Introduction

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Orsay
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Prospects on various aspects of the dilepton probe in hadronic physics

25 November 2021

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Strong interaction
QCD is everywhere... and badly understood!

Many questions in QCD remain open

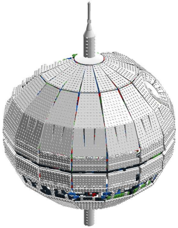
QCD is a highly non-linear theory, with a very rich phenomenology

- nuclear physics

  from quark-quark interaction to nucleon-nucleon interaction?
  - analogous to London forces between electrically neutral molecules
  - here hadrons are color neutral
  - residual force?
  - out of range analytically and even numerically

- physics of quark-gluon plasma
  - if a nucleus is heated sufficiently, can one create a deconfined state?
  - nucleus-nucleus collision (LHC)
  - what are the signals of formation of this deconfined state?

- hadronic physics: understanding hadron features
  - Mass
  - Spin
  - Charge
  - “‘D” term
  - ...



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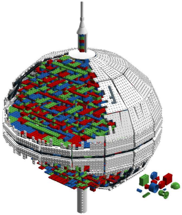
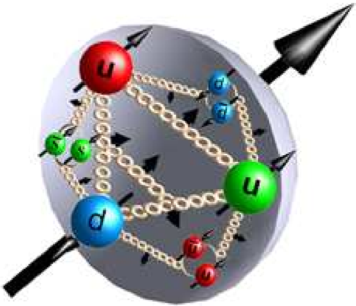


In terms of elementary colored bricks: quarks, gluons

Strong interaction
What about spin?

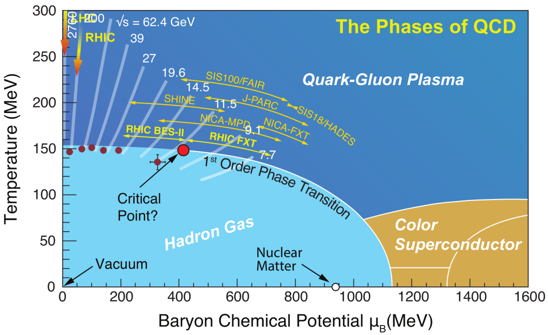
Proton spin puzzle



Proton has a spin 1/2

- quarks have spin 1/2
- gluons have spin 1
- quarks and gluons carry orbital momenta
- What is the contribution of each of these components to the total angular momentum?

QCD phase diagram



- cross-over between hadronic phases $\leftrightarrow$ QGP, at $\mu_B = 0$ and $T_c = 154 \pm 9$ MeV.
- 1st order transition expected at smaller T and rather high μ_B
- critical point expected, where the 1st order phase transition regime stops.
- at very high μ_B, other phases are expected (color super conductivity, with formation of Cooper quark-quark pairs, inside the nuclei of neutron stars)

This phase diagram is essentially unknown, neither theoretically nor experimentally.

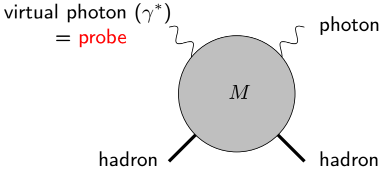
Theoretical tools

Factorization: short distance/long distance

How to handle with QCD?

example: Compton scattering

source of $\gamma^* = e^\pm$ or μ^- beam



- Goal: describe M (the scattering amplitude), separating:
  - non-perturbative quantities $\alpha_s \sim 1$

    - discretization of QCD on a 4-d euclidean lattice: numerical simulations
    - AdS/QCD correspondence
  - perturbative quantities $\alpha_s \ll 1$

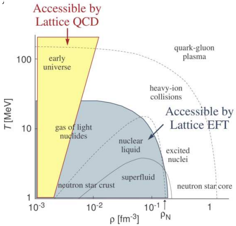
Theoretical tools
Non perturbative approaches

Strongly coupled sector of QCD and lattice QCD: $T \neq 0$

- lattice QCD at $\mu_B = 0$: get access to part of the QCD phase diagram
  phase transition (measure of T_c)
- Very hard to escape from the limit $\mu_B = 0$:
  - Grand canonical partition fonction: $Z = \mathrm{Tr} e^{-(\mathrm{H}-\mu\mathrm{N})/\mathrm{T}} = e^{-\mathrm{F}/\mathrm{T}}$
  - On the lattice: $Z = \int DUD\bar{\psi}D\psi\, e^{-S} = \int DU\, e^{-S_{\mathrm{YM}}} \det M(\mu)$,
    U: gauge link; $\psi, \bar{\psi}$ quark fields

    $$\text{QCD action:} \quad S = S_{\mathrm{YM}} + \int d^4x\, \bar{\psi} M \psi.$$
  - Simulations: $\rho(U) \sim e^{-S_{\mathrm{YM}}} \det M(\mu)$ = probability dist.
  - "sign problem":

    $$[\det M(\mu)]^* = \det M(-\mu^*) \in \mathbb{C} \Rightarrow \text{for } \mu \neq 0, \rho(U) \in \mathbb{C}.$$



the wave function changes of sign when exchanging two fermions (Pauli principle) $\Rightarrow$ the integral over fermions is strongly oscillating except if

 # (particules) = #(antiparticules) (i.e. $\mu = 0$).

- chiral nuclear EFT $\Rightarrow$ nuclear lattice simulations (one partially evades the sign problem thanks to the approximate spin-isospin $SU(4)$ symmetry of the nuclear interactions)

