# Selected Topics in the Theory of Heavy Ion Collisions

## Lecture 1

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# Heavy Ion Collisions - Experiments

- Alternating Gradient Synchrotron (AGS) at Brookhaven BNL
  - variety of beams, since mid 1980's

$$\sqrt{s_{NN}}\Big|_{Au+Au}^{AGS} \cong 2-5\,GeV$$

- CERN SPS fixed target experiments
  - variety of beams, Pb-beams since 1994

$$\sqrt{s_{NN}}\Big|_{Pb+Pb}^{SPS} \leq 17\,GeV$$

- Relativistic Heavy Ion Collider RHIC at BNL
  - since 2000, p+p, d+Au, Au+Au, Cu-Cu, …

$$\sqrt{s_{NN}}\Big|_{Au+Au}^{RHIC} \leq 200\,GeV$$

- Large Hadron Collider LHC
  - since 2000, so far p+p, Pb+Pb, …

$$\sqrt{s_{NN}}\Big|_{Pb+Pb}^{LHC} = 2.75\,TeV$$

- total cross section: $\sigma_{total}^{Pb+Pb} \approx 8\,barn = 8 * 10^{-24}\,cm^2$
- maximal luminosity: $L_{\max,LHC}^{Pb+Pb} \approx 10^{27}\,cm^{-2}s^{-1}$

$\Rightarrow$ 8000 collisions per second!

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# What is measured when at the LHC?

$\sigma_{total}^{Pb+Pb} \approx 8\, barn = 8 * 10^{-24}\, cm^2$ $L_{\max,LHC}^{Pb+Pb} \approx 10^{27}\, cm^{-2} s^{-1}$ $1\, month \approx 10^6\, s \approx 1\, LHCyr\; Pb+Pb$

| | | | | |
|---|---|---|---|---|
| When? | 15 min~$10^3$ s (ideal) | $1^{st}$ month, 2010 | 1 month, 2011 | 2-3 yrs |
| How much data? | $L_{\rm int}^{Pb+Pb} \approx 1\, \mu b^{-1}$ | $L_{\rm int}^{1st\, year} \approx 7-8\, \mu b^{-1}$ | $L_{\rm int}^{Pb+Pb} \approx 150\, \mu b^{-1}$ | p+Pb |

What?

- Event multiplicity
- Low-$p_T$ hadron spectra
- …

- Abundant high-$p_T$ processes such as jets

- Rare and leptonic processes

Strategy for these lectures:

- explain basic theory for data accessible at the LHC
  (and say where it is incomplete)

- explain theory in the order in which data will become accessible

- give motivation for measurement by explaining measurement
  (not before)

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# …last introductory remark…

Fundamental question:

How do collective phenomena and macroscopic properties of matter emerge from the interactions of elementary particle physics?

Heavy Ion Physics: addresses this question
- for Quantum Chromodynamics (QCD, i.e. non-abelian QFT)
- in the regime of the highest temperatures and densities accessible in the laboratory

How? 1. **Benchmark:** establish baseline, in which collective phenomenon is absent.
2. **Establish collectivity:** by characterizing deviations from baseline
3. **Seek dynamical explanation**, ultimately in terms of QCD.

These lectures give examples of this 'How?'

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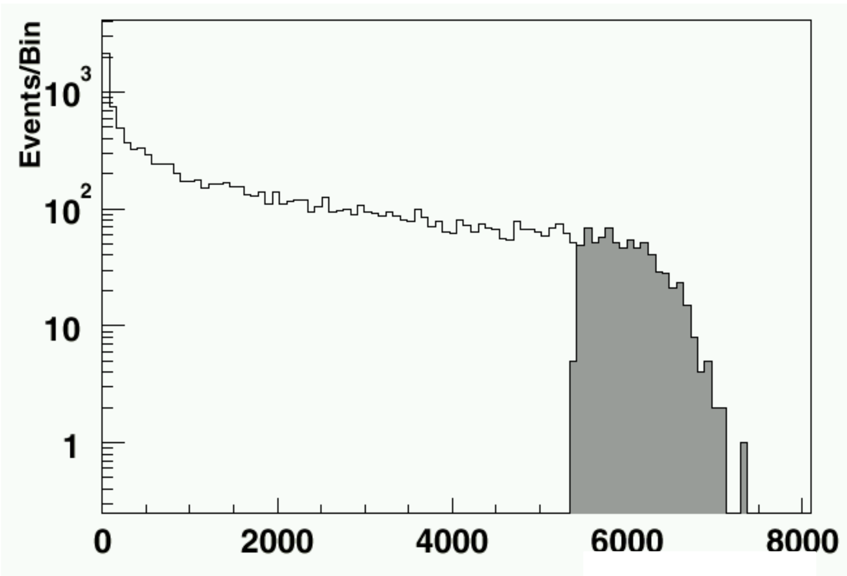
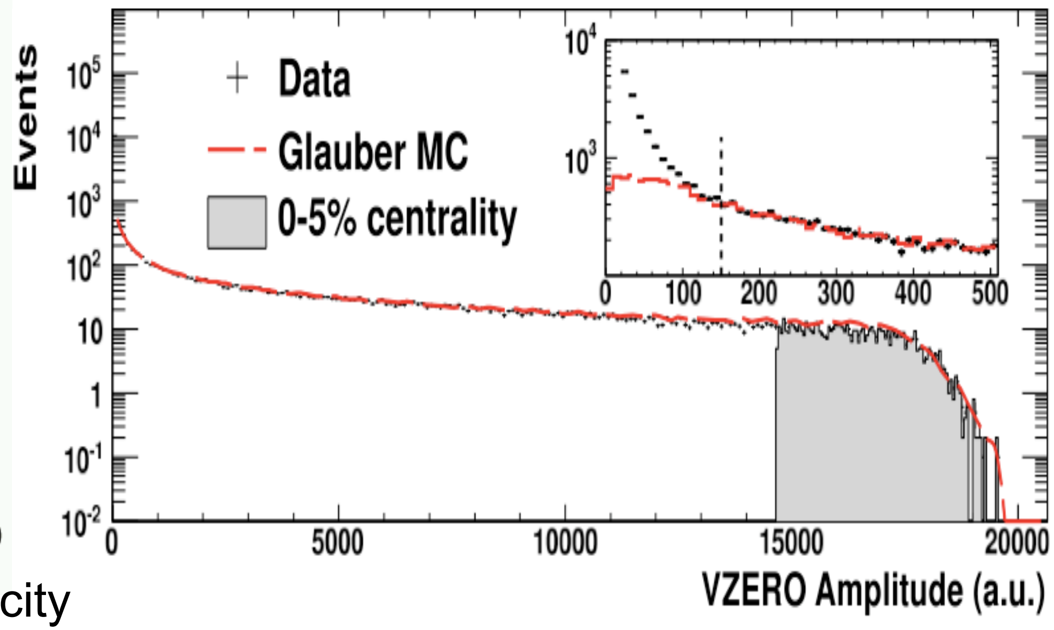
# I.1. The very first measurement at a Heavy Ion Collider

**PHOBOS, RHIC, 2000**




**ALICE, PRL 105 (2010) 252301, arXiv:1011.3916**




Signal proportional to multiplicity

What is the benchmark for multiplicity distributions?

Multiplicity in inelastic A+A collisions is incoherent superposition of inelastic p+p collisions.

(i.e. extrapolate p+p -> p+A -> A+A without collective effects)

→ **Glauber theory**

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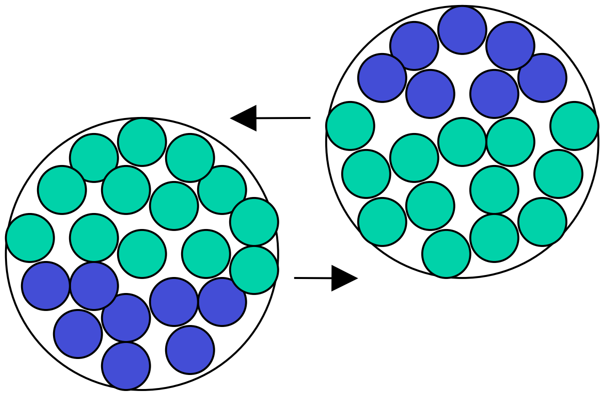
# I.2. Glauber Theory

**Assumption:** inelastic collisions of two nuclei (A-B) can be described by incoherent superposition of the collision of "an equivalent number of nucleon-nucleon collisions".
How many?
Establish counting based on

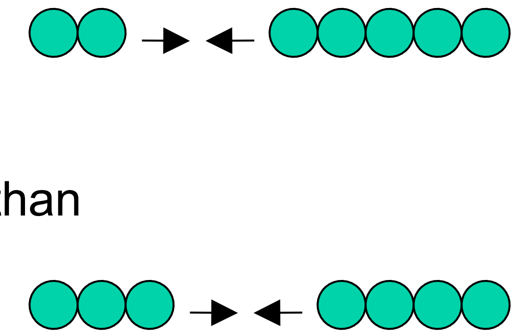


- Spectator nucleons (blue)
- Participating nucleons (green)

To calculate $N_{part}$ or $N_{coll}$, take

$\sigma$ = inelastic n-n cross section

A priori, no reason for this choice other than that it gives a useful parameterization.



