Relativistic Heavy-Ion Physics

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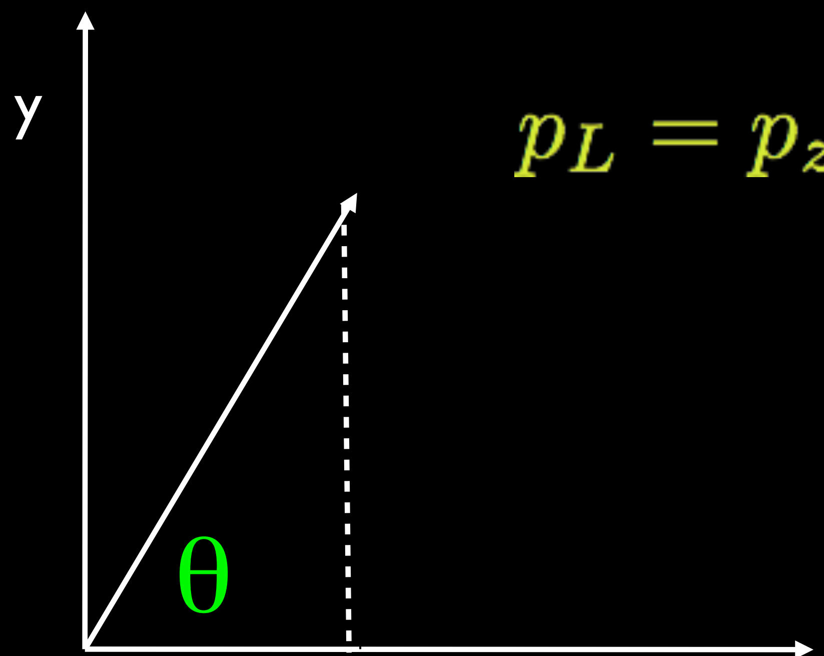
Recap lecture 1

- At temperatures above T_C ~150-170 MeV we expect a deconfined state of matter to exist
- Critical energy density around 0.6 GeV/fm^3
- Hadrons can no longer exist
- Quarks have their 'bare' masses
  - $m_U \sim m_D < 10$ MeV, $m_S \sim 100$ MeV

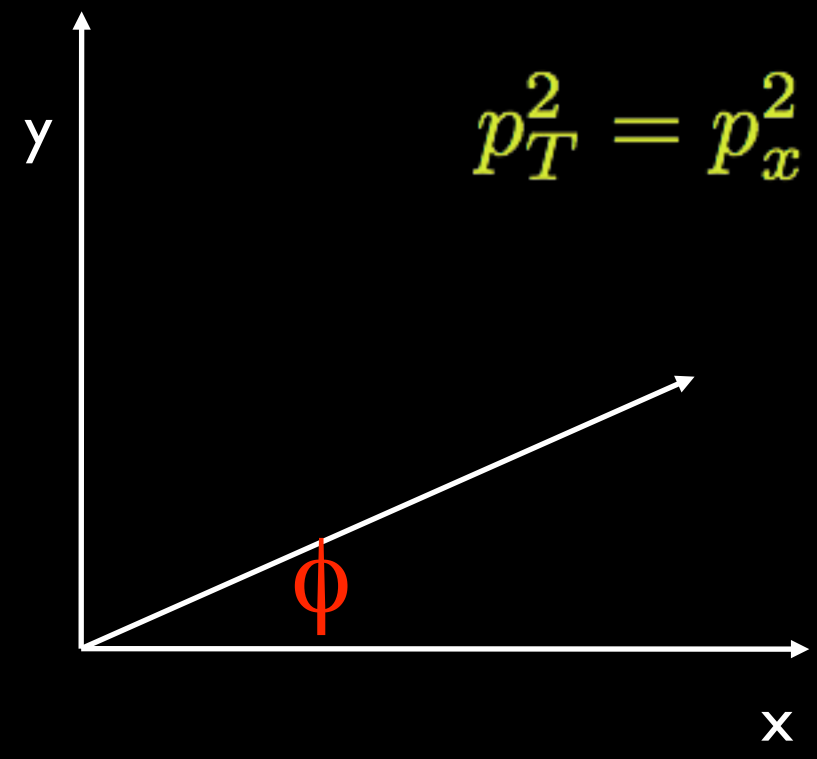
Experiment

- Have experiments achieved these conditions?
- ALL experiments observe hadrons (+leptons, photons) so we rely on *indirect* evidence
- Characterise events and particle production
  - Centrality, (pseudo-)rapidity and transverse momentum

Collider Co-ordinate system



$$p_L = p_z$$



$$p_T^2 = p_x^2 + p_y^2$$

z ≡ beam axis

Rapidity: $$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$$

Pseudorapidity: $$\eta = -\ln tan \frac{\theta}{2}$$

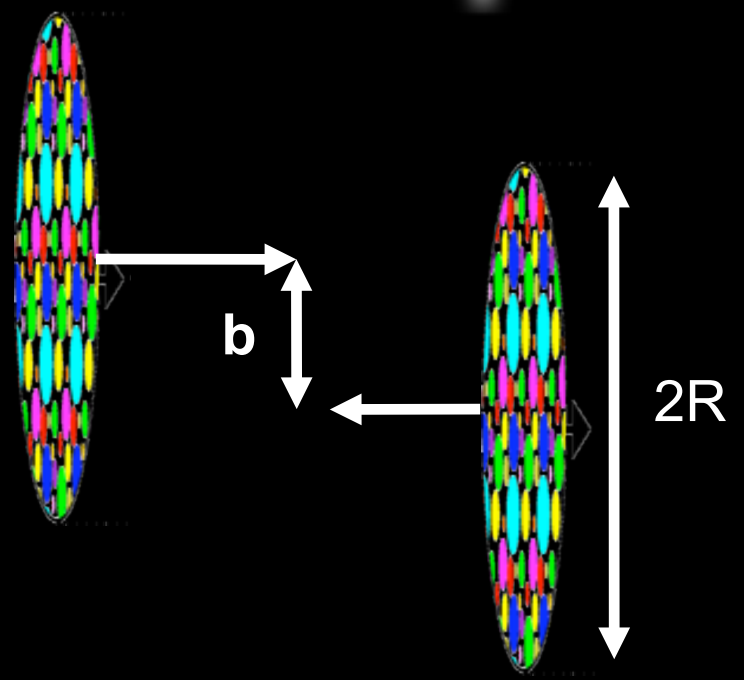
p_T: momentum transverse to the beam axis

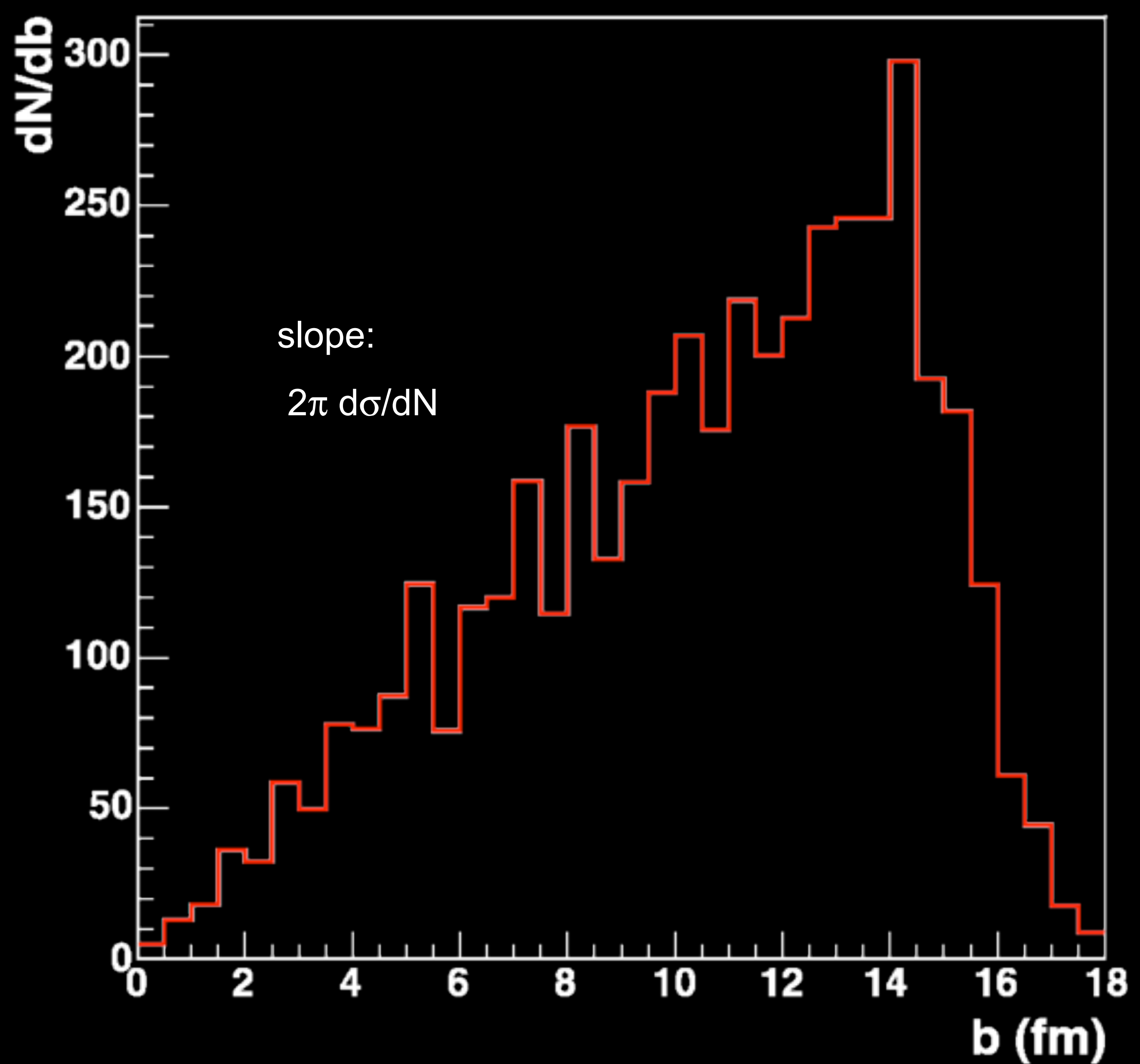
θ: Polar angle

Φ: Azimuthal angle

η is a one-to-one function of θ and η → y when E >>m

Impact Parameter

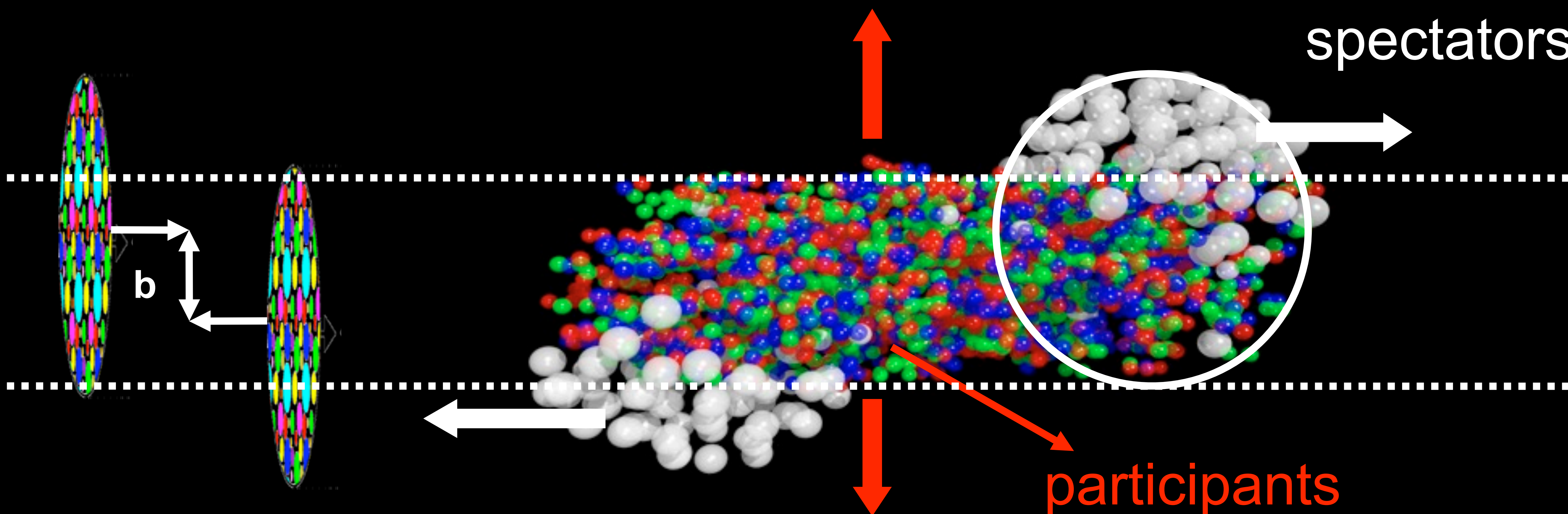




$$d\sigma = 2\pi b\, db$$

- impact parameter **b**
  - perpendicular to beam direction
  - connects centres of the colliding ions

