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 } illustrated with examples
- opportunities at HL-LHC } illustrated with examples
- next generation experiment at HL-LHC
- HE-LHC, FCC
- recommendations

European Strategy Update

Johanna Stachel, Universität Heidelberg
CERN Council Open Symposium on the Update of European Strategy for Particle Physics
13 - 16 May 2019 – Granada, Spain

HL-LHC for heavy ion collisions

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

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

CERN-LPCC-2018-07
February 26, 2019

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

PbPb interactions at 50 kHz (levelling) - a typical 1 month PbPb run ↔ 3.1 nb^{-1}

PbPb 10 nb^{-1} or 8 10^{10} collisions sampled, pPb, lighter ions also discussed

community: about 1250 exp. authors + 250? theory

⟶ **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 (described by 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 ± 1.5 MeV

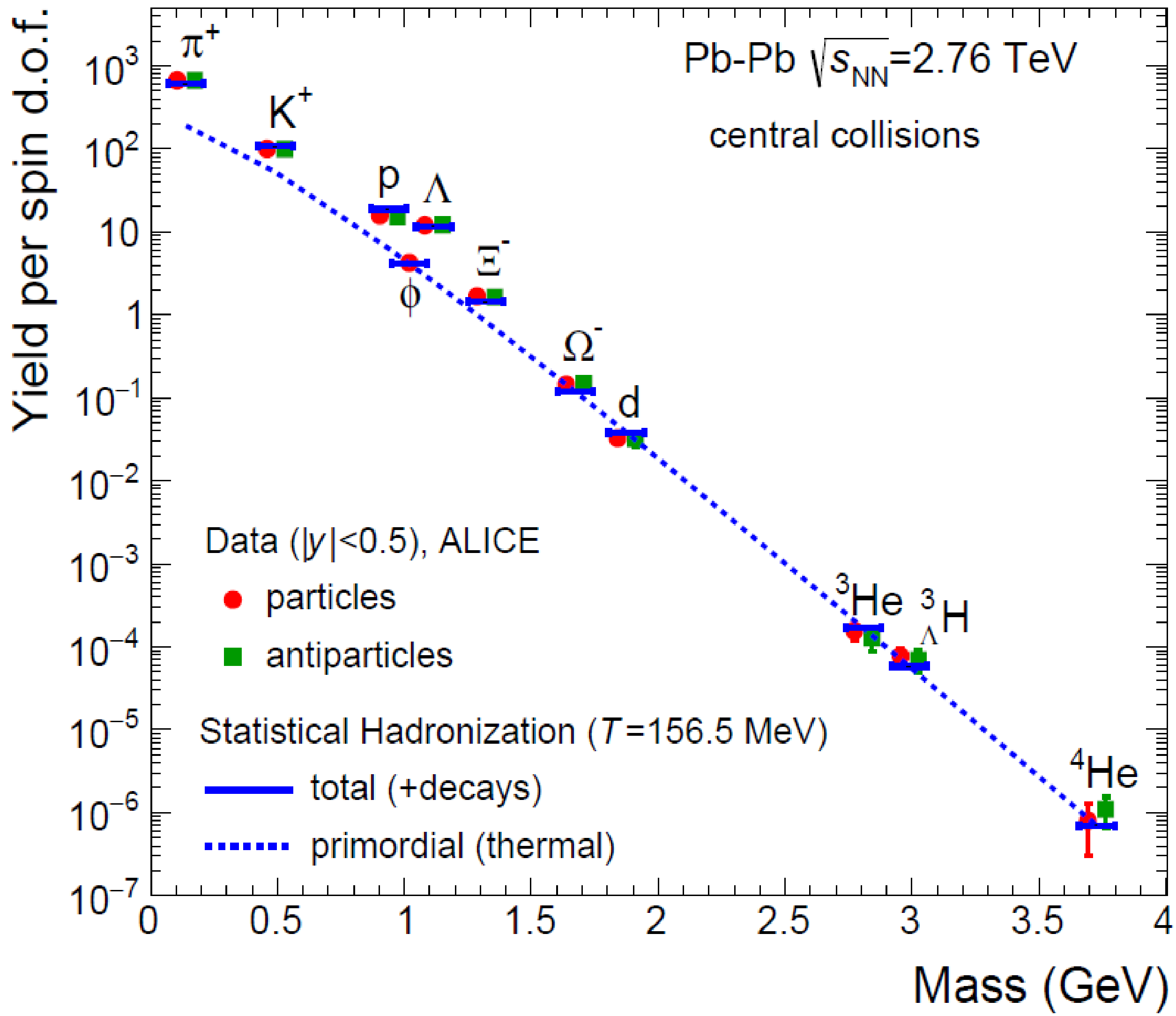
agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)

- 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



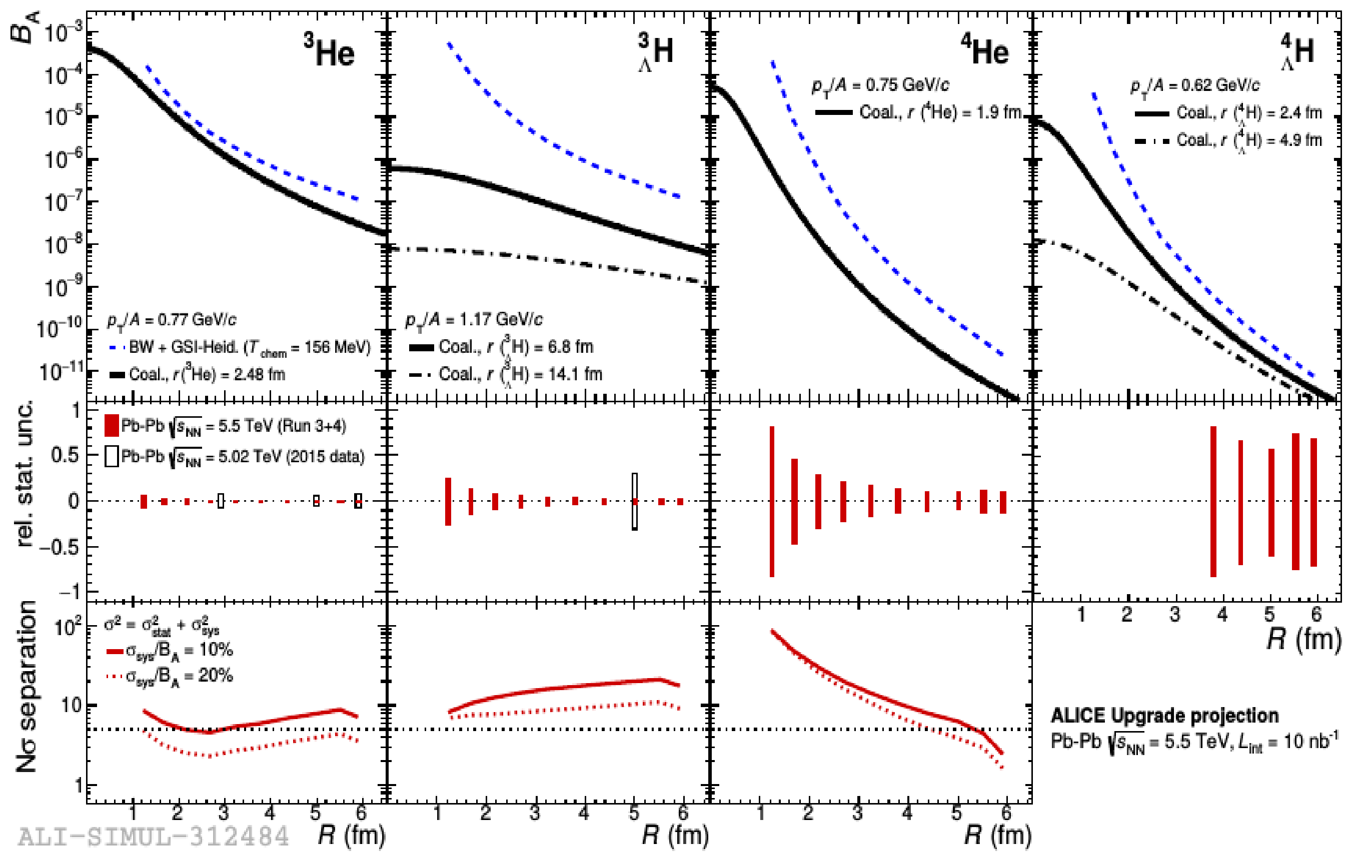
What to be added?

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

- 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 Σ-hypernuclei
- exotic QCD bound states



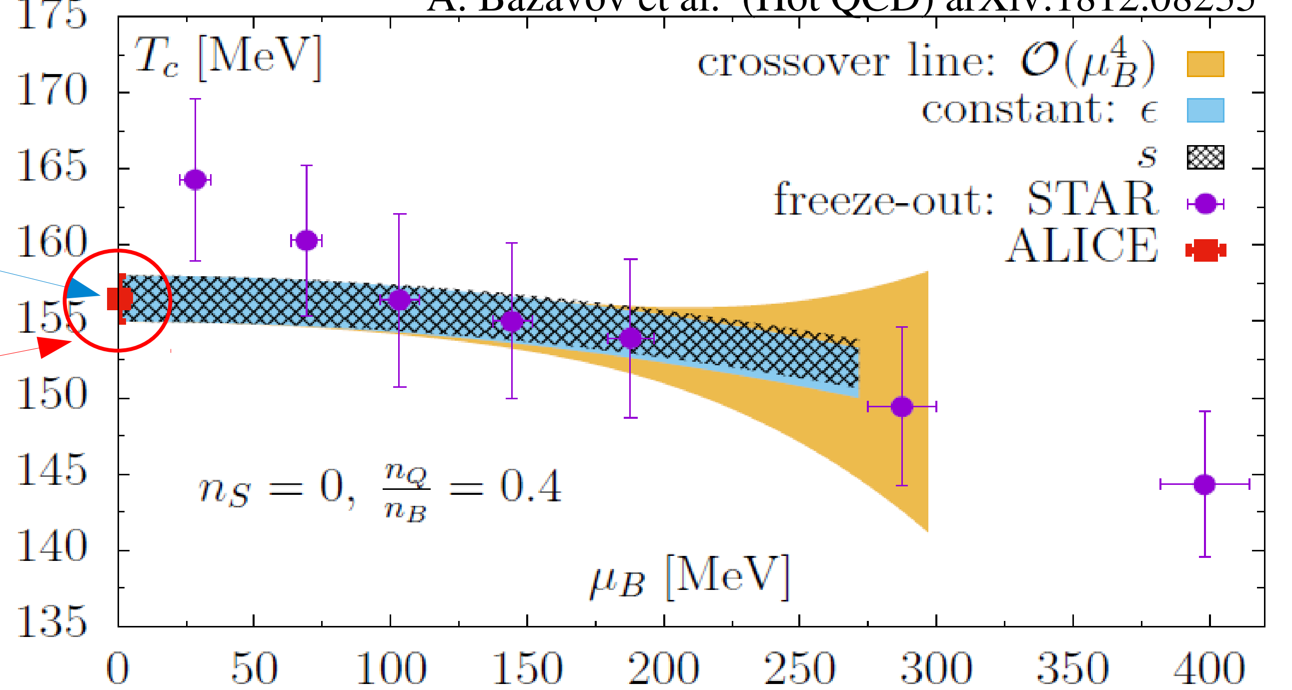
Pseudo-critical temperature from Lattice QCD

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

T_{pc} = 156.5 ± 1.5 MeV

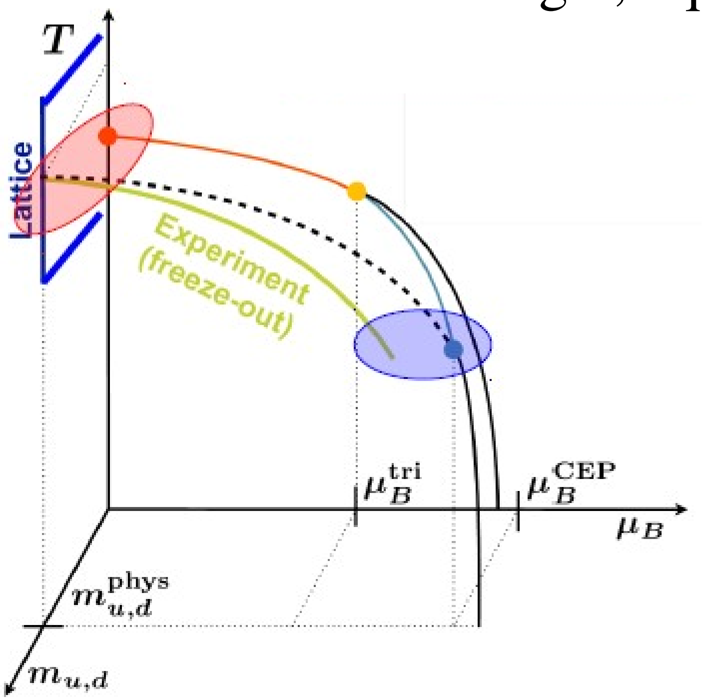
in exact agreement with
chemical freeze out temp
determined from ALICE data

A. Bazavov et al. (Hot QCD) arXiv:1812.08235



Nature of the chiral phase transition

for vanishing u,d quark masses, chiral PT conjectured 2nd 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

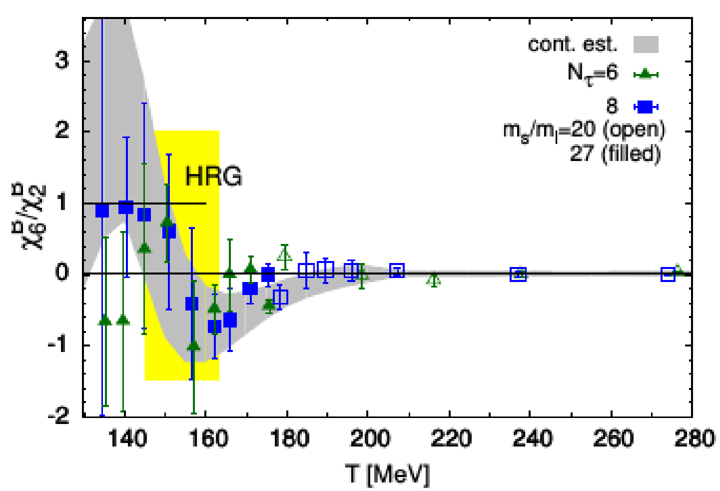
measurement of higher order fluctuations of conserved charges: can be directly compared to lattice QCD calculations

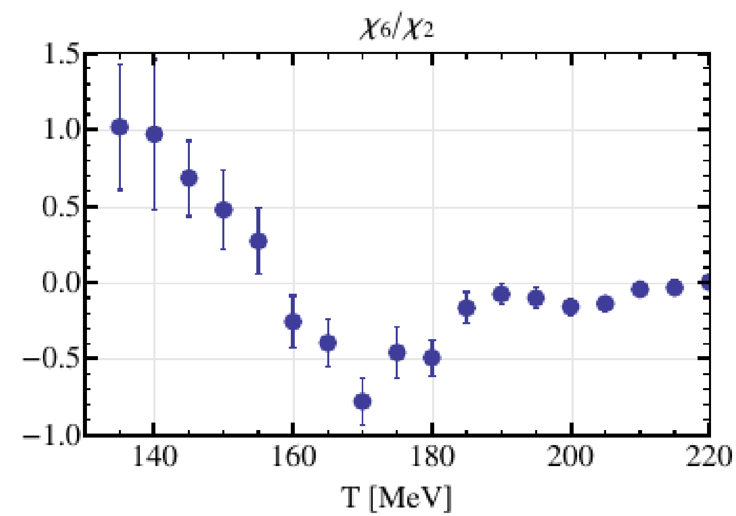
$$\chi_{ijk}^{BQS}(T) = \left.\frac{\partial P(T,\hat{\mu})/T^4}{\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k}\right|_{\hat{\mu}=0}$$

↔ cumulants of net baryon distribution

singular contribution to pressure for higher orders: visible starting with 6th order susceptibilities

measure in Run3/4 up to 6th moment of net proton distrib. ↔ holy grale





Shear and bulk viscosities of the QGP

relativistic hydrodynamics very successful in describing spectra and correlations, azimuthal anisotropies

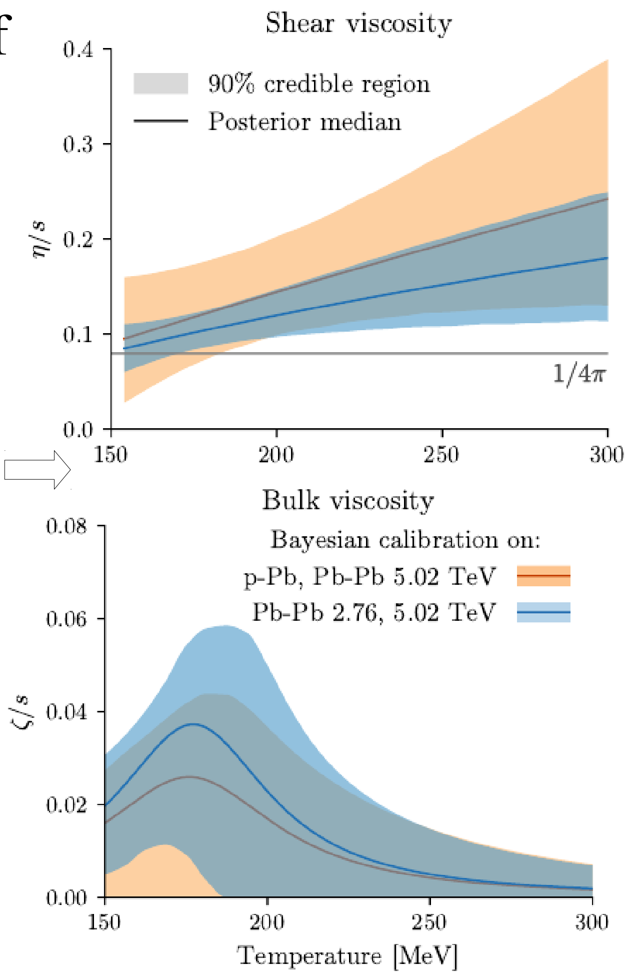
paradigm of QGP as nearly ideal fluid → determination of macroscopic properties of QGP fluid

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?

J.E. Bernhard, J.S. Moreland, S.A. Bass
arXiv:1808.02106

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

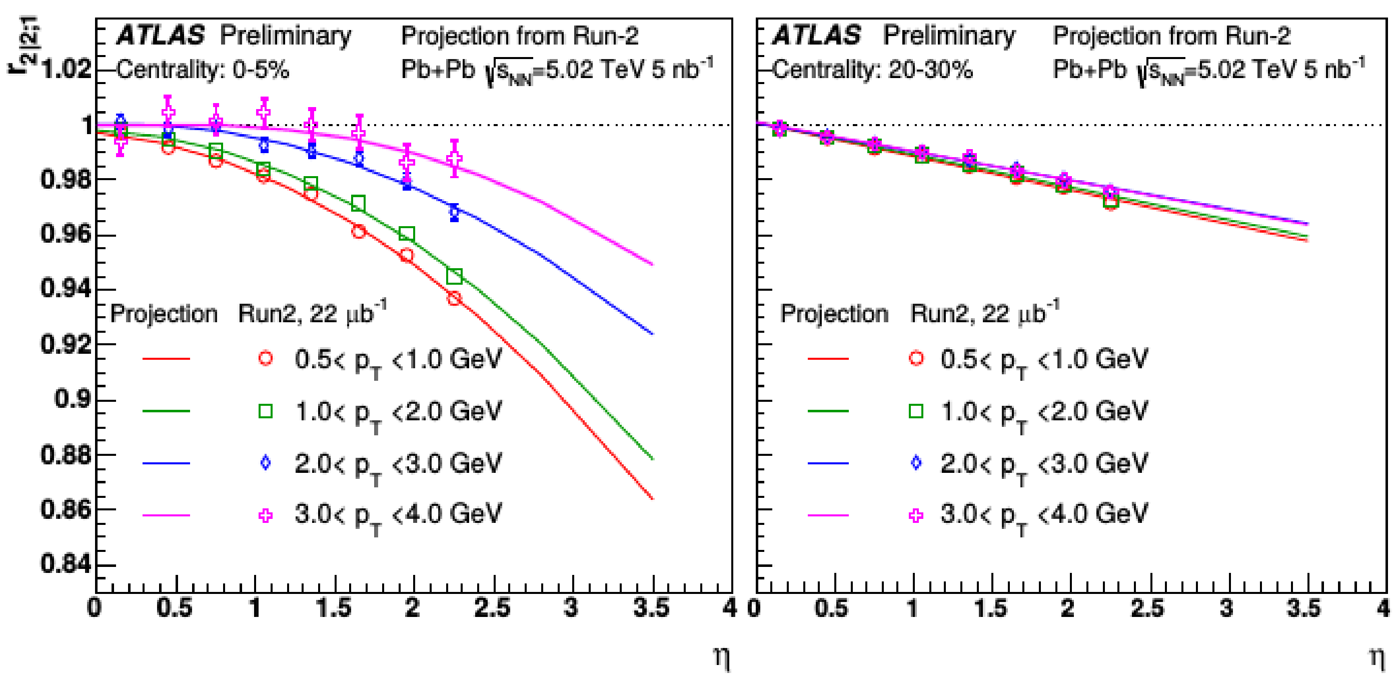
Flow decorrelation

related to time evolution of matter

$$r_{n|n;1}(\eta) = \frac{\langle \mathbf{v}_n(-\eta)\mathbf{v}_n^*(\eta_{\mathrm{ref}})\rangle}{\langle \mathbf{v}_n(\eta)\mathbf{v}_n^*(\eta_{\mathrm{ref}})\rangle}$$

measures relative difference between flow at η and -η
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



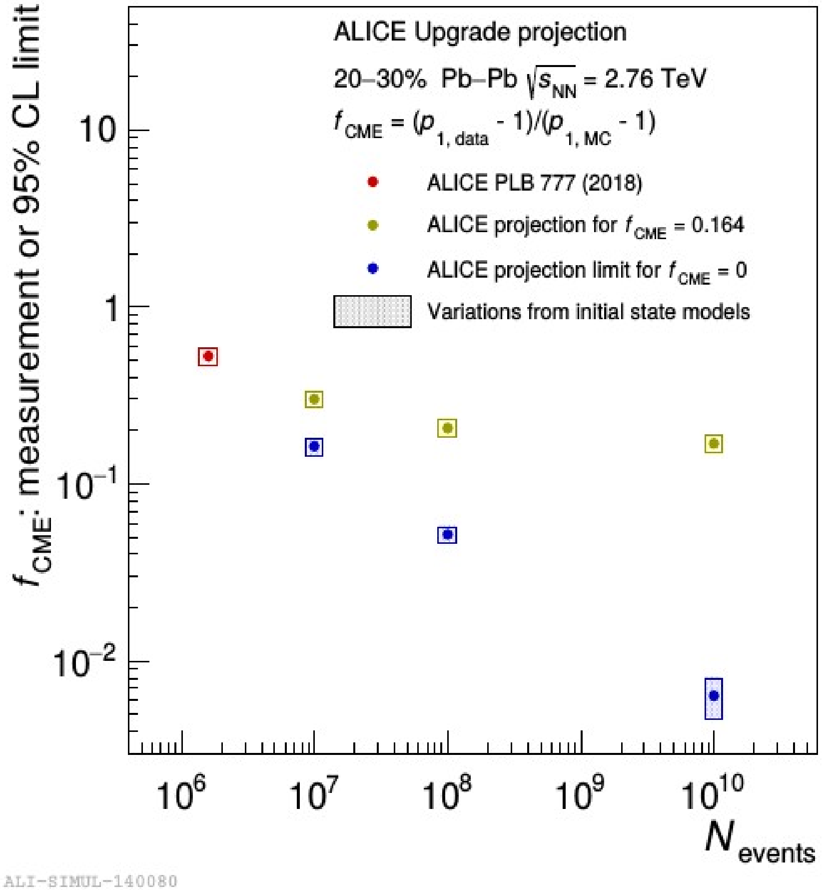
Limits on the chiral magnetic effect

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 $\gamma_{\alpha\beta}$

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

Run3/4 with 10 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)

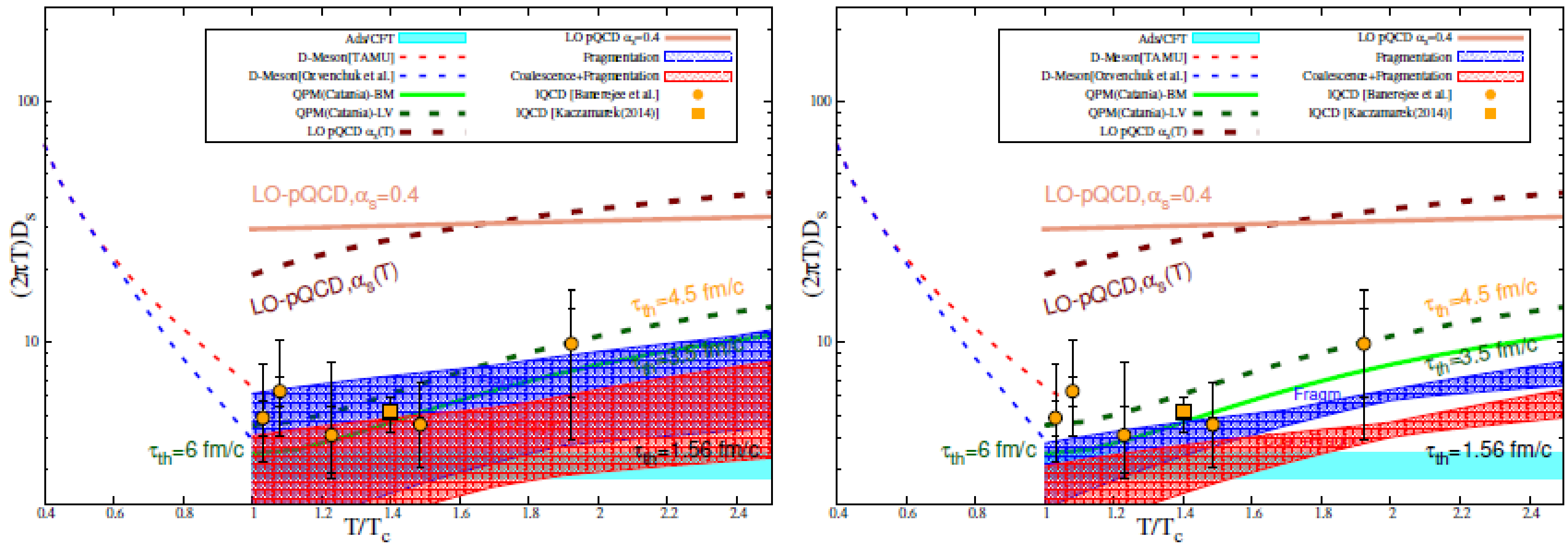
goals:

