UNIVERSITY OF BIRMINGHAM

Nuclear Matter at the Highest Energies: Results from ALICE

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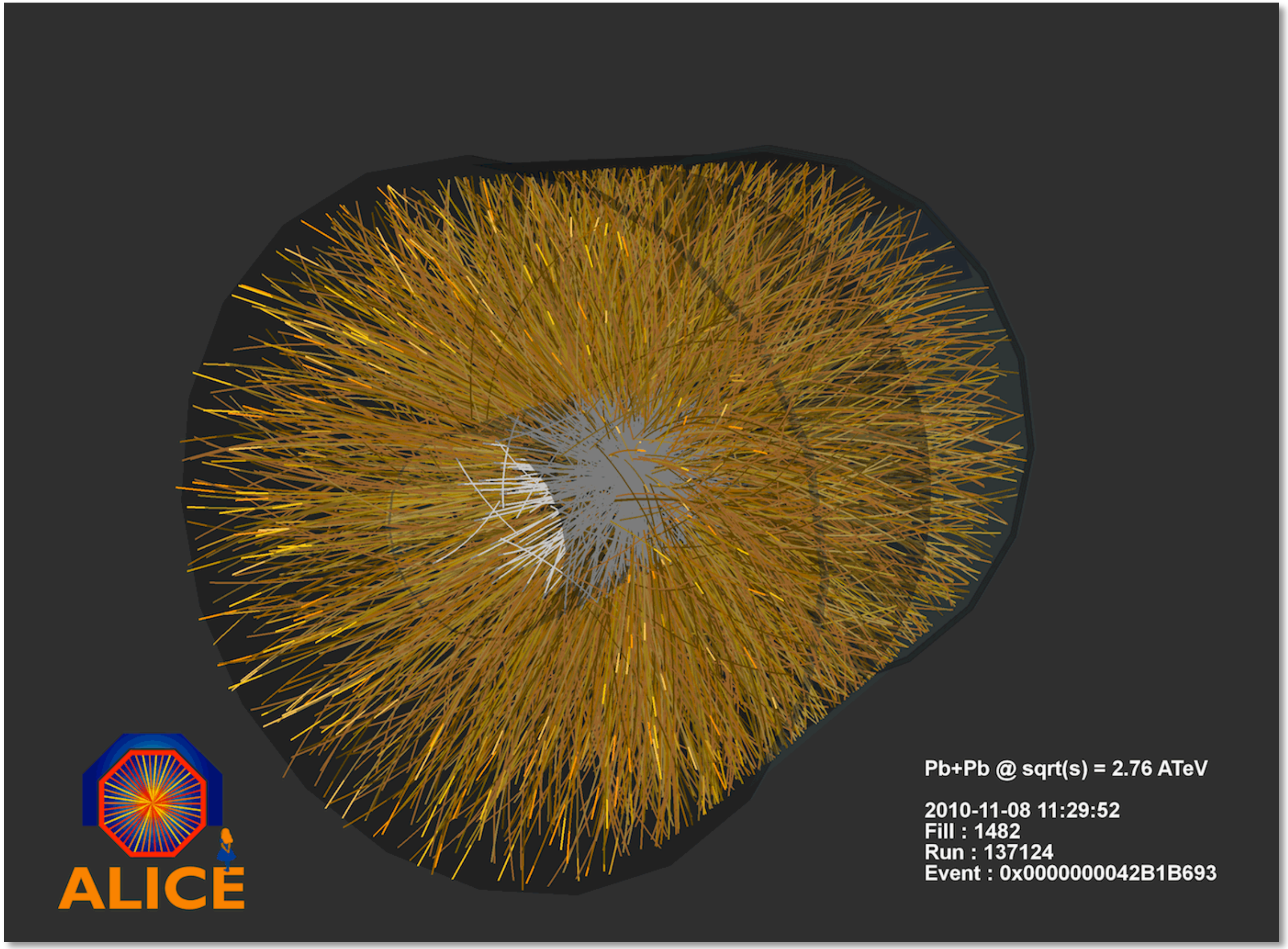
First Heavy Ion Collisions at the LHC

A central Pb+Pb collision at 2.76 TeV per nucleon



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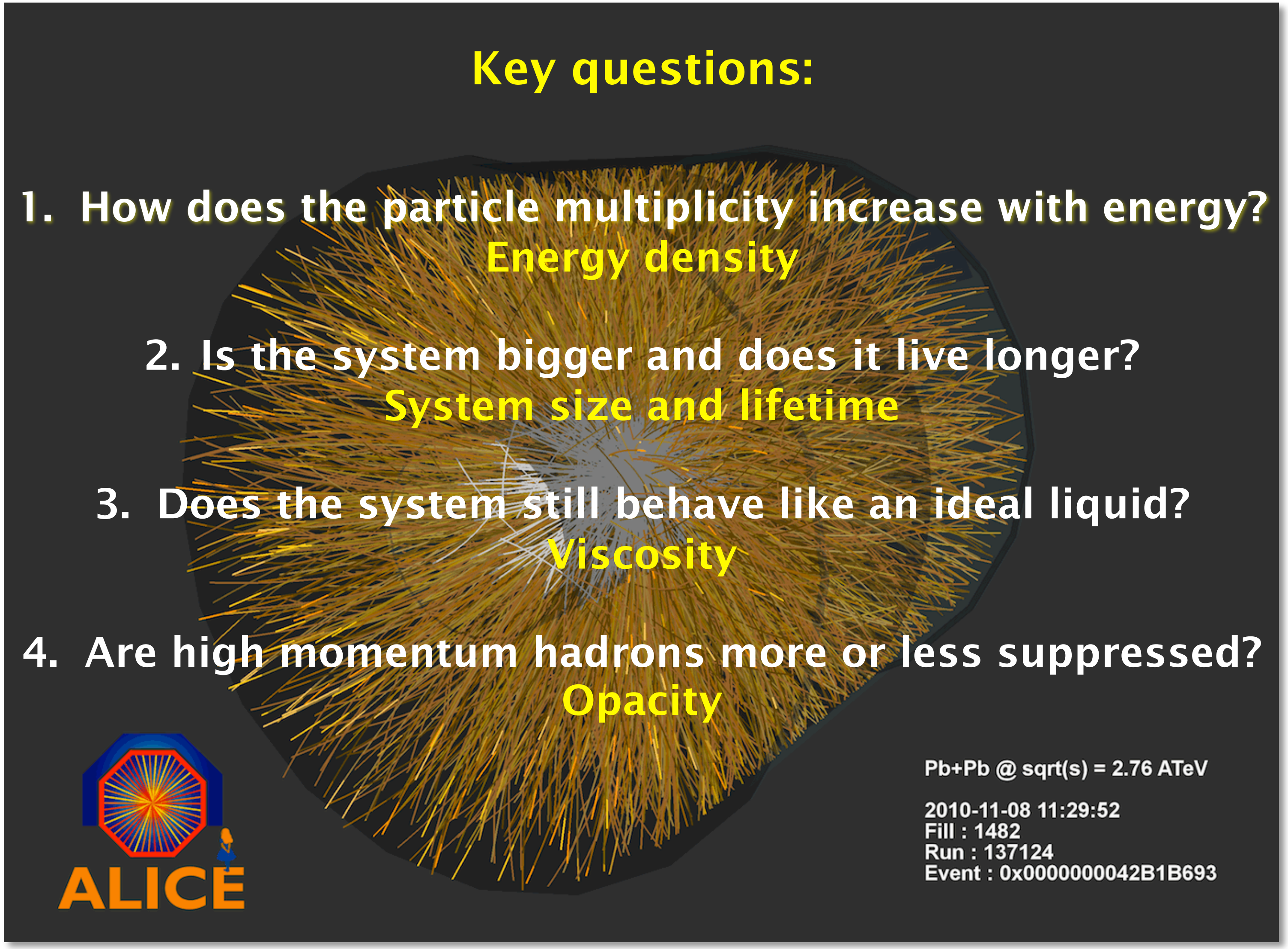


Key questions:

1. How does the particle multiplicity increase with energy?
   Energy density
2. Is the system bigger and does it live longer?
   System size and lifetime
3. Does the system still behave like an ideal liquid?
   Viscosity
4. Are high momentum hadrons more or less suppressed?
   Opacity

Outline

Prospect of forming the QGP in HI collisions at LHC

ALICE – A Large Ion Collider Experiment

Results from the first HI run:

Multiplicity – Energy density

Bose-Einstein correlations – Size and lifetime

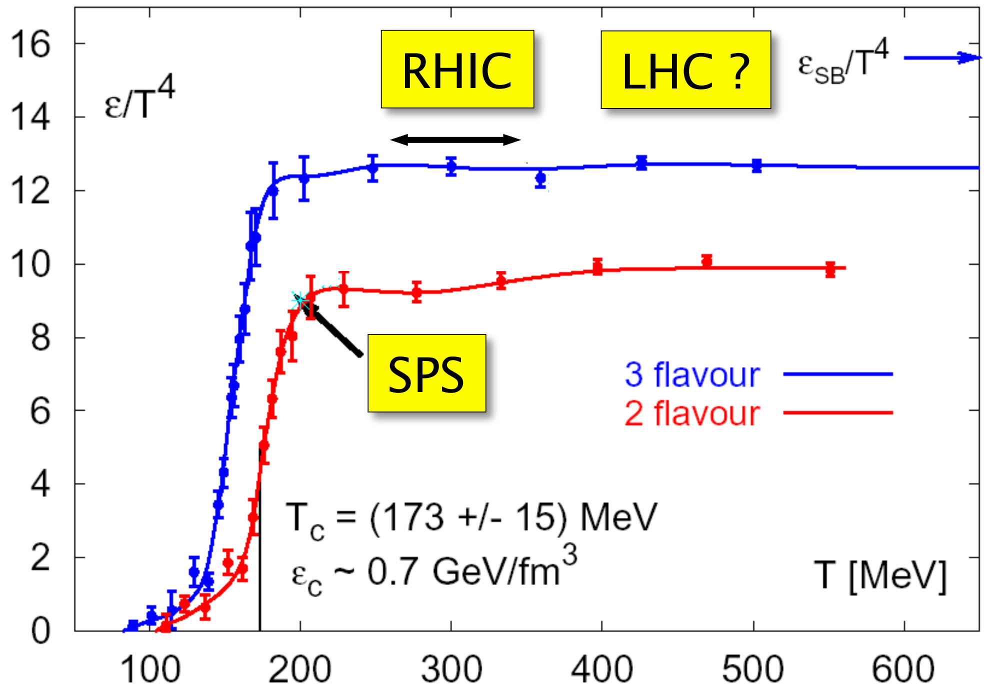
Flow – Viscosity

High p_T hadron suppression – Opacity

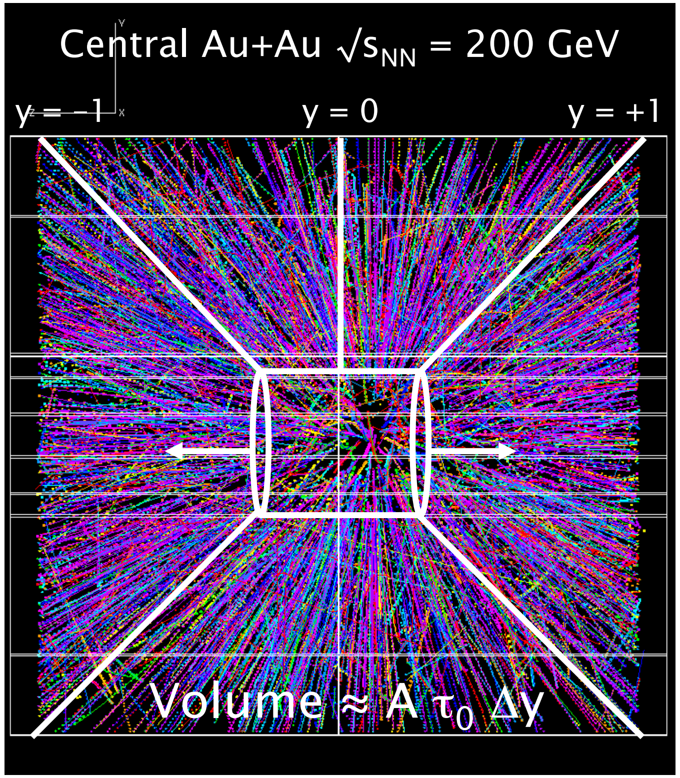
Summary and outlook

Prospects for quark deconfinement

Lattice QCD



F Karsch: Quark Gluon Plasma 3 (World Scientific)



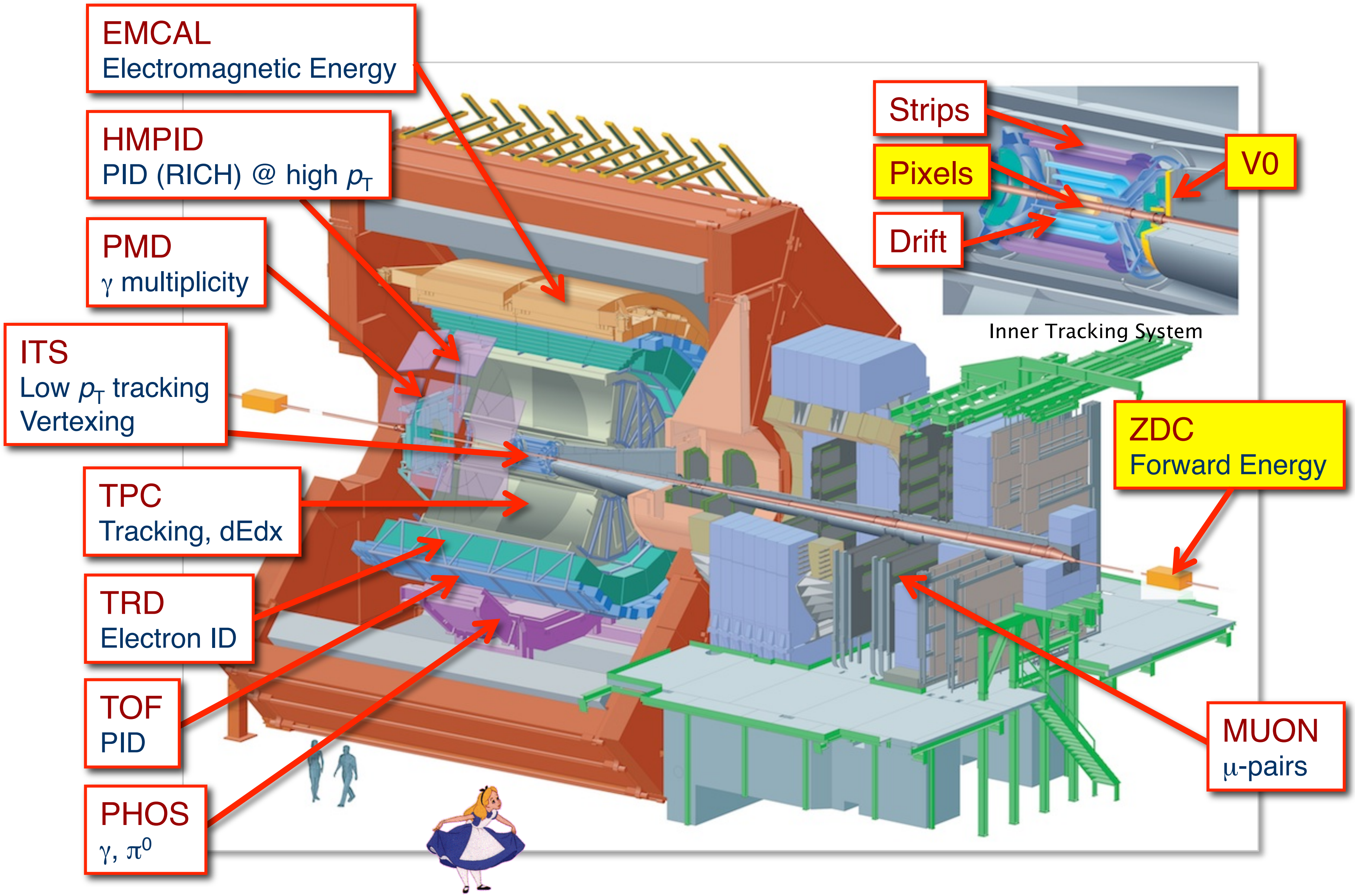
RHIC: $T_0/T_c \geq 1.5\text{–}2.0$

$$\varepsilon_0 = \frac{1}{\pi R^2 \tau_0} \left.\frac{dE_T}{dy}\right|_{y=0} = 5-15\ \mathrm{GeV/fm^3}$$

J D Bjorken: Phys. Rev. D 27 (1983) 40

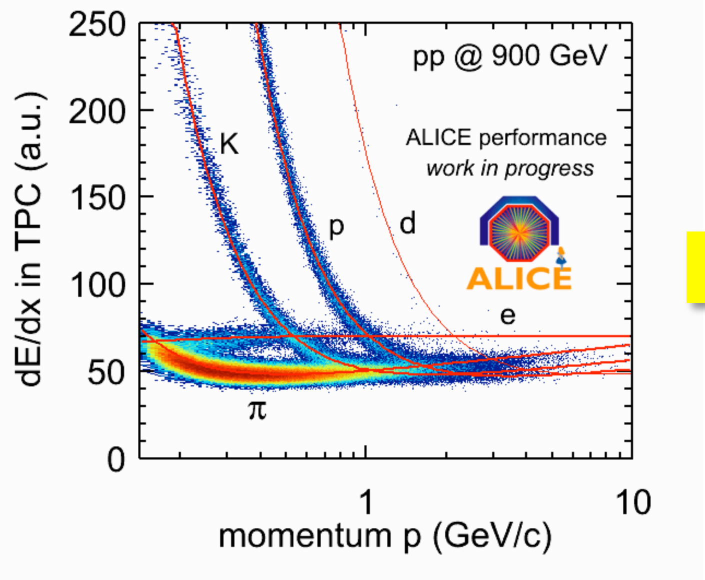
The LHC permits a detailed study of the high T phase of QCD

