ECFA High Luminosity LHC Experiments Workshop
Aix-les-Bains, Oct 1-3, 2013

Heavy Ion Physics prospects at HL-LHC

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thanks to: PG1 (A. Nisati, C. Hill, …),
B. Cole and A. Milov (ATLAS), P. Braun-Munzinger (ALICE),
C. Roland & J. Velkovska (CMS), B. Schmidt (LHCb)

Outline

- Introduction
- Timeline of HI running
- HI Physics programme at HL-LHC
- Summary

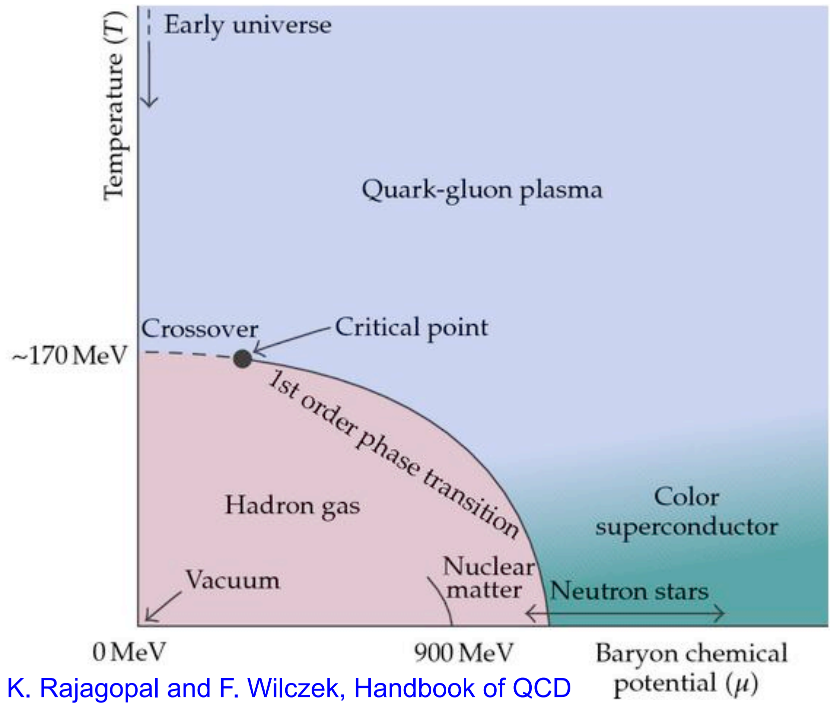
- Besides Pb-Pb: pp reference, pA, light ions

→ Next talk by J.Wessels

Heavy Ion Physics: the Little Bang in the laboratory

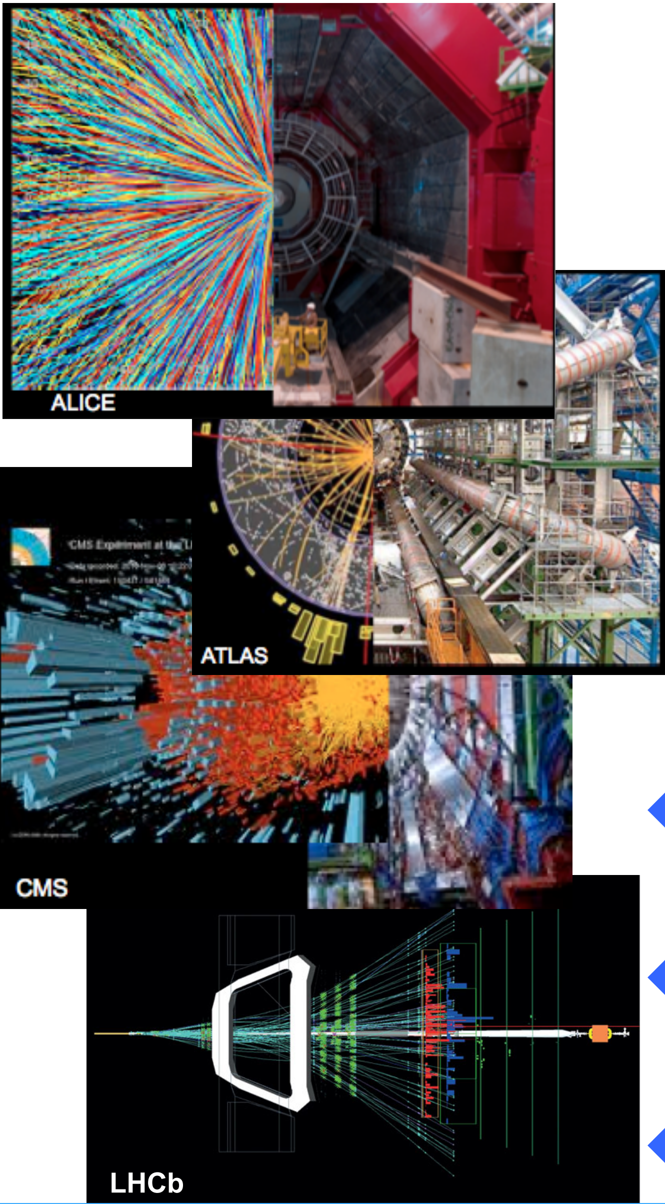
- Explore the deconfined phase of QCD matter
- **High-energy nucleus-nucleus → large energy density** (~15 GeV/fm^3 at LHC) over a **large volume** (~ 5000 fm^3 at LHC)

QCD Phase Diagram



K. Rajagopal and F. Wilczek, Handbook of QCD

Heavy Ions at the LHC: Run I



year	system	$\sqrt{s_{NN}}$ (TeV)	L_{int}
2010	**Pb-Pb**	**2.76**	**~ 10 μb^{-1}**
2011	pp	2.76	~ 250 nb^{-1}
2011	**Pb-Pb**	**2.76**	**~ 150 μb^{-1}**
2013	p-Pb	5.02	~ 30 nb^{-1}
2013	pp	2.76	~ 5 pb^{-1}

- 2011 Pb-Pb run: $5x10^{26}$! already above nominal luminosity
- First, very successful, p-Pb run (with all four large exp!)
- Two short pp reference runs at Pb-Pb $\sqrt{s}$

Heavy Ions at the LHC: Run 2

- Run 2 (LS1→LS2):
  - Pb-Pb ~1/nb or more, at $\sqrt{s_{NN}}$ ~ 5.1 TeV
  - p-Pb (at increased luminosity?)
  - pp reference at Pb-Pb energy (5.1 TeV)

- Goals (in short):
  - x5-10 times larger statistics: improve precision of current measurements, explore new observables
  - Extend Run 1 measurements to ~5 TeV (energy dependence)
  - But several measurements require 10/nb (*see following slides*)

Heavy Ions at the LHC: Runs 3, 4

- LS2: major ALICE and LHCb upgrades, important upgrades for ATLAS and CMS, LHC collimator upgrades

→ HL-HI-LHC = Runs 3+4

- Runs 3+4:
  - Experiments request: >10/nb Pb-Pb (ALICE: 10/nb at 0.5T + 3/nb at 0.2T)
  - p-Pb high lumi, pp reference 5.5 TeV, possibly light ions (e.g. Ar-Ar)
- HL-LHC: focus on rare probes, study their coupling with QGP medium and their (medium-modified) hadronization process

Requires: upgraded detectors, very large statistics, diverse trigger approaches, complementary strengths of the experiments

→ See exp's talks in the morning session

HL-LHC Programme

(not exhaustive!)

- **Jets:** characterization of energy loss mechanism both as a testing ground for the multi-particle aspects of QCD and as a probe of the medium density
  - Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high p_T (focus of **ATLAS** and **CMS**)
  - Flavour-dependent in-medium fragmentation functions (focus of **ALICE**)

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  - Multi-differential studies of Υ states (focus of **ATLAS** and **CMS**)

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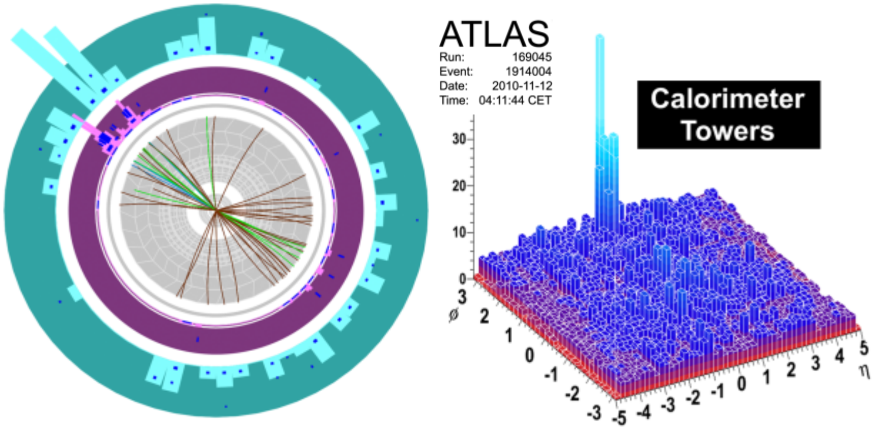
- **Low-mass di-leptons:** thermal radiation γ ($\rightarrow$ e^+e^-) to map temperature during system evolution; modification of ρ meson spectral function as a probe of the chiral symmetry restoration
  - (Very) low-p_T and low-mass di-electrons and di-muons (**ALICE**)

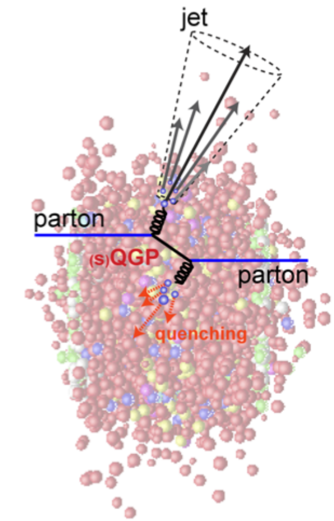
Jet quenching

- Pb-Pb events with large di-jet imbalance

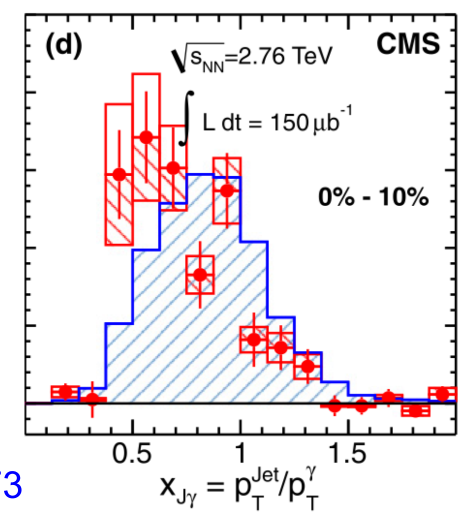


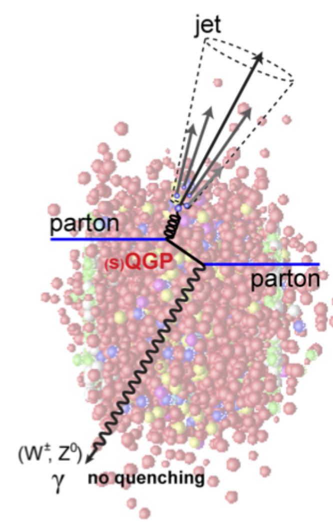
Direct observation of in-medium parton energy loss

ATLAS, PRL105 (2010) 252303
CMS, PLB712(2012) 176



- A powerful tool: γ/Z-jet correlations
  - $E^{\gamma/Z} = E^{\mathrm{jet}}$!
  - First measurement of γ-jet p_T imbalance p_T^{Jet}/p_T^{γ}