Theoretical tools

Non perturbative approaches

AdS/CFT and AdS/QCD correspondences

- correspondence between
  - a string theory defined on an anti de Sitter space (space with constant negative curvature) $AdS_5 \times S^5$
  - a supersymmetric conformal field theory N=4 in 4 dimensions, defined at the boundary of the string theory space
- duality between correlation functions defined for each of these two theories
- QCD is not conformal invariant (masses breaks scaling invariance)
  QCD = asymptotically free theory $\Rightarrow$ the analogy looks like reliable
- weakly coupled regime of string theory (SUGRA)
  $\leftrightarrow$ strong coupling regime of QCD:
  - exclusive and inclusive processes, small x physics
    moderate predictability ($\approx 30\%$)
  - for QGP: duality with a theory of black holes
    $\Rightarrow$ prediction of

$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}$$

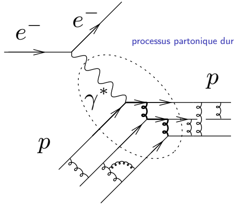
experimental result close to this lower bound:

QGP = perfect fluid strongly coupled

Factorization

- Goal: reduce the process to the interaction of a small number of *partons* (quarks, gluons), despite confinement
- This makes sense whenever the process is govern by short distance phenomena ($d \ll 1\,\mathrm{fm}$)
  $\Longrightarrow \alpha_s \ll 1$: perturbative methods
- One should collide a hadron violently enough

Example: proton form factor (elastic scattering $e^- p \to e^- p$)

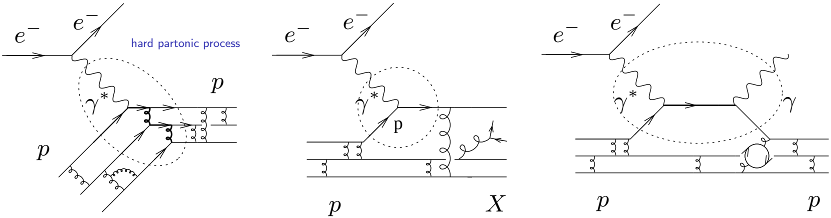


τ electromagnetic interaction $\sim \tau$ parton life-time after the scattering
$\ll \tau$ characteristic time-scale of strong interaction

$\Rightarrow$ hard process.

Factorization

- one needs a hard scale:
  - Virtuality of the electromagnetic probe
    - elastic scattering $e^{\pm}\, p \to e^{\pm}\, p$
    - Deep Inelastic Scattering (DIS) $e^{\pm}\, p \to e^{\pm}\, X$
    - Deeply Virtual Compton Scattering (DVCS) $e^{\pm}\, p \to e^{\pm}\, p\, \gamma$
    - Semi Inclusive Deep Inelastic Scattering (SIDIS) $e^{\pm}\, p \to e^{\pm}$ hadron $p\, X$
  - total center of mass energy in $e^+e^- \to X$ annihilation
  - Production of a heavy meson or of a high-mass $\ell^-\ell^+$ pair
- amplitude = convolution of the hadron partonic content with a perturbative amplitude



Theoretical tools

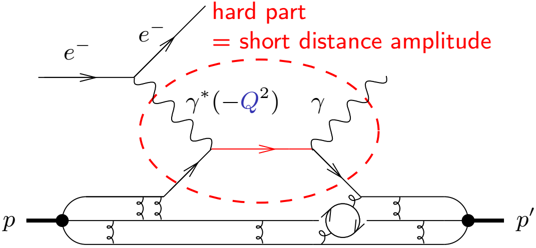
Factorization: short distance/long distance

"Collinear" factorisation of the scattering amplitude dfor DVCS

M = short distance amplitude $\otimes$ non-perturbatif content of the hadron

convolution

Deeply Virtual Compton Scattering:



Generalized Parton Distribution (GPD)

virtual photon γ^* = probe

$1/Q$ = spatial resolution

(Heisenberg inequality)

$M_{\gamma^* p \to \gamma p'}$

***perturbatives* corrections**

resummation ?

$$= \quad (\# + \#\,\alpha_s + \cdots)$$

$$+ \ \frac{1}{Q}(\# + \#\,\alpha_s + \cdots)$$

$\nwarrow$ ***power* ("twist") corrections**

$$+ \quad \cdots$$

HERA (H1, ZEUS, HERMES), JLab, COMPASS ... LHC ... EIC

Theoretical tools
NRQCD Factorization

Quarkonium production in NRQCD

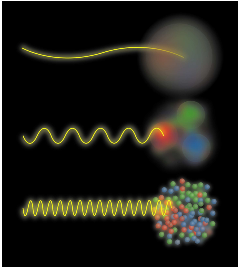
- Non Relativistic QCD expansion (NRQCD)
  Bodwin, Braaten, Lepage; Cho, Leibovich ....
- Proof of NRQCD factorization: NLO Nayak Qiu Sterman '05; all order Nayak '15.
- Expansion of the onium state (i.e. heavy $Q\bar{Q}$) in powers of its constituent velocity $v \sim \frac{1}{logM}$:

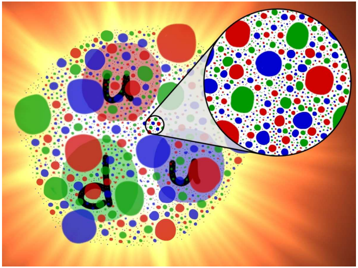
$$|J/\psi\rangle = O(1)\left|Q\bar{Q}[^3S_1^{(1)}]\right\rangle + O(v)\left|Q\bar{Q}[^3P_J^{(8)}]g\right\rangle + O(v^2)\left|Q\bar{Q}[^1S_0^{(8)}]g\right\rangle +$$
$$+O(v^2)\left|Q\bar{Q}[^3S_1^{(1,8)}]gg\right\rangle + O(v^2)\left|Q\bar{Q}[^3D_J^{(1,8)}]gg\right\rangle + ...$$

  - the whole non-perturbative physics is encoded in Long Distance Matrix Elements (LDME) extracted from $|J/\psi\rangle$
  - hard part (expansion in α_s): obtained through the usual Feynman diagrams expansion
  - cross section = convolution (hard part)^2 $\otimes$ LDME
- In NRQCD, Q and $\bar{Q}$ share democratically the quarkonium momentum: $p_V = 2q$
- The importance of color singlet versus color octet contributions is still a matter of discussions.

