High-Energy Heavy-Ion Collisions and Underlying QCD Phenomena

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Outline

- Introduction
- Initial State, Color Glass Condensate
- Hydrodynamical Evolution, Late Stages
- Tomography and Hard Probes
- Thermometric Probes
- Summary and Outlook

Introduction

Elementary forces in Nature

- Gravitation
- Electromagnetism
- Weak nuclear force
- **Strong nuclear force**

- Well tested microscopic quantum description for all but gravity
- Matter $\sim$ spin-$1/2$
- Force carriers $\sim$ spin-1 (spin-2 for gravity)
- Higgs $\sim$ spin-0 (non-zero vacuum expectation value)

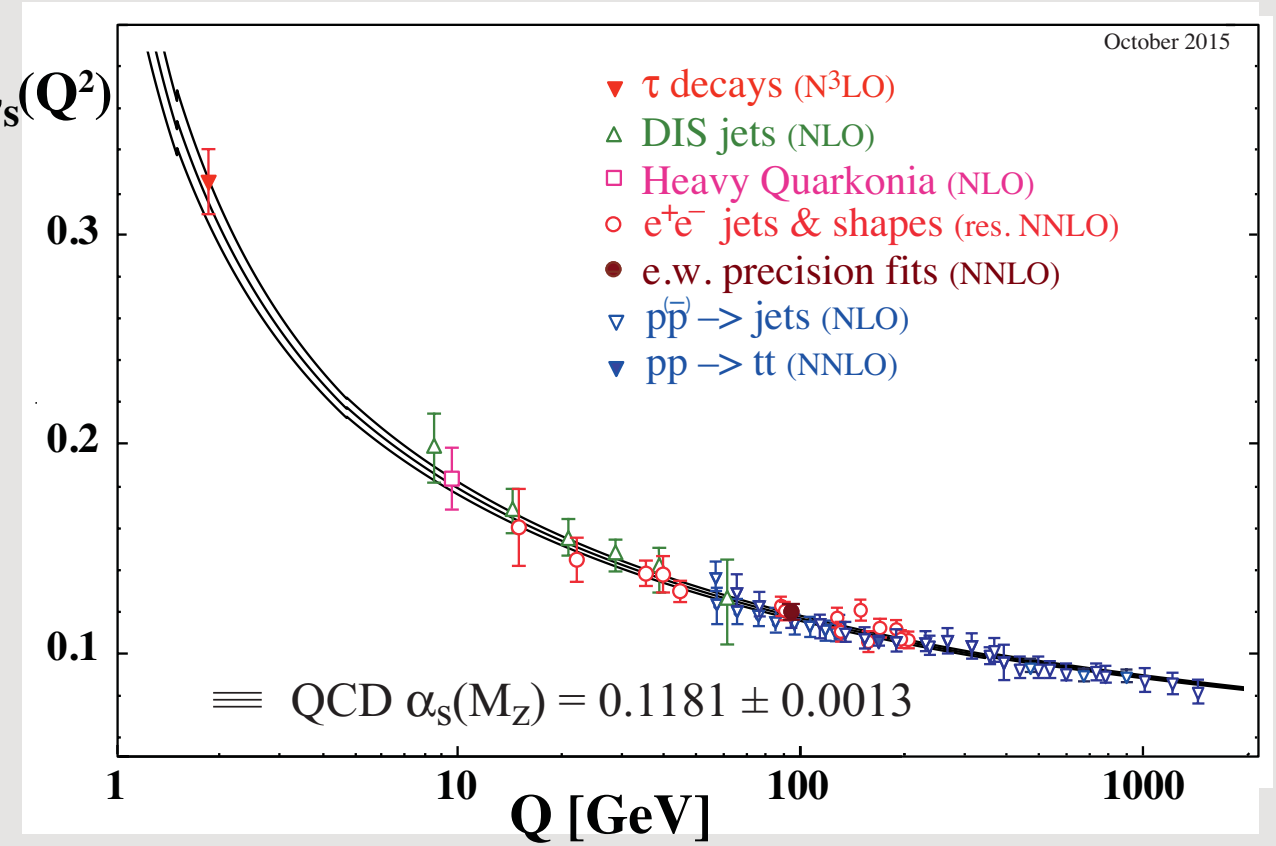
Strong nuclear force

- Fundamental theory: **Quantum ChromoDynamics**
- Matter fields: 6 families of 3 quarks and antiquarks
- Force carriers: 8 gluons
- *Asymptotic freedom*: interactions weaken at short distance

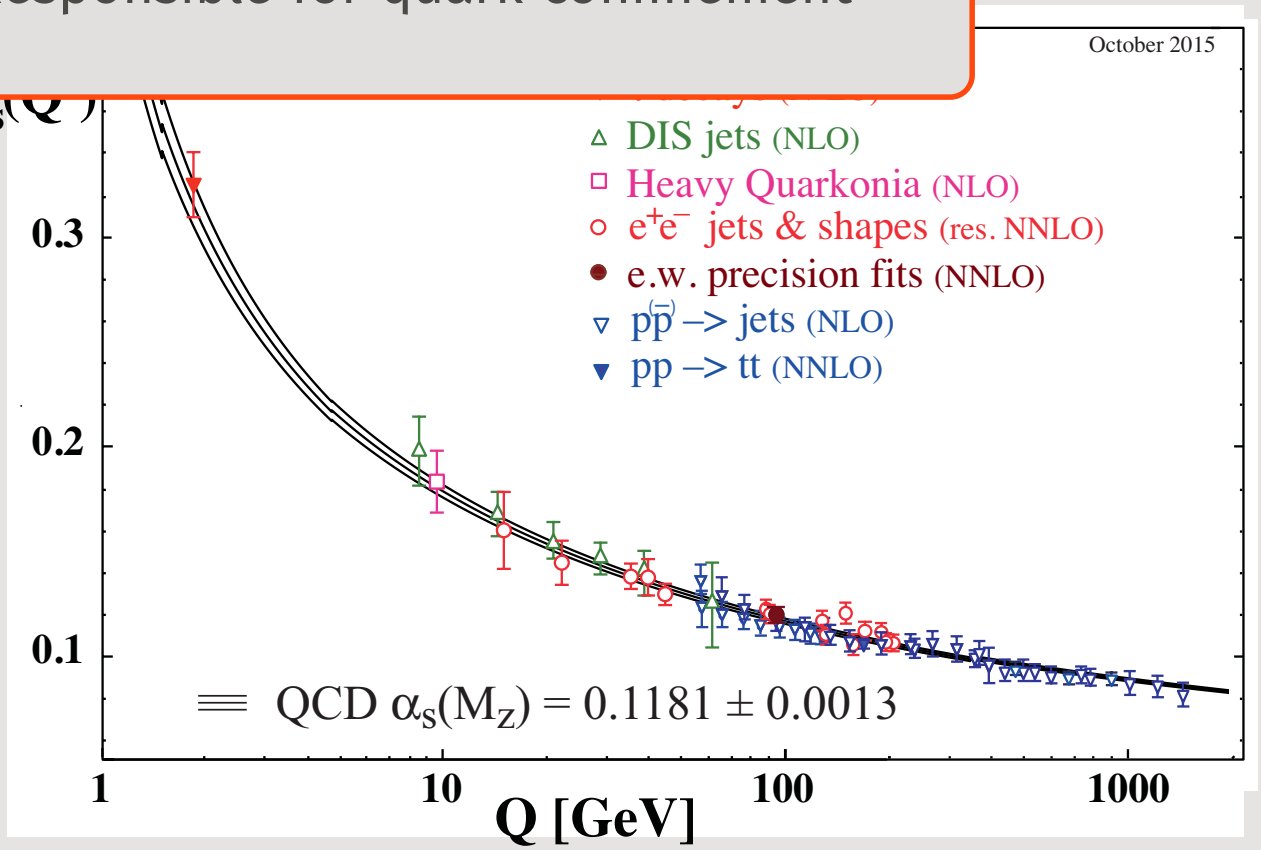
Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^2 + \sum_f \overline{\psi}_f (i\not{D} - m_f)\psi_f$$

- Free parameters : quark masses m_f, scale Λ_{QCD}
- Deceptively simple...


October 2015
$\alpha_s(Q^2)$
τ decays (N³LO)
DIS jets (NLO)
Heavy Quarkonia (NLO)
e⁺e⁻ jets & shapes (res. NNLO)
e.w. precision fits (NNLO)
p(p̄) –> jets (NLO)
pp –> tt (NNLO)
0.3
0.2
0.1
QCD $\alpha_s(M_Z) = 0.1181 \pm 0.0013$
1
10
100
1000
Q [GeV]

- Responsible for quark confinement



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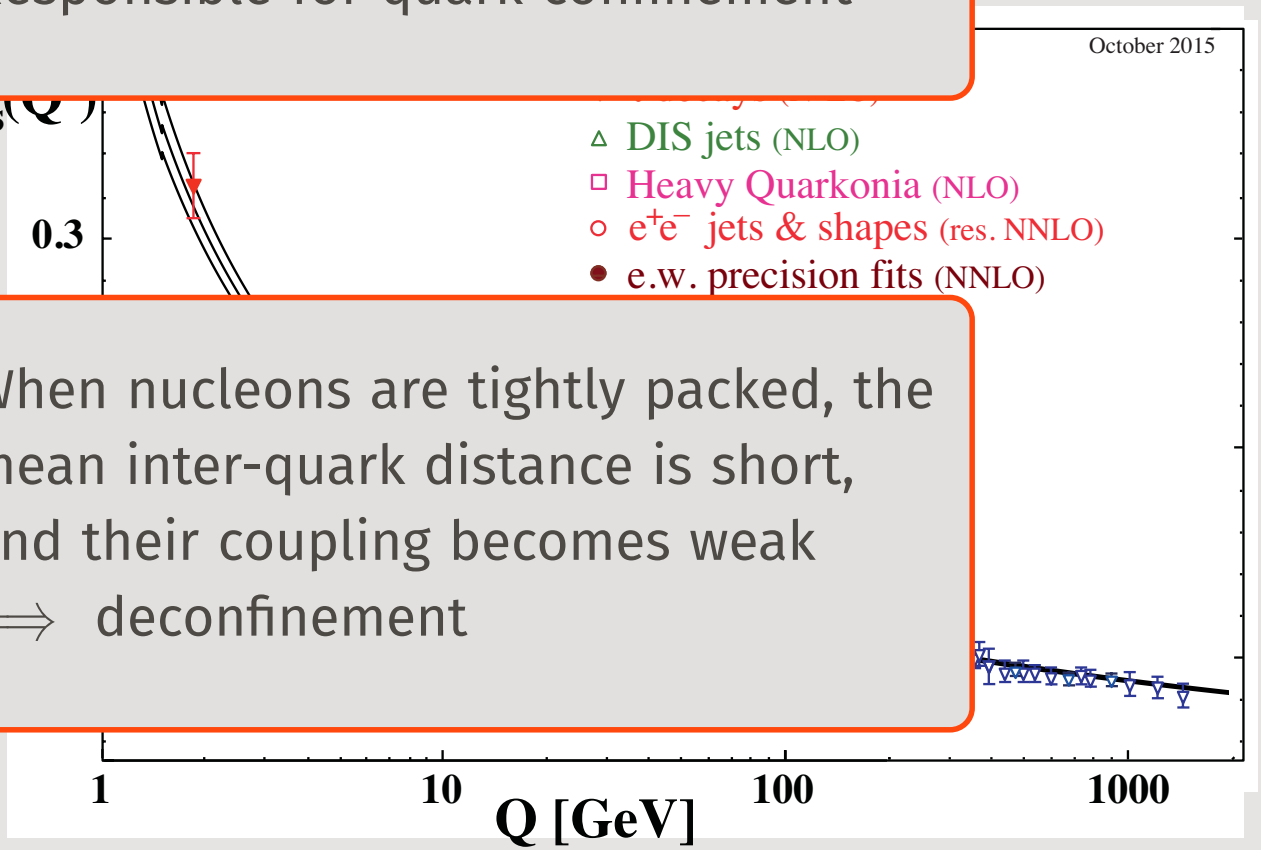
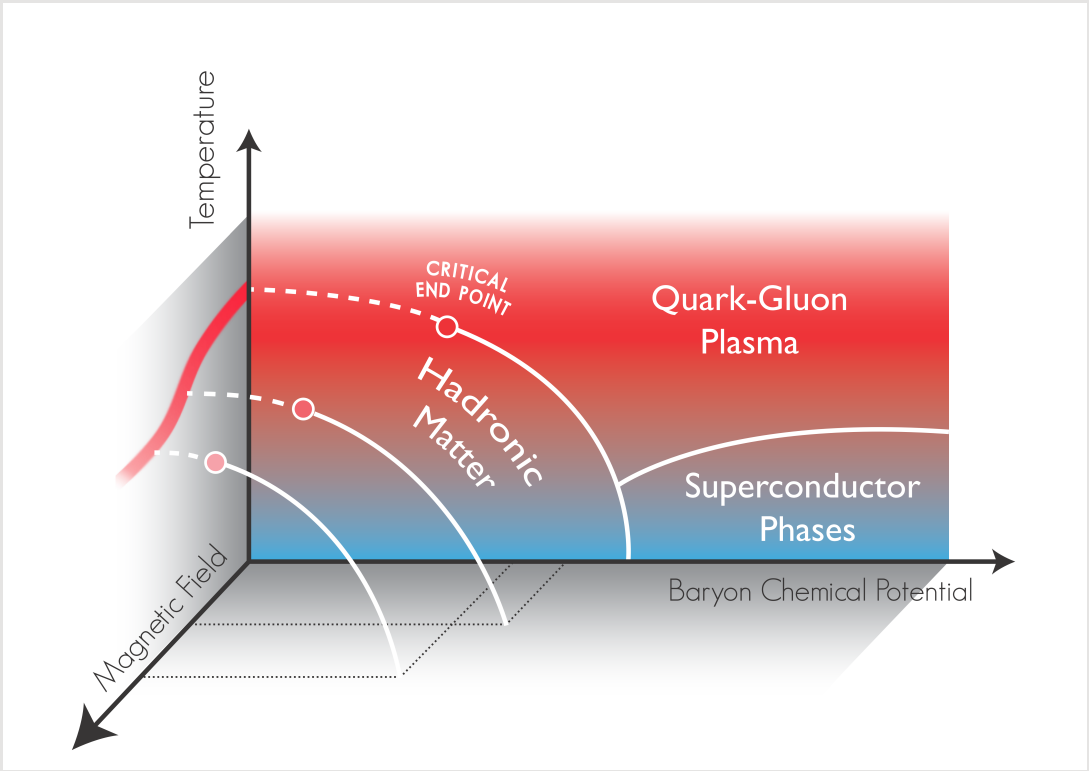


- When nucleons are tightly packed, the mean inter-quark distance is short, and their coupling becomes weak
  $\Longrightarrow$ deconfinement

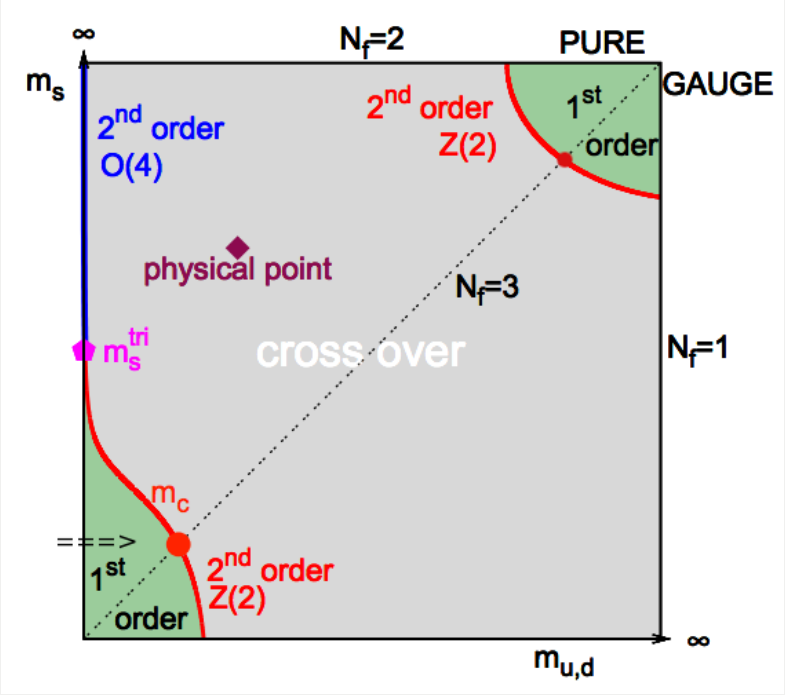
Phase diagram (sketch) of QCD matter



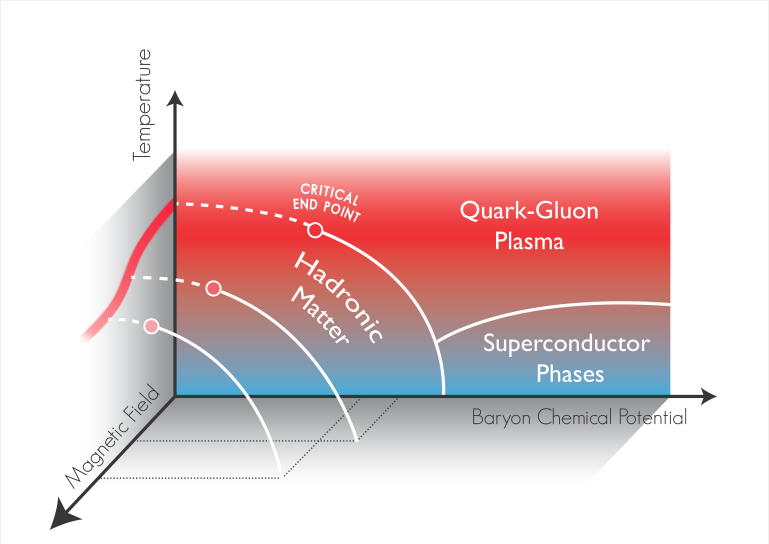
- **Control parameters :**
  - Temperature
  - Chemical potentials
  - External fields

Confinement-Deconfinement (lattice QCD)

- QCD is not tractable analytically in the region of the confinement-deconfinement transition
- Lattice QCD is a numerically tractable approximation of QCD, that becomes exact in the limit of an infinitesimal spacing
- Moreover, lattice QCD allows to vary some parameters (e.g., quark masses) that are fixed in Nature, to explore their role in controlling the transition

