Physique des ions lourds au LHC

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LLR – École polytechnique / IN2P3
ERC grant “QuarkGluonPlasmaCMS”

Prospectives du LLR, 21 octobre 2015

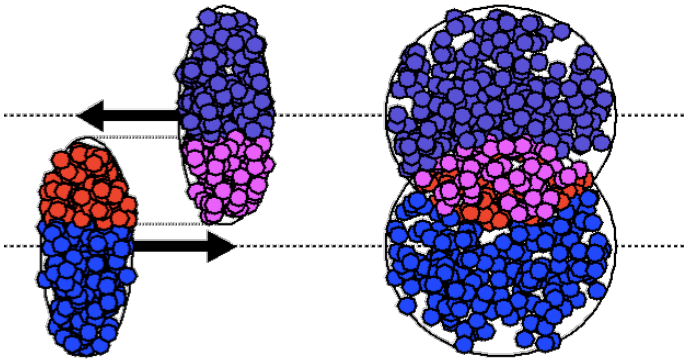
Cahier des charges

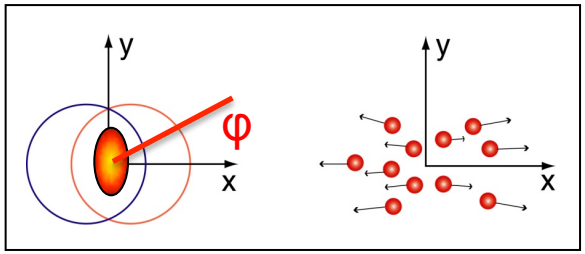
- *Comparaison des mérites des différentes manips, dans une optique de perspectives...* (Thomas)

- My biases:
  - Putting in perspective of what is done at LLR
    - Electroweak bosons, quarkonia, open heavy flavours, jets...
  - But still trying to cover the rest
    - Collectivity, particle identification
  - Reviewing observing capabilities, probe by probe
  - No time for debating the physics cases
    - Wait for Elena
  - Betting on the future
  - Illustrating with the past
  - Not forgetting RHIC is still running...

Some definitions

- Centrality
  - Related to impact parameter
  - Measured via final multiplicity
  - High centrality = hotter plasma
- Azimuthal anisotropy v_2
  - Initial lenticular shape
  - creating a pressure gradient
  - more particles in the reaction plane
- Nuclear modification factors R_{AA}
  - N_{coll} = number of N+N collisions
  - Hard probes supposed to scale with N_{coll} in absence of medium effect





$v_2 = \langle \cos 2\varphi \rangle$

$$R_{AA} = \frac{dN^{AA}}{dN^{PP} \times N_{coll}}$$

Complementary programmes

RHIC, up to AuAu @ 200 GeV

Period	Species	Energy
2001-09	AuAu, dAu, CuCu…	Top
2010-11	AuAu, pp	Scan
2012	UU, CuAu, pp	Top
2014	AuAu, He^3Au	Scan
2015	pp, pAu, pAl	Top

LHC, up to PbPb @ 2.76 TeV

Period	Species	Energy	Lumi*
Dec. 2010	Pb+Pb	2.76 TeV	7 μb^{-1}
Dec. 2011	Pb+Pb	2.76 TeV	150 μb^{-1}
Mar. 2011	p+p	2.76 TeV	230 nb^{-1}
Jan. 2013	p+Pb	5.02 TeV	35 nb^{-1}
Fev. 2013	p+p	2.76 TeV	5.4 pb^{-1}

(*CMS numbers)

@ RHIC, varying the species and energies

@ LHC, getting higher energies and luminosity

- Same N_{coll} scaled luminosities for pp, pPb, PbPb (as many Z's and W's, modulo the √s dependence)
- Lacking a pp reference for the pPb 5 TeV run

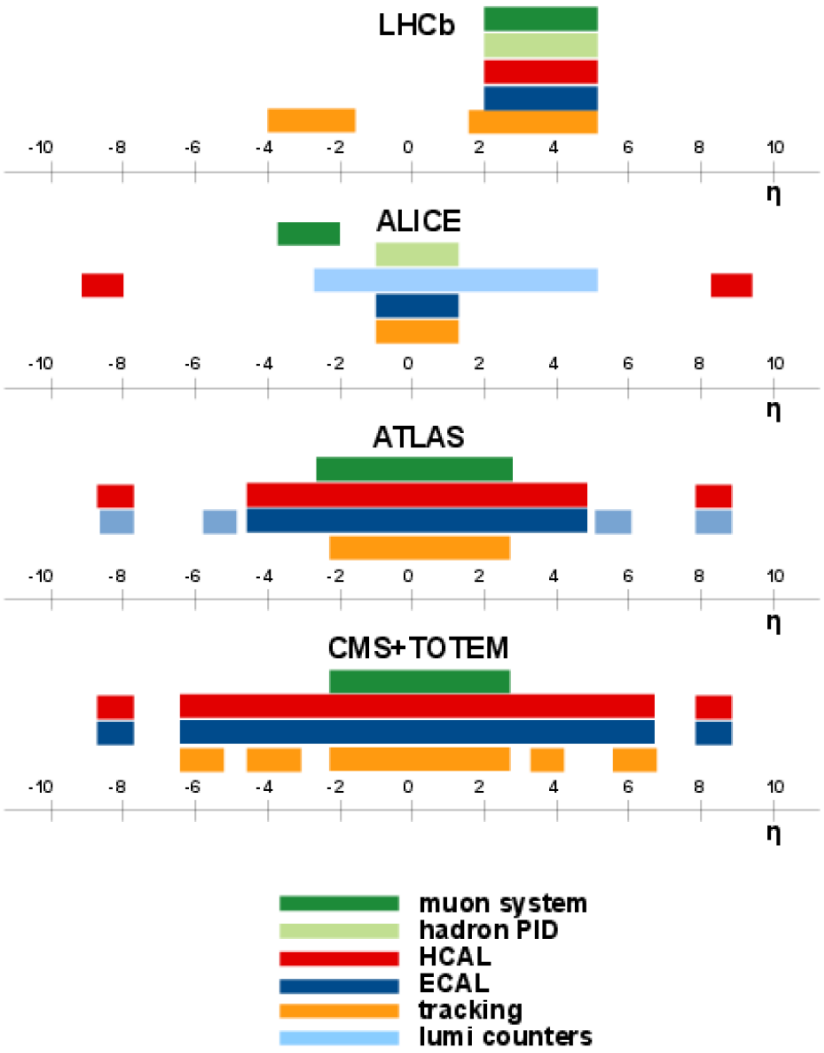
Recorded luminosity

Period	Species	Energy	CMS or ATLAS	ALICE central	ALICE muons	LHCb
Dec. 2010	Pb+Pb	2.76 TeV	7 μb^{-1}			
Dec. 2011	Pb+Pb	2.76 TeV	150 μb^{-1}	26 μb^{-1} (a)	69 μb^{-1}	0 (b)
Mar. 2011	p+p	2.76 TeV	230 nb^{-1}	15 nb^{-1} (c)	20 nb^{-1} (c)	
Jan. 2013	p+Pb	5.02 TeV	35 nb^{-1}	12 nb^{-1}	12 nb^{-1}	1.6 nb^{-1}
Fev. 2013	p+p	2.76 TeV	5.4 pb^{-1}	? (c)	(120 nb^{-1})	? (d)

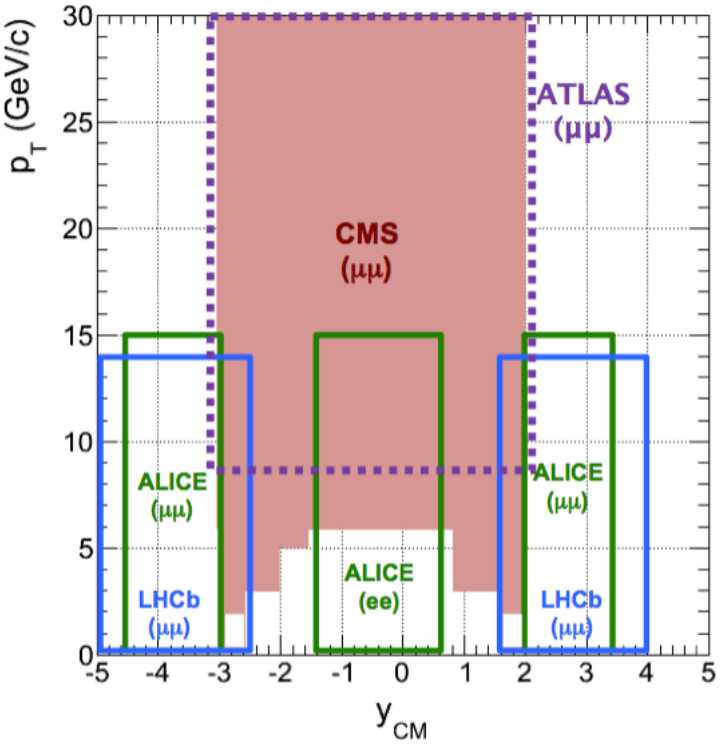
a) Alice central : difficult to quote, really depends on the observable (26 μb^{-1} is the maximum I found for 2010+11 data, either through a dedicated signal trigger, or through a top centrality 0-10% trigger)
b) LHCb expects to collect 50-70 μb^{-1} of PbPb collisions this year
c) Alice pp samples are limiting (instead, use of 7 TeV, FONLL, LHCb…), the 2013 being for now unused...
d) LHCb pp should not be a problem (rare decays…)

→ We shall expect that ALICE and LHCb will keep on recording lower luminosities than ATLAS and CMS

Complementary detectors



Concrete complementarity example
Published J/ψ coverage in pPb



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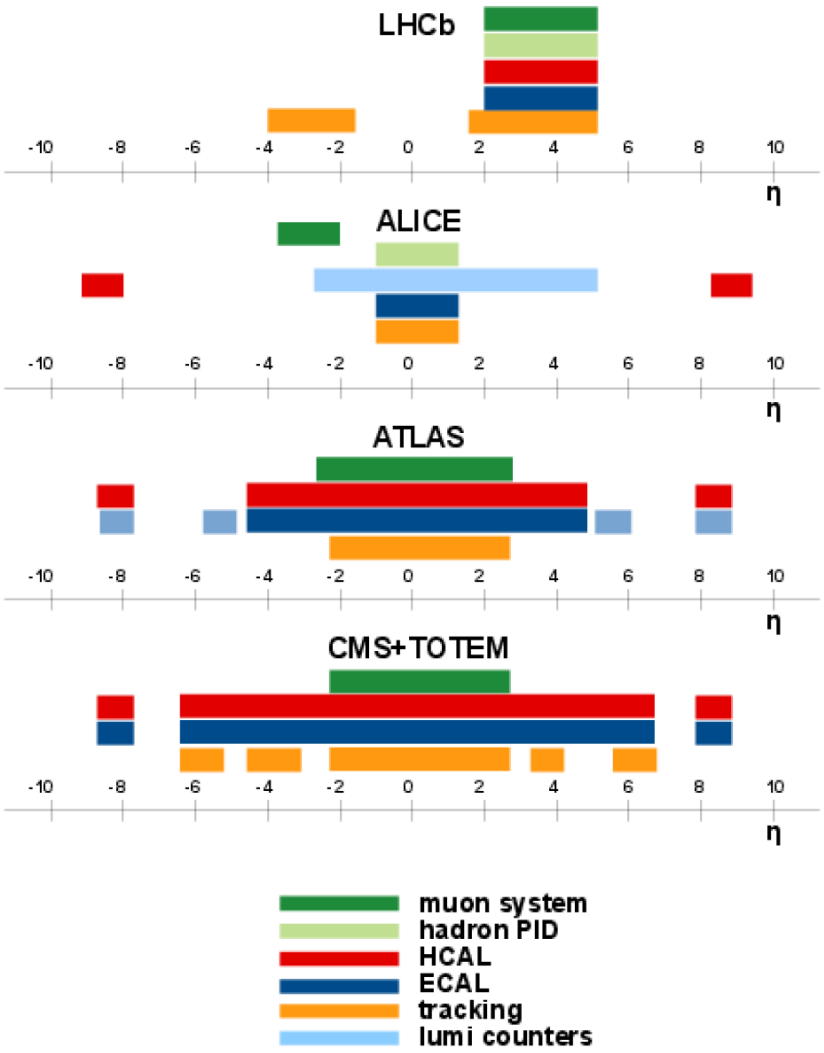

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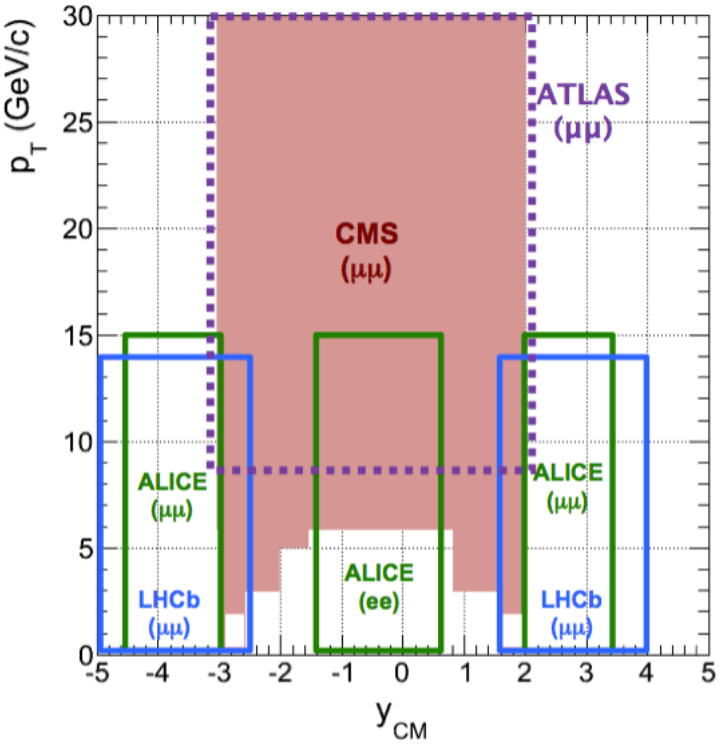


France is deeply involved in ALICE, LLR is in:

- CMS (RGdC+MN+postdocs+students, terminated ERC ☹) + FA associated theorist
- LHCb (FF, via LAL, welcoming an ERC ☺)

The LHCb special case (1/2)

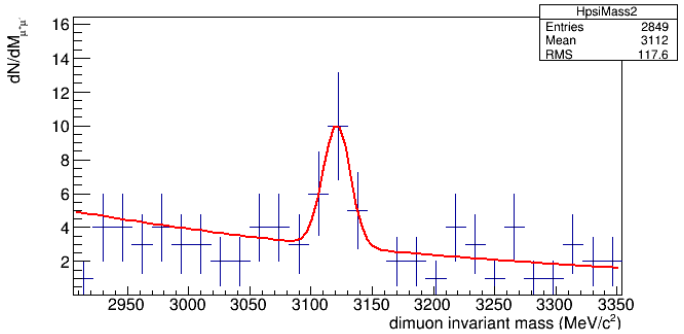
Fleuret @ CSLLR, Manca @ QM'15
Fleuret & Massacrier @ Etretat'15

1. Fixed target mode
   - SMOG aka System for Measuring Overlap with Gas
   - p (3.5 TeV) on gas → 69 GeV
   - Possible gas: He(4), Ne(20), Ar(40), Kr(84), Xe(131)
   - Pressure 10^{-6} to 10^{-7} mbar
   - Competition: keep an eye on upgraded STAR…

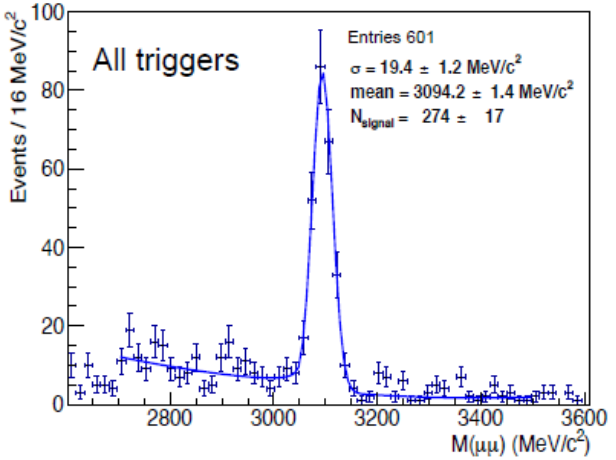
Expectations (for 2015):

- 3 days p+Ar (20 000 J/ψ)
- 21 days Pb+Ar (15 000 J/ψ)

Feb. 2013: 27 minutes
Pb+Ne @ 54 GeV
≈ 10 J/ψ



August 2015: 12 hours
p+Ne @ ~110 GeV
≈ 300 J/ψ



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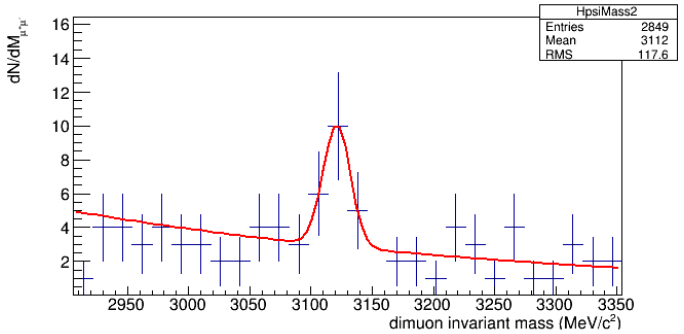

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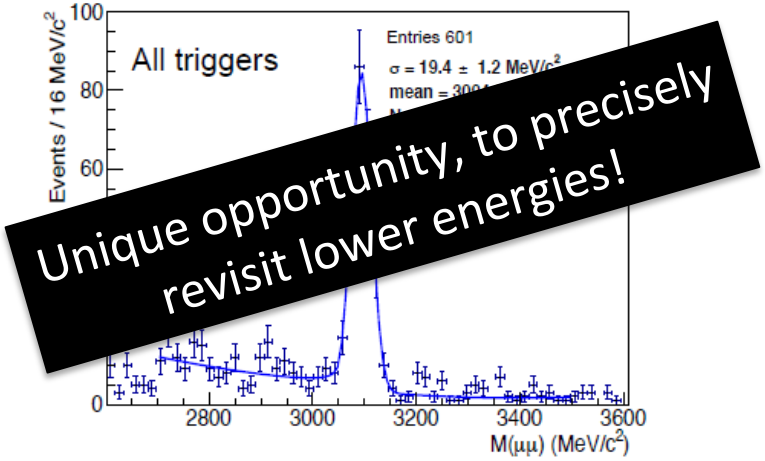


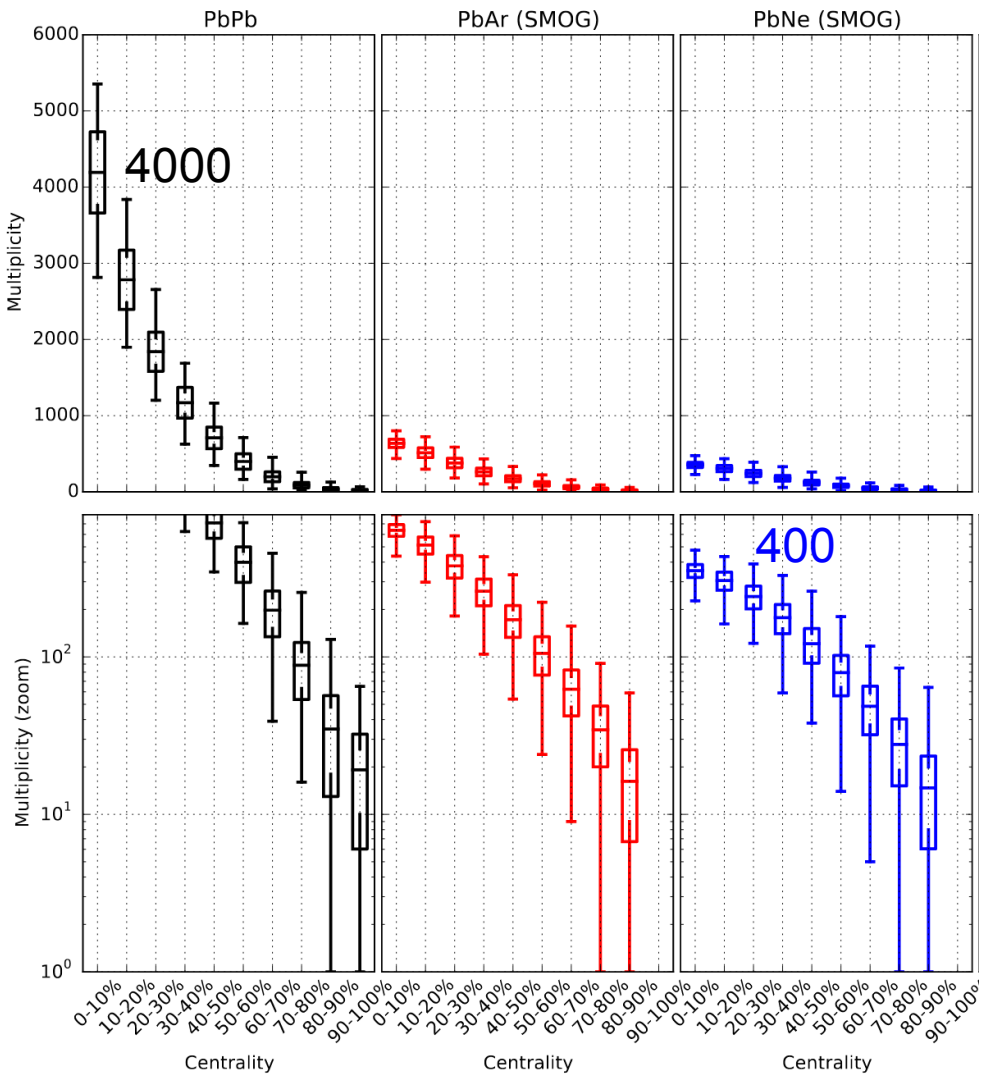
Unique opportunity, to precisely revisit lower energies!