$N_{part} = 7$

$N_{coll.} = 10$

$N_{quarks+gluons} = ?$

$N_{inelastic} = 1$

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# I.3. Glauber theory for n+A

We want to calculate:

$N_{part}$ = number of participants = number of 'wounded nucleons',
which undergo at least one collision

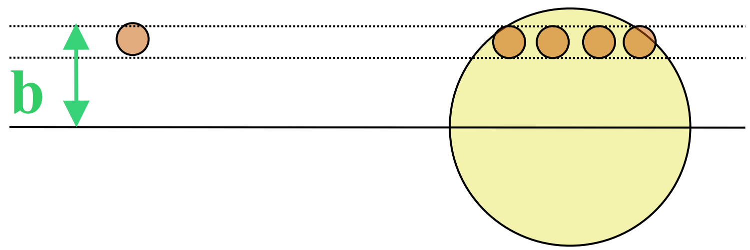
$N_{coll}$ = number of n+n collisions,
taking place in an n+A or A+B collision

We know the single nucleon probability distribution within a nucleus A, the so-called nuclear density

**(1.1)**

$$\rho(b,z)$$

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




Normally, we are only interested in the transverse density, the nuclear profile function

**(1.2)**

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

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# I.4. Glauber theory for n+A

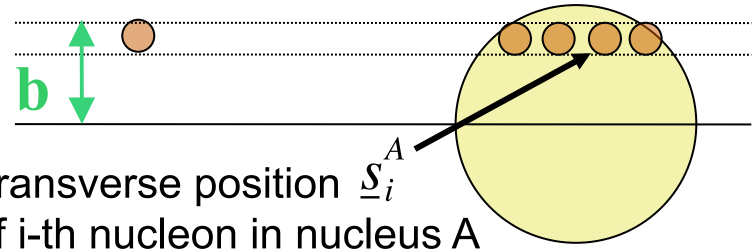
The probability that no interaction occurs at impact parameter b:

**(1.3)** $$P_0(\underline{b}) = \prod_{i=1}^{A}\left[1 - \int d\underline{s}_i^A T_A\left(\underline{s}_i^A\right)\sigma\left(\underline{b} - \underline{s}_i^A\right)\right] \qquad \int d\underline{s}\,\sigma(\underline{s}) = \sigma_{nn}^{inel}$$

If nucleon much smaller than nucleus

**(1.4)** $$\sigma(\underline{b} - \underline{s}) \approx \sigma_{nn}^{inel}\,\delta(\underline{b} - \underline{s})$$

**(1.5)** $$P_0(\underline{b}) = \left[1 - T_A\left(\underline{b}\right)\sigma_{nn}^{inel}\right]^A$$




Transverse position $\underline{s}_i^A$
of i-th nucleon in nucleus A

The resulting nucleon-nucleon cross section is:

**(1.6)** $$\sigma_{nA}^{inel} = \int d\underline{b}\left(1 - P_0\left(\underline{b}\right)\right) = \int d\underline{b}\left[1 - \left[1 - T_A\left(\underline{b}\right)\sigma_{nn}^{inel}\right]^A\right]$$

$$\xrightarrow{A>>n} \int d\underline{b}\left[1 - \exp\left[-AT_A\left(\underline{b}\right)\sigma_{nn}^{inel}\right]\right]$$ Optical limit

**(1.7)** $$= \int d\underline{b}\left[AT_A\left(\underline{b}\right)\sigma_{nn}^{inel} - \frac{1}{2}\left(AT_A\left(\underline{b}\right)\sigma_{nn}^{inel}\right)^2 + \ldots\right]$$

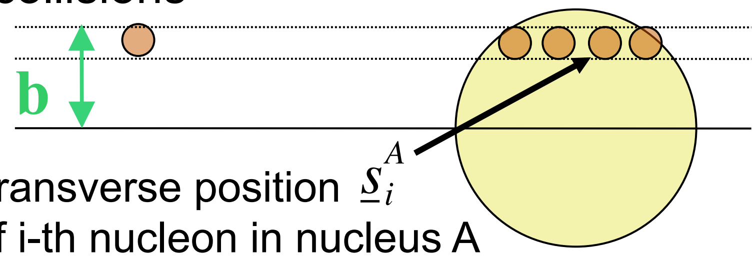
Double counting correction

# I.5. Glauber theory for n+A

To calculate number of collisions: probability of interacting with i-th nucleon in A is

**(1.8)** $$p(\underline{b},\underline{s}_i^A) = \int d\underline{s}_i^A T_A\left(\underline{s}_i^A\right)\sigma\left(\underline{b}-\underline{s}_i^A\right) = T_A(\underline{b})\,\sigma_{nn}^{inel}$$

Probability that projectile nucleon undergoes n collisions
= prob that n nucleons collide and A-n do not




**(1.9)** $$P(\underline{b},n) = \binom{A}{n}(1-p)^{A-n}\,p^n$$

Average number of nucleon-nucleon collisions in n+A

**(1.10)** $$\overline{N}_{coll}^{nA}(\underline{b}) = \sum_{n=0}^{A} n\,P(\underline{b},n) = \sum_{n=0}^{A} n\binom{A}{n}(1-p)^{A-n}\,p^n = A\,p$$

$$= A\,T_A(\underline{b})\,\sigma_{nn}^{inel}$$

Average number of nucleon-nucleon collisions in n+A

**(1.11)** $$\overline{N}_{part}^{nA}(\underline{b}) = 1 + \overline{N}_{coll}^{nA}(\underline{b})$$

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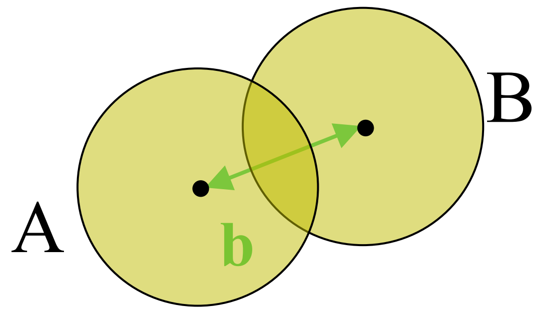
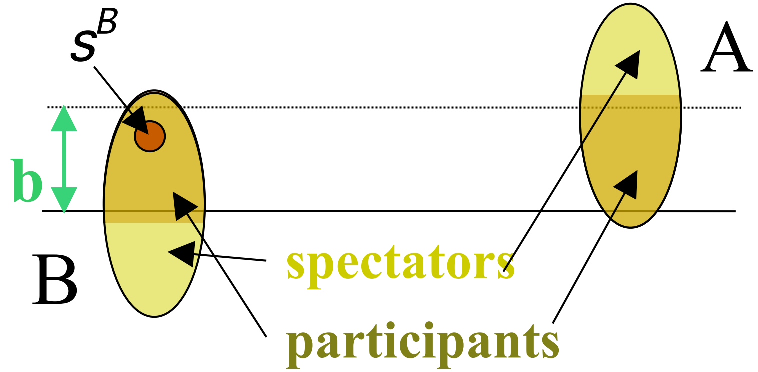
# I.6. Glauber theory for A+B collisions

We define the nuclear overlap function




**(1.12)**
$$T_{AB}(\vec{b}) = \int_{-\infty}^{\infty} d\vec{s}\; T_A(\vec{s})\, T_B(\vec{b} - \vec{s})$$

The average number of collisions of nucleon at $s^B$ with nucleons in A is




**(1.13)**
$$\overline{N}^{nA}_{coll}(\underline{b} - \underline{s}^B) = A\, T_A(\underline{b} - \underline{s}^B)\, \sigma^{inel}_{nn}$$

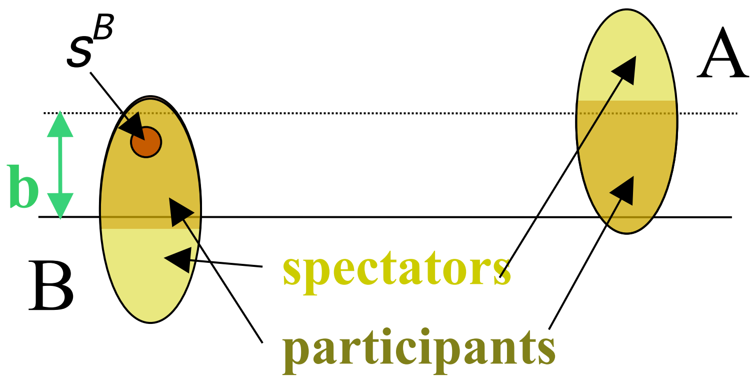
The number of nucleon-nucleon collisions in an A-B collision at impact parameter b is

