Quark Gluon Plasma (and more)

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TAE - Taller de Altas Energías - Workshop on High Energy Physics
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[One (2h) lecture on selected topics]

Yocto/LHC
Yoctosecond imaging of QCD collectivity using jet observables
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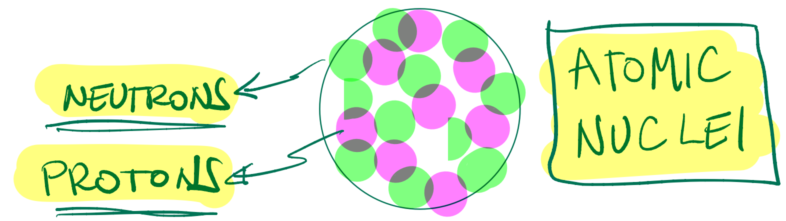
Centro CiUS R

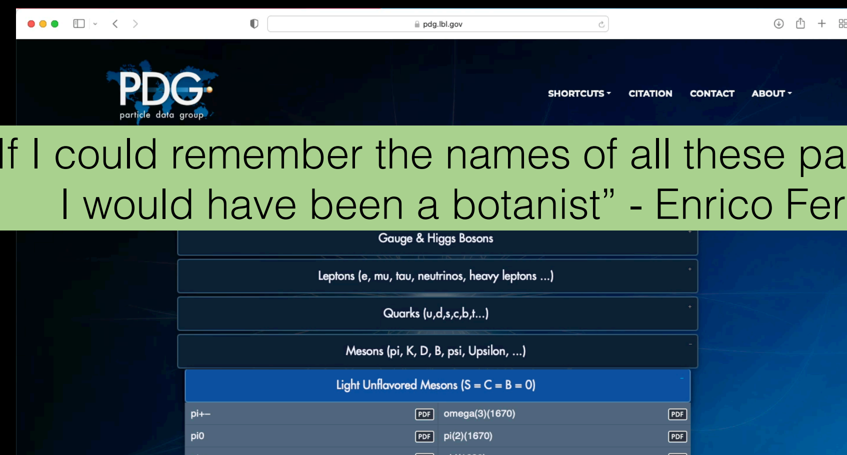
Excelencia María de Maeztu 2024-2029

QCD is the theory that describes the **Strong interaction** that binds together **protons and neutrons in the atomic nuclei**



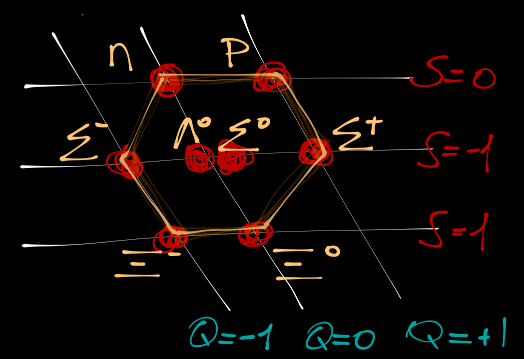
HADRONS = those particles that feel the strong interaction

PROTONS + NEUTRONS + COUSINS → TOO MANY!



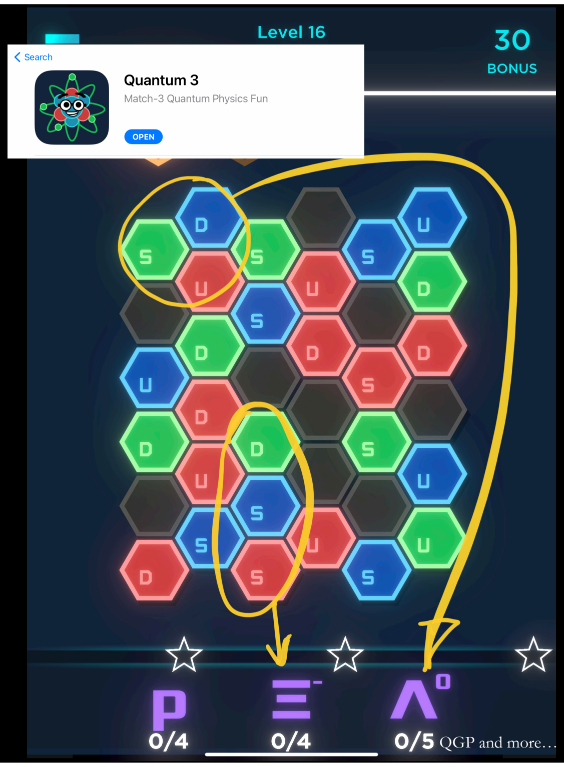
"If I could remember the names of all these particles, I would have been a botanist" - Enrico Fermi

"Periodic table" of hadrons

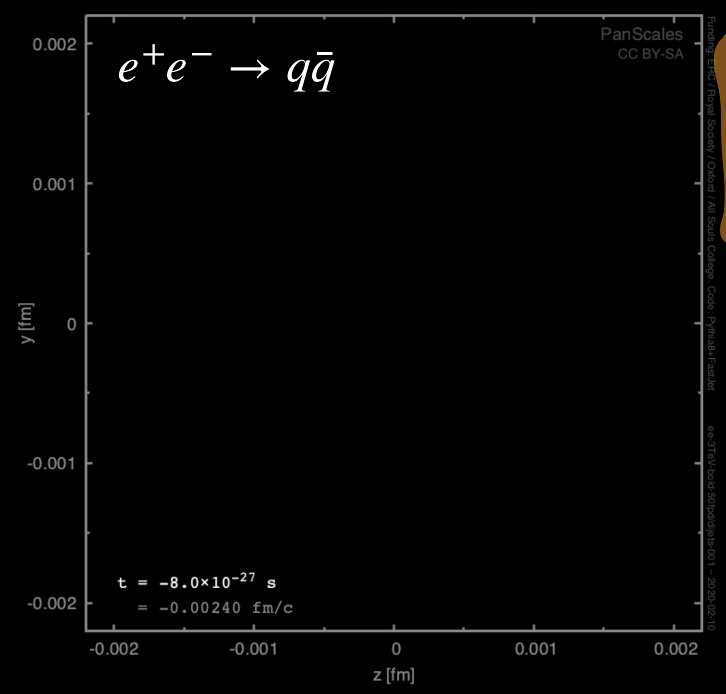


Hidden symmetry : internal structure

QUARKS



https://gsalam.web.cern.ch/gsalam/panscales/videos.html



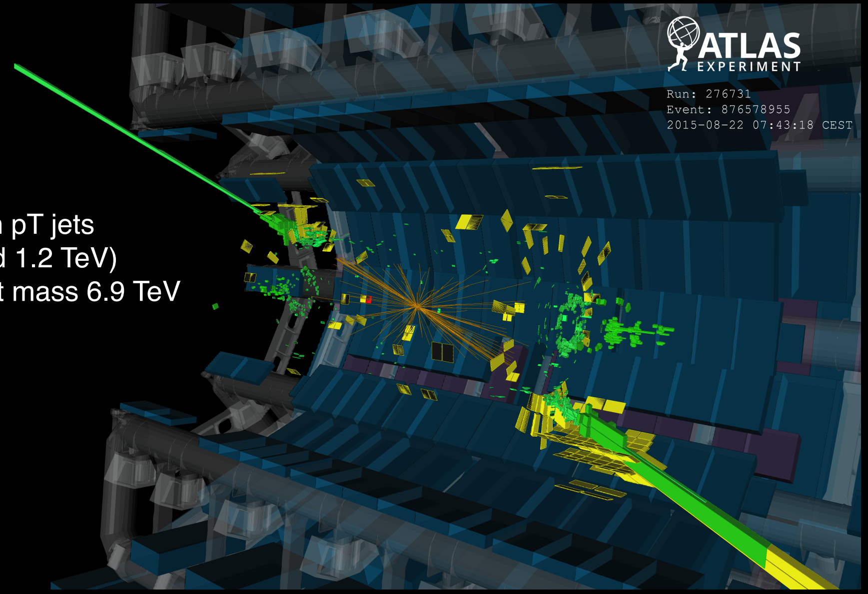
Can we "see" the quarks ?

3TeV e^+e^- events

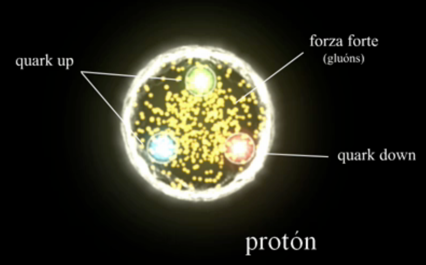
Initial particles in yellow
Intermediate particles in blue
Final particles in red
[details in the web page]

Jets in hadronic colliders

2 high pT jets
(1.3 and 1.2 TeV)
with invariant mass 6.9 TeV



The PROTON



Two (valence) up quarks + one (valence) down quark
+ a cloud of quarks, antiquarks and gluons - quantum fluctuations

QCD defined as our most perfect physical theory [Wilczek 2000]

An apparently simple lagrangian hides a plethora of **emerging** ...

[This animation was done before LHC started]

[Confinement; chiral symmetry breaking and mass generation; new phases of matter; a rich hadronic spectrum; a non-trivial vacuum structure; asymptotic freedom, etc]

QCD

QCD is the theory of strong interactions.

⇒ It describes interactions between hadrons (p, π, ...)

⇒ Quarks and gluons in the Lagrangian

- Asymptotic states.

⇒ No free quarks and gluons: Confinement.

- [illegible] conditions of temperature and density.

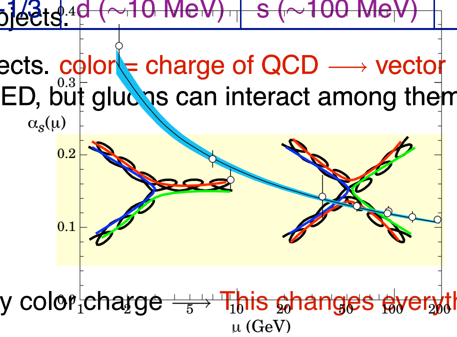
⇒ Strength smaller at smaller distances: Asymptotic freedom.

- Nuclear matter (us).

charge=+2/3	u (∼5 MeV)	c (∼1.5 GeV)	t (∼175 GeV)
charge=-1/3	d (∼10 MeV)	s (∼100 MeV)	b (∼5 GeV)

Don't blame QCD
Blame the Higgs!

- Colorless objects.
- Colorful objects. color = charge of QCD ⟶ vector
  Similar to QED, but gluons can interact among themselves

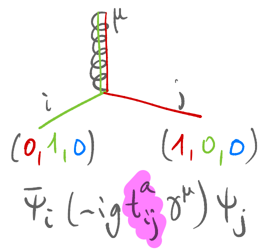


- Gluons carry color charge ⟶ This changes everything...