The LHCb special case (2/2)

Fleuret @ CSLLR, Manca @ QM'15
Fleuret & Massacrier @ Etretat'15

2. PbPb collision mode

- Starting in 2015
- 50-70 μb^{-1} expected (half what CMS already have)
- Cautious and gradual start
- *Can lead to parasitic collisions near ALICE and degrade beam lifetime*
- Key question: can LHCb cope with the most central collisions?
- 50-100% should work (eq. PbNe)
- But 10 times more multiplicity in the most central…



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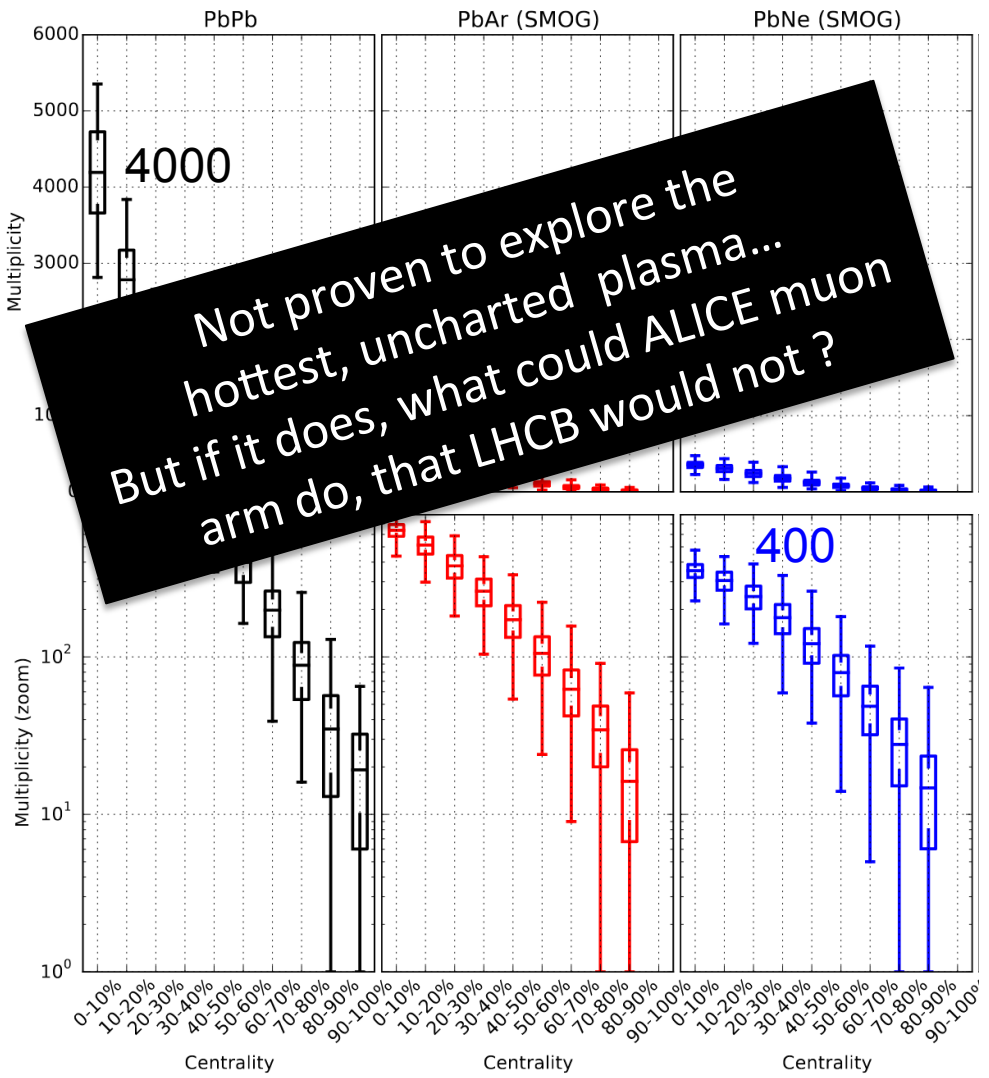
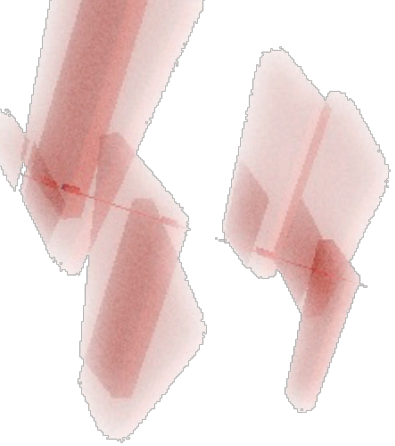


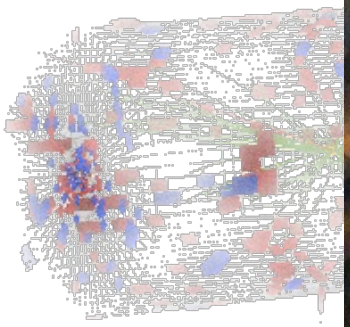
Summary

Particles	ALICE	ATLAS	CMS	LHCb
EWK bosons	☺	☺☺☺☺	☺☺☺☺	☺
Charmonia	☺☺☺	☺	☺☺	☺☺☺☺
Bottomonia	☺	☺	☺☺☺☺	☺☺☺
Charm	☺☺☺☺	-	☺	☺☺☺☺
Beauty	☺	-	☺☺☺☺	☺☺☺☺
Jets	☺☺	☺☺☺☺	☺☺☺ + ☺	-
Collectivity	☺☺	☺☺☺	☺☺☺	☺
PID	☺☺☺☺	-	-	?

A probably-biased and certainly-simplistic view of experiment potentials

Conclusion: Complementary programme, all experiments will be useful in the future (but see what LHCb can really do…)



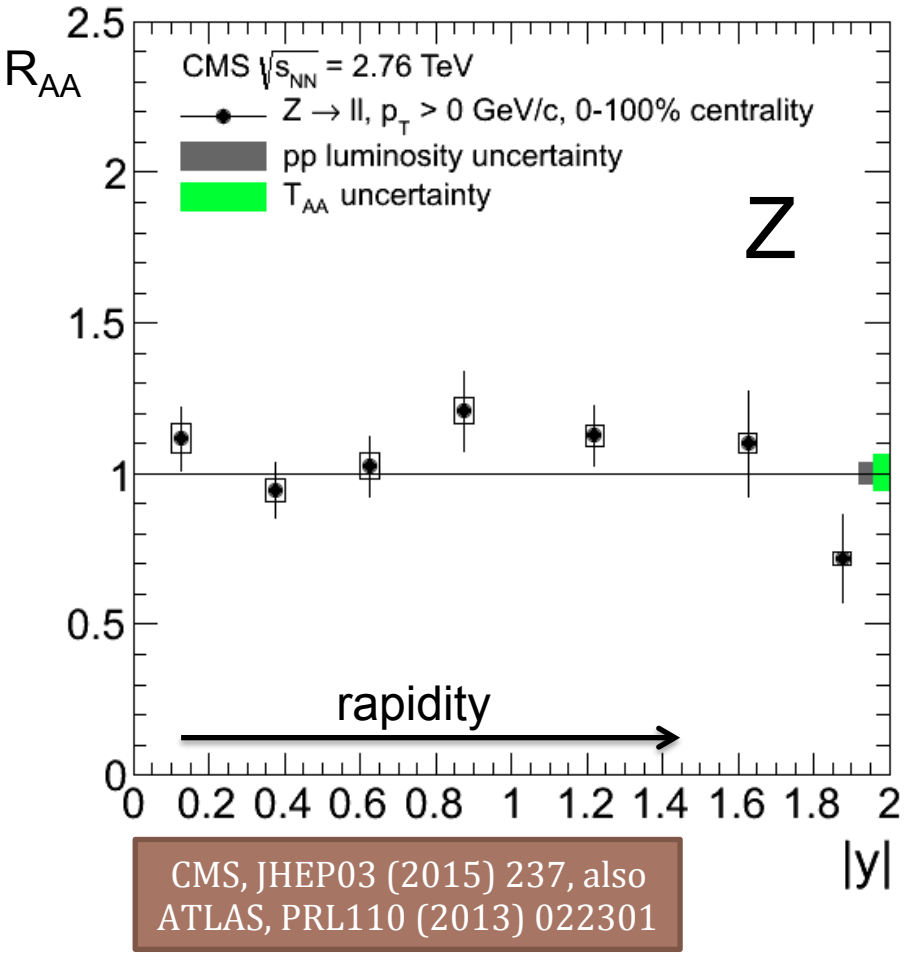


Insensitive to the QGP
standard candles of
heavy ion collisions

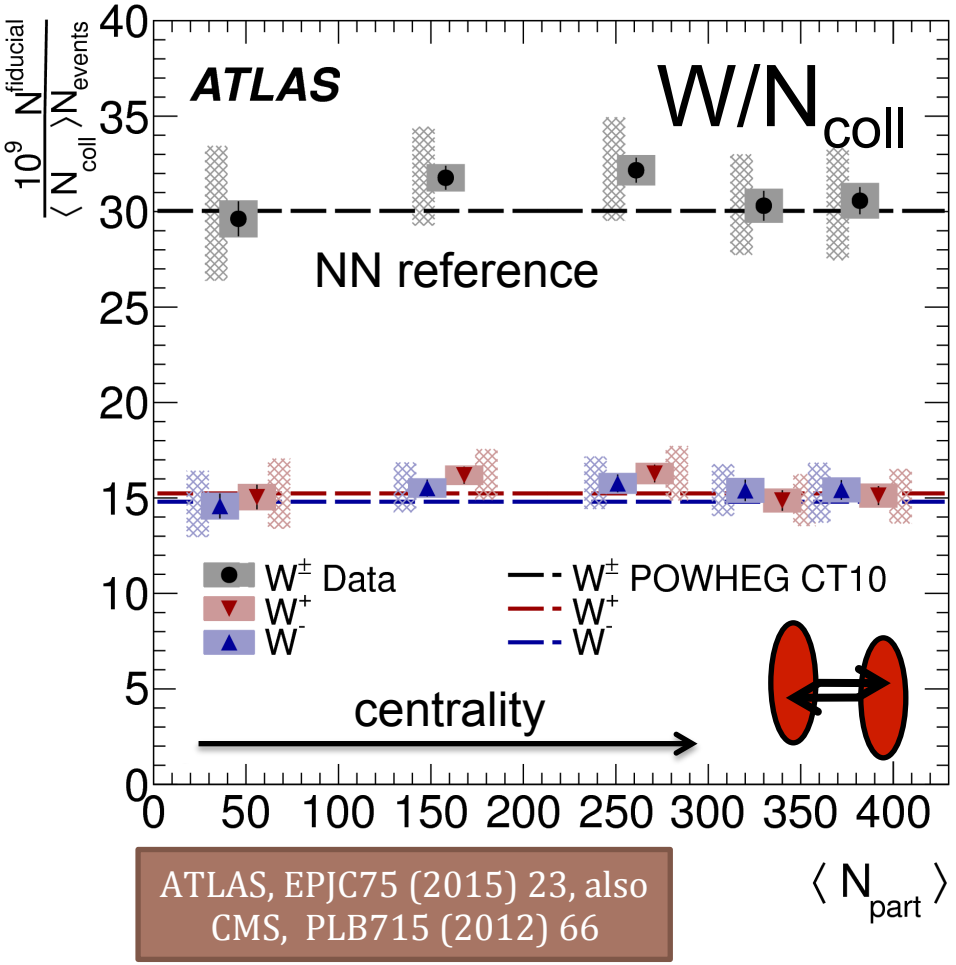
ELECTROWEAK BOSONS

© Vermeer

Z & W bosons in PbPb scale like N_{coll}



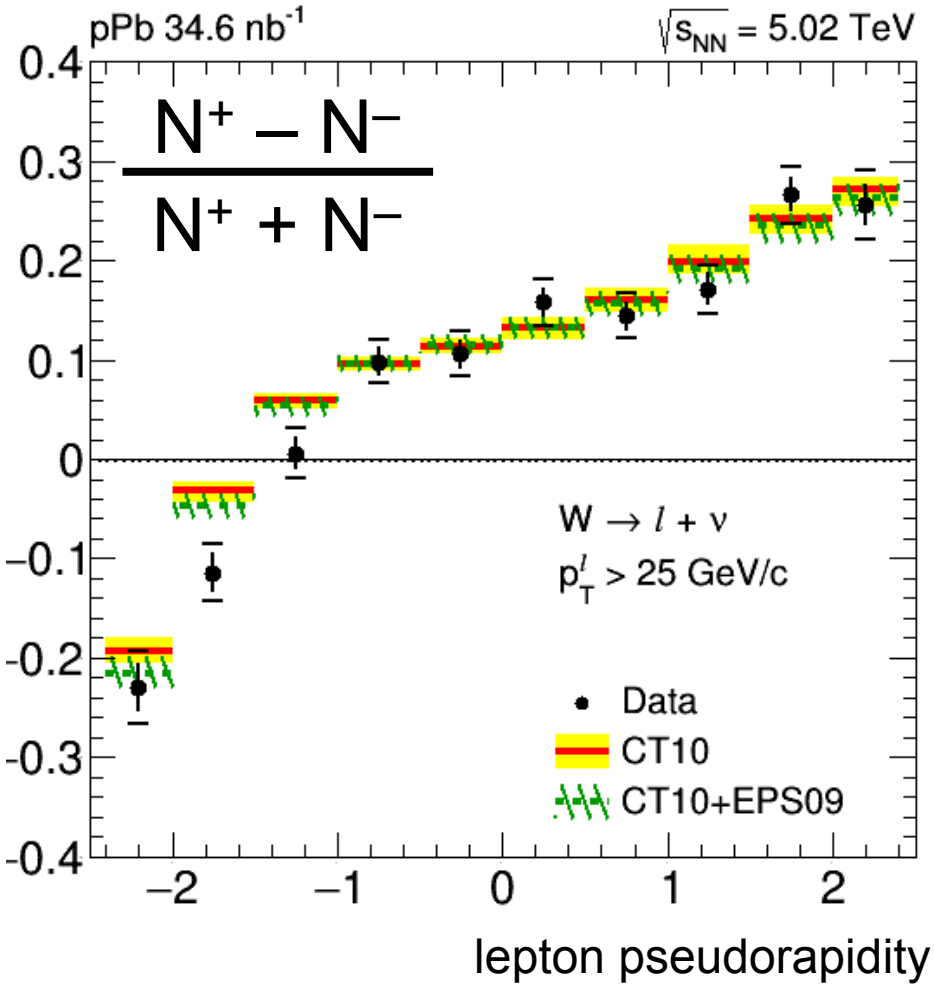
CMS, JHEP03 (2015) 237, also
ATLAS, PRL110 (2013) 022301



ATLAS, EPJC75 (2015) 23, also
CMS, PLB715 (2012) 66

No visible modification, $R_{AA} \approx 1$ (within ≈ 10%)

W^+ and W^- in pPb collisions



Charge asymmetry

Hint of a departure at backward rapidity…

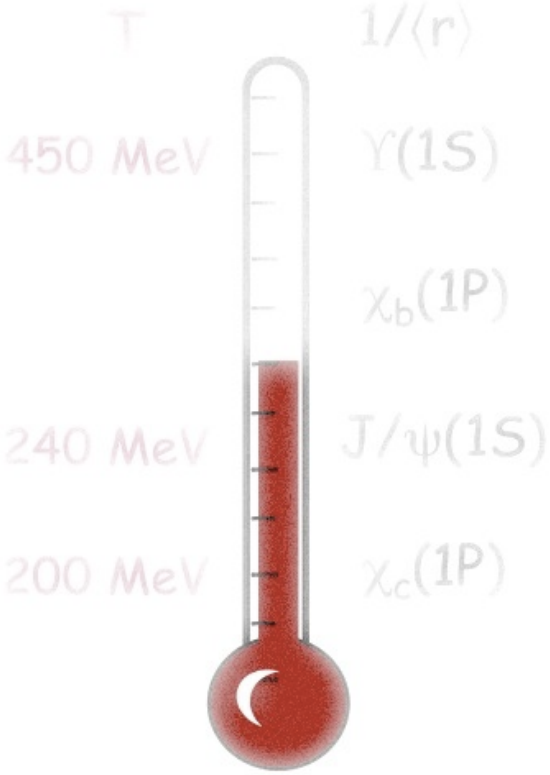
Could be a sign of different nuclear modification of (valence) up and down quarks (not in EPS09)

CMS, 1503.05825, accepted by
Alice Florent PhD thesis

EWK bosons

Particles	ALICE	ATLAS	CMS	LHCb
EWK bosons	☺	☺☺☺☺	☺☺☺☺	☺

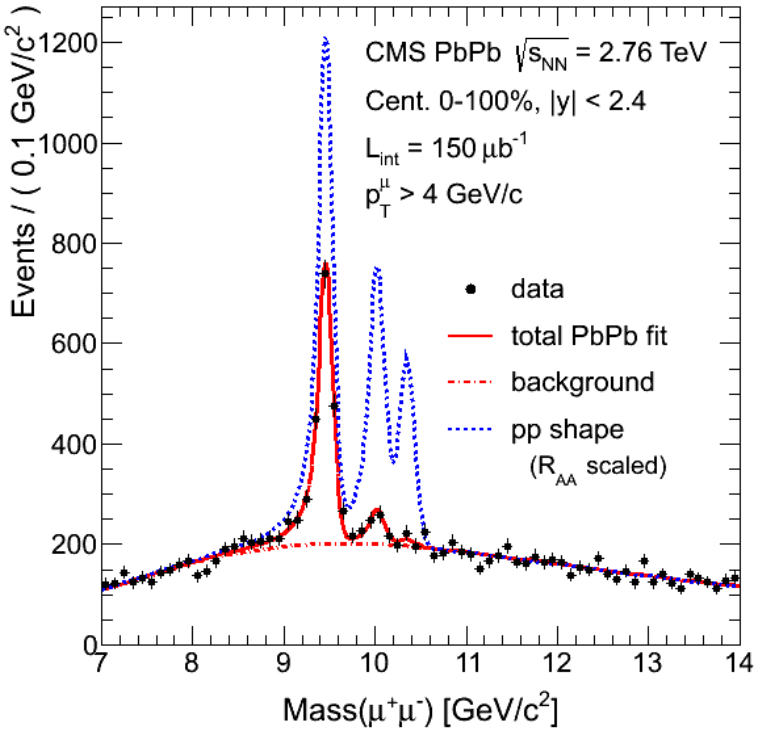
Rarest objects seen in heavy-ion collisions so far
Acceptance and luminosity matter a lot
→ ATLAS and CMS leading the show
Same reasoning applies to high-p_T photons, jets…
And will apply in the future: higher-p_T, Z+jet and top quarks



Are they melting in the Quark-Gluon Plasma?

