NATIONAL SCIENCE CENTRE

# Jet Quenching

Małgorzata Janik

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Lecture heavily based on CERN summer student lectures by Jan Fiete Grosse-Oetringhaus:
https://cds.cern.ch/record/2275404
https://cds.cern.ch/record/2275545

# Jet Quenching

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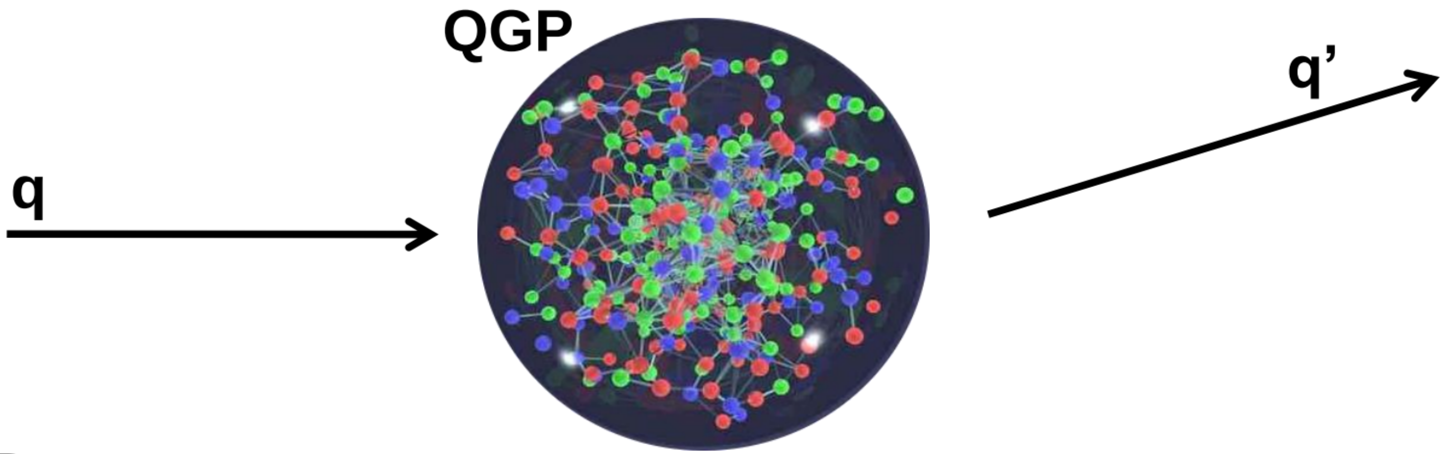
# Studying QGP

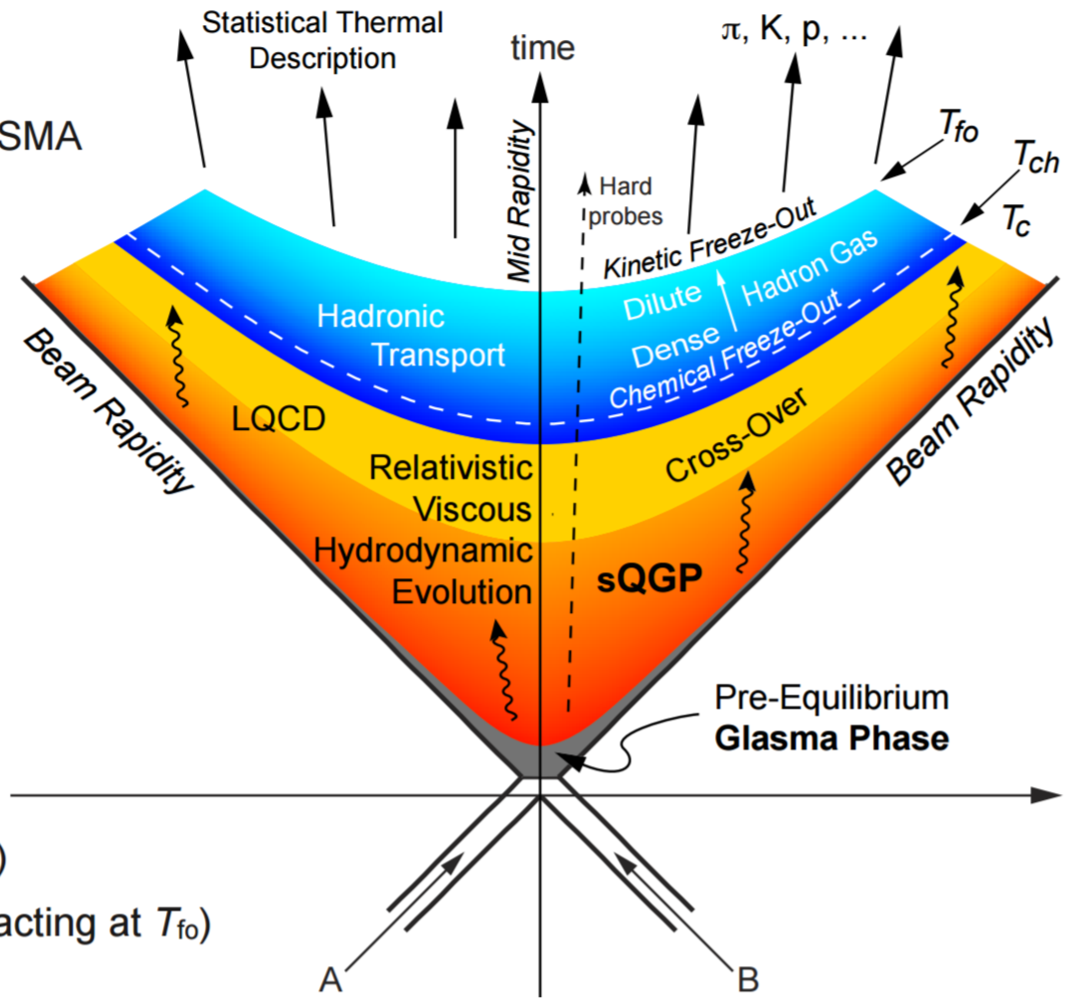
- Ideally : a Rutherford experiment




- But
  - QGP exists in the lab only for ~$10^{-23}$ s
  - No free color charges as probes
- Instead
  - Use probes generated in the heavy-ion collision itself
    → "self-generated" probes

# Heavy-ion collisions

- Initial state and pre-equilibrium
  - gluonic fields (Color Glass Condensate) GLASMA
- Hard parton scatterings
  - jet and heavy flavour production
- Creation of a Quark-Gluon Plasma
  - thermalisation of strongly interacting partons
- QGP expansion and cooling
  - 3D+1 relativistic viscous hydrodynamics
- Phase transition ($T_c$): parton→ hadrons
  - Lattice QCD, cross-over
- Hadronic phase
  - chemical freeze-out (abundances fixed at $T_{ch}$)
  - rescattering and kinetic freeze-out (stop interacting at $T_{fo}$)



# Self-generated probes

- Produced early, before the plasma forms
  $t \sim \hbar / Q$     $Q > 2$ GeV/*c* → $t < 0.1$ fm/*c*
- Production rate "known"
  - Ideally calculable perturbatively
  - Not produced in the medium
- Interact with dense medium (QGP)
- Large cross-section

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**<u>Per central LHC collision</u>**
**7 D mesons (> 2 GeV/c)**
**0.2 B mesons (> 10 GeV/c)**
**$10^{-3}$ jets above 100 GeV**
**$10^{-6}$ jets above 400 GeV**

**<u>LHC Run 1 (~ 150/ub)</u>**
**$10^{8}$ D mesons (> 2 GeV/c)**
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**$10^{5}$ jets above 100 GeV**
**120 jets above 400 GeV**

**Rec. efficiency, branching ratios factors ~ 1000**

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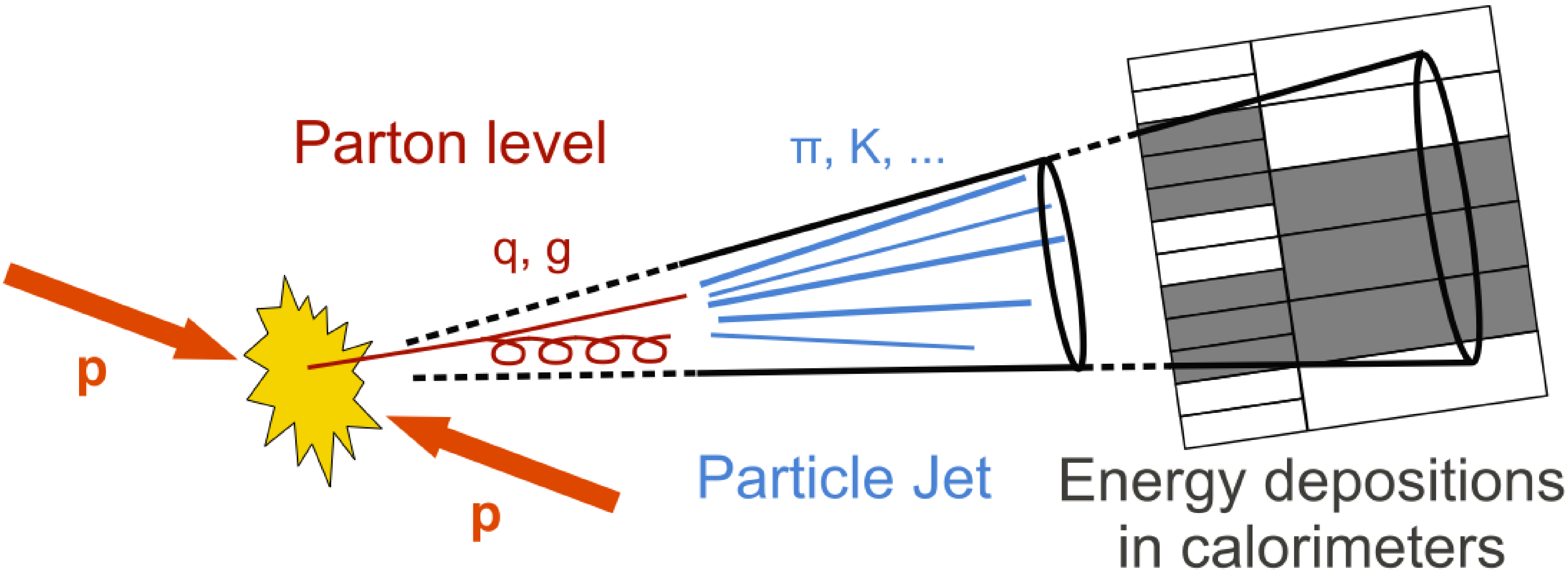
**Rec. efficiency, branching ratios factors ~ 1000**

***Today: jets***

# Jets – collimated spray of hadrons

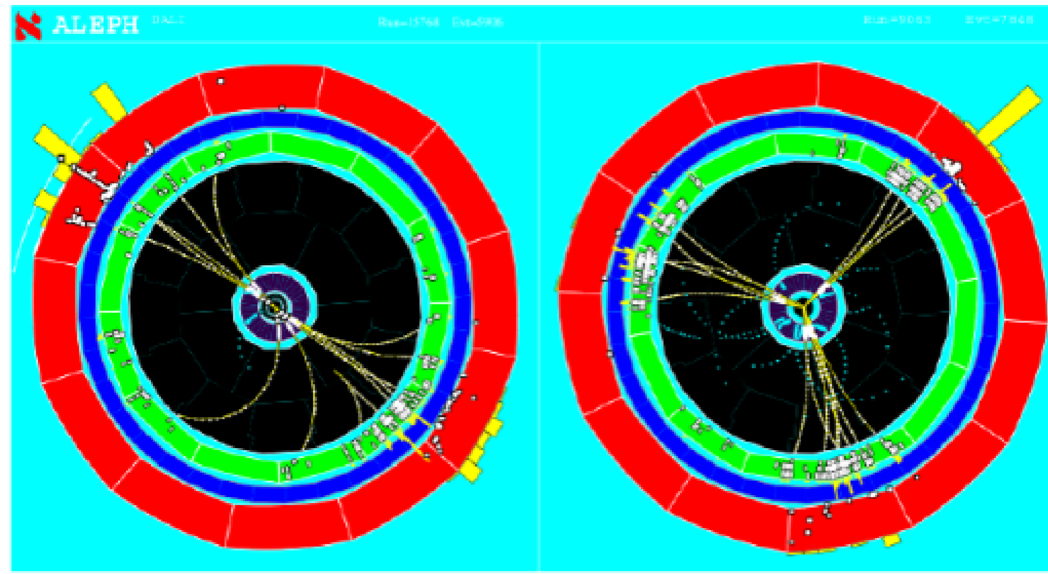



- experimental signatures of quarks and gluons produced in high-energy processes
- quarks and gluons cannot exist freely due to color-confinement
- instead, they come together to form colour-neutral hadrons, in a process that leads to production of **collimated spray of hadrons** called **a jet.**

# Partons in heavy-ion collisions
## (recap)

- hard partons are produced early and traverse the hot and dense QGP

- expect enhanced parton energy loss, (mostly) due to medium-induced gluon radiation: ‘jet quenching’

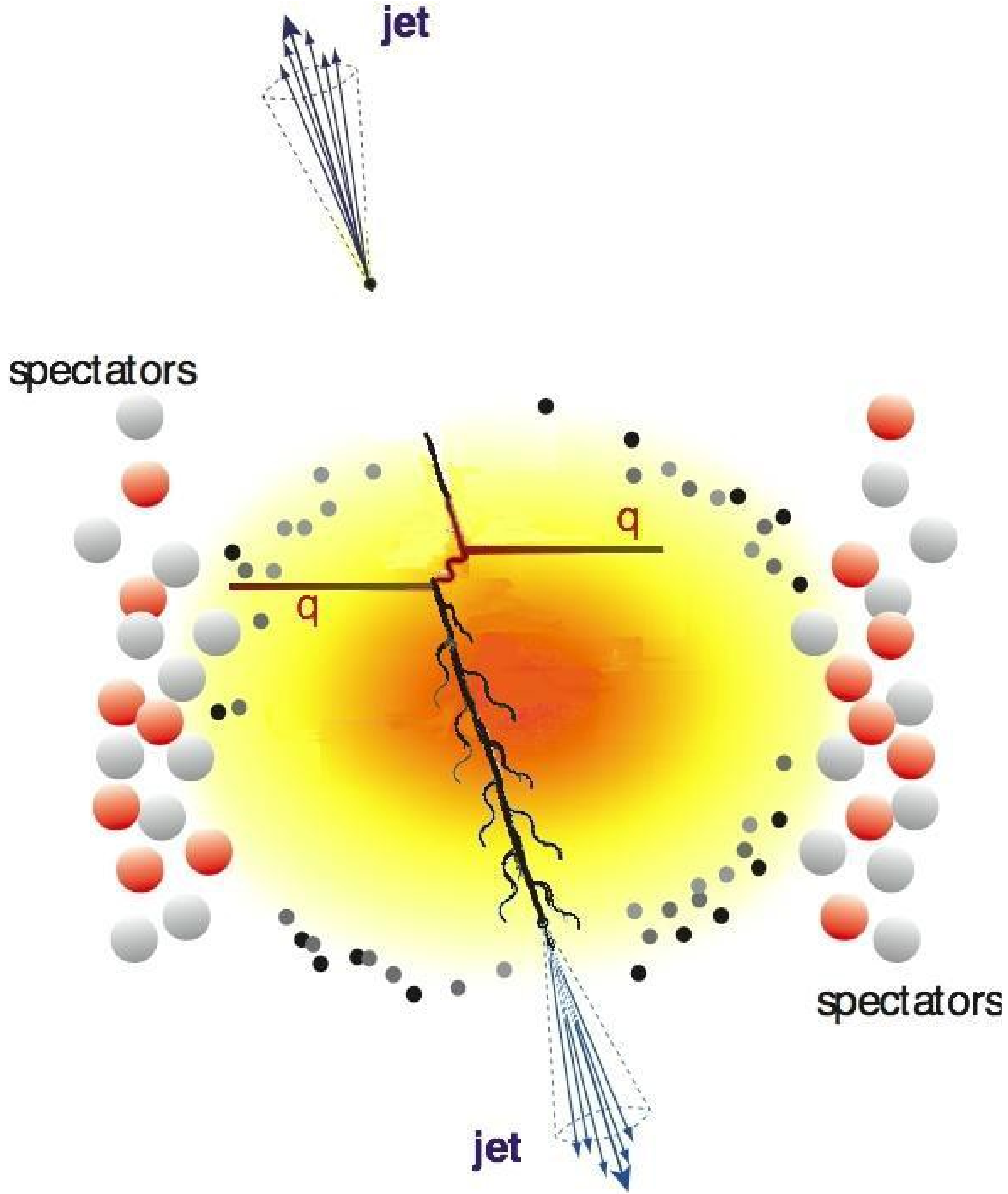



- jet: ‘collimated bunch of hadrons’

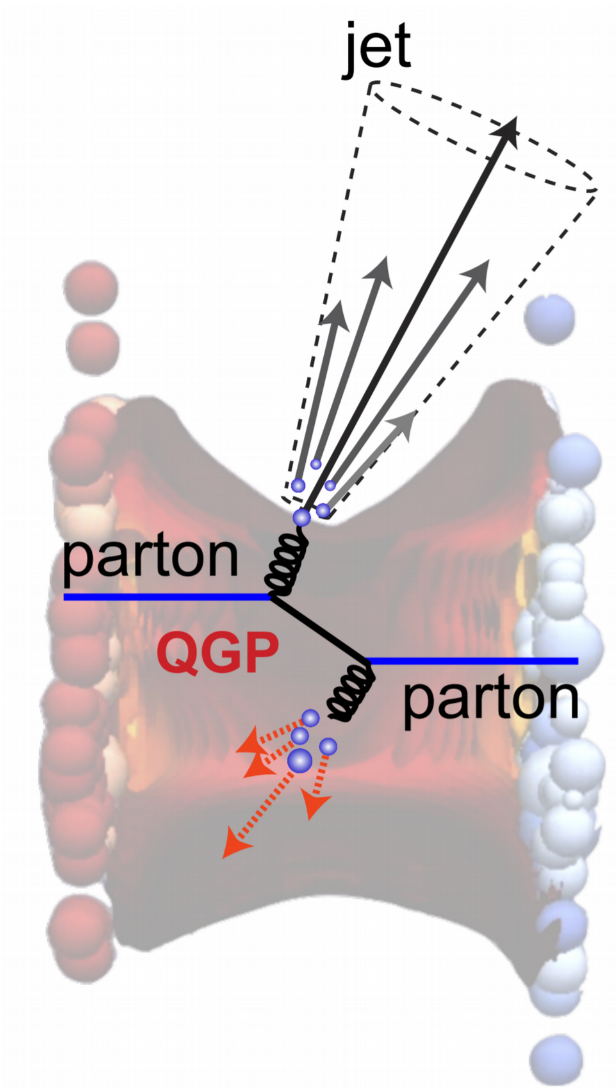
- the best available experimental equivalent to quarks and gluons

- ‘vacuum’ expectation calculable by pQCD: ‘calibrated probe of QGP’

# Jets in the QGP

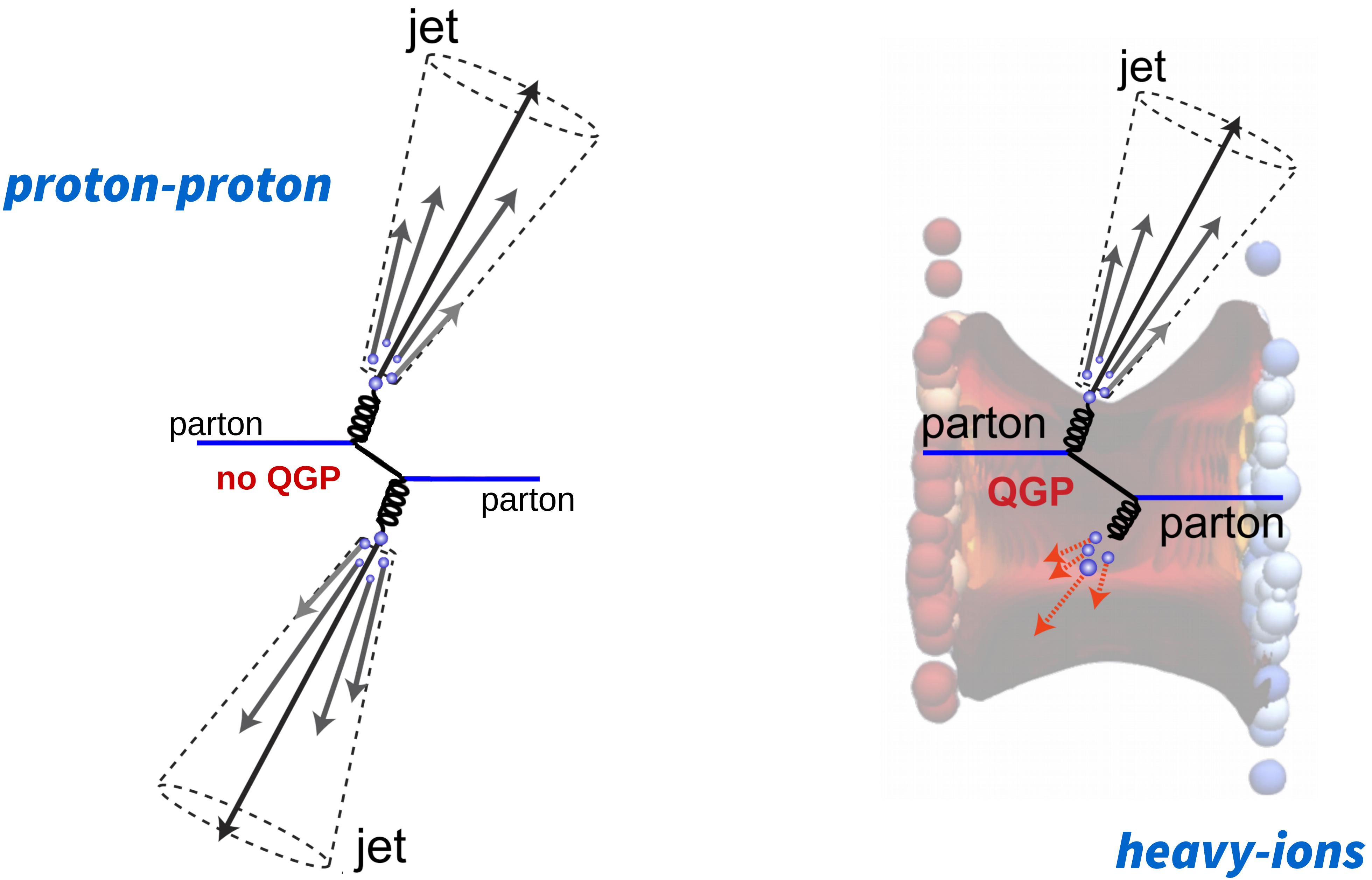


# Energy loss in the QGP



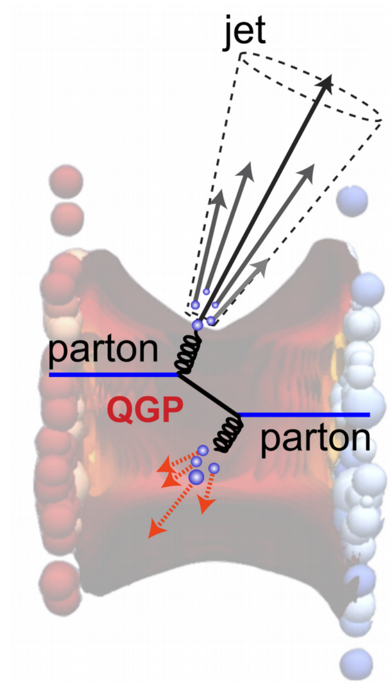

***How to measure?***

# Energy loss in the QGP

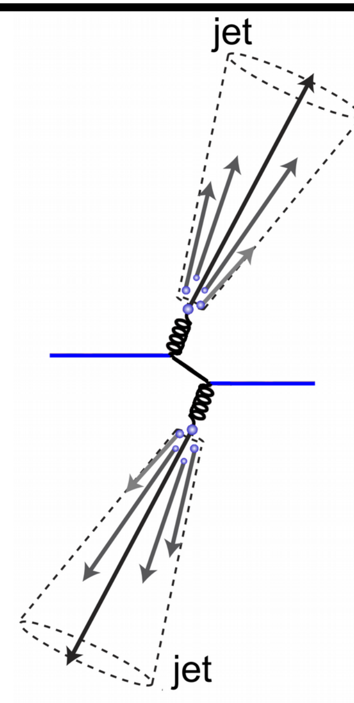


# Energy loss in the QGP

*heavy-ions*




*Ratio* =




*proton-proton*

*x*

*number of binary collisions*

# Energy loss and $R_{AA}$

- Estimate the opacity of the created medium
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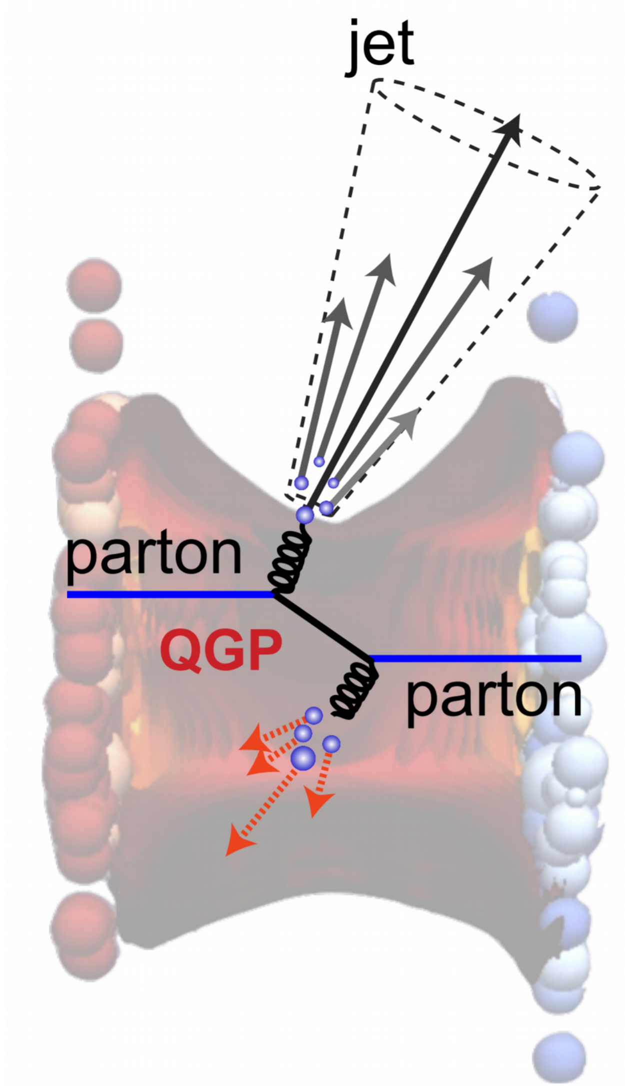
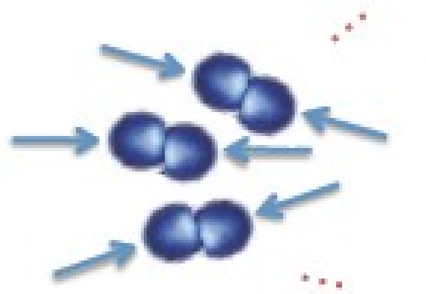
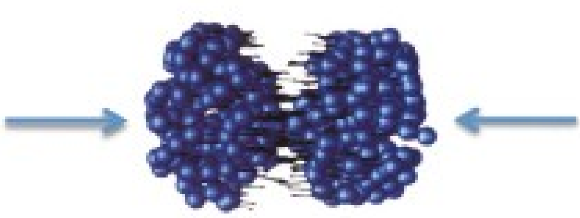
  - ➡ $R_{AA}$ equals unity means no modification at all