Gluons have color charge

Gluons change the color of the quark

[the corresponding vertex in QED does not change the charge of the electron]



[THIS IS JUST AN EXAMPLE]

$$\underbrace{(0,1,0)}_{\bar{\Psi}_i}\underbrace{\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{t^1_{ij}}\underbrace{\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}}_{\psi_j}$$

Color transformations with the Gell-Mann matrices $t_a = \frac{1}{2}\lambda_a$

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},\ \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},\ \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix},\ \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$

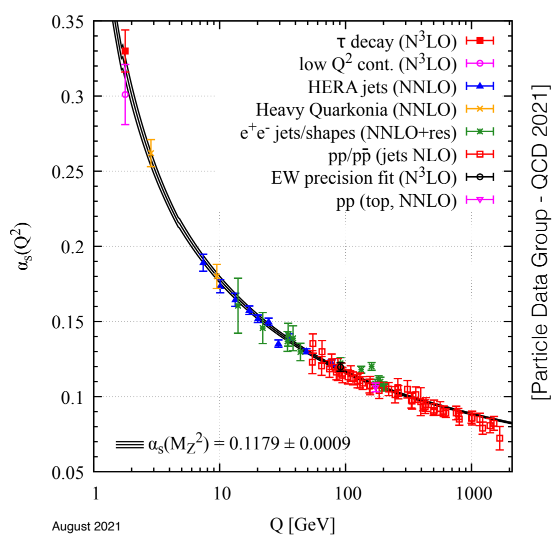
$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix},\ \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},\ \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix},\ \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & \frac{-2}{\sqrt{3}} \end{pmatrix},$$

Quark's color - fundamental representation of SU(3)

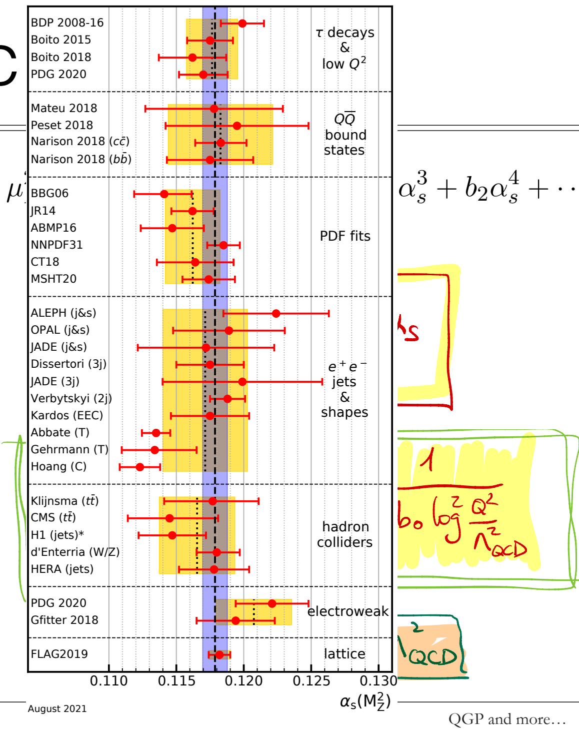
$$[t^a, t^b] = i f_{abc} t^c$$

Asymptotic

μ … $\alpha_s^3 + b_2\alpha_s^4 + \cdots)$



[Particle Data Group - QCD 2021]



Picture of confinement

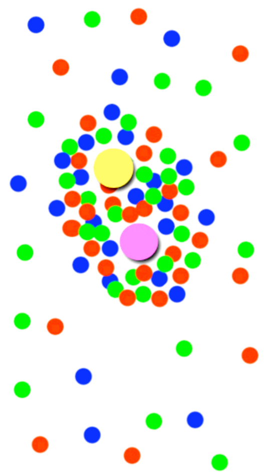
⇒ In quantum field theory, vacuum is a medium which can screen charge. (quarks or gluons disturb vacuum).

⇒ confinement $\Longrightarrow$ isolated quarks (gluons) = infinite energy

⇒ colorless packages (hadrons) $\Longrightarrow$ vacuum excitations.

⇒ masses:

	mass (GeV)	$\sum q_m$ (GeV)
p	$\sim$1	$2m_u + m_d \sim$0.03
π	$\sim$0.13	$m_u + m_d \sim$ 0.02



String picture

A way of visualizing a meson $\longrightarrow$ a $q\bar{q}$ pair join together by a string

- ⇒ Colorless object
- ⇒ The potential between a $q\bar{q}$ pair at separation r is

$$V(r) = -\frac{A(r)}{r} + Kr$$

- ⇒ When the energy is larger than $m_q + m_{\bar{q}}$ a $q\bar{q}$ pair breaks the string and forms two different hadrons.
- ⇒ In the limit $m_q \to \infty$ the string cannot break (infinite energy)

Chiral symmetry

In the absence of quark masses the QCD Lagrangian splits into
two independent quark sectors

$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm gluons} + i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{q}_R\gamma^\mu D_\mu q_R$$

⇒ For two flavors $(i = u, d)$ $\mathcal{L}_{\rm QCD}$ is symmetric under $SU(2)_L \times SU(2)_R$

⇒ However, this symmetry is not observed

Solution: the vacuum $|0\rangle$ is not invariant

$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0 \quad \longrightarrow \quad \text{chiral condensate}$$

⇒ Symmetry breaking

Golstone's theorem $\Longrightarrow$ massless bosons associated: pions

So, **properties of the QCD vacuum**

- Confinement
- Chiral symmetry breaking

Is there a regime where these symmetries are restored?

QCD phase diagram

Free quarks and gluons?

Asymptotic freedom: Quarks and gluons interact weakly at

@ Small distances — **increase density**

@ Large momentum — **increase temperatures**

QCD phase diagram

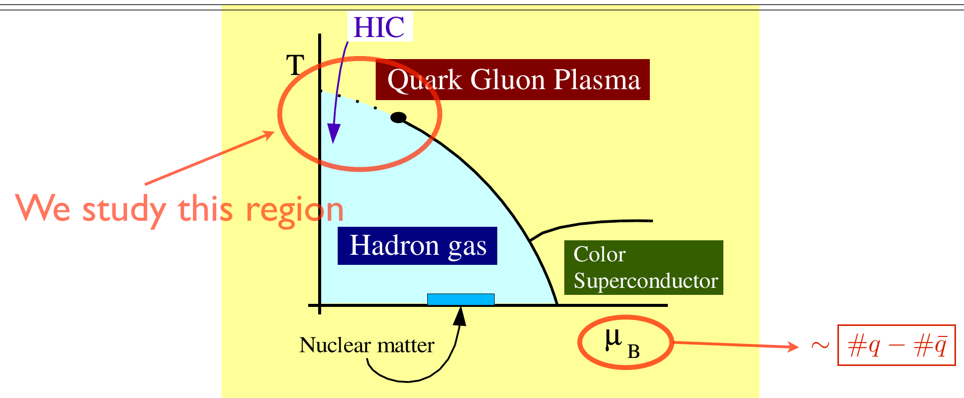


Fig. 1: Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

[Cabibbo and Parisi 1975]

- ⇛ First lattice calculation found a first order phase transition
- ⇛ Including quark masses probably not a first order
- ⇛ Present status: several different phases found.

QCD phase diagram

QCD — rich dynamical content, with emerging dynamics
that happens at scales easy to reach in collider experiments — e.g. EoS

Experimental tools

High-energy heavy-ion coll. [high T, low n_B]

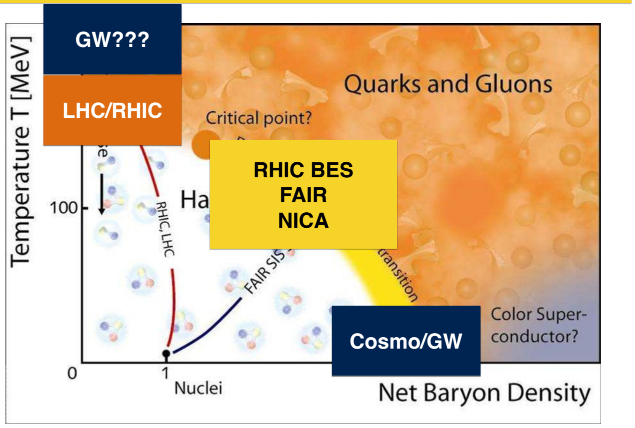
- LHC — pp, pPb, PbPb, XeXe, (other lighter ions under study)
- RHIC — pp, dAu, AuAu, CuCu, UU,…

Medium energies HIC [moderate T, high n_B]

- RHIC Beam Energy Scan
- FAIR at GSI
- NICA at Dubna

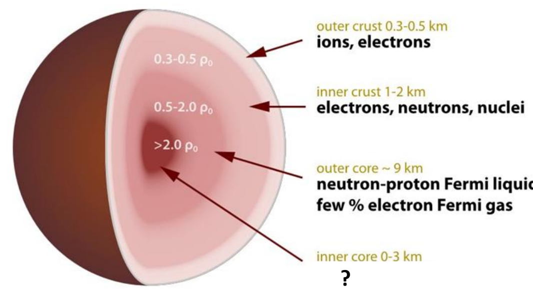
Cosmological observations — notably GWs

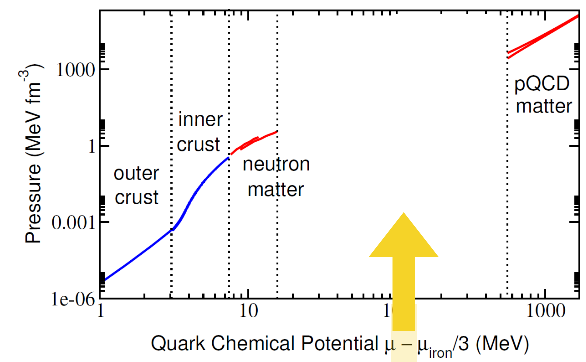
- Neutron star coalescence - **low T, high n_B**
- Future — access to QCD transition in early Universe?



Neutron stars

EoS determines neutron star structure



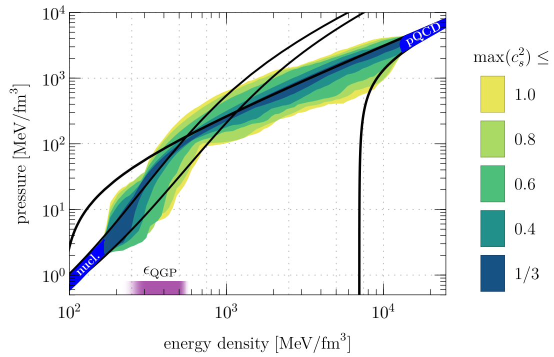


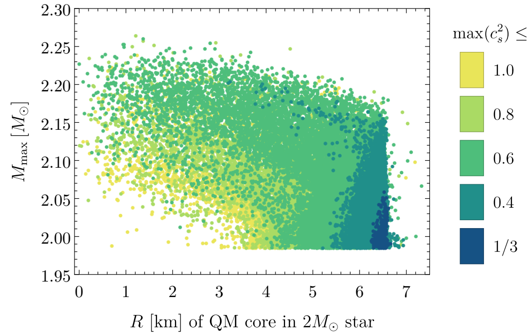
[A Vuorinen QM2018]

Lattice QCD
very challenging at finite μ_B

Region relevant for neutron star structure largely unknown

EoS constraints from GW





[Annala, Gorda, Kurkela, Vuorinen 2018; Annala, Gorda, Kurkela, Nattila, Vuorinen 2019;
also Most et al. 2018; Dexheimer et al. 2019 - More recent studies available, not shown]

The existence of quark-matter core found to be a common feature of the allowed EoS

Further constraints for the EoS at higher and higher baryon density in future experiments FAIR, NICA

QCD thermodynamics I

⇒ In the grand canonical ensemble, the thermodynamical properties are determined by the (grand) partition function

$$Z(T,V,\mu_i) = \mathrm{Tr}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}$$

where $k_B = 1$, H is the Hamiltonian and N_i and μ_i are conserved number operators and their corresponding chemical potentials.