QUARKONIA…

Three bottomonia Y(nS)

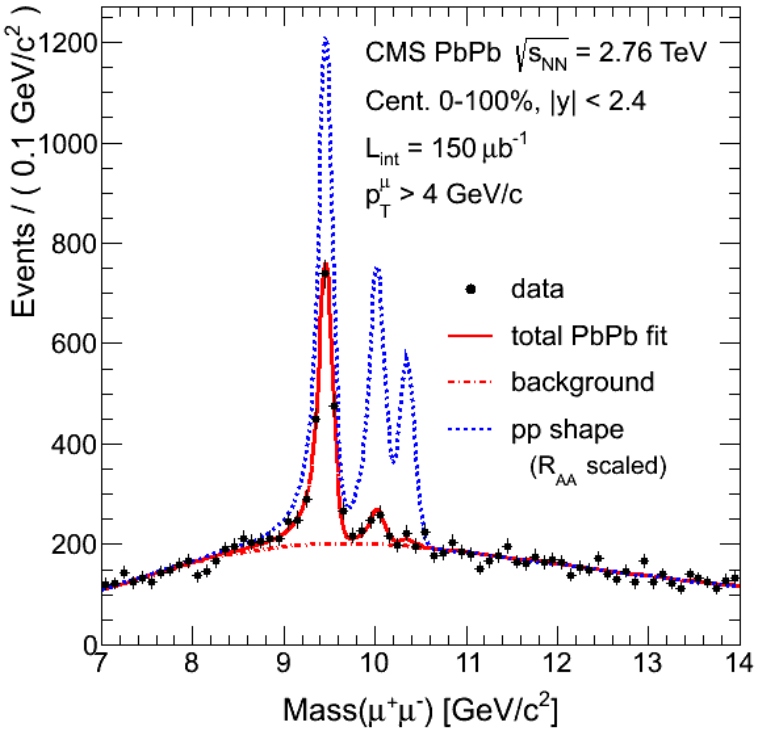


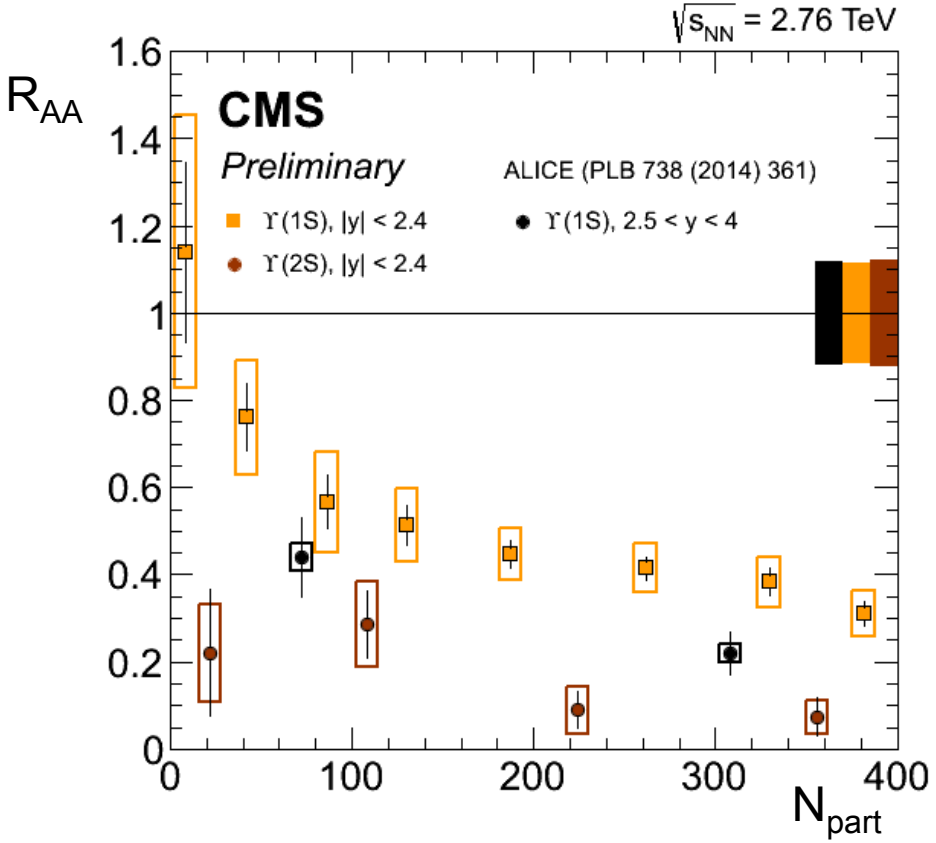
$R_{AA}(1S) = 0.425 \pm 0.029 \pm 0.070$
$R_{AA}(2S) = 0.116 \pm 0.028 \pm 0.022$
$R_{AA}(3S) < 0.14$ (95% CL)

CMS, PRL109 (2012) 222301 and HIN-15-001

Ordered suppression of the three Y states → Sequential melting (and half of the Y(1S) is coming from higher state decays…)

Three bottomonia Y(nS)





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ALICE, PLB738 (2014) 361

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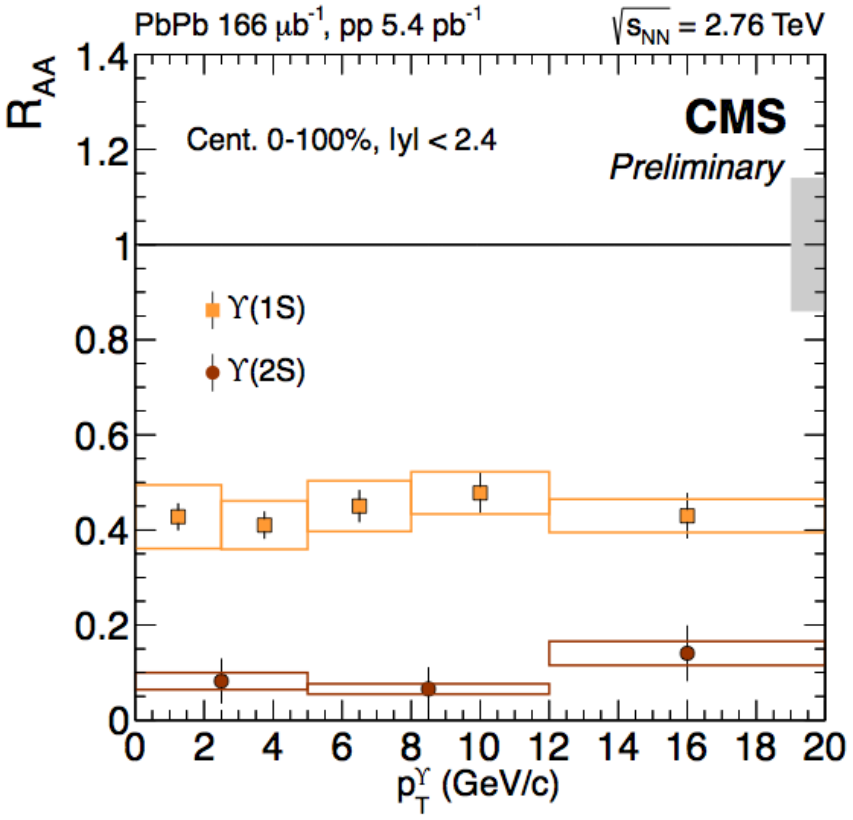
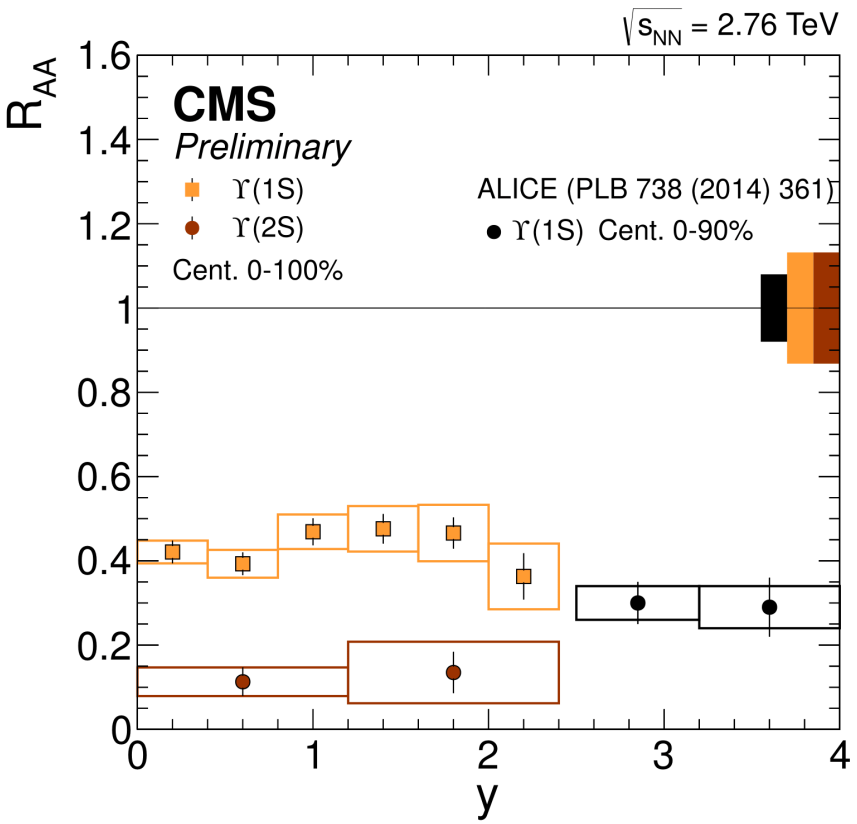
Upsilon kinematical dependences

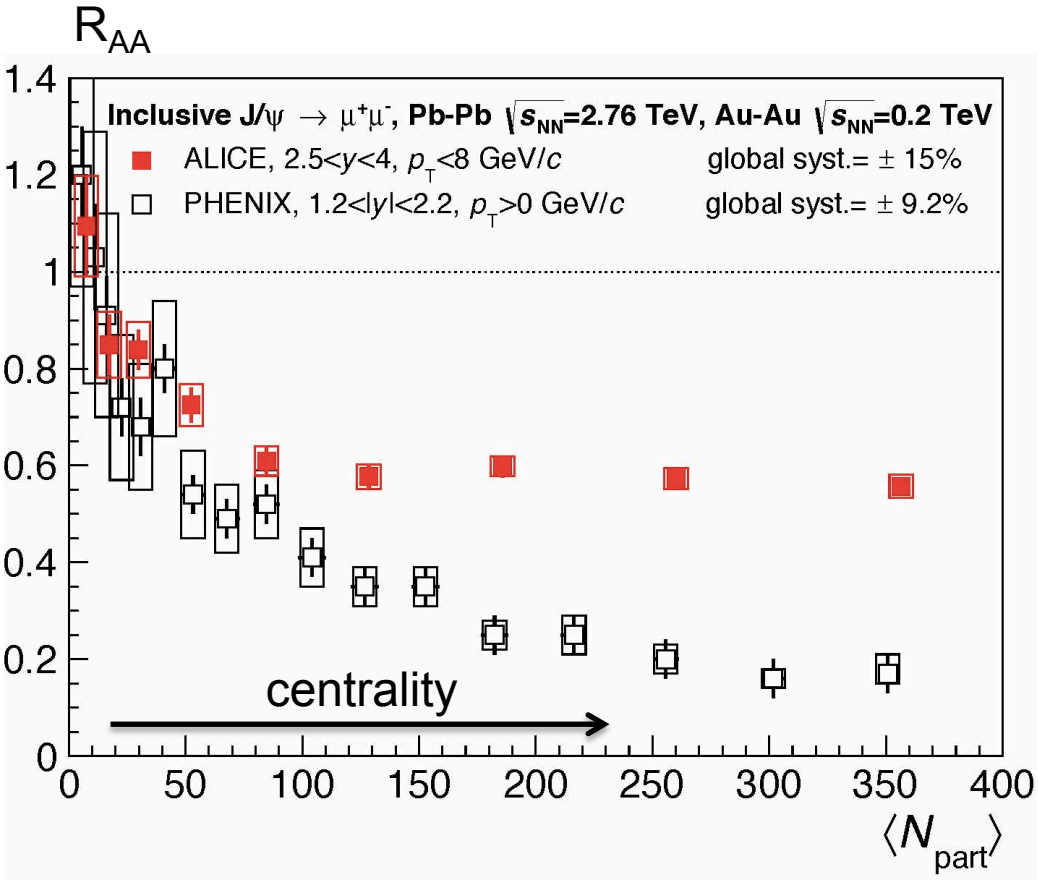




The Y(1S) suppression seems flat with p_T and rapidity
Simple, different than J/ψ, constraining models…

CMS, HIN-15-001, Nicolas Filipovic PhD thesis
ALICE, PLB738 (2014) 361

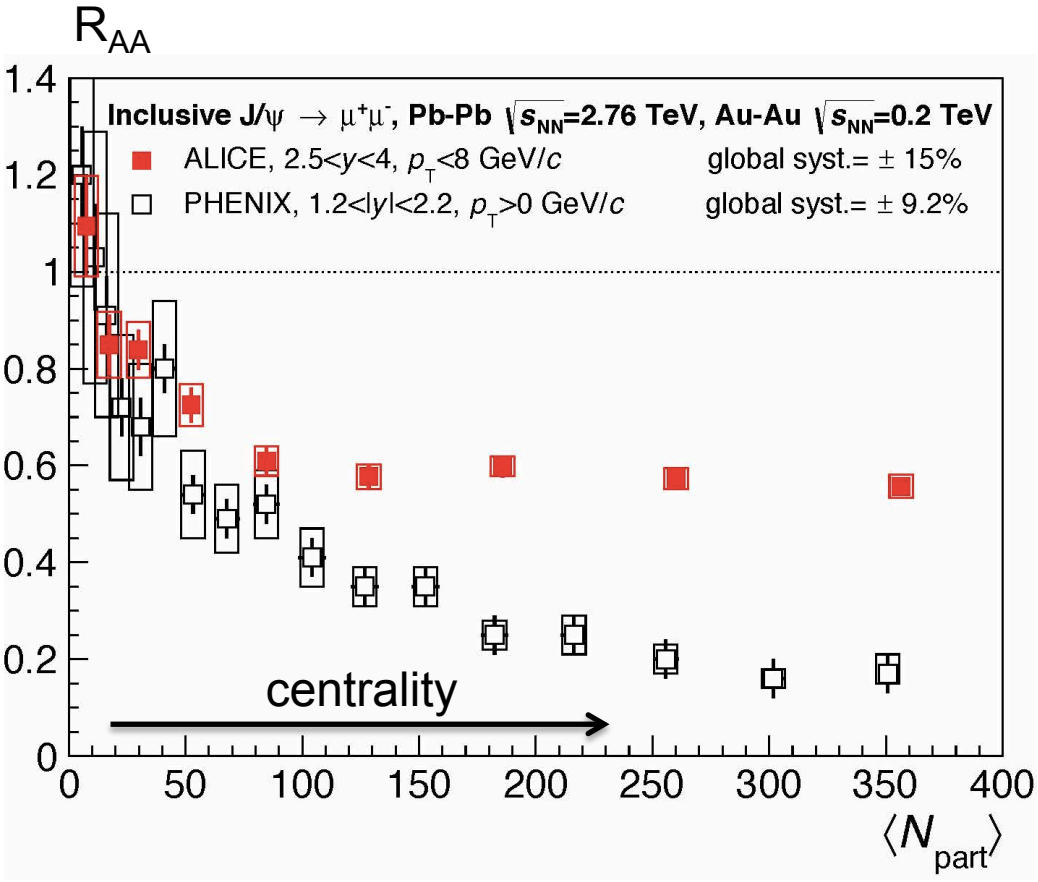
J/ψ from RHIC to LHC = ALICE @ low p_T

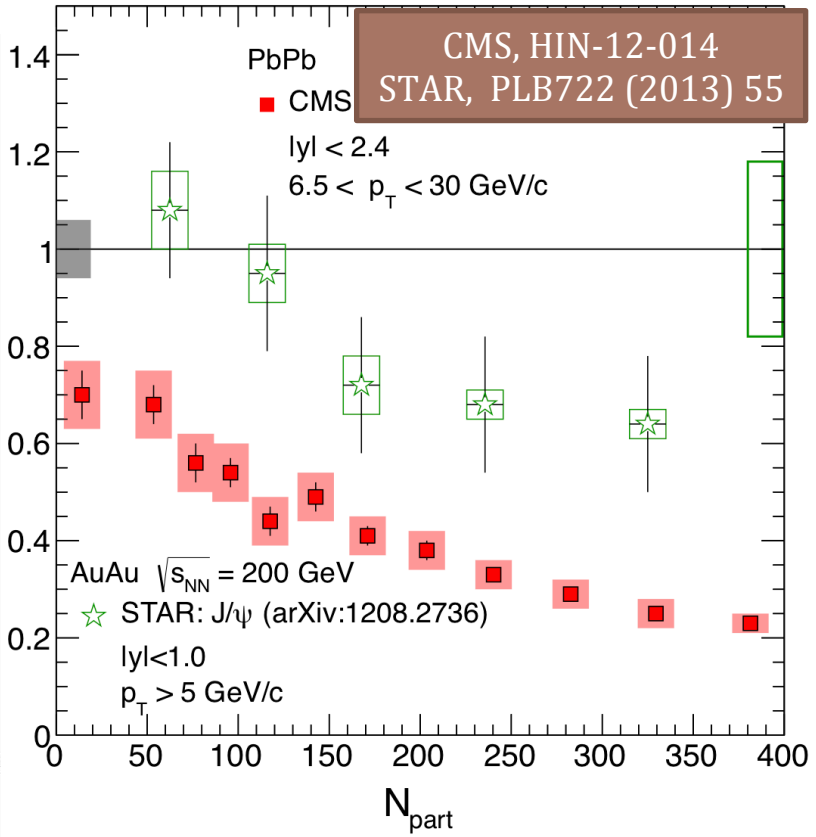


PHENIX, PRC84 (2011) 054912
ALICE, 1506.08804, already in PRL109 (2012) 072301

J/ψ are <u>less</u> suppressed at LHC than at RHIC
An indication that they are formed again from uncorrelated cc pairs (about 100 in a central collision)
→ Regeneration = reconfinement, hence deconfinement

J/ψ from RHIC to LHC = CMS @ high p_T





J/ψ are less suppressed at LHC than at RHIC at low p_T
J/ψ are more suppressed at LHC than at RHIC at high p_T
(where regeneration is unlikely)

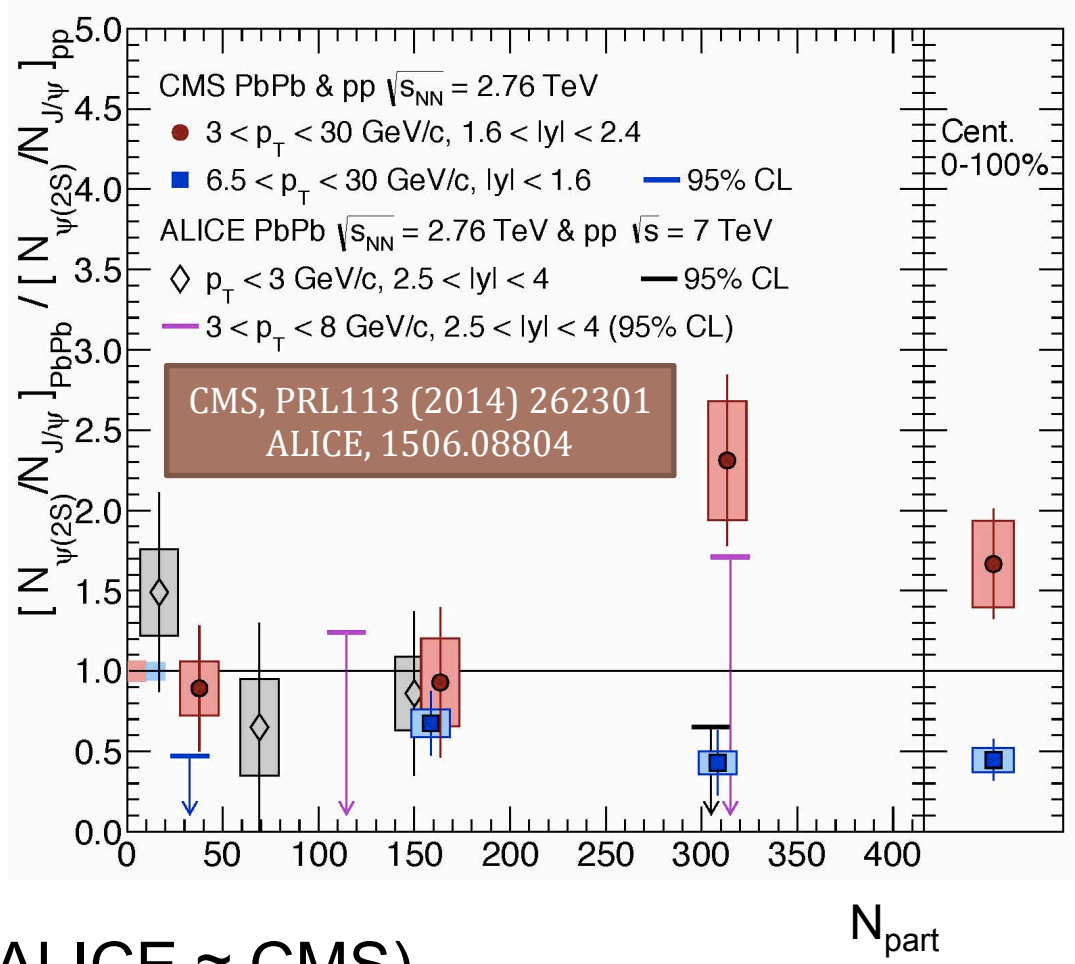
What is going on with the lesser bound ψ'?

R_{AA} (ψ') / R_{AA} (J/ψ) →

High p_T and mid rapidity
→ ψ' more suppressed

Moderate p_T and rapidity
→ ψ' less suppressed

Low p_T and forward
→ ψ' more suppressed



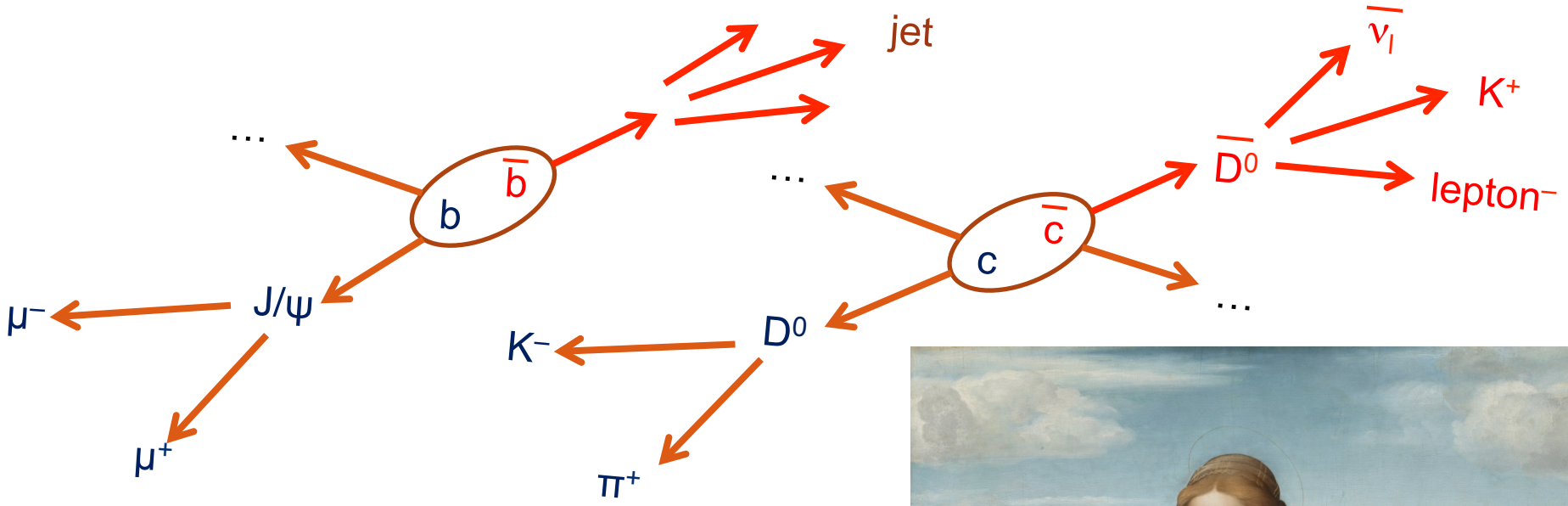
Much lower S/B for the ψ' (ALICE ≈ CMS)
Expected to be more fragile, a lower suppression is a surprise…
But large uncertainties, new data is necessary!