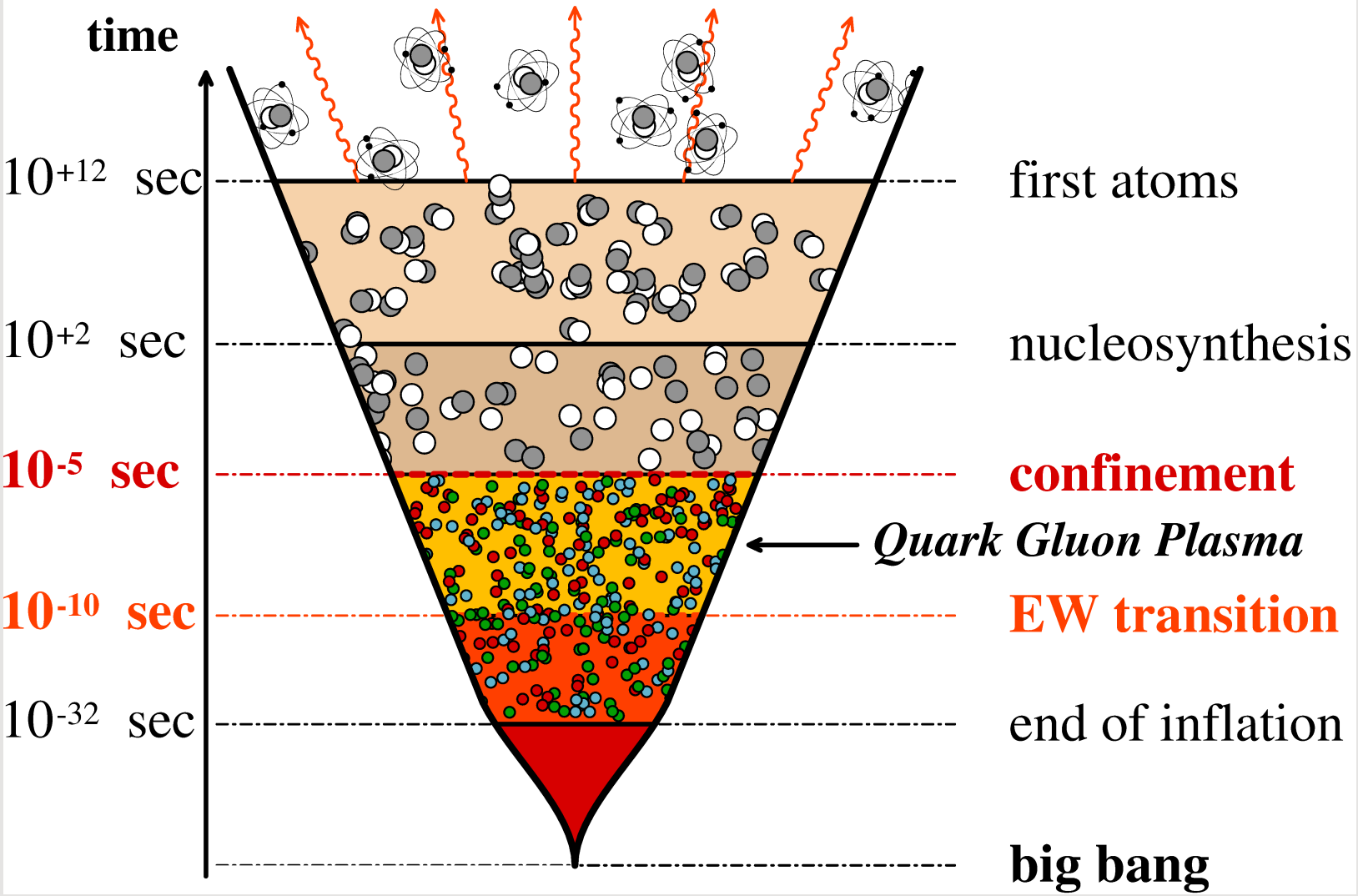


Limitations to know about

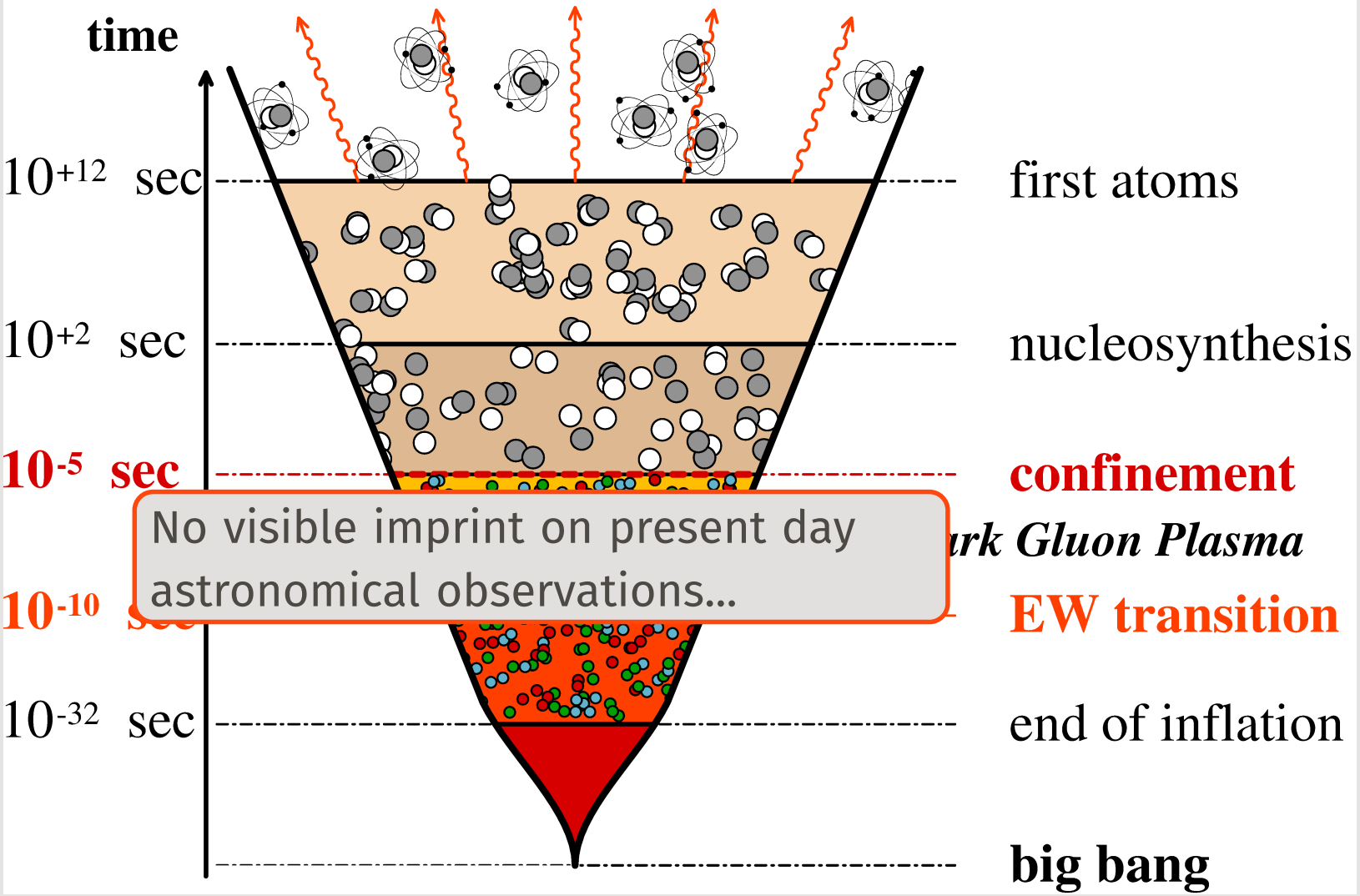


- At non-zero μ_B, lattice QCD involves requires integrating a complex-valued and oscillating quantity, preventing importance sampling (*"sign problem"*, exponentially hard)
  - Lattice QCD partly usable at small μ_B/T
  - Perturbation theory applicable at large μ_B and small T
  - No firm theoretical control outside these regions!

Confinement transion in the early Universe



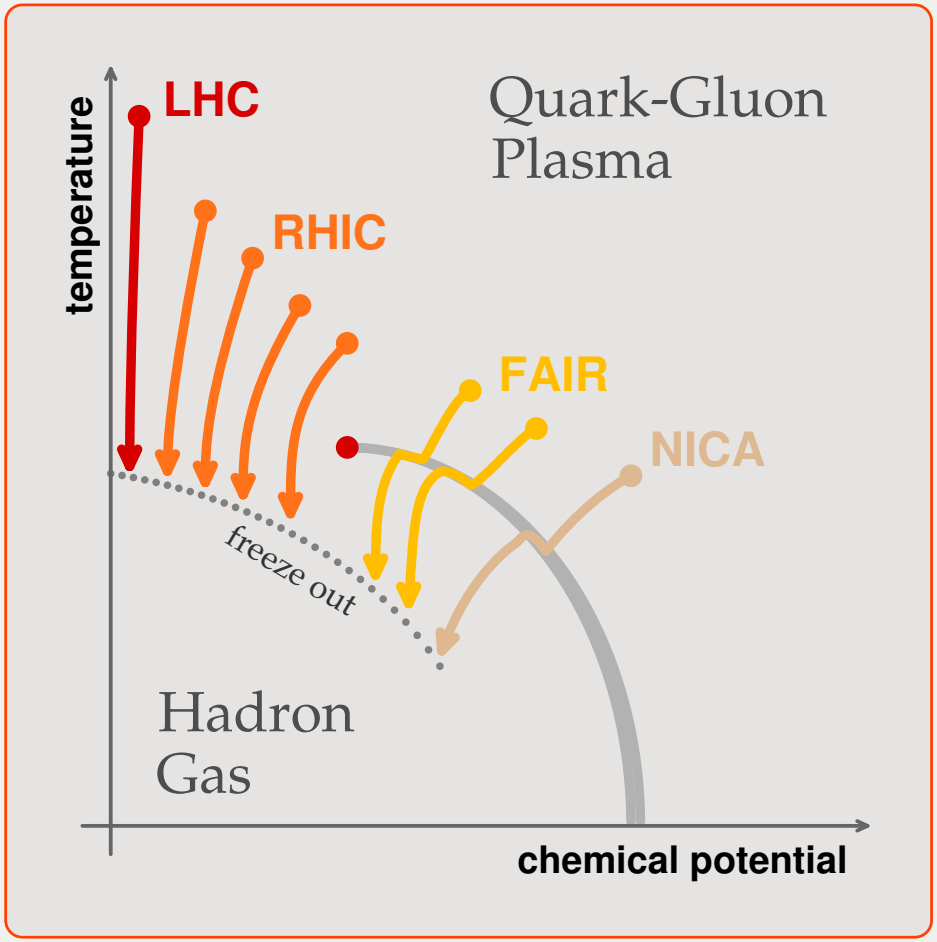
Confinement transion in the early Universe



No visible imprint on present day astronomical observations...

Heavy ion collisions

- Recreate the conditions of the deconfinement transition in the laboratory by colliding large nuclei at ultra-relativistic energies



- **Experimental handles :**
  - beam energy
  - ion species

Timeline of Heavy Ion facilities

Bevatron (Billions of eV Synchrotron) :
From 1954 to 1993 at Lawrence Berkeley National Laboratory, U.S

AGS (Alternating Gradient Synchrotron) :
Since 1960 at Brookhaven National Laboratory, U.S

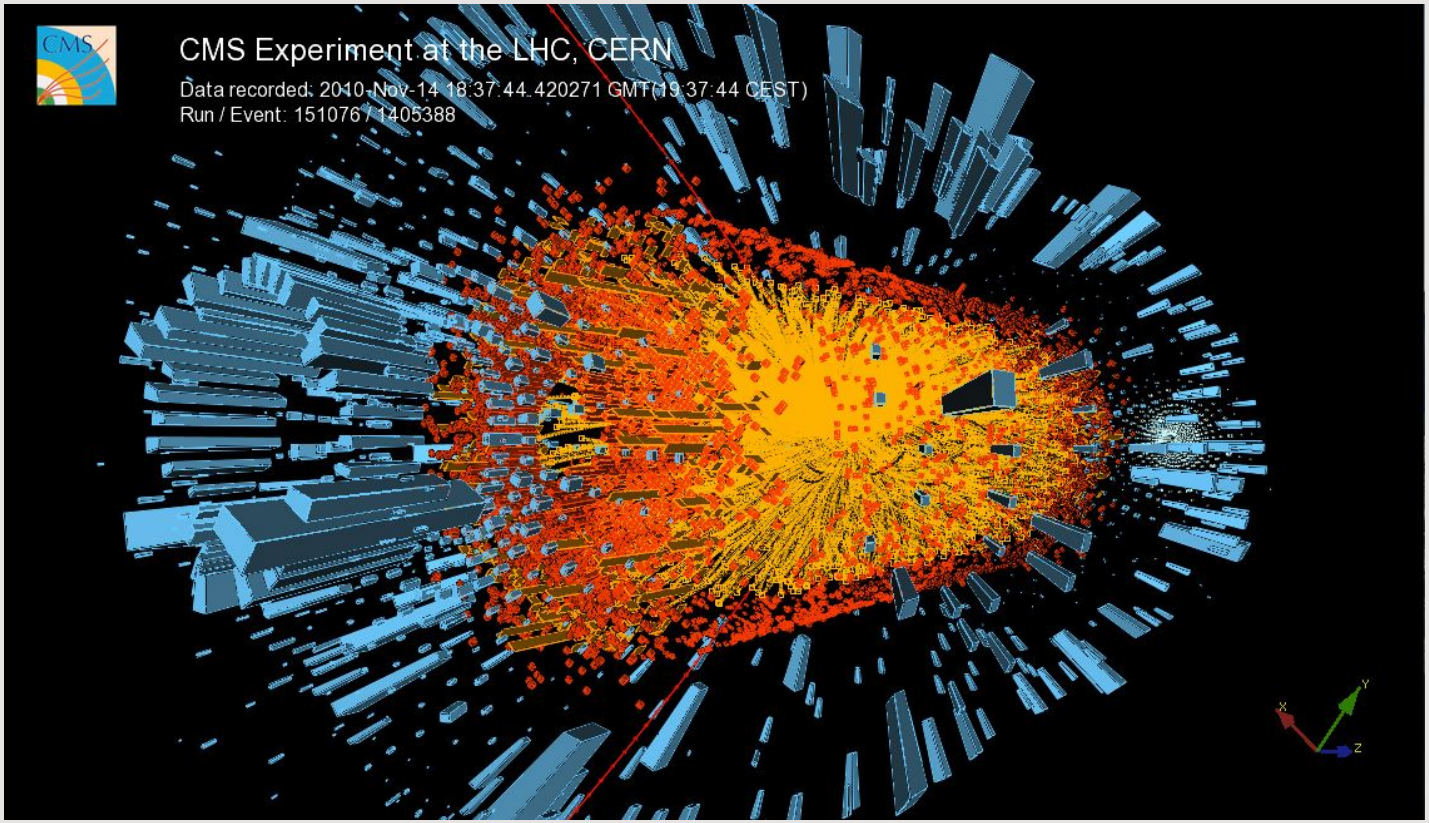
SPS (Super Proton Synchrotron) :
Since 1976 at CERN

SIS-18 (Schwer-Ionen-Synchrotron) :
Since 2001 at GSI

RHIC (Relativistic Heavy Ion Collider) :
Since 2000 at Brookhaven National Laboratory, U.S

LHC (Large Hadron Collider) :
Since 2009 at CERN

Heavy Ion Collision at the LHC



QCD

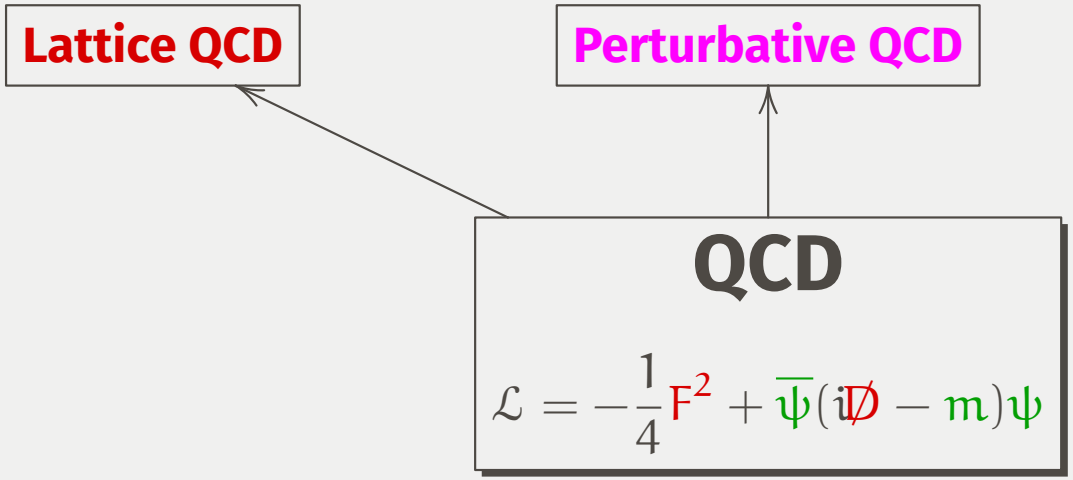
$$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$$

