

# Heavy Ion Physics using High Energy Beams

Prospects and Challenges for future experiments using heavy ion collisions with high energy beams at the LHC and perspectives at HL-LHC and beyond

- status of the field
  - opportunities at HL-LHC
  - next generation experiment at HL-LHC
  - HE-LHC, FCC
- } illustrated with examples

originally prepared for European Strategy  
Symposium May 2019



Johanna Stachel, Universität Heidelberg  
18th International Conference on Strangeness in Quark Matter  
10 – 15 June 2019, Bari, Italy

# HL-LHC for heavy ion collisions

## Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

CERN-LPCC-2018-07  
February 26, 2019

Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

**LHC Run3/Run4:** expect  $\mathcal{L}=6 \cdot 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$

PbPb interactions at 50 kHz (levelling) - a typical 1 month PbPb run  $\leftrightarrow 3.1 \text{ nb}^{-1}$   
PbPb  $13 \text{ nb}^{-1}$  or  $10^{11}$  collisions sampled, pPb, lighter ions also discussed



**➔ next: current status and physics program of Runs 3/4**

# Light flavor sector

Analysis of Run1/2 data has consolidated understanding of a standard model for production of light flavor hadrons in heavy ion collisions:

- particle chemistry (integrated particle yields) well described by thermal/statistical model
- $p_t$  spectra indicate kinetic equilibrium, described by thermal motion embedded in common radial expansion, governed by hydrodynamics

# Production of hadrons and (anti-)nuclei at LHC described quantitatively by GC statistical model

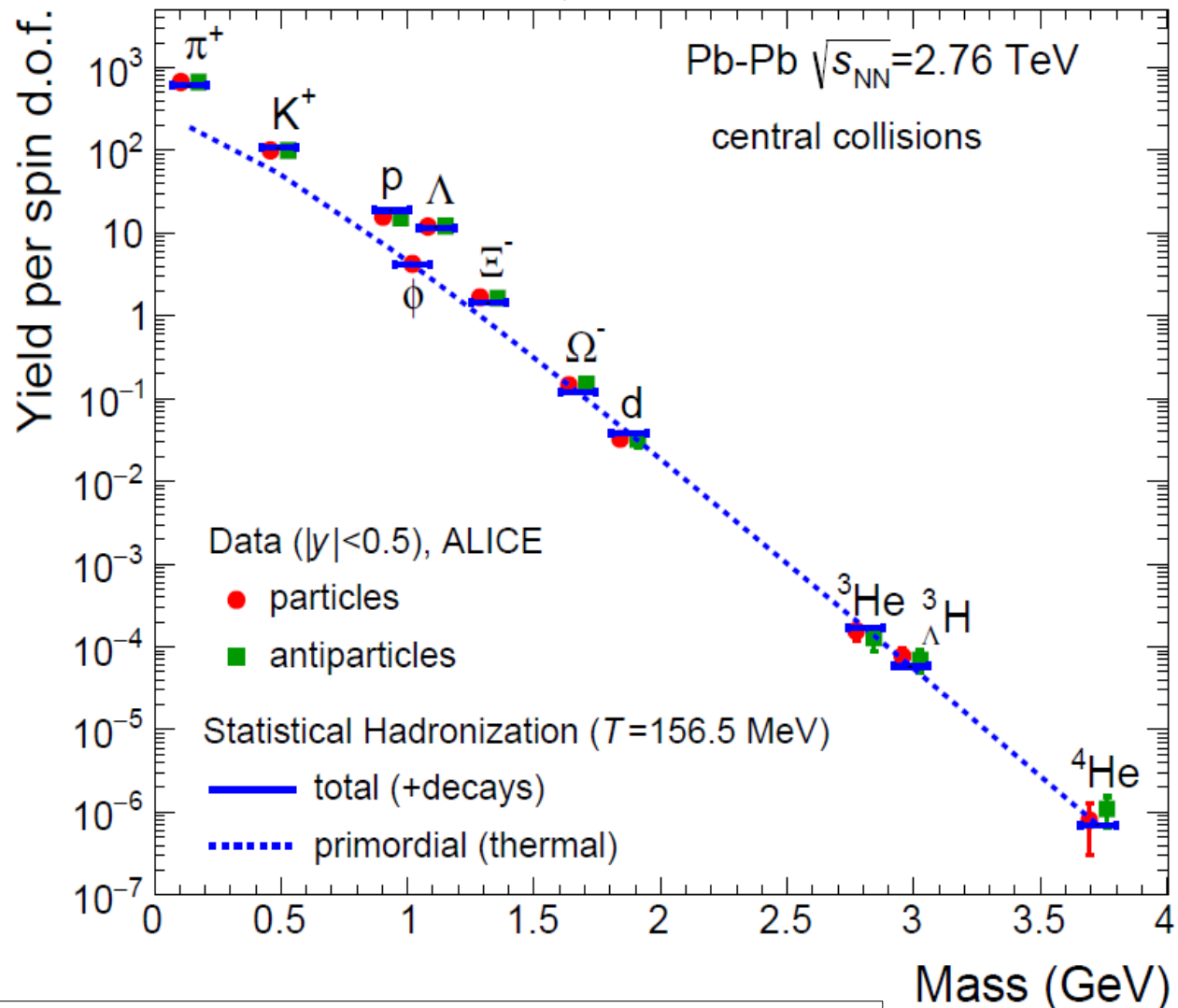
1 free parameter: temperature  $T$   
 $T = 156.5 \pm 1.5 \text{ MeV}$

agreement over 9 orders of magnitude with QCD statistical operator prediction  
 (- strong decays need to be added)

- matter and antimatter formed in equal portions
  - even large very fragile (hyper) nuclei follow the systematics
- suggestion: they are formed as compact multiquark states at hadronization and evolve into their wavefunctions

**needs testing in Run3/4**

A. Andronic, P. Braun-Munzinger, K. Redlich, JS Nature 561 (2018) 321



smooth evolution of yields from pp, pPb to PbPb  
 apparent scaling with multiplicity → backup

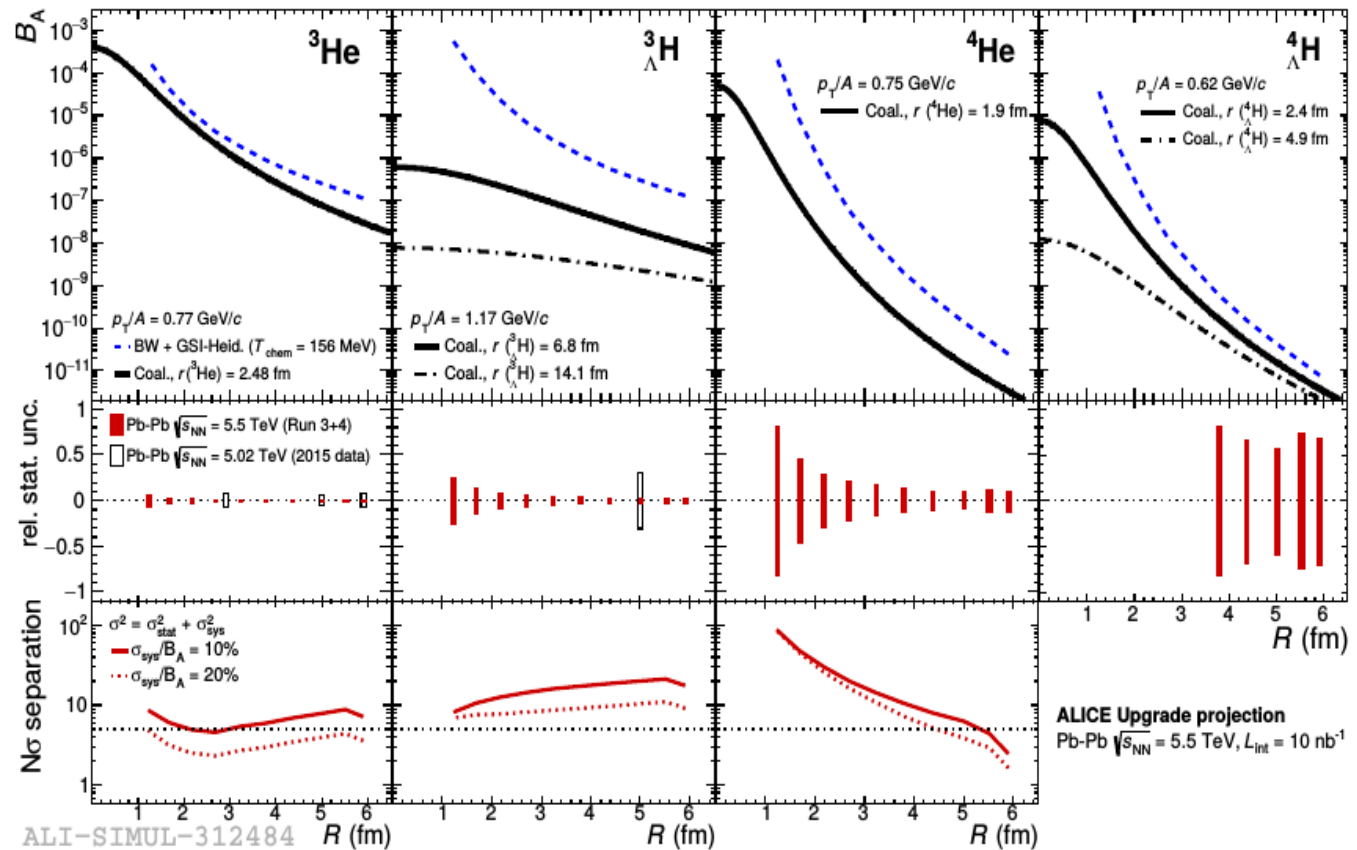


# What to be added?

thermal production vs coalescence not yet settled - question at heart of hadronization  
 utilize very different sizes of (hyper-)nuclei vs radius of fireball

## Run3/4:

- systematic multi-diff meas of  $A = 3,4$  nuclei and hyper-nuclei from small to large systems
- also:
- precision measurement of hypertriton lifetime
- search for  $\Sigma$ -hypernuclei
- exotic QCD bound states

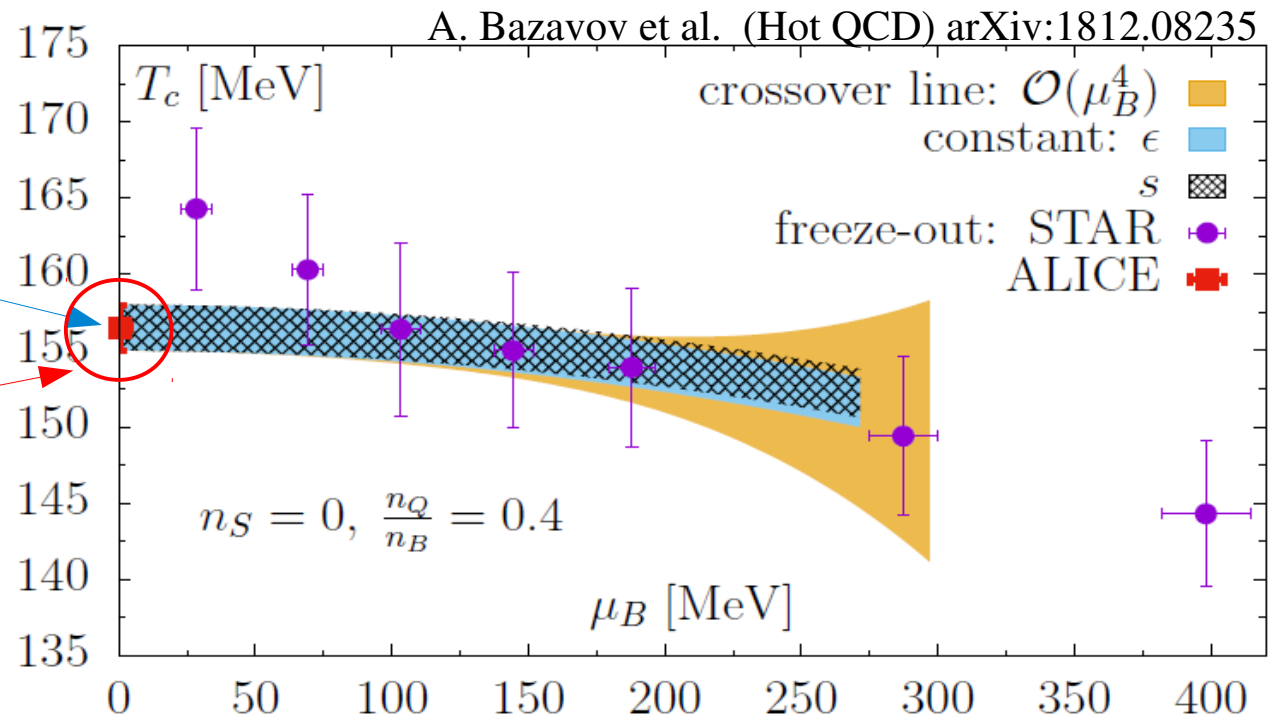


# Pseudo-critical temperature from Lattice QCD

recent breakthrough in IQCD:  
precise determination of pseudo  
critical temp of chiral cross over

$$T_{pc} = 156.5 \pm 1.5 \text{ MeV}$$

in exact agreement with  
chemical freeze out temp  
determined from ALICE data



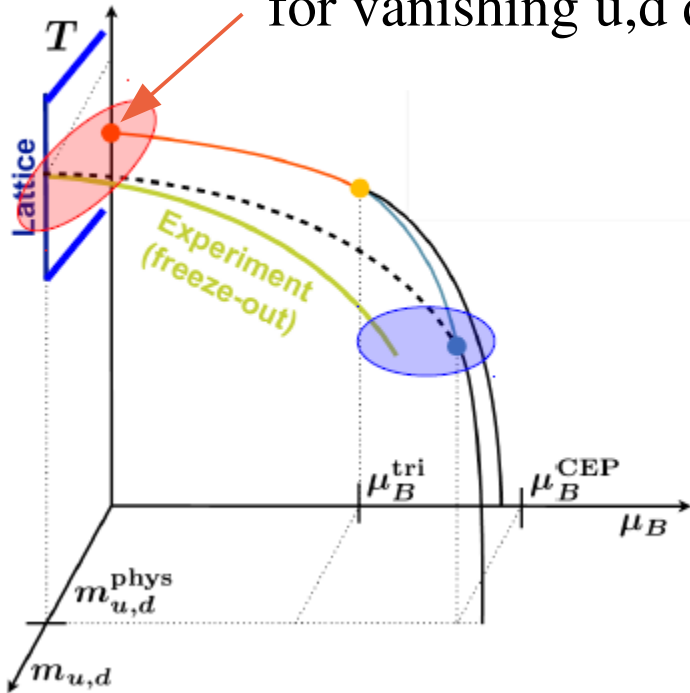
# Nature of the chiral phase transition

for vanishing u,d quark masses, chiral PT conjectured 2<sup>nd</sup> order O(4) univ.

**small u,d quark masses ↔ vicinity to O(4)**

**criticality → pseudo-critical features**

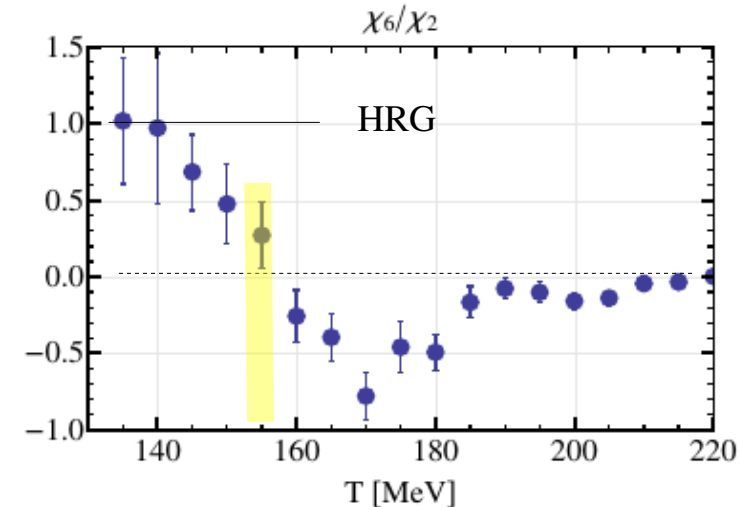
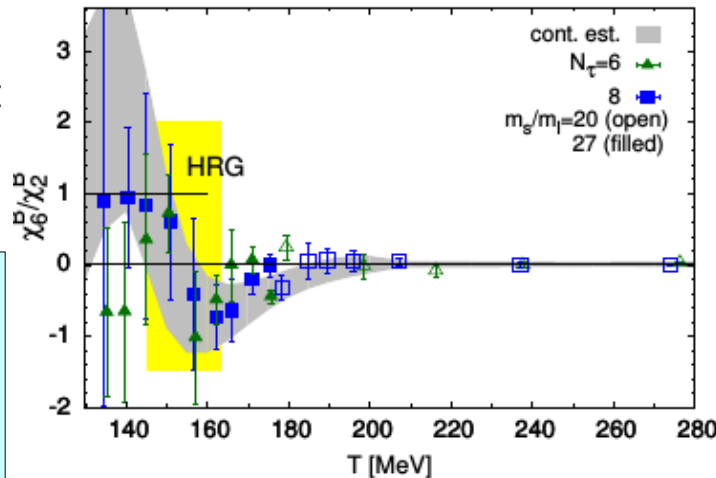
fluctuations linked to critical behavior assoc. with PT  
 measurement of higher order fluctuations of conserved charges: can be directly compared to lattice QCD calculations



$$\chi_{ijk}^{BQS}(T) = \left. \frac{\partial P(T, \hat{\mu}) / T^4}{\partial \hat{\mu}_B^i \partial \hat{\mu}_Q^j \partial \hat{\mu}_S^k} \right|_{\hat{\mu}=0}$$

cumulants of net baryon distribution

singular contribution to pressure for higher orders: visible starting with 6<sup>th</sup> order susceptibilities  
 measure in **Run3/4** up to 6<sup>th</sup> moment of net proton distrib. ↔ holy grail



# Shear and bulk viscosities of the QGP

relativistic hydrodynamics very successful in describing spectra and correlations, azimuthal anisotropies  
**paradigm of QGP as nearly ideal fluid** → determination of macroscopic properties of QGP fluid

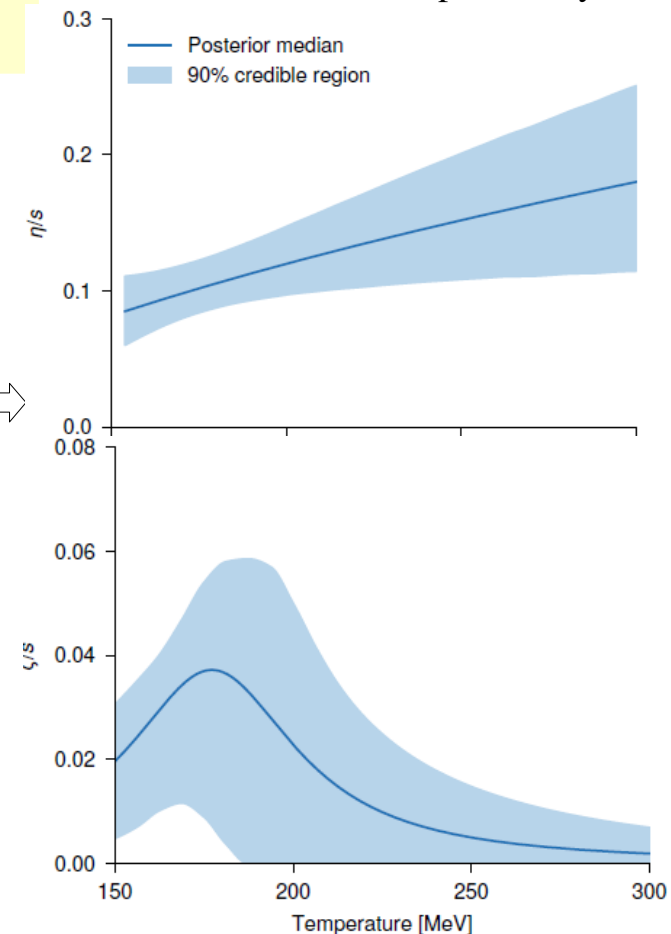
lesson of past decade: cannot be decoupled from description of initial state and mechanism of rapid therm. role of thermal fluctuations! role of strong initial fields? vorticity?

current state of the art

## program for Run3/4:

- stringent tests of collective dynamics via
- high-statistics particle-identified flow meas.
  - system size dependence of flow
  - longitudinal flow fluctuations

J.E. Bernhard, J.S. Moreland, S.A. Bass  
Nature, in print, May 2019

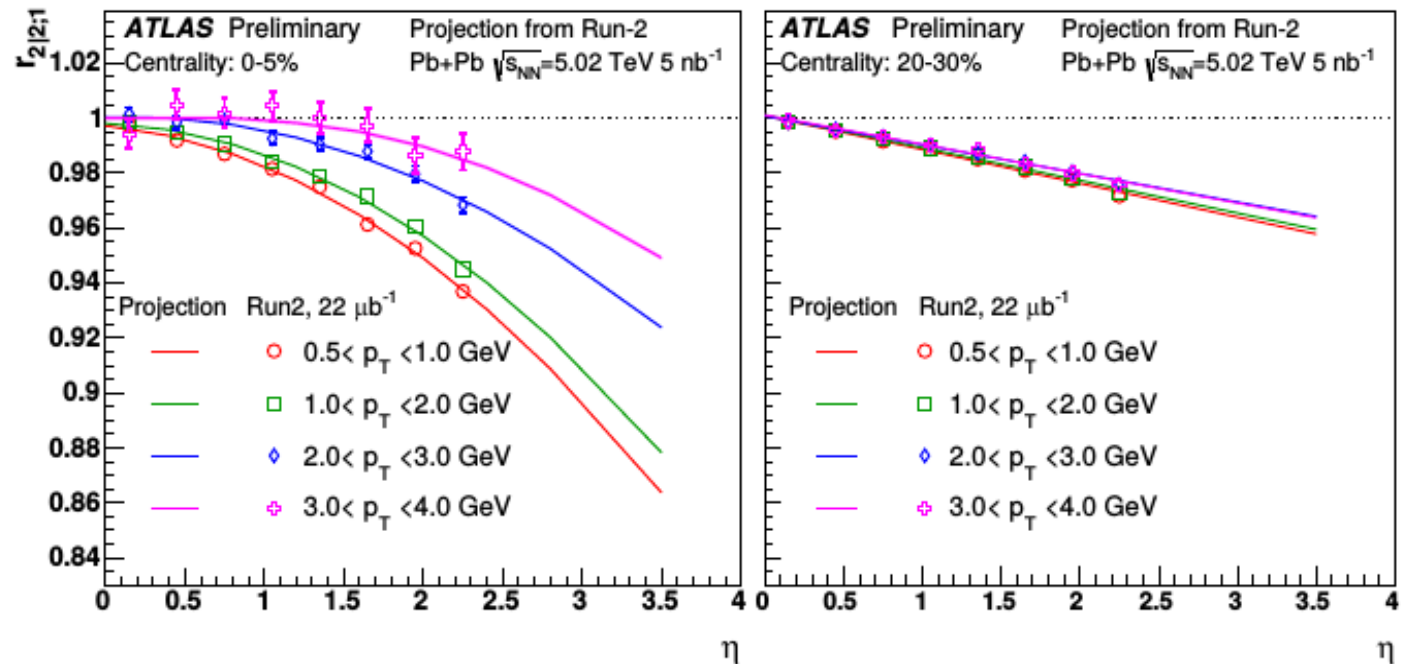


# Flow decorrelation

related to time evolution of matter

$r_{n|n;1}(\eta) = \frac{\langle \mathbf{v}_n(-\eta) \mathbf{v}_n^*(\eta_{\text{ref}}) \rangle}{\langle \mathbf{v}_n(\eta) \mathbf{v}_n^*(\eta_{\text{ref}}) \rangle}$ 
 measures relative difference between flow at  $\eta$  and  $-\eta$   
 flat equal unity for boost invariant scenario  
 decorrelation in data, faster in more central collisions

**Run4:** significant improvement due to increased tracking acceptance in ATLAS sensitivity to e-by-e fluctuations of initial energy density profile in long. direction





# Limits on the chiral magnetic effect

local parity violation in QCD possible due to non-trivial gluon field configurations (instantons, sphalerons) → imbalance between number of left- and right-handed quarks should manifest itself in charge dependent 3-particle correlator  $\gamma_{\alpha\beta} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_2) \rangle$

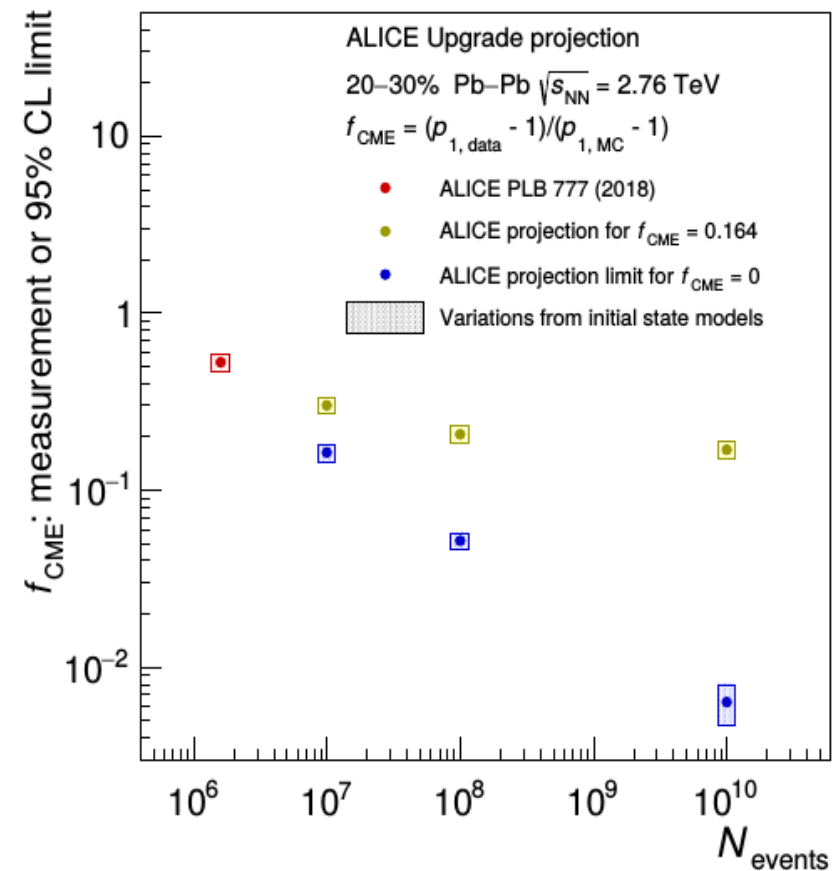
**Run2:** ALICE and CMS determine the CME contribution to  $\gamma_{\alpha\beta}$

ALICE 20-30% central: 16.4 %, but also consistent with 0

upper limit 10-50% central: 29 %

CMS 30-60% central: 7%

**Run3/4 with  $10 \text{ nb}^{-1}$  will settle question**



# Open heavy flavor

formed early in collision in hard scatterings, timescale  $1/2m_q$ , pQCD,  
in QGP energy loss by gluon radiation and elastic collisions

## Run1/2:

charm quarks largely thermalize in QGP until hadronization (spectra and flow)  
much less known about beauty quarks, energy loss is less

## Run3/4: will open new precision era for heavy flavor measurements

**increased statistics plus upgrades of tracking detectors**

**(for ALICE and LHCb after LS2, for ATLAS and CMS after LS3)**

### goals:

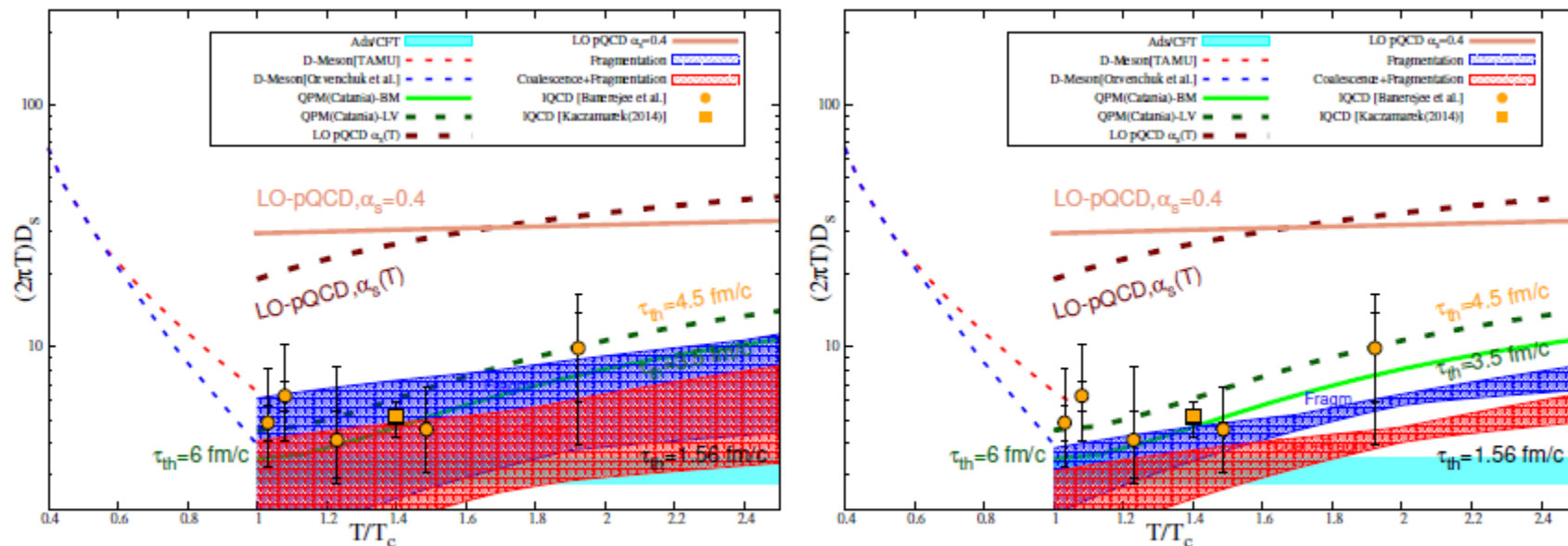
spectra and flow harmonics for mesons and baryons with c and b covering a  
large kinematic range down to  $p_t = 0$

→ total charm cross section in PbPb

- do abundances of charmed hadrons follow statistical hadronization?
- similar questions about stat. hadronization vs coalescence as for nuclei
- transport coefficients vs temperature

