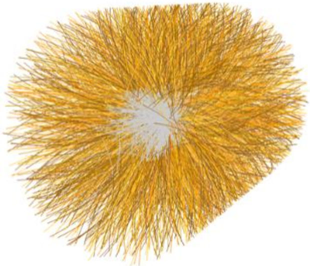


Introduction to Heavy-Ion Physics
Part I

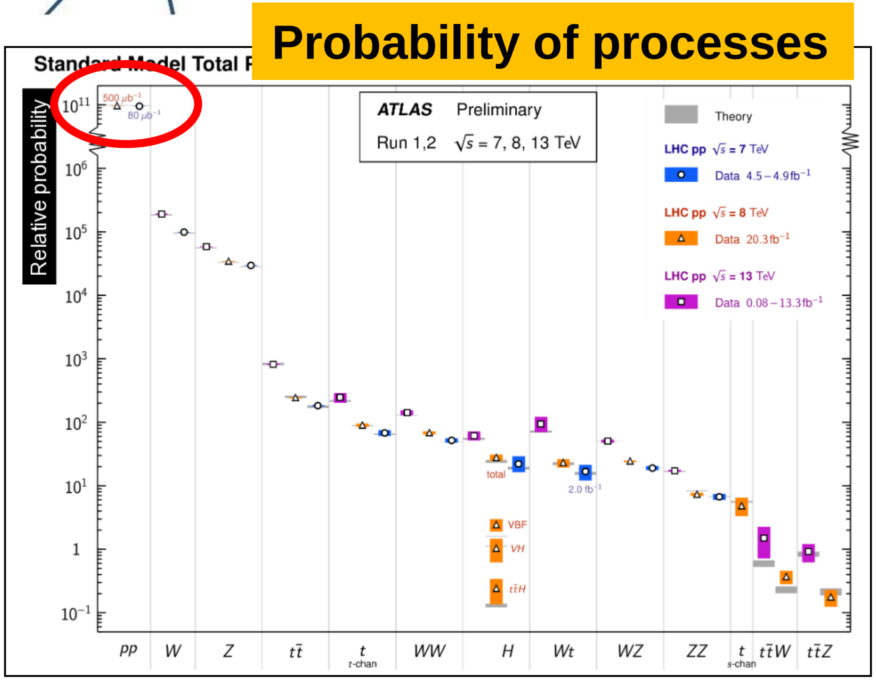
Jan Fiete Grosse-Oetringhaus, CERN

Summer Student Lectures 2018

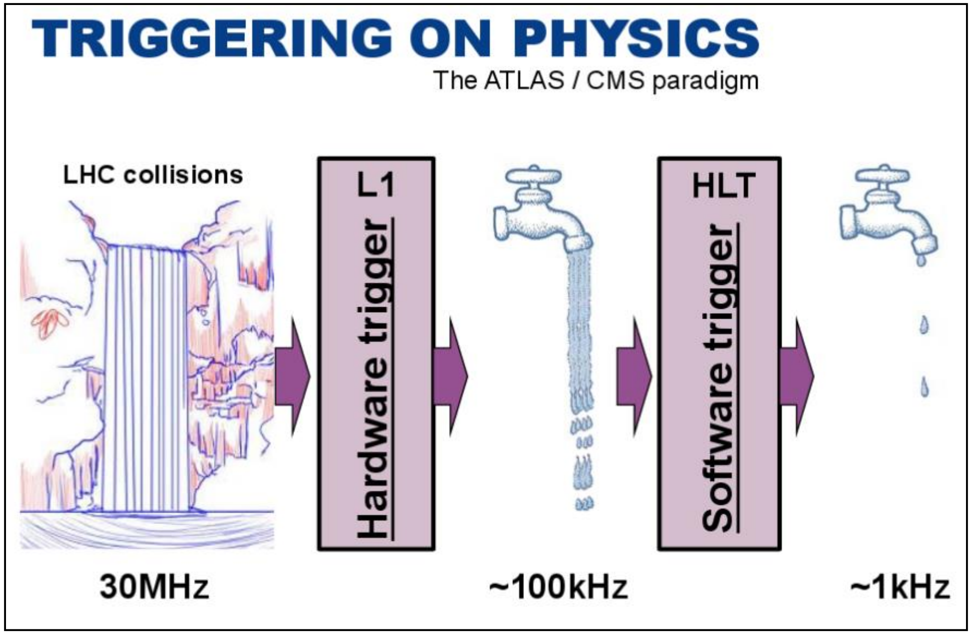
What is Heavy-Ion Physics?

- A way to study QCD
… without confinement
… with quarks at their bare masses
- A way to study matter
… at energy densities like 10 μs after the Big Bang
… at temperatures 10^5 times larger than in the sun core

Motivation


Probability of processes

shown by Tara Shears, Particle World



from Anna Sfyrla – from Raw Data to Physics Results

- Most searched for signals at the LHC are rare
- Triggers select very small fraction of all collision events

Today we discuss about the rest – the bulk of all LHC collisions

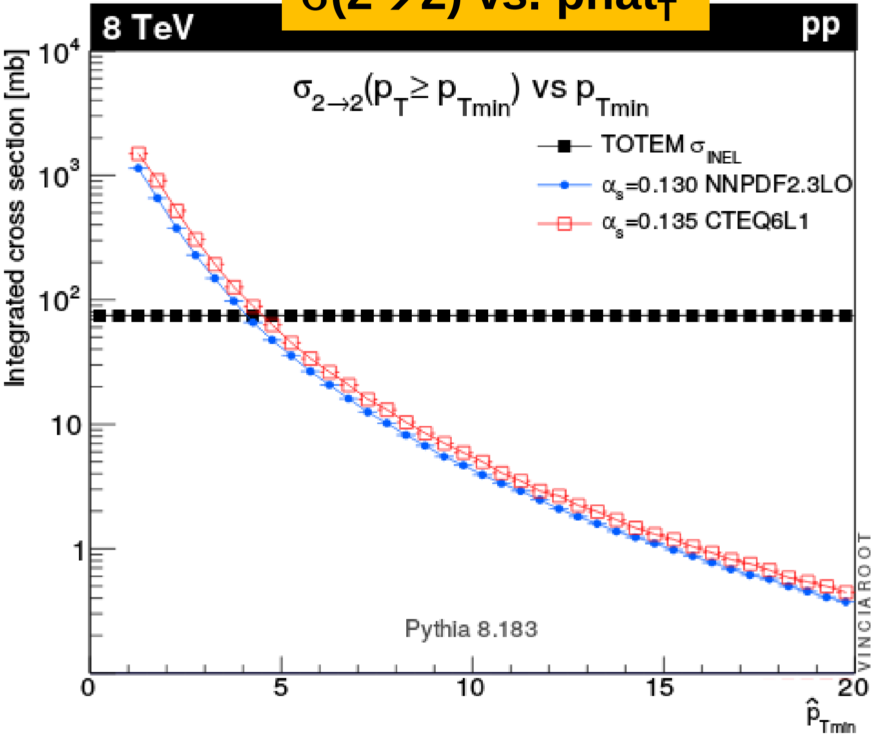
Bulk of LHC Physics

The bulk is…

… soft (small momentum transfer)

… governed by strong interaction

… in the non-perturbative regime



σ(2→2) vs. phat$_T$

Skands, Carrazza, Rojo, arXiv:1404.5630

This lecture discusses how heavy-ion physics helps the understanding of QCD in the non-perturbative regime

Strong-Interaction Physics

- Strong interaction
  - binds quarks into hadrons
  - binds protons and neutrons into nuclei
- QCD is a very successful theory…

  e.g. for jet production at high p_T and heavy-flavour production

… with some open puzzles

Confinement

Impossible to find an isolated quark or gluon

Why?

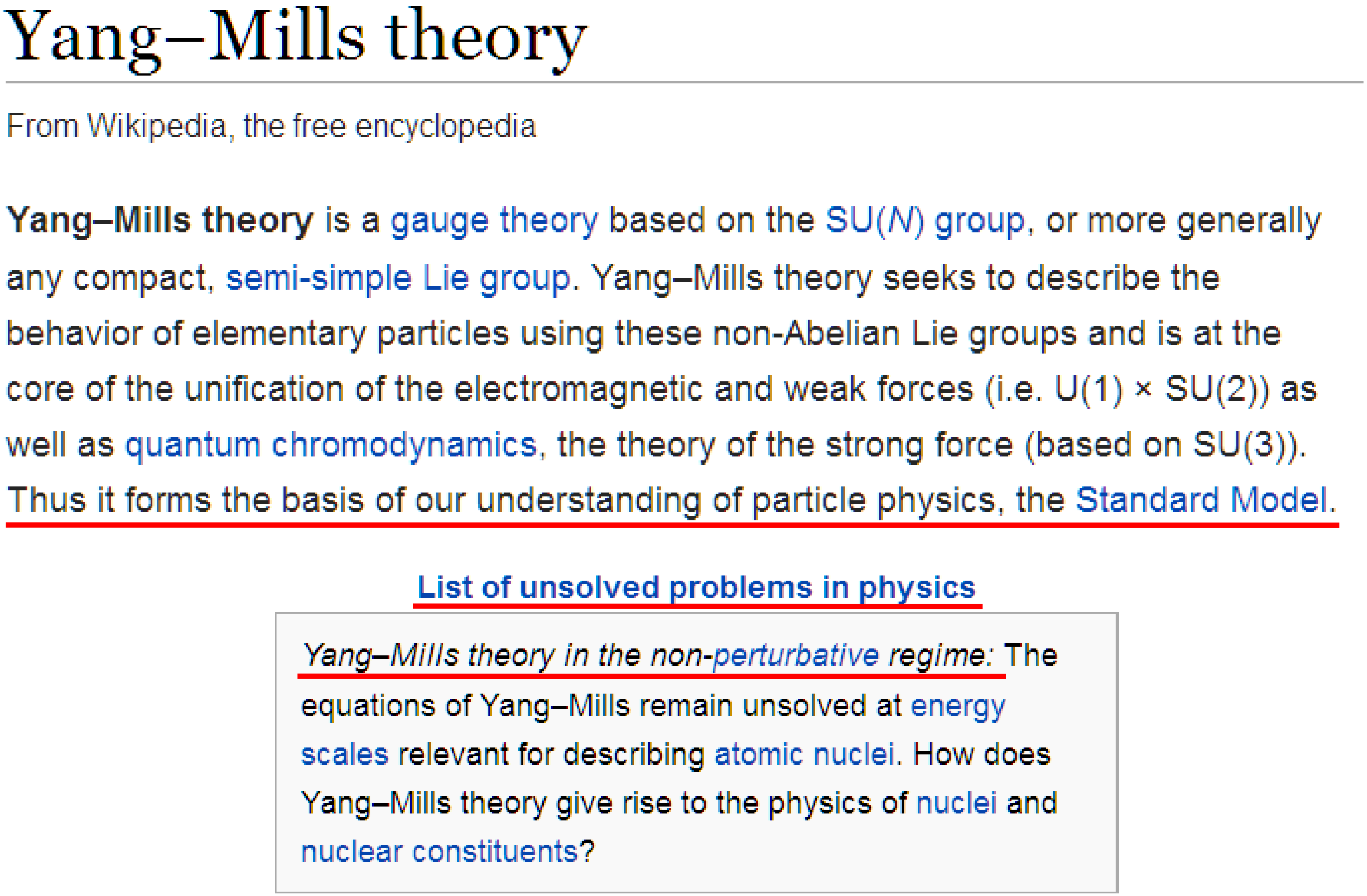
Hadron Masses

Proton consists of 2 u and 1 d quark
m_p = 938 MeV != ~10 MeV = m_{uud}

Where is the extra mass generated?

in a regime where perturbative methods are not applicable … unfortunately !

Fundamental Questions



Yang–Mills theory

From Wikipedia, the free encyclopedia

Yang–Mills theory is a gauge theory based on the SU(*N*) group, or more generally any compact, semi-simple Lie group. Yang–Mills theory seeks to describe the behavior of elementary particles using these non-Abelian Lie groups and is at the core of the unification of the electromagnetic and weak forces (i.e. U(1) × SU(2)) as well as quantum chromodynamics, the theory of the strong force (based on SU(3)). Thus it forms the basis of our understanding of particle physics, the Standard Model.

List of unsolved problems in physics

Yang–Mills theory in the non-perturbative regime: The equations of Yang–Mills remain unsolved at energy scales relevant for describing atomic nuclei. How does Yang–Mills theory give rise to the physics of nuclei and nuclear constituents?

https://en.wikipedia.org/wiki/Yang%E2%80%93Mills_theory

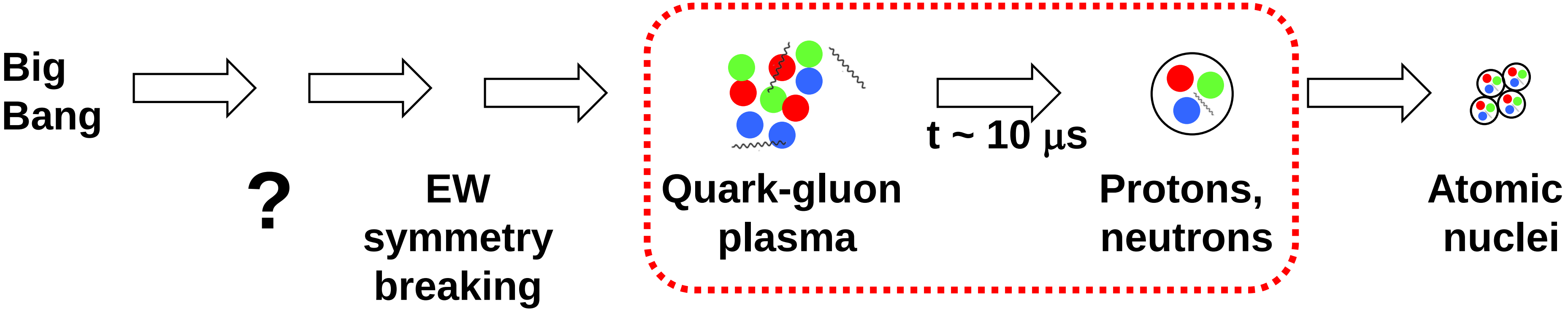
Fundamental Questions (2)

- How do “free” quarks and gluons behave?
- How do quarks and gluons behave when chiral symmetry is restored?
- What generates the constituent masses?

