WEEK 3:
BASICS OF HEAVY-ION PHENOMENOLOGY

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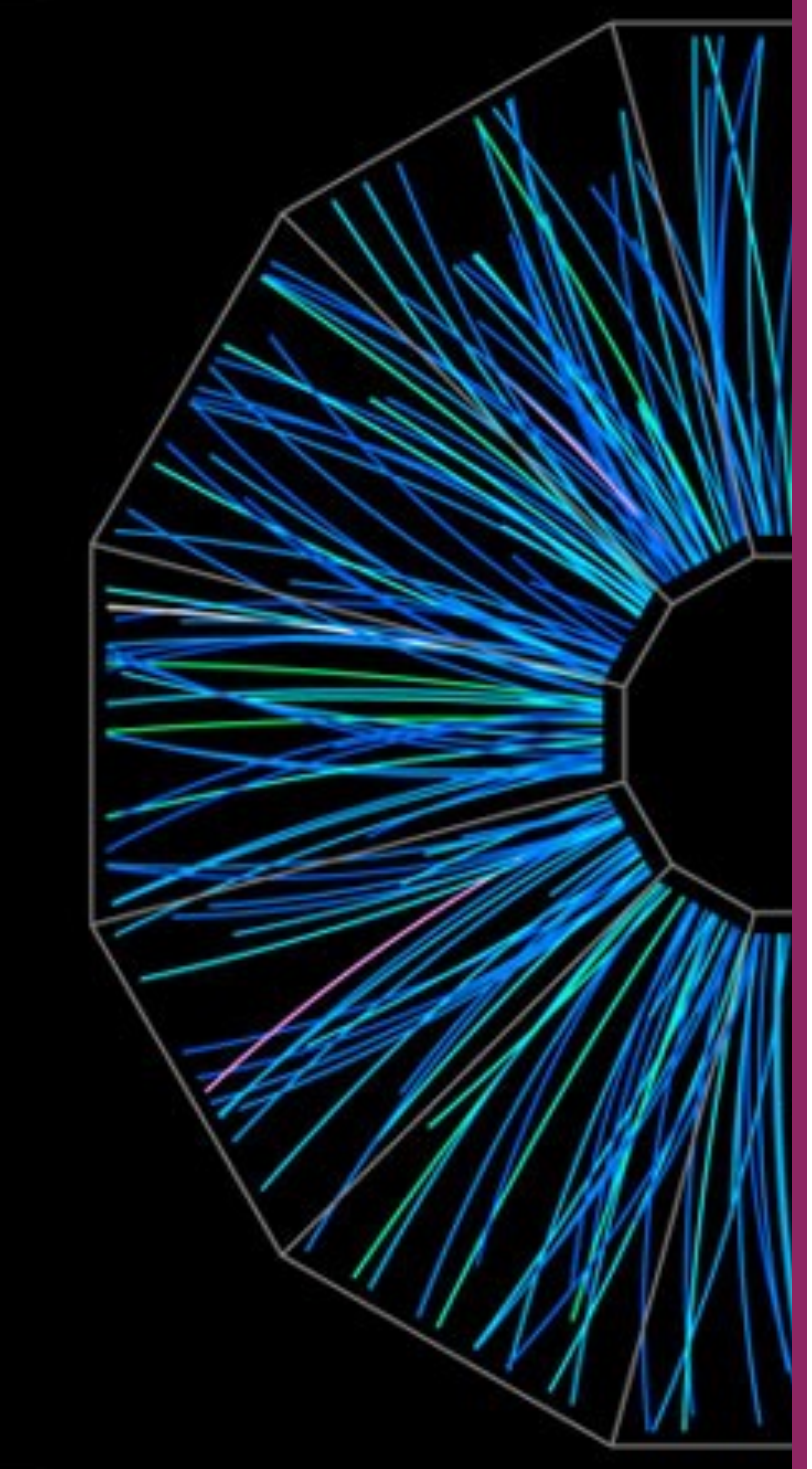


CONTENTS

- The Basics
- The Baseline: p+p collisions
- Nuclear collisions
- The Glauber Model

BASICS: THE CROSS-SECTION

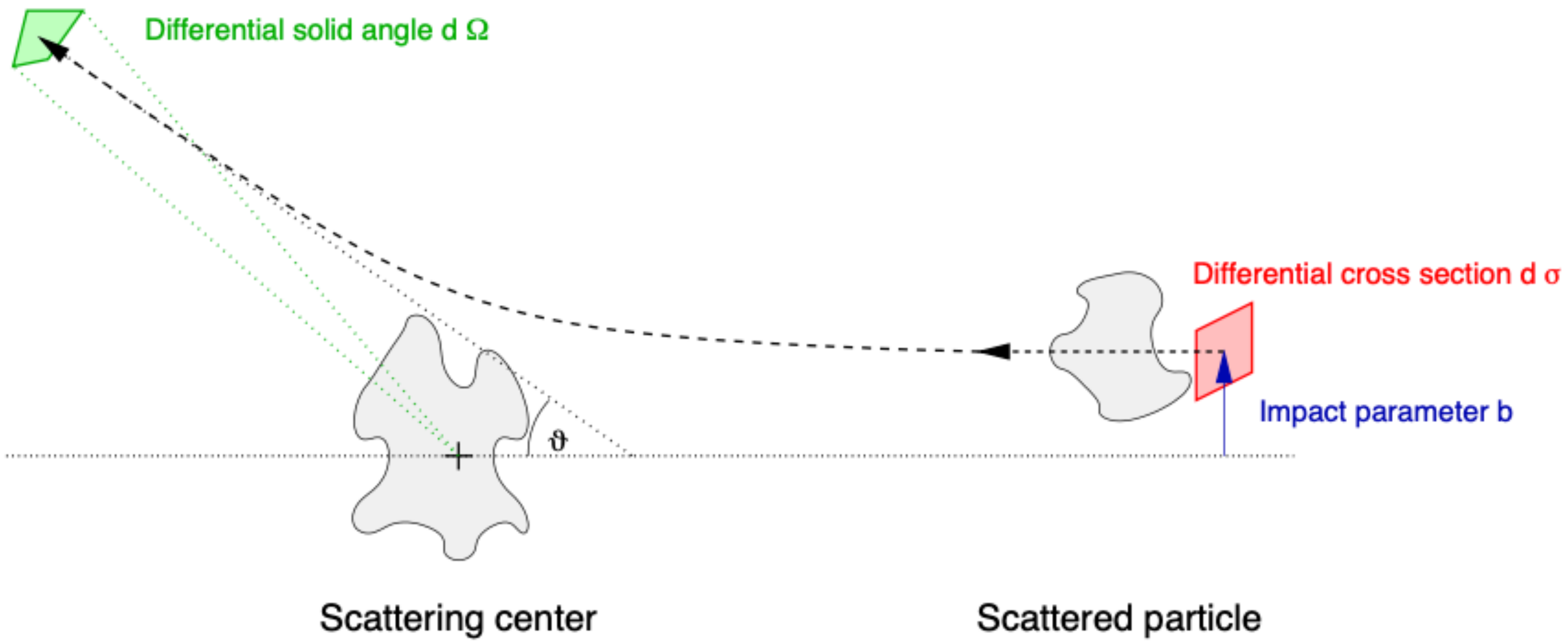
- We are performing scattering experiments, the cross section, σ , is the fundamental object.
- The cross-section describes the likelihood of two particles interacting under certain conditions. Say, the probability that a reaction happens.
- Example: Quantum scattering off a potential

$$d\sigma = |f(\Omega)|^2 d\Omega$$

$d\sigma$: Differential probability

$|f(\Omega)|^2$: Scattering amplitude

$d\Omega$: differential section of the phase space

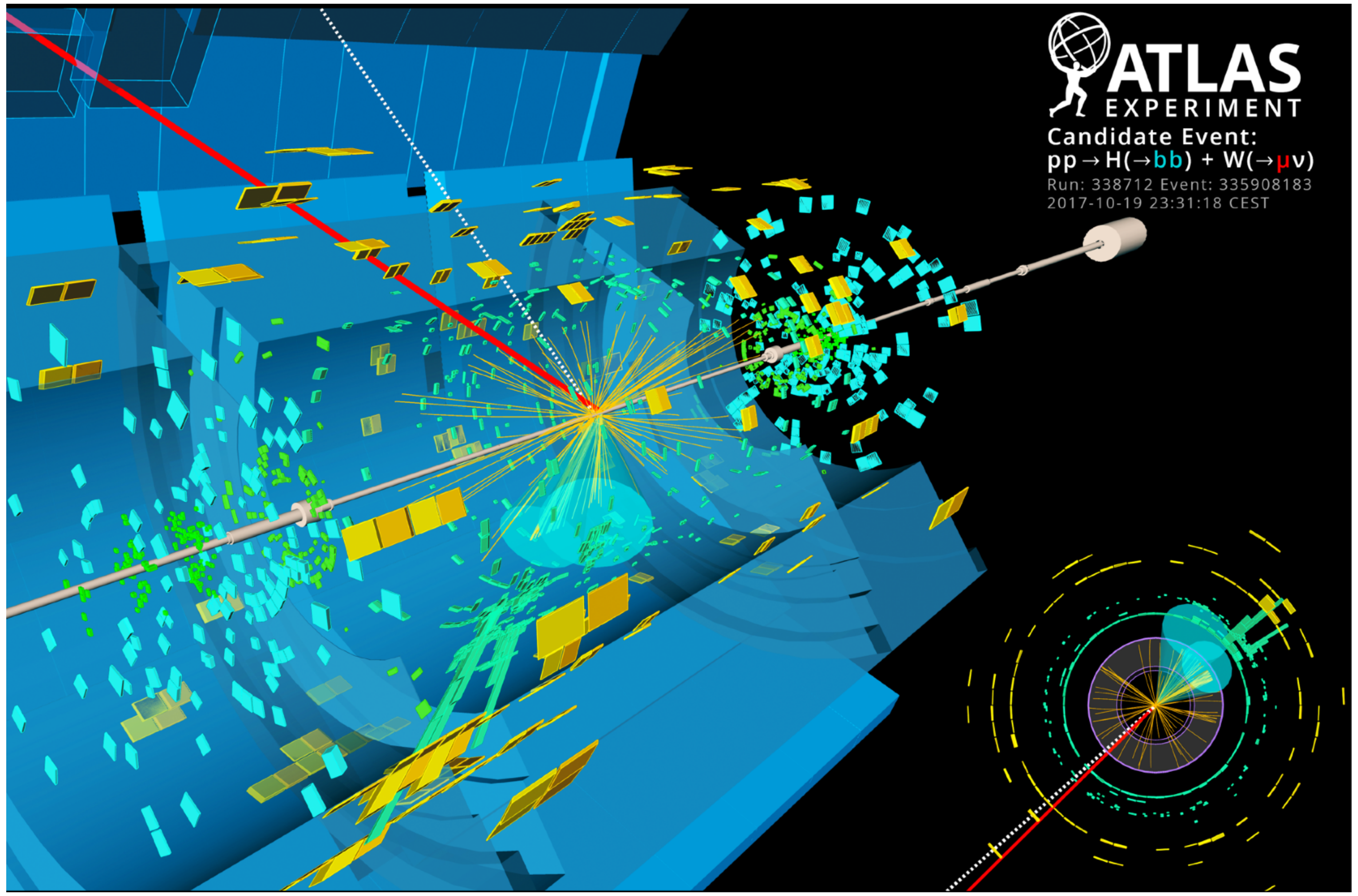


BASICS: THE CROSS-SECTION

- We are performing scattering experiments, the cross section, σ , is the fundamental object.
- The cross-section describes the likelihood of two particles interacting under certain conditions. Say, the probability that a reaction happens.
- In particle physics, it is a bit more complicated

$$\mathscr{P}(AB \to 12...) = \left(\prod_f \frac{d^3 p_f}{(2\pi)^3} \frac{1}{2E_f} \right) \left| {}_{out}\langle p_1 \, p_2 \ldots | \psi_A \, \psi_B \rangle \right|^2$$

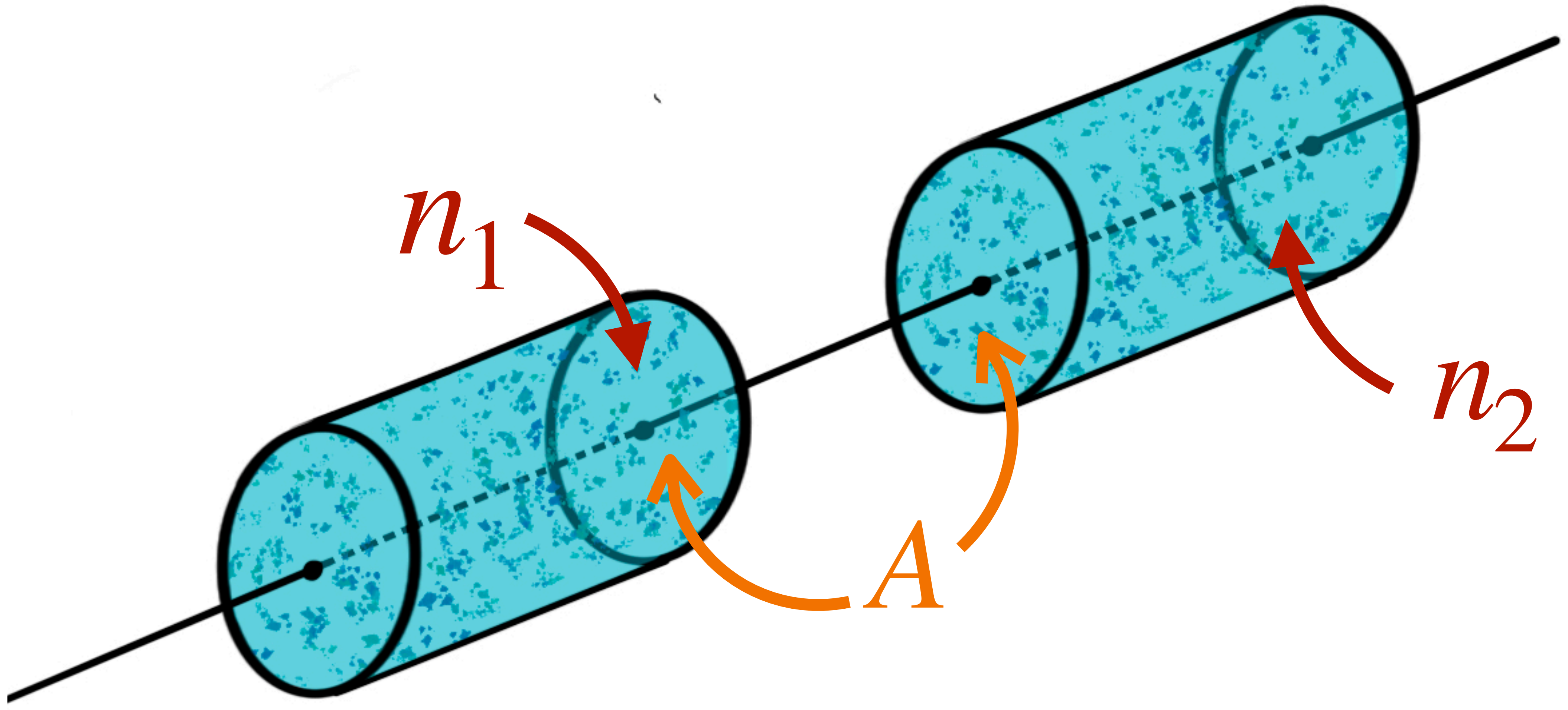
$$\Downarrow \quad d\sigma \qquad \Downarrow \quad d\Omega \qquad \Downarrow \quad |f(\Omega)|^2$$



LUMINOSITY AND CROSS SECTION

In collider experiments, collisions happen between batches of particles along the beam line. The number of reactions happening at any time can be estimated

$$\frac{dN_{int}}{dt} = \sigma L$$



Where

L = luminosity (in $s^{-1}cm^{-2}$)

$\frac{dN_{int}}{dt}$: Number of interactions of a certain type per second

σ= cross section for this reaction

Additionally, $$L = \frac{n_1 n_2 f_{\text{coll}}}{A}$$

Where

n_i = numbers of particles per bunch in the two beams

f_{coll} : bunch collision frequency at a given crossing point

A = beam crossing area

BASICS: FROM CROSS-SECTION TO THE YIELD

- Reaction cross section can be reduced by integrating over all final-states outside of particle species of interest

$$E_i \frac{d\sigma}{d^3p_i} \equiv \int d\Omega_{f/i} E_i E_1 \dots E_{N-1} \frac{d\sigma}{d^3p_i d^3p_1 \dots d^3p_{N-1}}$$

- Explore the symmetries

$$E_i \frac{d\sigma}{d^3p_i} = \frac{d\sigma}{d^2\mathbf{p}_{i,\perp} dy}$$ using $p_z = m_\perp \sinh y$

$$E_i \frac{d\sigma}{d^3p_i} = \frac{1}{2\pi p_{i,\perp}} \frac{d\sigma}{dp_{i,\perp} dy}$$ using azimuthal sym. (Homogenous in φ)

- The complete integration has as a result

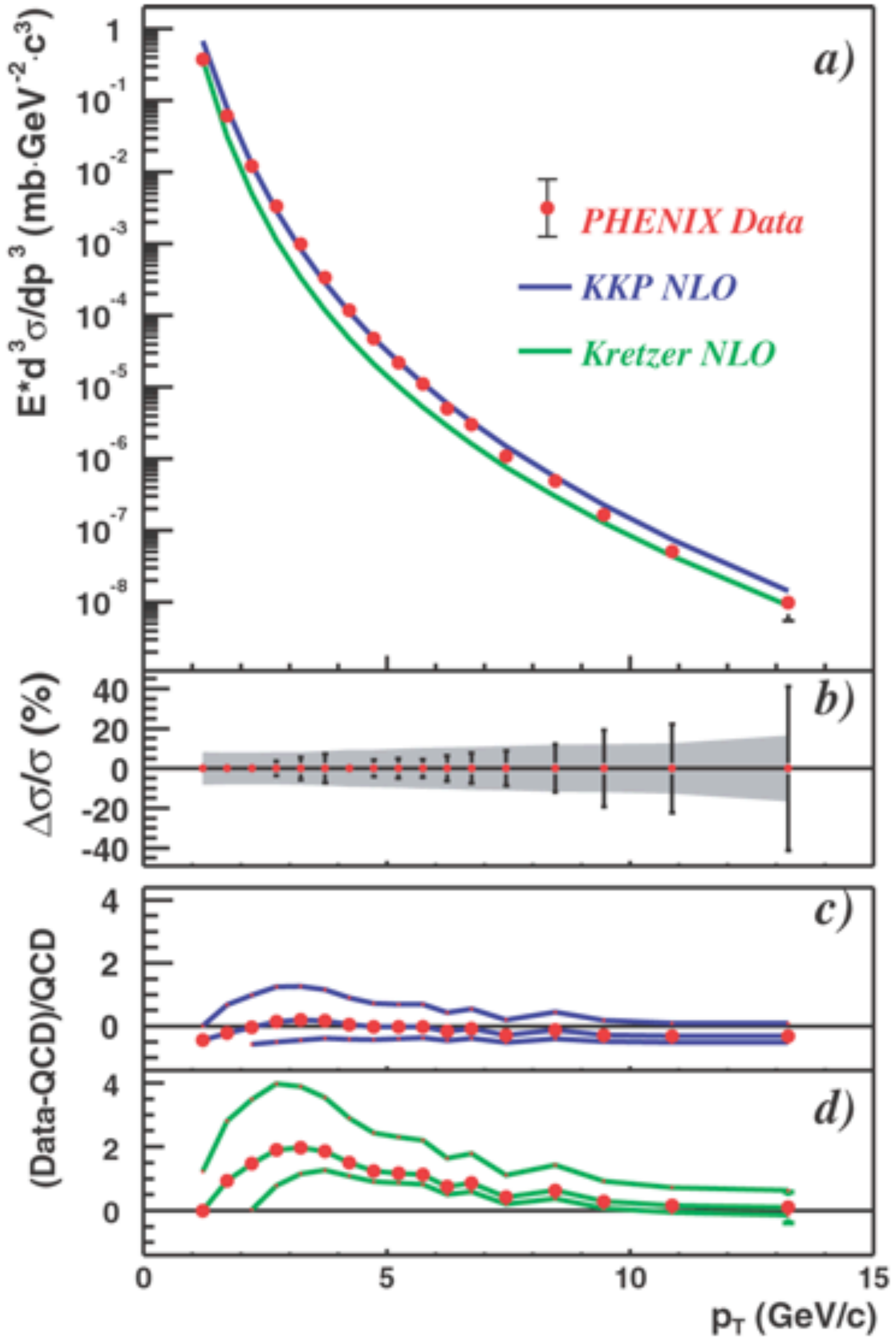
$$\int \frac{d^3p_i}{E_i} E_i \frac{d\sigma}{d^3p_i} = \sigma_{tot} \langle N_i \rangle$$

with $\langle N_i \rangle$: avg. yield of particle i per event

- Def. The yield

$$E_i \frac{dN_i}{d^3p_i} \equiv \frac{E_i}{\sigma_{tot}} \frac{d\sigma}{d^3p_i}$$

Example: Invariant cross section for neutral pion production in p+p at $\sqrt{s}$ = 200 GeV