⇒ The different thermodynamical quantities can be obtained from Z

$$P = T\frac{\partial \ln Z}{\partial V}\,, \quad S = \frac{\partial (T\ln Z)}{\partial T}\,, \quad N_i = T\frac{\partial \ln Z}{\partial \mu_i}$$

⇒ Expectation values can be computed as

$$\langle \mathcal{O}\rangle = \frac{\mathrm{Tr}\mathcal{O}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}}{\mathrm{Tr}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}}$$

QCD thermodynamics II

In order to obtain Z for a field theory with Lagrangian $\mathcal{L}$ one normally makes the change $-it = 1/T$, with this, the action

$$iS \equiv i\int dt\mathcal{L} \longrightarrow S = -\int_0^{1/T} d\tau\mathcal{L}_E$$

and the grand canonical partition function can be written (for QCD) as

$$Z(T,V,\mu) = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A^\mu \exp\{-\int_0^{1/T} dx_0 \int_V d^3x(\mathcal{L}_E - \mu\mathcal{N})\},$$

where $\mathcal{N} \equiv \bar{\psi}\gamma_0\psi$ is the number density operator associated to the conserved net quark (baryon) number.

Additionally, (anti)periodic boundary conditions in $[0, 1/T]$ are imposed for bosons (fermions)

$$A^\mu(0,\mathbf{x}) = A^\mu(1/T,\mathbf{x})\,, \quad \psi(0,\mathbf{x}) = -\psi(1/T,\mathbf{x})$$

QCD thermodynamics III

In order to solve these equations

⇒ Perturbative expansion

- $\alpha_S(T)$ small for large $T \longrightarrow$ bad convergence, but some results obtained.

⇒ Lattice QCD

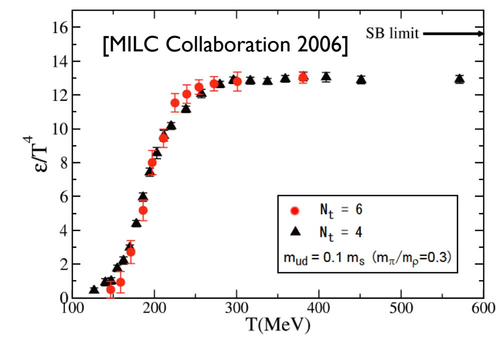
- Discretization in $(1/T, V)$ space
- Contributions to Z are computed by random configurations of fields in the lattice
- Most of the results for $\mu = 0$

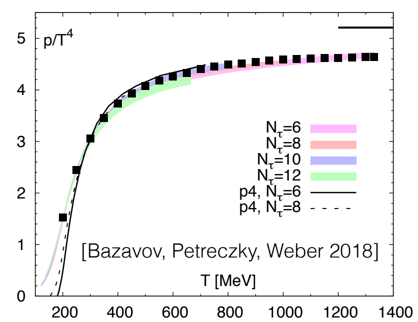
First example: EoS

Naïve estimation: Let's fix $\mu = 0$, the pressure of an ideal gas (of massless particles) is proportional to the number of d.o.f: $P \propto NT^4$

$$P_\pi \propto 3 \times T^4\,; \qquad P_{QGP} \propto (\underbrace{2\times 2\times 3}_{\text{quarks}} + \underbrace{2\times 8}_{\text{gluons}}) \times T^4$$

[notice that proportionality factors are different, Fermi/Bose-Einstein statistics]

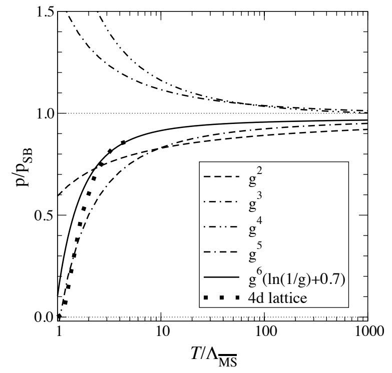




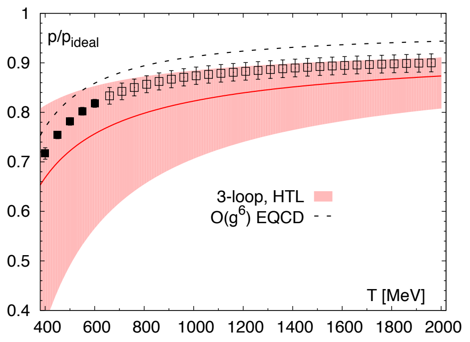
Perturbative calculations

Different orders in PT compared to lattice results

[Kajantie, Laine, Rummukainen, Schroder 2003]



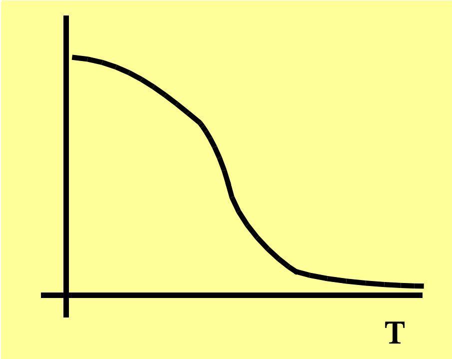
[Plot from Bazavov, Petreczky, Weber 2018]



Convergence for very large temperature

Order parameters

In order to know whether the change from a hadron gas to a QGP is a phase transition or a rapid cross-over order parameters are needed



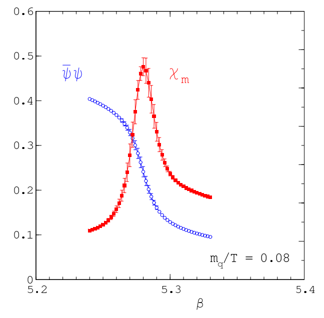
First order: discontinuity in the order parameter
Second order: discontinuity in the derivative
Crossover: continuous function

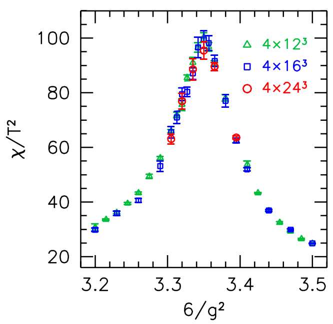
QCD order parameters I

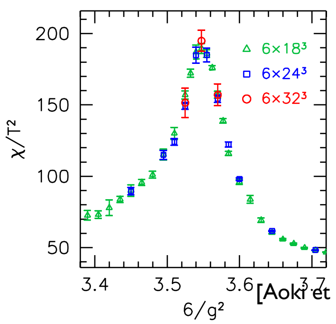
Chiral symmetry restoration: for $m_q = 0$
chiral condensate is the order parameter

Susceptibility: $\chi_m = \frac{\partial}{\partial m_q} \langle \bar{q} q \rangle$

$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0 \quad \xrightarrow[T\to\infty]{} \quad \langle 0|\bar{q}_L q_R|0\rangle = 0$$



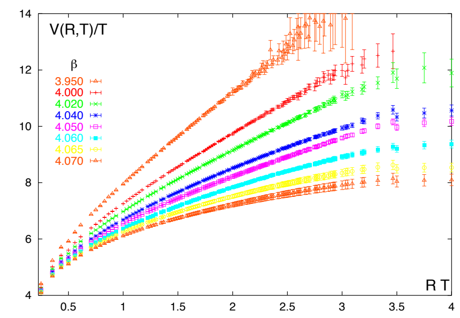




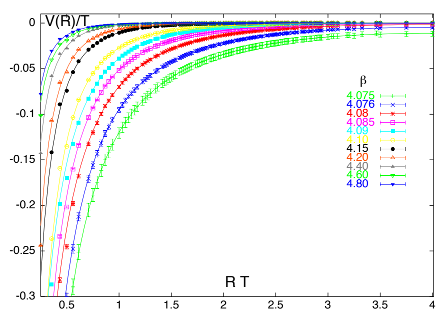
[Aoki et al 2006]

QCD order parameters II

Confinement: for. $m_q \to \infty$ the order parameter is the potential



$T < T_c$

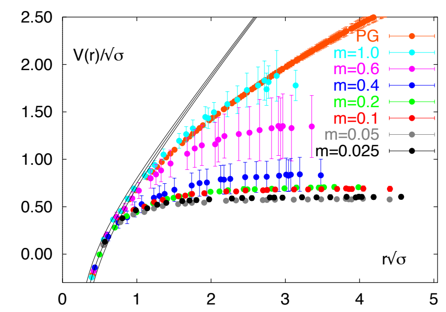


$T > T_c$

[Kaczmarek et al 2000]

However…

When masses are taken into account the potential is screened
even below T_c

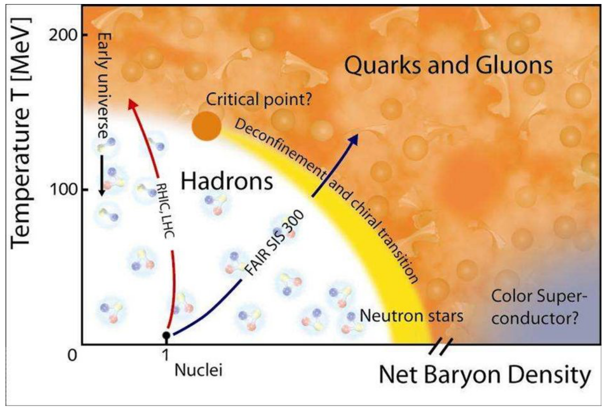


[Karsch, Laermann, Peikert 2001]

Light $\bar{q}q$ pair creation breaks the string

Physical quark masses

Two order parameters
$\Rightarrow m_q = 0 \longrightarrow$ Chiral condensate
$\Rightarrow m_q = \infty \longrightarrow$ Potential

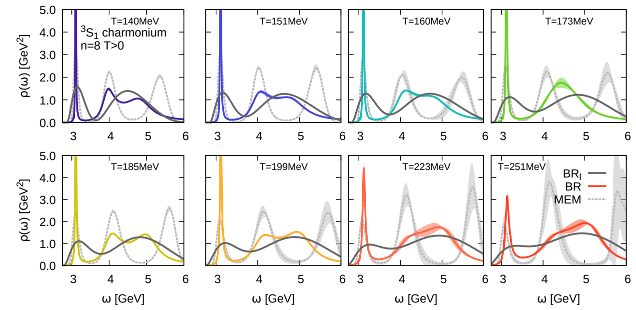


For physical masses, all results indicate a cross over

Quarkonia spectral functions

Naively, all bound states are destroyed in deconfinement. Quarkonia should then disappear at high T [Matsui, Satz 1986]. The situation is, however, more complicated

