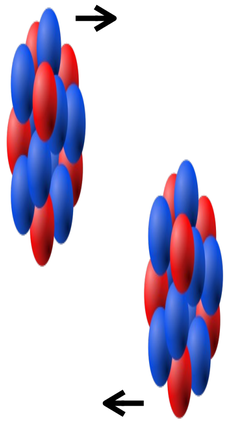
Timeline of a heavy-ion collision

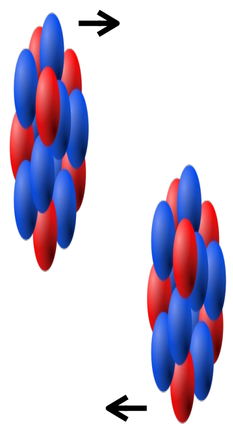
[Adapted from Guilherme Milhano]



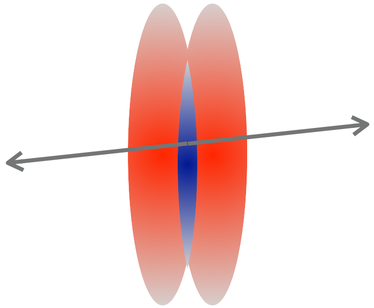
colliding nuclei

- need to know how likely it is to find energetic quarks and gluons in the nucleons [nuclear PDFs]
- geometry of collision [how head-on they are] is VERY important

Timeline of a heavy-ion collision



colliding nuclei



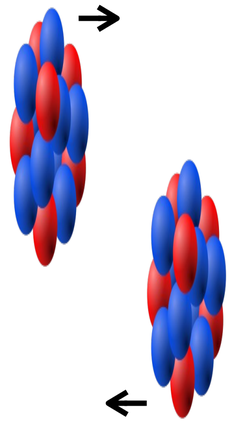
collision

- many soft [small momentum exchange] collisions
  - responsible for bulk low-momentum particle production
  - will quickly hydrodynamize
- very few hard [large momentum exchange] collisions
  - offspring will slowly relax towards hydrodynamization, yet remain out-of-equilibrium, while propagating through soft soup

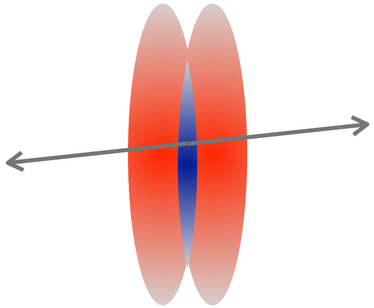
0

~0.1 fm/c
[10^{-25} s]

Timeline of a heavy-ion collision



colliding nuclei



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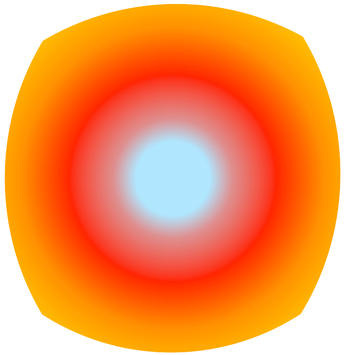
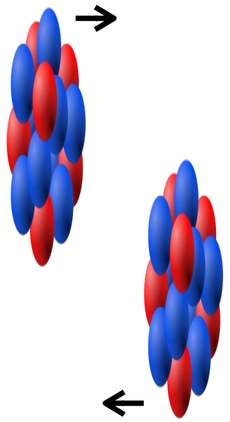


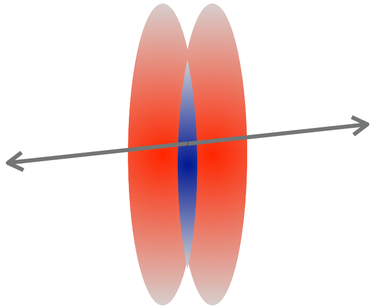
QGP

- hot, dense, coloured nuclear matter
- quark and gluons are the relevant d.o.f

Timeline of a heavy-ion collision



colliding nuclei



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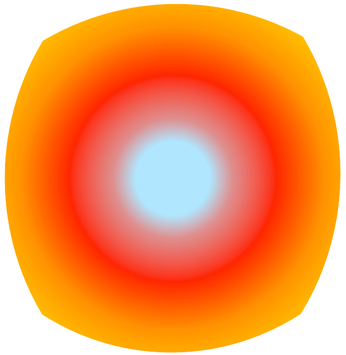
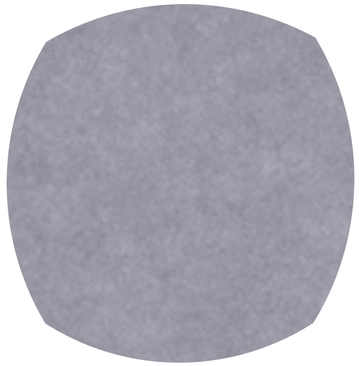


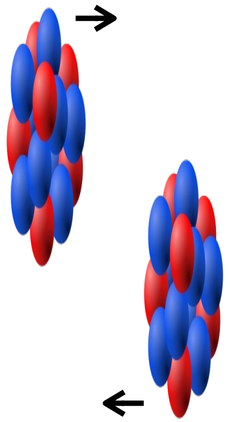
QGP



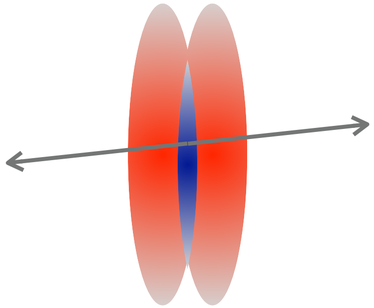
hadronization

- the QGP expands and thus cools down
- once T∼150 MeV back to hadronic matter

Timeline of a heavy-ion collision



colliding nuclei



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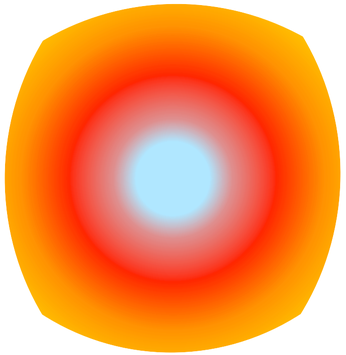

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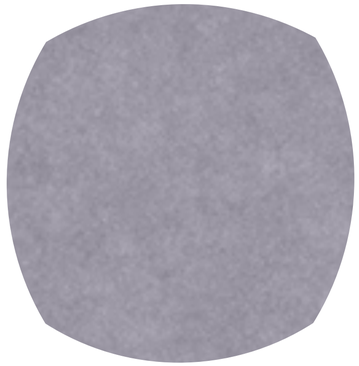

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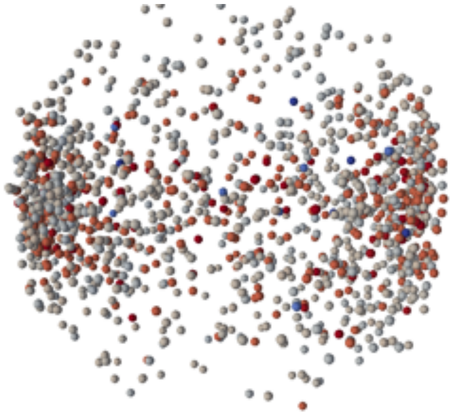
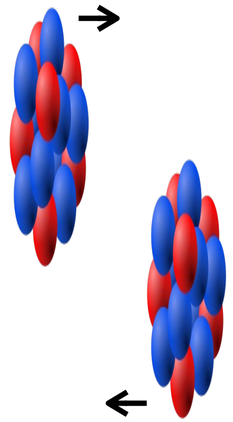


hadrons

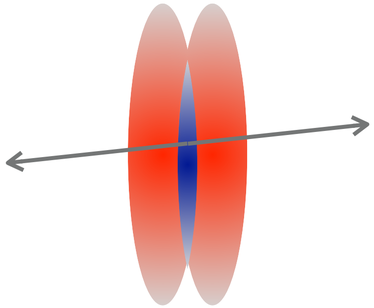
- rescattering possible
- free-stream to detector

Timeline of a heavy-ion collision

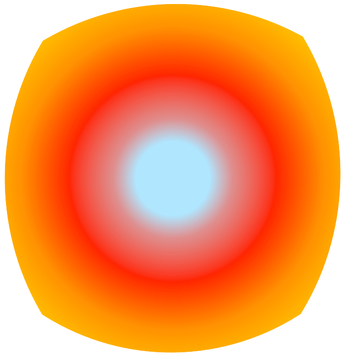


colliding nuclei

- what we can constrain in e+A experiments (e.g. EIC)

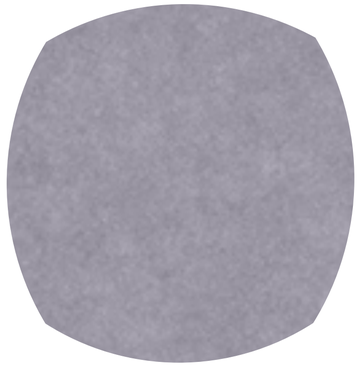


collision

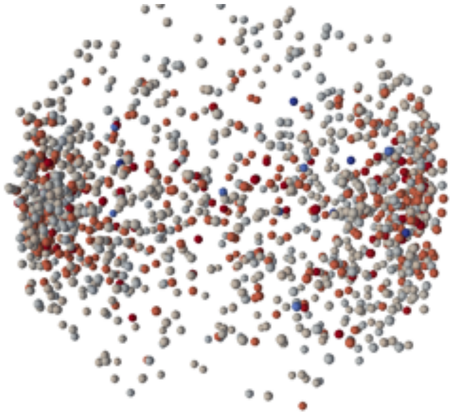


QGP

- what we want to understand:
  - how we get here?
  - what it is?
  - how it stops being?



