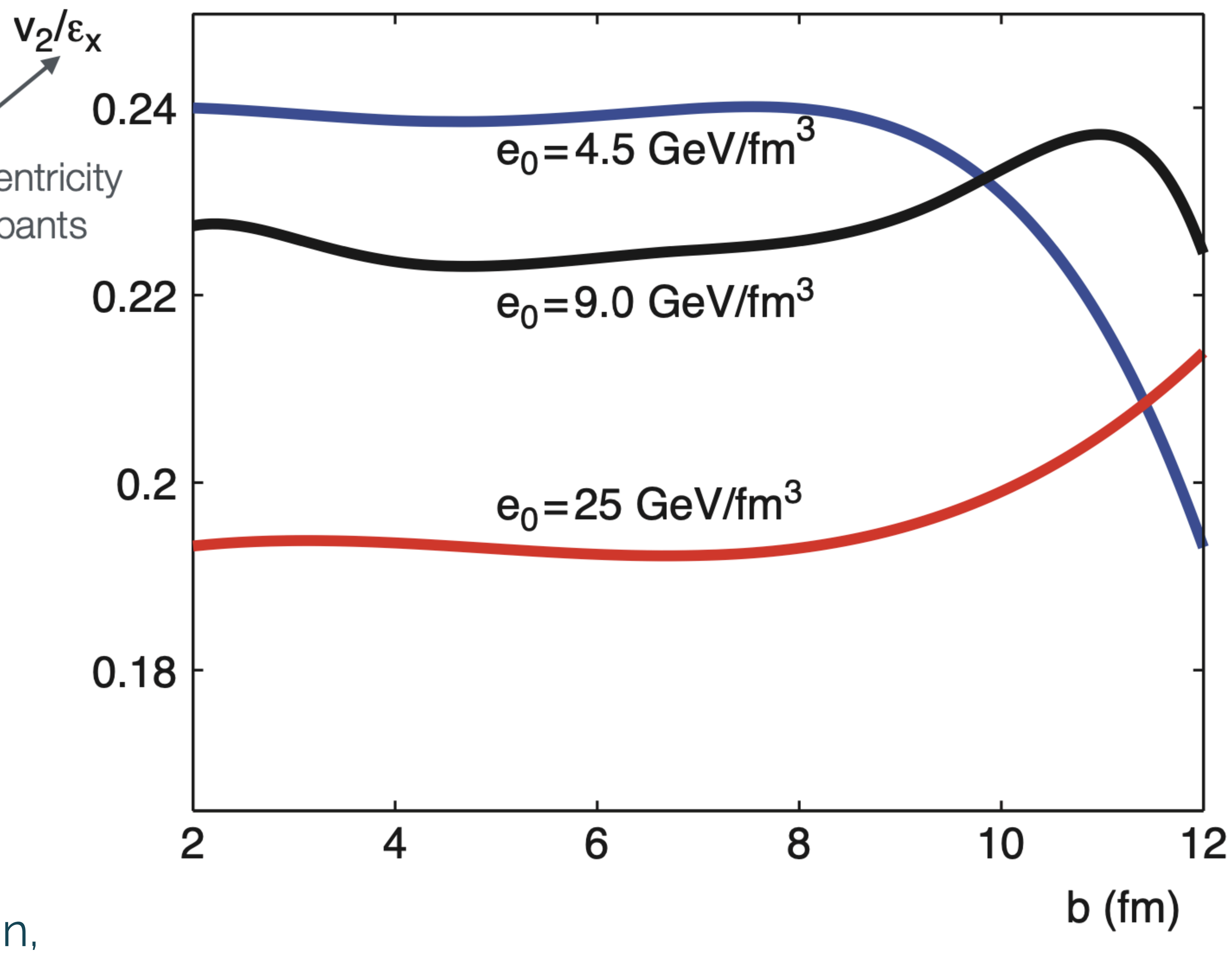
$$\varepsilon_n(y) = \frac{\int \mathrm{d}^2 r_\perp |\mathbf{r}_\perp|^n \, e^{in(\phi-\Phi_n)} \left[e(y,\mathbf{r}_\perp)\tau\right]_0}{\int \mathrm{d}^2 r_\perp \left[e(y,\mathbf{r}_\perp)\tau\right]_0}$$

The response function seems to be roughly constant

$$v_2 = \kappa\, \epsilon_2$$

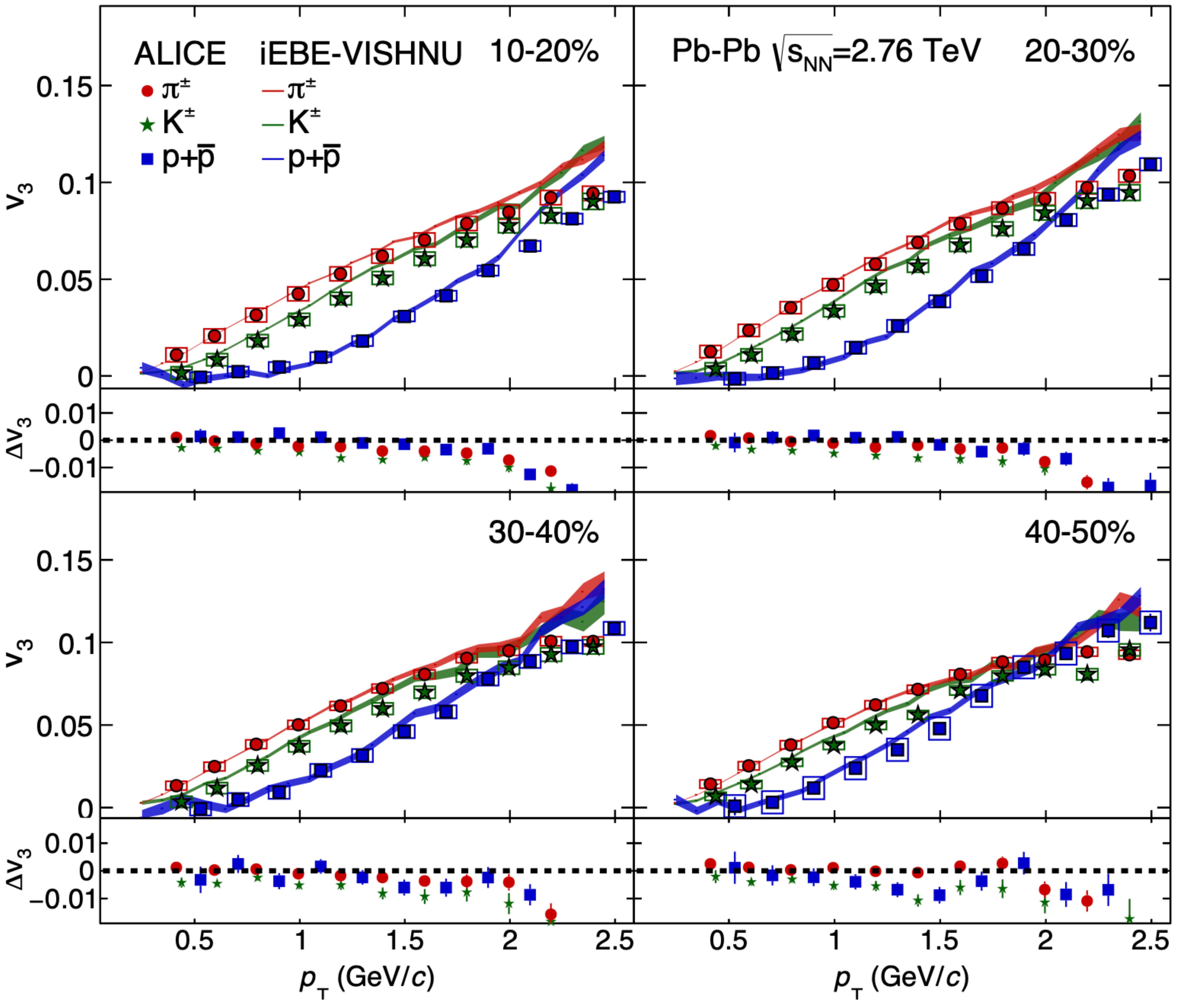
Where κ clearly depends on centrality, energy of collision, etc. However, it is remarkable that the dependence does not seem to be that strong!

ε_x: initial eccentricity of the participants



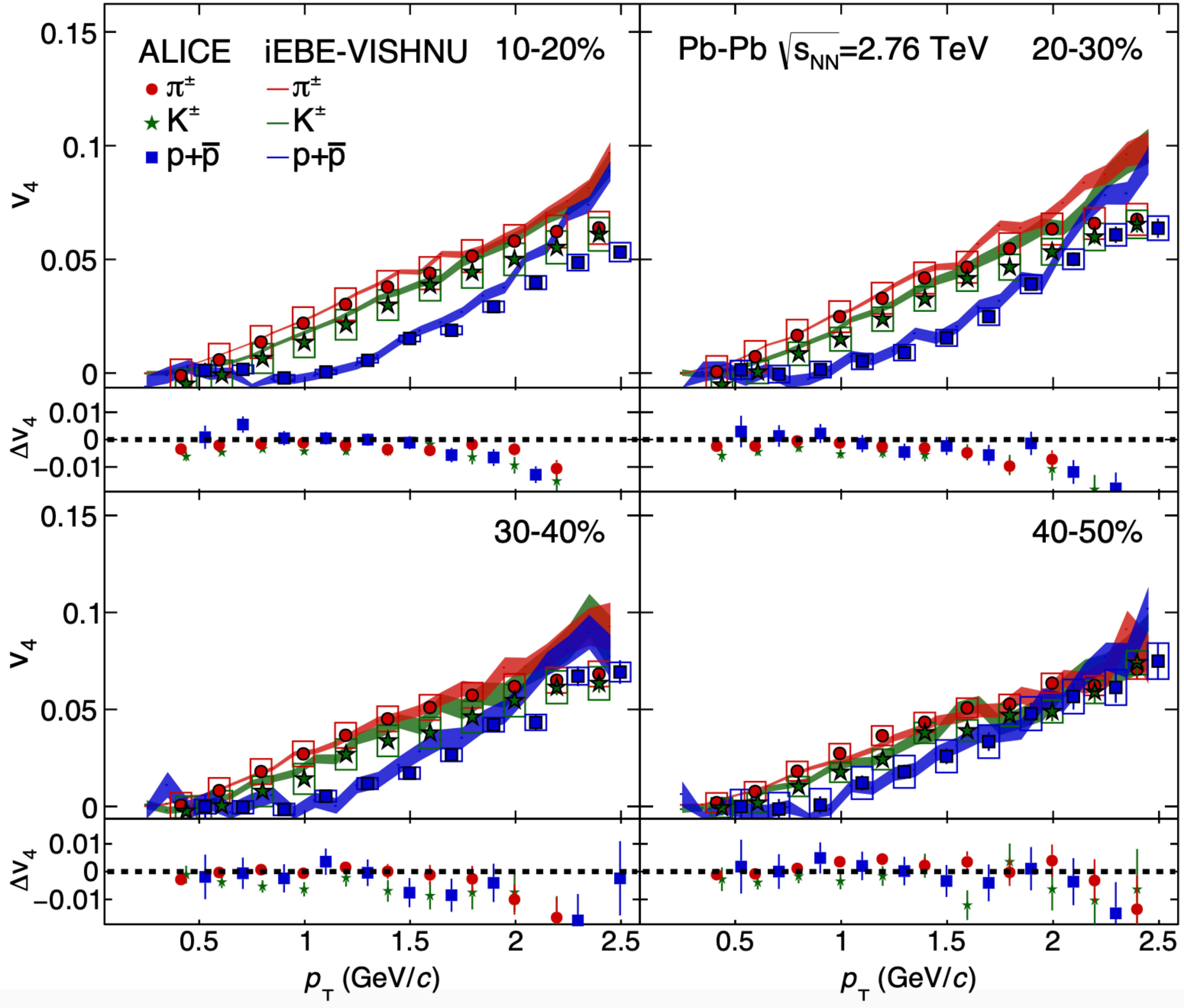
Ideal hydrodynamics gives $v_2 \approx 0.2 – 0\text{-}25\ \varepsilon$

WHAT ABOUT THE OTHER MOMENTS?



From arXiv: 1606.06057

WHAT ABOUT THE OTHER MOMENTS?



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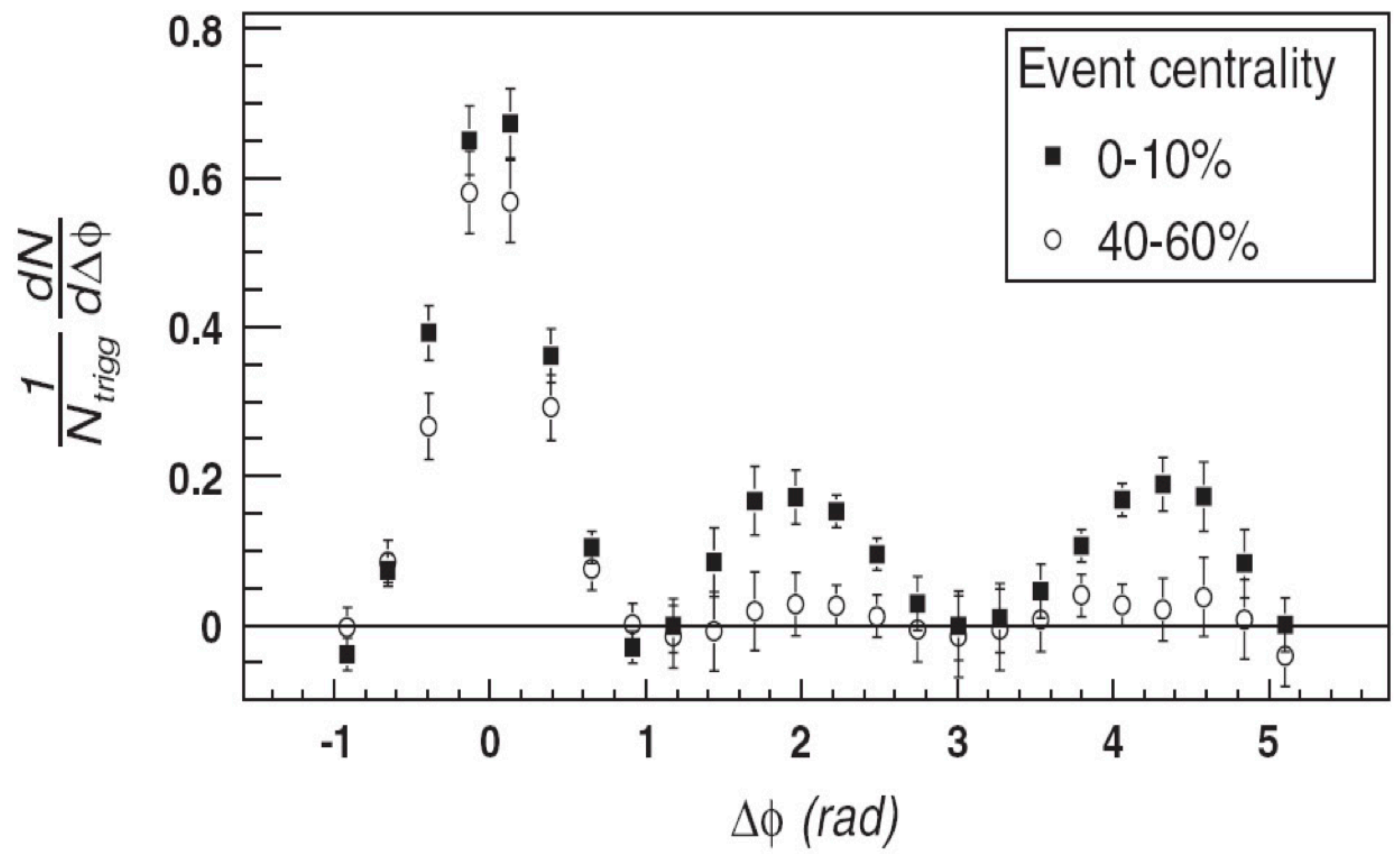
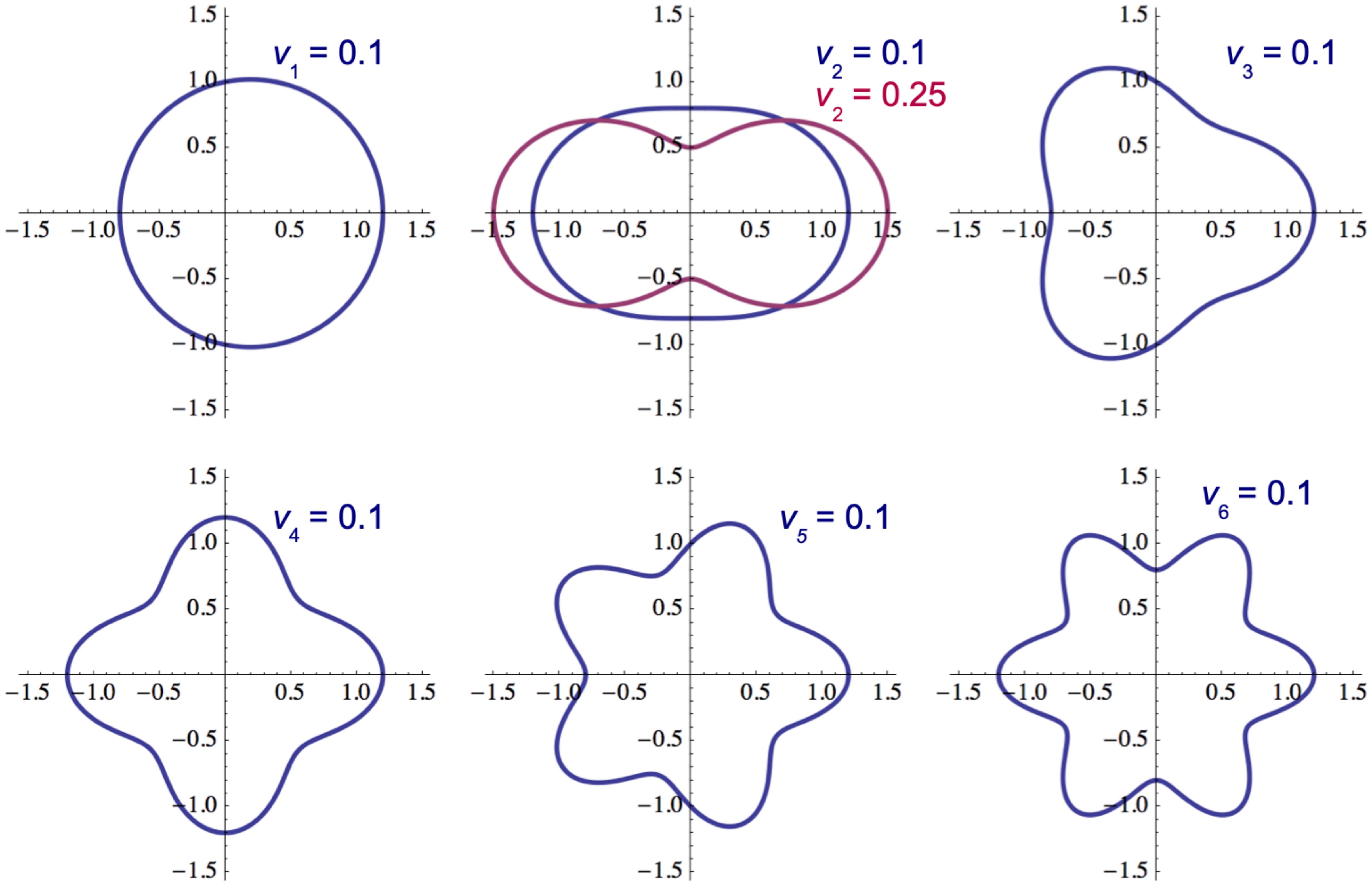
WHAT ABOUT THE OTHER MOMENTS?





$f(\varphi) = 1 + 2v_n \cos(n\varphi)$

If initial state is given by almond-like shape, one can still expect something non-trivial for v_{2n}

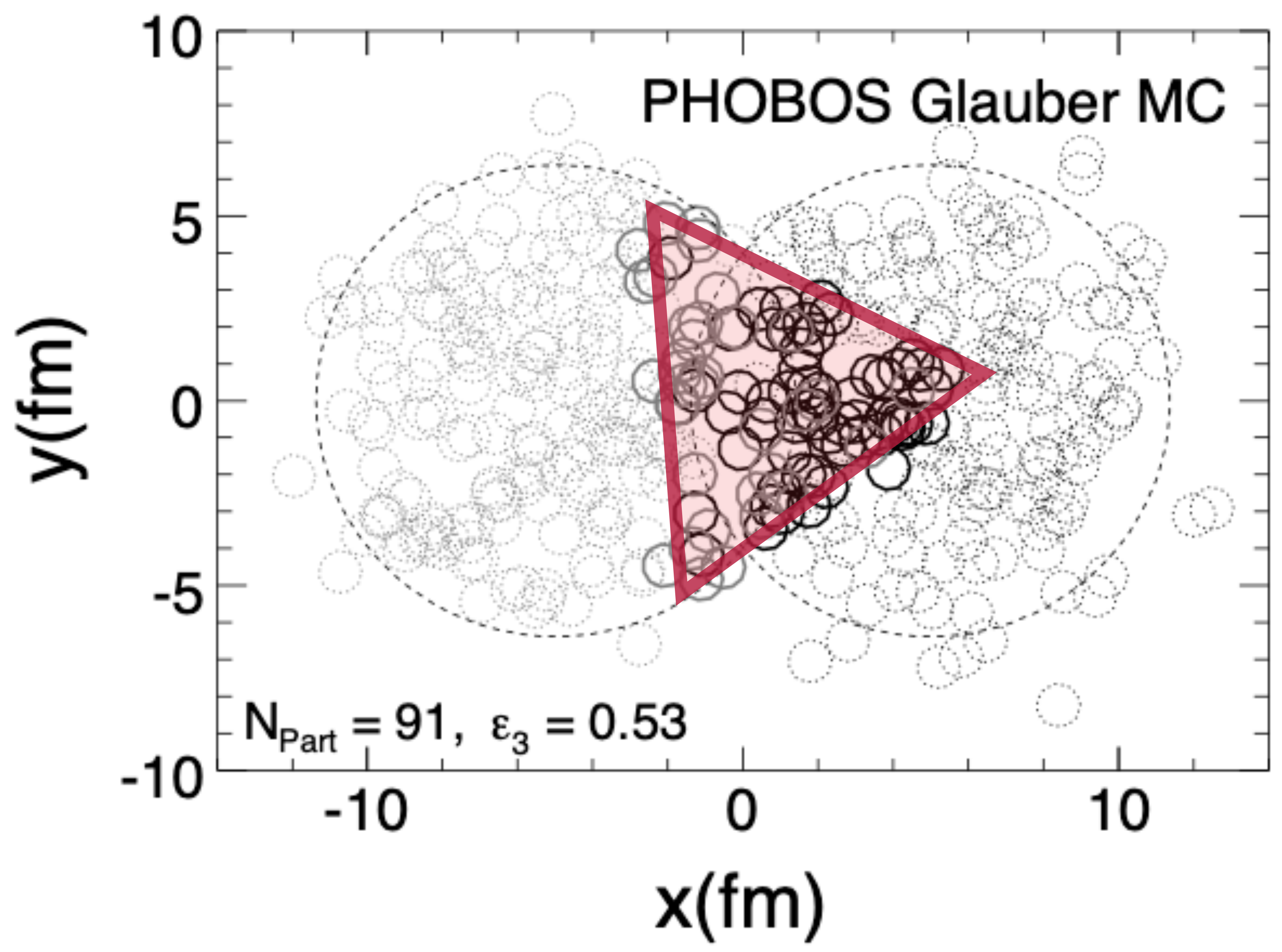
$$\epsilon_0 \sim (T_1^p + T_2^p)^{1/p}$$

D4,D6... D2N symmetries contain D2, but how does the odd v_3 appear??

v_{2n+1} are not allowed by initial symmetry of the system.... Right?

FALSE

Nucleonic/subnucleonic/clustering fluctuations in fact break the D2 symmetry



Odd flow coefficients are fully influenced by fluctuations!

HOW DO WE MEASURE THE FLOW COEFFICIENTS?

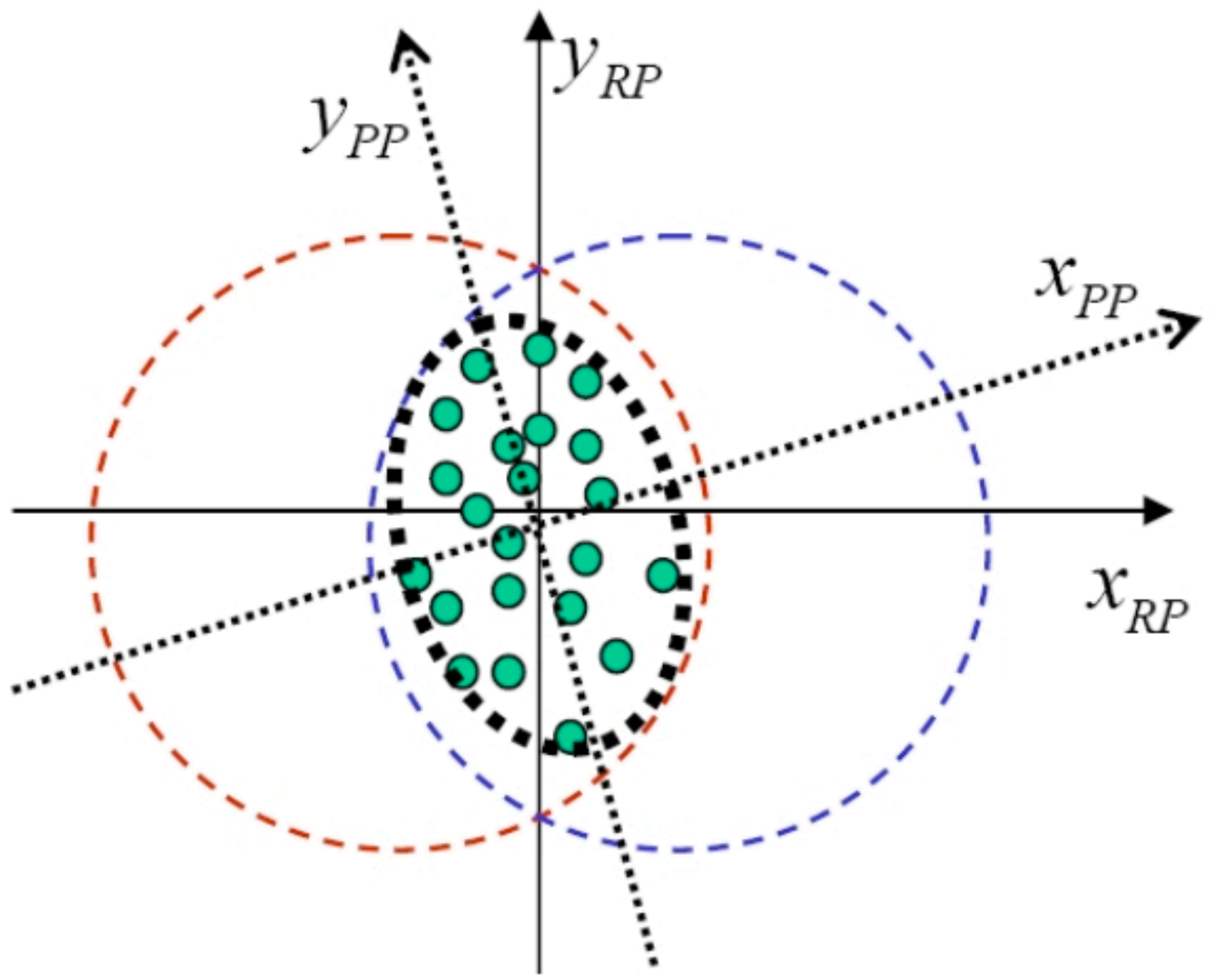
EVENT PLANE METHOD

Let's define the event flow-vector (2D)

$$Q_{n,x} = \sum_i w_i \cos(n\phi_i) = \mathbf{Q}_n \cos(n\Psi_n),$$
$$Q_{n,y} = \sum_i w_i \sin(n\phi_i) = \mathbf{Q}_n \sin(n\Psi_n),$$

The $w_i(y)$ are the weights of each detected particle, with $w_i(-y) = -w_i(y)$

And the *event plane angle*,
$\Psi_n = \arctan(Q_{n,y}/Q_{n,x})/n$



And so, the observed flow coefficient is given by

$$v_n^{obs}(p_\perp, y) = \langle\langle\cos\left[n(\phi_i - \Psi_n)\right]\rangle_p\rangle_e$$

Here p stands for particle avg. in one event and e for avg. over multiple events

However, because of finite multiplicity events (fluctuations, etc, we have a finite resolution)

$$\mathscr{R}_n = \left\langle \cos\left[n\left(\Psi_n - \Psi_{RP}\right)\right]\right\rangle$$

And finally we get the corrected flow, $v_n = v_n^{obs}/\mathscr{R}_n$

See 0809.2949 for more information!

HOW DO WE MEASURE THE FLOW COEFFICIENTS?

CUMULANTS METHOD

Define flow through n-particle correlations.

$$c_n\{2\} = \langle\langle e^{n\mathrm{i}[\phi_1-\phi_2]}\rangle_p\rangle_e$$

$$c_n\{4\} = \langle\langle e^{n\mathrm{i}[\phi_1+\phi_2-\phi_3-\phi_4]}\rangle_p\rangle_e - 2\,\langle\langle e^{n\mathrm{i}[\phi_1-\phi_2]}\rangle_p\rangle_e^2$$

Second moment of the 2-particle cumulating

$$\begin{aligned}\langle\langle e^{2\mathrm{i}[\phi_1-\phi_2]}\rangle_p\rangle_e &= \langle\langle e^{2\mathrm{i}[\phi_1-\Psi_{RP}-(\phi_2-\Psi_{RP})]}\rangle_p\rangle_e \\ &= \langle\langle e^{2\mathrm{i}[\phi_1-\Psi_{RP}]}\rangle_p\langle e^{-2\mathrm{i}[\phi_2-\Psi_{RP}]}\rangle_p\rangle_e + \delta_2 \\ &= \langle v_2^2\rangle + \delta_2\end{aligned}$$

Flow + extra correlations ("non-flow")

If all correlations are flow...

$$c_n\{2\} = \langle v_n^2\rangle$$

$$c_n\{4\} = \langle -v_n^4\rangle$$

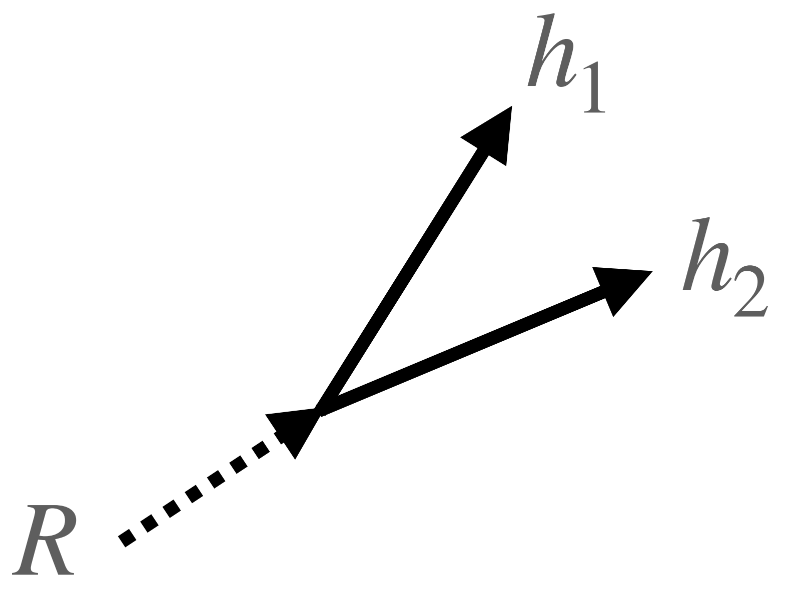
$c_n\{4\}$ is a cumulant also known as an excess kurtosis, meaning that if fluctuations are strictly gaussian, it vanishes

See 0809.2949 for more information!

