Heavy-ion physics

everything you always wanted to know about QCD and parton energy loss (and more)

Redmer Alexander Bertens - University of Knoxville, Tennessee

Forschung trifft Schule: CERN Summer School

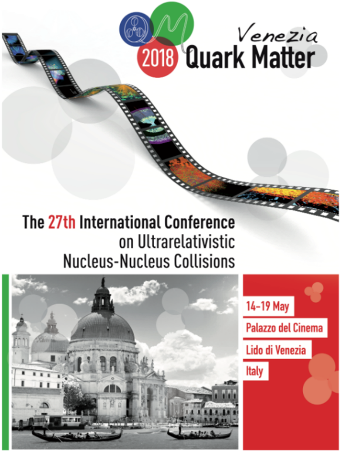
'Heavy-ion physics' ?

physics of the strong interaction

‘Heavy-ion physics’ ?

physics of the strong interaction

1) What do we study?
2) QCD crash course
3) Heavy-ion collisions
4) What did we learn so far ?


Venezia
2018 Quark Matter
The 27th International Conference
on Ultrarelativistic
Nucleus-Nucleus Collisions
14-19 May
Palazzo del Cinema
Lido di Venezia
Italy


HARD
PROBES
2018
International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
30 September 2018 to 5 October 2018 • Aix-Les-Bains • France
TOPICS FOR THE CONFERENCE INCLUDE:
nuclear parton distribution functions
early-time dynamics
jets and high-p_T hadrons
heavy quarks and quarkonia
high-p_T photons and weak bosons
future experimental and theoretical developments
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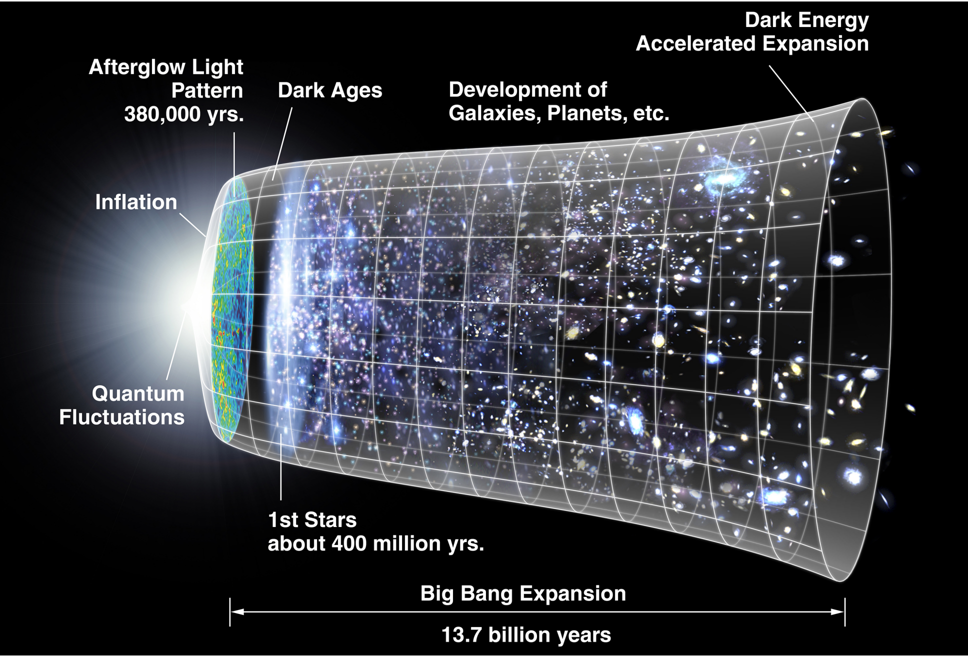
goal:

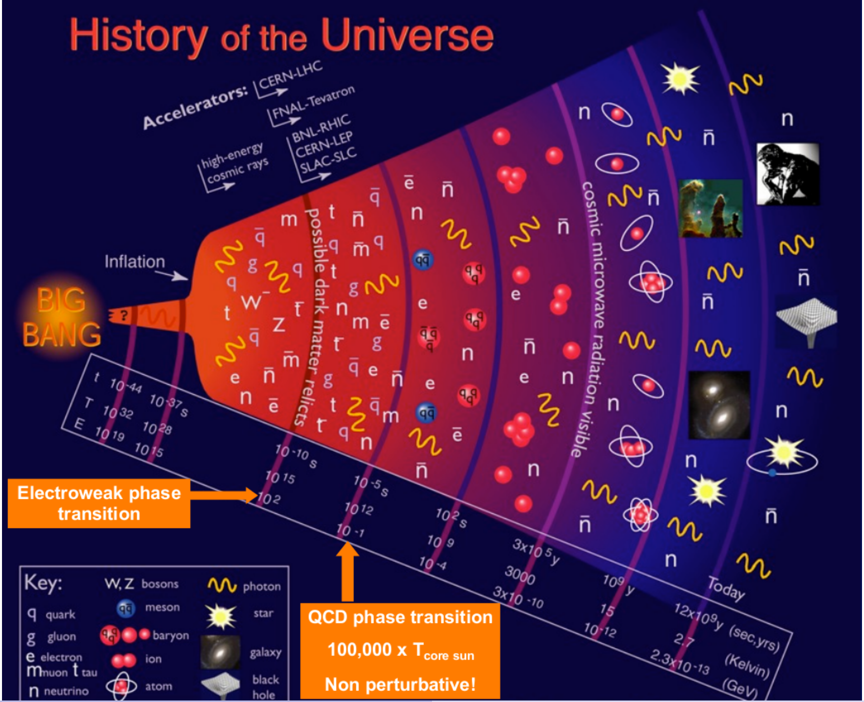
at the end of this talk, you will **understand** the titles of these conferences :) !

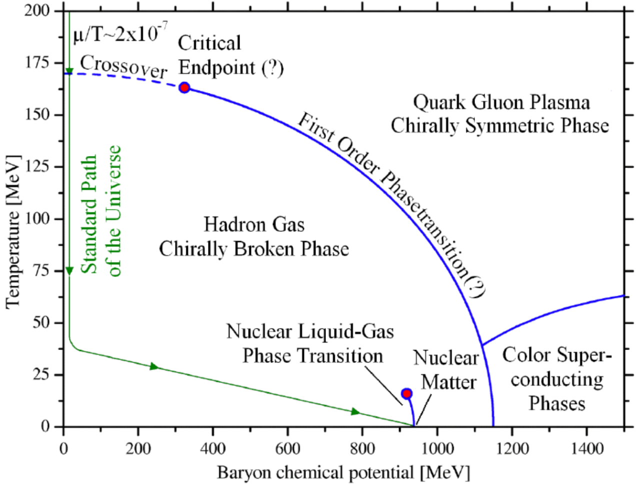
Chapter 1)

What do we study ?

'The history of the universe
in the lab'
(or just to learn about QCD)


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Electroweak phase transition
QCD phase transition
100,000 x T core sun
Non perturbative!
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
galaxy
e electron
ion
m muon
t tau
black hole
n neutrino
atom



at very high temperatures and densities a phase transition to **deconfined** matter occurs, where quarks and gluons are 'free'

the **Quark Gluon Plasma**

Heavy-ion physics

(re)create a **quark gluon plasma**
by colliding heavy ions

...

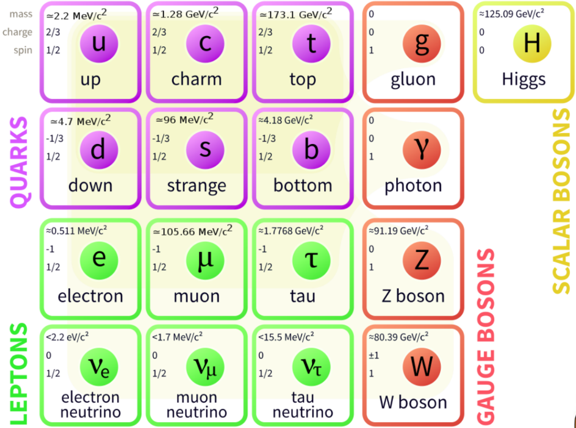
study QGP properties
governed by **strong interaction**

Chapter 2)

Crash course QCD

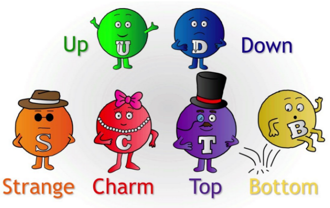
running coupling?
deconfinement?

The strong interaction - quarks and gluons

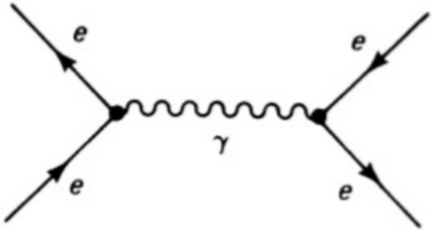


QCD: quantum chromo dynamics

quarks and **gluons**



The strong interaction - quarks and gluons



The strong interaction - quarks and gluons

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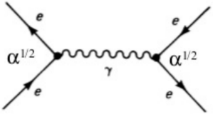
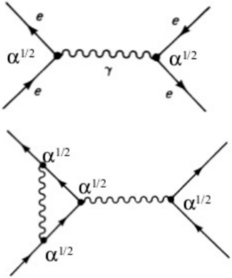


Amplitude is of order α.

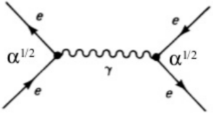
The strong interaction - quarks and gluons



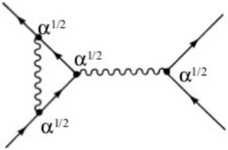
Amplitude is of order α.

Amplitude is of order α^2.

same INITIAL state
and FINAL state



Amplitude is of order α.



Amplitude is of order α^2.

but a different diagram !

The strong interaction - quarks and gluons

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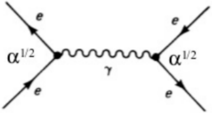
same INITIAL state
and FINAL state



Amplitude is of order α.

Amplitude is of order α^N.

but a different diagram !

same INITIAL state
and FINAL state

'virtual particles renormalize the coupling and make it dependent on the energy scale, μ , at which one observes the coupling'

.....

complicated way of saying: the coupling strength ('constant') is not really constant

.....

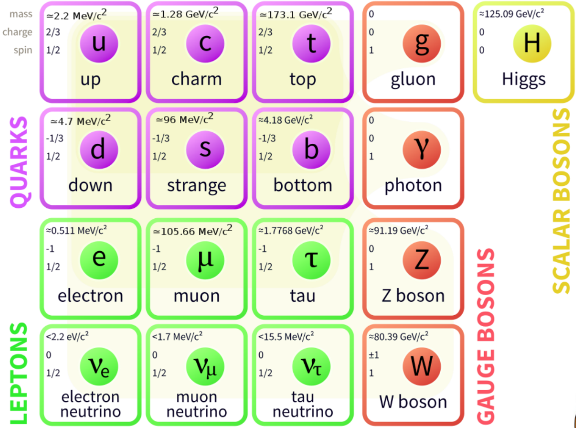
QED is easy: higher-order processes contribute with $\alpha^N \sim (1/137)^N$

$$\alpha(Q^2) = \alpha_0 + \Sigma_N \alpha_0^N \sim \alpha_0$$

in practice: at Q*Q = 1TeV (= 1000000000000 eV) this is a 1% correction ...

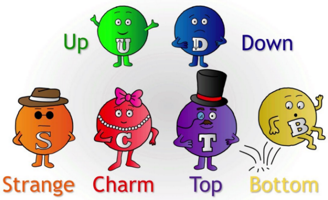
but a different diagram !