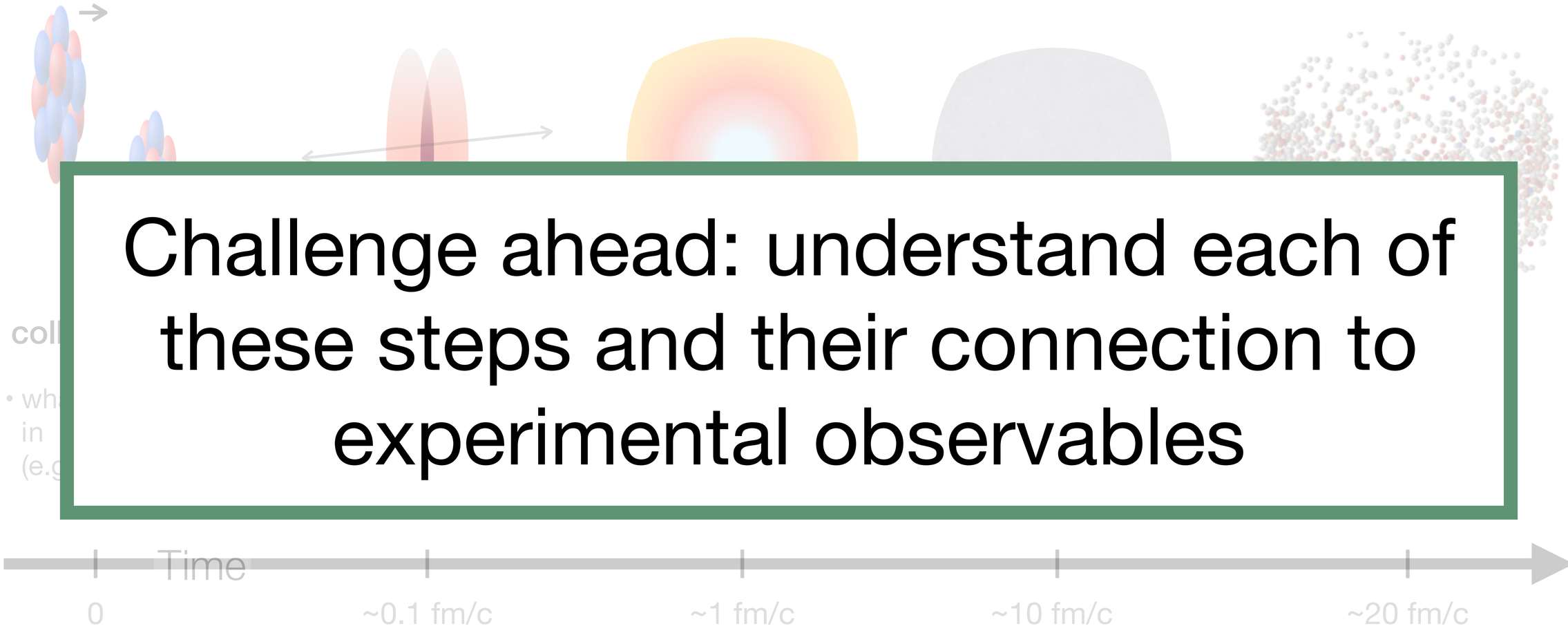
hadronization



hadrons

- all we have

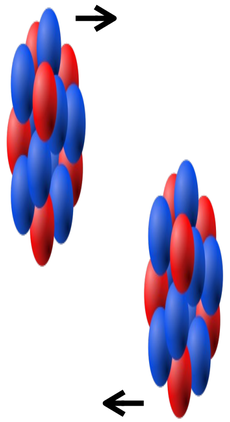
Timeline of a heavy-ion collision



Challenge ahead: understand each of these steps and their connection to experimental observables

Timeline of a heavy-ion collision

[Adapted from Guilherme Milhano]



colliding nuclei

- need to know how likely it is to find energetic quarks and gluons in the nucleons [nuclear PDFs]
- geometry of collision [how head-on they are] is VERY important

Parton Distribution functions (PDFs)

Probability to find a parton of a given flavour in a nucleon (PDF) changes with:

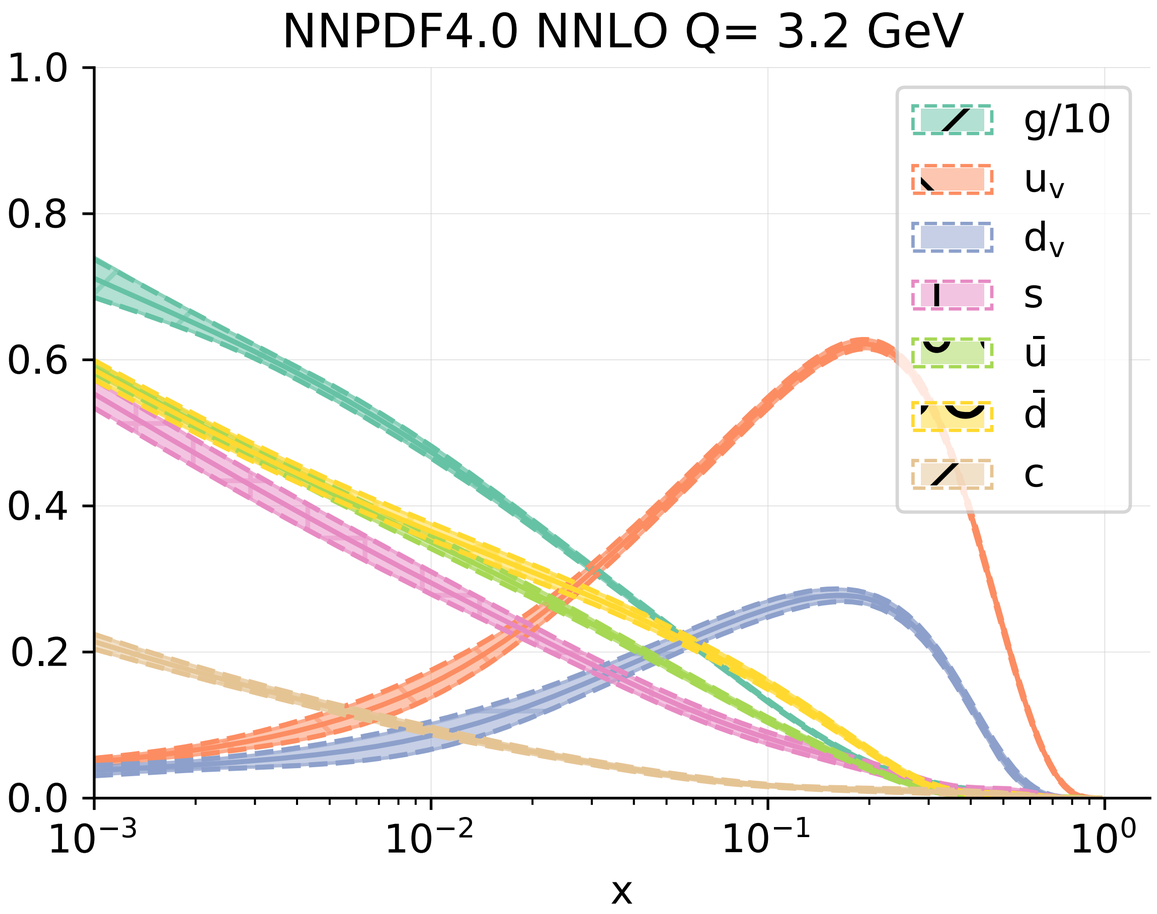
- x : energy fraction carried by the parton
- Q^2 : virtuality (inverse of the resolution power)