Concept of centrality



centrality characterized by:

1. N_{part}, $N_{wounded}$: number of nucleons which suffered at least one inelastic nucleon-nucleon collision
2. N_{bin}, N_{coll}: number of inelastic nucleon-nucleon collisions

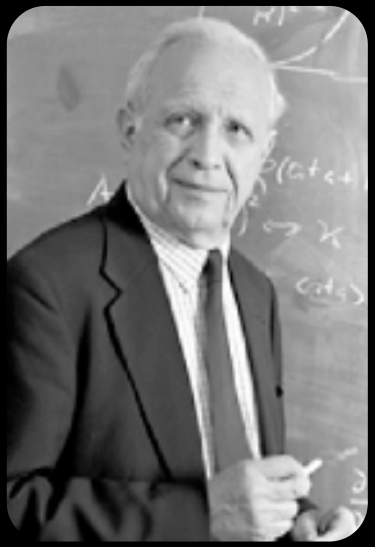
Glauber Model Calculations

- ✓ nuclear density from Wood-Saxon distribution

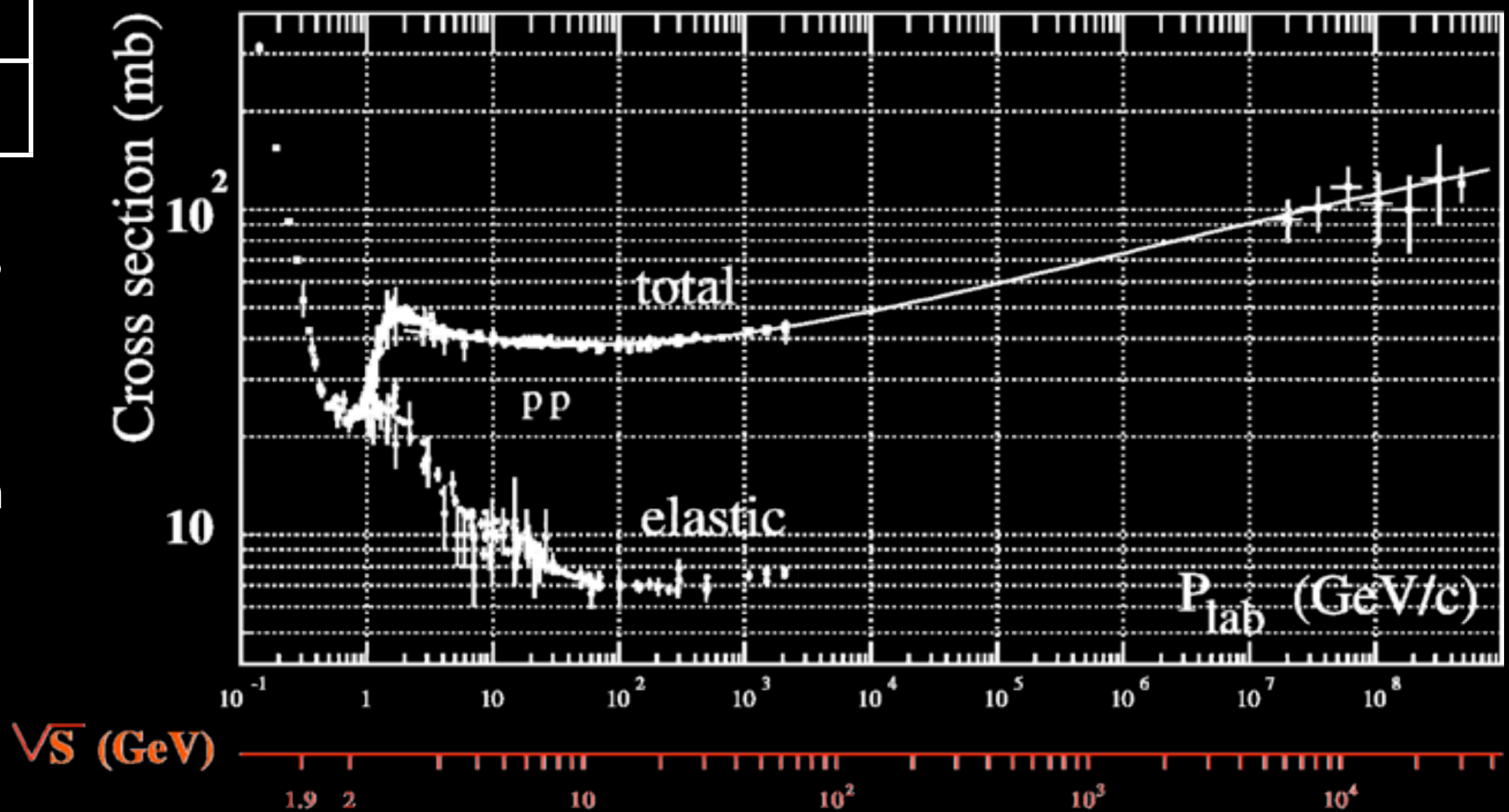
$$\rho\left(r\right)=\frac{\rho_0\left(1+wr^2/R^2\right)}{1+e^{(r-R)/a}}$$

Nucleus	A	R	a
Au	197	6.38	0.535
Pb	208	6.68	0.546

$\sqrt{S}$ (GeV)	$\sigma_{in,pp}$ (mb)
20	32
200	42
5500	~70

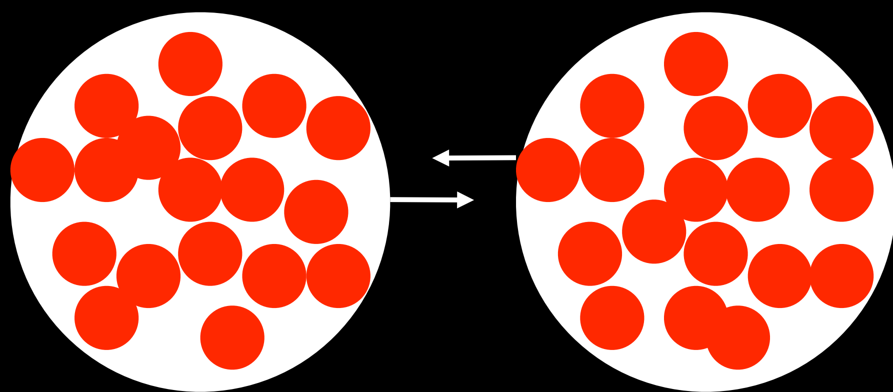


- ✓ nucleons travel on straight lines, no deflection after NN collision
- ✓ NN collision cross section from measured inelastic cross section in p+p
- ✓ NN cross section remains constant independent of how many collisions a nucleon suffered