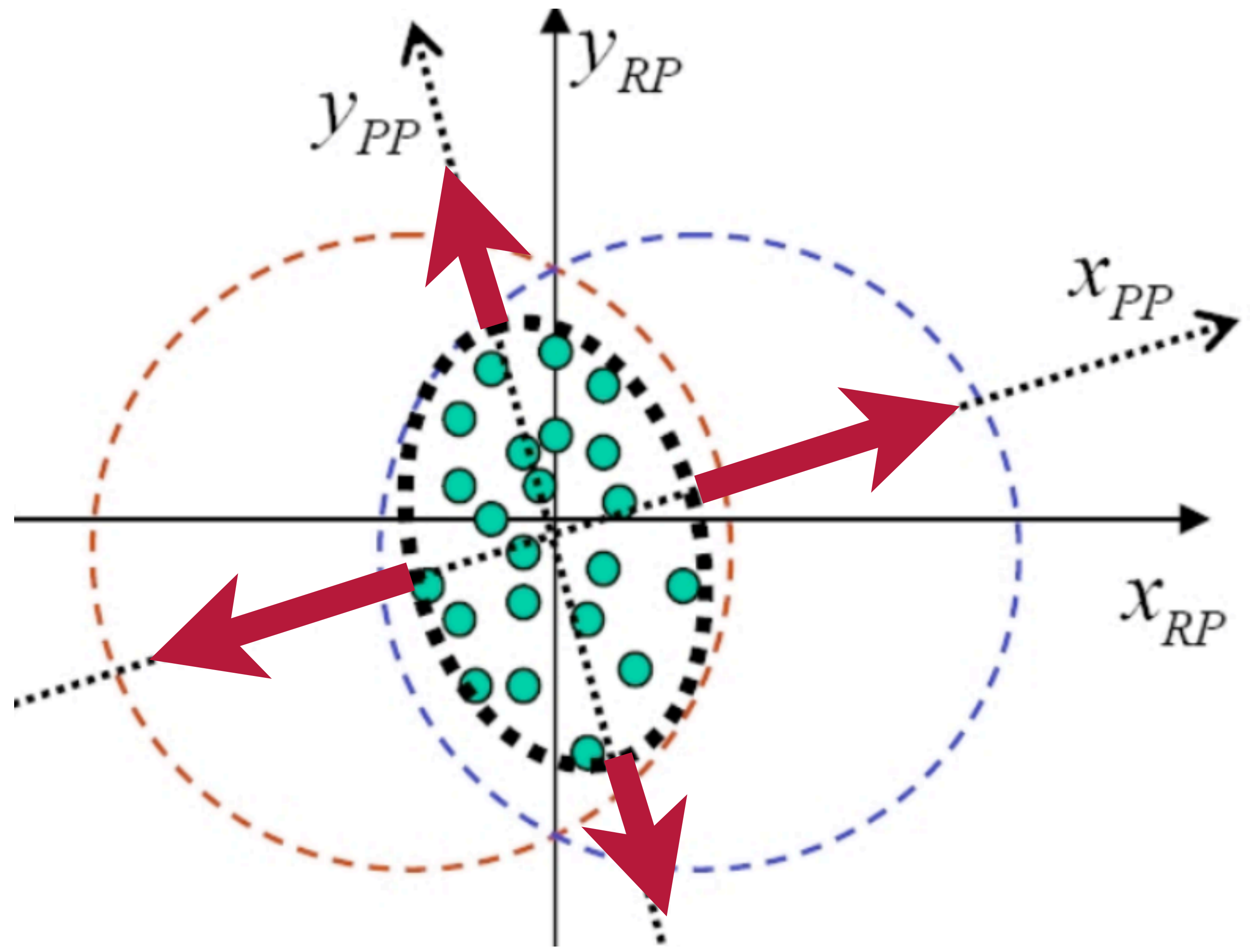
BASICS: YIELD DECOMPOSITION

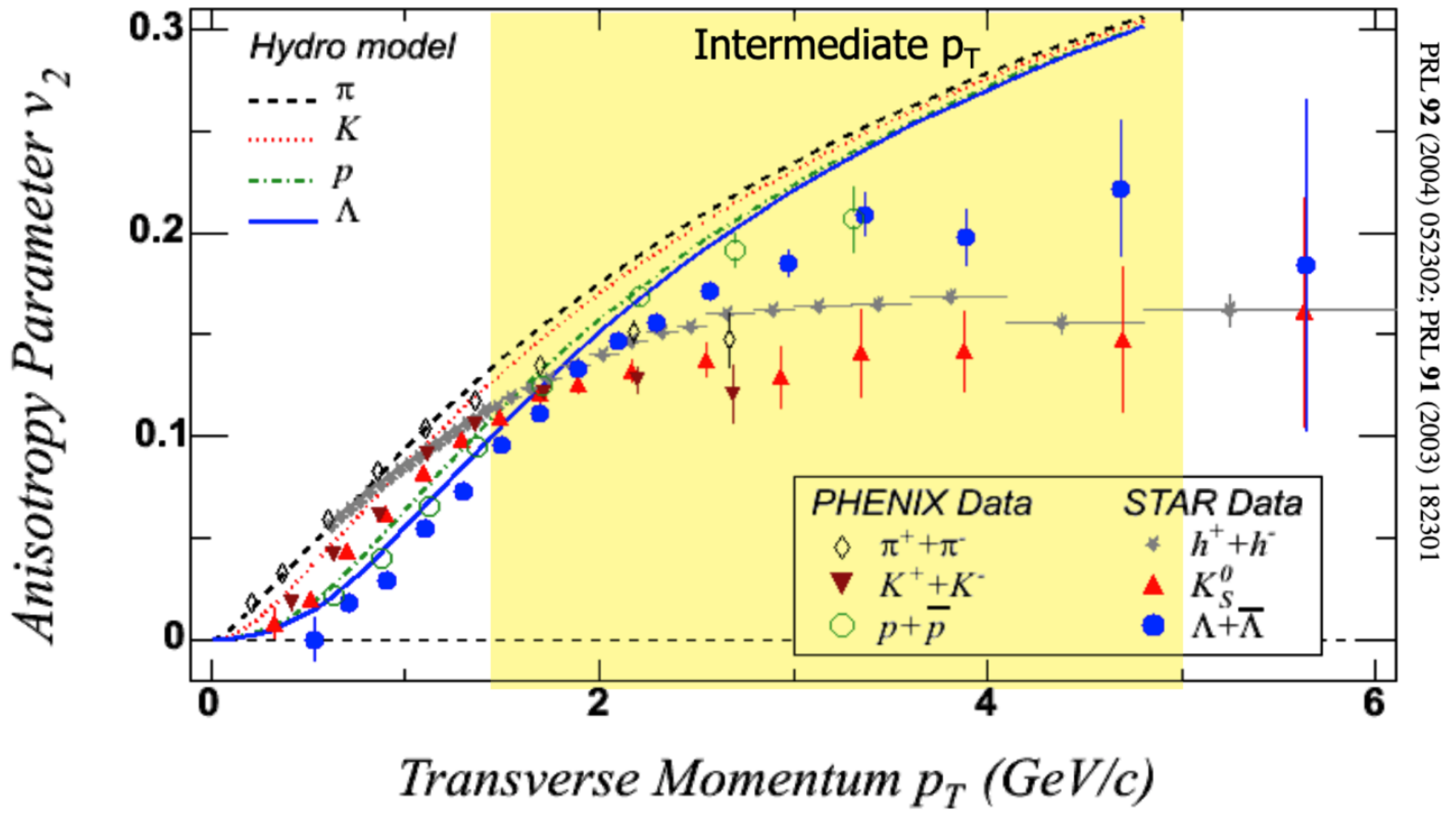
- Angular anisotropies found in particle spectra produced in Nucleus-Nucleus collisions

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

(Just a run-of-the-mill Fourier expansion...)

- Flow dynamics signals collectivity, medium creation





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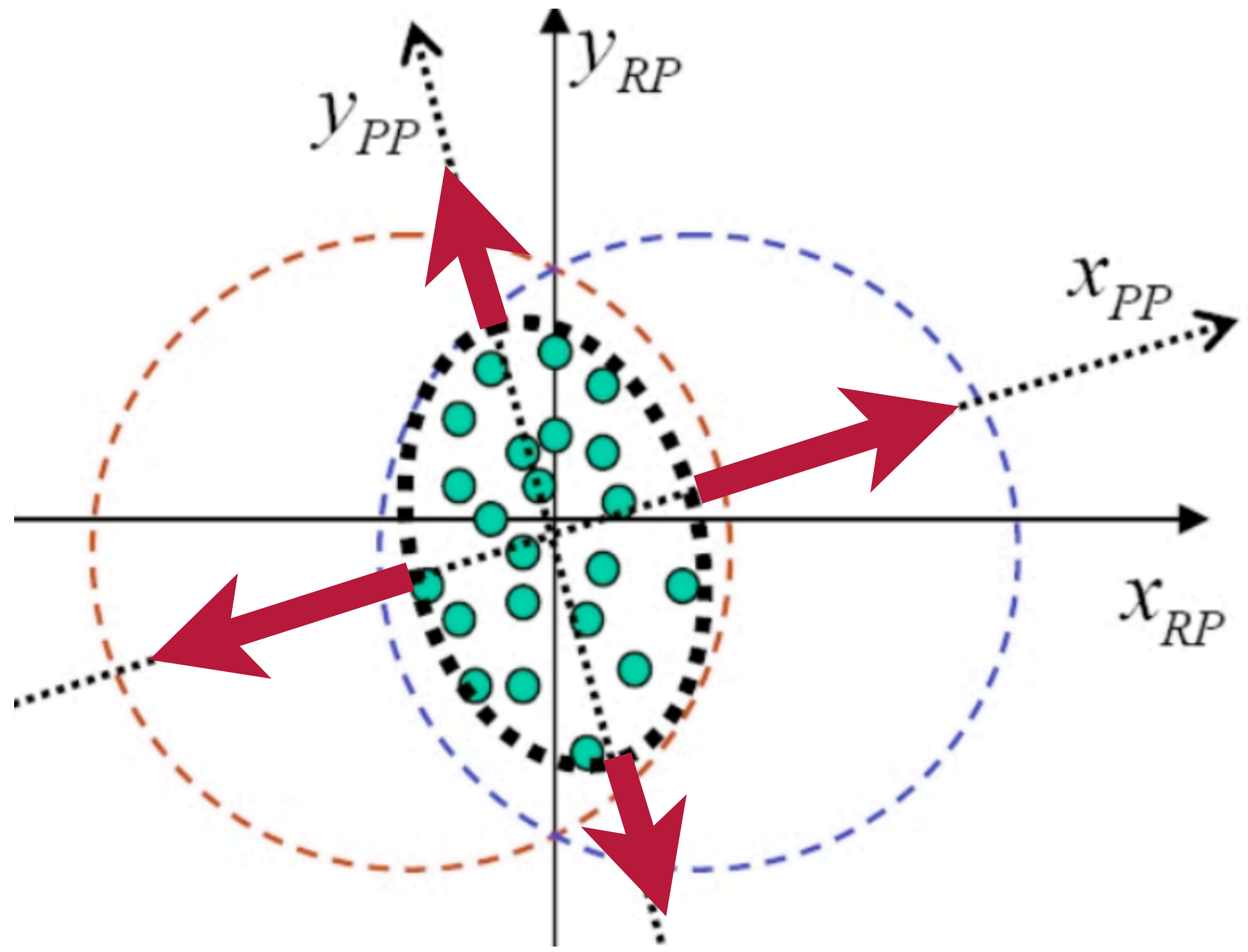
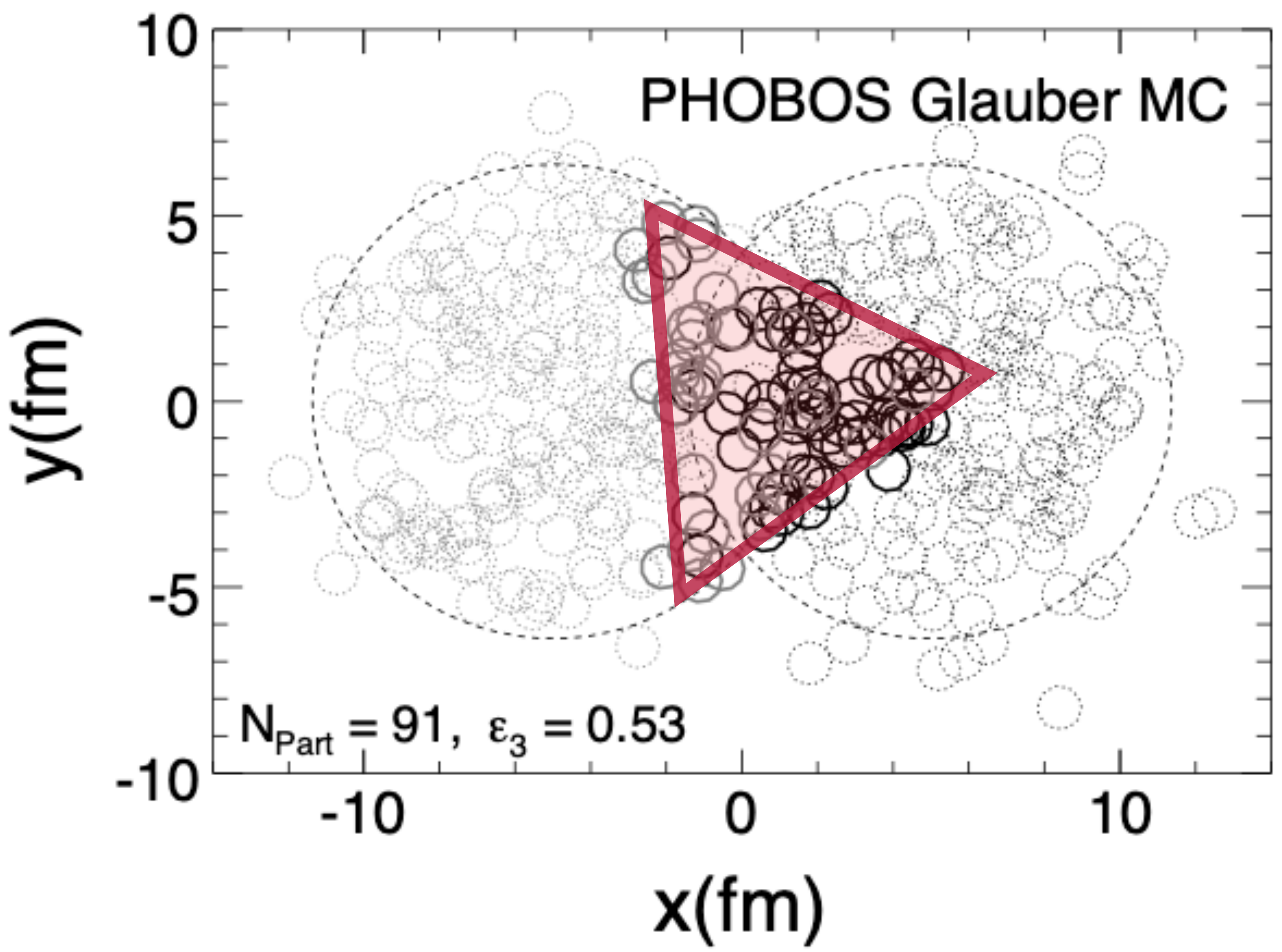
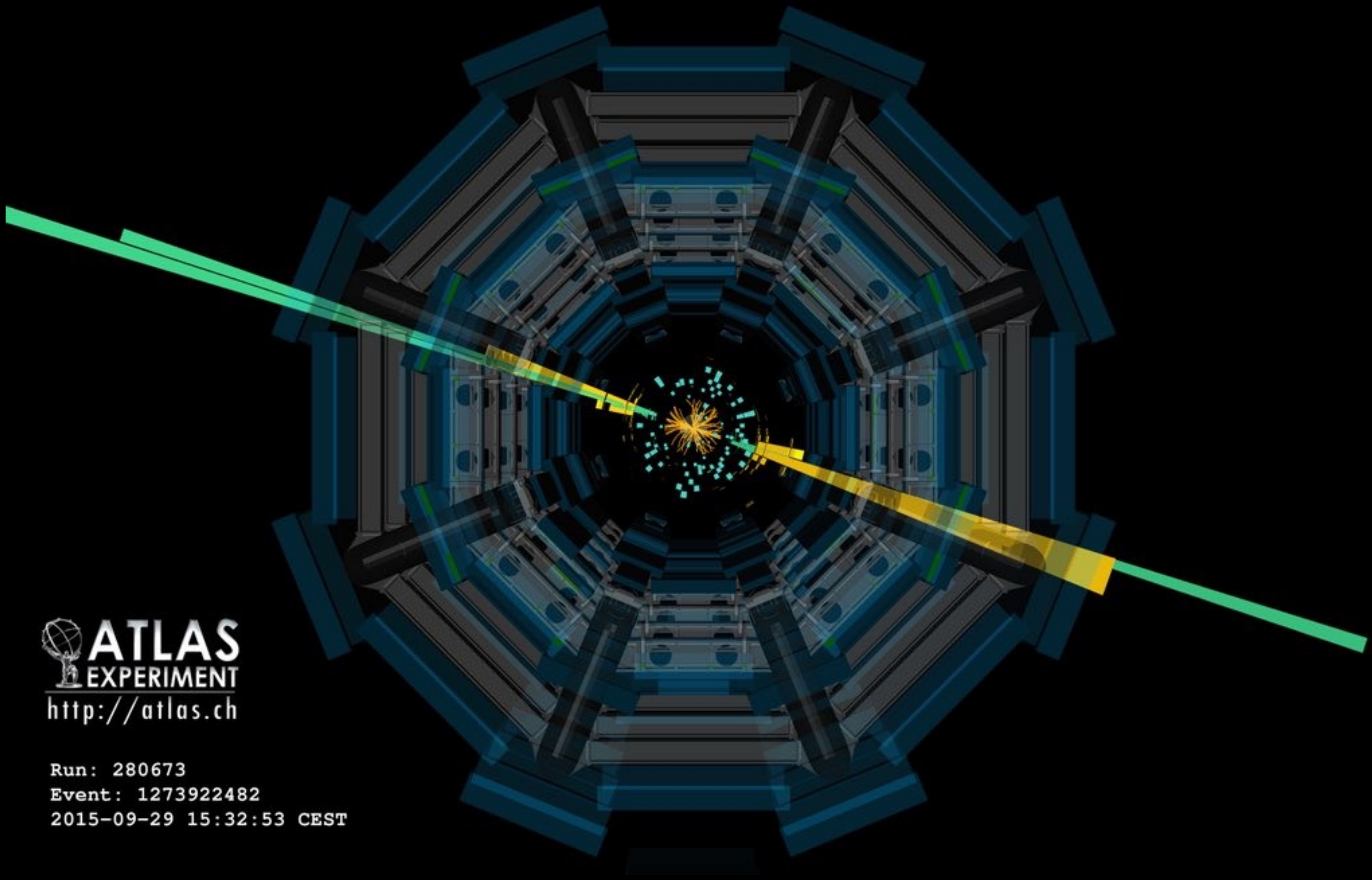
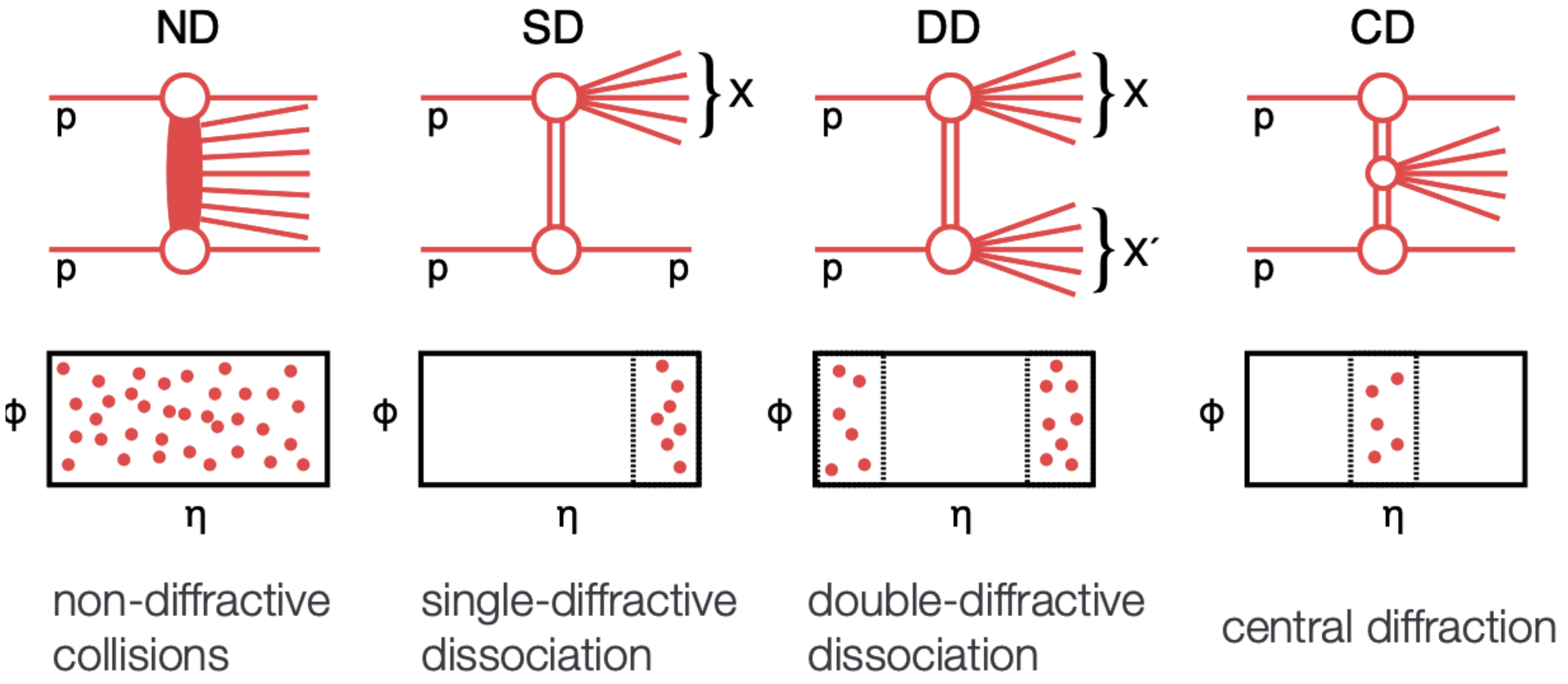