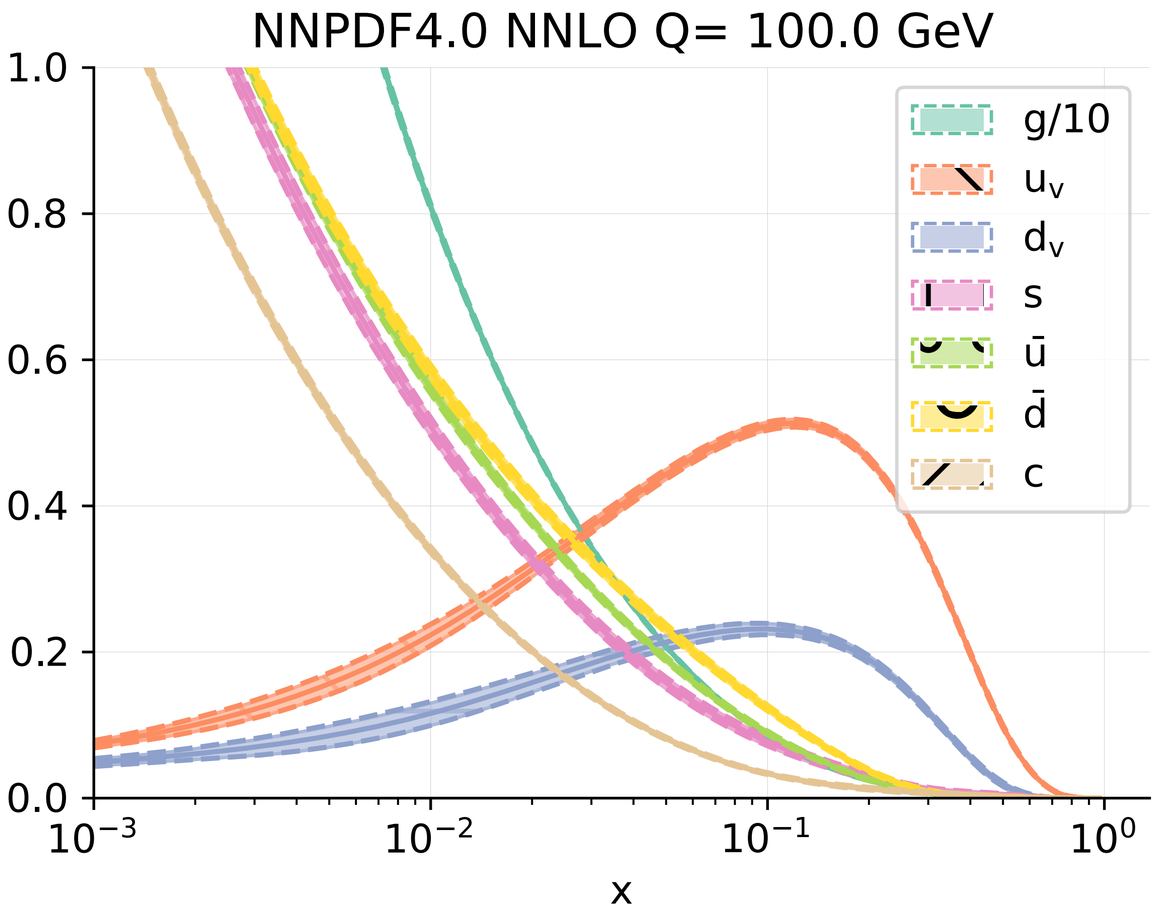
Universal object but not calculable from first principles in QCD. Strategy:

- Ansätz for the PDF at scale Q_0, e.g. a polynomial.
- Evolve PDF with QCD (DGLAP) and fit free parameters to data

Most recent global fit of PDFs

[NNPDF Collab EPJC 82 (2022) 5, 428]



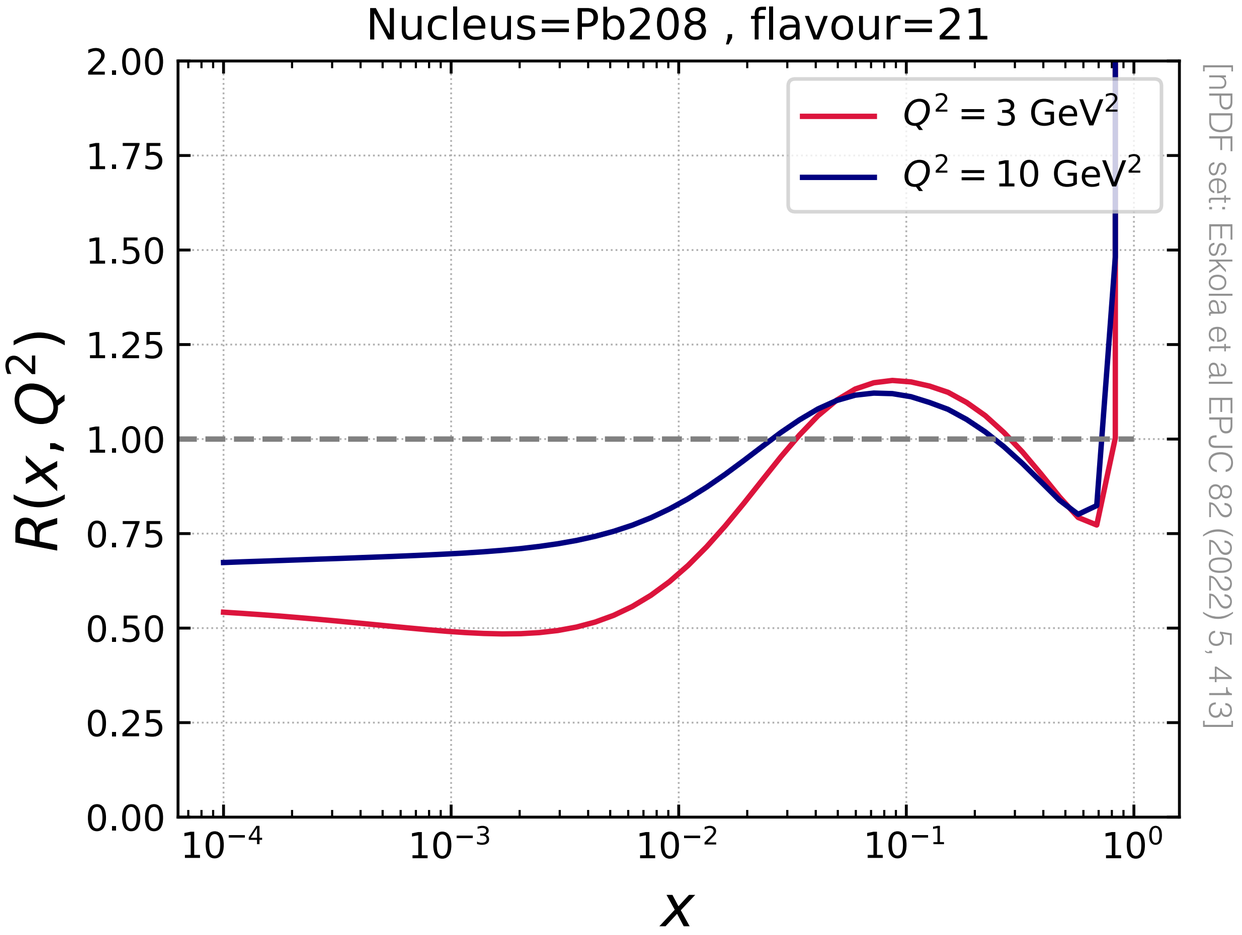


A proton, at high energies (small-x), is a collection of gluons

Nuclear Parton Distribution functions (nPDFs)

`2024-Granada-heavyion-lectures/npdfs.py`

PDFs in a bound nucleon are different than those of a free nucleon. Parametrize difference as