**No medium effect → $R_{AA} \approx 1$**



**Medium effect → $R_{AA} < 1$**

# Energy loss and $R_{AA}$

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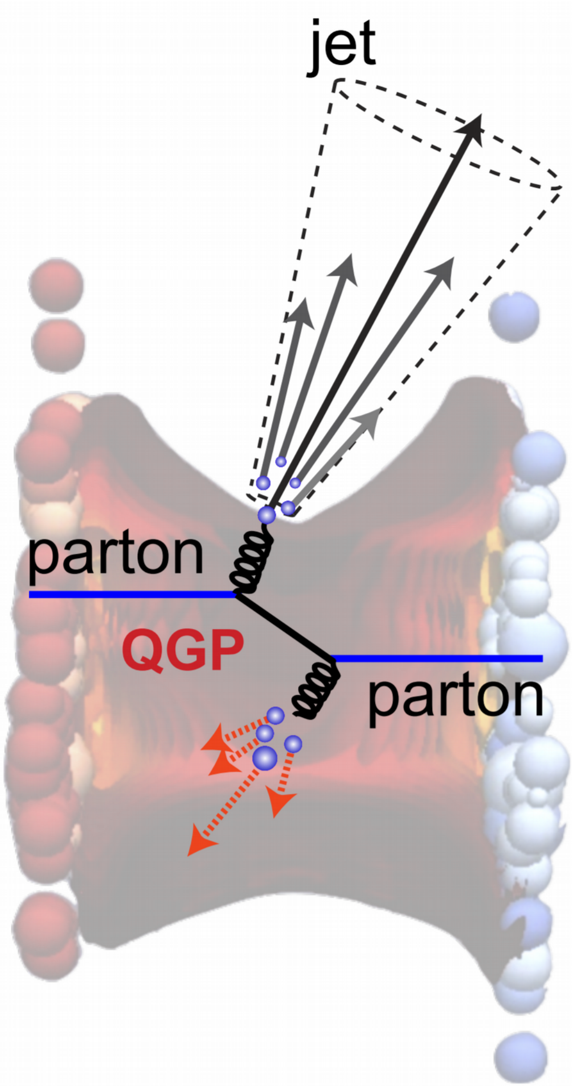
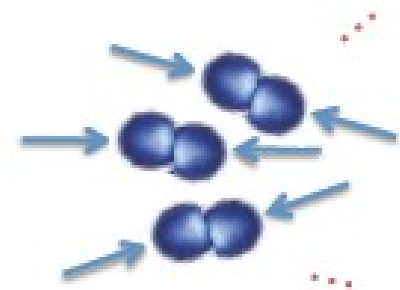
$$R_{AA} = \frac{\text{AA}}{\boxed{\text{rescaled}}\ \text{pp}} = \frac{d^2N_{AA}/dp_T dy}{\boxed{\langle N_{coll}\rangle} d^2N_{pp}/dp_T dy}$$

***What is $N_{coll}$?***



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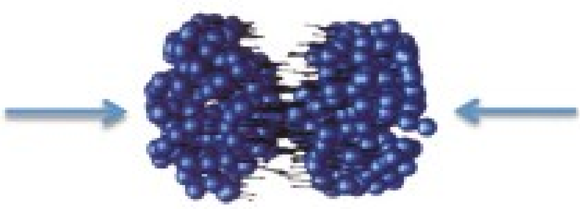

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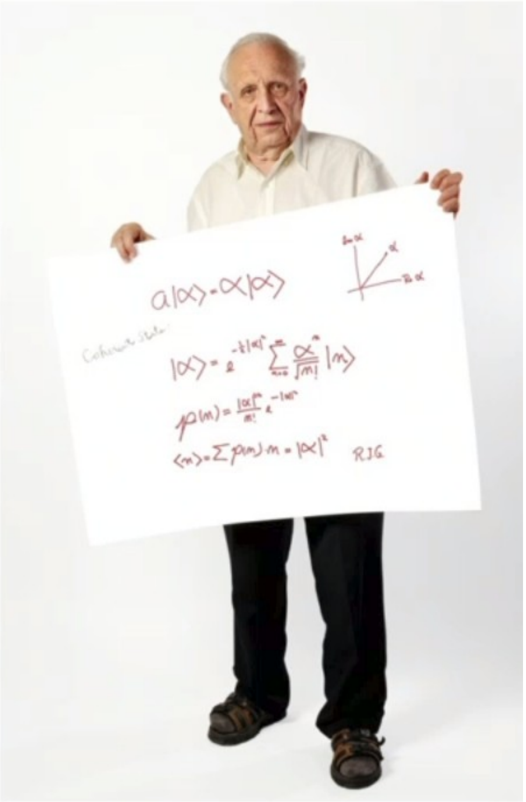
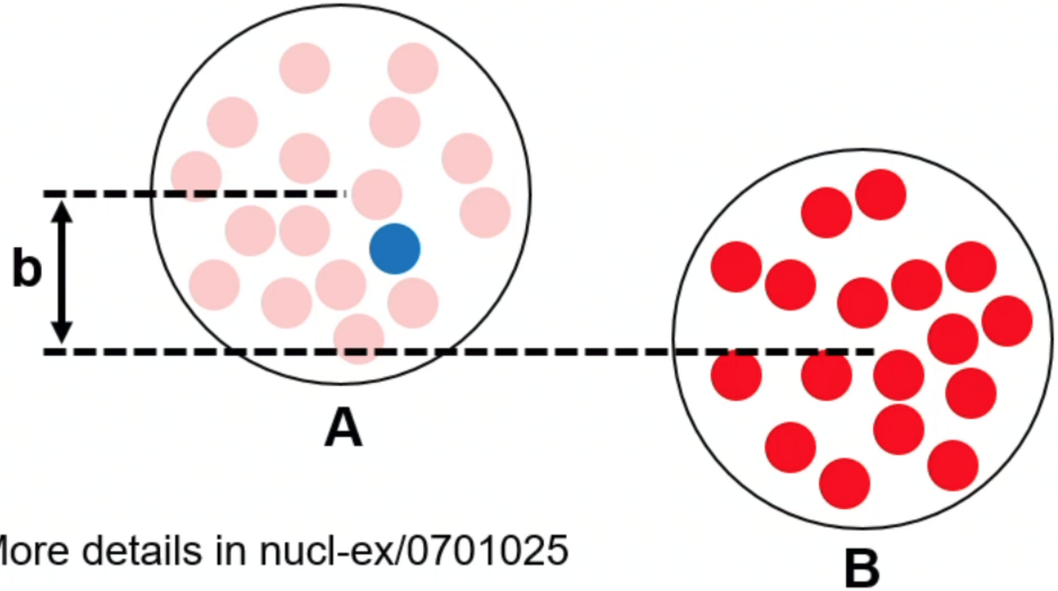
# Glauber Monte Carlo

- Nucleons travel on straight lines
- Collisions do not alter their trajectory (energy of nucleons large enough)
- No quantum-mechanical interference
- Interaction probability for two nucleons is nucleon-nucleon cross-section



Roy Glauber




More details in nucl-ex/0701025

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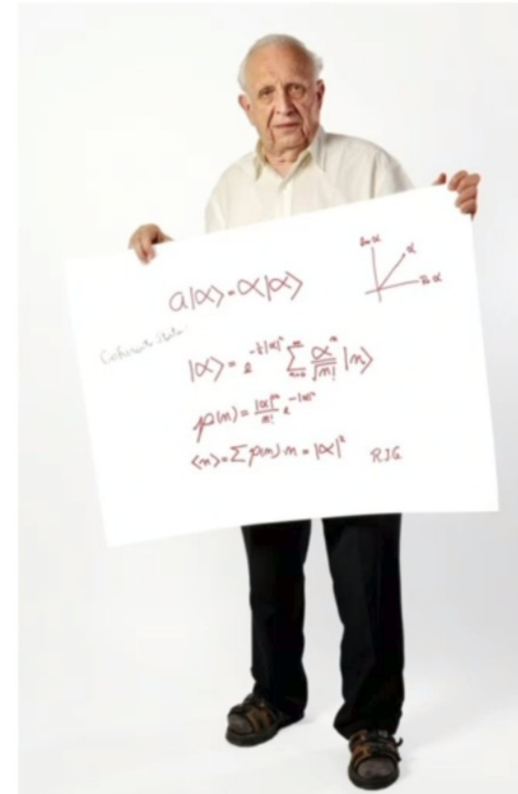
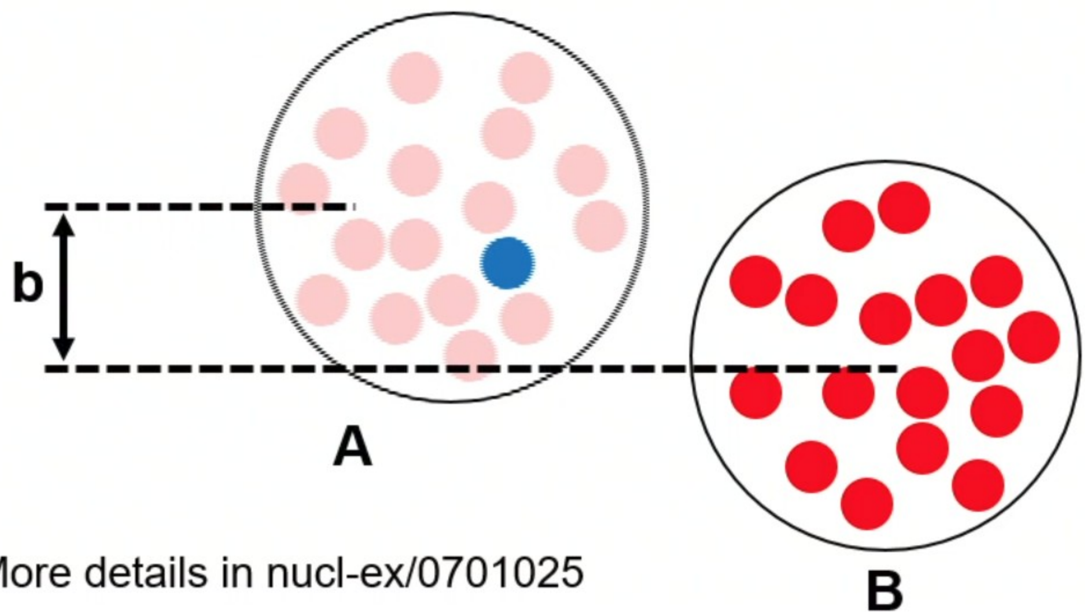


**Roy Glauber**




$N_{coll} = 0$

More details in nucl-ex/0701025

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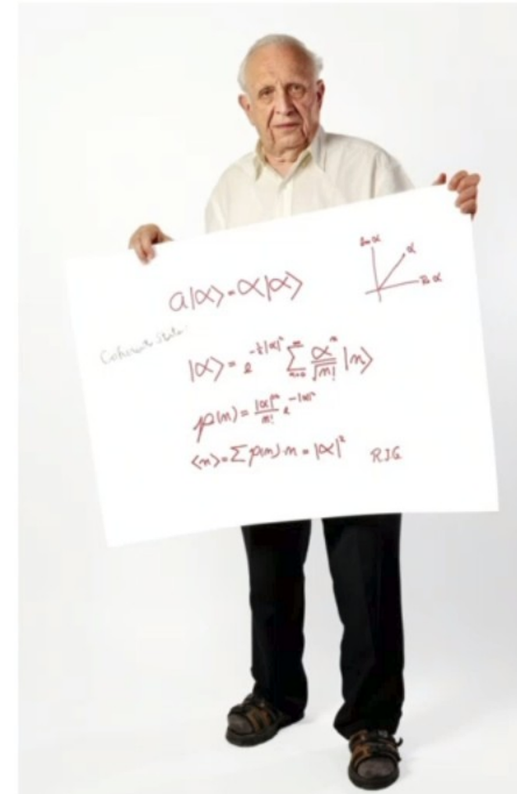

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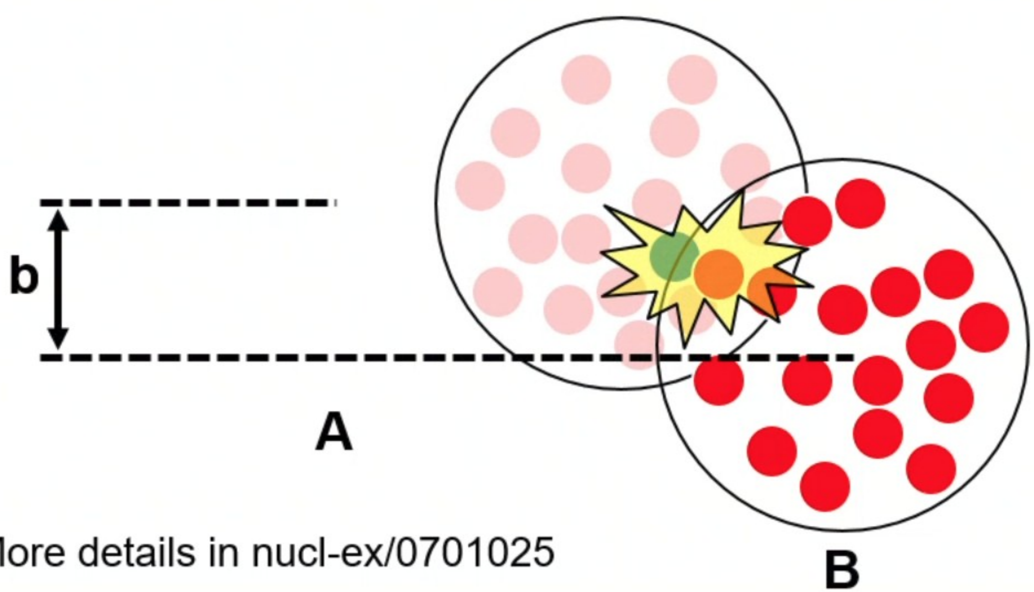


$N_{coll} = 1$

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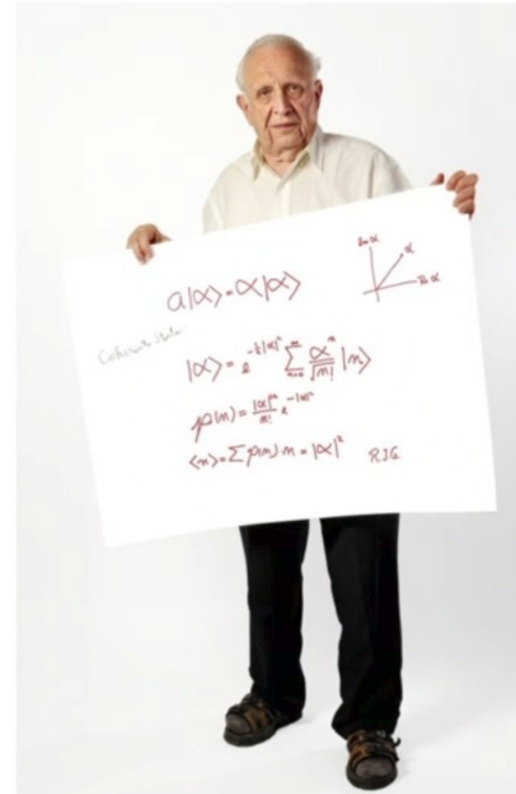

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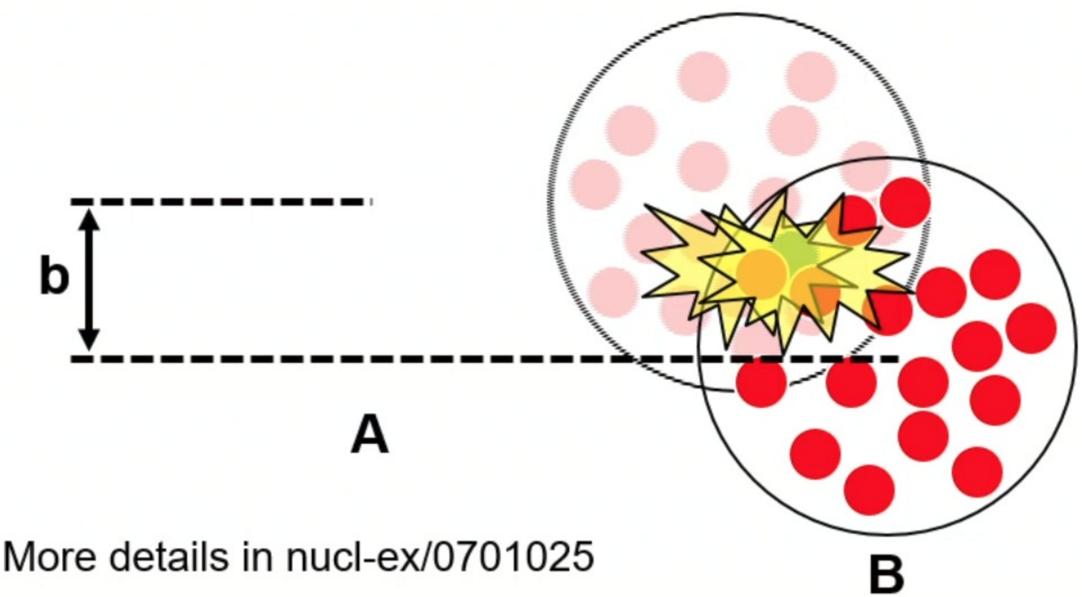
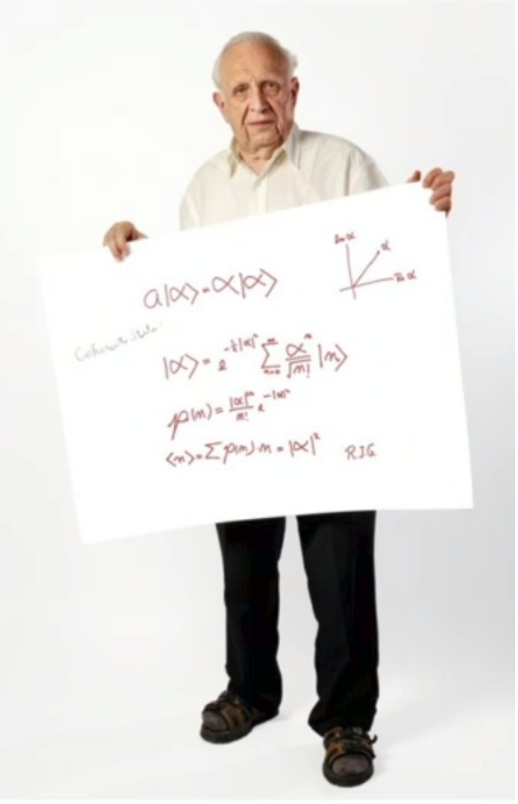



$N_{coll} = 2$

More details in nucl-ex/0701025

# Glauber Monte Carlo



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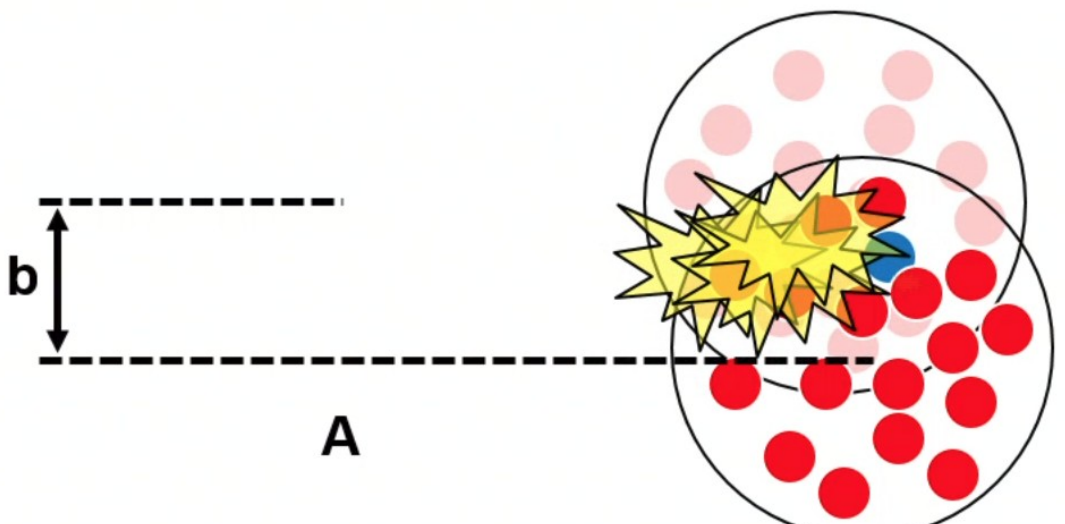


$$N_{coll} = 3$$

More details in nucl-ex/0701025

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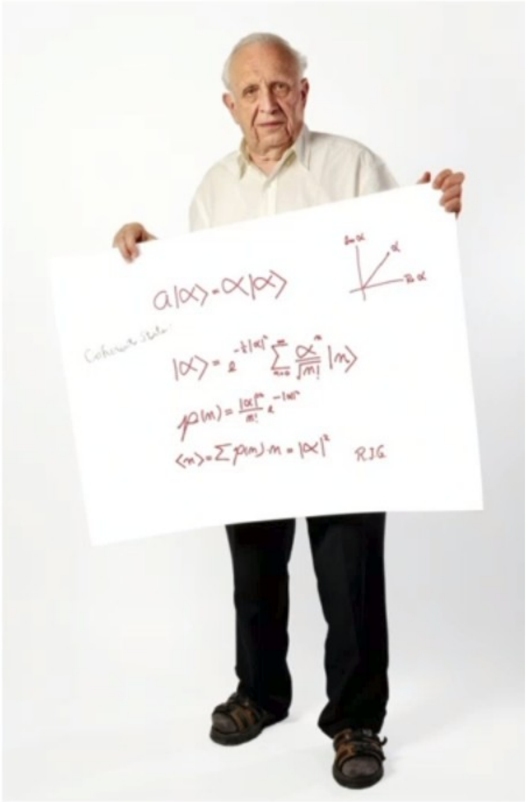
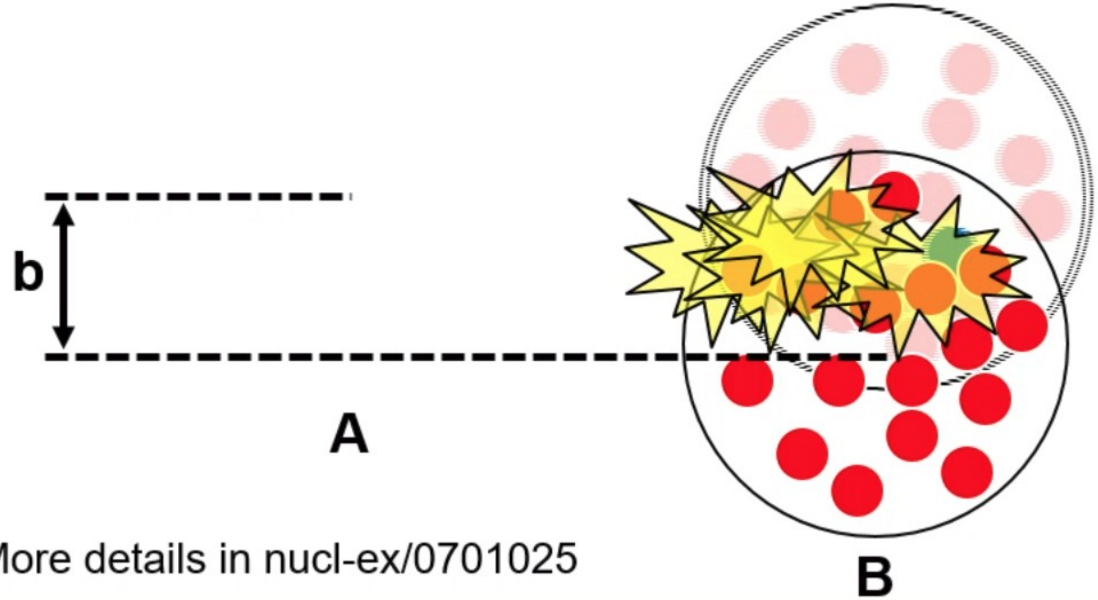


Roy Glauber




$N_{coll} = 4$

More details in nucl-ex/0701025

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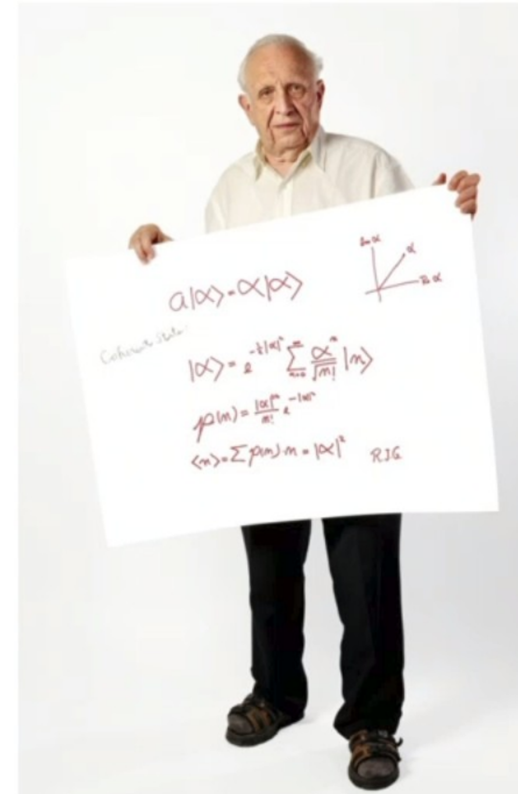

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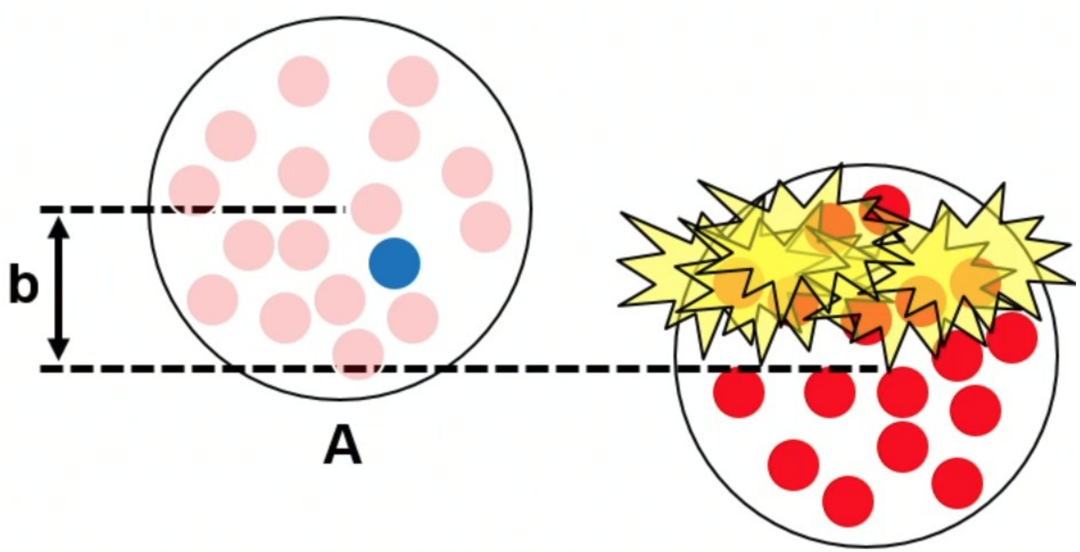