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 abundancies 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

equilibration time of heavy quark given by diffusion coefficient: $\tau_Q = \frac{m_Q}{T} D_s$
from simultaneaus fit of spectrum and v2 as function of p_t get $D_s(T)$

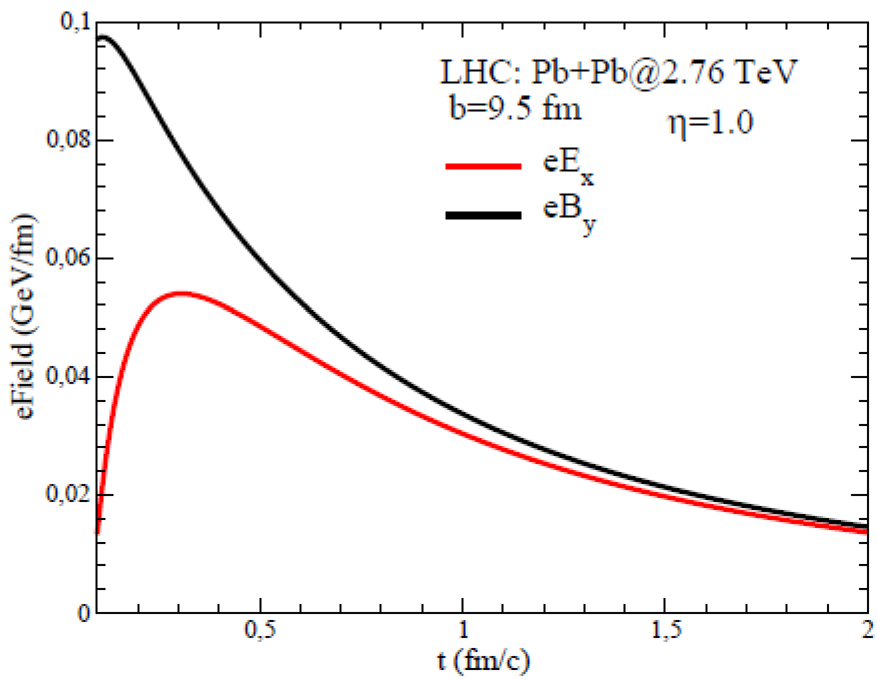


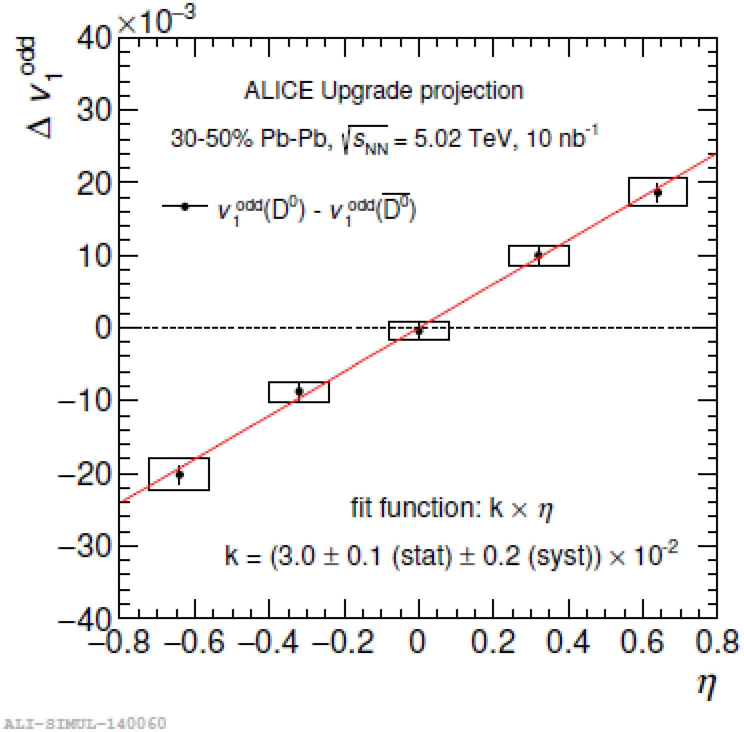
with Run3/4 statistics a meaningful physics conclusion possible

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

Sensitivity to extremely strong initial fields

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





based on S. Das et al. arXiv:1608.02231

measurable effect in Run3/4

Jets and parton energy loss

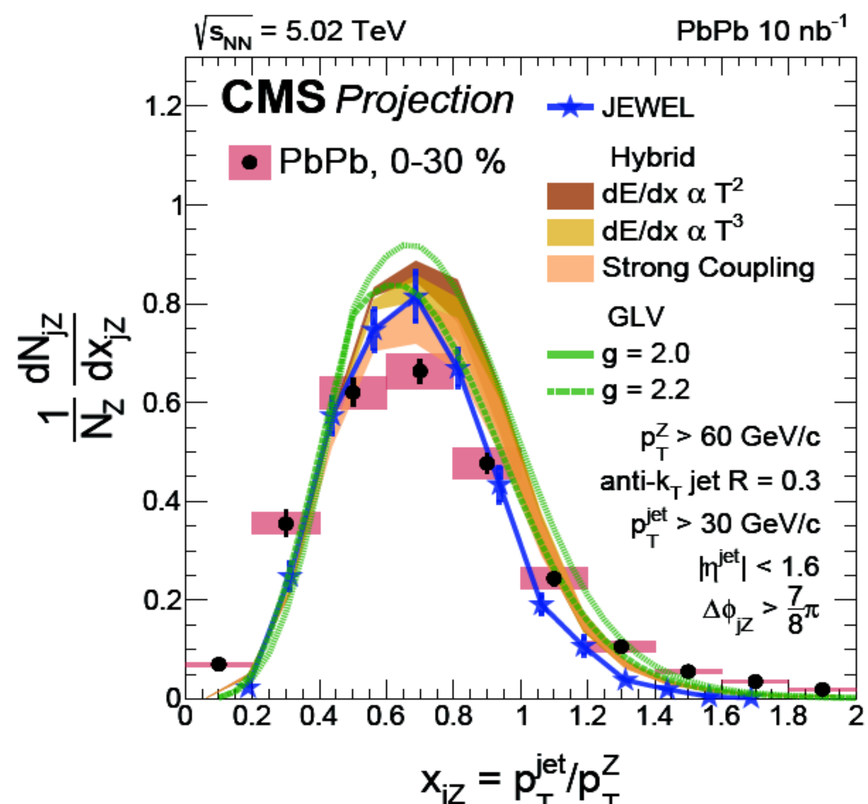
consensus after Runs1/2: strong energy loss of partons in color dense medium (QGP) characterized by a transport coefficient $\hat{q}$ = 1.9±0.7 GeV^2/fm (at T = 470 MeV)

- 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 → 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

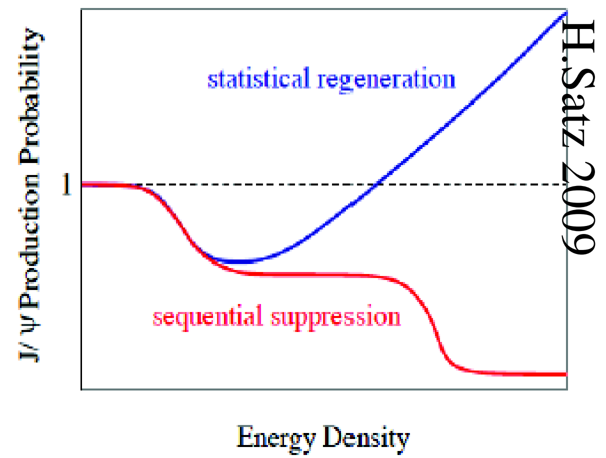
for jet observables an argument in favor of lighter beams has been made

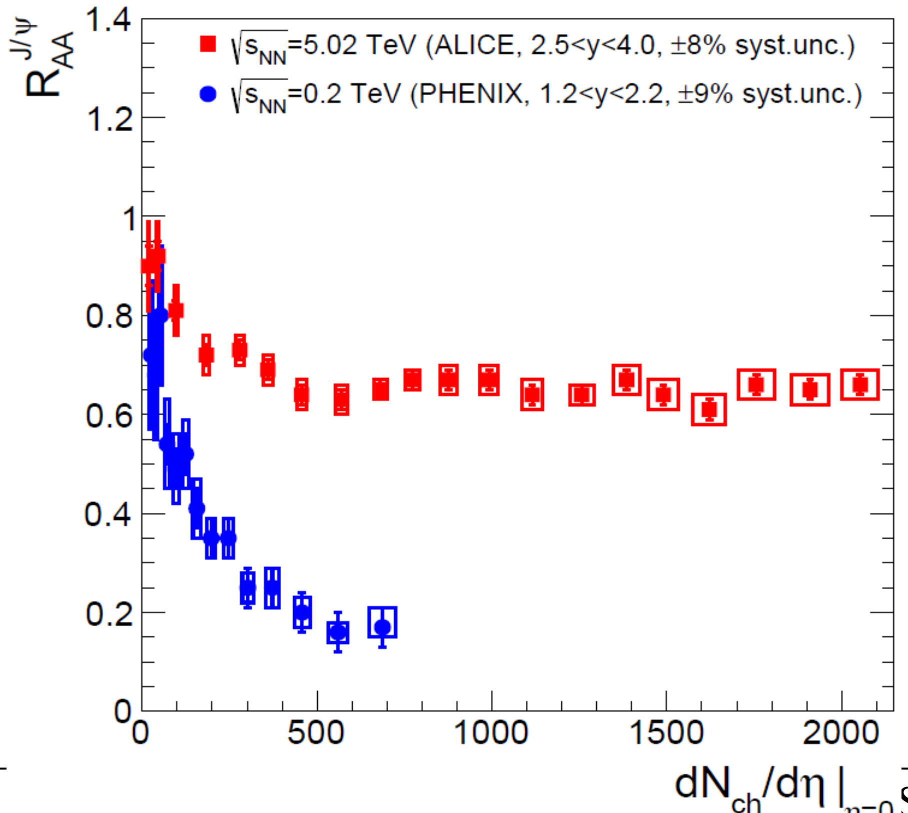


Charmonia – Debye screening in QGP

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.

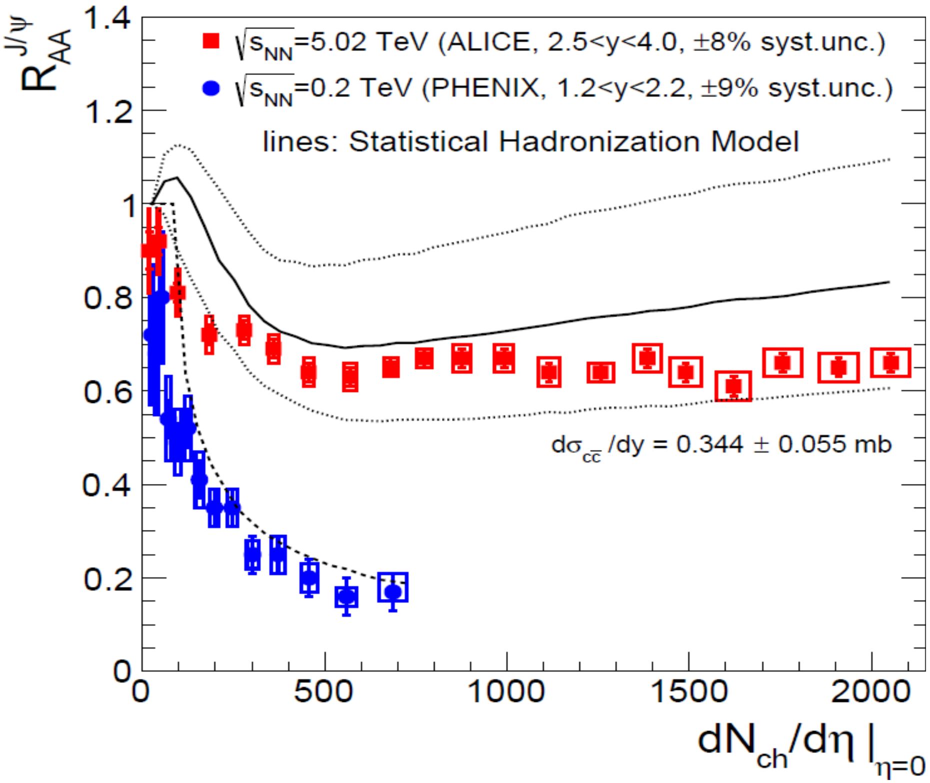


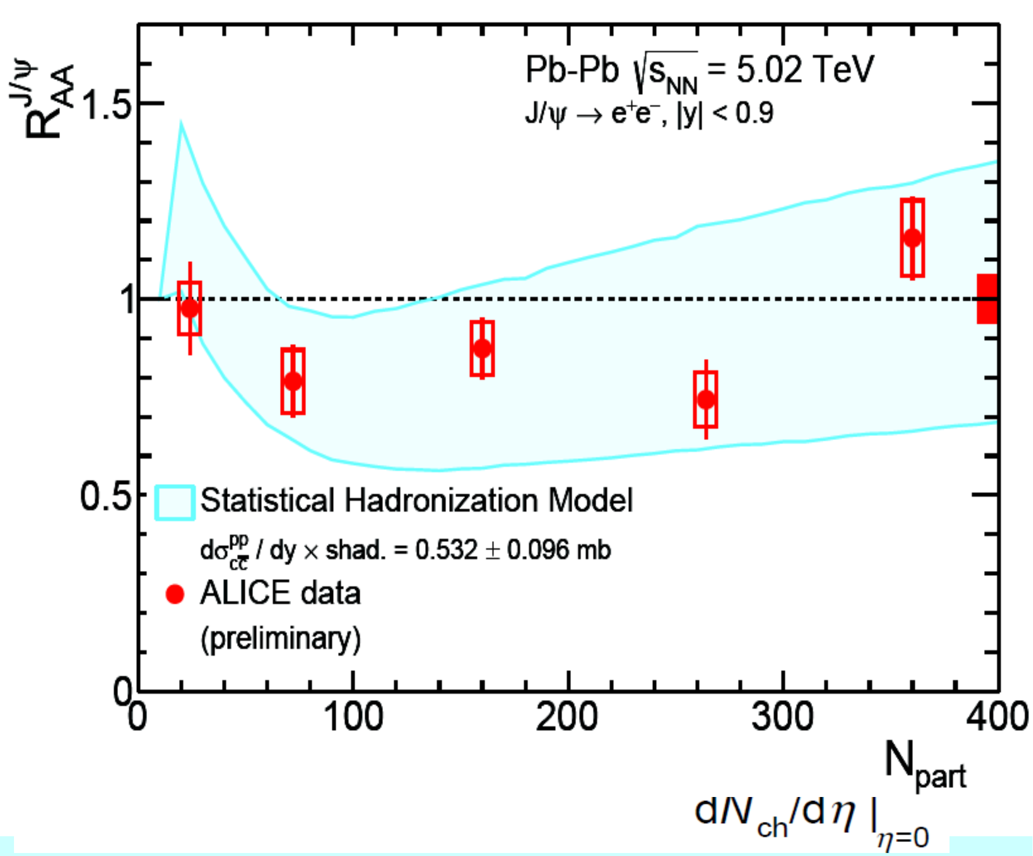


unambiguously answered by the data

biggest qualitative difference to lower energies!

J/ψ and statistical hadronization



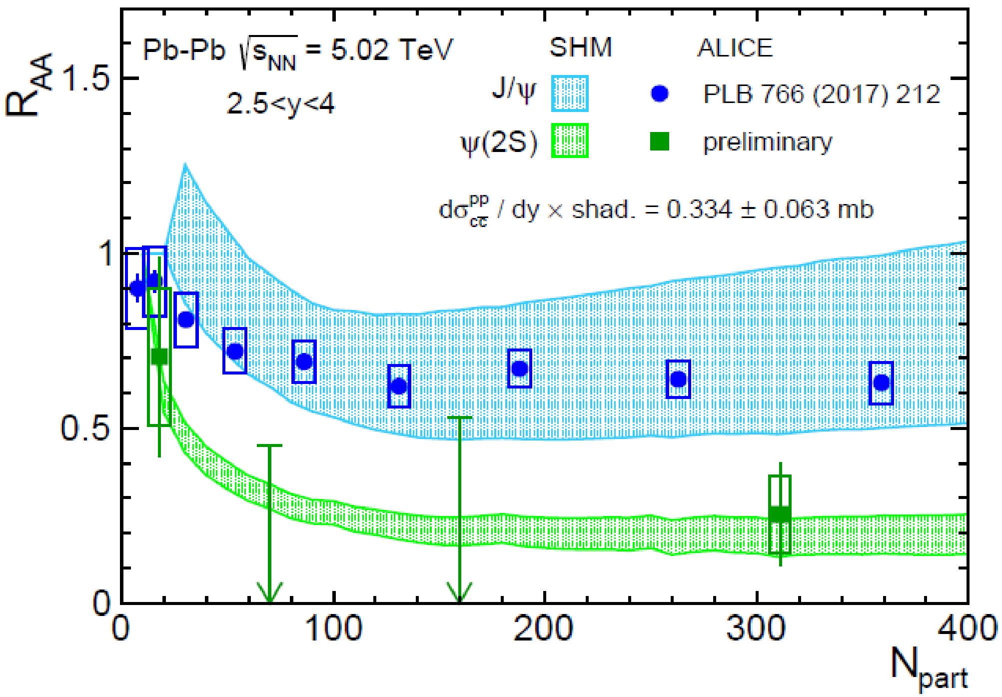


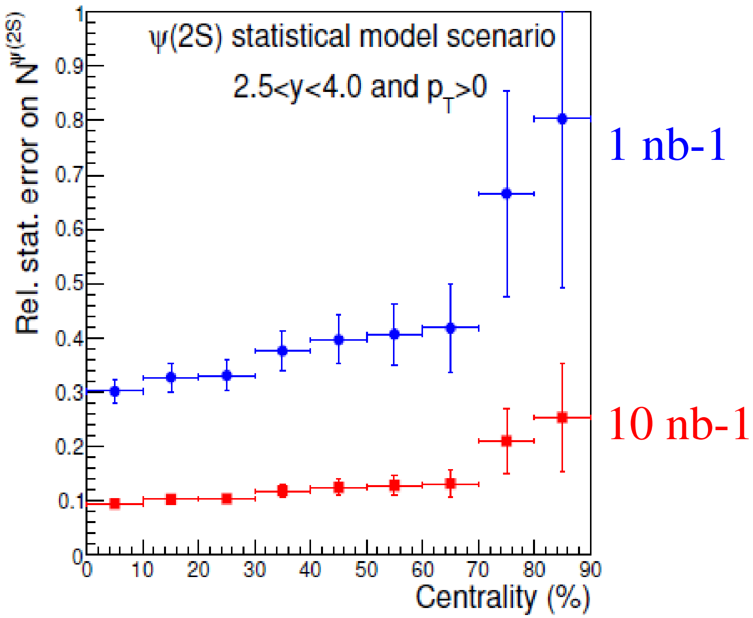
production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization - works also for differential distributions
- not unambiguous yet due to large uncertainty in open charm cross section in PbPb
(cf continuous destruction and reformation in QGP)

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

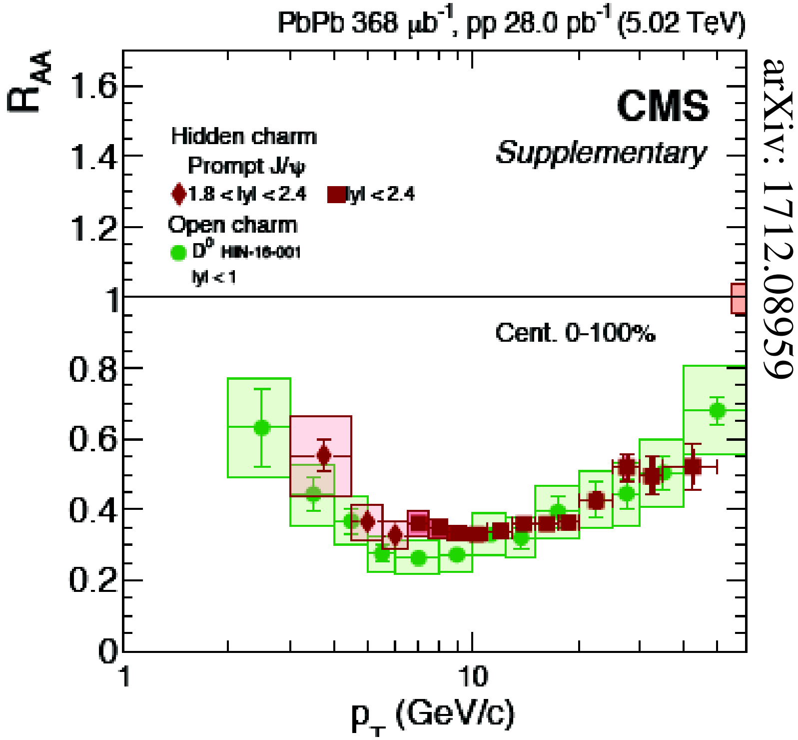
- yields of charmed mesons and baryons in PbPb, open charm cross section to 5 %
- precision spectra and azimuthal distributions
- excited state population

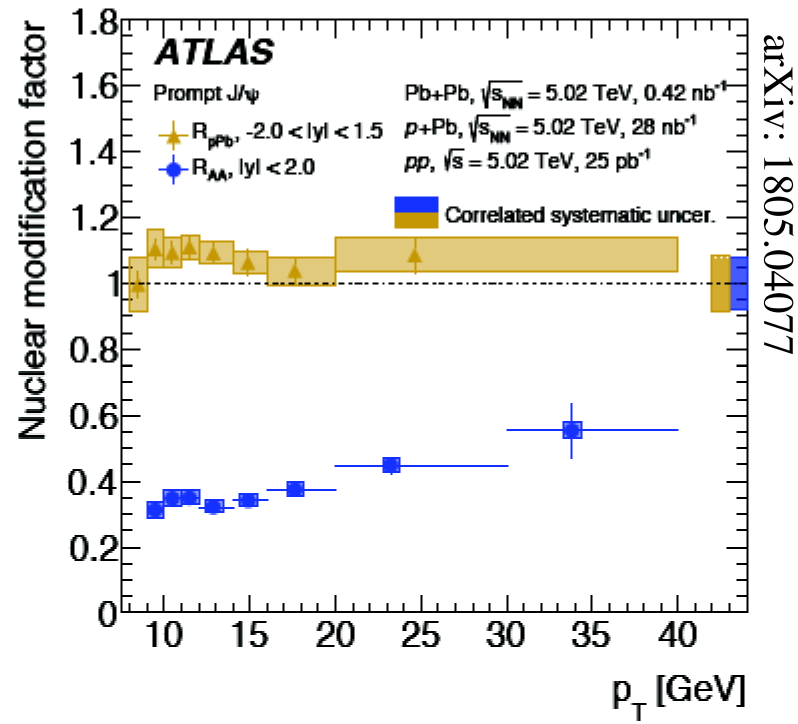




ambiguities between models will be resolved by Run3/4 data

J/ψ interesting physics at high p_t





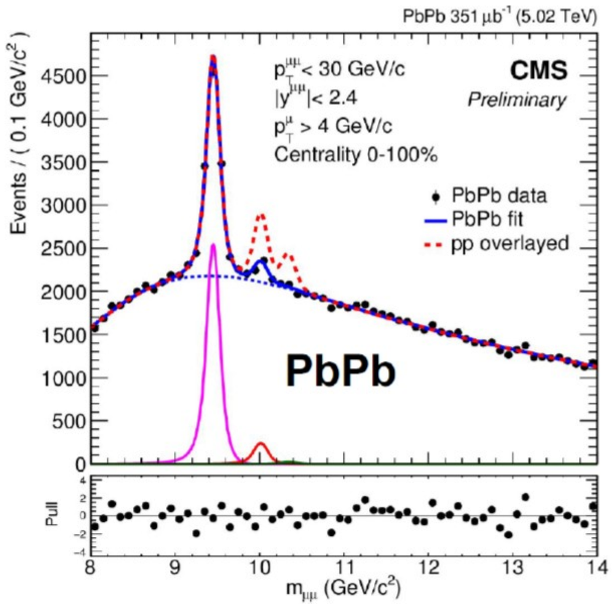
prompt J/ψ suppression in PbPb collision – R_{AA} rising at high p_t

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

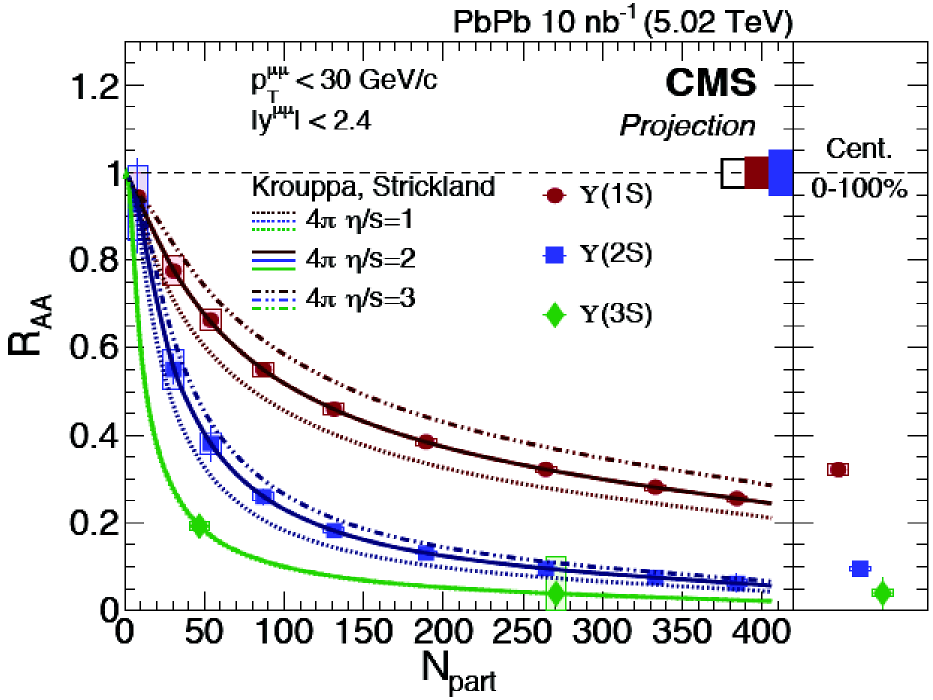
Bottomonia - sequential melting vs statistical hadronization



