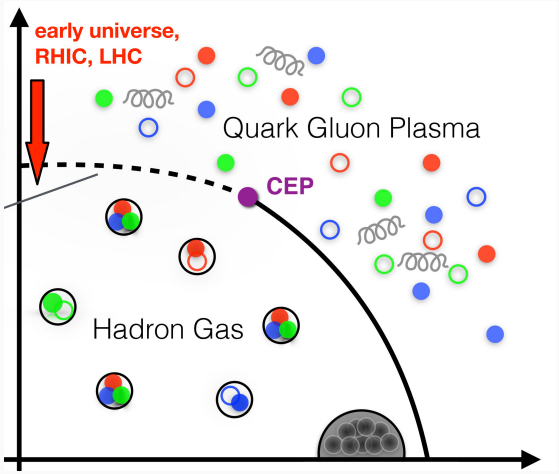
CLASHEP 2019
Heavy Ion Physics

Lecture 1



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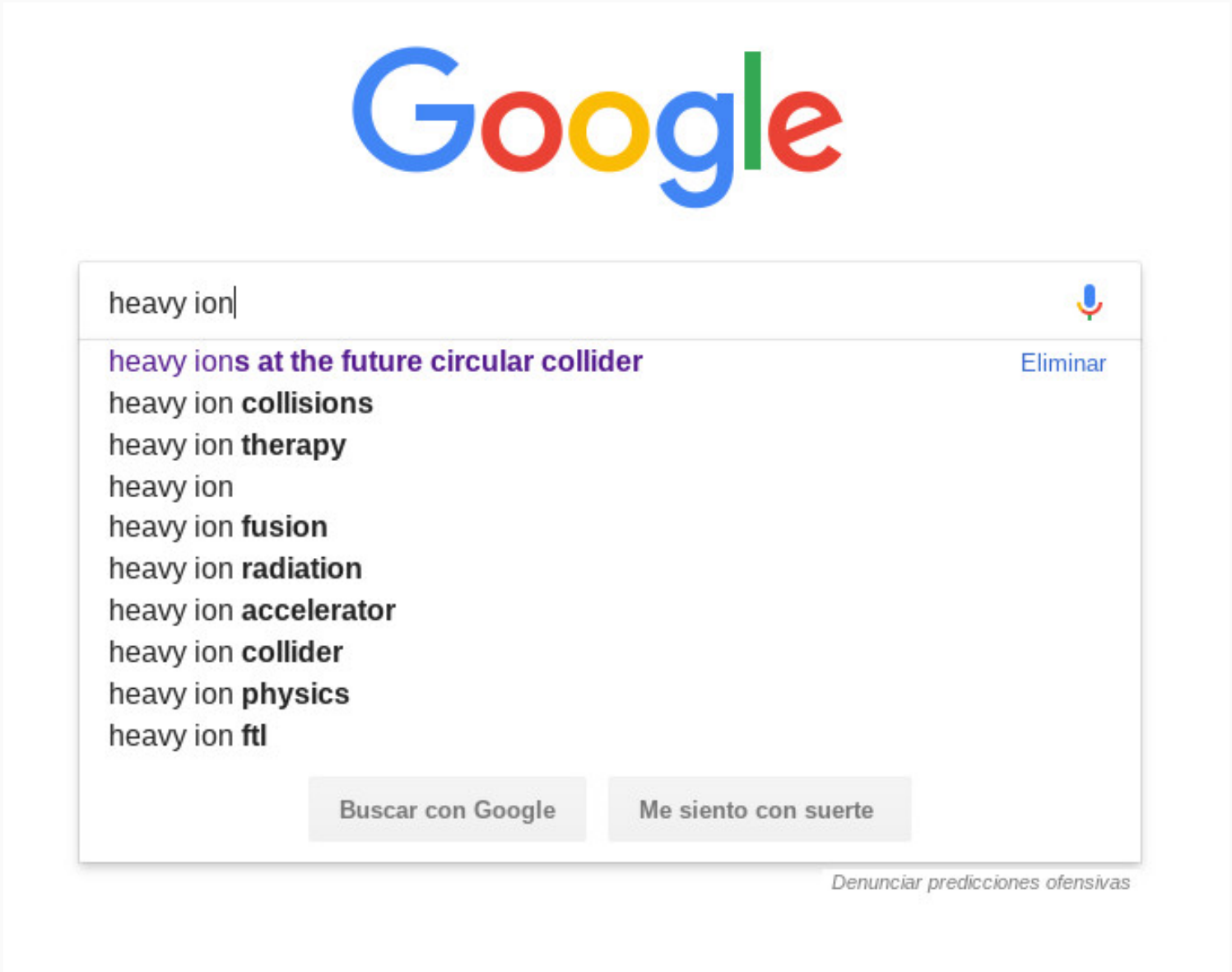
México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relativistic heavy ion **collider**
relativistic heavy ion **collisions**
relativistic heavy ion **physics**
relativistic heavy ion **collider (rhic)**
relativistic heavy ion **collider at brookhaven national laboratory**
relativistic heavy ion**s**
relativistic heavy ion **collider large hadron collider**
relativistic heavy ion **collisions quark gluon plasma**
relativistic heavy ion **experiments**
mit relativistic heavy ion **group**

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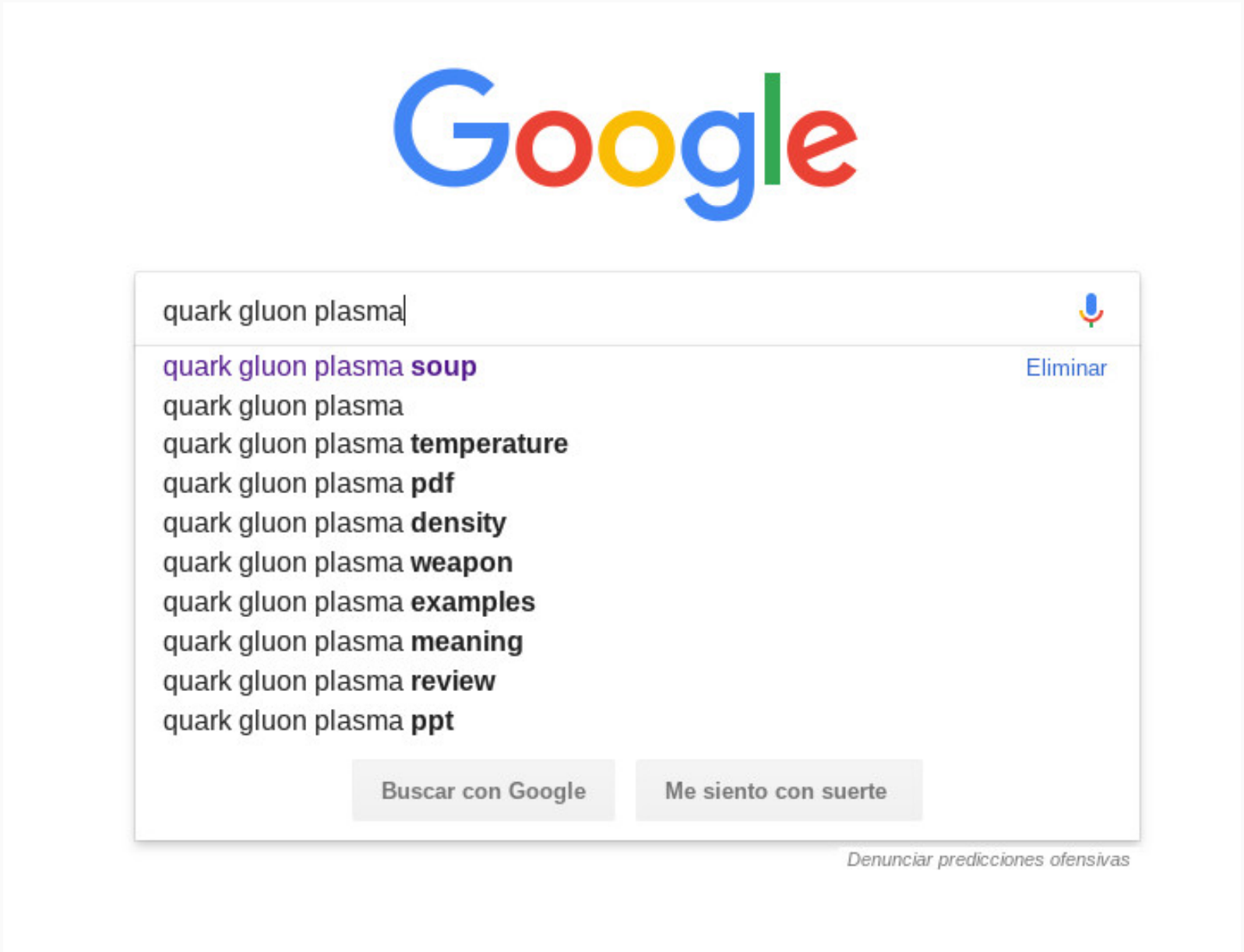
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qcd phase

qcd phase **diagram**
qcd phase **transition**
qcd phase **diagram and the critical point**
qcd phase**s**
qcd phase **transition early universe**
qcd phase **diagram an overview**
qcd phase **diagram review**
qcd phase**ndiagramm**
cosmological qcd phase **transition**
qcd **chiral** phase **transition**

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Denunciar predicciones ofensivas

Heavy Ion Collisions (HICs), why bother?

HICs are the means to explore regimes of QCD under **extreme** conditions. They are a tool to learn about the rich dynamical QCD phenomena that emerges under these conditions, an arena to further extend the vast knowledge we already have on hadron and QCD physics.

Look for answers using HIC experiments

- do we have an understanding of all the stages of a heavy ion collision?
- have any fundamentally new phenomena been seen? any unexplained phenomena?
- what new insights can we obtain, about the workings of QCD from analysis of heavy ion collision data and corresponding theoretical calculations?
- how well do we understand the initial stages of the collision process, up to the creation of QGP?
- which aspects involve weakly coupled dynamics, and which strongly coupled?
- what are the properties of QGP?
- what have we learned about the properties of strongly interacting matter, and about the dynamics of fast particles as they traverse strongly coupled matter?
- what new insights have we obtained about the formation of hadrons?

If you ask me

Opportunity to

- $\surd$ learn about phases of nuclear matter
- $\surd$ re-learn QCD, now under extreme conditions
- $\surd$ re-learn/adapt QFT old/new techniques
- $\surd$ develop/adapt code $p + p$ collisions $\Longrightarrow$ $A + A$ collisions
- $\surd$ look for answers in experiments around the corner:
  MPD-NICA (MexNICA Collaboration)

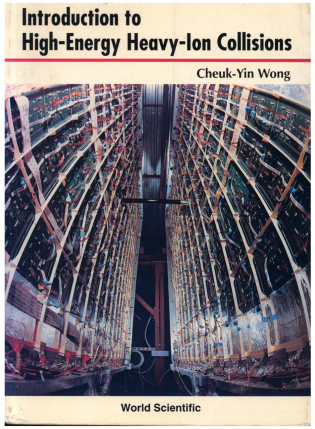
These 2 lectures: $\mathcal{T}\&\mathcal{F}^2$ of HICs

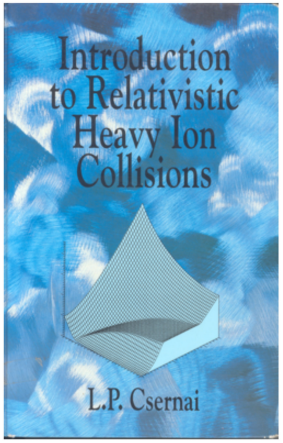
A small[1] HIC review of

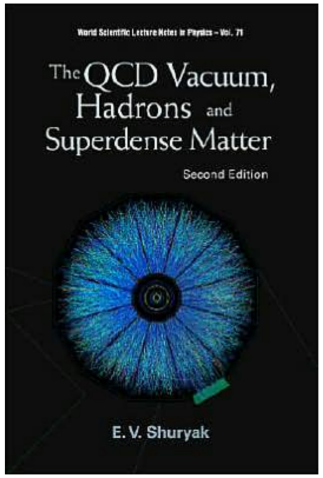
- experiments: kinematics, observables
- nuclear matter phase diagram
- model building and simulations
- discoveries

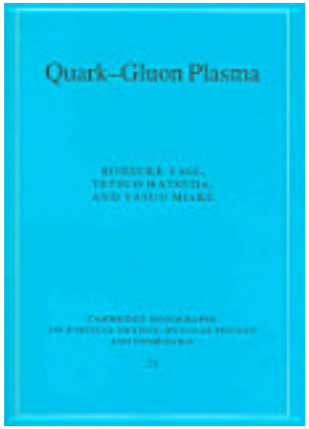
[1] QCD is in all of Daniel's lectures!
[2] Bread & Butter $\rightarrow$ Tortilla & Frijoles

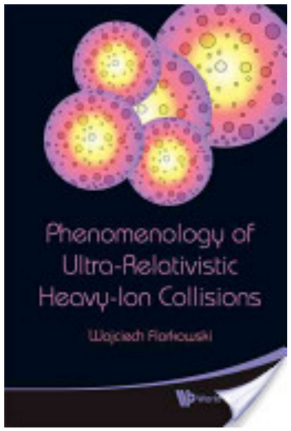
Recommended notes/books/articles

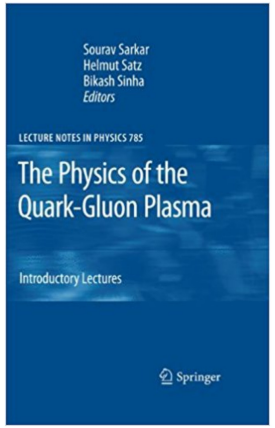












Recommended notes/books/articles

These lectures are based on:

- Talks given at QM 2018: K. Zapp, J. Jia, W. Zajc, etc.
- Talks given at Confinement: H. Sazdjian
- *Heavy Ion Collisions: The Big Picture, and the Big Questions* by W. Busza et. al. Ann. Rev. Nucl. Part. Sci. 2018. 68:149
- *A short course on Relativistic Heavy Ion Collisions* by A. K. Chaudhuri, arXiV:1207.7028 [nucl-th]
- *Quark-Gluon Plasma Physics* Lecture notes by K. Reygers, Heidelberg University (2017)
- Previous HI/XQCD lectures at CLASHEP: A. Ayala, E. Fraga, J. Takahashi

Table of contents

1. The QCD phase diagram

2. Relativistic heavy ion collisions

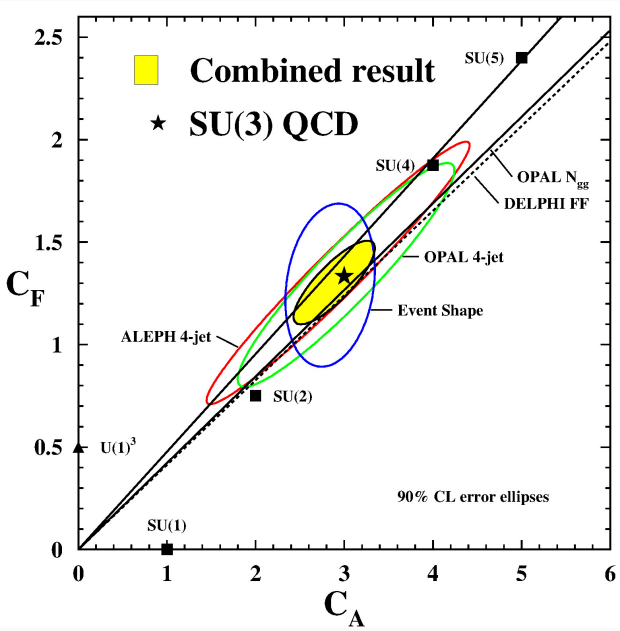
The QCD phase diagram

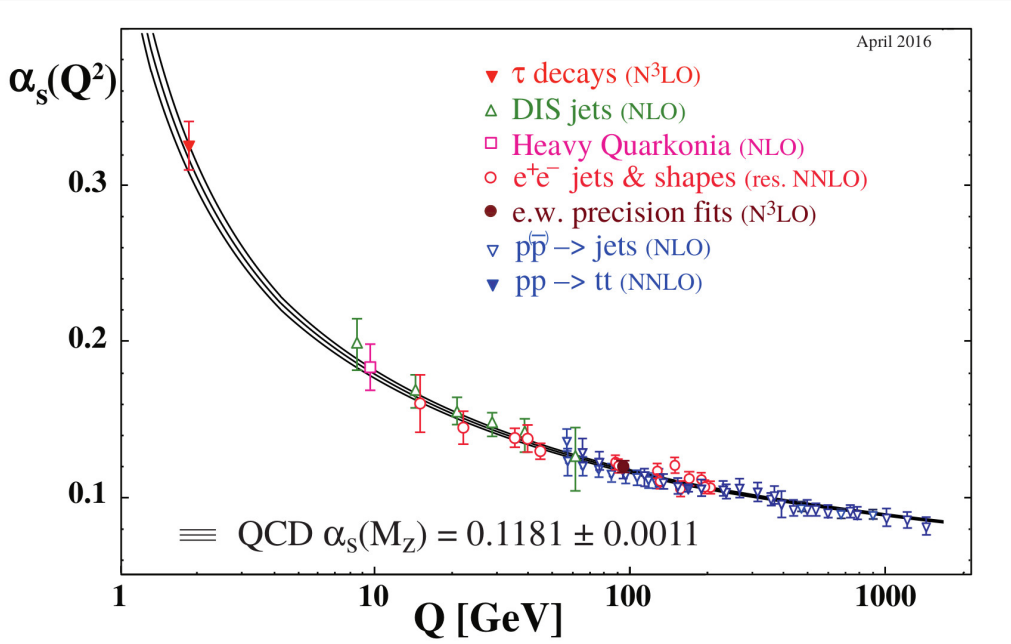
Status of pQCD

It is now carved in stone

*Rept.Prog.Phys.*69:1771-1846 (2006); PDG `pdg.lbl.gov`

- QCD: Nature favours $SU(3)$ gauge theory
- α_{QCD} running from all sorts of experiments and E scales





QCD

- Theory of strong interactions.
- Formulated in terms of elementary fields (quarks and gluons), whose interactions obey the principles of a relativistic QFT, with a non-abelian gauge invariance SU(3).
- Emergence of QCD as theory of strong interactions could be reviewed historically, analyzing the various experimental data and the theoretical ideas available in the years 1960 - 1973

QCD today

huge set of subjects describes/feeds from huge sets of data

structure/distribution functions

deep-inelastic scattering (DIS)

sum rules, polarized DIS

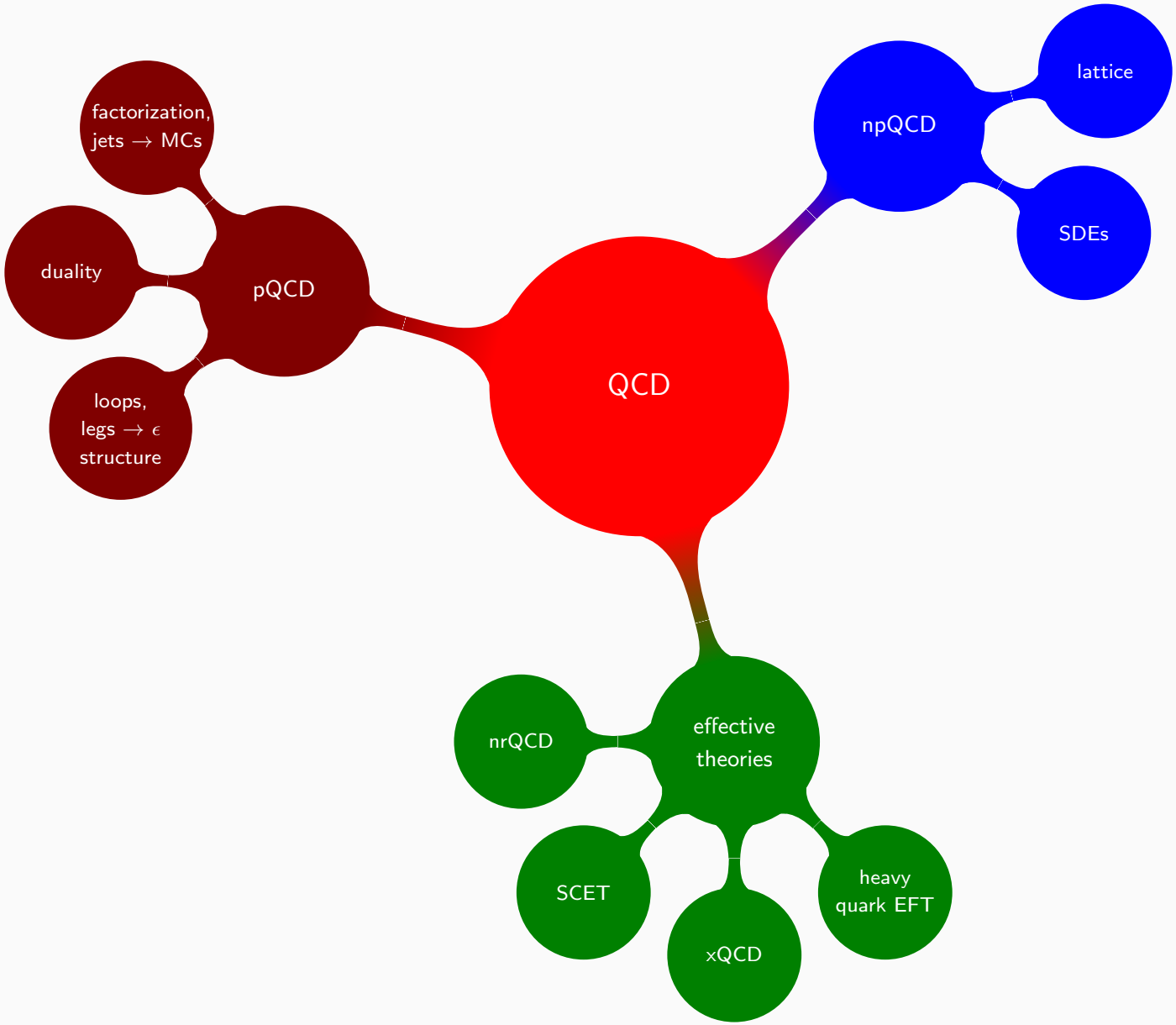
small x physics (hard pomerons, diffraction)

LEP, LHC, RHIC,...

Still relevant to ask

- What are the "fundamental" notions of QCD?
- What are its "fundamental" applications?
- Do we get to learn from QCD via QED, do we learn from dual theories, do we learn from effective theories?

QCD, QCD-style, QCD-ish, QCD-related



QCD: The theory of strong interactions

- Gauge theory with the **local** symmetry group $SU(N_c)$. (In the real world $N_c = 3$).
- Fundamental fields are **quarks** (matter fields) and **gluons** gauge fields.
- Each one of the N_f **quark fields** belong to the **fundamental representation** of the color group which is (N_c)–dimensional, **antiquark fields** to the **complex conjugate of the fundamental representation**, also (N_c)–dimensional and **gluon fields** to the **adjoint representation** which is $(N_c^2 - 1)$–dimensional.

$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{\psi}_i^a \left(i\gamma^\mu (\partial_\mu \delta^{ab} + i g_s A_\mu^{ab}) - m_i \delta^{ab} \right) \psi_i^b - \frac{1}{4} G_{\mu\nu}^\alpha G_\alpha^{\mu\nu};$$

$$G_{\mu\nu}^\alpha = \partial_\mu A_\nu^\alpha - \partial_\nu A_\mu^\alpha + g_s f^{\alpha\beta\sigma} A_\mu^\beta A_\nu^\sigma \; ; \qquad A_\mu^{ab} = A_\mu^\sigma (\tau_\sigma)^{ab}$$

a, b run from 1 to N_c; $\alpha,\ \beta,\ \sigma$ run from 1 to $N_c^2 - 1$.

Flavor symmetry

Consider the ideal case in which all N_f flavors have the same mass.
The Lagrangian corresponding to the quark sector becomes (we omit color indices for quarks and gluons)

$$\mathcal{L}_q = \sum_{i=1}^{N_f} \overline{\psi}_i \left(i\gamma^\mu (\partial_\mu + i g_s A_\mu) - m \right) \psi_i$$

- $\mathcal{L}_q$ is invariant under continuos **global transformations** of $SU(N_f)$

$$\begin{aligned} \psi_i \longrightarrow \psi_i' &= e^{-i\alpha^B (T^B)_i{}^j} \psi_j \\ \overline{\psi}_i \longrightarrow \overline{\psi}_i' &= \overline{\psi_j} e^{i\alpha^B (T^B)^j{}_i} \\ A_\mu \to A_\mu' &= A_\mu; \quad B \text{ runs from 1 to } N_f^2 - 1, \\ & \qquad\quad T^B \text{ are } N_f \times N_f \text{ matrices} \end{aligned}$$

- In **infinitesimal form**

$$\delta\psi_i = -i\delta\alpha^B (T^B)_i{}^j \psi_j; \qquad \delta\overline{\psi}_i = i\delta\alpha^B \overline{\psi}_j (T^B)^j{}_i; \qquad \delta A_\mu = 0$$

Flavor symmetry

- Using Noether's theorem, one finds **(exercise)** $N_f^2 - 1$ **conserved currents**

$$\begin{aligned} j_\mu^A(x) &= \overline{\psi}_i(x)\gamma_\mu (T^A)^j{}_i \psi^i \quad j(x) \\ \partial^\mu j_\mu^A &= 0 \end{aligned}$$

- The generators of the group **(the charges)** are obtained from j_0^A by space integration

$$Q^A = \int d^3x \; j_0^A(x)$$

- Q^A's satisfy the $SU(N_f)$ algebra

$$[Q^A, Q^B] = i f^{ABC} Q^C; \qquad A, B, C = 1, ..., N_f^2 - 1$$

Flavor symmetry

- Current conservation implies that **the generators** are independent of time and therefore they **commute with the Hamiltonian** H: $[H, Q^A] = 0$
- The transformation properties of the fields can be translated to the states.
- Introduce one-particle quark states (omit spin labels) $|\mathbf{p}, i\rangle$.
- **If the vacuum state is invariant under the group transformations (exercise)**

$$Q^A|\mathbf{p}, i\rangle = (T^A)^j{}_i|\mathbf{p}, j\rangle$$

- These states are also eigenstates of the Hamiltonian, all one-particle states of the fundamental representation multiplet have equal masses m

realised the symmetry à la **Wigner-Weyl**

Approximate flavor symmetry

Consider now the case where flavors have different masses

$$\mathcal{L}_q = \sum_{i=1}^{N_f} \overline{\psi}_i \left(i\gamma^\mu (\partial_\mu + igA_\mu) - m_i \right) \psi_i$$

- The mass term spoils $SU(N_f)$ invariance, therefore currents are not conserved and we find (exercise)

$$\partial^\mu j^A_\mu = -i \sum_{i,j=1}^{N_f} (m_i - m_j) \overline{\psi}_i (T^A)^i{}_j \psi^j \neq 0$$

- We could divide quarks into two groups: **light quarks** u, d, s and **heavy quarks** c, b, t. The mass difference between each group is large (> 1 GeV). An approximate symmetry could be realised for light quarks: $SU(2)$ for u, d or $SU(3)$ for u, d, s.