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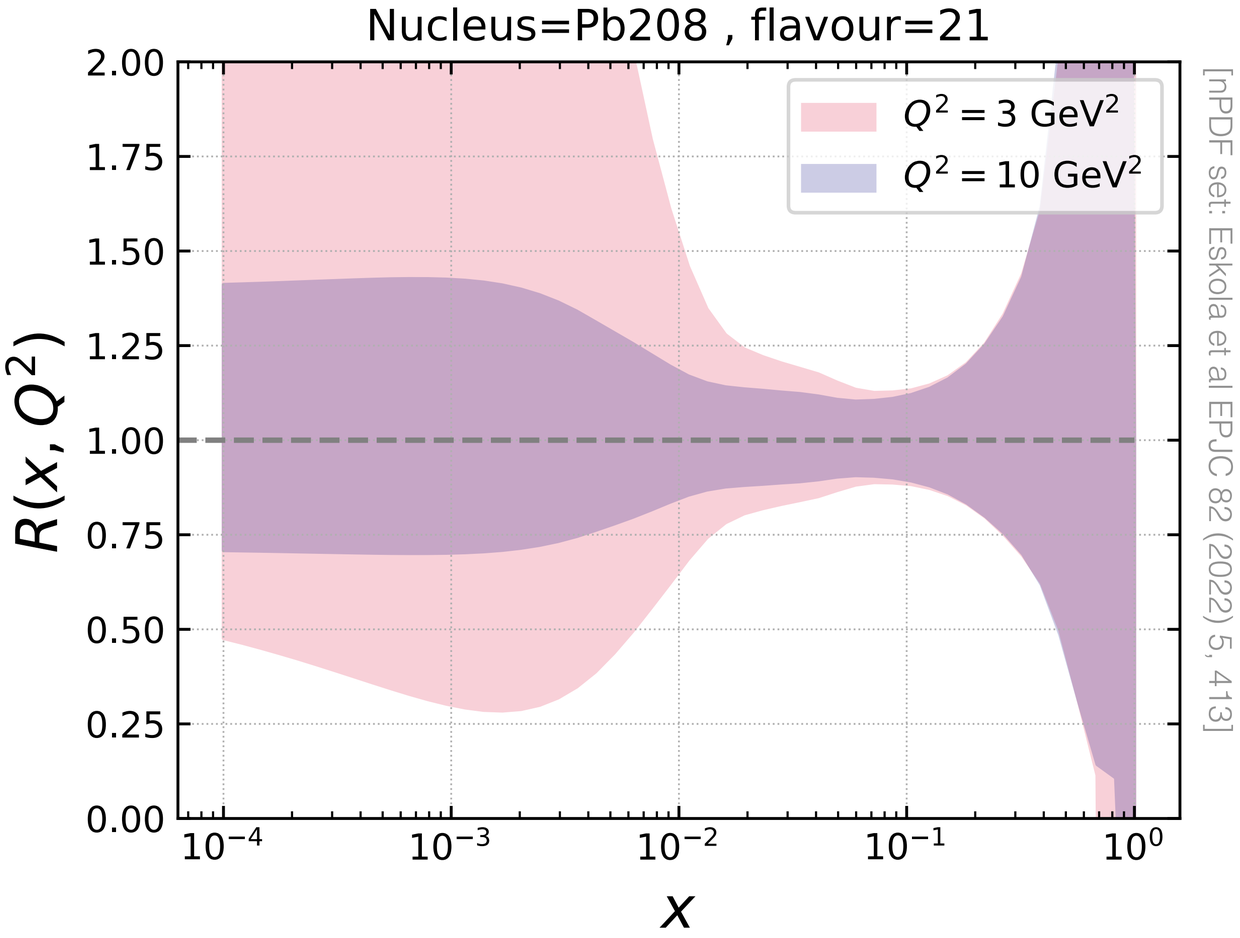
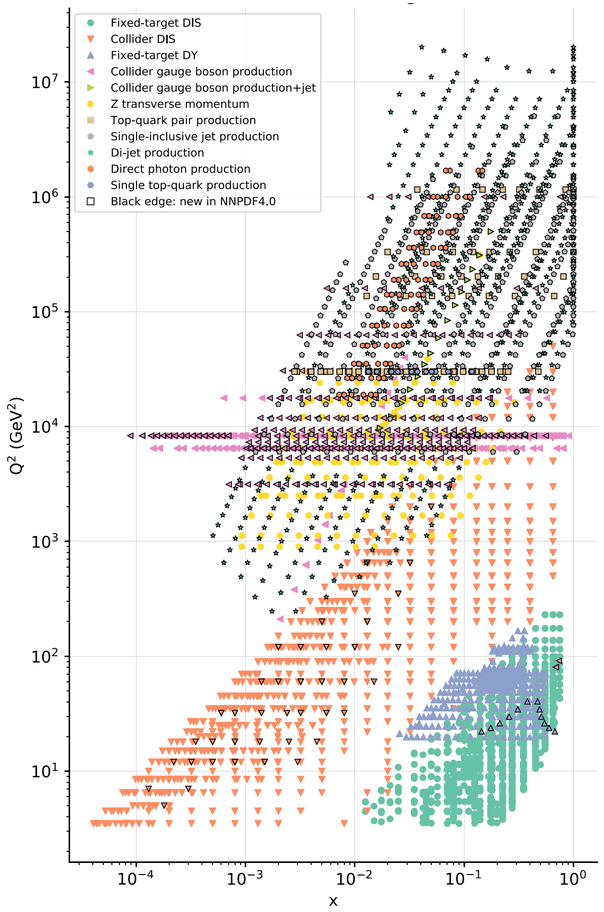


pp vs AA data set for PDF fits

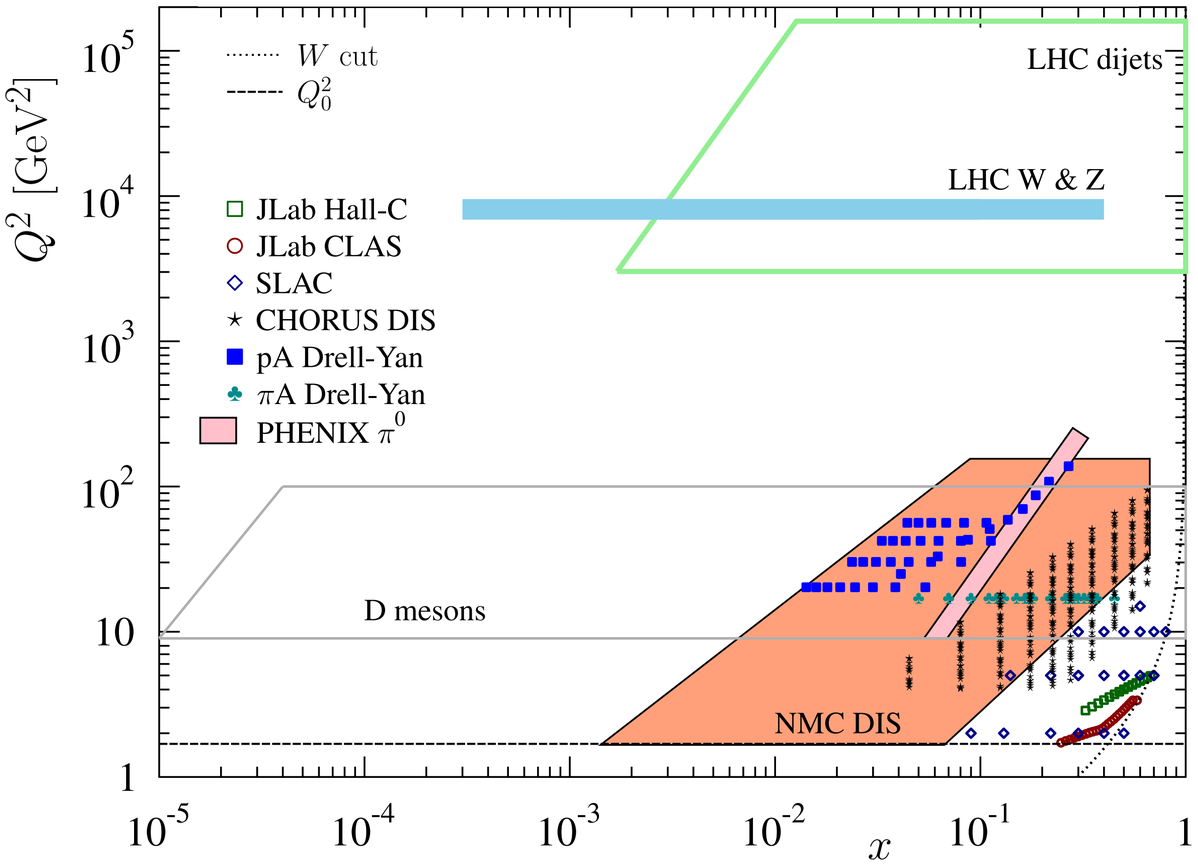
`2024-Granada-heavyion-lectures/npdfs.py`