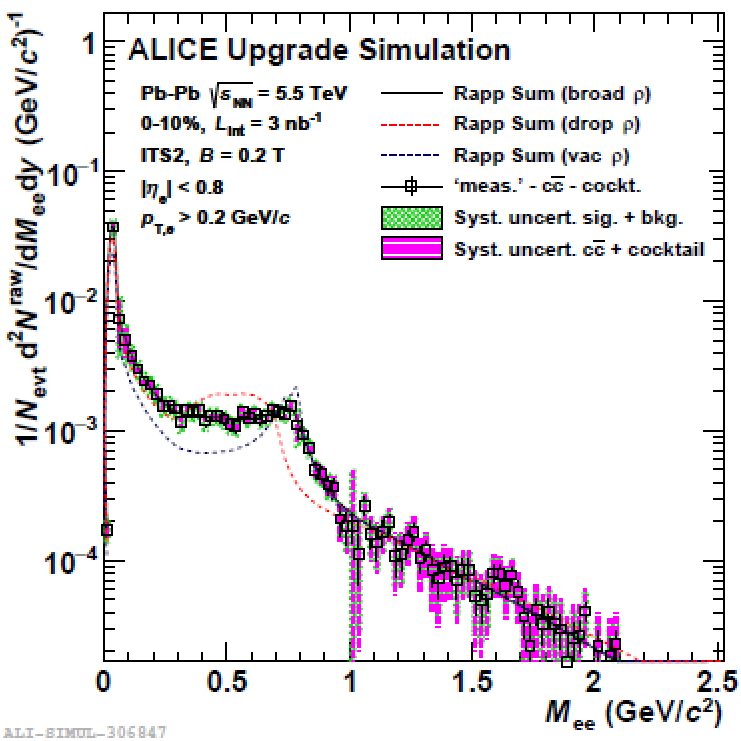
Run1/2 all Upsilon states strongly suppressed in central PbPb collisions

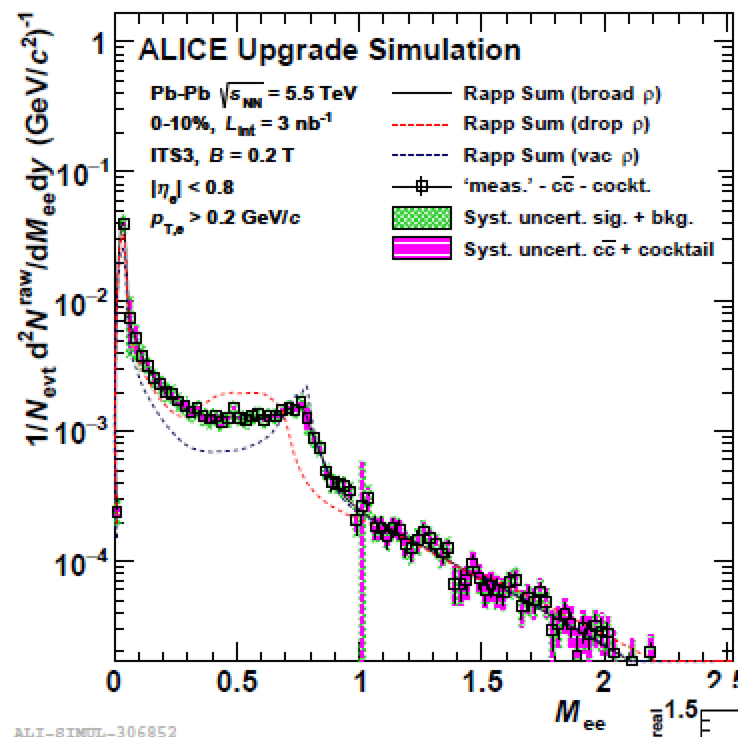
1S: 1/3 2S: 1/10 3S: unmeasurable

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



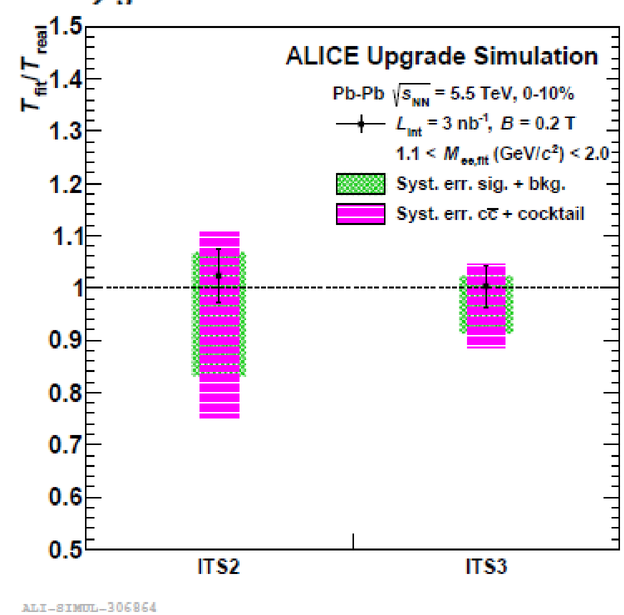


ITS3 see below

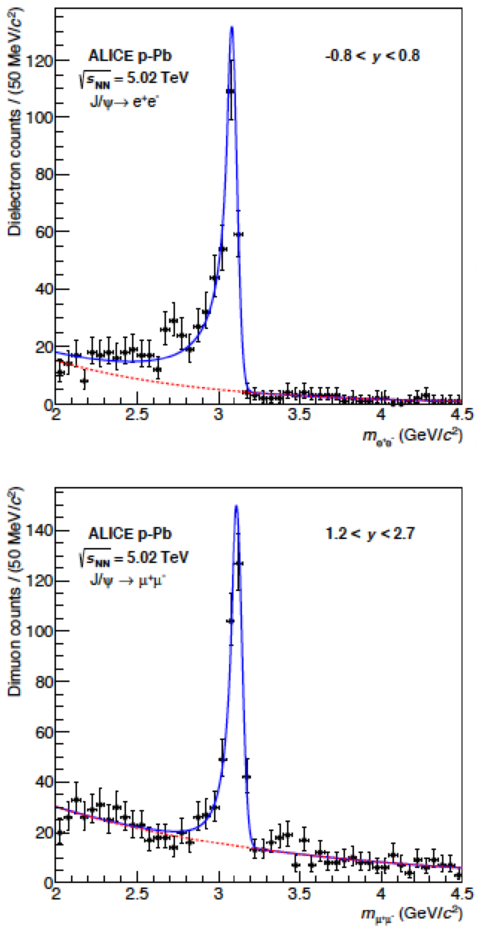
- chiral symmetry restoration: line shape of ρ meson
- thermal radiation: slope for m_{ee} = 1.1 – 2.5 GeV after subtracting heavy flavor decay component)

also to be measured via real photons

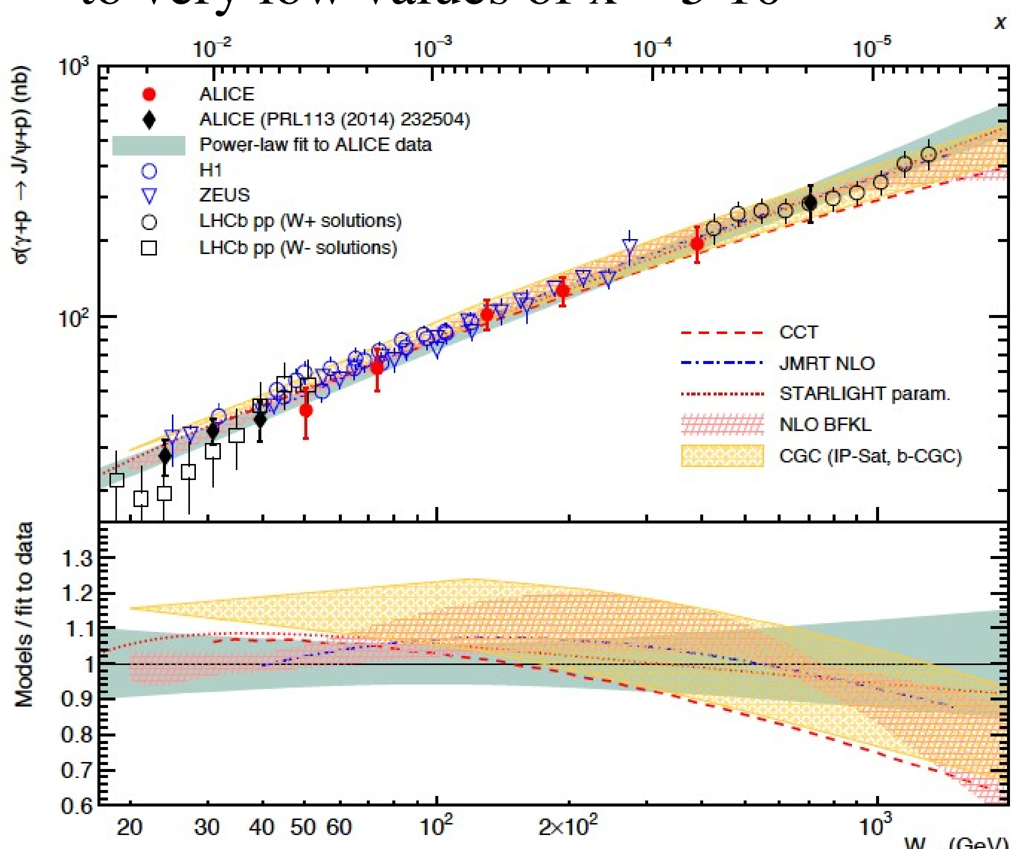
will be accessible with precision in Run3/4 of LHC



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 10^{-6}



future: more exclusive channels

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

A next generation LHC heavy ion experiment

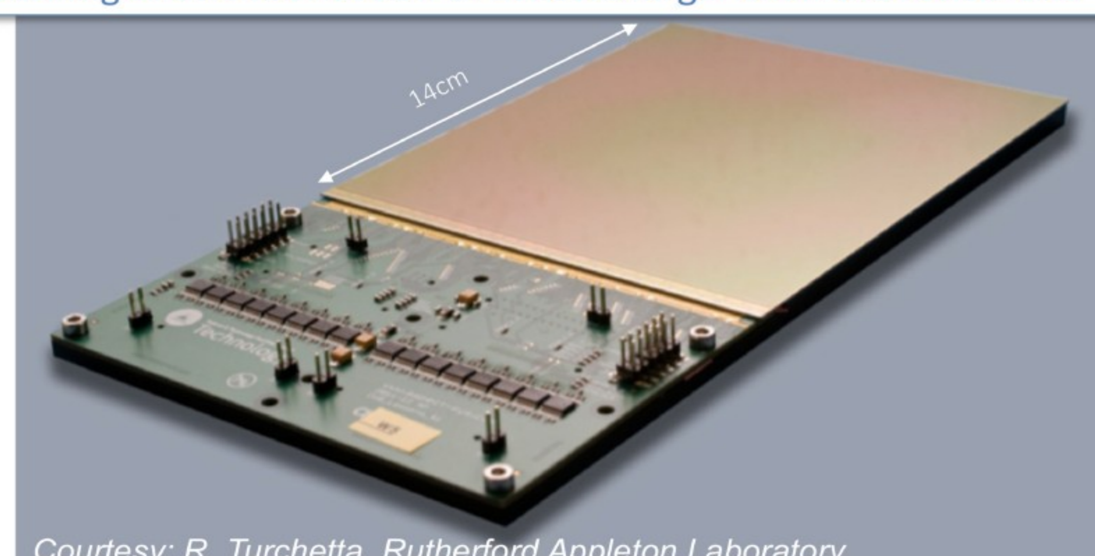
Ideas for a new heavy ion experiment for Run5 capable to handle extremely high rates for rare probes (heavy flavor, heavy quarkonia, light (anti-)(hyper-)nuclei) and measure ultra-low p_t particles

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

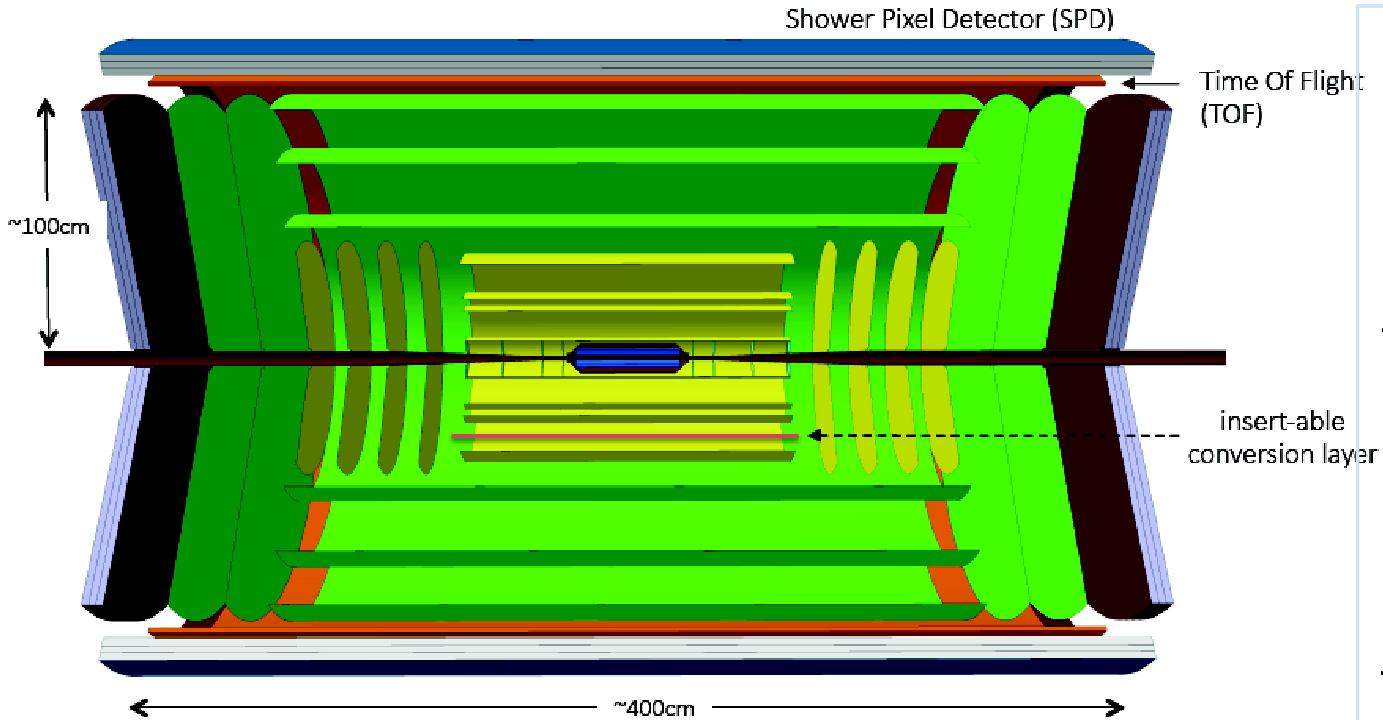
Ultra-thin chip (<50 um): flexible with good stability

Stitching allows fabrication of sensors larger than the reticle size



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 outer silicon layers
Electron ID: < 500 MeV via TOF, > 500 MeV pre-shower pixel detector



arXiv:1902.01211

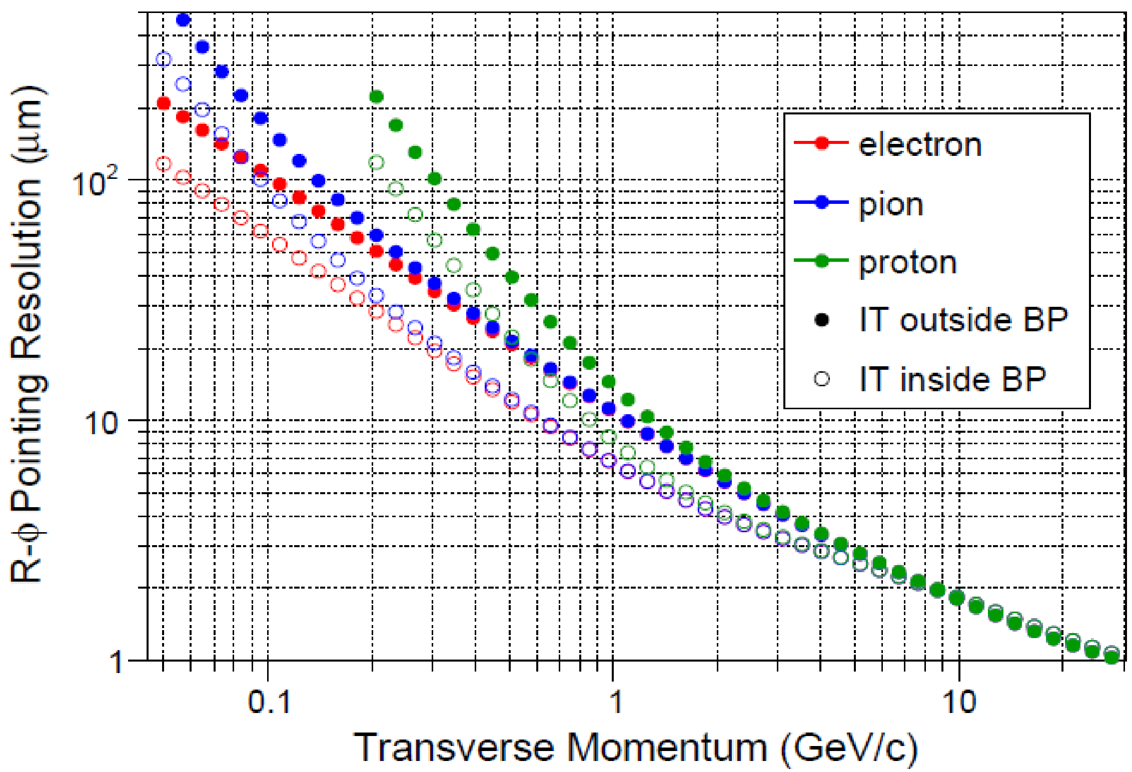
Preliminary studies

Magnetic field
$B = 0.5$ to 1 T

Spatial resolution
Inner most 3 layers: 10x10 μm^2
0.05 % X_0, $\sigma \sim 1\ \mu m$
Outer layers: 30x30 μm^2
0.5 % X_0, $\sigma \sim 5\ \mu m$

Time measurement
3 layers with $\sigma_t \sim 20$ ps

Envisaged performance



r-φ pointing resolution key for heavy flavor observables, but also photon conversions

low momentum tracking

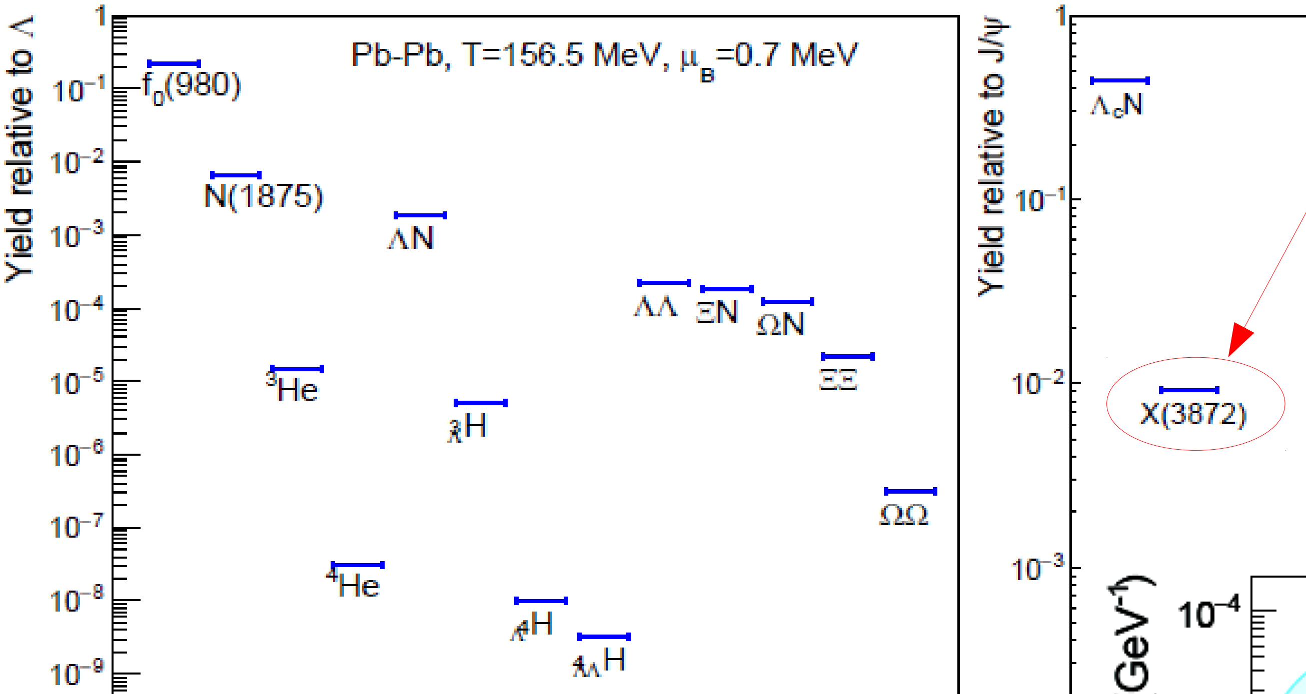
Physics potential

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:
  - P-states of quarkonia, p_t sprectra 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
  - 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^γ = 1-100 MeV in small forward spectrometer

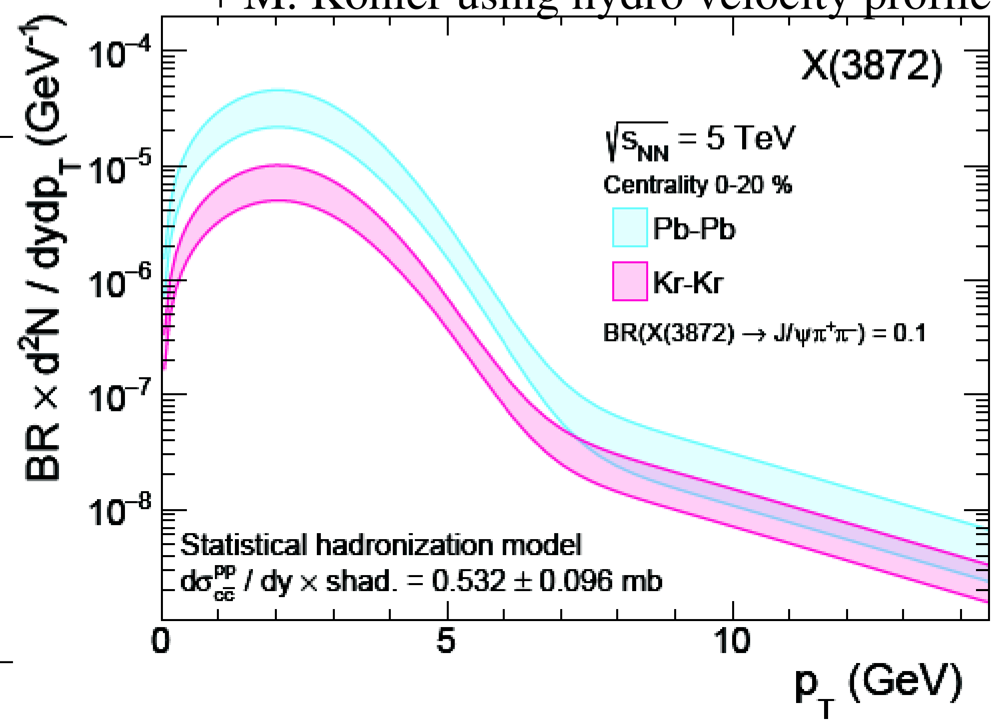
  arise as a consequence of structure of all gauge theories (Bloch, Nordsieck, Low) predicted controlled divergence – try to reach and test this limit
- other probes accessible with low p_t hadrons (DCC, ...)

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?