Partonic content
Electromagnetic probe

Accessing the internal content of proton using an electromagnetic probe

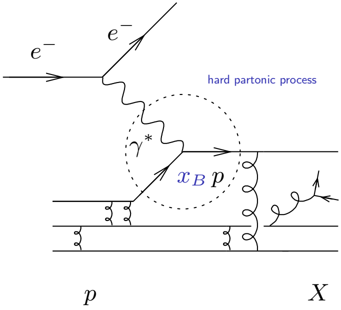




visible details are directly related to the wave length of the probe

Quark and gluon content of proton
Short remainder on the historical experiment: DIS

Deep Inelastic Scattering



$$s_{\gamma^* p} = (q^*_\gamma + p_p)^2 = 4\, E^2_{\text{c.m.}}$$

$$Q^2 \equiv -q^2_{\gamma^*} > 0$$

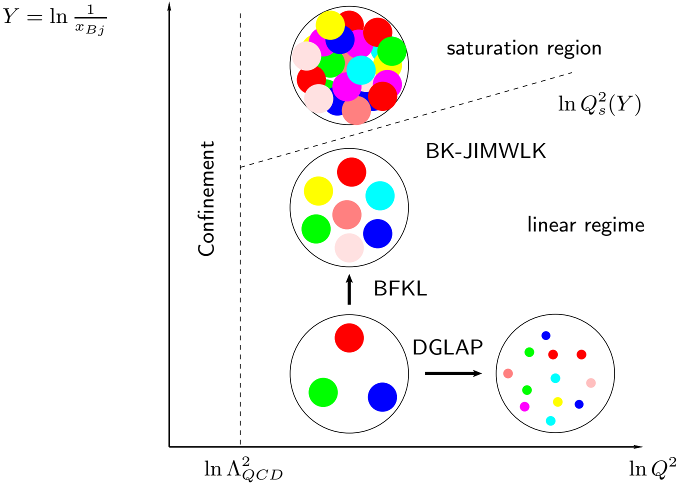
$$x_B = \frac{Q^2}{2\, p_p \cdot q^*_\gamma} \simeq \frac{Q^2}{s_{\gamma^* p}}$$

Bjorken-Feynman 1969

- x_B = momentum fraction of the proton momentum carried by the quark
- $1/Q$ = transverse resolution of the electromagnetic probe $\ll 1/\Lambda_{QCD}$

Quark and gluon content of proton
DIS

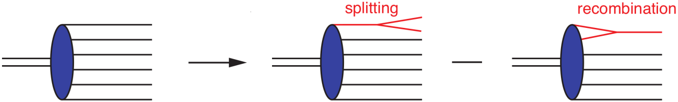
The various regime governing the perturbative content of the proton



High energy: Regge limit

Non-linear perturbative regime and Color Glass Condensate

Gluonic saturation

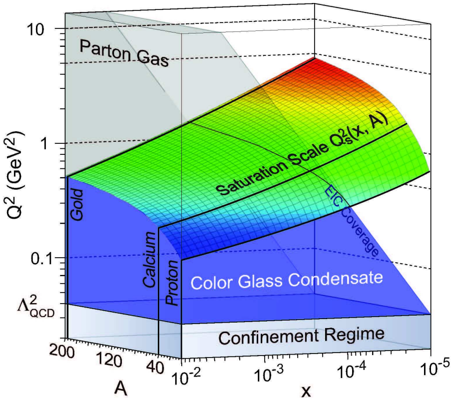


- $\alpha_s \ll 1$: weak coupling $\Rightarrow$ perturbative approach
- very dense system: very high occupation numbers
  $\Rightarrow$ gluons can recombine
- characteristic scale: saturation for $Q^2 \lesssim Q_s^2(x)$
  - number of gluons per surface unit:
    $$\rho \sim \frac{xG_A(x, Q^2)}{\pi R_A^2}$$
  - recombination cross-section:
    $$\sigma_{gg\to g} \sim \frac{\alpha_s}{Q^2}$$
  - effects are important when $\rho\, \sigma_{gg\to g} \gtrsim 1$

$$\text{i.e. } Q^2 \lesssim Q_s^2 \quad \text{with} \quad Q_s^2 \sim \frac{\alpha_s \; xG_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} x^{-0.3}$$