Uncertainties larger than ideal due to constraining data being sparse

Data included in NNPDF4.0 PDF fit

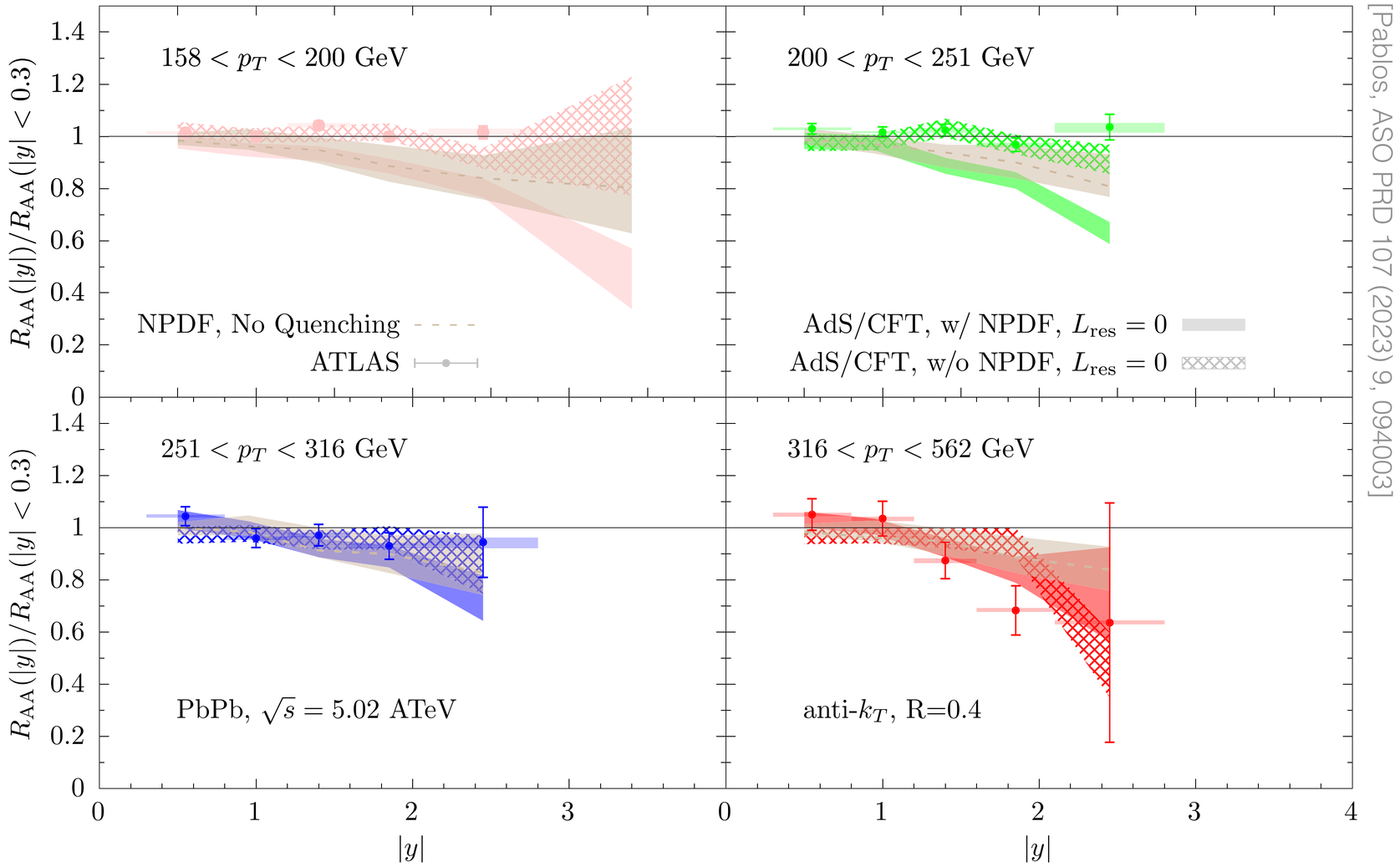


Data included in EPPS21 nPDF fit



Effect of nPDFs on LHC phenomenology

$R_{AA} = 1$ if PbPb = pp

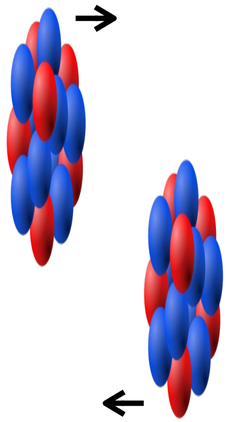


[Pablos, ASO PRD 107 (2023) 9, 094003]

No QGP, *just* coherence effects in nucleus wave function lead to 20% effect

Timeline of a heavy-ion collision

[Adapted from Guilherme Milhano]



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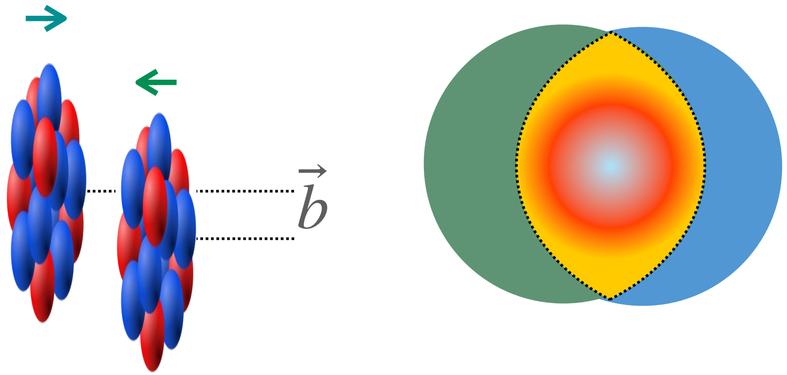
Collision geometry

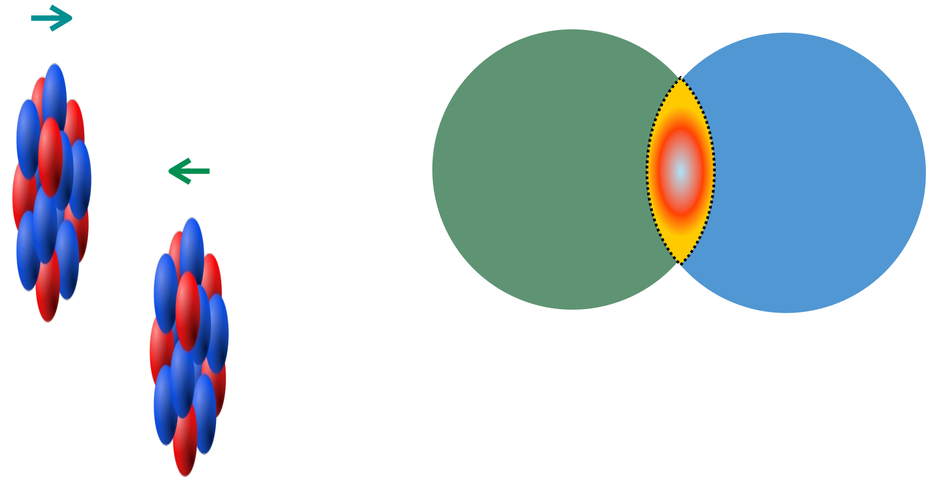
Impact parameter of collision, $\vec{b}$, defines initial geometry. It controls the extent of the medium that is created

Central collision



- Hotter medium
- Larger energy density
- More particles produced

Peripheral collision



- Cooler medium
- Smaller energy density
- Few particles produced

Collision geometry

Impact parameter of collision, $\vec{b}$, defines initial geometry. It controls the extent of the medium that is created

Impact parameter is an ideal event classifier. However, not measurable directly in experiment. Need a model !

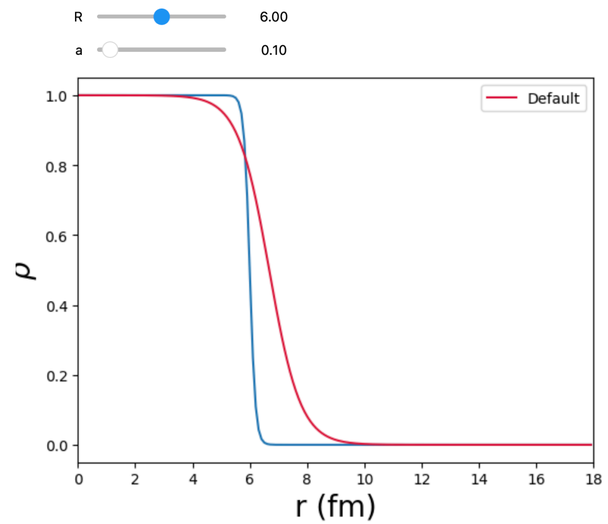
- Hotter medium
- Larger energy density
- More particles produced

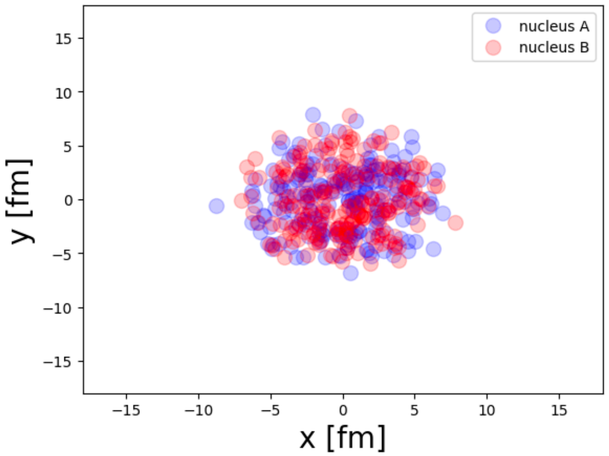
- Cooler medium
- Smaller energy density
- Few particles produced

Collision geometry: Glauber Monte Carlo

`2024-Granada-heavyion-lectures/mc-glauber.ipynb`

AA collision viewed as incoherent superposition of binary NN scatterings. Includes