Charmonia & Bottomonia

Particles	ALICE	ATLAS	CMS	LHCb
Charmonia	☺☺☺	☺	☺☺	☺☺☺☺
Bottomonia	☺	☺	☺☺☺☺	☺☺☺

Charmonia: Alice published landmark publications on J/ψ down to $p_T = 0$
Caveat: low statistics at midrapidity, no separation of the non-prompt at forward
LHCb has a potential to do this much better (best resolution, vertexing)

Bottomonia: CMS is the best (resolution, acceptance, luminosity, p_T inclusive, manpower…) LHCb has a great potential (but luminosity...)

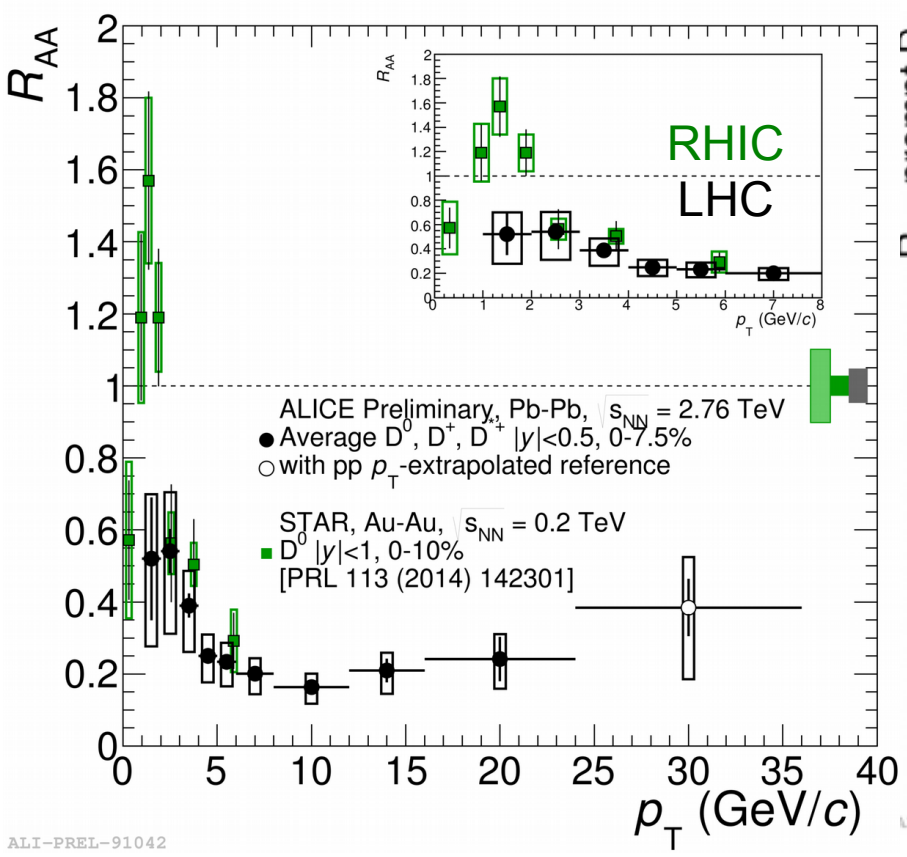


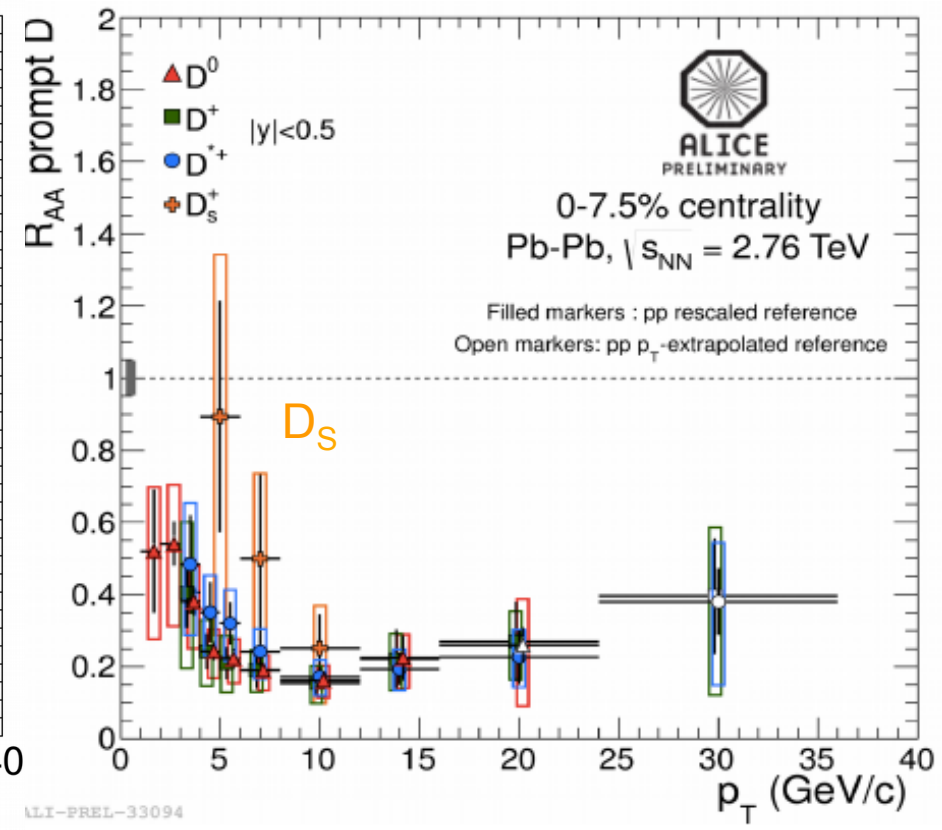
How sensitive to energy loss
and medium collectivity?

CHARM & BEAUTY

Charm @ LHC = ALICE !

ALICE preliminary, also
JHEP09 (2012) 112 & 1506.06604

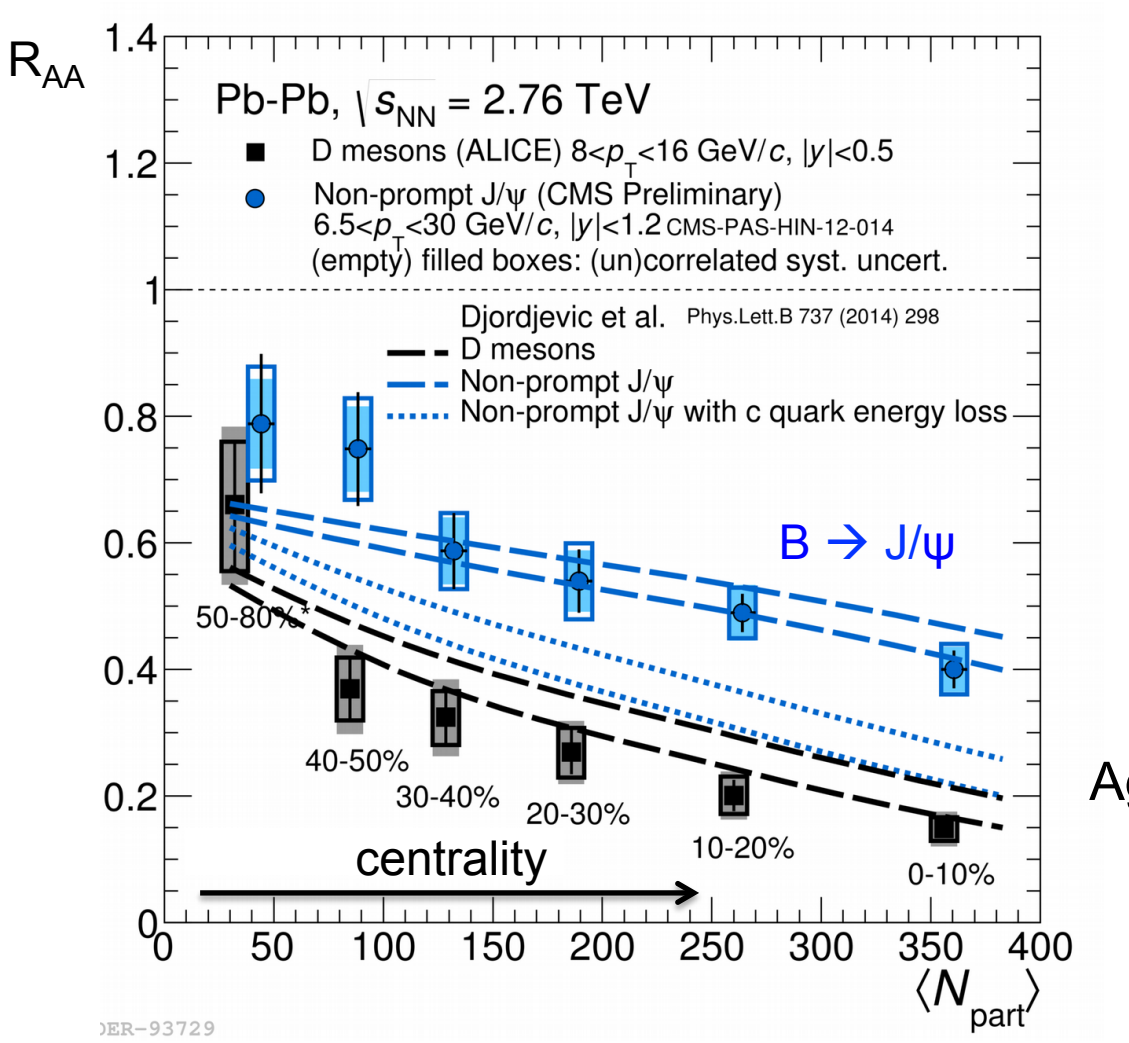




Alice measures D mesons, almost down to 0 GeV/c
Thanks to Pid ($D^0 \rightarrow K\pi$, $D^{\pm}$, D^*, D_S)

Beauty @ LHC = CMS !

CMS, HIN-12-014, JHEP05 (2012) 063
versus charm from ALICE, 1506.06604



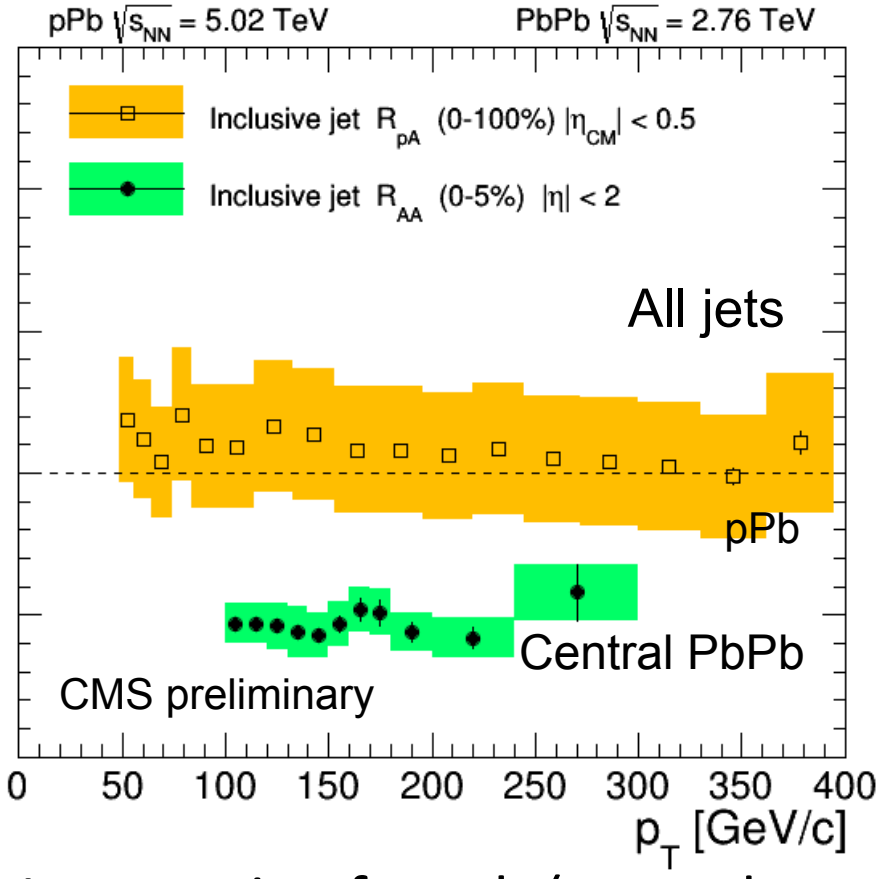
R_{AA} (D) < R_{AA} (J/ψ ← B)

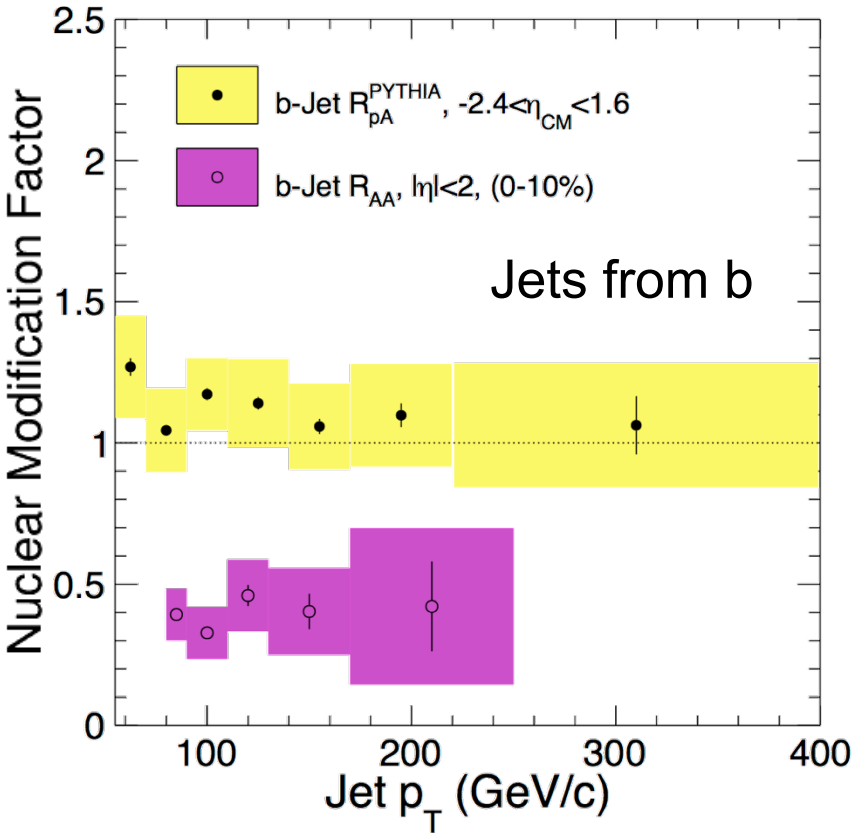
Charming Alice
more suppressed than
beautiful CMS

Flavour dependence
of jet quenching?
(but the devil might
be in the details)

Again, nice complementarity
between experiments

b quarks of much higher p_T: b-jet





Jets coming from b (second vertex), looks like inclusive jets…

- as suppressed ($R_{AA} \approx 0.5$)
- not suppressed in pPb ($R_{pA} \approx 1$)

(but more coming from gluon splitting)

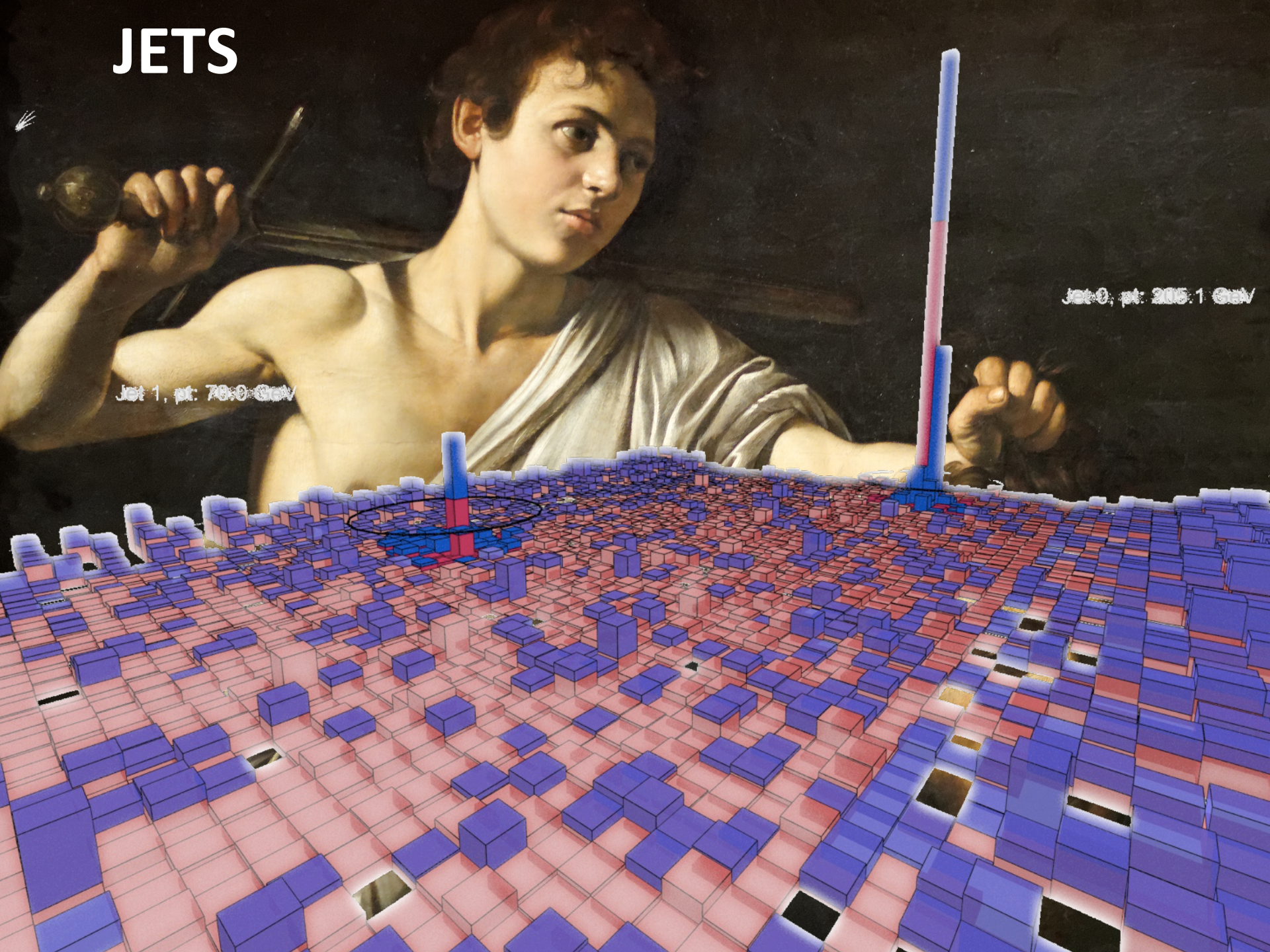
CMS, PRL113 (2014) 132301 (Matt's)
CMS, HIN-14-007

Open heavy flavours

Particles	ALICE	ATLAS	CMS	LHCb
Charm	☺☺☺☺	-	☺	☺☺☺☺
Beauty	☺	-	☺☺☺☺	☺☺☺☺

At this point, open heavy flavours is lead by ALICE (charm, thanks to PID) and CMS (beauty, thanks to vertexing)
LHCb, with PID + vertexing, has the potential to do both