Chiral symmetry

- Quarks can also be transformed by means of unitary transformations that include the γ_5 matrix. The transformations are called **axial flavor transformations**
- In infinitesimal form

$$\delta\psi_i = -i\delta\alpha^A (T^A)_i{}^j \gamma_5 \psi_j; \qquad \delta\overline{\psi}_i = i\delta\alpha^A \overline{\psi}_j \gamma_5 (T^A)^j{}_i; \qquad \delta A_\mu = 0$$

- Consider the quark part of the Lagrangian $\mathcal{L}_q$ with equal masses. Under these transformations $\mathcal{L}_q$ **is not invariant because of the mass**

$$\delta\mathcal{L}_q = 2im\delta\alpha^A \overline{\psi}^i (T^A)_i{}^j \gamma_5 \psi_j$$

Chiral symmetry

Invariance under axial flavor transformations requires vanishing of the quark mass. **Contrary to flavor symmetry transformations, equality of masses is not sufficient for invariance under axial flavor transformations**

- In the general case of different masses, we introduce the **mass matrix** $\mathcal{M} = \text{diag}(m_1, m_2, ..., m_{N_f})$
- The variation of the Lagrangian is (exercise)

$$\delta\mathcal{L}_q = i\delta\alpha^A\overline{\psi}^i\{M, T^A\}_i{}^j\gamma_5\psi_j; \quad \{,\} \text{ is the anticommutator}$$

Chiral symmetry: massless quarks

- Consider the **massless case.** The Lagrangian is invariant under **both** the flavor and the axial flavor transformations. The conserved currents are

$$\begin{aligned} j^A_\mu(x) &= \overline{\psi}_i(x)\gamma_\mu(T^A)^i{}_j\psi^j(x); \qquad \partial^\mu j^A_\mu = 0 \\ j^A_{5\mu}(x) &= \overline{\psi}_i(x)\gamma_\mu\gamma_5(T^A)^i{}_j\psi^j(x); \qquad \partial^\mu j^A_{5\mu} = 0 \end{aligned}$$

- The corresponding charges are

$$Q^A = \int d^3x\, j^A_0(x), \qquad Q^A_5 = \int d^3x\, j^A_{50}(x)$$

Chiral symmetry: massless quarks

Together the flavor and axial flavor transformations form the **chiral transformations.**

- The corresponding charges satisfy the commutation relations

$$[Q^A, Q^B] = if^{ABC} Q^C, \quad [Q^A, Q_5^B] = if^{ABC} Q_5^C, \quad [Q_5^A, Q_5^B] = if^{ABC} Q^C$$

- **The axial charges do not form an algebra.** However, if we define

$$Q_L^A = \frac{1}{2}(Q^A - Q_5^A), \qquad Q_R^A = \frac{1}{2}(Q^A + Q_5^A)$$

we obtain (exercise)

$$[Q_L^A, Q_L^B] = if^{ABC} Q_L^C, \qquad [Q_R^A, Q_R^B] = if^{ABC} Q_R^C, \qquad [Q_L^A, Q_R^B] = 0$$

Chiral symmetry

- The left-handed and right-handed charges decouple and operate separately. Each generate an $SU(N_f)$ group.
- The chiral group is decomposed into the direct product of two $SU(N_f)$ groups, labeled with the subscripts L and R.

$$\text{Chiral group} = SU(N_f)_L \otimes SU(N_f)_R$$

In the real world, chiral symmetry is not exact, **quark masses break it explicitly.**

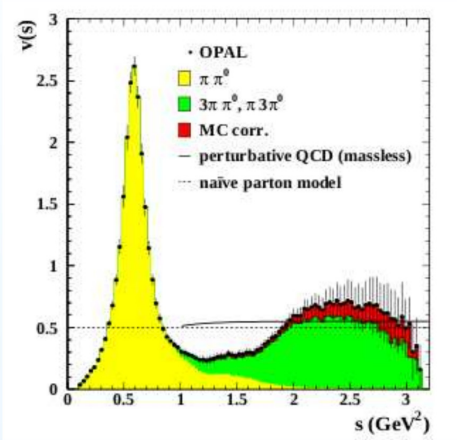
In the light quark sector, the breaking can be treated as a perturbation, the symmetry is approximate.

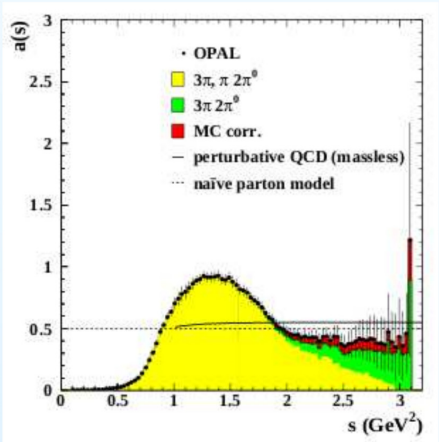
What is the signature of this approximate symmetry?

Parity doubling

Current Correlators in vacuum

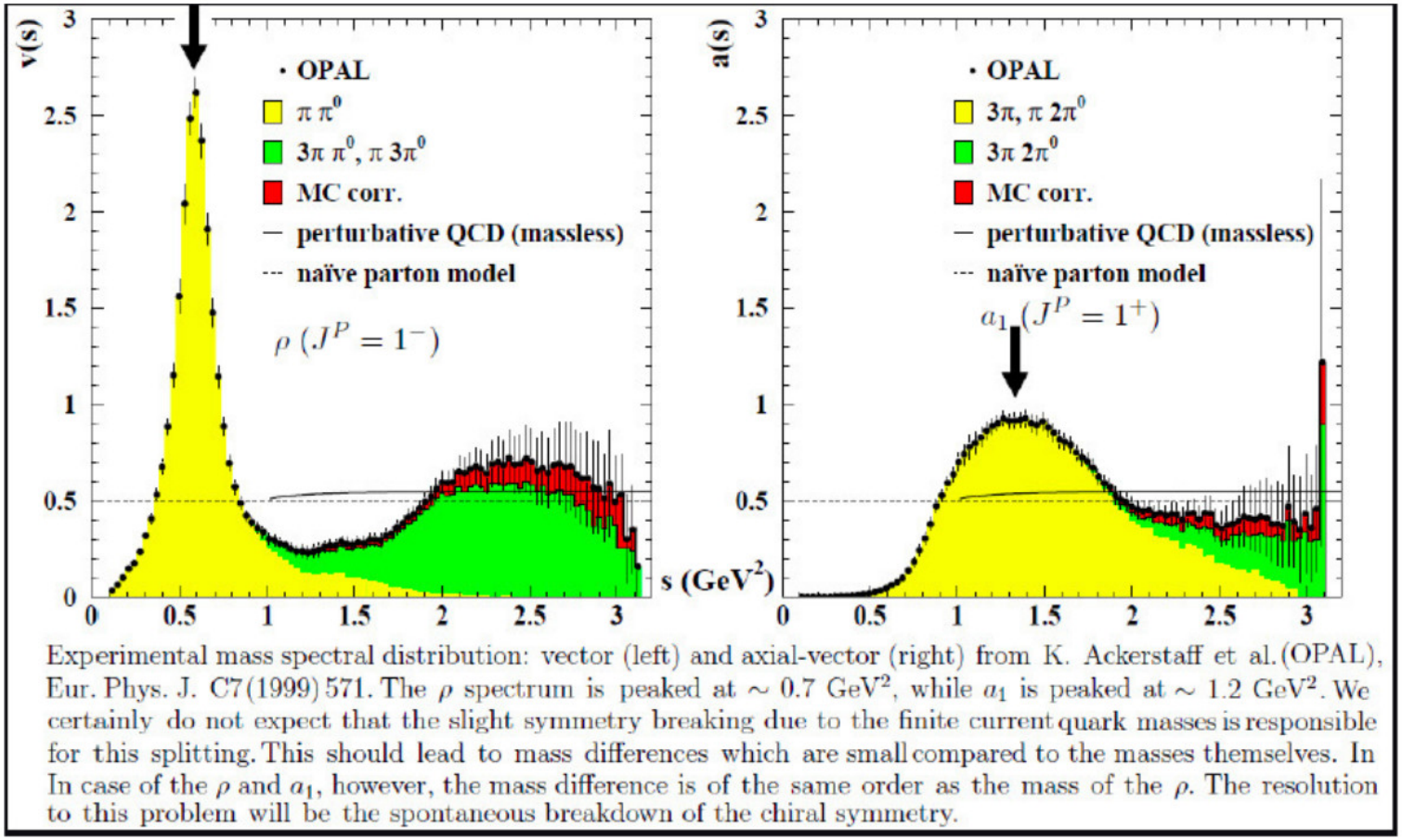
- The V and A correlators are identical to all orders in perturbation theory
  Chiral symmetry implies : $\mathrm{Im}\Pi_V(q) = \mathrm{Im}\Pi_A(q)$
- $\mathrm{Im}\Pi_V$ and $\mathrm{Im}\Pi_A$ have been measured at LEP in τ decays into even and odd number of pions $[\tau \rightarrow \nu_\tau + n\pi]$ by ALEPH and OPAL Collaborations
- the quantum numbers of $\vec{j}^{\mu}_V$ $[I^G(J^P) = 1^+(1^-)]$ and $\vec{j}^{\mu}_A$ $[I^G(J^P) = 1^-(1^+)]$ coincide with those of ρ and a_1 mesons - peaks dominate at low q^2
- very different spectral shape $\Rightarrow$ broken chiral symmetry in vacuum





EPJC 7 (1999) 571

Parity doubling



Experimental mass spectral distribution: vector (left) and axial-vector (right) from K. Ackerstaff et al. (OPAL), Eur. Phys. J. C7(1999) 571. The ρ spectrum is peaked at ~ 0.7 GeV^2, while a_1 is peaked at ~ 1.2 GeV^2. We certainly do not expect that the slight symmetry breaking due to the finite current quark masses is responsible for this splitting. This should lead to mass differences which are small compared to the masses themselves. In In case of the ρ and a_1, however, the mass difference is of the same order as the mass of the ρ. The resolution to this problem will be the spontaneous breakdown of the chiral symmetry.

OPAL Collaboration, EPJC 7 (1999) 571

Spontaneous chiral symmetry breaking

Suppose the symmetry is realized in the **Wigner-Weyl mode.**

- **In the massless quark limit** a chiral transformation acting on a massive state gives

$$Q_5^A|M, s, \mathbf{p}, +, i\rangle = (T^A)^j{}_i|M, s, \mathbf{p}, -, j\rangle$$

- This means that we should find **parity partners** for the massive states. **When we consider the light quark masses, the degeneracy within parity doublets is lifted, but the masses should remain close to each other.**
- No parity doublets are observed, thus the Wigner-Weyl mode realization of chiral symmetry does not happen for **ordinary conditions.**

The alternative is **spontaneous symmetry breaking, also known as Nambu-Goldstone mode.**

Spontaneous chiral symmetry breaking

- What happens if the generators of some transformations do not annihilate the vacuum?

$$Q_5^A|0\rangle \neq 0$$

- In this case we say that **the symmetry has been spontaneously broken.**
- The axial charges when applied to the vacuum state produce new states

$$Q_5^A|0\rangle = |A,-\rangle, \quad A = 1, ..., N_f^2 - 1$$

- The states have the same properties as the axial charges that generate it, in particular **they are pseudoscalar states.**

Spontaneous chiral symmetry breaking

- In the massless limit, **the charges commute with the Hamiltonian** therefore, **these states are massless (Goldstone theorem).**
- **Spontaneous chiral symmetry breaking** is manifested by means of the existence of $N_f^2 - 1$ pseudoscalar massless particles called **Nambu-Goldstone bosons.**
- The breaking of the symmetry involves only the axial sector. The ordinary flavor symmetry is still realized in the Wigner-Weyl mode.

$$SU(N_f)_L \otimes SU(N_f)_R \longrightarrow SU(N_f)_V$$

- If $N_f = 3$, this corresponds to **eight** pseudoscalar bosons (π, K, η) with small masses (exercise: how is the parity of a particle measured?).