ALICE Detector System

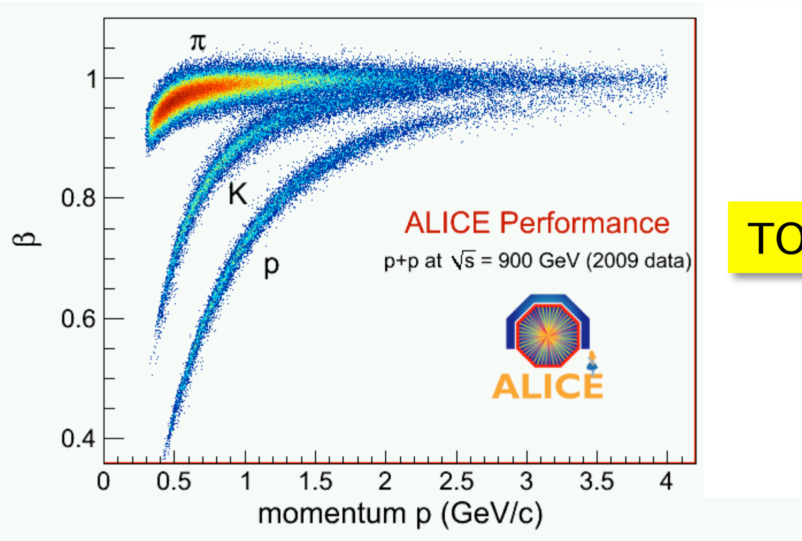


ALICE Performance

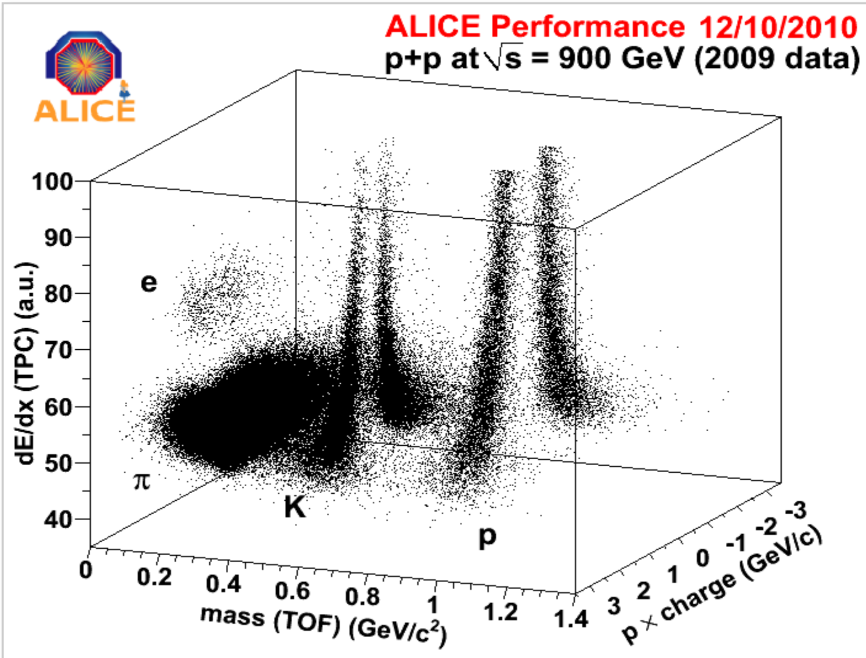
- Particle identification



TPC



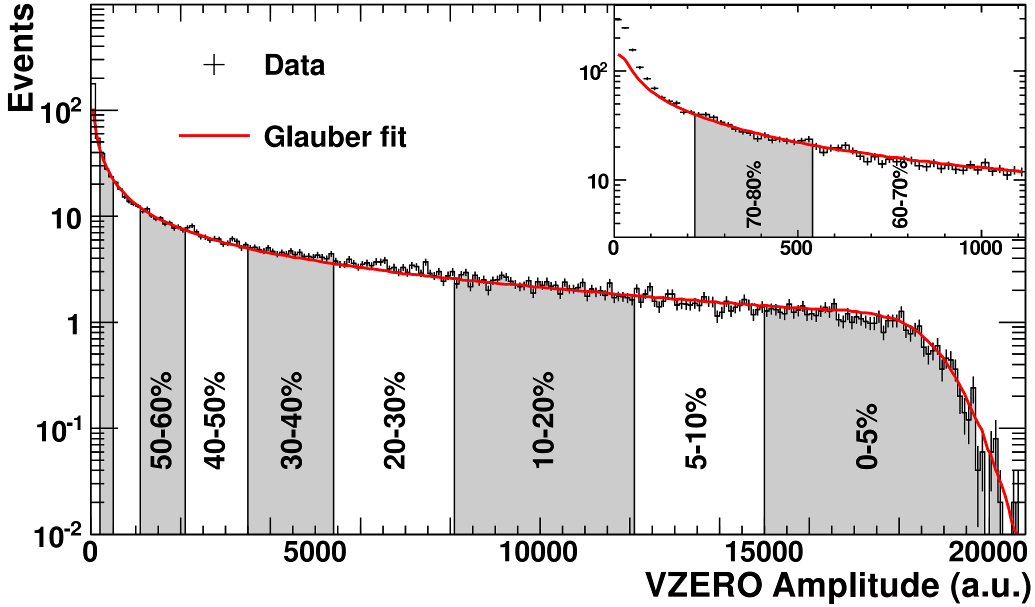
TOF

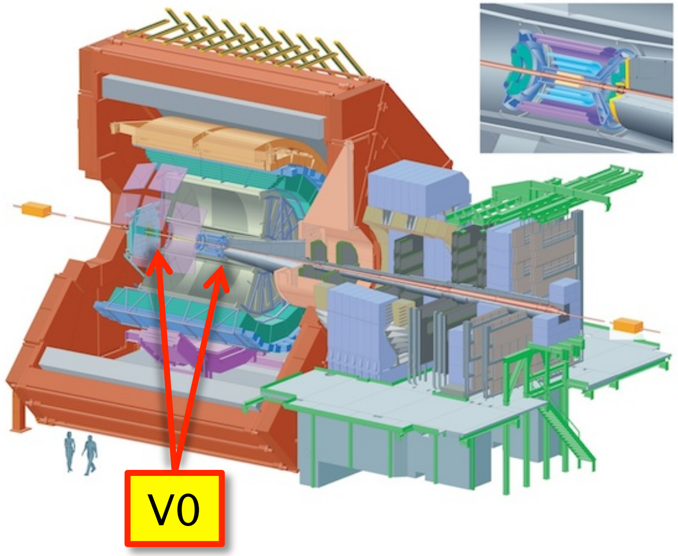


TPC+TOF combined

Impact parameter selection

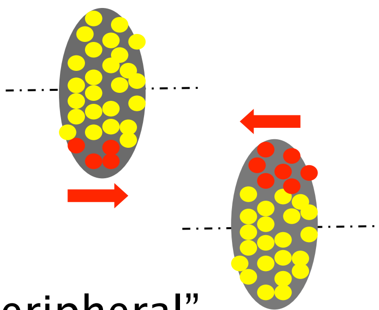
- Centrality definitions



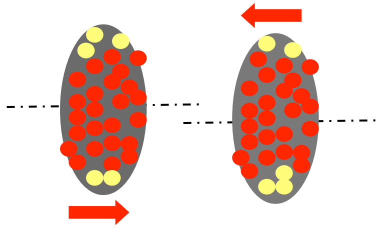


"A"-side "C"-side

V0A: $2.8 < \eta < 5.1$
V0C $-3.7 < \eta < -1.7$



"Peripheral"



"Central"

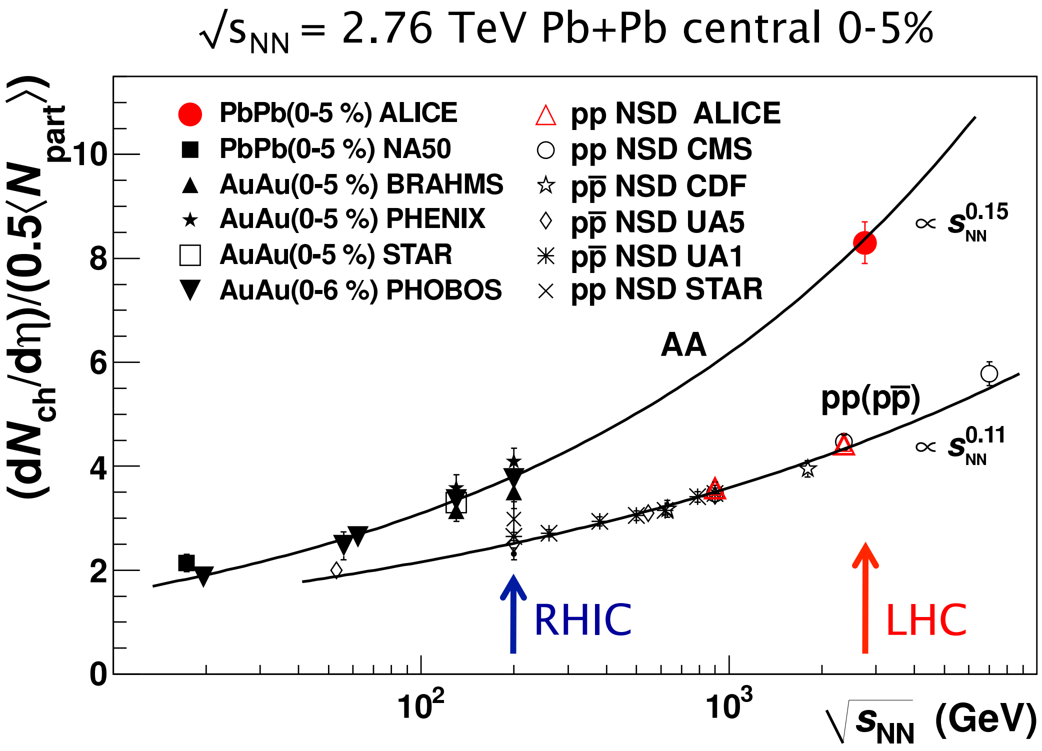
Other measures:
SPD hits
TPC tracks

Multiplicity

Energy density

Charged particle multiplicity in PbPb

- Multiplicity per participant pair



PbPb (2.76 TeV)

= 1.9 x pp (2.76 TeV)

= 2.2 x AuAu (0.2 TeV)

$<N_{part}>$ = 381 ± 18 (rms)

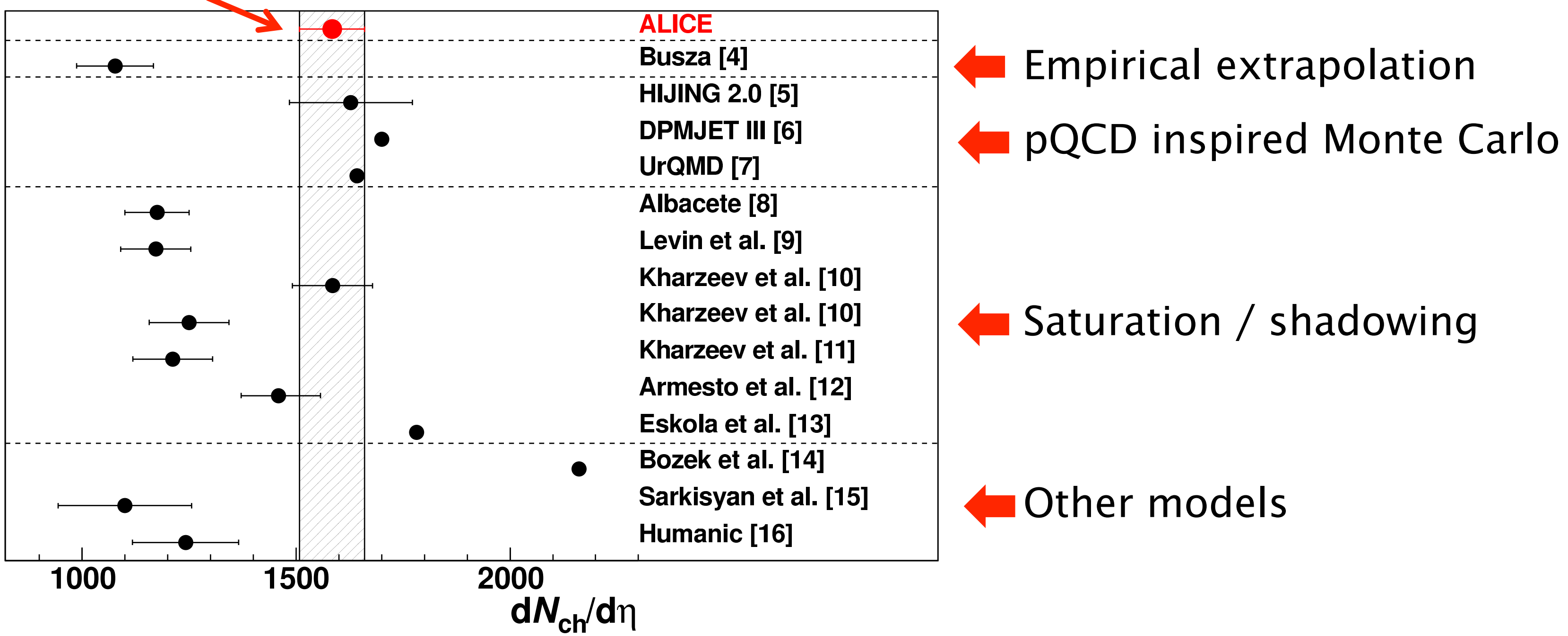
$dN_{ch}/d\eta\,|_{\eta=0}$ = 1584 ± 4 (stat) ± 76 (syst)