- Distribution of nucleons inside the nucleus

$$\rho(r; R, A) = \frac{\rho_0}{1 + e^{\frac{r-R}{a}}}$$

density in the center

nuclear radius

skin depth

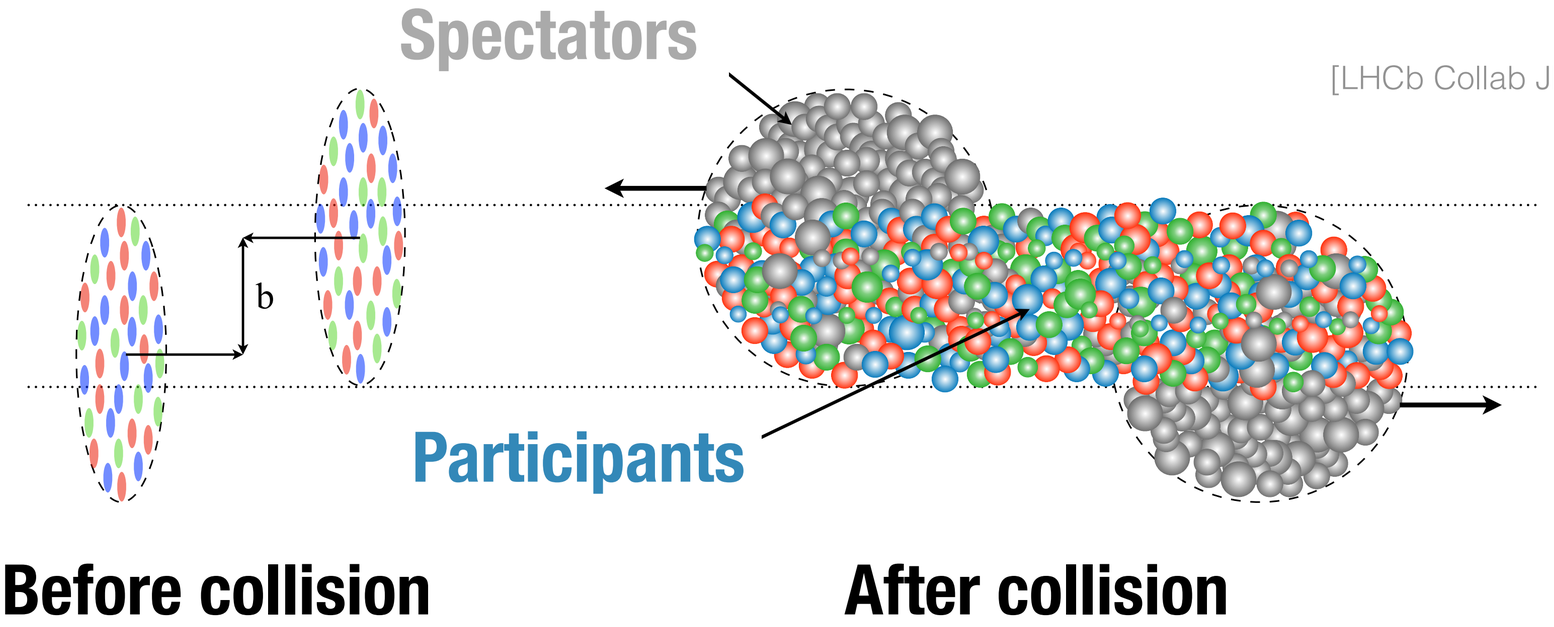
- Sample the 3D of each nucleon. Assume trivial (θ, ϕ)

Collision geometry: Glauber Monte Carlo

`2024-Granada-heavyion-lectures/mc-glauber.ipynb`

AA collision viewed as incoherent superposition of binary NN scatterings. Includes

- Geometric criterion to decide which nucleons collide

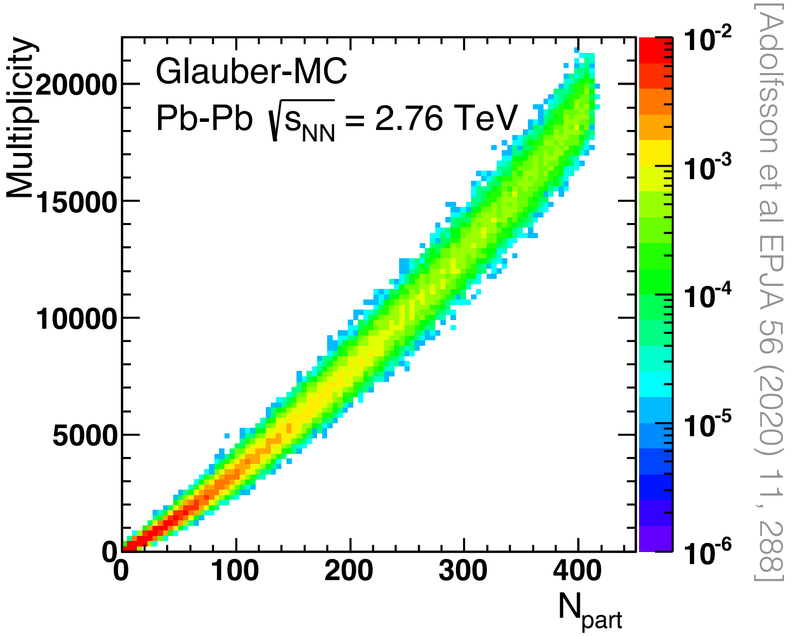


[LHCb Collab JINST 17 (2022) 05, P05009]

Next step: relate an observable to $N_{\text{coll}}, N_{\text{part}}$

Extracting collision geometry with Glauber MC

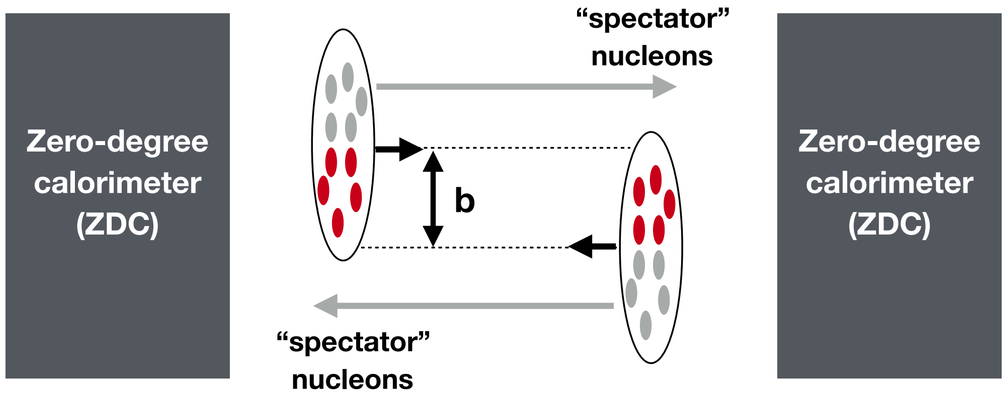
Activity of the event



[Adolfsson et al EPJA 56 (2020) 11, 288]