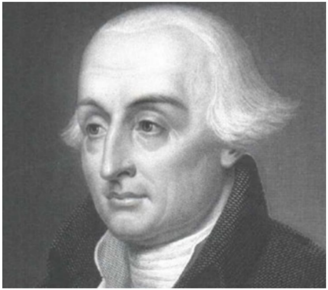
The strong interaction - quarks and gluons

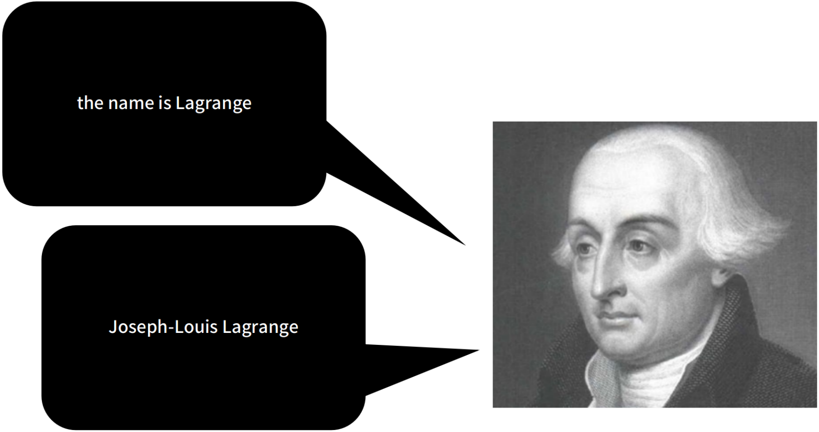


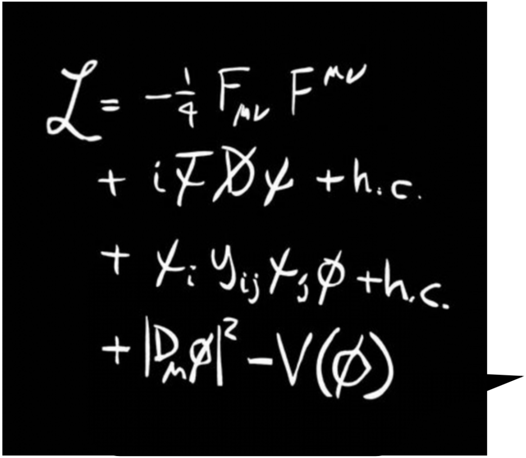
QCD: quantum chromo dynamics

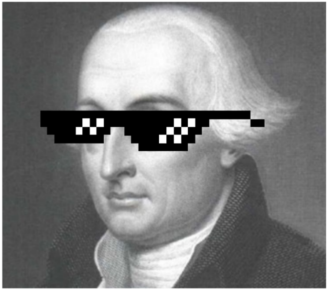
quarks and **gluons**






the name is Lagrange
Joseph-Louis Lagrange

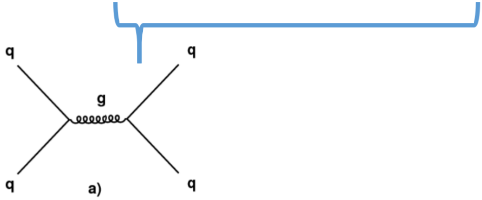

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$



$$\mathscr{L}_{\rm QCD} = \overline{q}(i\gamma^\mu d_\mu - m)q - g(\overline{q}\gamma^\mu \lambda_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - gf_{abc}A^b_\mu A^c_\nu$$

$$\mathscr{L}_{\rm QCD} = \underbrace{``\overline{q}q"}_{\text{q propagation}} + \underbrace{``A^2"}_{\text{g proparation}} + \underbrace{g``\overline{q}qA"}_{\text{qg interaction}} + \underbrace{g``A^3"}_{\text{ggg interaction}} + \underbrace{g^2``A^4"}_{\text{gggg interaction}}$$



The strong interaction - quarks and gluons

$$\mathscr{L}_{\text{QCD}} = \overline{q}(i\gamma^\mu d_\mu - m)q - g(\overline{q}\gamma^\mu \lambda_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

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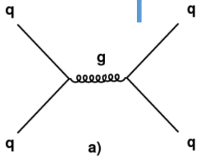

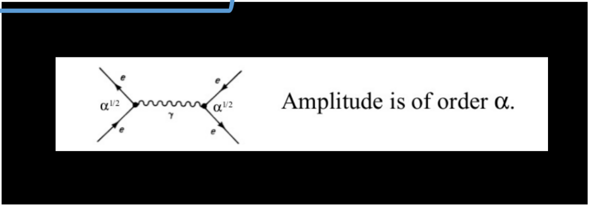

The strong interaction - quarks and gluons

$$\mathscr{L}_{\mathrm{QCD}} = \overline{q}(i\gamma^{\mu} d_{\mu} - m)q - g(\overline{q}\gamma^{\mu}\lambda_a q)A^a_{\mu} - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_{\mu}A^a_{\nu} - \partial_{\nu}A^a_{\mu} - g f_{abc}A^b_{\mu}A^c_{\nu}$$

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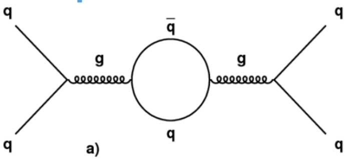

The strong interaction - quarks and gluons

$$\mathscr{L}_{\mathrm{QCD}} = \overline{q}(i\gamma^\mu d_\mu - m)q - g(\overline{q}\gamma^\mu \lambda_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

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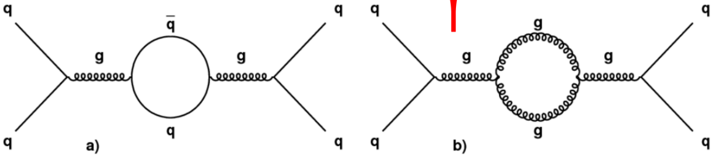
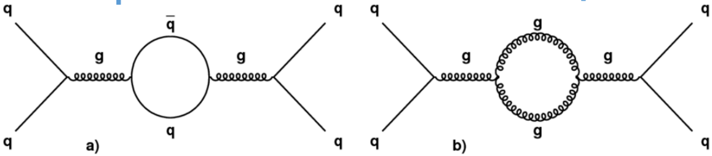


The strong interaction - quarks and gluons

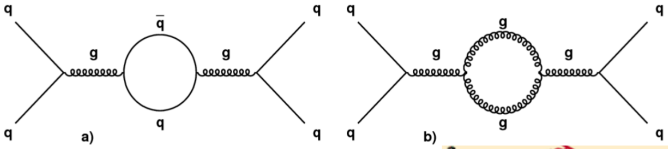
'screening'
$\alpha_s \downarrow$

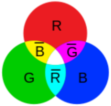
'anti-screening'
$\alpha_s \uparrow$

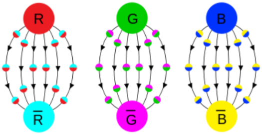


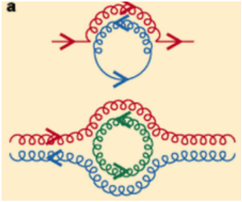
The strong interaction - quarks and gluons

strong interaction: exchange of **gluons** that carry **color charge**





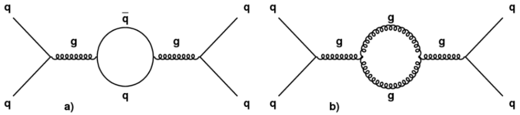




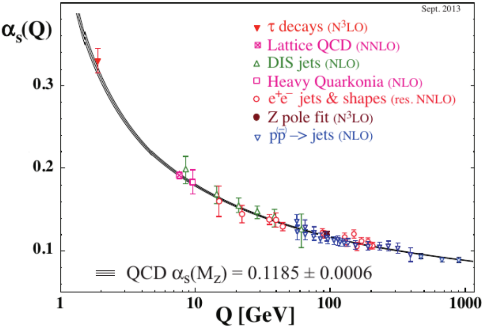
gluons always carry **two charged**
as a result, they can **self-interact !**

The strong interaction - quarks and gluons

'screening'
$\alpha_s \downarrow$



'anti-screening'
$\alpha_s \uparrow$

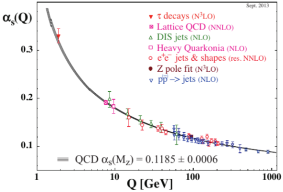


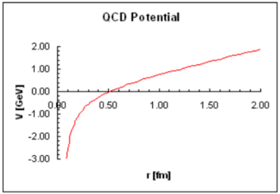
screening and anti-screening lead to a coupling constant that 'runs'

at high energies ('large Q') α_s vanishes

at low energies ('small Q') α_s gets huge

$$V(x) \propto -\frac{\alpha_s}{x} + \kappa x$$



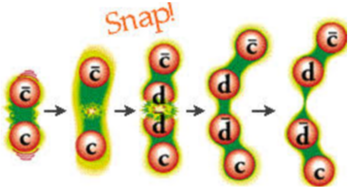


$$V(x) \propto -\frac{\alpha_s}{x} + \kappa x$$

QCD CONFINEMENT

QED-like at short distance r≤0.1 fm
Quarks are tightly bound $\alpha_s \approx 0.2$ .. 0.3
String tension -> Potential increases linearly

Quarks are **confined** into **baryons** (qqq) and **mesons** (qq)
collectively called **hadrons,** like in **LHC**



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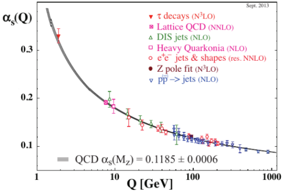
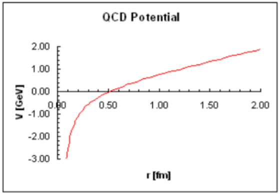
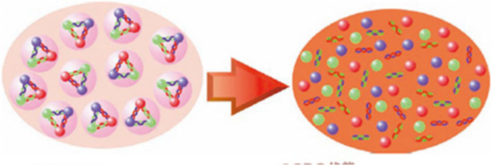


ASYMPTOTIC FREEDOM

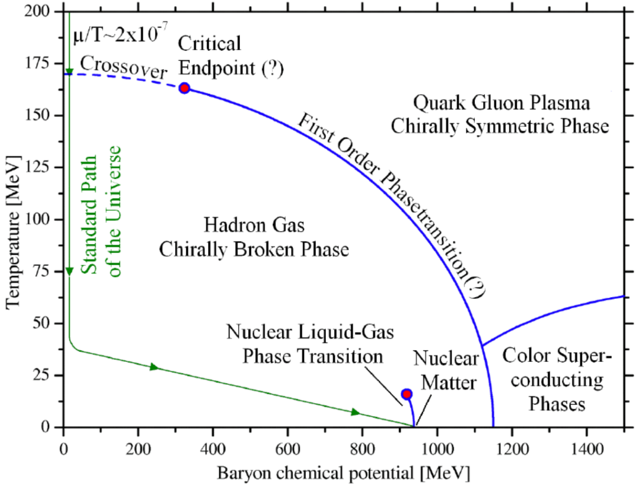
at HIGH energies, α_S decreases asymptotically
and quarks and gluons become 'asymptotically free'
they form a Quark Gluon Plasma (QGP)





$$V(x) \propto -\frac{\alpha_s}{x} + \kappa x$$

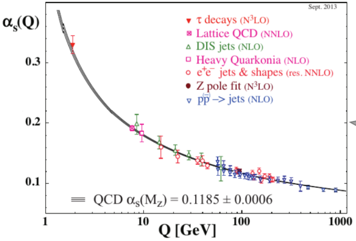
The strong interaction - quarks and gluons



now we know why at very high temperatures and densities a phase transition to **deconfined** matter occurs, where quarks and gluons are 'free'

The strong interaction - quarks and gluons

`QED is easy: higher-order processes contribute with $\alpha^N \sim (1/137)^N$
$\alpha(Q^2) = \alpha_0 + \Sigma_N \alpha_0^N \sim \alpha_0$ '



QCD:
$\alpha(Q^2) = \alpha + \Sigma_N \alpha^N \neq \alpha$

summation series become ~infinitly long
all terms are important

calculations in QCD are generally **impossible**
unless they involve **very energetic particles**

jargon: 'perturbative QCD': calculable
'non-perturbative QCD': uncalculable

The strong interaction - quarks and gluons

QCD

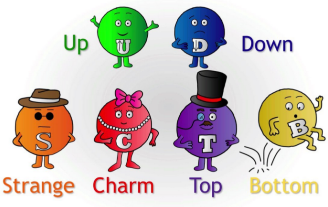
asymptotic freedom: quark gluon plasma

anti-screening

confinement: hadrons

screening

non-perturbative QCD



Chapter 3)

Heavy-ion collisions in practice

What do we need for a QGP?

What do we need for a QGP?

dense matter : heavy ions

What do we need for a QGP?

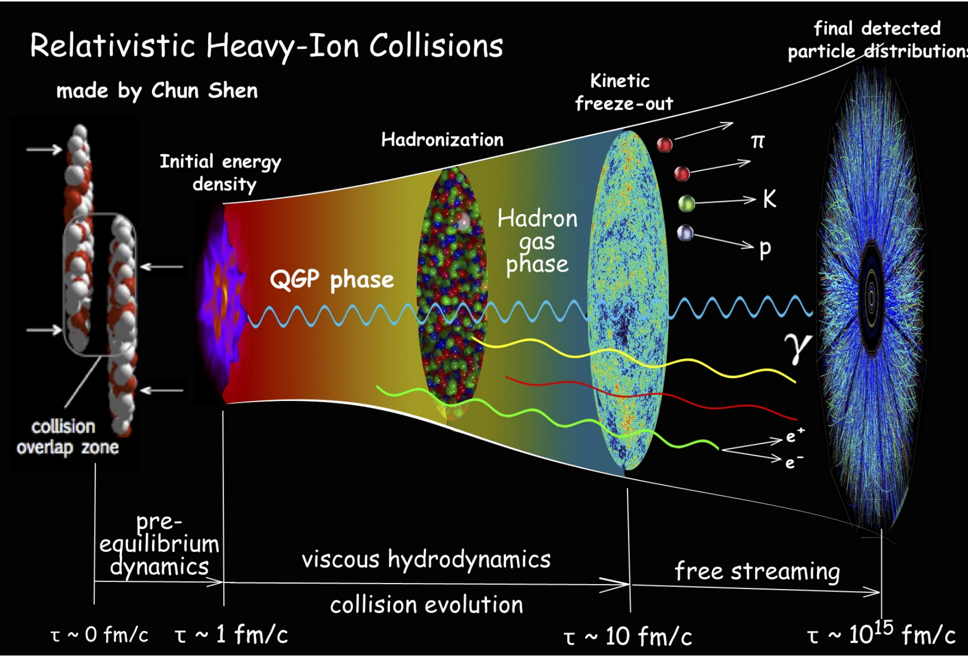
dense matter : heavy ions
high energy/temperature : accelerators

What do we need for a QGP?

