Heavy Ion Physics with CMS

LISHEP 2013
Universidade do Estado do Rio de Janeiro, Brazil

Dr. Magdalena Malek (UERJ)

on behalf of the

CMS Collaboration

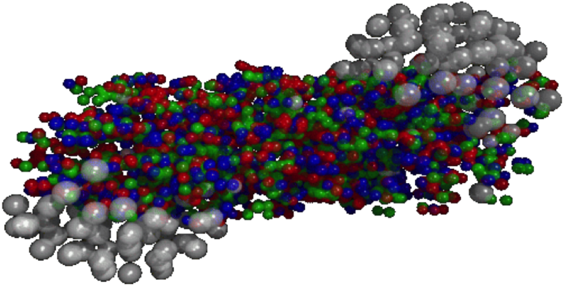
21/03/2013

Outline

- **Introduction :** QCD-reminder, detector, data taking and centrality
- **Pb+Pb** (selected) results
    - **global observables :** charged particle multiplicity, energy and transverse energy
    - **control probes :** isolated photons, electroweak bosons
    - **modified probes :** jet quenching, γ+jet, hadrons and jets R_{AA}, quarkonia
- **Summary**

Intro | Heavy Ion Physics...in one sentence

The main objective of Heavy Ion Collisions is to study the behavior of **matter under extreme condition**, to explore QCD phase diagram and to address the fundamental question of hadron confinement, which are related to the existence and properties of the **Quark-Gluon Plasma**

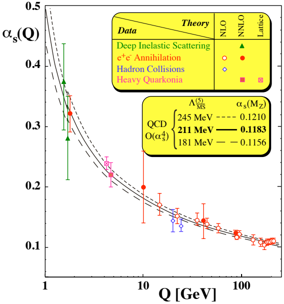


Intro | QCD reminder

- **fundamental** theory of the **strong** interaction: matter = quarks, interaction carriers = gluons
- evolution of **running coupling constant** α_s as a function of the energy scale Q^2

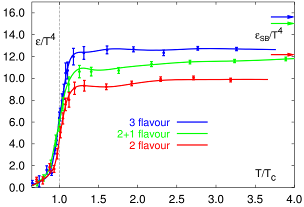
$\Rightarrow$Two **extreme** behaviors of the α_s:

- α_s increases when the energy Q^2 decreases
  $\hookrightarrow$ **confinement**
- α_s decreases when the energy Q^2 increases
  $\hookrightarrow$ **asymptotic freedom**



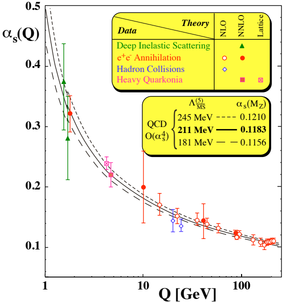
$\Rightarrow$ Lattice QCD:

- allows to treat the QCD in the **non-perturbative** regime
- predicts **deconfinement**: fast **variation** of the thermodynamical quantities during the phase transition
- **increase** in the number of **degrees of freedom** due to the liberation of quarks and gluons



Intro | QCD reminder

- **fundamental** theory of the **strong** interaction: matter = quarks, interaction carriers = gluons
- evolution of **running coupling constant** α_s as a function of the energy scale Q^2

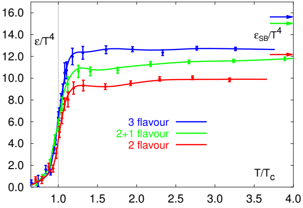


⇒Two **extreme** behaviors of the α_s:

- α_s increases when the energy Q^2 decreases
  $\hookrightarrow$ **confinement**
- α_s decreases when the energy Q^2 increases
  $\hookrightarrow$ **asymptotic freedom**

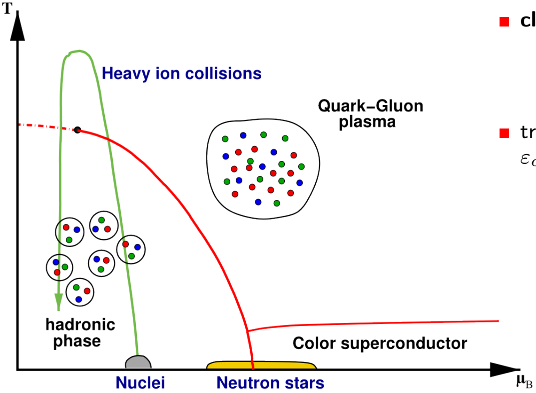
⇒ Lattice QCD:

- allows to treat the QCD in the **non-perturbative** regime
- predicts **deconfinement**: fast **variation** of the thermodynamical quantities during the phase transition
- **increase** in the number of **degrees of freedom** due to the liberation of quarks and gluons



can deconfinement be observed in laboratory?