Confinement

Under "ordinary" circumstances, quarks are **confined within hadrons.**

Color force characteristics:

1. Potential between two quarks at **"long"** distances of $\mathcal{O}(1\text{ fm})$, is linear.
2. Separation of quarks requires **"infinite"** amount of energy.
3. **Confinement** is a direct **consequence of gluon self-interaction.**
4. Quarks and gluons confined by QCD potential must combine into zero net color charge particles called **hadrons.**

Strong running coupling

Strength of strong interaction characterized by coupling ~~constant~~

$$\alpha_s = \frac{g_s^2}{4\pi}$$

Running α_s

1. Decreases with distance.
2. Bare color charge is **antiscreened** due to gluon self-interaction .

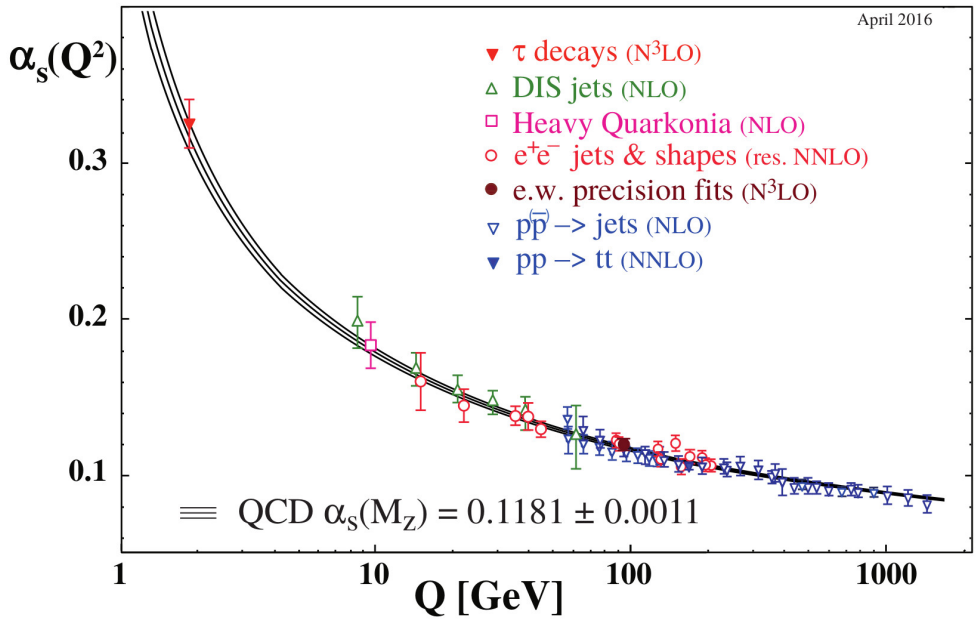


Figure 9.3: Summary of measurements of α_s as a function of the energy scale Q. The respective degree of QCD perturbation theory used in the extraction of α_s is indicated in brackets (NLO: next-to-leading order; NNLO: next-to-next-to leading order; res. NNLO: NNLO matched with resummed next-to-leading logs; N^{3}LO: next-to-NNLO).

Confinement + Running coupling

e.g. RG analysis of the gluon polarization tensor

$$\Pi^{\mu\nu}(q) = \Pi(q^2, \alpha_s)\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)$$

gauge invariance dictates that the gluon polarization tensor be transverse

$\Pi(q^2, \alpha_s)$ represents the un-renormalized gluon self-energy

Let us scale each factor of the momentum q appearing in Π by the renormalization ultraviolet energy scale $\tilde{\mu}$; $q^2 = \tilde{\mu}^2(q^2/\tilde{\mu}^2)$

The statement that Π should be independent of this scale is provided by the **Renormalization Group Equation (RGE)**

$$\left(\tilde{\mu}\frac{\partial}{\partial\tilde{\mu}} + \alpha_s\beta(\alpha_s)\frac{\partial}{\partial\alpha_s} - \gamma\right)\Pi(q^2;\alpha_s) = 0$$

Beta function

$$\alpha_s \; \beta(\alpha_s) = \tilde{\mu} \frac{\partial \alpha_s}{\partial \tilde{\mu}}$$

represents the rate of change of the renormalized coupling as the renormalization scale $\tilde{\mu}$ is increased

- The dependence of a given Green's function on $\tilde{\mu}$ happens through the counter-terms that subtract ultraviolet divergences.
- At lowest order

$$\beta = g_s \tilde{\mu} \frac{\partial}{\partial \tilde{\mu}} \left(-\delta_1 + \delta_2 + \frac{1}{2} \delta_3 \right) \equiv -b_1 \alpha_s$$

where δ_1, δ_2 and δ_3 are the counter-terms for the quark-gluon vertex, the quark self-energy and the gluon self-energy

Running coupling

Competition between color and flavor

$$\alpha_s(Q^2) = \frac{\alpha_s(\tilde{\mu}^2)}{\left[1 + b_1 \alpha_s(\tilde{\mu}^2) \ln\left(\frac{Q^2}{\tilde{\mu}^2}\right)\right]}$$

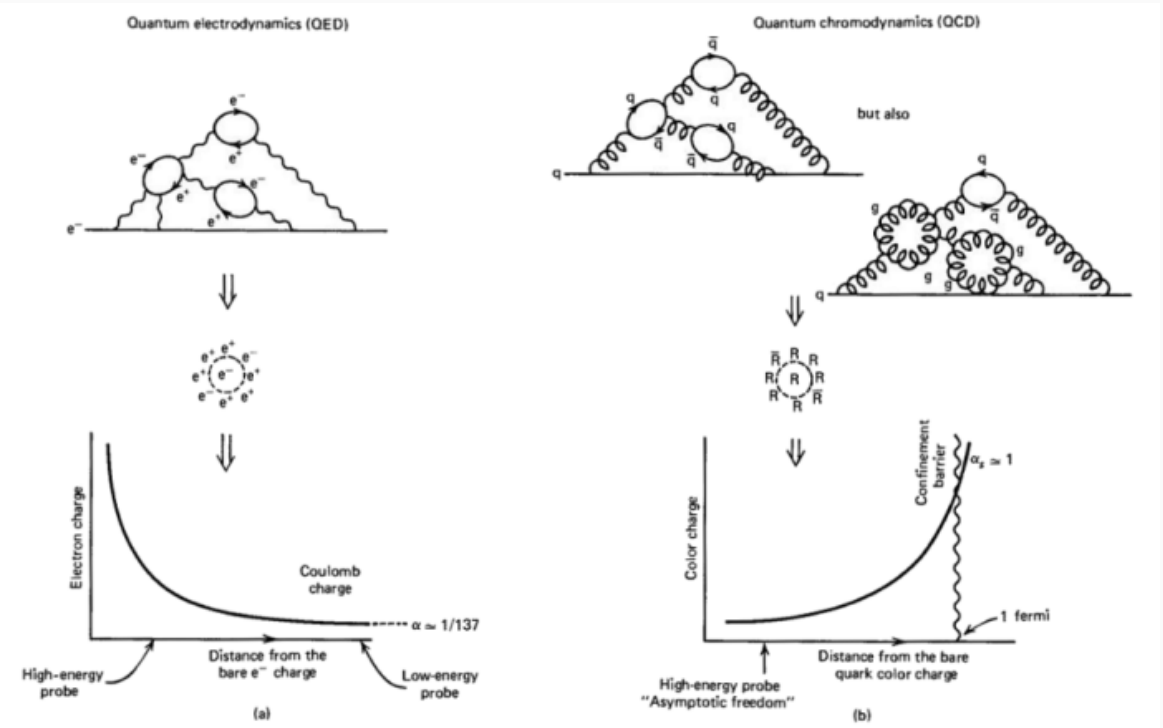
with

$$b_1 = \frac{11N_c - 2N_f}{12\pi}$$

and

$$N_c = 3, \quad N_f = 6 \quad \Longrightarrow \quad b_1 > 0$$

α_s decreases with Q



Halzen and Martin, Quarks & Leptons "black book"

Λ_{QCD}

Processes where perturbation theory can be applied are usually those where the transferred momentum satisfies $Q^2 \gtrsim 1$ GeV^2: **perturbative vs non-perturbative** regimes

- we can define a transferred momentum value Λ_{QCD} small enough such that the coupling blows up

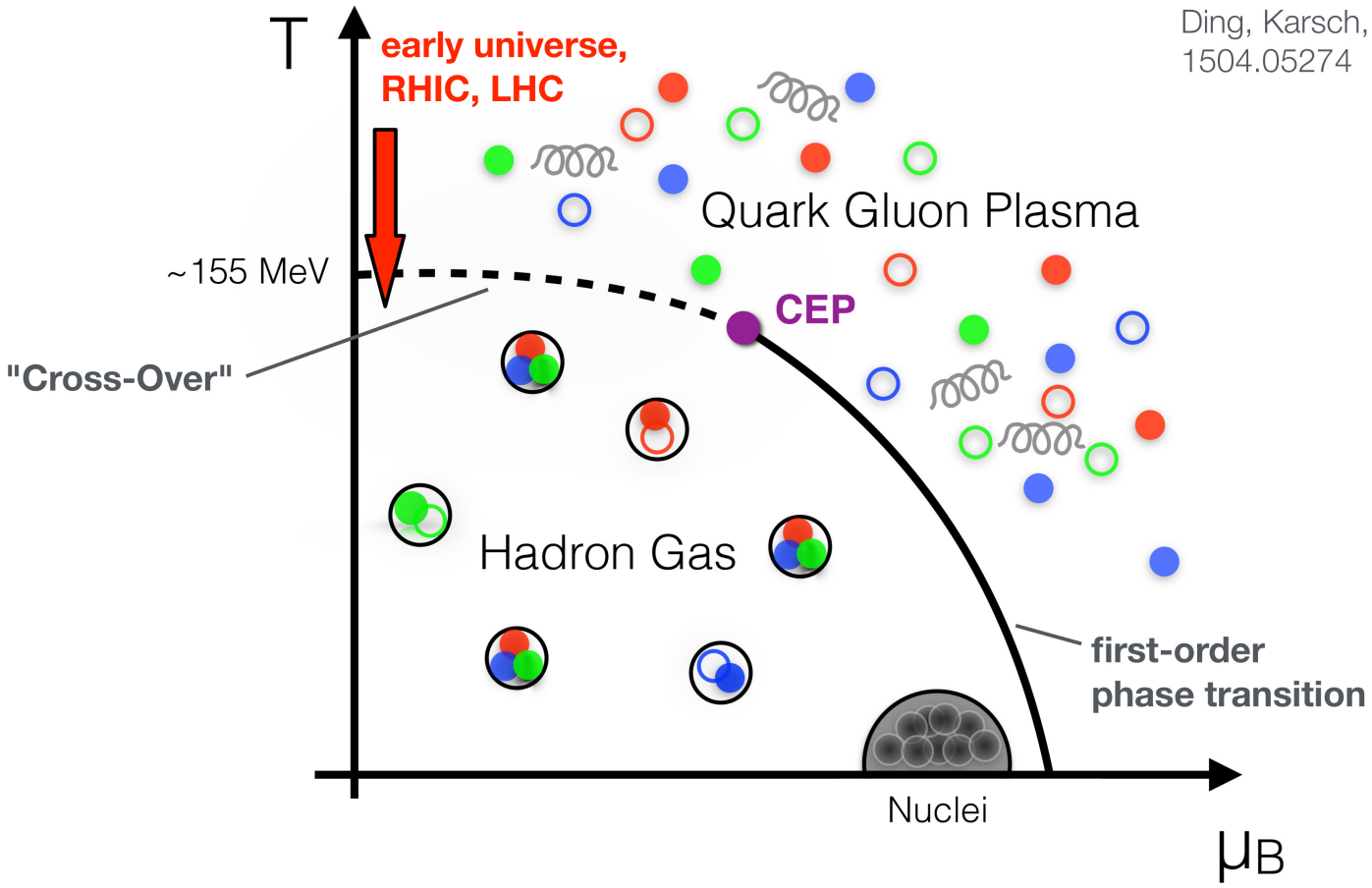
$$1 + b_1 \alpha_s(\tilde{\mu}^2) \ln(\Lambda_{QCD}^2/\tilde{\mu}^2) = 0, \quad \Lambda_{QCD}^2 = \tilde{\mu}^2 e^{-\frac{1}{b_1 \alpha_s(\tilde{\mu})}}$$

- where Λ_{QCD} is a renormalization scheme dependent quantity.
- in the $\overline{\text{MS}}$ scheme and for three active flavors, its value is of order $\Lambda_{QCD} \sim 200 - 300$ MeV.
- all dimensionful QCD results where the transferred momentum is small, scale with Λ_{QCD}
- the existence of this scale is a key ingredient for the emergence of baryon masses and thus of the mass of the visible universe

The phase diagram: QCD at finite T and μ_B.