[Kim, Petreczky, Rothkopf 2018]

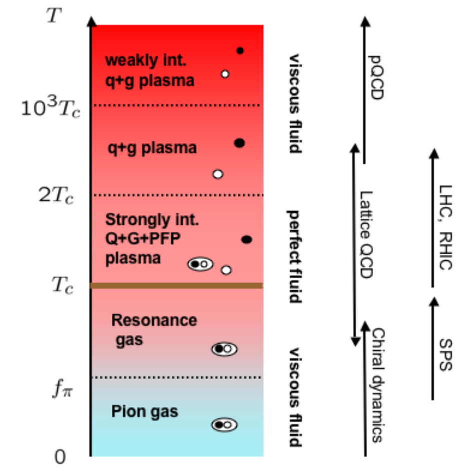


Different quarkonia states melt at different temperatures
[some bound states survive transition]

Sequential suppression

Υ	>2.63Tc
χ_{b1}	1.19 — 1.44 Tc
J/Ψ	1.29 — 1.35 Tc
χ_{c1}	1.19 Tc

A possible picture of hot QCD



[Taken from Hatsuda, J/Ψ workshop BNL, May 2006]

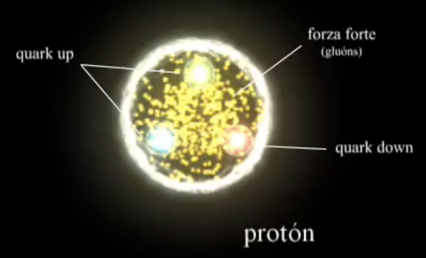
Experimenta tool

Heavy-ion collisions main goal

Study QCD under extreme conditions

↳ High density

↳ High temperature



High-densities/temperatures

- ☐ In the early Universe
- ☐ Core of neutron stars
- ☐ Heavy-ion collisions

QCD and collectivity

Standard Model built/discovered looking for the **highest possible degree of simplicity**

All particle content and interactions of the Standard Model discovered using this principle
— greatest success of the reductionistic approach in Physics

Also very successful — **Complex systems with emerging behavior**

[Strongly-coupling many body systems; quantum entanglement with many d.o.f…]

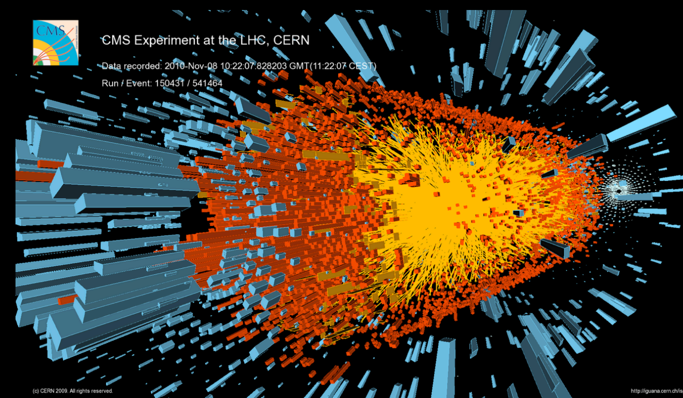
Region of transition — largely unknown

QCD — rich dynamical content, with emerging dynamics
that happens at scales easy to reach in collider experiments

Best available tool to study the first levels of complexity

Equilibrium AND non-equilibrium dynamics

High energy heavy ion collisions:



Produce "large" objects
↳ Macroscopic in QCD scales

Collide heavy nuclei

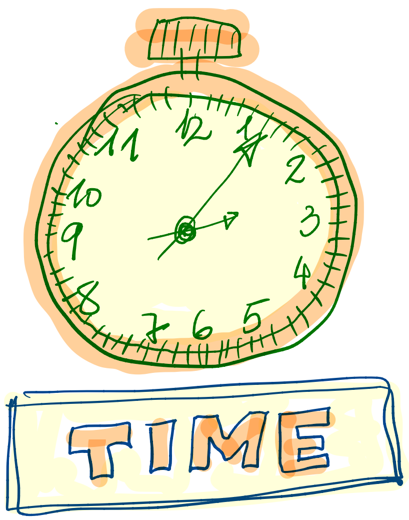
How do we extract QGP properties from data?

- QCD is an interesting theory, in part because an apparently simple Lagrangian hides a wealth of emerging phenomena as...
- phases of matter relevant for evolution the early Universe, some microseconds after de Big Bang or for neutron stars
- Some of these phenomena are related with symmetries which are broken in normal conditions but which can be restored at high temperatures and densities. In order to fulfill these conditions large energy densities need to be distributed in a macroscopic (in QCD scales) region. The LHC provide excellent conditions for the study of some of these phenomena with unprecedented precision by colliding heavy nuclei at the highest energies ever, reaching the TeV scales for the first time

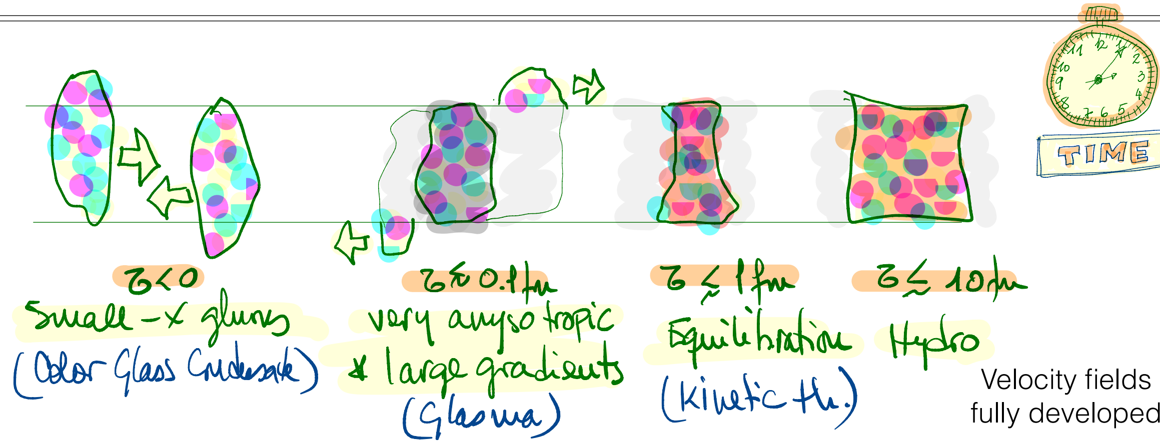
The study of QGP motivated the experiments of high energy HICs. Today the scope is wider but the characterization of the medium properties is still one of the main goals

Exploring fundamental questions

But also…

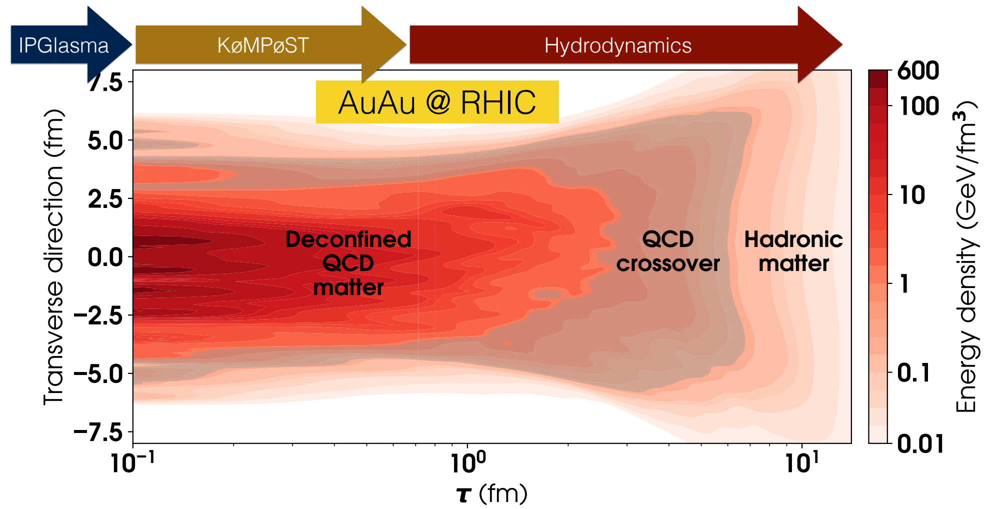


(A possible) Time evolution of a HIC



In contrast to usual HEP, **time and distance are relevant variables** in heavy-ion collisions
Building collectivity in extended (macroscopic) systems

(A possible) Time evolution of a HIC

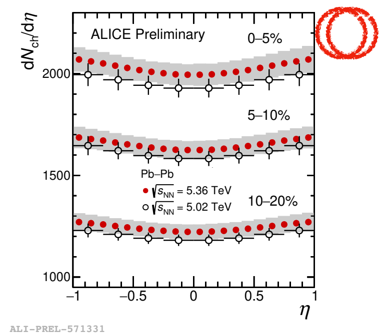


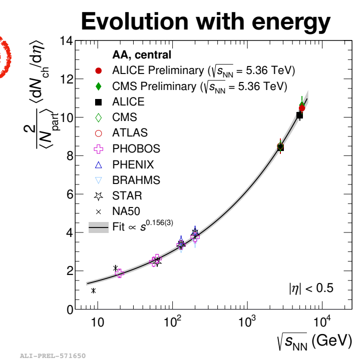
[Jean-François Paquet - talk at Initial Stages 2021]

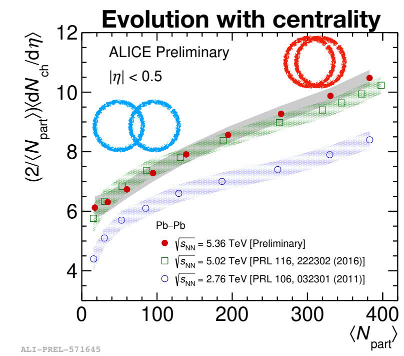
Initial state is very DENSE

Experimental data from ALICE in "centrality" and energy

[N. Jacazio ICHEP2024]

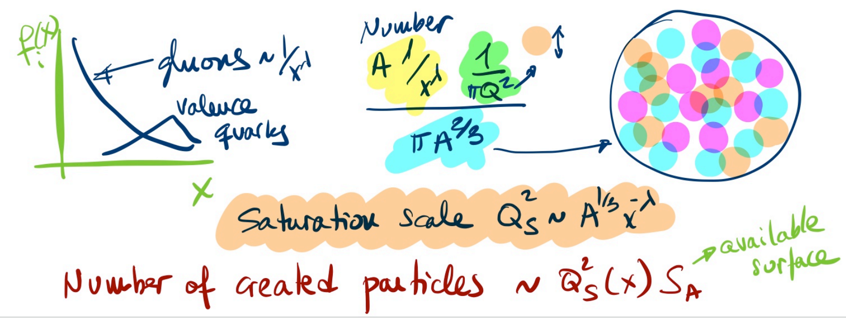


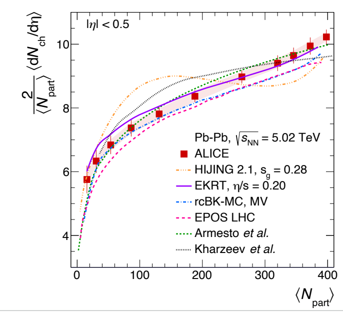




Huge multiplicities for central PbPb collisions

Initial conditions - Gluons saturate



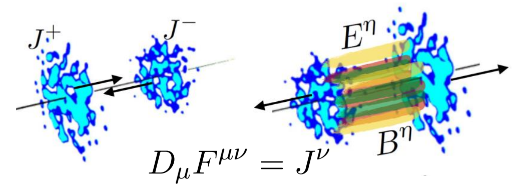


Color Glass Condensate

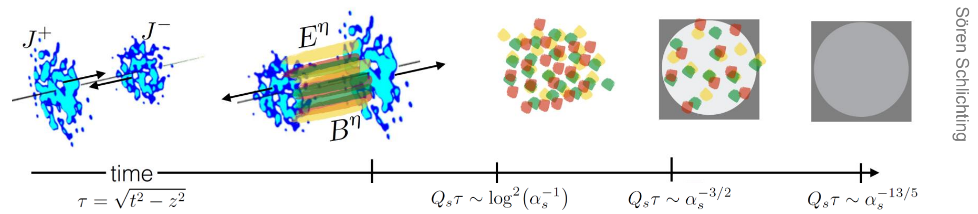
Large occupation numbers - classical fields

Quantum Corrections - evolution eqs.