# Charm quark spatial diffusion coefficient $D_s$

equilibration time of heavy quark given by diffusion coefficient:  $\tau_Q = \frac{m_Q}{T} D_s$   
 from simultaneous fit of spectrum and  $v_2$  as function of  $p_t \rightarrow D_s(T)$

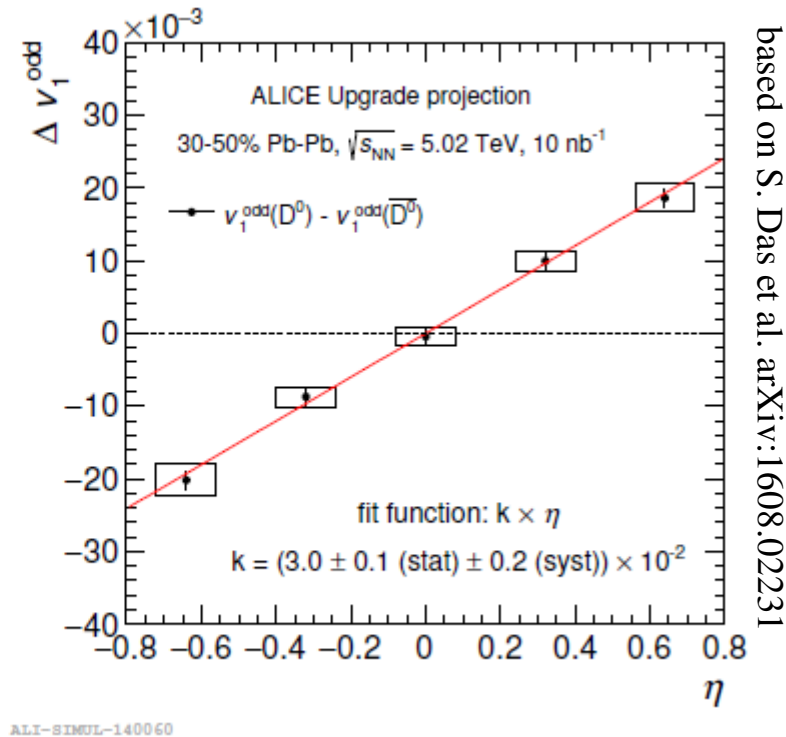
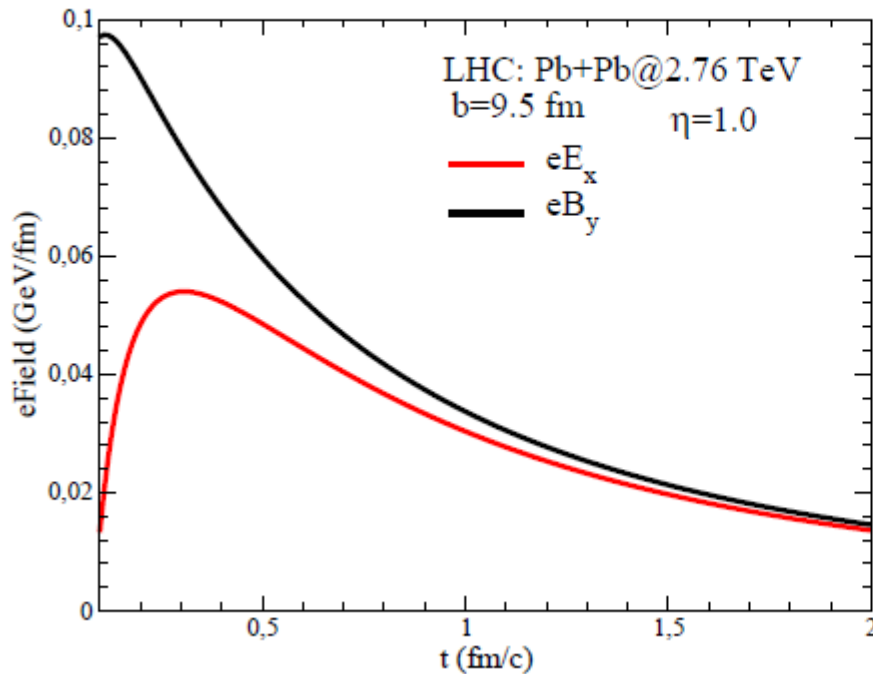


with Run3/4 statistics and combining charmed baryon and meson yields, a significant physics conclusion possible

- very interesting in era where precision QCD computations possible (lattice and funct. methods)

# Sensitivity to extremely strong initial fields

strength of B-field maximal at time when  $c\bar{c}$  pairs are formed  
 Lorentz force gives kick in x-direction (opposite for  $c$  and  $c\bar{c}$ ), if not wiped out during thermalization, visible as azimuthal anisotropy of D-mesons  
 effect much bigger than for light hadrons



measurable effect in Run3/4

# Jets and parton energy loss

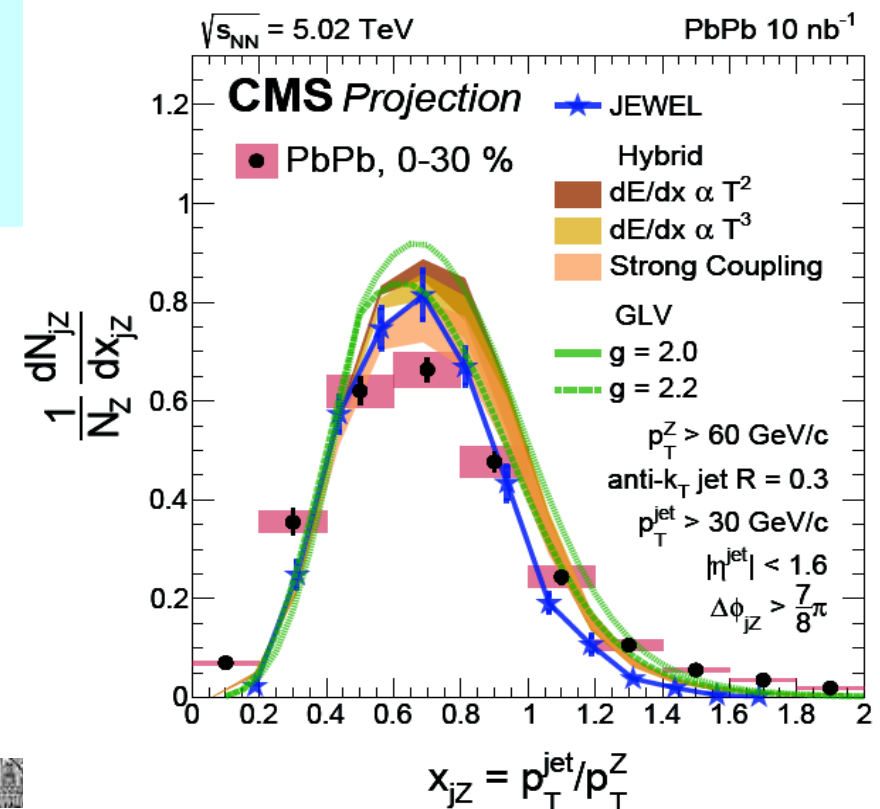
consensus after Runs 1/2: strong energy loss of partons in color dense medium (QGP) characterized by a transport coefficient  $\hat{q} = 1.9 \pm 0.7 \text{ GeV}^2/\text{fm}$  (at  $T = 470 \text{ MeV}$ )

- 2 oom larger than in cold nuclear matter!
- up to very high  $p_t$ , out-of-cone radiation leads to suppression by factor 2

**Run3/4:** factor 20 more statistics  $\rightarrow$  many (novel) jet observables can be confronted with models  
determine medium parameters,  
medium response as well as jet properties

example: Z-tagged jets allow to distinguish fine detail of quark energy loss

for jet observables an argument in favor of lighter beams has been made

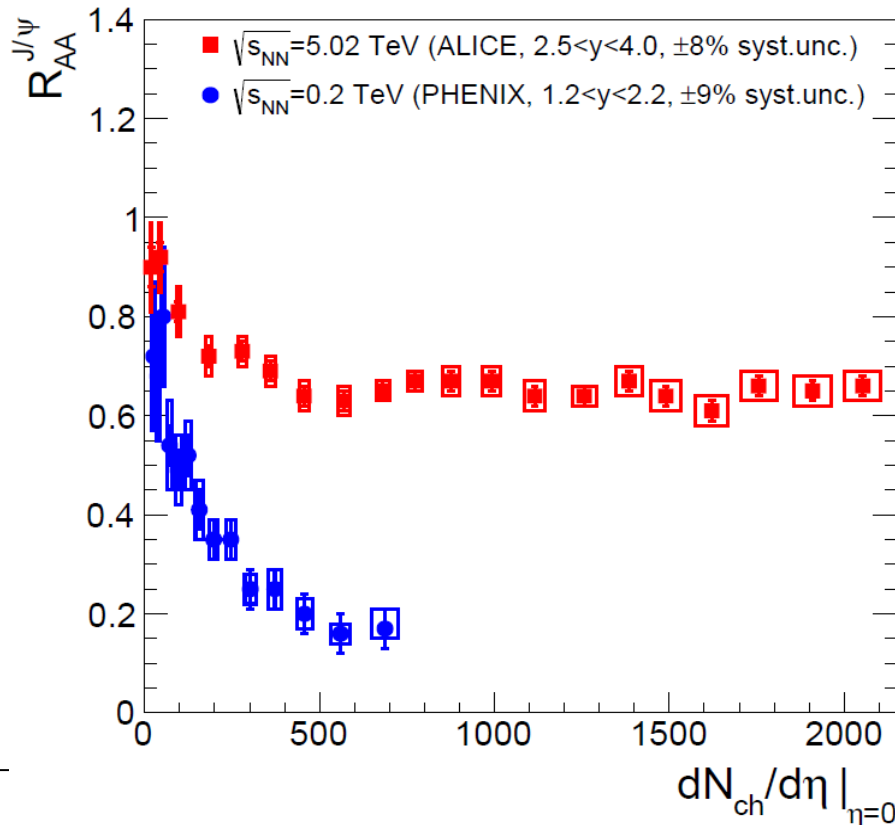
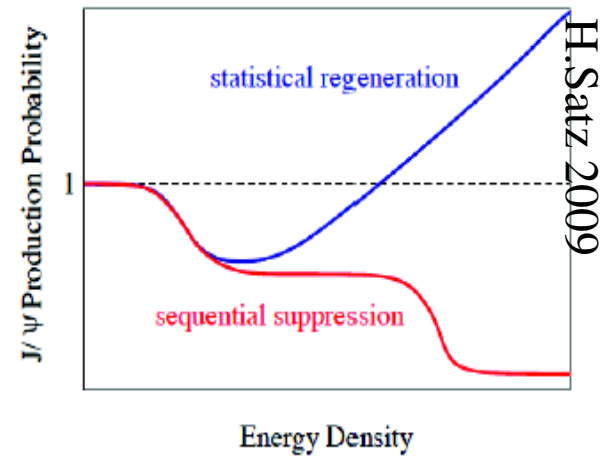




# Charmonia – Debye screening in QGP

after SPS and RHIC two possibilities for LHC:

1. Debye screening leads to nearly complete suppression of all charmonia
2. deconfined charm quarks form new quarkonia at hadronization, even more than were dissolved.

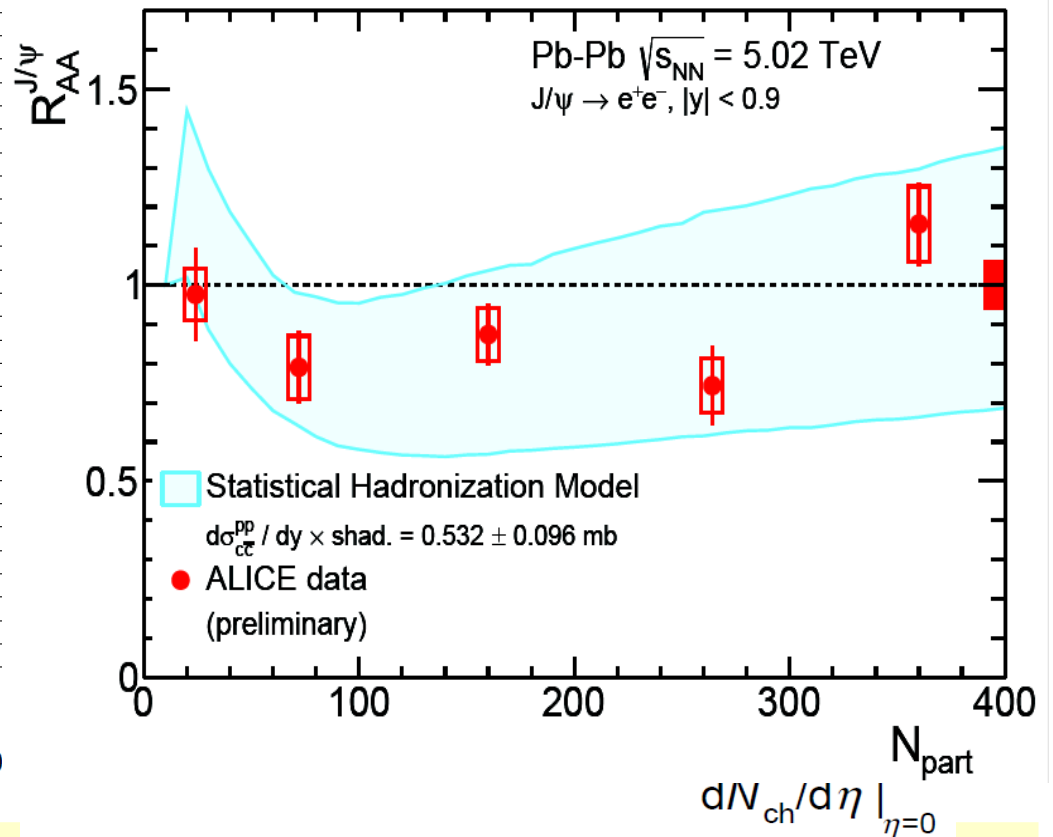
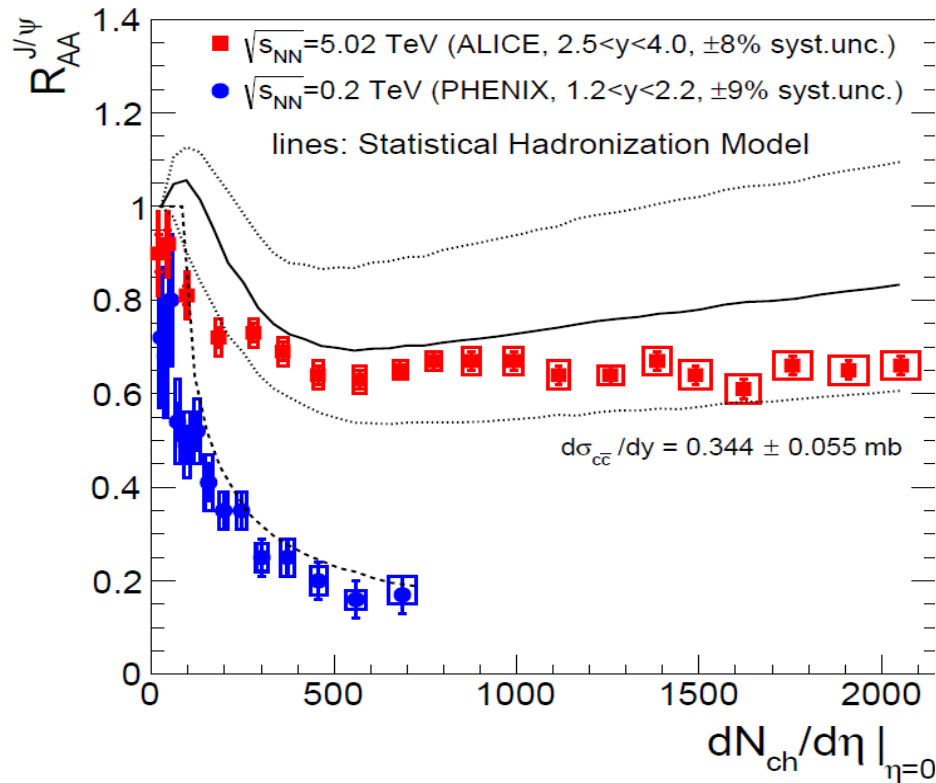


← unambiguously answered by the data

**Run1/2:** biggest qualitative difference to lower energies!



# J/ψ and statistical hadronization

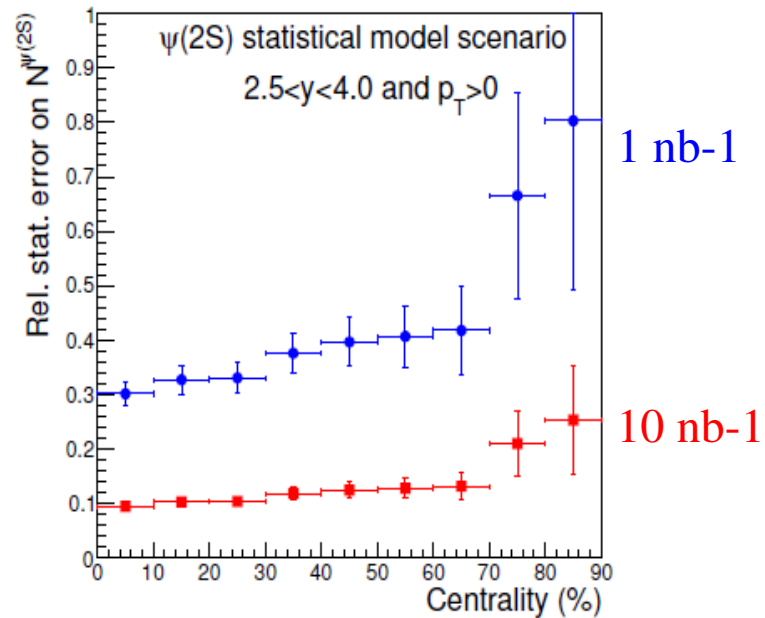
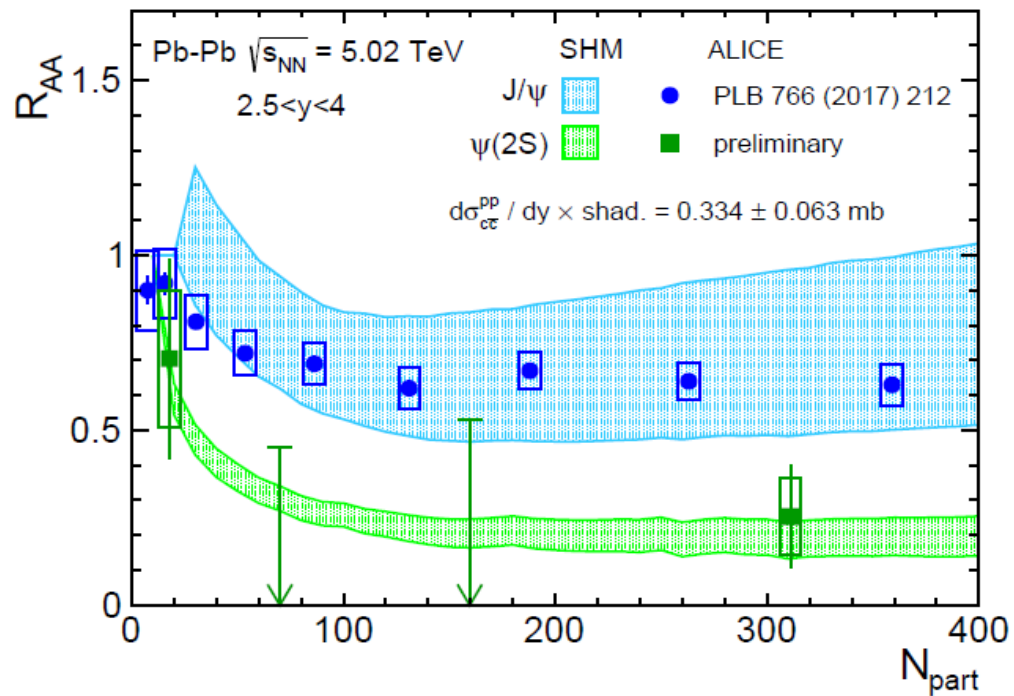


production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization - works also for differential distributions  
 - not unambiguous yet due to large uncertainty in open charm cross section in PbPb (cf continuous destruction and reformation in QGP)

**this is not a detail, but at the heart of a fundamental understanding of hadronization and confinement! colorless bound states in QGP???**

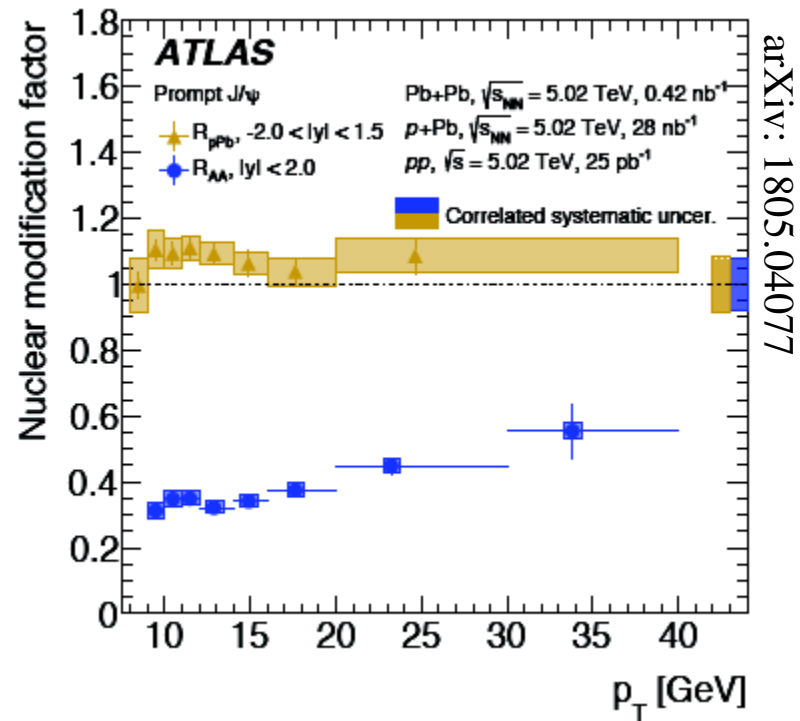
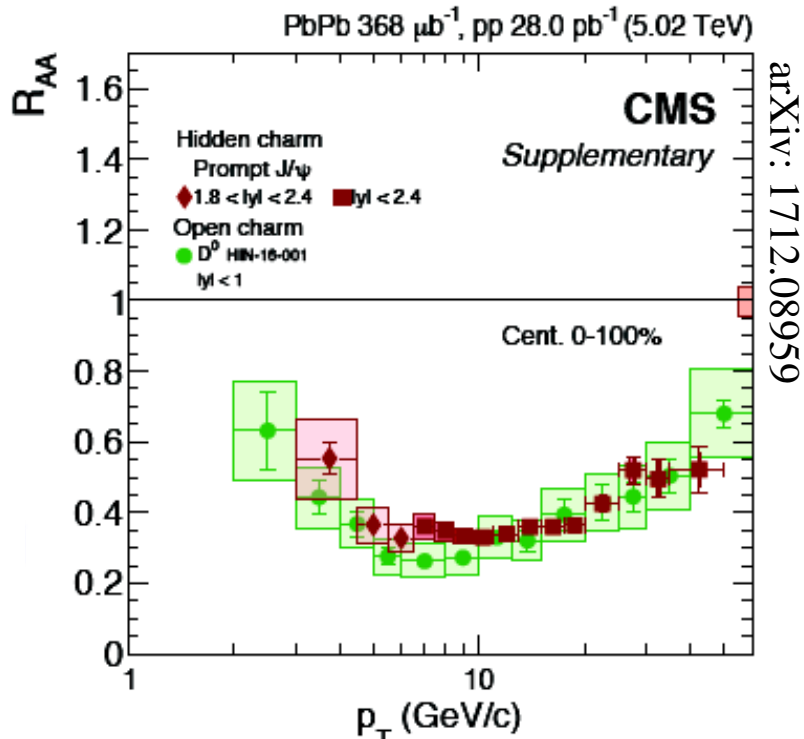
# Open issues and program Run3/4 charmonia

- yields of charmed mesons and baryons in PbPb, open charm cross section to 5 %
- precision spectra and azimuthal distributions
- excited state population



**ambiguities between models will be resolved by Run3/4 data**

# J/ψ interesting physics at high p<sub>t</sub>



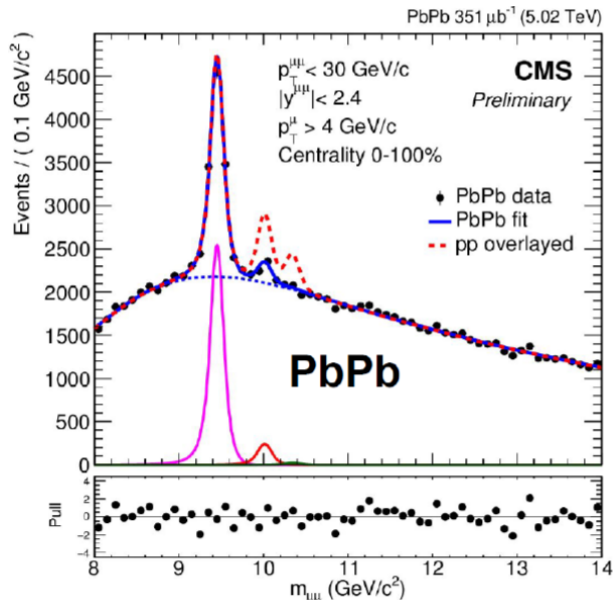
prompt J/ψ suppression in PbPb collision –  $R_{AA}$  rising at high  $p_t$   
 same shape and magnitude as charged particles and as D-mesons

J/ψ from gluon fragmentation? Interesting hints from D and J/ψ

fragmentation functions in pp (ATLAS and LHCb)

**Run3/4: Measure J/ψ in jets in pp and PbPb**

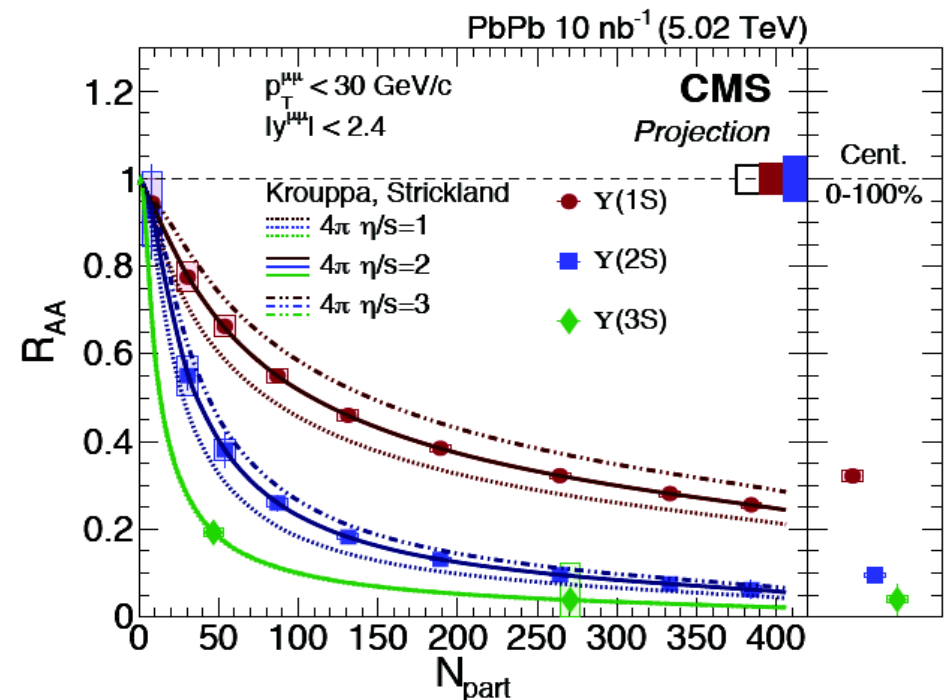
# Bottomonia - sequential melting vs statistical hadronization



**Run1/2:** all Upsilon states strongly suppressed in central PbPb collisions

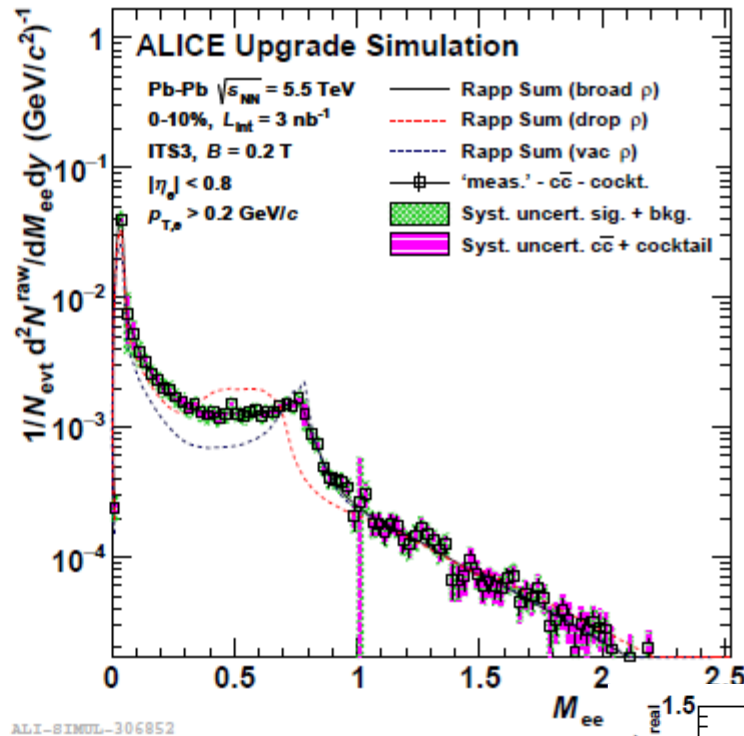
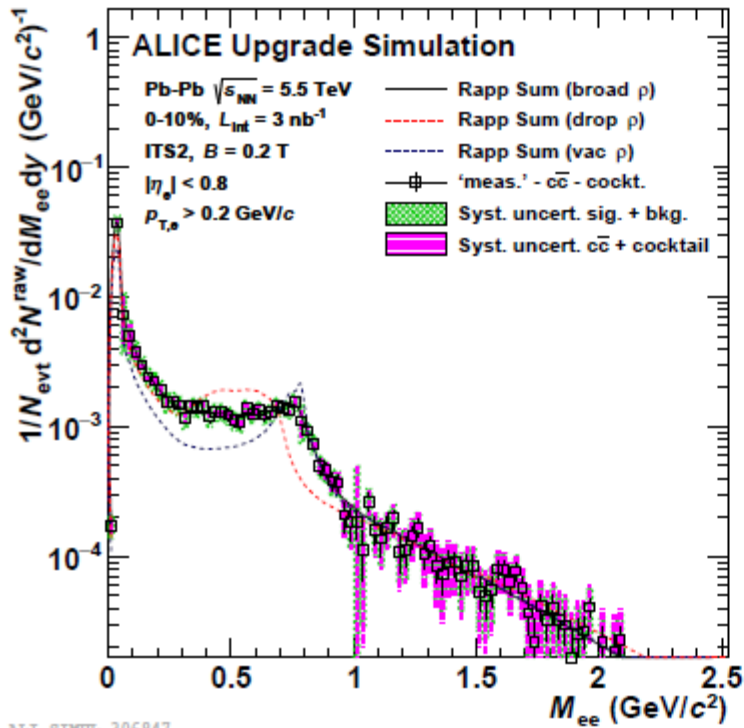
1S: 1/3    2S: 1/10    3S: unmeasurable