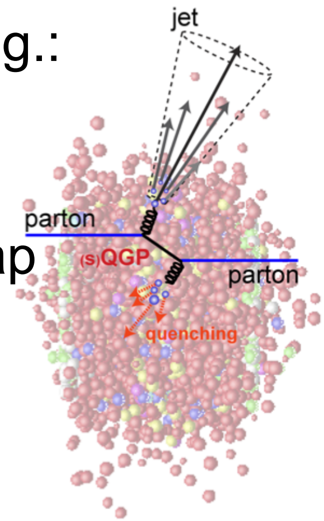


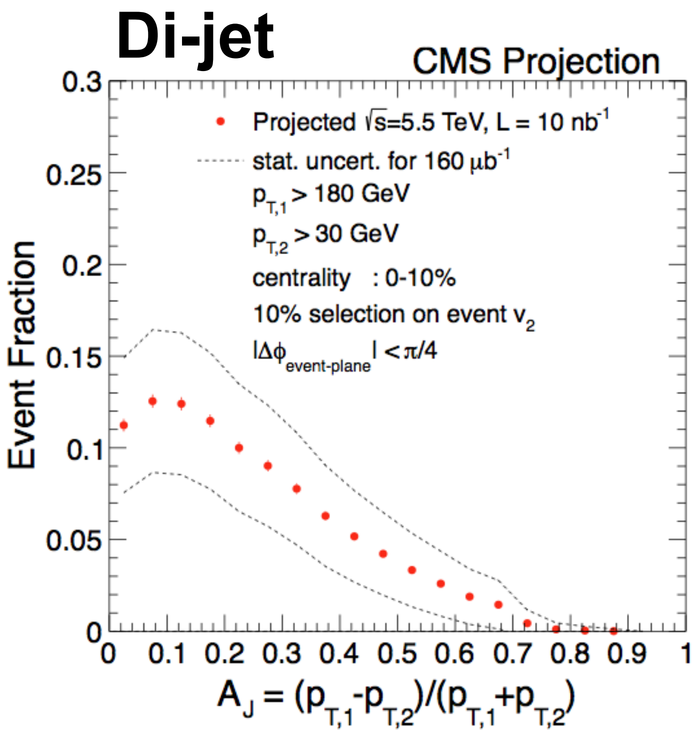


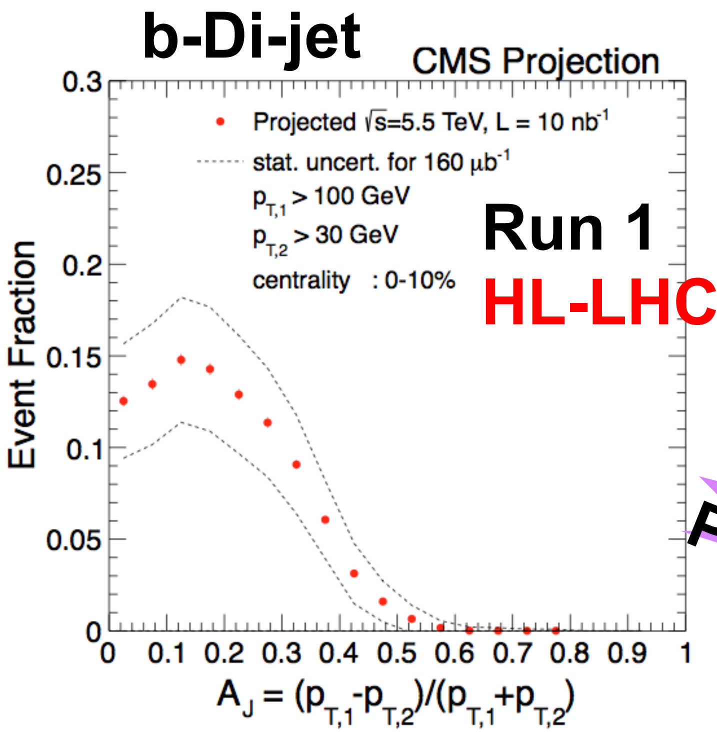
CMS, PLB718 (2013) 773

Jets: performance

- High precision γ-jet, Z-jet, di-jet correlations, also with b-jets. E.g.:
  - 10M di-jets with $p_{T,1}$>120 GeV/c (CMS, 10/nb)
  - 140k b-jets with p_T > 120 GeV/c (CMS, 10/nb)
- Understand medium response and energy radiation details, map path-Length dependence (e.g. radiative ~L^2, collisional ~L)







HL-HI-LHC Performance

CMS, PAS-FTR-13-025

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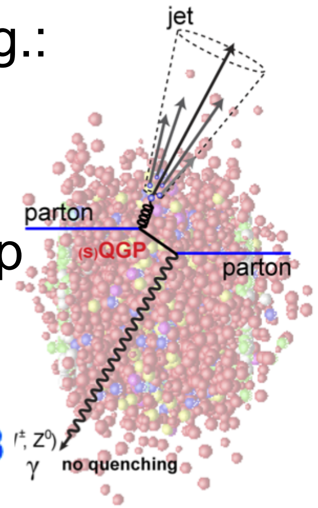
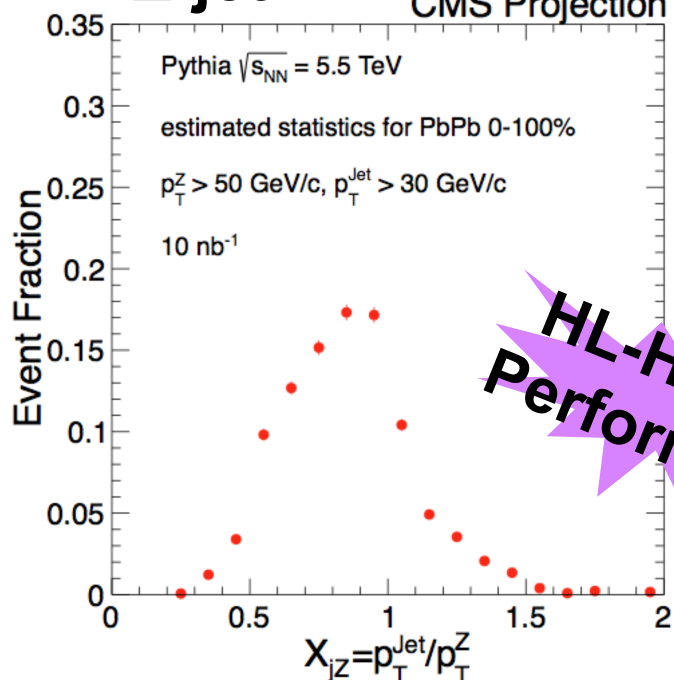
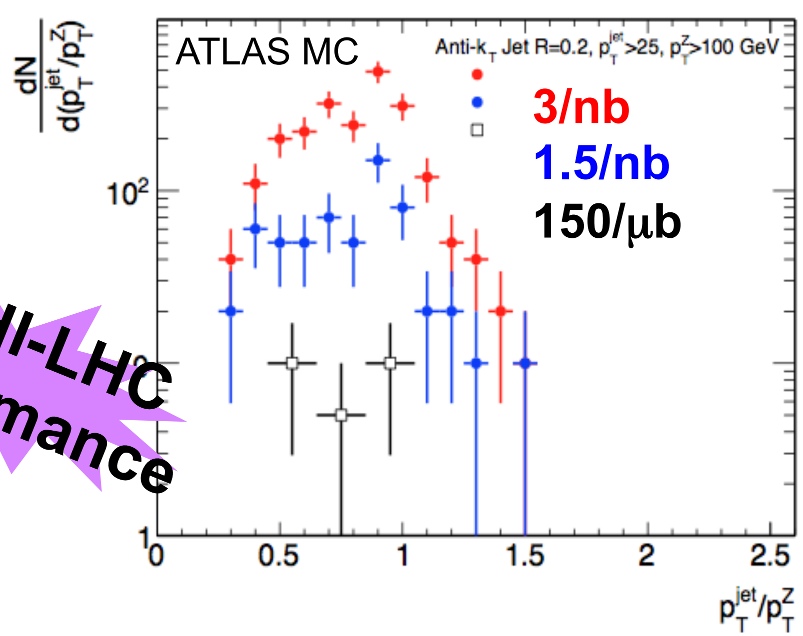


Z-jet



p_T^Z > 100, p_T^{jet} > 25 GeV, Δφ > 7π/8

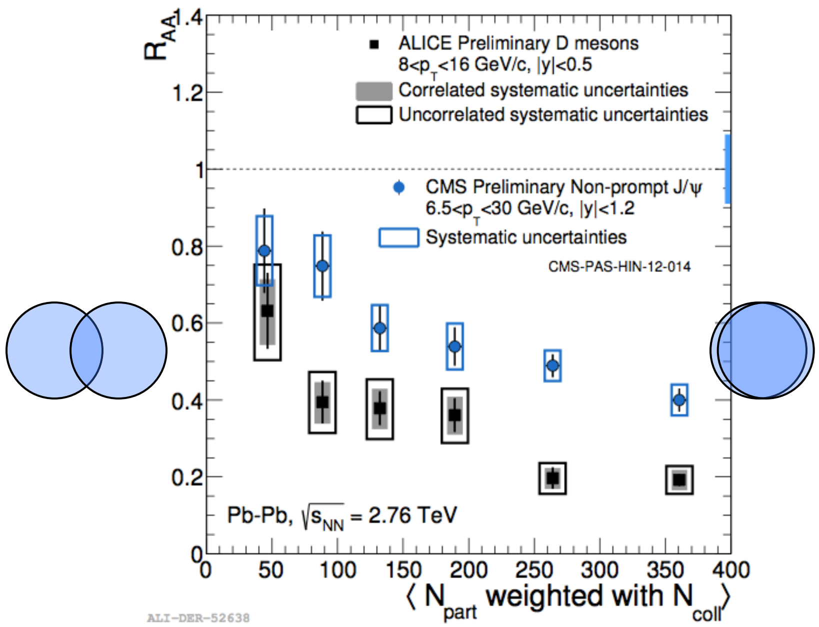


CMS, PAS-FTR-13-025

Heavy quark probes of the medium

- Energy loss expected to depend on parton mass
- First indication at LHC:

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



$R_{AA}{}^{B}$ (CMS) > $R_{AA}{}^{D}$ (ALICE)

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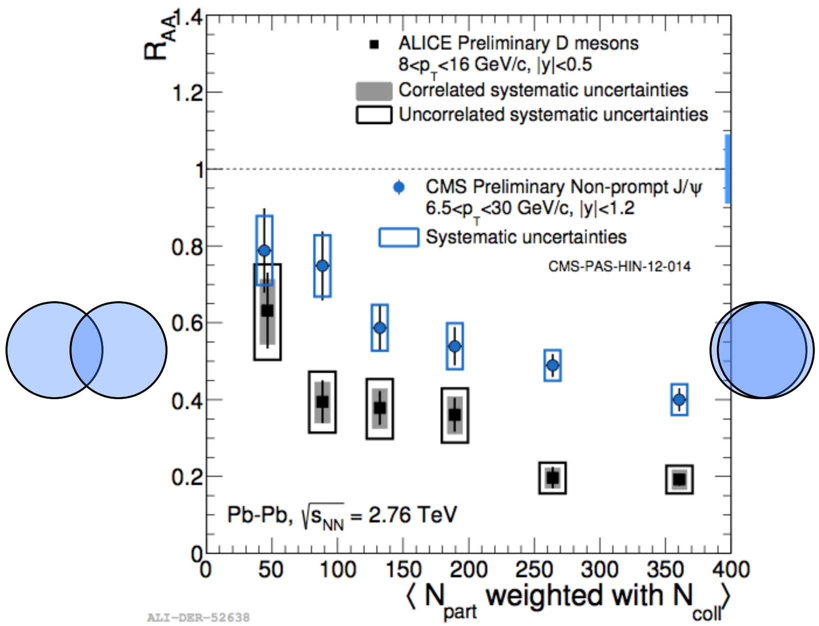
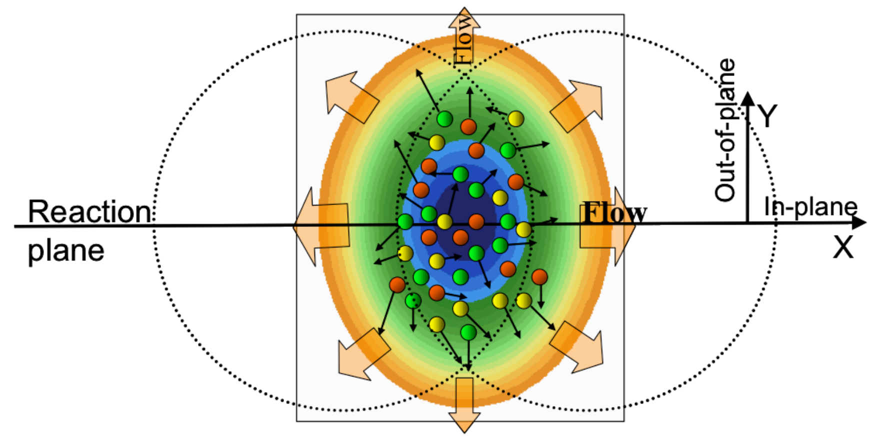


R_{AA}^{B} (CMS) > R_{AA}^{D} (ALICE)

- Azimuthal anisotropy v_2
  - strength of collectivity
  - mean free path of partons



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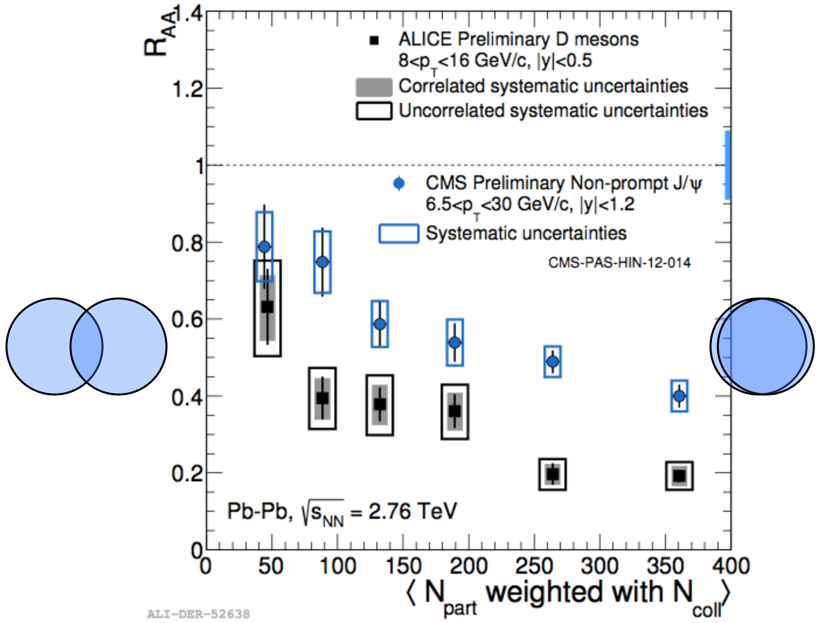
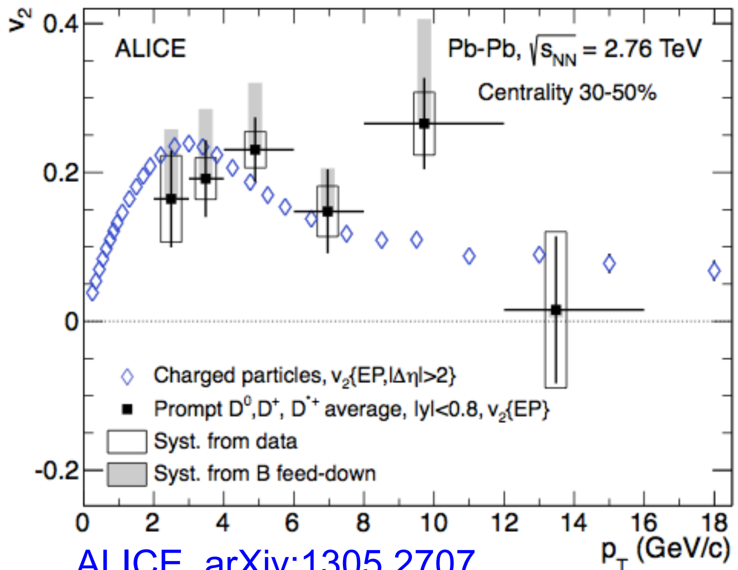


R_{AA}^{B} (CMS) > R_{AA}^{D} (ALICE)

- Azimuthal anisotropy v_2
  - strength of collectivity
  - mean free path of partons
- Charm hadrons have v_2>0, comparable to light hadrons



ALICE, arXiv:1305.2707

- Heavy quark collective flow?