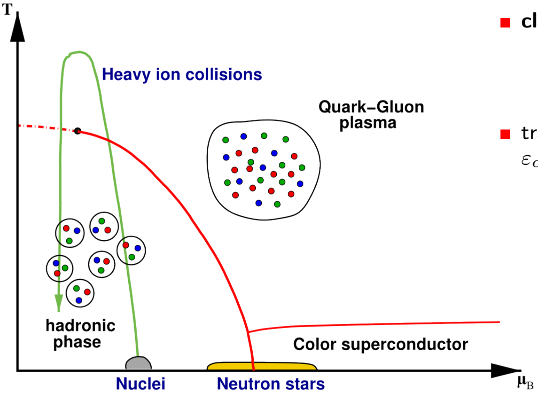
Intro | QCD phase diagram



- **classical** nuclear matter:
  - quark and gluons **confined** in hadrons
  - energy density $\varepsilon \approx 0{,}15$ GeV/fm^3
- transition to the **QGP** for: $\varepsilon_c \approx 1.0$ GeV/fm^3, T$_c \approx 150$ - 200 MeV

- **Q**uark-**G**luon **P**lasma: composed of **"colored"** matter: quarks and gluons can move **freely**
- the life time of the QGP is **very short** ($\sim 10^{-23}$ s): can't be observed directly

Intro | QCD phase diagram



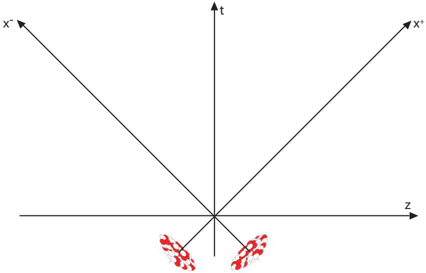
- **classical** nuclear matter:
  - quark and gluons **confined** in hadrons
  - energy density $\varepsilon \approx$ 0,15 GeV/fm^3
- transition to the **QGP** for: $\varepsilon_c \approx$ 1.0 GeV/fm^3, T$_c \approx$ 150 - 200 MeV

- **Q**uark-**G**luon **P**lasma: composed of **"colored"** matter: quarks and gluons can move **freely**
- the life time of the QGP is **very short** ($\sim 10^{-23}$ s): can't be observed directly

how can the QGP be created and studied?

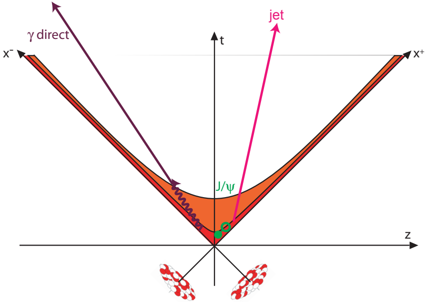
Intro | Evolution of the heavy ion collision

- $\tau < \mathbf{0}$ **fm/c** $\Rightarrow$ initial conditions: Lorentz contracted nuclei, gluon saturation
- $\tau \sim \mathbf{0}$ **fm/c** $\Rightarrow$ hard particles production: heavy quarks, jets, direct photons
- $\tau \sim \mathbf{0.2}$ **fm/c** $\Rightarrow$ semi-hard particles production: bulk of the reaction, $p_T \leq 2$ - 3 GeV
- $\mathbf{2} \leq \tau \leq \mathbf{10}$ **fm/c** $\Rightarrow$ Quark-Gluon Plasma
- $\mathbf{10} \leq \tau \leq \mathbf{20}$ **fm/c** $\Rightarrow$ Hadron gas
- $\tau > \mathbf{20}$ **fm/c** $\Rightarrow$ Freeze-out: chemical (density too small to have inelastic interactions), kinetic (no more elastic interactions)



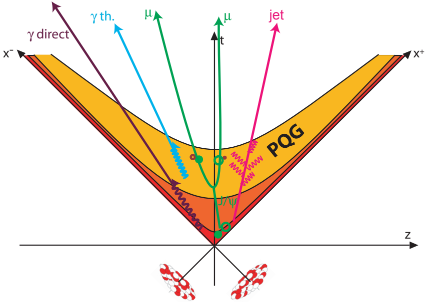
Intro | Evolution of the heavy ion collision

- $\tau < \mathbf{0}$ **fm/c** ⇒ initial conditions: Lorentz contracted nuclei, gluon saturation
- $\tau \sim \mathbf{0}$ **fm/c** ⇒ hard particles production: heavy quarks, jets, direct photons
- $\tau \sim \mathbf{0.2}$ **fm/c** ⇒ semi-hard particles production: bulk of the reaction, $p_T \leq 2 - 3$ GeV
- $\mathbf{2} \leq \tau \leq \mathbf{10}$ **fm/c** ⇒ Quark-Gluon Plasma
- $\mathbf{10} \leq \tau \leq \mathbf{20}$ **fm/c** ⇒ Hadron gas
- $\tau > \mathbf{20}$ **fm/c** ⇒ Freeze-out: chemical (density too small to have inelastic interactions), kinetic (no more elastic interactions)



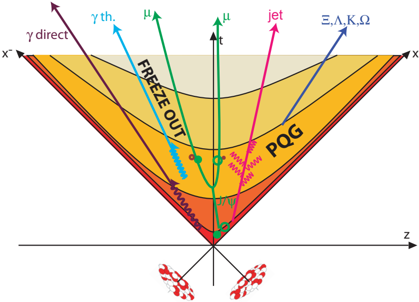
Intro | Evolution of the heavy ion collision