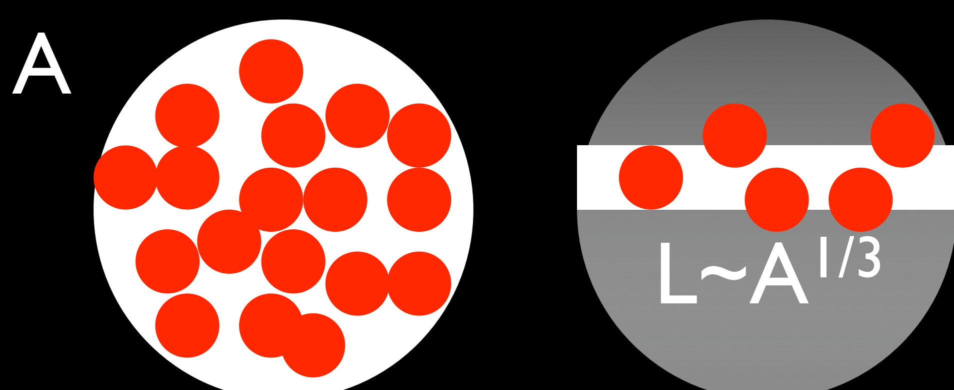
Wounded nucleons and binary collisions

wounded nucleon scaling

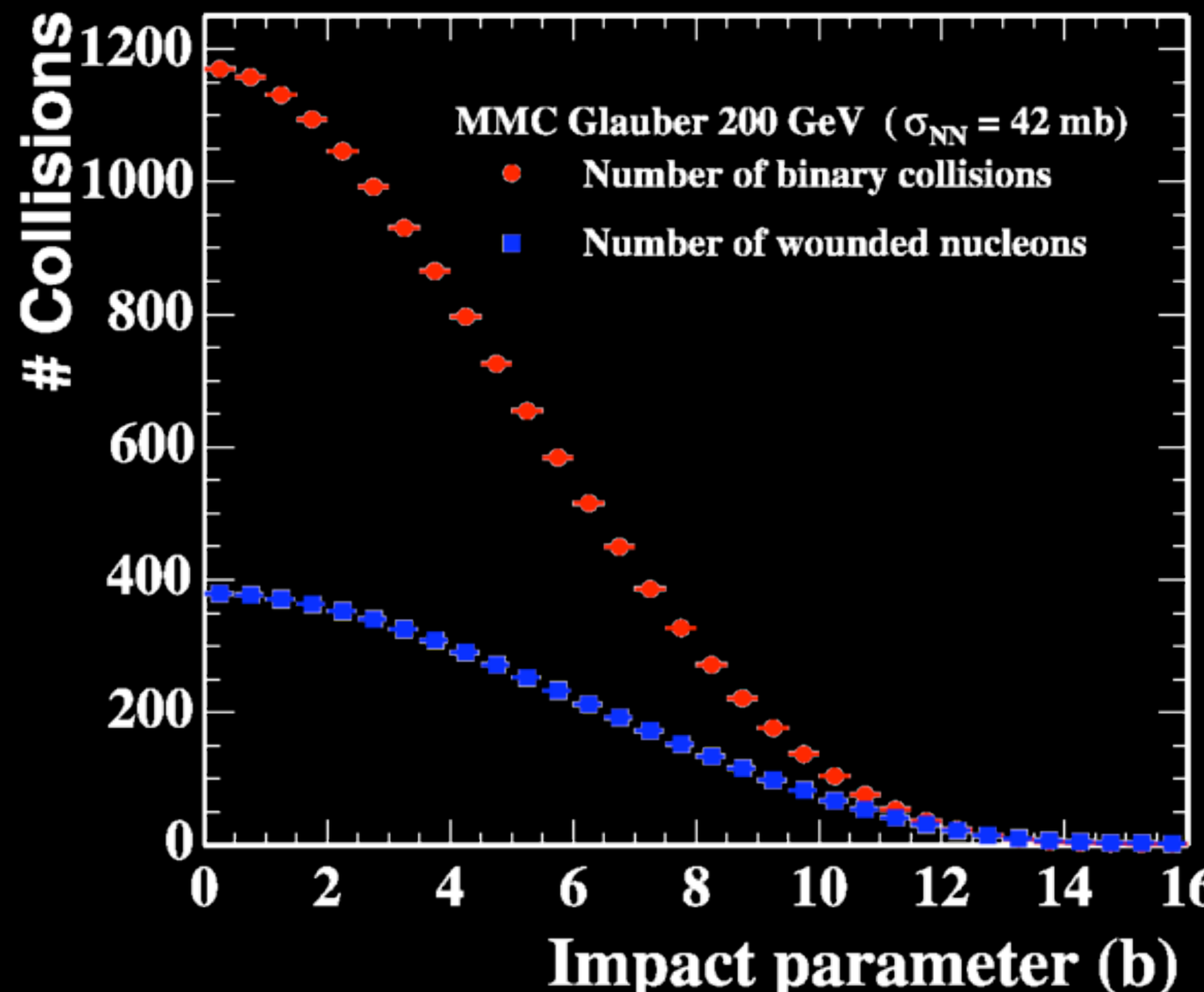


number of participating nucleons scales with volume ~ 2A

binary scaling

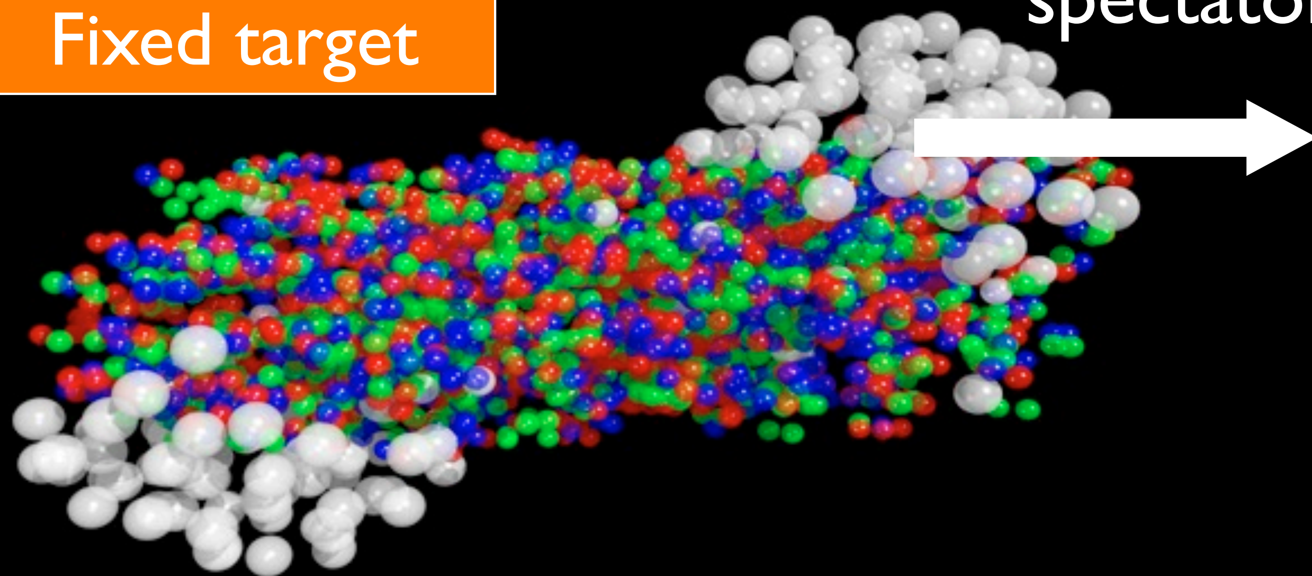


number of NN collisions, point like, scales with ~ $A^{4/3}$



Measuring centrality

Fixed target

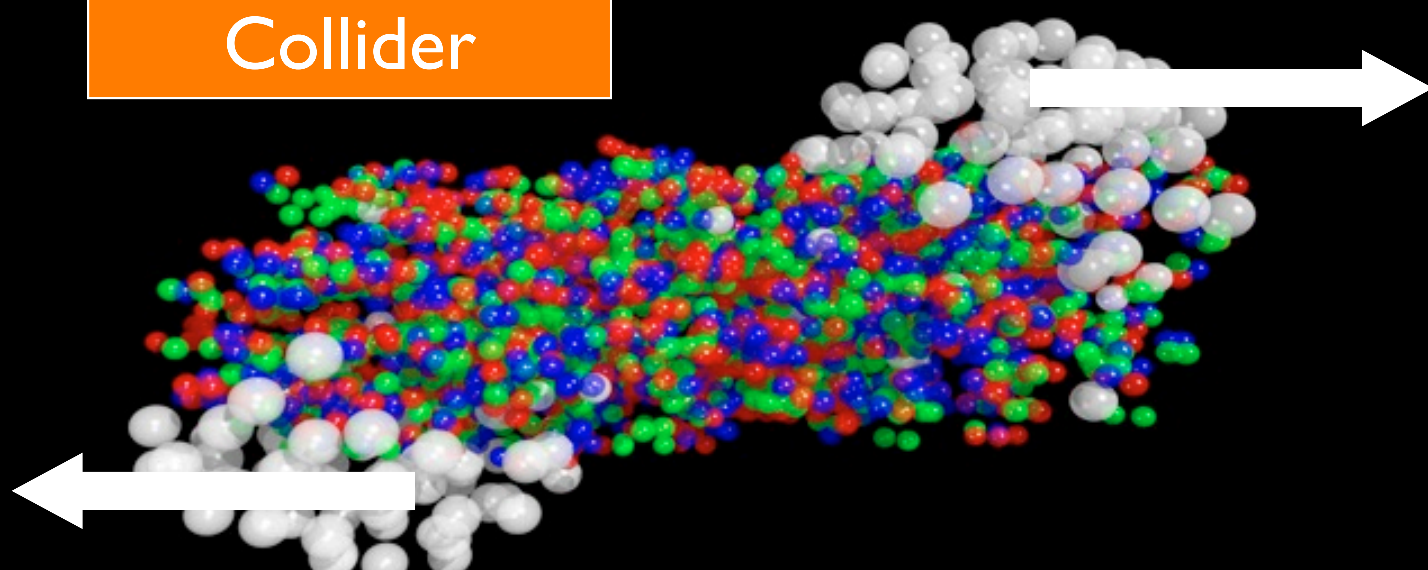


Zero-Degree-Calorimeter (ZDC) measures energy of all spectator nucleons

$$N_{\mathrm{spec}} \approx E_{\mathrm{ZDC}} / \left(E_{\mathrm{beam}} / A\right),$$

$$N_{part} \approx 2 \cdot \left(A - N_{\mathrm{spec}}\right)$$

Collider



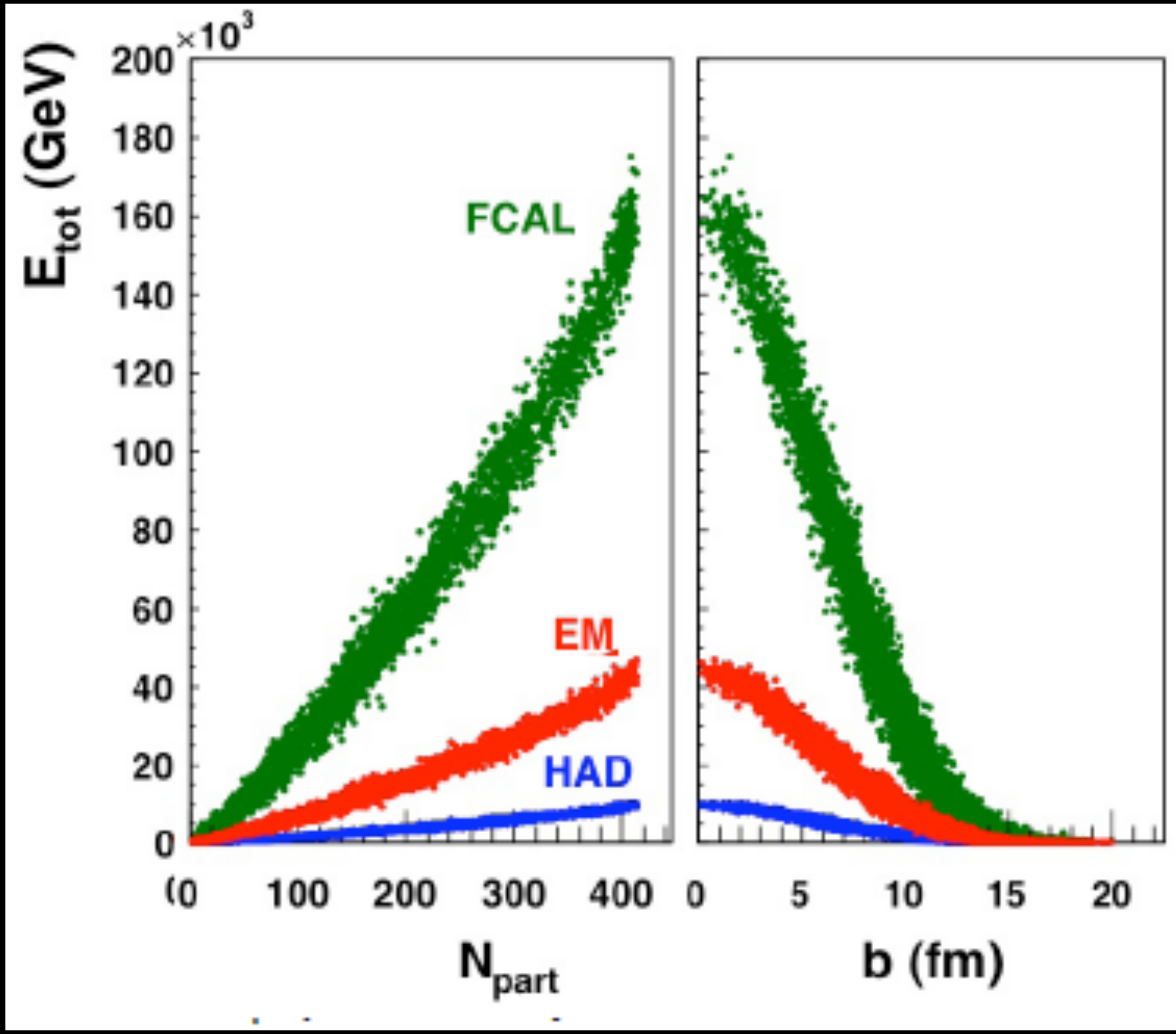
Zero-Degree-Calorimeter (ZDC) measures energy of all unbound spectator nucleons

- ➡ charged fragments (p, d, and heavier) are deflected by accelerator magnets
- ➡ E_{ZDC} small for very central and very peripheral collisions, ambiguous