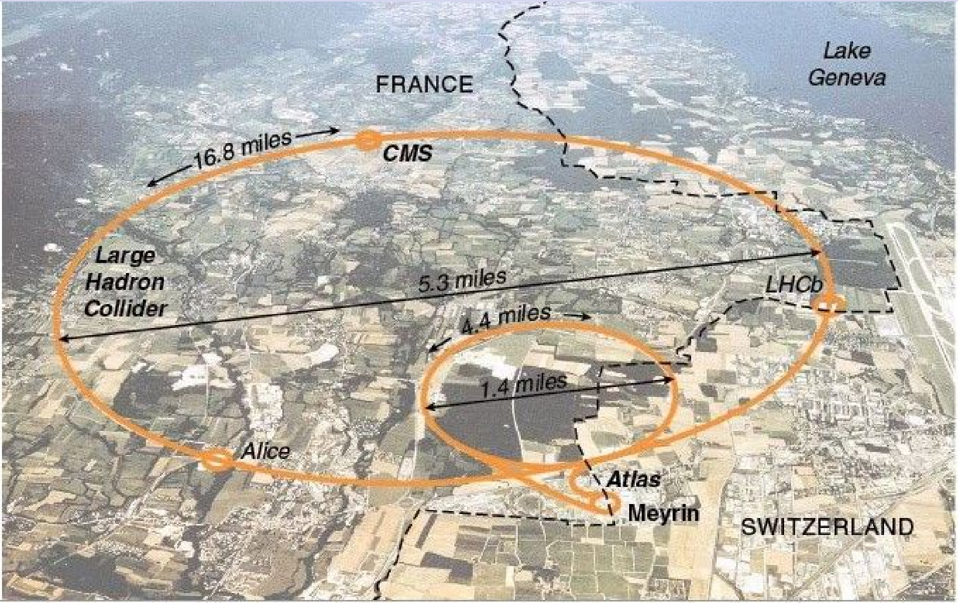
dense matter : heavy ions
high energy/temperature : accelerators
collisions : create a QGP

What do we need for a QGP?

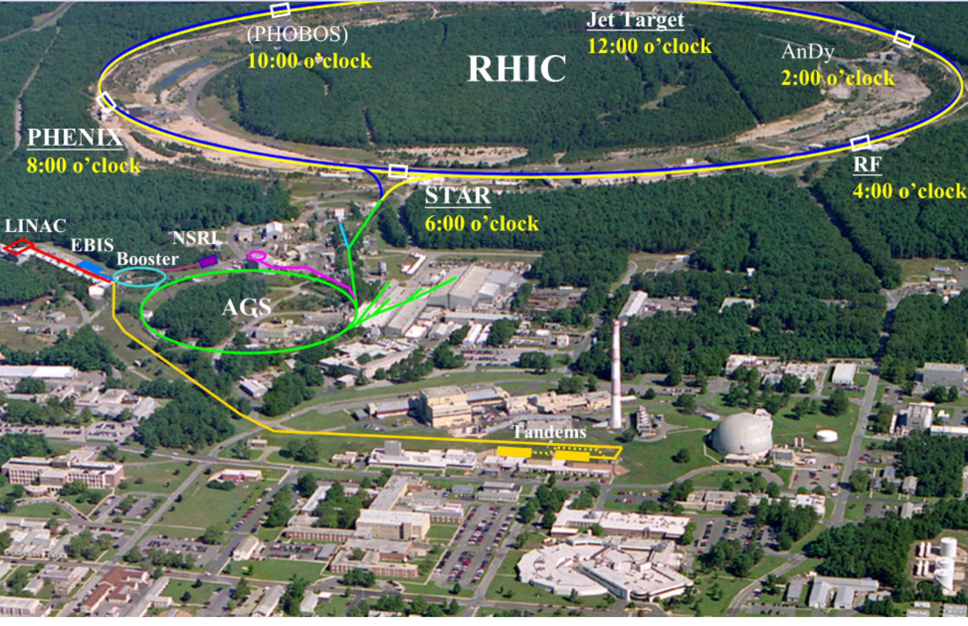
dense matter : heavy ions
high energy/temperature : accelerators
collisions : create a QGP
detectors to ‘look’ at the collisions


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected
particle distributions
Kinetic
freeze-out
Hadronization
Initial energy
density
π
K
p
Hadron
gas
phase
QGP phase
γ
e+
e-
collision
overlap zone
pre-
equilibrium
dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

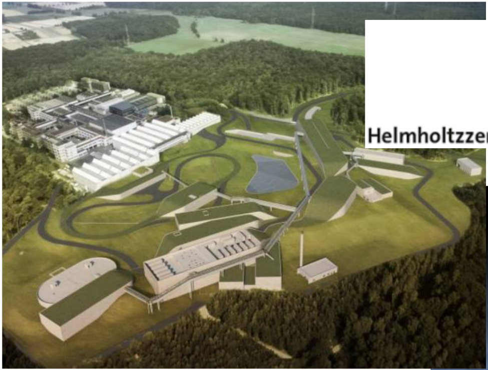
The Large Hadron Collider at CERN



RHIC at BNL

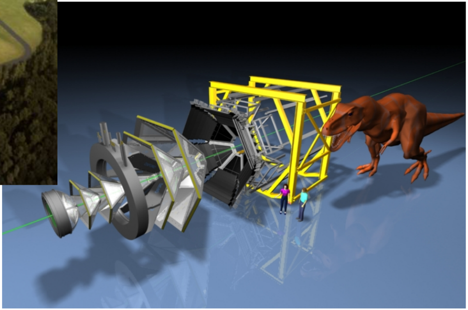


(PHOBOS)
10:00 o'clock
RHIC
Jet Target
12:00 o'clock
AnDy
2:00 o'clock
PHENIX
8:00 o'clock
RF
4:00 o'clock
STAR
6:00 o'clock
LINAC
EBIS
Booster
NSRL
AGS
Tandems

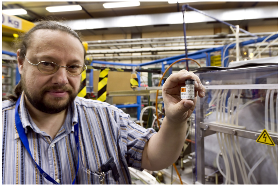


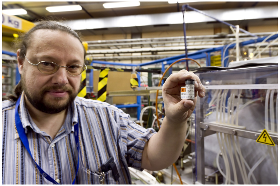
GSI

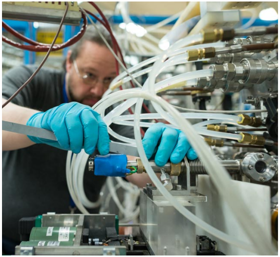
Helmholtzzentrum für Schwerionenforschung GmbH



Where it all starts ... (LHC perspective)







Where do we get our ions from ?

- Solid lead-208 is heated until it vaporizes at $\approx$ 800 degrees Celsius (1472 Fahrenheit)
- Vapor is ionized
- Ions are carried away by a EM field

Where it all starts ... (LHC perspective)

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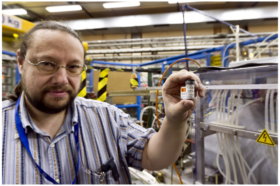

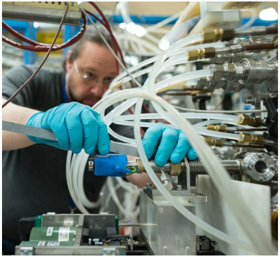

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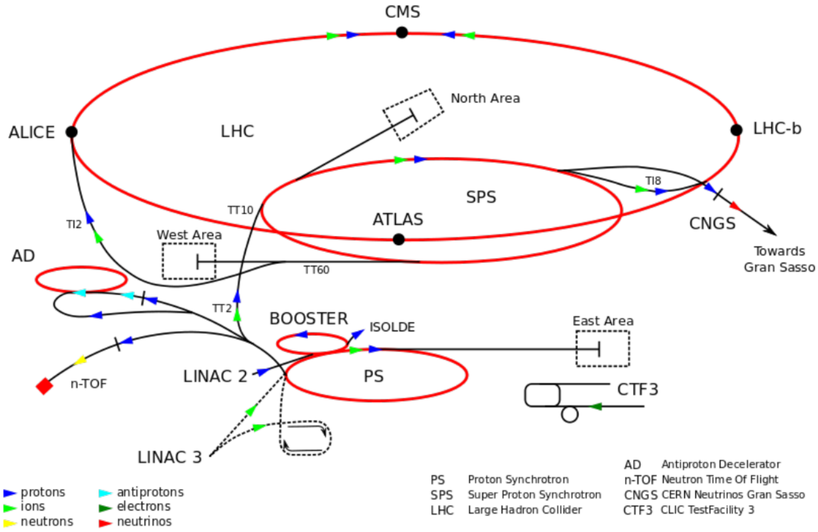
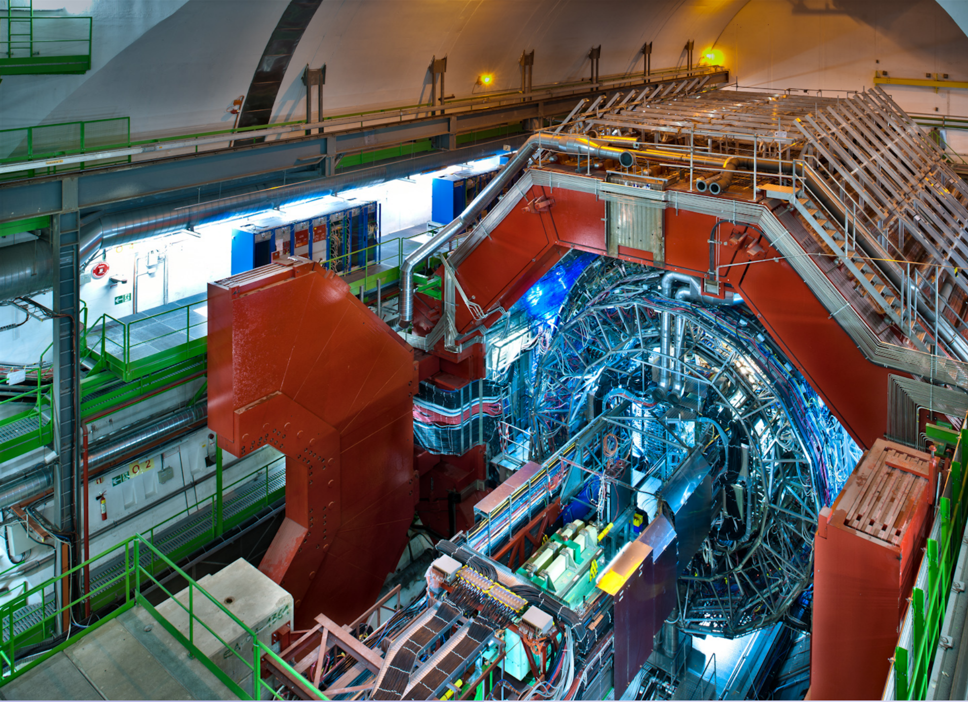
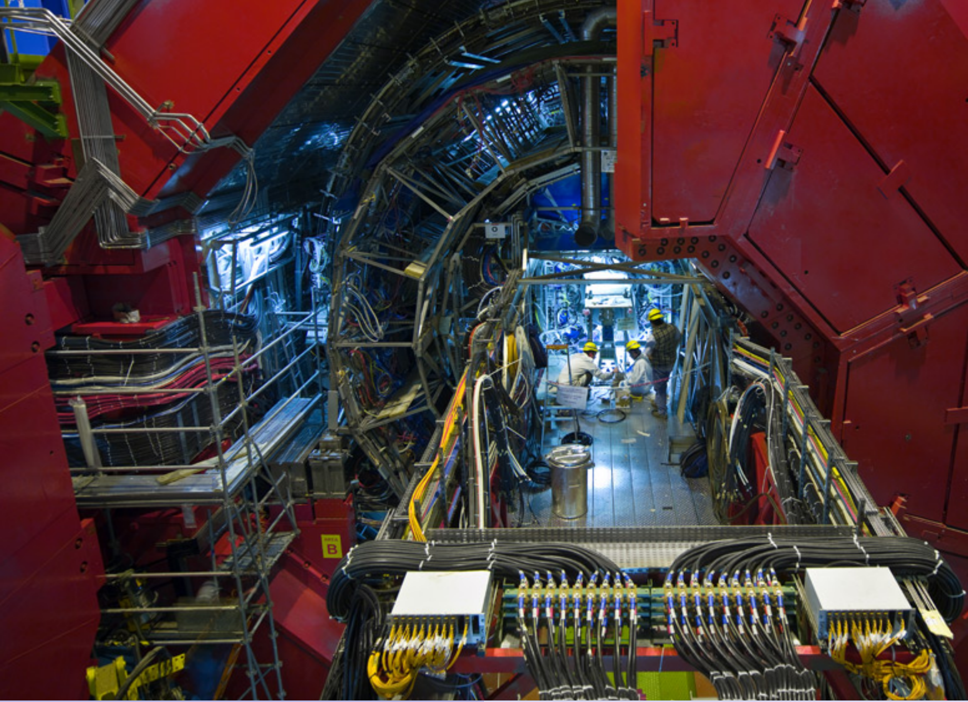
The LHC accelerates lead ions for $\approx$ 1 month per year