P+P COLLISIONS

P+P COLLISIONS: PROCESSES



$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}, \quad \sigma_{\text{inel}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}$$

DIFFRACTIVE COLLISIONS

- Important concept: diffraction in p+p: "Projectile" proton is excited to a hadronic state ***X*** with mass ***M***

$$p_{proj} + p_{targ} \rightarrow X + p_{targ}$$

- The excited state **X** fragments, giving rise to the production of (a small number) of particles in the forward direction
- Theoretical view:
  - Diffractive events correspond to the exchange of a Pomeron, a gluon configuration which carries quantum numbers of the vacuum (JPC = 0++)
  - In a QCD picture the Pomeron can be considered as a two- or multi-gluon state
  - Thus, there is no exchange of quantum numbers like color or charge

UA5, Z. Phys. C33, 175, 1986

$p+\bar{p}$	$\sqrt{s}$ = 200 GeV	$\sqrt{s}$ = 900 GeV
Total inelastic	(41.8 ± 0.6) mb	(50.3 ± 0.4 ± 1.0) mb
Single-diffractive	(4.8 ± 0.5 ± 0.8) mb	(7.8 ± 0.5 ± 1.8) mb
Double-diffractive	(3.5 ± 2.2) mb	(4.0 ± 2.5) mb
Non-diffractive	≈ 33.5 mb	≈ 38.5 mb

Fraction of diffractive dissociation events with respect to all inelastic collisions is about 20–30% (rather independent of $\sqrt{s}$)

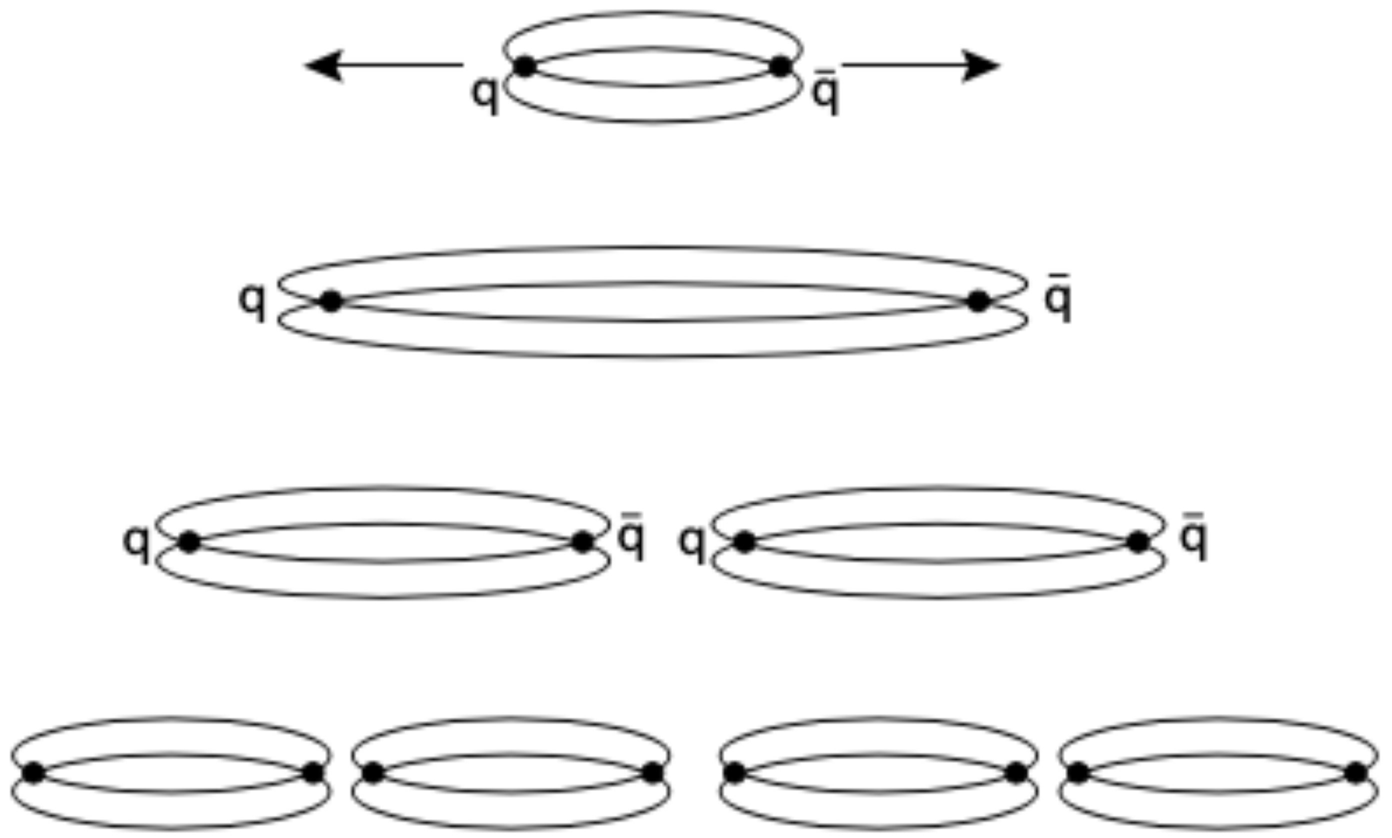
See also ATLAS, arXiv:1201.2808

P+P: SCALES

- Low $p_\perp$: Soft processes ($p_\perp < 2\,\mathrm{GeV}$)

  Complicated dynamics, modelling is necessary whenever hadronic DoFs are involved.

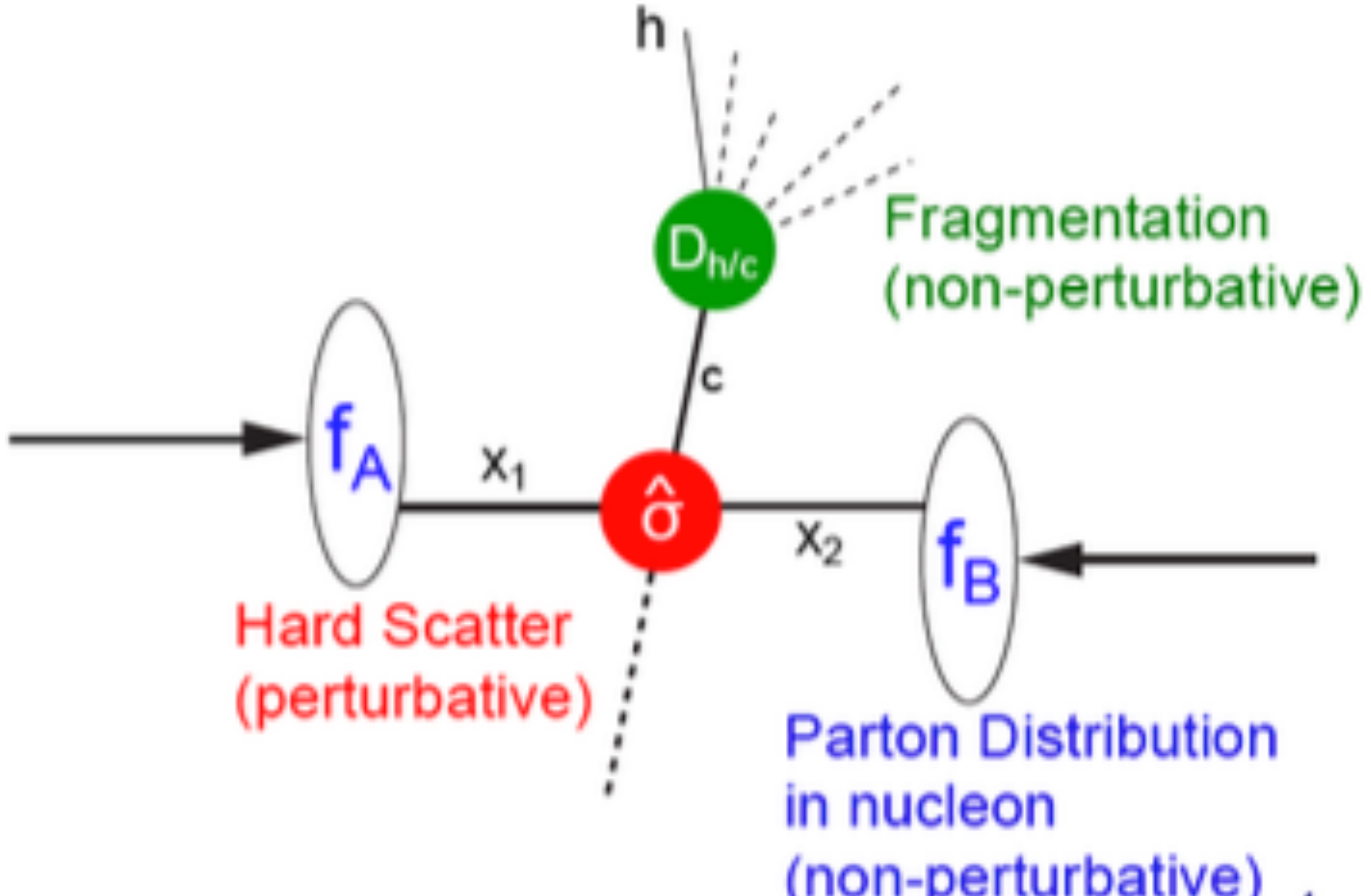
  - Lund string model



- High $p_\perp$: Hard processes,

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

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



TRANSVERSE MOMENTUM DISTRIBUTIONS

- Low $p_\perp$: Soft processes ($p_\perp < 2\,\mathrm{GeV}$)

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p} = A(\sqrt{s})\cdot e^{-\alpha p_\mathrm{T}},\ \alpha \approx 6/(\mathrm{GeV}/c)$$

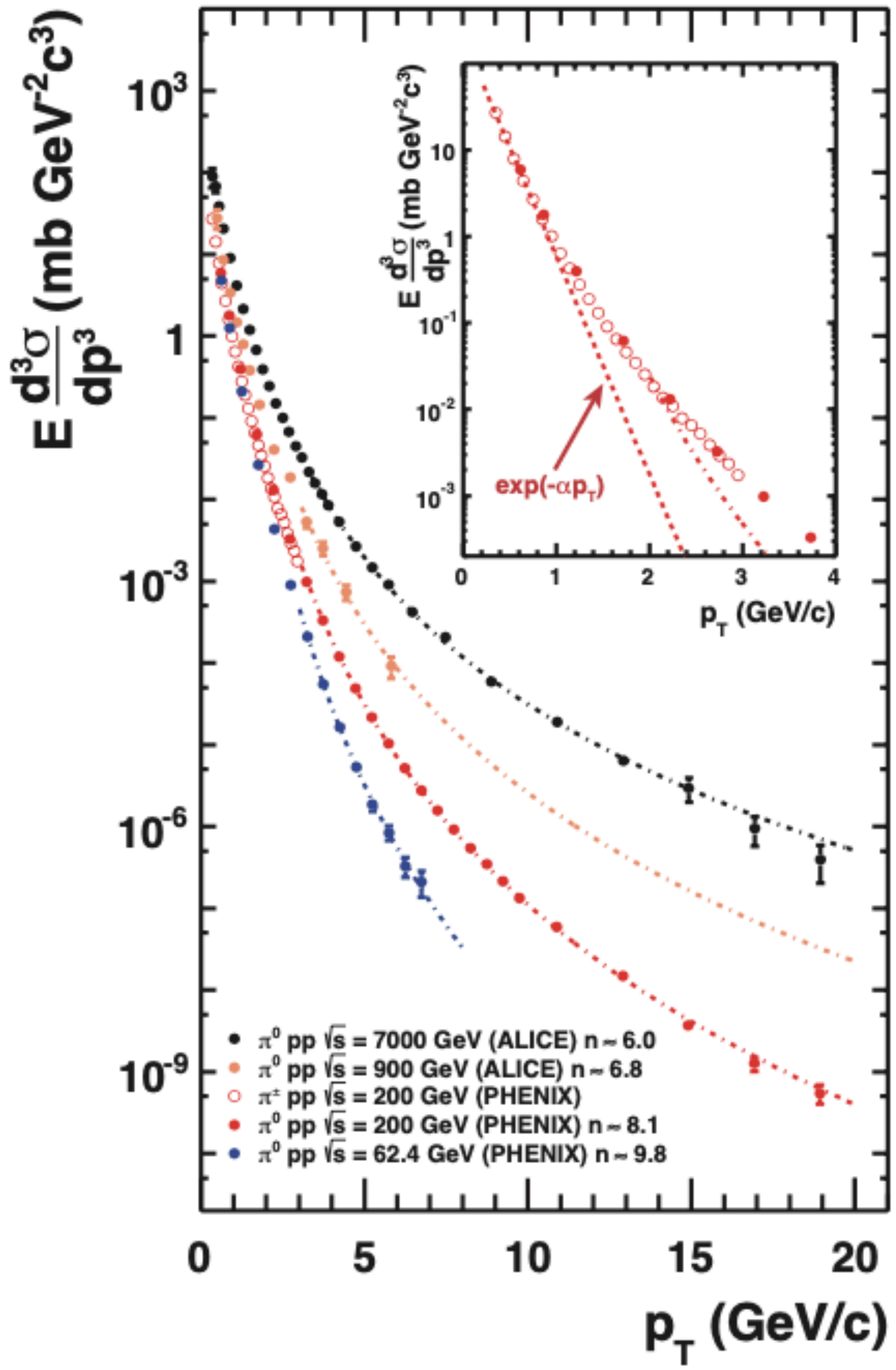
- High $p_\perp$: Hard processes,

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p} = B(\sqrt{s})\cdot \frac{1}{p_\mathrm{T}^{n(\sqrt{s})}}$$

- Average $p_\perp$

$$\langle p_\mathrm{T}\rangle = \frac{\int_0^\infty p_\mathrm{T}\frac{\mathrm{d}N_x}{\mathrm{d}p_\mathrm{T}}\mathrm{d}p_\mathrm{T}}{\int_0^\infty \frac{\mathrm{d}N_x}{\mathrm{d}p_\mathrm{T}}\mathrm{d}p_\mathrm{T}} \approx 300 - 400\mathrm{MeV}/c$$

pretty energy-independent for $\sqrt{s} < 100$ GeV



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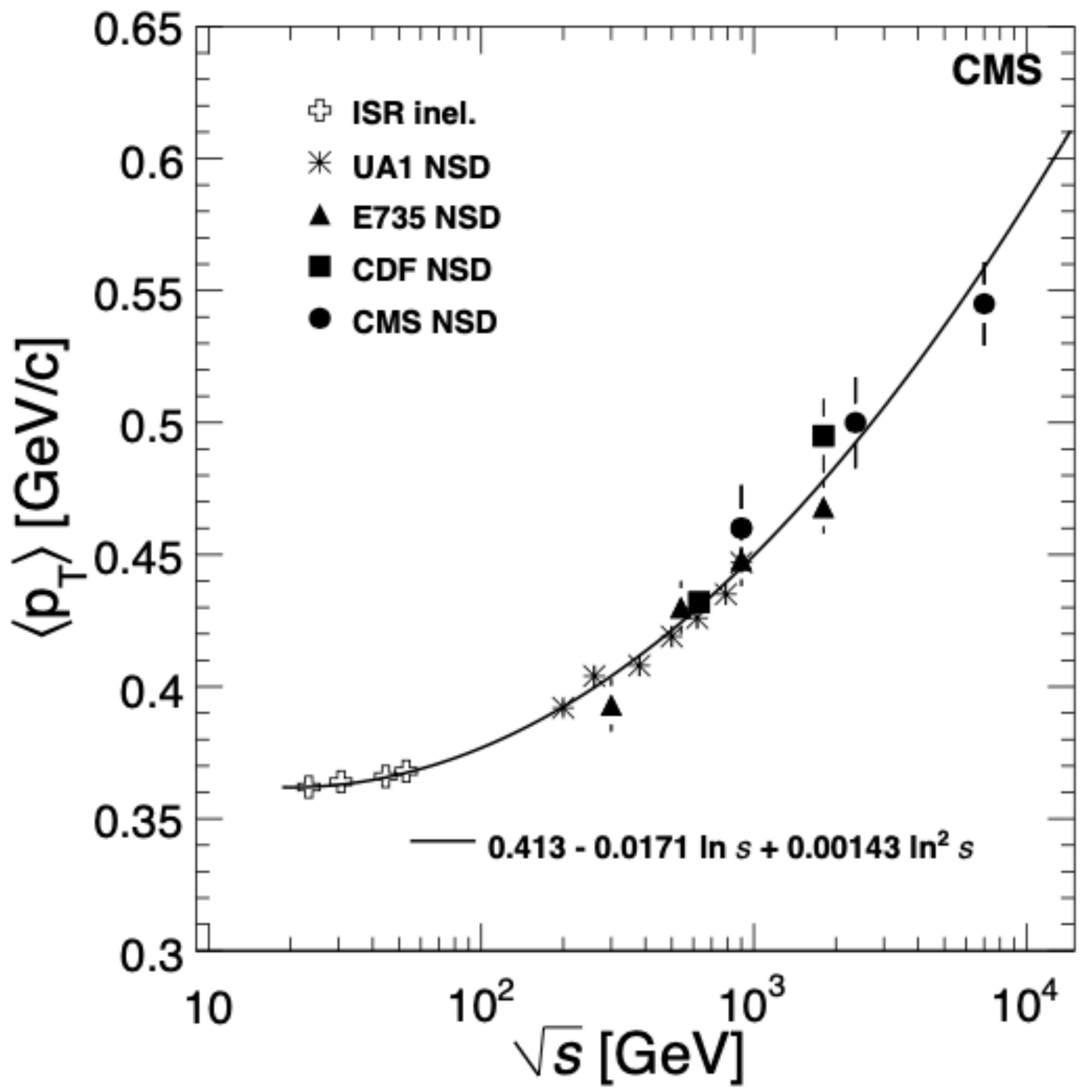


TRANS. MASS SCALING IN P+P COLLISIONS

- Transverse mass spectrum $m_\perp$: use $m_\perp dm_\perp = p_\perp dp_\perp$

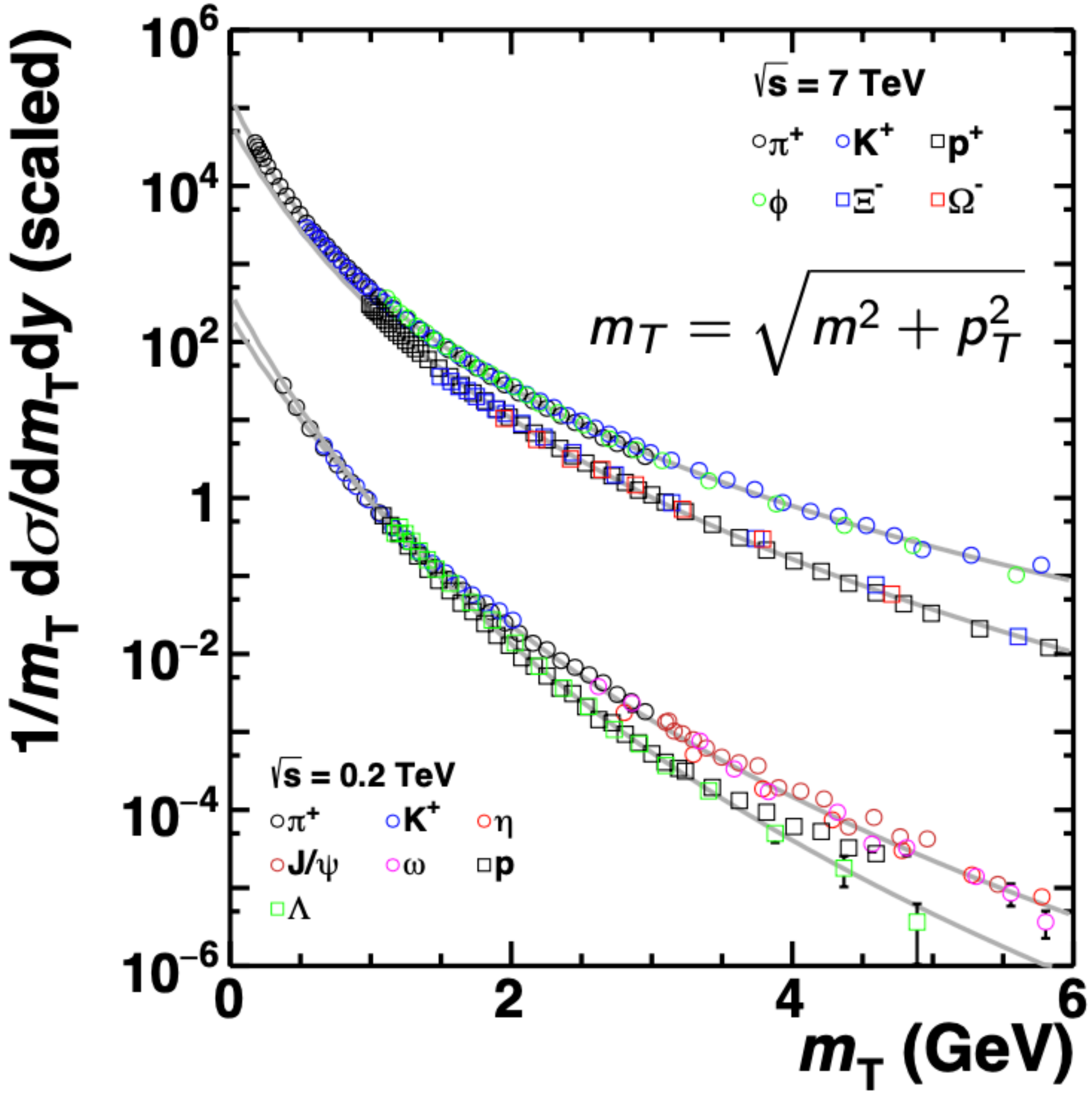
$$\frac{1}{2\pi p_\perp}\frac{\mathrm{d}N}{\mathrm{d}p_\perp \mathrm{d}y} = \frac{1}{2\pi m_\perp}\frac{\mathrm{d}N}{\mathrm{d}m_\perp \mathrm{d}y}$$

- $m_\perp$ scaling:
  - Shape of spectra is the same for different hadron species

$$\frac{\mathrm{d}N_\eta/\mathrm{d}m_\perp}{\mathrm{d}N_{\pi^0}/\mathrm{d}m_\perp} \approx 0.45$$

- In RHIC and LHC: Scaling (approximately) satisfied, different universal function for mesons and baryons

- Next lectures: Possible Interpretation, thermal models?