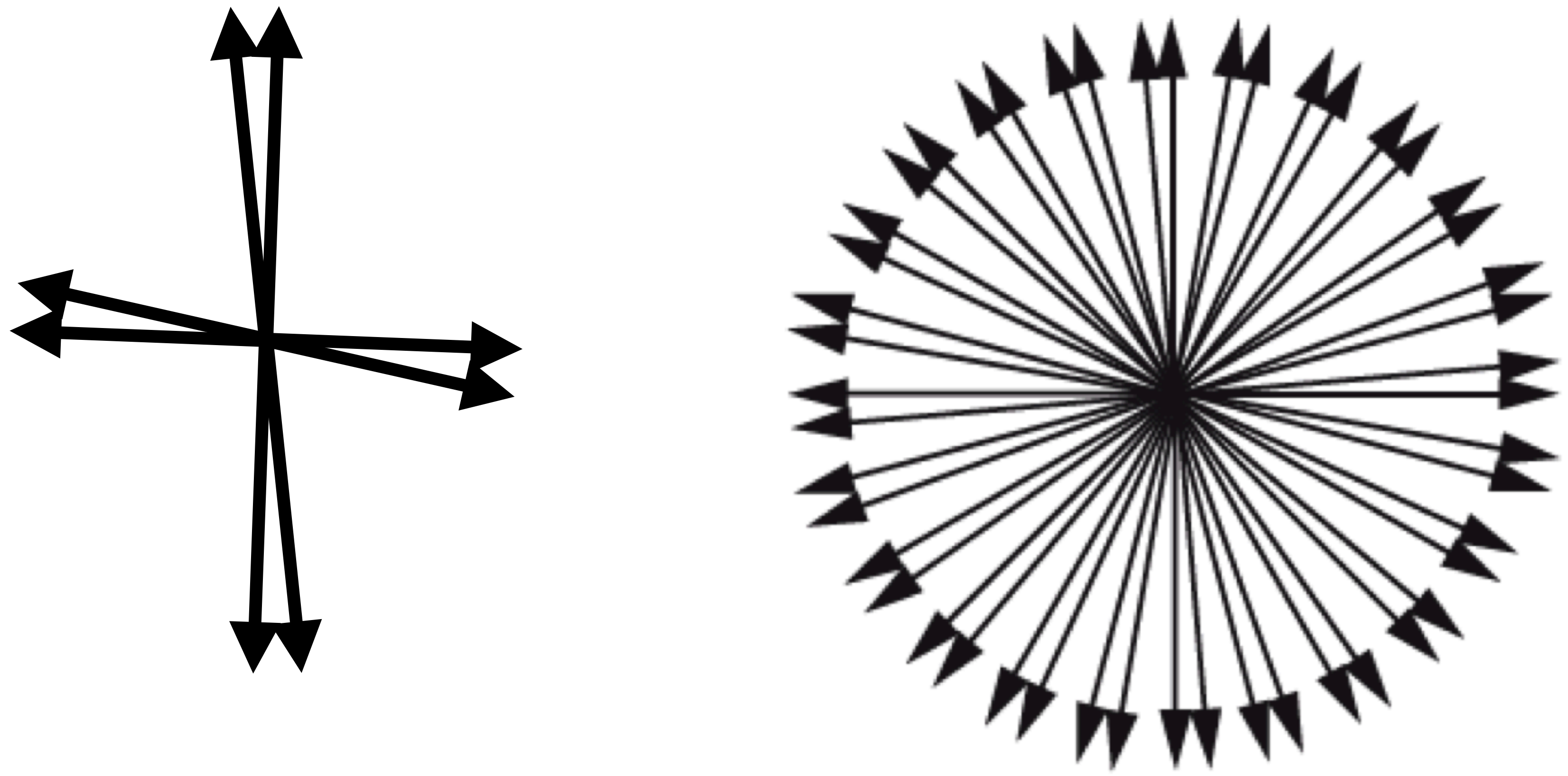
NON-FLOW

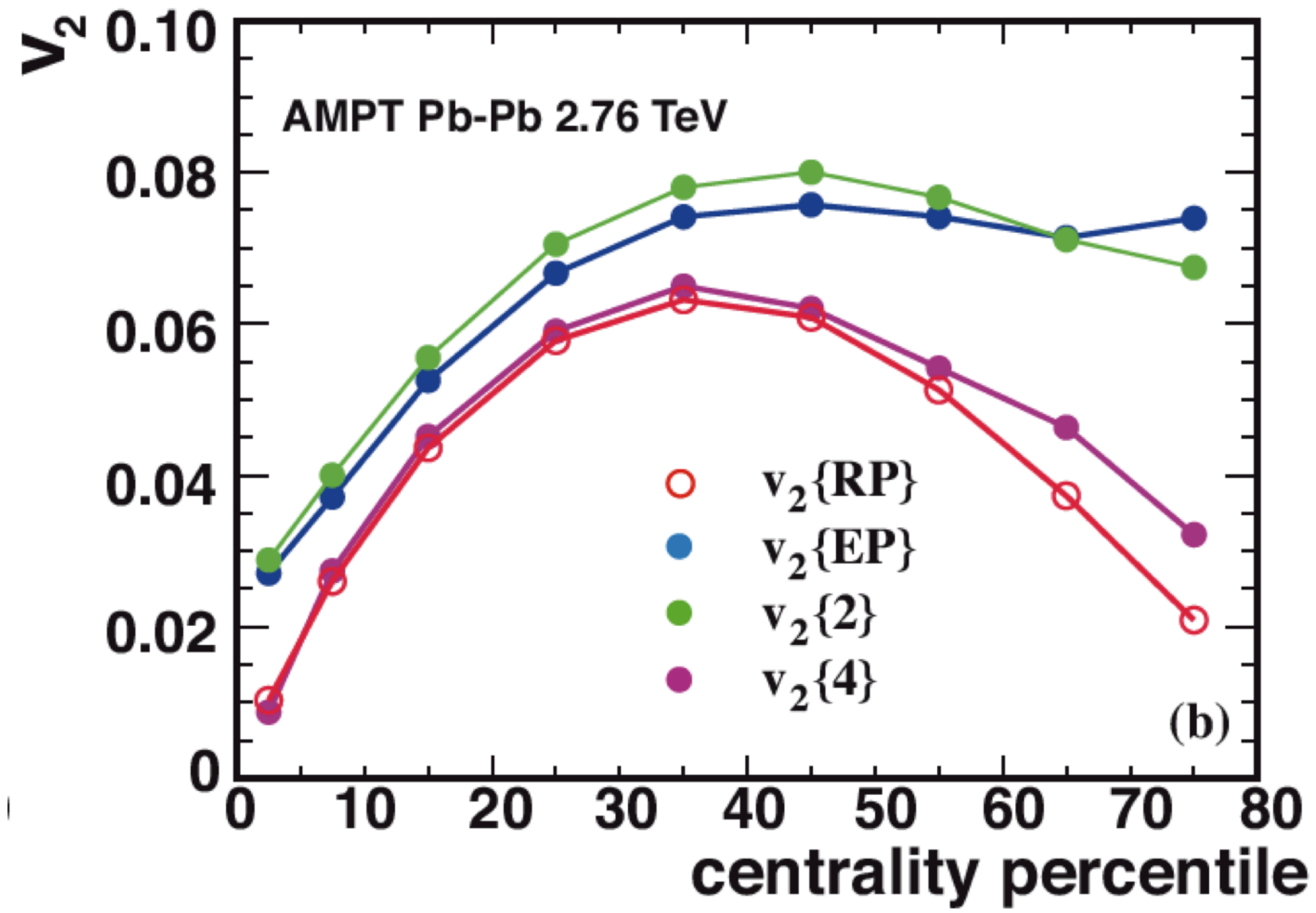
One can create anisotropy due to effects which are not collective flow: For example: **resonance decays, jets, ...**

e.g. Decays

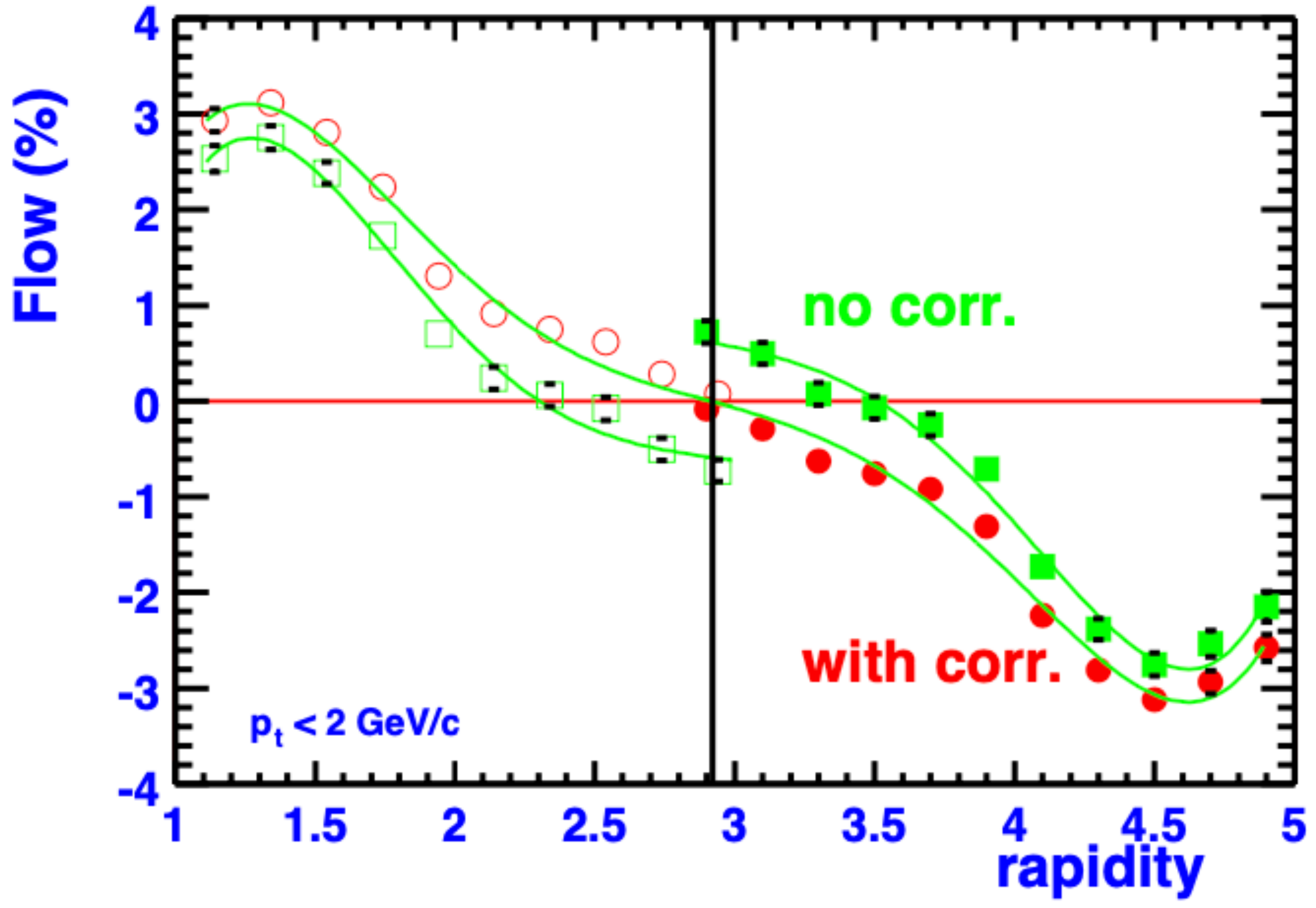


$v_2 = 0,\ v_2\{2\} > 0$



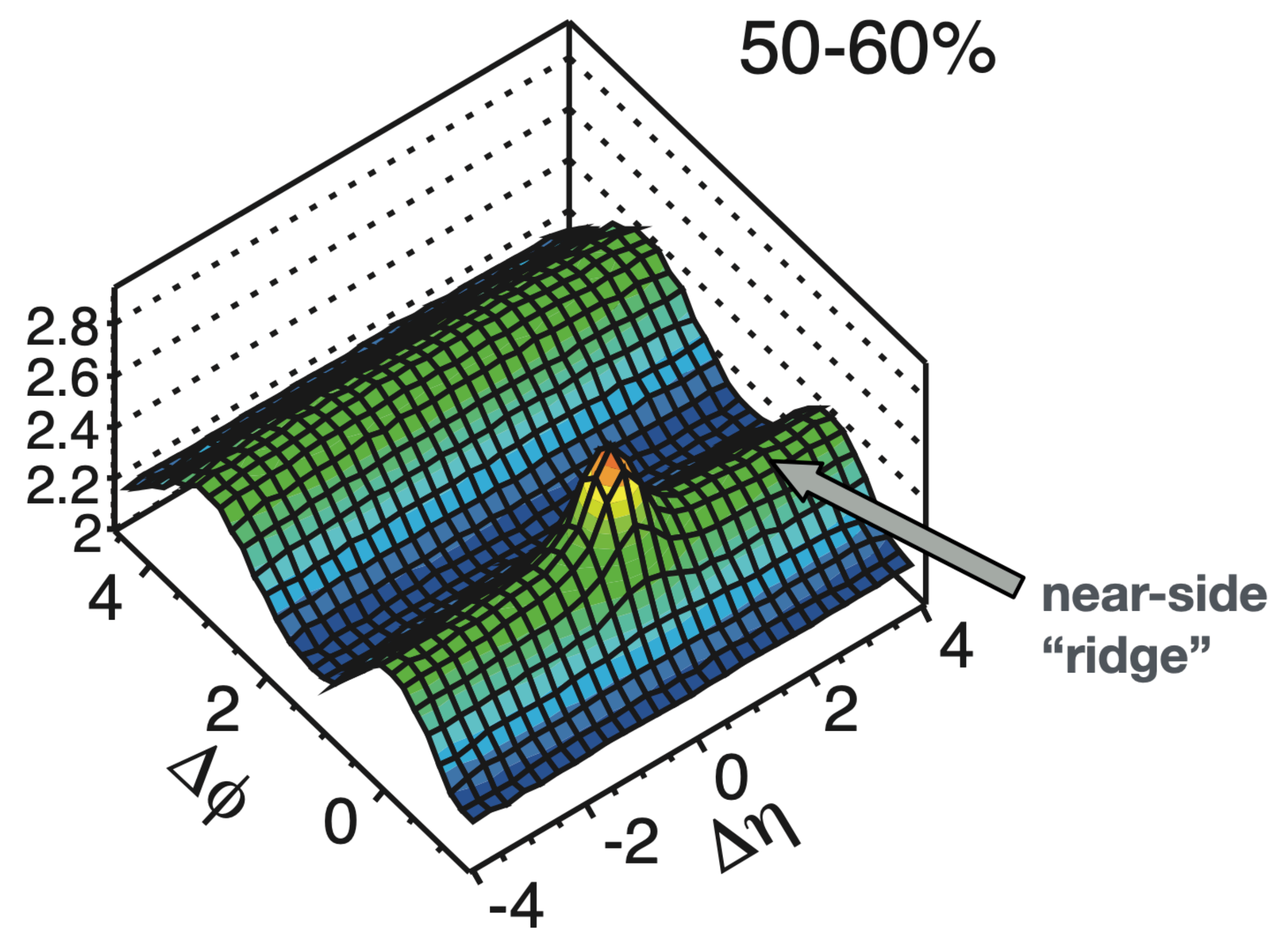


Different methods have different sensitivities to nonflow effects. The 4-particle cumulant method is significantly less sensitive to nonflow effects than the 2-particle cumulant method



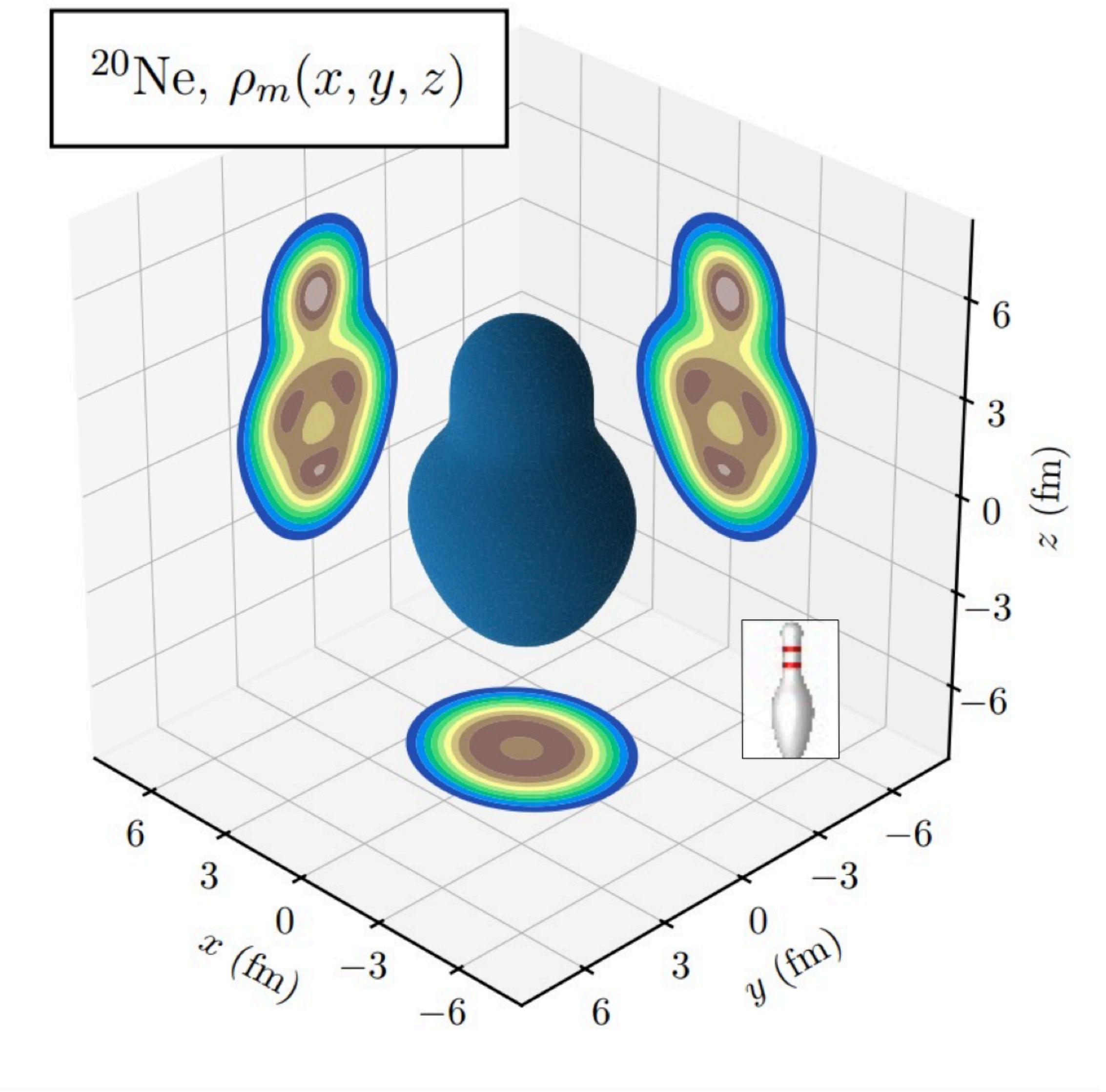
See 0809.2949 for more information!

SMALL SYSTEMS

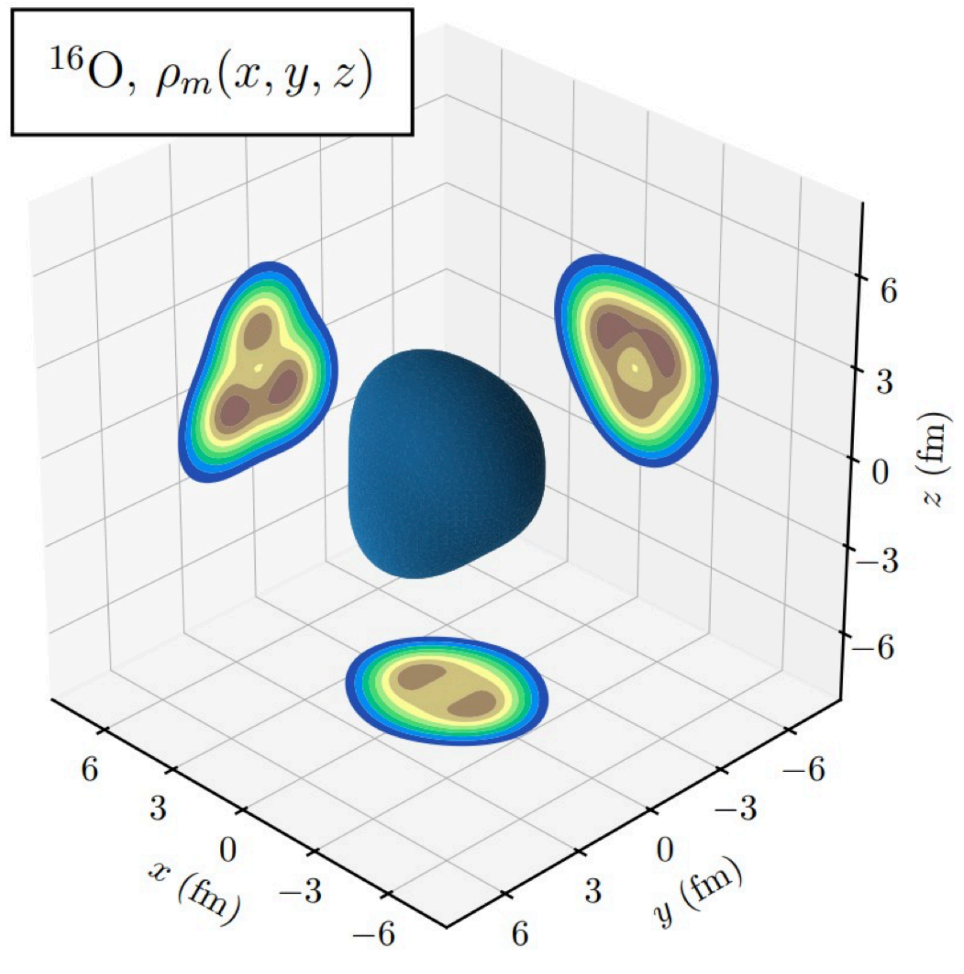


BUT WHAT ARE SMALLS SYSTEMS?

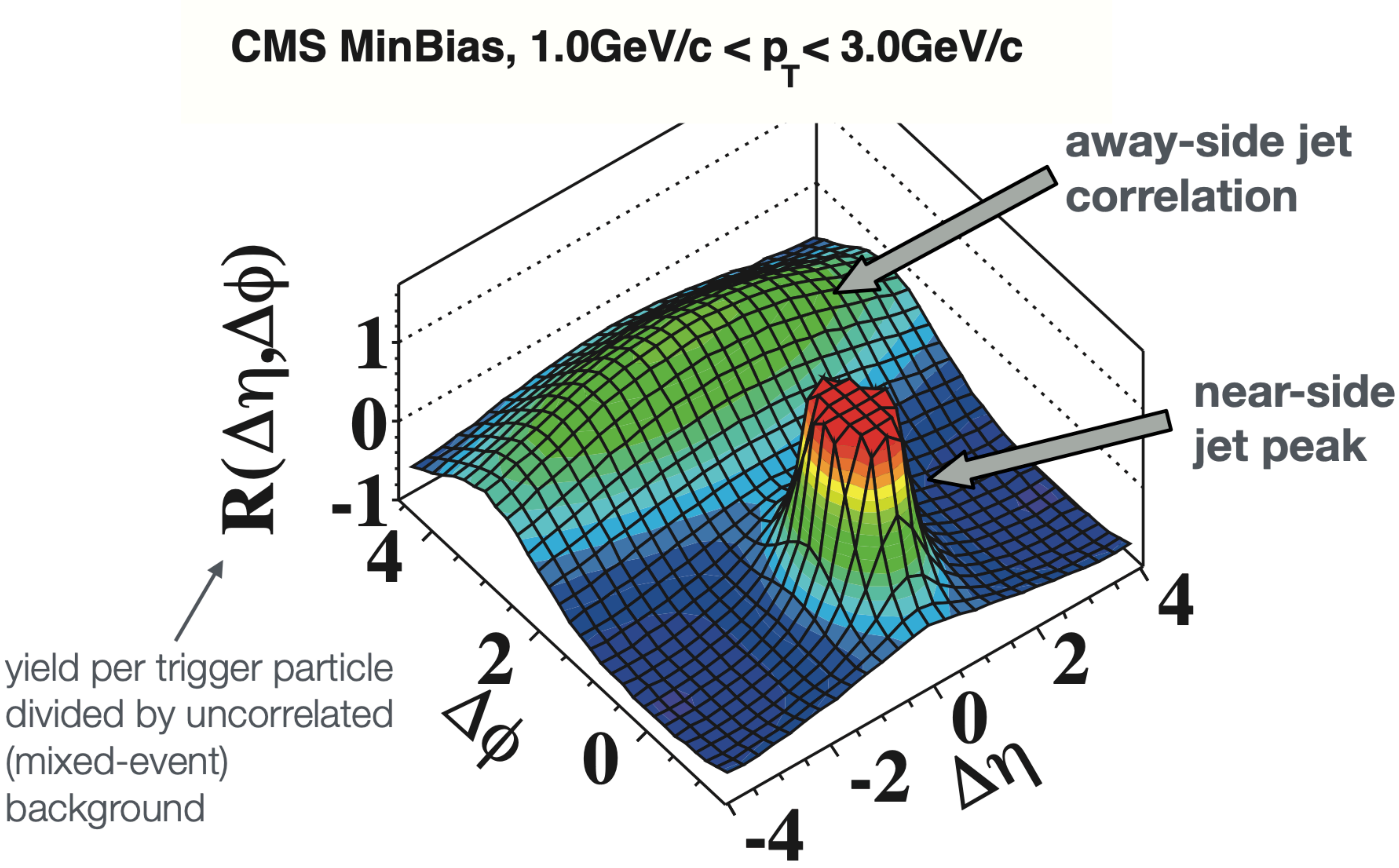
Difficult to properly define, but what we mean is smaller in volume, p-p, pd, pA, dA, ...



However small ion collisions can also be considered somewhat small systems... Be-Be, O-O Ne-Ne, collisions etc.