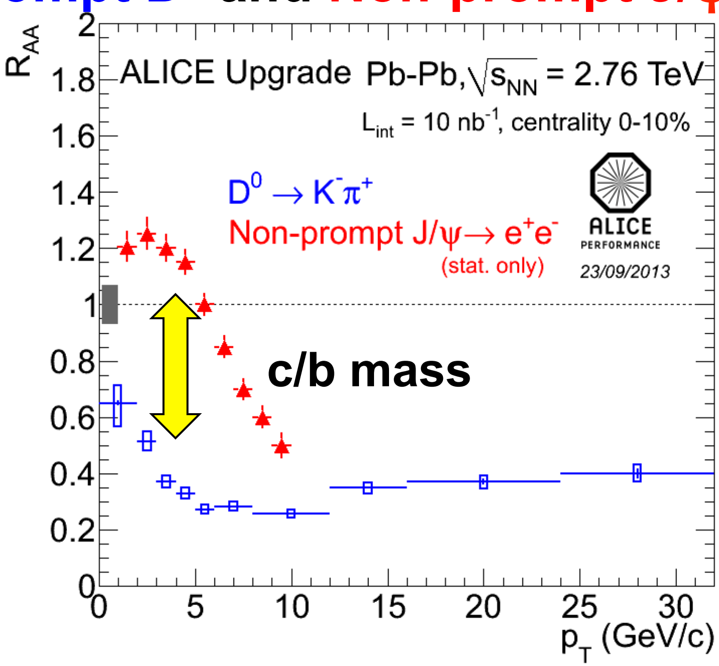
HF suppression and flow: performance

HL-LHC → exploit the potential of HQ as probes the in-medium interactions and of its thermalization

- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

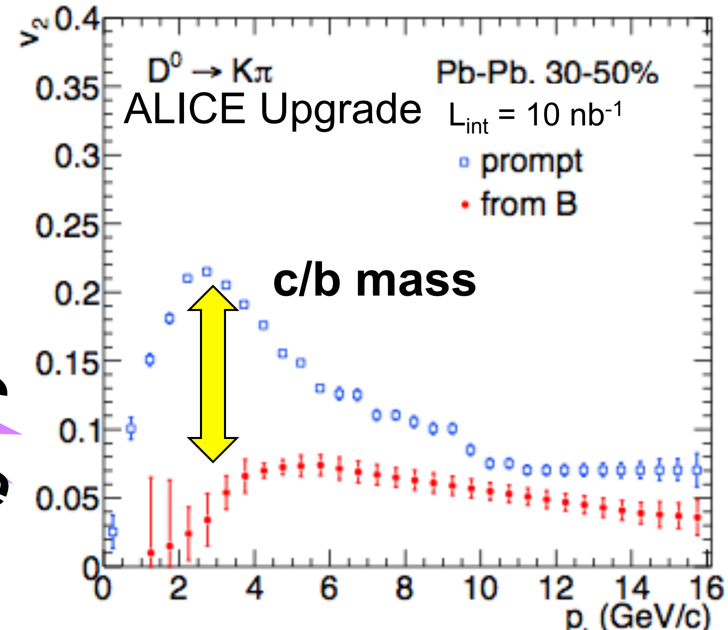
→ R_{AA} and v_2 of D and B in a wide p_T range

Prompt D^0 and Non-prompt J/ψ R_{AA}



HL-HI-LHC Performance

Prompt and non-prompt D^0 v_2



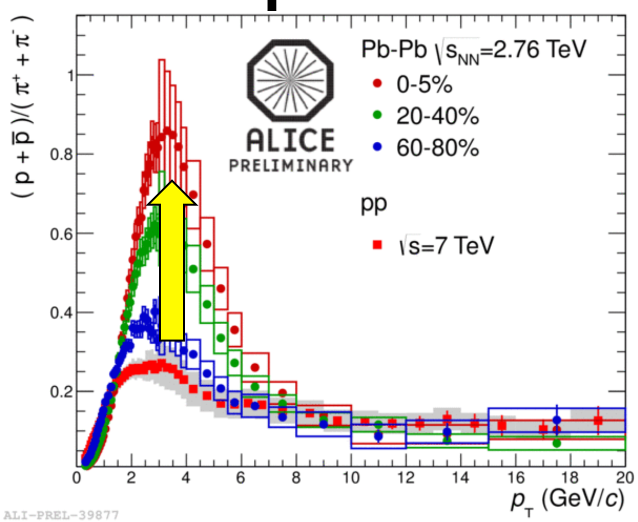
Input values from BAMPS model:
C. Greiner et al. arXiv:1205.4945

ALICE, CERN-LHCC-2012-012

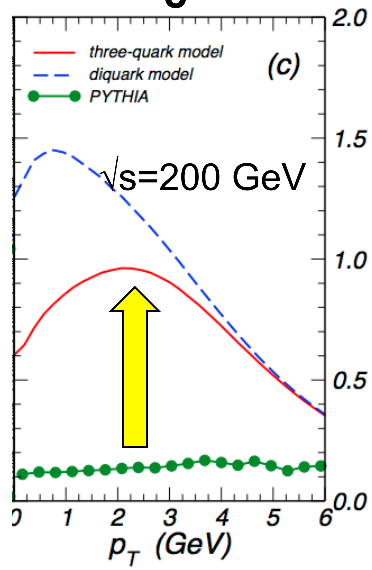
Heavy flavour in-medium hadronization?

- Baryon/meson enhancement and strange-enh. → most direct indication of light-quark hadronization in a partonic system
  - Measure this in the HF sector! Does it hold for charm?
  - Charm baryons (Λ_c) and charm-strange mesons (D_s)

p/π

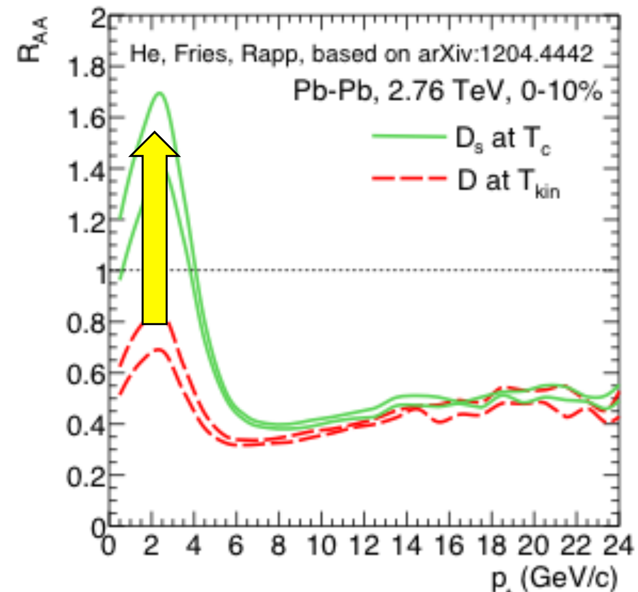


Λ_c/D



Ko et al. PRC79

D_s vs D

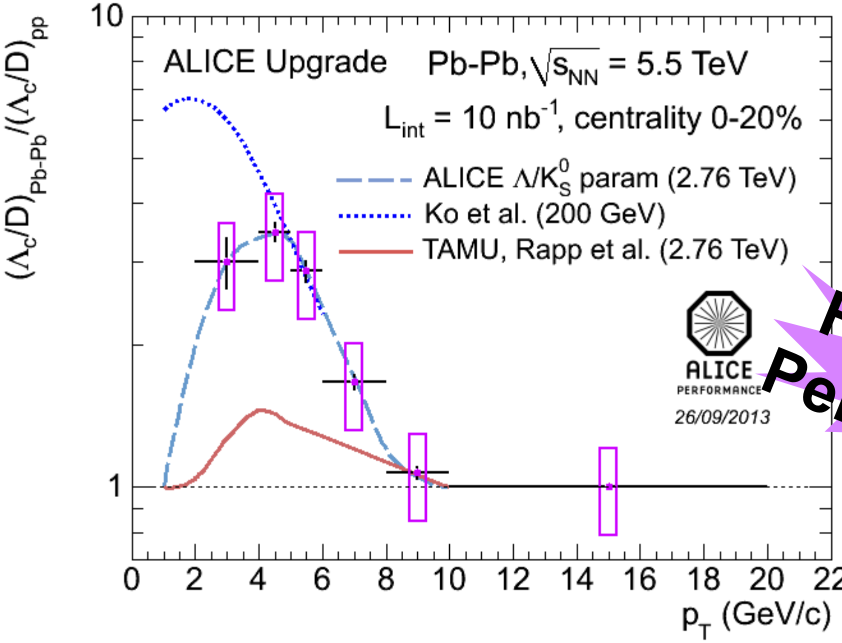


Rapp et al. arXiv:1204.4442

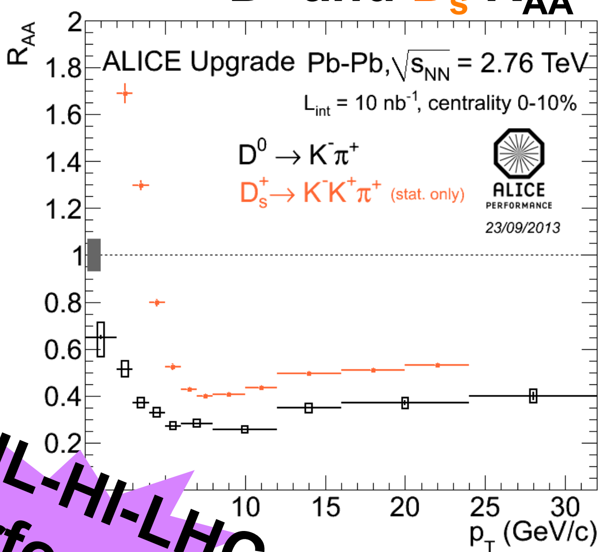
Low-p_T charm: performance

- $\Lambda_c \rightarrow pK\pi$ and $D_s \rightarrow KK\pi$ ($c\tau$=60 and 150 μm) measured with good precision in ALICE with upgrades and 10/nb

Λ_c/D enhancement
(full detector sim.)

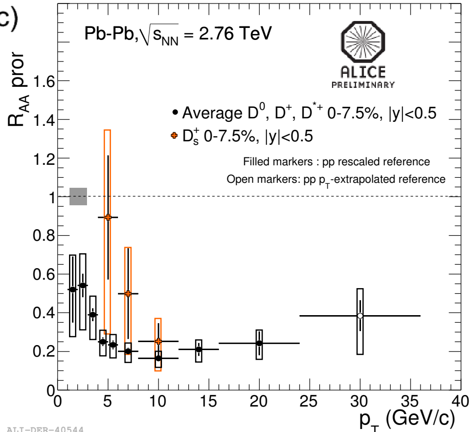


D^0 and D_s R_{AA}



HL-HI-LHC Performance

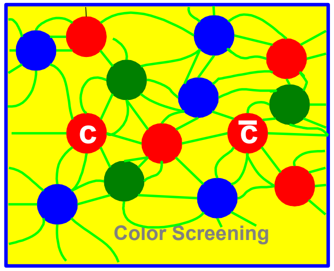
2011 data

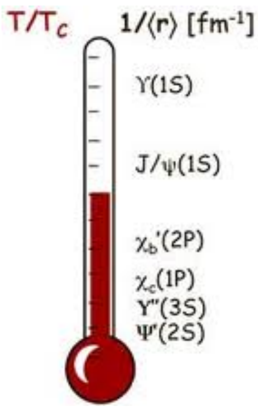


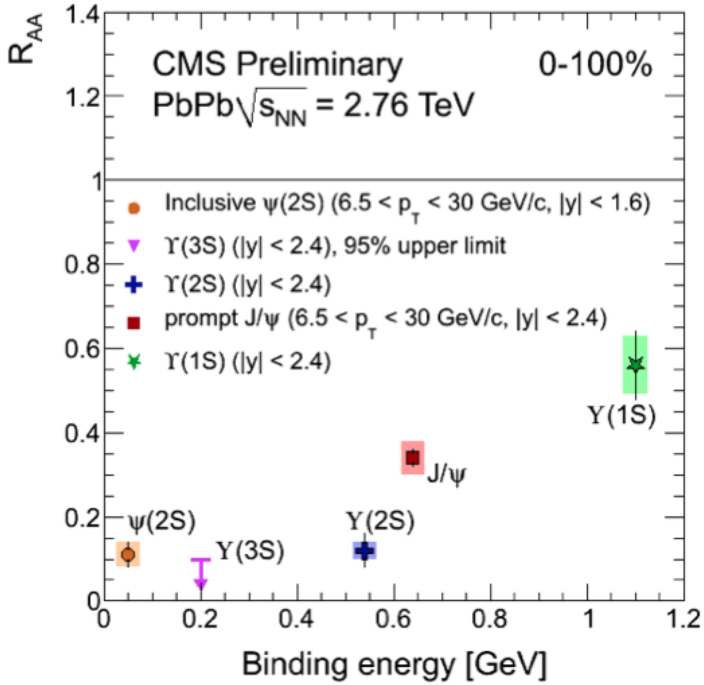
Needs minimum-bias trigger (low S/B)
→ HL-LHC = 100x Run2 stat.

