Heavy ions at HL-LHC: experimental prospects

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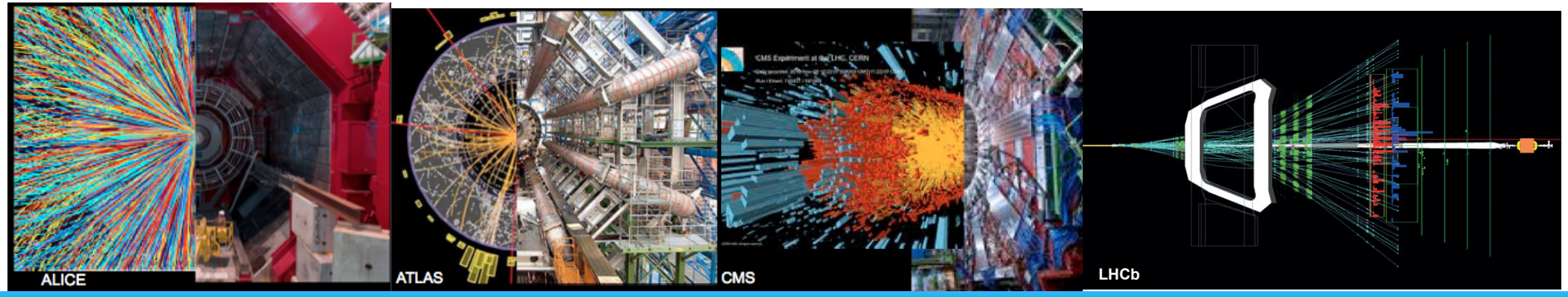
for the ALICE, ATLAS, CMS, LHCb Collaborations

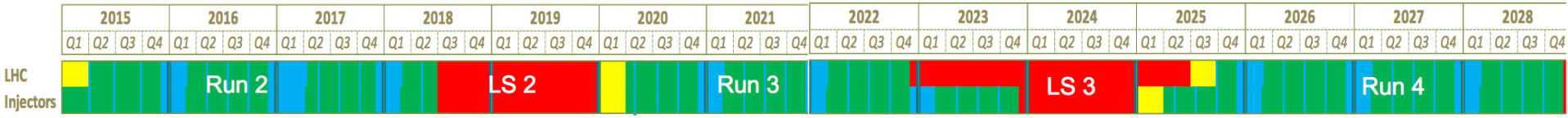
thanks to: PG1, B. Cole, J. Jia & A. Trzupek (ATLAS),
P. Braun-Munzinger, T. Peitzmann, A. Uras & M. van Leeuwen (ALICE),
M. Nguyen & C. Roland (CMS), G. Manca (LHCb)

Outline

- Timeline of future HI running
- AA physics programme at HL-LHC
- Besides Pb-Pb: pA, pp reference, light ions
- Experiment upgrades and strategies
- Selected performance studies
- Summary



Timeline of future HI running at the LHC



- Run 2:
  - 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)
- LS2: LHC collimator upgrades (Pb-Pb interaction rate may reach 50 kHz); ALICE upgrade; upgrades relevant to HI also for ATLAS, CMS (LS2 and LS3) and LHCb
- Runs 3+4: **"HL-HI-LHC"**
  - Experiments request for **Pb-Pb: >10/nb** (ALICE: 10/nb at 0.5T + 3/nb at 0.2T)
  - + other systems (→ slide 8)
- HL-LHC: focus on rare probes, their coupling with QGP medium and their (medium-modified) hadronization process

HL-LHC Programme (AA) (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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- **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**)

Besides Pb-Pb: pp reference, pA, lighter 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 at high luminosity has two-fold interest:
  - Explore partonic structure of high-energy nuclei → also needed as "control experiment" for the QGP studies
  - Study development of collective effects in high-particle-density collisions

  → Requested by all 4 experiments
- Lighter nuclei (e.g. Ar): a possibility to be considered for schedule after LS2
  - Study system size dependence and onset of QGP effects
  - Larger instantaneous luminosity compensates the reduced yields for hard processes (which scale with A^2, e.g. Ar-Ar/Pb-Pb = 1/27)

Focus ALICE

- Detector specificities (preserved / strengthened with the upgrades): hadron and lepton ID, light-weight and precise trackers, low magnetic field
- Main focus on “untriggerable” signals (extremely low S/B)
- → Trigger approach: write all events at up to 50 kHz in Pb-Pb (now 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

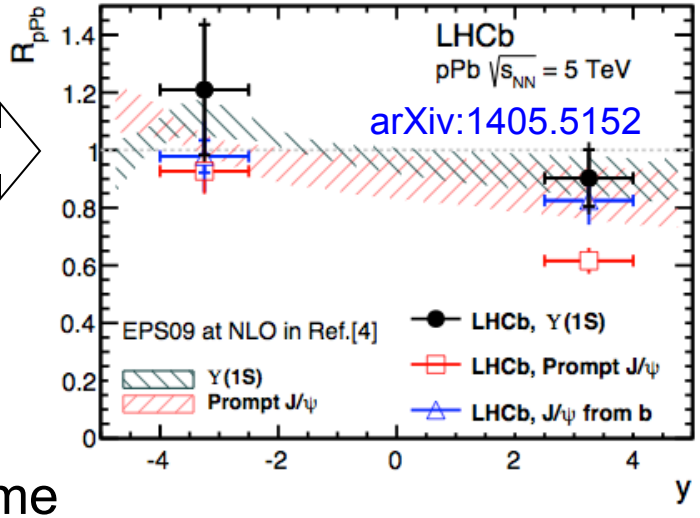
- Detector specificities (strengthened with the upgrades): muon ID, precise tracker, calorimetry
- Main focus on muon, jet, displaced track triggers
- → Trigger/DAQ approach: strong data reduction

50 kHz → L1 → ~ few kHz → HLT → ~ 100 Hz

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

Focus on LHCb (pA)

- LHCb participation to the 2013 p-Pb run very successful
- Immediate impact of LHCb unique features: forward, vertexing, PID
  - Cold nuclear matter effects on prompt and non-prompt J/ψ, and Υ(1S)
  - First observation of Z production in p-Pb



- Participation to next p-Pb run confirmed
  - test LHCb potential in heavy-ion programme
- Upgrades (LS2) most relevant to HI:
  - New trackers (pixel, strip, scintillating fiber)
  - Readout upgrade: up 40 MHz (pp) → will allow to exploit full delivered p-Pb luminosity

Outline

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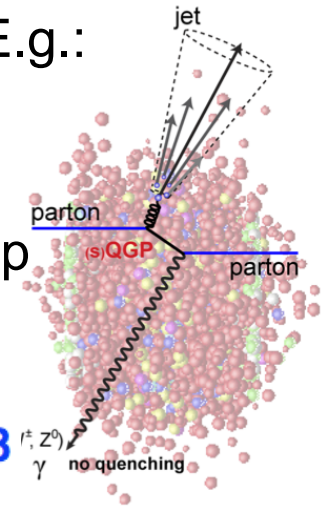
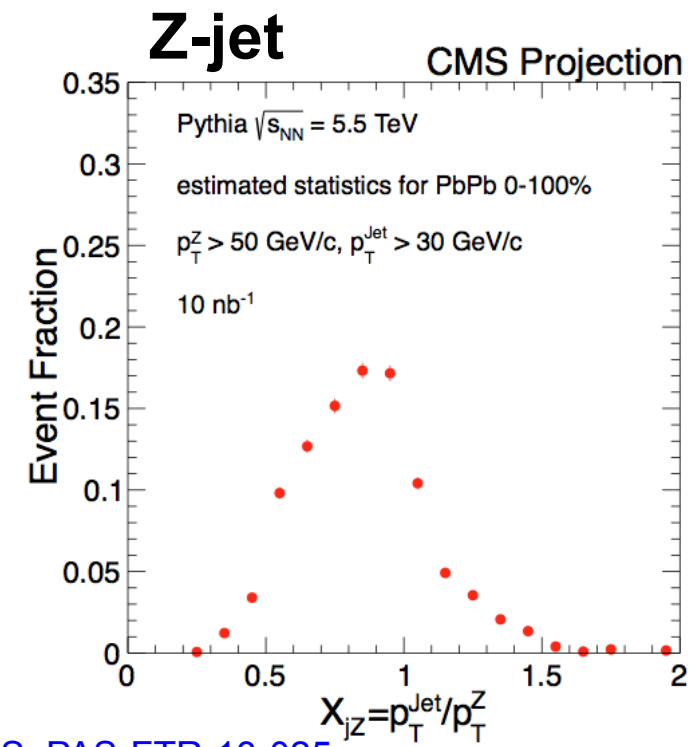
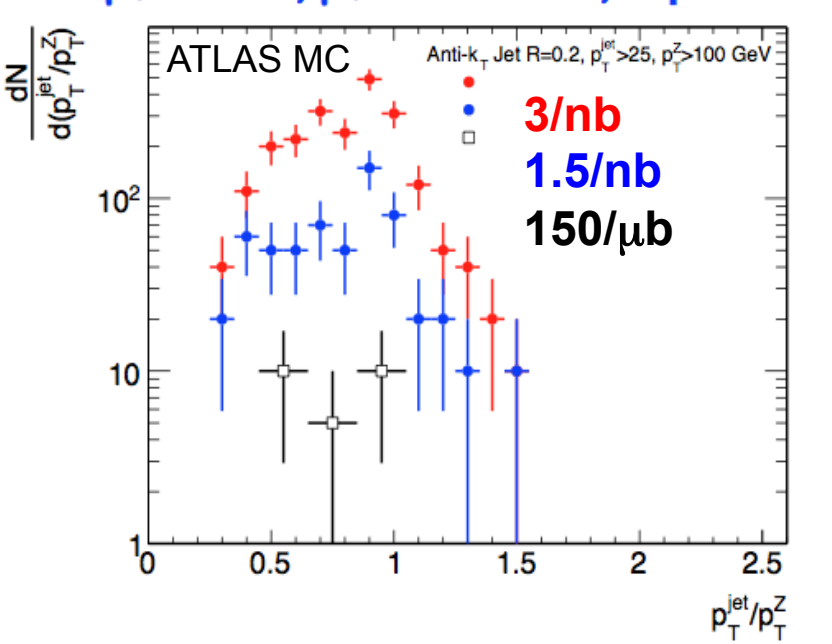
Find more in last year's talk:
https://indico.cern.ch/event/252045/session/4/contribution/12/material/slides/0.pdf

Jet quenching: performance

- High precision γ-jet, Z-jet ($E^{\gamma/Z} = E^{jet}$!), di-jets, 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-*L*ength dependence (e.g. radiative ~L^2, collisional ~L)







CMS, PAS-FTR-13-025

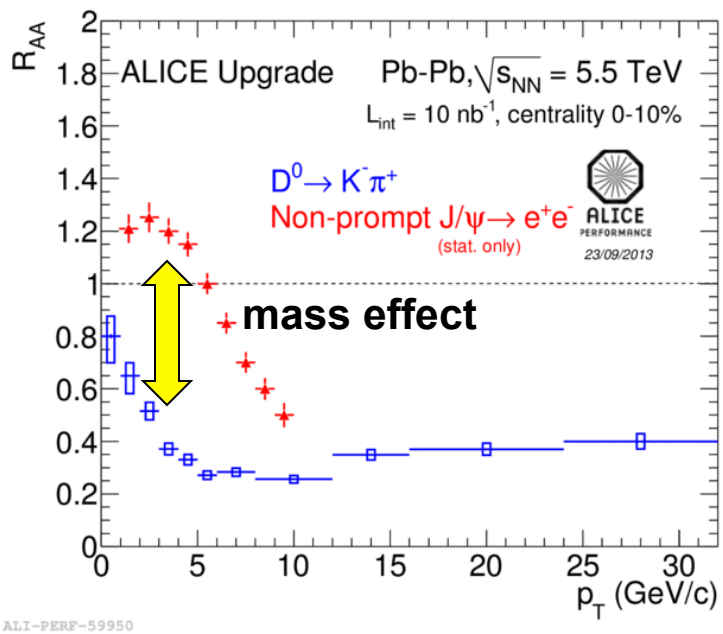
HF central rapidity: performance

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

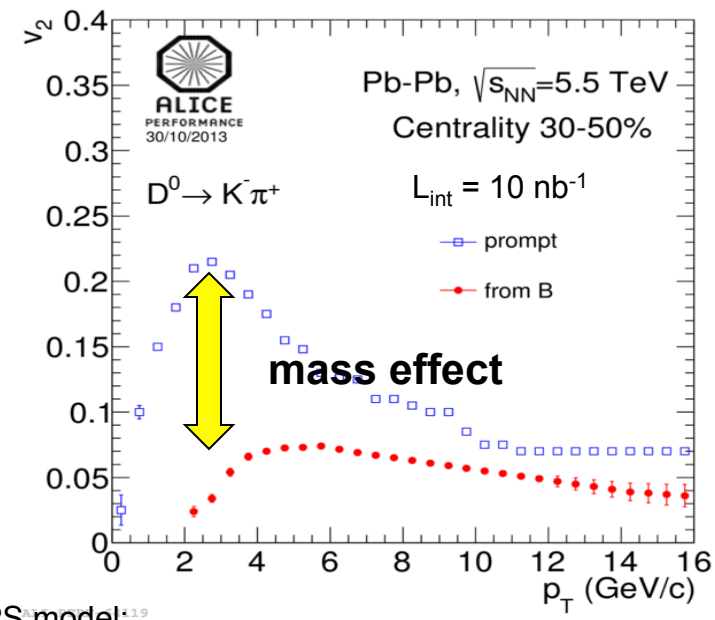
- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

→ 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}



Prompt and non-prompt D^0 v_2

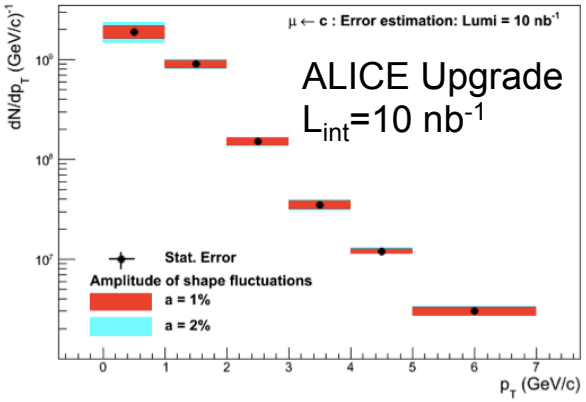


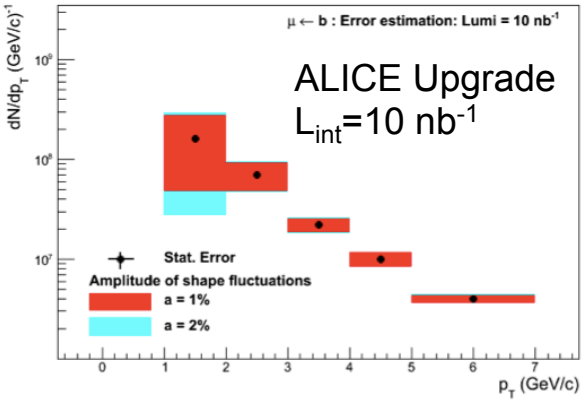
Input values from BAMPS model: C. Greiner et al. arXiv:1205.4945

ALICE, CERN-LHCC-2013-024

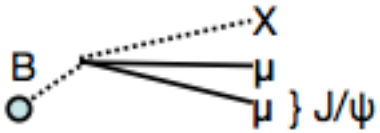
HF forward rapidity: performance

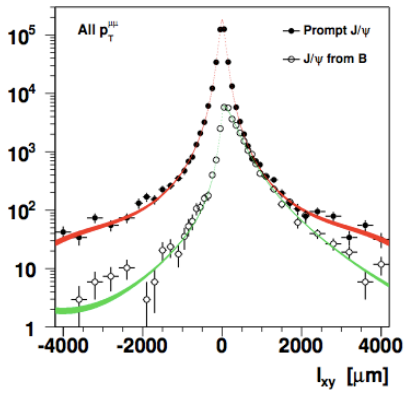
- ALICE Muon Forward Tracker: pixel tracker ($2.5<\eta<3.5$) in front of the muon spectrometer; enables separation of beauty decay vertices
- Open Heavy Flavour down to p_T~0:
  - Single muons via offset at primary vertex (charm, beauty)

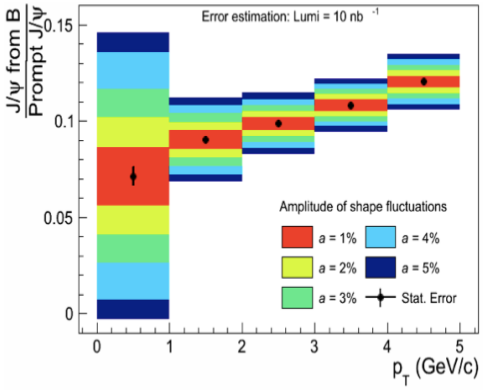




  - Displaced J/ψ via pseudo-proper decay length (beauty)





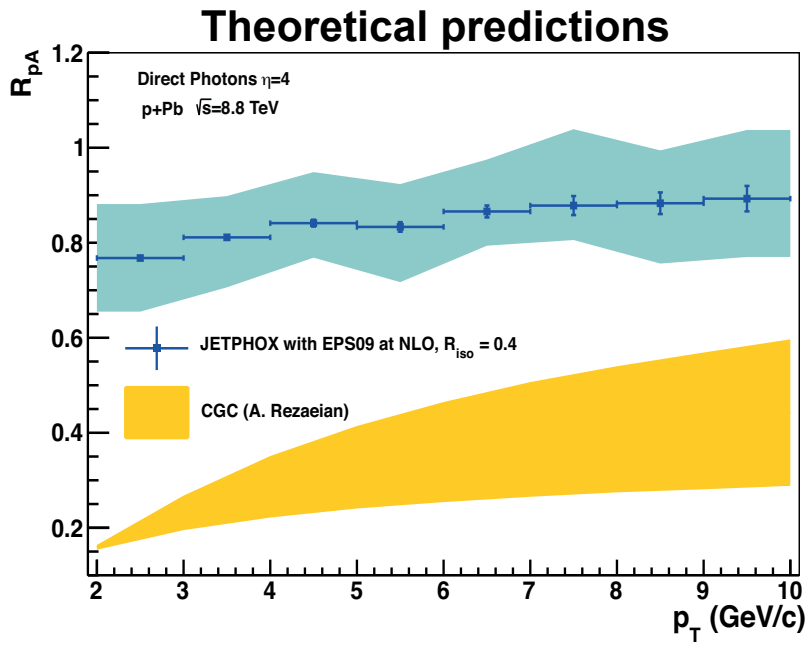


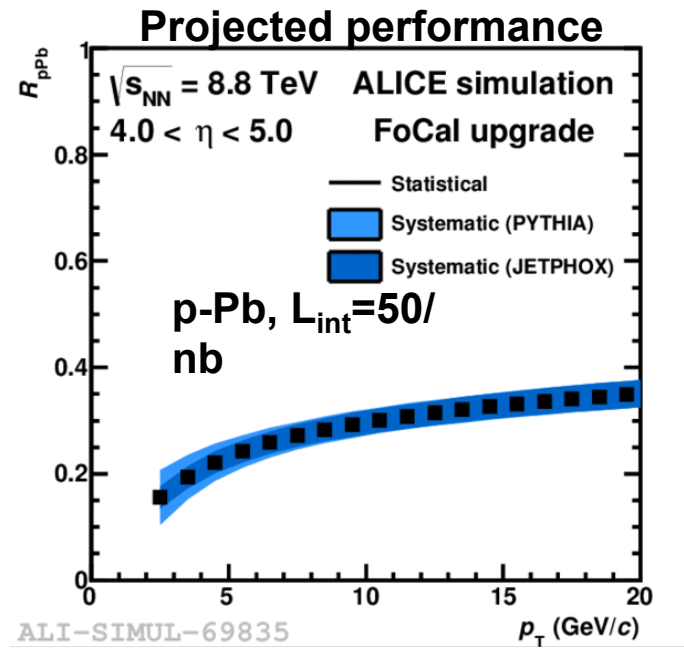
ALICE Upgrade
L_{int}=10 nb^{-1}

CERN-LHCC-2013-014

Forward photons in p-Pb: performance

- FoCal in ALICE: R&D for a new high-granularity calorimeter at η~3-5, with main focus on saturation physics studies
- Photons at $4 < \eta < 5$ are sensitive to Bjorken-$x < 10^{-5}$





- Signature of gluon saturation in high-energy nuclei: strong suppression of forward R_{pA} = p-Pb/(N_{coll}-scaled-pp), not described within collinear factorization (NLO pQCD) + PDF shadowing

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

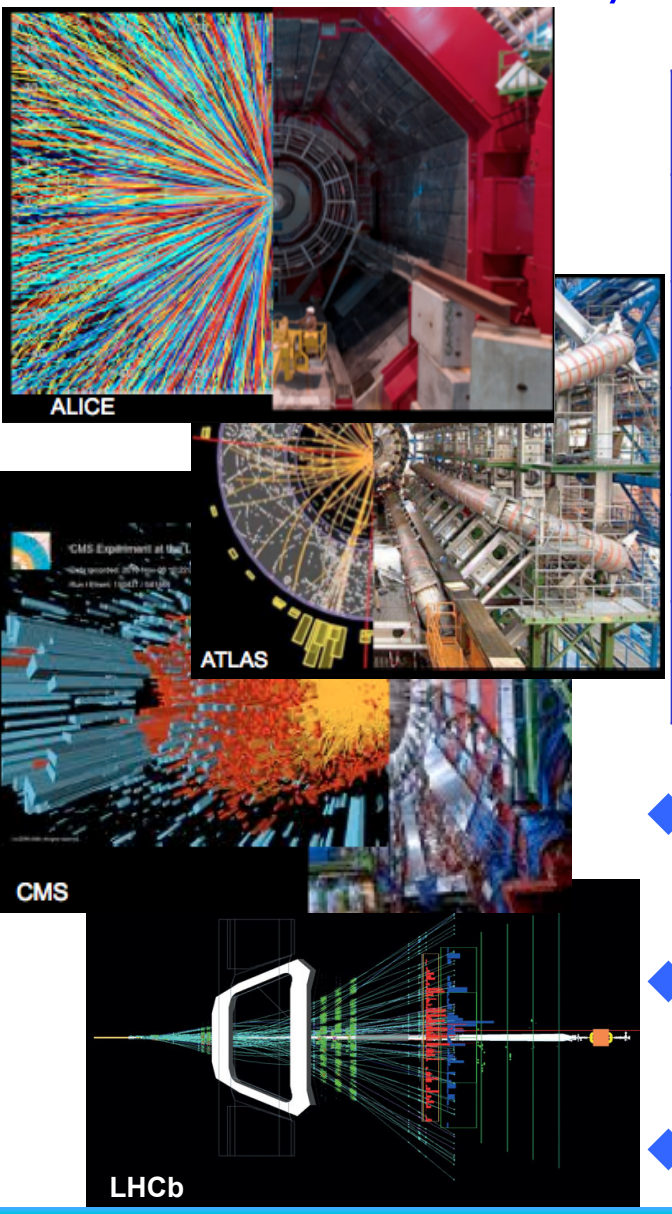
- Goals:
  - Pb-Pb >10/nb → x10 wrt Run 2, x100 for minimum bias (ALICE)
  - pp reference at Pb-Pb energy; p-Pb; possibly light ions

EXTRA SLIDES

Available Documents

- ALICE Upgrade LOI: CERN-LHCC-2012-012
  - Addendum (Muon Forward Tracker): CERN-LHCC-2013-014
- ALICE inner tracker upgrade TDR: CERN-LHCC-2013-024
- 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

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: 5×10^{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)

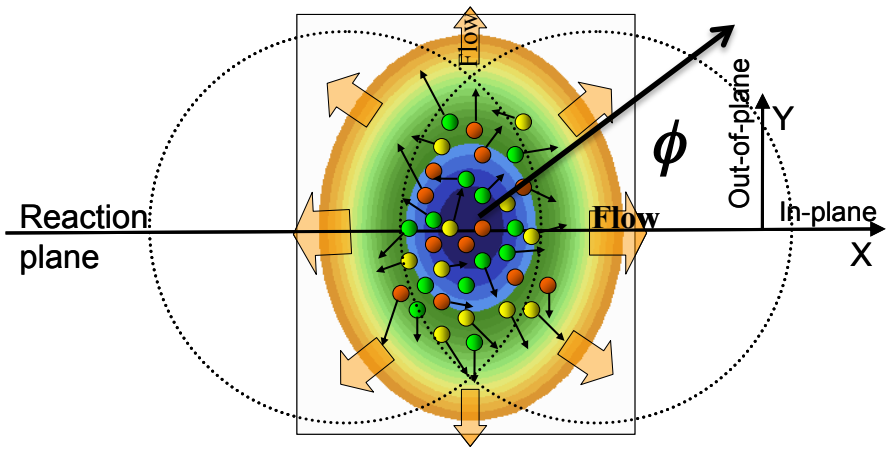
- Goals (in short):
  - > x10 times larger statistics: improve precision of current measurements, explore new observables
  - Extend Run 1 measurements to ~5 TeV (energy dependence)
  - But several measurements require detector upgrades and much larger luminosity (*see following slides*)

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 integrated Online-Offline: x100 faster readout (up to 50 kHz for Pb-Pb)
- 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
  - Upgrade of trigger and DAQ, L1 calorimeter trigger (LS1): enables L1 rejection at 95%, e.g. (after LS2) from 50 kHz to <3 kHz (HLT input)
  - New pixel tracker (YES15-16), then new tracker (LS3): tracking and b-tag
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade forward calorimeter (LS3): forward jets in HI
- LHCb (LS2)
  - Upgrade includes new vertexing and tracking detectors (not focused on HI)

Azimuthal anisotropy: collective flow

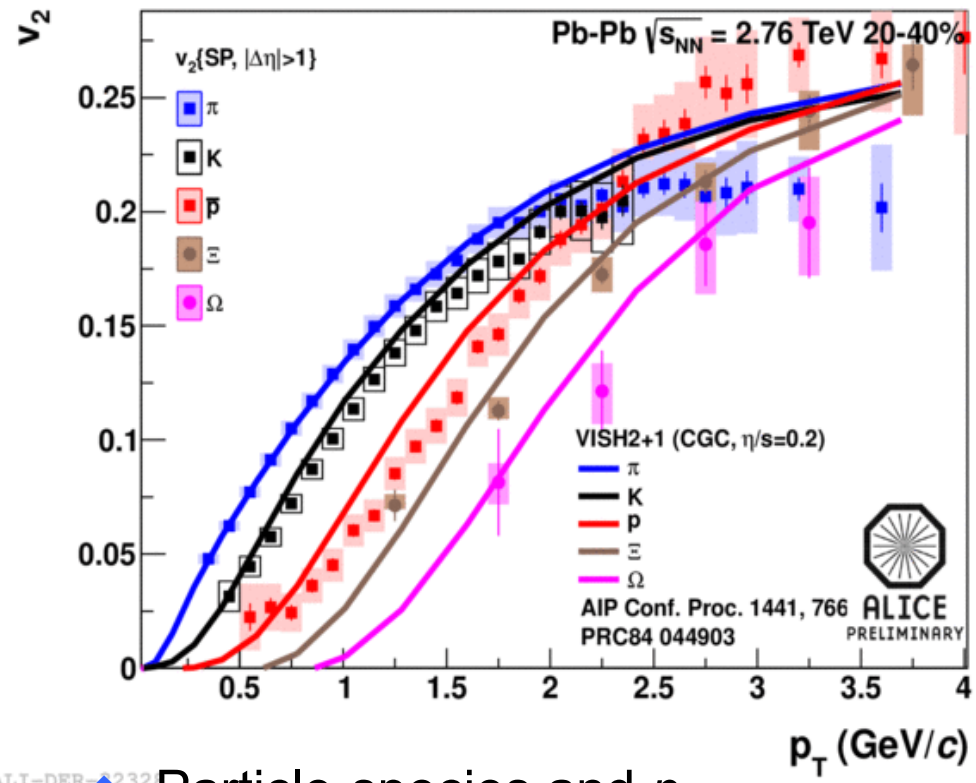


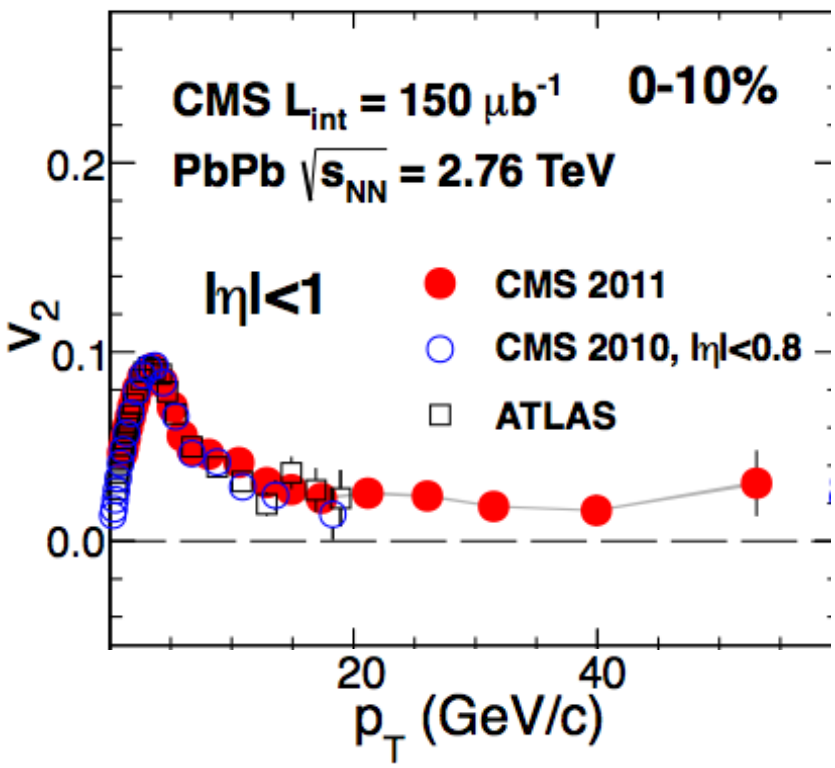
- System geometry asymmetric in non-central collisions
- Expansion under azimuth-dep. pressure gradient results in azimuth-dep. momentum distributions
- Measured by the elliptic flow parameter $v_2(p_T)$

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

- 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



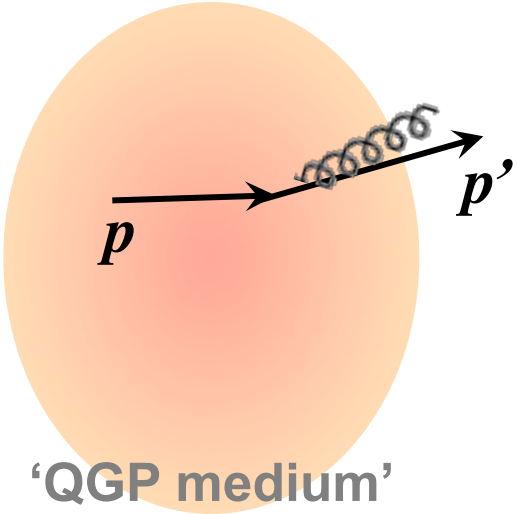


- Particle-species and p_T dependence follow expectations from hydrodynamic models
  - in which v_2 is built at partonic level from collective expansion
  - proton v_2 still not fully described

- 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



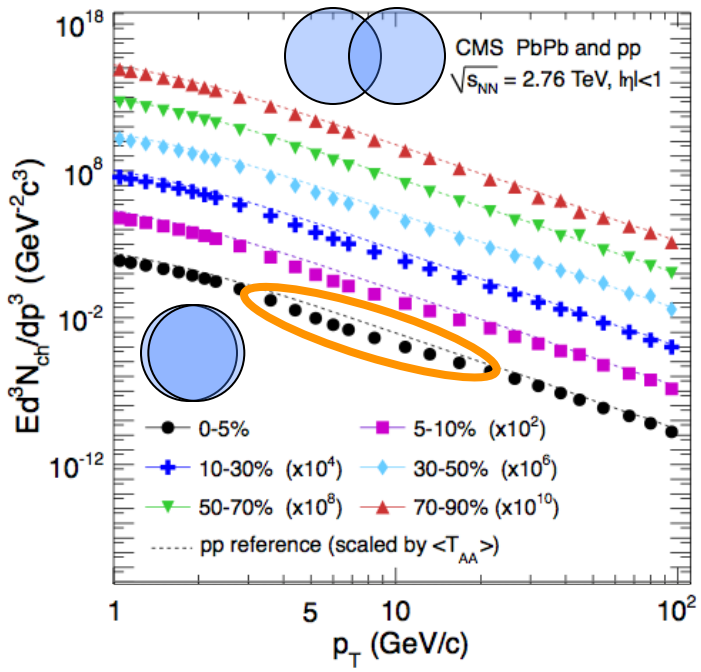
Parton Energy Loss by
- medium-induced gluon radiation
- collisions with medium gluons

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

Nuclear modification factor:

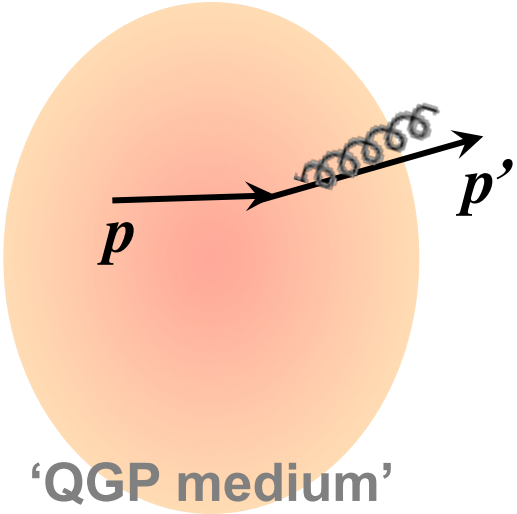
$$dN_{AA}/dp_T < \langle N_{coll} \rangle dN_{pp}/dp_T$$

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



CMS, EPJ C72 (2012) 1945

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



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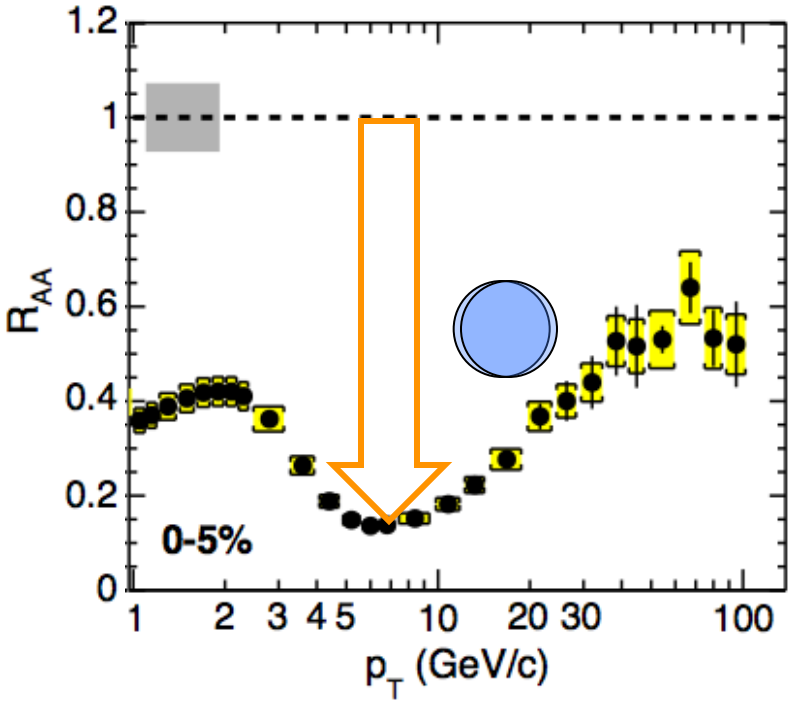
(p-Pb data crucial to measure effect of nuclear initial state)



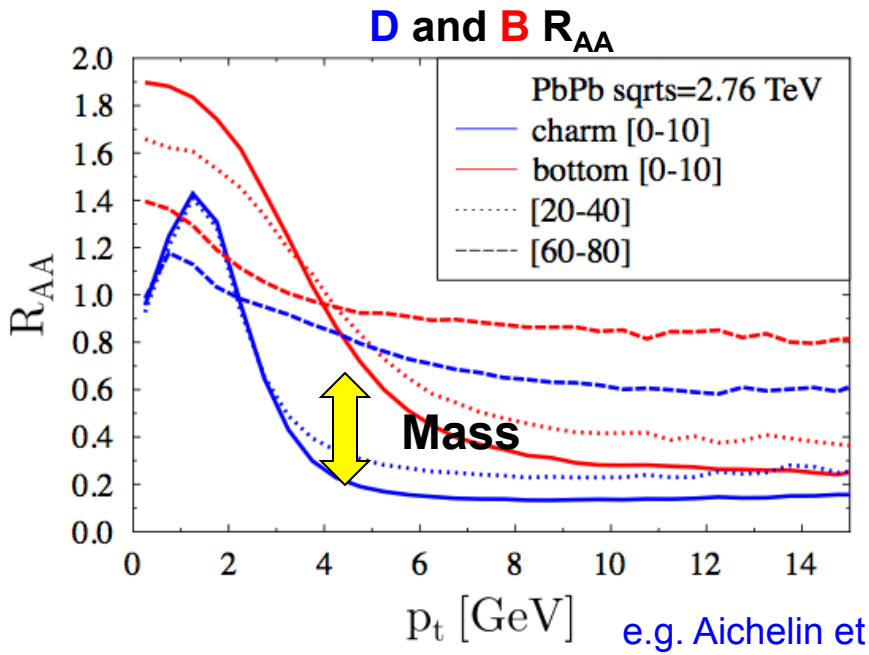
CMS, EPJ C72 (2012) 1945

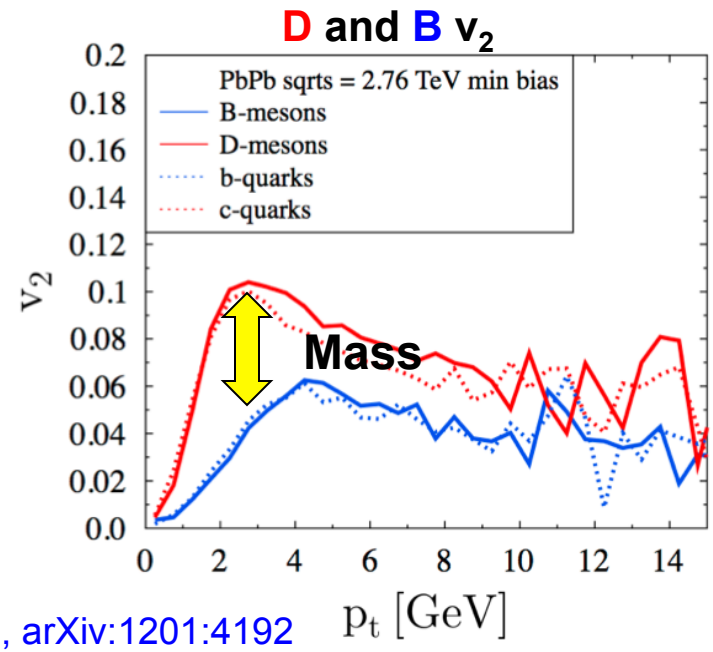
Heavy quark probes of the medium

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

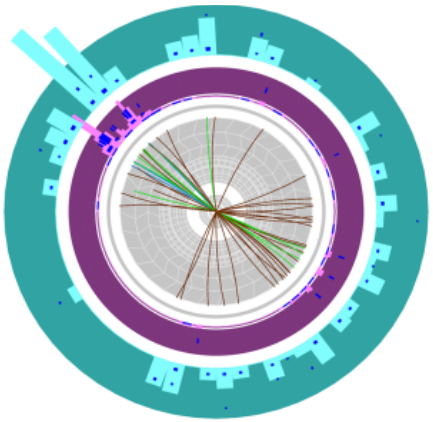


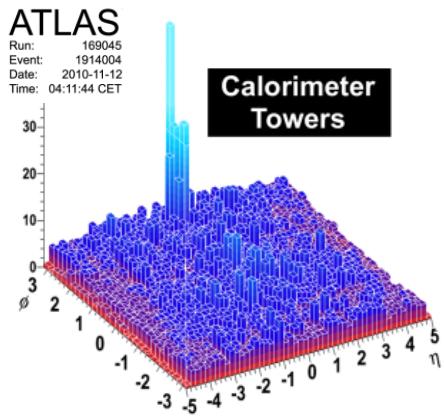


e.g. Aichelin et al., arXiv:1201:4192

Jet quenching

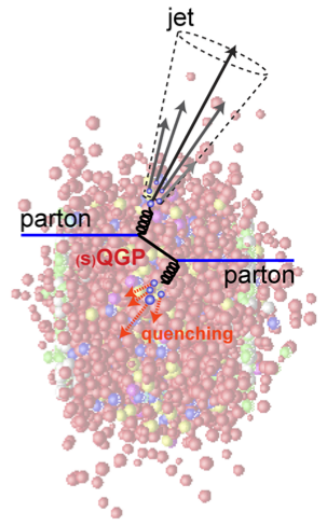
- Pb-Pb events with large di-jet imbalance



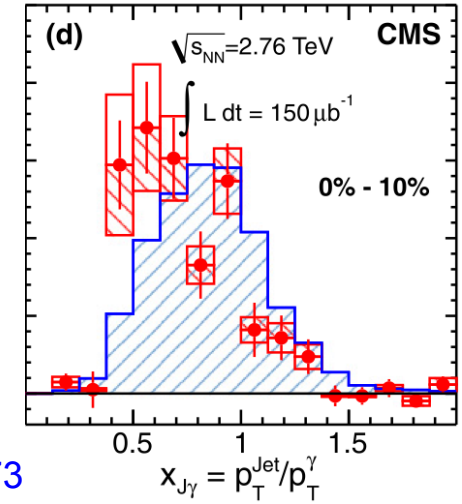


Direct observation of in-medium parton energy loss

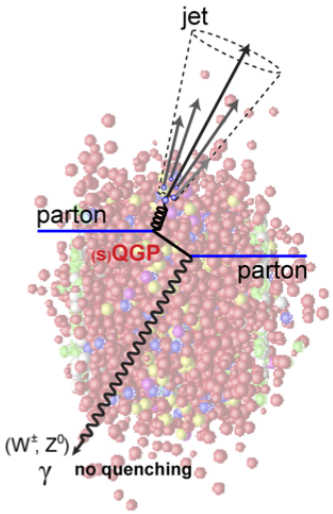
ATLAS, PRL105 (2010) 252303
CMS, PLB712(2012) 176



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

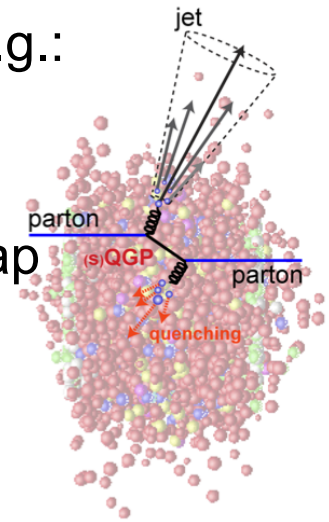


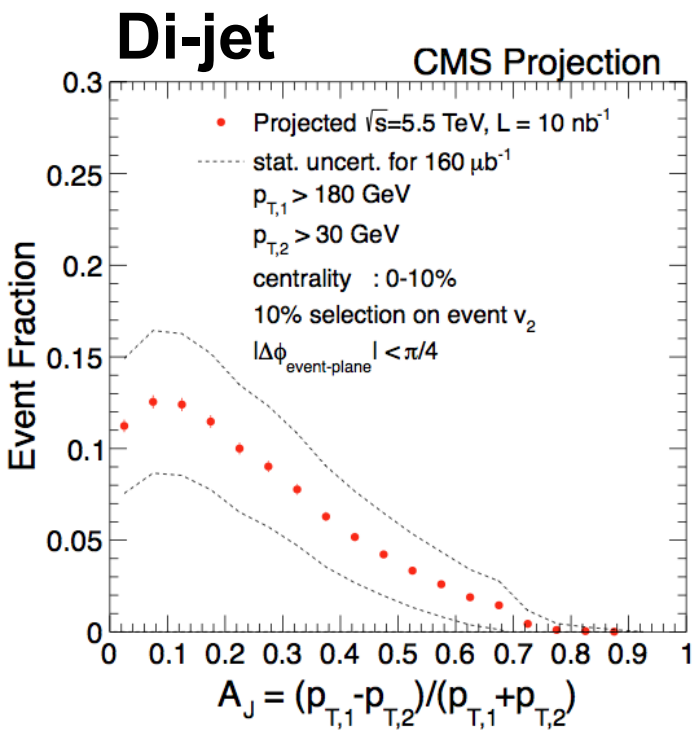
CMS, PLB718 (2013) 773

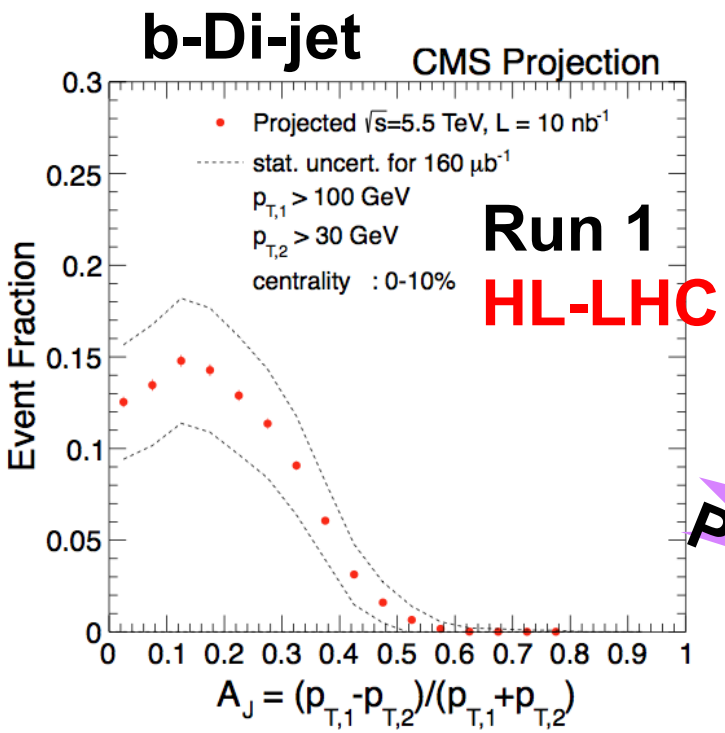


Jets: performance

- 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-*L*ength dependence (e.g. radiative ~L^2, collisional ~L)







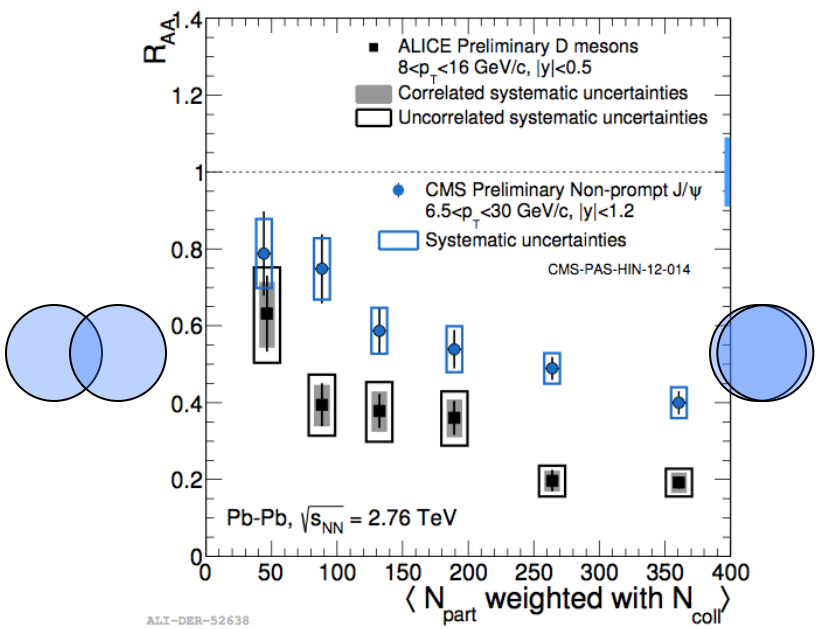
HL-HI-LHC Performance

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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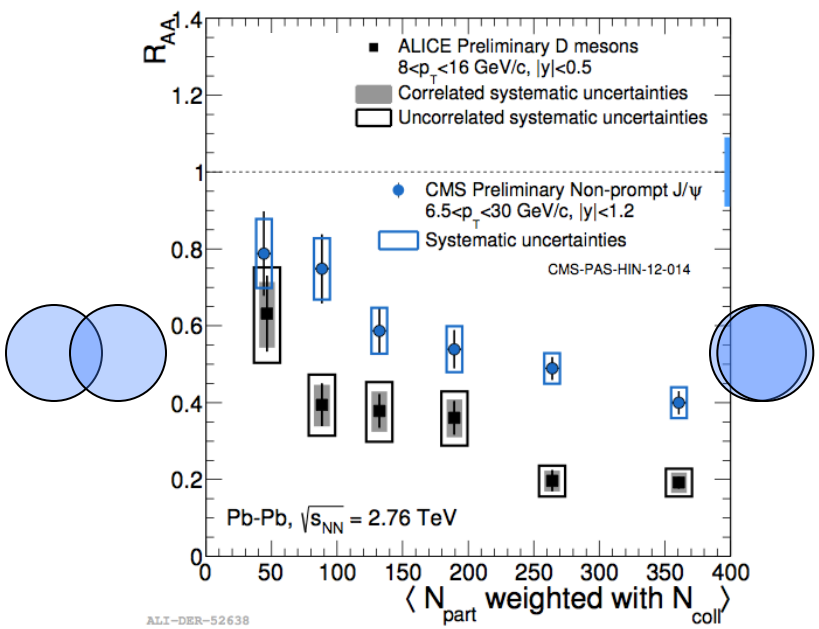
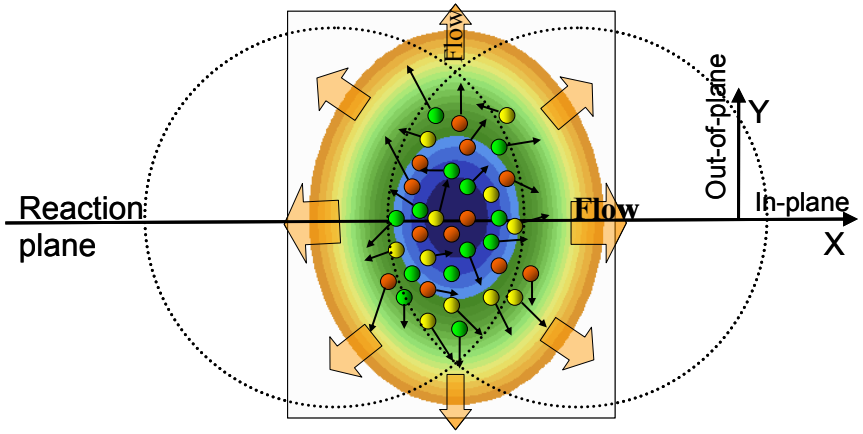


R_{AA}^{B} (CMS) > R_{AA}^{D} (ALICE)

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



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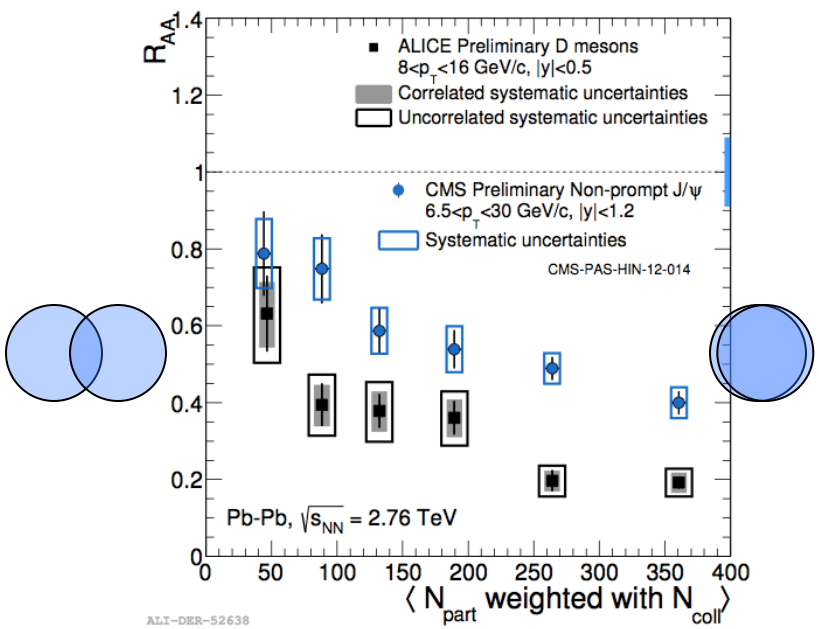
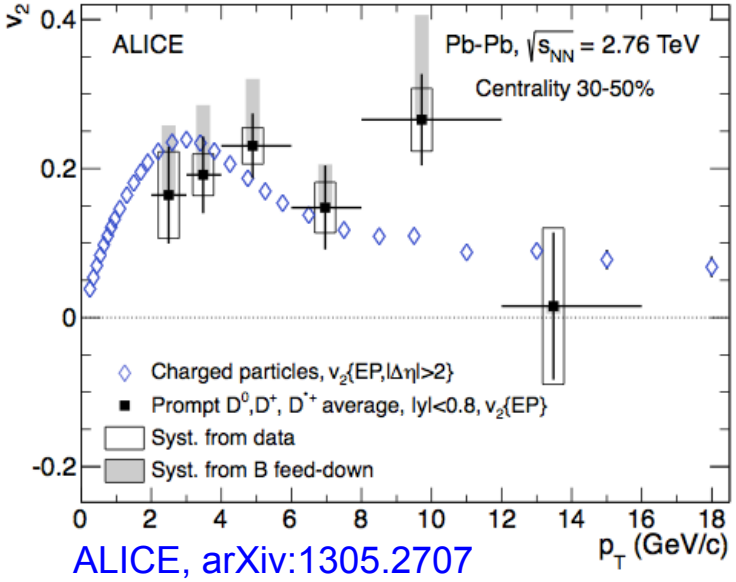


R_{AA}^{B} (CMS) > R_{AA}^{D} (ALICE)

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

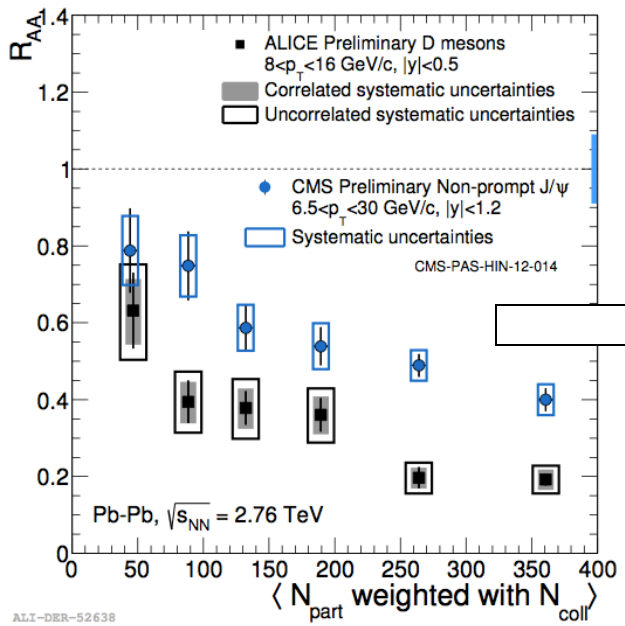


ALICE, arXiv:1305.2707

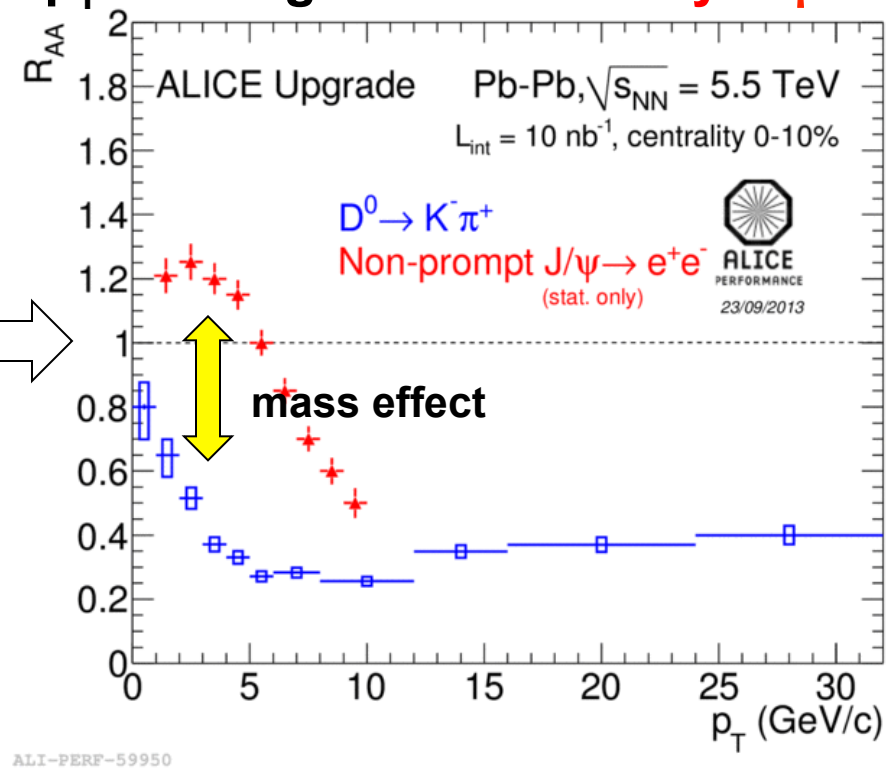
- Heavy quark collective flow?

Heavy flavour R_{AA}: Upgrade

Present data at p_T~10 GeV



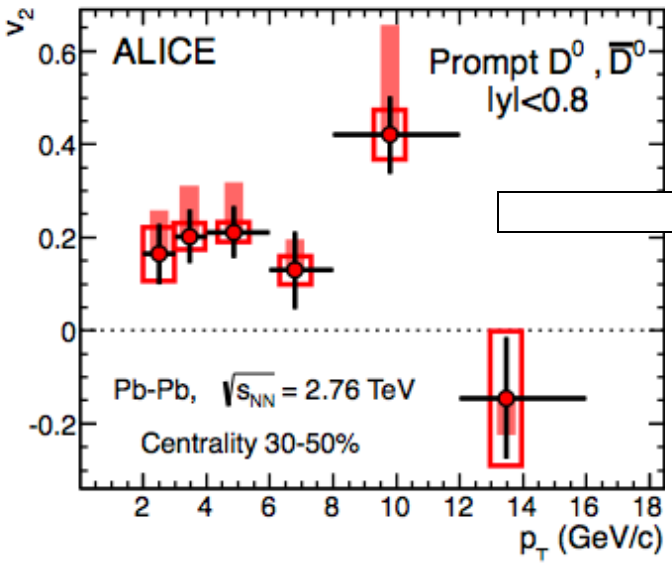
Upgrade: Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ



ALICE, CERN-LHCC-2013-024

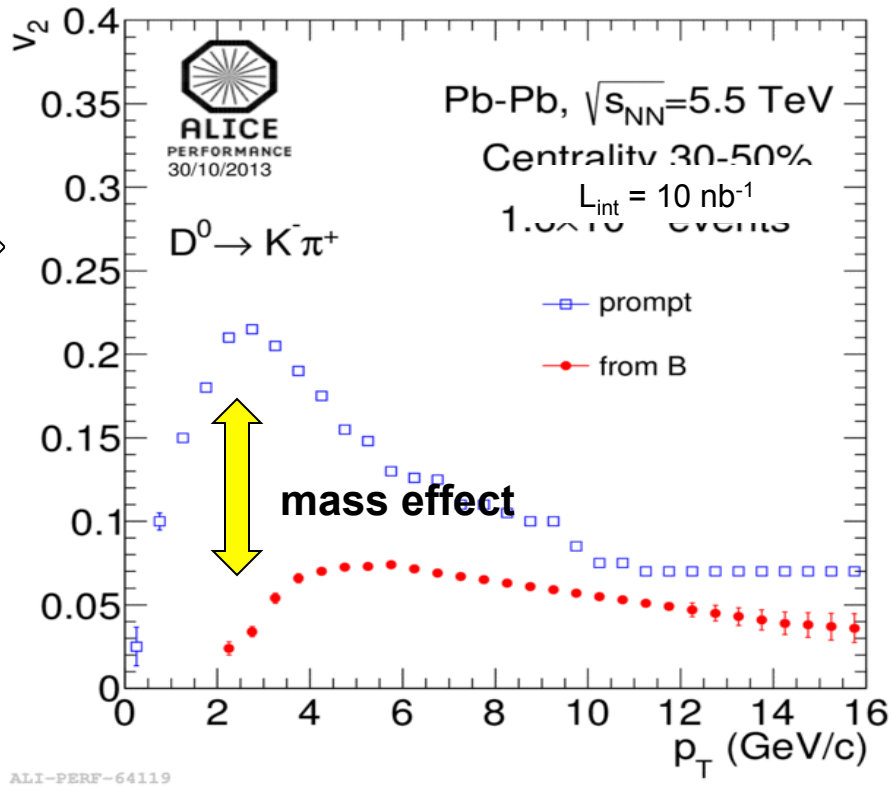
Heavy flavour flow: Upgrade

Present data on charm v_2



ALICE, PRL 111 (2013) 102301

Upgrade: Charm and beauty v_2 down to p_T~0 using prompt and B-decay D^0



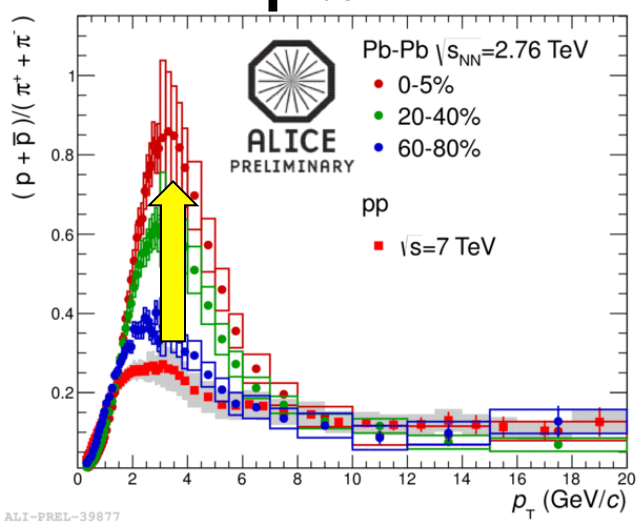
ALICE, CERN-LHCC-2013-024

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

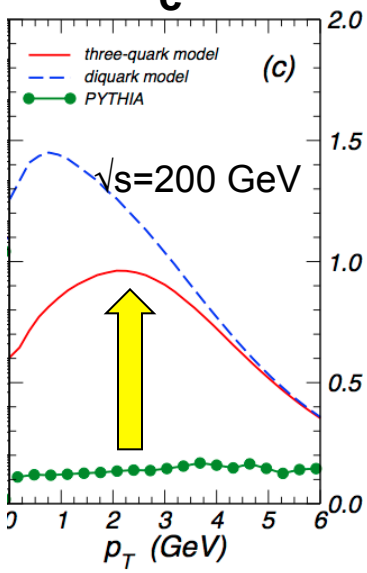
Heavy flavour in-medium hadronization?

- 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

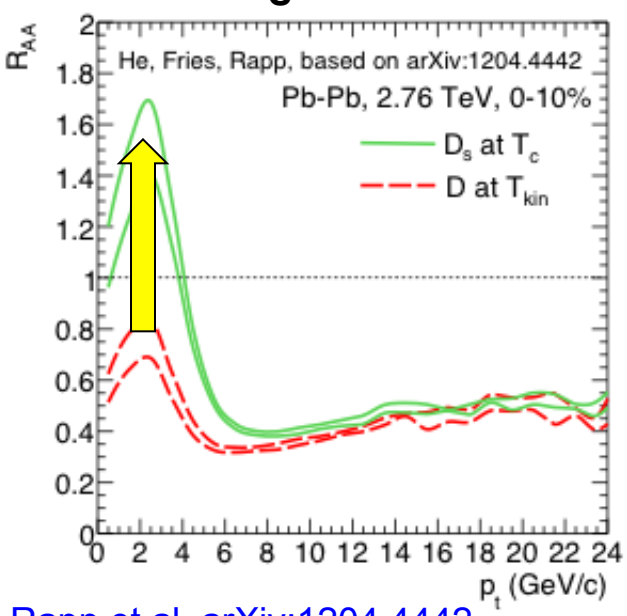


Λ_c/D



Ko et al. PRC79

D_s vs D

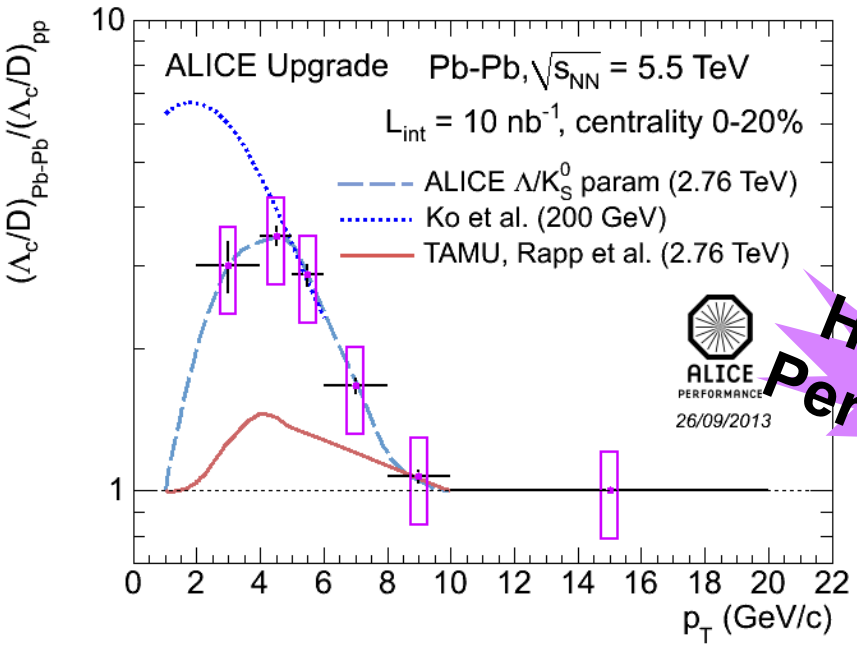


Rapp et al. arXiv:1204.4442

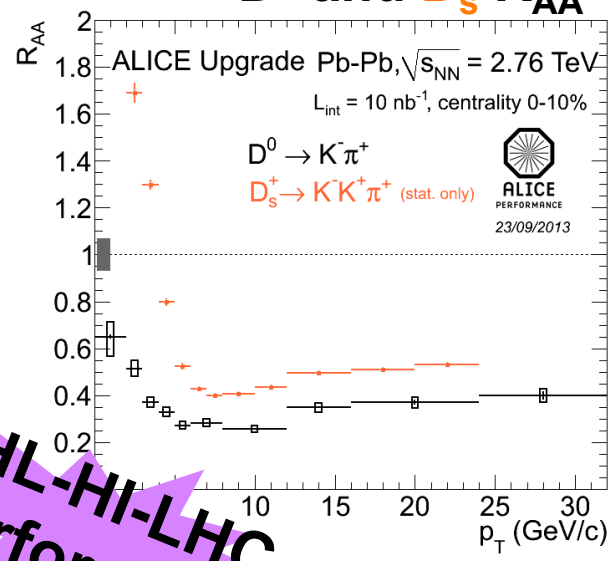
Low-p_T charm: performance

- $\Lambda_c \rightarrow pK\pi$ 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.)

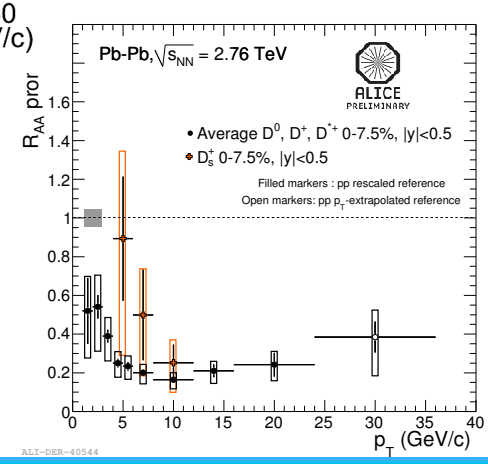


D^0 and D_s R_{AA}



HL-HI-LHC Performance

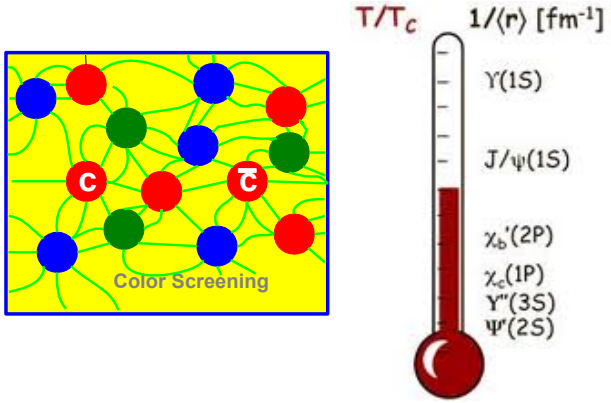
2011 data

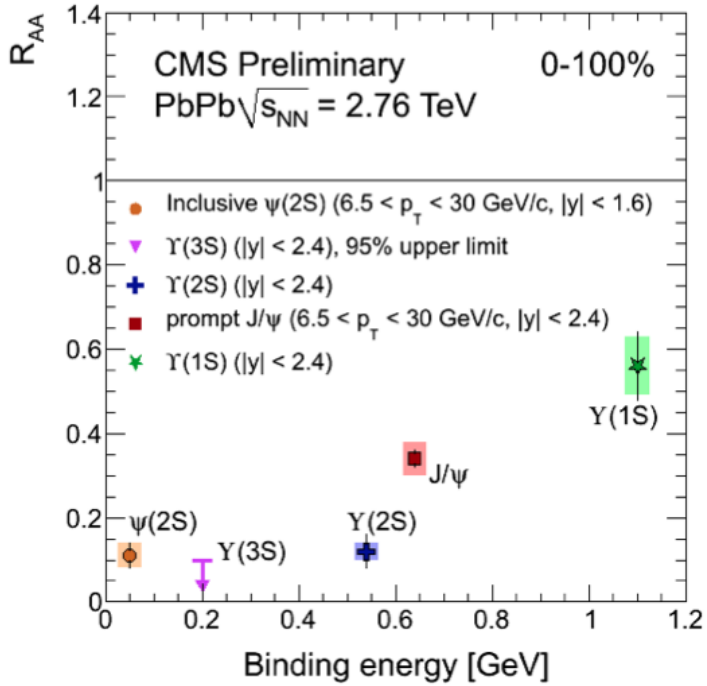


Needs minimum-bias trigger (low S/B)
→ HL-LHC = 100x Run2 stat.

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

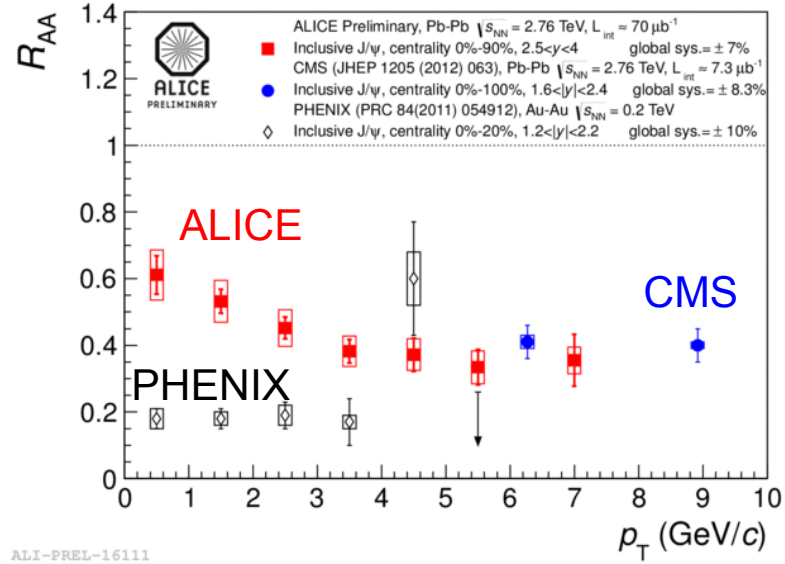
CMS, arXiv:1208.2826 and PRL 109 (2012) 222301

CMS, PAS-FTR-13-025

Low-p_T charmonium: performance

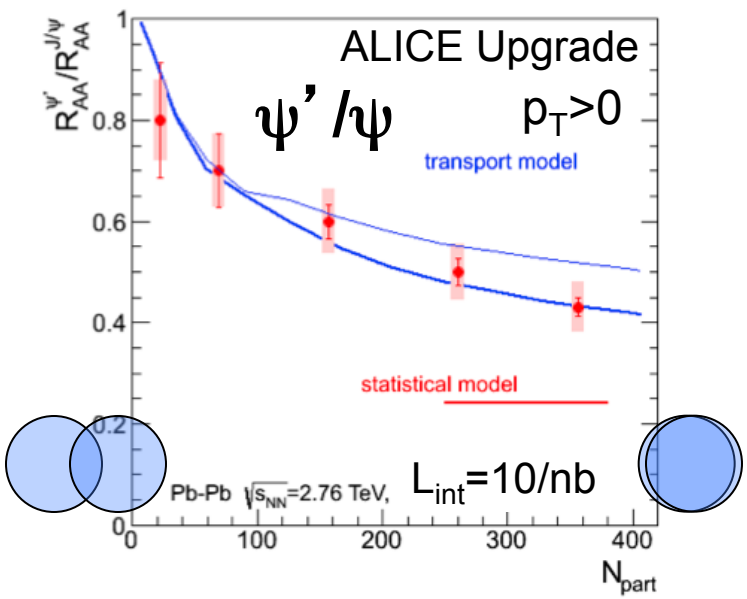
- Low-p_T J/ψ at the LHC is less suppressed than at RHIC
  - Despite the x2-3 higher density
- ψ regeneration from uncorrelated c and $\bar{c}$ in a deconfined medium?

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



High statistics → explore this "new" probe of deconfinement

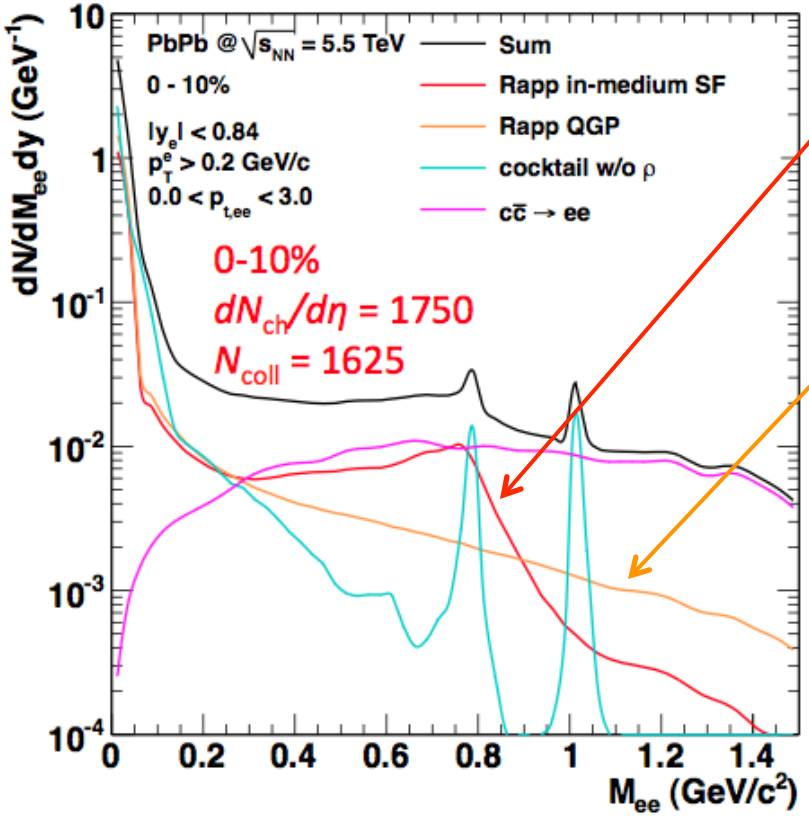
- Understand the underlying mechanism that binds deconfined heavy quark pairs
- Add information! E.g. low-p_T ψ' /ψ discriminates between models



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 $\gamma \rightarrow l^+l^-$

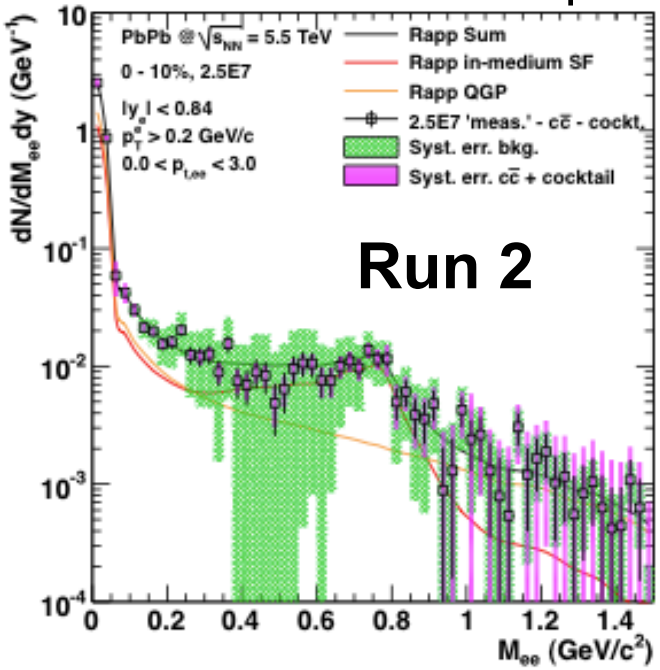
Low-mass di-leptons: performance

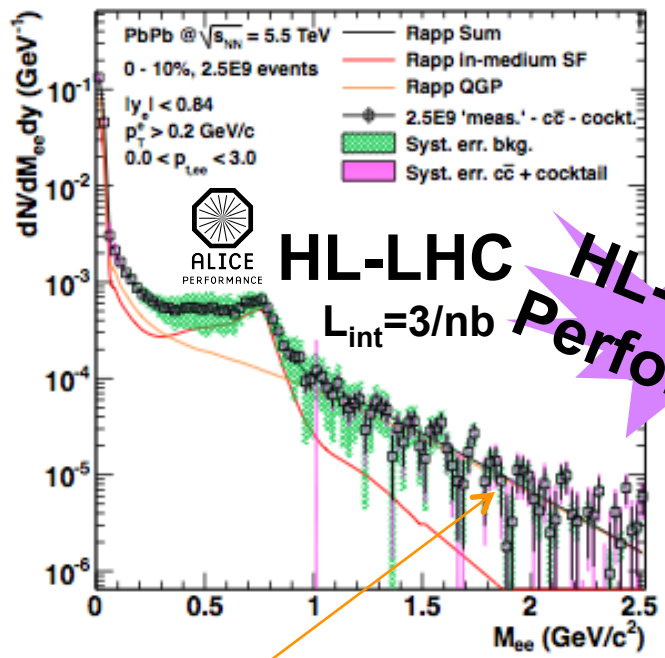
- ALICE: new inner tracker **+ dedicated run at 0.2 T (+3/nb)**

  → 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:



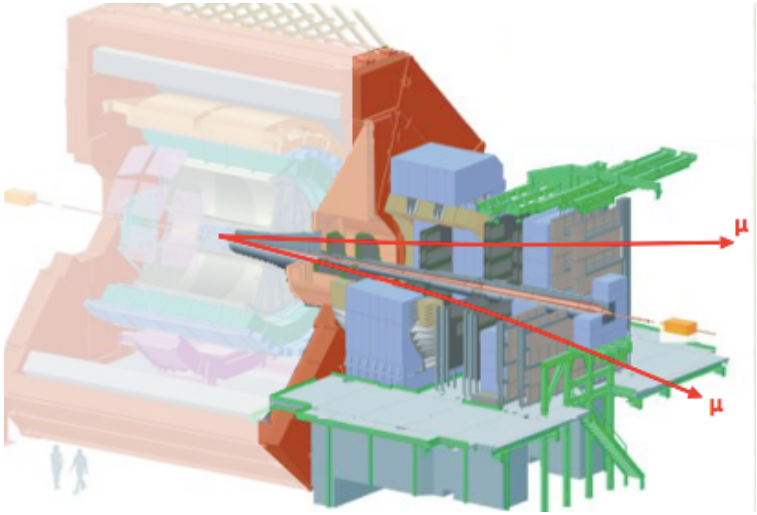


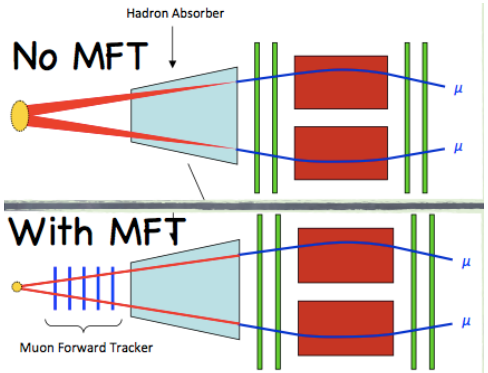
HL-HI-LHC Performance

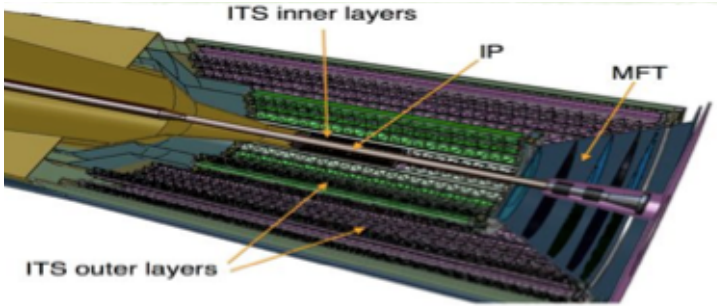
Precision of ~10% on the inverse slope → *T*

ALICE, CERN-LHCC-2012-012

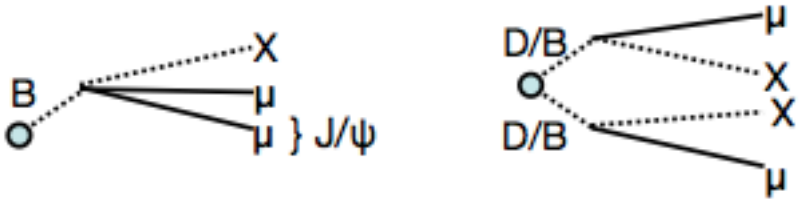
ALICE MFT: (di)muons at forward rapidity 2.5<η<3.5







- Silicon pixel tracker in front of the muon spectrometer, covering 2.5<η<3.5
- Enables separation of beauty decay vertices:

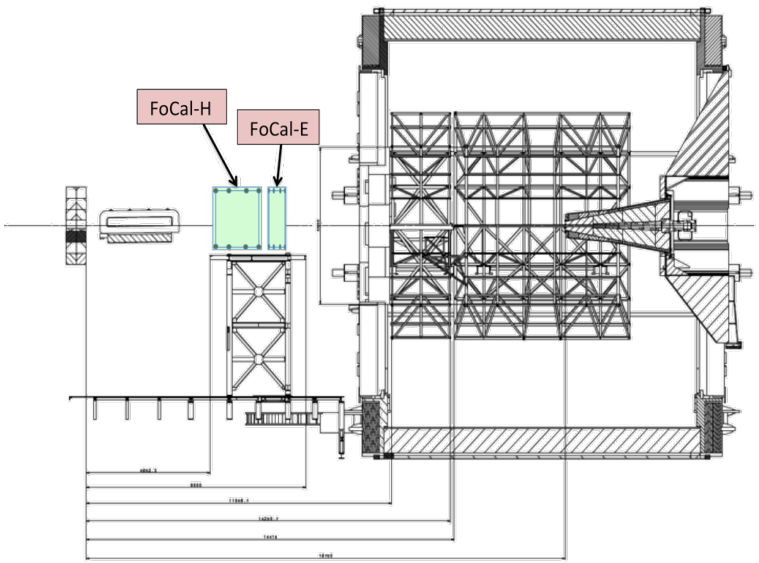


- ALICE Upgrade LOI Addendum (Muon Forward Tracker) approved by LHCC at the end of 2013
- TDR planned for Dec 2014

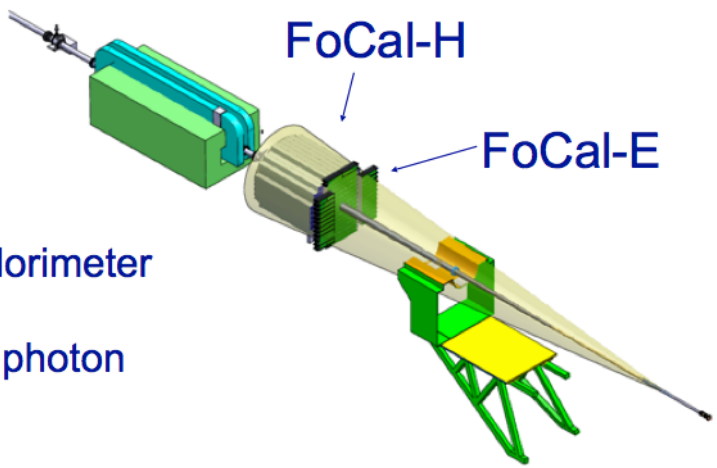
ALICE Upgrade LOI Addendum, CERN-LHCC-2013-014

Study for a forward calorimeter in ALICE

- FoCal: a new high-granularity calorimeter at η~3-5 for saturation physics studies
- Benchmark measurement: forward direct photons (see next slide)



- Discussion in ALICE ongoing, internal LOI in preparation
- After internal approval, installation possibility during LS3 will be evaluated



FoCal-E: high-granularity Si-W calorimeter for photons and π^0
FoCal-H: hadronic calorimeter for photon isolation and jets