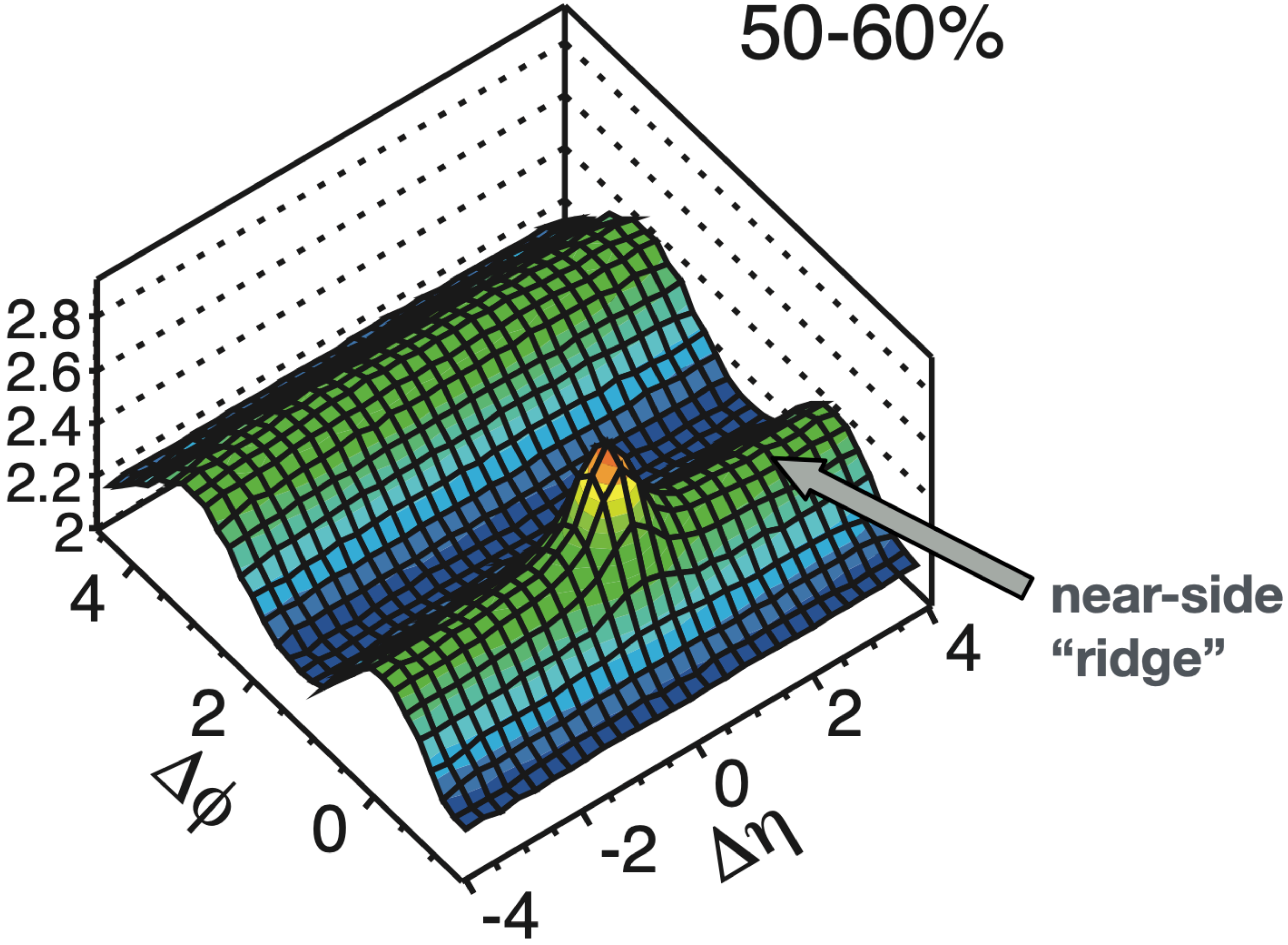


COLLECTIVITY IN SMALL SYSTEMS



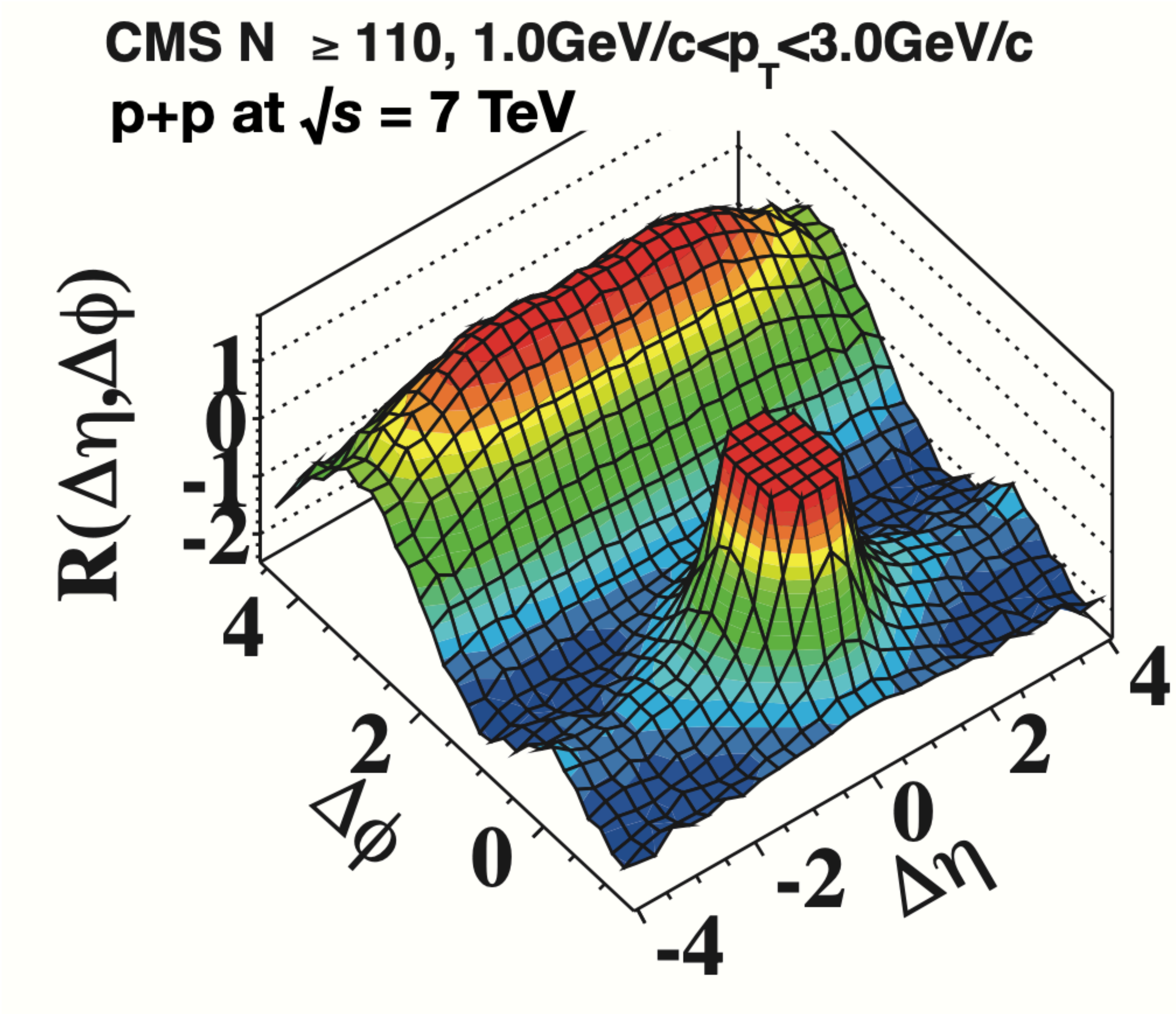
No indication for collective effects in minimum bias pp collisions at 7 TeV

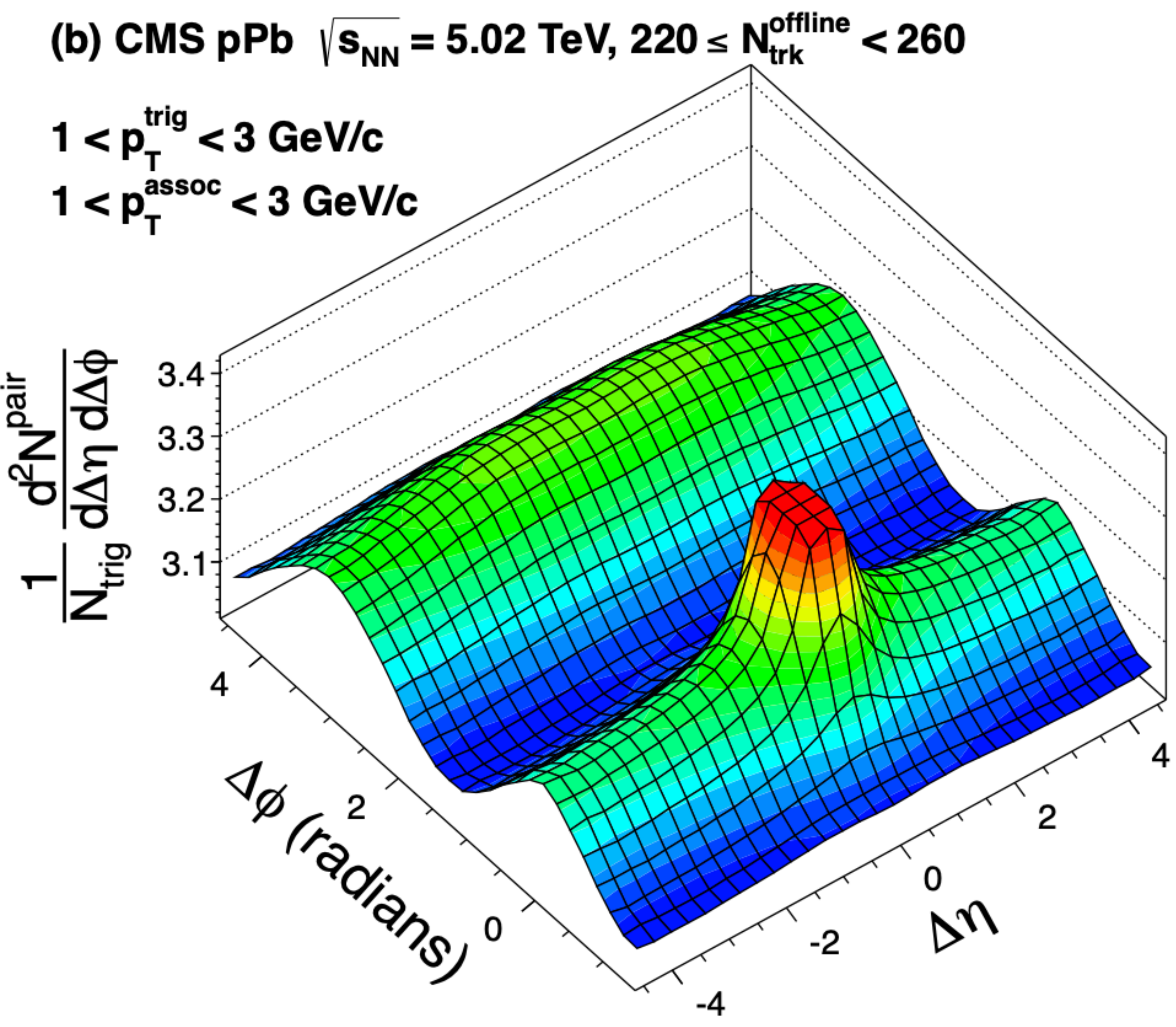
COLLECTIVITY IN LARGE SYSTEMS



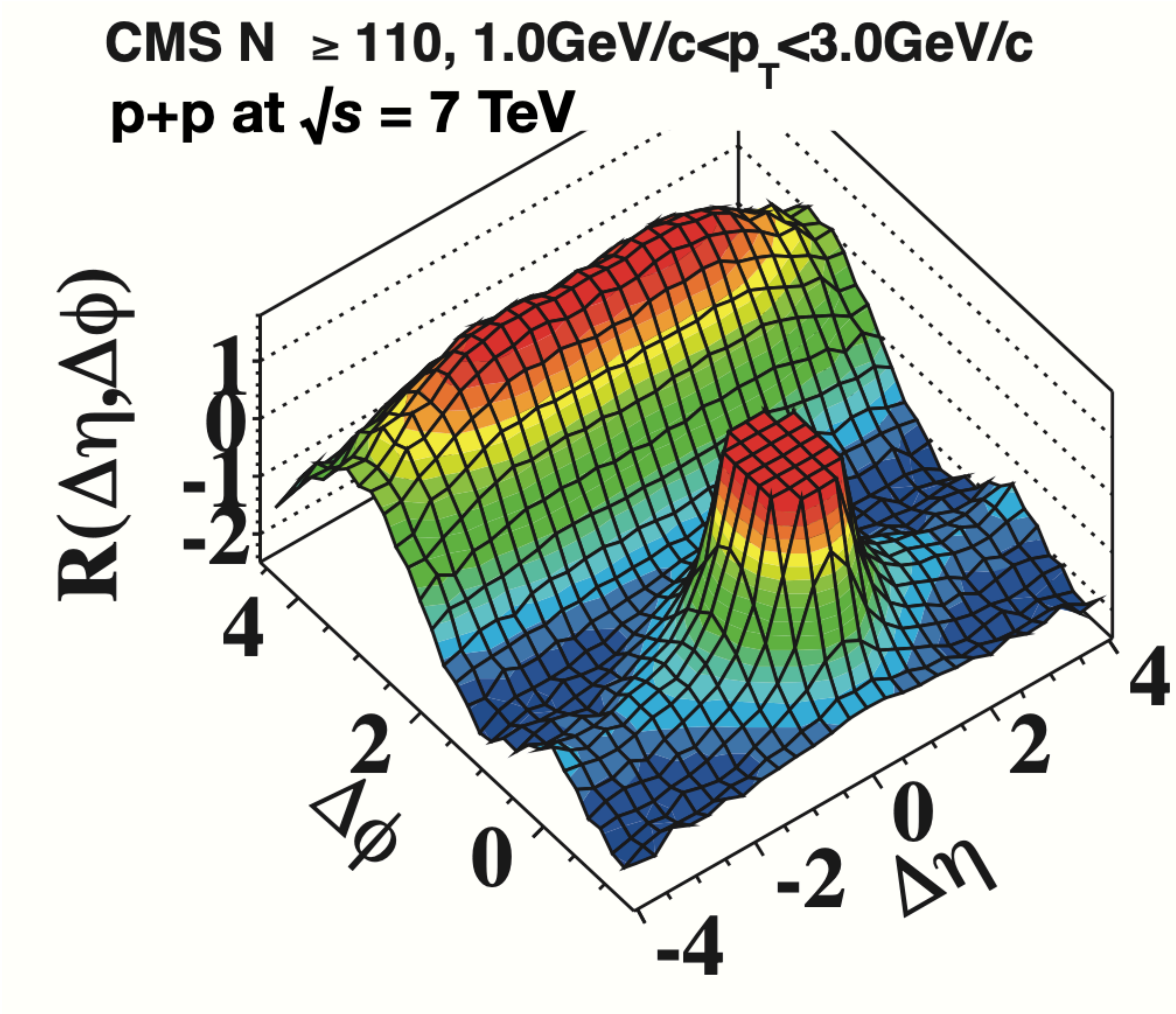
Long distance correlations indicate collectivity

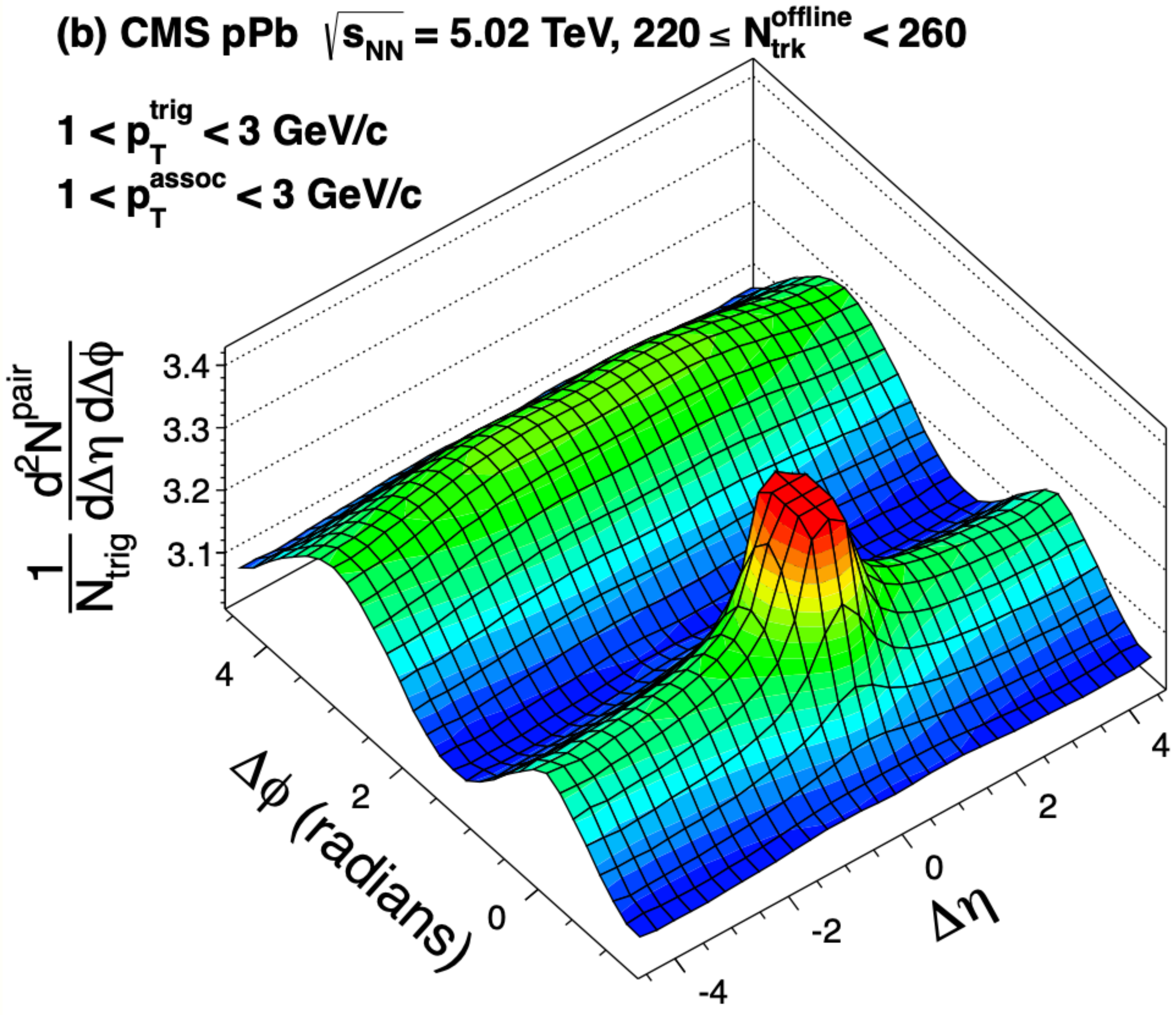
COLLECTIVITY IN SMALL SYSTEMS





COLLECTIVITY IN SMALL SYSTEMS



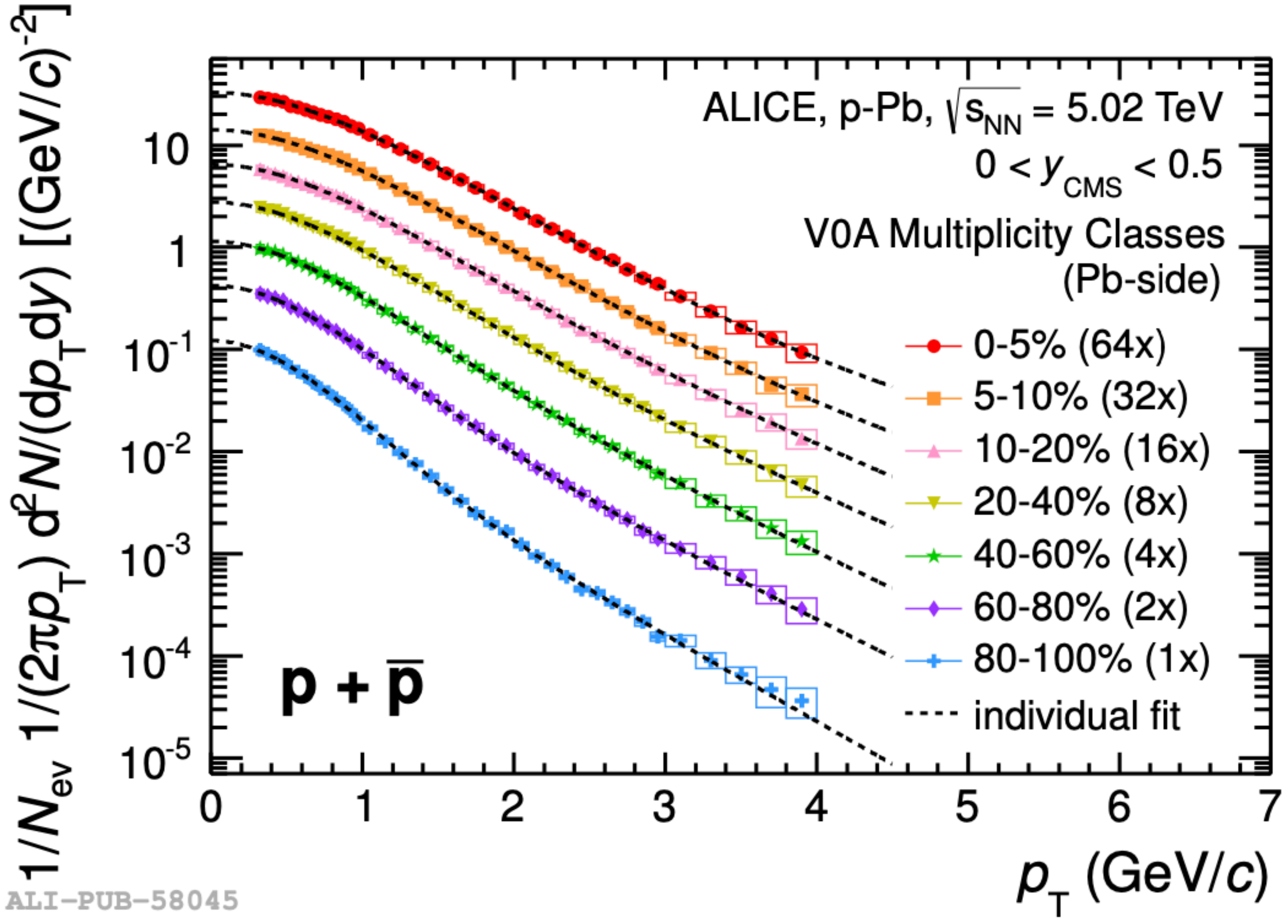


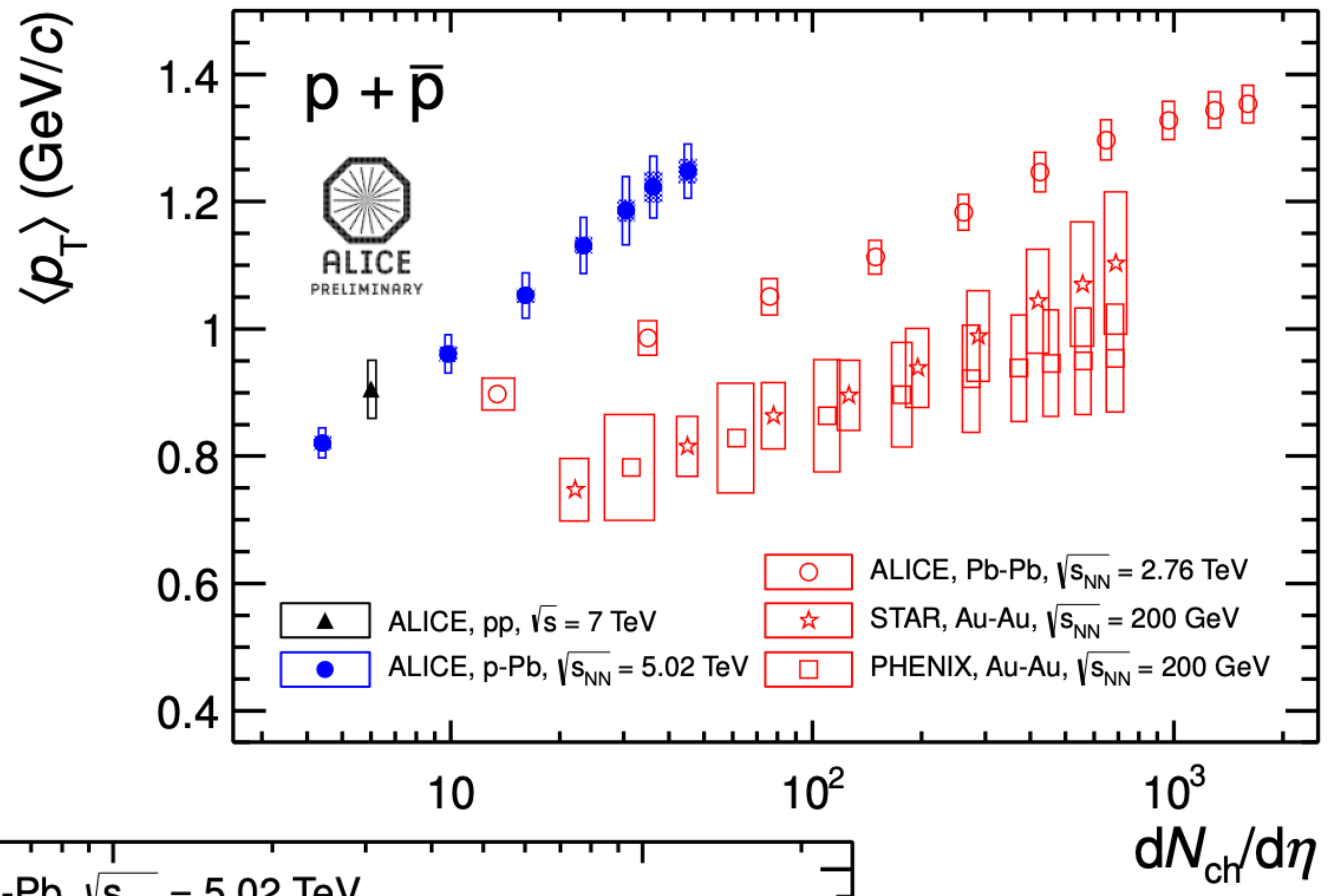
EVIDENCE FOR RADIAL FLOW

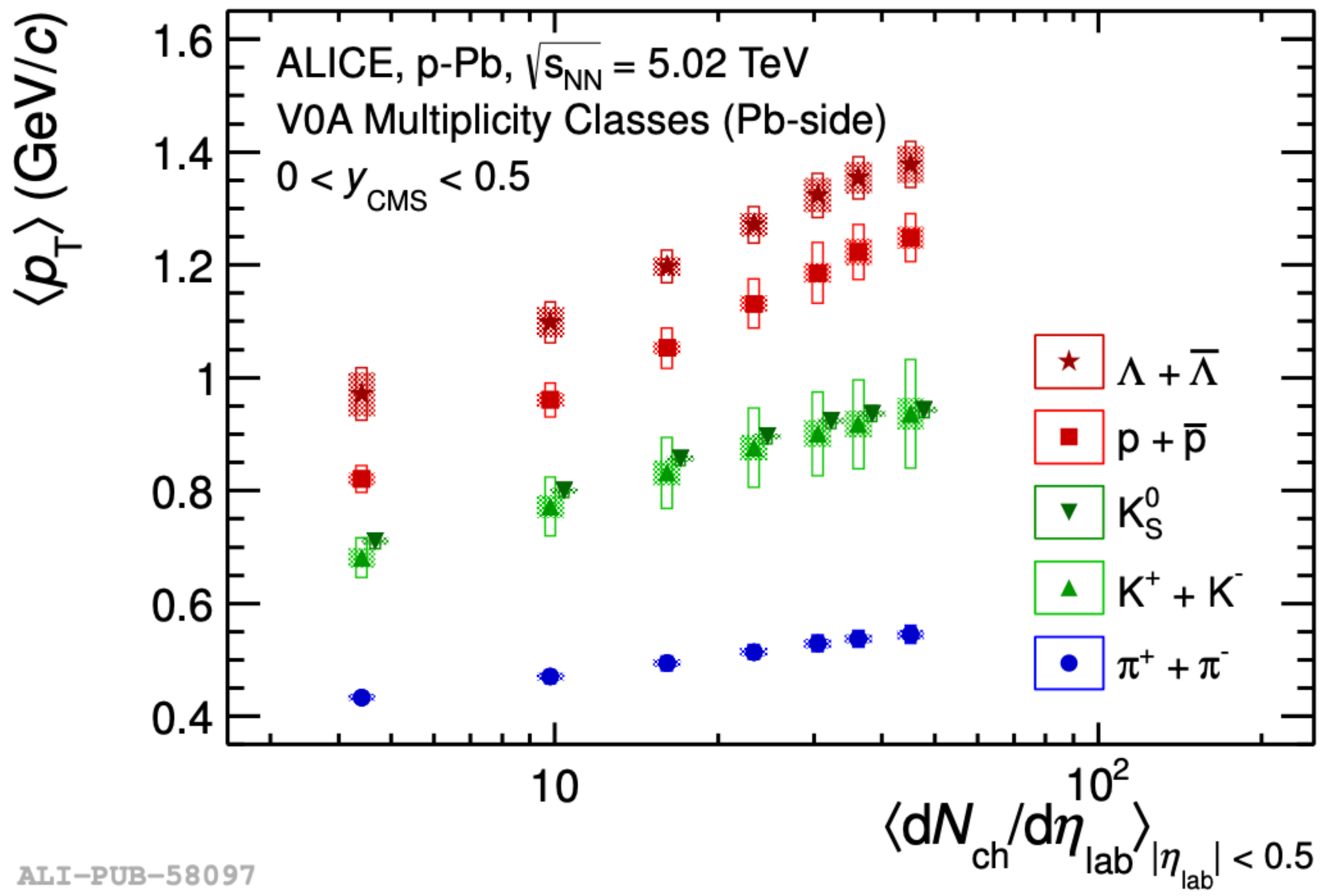
Shape of spectra changes with *multiplicity,* and with that increase of $\langle p_T \rangle$

Particles boosted differently for different evolution backgrounds?

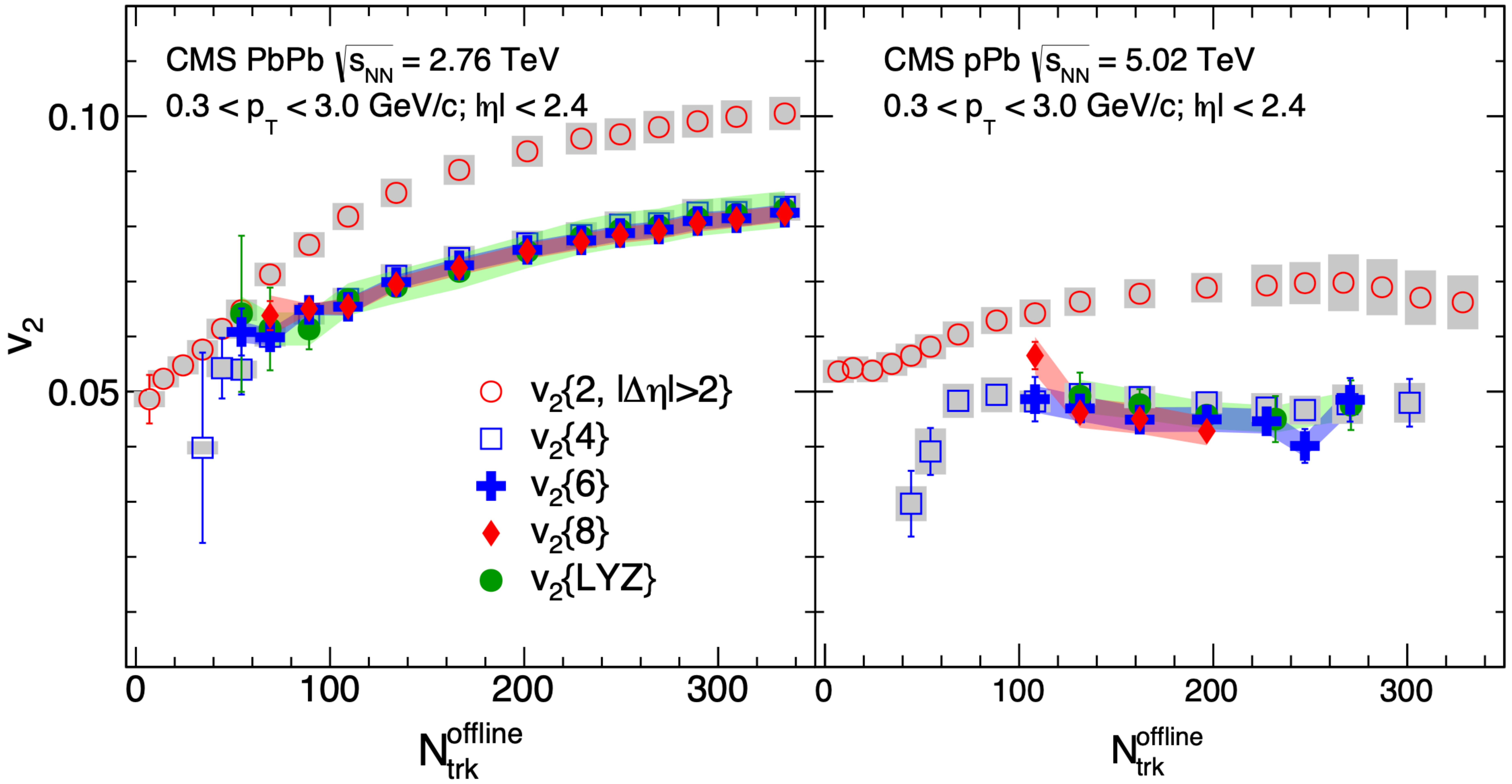
Is radial flow responsible for this?