**Run3/4:** significant measurement up to 3S in all 4 expts. will be sensitive even at level of Boltzmann suppression



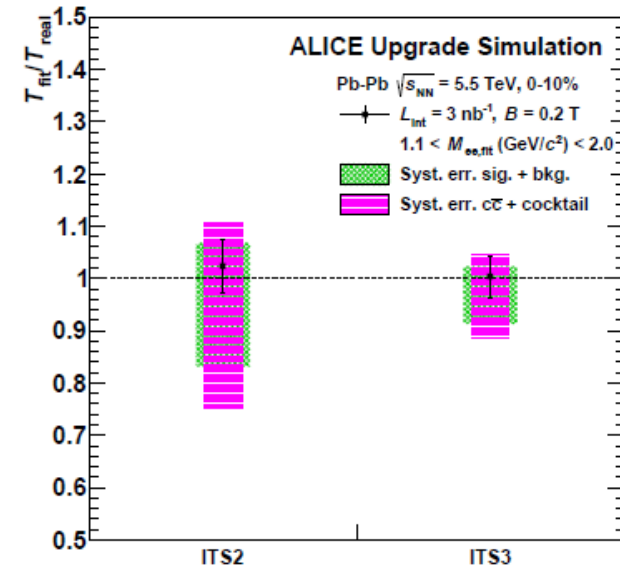


# Low mass di-leptons: chiral symmetry restoration and temperature of QGP



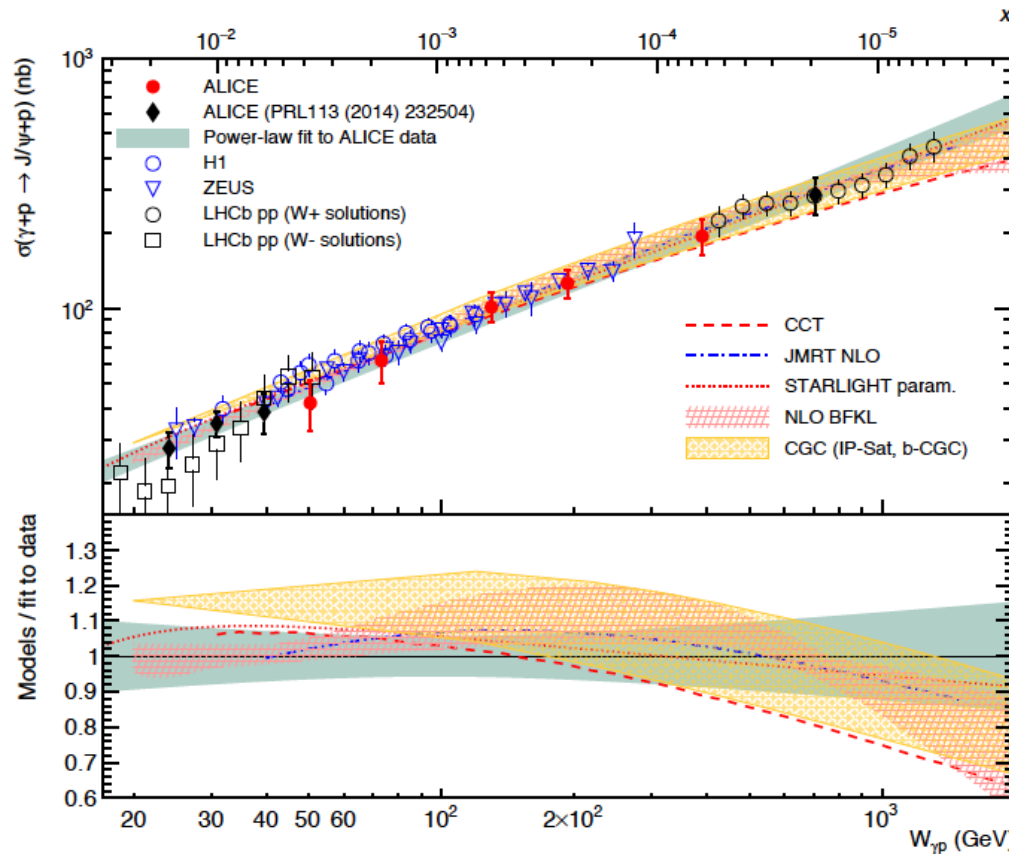
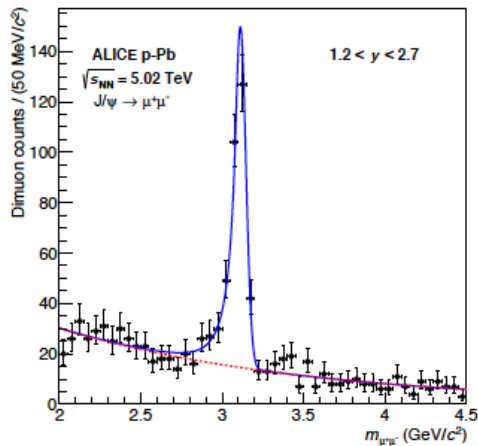
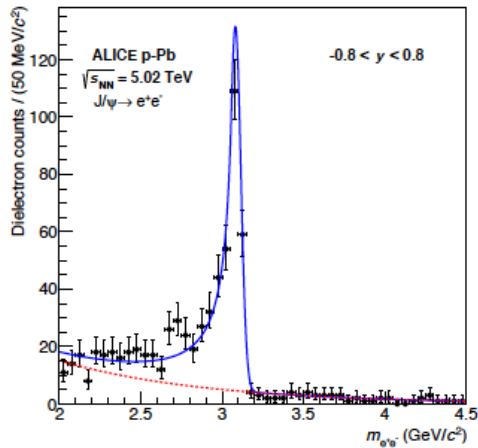
ITS3 in Run4  
see below

- chiral symmetry restoration: line shape of  $\rho$  meson
  - thermal radiation: slope for  $m_{ee} = 1.1 - 2.5$  GeV (after subtracting heavy flavor decay component) also to be measured via real photons
- will be accessible with precision in Run3/4 of LHC**



# Energy dependence of exclusive J/ψ photo prod. in ultra-peripheral pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

data from ALICE and LHCb follow power law of photo-production cross section established at HERA to very low values of  $x = 5 \cdot 10^{-6}$



arXiv:1809.03235

future: more exclusive channels

**window of opportunity for Run3/4: low-x physics at the LHC**

# A next generation LHC heavy ion experiment

Ideas for a new heavy ion experiment for Run5 based on CMOS MAPS capable to:

- handle very high rates for rare probes (heavy flavor, quarkonia, (anti-)(hyper-)nuclei)
- and measure ultra-low  $p_t$  particles

Technological innovation of silicon detectors for a fast and light future experiment

3 key ingredients:

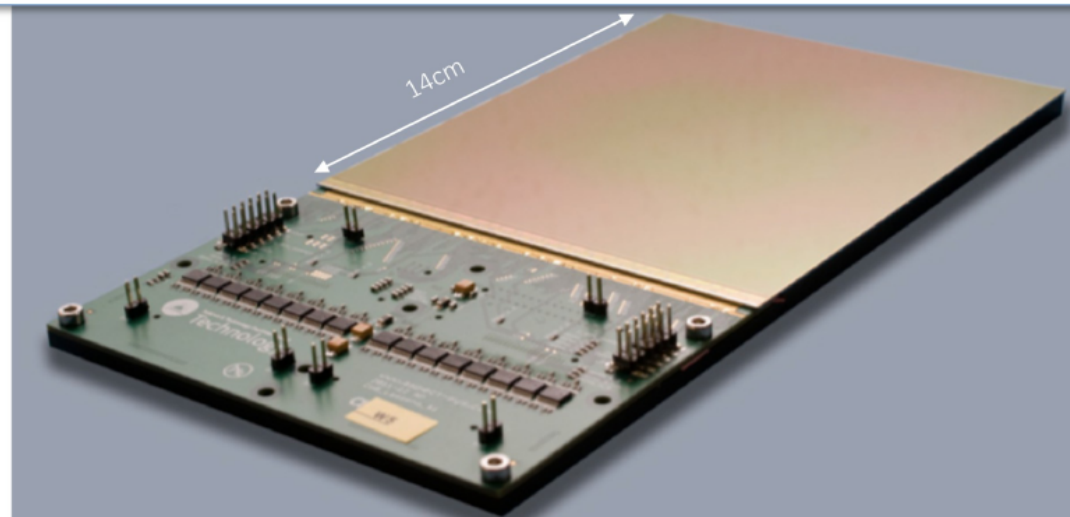
- Thinning of wafers to realize curved silicon chips
- Stitching to fabricate wafer scale sensors
- Ultra-fast CMOS pixels for time-of-flight measurements for PID

*Silicon Genesis: 20 micron thick wafer*



Ultra-thin chip (<50 um): flexible with good stability

Stitching allows fabrication of sensors larger than the reticle size



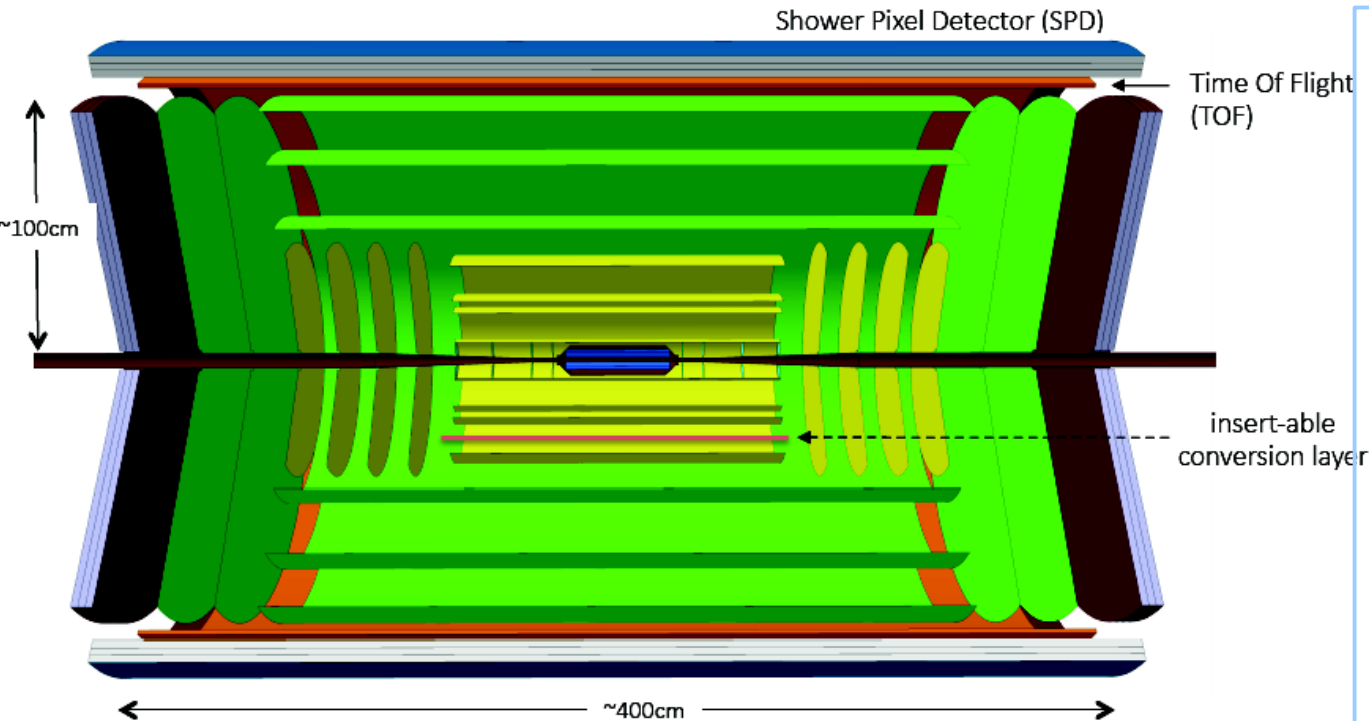
*Courtesy: R. Turchetta, Rutherford Appleton Laboratory*

# Concept of an all silicon detector

Tracker: ~10 tracking barrel layers (blue, yellow, green) based on CMOS sensors  $|\eta| < 1.4$   
plus 2 endcaps with ~ 10 disks  $1.4 < |\eta| < 4$

Hadron ID: TOF with 3 outer silicon layers (red)

Electron ID:  $< 500$  MeV via TOF,  $> 500$  MeV pre-shower pixel detector (blue)



## Preliminary studies

Magnetic field

$$B = 0.5 \text{ to } 1 \text{ T}$$

Spatial resolution

Inner most 3 layers:  $10 \times 10 \mu\text{m}^2$

$$0.05 \% X_0, \sigma < 3 \mu\text{m}$$

Outer layers:  $30 \times 30 \mu\text{m}^2$

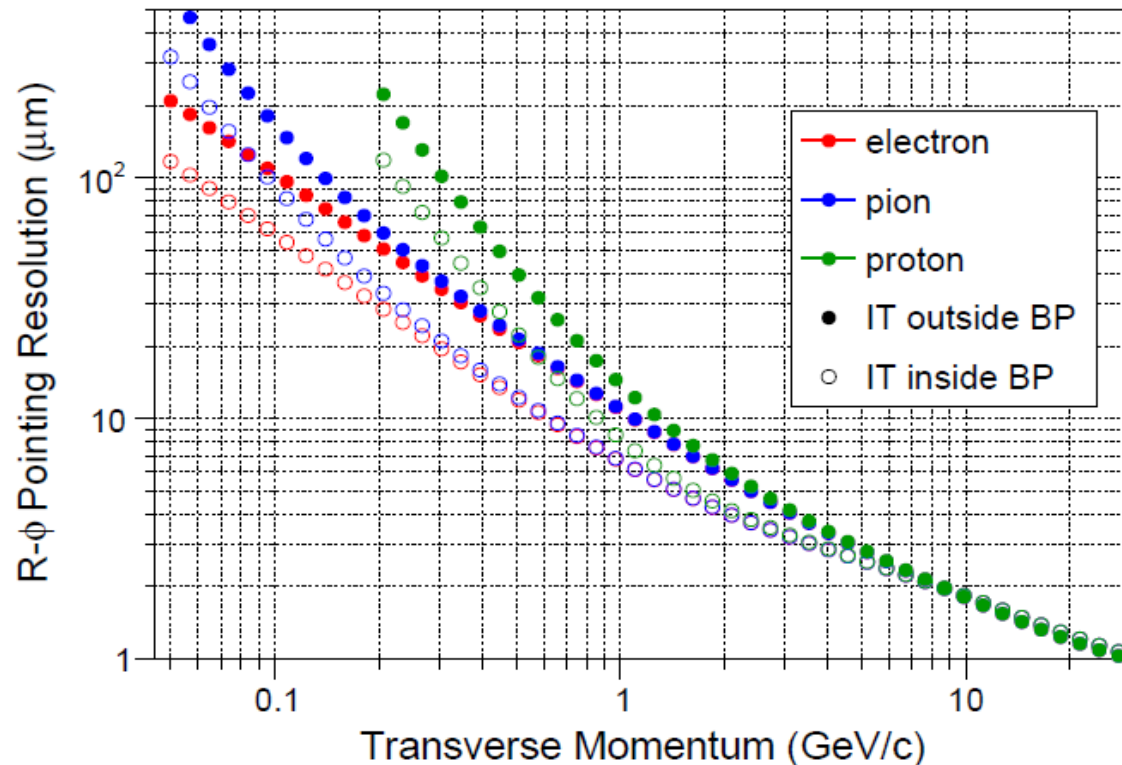
$$0.5 \% X_0, \sigma \sim 5 \mu\text{m}$$

Time measurement

3 layers with  $\sigma_t \sim 20 \text{ ps}$

arXiv:1902.01211

# Envisaged performance



- r- $\phi$  pointing resolution key for heavy flavor observables, but also photon conversions
- low momentum tracking
- capability to run at 20-50 times luminosity of upgraded ALICE (i.e. MHz)



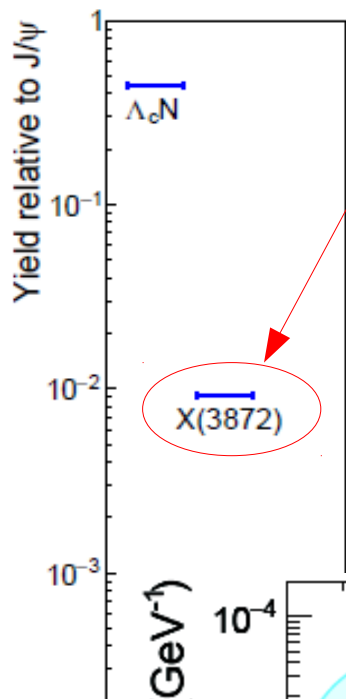
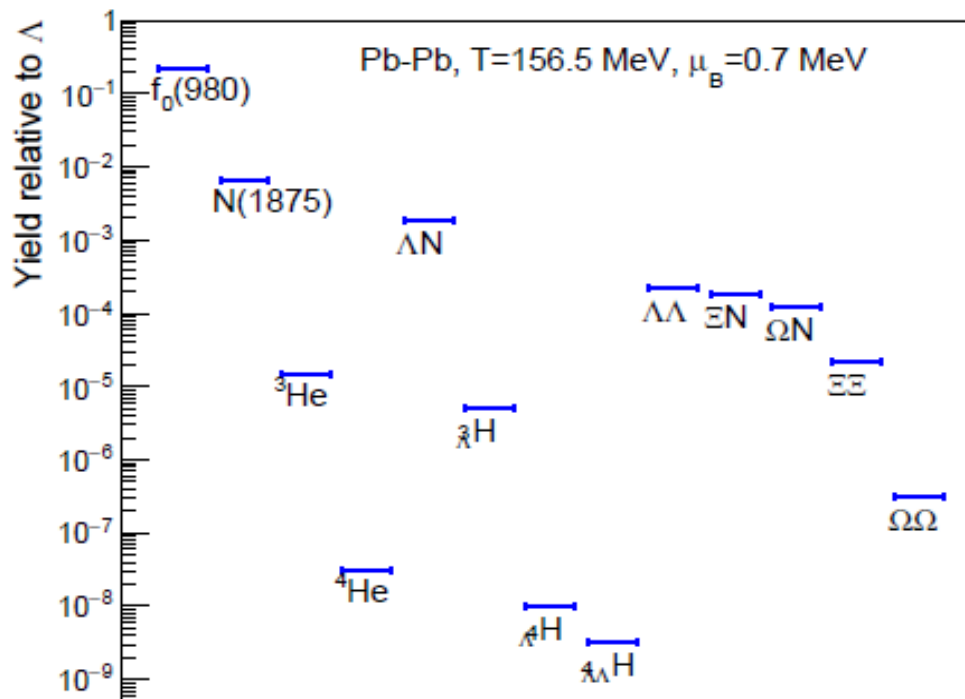
# Physics potential

main physics opportunity: open new window to study soft phenomena in hadronic collisions, allowing to address some longstanding, fundamental physics questions that could not be tackled so far

- heavy flavor and quarkonia: (requires high luminosity)
  - P-states of quarkonia,  $p_t$  spectra and  $v_n(p_t)$  for excited quarkonia
  - multiply heavy flavored baryons & mesons in pp, pA, AA
  - exotic quarkonia
- low mass di-leptons
  - low mass continuum and possible structure due to dark photon
  - chiral symmetry restoration and temperature of hot QGP fireball
- soft and ultra-soft photons
  - real soft photons from QGP, extend  $p_t$  range from 1 GeV down to 50-100 MeV
  - ultra-soft photons  $p_t^\gamma = 1-100$  MeV in small forward spectrometer

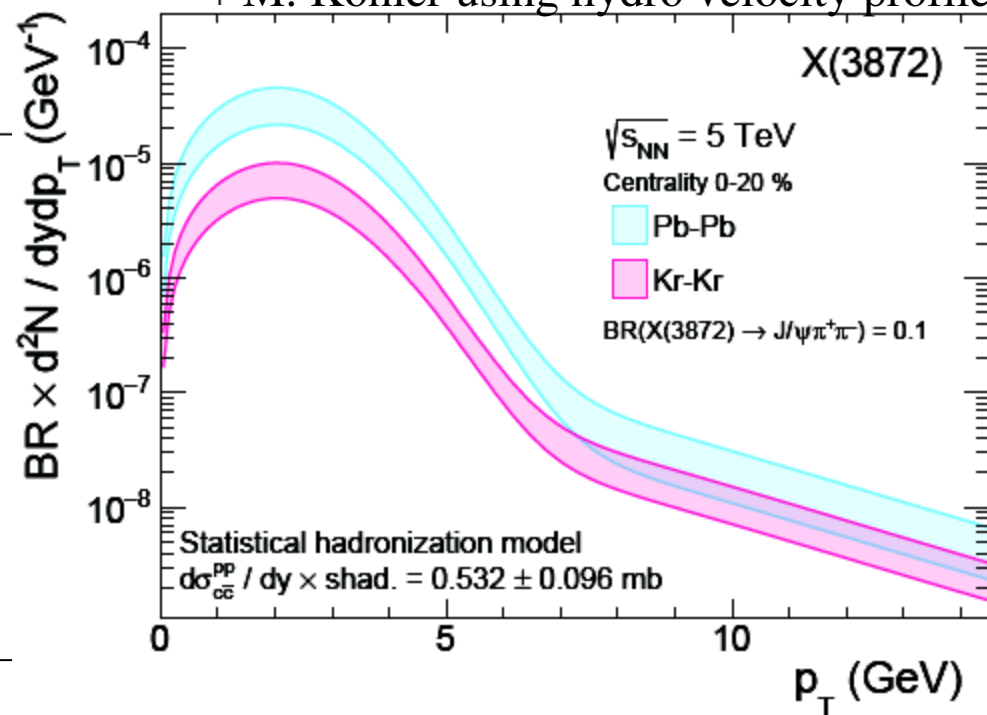
arise as a consequence of structure of all gauge theories (Bloch, Nordsieck, Low)  
predicted controlled divergence – try to reach and test this limit
- other probes accessible with low  $p_t$  hadrons (DCC, ...)

# Are nuclei and exotic hadrons formed as virtual compact multi-quark states at the phase boundary?



$X(3872)$  via decay  $J/\psi \pi^+ \pi^-$   
 tetraquark of molecule?  
 is it formed like (hyper)nuclei?

M. Köhler using hydro velocity profile

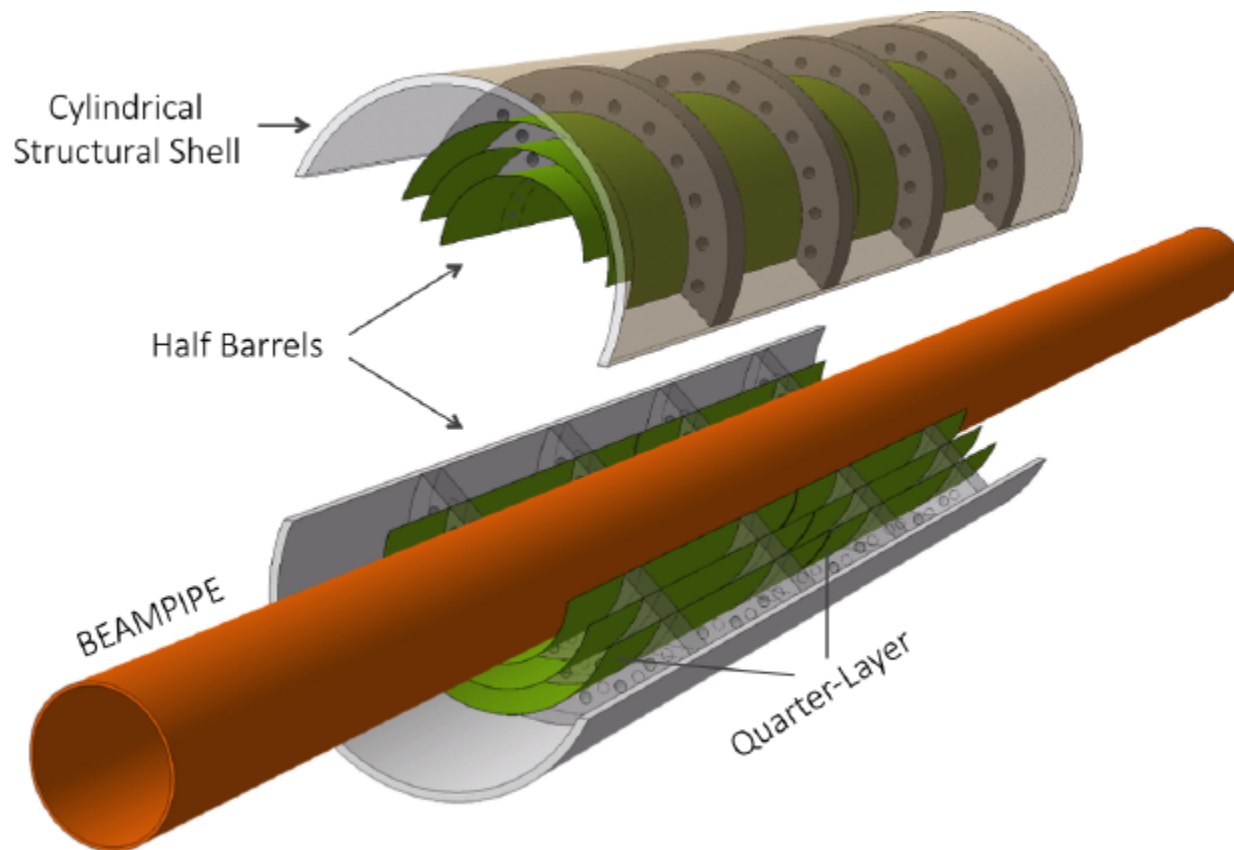


key observable: transverse momentum spectrum down to low  $p_t$  for (hyper-)nuclei,  $J/\psi$ ,  $\psi'$ ,  $X(3872)$ ,  $B_c$ , ... in PbPb collisions at LHC energy

# Proposed ITS3 in ALICE

3 layers of stitched CMOS MAPS sensors of up to 508 cm<sup>2</sup>  
with 500 M pixels (10 x 10 μm<sup>2</sup>)

near-term realization  
of this technology in a  
running experiment will  
revolutionize vertexing

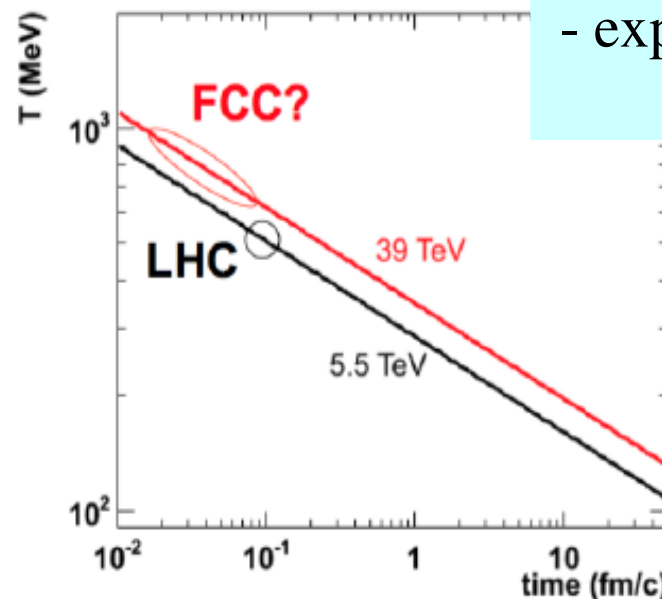
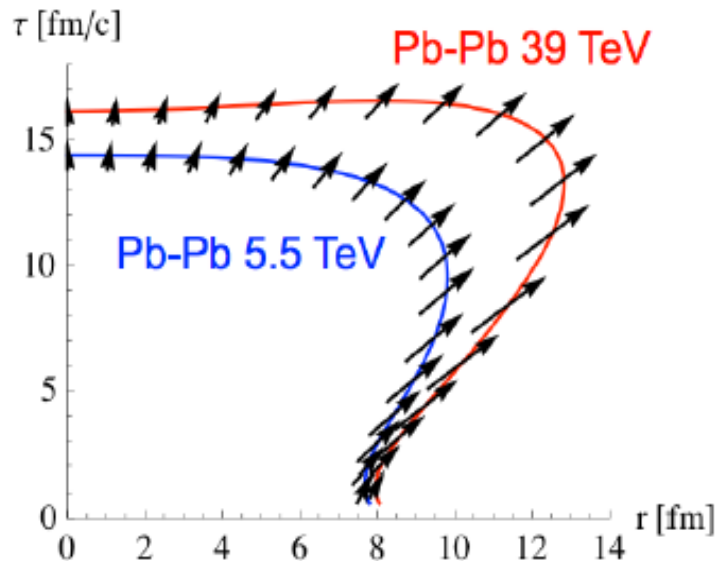


expression of interest for an ALICE ITS upgrade in LS3 – ALICE-PUBLIC-2018-013

# HE-LHC and FCC initial and final conditions for HI collisions

System, $\sqrt{s_{NN}}$ (TeV)	Pb-Pb, 2.76	Pb-Pb, 5.5	Pb-Pb, 10.6	Xe-Xe, 11.5	Pb-Pb, 39.4
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	2400	1500	3600
$dE_T/d\eta$ at $\eta = 0$ (TeV)	1.7–2.0	2.3–2.6	3.1–3.4	$\approx 1.5$	5.2–5.8
Homogeneity volume $\text{fm}^3$	5000	6200	7400	4500	11000
Decoupling time (fm/c)	10	11	11.5	10	13
$\varepsilon$ at $\tau = 1 \text{ fm/c}$ ( $\text{GeV}/\text{fm}^3$ )	12–13	16–17	22–24	$\approx 15$	35–40