Lattice QCD

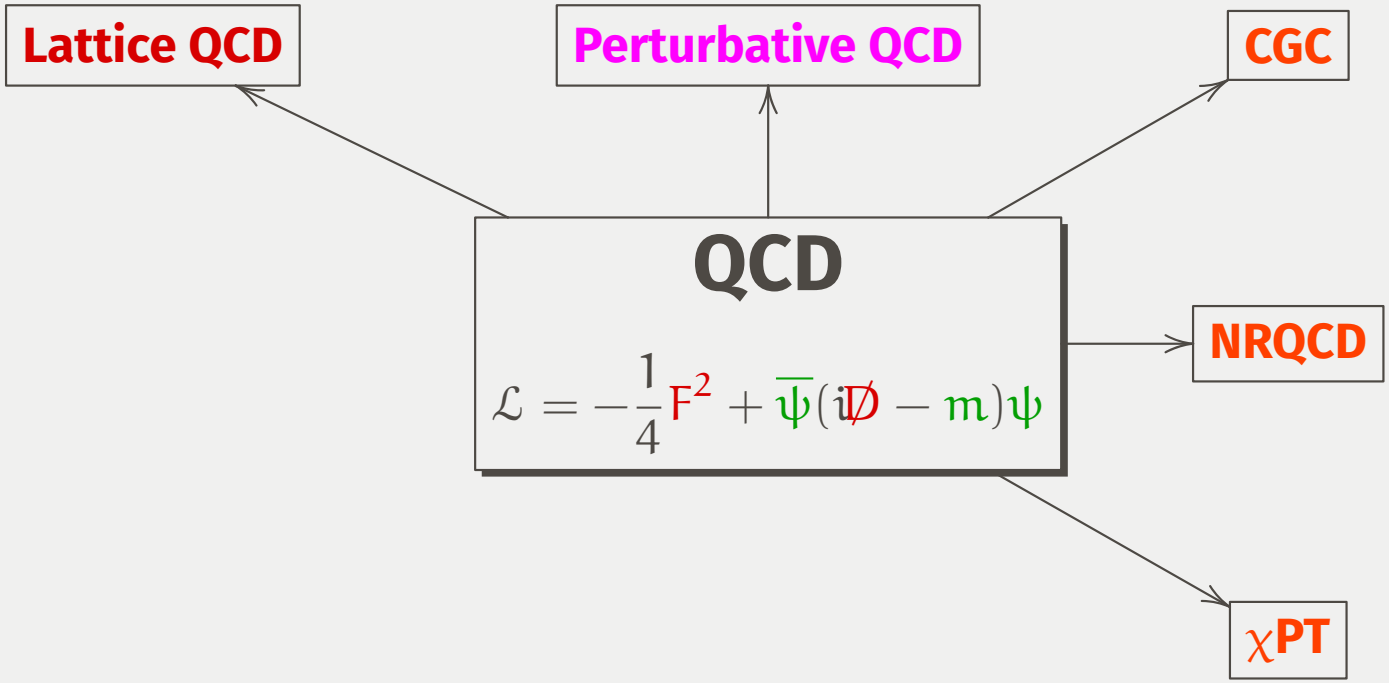
QCD

$$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$$

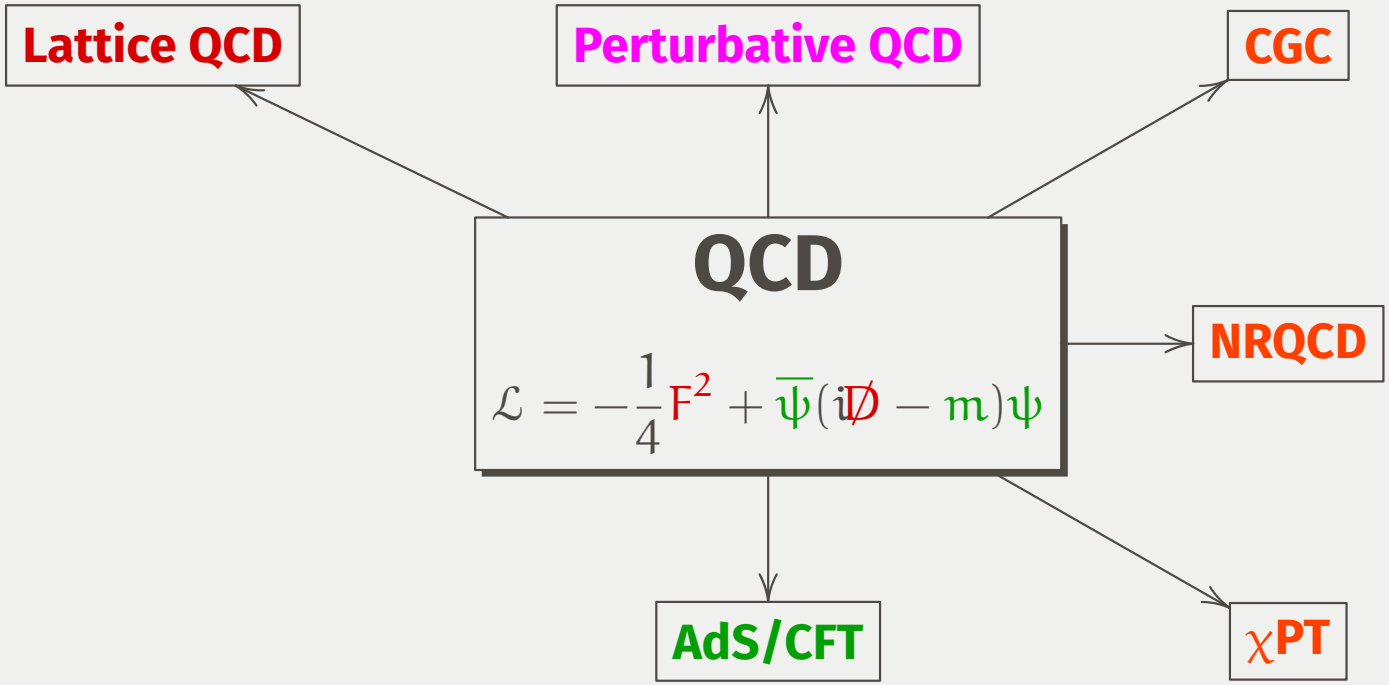
Theory


Lattice QCD
Perturbative QCD
QCD
$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$

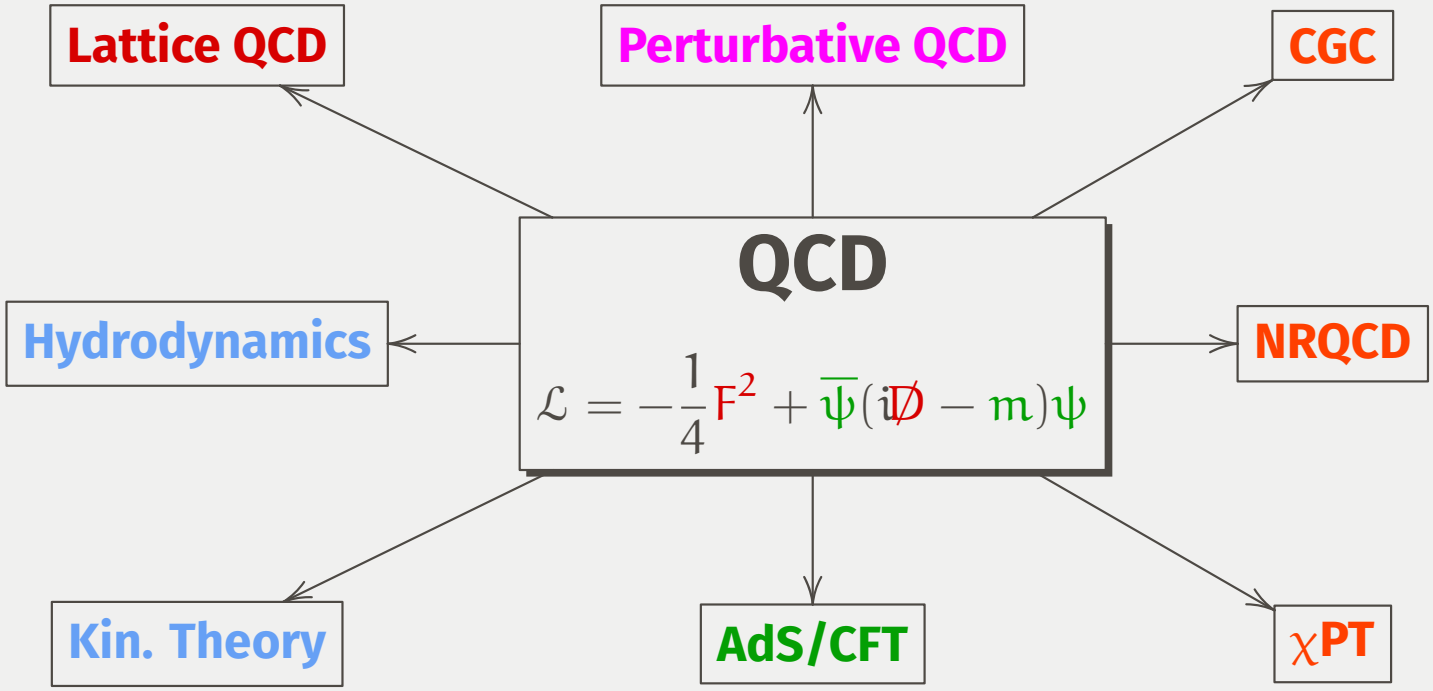
Theory


Lattice QCD
Perturbative QCD
CGC
QCD
$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$
NRQCD
χPT

Theory


Lattice QCD
Perturbative QCD
CGC
QCD
$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$
NRQCD
AdS/CFT
χPT

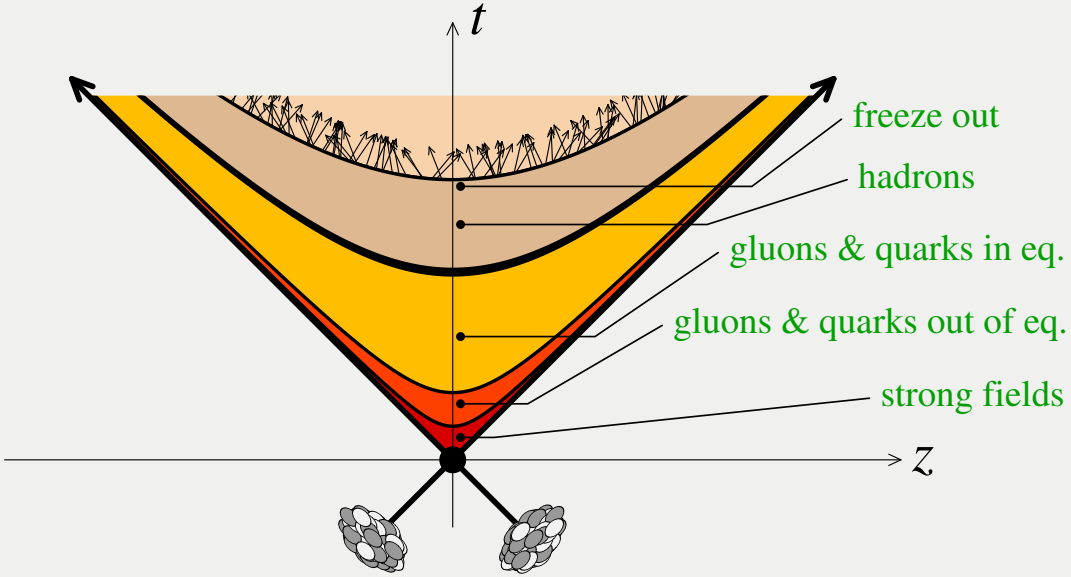
Theory


Lattice QCD
Perturbative QCD
CGC
Hydrodynamics
QCD
$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$
NRQCD
Kin. Theory
AdS/CFT
χPT

Theory

- **Thermodynamics :**
  - Equation of state
  - Susceptibilities
  - Transport coefficients
- **Dynamical evolution :**
  - Thermalization / Isotropization
  - Expansion and cooling
  - Hadronization
- **Investigation of medium properties with perturbative probes**
  - Jets
  - Photons
  - Heavy quarkonia

Stages of a Heavy-Ion Collision



- Note: this is mostly a theorist's view, suggesting to use different effective descriptions for the various stages
  Experimentally, only particles emitted from the freeze-out surface are accessible
- Approximate boost invariance at high energy: use proper time $\tau \equiv \sqrt{t^2 - z^2}$ and rapidity $\eta \equiv \frac{1}{2}\ln((t+z)/(t-z))$

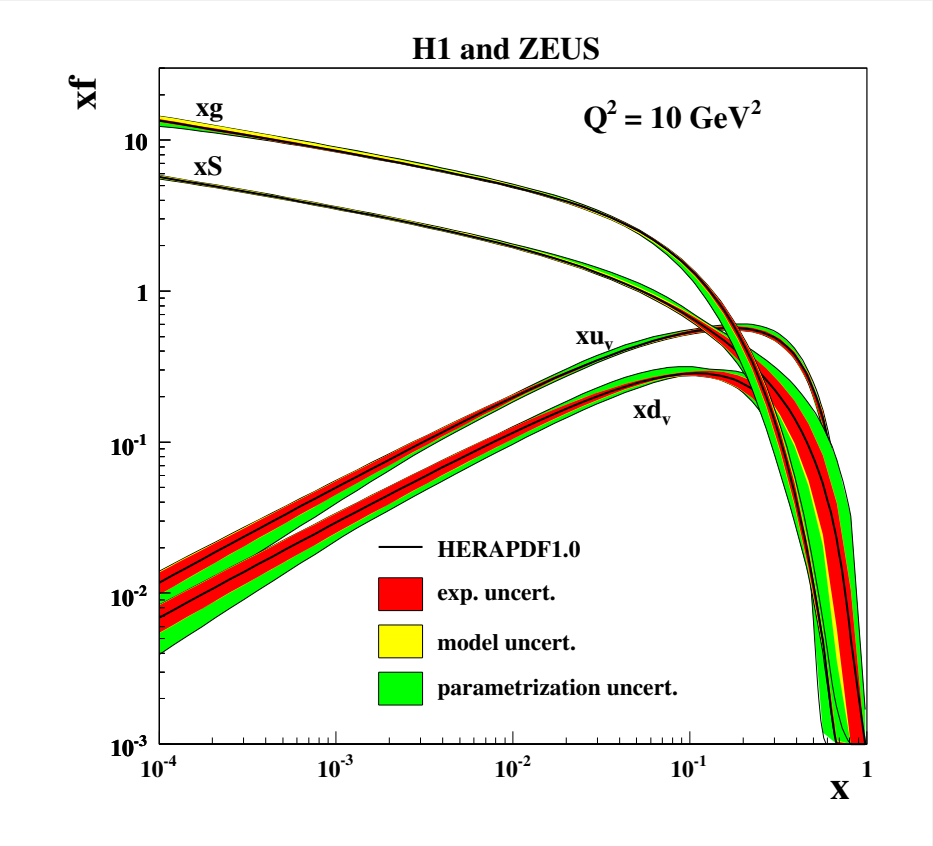
Besides QCD, there are also a number of mundane details...

i. Nuclei are approximately spherical
ii. Their diameter is about 12 fermis
iii. They contain $A \approx 200$ nucleons
iv. The positions of these nucleons fluctuate event-by-event

- These properties have all an incidence on some observables
- None of them is interesting from the point of view of QCD
- We need observables that are independent of these trivial aspects of nuclear physics, or we need good models for them

Initial State, Color Glass Condensate

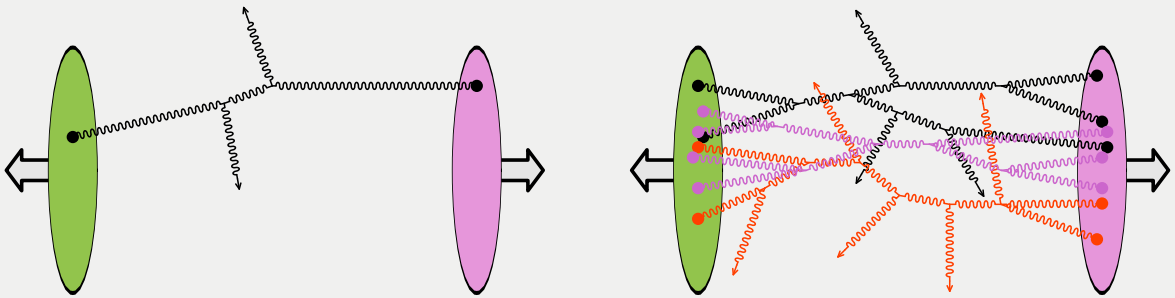
Growth of the gluon distribution at small x



- Gluons dominate at any $x \leq 10^{-1}$

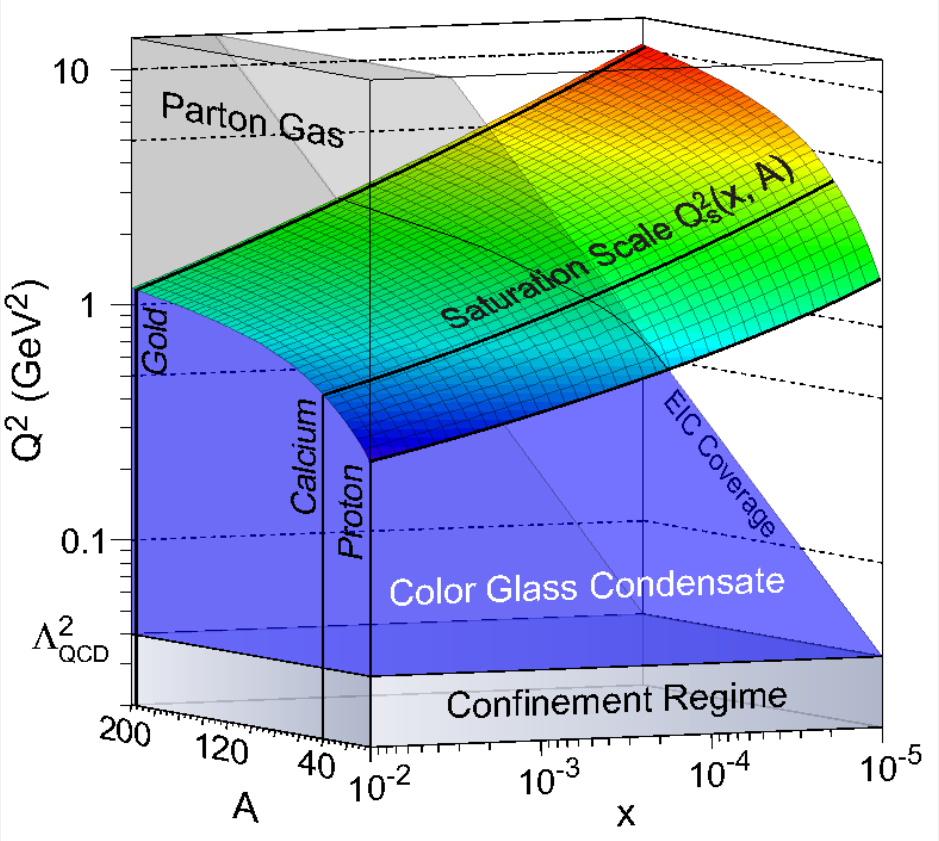
Dilute versus Dense

- Parton densities in hadrons/nuclei depend on parton momentum (i.e., on Q and x)
- When parton densities are large, scattering probabilities are no longer linear in the densities:



- The nonlinear regime is called *"saturation"*
- Saturation criterion: $Q \lesssim Q_s(x)$ ($Q_s \equiv$ "saturation momentum")
- For a nucleus of atomic number A: $Q_s^2 \sim A^{1/3} x^{-0.25}$