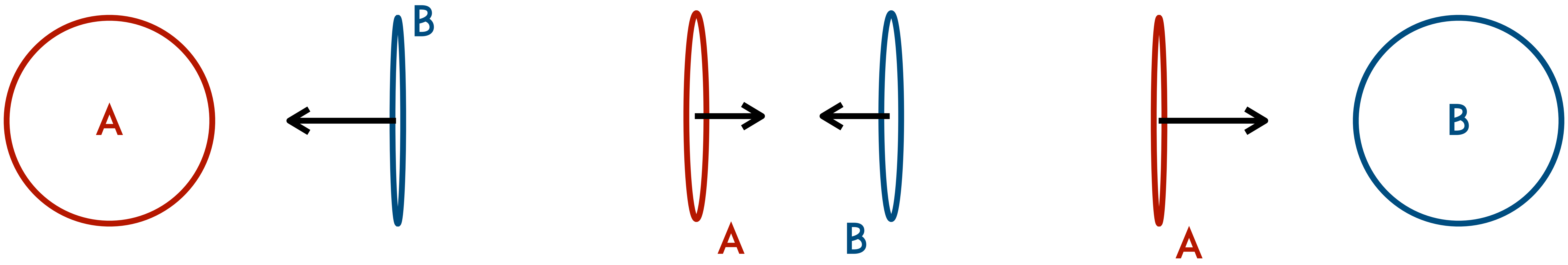


m_T scaling (early ref's):
Nucl. Phys. B70, 189–204 (1974)
Nucl.Phys. B120 (1977) 14-22

NUCLEAR COLLISIONS

NUCLEAR COLLISIONS

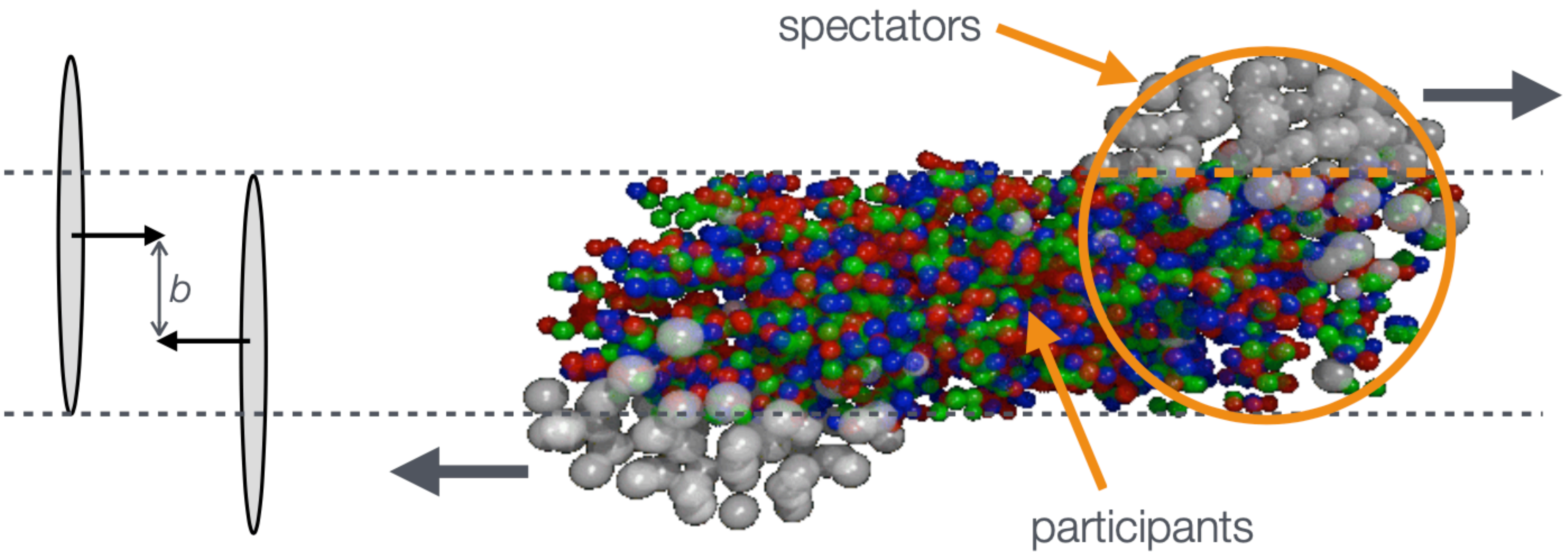
- Nuclei are extended objects. Lorentz contraction for a finite longitudinal size



Rest frame of **A** | Center of momentum frame | Rest frame of **B**

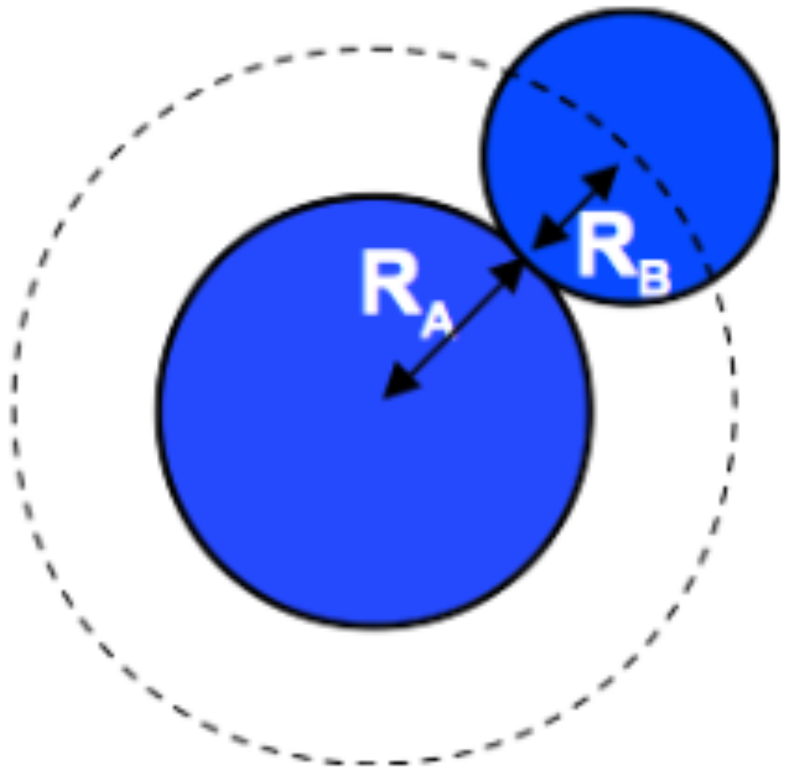
NUCLEAR COLLISIONS

- Nuclei are extended objects. Lorentz contraction for a finite longitudinal size
- **Wounded Nucleon** model: separation between **participants** and **spectators**
- Wave character of the nucleon can be neglected for the estimation of the total cross section



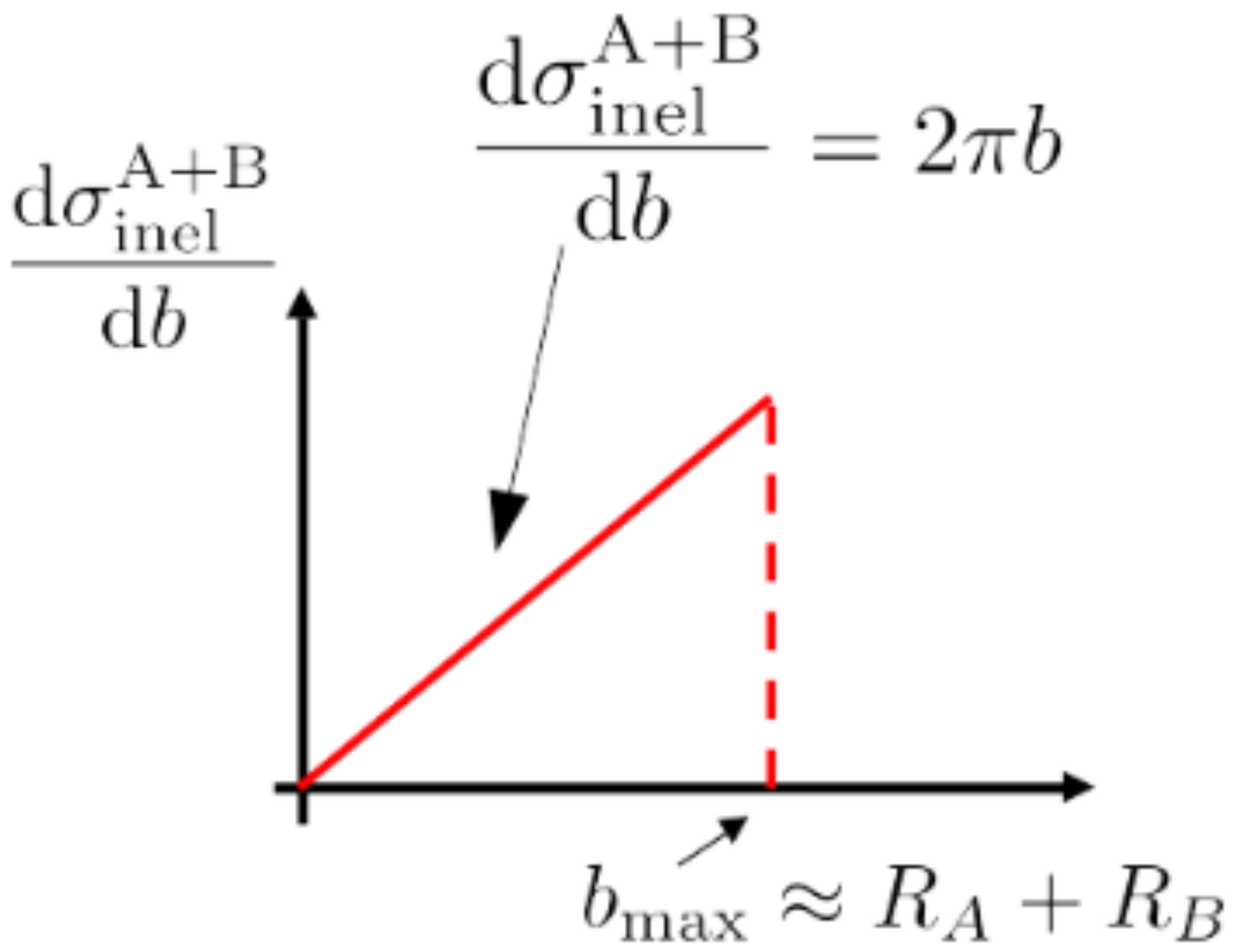
NUCLEAR COLLISIONS

- Nucleus-Nucleus collision can be considered as a collision of two black disks



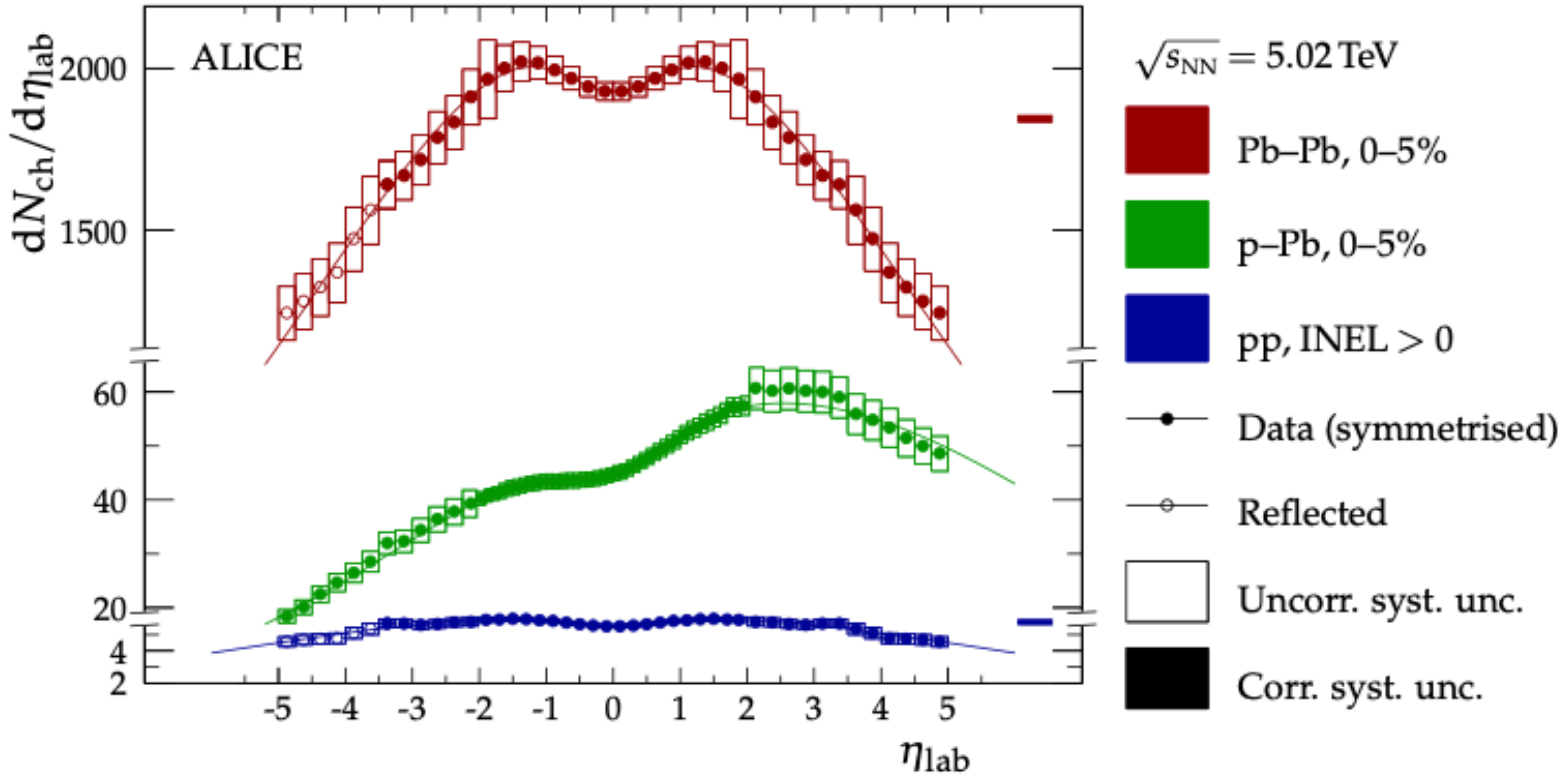
$$R_A \approx r_0 \cdot A^{1/3}, \;\; r_0 = 1.2\,\mathrm{fm}$$

$$\sigma_{\mathrm{inel}}^{\mathrm{A+B}} \approx \sigma_{\mathrm{geo}} \approx \pi r_0^2 (A^{1/3} + B^{1/3})^2$$



In reality, there is a linear increase with impact parameter until a smooth fall-off.

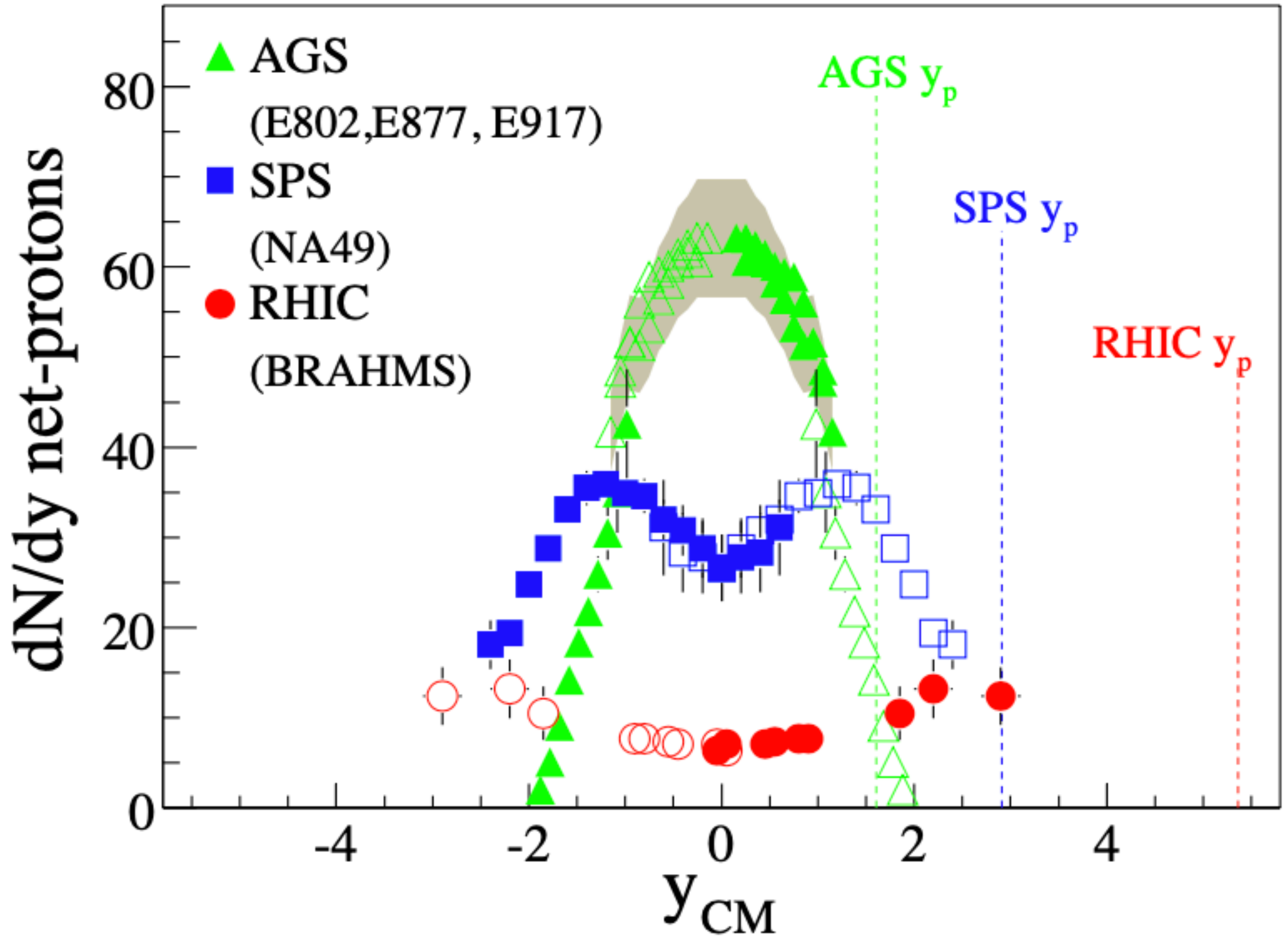
NUCLEAR CHARGED PARTICLE PSEUDORAPIDITY DISTRIBUTIONS FOR DIFFERENT SYSTEM SIZES



NUCLEAR STOPPING POWER

Brahms, PRL 93:102301, 2004

For Au-Au collisions in RHIC @ 200 GeV, the incoming projectiles are originally at a rapidity $y_p = 5.36$



Define the net baryon yield $$\frac{\mathrm{d}N_{B-\bar{B}}}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y} = \frac{\mathrm{d}N_B}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y} - \frac{\mathrm{d}N_{\bar{B}}}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y}$$

Get the average rapidity after collision

$$\langle y \rangle = \frac{2}{N_{part}} \int_0^{y_p} \frac{\mathrm{d}N_{B-\bar{B}}}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y}$$