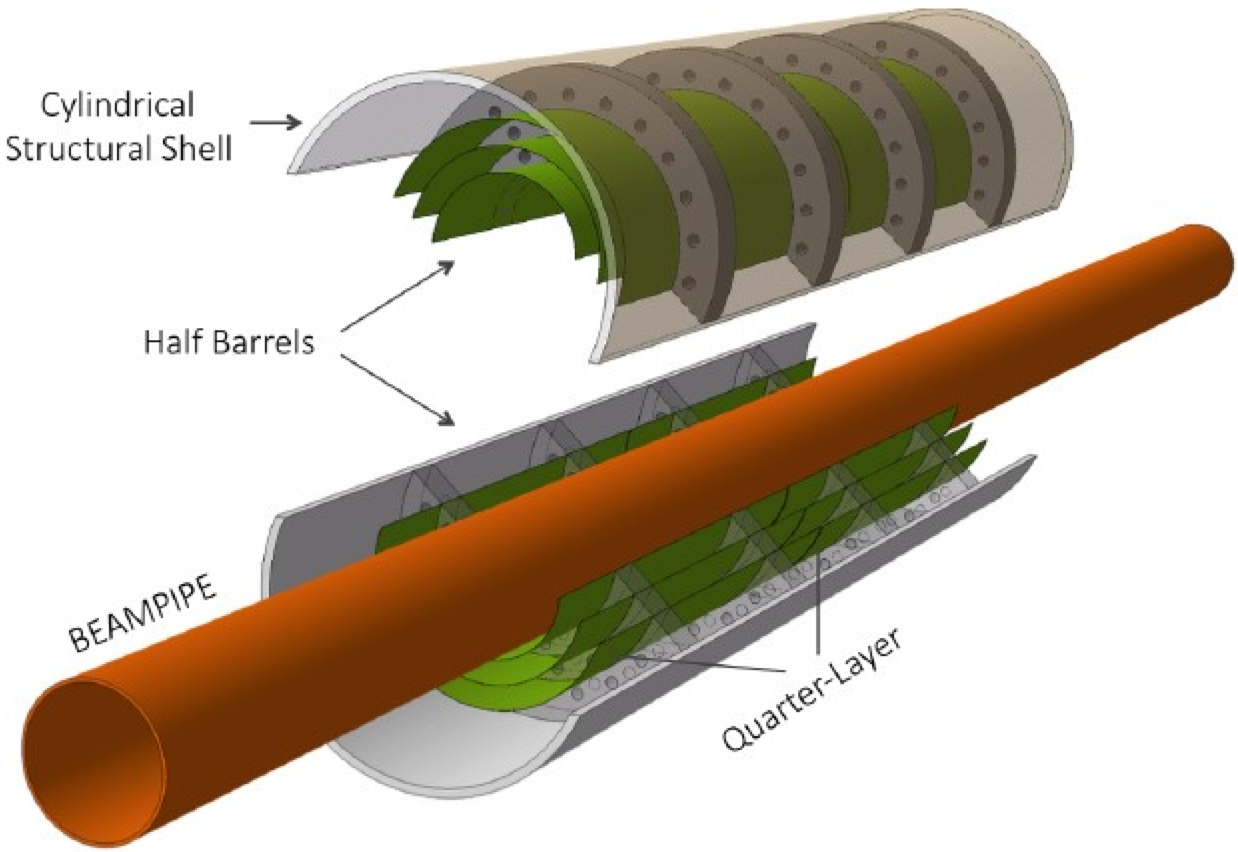
M. Köhler using hydro velocity profile



<u>key observable:</u> transverse momentum spectrum down to low p_t for (hyper-)nuclei, J/ψ, ψ', X(3872),... and B_c in PbPb collisions at LHC energy

Proposed ITS3 in ALICE

3 layers of stitched CMOS MAPS sensors of up to 508 cm^2
with 56 M pixels (30 x 30 μm^2)



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

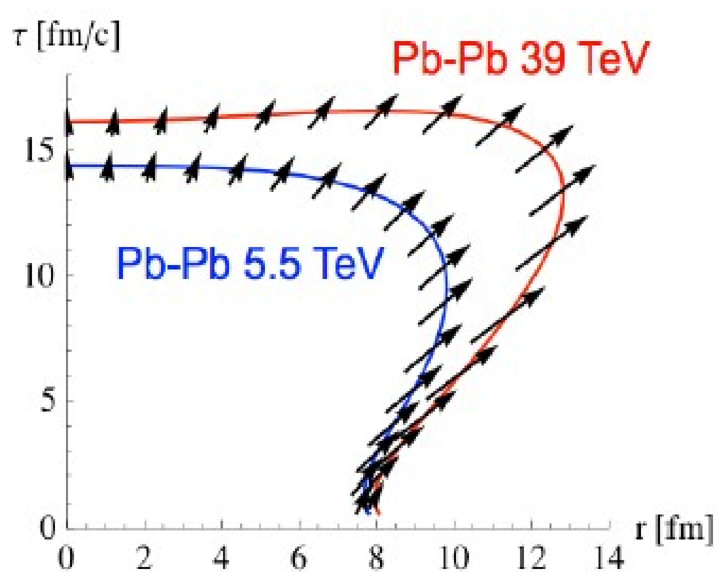
expression of interest for an ALICE ITS upgrade in LS3 – ALICE-PUBLIC-2018-013

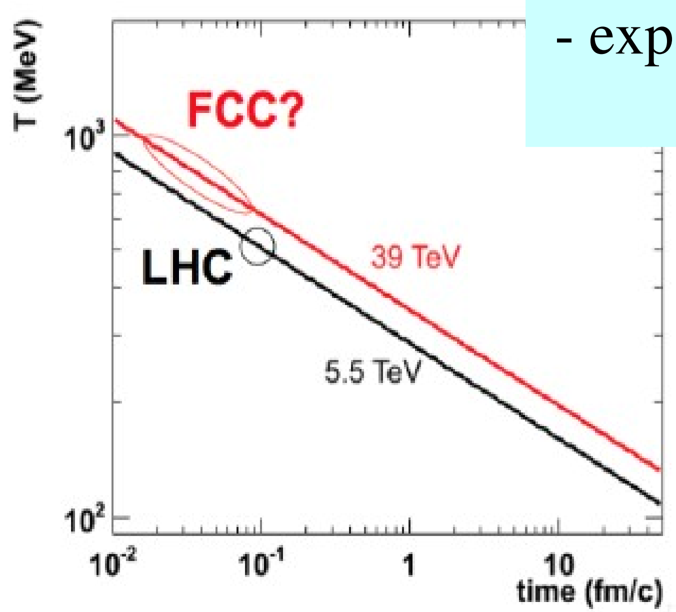
HE-LHC and FCC initial and final conditions for HI collisions

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	≈ 1.5	5.2–5.8
Homogeneity volume fm^3	5000	6200	7400	4500	11000
Decoupling time (fm/c)	10	11	11.5	10	13
ε at $\tau = 1$ fm/c (GeV/fm^3)	12–13	16–17	22–24	≈ 15	35–40

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

incremental changes





FCC and HE-LHC: new opportunities for HI collisions

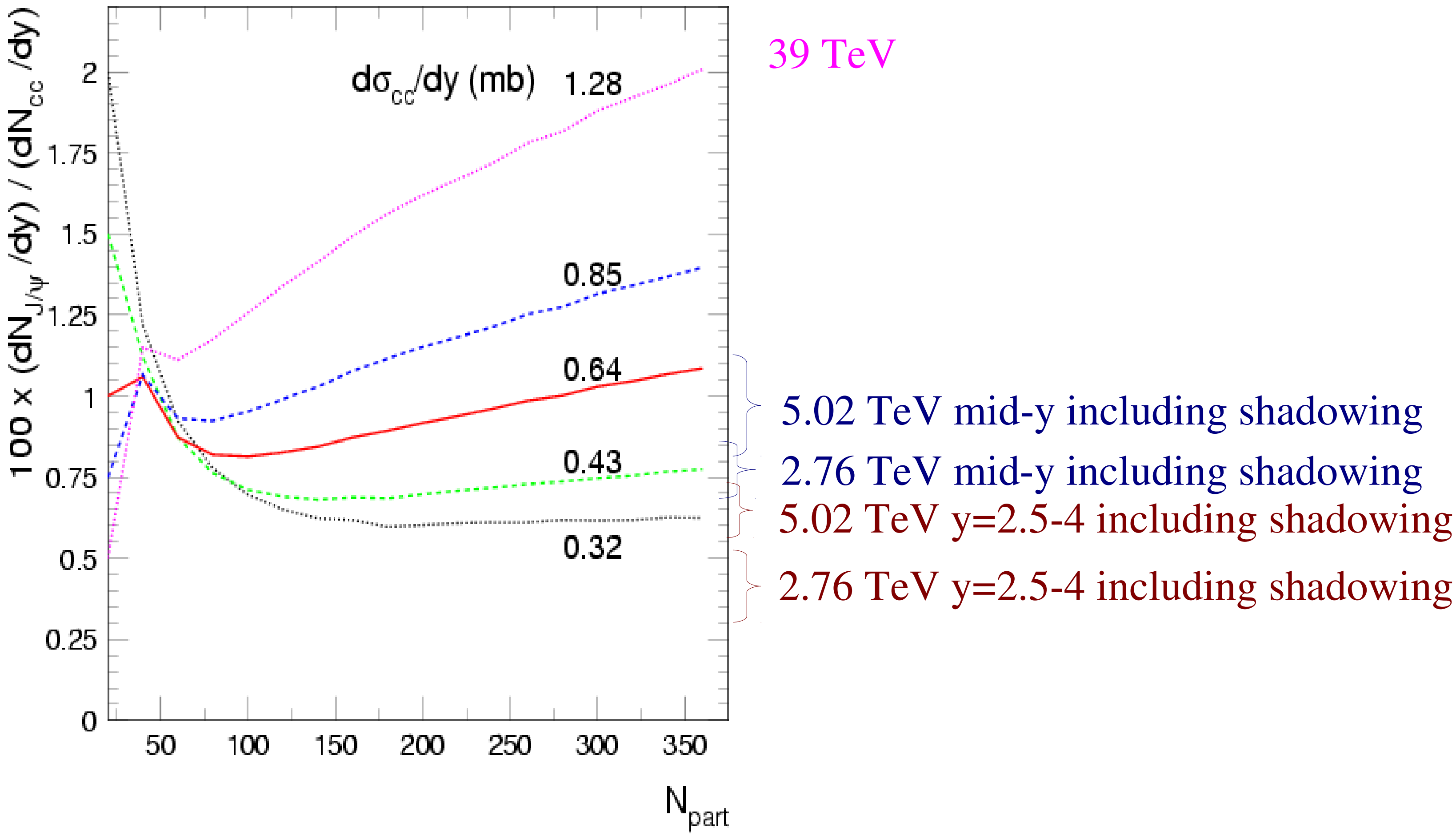
while the QGP created at FCC is presumably not radically different from LHC, the strong increase of cross sections and virtual photon flux make new probes available

examples:

- σ_{ccbar} and σ_{bbbar}: qualitative changes in J/ψ 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/ψ → $W_{\gamma p}$ = 10 TeV and thereby probe $x = 10^{-7}$
- γγ → H → bbar 1.75 nb in PbPb
  γγ → γγ enhanced factor 200, sensitivity to BSM physics via new heavy charged particle in virtual loop, search for monopoles or axions

Expectations for J/ψ at FCC

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



Conclusions and recommendations- 1

- **Heavy ion collisions at substantially increased luminosity open an excellent window to study strongly interacting matter at high temperature**

- here a quark-gluon plasma is formed similar to the conditions as they existed in the early universe and as also accessible theoretically in lattice QCD
- in the future, it will be possible to uncover connections between macroscopic properties of the relativistic quantum fluid and the underlying microscopic QCD Lagrangian
- this will be possible using new, up to now not accessible observables

Conclusions and recommendations - 2

- the development of a new nearly massless detector, using the most modern radiation hard silicon technologies is now possible
- measurements of identified particles at very low transverse momenta ($p_t < 20$ MeV/c) are of particular interest to characterize the macroscopic properties of the expanding QCD fluid

- **Measurements with such a next generation experiment could already take place at the HL-LHC starting from 2030 and might find a natural continuation at accelerators with even higher energies**

- **the community is encouraged to push the technology and the physics ideas to a maturity that allows a concrete experiment proposal**

Conclusions and recommendations - 3

Nuclear collisions at significantly higher energies will allow studies of the QGP at correspondingly higher energy density and temperature. At FCC energies new probes will become accessible.

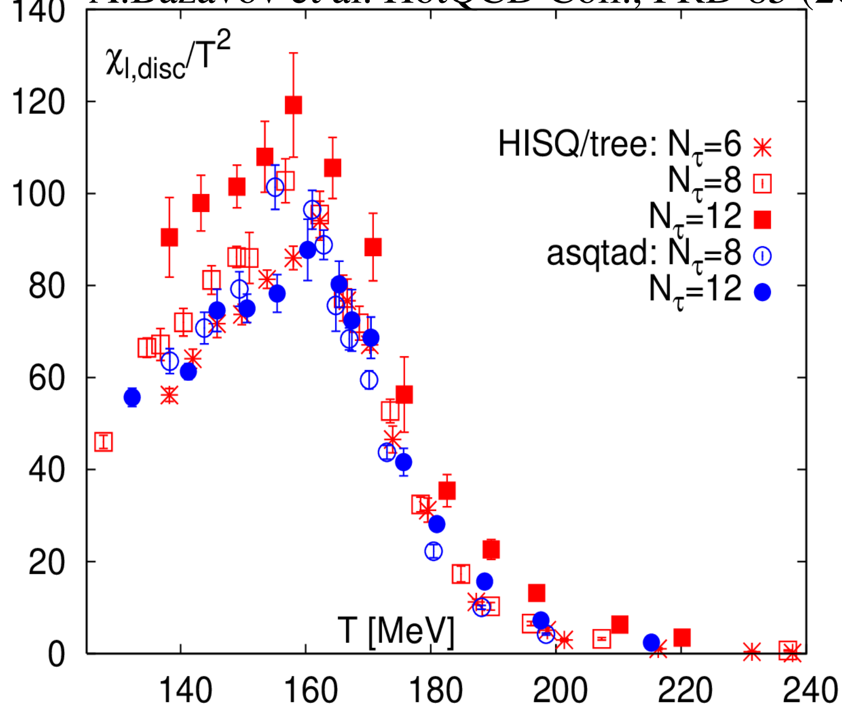
- **Prospects for a highly attractive heavy ion program at the HE-LHC and the FCC are recognized**

backup

Measure for chiral symmetry restoration in lQCD

order parameter: chiral condensate, its susceptibility peaks at T_c

S.Borsayi et al. Wuppertal-Budapest Coll., JHEP 1009 (2010) 073
A.Bazavov et al. HotQCD Coll., PRD 85 (2012) 054503



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

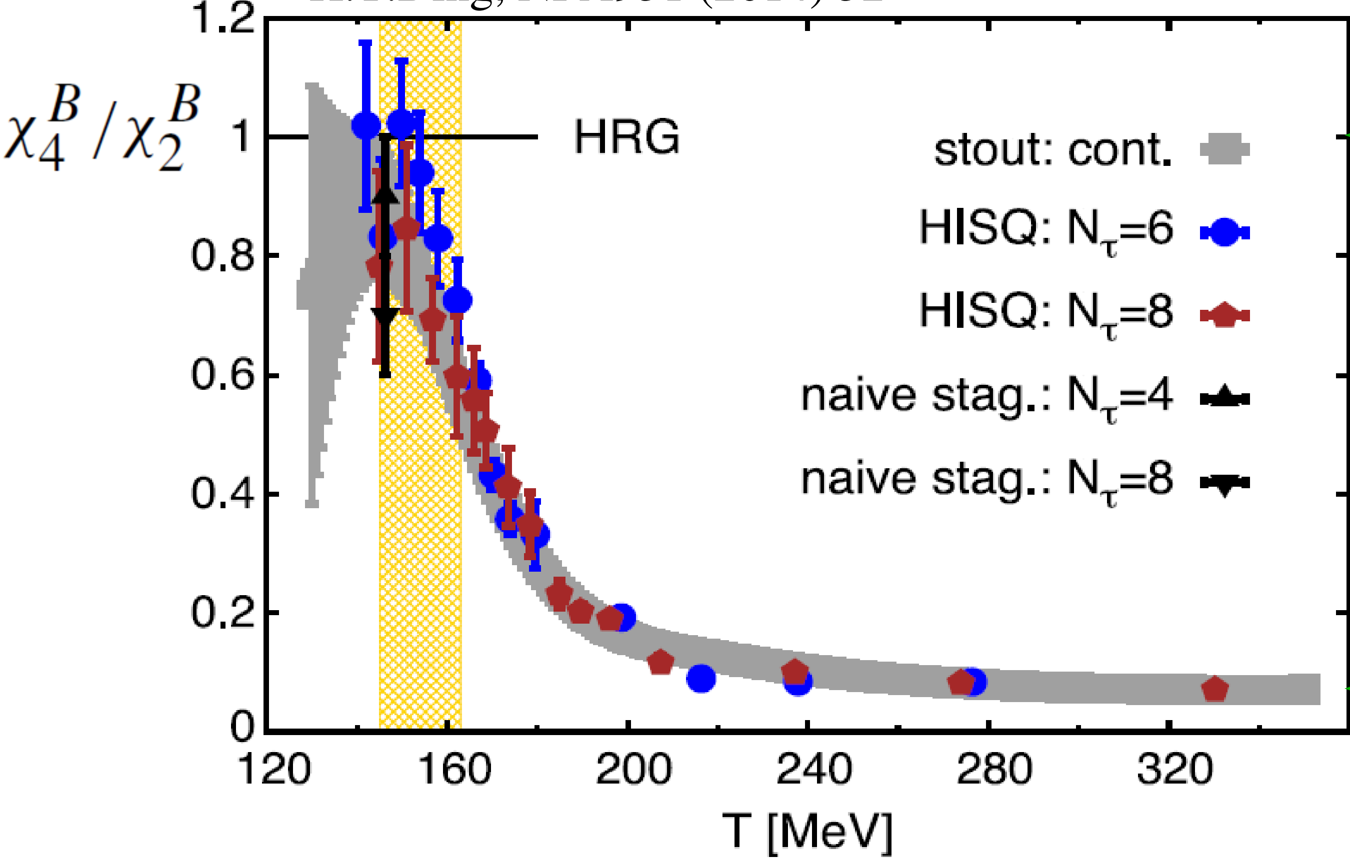
$$\chi_{\bar{\Psi}\Psi} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m^2}$$

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

Measure of deconfinement in lQCD

$\chi_4^B/\chi_2^B \propto$ baryon number^2

H.T.Ding, NPA931 (2014) 52



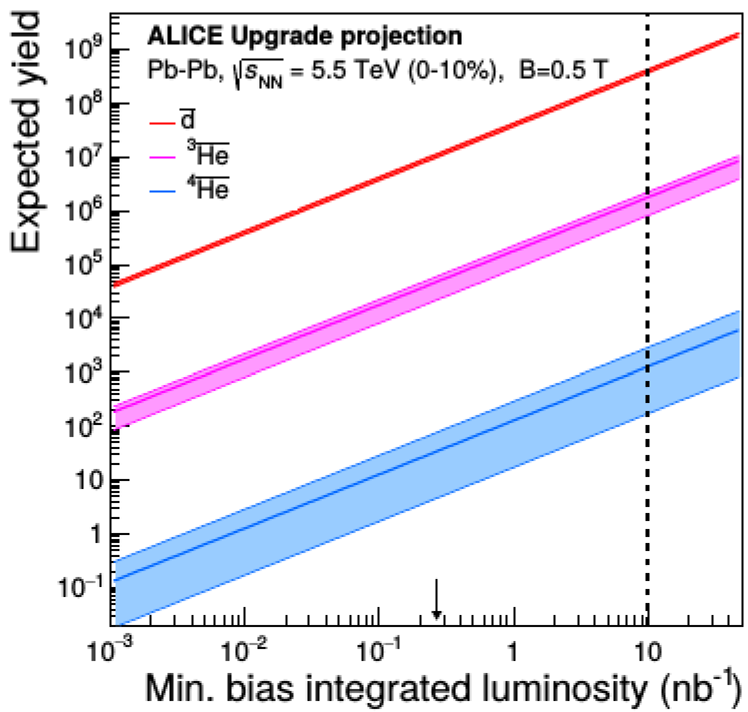
confined: 1

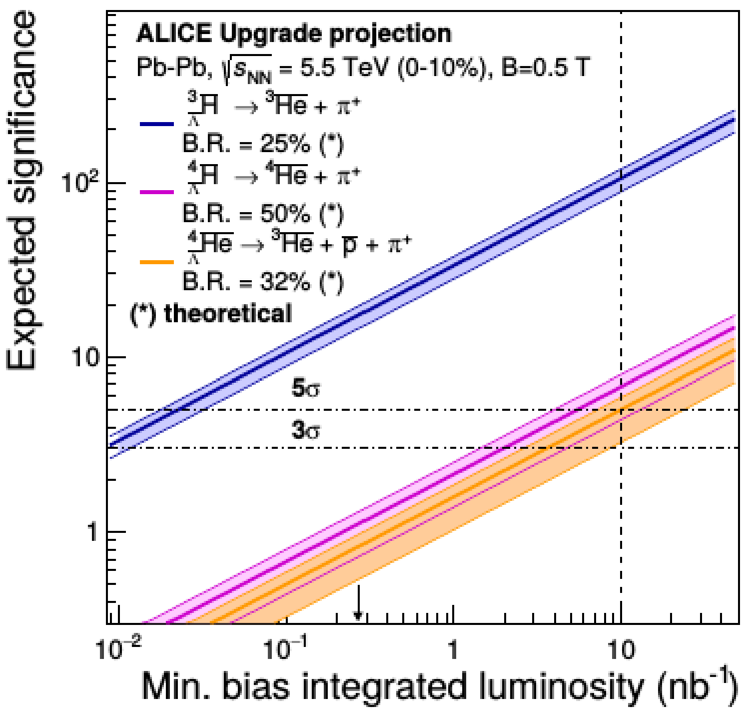
measure suggested by Ejiri, Karsch, Redlich (2006)

deconfined: $6/9\pi^2$

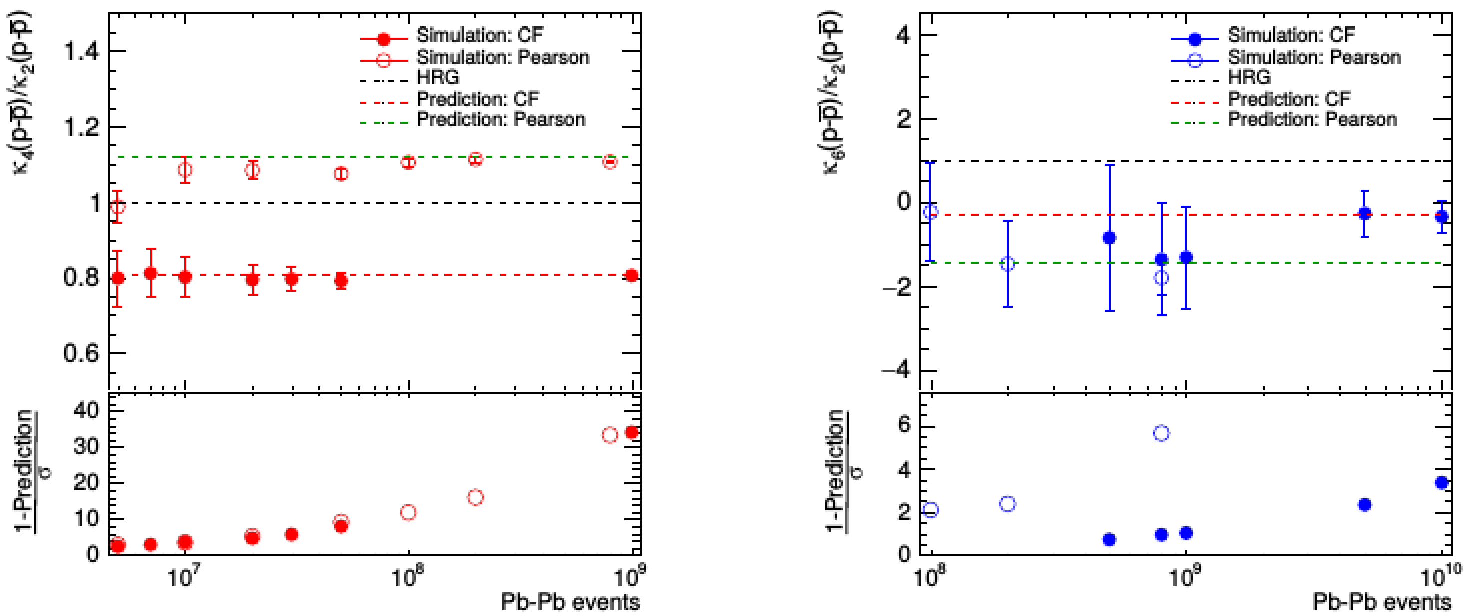
rapid drop suggests: chiral cross over and deconfinement appear in the same narrow temperature range

Nuclei and hypernuclei in Runs 3 and 4



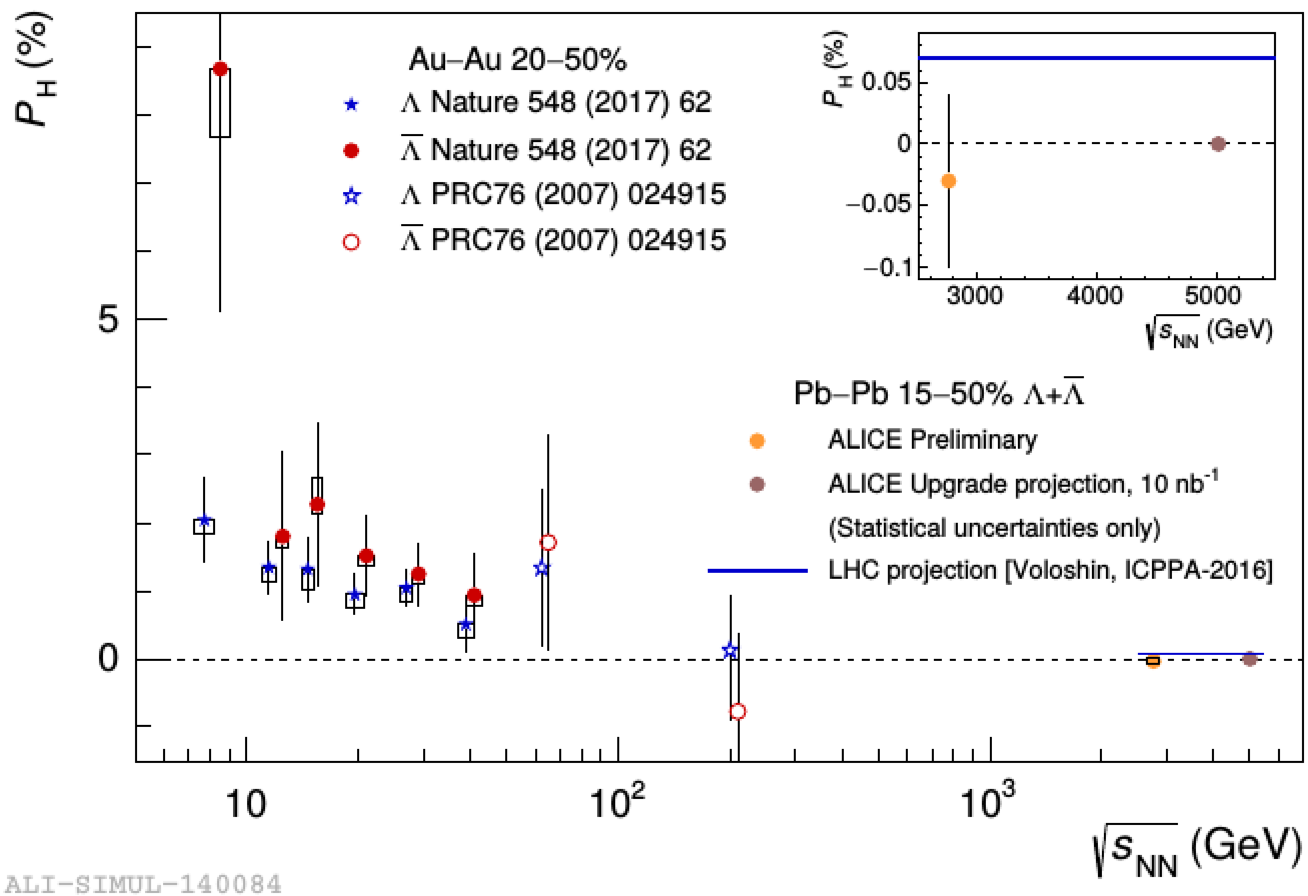


Proton fluctuations measured in Run3/4

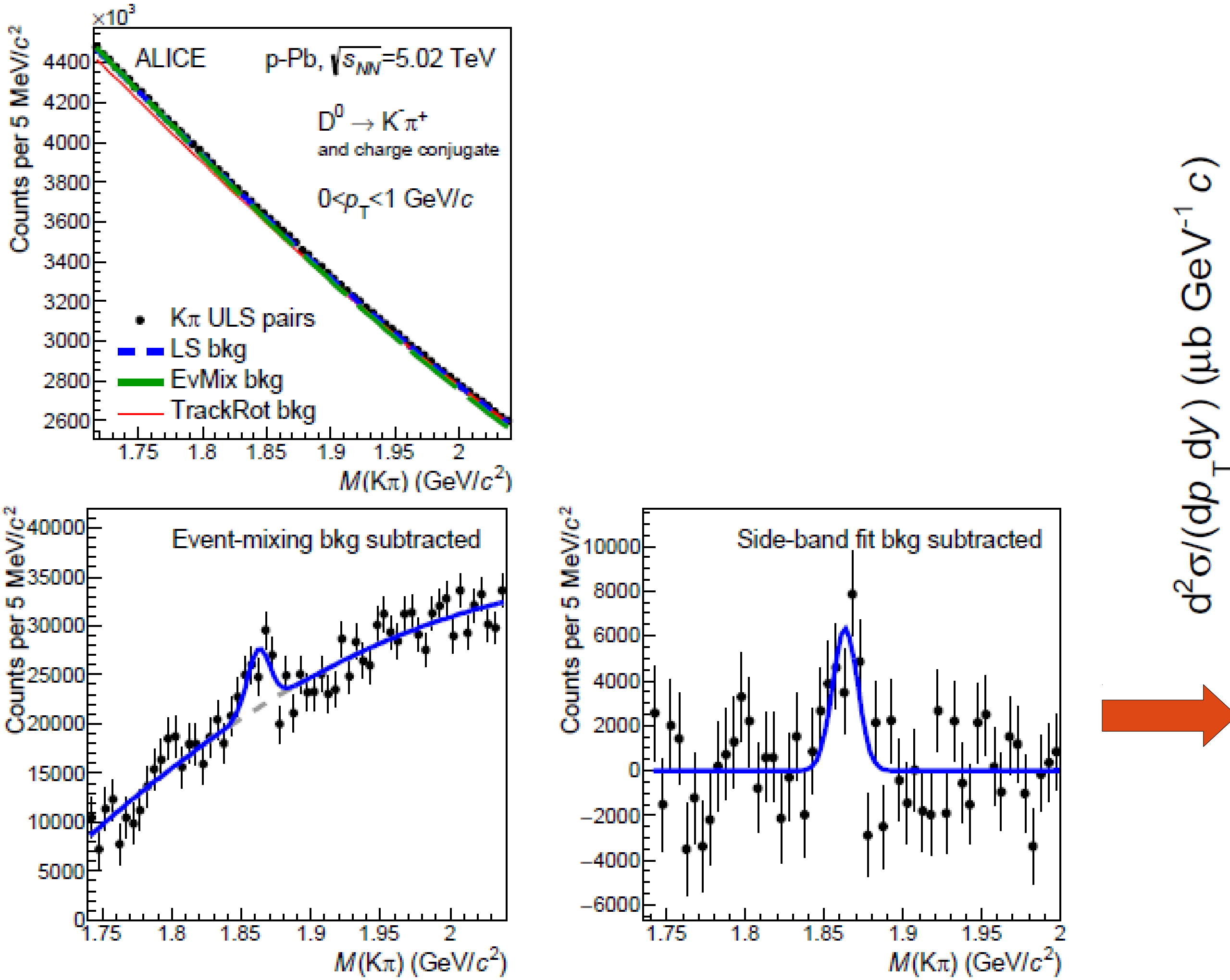


with 13 nb-1, critical phenomena contained in the 6th order cumulants will be probed