- τ < **0 fm/c** $\Rightarrow$ initial conditions: Lorentz contracted nuclei, gluon saturation
- $\tau \sim$ **0 fm/c** $\Rightarrow$ hard particles production: heavy quarks, jets, direct photons
- $\tau \sim$ **0.2 fm/c** $\Rightarrow$ semi-hard particles production: bulk of the reaction, $p_T \leq 2$ - 3 GeV
- **2** $\leq \tau \leq$ **10 fm/c** $\Rightarrow$ Quark-Gluon Plasma
- **10** $\leq \tau \leq$ **20 fm/c** $\Rightarrow$ Hadron gas
- τ > **20 fm/c** $\Rightarrow$ Freeze-out: chemical (density too small to have inelastic interactions), kinetic (no more elastic interactions)



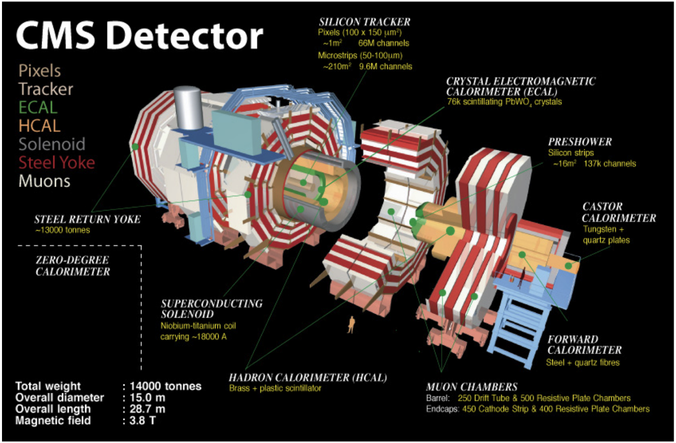
Intro | Evolution of the heavy ion collision

- τ **< 0 fm/c** ⇒ initial conditions: Lorentz contracted nuclei, gluon saturation
- $\tau \sim$ **0 fm/c** ⇒ hard particles production: heavy quarks, jets, direct photons
- $\tau \sim$ **0.2 fm/c** ⇒ semi-hard particles production: bulk of the reaction, $p_T \leq 2$ - 3 GeV
- **2** $\leq \tau \leq$ **10 fm/c** ⇒ Quark-Gluon Plasma
- **10** $\leq \tau \leq$ **20 fm/c** ⇒ Hadron gas
- τ **> 20 fm/c** ⇒ Freeze-out: chemical (density too small to have inelastic interactions), kinetic (no more elastic interactions)



each stage is characterized by specific observables !

Intro | CMS detector



- inner **tracking** system ($|\eta| < 2.5$)
- **calorimeters** (electromagnetic: $|\eta| < 3$, hadronic: $|\eta| < 5$)
- **muon** system ($|\eta| < 2.4$)
- **forwards** detectors (CASTOR: $-6.6 < \eta < -5.2$ and ZDC: $|\eta| > 8.3$)
- magnetic field of 3.8 T

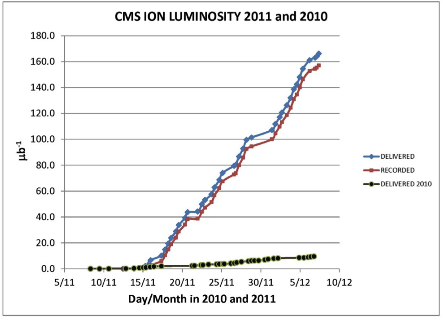
Intro | Data taking/centrality

- PbPb: $\sim$ 8.7 [150] μb^{-1} in 2010 [2011]
- pp (at 2.76 TeV): $\sim$ 230 nb^{-1} in 2011
- comparing PbPb results to pp reference

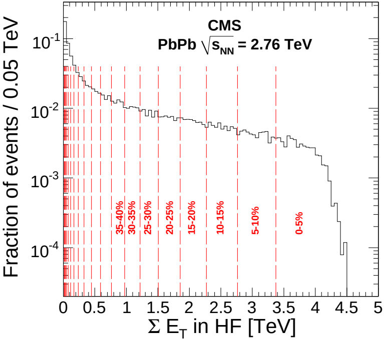
  $R_{AA} = \frac{1}{N_{coll}} \cdot \frac{N_{AA}}{N_{pp}}$

  N_{coll}: number of elementary NN collisions or

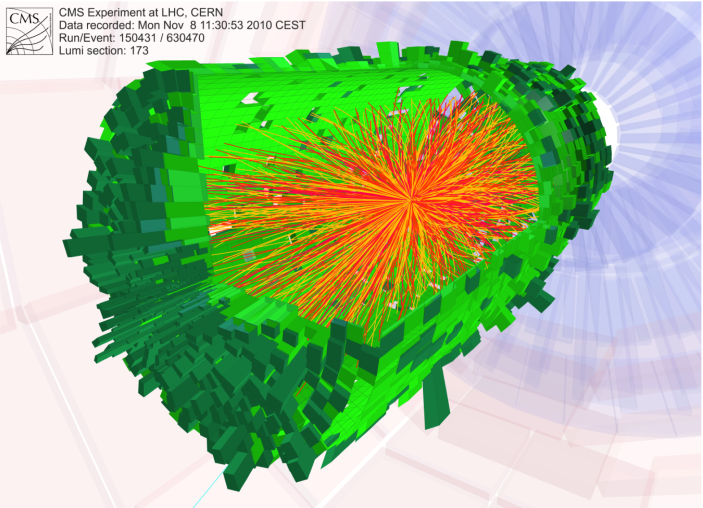
  $T_{AA} = N_{coll}/\sigma_{pp}$



- centrality concept: Pb ions are extended objects, particle production depends on the impact parameter
- reflects the geometrical overlap of the two colliding nuclei
- energy deposit in forward calorimeters