- Requires extra modelling to go from geometry to particle production

Energy deposited by the spectators

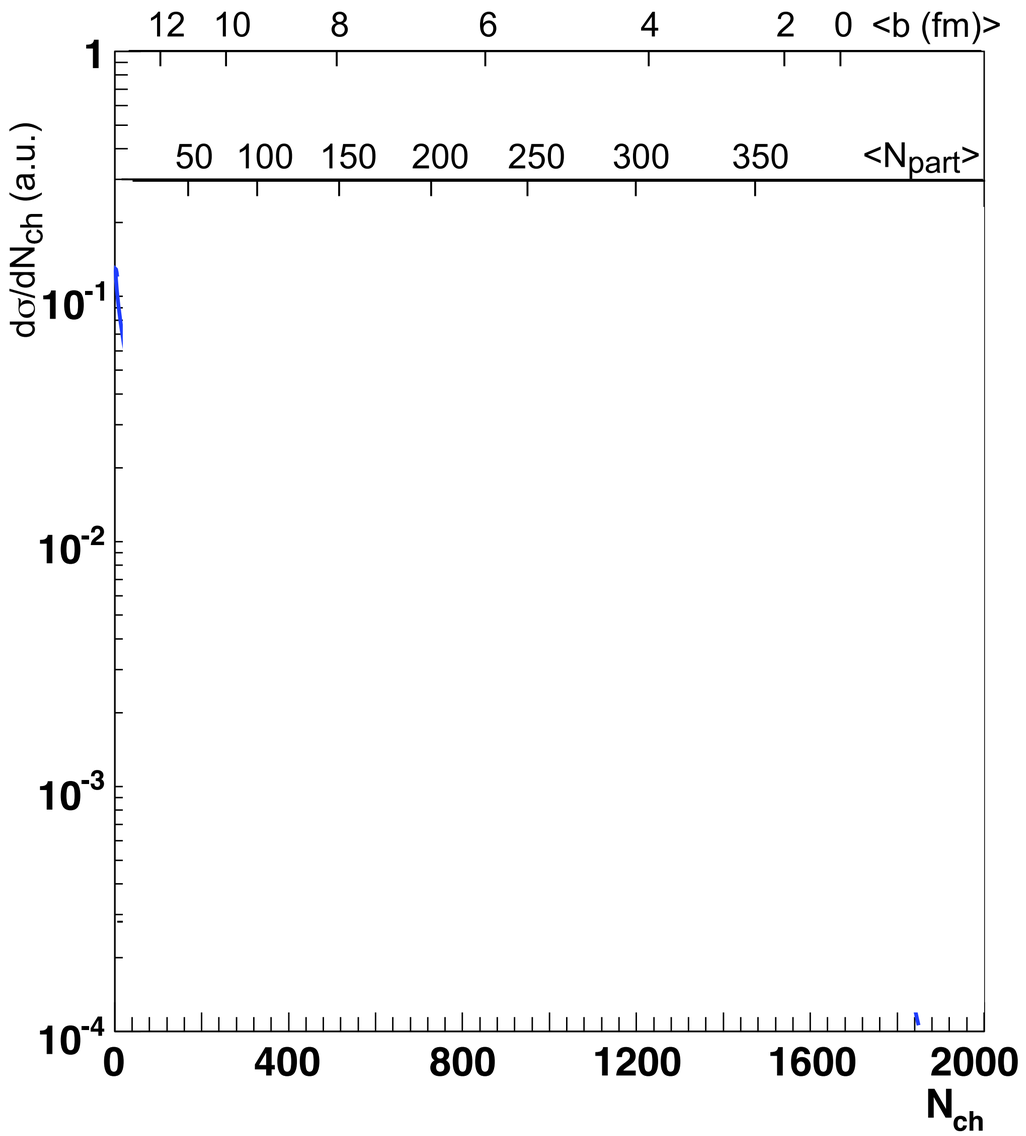


[Adapted from Gian Michele Innocenti]

- Monotonic relation between E^{ZDC} and b breaks down in peripheral collisions

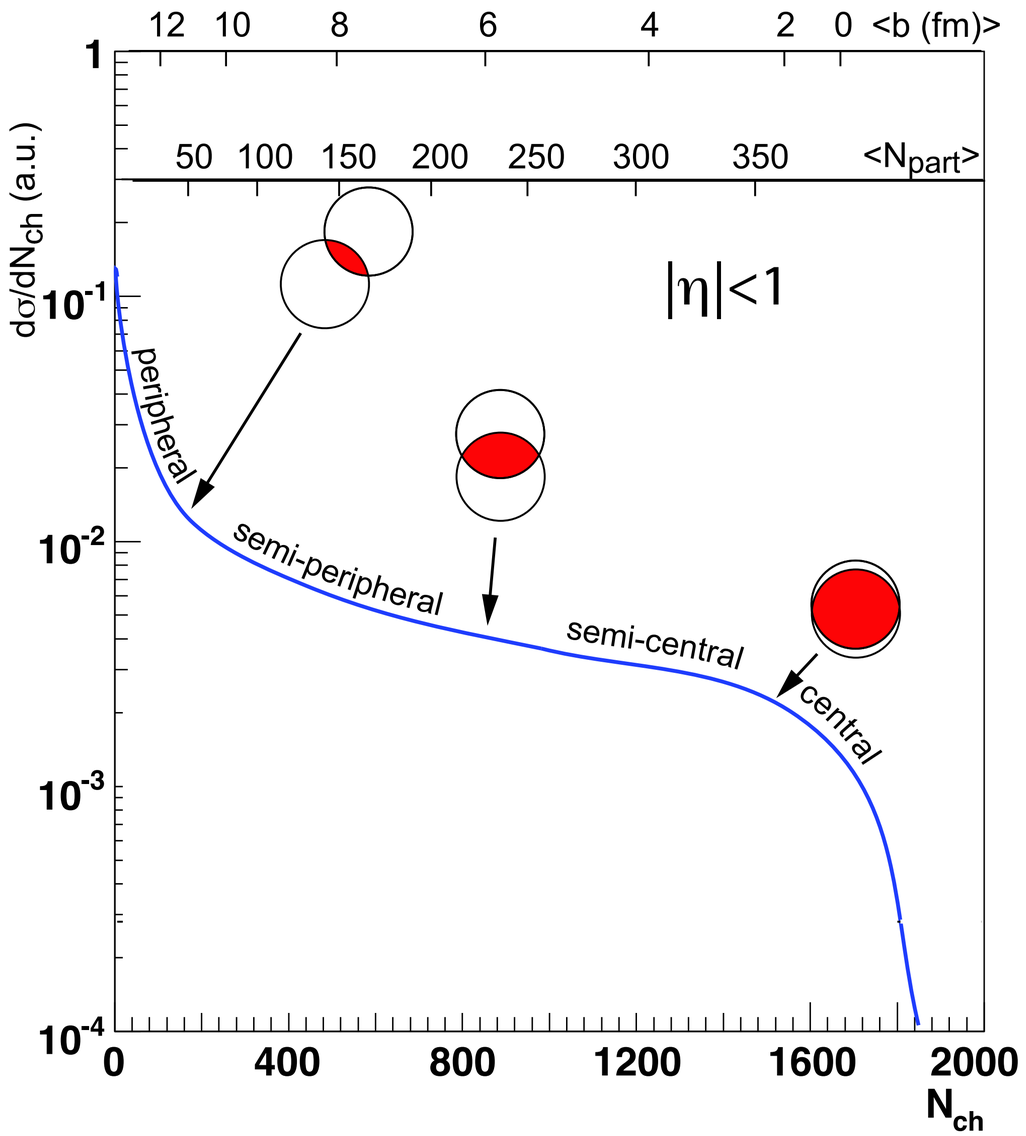
Extracting collision geometry with Glauber MC from N^{ch}

[Adapted from Liliana Apolinario]



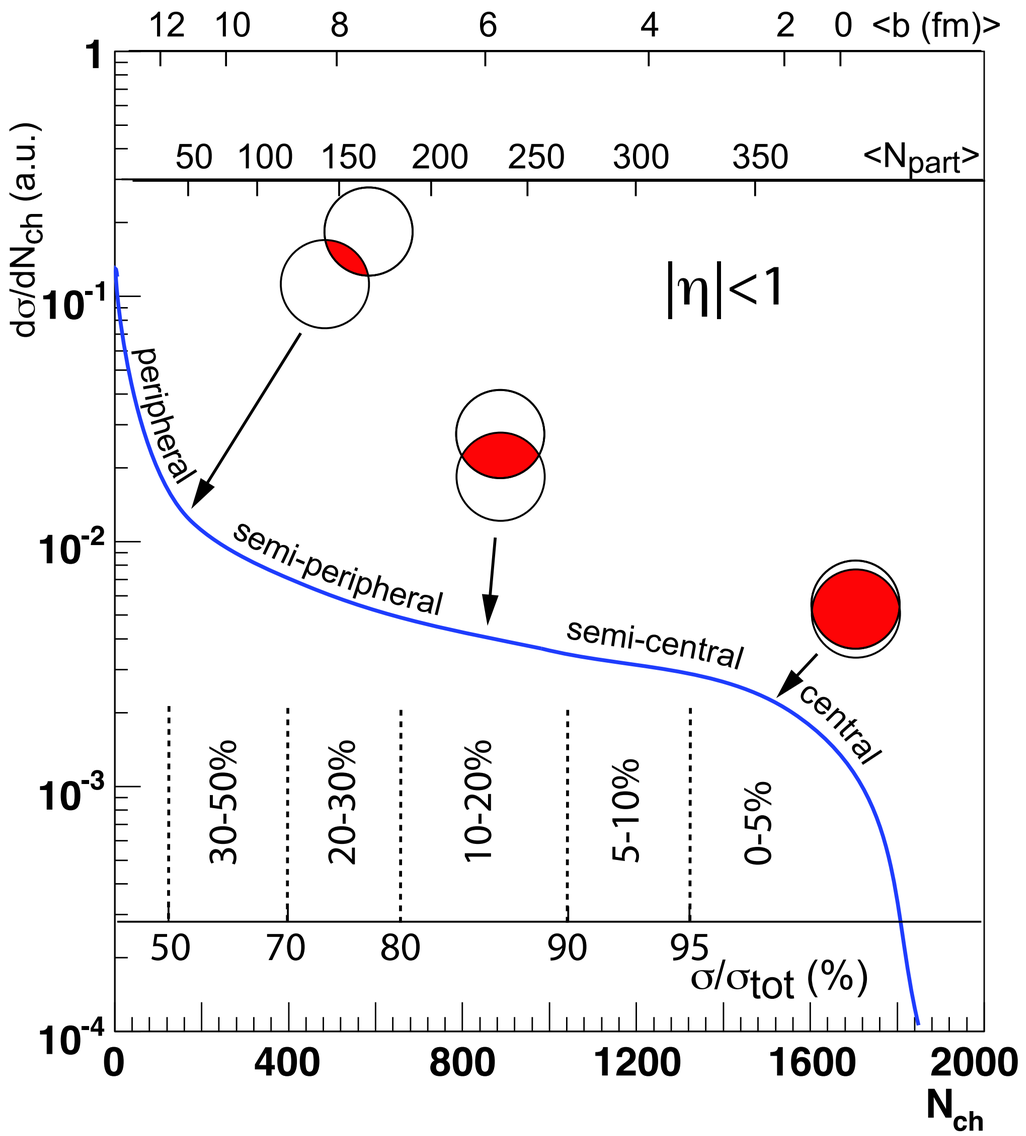
- Glauber naturally relates N_{part}, b

Extracting collision geometry with Glauber MC from N^{ch}



- Glauber naturally relates N_{part}, b
- After additional modelling $(N_{\mathrm{part}}, b, N_{\mathrm{ch}})$