Color Glass Condensate provides a general framework to compute initial stages



A picture for equilibration



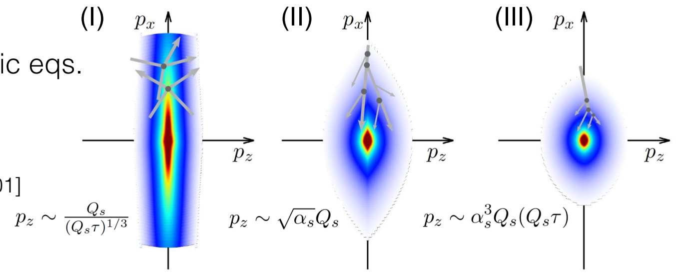
[Classical statistical/lattice gauge theory…]

Evolution of boost-invariant system with kinetic eqs.

$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

[Bottom-up thermalization — Baier, Mueller, Schiff, Son 2001]

[Arnold, Moore, Yaffe 2001; Kurkela, Zhu 2015; Keegan, Kurkela, Mazeliauskas, Teaney 2016; Kurkela Mazeliauskas, Paquet, Schlichting, Teaney 2019; Barrera, Salgado, Wu 2022…]



Hydrodynamics $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu} + \text{viscosity corrections}$$

(+ Equation of State)

+ initial time
+ freeze-out temperature

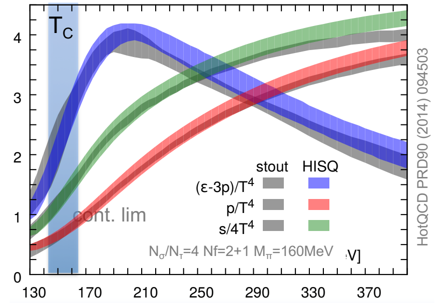
Far from equilibrium initial state needs to equilibrate fast (~1 fm/c or less)

Most of the theoretical progress in the last years:

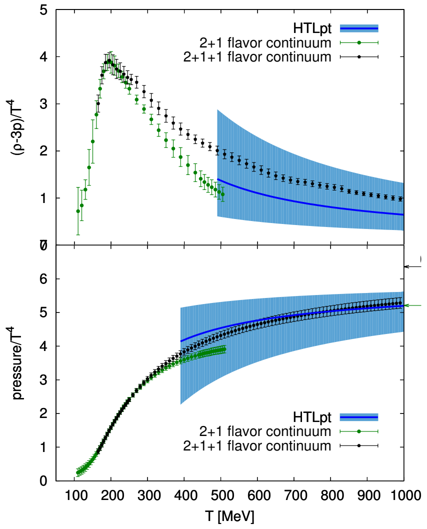
- Viscosity corrections and consistency
- Fluctuations in initial conditions
- Emergence of hydro from kinetic eqs, holography, etc…

EoS — high temperature

Equation of state at μ_B=0 is rather well known by lattice at moderate temperature — reasonably good matching with perturbative at $T \lesssim 1GeV$



[Included in hydro simulations]



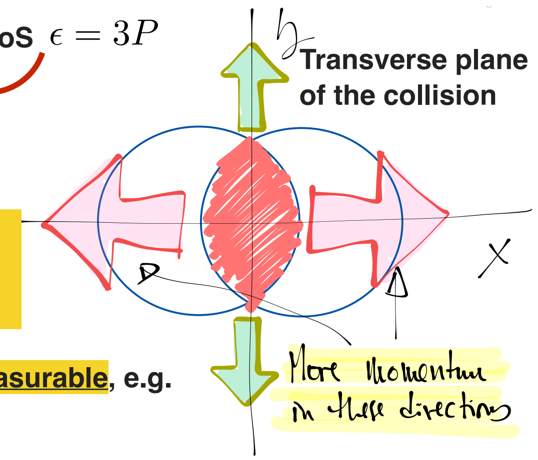
[Borsanyi et al Nature 539 (2016) no.7627, 69-71]

Harmonics: the golden measurement

[simplified discussion]

Remember the Euler eqs. — and use conformal EoS $\epsilon = 3P$

$$\frac{\partial \beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P \propto -\nabla \epsilon$$



Initial state <u>spatial</u> anisotropies → **Final state <u>momentum</u> anisotropies**

These final state momentum anisotropies are <u>measurable</u>, e.g.

$$\frac{dN}{d\phi} \propto 1 + 2 v_2 \cos 2\phi$$

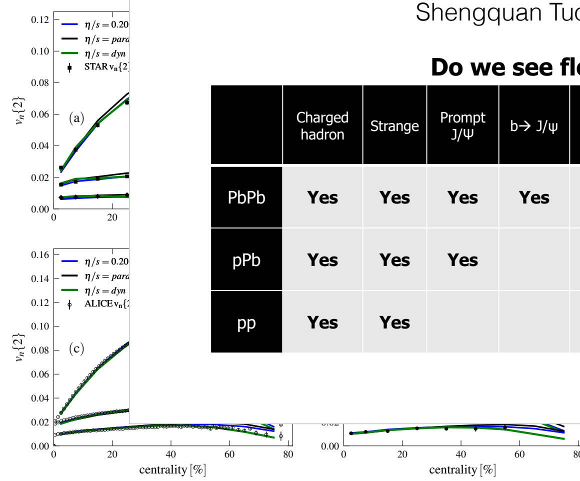
↳ Elliptic Flow

Description of data and viscosity

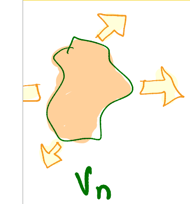
Shengquan Tuo ICHEP 2022

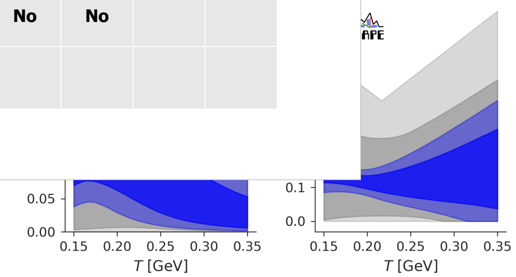
Do we see flow signals?

	Charged hadron	Strange	Prompt J/Ψ	b→ J/ψ	Prompt D^0	b→ D^0	Υ(1S/2S)	Dijet	Z boson
PbPb	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**
pPb	**Yes**	**Yes**	**Yes**		**Yes**	**No**	**No**		
pp	**Yes**	**Yes**			**Yes**				



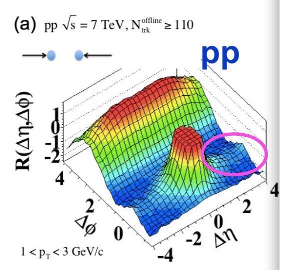
her harmonics





[Everett et al. 2021]

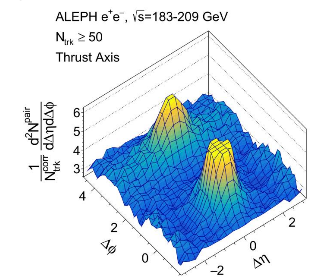
Hydro works in all systems from small to large ??



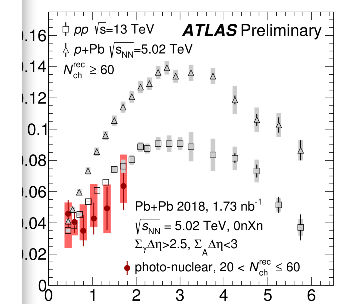
Hydro models able

Yen-Jie Lee ICHEP2022

Hits of a ridge in (reanalysed) high multiplicity ALEPH data?



What does it mean?

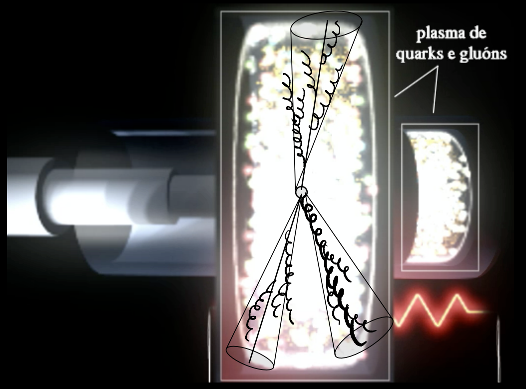


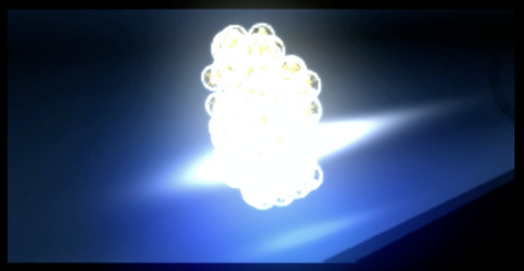
Hydrodynamics se ... large multiplicities

For some classes of problems hydro equations have attractors

[universal solutions, independent on initial conditions]

