

Heavy Ion Collisions at LHC: physics prospects beyond 1/nb

Outline:

- **Present status in 4 slides**
- **expectations and goals for campaign after LS2**

ATLAS

CMS

ALICE (main emphasis)

Peter Braun-Munzinger
LHC France 2013
Annecy, April 6, 2013

Heavy ion running at LHC and near future

2 PbPb runs

- 2010 $O(10 \mu\text{b}^{-1})$
- 2011 $O(150 \mu\text{b}^{-1})$

luminosity reached $\mathcal{L}=2 \cdot 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ twice design lumi at this energy

1 pPb run

- 2012/2013 $O(30 \text{ nb}^{-1})$

from 2/2013 until end of 2014 LS1: consolidation of LHC to allow full energy

2015-2017 PbPb running at $\sqrt{s_{\text{NN}}} = 5.5 \text{ TeV}$ at up to 4 x design lumi
to achieve approved initial goal of 1 nb^{-1}

2018 start LS2 – increase of LHC luminosity (timing to be optimized in 9/13)

Achievement with 1nb⁻¹

from data analyzed up to now we can extrapolate:

physics goals with hadrons in the uds sector and for $p_t < 10$ GeV achieved

- abundances, spectra, R_{AA} , flow, correlations

large cross section issues in heavy quark sector solved as well

Main results for Pb-Pb collisions at the LHC in 4 exemplary slides

R_{AA} = medium/vacuum

$R_{AA} = 1$ if no dense medium is formed

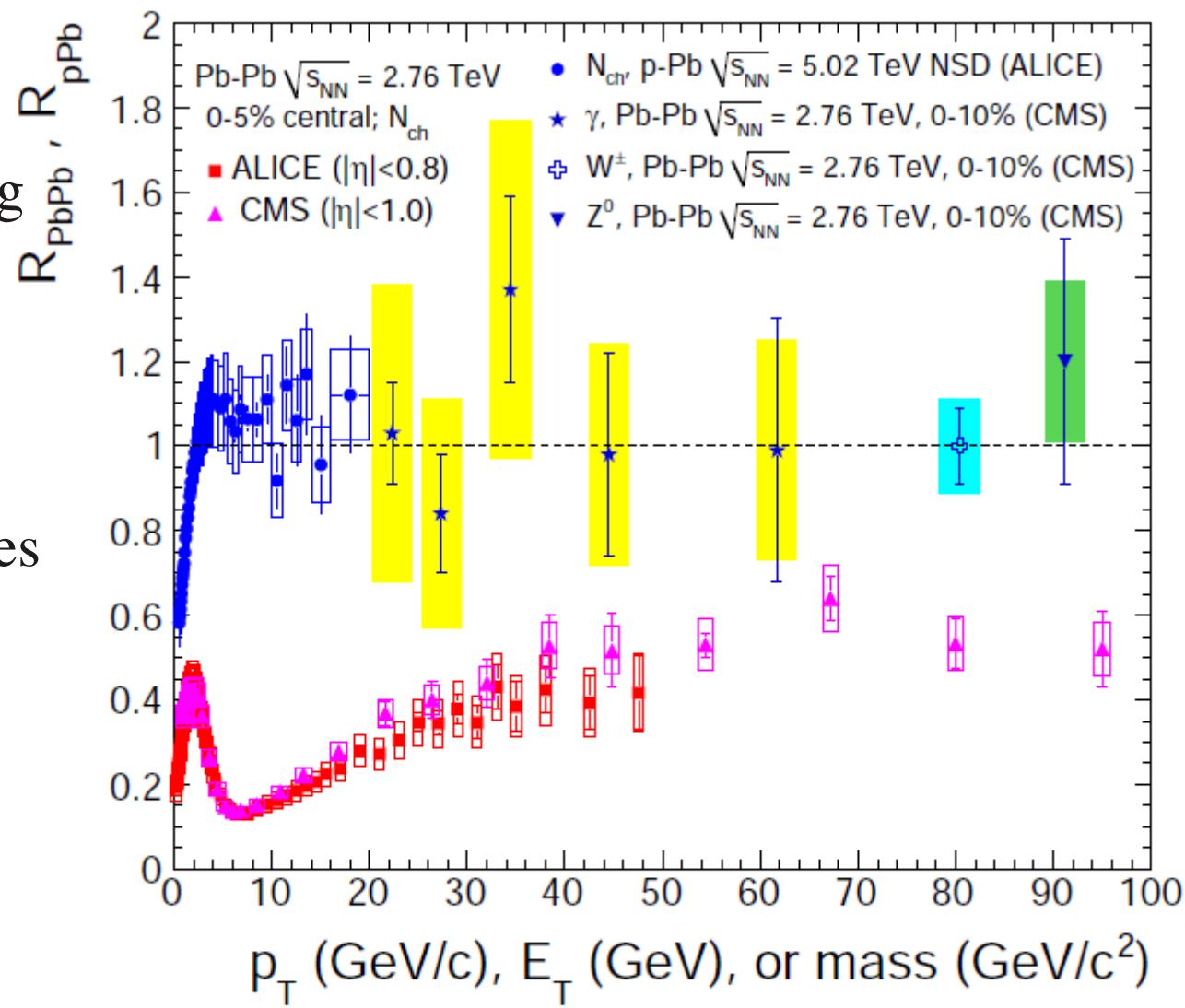
or

if one looks at electro-weak probes

Nuclear Modification Factor

$R_{AA} \ll 1$ for
strongly interacting
probes, even for
large transverse
momenta,

electro-weak probes
don't
see the dense
medium

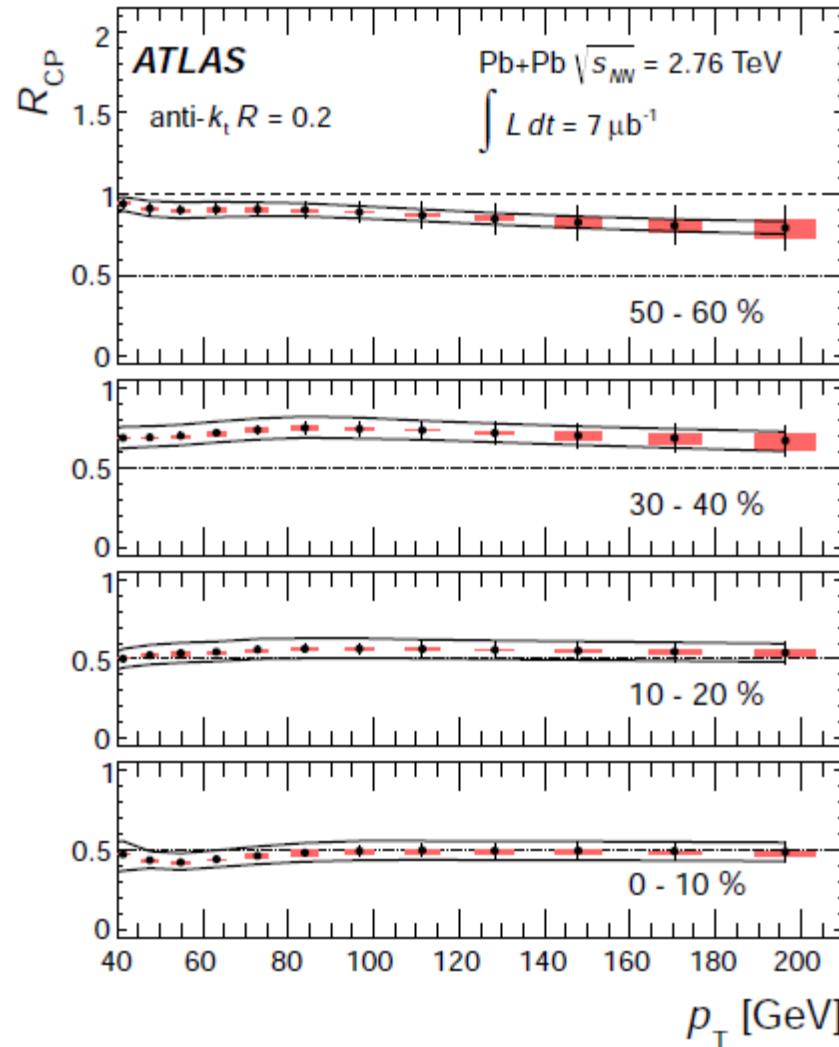


Saturation for Pb-Pb at high pt ?

Figure 5.5: Compilation of nuclear suppression factors R_{PbPb} and $R_{p\text{Pb}}$ for different observed species as function of the transverse scale (p_T , E_T , or M_T). The data are from ALICE $p\text{-Pb}$ [29], ALICE charged particles [30], CMS charged particles [31], CMS γ [32], CMS W [33], CMS Z [34].