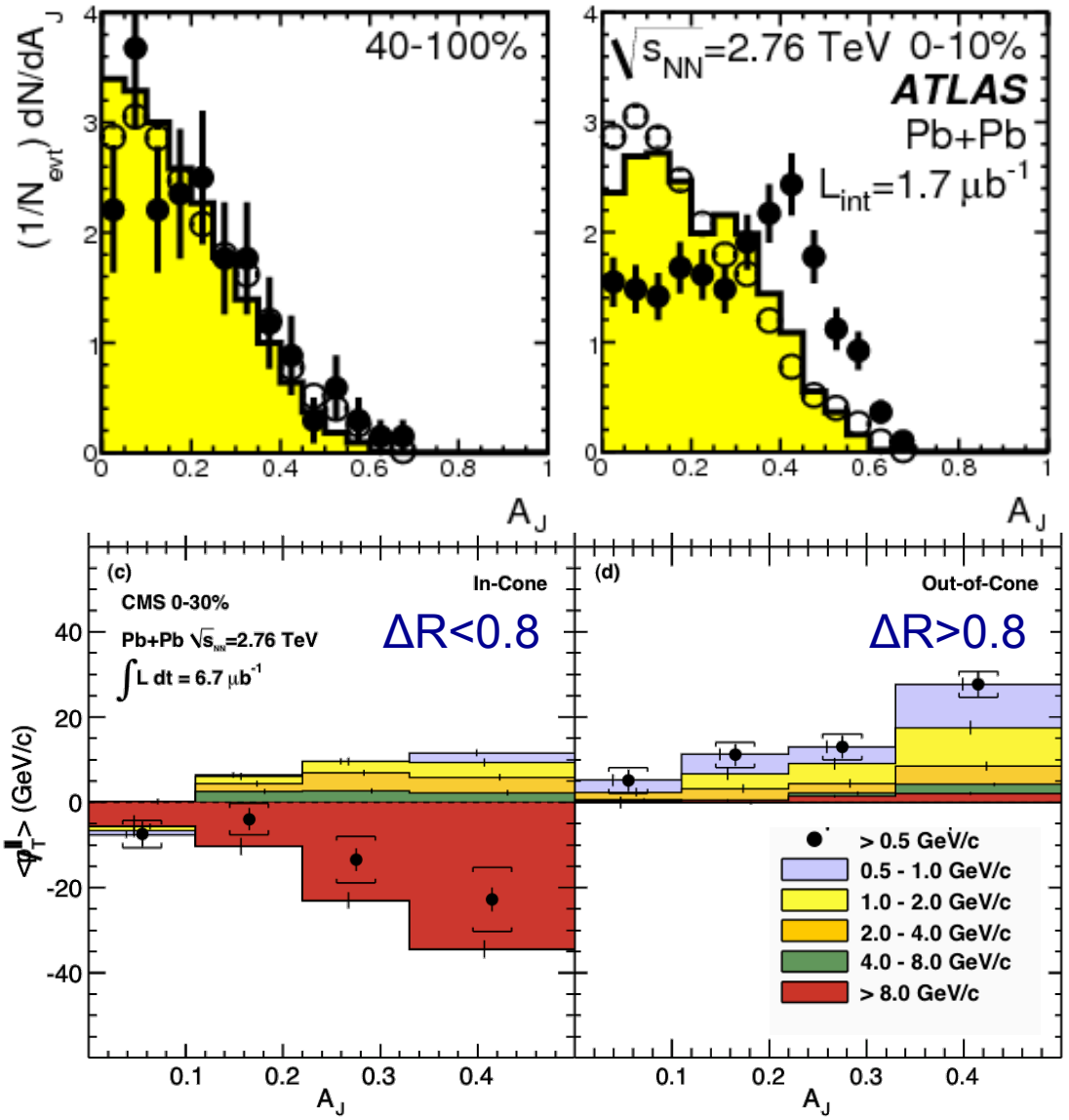
JETS



JETS

Jet quenching: first LHC surprise in PbPb

PRL cover
ATLAS 17/12/10



ATLAS, PRL105(2010)252303
CMS, PRC84(2011)024906

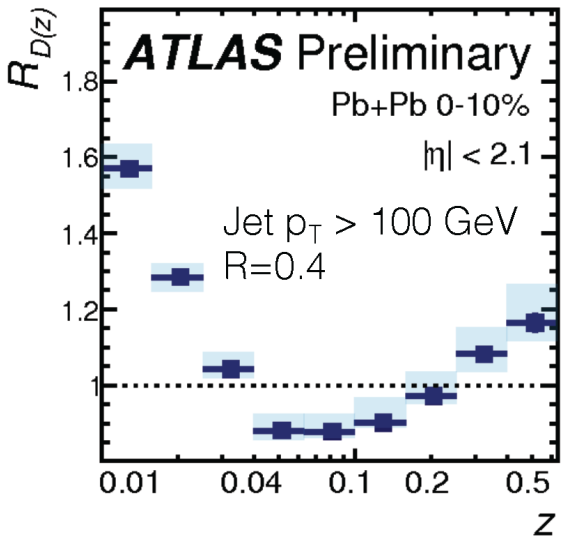
ATLAS & CMS are after jets since day 1

Looking inside jets

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}p_T^{\text{track}}}{p_T^{\text{jet}}}$$

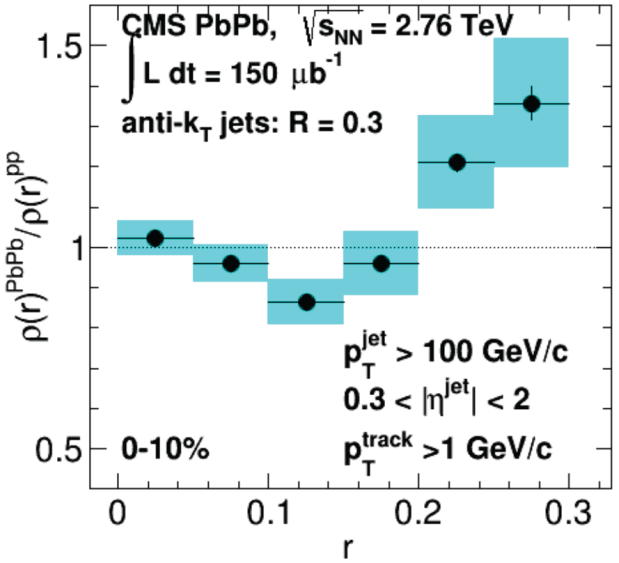
Jet fragmentation (longitudinal)

ATLAS-CONF-2015-055



Jet shape (transverse)

CMS PLB 730 (2014) 243



- Excess at low p_T and large angle clearly a feature of jet quenching
- Modest modification of jet structure at small angle & medium to high p_T
- To what extent is this due to quenching changing the q/g fraction?

16

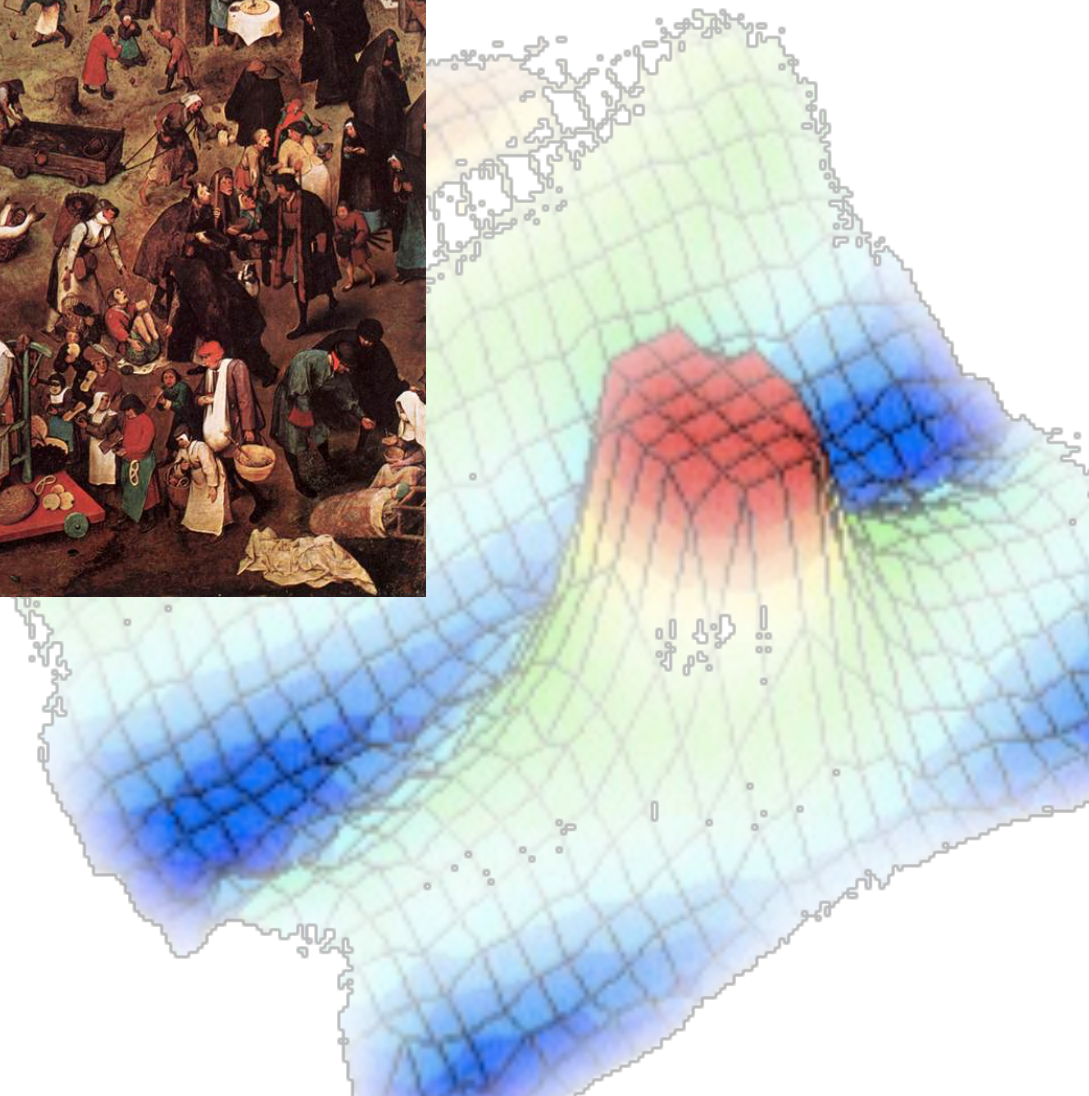
M. Nguyen, jet overview, QM'15

Jets

Particles	ALICE	ATLAS	CMS	LHCb
Jets	☺☺	☺☺☺☺	☺☺☺ + ☺	-

Since the first and early observation of di-jet imbalance,
reconstructing full jets in heavy ions is a playground for CMS & ATLAS
Little sister ALICE also playing, and the only to do hadrochemistry in jets (K's, Lambda…)
Future: Repeat all jet measurements in a less biased way with gamma+jet
Also Z+jet, trijets... Disentangle quark/gluon, and heavy quarks...

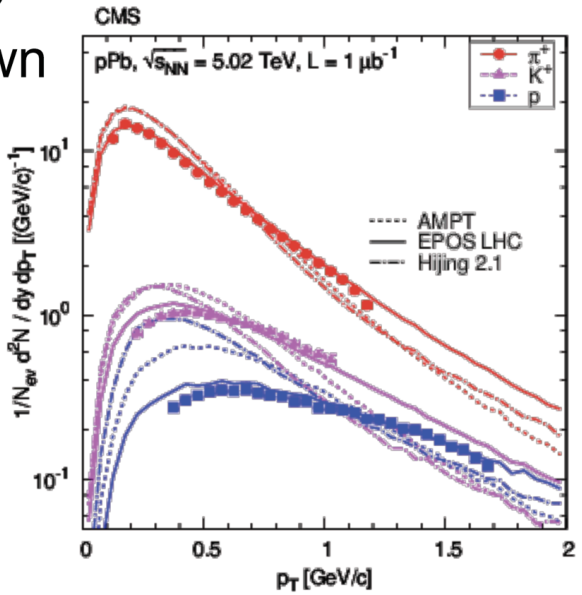
COLLECTIVITY



All running after collectivity in all systems

Summary (1/4) collectivity

- pPb looks a lot like PbPb, and as hydro predicts!
  1. Strong v_2 from multiparticle correlations
  2. Similar mass ordering
  3. v_2 depending on η in pPb
  4. Same v_3 versus multiplicities
  5. Same factorization breakdown
  6. Similar HBT radii (5 fm)
  7. and the spectra are better reproduced by generators incl. hydro (EPOS) →



arXiv:1307.3442, EPJC-accepted

High-multiplicity pPb collisions show collectivity!

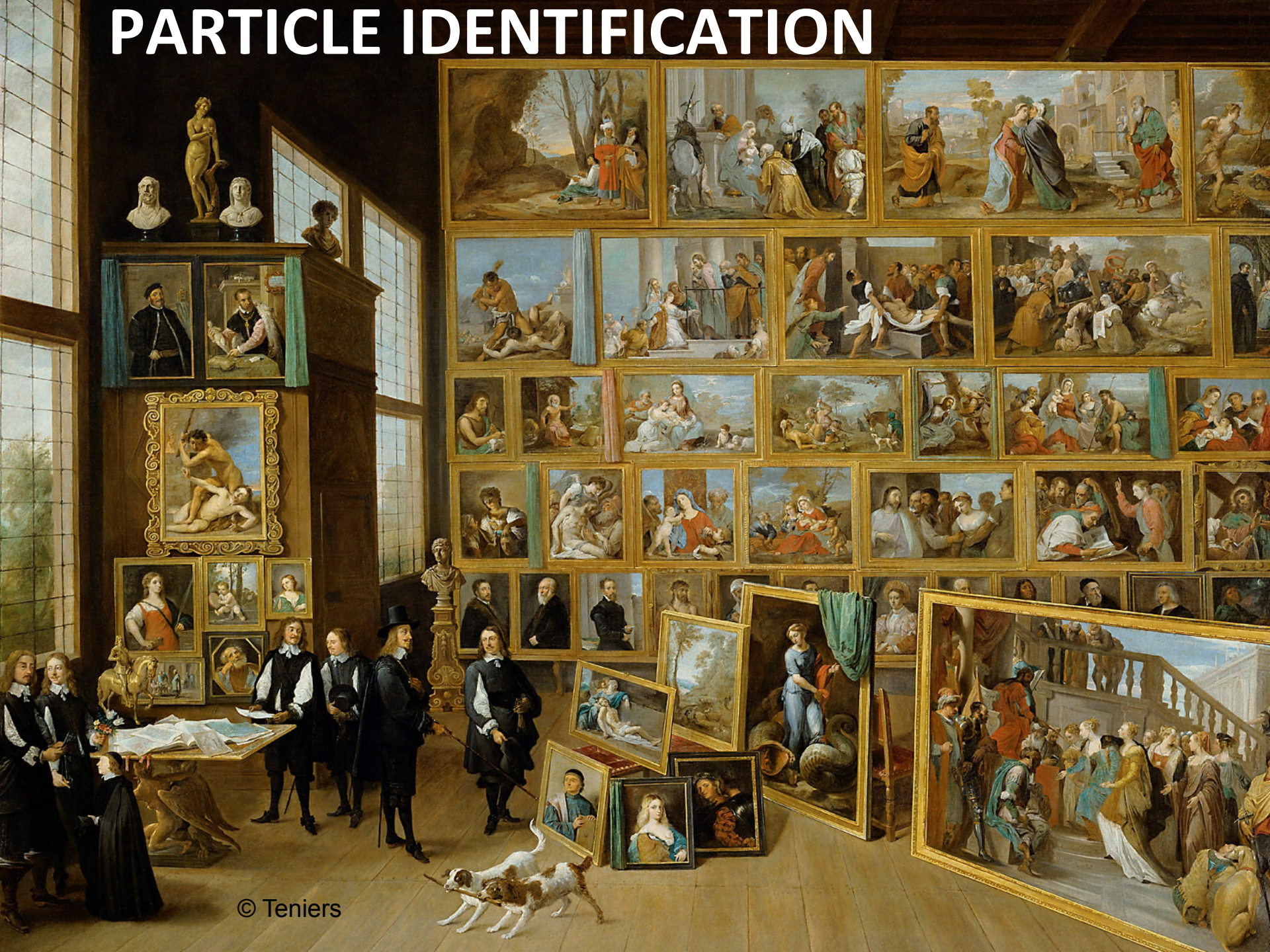
RGdC, CMS overview, QM'14
Larger part of the talk...

Collectivity

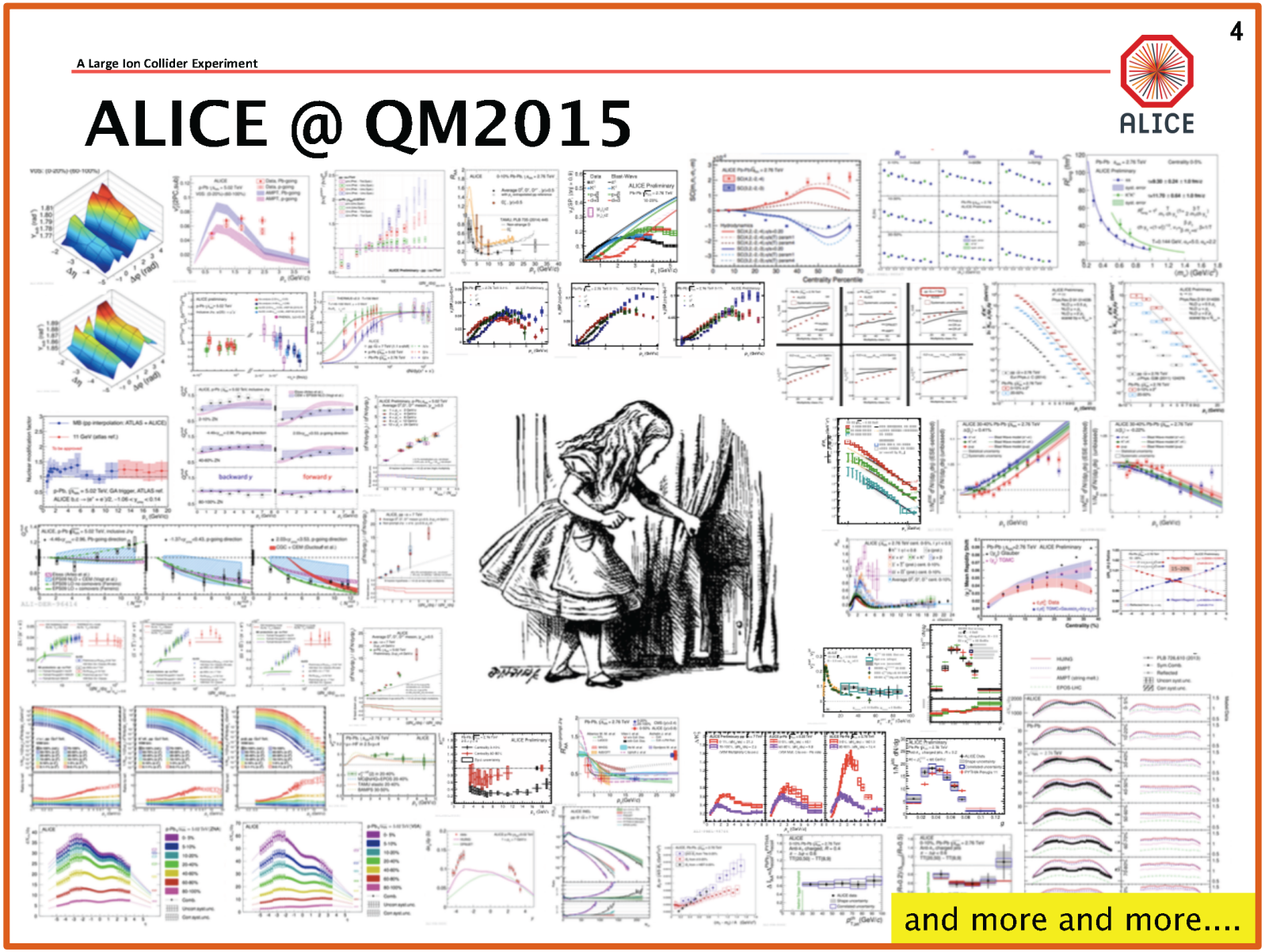
Particles	ALICE	ATLAS	CMS	LHCb
Collectivity	☺☺	☺☺☺	☺☺☺	☺

CMS “ridge” in pp @ 7 TeV in 2010, found back by ATLAS et al @ 14 TeV in 2015…
Signs of collectivity in pPb collisions (CMS a bit ahead...)
Here also, acceptance matter, and ATLAS and CMS go down to low p_T...

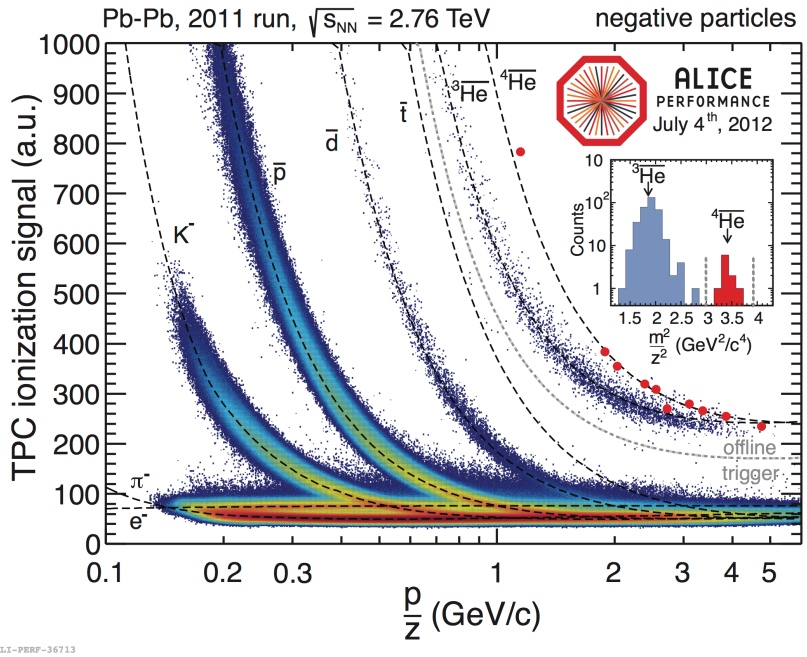
PARTICLE IDENTIFICATION

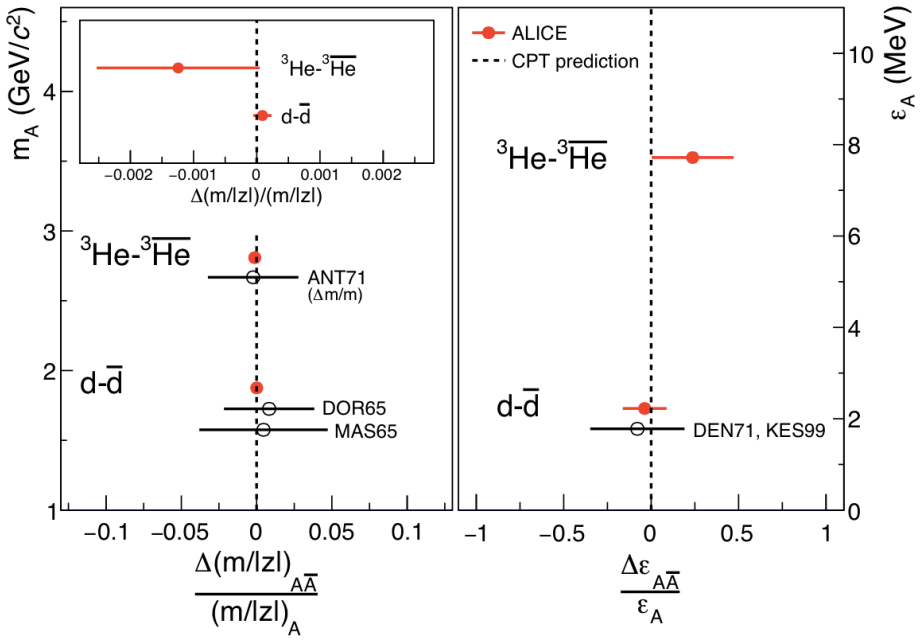


Alice in wonderland



One example: Anti-atoms in the TPC





Testing CPT invariance → Publishing in Nature

ALICE, Nature Physics 11 (2015) 811

Particle Identification…

Particles	ALICE	ATLAS	CMS	LHCb
PId	☺☺☺☺	-	-	?