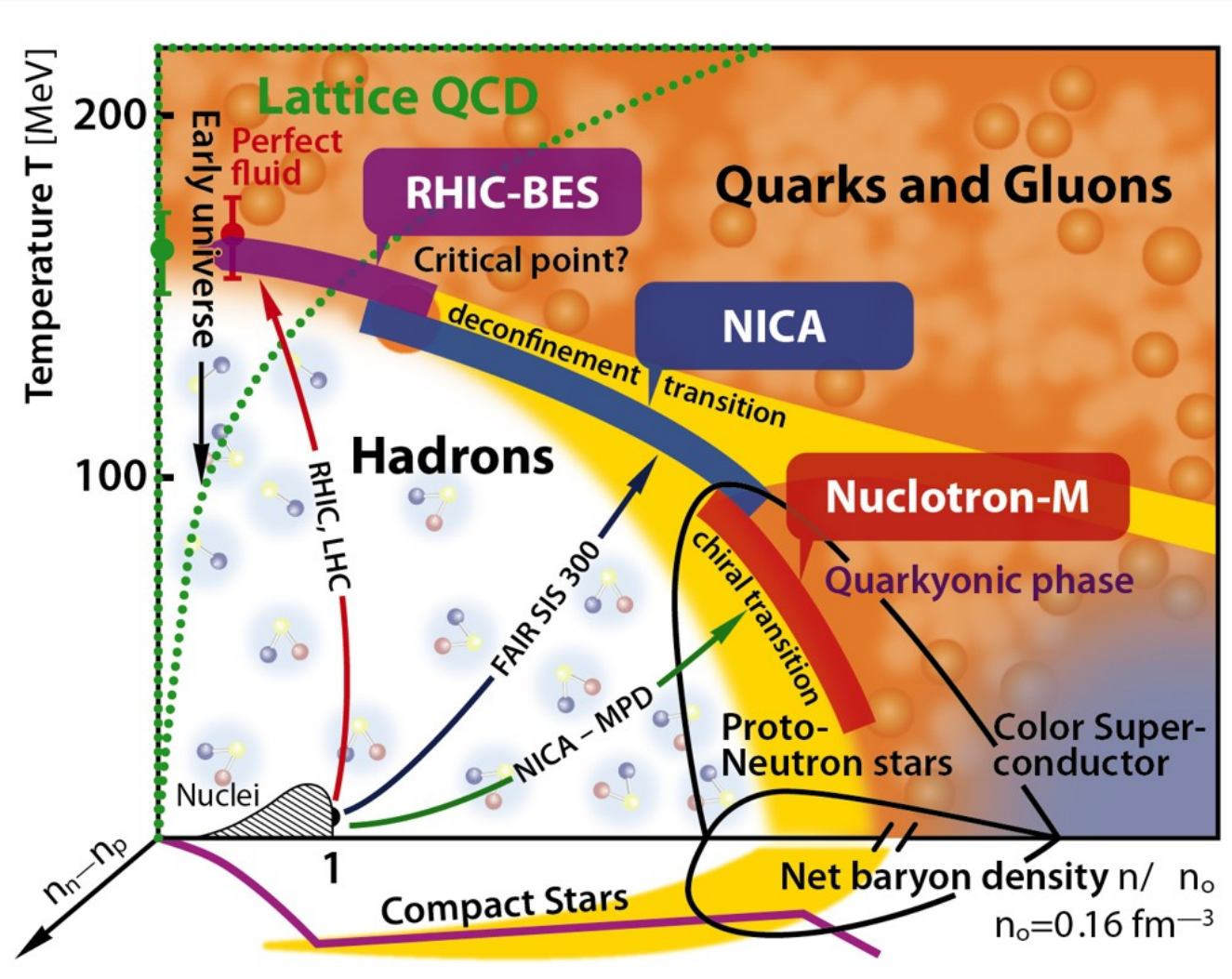
- two important parameters for QCD in equilibrium: The **temperature** T and the **baryon number density** n_B (or its conjugate variable $\mu_B = 3\mu_q$).
- the intrinsic scale of QCD is $\Lambda_{QCD} \sim 200$ MeV, one expects a transition around $T \simeq \Lambda_{\mathrm{QCD}} \sim 200$ MeV, $n_B \sim \Lambda^3_{QCD} \sim 1$ fm^{-3}.
- the coupling constant runs towards smaller values with increasing energy scale **it is natural to anticipate that confined and chiral symmetry broken QCD matter undergoes a phase transition at high energy densities**

(Conjectured) QCD phase diagram



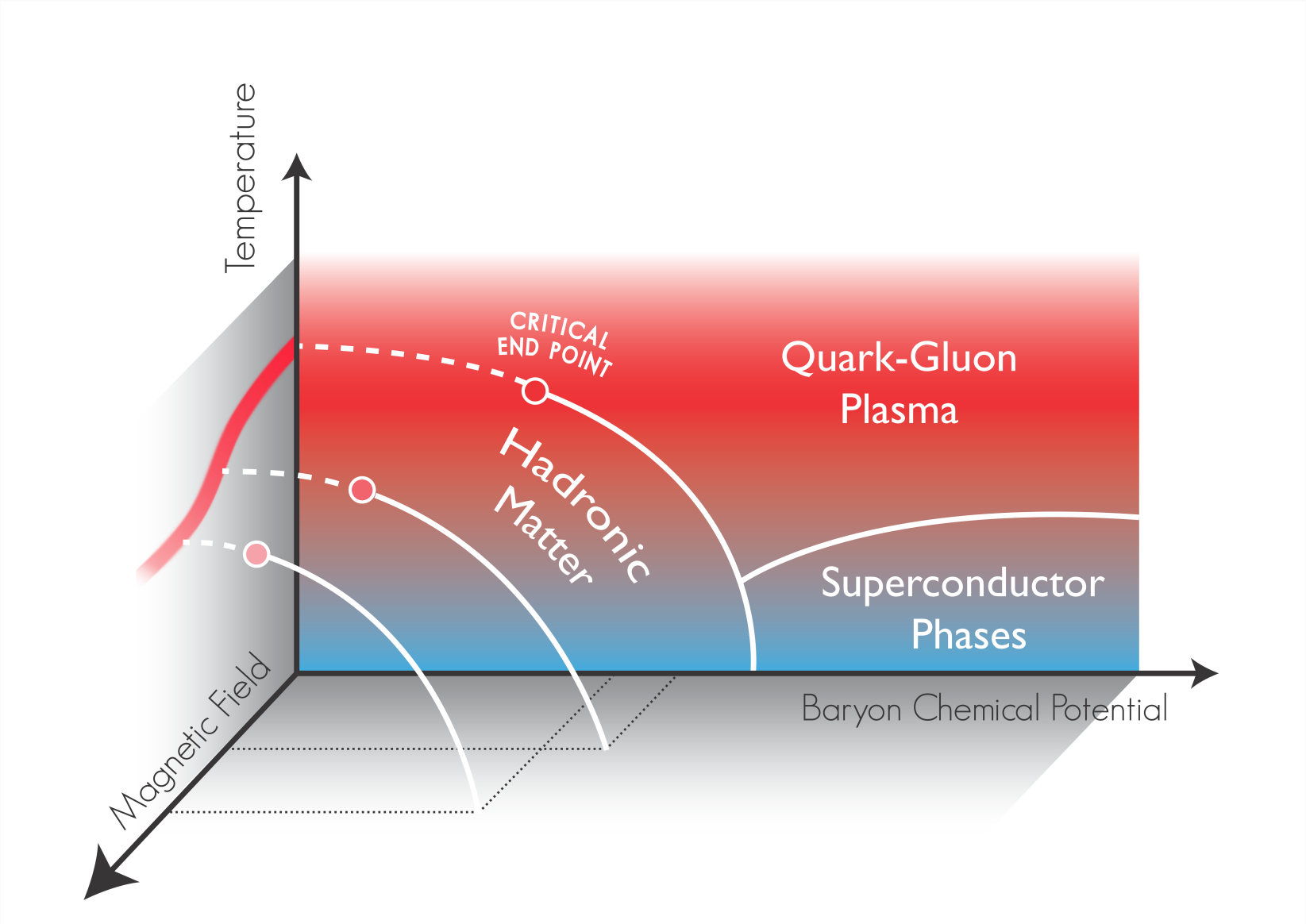
ultimate goal: contact with first-principles QCD calculations

QCD phase diagram explored with HICs



http://nica.jinr.ru/

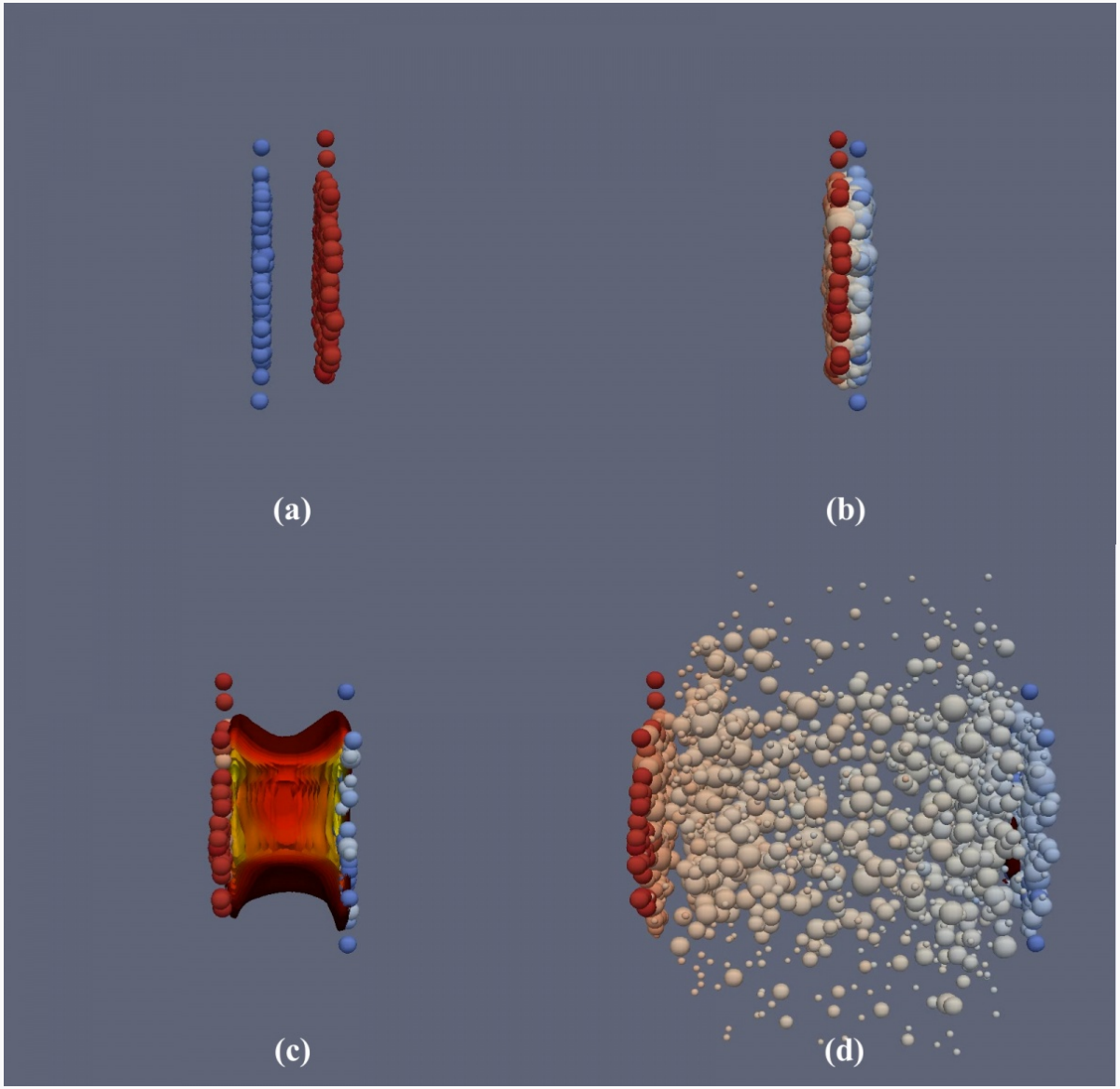
QCD phase diagram beyond HICs



https://compstar.uni-frankfurt.de/outreach/

Relativistic heavy ion collisions

What happens when two ultra relativistic nuclei collide?



https://sciencenode.org/feature/modeling-heavy-ion-collisions-open-science-grid.php

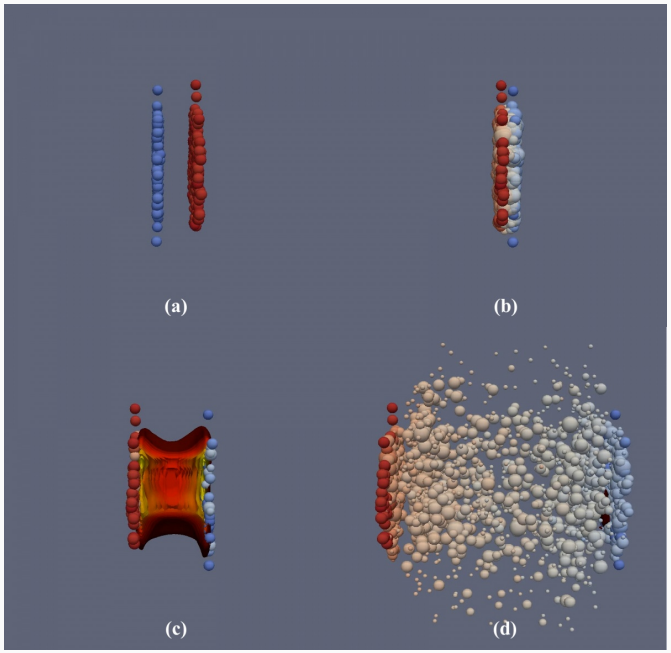
HICs initial state specs

- "lab frame" at a collider: CM frame
- each incident nucleus is a Lorentz contracted disc
- diameter of disc: 14 fm (femtometer or Fermi) for A = Pb, Au
- thinkness of disc: $14/\gamma$
- Lorentz factor: $\gamma \sim 100$ at RHIC, $\gamma \sim 2500$ at LHC
- Rapidity: $y \sim 5.3$ at RHIC, $y \sim 8.5$ at LHC

Rapidity (y)

(momentum) rapidity is $\cosh(y) \equiv \gamma$ where $\gamma = \sqrt{1 - v_z^2}$ and v_z along the beam direction - could also define $\tanh(y_s) \equiv z/t$ (with z and t centered at the collision), why don't we use y_s? (exercise). In a boost invariant flow where $v_z = z/t$, then $y = y_s$.

What happens when two ultra relativistic nuclei collide?