Gluonic saturation
Experimental future

Gluonic saturation with a perturbative control



- At EIC, the saturation scale Q_s will be in the perturbative range

$$Q_s^2 \sim \left(\frac{A}{x}\right)^{1/3}$$

  - Moderate center of mass energy
  - Compensated by large A

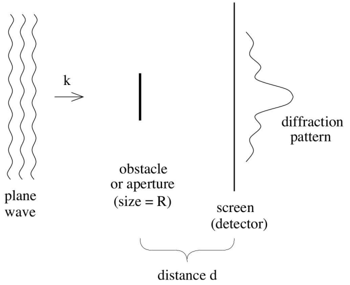
- Large perturbative domain

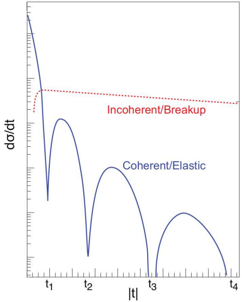
$$\Lambda^2_{QCD} \ll Q^2 \ll Q_s^2$$

  in which saturation is under control

Diffraction

Diffraction on a nucleus





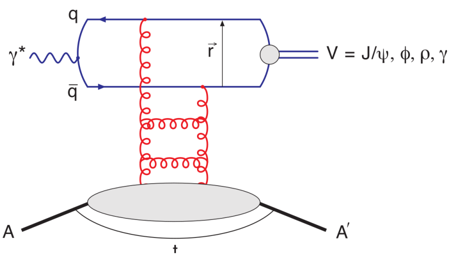
incoherent diffraction: the nucleus breaks, nucleons remain intact

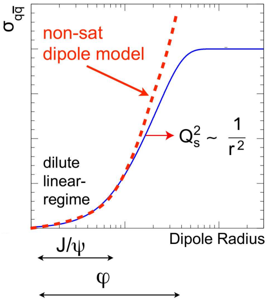
coherent diffraction: the nucleus remains intact

- the diffraction pattern contains information on the size R of the obstacle and on its optical opacity
- in optics, function of θ
- in high energy physcs, $t = -(k \sin\theta)^2$

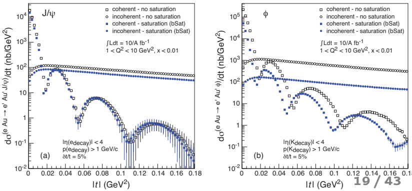
Diffraction
Exclusive case

Diffraction on a nucleus
Production of an exclusive state: meson





- the dipole cross-section $\sigma_{q\bar{q}}(r)$ saturates in the black disk limit
- the meson size plays the role of a filter:
  - J/ψ = small size
    $\Rightarrow$ dominated by the linear regime
  - ϕ, ρ = large size
    $\Rightarrow$ important contribution from the saturated non-linear regime



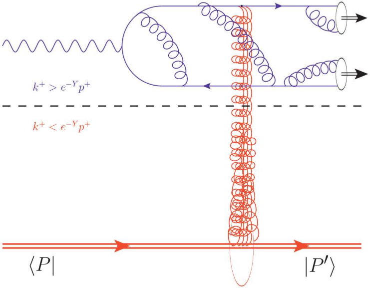
Gluonic saturation in diffraction
Towards a precision era

Gluonic saturation at NLO

Providing evidence of gluonic saturation which underlies the color glass condensate (CGC) framework requires a complete NLO treatment

- Shock-wave approach :
  in the probe frame,
  the exchanged gluonic field is localized at time $x^+ = 0$
  (on the light-cone)
  $\Rightarrow$ effective theory
- The CGC evolution is now known at NLO
- The first impact factors (describing the probe-CGC coupling) have been made available recently at NLO (dijets production, meson)

LHC, EIC

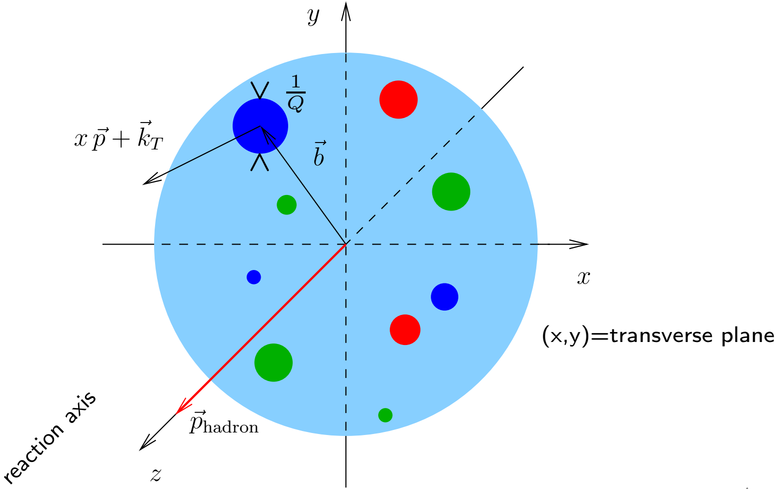


rapidity separation between quantum and classical mode

diffractive production of a dijet

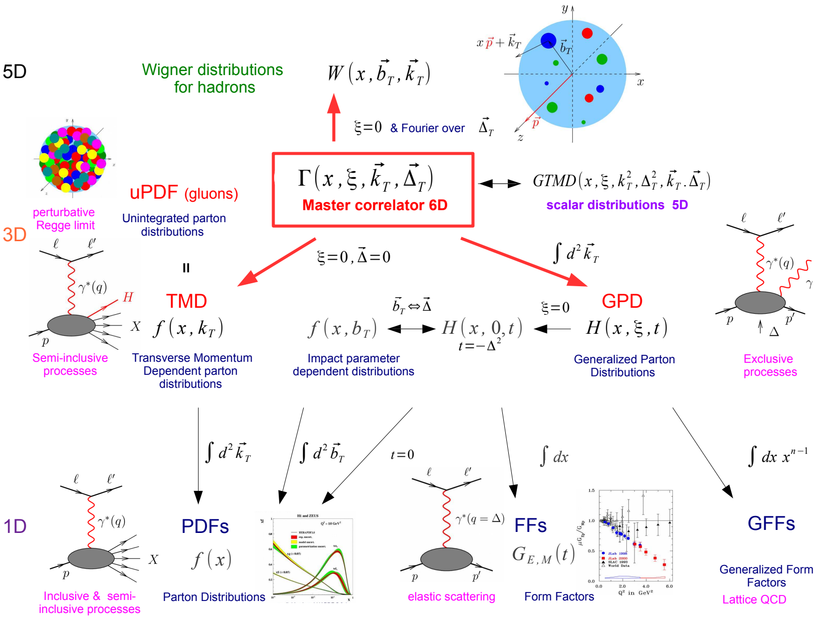
Quark and gluon content of proton
Beyond DIS