- Billions of collisions
- Analysis for 1000s of physicists
- Costs $\approx$ 5 grams of lead

And where it all goes

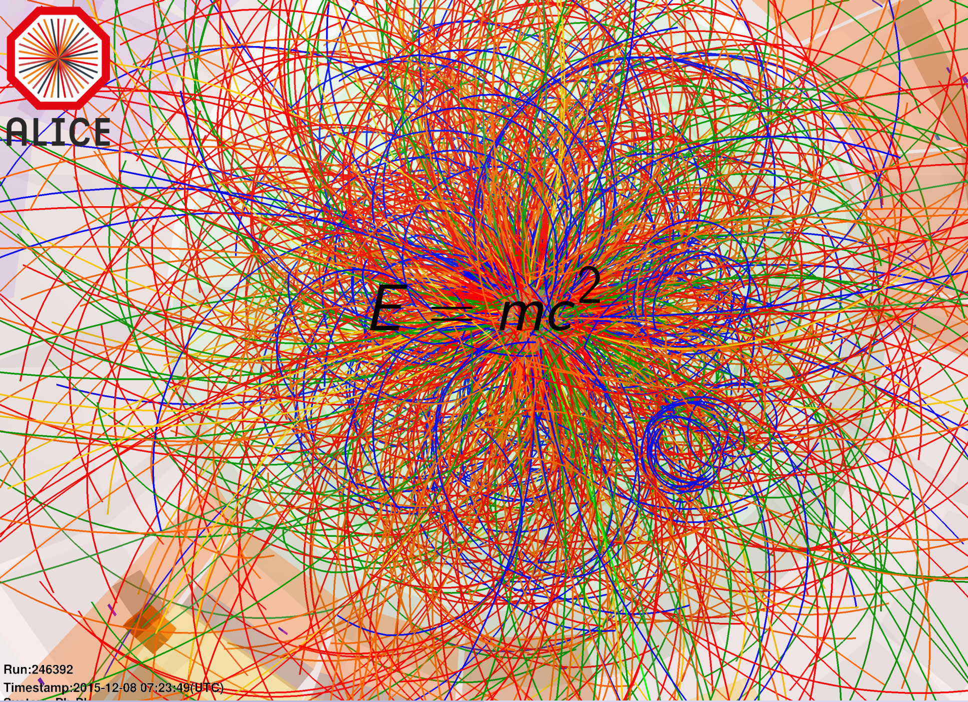





AREA
B

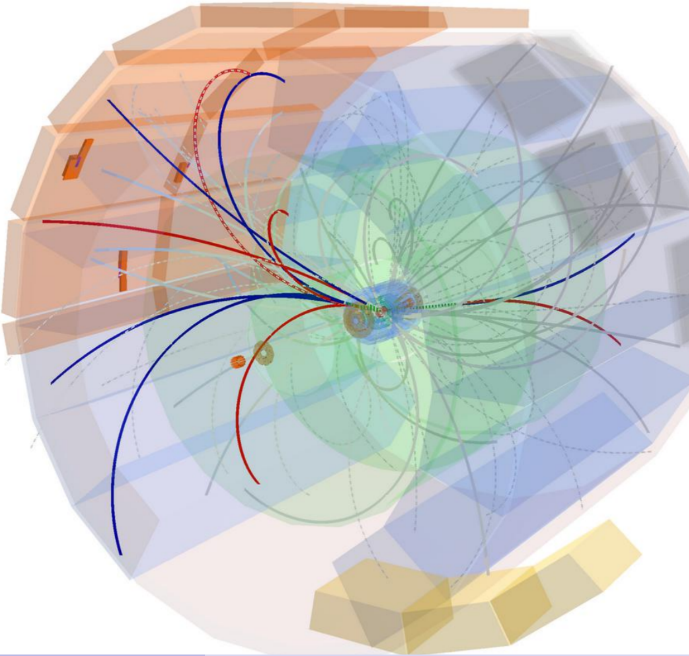
but **true beauty** is found on the **inside**


ALICE
Run:246392
Timestamp:2015-12-08 07:23:49(UTC)



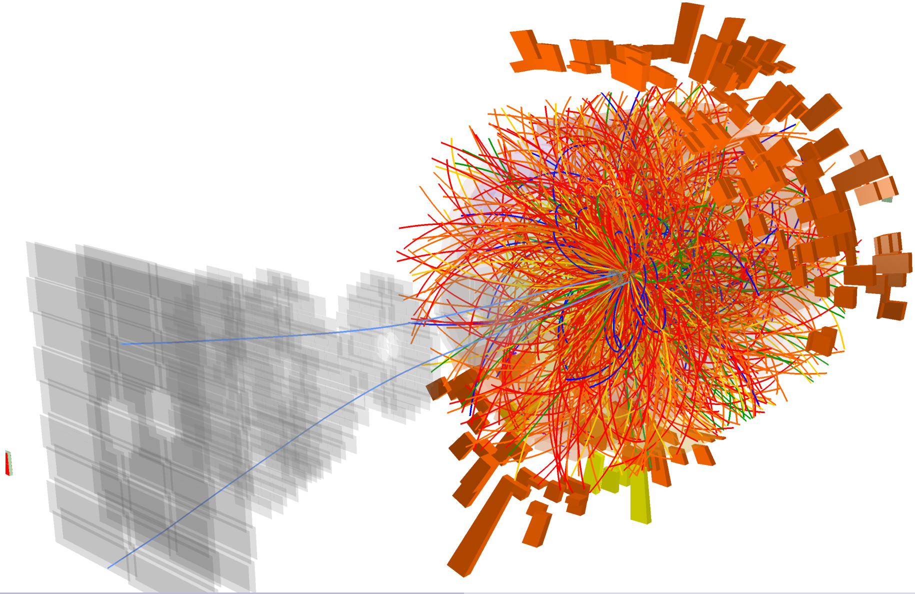
$$E = mc^2$$

ALICE

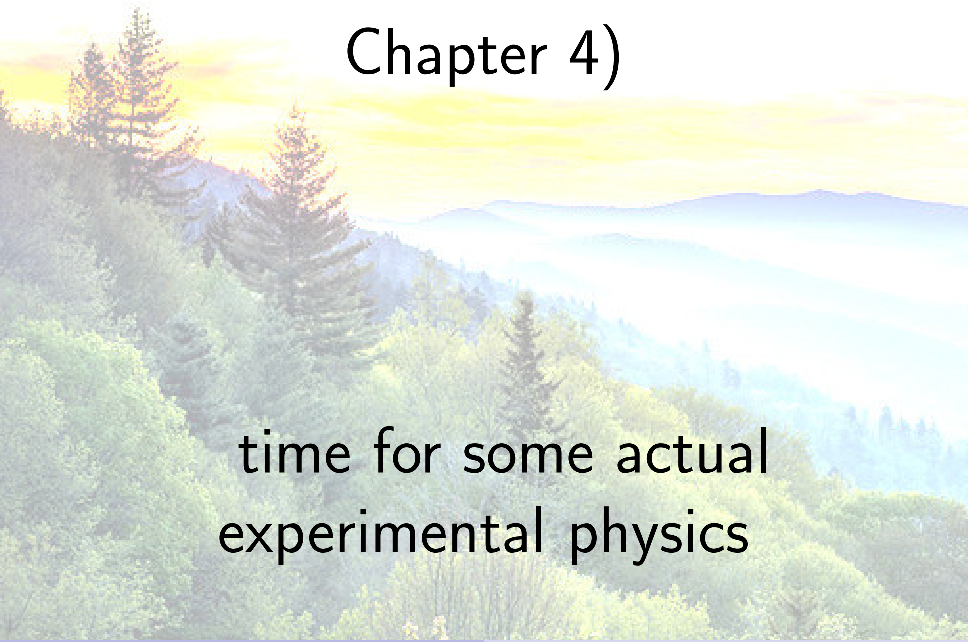


Run:197584
Timestamp:2013-02-13 04:00:21(UTC)
System: p-p
Energy: 2.76 TeV

Let's zoom out a bit



Chapter 4)



time for some actual experimental physics

QGP is a plasma

a plasma has a certain **viscosity** ('internal friction'), density, temperature, EOS, etc ...

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QCD is (largely) non-perturbative, math doesn't help us

QGP is a plasma

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QCD is (largely) non-perturbative, math doesn't help us

---

brute force approach: what about shooting particles through the plasma and seeing if they slow down ?

Hard probes - what and why?

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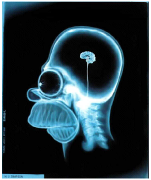
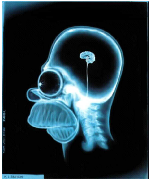


Tomography

'imaging through **modification** *of penetrating wave'*

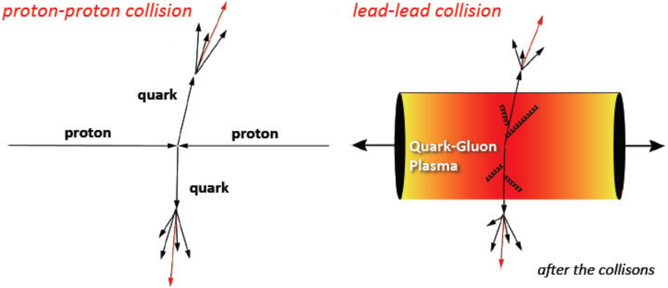


Tomography

'imaging through ***modification*** *of penetrating wave'*

'**Hard probe** means highly energetic particle

- Small α_s, properties known from QCD
- Deduce QGP properties from **modification** of the probe by the QGP
- Similar to x-ray : modification of γ wavelength by tissue



Nuclear modification factor R_{AA}

'Simplest' probe: (high-p_{T}) particle production in **vacuum** vs. in **plasma**

$$R_{\mathrm{AA}} = \frac{d^2N^{\mathrm{AA}}/dp_{\mathrm{T}}d\eta}{\langle T_{\mathrm{AA}}\rangle \cdot d^2\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}d\eta} \approx \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

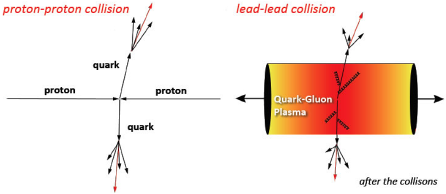
$\langle T_{\mathrm{AA}}\rangle \propto \langle N_{\mathrm{coll}}\rangle$ = no. of binary nucleon-nucleon collisions

Possible scenarios

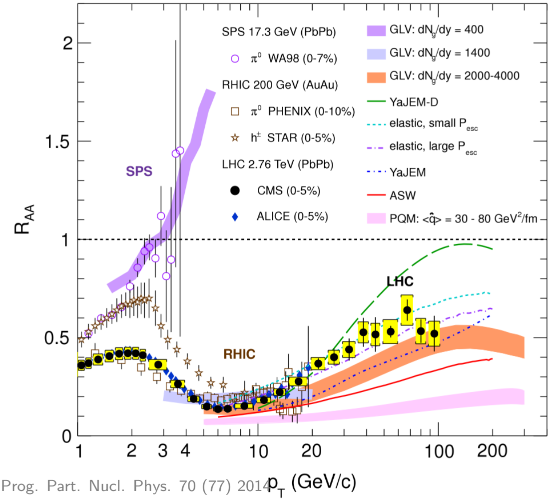
- $R_{\mathrm{AA}} > 1$ (enhancement)
- $R_{\mathrm{AA}} = 1$ (no plasma effect)
- $R_{\mathrm{AA}} < 1$ (**suppression**)

Assumption

- partons **lose** energy in the plasma
- $\boldsymbol{R_{\mathrm{AA}} < 1}$



R_{AA} - from SPS to RHIC to LHC



Prog. Part. Nucl. Phys. 70 (77) 2014

Results from LHC and RHIC are qualitatively similar

- $R_{AA} < 1$ points at **energy loss**

Decrease of R_{AA} with increasing $\sqrt{s_{NN}}$

- Indicative of higher plasma **density** at the LHC compared to RHIC

Data (and models) suggest **decrease** of relative e-loss at high p_T

so the R_{AA} s a nice ‘educational’ tool

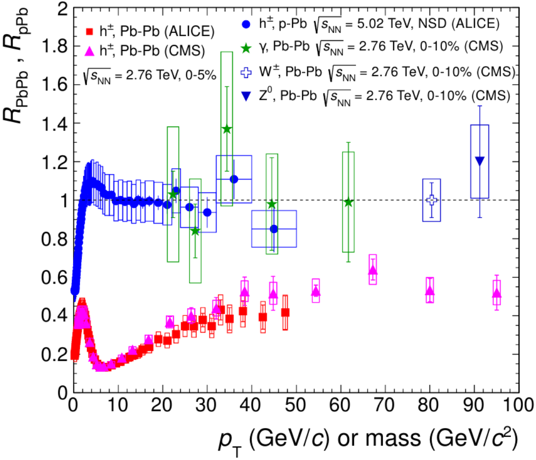
Is it really the strong interaction ?