$N_{coll} = 5$

***For blue. We have to repeat for all other nucleons in A.***

More details in nucl-ex/0701025

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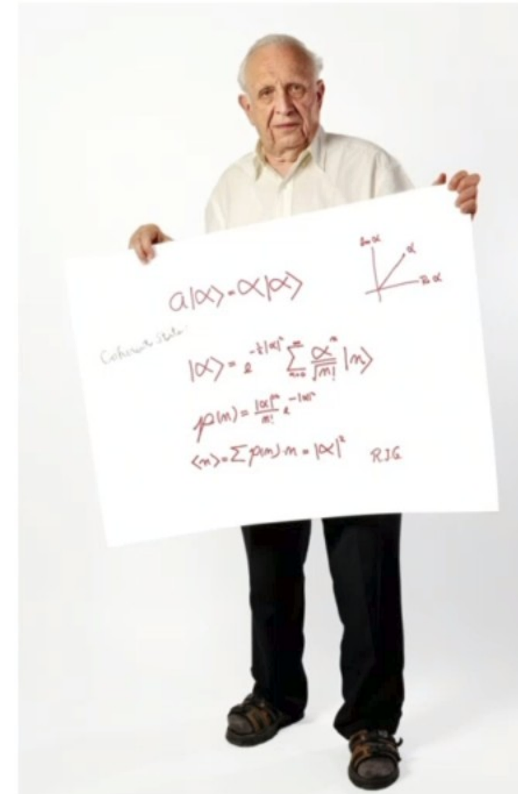

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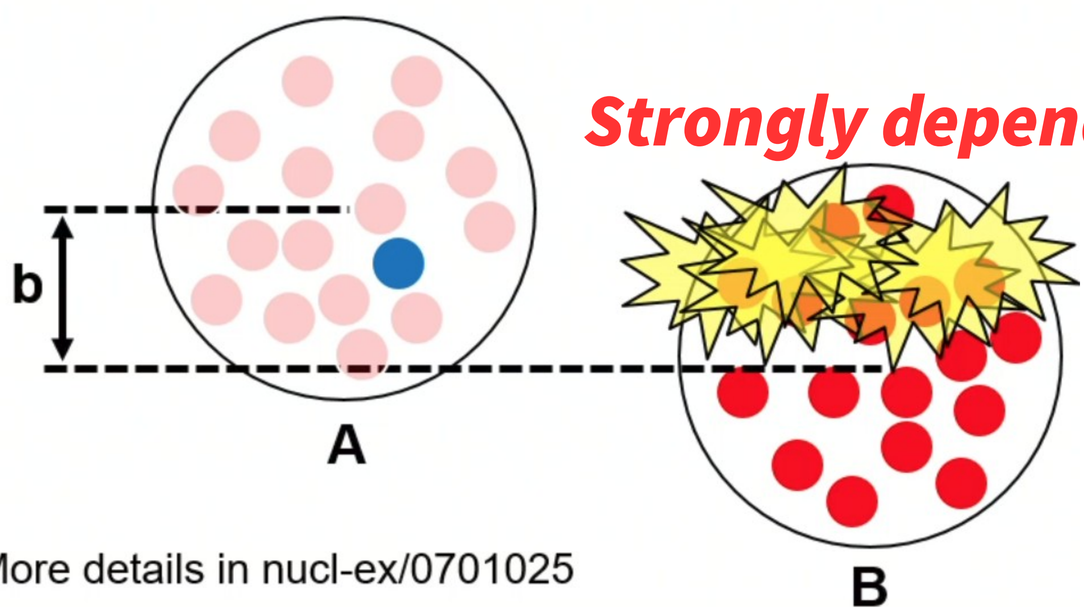
***Strongly depends on impact parameter!***

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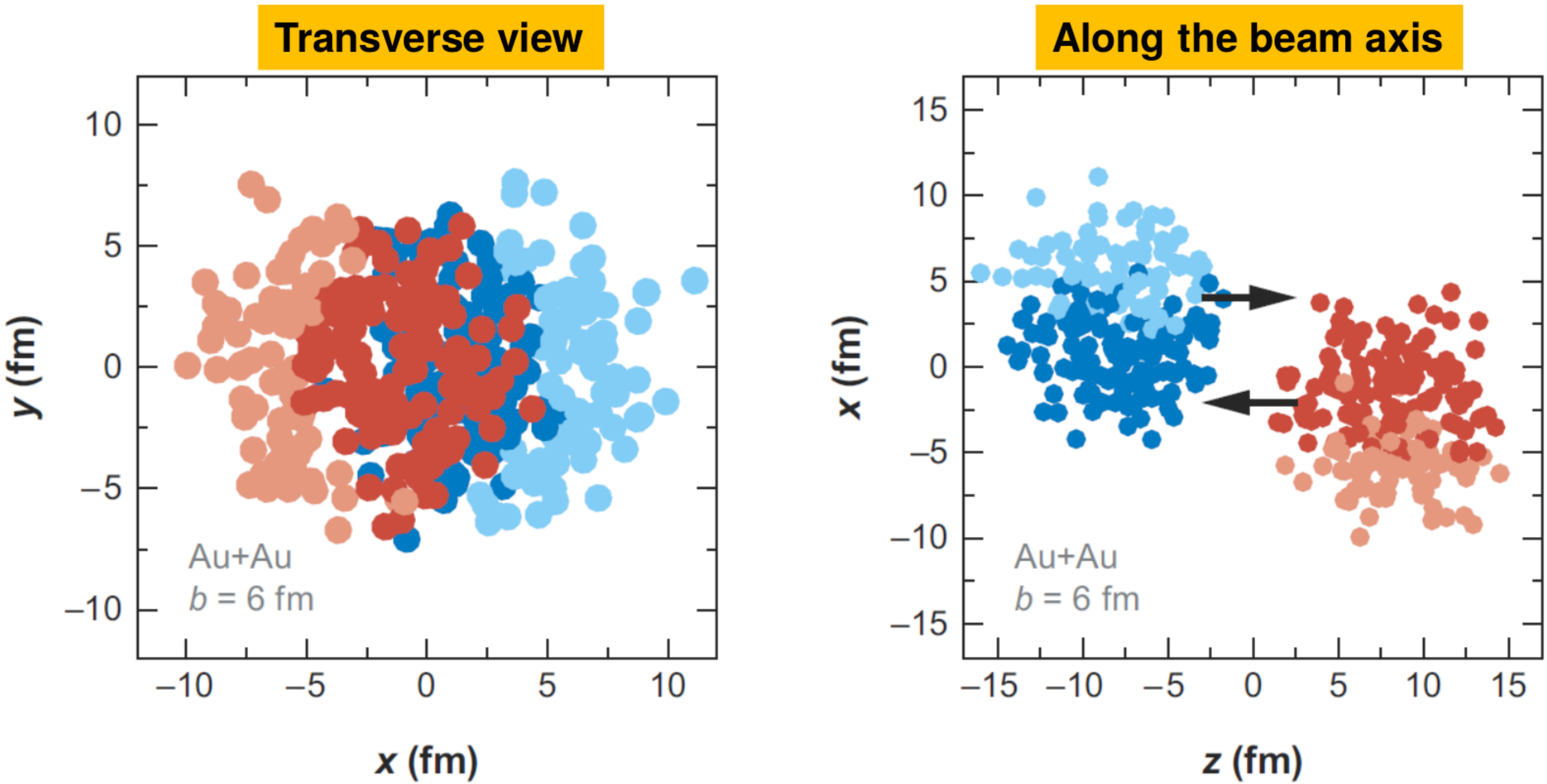
More details in nucl-ex/0701025

# Realistic Example

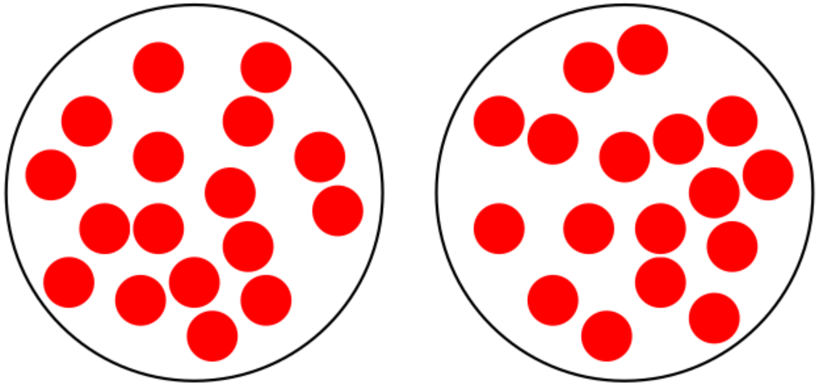



**light nucleons: have not participated (spectators)**
**dark nucleons: have participated**

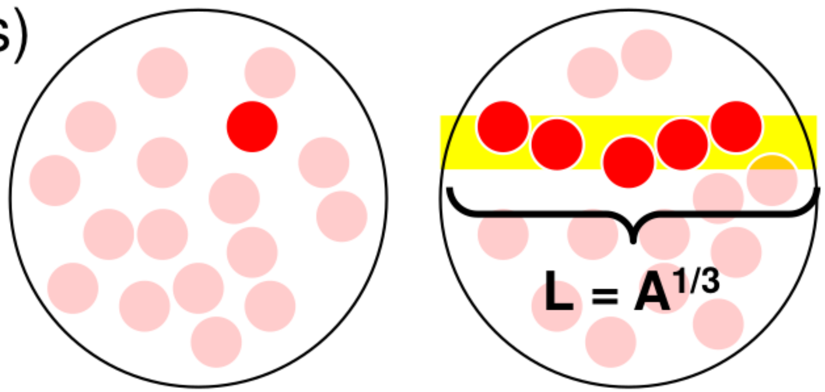
Figure: nucl-ex/0701025

# Glauber MC Output

- Number of spectators
  - Nucleons which did not collide
- Participant/wounded nucleons
  - Collided at least once
  - Called $N_{part}$
  - Scale with 2A (A = number of nucleons)
- Number of binary collisions
  - Called $N_{coll}$
  - Scales with $A^{4/3}$
- Rule of thumb
  - Soft (low $p_T$) observables scale with $N_{part}$
  - Hard (high $p_T$) observables scale with $N_{coll}$



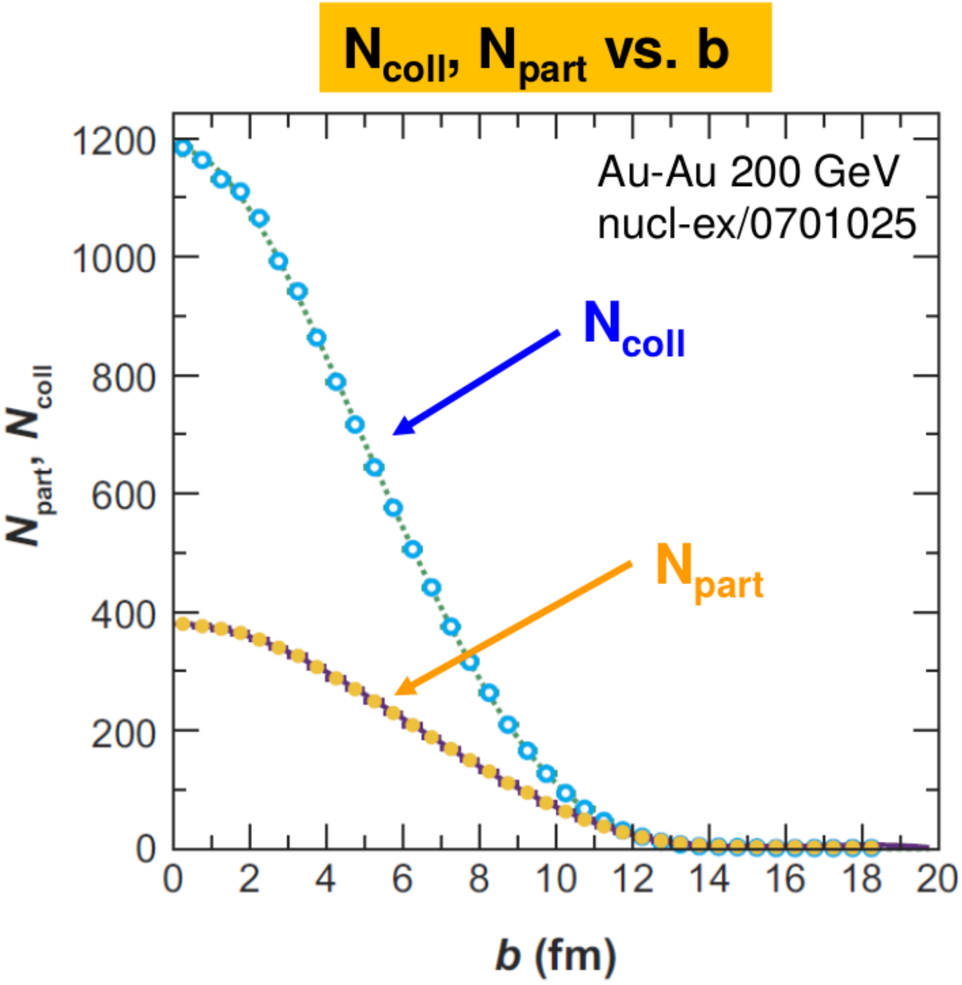
$N_{part} \sim A + A$




$N_{coll} \sim A \cdot L = A^{4/3}$

# Glauber MC Output

- 10% most central at RHIC (Au-Au, 200 GeV)
  - $N_{coll}$ ~ 1200
  - $N_{part}$ ~ 380
- 5% most central collisions at LHC (Pb-Pb, 5 TeV)
  - $N_{coll}$ ~ 1770
  - $N_{part}$ ~ 384
- Difference mainly due to cross-section increase



# Energy loss and $R_{AA}$

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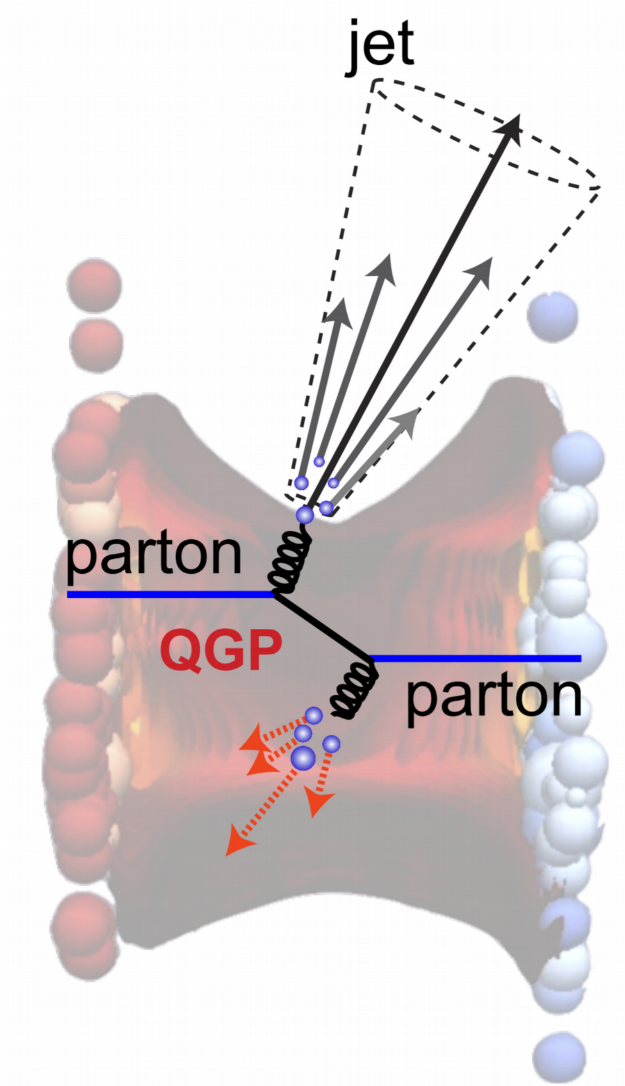
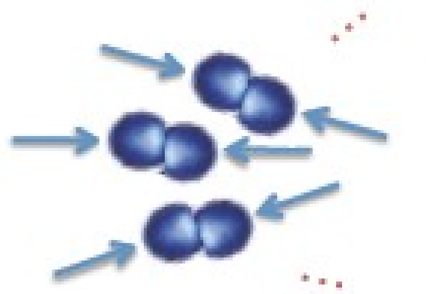
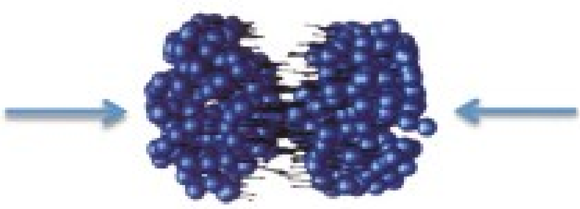


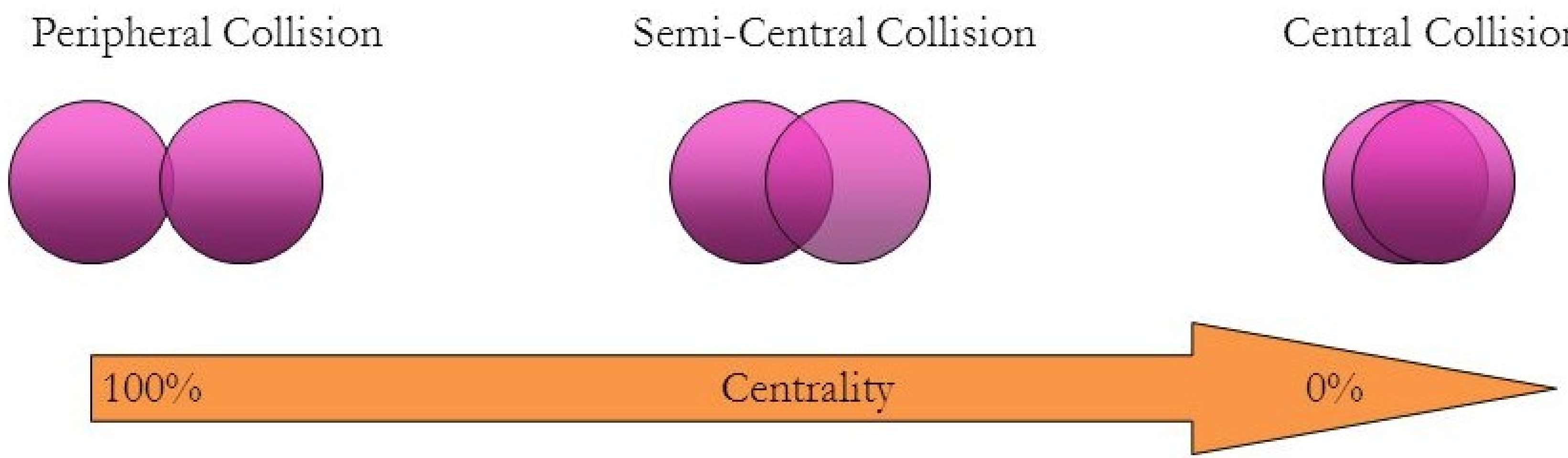



**No medium effect → $R_{AA}$ ≈ 1**



**Medium effect → $R_{AA}$ < 1**

# Centrality

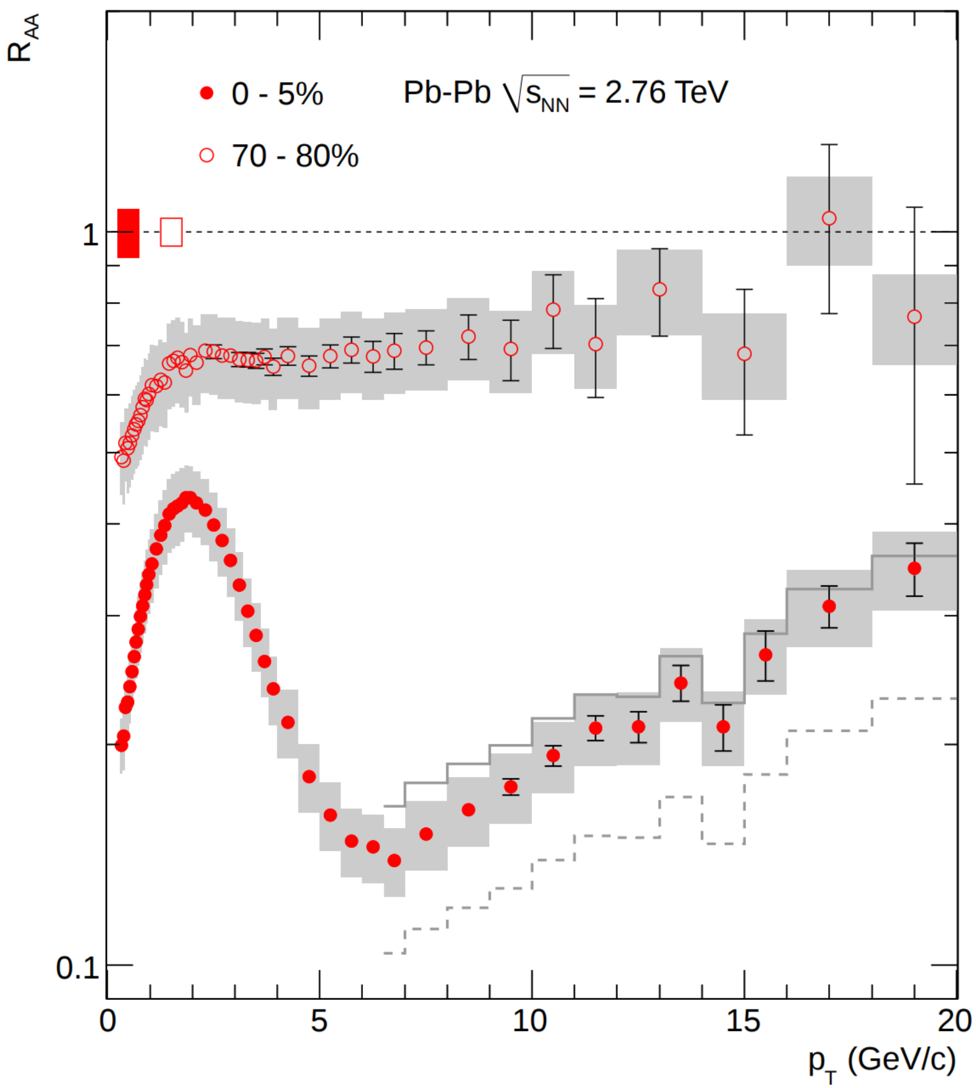



***More central: bigger QGP droplet.***
***Bigger energy loss.***

***More peripheral: smaller QGP droplet.***
***Smaller energy loss.***

# $R_{AA}$

$$R_{AA} = \frac{\mathrm{AA}}{\text{rescaled pp}} = \frac{d^2N_{AA}/dp_Tdy}{\langle N_{coll}\rangle d^2N_{pp}/dp_Tdy}$$




**$R_{AA}$ = 1 → no modification**

ALICE, PLB696 (2011) 30

# $R_{AA}$

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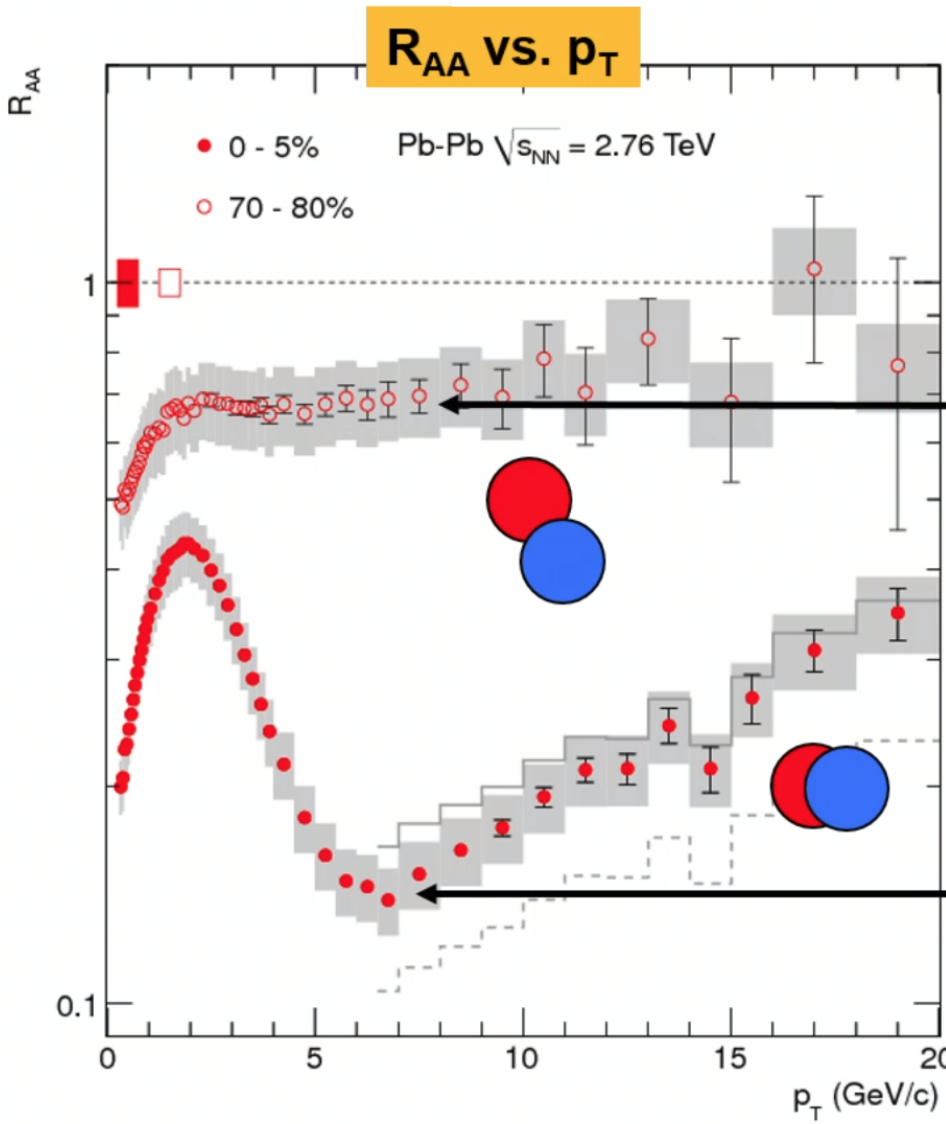