Accessing multidimensional quark and gluons distributions for hadrons?
5-dimensional information



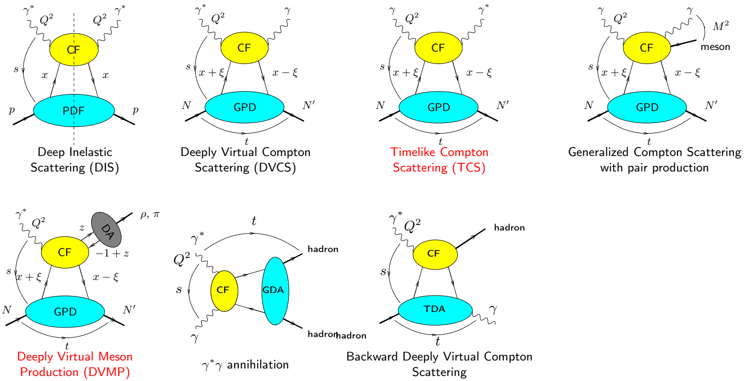
Quark and gluon content of proton

The ultimate picture



Quark and gluon content of proton... and of nuclei

From DIS to exclusive processes

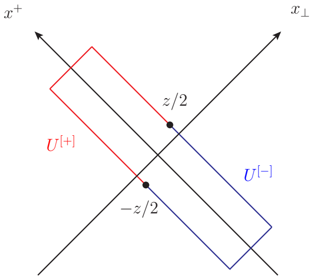


- Test of factorization (and of universality of non perturbative distributions)
- complementarity of processes in order to extract GPDs
- requires to control radiative corrections (NLO) and power corrections (e.g.: DVMP for π^0)
- extension to nuclei is promising
- the kinematical range should be extended: in ξ, in t, in Q^2: JLab, COMPASS, ... LHC en UPC, EIC

TMDs
TMD's gauge links

"Non-universality" of quark TMD distributions

Gauge links can be future-pointing or past-pointing



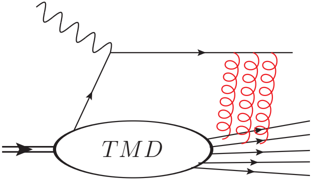
$$q^{[+]}(x,k_\perp) \propto \left\langle P \left| \bar{\psi}\left(\frac{z}{2}\right) \mathcal{U}^{[+]}_{\frac{z}{2},-\frac{z}{2}} \psi\left(-\frac{z}{2}\right) \right| P \right\rangle$$

$$q^{[-]}(x,k_\perp) \propto \left\langle P \left| \bar{\psi}\left(\frac{z}{2}\right) \mathcal{U}^{[-]}_{\frac{z}{2},-\frac{z}{2}} \psi\left(-\frac{z}{2}\right) \right| P \right\rangle$$

For naive T-odd distributions, $q^{[+]} = -q^{[-]}$: Sivers sign change

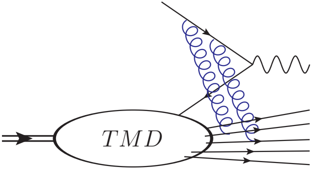
TMDs
The Sivers effect

SIDIS



Final state interactions: $q^{[+]}$

Drell-Yan



Initial state interactions: $q^{[-]}$

The Sivers distribution comes with a relative $-$ sign between SIDIS and Drell Yan: different gauge links for a naive T-odd quantity!

Heavy ion collision

Standard model of a collision

Particles Detection
$t \approx 10^{15} fm/c$

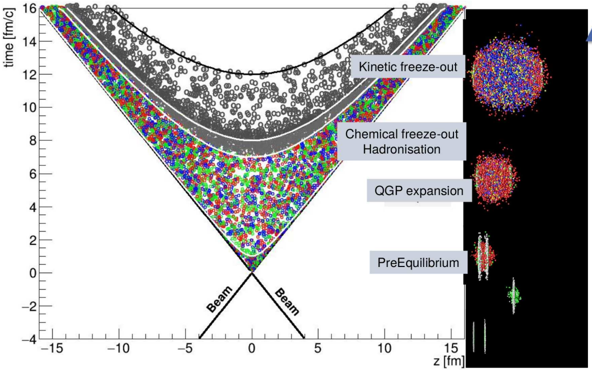
Kinetical freeze-out
$t \approx 10 fm/c$

Chemical freeze-out

Hydrodynamical evolution
$t \approx 0.5 fm/c$

Pre -hydrodynamization

Collision
$t = 0 fm/c$



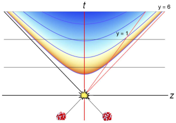
T ~ 90 MeV

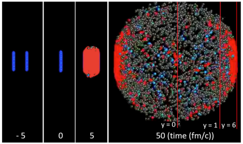
System cools down by (isentropic) expansion

T > 300 MeV

fixed proper time

fixed rapidity y





QGP drops

Heavy ion collision

Soft and hard probes

- soft part of the p_T spectrum: thermal distribution, hydrodynamical flow
- hard part: jets physics, quarkonia, etc.

In practice:
at LHC energies, 98% of particles are produced with $p_t < 2$ GeV
80% pions, 13% kaons, 4% protons

$\Rightarrow$ perturbative QCD inapplicable in most cases. This does not prevent theoretical approaches...