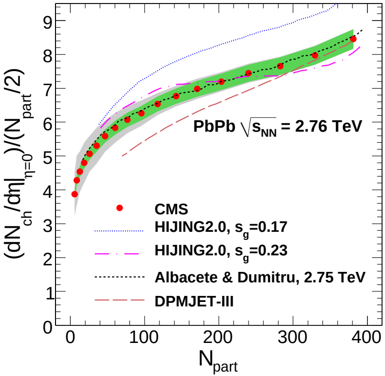
Intro | Event display

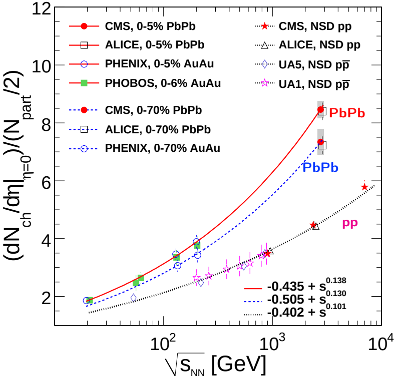


Global observables
↪ basic information on the created system

Global observables | Charged particles multiplicity [JHEP 08 (2011) 141]

- **hadron** rapidity **density** $\propto$ number of **initially** released **partons** at a given η: reduced multiplicity in saturation models

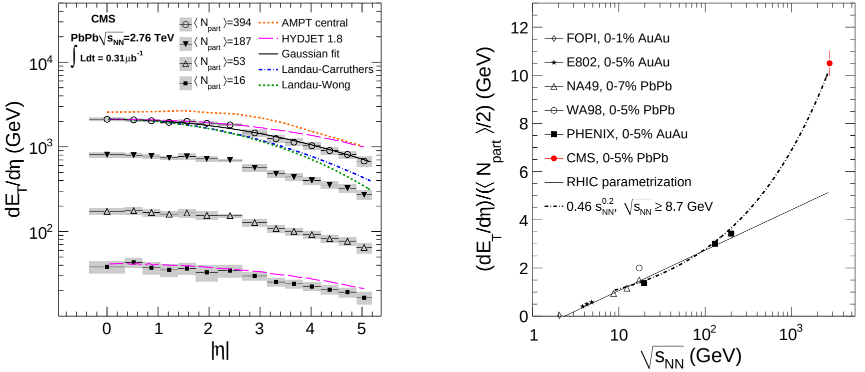




- charged hadron density for 0-5% collisions: 1612±55
- $dN_{ch}/d\eta$ is $\sim$ flat over $|\eta|$ <2.5 ($<$ 10% variation)
- similar N_{part} dependence for all $\sqrt{s_{NN}}$
- good description of the data by a parton saturation approach
- $\sqrt{s_{NN}}$ dependence follows power law behavior with exponent $s^{0.13}$

Global observables | Transverse energy [PRL 109 (2012) 152303]

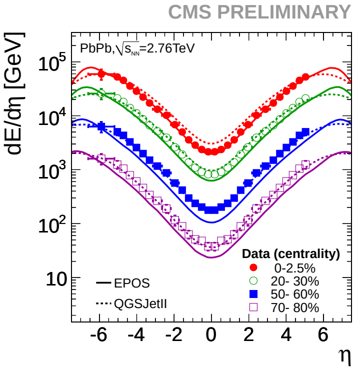
- initial distribution of partons (via N$_{part}$) and hydrodynamic flow that builds up after thermalization (via η); energy density via Bjorken's formula $\epsilon_{\rm BJ} = \frac{dE_T}{dy} \cdot \frac{1}{\tau_0 \pi R^2}$

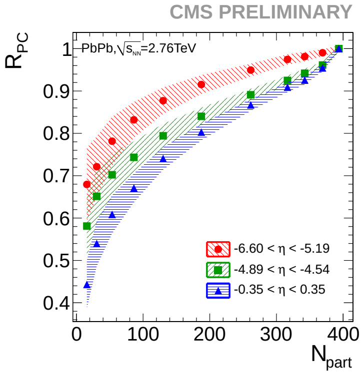


- $\sim$ 2.1 TeV at $\eta = 0$; at least 3 times larger than at RHIC
- shape consistent with a Gaussian with $\sigma_\eta = 3.4 \pm 0.1$: larger than predicted by Landau hydro but narrower than given by HYDJET; AMPT overestimates
- $(dE_T/d\eta)/(0.5\langle N_{part}\rangle)$ increases with N_{part} for all η
- for τ_0 = 1 fm/c and R = 7.1 fm: energy density of ≈ 14 GeV/fm^3
- for $\sqrt{s_{NN}} \geq$ 8.7 GeV, E_T at $\eta = 0$ reproduced by a power-law dependence $s^n_{\rm NN}$ with $n \approx 0.2$