$R_{AA}$ = 1
→ no modification

70-80% (peripheral)
→ $R_{AA}$ ~ 0.7

0-5% (central)
→ $R_{AA}$ drops to 0.14

ALICE, PLB696 (2011) 30

# $R_{AA}$

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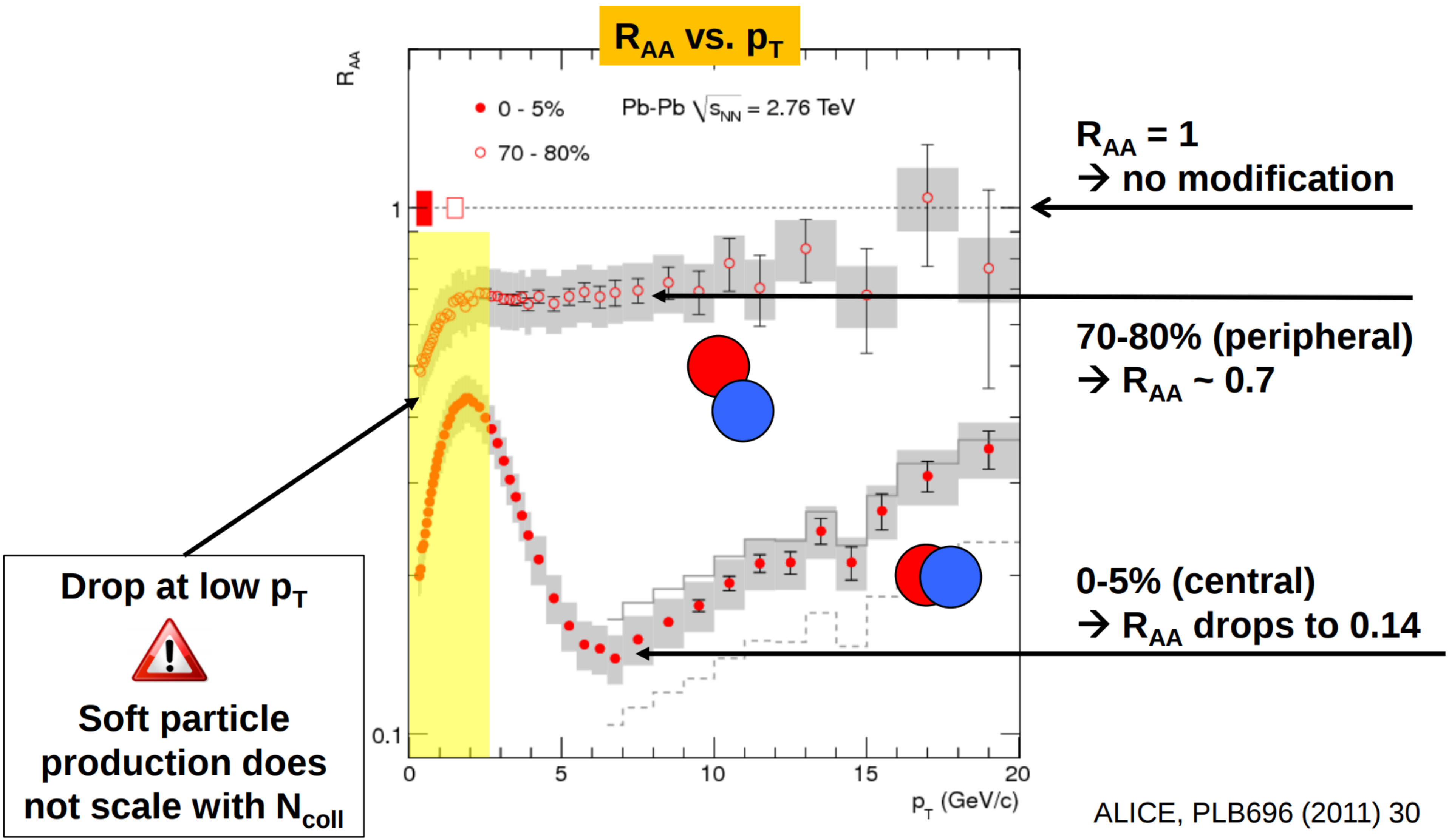
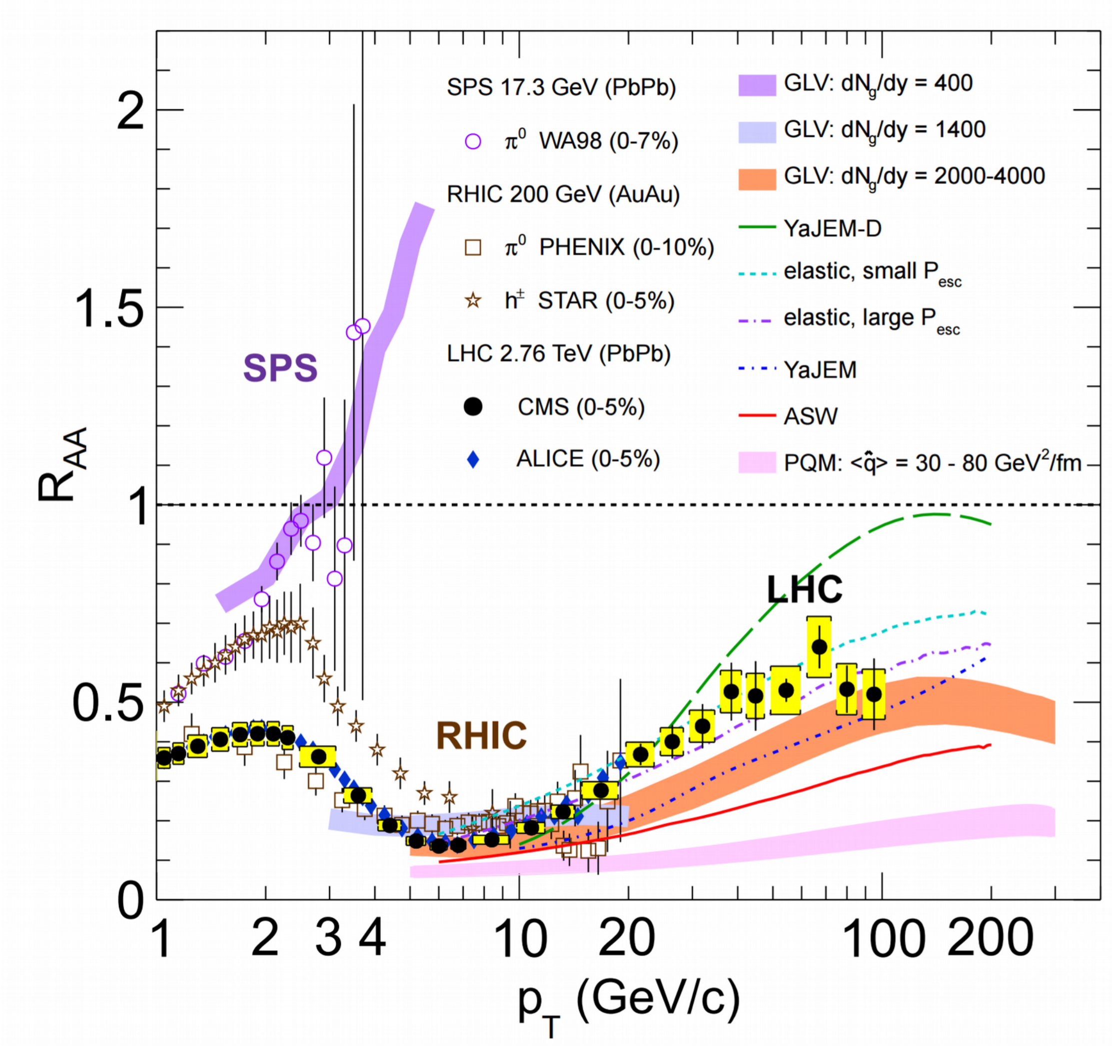



ALICE, PLB696 (2011) 30

# $R_{AA}$ of charged particles




The LHC measurements show a slightly **stronger suppression** than those from RHIC

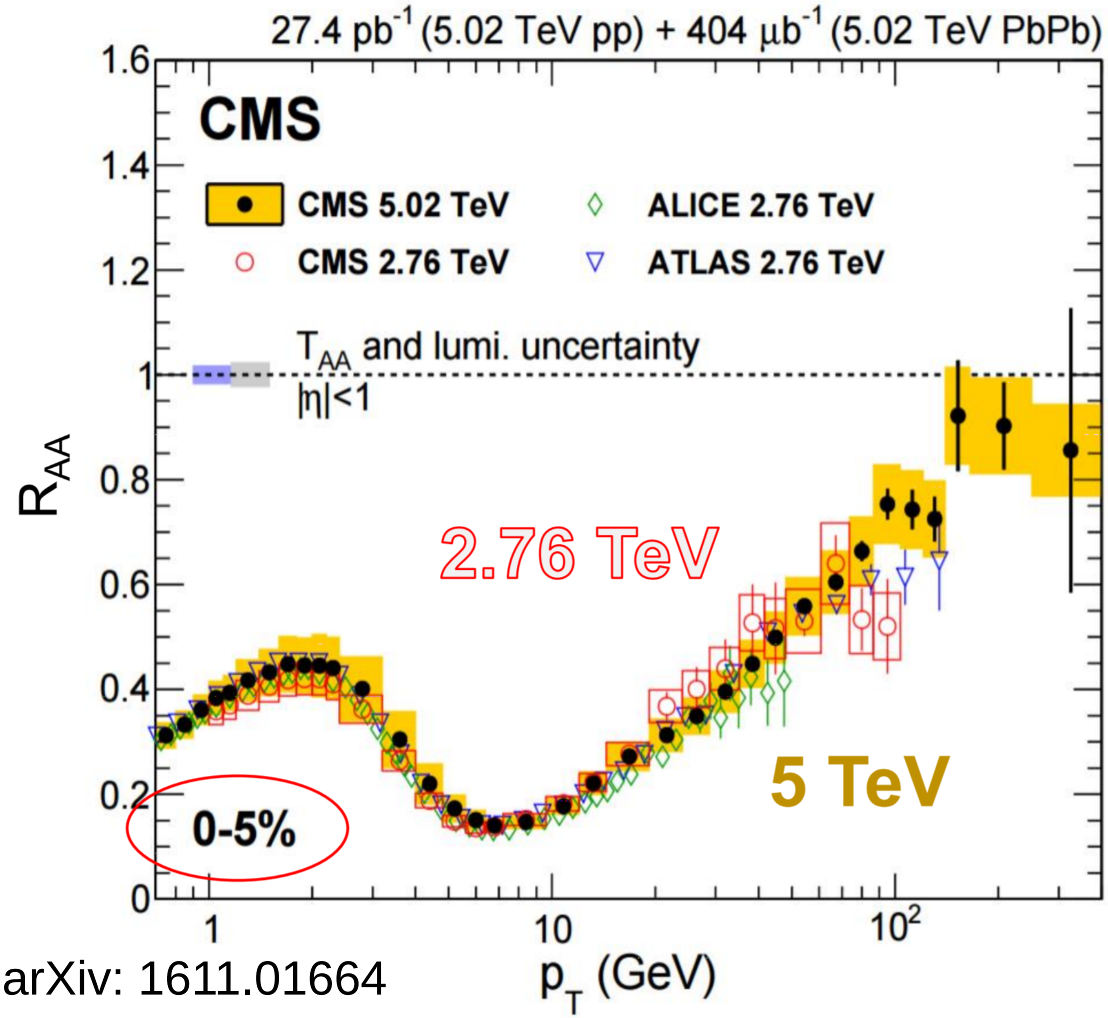
- LHC a factor of ~7,
- RHIC a factor of ~5

A completely new observation at the LHC is that **with increasing $p_T$ the suppression becomes smaller**, i.e. RAA increases

Even very energetic **partons of the highest $p_T$ suffer considerable energy loss** interacting with the medium

**Strong suppression in central Pb-Pb fingerprint of**
**hot QCD matter !!**

# $R_{AA}$ of charged particles




arXiv: 1611.01664

**All experiments agree very well**

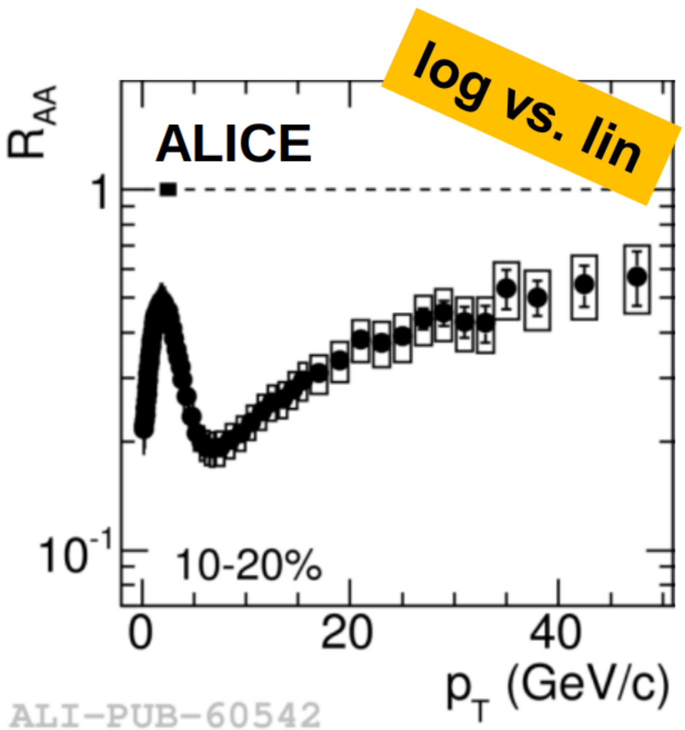
**With increasing $p_T$ the suppression becomes smaller**

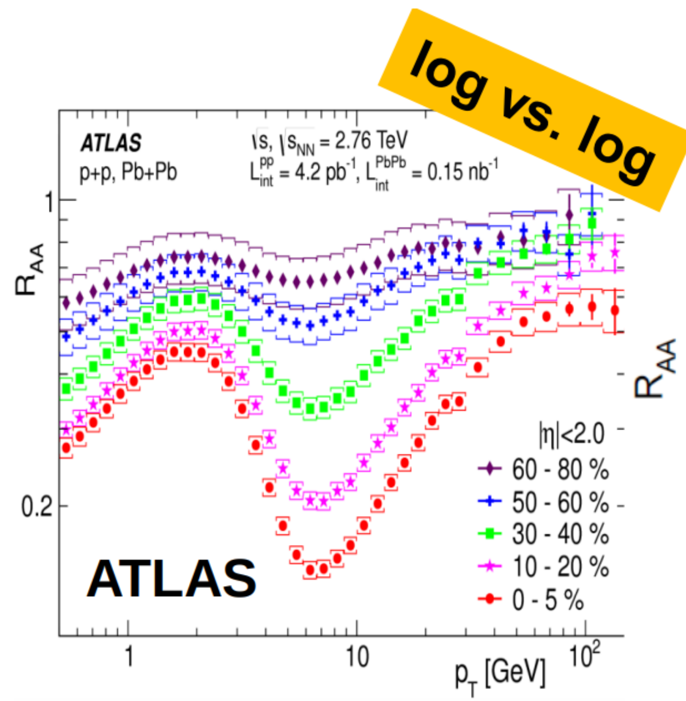
**Almost no suppression at very high $p_T$ compared to pp reference**

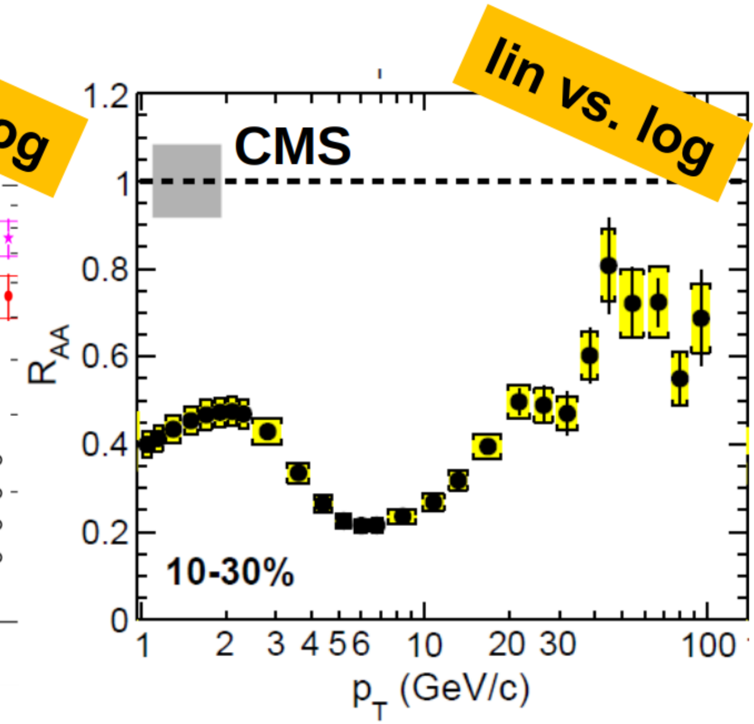
**Measurement extended up to 400 GeV!**

# $R_{AA}$ measurements

***Comparing results from different experiments***



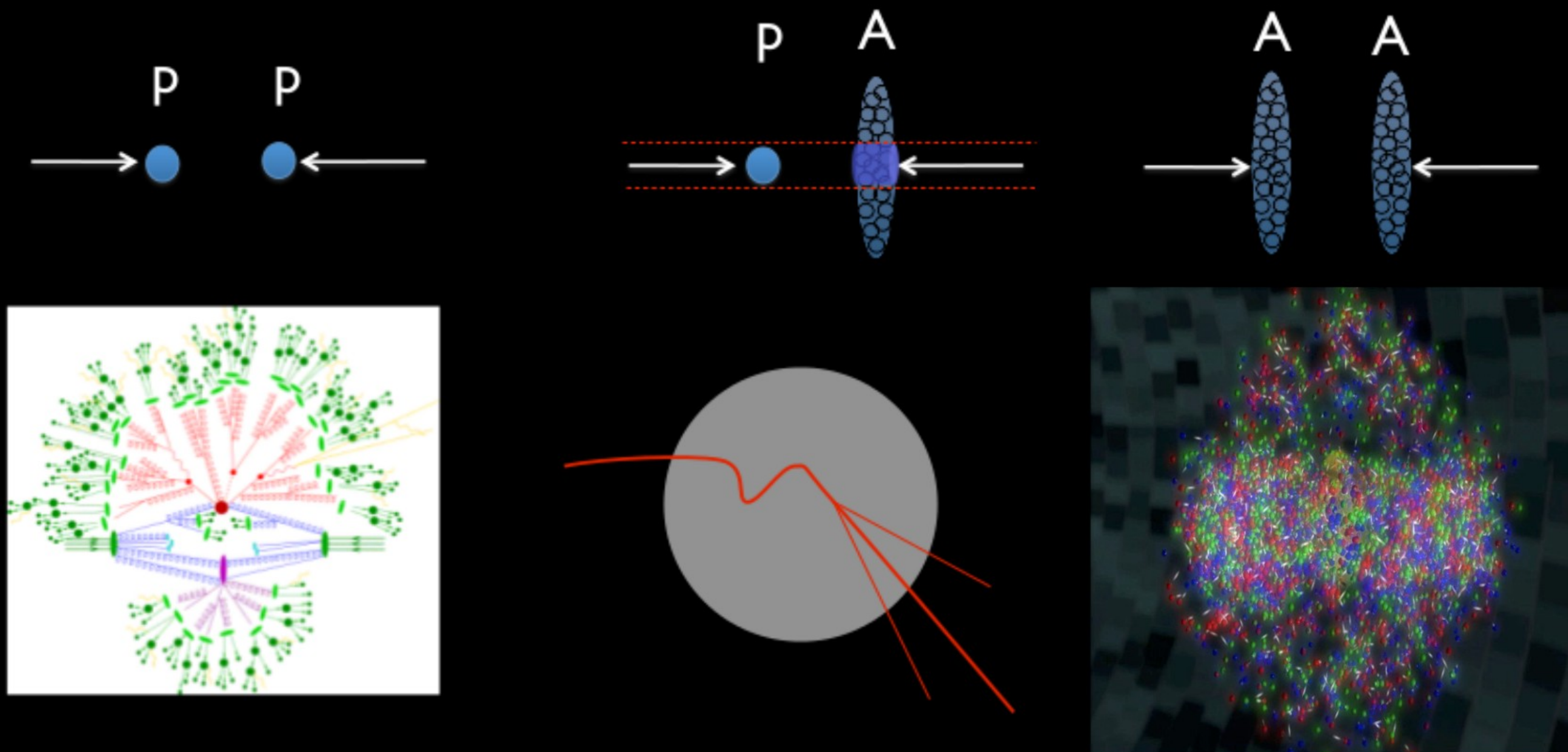




- … but all consistent ☺

ALICE, PLB720(2013) 52-62
ATLAS, arXiv:1504.04337
CMS, EPJC 72 (2012) 1945

# Strategy of Heavy-Ion Physics
## measure all these systems

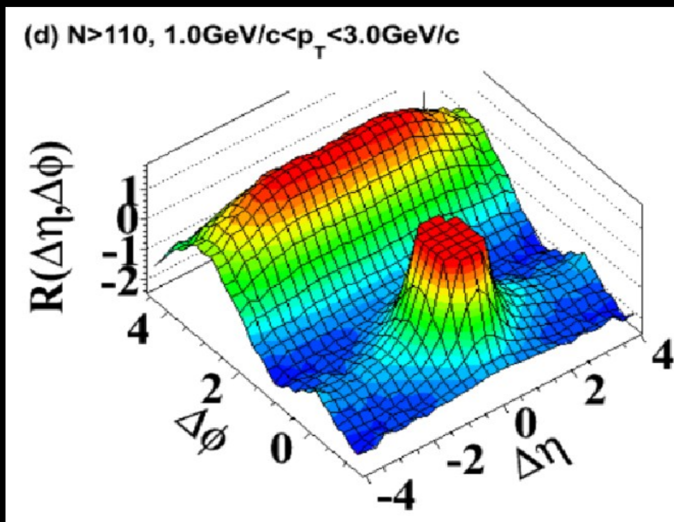


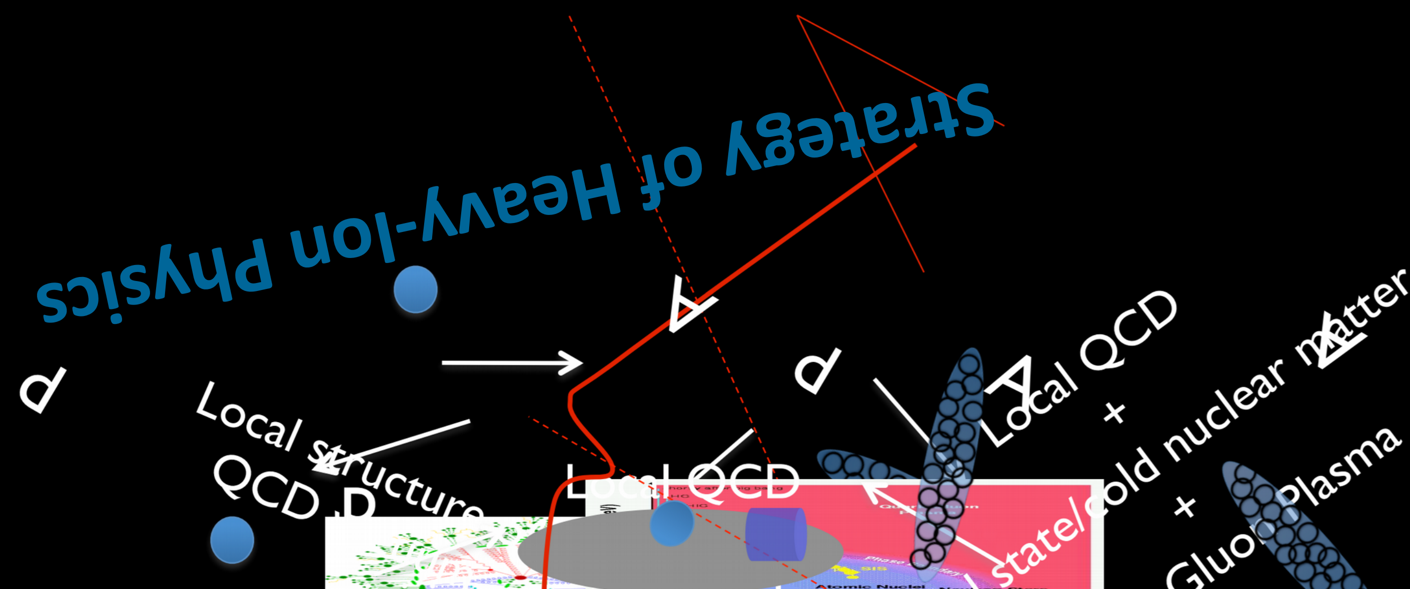

Local structure of QCD vacuum

Local QCD
+
initial state/cold nuclear matter

Local QCD
+
initial state/cold nuclear matter
+
Quark-Gluon Plasma

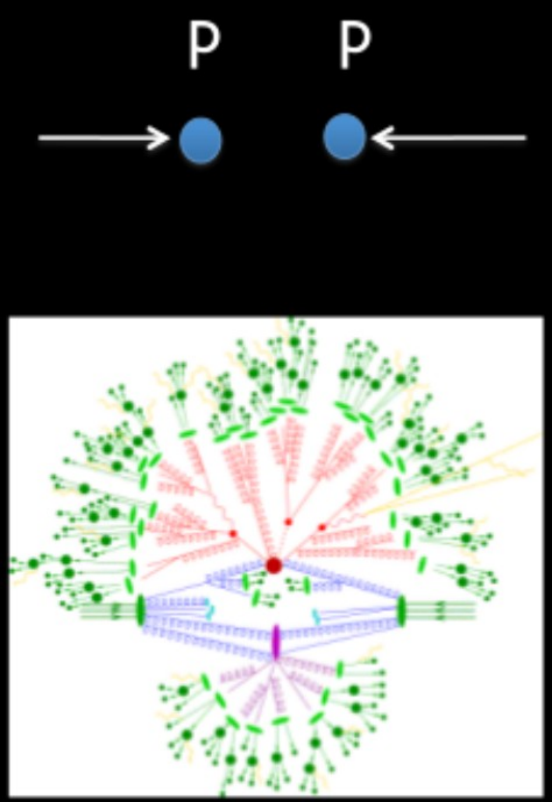
from G. Roland (IS 2013) modified by C. Loizides (QM 2014)



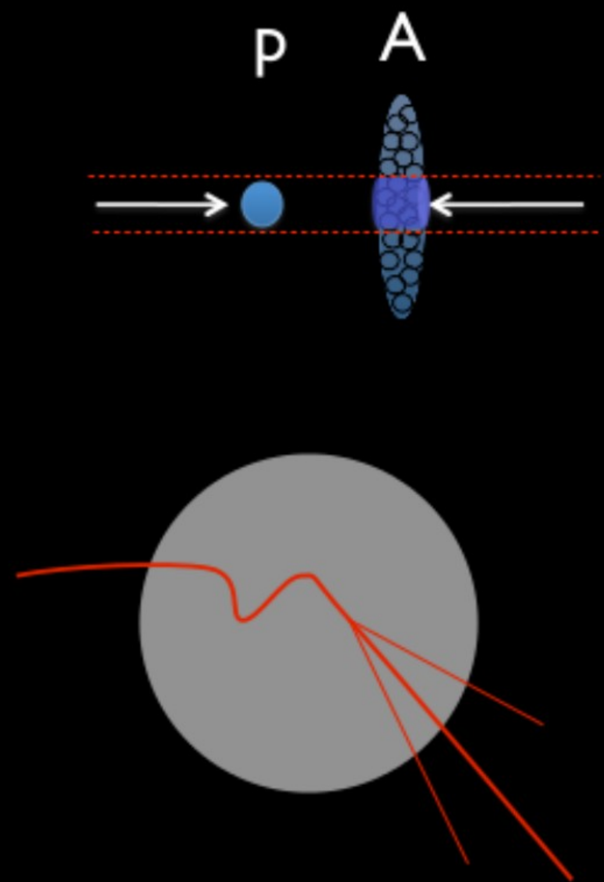




# Using pp and pA to cleanse AA from initial state physics

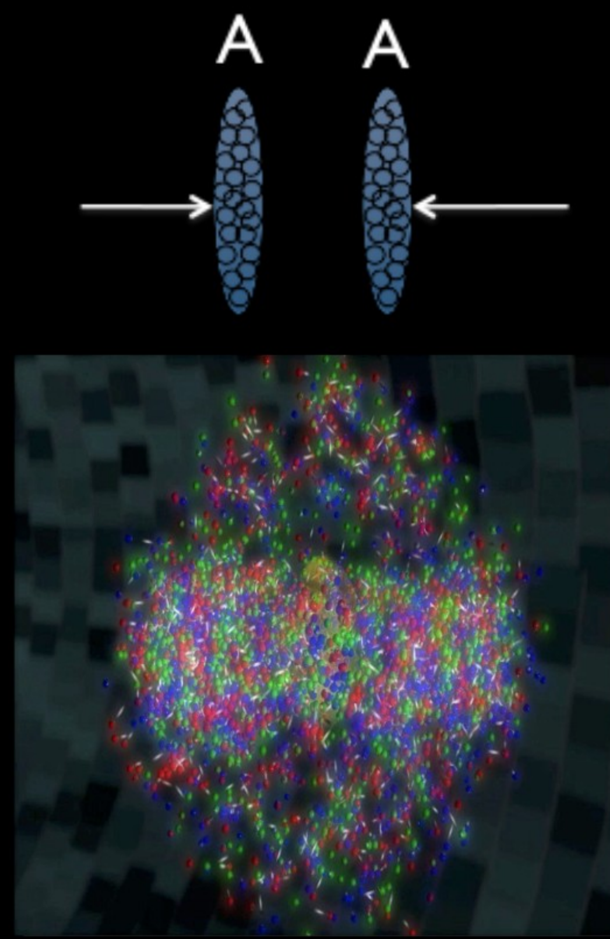
# Strategy of Heavy-Ion Physics
## measure all these systems