- initial energy density of QGP can be doubled
  - system lives longer
  - expands more rapidly
- incremental changes**



FCC study Vol 1  
Eur Phys. J. C

# FCC and HE-LHC: new opportunities for HI collisions

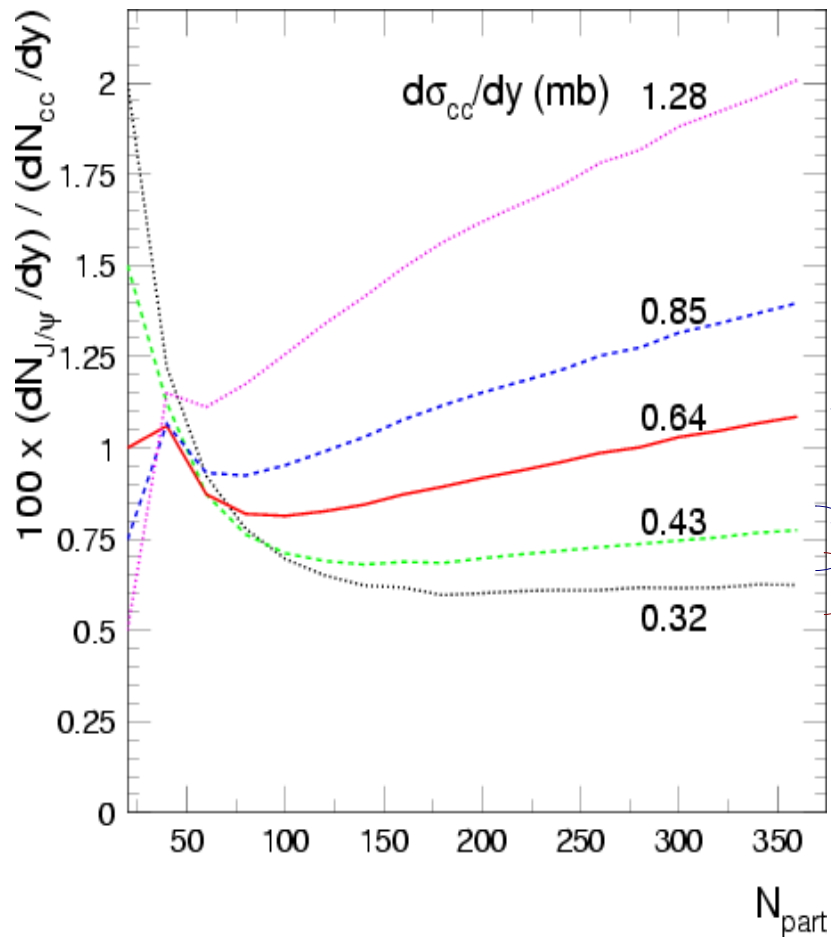
while the QGP created at FCC is presumably not radically different from LHC, the strong increase of cross sections and virtual photon flux make new probes available

examples:

- $\sigma_{ccbar}$  and  $\sigma_{bbbar}$ : qualitative changes in  $J/\psi$  and  $Y$  statistical formation
- decay of boosted tops via  $W$  to jets: jets exposed to energy loss with delay  
→ probe space-time evolution of QGP
- exclusive photoproduction of  $J/\psi$  →  $W_{\gamma p} = 10$  TeV and thereby probe  $x = 10^{-7}$
- $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$  1.75 nb in PbPb  
 $\gamma\gamma \rightarrow \gamma\gamma$  enhanced factor 200, sensitivity to BSM physics via new heavy charged particle in virtual loop, search for monopoles or axions

# Expectations for $J/\psi$ at FCC

A. Andronic, P. Braun-Munzinger, K. Redlich,  
J. Stachel Phys. Lett. B652 (2007) 259



39 TeV

- 5.02 TeV mid-y including shadowing
- 2.76 TeV mid-y including shadowing
- 5.02 TeV y=2.5-4 including shadowing
- 2.76 TeV y=2.5-4 including shadowing

## Outlook - towards a bright future for high energy heavy ion collisions

- **heavy ion collisions at the LHC at substantially increased luminosity open an excellent window to study strongly interacting matter at high temperature**
- **measurements with a next generation nearly massless all-Si detector could already take place at the HL-LHC starting from 2030 and might find a natural continuation at accelerators with even higher energies**
- **there are prospects for a highly attractive heavy ion program at the HE-LHC and the FCC**
- **needs for success concomitant significant theory effort**



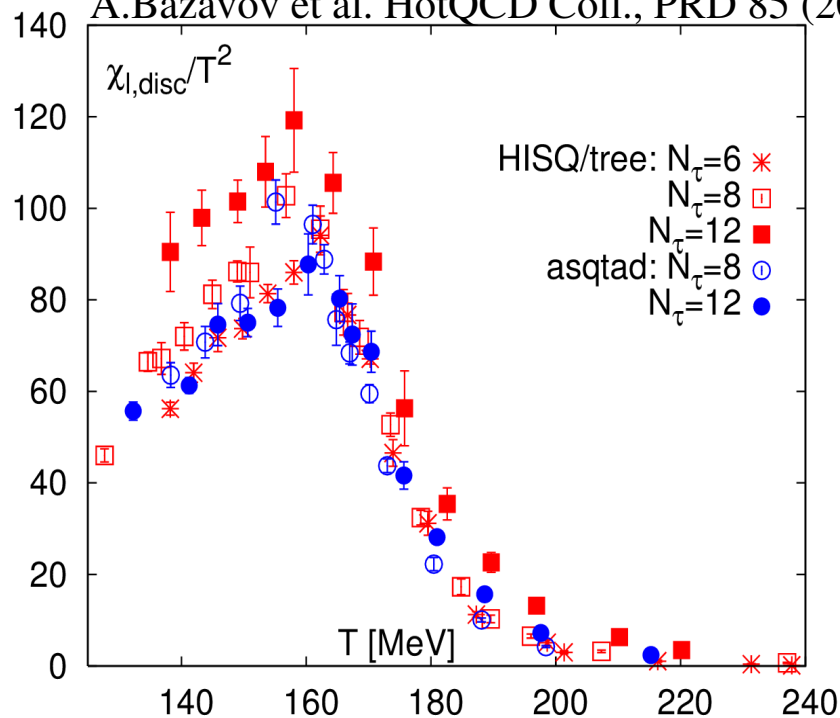
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# Measure for chiral symmetry restoration in IQCD

order parameter: chiral condensate, its susceptibility peaks at  $T_c$

S.Borsanyi et al. Wuppertal-Budapest Coll., JHEP 1009 (2010) 073

A.Bazavov et al. HotQCD Coll., PRD 85 (2012) 054503



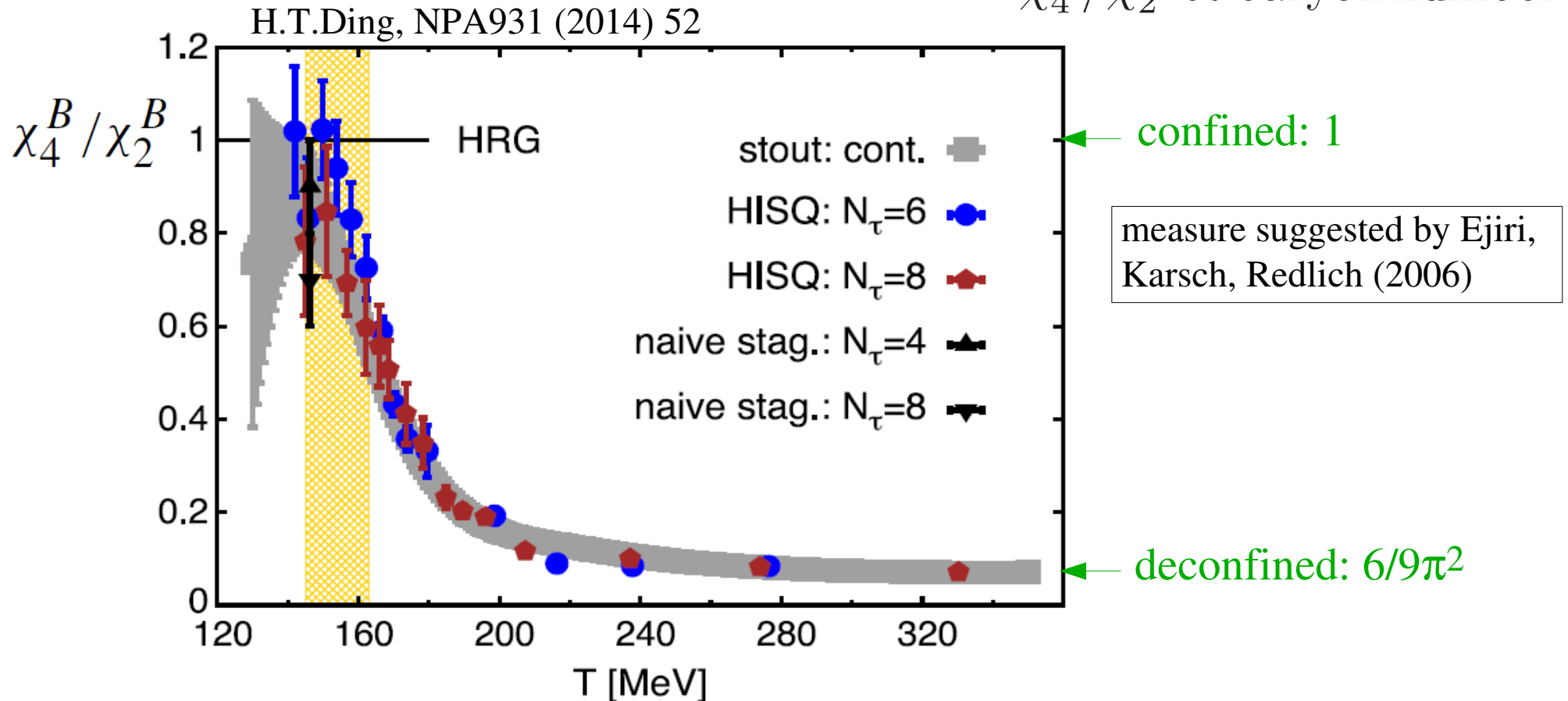
$$\langle \bar{\Psi} \Psi \rangle = \frac{T}{V} \frac{\partial \ln Z}{\partial m}$$

$$\chi_{\bar{\Psi} \Psi} = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial m^2}$$

comparing different measures and different fermion actions, consensus:  
pseudocritical temperature  $T_c = 154 \pm 9$  MeV for chiral restoration

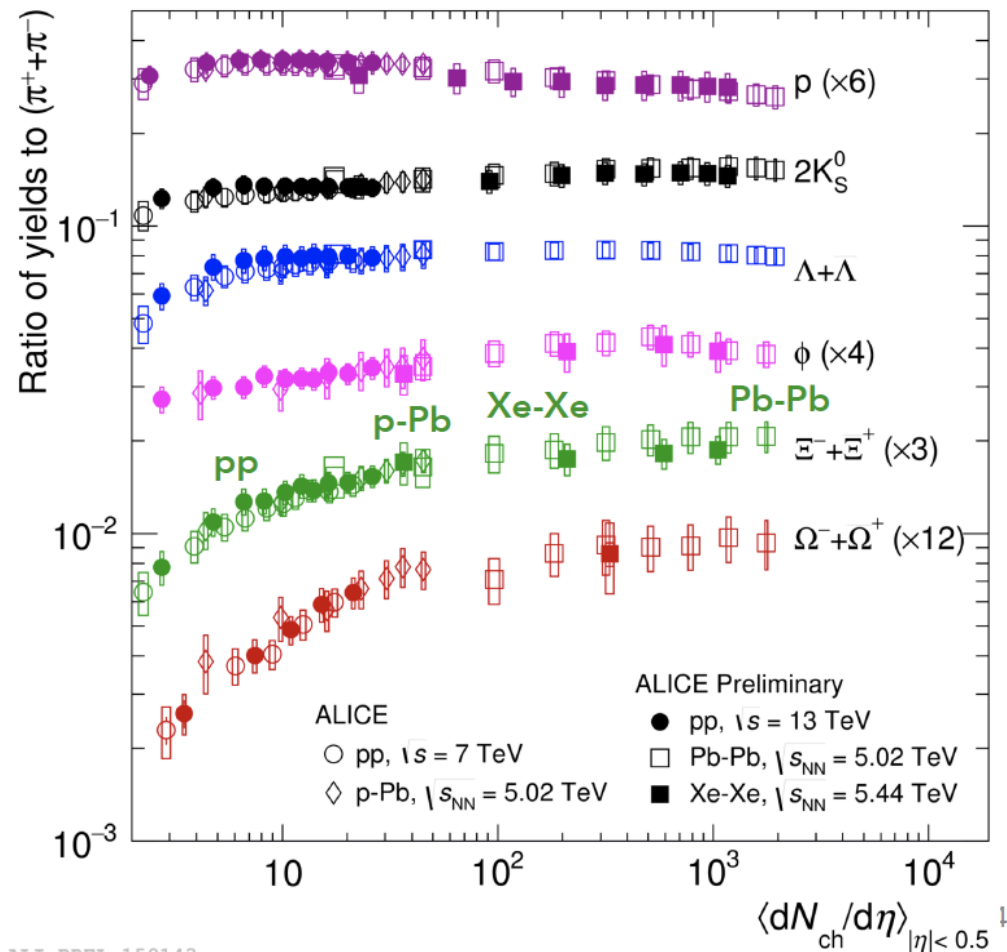
# Measure of deconfinement in IQCD

$$\chi_4^B / \chi_2^B \propto \text{baryon number}^2$$



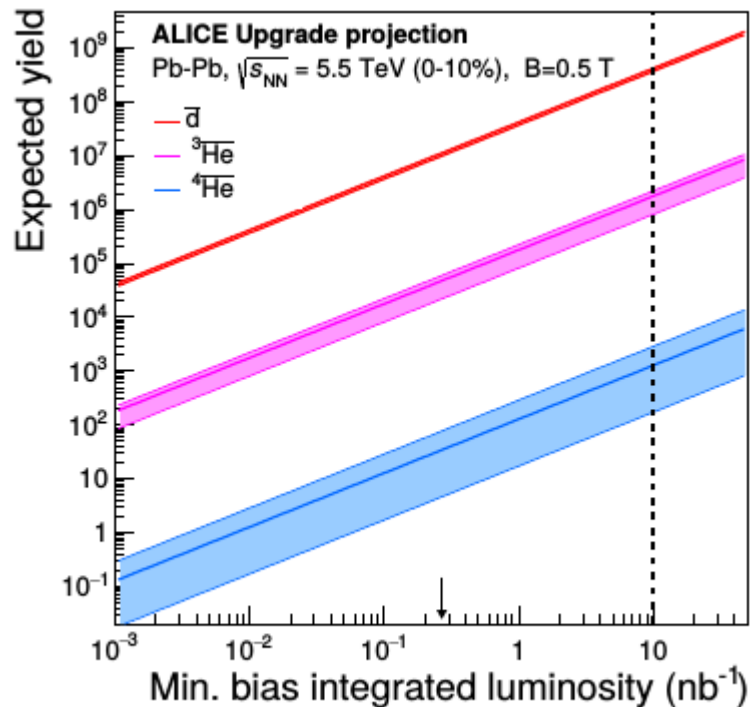
rapid drop suggests: chiral cross over and deconfinement appear in the same narrow temperature range

# From pp to PbPb collisions: smooth evolution

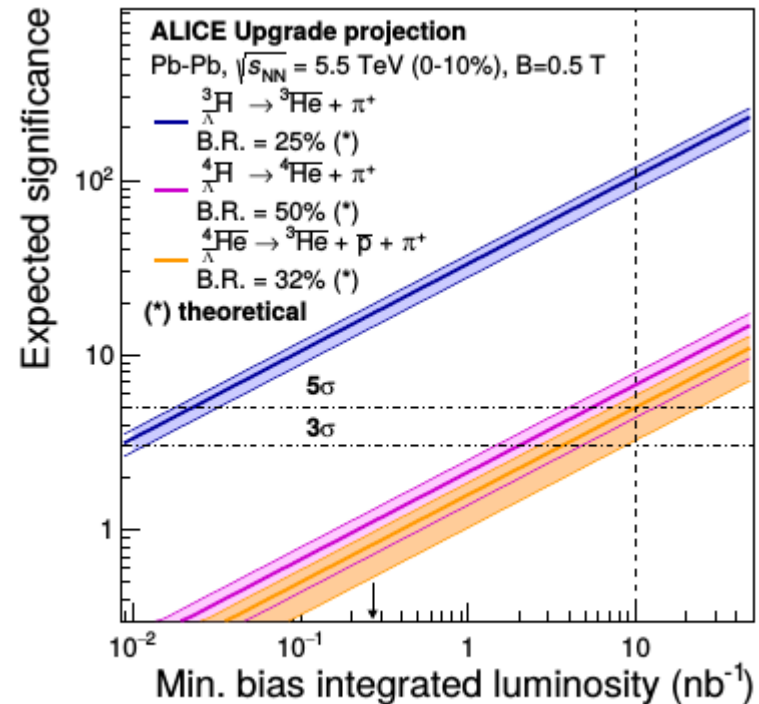


universal hadronization can be described with few parameters in addition to  $T$ ,  $\mu_B$   
 transition from canonical to grand-canonical thermodynamics

# Nuclei and hypernuclei in Runs 3 and 4

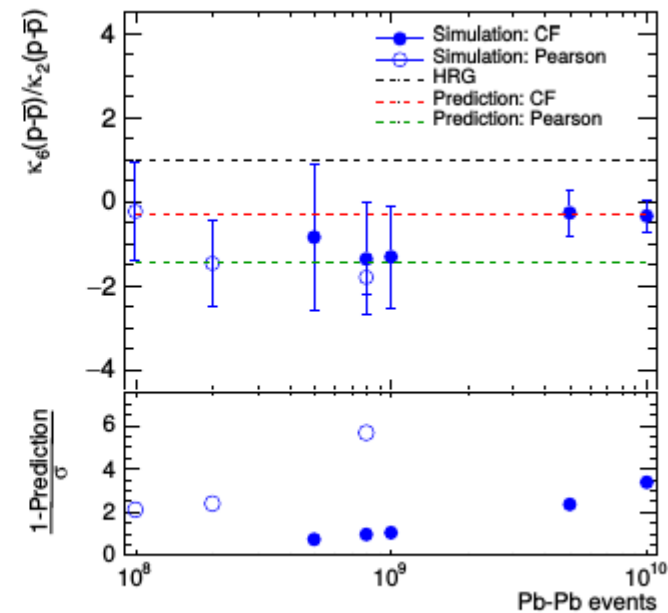
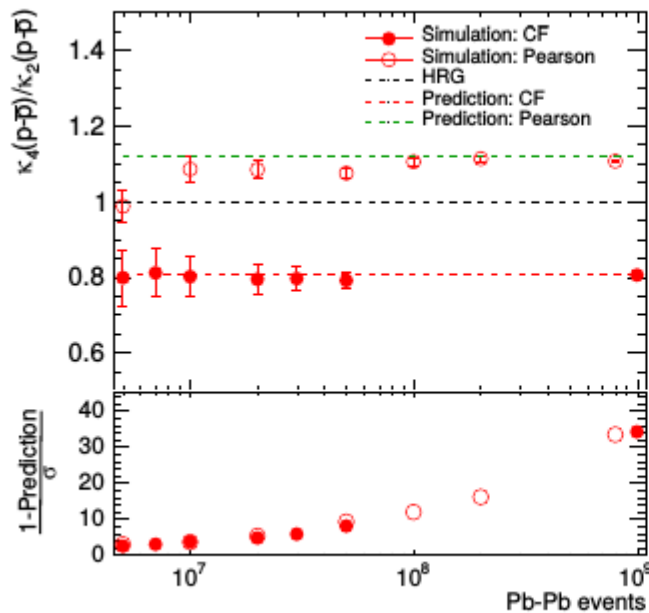


ALI-SIMUL-312336



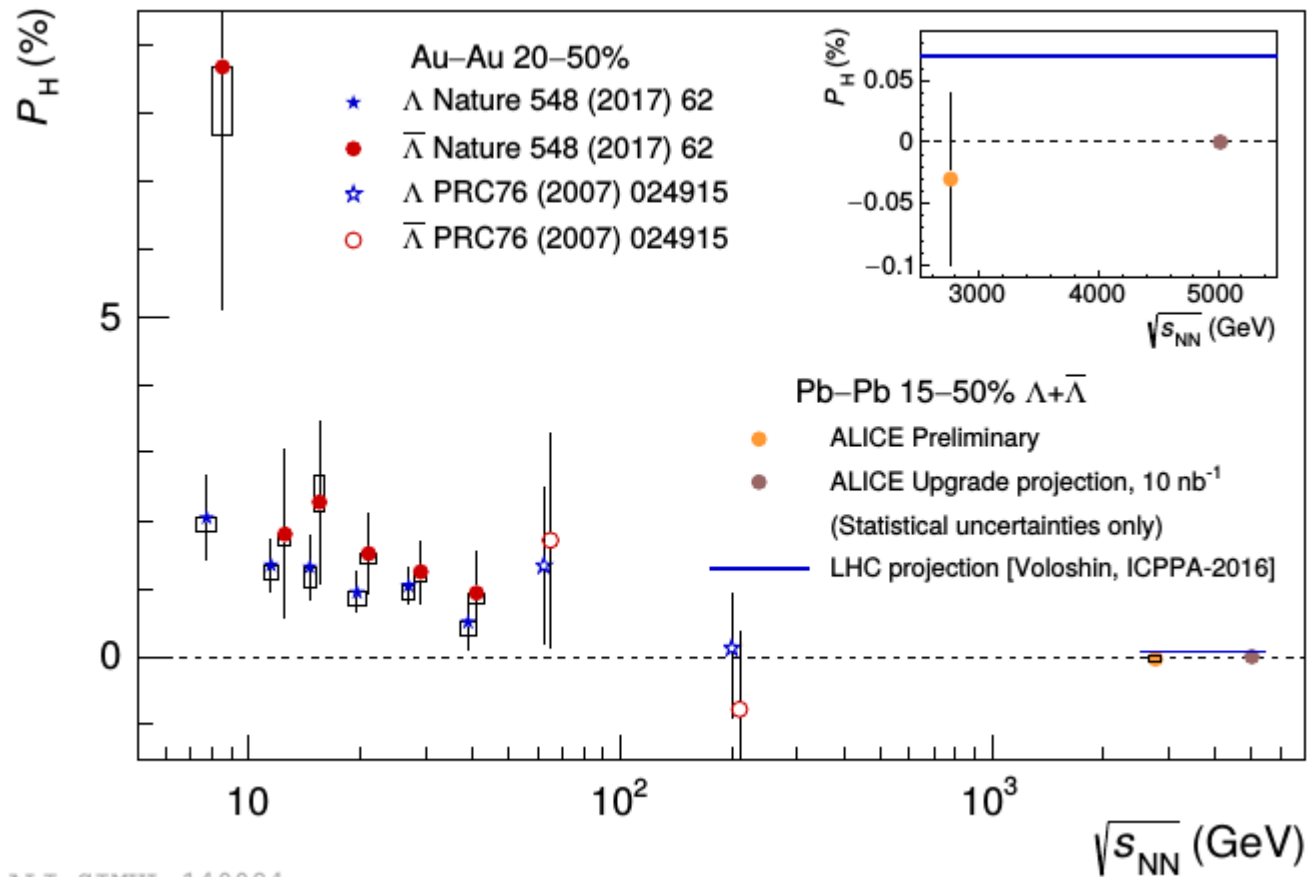
ALI-SIMUL-312332

# Proton fluctuations measured in Run3/4



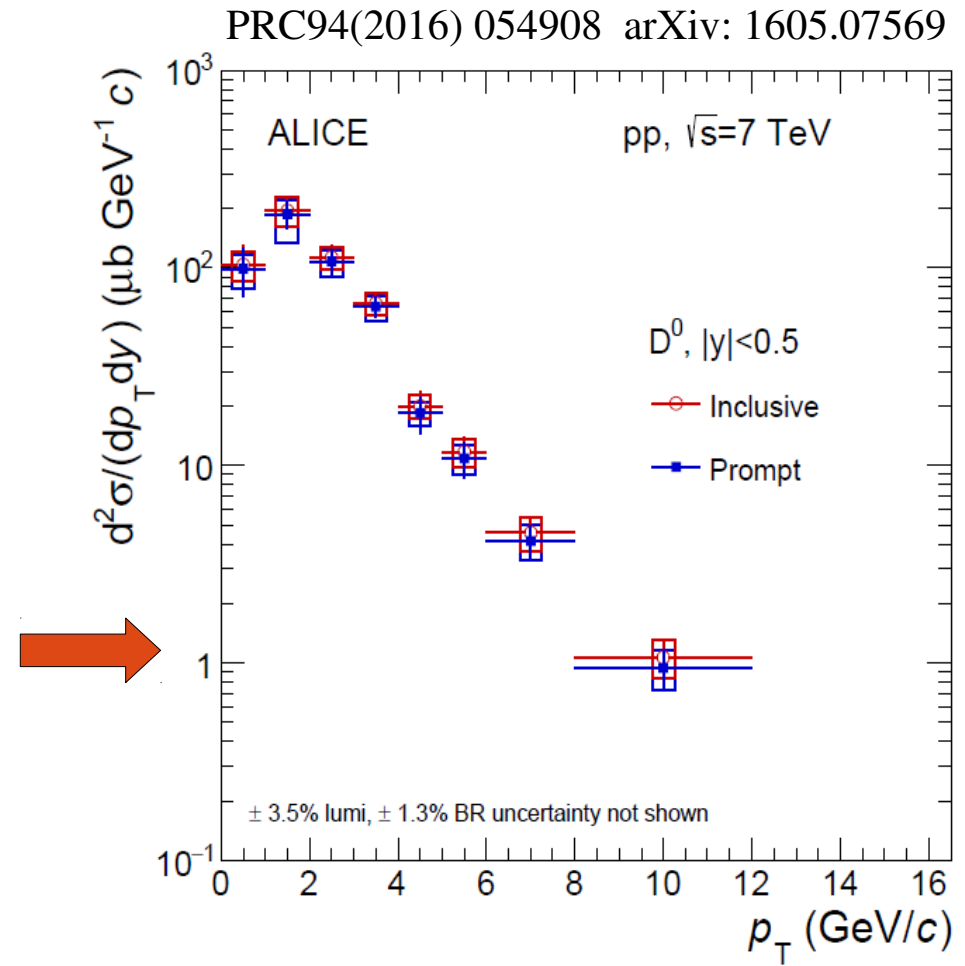
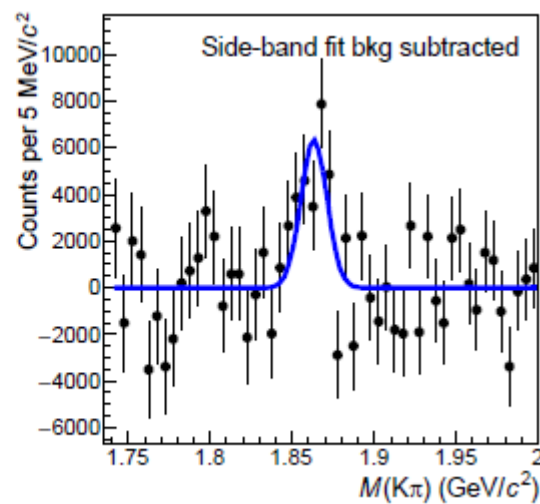
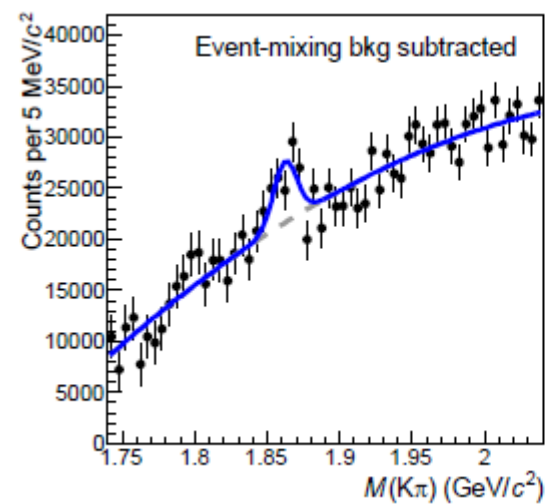
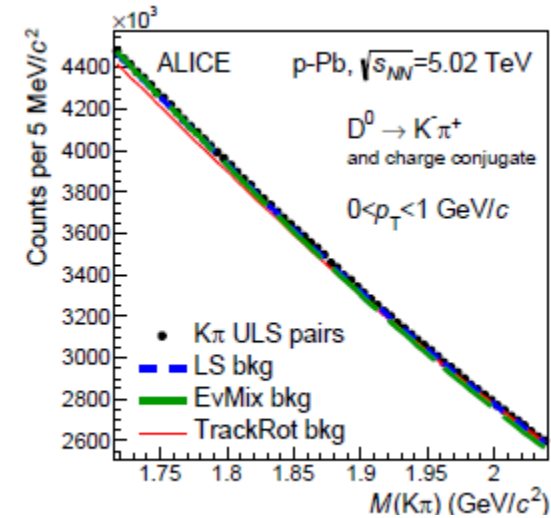
with 13 nb-1, critical phenomena contained in the 6<sup>th</sup> order cumulants will be probed