ALICE in Wonderland…
→ Hadrochemistry, exotic nuclei, charm...

Summary

Particles	ALICE	ATLAS	CMS	LHCb
EWK bosons	☺	☺☺☺☺	☺☺☺☺	☺
Charmonia	☺☺☺	☺	☺☺	☺☺☺☺
Bottomonia	☺	☺	☺☺☺☺	☺☺☺
Charm	☺☺☺☺	-	☺	☺☺☺☺
Beauty	☺	-	☺☺☺☺	☺☺☺☺
Jets	☺☺	☺☺☺☺	☺☺☺ + ☺	-
Collectivity	☺☺	☺☺☺	☺☺☺	☺
PID	☺☺☺☺	-	-	?

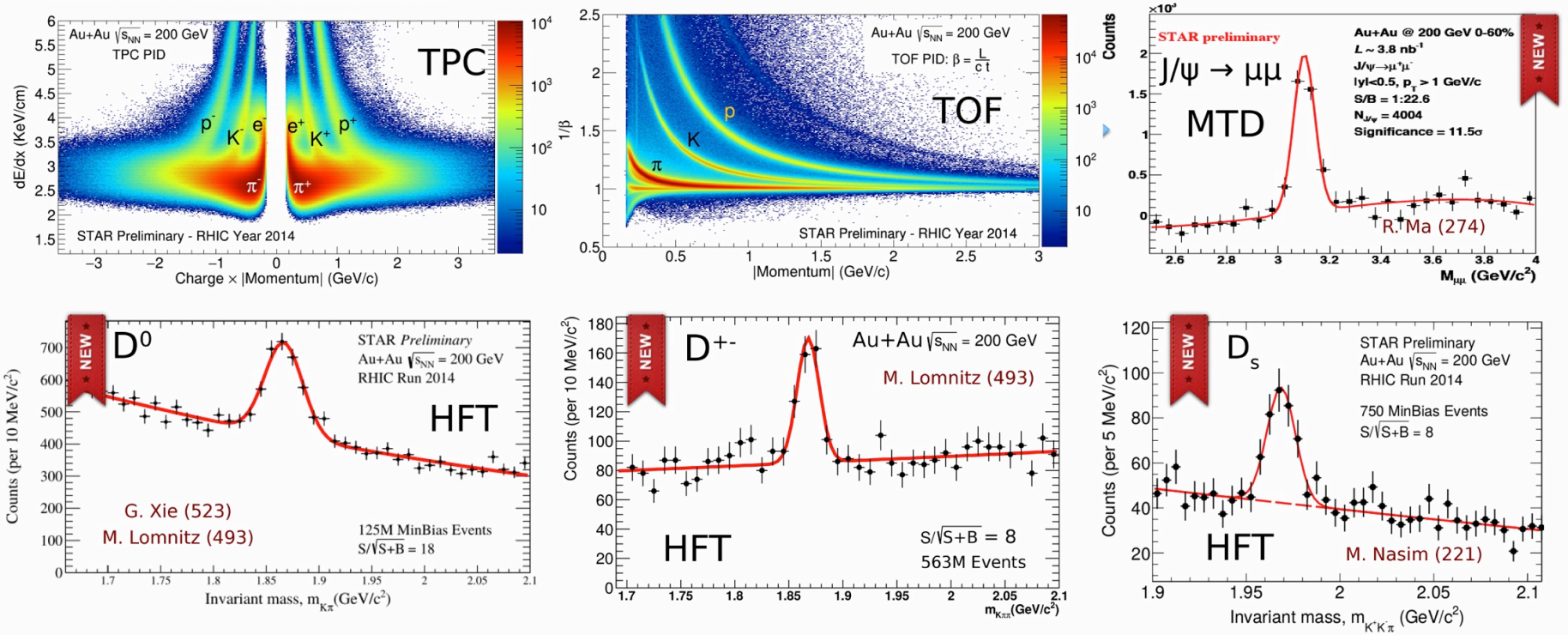
A probably-biased and certainly-simplistic view of experiment potentials

Conclusion: Complementary programme, all experiments will be useful in the future (but see what LHCb can really do…)

BACK-UP SLIDES…

Keep an eye on STAR…

Particle Identification

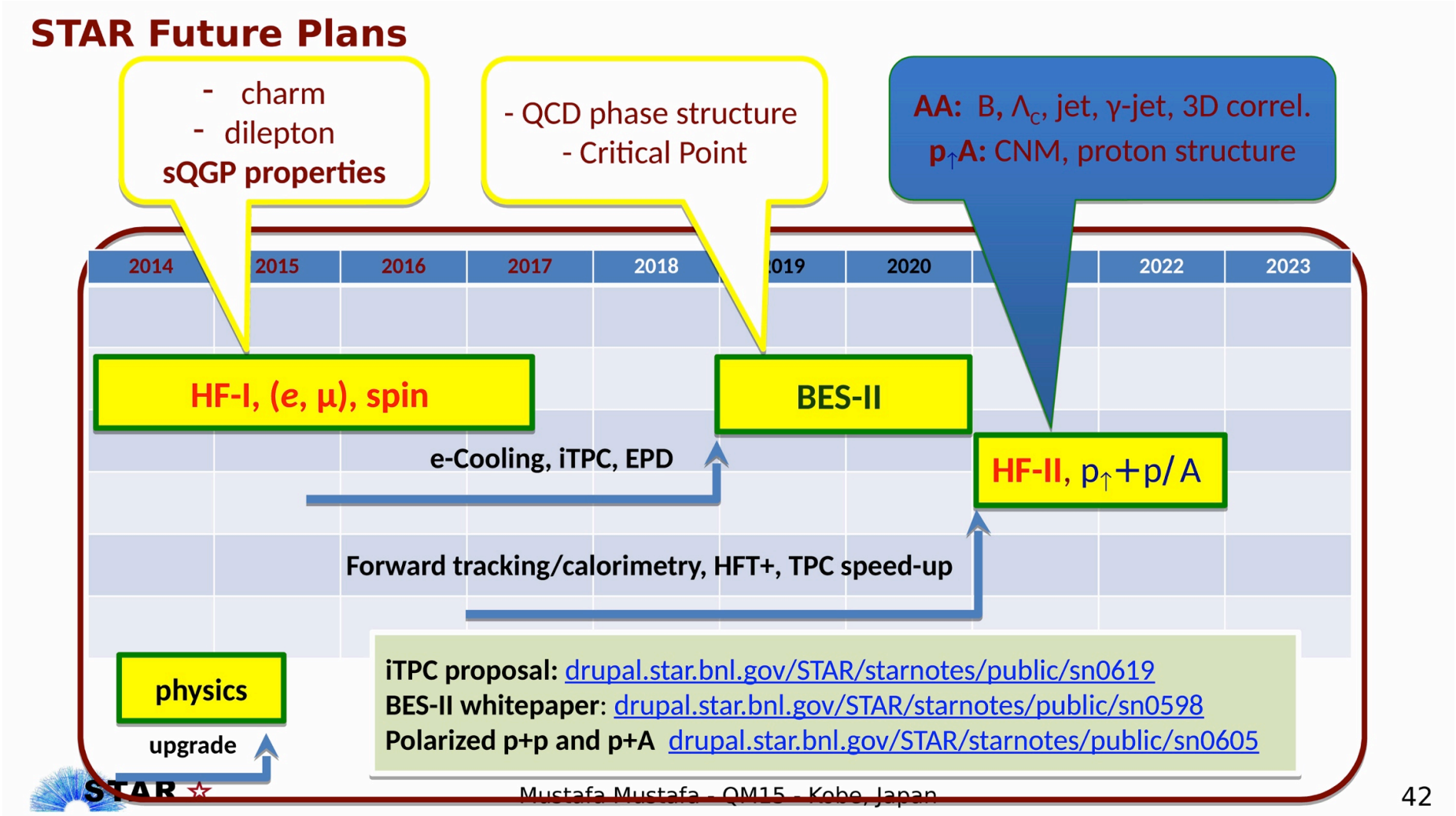


Excellent long-lived hadron and electron identification

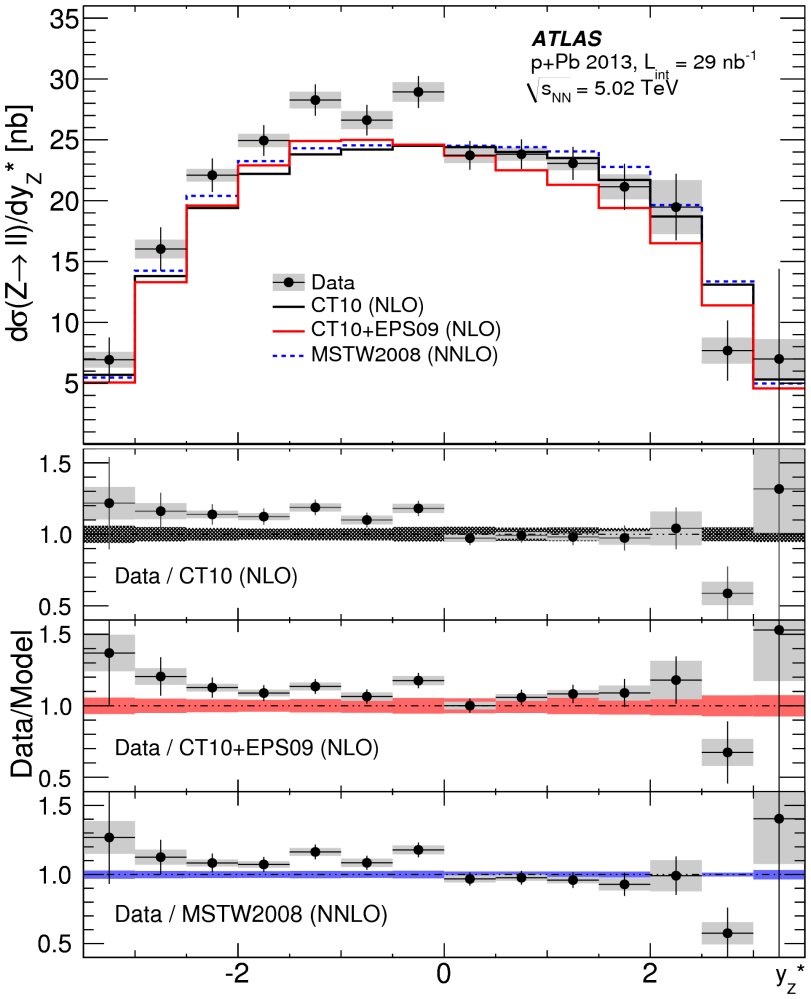
Secondary vertex reconstruction with HFT → Full kinematics reconstruction of charmed hadron

Muon/Quarkonia identification using MTD

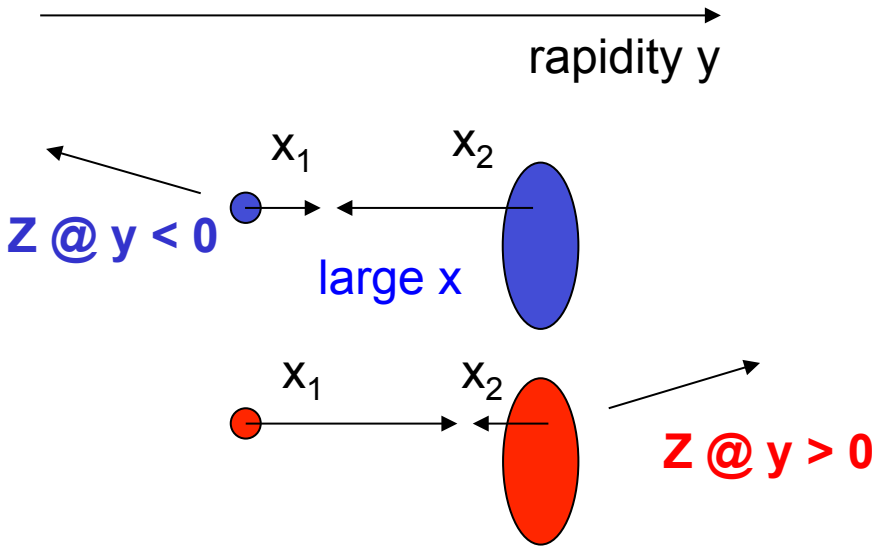
Keep an eye on STAR…



Z in pPb collisions



ATLAS, 1507.06232, also CMS, HIN-15-002

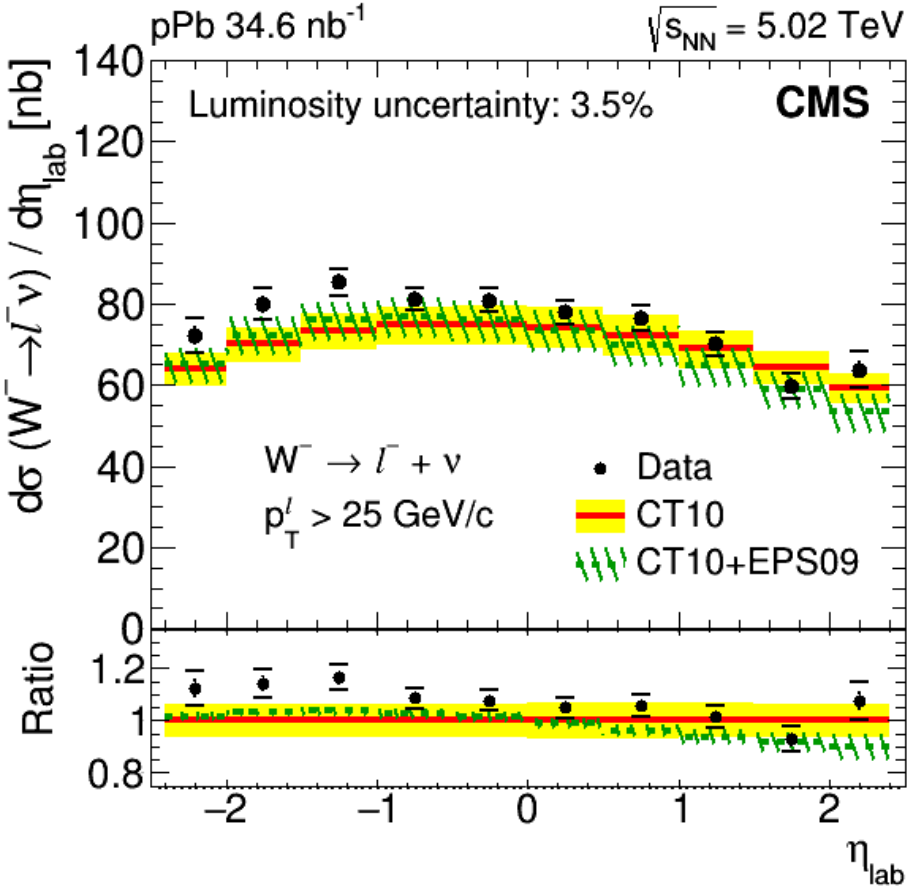


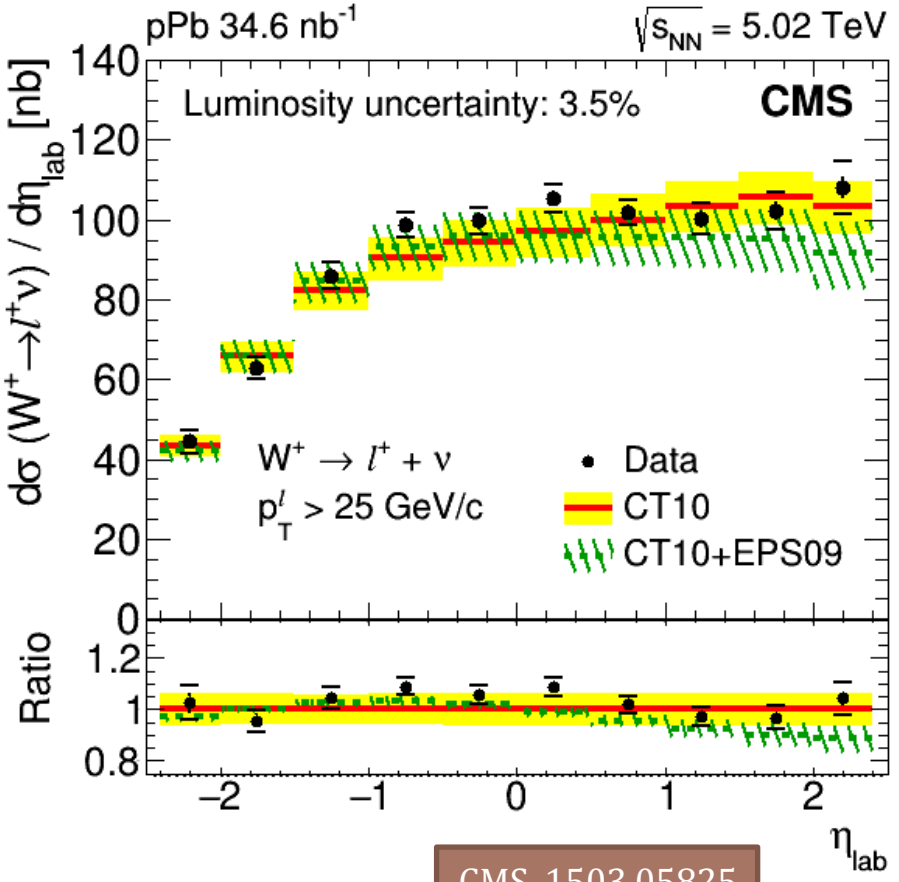
Hints of a backward / forward asymmetry

Shape is better fitted with nuclear PDF (EPS*09)

* Not the European Physical Society but Eskola, Paukkunen, Salgado

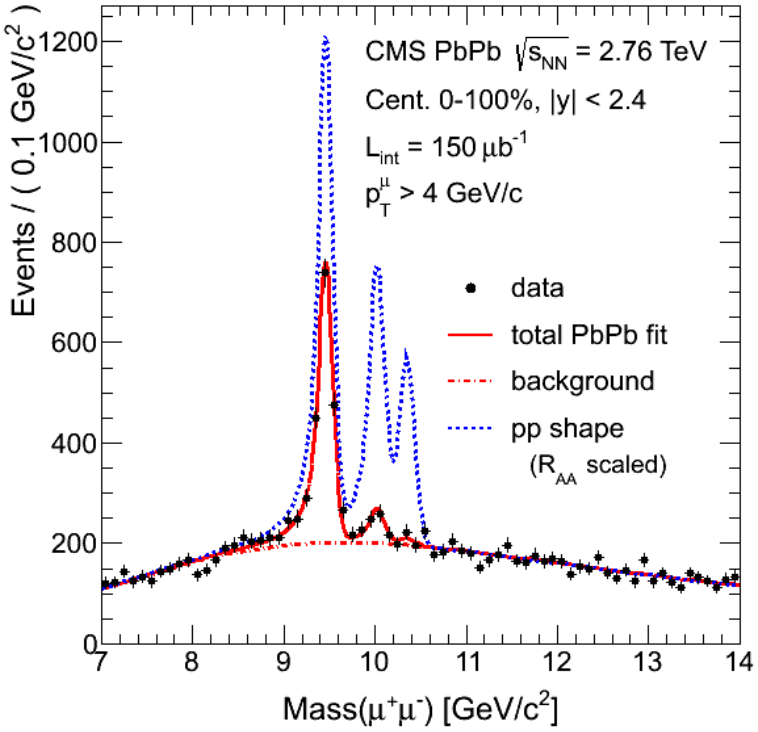
W in pPb collisions, full picture



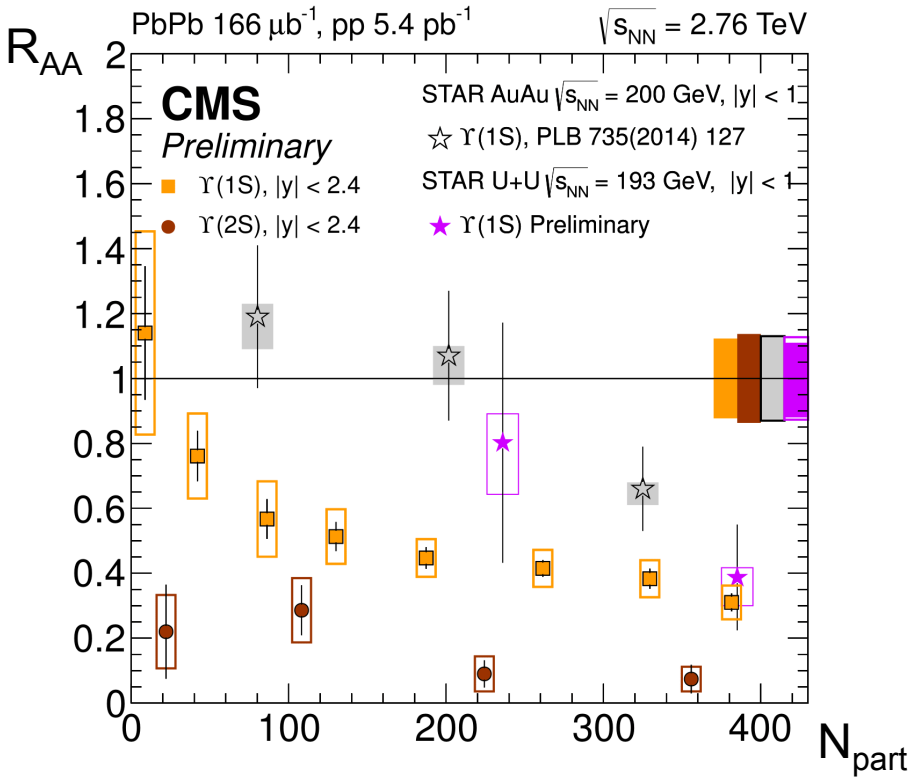


CMS, 1503.05825

Three bottomonia Y(nS)