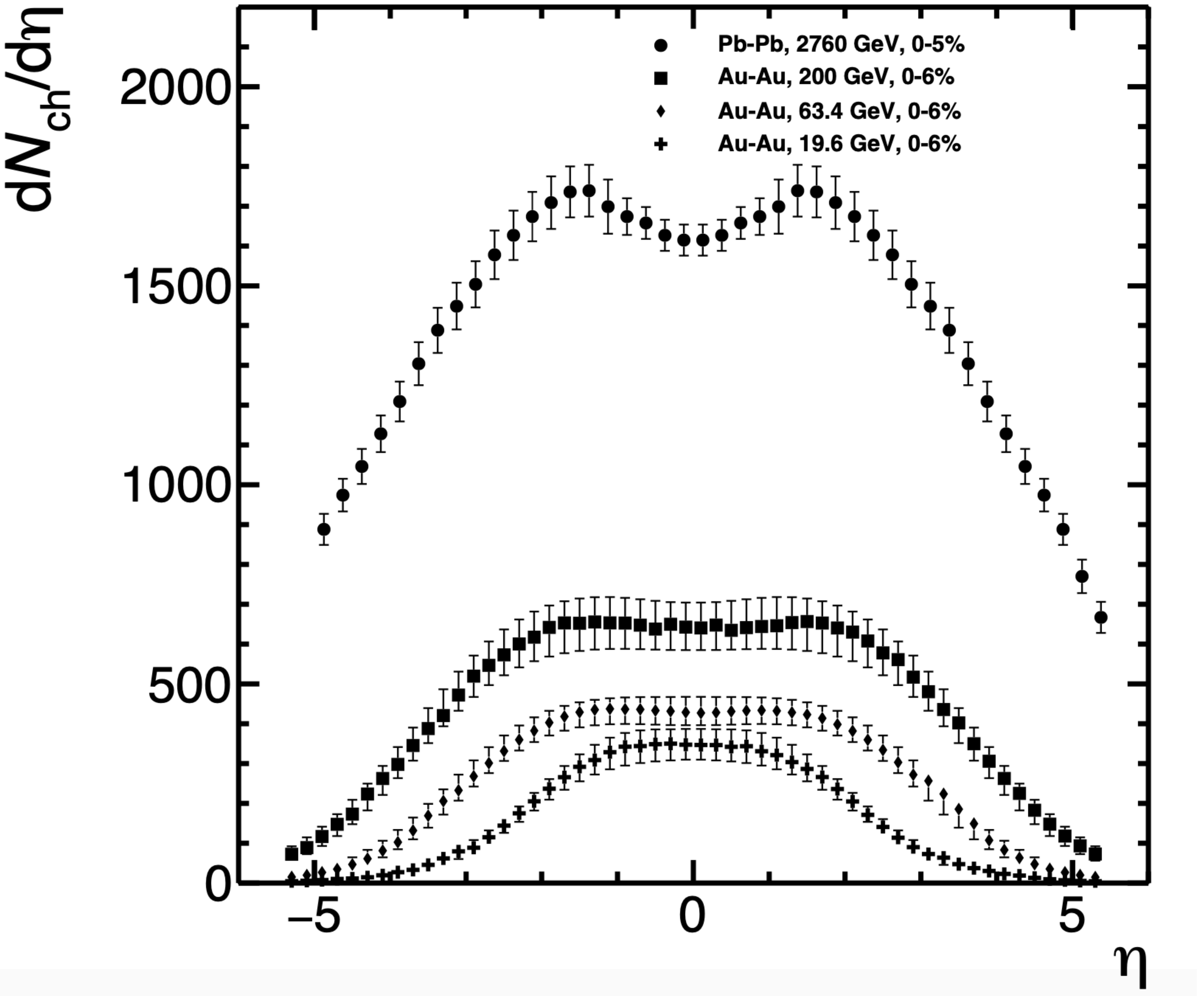
and define the rapidity loss $\delta y = y_p - \langle y \rangle \sim 2$. Finally, define the average energy after collision

$$\langle E \rangle = \frac{1}{N_{part}} \int_{-y_p}^{y_p} dy \, \langle m_\perp \rangle \cosh y \, \frac{\mathrm{d}N_{B-\bar{B}}}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y} = 27 \pm 6\,\mathrm{GeV}$$

Since. $E_p = 100\,\mathrm{GeV}$ then. $\delta E = E_p - \langle E \rangle = 73 \pm 6\,\mathrm{GeV}$

Then, the average energy loss of a nucleon in central Au+Au@200GeV is 73 ± 6 GeV

NUCLEAR CHARGED PARTICLE PSEUDORAPIDITY DISTRIBUTIONS FOR DIFFERENT SYSTEM ENERGIES



THE GLAUBER MODEL

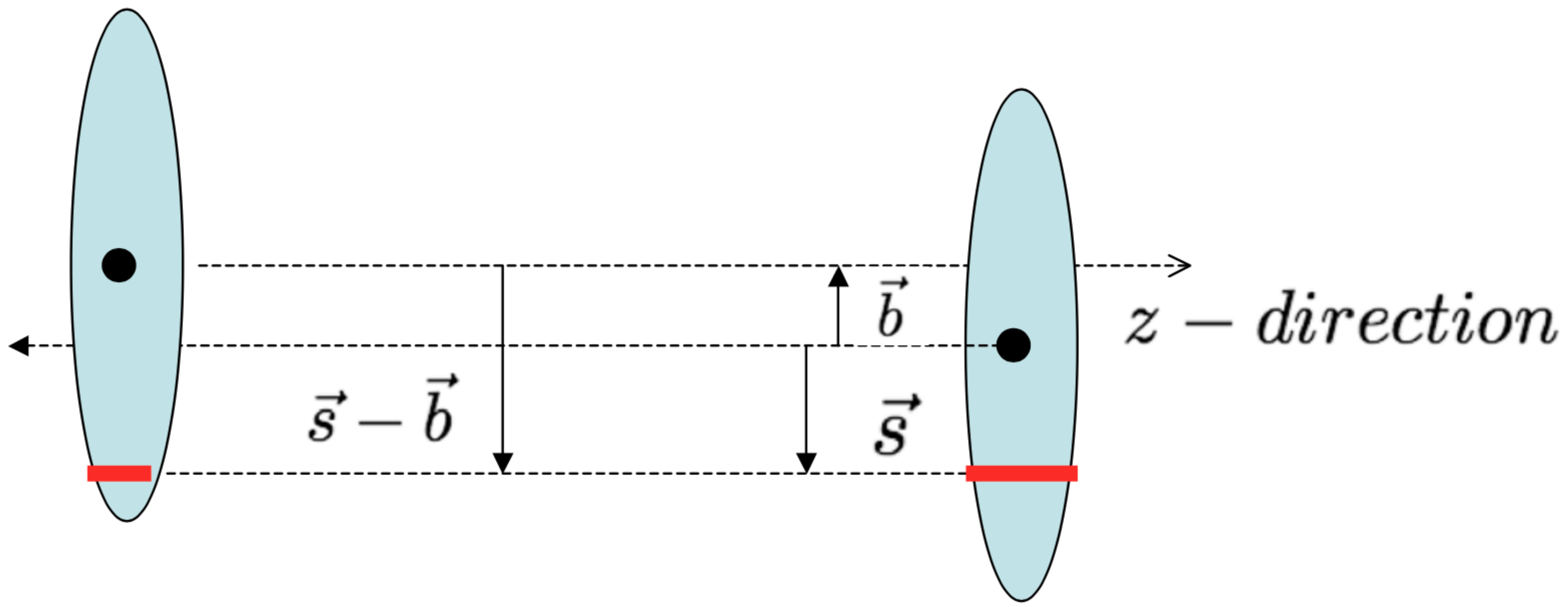
- Nuclei are extended objects… complications ensue
- Input for Glauber: inelastic nucleon- nucleon cross section, density profile of nucleus
  - Woods-Saxon parameters typically from $e + A$ scattering (sensitive to charge distribution only)

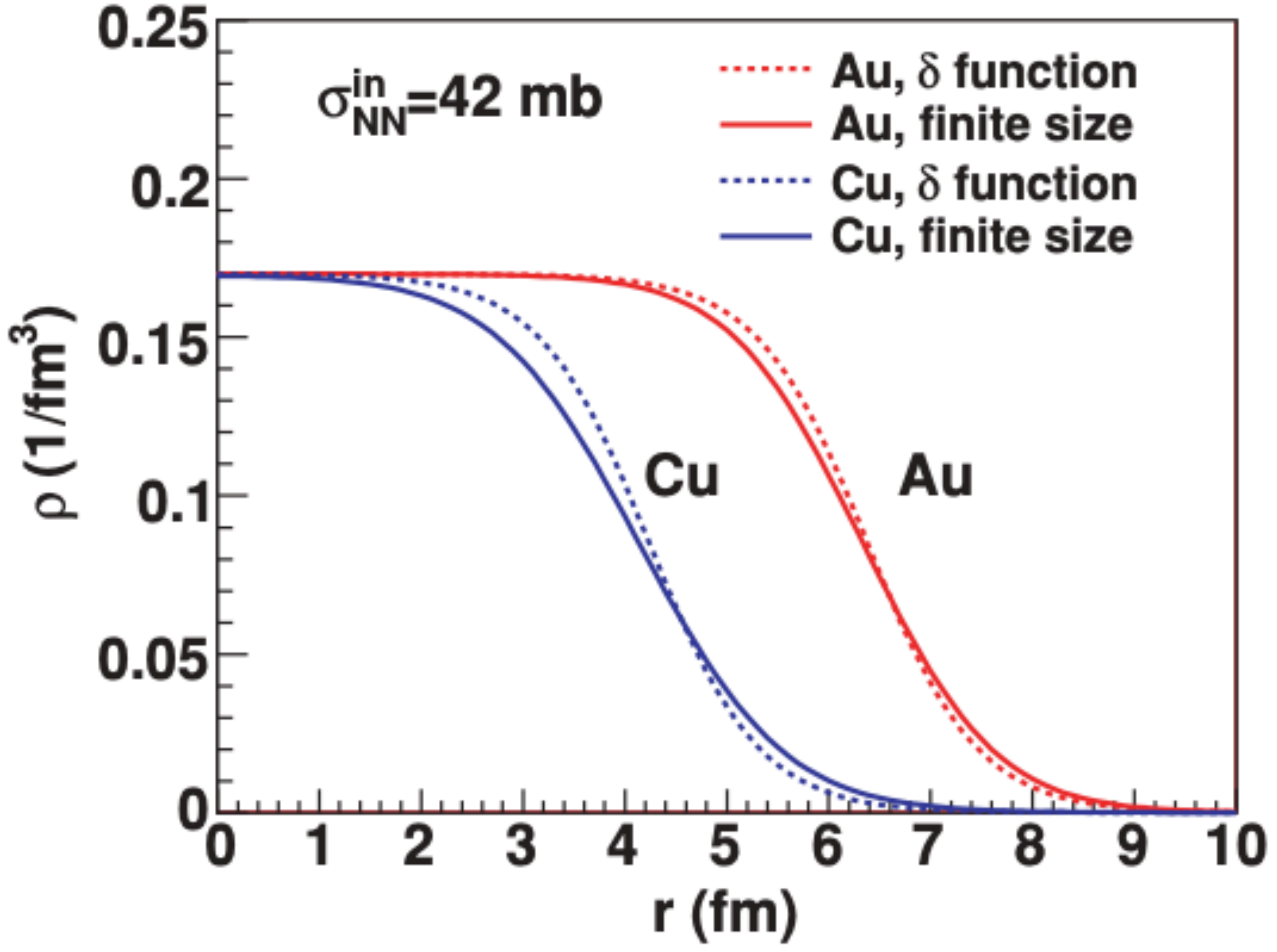
$$\rho(r) = \rho_0 \frac{1 + wr^2/R^3}{1 + \exp\left[(r - R)/a\right]}$$

ρ_0 : normalization [fm-2]

R : nuclear radius [fm]

a: nuclear diffusivity constant [fm]





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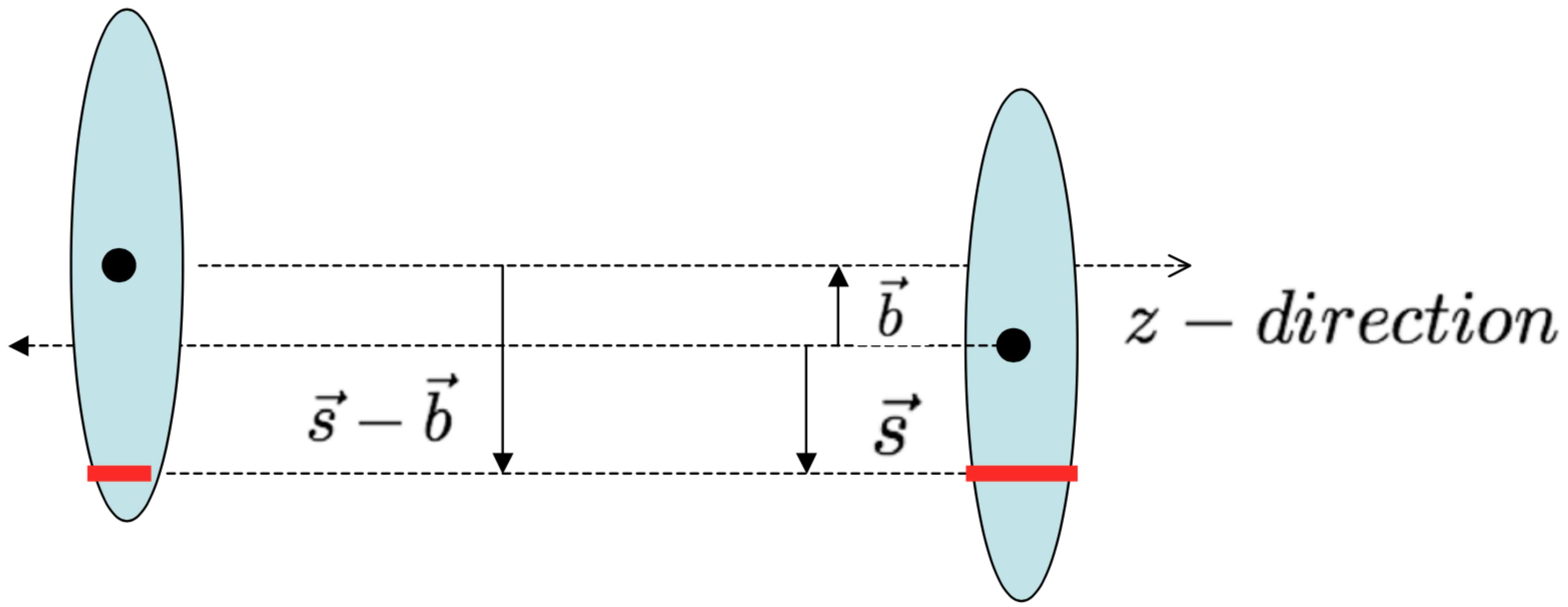

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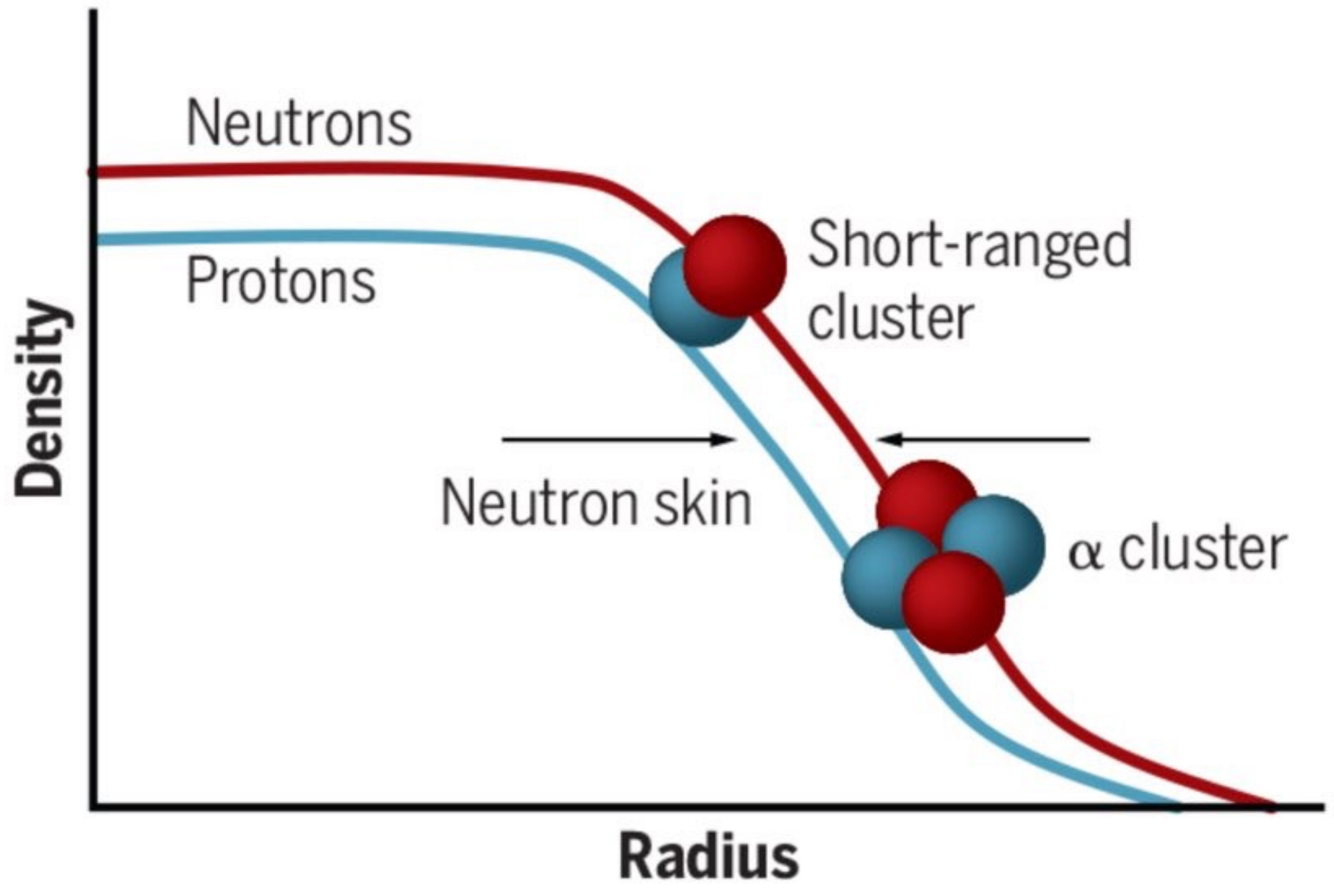
- Difference between neutron and proton distribution small and typically neglected

Nucleon density in neutron-rich nuclei



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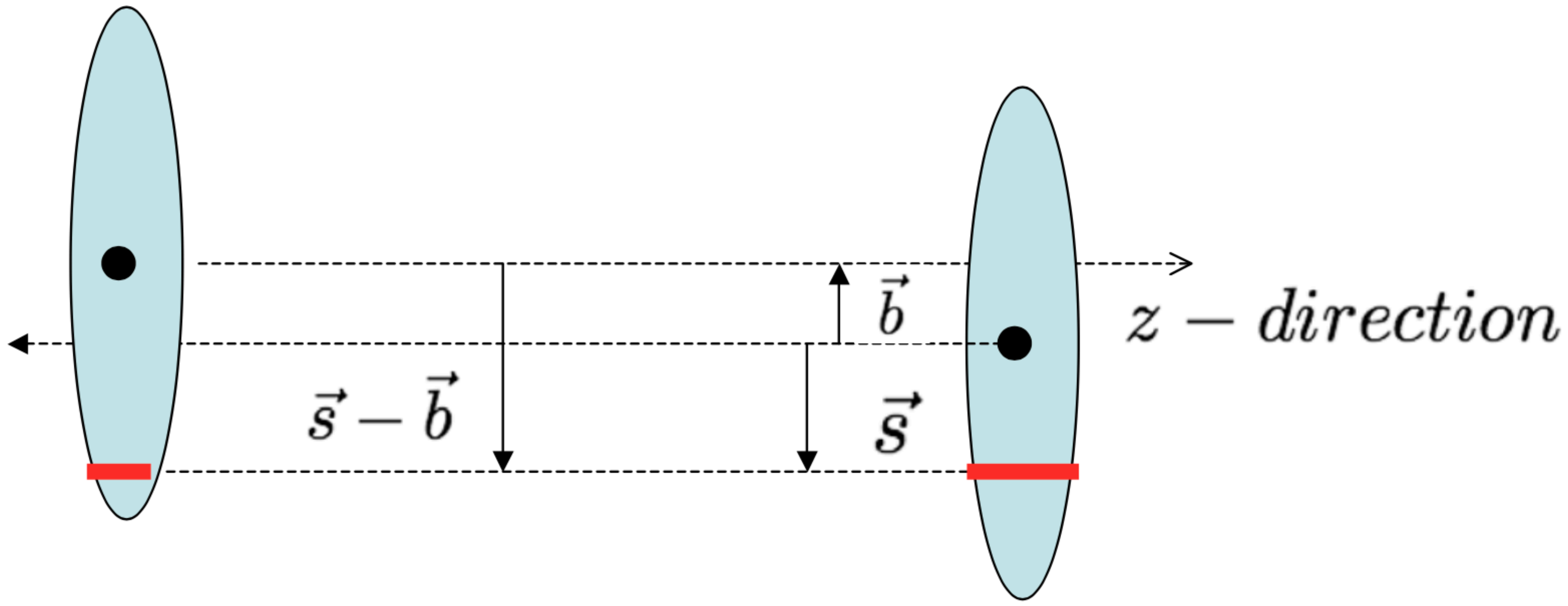