R_{pPb} is expected to be sensitive to initial state, but not final state effects

R_{pPb} is consistent with unity for $p_T > 2$ GeV/c

- Small Cronin-like enhancement visible at low p_T
- Consistent with R_{AA} of particles which are not sensitive to QGP dynamics (γ, $W^{\pm}$, Z^0)

Suppression of hadron production in Pb–Pb collisions is *final* state effect

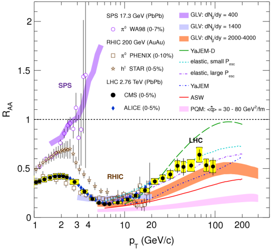


PRL 110, 082302 (2013)

R_{AA} gives us an intuitive **tomographic** picture

- The energy of our probe is **absorbed** in the plasma ($R_{AA} < 1$)
- With a bit of confidence we can say: '*partons lose energy in QGP, $\sqrt{s_{NN}}$ and density dependent*'

But that statement is still not very **precise** ...



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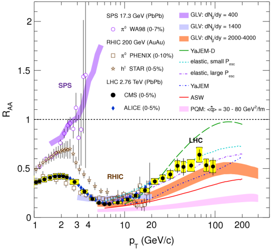
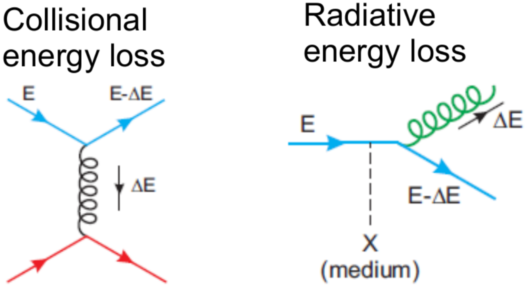


If we want to learn more, we need to

- Investigate the **energy loss mechanisms** that we can expect
- Perform **calculations** using these mechanisms
- Define a universal 'interface' (a **plasma property**) that we'll use to quantify the energy loss
- Make a **systematic** comparison of models to available data

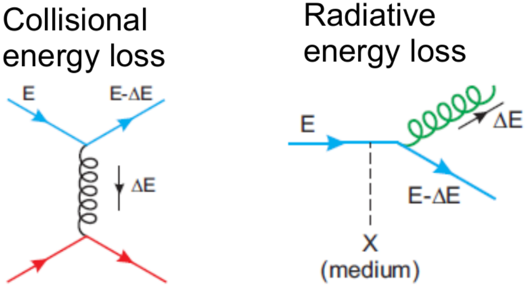
Let's look at all this in some more detail

in the **'classic'** (vs. AdS/CFT) QCD picture energy loss is either **collisional** or (induced) **radiative**



How do 'hard probes' lose energy?

in the **'classic'** (vs. AdS/CFT) QCD picture energy loss is either **collisional** or (induced) **radiative**



both mechanisms have an explicit dependence on the **length** of the parton's tracjectory through the QGP (L, L^2) and plasma **density**

.

As a 'back of the envelope' thought, ingredients for **collisional** energy loss where $\omega = E^{\text{initial}} - E^{\text{final}}$ is transferred one can write

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \underbrace{\sum_{p=q,g} \int d^3k}_{\text{sum over states}} \overbrace{\rho_p(k)}^{\text{plasma density}} \int \mathrm{d}q^2 \overbrace{J}^{\text{flux}} \omega \underbrace{\frac{\mathrm{d}\sigma^{Qp\to Qp}}{\mathrm{d}q^2}}_{\text{cross section}}$$

Collisional energy loss - an incomplete picture

As a 'back of the envelope' thought, ingredients for **collisional** energy loss where $\omega = E^{\text{initial}} - E^{\text{final}}$ is transferred one can write

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with a **some trickery** this can be integrated

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \pi\alpha_s^2 \sum_p C_p \int \frac{d^3k}{k}\rho_p(k) \ln\left(\frac{q^2_{\text{max}}}{q^2_{\text{min}}}\right)$$
$$\simeq \frac{4\pi\alpha_s^2 T^2}{3}\left(1 + \frac{N_f}{6}\right) \ln\left(\frac{cE}{\alpha_s T}\right)$$

do not try to remember this !

The energy loss for **radiative** processes is directly connected to the **energy of the radiated gluon** ω

$$\langle \Delta E \rangle = \int \mathrm{d}\omega \mathrm{d}z \; \omega \frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}z}$$

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The difficulty enters here: gluons have a finite **formation time** during which the parent particle and gluon are still a **coherent** object

$$\tau_f \simeq \frac{\omega}{k_\perp^2}$$

Radiative energy loss - an incompleter picture

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if parent particle and gluon are still in a **coherent state** further radiation is **suppressed** - this effect is known as **LPM interference**

LPM interference in radiative processes

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Because of the finite τ_f the gluon spectrum has **three** distinct regimes depending on mean free path λ and screening mass μ

$$\omega \frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}z} \simeq \begin{cases} \frac{\alpha_s}{\lambda} & \omega < \omega_{\mathrm{BH}} \\ \frac{\alpha_s}{\lambda}\sqrt{\frac{\lambda \mu^2}{\omega}} & \omega_{\mathrm{BH}} < \omega < \omega_{\mathrm{fact}} \\ \frac{\alpha_s}{L} & \omega_{\mathrm{fact}} < \omega < E \end{cases}$$

1. **Low** gluon energies: **all constituents** act as single sources of radiation
2. **Intermediate** energies: **multiple** constituents act as a **coherent** scattering source (LPM interference)
3. **Highest** energies: the entire plasma acts as **one** scattering center

$$\langle \Delta E \rangle (L) \sim c_1 \alpha_s E + c_2 \alpha_s \frac{\mu^2 L^2}{\lambda}$$

remember that we can do these calculations because our ‘hard probe’ has large energy: perturbation theory works

⋮

how do we relate it to a **macroscopic** plasma property ?

Transport coefficient $\hat{q}$

In the most general sense, a **transport coefficient** γ measures how rapidly a perturbed system returns to equilibrium ...

$$\gamma = \int_0^\infty \langle \dot{A}(t)\dot{A}(0)\rangle$$

Transport coefficient $\hat{q}$

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$$\gamma = \int_0^\infty \langle \dot{A}(t)\dot{A}(0)\rangle$$

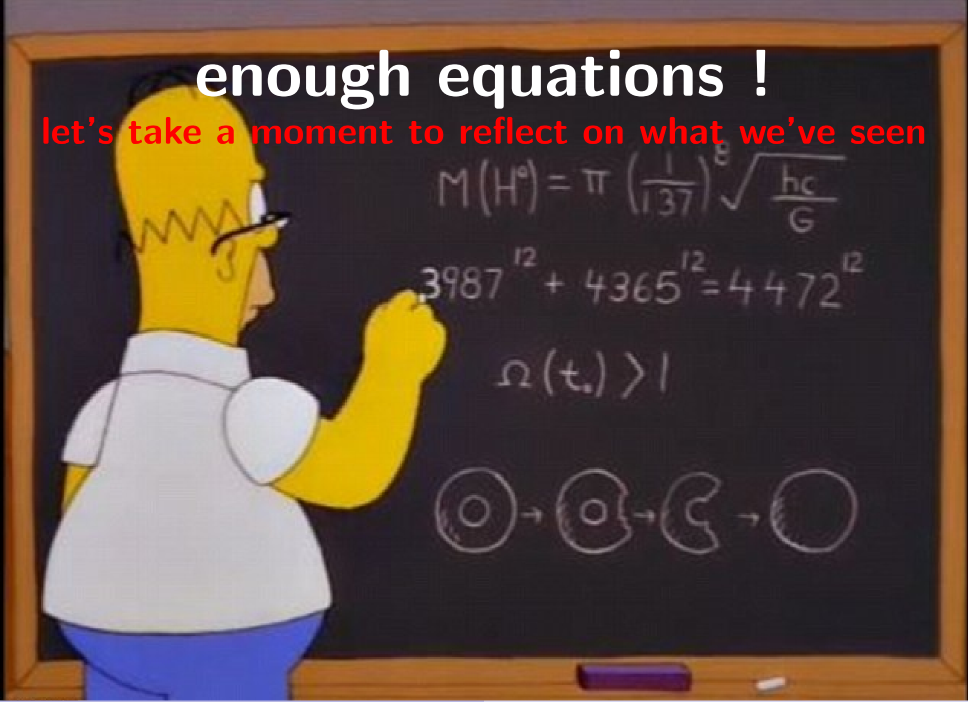
... but I (I don't do quantum mechanics every day ...) know them best as **viscosity** η or the **transverse momentum diffusion** coefficient $\hat{q}$

$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda} \qquad \underbrace{\Delta E}_{!!!} \simeq \alpha_s \hat{q} L^2$$

$\hat{q}$ quantifies momentum diffusion between a probe particle and a given material as the average squared momentum transfer $\langle q_\perp^2 \rangle$ per unit length λ, where $_\perp$ is perpendicular to the partons' trajectory

enough equations !

let's take a moment to reflect on what we've seen



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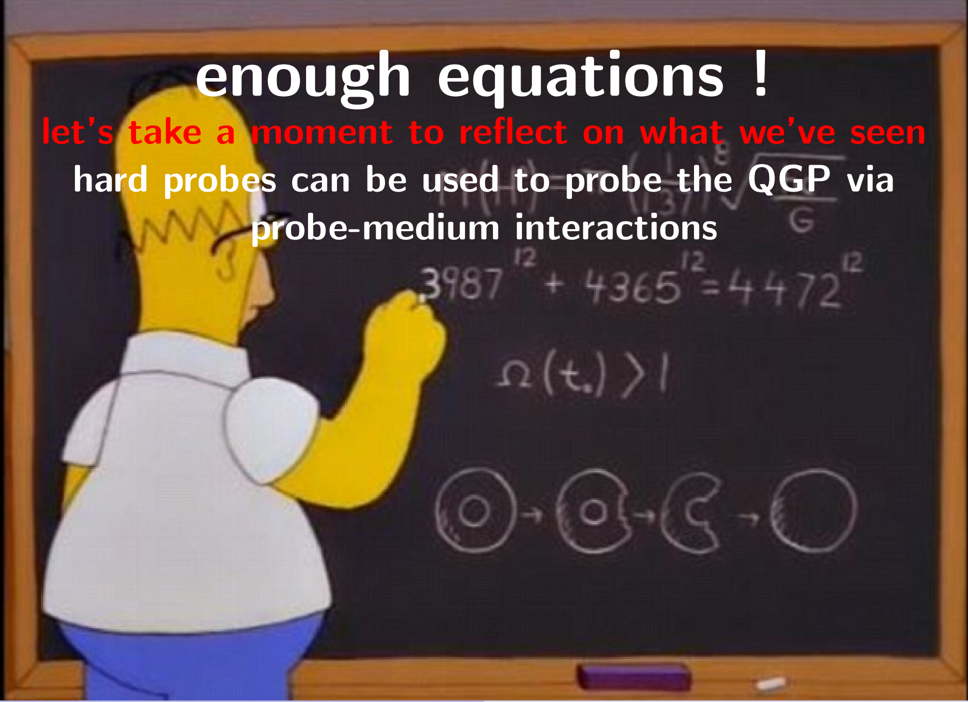
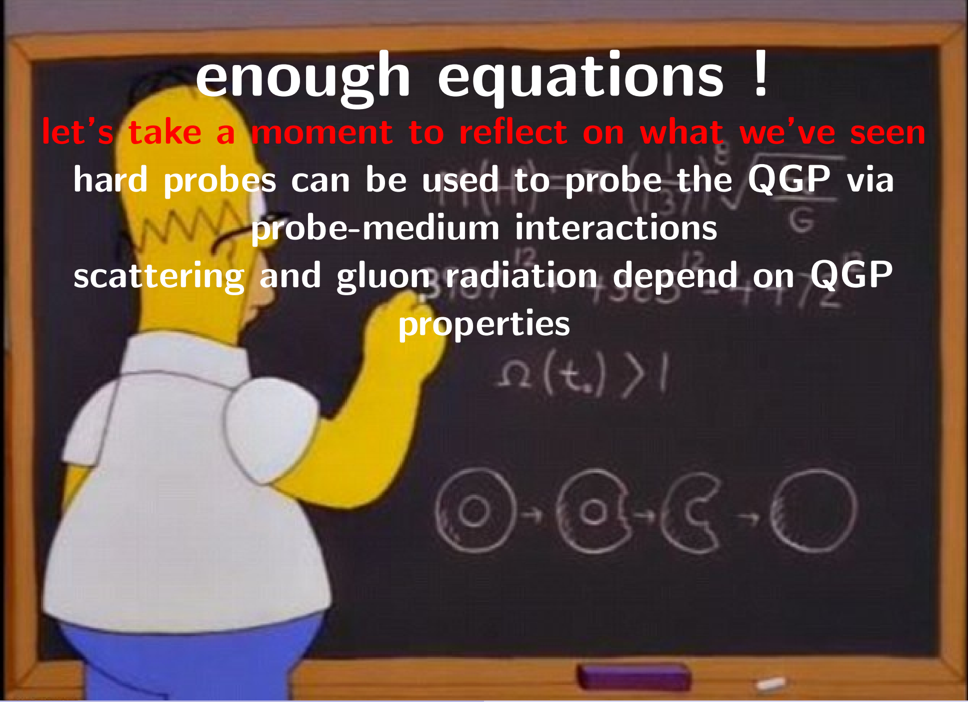
hard probes can be used to probe the QGP via probe-medium interactions