- In the early universe a phase with free quarks and gluons and restored chiral symmetry has existed
  - *Quark-gluon plasma* (QGP)
  - Recreate in the laboratory with heavy-ion collisions

- How does matter behave at very large densities and temperatures?

Big Bang



Big Bang

?

EW symmetry breaking

Quark-gluon plasma

t ~ 10 μs

Protons, neutrons

Atomic nuclei

Basic Concepts

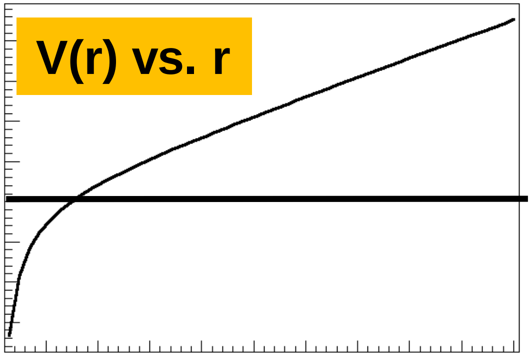
Confinement

- QCD vacuum
  - Gluon-gluon self-interaction (non-abelian)
  - QCD field lines compressed in flux tube
- Potential grows linearly with distance

$$V(r) = -\frac{\alpha}{r} + \sigma r$$

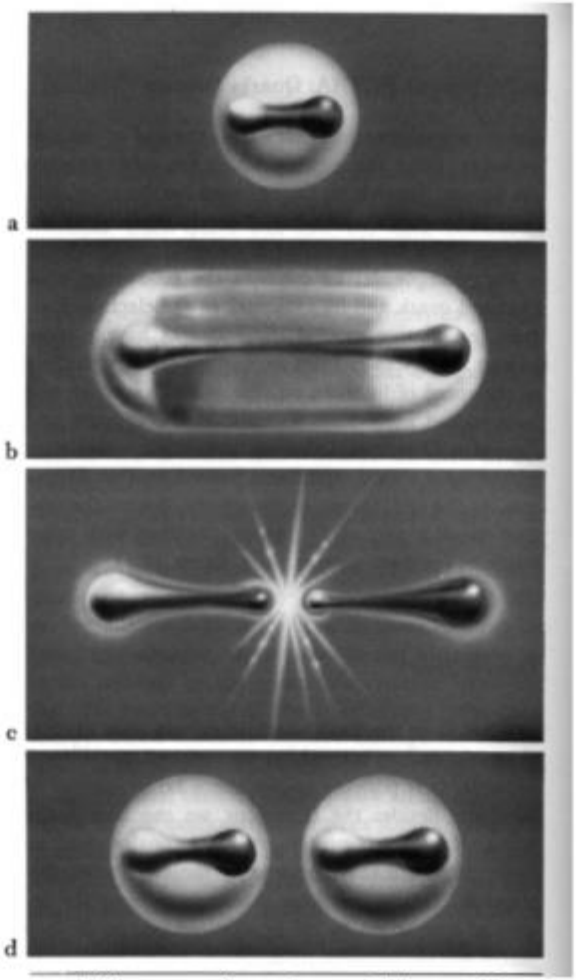
qqg part
“Coulomb”-like

gg part



- Pulled apart, energy in string increases
- New q-qbar pair is created once energy is above production threshold

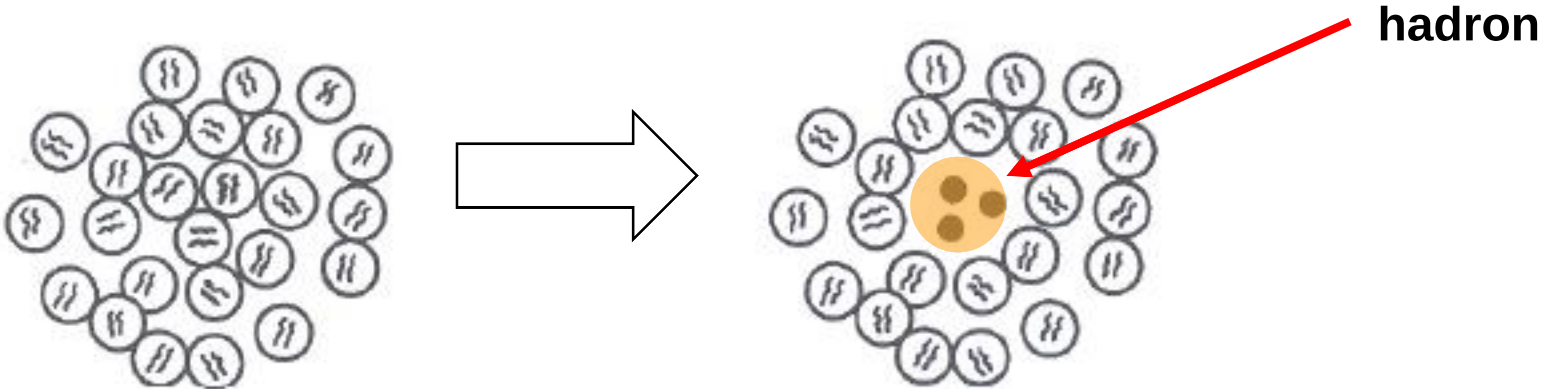
No free quark can be obtained → confinement



[illustration from Fritzsch]

Phenomenology of Confinement

- QCD vacuum can be seen as liquid of gluon-gluon pairs
- Why does this create confinement?
- *MIT bag model* : hadrons are confined in bubbles of perturbative (= empty) vacuum
  - Surrounded by QCD vacuum exerting pressure



PRD9, 3471 (1974)

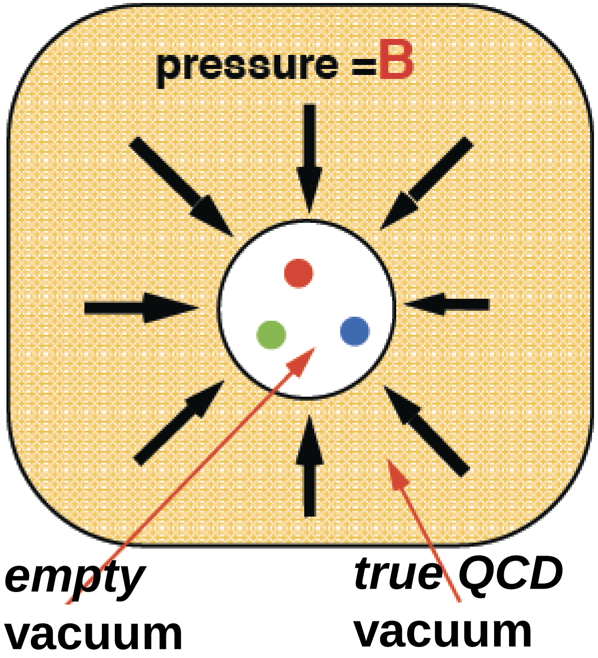
Bag Model

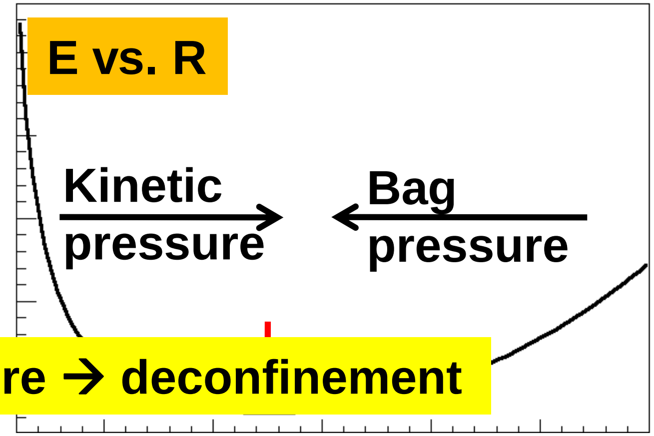
- Quarks in bubble → kinetic pressure
- QCD vacuum → bag pressure
- Bag pressure = phenomenological quantity for non-perturbative effects of QCD
- Massless fermions in spherical cavity

$$E = \frac{2.04N}{R} + \frac{4\pi}{3}R^3 B$$

N quarks
R radius
B bag pressure

- Equilibrium defines bag radius
- Proton radius (~0.8 fm)
  → $B^{1/4}$ ~ 206 MeV





If kinetic pressure exceeds bag pressure → deconfinement

PRD9, 3471 (1974)

Bag Model (2)

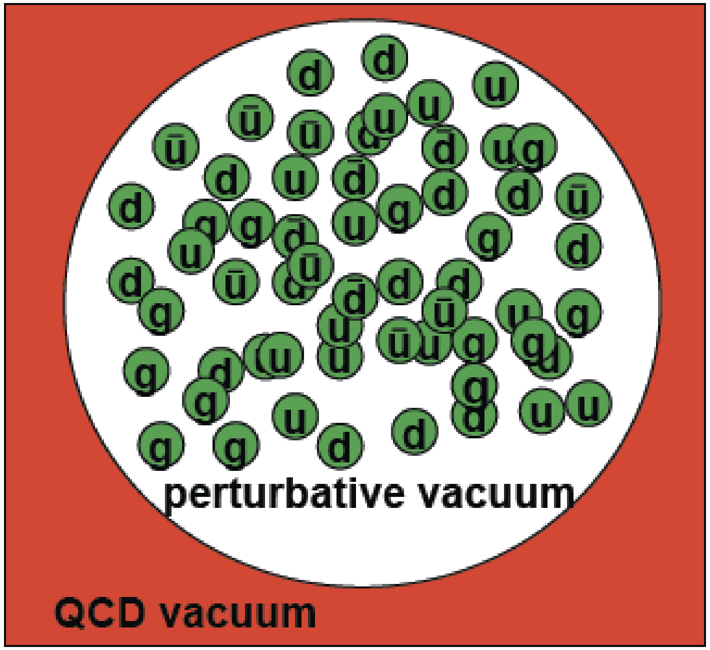
- If kinetic pressure exceeds bag pressure → deconfinement
- Relativistic massless quark gas

$$p = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

$$g_B = 16 \quad g_F = 24$$

8 gluons x 2 spins

2 quarks x 2 spins x 3 colors + antiquarks



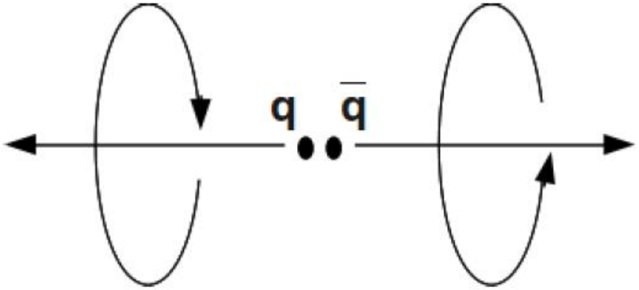
- Pressure exceeds bag pressure (p > B) at T_C ~ 144 MeV
  - Quark-gluon plasma above T_C

→ **More thorough estimate of the phase transition temperature can be done with lattice QCD → T_C ~ 156 MeV**

Chiral Symmetry

- QCD Lagrangian symmetric under $SU(2)_L \times SU(2)_R$
- Light quarks have finite (small) bare masses
  - Explicit chiral symmetry breaking
- Creation of coherent q-qbar pairs in QCD vacuum (compare to cooper pairs in superconductivity)
  - Has a chiral charge
  - Not symmetric under $SU(2)_L \times SU(2)_R$

  → Spontaneous symmetry breaking (pseudo-goldstone bosons: pions)



$\Sigma p = 0$ $\Sigma L = 0$
→ chirality != 0

- Quarks acquire ~350 MeV additional mass
  - *Constituent mass*
  - Relevant only for u, d, s

Spontaneous Breaking of Chiral Symmetry

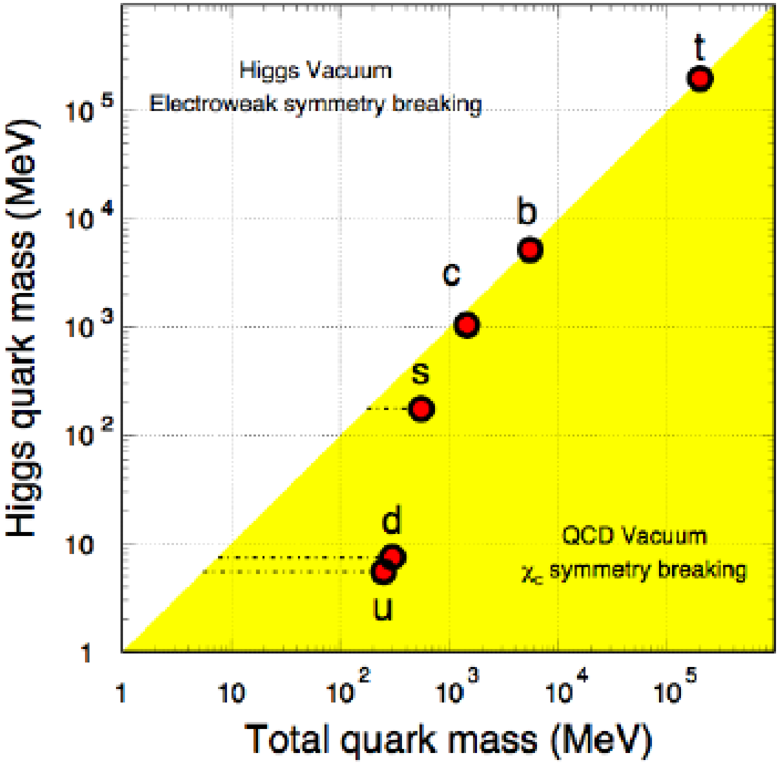
- Consequences
  - m(u) $\approx$ m(d) → isospin symmetry

Isospin symmetry is not based on a fundamental relation, but an 'accident' because acquired masses are much larger than bare masses

- m(p) >> m(bare 2u+1d)
  938 MeV >> 10 MeV

- In the QGP, spontaneous chiral symmetry breaking is expected to be restored (*partial restoration*)

Bare vs. constituent mass



X.Zhu et al., PLB 647 (2007) 366

Two Phase Transitions

- Spontaneous breaking of chiral symmetry
  - Present below T_{SSB} (~170 MeV, lattice QCD)
  - Quark masses enhanced to constituent masses
- Confinement/deconfinement transition
  - Confinement scale depends on quark masses