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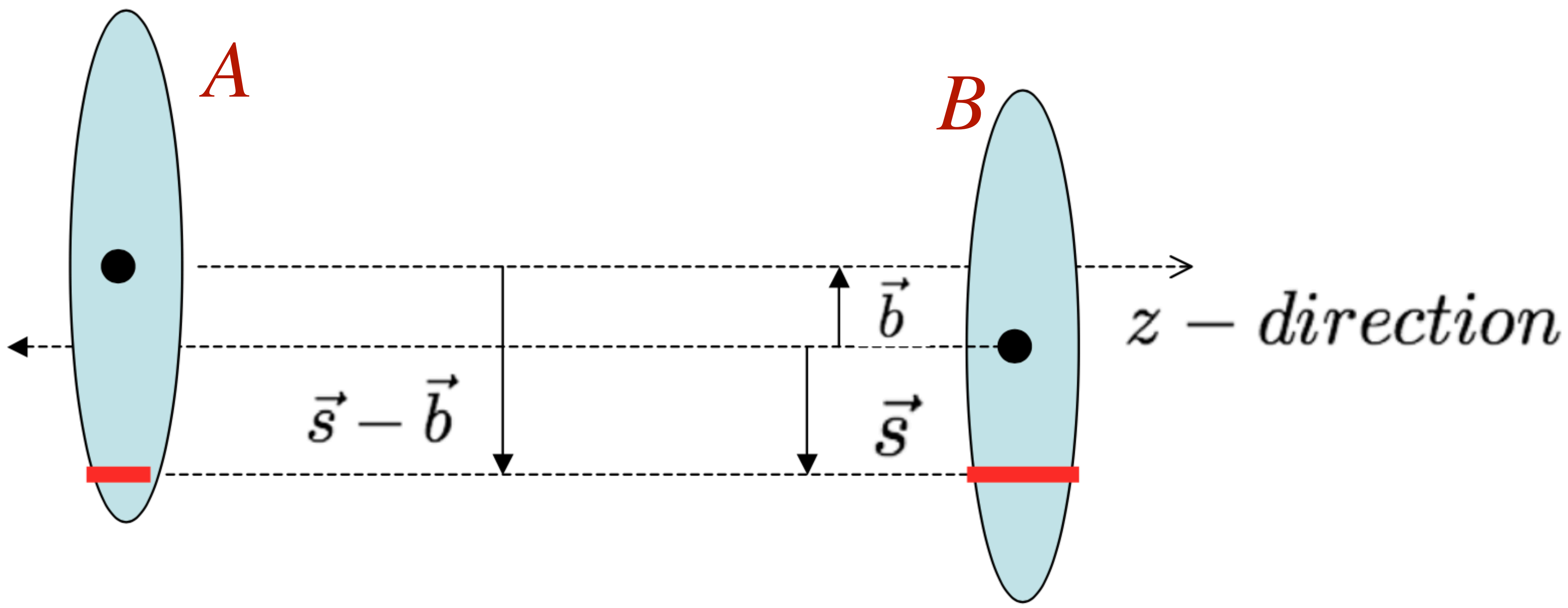
- Difference between neutron and proton distribution small and typically neglected

Name	R (fm)	a (fm)	w (fm)
f p[a]	0.023		
d[b]	0.01	0.5882	0
H3[c]			
He3[b]			
^{16}O	2.608	0.513	−0.51
^{28}Si	3.34	0.580	−0.233
^{32}S	2.54	2.191	0.16
^{40}Ca	3.766	0.586	−0.161
^{58}Ni	4.309	0.517	−0.1308
^{62}Cu	4.2	0.596	0
^{62}CuHN	4.28	0.5	0
^{186}W	6.58	0.480	0
^{197}Au	6.38	0.535	0
^{197}AuHN	6.42	0.44	0
^{207}Pb[d]	6.62	0.546	0
^{207}PbHN	6.65	0.46	0

Name	R (fm)	a (fm)	β_2	β_4
^{28}Si2	3.34	0.580	−0.478	0.239
^{62}Cu2	4.2	0.596	0.162	−0.006
^{197}Au2	6.38	0.535	−0.131	−0.031
^{238}U2	6.67	0.44	0.280	0.093
^{238}U[e]				

THE GLAUBER MODEL

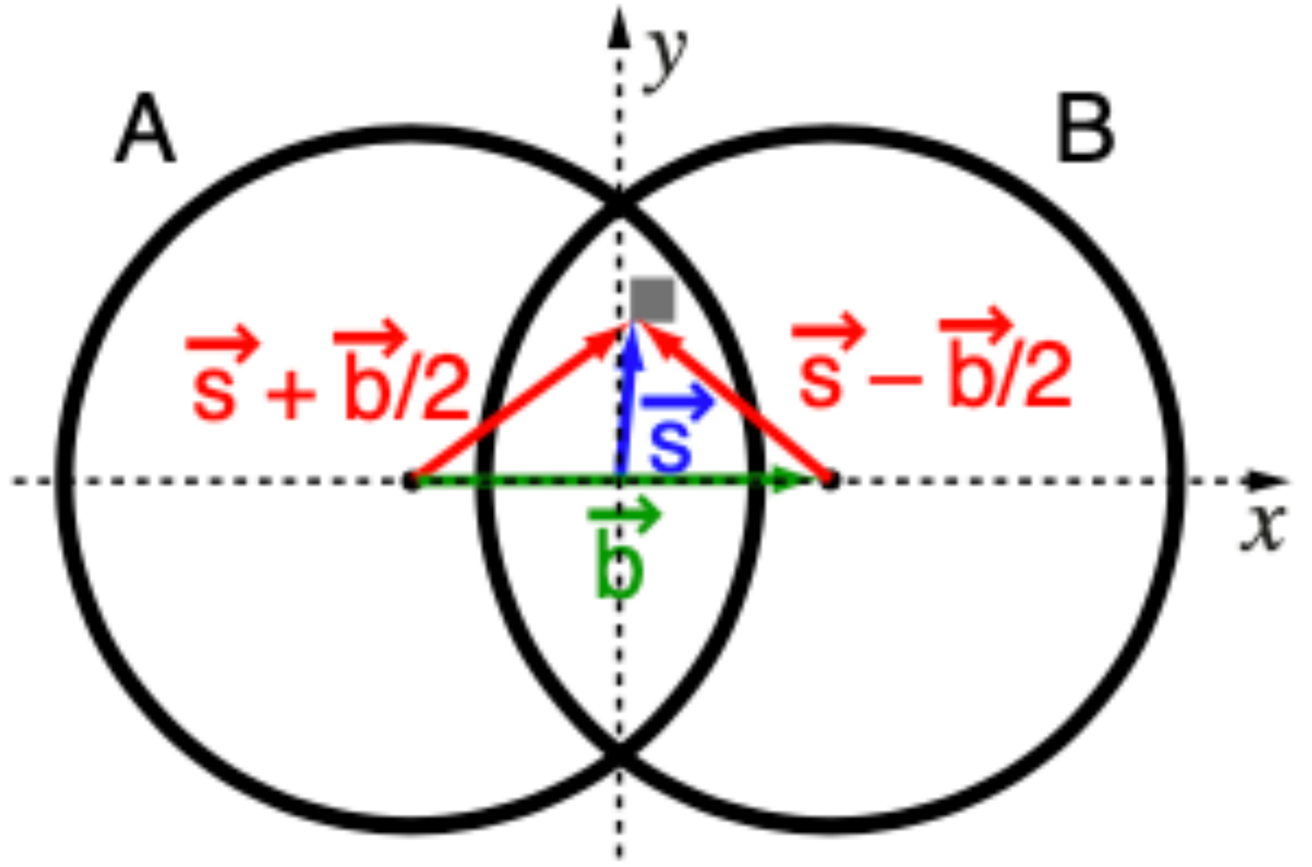


- Introducing: the thickness function

$$T(\mathbf{x}_\perp) = \int \mathrm{d}z\, \rho\left(\mathbf{x}_\perp, z\right)$$

Nothing more than a reduced/projected density

Transverse view



- Probability of finding one nucleon of each one of the nuclei on a transverse volume $\mathrm{d}^2\mathbf{x}_\perp$

$$\mathrm{d}T_{AB}(\mathbf{x}_\perp, \mathbf{b}_\perp) = T_A(\mathbf{x}_\perp + \mathbf{b}_\perp/2)T_A(\mathbf{x}_\perp - \mathbf{b}_\perp/2)\mathrm{d}^2\mathbf{x}_\perp$$

When integrated, $T_{AB}(\mathbf{b}_\perp) = \int \mathrm{d}^2\mathbf{x}_\perp T_A(\mathbf{x}_\perp + \mathbf{b}_\perp/2)T_A(\mathbf{x}_\perp - \mathbf{b}_\perp/2)$

it becomes the so-called nuclear overlap function.

- Differential probability of interaction via two interacting nucleons slabs

$\mathrm{d}N_{coll} = \sigma_{NN}\, \mathrm{d}T_{AB}(\mathbf{x}_\perp, \mathbf{b}_\perp)$ with $N_{coll} = \sigma_{NN}\, T_{AB}(\mathbf{b}_\perp)$ and σ_{NN} : the total inelastic nucleon-nucleon cross section [mb]

THE GLAUBER MODEL

- Introducing: the thickness function

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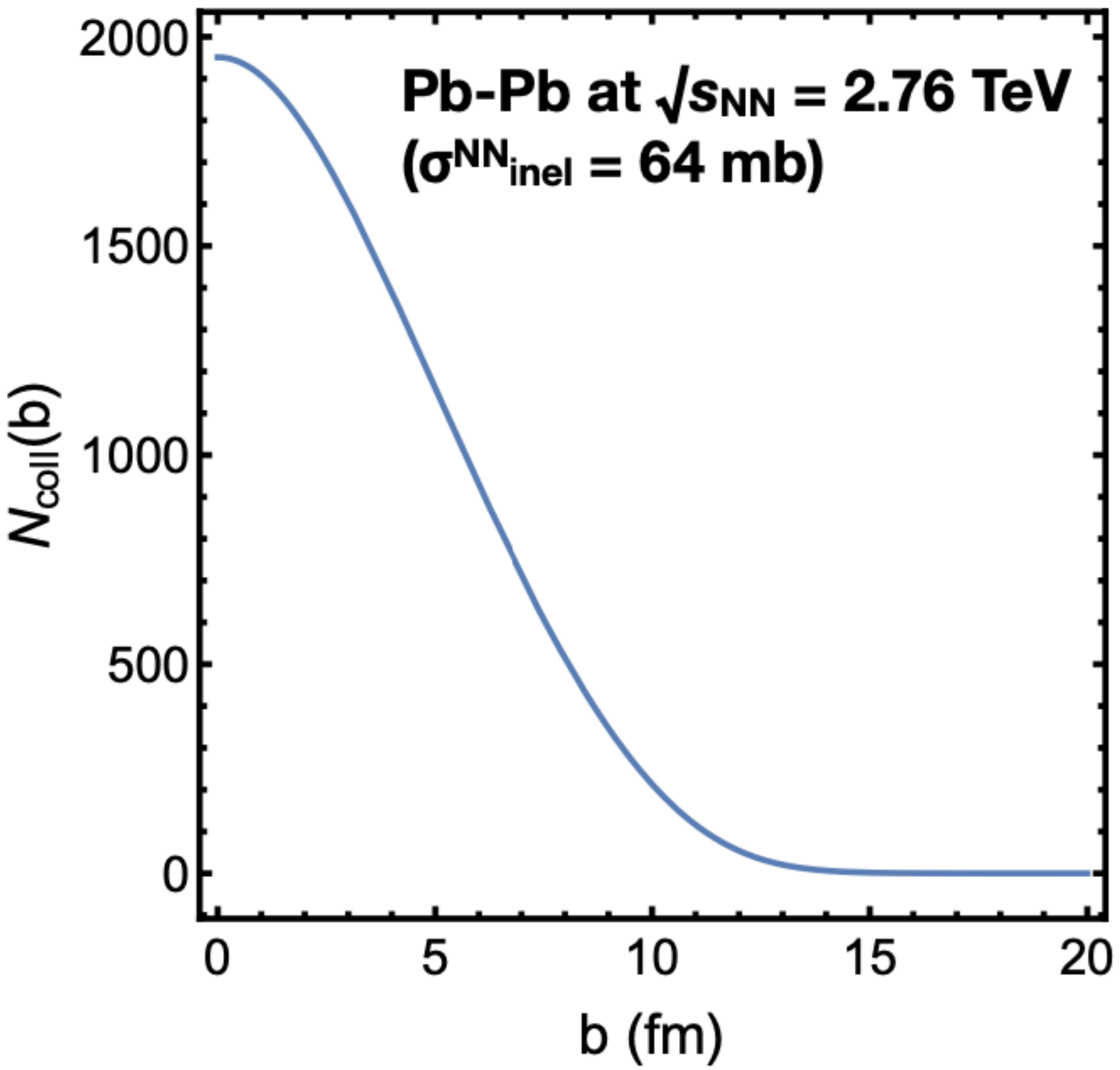

- Differential probability of interaction via two interacting nucleons slabs

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THE GLAUBER MODEL

- Introducing: the thickness function

$$T(\mathbf{x}_\perp) = \int \mathrm{d}z\, \rho\left(\mathbf{x}_\perp, z\right)$$

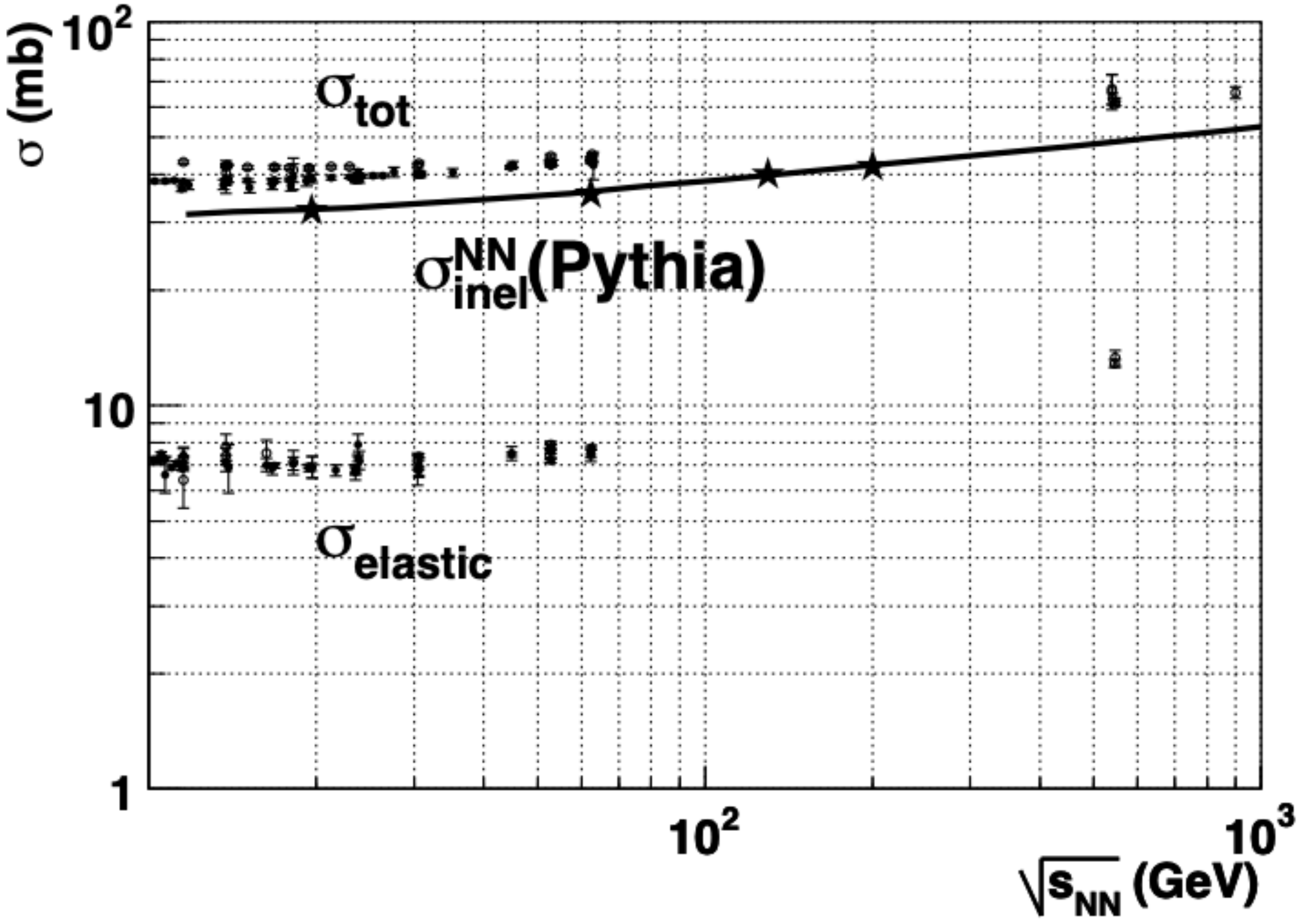
Nothing more than a reduced/projected density

- Probability of finding one nucleon of each one of the nuclei on a transverse volume $\mathrm{d}^2\mathbf{x}_\perp$

$$\mathrm{d}T_{AB}(\mathbf{x}_\perp, \mathbf{b}_\perp) = T_A(\mathbf{x}_\perp + \mathbf{b}_\perp/2)T_A(\mathbf{x}_\perp - \mathbf{b}_\perp/2)\mathrm{d}^2\mathbf{x}_\perp$$

When integrated, $T_{AB}(\mathbf{b}_\perp) = \int \mathrm{d}^2\mathbf{x}_\perp T_A(\mathbf{x}_\perp + \mathbf{b}_\perp/2)T_A(\mathbf{x}_\perp - \mathbf{b}_\perp/2)$

it becomes the so-called nuclear overlap function.



- Differential probability of interaction via two interacting nucleons slabs

$\mathrm{d}N_{coll} = \sigma_{NN}\, \mathrm{d}T_{AB}(\mathbf{x}_\perp, \mathbf{b}_\perp)$ with $N_{coll} = \sigma_{NN}\, T_{AB}(\mathbf{b}_\perp)$ and σ_{NN} : the total inelastic nucleon-nucleon cross section [mb]

THE GLAUBER MODEL

PROBABILITY FOR AN INELASTIC A+B COLLISION

- Let's normalize again the thickness functions for nuclei with **A** and **B** nucleons

$$T_A(\mathbf{x}_\perp) = A\tilde{T}_A(\mathbf{x}_\perp) \quad \text{and} \quad T_B(\mathbf{x}_\perp) = B\tilde{T}_B(\mathbf{x}_\perp) \quad \Longrightarrow \quad T_{AB}(\mathbf{b}_\perp) = AB\,\tilde{T}_{AB}(\mathbf{b}_\perp)$$

- Which is nice since we can see now that the probability of collision of any two nucleons is just given b

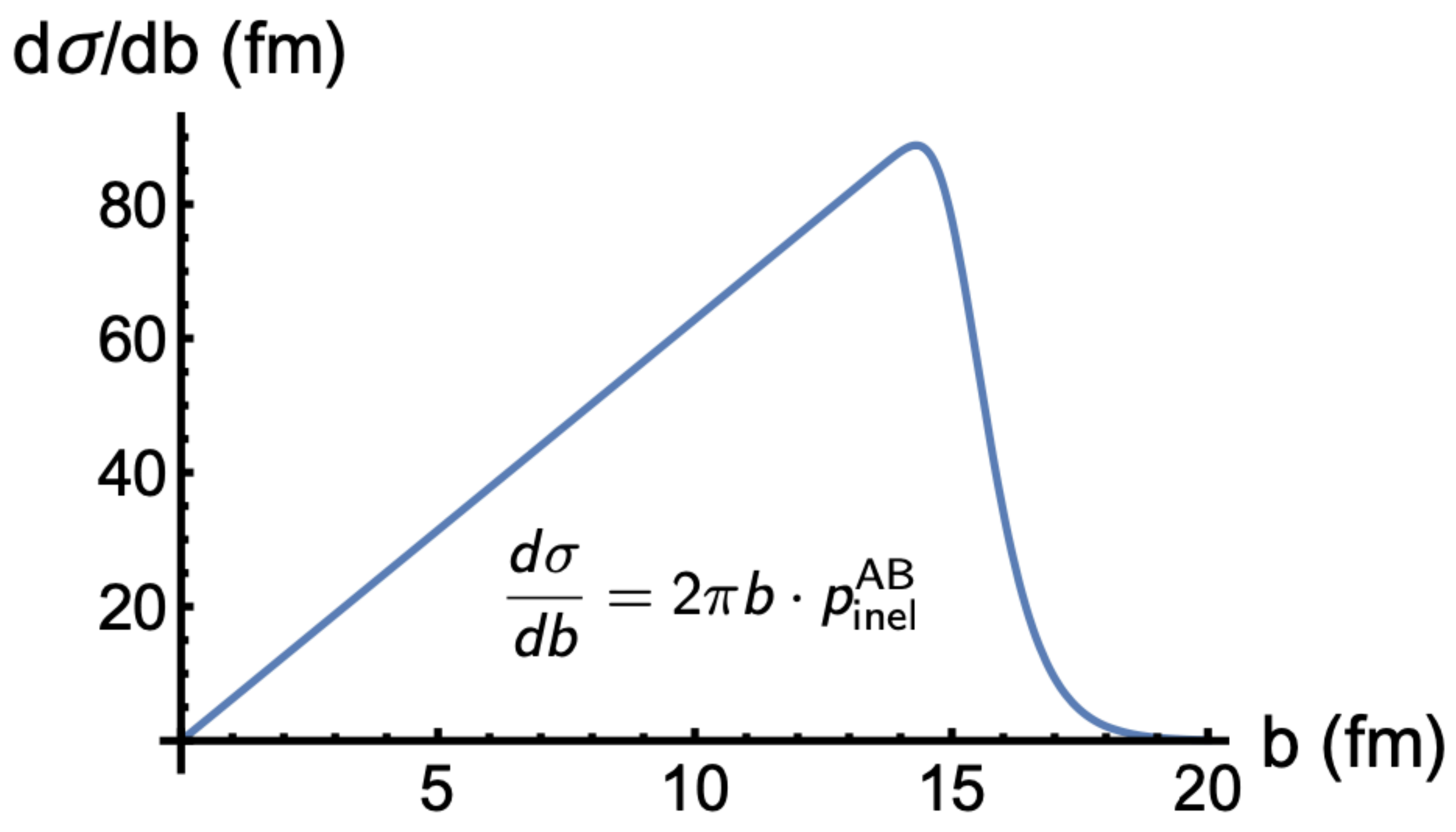
$$p_{NN}(\mathbf{b}_\perp) = \sigma_{NN}\tilde{T}_{AB}(\mathbf{b}_\perp) \quad \Longrightarrow \quad N_{coll}(\mathbf{b}_\perp) = AB\,p_{NN}$$

