LHC experiments plans for "HL-LHC" HI running (ca. 2020-2027)

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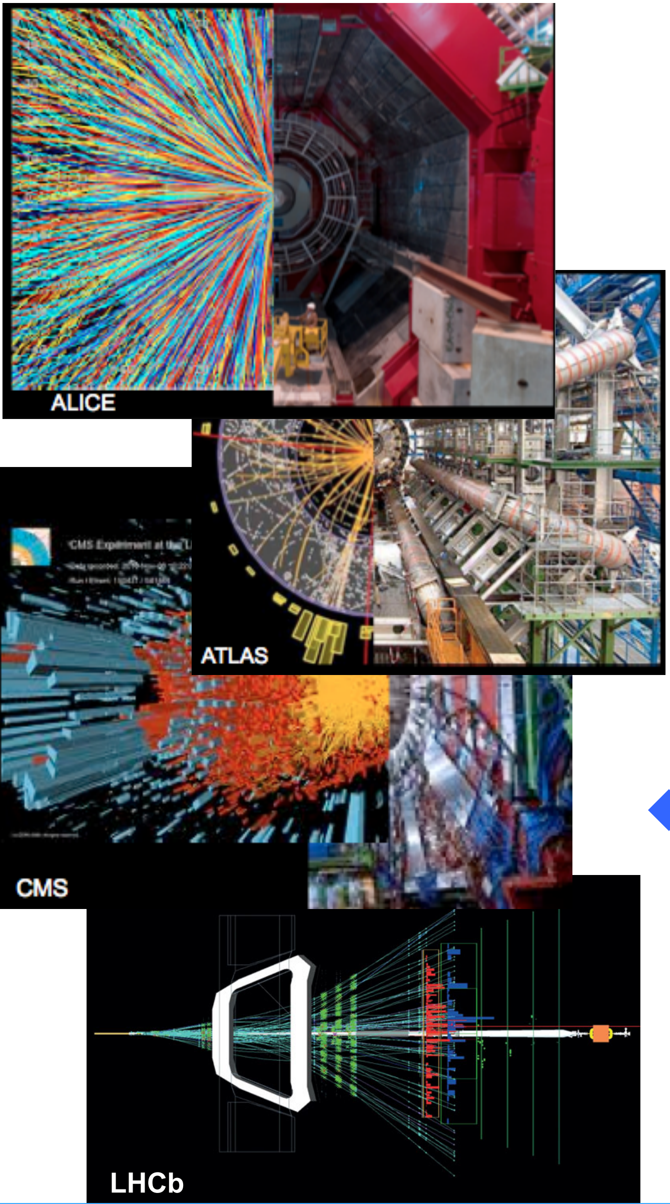
based on presentation at the
"ECFA High Luminosity LHC Experiments Workshop"
Aix-les-Bains, Oct 1-3, 2013

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

Outline

- Timeline of HI running
- HI Physics programme at HL-LHC
- Besides Pb-Pb: pp reference, pA, light ions

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

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 (2018-19): major ALICE and LHCb upgrades, important upgrades for ATLAS and CMS, LHC collimator upgrades

- Run 3 (2020-22?) + Run 4 (2025-27?): Pb-Pb
  - Experiments: >10/nb Pb-Pb (ALICE: 10/nb at 0.5T +3/nb at 0.2T)
- pp reference at 5.5 TeV
  - ALICE (for HF and charmonia): **~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)

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**)

Experiment upgrades most relevant to HI

- 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

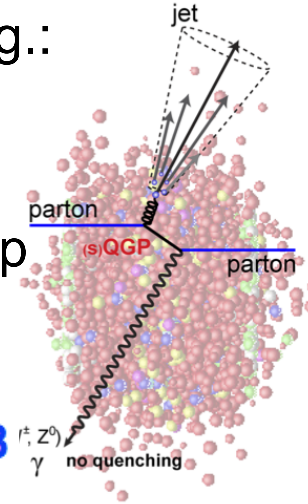
50 kHz → **L1** → **~ few kHz** → **HLT** → **~ 100 Hz**

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

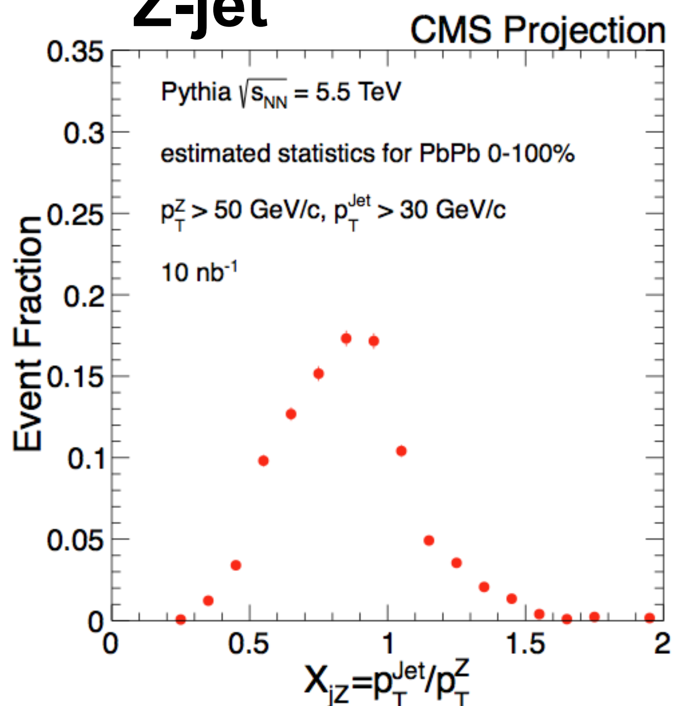
Jets: performance

→ Next talk by C. Roland

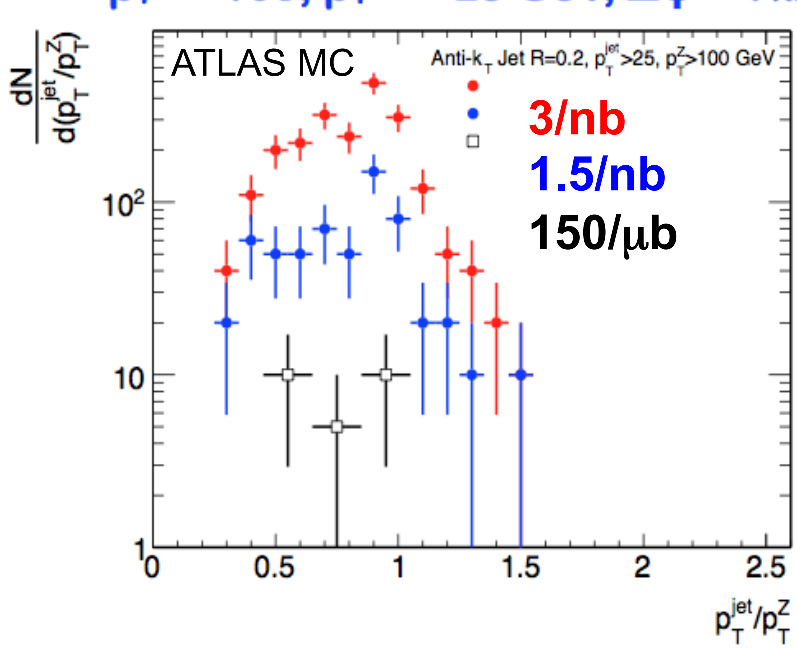
- High precision γ-jet, Z-jet, di-jet correlations, also with b-jets. E.g.:
  - 10M di-jets with $p_{T,1}$>120 GeV/c (CMS, 10/nb)
  - 140k b-jets with p_T > 120 GeV/c (CMS, 10/nb)
- Understand medium response and energy radiation details, map path-*L*ength dependence (e.g. radiative ~L^2, collisional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



Z-jet



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



CMS, PAS-FTR-13-025

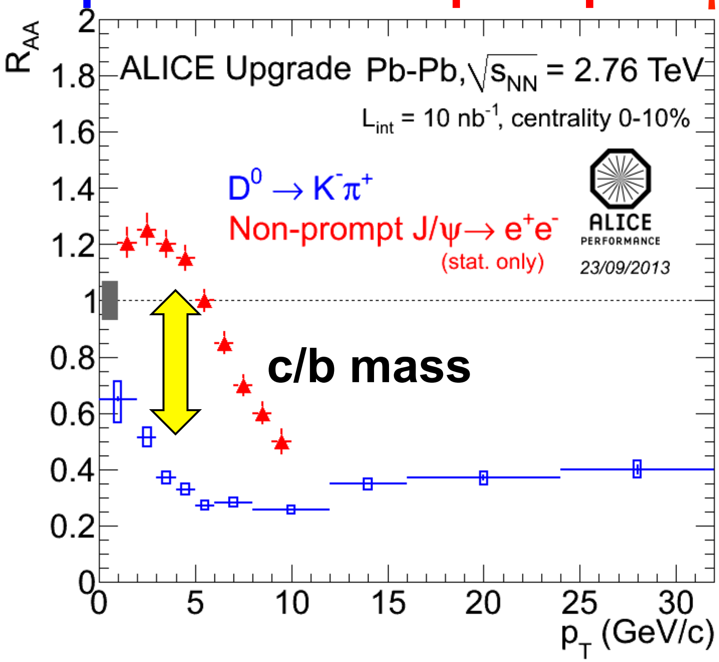
HF suppression and flow: performance

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

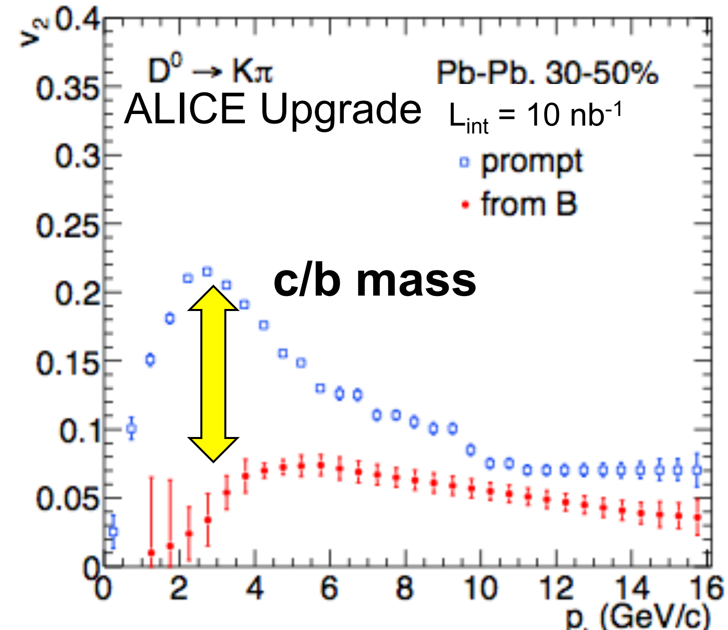
- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

→ 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}



Prompt and non-prompt D^0 v_2



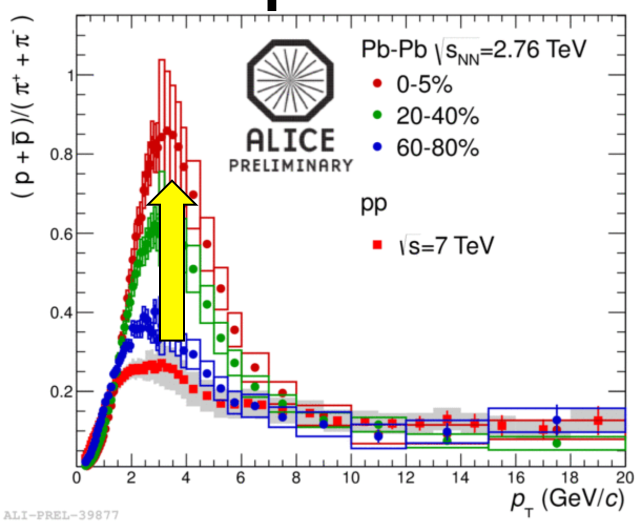
Input values from BAMPS model:
C. Greiner et al. arXiv:1205.4945

ALICE, CERN-LHCC-2012-012

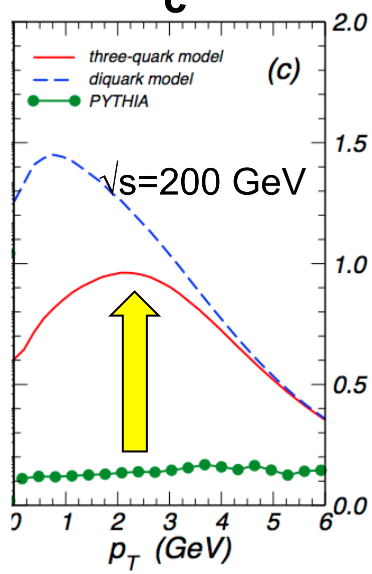
Heavy flavour in-medium hadronization?

- 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

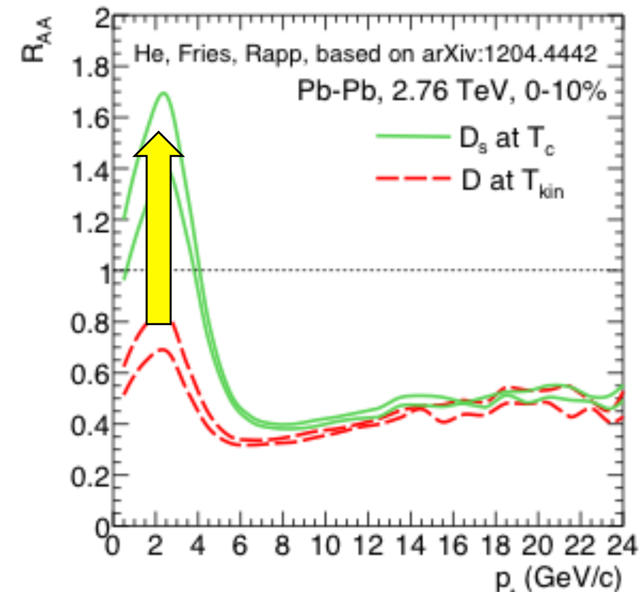


Λ_c/D



Ko et al. PRC79

D_s vs D

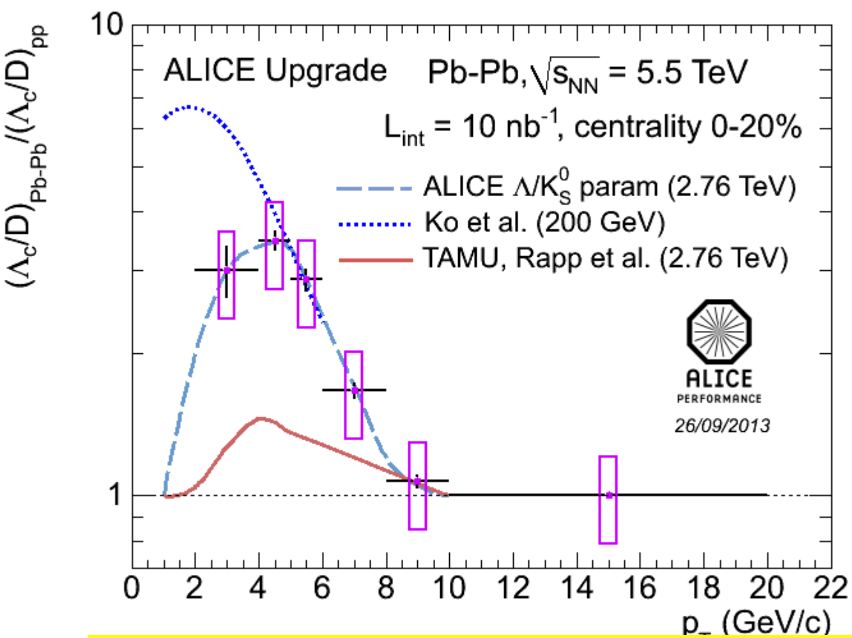


Rapp et al. arXiv:1204.4442

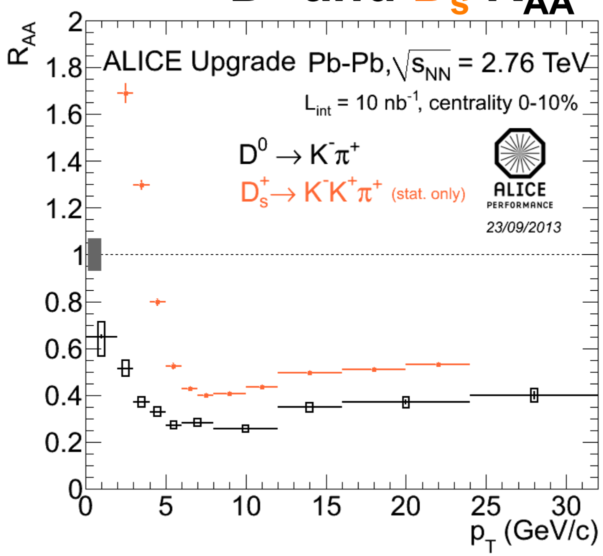
Low-p_T charm: performance

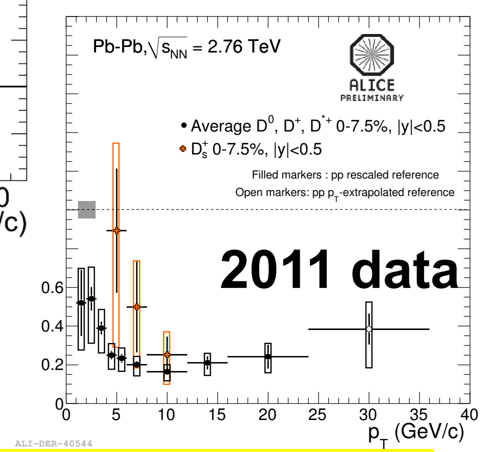
- $\Lambda_c \rightarrow pK\pi$ and $D_s \rightarrow KK\pi$ ($c\tau$=60 and 150 μm) measured with good precision in ALICE with upgrades and 10/nb

Λ_c/D enhancement
(full detector sim.)



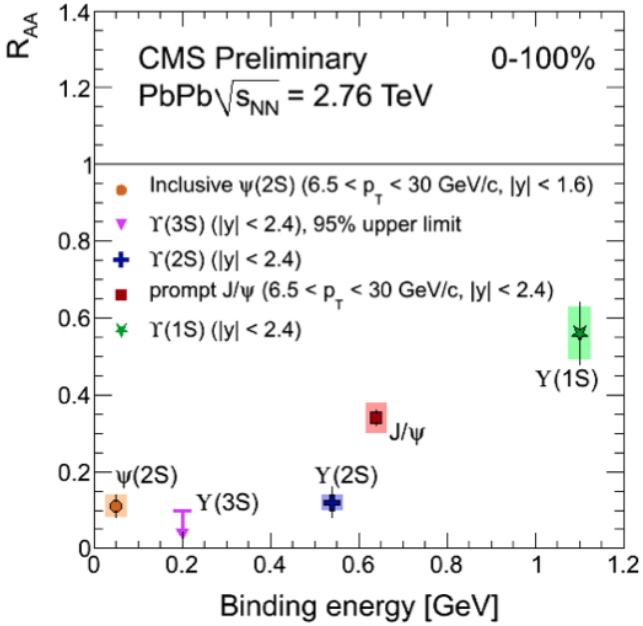
D^0 and D_s R_{AA}





FHC: spectacular effects if thermal charm production?
\+ doubly and triply charmed hadrons? What would we learn?

Quarkonium melting

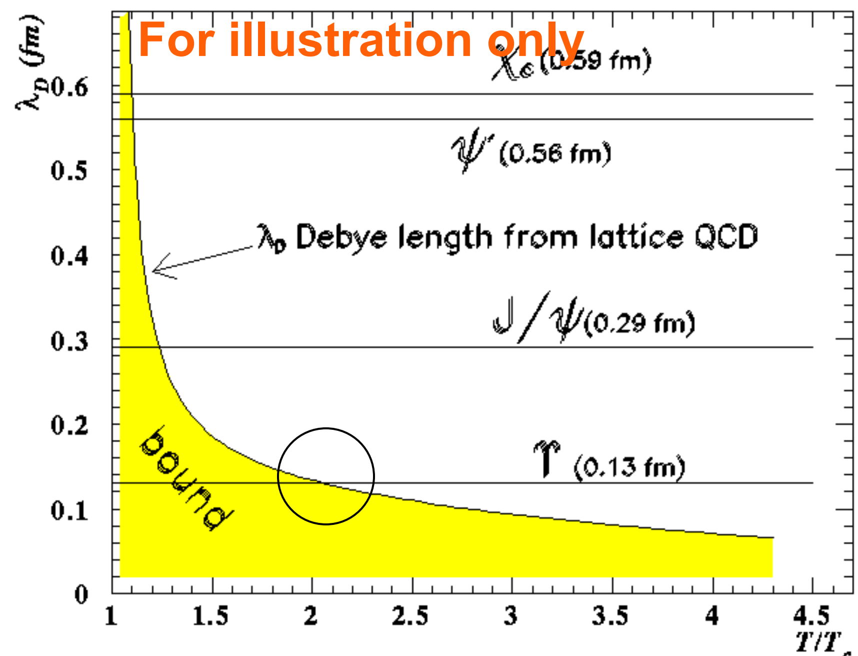


- Υ(1S) R_{AA}~0.5: consistent with suppression of higher states only?
- Υ(1S) may not melt at LHC energy? (not even at 5.5 TeV?)
- Interesting for FHC?

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

Υ(1s)	Υ(2s)	Υ(3s)
270k	40k	7k

CMS, PAS-FTR-13-025



Digal,Petrecki,Satz PRD 64(2001) 0940150

LHC vs. FHC: luminosity

TABLE 1. Peak luminosity and Integrated luminosity per month of running.

	LHC Run 2 [1]	LHC after LS2 [1]	FHC [2]
Pb–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{27}	5×10^{27}	13×10^{27}
Pb–Pb L_{int} / month (nb^{-1})	0.8	1	5
p–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{29}	t.b.d.	3.5×10^{30}
p–Pb L_{int} (nb^{-1})	80	t.b.d.	1000

Pb-Pb L_{int}/month larger by x5 at FHC: e.g. 25/nb for a program of 5 years.

Note that LHC experiments goal for HL-LHC is 10/nb for a program of 3-4 years… i.e. ~2.5/nb per month (LHC todays "commits" only to 1/nb per month)

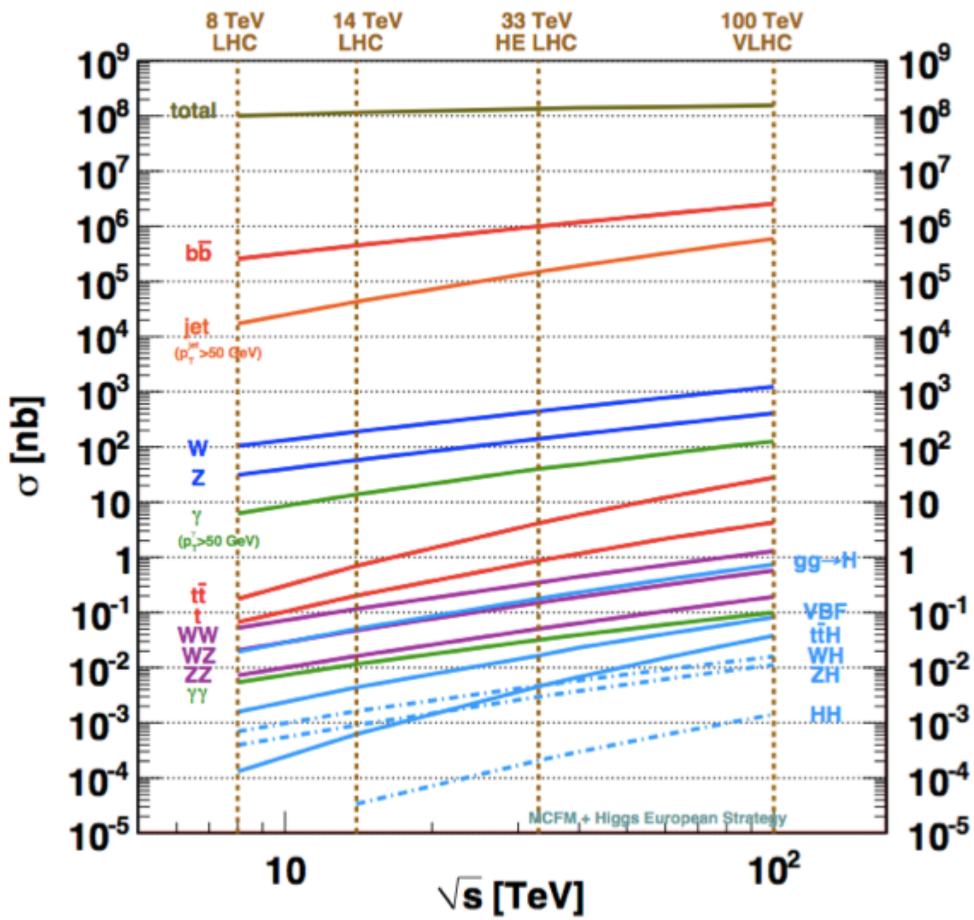
Can/should we consider more ambitious numbers, e.g. FHC = 5xLHC~50/nb?

LHC vs. FHC:
Pb-Pb system properties

Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c
T at $\tau = 1$ fm/c	280 MeV	300 MeV	365 MeV
ϵ at $\tau = 1$ fm/c	12 GeV/fm^3	16 GeV/fm^3	35 GeV/fm^3

Temperature and energy density increase only by factors 1.2 and 2 (resp), <u>if we consider the same time τ</u>.

LHC vs. FHC: cross sections



J. M. Campbell, K. Hatakeyama, J. Huston, F. Petriello, J. R. Andersen, L. Barze, H. Beauchemin and T. Becher *et al.*, arXiv:1310.5189 [hep-ph].

EXTRA SLIDES

About “boosted” top

- The ttbar cross section increases by a factor more than 50
- With L_{int}=50/nb (ambitious!), x250 top wrt HL-LHC
- CMS estimates to get 500 reconstructed ttbar with 10/nb
- So, with a detector similar to CMS, we have ~10^5
  - The pT distribution is shown here (slide 6)https://indico.cern.ch/getFile.py/access?contribId=0&resId=0&materialId=slides&confId=284799
- Expected decay time (5×10^{-25} s) + mass → L_{decay}~1 fm*p[TeV]
- What happens to a top quark in the medium? does it radiated gluons? (m/E ~ 0.1 at 2 TeV, like a 15 GeV c quark)
- Top cross section drops by 3.5 orders of magnitude at pT=1 TeV and almost 5 orders of magnitude at 2 TeV
- So, one expects a few tens of tops at 1 TeV
- How about lower pT tops? Can they still be considered "interesting"?

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

Jets: performance

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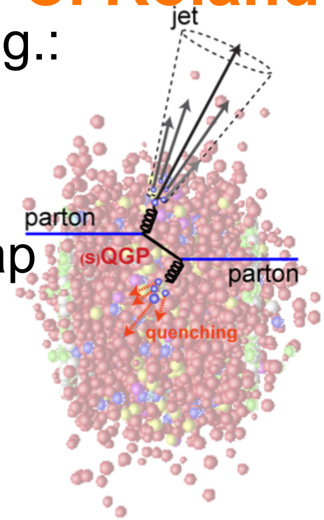
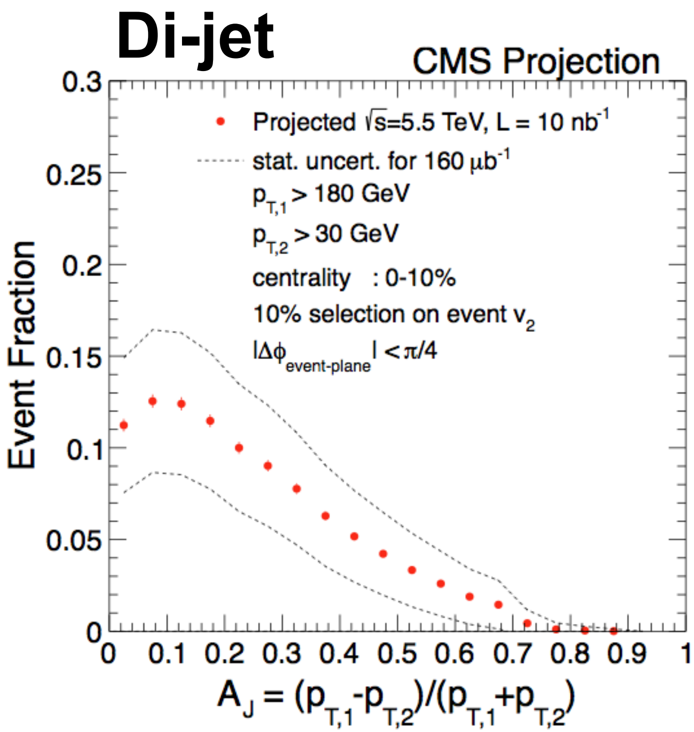
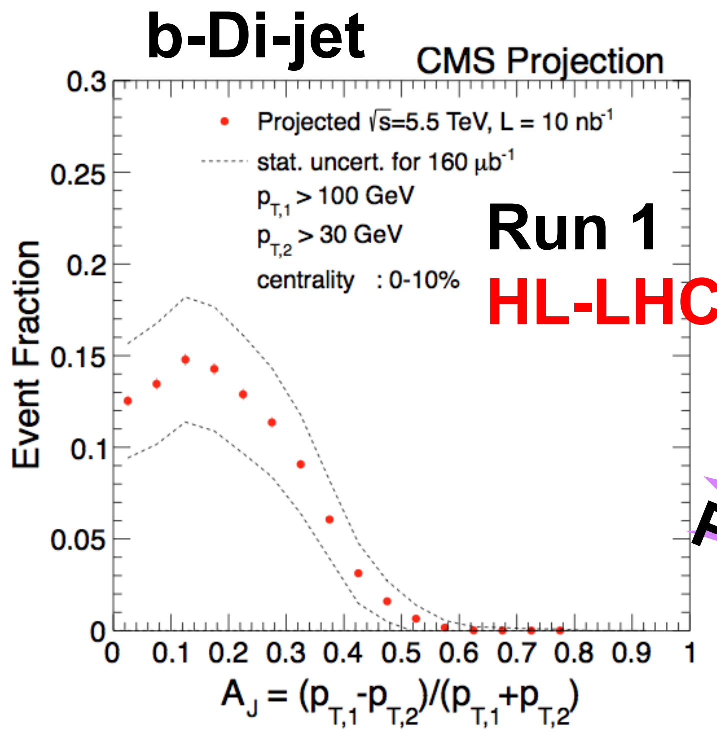






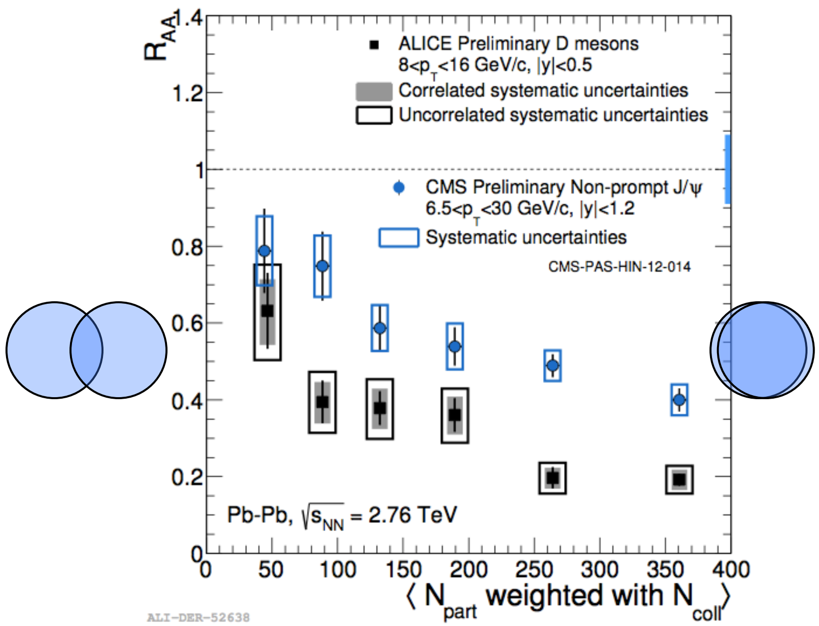
HL-HI-LHC Performance

CMS, PAS-FTR-13-025

Heavy quark probes of the medium

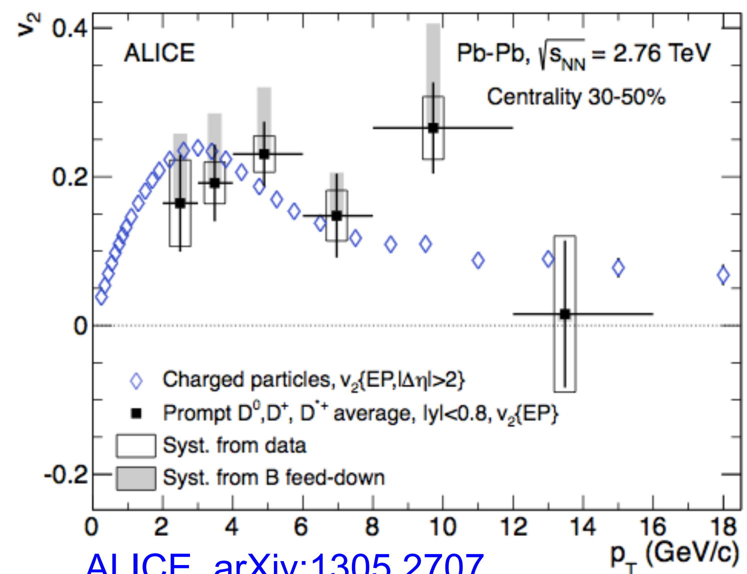
- Energy loss expected to depend on parton mass
- First indication at LHC:

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



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

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



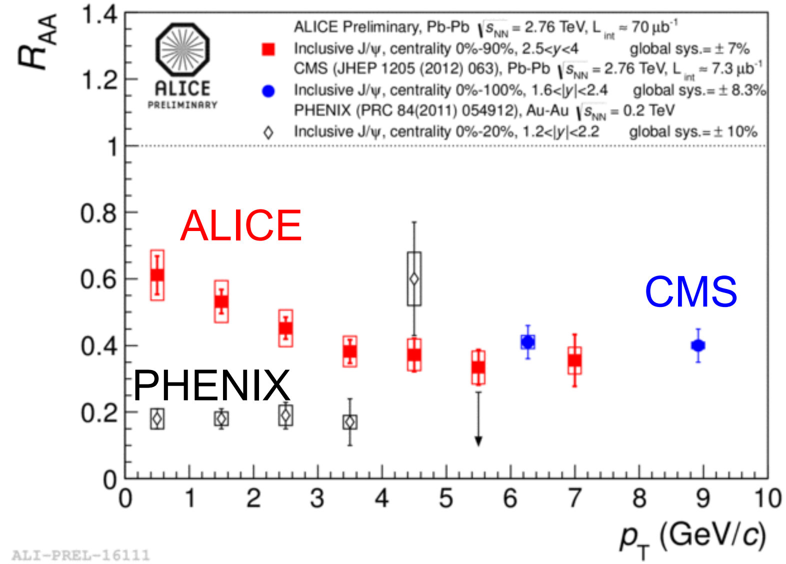
ALICE, arXiv:1305.2707

- Heavy quark collective flow?

Low-p_T charmonium: performance

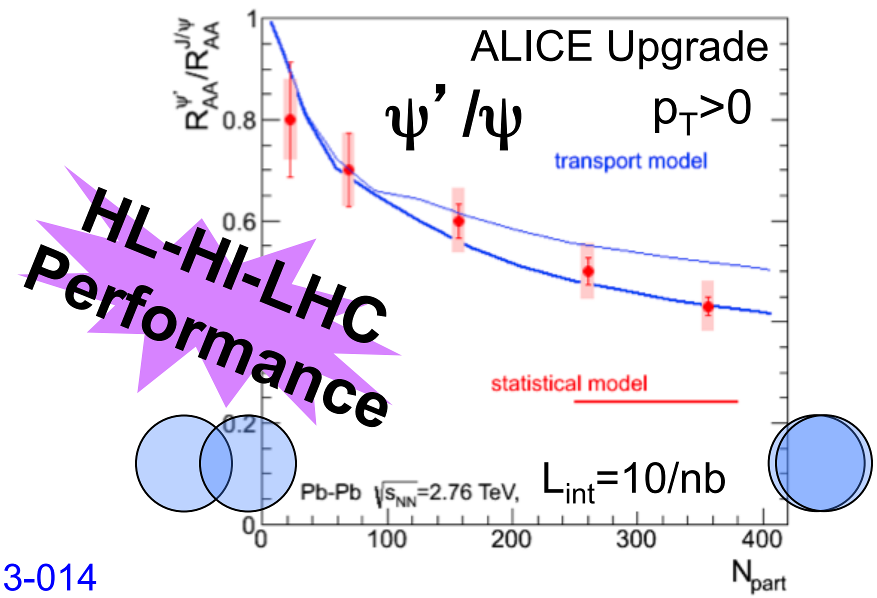
- Low-p_T J/ψ at the LHC is less suppressed than at RHIC
  - Despite the x2-3 higher density
- ψ regeneration from uncorrelated c and $\bar{c}$ in a deconfined medium?

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



High statistics → explore this "new" probe of deconfinement

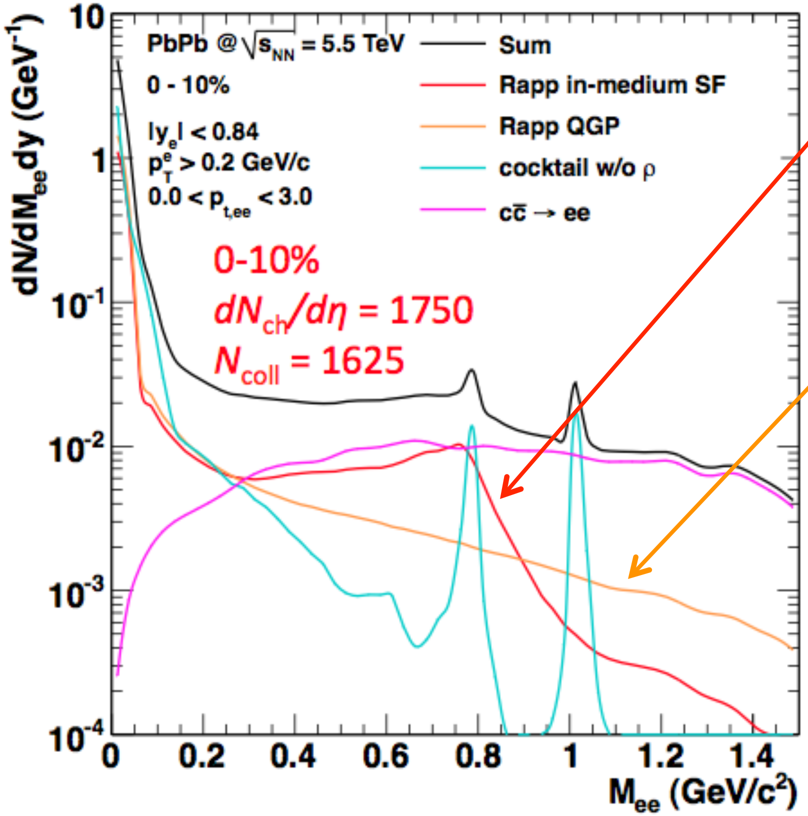
- Understand the underlying mechanism that binds deconfined heavy quark pairs
- Add information! E.g. low-p_T ψ' /ψ discriminates between models



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 $\rho \to l^+l^-$

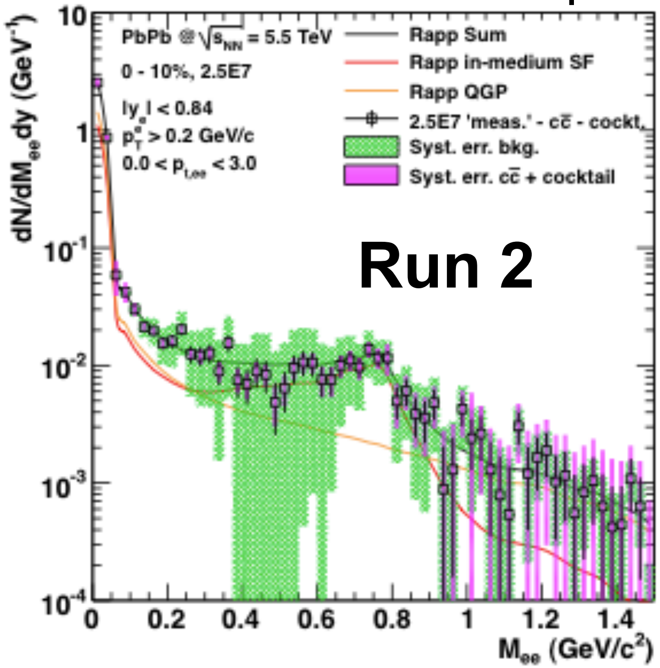
Profile system temperature during its evolution → Di-leptons from real and virtual photons $\gamma \to l^+l^-$

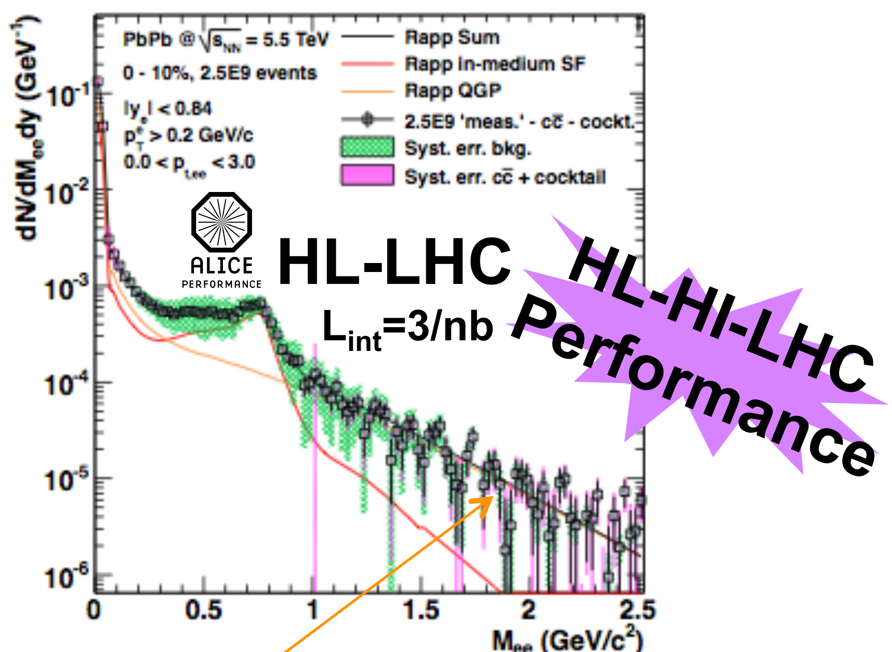
Low-mass di-leptons: performance

- 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