$\underline{T < T_{SSB}}$
Quarks: constituent masses

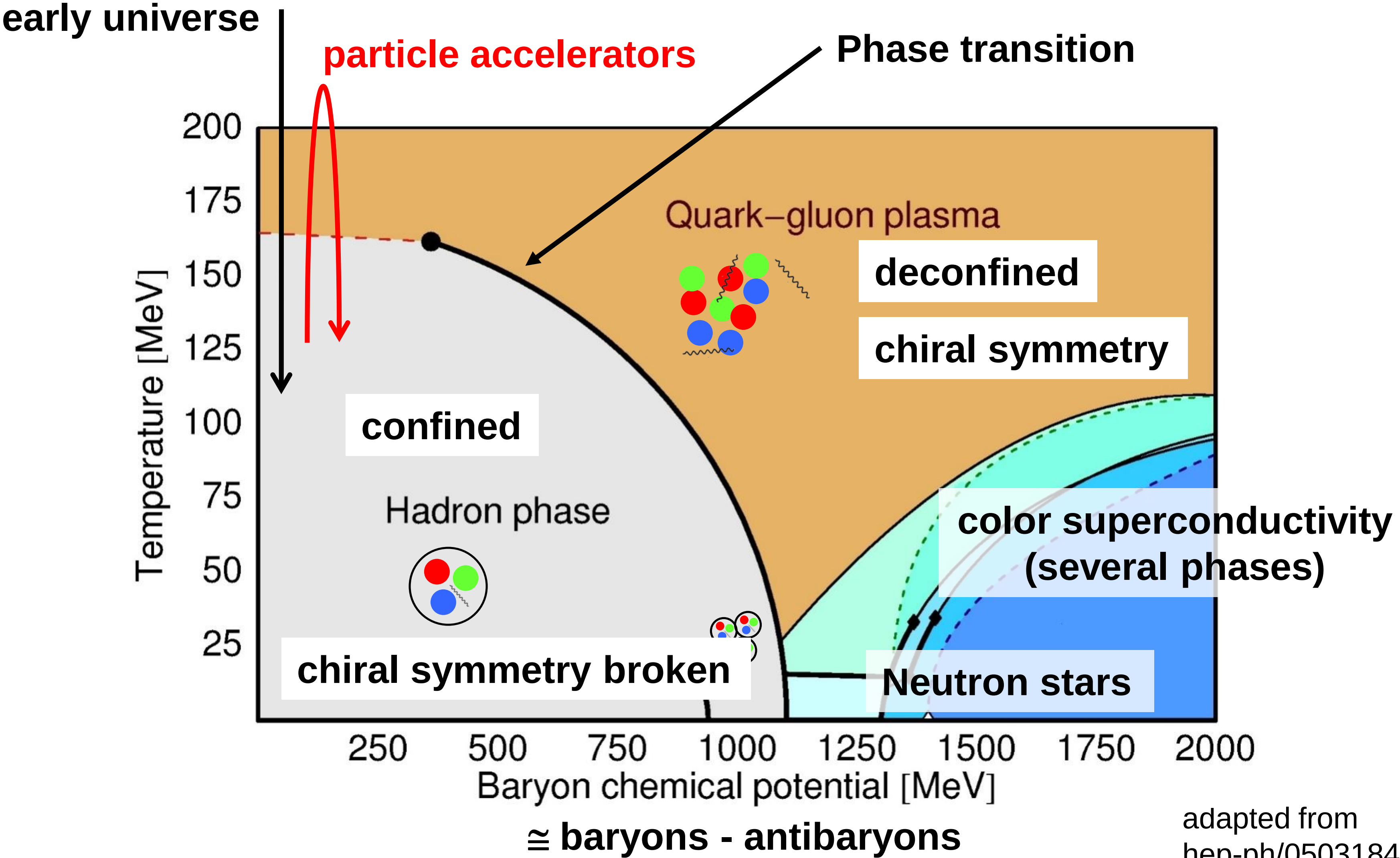
→ Confinement

$\underline{T > T_{SSB}}$
Quarks: bare masses

→ Deconfinement

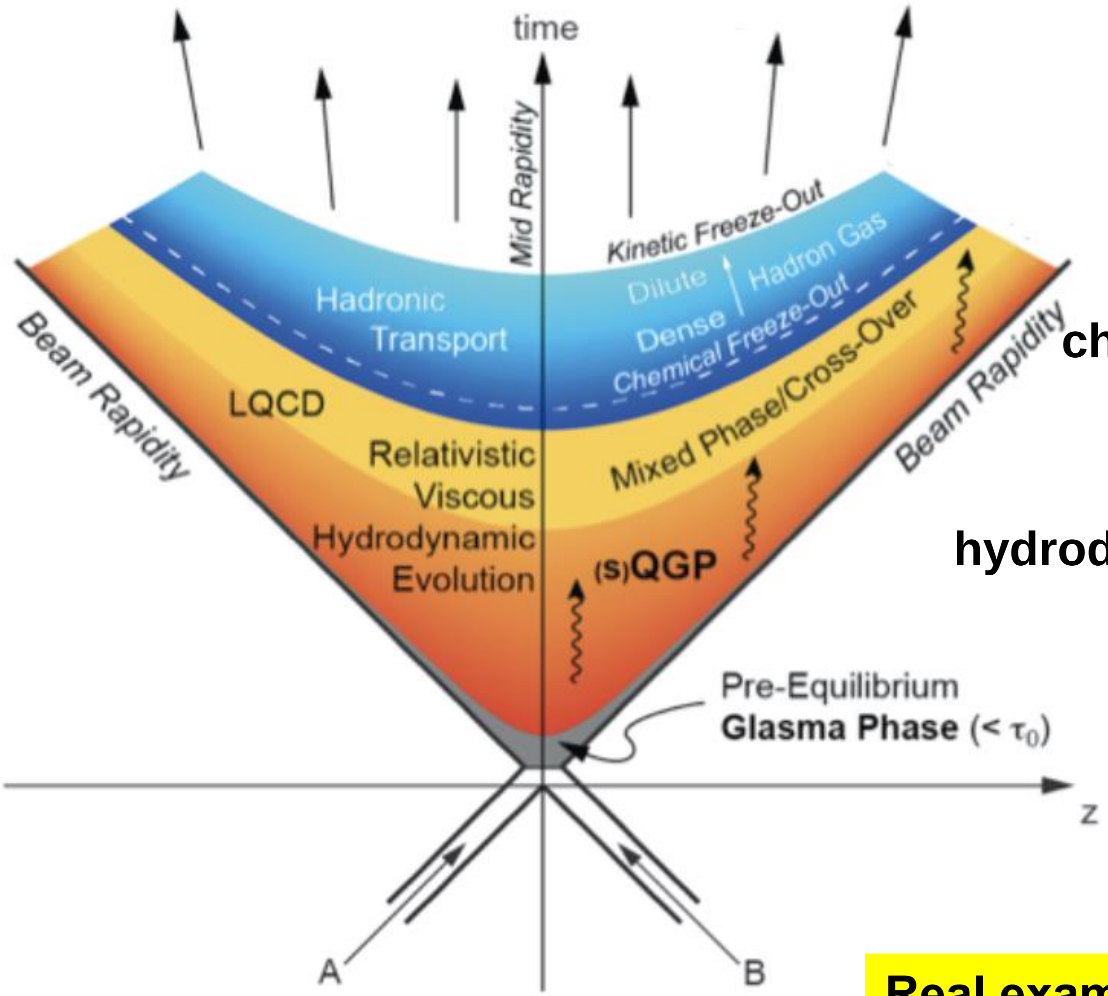
⚠ **Both phase transition occur at the same T**
(again an accident – not linked from first principles)

QCD Phase Diagram



adapted from
hep-ph/0503184

Phases Heavy-Ion Collision



Courtesy B.Hippolyte

Time

particle detection **t = 4 cm/c**

kinetic freeze-out **t = 10 fm/c**

chemical freeze-out
hadronization

hydrodynamic evolution

pre-equilibrium **t = ~1 fm/c**

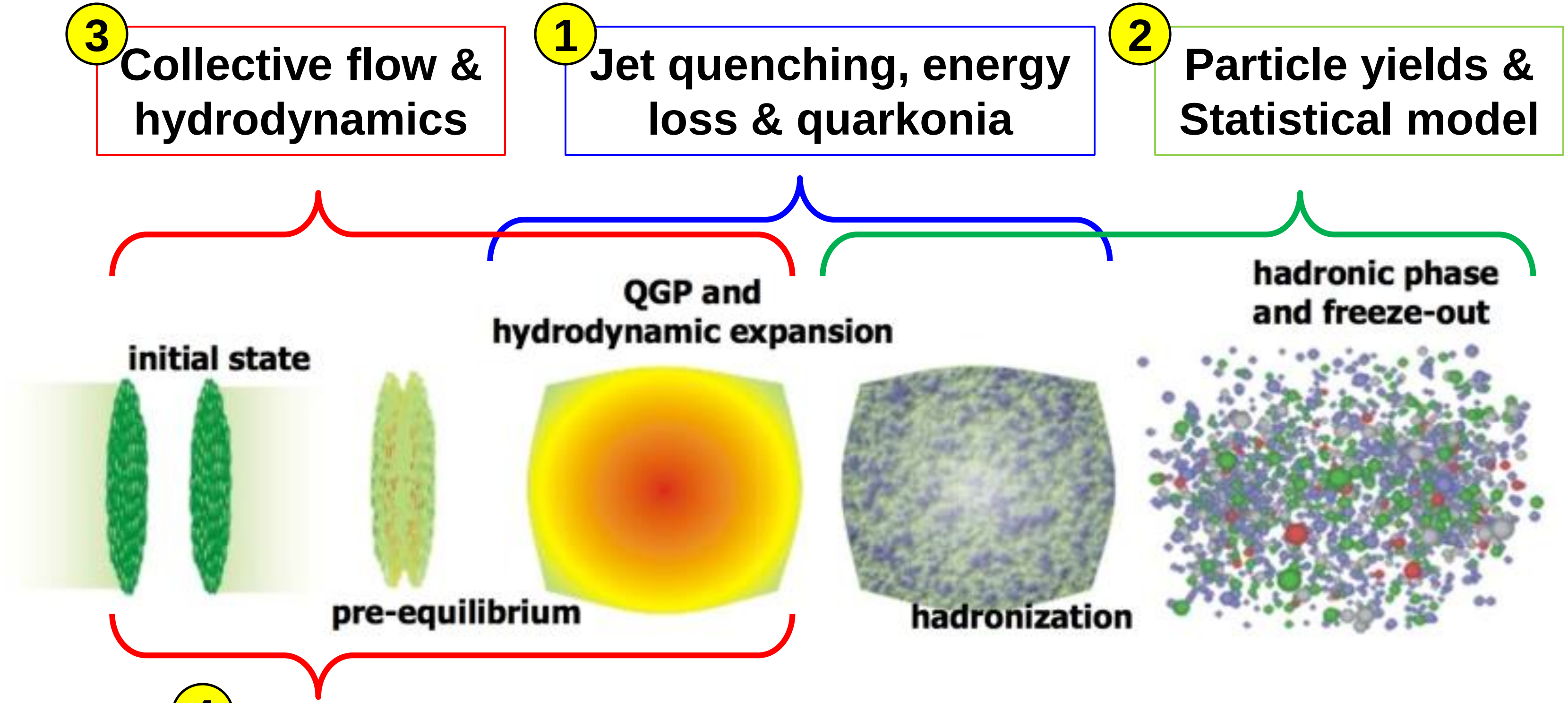
collision **t = 0 fm/c**

Real example…

1 fm/c = 3 · 10^{-24} s

Outline of the Lecture

- How to use a particle detector to learn about the QGP?
- This lecture will focus on the main topics



③ **Collective flow & hydrodynamics**

① **Jet quenching, energy loss & quarkonia**

② **Particle yields & Statistical model**

- And ④ **Collectivity in small systems** the currently *hottest* topic

Outline of the Lecture

what I have no time to cover…

Direct Photons

Femtoscopy

Nuclear Parton Distribution Functions

Collective flow & hydrodynamics

Jet quenching, energy loss & quarkonia

Particle yields & Statistical model

Jet Reconstruction

Global Event properties

Higher Moments

Dileptons

Jet Structure

Fragmentation Functions

Creating Heavy-Ion Beams

Ultra-peripheral collisions

Diffraction

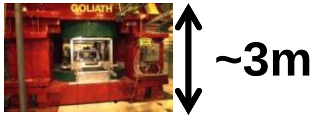
Collectivity in small systems

Heavy-Ion Experiments

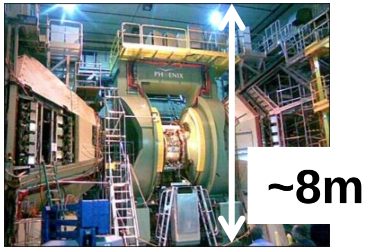
Accelerators

	SPS	RHIC	LHC
top $\sqrt{s_{NN}}$ (GeV)	17	200	5020 (5500)
Volume at freeze-out (fm^3)	1200	2300	5000
Energy density (GeV/fm^3)	3-4	4-7	10
Life time (fm/c)	4	7	10

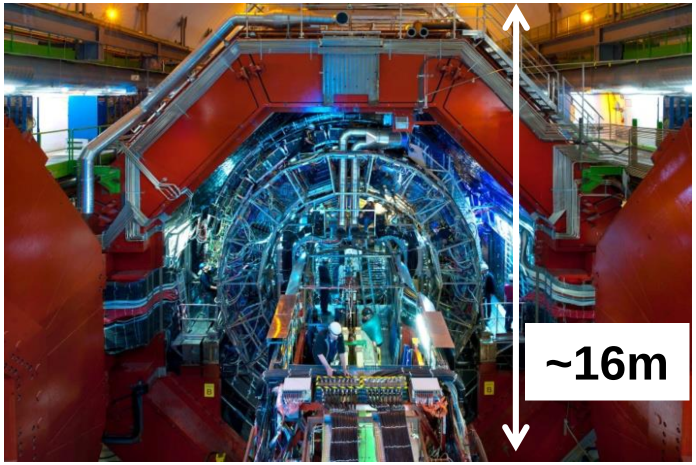
Heavy-ion collisions:
$\sqrt{s}$ given per nucleon pair ($\sqrt{s_{NN}}$)
$\sqrt{s_{NN}} = 5$ TeV → $\sqrt{s_{Pb\text{-}Pb}} = 1040$ TeV



NA57 (SPS)



PHENIX (RHIC)



ALICE (LHC)

