Mini Review on Open Heavy Flavor and Quarkonia in Heavy Ion Collisions

Sonia Kabana, University of Nantes
and SUBATECH, France

International Conference on
High Energy Physics
10-15 December 2018, Chennai, India

Outline

I Introduction

II Accelerator facilities and experiments

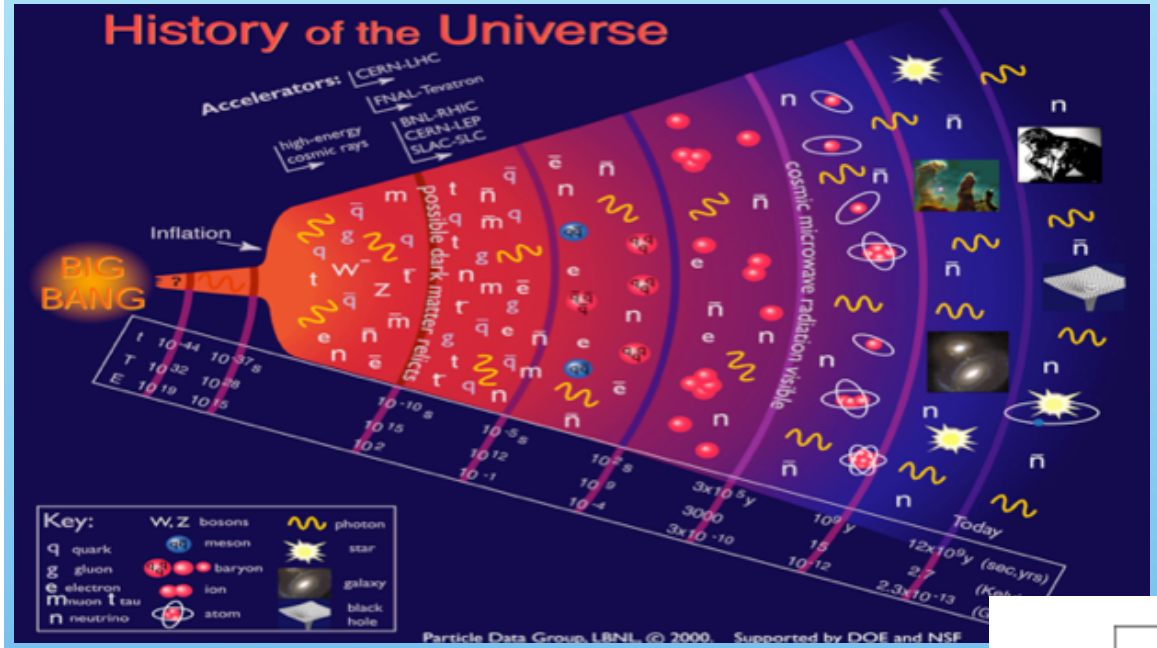
III Open heavy flavor

IV Quarkonia

V Conclusions and outlook

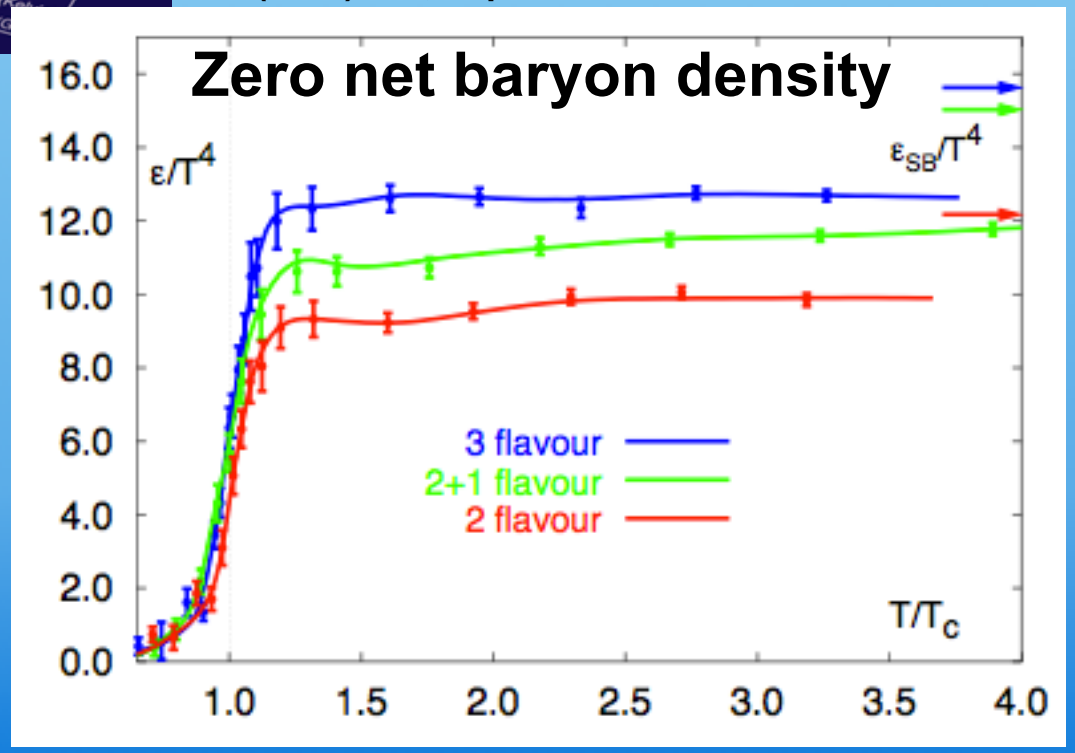
I Introduction

The QCD phase transition



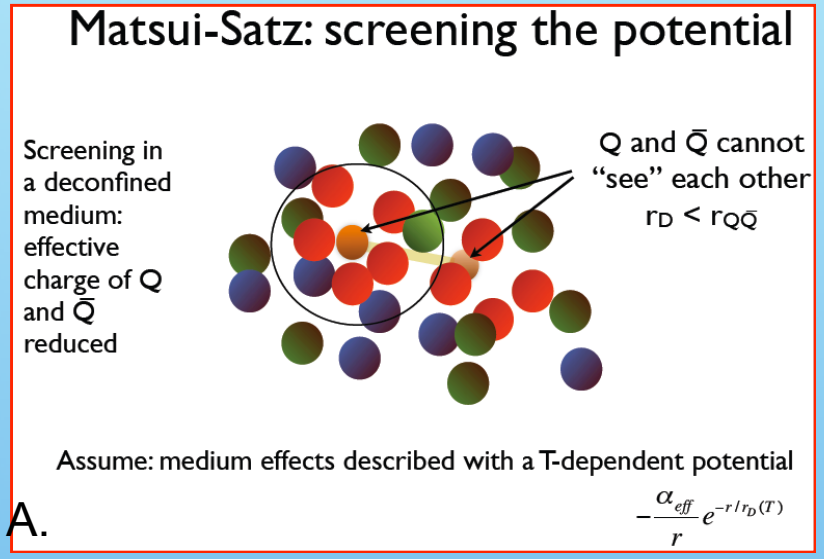
QCD on the lattice predicts a cross over at zero net baryon density with critical temperature Tc~154+-9 MeV (2014), critical energy density ~0.6 GeV/fm^3

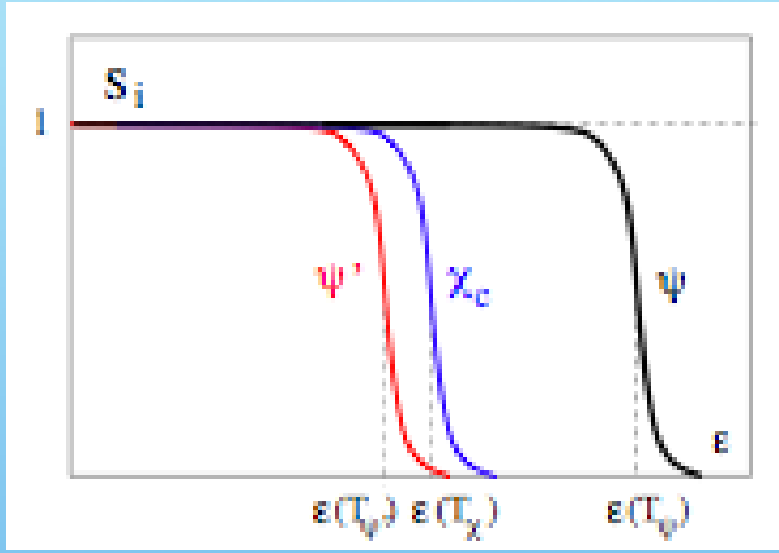
F. Karsch, Lect. Notes Phys. 583 (2002) 209, hep-lat/0106019



The transition from quarks and gluons to hadrons is believed that took place few 10-6 sec after the Big Bang

Quarkonia suppression as QGP signature





state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

Many effects play a role like

dissociation in QGP,

cold matter interaction,

recombination/coalescence from c, cbar,

feeding, eg B mesons carry 10-25% of charmonia yields

Open Heavy Flavor crucial observable for QGP physics

- **Produced in hard scattering processes in the initial stage of the collision**
- **Calculated by pQCD**
- **Can test jet quenching**
- **Can test thermalization**
- **Help understand quarkonia**

"The nuclear modification factor" R_{AA} compares A+A to expectations from p+p :

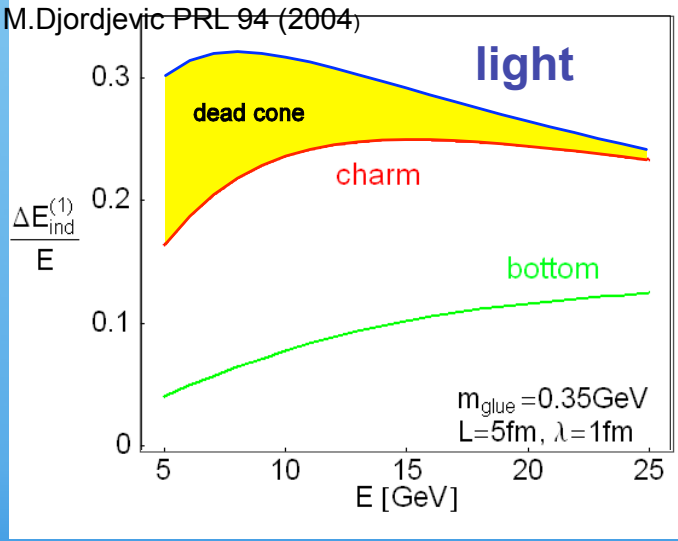
$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\times\langle N_{coll}\rangle}$$

N coll : Average number of NN collisions in AA collision

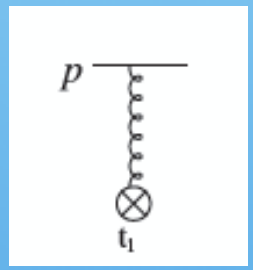
Suppression of jets in AuAu: $R_{AA} < 1$

Partons interact with the medium and loose energy through eg gluon radiation

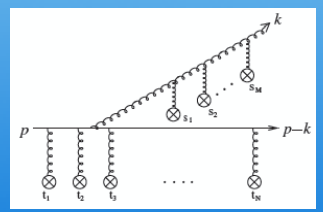
M.Djordjevic PRL 94 (2004)



Collisional "elastic" energy loss: elastic interaction with the medium

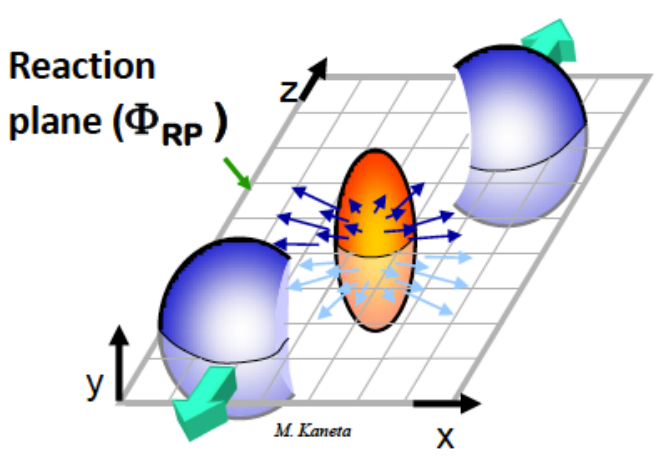


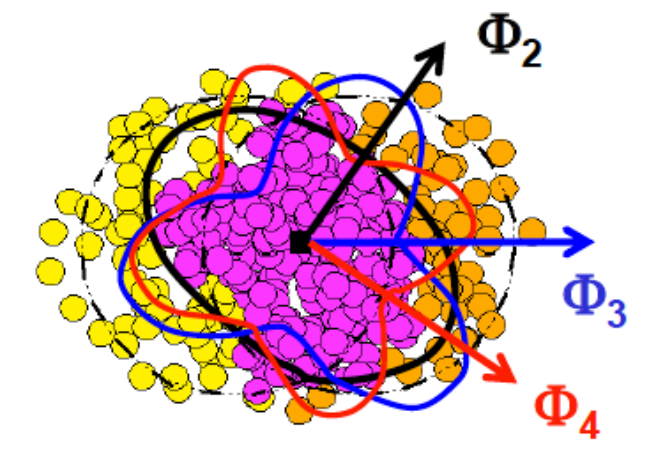
Radiative energy loss: parton radiation due to interaction with the medium



Quarks are expected to exhibit different radiative energy loss depending on their mass (D.Kharzeev et al. Phys Letter B. 519:1999)

Test collective behaviour with Flow coefficients v_n, n=1,2,3..





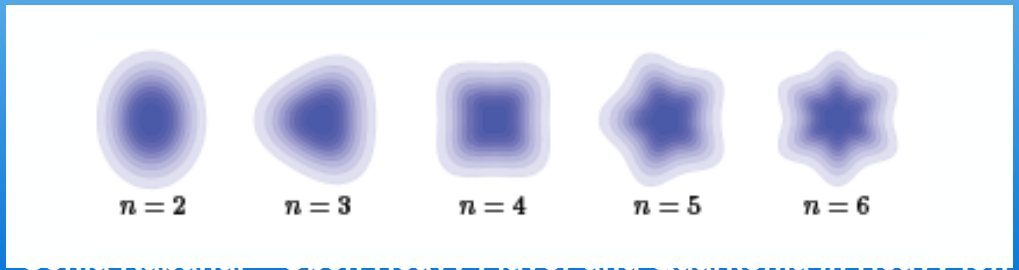
Matter in the overlapp area of two colliding nuclei gets compressed and heated

Initial anisotropy gets transfered into the momentum space via pressure gradients

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]$$

$$v_n = \langle \cos[n(\phi - \Phi_n)] \rangle$$

v : flow coefficients
(v1: directed flow,
v2: elliptic flow, ...)

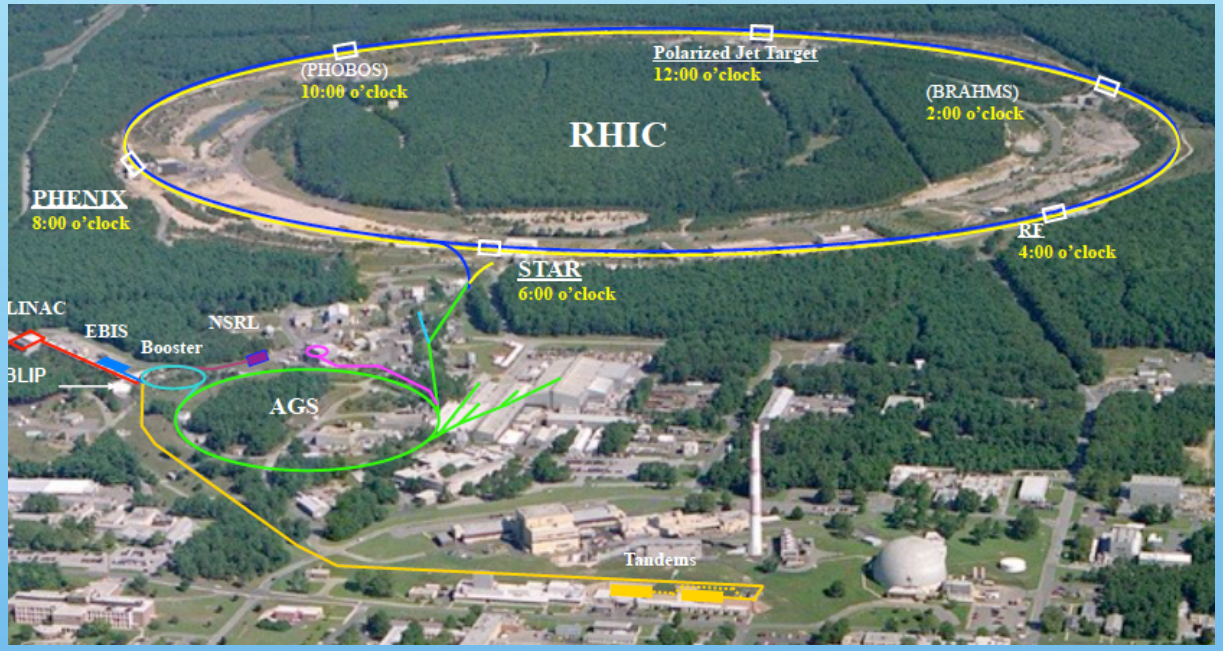


Higher harmonics

II Accelerator facilities and experiments today

Relativistic Heavy Ion Collider

at the Brookhaven Lab, Long Island, New York, USA



RHIC has been exploring nuclear matter at extreme conditions over the last 18 years, since 2000

4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

Still runing: STAR

Still analysing data: PHENIX

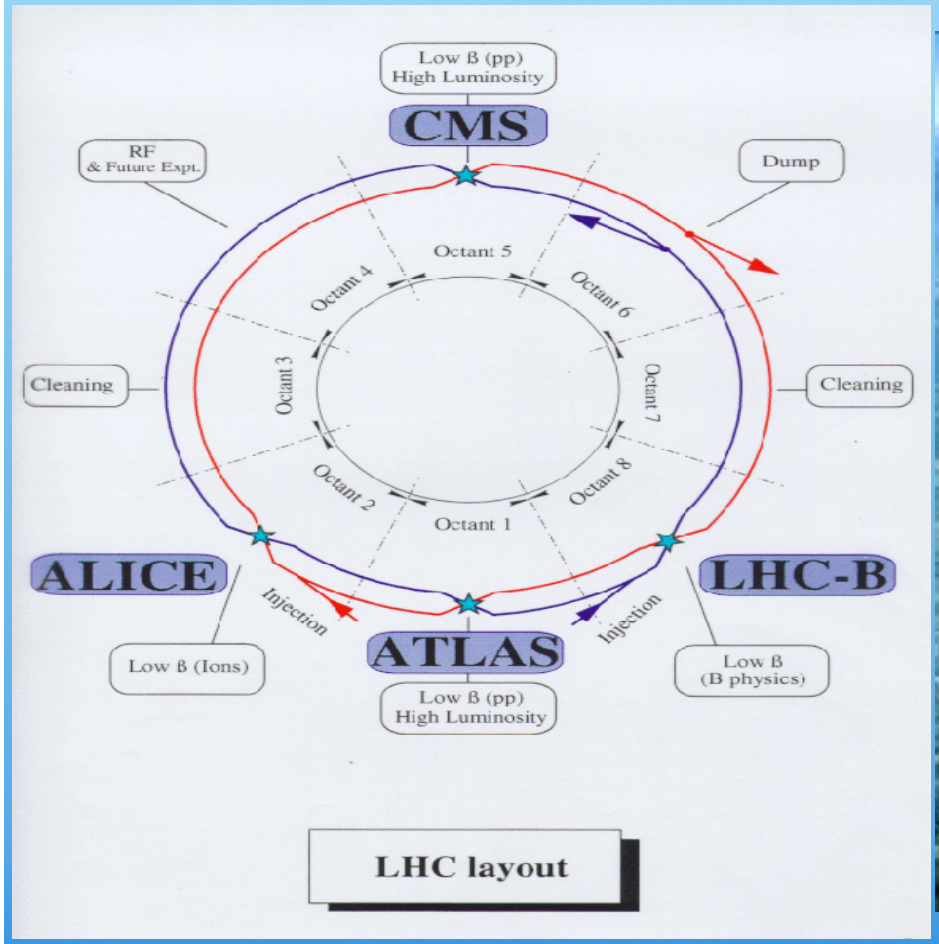
Main colliding systems:

p+p, p+A, d+Au, Cu+Cu, Au+Au
Cu+Au, U+U, Zr+Zr, Ru+Ru

Main energies A+A :

$\sqrt{s_{NN}}$ = 62, 130, 200 GeV
and low energy scan
7.7, 11.5, 19.6, 22.4, 27, 39, 54 GeV
+ Fixed target

Large Hadron Collider (LHC) at CERN



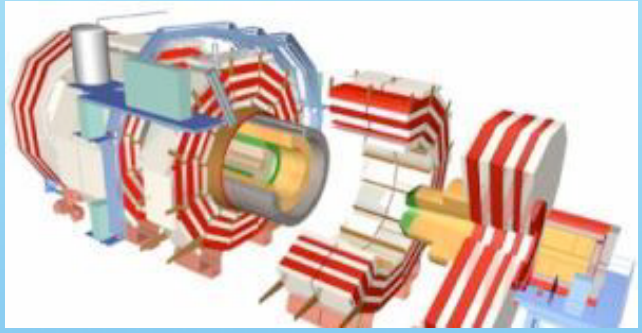
run-1 (2009-13) : p+p $\sqrt{s_{NN}}$ =0.9, 2.76, 7, 8 TeV, p+Pb $\sqrt{s_{NN}}$ =5.02 TeV, Pb+Pb at $\sqrt{s_{NN}}$ =2.76 TeV

run-2 (2015-18) : p+p $\sqrt{s_{NN}}$ = 5.02, 13 TeV p+Pb 5.02, 8.16 TeV Pb+Pb at $\sqrt{s_{NN}}$ =5.02 TeV Xe+Xe

Current Experiments with Heavy Ion program

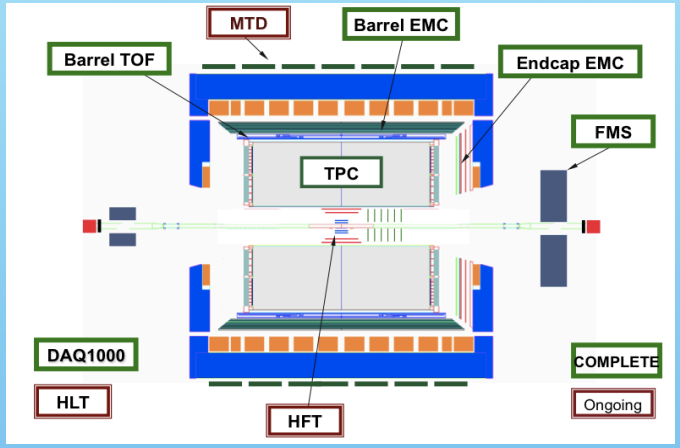
LHC

CMS

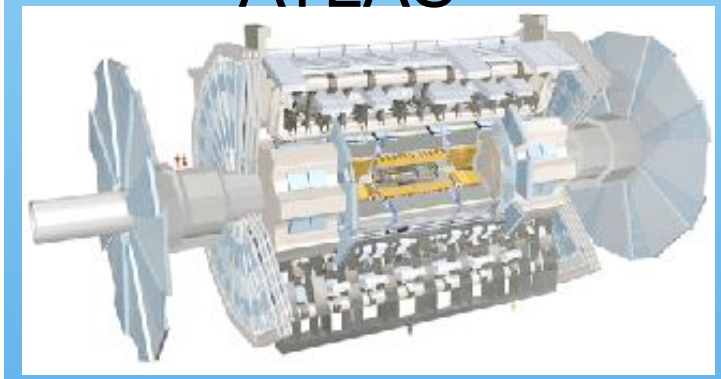


LHCb

STAR at RHIC

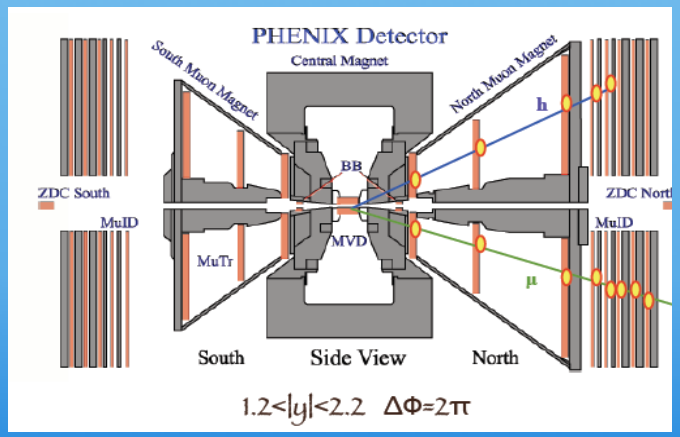


ATLAS

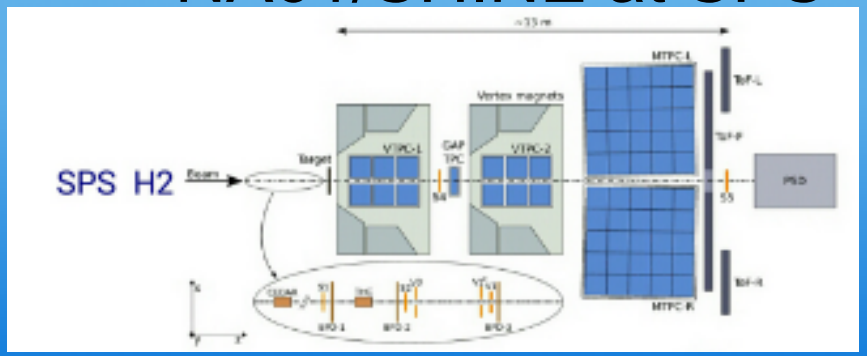


ALICE

PHENIX at RHIC

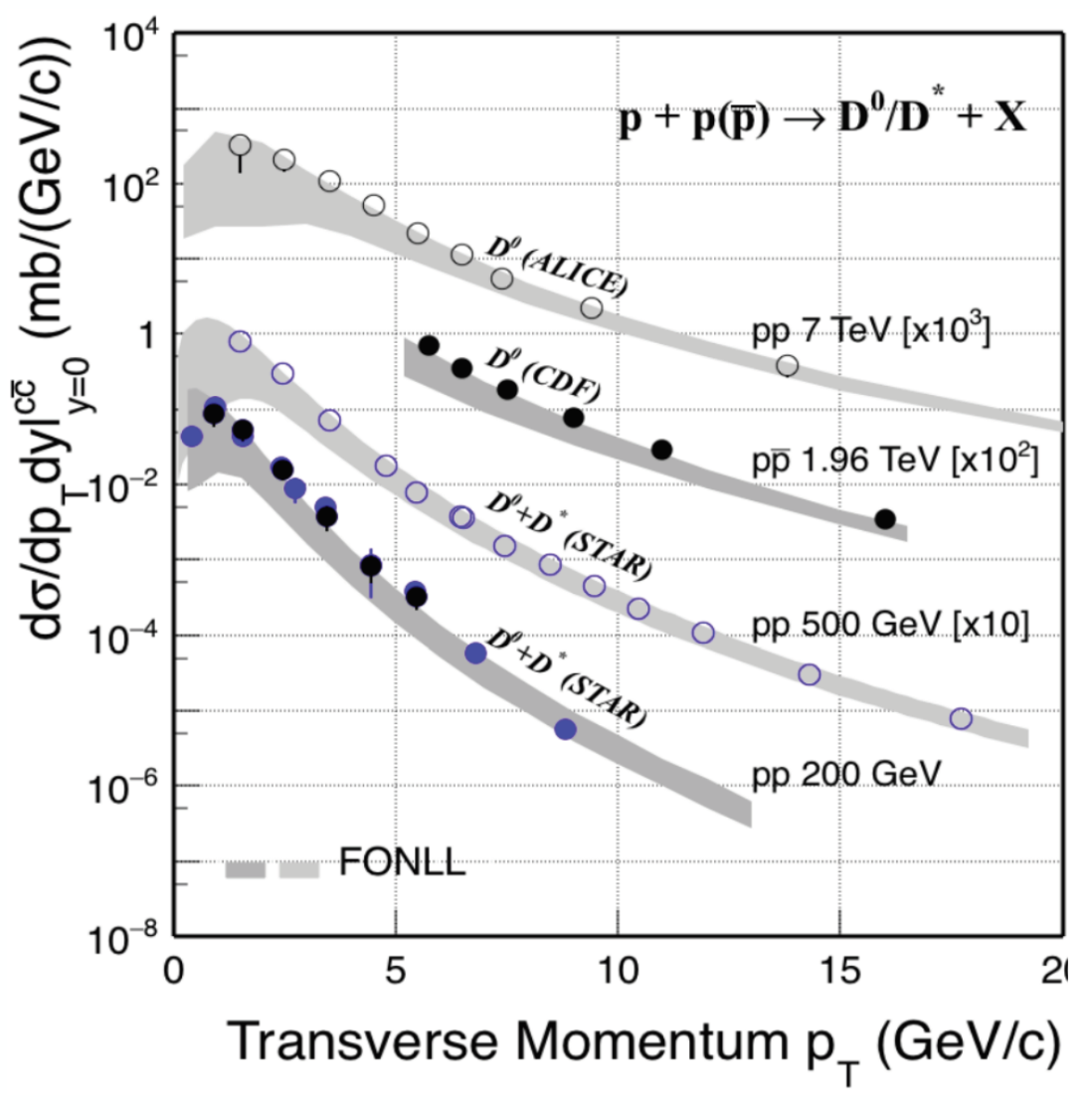


NA61/SHINE at SPS



Open Heavy Flavor results

D meson pT distribution different energies vs FONLL



LHC P+P

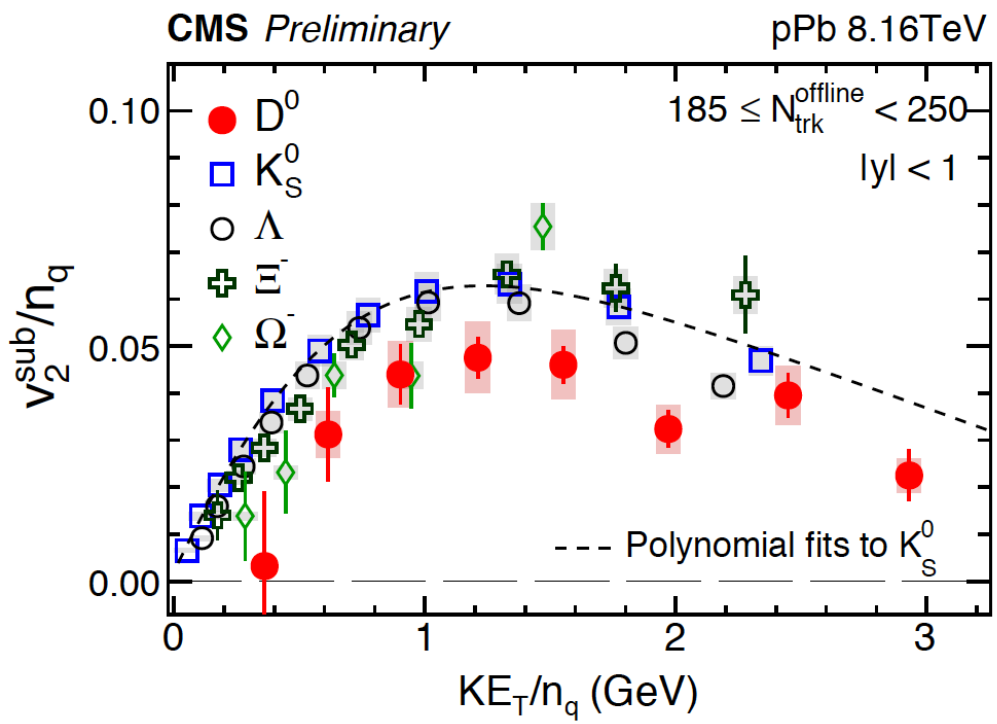
TEVATRON P+PB

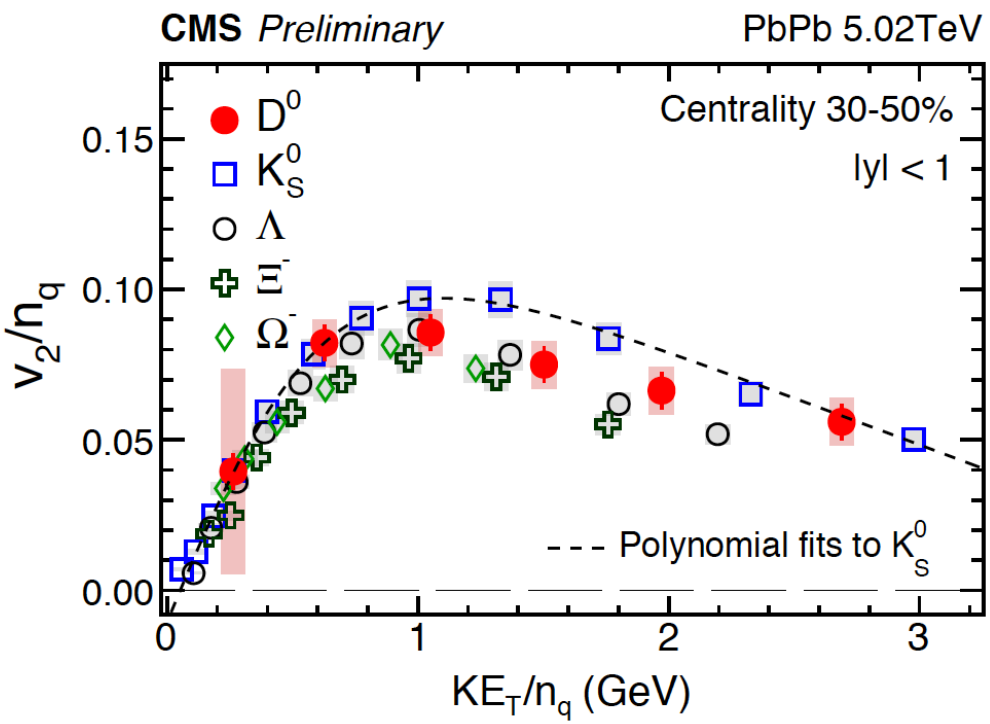
RHIC P+P

Deepa Thomas, Hard Probes 2018

CMS D0 and strange particles in pPb, PbPb

CMS 1705.01974

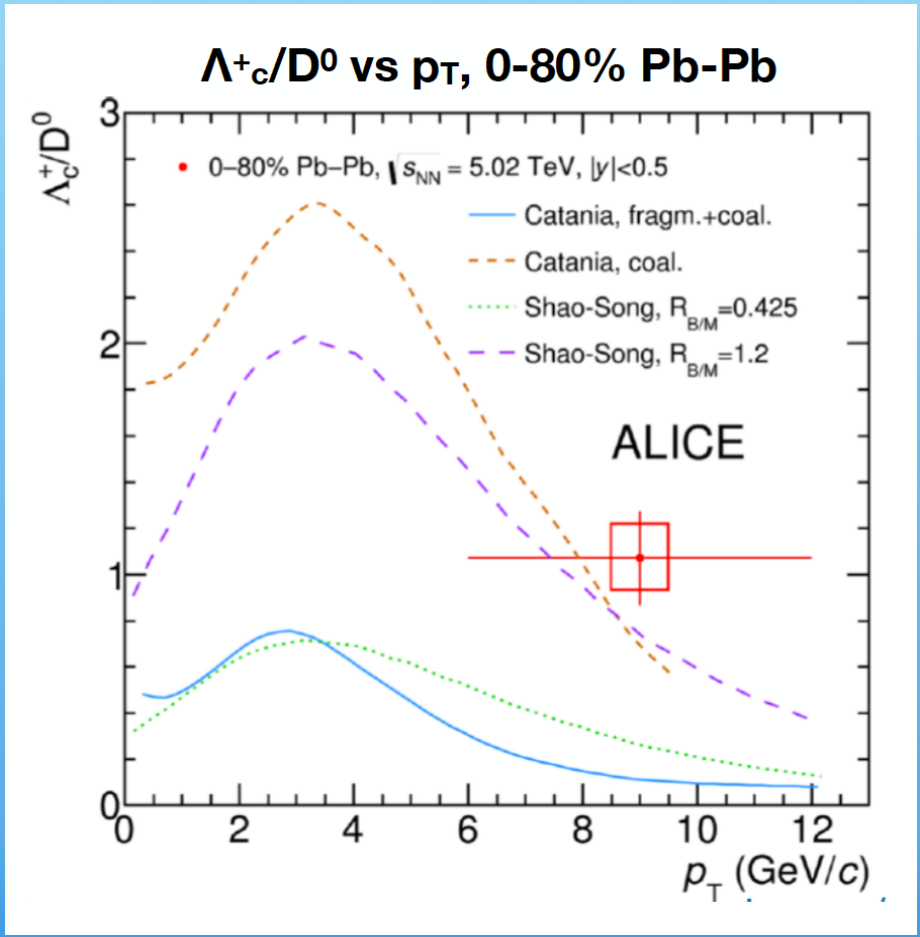




Left, pPb at high mult: v2/nq of strange particles tend to lie on a universal curve below 1.5 GeV, while D0 fall below indicating weaker collective behaviour for charm quarks

Right, PbPb semiperiph.: v2/nq of strange particles and D0 tend to lie on a universal curve below 1.0 GeV, indicating strong collective behaviour of D0, similar to the bulk of QGP medium

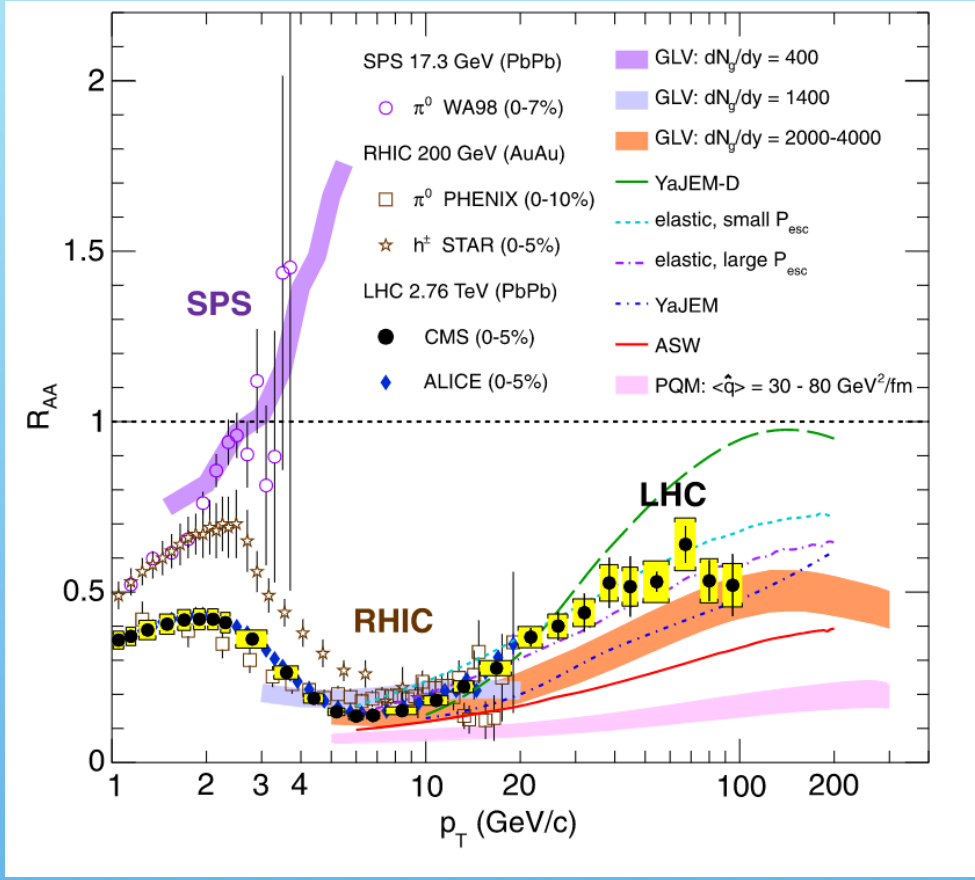
Baryon/meson enhancement tests coalescence



The Lambda_c to D0 ratio suggests production via coalescence

Jet quenching hadrons
Collision energy dependence

CMS, EPJC
(2012) 72:1945

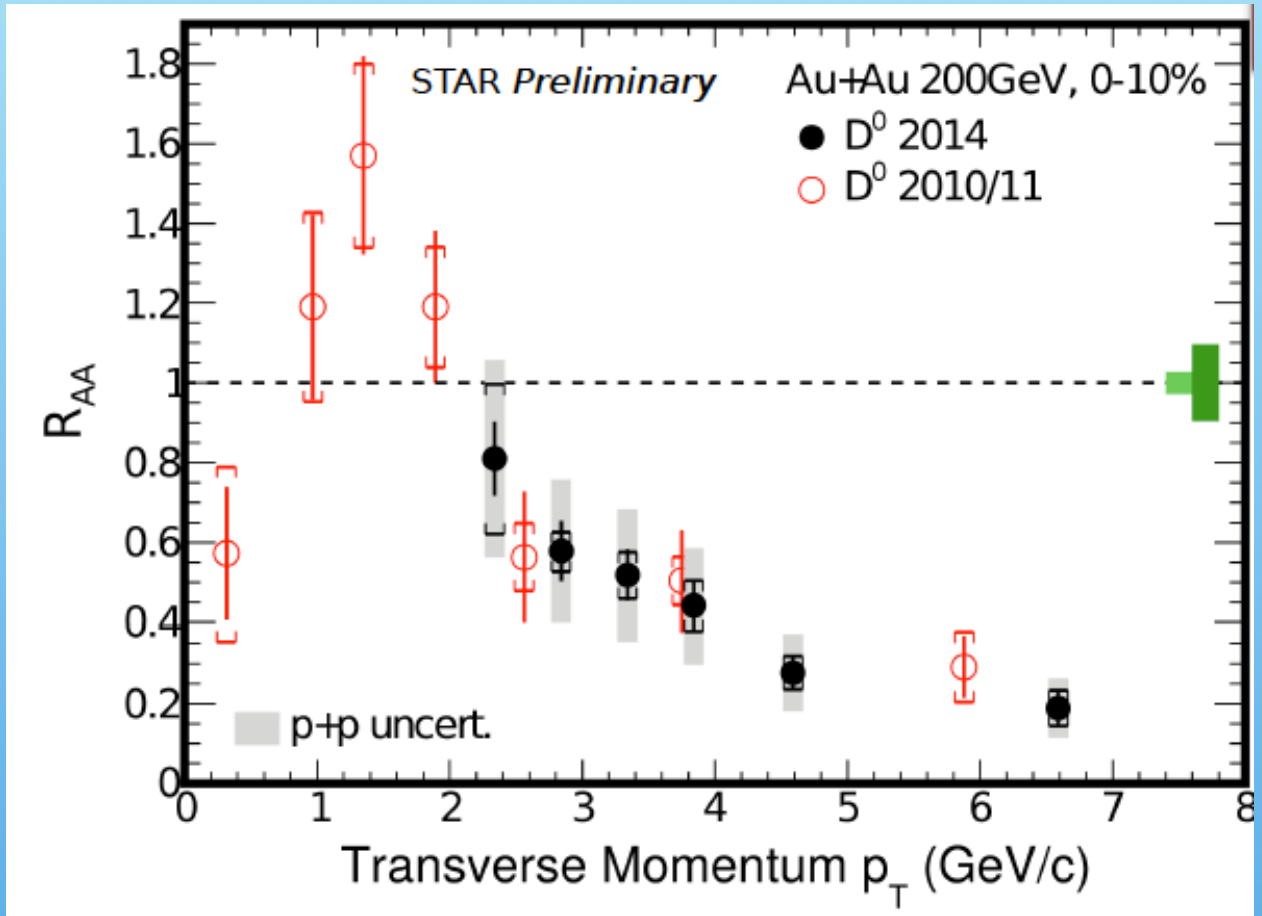


RAA compared to models for energy loss allows for an estimate of gluon density dN/dy(gluon)
Here as an example we get (GLV model):

dN/dy(g)=400 for SPS
dN/dy(g)=1400 for RHIC
dN/dy(g)=2000-4000 for LHC

To estimate with confidence dN/dy(g), we should understand the mechanism of jet quenching via studies of its dependence from pT, energy, event plane, path length, centrality, quark mass etc

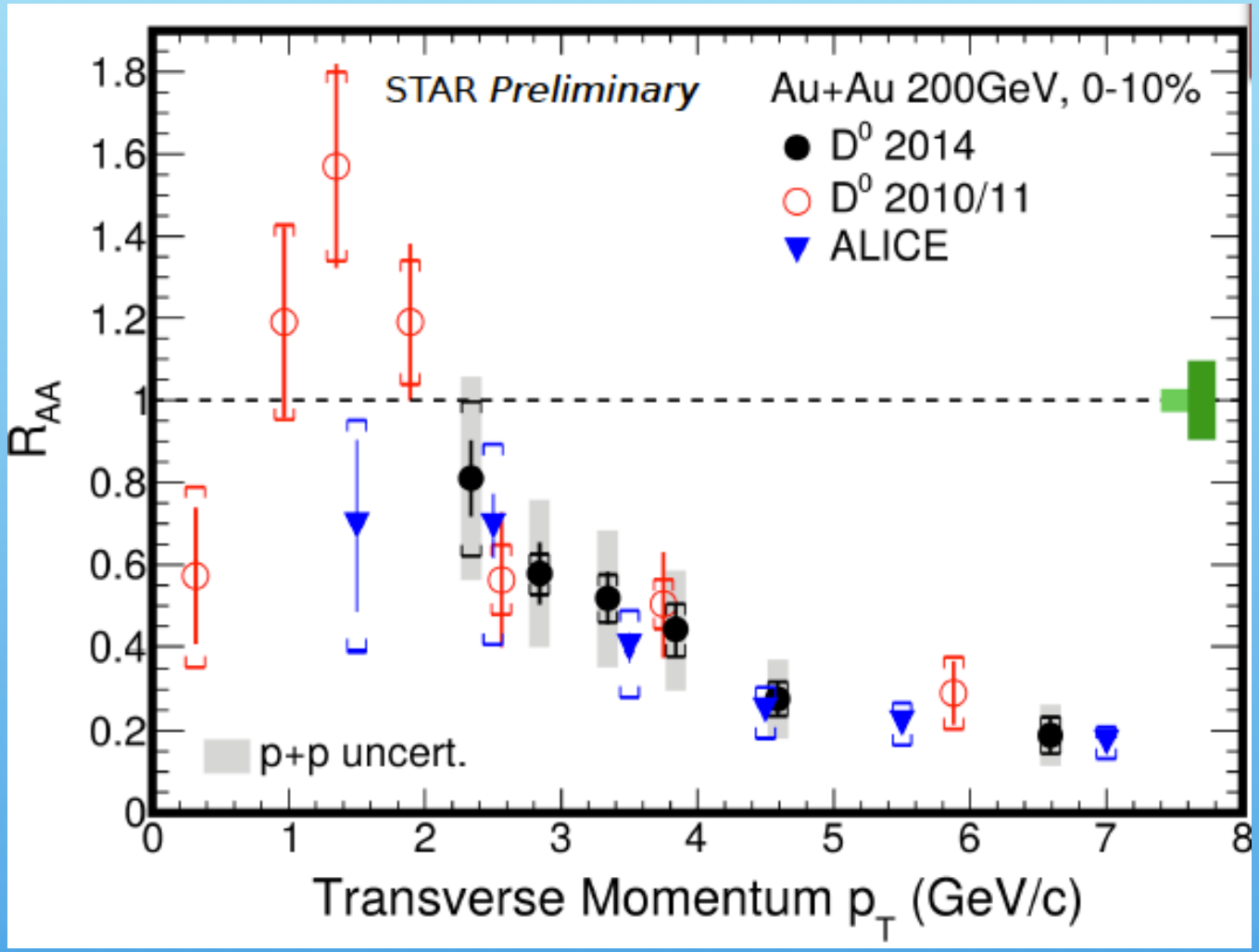
D0 nuclear modification factor in Au+Au 200 GeV from HFT



STAR, QM15

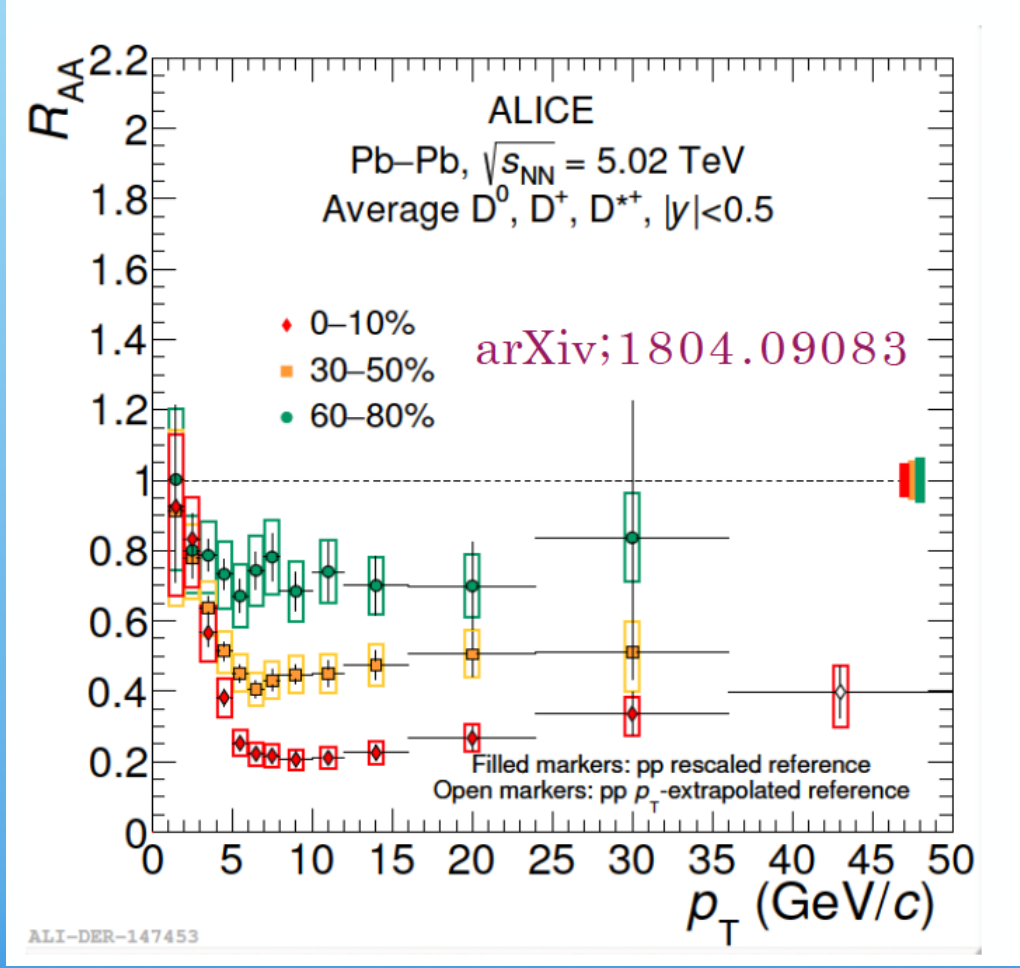
Suppression of D0 at high pT
Enhancement of D0 at pT<2 GeV/c

Comparison RHIC to LHC

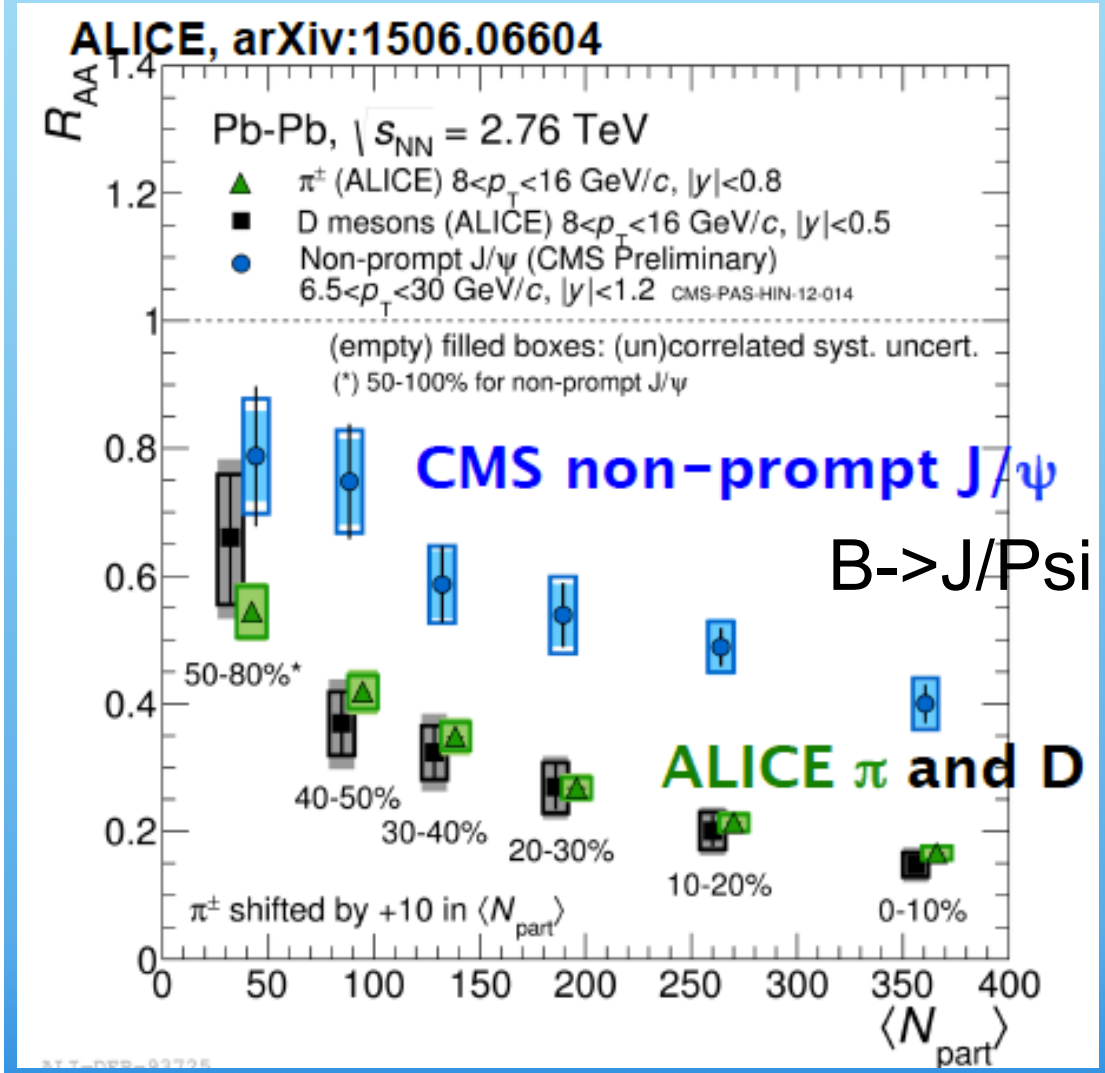


RAA of D0 mesons is similar in RHIC and LHC at pT>2 GeV/c

D mesons pT distribution ALICE



RAA of open charm and beauty at the LHC



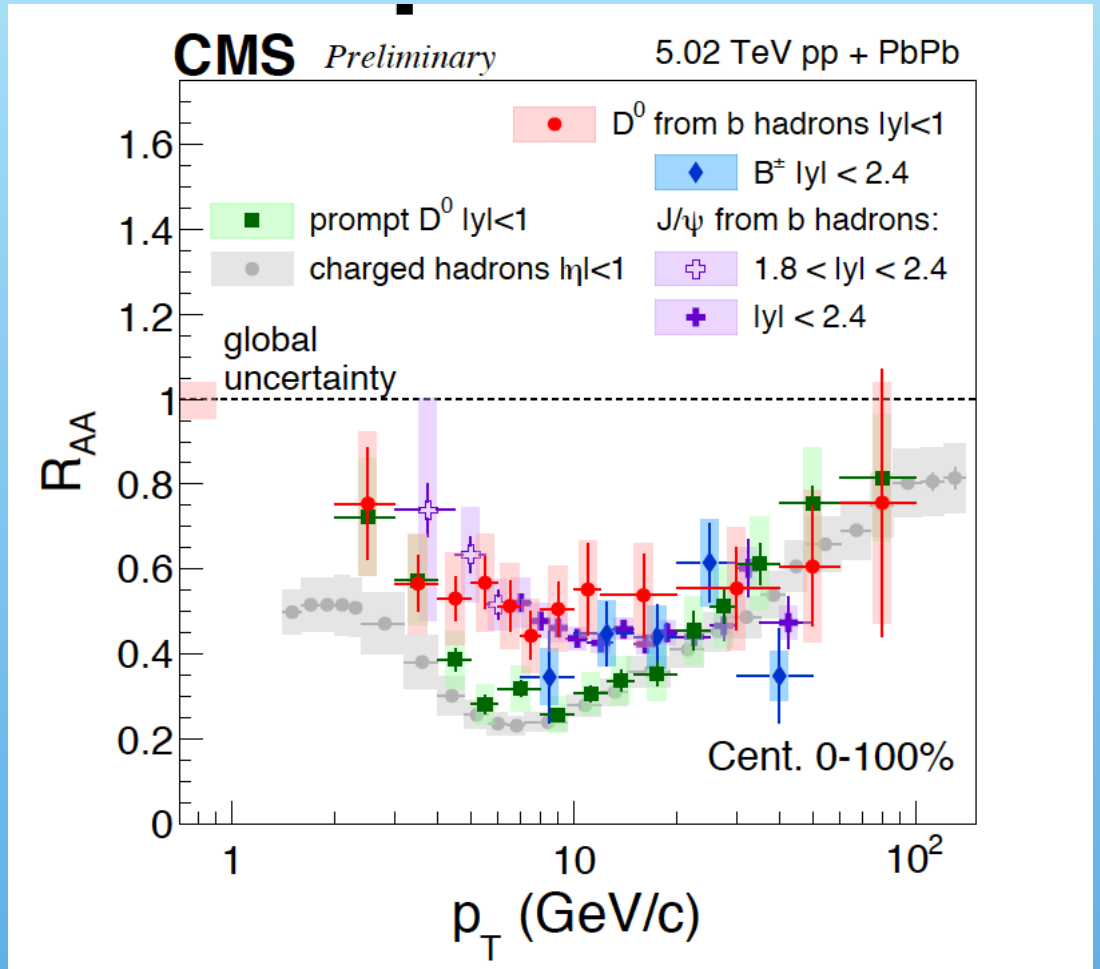
ALICE, QM2015

Pb+Pb ALICE, CMS:

RAA of D mesons is much smaller than RAA of non-prompt J/Psi representing open beauty (B->J/Psi X) (but pT range different)

RAA of pions and D mesons is consistent (pT range is the same)

CMS: non prompt D0 from b hadron

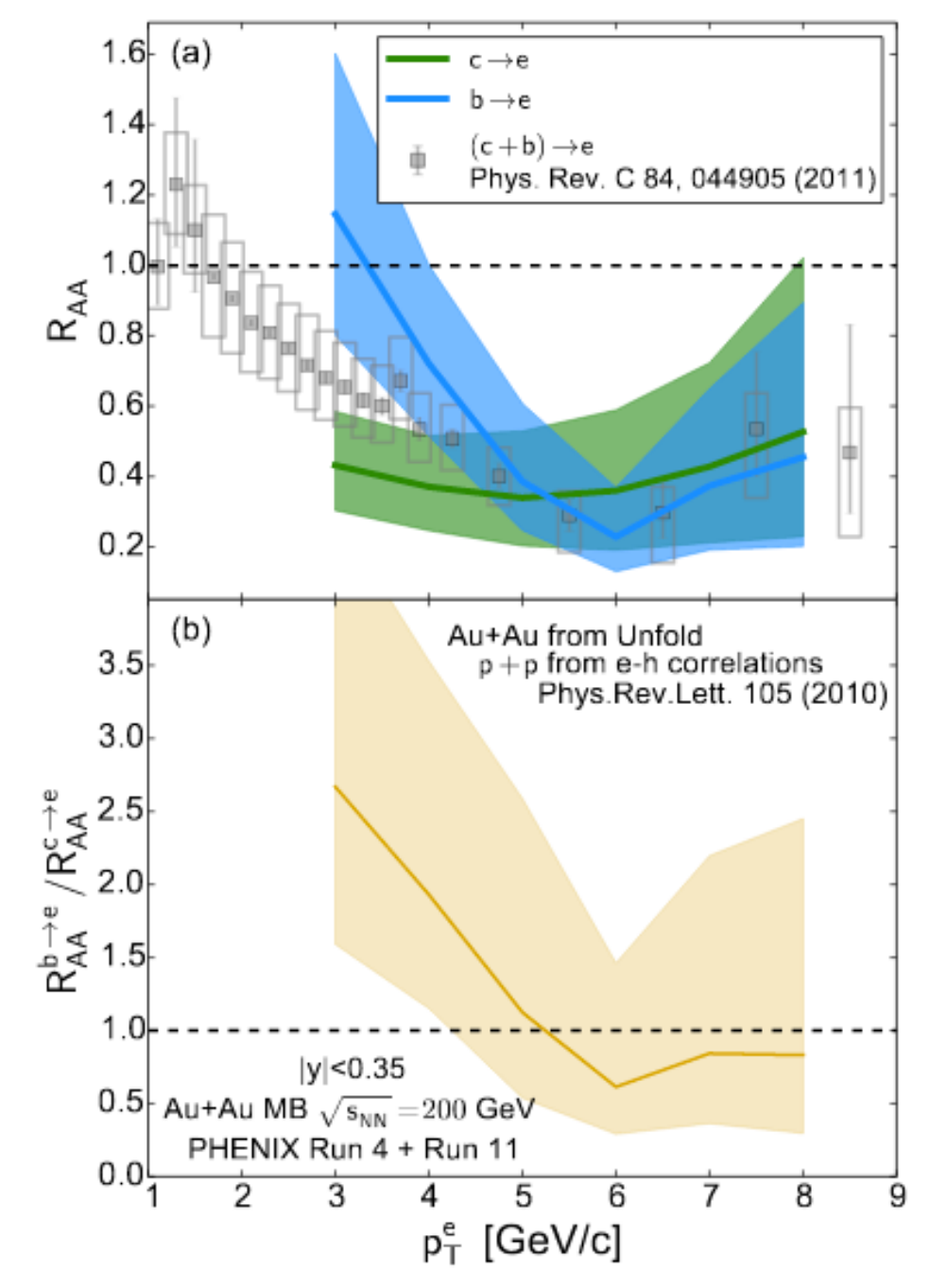


CMS Coll. QM2018

For $5<p_T<15$ GeV

Non-prompt D^0 and J/ψ less suppressed than D^0 and charged hadrons

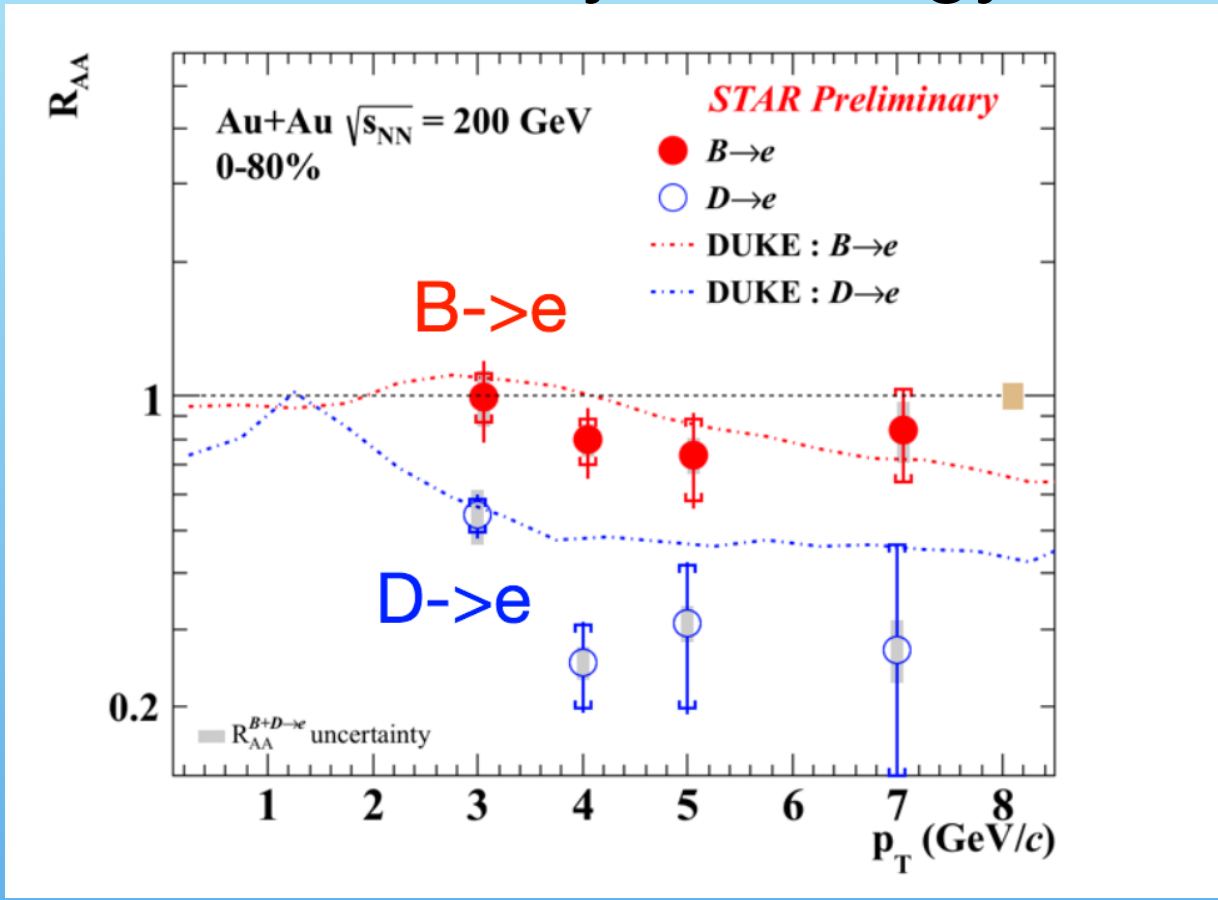
RAA of Charm and Beauty in min. bias Au+Au at 200 GeV



PHENIX: arXiv:1509.04662 (2015)

RAA of (b->e) is less suppressed than RAA of (c->e) in pT=3-4 GeV/c

STAR Beauty vs Charm in Au+Au 200 GeV 0-80%, mass hierarchy of energy loss

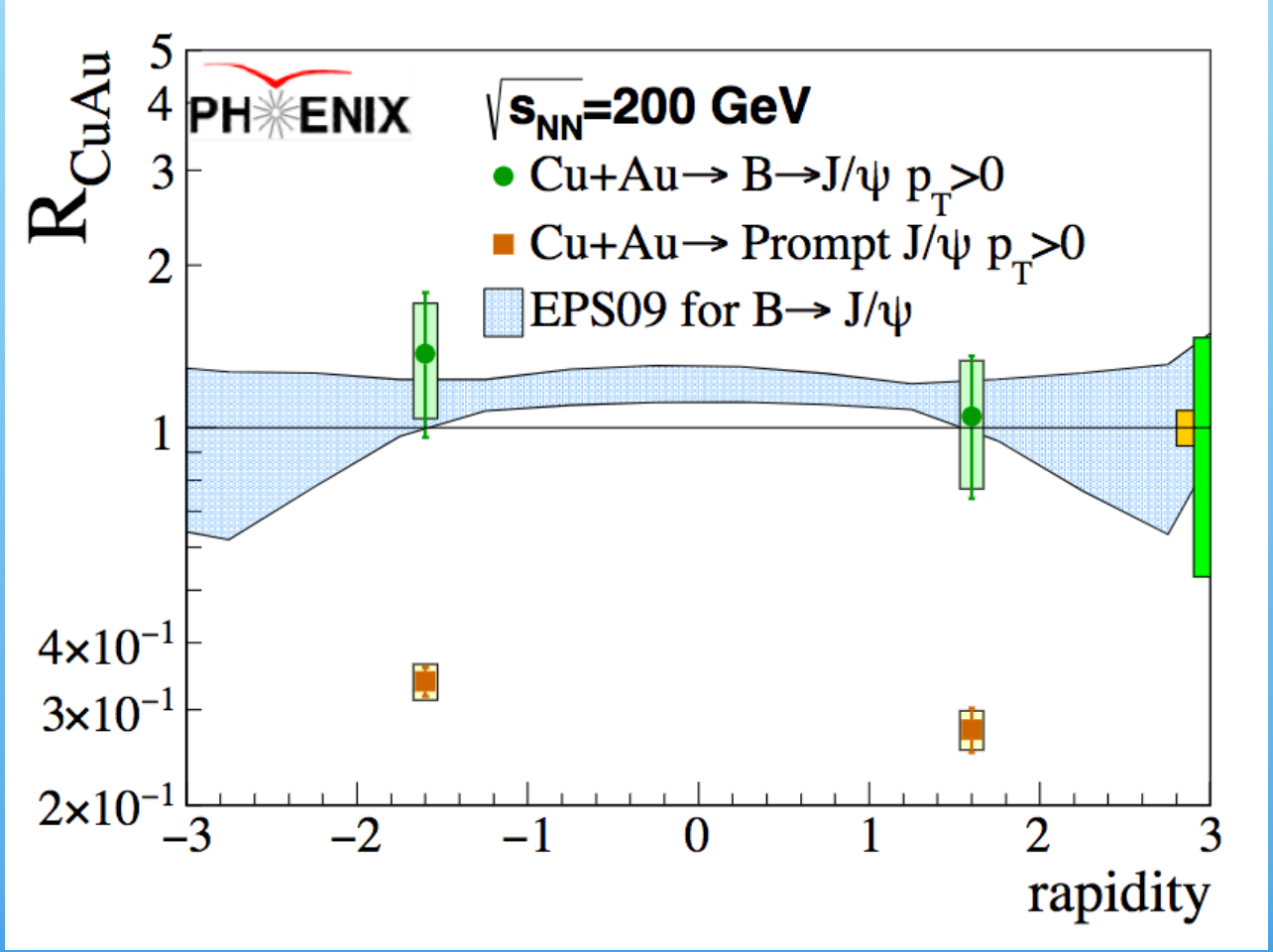


Li Yi, STAR coll.
Santa Fe work.
Jan 2018

*** Using the new STAR HFT silicon tracker with excellent resolution**

*** Electrons from B quark are less suppressed than electrons from D**

PHENIX B->J/Psi in Cu+Au collisions

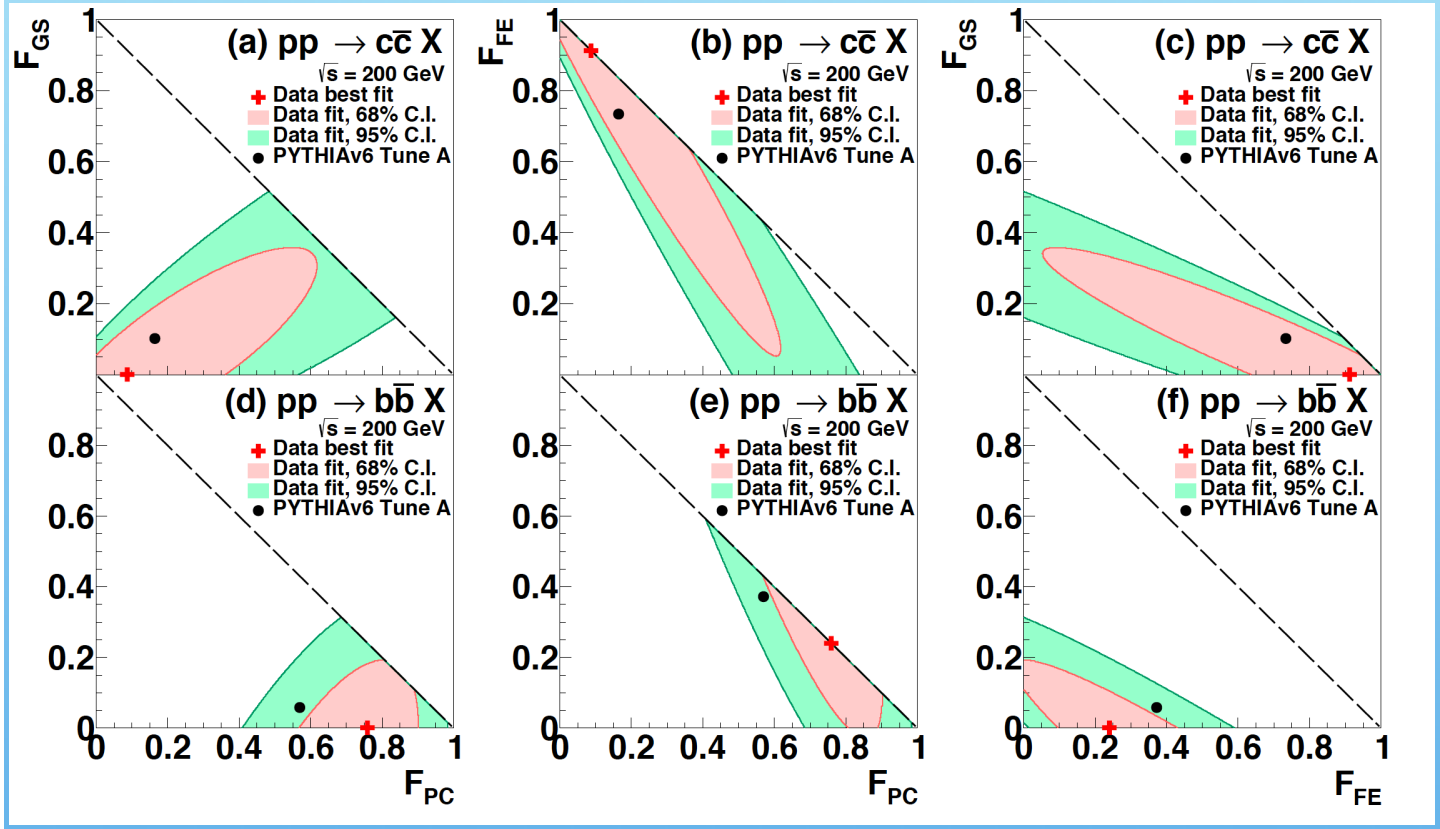


Prompt J/Psi in Cu+Au is suppressed

B->J/Psi, (displaced J/Psi) is not suppressed

https://arxiv.org/pdf/1702.01085.pdf

New PHENIX results: ccbar and bbar production mechanisms in p+p at 200 GeV



1805.04075

- Measurement of angular correlations of e-e, e-mu, mu-mu pairs from ccbar and bbar decays

-Data are consistent with Pythia Tune A

(PC= Pair creation, FE= Flavor excitation, GS=Gluon Splitting)

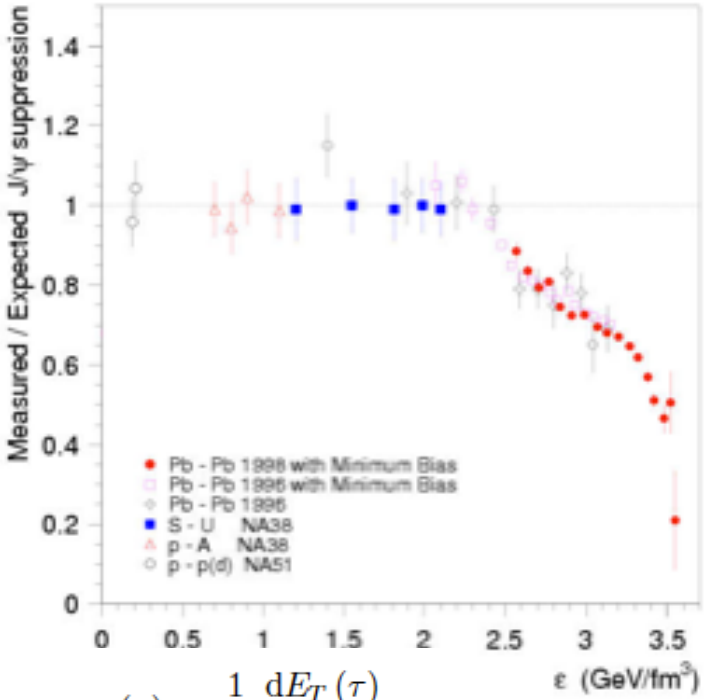
In p+p collisions at 200 GeV the data indicate that

- **ccbar production is dominated by the NLO flavor excitation**
- **bbar production is dominated by the Leading Order pair production**

5. Quarkonia suppression

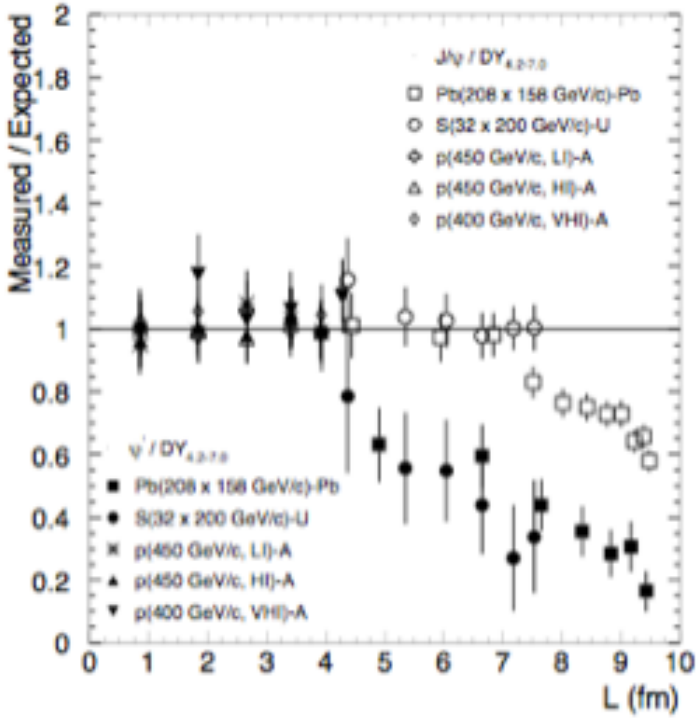
Sequential Psi prime and J/Psi suppression has been observed at CERN SPS Pb+Pb 158 A GeV

NA50, Phys Lett B 477 (2000) 28

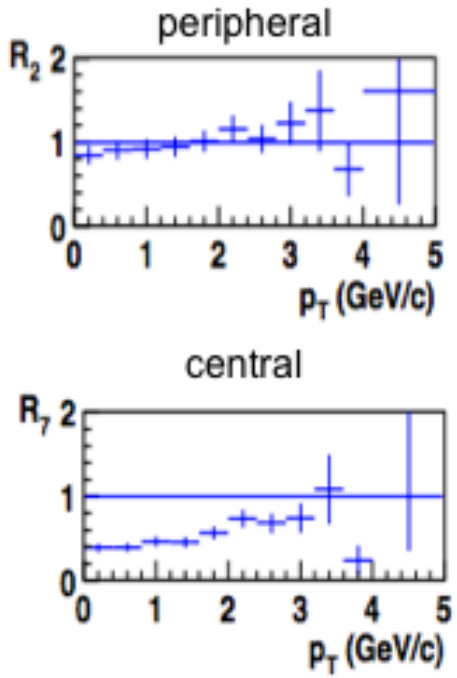


$$\varepsilon_{Bj}(\tau) = \frac{1}{A\tau}\frac{\mathrm{d}E_T(\tau)}{\mathrm{d}y},$$

Eur Phys J C 49 (2007) 559



J/Psi/DY n-bin/1st bin

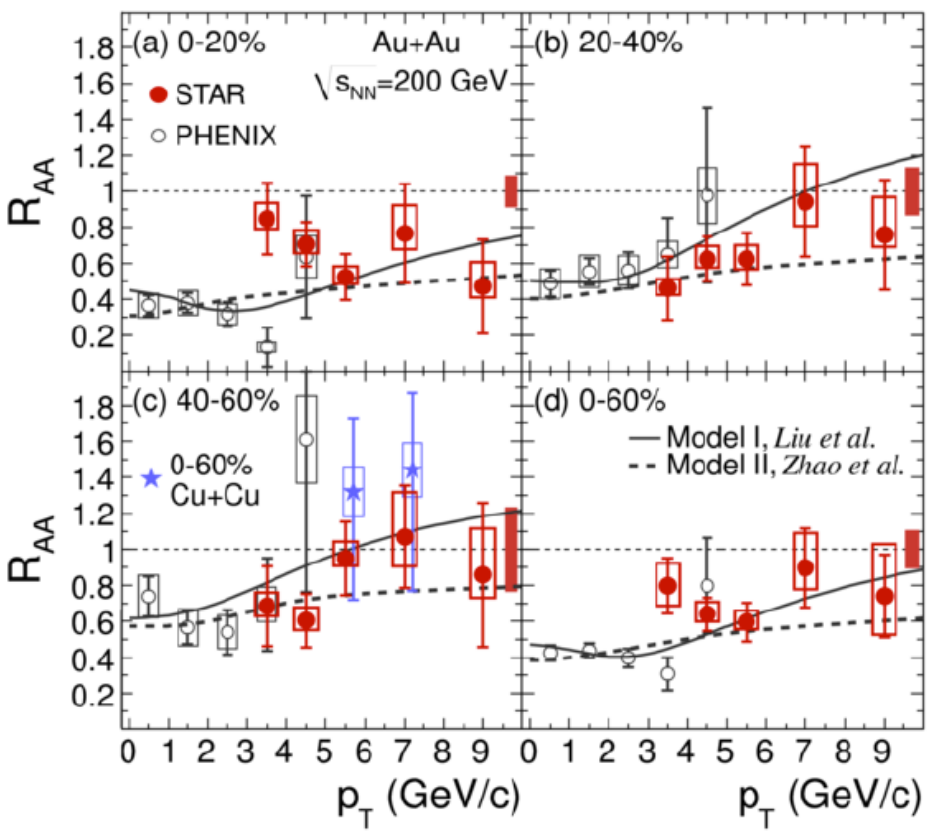


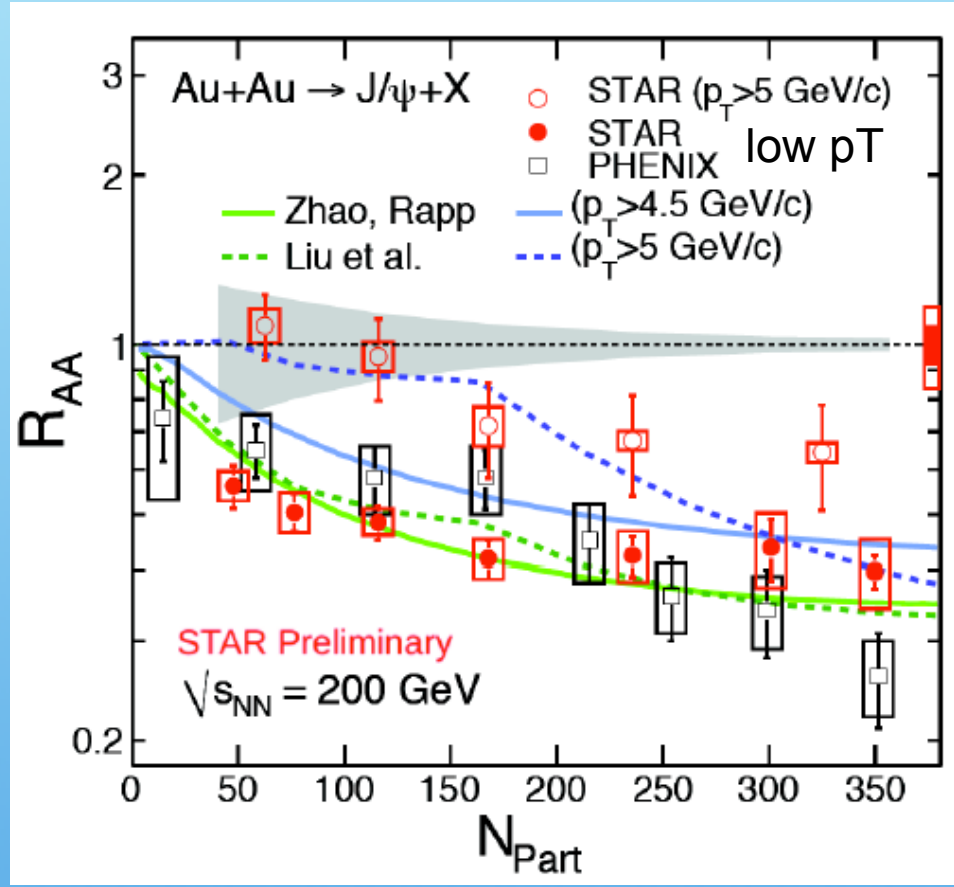
A Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004

* **Psi prime is suppressed from 1.23 GeV/fm^3 on**
* **J/Psi is suppressed from ~2.4 GeV/fm^3 on**
* **J/Psi supression occurs mainly at low pT**

p_T dependence of J/Psi suppression in Au+Au, Cu+Cu 200 GeV

PLB 722 (2013) 55





Liu et al, PLB 678 (2009) 72
Zhao et al, PRC 82 (2010) 064905

- J/Psi not suppressed at high p_T's in non-central collisions

- J/Psi suppressed at all p_T's for most central events

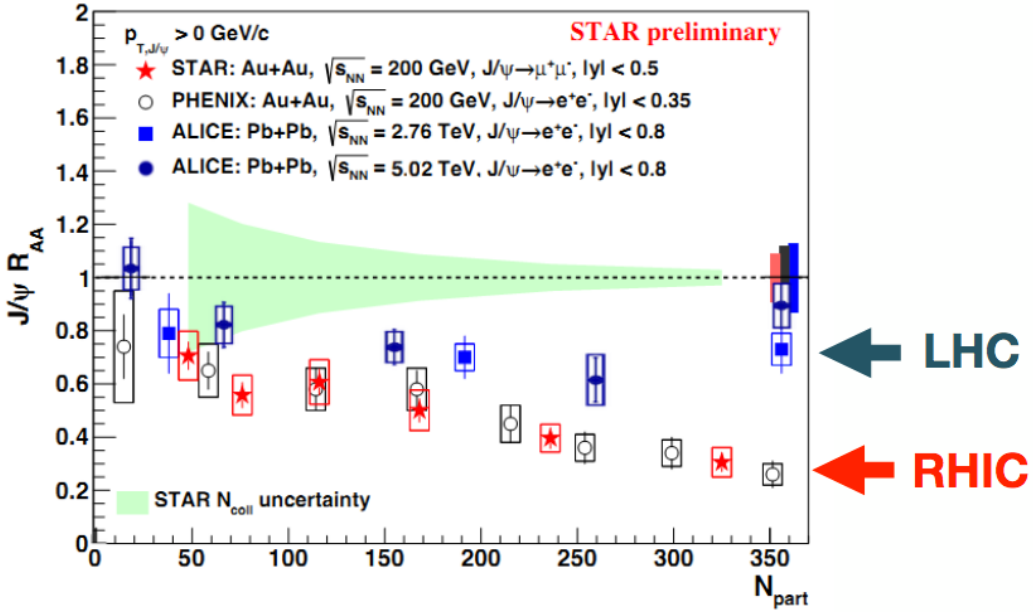
- R_{AA} of J/Psi is systematically larger for higher p_T. Low pT J/Psi is more suppressed

J/ψ Suppression in Au+Au Collisions

PHENIX: PRL **98** (2007) 232301
ALICE: PLB **734** (2014) 314
ALI–PREL–121481

CMS: EPJC77(2017) 252
Tsinghua at RHIC: PLB **678** (2009) 72
Tsinghua at LHC: PRC **89** (2014) 054911
TAMU at RHIC: PRC **82** (2010) 064905
TAMU at LHC: NPA **859** (2011) 114

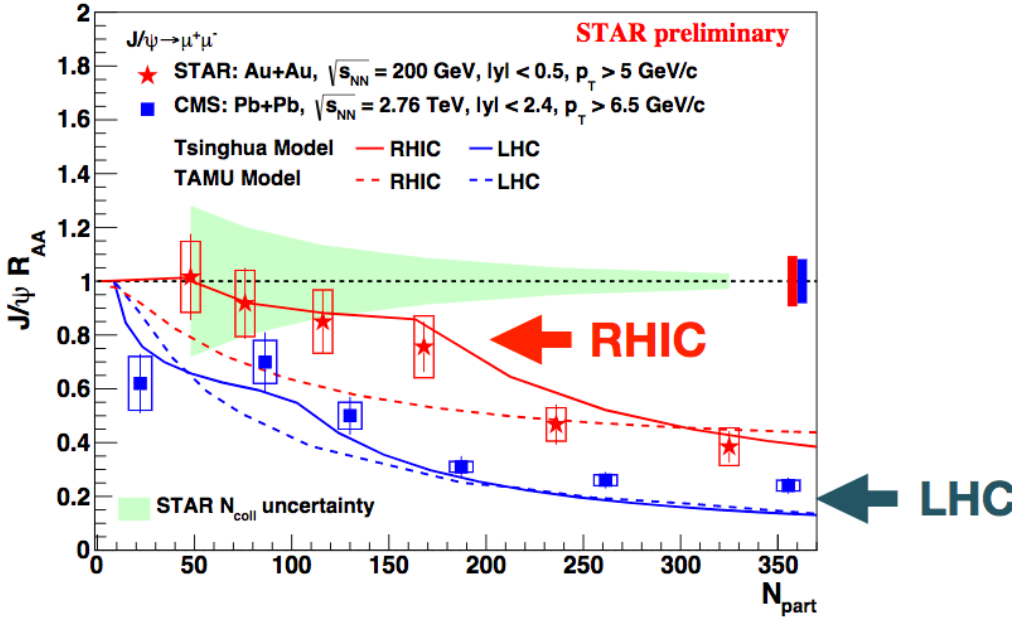
Low p_T J/ψ in central collisions:



R_{AA}(200 GeV) < R_{AA}(2.76 TeV) ~ R_{AA}(5.02 TeV)

Less regeneration at RHIC

High p_T J/ψ in all centralities:



R_{AA}(200 GeV) > R_{AA}(2.76 TeV) ~ R_{AA}(5.02 TeV)

Less color screening at RHIC

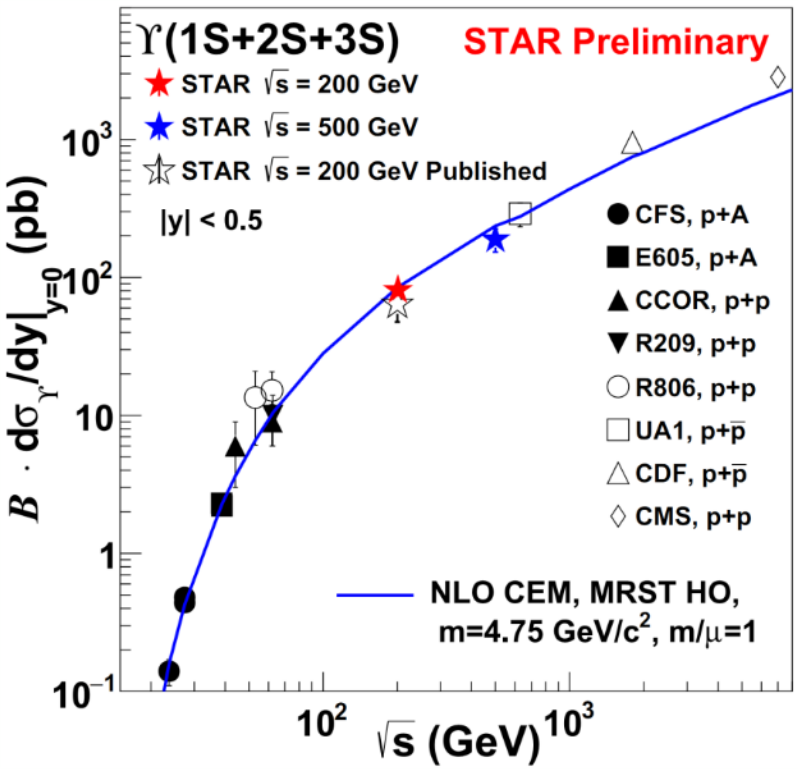
Li Yi (STAR coll.) Santa Fe 2018

Υ in p+p p+A

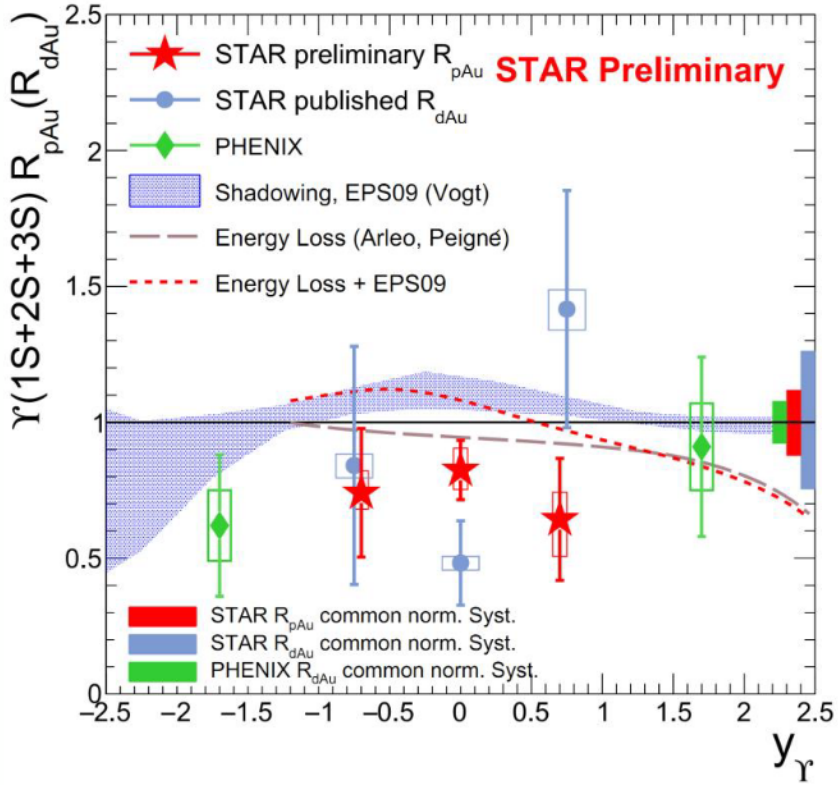
R. Vogt ,Phys. Rept. **462**(2008) 125

R. Vogt, et. al, PoS ConfinementX **203**(2012
F. Arleo, S. Peigne, JHEP **1303**(2013) 122
K. J. Eskola, et. al, JHEP **0904**(2009) 065

p+p



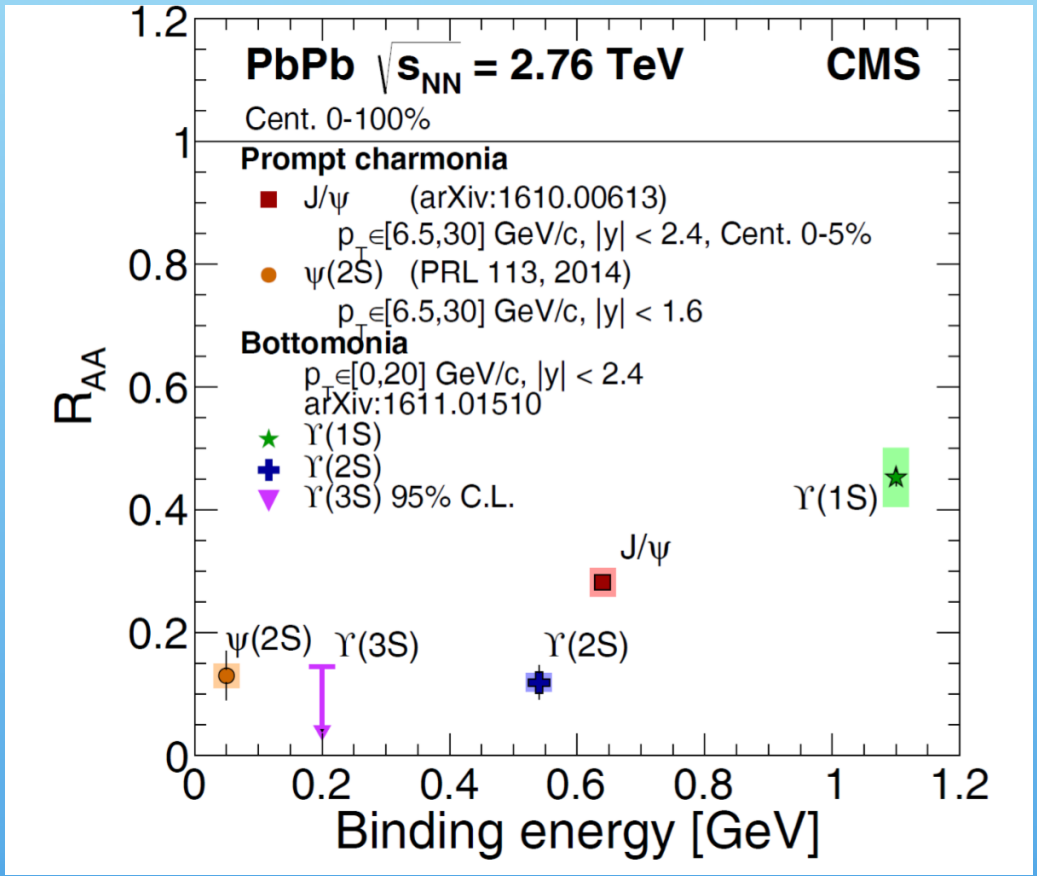
p+Au



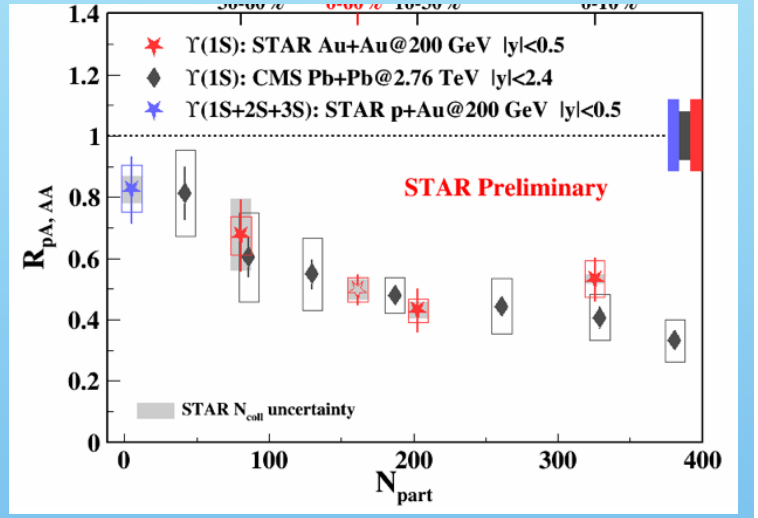
- Yields consistent with NLO model
- R_{pA} quantifies CNM effects

Hierarchy of quarkonia suppression has been observed at RHIC and LHC

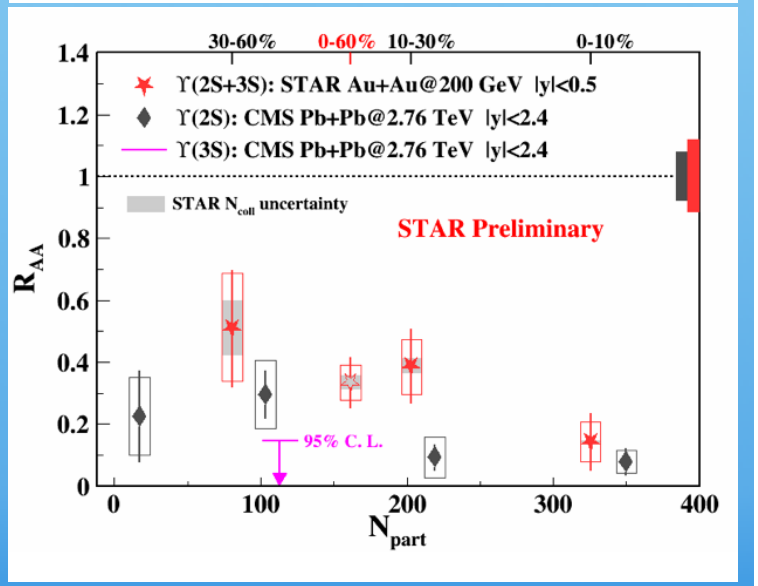
STAR, Z. Ye, QM2017



Y(1S)

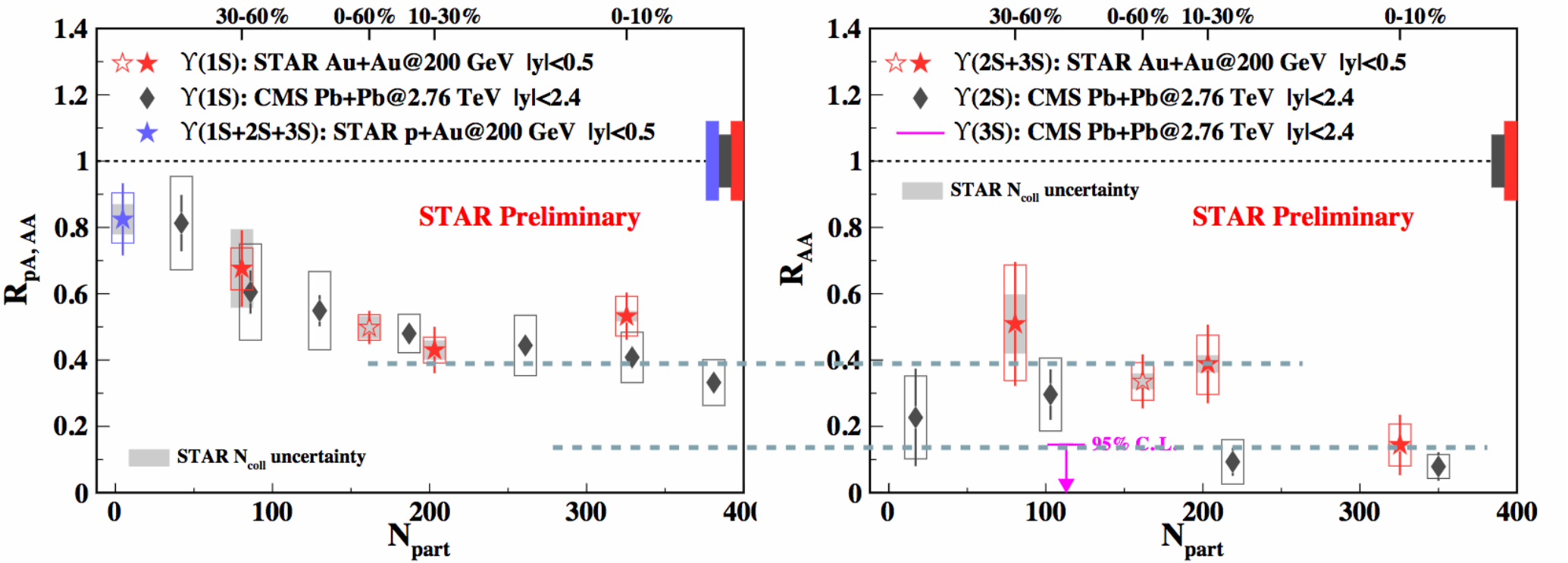


Y(2S+3S)



In central collisions Y(2S+3S) more suppressed than Y(1S)

ϒ Suppression in Au+Au Collisions



lines are to guide eyes only

Sequential melting observed at both RHIC and LHC energies

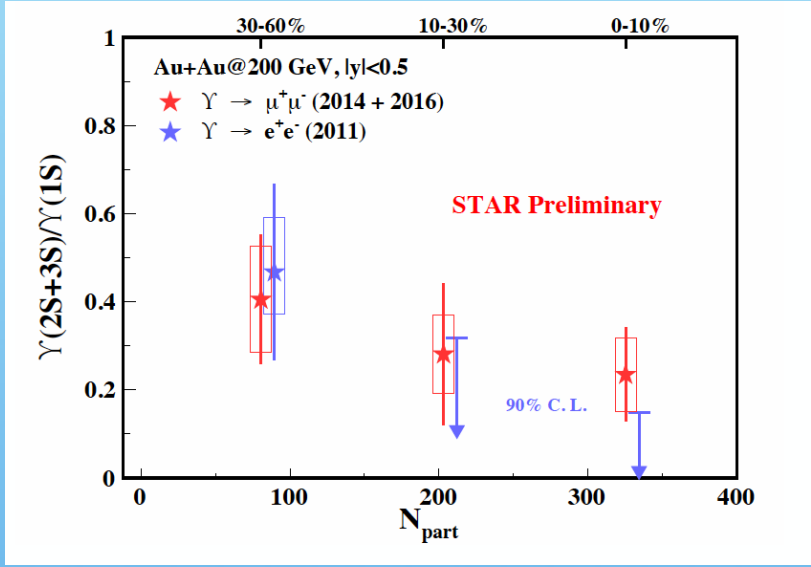
CMS, PLB 770 (2017) 357

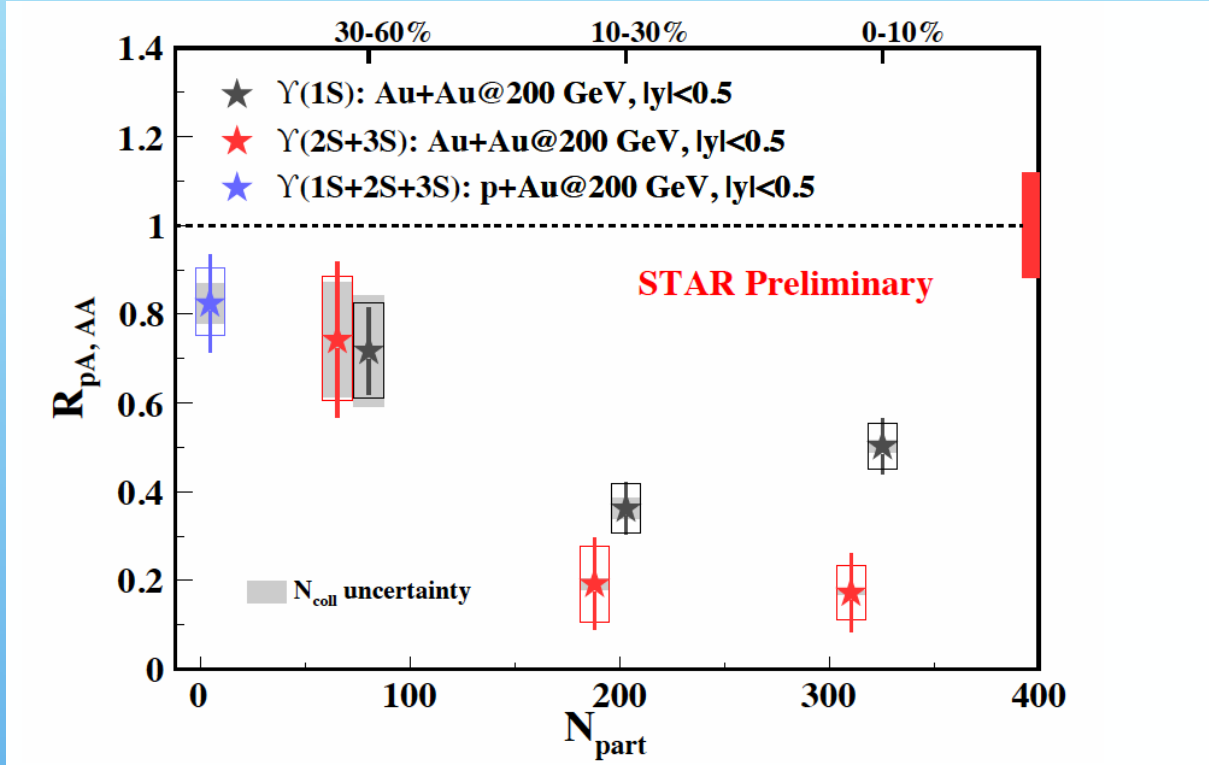
Li Yi (STAR coll.) Santa Fe 2018

Upsilon

Combined results from Y-> e^+e^- and Y-> $\mu^+\mu^-$ improve precision of Y measurements

Y->e+e- vs Y->mu+mu-



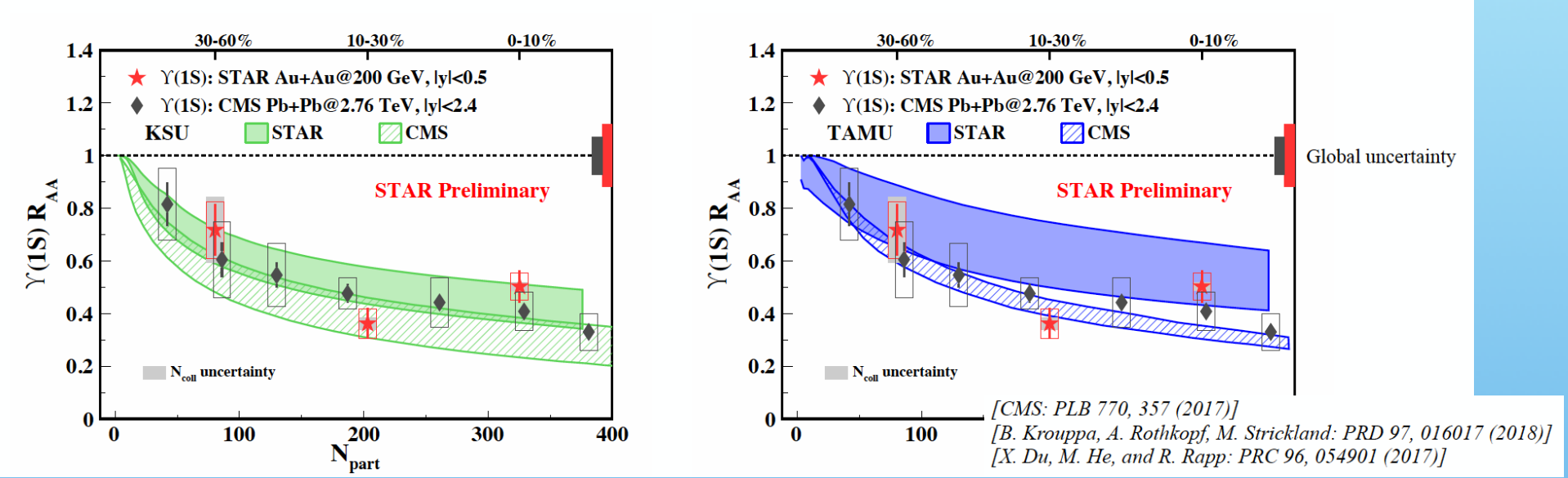


Y-> $\mu^+\mu^-$ with the Muon Telescope Detector (MTD):
Less Bremstrahlung allows to separate the Y(1S) from Y(2S+3S)

Y(2S+3S) more suppressed than Y(1S) in the most central Au+Au collisions (0-10% centrality)

ϒ(1S) R_{AA}: 0.50 ± 0.06 (stat.) ± 0.05 (sys.)
ϒ(2S+3S) R_{AA}: 0.17 ± 0.09 (stat.) ± 0.06 (sys.)

Upsilon Y(1S): STAR vs LHC vs models

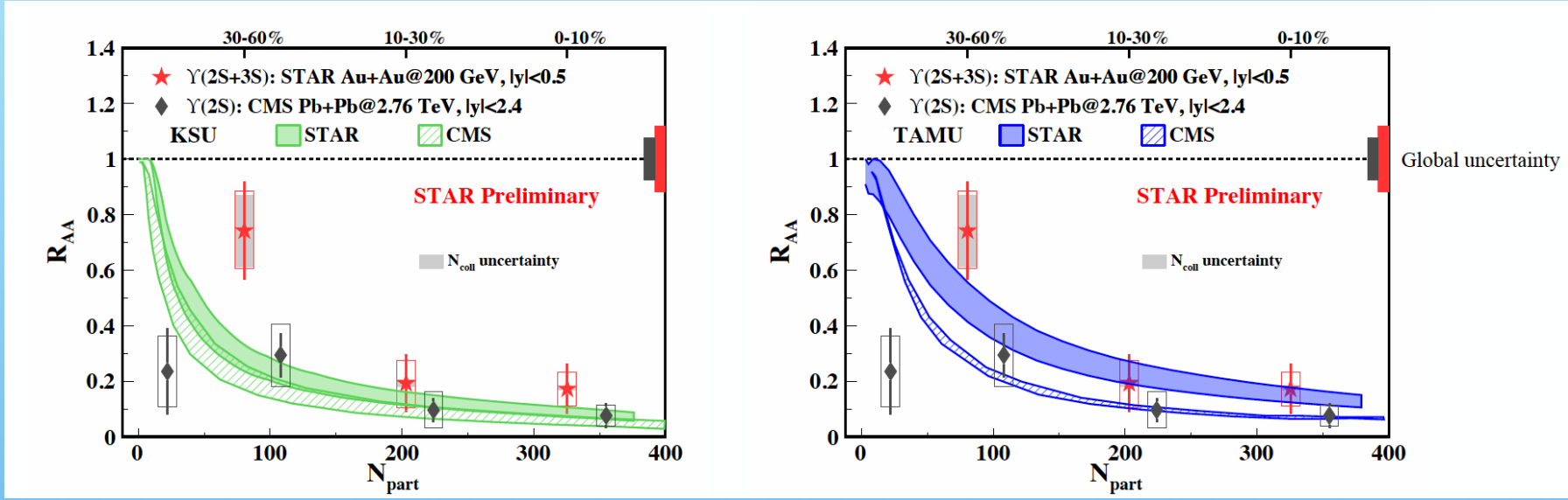


KSU model: use a lattice-vetted heavy-quark potential
TAMU model: use in-medium binding energies predicted by thermodynamic T-matrix calculations using internal-energy potentials, from lattice QCD

T_0^{QGP} (MeV)	RHIC (0.2 TeV)	LHC (2.76 TeV)
KSU	440	546
TAMU	310	555

STAR data on Y(1S) are consistent with LHC data
KSU and TAMU models are consistent with data on Y(1S) from RHIC (STAR) and LHC (CMS)

Upsilon Y(2S+3S): STAR vs LHC vs models



ϒ(2S+3S):

- **Indication of less suppression at RHIC than at LHC**

STAR: ϒ(2S+3S) R_{AA}: 0.35 ± 0.08 (stat.) ± 0.10 (sys.) ($0 < p_T < 10$ GeV/c, 0-60%)

CMS: ϒ(2S) R_{AA}: 0.08 ± 0.05 (stat.) ± 0.03 (sys.) ($0 < p_T < 5$ GeV/c, 0-100%)

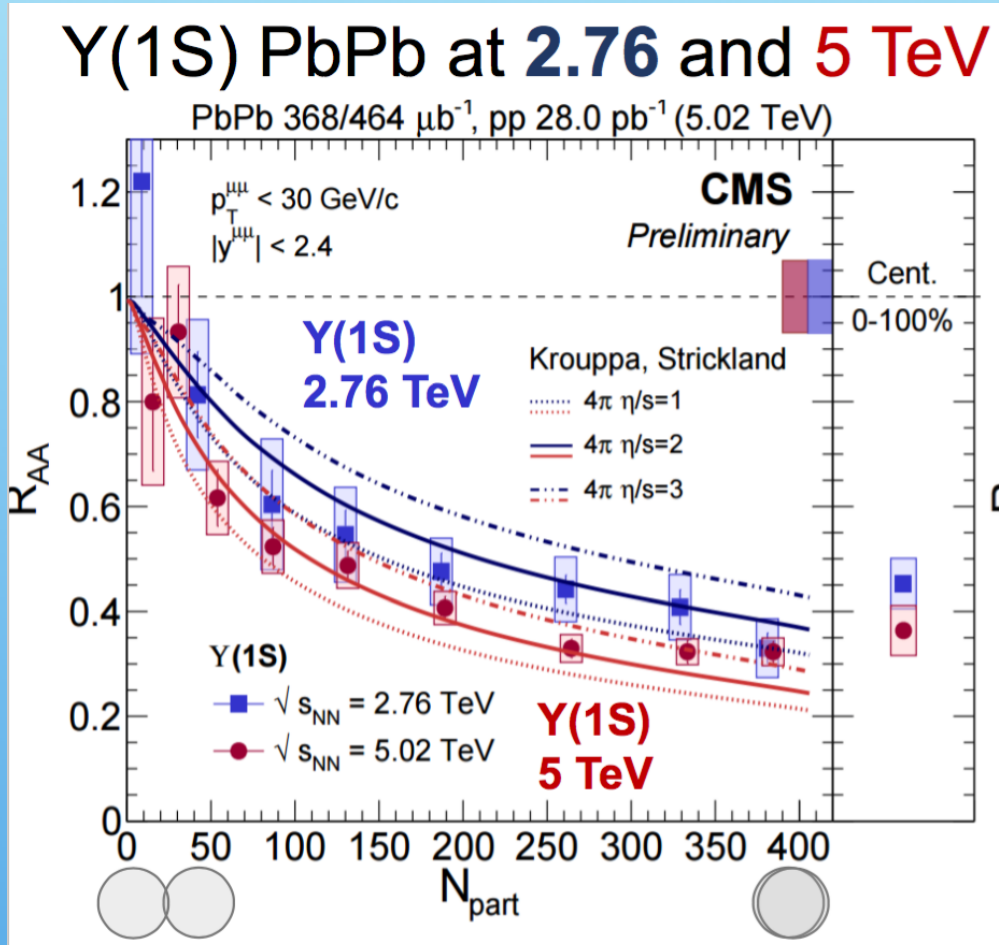
[CMS: PLB 770, 357 (2017)]
[B. Krouppa, A. Rothkopf, M. Strickland: PRD 97, 016017 (2018)]
[X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)]

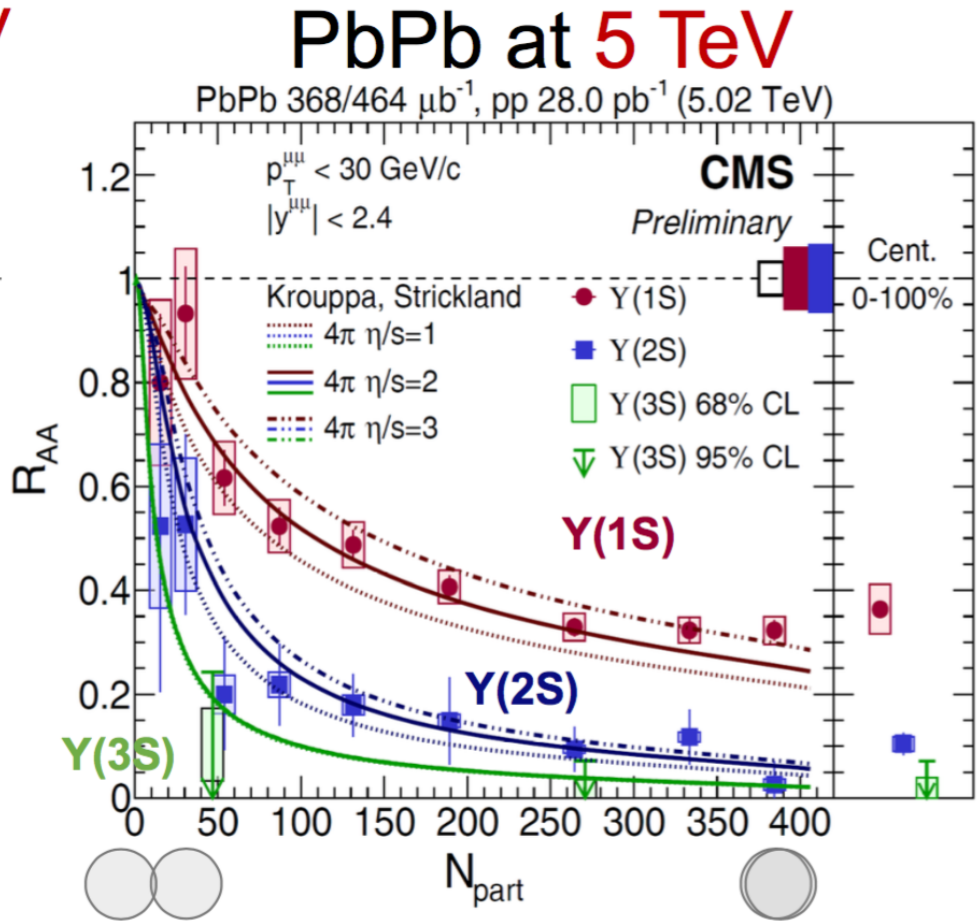
KSU and TAMU models are consistent with data on Y(2S+3S) in central and semi-central collisions from RHIC (STAR) and LHC (CMS)

STAR Y data in central A+A collisions are consistent with "sequential melting" in QGP

Quarkonia at 5 TeV PbPb

CMS,J. J. Lee, QM2017 Y(1S) and Y(2S)



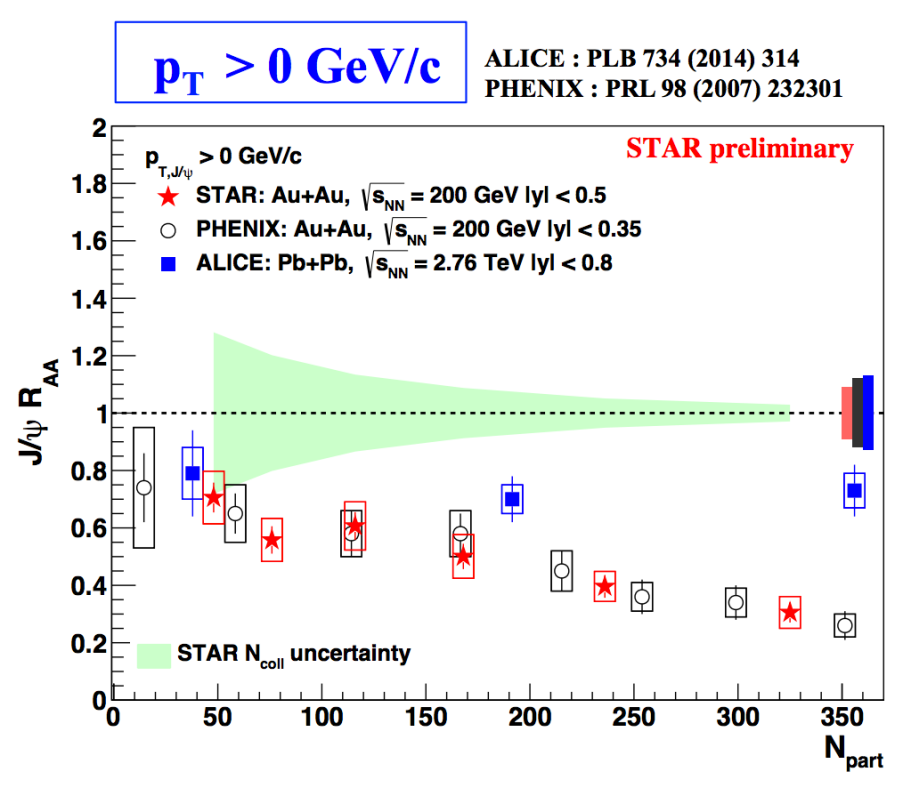


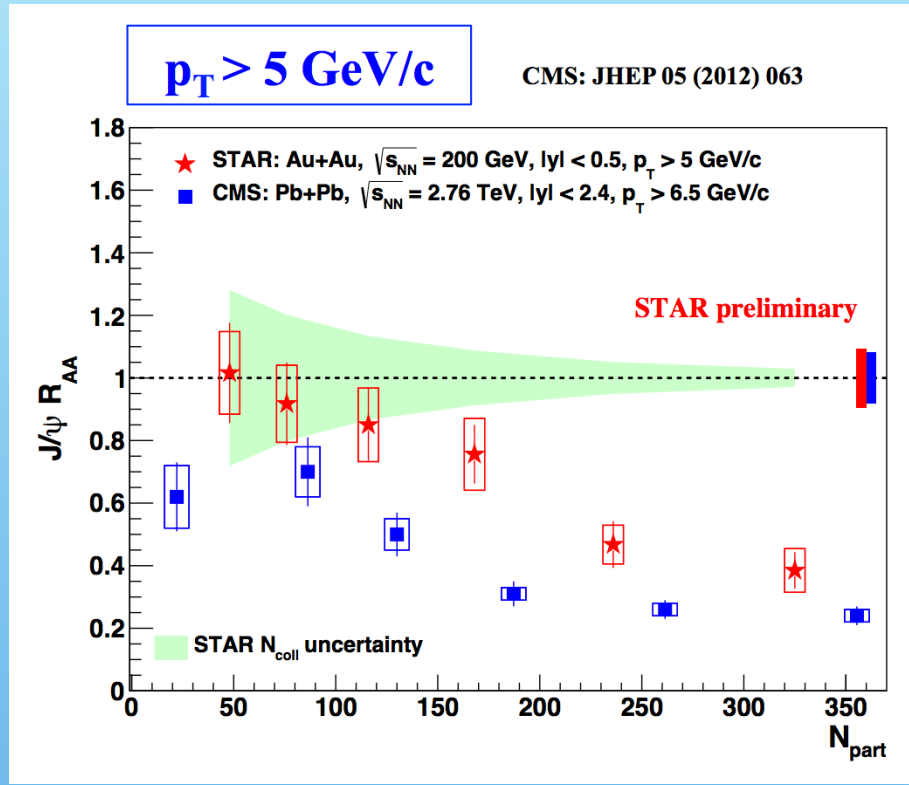
- Indication of larger suppression at 5 TeV
- Consistent with predictions from a **hotter** and **denser** medium

- Highest precision measurement
- Upsilon sequential suppression at 5 TeV
- Still no sign of Y(3S) with high statistics data

arXiv: 1611.01510
Submitted to PLB

J/Psi recombination at LHC ?





Low pT: RAA(ALICE) > RHIC

High pT : RAA at LHC more similar to RHIC

STAR, Z. Miller, WWND2017

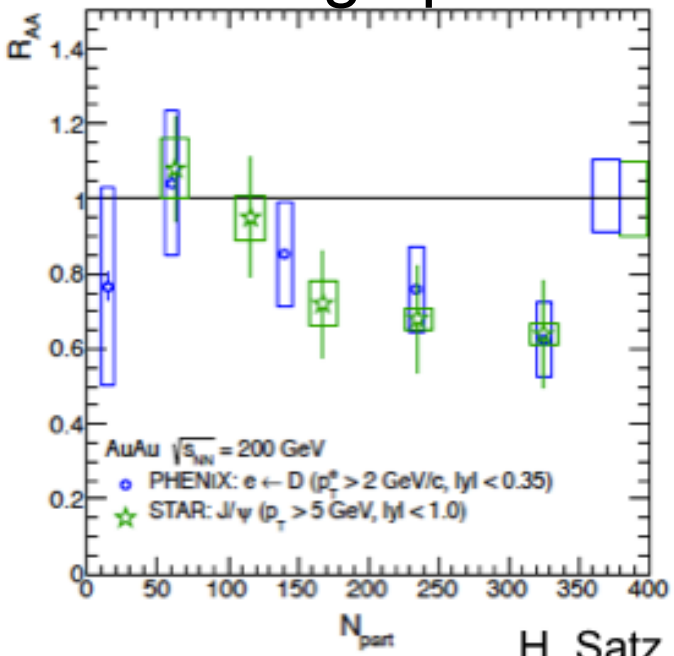
RAA of J/Psi in Pb+Pb at LHC is below 1

RAA of J/Psi is less suppressed at low pT, in central collisions ->

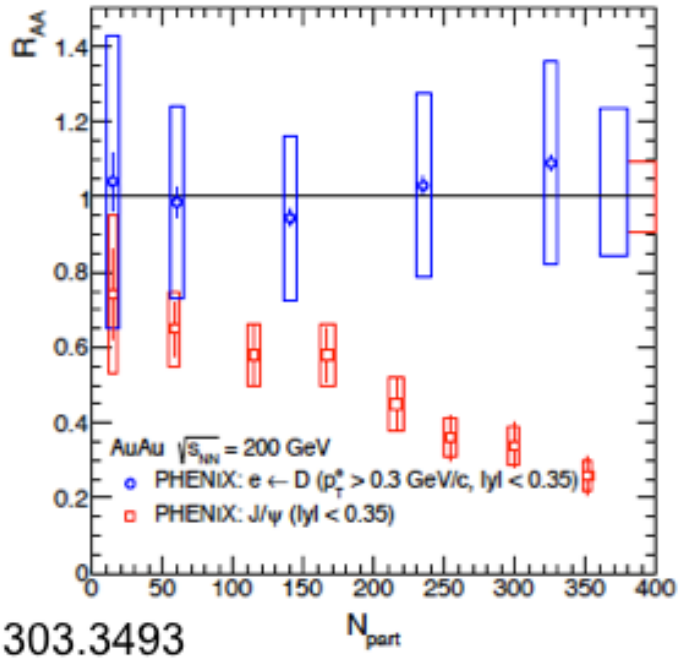
Indication of J/Psi regeneration at LHC at low pT

J/Psi compared to open charm - RHIC

High pT



Low Pt



H. Satz, arXiv 1303.3493

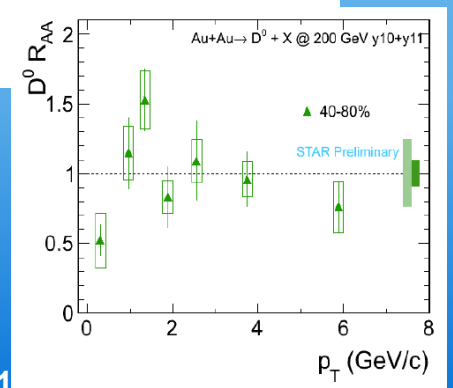
High pT

* J/Psi seems to be neither suppressed nor enhanced with respect to open charm at all centralities at high pT (However pT range is not exactly the same)

Low Pt

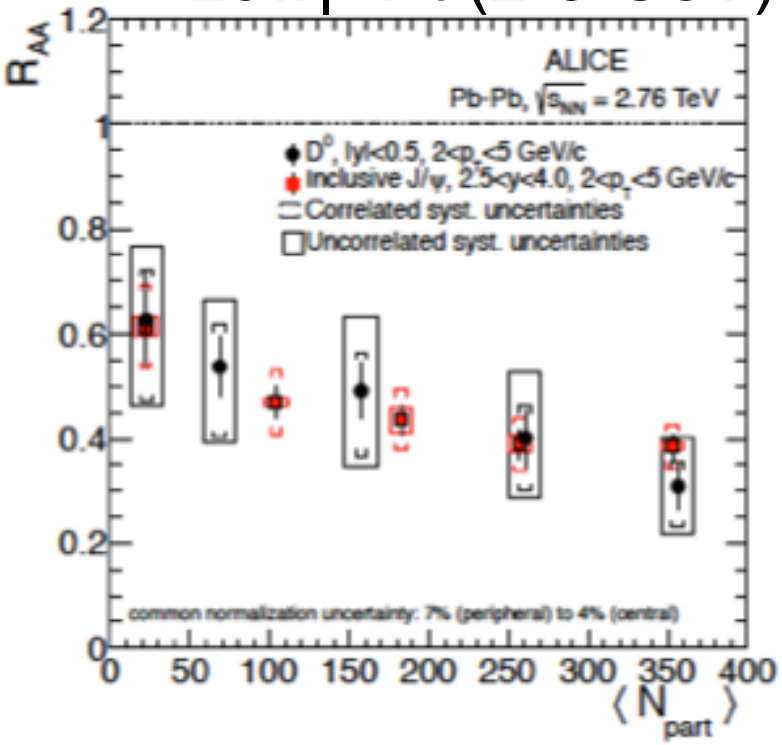
* J/Psi seems to be significantly suppressed with respect to open charm at low pT in central Au+Au events (same acceptance here)

STAR : RAA(D0) shows no suppression for peripheral collisions

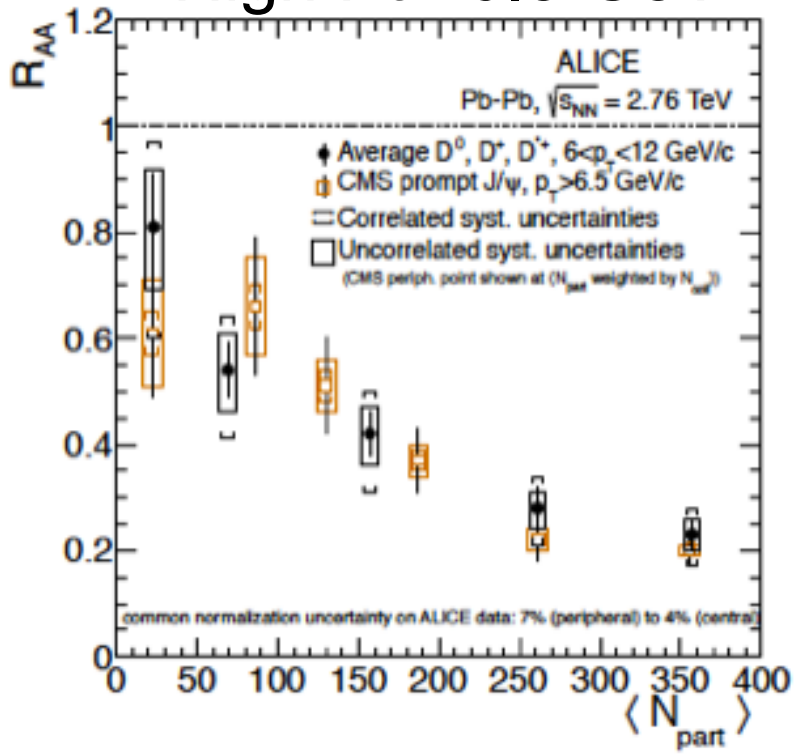


J/Psi compared to open charm - LHC

"Low|" Pt (2-5 GeV)



High Pt> 6.5 GeV

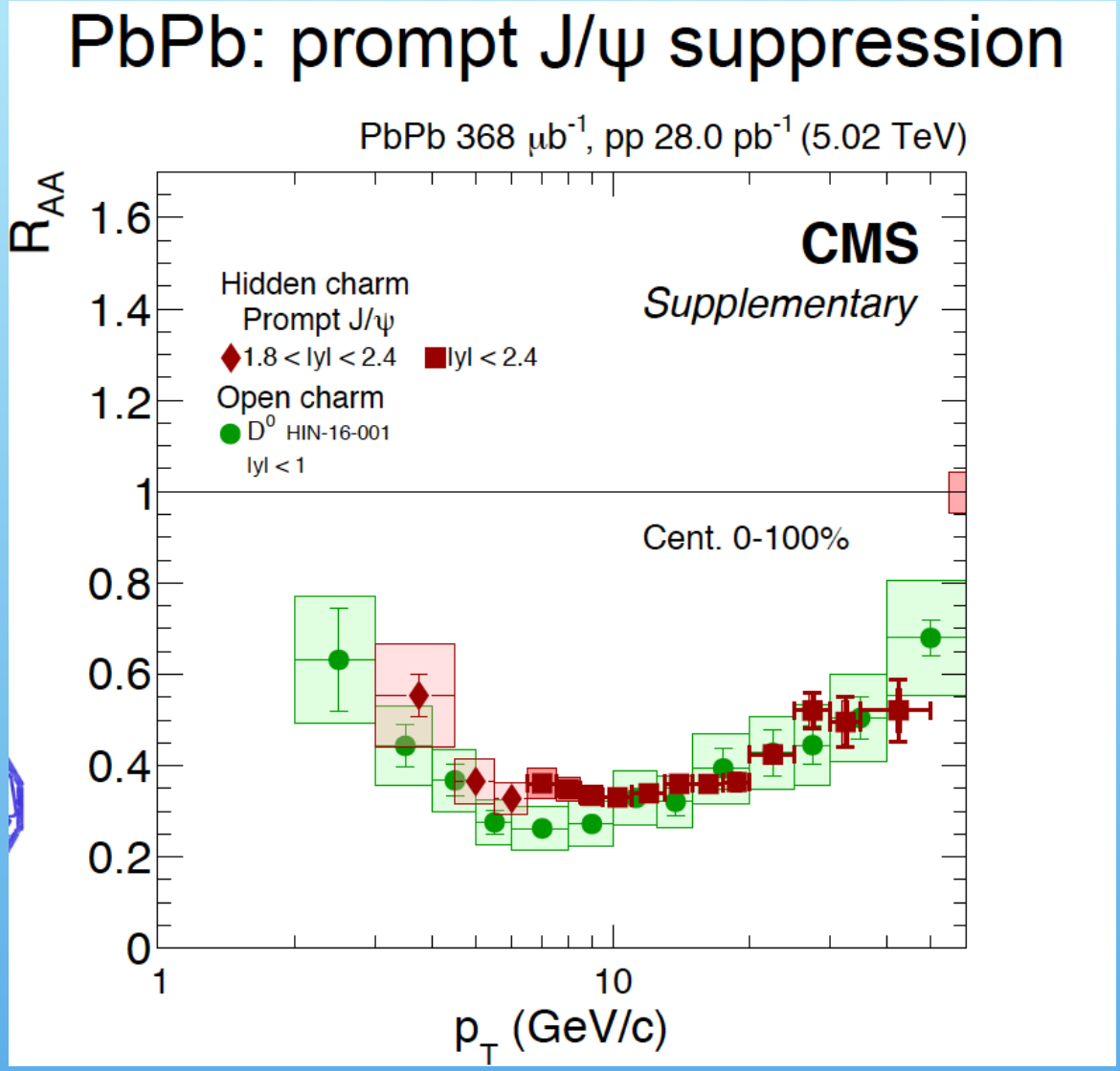


H. Satz, arXiv 1303.3493

J/Psi seems to be neither suppressed nor enhanced with respect to open charm at all centralities, at intermediate (pT=2-5 GeV) and high pT>6.5 GeV

However experiments should compare more precisely within exactly same acceptance (here different y) and at low pT too

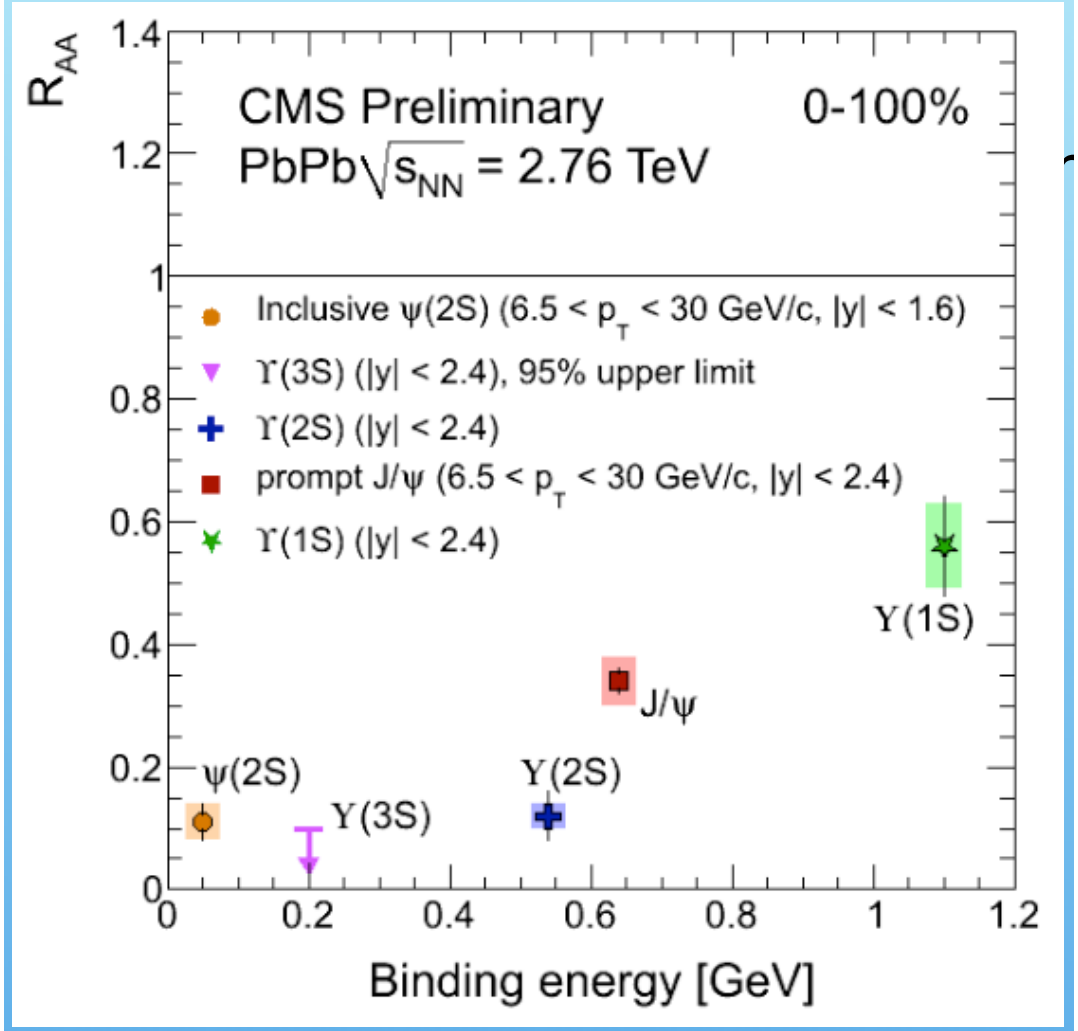
J/Psi vs D0 (CMS)

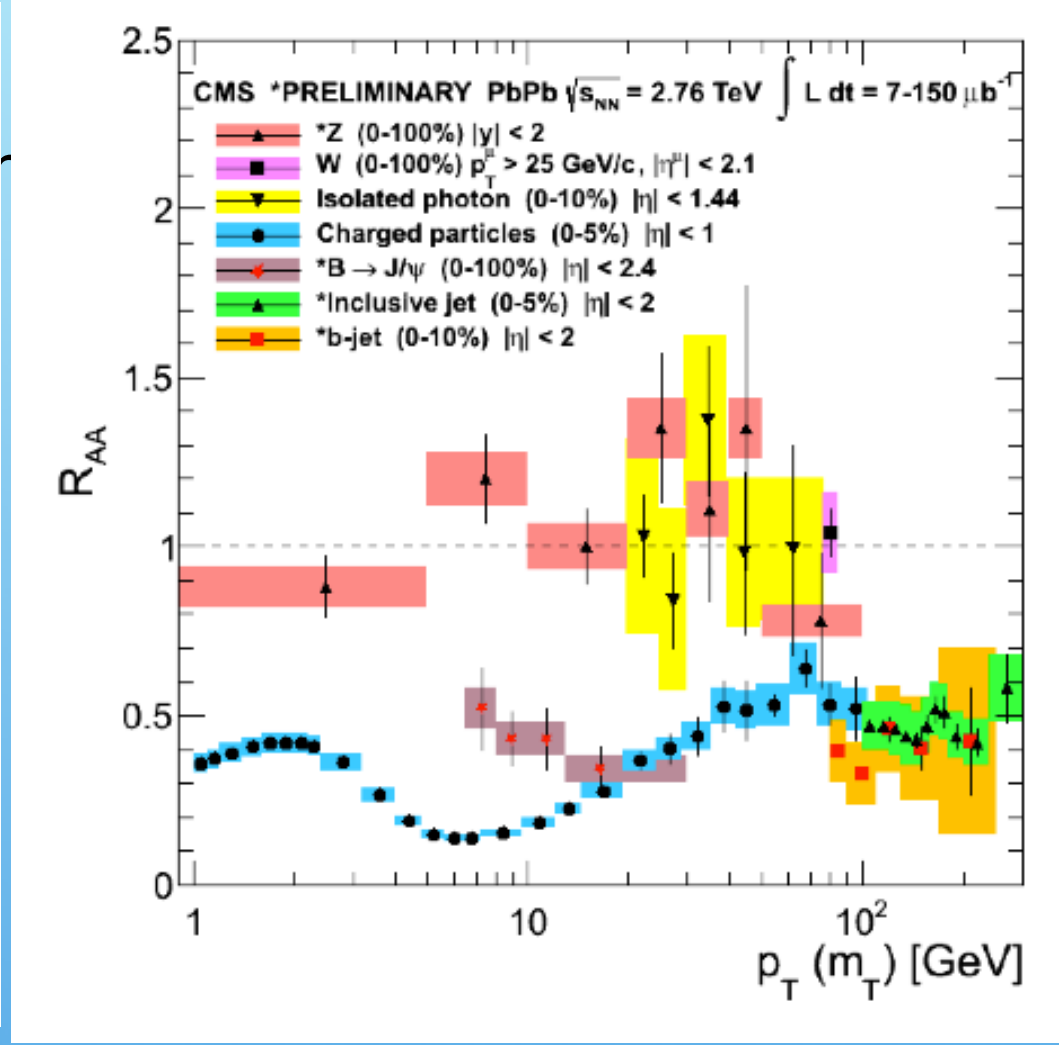


J/ψ suppression similar to D^0 suppression
Jet quenching for charmonia?

Beauty

M. Jo et al CMS, Etretat QGP 2014



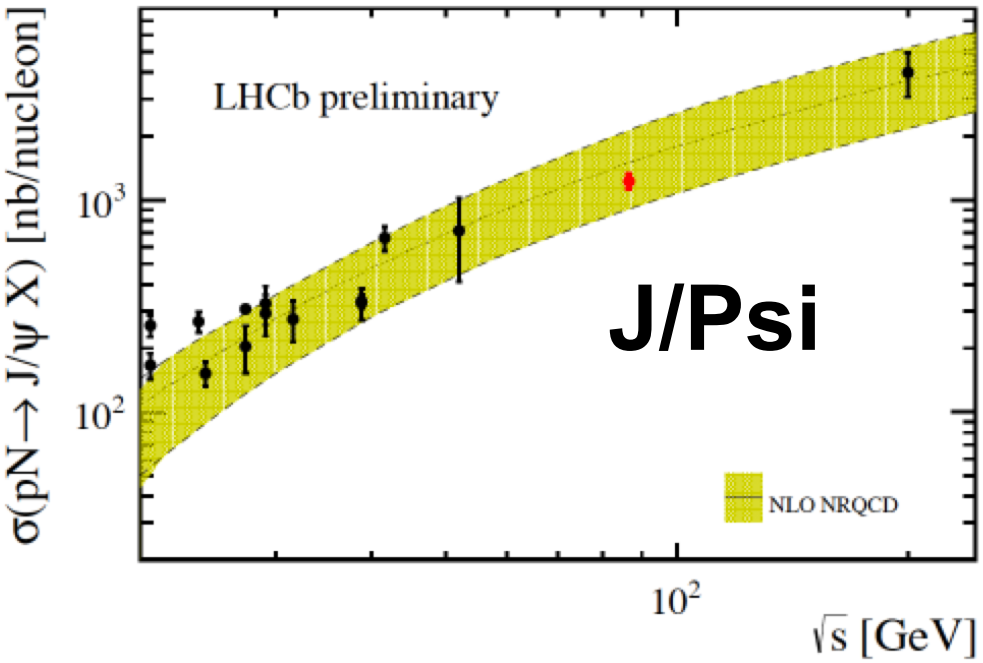


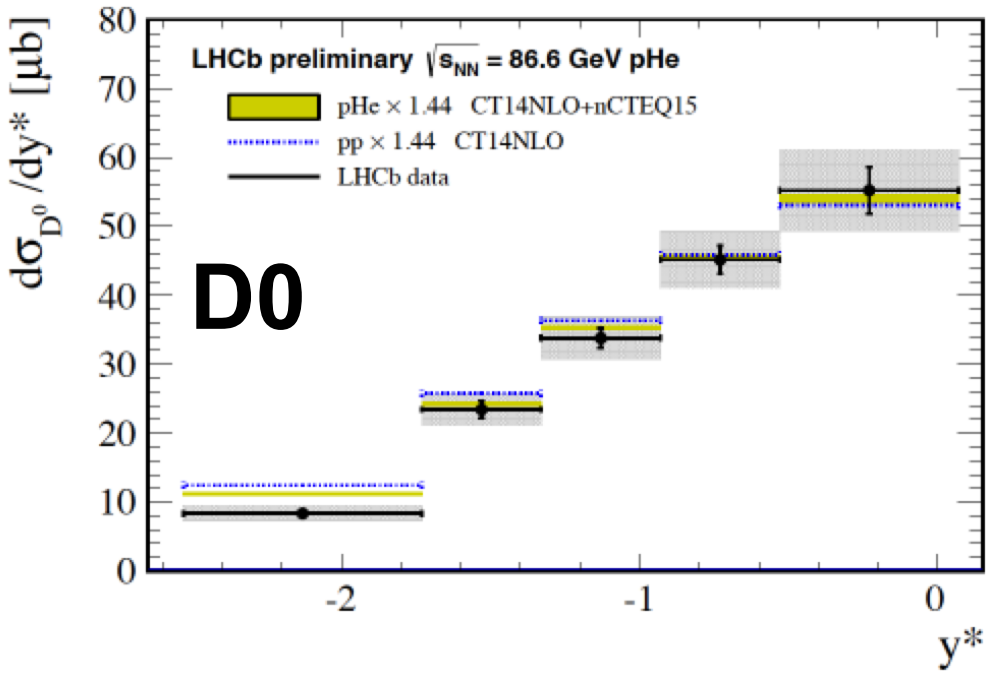
Y(1S) in PbPb seem less suppressed than open beauty in PbPb (needs better stat) if so -> no Y(1S) suppression

Y(2S), Y(3S) in PbPb seem more suppressed than open beauty in PbPb -> compatible with Y(2S) and Y(3S) suppression

LHCb fixed target run

D^0 and J/ψ production in pHe fixed target: first cross sections **sqrt(s)=69 GeV**





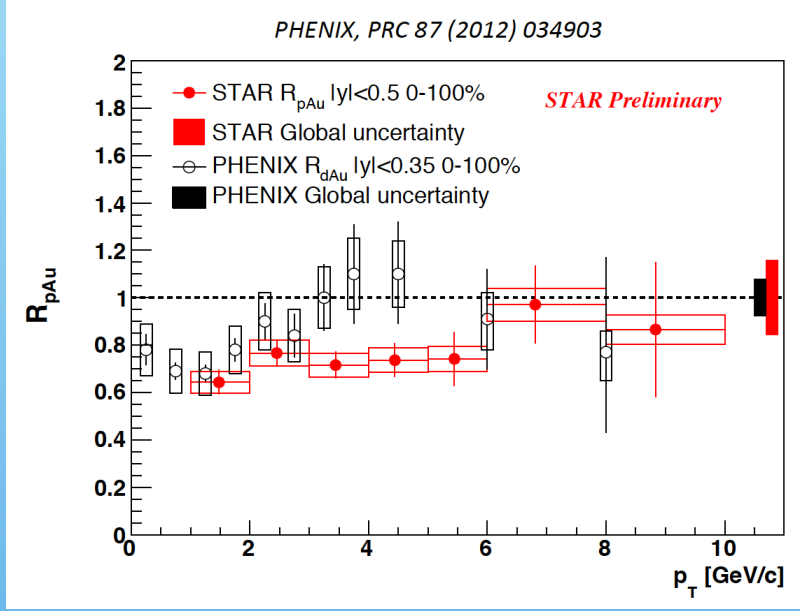
LHCb-PAPER-2018-022, in preparation.

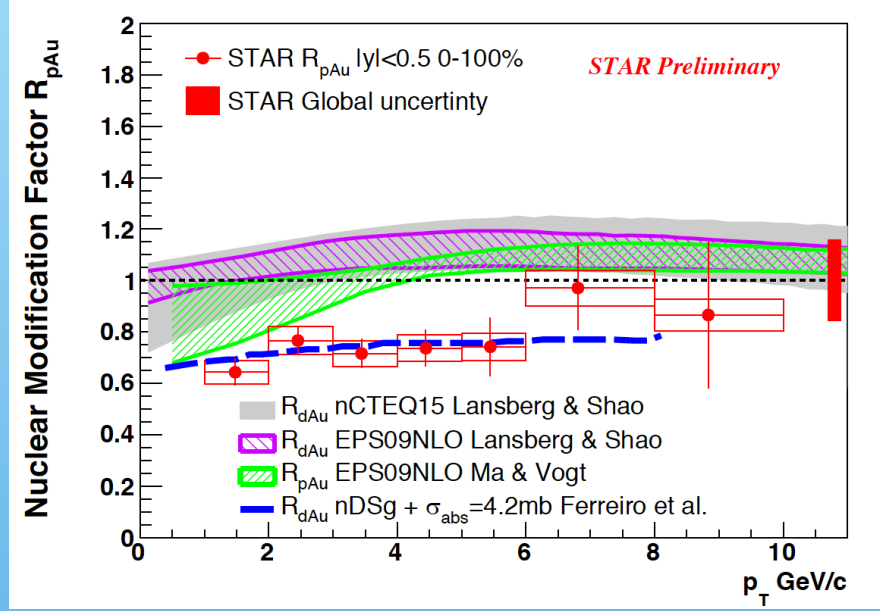
Shanzhen Chen, **QM2018, Venezia**

First measurement on R_{pAu} of J/ψ at RHC

nCTEQ, EPS09+NLO, Lansberg &
Eur. Phys. J. C77 (2017) 1
Comp. Phys. Comm. 198 (2016)
Comp. Phys. Comm. 184 (2013)

Ferreriro et al., Few Body Syst. 5

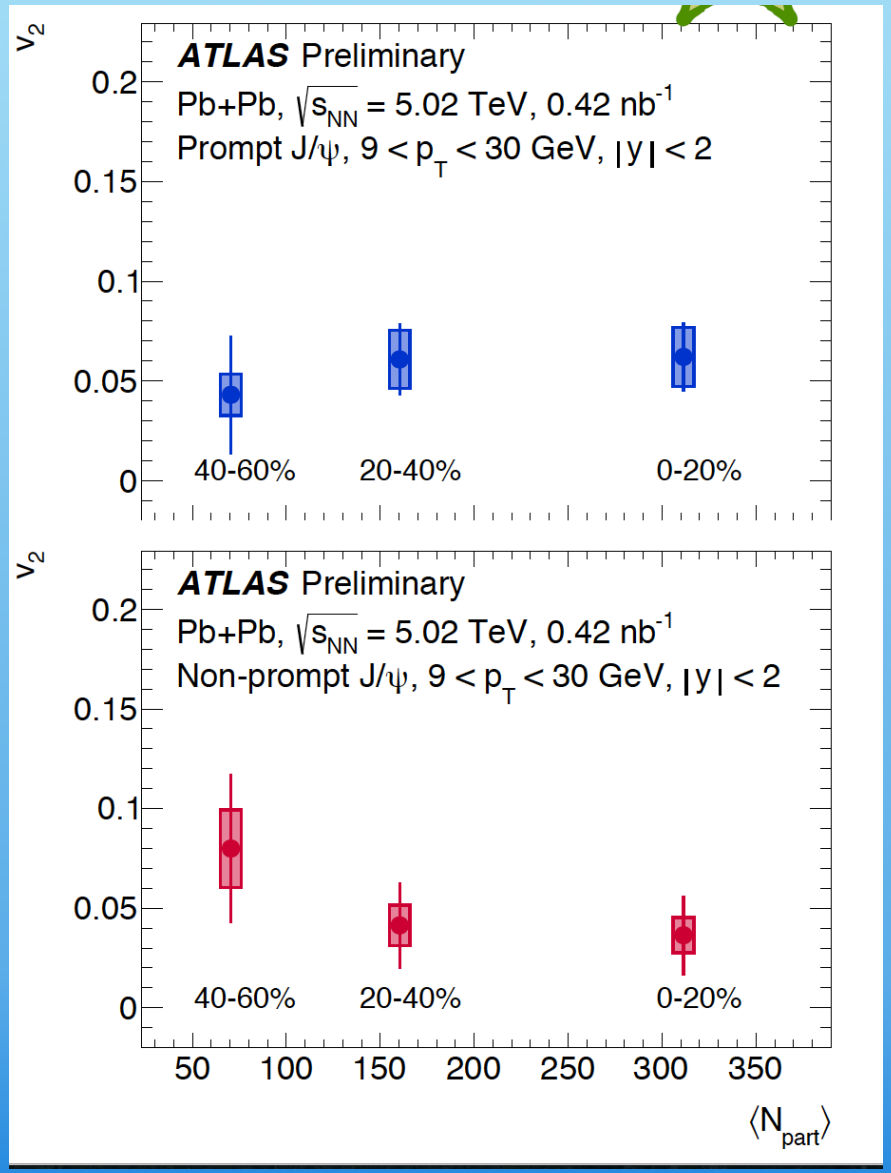




- R_{pAu} is consistent with R_{dAu} within uncertainty
  - There seems to be tension at $3 < p_T < 5$ GeV/c with 1.4σ significance
- Suggests similar CNM effects in these collision systems

- Model calculations with only shadowing effect can touch the upper limit of data within uncertainties
- Additional nuclear absorption is favored by data

ATLAS: Flow of prompt and non-prompt J/Psi



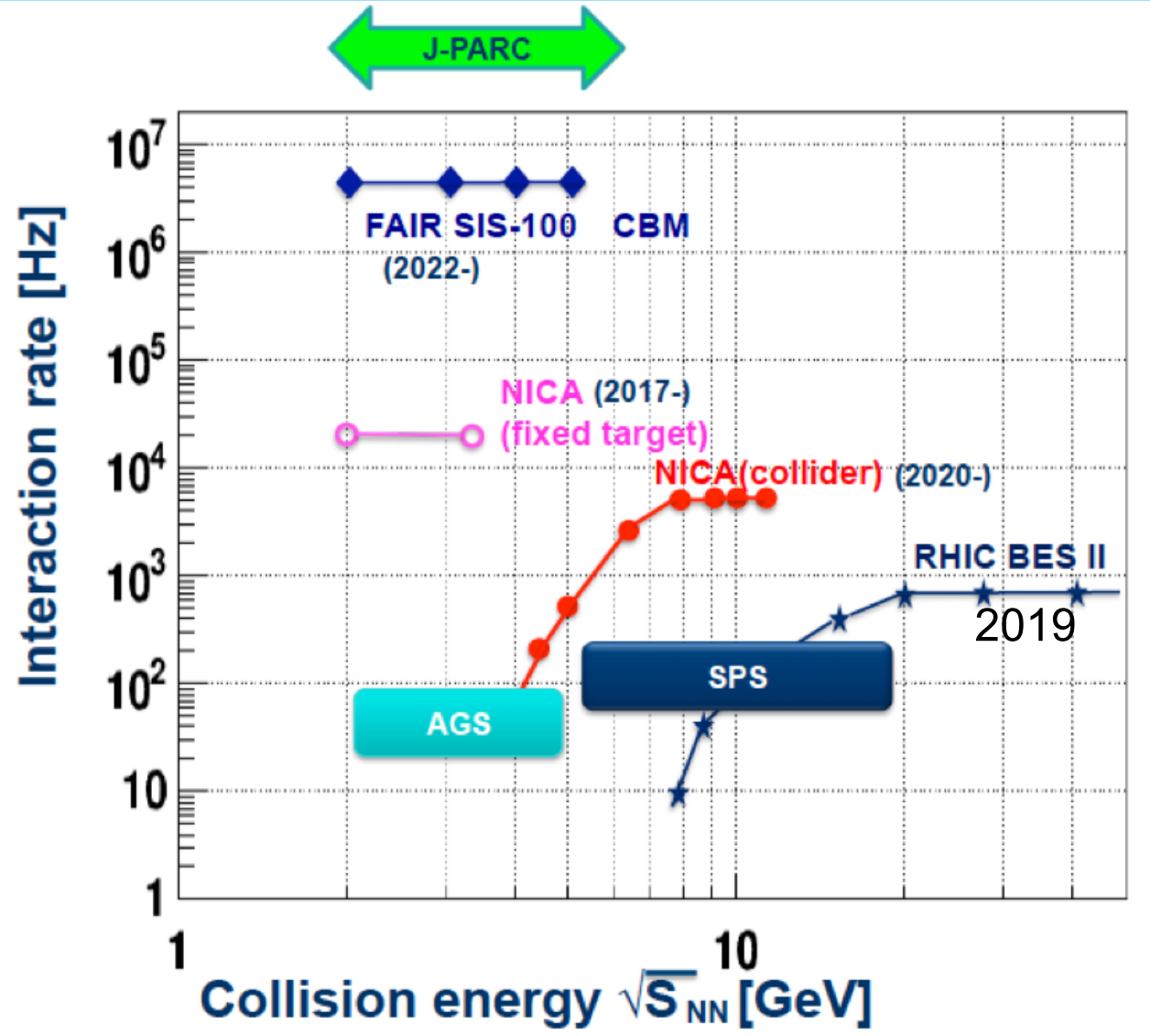
- Prompt and non-prompt J/ψ mesons have non-zero elliptic flow
- **No observed dependence on rapidity or centrality**

ATLAS Coll. QM2018

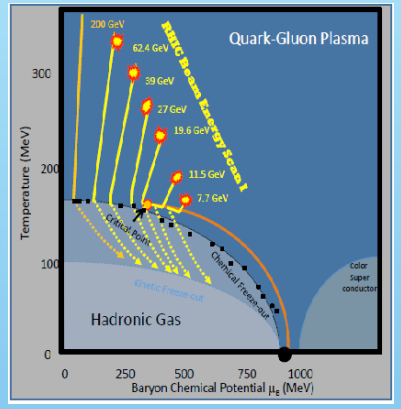
6. Future

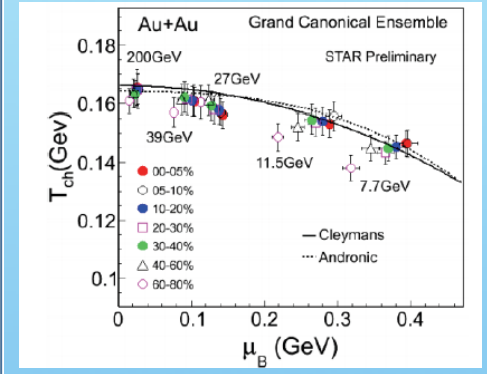
Energy scans with Heavy Ions
Future: BESII, NICA, FAIR, J-PARC

T. Sakaguchi, QM2017

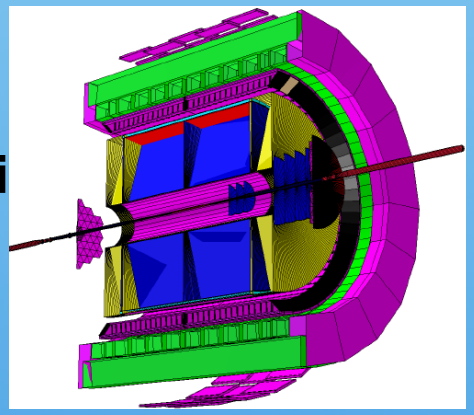


STAR future plans





Beam Energy Scan (BES) II 2019-2020
Will continue the BES I program
"Hot" QCD, search for a possible critical point and discontinuities in the energy dependence of QGP signatures
-> FAIR and NICA



STAR forward rapidity program (2.5-eta-4): Hcal, Ecal, tracki (Silicon and sTGCs)
"Cold" QCD, Proton TMDs, gluon saturation
Test Electron Ion Colider (EIC) detector technologies
Milestone: 2021 p+p run and sPHENIX data taking 2022+
-> EIC

STAR goals

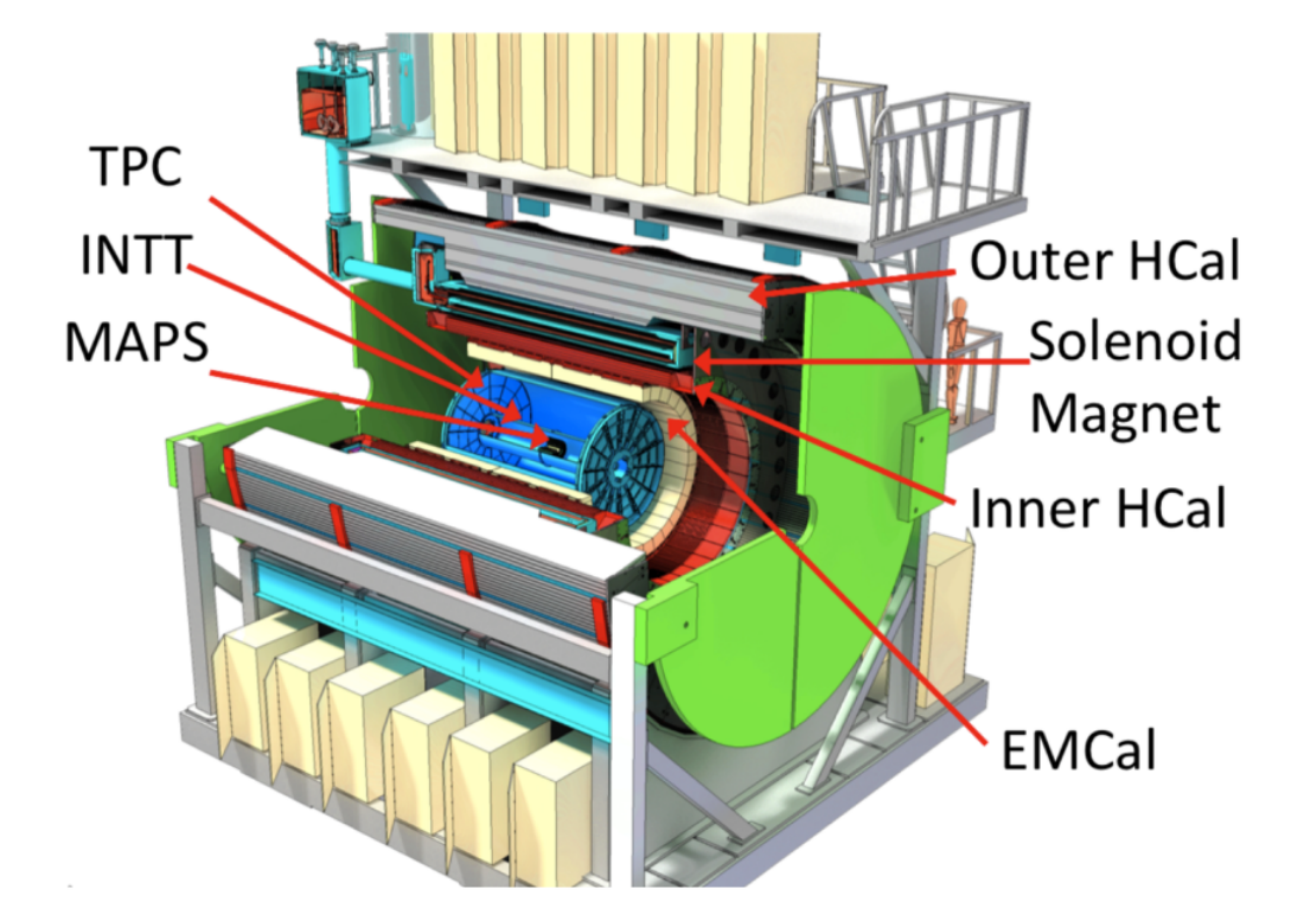
Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events
9.8	19.6	205	4.5 weeks	400M
7.3	14.5	260	5.5 weeks	300M
5.75	11.5	315	5 weeks	230M
4.55	9.1	370	9.5 weeks	160M
3.85	7.7	420	12 weeks	100M
31.2	7.7 (FXT)	420	2 days	100M
19.5	6.2 (FXT)	487	2 days	100M
13.5	5.2 (FXT)	541	2 days	100M
9.8	4.5 (FXT)	589	2 days	100M
7.3	3.9 (FXT)	633	2 days	100M
5.75	3.5 (FXT)	666	2 days	100M
4.55	3.2 (FXT)	699	2 days	100M
3.85	3.0 (FXT)	721	2 days	100M

SK for the STAR Collaboration, ICNFP2018

* New detector project at RHIC: sPHENIX

sPHENIX: start data taking 2022

Extended Calorimetry
precision vertexing
and tracking for
jet quenching, charm,
beauty

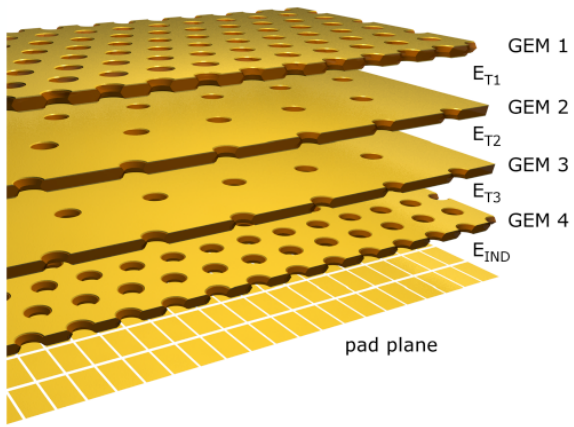


M. Connors,
Nucl.Phys. A967 (2017) 548-551

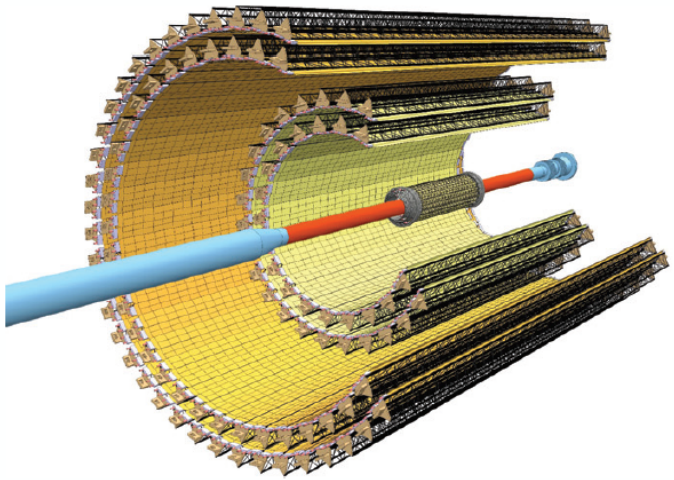
LHC experimental upgrades

ALICE upgrades for run-3

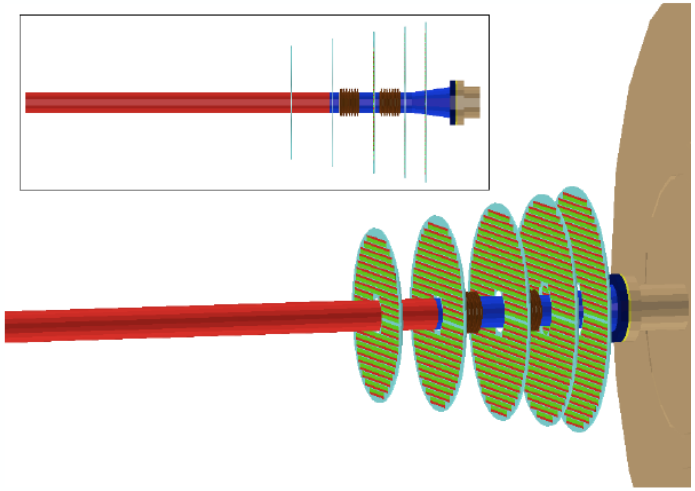
GEM-TPC



ITS



MFT



MFT: will provide secondary vertex reconstruction in forward rapidity

ITS : low pT reach and improved accuracy

High rate

A view into the far Future : FCC

plot from M. Koratzinos, ICNFP2017

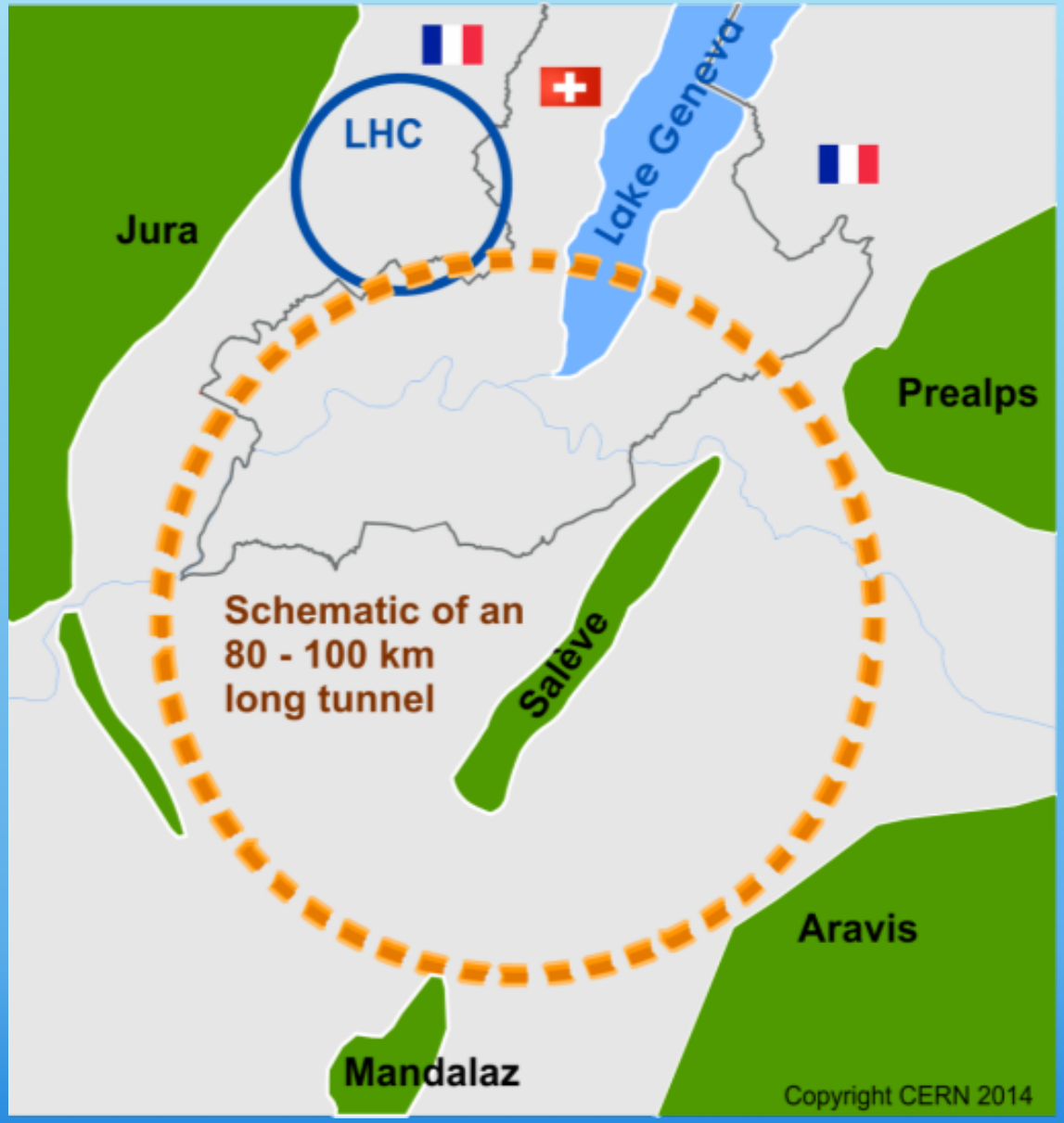
FCC: The Vision

~100 km tunnel, 16 T magnets
sqrt(s)= 100 TeV pp collisions

FCC-hh
FCC-ee
FCC-he

Possible first steps
***FCC-ee, E_CM=90-400 GeV**
******HE-LHC*** **16T 28 TeV**
in LEP/LHC tunnel

FCC-AA : sqrt(s)NN=40 TeV



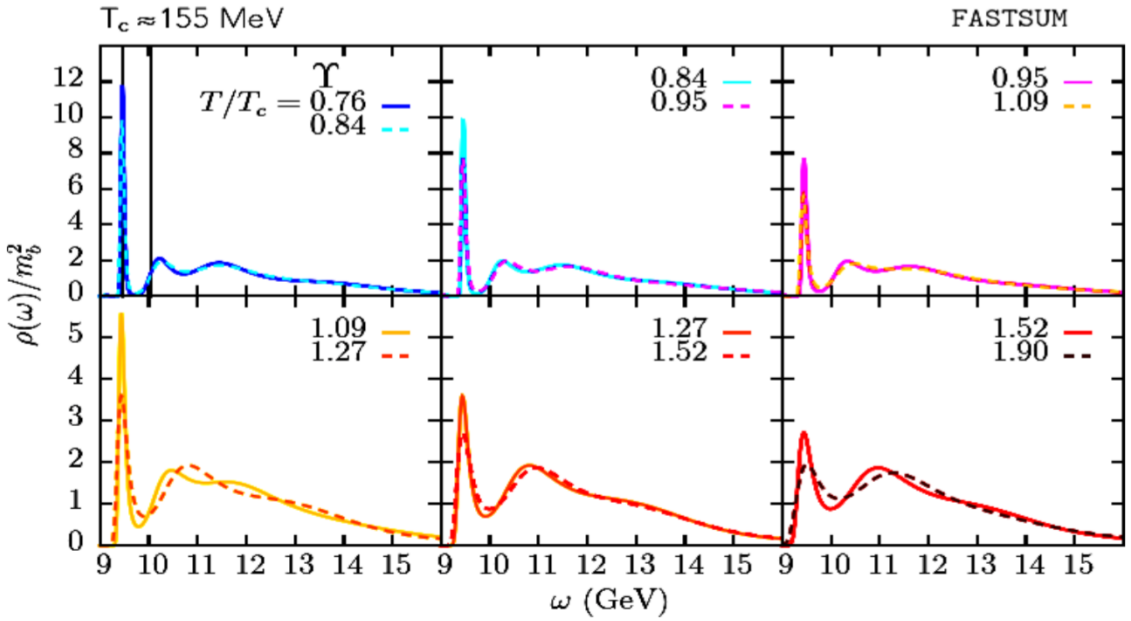
FCC quarkonia

- **p+p at sqrt(s)=100 TeV, Pb+Pb at sqrt(s)=39 TeV**

D. d Enterria, QM2017

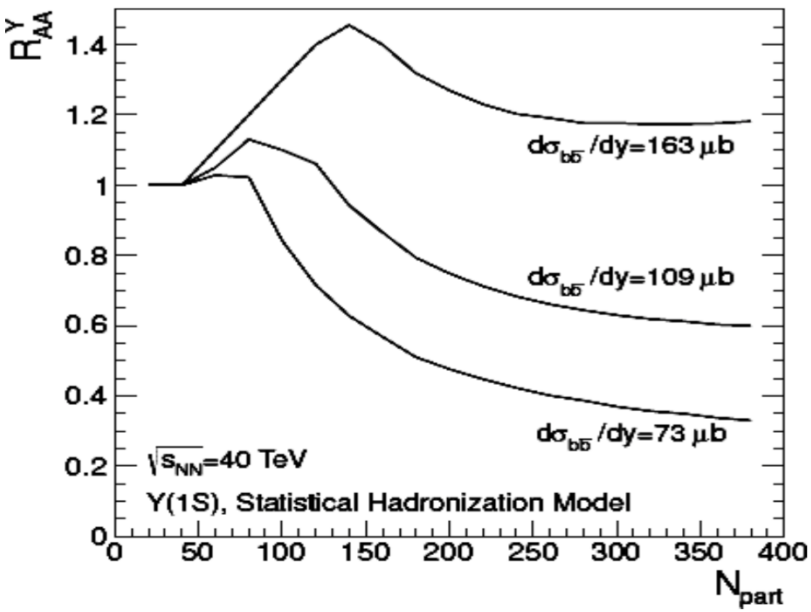
- FCC-AA (T_0~1GeV) can probe Y(1S) "melting" expected by latt-QCD at T=4–5 T_c

[G. Aarts et al, JHEP 07 (2014) 097]



- Density of bbbar pairs large enough for Y(1S) recombination?

[A.Andronic, et al., JPG38 (2011) 124081]



IV Conclusions

- QGP signatures observed in central Au+Au and Pb +Pb collisions at RHIC and LHC as well as at SPS.

- Open Heavy Flavor and Quarkonia give insights into QGP formation and characteristics

  Sequenctial quarkonia suppression observed
  -> inferred QGP temperatues of 400-550 MeV

- Flavor dependence of jet quenching observed in B and D

IV Conclusions

Further studies are needed to study in detail and understand jet quenching, quarkonia suppression and other phenomena.

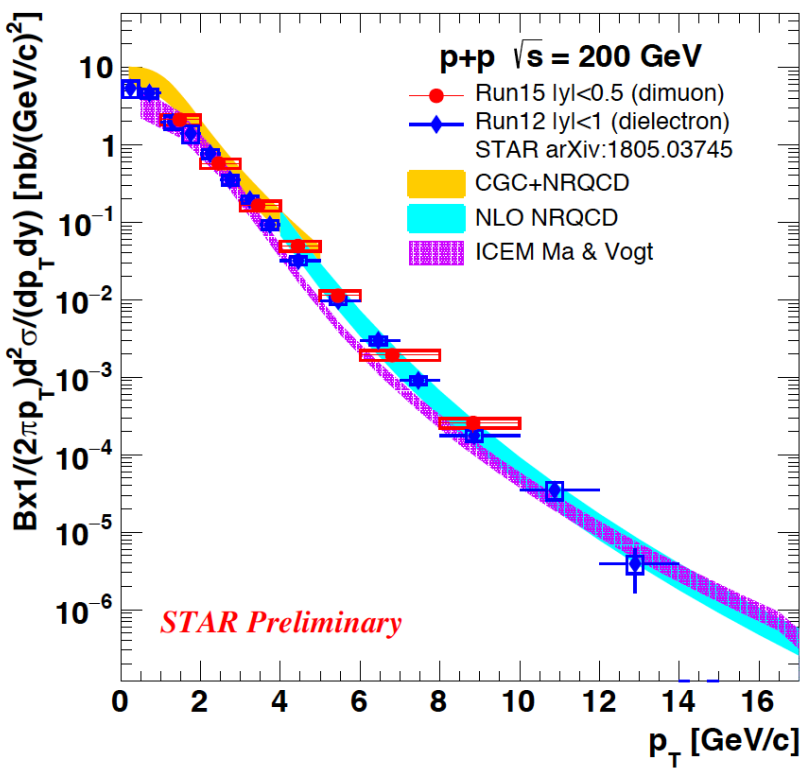
- **RHIC BESII (2019-2020), sPHENIX (2020+)**
- **LHC with future upgrades**
- **NICA in Dubna, Russia and**
- **FAIR in GSI, Germany and**
- **J-PARC in Japan,**

Center of mass energy (sqrt(s)NN):
FAIR: 2-6 (10) GeV, NICA: 4-11 GeV, RHIC: 7 (2.5) - 200 GeV LHC: 2.76, 5 TeV
J-PARC: 1-10 GeV
FCC (100 km circular ring, p+p at sqrt(s)=100 TeV, Pb +Pb at sqrt(s)=39 TeV)

Thank you very much for your attention

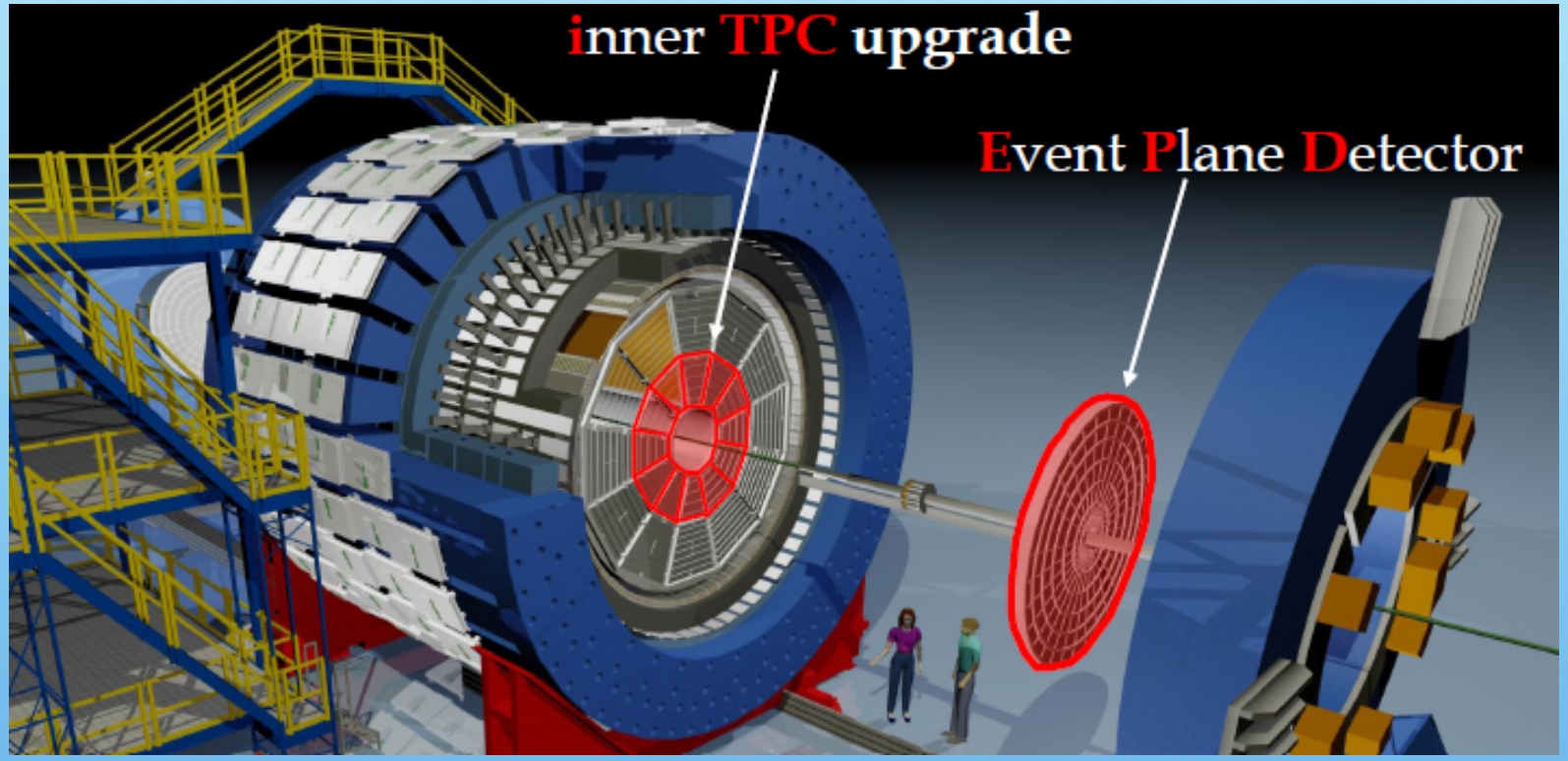
J/ψ production in p+p 200 GeV

STAR, arXiv:1805.03745



CGC+NRQCD, Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
ICEM, Ma & Vogt, PRD 94 (2016) 114029

- Inclusive J/ψ cross section is measured in $0 < p_T < 14$ GeV/c
- CGC+NRQCD & NLO NRQCD (prompt J/ψ) model calculations can describe data in the full p_T range
- Improved CEM model (direct J/ψ) describes data well at low p_T
  - Data are above ICEM calculation at $3.5 < p_T < 12$ GeV/c
- ~10-25% feed-down contribution from bottom hadrons in $4 < p_T < 14$ GeV/c. *[Bedjidian et al., arXiv:hep-ph/0311048; Cacciari, Nason, and Vogt, PRL 95 (2005) 122001]*

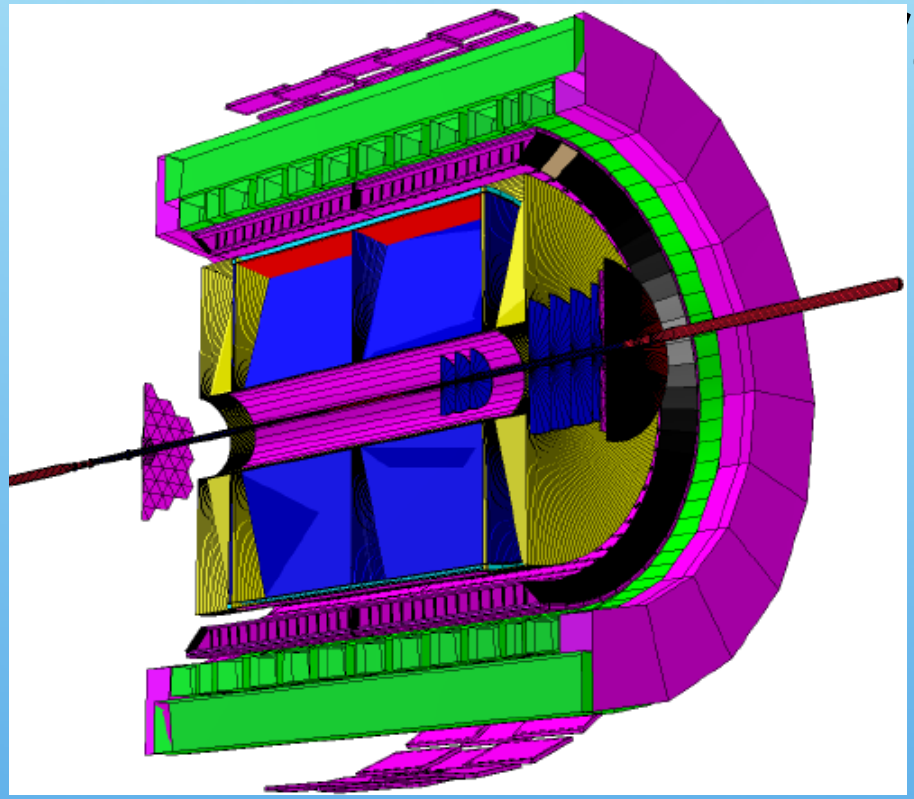


iTPC: inner sector of TPC. Extends peudorapidity acceptance from 1 to 1.5. Improves dE/dx

Endcap TOF: particle identification 0.9-eta-1.5

Event Plane Detector: will provide better and independent determination of centrality and event plane

STAR forward rapidity



am

3 Silicon discs

4 Small-strip Thin Gap Chambers

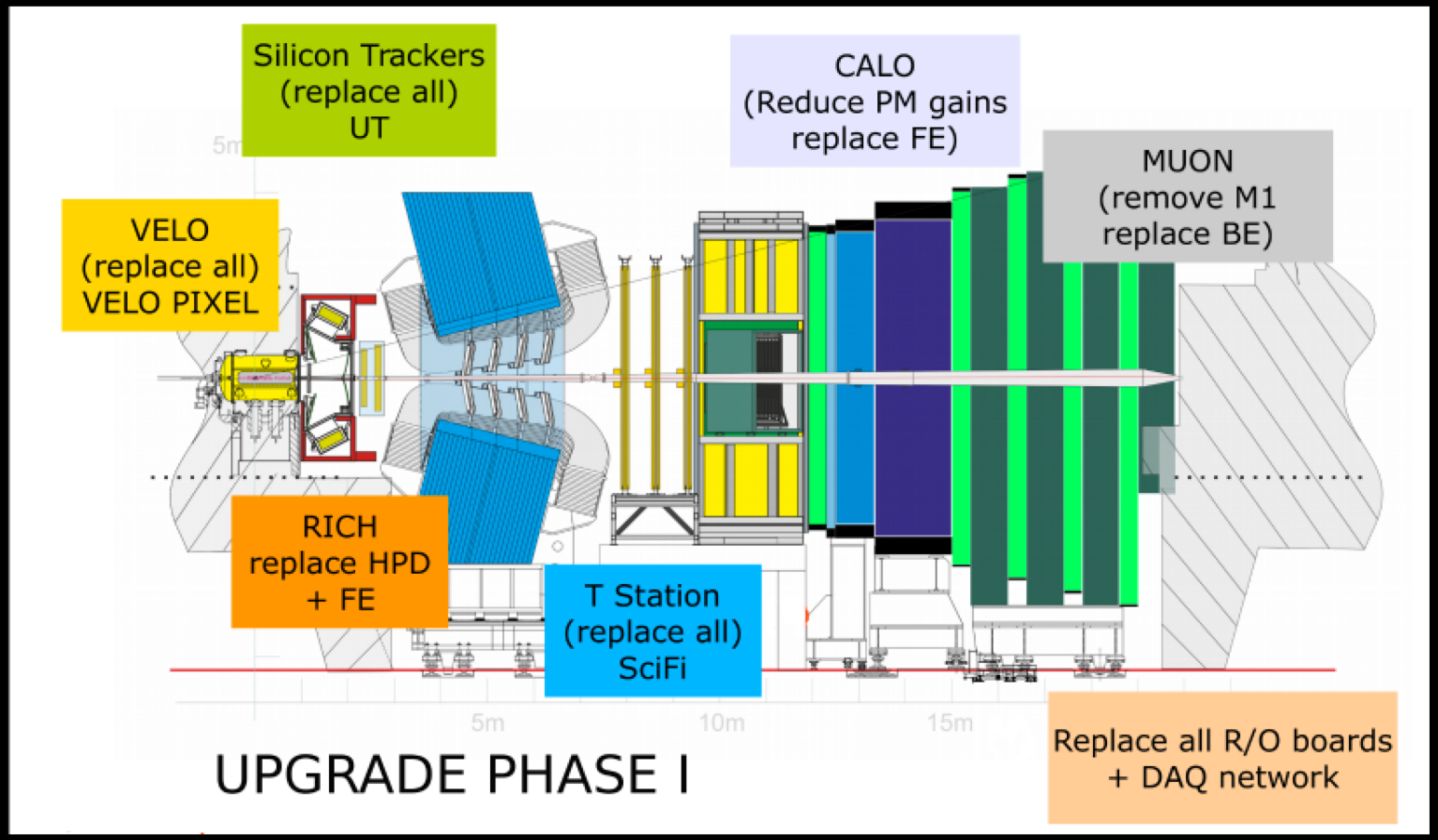
ECal: use upgraded PHENIX PbSc calorimeter

HCal: Iron-scintillator

LHCb upgrades: unique opportunities

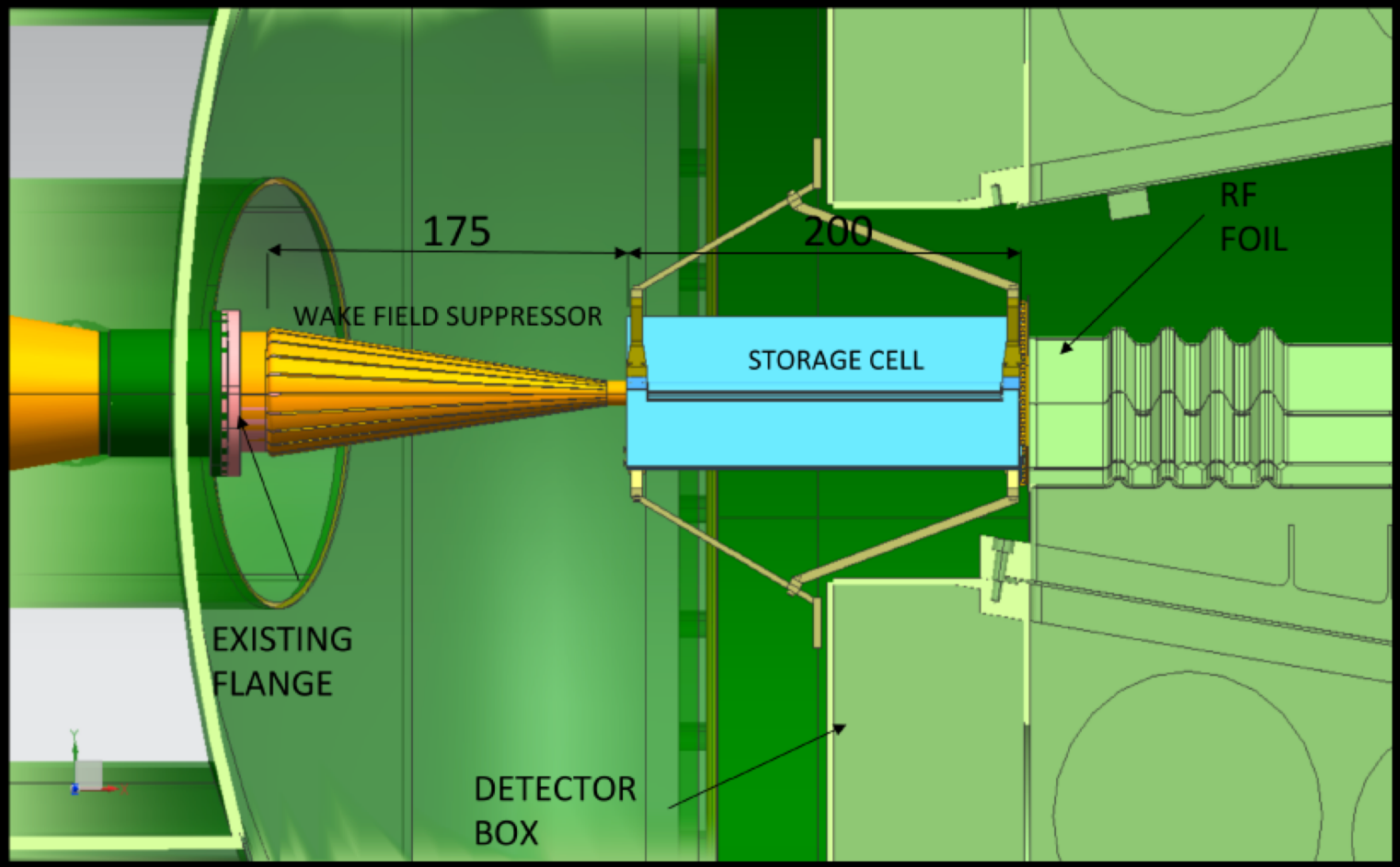
- Phase I: $\rightarrow \approx 5 \times L_{inst}$(Run II)
  extent ion-ion capabilities
  increase pA luminosity for low-x sector
- Phase II in design phase: $\approx 50 \times L_{inst}$(Run II)
  dream detector for heavy-ion physics

LHCb detector upgrades phase I



- replace full tracker for 5 times higher pile-up in *pp*
- inspect 30 MHz rate in software trigger in *pp*
- magnet stations for low-p_{T} tracks & TOF for low momentum PID in consideration for Phase I consilidation or Phase II

LHCb fixed target upgrade phase I: higher luminosity & more targets



- storage cell upstream: allow also for non-noble gas targets
- target with 10-100 $\times$ larger instant. luminosity per unit length

Backup slides

A view into the far Future : FCC

plot from M. Koratzinos, ICNFP2017

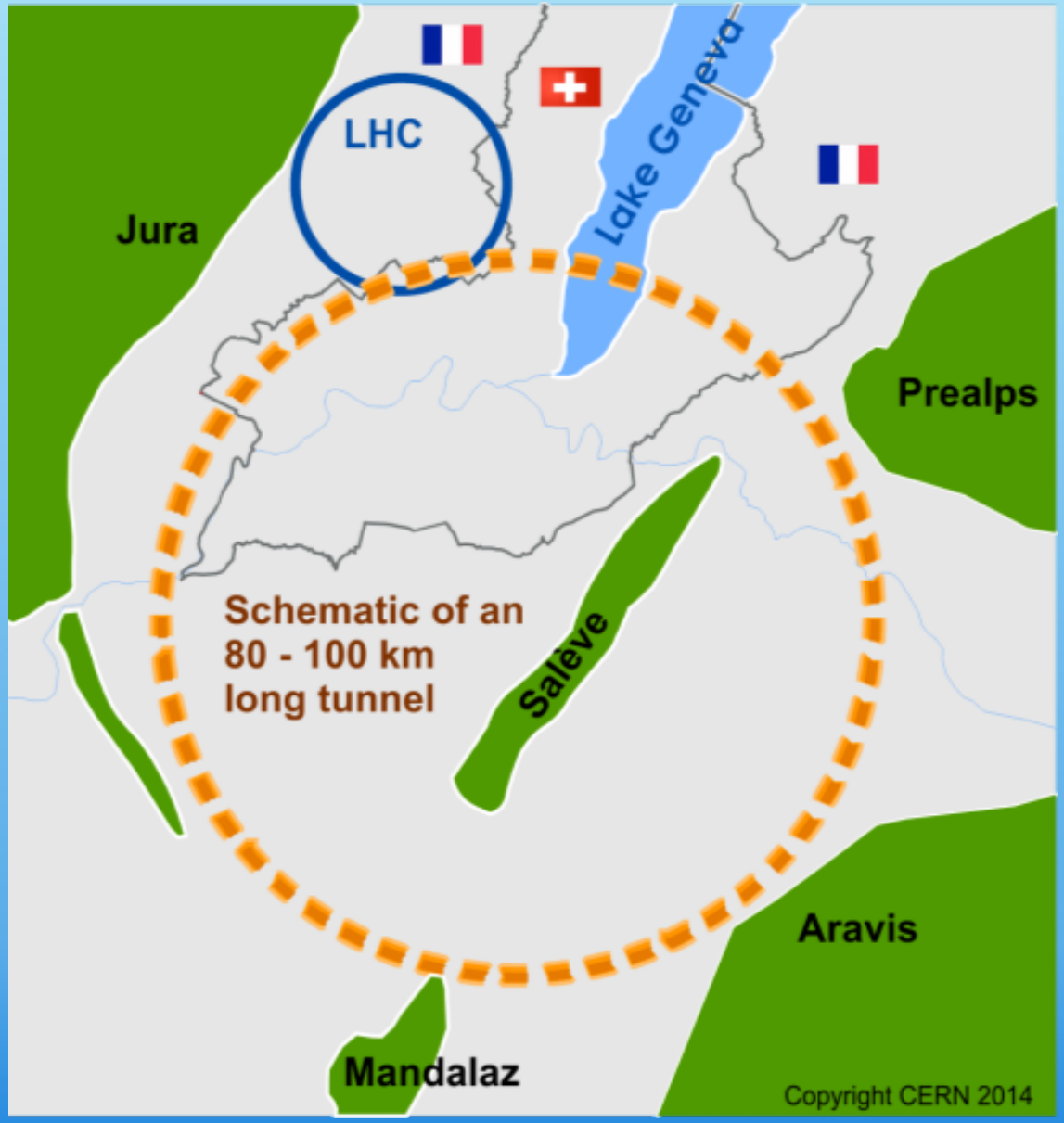
FCC: The Vision

~100 km tunnel, 16 T magnets
sqrt(s)= 100 TeV pp collisions

FCC-hh
FCC-ee
FCC-he

Possible first steps
***FCC-ee, E_CM=90-400 GeV**
******HE-LHC*** **16T 28 TeV**
in LEP/LHC tunnel

FCC-AA : sqrt(s)NN=40 TeV



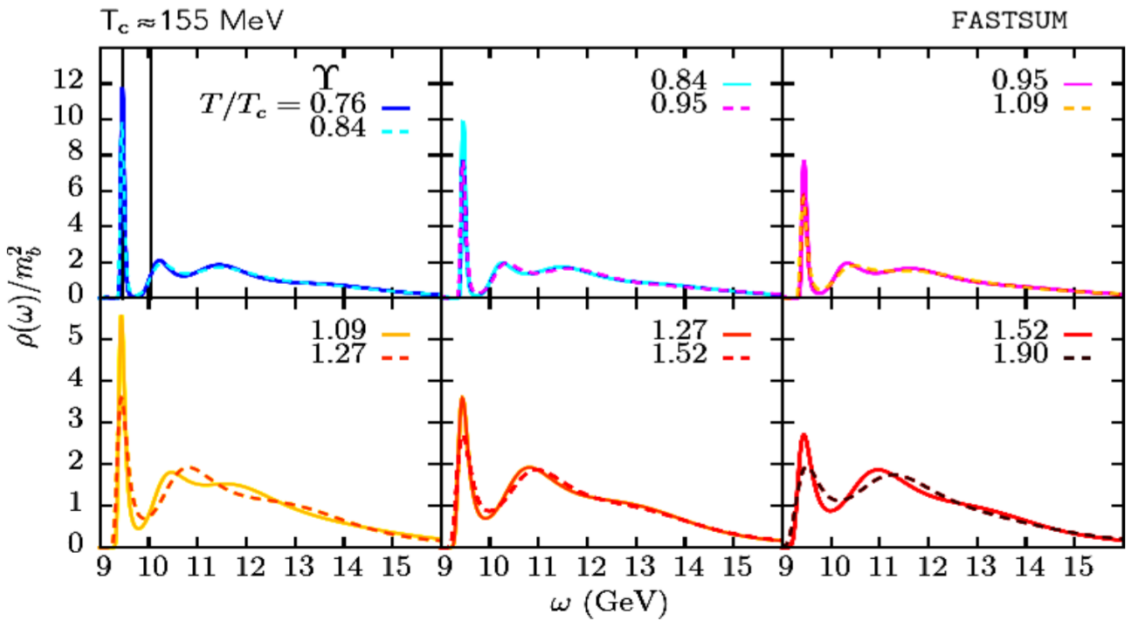
FCC quarkonia

- **p+p at sqrt(s)=100 TeV, Pb+Pb at sqrt(s)=39 TeV**

D. d Enterria, QM2017

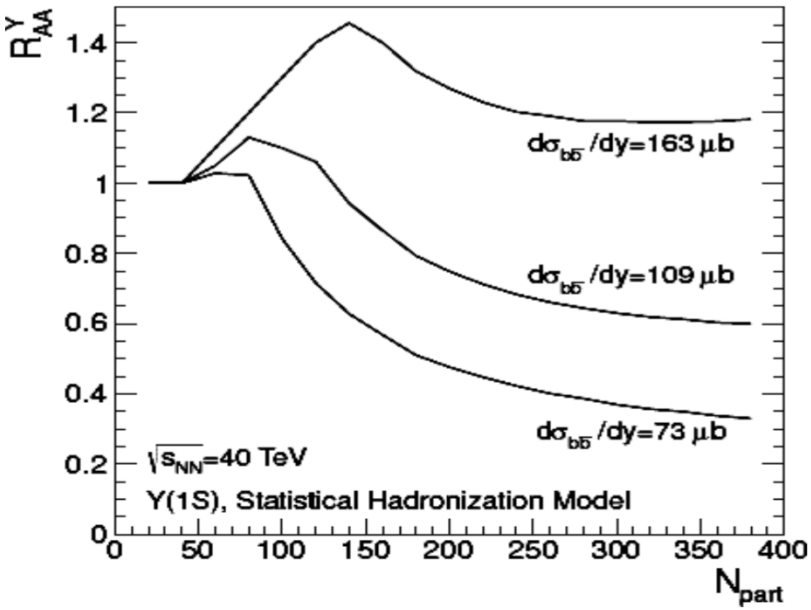
- FCC-AA (T_0~1GeV) can probe Y(1S) "melting" expected by latt-QCD at T=4–5 T_c

[G. Aarts et al, JHEP 07 (2014) 097]



- Density of bbbar pairs large enough for Y(1S) recombination?

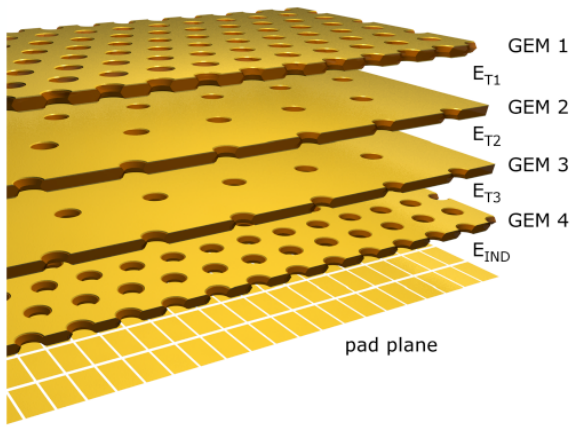
[A.Andronic, et al., JPG38 (2011) 124081]



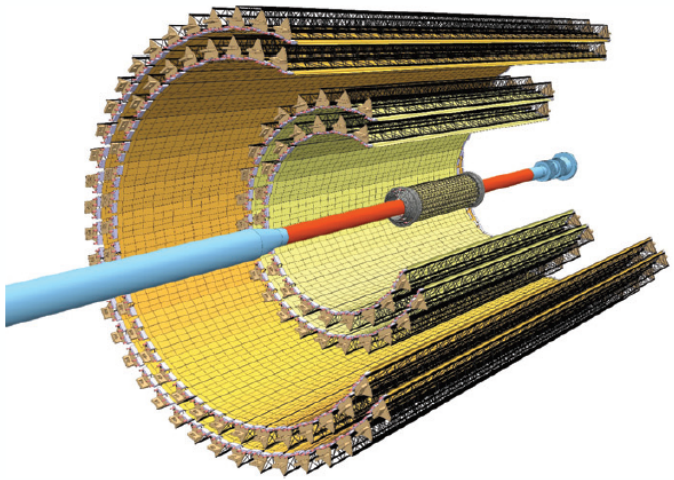
LHC experimental upgrades

ALICE upgrades for run-3

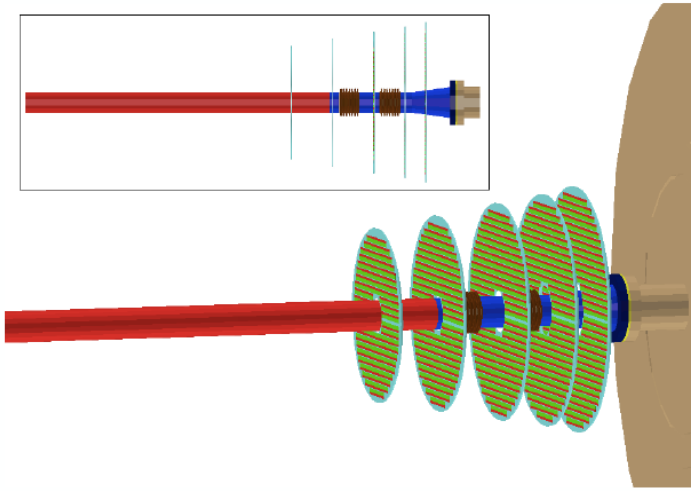
GEM-TPC



ITS



MFT



MFT: will provide secondary vertex reconstruction in forward rapidity
ITS : low pT reach and improved accuracy
High rate

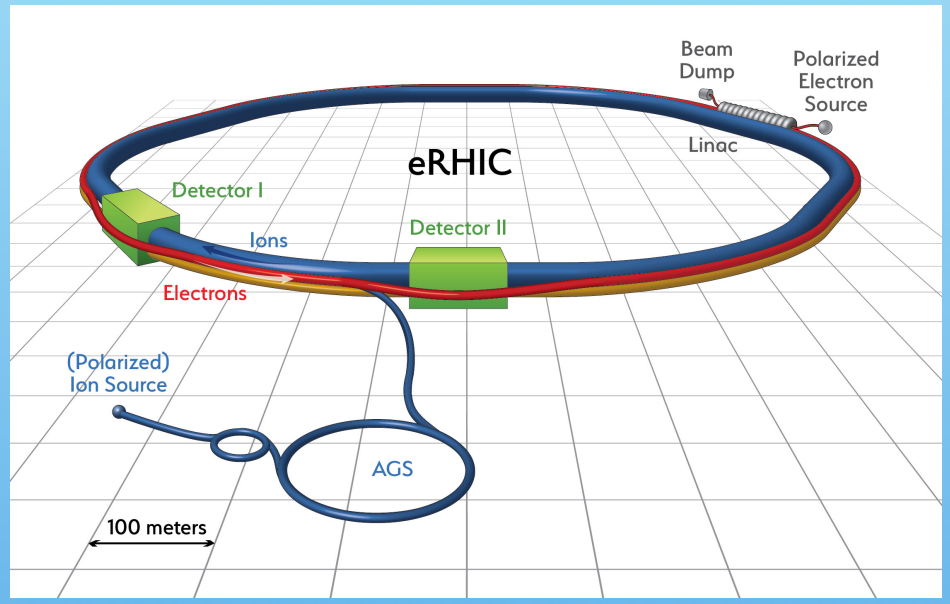
Beam Energy Scan Phase II

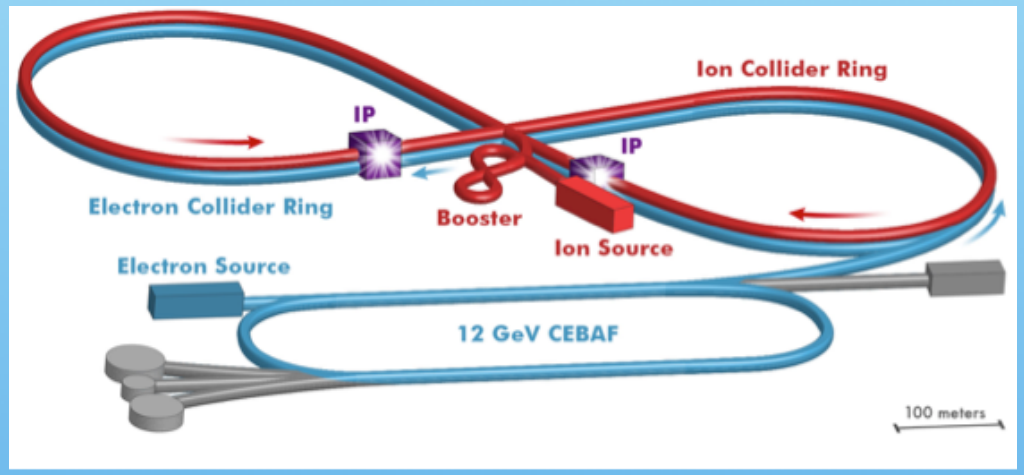
Collision Energies (GeV)	7.7	9.1	11.5	14.5	19.6	*Related to*
Chemical Potential (MeV)	420	370	315	260	205	
Observables	Millions of Events Needed					
R_{cp} up to p_T 5 GeV	N/A	N/A	160	125	92	*Turn-off of QGP signature*
Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400	
Local Parity Violation (CME)	50	50	50	50	50	
Directed Flow studies(v_1)	50	75	100	100	200	*1st order phase transition*
asHBT (proton-proton)	35	40	50	65	80	
Net-proton kurtosis	80	100	120	200	300	*Critical point*
Dileptons	100	160	230	300	400	*Chiral*
Proposed Event Goals	100	160	230	300	400	
BES I Event	4	N/A	12	20	36	

Only part of physics topics in BES II are shown here!

Electron Ion Collider EIC
eRHIC at BNL / JLEIC at JLAB

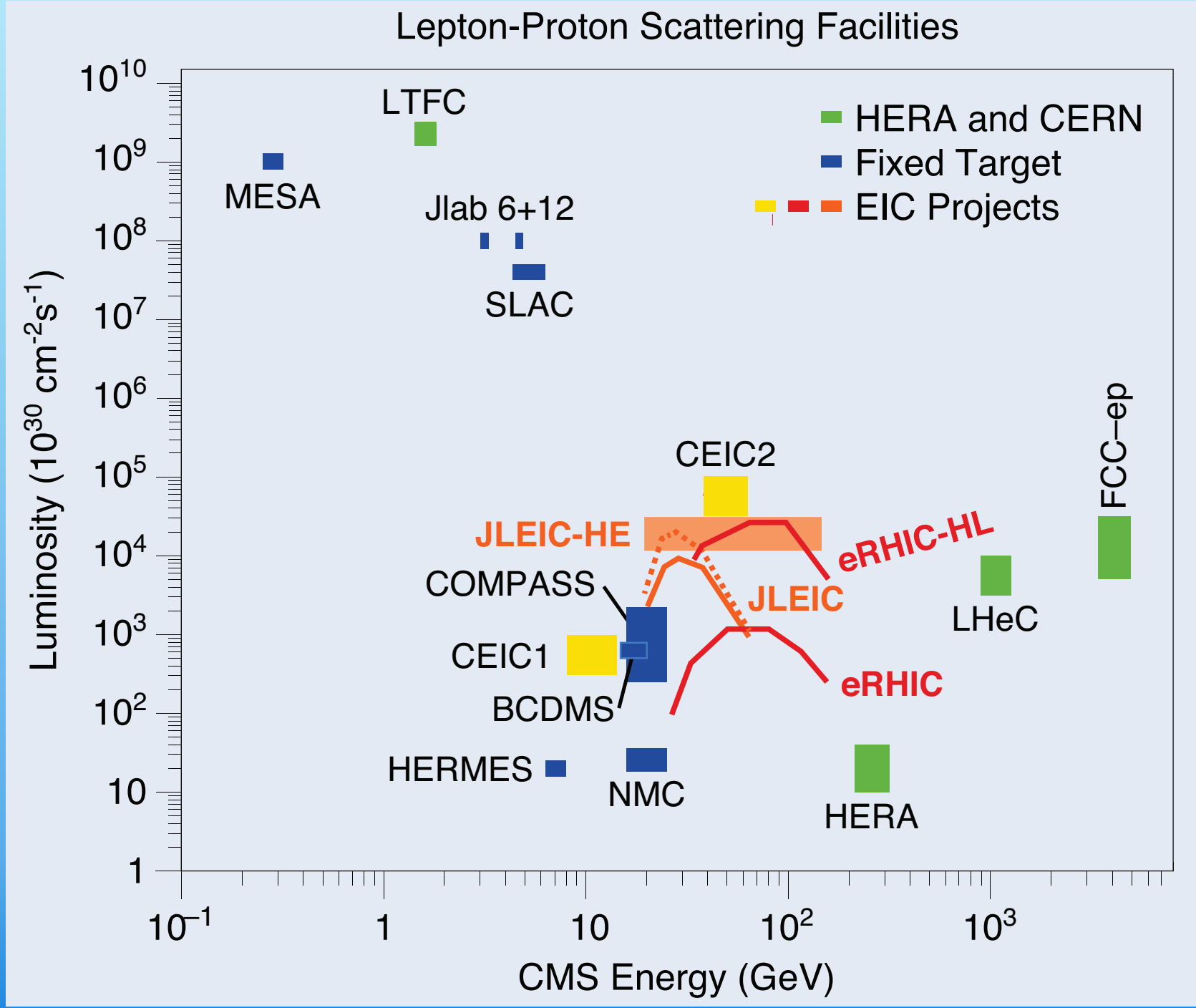
Start of construction estimated: 2022-2023





eRHIC	JLEIC
ep: $\sqrt{s_{max}} = 140$	ep: $\sqrt{s_{max}} = 63$
eAu: $\sqrt{s_{max}} = 90$	eAu: $\sqrt{s_{max}} = 40$
nuclei from deuterium to Uranium	

E. Aschenauer, ICNFP2017



E. Aschenauer, ICNF2017

Example of results II:

EoS of QGP Matter

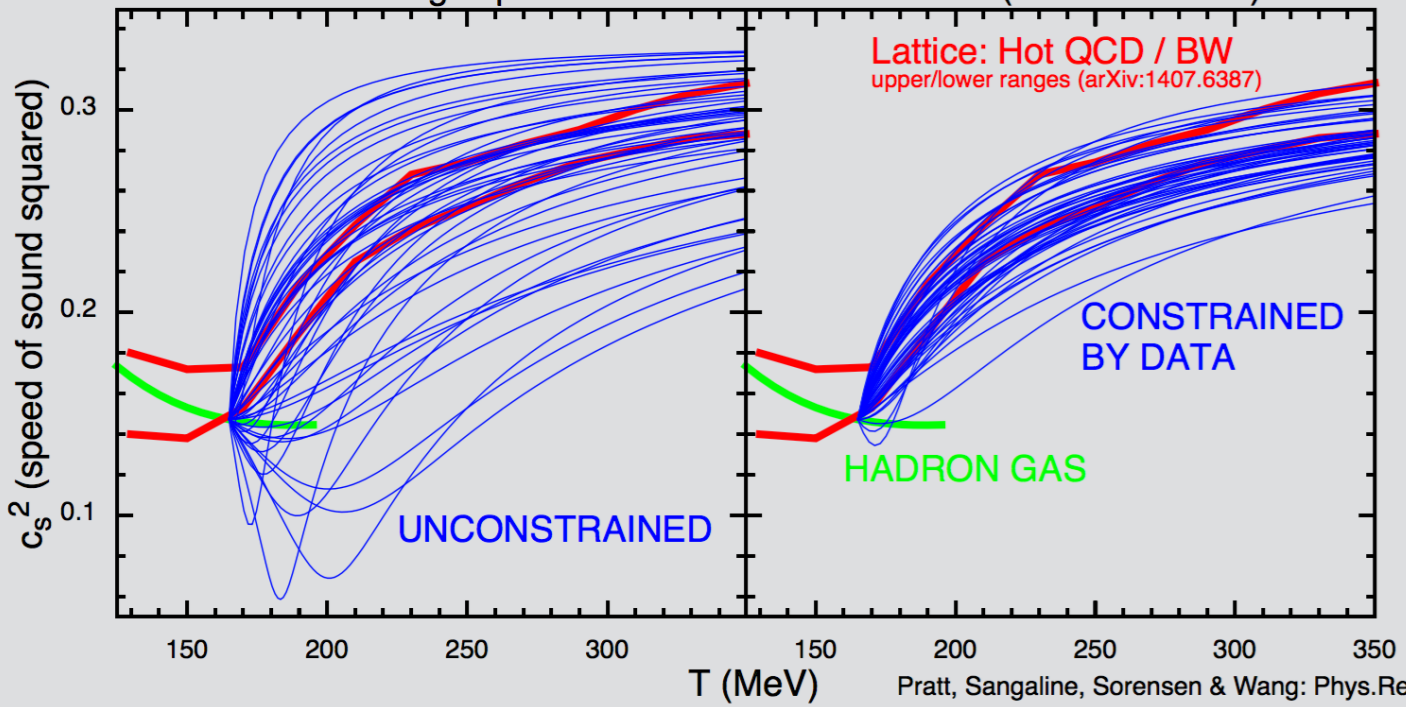
Example: determine the EoS of QGP matter from experimental measurements

what equation of state would the physics model choose to best describe the experimental data?

- create set of QCD Equations of State (aka the *prior*)
- run physics model with each EoS
- use comparison with RHIC/LHC data to determine which Equations of State are consistent with data (i.e. the *posterior*)

▸ **posterior is very similar to Lattice EoS!!**

Constraining Eq. of State with RHIC/LHC Data (MADAI Collab.)



Pratt, Sangaline, Sorensen & Wang: Phys.Rev.Lett. **114** (2015) 202301

1986-2000: Discovery of a new state of matter at CERN

$$\varepsilon_{Bj}(\tau) = \frac{1}{A\tau}\frac{\mathrm{d}E_T(\tau)}{\mathrm{d}y},$$

Evidence:

ccbar suppression

Strangeness enhancement

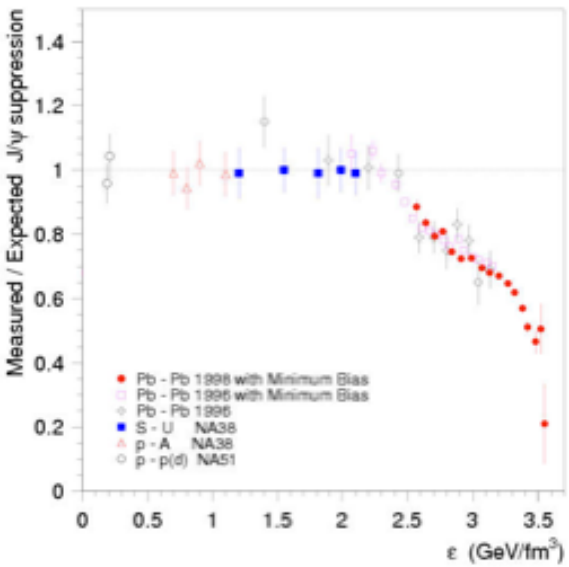
T(chem. freee out) ~ T (critical

Direct gammas consistent with T > Tcritical

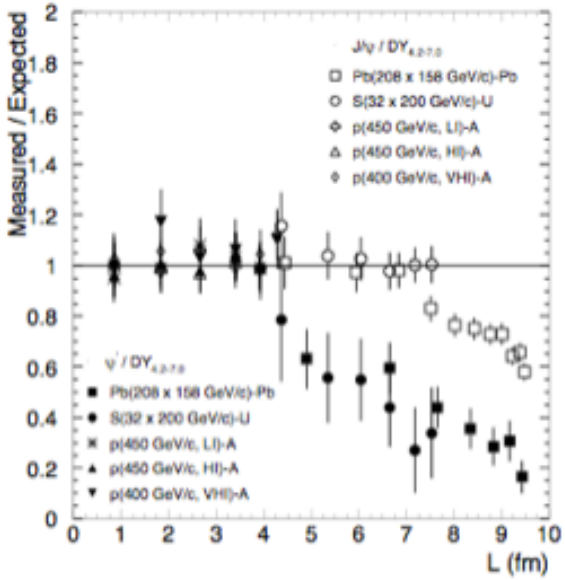
and other results

Sequential Psi prime and J/Psi suppression has been observed at CERN SPS Pb+Pb 158 A GeV

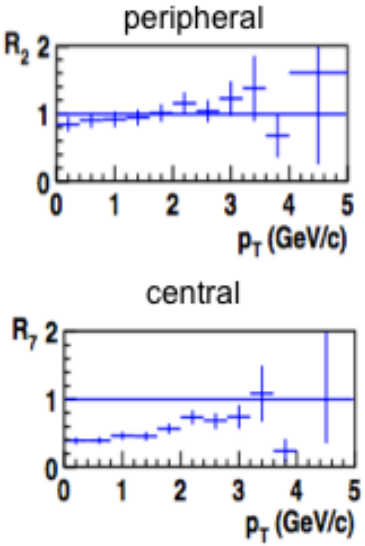
NA50, Phys Lett B 477 (2000) 28



Eur Phys J C 49 (2007) 559



J/Psi/DY n-bin/1st bin

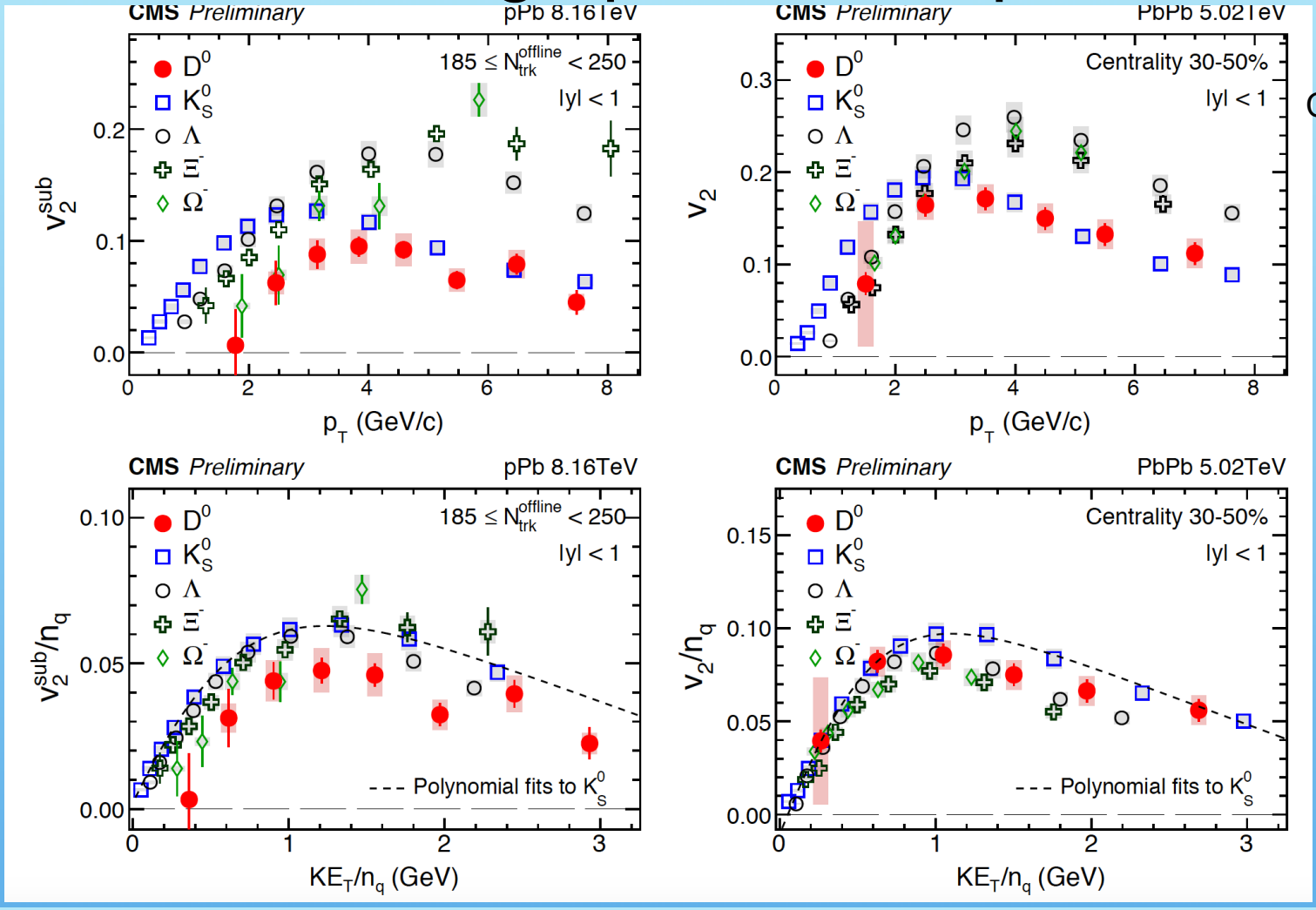


A Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004

* **Psi prime is suppressed from 1.23 GeV/fm^3 on**
* **J/Psi is suppressed from ~2.4 GeV/fm^3 on**
* **J/Psi supression occurs mainly at low pT**

CERN press release 2000

CMS D0 and strange particles in pPb, PbPb

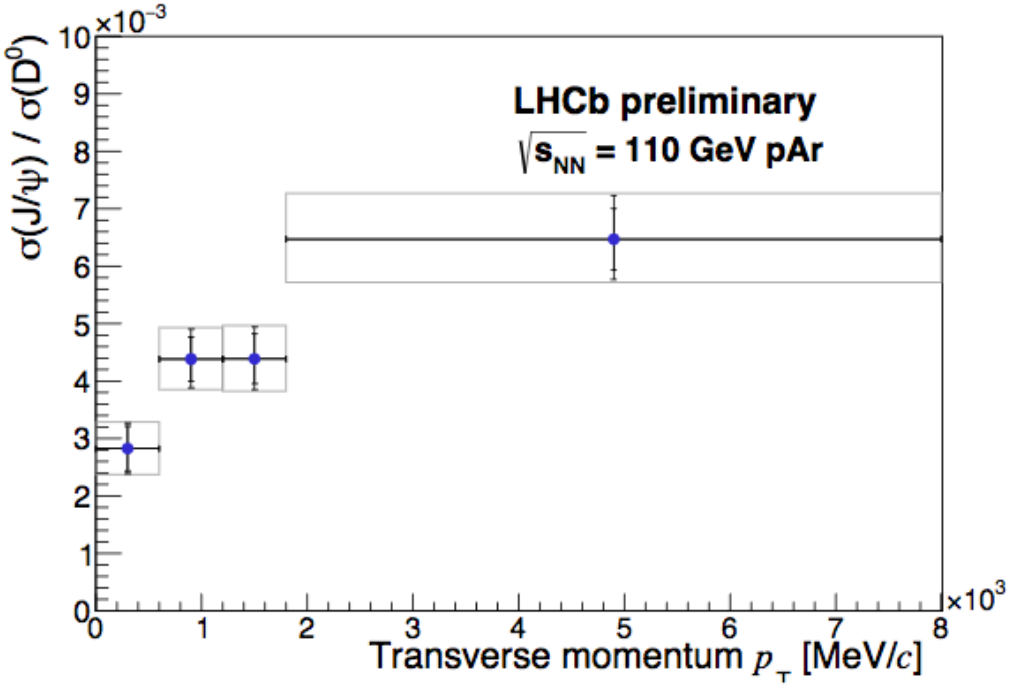


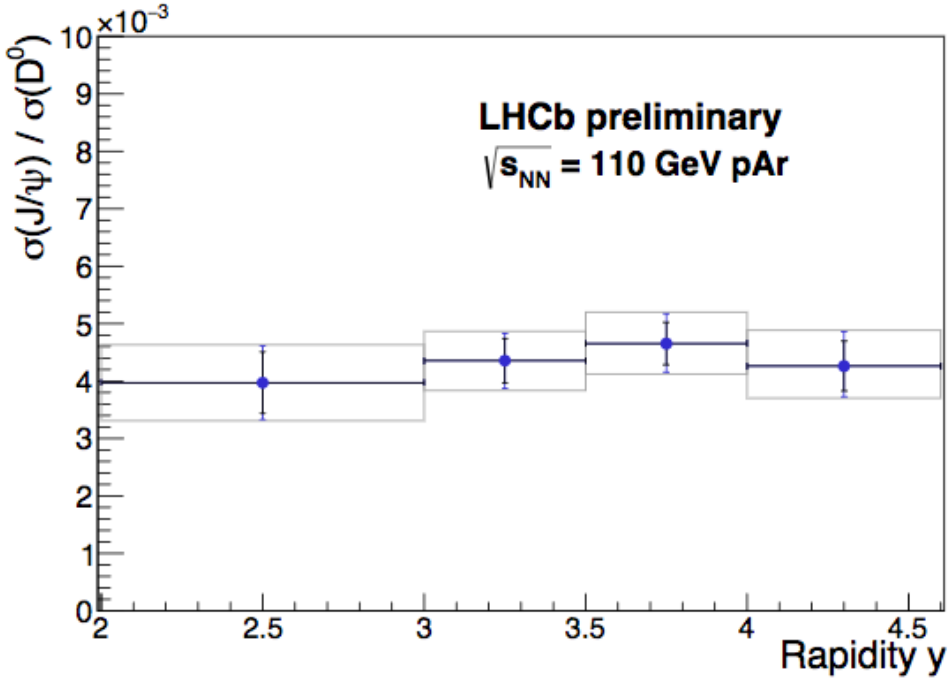
CMS 1705.01974

pPb at high mult: v2/nq of strange particles tend to lie on a universal curve below 1.5 GeV, while D0 fall below indicating weaker collective behaviour for charm quarks

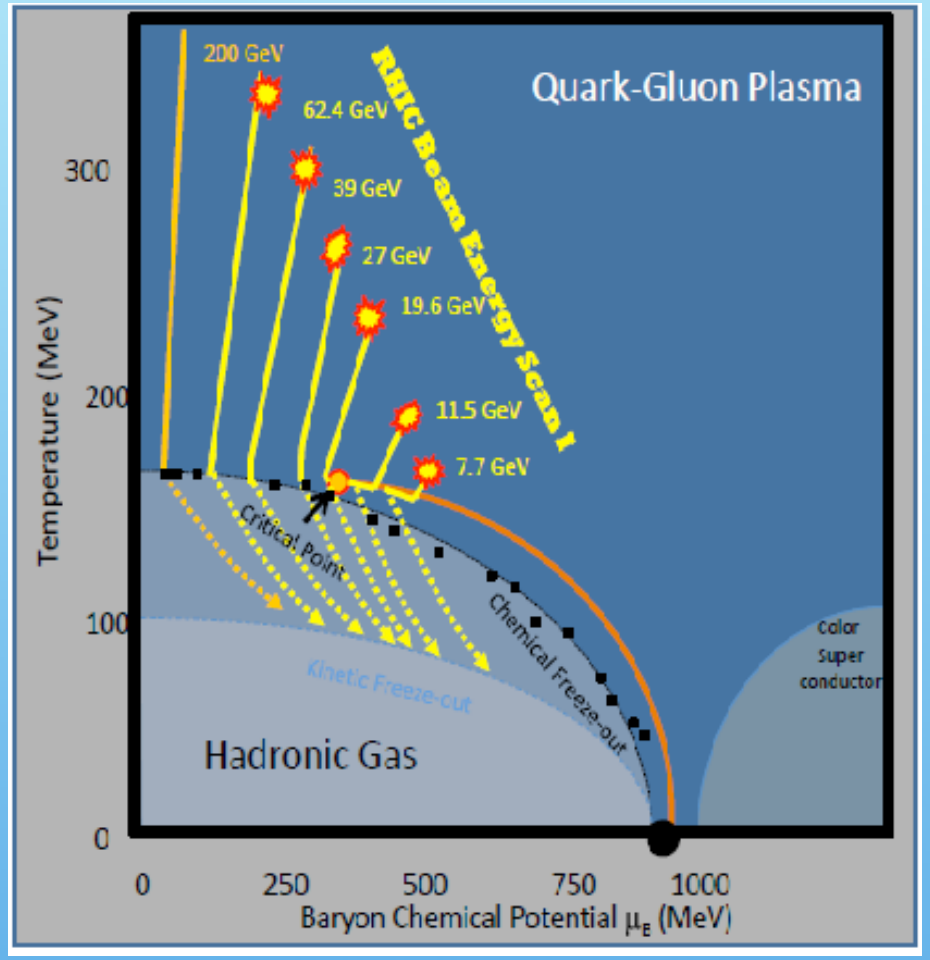
PbPb semiperiph.: v2/nq of strange particles and D0tend to lie on a universal curve below 1.0 GeV, indicating strong collective behaviour of D0 similar to the bulk of QGP medium

LHCb p+Ar at sqrt(s)=110 GeV fixecd taget mode SMOG





The expected QCD phase diagram



Phases of QCD Matter

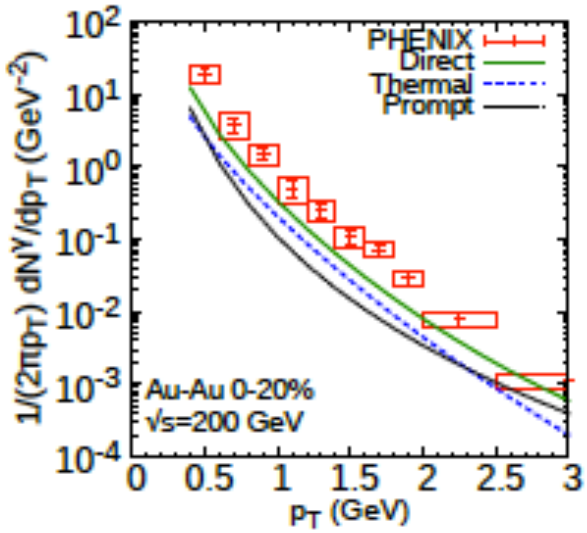
Areas of different net baryon densities and temperatures can be probed using different collision energies and nuclei.

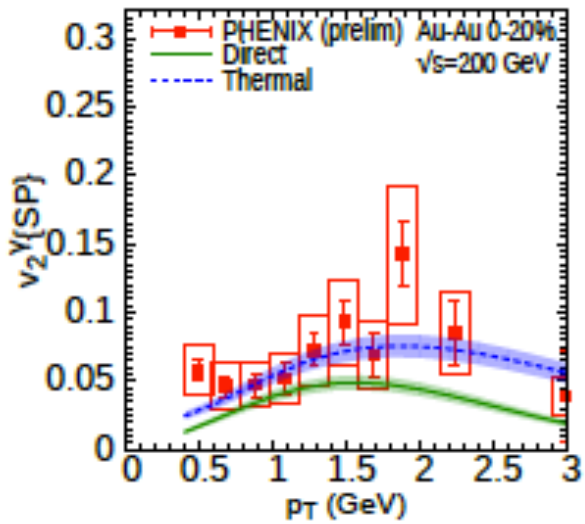
The order of the transition is expected to change with the net baryon density.

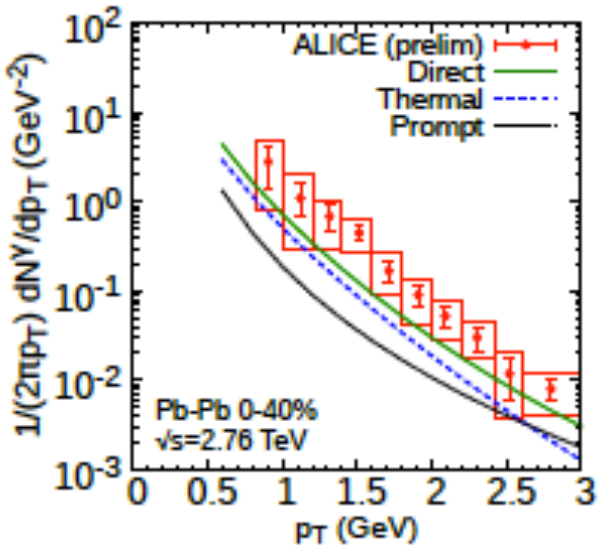
Goal: explore experimentally the QCD phase diagram (order of transition, critical point, properties of the QGP).