Quarkonium suppression

- Quarkonium sequential dissociation: direct probe of deconfinement and of the medium temperature
- First hint of sequential pattern







High statistics → precise multi-differential measurements
E.g. (CMS, 10/nb):

ϒ(1s)	ϒ(2s)	ϒ(3s)
270k	40k	7k

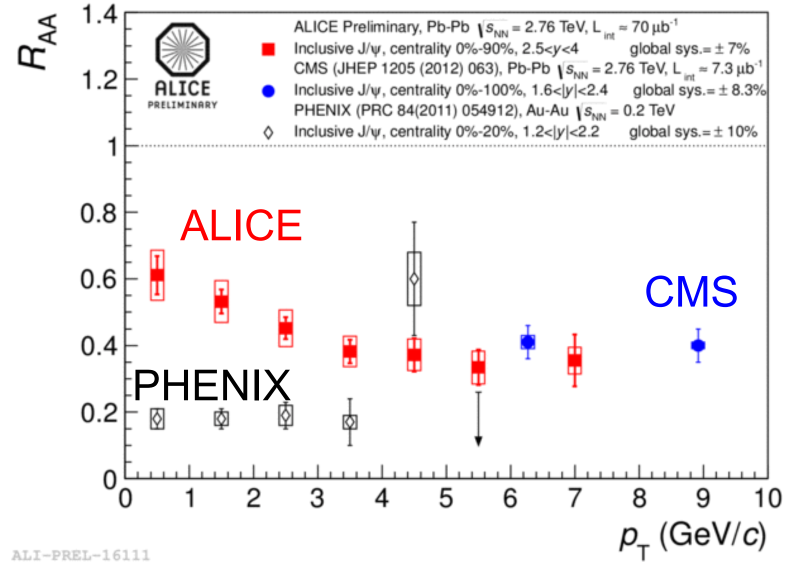
CMS, arXiv:1208.2826 and PRL 109 (2012) 222301

CMS, PAS-FTR-13-025

Low-p_T charmonium: performance

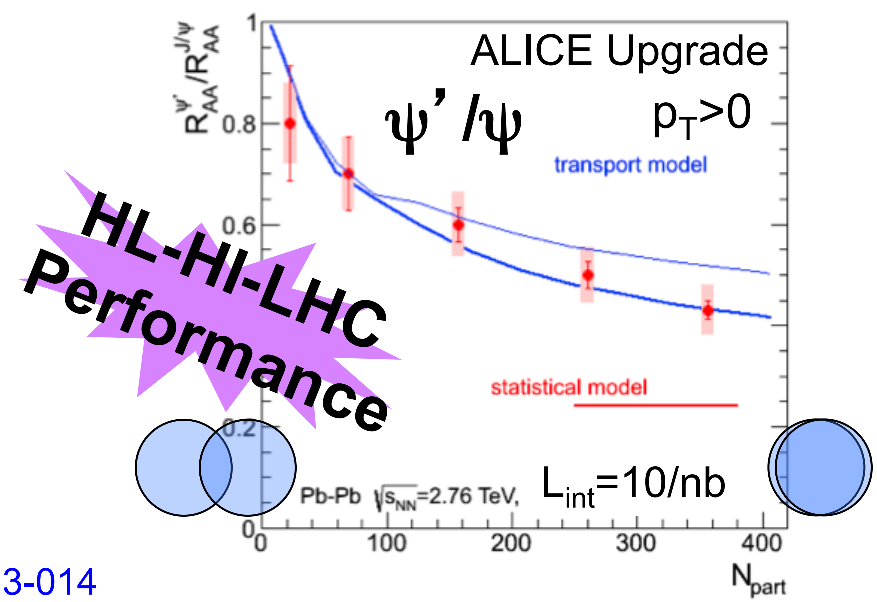
- Low-p_T J/ψ at the LHC is less suppressed than at RHIC
  - Despite the x2-3 higher density
- ψ regeneration from uncorrelated c and $\bar{c}$ in a deconfined medium?

Braun-Muzinger and Stachel, PLB490(2000) 196
Thews et al, PRC63 (2001) 054905



High statistics → explore this "new" probe of deconfinement

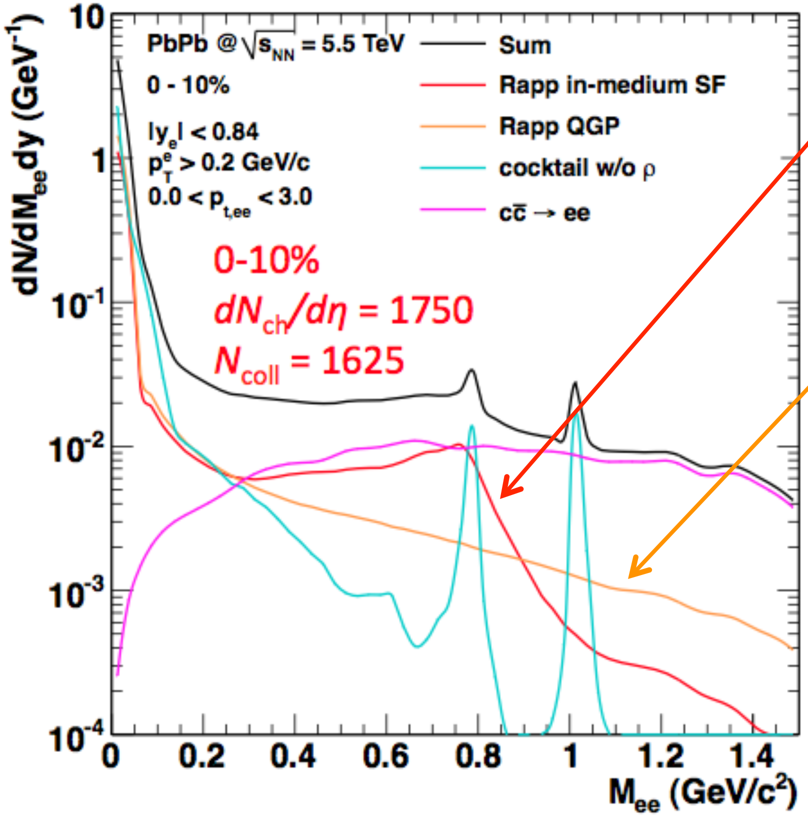
- Understand the underlying mechanism that binds deconfined heavy quark pairs
- Add information! E.g. low-p_T ψ' /ψ discriminates between models



ALICE, CERN-LHCC-2013-014

Low-mass di-leptons

- Comprehensive measurement of low-mass di-leptons allows to address these fundamental questions:



Restoration of the chiral symmetry
→ Melting/broadening of the ρ meson, via $\rho \rightarrow l^+l^-$

Profile system temperature during its evolution
→ Di-leptons from real and virtual photons $\gamma \rightarrow l^+l^-$

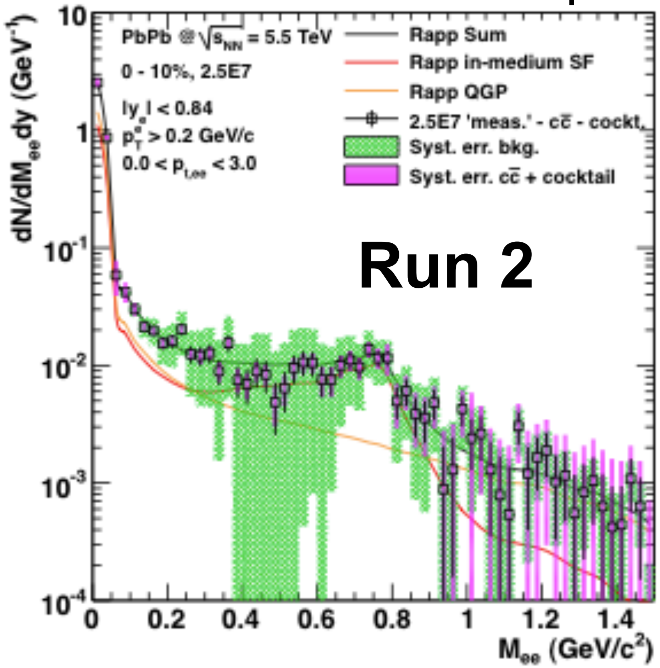
Low-mass di-leptons: performance

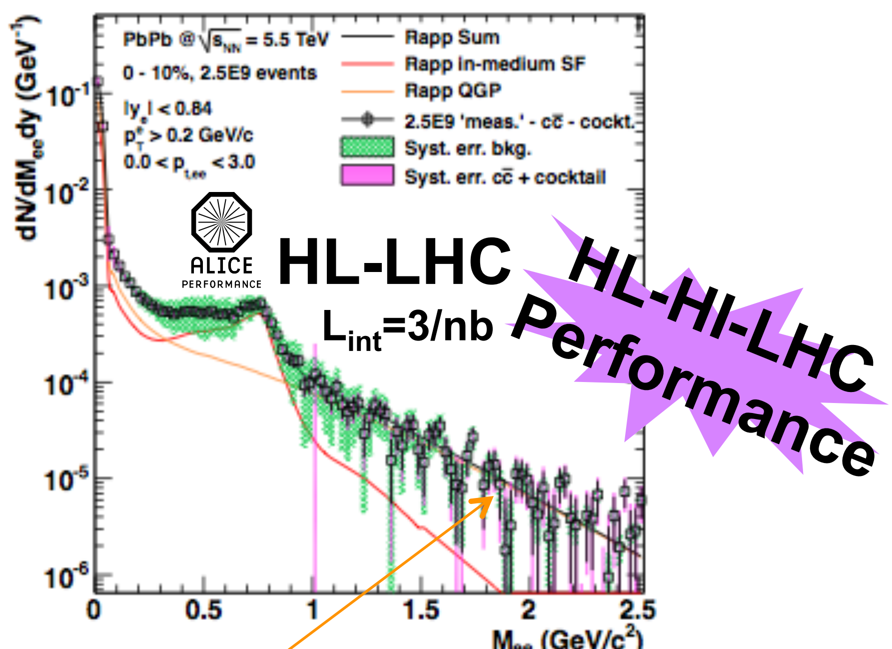
- ALICE: new inner tracker **+ dedicated run at 0.2 T (+3/nb)**

  → electron acceptance down to p_T = 50 MeV/c

Needs minimum-bias trigger (low S/B)
→ HL-LHC = 100x Run2 stat.

Di-electron mass spectrum after bkg subtraction:





Precision of ~10% on the inverse slope → T

ALICE, CERN-LHCC-2012-012

Summary

- "HL-HI-LHC" (Runs 3+4): fully exploit the potential of the machine as a high-luminosity HI collider

- Rich Physics programme prepared by the experiments
  - Upgraded detectors, very large statistics, diverse trigger approaches, complementary strengths of the experiments

- Goals:
  - Pb-Pb >10/nb → x10 wrt Run 2, x100 for minimum bias (ALICE)
  - pp reference at Pb-Pb energy; p-Pb; possibly light ions

EXTRA SLIDES

Available Documents

- ALICE Upgrade LOI: CERN-LHCC-2012-012
  - Addendum (Muon Forward Tracker): CERN-LHCC-2013-014
- ALICE inner tracker upgrade CDR: CERN-LHCC-2012-013
  - TDR in preparation (also for TPC, electronics, DAQ-HLT-Offline)
- CMS HI HL-LHC projections: CMS-PAS-FTR-13-025
- Presentations at the Heavy Ion Town Meeting (June 2012):
  - http://indico.cern.ch/event/HItownmeeting
- Inputs by ALICE, ATLAS, CMS to the ESPG meeting Cracow (Sep 2012)
  - http://indico.cern.ch/confId=182232
  - HI community presentation (H. Appelshaeueser) http://indico.cern.ch/getFile.py/access?contribId=16&sessionId=2&resId=0&materialId=slides&confId=182232

pp reference, pA, light nuclei

- pp reference at 5.5 TeV required
  - ALICE (for HF and charmonia needs): **~10/pb** (see CERN-LHCC-2012-012)
  - ATLAS / CMS: match Pb-Pb yields for high-p_T process, **~300/pb**
- p-Pb run at high luminosity (exploit upgraded detectors)
  - Requested by ALICE, ATLAS, CMS and LHCb
- p-Ar and Ar-Ar: a possibility to be considered for schedule after LS2, with priority that will be defined based on the outcome of the future data analysis (high statistics Pb-Pb and p-Pb from Run 2)

→ More in next talk by J.Wessels

Experiment upgrades most relevant to HI

See talks this morning

- ALICE (LS2)
  - New inner tracker: precision and efficiency at low p_T
  - New pixel muon tracker: precise tracking and vertexing for μ
  - New TPC readout chambers, upgraded readout for other detectors and new DAQ-HLT: x100 faster readout
- ATLAS
  - Additional pixel layer (LS1), then new tracker (LS3): tracking and b-tag
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
- CMS
  - New pixel tracker (LS2), then new tracker (LS3): tracking and b-tag
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade of trigger and DAQ (LS2): HI-specific development to reach necessary L1 rejection at 95%, from 50 kHz to <3 kHz (HLT)
- LHCb (LS2)
  - Upgrade includes new vertexing and tracking detectors (not focused on HI)