Charged particle multiplicity in PbPb

- Total charged particle multiplicity – model comparison

$\sqrt{s_{NN}}$ = 2.76 TeV Pb+Pb central 0-5%

$dN_{ch}/d\eta|_{\eta=0} = 1584 \pm 4\ (\text{stat}) \pm 76\ (\text{syst})$



$$\varepsilon(\tau_0) = \frac{E}{V} = \frac{1}{A\tau_0}\frac{dE_T}{dy}\bigg|_{y=0} \approx \frac{1}{A\tau_0}\frac{dN}{d\eta}\bigg|_{\eta=0} \times \langle m_T \rangle \Rightarrow \varepsilon(\tau_0)_{LHC} \geq 3 \times \varepsilon(\tau_0)_{RHIC}$$

Energy density scales with multiplicity

Bose-Einstein Correlations

System size and lifetime

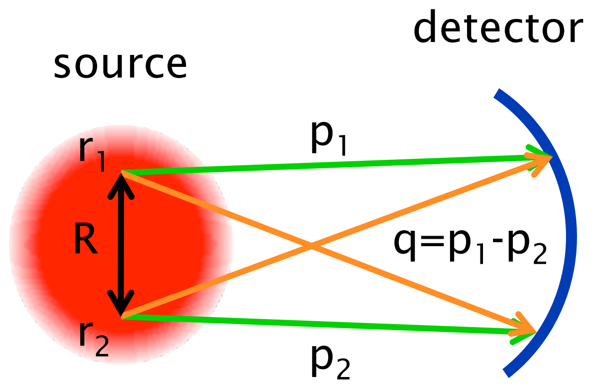
Bose-Einstein Correlations

- Brief description of method

Hanbury Brown and Twiss first used it in 1956 to measure the angular size of stars

Goldhaber, Goldhaber, Lee and Pais used it in 1965 to measure size of proton-antiproton collisions

For each pair of identical pions there are two indistinguishable processes



$$\Psi(p_1,r_1,p_2,r_2) \sim e^{i(p_1\cdot r_1+p_2\cdot r_2)} \pm e^{i(p_1\cdot r_2+p_2\cdot r_1)}$$

$$P(p_1,p_2) \sim 1+\cos((p_1-p_2)\cdot(r_1-r_2)) = 1+\cos(q\cdot R)$$

Enhancement at small momentum difference, q

By measuring P as a function of q we can extract R

System size and lifetime

- Experimental correlation

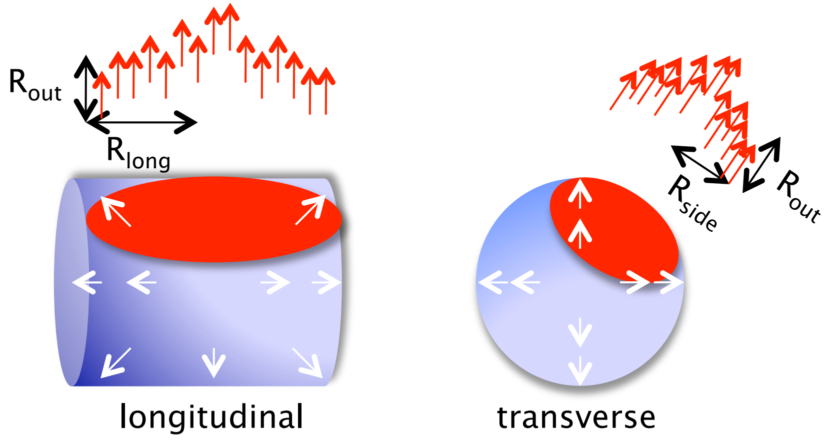
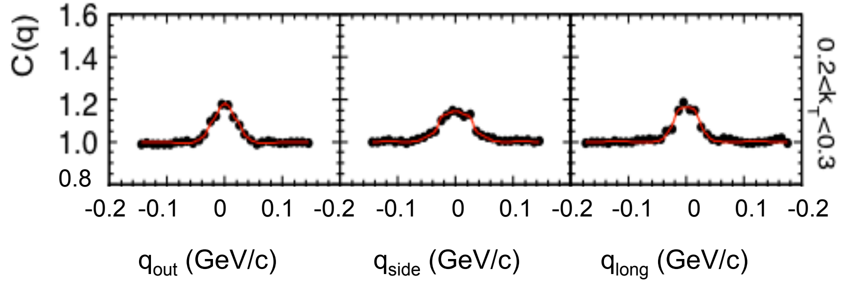
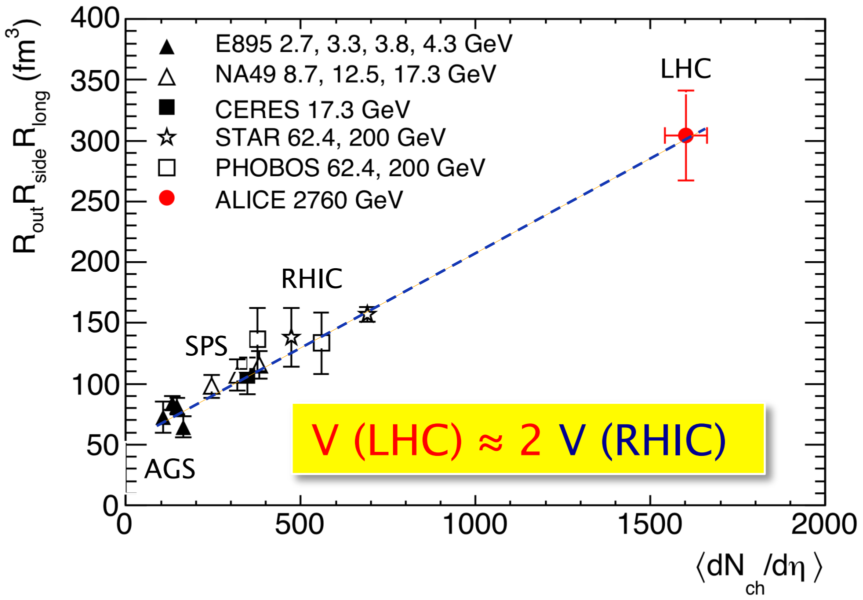
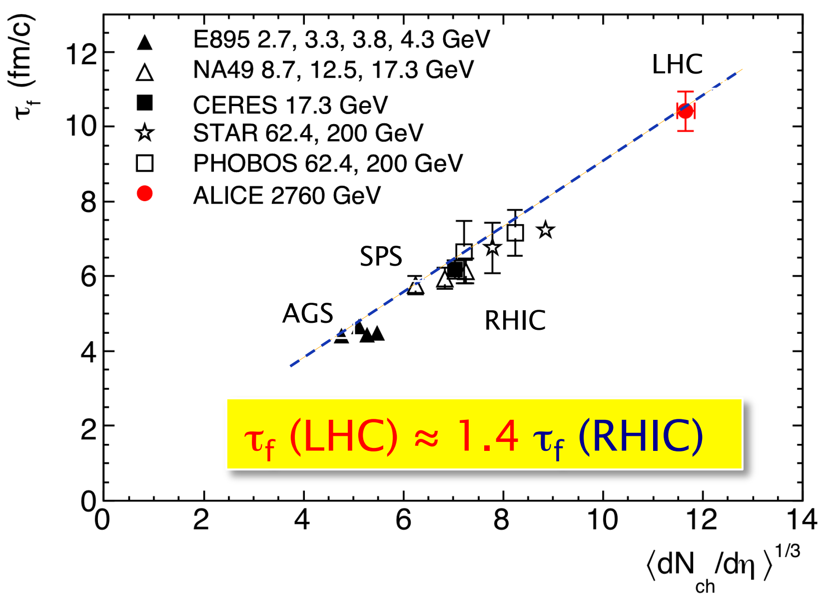


Figure adapted from Lisa et al., Ann. Rev. Nucl. Part. Sci. 2005. 55:357-402

$$C(q) = \frac{f(p_1,p_2)}{f(p_1)f(p_2)} \qquad R \approx \frac{\hbar}{\Delta q} = 7 - 8 \text{ fm}$$