Hard processes



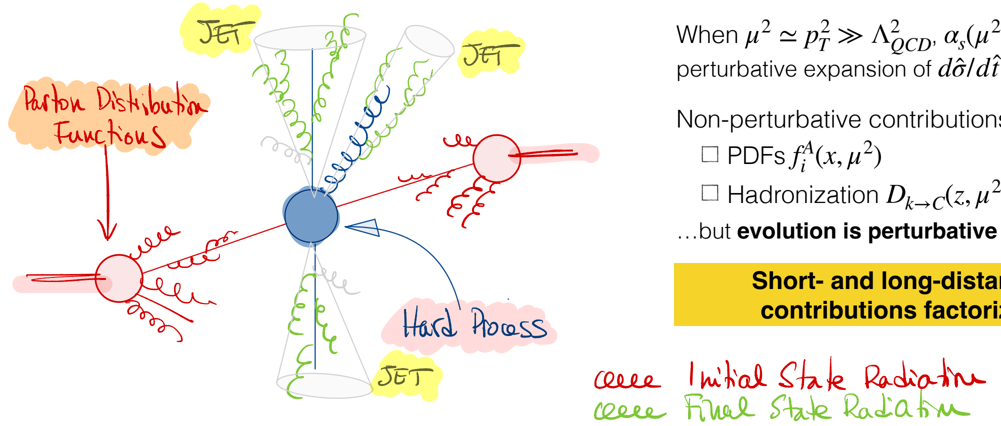


Excellent probes →

- Produced very early $\sim 1/Q$ — production computed in pQCD
- Many different probes and scales
- Jets are extended objects that evolve in times $1/E_{jet} < t \lesssim 1\mathrm{fm/c}$

Hard processes in QCD

$$\frac{d\sigma^{AB\to C+X}}{dp_T} = f_i^A(x_1,\mu^2)\otimes f_j^B(x_2,\mu^2)\otimes \frac{d\hat{\sigma}^{i,j\to k}}{d\hat{t}}\otimes D_{k\to C}(z,\mu^2)$$



When $\mu^2 \simeq p_T^2 \gg \Lambda^2_{QCD}$, $\alpha_s(\mu^2) \ll 1$ perturbative expansion of $d\hat{\sigma}/d\hat{t}$ possible

Non-perturbative contributions:

- ☐ PDFs $f_i^A(x,\mu^2)$
- ☐ Hadronization $D_{k\to C}(z,\mu^2)$

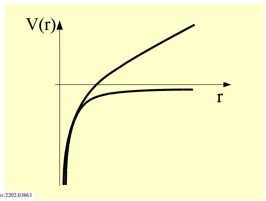
…but **evolution is perturbative** (DGLAP…)

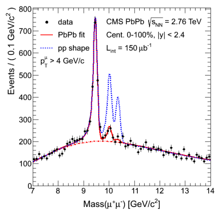
Short- and long-distance contributions factorize.

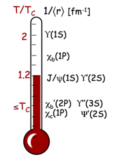
Quarkonia suppression

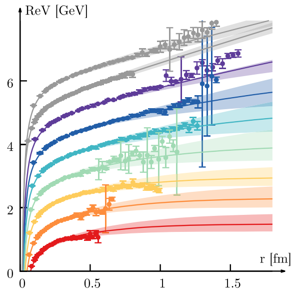
Simple intuitive picture [Matsui & Satz 1986]

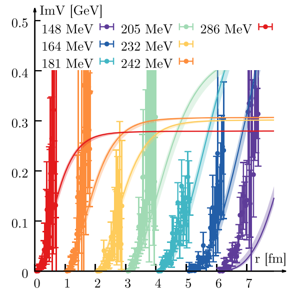
- Potential screened at high-T
- Quarkonia suppressed
- Sequential suppression of excited states
- **Quarkonia as a thermometer**











[Lafferty, Rothkopf 2020]

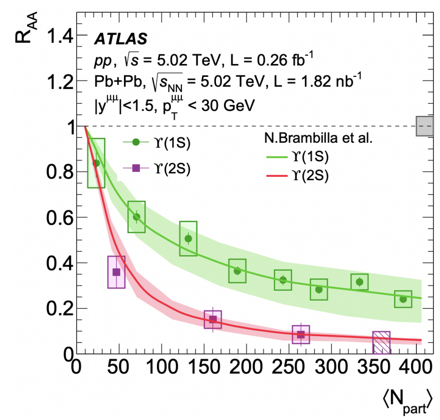
Dynamical picture:

- different effects:
  - screening / rescattering / recombination
- Induced transition between quarkonia states

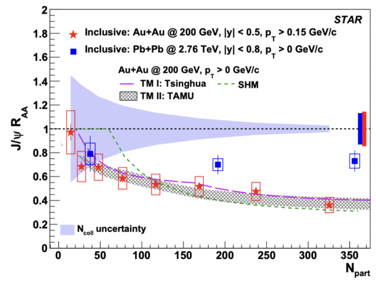
Quarkonia as an open quantum system

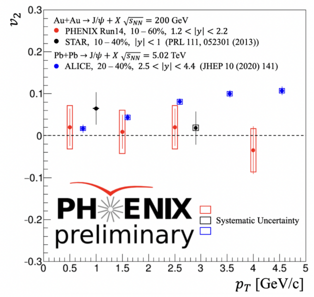
[Bambrilla, Soto, Escobedo, Vairo, Ghiglieri, Petreczky, Strickland, Blaizot, Rothkopf, Kaczmarek, Asakawa, Katz, Gossiaux, Kajimoto, Akamatsu, Borghini …]

Quarkonia suppression

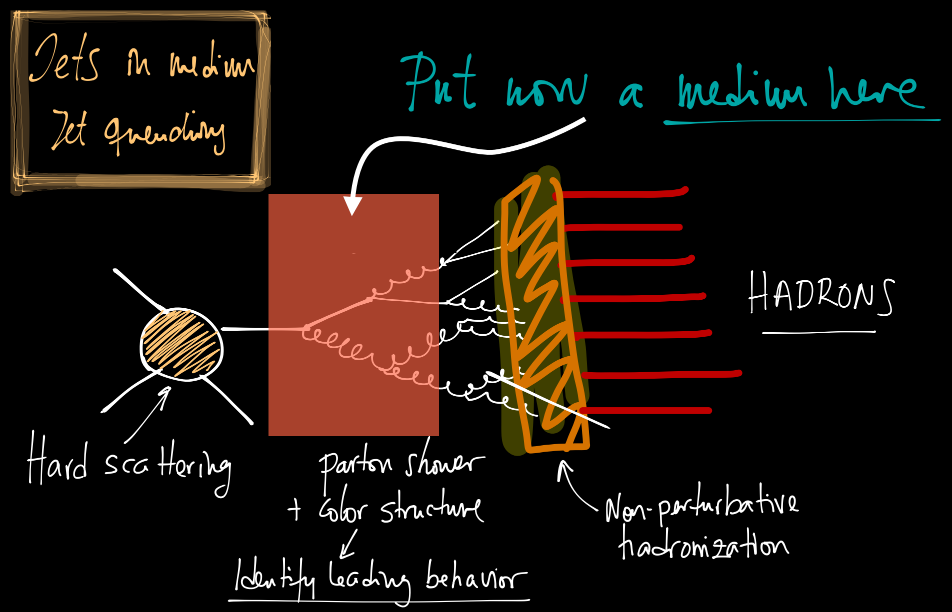


Bottomonia
sequential suppression



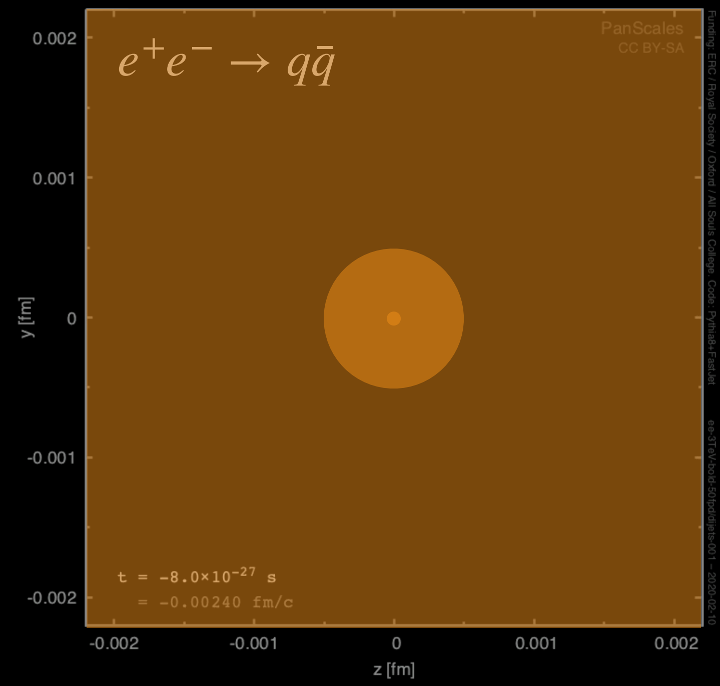


Charmonia
Mass is small enough so that many charm quarks are produced and almost thermalize. Charmonia is “regenerated”



Jets are extended objects - ideal to study space-time evolution

https://gsalam.web.cern.ch/gsalam/panscales/videos.html



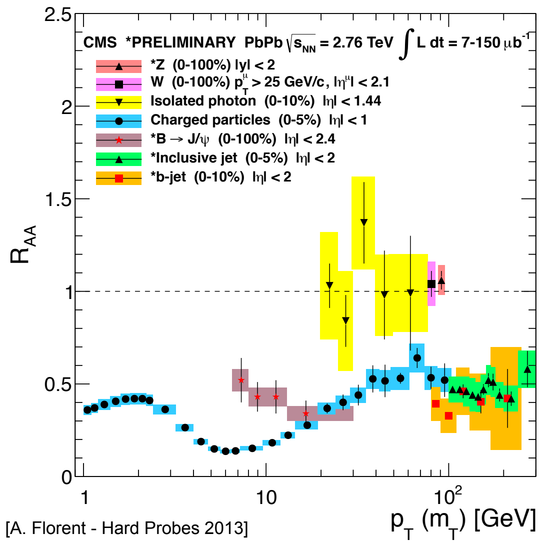
Remember the jets

The size of the medium is ~10fm

3TeV e^+e^- events

Initial particles in yellow
Intermediate particles in blue
Final particles in red
[details in the web page]

Particles traversing the QGP

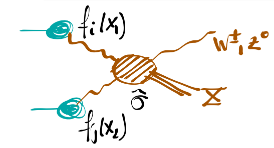


[A. Florent - Hard Probes 2013]

Medium-modification factor

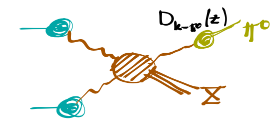
$$R_{AA} = \frac{dN^{AA}/dp_t}{\langle N_{coll}\rangle dN^{pp}/dp_t}$$

$R_{AA} \to 1$ — no effect



Color-less particles

$R_{AA} \sim 1$

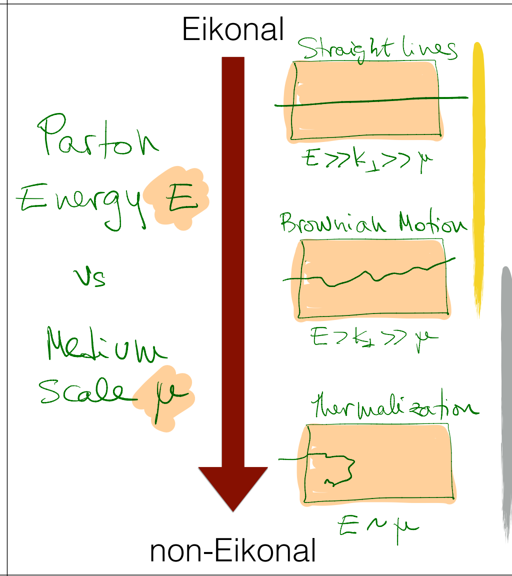


Colored particles

$R_{AA} < 1$

Energy-loss (mainly radiation)