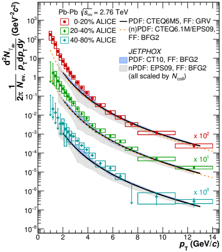
This is the main difference with the world of electromagnetic probes.

Heavy ion collision
QGP temperature

Spectrum of direct γ and γ^*

γ weakly interact with the QGP, thus their spectrum is governed by the beginning of the scattering

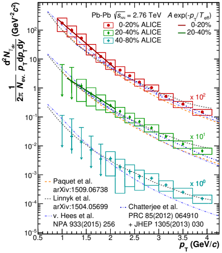
- hard photon contribution dominated by perturbative QCD



- excess in the low p_T spectrum of emitted γ during the hydrodynamical expansion of the QGP, for central collisions

$$\frac{dN}{dp_T} \approx \exp[-p_T/T]$$

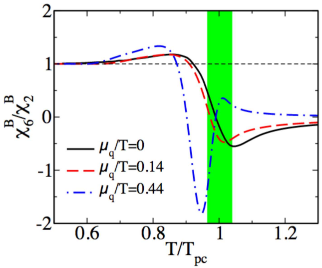
- $T = 297 \pm 12 \pm 41$ MeV LHC
  RHIC: $T = 220$ up to 240 MeV
- one can also study the spectrum of produced γ^* through the annihilation of $q\bar{q}$ pairs of the medium $\Rightarrow$ dileptons spectrum



Heavy ion collision
Chiral symmetry

Restoration of chiral symmetry

- lattice QCD:
  restoration of chiral symmetry $\leftrightarrow$ deconfinement:
  same temperature on the lattice, not expected from first principles
- verification/experimental test:
  chiral symmetry: event by event fluctuation of QCD conserved charges (nombre baryon number, strangeness, electric charge)



study of cumulants χ_n of $N_p - N_{\bar{p}}$ (skewness, kurtosis, ...)

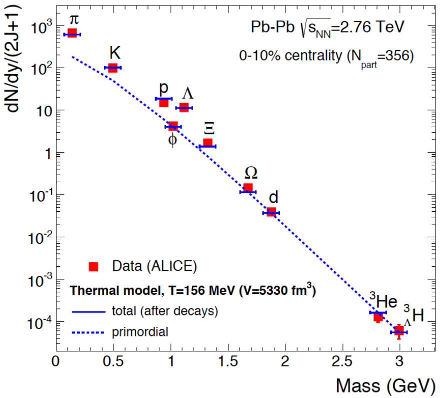
Experimental proof that these two temperature are identical
connection with the ρ-spectral function and the low-mass dilepton spectra

- connection with the ρ-spectral function, accessible through the low-mass dilepton spectra

Chemical equilibrium

Chemical equilibrium for the reaction products: excellent description, over 7 orders of magnitude, with T_{ch} of chemical freeze-out $\approx$ 156 MeV

$\Rightarrow$ extraction of T and μ_B by adjusting the Boltzmann distribution on the measured distribution of reaction products

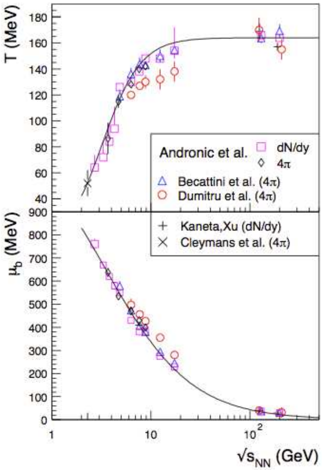


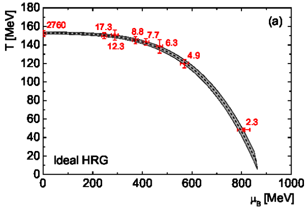
$$\frac{dN}{dy} \approx \exp[-m/T_{ch}]$$

(obtained from the partition function)

Heavy ion collision
Chemical equilibrium

Scan in T and μ_B through a scan in s_{NN}





s_{NN} in GeV

- the freeze-out line is observed
- at very high s, $T_{ch}|_{max} \simeq 160$ MeV close to the lattice QCD value
- frontiers
  - at high energie: LHC (CMS, ALICE, LHCb, ATLAS, NA-61)
  - at low energies: Beam Energy Scan (BES) program at RHIC and scan possible in the future at FAIR and NICA.

Heavy ion collision

Hydrodynamical treatment of QGP expansion

Relativistic hydrodynamics
Theoretical framework

- hypothesis: *local* thermodynamical equilibrium ($\neq$ global)

$$\begin{aligned} \partial_\mu T^{\mu\nu} &= 0 \quad \text{conservation of the energy-momentum tensor} \\ \partial_\mu j_B^\mu(x) &= 0 \quad \text{conservation of the baryon number} \end{aligned}$$

- 5 independent equations, 6 variables:
  - energy density $\epsilon(x)$
  - momentum density $P(x)$
  - fluid velocity $\vec{v}(x)$

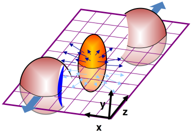
- key role of dissipative effects
  $\Rightarrow$ additional terms in the RHS, involving shear η and volume ζ viscosities
  gradient expansion around a local equilibrium

- valid in the limit $Kn = \frac{\ell_{mfp}}{R} \ll 1$:
  system size R large wrt mean free path ℓ_{mfp}.
  For a relativistic system, this amounts to:

$$\frac{1}{Kn} \sim Re \gg 1 \qquad \text{i.e. } \eta \text{ small: low-viscosity fluid}$$