Jet quenching at the LHC

Quenching of reconstructed jets

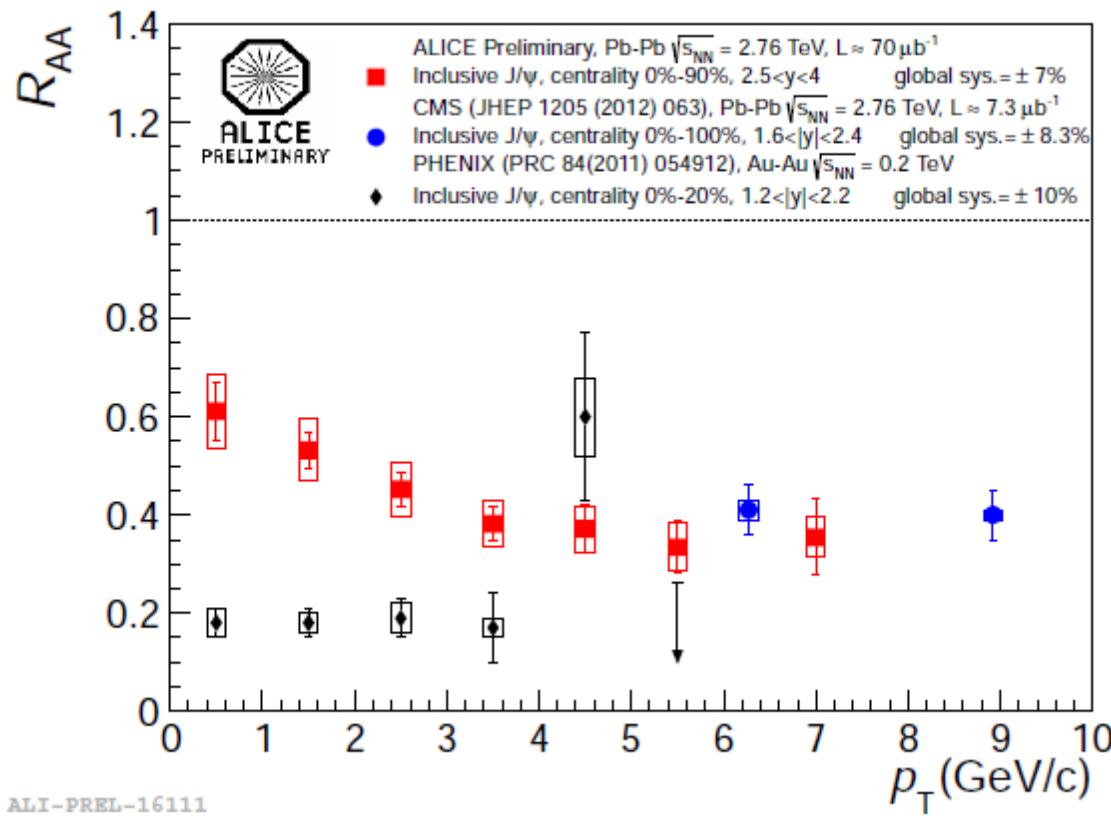


R_AA never reaches unity

R_AA for charmonium – RHIC vs LHC

Qualitatively new pt dependence of RAA for J/psi production at LHC

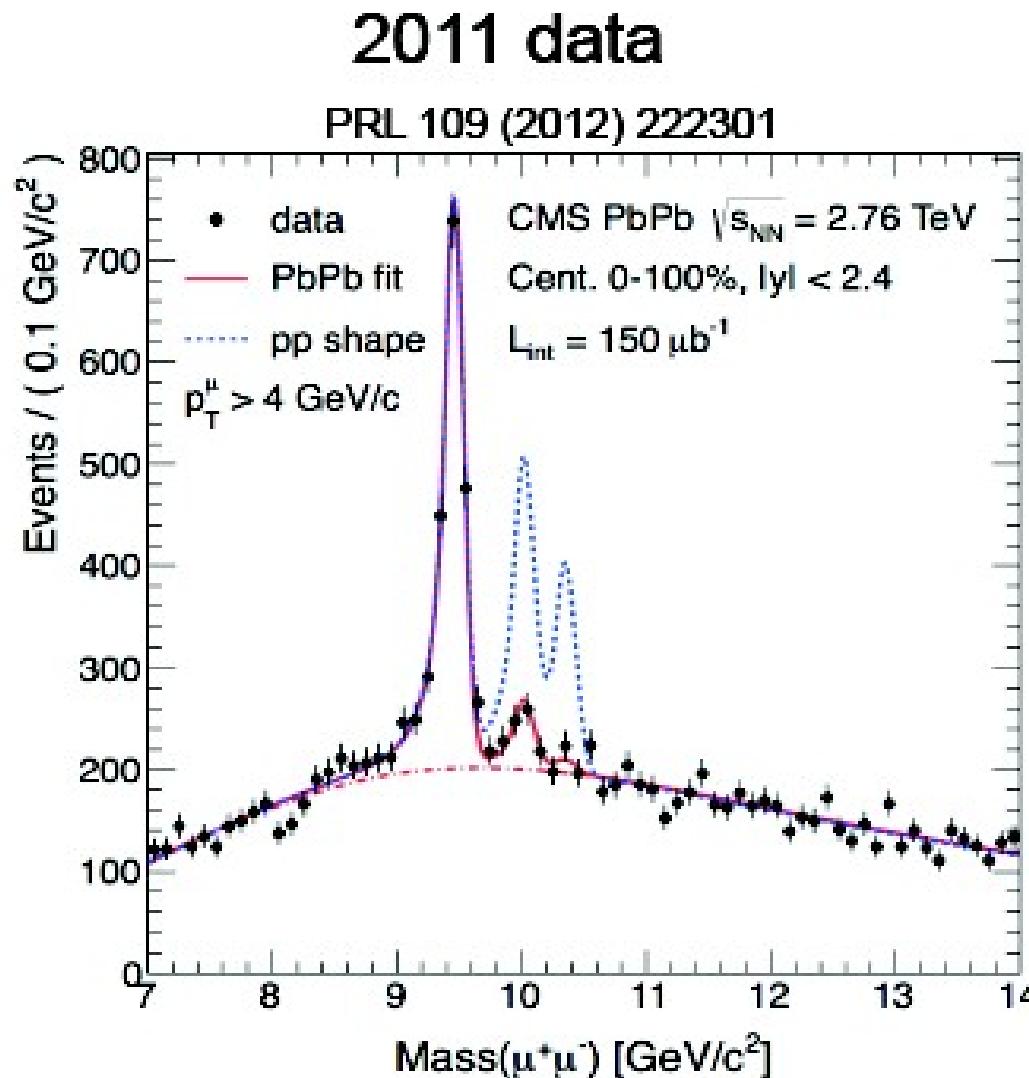
ALICE
CMS
PHENIX



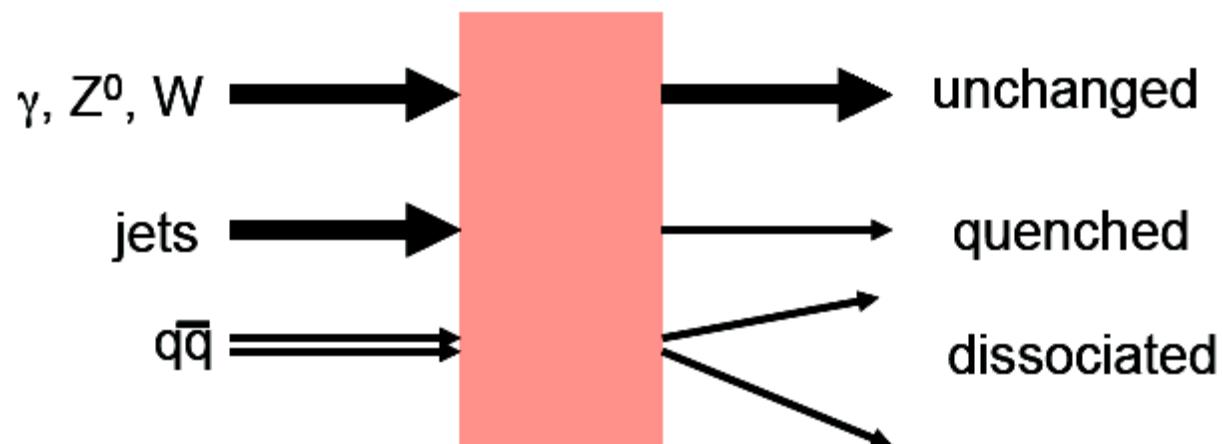
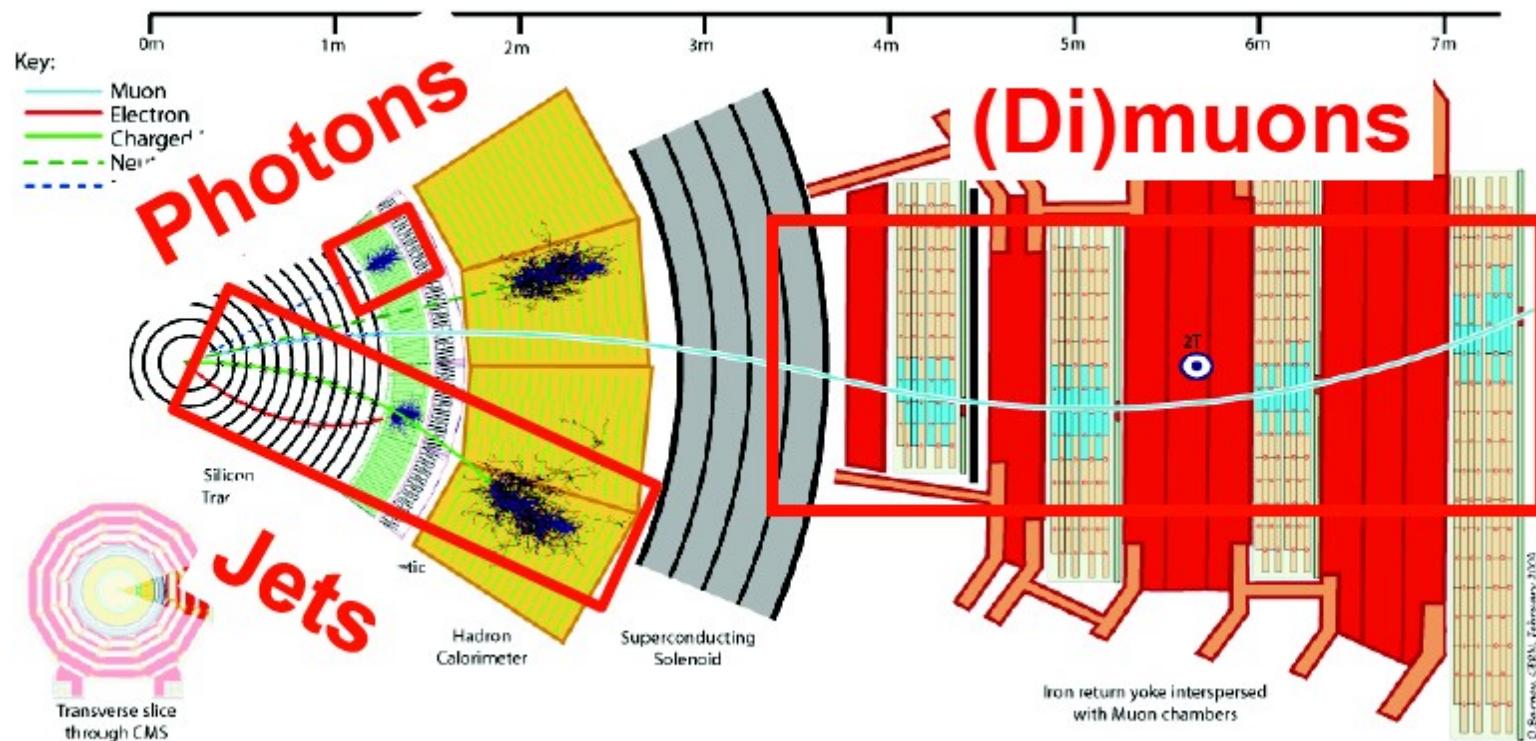
Despite increased energy density at LHC energy, R_{AA} increases at low transverse momenta when going from RHIC to LHC energy
→
complete color screening and deconfinement for charm quarks

Y Suppression in CMS Pb-Pb Collisions

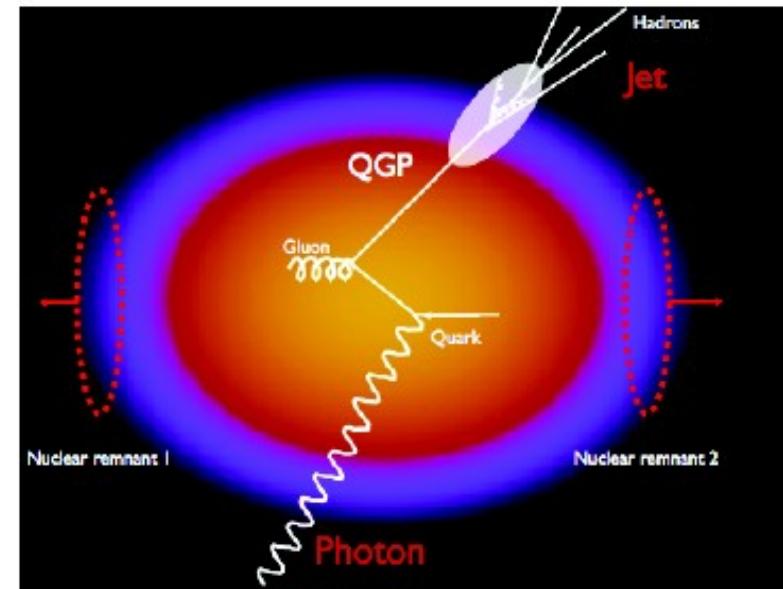
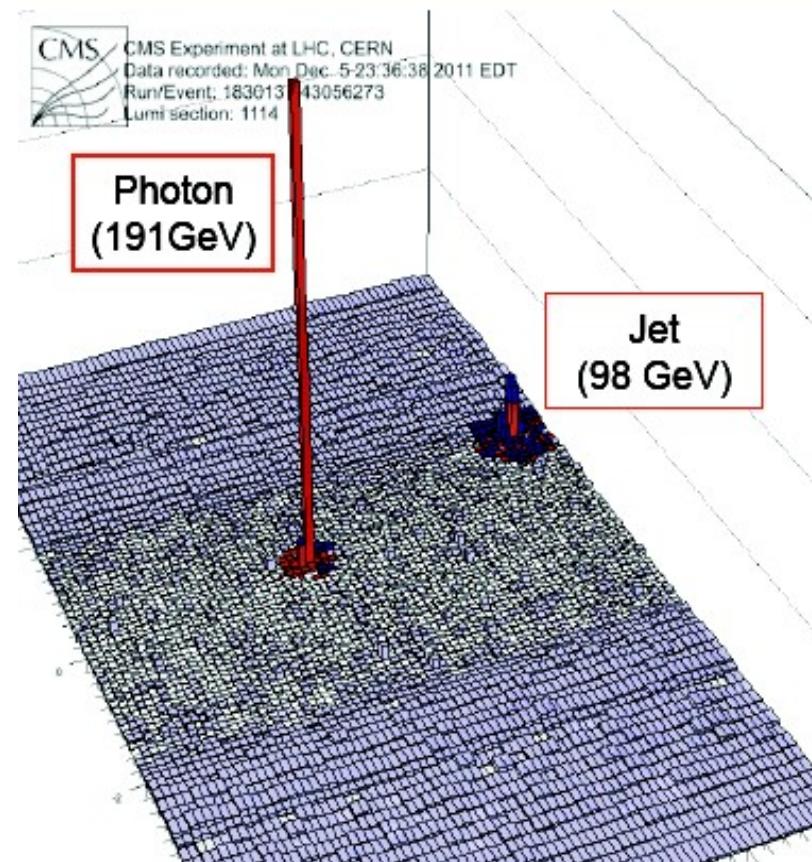
Y states are suppressed relative to pp measurements – CMS



CMS – Focus on Hard Probes



$\gamma + \text{jet}$: u,d quark energy loss



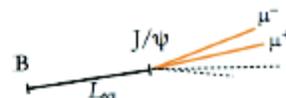
Photon tag:

- Identifies jet as u,d quark jet
- Provides initial quark direction
- Provides initial quark p_T

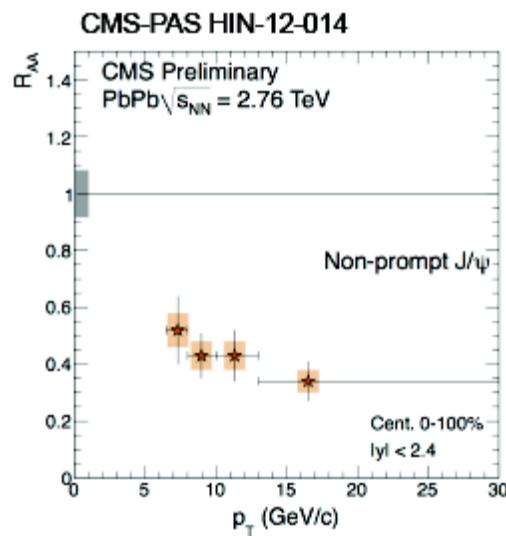
B-tagging in PbPb

Study quark mass dependence of energy loss

$6.5 < p_T < 30 \text{ GeV}$:
Displaced $J/\psi \rightarrow \mu\mu$

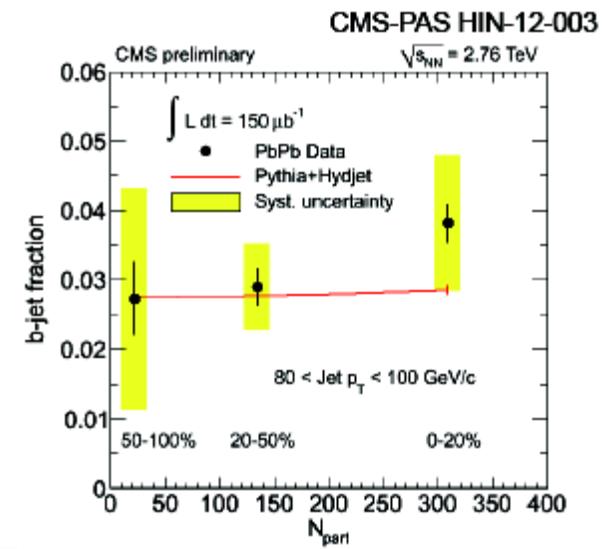


Obtain $B R_{AA}$



$p_T > 80 \text{ GeV}$:
Jet + high mass
secondary vertex

Obtain *b-jet fraction*

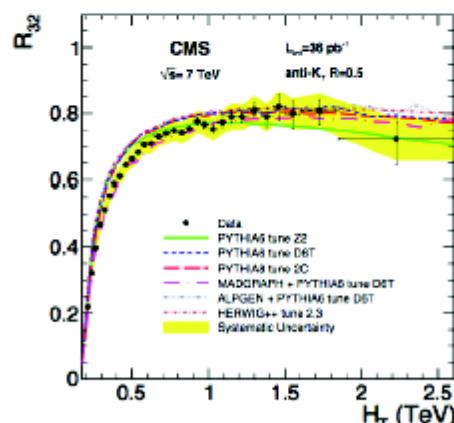


After LS1: Precision + Accuracy

- For now, “Golden channels” suffer from limited statistics
 - γ +jet, Z^0 +jet, $Y(nS)$ vs N_{part}
- Expect further increase in luminosity
 - Machine predictions have been very conservative
- Key issue in CMS: Selectivity of L1 trigger
 - PbPb input rate for high level trigger limited to < 3kHz
 - E.g. 50kHz PbPb requires 95% rejection at L1
 - Current configuration limited to 50% for jet triggers
 - requires background subtraction at L1
- L1 upgrade proposal approved by CMS
 - (Moderate) funding request for 2013-15 (HEP+NP)

LS2 and beyond: New Frontiers

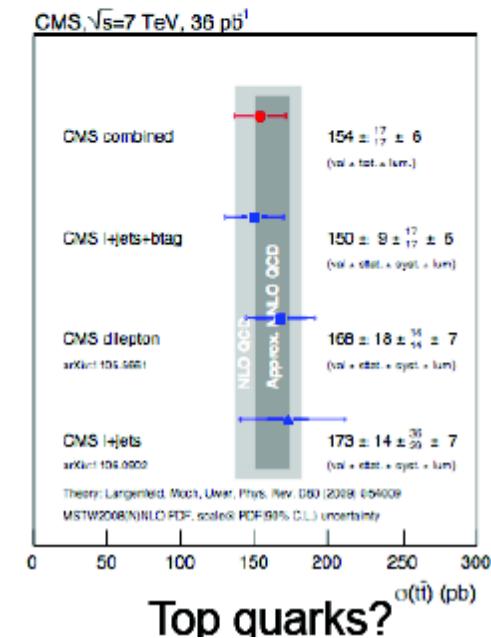
- CMS upgrade for HL-LHC
 - Trigger/DAQ ready for highest conceivable PbPb rates
 - Major upgrades for silicon tracker, calorimeters, trigger
- 10/nb PbPb corresponds to several 100/pb pp



Multi-jet ratios!

Statistics to pursue
sophisticated
QCD measurements

Full arsenal of pp
heavy-flavor analyses
(b-physics, top)



Top quarks?

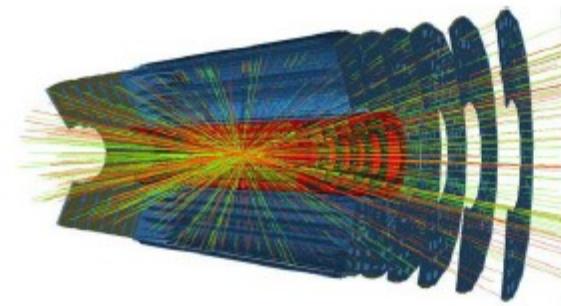
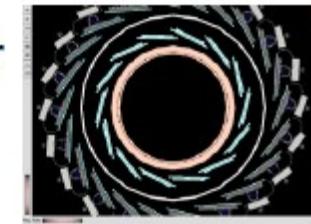
ATLAS – Focus on Hard Probes



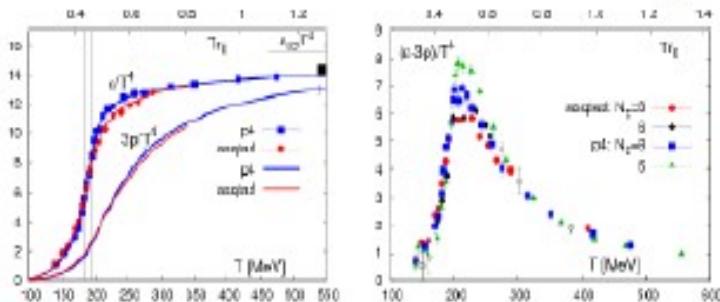
ATLAS detector upgrades

Multi-step upgrade strategy

- Phase 0 – LS1 (2013-2014)
 - Insertable B Layer inside the current pixel detector
 - Fourth layer added closer to the beam pipe
 - A new smaller beam pipe
- Phase 1 – LS2 (2018)
 - FTK – Fast tracking trigger
 - LAr calorimeter read-out and trigger
 - New forward muon detectors
 - Forward proton detectors and trigger/DAQ upgrades
- Phase 2 – LS3 (2022)
 - New Inner Detector
 - LAr upgrades
 - Tile upgrades
 - Trigger/DAQ



ATLAS HI program prior to LS3



Is QCD weakly or strongly coupled at high T?

Study the interactions of color charges in the QGP:

- Using high- p_T jets, dijets, and multi-jet final states
- Using b-tagged jets
- Perform precision measurements with γ -jet and Z-jet pairs.
- Use quarkonia, particularly the $\Upsilon(1S)$ and excited states, to study Debye screening in the QGP
- Study global features of the final state using charged particle measurements over $|\eta| < 2.5$ and calorimetric measurements over $|\eta| < 5$
- Study low-x and initial-state effects in p+A collisions

Need more luminosity? Yes!

- Even with x10-40 we will be statistics limited for heavy flavor, more differential observables:
 - e.g. b-tagged dijets, γ/Z -b jet
 - $\Delta\varphi$ -dependent γ -jet, Z-jet
 - γ -jet, Z-jet fragmentation @ high z
 - γ/Z - multijet
 - fragmentation photons
 - $Z \rightarrow b\bar{b}$
 - ...
- ➡ Too soon to know which of these might be useful or essential for accomplishing physics goals.