Saturation momentum



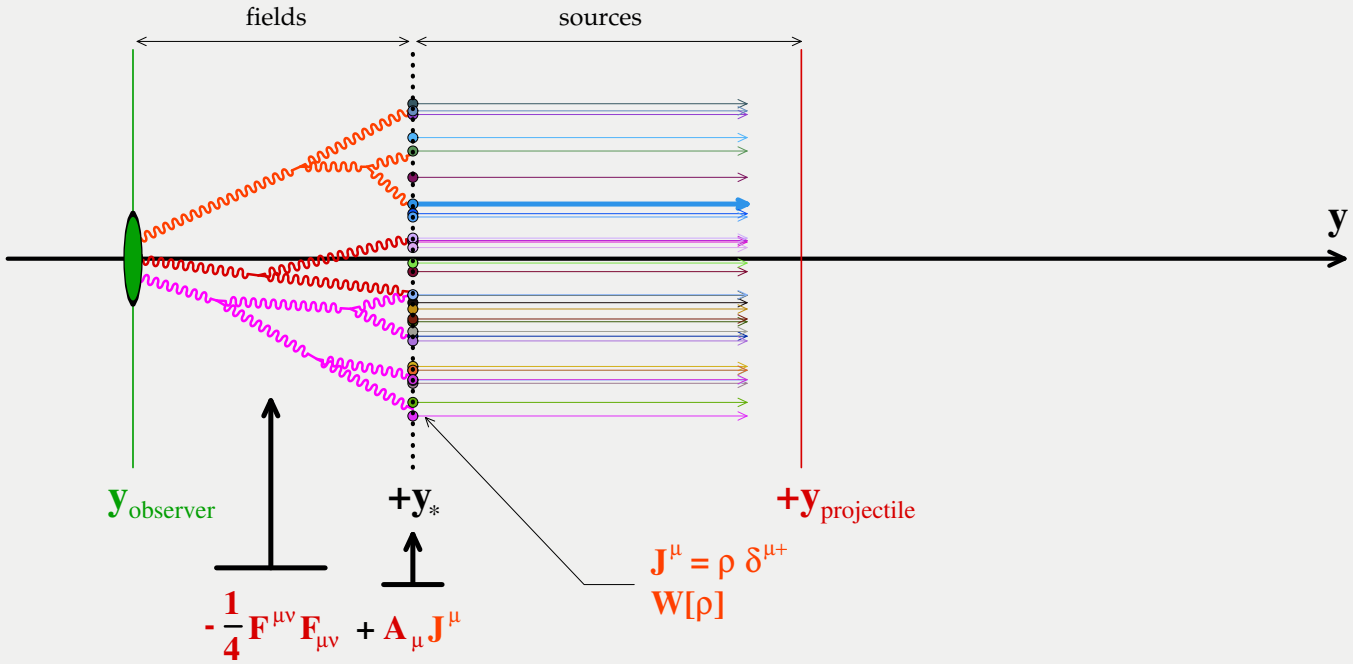
- $x \sim p_\perp/\sqrt{s}$
- $p_\perp$ of typical particle $\sim$ 1 GeV, $\sqrt{s} = 5.5$ TeV at LHC
  $\Longrightarrow$ the bulk of particle production affected by saturation

Color Glass Condensate (CGC)

- CGC = approximation of QCD valid in the saturation regime
- Incoming nucleus $\equiv$ stream of color charges ("sources")
- Lorentz time dilation: static charges
- Lorentz contraction: 2-dimensional charge distribution

$$J^\mu_a(x) = \delta^{\mu+}\delta(x^-)\rho_a(\mathbf{x}_\perp)$$

- At rapidities close to the observer: normal gluon fields



Color Source distribution

- The source distribution $\rho_a(\mathbf{x}_\perp)$ reflects the position in transverse plane of the color charges *at the time of the collision* $\Longrightarrow$ it is a random quantity that cannot be predicted
- Its probability distribution $W[\rho]$ is approximately Gaussian for a very large nucleus (central limit theorem, McLerran-Venugopalan model)
- $W[\rho]$ depends on the rapidity y_* chosen as separation between the currents and the fields. This effect (due to loop corrections) ensures that physics does not depend on the separation scale:

$$\frac{\partial W[\rho]}{\partial y_*} = \frac{\delta}{\delta \rho_a} \chi_{ab} \frac{\delta}{\delta \rho_b} W[\rho]$$

  - can be solved numerically (but expensive)
  - can be approximated by the simpler Balitsky-Kovchegov equation

Pre-equilibrium evolution (CGC at leading order)

- CGC at leading order $\Longleftrightarrow$ classical color fields:

$$T^{00}_{\rm LO} = \frac{1}{2}\big[\underbrace{\mathbf{E}^2 + \mathbf{B}^2}_{\text{class. fields}}\big], \qquad T^{0i}_{\rm LO} = \big[\mathbf{E}\times\mathbf{B}\big]^i,$$

$$T^{ij}_{\rm LO} = \frac{\delta^{ij}}{2}\big[\mathbf{E}^2 + \mathbf{B}^2\big] - \big[\mathbf{E}^i\mathbf{E}^j + \mathbf{B}^i\mathbf{B}^j\big],$$

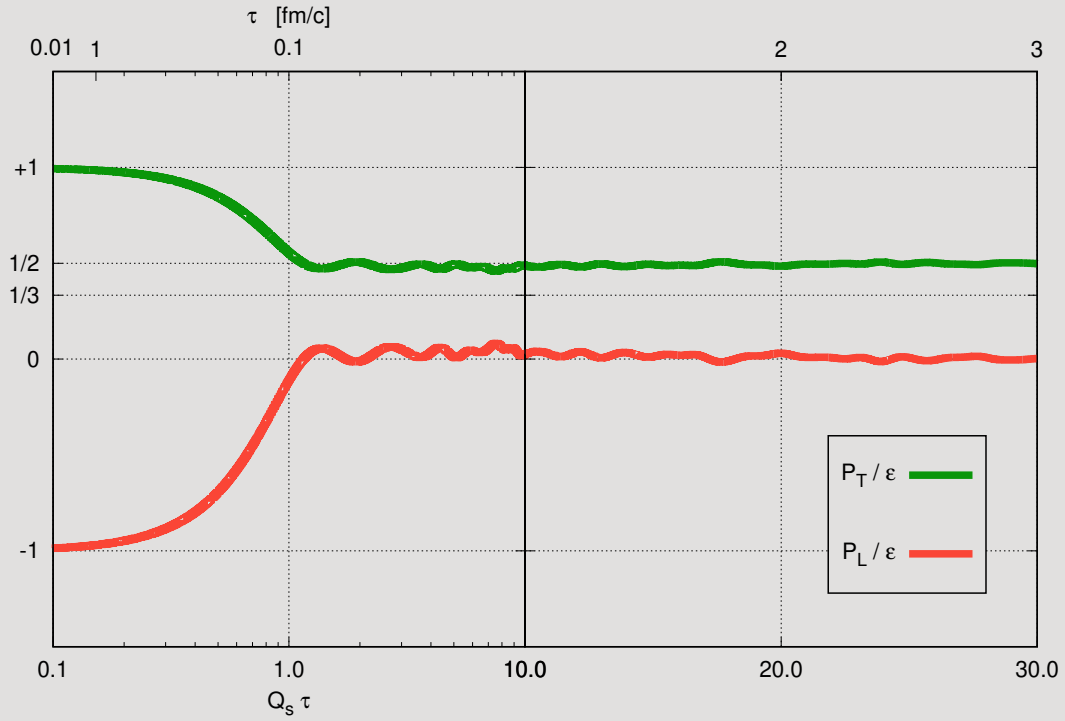
- $\mathbf{E}$ and $\mathbf{B}$ aligned with collision axis (at $\tau = 0$):

$$T^{0i}_{\rm LO} = 0, \quad P_{\rm T} = \epsilon, \quad P_{\rm L} = -\epsilon$$

Pre-equilibrium evolution (CGC at leading order)

- CGC at leading order $\Longleftrightarrow$ classical color fields:

No isotropization at leading order :



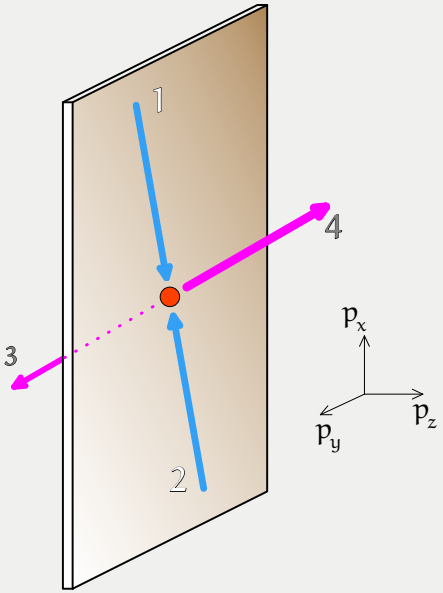
- E anc

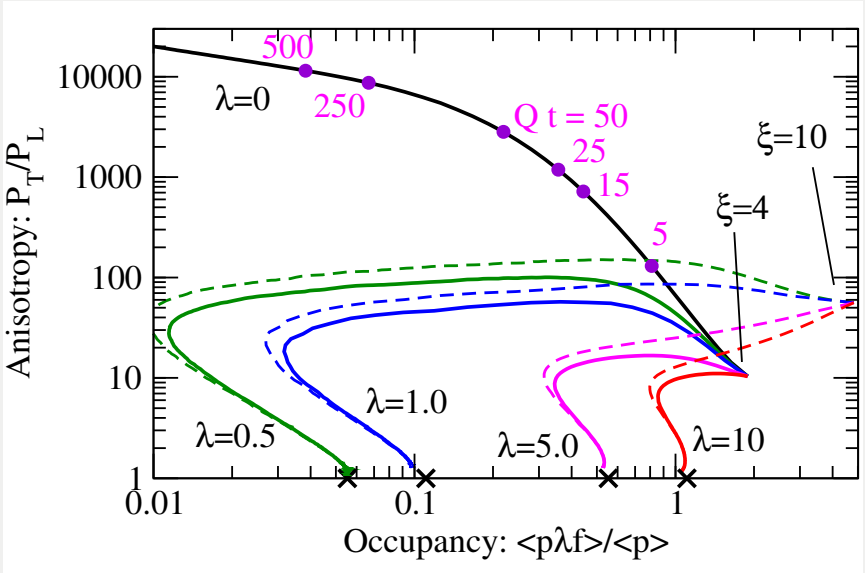
Pre-equilibrium evolution (CGC beyond leading order)

- Next to leading order:
  - tends to increase longitudinal pressure
  - but suffers from instabilities that limit its applicability
- Classical Statistical Approximation:
  - resummation beyond LO+NLO
  - exists in two flavors: one that lacks continuum limit, and one that lacks contributions essential for isotropization...
- Better approach: 2PI resummation (doable, but challenging within the expanding geometry of heavy ion collisions)
- Cheaper approach: kinetic theory description

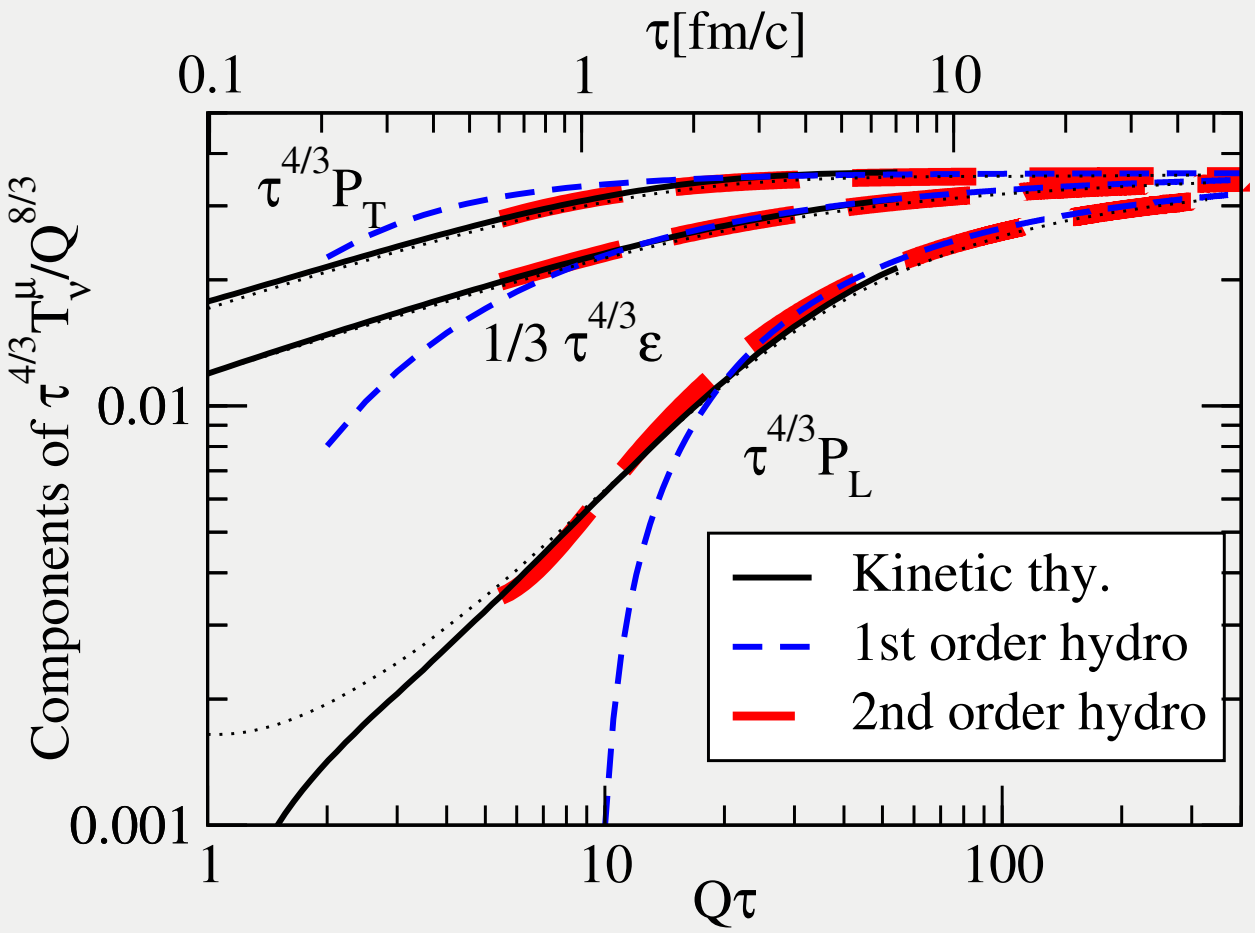
Pre-equilibrium evolution (kinetic theory)

$$(\partial_t + \boldsymbol{v}_1 \cdot \boldsymbol{\nabla})\, f_1 = \int_{\mathbf{p}_{2,3,4}} |M(12 \to 34)|^2\, \delta(p_1 + p_2 - p_3 - p_4)$$
$$\times \Big\{ \underbrace{f_3 f_4 (f_1 + f_2) - f_1 f_2 (f_3 + f_4)}_{\text{seemingly dominant at large } f} + f_3 f_4 - \underbrace{f_1 f_2}_{\text{dominates if } f \text{ anisotropic}} \Big\}.$$

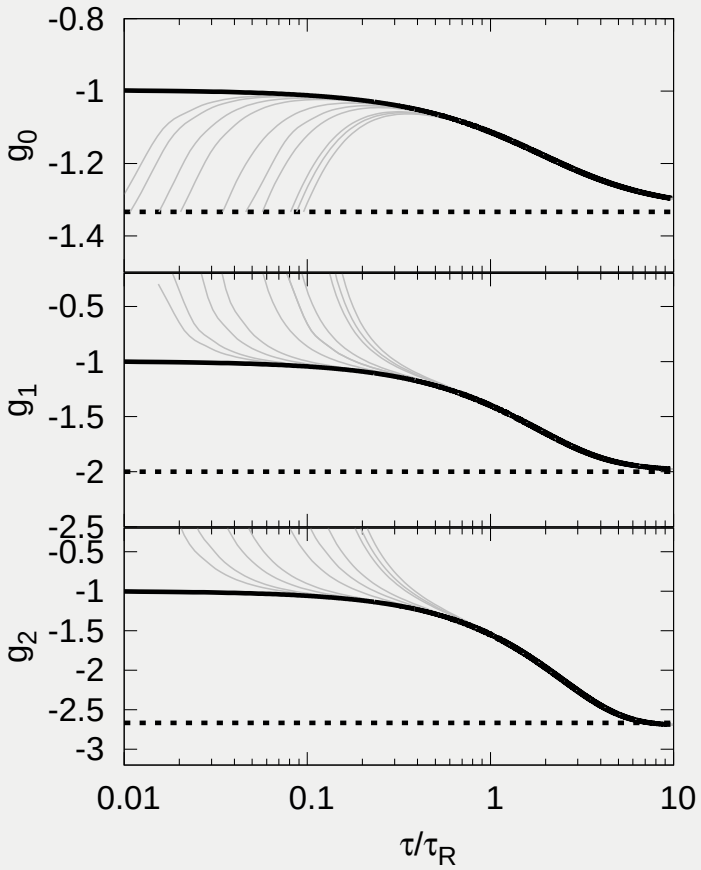




Kinetic Theory matches Hydrodynamics



Kinetic Theory attractors



- $g_n =$ exponents that characterize the degree of anisotropy of the system ($g_n = -1$: *free streaming*, dotted line: *isotropic*)

Hydrodynamical Evolution, Late Stages

Hydrodynamics in a nutshell

- Hydrodynamics $\equiv$ long distance description, where the dynamics depends almost exclusively on conservation laws

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu J^\mu_B = 0, \quad \cdots$$

- Perfect fluid:

$$\begin{aligned} T^{\mu\nu} &\underset{\text{perfect}}{=} (\epsilon + p) u^\mu u^\nu - p\, g^{\mu\nu} \\ &= \epsilon\, u^\mu u^\nu + p\, \Delta^{\mu\nu} \quad (\Delta^{\mu\nu} = \text{projector to local fluid frame}), \end{aligned}$$

  In the fluid rest frame:
  $D\epsilon = -(\epsilon + p)\nabla_\mu u^\mu, \quad Du^\mu = -(\epsilon + p)^{-1}\, \nabla^\mu p$

  Equation of state: $p = f(\epsilon)$ (sufficient to close the equations)

- Boost invariant flow of a perfect fluid:

$$\frac{d\epsilon}{d\tau} = -\frac{\epsilon + p}{\tau}$$

Viscous corrections (1st order)

- Allow deviation of $T^{\mu\nu}$ from perfect fluid:

$$T^{\mu\nu} = T^{\mu\nu}_{\text{perfect}} + \pi^{\mu\nu} + \Pi\,\Delta^{\mu\nu}$$

- Relate deviations to gradients:

$$\pi^{\mu\nu} = -\eta\,\sigma^{\mu\nu} \quad \text{with} \quad \sigma^{\mu\nu} \equiv \nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\,(\nabla_\rho u^\rho),$$

$$\Pi = -\zeta\,(\nabla_\rho u^\rho)$$

($\eta, \zeta =$ viscosity coefficients, calculable from underlying microscopic theory)

- Close to perfect fluid if

$$\frac{\eta}{s} \ll \tau T \quad \Longleftrightarrow \quad \text{mean free path} \ll \tau$$

Causality, Second order hydrodynamics

- Correction to the stress tensor follows instantaneously any modification to the velocity field $\Longrightarrow$ acausal
- Simple fix: replace these relationships by relaxation equations (requires a microscopic time τ_π)
- More fundamental approach: start from expansion to second order in gradients (introduces many more transport coefficients, in principle calculable from underlying microscopic theory)