**(1.14)**
$$\overline{N}^{AB}_{coll}(\underline{b}) = B \int d\underline{s}^B\, T_B(\underline{s}^B)\, \overline{N}^{nA}_{coll}(\underline{b} - \underline{s}^B)$$
$$= AB \int d\underline{s}\, T_B(\underline{s})\, T_B(\underline{b} - \underline{s})\, \sigma^{inel}_{nn}$$
$$= A\, B\, T_{AB}(\underline{b})\, \sigma^{inel}_{nn}$$

determined in terms of nuclear overlap only

# I.7. Glauber theory for A+B collisions

Probability that nucleon at $s^B$ in B is wounded by A in configuration $\{s_i^A\}$




**(1.15)** $$p(\underline{s}^B,\{\underline{s}_i^A\}) = 1 - \prod_{i=1}^{A}\left[1-\sigma(\underline{s}^B - \underline{s}_i^A)\right]$$

Probability of finding $w_B$ wounded nucleons in nucleus B:

**(1.16)** $$P(w_b,\underline{b}) = \binom{B}{w_B}\left(\prod_{i=1}^{A}\prod_{j=1}^{B}\int d\underline{s}_i^A\, d\underline{s}_j^B\, T_A(\underline{s}_i^A)\, T_B(\underline{s}_j^B - \underline{b})\right) p(\underline{s}_1^B,\{\underline{s}_i^A\})\dots$$
$$\dots p(\underline{s}_{w_B}^B,\{\underline{s}_i^A\})\left[1-p(\underline{s}_{w_B+1}^B,\{\underline{s}_i^A\})\right]\dots\left[1-p(\underline{s}_B^B,\{\underline{s}_i^A\})\right]$$

Nuclear overlap function defines inelastic A+B cross section.

**(1.17)** $$\sigma_{AB}^{inel} = \int d\underline{b}\,\sigma_{AB}(\underline{b}) = \int d\underline{b}\, P(w_B = 0,\underline{b})$$
$$= \int d\underline{b}\left[1-\left(\prod_{i=1}^{A}\prod_{j=1}^{B}\int d\underline{s}_i^A\, d\underline{s}_j^B\, T_A(\underline{s}_i^A)\, T_B(\underline{s}_j^B - \underline{b})\right)\prod_{j=1}^{B}\left[1-p(\underline{s}_j^B,\{\underline{s}_i^A\})\right]\right]$$
$$\approx \int d\underline{b}\left[1-\left[1-T_{AB}(b)\,\sigma_{NN}^{inel}\right]^{AB}\right]$$

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# I.8. Glauber theory for A+B collisions

It can be shown

Problem 1: derive the expressions (1.17), (1.19)
Use e.g. A. Bialas et al., Nucl. Phys. B111 (1976) 461

**(1.18)** Number of collisions: $\overline{N}^{AB}_{coll}(\underline{b}) = AB\,T_{AB}(\underline{b})\,\sigma^{inel}_{NN}$

**(1.19)** Number of participants: $\overline{N}^{AB}_{part}(\underline{b}) = \frac{A\sigma^{inel}_{B}(\underline{b})}{\sigma^{inel}_{AB}(\underline{b})} + \frac{B\sigma^{inel}_{A}(\underline{b})}{\sigma^{inel}_{AB}(\underline{b})} \neq \overline{N}^{AB}_{coll}(\underline{b}) + 1$

1. There is a difference between 'analytical' and 'Monte Carlo' Glauber theory: For 'MC Glauber, a random probability distribution is picked from $T_A$.

2. The nuclear density is commonly taken to follow a Wood-Saxon parametrization (e.g. for A > 16)

**(1.20)** $$\rho(\vec{r}) = \rho_0 \Big/ \left(1 + \exp\left[-(r-R)/c\right]\right); \qquad R \equiv 1.07\,A^{1/3}\,fm, c = 0.545\,fm.$$

C.W. de Jager, H.DeVries, C.DeVries, Atom. Nucl. Data Table 14 (1974) 479

3. The inelastic Cross section is energy dependent, typically

**(1.21)** $$\sigma^{inel}_{nn} \approx 40\,(65)\,mb \qquad at \qquad \sqrt{s_{nn}} = 100\ \ (2700)\ GeV.$$

But $\sigma^{inel}_{nn}$ is sometimes used as fit parameter.

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# I.9 Event Multiplicity in wounded nucleon model

Model assumption: If $\overline{n}_{nn}$ is the average multiplicity in an n-n collision, then

**(1.22)**

$$\overline{n}_{AB}(b) = \left( \frac{1-x}{2} \overline{N}^{AB}_{part}(b) + x\,\overline{N}^{AB}_{coll}(b) \right) \overline{n}_{NN}$$

is average multiplicity in A+B collision
(x=0 defines the wounded nucleon model).

The probability of having $w_b$ wounded nucleons fluctuates around the mean,
so does the multiplicity n per event (the dispersion d is a fit parameter, say d~1)

**(1.23)**

$$P(n,\underline{b}) = \frac{1}{\sqrt{2\pi\, d\, \overline{n}_{AB}(\underline{b})}} \exp\left( -\frac{\left[n - \overline{n}_{AB}(\underline{b})\right]^2}{2d\,\overline{n}_{AB}(\underline{b})} \right)$$

How many events $dN_{events}$ have event multiplicity dn?

**(1.24)**

$$\frac{dN_{events}}{dn} = \int db\, P(n,b) \underbrace{\left[1 - \left(1 - \sigma_{NN} T_{AB}(b)\right)^{AB}\right]}_{1-P_0(b)}$$

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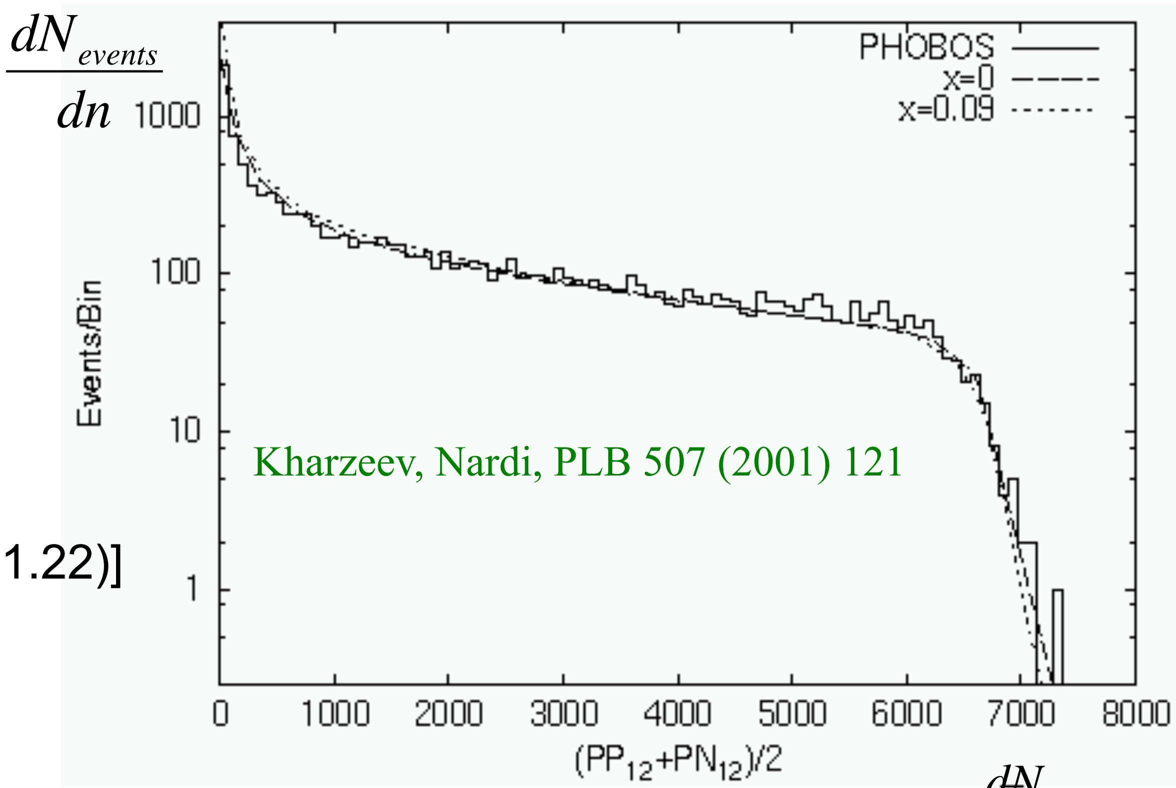
# I.10 Wounded nucleon model vs. multiplicity

Compare data to multiplicity distribution (1.24): $\frac{dN_{events}}{dn} = \int d\underline{b}\, P(n,\underline{b})\left[1 - P_0(\underline{b})\right]$

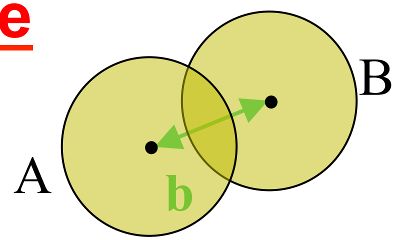



- dominated by geometry
- only weakly sensitive to details of particle production [e.g. weak dependence on x in (1.22)]
- insensitive to collective effects

Sensitivity to geometry but insensitivity to model-dependent dynamics makes $\frac{dN_{events}}{dn}$