Heavy ion collision

Flow and azimuthal anisotropy

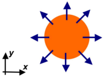


Relativistic hydrodynamics in action

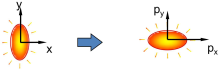
Azimuthal harmonics expansion:

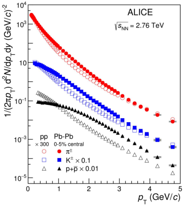
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right),$$

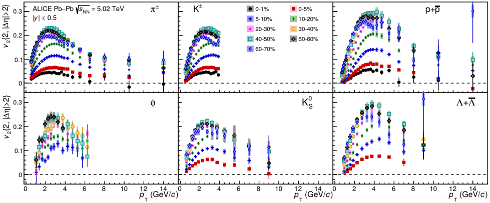
radial flow



elliptic flow







radial flow and elliptic flow v_2 are:

- maximal for medium centralities
- increase with m ($m_p > m_K > m_\pi$): boost effect: $p_T = \beta\gamma m$ with β universal
- large p_T-spectra gets more populated for central collisions

dileptons spectrum (both in p_T *and* $M_{\ell\ell}$) provides informations on these flows

Heavy ion collision

Flow anisotropy and viscosity measurement

- Elliptic flow dominated by contributions from early times of the scattering:
  - universal ratio $\frac{v_2}{n_q}$ $\Rightarrow$ sign of an initial compression of the system at quarks level and not at hadrons level near the final state
  - a simple hard partonic approach does not describe data

- comparison experiment/hydrodynamical simulations:

  v_2 diminishes when η/s increases

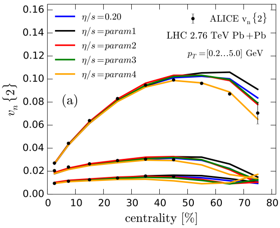
  (shear viscosity / entropy production rate) dissipation allows for a loss of memory of the initial geometry through the hydro. expansion

  models:

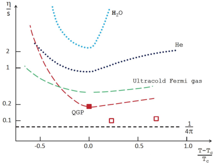
  pQCD + saturation + hydrodynamics

  $\Rightarrow$ η/s measurement:

  quasi perfect fluid



v_2 **(haut)**, v_3 **(milieu)**, v_4 **(bas)**



Heavy ion collision
Hydrodynamical approaches

Relativistic hydrodynamics
Applicability

various estimations provide

- the temperature for the QGP to exist

$$\ell_{mfp} \sim (2\ \text{fm}) \left(\frac{T_0}{T}\right)^3 \frac{\sigma_1}{\sigma}$$

  - T = QGP temperature
  - T_0 = 200 MeV   scale, $\neq T_{transition}$
  - σ = parton-parton cross-section
  - σ_1 = 1 mb

  $\Rightarrow$ for a heavy nucleus $R \sim 6 - 7$ fm
  $Kn \lesssim 0.1$ for T up to $\sim$ 200 MeV

- minimal size of a QGP drop
  - success of the azimuthal harmonics expansion for the flow
  - η/s very small: ℓ_{mfp} above is over-estimated

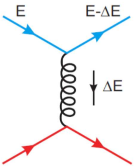
  $R_{QGP} \gtrsim 1$ fm

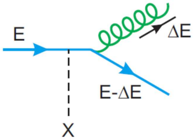
$\Rightarrow$ why not pp and pA?

Jet energy loss

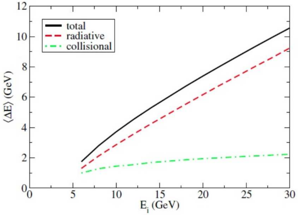
Two kinds of energy loss

BDMPS-Z, etc.

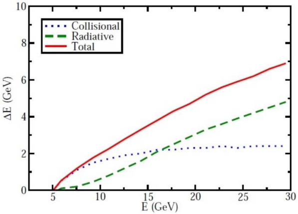




collision (dominates for low p_T) Bremstrahlung (dominates for large p_T)



light quark (RHIC, centrality 0-5%)



heavy quark (b) (LHC, centrality 0-7.5%)

radiation: dead cone effect at small p_T

Jet energy loss

Radiative loss

two key parameters:

- typical formation time of a $(parton\ g)$ pair: $\tau_f \sim 2\omega/k_\perp^2$
  $\omega, k_\perp$ = transfered energy, momentum)
- mean free-path of a parton in the medium: λ

two typical regimes:

- $\tau_f < \lambda$: independent multiple scatterings Bethe-Heitler
- $\tau_f > \lambda$: **non** independent multiple scatterings, quantum treatment
  $\Longrightarrow$ spectrum reduction wrt Bethe-Heitler $\Delta E \propto \alpha_S C_R \hat{q} L^2$
  L = longitudinal nucleon size, C_R = parton Casimir

the medium is characterized by transport coefficients

$$\hat{q} = \frac{d\langle \Delta q_T^2 \rangle}{dL}$$

= mean $(\text{momentum})^2$ transfer per length unit of crossed medium

Common features of the different theoretical approaches at one emission order:

- eikonal treatment:
  energies E (incoming parton) and ω (radiated gluon) $\gg q_\perp$ (momentum exchange with the medium)
- collinear approx.: $\omega \gg k_\perp$ (transverse momentum of the emitted gluon)
- spatial localization of the momentum transfer: $\lambda \gg \lambda_{Debye}$