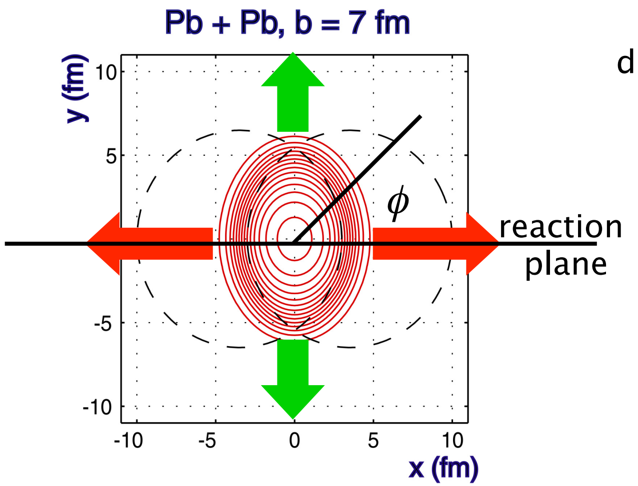


Flow

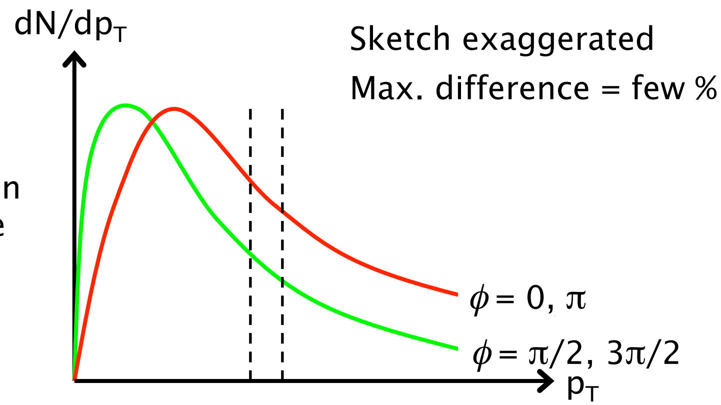
Viscosity

Origin of collective flow

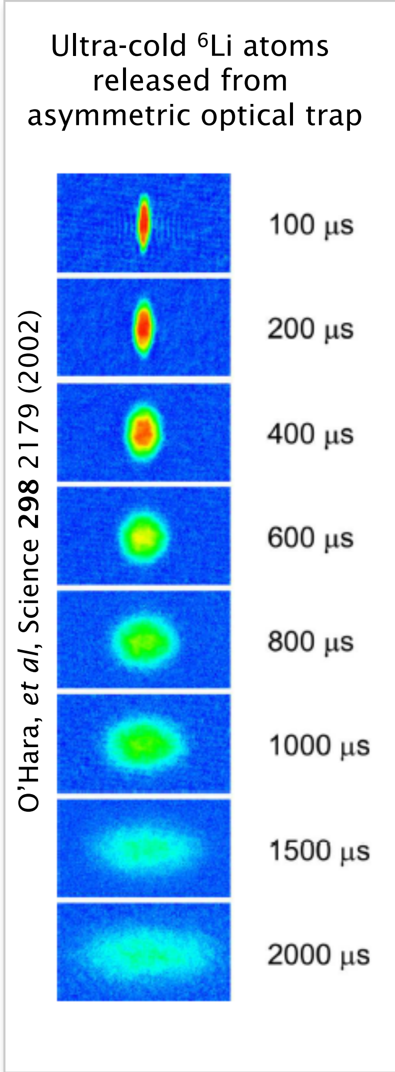
- Particle flows are generated by pressure gradients



Initial-state spatial anisotropy



Final-state momentum anisotropy



Fourier coefficient

Angle of reaction plane

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi - \Psi_r\right)\right]\right)$$

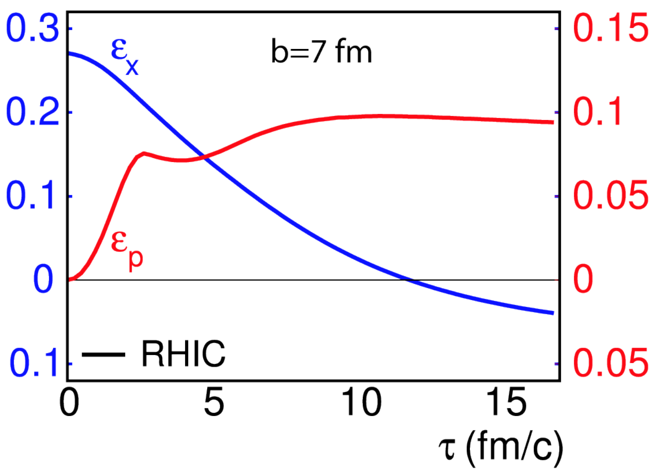
$$v_2 = \left\langle \cos\left[2\left(\phi - \Psi_r\right)\right]\right\rangle$$

Hydrodynamics and flow

- RHIC results were consistent with ideal hydrodynamics

Hydrodynamics Calculations

Input = Initial conditions
(Spatial anisotropy, ε_0, τ_{th})
+
Ideal hydrodynamic evolution
λ_{mfp}=0, η=0, EoS
Realistic freeze-out conditions
⇓
Output = Momentum anisotropy



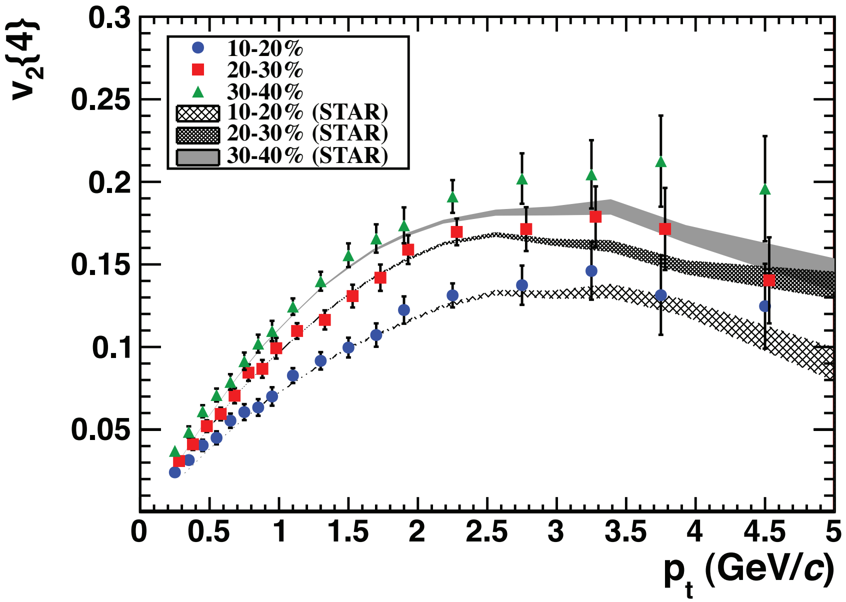
Tunable (RHIC) parameters are:
ε_0 – initial energy density (25 GeV/fm^3)
τ_{th} – thermalisation time (0.6 fm/c)
η/s – viscosity/entropy (0.2)
EoS – Equation of State (QGP)

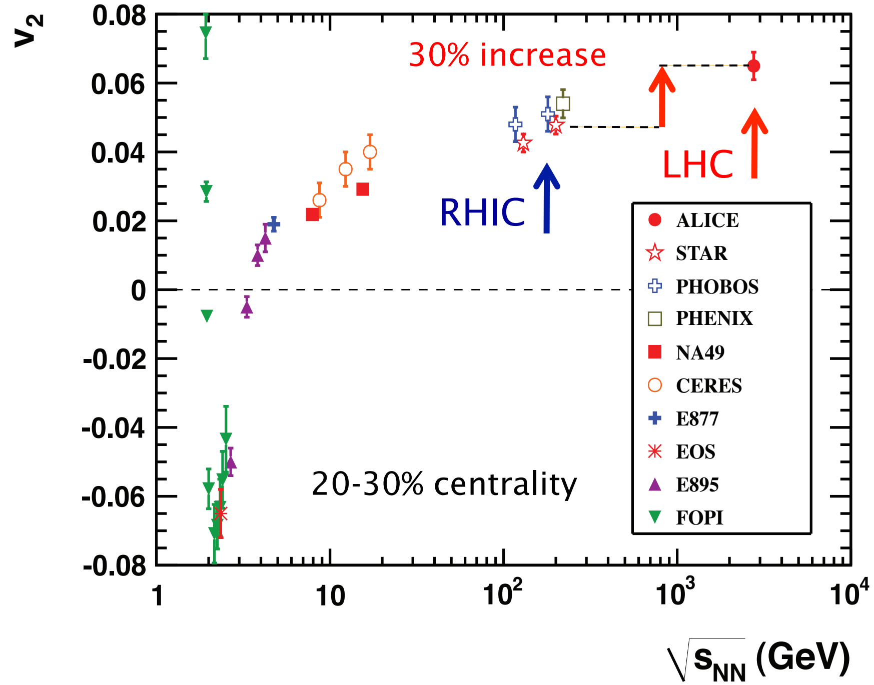
Lq Helium	$\eta/s \sim 0.7$
Ultra-cold Li atoms	$\eta/s \sim 0.5$
sQGP	$\eta/s \sim 0.2$

Two (related) open questions:
1. Does flow saturate in QGP phase?
2. If not, do viscous effects in the hadronic phase limit v_2?

Flow at LHC

- Flow results for unidentified charged particles





$v_2(p_T)$ is very similar comparing ALICE (LHC) and STAR (RHIC)

Calculate average v_2

$$v_2 = \int N(p_T)\, v_2(p_T)\, dp_T \Big/ \int N(p_T)\, dp_T$$

Integrated v_2 30% higher than at RHIC

Consequence of higher $\langle p_T \rangle$ at LHC

Larger than expected from ideal hydro

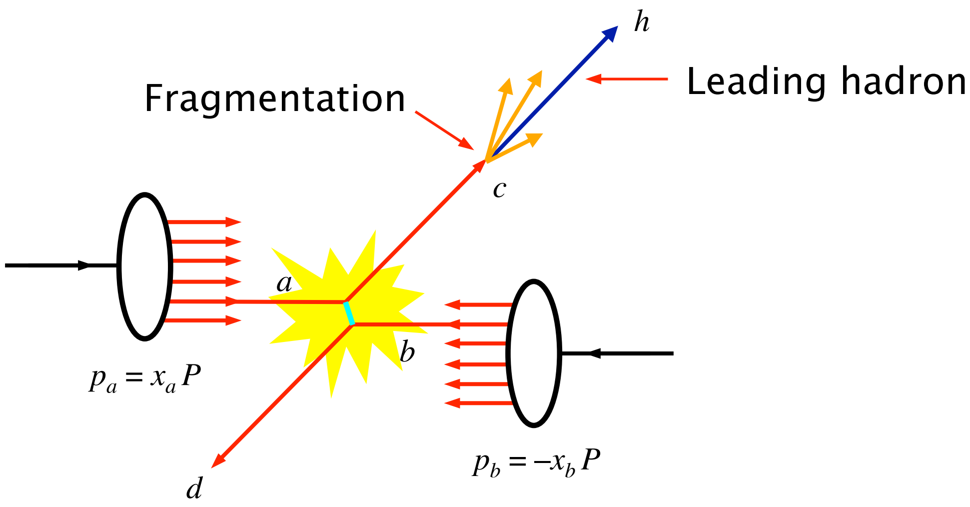
Viscosity important at RHIC after all?