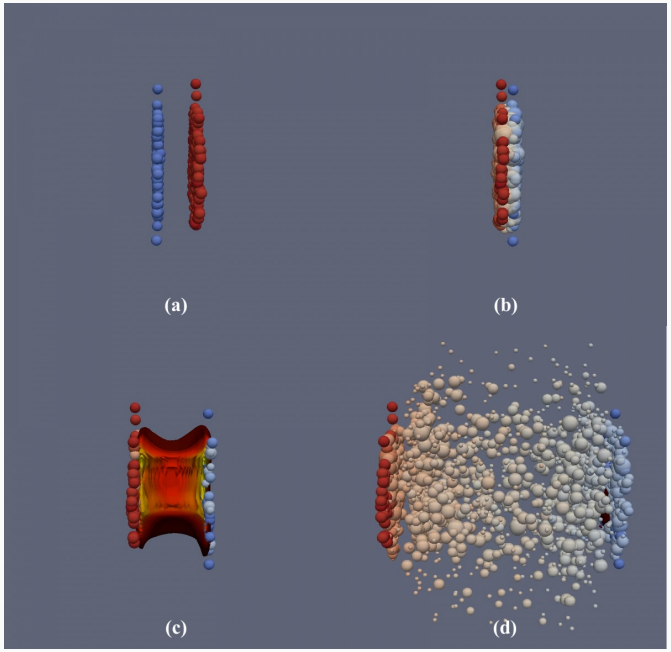


- each disc with many colored q and $\bar{q}$
- $\#q > \#\bar{q}$ per nucleon in the incident nuclei
- $q\bar{q}$ pairs coming from quantum fluctuations

- time dilated initial-state wave function are "almost real"
- all q and $\bar{q}$ become sources of colored gluons
- greater area density of all partons with higher velocity of nuclei
- non-uniform area density that fluctuates from nucleus to nucleus
  - incident nuclei: complex parton system long mom dist -structure func-
  - nuclei structure func $\sim$ superposition of individual nucleons + small modifications - proximity + motion of nucleons in nuclei

What happens when two ultra relativistic nuclei collide?

- most of the incident partons lose some energy but are not kicked by any large angle - soft intns, little transverse momentum transfer -
- some color charge exchange occurs between the discs: longitudinal color fields are produced
- long color fields fill the space between the receding two discs, reducing the energy in the discs themselves, and then gradually decay $q\bar{q}$ pairs + gluons
- small fraction of the incident partons under hard intns: relatively improbable but VIP of particles with high p_T



- thin discs -of strongly interacting transverse color fields and associated color charges- collide/overlap

HI collision specs

Collision energy ($\sqrt{s_{NN}}$)

Total collision energy per nucleon-nucleon pair in the center of mass frame, e.g. 200 GeV at RHIC, 2.76 TeV at LHC.

Pseudorapidity (η)

$\eta \equiv -\log[\tan(\theta/2)]$ where θ is the polar angle in momentum space, relative to the beam direction. Standard proxy for rapidity (y) since $\eta = y$ for massless particles.

HIC ϵ estimate (exercise)

As the two highly Lorentz contracted nuclei collide, ϵ_{max}: system far from equilibrium, so what is $\langle\epsilon\rangle$ **1 fm/c after the collision**? How far apart are the two discs?

$\rightarrow$ around the midpoint between the two discs, where the collision occurred, $\epsilon \gg 500$ MeV/fm^3 ($\sim \epsilon_{hadron}$)... how much greater?

- LHC ($\sqrt{s_{NN}} = 2.76$ TeV - $\gamma = 1400$ and $y = 8$), particles with $-0.5 < \eta < 0.5$ (how much longitudinal velocity?) measured to have total transverse $\epsilon = 1.65 \pm 0.1$

$$\langle\epsilon\rangle \sim \frac{1.65 \text{ TeV}}{\pi(7 \text{ fm})^2(0.92 \text{ fm})} \sim 12 \text{ GeV/fm}^3 \sim 20\ \epsilon_{hadron}$$

ALICE Collaboration, A. Toia, J.Phys. G38, 124007 (2011), arXiv:1107.1973

HICs: large energy density (ϵ) and entropy (s)

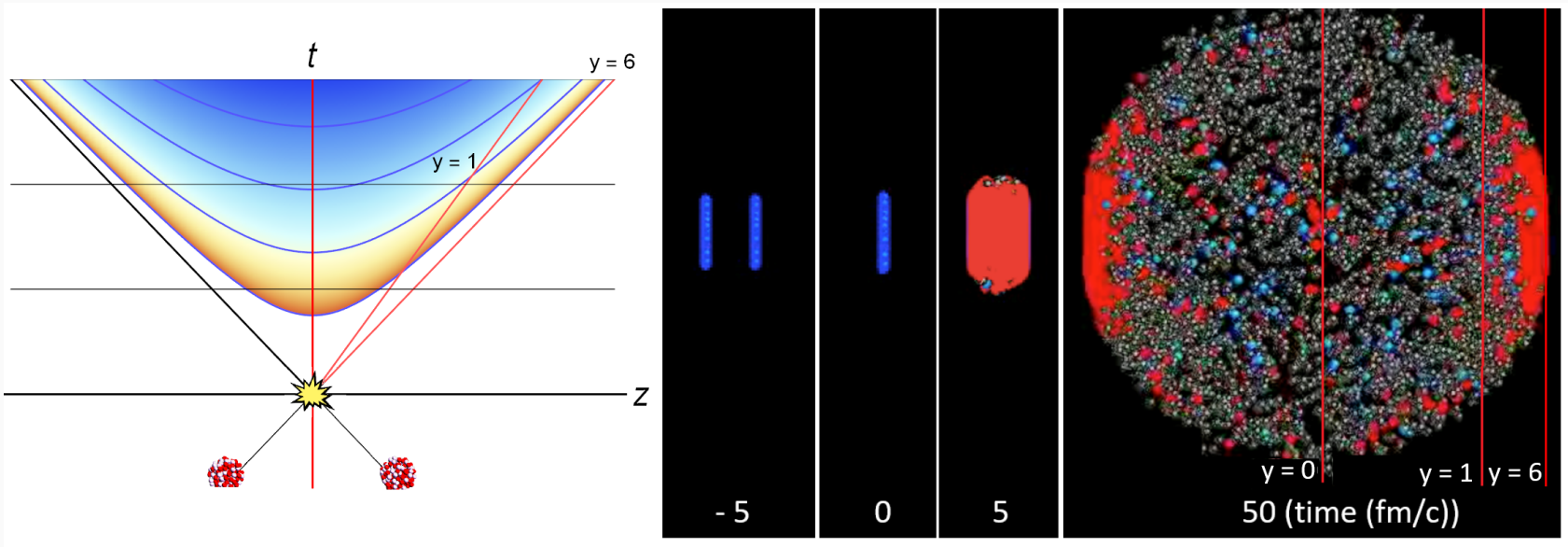
- $\surd$ Our estimate (LHC): $\langle\epsilon\rangle \sim 20\ \epsilon_{hadron}$
- $\surd$ Lattice QCD: matter in thermal equilibrium at $T \sim 300$ MeV has $\epsilon \sim 12\ T^4 = 12.7$ GeV/fm^3
- medium formed after collision cannot be described as a collection of distinct individual hadrons, but rather it is made out of a high density of quarks and gluons
- before the collision the entropy of the two incident nuclei is essentially zero
- after the collision the final state can contain as many as 30,000 particles
- most of this entropy is produced quickly, in the initial moments after the collision

$\rightarrow$ see later

New state of nuclear matter in HICs

Quark-Gluon Plasma (QGP)

q's + g's strongly coupled, collective medium that expands and flows as a relativistic hydrodynamic fluid with low viscosity to entropy density ratio $\frac{\eta}{s} \sim \frac{1}{4\pi}$ for $t \lesssim 1$ fm/c (fluid rest frame)



Busza, Rajagopal, van der Schee, Ann. Rev. Nucl. Part. Sci. 2018

QGP expansion in HICs

droplet of fluid flows hydrodynamically: its initial high pressure drives fluid motion, expansion, and consequent cooling...

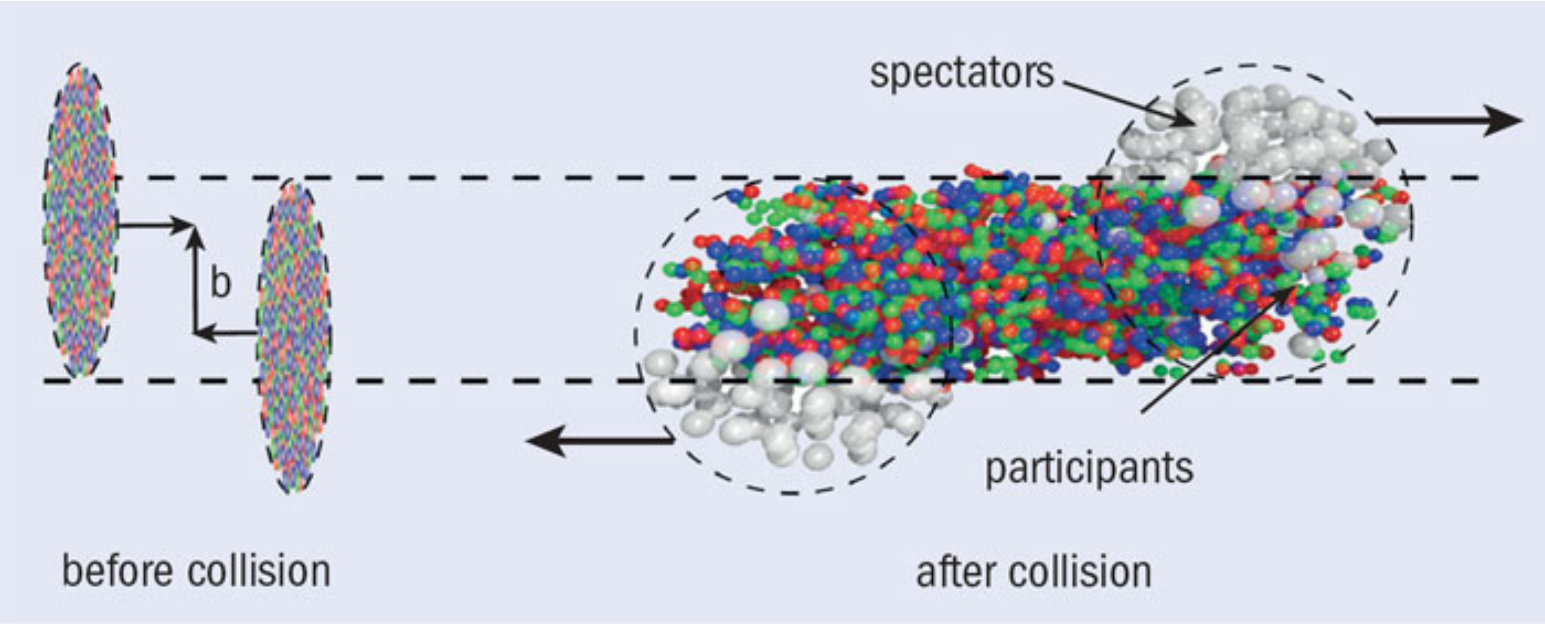
...until $\epsilon_{droplet} < \epsilon_{hadron}$

...then *mist* of hadrons that scatter off each other a few times and then stream away freely

A+A vs p+p particle production

This particle production mechanism (hydro + hadronization), via an intermediate epoch during which a hydrodynamic fluid forms and expands, is quite different from the current understanding of particle production in elementary collisions in which only a few new particles are created.

Centrality in HICs



https://cerncourier.com/participants-and-spectators-at-the-heavy-ion-fireball/

Central and off-central or peripheral HICs

Ions colliding head-on vs ions only partially overlapping at collision

In the overlap region again the droplet of QGP forms, but now its initial shape in transverse plane is not as perfectly **lenticular** as with head-on/central collisions.

Centrality in HICs

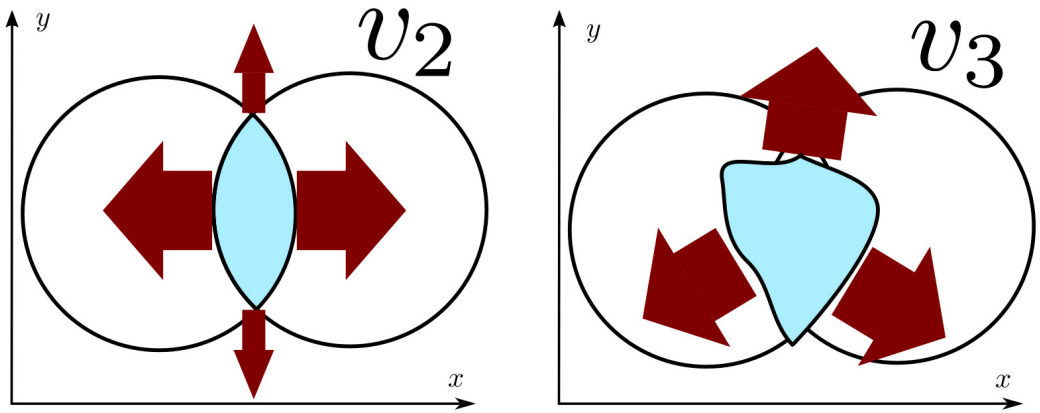


Figure 2.1: Illustration of the overlap region (shaded area) of two colliding nuclei (circles). The arrows indicate the hydrodynamic flow. (a) The event averaged "almond shaped" overlap of peripheral collisions driving the elliptic flow v_2. (b) Triangular deformations due to event-by-event fluctuations causing the triangular flow v_3. arXiV: 1702.01202

Hadron azimuthal momentum dist from HICs

Deviations from circular symmetry in the initial shape of the QGP - due to off-center collisions or lumpiness and fluctuations of the incident nuclei $\rightarrow$ preassure anisotropies in hydro fluid $\rightarrow$ anisotropies in the expansion velocity $\rightarrow$ azimuthal momentum distribution of the finally produced particles

Participants vs spectators in HICs

1. participants: nucleon that collides with at least another nucleon
2. spectators: nucleon that does not collide and hence keeps on moving along the beam direction
3. binary collisions: total number of nucleon pairs that collide, assuming transparency of the collision

At early times, spectators/participants create magnetic fields in the collision zone whose effects are the subject of much discussion $\rightarrow$ see later

Later, they fragment into excited nuclei and hadrons, moving with almost the full rapidity of the incident nuclei.