ALICE – Focus on Low p_t Processes in Charm, Beauty, and (Virtual) Photon Sectors

Future after LS2

achieve for PbPb 10 nb^{-1} corresponding to $8 \cdot 10^{10}$ collisions sampled plus a low field run of 3 nb^{-1}

pp reference running 6 pb^{-1} or $1.4 \cdot 10^{11}$ collisions

pPb sample 50 nb^{-1}

this is a program of about 6 years probably interrupted by another 2 year long shutdown around 2022/23 leading us to 2026 or so

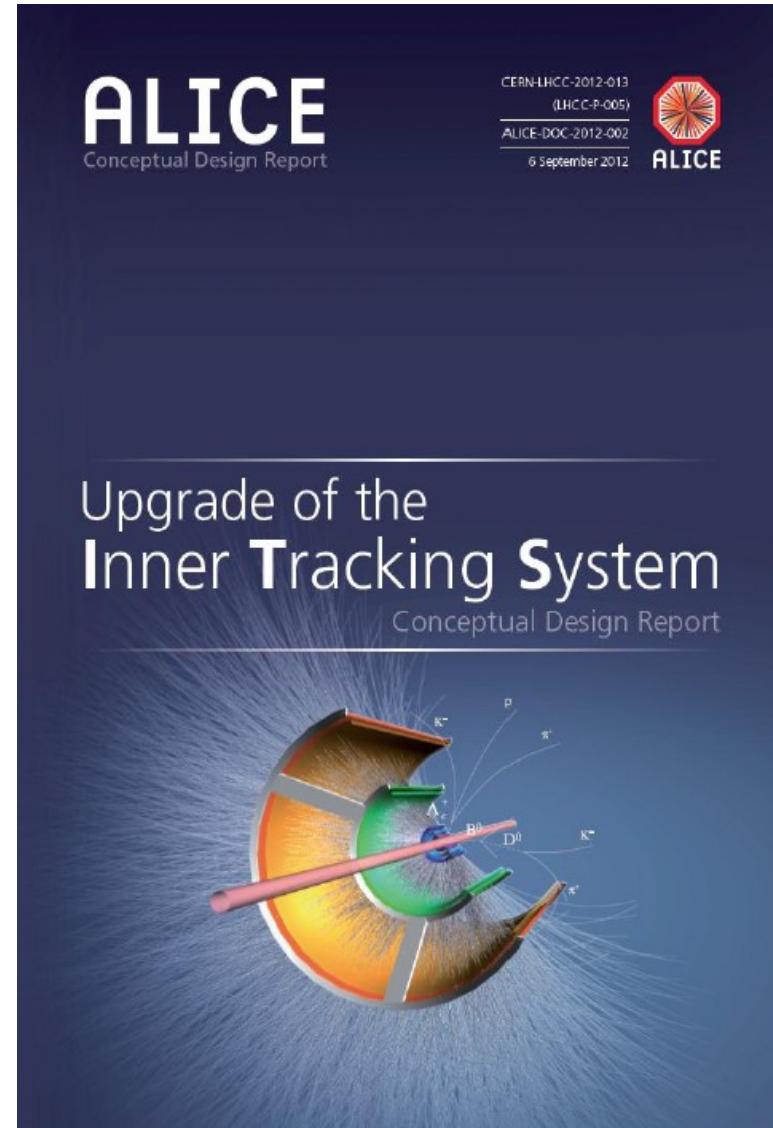
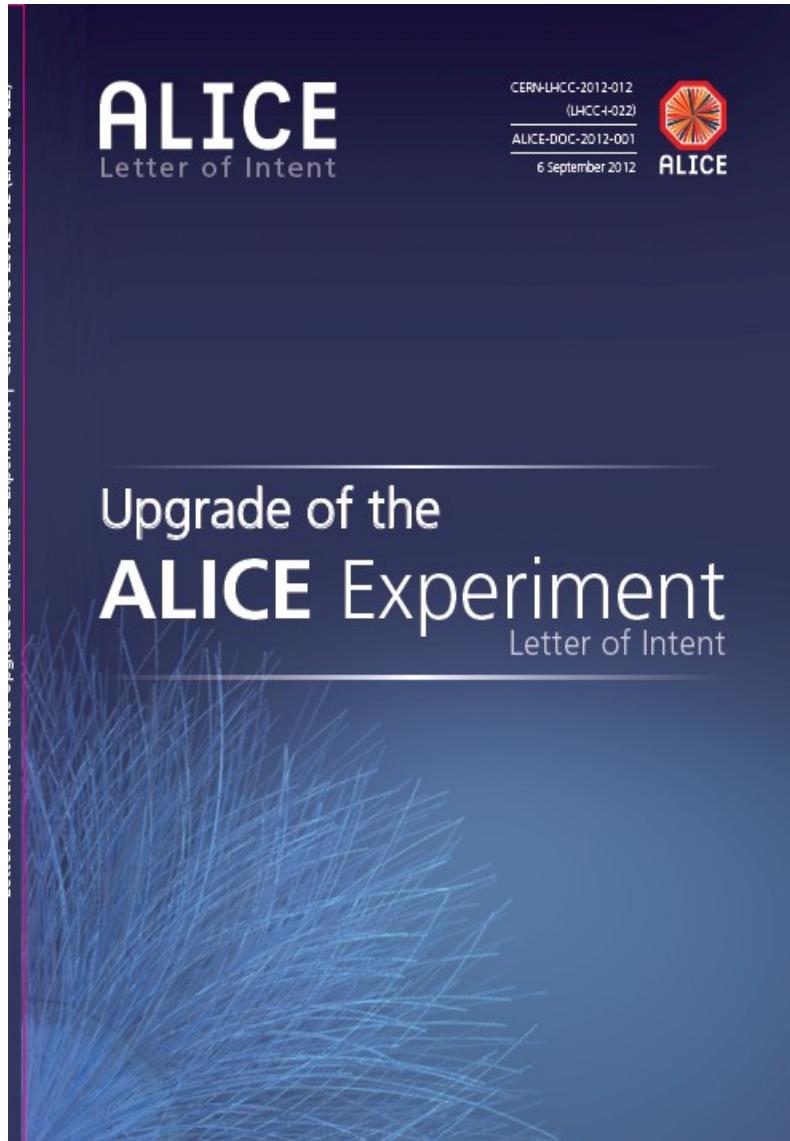
envisage PbPb peak luminosities of $\mathcal{L} = 6 \cdot 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ corresponding to interaction rates of 50 kHz – **more than 6 x design lumi**

detector upgrades with **continuous read-out**

to cope with this luminosity and

to achieve physics goals aimed for with this integrated luminosity
improved tracking and vertexing and excellent PID

2 letters of intent endorsed by LHCC and approved by Research Board

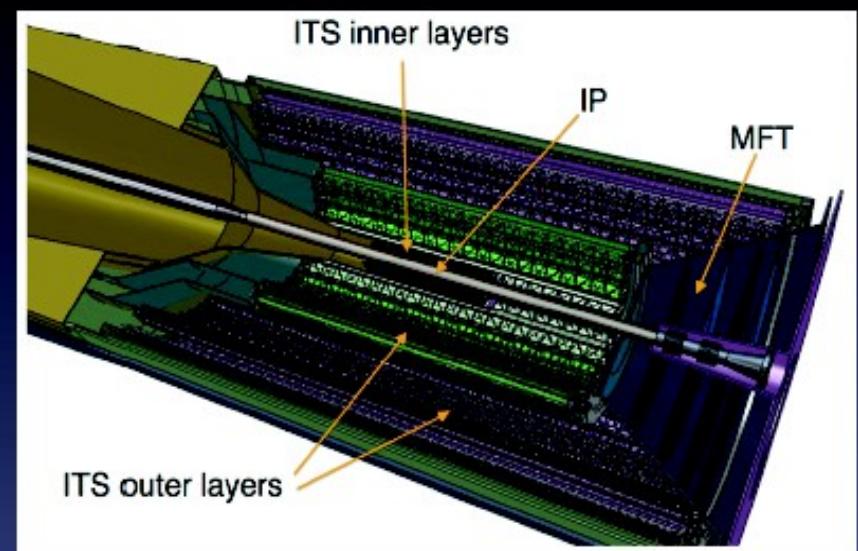
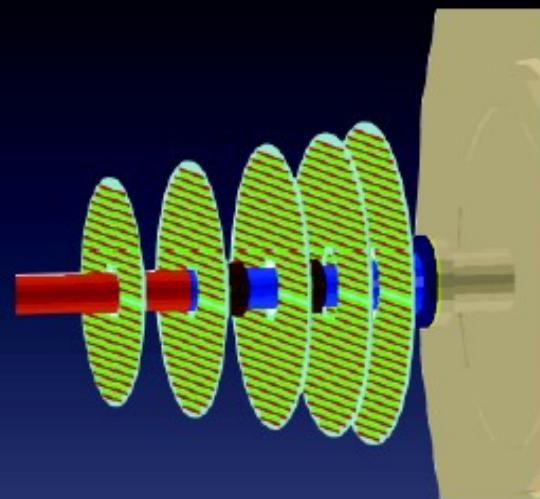


Recently approved by ALICE for a LoI to LHCC



The Muon Forward Tracker apparatus

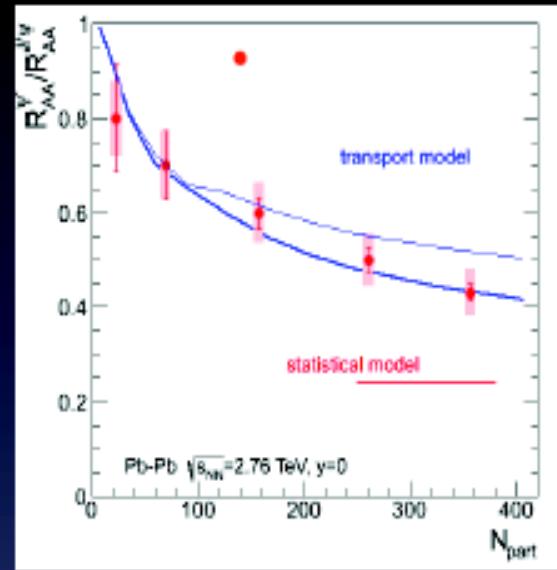
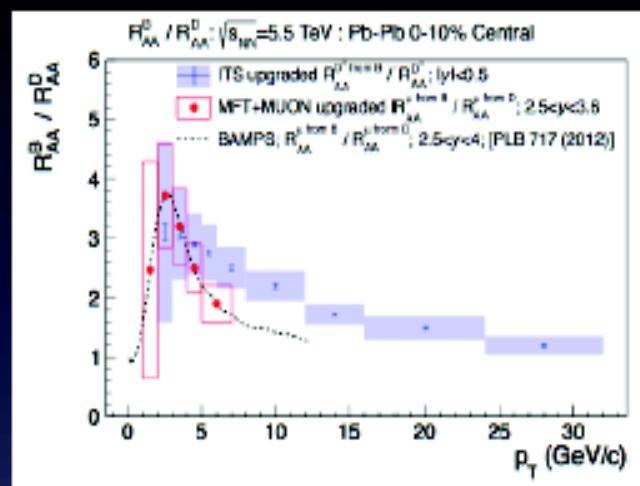
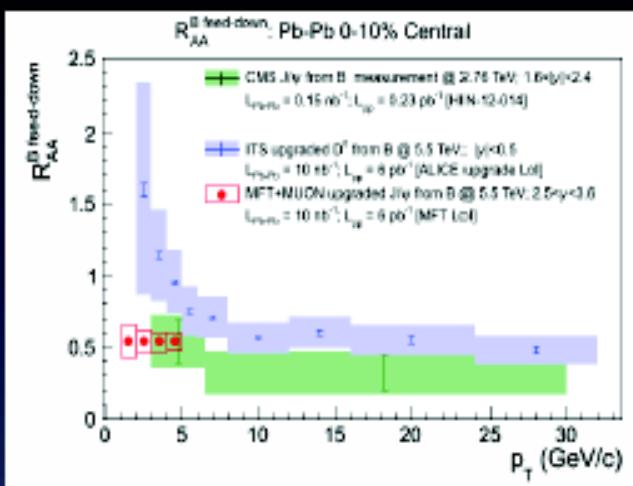
- 5 planes of CMOS silicon pixel sensors
- Placed between IP and front absorber
- Covering most of the MUON acceptance ($3^\circ < \theta < 9^\circ$, $-3.6 < \eta < -2.5$)
- Same Technology as for new ITS \Rightarrow numerous synergies in R&D





Major impact on ALICE physics capabilities

- Separate Charm and Beauty to low p_T in single muon and dimuon
- Access Beauty down to zero p_T thanks to displaced J/ ψ measurement
⇒ Test heavy quarks energy loss models
- Improved S/B allows precise ψ'/ψ measurement
⇒ Discrimination between statistical and transport models



MFT+MUON equivalent performances than new ITS in a complementary rapidity domain

ALICE Physics goals for future heavy ion running

precision measurements in

- charm sector – charmonia, open charm, thermal charm, flow and equilibration, fundamental issues with bound quarks in QGP
 - beauty sector – question of thermalization/equilibration
 - low mass lepton pairs – chiral restoration and thermal radiation
 - real (and virtual) photons – evolution of temperature and quark fugacities, role of hadronic phase
 - jets
 - search for exotica
- aim to reach text book level results**

Fundamental questions such as:

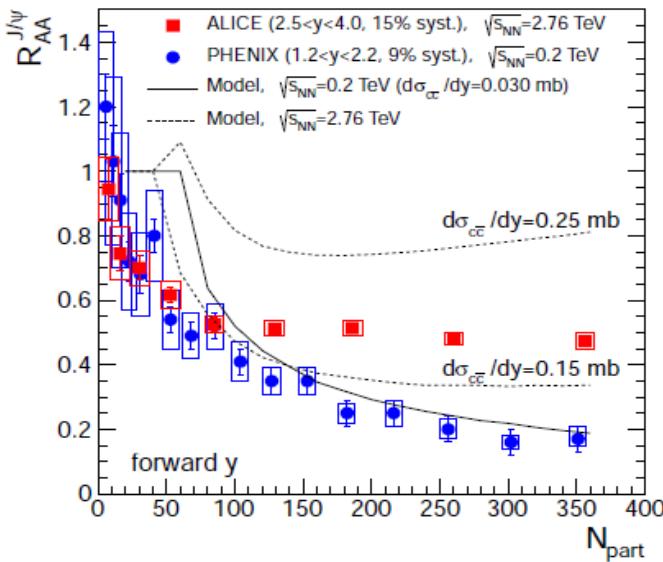
Is there a common phase boundary for all quark flavors?

Are there hadronic bound states at $T > T_c$?

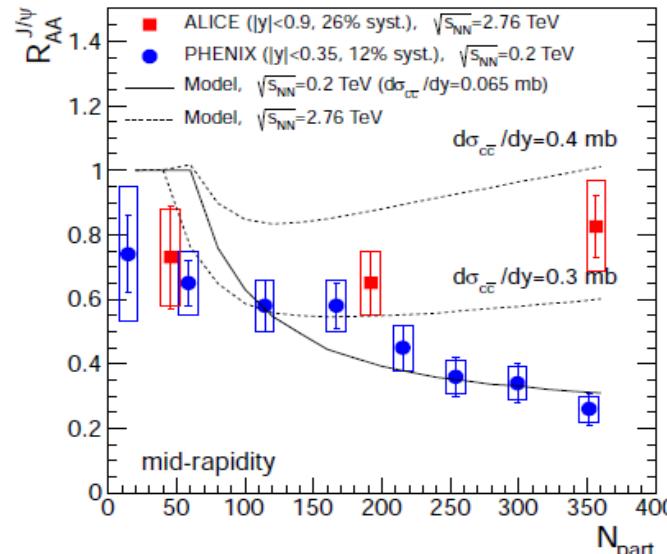
Can critical behavior near T_c be detected?