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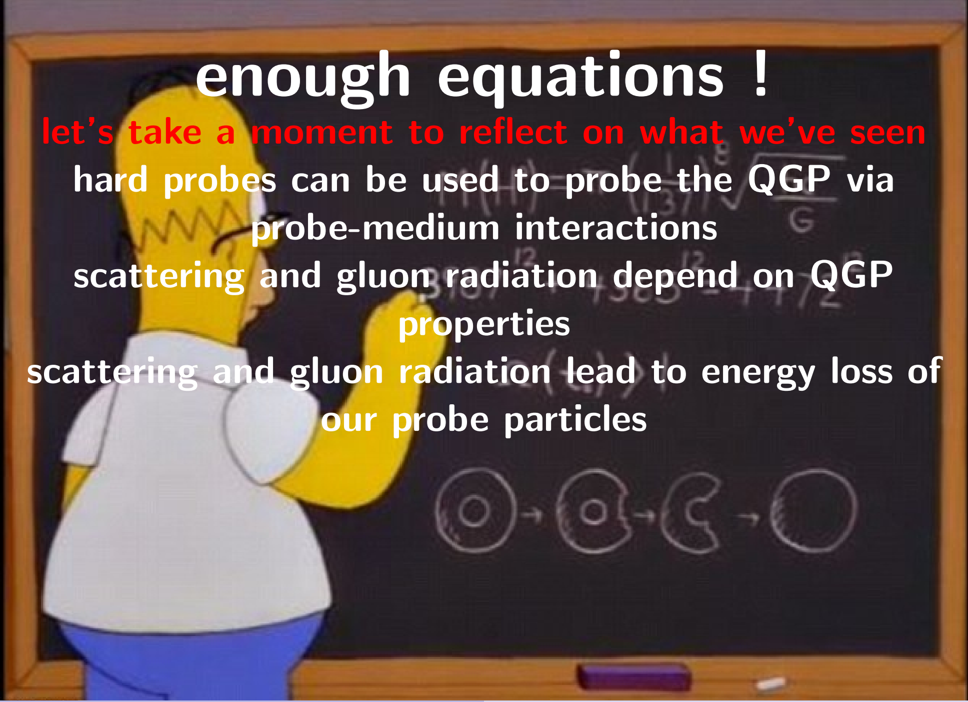

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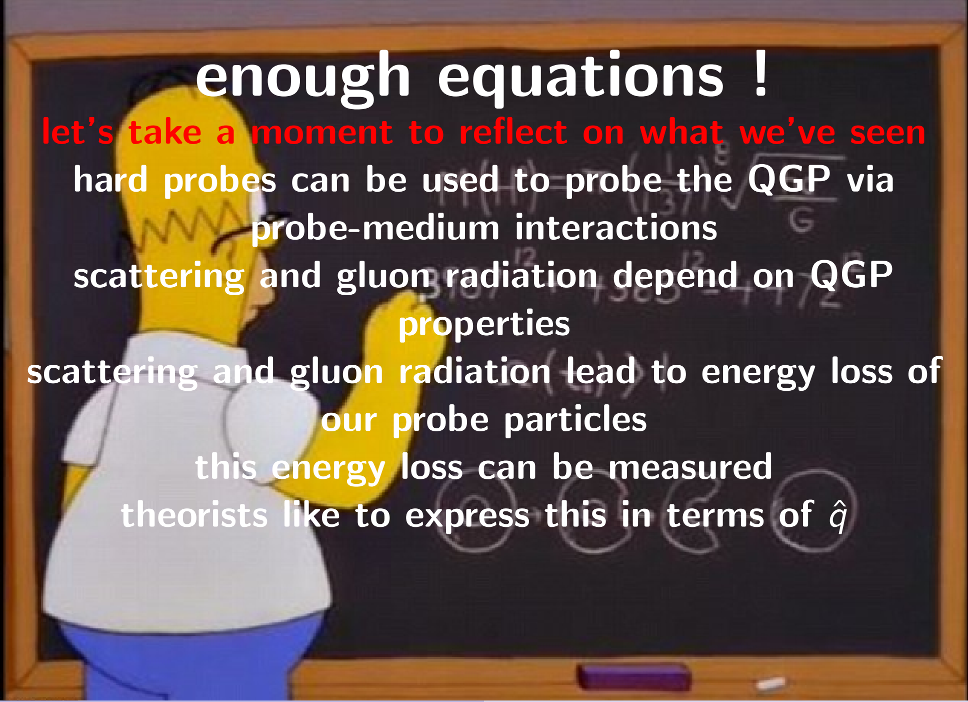

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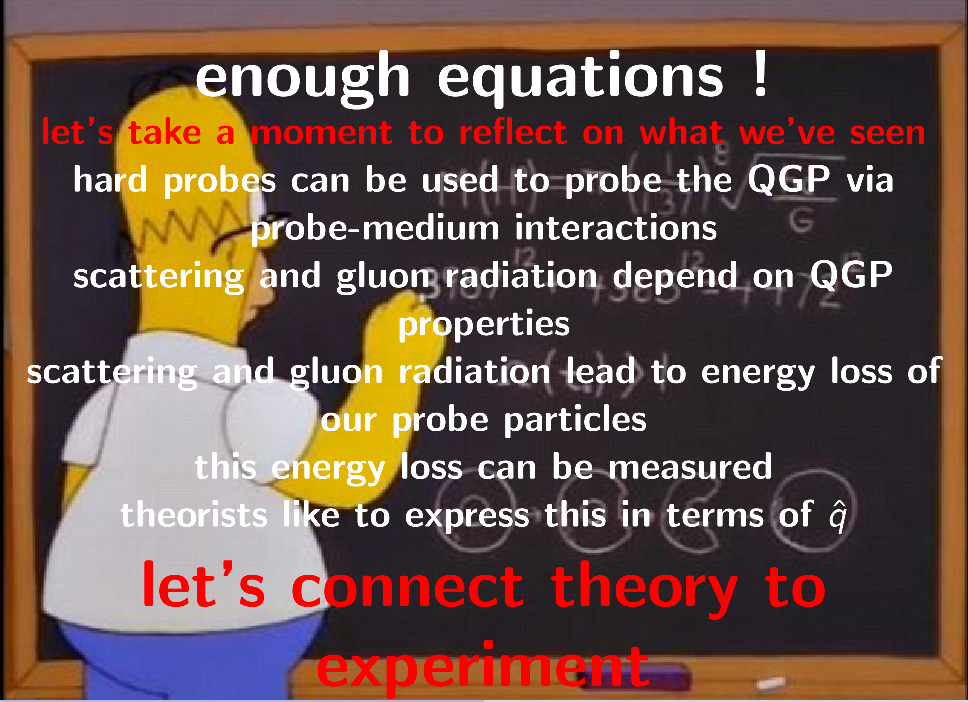

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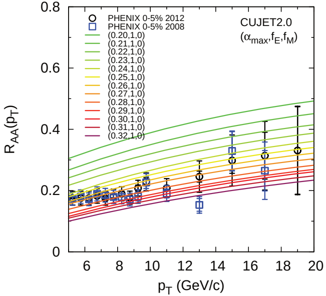
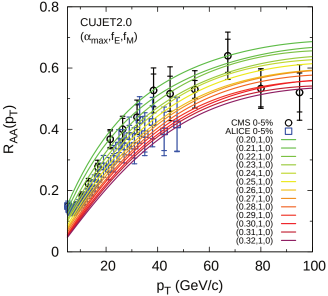
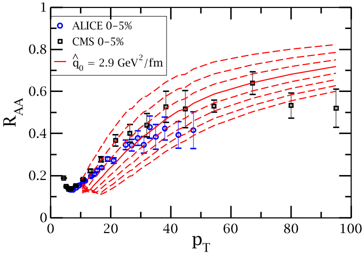
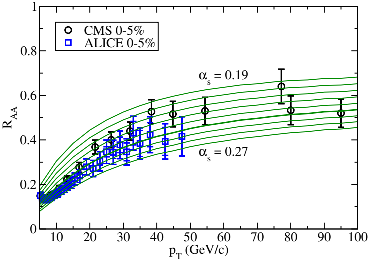
let's connect theory to experiment

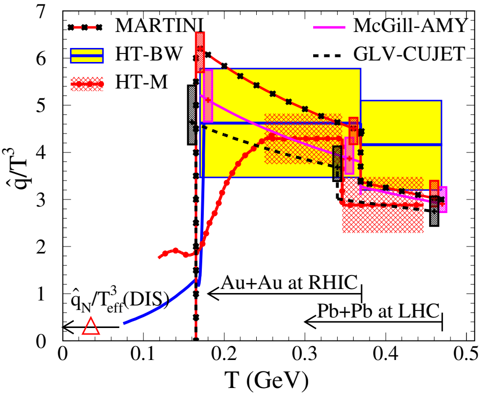
The tuning process











$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 \text{ (RHIC)} \\ 3.7 \pm 1.4 \text{ (LHC)} \end{cases}$$

AdS/CFT correspondence **compatible** using CUJET α_s:

$$\frac{\hat{q}}{T^3} = 2.27 - 3.64$$

For a 10 GeV/c quark jet

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \frac{\text{GeV}^2}{\text{fm}} \text{at T=370 MeV} \\ 1.9 \pm 0.7 \frac{\text{GeV}^2}{\text{fm}} \text{at T=470 MeV} \end{cases}$$

$\hat{q}$ **determined with $\approx$ 35% certainty**

combined effort of **five** theory groups, **RHIC** and **LHC**

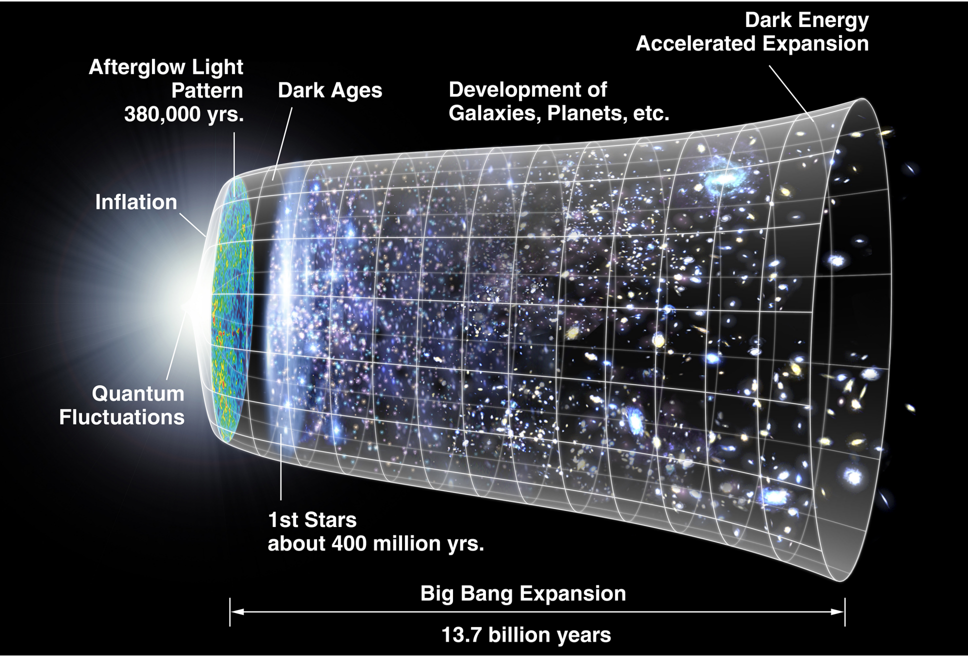
... so ... $\hat{q} \approx 2$ ... doesn't sound too impressive ...

.

but realize that this is 20 years or RHIC / 20 years of LHC / 20 years of theory and a first **'telescope'** to the very early universe

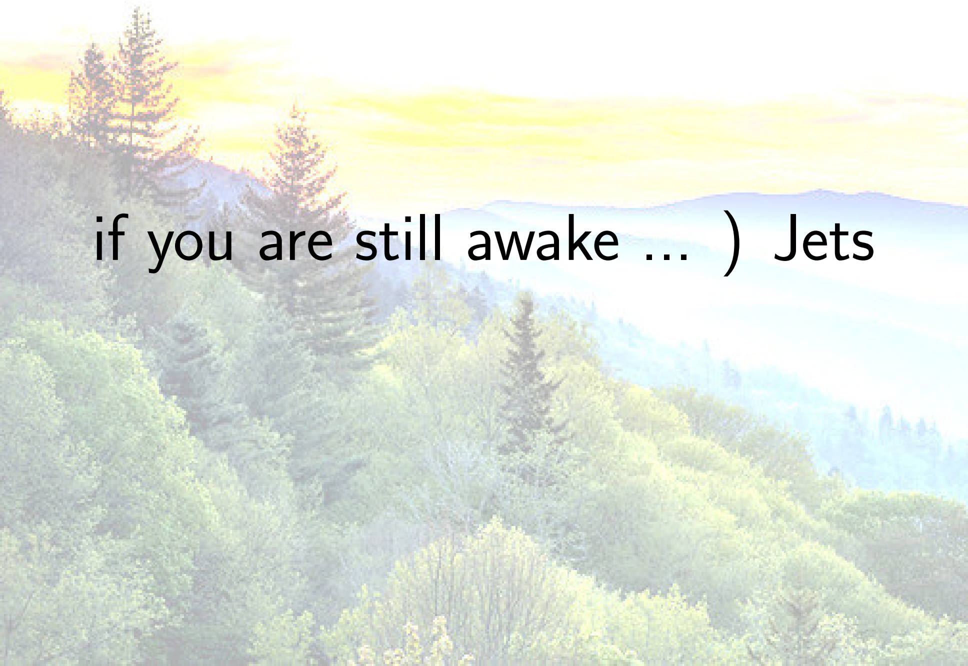
.

that teaches us about temperature, density, viscosity, EOS of the QGP


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

goal:

at the end of this talk, you will **understand** the titles of these conferences :) !



if you are still awake ...) Jets

so in summary, R_{AA} teaches us a lot - but it has it's limitations because we look at **hadronized** particles, not **partons**, and we don't know what **'path'** the parton took through the plasma

.