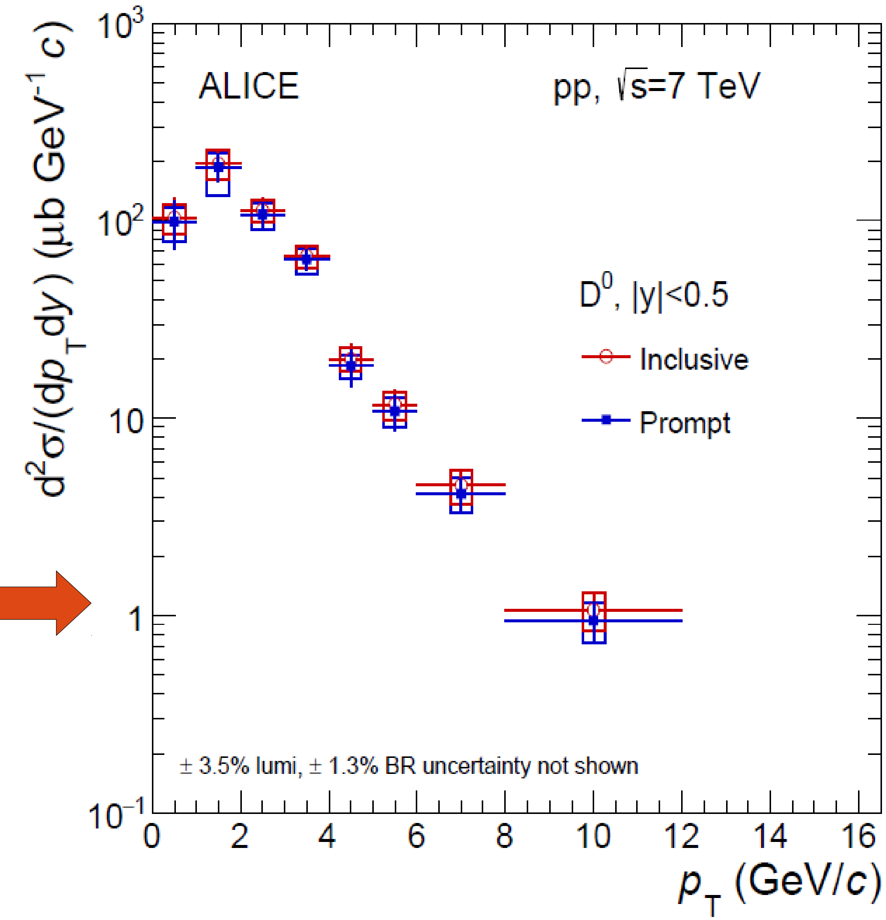
Vorticity and polarization



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

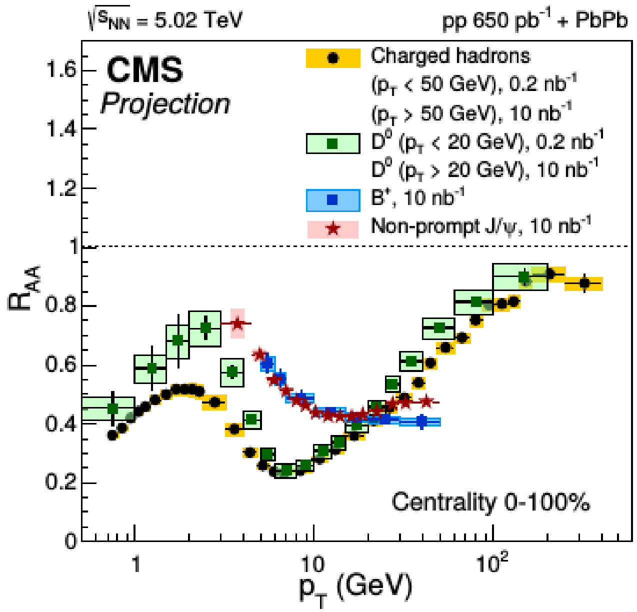


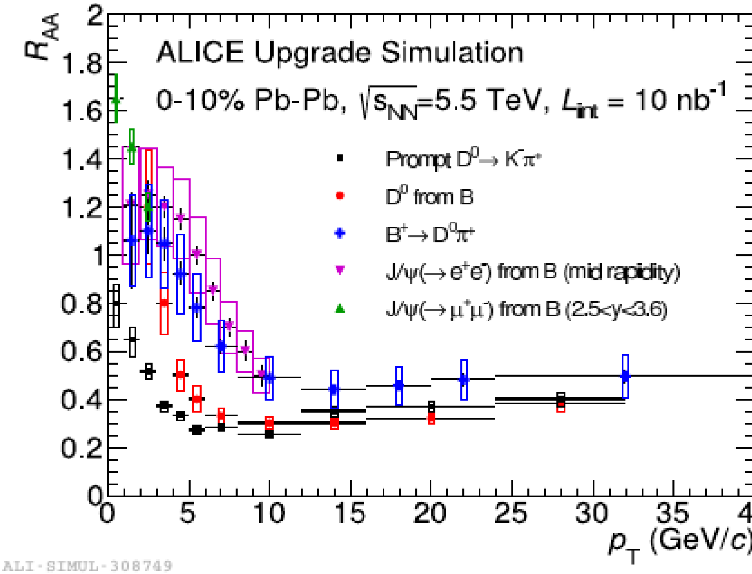
PRC94(2016) 054908 arXiv: 1605.07569

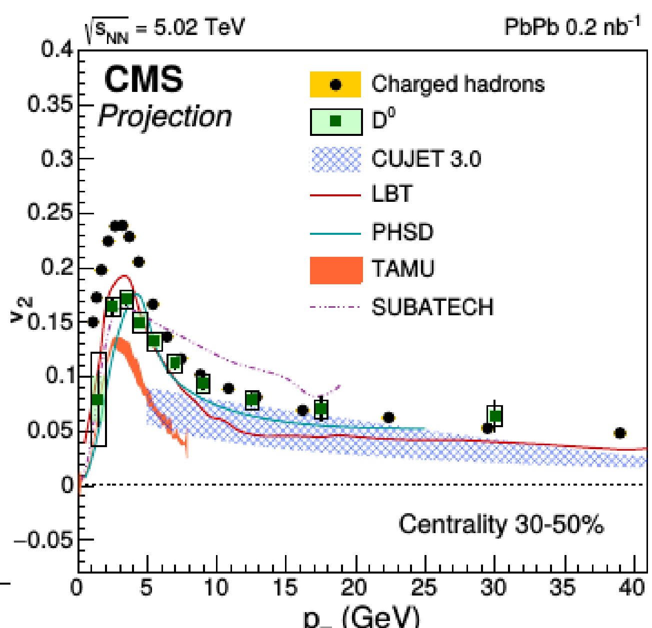


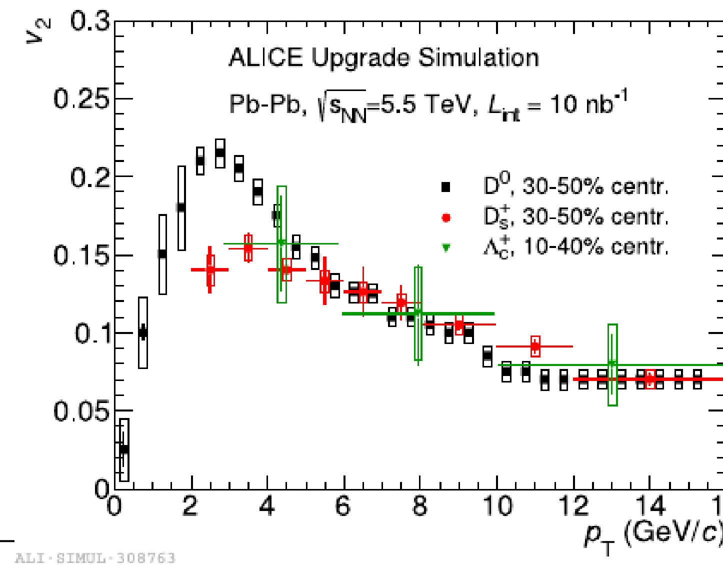
very hard struggle to deal with (irreducible) combinatorial background, successful

D and B R_{AA} and v_2



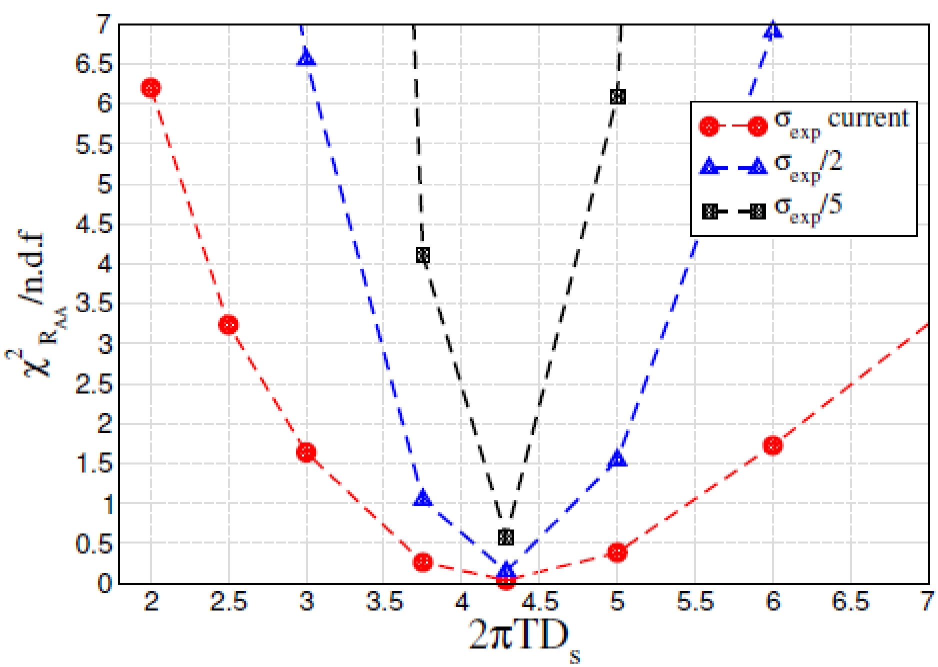






Charm quark spatial diffusion coefficient

equilibration time of heavy quark given by diffusion coefficient: $\tau_Q = \frac{m_Q}{T} D_s$
from simultaneous fit of spectrum and v2 as function of p_t get $D_s(T)$

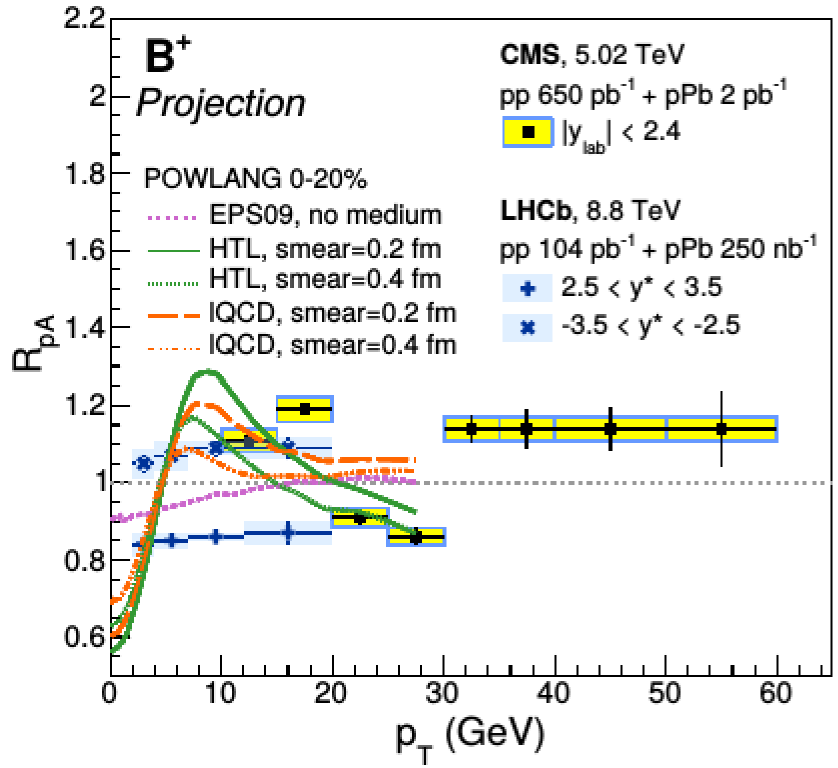


temperature dependence highly nontrivial
- decrease for liquid
- increase for gas

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

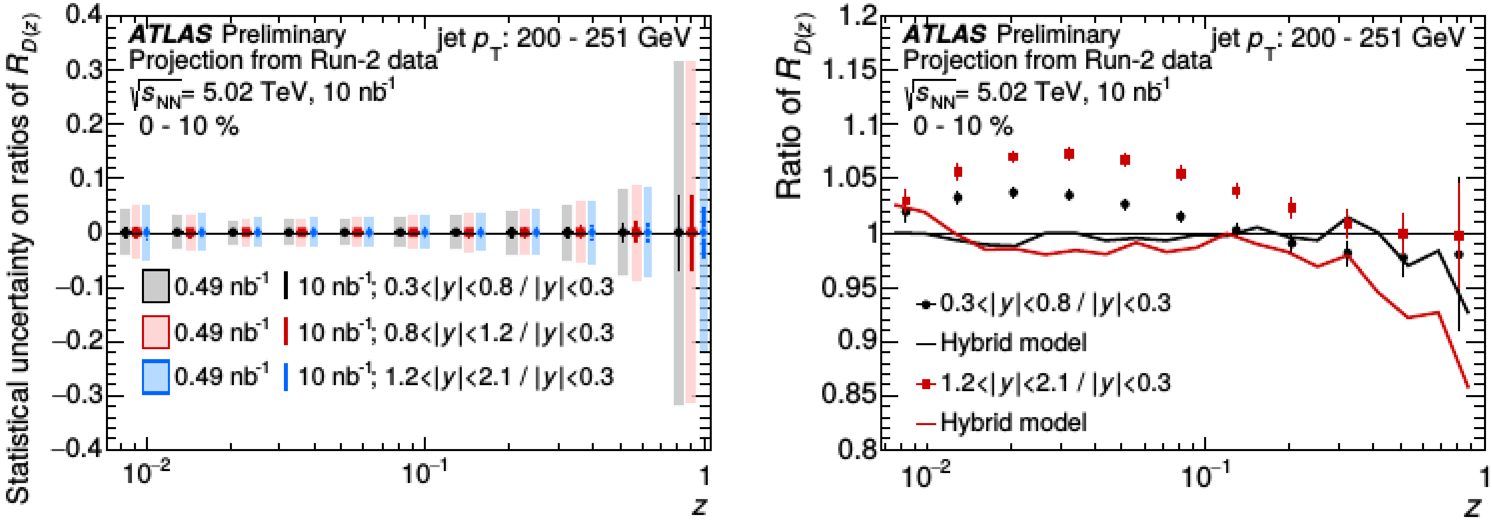
very interesting in era where precision QCD computations possible (lattice and funct. methods)

Projected accuracy B-meson modification in pPb



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

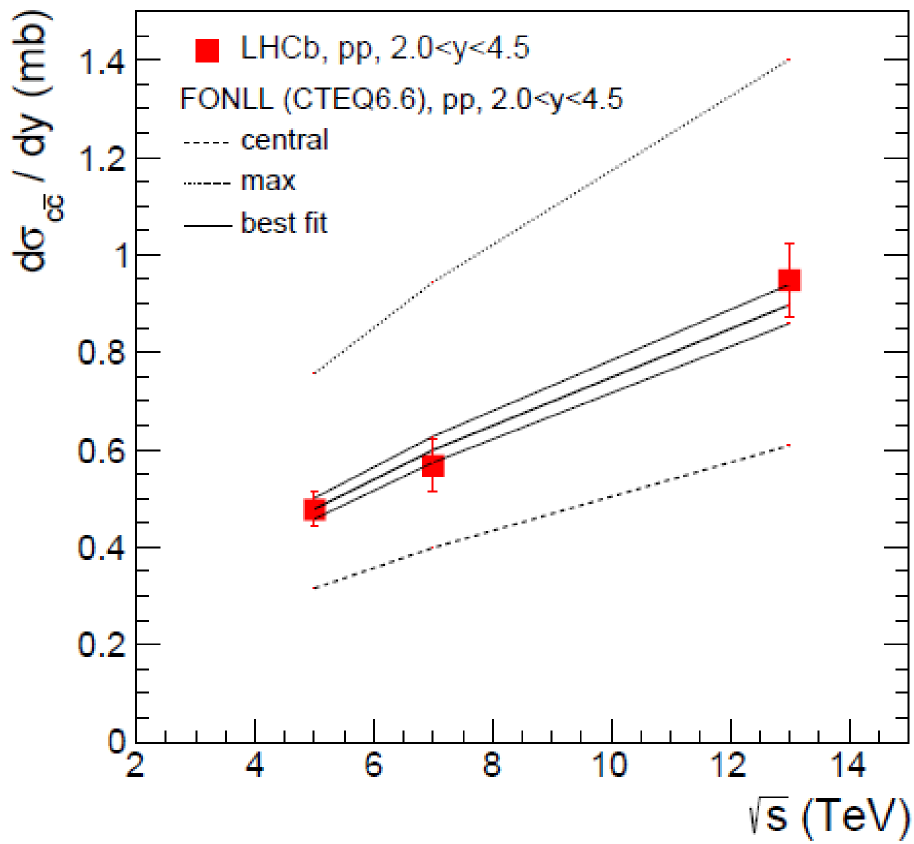
Modification on jet fragmention in PbPb

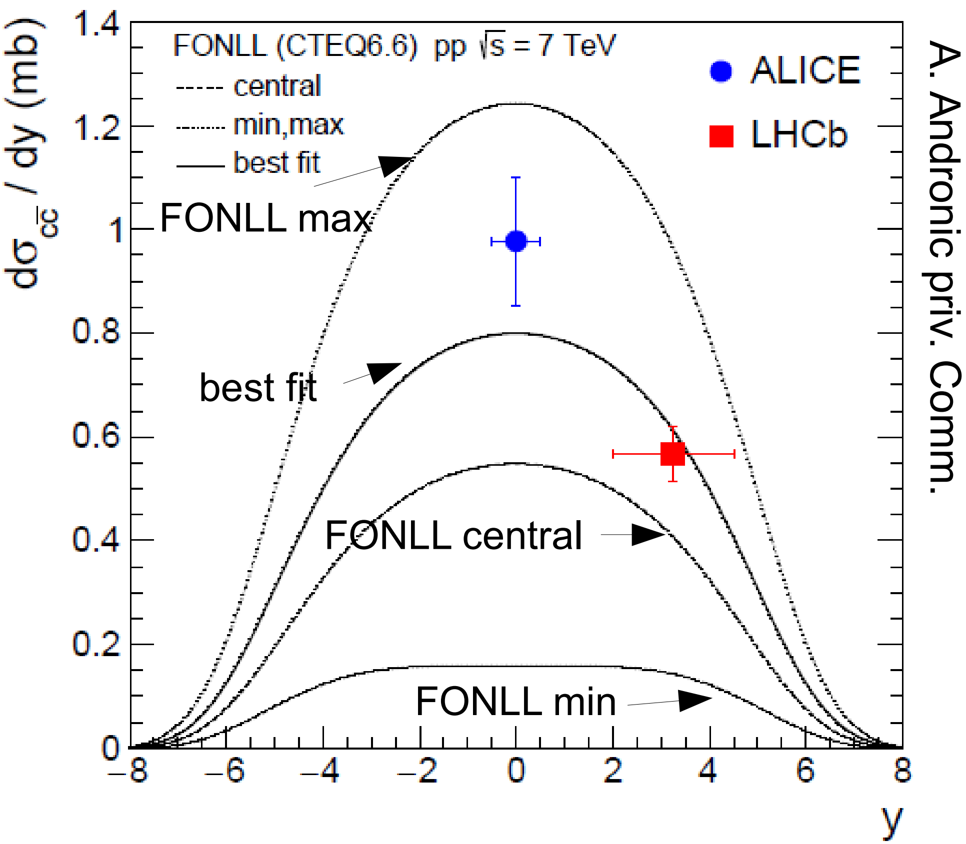


Run3/4: Superb sensitivity to details of fragmentation function at %-level

the baseline for the interpretation of PbPb data

use shape of FONLL to interpolate to proper √s and y-interval

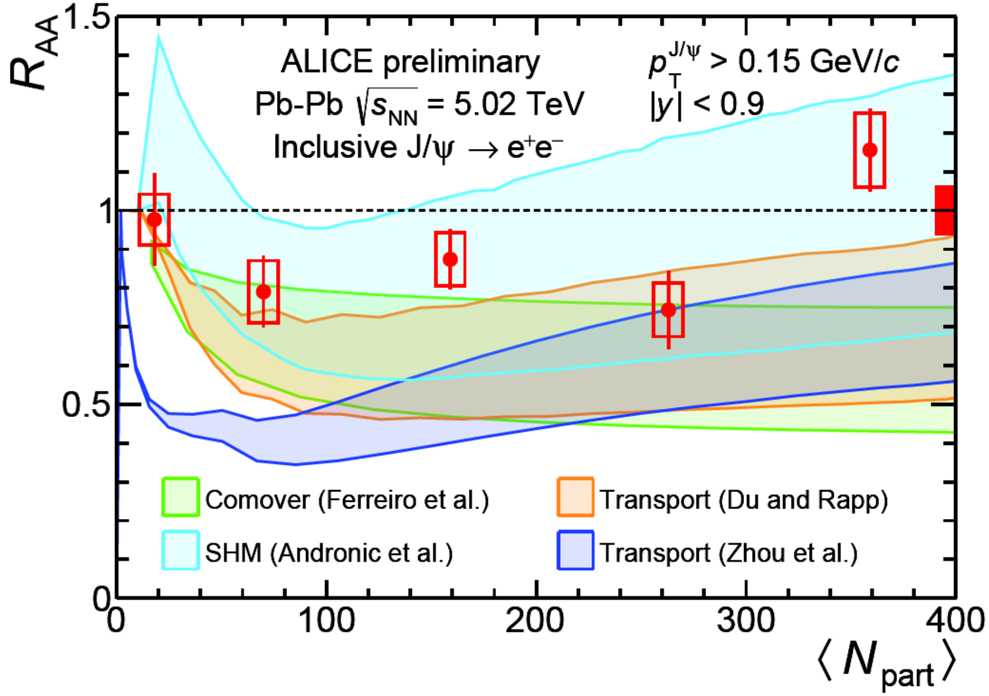


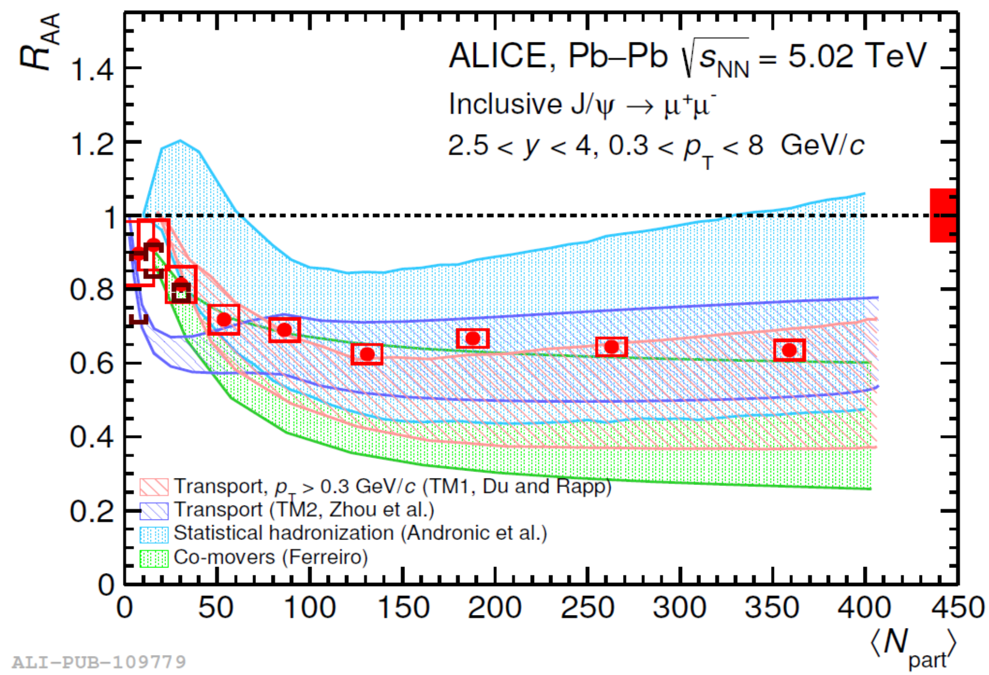


LHCb: 5 TeV arXiv:1610.02230
7 TeV NPB 871 (2013) 1
13 TeV JHEP 03 (2016) 159
plus erratum