J/psi as probe of deconfinement

forward rapidity



mid rapidity

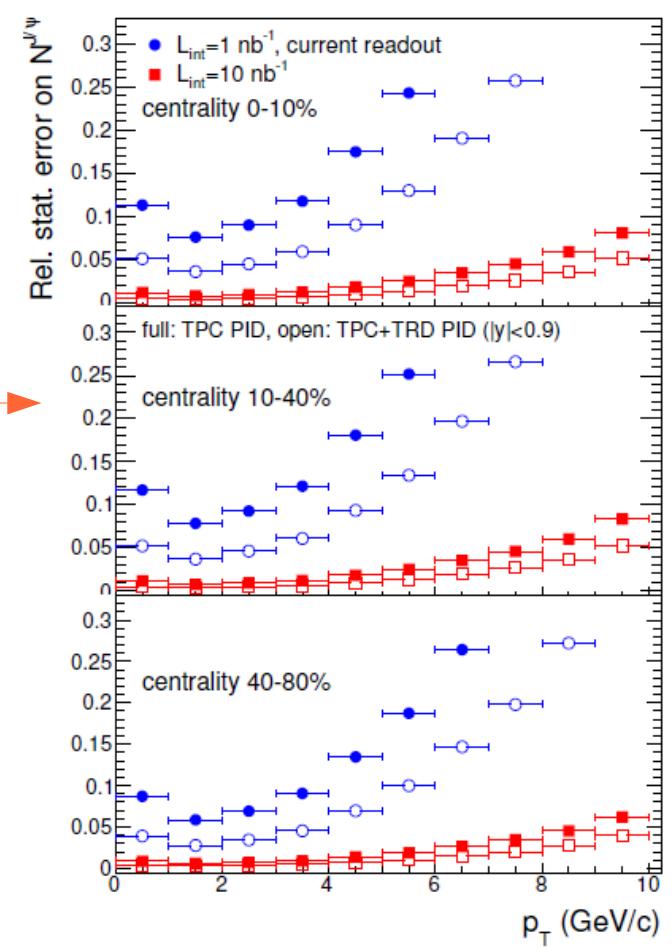


at $y = 0$ and low p_T , no trigger possible

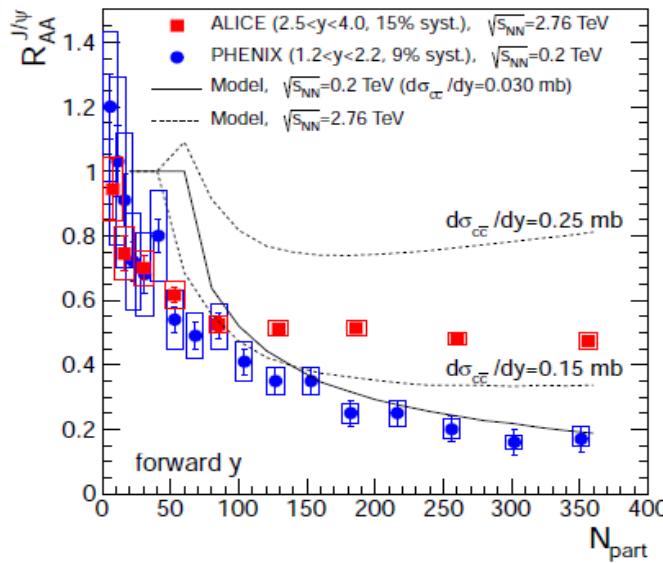
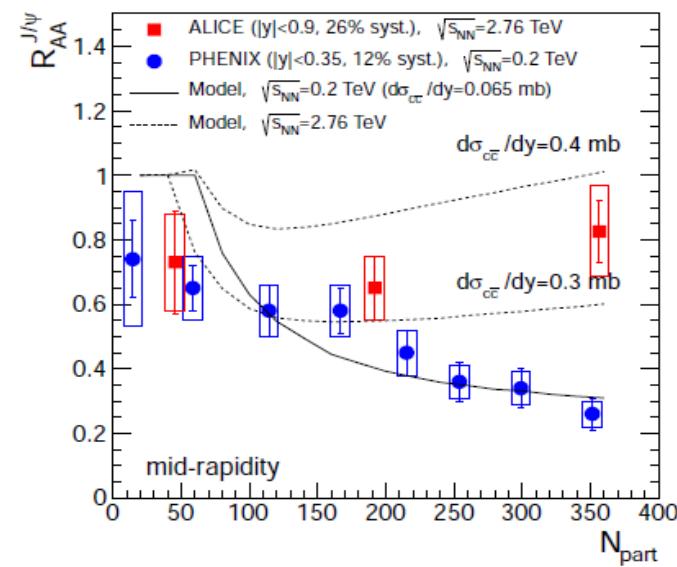
di-electrons statistics limited, 10 nb-1 will have huge effect

syst uncertainties will decrease with upgrade:

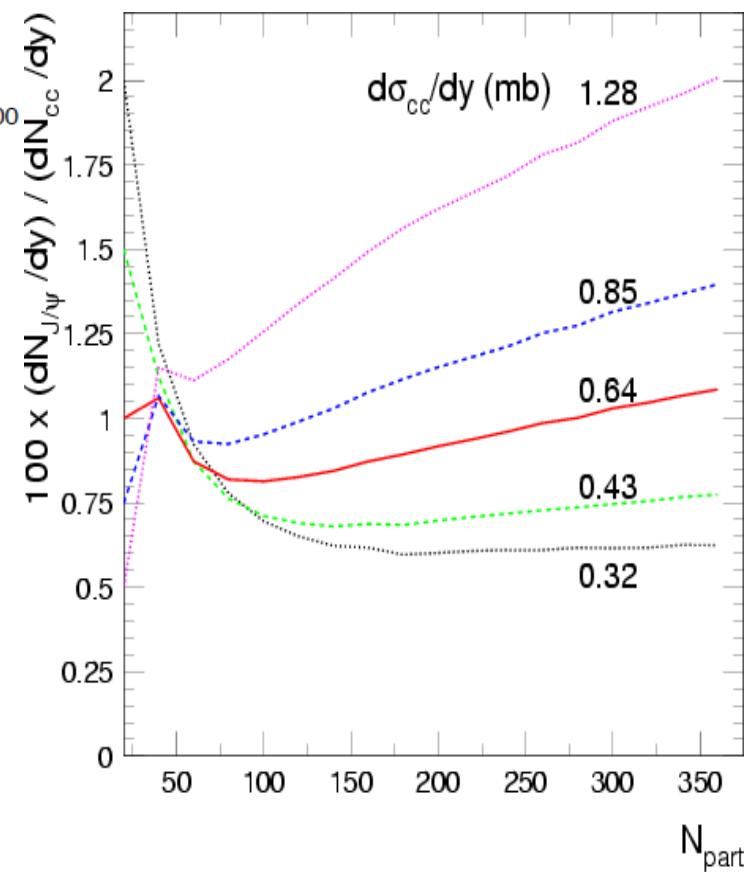
TRD for electron id - reduced comb background
thinner ITS - reduced radiation tail



J/psi as probe of deconfinement

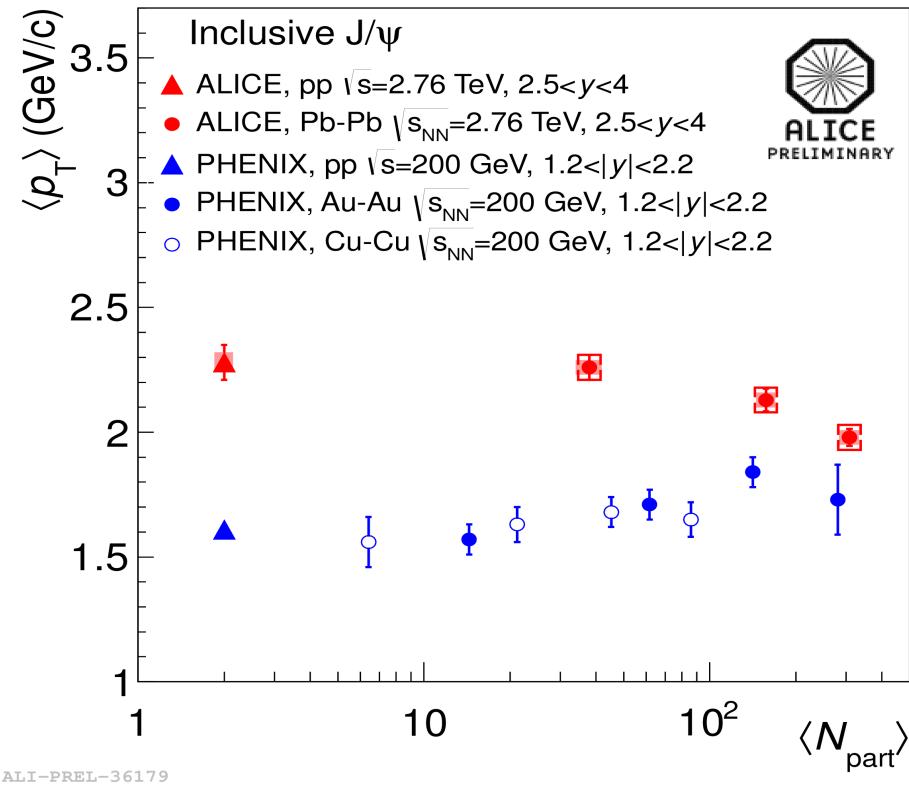


Andronic et al,
J.Phys. G35 (2008) 104155



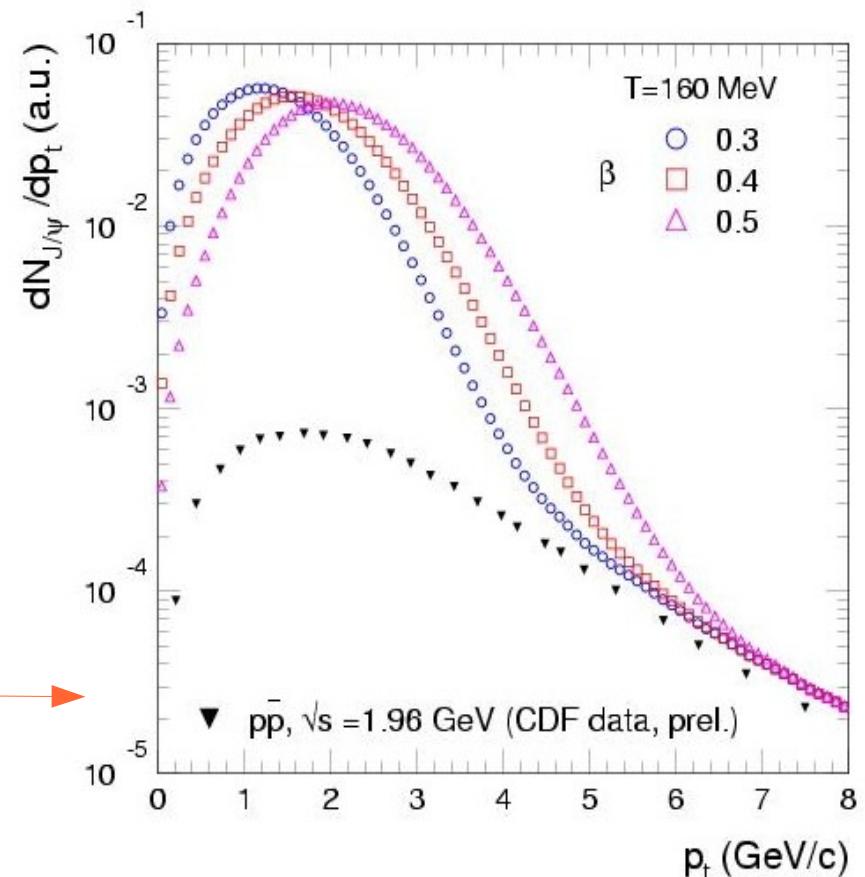
firm physics conclusion needs precise open charm cross section
in statistical hadronization picture this enters quadratically
get leverage from beam energy dependence and rapidity dependence

Spectral distribution is key to thermalization



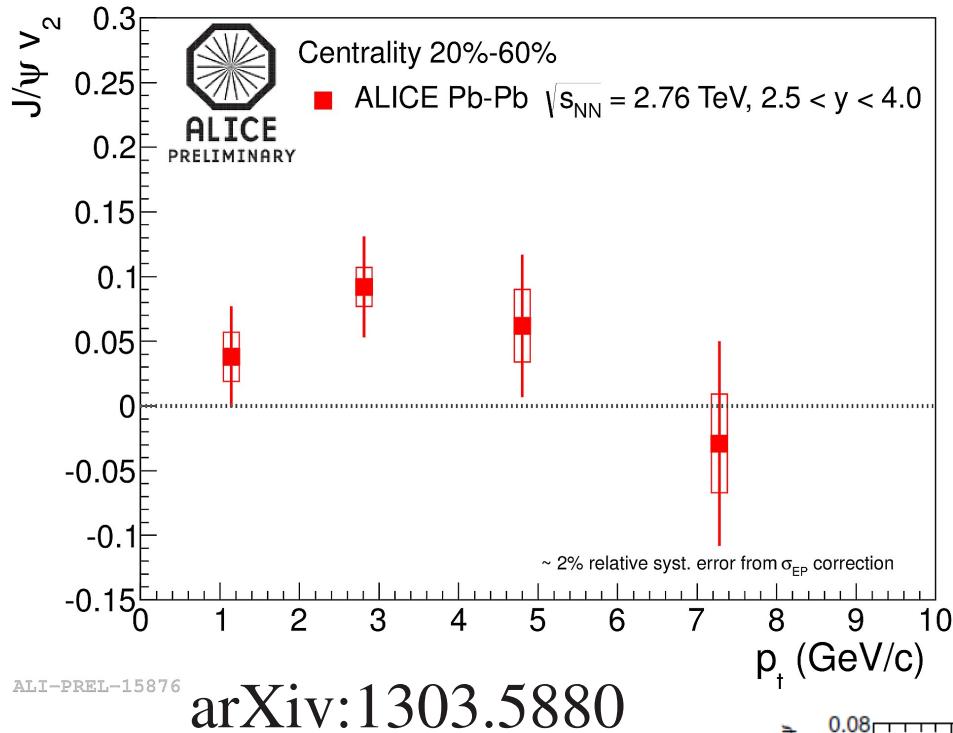
at LHC shift of paradigm:

more central collision → narrower momentum distribution
→ thermalization



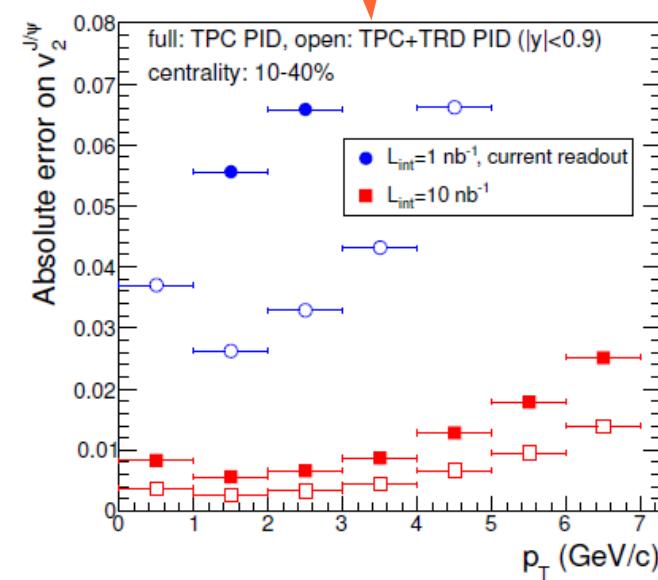
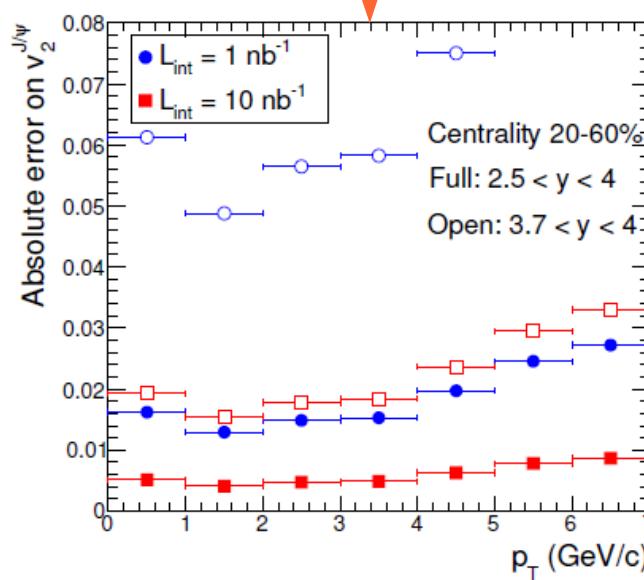
if charm quarks thermalize, their spectral distributions should also reflect collective flow of liquid → p_t distribution very different from pp case

J/psi from thermalized charm quarks should exhibit collective flow

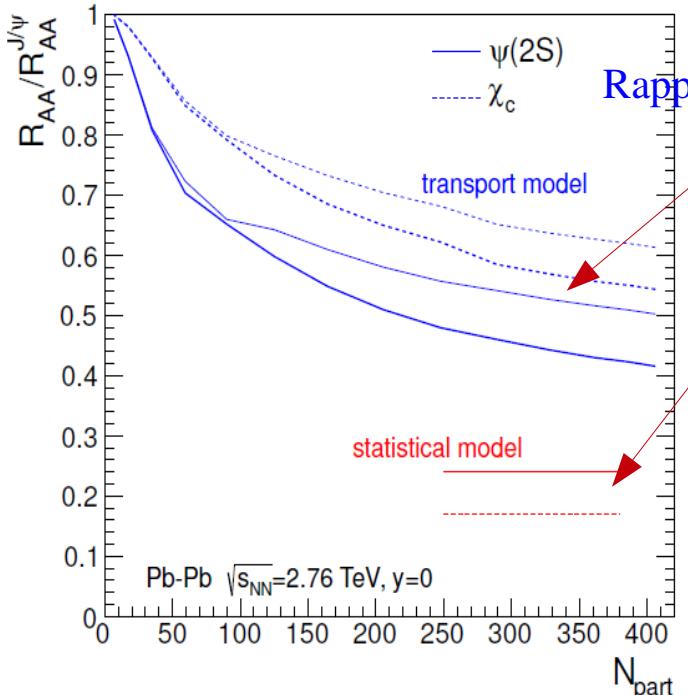
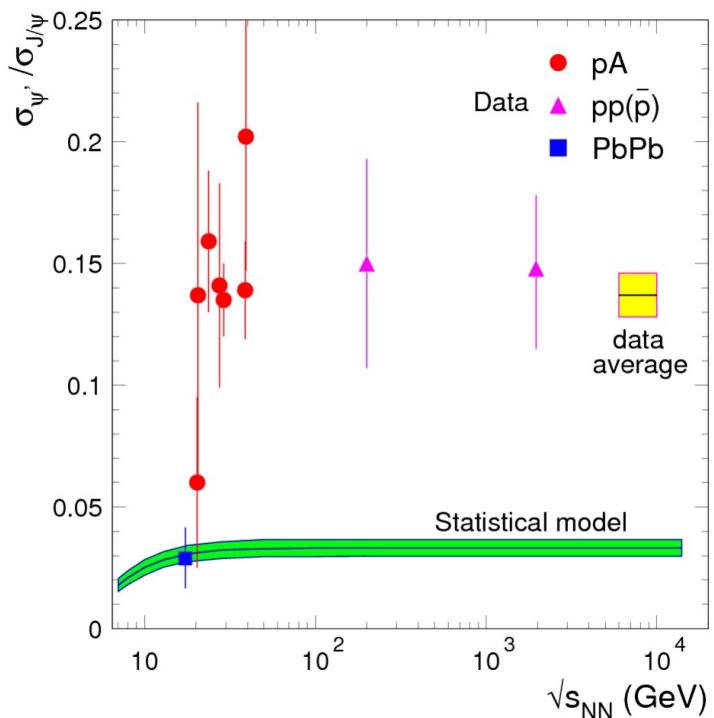


observation of flow with muon arm
presently 3 sigma
needs statistics to make model comparison
meaningful