In-medium parton propagation

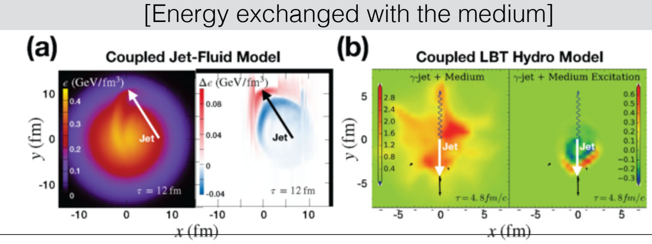


Medium is a background field: color rotation
[Energy of the parton unmodified]

$$W(x_\perp) = \mathcal{P}\exp\left\{ig\int d\xi\, n\cdot A(\xi, x_\perp)\right\}$$

$$G(x_\perp; y_\perp) = \mathcal{P}\int \mathcal{D}\mathbf{r}\exp\left\{i\frac{E}{2}\int d\xi\left[\frac{d\mathbf{r}}{d\xi}\right]^2 + ig\int d\xi\, n\cdot A(\xi, \mathbf{r})\right\}$$

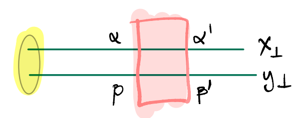
Medium is **dynamical**
[Energy exchanged with the medium]



[Tachibana 2019]

Scattering amplitudes

Color dipole - The simplest configuration



Background field
Color Rotation

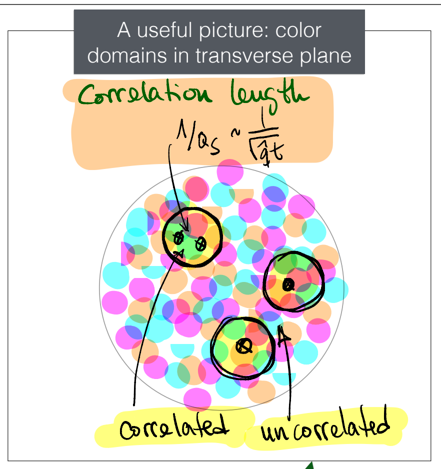
S-Matrix

$$|\alpha'\beta'\rangle = S_{\alpha'\beta'\alpha\beta}|\alpha\beta\rangle = W_{\alpha'\alpha}(x_\perp)\, W^\dagger_{\beta'\beta}(y_\perp)\,|\alpha\beta\rangle$$

Survival Probability

$$S(x_\perp, y_\perp) = \frac{1}{N_c}\,\mathrm{tr}\left[W(x_\perp)\, W^\dagger(y_\perp)\right]$$

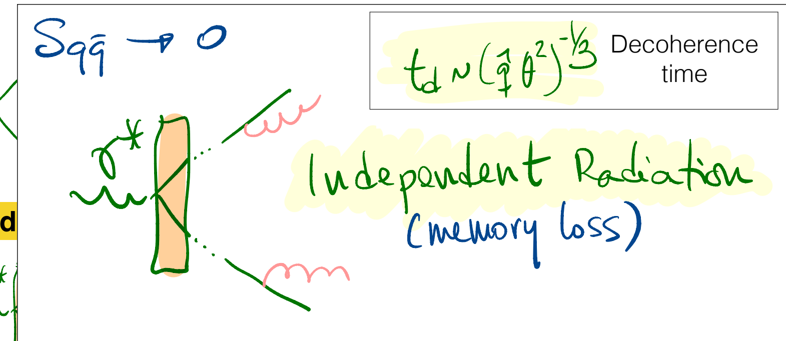
Average over configurations $\frac{1}{N_c}\langle \mathrm{tr}\left(W(x_\perp)W^\dagger(y_\perp)\right)\rangle_{med}$



Intra-jet color coherence

[Mehtar-Tani, Salgado, Tywoniuk; Iancu, Casalderrey-Solana, … 2010-]

QCD antenna - classical calculation including color coherence *[angular ordering]*



The QCD med … of q and qbar

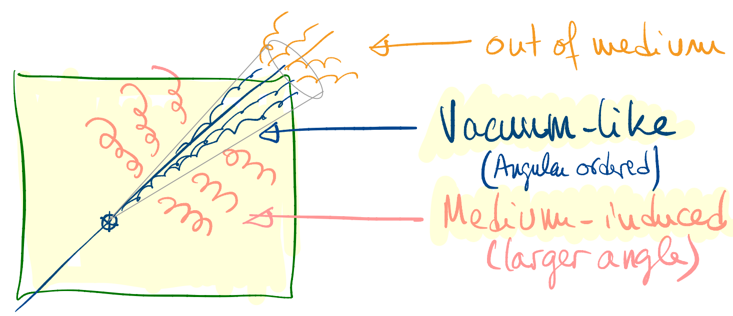
$$S(x_\perp, y_\perp) \equiv \frac{1}{N_c^2-1}\mathrm{Tr}\left\langle W(x_\perp)W^\dagger(y_\perp)\right\rangle_{\mathrm{med}} \simeq \exp\left\{-\frac{1}{4}\hat{q}\,\theta_{q\bar{q}}^2\,L^3\right\}$$

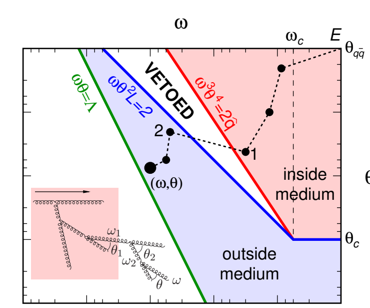
Survival probability
$\hat{q}$ - jet quenching parameter

Vacuum-like emissions

Hard splittings with small formation time $t_f \ll t_d$ cannot be resolved by the medium

First hard splitting + DLA — **most of the cascade is vacuum-like** (with energy loss on top)





[Caucal, Iancu, Mueller, Soyez 2018]

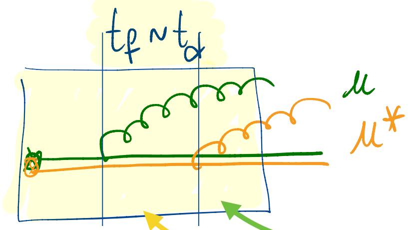
Color coherent sub-jets provide organizational principle for in-medium cascade

[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2012]

Medium-induced radiation

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others… starting in the mid-90's]

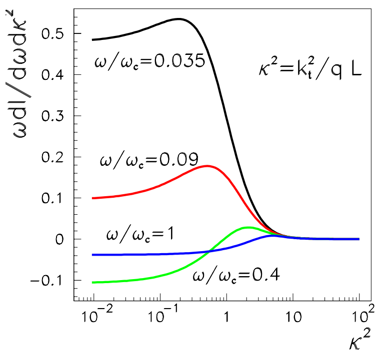
For fluctuation with $t_f \sim t_d$ the gluon is resolved: **medium-induced radiation**



$$\omega \frac{dN}{d\omega d^2\mathbf{k}} \sim \frac{\alpha_s C_R}{\omega^2} \mathrm{Re} \int_{t',t} \int_{\mathbf{p},\mathbf{q}} \mathbf{p}\cdot\mathbf{q}\,\tilde{\mathcal{K}}(t',\mathbf{q};t,\mathbf{p})\,\mathcal{P}(L,\mathbf{k};t',\mathbf{q})$$

$$\mathcal{K}(t',\mathbf{z};t,\mathbf{y}) = \int \mathcal{D}\mathbf{r}\, \exp\left[\int_t^{t'} ds \left(\frac{i\omega}{2}\dot{\mathbf{r}}^2 - \frac{1}{2} n(s)\sigma(\mathbf{r})\right)\right]$$

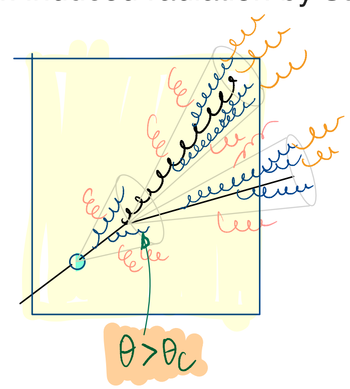
For fluctuation with $t_f > t_d$
LPM suppression



A picture of in-medium jets

[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2012]

Color coherence provides a clean picture of parton shower in medium
Medium induced radiation by **subjets** defined by **resolution scale** of the medium



$$S(r_\perp) = e^{-\frac{1}{4}\int dt\, \hat{q}\, r^2(t)}$$

$$r(t) = \theta t \Rightarrow \theta_c \sim \frac{1}{\sqrt{\hat{q} t^3}}$$

Resolution power

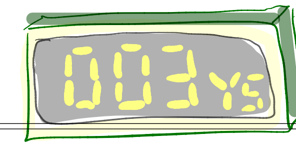
$$\Lambda_\perp \sim \frac{1}{\sqrt{\hat{q} t}} \equiv \frac{1}{Q_s}$$

Inner core of the jet (subjet) is mildly modified

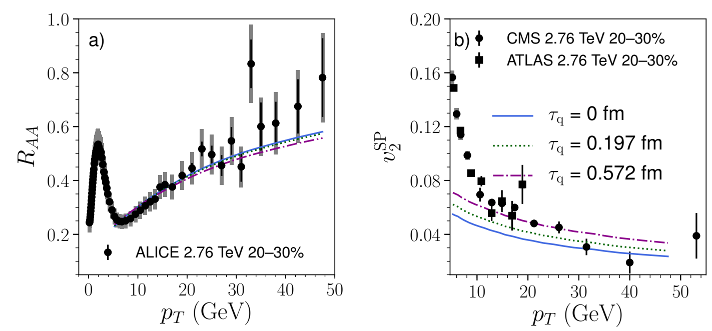
Medium-induced radiation at **large angles**

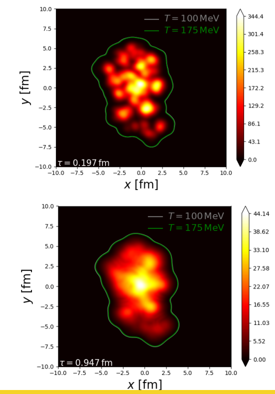
Subjets are effective emitters

First ~3ys…



Main question - can we access the initial stages with jet quenching?





[Andres, Armesto, Niemi, Paatelainen, Salgado 2019]

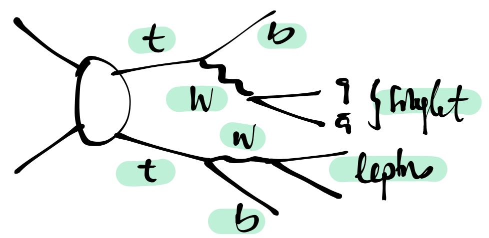
Initial stages (thermalisation period) affect jet quenching -
Opens completely new possibilities - study early times with jet observables

A yoctosecond chronometer

[late times]

Can we **more directly measure the space-time** development with jet observables?