ALICE: 7 TeV PRC94(2016) 054908
and 1702.00766

J/psi and transport models (and stat hadronization)





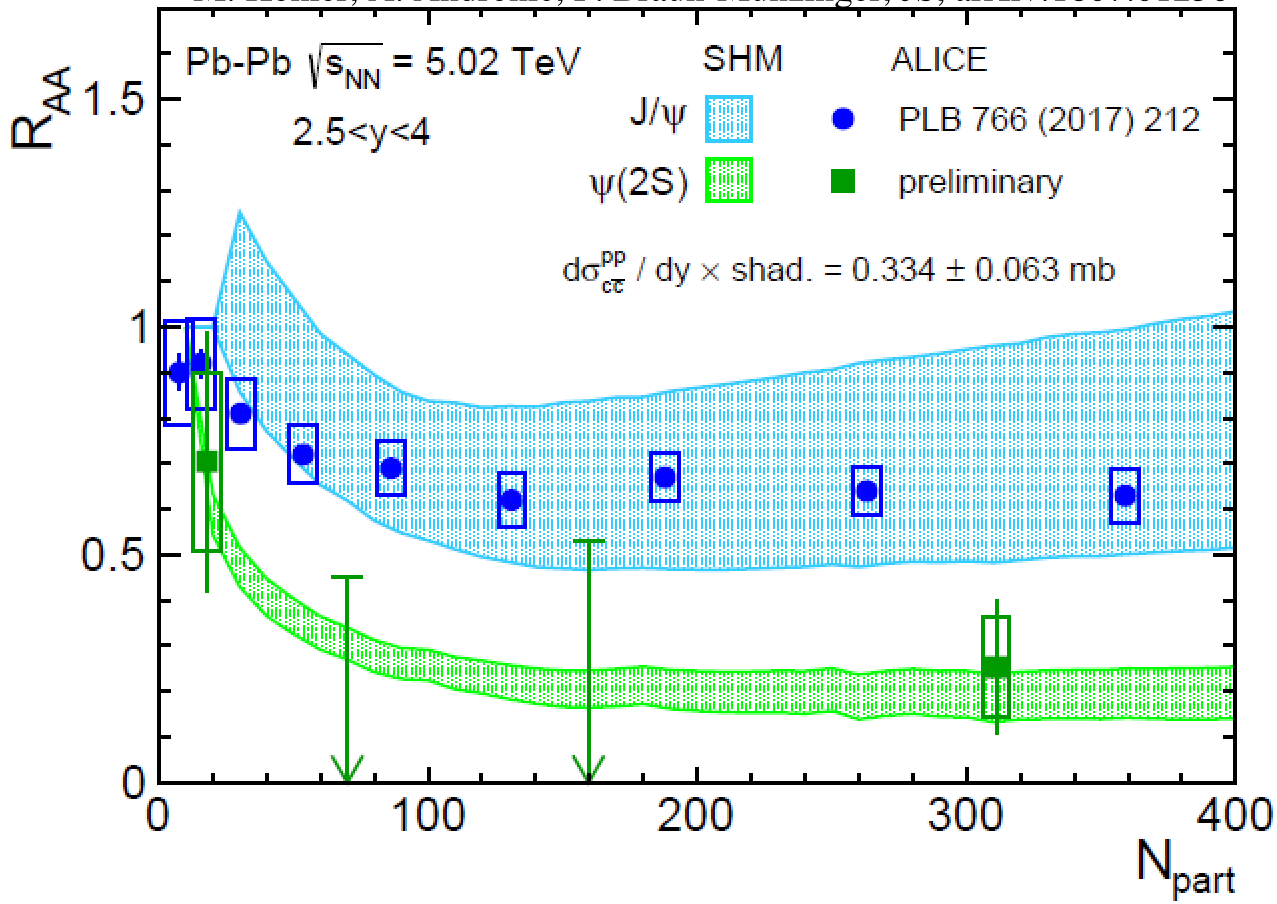
in transport models (Rapp et al. & Zhuang et al.) J/psi generated both in QGP and at hadronization

- 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 ψ(2S)?

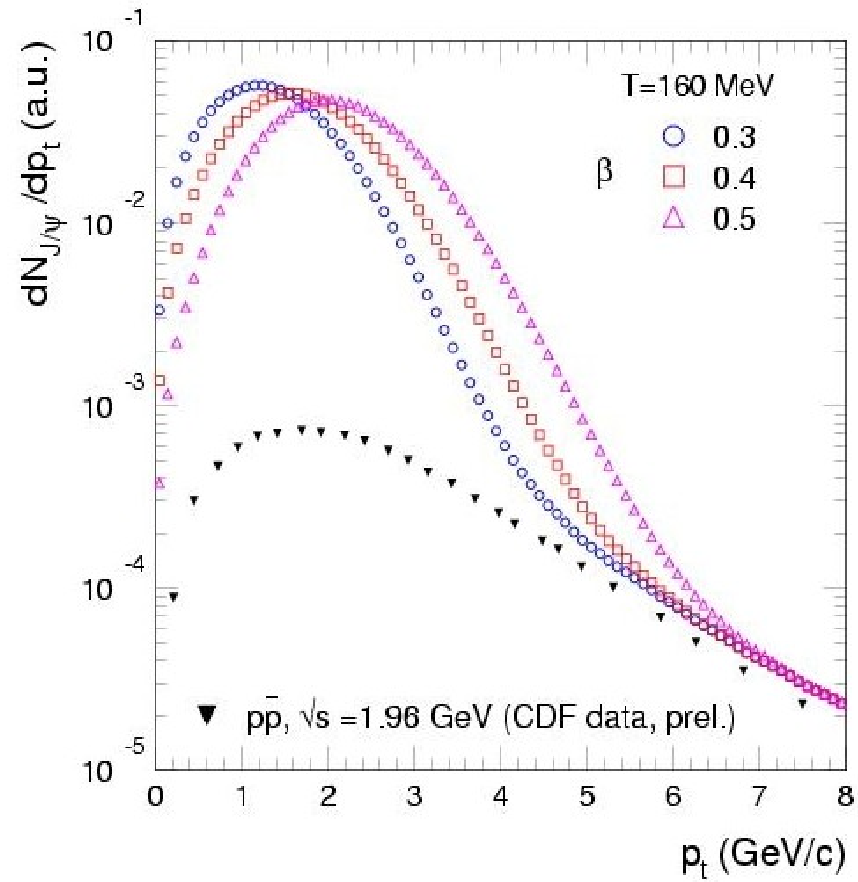
M. Köhler, A. Andronic, P. Braun-Munzinger, JS, arXiv:1807.01236



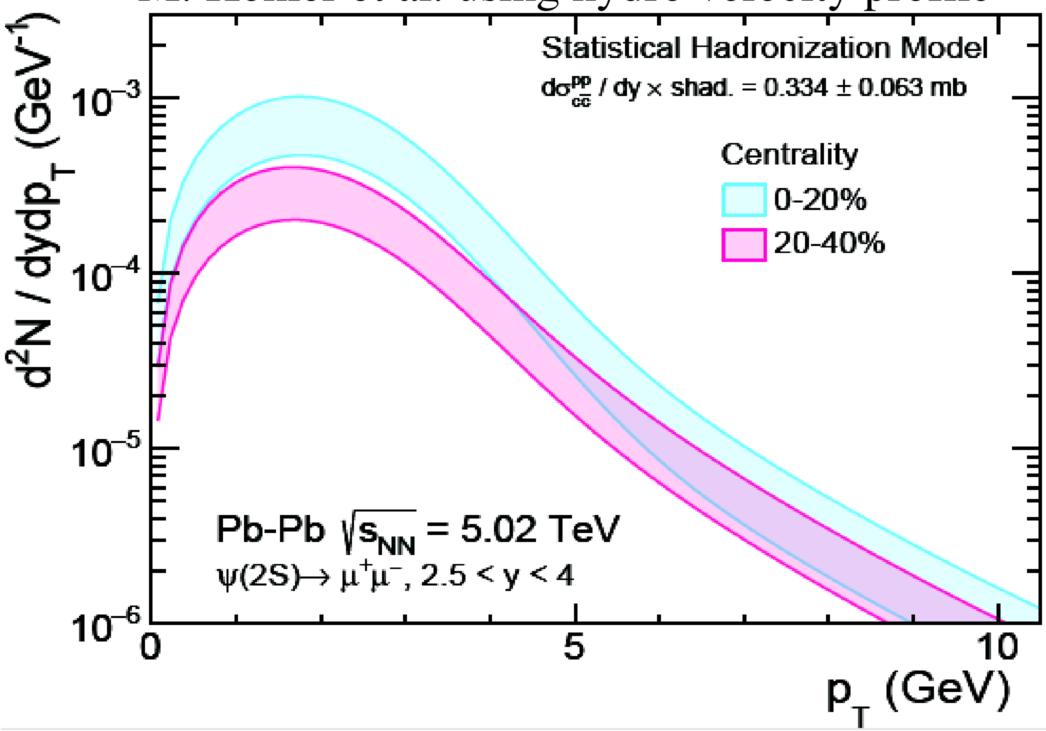
also excited state completely in line, suppressed by Boltzmann factor
but errors need to decrease with more data to make a meaningful statement!

Spectral distribution is key to thermalization

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

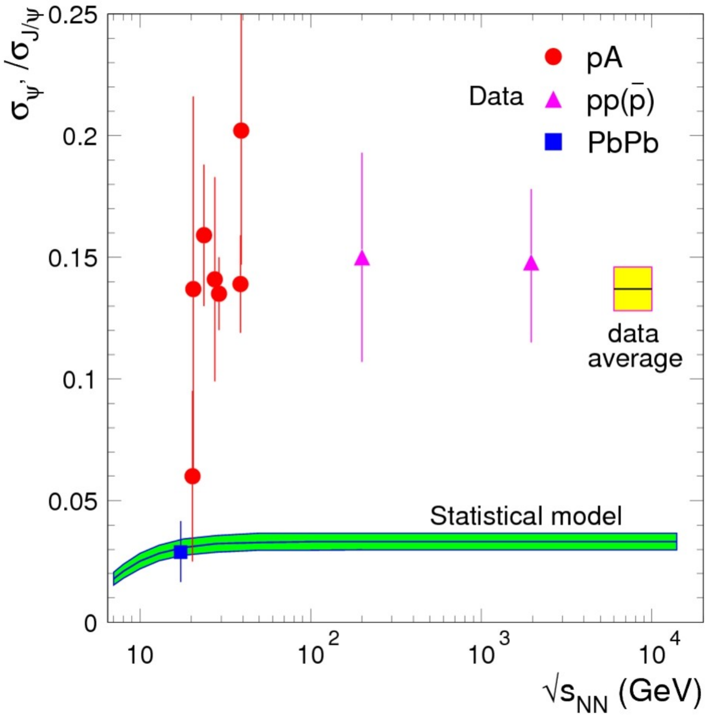


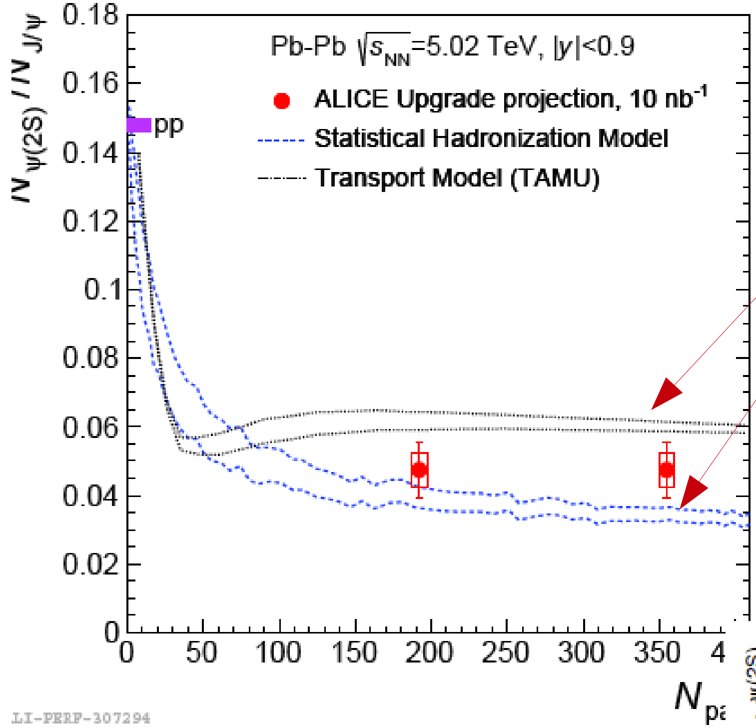
M. Köhler et al. using hydro velocity profile



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

excited charmonia crucial to distinguish between models

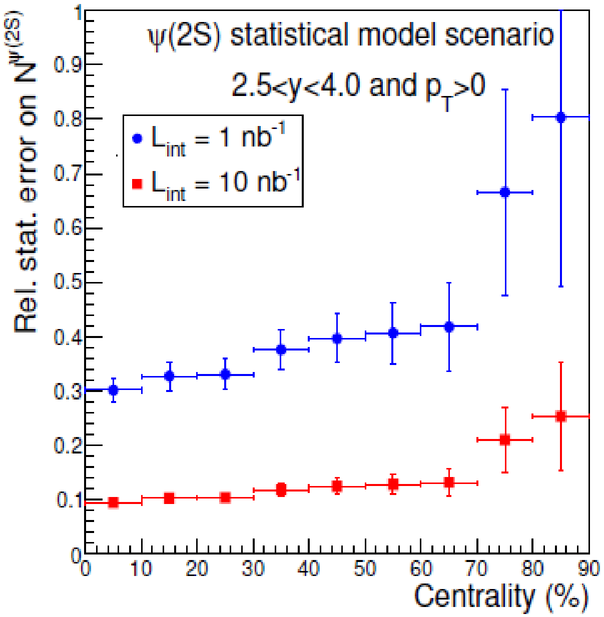




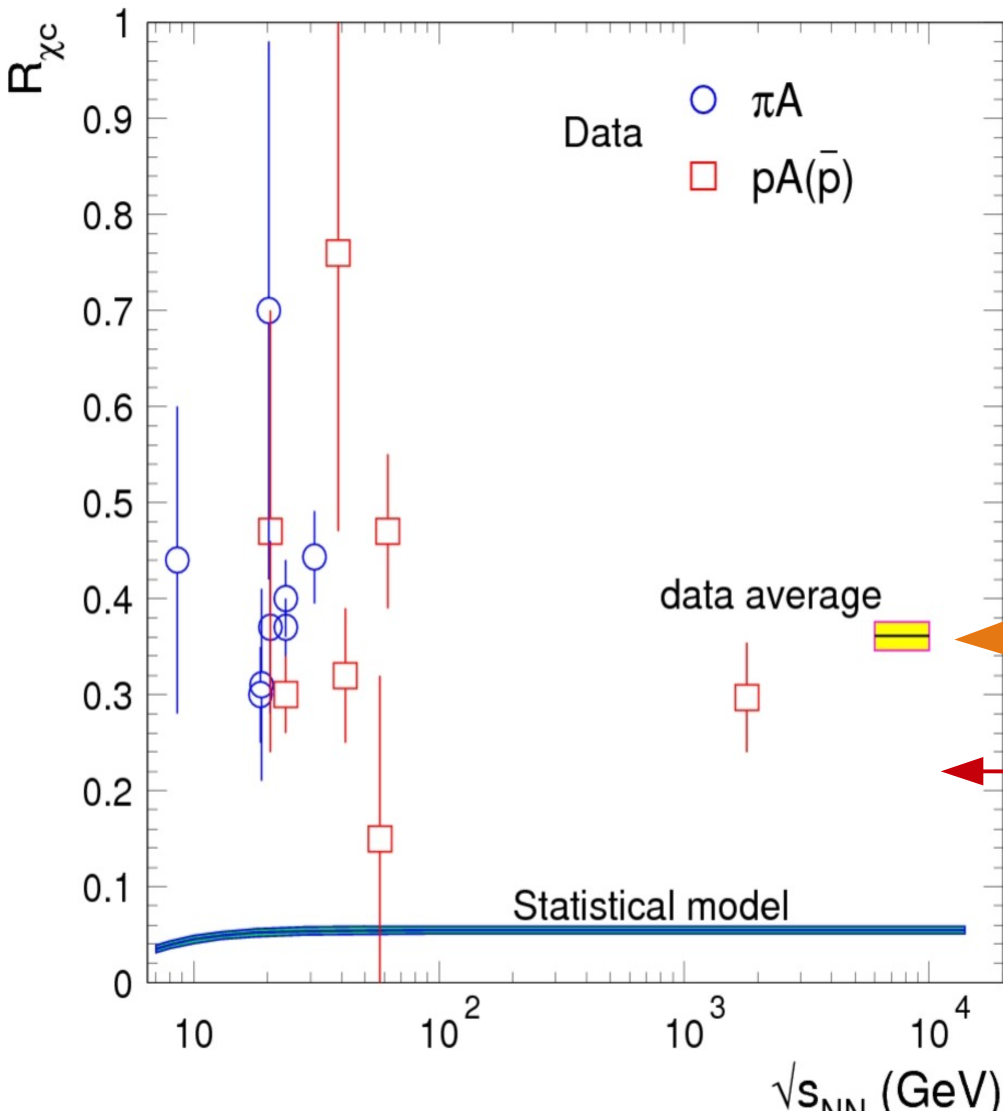
in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

for statistical hadronization need to see suppression by Boltzmann factor

expected ALICE performance muon arm run2 and run3



Situation even more dramatic for P-states



pA and πA data on average factor 7 avove statistical model prediction

Transport model (Rapp)

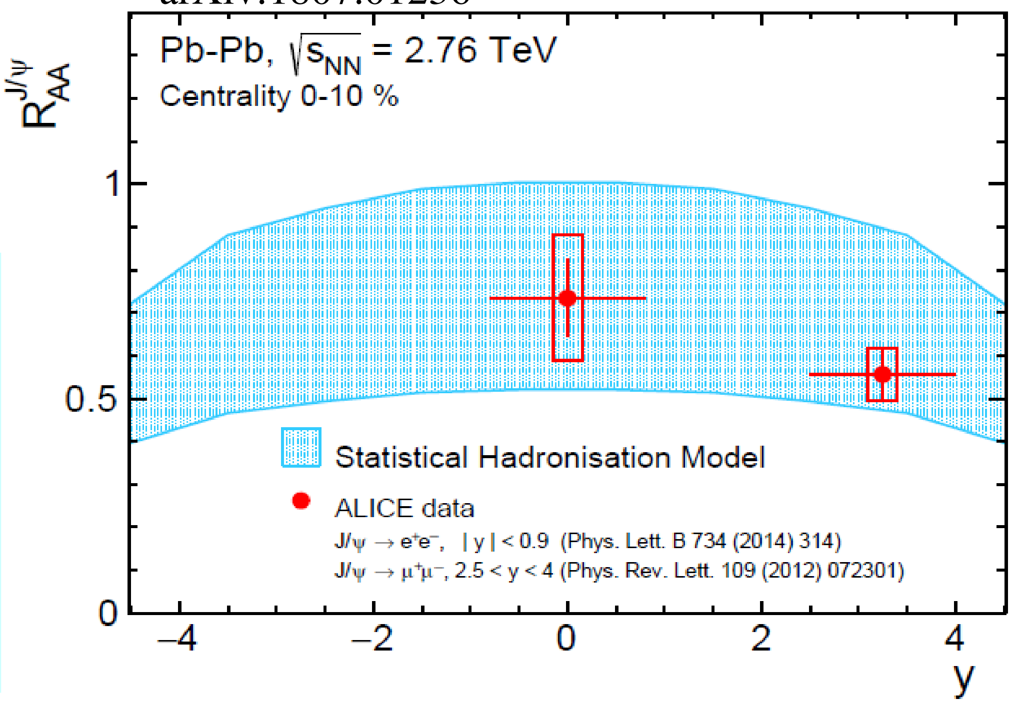
A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B678 (2009) 350

Rapidity dependence of R_{AA}

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

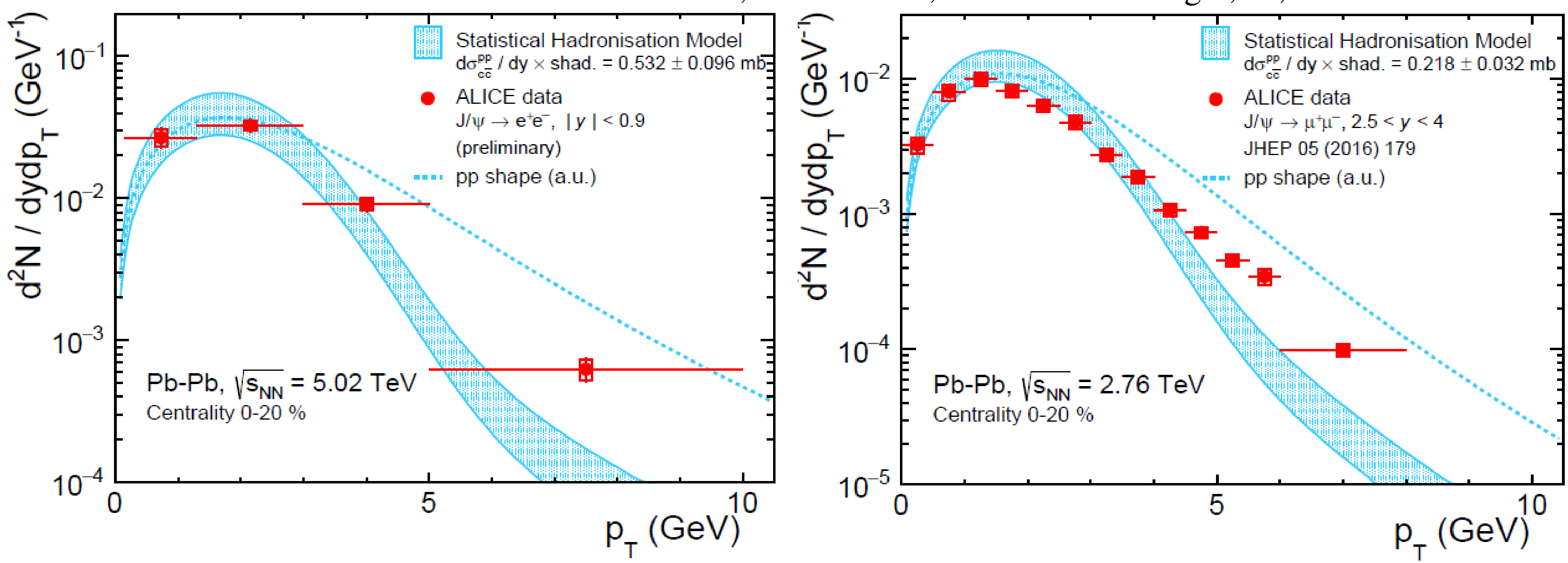
for statistical hadronization J/ψ yield proportional to N_c^2 - higher yield at mid-rapidity predicted in line with observation
(at RHIC and LHC)

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



J/ψ transverse momentum spectra from stat. hadr.

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



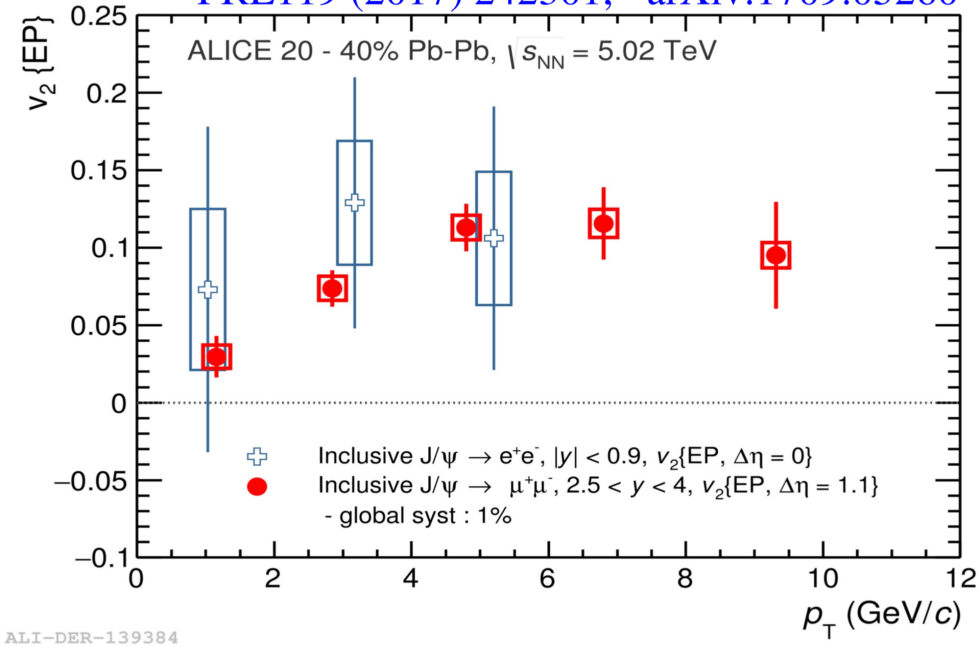
quite reasonable agreement without any free parameters

J/ψ formed at hadronization at T_c from thermalized charm quarks flowing with the rest of the medium

need to increase statistics!