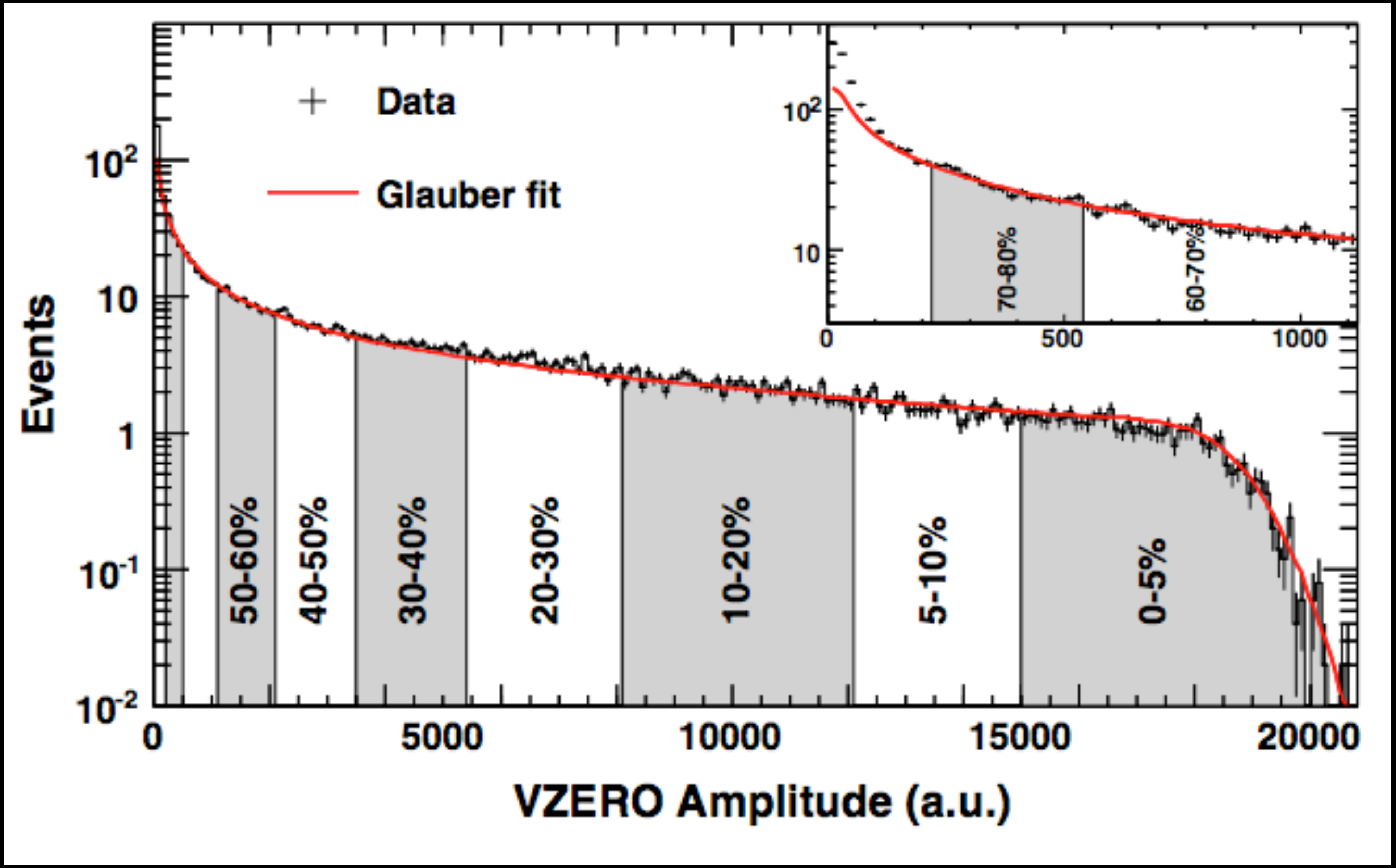
Centrality measurement

- Use multiplicity of produced particles in the acceptance of a given detector

ATLAS Experiment



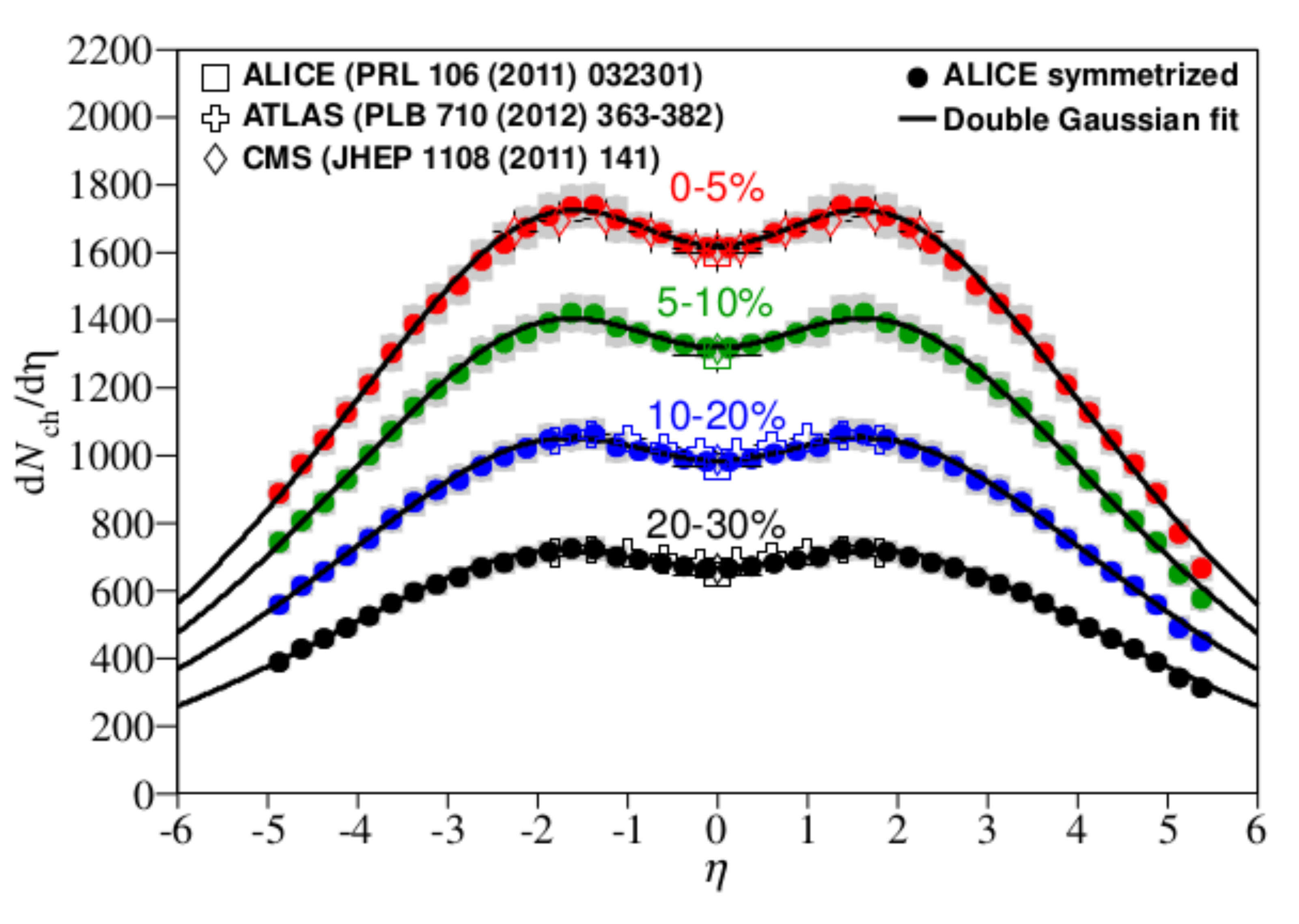
Centrality in ALICE



VZERO - detects charged particles $2<\eta<4$

Multiplicity distribution

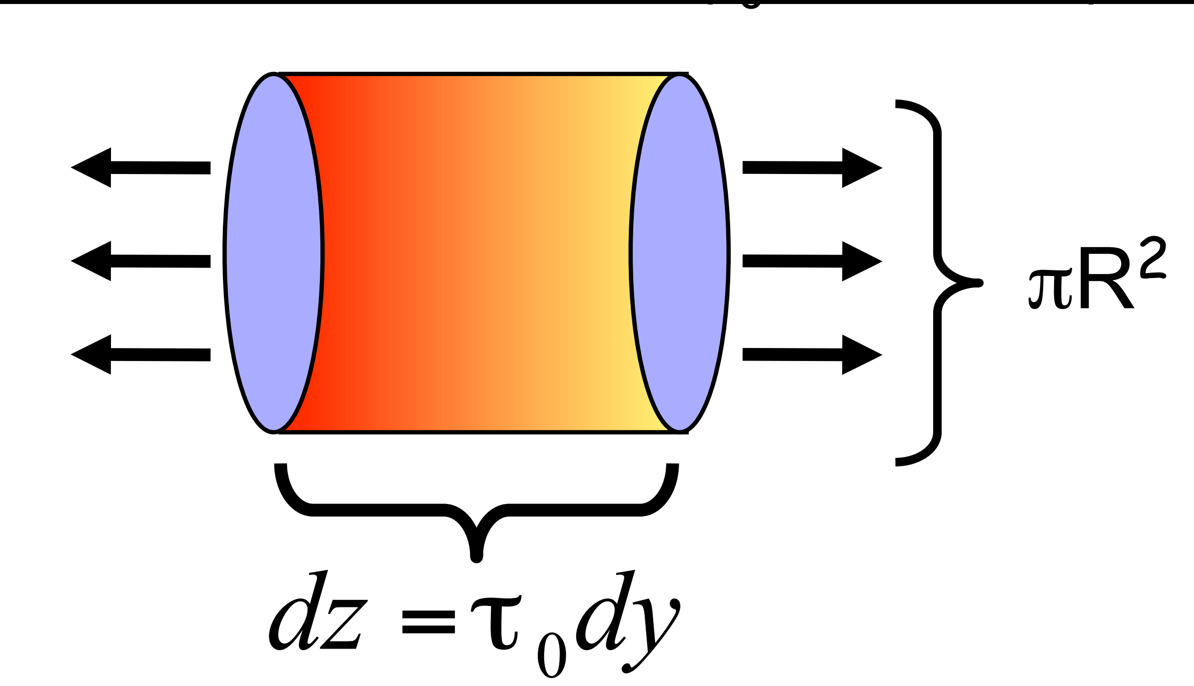
- Central collisions at LHC: ~17,000 charged particles!
- dN/dη ≈ 1600 for central collisions



Energy density: Bjorken

- Estimate energy density, evaluated close to y=0 (centre of mass)
- τ_0 - formation time ≤ 1 fm/c
- S - transverse dimension
    - 160 fm^2 from r = 1.2A$^{1/3}$
- Energy density at least 10 GeV/fm^3

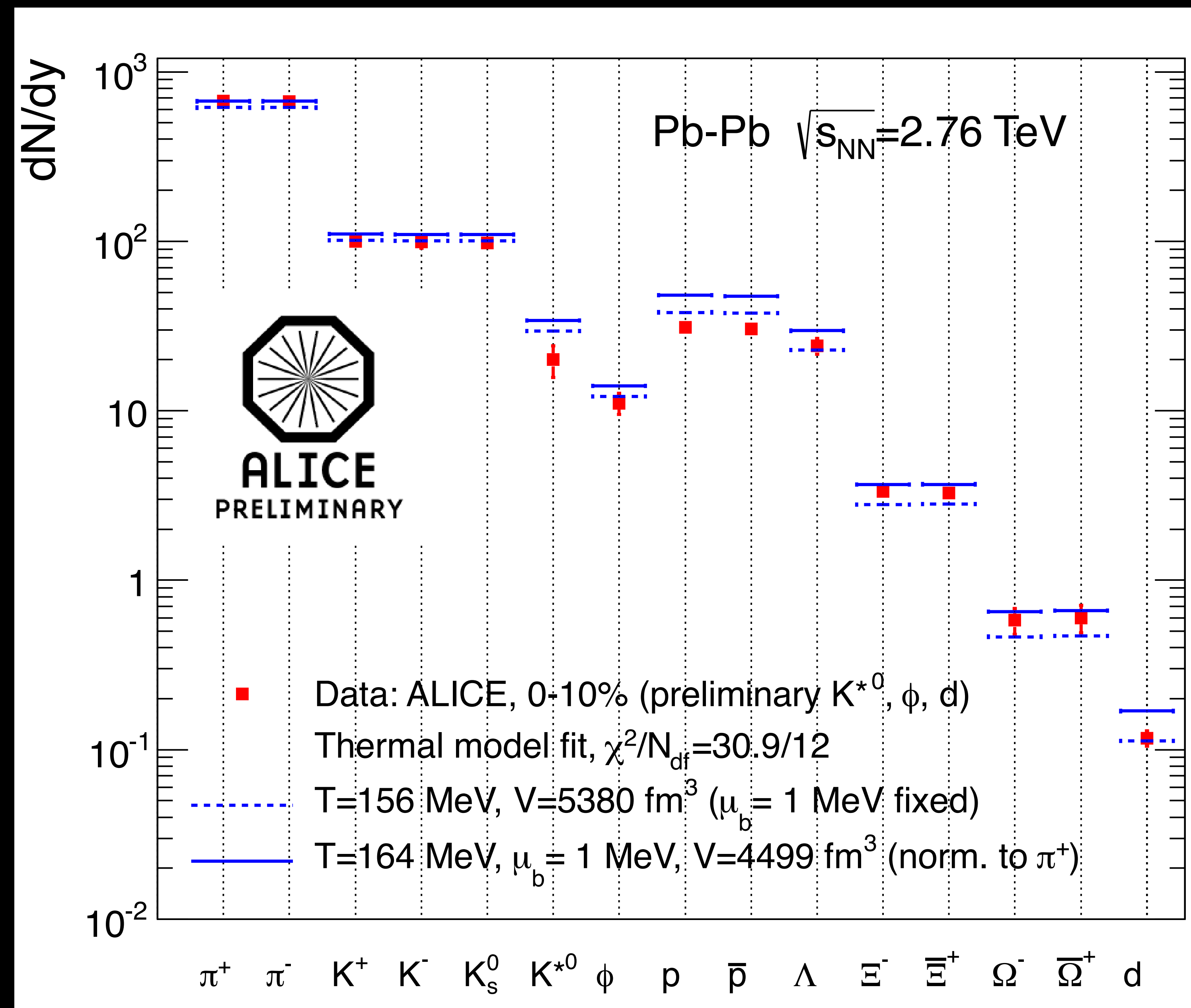
$$\epsilon = \frac{E}{V} = \frac{1}{Sc\tau_0}\frac{dE_T}{dy}$$



Temperature?