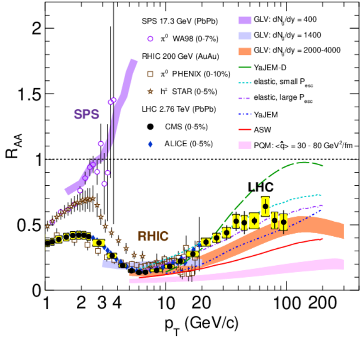
Energy loss

Observables

Single production of a hadron or a jet at large p_T

- nuclear modification factor

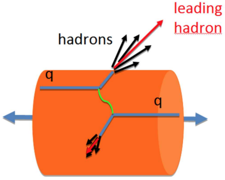
$$R_{AA}^{jet,hadron} = \frac{dN_{AA}^{jet,hadron}/dE_T dy}{N_{coll} dN_{pp}^{jet,hadron}/dE_T dy}$$



- R_{AA} strongly diminishes when crossing the nuclear medium in a central collision (0-5%)
- no analogous effect in pA

Energy loss

Observables
Correlation effects between jet/hadron/photon



Jet quenching

primary jet $p_{T,1} > 120$ GeV/c

secondary jet $p_{T,1} > 50$ GeV/c

- dijets asymmetry ratio:

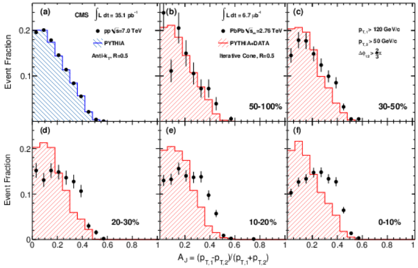
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

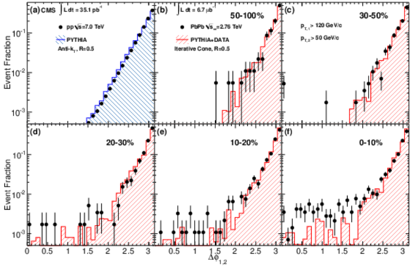
  - $p_{T,1} \approx p_{T,2} : A_J \approx 0$
  - $p_{T,1} \gg p_{T,2} : A_J \approx 1$

- relative azimuthal distribution

Significant effect for central collisions:

loss due to the QGP crossing





Evaporation of quarkonia

Shrinkage of strong interaction on $Q\bar{Q}$

- Case of Υ:
  - typical size of Υ resonances:

$$r(\Upsilon(1S)) < r(\Upsilon(2S)) < r(\Upsilon(3S))$$

  - typical range of shrinkage:

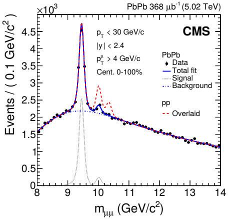
$$d_{Debye} \searrow \text{ when } T \nearrow$$

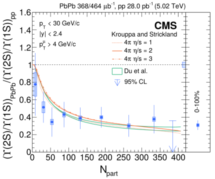
  - when T_{QGP} is such that

$$r(\Upsilon(1S)) < d_{Debye} < r(\Upsilon(2S)) < r(\Upsilon(3S))$$

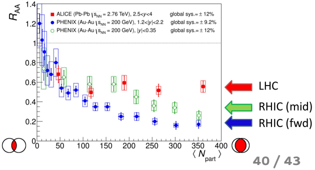
    evaporation of $\Upsilon(2S))$ and $\Upsilon(3S)$
    while $\Upsilon(1S)$ remains bounded.

    dependence wrt to collision centrality: effect of QGP





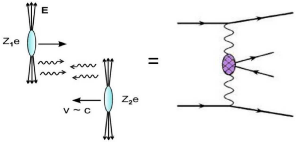
- J/Ψ:
  - additional effect:
    $c\bar{c}$ produced pairs in the medium: regeneration of J/Ψ during hadronization
  - weaker suppression at LHC than at RHIC!



Complementarity ep/eA and pp, pA, AA

Ultraperipheral collisions at LHC

A heavy ion is a high energy and intense source of photon:



large $A \Rightarrow$ large Z: strong electric charge

- Fourier transf.: large $b \longleftrightarrow$ small t:
  - suppression of hadronic echange contributions (pomeron, odderon, etc.)
  - dominance of the γ Coulomb peak
- provides an access to a large number of observables, in a new unexplored kinematical domain
  - exclusive processes: TCS, diffraction (meson, dijets, meson-γ, $\gamma\gamma$, quarkonia)
  - interface collinear regime / small x physics

Complementarity ep/eA and pp, pA, AA

pp, pA, AA: QCD phase diagram

besides QGP studies:

- pp, pA, AA collisions do not provide a direct access to the $(x,\, Q^2)$ plane
- multicolor exchanges very intricate
    - multi-parton interactions (MPI) (two simultaneous hard sub-processes)? sizable whenever:
        - the observables are more differential in p_T
        - parton distributions increase
    - CGC contributions very complex (two simultaneous strong field $\Rightarrow$ no simple factorization)
    - link between MPI (in collinear factorization) and CGC descriptions (high energy factorization) to be explored
        - per se, exist independently of QGP formation
        - mixes with other cold nuclear effects (nuclear PDFs, shadowing, etc.)
- it is a prerequisite to know nuclear PDFs and their dynamics in a wide kinematical range
- specific studies of initial states effects: Drell-Yan process

Complementarity ep/eA and pp, pA, AA

eA: multidimensional structure of nucleons and nuclei

eA : the probe is by definition well known
but no access to the phase diagram

- controllable access to gluonic saturation
  important in order to describe the initial state (CGC) before the formation of QGP in AA (and pA, pp)
- diffraction: one increases the number of independent kinematical variables
  $\Rightarrow$ multidimensional information
- correlations di-hadron, reduced uncertainties w.r.t. pA
- spin physics: possibility of polarizing both beams.