J/psi elliptic flow

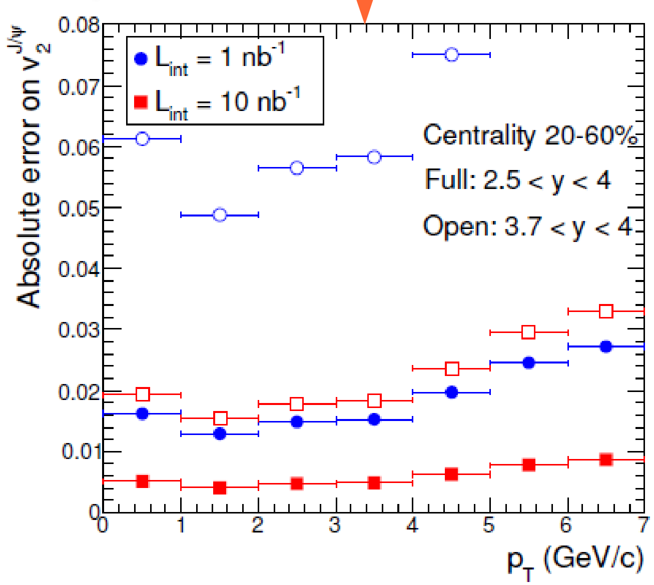
PRL119 (2017) 242301, arXiv:1709.05260

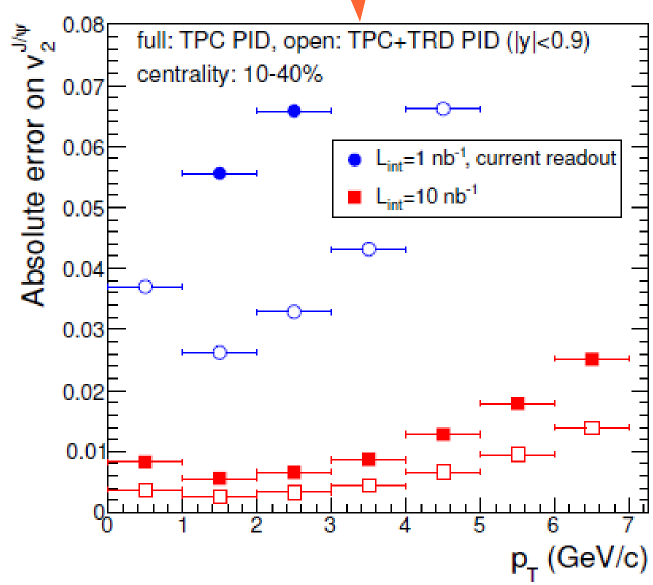


future statistical errors

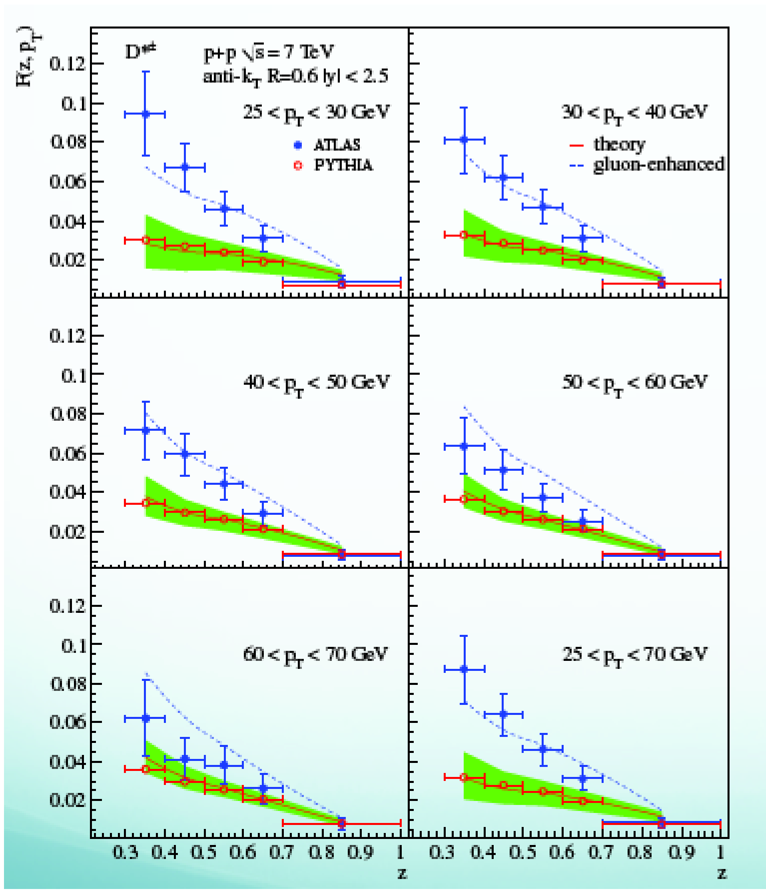
muon arm

central barrel



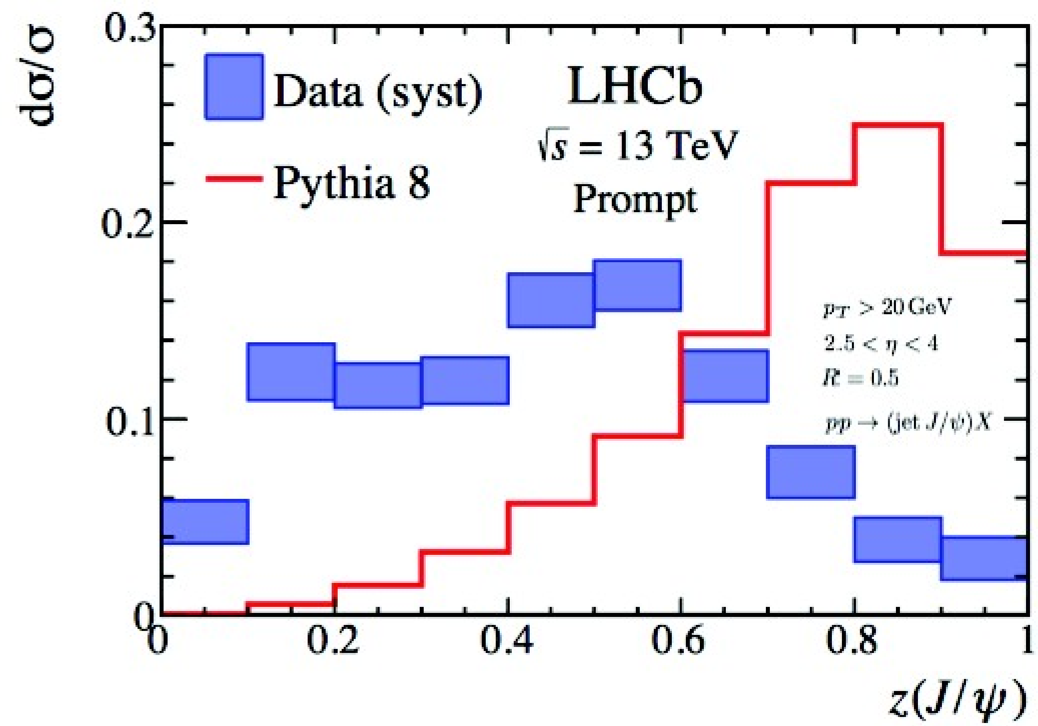


D meson and J/ψ fragmentation functions surprizing



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

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

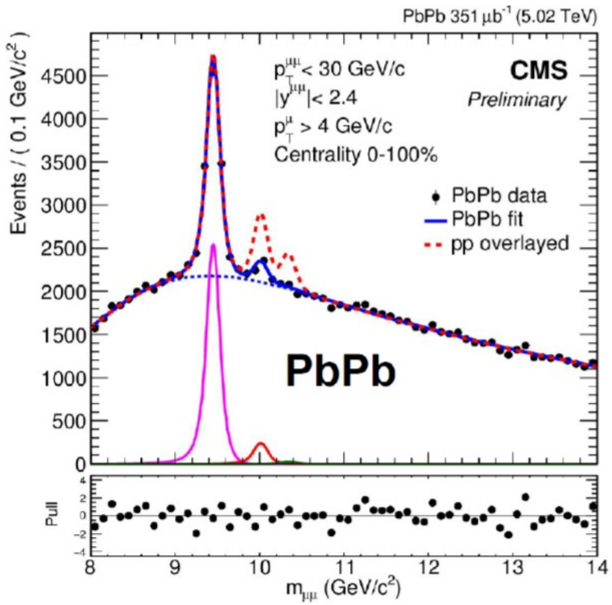


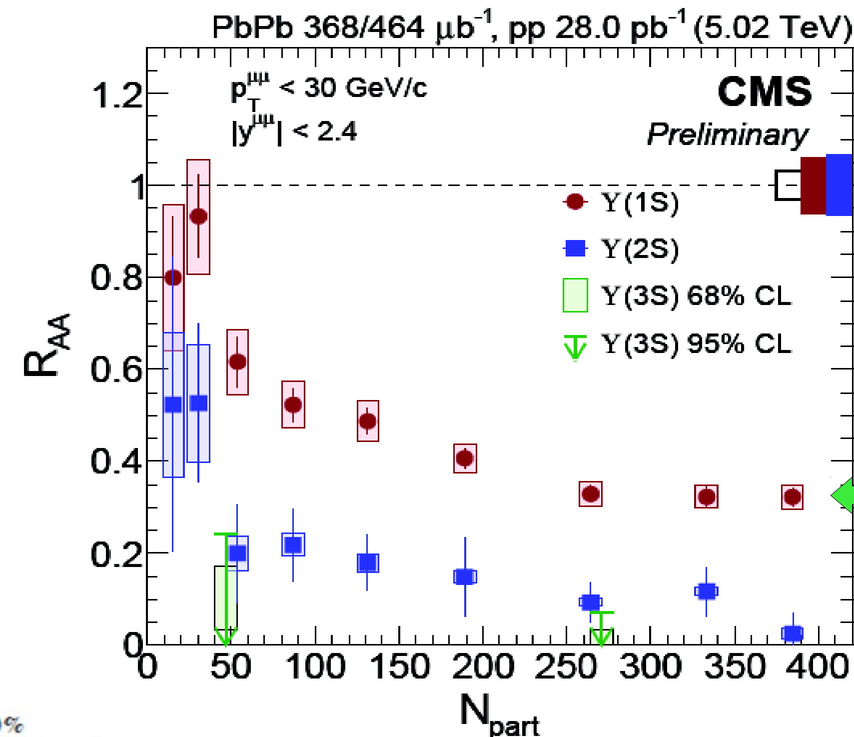
H.Xing (Wuhan 10/2018) : data prefers that jet was initiated by a single parton fragmentation, while PYTHIA starts from a ccbar

Gluon fragmentation into J/ψ could well be the mechanism explaining the high p_t R_{AA}

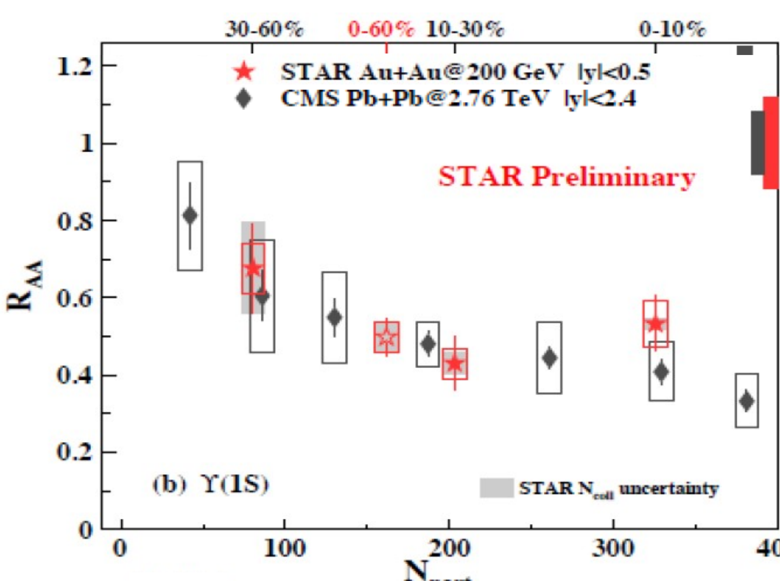
measure J/ψ in jets in pp and PbPb

Suppression of Upsilon states



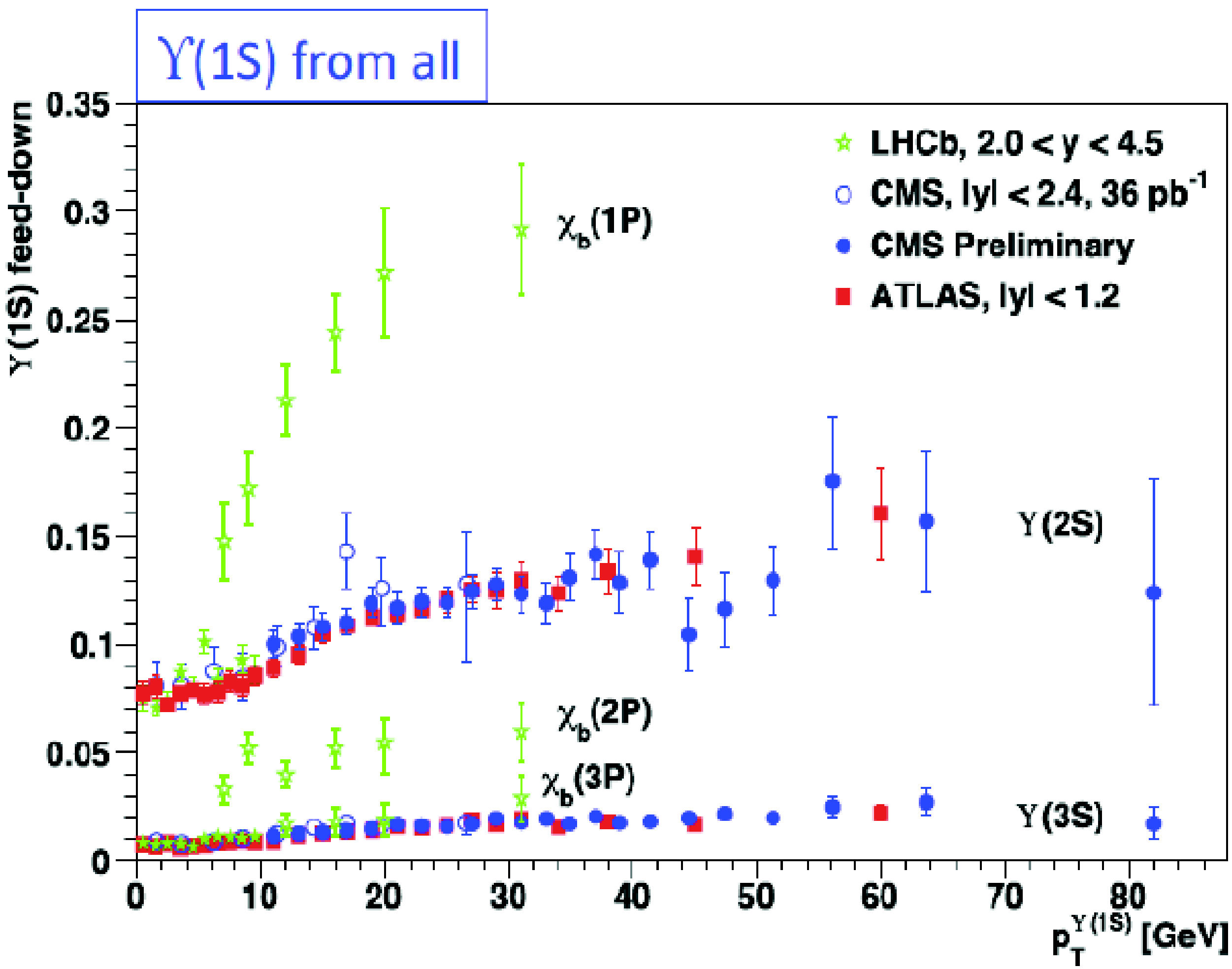


not consistent with just excited state suppression (LHCb data: only 25 % feed-down in pp at LHC)



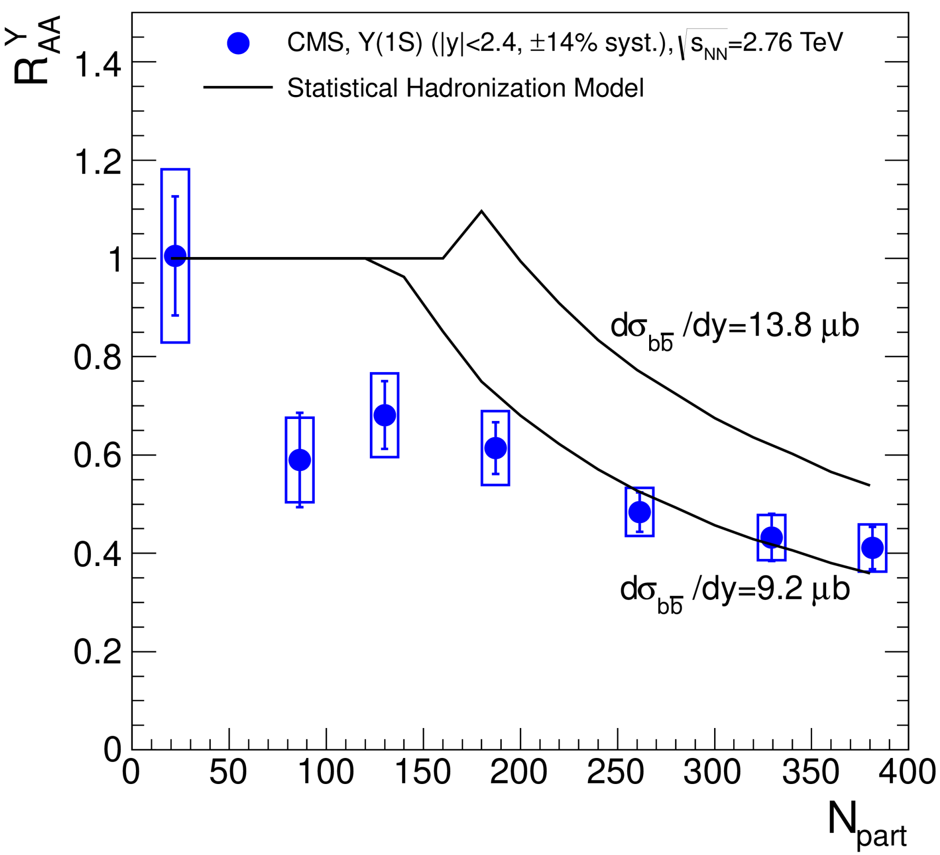
genuine Upsilon suppression
- real and imaginary part of potential at finite temperature play a role
- similarity of RHIC and LHC suppression reminiscent of SPS and RHIC for J/ψ
- possibility of statistical hadronization?

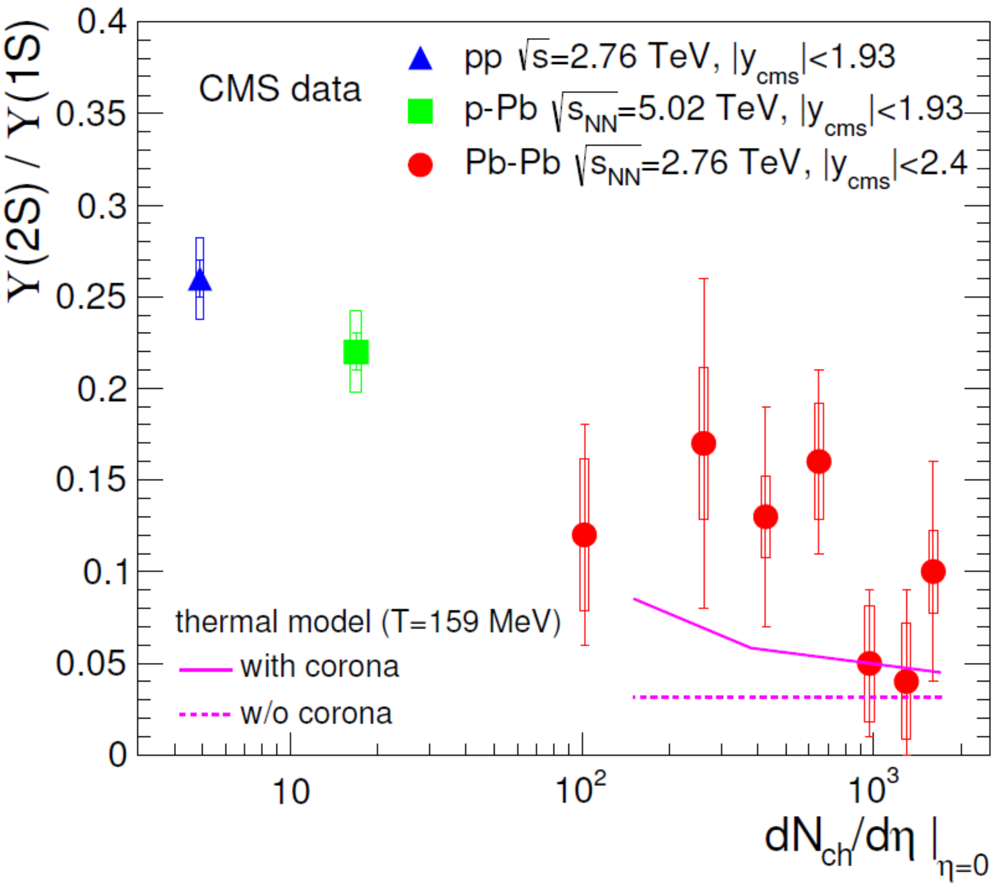
Feeding into Upsilon (1S)



the Upsilon could also come from statistical hadronization

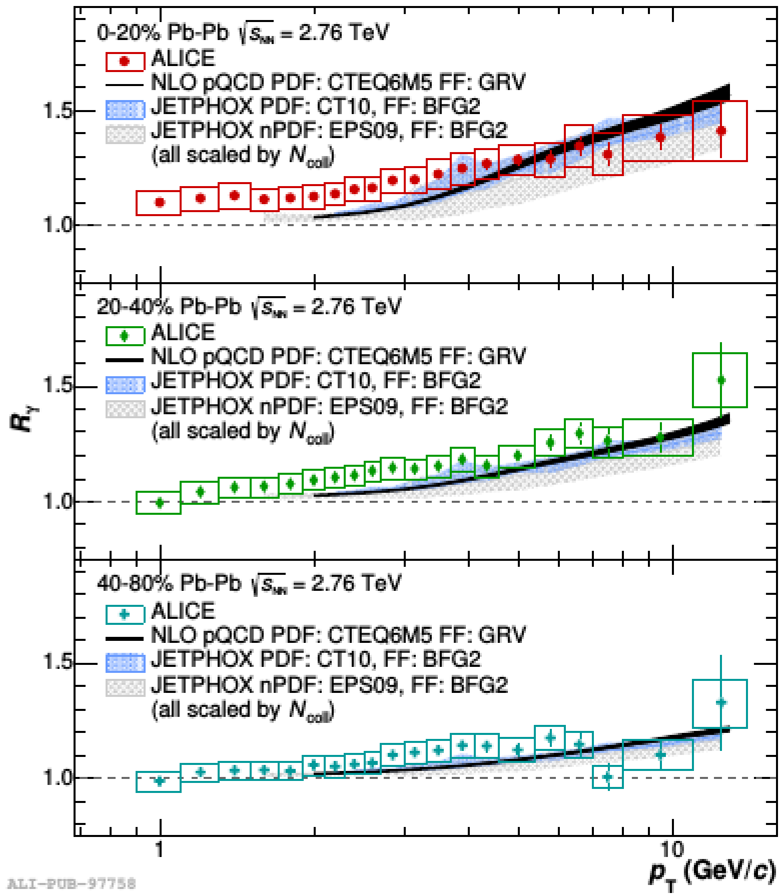
SHM/thermal model: Andronic et al.

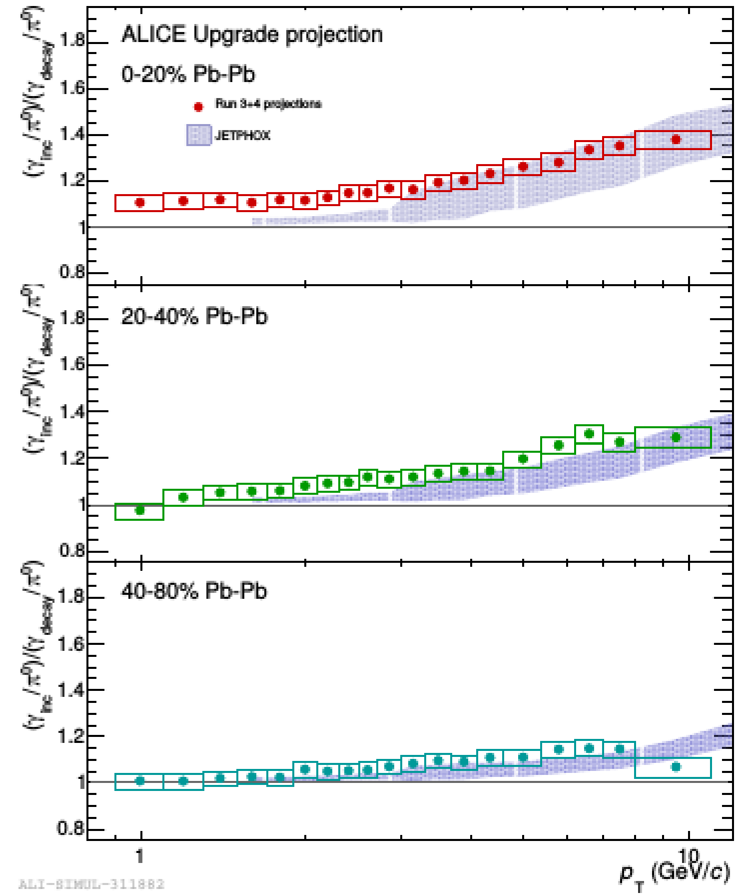




in this picture, the entire Upsilon family is formed at hadronization
but: need to know first – do b-quark thermalize at all? spectra of B
- total b-cross section in PbPb

Real photons in PbPb

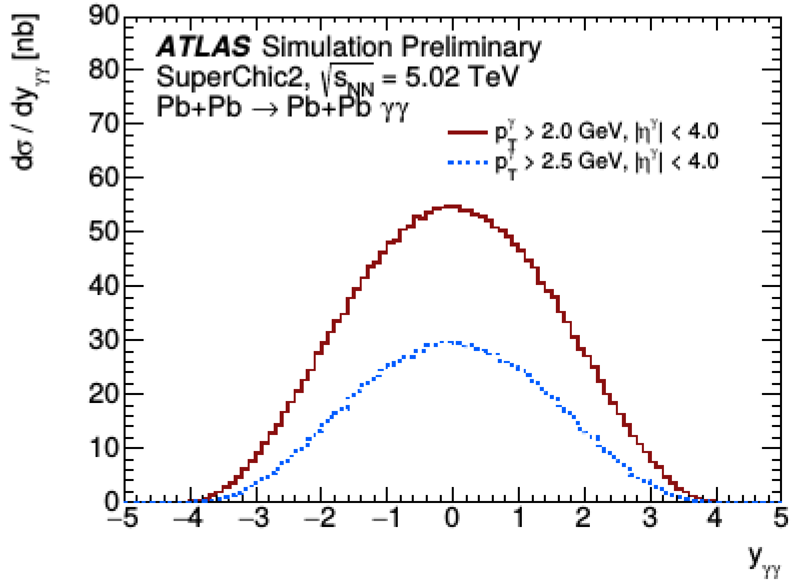


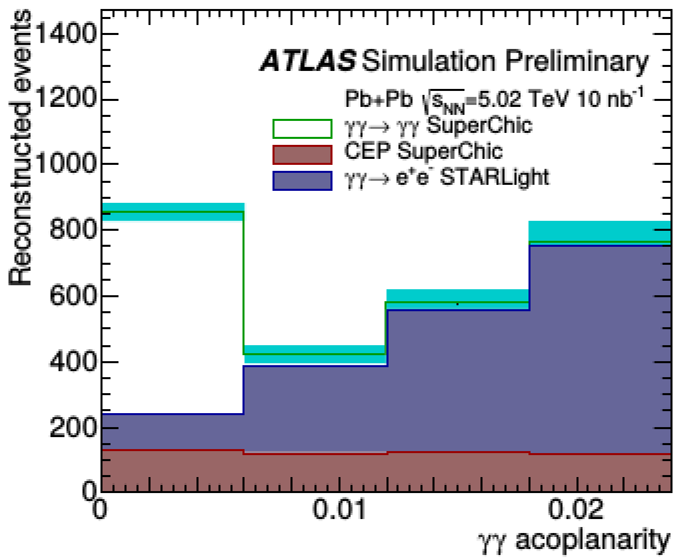


Run3/4: even with current, relatively small R_γ, 3 σ sensitivity can be reached also for v_2^γ

Light by light scattering in PbPb

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





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

Luminosity requirements in WG5 report & running

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

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

doorway state hypothesis:
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, pbm, Redlich, Stachel, 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

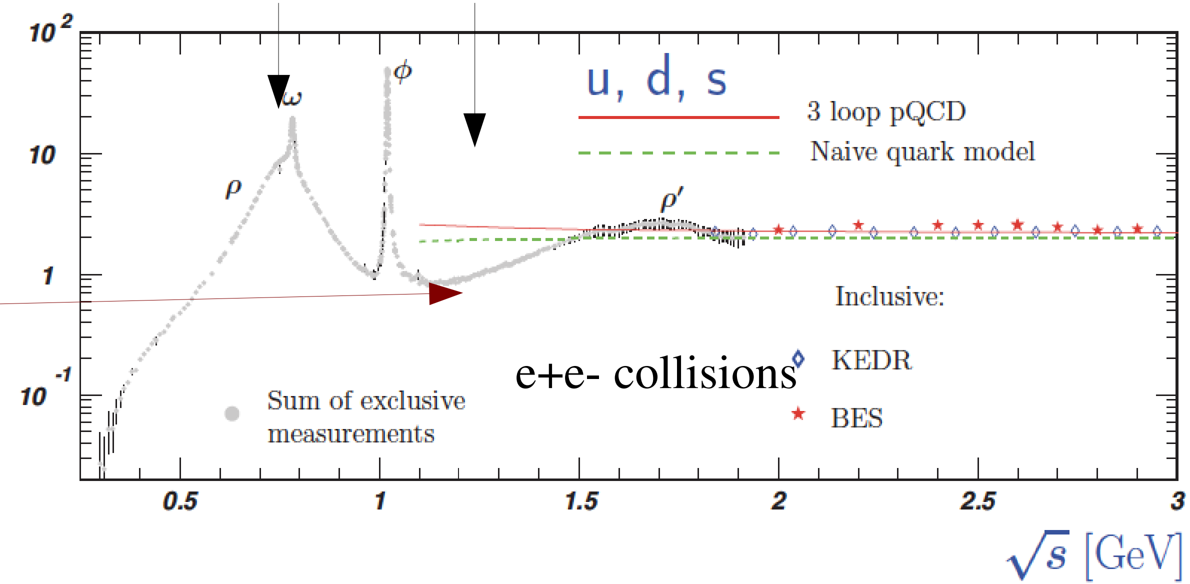
a major new opportunity for ALICE
beyond LS4 for X,Y,Z , multi-charm, charm-beauty and penta-quark states

The detection and quantitative measurement of χ_c states involves the identification of a low energy (about 300 - 440 MeV near mid-rapidity) photon in addition to a J/ψ 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 χ_c states one needs a photon energy resolution of about 5% near 400 MeV corresponding to $\frac{\delta E_\gamma}{E\gamma} \approx 3\%/\sqrt{E_\gamma(GeV)}$ 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.