$$dn_i \approx \exp^{-\frac{E-\mu_B}{T}} d^3p$$

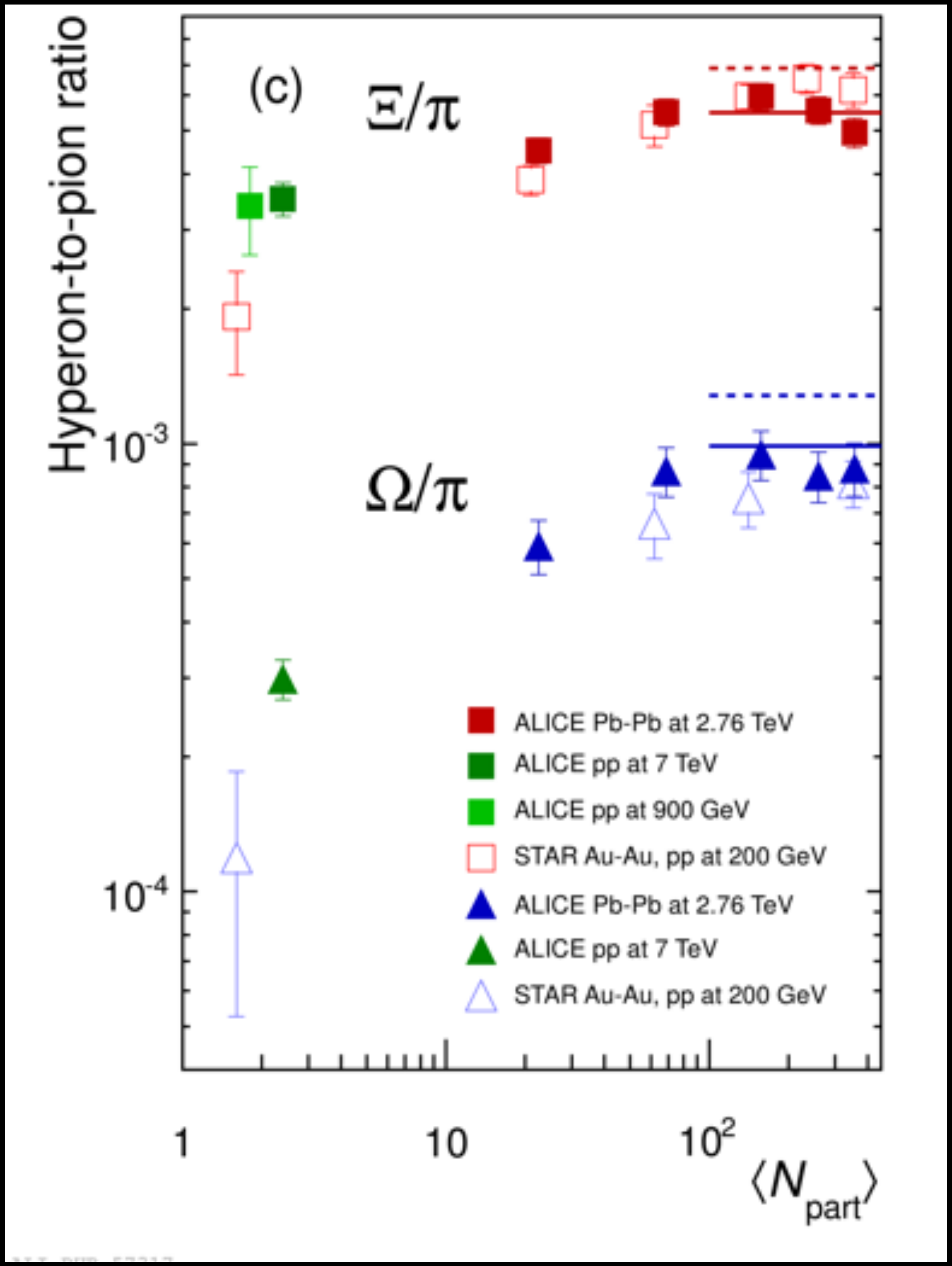
- Statistical model fit relate abundance of species to mass and temperature
- T ~ 160 MeV
- Also indirect evidence for deconfinement
  - necessary but not sufficient



Strangeness d.o.f

- Abundance of multi-strange particles in nucleus-nucleus collisions is large relative to proton-proton collisions

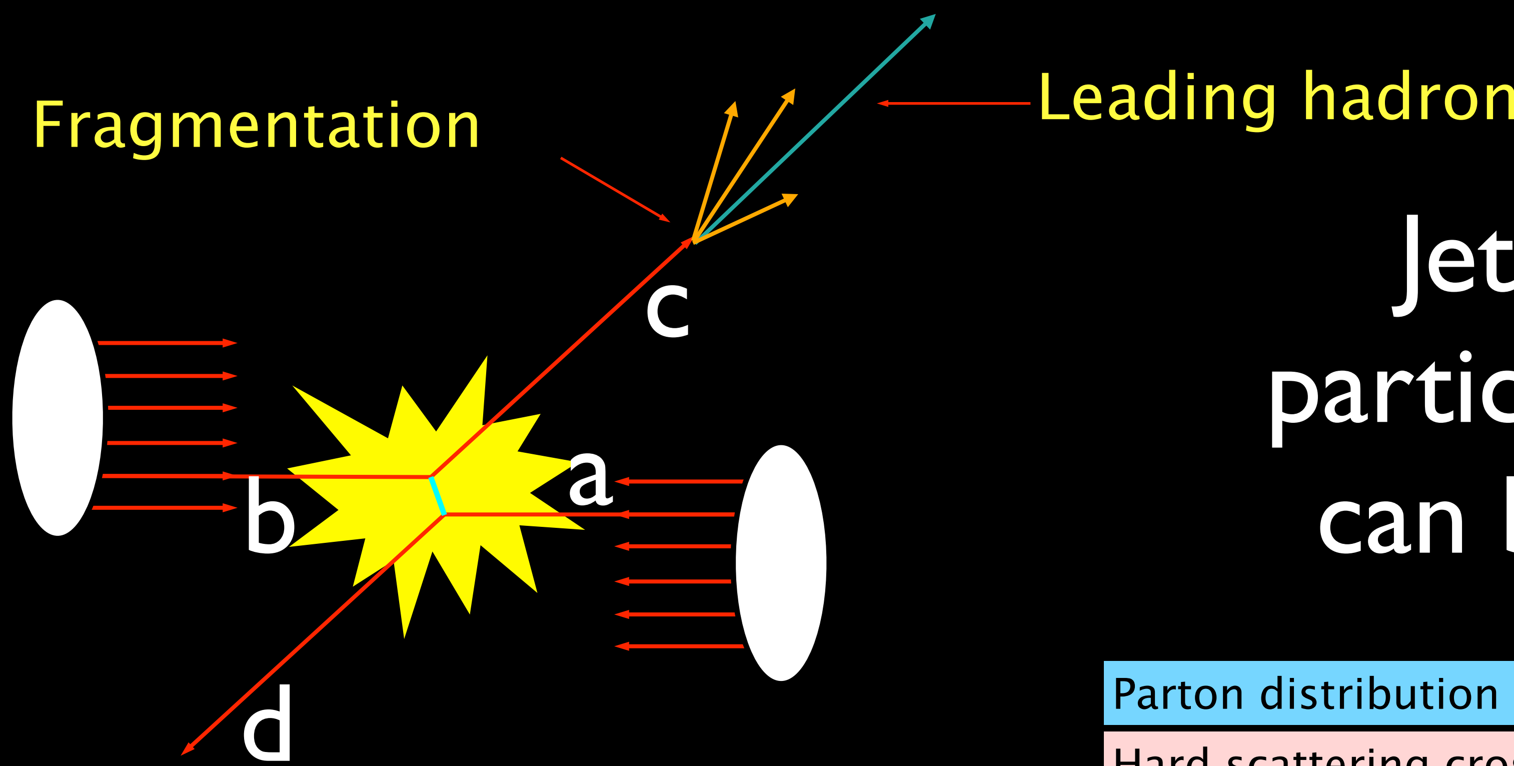
- *Indirect* evidence of liberated strange quarks



Probing the plasma

- Usually in physics probe the structure of a system by ‘shining’ something on it (laser, X-rays, electrons, neutrons…)
- Can’t do this with our QGP
  - no third beam!
- Need self-generating probes for which rates can be calculated

Jets as probes

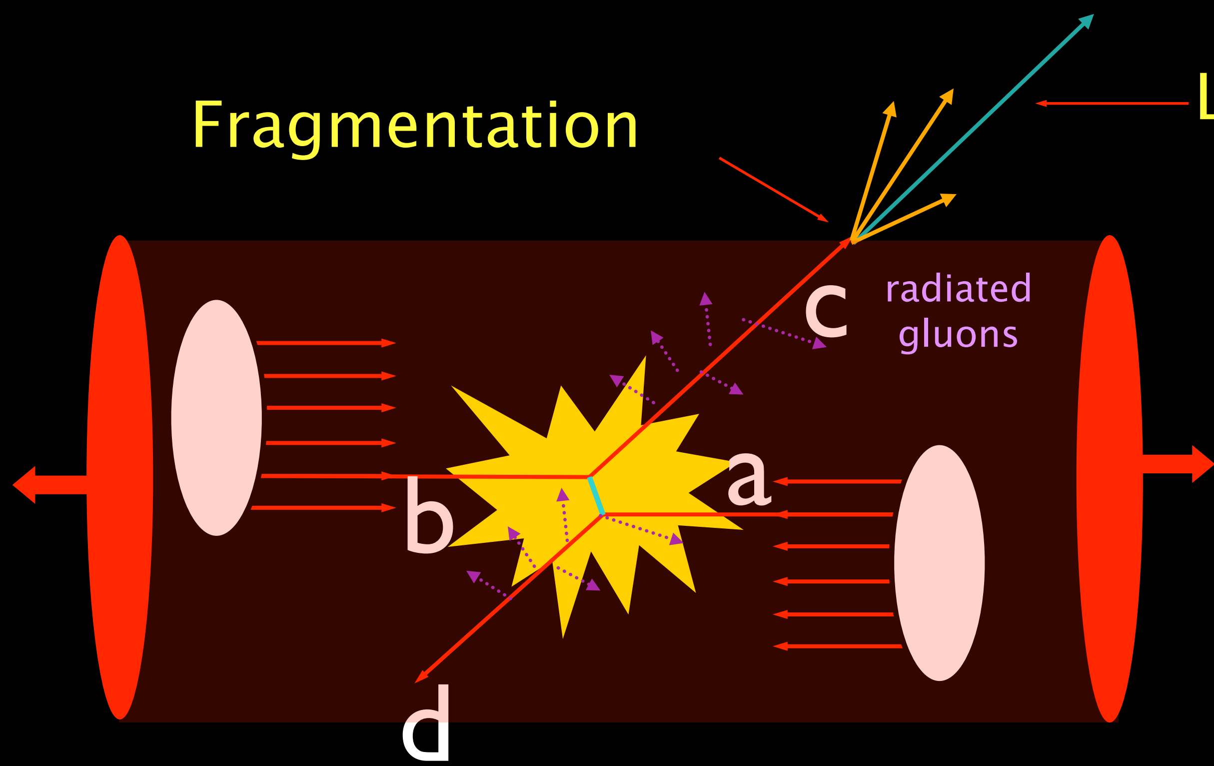


Jet or high-p_T particle production can be calculated

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

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

Jets as probes



Prediction that jets are *quenched*

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

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

High p_T hadron suppression

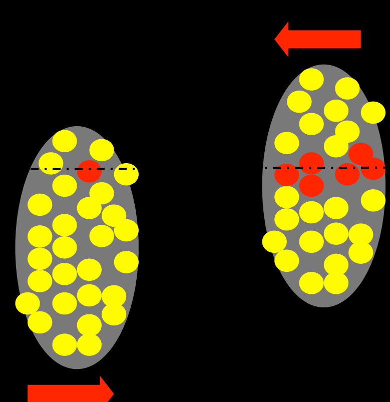
$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{N_{binary}\,dN^{pp}/dp_T}$$