Global observables | Energy [CMS-PAS-HIN-12-006]

- CASTOR coverage up to η=-6.6 (y_{beam} ~8); peak of the $dE/d\eta$
- HYDJET 1.8 and EPOS-LHC: good agreement for central data
- QGSJetII.3: describe better peripheral data; AMPT: quantitative agreement to the data



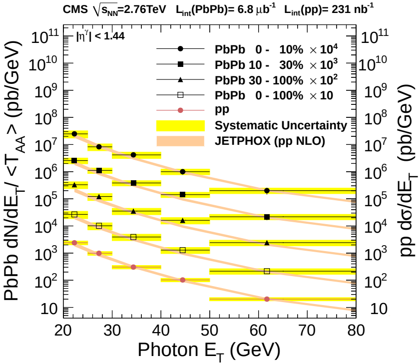


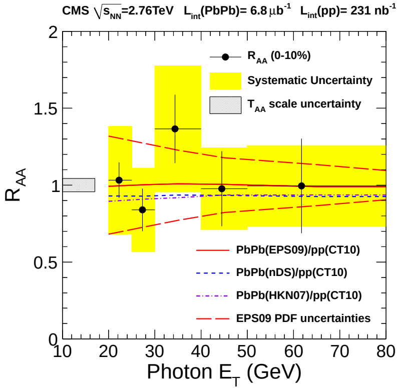
- $R_{pc} = \frac{\langle E\rangle(\eta, N_{part})}{\langle E\rangle(\eta, N_{part}^{max})} \cdot \frac{N_{part}^{max}}{N_{part}}$
- shape change in the forward η; flattening region for central events at high η
- data is challenging for models

Control probes
↪ **not affected by the medium**

Control probes | Isolated photons [PLB 710 (2012) 256]

- sources of high-p_T photons:
  - isolated (no hadronic activity): blind to the created medium
  - not-isolated (fragmentation, meson decay,...): affected by the medium
- first adaptation of p+p photon identification methods to heavy ion experiment

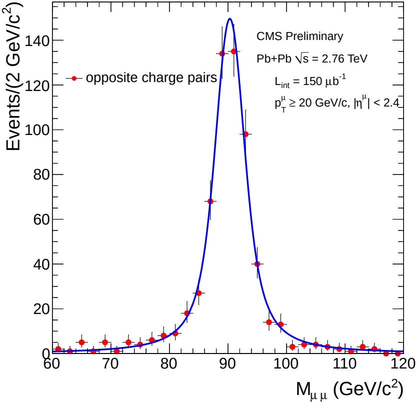


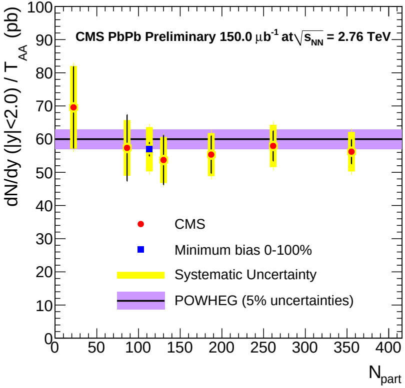


- consistent with the NLO calculation at all transverse energies (within uncertainties)
- R_{AA} vs E_T is flat
- no dependence of R_{AA} on N_{part}

Control probes | Z $\rightarrow \mu^+\mu^-$ [CMS-PAS-HIN-12-008]

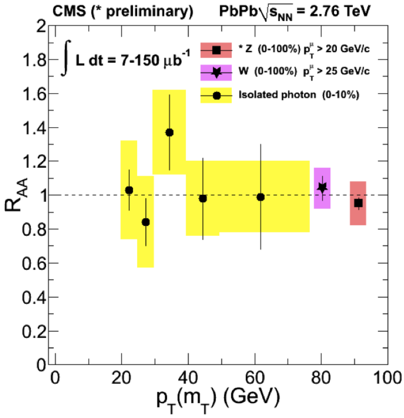
- for the mass range 60-120 GeV/c^2: 616 events with opposite-sign muons; no events with same-sign muons
- very low pp statistics for 2.76 TeV: comparison to POWHEG generator (well tested at Tevatron and LHC at 7TeV)





- R_{AA} = 0.95 ± 0.03 ± 0.13

Control probes | Electroweak bosons: summary

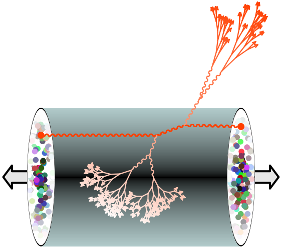


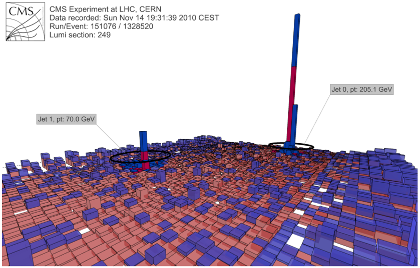
- also W $\rightarrow \mu\nu$ studies **[PLB 715 (2012) 66]**
- electroweak bosons are not affected by the medium (within uncertainties)
- confirmation of the validity of the binary (N_{coll}) scaling
- more precision: access to the nuclear PDFs