Interesting new opportunities arose with recent findings by Belle2 and LHC$_b$ that the $\chi_c \to l^+l^-J/\psi$ is of order 10^{-4}. This would imply that the $\chi_c \to 4leptons$ becomes an attractive channel to study the production of χ 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$_b$ 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 and the ρ - a_1 region

vacuum masses: ρ 770 MeV, a_1 1230 MeV

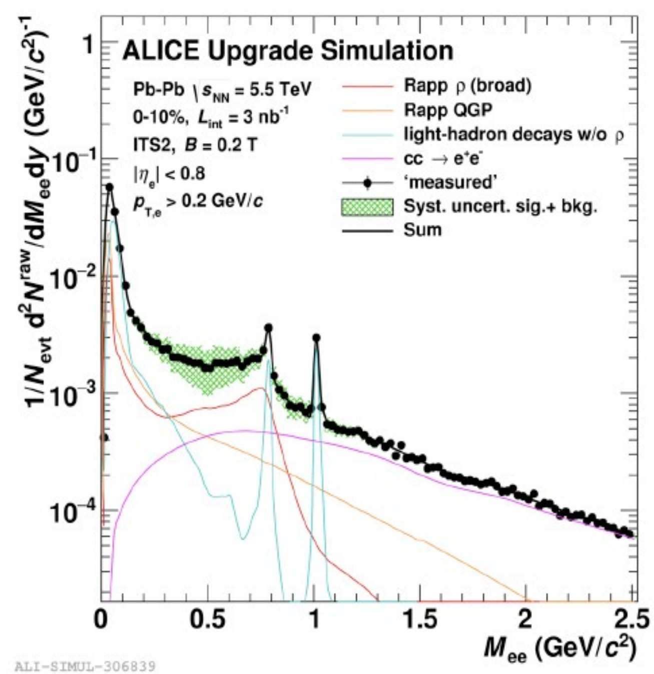


<u>the idea:</u> the ρ and a_1 mesons are chiral partners. In vacuum, chiral symmetry is broken, the ρ couples to e^+e^-, but not the a_1.

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

<u>to detect this:</u> 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

<u>the challenge:</u> 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

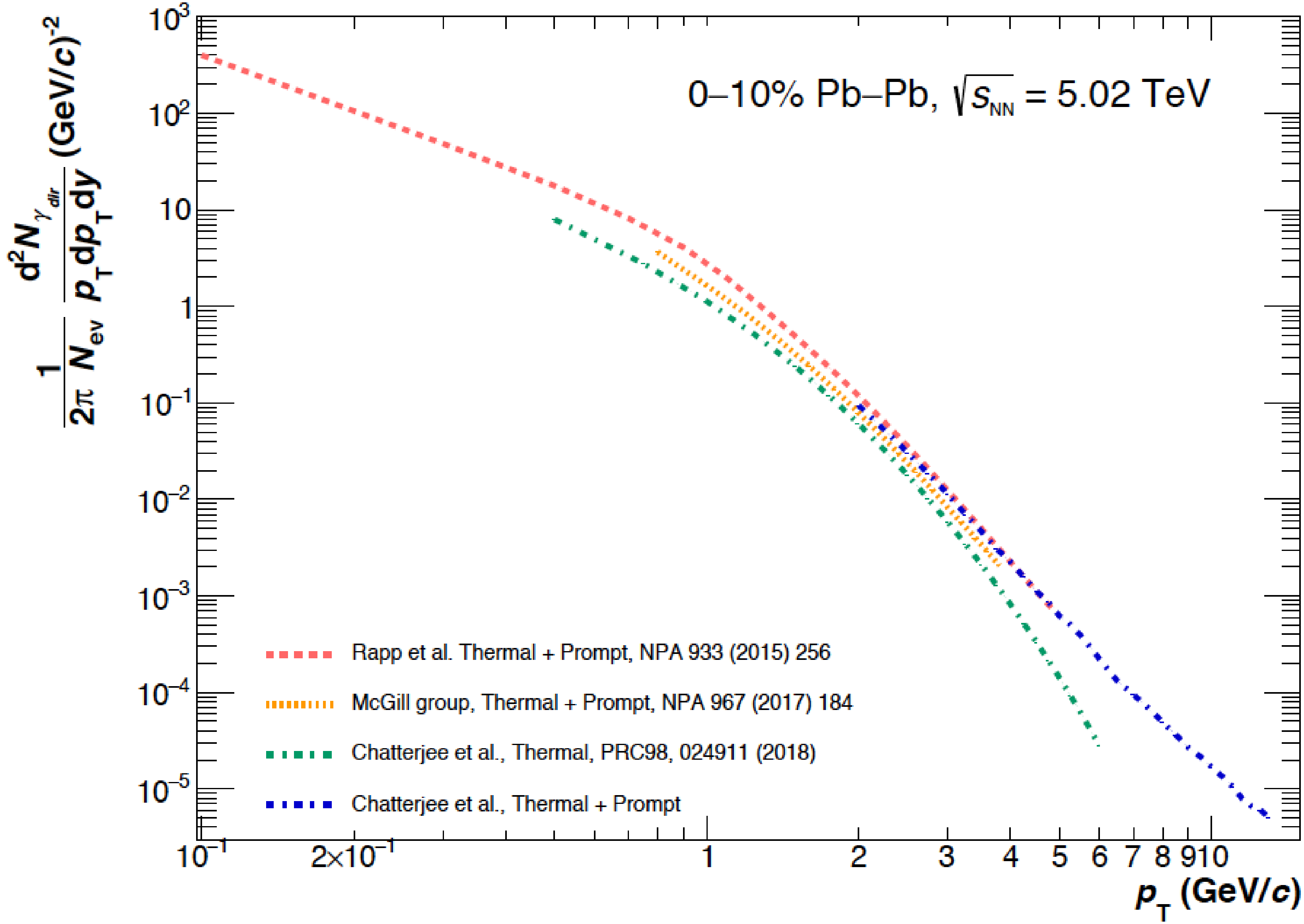


figure from CERN yellow report HL-LHC 2018

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)

5. 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^μ 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

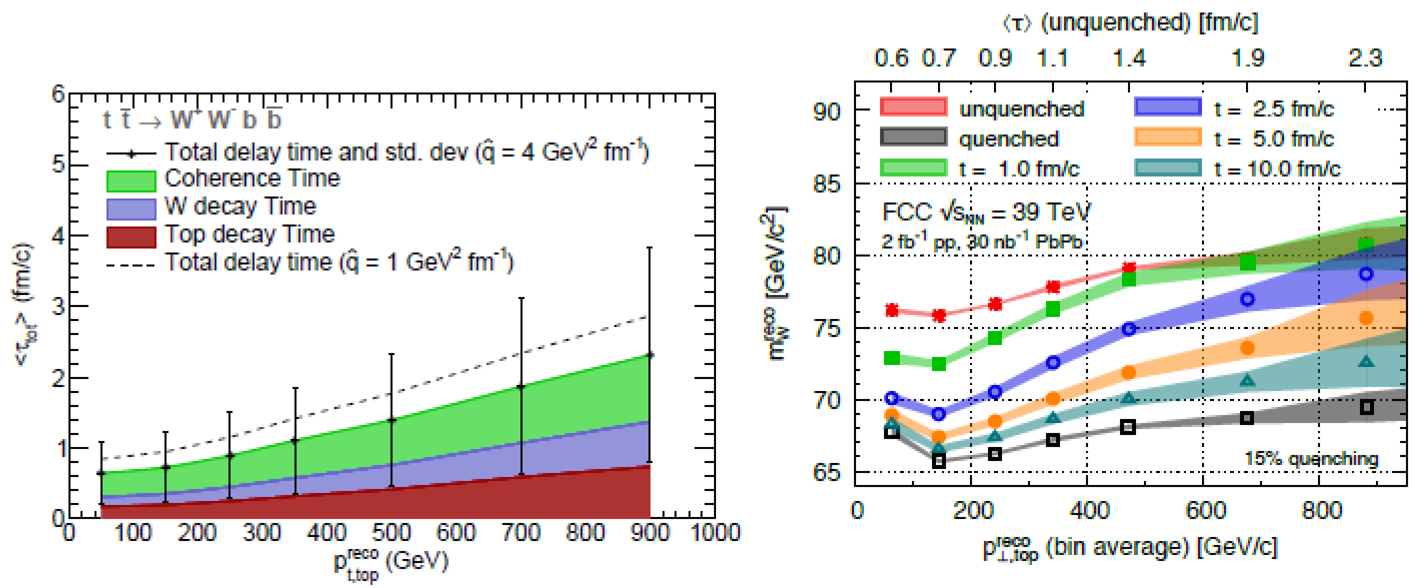
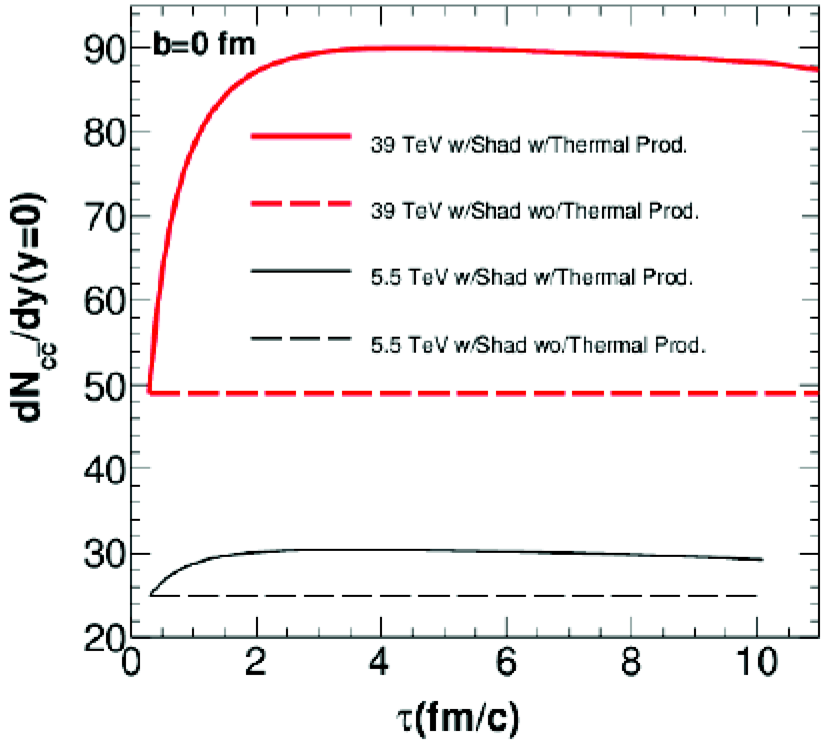
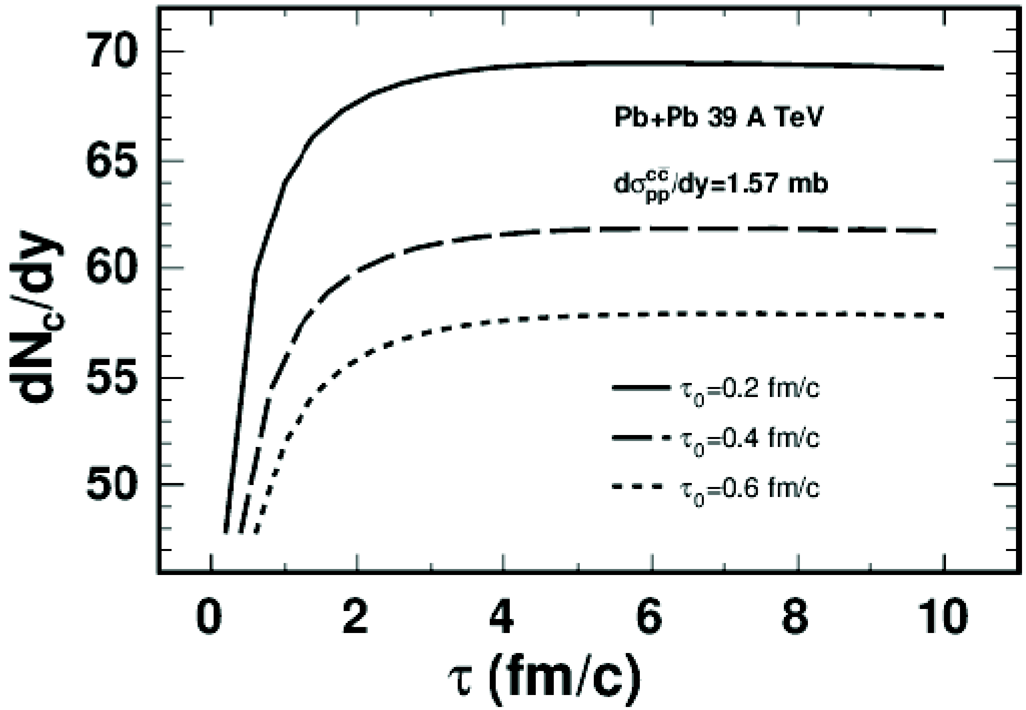


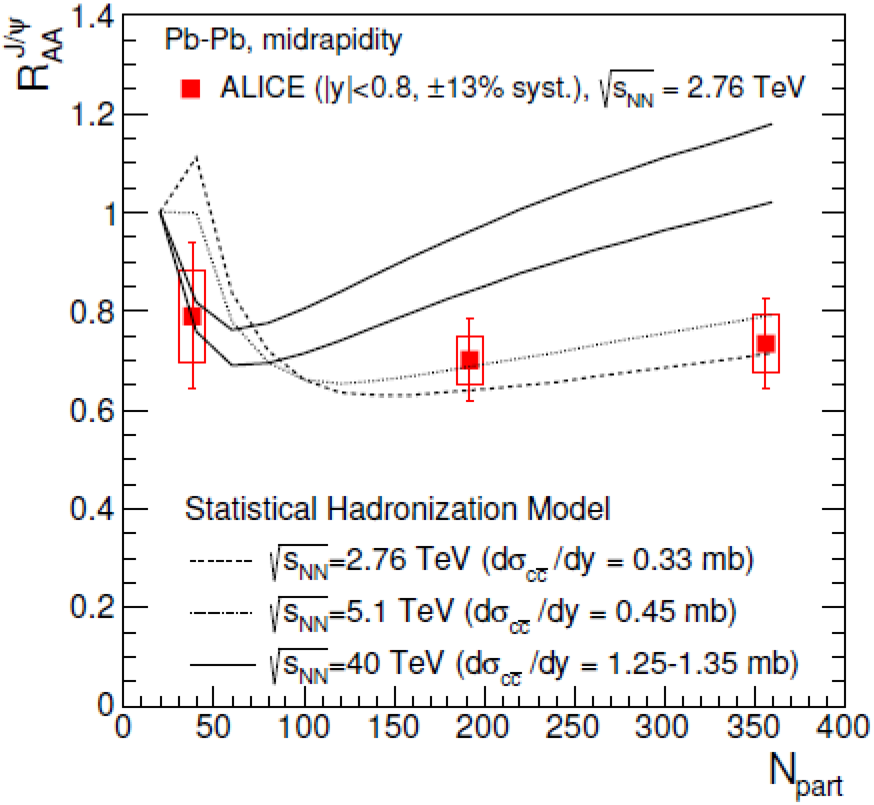
Figure 16.3: Left: Total delay time for $\hat{q} = 4$ GeV^2/fm as a function of the top transverse momentum (black dots) and its standard deviation (error bars). The average contribution of each component is shown as a coloured stack band. The dashed line corresponds to a $\hat{q} = 1$ GeV^2/fm. Right: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

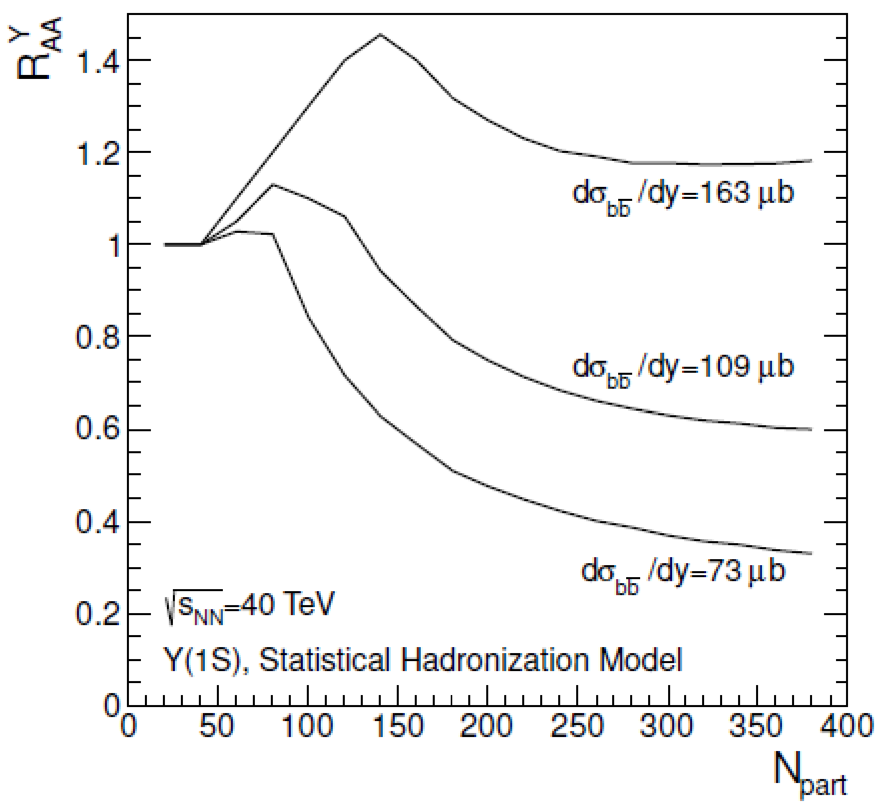
FCC thermal charm production



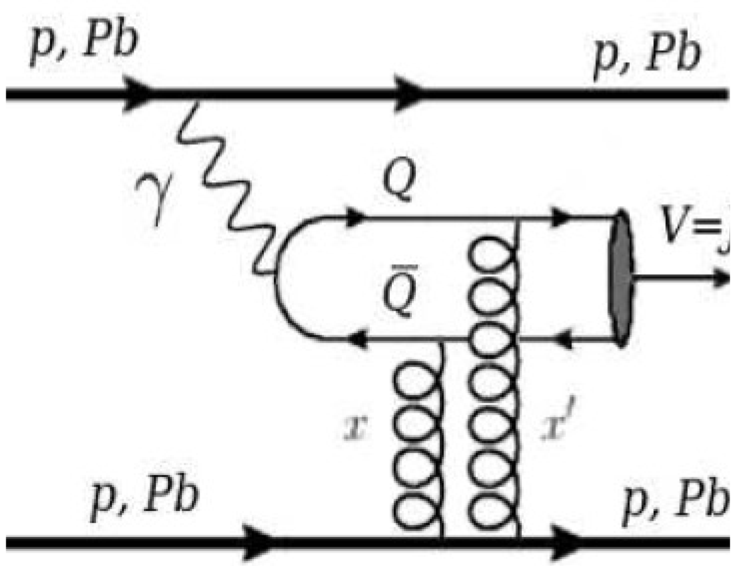


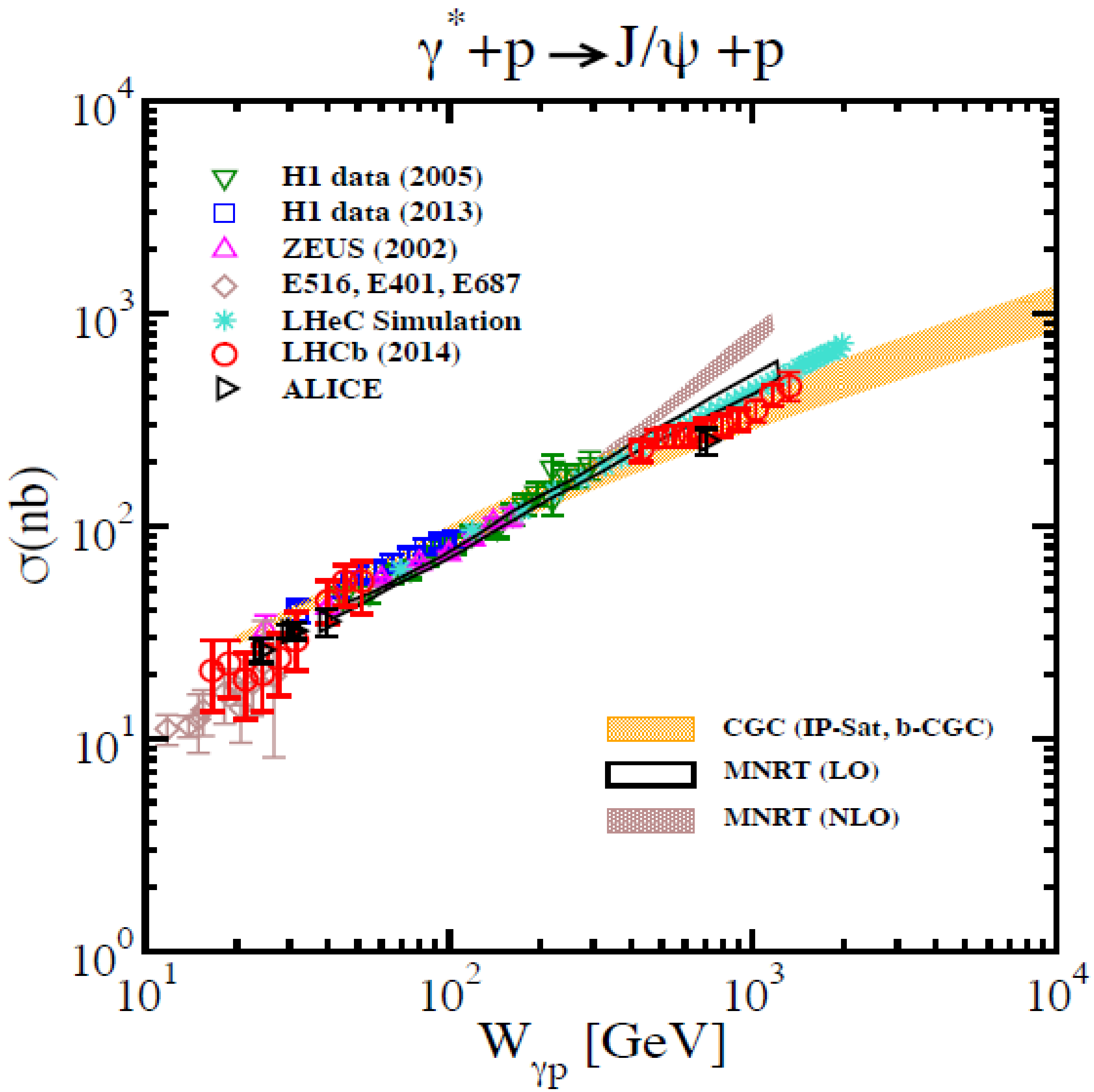
FCC J/psi and Upsilon





FCC photoproduction of J/psi





FCC: gamma-gamma