Viscosity in various limiting cases

- Kinetic theory wisdom:

$$\frac{\eta}{s} \sim \frac{\text{mean free path}}{\text{quantum wavelength}}$$

- Weak coupling, perturbative QCD:

$$\frac{\eta}{s} \sim \frac{1}{\alpha_s^2 \ln(\alpha_s^{-1})} \gg 1$$

- Strong coupling, AdS/CFT (for a cousin theory of QCD):

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

- Weak coupling, large gluon occupation ($\sim \alpha_s^{-1}$):

$$\frac{\eta}{s} \sim \alpha_s^0$$

Transport coefficients

- $J \equiv$ current that couples to the quantity to be transported
- Green-Kubo formula:

$$\sigma \propto \lim_{\omega \to 0} \frac{\rho(\omega, \mathbf{k} = 0)}{\omega} \quad (\rho = \langle [J, J] \rangle)$$

- Lattice QCD: one has direct access only to imaginary time correlators $\Longrightarrow$ indirect and delicate determination of the spectral function ρ

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- Lattice QCD: one has direct access only to imaginary time correlators $\Longrightarrow$ indirect and delicate determination of the spectral function ρ
- Alternate approach:
  - loop expansion of $\langle [J, J] \rangle$ in terms of the exact propagator
  - non-perturbative propagator obtained from functional renormalization group

Transport coefficients

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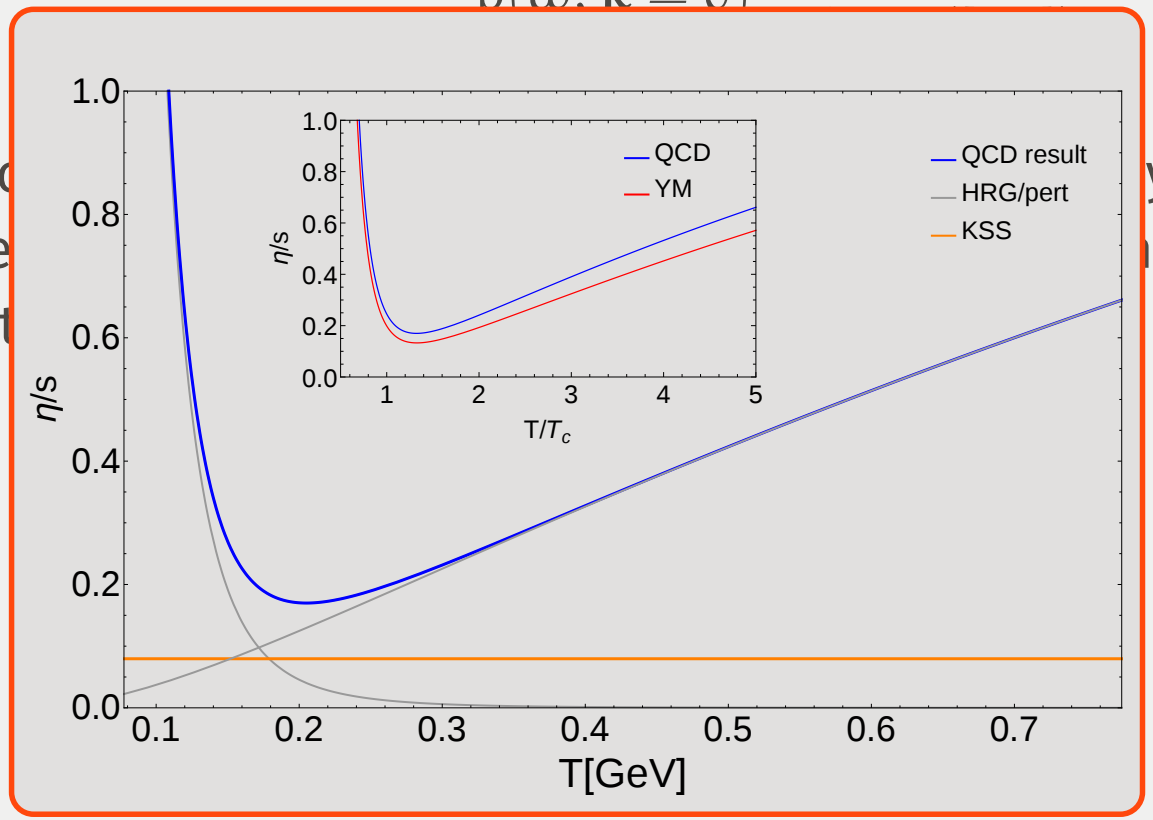
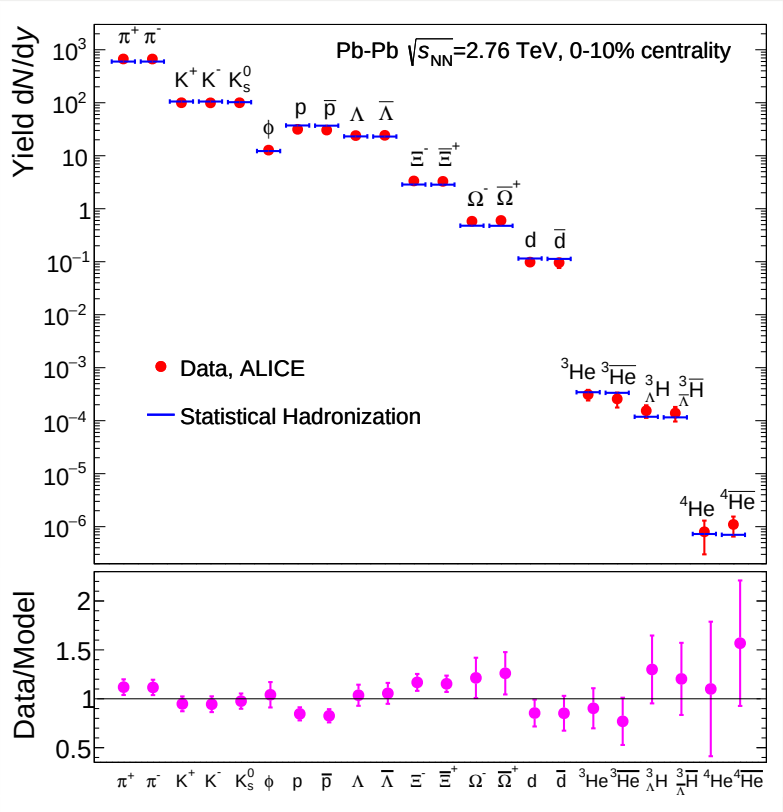
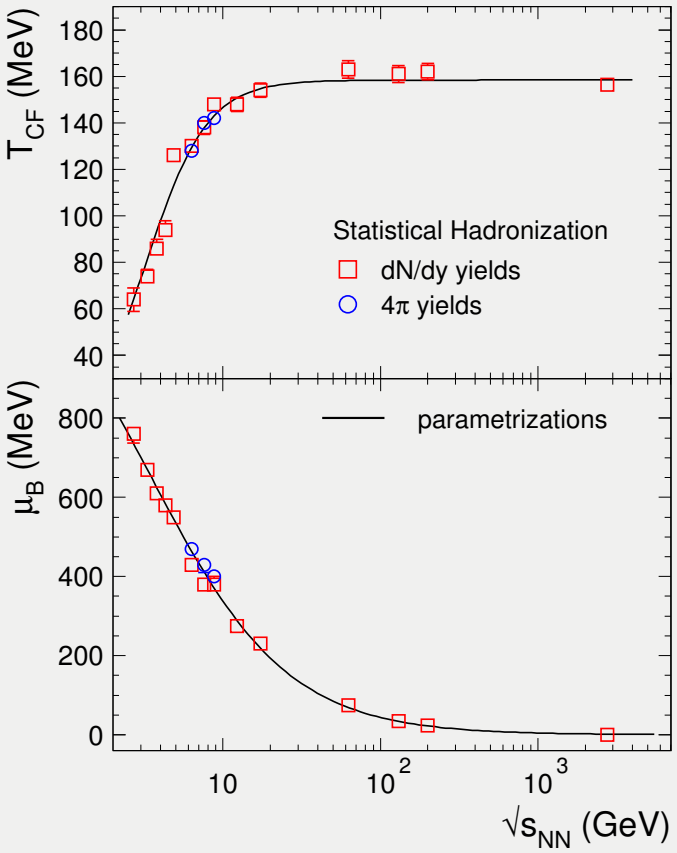
$$\rho(\omega, \mathbf{k} = 0)$$

- Lattic y time corre n of the spect



Freeze-out from abundance ratios



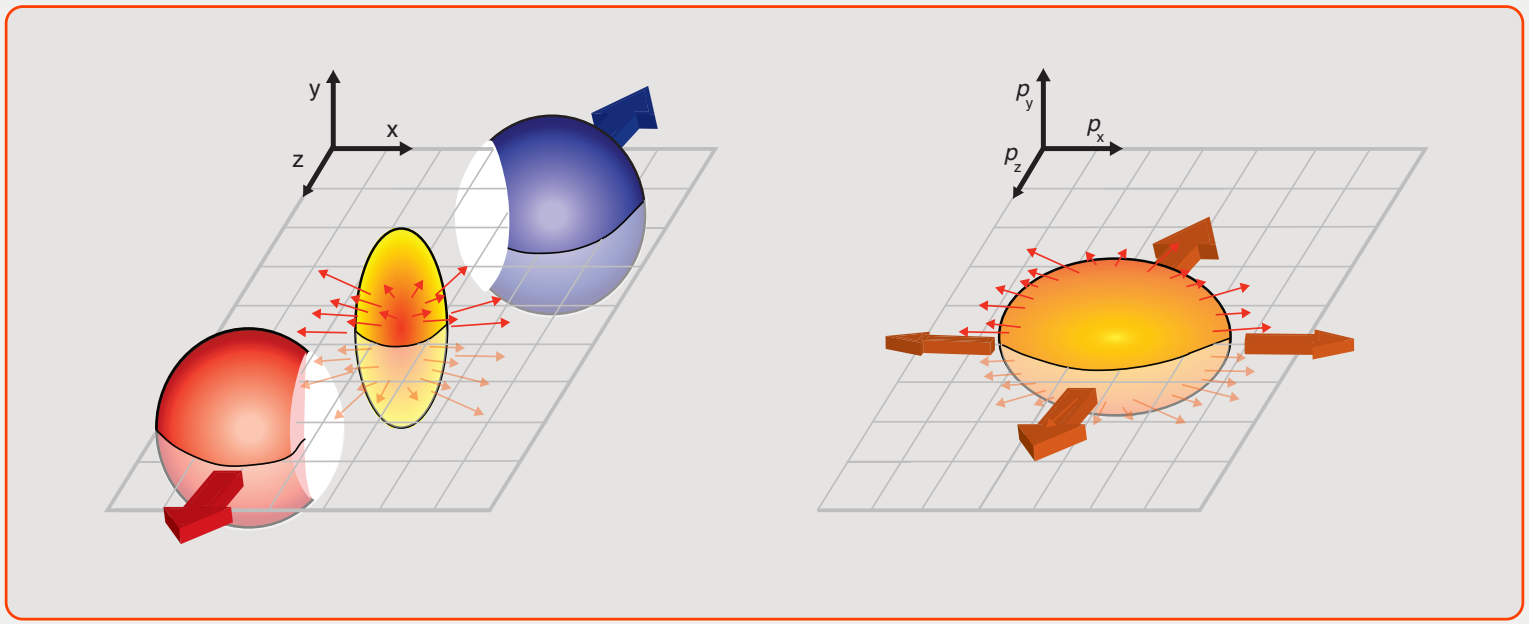


Freeze-out from Cooper-Fry formula

$$E_{\mathbf{p}} \frac{dN}{d^3\mathbf{p}} = \frac{1}{(2\pi)^3} \int_{\Sigma} d^3S_\mu \, P^\mu \, f(P \cdot u),$$

- $f(p) = f_{eq}(p) + \delta f(p)$
  The form of δf is related to viscous corrections and transport coefficients
- Note: in this approach, the freeze-out T and μ_B are free parameters (common to all particle species)
- Alternative: convert to a kinetic description earlier, and let each particle species decouple according to its interaction rates (encoded in cross-sections) with the other particles

Flow observables



Flow observables

Goals :

- Assess the transport properties of the QGP (viscosity, etc..)
- Provide constraints on its equation of state
- Validate models of bulk evolution that are used in the computation of other observables
- Constrain the initial state

Flow observables

Goals :

- Assess the transport properties of the QGP (viscosity, etc.)

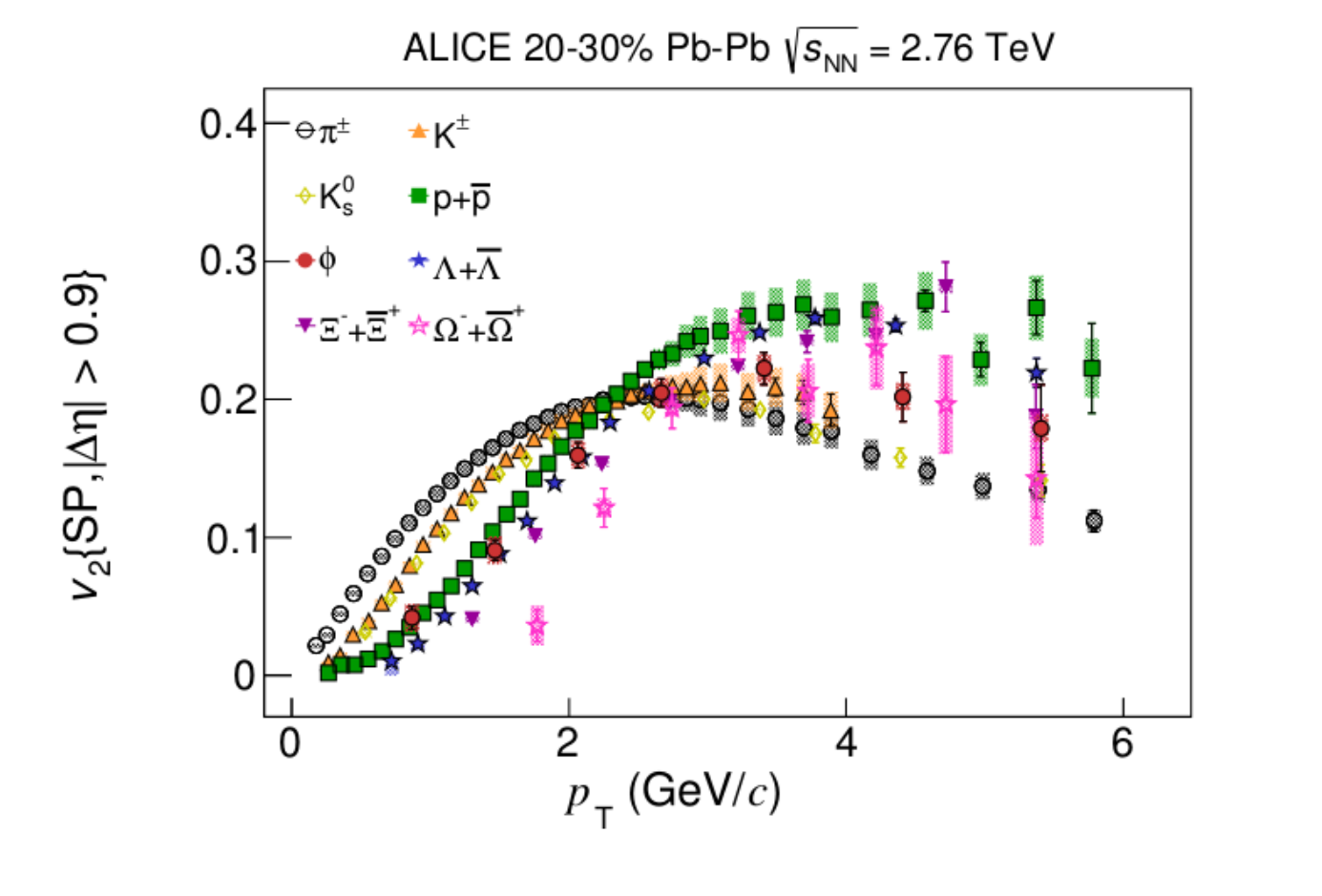
Observables :

- Azimuthal distribution of the produced particles
- Fourier coefficients v_1, v_2, v_3,...
- Orientations of the principal axes Ψ_1, Ψ_2, Ψ_3,...