- What is the probability of having **n** such collisions? A binomial distribution...

$$P_k(\mathbf{b}_\perp) = \binom{AB}{n} p_{NN}^k \left(1 - p_{NN}\right)^{AB-k}$$

- We can derive then the total cross-section for the collision

$$\frac{\mathrm{d}\sigma_{inel}^{A+B}}{\mathrm{d}^2\mathbf{b}_\perp} = p_{inel}^{AB} \sum_k^{AB} P_k(\mathbf{b}_\perp) = 1 - \left[1 - p_{NN}\right]^{AB}$$



THE GLAUBER MODEL

PROBABILITY FOR AN INELASTIC A+B COLLISION

- Probability that a test nucleon of nucleus A interacts with a certain nucleon of **B** $\Rightarrow$ $p_{NN,A}(\mathbf{x}_\perp) = \sigma_{NN}\tilde{T}_B(\mathbf{x}_\perp)$
- Now, the probability that the test nucleon does not interact with any of the *B* nucleons of nucleus **B** is given by $\Rightarrow$ $[1 - p_{NN,A}(\mathbf{x}_\perp)]^B$
- An interesting limit is the probability that the nucleon interacts at least **once**

$$p_{int,A} = 1 - [1 - p_{NN,A}(\mathbf{x}_\perp)]^B \sim 1 - \exp[-B\, p_{NN,A}(\mathbf{x}_\perp)]$$

- The number of participants of **A** is then the convolution of the density of nucleons with the probability of interacting at least once, $p_{int,A}$

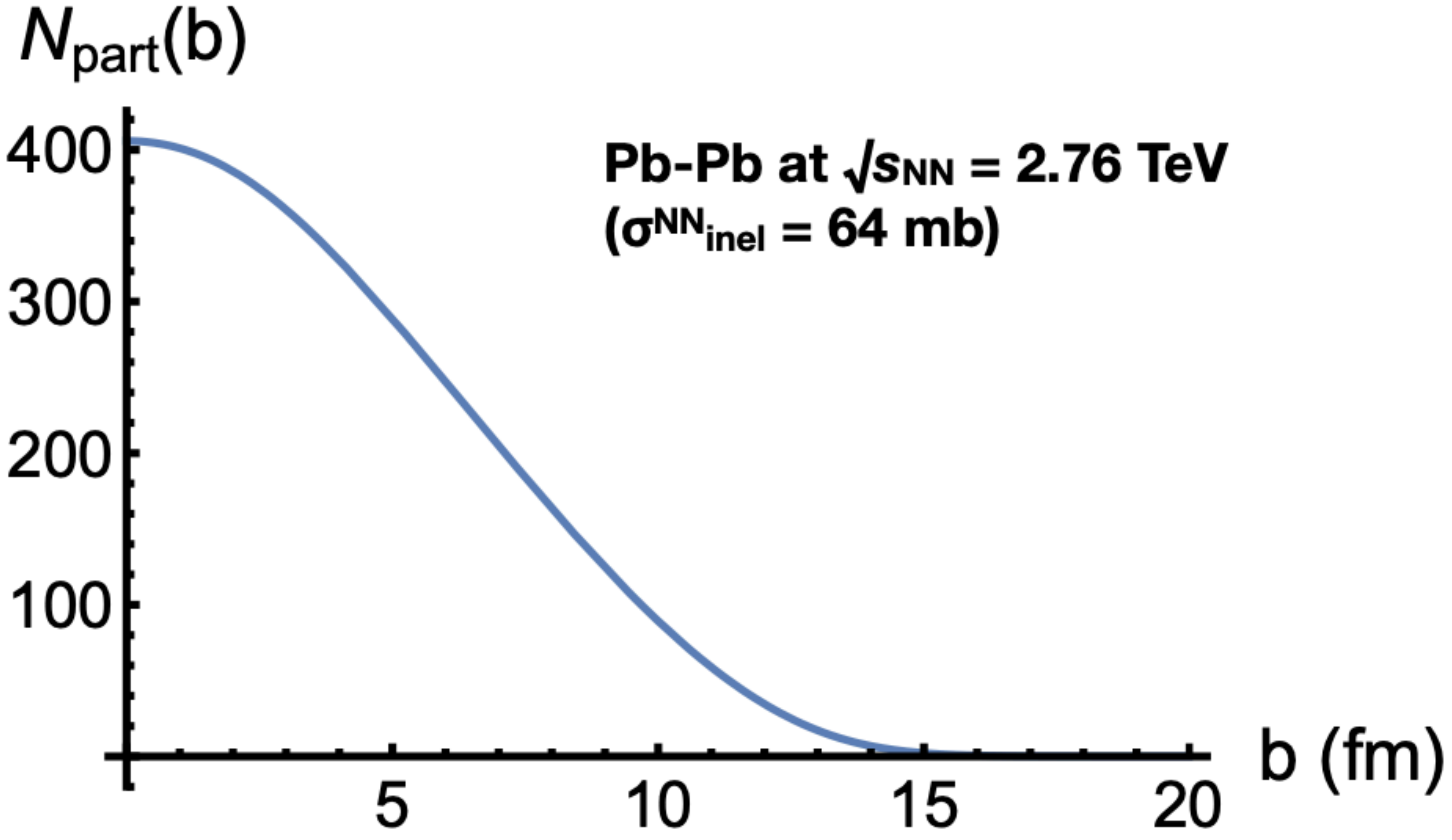
$$N_{part,A} = \int \mathrm{d}^2\mathbf{x}_\perp T_A(\mathbf{x}_\perp + \mathbf{b}_\perp/2)\ \left\{1 - \exp[-B\, p_{NN,A}(\mathbf{x}_\perp)]\right\}$$

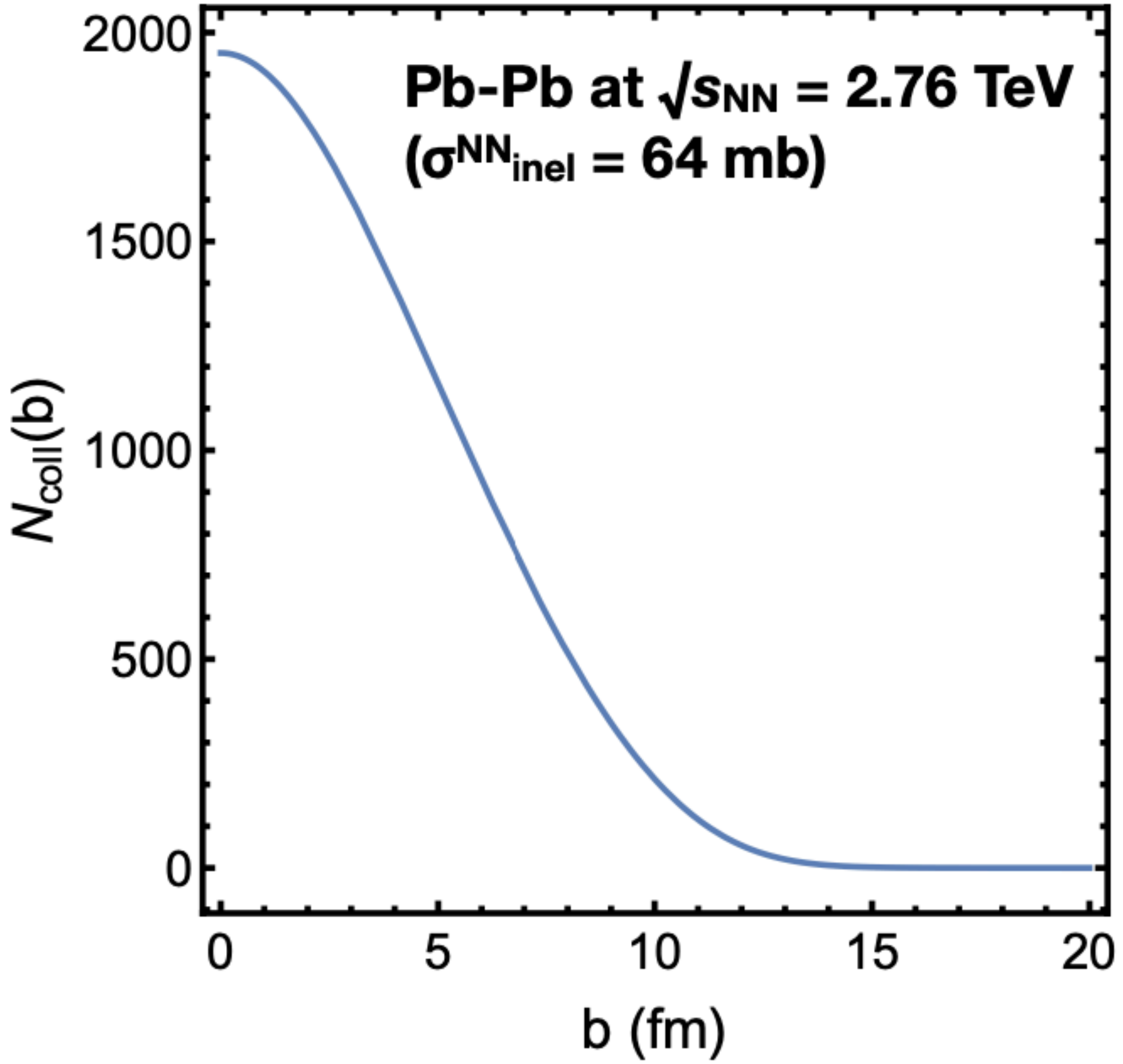
- The same can be done for the opposite case,

$$N_{part,B} = \int \mathrm{d}^2\mathbf{x}_\perp T_B(\mathbf{x}_\perp + \mathbf{b}_\perp/2)\ \left\{1 - \exp[-A\, p_{NN,A}(\mathbf{x}_\perp)]\right\}$$

- And naturally, we get the total amount of participants by adding them, $N_{part} = N_{part,A} + N_{part,B}$

PARTICIPANTS AND COLLISIONS



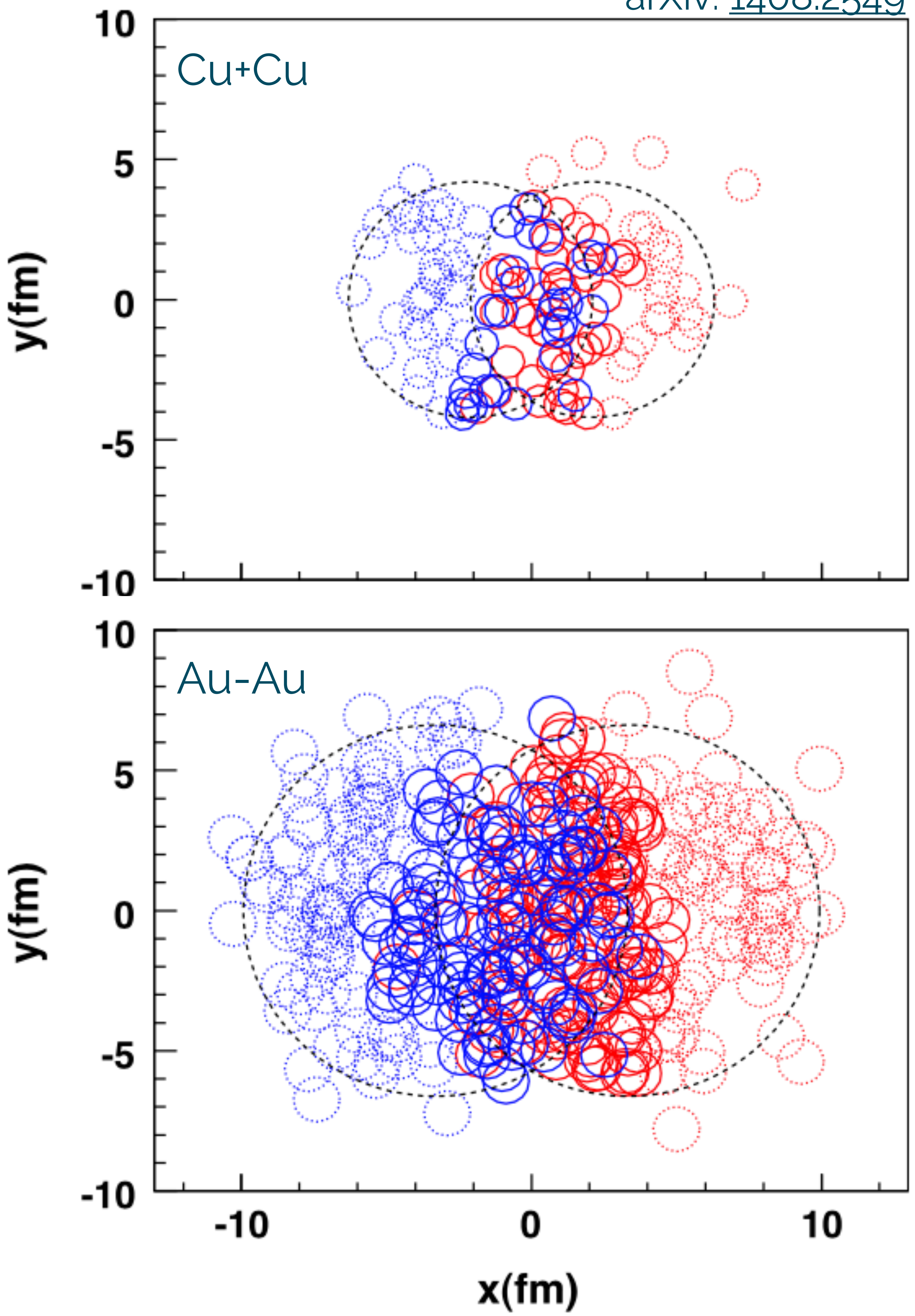


THE MONTE CARLO GLAUBER

- Nucleus is not smooth. In a single shot of the experiment, nucleus has different configurations
  - Monte-Carlo (stochastic) modelling
- The -general- algorithm:
  - 1) Draw random $\mathbf{b}_\perp$
  - 2) Distribute nucleons of two nuclei according to nuclear density (Wood-Saxons) distribution
  - 3) List all pairs of nucleons (one from **A** and one from **B**)
  - 4) Pair collides if criterion is satisfied

    e.g. distance in transverse plane is $d < \sqrt{\sigma_{NN}/\pi}$, but are more sophisticated criteria
  - 5) Repeat, profit.
- Quantities like N_{part}, N_{coll} can be obtained as expectation values.