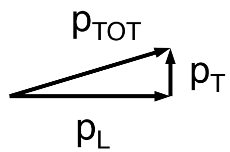
High p_T particle production

Opacity to jets

High p_T particle production

- Jets in p+p and modification in A+A





$$\frac{d\sigma^h_{pp}}{dy\, d^2 p_T} = K \sum_{abcd} \int dx_a dx_b\, f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \frac{D^0_{h/c}}{\pi z_c}$$

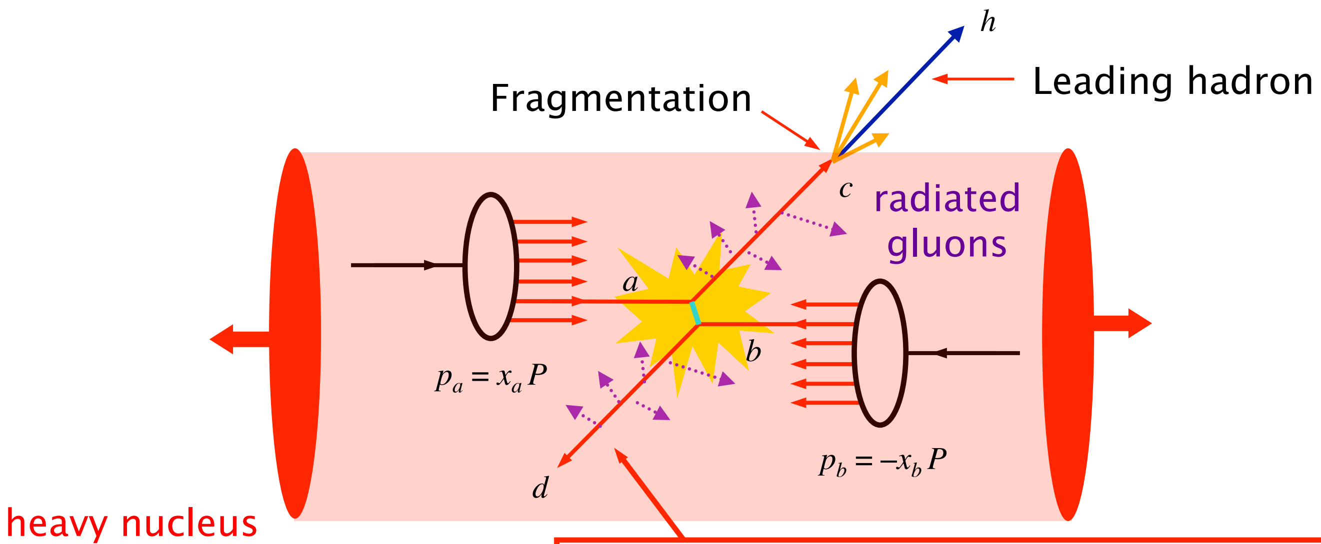
Parton distribution functions – initial state (HERA)

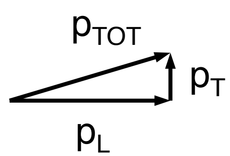
Hard scattering cross-section – pQCD calculable

Fragmentation function – final state (LEP)

High p_T particle production

- Jets in p+p and modification in A+A





key prediction: jets are quenched

X.-N. Wang and M. Gyulassy, *Phys. Rev. Lett.* **68** (1992) 1480

$$\frac{d\sigma^h_{pp}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b \, f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab \rightarrow cd) \frac{D^0_{h/c}}{\pi z_c}$$

Parton distribution functions	– initial state (HERA)
Hard scattering cross-section	– pQCD calculable
Fragmentation function	– final state (LEP)

High p_T hadron suppression

- Form ratio to scaled pp distribution

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{N_{binary} dN^{pp}/dp_T}$$

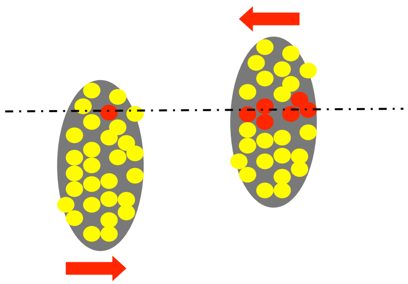
scale factor

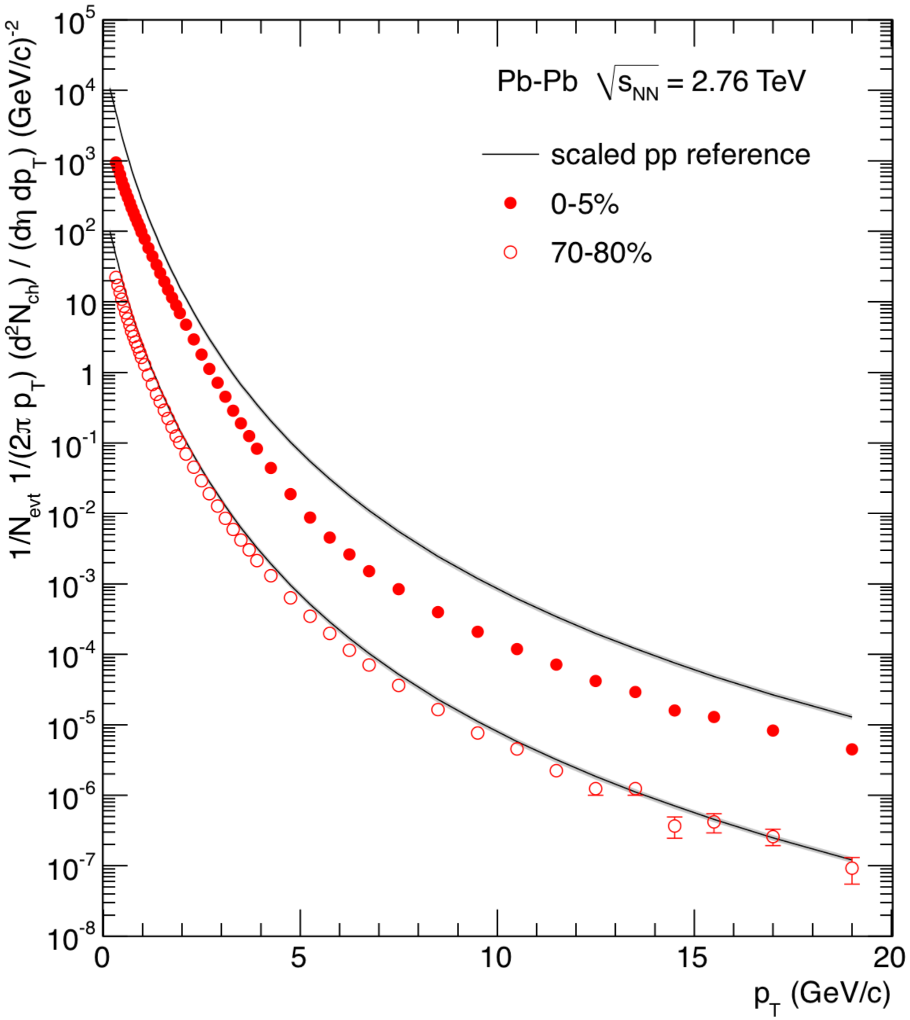
pp reference

pp reference

1. Interpolation between 0.9 and 7 TeV
2. 7 TeV scaled by NLO QCD calculations

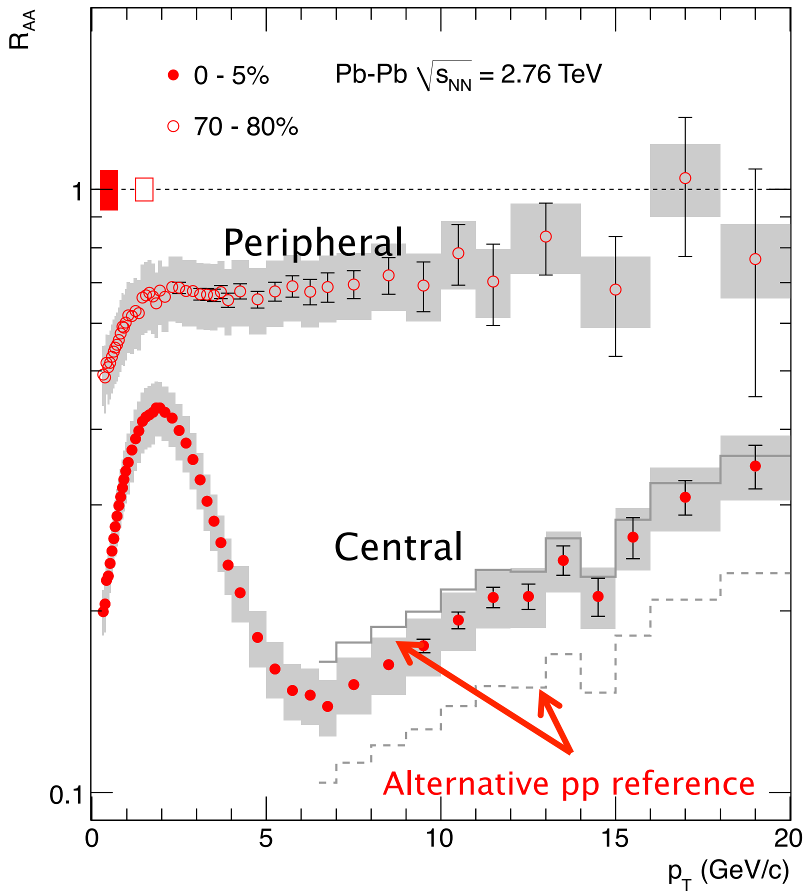
N_{binary} is the number of independent nucleon-nucleon collisions