➡ **A well-suited centrality measure**

(i.e. a measure of the impact parameter b)

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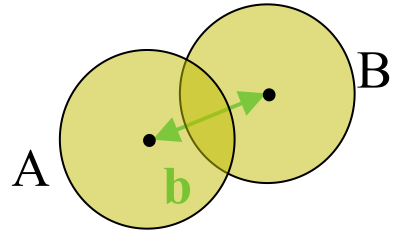
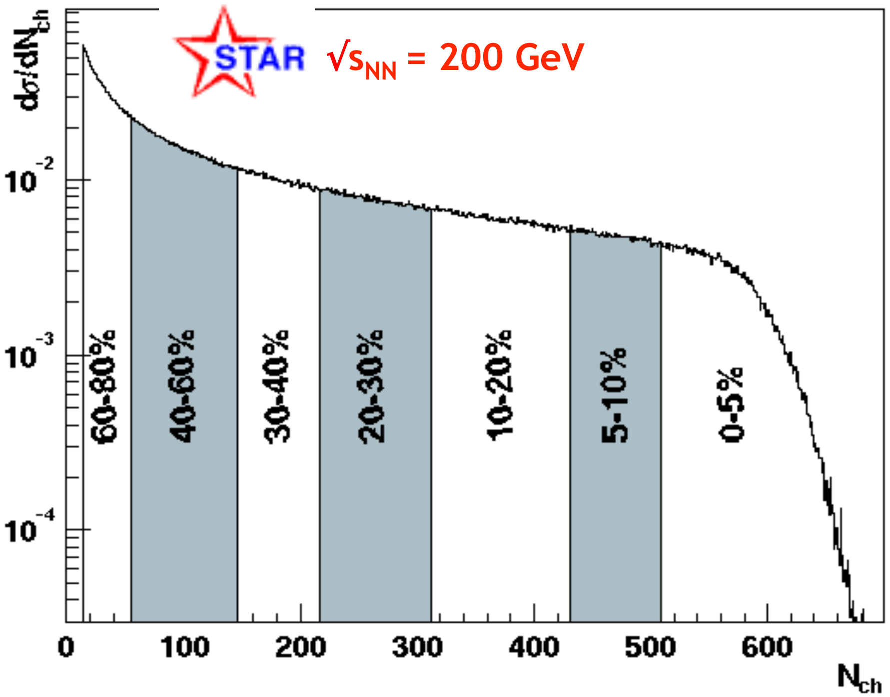
# I.11. Multiplicity as a Centrality Measure

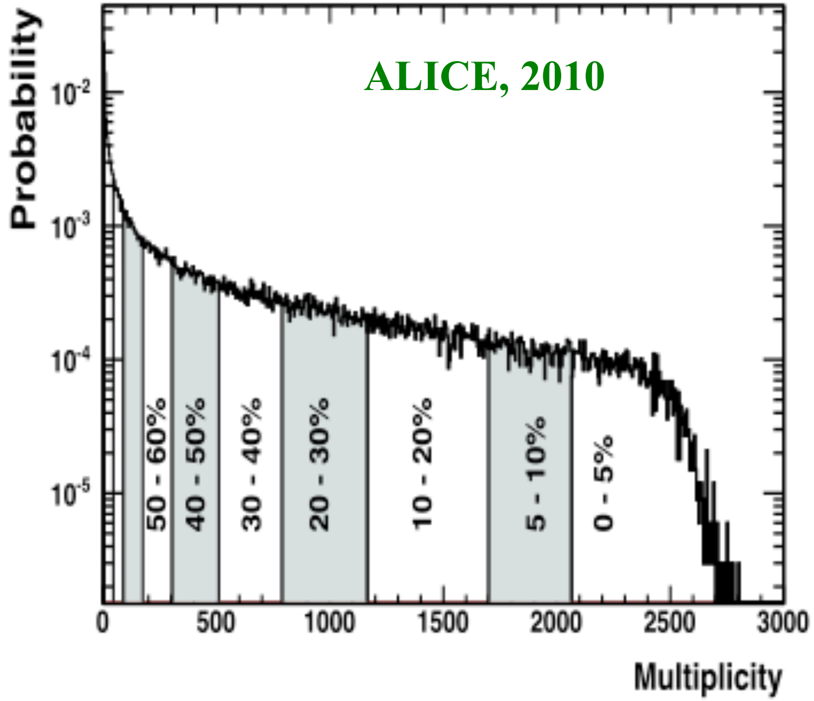
The connection between centrality and event multiplicity can be expressed in terms of

$$\text{(1.25)}\quad \left\langle N_{part}^{A+A} \right\rangle_{n>n_0} = \frac{\int_{n_0} dn \int d\underline{b}\, P(n,\underline{b}) \left[1 - P_0(\underline{b})\right] N_{part}(\underline{b})}{\int_{n_0} dn \int d\underline{b}\, P(n,\underline{b}) \left[1 - P_0(\underline{b})\right]}$$




- Centrality class = percentage of the minimum bias cross section

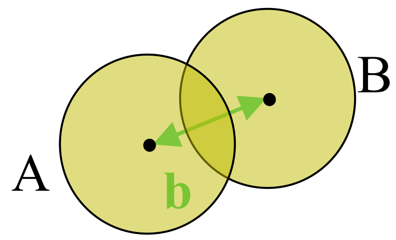


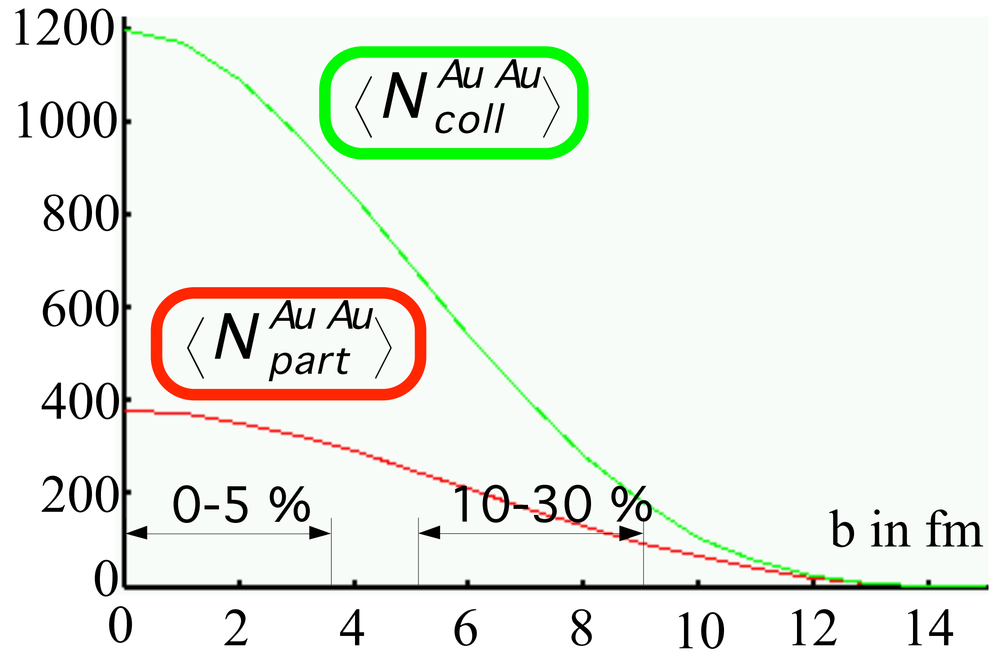
# I.12. Centrality Class fixes Impact Parameter

The connection between centrality and event multiplicity can be expressed in terms of

**(1.25)** $$\left\langle N_{part}^{A+A} \right\rangle_{n>n_0} = \frac{\int_{n_0} dn \int db\, P(n,\underline{b}) \left[1 - P_0(\underline{b})\right] N_{part}(\underline{b})}{\int_{n_0} dn \int d\underline{b}\, P(n,\underline{b}) \left[1 - P_0(\underline{b})\right]}$$