Ultraperipheral collisions:

The extreme limit of an off-center collision, the nuclei miss each other but the Lorentz-contracted disc of EM fields around them do interact. These collisions give rise to $\gamma\gamma$ and γA interactions which dominate the total nucleus-nucleus x-sec

How do we access the different stages of a HIC?

We have only two quantities under our direct control: which two nuclei we collide and at what energies (to high precision).

But knowing the colliding nuclei $\neq$ knowing the colliding systems.

We have to infer, event by event, from the observed outcome of the collision (and from other experiments):

1. impact parameter b: transverse distance between CoM of 2 nuclei
2. location and motion of nucleons in nuclei
3. location and motion of partons in nucleons

How do we access the different stages of a HIC?

After the fact, it is possible to select an ensemble of collisions with a *relatively narrow distribution of b*.

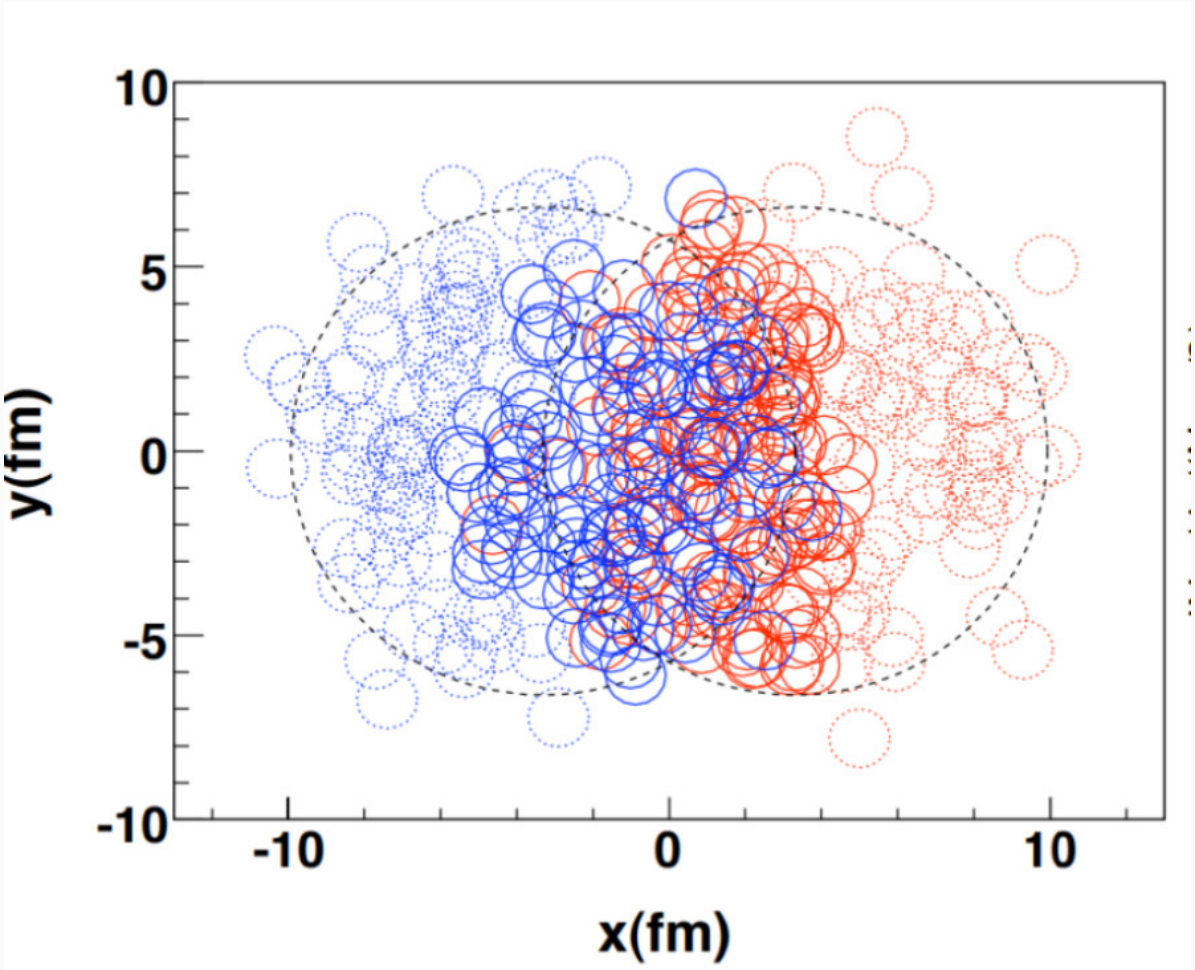
PoV of RHIC studies + nuclear and particle phys studies: the nuclei can instantaneously be *reasonably well* approximated by a collection of nucleons, dist on avg according to a well-determined 3D dist.

Average quark and gluon content of the nucleons in nuclei in terms of PDFs: nPDFs (PDFs of nucleons in nuclei) $\approx$ PDFs (free nucleons)

Use the measured tot inel pp x-sec $\sigma_{pp}(\sqrt{s})$: model the nucleons in the nucleus as hard spheres with a radius that depends on energy

N_{part}, N_{spec}, N_{coll} and all that

Imagine the colliding nuclei made of A - transparent - spheres of radius $\sqrt{\sigma_{pp}/4\pi}$. Say the number of nucleons inside the left- and right-moving nuclei are A_L and A_R.



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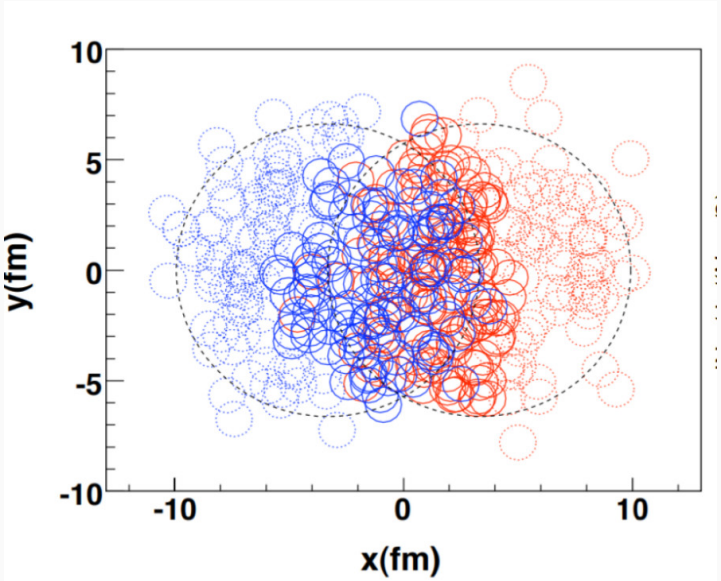


N_{spec}: # nucleons down the beam pipe dashed circles :(

N_{part}: # wounded nucleons, collide with at least one other nucleon

$$N_{spec} + N_{part} = A_L + A_R$$

N_{coll}: # of encounters between nucleons in A_L and in A_R

N_{part}, N_{spec}, N_{coll} and all that

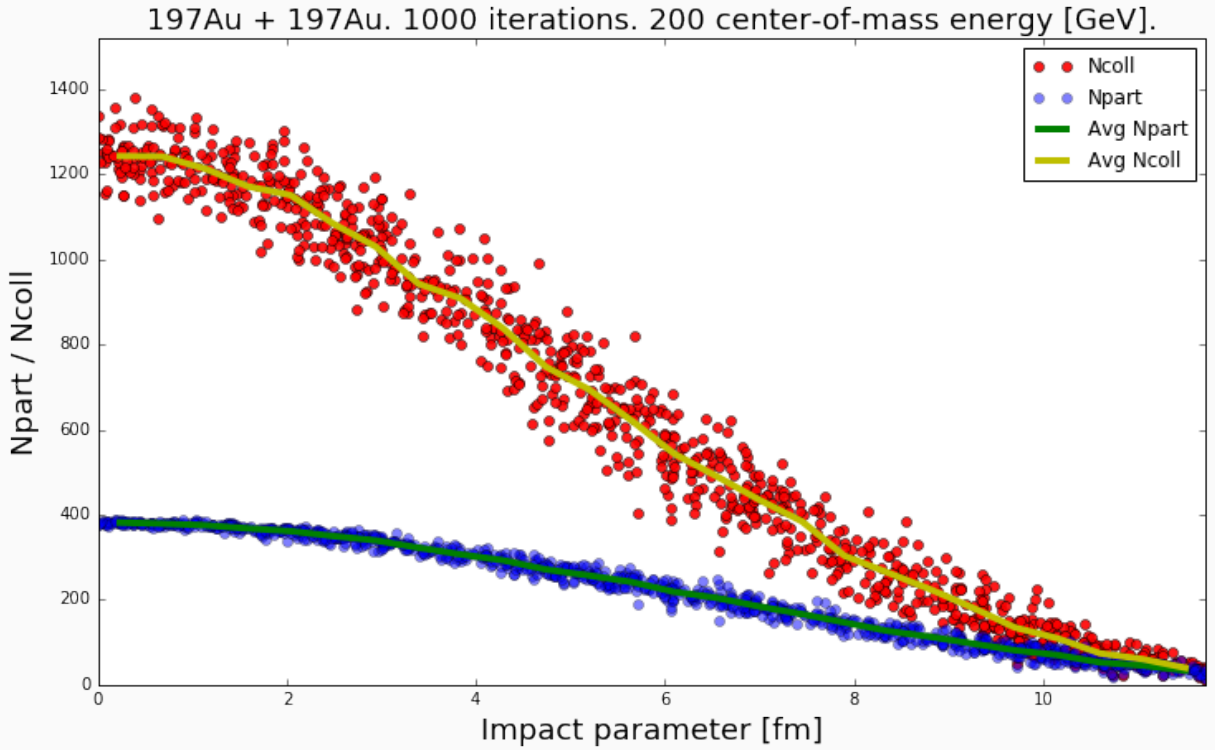
Imagine the colliding nuclei made of A - transparent - spheres of radius $\sqrt{\sigma_{pp}/4\pi}$. Say the number of nucleons inside the left- and right-moving nuclei are A_L and A_R.

Example: a "nucleus" of 7 nucleons lined up in a row and it collides head-on ($b = 0$) with a "nucleus" of 4 nucleons in a row:

$$N_{part} = 11, N_{coll} = 28, N_{spec} = 0$$

Real central HICs: nucleon at the center of nucleus will -on average- hit about 12 nucleons from the other, but less if it is located at the edge of the collision: $N_{coll} \gg N_{part}$, even more so for the more central collisions.

Glauber Model and $p + A$ vs $A + A$



https://github.com/MCGlauber

In $p + A$ collisions, ratio of inel x-secs σ_{pp}/σ_{pA} is probability of the proton hitting another nucleon.

Then it is possible to determine $\langle N_{coll} \rangle$ as $N_{part} - 1 = A\ \sigma_{pp}/\sigma_{pA}$: can be measured directly :) (exercise)

Experimental data on pA collisions with widely varying A and collision energies (going back to the 1970s): # particles produced in these collisions $\sim N_{part}$

Glauber model - initial conditions

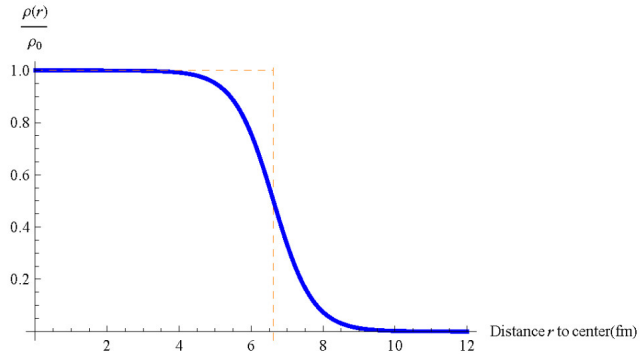
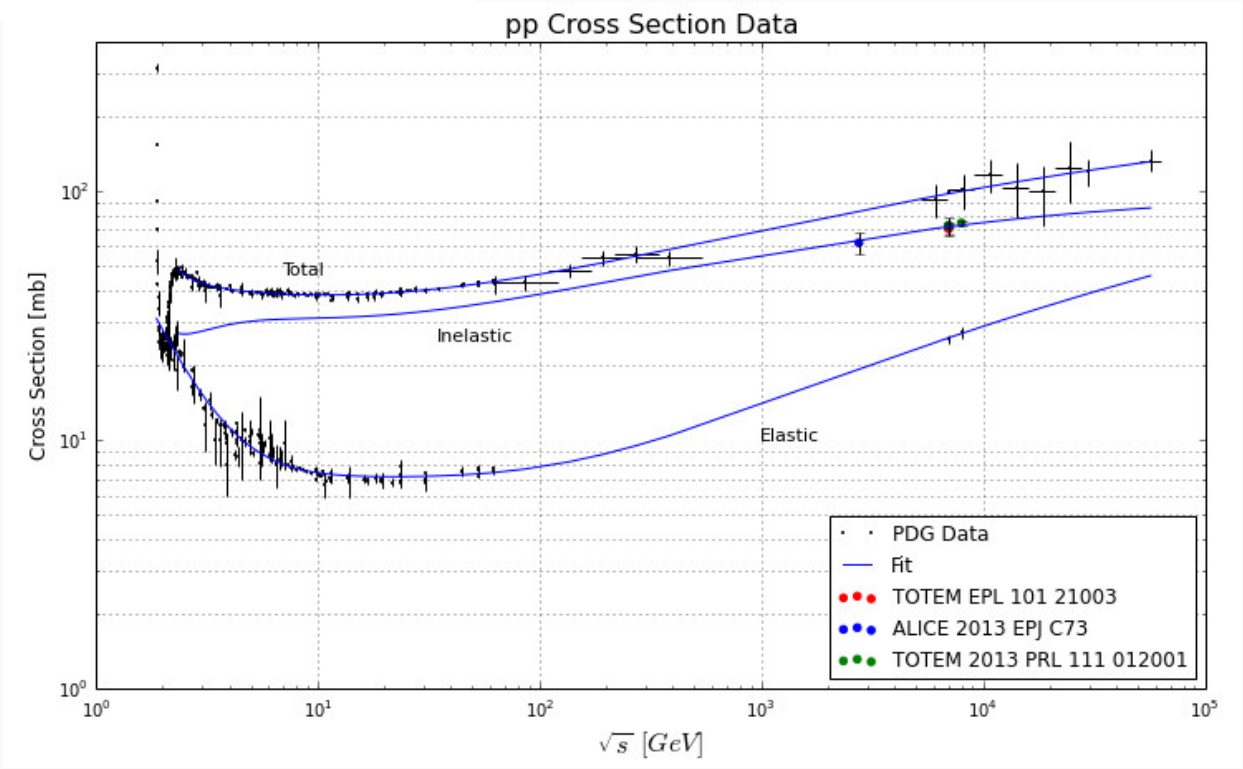