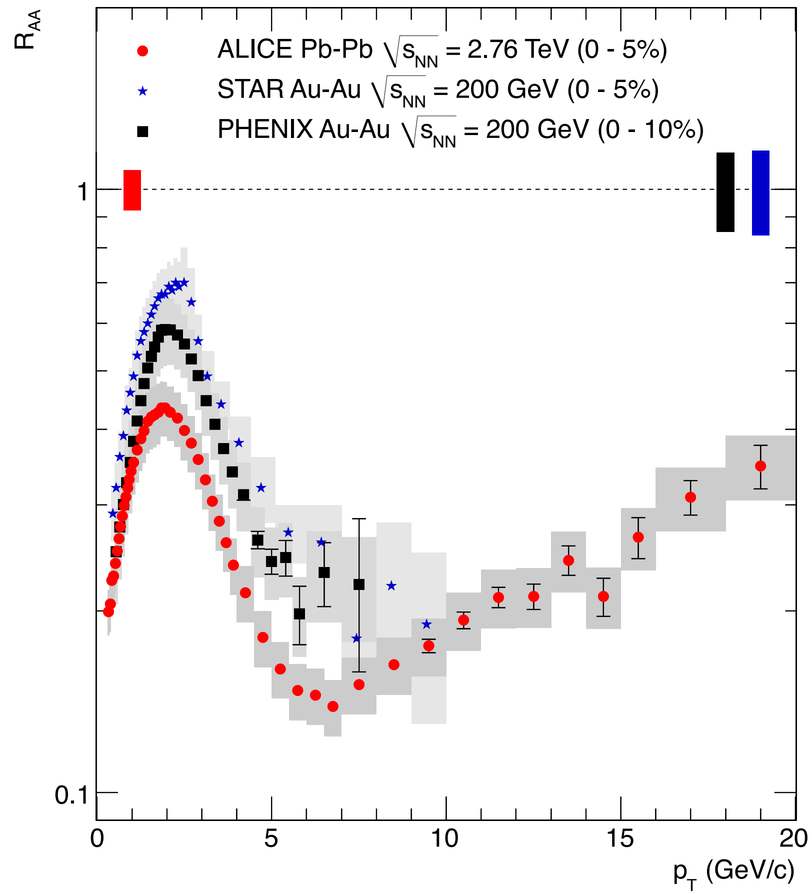




High p_T hadron suppression

- Centrality dependence and comparison to RHIC





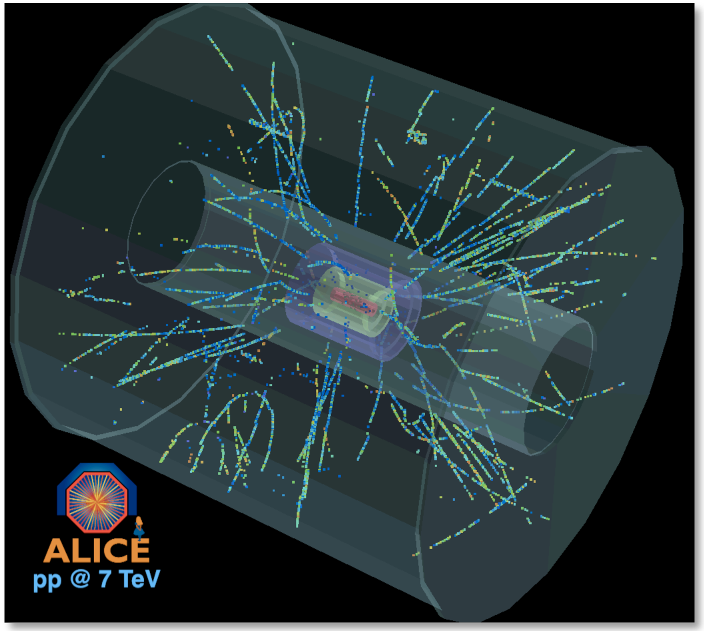
Suppression in central events is greater than suppression in peripheral events

Minimum LHC ~ 0.5 RHIC
R_{AA} rises p_T > 7 GeV/c

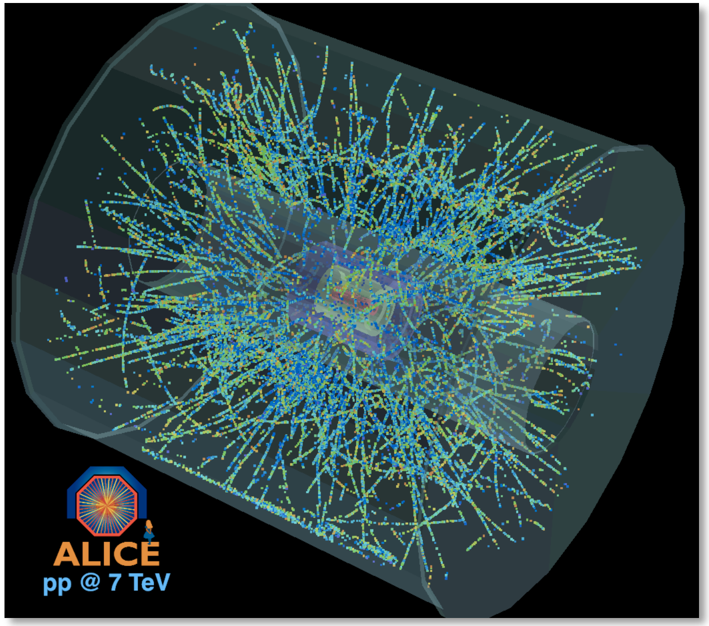
High multiplicity pp collisions

QGP in pp collisions?

- Trigger on high multiplicity pp events



Minimum bias



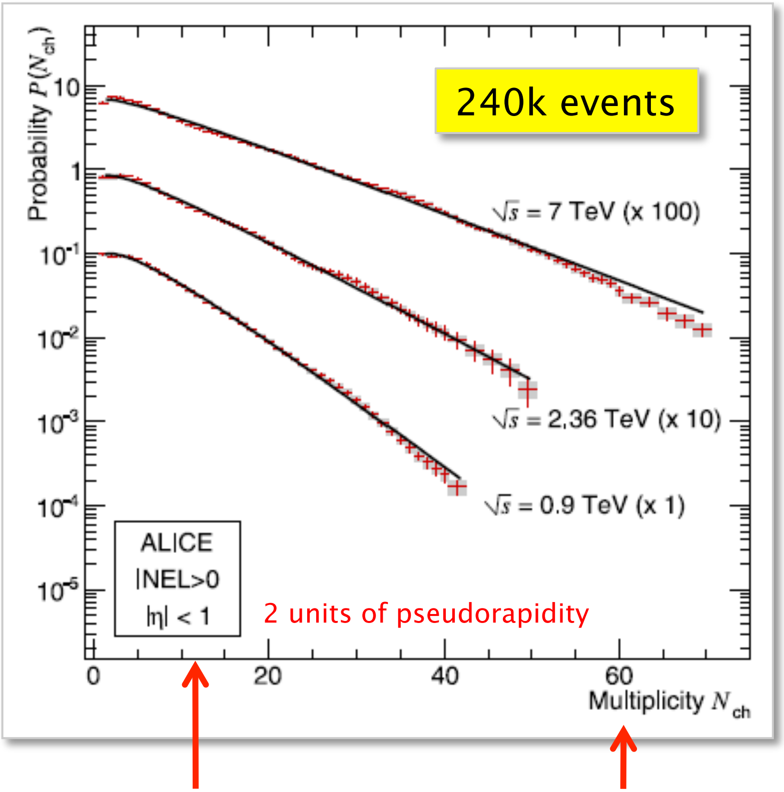
High multiplicity

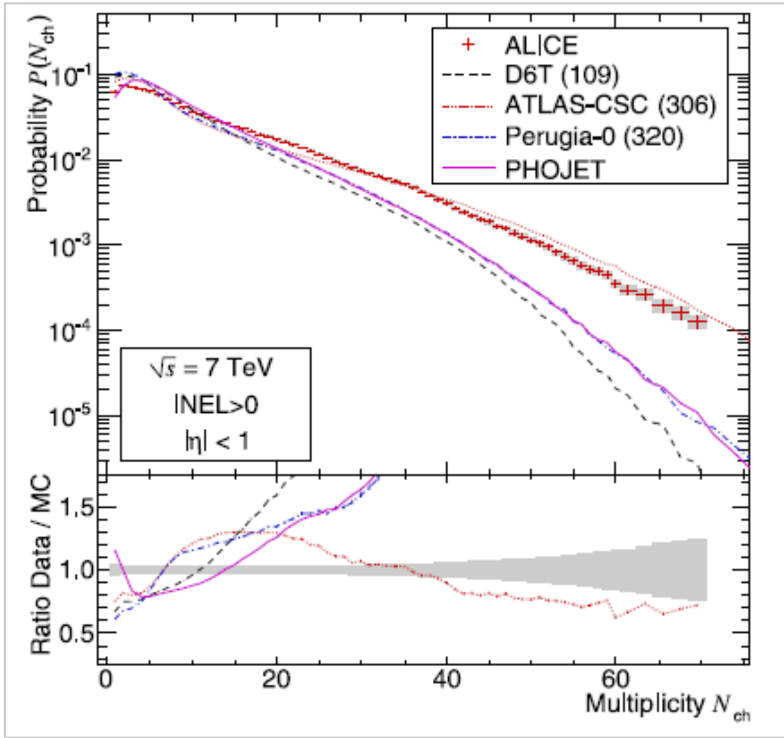
These rare high multiplicity events are interesting in their own right

Evidence of QGP in pp collisions or QCD minijets?

Multiplicity in pp collisions

- Multiplicity distributions





$<dN_{ch}/d\eta> \approx 6$ @ 7 TeV

$dN_{ch}/d\eta \approx 30$

~1:100 events

Poses a challenge to models

PYTHIA ATLAS-CSC tune closest to data, but significant discrepancies.

Summary and Outlook

Summary

ALICE has performed extremely well

Some tantalising early HI results:

System is hotter, bigger and longer-lived

Flow measurement possibly reveals importance of viscous effects

High p_T suppression appears to be stronger than at RHIC

Outlook

LHC long shutdown now delayed until 2013

Heavy ion runs now expected in 2011 and 2012

Finish study of global observables:

ε, T_{th}, T_{ch}, μ_B, v_n

Start detailed exploration of the early QGP phase:

Jets, heavy-flavour, …

Backup slides

ALICE Data

Year	Beam	$\sqrt{s_{NN}}$ TeV	Events
2009	p+p	0.9	3 x 10^5 (MB)
2009	p+p	2.36	4 x 10^4 (MB)
2010	p+p	0.9	8 x 10^6 (MB)
2010	p+p	7.0	8 x 10^8 (MB)
			1 x 10^8 (muons)
			2 x 10^7 (high N_{ch})
2010	Pb+Pb	2.76	few x 10^7