- Centrality class specifies range of impact parameters

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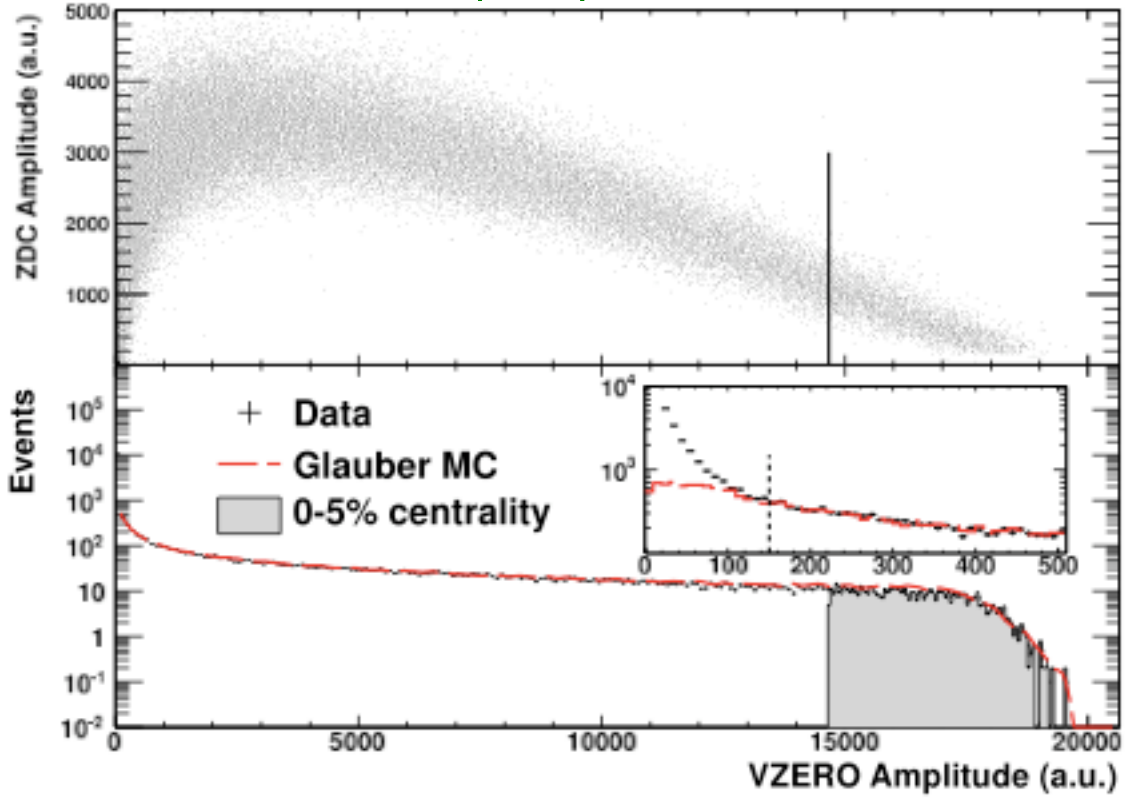
# I.13. Cross-Checking Centrality Measurements

The interpretation of min. bias multiplicity distributions in terms of centrality measurements can be checked in multiple ways, e.g.

1. Energy $E_F$ of spectators is deposited in Zero Degree Calorimeter (ZDC)

$$E_F = \left(A - N_{part}(b)/2\right)\sqrt{s}/2$$

**ALICE, PRL 105 (2010) 252301, arXiv:1011.3916**

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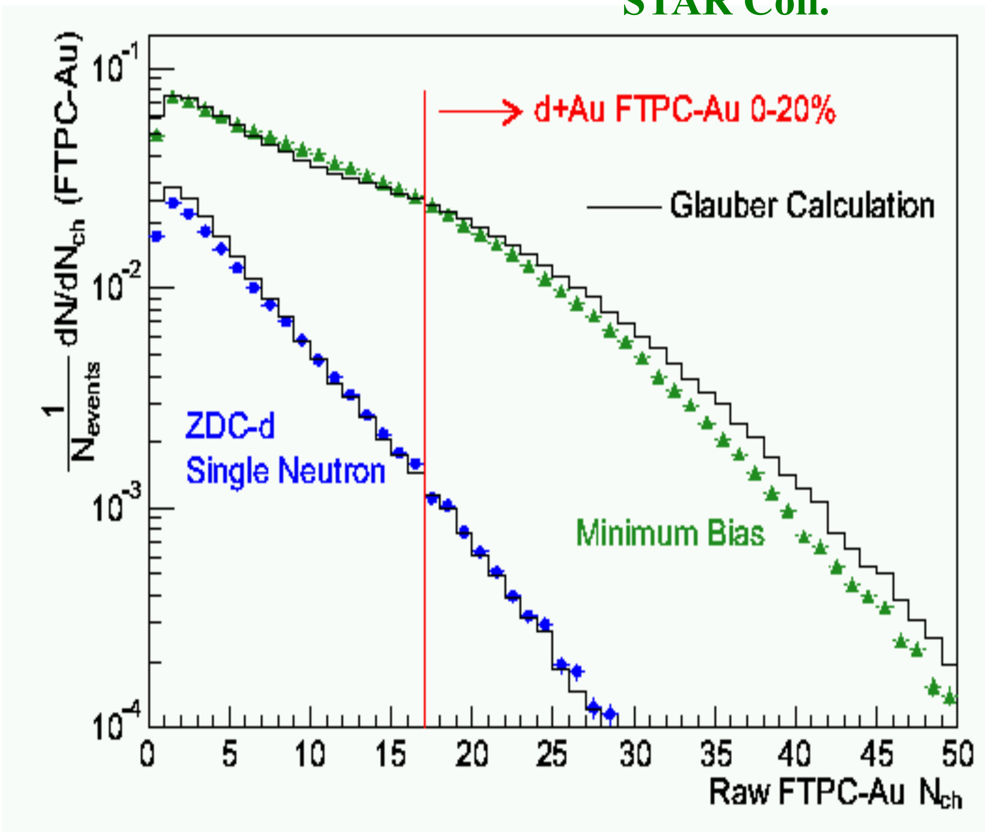
# I.14. Cross-Checking Centrality Measurements

The interpretation of min. bias multiplicity distributions in terms of centrality measurements can be checked in multiple ways, e.g.

2. Testing Glauber in d+Au and in p+Au(+ n forward)

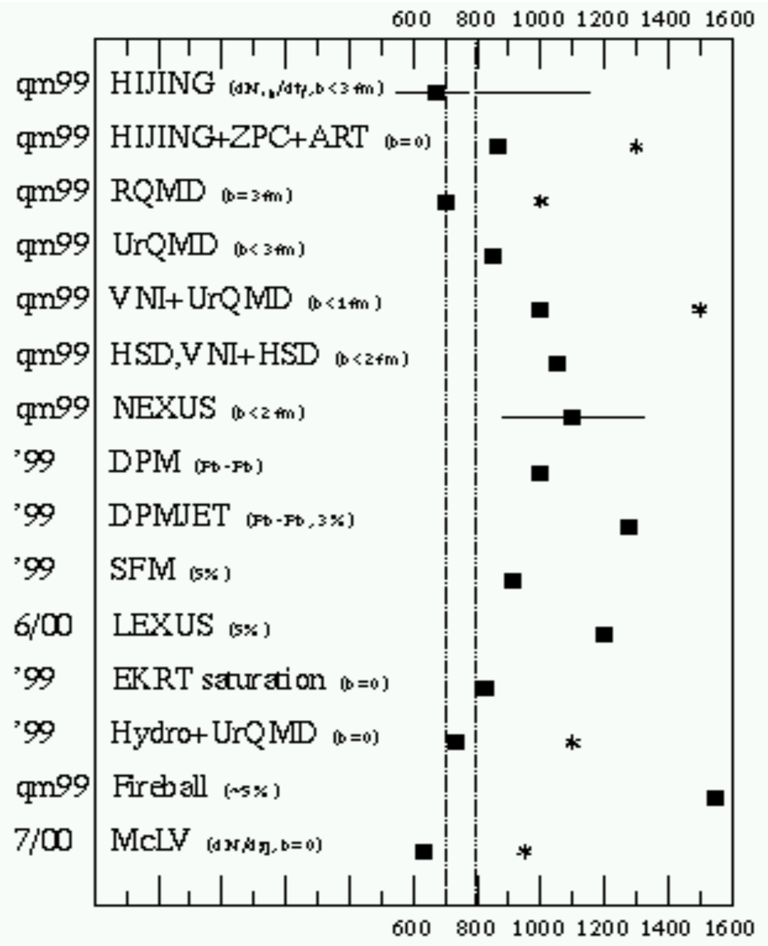
STAR Coll.



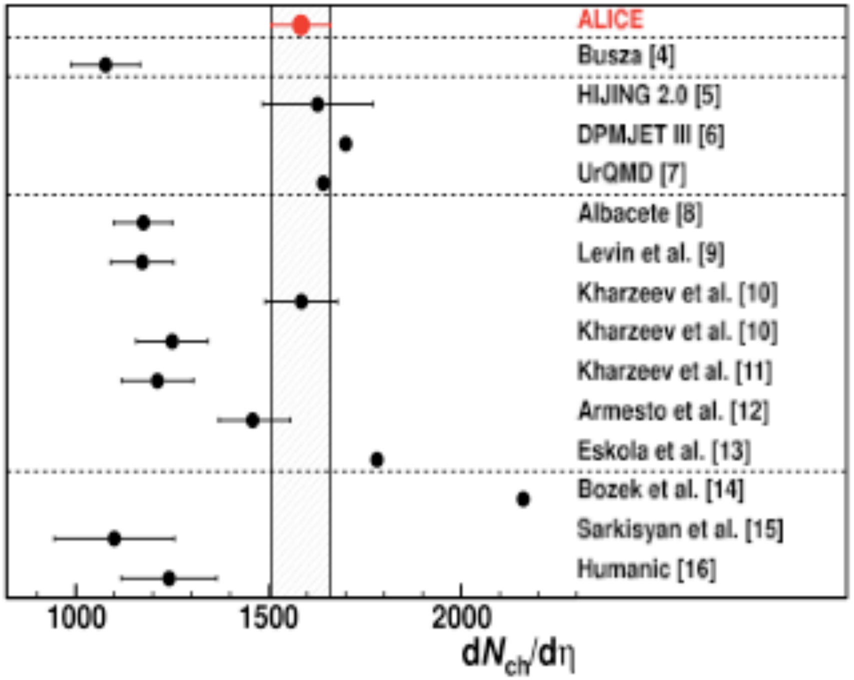
# I.15. Final remarks on event multiplicity in A+B