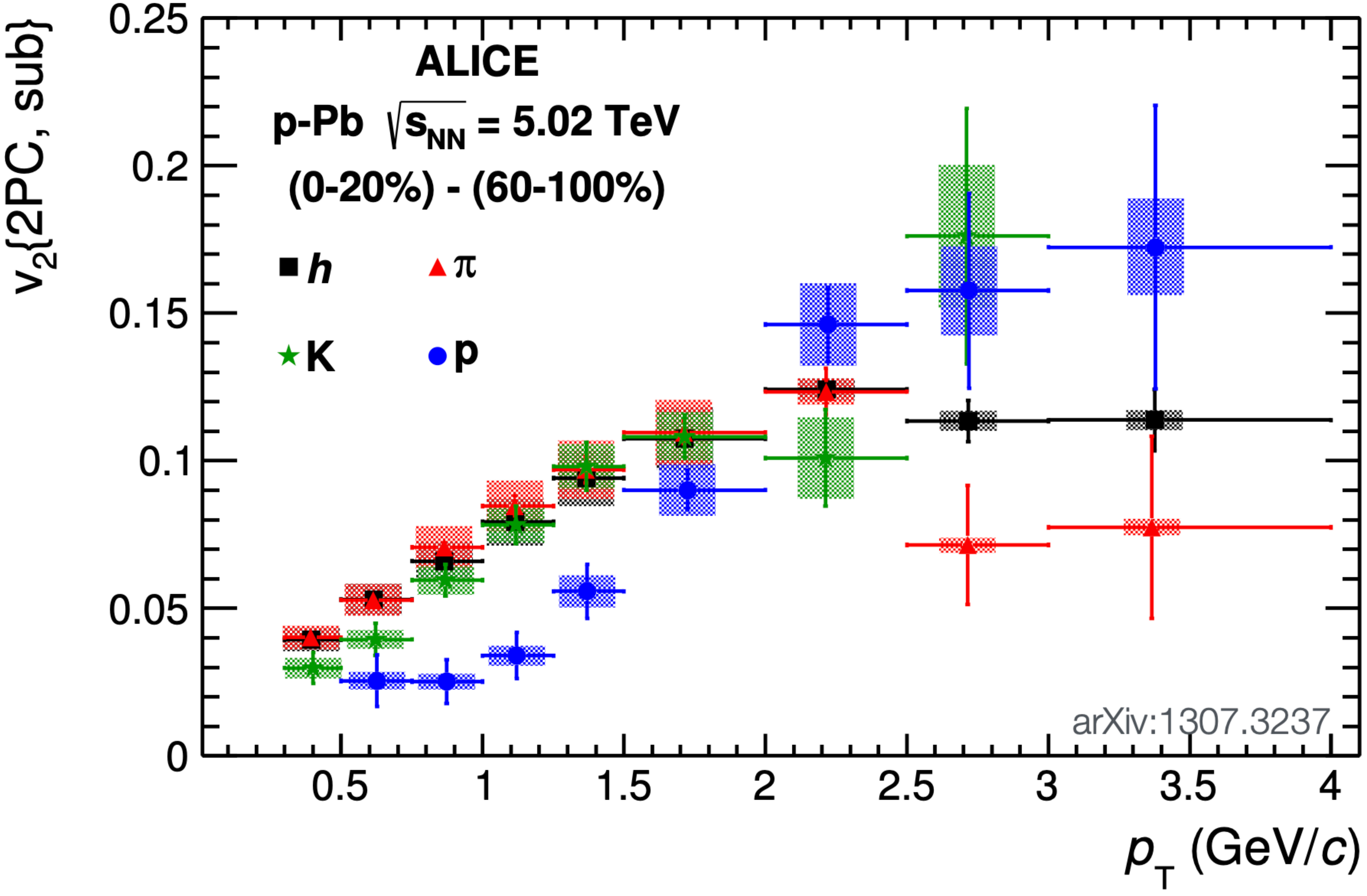
PARTICLE CUMULANTS IN SMALL SYSTEMS



Particle cumulants are consistently measured in small systems,
and are only a small fraction smaller than in AA

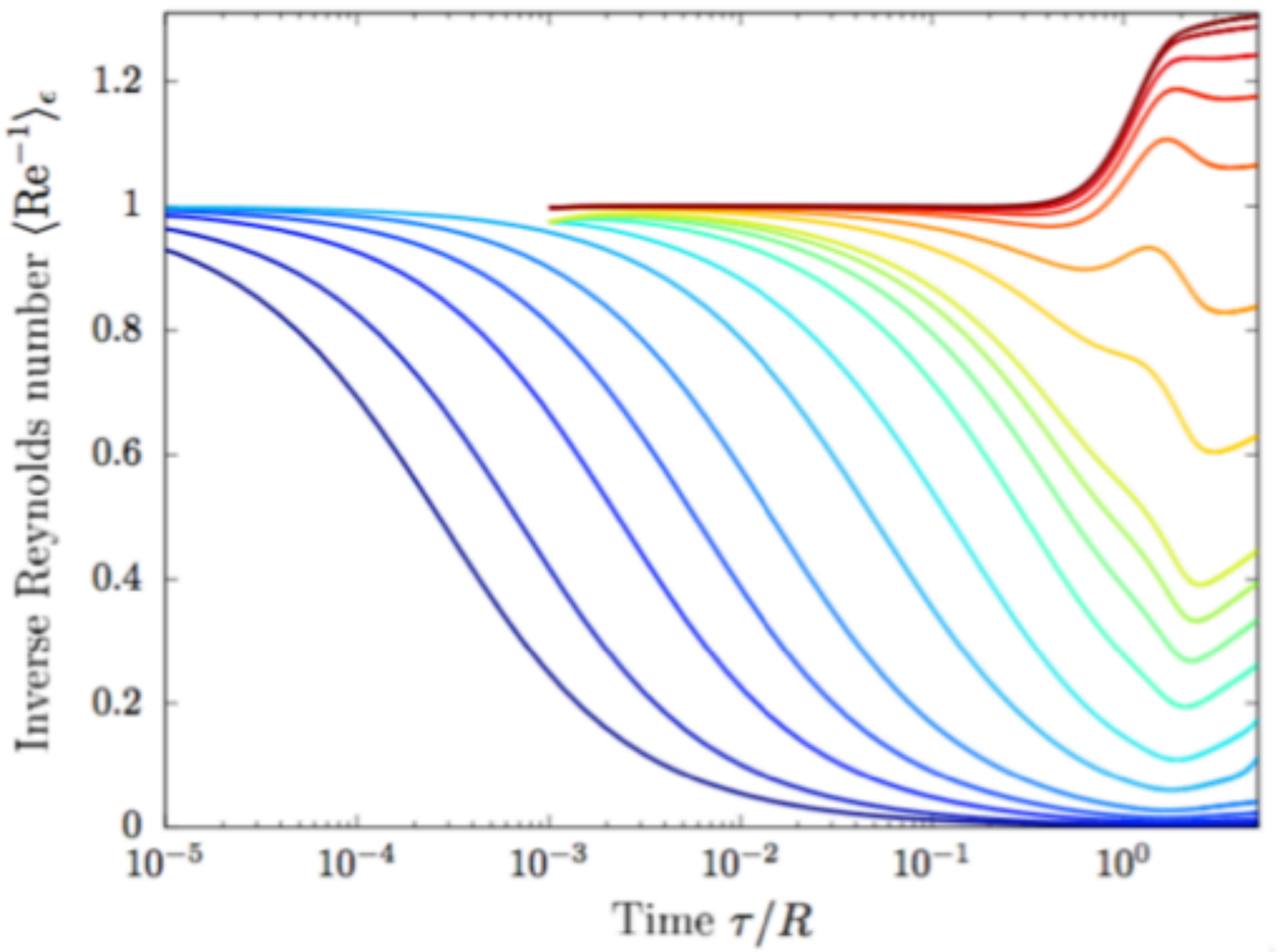
MASS ORDERING IN P-PB

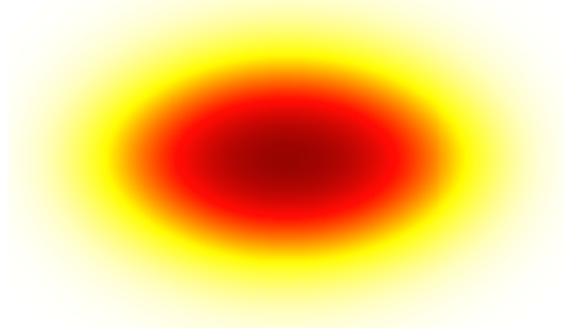
v_2 from fit of two-particle correlation, jet-like correlation removed by taking the difference between central and peripheral p-Pb collisions



SO, IS IT ALL HYDRO?

Not really, there is theoretical evidence that the system breaks down before it has time to hydrodynamize





Opacity parameter

$$\hat{\gamma} = \left(5\frac{\eta}{s}\right)^{-1}\left(\frac{1}{a\pi}R\frac{\mathrm{d}E_\perp^{(0)}}{\mathrm{d}\eta}\right)^{1/4}$$

For fixed profile, $\hat{\gamma} \sim C\,(4\pi\eta/s)$ where $C \sim 11$

Inverse Reynolds number measures relative size of non-equilibrium effects

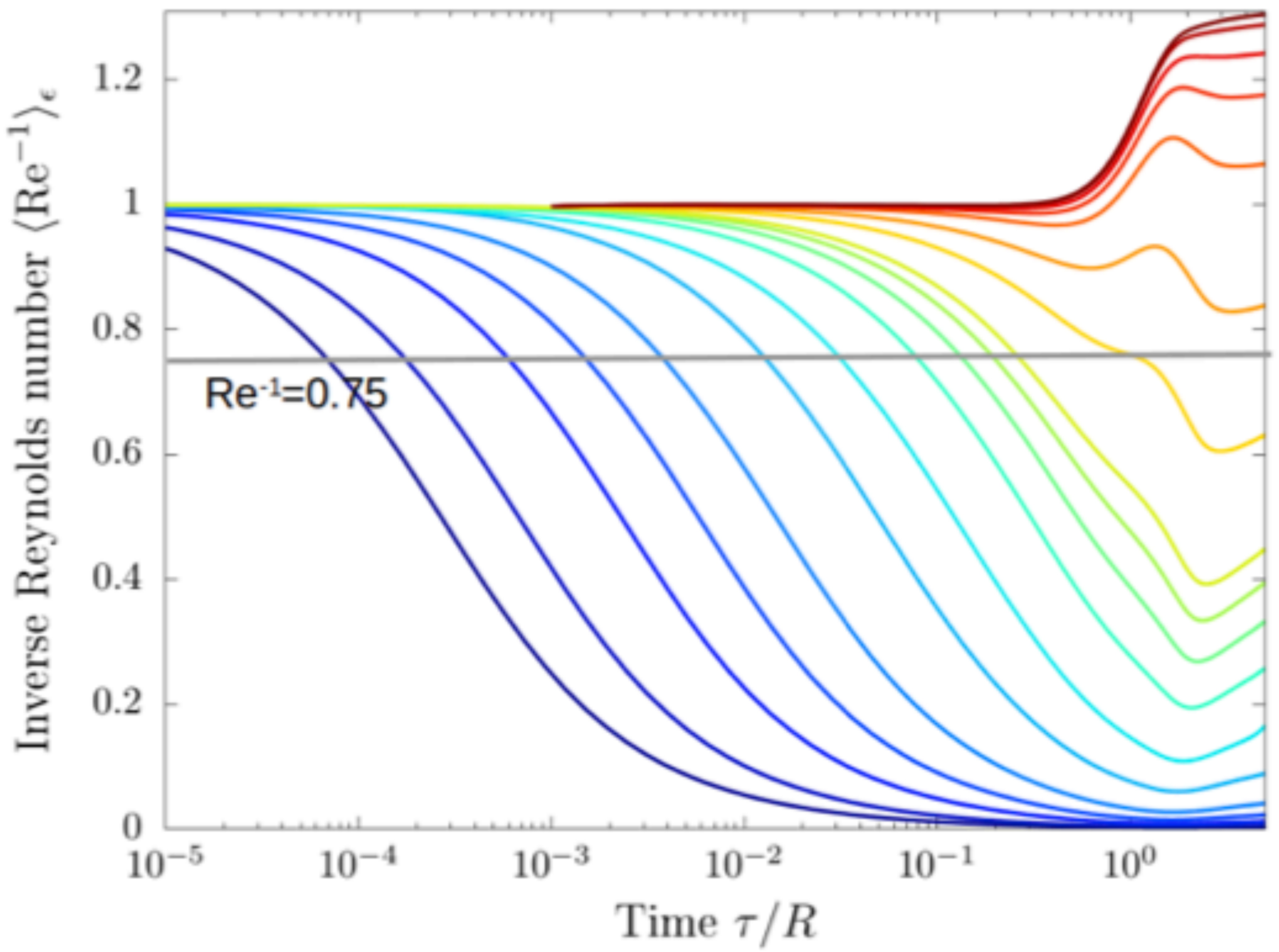
$$\mathrm{Re}^{-1} = \left(\frac{6\pi^{\mu\nu}\pi_{\mu\nu}}{e^2}\right)^{1/2} < 1$$

If you are interested, see *EPJC 79 (2019) 965* and *PRC 107 (2023), 034905*

SO, IS IT ALL HYDRO?

Not really, there is theoretical evidence that the system breaks down before it has time to hydrodynamize

Taking the criterion seriously for hydrodynamics $\hat{\gamma} > 3$



$Re^{-1} < 0.75$

$$\mathrm{p+p}: \quad \hat{\gamma} \overset{\text{min.bias}}{\sim} 0.7 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{0.12\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{7.1\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{42.25}\right)^{-1/4}$$

far from hydrodynamic behaviour

$$\mathrm{p+Pb}: \quad \hat{\gamma} \overset{\text{min.bias}}{\sim} 1.5 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{0.81\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{24\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{42.25}\right)^{-1/4} \overset{\text{high mult.}}{\lesssim} 2.7$$

very high multiplicity events approach regime of applicability, but do not reach it

$$\mathrm{O+O}: \quad \hat{\gamma} \overset{30-40\%}{\sim} 2.2 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{1.13\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{55\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{42.25}\right)^{-1/4} \sim \overset{70-80\%}{1.4} - \overset{0-5\%}{3.1}$$

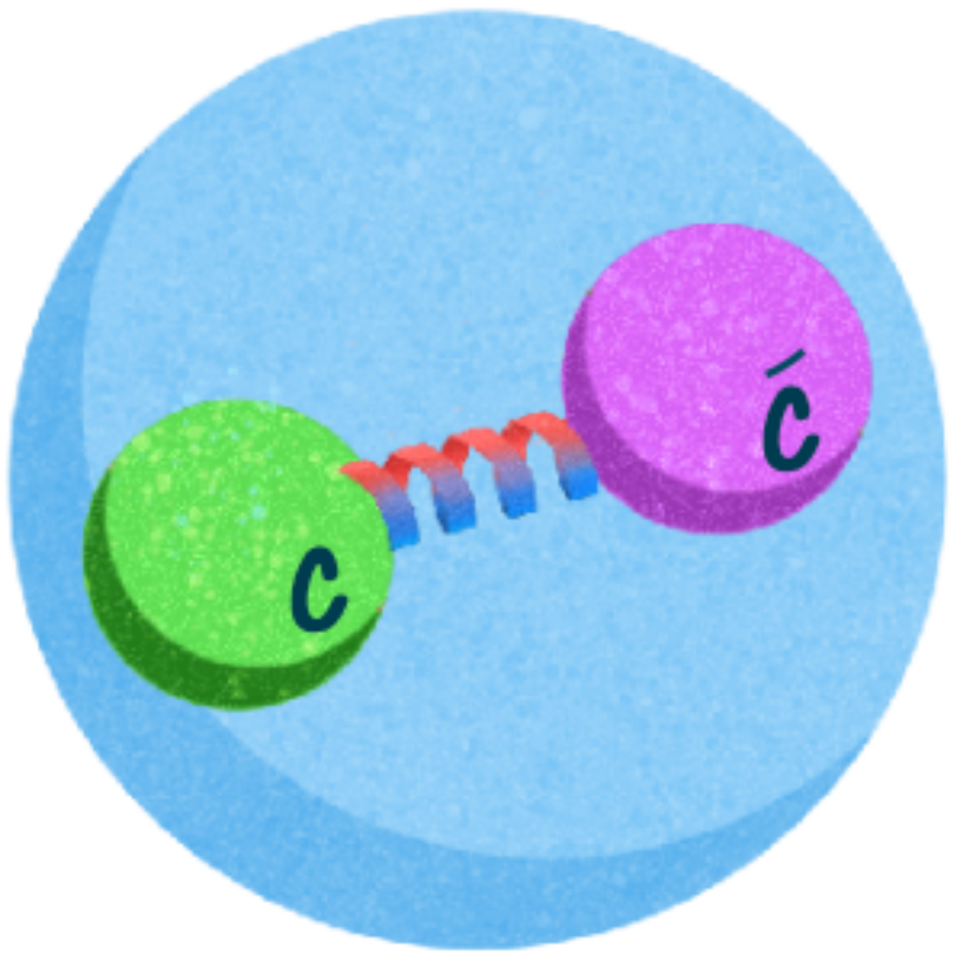
probes transition region to hydrodynamic behaviour

$$\mathrm{Pb+Pb}: \quad \hat{\gamma} \overset{30-40\%}{\sim} 5.7 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{2.78\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{1280\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{42.25}\right)^{-1/4} \sim \overset{70-80\%}{2.7} - \overset{0-5\%}{9.0}$$

hydrodynamic behaviour in all but peripheral collisions

If you are interested, see *EPJC 79 (2019) 965* and *PRC 107 (2023), 034905*

QUARKONYA



J/Psi

QUARKONYA

Heavy $q\bar{q}$ bound states are called *quarkonya.* Specifically we have charmonium states and bottomonium states, $c\bar{c}$ and $b\bar{b}$, respectively.

$$m_c \sim 1.3\,\mathrm{GeV} \qquad m_b \sim 4.7\,\mathrm{GeV}$$

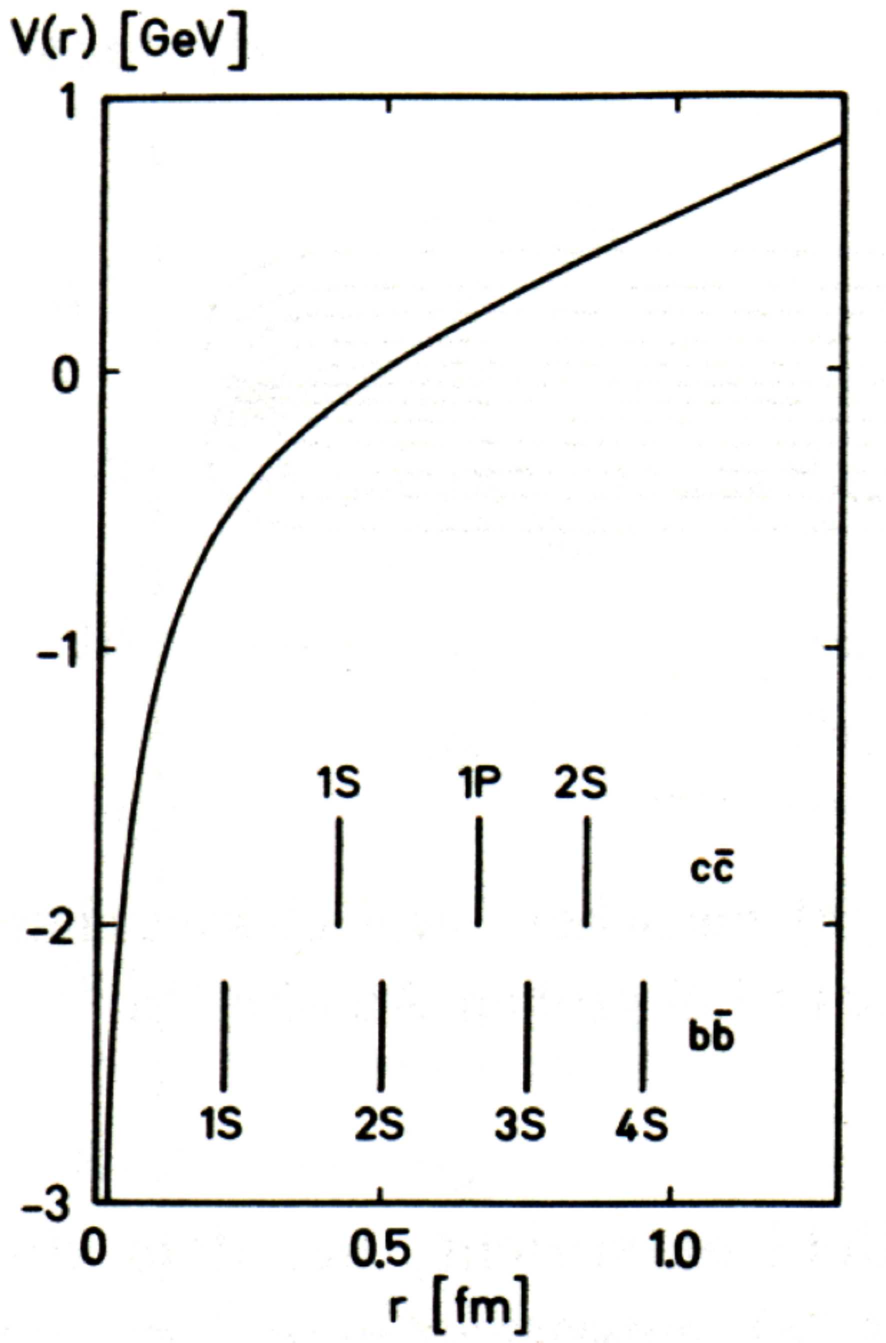
Heavy quarks behave non-relativistic, one can extract a potential, and use versions of the Schrödinger eq. to solve the spectra.

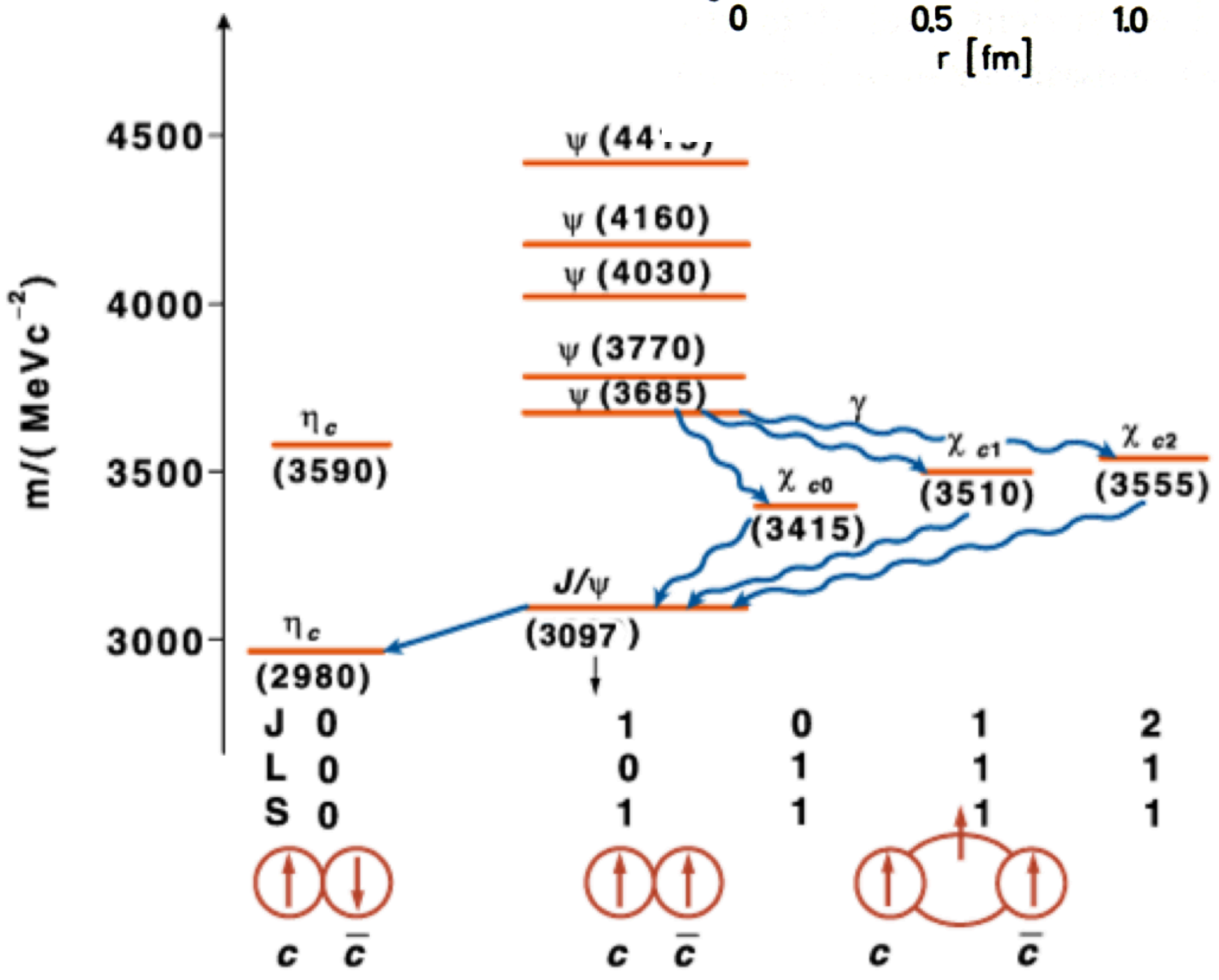
$$V_{q\bar{q}}(r) = \frac{-\alpha}{r} + \sigma r$$

Coulomb-like interactions

String -like interactions

Charmonium is tightly bound. Smaller radius than light mesons





DEBYE SCREENING IN THE QGP

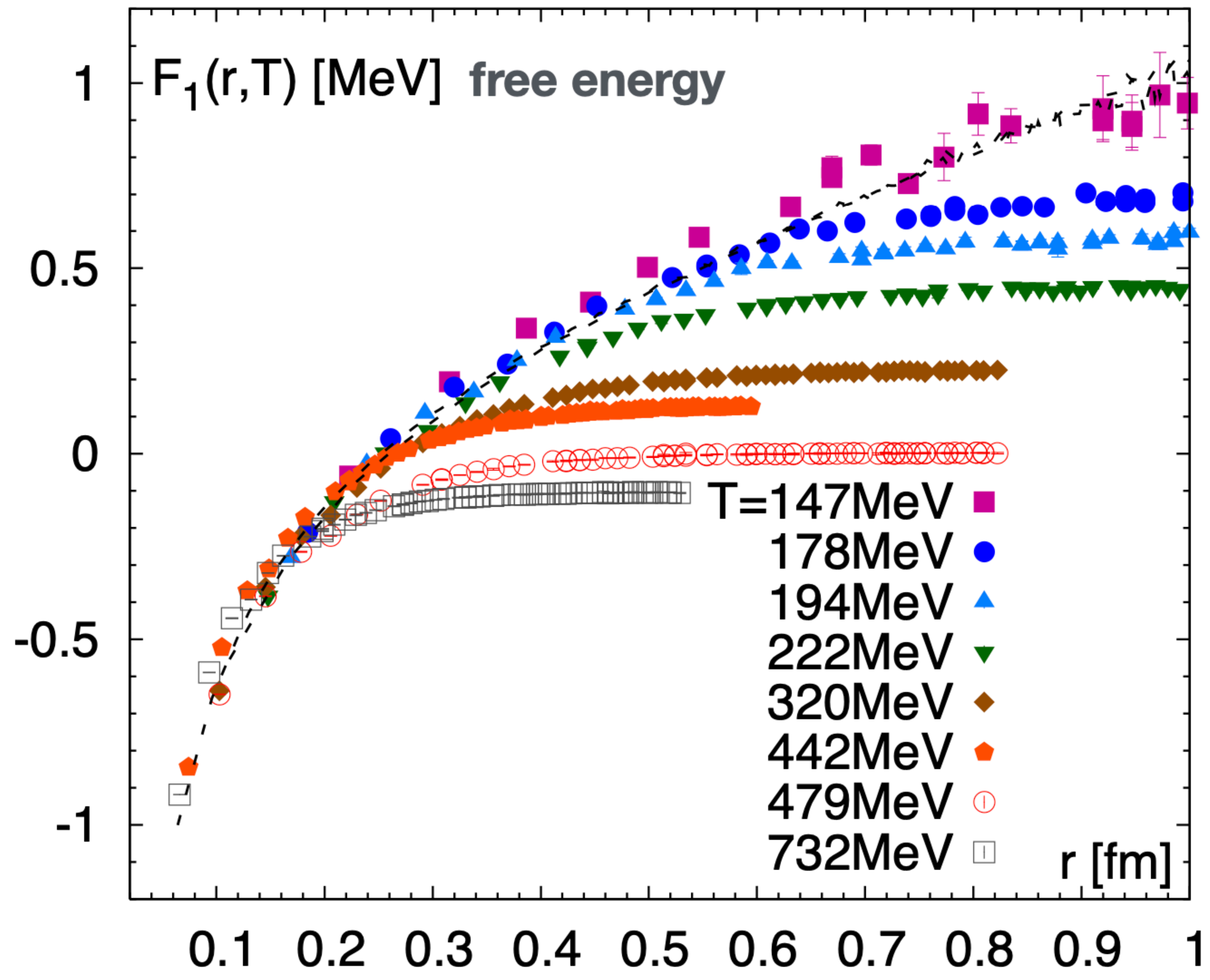
The $q\bar{q}$ potential is modified at finite T, color screening debilitates the binding of the pair.