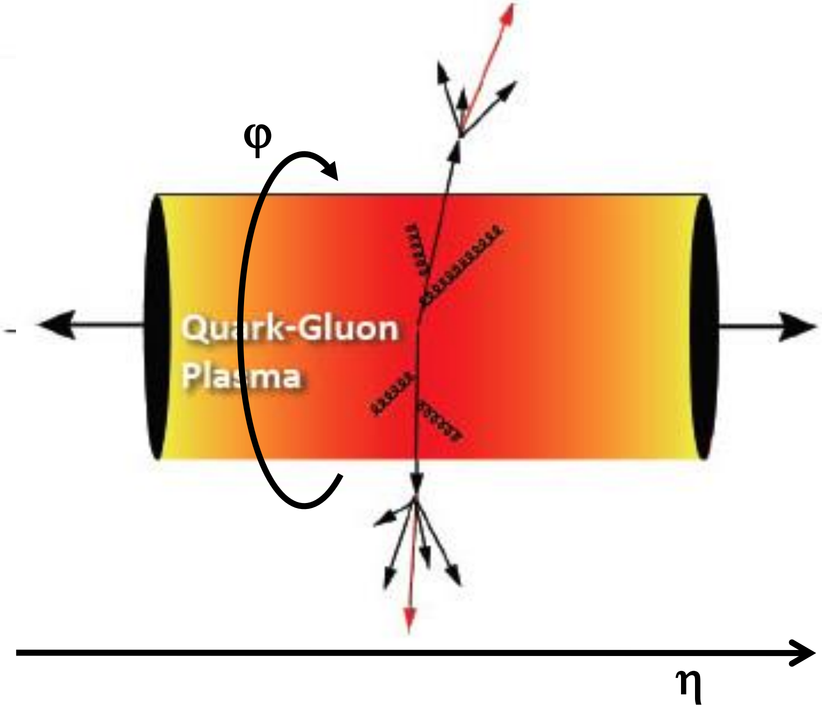
Literature

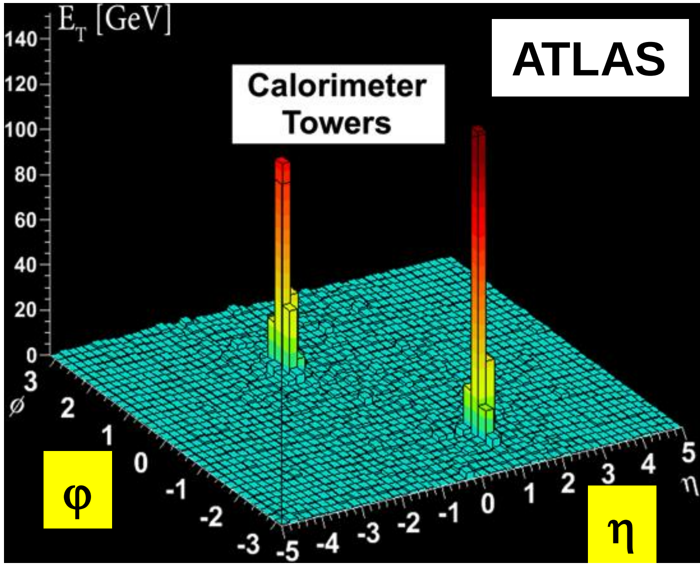
- Lectures
  - J. Stachel, K. Reygers (2011)
    http://www.physi.uni-heidelberg.de/~reygers/lectures/2011/qgp/qgp_lecture_ss2011.html
  - P. Braun-Munzinger, A. Andronic, T. Galatyuk (2012)
    http://web-docs.gsi.de/~andronic/intro_rhic2012/
  - Quark Matter Student Day (2014)
    https://indico.cern.ch/event/219436/timetable/#20140518.detailed
  - Quark Matter Student Day (2018)
    https://indico.cern.ch/event/656452/timetable/#20180513.detailed
- Books
  - C.Y. Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994
    http://books.google.de/books?id=Fnxvrdj2NOQC&printsec=frontcover
  - L. P. Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994 (**free as pdf**)
    http://www.csernai.no/Csernai-textbook.pdf
  - E. Shuryak, The QCD vacuum, hadrons, and superdense matter, World Scientific, 2004
    http://books.google.de/books?id=rbcQMK6a6ekC&printsec=frontcover
  - Yagi, Hatsuda, Miake, Quark-Gluon Plasma, Cambridge University Press, 2005
    http://books.google.de/books?id=C2bpxwUXJngC&printsec=frontcover
  - R. Vogt, Ultrarelativistic Heavy-ion Collisions, Elsevier, 2007
    http://books.google.de/books?id=F1P8WMESgkMC&printsec=frontcover
  - W. Florkowski, Phenomenology of Ultra-Relativistic Heavy-Ion Collisions, World Scientific, 2010
    http://books.google.de/books?id=4gIp05n9lz4C&printsec=frontcover
  - S. Sarkar, H. Satz and B. Sinha, The physics of the quark-gluon plasma, Lecture notes in physics, Volume 785, 2010 (**free within CERN/university network**)
    https://link.springer.com/book/10.1007%2F978-3-642-02286-9

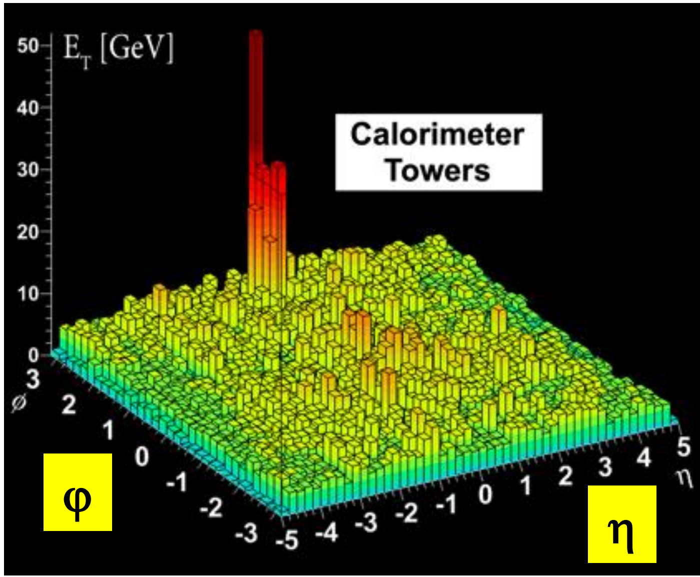
Jet Quenching
&
Energy Loss

How does a quark-gluon plasma
affect particles traversing it?

A Back-to-Back Jet







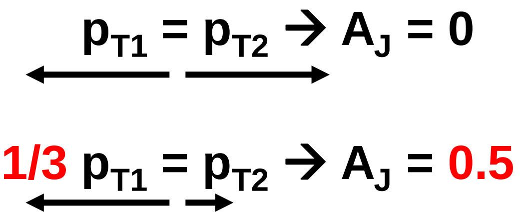
One jet disappears in the QGP
→ "Jet quenching"

ATLAS, PRL105:252303,2010
Drawing: A. Mischke

Dijet Asymmetry

- How often do jets lose lot of energy?
- Quantify by dijet asymmetry
- 2 highest energy jets with $\Delta\varphi > 2\pi/3$

$$A_J = \frac{\left|p_{T1} - p_{T2}\right|}{p_{T1} + p_{T2}}$$



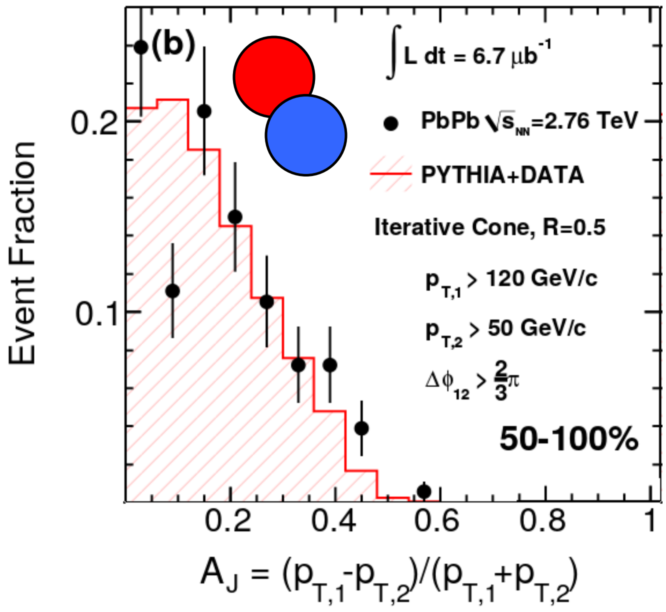
$p_{T1} = p_{T2} \rightarrow A_J = 0$

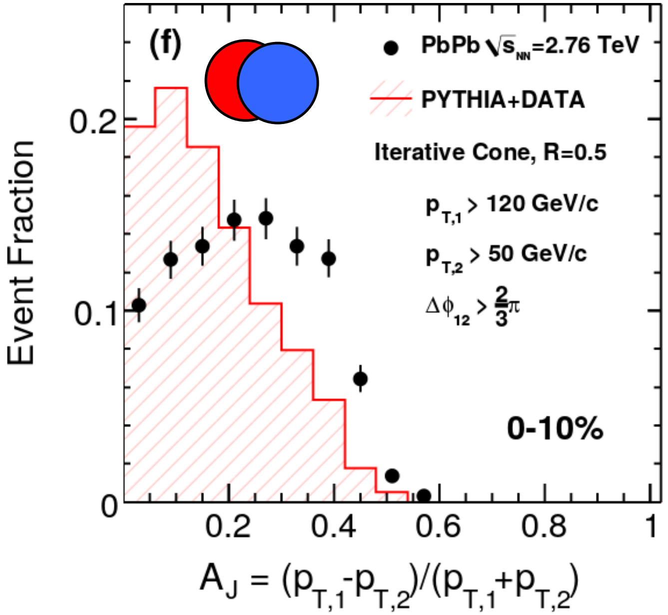
$\frac{1}{3} p_{T1} = p_{T2} \rightarrow A_J = 0.5$

- Peripheral collisions: Pb-Pb ~ Pythia
- Central collisions: Significant difference

Central / peripheral will be introduced soon

PRC 84 (2011) 024906
PRL105:252303,2010



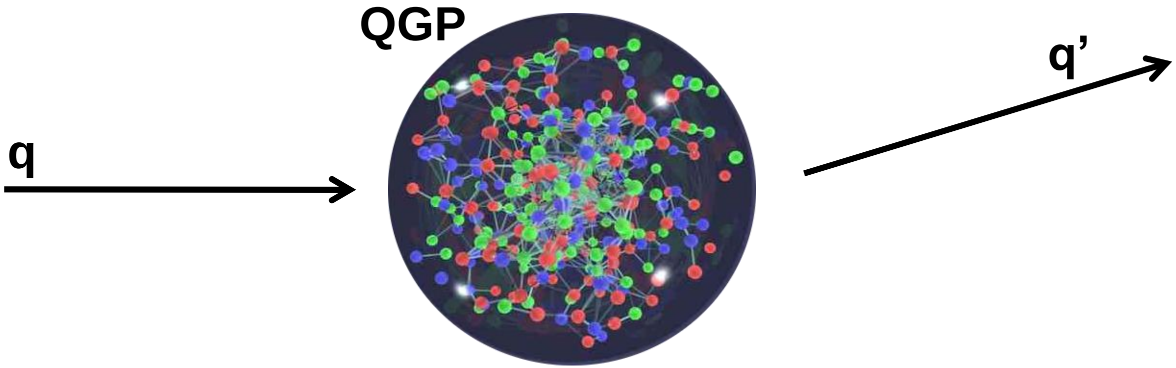


Jets lose up to two thirds of their energy !

Something significant happening
in heavy-ion collisions !

Hard Probes

- 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

Self-Generated Probes

- Produced early, before the plasma forms
  t ~ □ / 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

… as usual there is no such thing as a free lunch …

Per central LHC collision
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

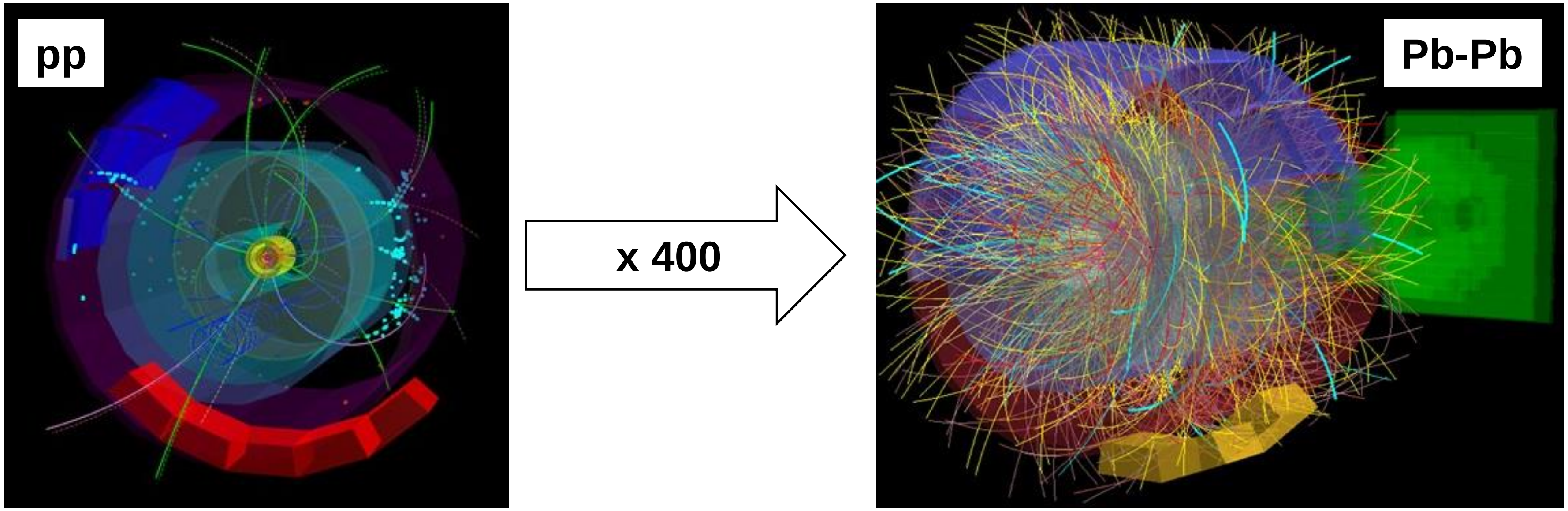
LHC Run 1 (~ 150/ub)
10^{8} D mesons (> 2 GeV/c)
10^{7} B mesons (> 10 GeV/c)
10^{5} jets above 100 GeV
120 jets above 400 GeV