Note :

- Initial geometrical fluctuations play a crucial role in these studies

Example : p_T-dependence of v_2 of identified hadrons



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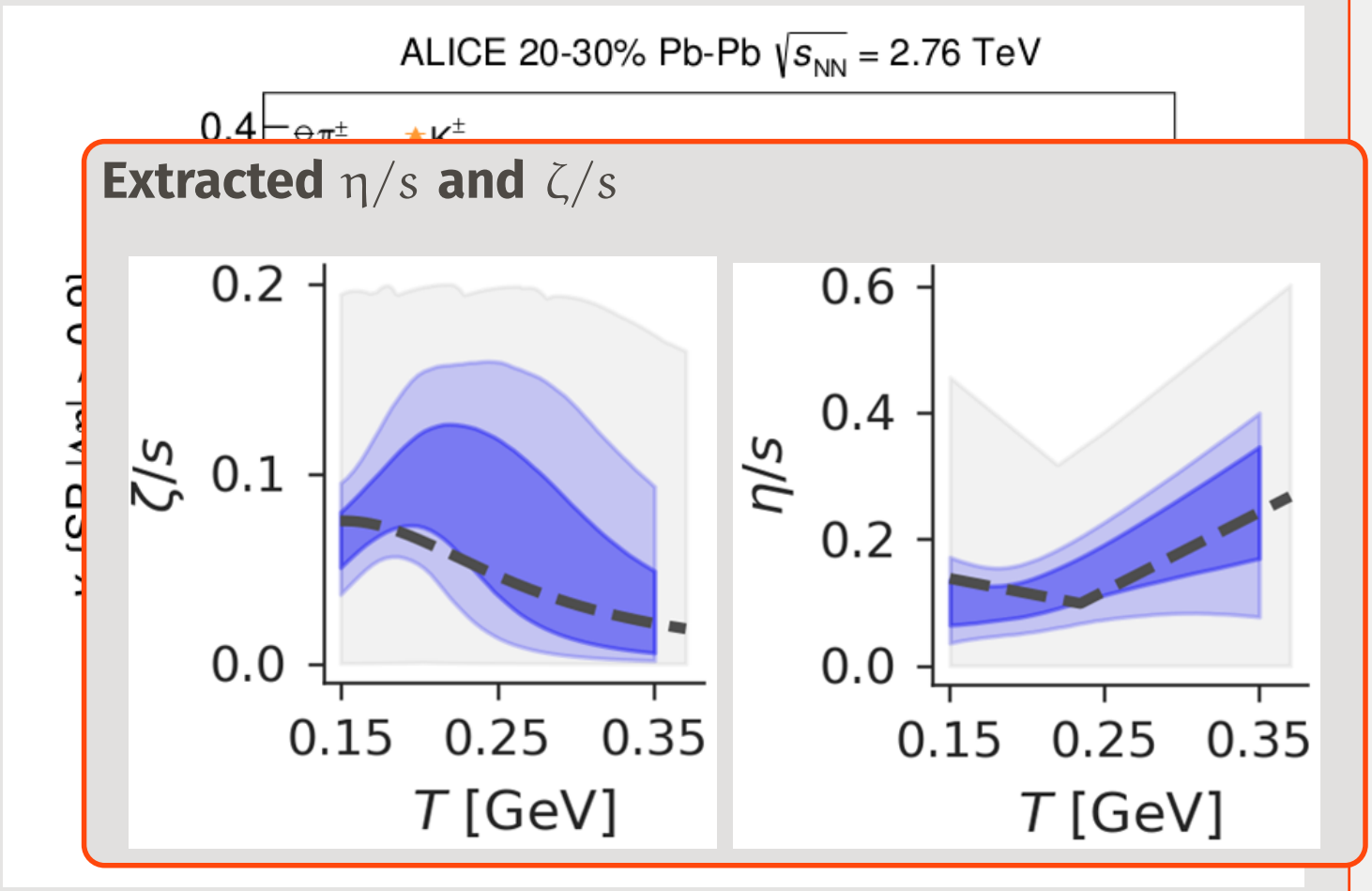
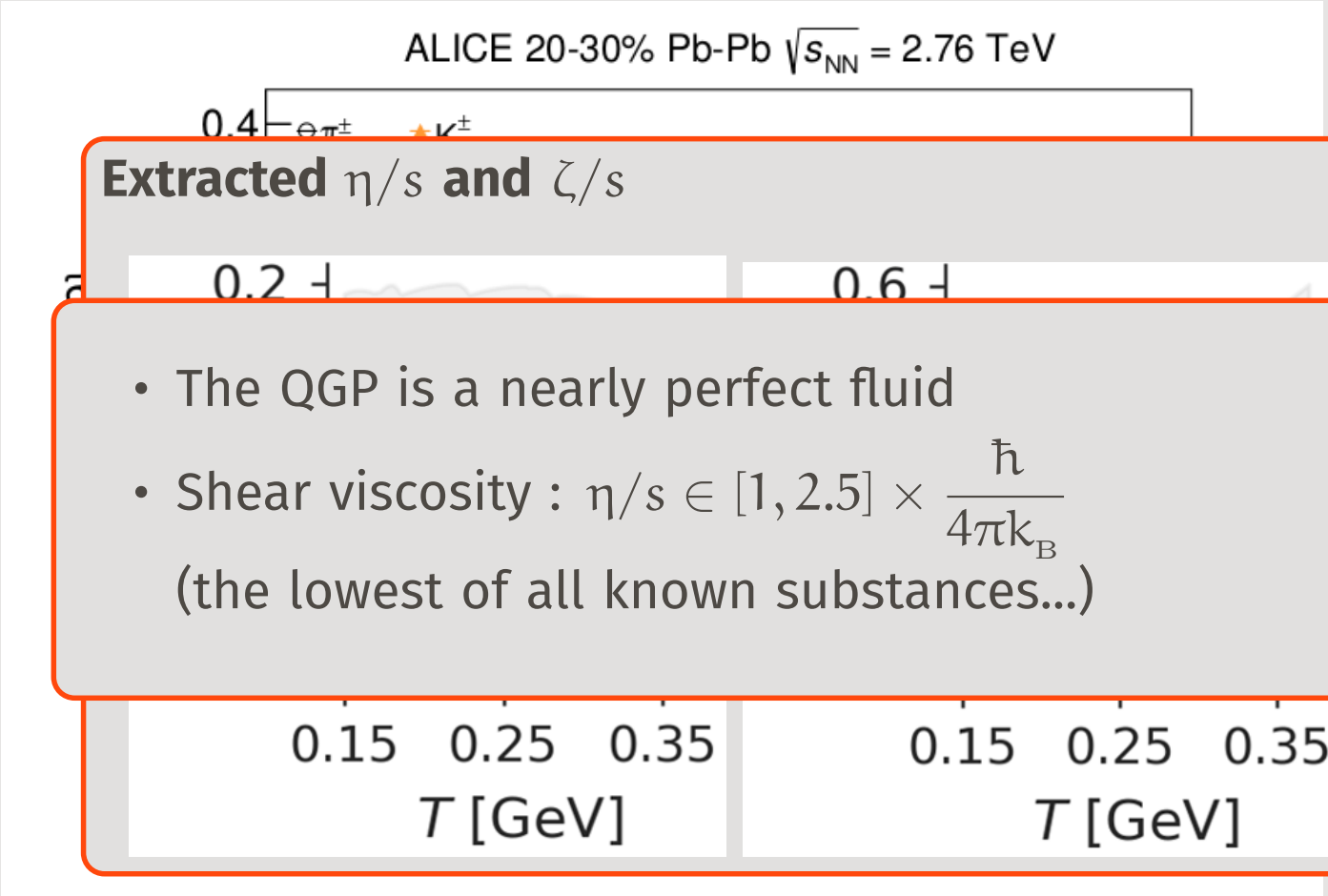


Example : p_T-dependence of v_2 of identified hadrons

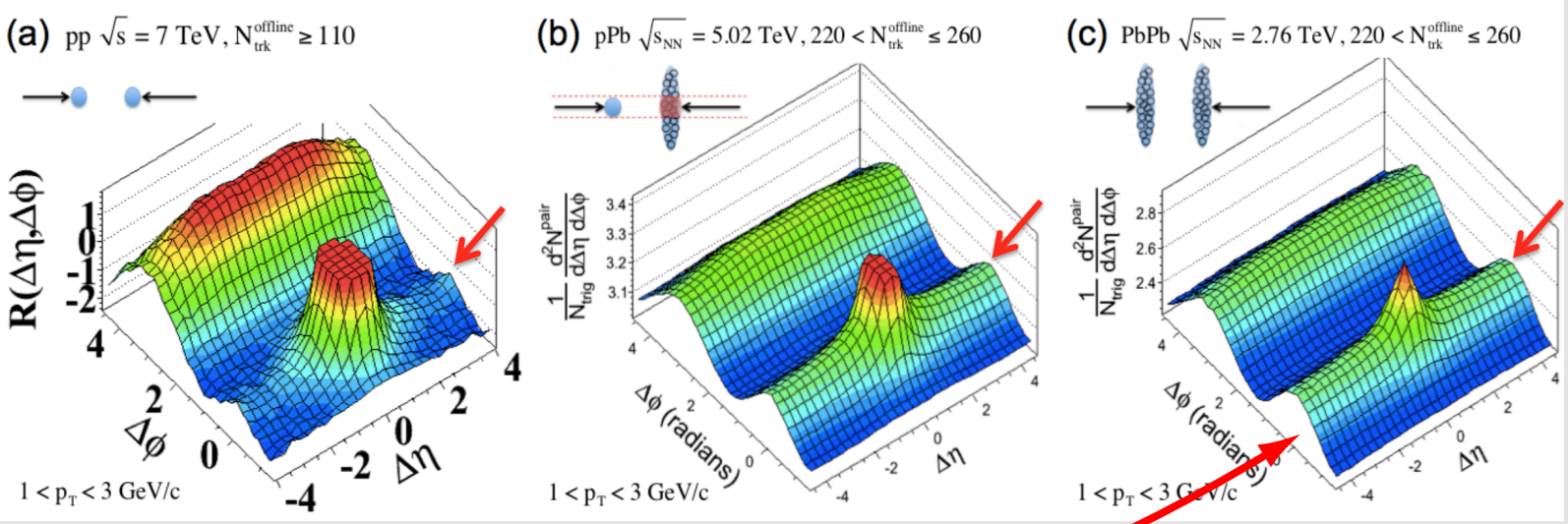


Extracted η/s and ζ/s

- The QGP is a nearly perfect fluid
- Shear viscosity : $\eta/s \in [1, 2.5] \times \dfrac{\hbar}{4\pi k_B}$

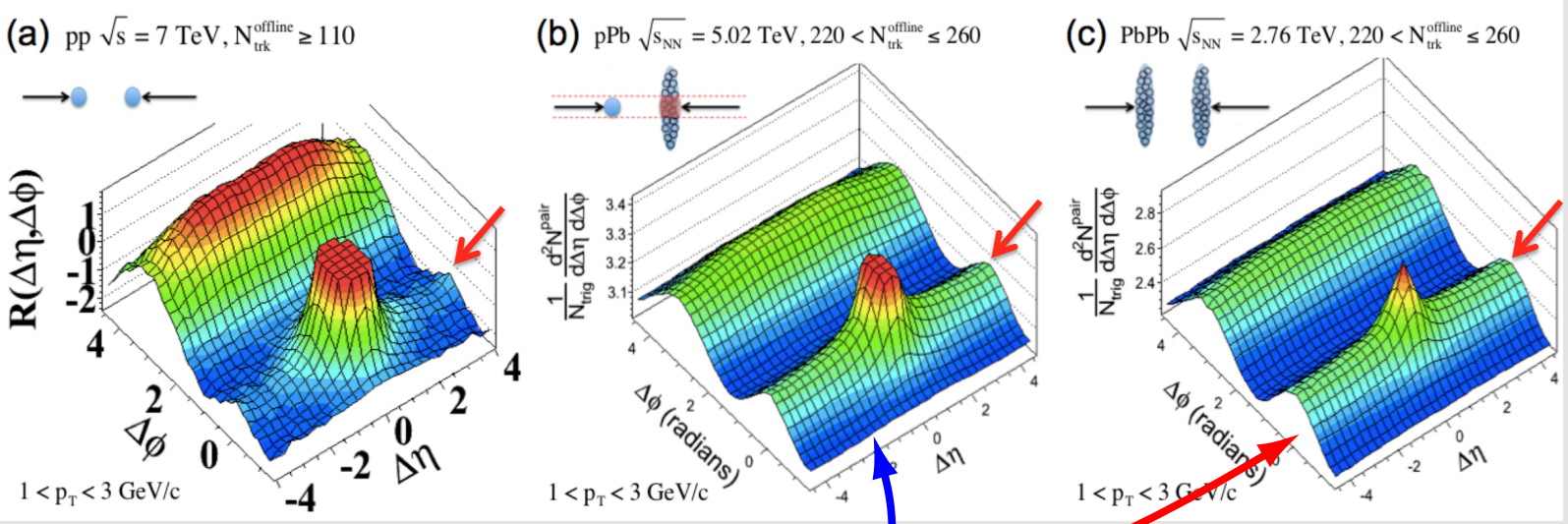
  (the lowest of all known substances...)

Flow in small systems



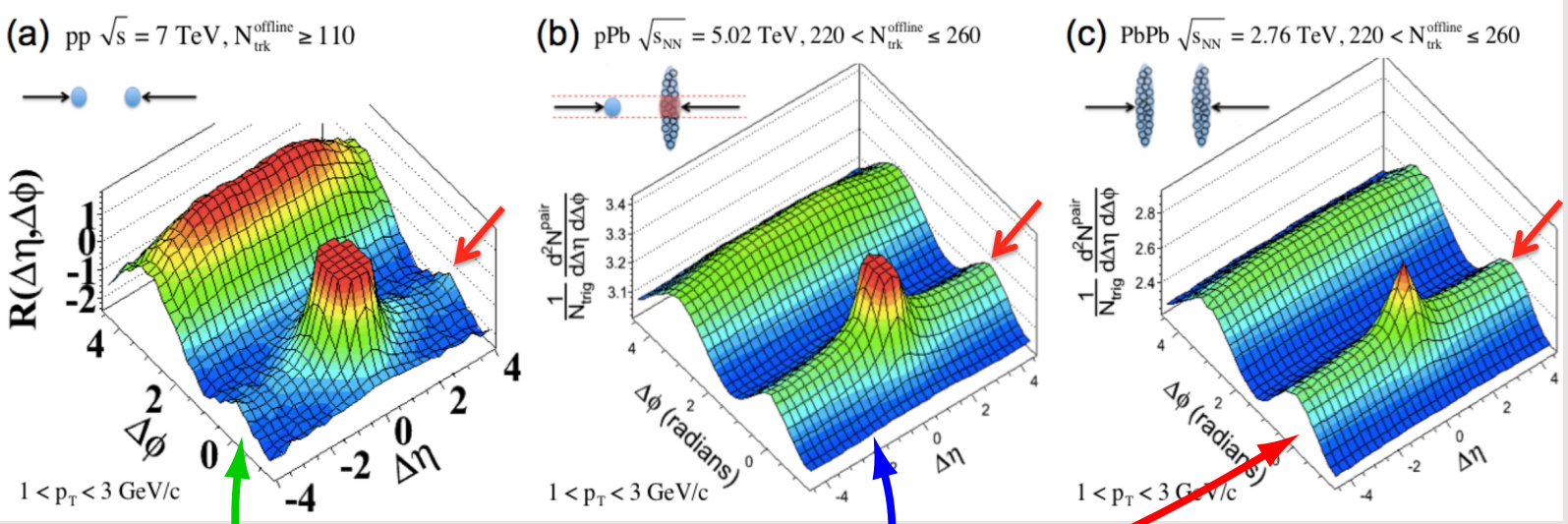
- AA collisions : this is flow !

Flow in small systems

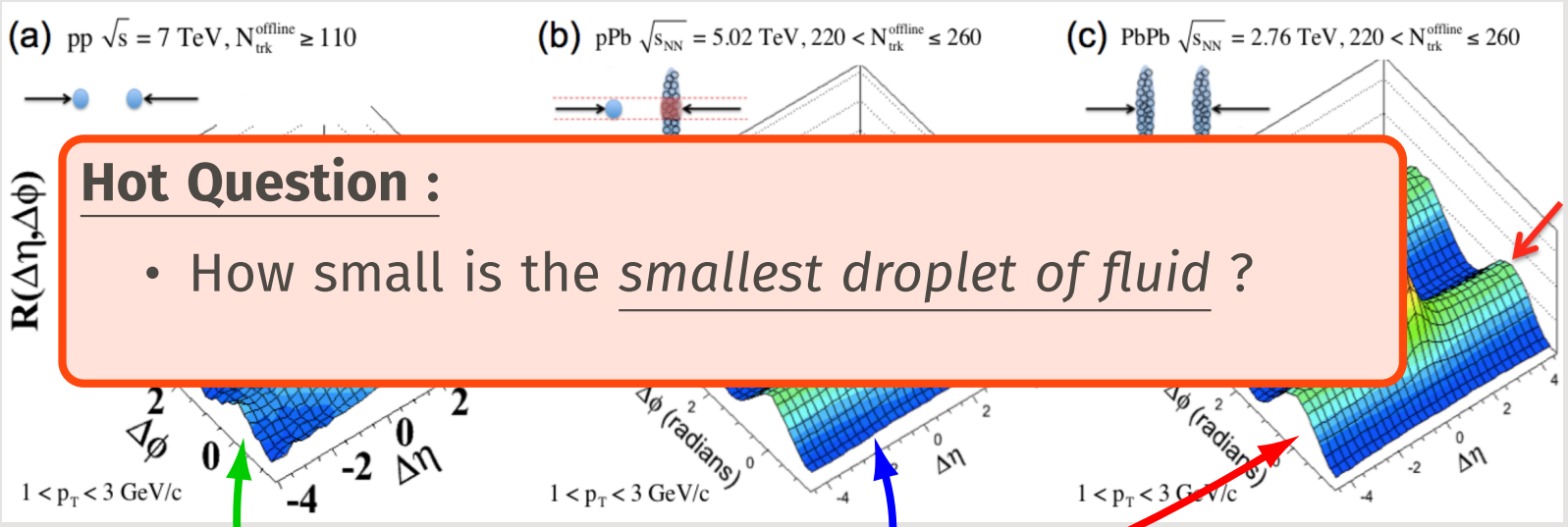


- AA collisions : this is flow !
- pA collisions : maybe flow ?

Flow in small systems



- AA collisions : this is flow !
- pA collisions : maybe flow ?
- pp collisions : could it still be flow ?!



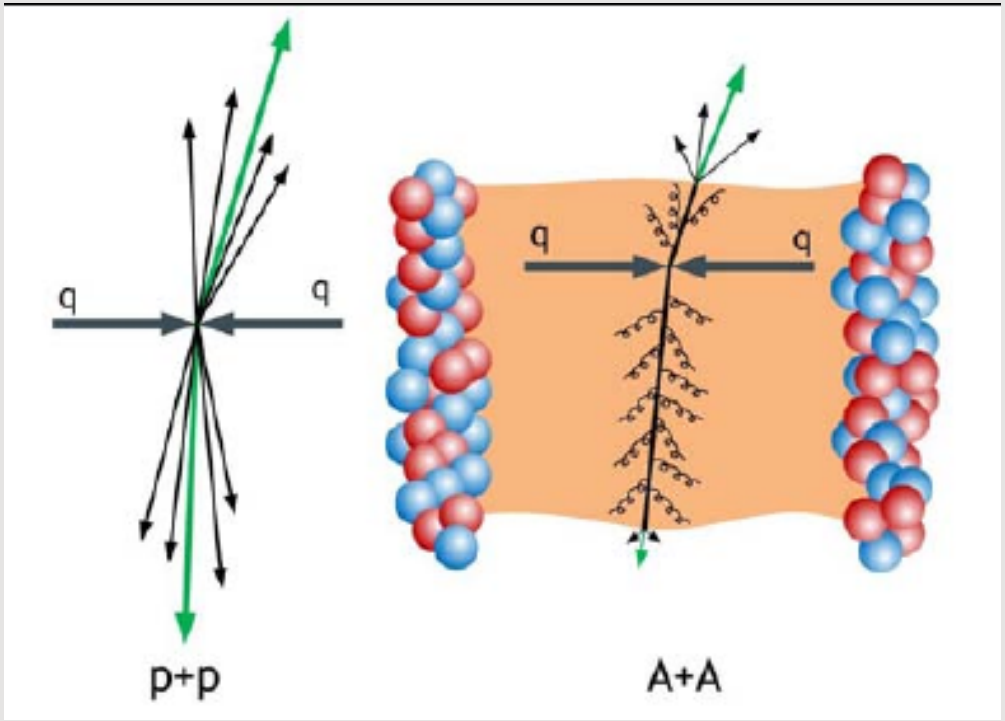
Hot Question :

- How small is the *smallest droplet of fluid* ?

- AA collisions : this is flow !
- pA collisions : maybe flow ?
- pp collisions : could it still be flow ?!