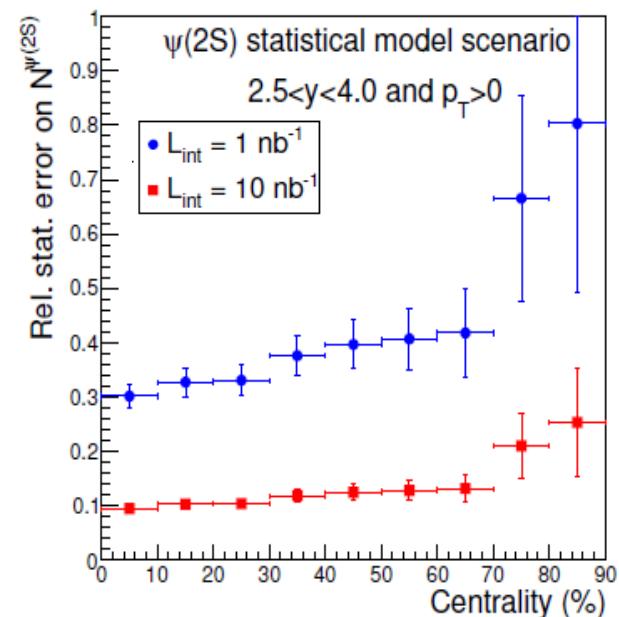
future statistical errors
muon arm central barrel



formation of charmonia from deconfined quarks: psi' is crucial cornerstone



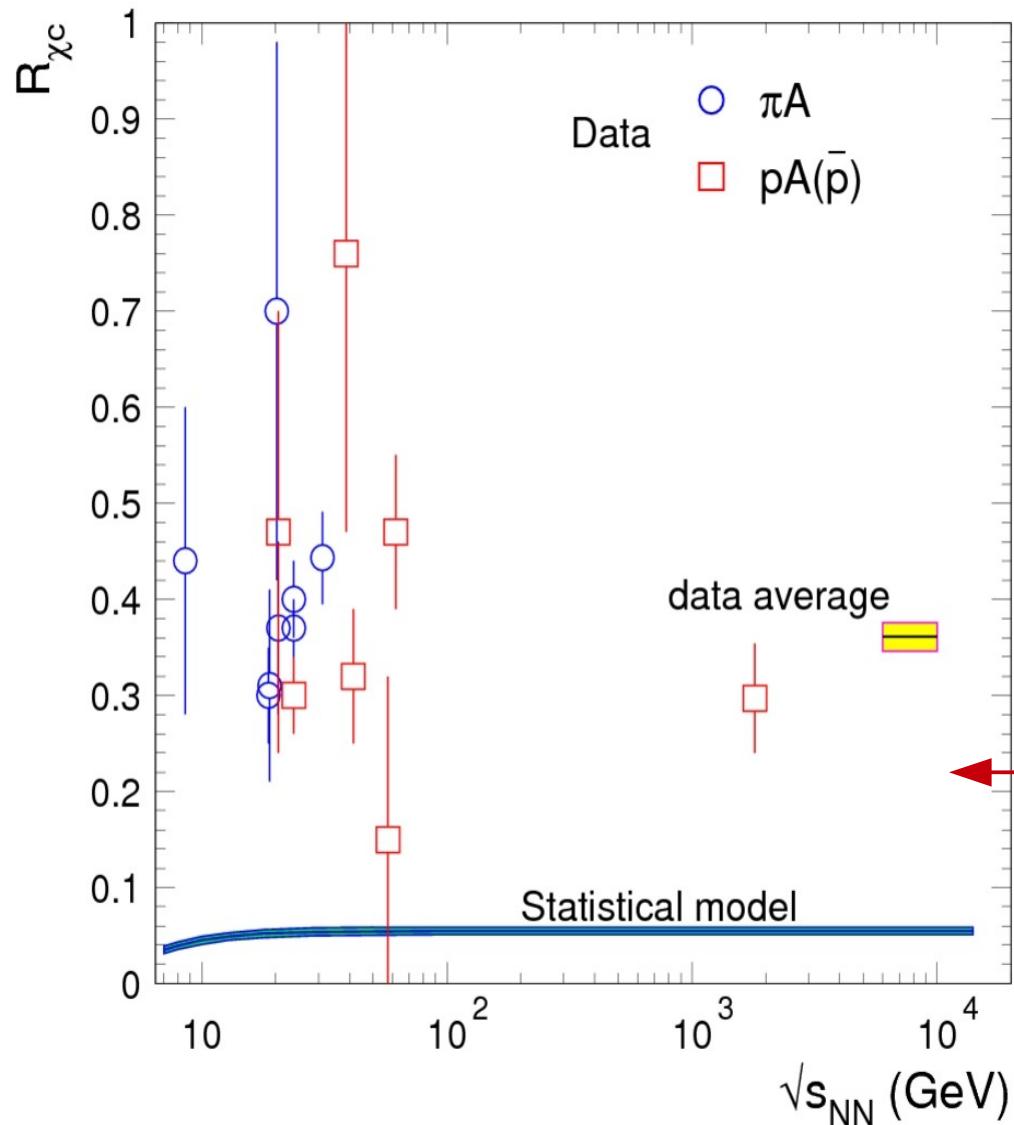
in fact: here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!



for statistical hadronization need to see suppression by Boltzmann factor

expected ALICE performance →
muon arm, factor 2 improvement
expected with MFT

chi_c: clear distinction of statistical hadronization mechanism



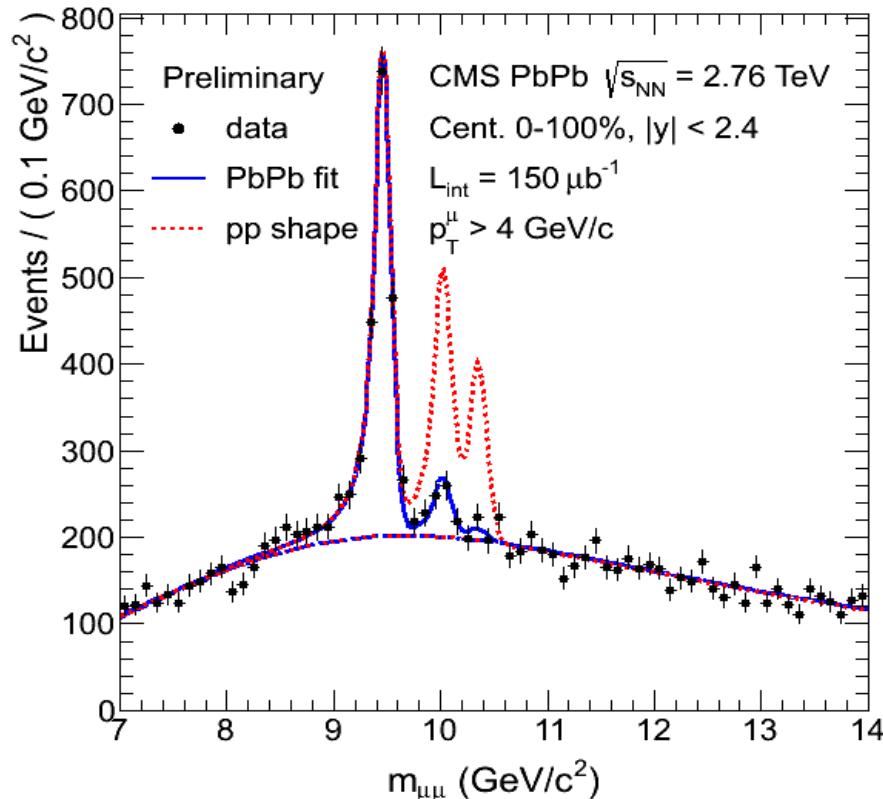
in statistical hadronization of charm
(and other) quarks reduction in chi_c
by factor 7 expected

Transport model (Rapp)

feasibility currently being
studied

CMS Upsilon state population indicative of deconfinement?

Sequential melting? story very complicated due to unmeasured feeding
also in statistical hadronization picture 2S and 3S strongly suppr. by Boltzmann factors

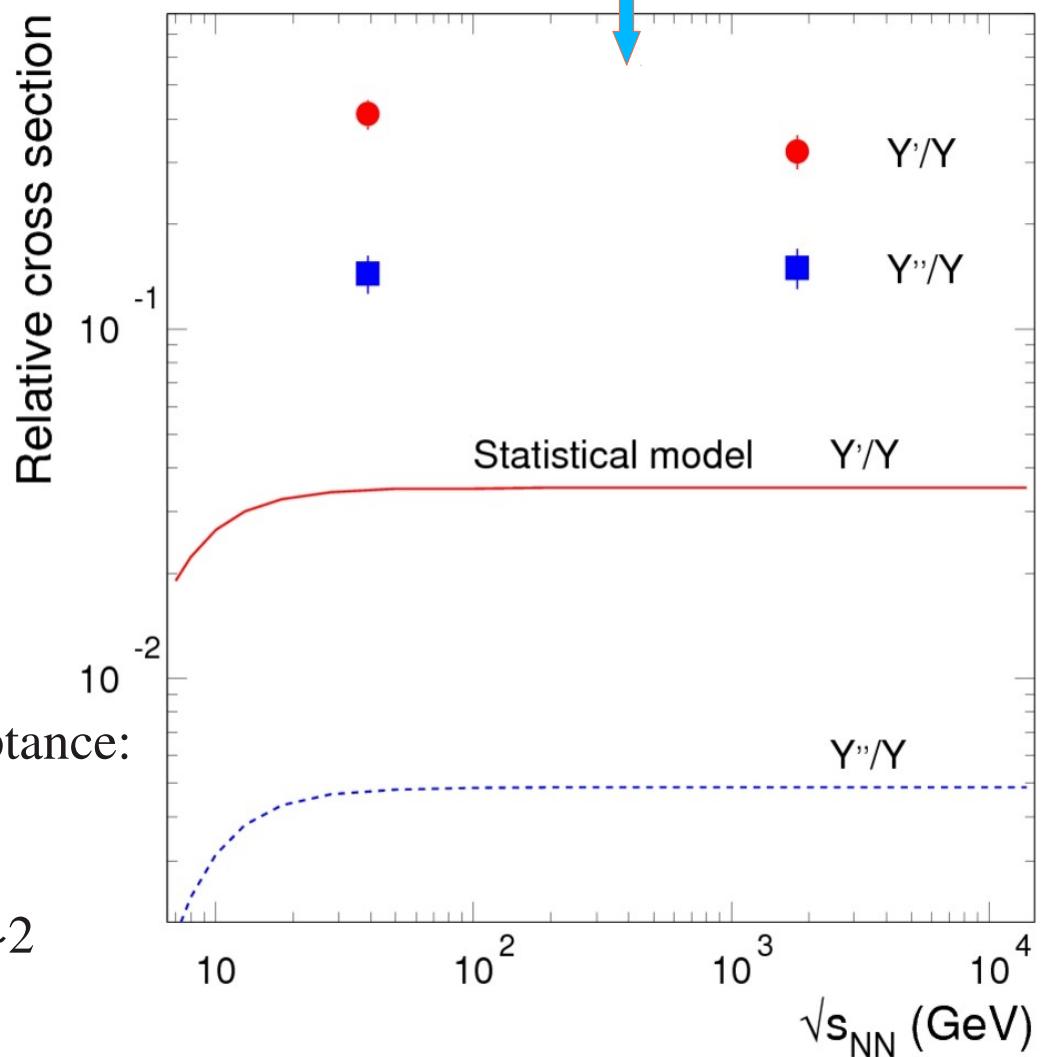


centrality integrated and not corrected for acceptance:

$$2S/1S \text{ PbPb} = 0.12 + 0.03 + 0.02$$

$$3S/1S \text{ PbPb} = 0.02 + 0.02 + 0.02$$

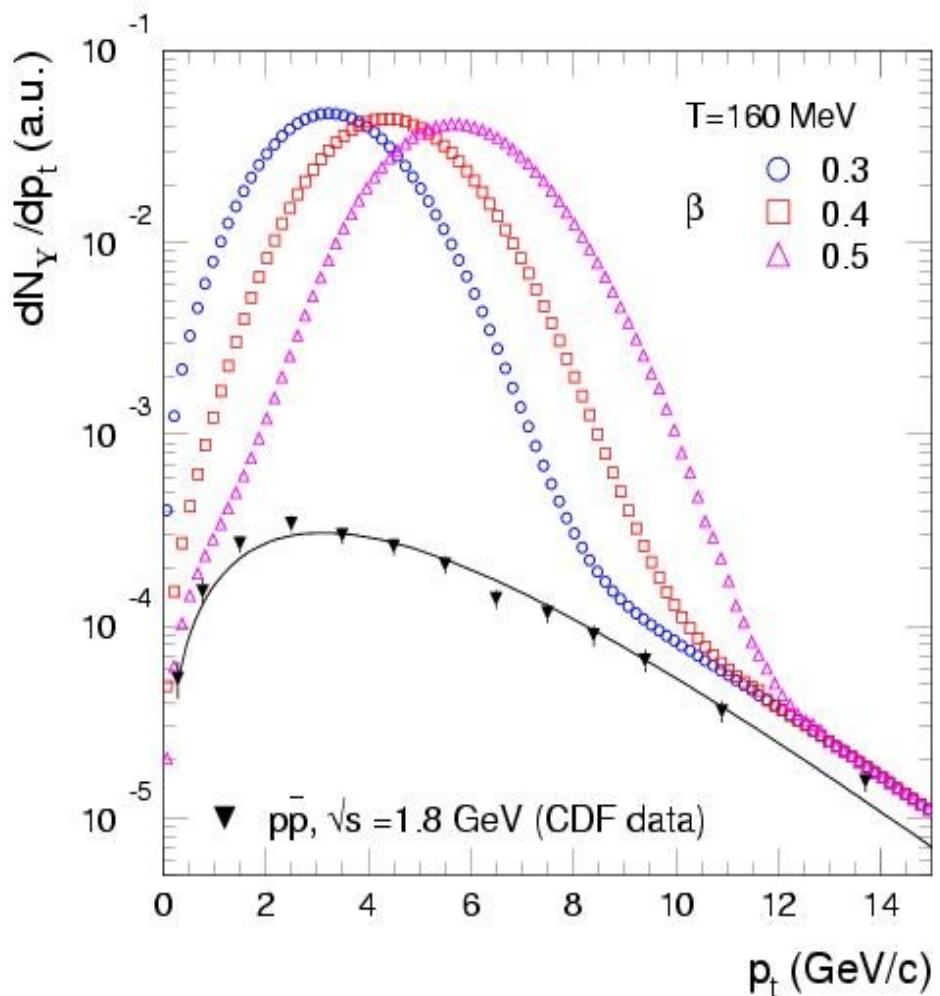
both ratios dropping with centrality by factors ~2



Precision measurement of Y spectra would resolve the story

for potential picture to apply (and therefore Debye screening),
beauty needs to be in equilibrium
i.e. thermalized