Measuring multiplicity

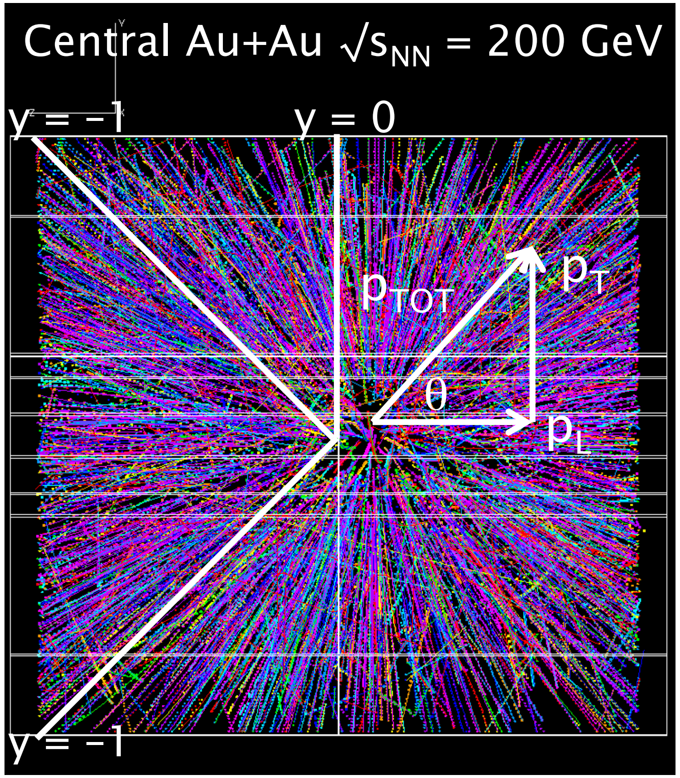
- Choice of variables

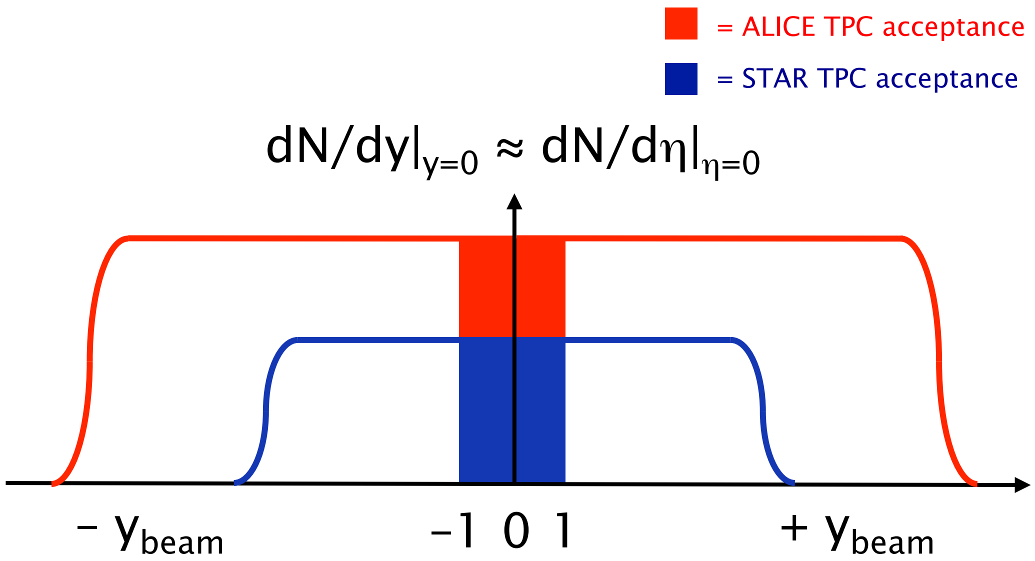
Rapidity

$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

Pseudo-rapidity

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$



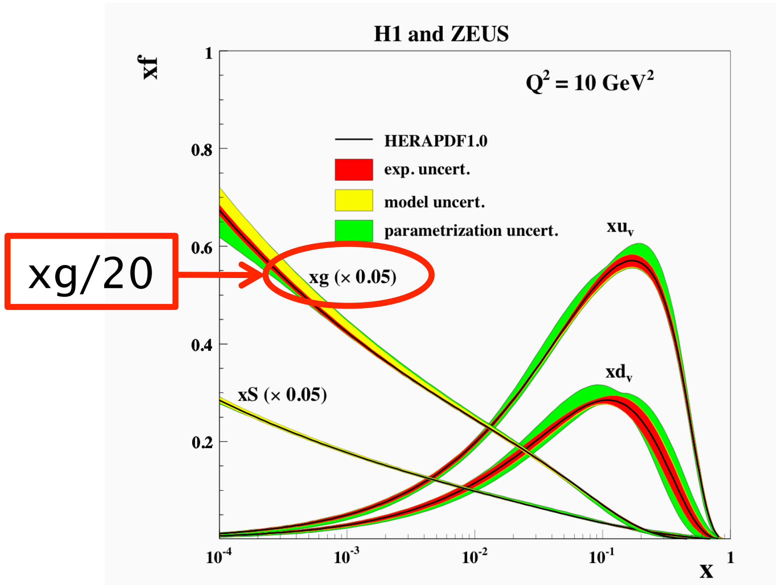


$$y_{beam}^{RHIC} = 5.3$$

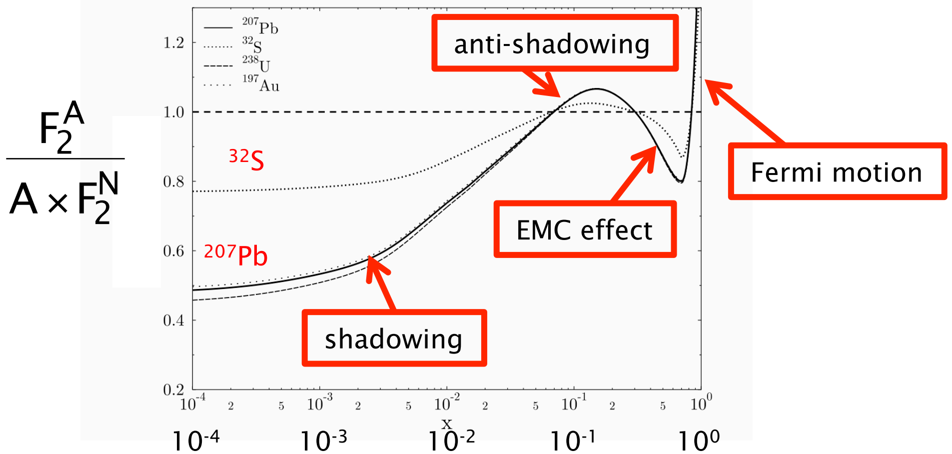
$$y_{beam}^{LHC} = 7.9 - 8.3$$

Charged particle multiplicity in PbPb

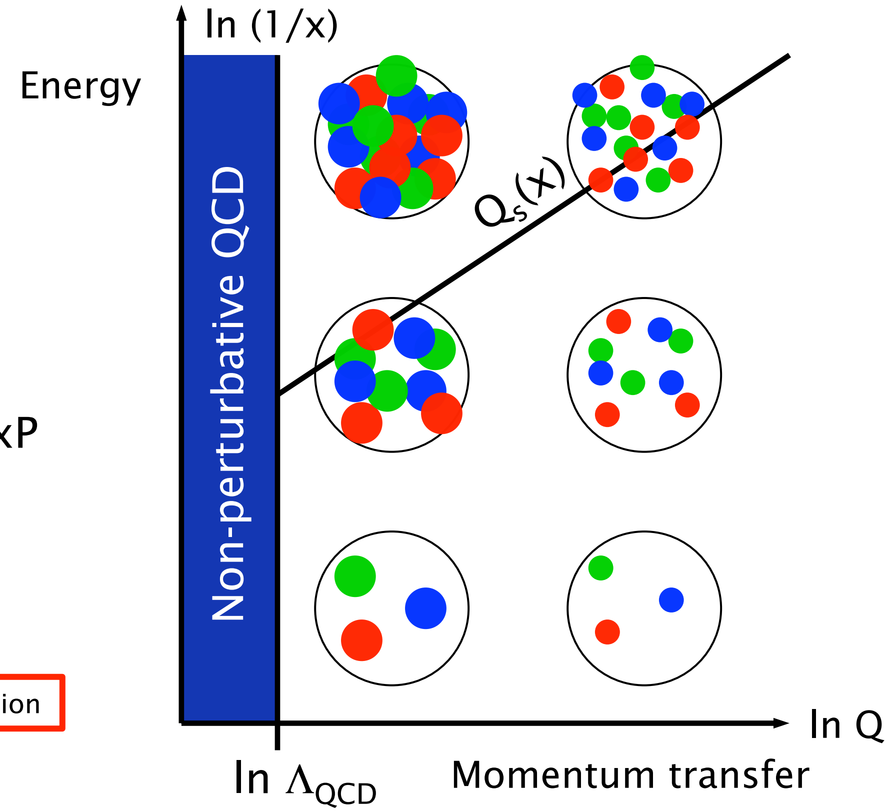
- Sensitivity to saturation/shadowing effects



$p_{q,g}=xP$



Ratio of nuclear and proton PDFs



Charged particle multiplicity in PbPb

- Centrality dependence and sensitivity to saturation

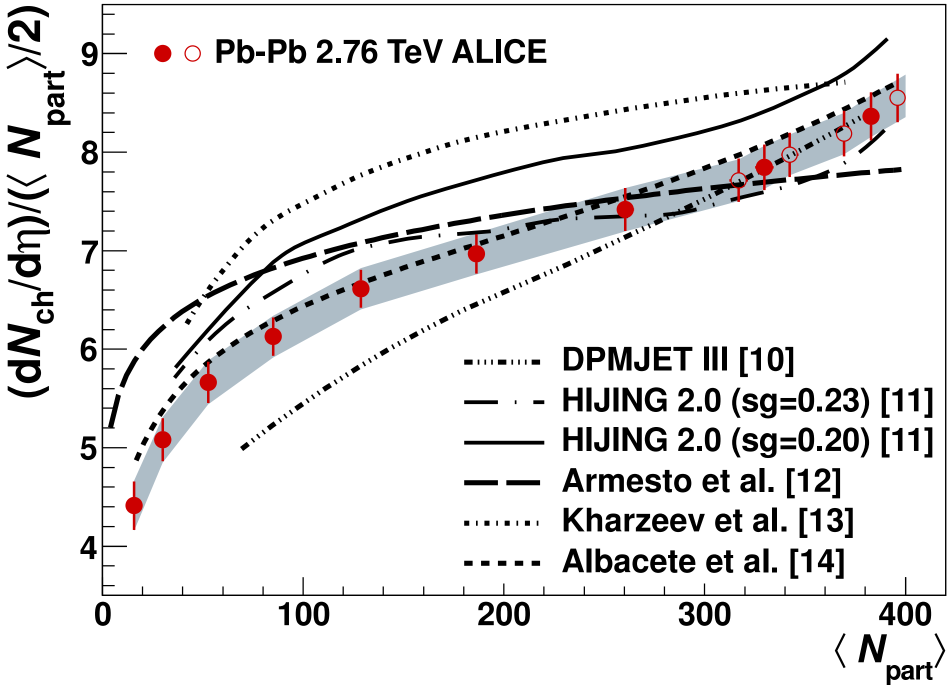
Shadowing/saturation limits the number of soft gluons

Effectively reduces number of scattering centres and limits rise in multiplicity

Importance increases with $\sqrt{s_{NN}}$ and N_{part}

Alternatively, we are just seeing the interplay between soft and hard QCD processes

Importance of hard scattering also increases with $\sqrt{s_{NN}}$ and N_{part}



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