There is **no 1st principle QCD calculation** of event multiplicity, neither in p+p nor in A+B

- Total charged event multiplicity: models failed to predict RHIC




- and failed to predict LHC

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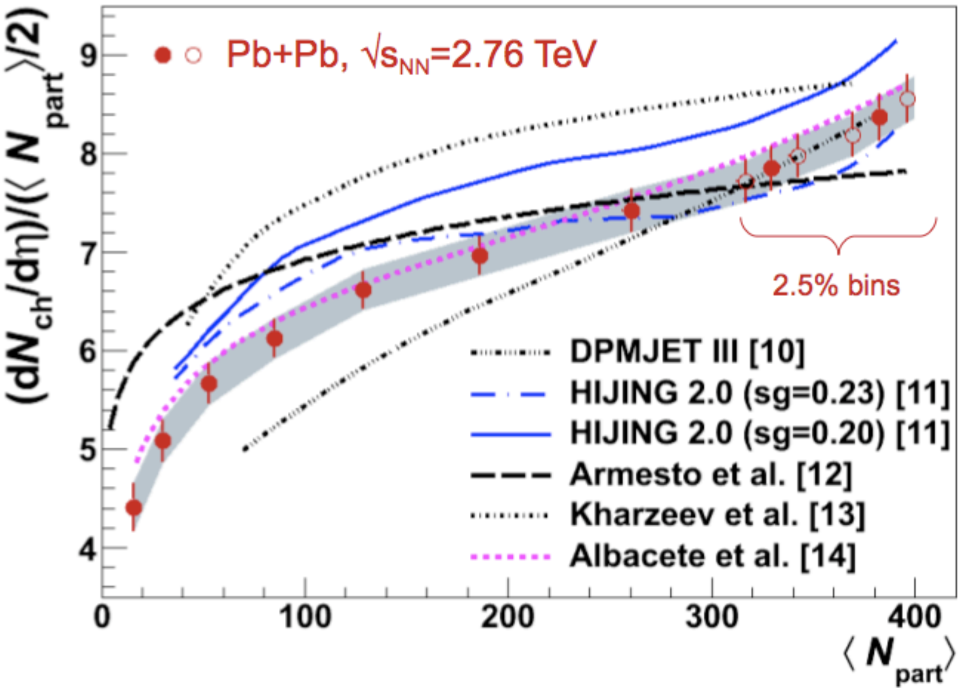
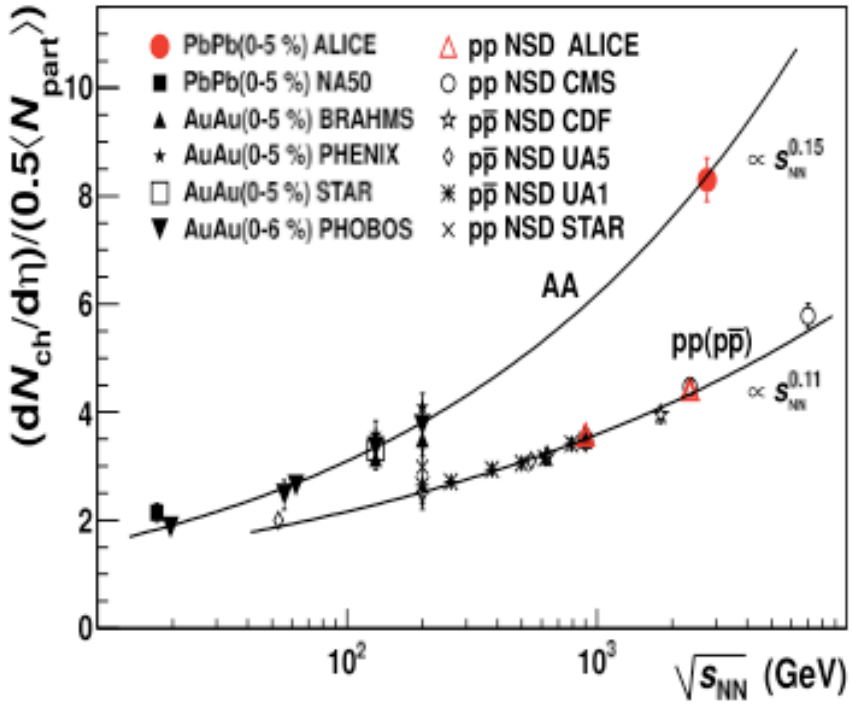
# I.16. Final remarks on event multiplicity in A+B

There is **no 1st principle QCD calculation** of event multiplicity, neither in p+p nor in A+B

- Clear deviations from multiplicity of wounded nucleon model
- $\sqrt{s}$ - dependence of event multiplicity not understood in pp and AA

**ALICE Coll., PRL 106, 032301 (2001) arXiv:1012.1657**

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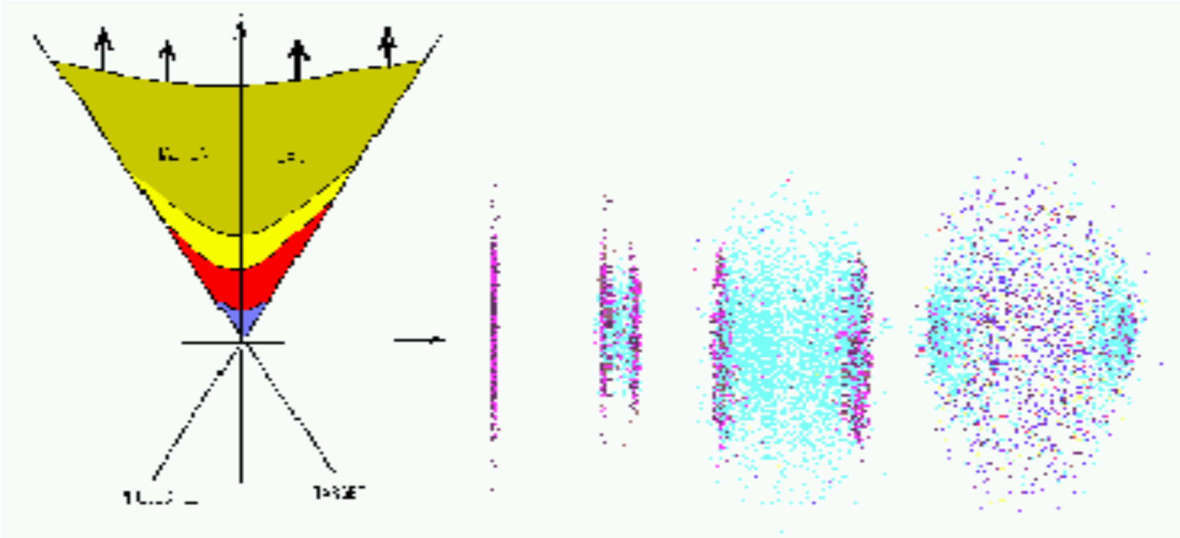
# I.17. Final remarks on event multiplicity

Multiplicity distribution is not only used as centrality measure but:



Multiplicity (or transverse energy) constrains density of produced matter

**Bjorken estimate**

$$\varepsilon(\tau_0) = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

$$\frac{dE_T}{dy} \approx \frac{dN}{dy} \langle E_T \rangle$$

This estimate is based on geometry, thermalization is not assumed, numerically:

$$\varepsilon(\tau_0 \cong 1 fm/c) = 3 - 4 GeV/fm^3$$

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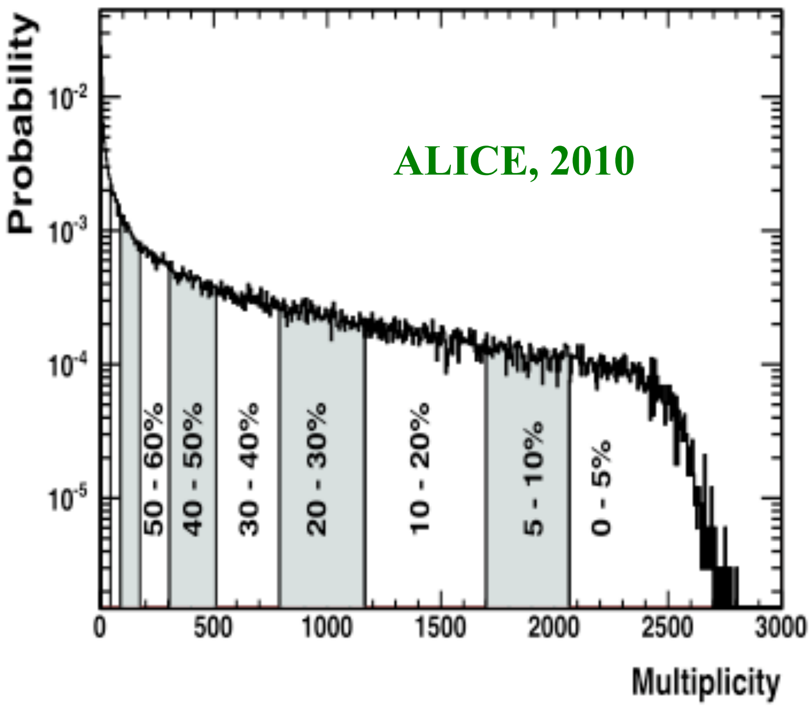
# II.1. Azimuthal Anisotropies of Particle Production

We know how to associate an impact parameter range $b \in [b_{\min}, b_{\max}]$ to an event class in A+A, namely by selecting a multiplicity class.