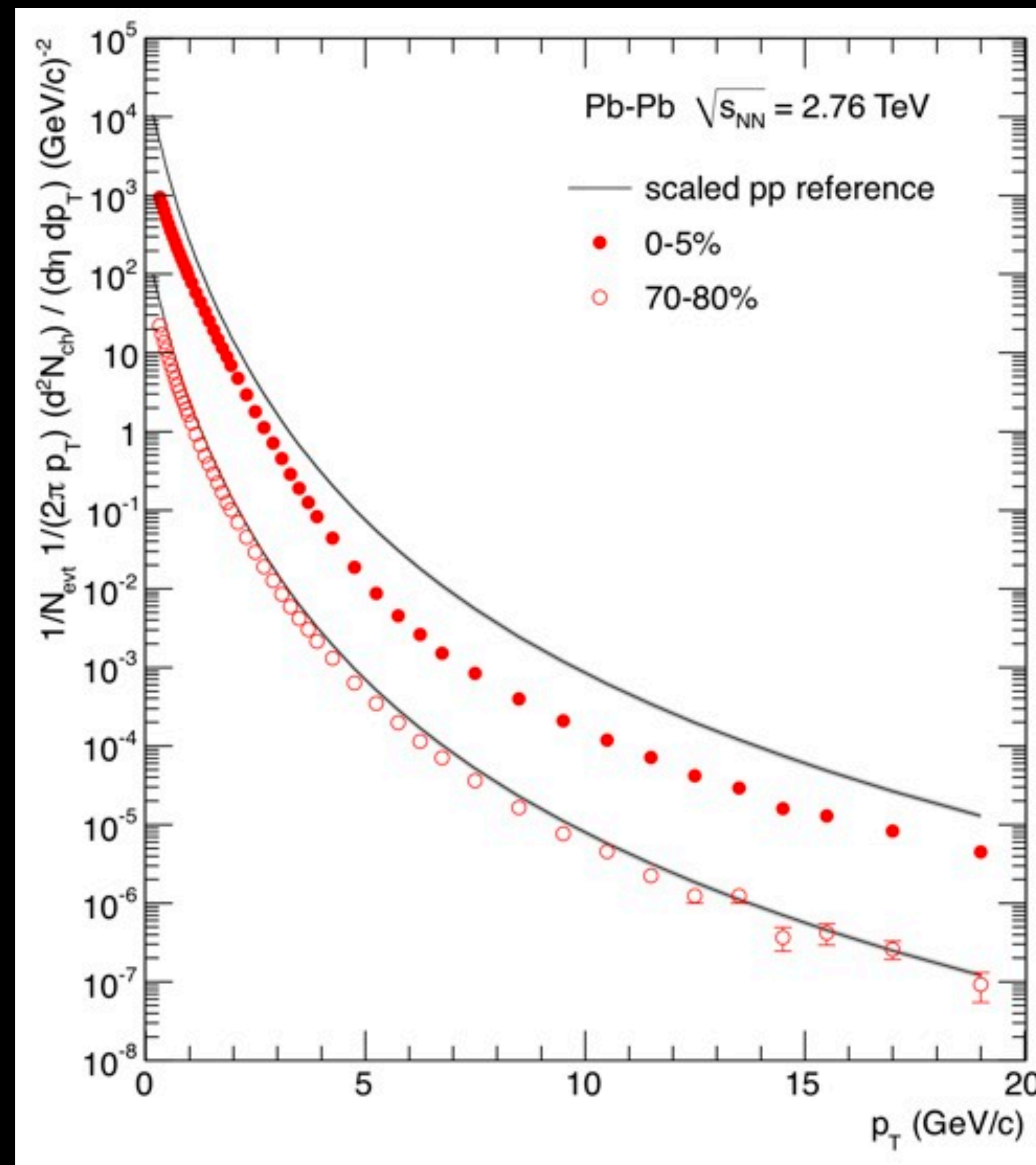
scale factor

pp reference

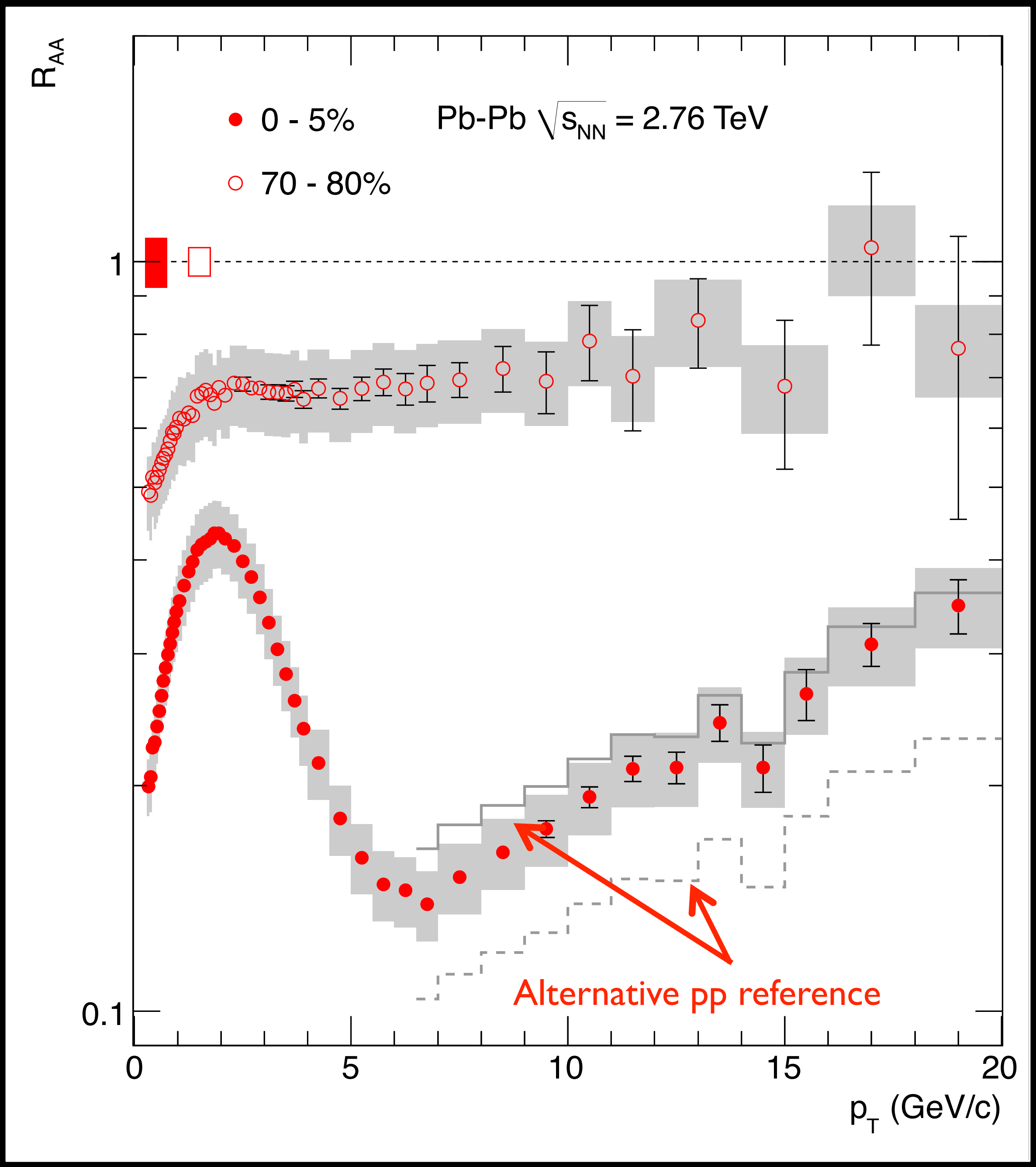
Form ratio to scaled pp distribution

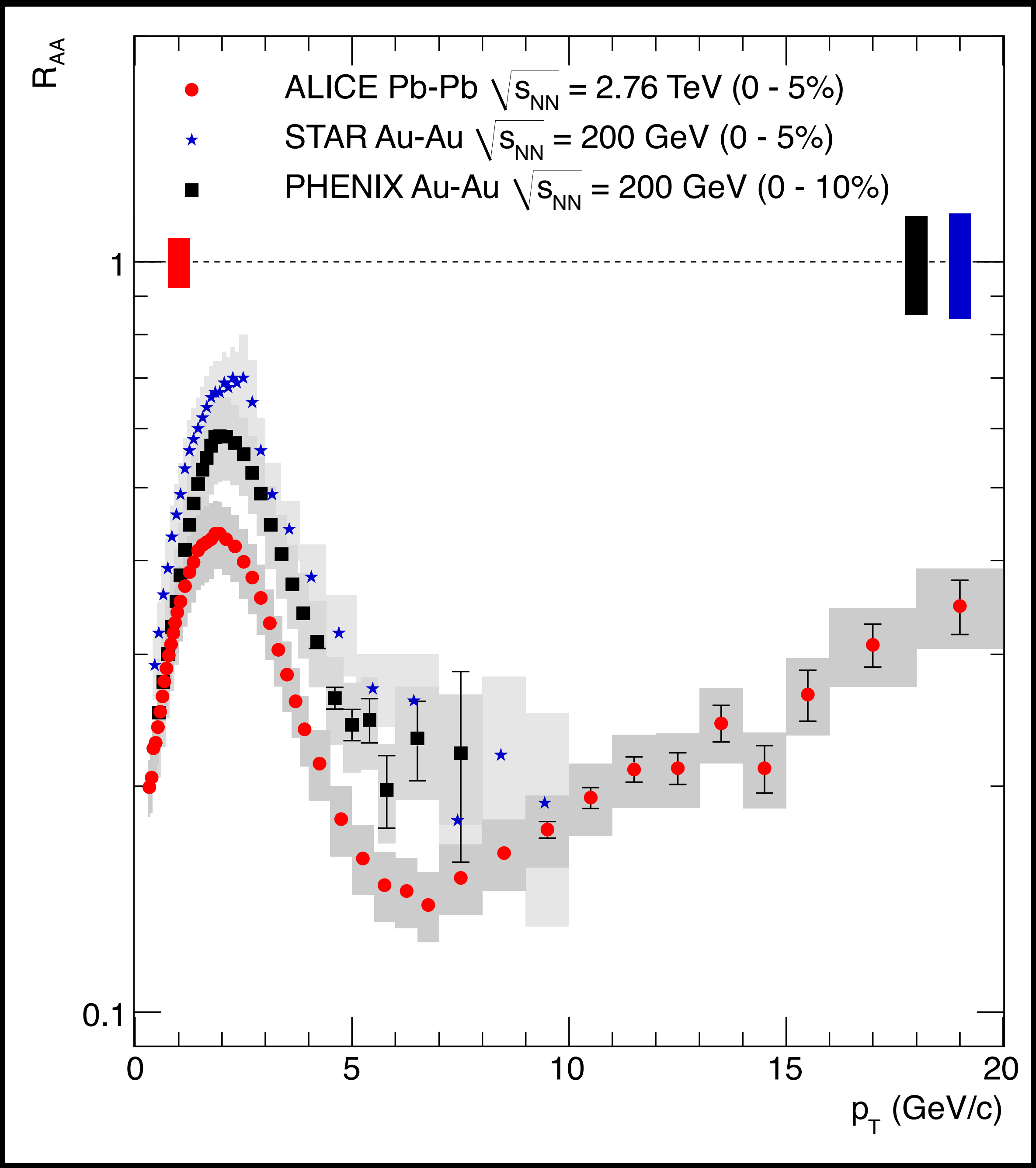
N_{binary} is the number of independent nucleon-nucleon collisions