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so in summary, R_{AA} teaches us a lot - but it has it's limitations because we look at **hadronized** particles, not **partons**, and we don't know what **'path'** the parton took through the plasma

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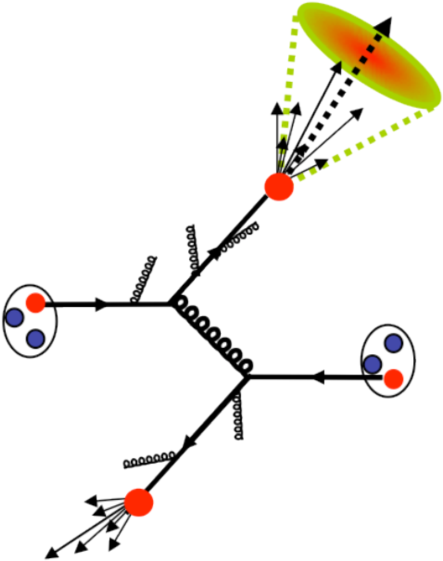
to **understand** the nature of energy loss, experiments must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution

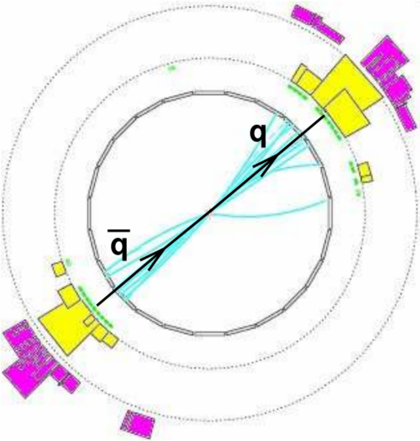
Jets in heavy-ion collisions in a nutshell

Hard scattering ($Q^2 > 1$ $(\mathrm{GeV}/c)^2$)

- Parton travels through the QGP, **scattering** and **radiation** of quarks and gluons
- Hadronization into colorless spray: **'jet'**
- Reconstructed jet: as close as one can experimentally get to **original parton (the scattered quark or gluon**
- 'Removes' ill-understood hadronization from modeling

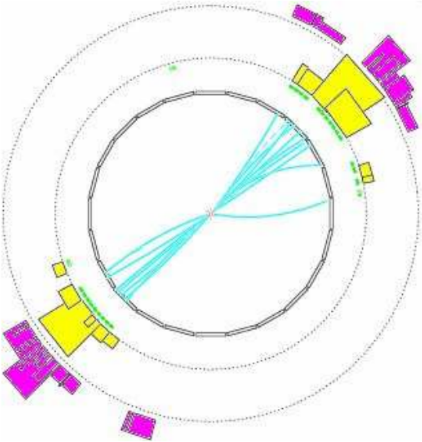
But jet analysis is **tricky!**





Jets are what we see.
Clearly(?) 2 jets here

How many jets do you see?
Do you really want to ask yourself
this question for 10^9 events?



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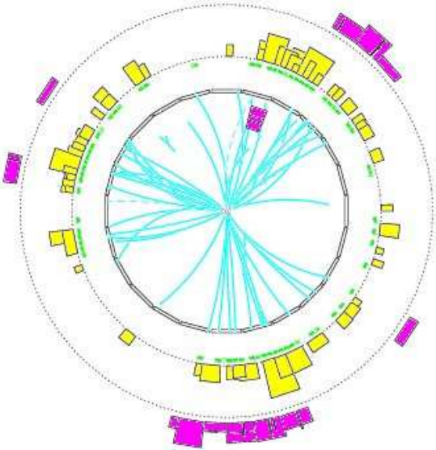

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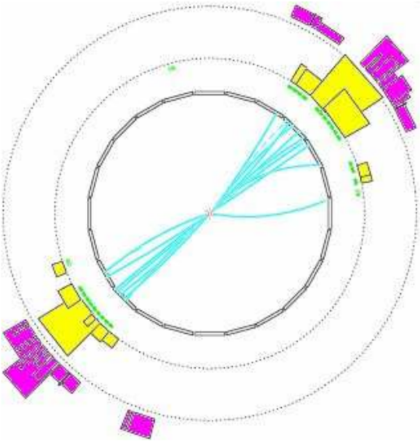

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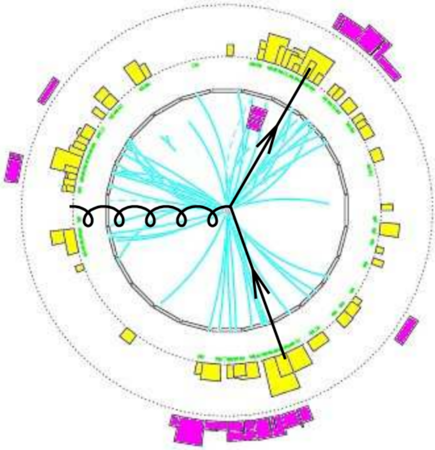

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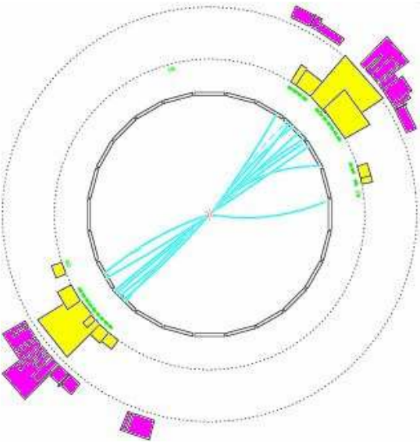

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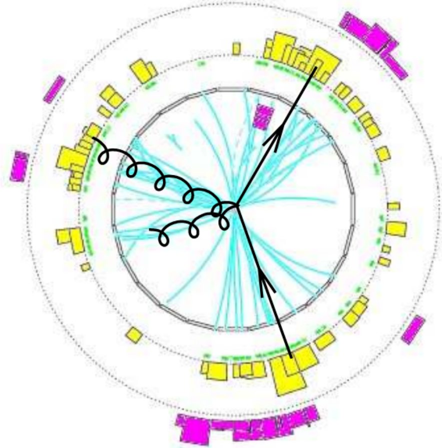

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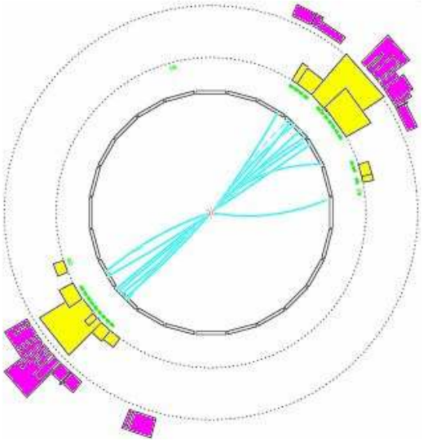

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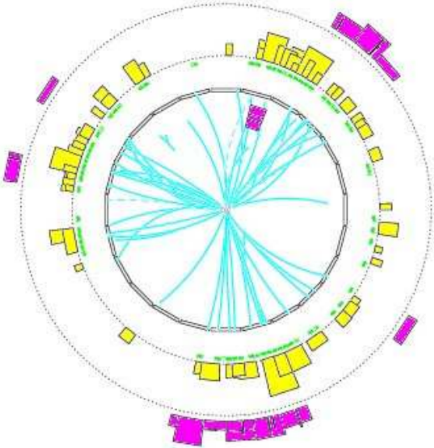

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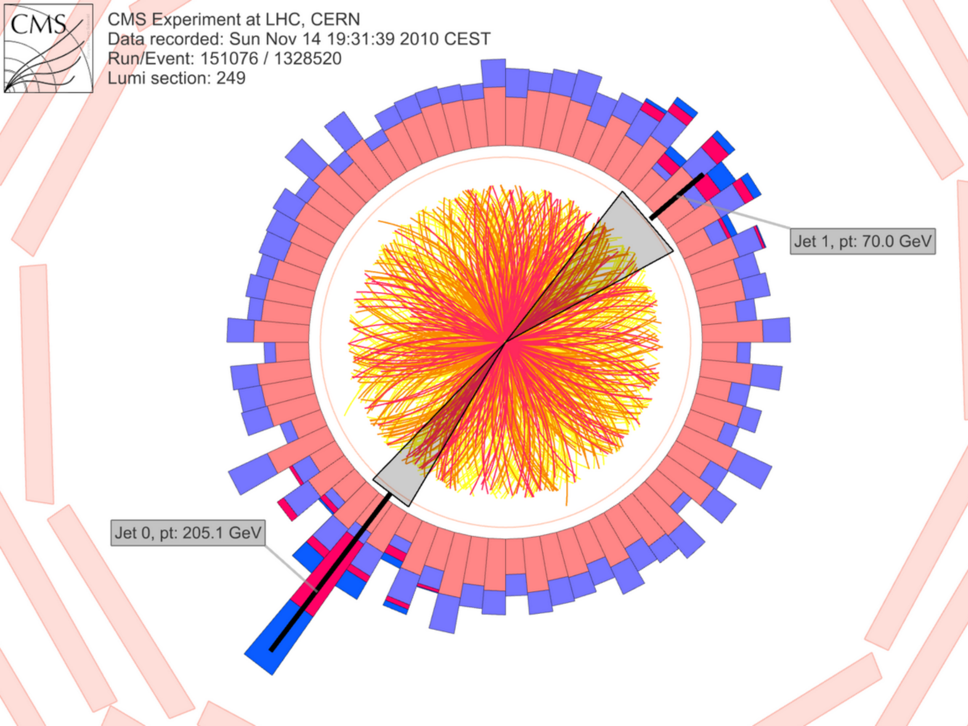
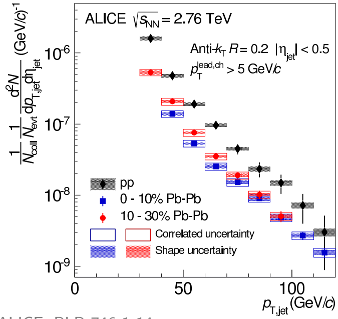

CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

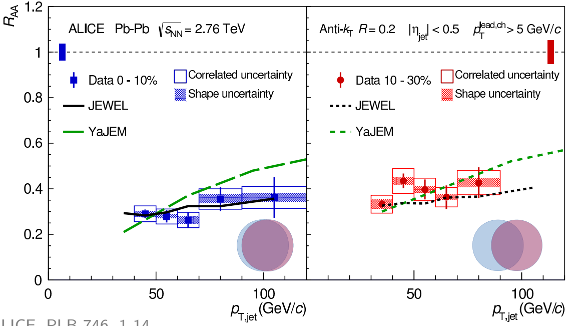
so if time permits, **two** questions

are jets **quenched**?
can we determine the **path** of the jet through the plasma?

Out-of-cone radiation: R_{AA} of jets



ALICE, PLB 746 1-14



ALICE, PLB 746, 1-14

$$R_{AA} = \frac{d^2 N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle \cdot d^2\sigma_{pp}/dp_T d\eta} \approx \frac{\text{QCD in medium}}{\text{QCD in vacuum}}$$

- **Strong** suppression in central and semi-central colisions
- Resonable model agreement (JEWEL[1], YaJEM[2])

Indication of **out-of-cone** radiation

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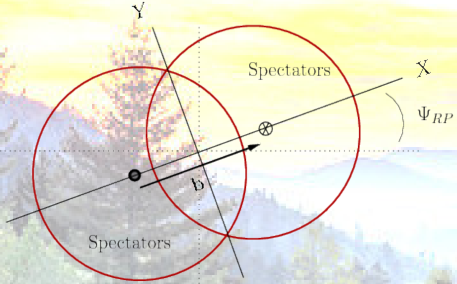
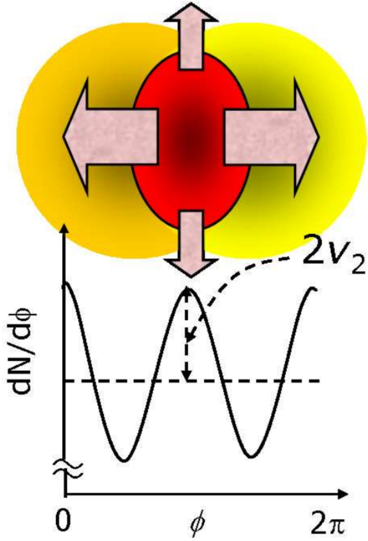
[1] K.C.Zapp *et al.* JHEP 1303 080

[2] T.Renk, PRC 78 034908

what **path** did the jet take through the plasma?



event-plane dependence of jet production



$v_2^{\text{ch jet}}$: comparing short to long L at fixed medium density

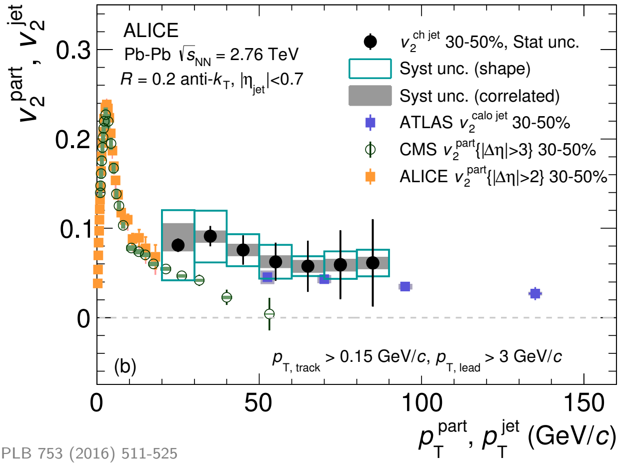
$\langle L_{\text{in}} \rangle \approx \langle L_{\text{out}} \rangle$

$v_2^{\text{ch jet}} \approx 0$?