Local structure of QCD vacuum



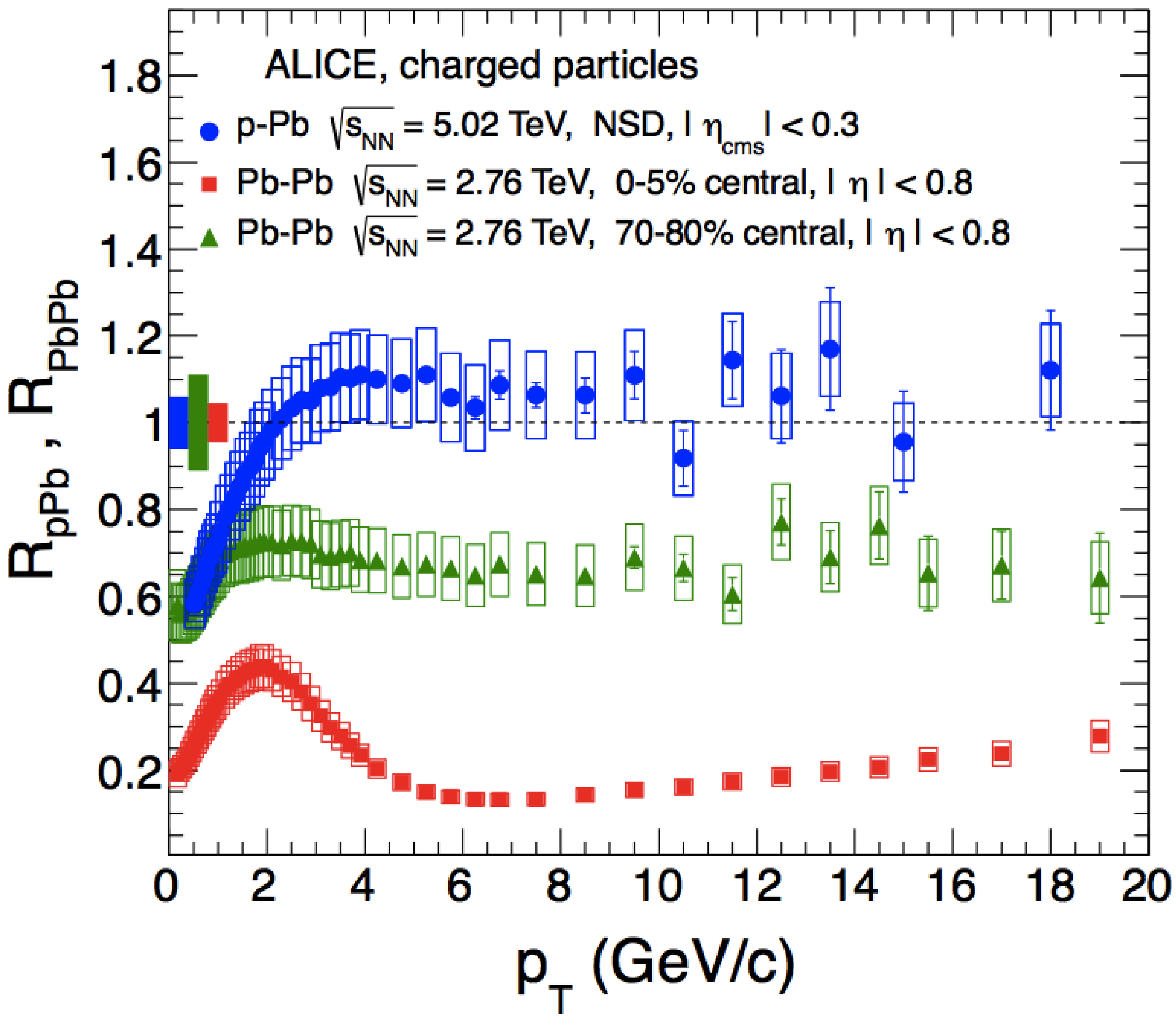

Local QCD
+
initial state/cold nuclear matter




Local QCD
+
initial state/cold nuclear matter
+
Quark-Gluon Plasma

from G. Roland (IS 2013) modified by C. Loizides (QM 2014)

# $R_{AA}$ of charged particles in pPb




**$p_T$ < 2 GeV/*c* : suppression**

**2 < $p_T$ < 4 GeV/*c* : rise to 1.1**

(Cronin effect)

**$p_T$ > 6 GeV/*c*:**
**consistent with unity**

Similar trend with dAu at RHIC
less enhancement

**strong suppression observed in PbPb**
**is NOT an initial-state effect**
**→ hot QCD matter effect**

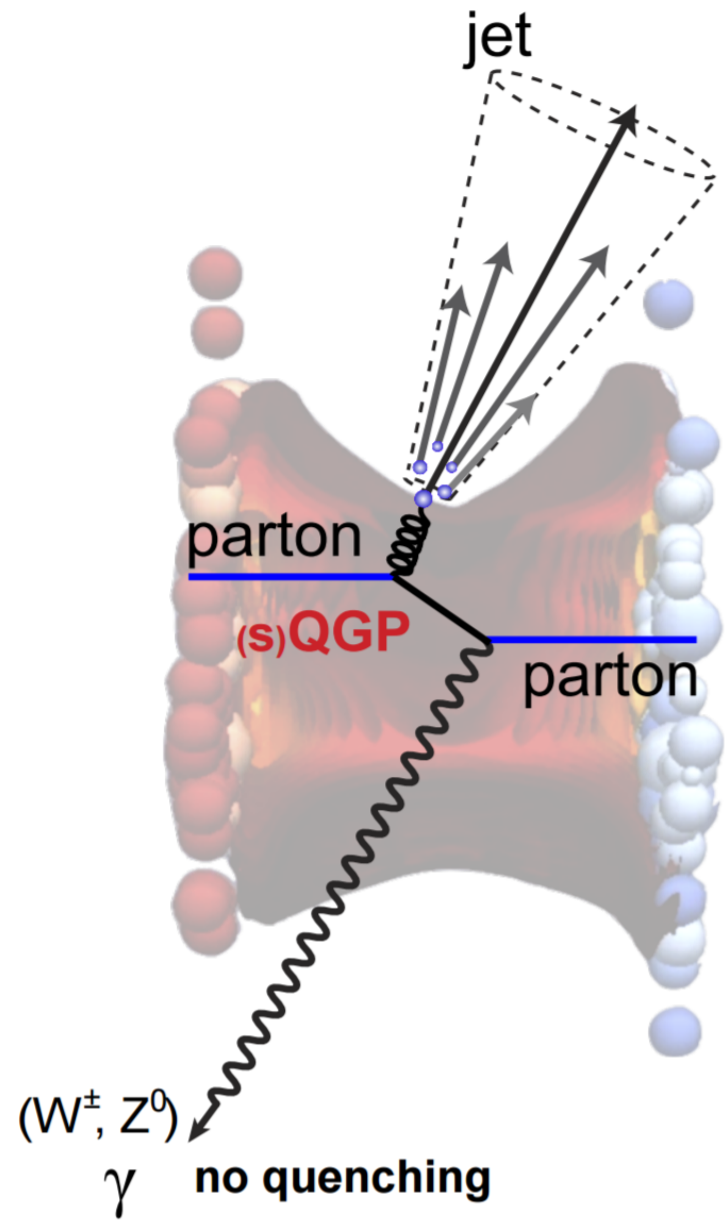
**ongoing comparison with models**

arXiv:1210.4520 [nucl-ex] PLB 696, 30 (2011)

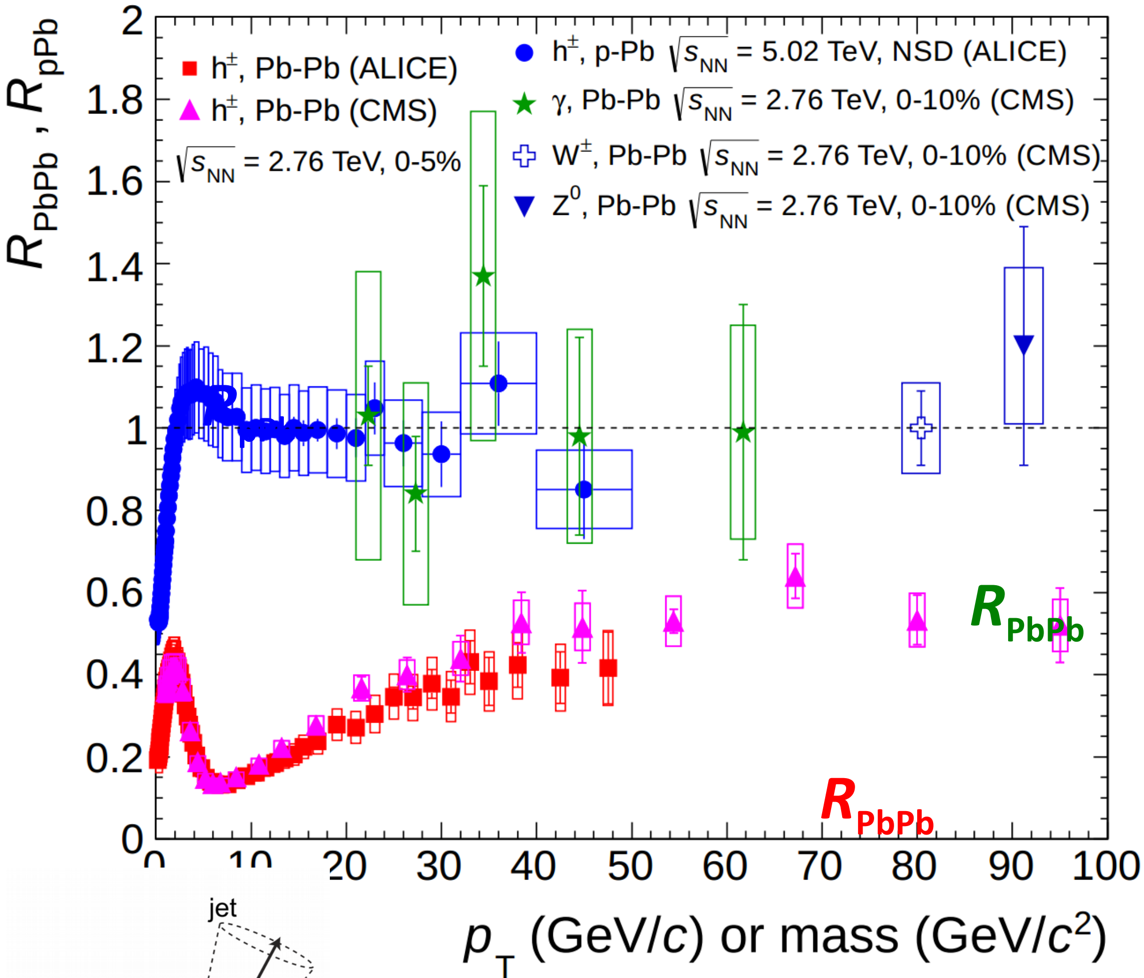
# Gamma, W, $Z^0$ unaffected

***We expect no suppression for color-neutral probes:***

- ***No interaction with QGP***
- ***Experimental check of the method***



# $R_{AA}$ of charged particles



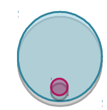

**γ, W, Z unaffected**

**pPb control experiment for PbPb**

$p_T$ < 2 GeV/$c$ : suppression

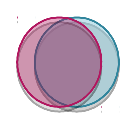
2 < $p_T$ < 4 GeV/$c$ : rise to 1.1

(Cronin effect)



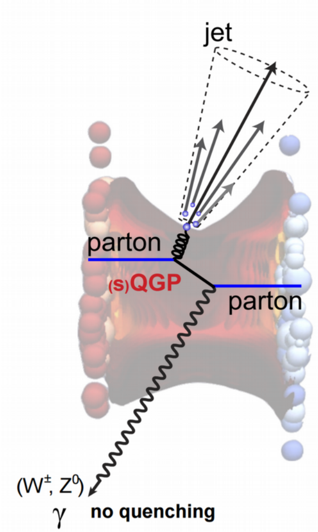
**$R_{pPb}$ ~1 $p_T$ > 6 GeV/$c$**

- **Absence of nuclear modification**



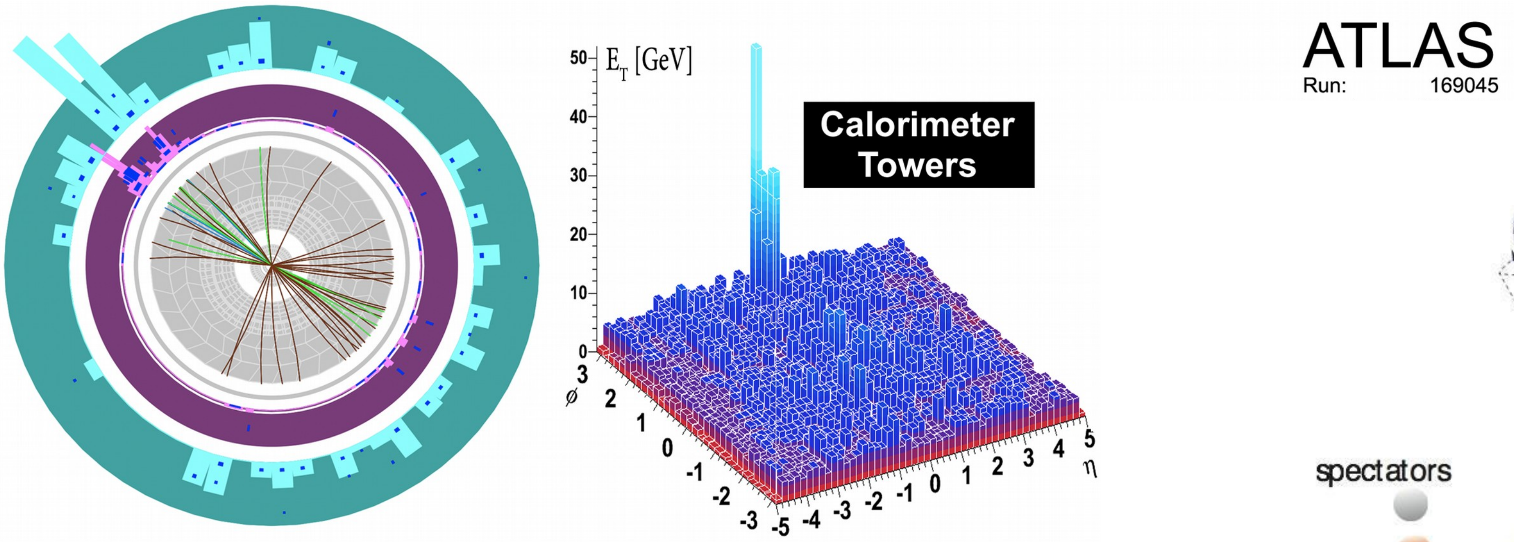
**$R_{PbPb}$ strong suppression**

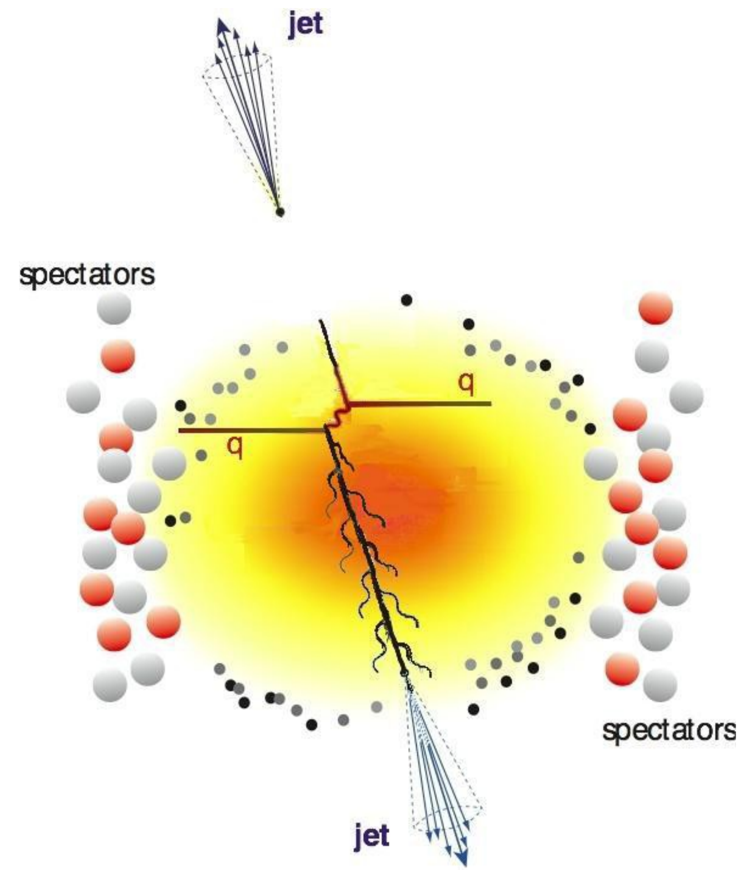
- Increases with centrality
- **NOT initial state effect**
- Final state effect




**Strong suppression in central Pb-Pb**
**fingerprint of**
**hot QCD matter !!**

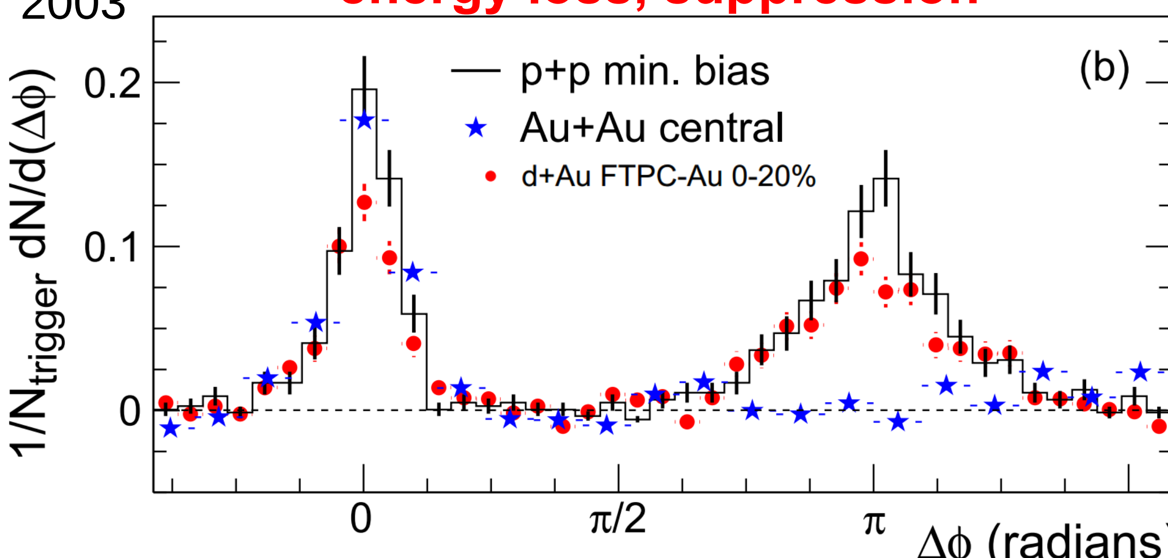
# Angular correlations



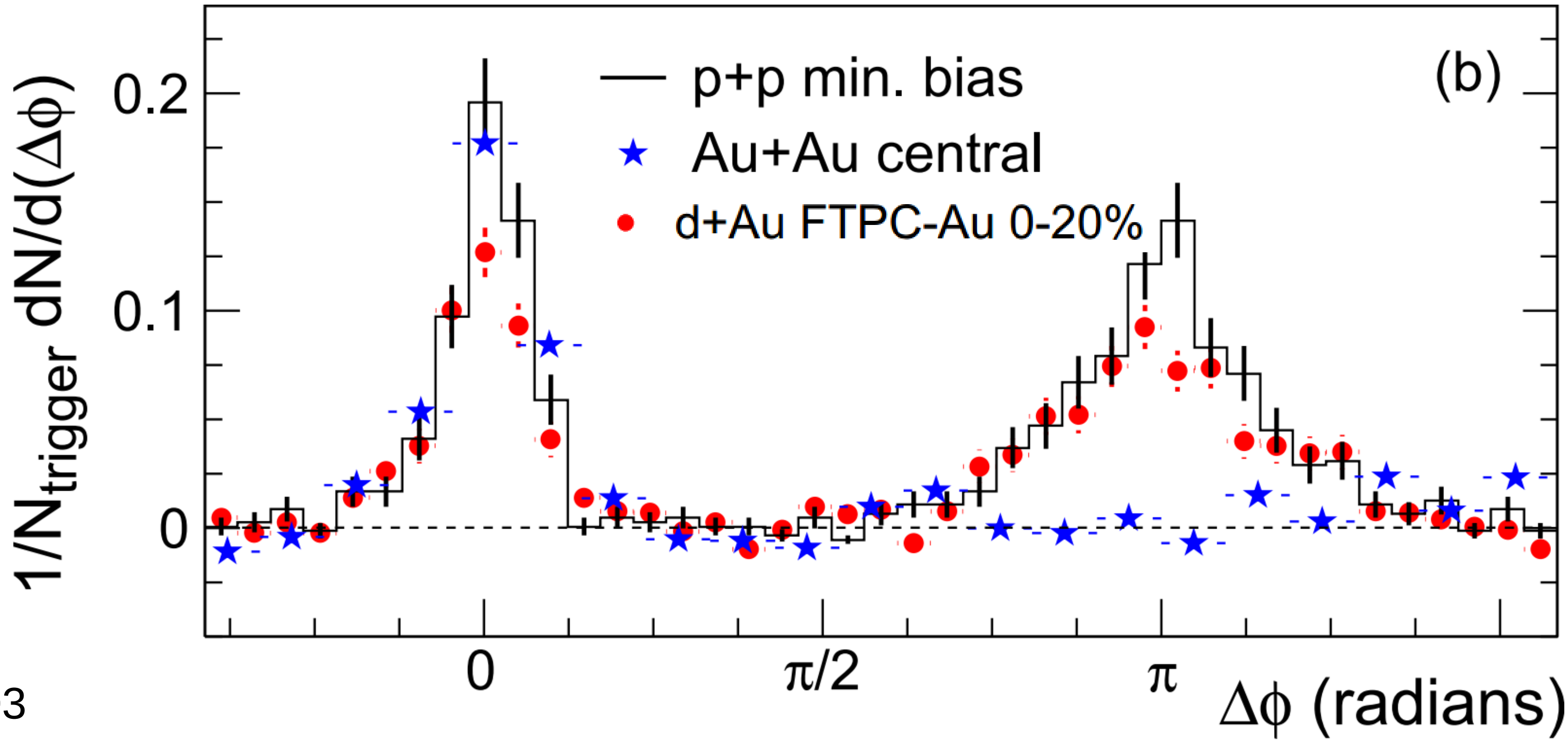




**Interaction of gluons, light and heavy quarks inside the medium**
**→ energy loss, suppression**

2003



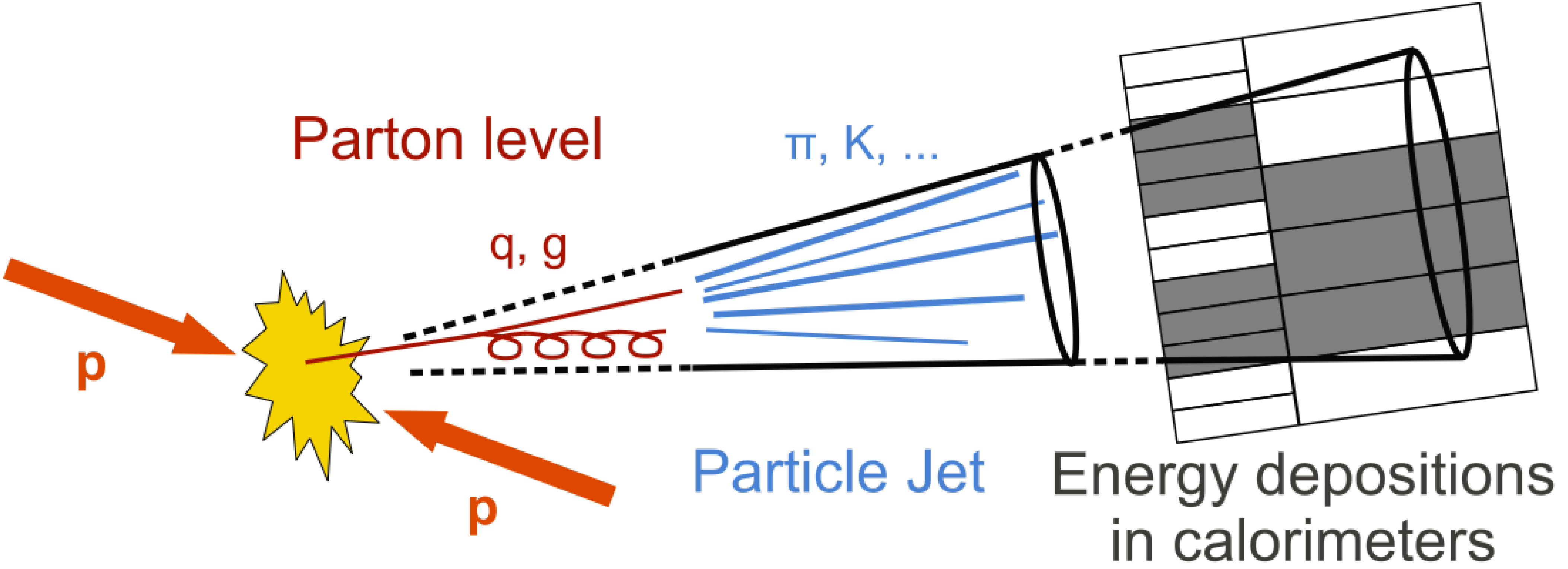
# Angular correlations




2003

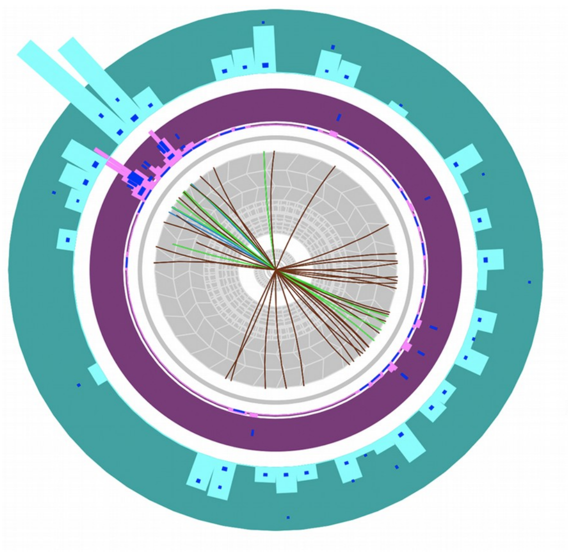
**Interaction of gluons, light and heavy quarks inside the medium**
**→ energy loss, suppression**

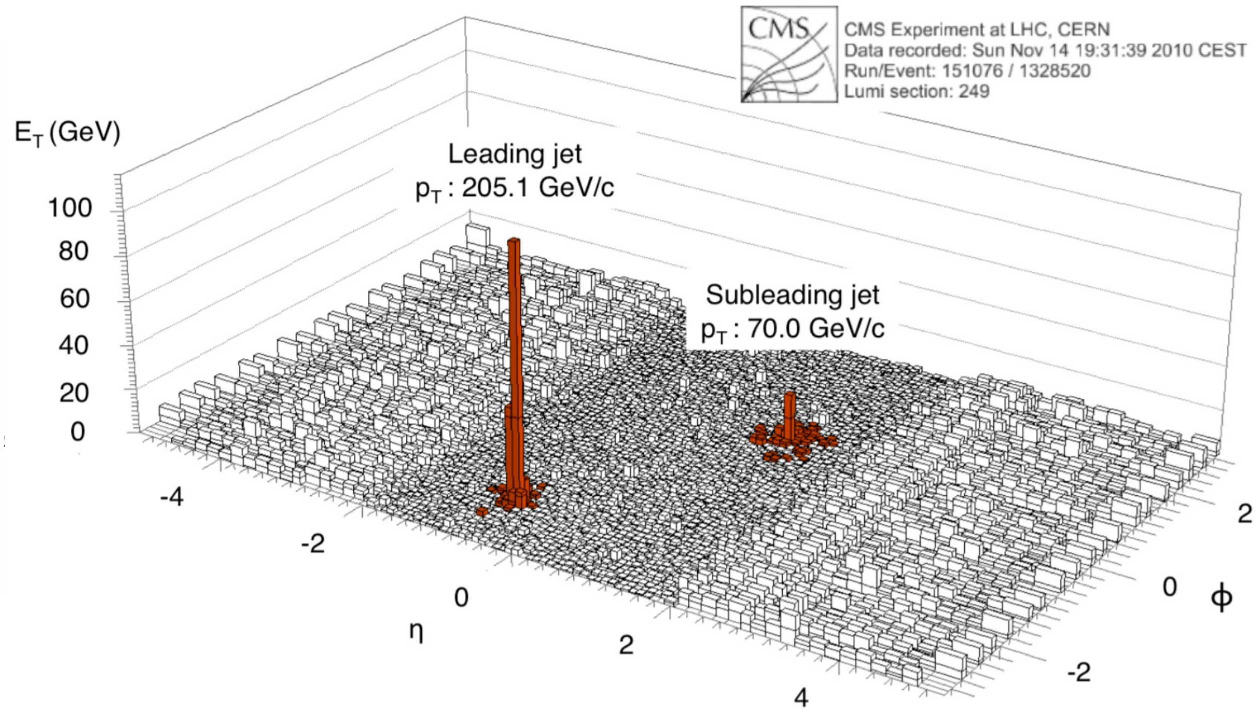
# Jets – collimated spray of hadrons




- experimental signatures of quarks and gluons produced in high-energy processes
- quarks and gluons cannot exist freely due to color-confinement
- instead, they come together to form colour-neutral hadrons, in a process that leads to production of **collimated spray of hadrons** called **a jet.**

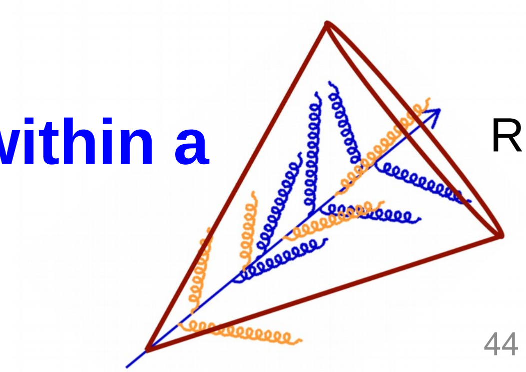
# Reconsructed jets



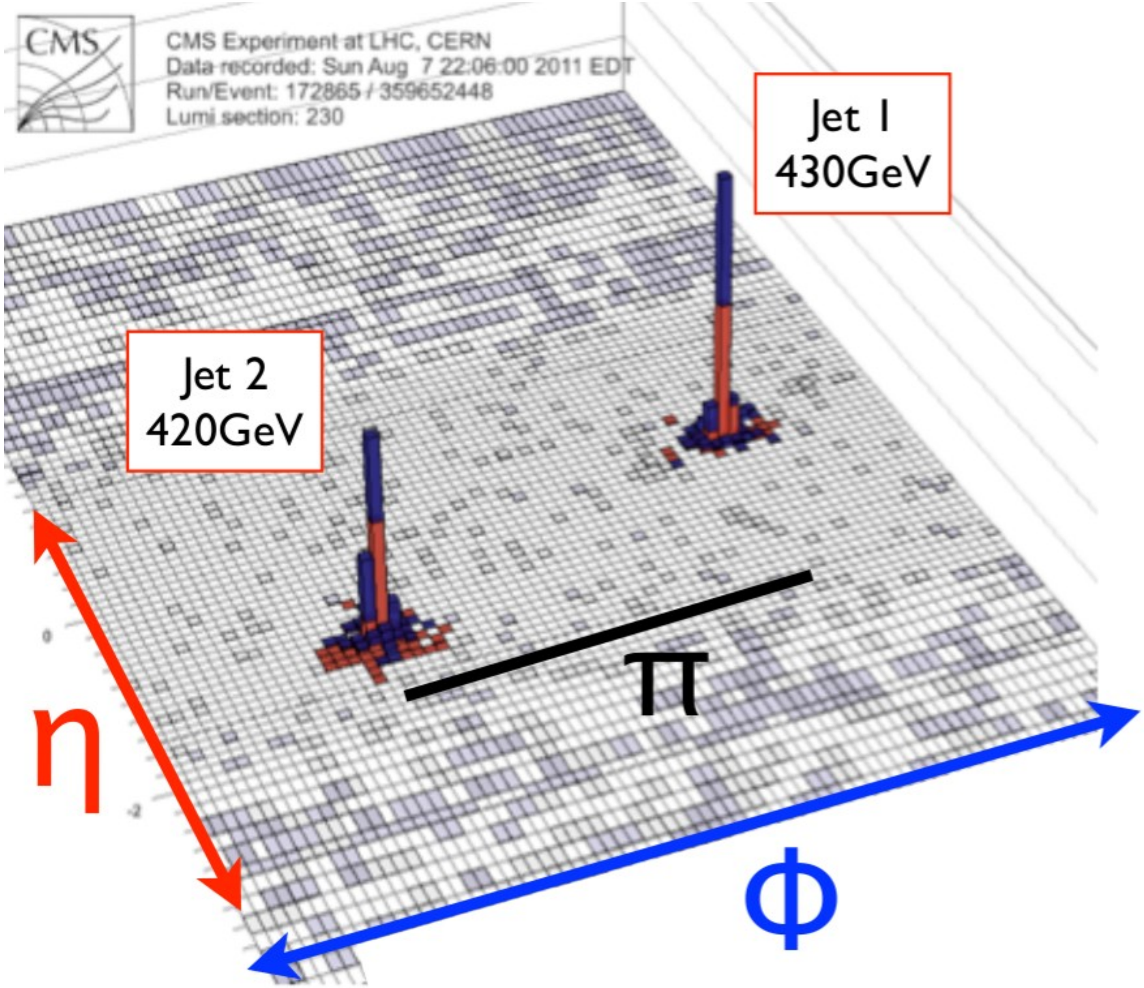



**Jets can be reconstructed using a combination of tracking of charged particles and measurements in electromagnetic and hadronic calorimeters.**

**Typically the detected particles are grouped within a given angular region,**
**i.e. a cone with radius R.**



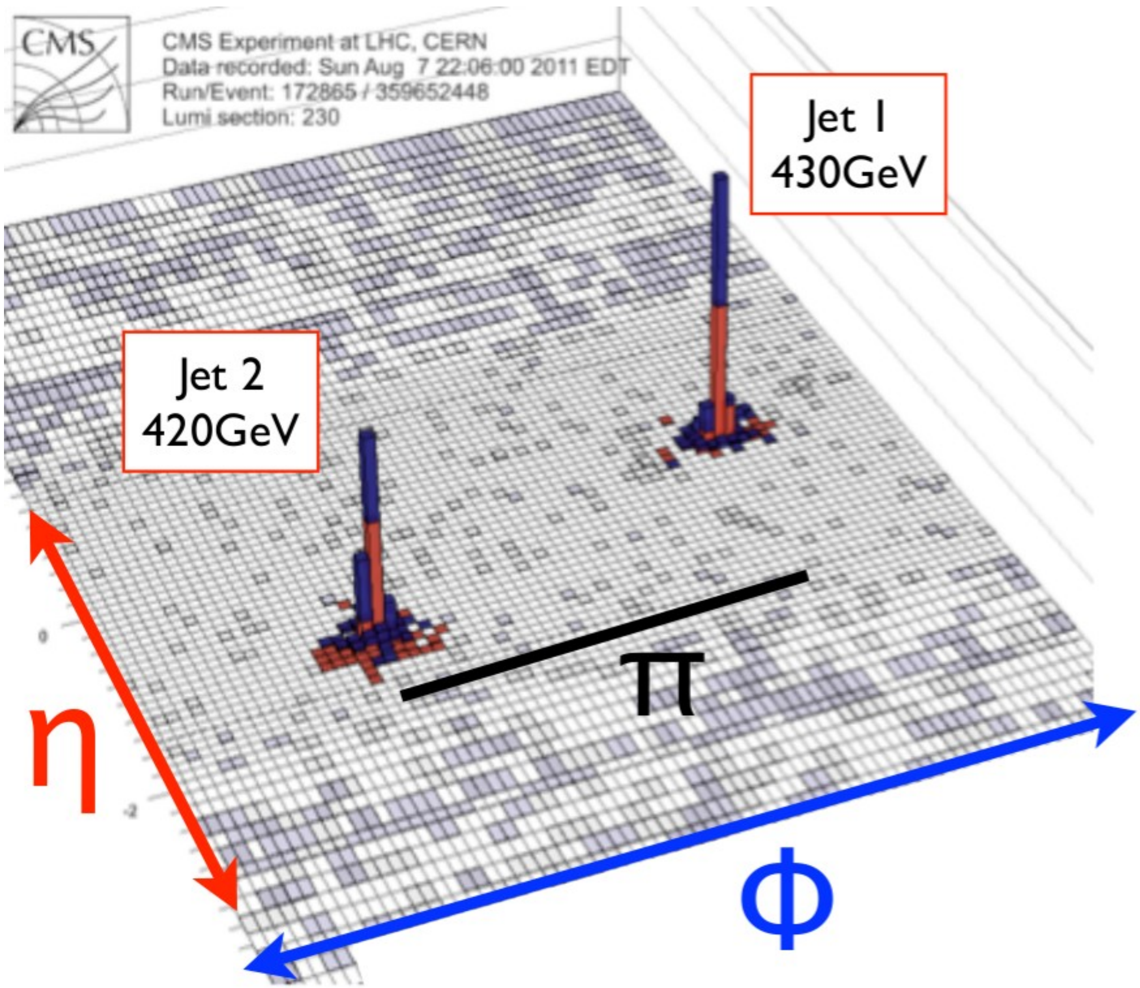
# What's a jet?

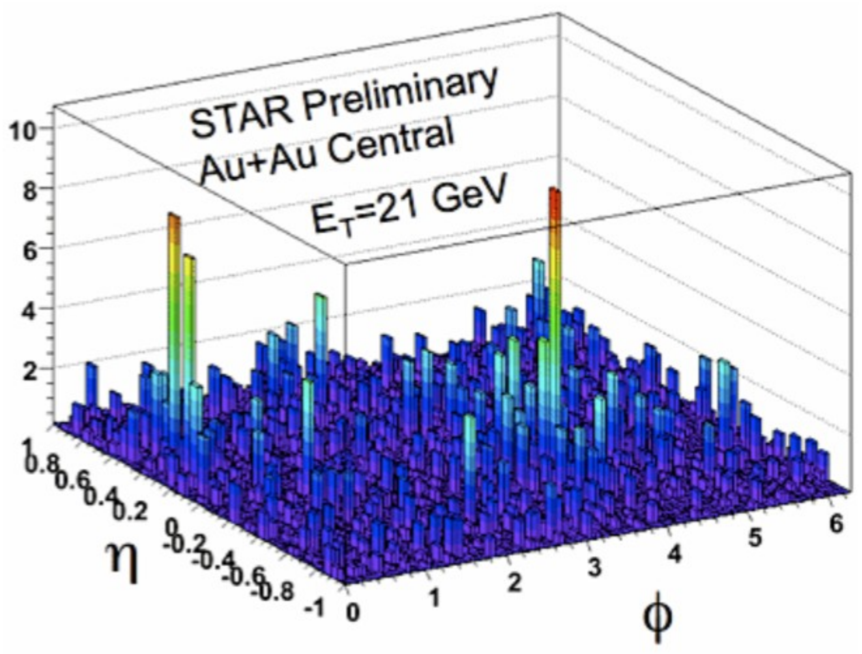



Jet finding is easy…

High $p_T$ jets, pp collision

# What's a jet?




Jet finding is easy…

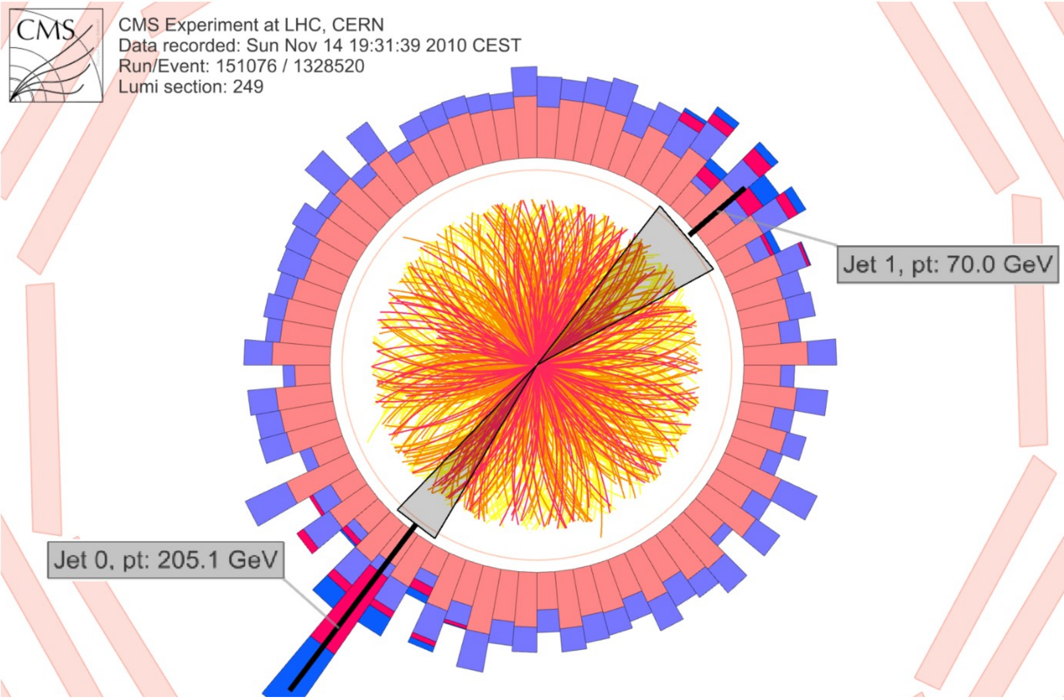
High $p_T$ jets, pp collision

…until it isn't

Low $p_T$ jets, central heavy-ion collision UE

# Jet and Underlying Event

Thousands of particles are produced and the underlying event backgrounds are enormous



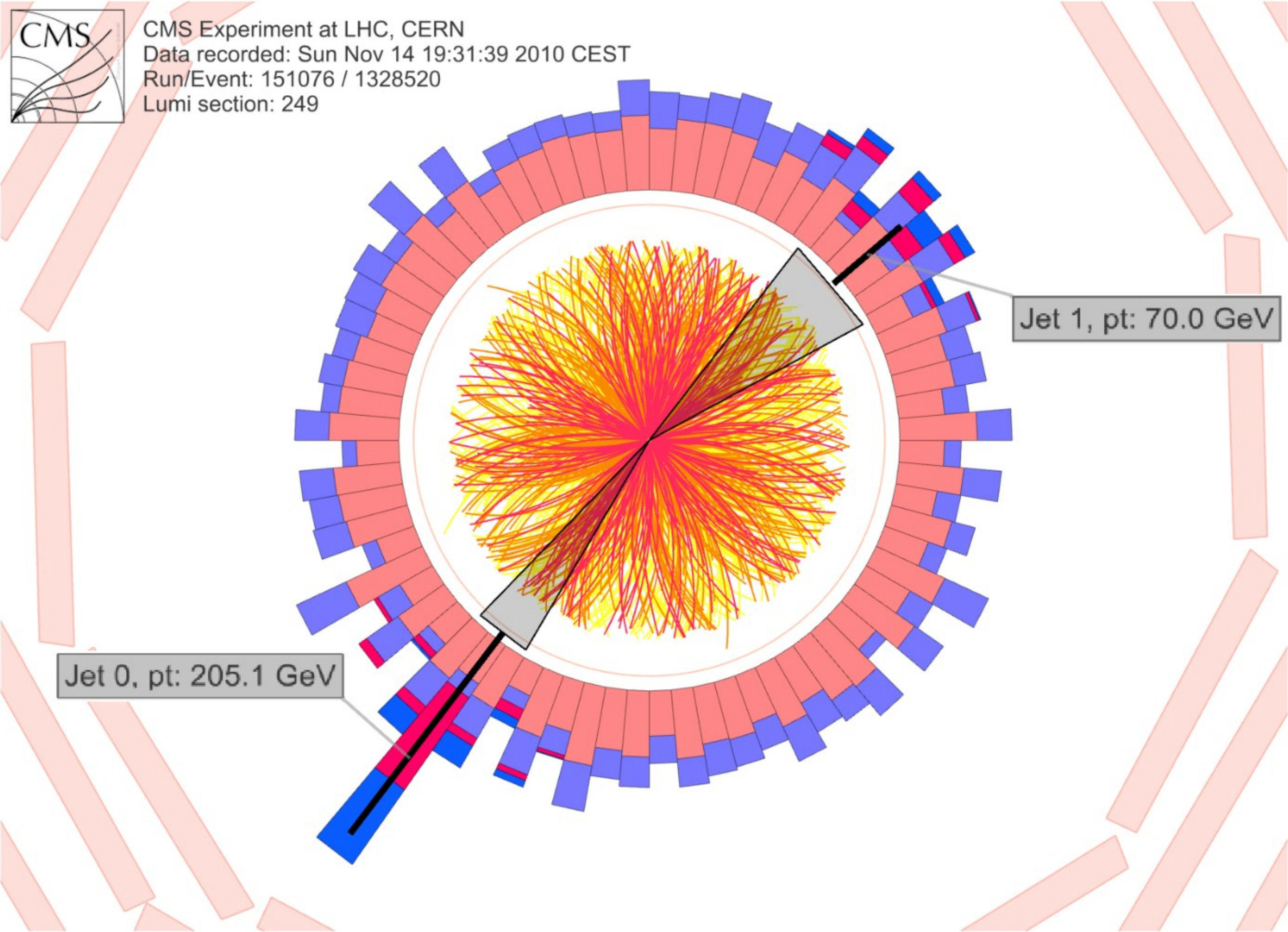

Jets in heavy-ion collisions sit on top of large underlying event (UE)
Need to ***decide*** which particles are part of jet and which belong to UE:
**UE subtraction**

Current methods assume that local UE (under jet) is the same as elsewhere in the event
I.e., UE modification due to jet would manifest as modification of observed jet

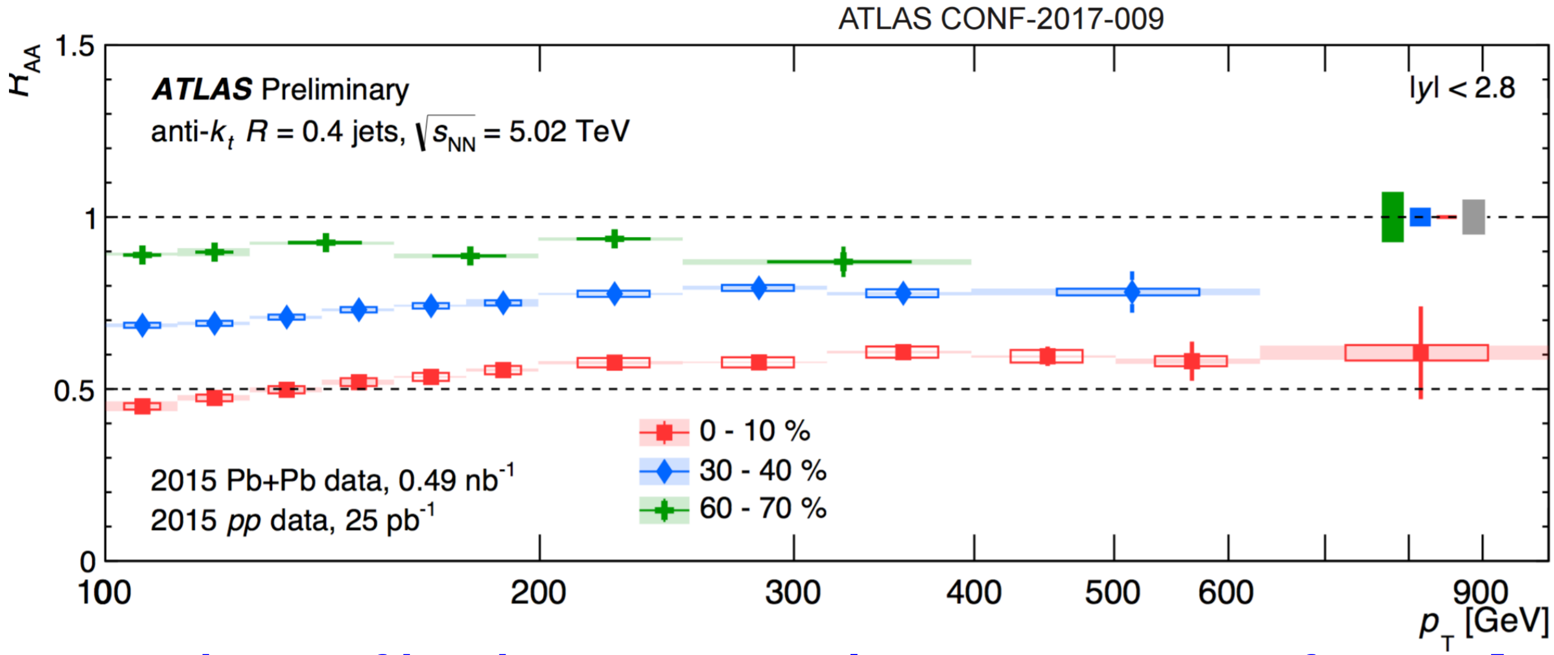
# Suppression of jets

Jets are not only embedded in a huge background but also modified.

**Dramatic suppression of jets** and momentum imbalance **is observed.**



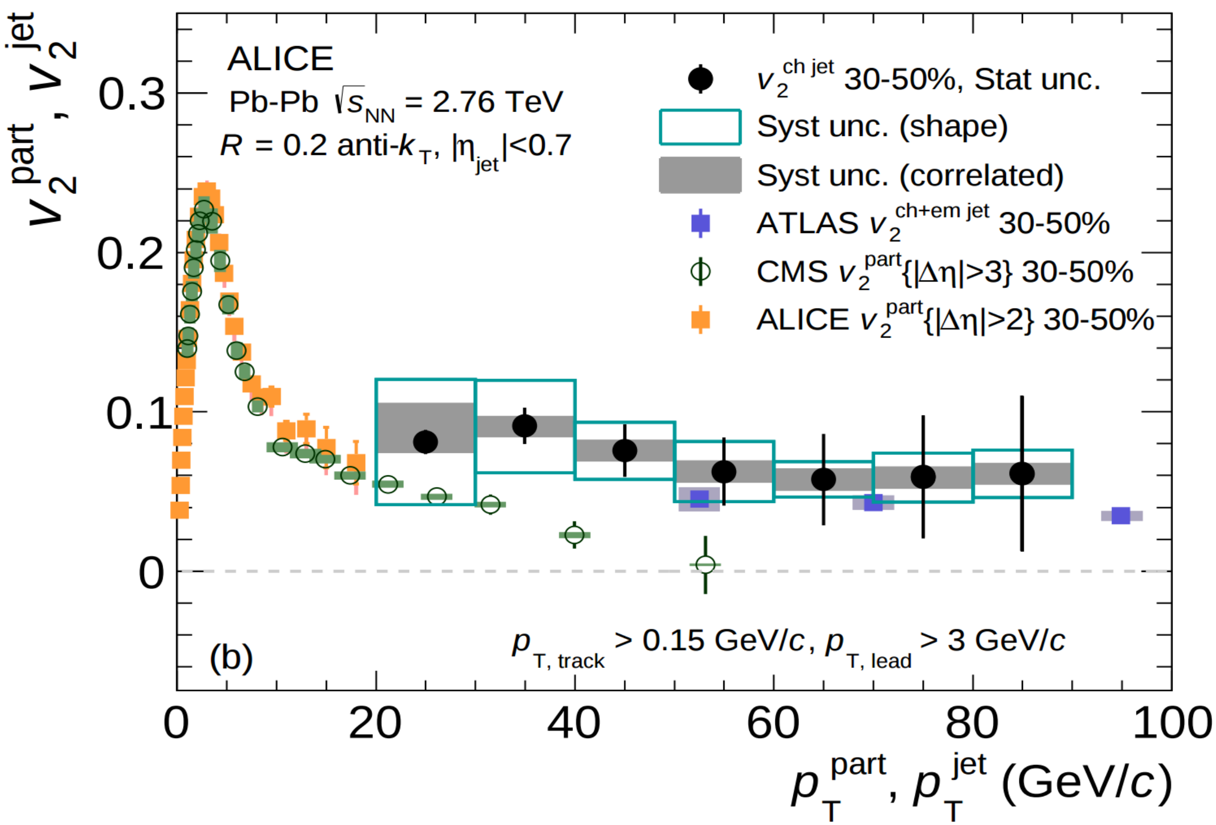
# $R_{AA}$ of jets

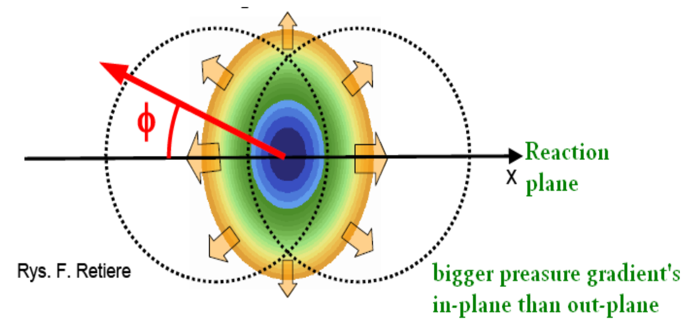



**ATLAS measured RAA of jets in 0-10% central events at 5.02 TeV for pT ∈[0.1 - 1 TeV]**

- **strong suppression in Pb–Pb collisions at LHC persists up to the highest measured pT, extended up to 1 TeV/c.**
- **the medium created in Pb–Pb collisions is so opaque that it can quench even the most energetic jets.**
- **a clear centrality dependence is observed, as for single hadrons**

# $v_2$ of charged particles and jets




**Significant positive $v_2$ :**

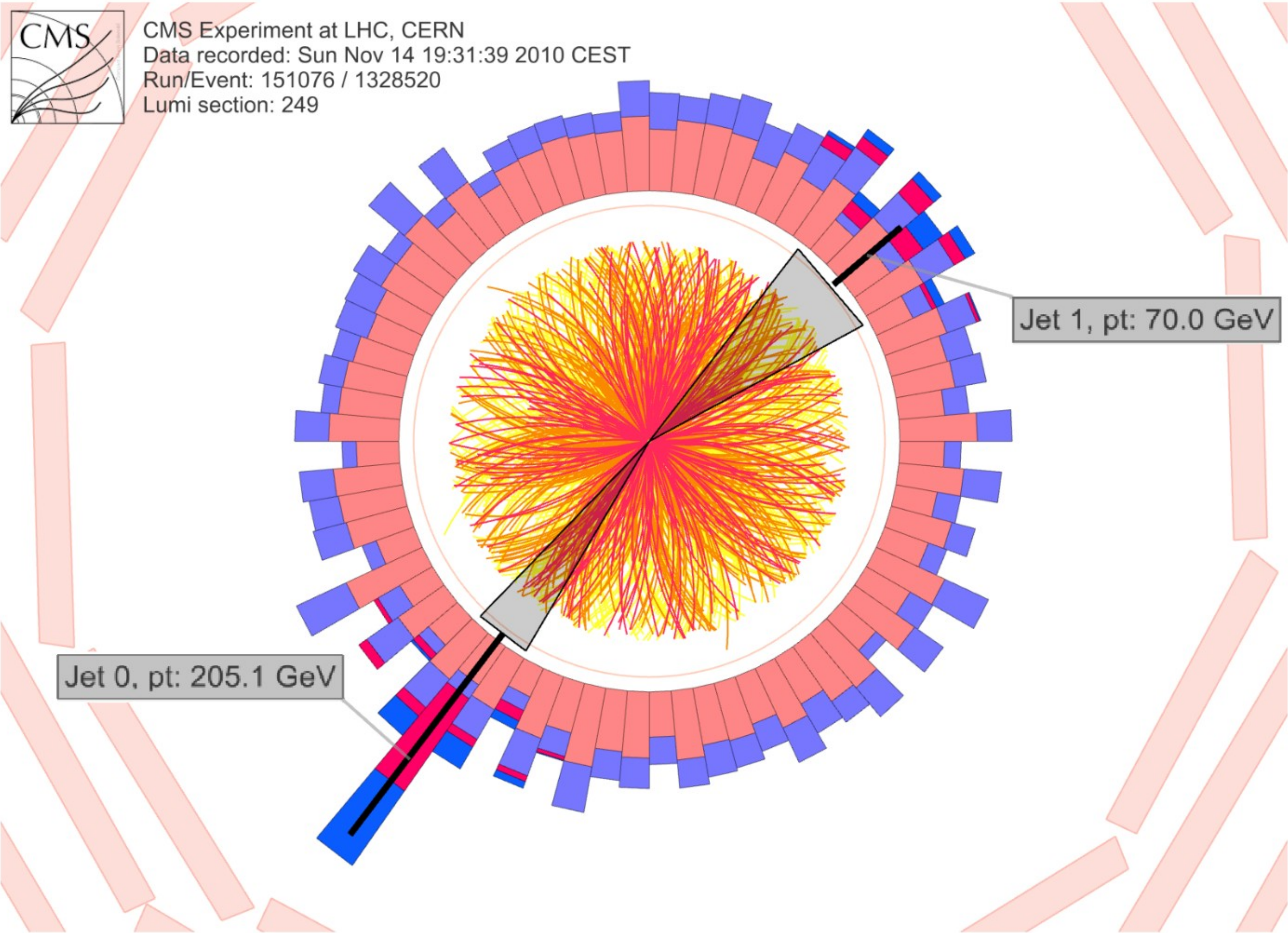
- relationship between the measured jet suppression and the details of the initial nuclear geometry;
- confirms expectation that the jet suppression is strongest in the out-of-plane direction where partons traverse the largest amount of hot and dense matter

**Simultaneous measurements of charged particles and jets $R_{AA}$ and v2**

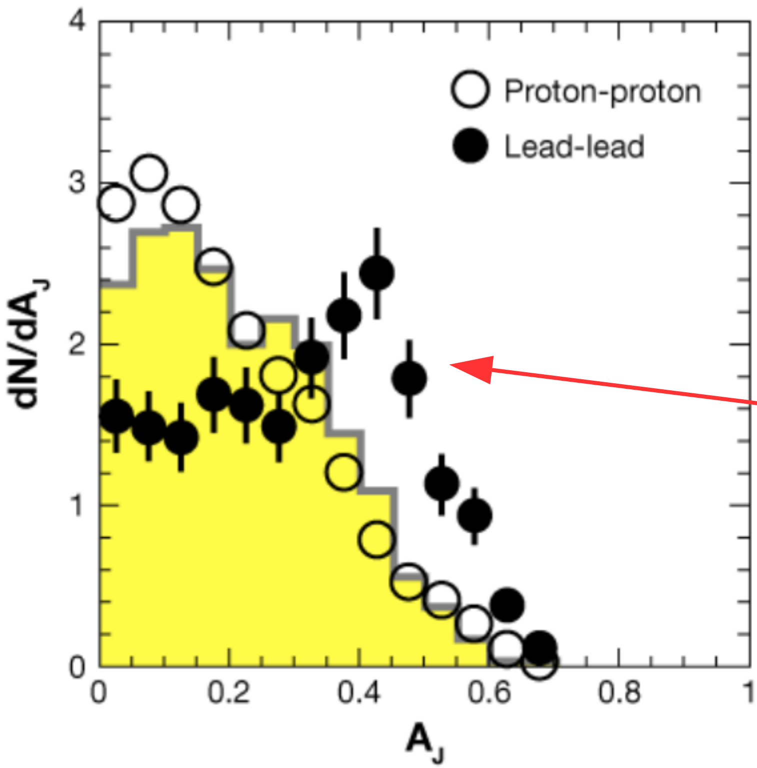
# Momentum imbalance

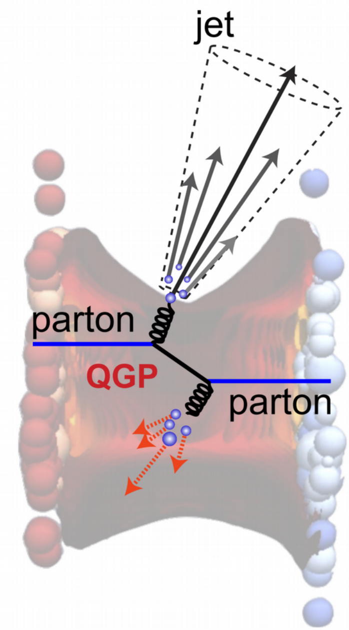
Jets are not only embedded in a huge background but also modified.

Dramatic suppression of jets and **momentum imbalance is observed.**



# Dijet Asymmetry

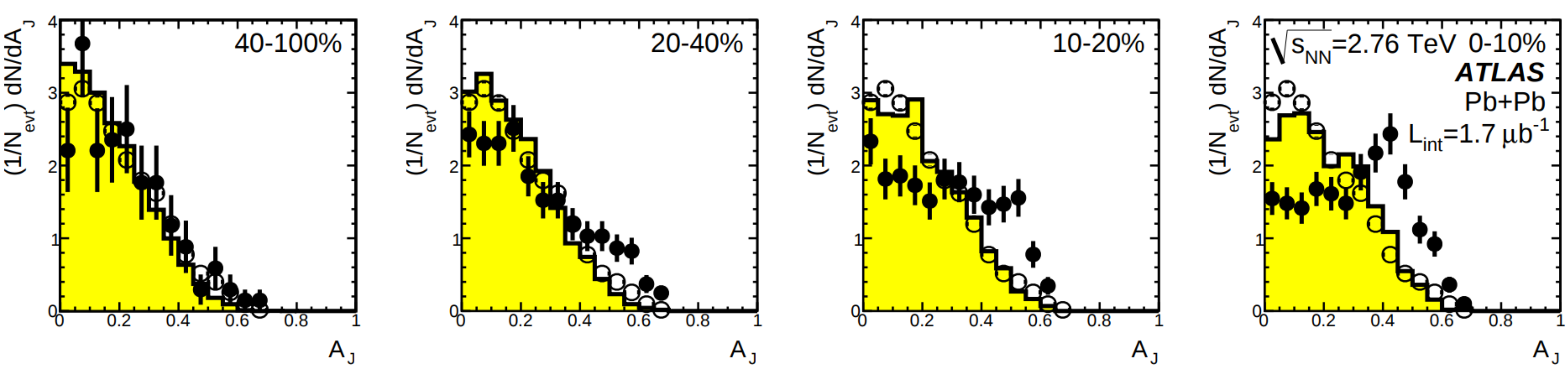


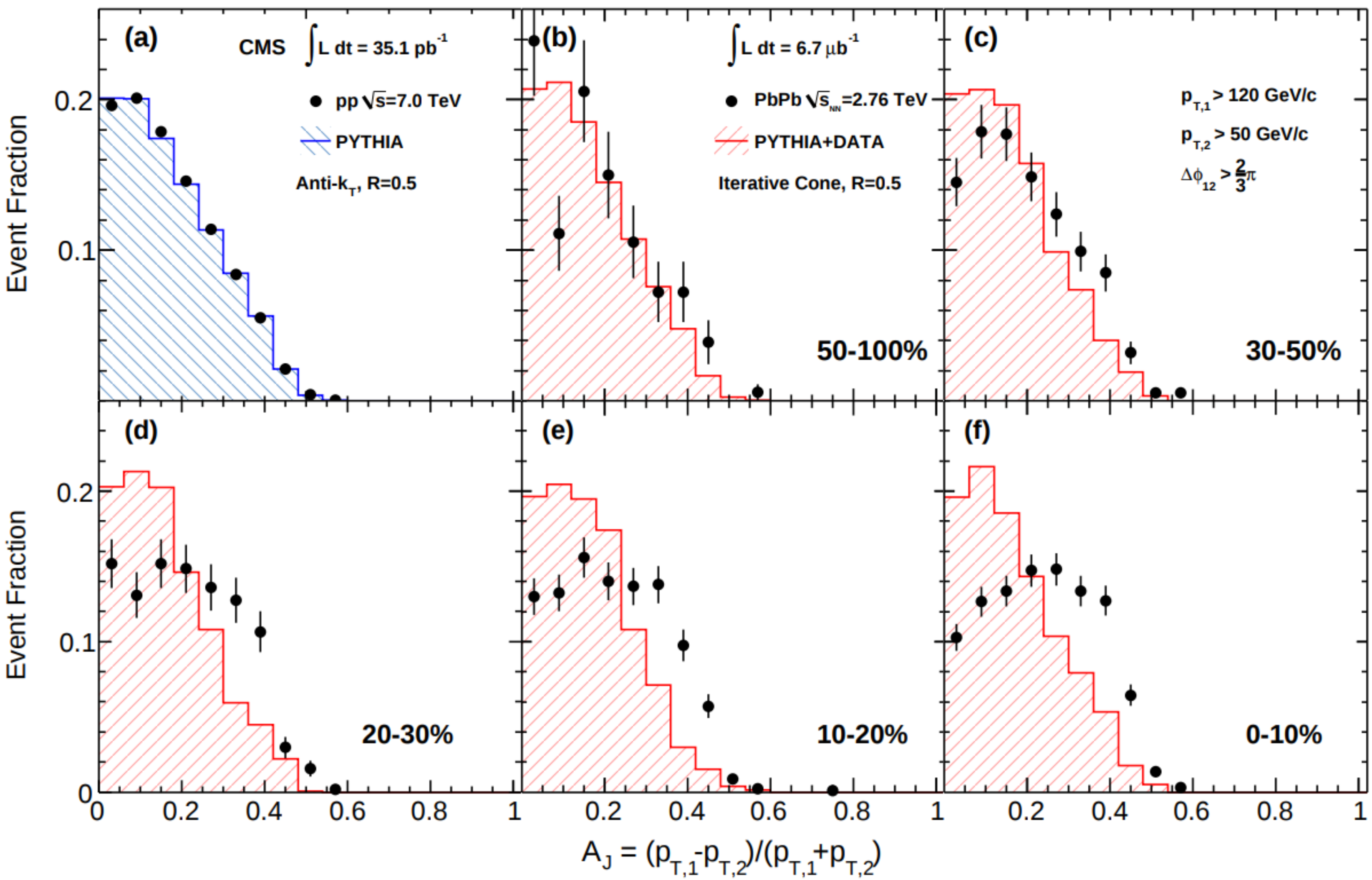

This is how it started in 2010

$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Excess of imbalanced jets in AA collisions



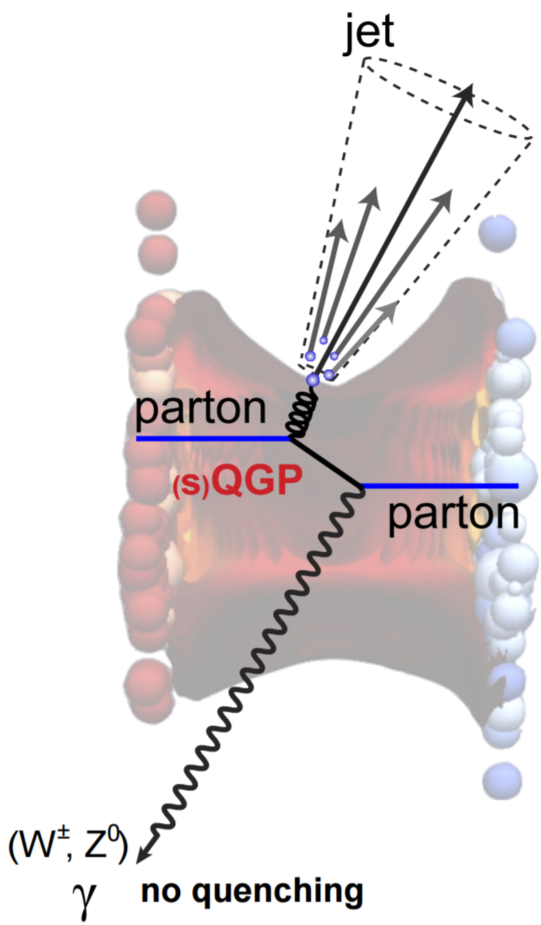
# Dijet Asymmetry




$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

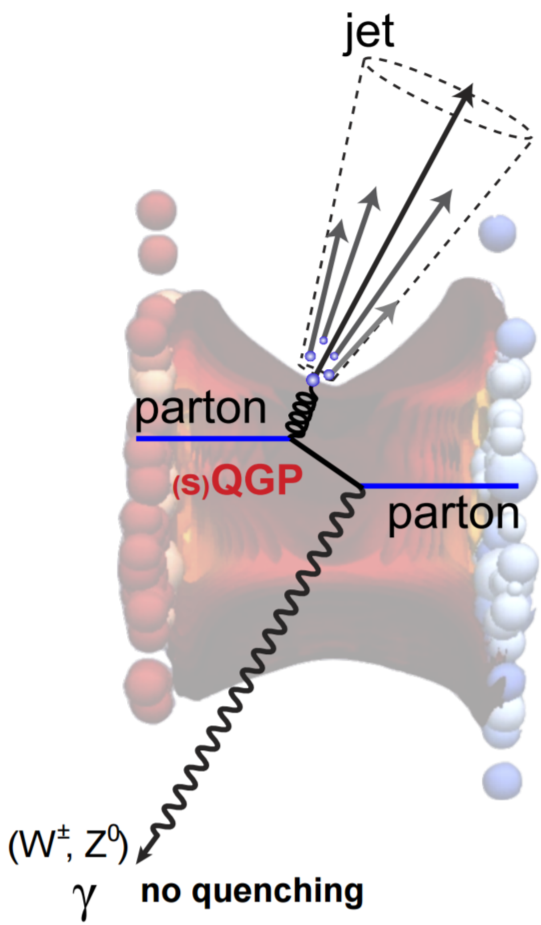
Excess of imbalanced jets in AA collisions

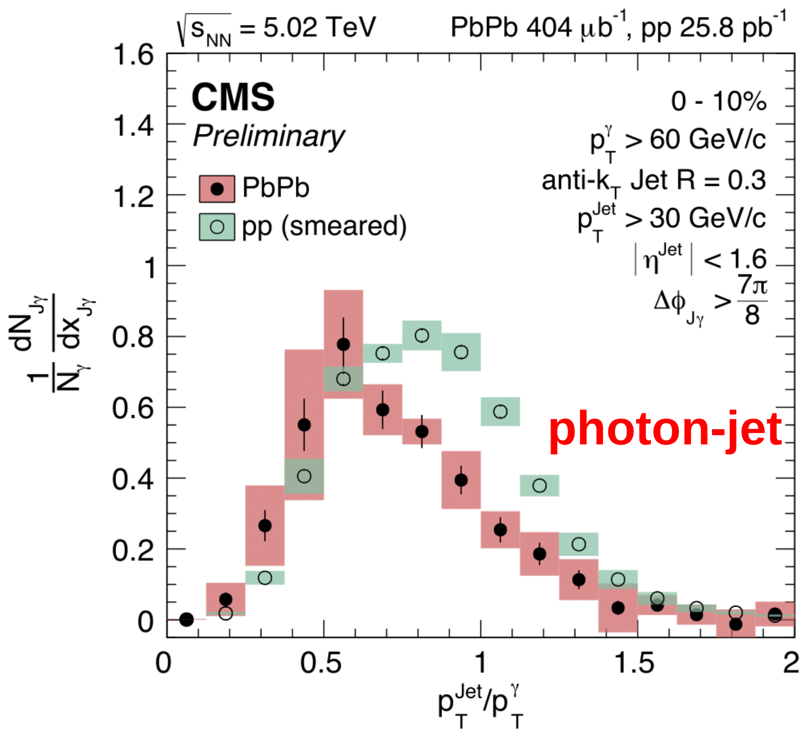
# Photon-jet and Z-jet correlations




**γ, W, Z unaffected by the medium**

# Photon-jet and Z-jet correlations

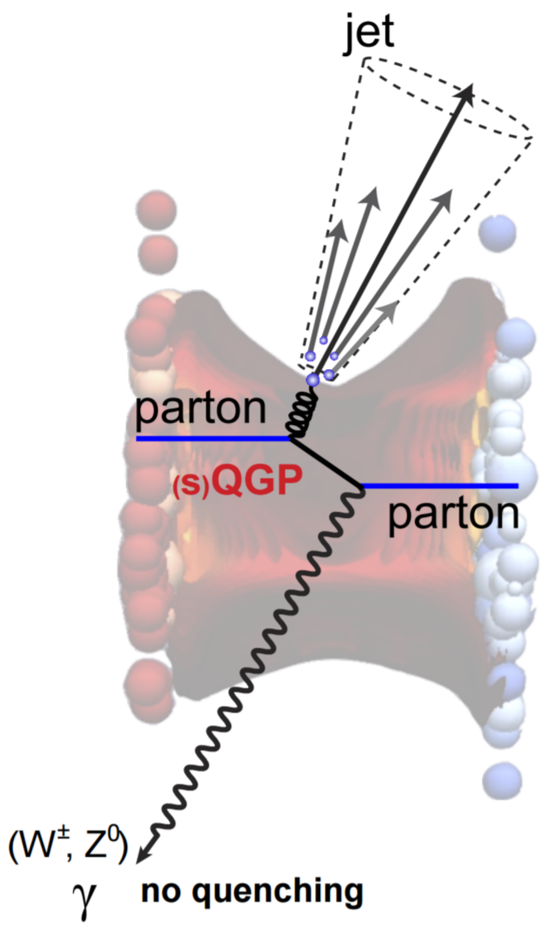


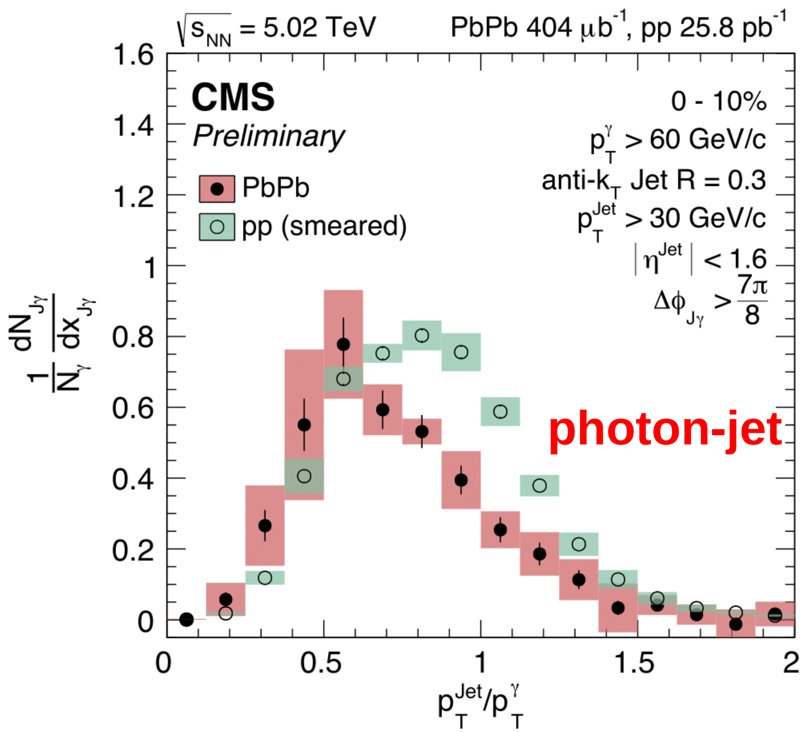

**Measured "absolute energy loss" (out of the jet cone) by comparing photon/Z and jet transverse momentum**

**γ, W, Z unaffected by the medium**

# Photon-jet and Z-jet correlations

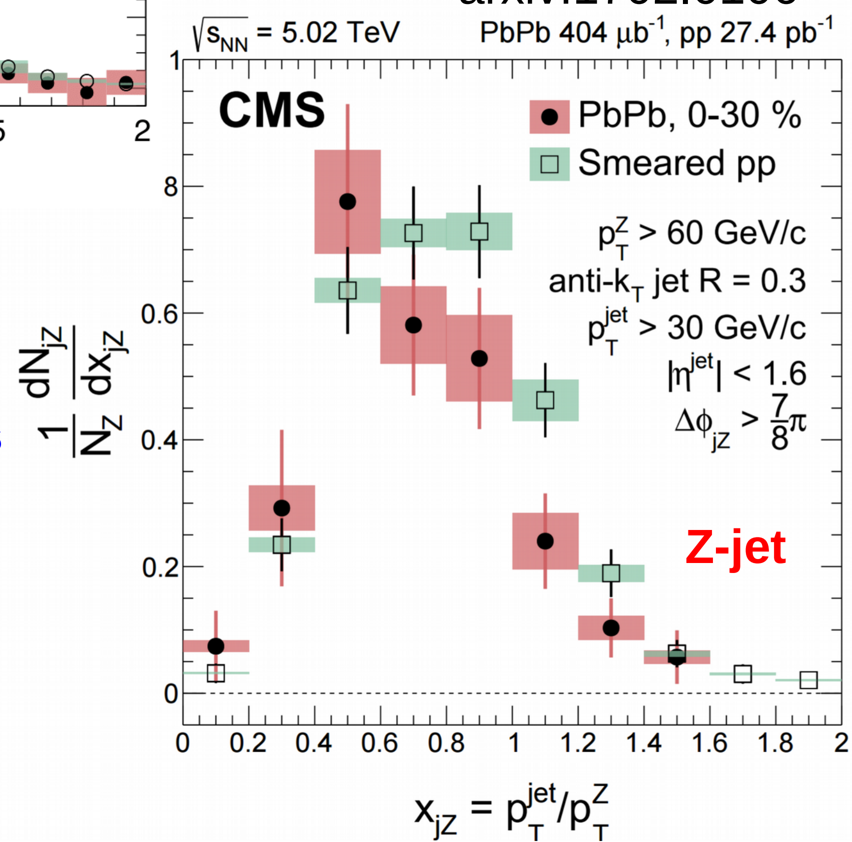



**γ, W, Z unaffected by the medium**



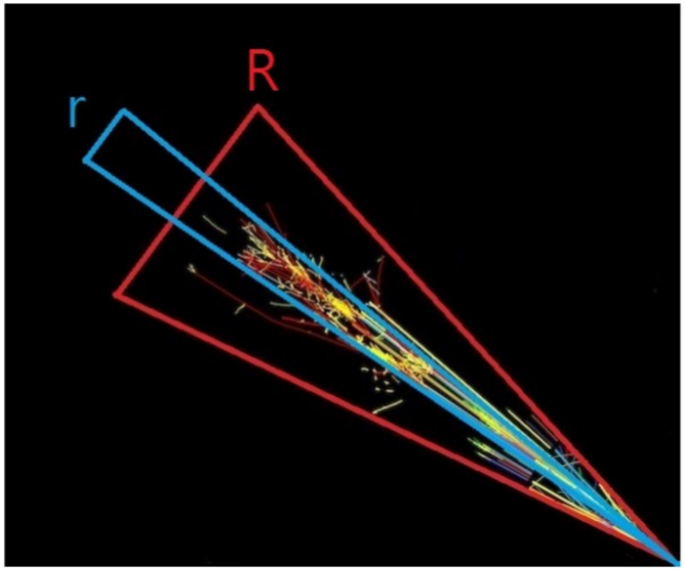

**Measured "absolute energy loss" (out of the jet cone) by comparing photon/Z and jet transverse momentum**

arxiv:1702.0106



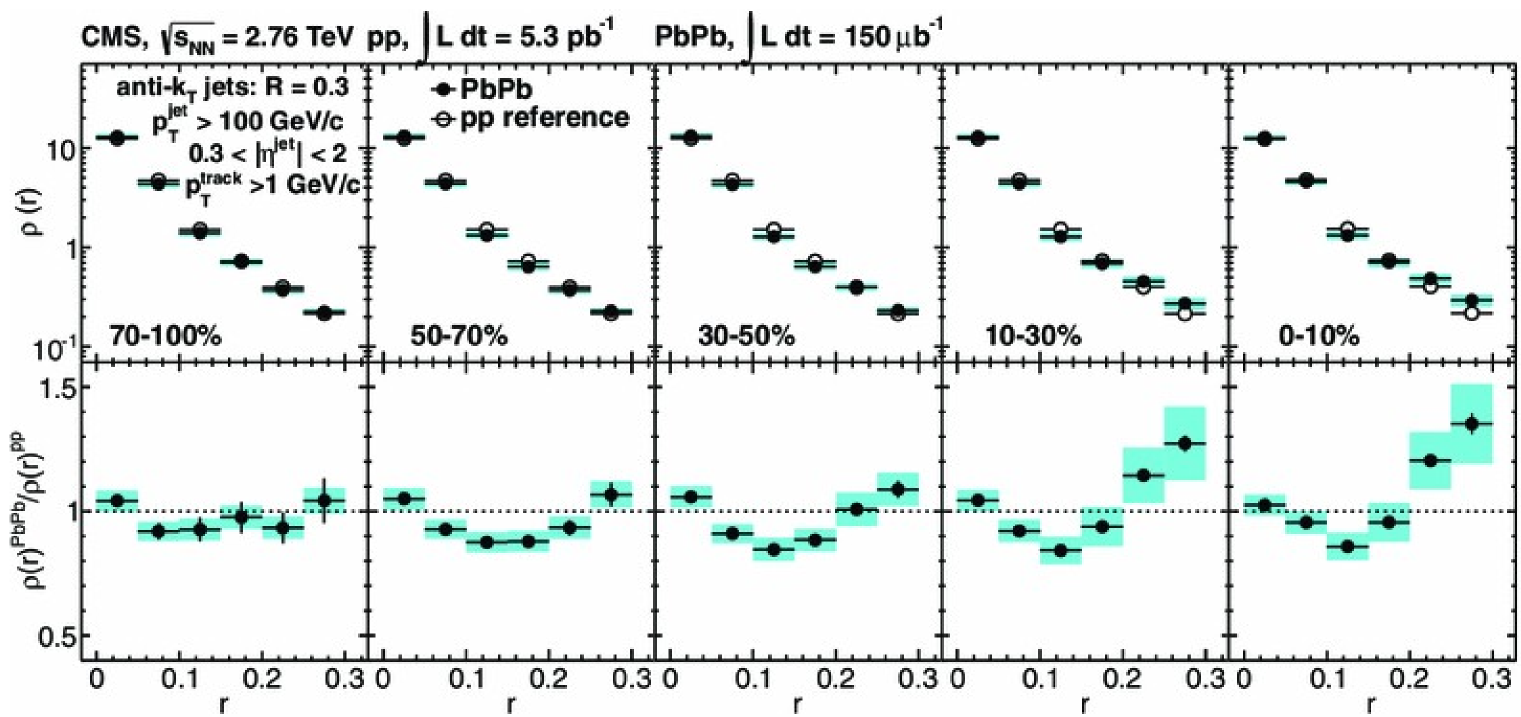

**First evidence of Z-Jet momentum imbalance, Consistent with results from photon-jet**

# Jet substructure




- Differential jet shape **ρ(r)** describes radial distribution of transverse momentum inside jet cone. It is measured in **r** slices.
- If we compare jet shape between pp and PbPb we can observe big differences for large radii in most central collisions.
- Details seen in the ratios. Deviations from 1 indicate modification of jet structure in QGP.
- Energy that the jets lose in the medium is redistributed at large distances from the jet axis