ALICE Results - Centrality dependence and comparison to RHIC



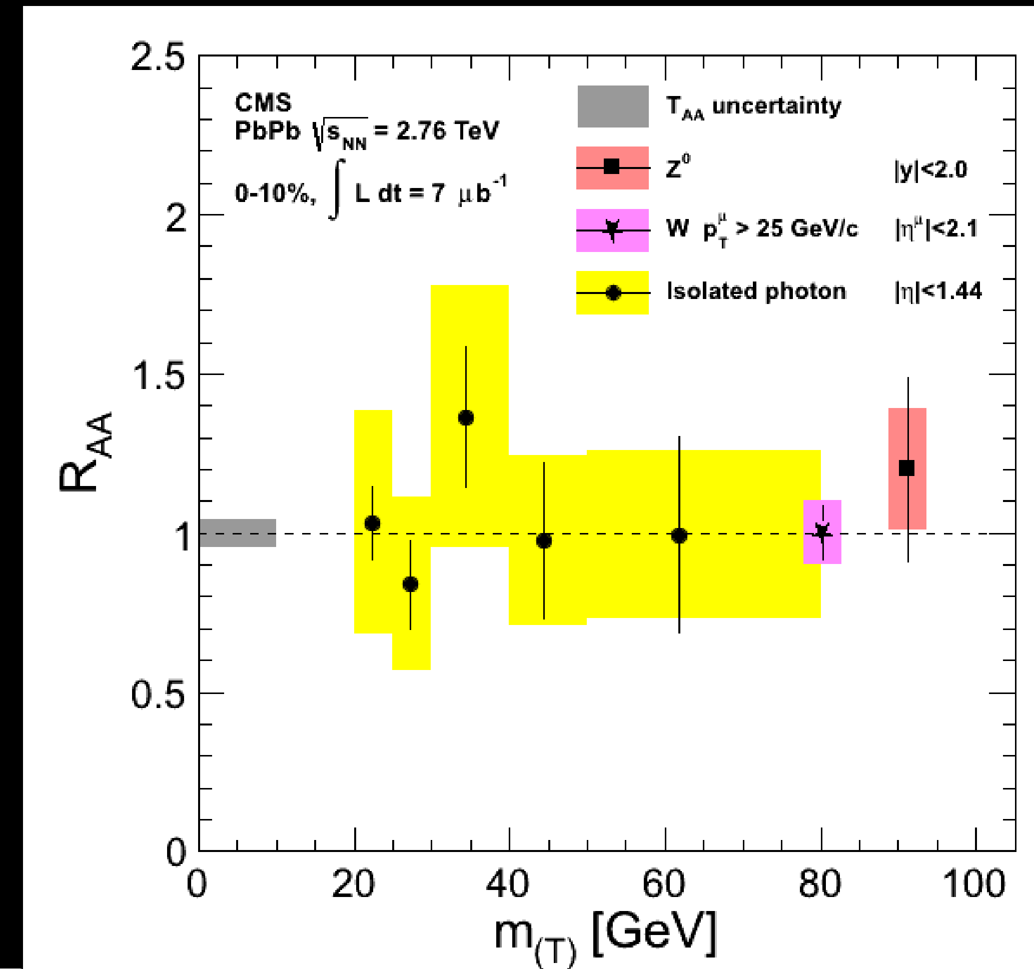


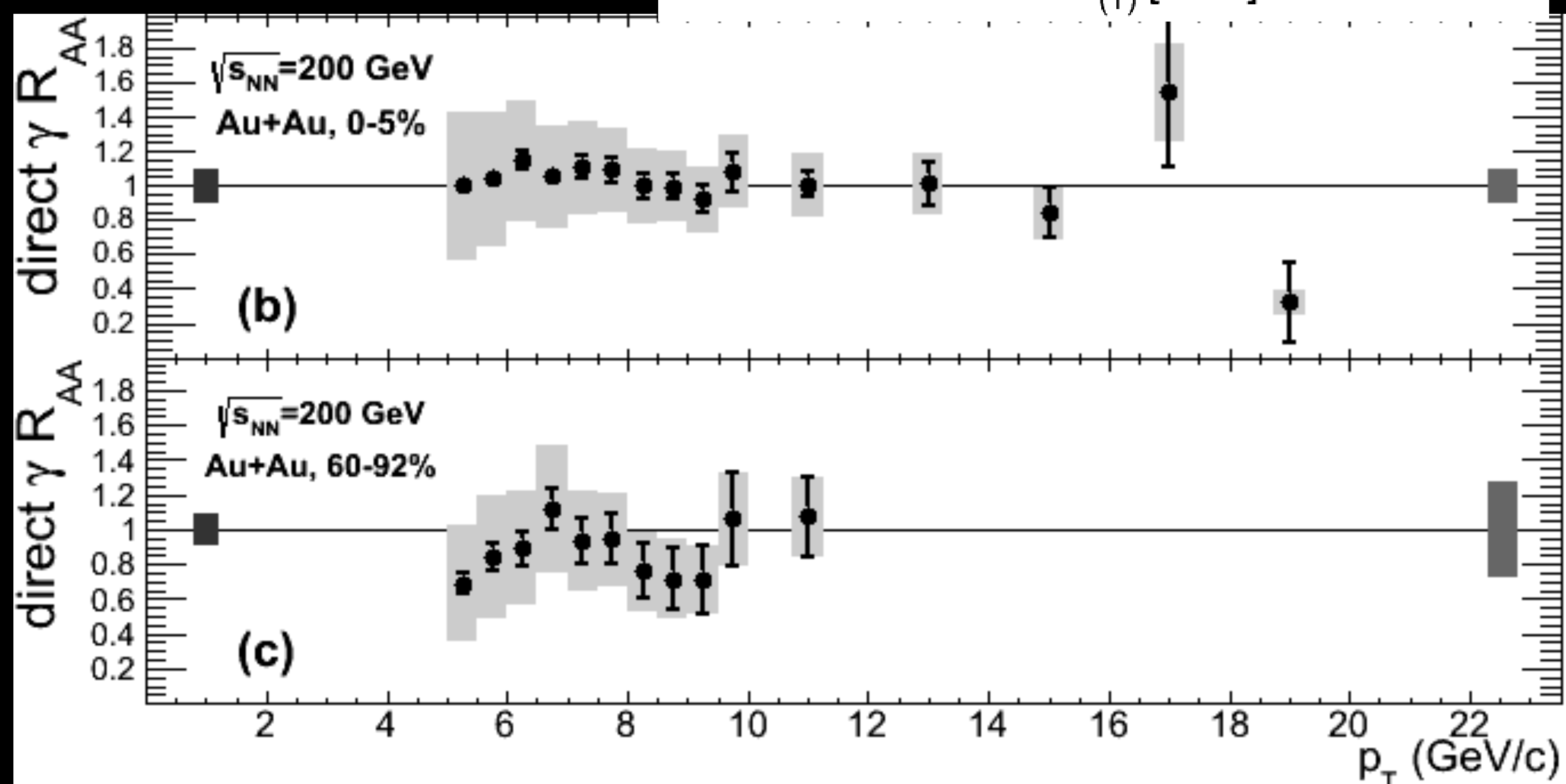
Suppression in central events is greater than suppression in peripheral events

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

Control experiment

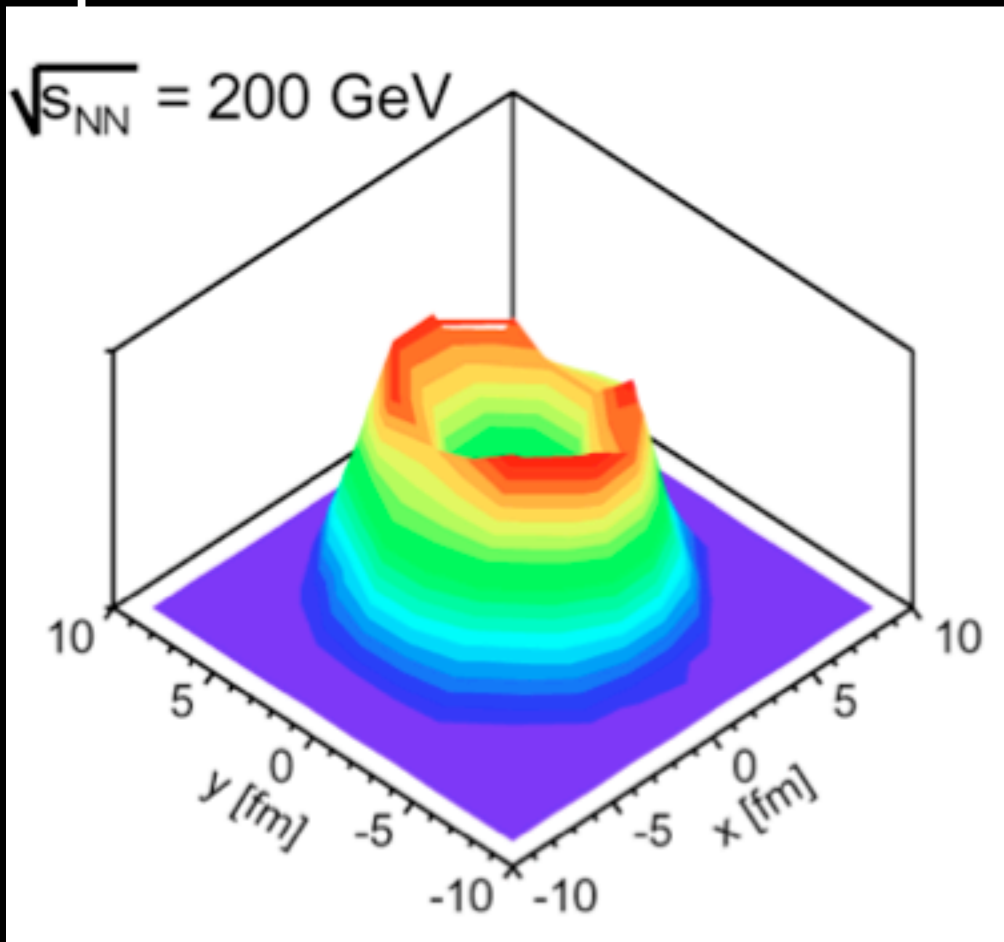
- Colour blind probes
- Photon (PHENIX expt)
- W boson (CMS expt)