Modified probes
↪ **affected by the medium**

Modified probes | Jet quenching

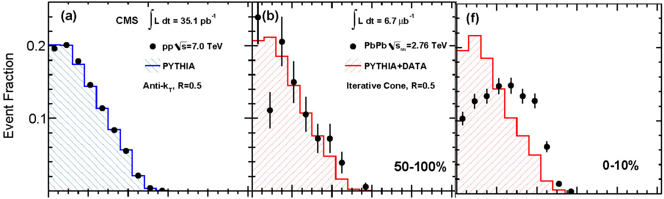
- jets are produced at the initial impact
- jets traveling through the QGP
  - energy loss: sensitive to the energy density of the medium, depends on the path length
  - azimuthal correlations between produced jets: for p+p or p+A peak at $\Delta\phi=180^\circ$
  - for A+A important modification of the azimuthal correlations: the away side jets are suppressed
- investigating modification of jets: very useful tool for probing the QGP properties



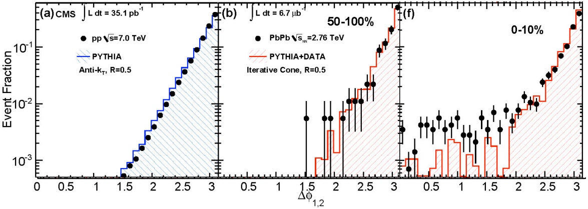


Modified probes | Jet quenching: calorimeter jets [PRC 84 (2011) 024906]

- dijet asymmetry: $A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$ ($p_{T,1}$ for leading, $p_{T,2}$ for sub-leading)
- here only calorimeter dijets: leading $p_T > 120$ GeV, sub-leading $p_T > 50$ GeV
- p_T imbalance (i.e. A_J) increases with the centrality

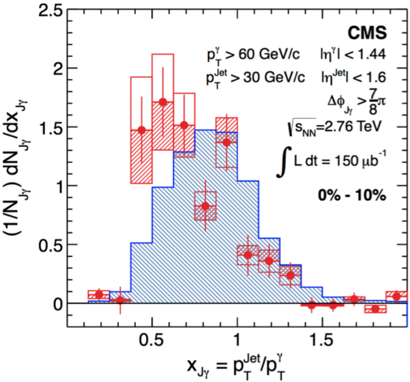


- azimuthal decorrelation $\Delta\phi_{1,2}$: back-to-back ($\Delta\phi_{1,2} \sim \pi$) for all centralities

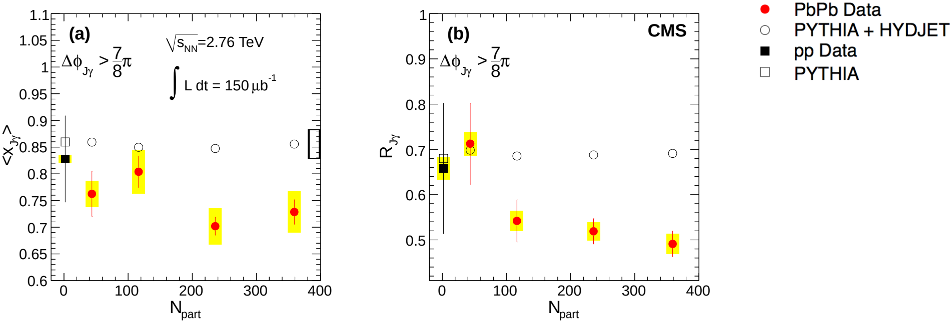


Modified probes | γ+jet [PLB 718 (2013) 773]

- at LO photons produced back-to-back with an associated parton (jet): $p_T^{\gamma} \sim p_T^{Jet}$
- transverse momentum balance $x_{J\gamma} = \frac{p_T^{Jet}}{p_T^{\gamma}}$
- when increasing the centrality of the collision
  - shift of the $x_{J\gamma}$ distribution towards lower values
  - reduction of the fraction of photons with an associated jet



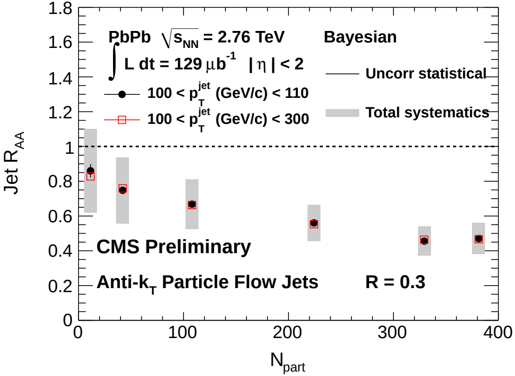
Modified probes | γ+jet [PLB 718 (2013) 773]