Tomography and Hard Probes

Energy loss, Jet quenching



- The QGP enhances the radiative energy losses of hard partons
  $\Longrightarrow$ use these observables as a “tomographic” tool

Basics of QCD radiation

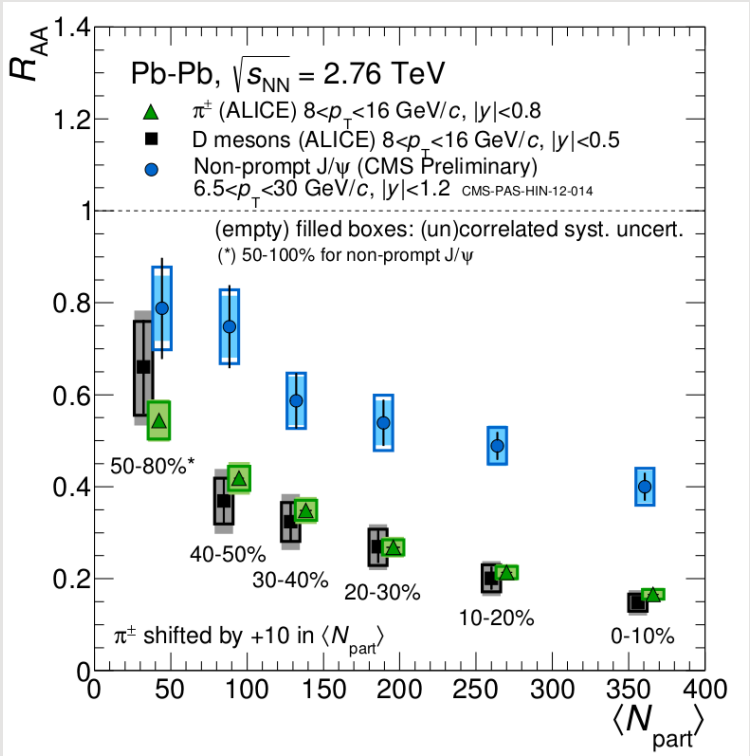
$$\begin{pmatrix} \text{Radiation} \\ \text{Probability} \end{pmatrix} \propto \alpha_s \, \frac{d^2 \mathbf{k}_\perp}{k_\perp^2} \, \frac{dz}{z}$$

- Soft ($z = 0$) and Collinear ($k_\perp = 0$) divergences
- Jet cross-sections are immune to these singularities (unlike more exclusive hadron spectra)

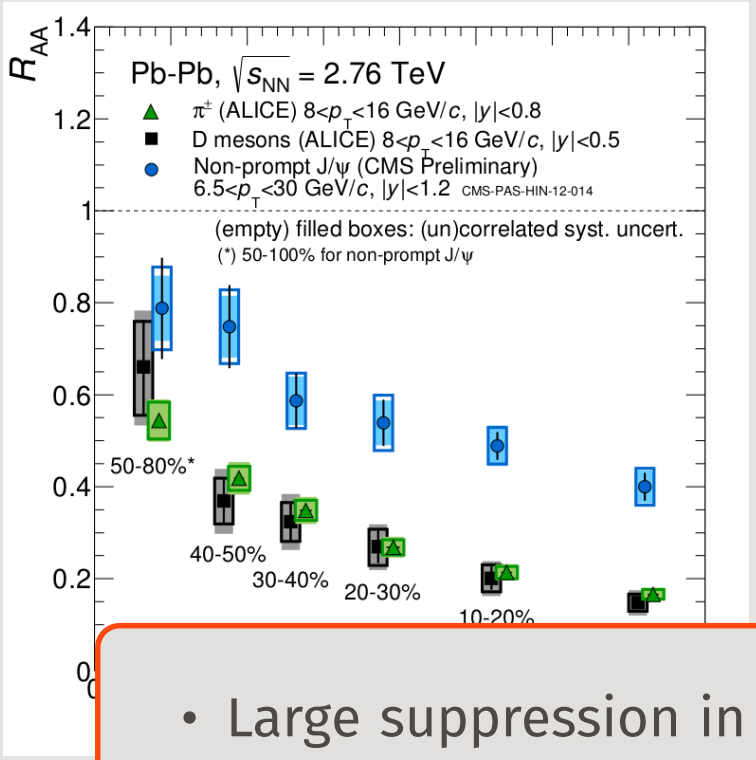
- Soft
- Jet c
mor

In-medium modifications:

- Production of hard probes is unmodified (saturation effects not important for $p_\perp \gg Q_s$); but we need also parton distributions of the neutron (accessible via DIS on deuterium)
- Gluon formation time: $t_f \sim E/k_\perp^2$
- $k_\perp^2$ increased by random kicks that occur within one formation time: $k_\perp^2 = \hat{q} t_f \implies t_f = \sqrt{E/\hat{q}}$
- Effect important when t_f larger than mean free path λ, i.e., $E > \hat{q}\lambda^2$



- **Nuclear modification ratios :** ratio of inclusive hadron yields in AA collisions and a reference. Measured as a function of:
  - transverse momentum
  - rapidity
  - centrality
  - hadron species



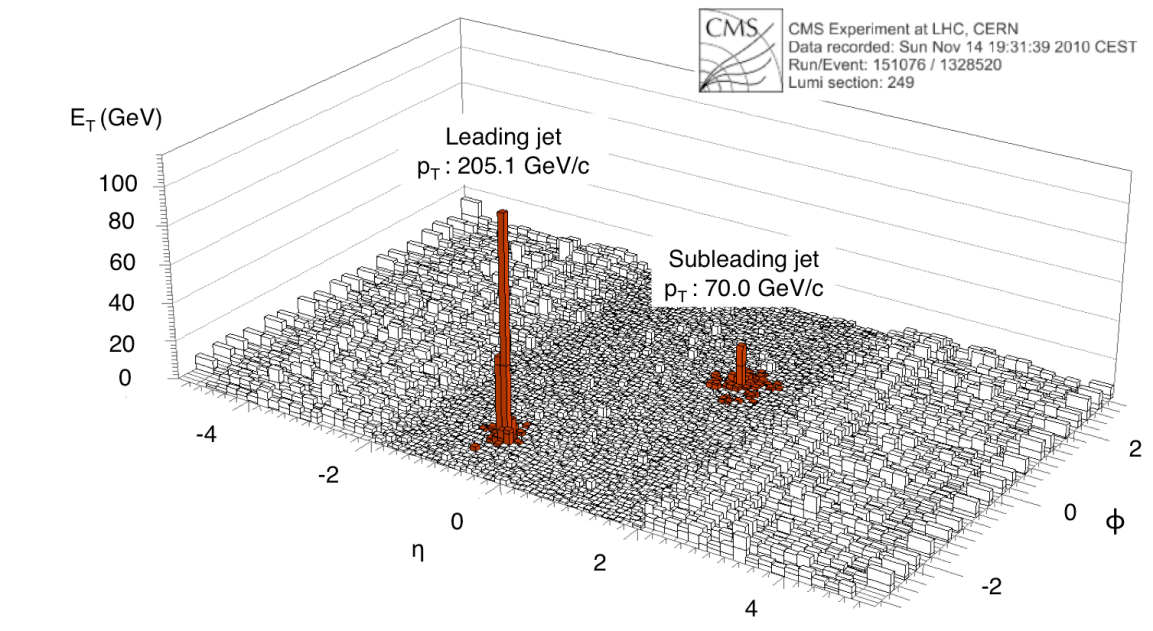
- **Nuclear modification ratios :** ratio of inclusive hadron yields in AA collisions and a reference. Measured as a function of:
  - transverse momentum
  - rapidity
  - centrality

- Large suppression in central collisions for all "light" partons (including charmed quarks)
- Smaller suppression for bottom quarks

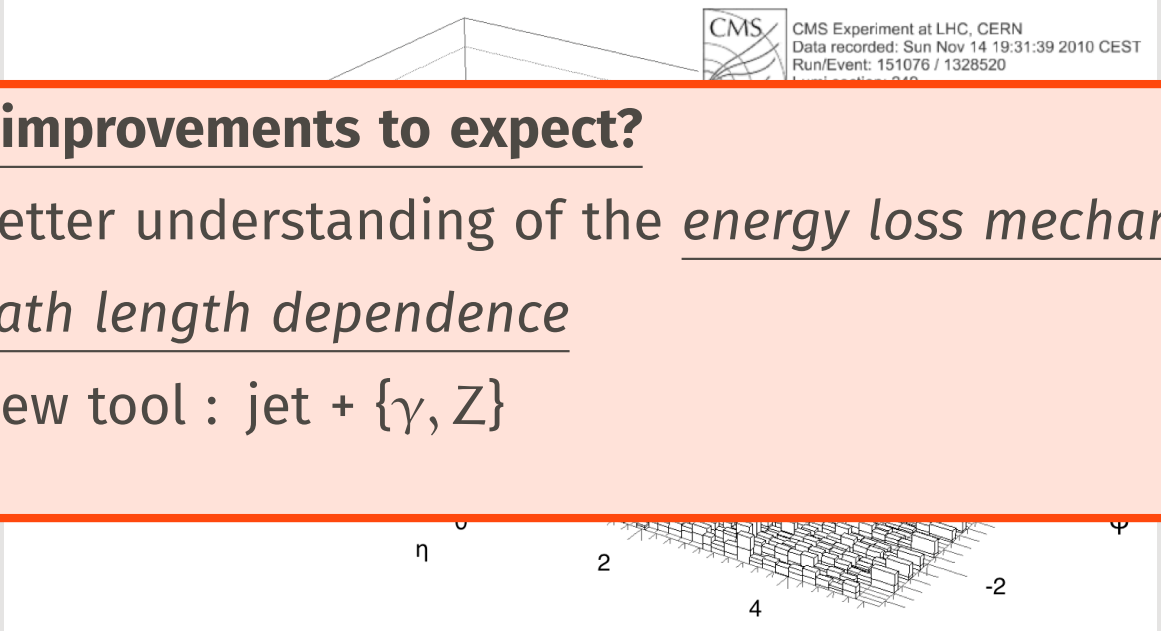
  $\Longrightarrow$ in agreement with theoretical expectations (*dead cone effect*)

Jet modifications

- The (rather hard) emissions responsible for $R_{AA} < 1$ are quite collinear and tend to remain inside the jet cone
- Softer emissions are affected by the medium in two ways:
  - tend to be emitted at larger angles due to rescatterings
  - scatterings of the *emitters* randomize their colors, which suppresses the interferences that would normally prevent radiation outside of the jet cone (happens when the separation $r_\perp$ between two emitters is larger than the coherence length of the medium color field $\Longrightarrow$ jets with a large opening angle are more affected)
- Jets are quenched by increased soft emissions outside of the jet cone (lost energy can be recovered outside of the jet cone in the form of soft particles)



- Now feasible : direct observation of reconstructed jets
- Provides a handle on the energy of the jet before quenching
- New handles to characterize energy loss (jet opening angle)



What improvements to expect?

- Better understanding of the *energy loss mechanism(s)*
- *Path length dependence*
- New tool : jet + $\{\gamma, Z\}$

- Now feasible : direct observation of reconstructed jets
- Provides a handle on the energy of the jet before quenching
- New handles to characterize energy loss (jet opening angle)

Thermometric Probes

- Thermometric probes $\equiv$ observables that are sensitive to the local temperature of the medium
  - Photon/dilepton yields (hotter $\Longrightarrow$ more photons)
  - Heavy quarkonia (hotter $\Longrightarrow$ more dissociation)
- Note: real life is more complicated because the temperature is not spatially homogeneous and evolves in time

Thermal photons in data

- Many sources of photons:
  - Decay photons (mostly from π^0)
  - Hard partonic interactions at the impact of the two nuclei
  - Pre-equilibrium photons
  - Thermal photons from QGP
  - Thermal photons from hadron gas
  - (hard non thermalized quark,gluon)+ QGP interaction

- Strategy:
  - remove decay photons (requires a good handle on their sources)
  - compare remaining “direct” photons with known non-thermal sources

Thermal

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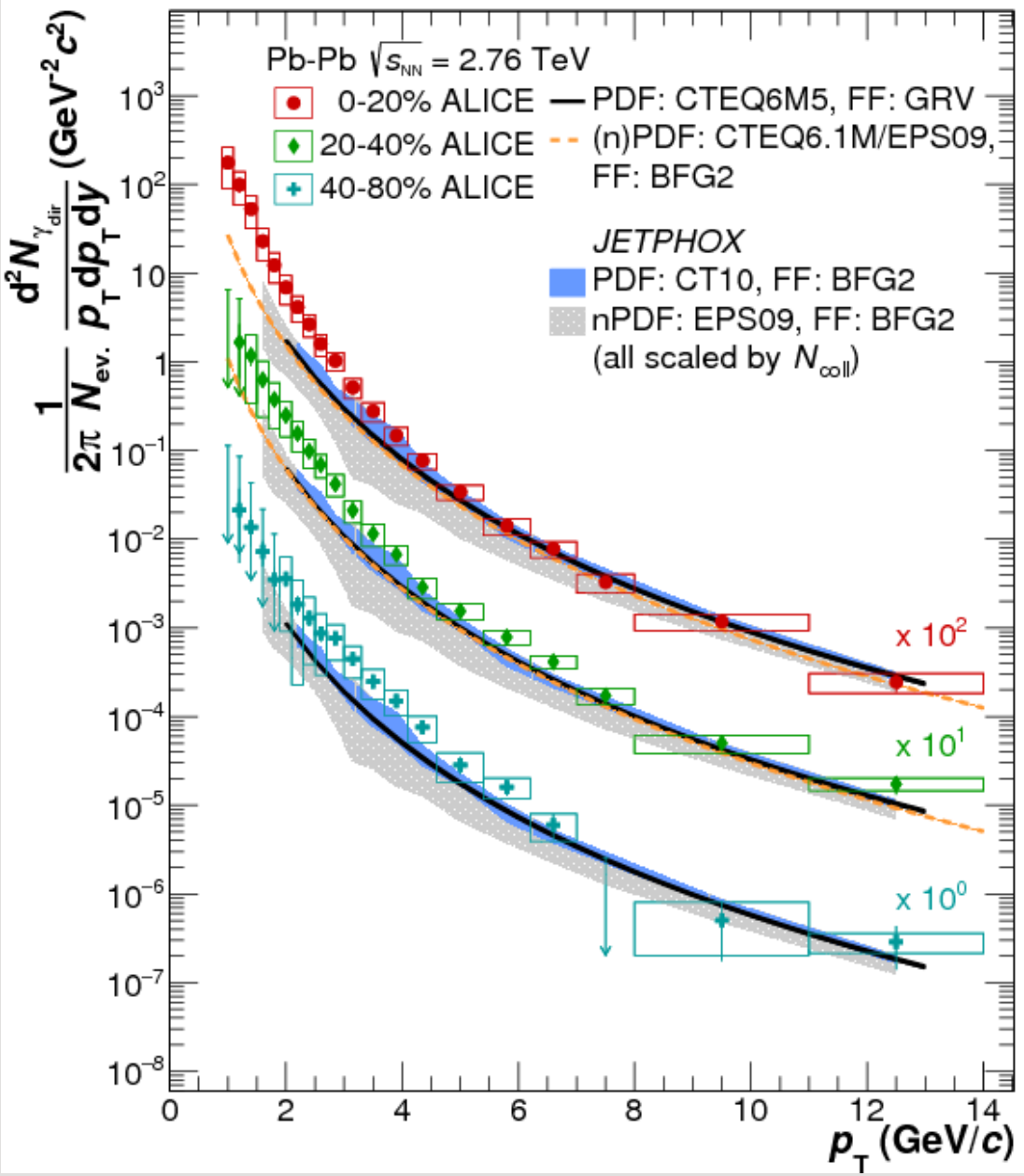

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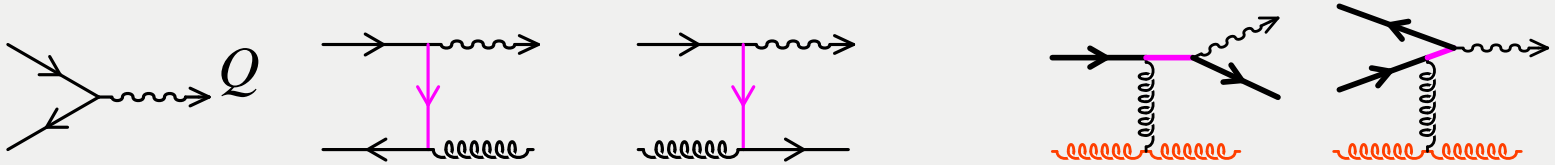
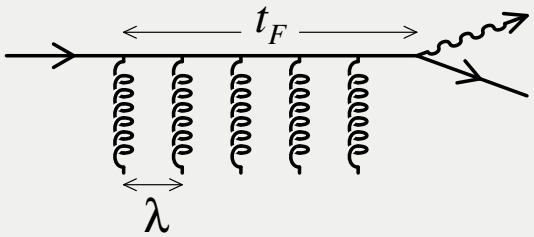
Thermal photons and dileptons (from QGP)

- Fireball smaller than photon mean free path $\Longrightarrow$ photons do not thermalize with the quarks and gluons; escape without further interactions
- Main processes for production by the QGP:



- Landau-Pomeranchuk-Migdal effect (yield reduced if $t_f > \lambda$):



  - Formation time: $t_f^{-1} = E_\gamma(k_\perp^2 + m^2)/E_{\text{quark}}^2$
  - Affects soft photons or hard photons emitted collinearly

Thermal photons and dileptons (from hadron gas)

- Also obtained from a $\langle J^\mu J^\nu \rangle$ correlator
- But: not directly calculable from the QCD Lagrangian that has quarks and gluons degrees of freedom
- One may use: chiral effective theory, functional RG, ...
- Particularly important are the modifications (shift, broadening) of the spectral function of the ρ

Thermal photons and dileptons (from hadron gas)

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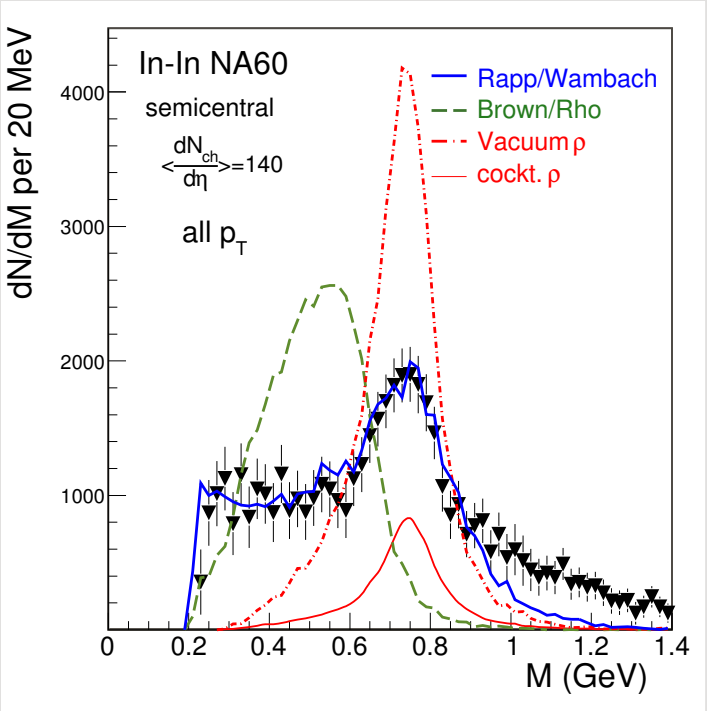
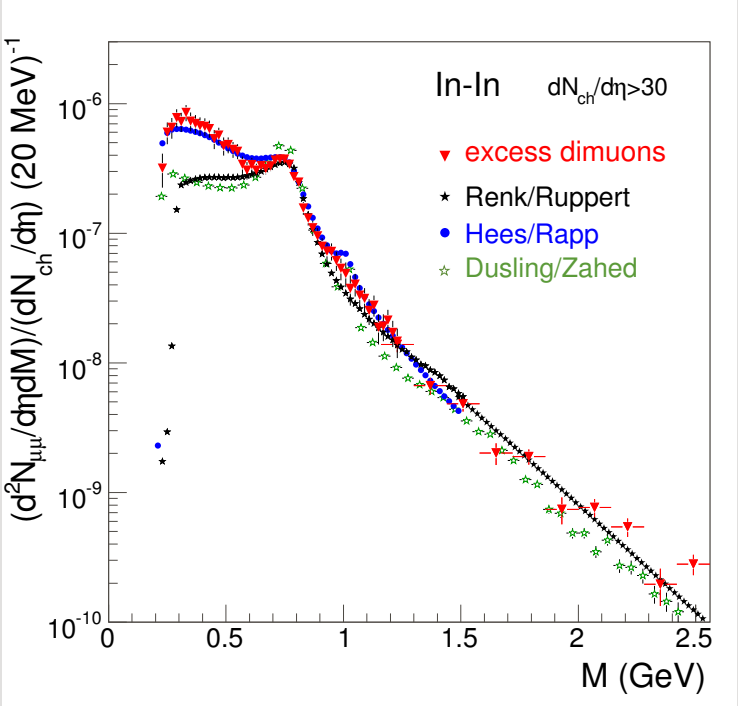
Exp. data versus effective models:

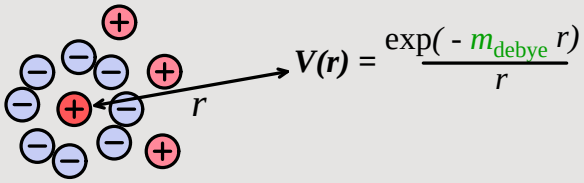




From local photon rates to photon yields...