Rough parametrisation of the in-medium thermal potential, a.k.a, screened potential

$$V(r,T) = -\frac{\alpha}{r}e^{-\mu r} + \sigma r \frac{1-e^{-\mu r}}{\mu r}$$

where the scale is set to $r_D = 1/m_D$. The Debye screening mass/scale is $m_D \sim g(T)\,T$, or $m_D^2 \sim \alpha_S(T)\,T^2$

arXiv:1302.2180v1



Suppression of the J/ψ meson is a QGP signal.

state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

arXiv:0706.2183

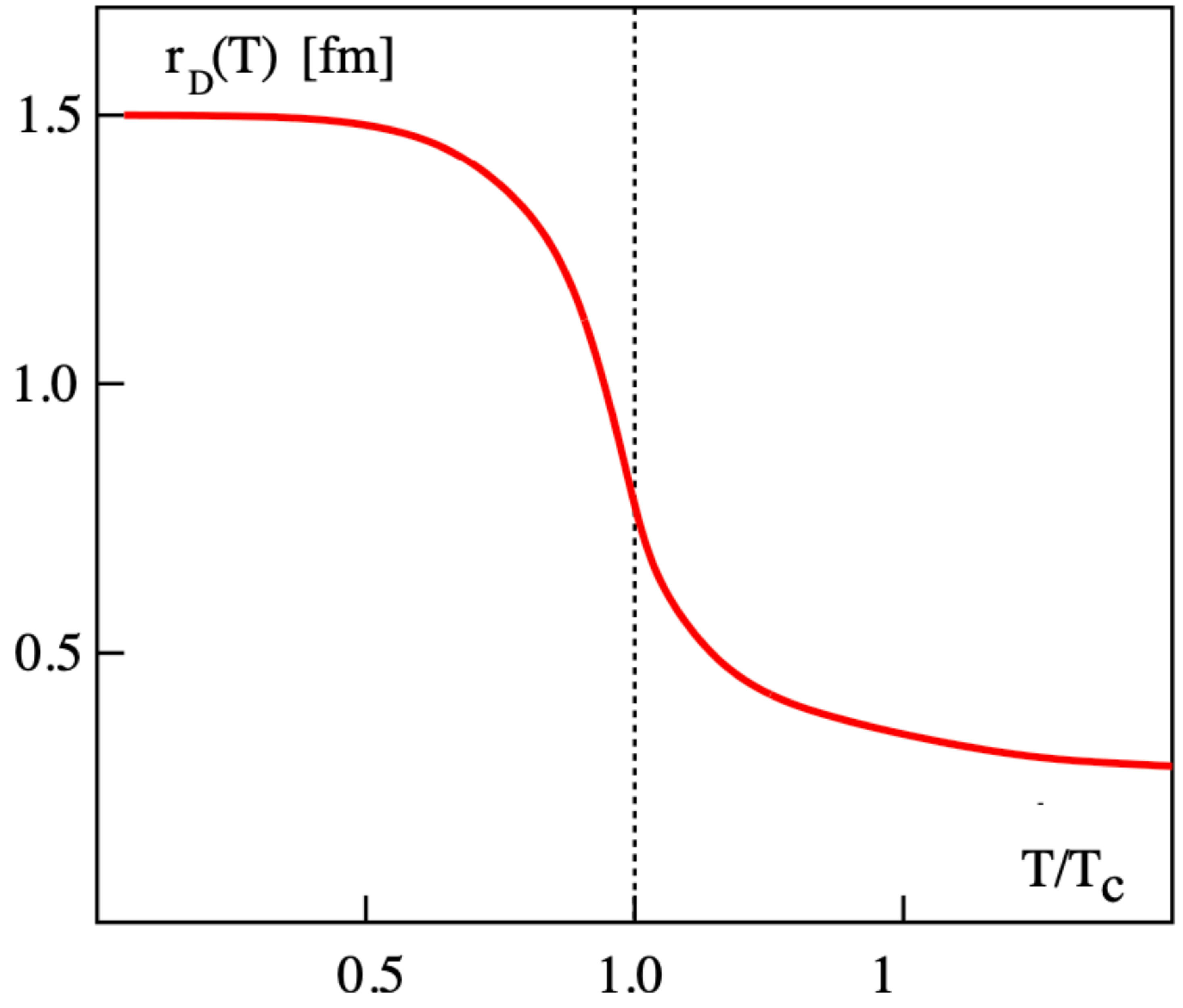
More interestingly, each state has a dissociation temperature.
Sequential melting is the increase with the resonant mass..

$c\bar{c}$ as thermometer of the QGP??

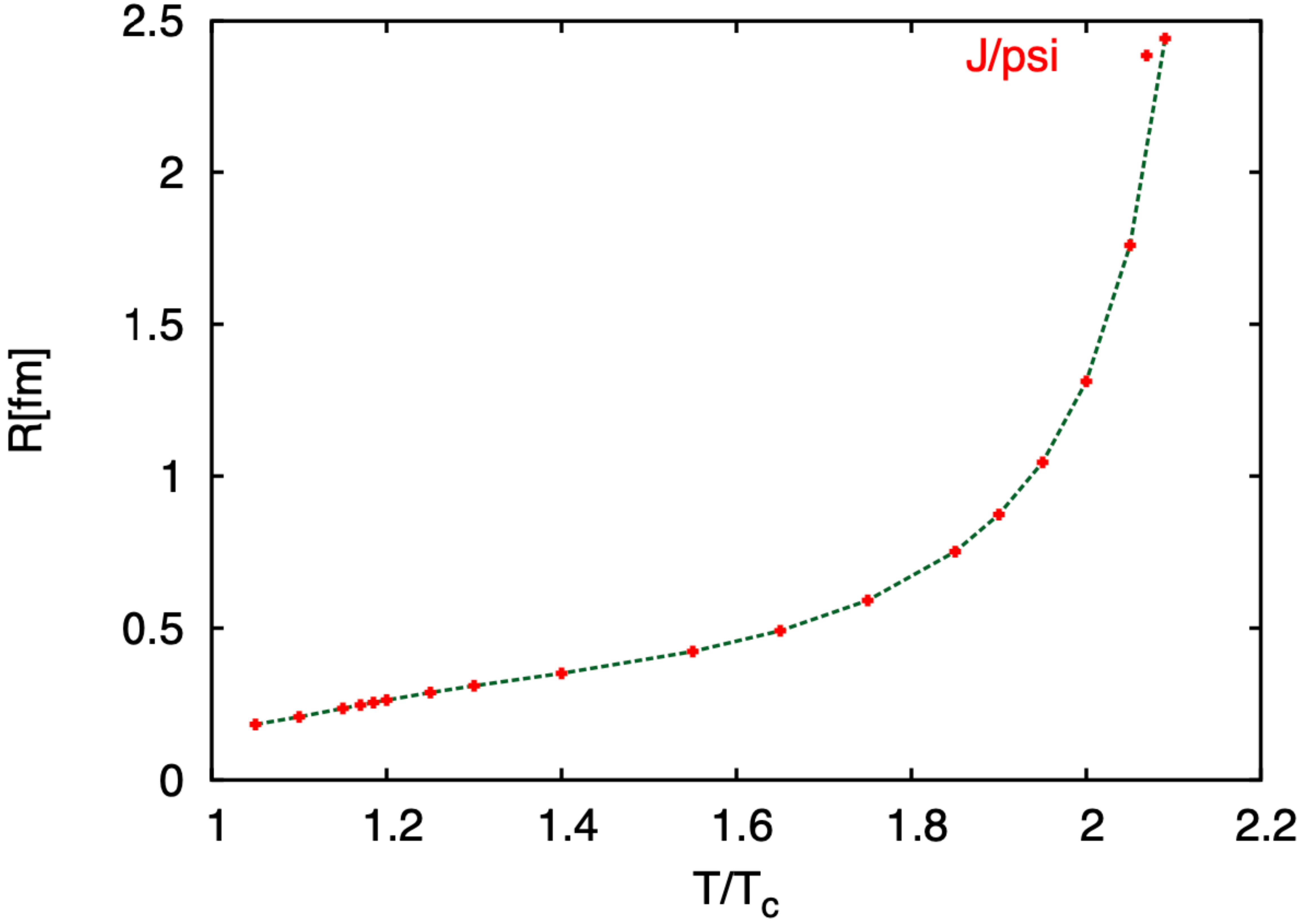
Phys. Lett. B 178 (1986))

INTERACTION RANGE AND J/Ψ RADIUS IN THE MEDIUM AS A FUNCTION OF THE TEMPERATURE

Interaction range vs T



J/ψ radius vs. T



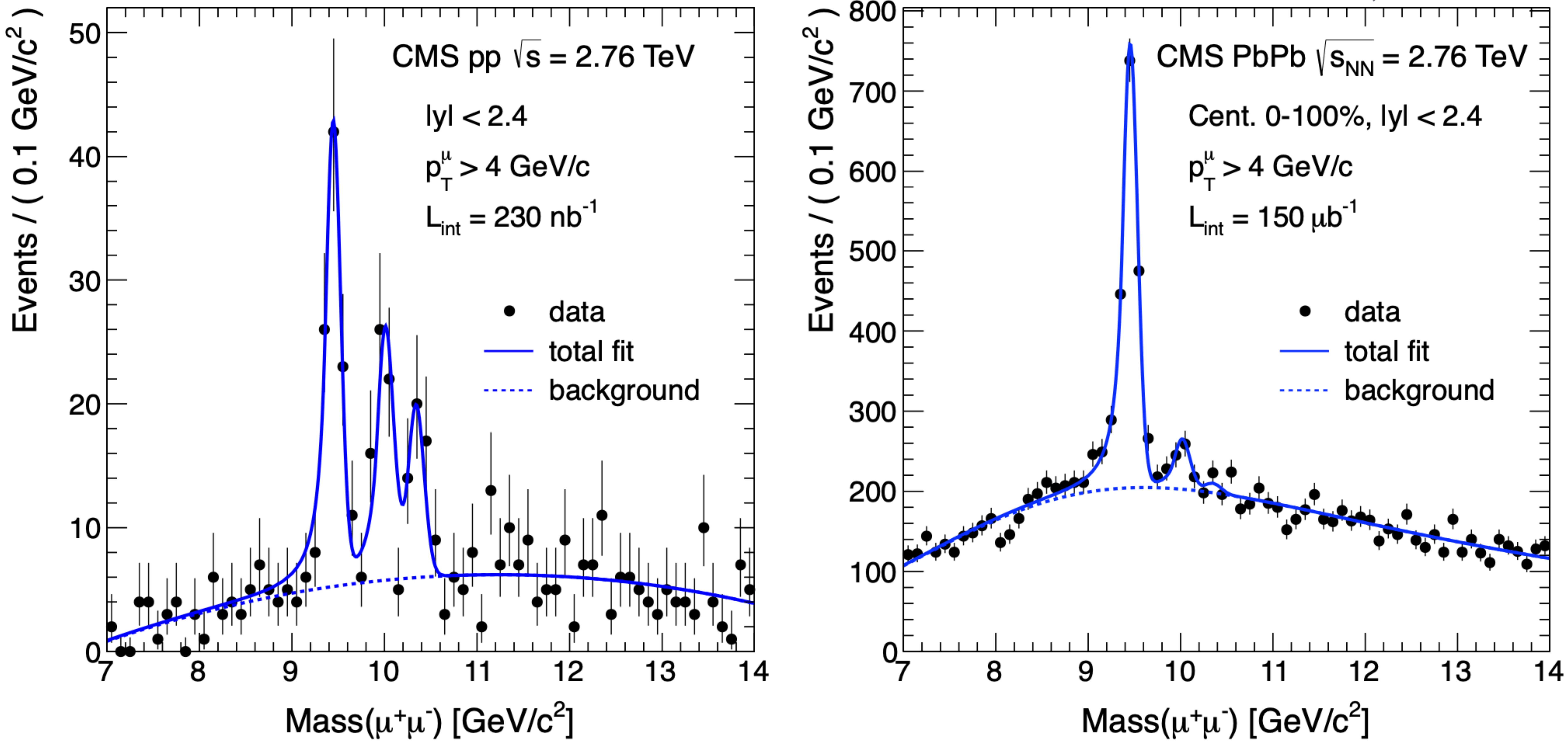
No more bound J/ψ at $T > 2T_C$!!

H. Satz, hep-ph/0512217

MELTING OF RESONANT Υ-STATES

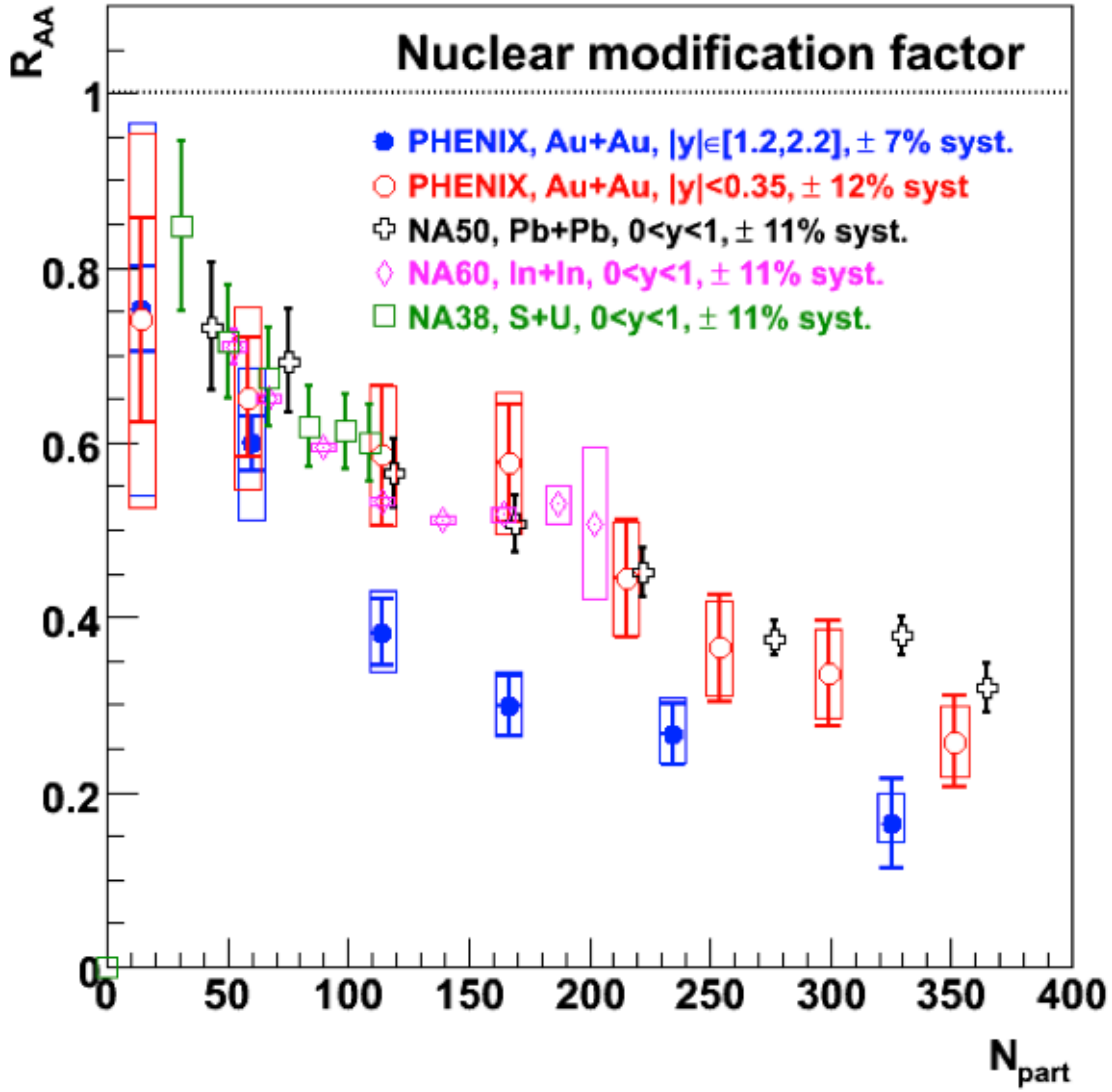
Υ(2S) AND Υ(3S) SUPPRESSED WITH RESPECT TO Υ(1S)

CMS, 1208.2826



Consistent with sequential melting!

HOWEVER…



Same suppression at midrapidity at the CERN SPS and at RHIC, in spite of larger energy density at RHIC

RHIC: suppression large at forward rapidity, in spite of larger energy density at mid- rapidity

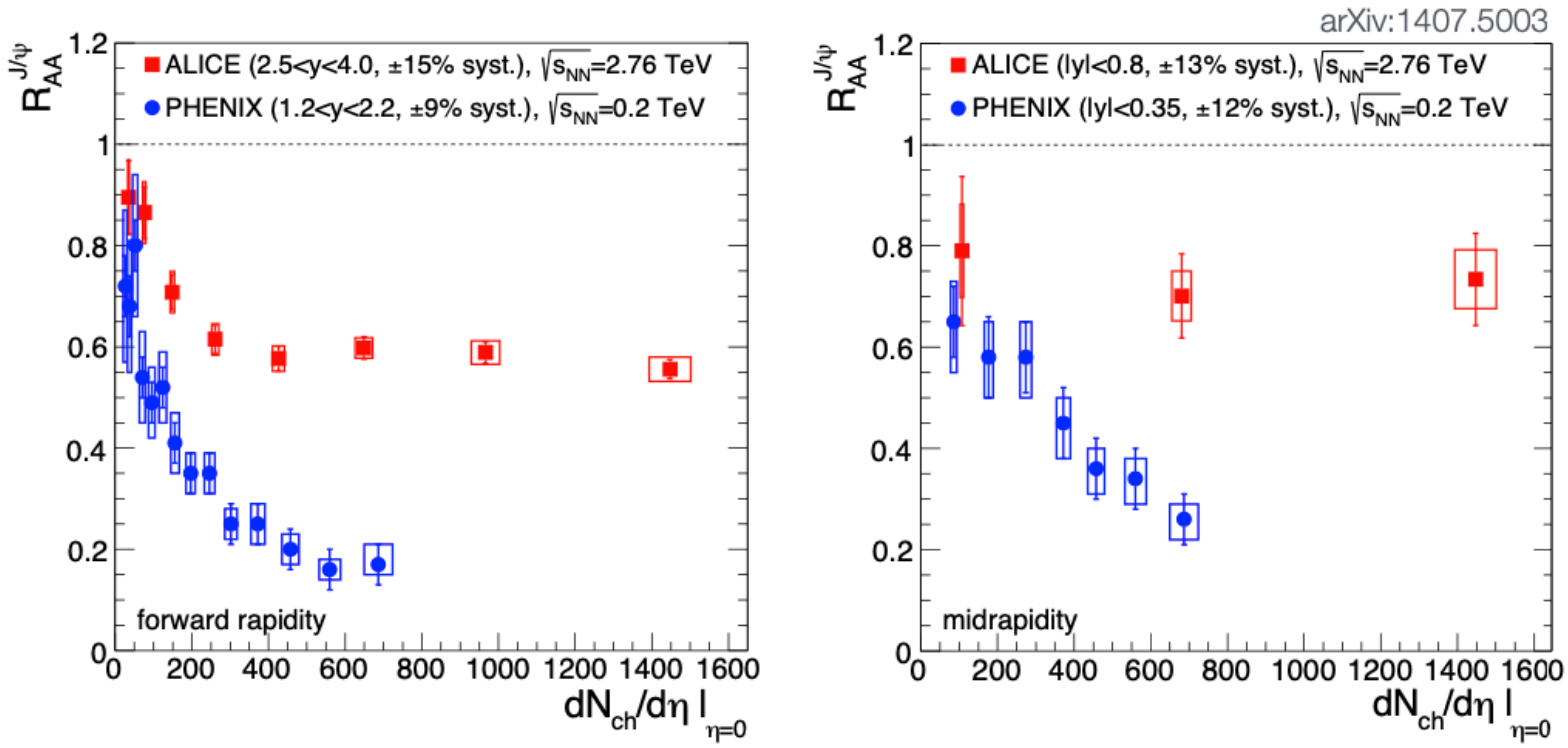
Makes no sense in the purely dissociation picture.
Why? Higher energies/multiplicity $\Rightarrow$ higher T

Larger rapidity $\Rightarrow$ less energy density!

$$R_{AB} = \frac{\mathrm{d}N/\mathrm{d}p_T|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}}\rangle \times \mathrm{d}\sigma_{\mathrm{inv}}/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{p+p}}},$$

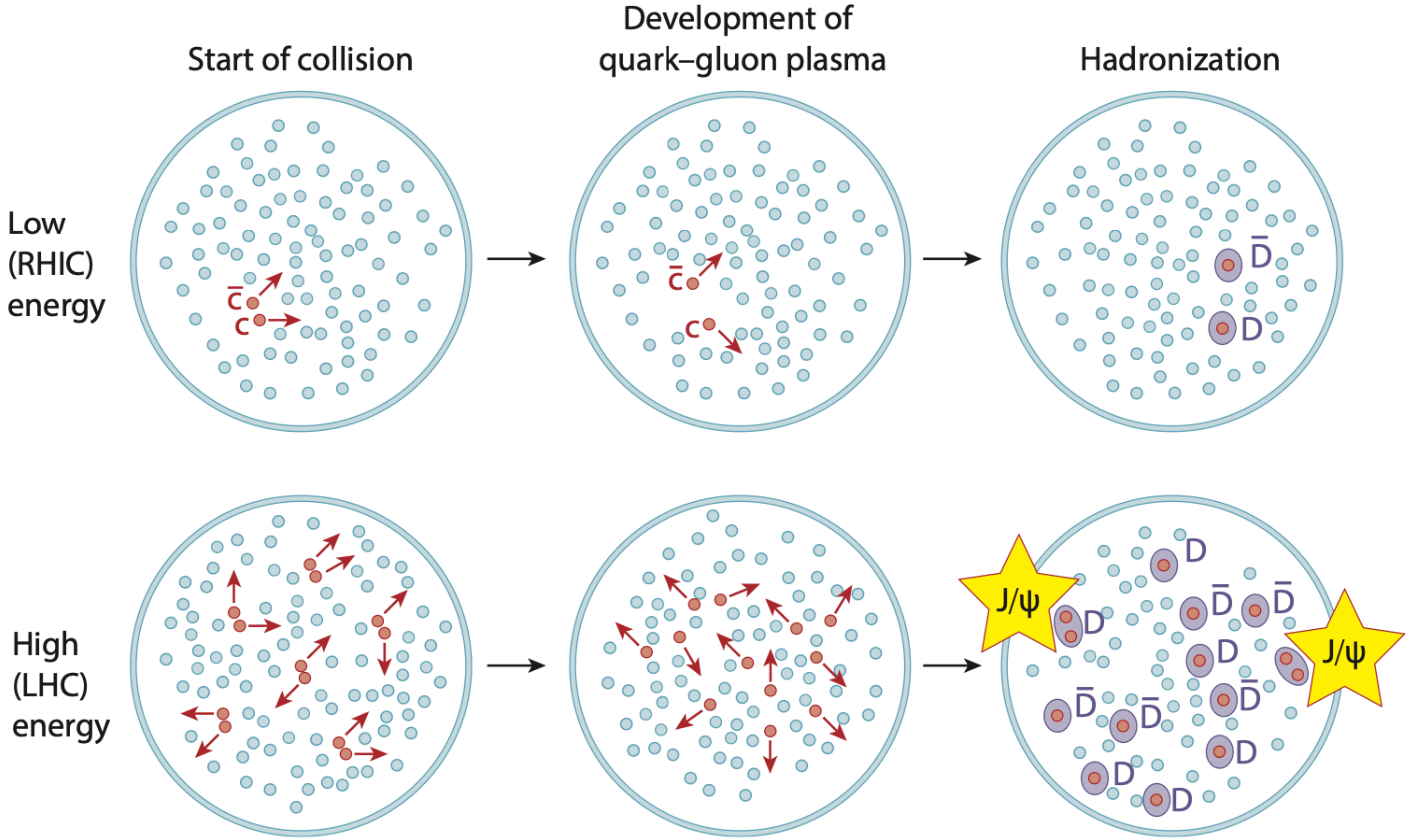
$$\text{where} \quad \langle T_{\mathrm{AB}}\rangle = \langle N_{\mathrm{coll}}\rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

EVEN WORSE



Much less suppression at the LHC in spite of larger energy density

COMPETING EFFECTS



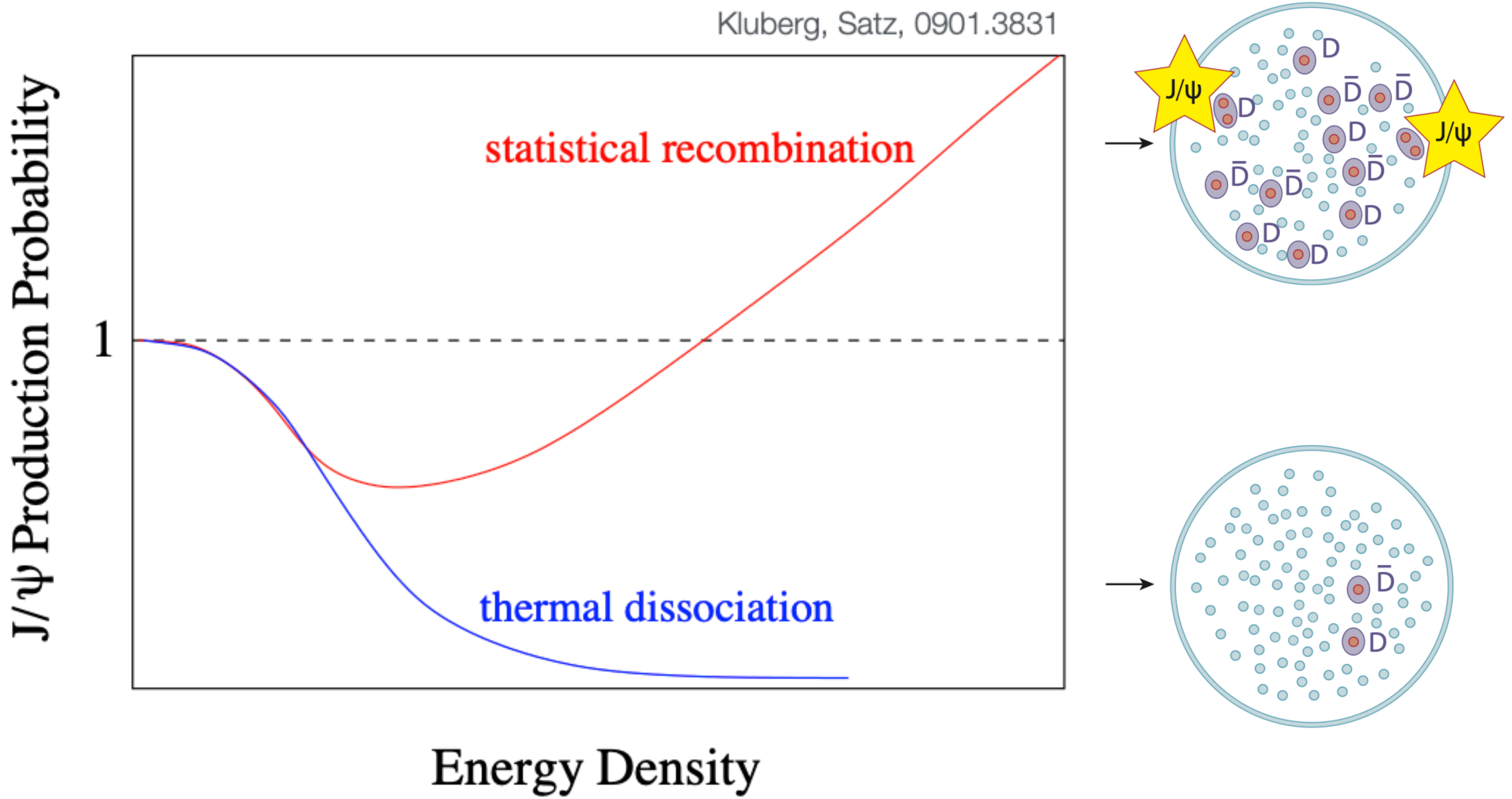
Dissociation

"Regeneration"

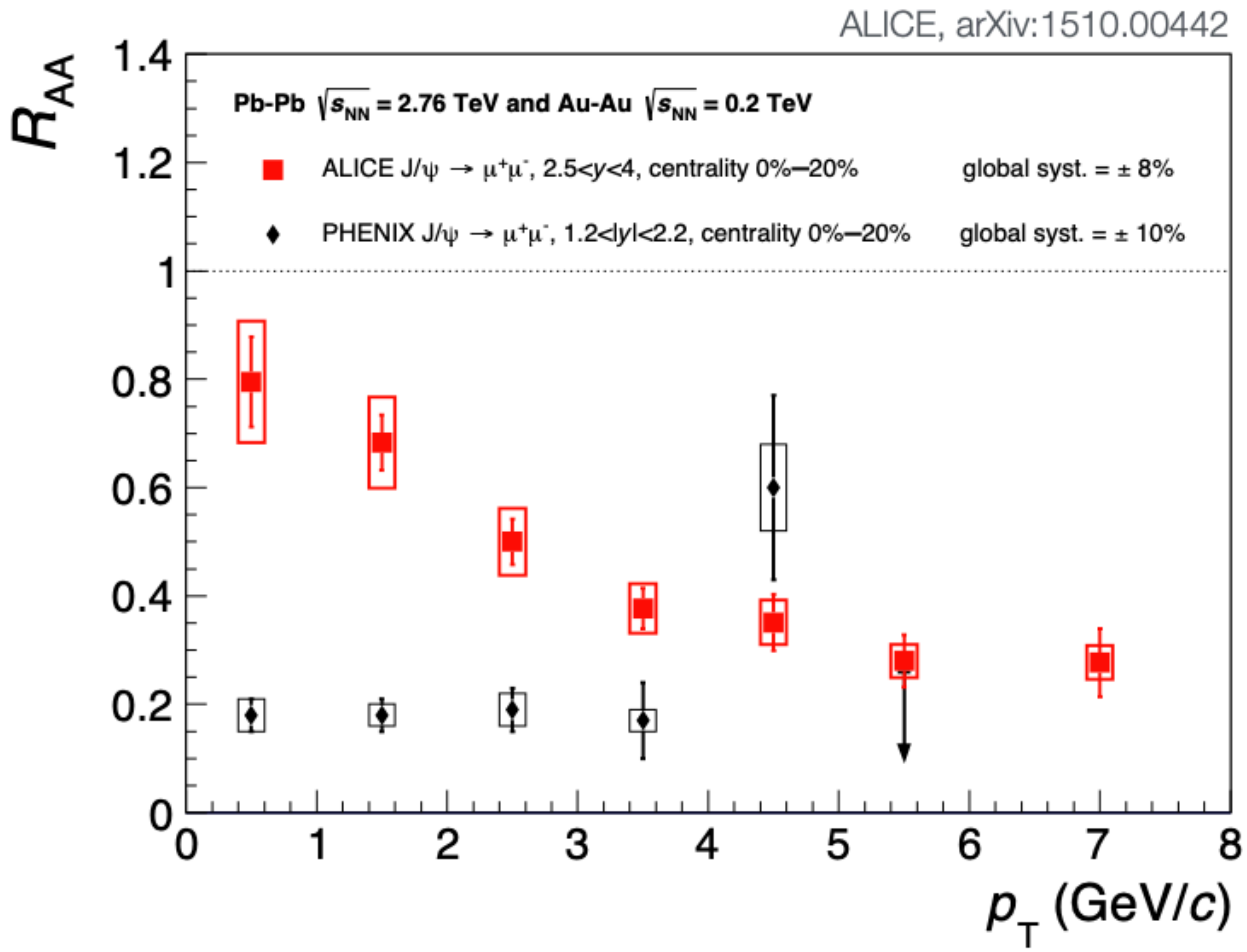
Requires large number of initially produced c cbar pairs: $N_{J/\Psi} \propto N_{c\bar{c}}$

Expect J/ψ suppression at SPS, RHIC and J/ψ enhancement at high energies (LHC)