# Vorticity and polarization



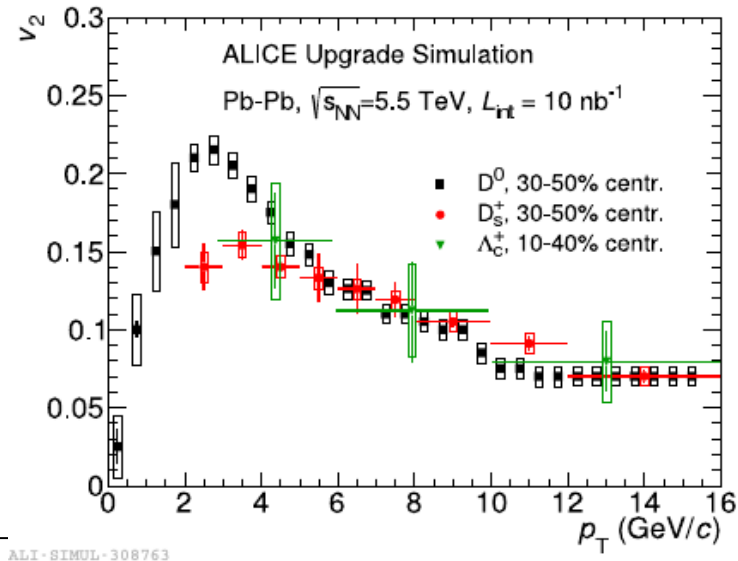
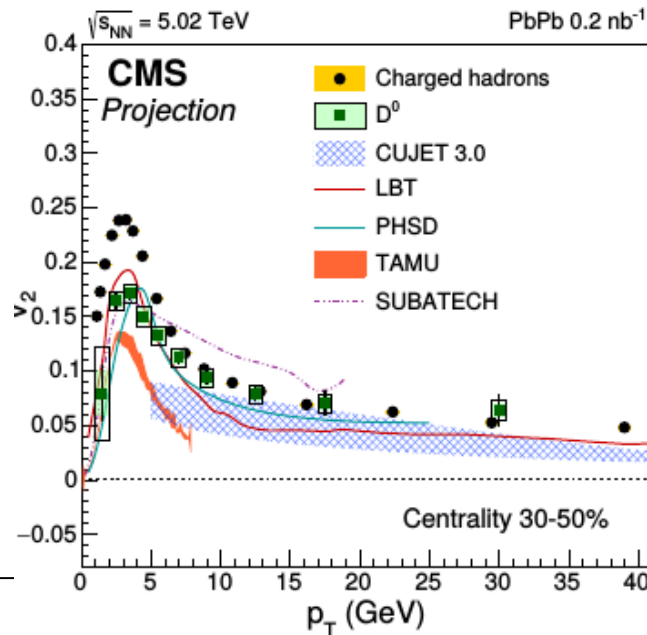
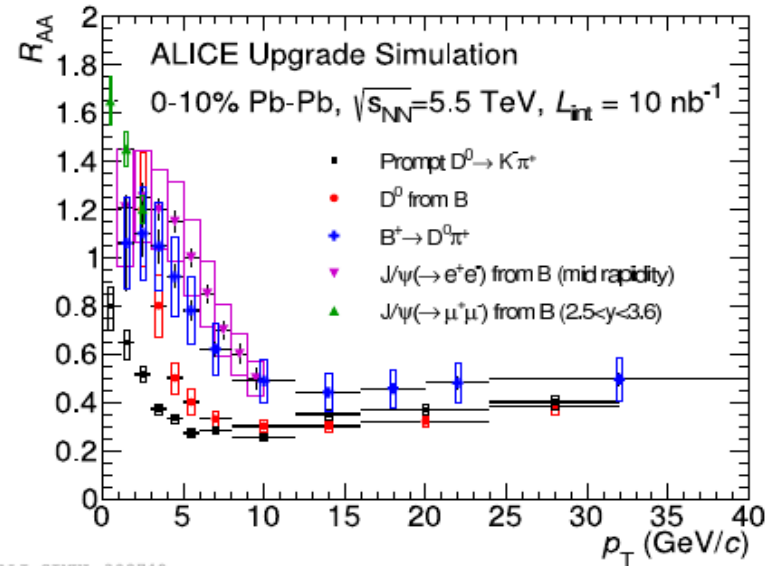
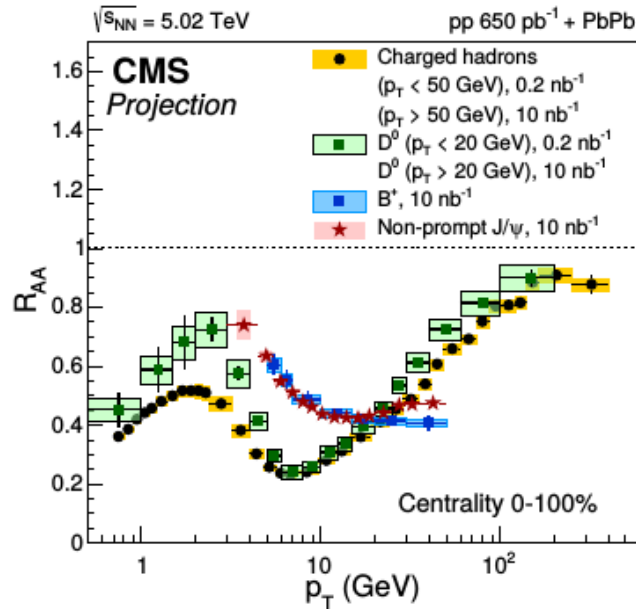


# First measurements of open charm cross section down to $p_t = 0$ at mid-rapidity



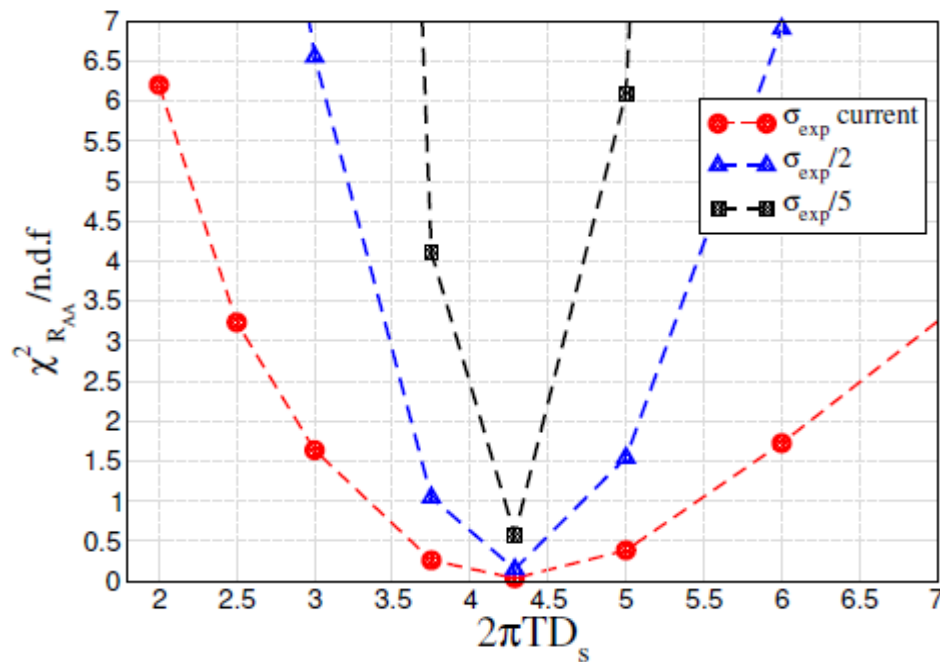
very hard struggle to deal with (irreducible) combinatorial background, successful

# D and B $R_{AA}$ and $v_2$



# Charm quark spatial diffusion coefficient

equilibration time of heavy quark given by diffusion coefficient:  $\tau_Q = \frac{m_Q}{T} D_s$   
 from simultaneous fit of spectrum and  $v_2$  as function of  $p_t$  get  $D_s(T)$



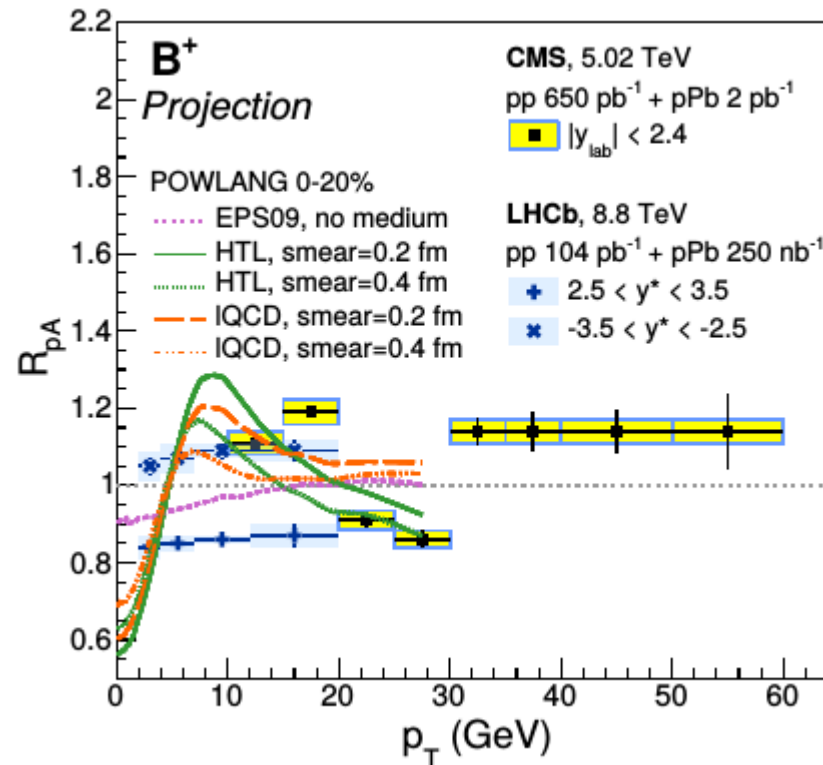
temperature dependence highly nontrivial

- decrease for liquid
- increase for gas

**Run3/4 data will improve stat. accuracy by factors 2-5 for  $D^0$  and make b-quark accessible for first time**

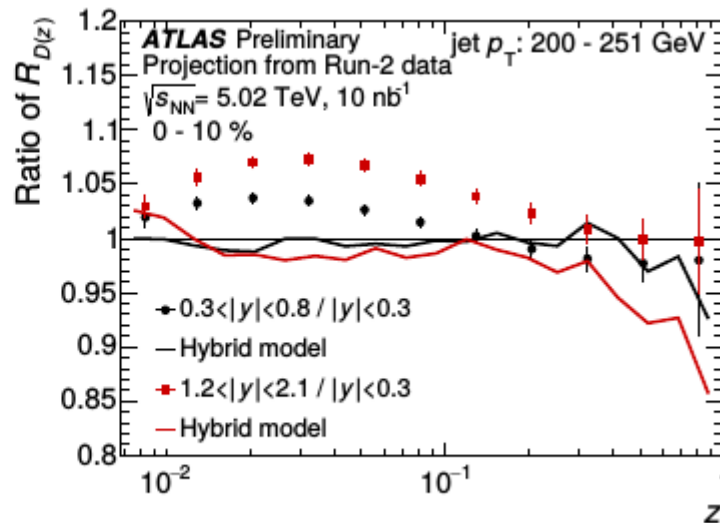
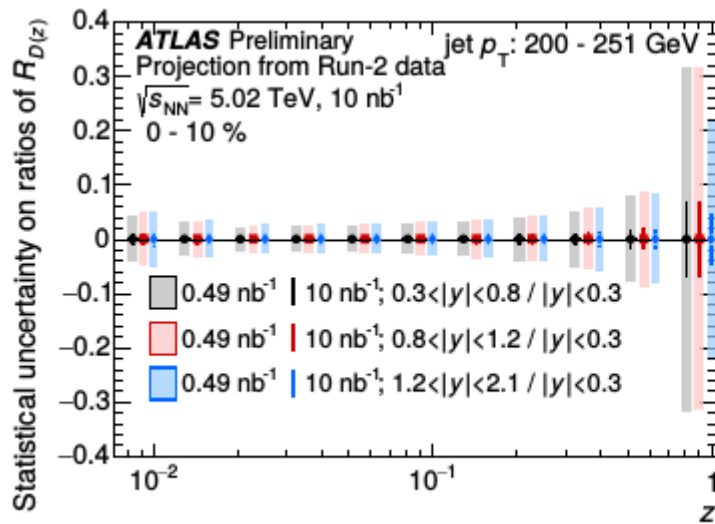
very interesting in era where precision QCD computations possible (lattice and funct. methods)

# Projected accuracy B-meson modification in pPb



Run3/4: sensitive to any in-medium effects beyond initial state modification

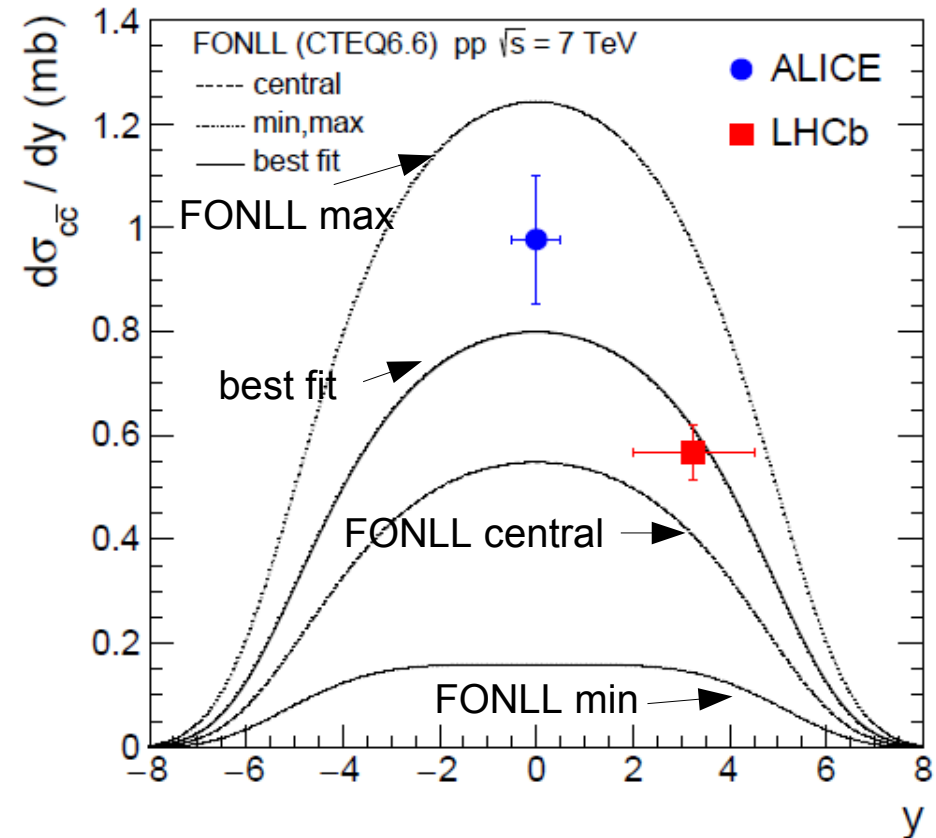
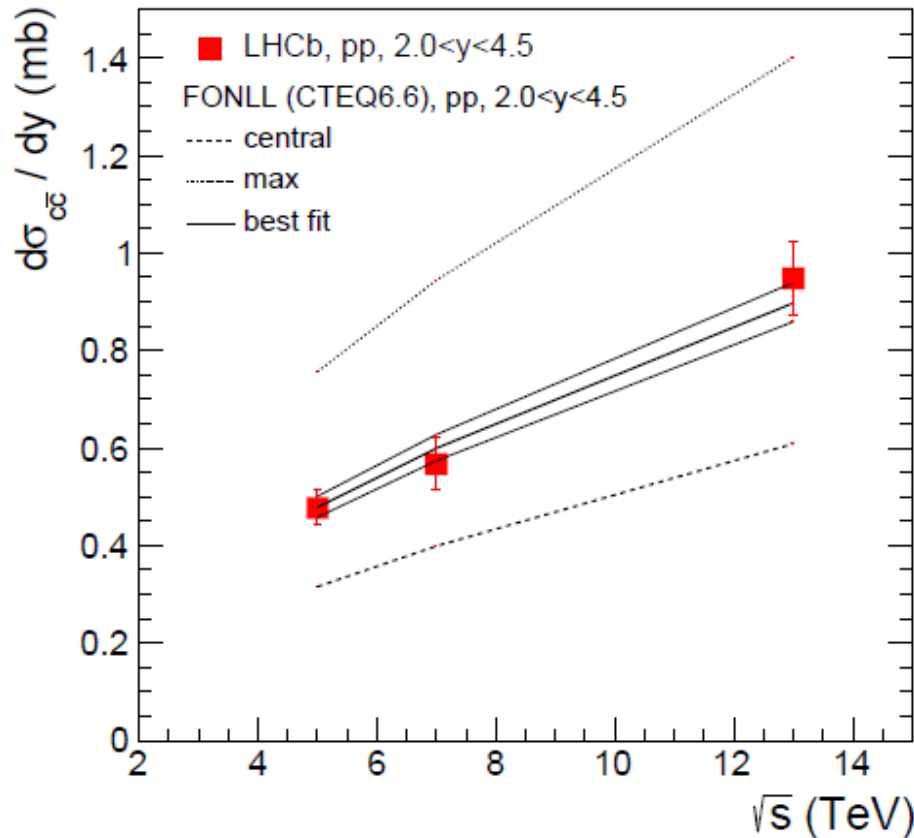
# Modification on jet fragmentation in PbPb



Run3/4: Superb sensitivity to details of fragmentation function at %-level

# the baseline for the interpretation of PbPb data

use shape of FONLL to interpolate to proper  $\sqrt{s}$  and  $y$ -interval

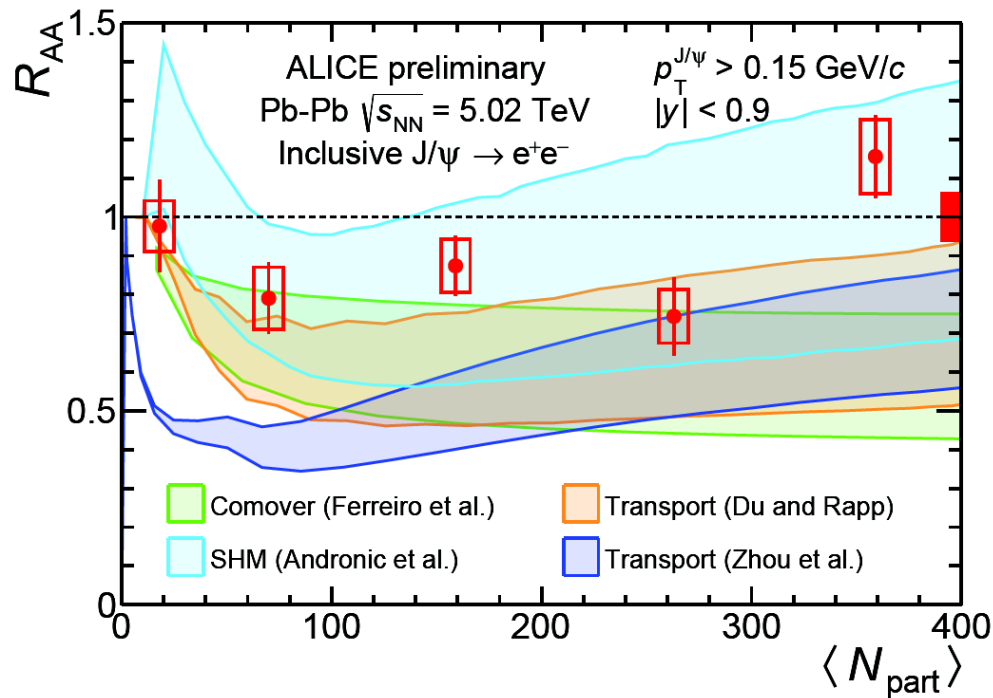


A. Andronic priv. Comm.

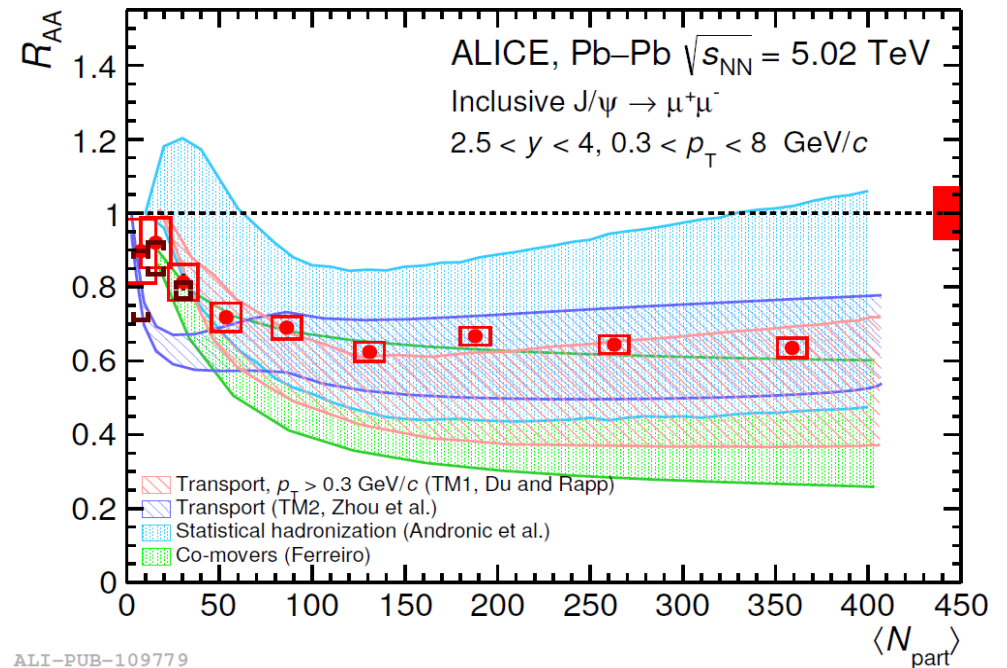
LHCb: 5 TeV arXiv:1610.02230  
 7 TeV NPB 871 (2013) 1  
 13 TeV JHEP 03 (2016) 159  
 plus erratum

ALICE: 7 TeV PRC94(2016) 054908  
 and 1702.00766

# J/ψ and transport models (and stat hadronization)



ALI-PUB-109779



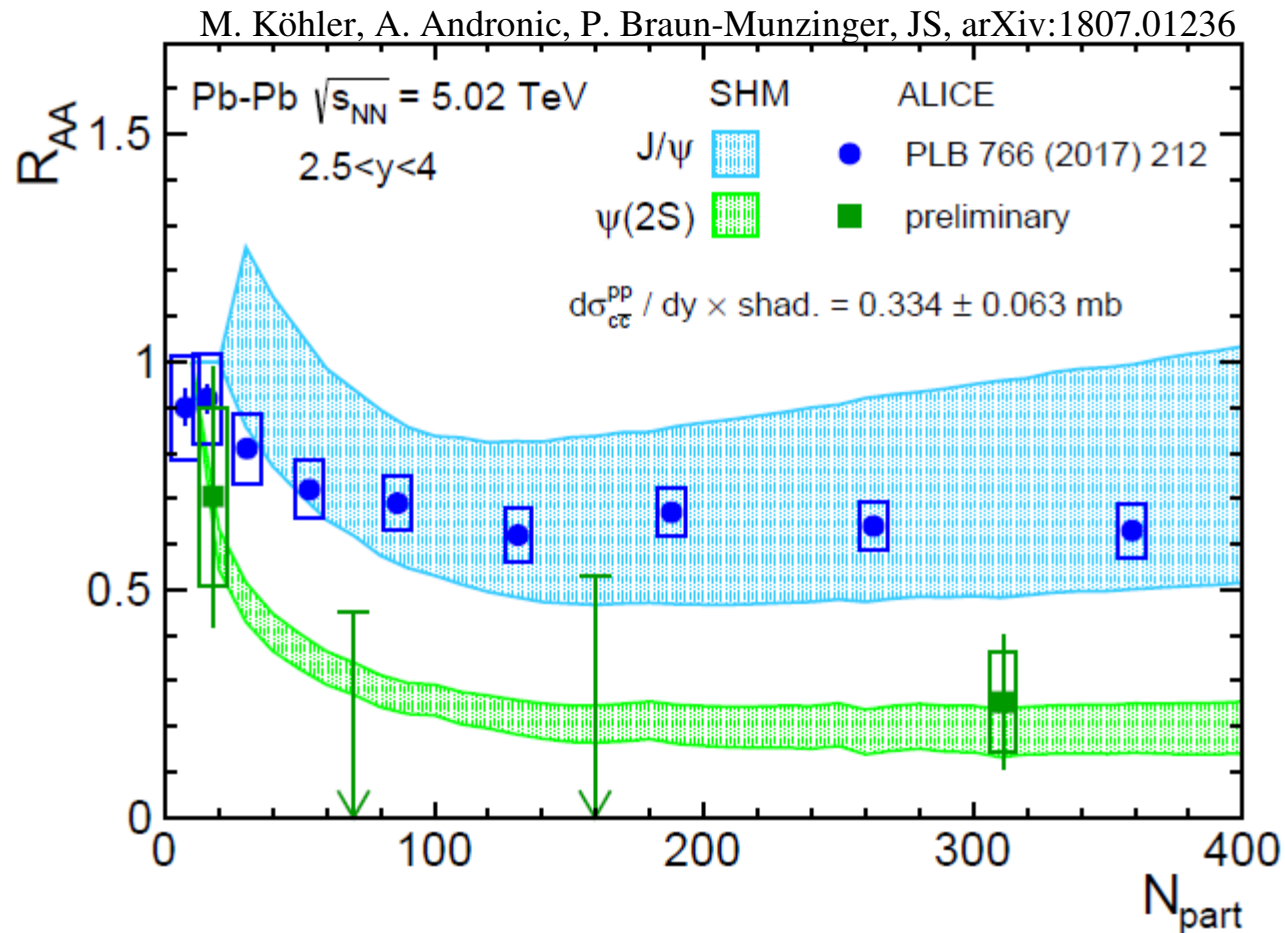
in transport models (Rapp et al. & Zhuang et al.) J/psi generated both in QGP and at hadronization

- transport models also in line with  $R_{AA}$  but larger open charm cross section used

the confusing situation only arises because of large uncertainty in open charm cross section, i.e. the freedom how to extrapolate from pp to PbPb



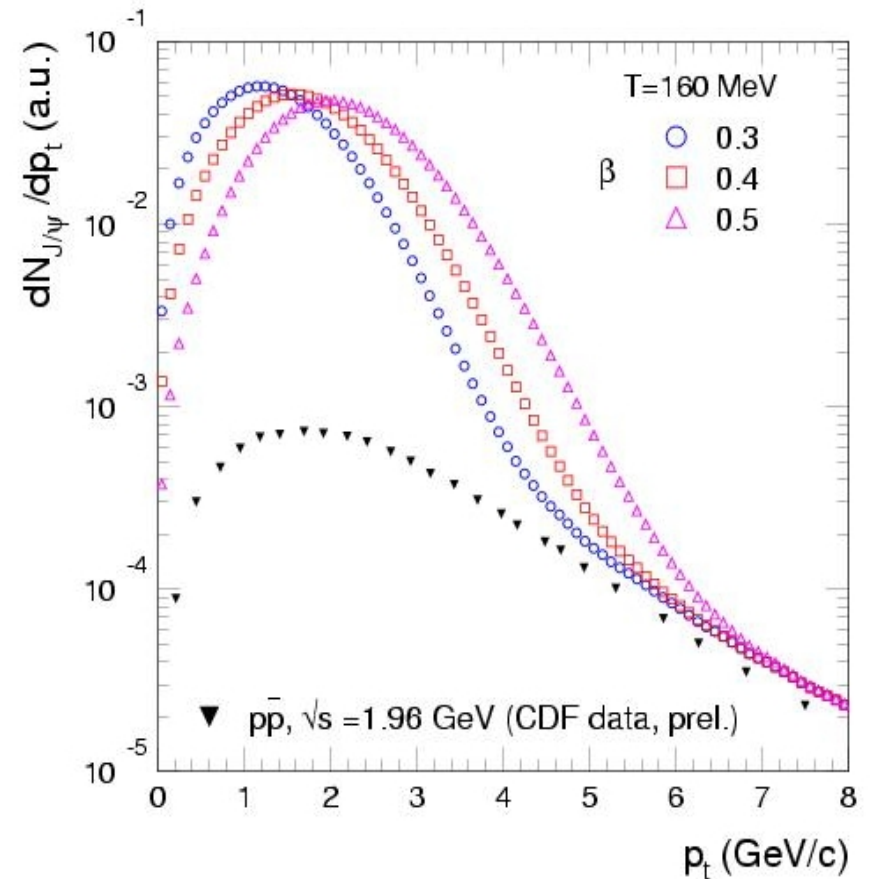
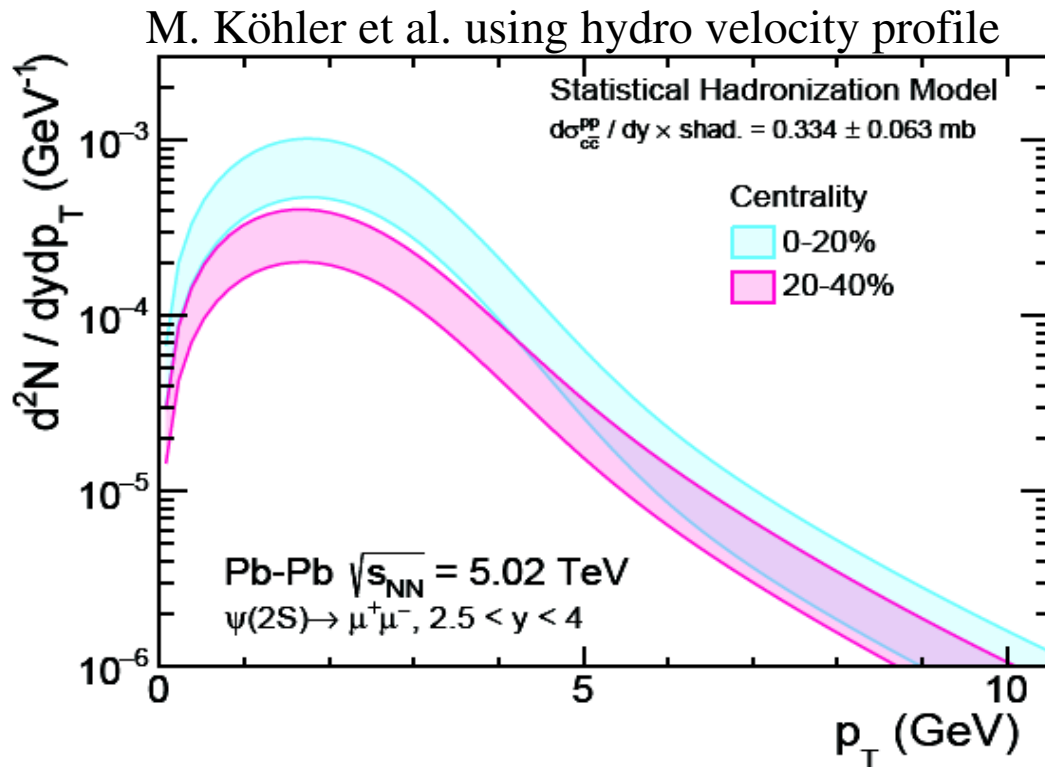
# What about $\psi(2S)$ ?



also excited state completely in line, suppressed by Boltzmann factor  
but errors need to decrease with more data to make a meaningful statement!