- in that case, spectra should show
global flow of the system



Interesting physics questions related to Lambda_c

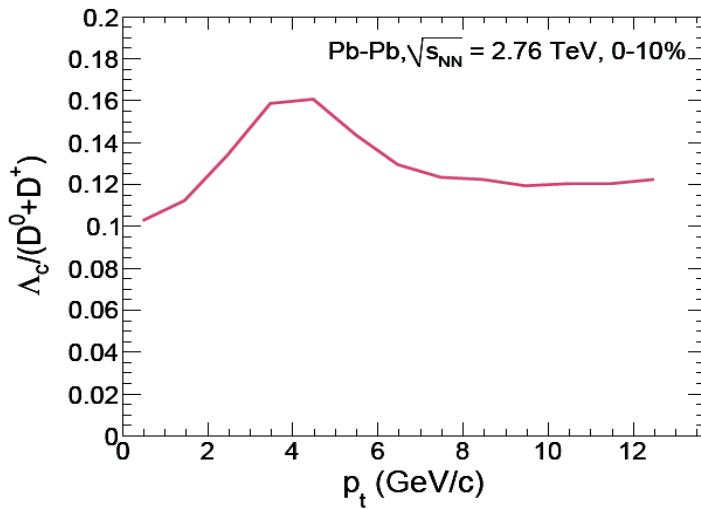
baryon anomaly also in charmed baryon sector?

cf proton/pion and Lambda/kaon

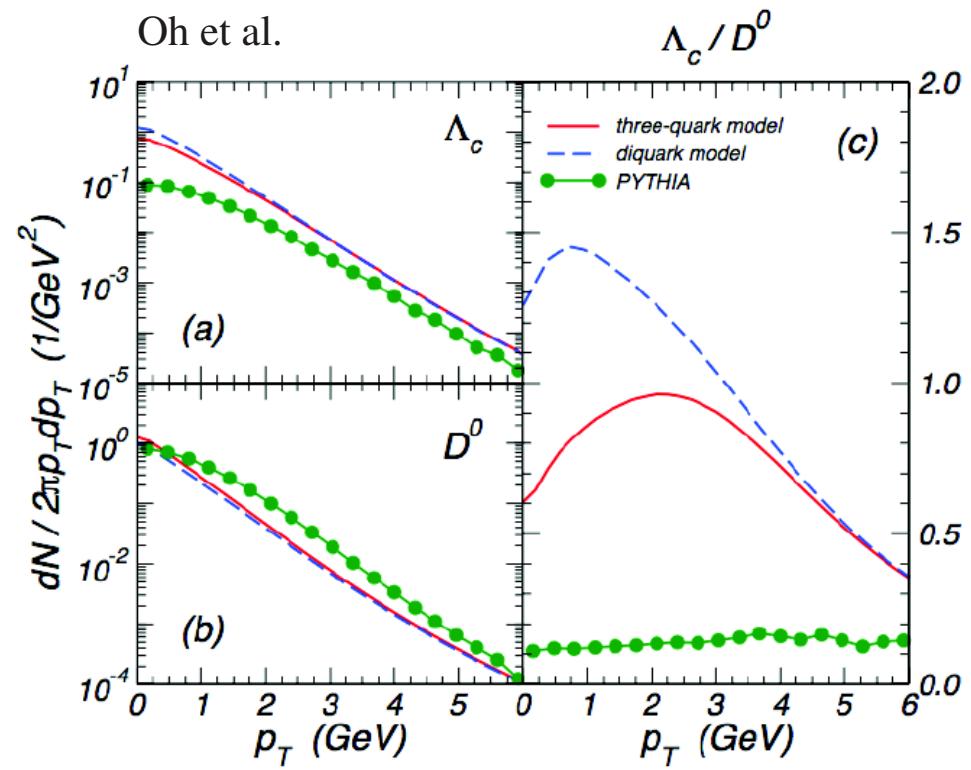
role of coalescence

diquarks in the QGP? Fundamental issue of bound quarks in QGP

He et al.

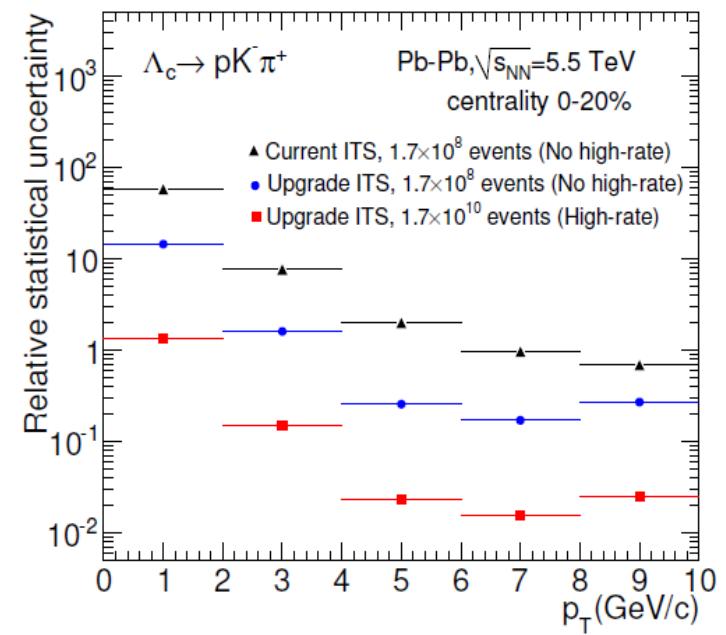
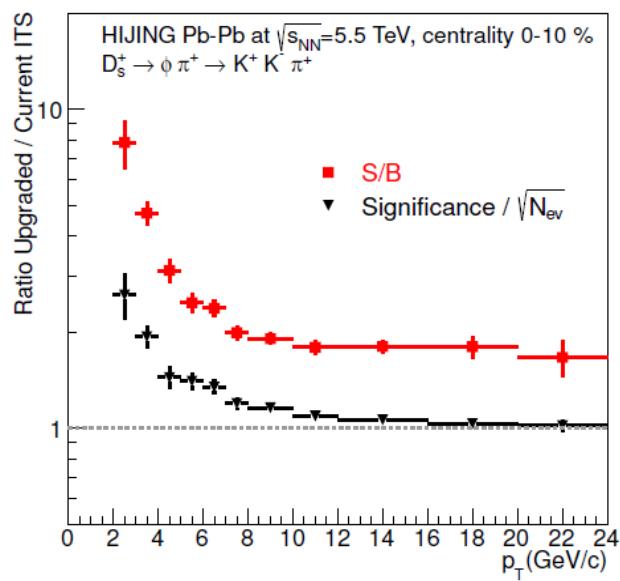
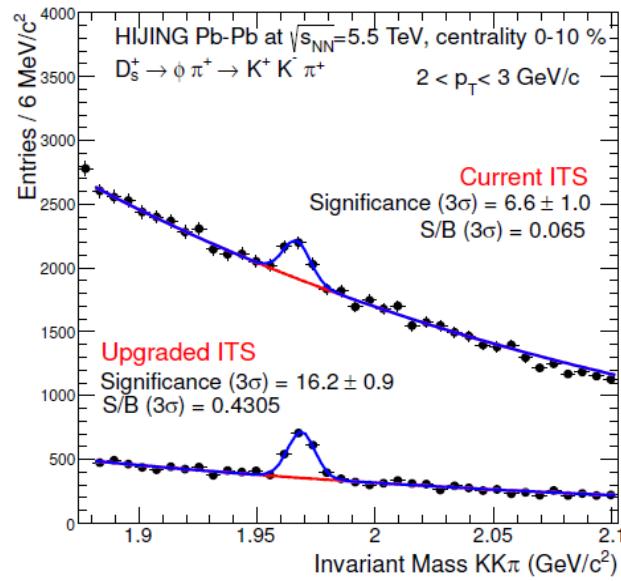


Oh et al.



need to measure with $O(10\%)$ precision down to low p_t

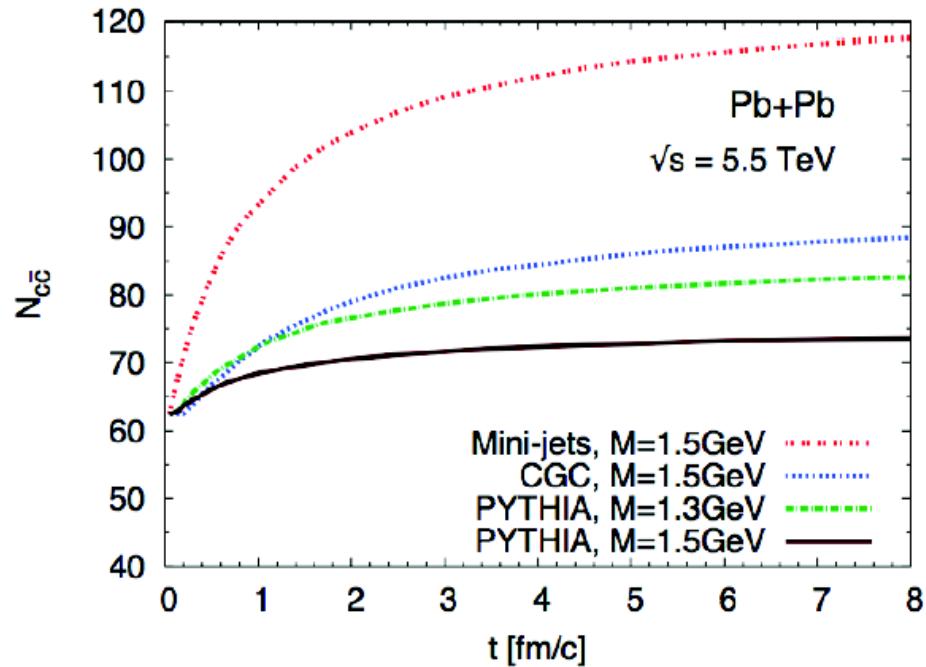
Expected performance for charmed hadrons with ALICE upgrade



Thermal charm production

first studied in 2000 (pbm, Redlich): at high T this will be relevant

recent calculation by J. Uphoff et al.
results strongly dependent on
initial gluon density and
charm quark mass



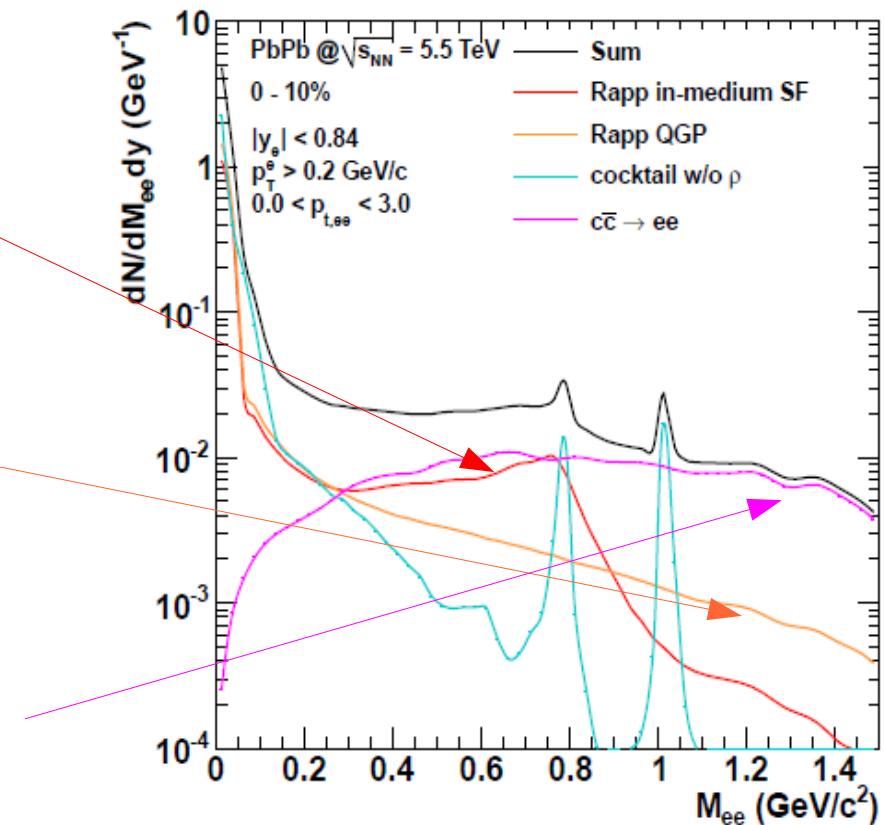
need to measure charm cross section precisely in PbPb collision and as function of centrality

Low mass electron pairs

physics motivation 2-fold: chiral symmetry restoration and thermal history
basically: below $1 \text{ GeV}/c^2$ region close to T_c dominates via rho in-medium spectral function - chiral restoration

above 1 GeV (φ) sensitivity the temperature – thermal virtual photons

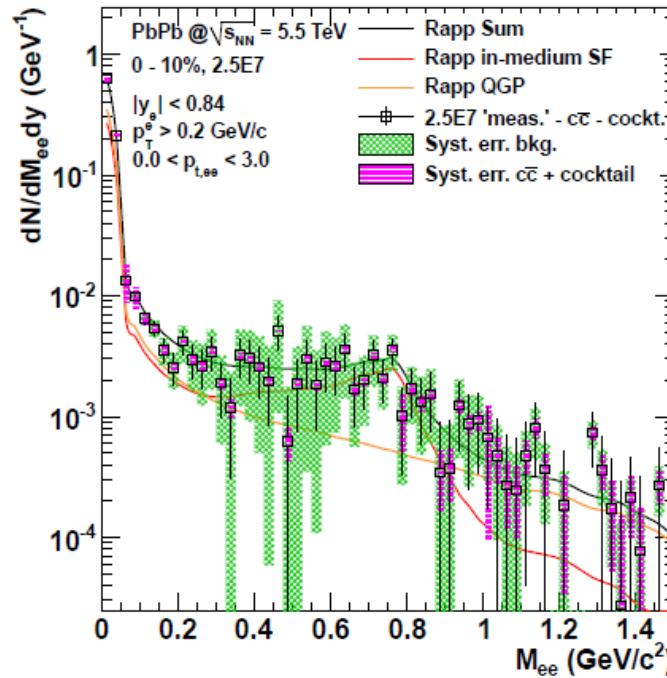
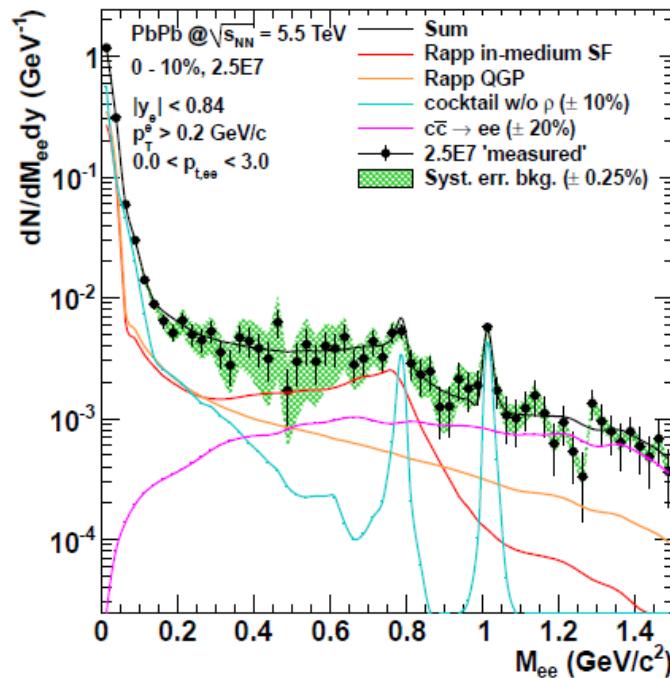
but: need good knowledge of open charm cross section!



a precision measurement will disentangle early and late contributions and hence give detailed access to evolution of collision and fund properties related to transport coefficients and equation of state