COMPETING EFFECTS

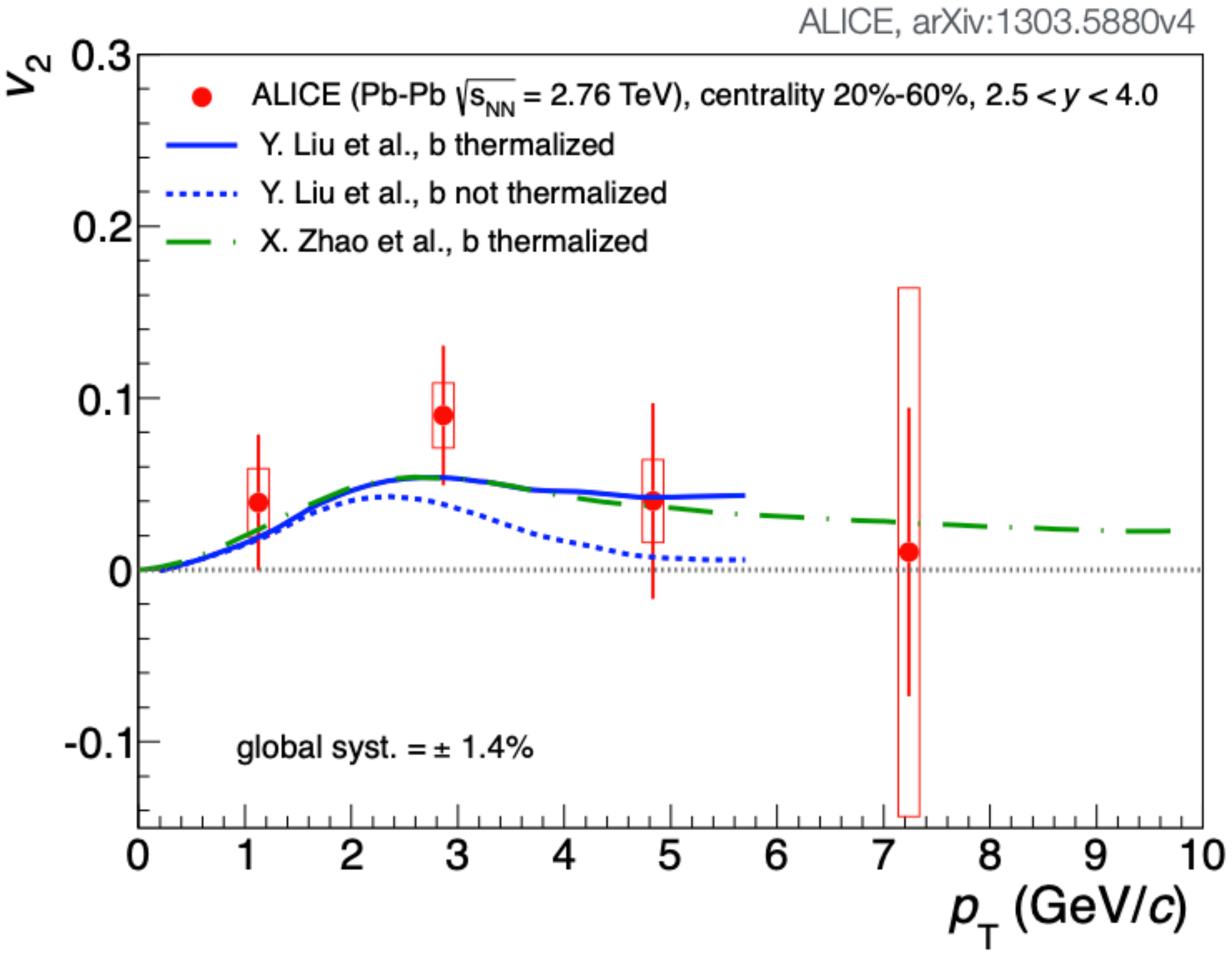


J/Ψ R_{AA} VS p_T AT RHIC AND THE LHC (0-20%)



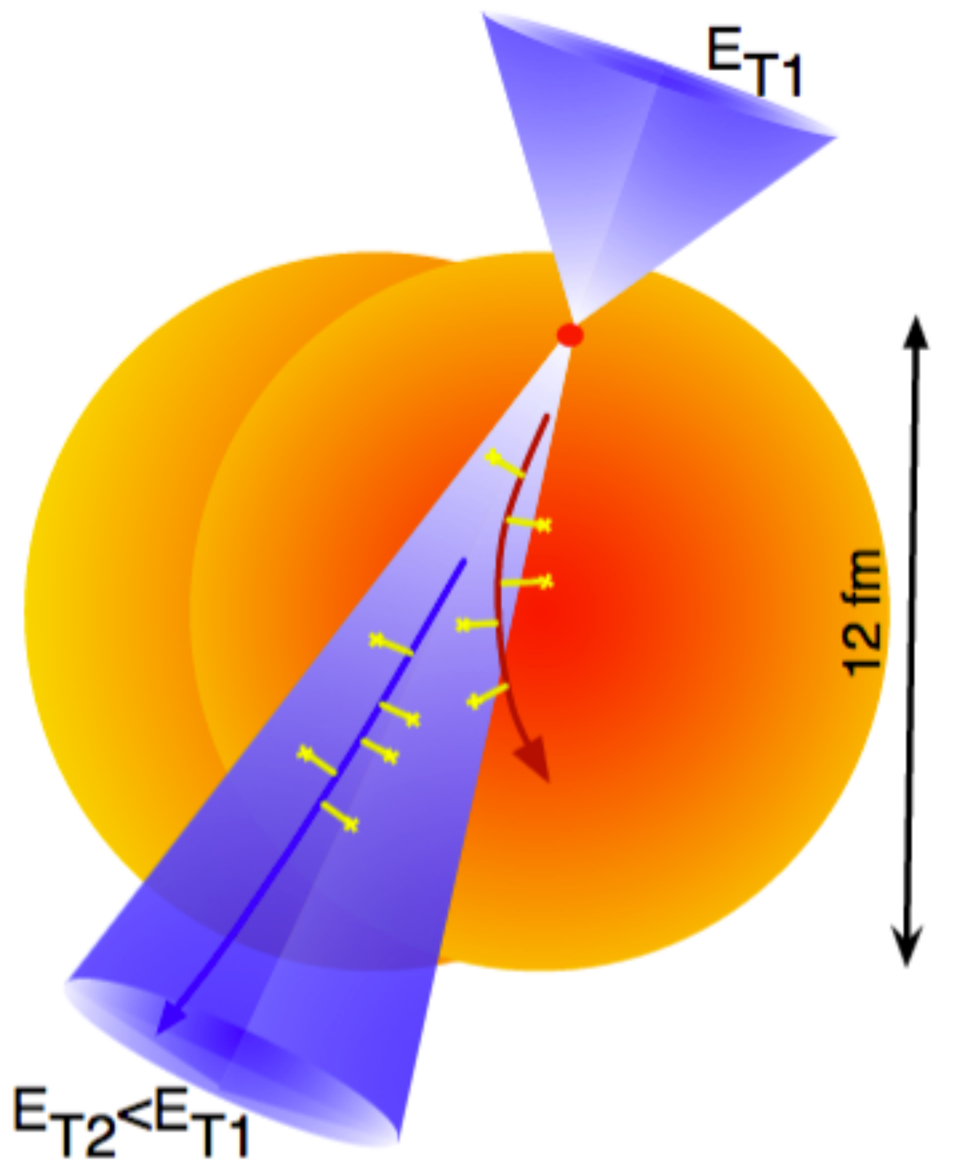
Much less suppression at low p_T, consistent with regeneration picture

J/Ψ FLOWS TOO.



Support for thermalization of charm quarks in the QGP??

JET QUENCHING

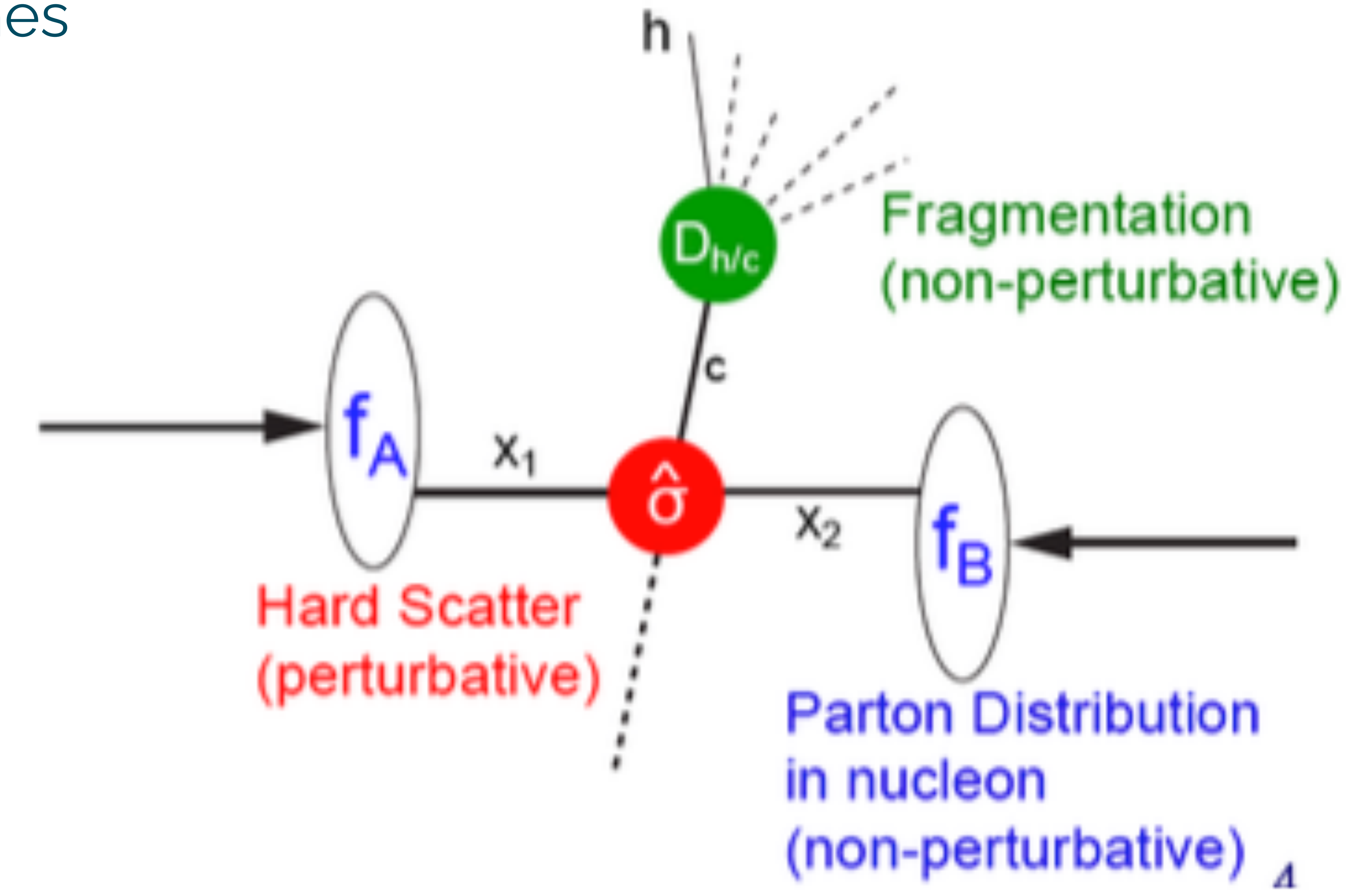


JET PRODUCTION

High $p_\perp$: Hard processes,
Description Scattering of pointlike partons described by QCD perturbation theory (pQCD)

Description of particle production available to perturbative methods only at sufficiently large pT (so that α_S becomes sufficiently small)

- Parton distributions (PDF)
- Parton-parton cross section from Perturbative QCD (pQCD)
- Fragmentation functions (FF)

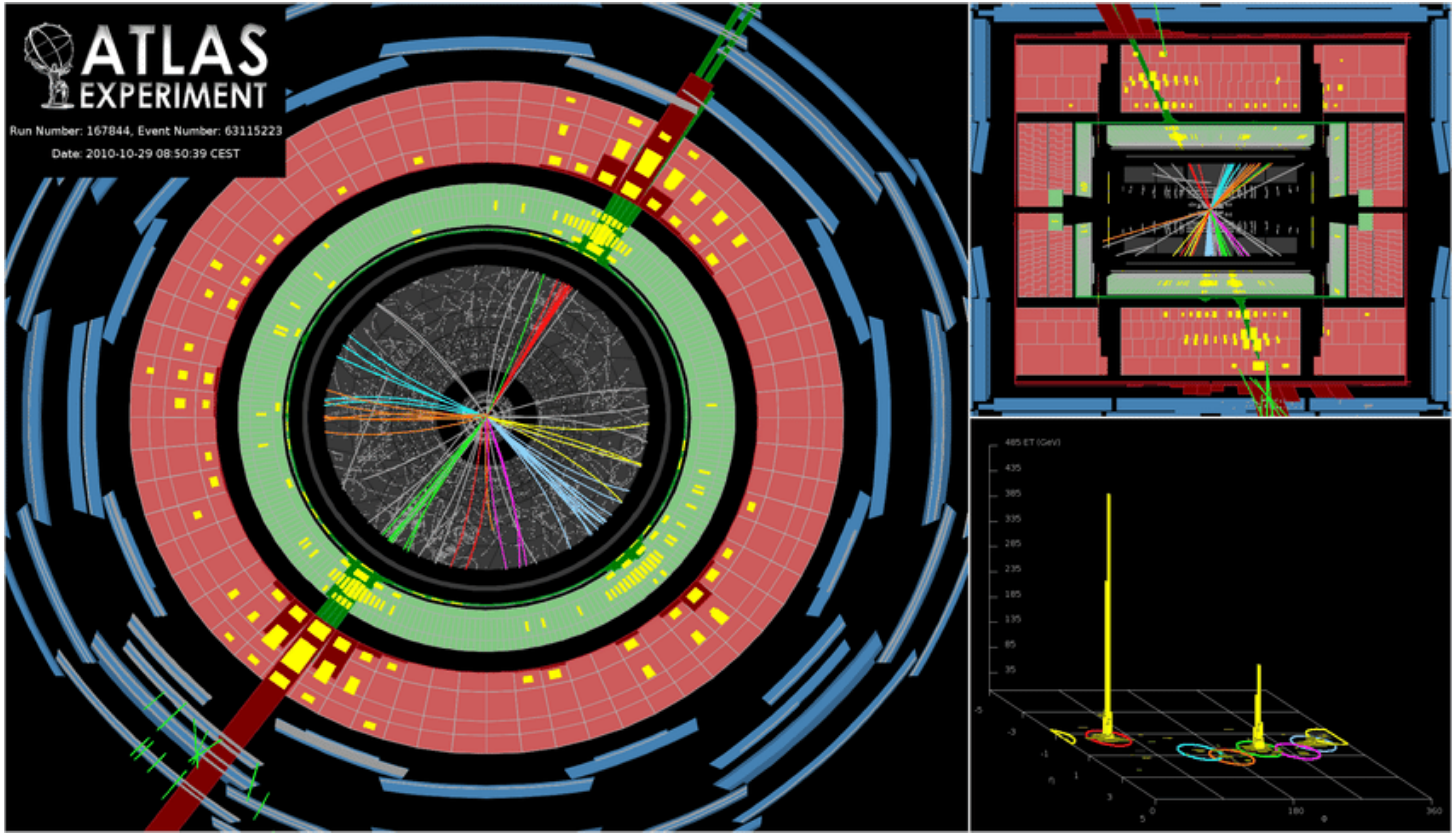


FFs and PDFs are universal functions from other experiments

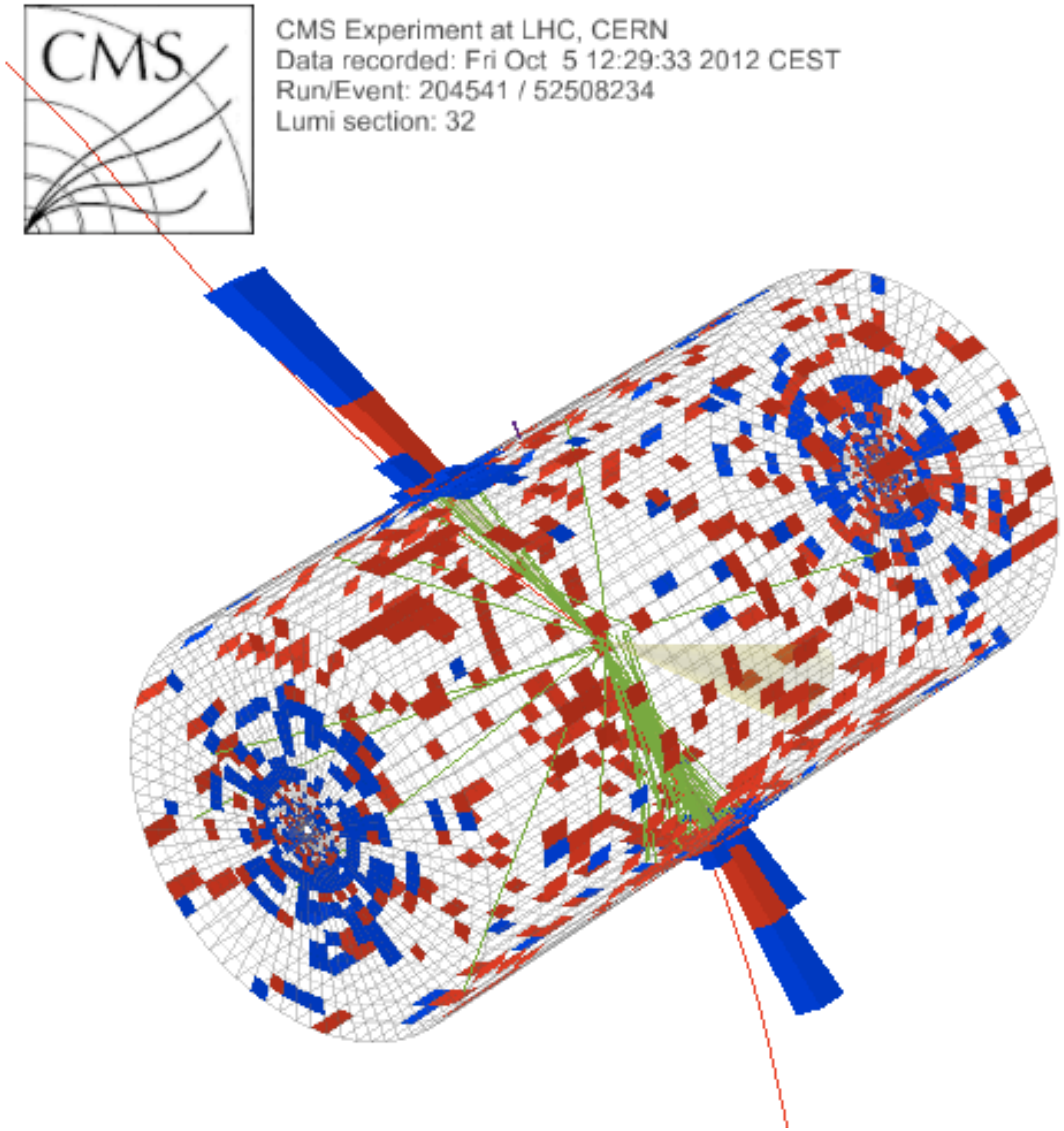
Particle production dominated by hard scattering for $pT \gtrsim 3$ GeV/c

However, 99% or so of all particle from soft processes

WHAT'S A JET?

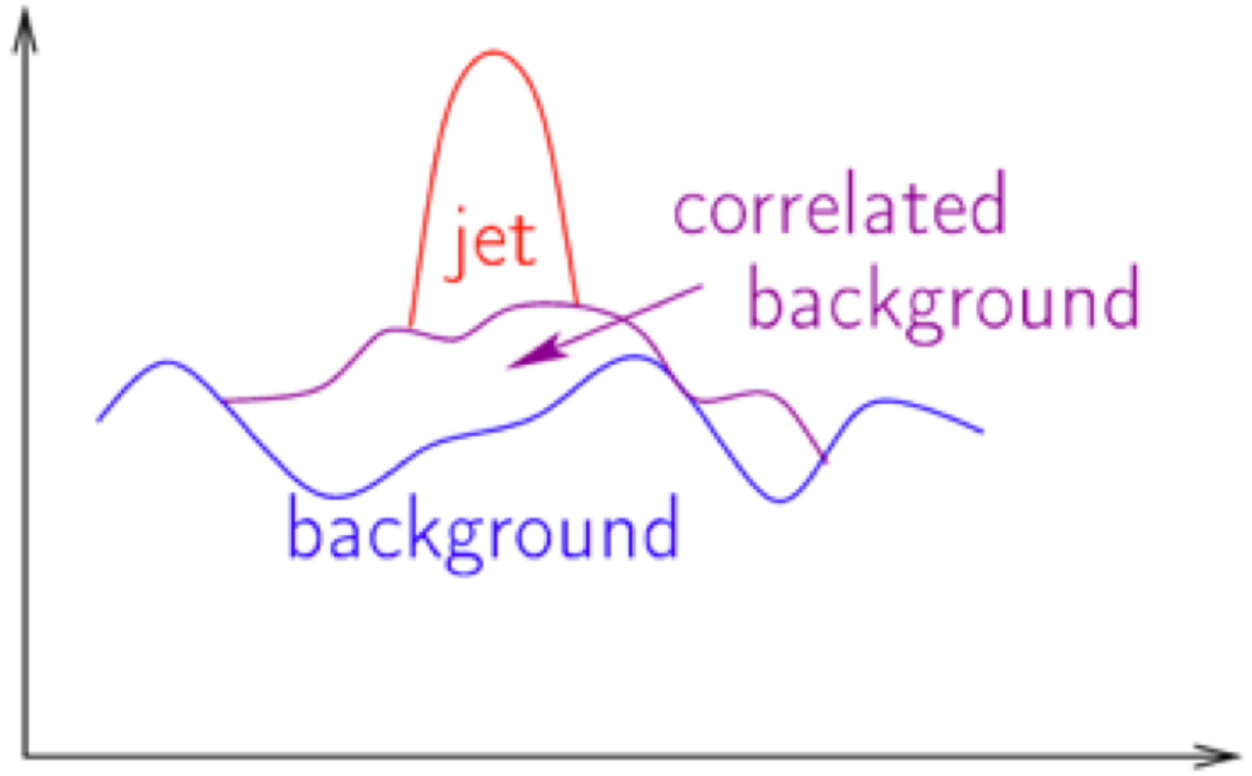

ATLAS
EXPERIMENT
Run Number: 167844, Event Number: 63115223
Date: 2010-10-29 08:50:39 CEST

WHAT'S A JET?



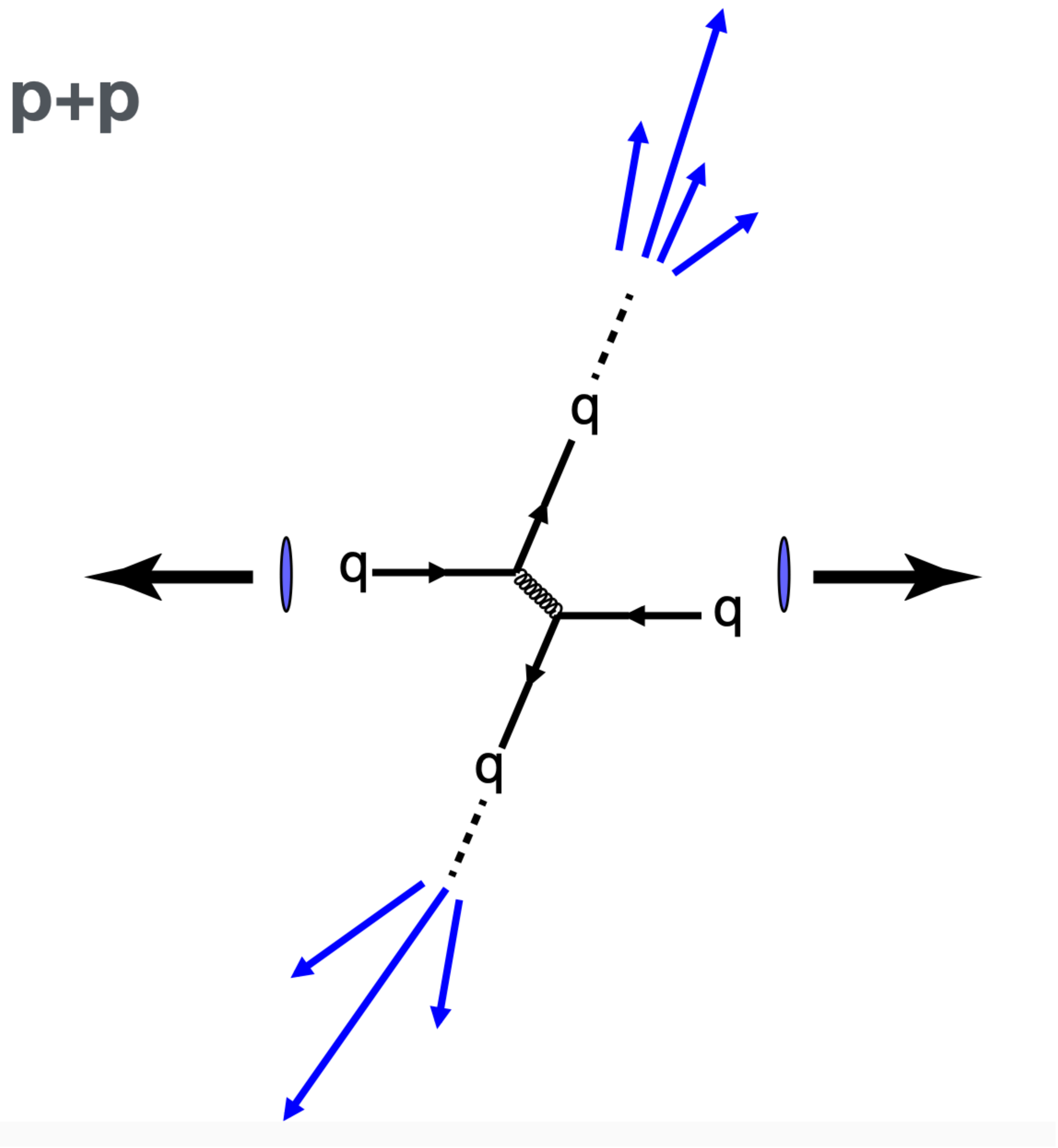
More than a "physical object" is a book-keeping device.

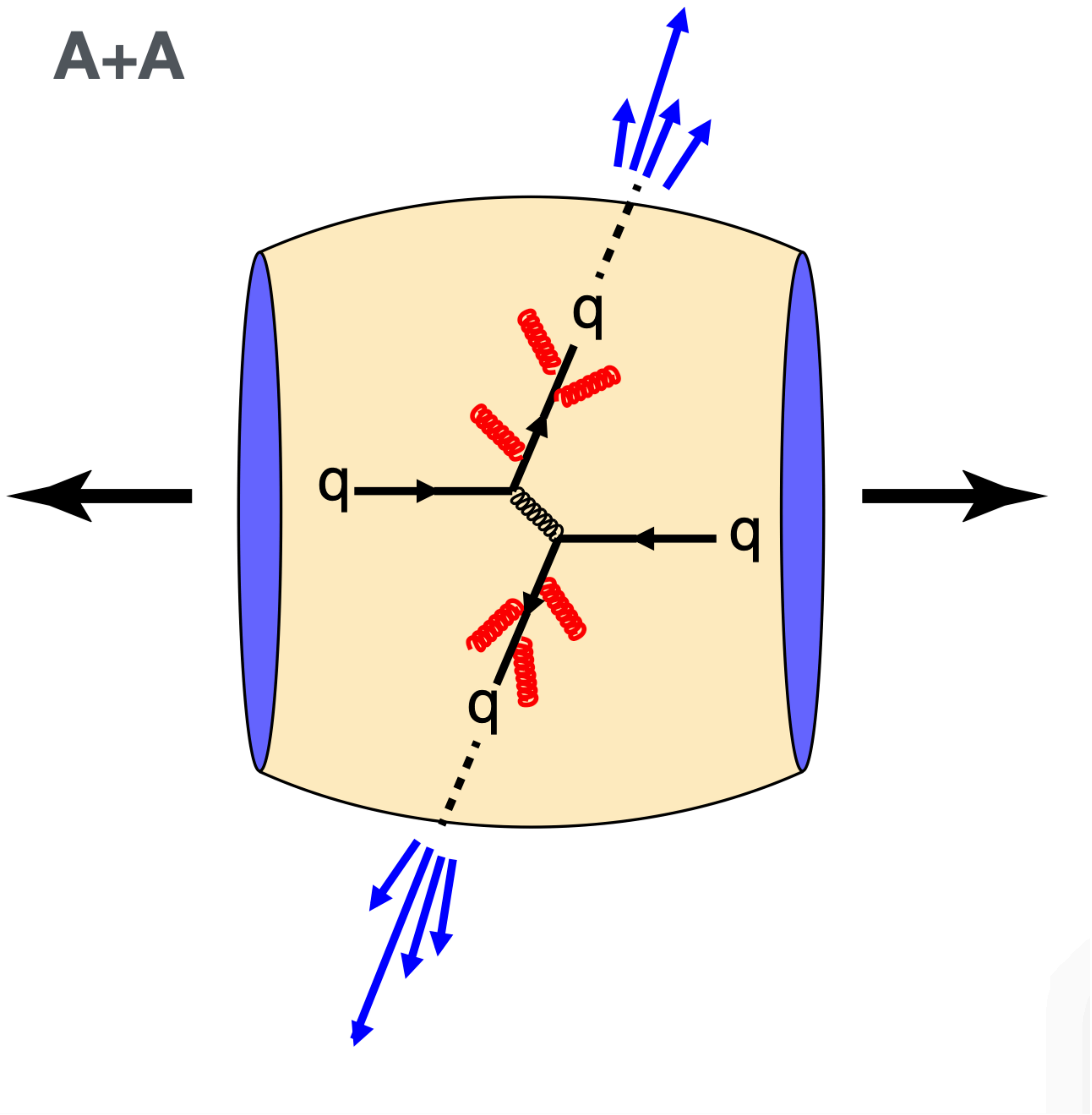
Why? There is no unbiased way of defining it. ***Jet-clustering algorithms*** needed to detect them.



But we can learn a whole bunch out of them!