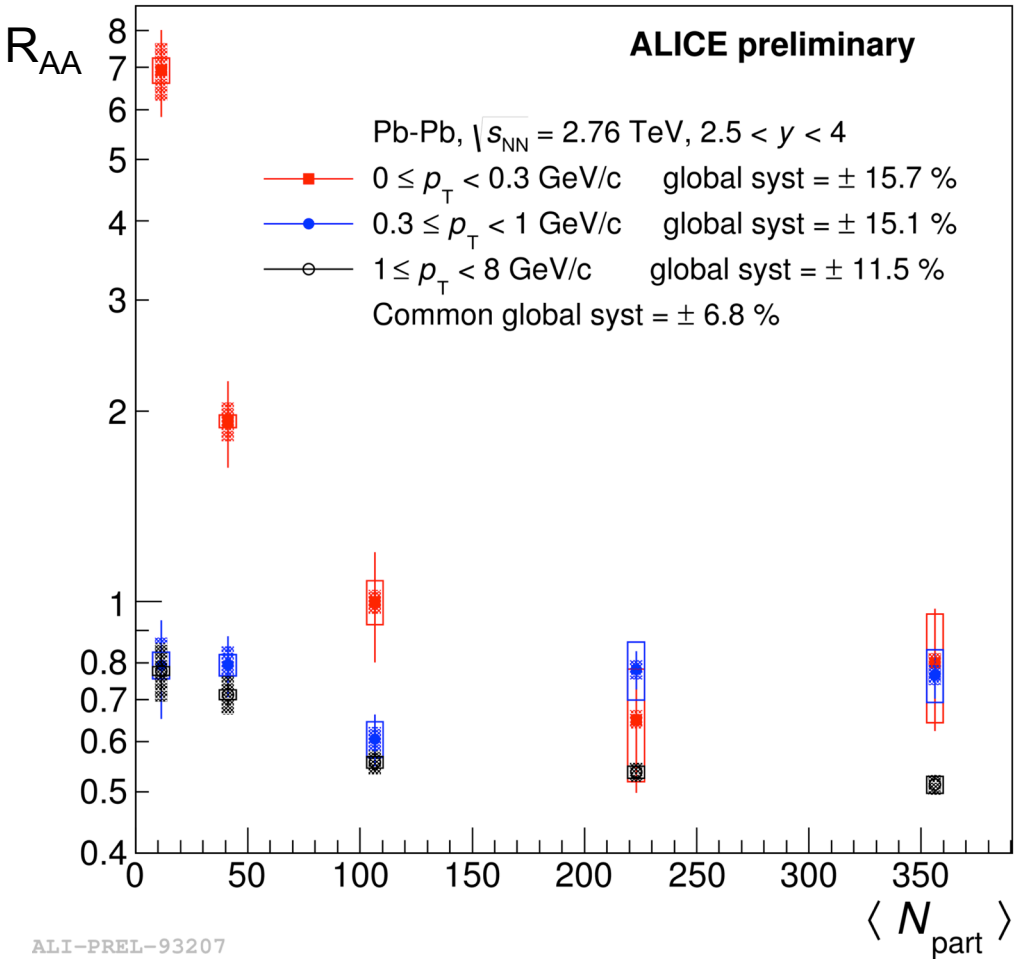
$R_{AA}(1S) = 0.425 \pm 0.029 \pm 0.070$
$R_{AA}(2S) = 0.116 \pm 0.028 \pm 0.022$
$R_{AA}(3S) < 0.14$ (95% CL)



CMS, PRL109 (2012) 222301 and HIN-15-001
STAR, PLB735 (2014) 127 and preliminary U+U

Ordered suppression of the three Y states → Sequential melting
U+U collisions in STAR reaching the same Y(1S) suppression

A curiosity: J/ψ at very low pt…



$R_{AA} \approx 7$! For $p_T < 300$ MeV and peripheral collisions

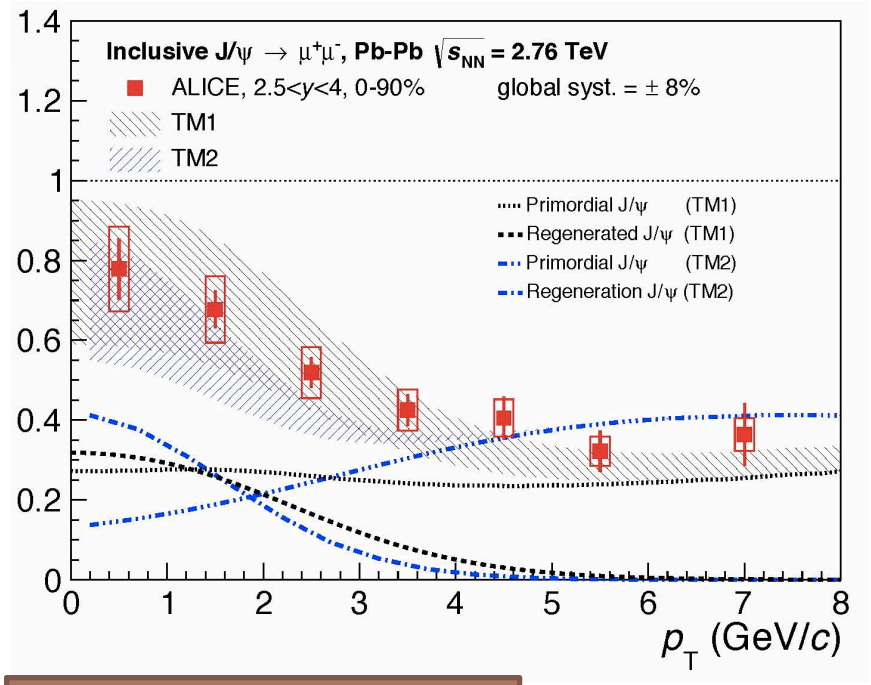
Probably photo-produced, from a photon coupling to the large field of the nucleus

(also seen in "ultraperipheral" non-hadronic collisions)

ALICE preliminary
Lardeux @ HardProbes'15

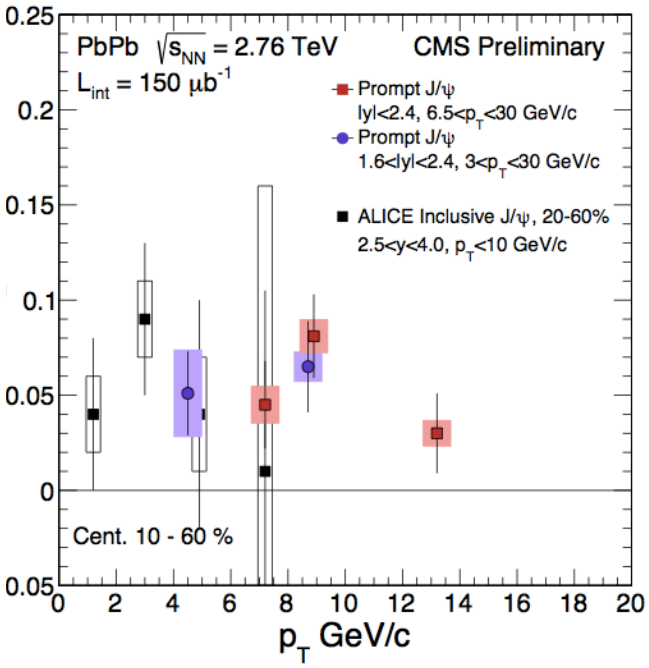
Two more regeneration hints: low p_T and v_2

R_{AA}



ALICE, 1506.08804
Higher p_T in CMS HIN-12-014

v_2

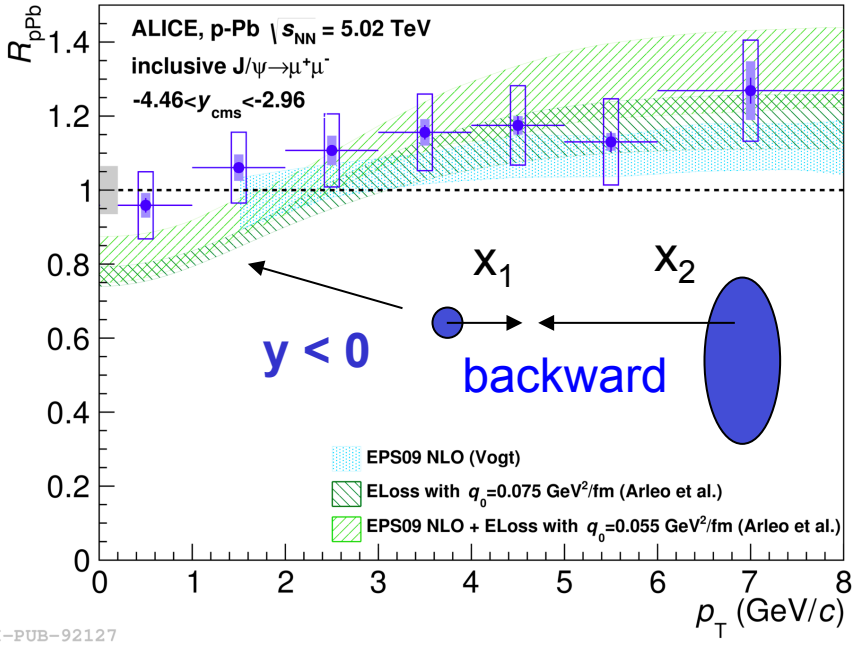


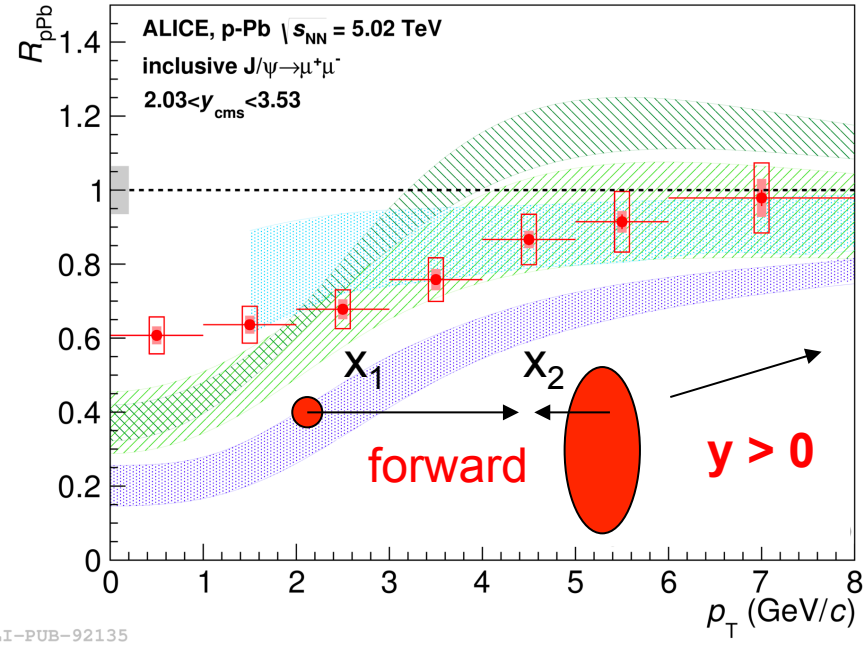
ALICE, PRL111 (2013) 1662301
CMS, HIN-12-001

1/ Less suppression at low p_T, where regeneration is stronger
2/ Some elliptic flow, probably inheriting the charm quark flow…

J/ψ in pPb

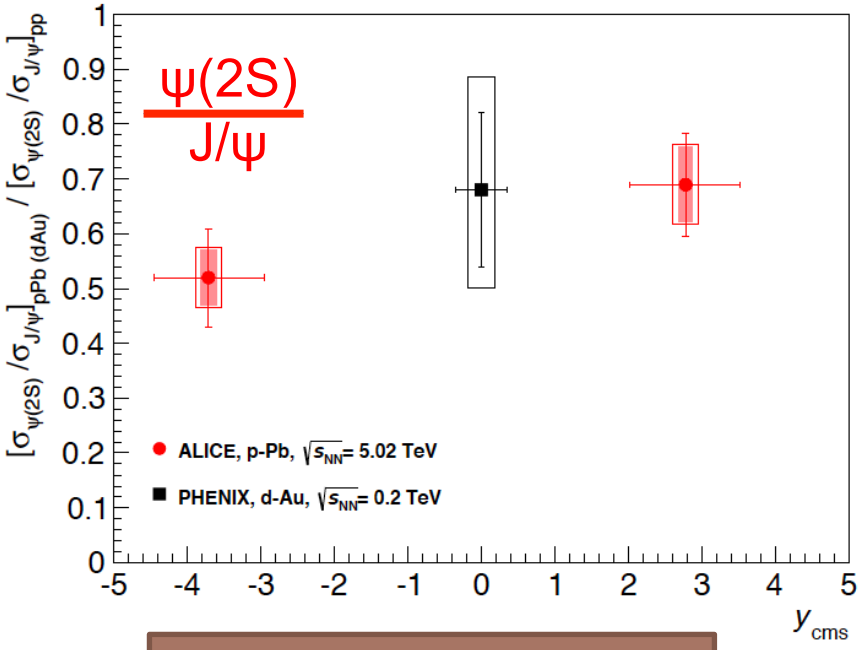
ALICE, 1503.07179
LHCb, JHEP 02, 2014, 072
ATLAS, 1505.08141
CMS, HIN-14-009





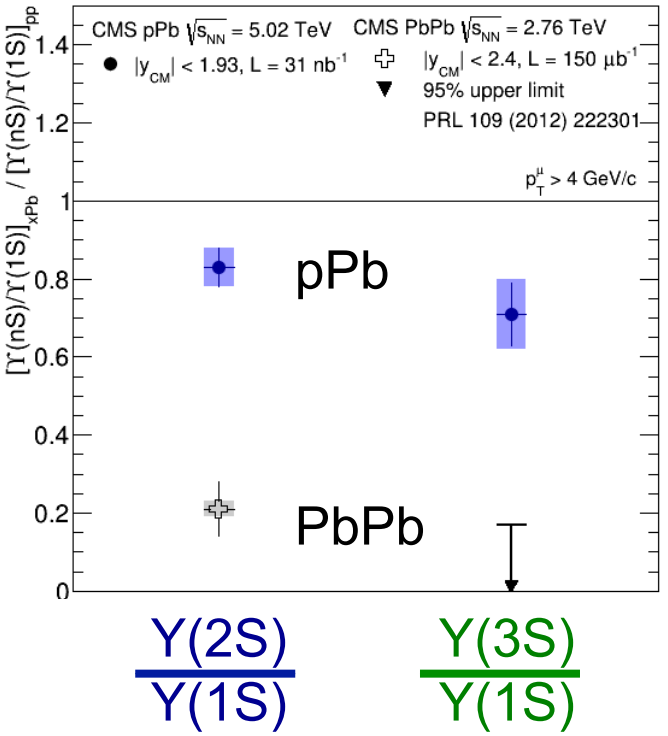
Some suppression observed in the forward (p-going) direction, corresponding to low Bjorken x in the Pb ion (also at RHIC)
Approximately reproduced by nuclear PDF + eloss
Higher pPb suppression → higher PbPb recombination

The fragility of excited states in pPb…



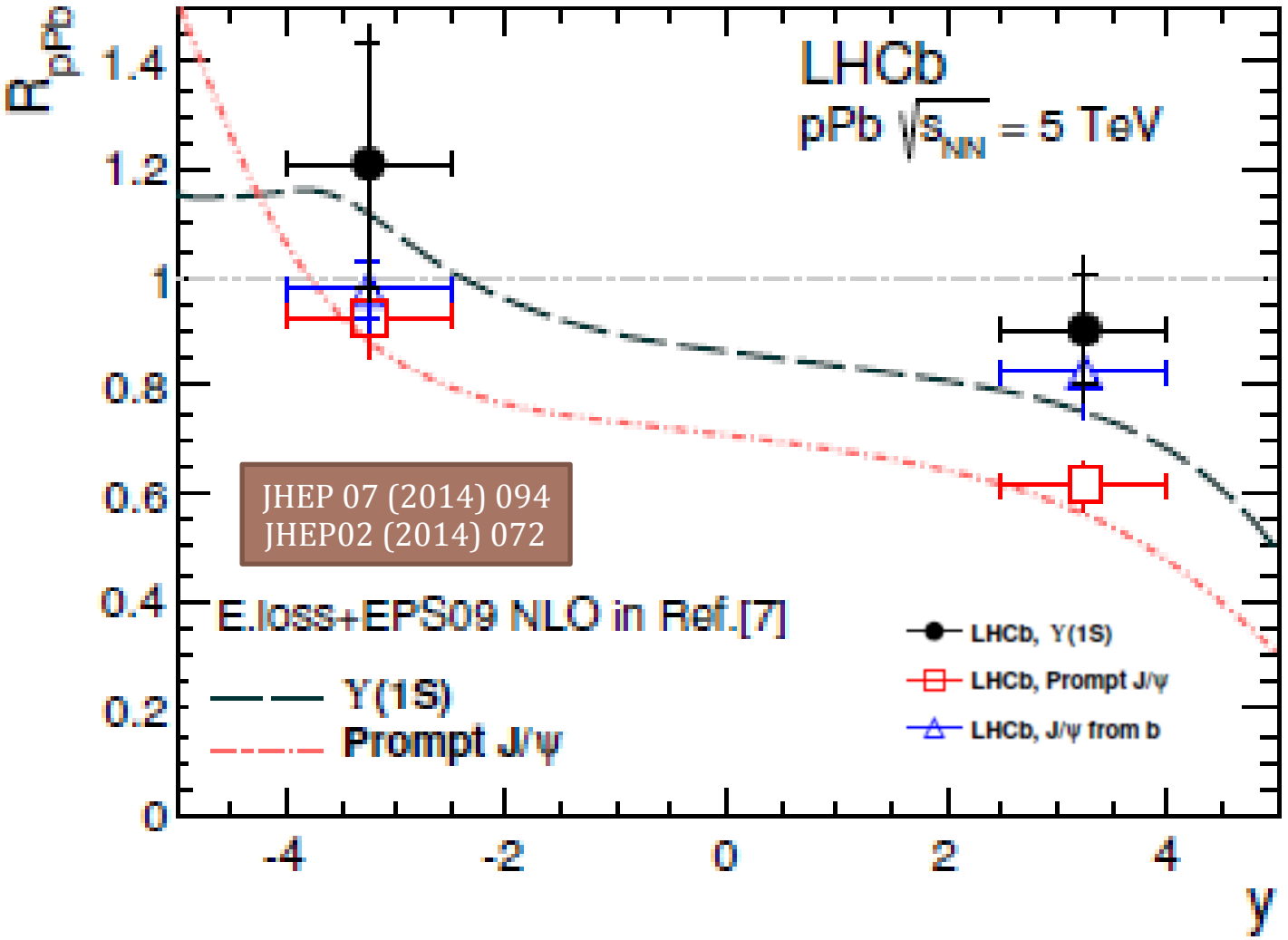
ALICE, 1405.3796
PHENIX, PRL111 (2013) 202301