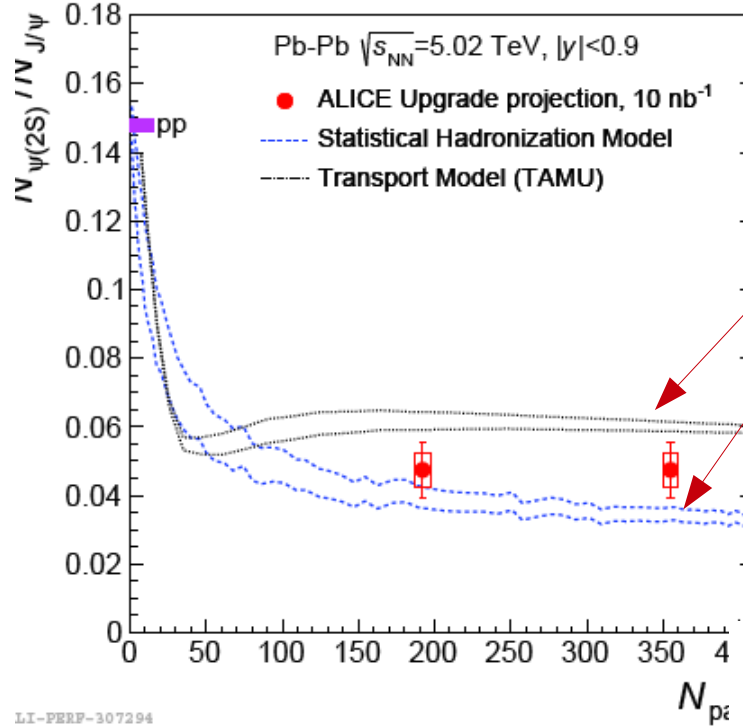
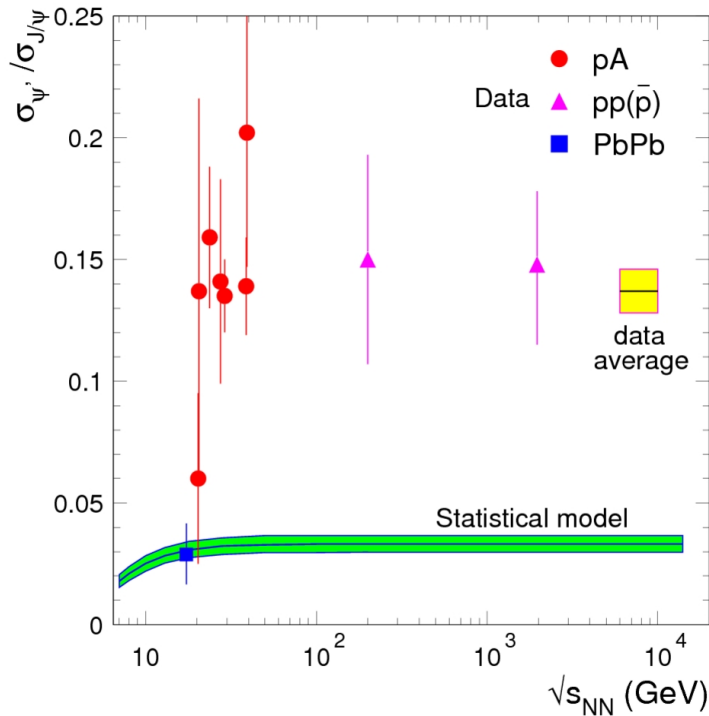
# Spectral distribution is key to thermalization

if charm quark thermalize, their spectral distributions should also reflect collective flow of liquid



first spectra a mid-y appearing  
 much more to come  
 we are computing spectra

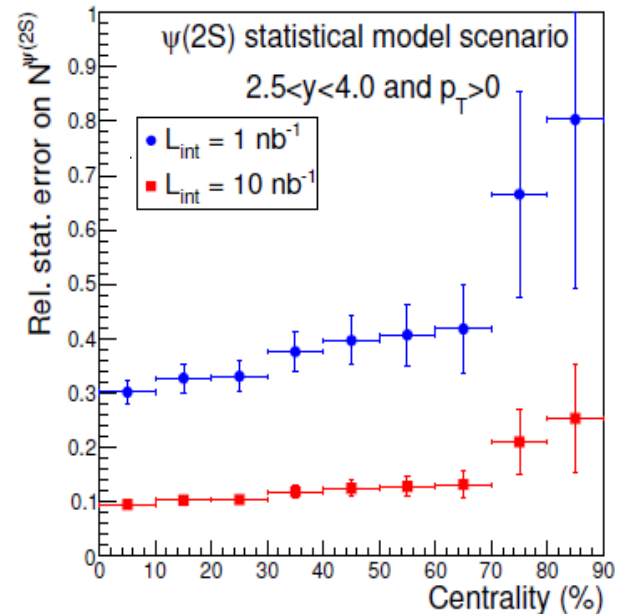
# excited charmonia crucial to distinguish between models



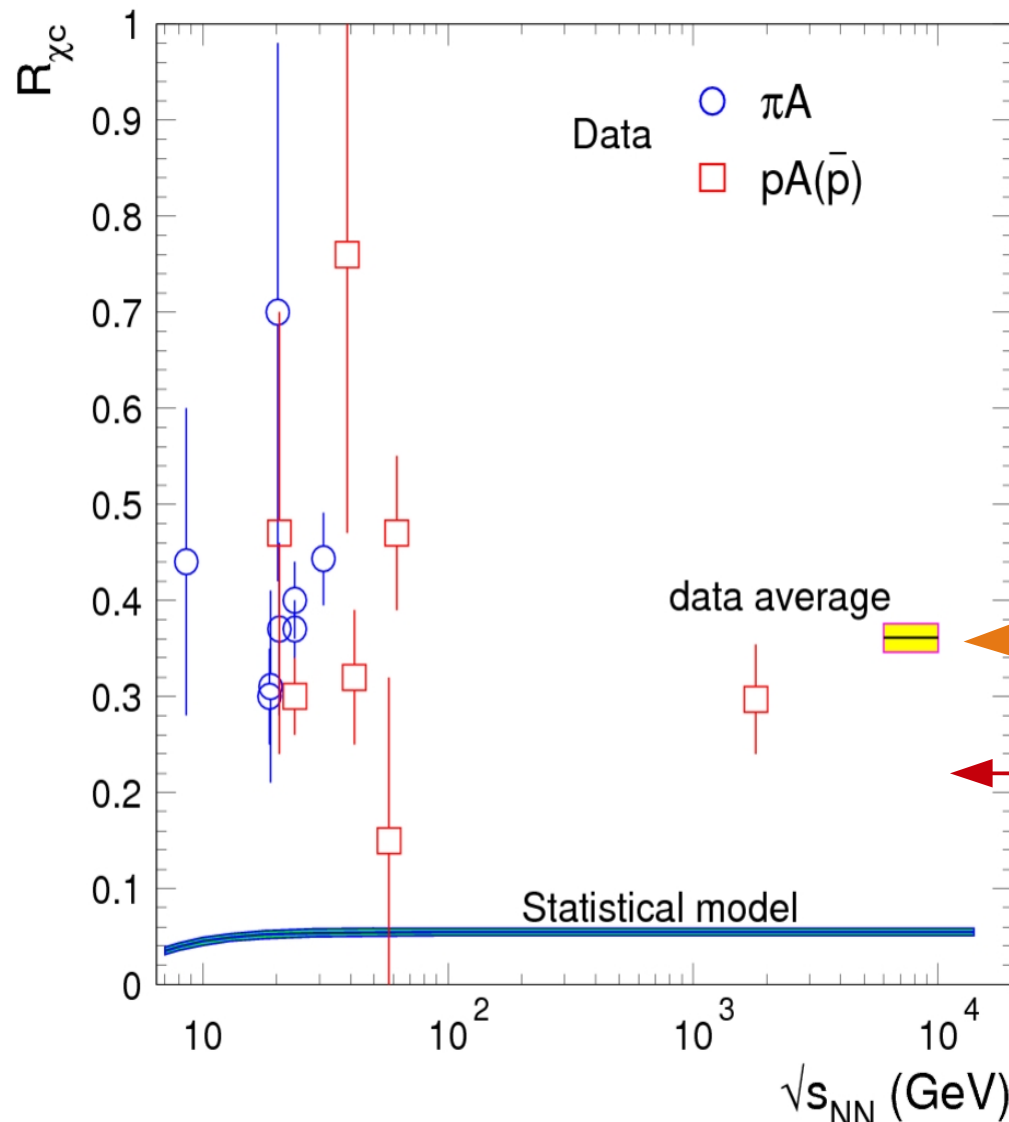
in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

for statistical hadronization need to see suppression by Boltzmann factor

expected ALICE performance  $\longrightarrow$   
muon arm run2 and run3



# Situation even more dramatic for P-states



$pA$  and  $\pi A$  data on average factor 7 above statistical model prediction

Transport model (Rapp)

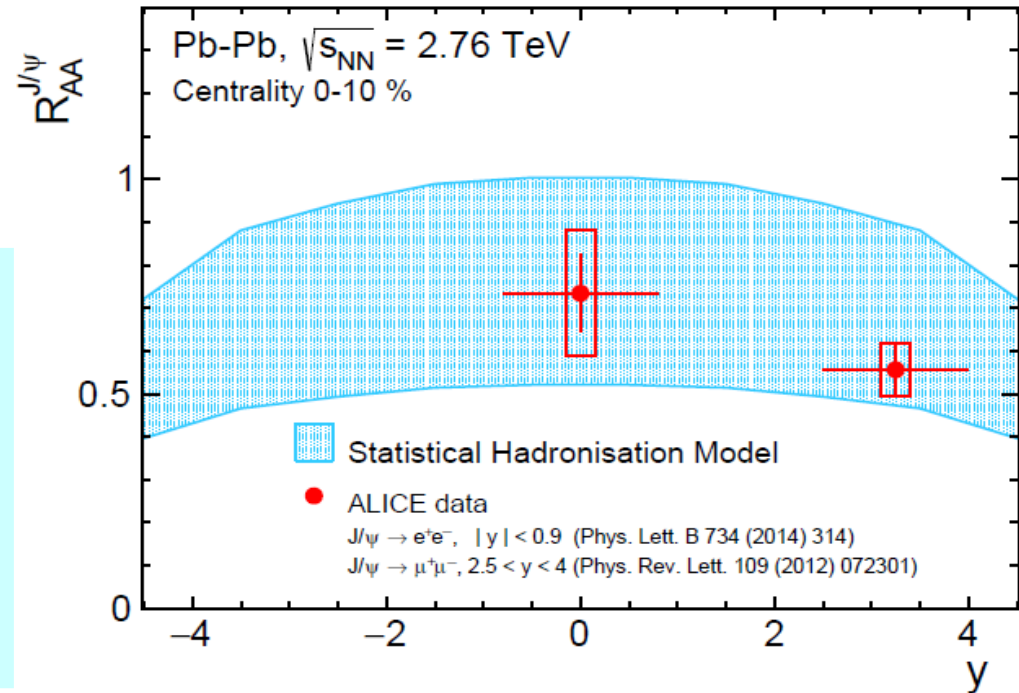
A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich,  
J. Stachel Phys. Lett. B678 (2009) 350

# Rapidity dependence of $R_{AA}^{J/\psi}$

yield in PbPb peaks at mid- $y$   
where energy density is largest  
?

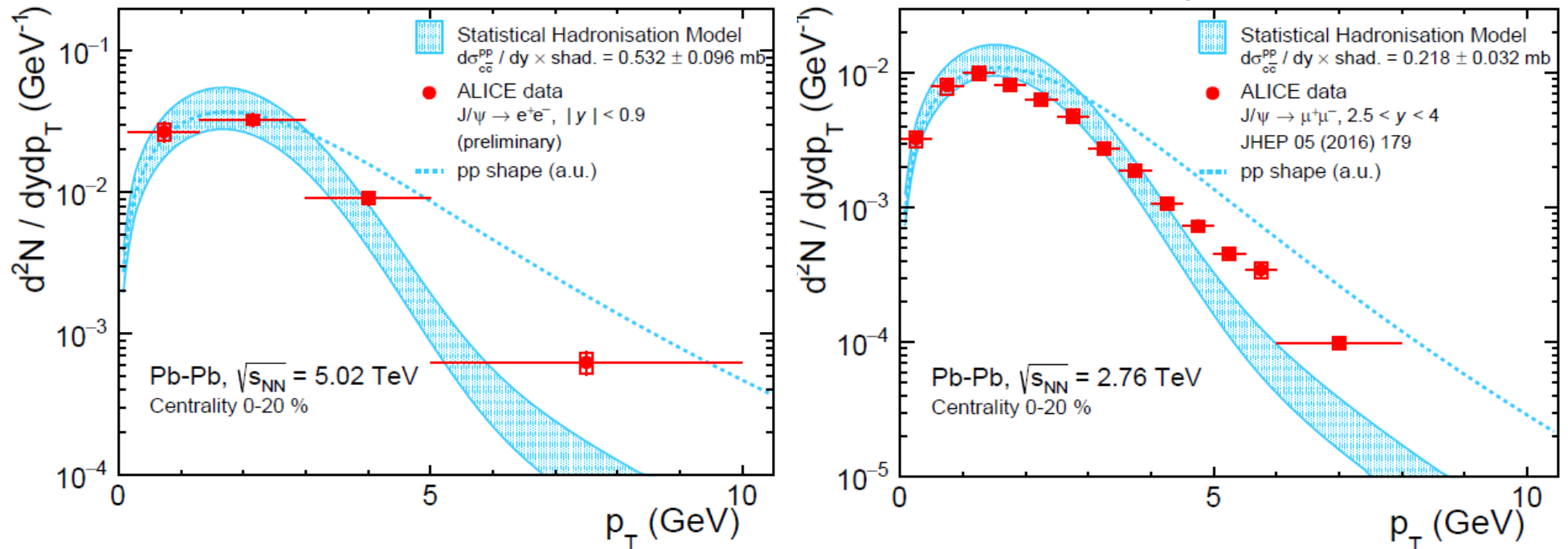
for statistical hadronization  $J/\psi$  yield  
proportional to  $N_c^2$  - higher yield at  
mid-rapidity predicted in line with  
observation  
(at RHIC and LHC)

M. Köhler, A. Andronic, P. Braun-Munzinger, JS  
arXiv:1807.01236



# J/ $\psi$ transverse momentum spectra from stat. hadr.

M. Köhler, A. Andronic, P. Braun-Munzinger, JS, arXiv:1807.01236



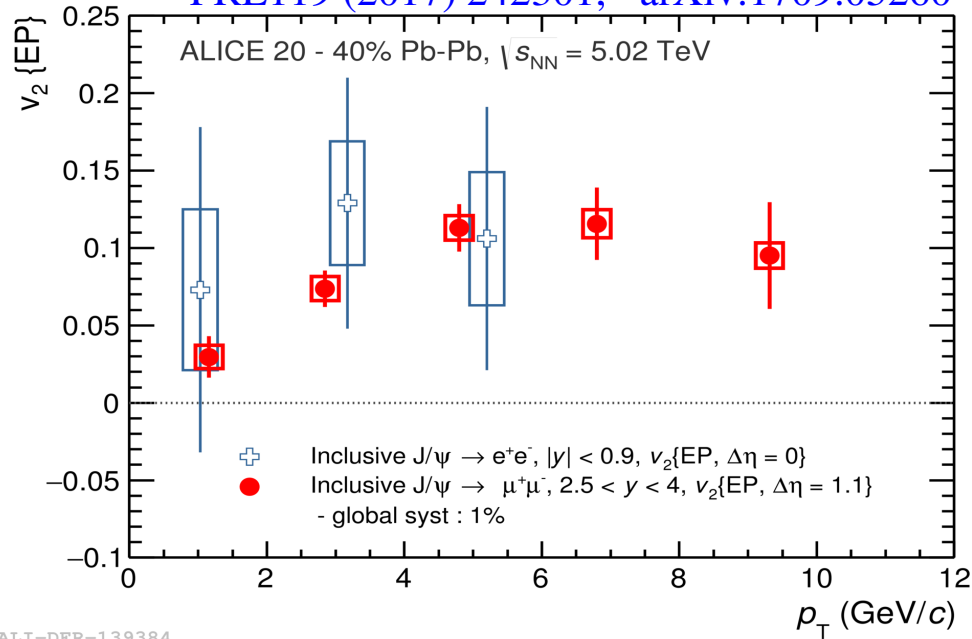
quite reasonable agreement without any free parameters

J/ $\psi$  formed at hadronization at  $T_c$  from thermalized charm quarks flowing with the rest of the medium  
need to increase statistics!



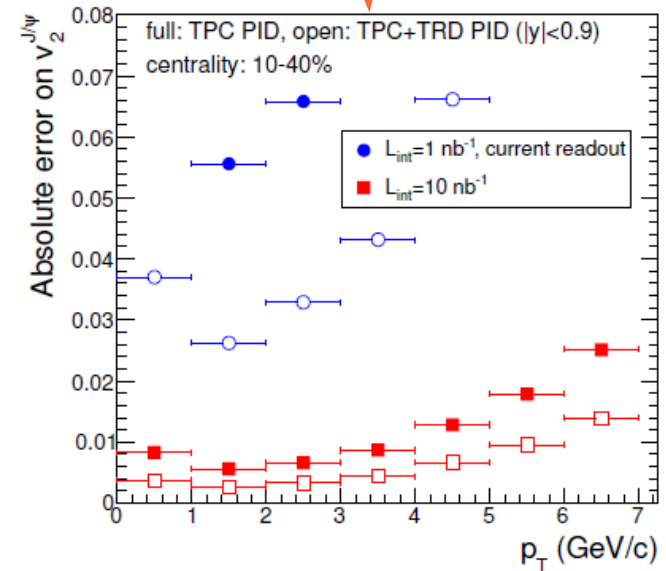
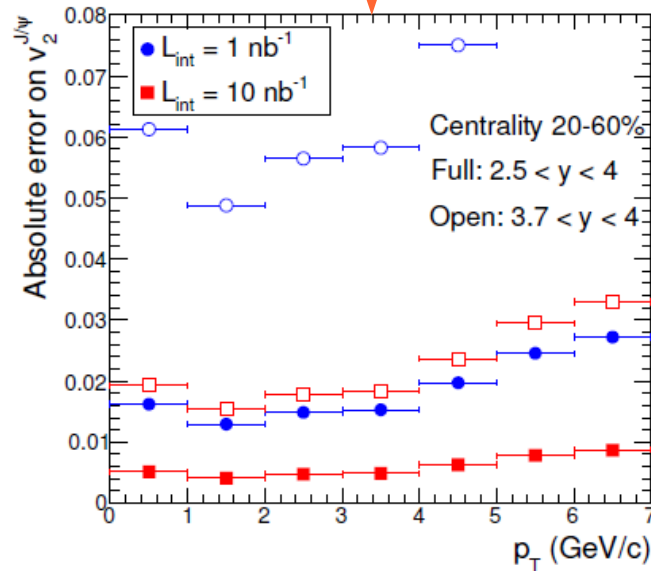
# J/ψ elliptic flow

PRL119 (2017) 242301, arXiv:1709.05260

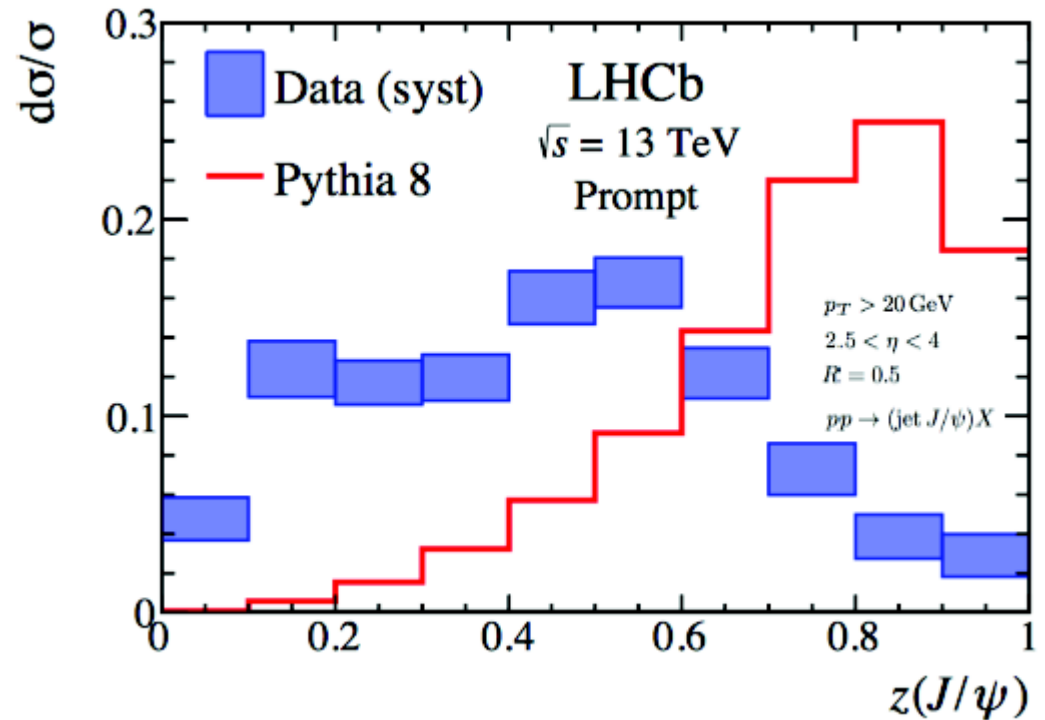
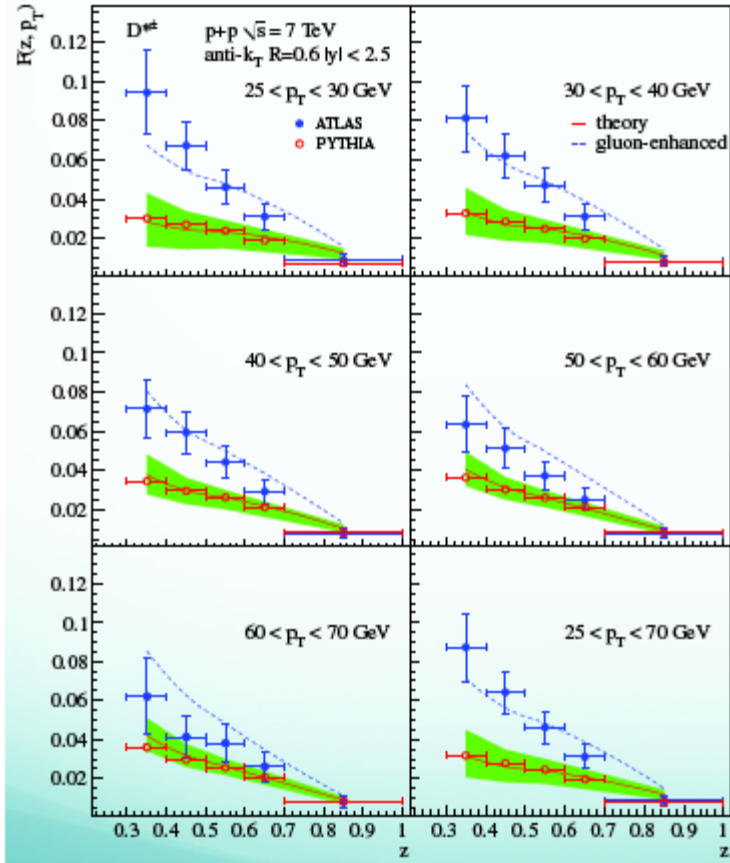


future statistical errors  
muon arm      central barrel

ALI-DER-139384



# D meson and J/ψ fragmentation functions surprising



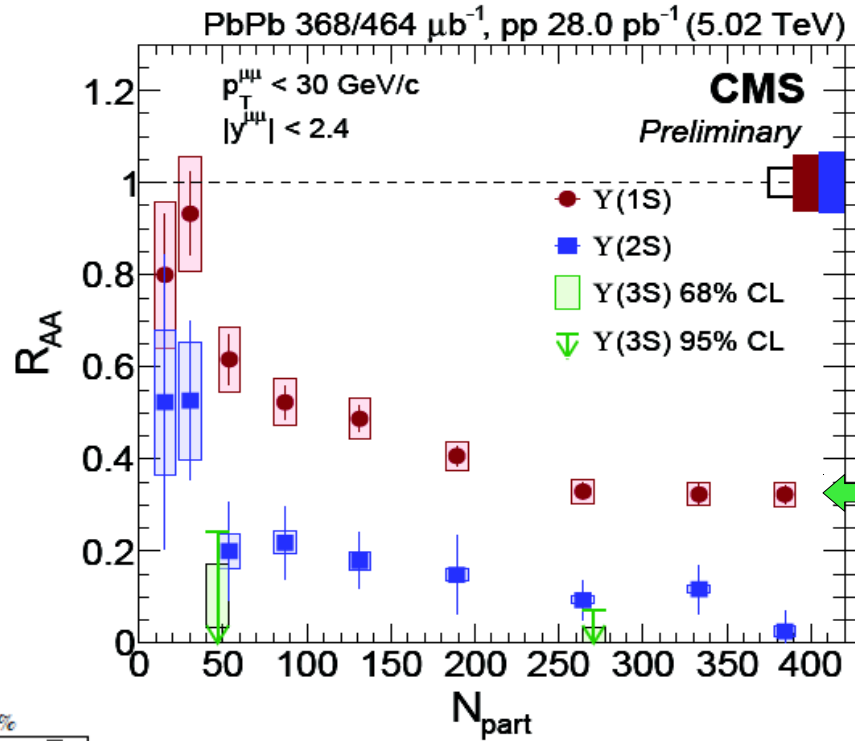
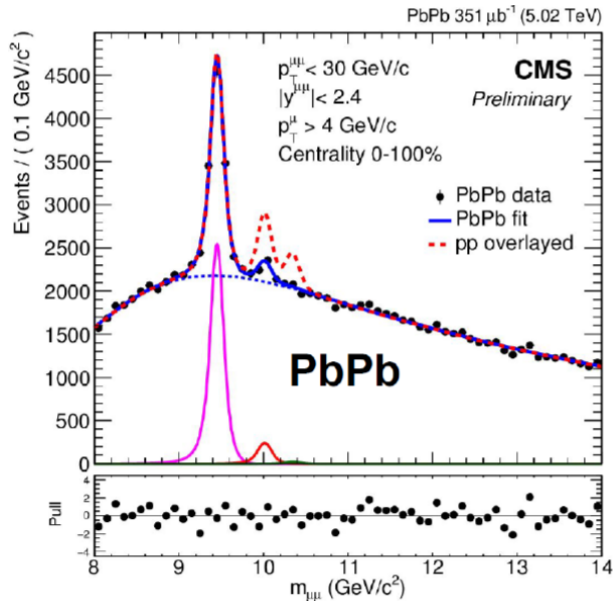
H.Xing (Wuhan 10/2018) : data prefers that jet was initiated by a single parton fragmentation, while PYTHIA starts from a  $c\bar{c}$

Gluon fragmentation into J/ψ could well be the mechanism explaining the high  $p_t$   $R_{AA}$  measure J/ψ in jets in pp and PbPb