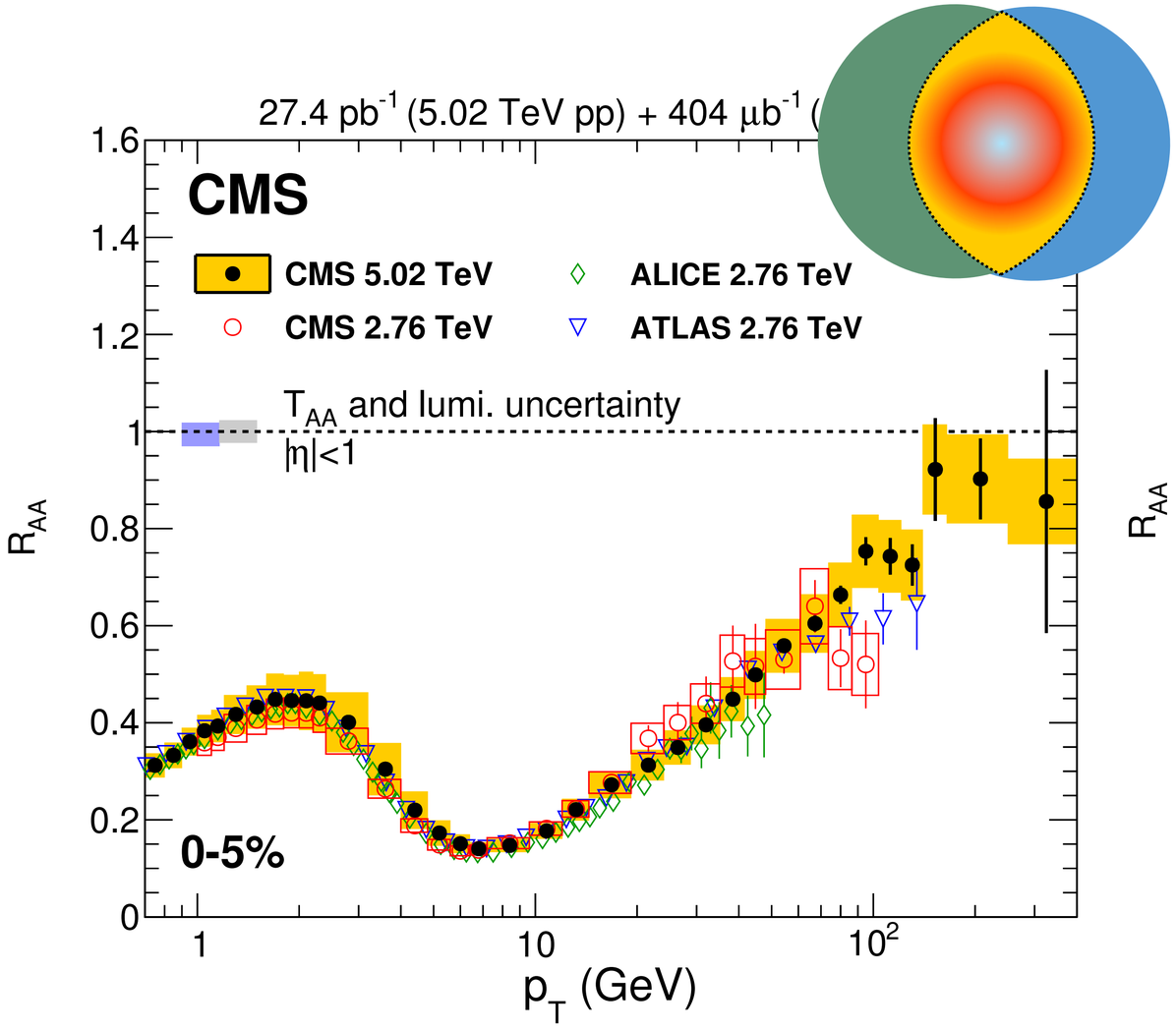
Extracting collision geometry with Glauber MC from N^{ch}

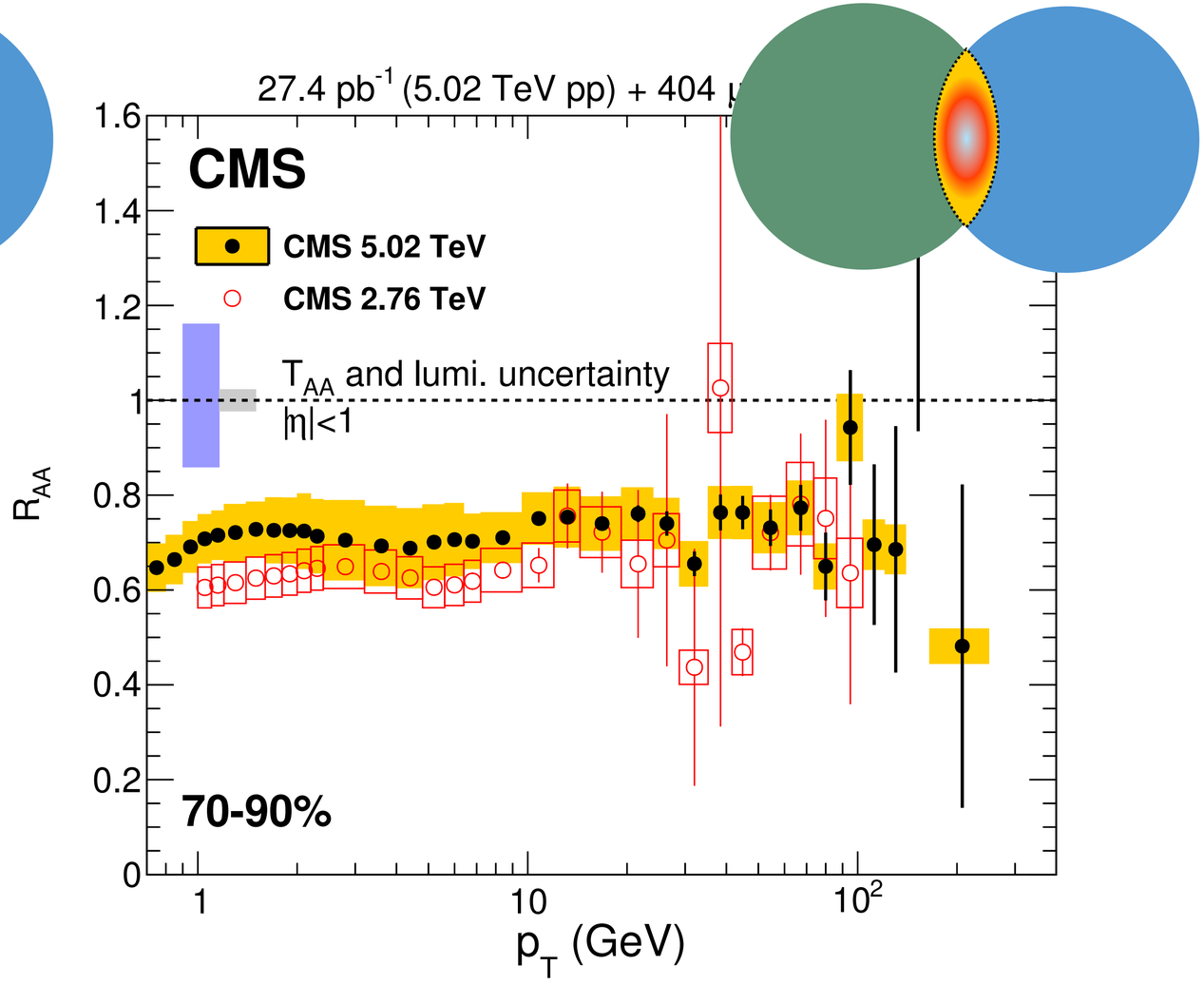


- Glauber naturally relates N_{part}, b
- After additional modelling $(N_{\mathrm{part}}, b, N_{\mathrm{ch}})$
- Centrality class defined as percentile ranges of minimum- bias cross section

Heavy-ion observable as a function of centrality

$R_{AA} = 1$ if PbPb = pp





Suppression is reduced in the presence of a cooler medium