Focus on ALICE

- Main observables:
  - Low-p_T heavy flavour
  - Low-p_T charmonia
  - (Very) low-p_T and low-mass di-leptons
- Exploit detector specificities (strengthened with the upgrades):
  - hadron and lepton ID
  - light-weight and precise tracker
  - low magnetic field
- Mostly "untriggerable" because of extremely low S/B

→ Trigger approach: write all events with continuous central barrel readout at up to 50 kHz in Pb-Pb (currently 0.5 kHz)

~1 TB/s → **HLT/DAQ** → **~10 GB/s**

→ HL-LHC: increase of minimum-bias sample **x100** wrt Run 2

Focus on ATLAS and CMS

- **Main observables:**
  - Differential studies of jets at very high p_T
  - b-jets
  - Multi-differential studies of Υ states
- **Exploit detector specificities (strengthened with the upgrades):**
  - muon ID
  - precise tracker
  - calorimetry
- Mostly based on muon, jet, displaced track triggers

→ Trigger/DAQ approach: strong data reduction

50 kHz $\xrightarrow{\text{L1}}$ **~ few kHz** $\xrightarrow{\text{HLT}}$ **~ 100 Hz**

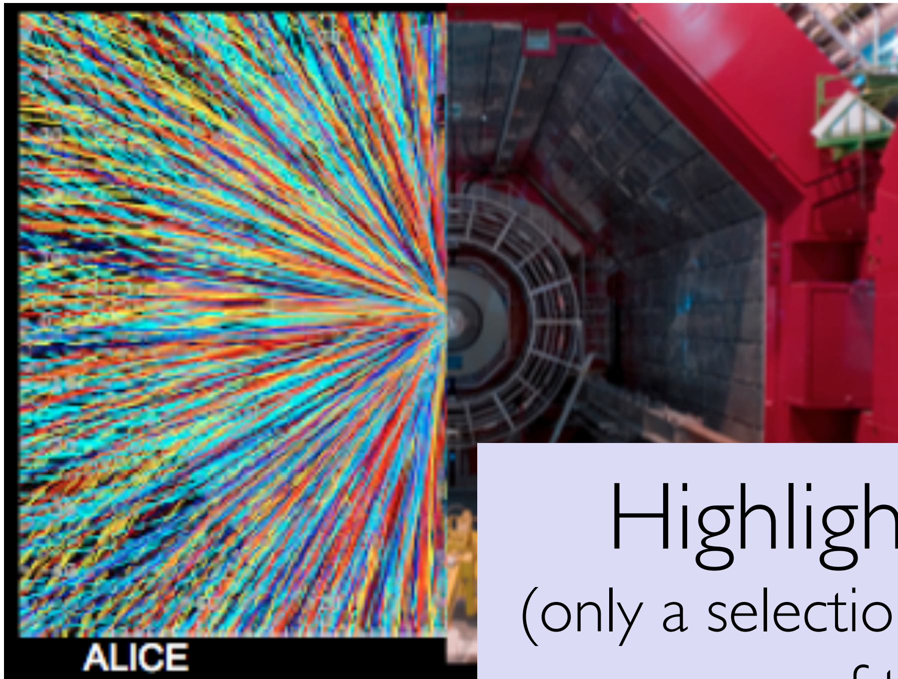
→ HL-LHC: increase of sample **x10** wrt Run 2

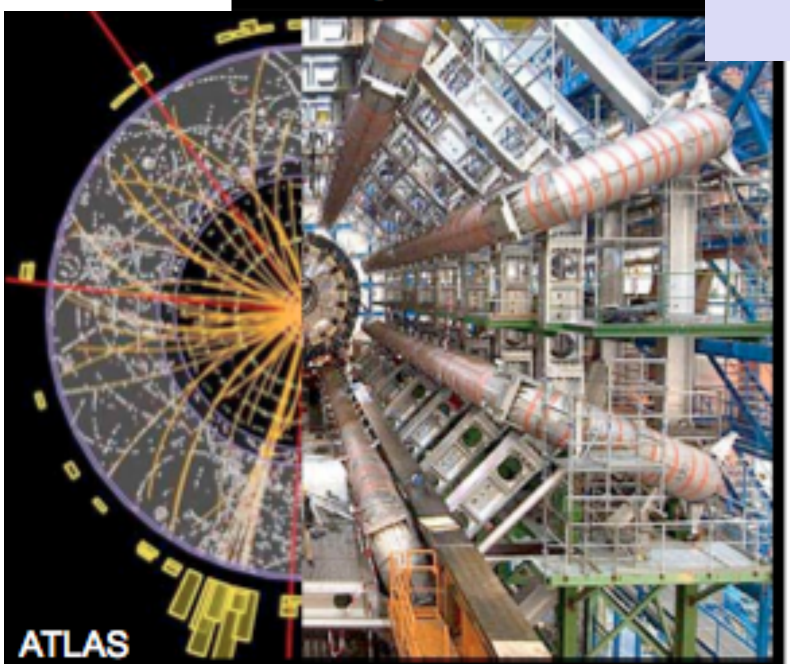
(Ultra-relativistic) Heavy Ions

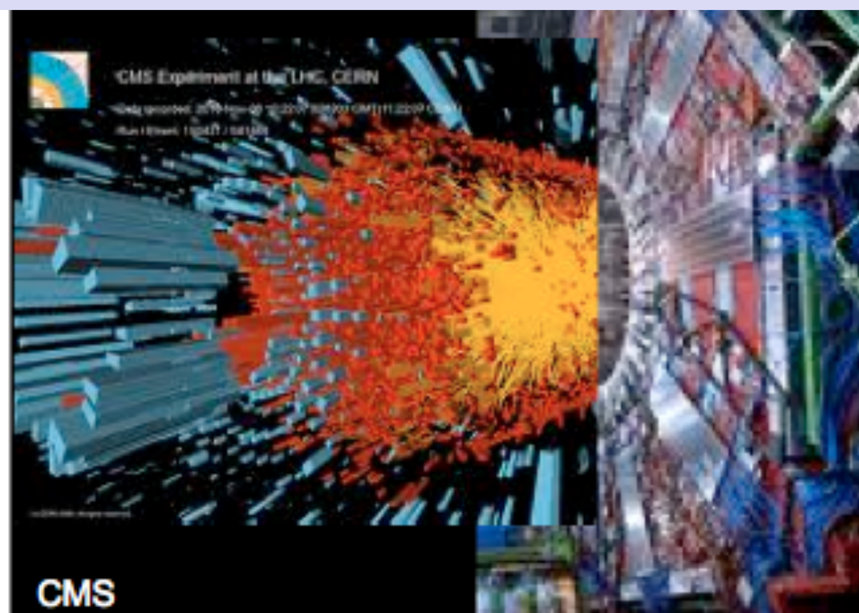
- **SPS**, Pb-Pb up to $\sqrt{s_{NN}} = 17\ \mathrm{GeV}$
  - Estimated energy density ~ 1 × critical value ε_c
  - First signatures of deconfinement
- **RHIC**, Au-Au $\sqrt{s_{NN}} = 8 - 200\ \mathrm{GeV}$
  - Estimated energy density ~ 10 × critical value ε_c
  - Evidence for strongly-coupled medium (quenching, flow, …)
- **LHC**, Pb-Pb $\sqrt{s_{NN}} = 2.76 - 5.5\ \mathrm{TeV}$
  - Estimated energy density ~ 15-30 × critical value ε_c
  - Goal: precise characterization with hard, calibrated probes
  - First Run: measured bulk properties of the system; new observations and insights; prototyped usage of novel probes
- **HL-LHC**: fully exploit the potential of the machine as a high-luminosity HI collider and of the upgraded (faster and more precise) detectors

Highlights from Run 1

(only a selection! also used to introduce some of the HI observables)



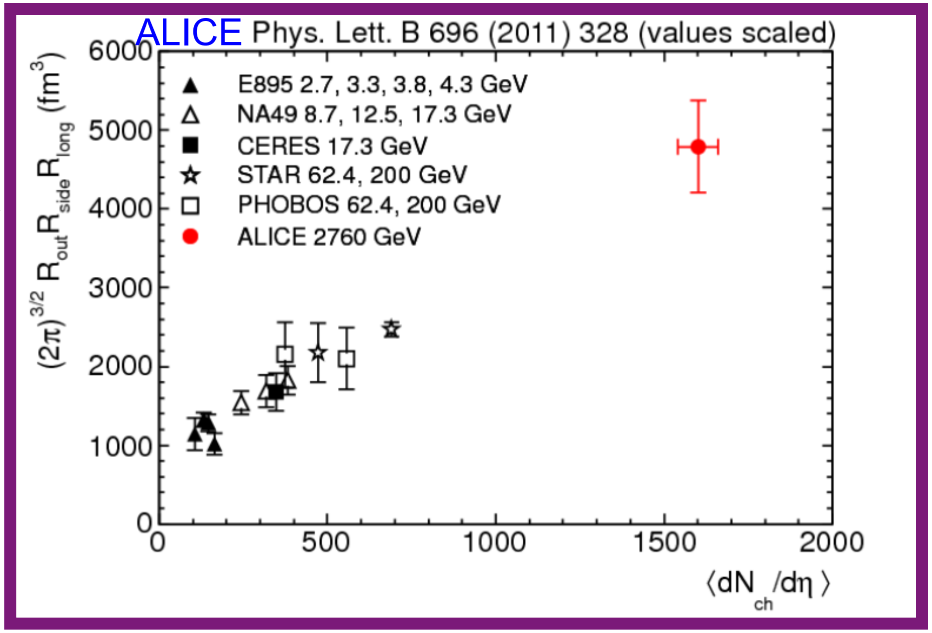




Global properties

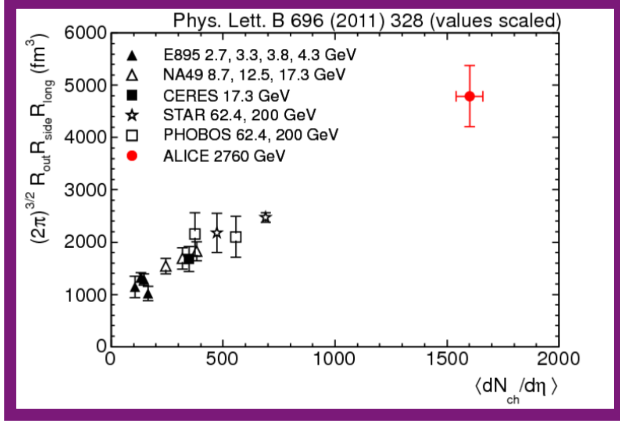
- Fireball at LHC: larger, longer lived, denser, and hotter than at RHIC
    - **Volume ≈ 2 x RHIC** **(≈ 5000 fm^3)**

Pion-pion interferometry

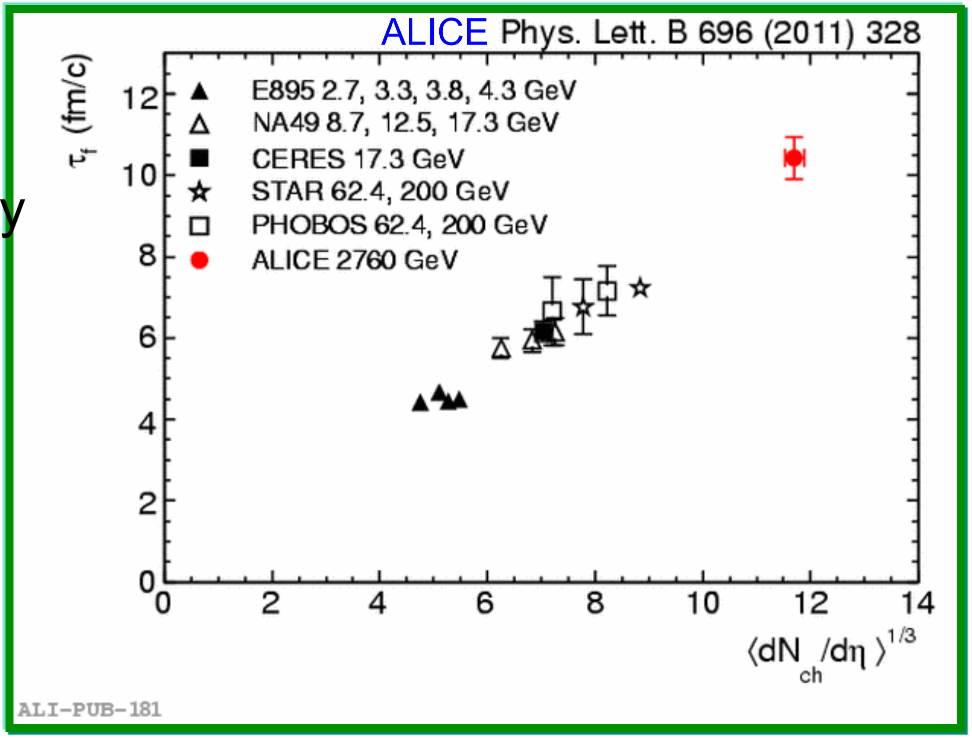


Global properties

- Fireball at LHC: larger, longer lived, denser, and hotter than at RHIC
  - **Volume ≈ 2 x RHIC** **(≈ 5000 fm^3)**
  - **Lifetime ≈ +20%** **(≈ 10 fm/*c*)**