- average γ-jet p_T balance decreases by ~14% compared to pp
- fraction $R_{J\gamma}$ of γ with an associated jet partner drops by ~20%

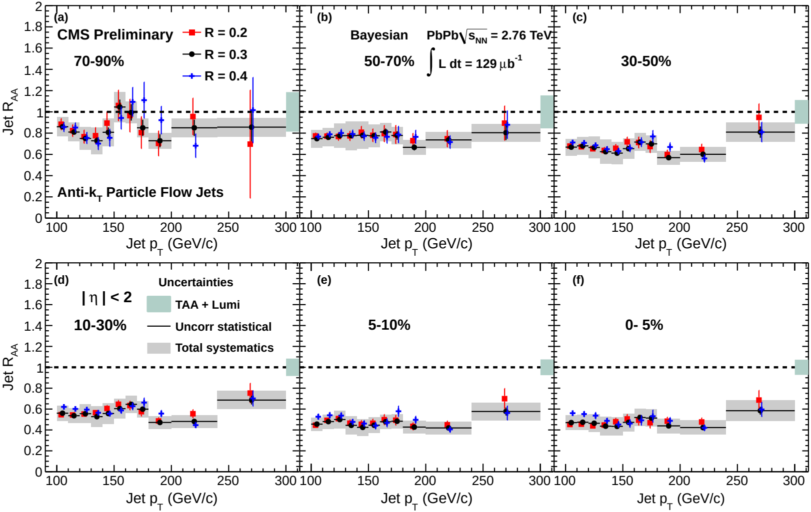
Modified probes | High p_T jets [CMS-PAS-HIN-12-004]

- online PbPb jet trigger threshold of 80 GeV/c; offline: $p_T > 100$GeV/c and $|\eta| < 2$



- suppression factor of ~0.5 in central PbPb when comparing to pp
- no suppression (within uncertainties) in the most peripheral PbPb
- R_{AA} is approximately independent of p_T in the measured range

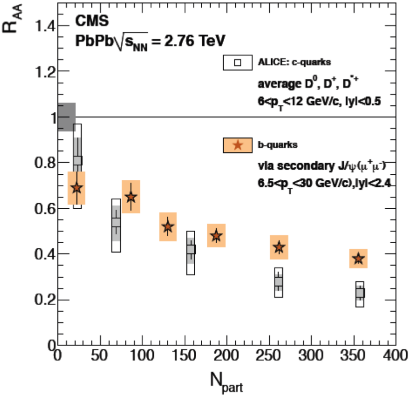
Modified probes | High p_T jets [CMS-PAS-HIN-12-004]



- no change in level of suppression due to jet cone size

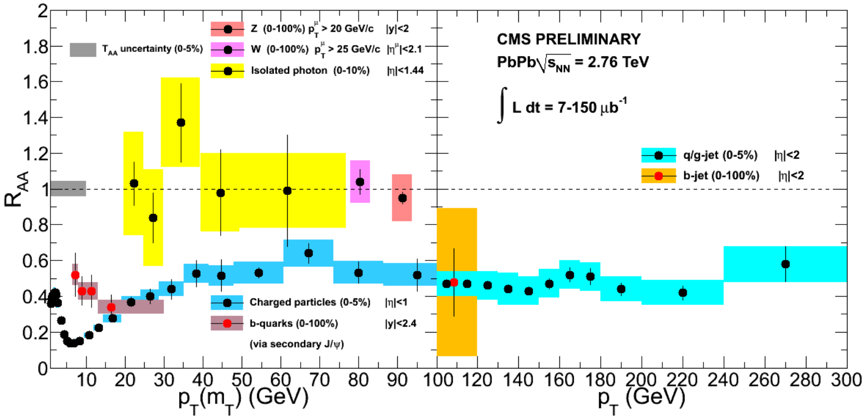
Modified probes | Open c and b [CMS-PAS-HIN-12-014; ALICE: arXiv:1205.6443]

- b from non-promt J/ψ: produced at large distance from the primary vertex; p_T <30 GeV/c
- the identification of J/ψ coming from B hadron decays relies on the measurement of a secondary $\mu^+\mu^-$ vertex displaced from the primary collision vertex. The distance between the $\mu^+\mu^-$ vertex and the primary vertex is measured in the plane transverse to the beam direction.
- D's from ALICE



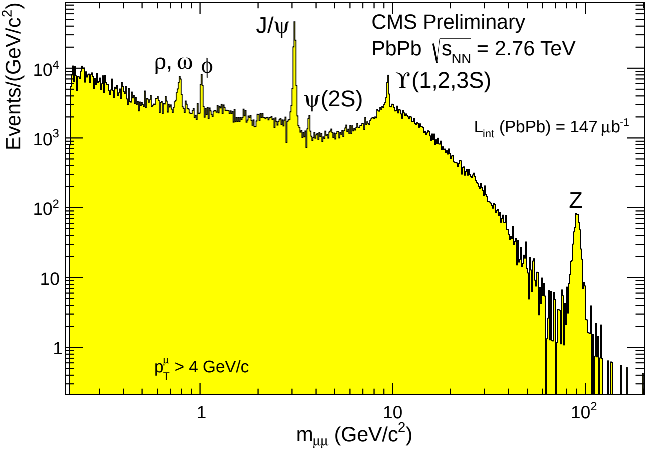
- in theory: energy loss depends on the quark mass
- $R^b_{AA} > R^c_{AA}$: b-quarks are less suppressed than c-quarks