JET PRODUCTION IN "VACUUM"





AA collision: shower evolution in the medium, energy loss of the leading parton

THE IDEA BEHIND IT: ENERGY LOSS

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

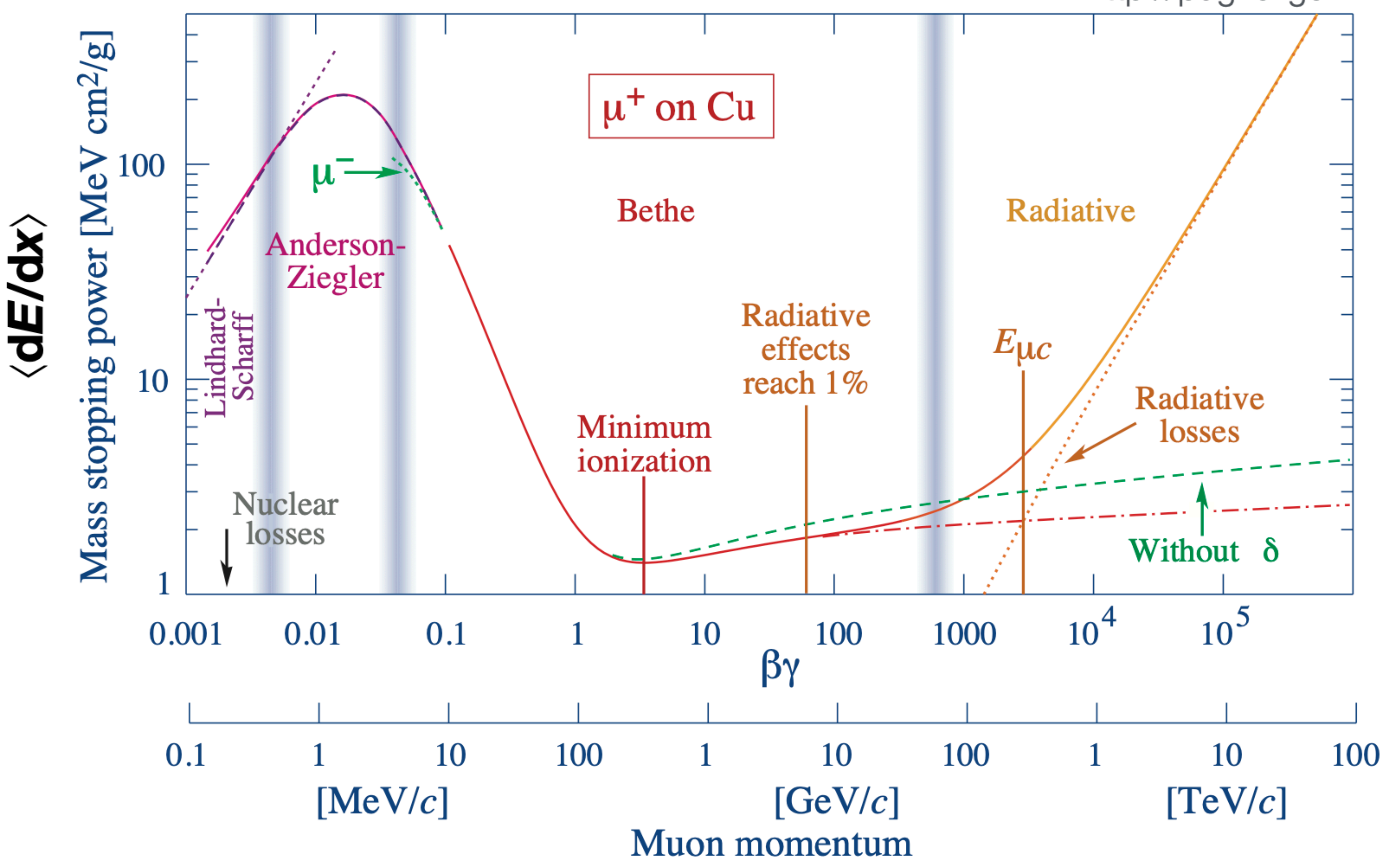
J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

Why? Analogous to energy loss in normal media

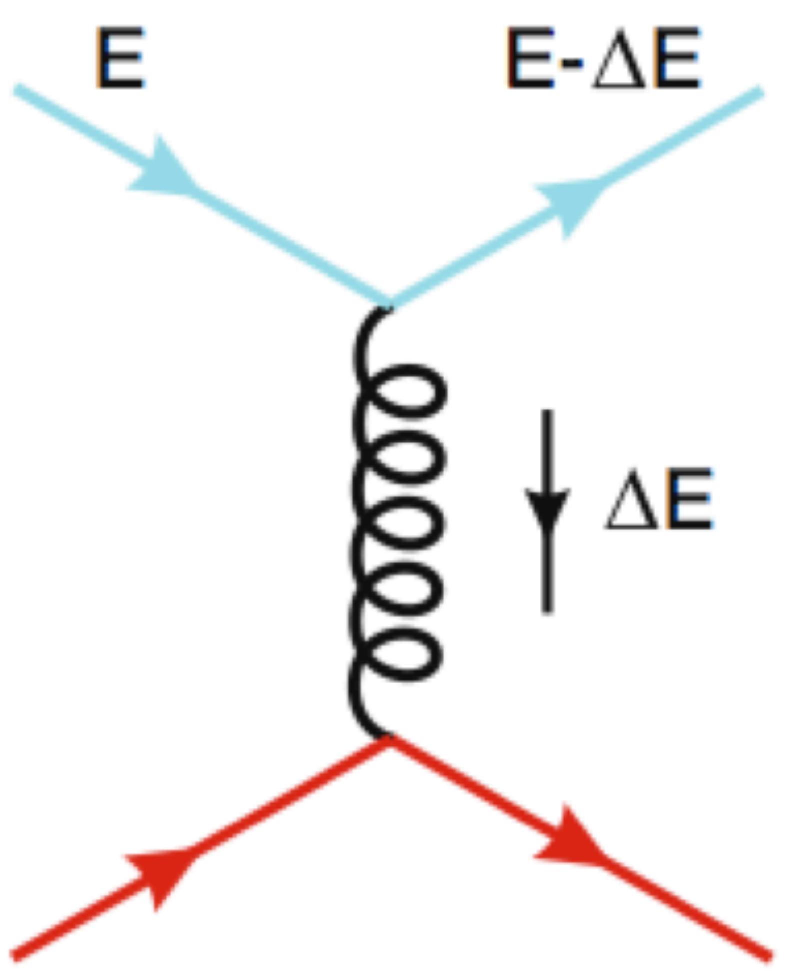
http://pdg.lbl.gov



μ^+ on Cu: Radiational energy loss ("bremsstrahlung") starts to dominate overcollisional energy loss ("Bethe-Bloch") for $p \gg 100$ GeV/c

THE IDEA BEHIND IT: ENERGY LOSS

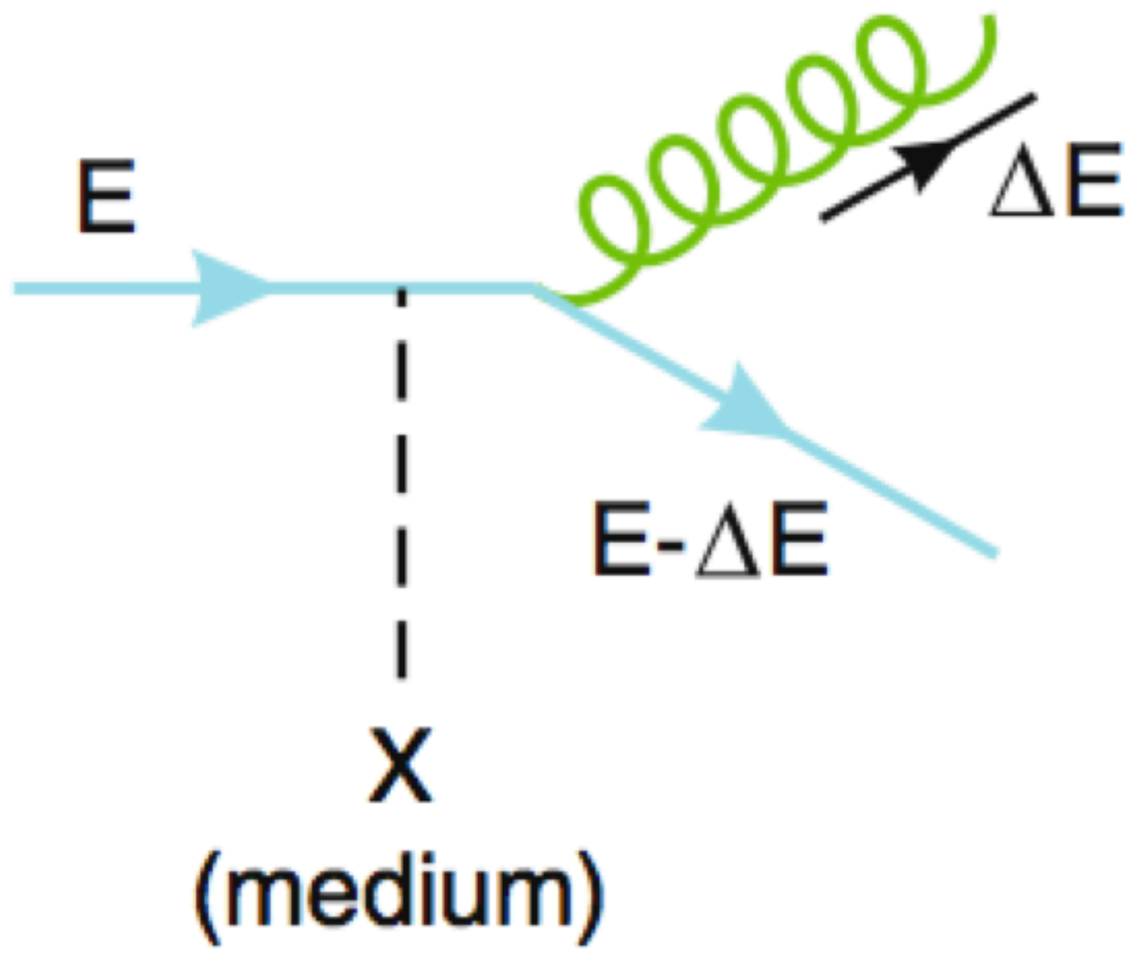
Collisional energy loss:



Elastic scatterings with medium constituents

Important at lower momenta

Radiative energy loss:



Inelastic scatterings enabled through interaction with the medium

Dominates at higher momenta

THE IDEA BEHIND IT: ENERGY LOSS

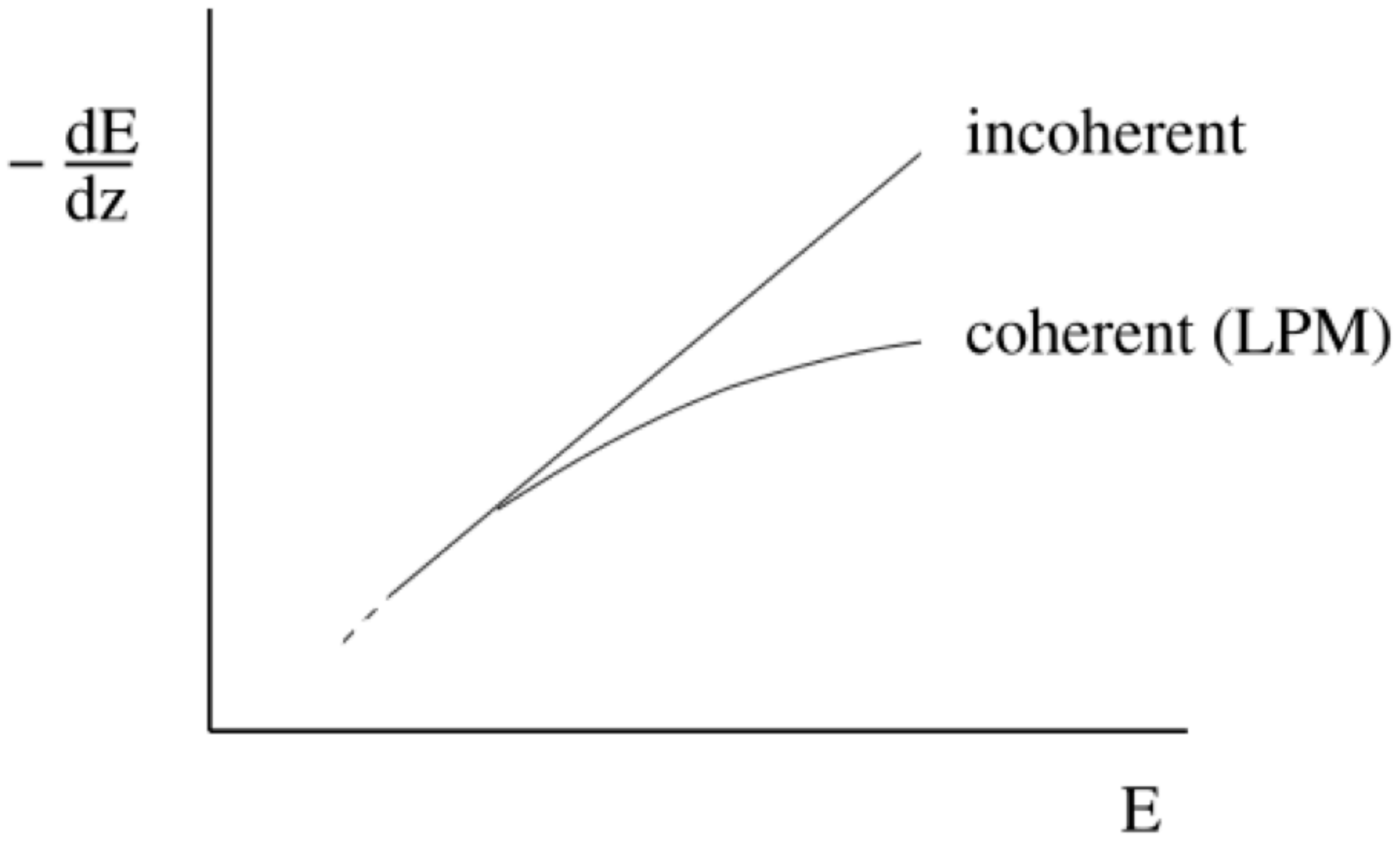
Energy loss E in a static medium of length L for a parton energy $E \rightarrow \infty$ (Time dependent T and finite media are currently a hot topic or research!)

$$\Delta E \propto \alpha_s C_F \hat{q} L^2 \qquad \hat{q} = \frac{\mu^2}{\lambda} \qquad C_F = \begin{cases} 3 & \text{for gluon jets} \\ 4/3 & \text{for quark jets} \end{cases}$$

μ^2 : typical momentum transfer from medium to parton per collision

λ : mean free path length in the medium

BDMPS result, Nucl. Phys. B 483, 291, 1997



Landau-Pomeranchuk-Migdal (LPM)

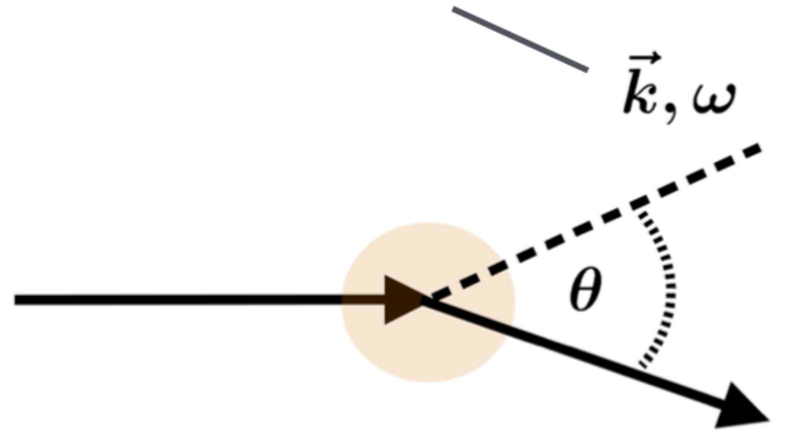
Parton scatters coherently off many medium constituents $\Rightarrow$ destructive interference

Clearly, less radiative energy loss

THE IDEA BEHIND IT: ENERGY LOSS

Formation time (or length) of a radiated gluon:
("time for the fast parton to get rid of its virtuality"

$$z_{coh} = t_{coh} \simeq \frac{\omega}{k_T^2} \simeq \frac{1}{\omega\theta^2}$$



The gluon acquires additional transverse momentum if it scatters with medium constituents within its formation time (or formation length z_c):

$$k_T^2 \simeq \hat{q} z_{coh} = \frac{\mu^2}{\lambda} z_{coh}$$

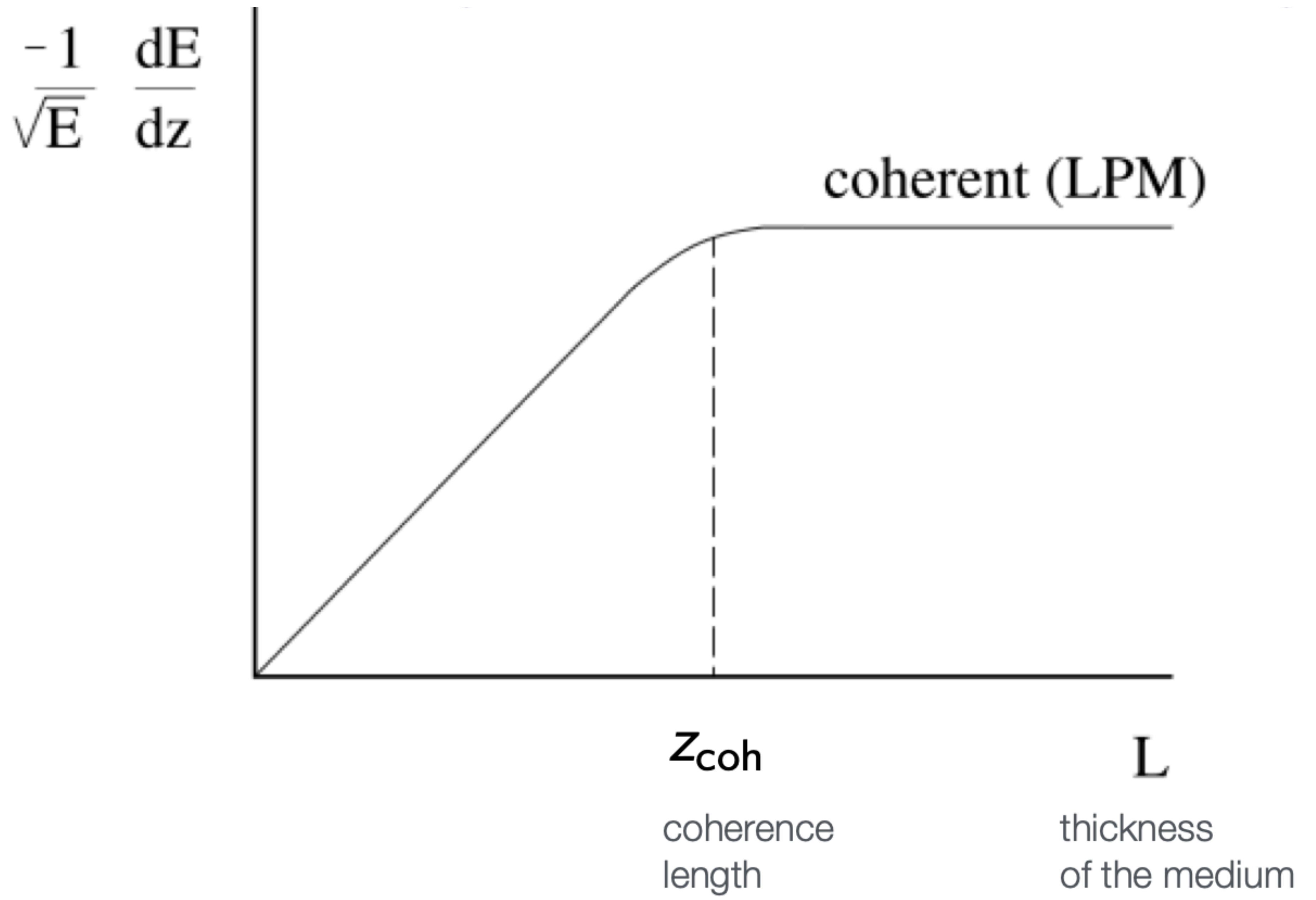
This results in a medium-modified formation length:

$$z_{coh} \simeq \frac{\omega}{k_T^2} \simeq \sqrt{\frac{\omega}{\hat{q}}}$$

$\lambda < z_{coh}$: Coherent scattering with destructive interference

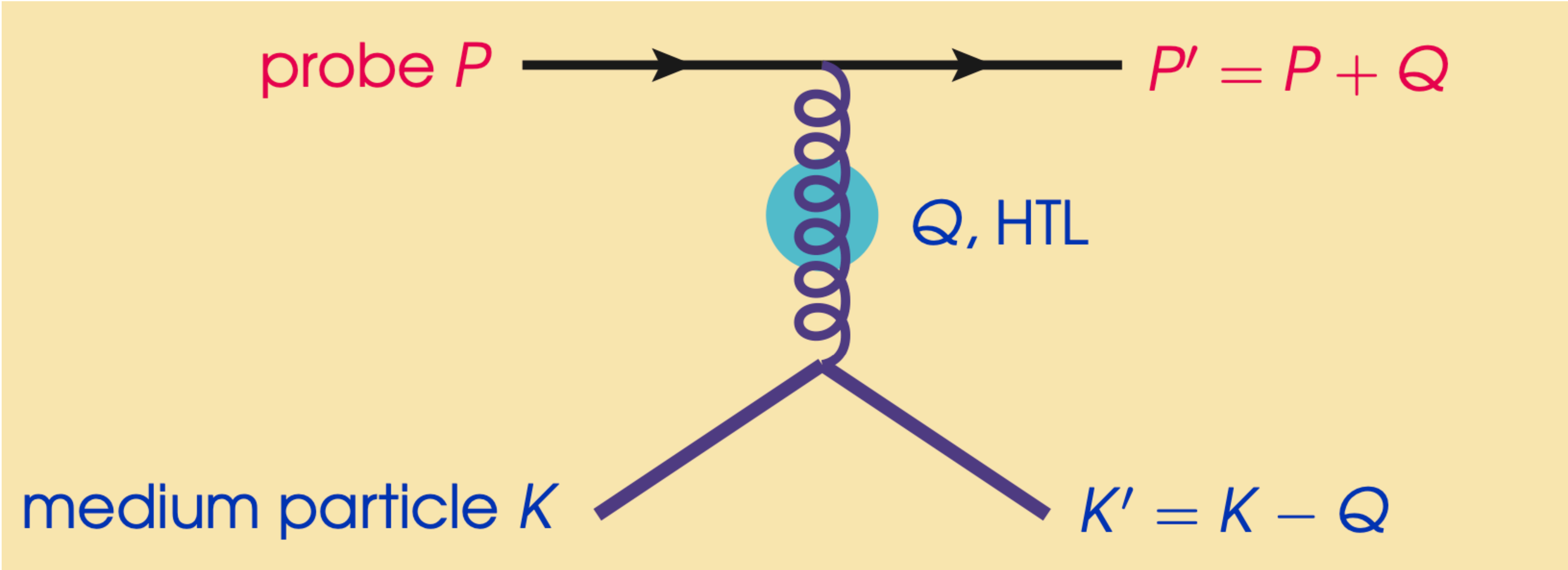
$\lambda > z_{coh}$: incoherent multiple scattering

dE/dz increases linearly with medium thickness L as long as L is smaller then the coherence length z_{coh}



$\hat{q}$ - THE JET QUENCHING PARAMETER

The measure of how much a jet broadens as it traverses the medium is given by the *jet quenching parameter,* $\hat{q}$

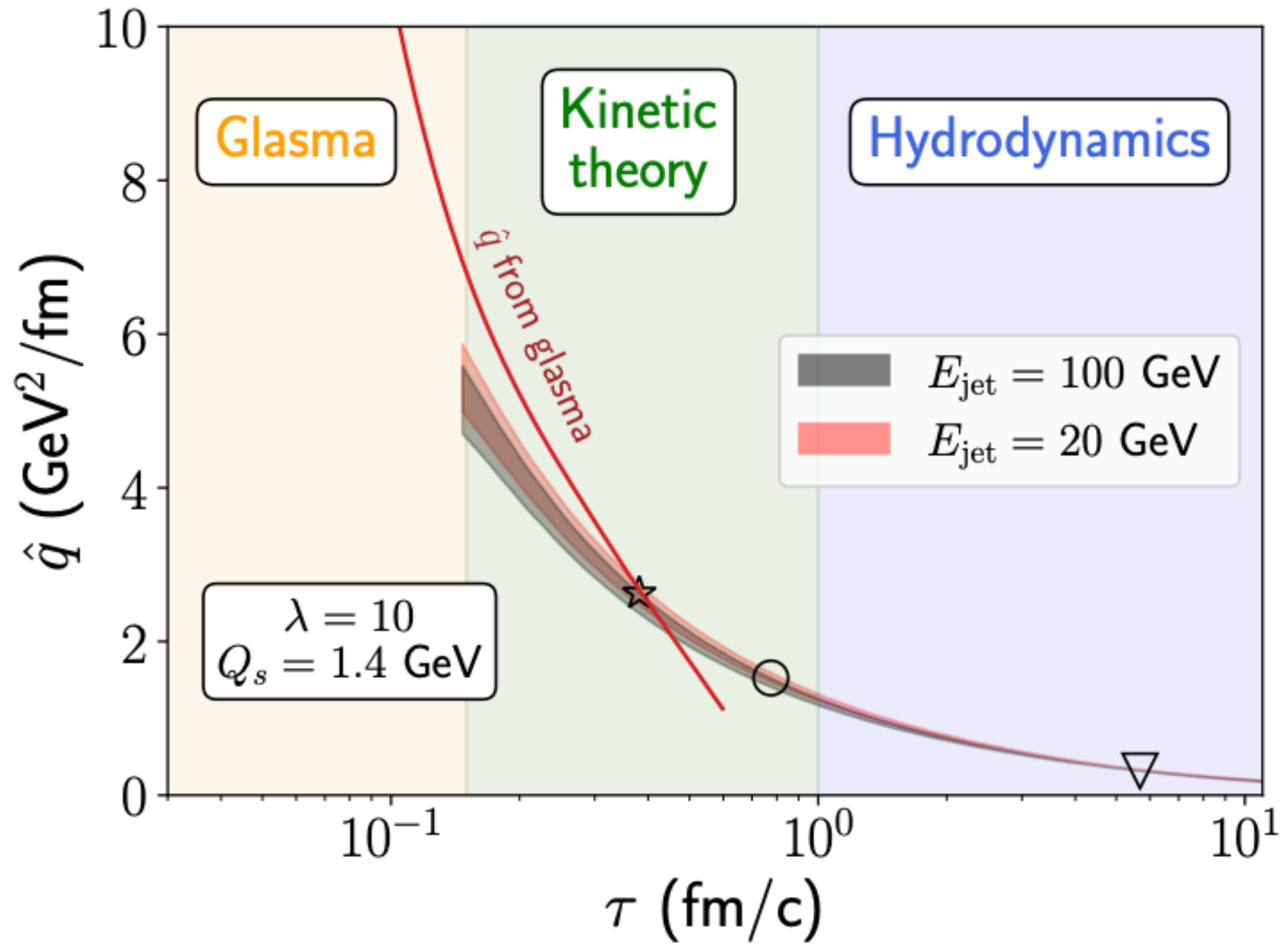


$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm} \;\; \text{at} \;\; \begin{matrix} \text{T=370 MeV,} \\ \text{T=470 MeV,} \end{matrix}$$

Jet Coll., Phys.Rev. C90 (2014) 014909

Jet transport parameter loss for radiative energy loss at the highest temperatures reached (for E_{parton} = 10 GeV, QGP thermalization at τ_0 = 0.6 fm/c). Result relies on standard hydro description of the medium evolution



Conjectured relation to η/s

$$\frac{T^3}{\hat{q}} = K \frac{\eta}{s}$$

weakly-coupled QGP: $K \approx 1$

strongly-coupled QGP: $K \ll 1$

Majumder, Müller, Wang, PRL, 99 (2007) 192301

“A” METHOD: EFFECTIVE KINETIC THEORY (EKT)

- Challenge: Description of jet thermalization requires theoretical description which is valid at scales $E \sim E_{jet}$ (hard fragments) down to scales $E \sim T_{med}$ (soft fragments & thermal medium)

Kinetic description: in-medium evolution jet fragments as collection of on-shell partons in QCD EKT. Evolution is given by

$$\left(\partial_t + \frac{\boldsymbol{p}}{|\boldsymbol{p}|} \cdot \nabla_x\right) f_a(\boldsymbol{p}, \mathbf{x}, t) = -C_a^{2\leftrightarrow 2}[\{f_i\}] - C_a^{1\leftrightarrow 2}[\{f_i\}]$$

- Here, the *jet* is a linearized perturbation on top of (static) equilibrium background $\Rightarrow$ $\left(\partial_t + \frac{|\boldsymbol{p}|}{\boldsymbol{p}} \cdot \nabla_x\right) \delta f = C[T; \delta f]$

- Rephrase the evolution thinking about the energy distribution $D(t, x, \theta) = x \dfrac{dN}{dx\, d\cos(\theta)}$

Effective calculation of the Green’s function for a perturbation (hard Parton) in a medium

(c.f. Arnold,Moore,Yaffe (LO); Ghiglieri,Moore,Teaney (NLO))

"A" METHOD: EFFECTIVE KINETIC THEORY (EKT)

- Elastic interactions provide momentum broadening outside of the jet cone.