⚠
Rec. efficiency, branching ratios factors ~ 1000

Heavy-Ion Environment

- Measurements in an environment with $dN_{ch}/d\eta$ up to 1600 ($\sqrt{s_{NN}}$ = 2.76 TeV)
  = 400 pp MB collisions = 1 event with 399 pile-up events
  (ATLAS/CMS reconstruct up to 100)
- In one collision, there are in the tracker acceptances
  - 3200 tracks in ALICE | 8000 tracks in CMS/ATLAS

for comparison
pp : $dN_{ch}/d\eta$ ~ 4



Probes Traverse the QGP

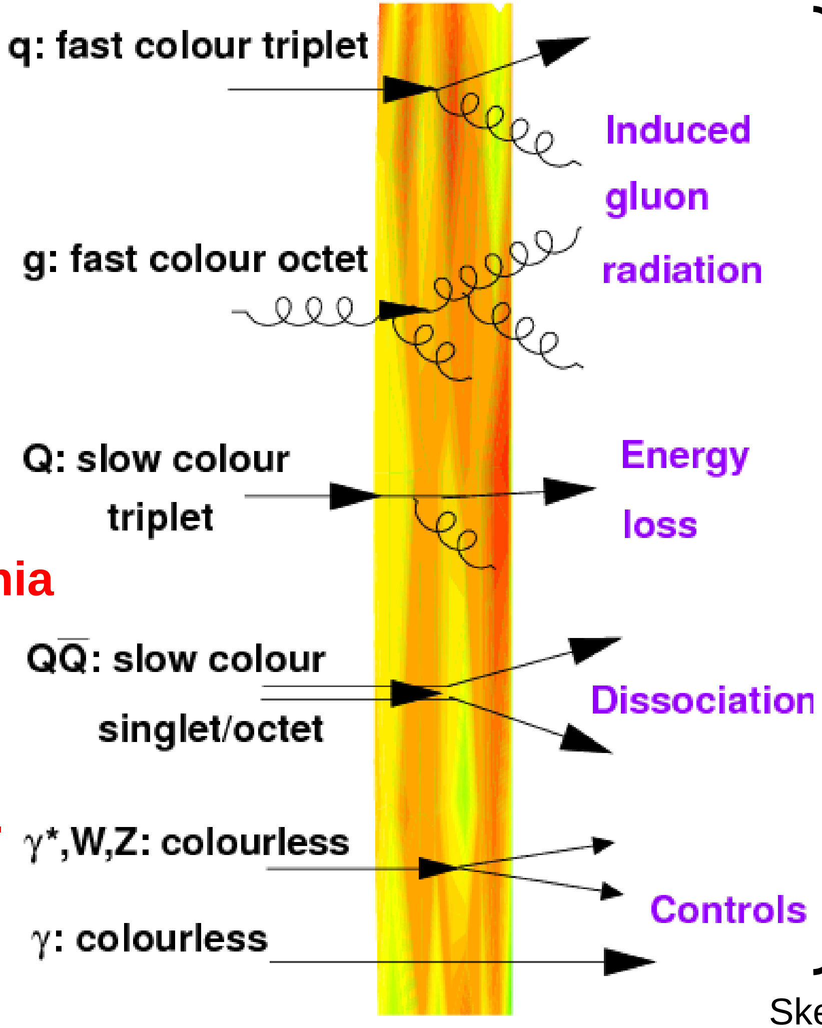
Quark-Gluon Plasma

Initial state

Quarks and gluons

Heavy quarkonia

Electro-weak probes

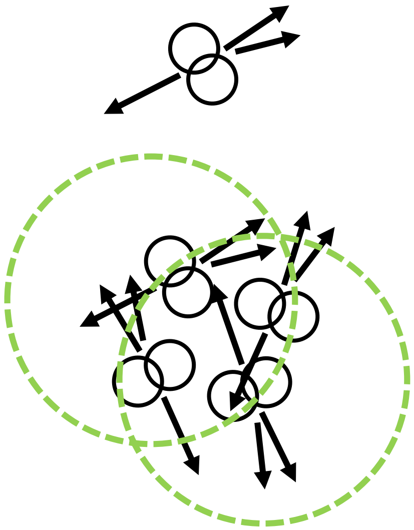


Final state

Detector

Sketch: d'Enterria: arXiv:1207.4362

Nuclear-Modification Factor



- Hard processes occur in nucleon-nucleon (NN) collisions
- Heavy-ion collision : many NN collisions
  - Hard process is independent of number of NN collisions
- Without QGP, HI collision is superposition of NN collisions with incoherent fragmentation

$$dN_{AA}/dp_T = \langle N_{coll} \rangle \boxed{dN_{pp}/dp_T} \longleftarrow$$

any object, e.g. charged particles, jets, J/ψ, D, …

- Let’s turn this into an observable

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

R_{AA} = 1 → no modification

R_{AA} != 1 → medium effects

Nuclear-Modification Factor (2)

- How do we measure this quantity?

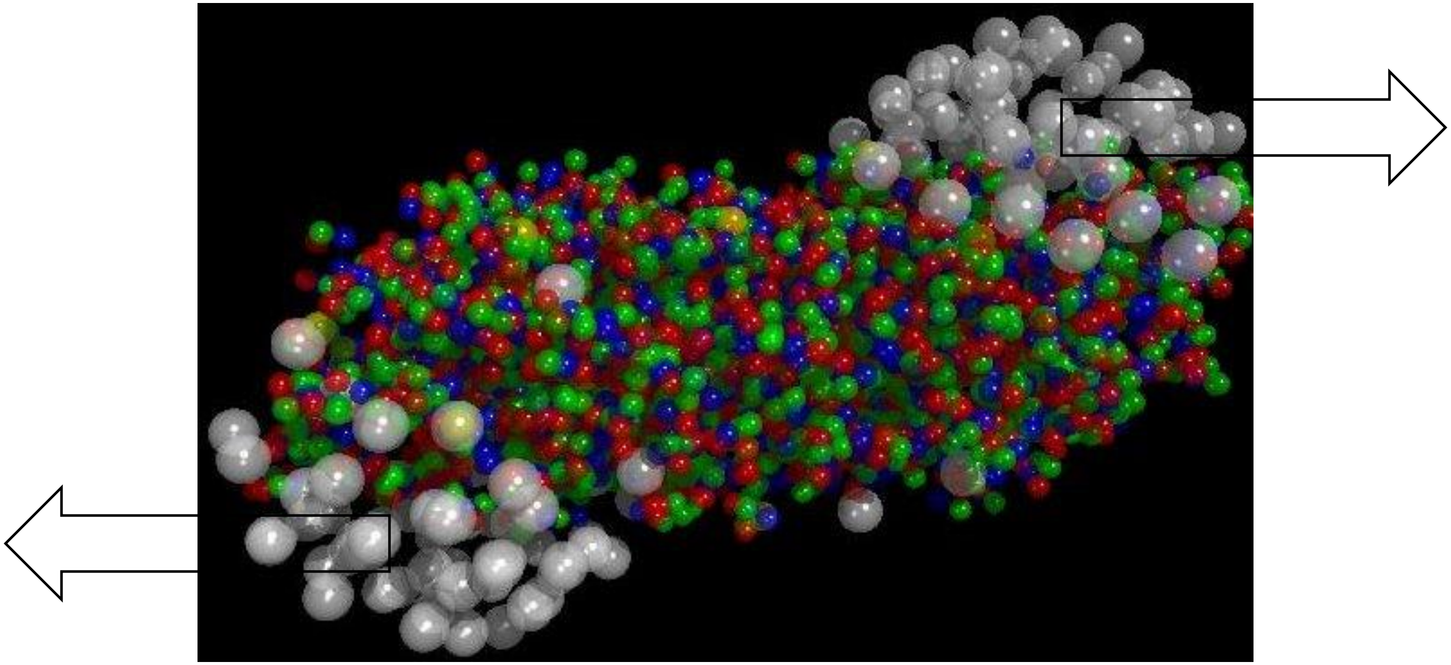
For example:
p_T distribution in AA collisions
- **Select events**
- **Select & count tracks**
- **Correct for detector effects**
- **Estimate systematic uncertainties**

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

Number of binary collisions N_{coll}
- **Glauber modelling (see next slides)**
- **Centrality (see next next slides)**

p_T distribution in pp collisions

How to Measure N_{coll}?

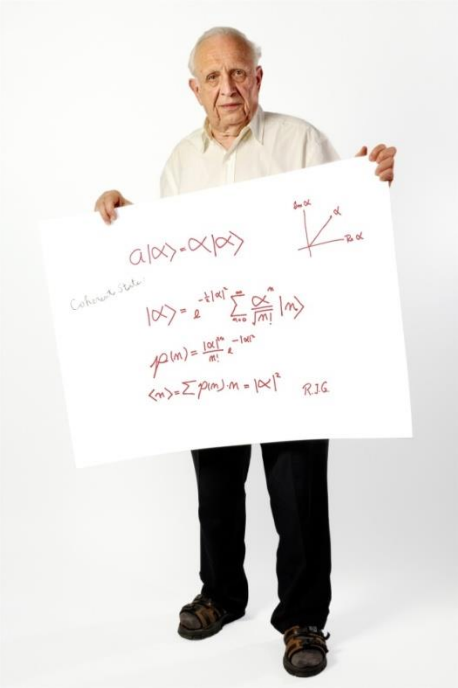


- Each nucleon (Pb-Pb: 2x208) has momentum and energy
- Calculating the number of collisions is in principle a 2x(208+208+1) = 834-dimensional integral

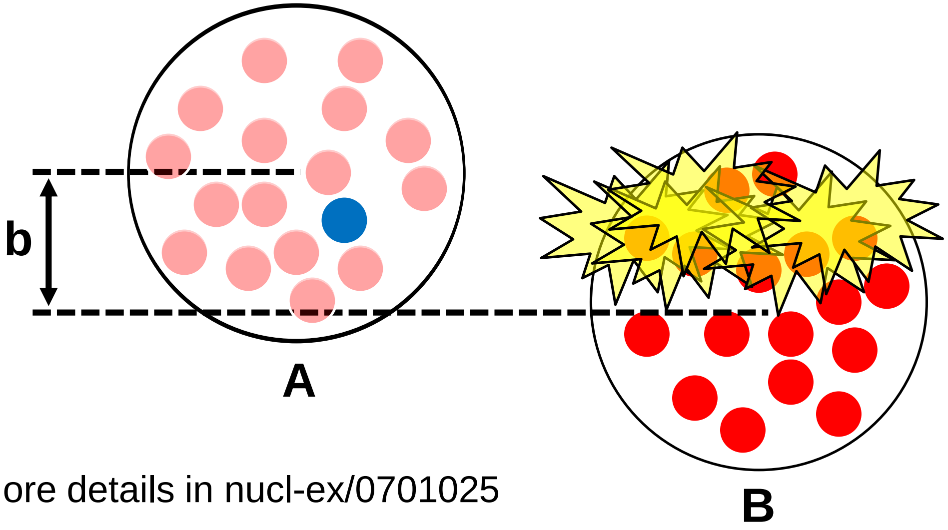
Some simplification seems to be needed…

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



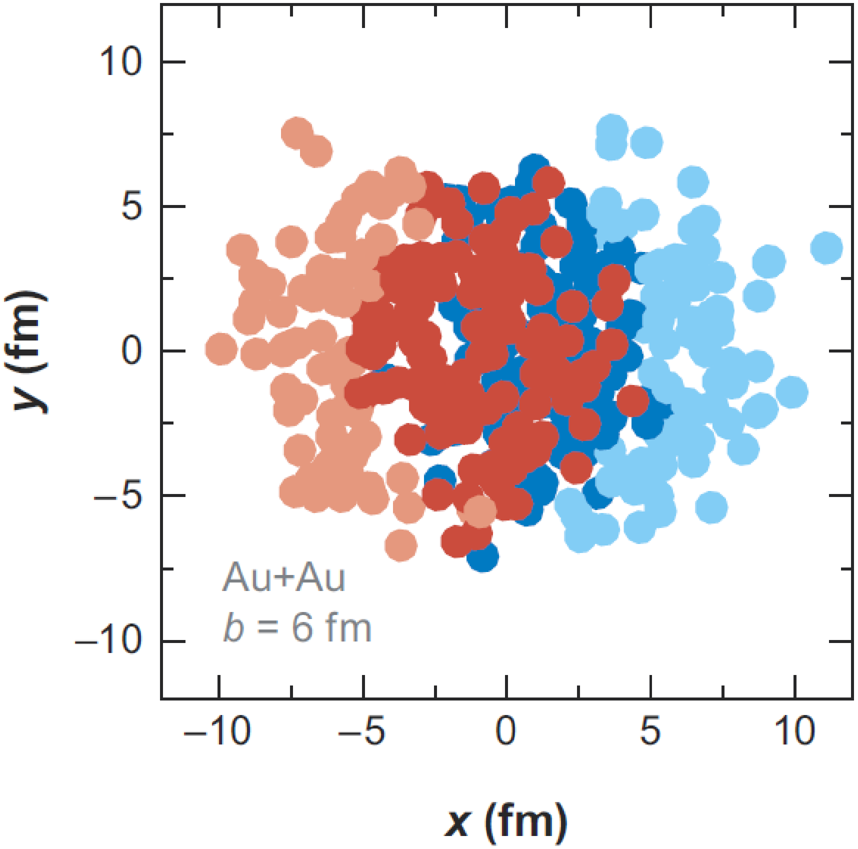
"Blue" nucleon has suffered 5 NN collisions