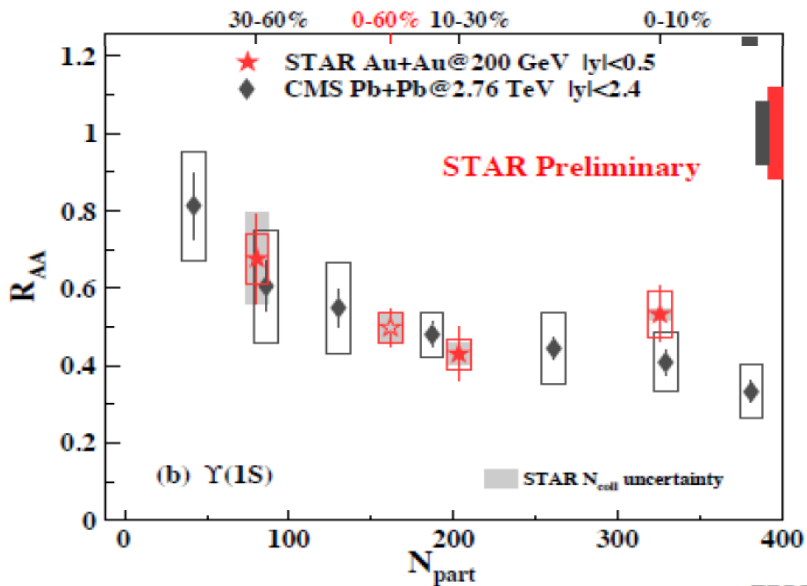
Using ZM-VFNS scheme:  
Chien, Kang, Ringer, Vitev, Xing,  
1512.06851, JHEP 16

$$- - - D_g^D(z, \mu) \rightarrow 2D_g^D(z, \mu)$$

# Suppression of Upsilon states



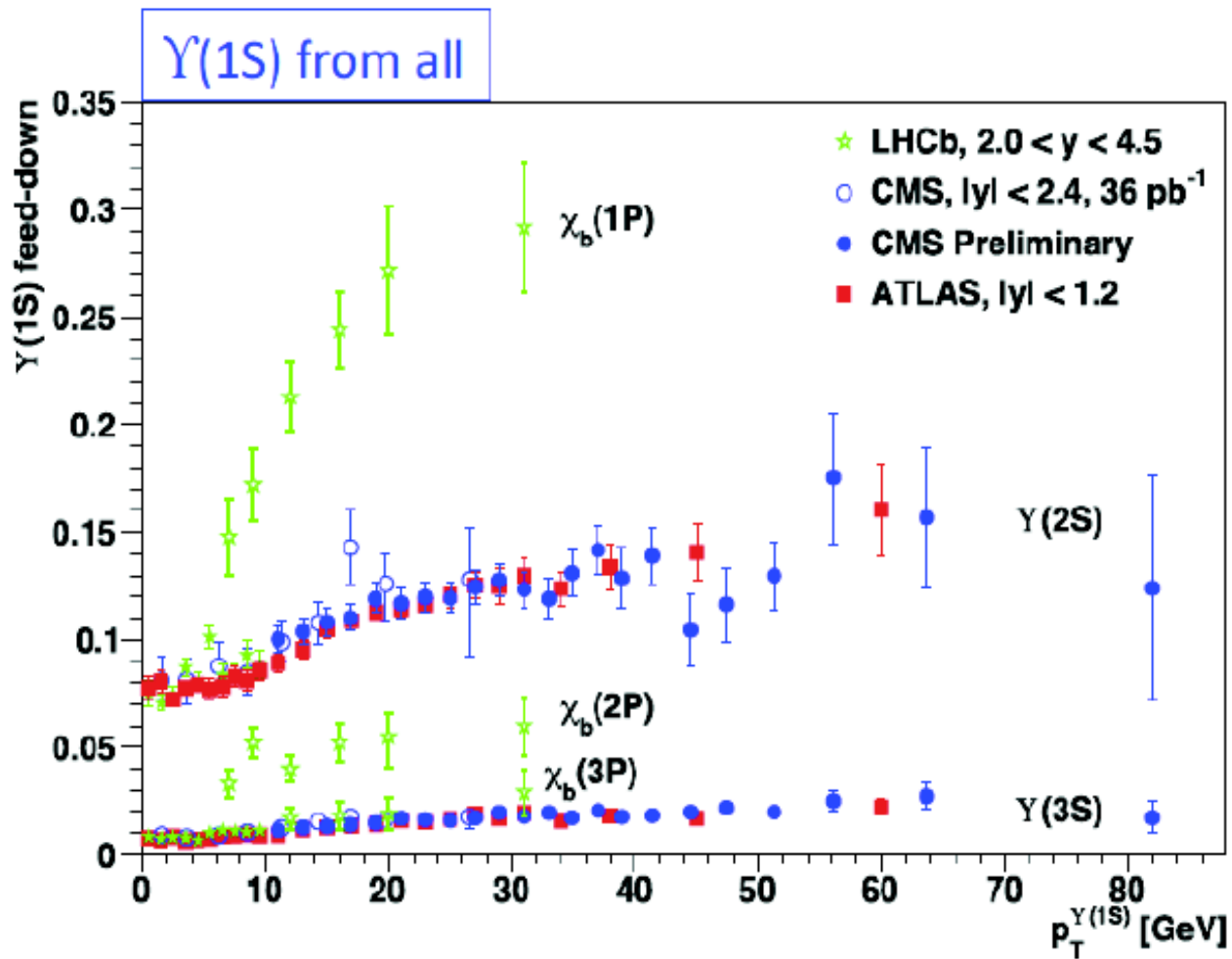
not consistent with just excited state suppression (LHCb data: only 25 % feed-down in pp at LHC)



genuine Upsilon suppression

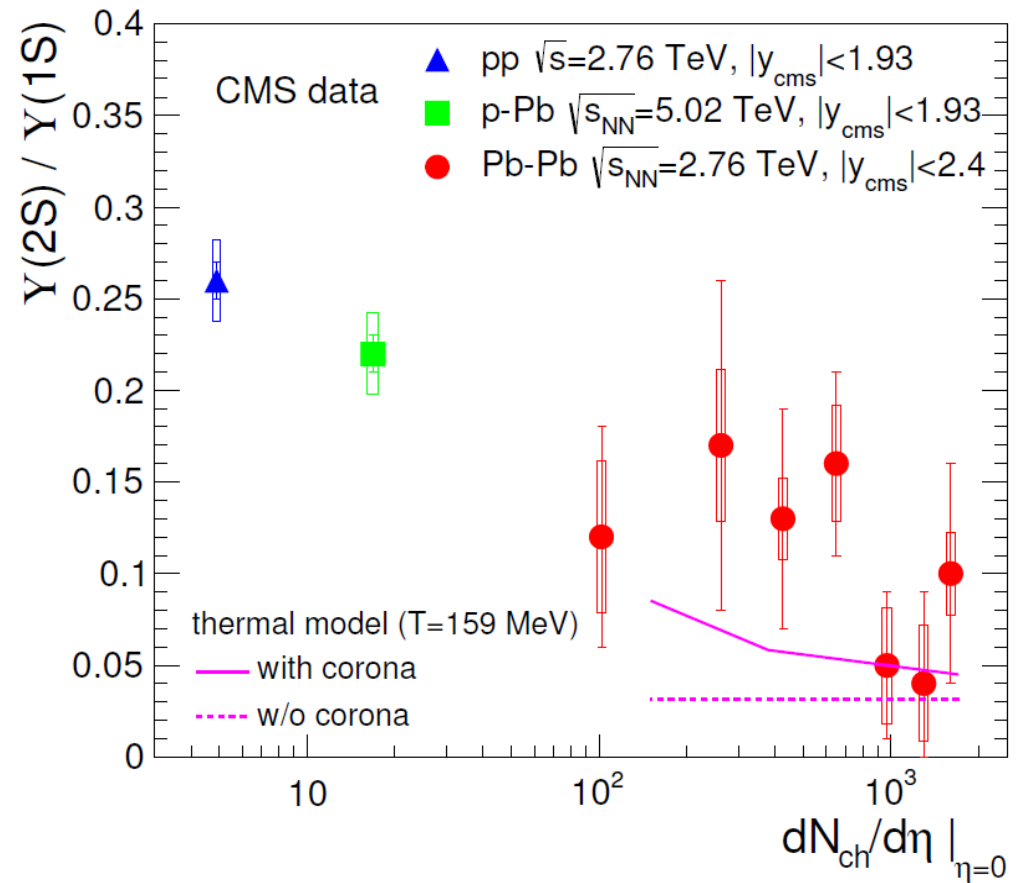
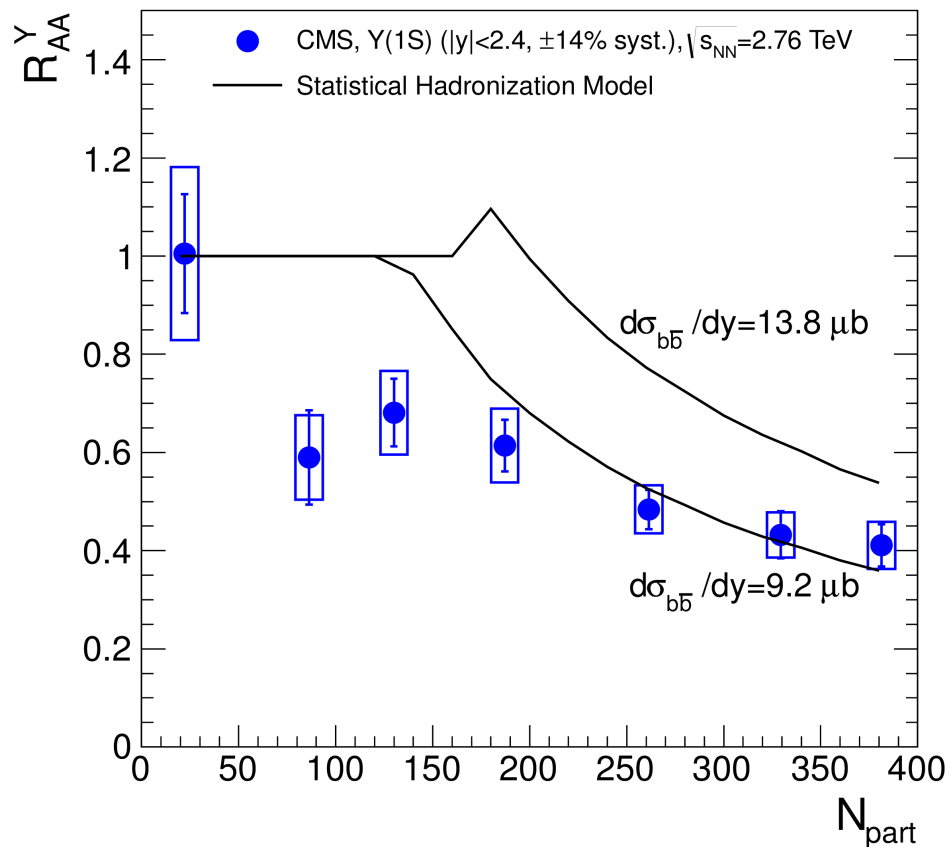
- real and imaginary part of potential at finite temperature play a role
- similarity of RHIC and LHC suppression reminiscent of SPS and RHIC for  $J/\psi$
- possibility of statistical hadronization?

# Feeding into Upsilon (1S)



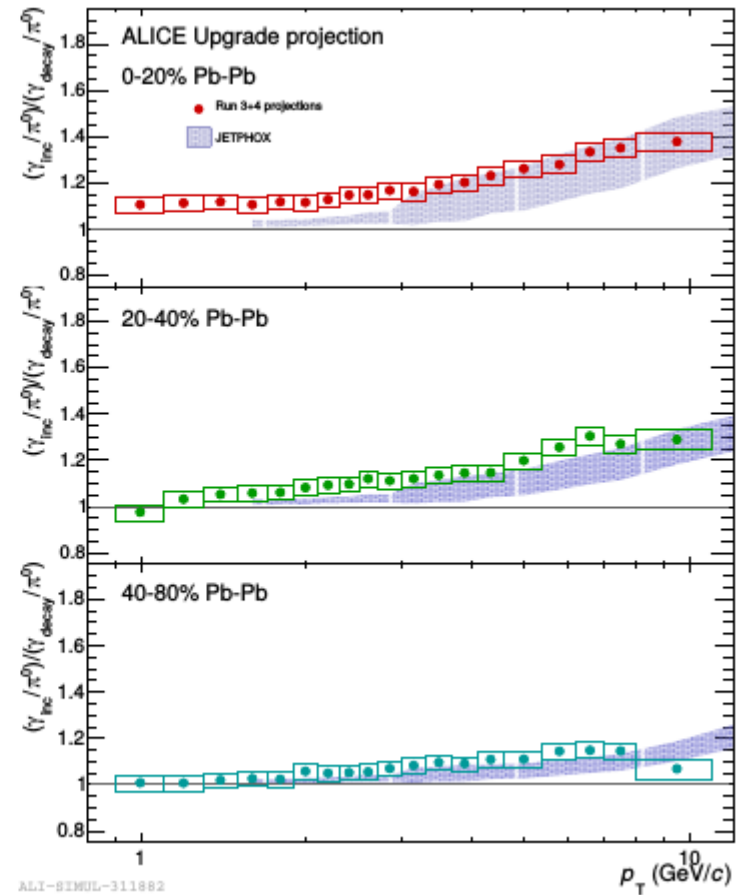
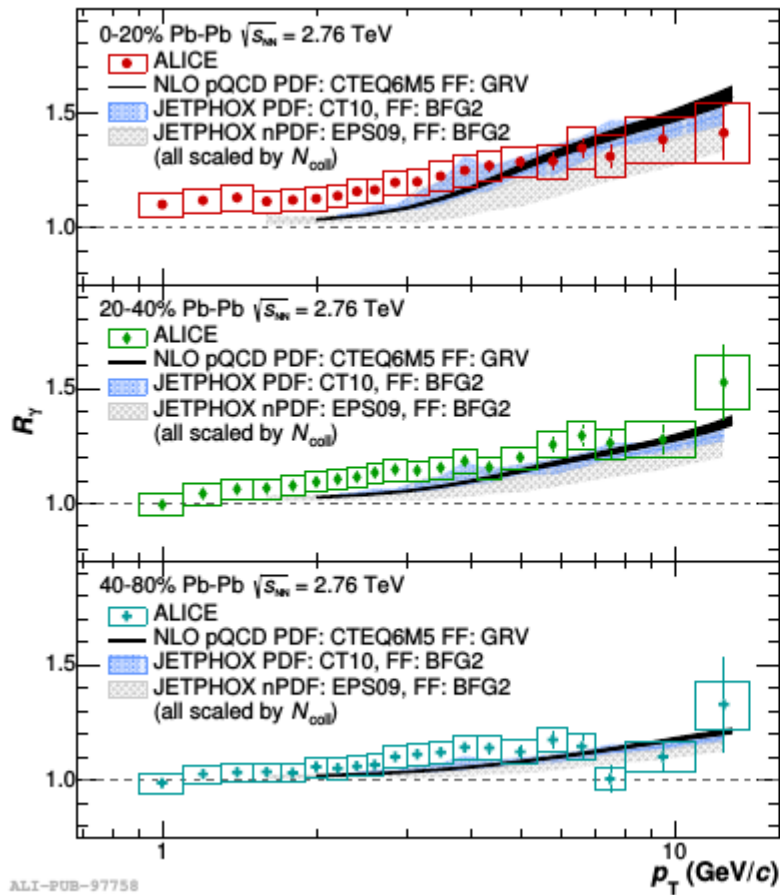
# the Upsilon could also come from statistical hadronization

SHM/thermal model: Andronic et al.



in this picture, the entire Upsilon family is formed at hadronization  
 but: need to know first – do b-quark thermalize at all? spectra of B  
 - total b-cross section in PbPb

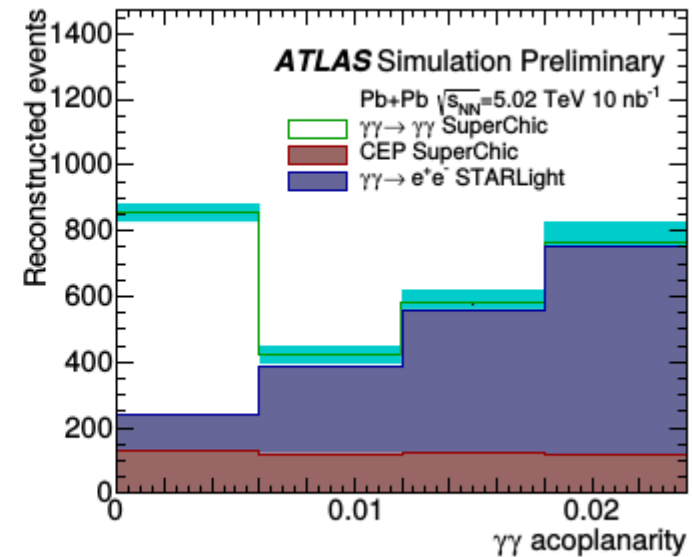
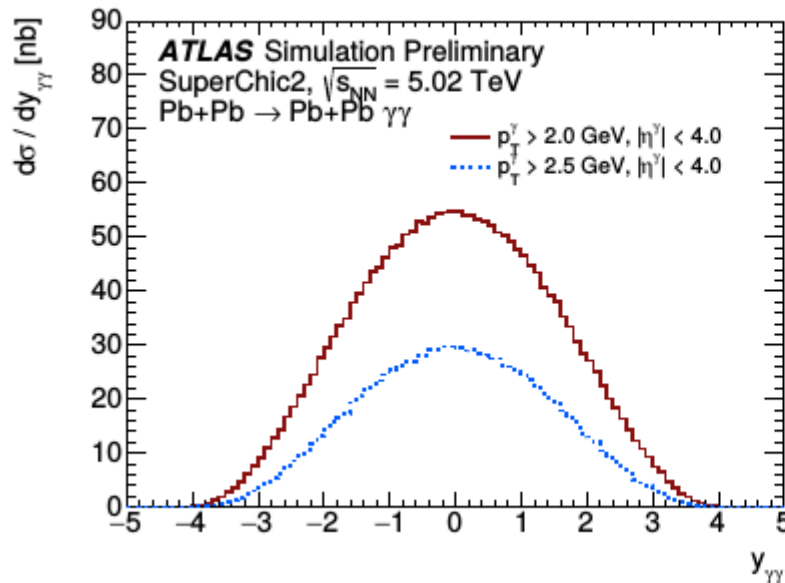
# Real photons in PbPb



Run3/4: even with current, relatively small  $R_\gamma$ ,  $3 \sigma$  sensitivity can be reached also for  $v_2^\gamma$

# Light by light scattering in PbPb

discovered by ATLAS and CMS in PbPb 2015,  $0.4 \text{ nb}^{-1}$



projection Run3/4: factor 50 increase of accepted LbyL counts after cuts  
(optimize)



# Light-by-light scattering

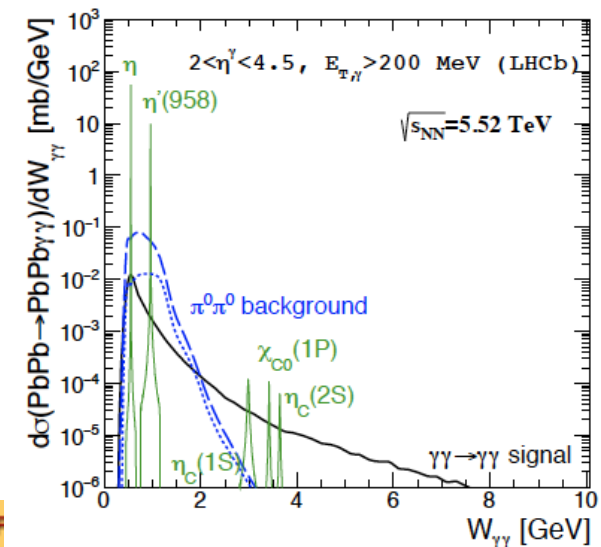
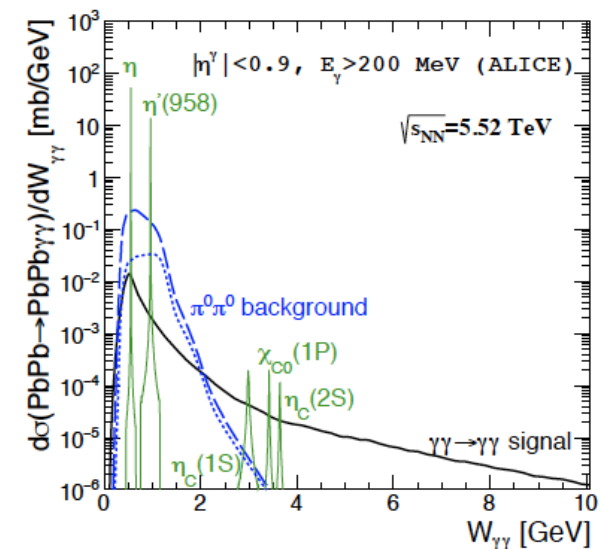
evidence for this rare process has been obtained by ATLAS and CMS with  $0.4 \text{ nb}^{-1}$  integrated luminosity for Pb-Pb collisions in Run2.

ATLAS Collaboration, M. Aaboud et al. *Nature Phys.* 13 (2017) no. 9, 852–858, arXiv:1702.01625 [hep-ex]  
CMS Collaboration, A. M. Sirunyan et al. arXiv:1810.04602 [hep-ex]

process is potentially sensitive to new particles with substantial increase in integrated luminosity and if lower  $p_t$  photons can be used. Needs improved triggering (ATLAS, CMS) or continuous read-out (ALICE, LHCb). Much more than 1 oom increase in sensitivity is expected.

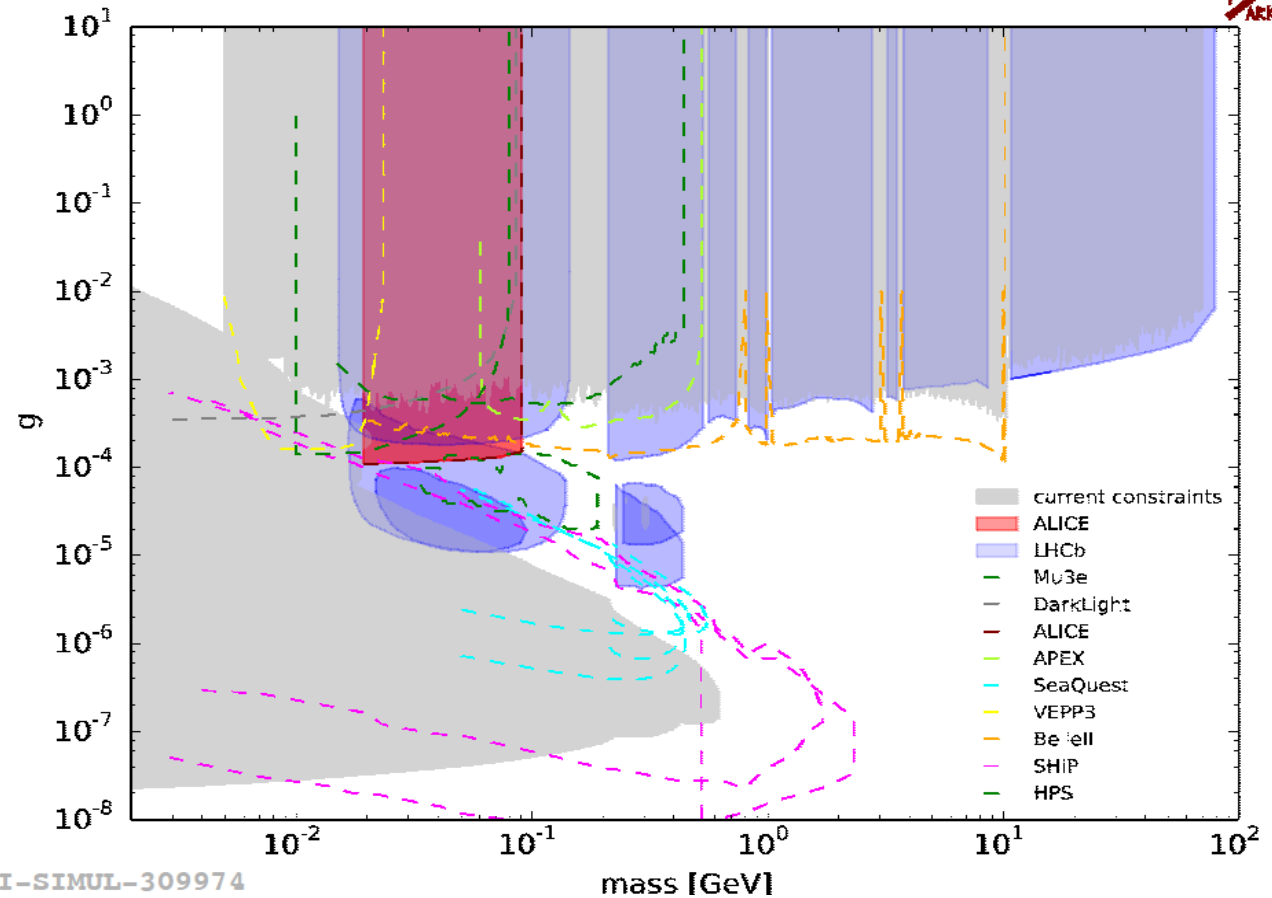
both ALICE and LHCb can after upgrade measure LbyL scattering at di-photon invariant masses above 2 GeV in Run3/4 with substantial yields ( $\gg 1000$  events).

for more details see CERN YR 1812.06772.



# Search for dark photons

Search for narrow structures in  $e^+e^-$  or  $\mu^+\mu^-$  invariant mass distributions



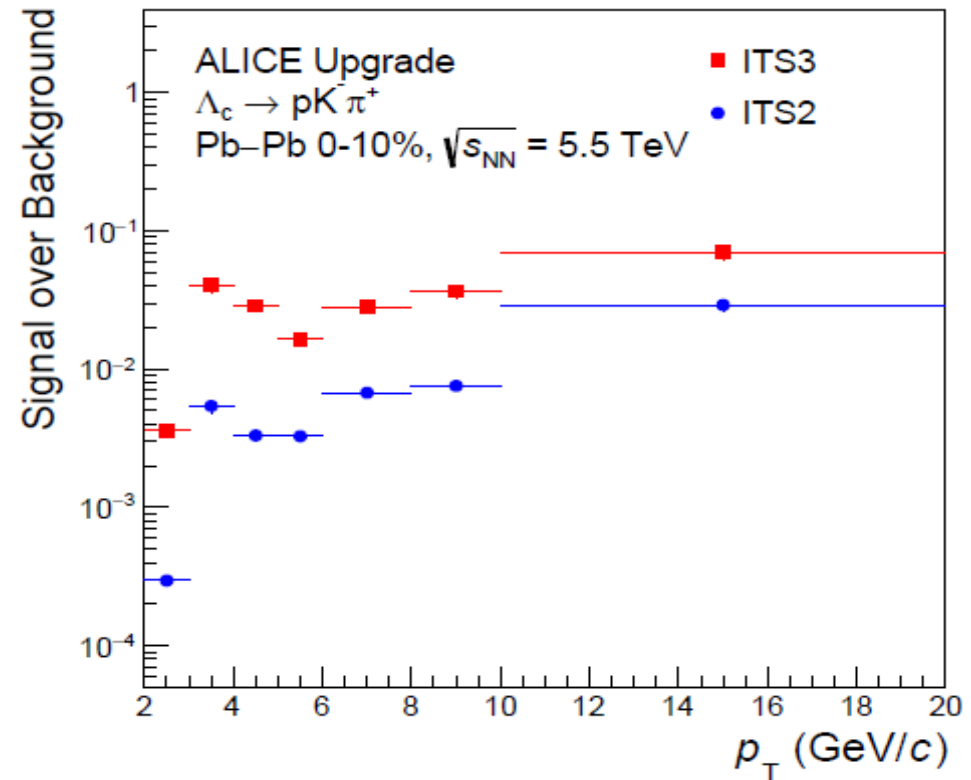
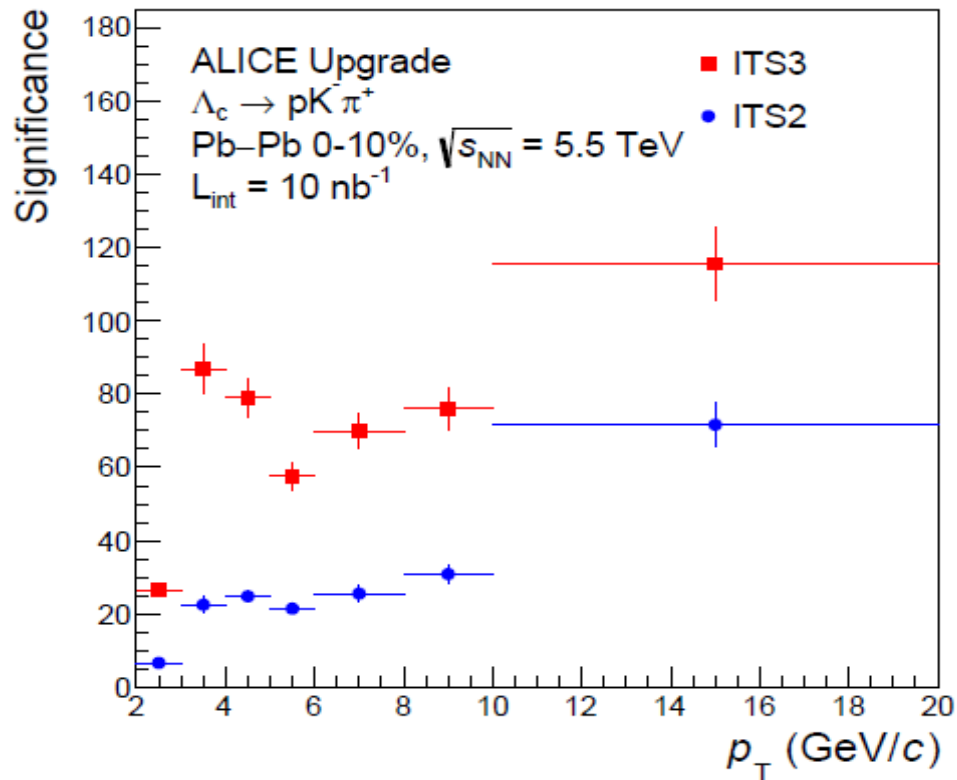
substantial improvements of limits are expected by ALICE and LHCb in Run3/4 after the upgrade

# Luminosity requirements in WG5 report & running

- **Pb–Pb at  $\sqrt{s_{NN}} = 5.5 \text{ TeV}$** ,  $L_{\text{int}} = 13 \text{ nb}^{-1}$  (ALICE, ATLAS, CMS),  $2 \text{ nb}^{-1}$  (LHCb)
- **pp at  $\sqrt{s} = 5.5 \text{ TeV}$** ,  $L_{\text{int}} = 600 \text{ pb}^{-1}$  (ATLAS, CMS),  $6 \text{ pb}^{-1}$  (ALICE),  $50 \text{ pb}^{-1}$  (LHCb)
- **pp at  $\sqrt{s} = 14 \text{ TeV}$** ,  $L_{\text{int}} = 200 \text{ pb}^{-1}$  with low pileup (ALICE, ATLAS, CMS)
- **p–Pb at  $\sqrt{s_{NN}} = 8.8 \text{ TeV}$** ,  $L_{\text{int}} = 1.2 \text{ pb}^{-1}$  (ATLAS, CMS),  $0.6 \text{ pb}^{-1}$  (ALICE, LHCb)
- **pp at  $\sqrt{s} = 8.8 \text{ TeV}$** ,  $L_{\text{int}} = 200 \text{ pb}^{-1}$  (ATLAS, CMS, LHCb),  $3 \text{ pb}^{-1}$  (ALICE)
- **O–O at  $\sqrt{s_{NN}} = 7 \text{ TeV}$** ,  $L_{\text{int}} = 500 \mu\text{b}^{-1}$  (ALICE, ATLAS, CMS, LHCb)
- **p–O at  $\sqrt{s_{NN}} = 9.9 \text{ TeV}$** ,  $L_{\text{int}} = 200 \mu\text{b}^{-1}$  (ALICE, ATLAS, CMS, LHCb)
- **Intermediate AA**, e.g.  $L_{\text{int}}^{\text{Ar–Ar}} = 3\text{--}9 \text{ pb}^{-1}$  (about 3 months) gives NN luminosity equivalent to Pb–Pb with  $L_{\text{int}} = 75\text{--}250 \text{ nb}^{-1}$

Year	Systems, $\sqrt{s_{NN}}$	Time	$L_{\text{int}}$
2021	Pb–Pb 5.5 TeV	3 weeks	$2.3 \text{ nb}^{-1}$
	pp 5.5 TeV	1 week	$3 \text{ pb}^{-1}$ (ALICE), $300 \text{ pb}^{-1}$ (ATLAS, CMS), $25 \text{ pb}^{-1}$ (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	$3.9 \text{ nb}^{-1}$
	O–O, p–O	1 week	$500 \mu\text{b}^{-1}$ and $200 \mu\text{b}^{-1}$
2023	p–Pb 8.8 TeV	3 weeks	$0.6 \text{ pb}^{-1}$ (ATLAS, CMS), $0.3 \text{ pb}^{-1}$ (ALICE, LHCb)
	pp 8.8 TeV	few days	$1.5 \text{ pb}^{-1}$ (ALICE), $100 \text{ pb}^{-1}$ (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	$3.8 \text{ nb}^{-1}$
	pp 5.5 TeV	1 week	$3 \text{ pb}^{-1}$ (ALICE), $300 \text{ pb}^{-1}$ (ATLAS, CMS), $25 \text{ pb}^{-1}$ (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	$0.6 \text{ pb}^{-1}$ (ATLAS, CMS), $0.3 \text{ pb}^{-1}$ (ALICE, LHCb)
	pp 8.8 TeV	few days	$1.5 \text{ pb}^{-1}$ (ALICE), $100 \text{ pb}^{-1}$ (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	$3 \text{ nb}^{-1}$
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar $3\text{--}9 \text{ pb}^{-1}$ (optimal species to be defined)
	pp reference	1 week	

# ITS3 in ALICE



**significant improvement in heavy flavor sector due to superb vertexing capability particularly important for baryons**

## Doorway state hypothesis tested in new expt.

**all nuclei and hyper-nuclei, penta-quark and X,Y,Z states are formed as virtual, compact multi-quark states at the phase boundary. Then slow time evolution into hadronic representation. Excitation energy about 20 MeV, time evolution about 10 fm/c**

Andronic, Braun-Munzinger, Redlich, JS, Nature 2018, arXiv :1710.09425

### **How can this be tested?**

precision measurement of spectra and flow pattern for light nuclei and hyper-nuclei, penta-quark and X,Y,Z states from pp via pPb to Pb-Pb

**a major new opportunity for ALICE**

**beyond LS4 for X,Y,Z , multi-charm, charm-beauty and penta-quark states**

## Holy grail for statistical hadronization of charm: opportunities of new experiment

The detection and quantitative measurement of  $\chi_c$  states involves the identification of a low energy (about 300 - 440 MeV near mid-rapidity) photon in addition to a  $J/\psi$  meson. To measure this we will pursue two options. In option 1 the low energy photon is measured with large efficiency and over the full solid angle in the pre-shower detector. To separate the  $\chi_c$  states one needs a photon energy resolution of about 5% near 400 MeV corresponding to  $\frac{\delta E_\gamma}{E_\gamma} \approx 3\% / \sqrt{E_\gamma(\text{GeV})}$  which should be achievable in the preshower detector. For the second option, with lower efficiency but excellent photon energy resolution we plan to introduce, very close to the beam pipe, a (removable) external converter of thickness of 5 - 10% of a radiation length. A photon can then be identified by the absence of tracks in the inner Si layers and by two tracks of opposite charge whose combined momentum precisely points to the primary interaction vertex.