Expected performance for low mass di-electrons before upgrade

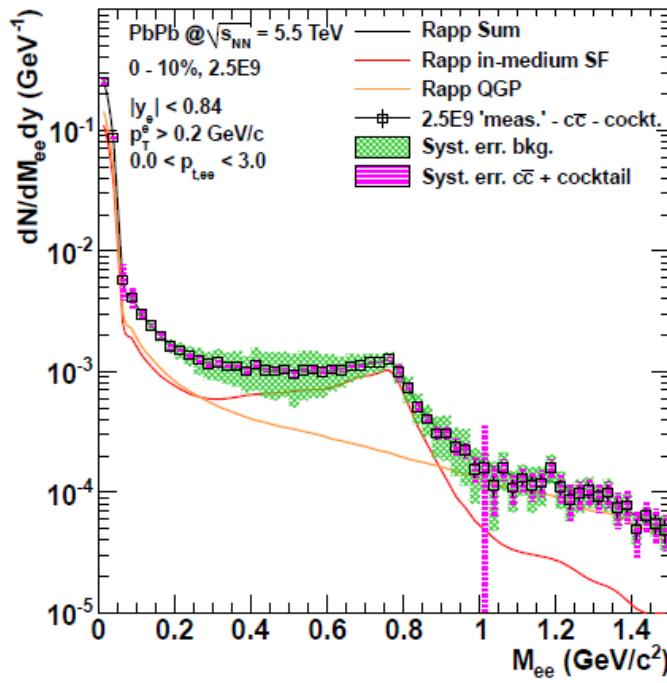
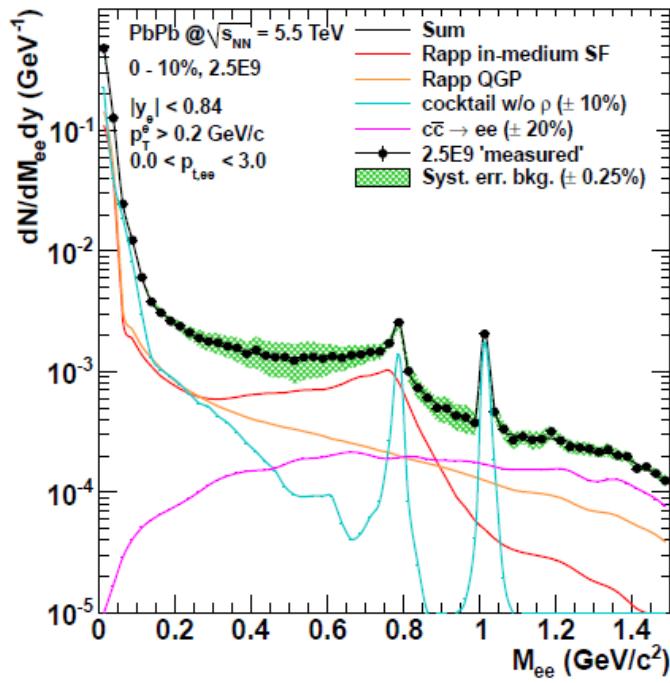
excess over hadronic decay cocktail



dedicated PbPb run with $B=0.2 \text{ T}$ sampling $2.5 \cdot 10^7$ collisions

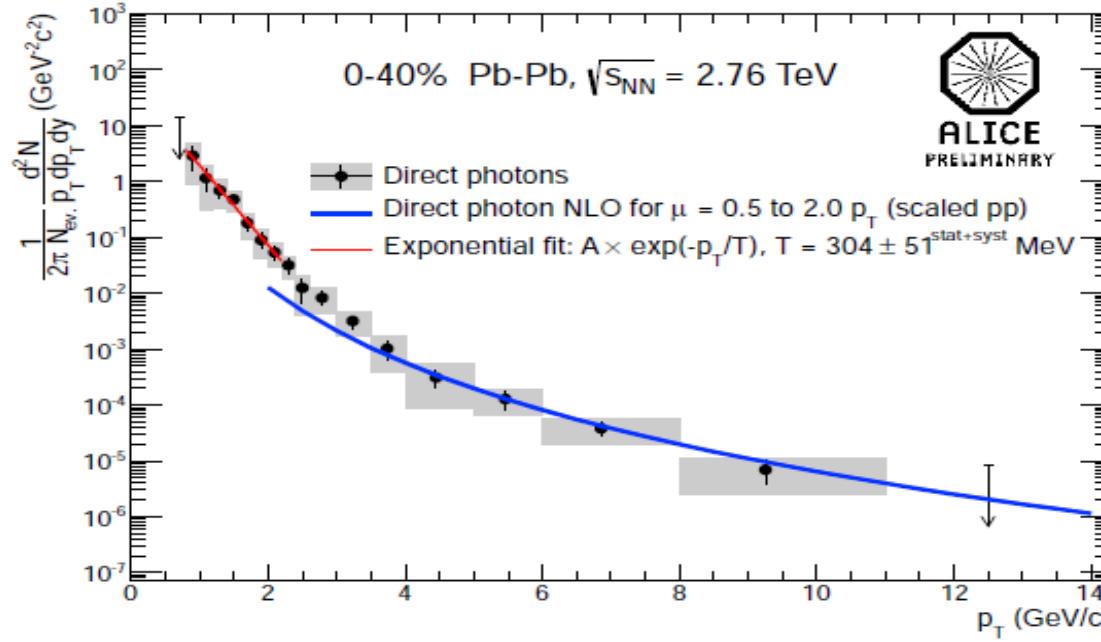
Expected performance for low mass di-electrons

excess over hadronic decay cocktail



dedicated PbPb run with $B=0.2 \text{ T}$ sampling 3 nb^{-1}
 $2.5 \cdot 10^9$ collisions in 0-10% centrality bin
 $5 \cdot 10^9$ for 40-60%

Direct photons - present data from conversion method



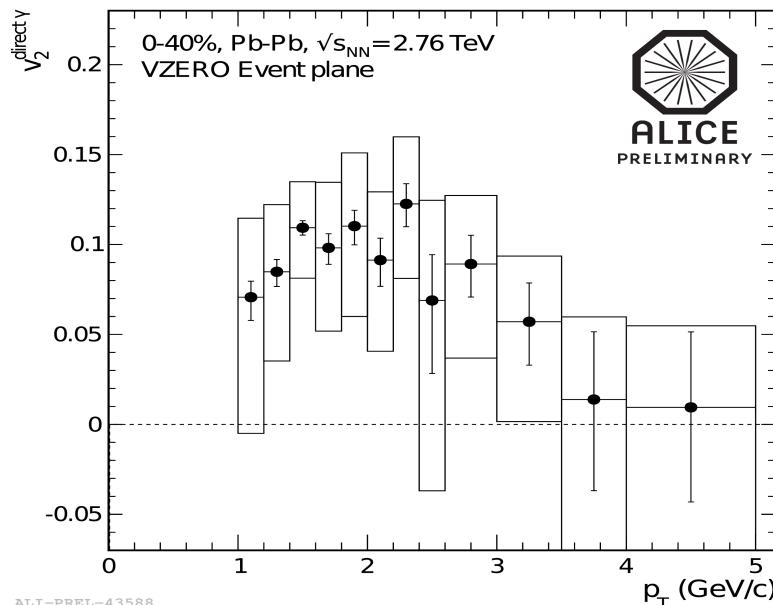
at low p_T , conversion method beats all calorimeters!

2 domains:

- direct photons from hard scattering (above 4 GeV/c)
- thermal photons

hard scattering looks ok and thermal photons exciting data but

where is photon flow coming from?

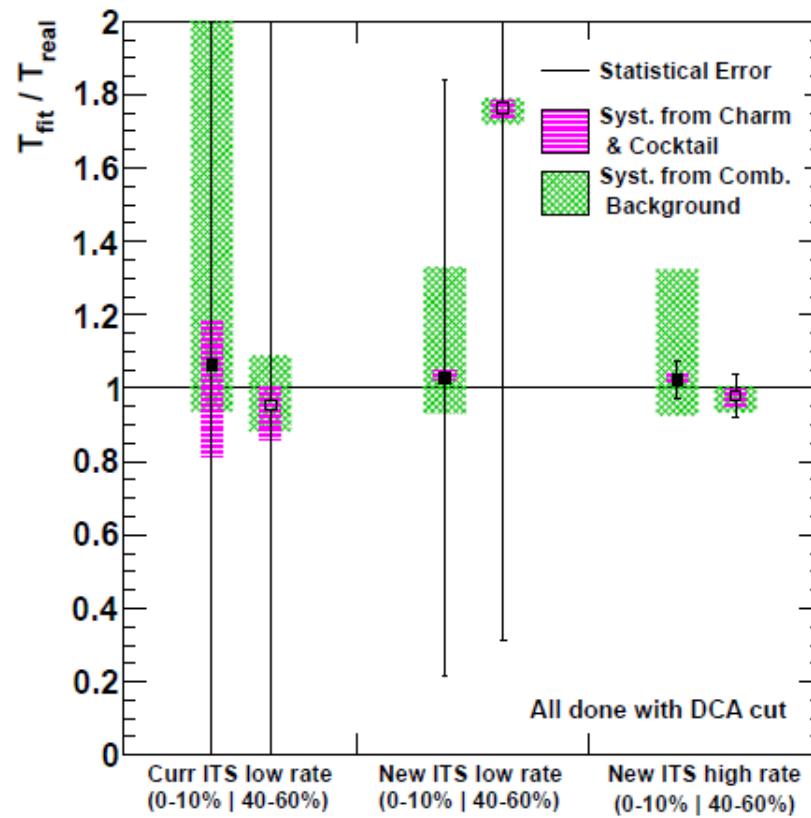


future improvements:

more statistics \rightarrow smaller systematic errors
smaller centrality bins
as well as cross check with virtual photons $\rightarrow e+e-$
both at $m=0$ and $m>1$ GeV/c²
thinner inner tracking system by factor 3 means
 X/X_0 goes from 11.4 ± 0.5 to 6.2%
possibility to introduce a converter ?

Temperature extraction from thermal di-electrons

ALICE performance before and after upgrade



Update of the European Strategy for Particle Physics

by the European Strategy Group for Particle Physics

As approved by CERN Council in March 2013

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

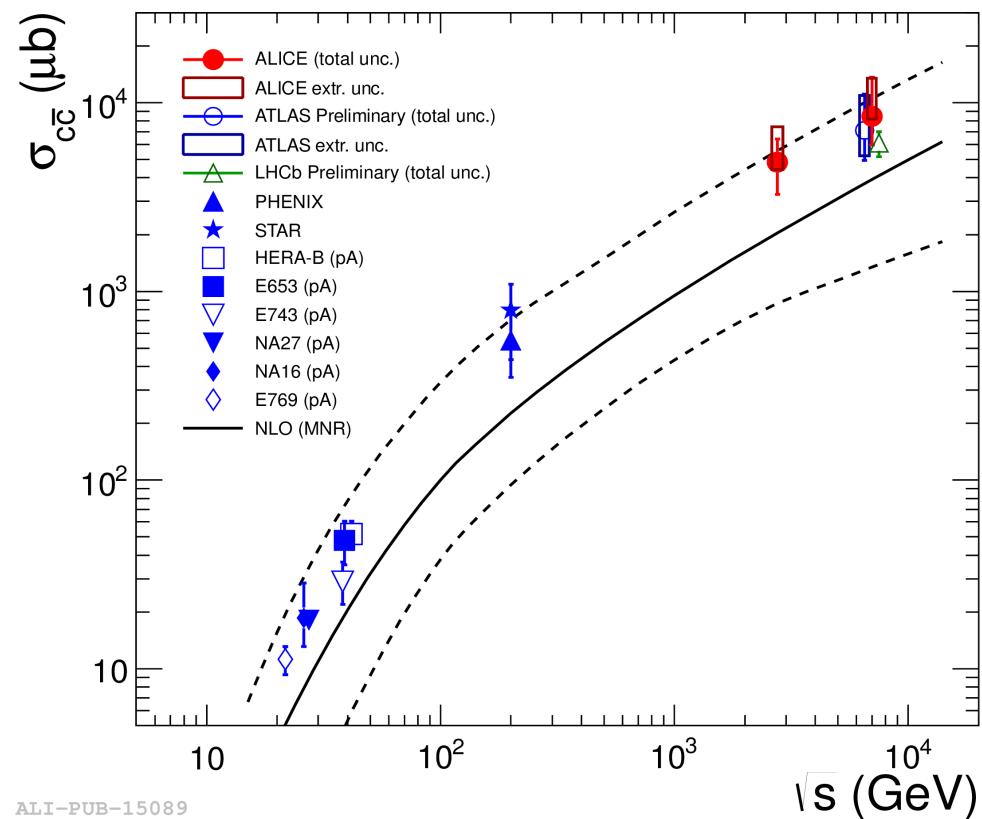
- c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

Heavy Ion Physics with ALICE, ATLAS, and CMS will be part of the LHC menu for the coming decade with an interesting menu of fundamental measurements to look forward to.

backup

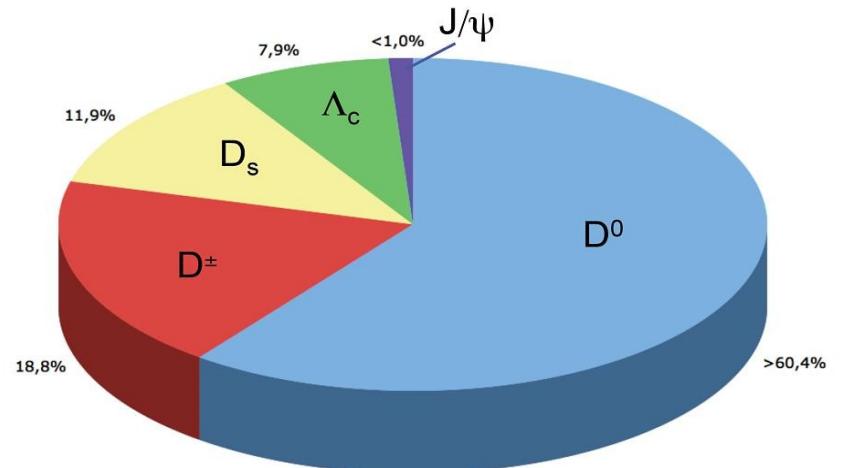
a first try at the total ccbar cross section in pp

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ALI-PUB-15089

- large syst. error due to extrapolation to low p_t , need to push measurements in that direction
- need to measure all channels including charmed baryons
- need this cross section for PbPb and pPb
 - here low p_t extrapolation much (!) harder



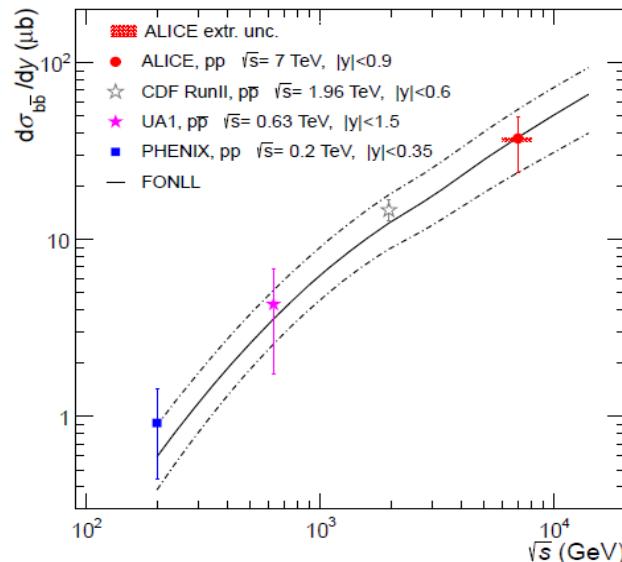
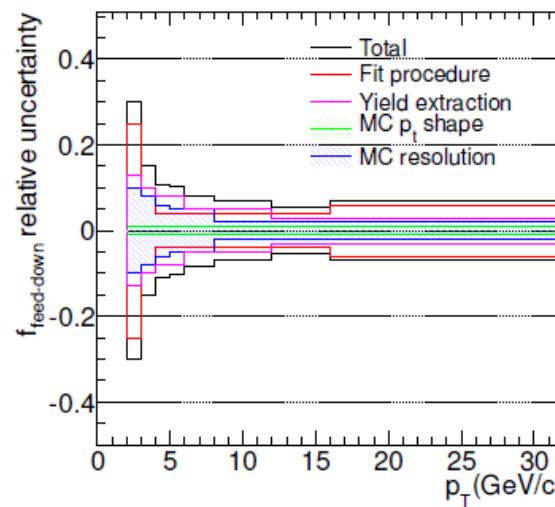
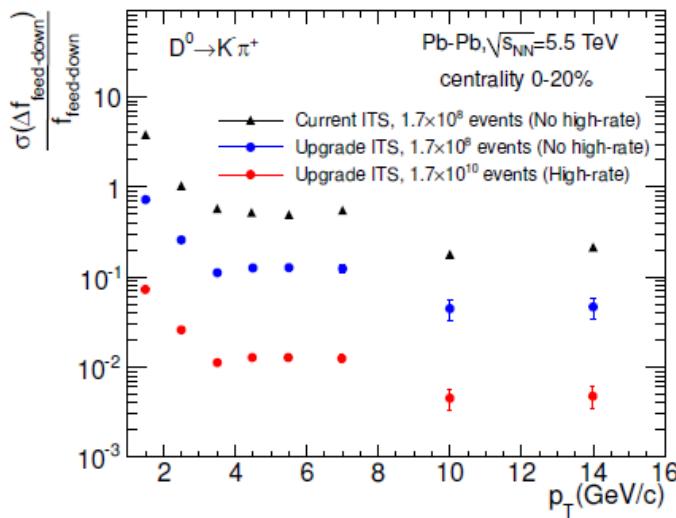
Open Beauty for cross section, R_{AA}, and flow

7 TeV pp

Current methods:

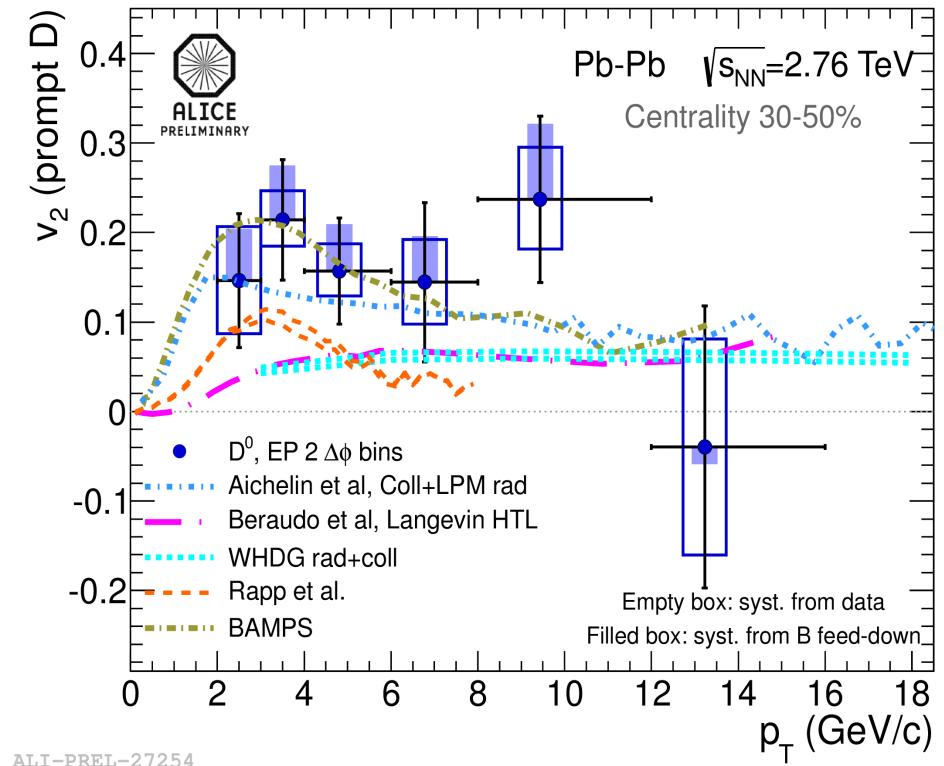
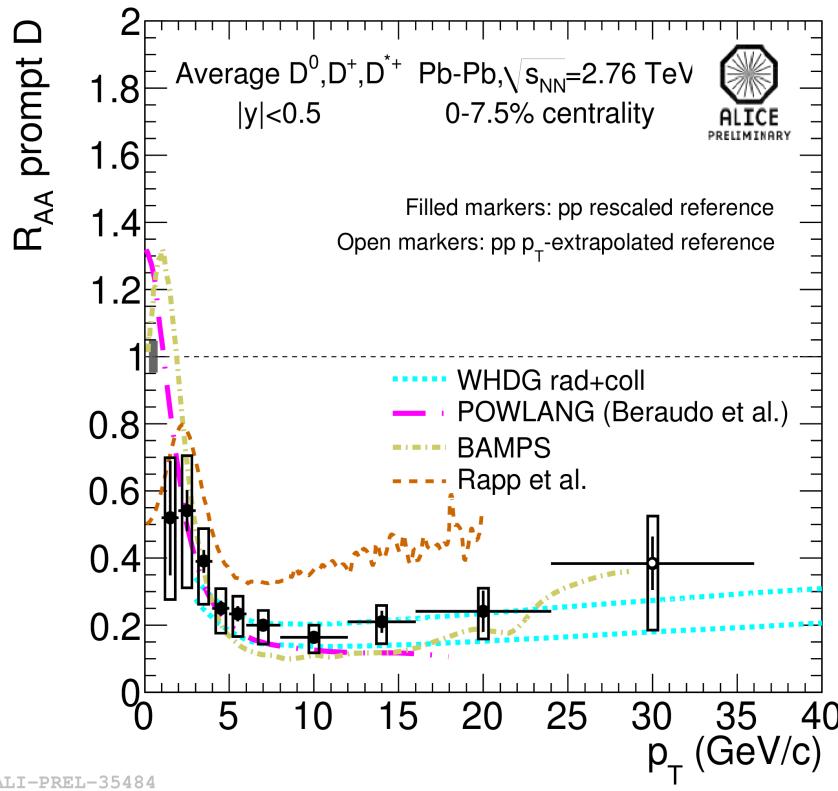
- semi-leptonic decays
- B from secondary J/psi

- powerful method for future ALICE:
get beauty from non-prompt D⁰



note the p_T coverage
down to 1 GeV/c!

Energy Loss and Flow of D-mesons - current status



both are determined by transport properties of the medium (QGP)
simultaneous description still a challenge for some models
but also errors of data still too large for precision physics conclusion

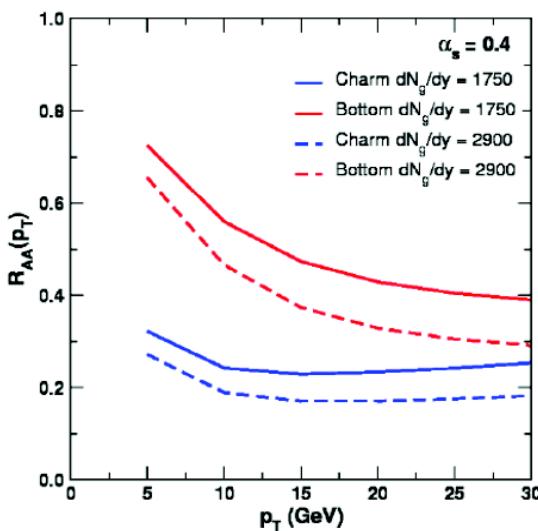
what does it take to establish heavy quark thermalization?

need precise measurements of R_{AA} and v_2 for D and B

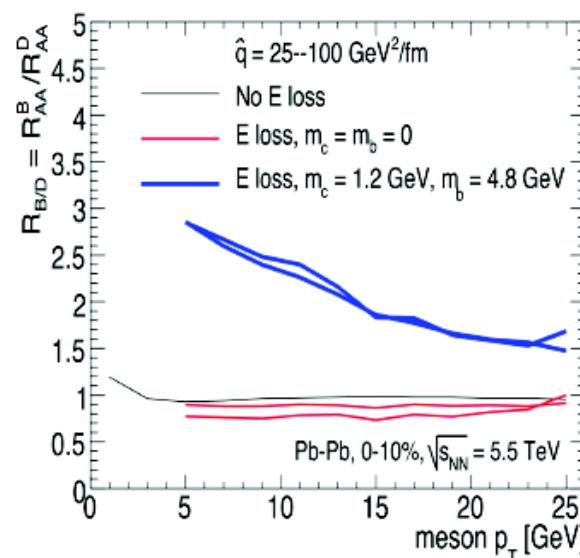
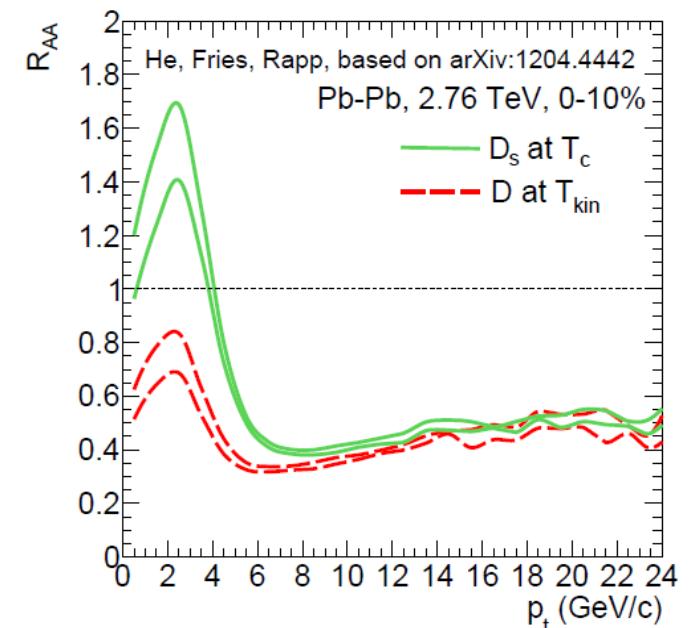
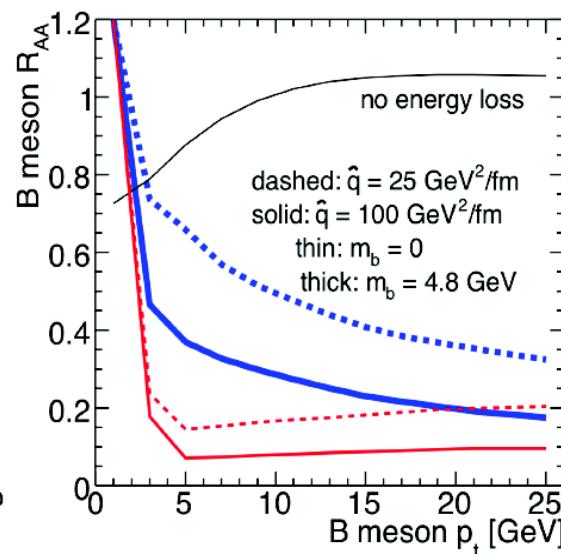
sensitivity to gluon density/transport coefficients

- i.e. medium properties

Wicks et al.



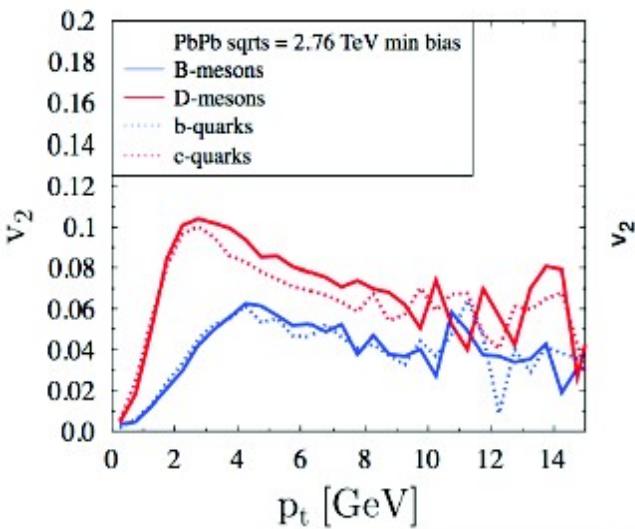
Armesto et al.



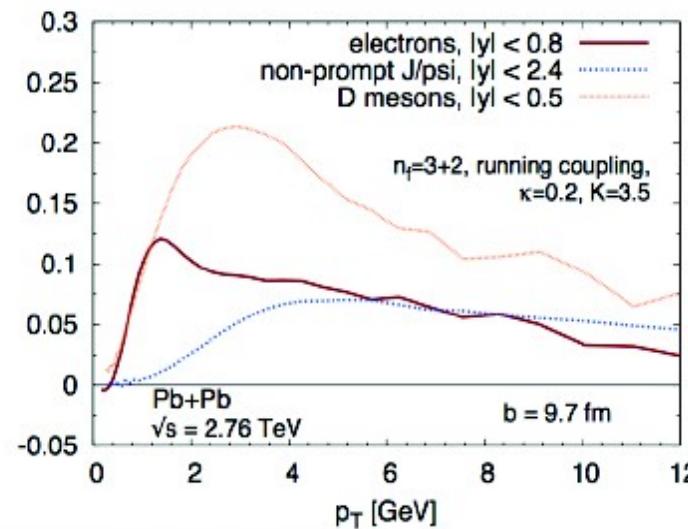
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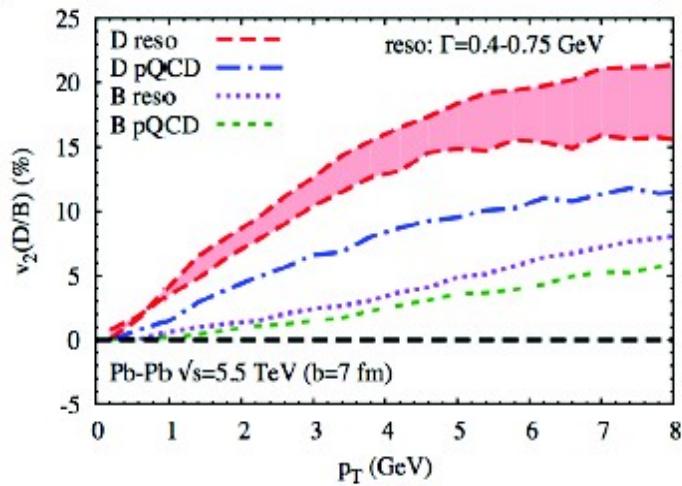
Aichelin et al.



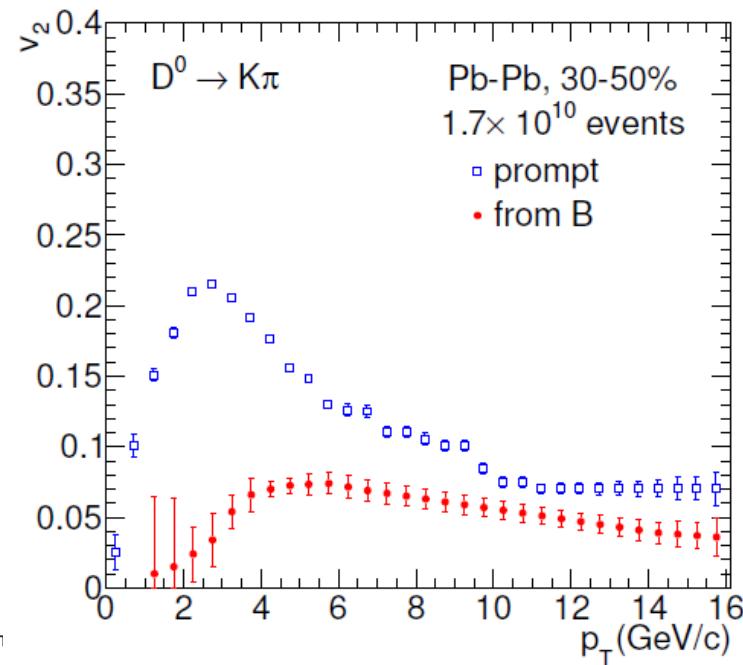
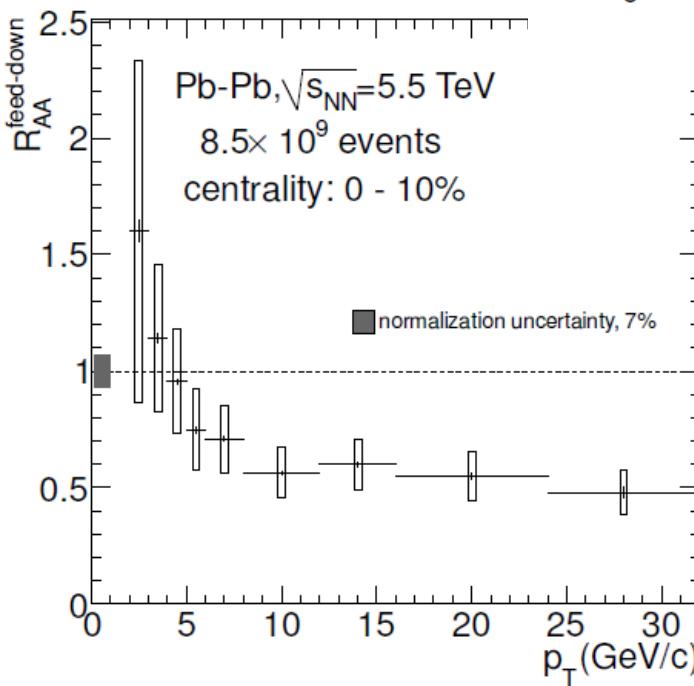
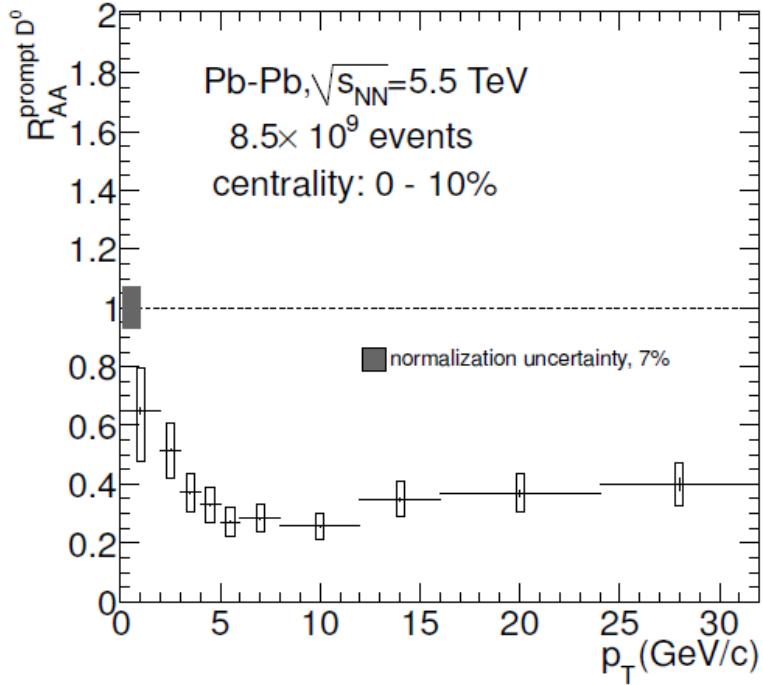
Uphoff et al.



Greco et al.



Expected performance for D⁰ and B



Dielectrons - performance before and after upgrade