arXiv: 1408.2549



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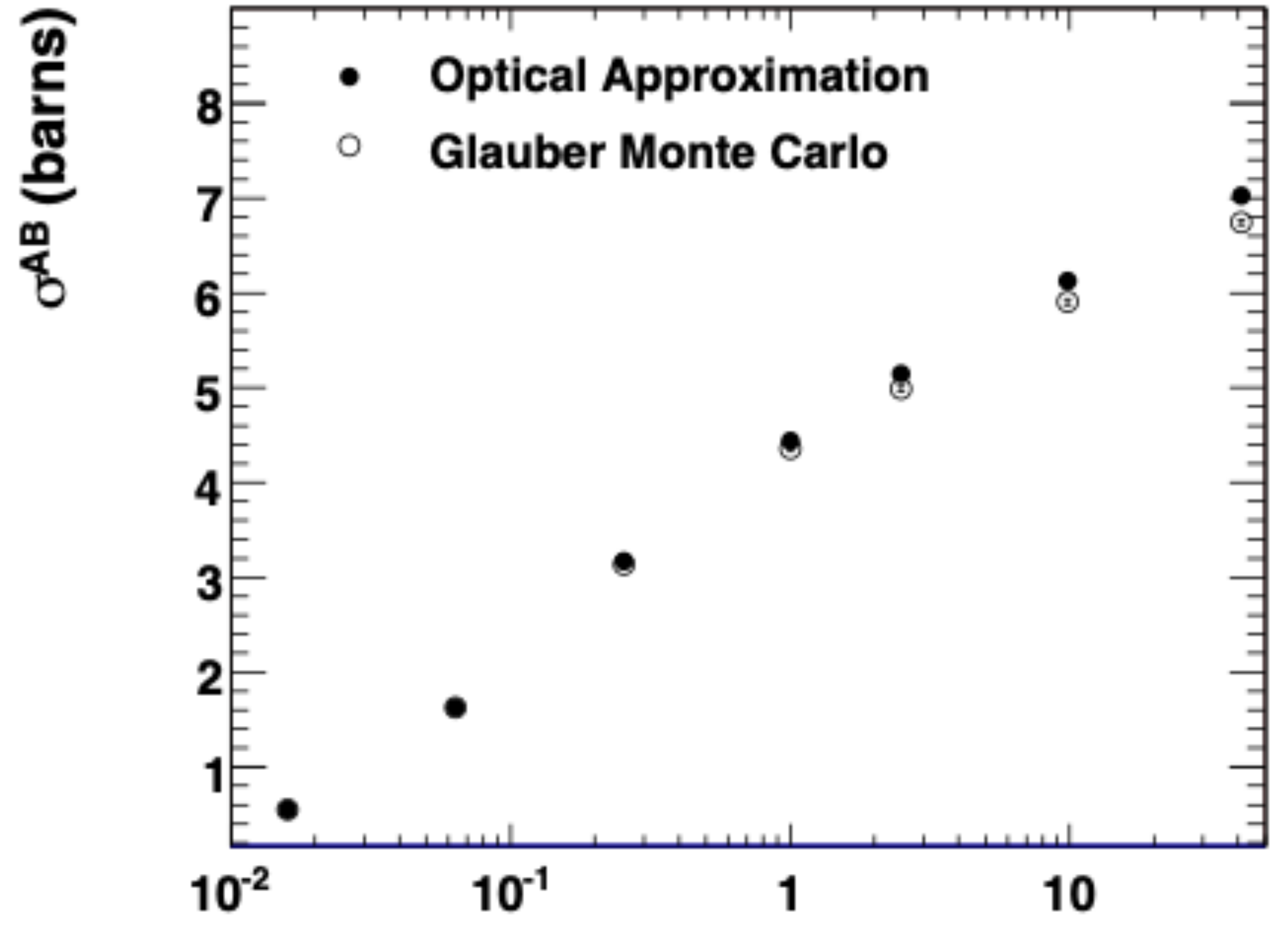
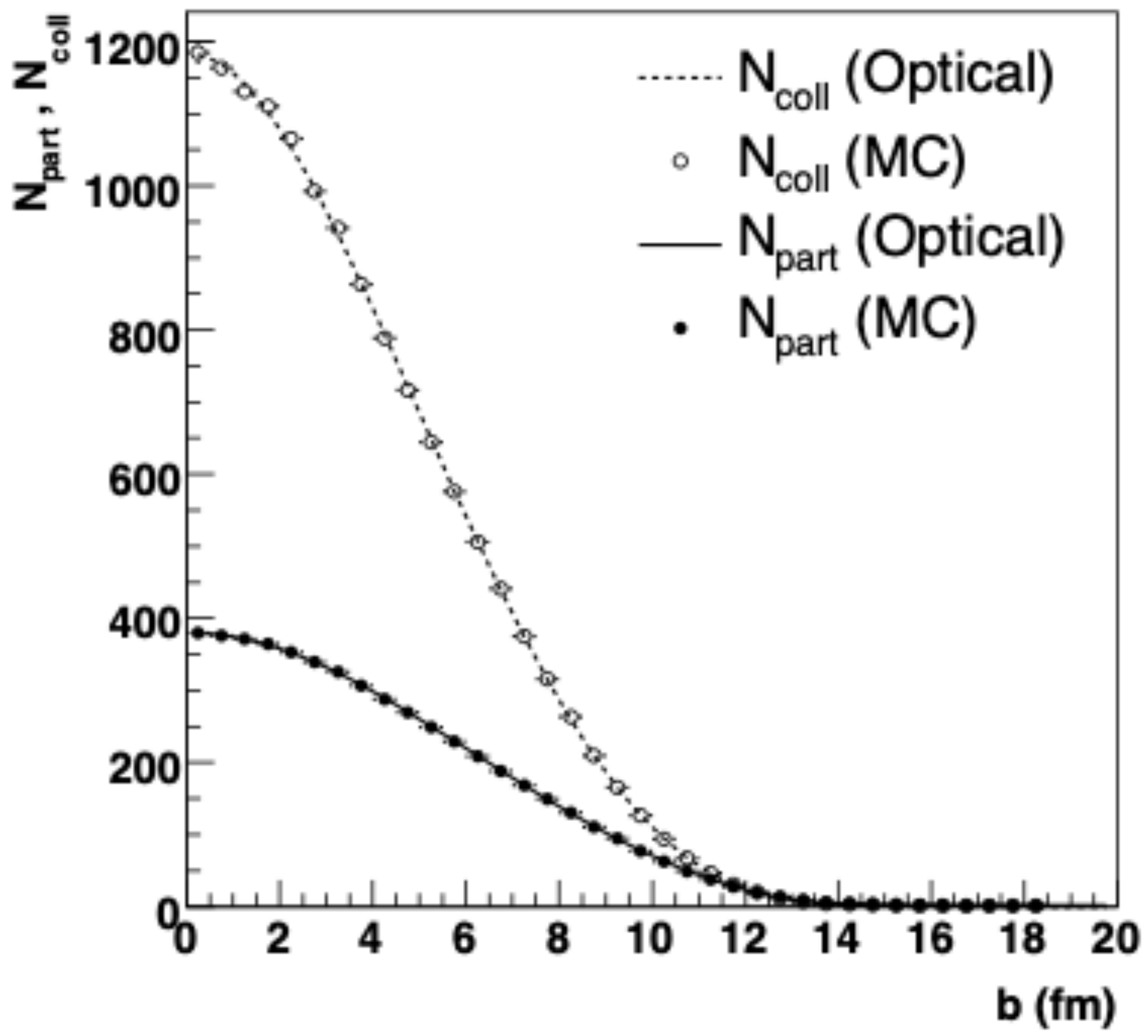
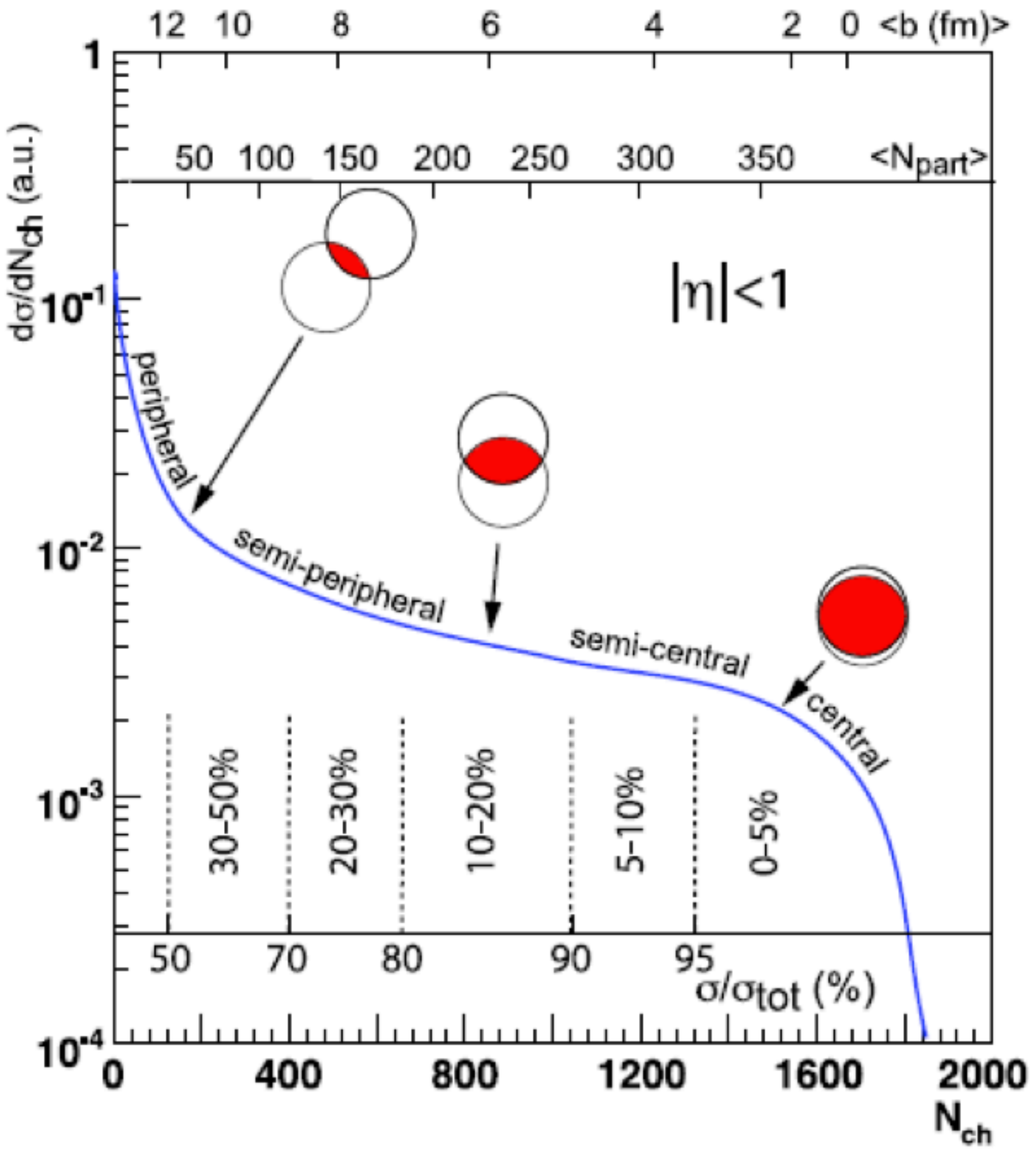
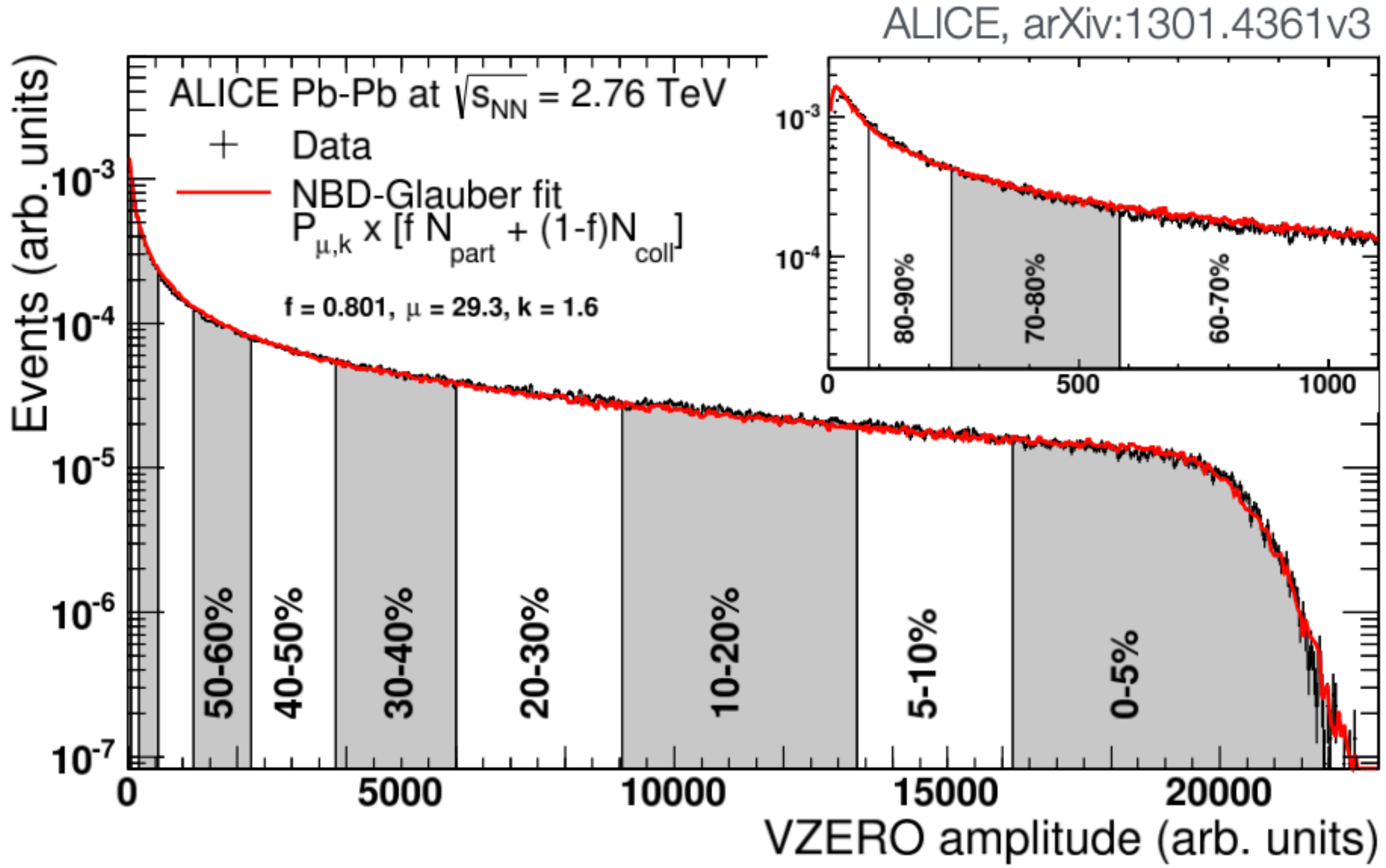




CENTRALITY SELECTION

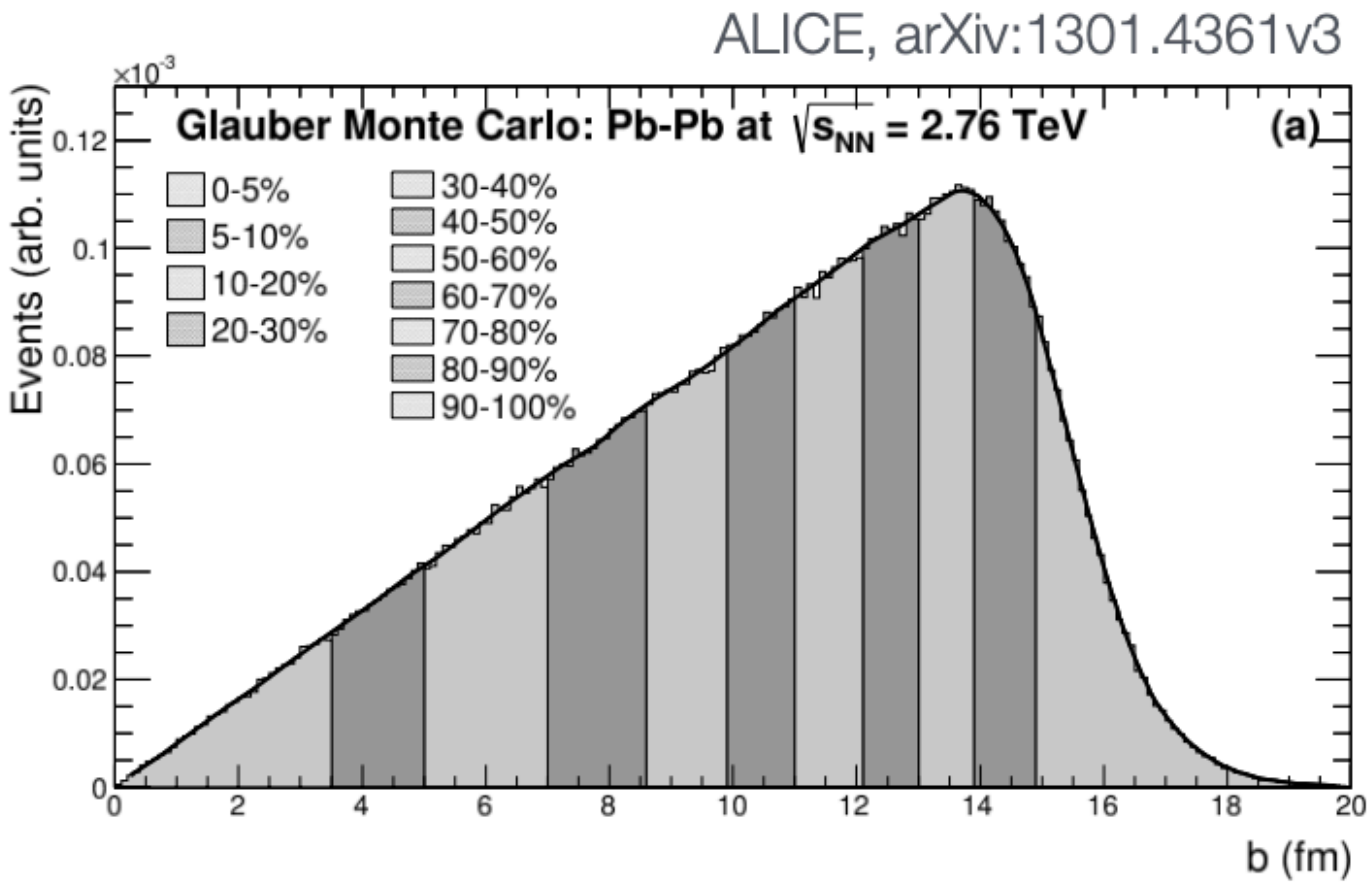


Fixing with multiplicity



Fixing with VZERO amplitude

THE GLAUBER MODEL



MC Glauber needed for two main reasons:

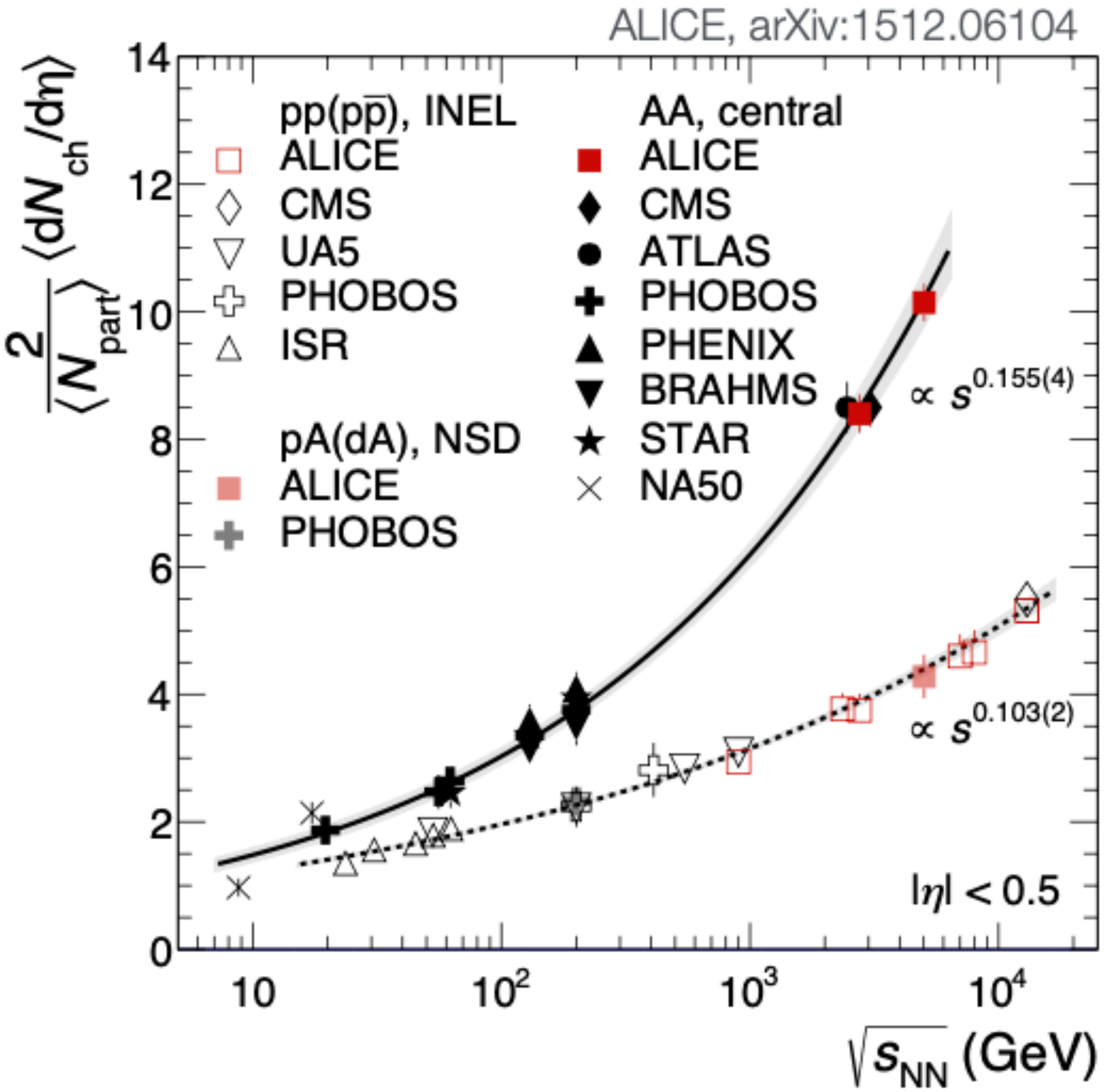
- Fix the 100% value of events (background
- Find impact parameter interval which corresponds

Centrality	b_{min} (fm)	b_{max} (fm)	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$	$\langle T_{AA} \rangle$ 1/mbarn
0–5%	0.00	3.50	382.7	1685	26.32
5–10%	3.50	4.94	329.4	1316	20.56
10–20%	4.94	6.98	260.1	921.2	14.39
20–40%	6.98	9.88	157.2	438.4	6.850
40–60%	9.88	12.09	68.56	127.7	1.996
60–80%	12.09	13.97	22.52	26.71	0.4174
80–100%	13.97	20.00	5.604	4.441	0.06939

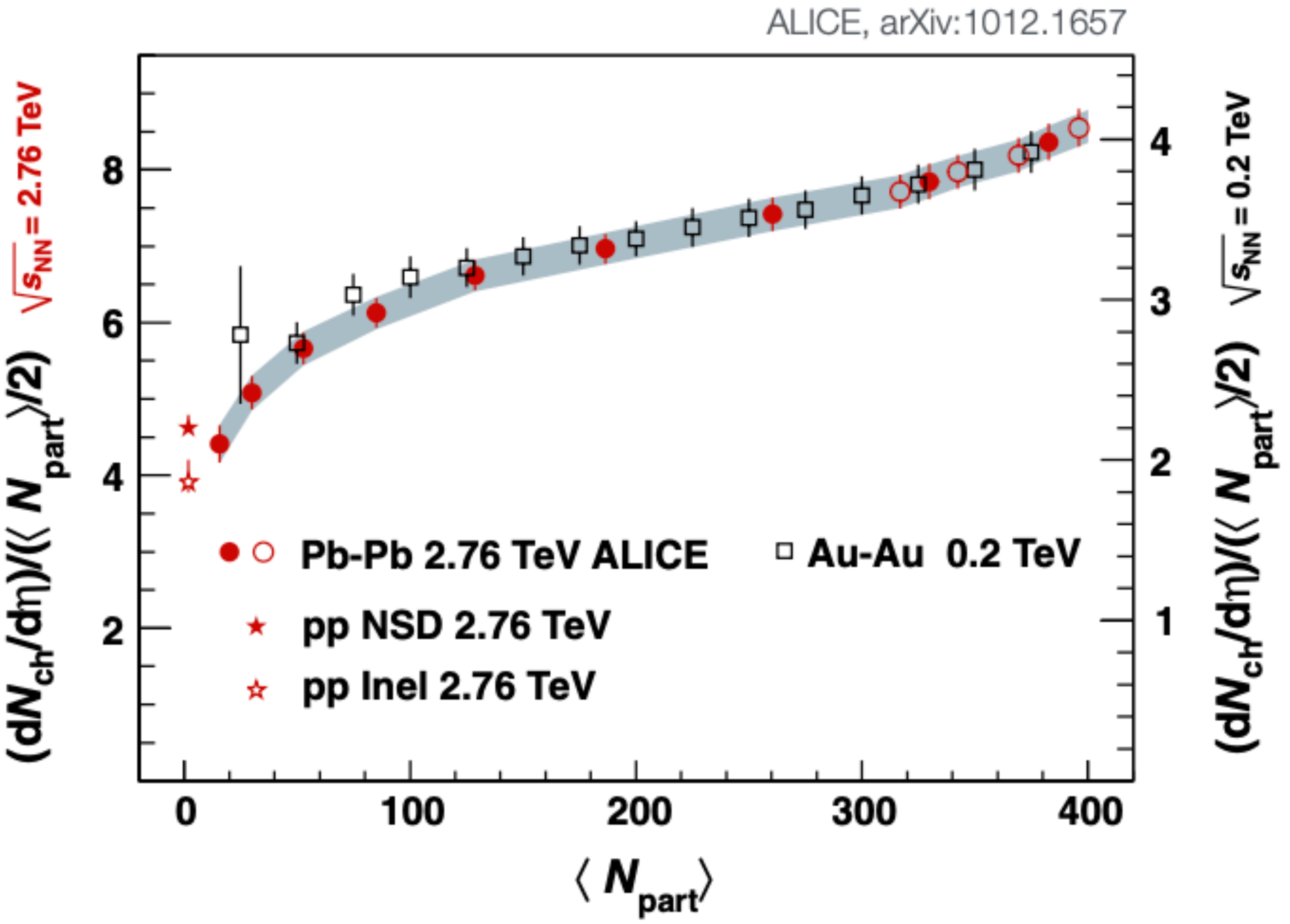
ENERGY DEPENDENCE OF MULTIPLICITY

$\frac{dN_{ch}}{d\eta}$ scales as a power of the CoM energy, $\sqrt{s_{NN}}$

Increase is stronger in AA than in pp



CENTRALITY DEPENDENCE OF YIELDS



$\frac{1}{N_{part}}\frac{dN_{ch}}{d\eta}$ increases with centrality (multiplicity)

Scaling for different systems,
Geometry is important!