- One may (in principle) calculate the photon/dilepton production rate given the local temperature and chemical potential
- This must be folded within the bulk evolution of the system:
  - at each point, boost by the local fluid velocity
  - integrate over space and time
- Note: even if a thermal photon excess admits a fit $\sim \exp(-E_\gamma/T_{\rm eff})$, the fit parameter $T_{\rm eff}$ does not have a direct interpretation as the temperature of the plasma (among other effects, this temperature is blue-shifted by the radial flow)
- This blue-shift is avoided with dileptons if one measures the yield as a function of their invariant mass (but the extracted temperature still reflects a spacetime average)

Debye screening



- Debye screening weakens the binding of $Q\overline{Q}$ pairs
- Sequential suppression pattern depending on the binding energies

Quarkonia suppression

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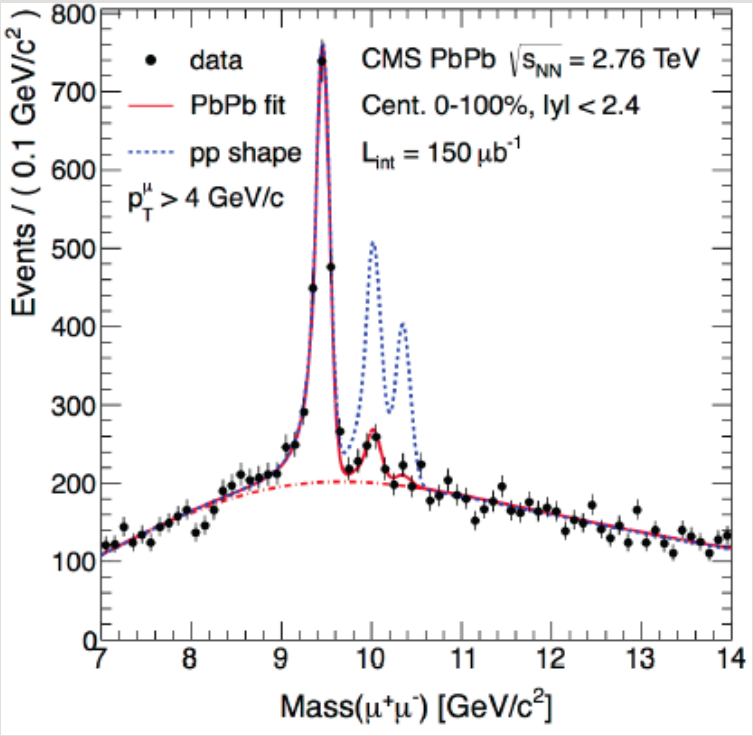

- Differential suppression of the 1S, 2S and 3S states of Υ

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binding of $Q\overline{Q}$ pairs

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tern depending on the
ding energies

In-medium quarkonia states

- Ab-initio approach: extract the $Q\overline{Q}$ spectral function

$$G(\tau, \mathbf{p}) = \int d\omega \; \rho(\omega, \mathbf{p}) \, \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}$$

- $G(\tau, \mathbf{p})$ computable in lattice QCD, but only at a finite set of τ's
- Possible approaches:
  - *Maximal Entropy Method*: Bayesian method for finding the most likely spectral function consistent with the computed values of G and some additional constraints (e.g., positivity)
  - Theory-inspired modeling of the spectral function, and standard parameter fit
- Other interesting object: singlet $Q\overline{Q}$ potential, $V_{\text{singlet}}(r)$
  - at high T, disappearance of the linear rise at large distance
  - appearance of an imaginary part (due to transitions from singlet to octet)

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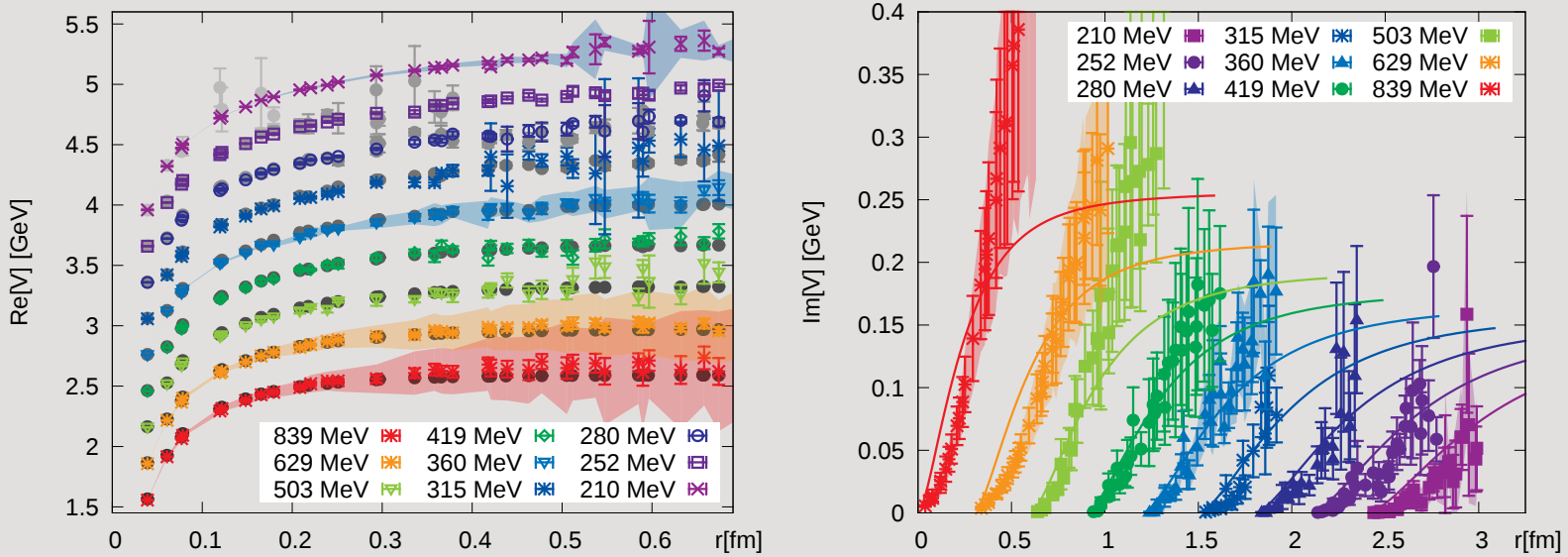
$$\cosh(\omega(\tau - 1/2T))$$



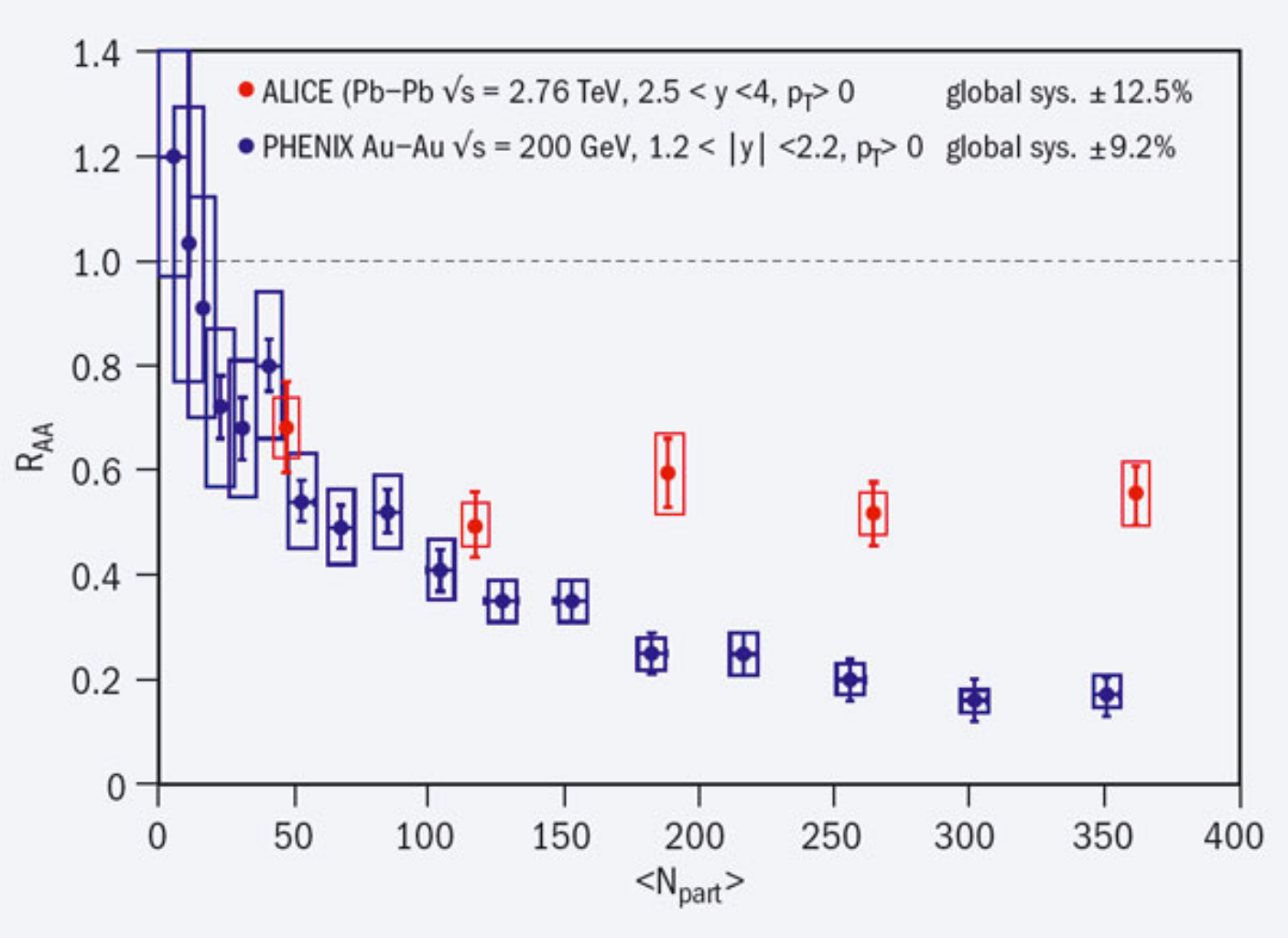
- Other interesting object: singlet QQ potential, $V_{\text{singlet}}(r)$
  - at high T, disappearance of the linear rise at large distance
  - appearance of an imaginary part (due to transitions from singlet to octet)

Quarkonia regeneration

- Most common outcome: after a $Q\overline{Q}$ bound state is dissociated, the Q and $\overline{Q}$ evolve independently, and eventually bind with one of the (more abundant) light quarks around to form heavy-light mesons (e.g., D, B)

- At LHC : copious production of $c, \overline{c}$ $\Rightarrow$ large density
  $\Rightarrow$ formation of J/ψ by recombination of unrelated c and $\overline{c}$

J/ψ suppression at RHIC and LHC



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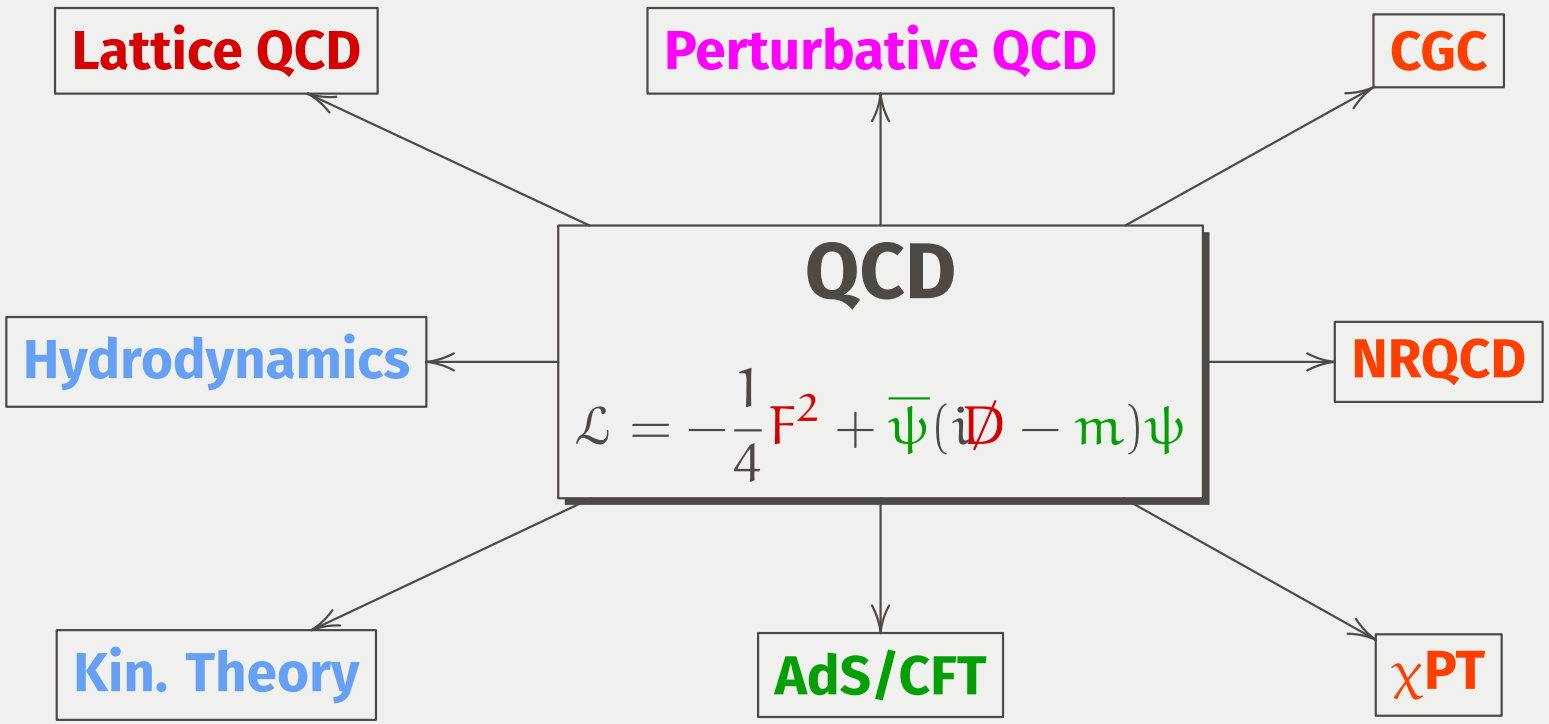
Summary and Outlook



- Although the underlying theory (QCD) is well known, it is often too difficult to perform ab initio computations
- One uses a variety of alternate approaches to simplify the problem

What have we learned so far? (1/2)

- The QGP is a nearly perfect fluid,
- Its shear viscosity to entropy ratio is in the range $[1, 2.5]$ (in units of $\hbar/4\pi$), making it the substance with the smallest ratio so far,
- Its equation of state is consistent with lattice QCD expectations, and with the deconfinement of the color degrees of freedom,
- The yield of "light" partons, including charm quarks, is significantly suppressed compared to rescaled proton-proton collisions,
- The suppression of bottom quarks is less pronounced, in agreement with theoretical expectations (dead-cone effect due to the mass of the emitter),

What have we learned so far? (2/2)

- The studies of energy loss can now be supplemented by direct observations of reconstructed jets. This has allowed to determine that a large amount of energy is radiated by soft emissions at large angle,
- A sequential pattern has been observed in the disappearance of $b\overline{b}$ bound states, consistent with the theoretical understanding of the dissociation phenomenon,
- At the highest energies, the production of charm quarks is copious enough to lead to the formation of J/ψ bound states by recombination of uncorrelated quarks and antiquarks.

What progress may we expect?

- Determine the temperature dependence of the shear viscosity,
- Obtain a better determination of the bulk viscosity,
- Better disentangle the mechanisms of energy loss, especially in the case of jets,
- Characterize when heavy quark bound states are formed,
- Estimate the initial temperature from thermal photons and the melting of quarkonia,
- Clarify to what extent the concept of flow applies to the system formed in proton-proton collisions (for this, need to disentangle initial flow from the subsequent hydrodynamically generated flow)

Thank You !