CMS, JHEP04 (2014) 103

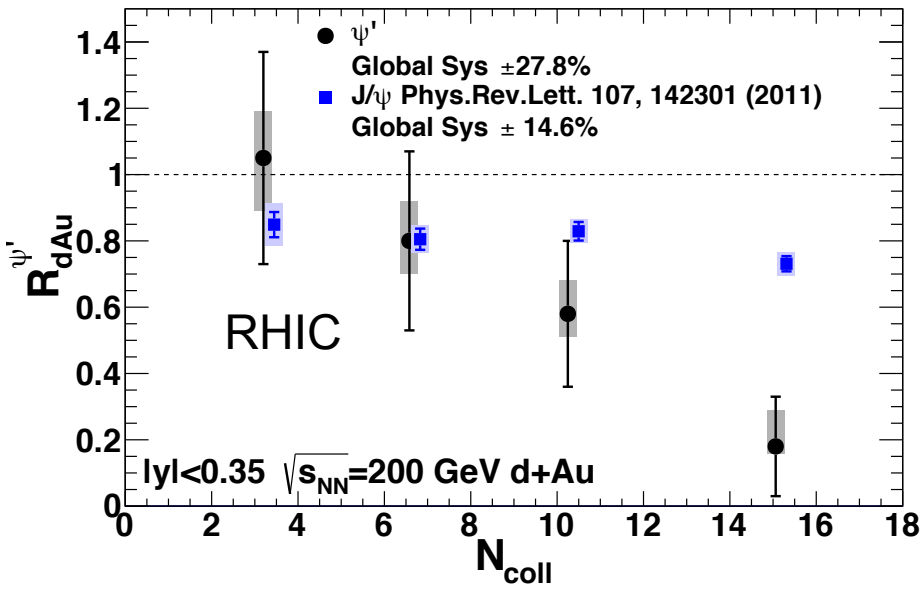


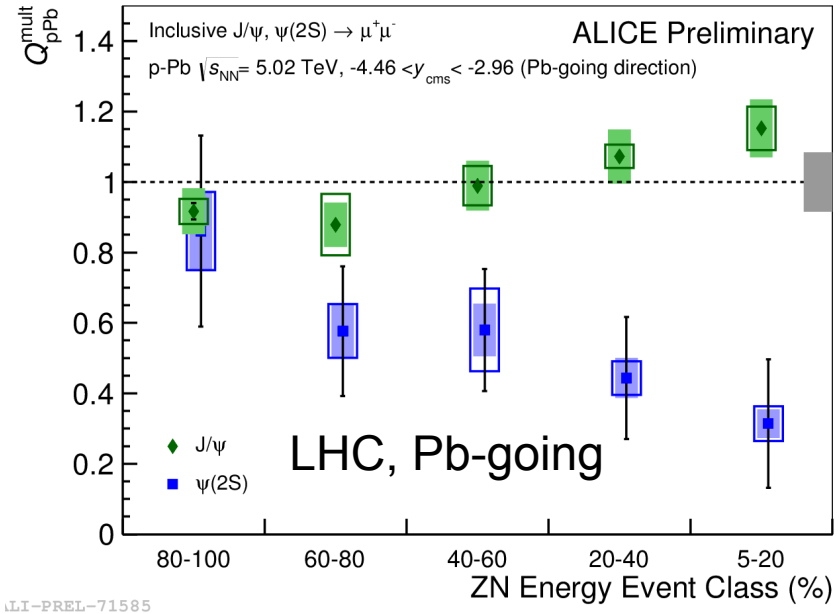
In pA collisions, the excited states suffer more suppression
(but still less than in PbPb collisions in the Y case)
Highly non trivial dependence on the event activity (incl. pp)

LHCb

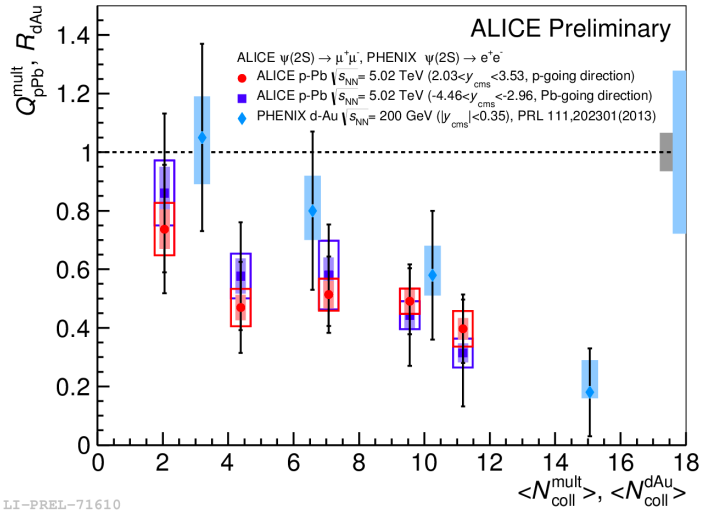

R_{pPb}
LHCb
pPb $\sqrt{s_{NN}}$ = 5 TeV
JHEP 07 (2014) 094
JHEP02 (2014) 072
E.loss+EPS09 NLO in Ref.[7]
Υ(1S)
Prompt J/ψ
LHCb, Υ(1S)
LHCb, Prompt J/ψ
LHCb, J/ψ from b
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-4
-2
0
2
4
y

Ψ(2S) in pPb…





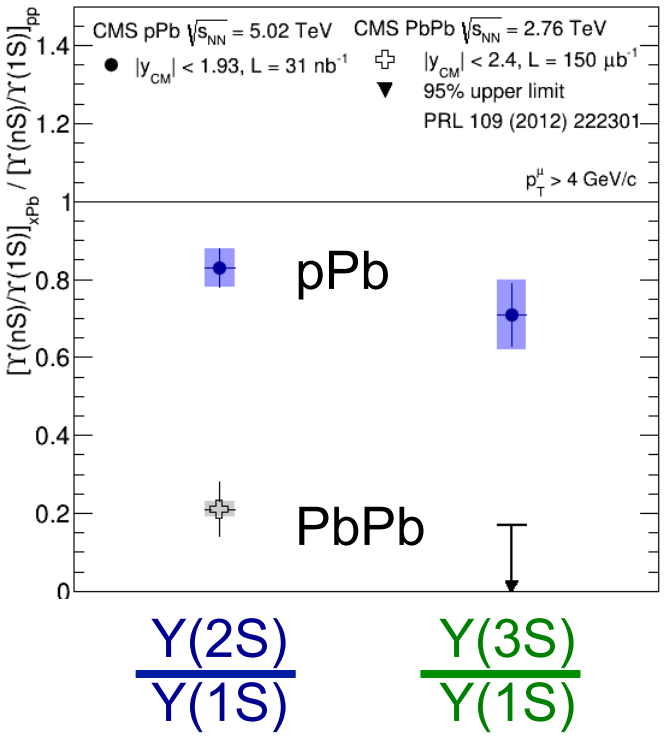
PHENIX, PRL111 (2013) 202301
ALICE, preliminary

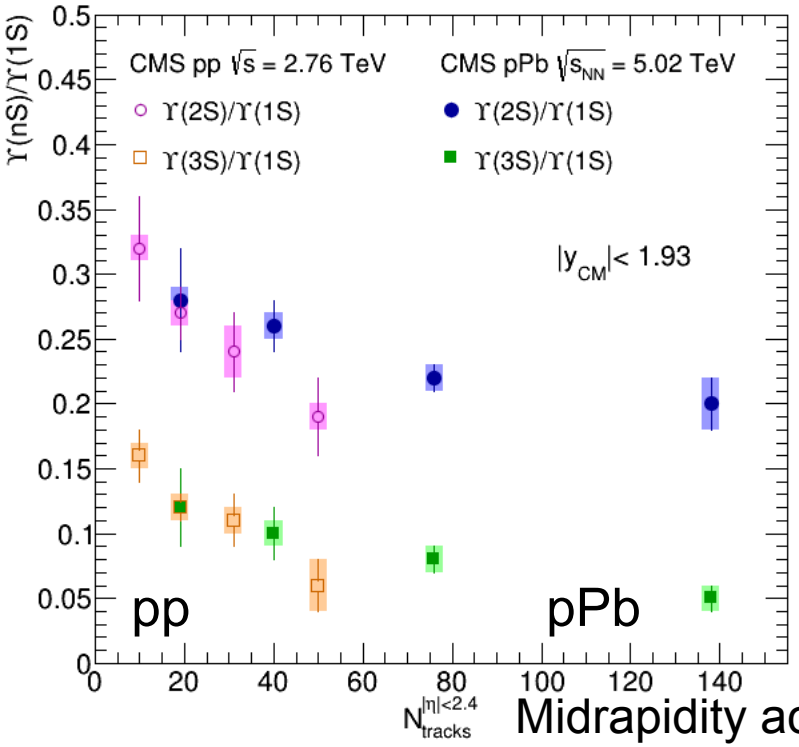


Are the Y(2S) and Y(3S) fragile?

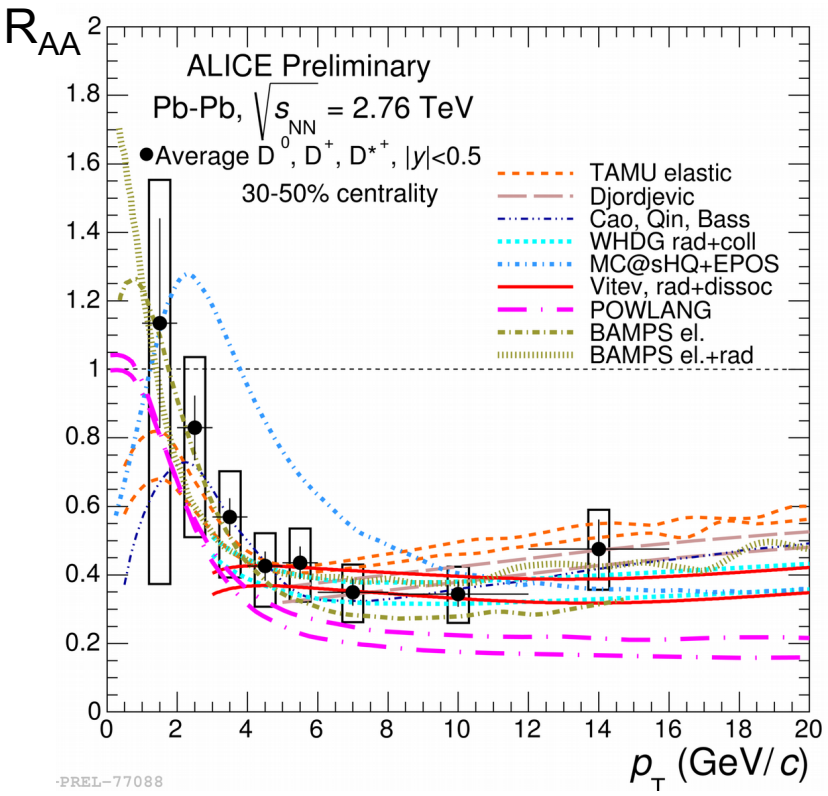
- Excited states less suppressed than in PbPb
- Excited/ground state ratio appears to vary w.r.t. the pPb and pp(!) event multiplicity (at midrapidity)
  - Excited states adding multiplicity?
  - Activity suppressing the excited states?

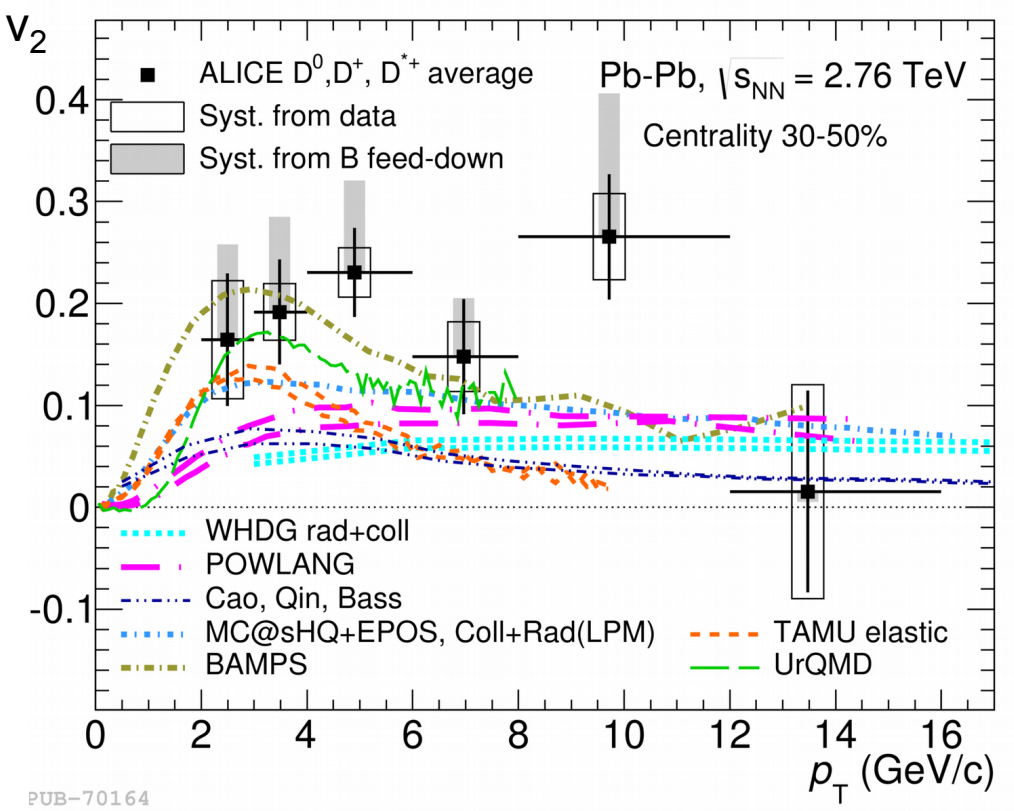
CMS: JHEP04 (2014) 103





Charm also flow @ LHC



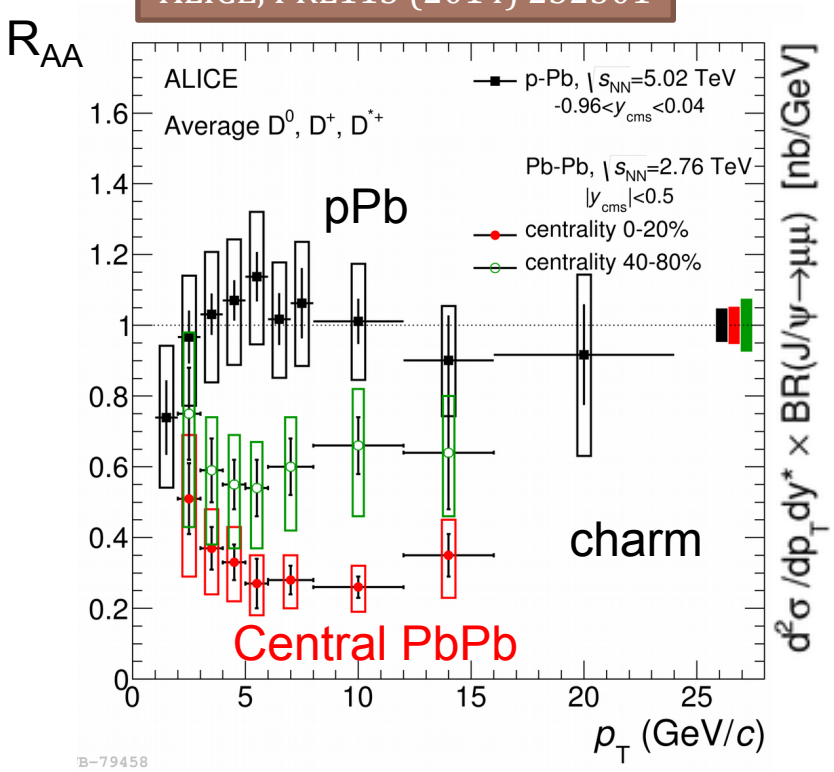


ALICE, PRL111 (2013) 102301

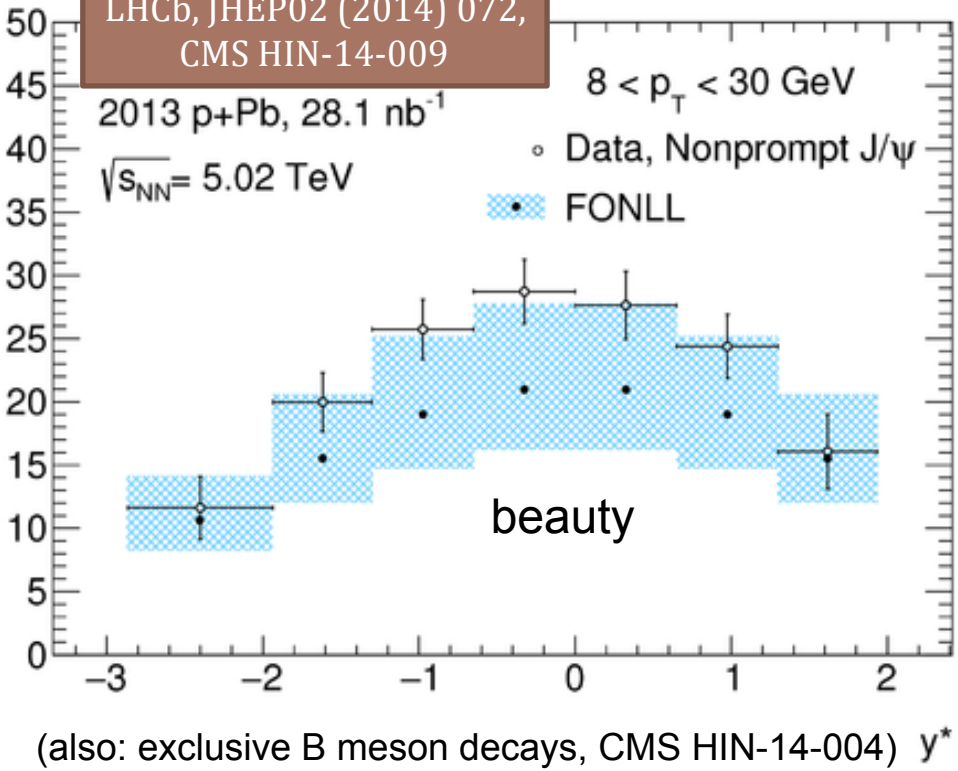
Simultaneous and quantitative description of R_{AA} and v_2 is a challenge for theorists (here @ LHC, but also @ RHIC)

Charm and beauty in pPb @ LHC

ALICE, PRL113 (2014) 232301



ATLAS, 1505.08141, also LHCb, JHEP02 (2014) 072, CMS HIN-14-009

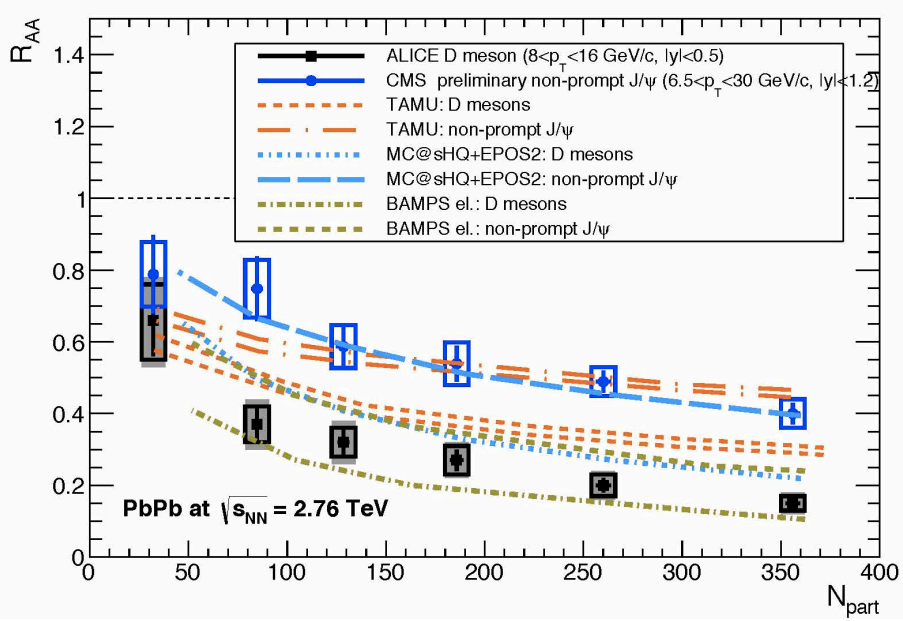


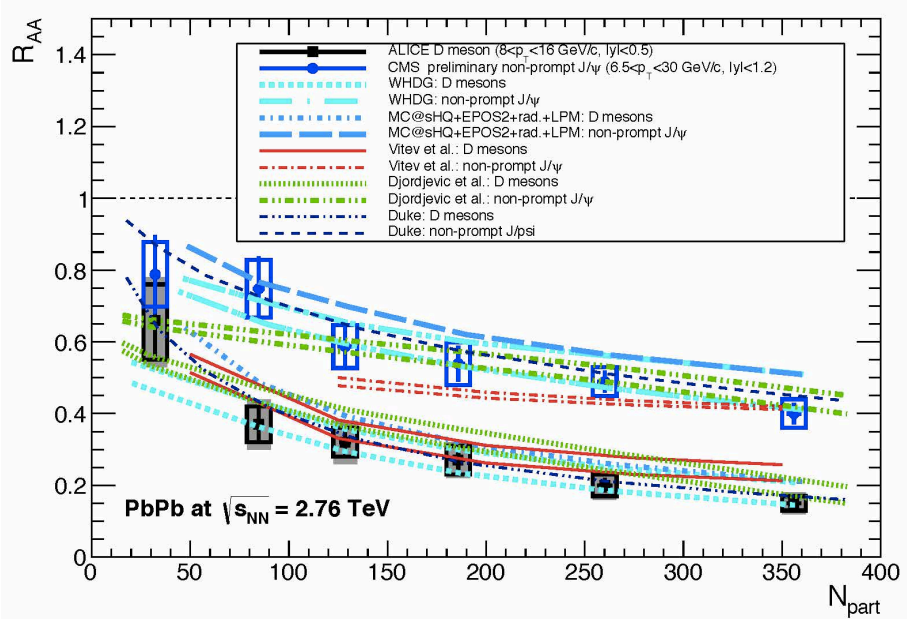
(also: exclusive B meson decays, CMS HIN-14-004)

Large theoretical uncertainty → Need pp reference data @ 5 TeV

But no suppression seen in pPb → final state effect in PbPb

D versus B, more models





Review, 1506.03981