## Other new dilepton channels in new expt.

Interesting new opportunities arose with recent findings by Belle2 and LHC<sub>b</sub> that the  $\chi_c \rightarrow l^+l^-J/\psi$  is of order  $10^{-4}$ . This would imply that the  $\chi_c \rightarrow 4leptons$  becomes an attractive channel to study the production of  $\chi$  states with very high resolution. Also it would be very interesting in this context to measure the production of  $B_c^+$  in Pb–Pb collisions. Recent LHC<sub>b</sub> findings indicate substantial branching ratios into  $J/\psi\pi^+$  which could be detected in the planned detector with good accuracy. Very large enhancements are predicted for  $B_c^+$  production in the statistical hadronization model. A measurement in this channel would hence be very illuminating.



# Chiral symmetry restoration: the $\rho$ - $a_1$ region in new expt.

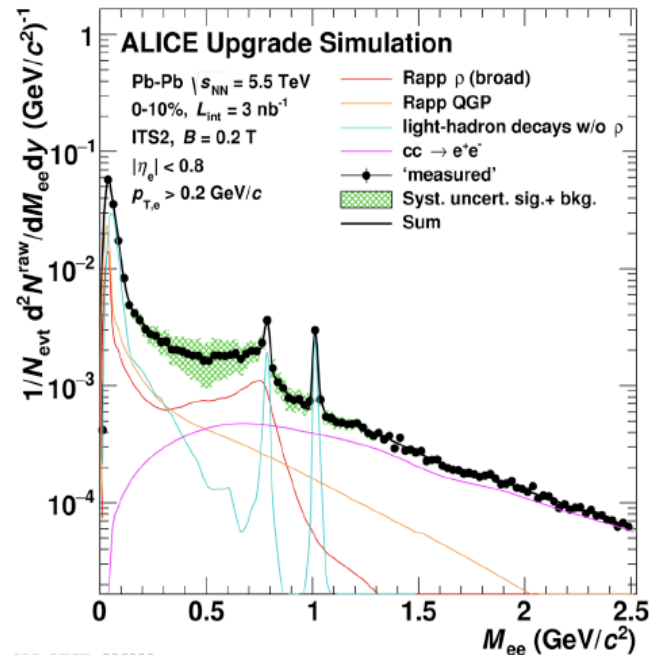
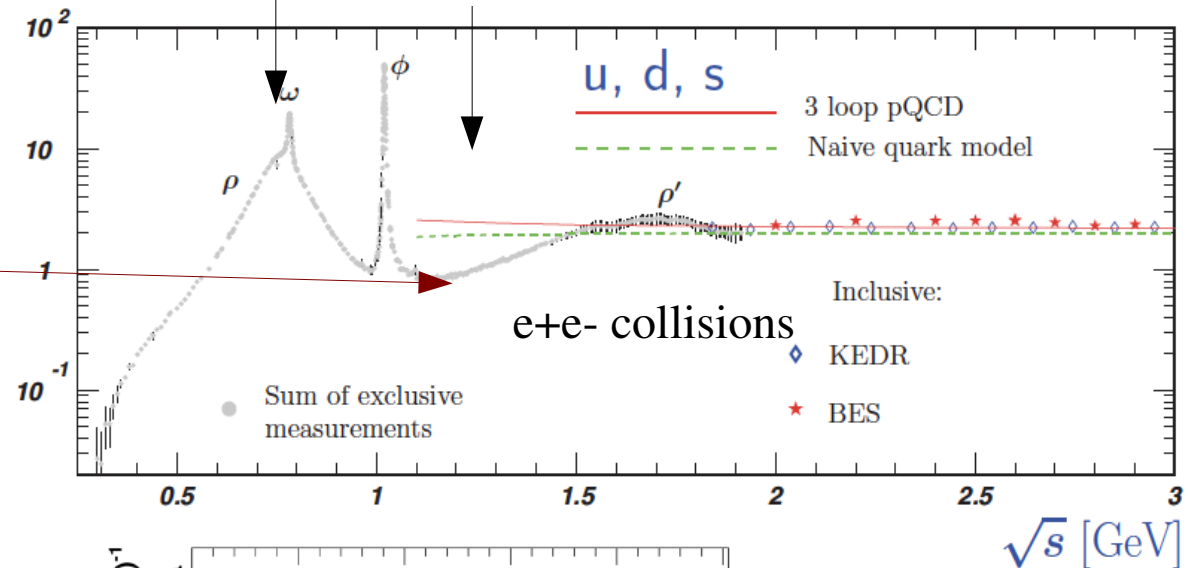
vacuum masses:  $\rho$  770 MeV,  $a_1$  1230 MeV

the idea: the  $\rho$  and  $a_1$  mesons are chiral partners. In vacuum, chiral symmetry is broken, the  $\rho$  couples to  $e^+e^-$ , but not the  $a_1$ .

in medium, chiral symmetry is restored, the chiral partners mix, and the hole in the spectral distribution should be filled.

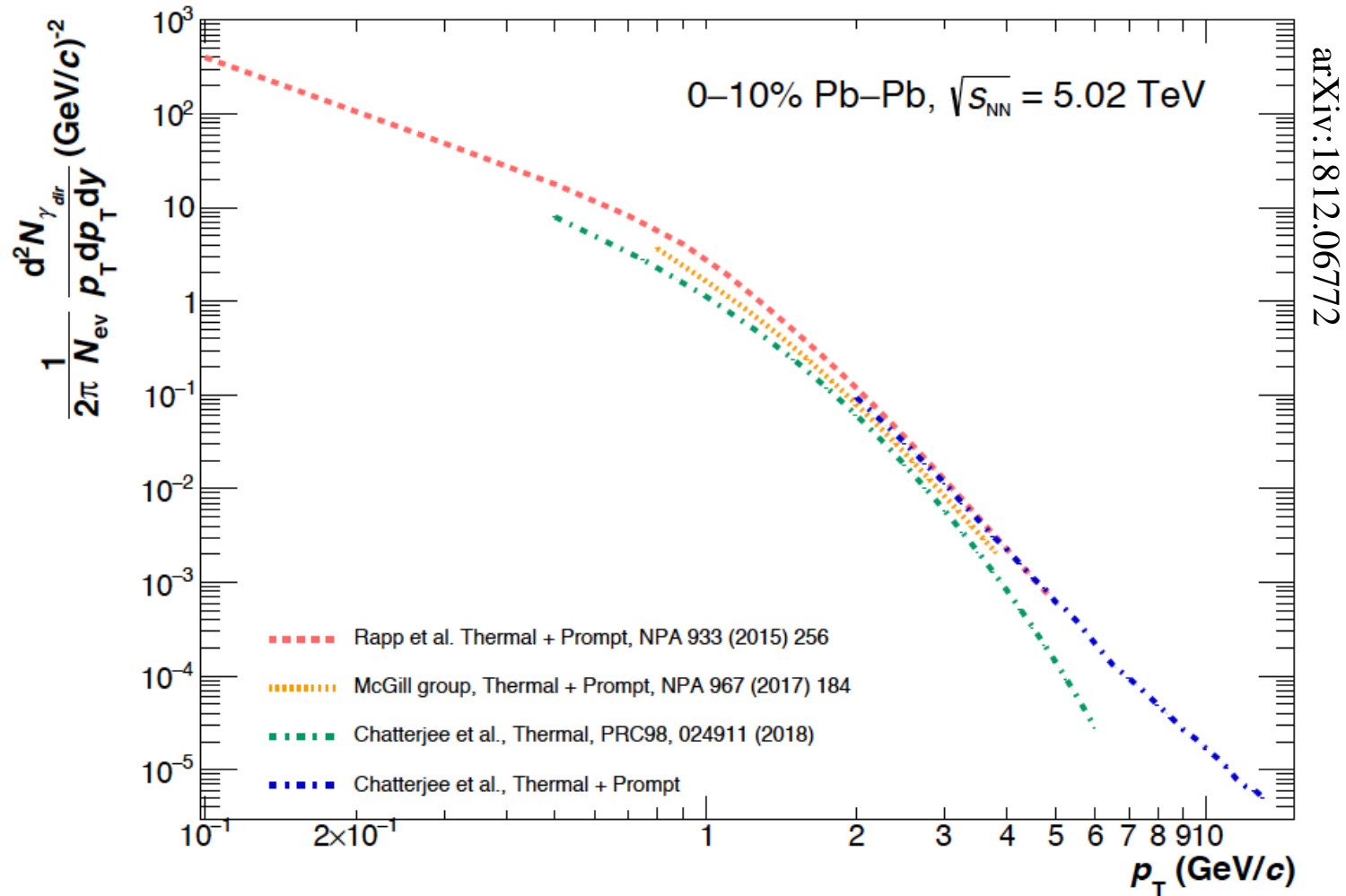
to detect this: measure dilepton mass distribution in the mass range 1.0 – 2.5 GeV in Pb-Pb collisions with precision and at low transverse momentum,  $p_T < 50$  MeV and compare with pp and  $e^+e^-$  results

the challenge: at LHC energies, the dominant dilepton decays from open charm and beauty need to be quantitatively removed → **new massless detector**



note: the background from Drell-Yan production is negligible at LHC energy

# Direct and thermal photons in Pb-Pb collisions at LHC energy: big chance for new expt.



is the range below 2 GeV measurable? can one go further down in  $p_t$ ?

# Production of real and virtual photons with very low mass ( $<10$ MeV) and very low $p_t$ ( $< 20$ MeV)

production of low mass photons and dileptons consequence of structure of all gauge theories

→ development of 'soft theorems' a la Francis Low

→ number of soft real and virtual photons (dileptons) diverges towards low  $p_T$  'in a highly controlled manner, central to the consistency of quantum field theory'.

- it would be of prime importance to reach the experimental sensitivity to test this prediction!

needs measurement at very low mass or  $p_T$

- important to measure dilepton mass distribution down to scale  $1/r$  of system under consideration

with e.g.  $R = 10$  fm for fireball size in Pb-Pb at LHC →  $p_T < 20$  MeV

currently in ALICE typically  $p_T > 200$  MeV

recently at low B field in pp down to 75 MeV

- such measurements require special, very thin detector (in forward direction)

## Spectral distortions at very low transverse momentum for pions

- Is the spectrum of hadrons in the low- $p_T$  regime a Bose-Einstein or Fermi-Dirac spectrum (depending on spin) governed by a common temperature  $T$  and fluid velocity  $u^\mu$  on the freeze-out surface?
- Can deviations from ideal gas occupation numbers on the freeze-out surface due to dissipative terms and interactions be understood quantitatively in terms of dissipative fluid dynamics, kinetic theory or non-equilibrium quantum field theory?
- Are the effect of quantum statistics visible in spectra of light hadrons, in particular pions, at low transverse momentum?
- Is maybe even a condensate or coherent fraction of pions or kaons visible in the spectrum and correlation functions at low transverse momentum?

# FCC delayed decays probing space-time evol of QGP

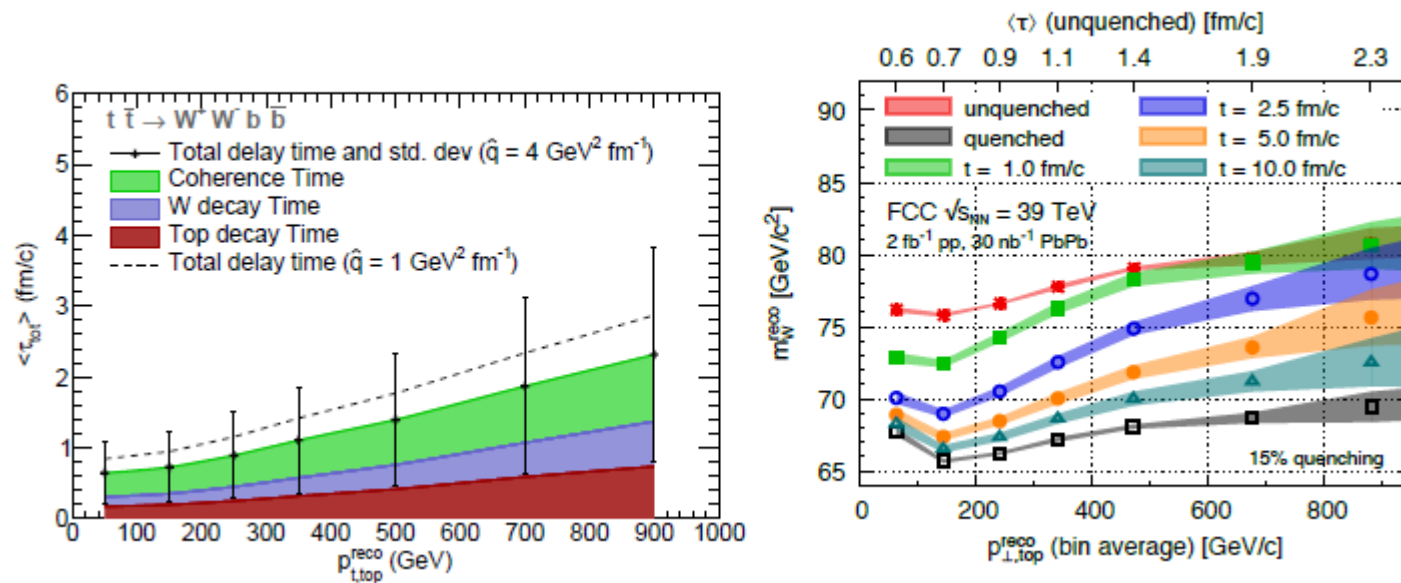
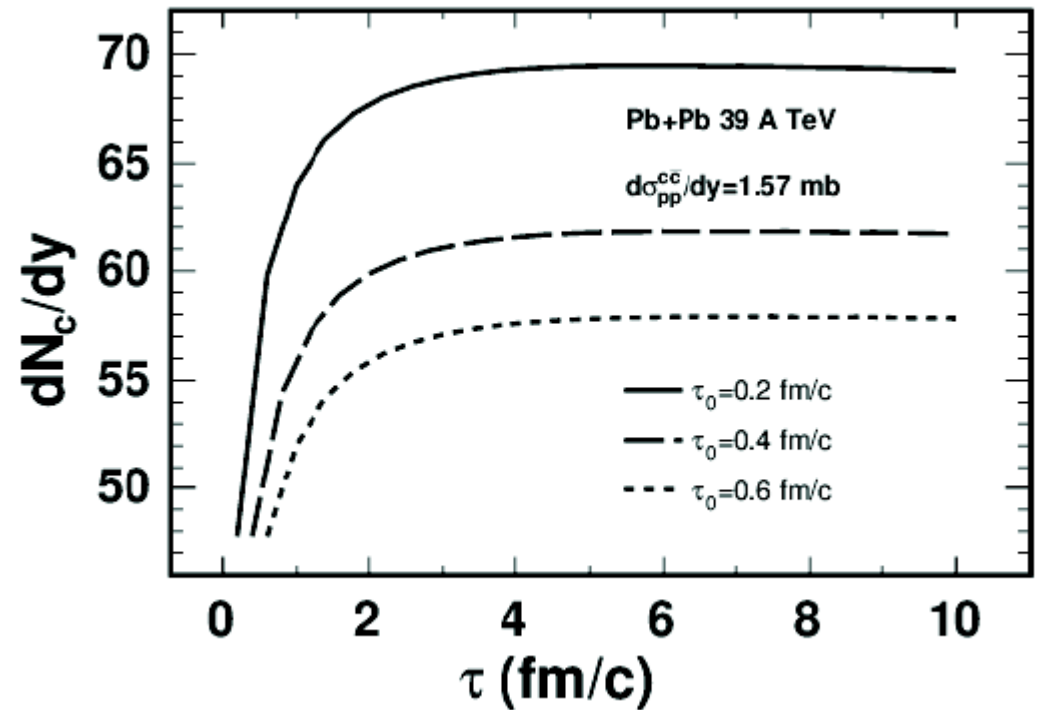
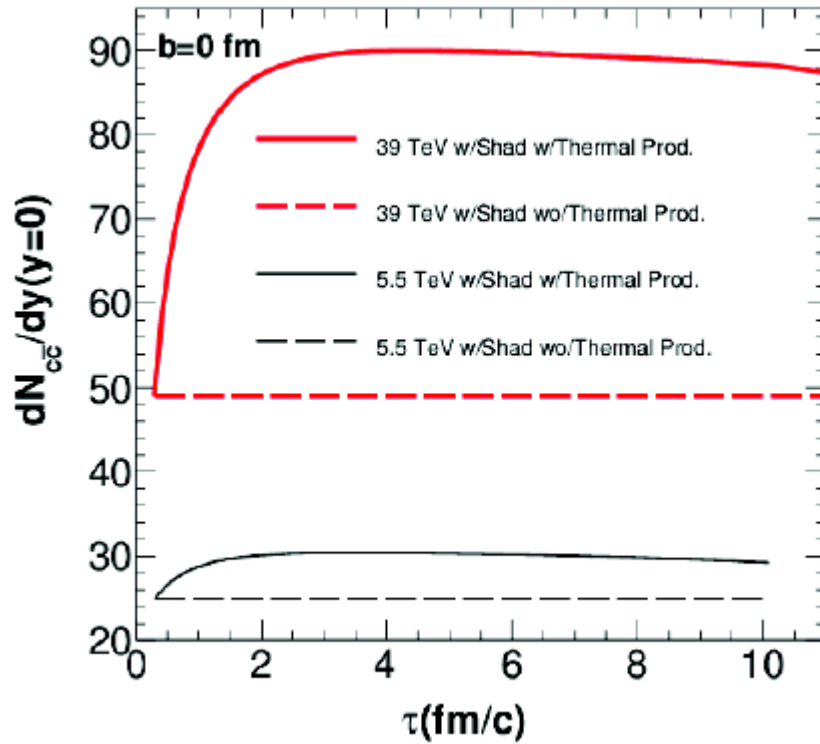
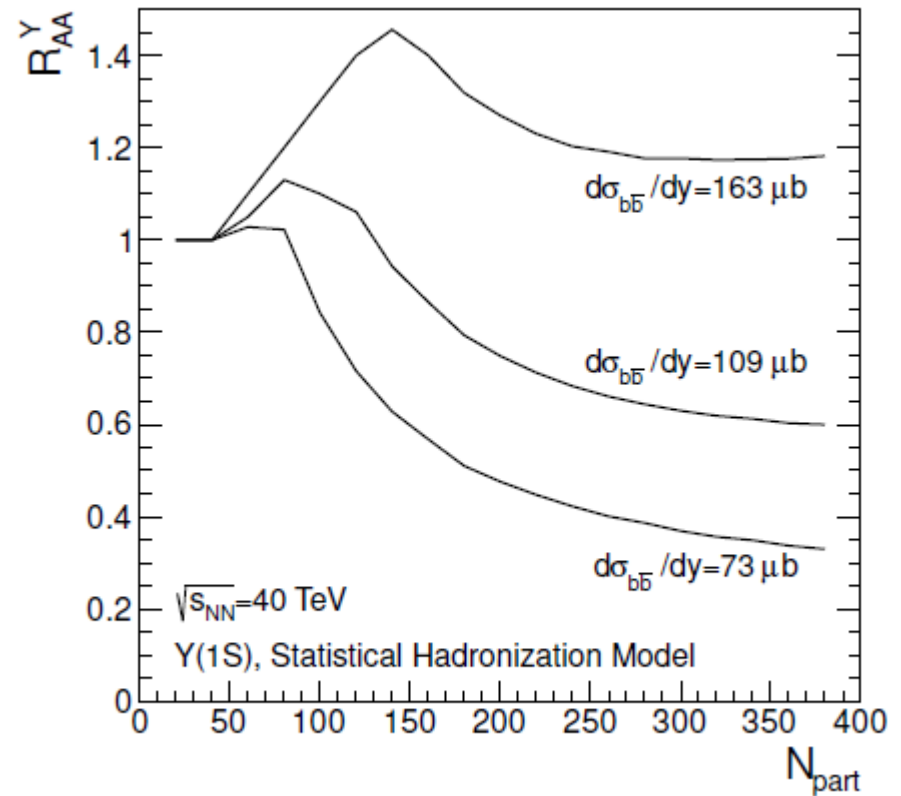
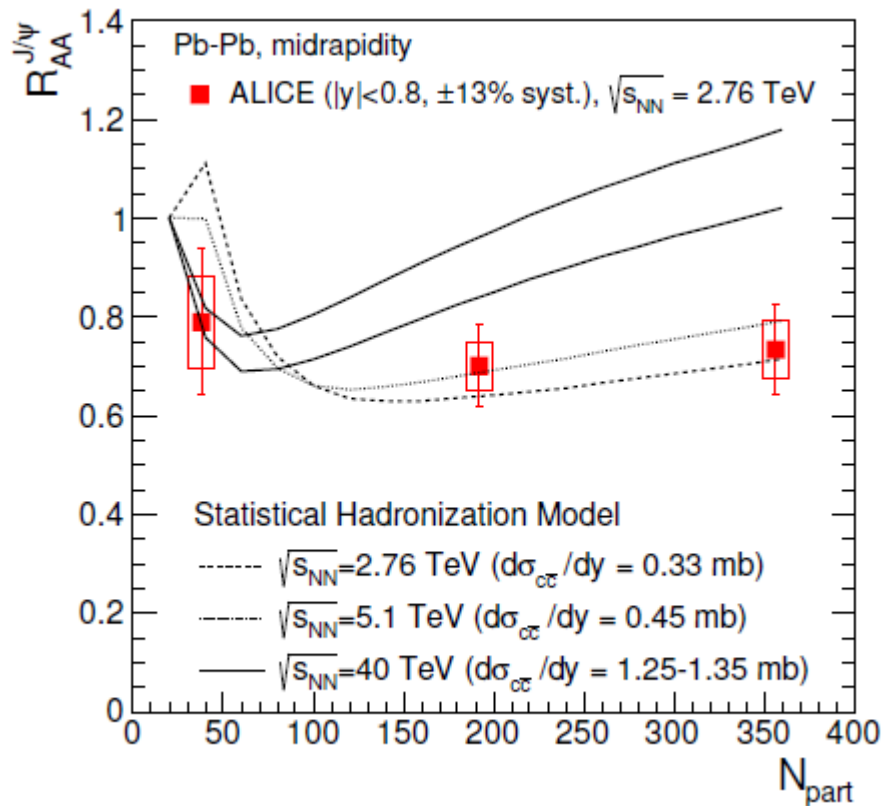


Figure 16.3: Left: Total delay time for  $\hat{q} = 4 \text{ GeV}^2/\text{fm}$  as a function of the top transverse momentum (black dots) and its standard deviation (error bars). The average contribution of each component is shown as a coloured stack band. The dashed line corresponds to a  $\hat{q} = 1 \text{ GeV}^2/\text{fm}$ . Right: Reconstructed W boson mass at FCC energies  $\sqrt{s_{\text{NN}}} = 30 \text{ TeV}$ , as a function of the top  $p_T$ . The upper axis refers to the average total time delay of the corresponding top  $p_T$  bin.

# FCC thermal charm production

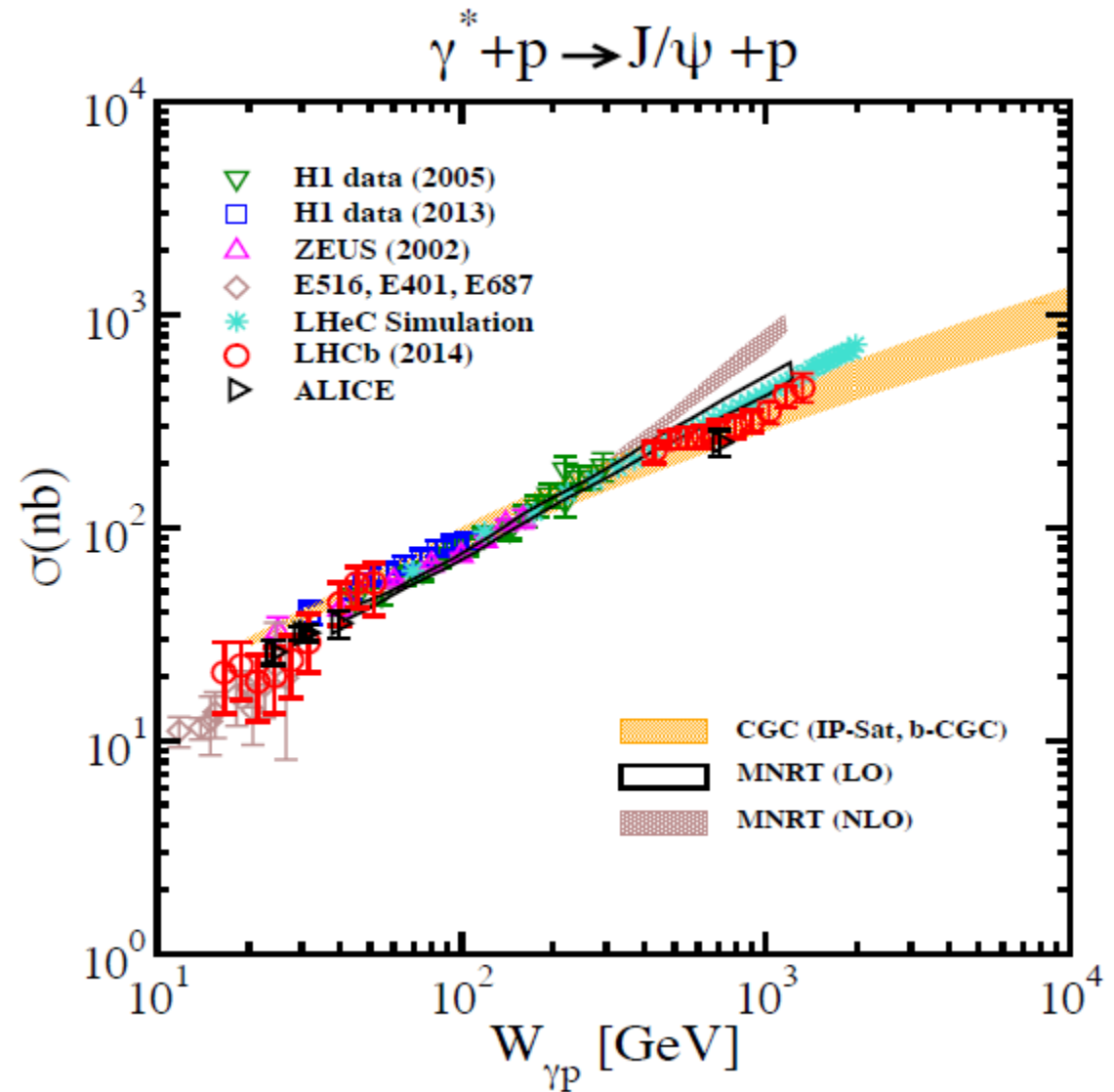
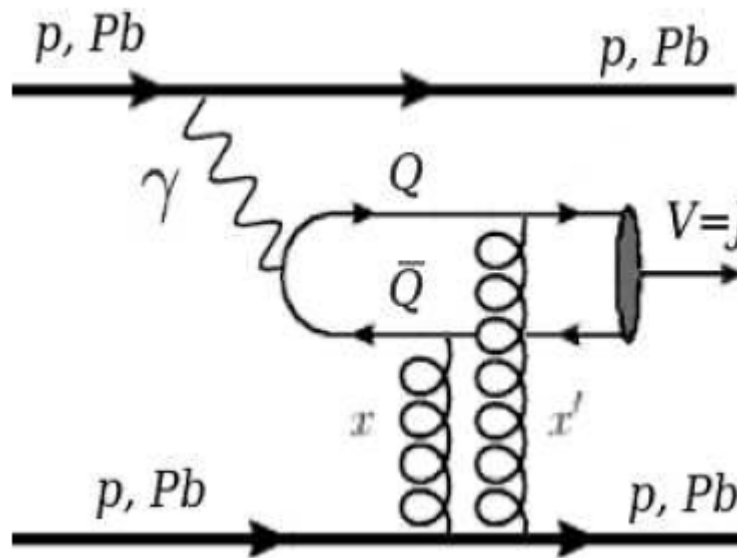


# FCC J/ $\psi$ and Upsilon





# FCC photoproduction of $J/\psi$



# FCC: gamma-gamma