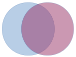
$\langle L_{\text{in}} \rangle < \langle L_{\text{out}} \rangle$

$v_2^{\text{ch jet}} > 0$?

so this is **not** hydro flow! the contribution of v_n to $v_2^{\text{ch jet}}$ has been **removed**



PLB 753 (2016) 511-525



$\langle L_{in} \rangle < \langle L_{out} \rangle$

$v_2^{\text{ch jet}} > ?$

Non-zero $v_2^{\text{ch jet}}$ over full p_T range - strong path length dependence
Good agreement between measurements of ALICE, ATLAS, CMS

Path-length dependence: di-jet systems

THE UNIVERSITY OF TENNESSEE KNOXVILLE

'so to **understand** the nature of energy loss, we must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution' 'so to **understand** the nature of energy loss, we must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution'

Di-jet system: $2 \longrightarrow 2$ process

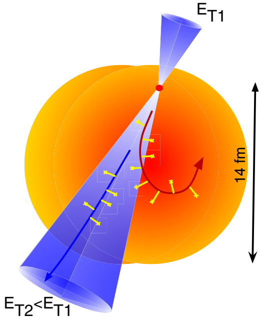
- Jets traveling in **opposite** direction with **equal** initial transverse momentum $p_{T1} = p_{T2}$
- $L_1 \neq L_2$
- $\Delta E_1 \neq \Delta E_2$
- **Final** state p_T is **not** equal $p_{T1} \neq p_{T2}$

Some caveats ... in all collision systems $p_{T1} \neq p_{T2}$

- pp: recoil, out-of-cone radiation (vacuum fluctuations)
- AA: energy loss **fluctuations**, **different path-lengths**

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

$$x_j = p_{T1}/p_{T2}$$

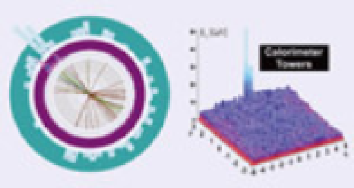


... a bit of history ...

CERN COURIER

Jan 25, 2011

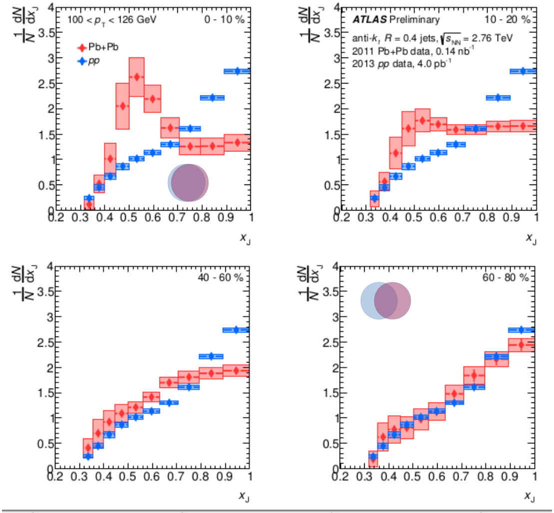
ATLAS observes striking imbalance of jet energies in heavy ion collisions



Highly asymmetric dijet event

The ATLAS experiment has made the first observation of an unexpectedly large imbalance of energy in pairs of jets created in lead-ion collisions at the LHC (G Aad *et al.* 2010). This striking effect, which is not seen in proton–proton collisions, may be a sign of strong interactions between jets and a hot, dense medium

Di-jet imbalance $x_j = p_{T1}/p_{T2}$



Asymmetry quantified as

$$x_j = p_{T1}/p_{T2}$$

Fully **unfolded**

- Direct comparison to **theory**
- ... and (eventually) other experiments

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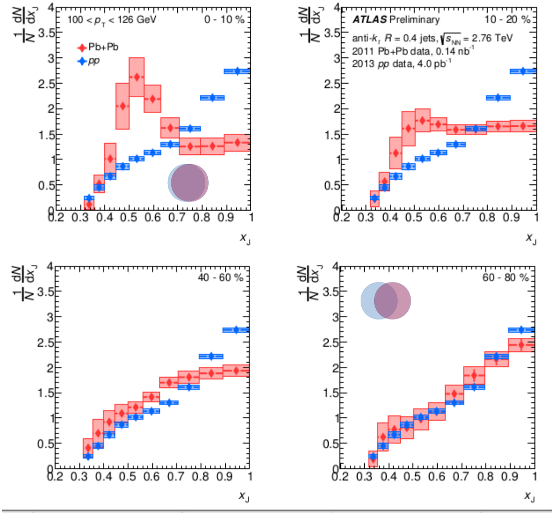

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In **pp**

- most probable dijet configuration: $x_j \approx 1$

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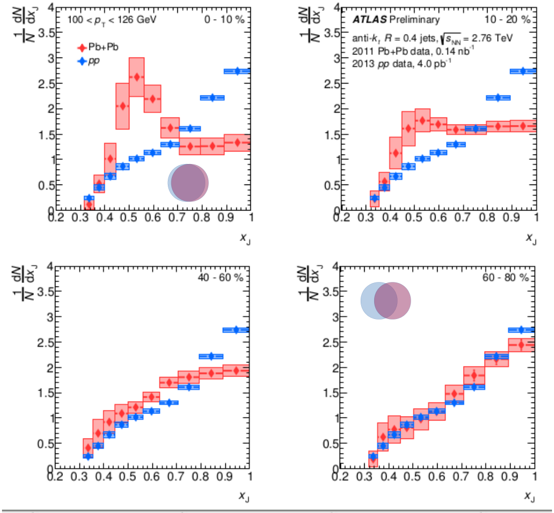

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- Direct comparison to **theory**
- ... and (eventually) other experiments

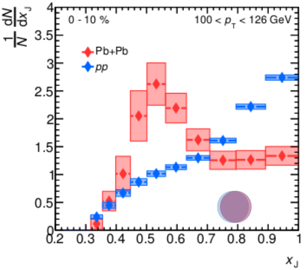
In **pp**

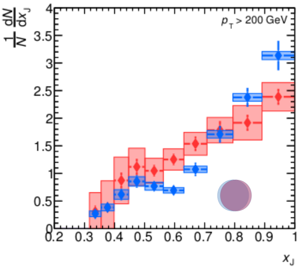
- most probable dijet configuration: $x_j \approx 1$

In **Pb–Pb**

- most probable configuration: subleading jet has **half** as much energy as leading jet

Strong **centrality** dependence

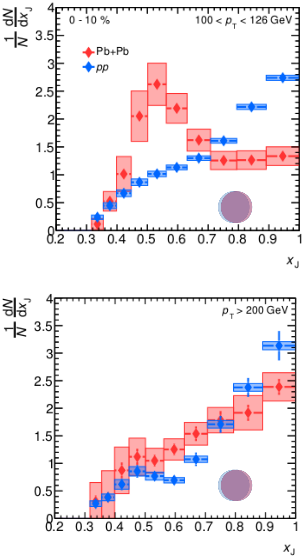




Asymmetry: $x_j = p_{\mathrm{T}1}/p_{\mathrm{T}2}$

- With **increasing** $p_{\mathrm{T}} \longrightarrow x_j$ goes **towards 1**

Di-jet imbalance $x_j = p_{T1}/p_{T2}$



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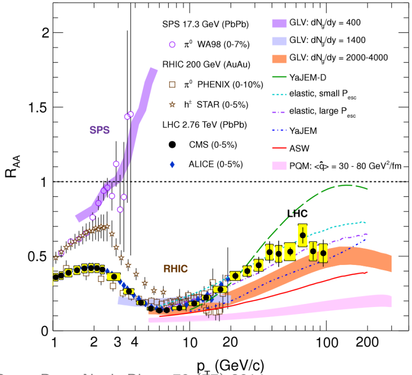
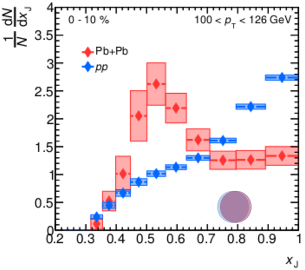
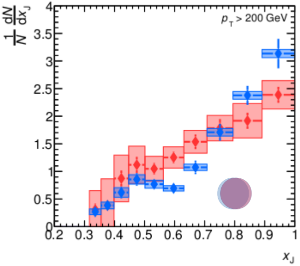


Prog. Part. Nucl. Phys. 70 (77) 2014

confirms sl. 6 'Relative loss decreases with p_T'





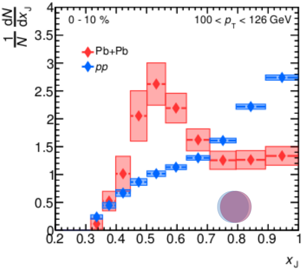
In summary

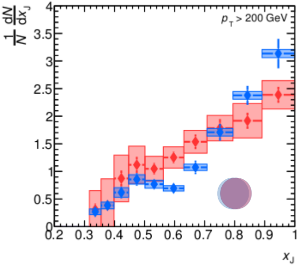
- R_{AA}: moderate **average** energy loss
- di-jets: **wide variation** in possible energy loss

So di-jet asymmetry very nicely illustrates

- centrality dependence hints on **path length** dependence
- e-loss is a **distribution**

Di-jet imbalance $x_j = p_{T1}/p_{T2}$





In summary

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So di-jet asymmetry very nicely illustrates

- centrality dependence hints on **path length** dependence
- e-loss is a **distribution**

But it doesn't tell what the **balance** is between

- **per-jet** energy loss **fluctuations**? (analogous to fluctuations in vacuum radiation)
- **average** energy loss from **kinematics**, **medium compisition** and **geometry**?

‘to **understand** the nature of energy loss, experiments must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution’ ‘to **understand** the nature of energy loss, experiments must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution’

$\vdots$

so let’s give that a go from both the **experimental** and **theory** side

How-to: constrain QGP properties ?

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Which **processes** is dominant?
(radiative, elastic)

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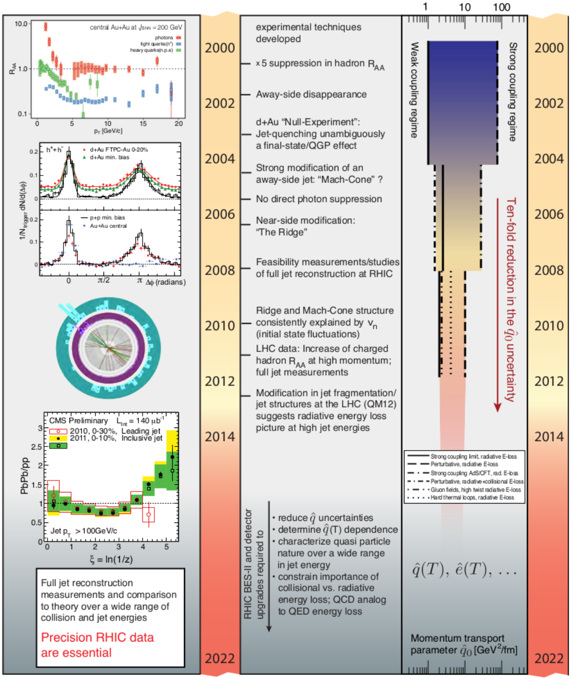
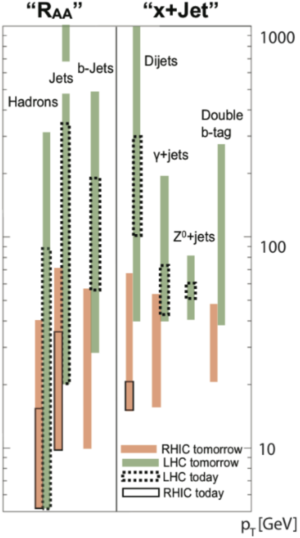
$\#$questions $\gg$ $\#$answers





'Hot and Dense QCD matter, Unraveling the Mysteries of the Strongly Interacting QGP' & 'The Hot QCD White Paper' *fin*

thanks for your attention / patience

BACKUP