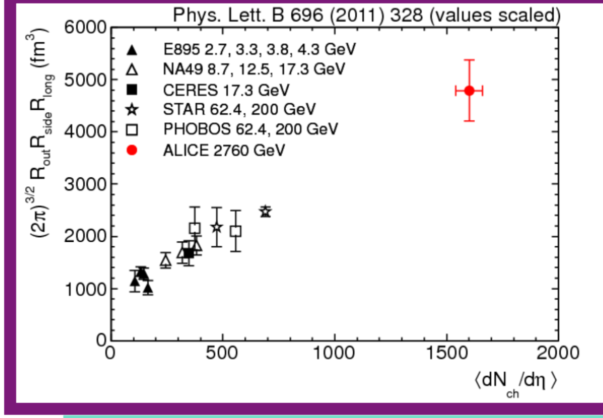


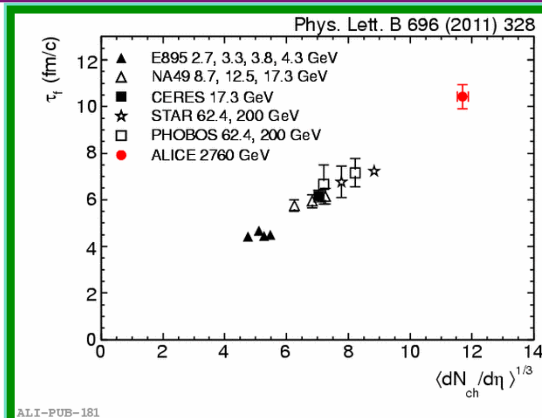
Pion-pion interferometry



Global properties

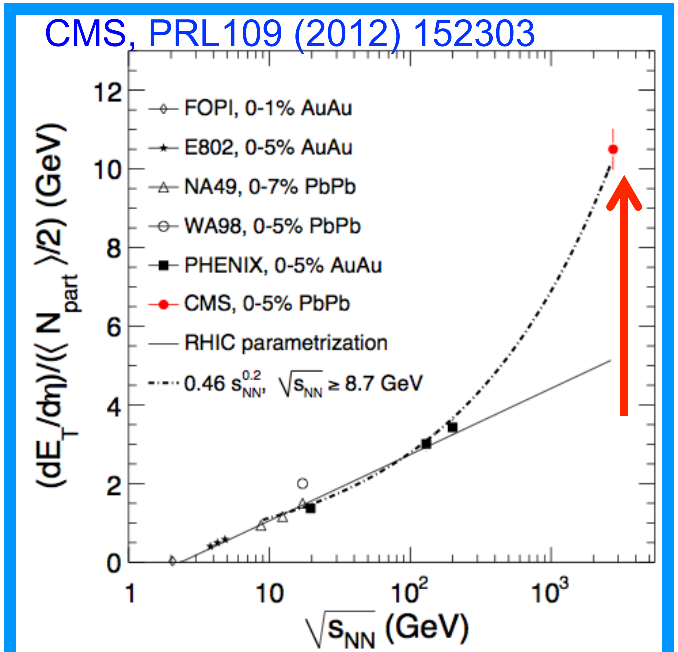
- Fireball at LHC: larger, longer lived, denser, and hotter than at RHIC
  - **Volume ≈ 2 x RHIC (≈ 5000 fm^3)**
  - **Lifetime ≈ +20% (≈ 10 fm/*c*)**
  - **Energy density ≈ 3 x RHIC (≈ 12 GeV/fm^3)**





Transverse energy density

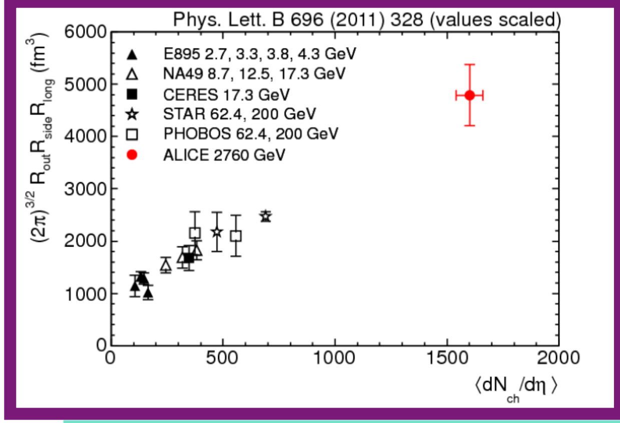
$$\left.\frac{dE_T}{dy}\right|_{y=o} \approx 2\ \mathrm{TeV}$$

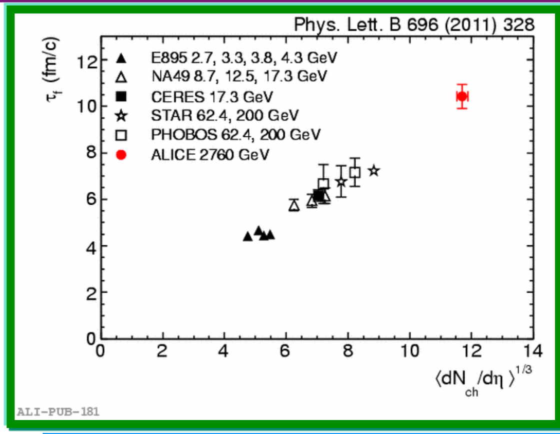


$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dE_T}{d\eta}$$

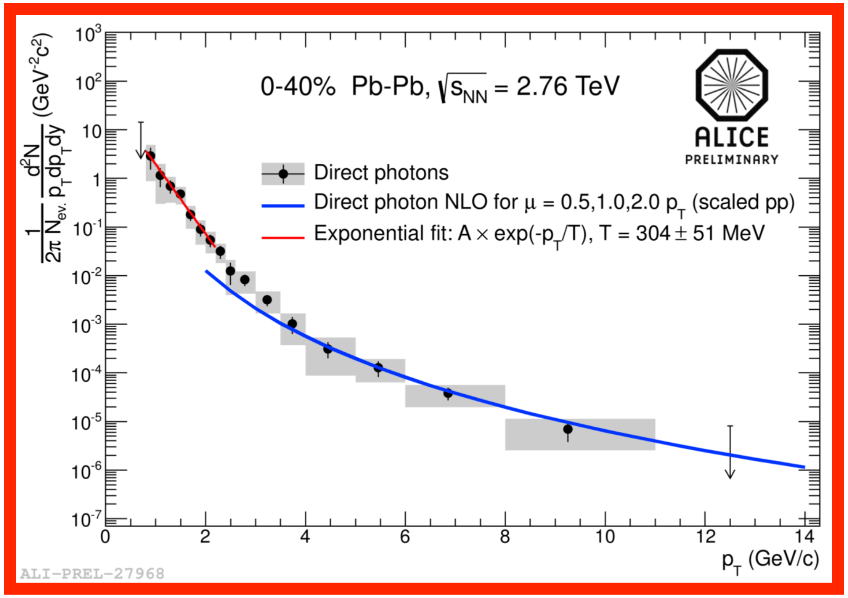
Global properties

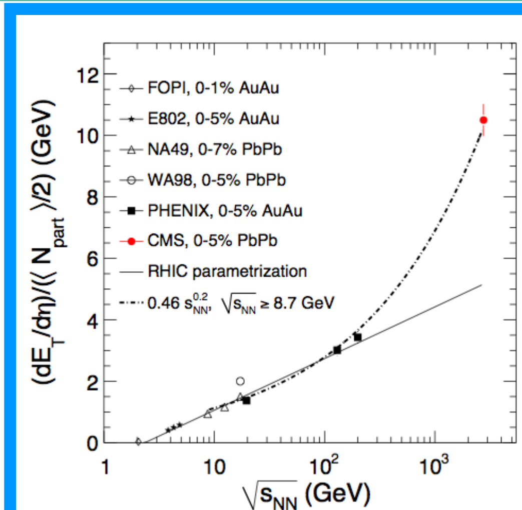
- Fireball at LHC: larger, longer lived, denser, and hotter than at RHIC
  - **Volume ≈ 2 x RHIC** **(≈ 5000 fm^3)**
  - **Lifetime ≈ +20%** **(≈ 10 fm/*c*)**
  - **Energy density ≈ 3 x RHIC** **(≈ 12 GeV/fm^3)**
  - ***T*** **≈ +30%** **(≈ 300 MeV)**





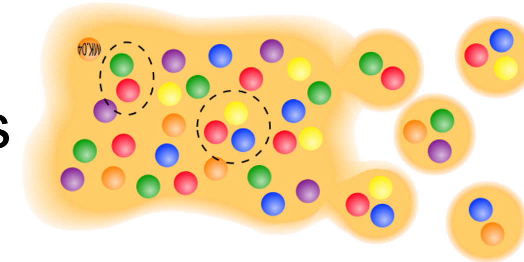
Slope of direct γ spectrum





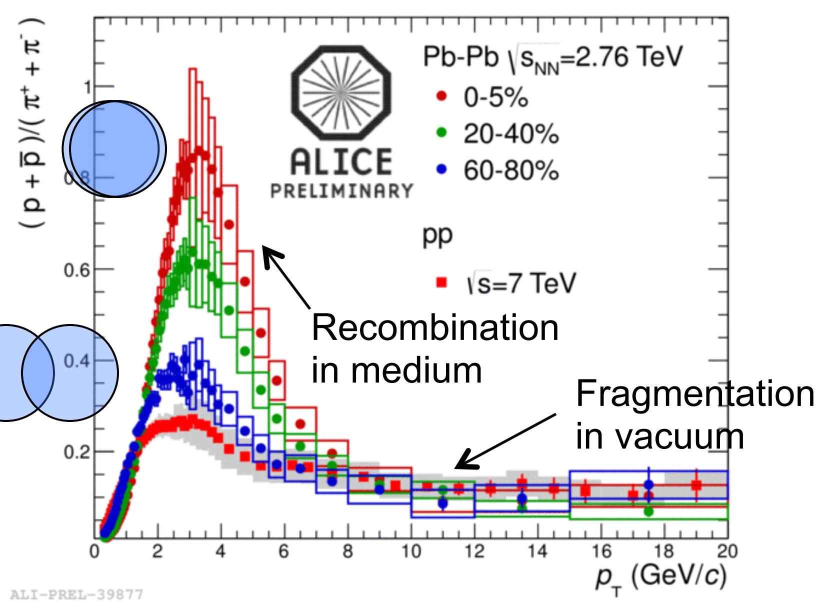
Bulk particle production: hadronization from a partonic system?

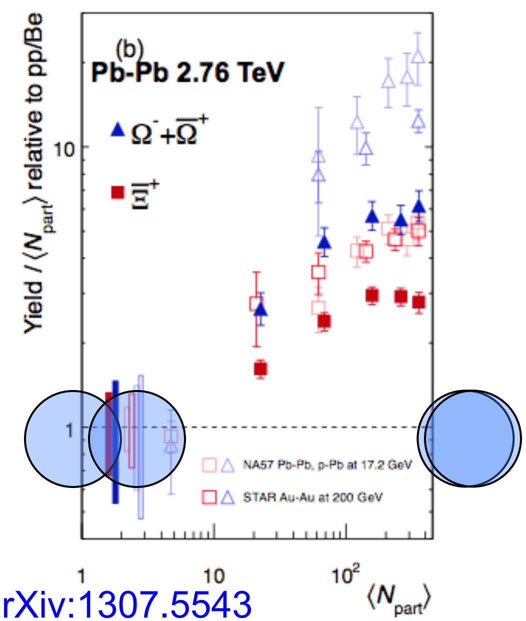
- Hadron yields suggest that hadronization occurs from a system with partonic degrees of freedom



Baryon(3*q*)/Meson(2*q*) ratios (e.g. p/π) enhanced at intermediate p_T
→ qualitatively consistent with hadron formation from medium constituents

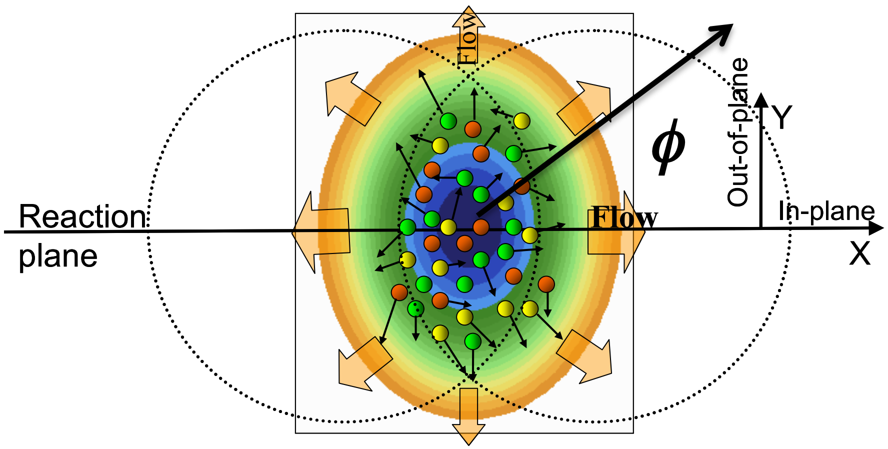
Multi-strange baryons (Ξ=*ssd*,Ω=*sss*) enhanced up to x7 wrt pp
→ formed by recombination in a system with abundant *s* quarks?





ALICE, arXiv:1307.5543

Azimuthal anisotropy: collective flow

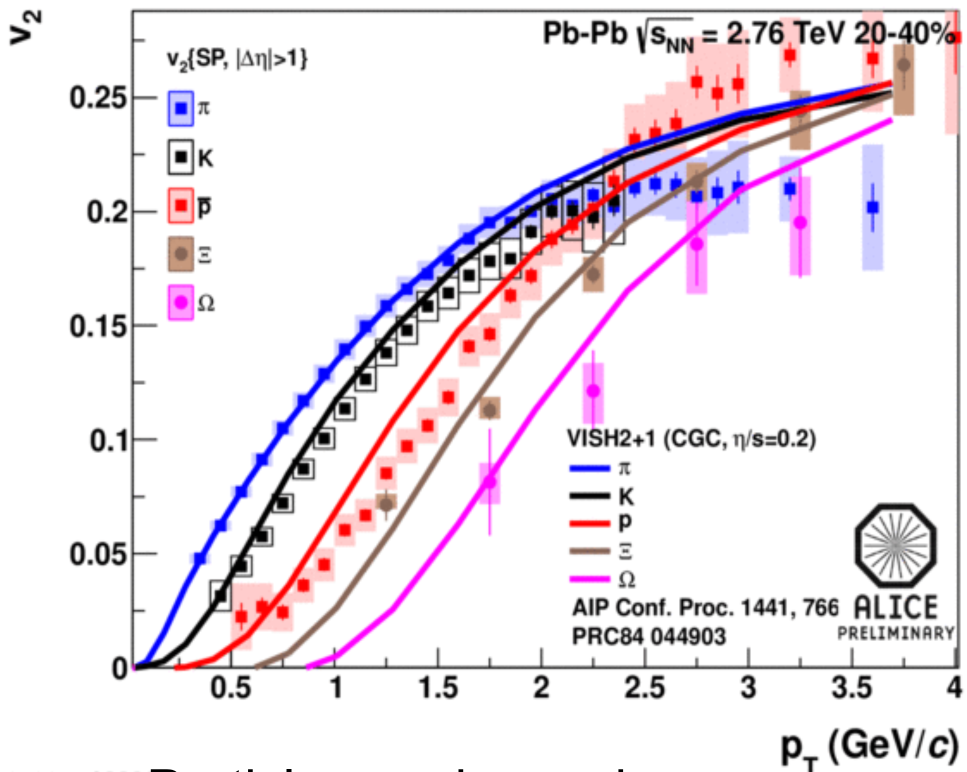


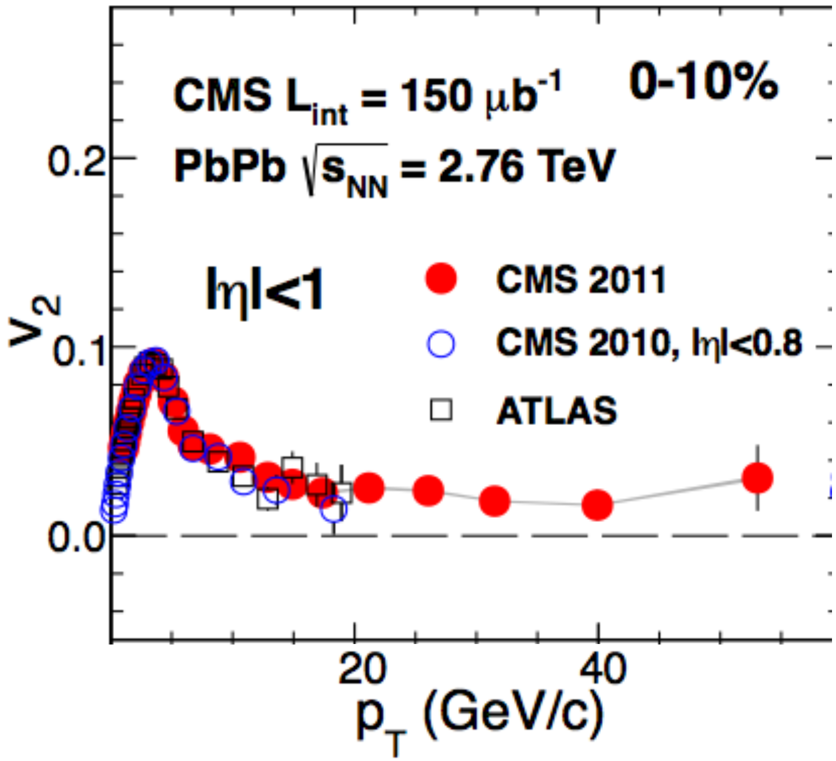
- System geometry asymmetric in non-central collisions
- Expansion under azimuth-dep. pressure gradient results in azimuth-dep. momentum distributions
- Measured by the elliptic flow parameter $v_2(p_T)$

$$\frac{dN}{Nd\phi} \sim 1 + 2v_2 \cos\left(2(\phi - \Psi_{RP})\right) + \textit{higher harmonics } (v_3, v_4, \ldots)$$

- v_2 at low p_T provides a measure of the strength of collectivity (mean free path of outgoing partons)

Azimuthal anisotropy at the LHC

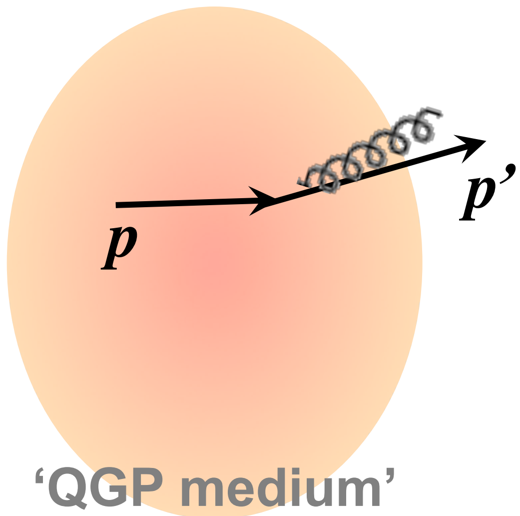




- Particle-species and p_T dependence follow expectations from hydrodynamic models
  - in which v_2 is built at partonic level from collective expansion
  - proton v_2 still not fully described
- v_2 decreases at large p_T
  - Hydrodynamic expansion not effective
- But remains >0 up to 50 GeV/c
  - Path length dependent energy loss

CMS, PRL 109 (2012) 022301
ATLAS, PLB 707 (2012) 330

Medium opacity to energetic partons: parton energy loss and jet quenching



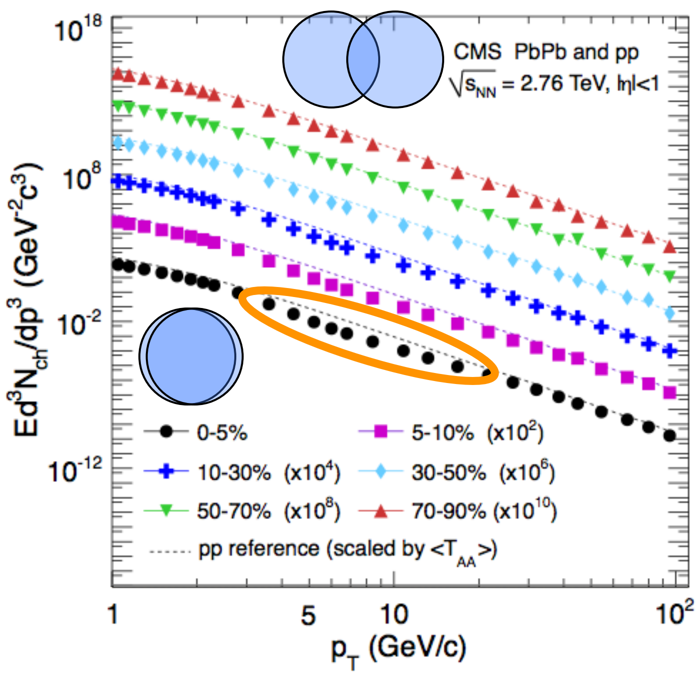
Parton Energy Loss by
- medium-induced gluon radiation
- collisions with medium gluons

$$p' = p - \Delta E(\varepsilon_{medium})$$

Nuclear modification factor:

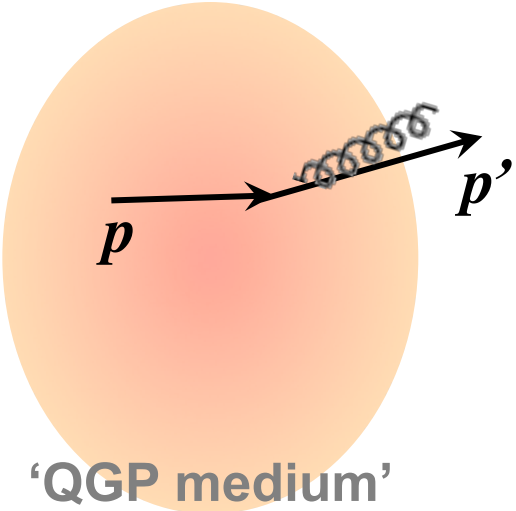
$$\boxed{dN_{AA}/dp_T} < \langle N_{coll}\rangle dN_{pp}/dp_T$$

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll}\rangle}\frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} < 1$$



CMS, EPJ C72 (2012) 1945

Medium opacity to energetic partons: parton energy loss and jet quenching



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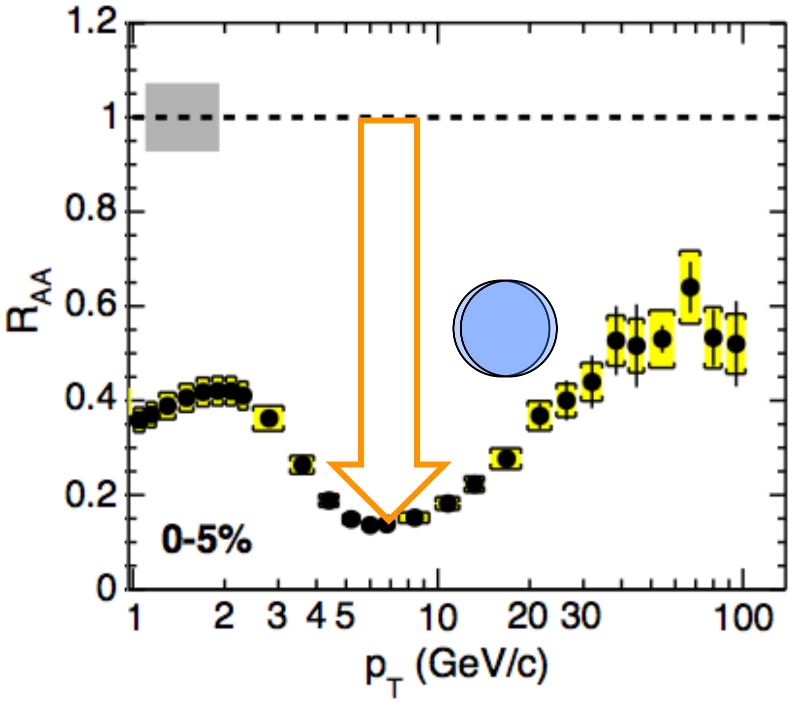
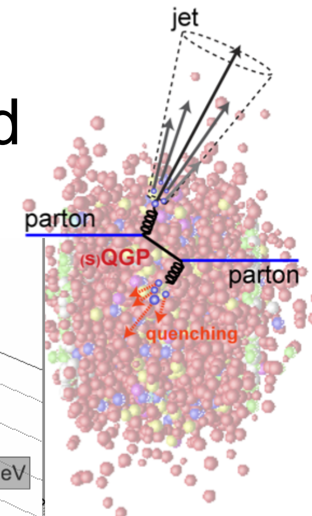
(p-Pb data crucial to measure effect of nuclear initial state)

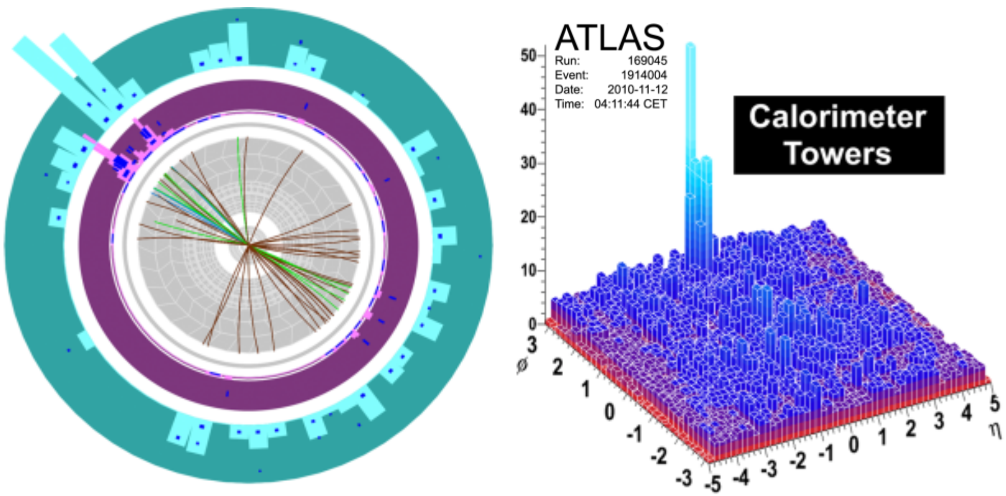


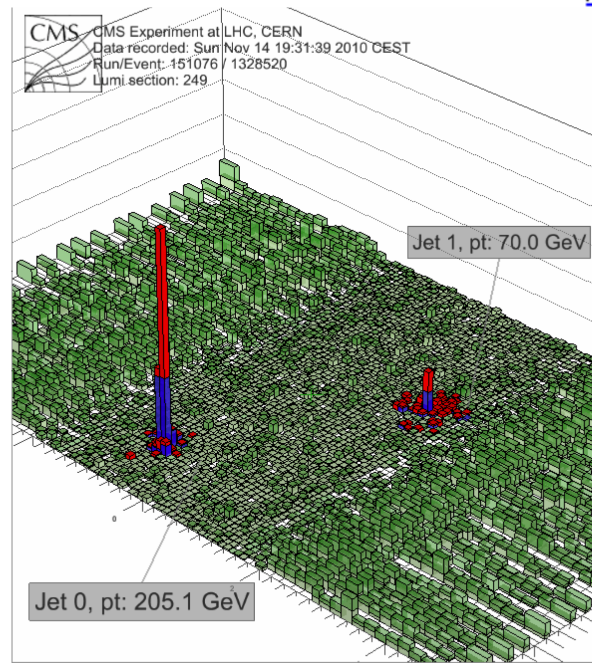
CMS, EPJ C72 (2012) 1945

Jet quenching at the LHC!

- Jets and Di-jets with ~100 GeV energies
- Pb-Pb events with large di-jet imbalance observed

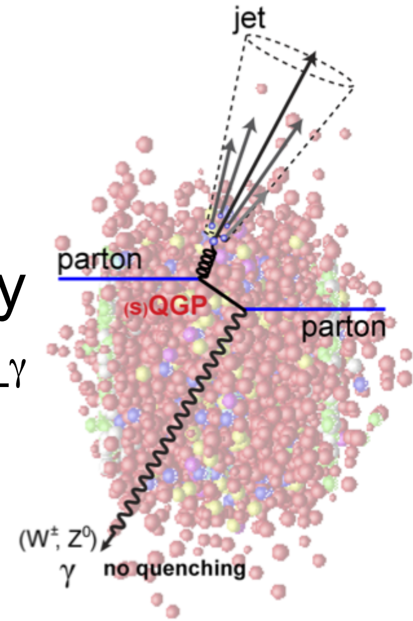




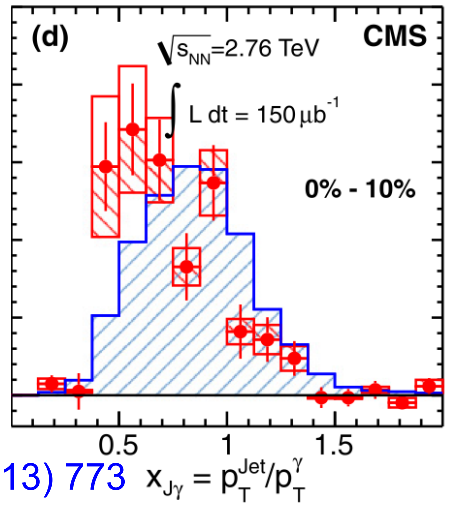


ATLAS, PRL105 (2010) 252303
CMS, PLB712(2012) 176

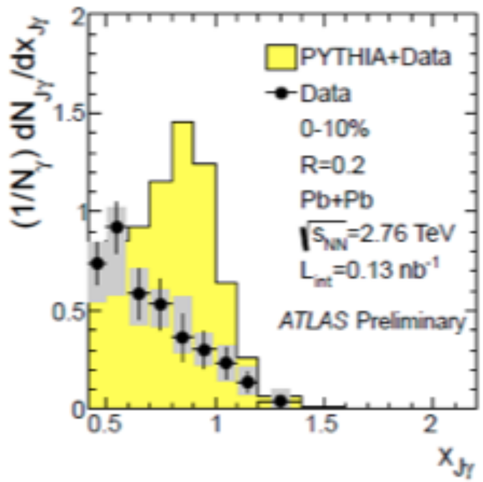
A powerful tool: jet-boson (γ, Z) correlation



- $E^{\gamma} = E^{jet}$! Direct measurement of total jet energy
- First measurement of γ-jet p_T imbalance p_T^{Jet}/p_T^{γ}



CMS, PLB718 (2013) 773



Large imbalance observed in central collisions

Needs HL-HI-LHC

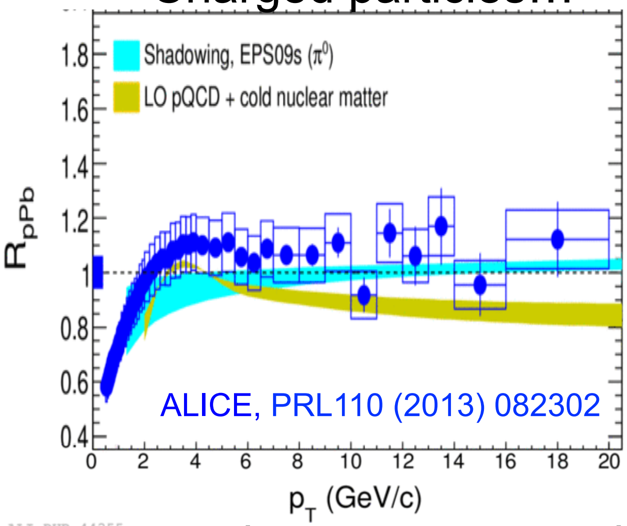
High statistics:

→ Precise measurement of the medium-modified fragmentation function

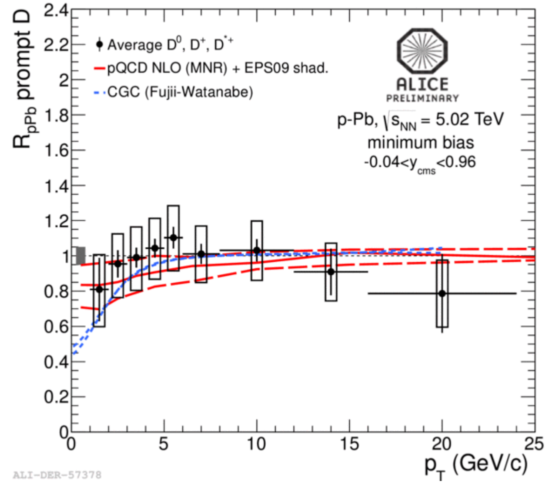
→ Differential studies as a function of event geometry

p-Pb control experiment: crucial to disentangle initial-state and QGP effects

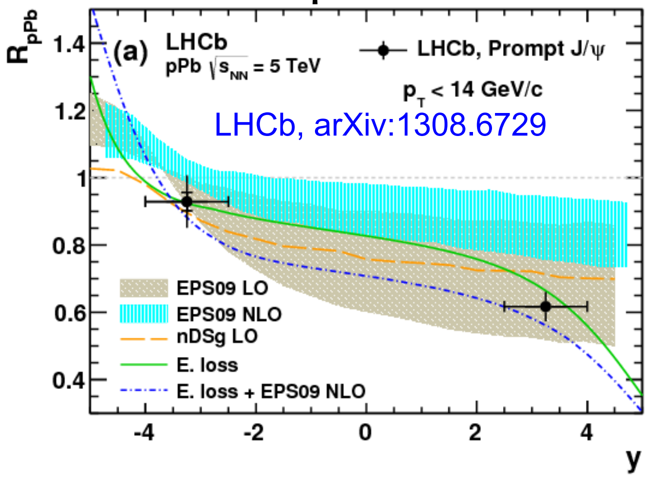
Charged particles…



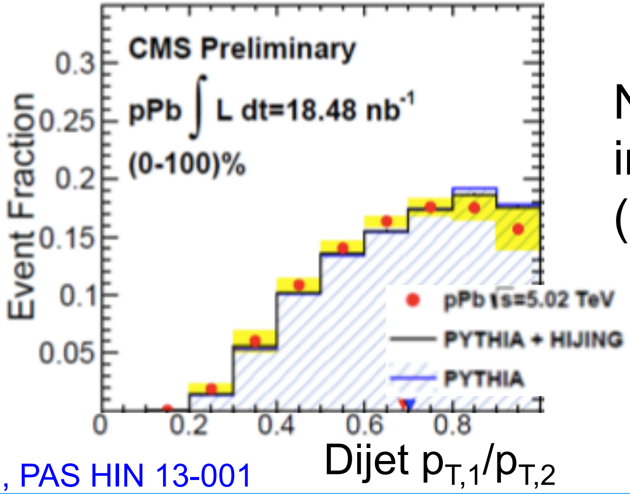
D mesons …



J/ψ…



… important constraints on expected "cold nuclear matter" effects



CMS, PAS HIN 13-001

No dijet momentum imbalance observed ($p_{T,1}/p_{T,2}$ like in pp)

More on p-Pb in the talk by J.Wessels

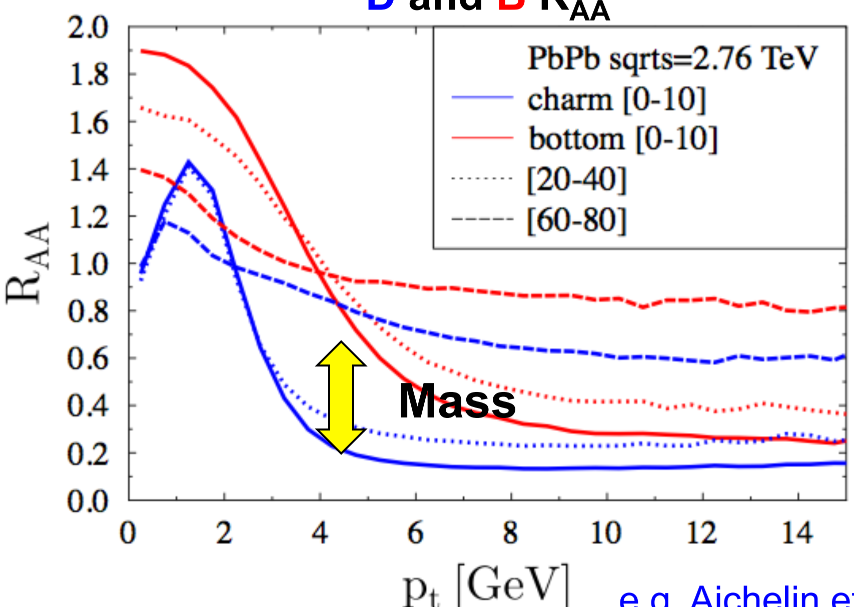
Heavy quark probes of the medium

HL-LHC → exploit the potential of HQ as probes the in-medium interactions and of its thermalization

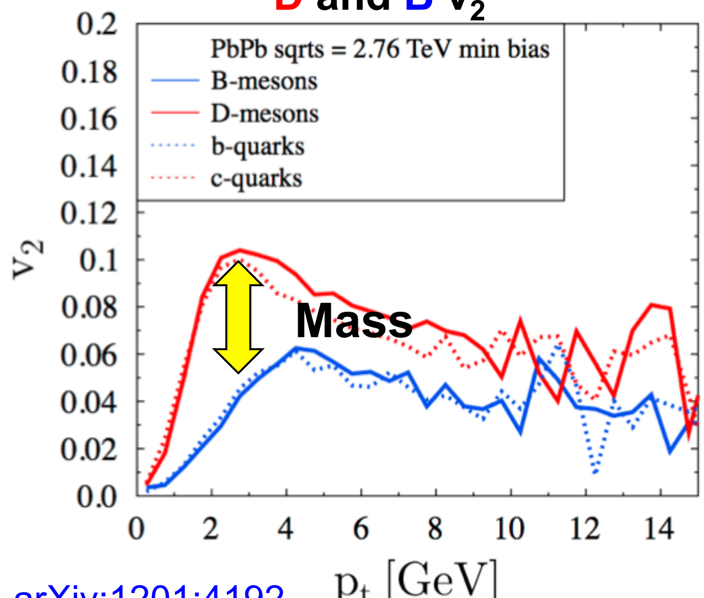
- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

➡ Measure precisely R_{AA} and v_2 of D and B in a wide p_T range

D and B R_{AA}



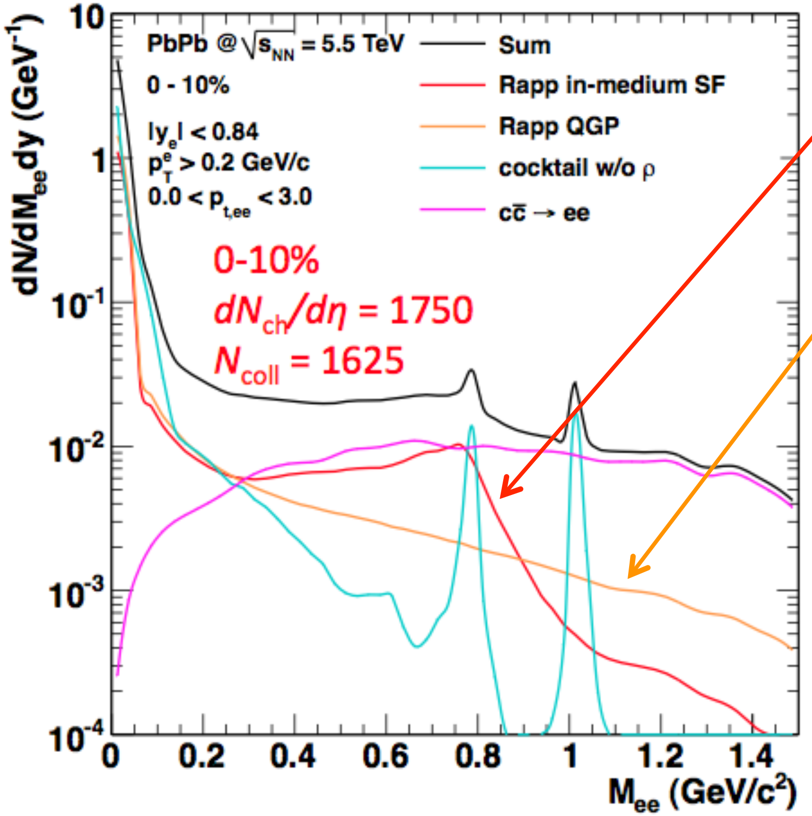
D and B v_2



e.g. Aichelin et al., arXiv:1201:4192

Low-mass di-leptons

- Comprehensive measurement of low-mass di-leptons allows to address these fundamental questions:



Restoration of the chiral symmetry
→ Melting/broadening of the ρ meson

Real and virtual photon production (medium temperature)
→ Measurement differential in p_T and mass to map temperature evolution

R. Rapp Acta Phys.Polon. B42 (2011)