Need to repeat for all other nucleons in A

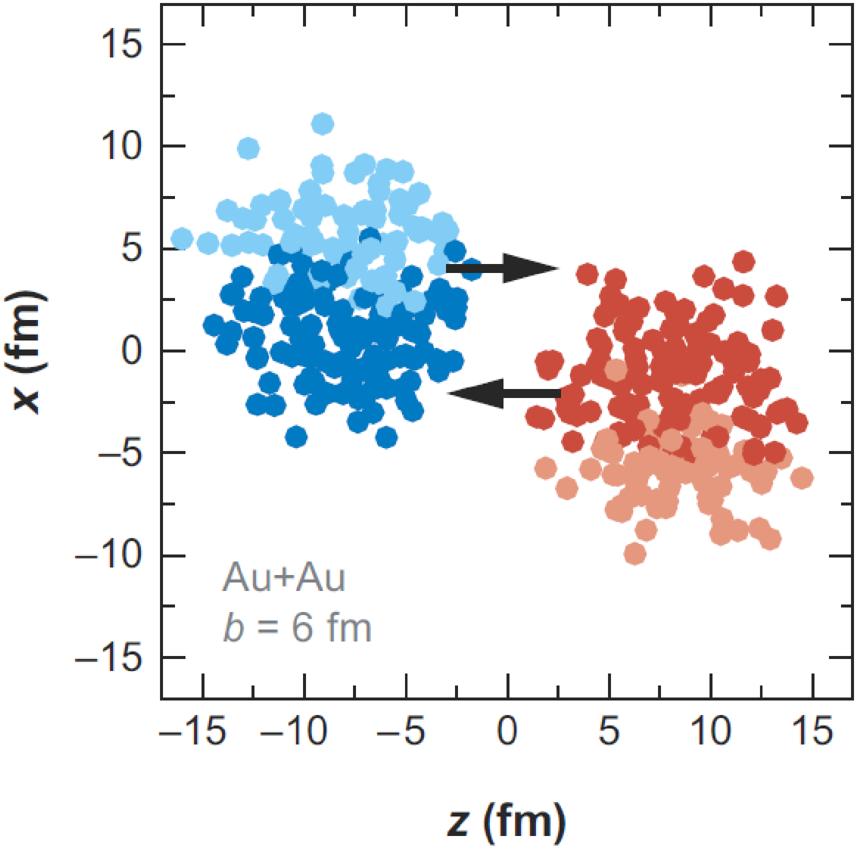
Strongly dependent on *impact parameter* b

More details in nucl-ex/0701025

Realistic Example



Transverse view



Along the beam axis

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

Figure: nucl-ex/0701025

Input to Glauber MC

- Distribution of nucleons in nuclei
  - Based on nuclear density
  - Typically Woods-Saxon distribution

$$\rho(r) = \rho_0 \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

Nuclear radius R

Skin depth a

Density in the center

- Nucleon-nucleon cross-section
  - From pp measurements / extrapolations

ρ(r)/ρ(0) vs. r

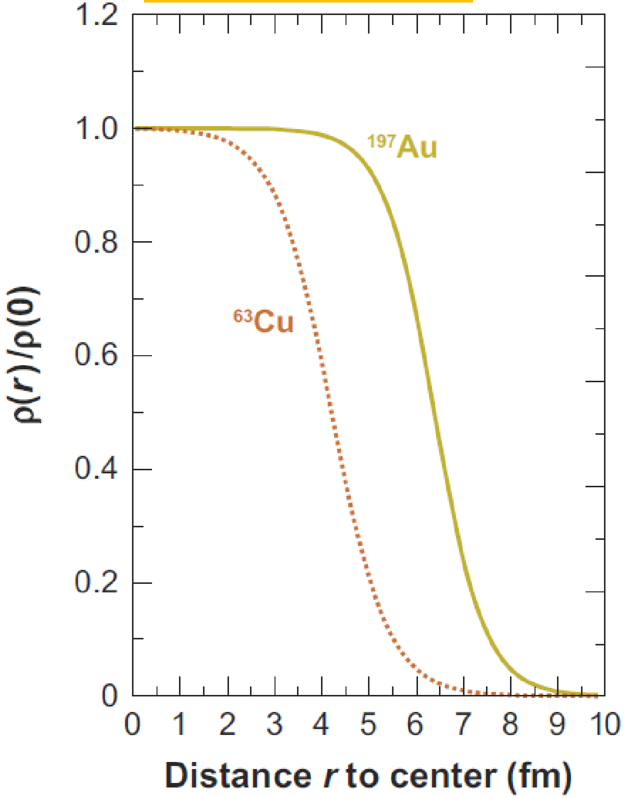
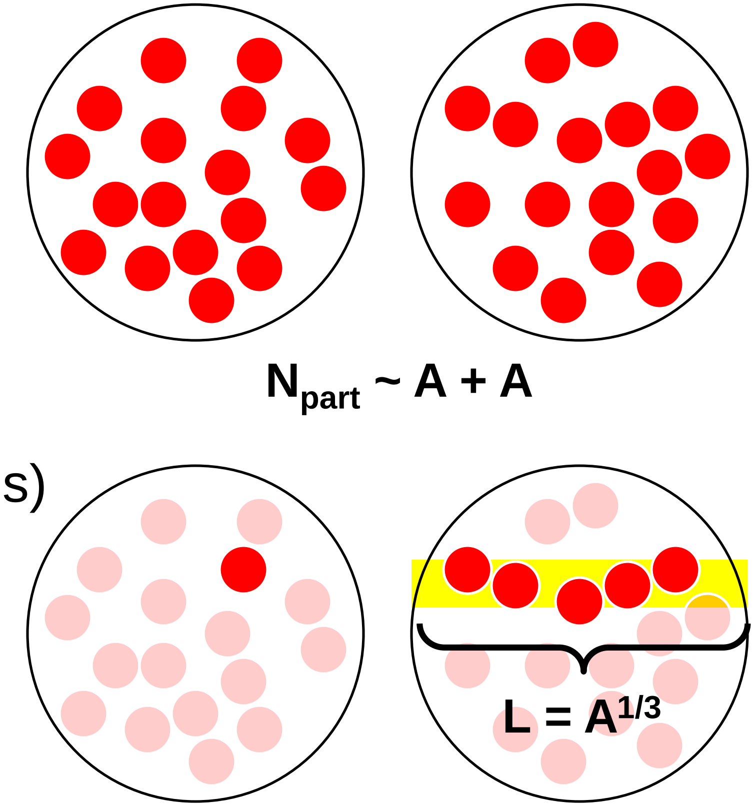


Figure: nucl-ex/0701025

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}



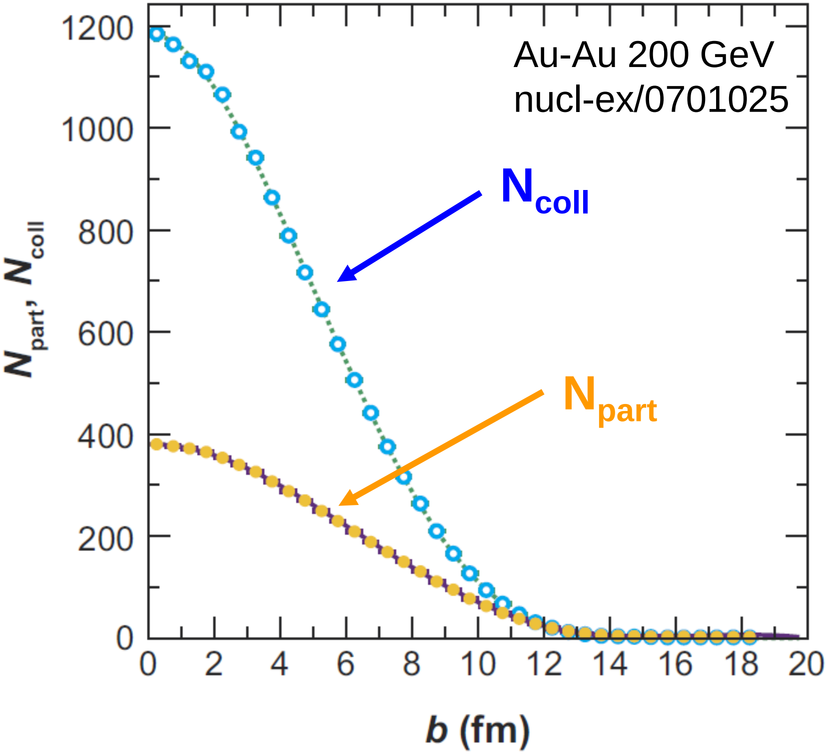
$\mathbf{N_{part} \sim A + A}$

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

Glauber MC Output (2)

- 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

N_{coll}, N_{part} vs. b



Can also be calculated analytically: Optical Glauber (see backup)

Recap

- We are trying to understand heavy-ion collisions
- For that, we are trying to measure the difference between AA and pp collisions, expressed as R_{AA}

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

- For that we need to estimate the number of nucleon-nucleon collisions N_{coll}
- Using the Glauber Monte Carlo, for a given impact parameter b, we are now able to estimate N_{coll}

How do we measure b?

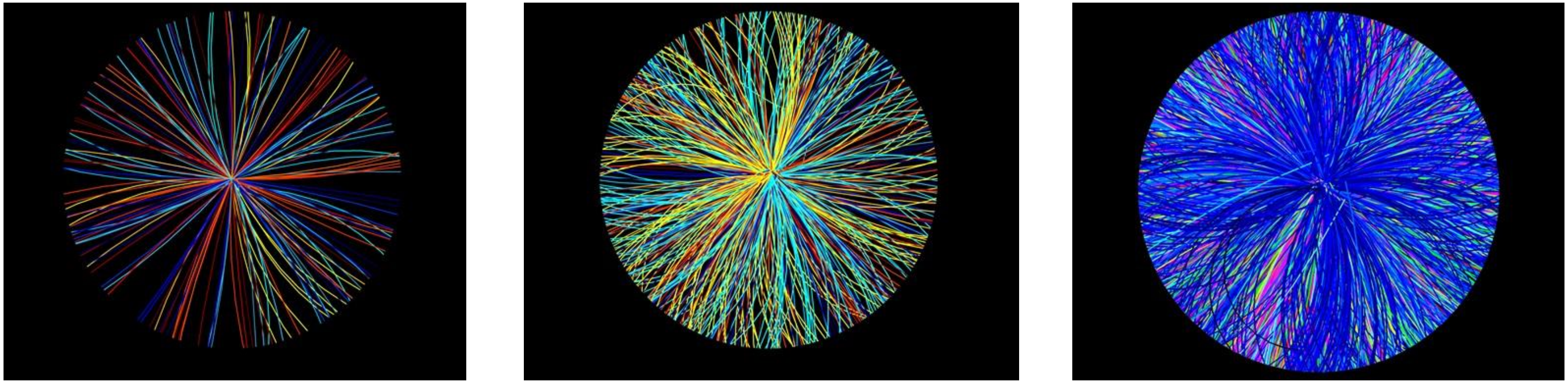
Centrality

- How do measure the impact parameter b?

Peripheral
b > 0

→

Central
b = 0



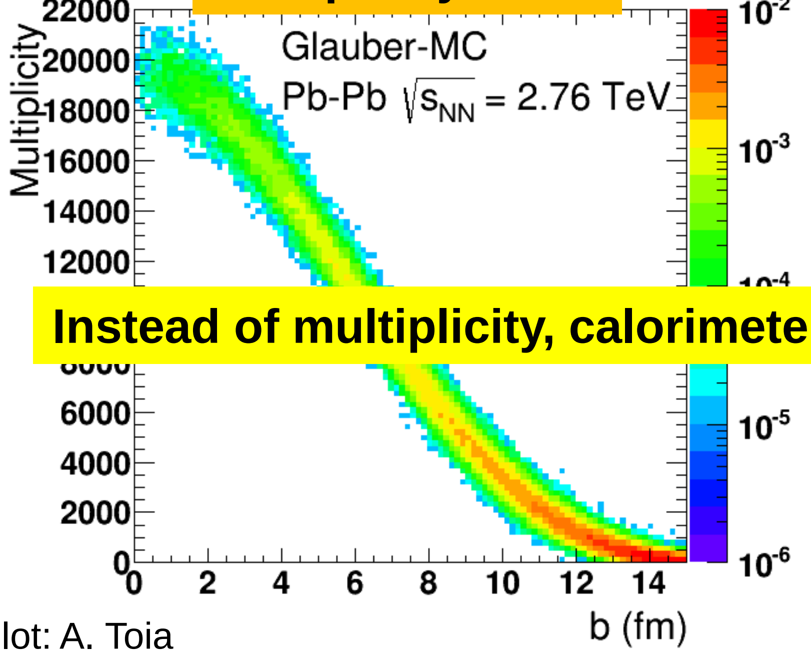
Low multiplicity → **High multiplicity**

Striking relation between b and multiplicity

Centrality (2)

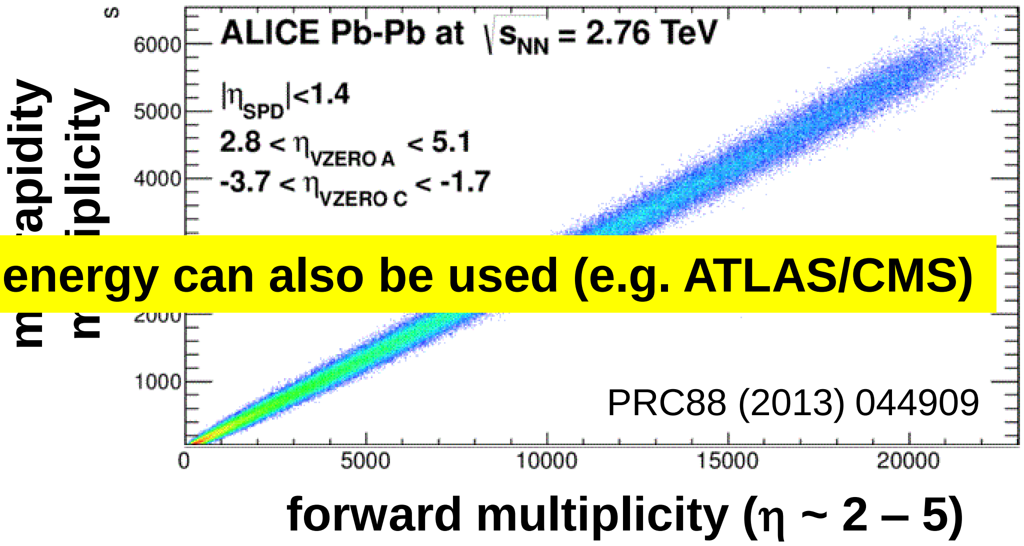
- Multiplicity anti-proportional to b
  - Glauber MC + particle production model calculates multiplicity
- Multiplicity correlated in different phase space (e.g. forward and mid rapidity) regions in HI collisions

Multiplicity vs. b



Plot: A. Toia

Mid rapidity vs. forward multiplicity

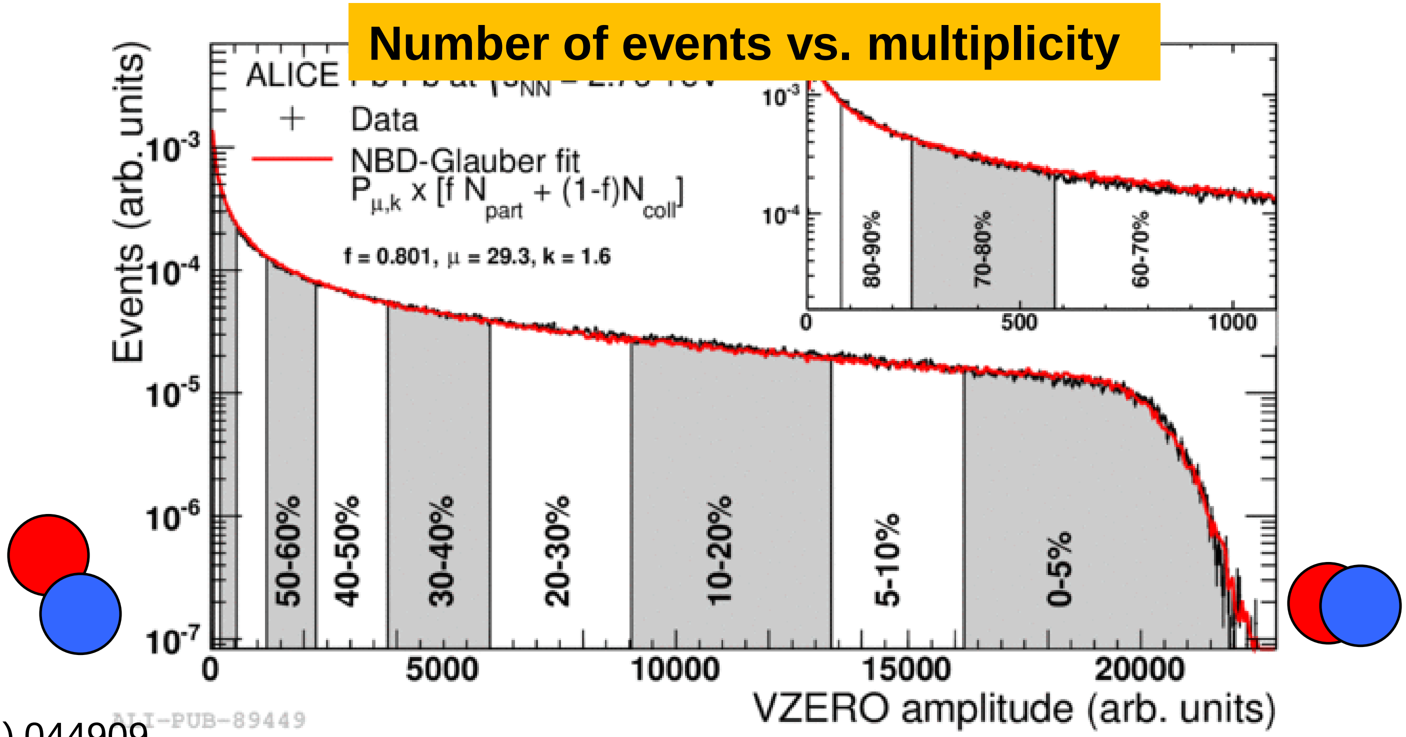


PRC88 (2013) 044909

Instead of multiplicity, calorimeter energy can also be used (e.g. ATLAS/CMS)

Centrality (3)

- Use multiplicity to split events into *classes*
- Called 0-5%, 5-10%, … 100% (“0%” = most central)
- Glauber MC calculates N_{part} and N_{coll} per class


Number of events vs. multiplicity

PRC88 (2013) 044909

Recap

- We are trying to measure R_{AA}

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

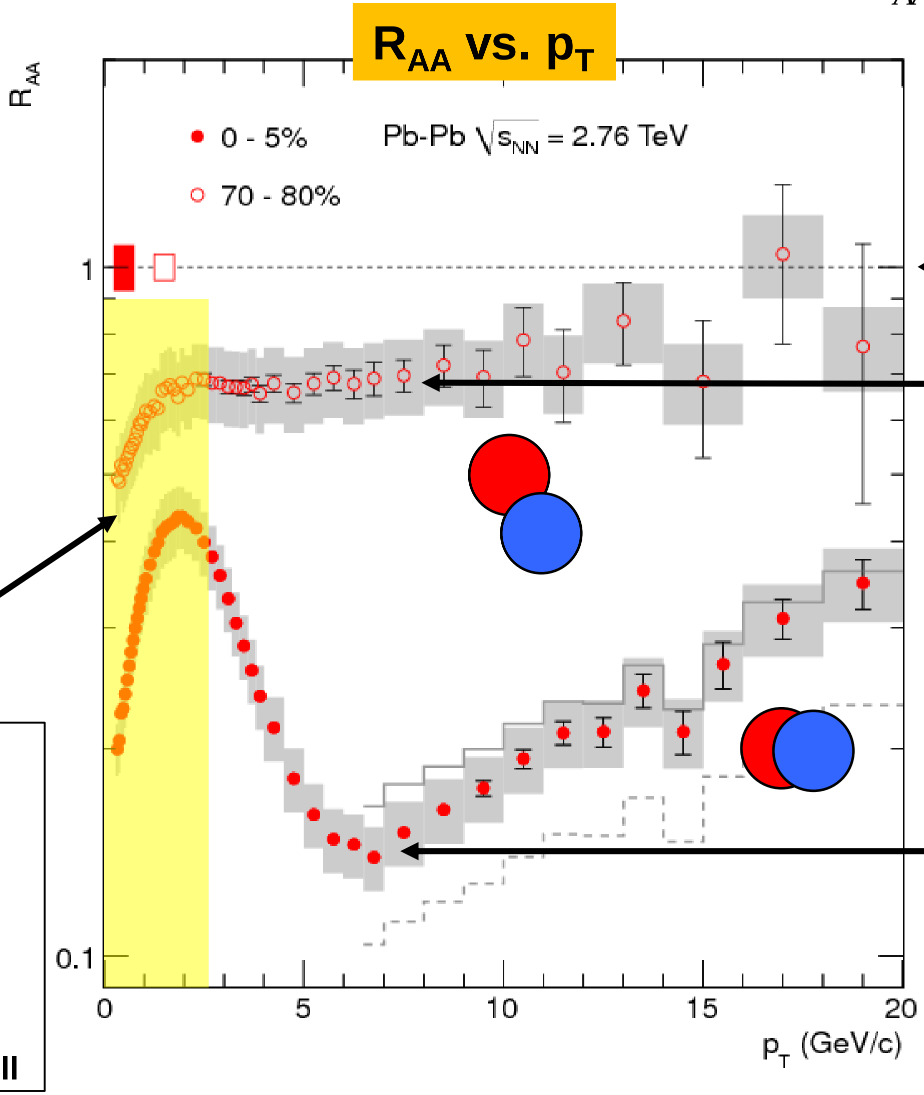
- We will do this in different event classes based on the event multiplicity
- For each class we can estimate the number of nucleon-nucleon collisions N_{coll} using the Glauber Monte Carlo

So… let's go !

R_{AA}

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

R_{AA} vs. p_T



R_{AA} = 1
→ no modification

70-80% (peripheral)
→ R_{AA} ~ 0.7

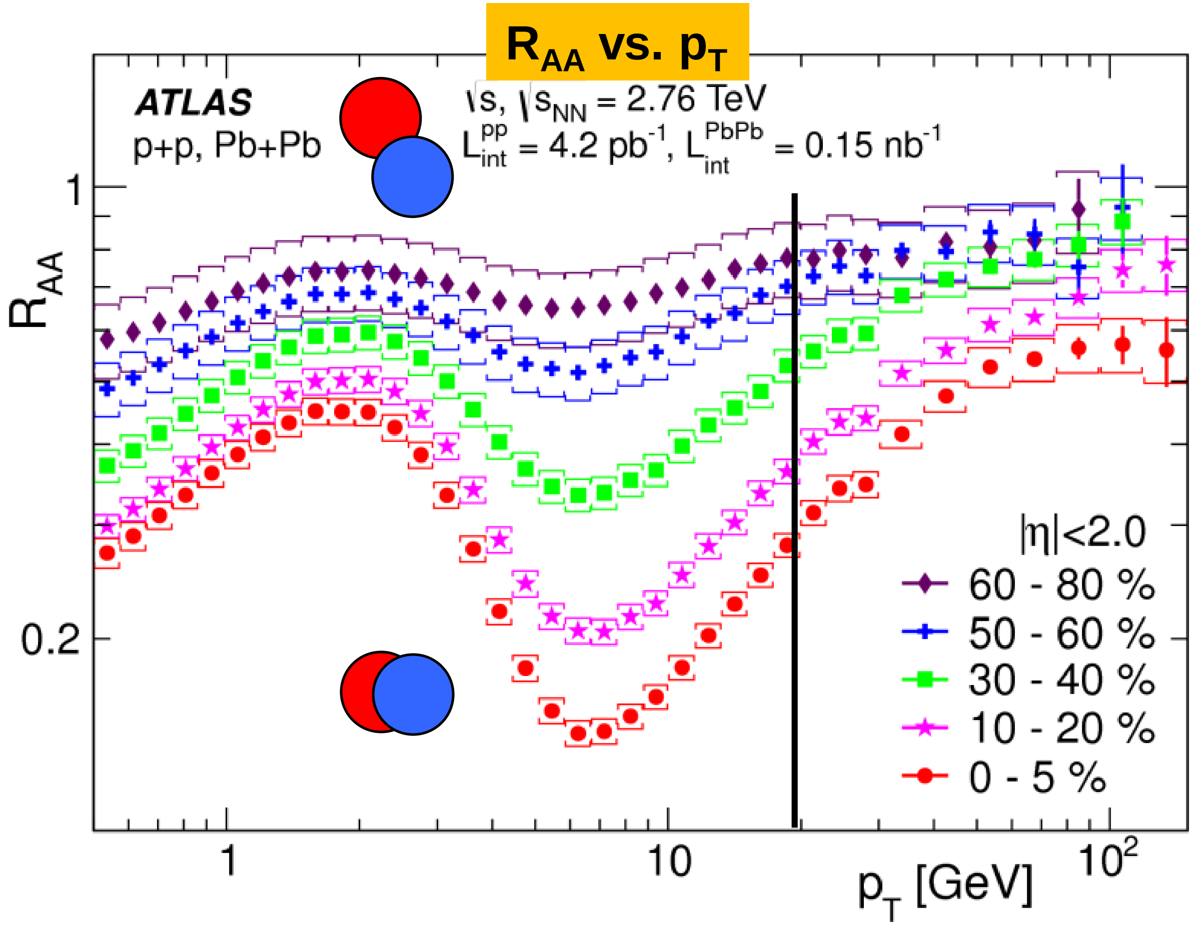
0-5% (central)
→ R_{AA} drops to 0.14

Drop at low p_T

Soft particle production does not scale with N_{coll}

ALICE, PLB696 (2011) 30

R_{AA} at High p_T



R_{AA} vs. p_T

60-80% (peripheral)
→ R_{AA} increases up to 0.9

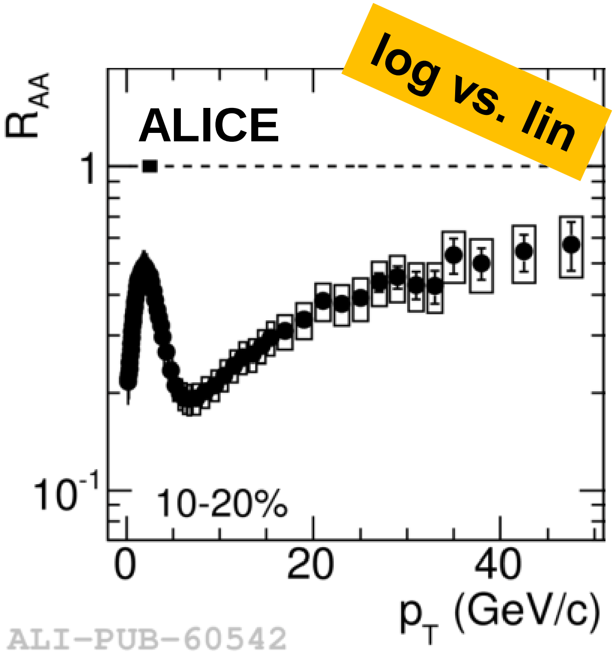
0-5% (central)
→ R_{AA} increases up to 0.6