[Apolinario, Milhano, Salgado, Salam 2019]



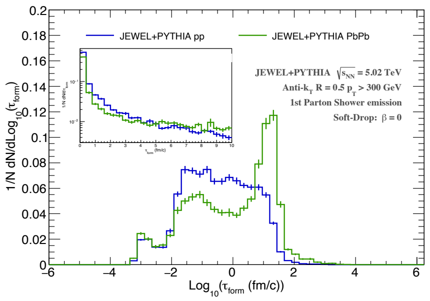
Boosted tops

Difficult with LHC PbPb luminosity - lighter ions?

Charm/Bottom quarks? [Attems, et al 2022]

New time reclustering algorith

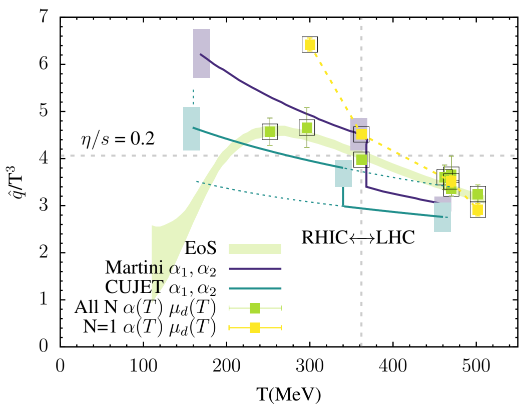
Very promising

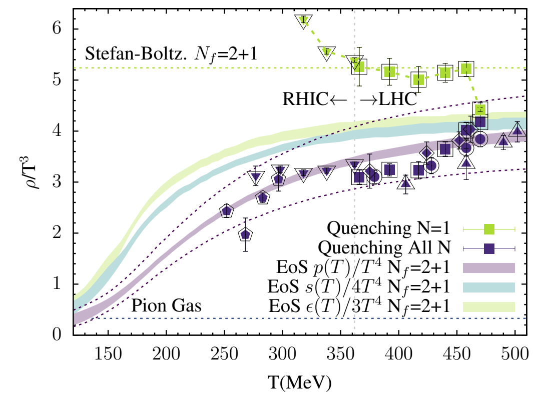


[Apolinario, Cordeiro, Zapp 2021]

Jet quenching parameter

Information about the medium properties usually encoded in the jet quenching parameter $\hat{q}$



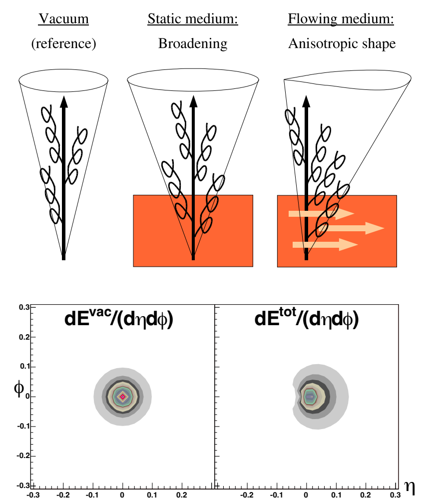


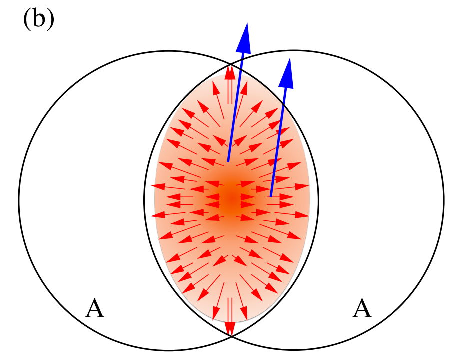
[Feal, Salgado, Vazquez 2019]

Agreement with cross sections from thermal-QCD — resummation of multiple scatterings needed

Coupling jet-hydro

[Armesto, Salgado, Wiedemann 2004]

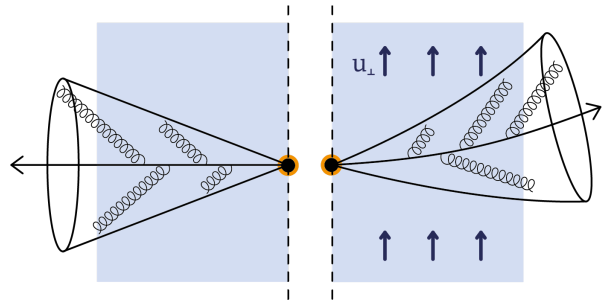


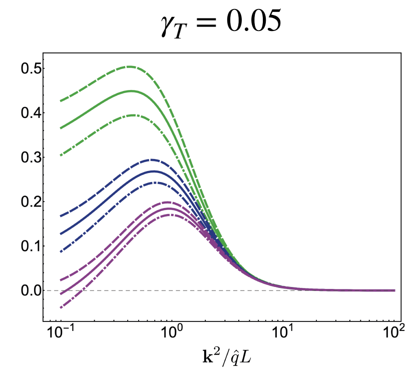


What is the effect of the velocity fields and the (density/temperature) gradients in jet quenching observables?

Anisotropic radiation

Medium modelling modified - propagators now have coupling to anisotropies





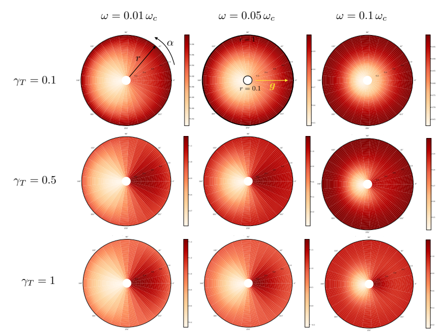
[Barata, Mayo, Sadofyev, Salgado 2022]

Where the gradient parameter $\gamma_T = |\nabla T/T^2|$

Softer radiation more sensitive to gradient fields [effect subleading in ω]

Anisotropic jet angular distributions

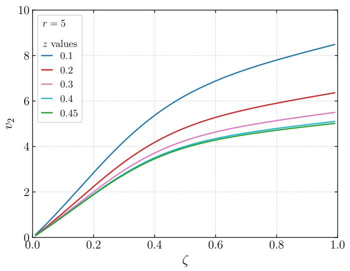
Jet shapes

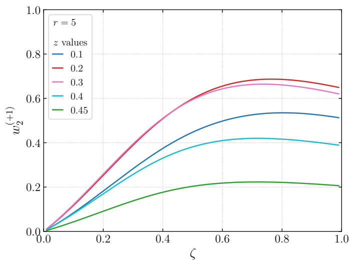


[Barata, Milhano, Sadofyev 2023]

Intra-jet v2 (and w2)

[Barata, Salgado, Silva 2024]





v2 large due to jet anisotropy

w2 correction due to spin in a $q\bar{q}$ antenna

Conclusions

QCD has a **rich dynamical content**
- Confinement and chiral symmetry breaking in vacuum
- New phases of matter at high energies/densities
- Quark gluon plasma universal form of matter at high enough energies

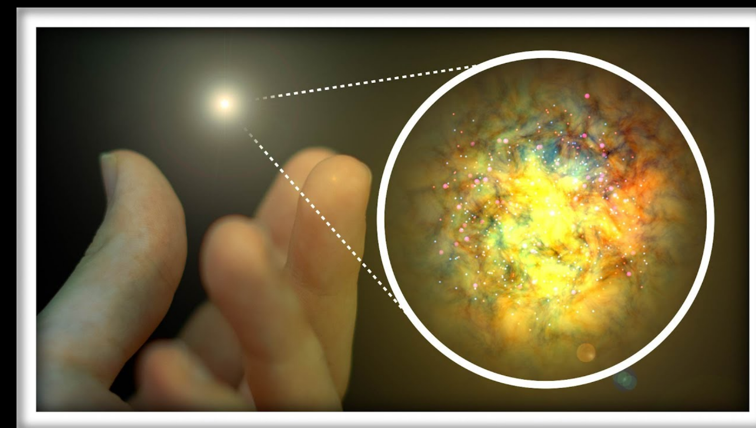
Heavy ion collisions are the experimental tools

However, QGP is only one of the manifestations of a **wider and richer accessible physics**

QCD is the only sector in the Standard Model where studies of collectivity at the fundamental level are experimentally possible

For Fun

Youtube video - QGP (in Spanish)



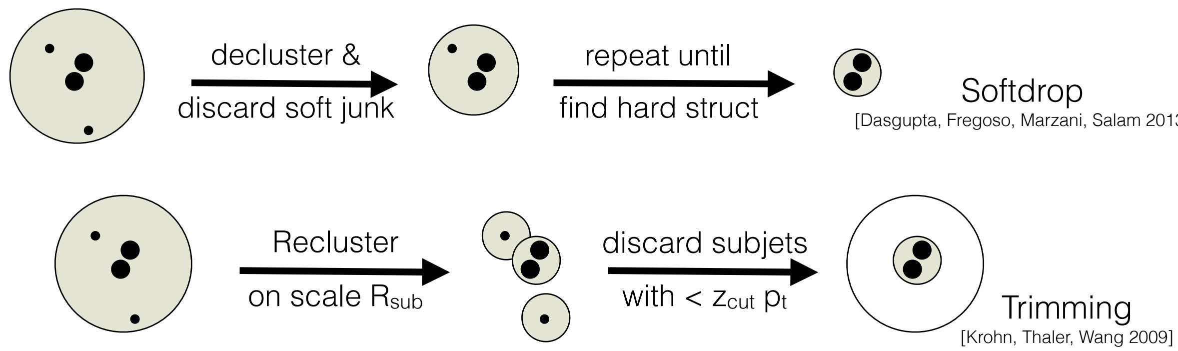
https://youtube.com/watch?v=JdahywF2_D4

Jet substructure and time evolution

Find different substructures in identified jets

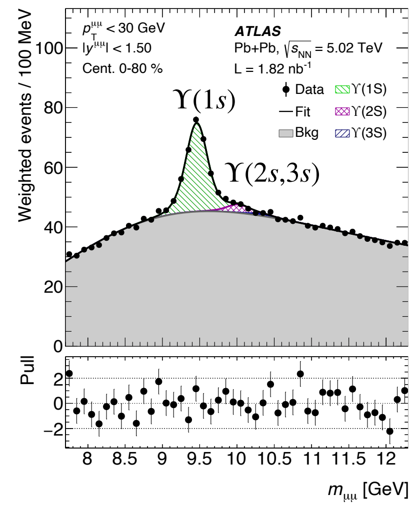
[very active area, lots of results in the last years]

[Figs from G Salam]



Also to identify two-pronged jet structures - boosted H/W/Z

Acknowledgements


$p_T^{\mu\mu} < 30$ GeV
$|y^{\mu\mu}| < 1.50$
Cent. 0-80 %
ATLAS
Pb+Pb, $\sqrt{s_{NN}} = 5.02$ TeV
L = 1.82 nb^{-1}
Data
Fit
Bkg
Υ(1S)
Υ(2S)
Υ(3S)
$\Upsilon(1s)$
$\Upsilon(2s,3s)$
Weighted events / 100 MeV
Pull
$m_{\mu\mu}$ [GeV]