Arxiv 1310.0878



# Jet measurements

| Measurement | Colliding system | $\sqrt{s_{\mathrm{NN}}}$ (Tev) | R | Observables (variables) | Ref. |
|---|---|---|---|---|---|
| **ALICE** | | | | | |
| Charged jets | Pb–Pb | 2.76 | 0.2, 0.3 | yields($p_{\mathrm{T}}$,cent.), $R_{CP}(p_{\mathrm{T}})$, $R_{CP}$(cent.) | [209] |
| | | | 0.2 | $v_2^{\mathrm{chjet}}(p_{\mathrm{T}}$,cent.) | [63] |
| Charged + neutral jets | | | 0.2 | yields($p_{\mathrm{T}}$,cent.), $R_{\mathrm{AA}}(p_{\mathrm{T}}$,cent.) | [73] |
| Hadron-jet | | | 0.2, 0.4, 0.5 | $\Delta_{\mathrm{recoil}}$, $\Delta I_{\mathrm{AA}}$ | [210] |
| **CMS** | | | | | |
| Particle flow jets | Pb–Pb | 2.76 | 0.2, 0.3, 0.4 | yields($p_{\mathrm{T}}$,cent.), $R_{\mathrm{AA}}(p_{\mathrm{T}}$,cent.) | [211] |
| Dijets | | | 0.5 | Ev. frac. ($p_{\mathrm{T}}^{\text{leading jet}}$, $\Delta\phi_{1,2}$, $A_J$), $\left\langle p_T^{\parallel}\right\rangle(A_J$, cent., ΔR); $\langle(p_{T,1}-p_{T,2})/p_{T,1}\rangle(p_{\mathrm{T},1})$ | [76] |
| | | | 0.3 | Ev. frac. ($\Delta\phi_{1,2}$, $A_J$, $x_j = p_{T,2}/p_{T,1}$) $\langle p_{T,2}/p_{T,1}\rangle(p_{\mathrm{T},1})$ | [212] |
| | | | 0.2–0.5 | $\left\langle \not{p}_T^{\parallel}\right\rangle(\Delta, A_J)$ | [93] |
| Photon-jet | | | 0.3 | distribution of $x_{J\gamma} = p_T^{\mathrm{Jet}}/p_T^{\gamma}$ | [83] |
| Jet fragmentation | | | 0.3 | fragm. fun. $\xi = ln(1/z)$ ($p_{\mathrm{T}}$> 4 GeV/$c$) | [84] |
| | | | | fragm. fun. $\xi = ln(1/z)$ ($p_{\mathrm{T}}$> 1 GeV/$c$) | [85] |
| Jet shapes | | | 0.3 | $\rho(r)$ | [88] |
| Jet-track correlations | | | 0.3 | jet-track correlations ($p_{\mathrm{T}}$,$\Delta\eta$, $\Delta\phi$) | [91] |
| | | | 0.3 | redistribution of mom. in dijet events ($p_{\mathrm{T}}$,$\Delta\phi$) | [213] |
| **ATLAS** | | | | | |
| Inclusive jets | Pb–Pb | 2.76 | 0.2 | $R_{\mathrm{AA}}^{\mathrm{jet}}(p_{\mathrm{T}}$, $\lvert y\rvert$, cent.) | [70] |
| | | | | $v_2^{\mathrm{jet}}(p_{\mathrm{T}}$, cent.) | [40] |
| Dijets | | | 0.4 | distribution of $A_J$,$\Delta\phi$ | [214] |
| Jet size | | | 0.2 - 0.5 | $R_{CP}^{R}/R_{CP}^{0.2}(p_{\mathrm{T}})$ | [215] |
| Jet fragmentation | | | 0.4 | $D(z)$, $R_{D(z)}(z, p_T)$ | [216] |
| Neighbouring jets | | | 0.2, 0.3, 0.4 | $\mathrm{d}R_{\Delta R}/\mathrm{d}E_T^{\mathrm{nbr}}(E_T^{\mathrm{nbr}}$, cent.), $\rho_{R_{\Delta R}}(E_T^{\mathrm{nbr}}$, cent.) | [217] |

For references see:
Reviews in Physics 1 (2016) 172-194
https://arxiv.org/abs/1702.07231

# Energy Loss in QGP

- QGP: high density of quarks and gluons / color sources
- Traversing quark / gluon feels color fields
- Collisional energy loss
  - Elastic scatterings
  - Dominates at low momentum
- Radiative energy loss
  - Inelastic scatterings
  - Dominates at high momentum
  - Gluon bremsstrahlung

$$\Delta E = \Delta E_{coll} + \Delta E_{rad}$$

***How does medium achieve the suppression?***

# Radiative Energy Loss

***Short version of extensive formalizm***

- BDPMS formalism
  - Baier, Dokshitzer, Mueller, Peigné, Schiff
  - Infinite energy limit
  - Static medium

$$\Delta E \sim \alpha_S C_R \hat{q} L^2$$

**L path length, driven by:**
- **gluon-gluon self interactions**
- **quantum interference**

- Energy loss depends on
  - Path length through medium **squared**
  - Casimir factor
    - $C_R$ = 4/3 (quarks)
    - $C_R$ = 3 (gluons)
  - Medium parameter "q hat"

$$\hat{q} = \frac{\mu^2}{\lambda}$$

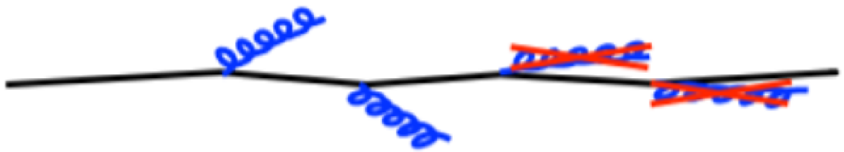
$\mu^2$ ← **average transverse momentum transfer**

$\lambda$ ← **mean free path**

Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291

# Dead Cone Effect

- Due to kinematical constraints, gluon radiation in vacuum suppressed for angles $\theta < m/E = 1/\gamma$ by $\left(1 + \frac{m/E}{\theta}\right)^2$
  - Massless parton m = 0 → no suppression



- Similar effect in the medium
  - Significant for charm and beauty
  - Radiative energy loss reduced by 25% (c) and 75% (b) [$\mu$ = 1 GeV/$c^2$]
- Implies quark mass dependence

$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$

# Collisional Energy Loss

- For light quarks and gluons

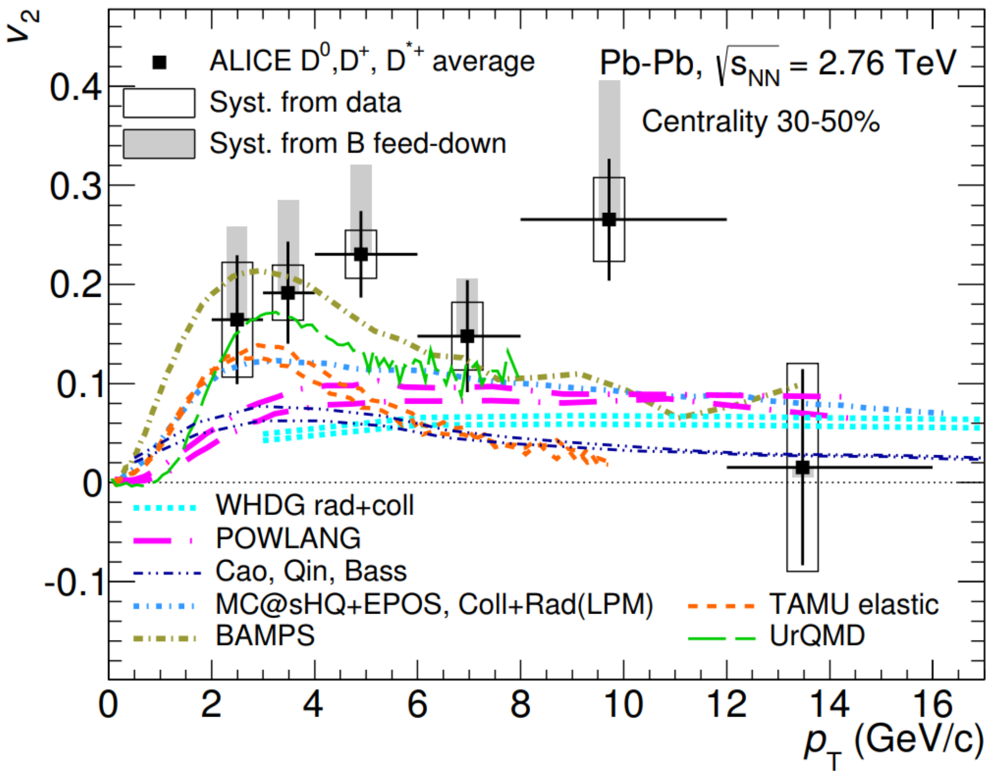
$$\Delta E_{q,g} \sim \alpha_S \, C_R \, \mu^2 \, L \ln \frac{ET}{\mu^2}$$

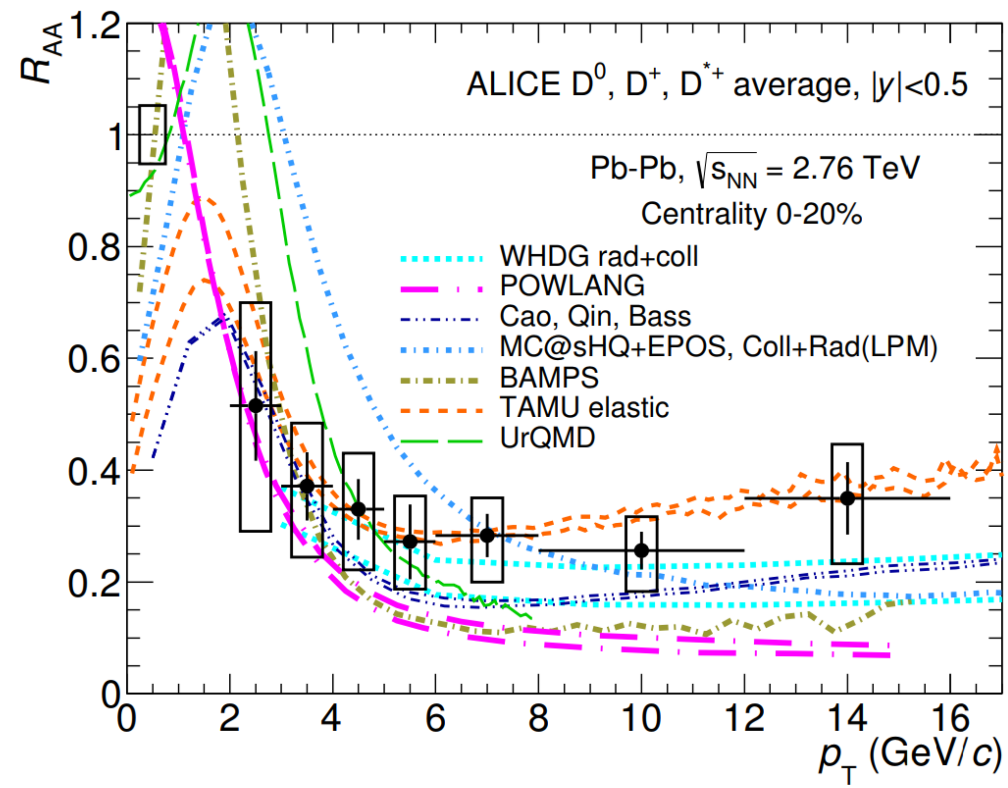
- For heavy quarks additional term

$$\alpha_s^2 T^2 \, C_R \, \mu^2 \, L \ln \frac{ET}{M^2}$$

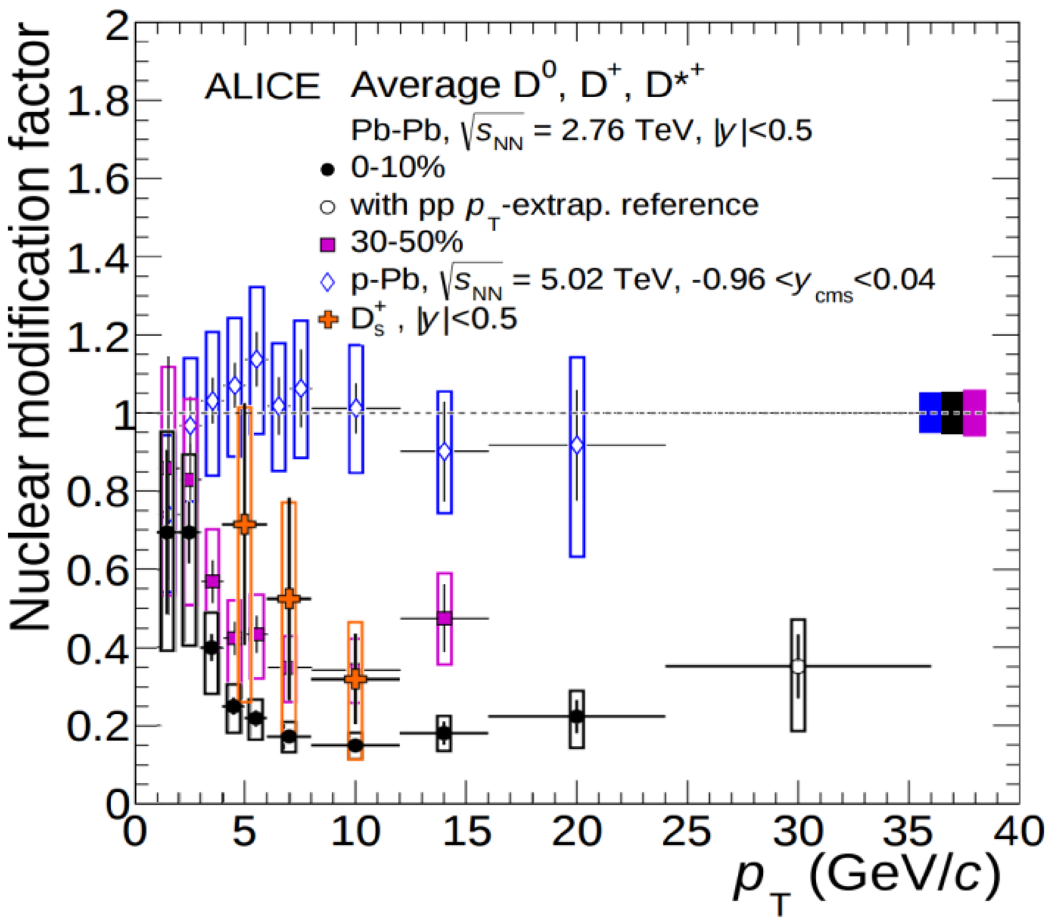
- Energy loss depends on
  - Path length through medium **linear**
  - Parton type (light or heavy)
  - Temperature T
  - Mass of heavy quark M
  - Medium parameter μ (average transverse momentum transfer)

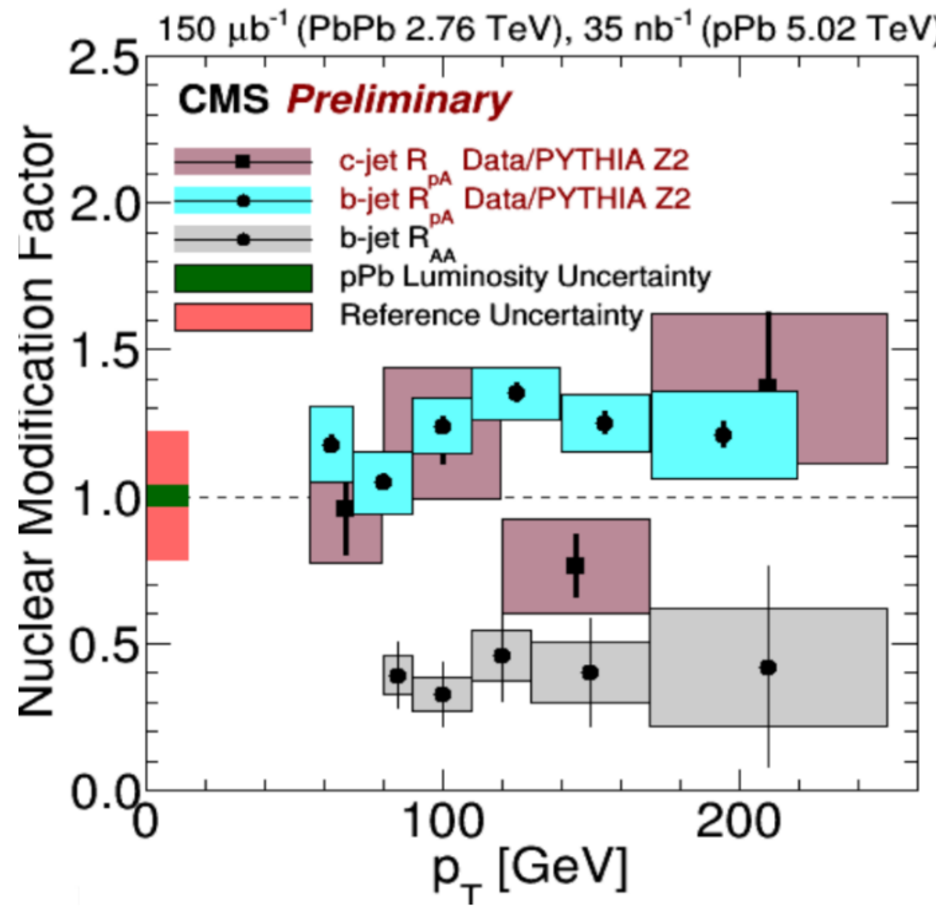
# Comparisons with theory



# Heavy Partons



# Summary

- Energy loss occurs by radiative and collisional processes
- Theoretical calculations extract medium properties like density, average momentum transfer, mean free path, $\hat{q}$
- We have seen significantly suppression of charged hadron spectra
  - Dominated by light quarks / gluons
- Calculations more accurate for heavy quarks
- Dependence of energy loss on quark mass expected

Expectation $R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$

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**A dense strongly coupling medium is produced in HI collisions**

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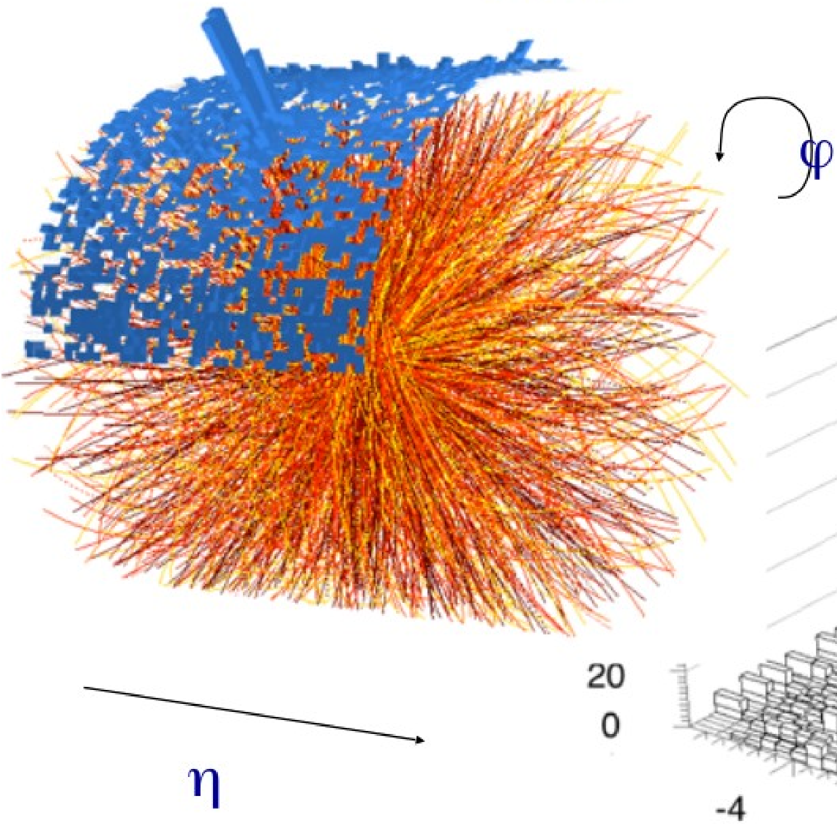
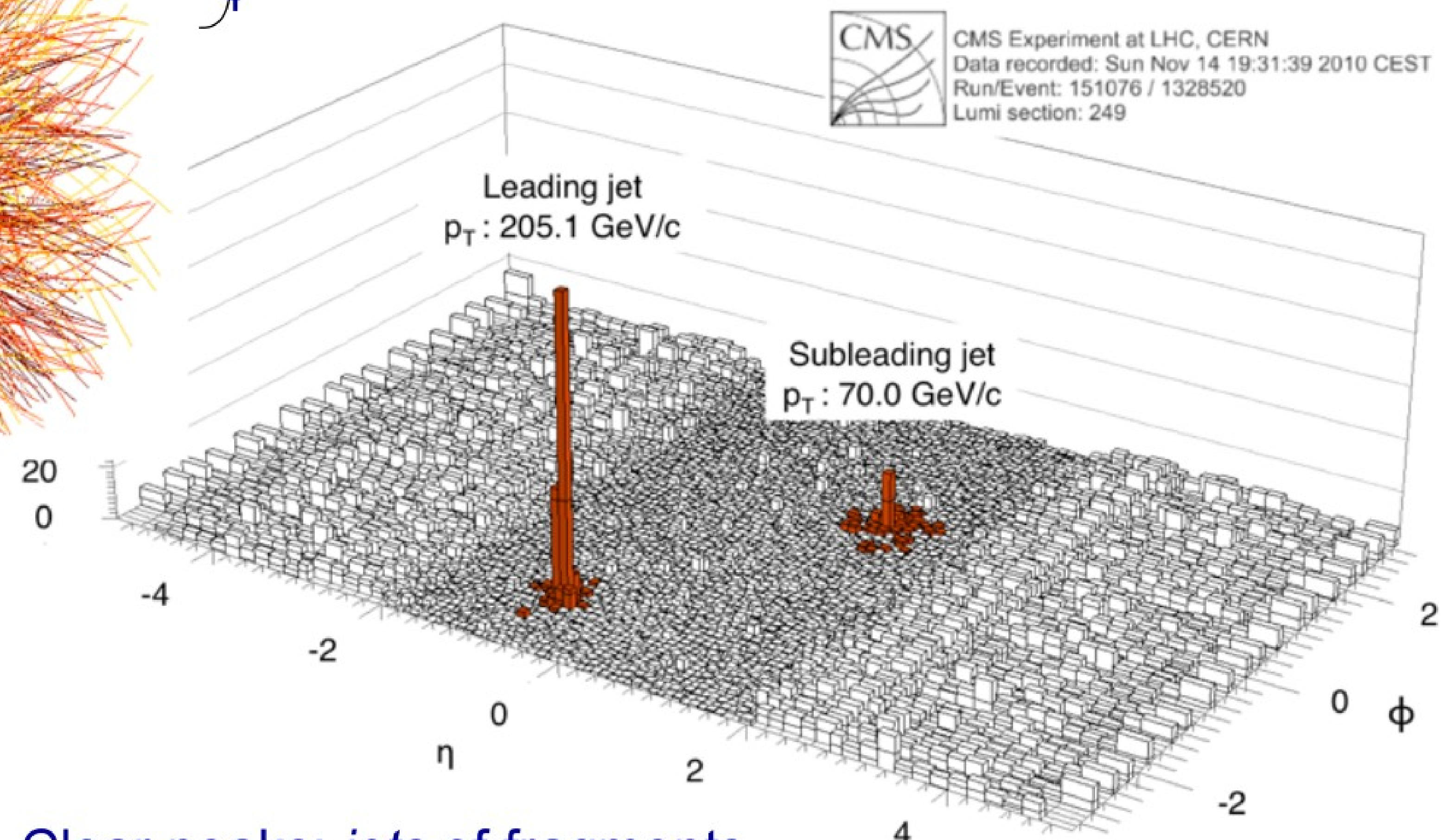
# Backup

# Jets at LHC




**Transverse energy map of 1 event**




Clear peaks: *jets* of fragments from high-energy quarks and gluons

And a lot of uncorrelated 'soft' background