R_{AA} reaches asymptotic value for p_T > 50 GeV/c

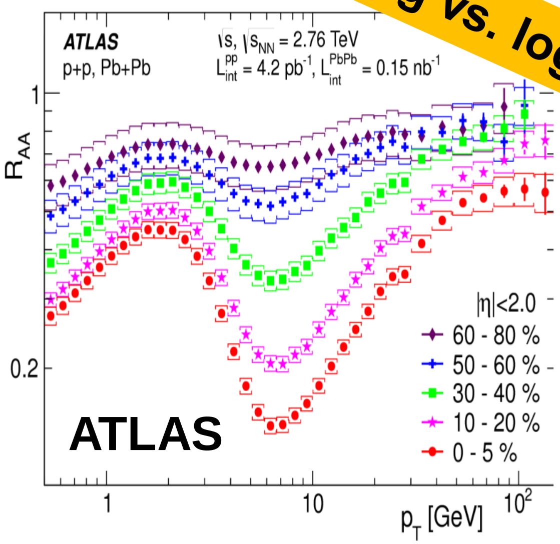
ATLAS, JHEP09(2015)050

Recent R_{AA}

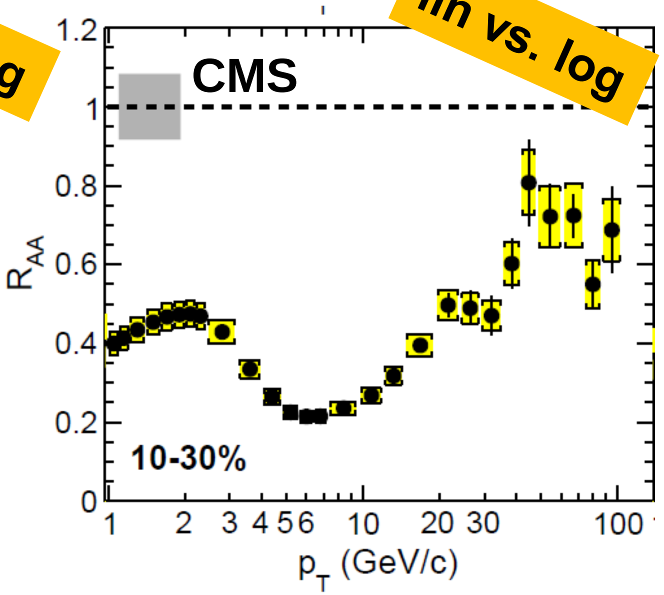
- If you were wondering how to compare the plots on the previous slides…



log vs. lin



log vs. log

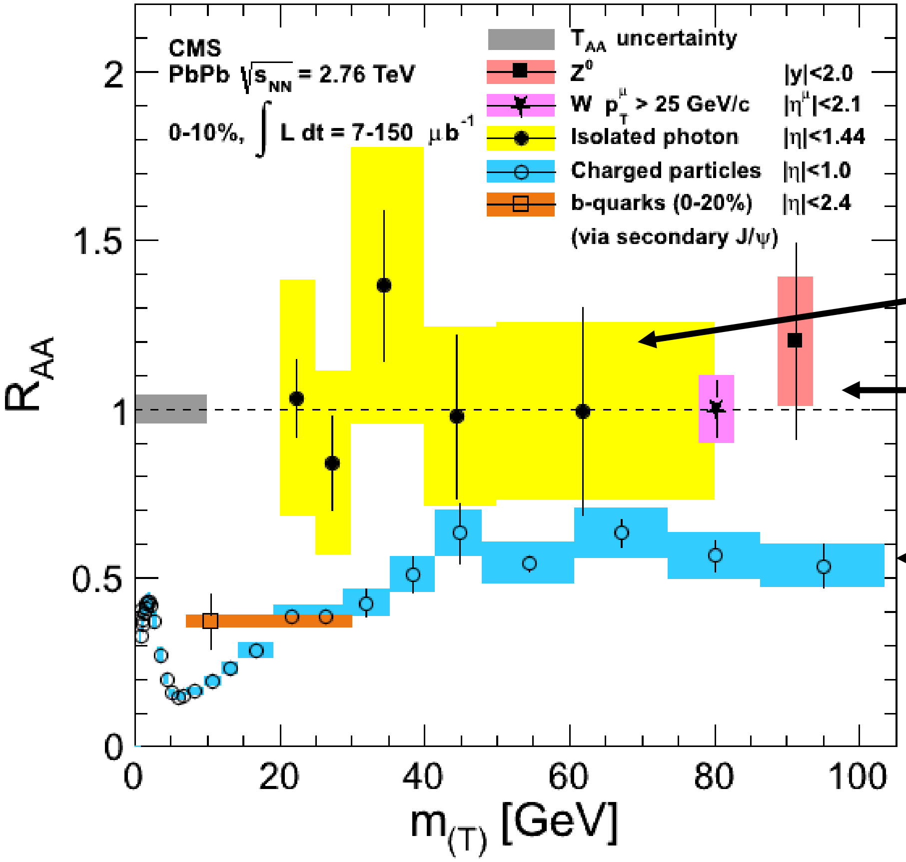


lin vs. log

- … but all consistent ☺

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

R_{AA} for Color-Neutral Probes



Photons

W, Z^0

charged particles

EPJC 72 (2012) 1945

No suppression for color-neutral probes

→ No interaction with QGP

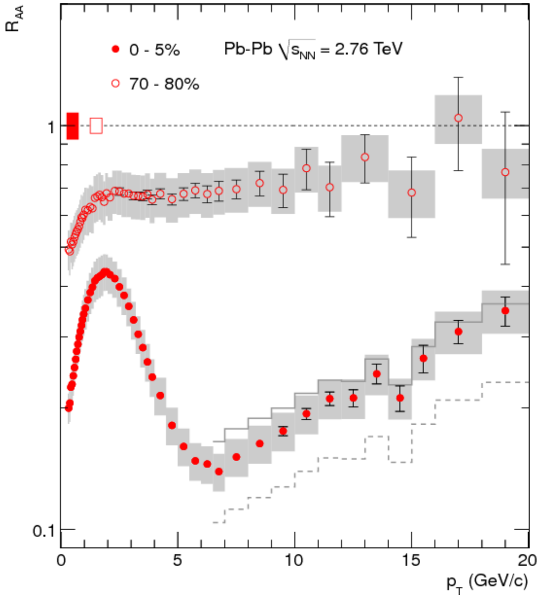
→ Experimental check on N_{coll} calculation (and nuclear PDFs)

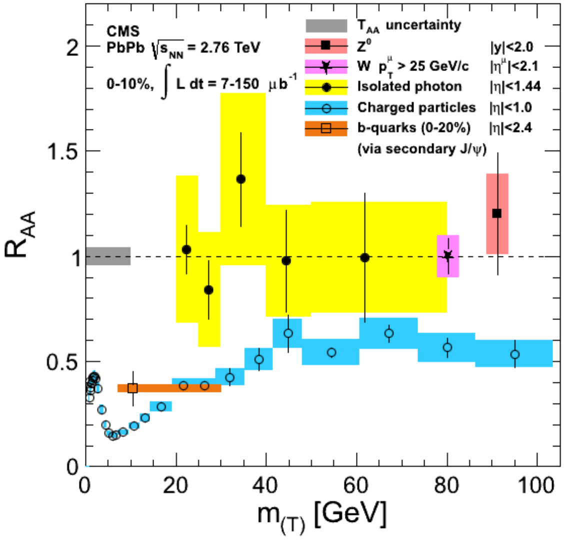
Recap

- Peripheral collisions
  - R_{AA} ~ 0.8 – 0.9 for colored probes
- Central collisions
  - R_{AA} ~ 0.14 at p_T ~ 6-7 GeV/c
  - R_{AA} ~ 0.6 at high p_T
- R_{AA} ~ 1 for color-neutral probes
- Interpretation
  - R_{AA} ~ 0.14 ~ 1/7 → naïve conclusion : only 1 out of 7 particles escape the QGP?

We are looking at a ratio and the particle spectrum is shifted by energy loss

Let's try to understand this in more detail…



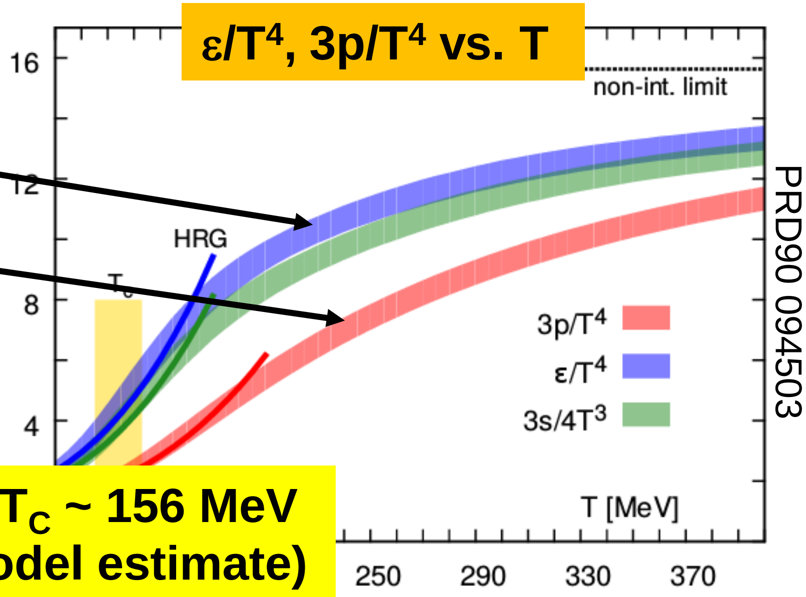


Backup

Lattice QCD

- More thorough estimate of the phase transition temperature can be done with lattice QCD
- Approach to solve non-perturbative QCD
- Discretize the QCD Lagrangian on a space-time grid
- Limited to chemical potential $\mu_B = 0$ (some workarounds exist)
- Calculate T dependence of
  - energy density
  - pressure
- Steep rise = change in number of degrees of freedom → phase transition

ε/T^4, $3p/T^4$ vs. T



PRD90 094503

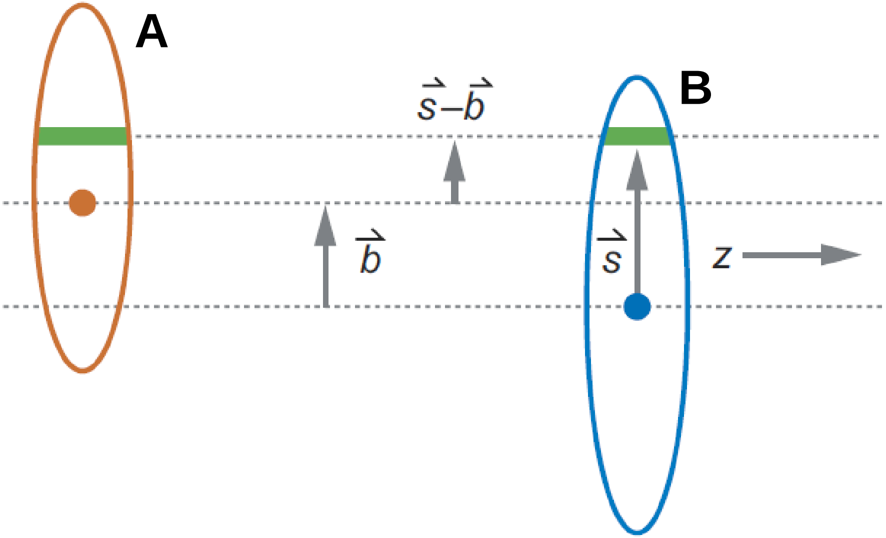
156 MeV ≈ 2 10^{12} K (Sun core: 1.5 10^7 K)

Transition temperature T_C ~ 156 MeV (consistent with bag model estimate)

Optical Glauber

- Probability to find a specific nucleon at *s*

$$T_A(s) \qquad\qquad T_B(s)$$



- Overlap function

$$T_{AB}(b) = \int \boxed{T_A(s-b)T_B(s)}\, ds$$

probability that a nucleon in A and in B are "in the same place"

  - Effective overlap area for which a specific nucleon in A can interact with a given nucleon in B

- Probability for interaction

$$T_{AB}(b)\,\sigma_{NN}$$

Figure: nucl-ex/0701025

Optical Glauber (2)

- Probability for *n* interactions

$$P(n,\mathbf{b}) = \binom{AB}{n}\left[\hat{T}_{\mathrm{AB}}(\mathbf{b})\,\sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^{n}\left[1-\hat{T}_{\mathrm{AB}}(\mathbf{b})\,\sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^{AB-n}$$

A,B number of nucleons

- Number of collisions

$$N_{\mathrm{coll}}(b) = \sum_{n=1}^{AB} n\,P(n,b) = AB\,\hat{T}_{\mathrm{AB}}(b)\,\sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

- Number of participants

$$\begin{aligned} N_{\mathrm{part}}(\mathbf{b}) \;=\; & A\int \hat{T}_{\mathrm{A}}(\mathbf{s})\left\{1-\boxed{\left[1-\hat{T}_{\mathrm{B}}(\mathbf{s}-\mathbf{b})\,\sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^{B}}\right\}d^{2}s \\ & +B\int \hat{T}_{\mathrm{B}}(\mathbf{s}-\mathbf{b})\left\{1-\left[1-\hat{T}_{\mathrm{A}}(\mathbf{s})\,\sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^{A}\right\}d^{2}s \end{aligned}$$

probability for not a single nucleon in a specific place

nucl-ex/0701025

Optical Glauber (3)

- Overlap function T_{AA} allows to rewrite nuclear-modification factor in terms of pp cross-section

$$R_{AA} = \frac{dN_{AA} / dp_T}{\langle N_{coll} \rangle dN_{pp} / dp_T}$$

Identical nuclei:
AB → A^2

$$N_{coll}(b) = A^2 T_{AA}(b) \sigma^{NN}$$

$$R_{AA} = \frac{dN_{AA} / dp_T}{\boxed{A^2 \langle T_{AA} \rangle} d\sigma_{pp} / dp_T}$$

sometimes factor A^2 included in $\langle T_{AA} \rangle$

- Reduces uncertainties if cross-section measurement is available

Optical vs. MC Glauber

- Optical Glauber calculates the average N_{coll} / N_{part} analytically
  - Exact

- MC Glauber arrives within MC approach at same values
- Advantage: Initial state fluctuations can be included (random distributions of nucleons in nuclei) → needed to describe many observables

dσ/db vs. b

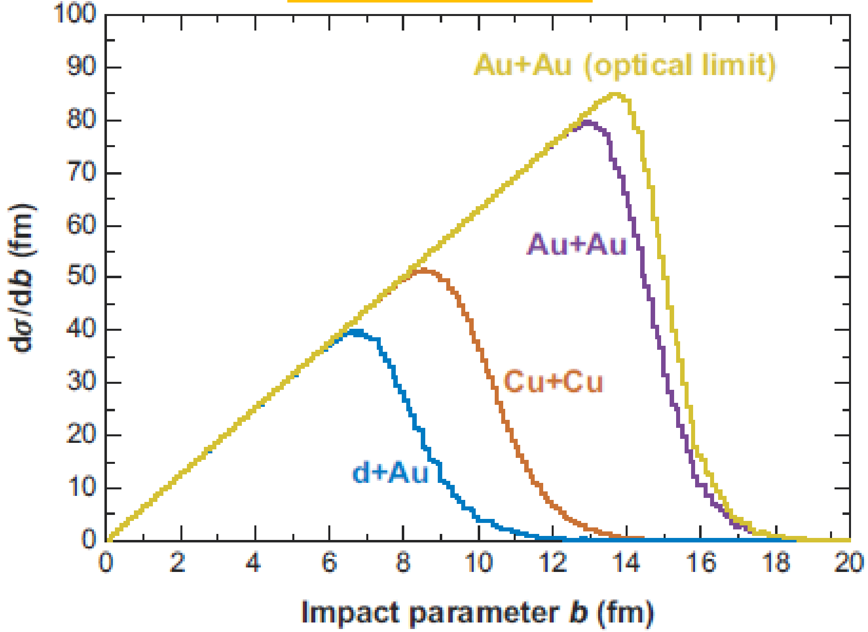


Figure: nucl-ex/0701025