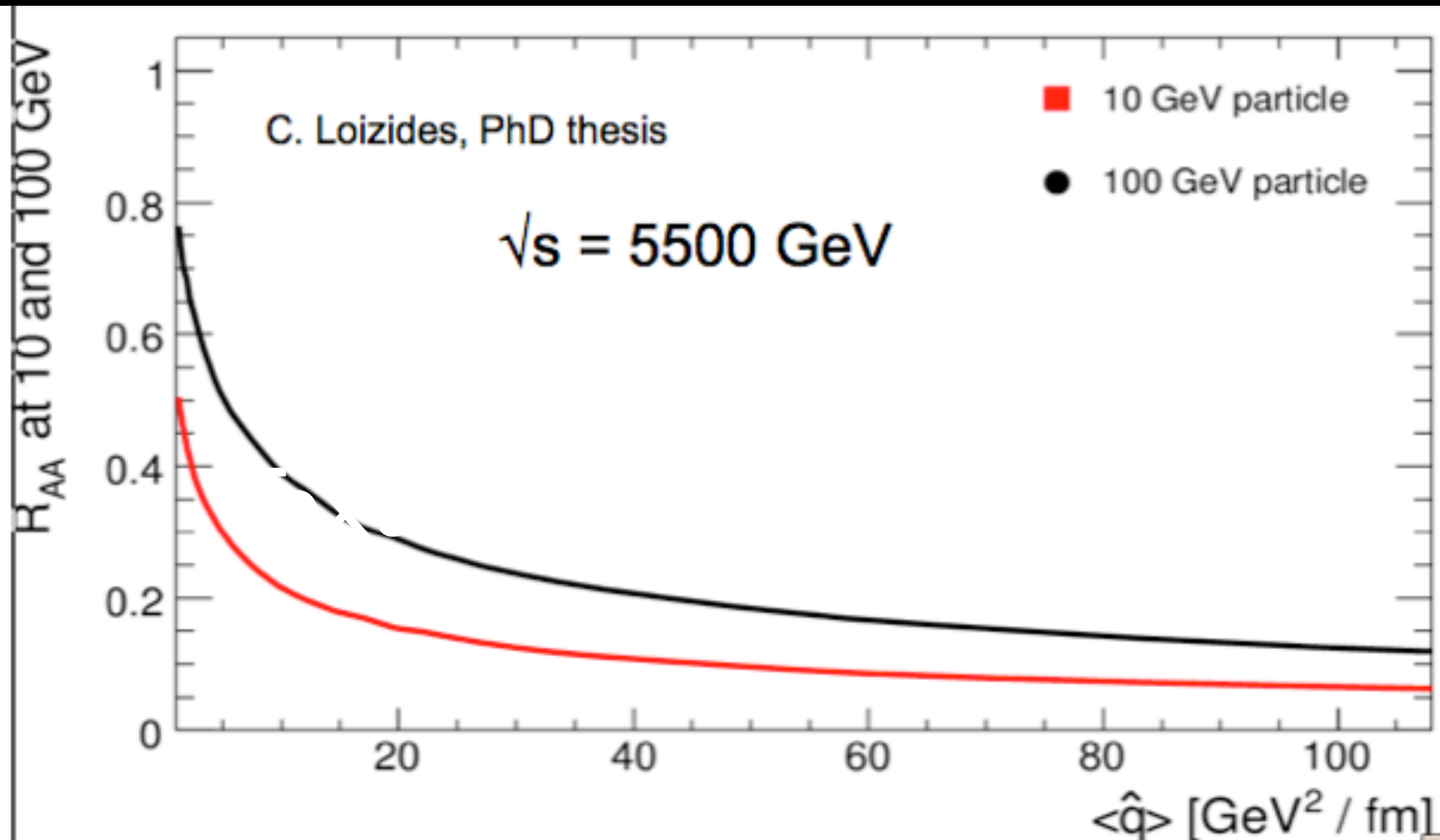




Interpretation

Origin of emerging particles





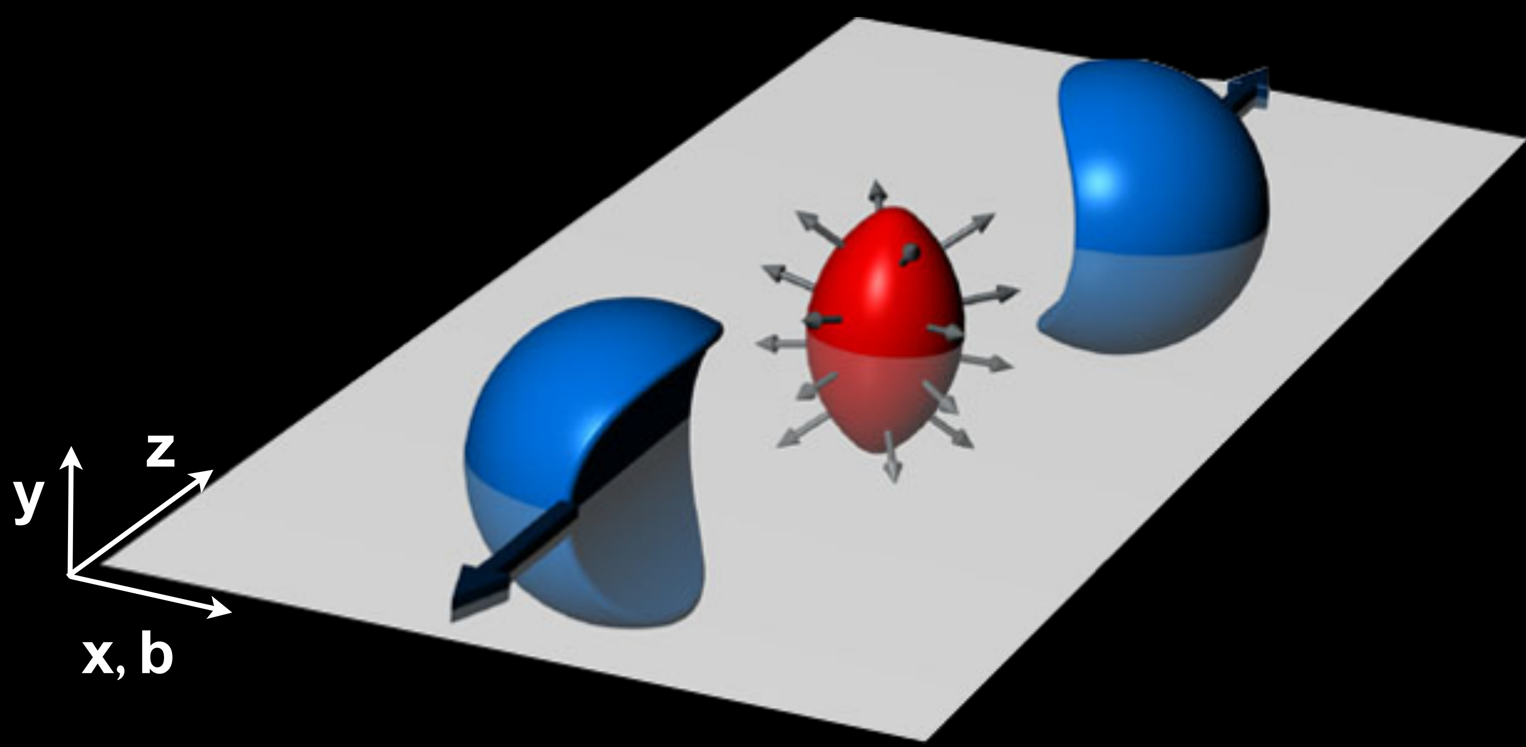
Matter highly opaque

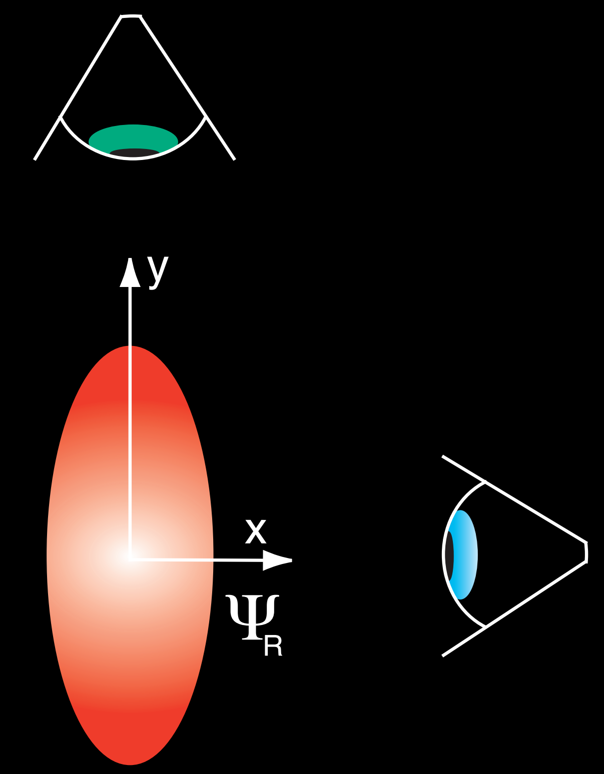
$\hat{q}$ is transport coefficient

Conclusions

- Heavy Ion Collisions can be used to create hot dense QCD matter
  - Temperature and energy density exceed critical values
- Experiments studying these collisions at LHC and RHIC have begun to measure the properties of this matter

The Reaction Plane



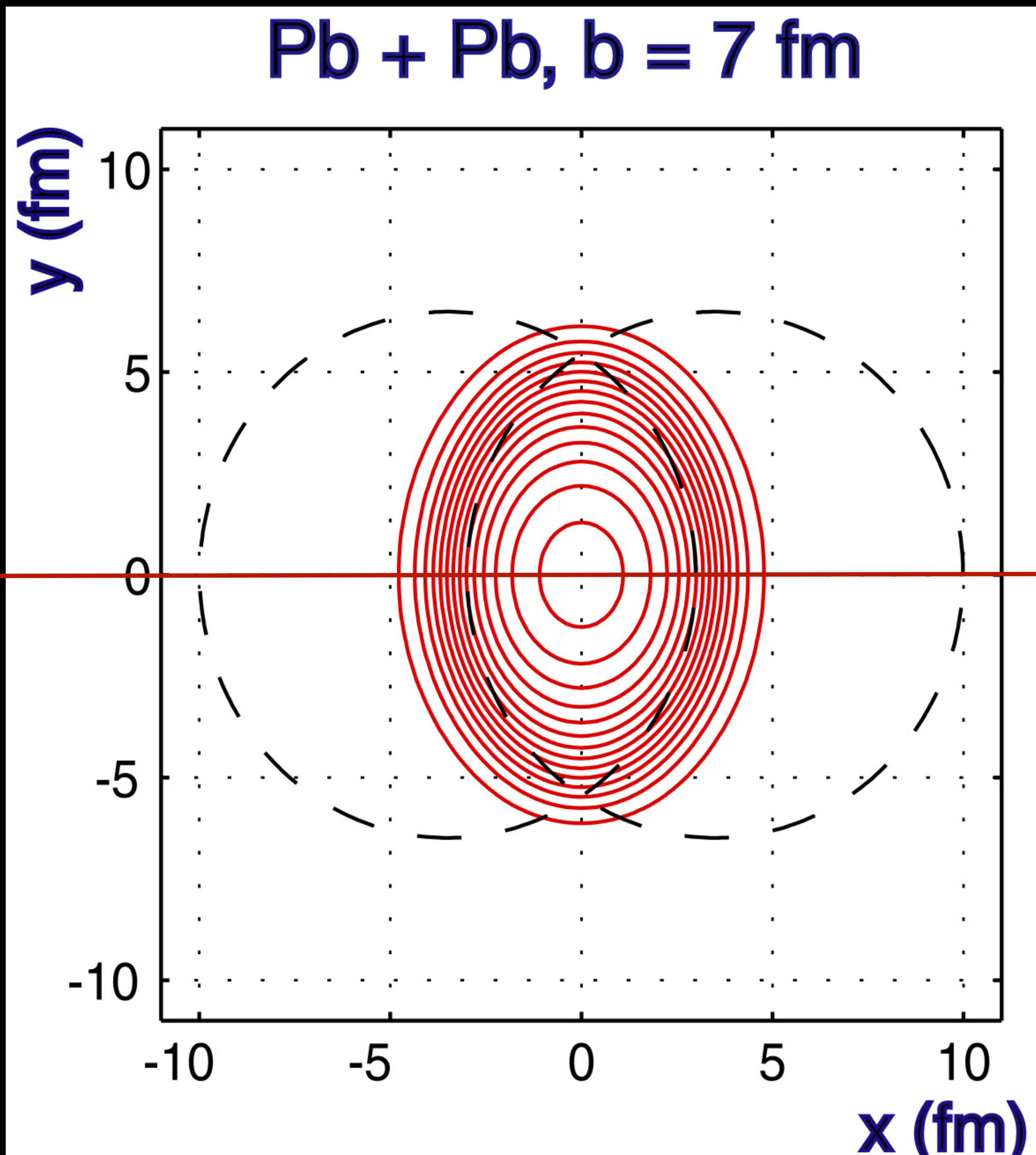


$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_t dp_t dy d(\phi - \Psi_R)}$$

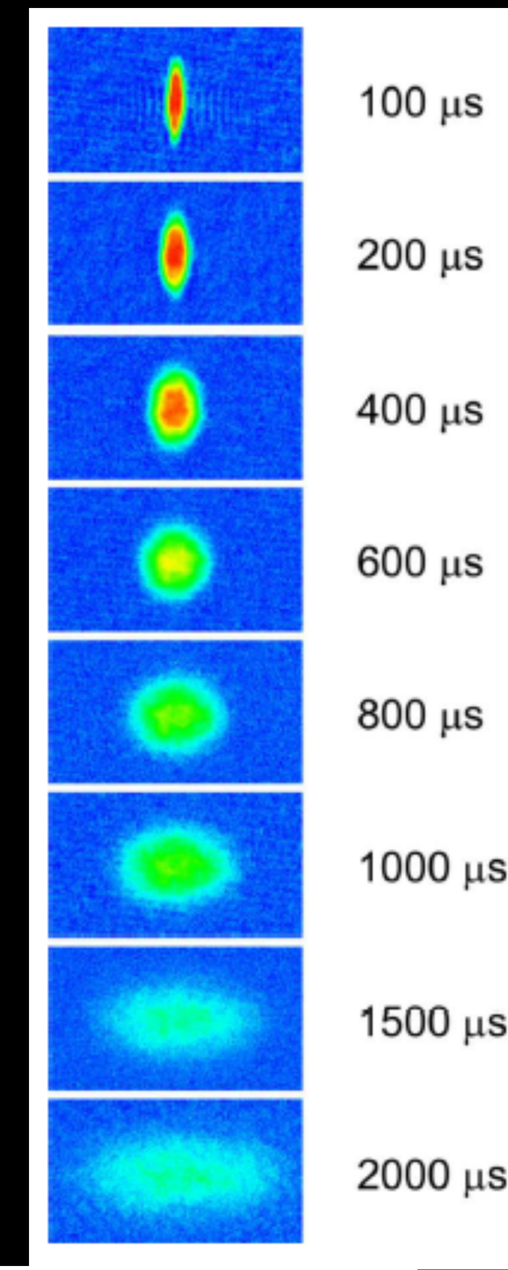
determine the angle of the reaction plane ψ_R

Flow concept

Example from another field: Ultra cold atoms



Reaction plane



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

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