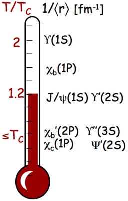
Modified probes | R_{AA}: summary



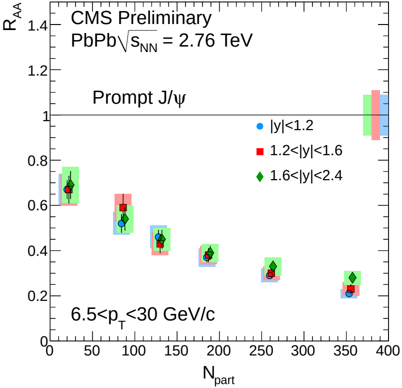
Modified probes | Quarkonia: di-muon spectrum

- **color screening** of static potential between heavy quarks
- quarkonia **melting** depending on the binding energy: **thermometer** of the medium





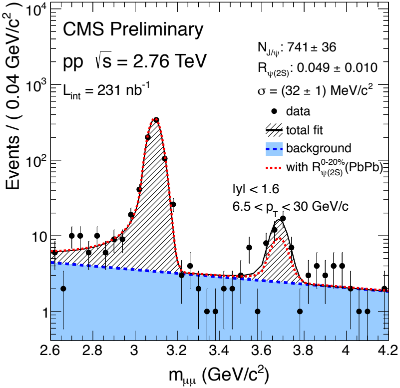
Modified probes | Prompt J/ψ [CMS-PAS-HIN-12-014]



- 6.5< p_T <30 GeV/c: no rapidity dependence
- central collisions: suppression by factor ∼5
- high y: low p_T suppressed less than high p_T

Modified probes | J/ψ and ψ(2S) [CMS-PAS-HIN-12-007]

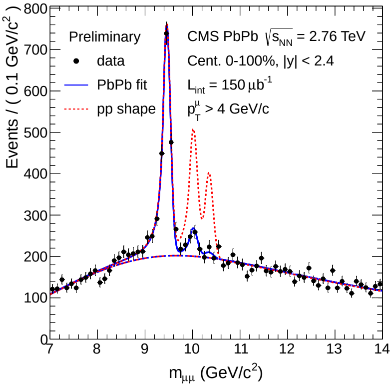
- first look at ψ(2S); raw ratios: $R_{\psi(2S)} = N_{\psi(2S)}/N_{J/\psi}$
- red curves: PbPb fit
- $|y|$ <1.6 and 6.5< p_T <30 GeV/c

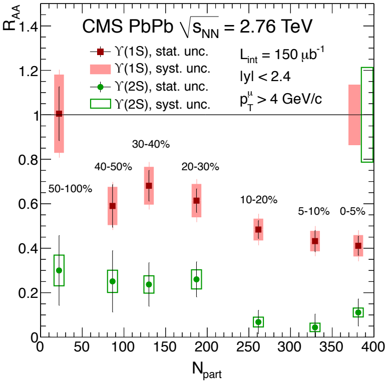


- relatively less ψ(2S) than J/ψ
- $R^{PbPb}_{\psi(2S)} \sim$ 0.5 $R^{pp}_{\psi(2S)}$

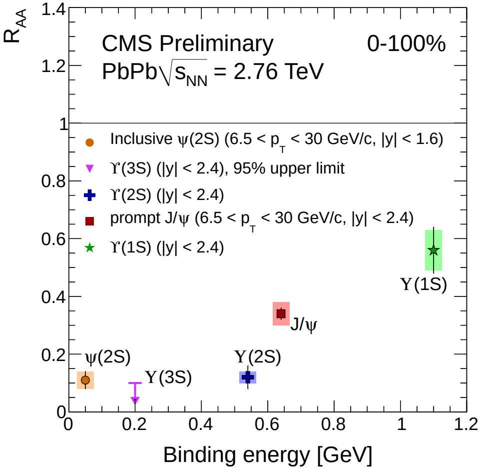
Modified probes | Υ family [PRL 109 (2012) 222301]

- excellent mass resolution ($\sim$1%): clear separation; acceptance down to $p_T = 0$ GeV/c
- centrality-integrated $R_{AA}(\Upsilon(nS))$





- $R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08 \pm 0.07$
- $R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04 \pm 0.02$
- $R_{AA}(\Upsilon(3S)) <$0.1 (95% CL)
- ordered suppression



- centrality-integrated R_{AA} vs binding energy seems ordered: looser bound states are more suppressed
- but has to be done with more data: centrality dependence, feed-down contributions, cold nuclear matter effects (pA)

Summary

- Pb+Pb data taking periods were very successful !
- CMS collected a significant amount of data

thanks to CERN for fantastic LHC performance!

- detailed measurements of global properties of medium in Pb+Pb collisions
- measurement of control probes (γ, Z and W): unmodified as expected
- jet quenching ... including b !!!
- quarkonium suppression
- and much more results not discussed here :
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN