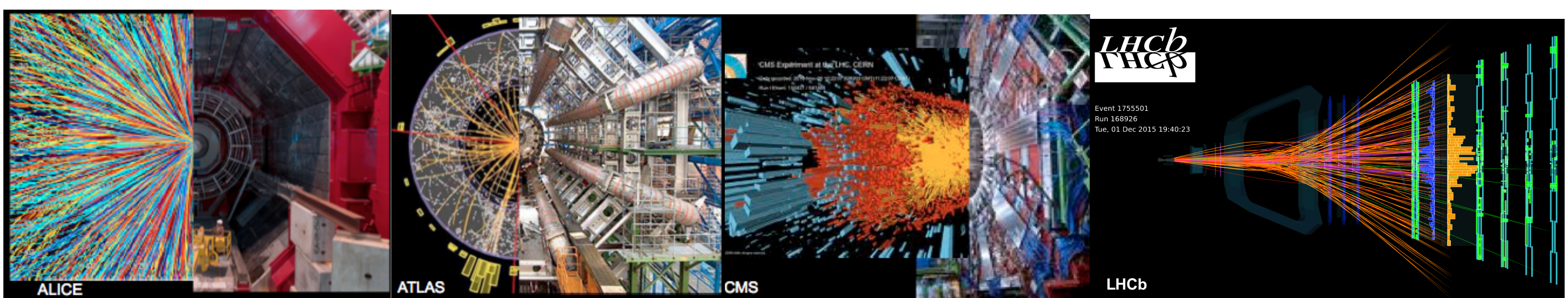
Physics with heavy ion collisions at LHC beyond Run-2

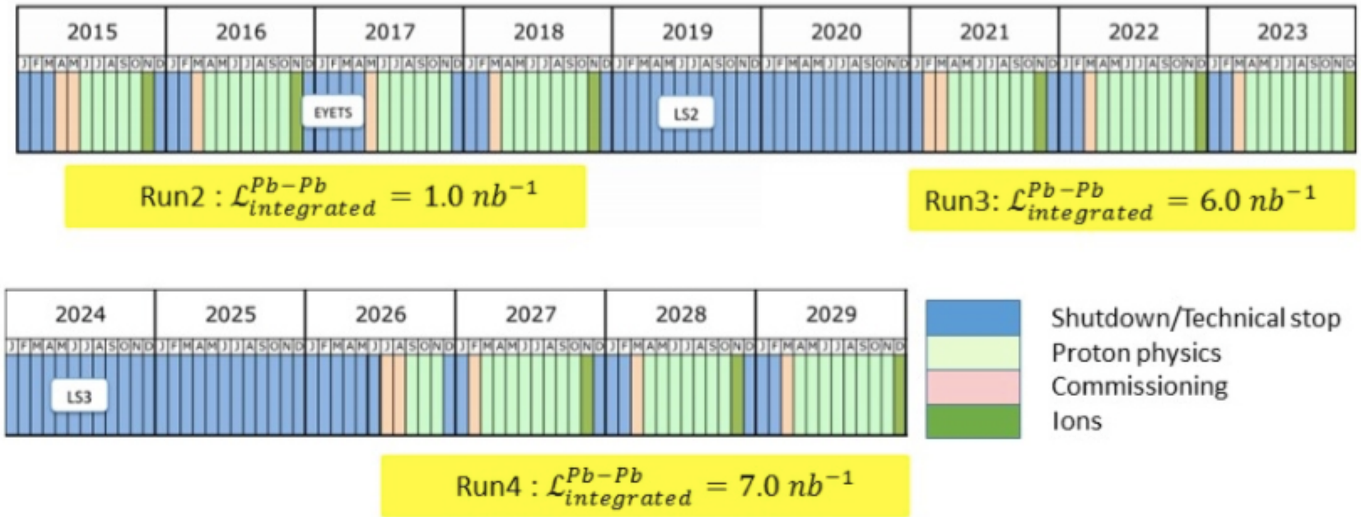
Andrea Dainese
(INFN Padova, Italy)

Outline

- Timeline of future HI running
- HI physics programme beyond Run-2
- Experiment upgrades and strategies
- Selected performance studies
- Besides Pb-Pb: pA, pp reference, light ions
- Summary



Timeline of HI running at the LHC



- Run 2:
  - Pb-Pb: few/nb (0.7/nb in 2015, ~1/nb in 2018), at $\sqrt{s_{NN}}$ = 5 TeV
  - p-Pb at 5 and 8 TeV (in 2016)
  - pp reference at Pb-Pb energy (5 TeV, Nov 2017)
- LS2:
  - LHC injector upgrades; bunch spacing reduced to 50 ns (possibly 25); Pb-Pb interaction rate up to 50 kHz (now <10 kHz)
  - Experiments upgrades (LS2 and LS3)
- Runs 3+4:
  - Experiments request for **Pb-Pb: >10/nb** (ALICE: 10/nb at 0.5T + 3/nb at 0.2T)
  - In line with projections by machine group (Chamonix 2017): 3.1/nb/month

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 medium density &dofs
  - Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high p_T
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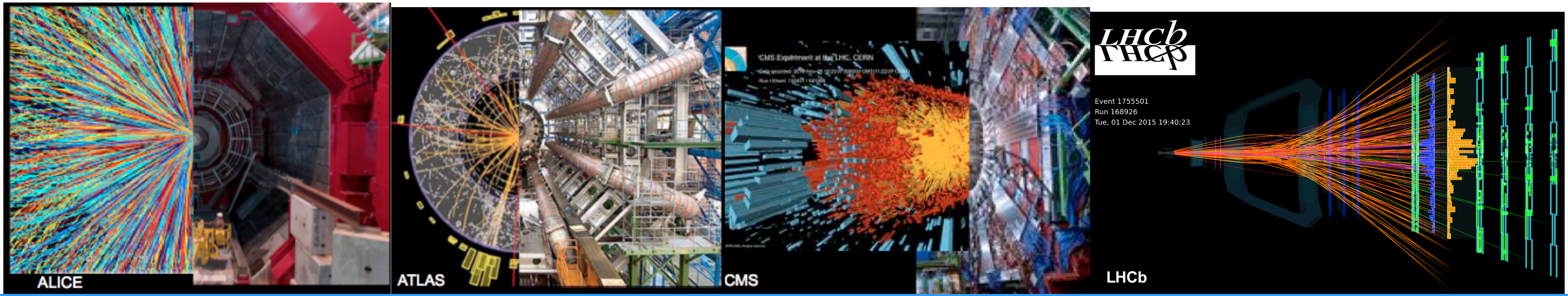

Detector upgrades most relevant to HI

- ALICE (LS2)
  - New inner tracker: precision and efficiency at low p_T
  - New pixel forward muon tracker: precise tracking and vertexing for μ
  - New TPC readout chambers, upgraded readout for other detectors and new integrated Online-Offline: x50 faster readout (up to 50 kHz for Pb-Pb)
- ATLAS (LS2/LS3)
  - Completely new tracker (LS3): tracking and b-tag
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
- CMS (mainly LS3)
  - Completely new tracker (LS3): tracking and b-tag up to η=4
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade forward calorimeter (LS3): forward jets in HI
- LHCb (LS2)
  - New vertexing and tracking detectors: full-rate readout in Pb-Pb; track reconstruction being verified
  - Fixed-target programme with SMOG + possible extensions

ALICE (and LHCb) trigger/readout

- Main focus on "untriggerable" signals (extremely low S/B)
- → Trigger approach: write all events at 50 kHz in Pb-Pb

  e.g. ALICE: ~1.1 TB/s **O^2 facility** → **~90 GB/s (50 kHz)**
- → increase of minimum-bias sample **x50-100** wrt Run-2

ATLAS and CMS trigger/readout

- Main focus on muon, jet, displaced track triggers
- → Trigger approach: strong event number reduction

  e.g. CMS: 50 kHz **L1** → **~ few kHz** **HLT** → **~ 100 Hz**
- → increase of (rare-trigger) sample **x10** wrt Run-2

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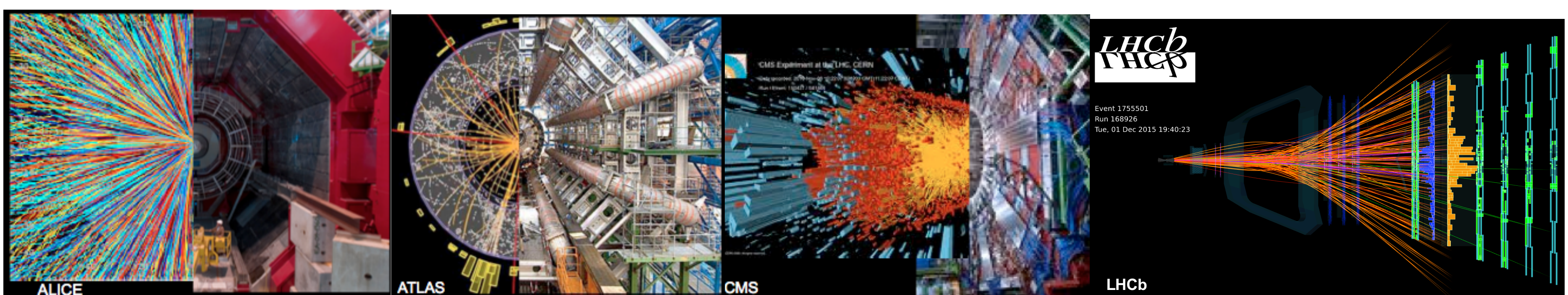

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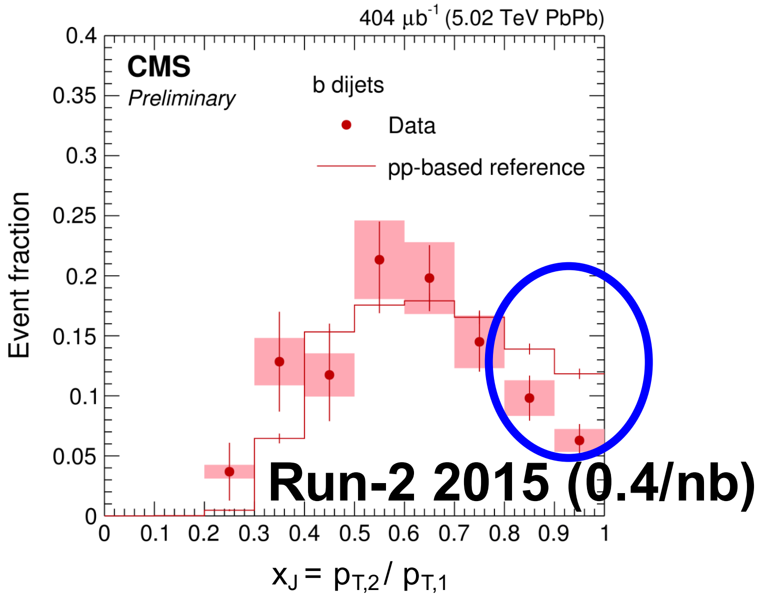
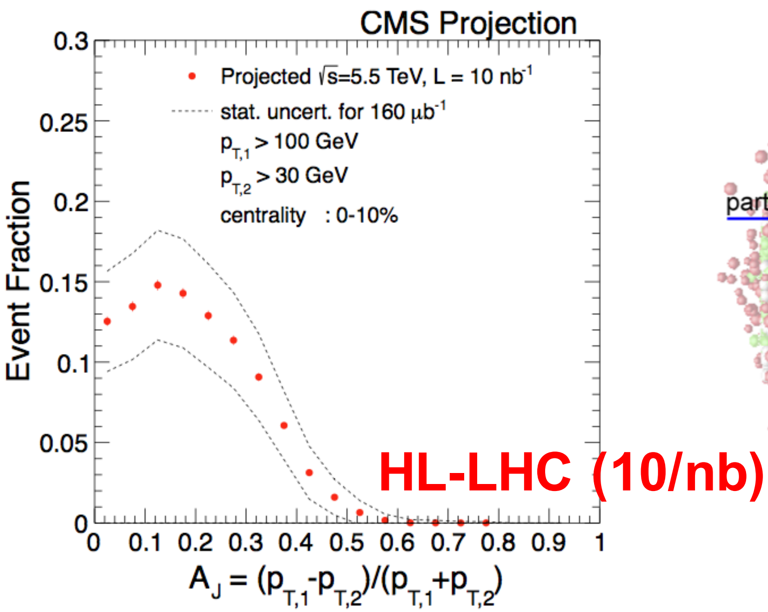
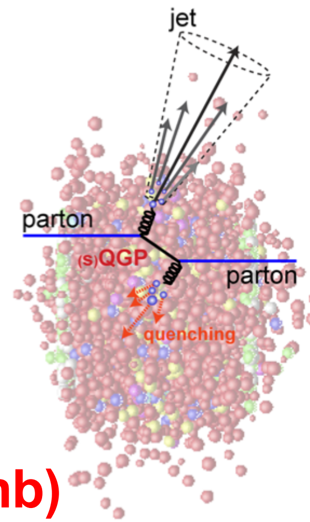
Jet quenching: (some) future directions

- Increased luminosity and detector upgrades enable:
  - Increased precision
  - More exclusive and theoretically well-defined final states
- High precision γ-jet, Z-jet, di-jet correlations, also with b-jets (quark tag)

E.g.: b-tagged di-jets → select quark-quark state and compare with g-g







CMS, PAS-HI-16-005

CMS, PAS-FTR-13-025

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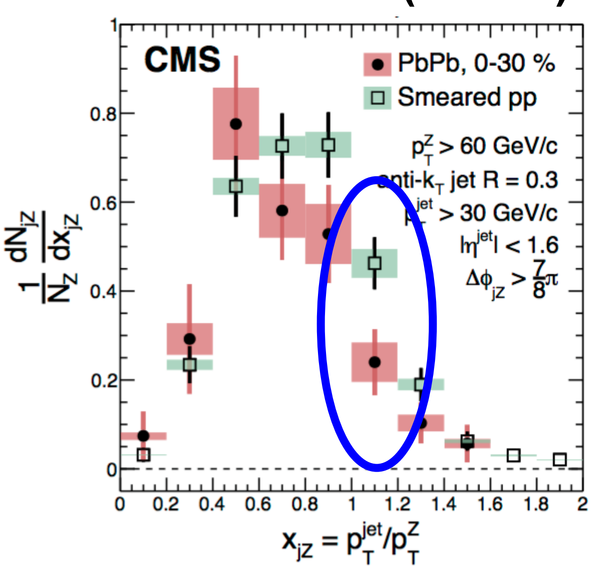
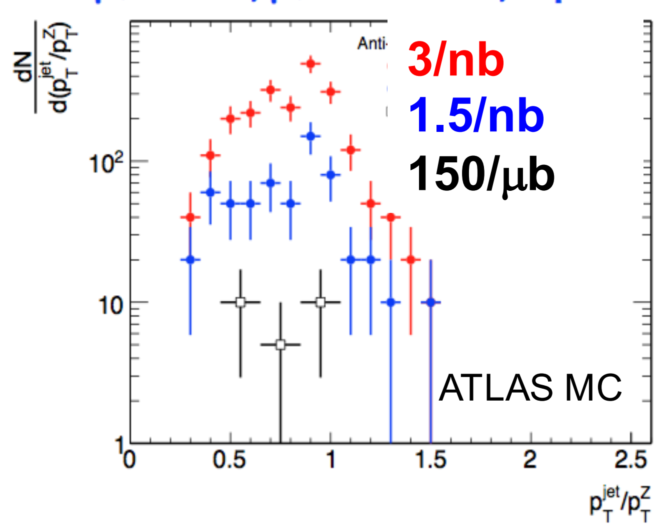
E.g.: Z-jet → "select" initial jet energy

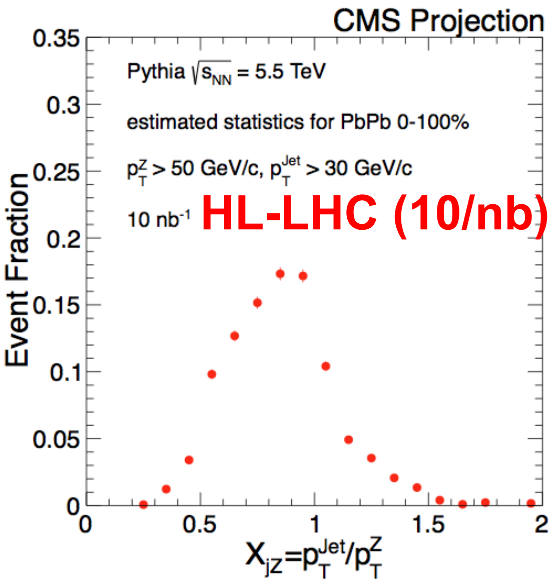
Run-2 2015 (0.4/nb)



CMS, arXiv:1702.01060

$p_T^Z > 100$, $p_T^{jet} > 25$ GeV, $\Delta\varphi > 7\pi/8$





CMS, PAS-FTR-13-025

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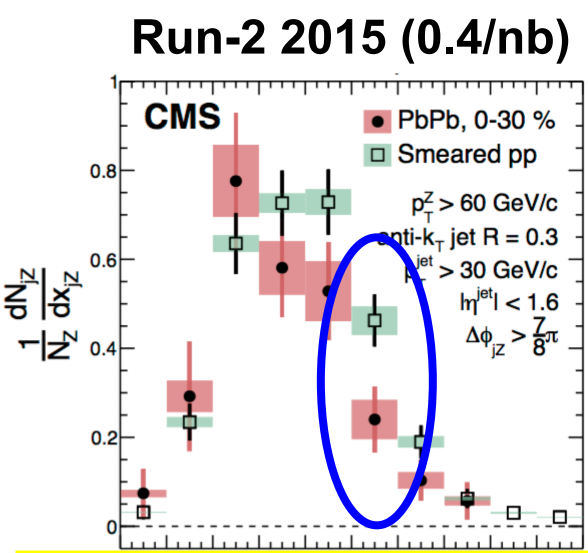
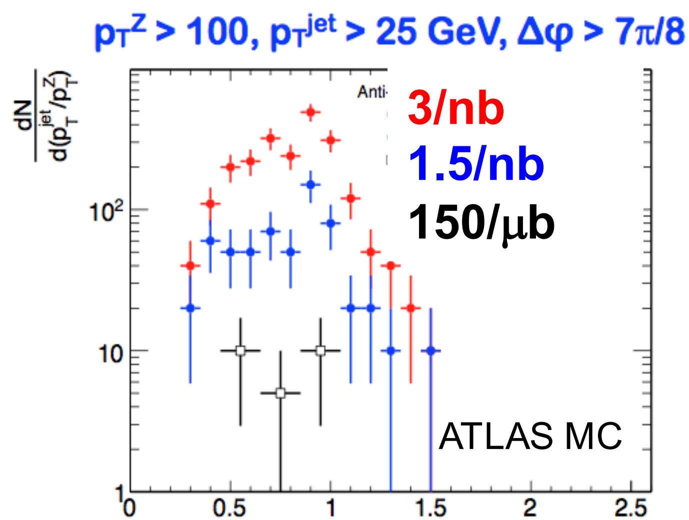
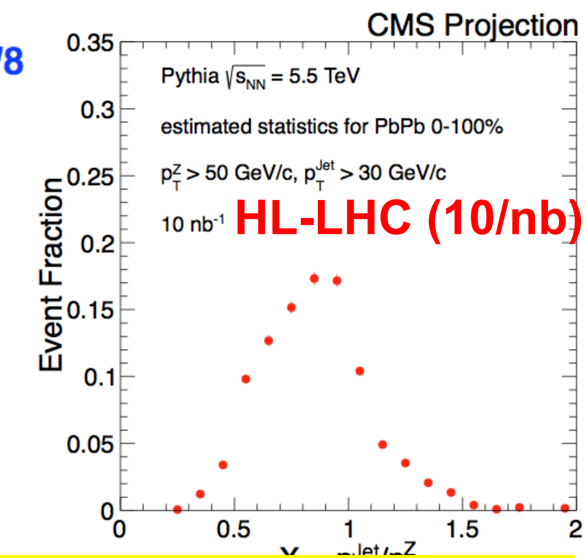




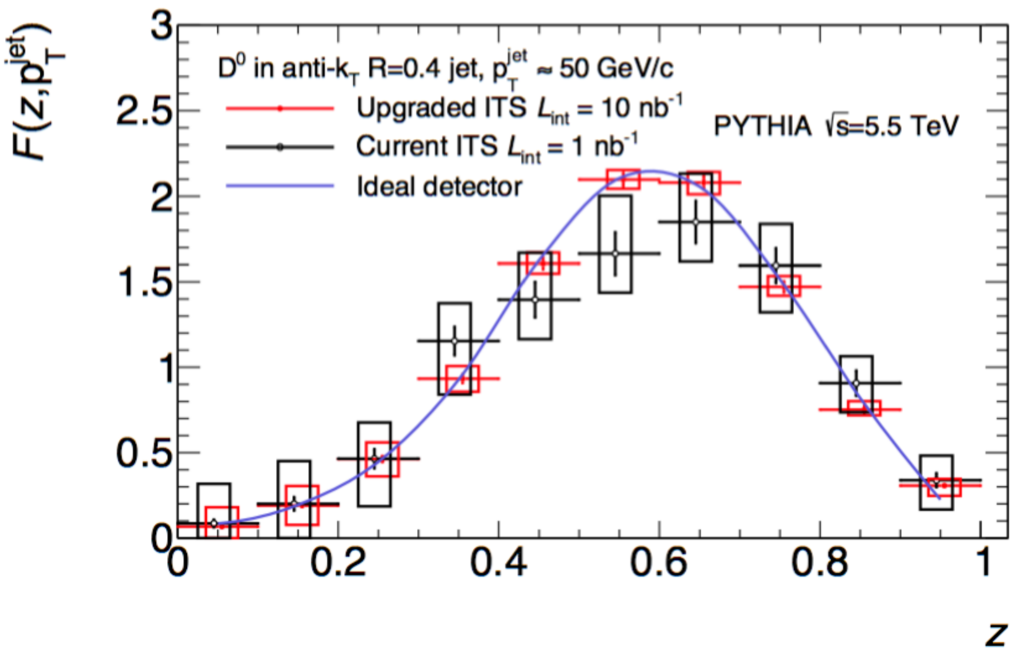


Q: can this become one of the main ways to search for jet quenching in high-mult pp or p-Pb? how much L_{int}?

Jet quenching: (some) future directions

- Increased luminosity and detector upgrades enable:
  - Increased precision
  - More exclusive and theoretically well-defined final states
- Fragmentation functions (FF) and substructure measurements for jets with leading (identified) light and heavy flavour hadrons

E.g.: D-in-jet FF → select quark jet and study flavour-depence of FF modification



ALICE, CERN-LHCC-2013-024

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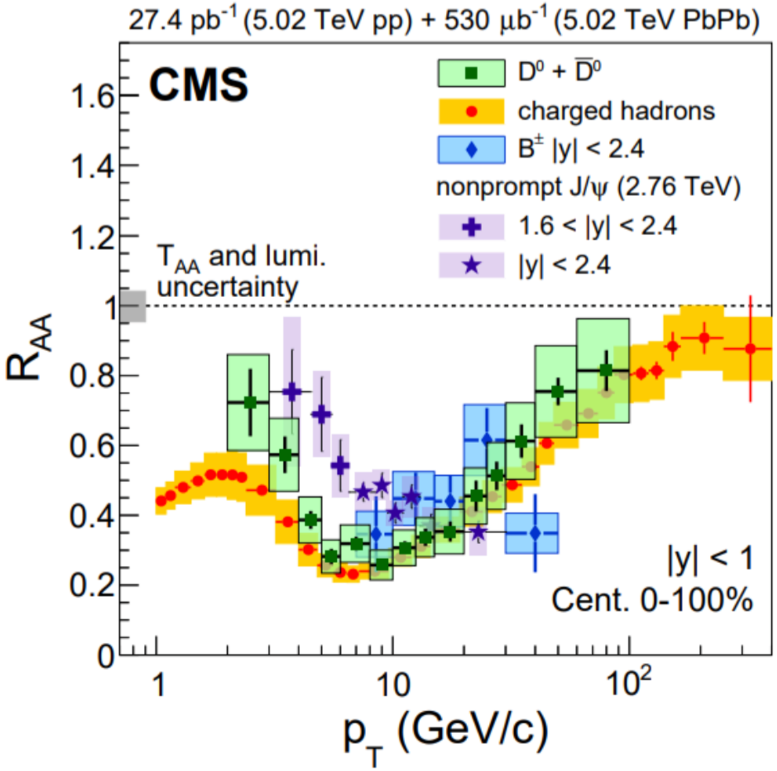
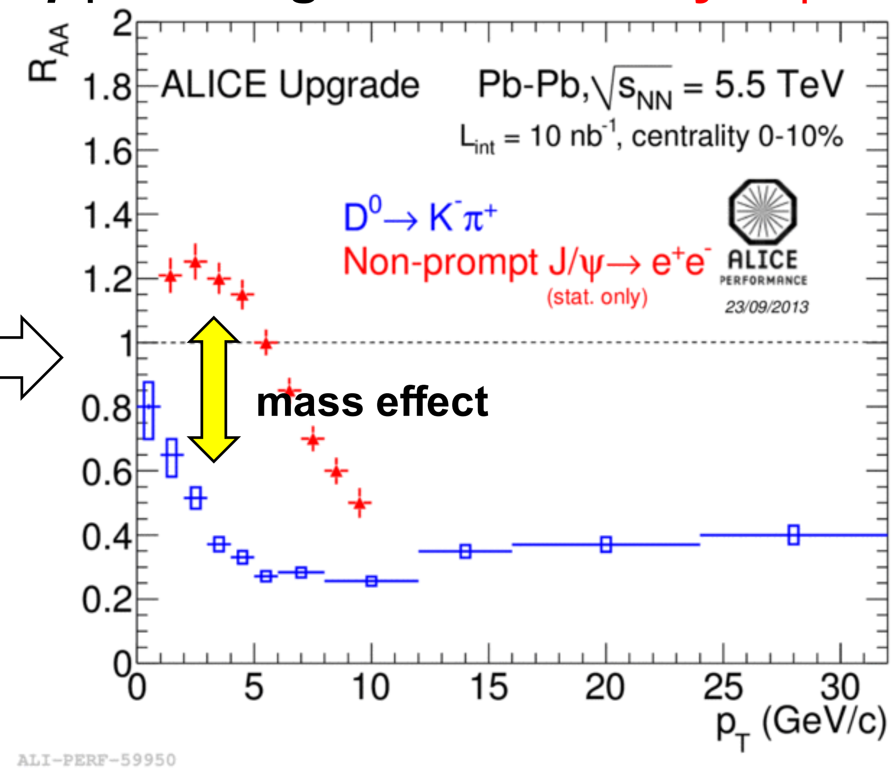
Heavy flavour R_{AA} after LS2

Present data (example)



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



ALICE, CERN-LHCC-2013-024

→ Large uncertainties for D p_T → 0 and no measurement for B p_T → 0

Heavy flavour R_{AA} after LS2

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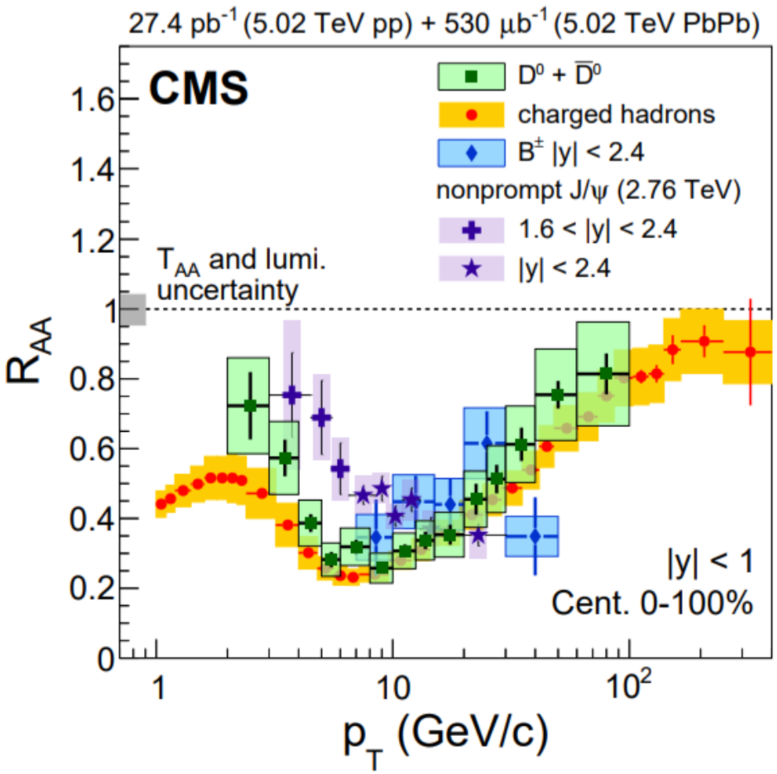

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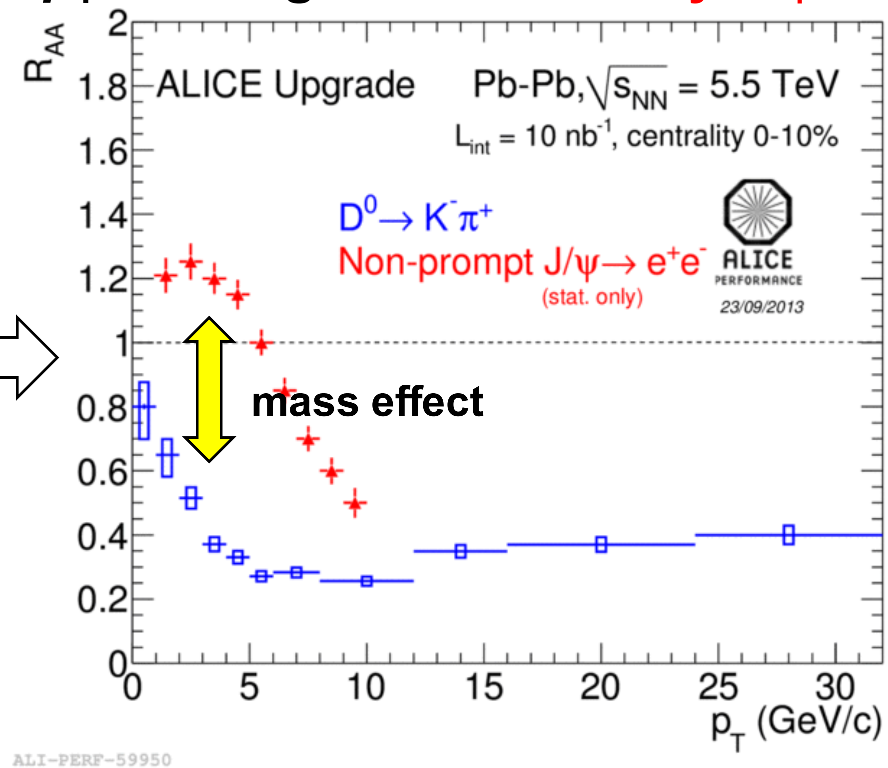
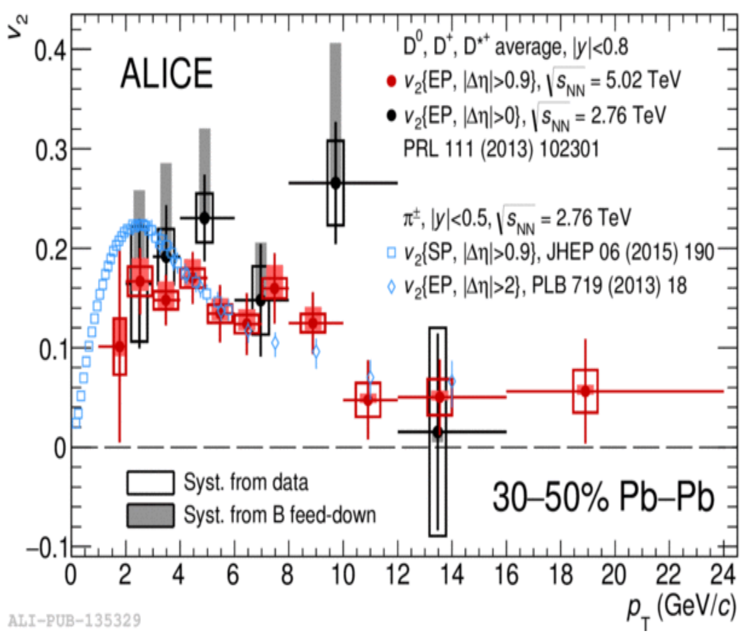


ALICE, CERN-LHCC-2013-024

Q: how can we disentangle different E-loss dependencies and different radial flow effects for π, D and B?

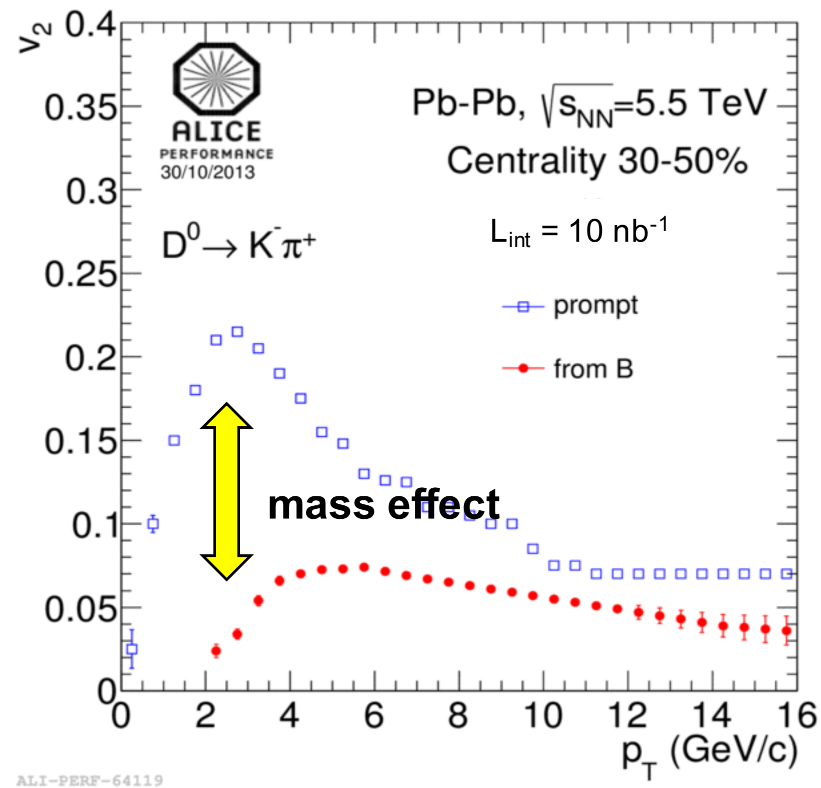
Heavy flavour v_2 after LS2

Present data (example)



→ Need it also for beauty, which can be calculated more accurately in lattice QCD

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



ALICE, CERN-LHCC-2013-024

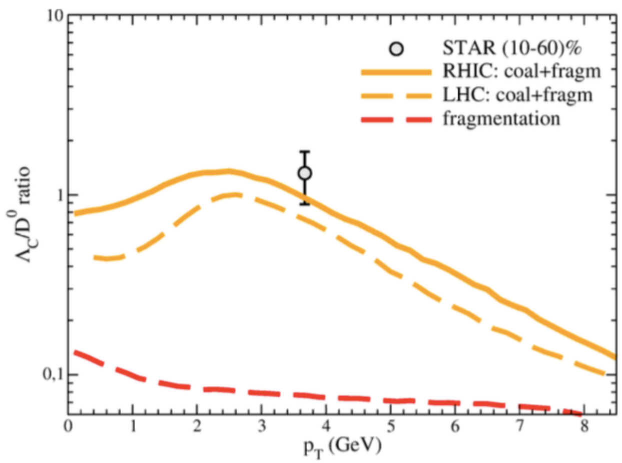
+ v_3, ESE (→ v_2^D vs v_2^π), new studies being done

In-medium heavy-flavour hadronization?

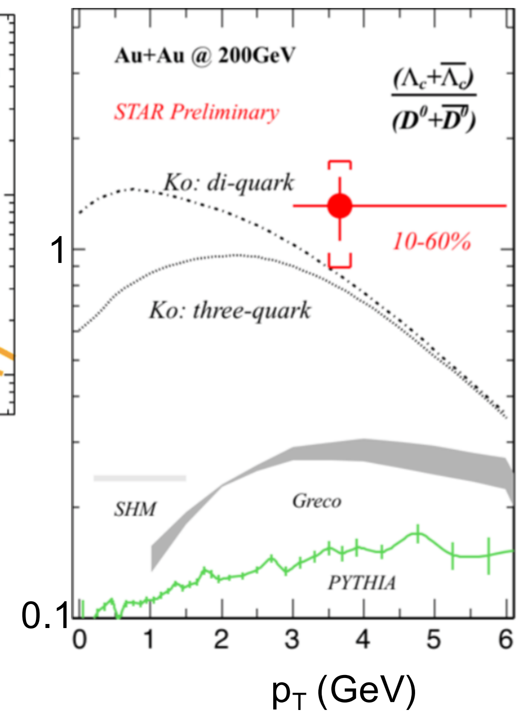
- From RHIC and LHC data, some hints that charm *could* recombine in the medium (J/ψ regeneration, D meson flow, D_s R_{AA} in ALICE, Λ_c/D in STAR)

→ Precise measurements of HF mesons (non-strange and strange) and baryons

Example: charm recombination
→ enhancement of Λ_c/D
(also $D_s/D^{0,+}$ and Λ_b/B)



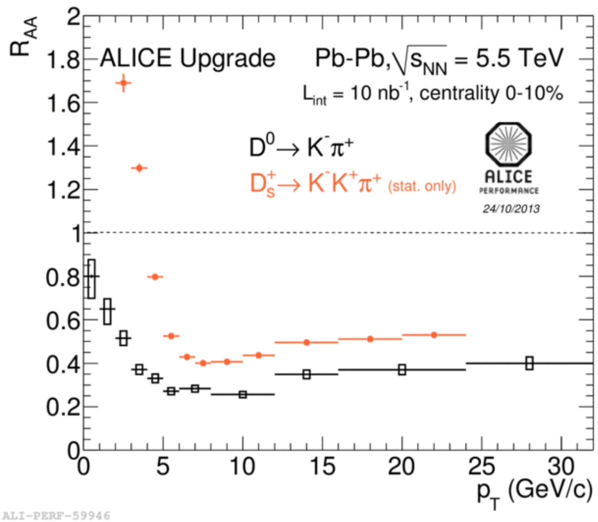
Plumari et al. SQM2017



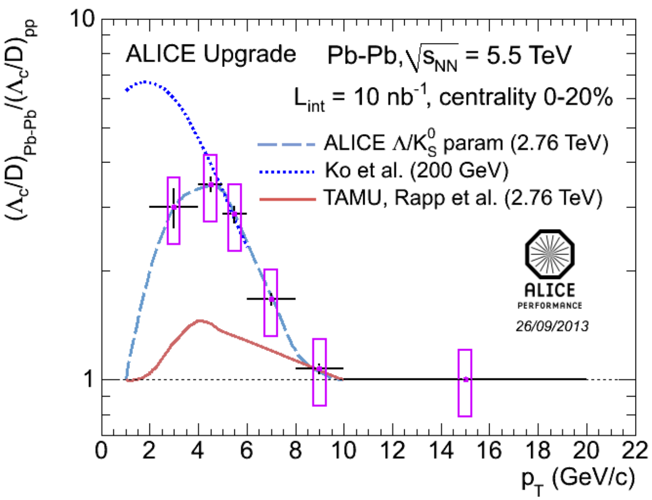
HF "hadrochemistry" after LS2

- ALICE inner tracker upgrade and x100 min.bias Pb-Pb sample
  - Λ_c and D_s ($c\tau$=60 and 150 μm) will be measured with good precision for p_T>2 GeV/c
  - Λ_b ($c\tau$=450 μm) accessible for p_T>7 GeV/c

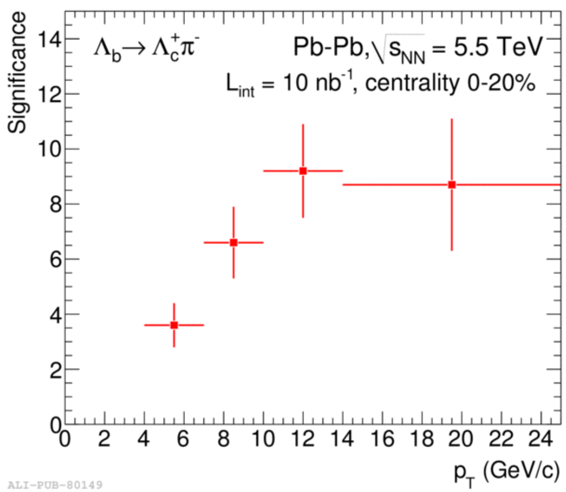
D^0 and D_s R_{AA}



Λ_c/D "enhancement"



Λ_b significance



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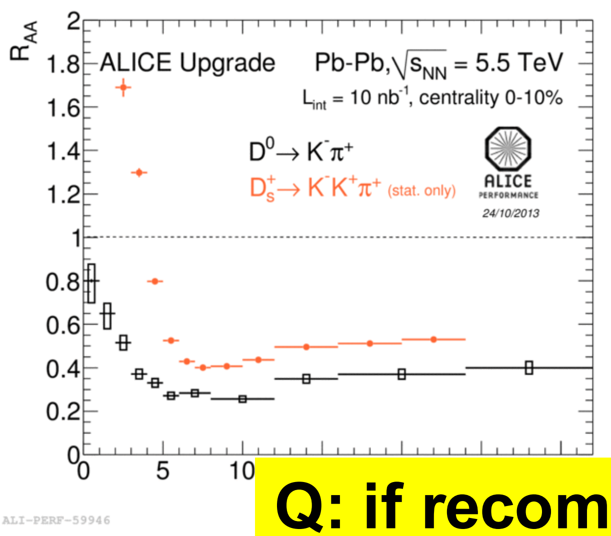

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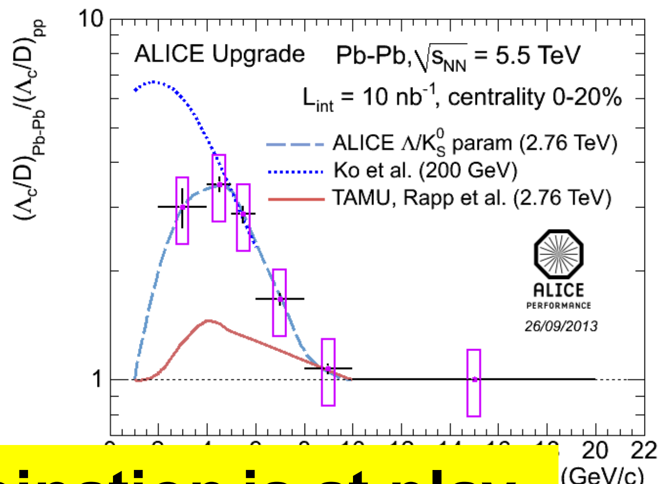

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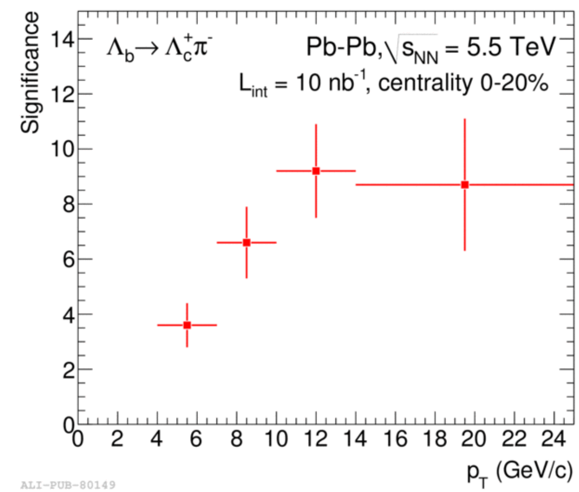

Q: if recombination is at play, which observables are more informative on its dynamics?

ALICE, CERN-LHCC-2013-024

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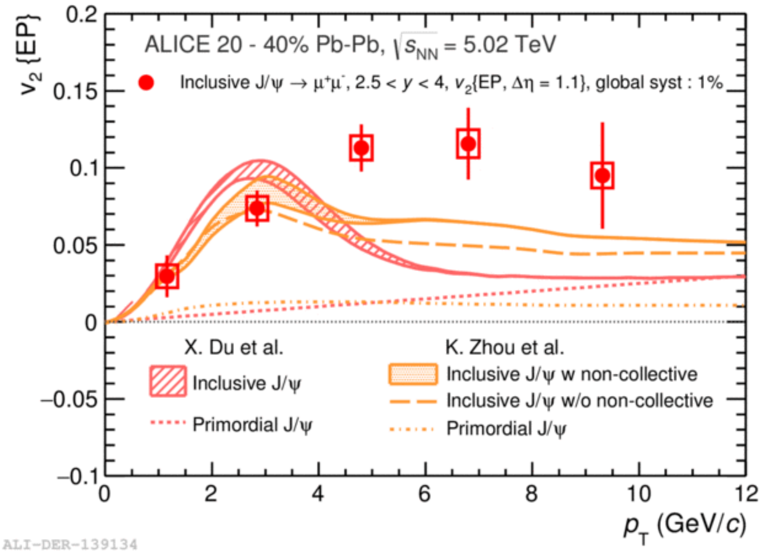
J/ψ v_2: Run-2 vs. Upgrade

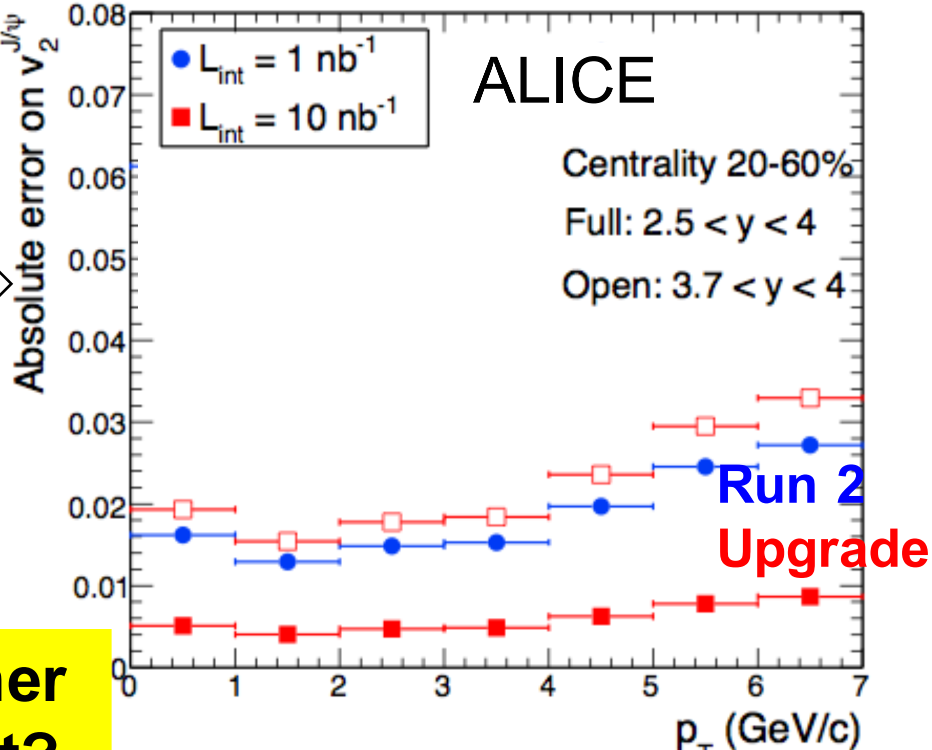
- Is J/ψ v_2 consistent with that of D mesons in a regeneration scenario?
- J/ψ v_2 with expected precision better than 0.005 (x3 better than in Run-2), also for *prompt* J/ψ (more direct comparison with models)

Run 2



ALICE, arXiv:1709.05260

Upgrade: x3 better precision



CERN-LHCC-2012-012

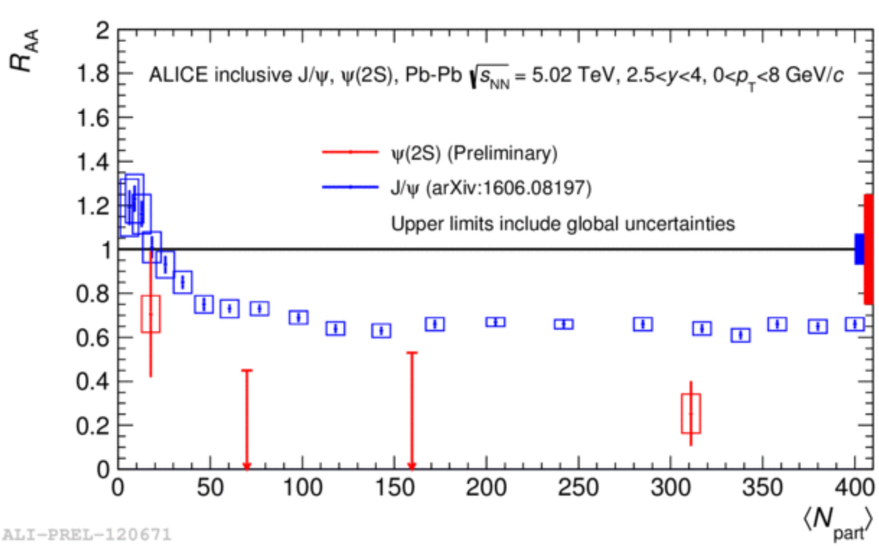
Q: puzzle at high p_T? which other measurements could shed light?

Low-p_T charmonium: Run 1 vs. Upgrade

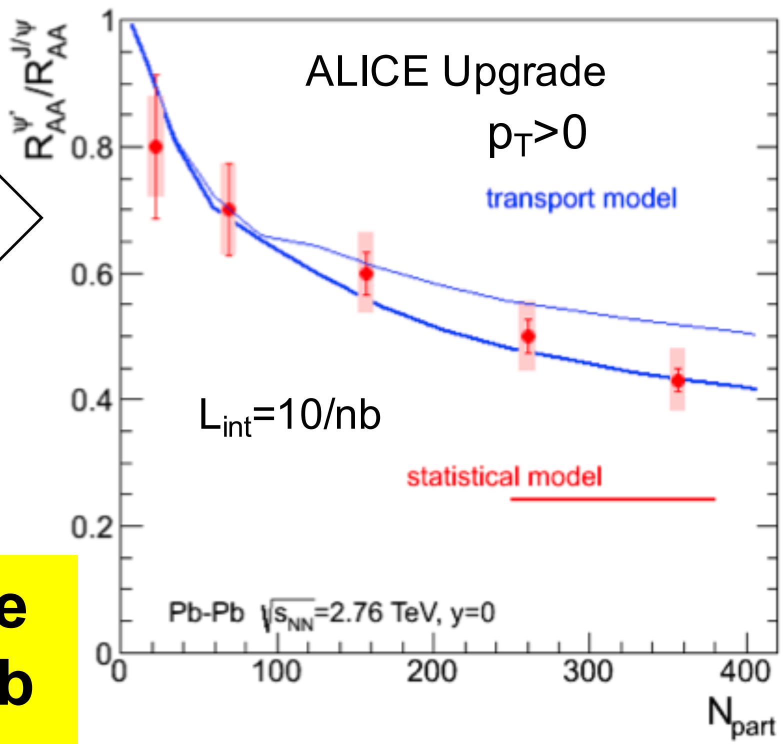
- Low-p_T ψ'/ψ could allow to discriminate between models of recombination (transport vs. statistical)

$R_{AA}(\psi')/R_{AA}(\psi)$

Run 2: limited precision for $R_{AA}(\psi')$



Upgrade: precision <10%

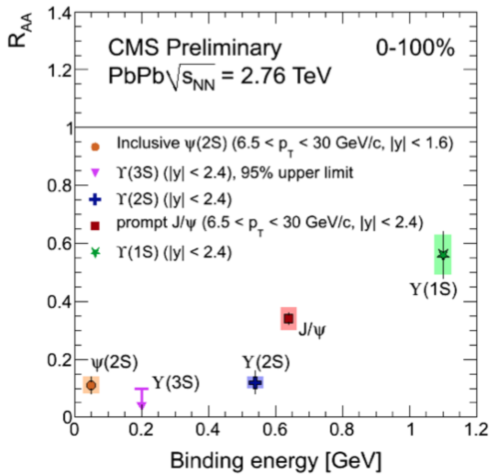


Q: is ψ' too fragile to be informative about in-medium effects? (see p-Pb high-mult)

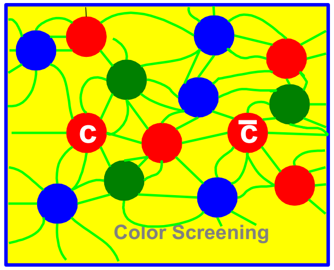
ALICE, CERN-LHCC-2013-014

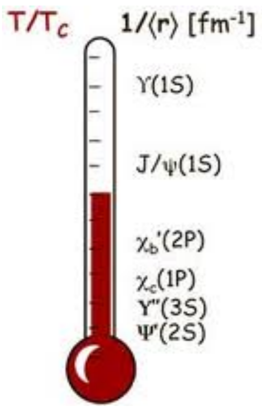
Quarkoniun suppression

- First hint of sequential pattern

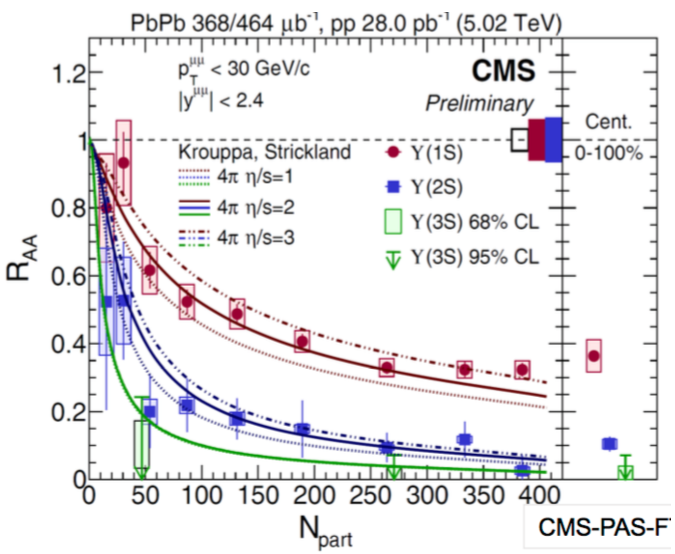


CMS, arXiv:1208.2826 and PRL 109 (2012) 222301





- Sensitivity to η/s?



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

Υ(1s)	Υ(2s)	Υ(3s)
270k	40k	7k

CMS, PAS-FTR-13-025

+ ALICE&LHCb at forward rapidity

Q: is it still conceivable to extract "a" temperature from quarkonium data? Is it still the goal?

HL-LHC Programme (AA) (not exhaustive!)

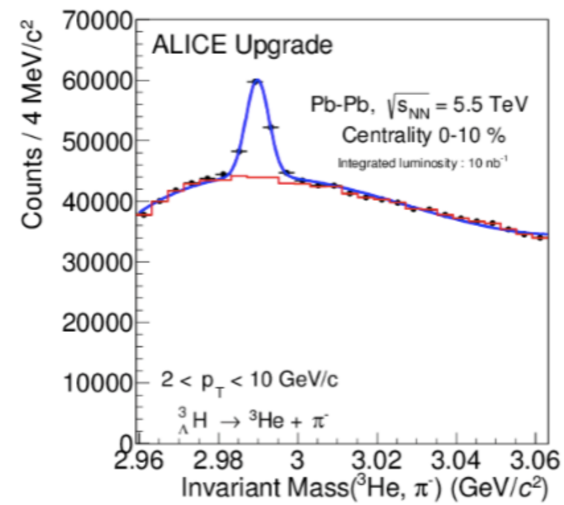
- **Jets:** characterization of energy loss mechanism both as a testing ground for the multi-particle aspects of QCD and as a probe of the medium density
  - Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high p_T
  - (Flavour-dependent) in-medium fragmentation functions and jet structure observables
- **Heavy flavour:** colour charge and mass dependence of E loss, HQ thermalization and hadronization, as a probe of QGP transport properties
  - Production and elliptic flow of several HF hadron species from 0 to high p_T
- **Quarkonium:** precision study of quarkonium dissociation pattern and regeneration, as probes of deconfinement and of the medium temperature
  - Low-p_T charmonia (J/ψ and ψ(2S)) and their elliptic flow
  - Multi-differential studies of Υ states
- **Low-mass di-leptons:** thermal radiation to map time-dep. of temperature; modification of ρ spectral function and chiral symmetry restoration at μ_B=0
  - Low-mass di-electrons and di-muons
- **"Light" nuclear states:** production mechanisms of multi-baryon bound states (recombination? coalescence?); search for exotic states with hyperons
  - Yield and flow harmonics of (anti-)nuclei and hypernuclei

Light multi-baryon bound states

- Abundant (hyper)nuclei and (strange) exotica
  - Dynamical coalescence vs. statistical thermal production (dynamics?)
  - Sensitivity to freeze-out temperature
- Discovery potential
  - (anti-)(hyper-)nuclei with A = 4 (A = 5?)
  - Discovery/exclusion for ΛΛ and Λn dibaryon beyond currently set limit [PLB 752 (2016) 267]
  - Search for strange dibaryon ΞΞ, ΩΩ
- Precision
  - (improved) precision measurement of the $^{3}_{\Lambda}H$ lifetime and spectrum

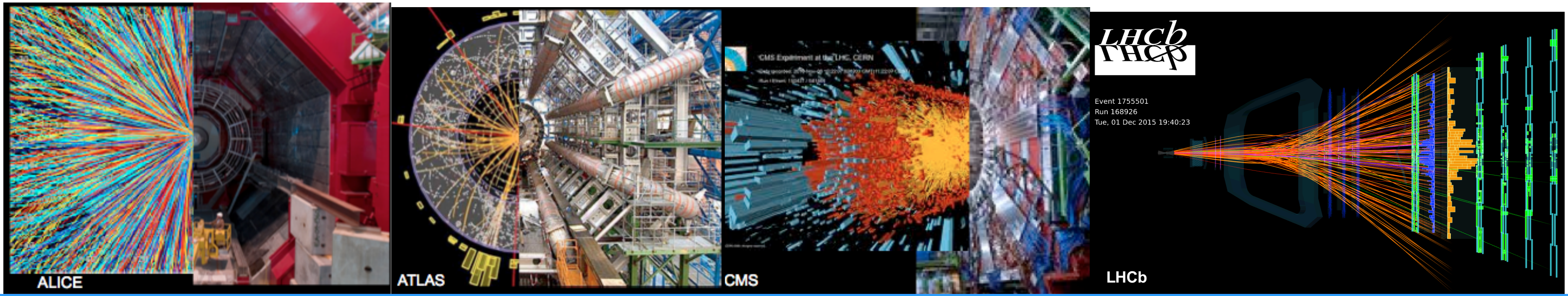
Statistical model: 10/nb

Particle	Yield
Anti-alpha $^{4}\overline{\mathrm{He}}$	3.0×10^{4}
Anti-hypertriton $^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ $(\bar{\Lambda}\bar{p}\bar{n})$	3.0×10^{5}
$^{4}_{\bar{\Lambda}}\overline{\mathrm{H}}$ $(\bar{\Lambda}\bar{p}\bar{n}\bar{n})$	8.0×10^{2}
$^{5}_{\bar{\Lambda}}\overline{\mathrm{H}}$ $(\bar{\Lambda}\bar{p}\bar{n}\bar{n}\bar{n})$	3.0
$^{4}_{\bar{\Lambda}\bar{\Lambda}}\overline{\mathrm{H}}$ $(\bar{\Lambda}\bar{\Lambda}\bar{p}\bar{n})$	3.4×10^{1}
$^{5}_{\bar{\Lambda}\bar{\Lambda}}\overline{\mathrm{H}}$ $(\bar{\Lambda}\bar{\Lambda}\bar{p}\bar{n}\bar{n})$	0.2
H-Dibaryon (ΛΛ)	5.0×10^{6}
ΞΞ	1.5×10^{5}
Λn	8.0×10^{7}



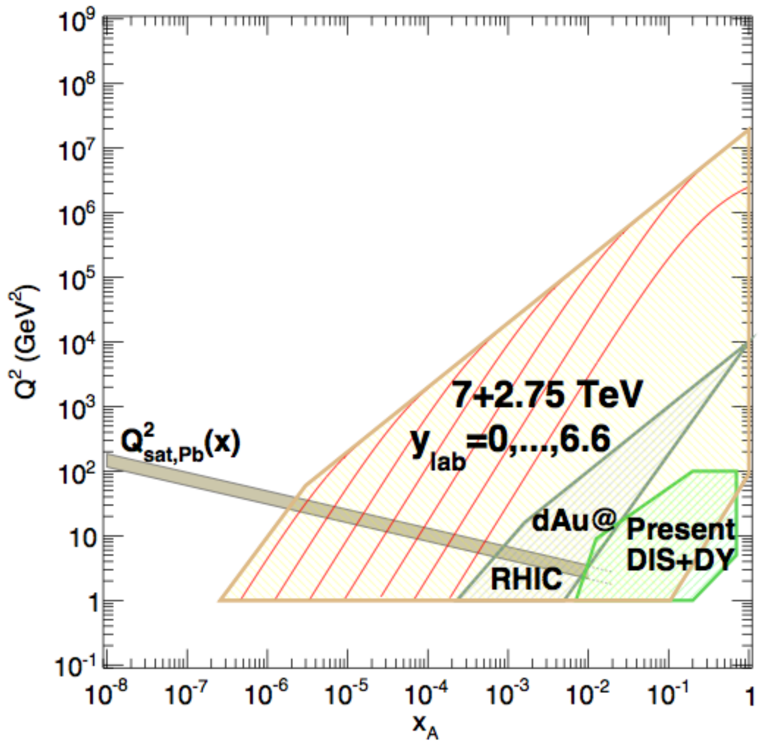
Outline

- Timeline of future HI running
- HI physics programme beyond Run-2
- Experiment upgrades and strategies
- Selected performance studies
- Besides Pb-Pb: pA, pp reference, light ions
- Summary



Small systems: pp, p-Pb

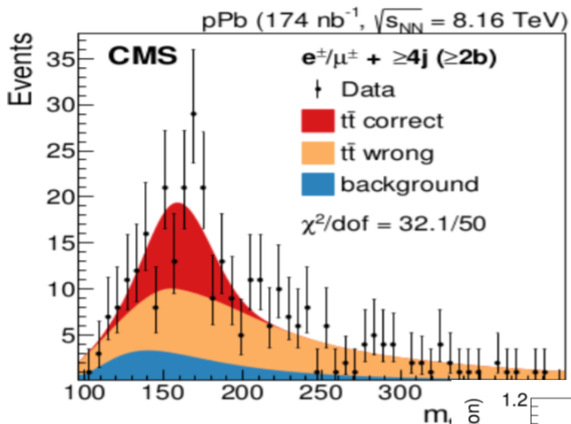
- pp reference at 5.5 TeV required by all experiments
- p-Pb at high luminosity: explore partonic structure of high-energy nuclei
  → also to disentangle cold nuclear matter effects for the QGP studies



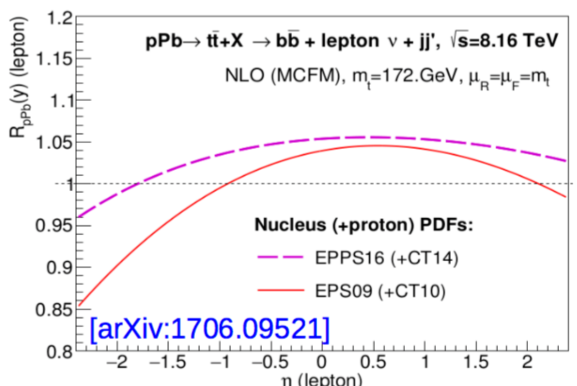
Small systems: pp, p-Pb

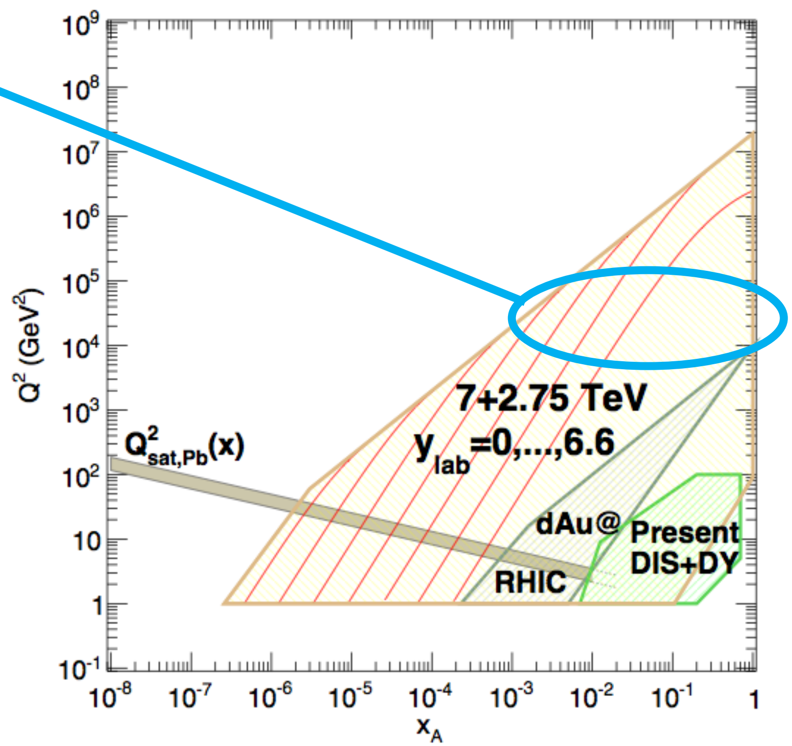
- pp reference at 5.5 TeV required by all experiments
- p-Pb at high luminosity: explore partonic structure of high-energy nuclei
  → also to disentangle cold nuclear matter effects for the QGP studies

Constrain high-Q^2 and high-x nPDFs with W,Z, top production in p-Pb



CMS, arXiv:1709.07411

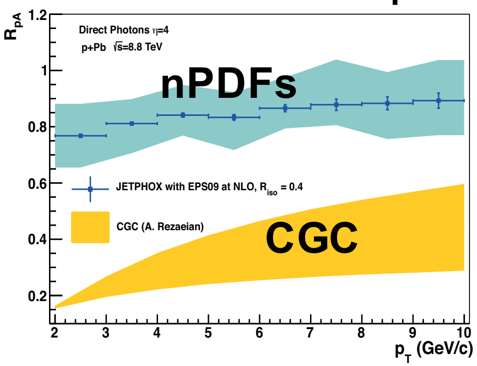




Small systems: pp, p-Pb

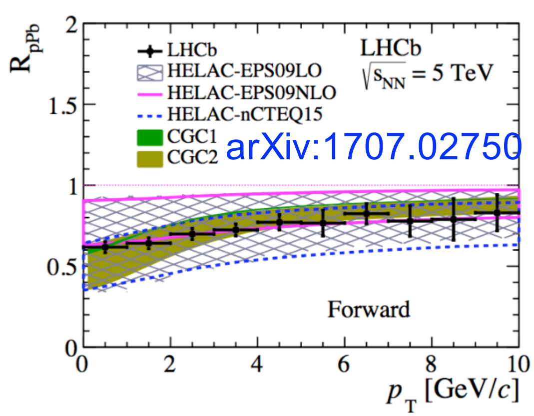
- pp reference at 5.5 TeV required by all experiments
- p-Pb at high luminosity: explore partonic structure of high-energy nuclei → also to disentangle cold nuclear matter effects for the QGP studies

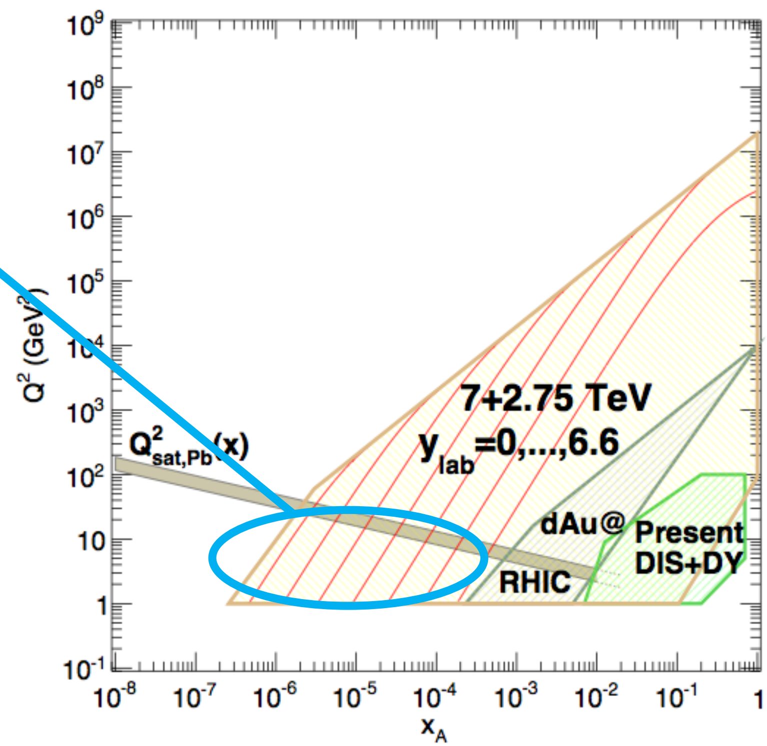
Constrain low-Q^2 and low-x nPDFs and search for onset of saturation with charm, quarkonia, photons, di-hadrons at low p_T and forward rapidity in p-Pb (+UPC)



Forward direct γ → ALICE FoCal?

Forward D meson in LHCb





Small systems – high multiplicity

- pp 14 TeV (and p-Pb 8 TeV)
  - Higher statistics for already covered multiplicity region → charm?
  - Extension to higher multiplicities
    - 5-6 x <$N_{ch,pp}$> with Run-2
    - 10 x <$N_{ch,pp}$> with Run-3 (~10 /pb)
    - 15 x <$N_{ch,pp}$> needs > 1/fb; out of reach?

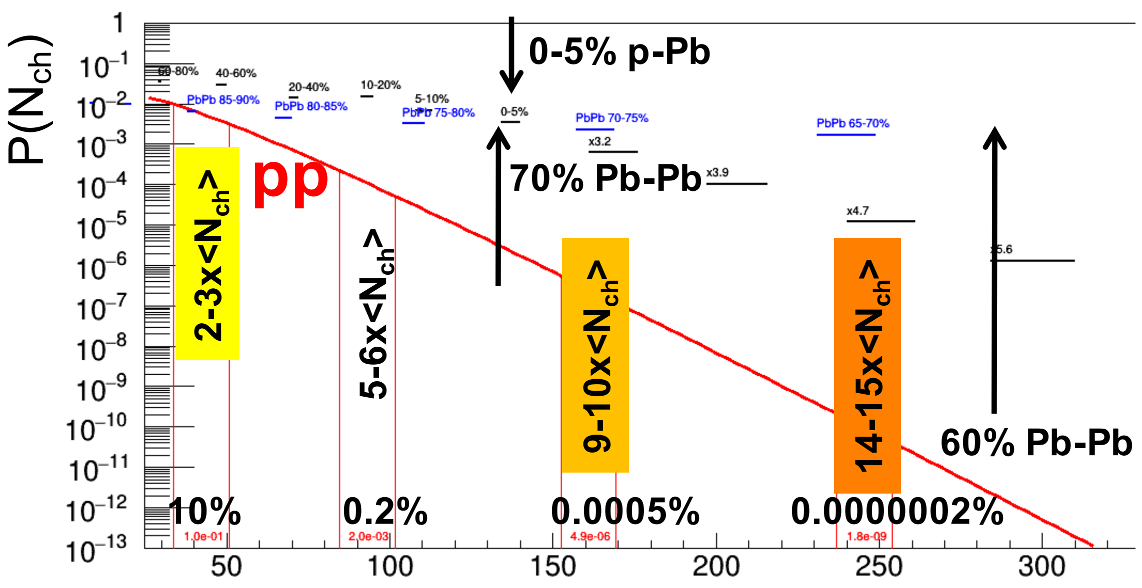
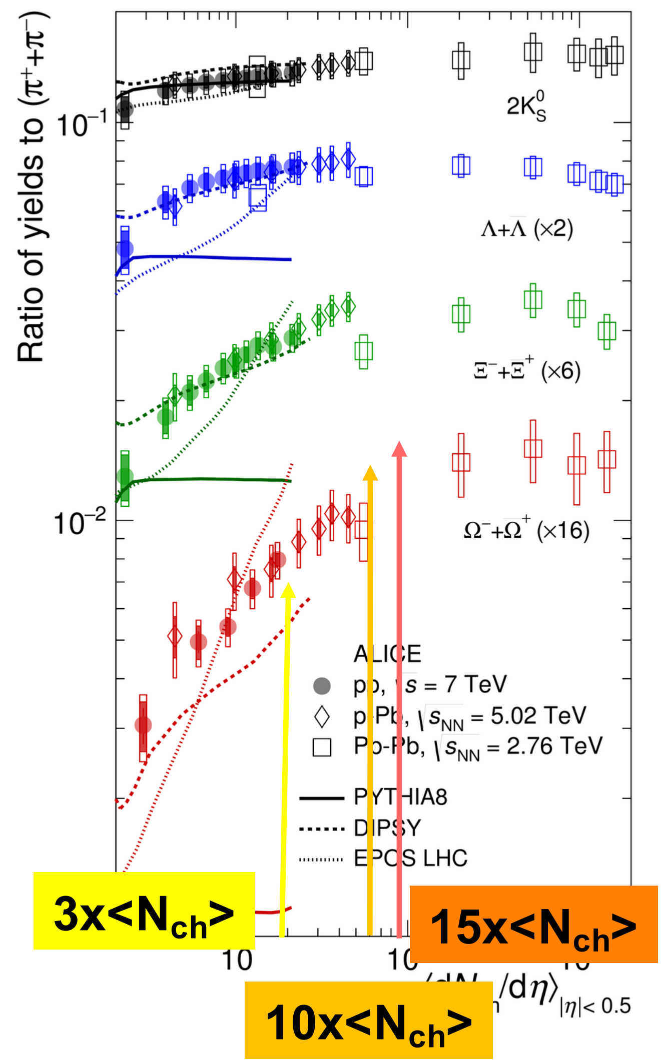


Figure by J.F. Grosse-Oetringhaus

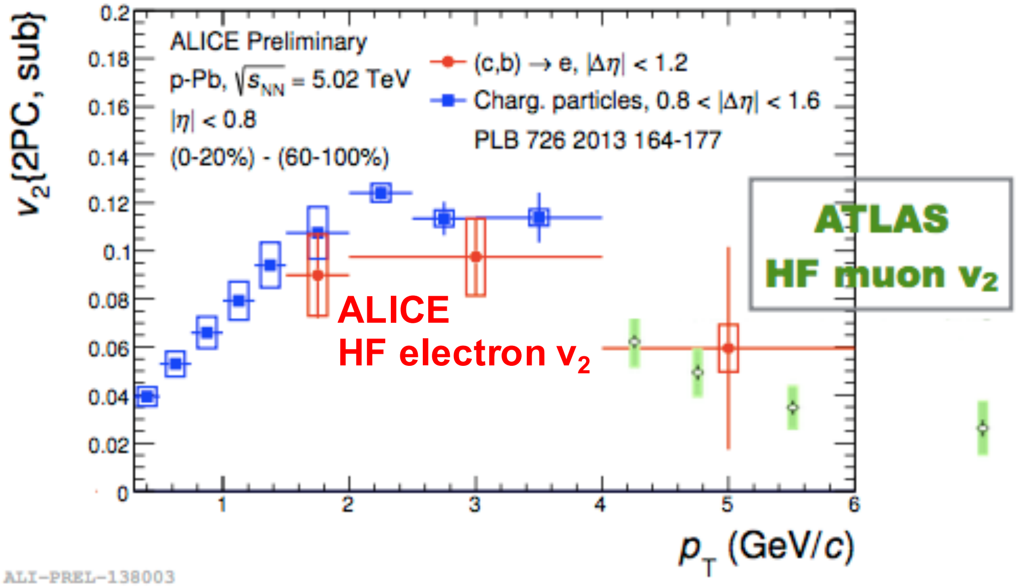


Nature Phys.13(2017)535

Small systems: looking for small signals

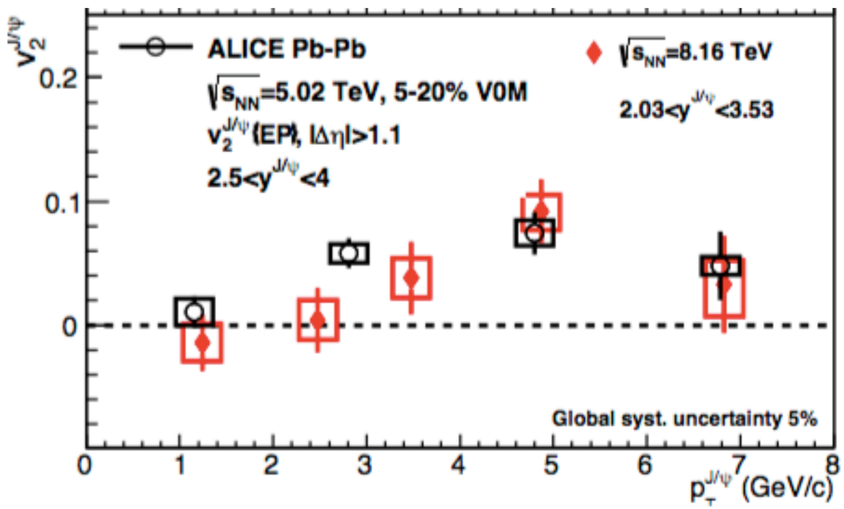
- Very large statistics at few x <N_{ch}> in pp and p-Pb, together with the upgraded detectors:
  - Precise measurements of "flow-like" effects for open HF and quarkonia

HF (decay lepton) v_2



ALICE and ATLAS, Initial Stages 2017

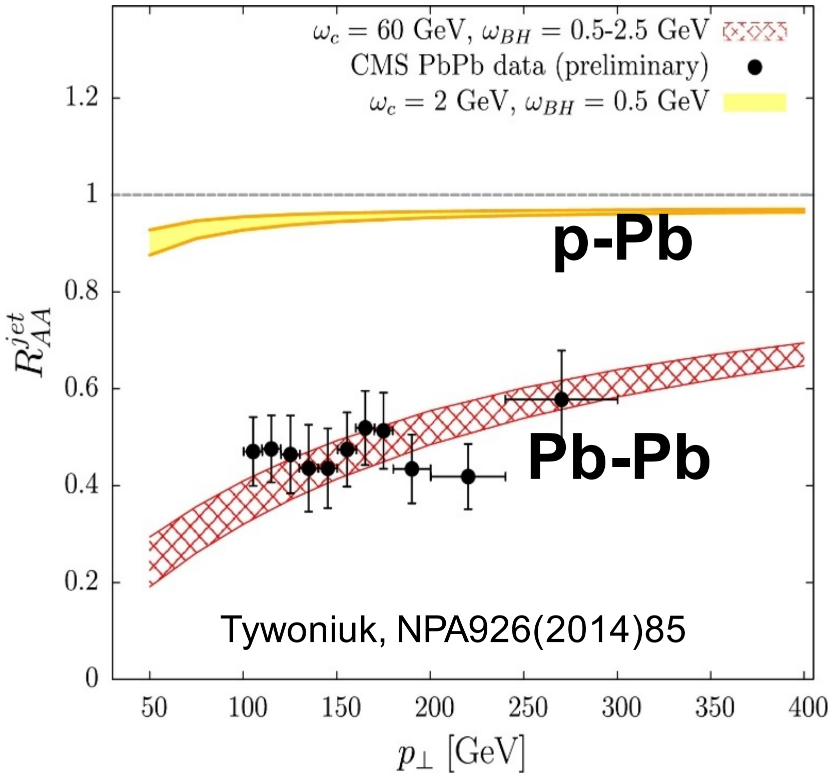
J/ψ v_2

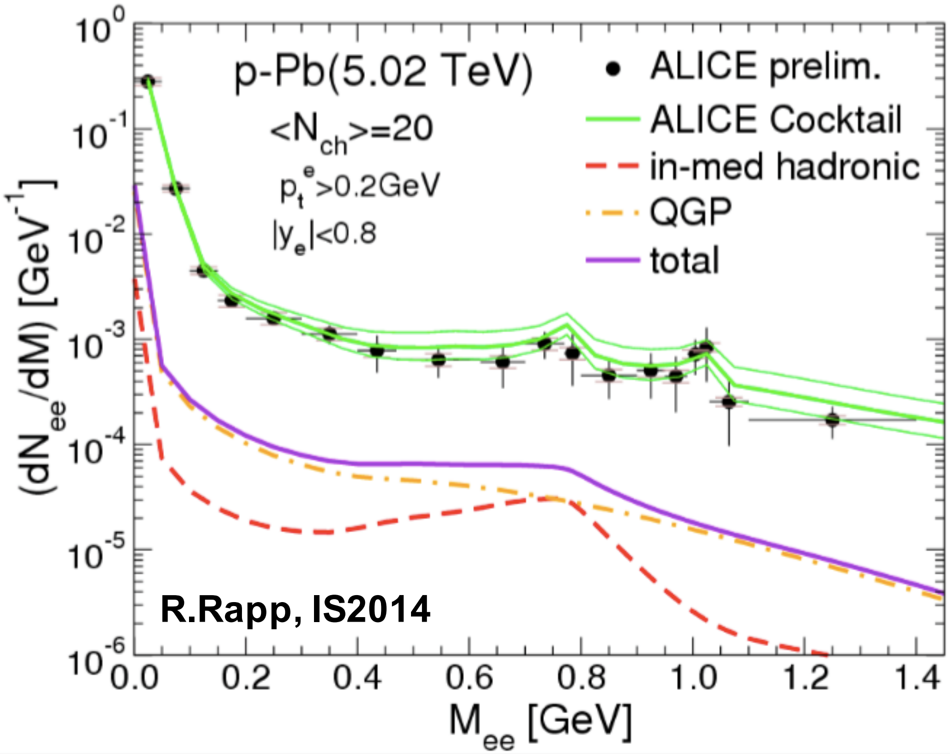


ALICE, arXiv:1709.06807

Small systems: looking for small signals

- Very large statistics at few x <N_{ch}> in pp and p-Pb, together with the upgraded detectors:
  - Searches for two of the classical hot-medium signals in small systems, namely parton energy loss (γ-jet?) and thermal radiation





Running with lighter ions at LHC ?

- Lighter ions would allow to reach higher inst. luminosity than Pb-Pb
  - BFPP cross section drops with Z^7, EMD cross section with Z^4
  - Increase in lumi is larger than decrease in N_{coll} (x0.5 from Pb-Pb to Xe-Xe) → higher yields for hard processes
  - No detailed machine studies yet, first estimates in this thesis http://cds.cern.ch/record/2241364/files/CERN-THESIS-2016-230_3.pdf
  - Nucleon-nucleon lumi ($L_{NN}=A^2 * L_{AA}$) – hard yields scale with L_{NN} –
    - **L_{NN}^{XeXe} (cons) ~ 1.5 L_{NN}^{PbPb}; L_{NN}^{ArAr} (cons) ~ 4.5 L_{NN}^{PbPb}**
- Physics?
  - Xe-Xe: similar QGP as Pb-Pb, but no large gain in yields?
  - Ar-Ar: lower size/density QGP
    - → smaller jet quenching signals
    - → interesting overlap in N_{ch} with pp, p-Pb, Pb-Pb, but needed?
    - → additional constraints for quarkonium suppression vs. regeration?
  - Pilot Xe-Xe run in two days will help to clarify the LHC performance and (partly) the physics motivation

Summary

- Beyond LS2: fully exploit the potential of the machine as a high-luminosity HI collider

- Rich baseline programme prepared by the experiments
  - Upgraded detectors, very large samples, diverse trigger approaches

- LHC findings in small systems / high-mult have opened many new questions that need luminosity and precision
  - Now it is the time to optimize the future programme to address these

HL-LHC Physics WS (Oct 30-Nov 1)

https://indico.cern.ch/event/647676/

EXTRA SLIDES

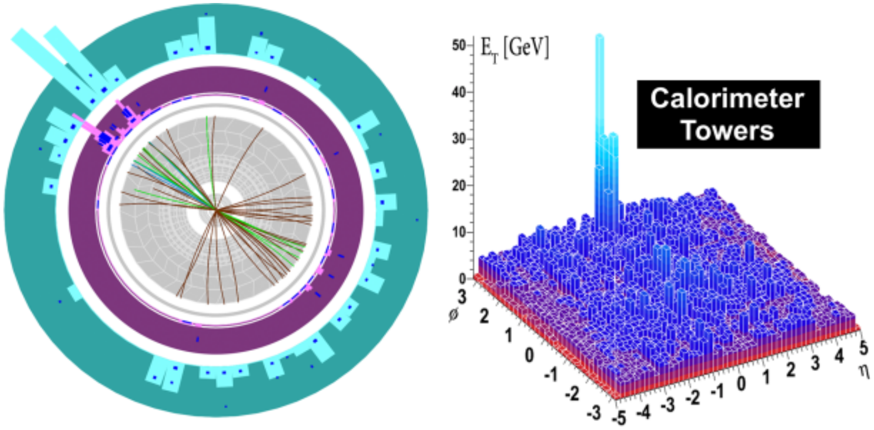
Available Documents

- ALICE Upgrade LOI: CERN-LHCC-2012-012
  - Addendum (Muon Forward Tracker): CERN-LHCC-2013-014
- ALICE inner tracker upgrade TDR: CERN-LHCC-2013-024
- ALICE muon tracker upgrade TDR: CERN-LHCC-2015-001
- 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

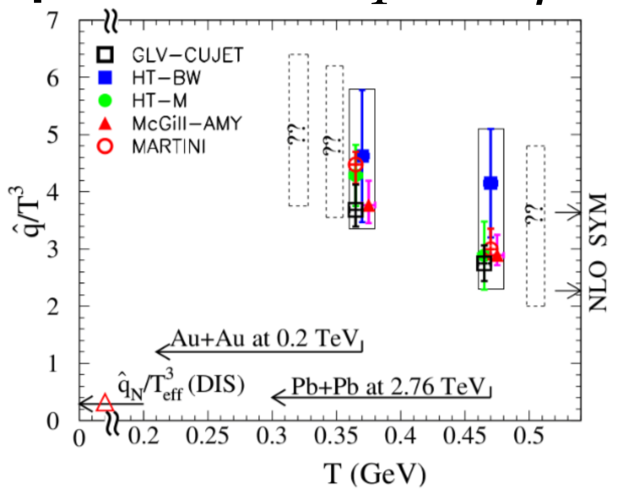
Jet quenching: where are we ?

- Some lessons from LHC data on jets:
  - Hadron and jet R_{AA} (AA/pp) “suppressed” out to p_T ~ 1 TeV/c
  - First direct observation of energy loss via di-jet momentum balance
  - “Lost energy” goes to low p_T particles at large angles (“out of cone”)
  - Moderate modification of fragm. functions and little/no mod. of jet shapes
  - Can tag parton energy and flavour: γ/Z-jet balance, b-jet tagging
- Lively theoretical development, first studies to extract QGP properties

Di-jet imbalance



Transport coeff. $\hat{q} \sim \sigma \cdot \rho$

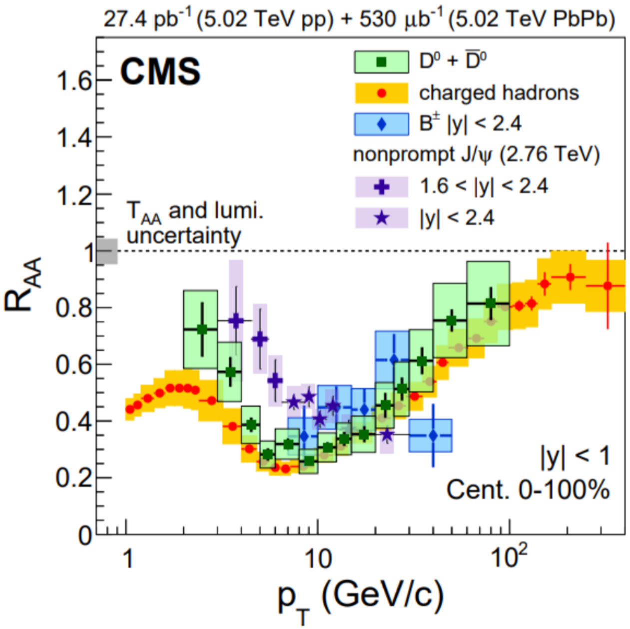


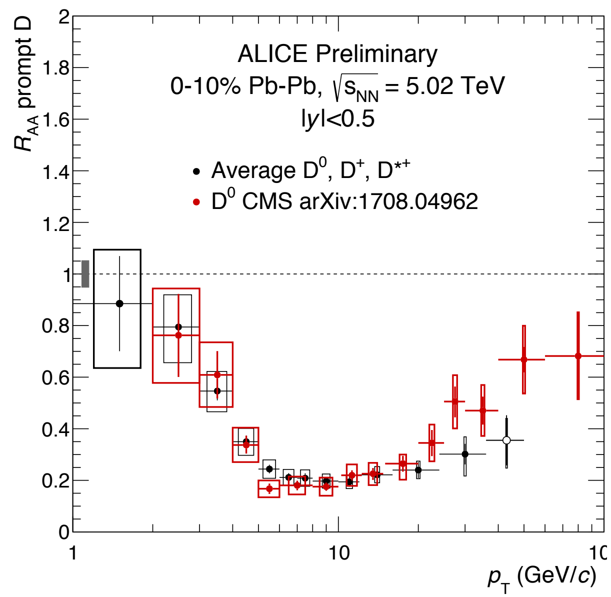
ATLAS, PRL105 (2010) 252303, CMS, PLB712(2012) 176

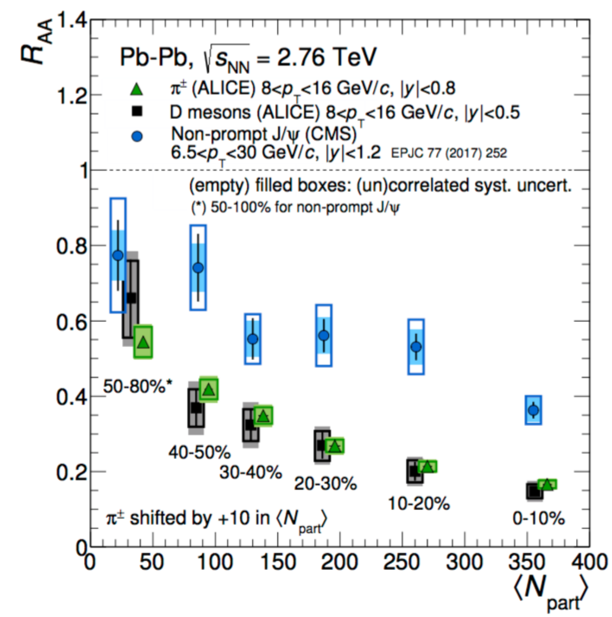
JET Coll., PRC90(2014)014909

Heavy flavour: where are we ?

- Suppression of D mesons measured up to 100 GeV/c, similar to charged hadrons (pions) above 5 GeV/c
- First indication of mass dependence of energy loss: $R_{AA}^{J/\psi \text{ from B}} > R_{AA}^{D}$





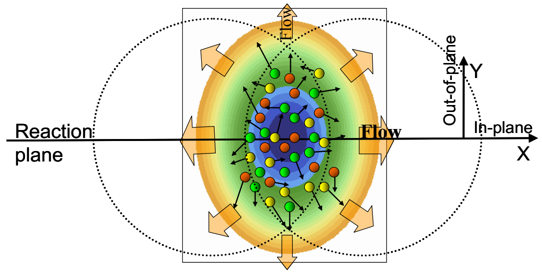


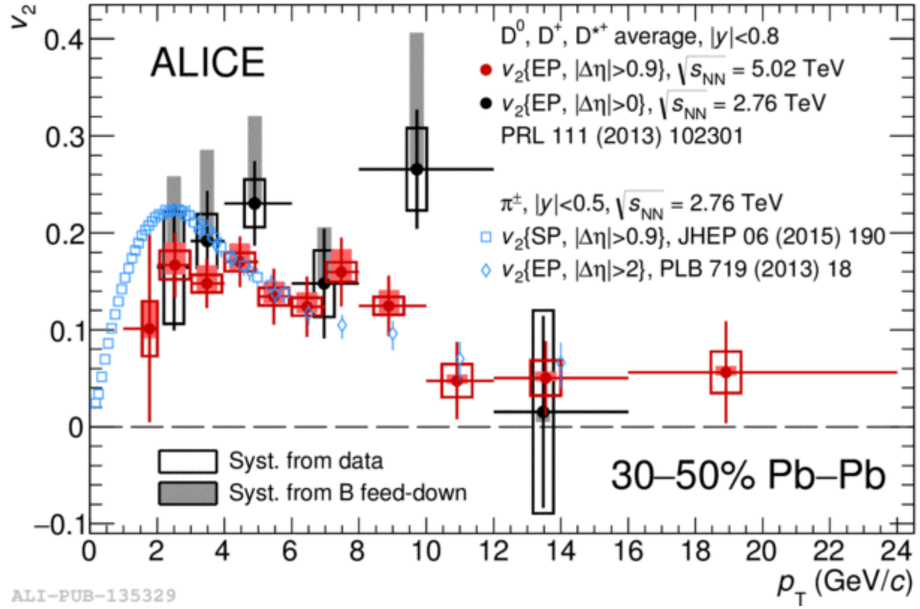
ALICE, JHEP 1511(2015)205, ALICE-PUBLIC-2017-003, CMS, EPJC77(2017)252, arXiv:1708.04962

→ Large uncertainties for D $p_T \rightarrow 0$ and no measurement for B $p_T \rightarrow 0$

Heavy flavour: where are we ?

- D mesons have elliptic flow v_2>0
- QGP expansion transmitted to charm quarks via multiple scatterings (diffusion mechanism)

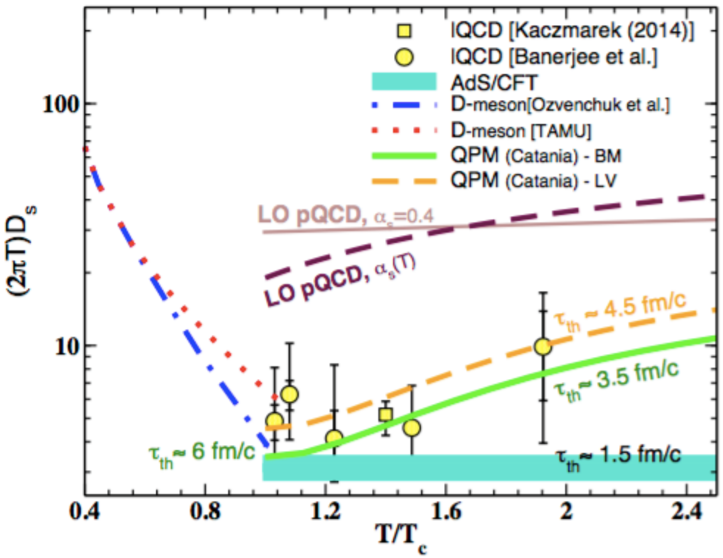




ALICE, arXiv:1707.01005, CMS, arXiv:1708.03497

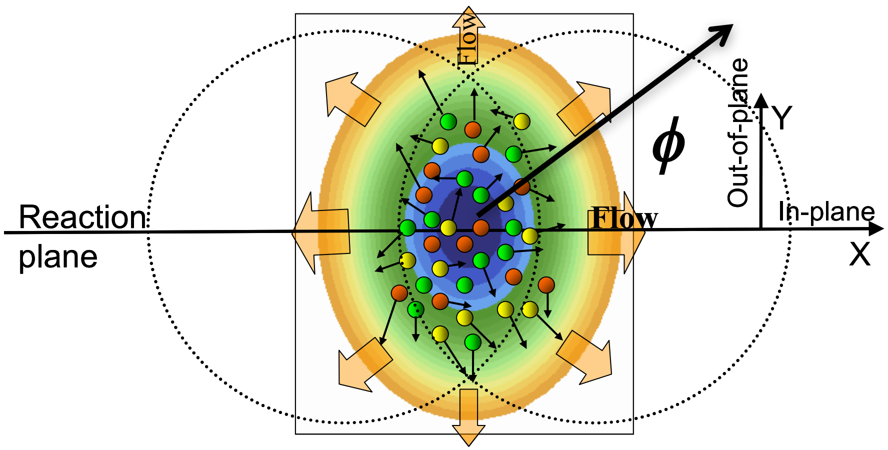
→ Need it also for beauty, which can be calculated more accurately in lattice QCD

- Model calculations extract c-quark diffusion coefficient in the QGP: can be compared with first-principle QCD calculations on the lattice



Catania group, arXiv:1707.05452
Also: Duke group, Nucl.Phys. A967 (2017) 668

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 $v_2(p_T)$

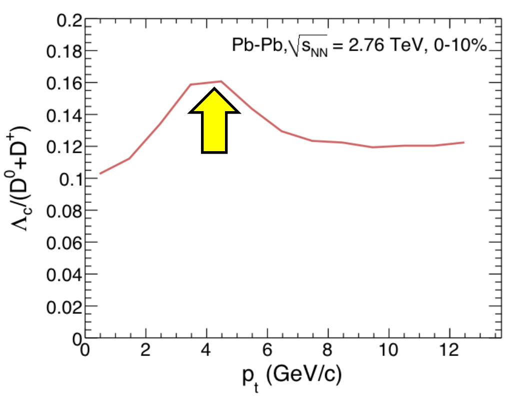
$$\frac{dN}{Nd\phi} \sim 1 + 2v_2 \cos(2(\phi - \Psi_{RP})) + \textit{higher harmonics } (v_3, v_4, \ldots)$$

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

In-medium heavy-flavour hadronization?

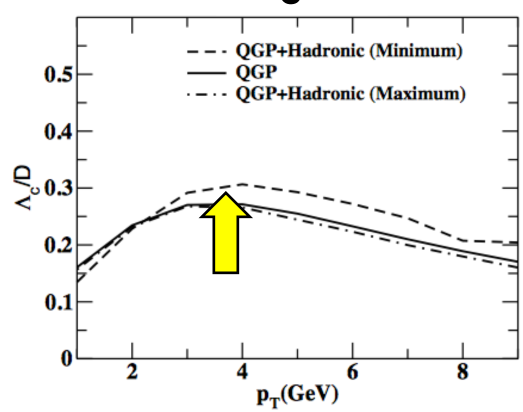
- From LHC Run 1 data, some hints that charm *could* recombine in the medium
  - → Precise measurements of HF mesons (non-strange and strange) and baryons
  - → Precise measurements of their v_2 (+ that of J/ψ, discussed later)

Λ_c/D



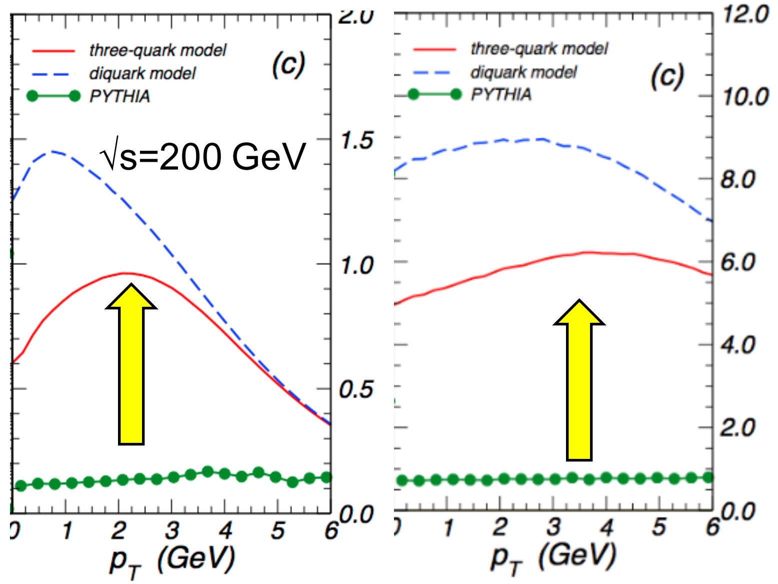
Rapp et al., based on PRL110 (2013)

Λ_c/D



Greco et al. PRD90 (2014)

Λ_c/D and Λ_b/B

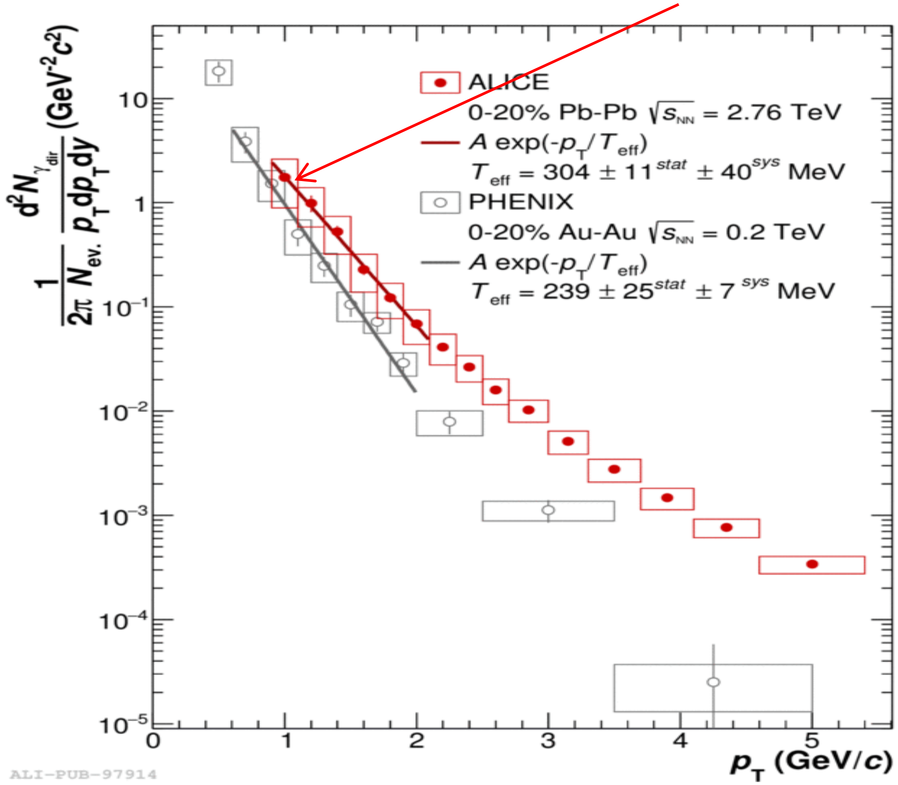


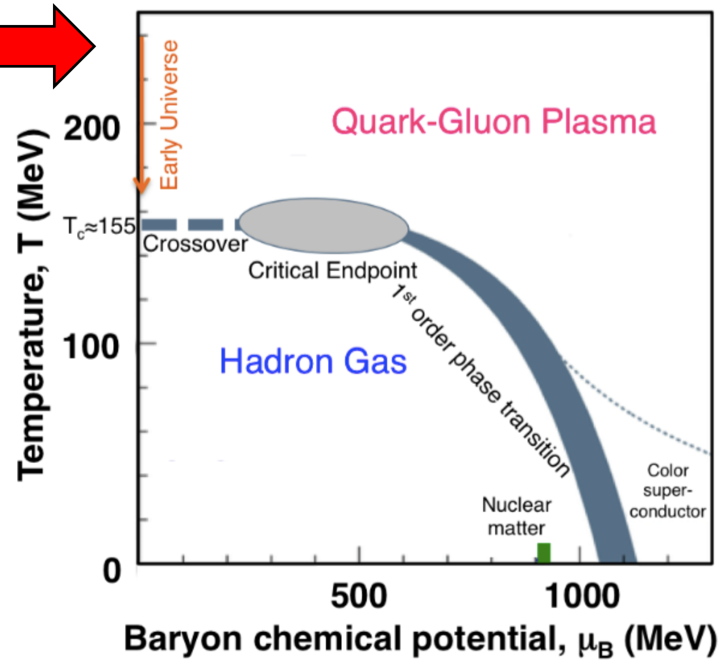
Ko et al. PRC79 (2008)

QGP temperature: where are we ?

- Temperature from QGP radiation
  - Additional handle on temperature from quarkonium melting (not discussed today)
- First measurement at LHC from soft exponential component of photon p_T spectrum: ***T* ≈ 300 MeV**

An effective temperature, averaged over system evolution (and cooling)

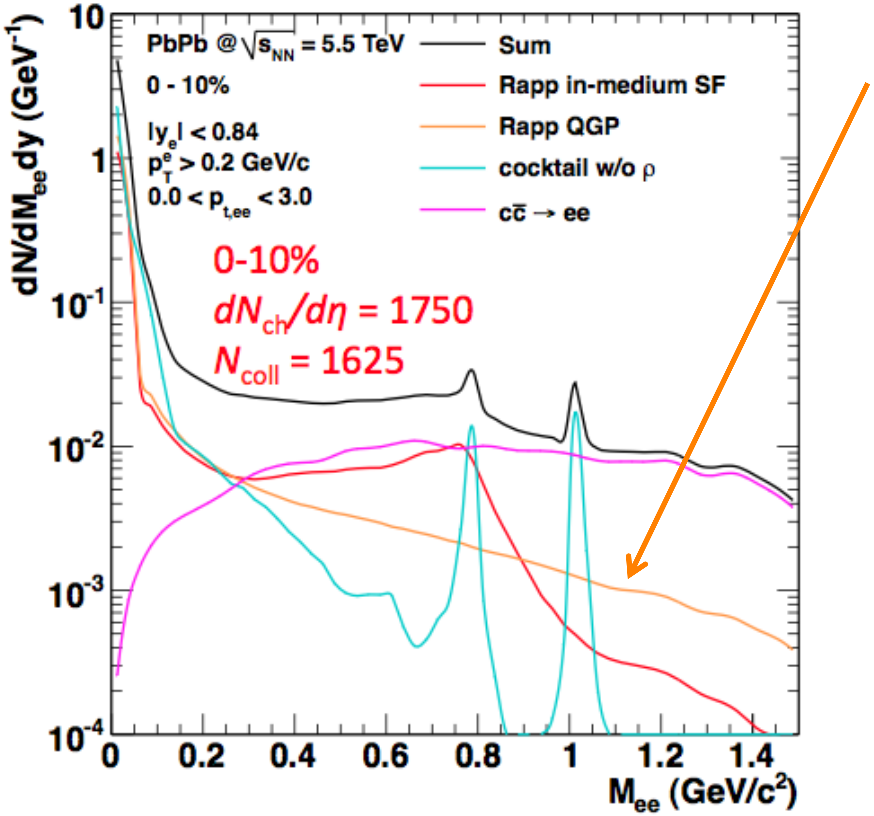




ALICE, PLB754 (2016) 235

Temperature evolution: low-mass di-leptons

- Measurement of low-mass di-leptons allows mapping the temperature during the system evolution

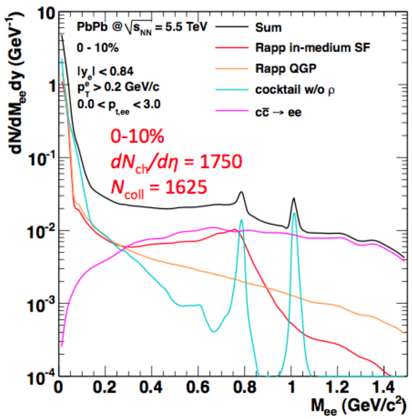


Di-leptons from real and virtual photons $\gamma \rightarrow e^+e^-$

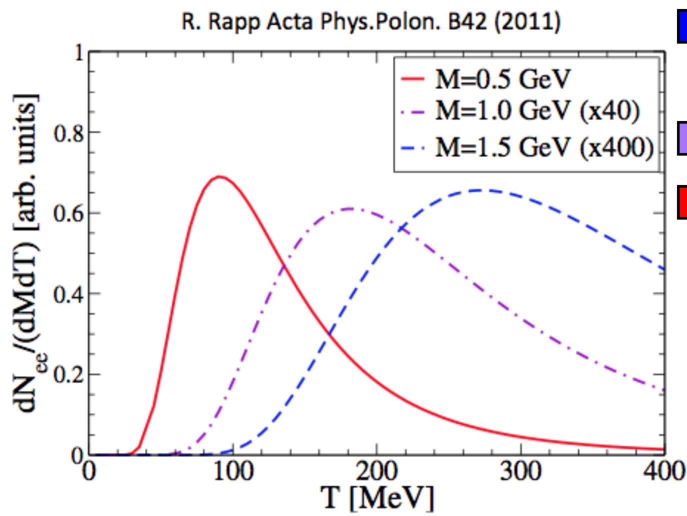
Complex measurement: need to disentangle all di-lepton sources

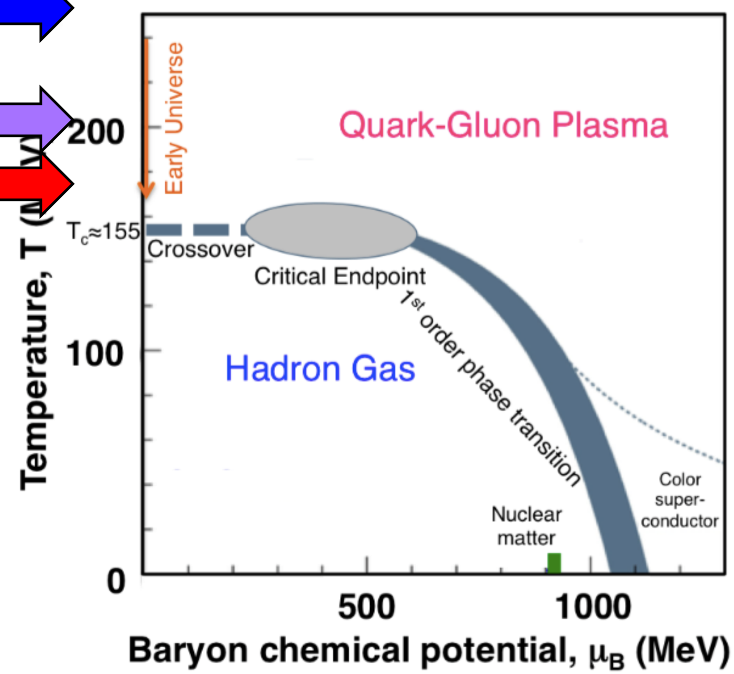
Temperature evolution: low-mass di-leptons

- Measurement of low-mass di-leptons allows mapping the temperature during the system evolution



Di-leptons from real and virtual photons $\gamma \to e^+e^-$





High masses → high T, early stage

Intermediate masses

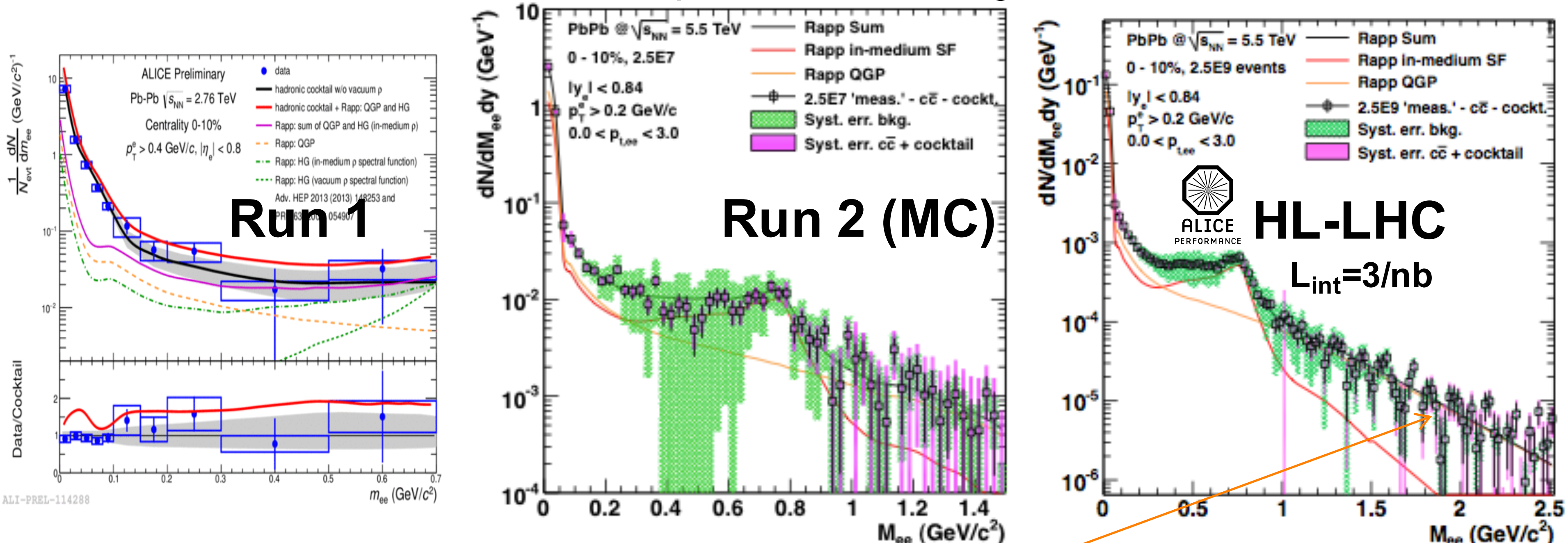
Low masses → low T, late stage

Low-mass di-leptons after LS2

- ALICE: lighter tracker **+ dedicated run at low B (0.2 T)**
  → 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:

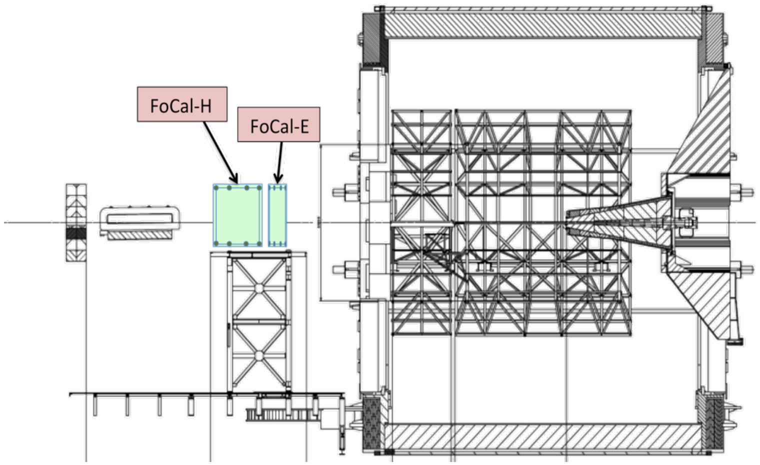


Precision of ~10% on the inverse slope → *T*

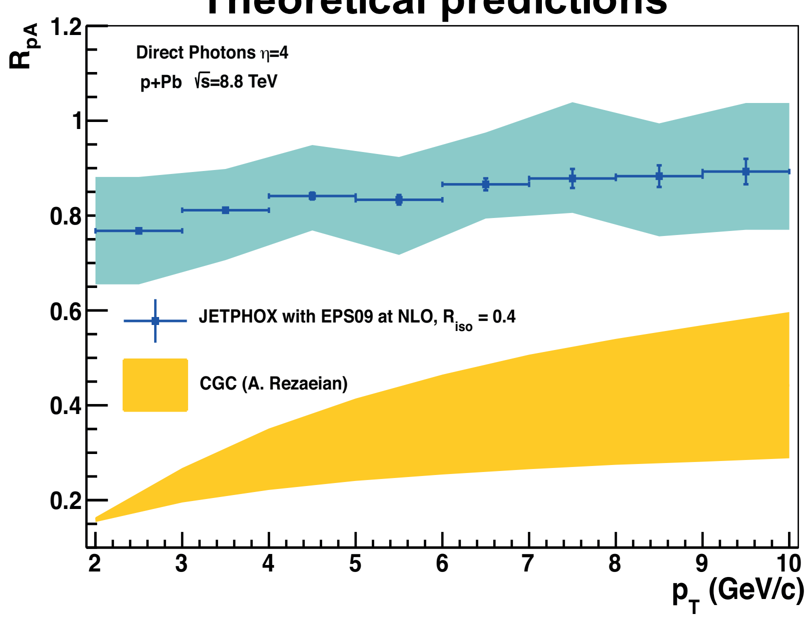
ALICE, CERN-LHCC-2013-024

Study for a forward calorimeter in ALICE

- FoCal: R&D for a high-granularity calorimeter at η~3-5 with focus on saturation physics studies
  - Possible installation during LS3
- Benchmark measurement: direct photons η~4-5 in p-Pb ($x \sim 10^{-5}$)
  - Sensitive to Shadowing vs. Saturation



Theoretical predictions



Projected performance