What can we learn by characterizing not only the modulus $b$ , but also the orientation $\underline{b}$ ?

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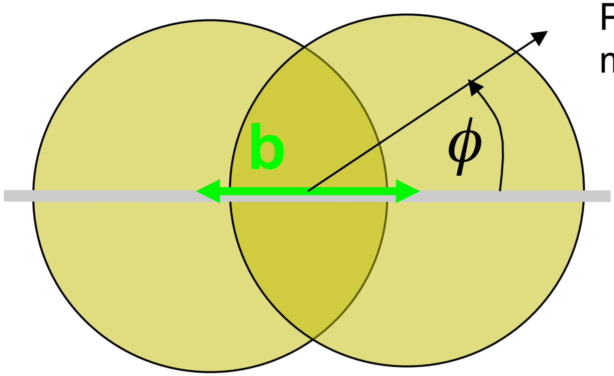
# II.2. Particle production w.r.t. reaction plane

Consider single inclusive particle momentum spectrum




**(2.1)** $$f(\vec{p}) \equiv dN / E\, d\vec{p}$$

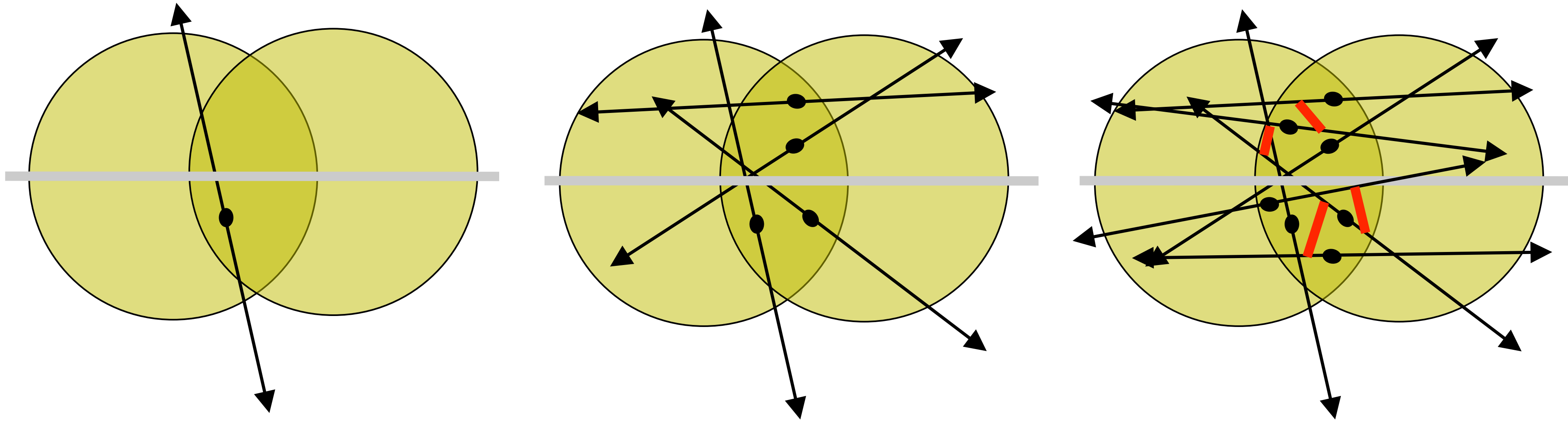
**(2.2)** $$\vec{p} = \begin{pmatrix} p_x = p_T \cos\phi \\ p_y = p_T \sin\phi \\ p_z = \sqrt{p_T^2 + m^2}\,\sinh Y \end{pmatrix}$$

To characterize azimuthal asymmetry, measure n-th harmonic moment of (2.1) in some detector acceptance *D* [phase space window in ($p_T$,Y)-plane].

**(2.3)** $$v_n \equiv \left\langle\left\langle e^{i n \phi} \right\rangle\right\rangle = \left\langle \frac{\int_D d\vec{p}\, e^{i n \phi} f(\vec{p})}{\int_D d\vec{p}\, f(\vec{p})} \right\rangle_{\substack{event \\ average}}$$ **n-th order flow**

Problem: Eq. (2.3) cannot be used for data analysis, since the orientation of the reaction plane is not known a priori.

# II.3. Why is the study of $v_n$ interesting?



- Single 2->2 process
- Maximal asymmetry
- NOT correlated to the reaction plane

- Many 2->2 or 2-> n processes
- Reduced asymmetry $\sim 1/\sqrt{N}$
- NOT correlated to the reaction plane

- final state interactions
- asymmetry caused not only by multiplicity fluctuations
- collective component is correlated to the reaction plane

The azimuthal asymmetry of particle production has a collective and a random component. Disentangling the two requires a statistical analysis of finite multiplicity fluctuations.

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# II.4. Cumulant Method

If reaction plane is unknown, consider particle correlations

**(2.4)** $$\left\langle e^{i\,n\,(\phi_1-\phi_2)}\right\rangle_{D_1 \wedge D_2} = \frac{\int_{D_1 \wedge D_2} d\vec{p}_1 d\vec{p}_2\, e^{i\,n\,(\phi_1-\phi_2)} f(\vec{p}_1,\vec{p}_2)}{\int_{D_1 \wedge D_2} d\vec{p}_1 d\vec{p}_2\, f(\vec{p}_1,\vec{p}_2)}$$

A two-particle distribution has an uncorrelated and a correlated part

**(2.5)** $$f(\vec{p}_1,\vec{p}_2) = f(\vec{p}_1)f(\vec{p}_2) + f_c(\vec{p}_1,\vec{p}_2)$$

**(2.6)** Short hand $$(1,2) = (1)(2) + (1,2)_c$$

Correlated part

Assumption: Event multiplicity N>>1

⇒ correlated part is O(1/N)-correction to $f(\vec{p}_1)f(\vec{p}_2)$

**(2.7)** $$\left\langle\left\langle e^{i\,n(\phi_1-\phi_2)}\right\rangle\right\rangle = v_n\{2\}\, v_n\{2\} + \underbrace{\left\langle\left\langle e^{i\,n(\phi_1-\phi_2)}\right\rangle^{corr}\right\rangle}_{O(1/N)}$$

Flow via 2nd order cumulants

"Non-flow effects"

**(2.8)** If $v_n\{2\} >> \frac{1}{\sqrt{N}}$ ,then non-flow corrections are negligible.

What, if this is not the case?

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# II.5. 4-th order Cumulants

2nd order cumulants allow to characterize $v_n$, if $v_n \gg 1/\sqrt{N}$.
Consider now 4-th order cumulants:

**(2.9)**
$$\begin{aligned}(1,2,3,4) = (1)(2)(3)(4) + (1,2)_c(3)(4) + \dots \\ + (1,2)_c(3,4)_c + (1,3)_c(2,4)_c + (1,4)_c(2,3)_c \\ + (1,2,3)_c(4) + \dots \\ + (1,2,3,4)_c\end{aligned}$$

If the system is isotropic, i.e. $v_n(D)=0$, then k-particle correlations are unchanged by rotation $\phi_i \rightarrow \phi_i + \phi$ for all i, and only labeled terms survive. This defines

**(2.9)**
$$c_n\{4\} \equiv \left\langle\left\langle e^{i\,n(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\right\rangle - \left\langle\left\langle e^{i\,n(\phi_1-\phi_3)}\right\rangle\right\rangle\left\langle\left\langle e^{i\,n(\phi_2-\phi_4)}\right\rangle\right\rangle - \left\langle\left\langle e^{i\,n(\phi_1-\phi_4)}\right\rangle\right\rangle\left\langle\left\langle e^{i\,n(\phi_2-\phi_3)}\right\rangle\right\rangle$$

For small, non-vanishing $v_n$, one finds

Borghini, Dinh, Ollitrault, PRC (2001)

**(2.10)**
$$c_n\{4\} = -v_n^4\{4\} + O\left(\tfrac{1}{N^3}, \tfrac{v_{2n}^2}{N^2}\right)$$

Improvement: signal can be separated from fluctuating background, if $v_n\{4\} \gg \frac{1}{N^{3/4}}$