- Elastic scattering processes treated with leading order Hard Thermal Loops (HTL) screened matrix elements

$$C_a^{2\leftrightarrow 2}[\{f_i\}] = \frac{1}{2|p_1|\nu_a} \sum_{bcd} \int d\Omega^{2\leftrightarrow 2} \left| \mathcal{M}_{cd}^{ab}(\boldsymbol{p}_1, \boldsymbol{p}_2; \boldsymbol{p}_3, \boldsymbol{p}_4) \right|^2 \delta\mathcal{F}(\boldsymbol{p}_1, \boldsymbol{p}_2; \boldsymbol{p}_3, \boldsymbol{p}_4)$$

  - Including quantum statistics (Fermi suppression/Bose enhancement)effects,

$$\delta\mathcal{F}(\boldsymbol{p}_1, \boldsymbol{p}_2, \boldsymbol{p}_3, \boldsymbol{p}_4) \supset \delta f_a(\boldsymbol{p}_1) \left[\pm_a n_c(p_3) n_d(p_4) - n_b(p_2)(1 \pm n_c(p_3) \pm n_d(p_4))\right]$$

- Detailed balance allows for exact **conservation of *energy*, momentum and valence charge** of the jet allows to study evolution from $E \sim E_{jet}$ to $E \sim T_{med}$ including thermalization of the jet

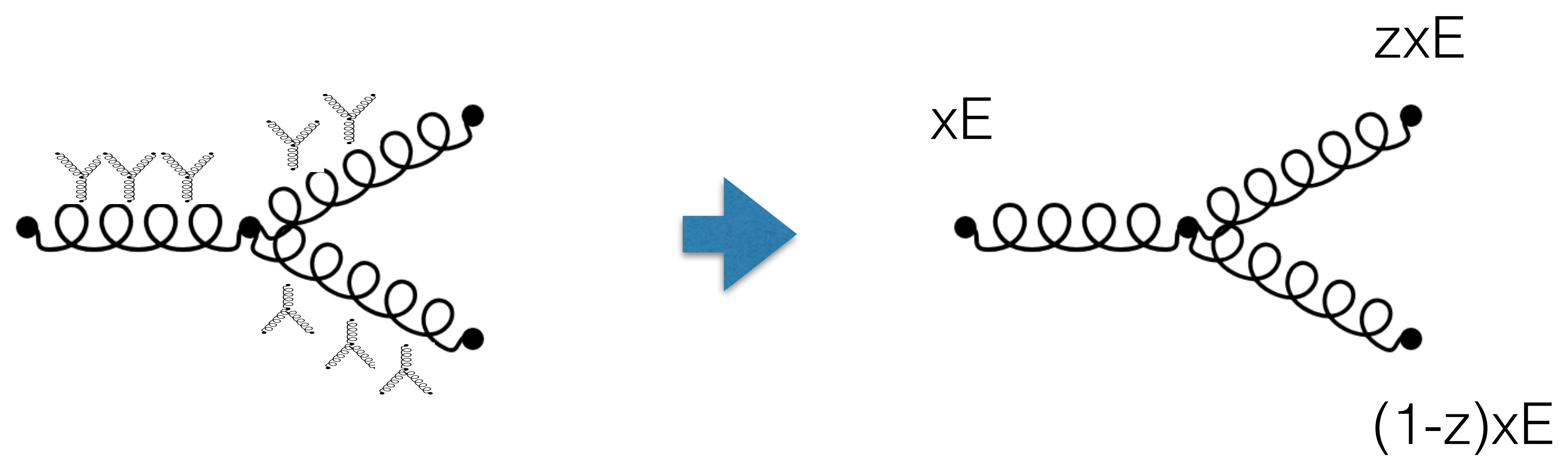
THE METHOD: EFFECTIVE KINETIC THEORY (EKT)

- Inelastic interactions are responsible for the radiative break-up of hard partons

- Numerical studies re-construction of in-medium rates in the AMY framework (incl. LPM & Bethe-Heitler regime) for an infinite medium

$$C_g^{g\leftrightarrow gg}[\{D_i\}] = \int_0^1 dz \frac{d\Gamma_{gg}^g\left(\left(\frac{xE}{z}\right), z\right)}{dz}\left[D_g\left(\frac{x}{z}\right)\left(1 + n_B(xE) + n_B\left(\frac{\bar{z}xE}{z}\right)\right) + \frac{D_g(x)}{z^3}\left(n_B\left(\frac{xE}{z}\right) - n_B\left(\frac{\bar{z}xE}{z}\right)\right) + \frac{D_g\left(\frac{\bar{z}xE}{z}\right)}{\bar{z}^3}\left(n_B\left(\frac{xE}{z}\right) - n_B(xE)\right)\right]$$
$$-\frac{1}{2}\int_0^1 dz \frac{d\Gamma_{gg}^g(xE, z)}{dz}\left[D_g(x)(1 + n_B(zxE) + n_B(\bar{z}xE)) + \frac{D_g(zx)}{z^3}(n_B(xE) - n_B(\bar{z}xE)) + \frac{D_g(\bar{z}x)}{\bar{z}^3}(n_B(xE) - n_B(zxE))\right],$$

- Quantum statistics (Fermi suppression/Bose enhancement)effects are important at the temperature scale



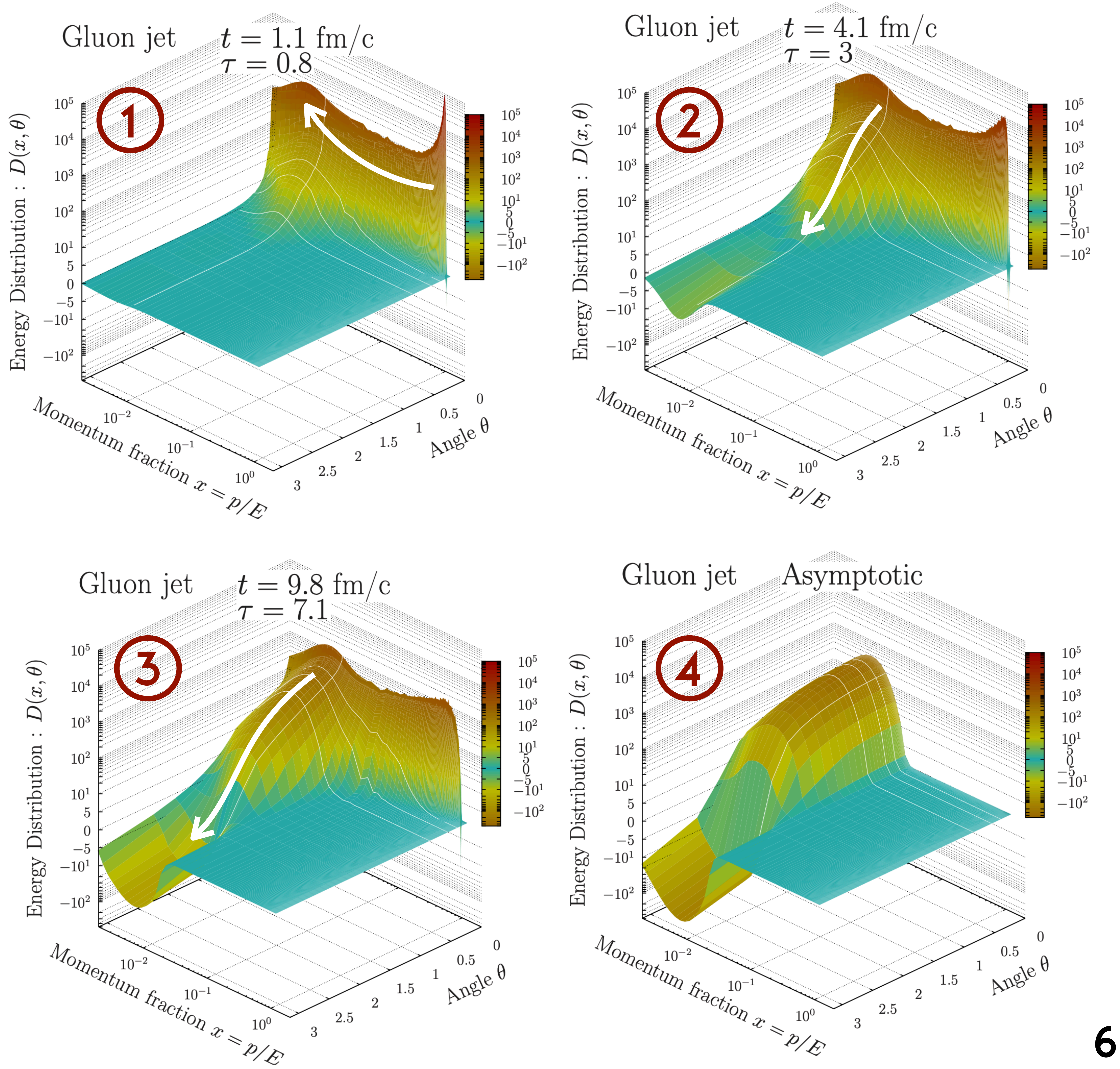
EVOLUTION OF THE JET

1 **Collinear energy cascade** towards the soft sector confined to narrow cone θ<0.3

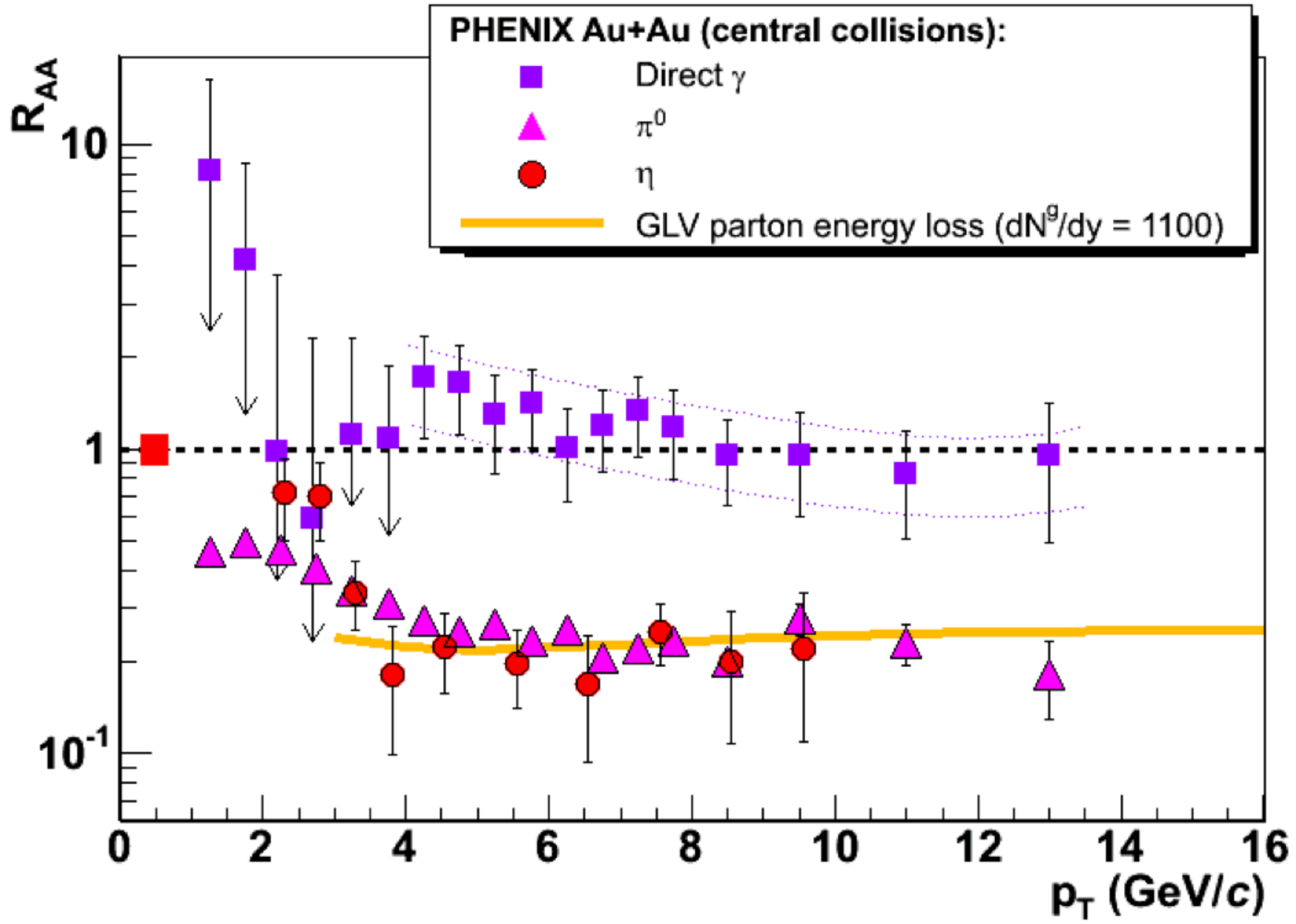
Radiative break-up of the parton is the main contribution

2 + 3 **Angular cascade:**
Soft fragments $x \sim T/E$ spread out to large angles (θ~1) via elastic interactions

4 Jet thermalizes in a parametrically long time, when all hard partons have decayed

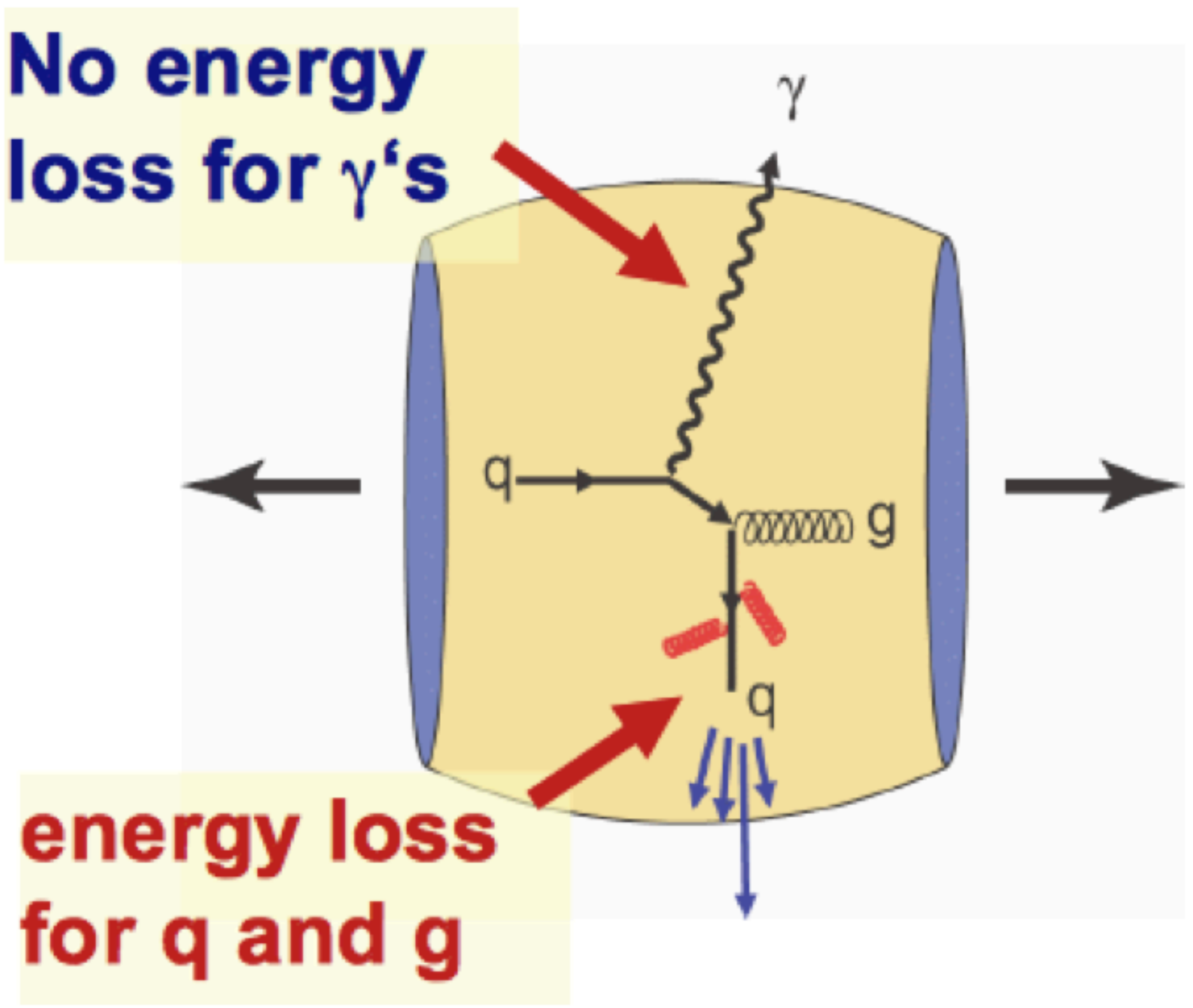


DISCOVERY OF JET QUENCHING (RHIC)



$$R_{AB} = \frac{\mathrm{d}N/\mathrm{d}p_T|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}}\rangle \times \mathrm{d}\sigma_{\mathrm{inv}}/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{p+p}}},$$

where $\langle T_{\mathrm{AB}}\rangle = \langle N_{\mathrm{coll}}\rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$



Hadrons are suppressed, ***direct photons are not***

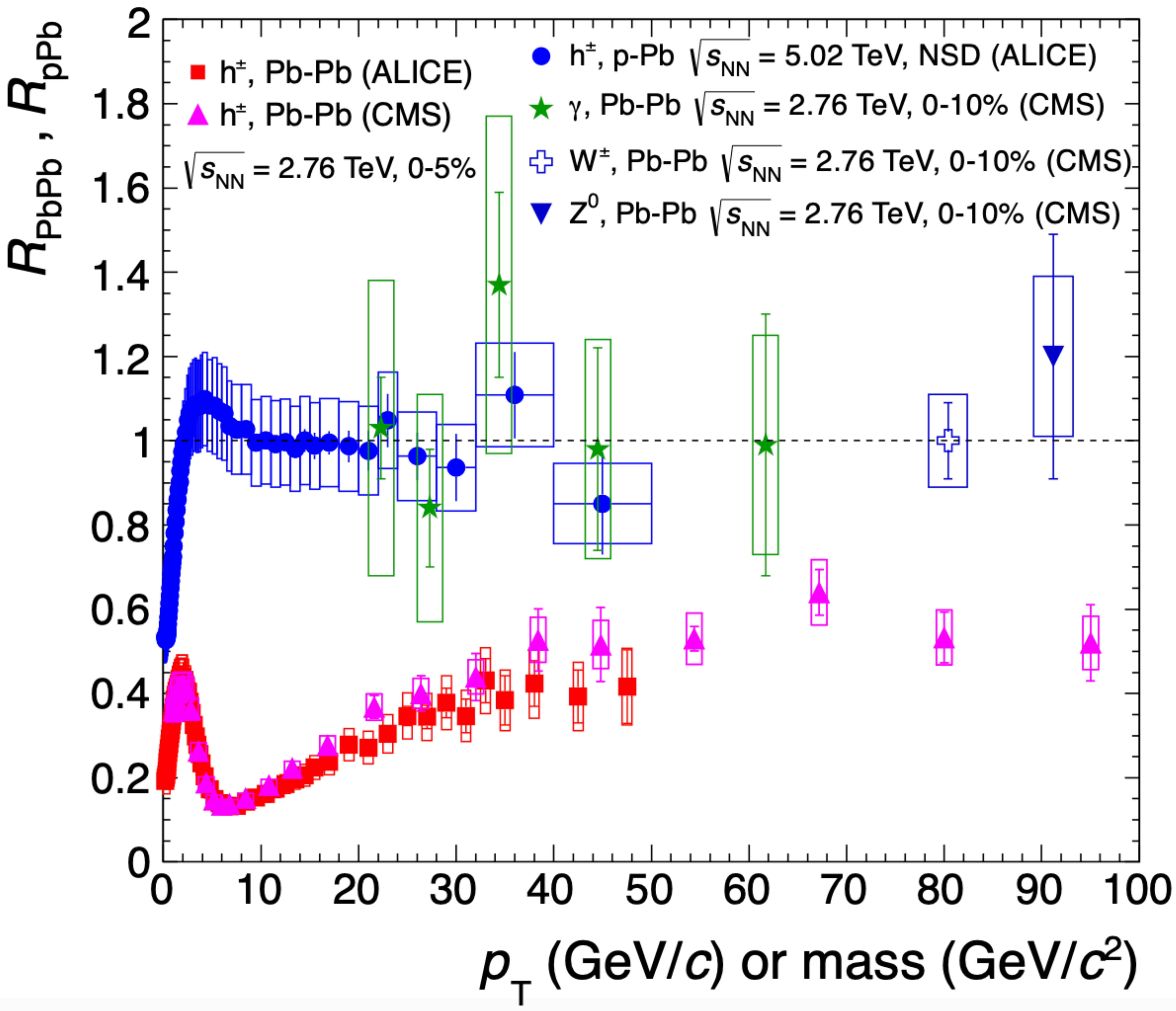
⇒Evidence for parton energy loss

JET QUENCHING AT LHC ENERGIES

⇒No suppression for γ, W^{+-}, Z^0 in Pb-Pb

⇒No suppression of hadrons in p-Pb

⇒Strong suppression of hadrons in Pb-Pb



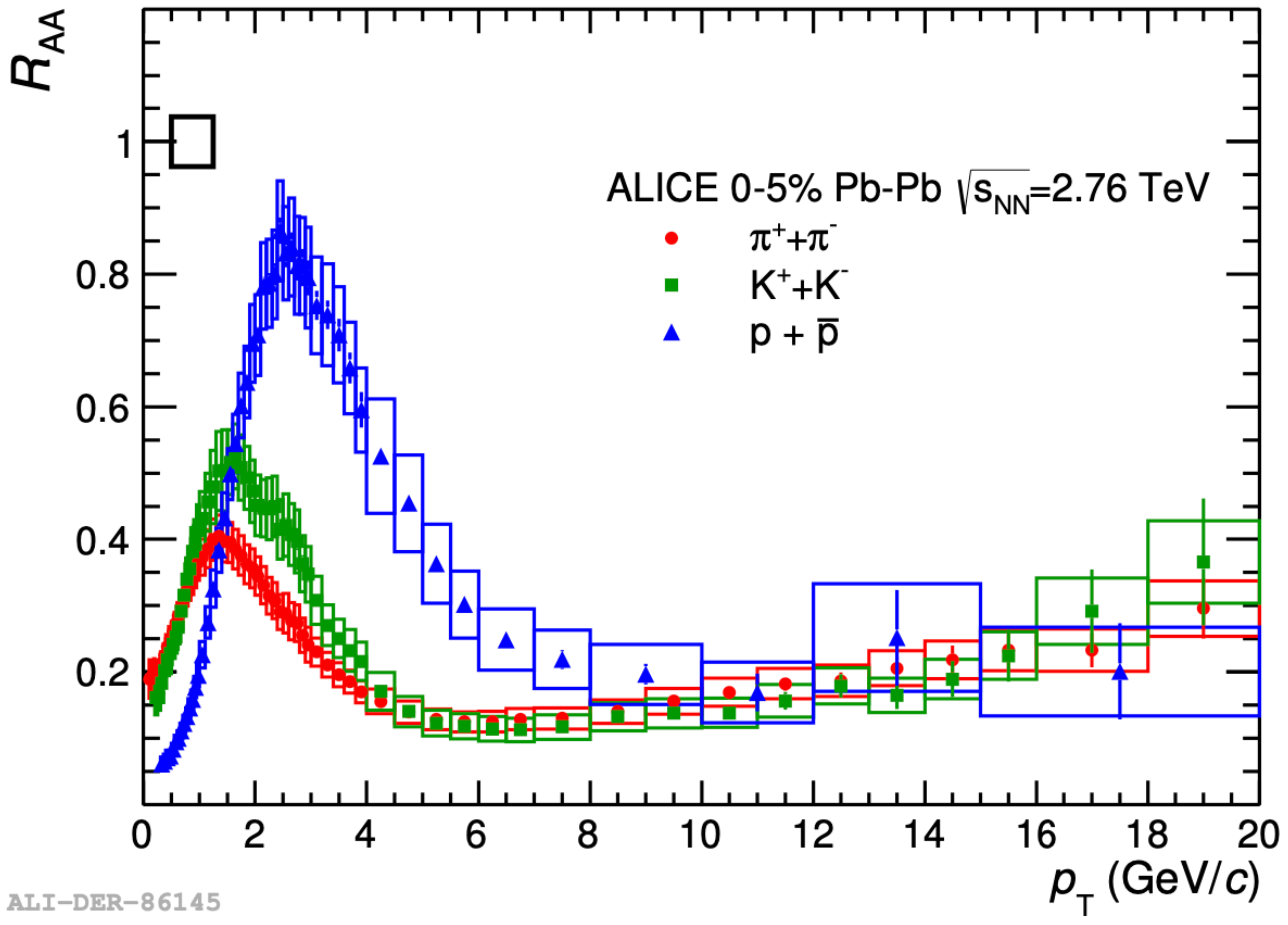
π, K, p : R_{AA}- SUPPRESSION INDEPENDENT OF HADRON SPECIES FOR $p_\perp \gtrsim$ 8 GEV/*C*

⇒Leading-parton energy loss followed by fragmentation in QCD vacuum (as in pp) for $p_{T,\mathrm{hadron}} > 8$ GeV/*c*?

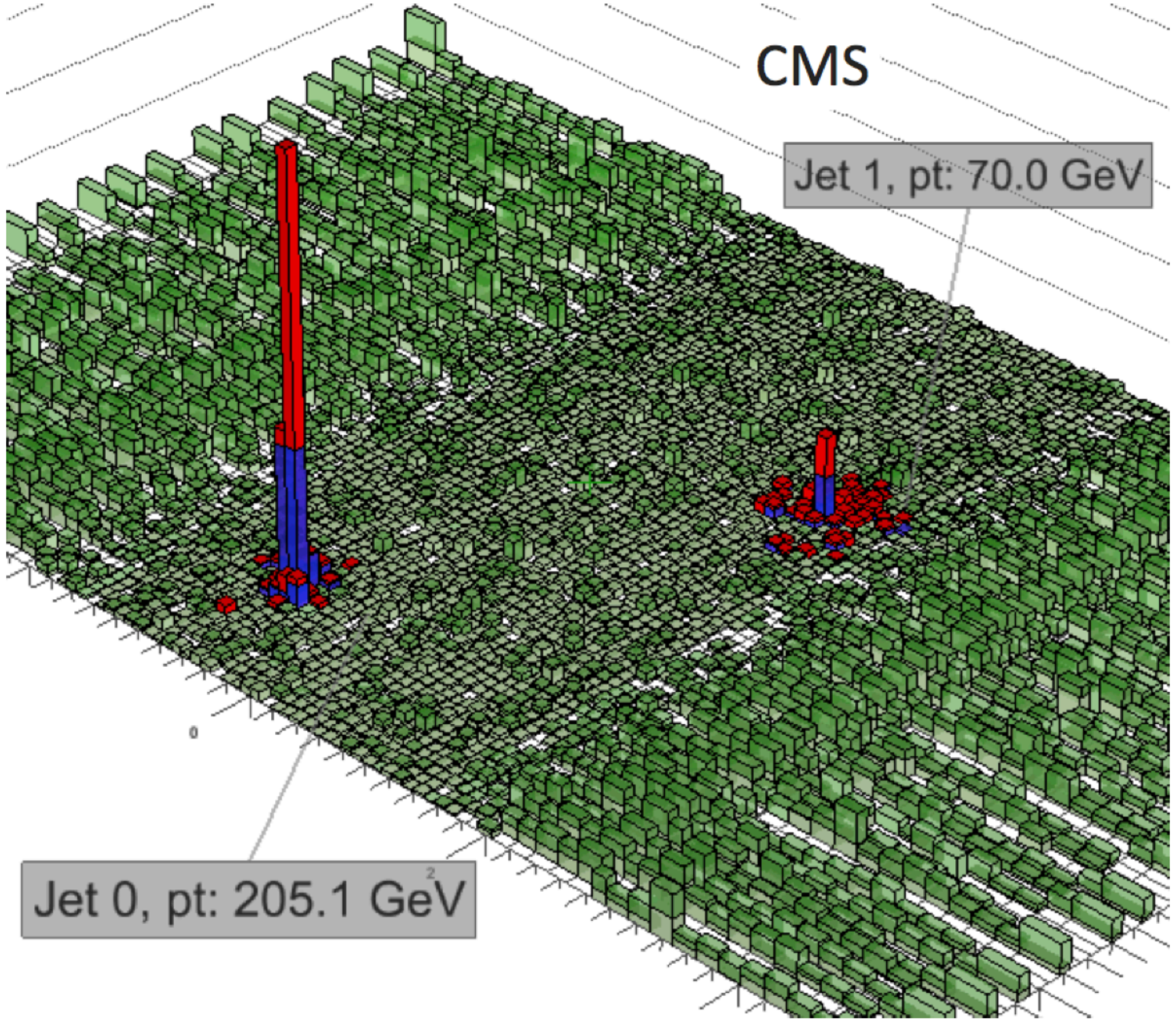
⇒ $R_{AA}(p) > R_{AA}(K) \approx R_{AA}(\pi)$ for $3 < p_T < 8$ GeV/c

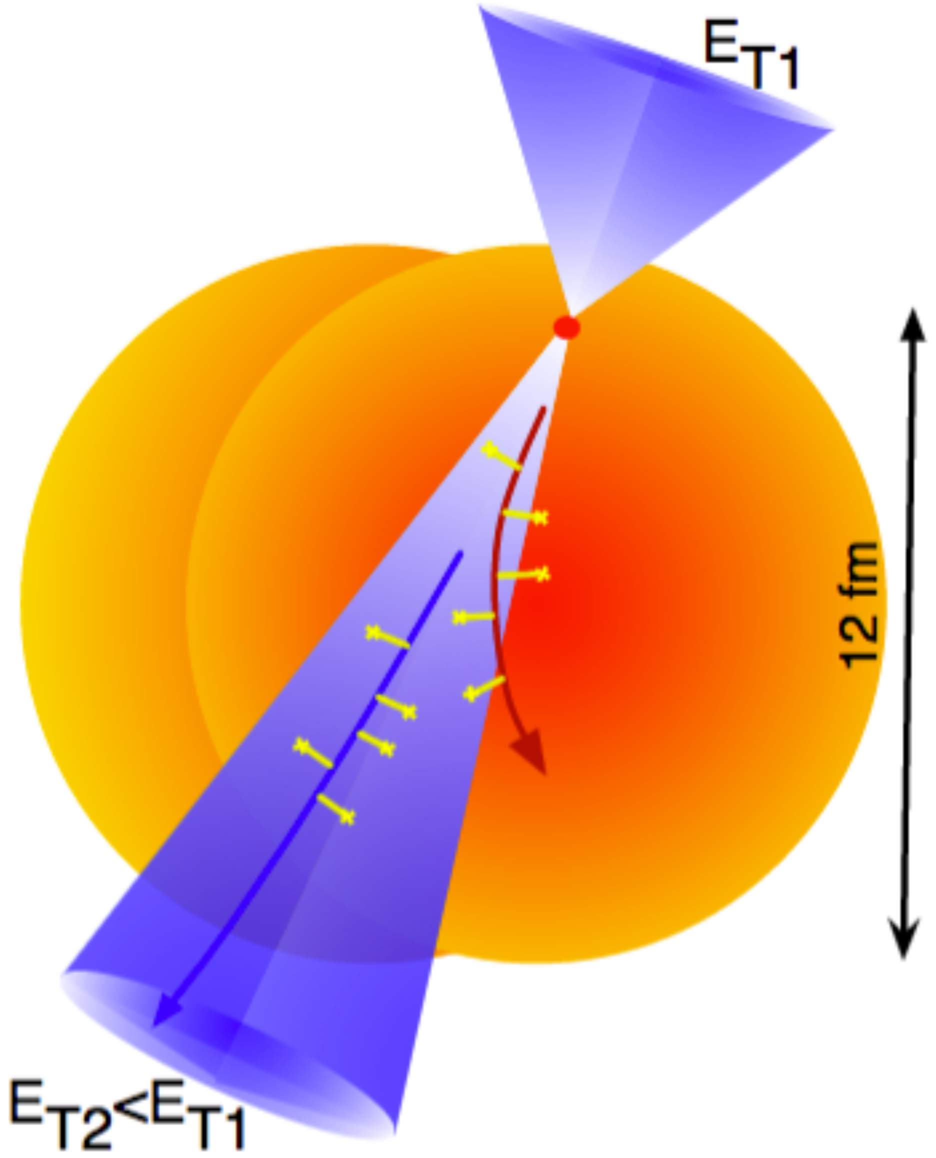
⇒Similar p, K and π R_{AA} for $p_T > 8$ GeV/*c*

ALICE, arXiv:1506.07287



LARGE DIJET ENERGY ASYMMETRIES IN PB-PB





$\Rightarrow$Confirms the energy loss picture!

SUMMARY

If your are going to take three sentences home take these with you:

1) Heavy-Ion research is all about the rise of complexity. For us, is how many quantum nuclear DoF become a complex, collective fluid-like system.

2) Heavy Ion Collisions is an area at the crossroads of many areas. Quantum systems, kinetic theory, hydrodynamics, nuclear physics, etc.

3) Basically nothing is settled yet. We need more research (ers)