Figure 1: Density distribution for Pb-207 nuclei.

nuclear charge density: Wood-Saxon
$\rho = \rho_0 \ [1 + \exp\{(r - R)/a\}]^{-1}$
inelastic xsec σ^{NN} (the only non trivial input)



https://github.com/MCGlauber

Glauber model - initial conditions

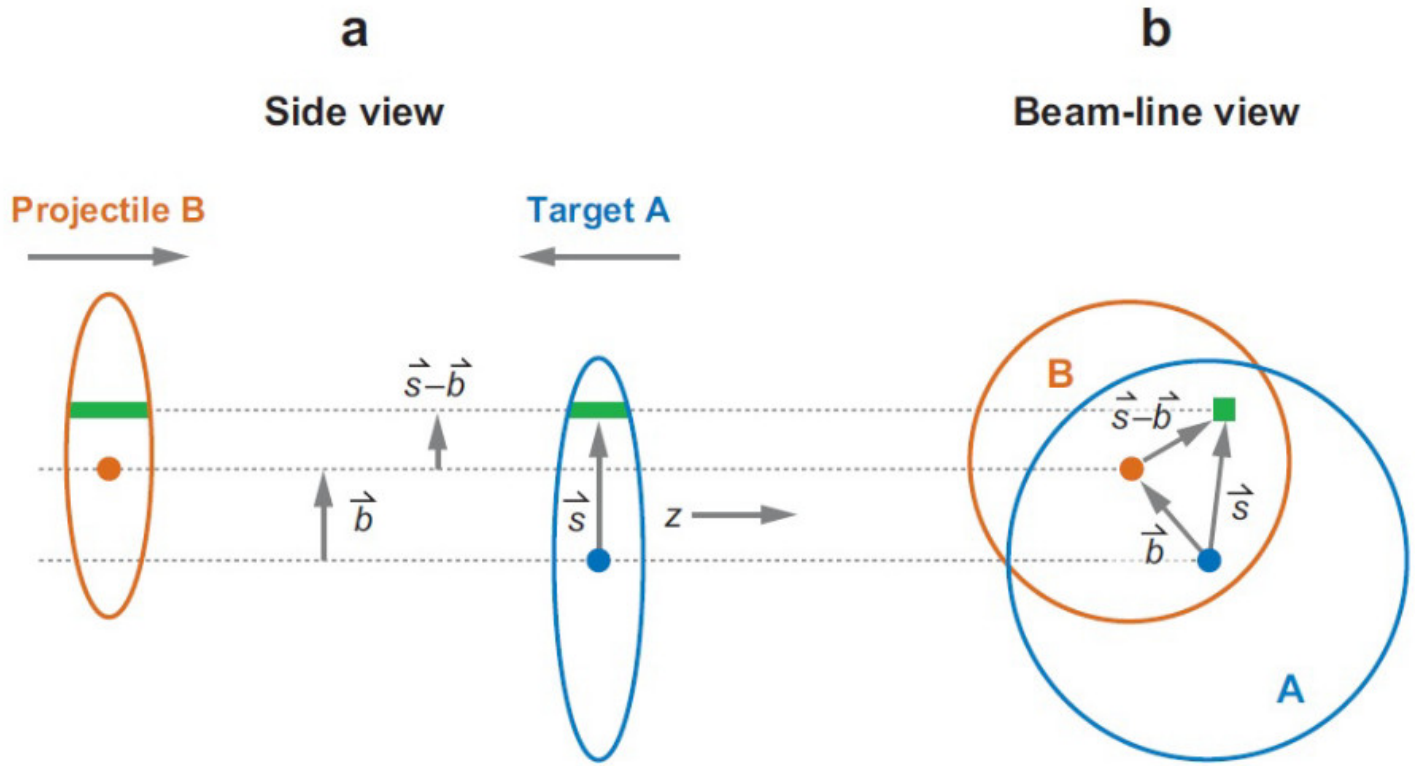
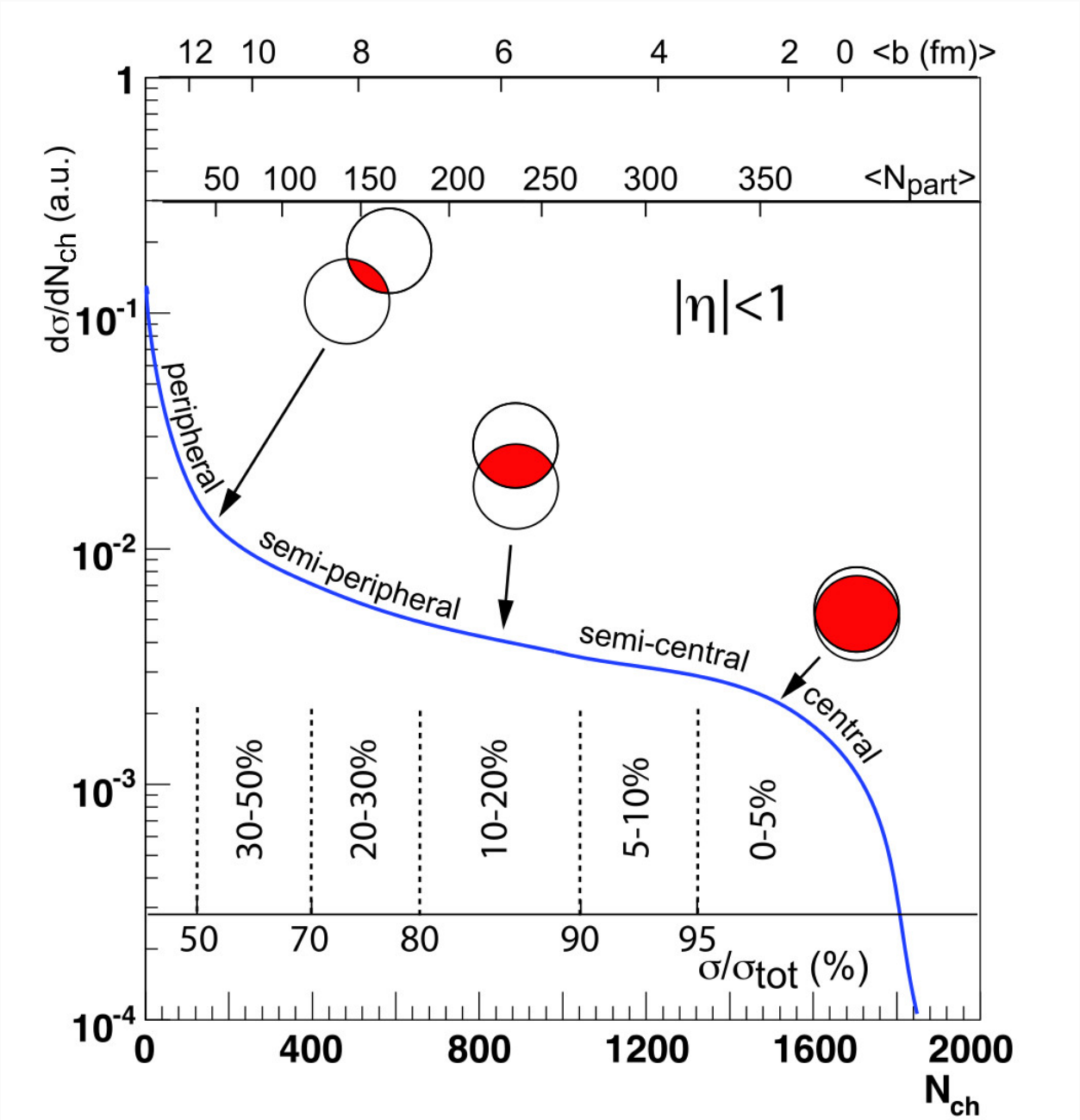


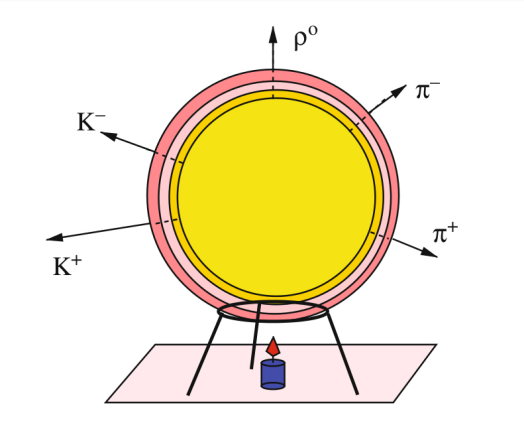
Figure 2: Schematic representation of the Optical Glauber model geometry, with transverse (a) and longitudinal (b) views.

Glauber model: centrality, $\langle b \rangle$, $\langle N_{part} \rangle$

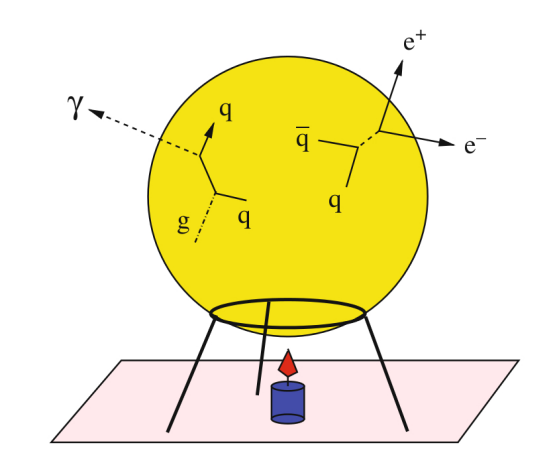


Probes of the QGP in HICs

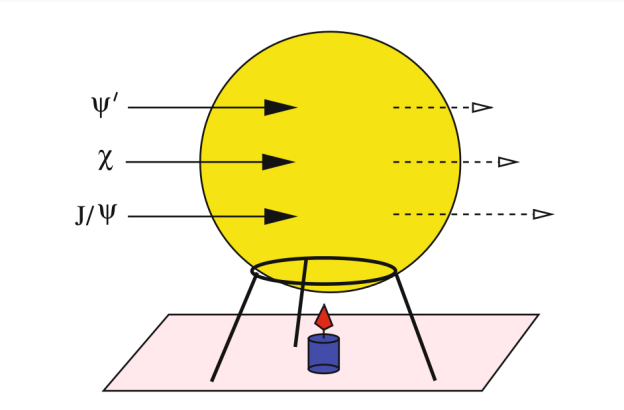
hadronic radiation



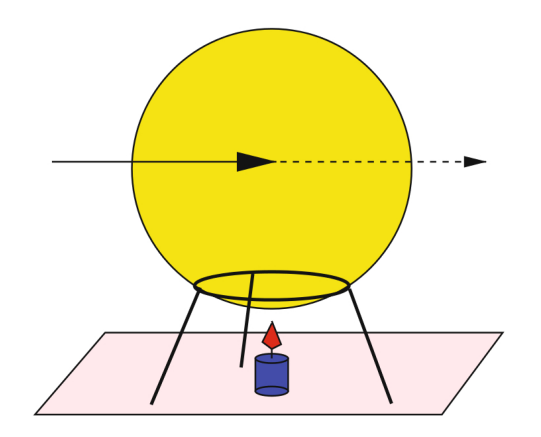
electromagnetic radiation



quarkonia dissociation



parton/jet energy-loss



H. Satz, J. Phys. G: Nucl. Part. Phys. 32 R25 (2006)

Hard probes of the QGP in HICs

Partonic hard collisions in the incident nuclei that produce high p_T (tens of GeV) particles, are rare but VIP.

Produce high-energy parton pairs and EW bosons at the earliest times of the overall collision process

The high-energy partons evolve, decay, radiate and finally produce a cone-shaped spray or *jet* of hadrons and/or high-energy photons, leptons or heavy $Q\bar{Q}$ pairs, all while traversing a region where QGP is in the process of being produced and evolving.

They *x-ray* the medium, and on how partons lose energy or disturb the medium as they interact with it. $\rightarrow$ see later