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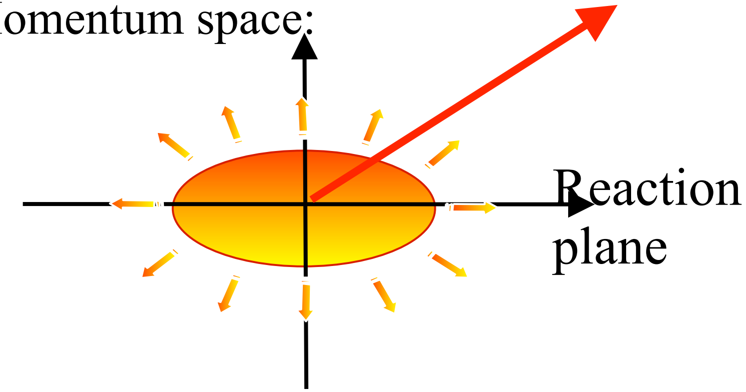
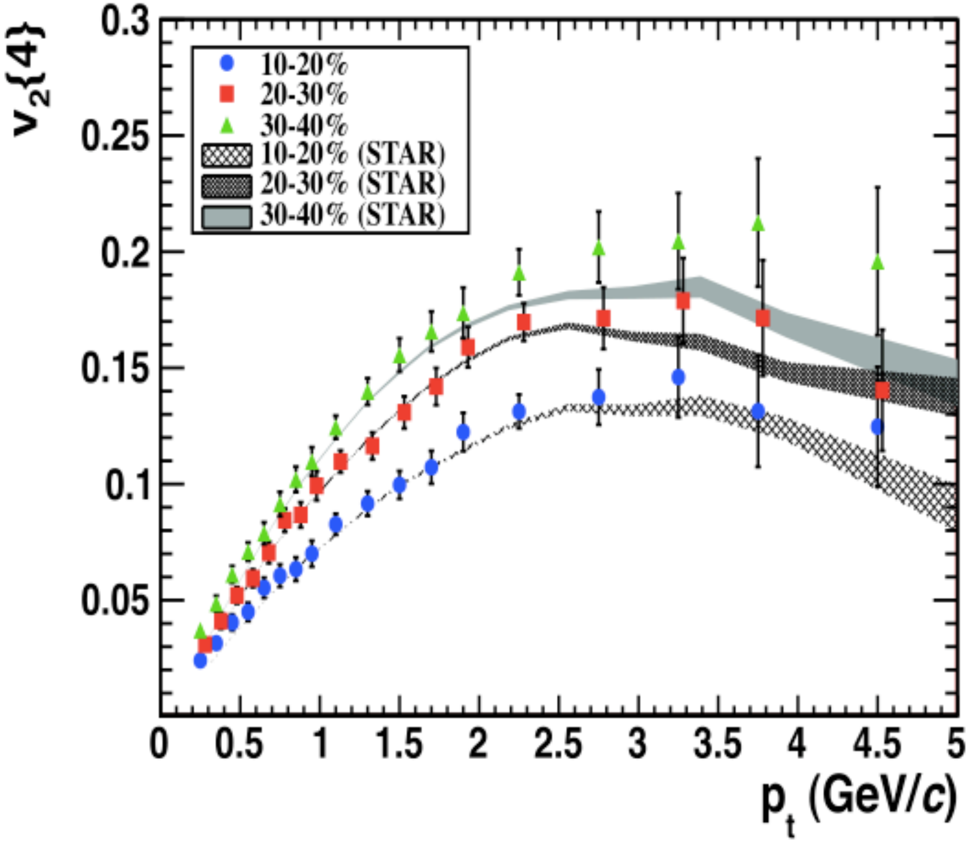
# II.6. LHC and RHIC Data on Elliptic Flow: $v_2$

**(2.11)** $$E\frac{dN}{d^3p} = \frac{1}{2\pi}\frac{dN}{p_T dp_T d\eta}\left[1 + 2v_2(p_T)\cos\left(2(\phi - \psi_{reaction\ plane})\right)\right]$$

- Momentum space:




- Signal $v_2 \approx 0.2$ implies 2-1 asymmetry of particles production w.r.t. reaction plane.

- 'Non-flow' effect for 2nd order cumulants

**(2.12)** $$N \sim 100 \Rightarrow 1/\sqrt{N} \sim O(v_2)$$

2nd order cumulants do not characterize solely collectivity.

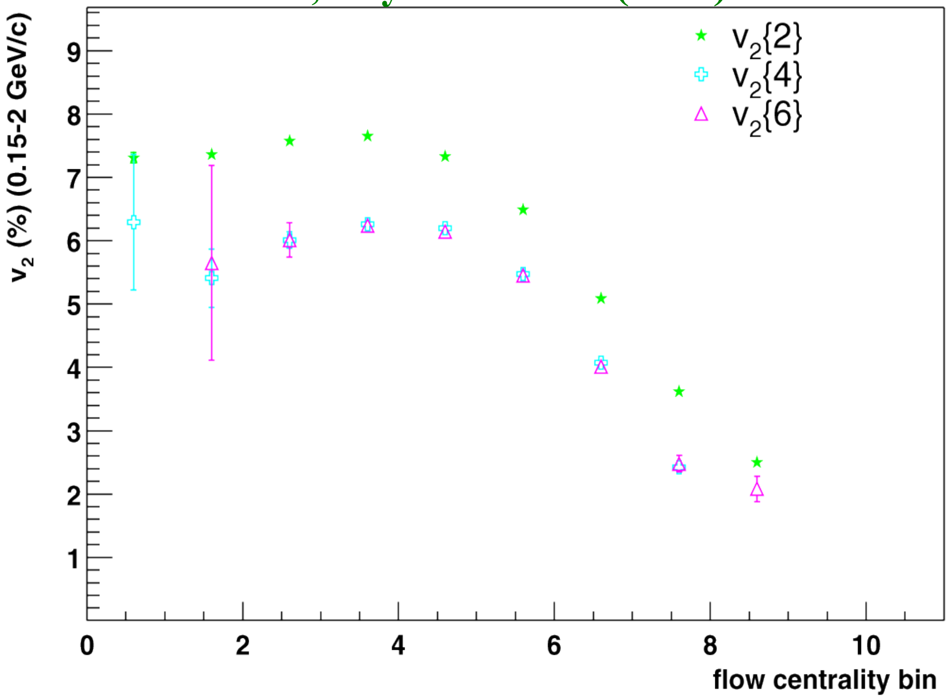
**(2.13)** $$1/N^{3/4} \sim 0.03 \ll v_2$$

Non-flow effects should disappear if we go from 2nd to 4th order cumulants.

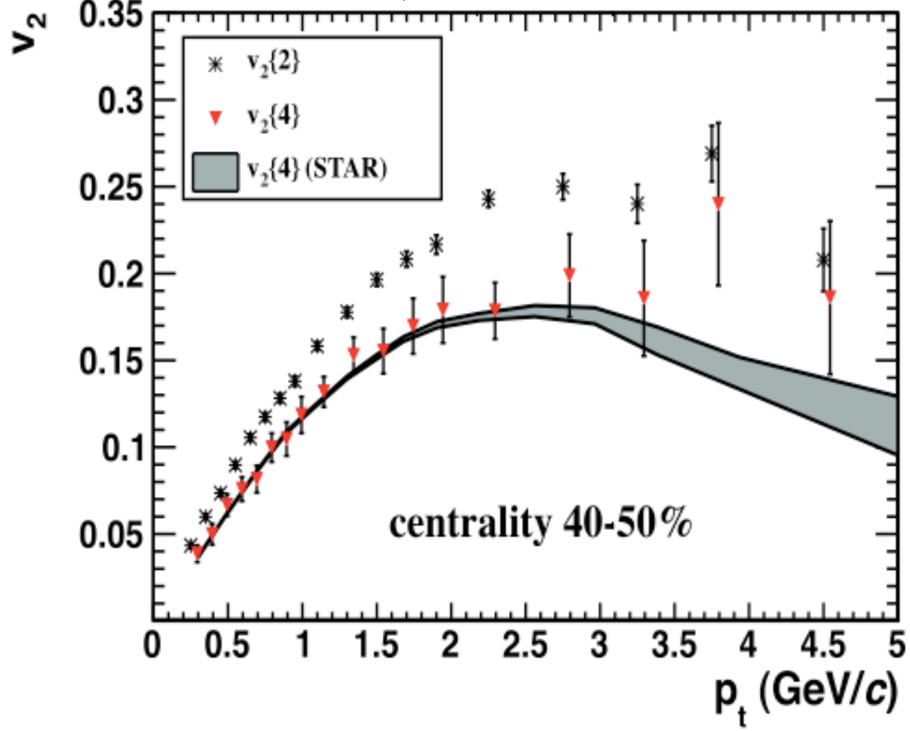
# II.7. Establishing collectivity in $v_2$

- pt-integrated v2 stabilizes at 4th order cumulants
- pt-differential v2 from 2nd and 4th order cumulants

STAR Coll, Phys. Rev. C66 (2002) 034904




ALICE Coll., arXiv:1011.3914




Elliptic flow signal is stable if reconstructed from higher order cumulants.

➡ We have established a **strong collective effect**, which cannot be mimicked by multiplicity fluctuations in the reaction plane.

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