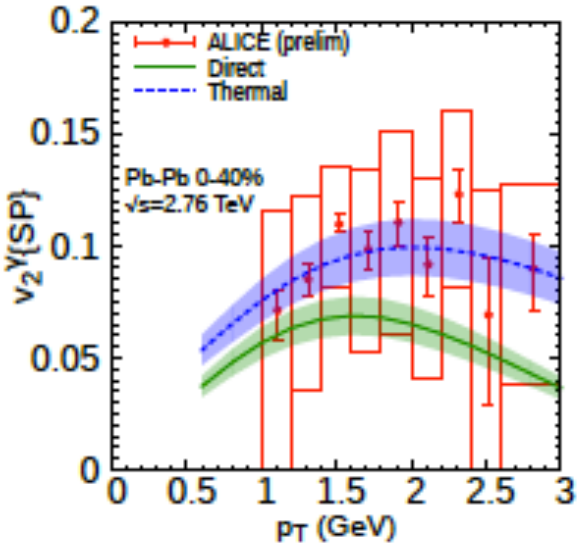
Direct photons flow too

J. F. Paquet et al,1509.06738









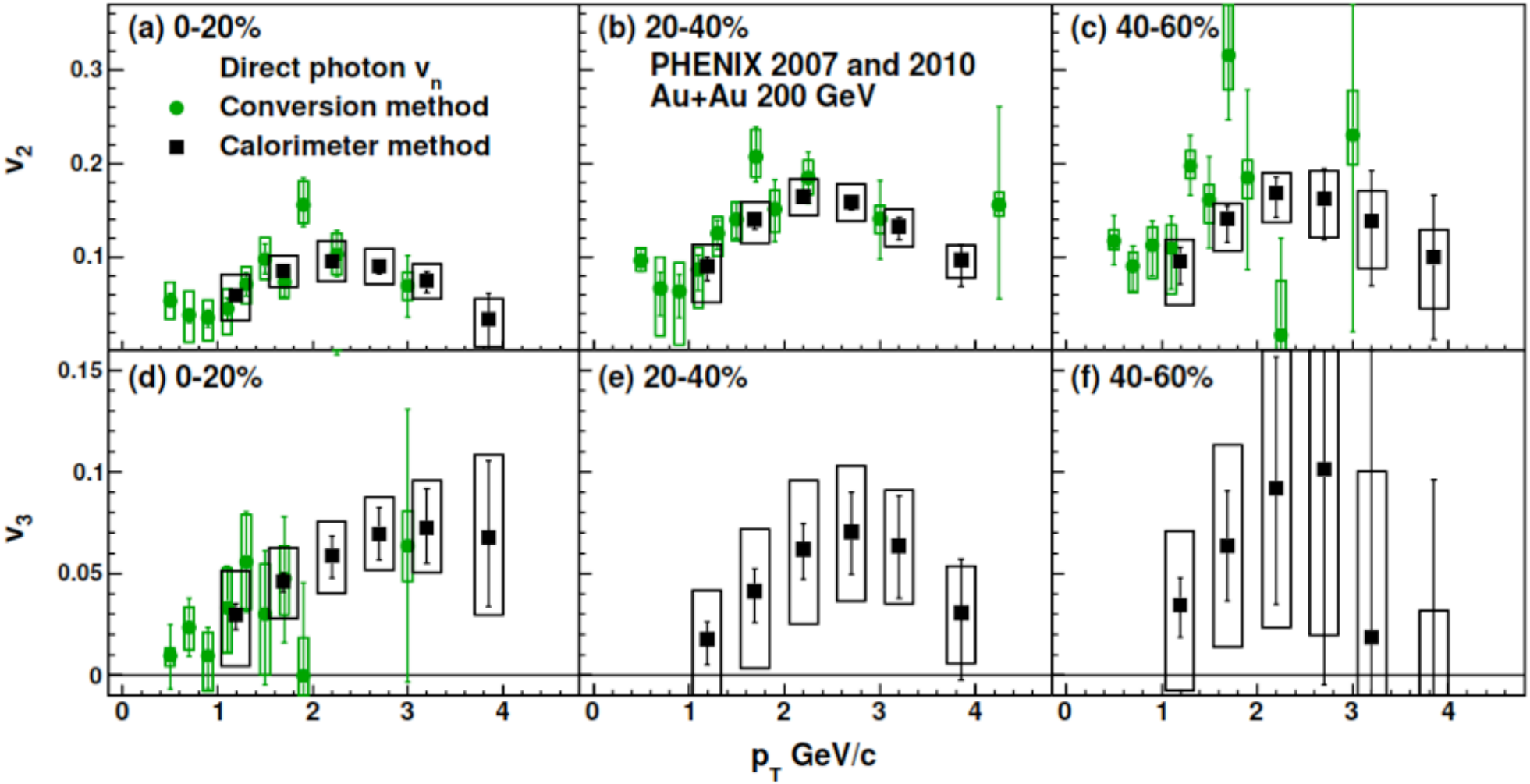
Difficult for models to describe both cross section and v2 flow of direct photons

Hydrodynamic model describes approx. the v2 data at RHIC and LHC.

Suggests that excess of direct photons is due to thermal photons

PHENIX, arXiv:1509.07758

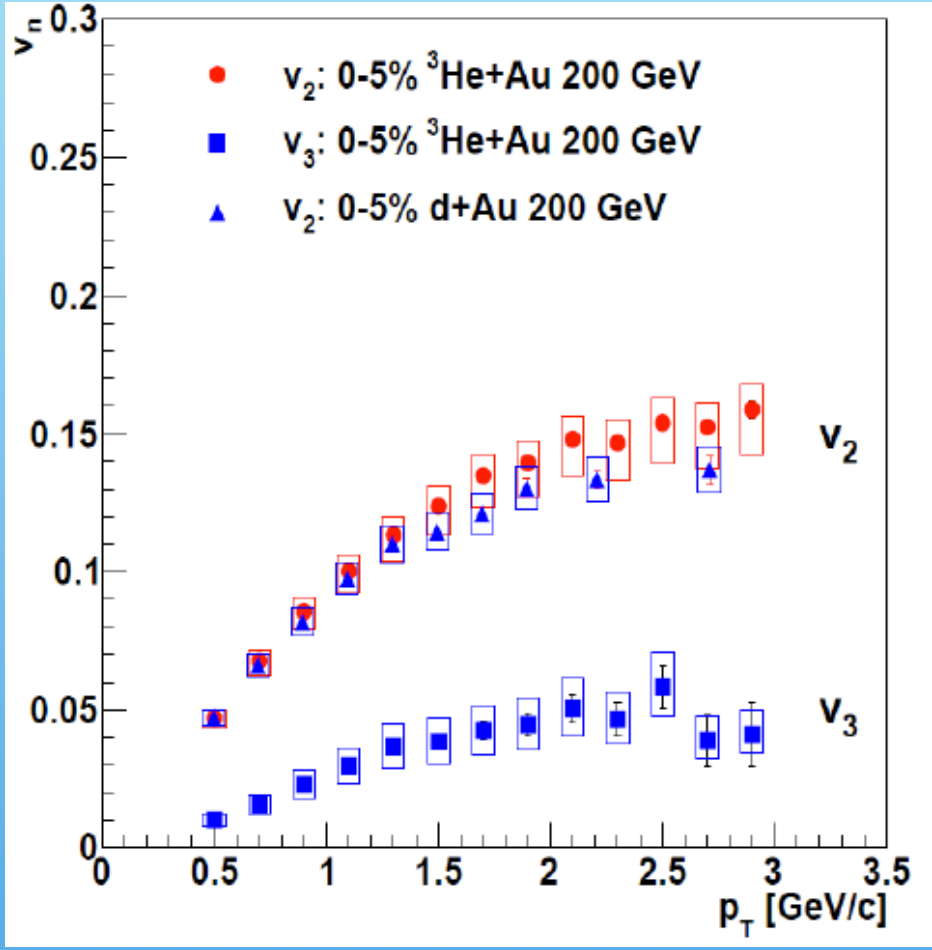
Anisotropic emission of direct photons

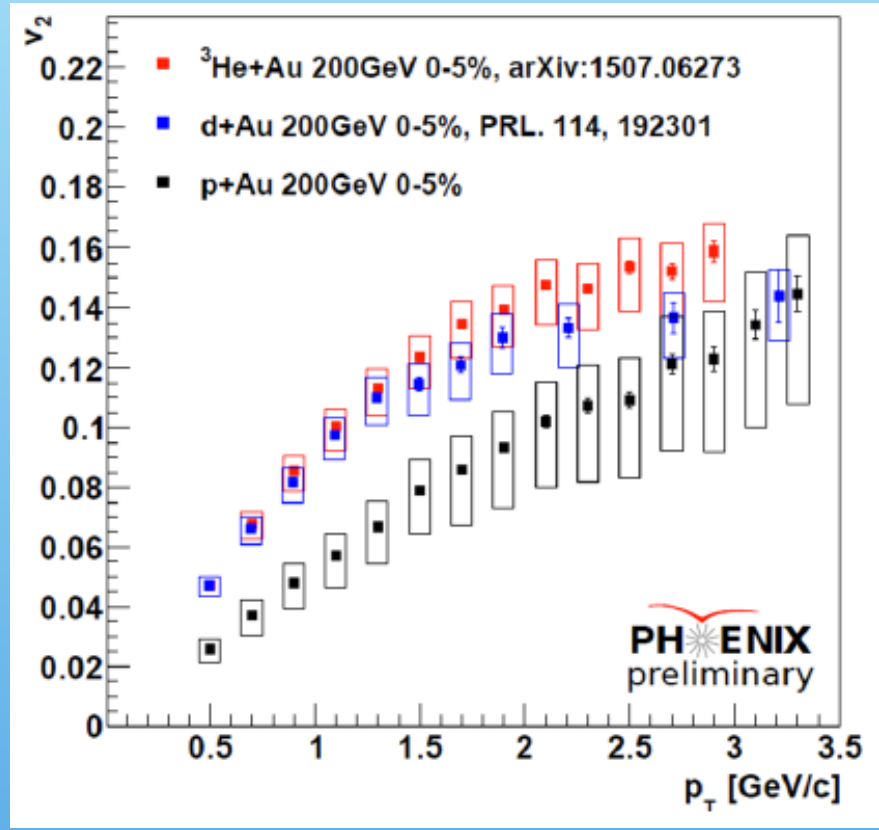


Large v_2 and v_3 of direct photons in Au+Au at 200 GeV studied vs pT and centrality

RHIC: results from 2015 p+Au run and results from 2014 3He+Au at 200 GeV

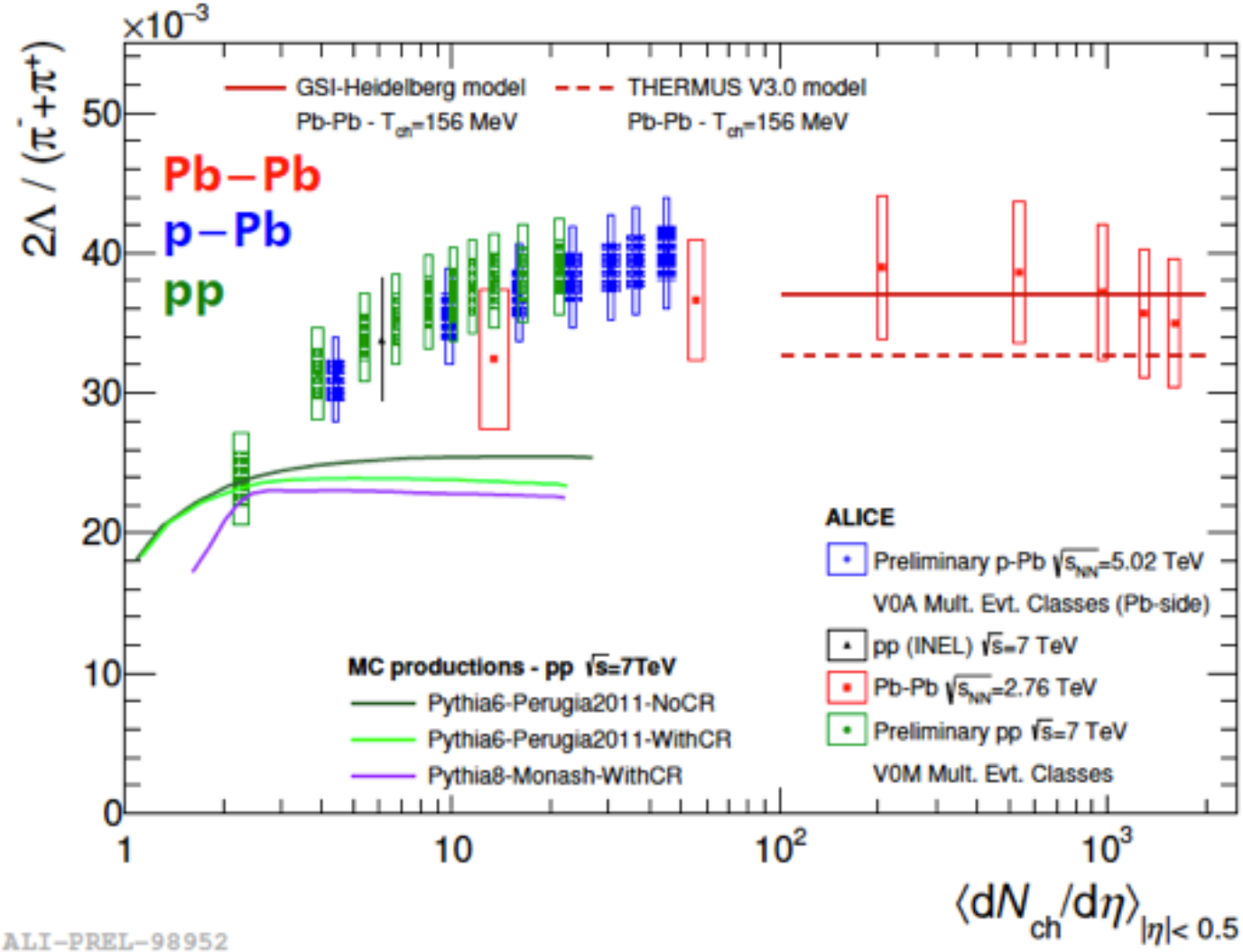
PHENIX ₃HeAu: Phys. Rev. Lett. 115, 142301 (2015)
PHENIX dAu: Phys. Rev. Lett. 114, 192301 (2015)





Large v2, v3 components in 0-5% 3He+Au, d+Au and p+Au from 2015 run

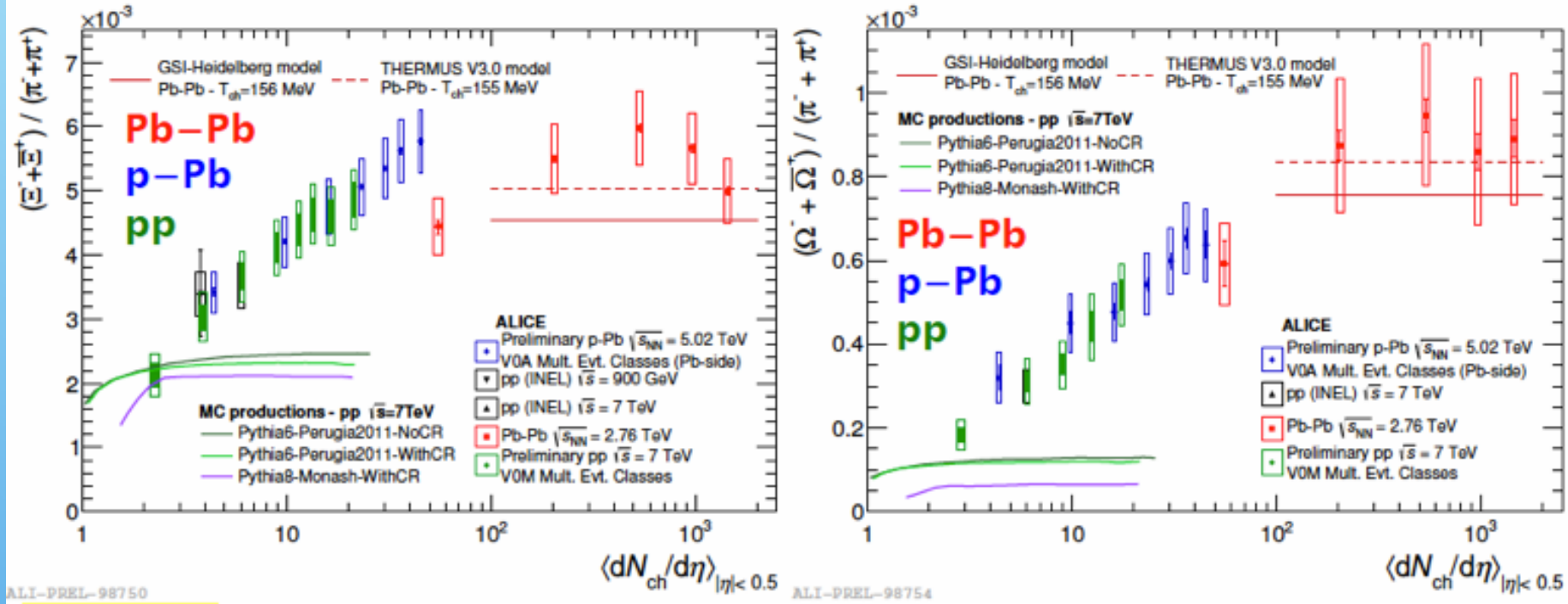
Λ/π vs. $dN_{ch}/d\eta$



L. Bianchi
QM2015

- Λ/π ratio reaches Grand Canonical limit in Pb–Pb
- Similar multiplicity dependence in pp and p–Pb
  - ✓ Neither PYTHIA6 nor 8 reproduce data in any of the tunes tested

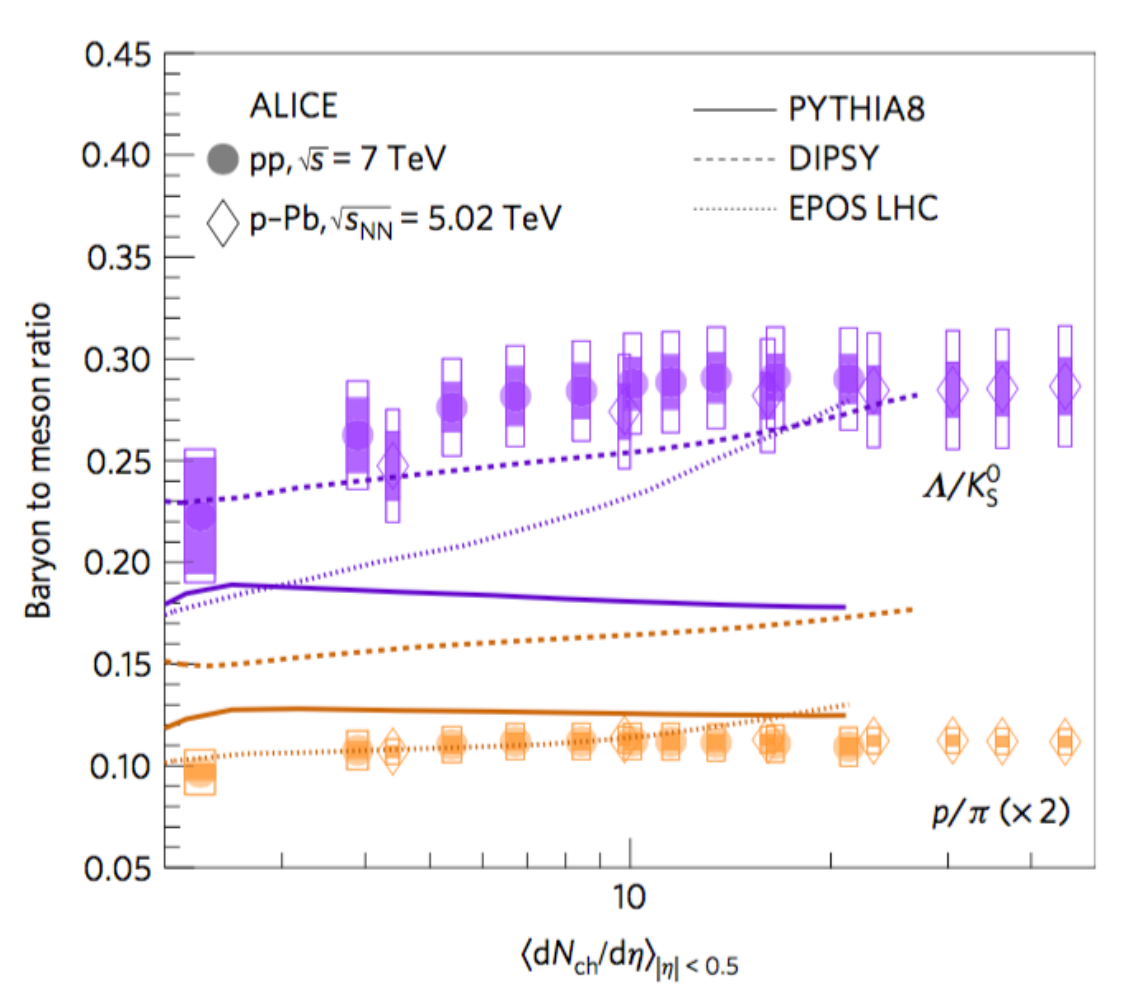
Ξ/π and Ω/π vs. $dN_{ch}/d\eta$



L. Bianchi
QM2015

- Ξ/π and Ω/π reach Grand Canonical limit in Pb–Pb
- Similar multiplicity dependence in pp and p–Pb
  - ✓ Neither PYTHIA6 nor 8 reproduce data in any of the tunes tested

ALICE

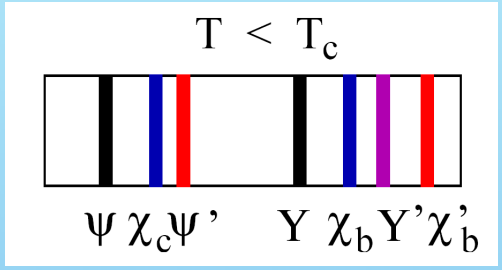


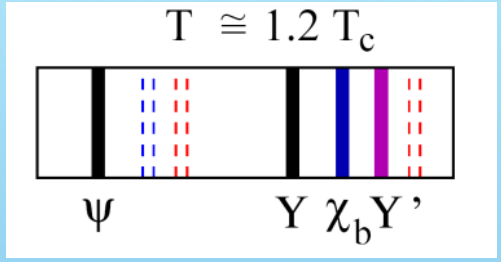
The ratios L/K0s and p/pi do not change significanctly with the charged multiplicity demonstrating that the observed enhancement of strange hadrons over pions is not due to the different hadron masses

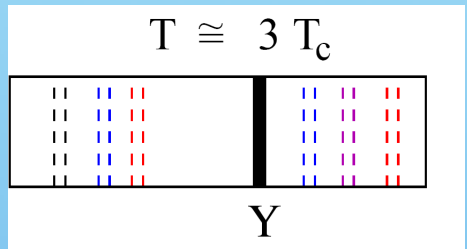
The models cannot reproduce simoultaneously the observation of strangeness enhancement over pions as a function of multiplicity and the constant p/pi ratio ve multiplicity.

DIPSY: model that describes data best includes color ropes that cause enhanced production of strange particles and baryons

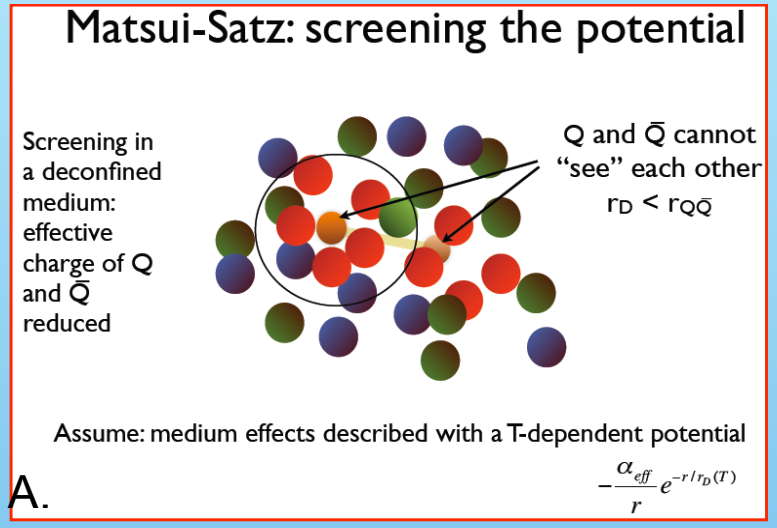
Quarkonia





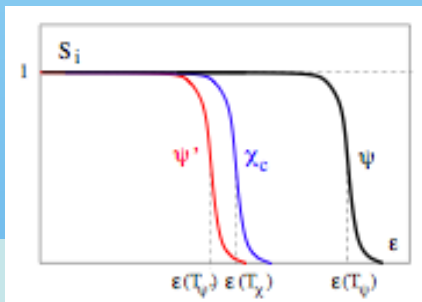


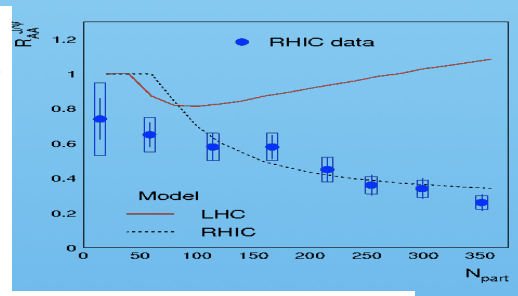
H. Satz, Nucl. Phys. A (783): 249-260(2007)

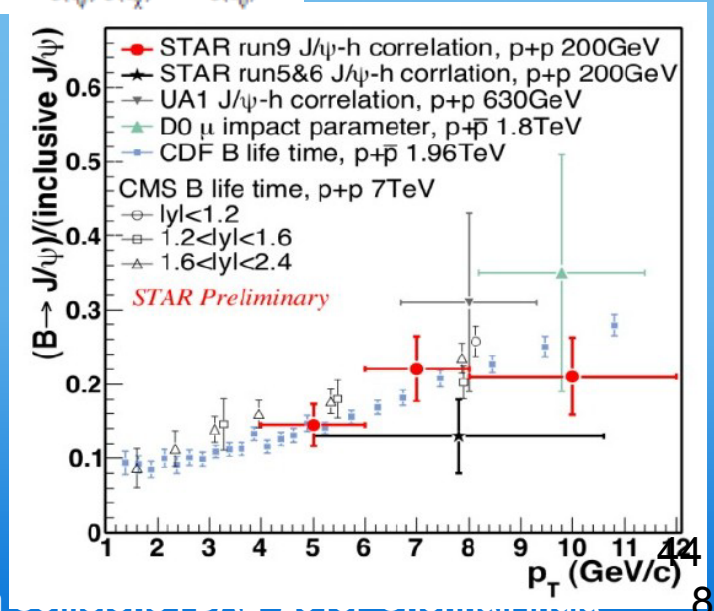


A.

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17







Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

Many effects play a role like dissociation in QGP, cold matter absorption, recombination/ coalescence from c, cbar, feeding, eg B mesons carry 10-25% of charmonia yields (B->J/Psi from J/Psi-h correlation STAR measurement)

Other models: B. Kopeliovich et al, D. Kharzeev, E. Ferreiro, A. Capella, A. Kaidalov et al etc.

Multi-parameter estimates from a variety of data

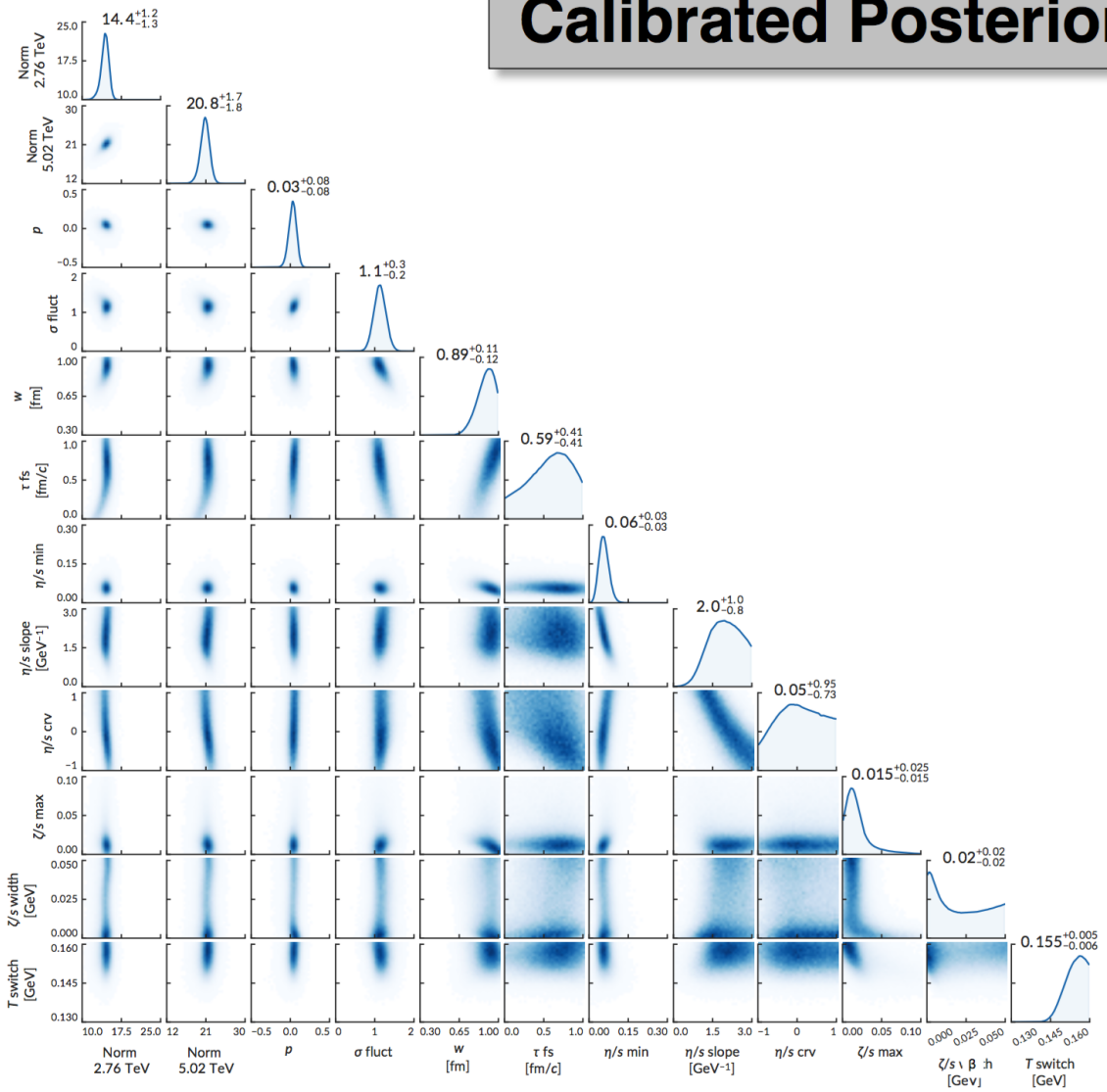
Multiple parameter estimation

Important progress in estimating properties of QGP using statistical analysis methods and a multi-parameter model-to-data comparison, with many different data (flow, spectra, etc)

S Bass et al Phys.Rev. C94 (2016) no.2, 024907, and others

Review: S. Bass, QM2017,

Calibrated Posterior Distribution



- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

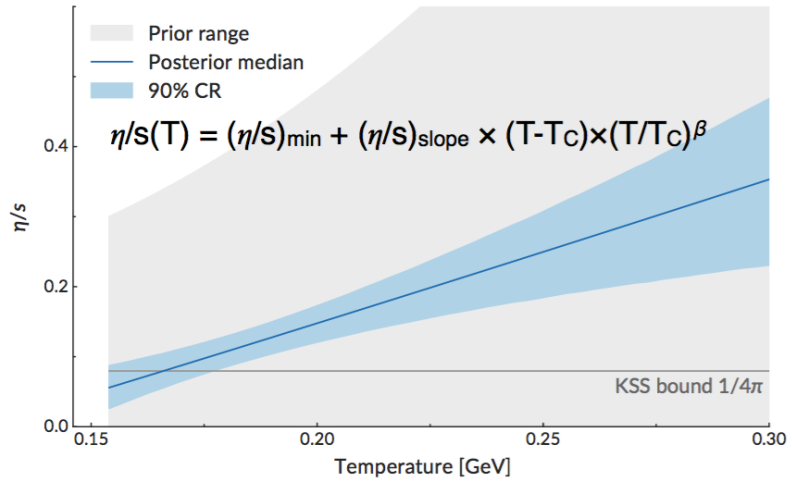
Example of results I: Review: S. Bass, QM2017,

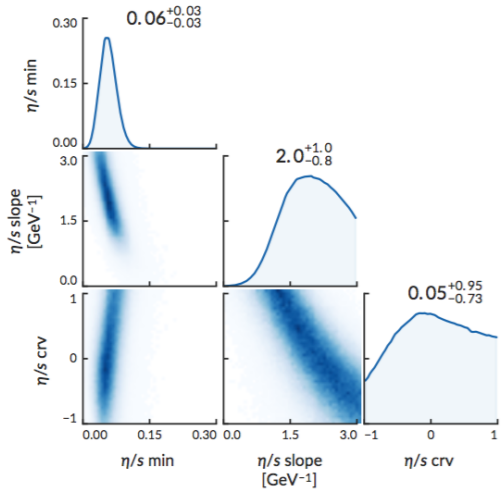
Temperature Dependence of Shear & Bulk Viscosities

temperature dependent shear viscosity:

- analysis favors small value and shallow rise
- results do not fully constrain temperature dependence:
  - inverse correlation between $(\eta/s)_{slope}$ slope and intercept $(\eta/s)_{min}$
  - insufficient data to obtain sharply peaked likelihood distributions for $(\eta/s)_{slope}$ and curvature β independently
- current analysis most sensitive to T< 0.23 GeV

▸ **RHIC data may disambiguate further**



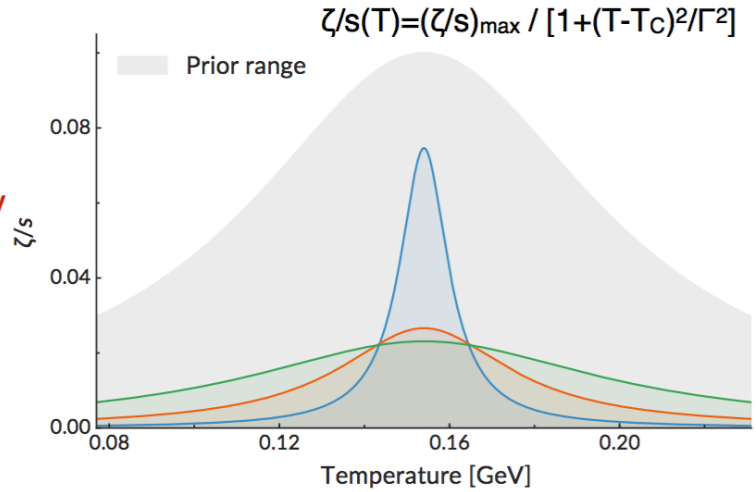


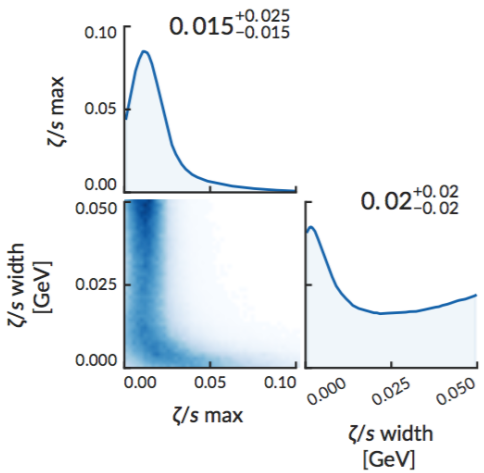
temperature dependent bulk viscosity:

- setup of analysis allows for vanishing value of bulk viscosity
- significant non-zero value at T_C favored, confirming the presence / need for bulk viscosity
- either high sharp peak or broad & shallow temperature dependence

caveat of current analysis:

- bulk-viscous corrections are implemented using relaxation-time approximation & regulated to prevent negative particle densities





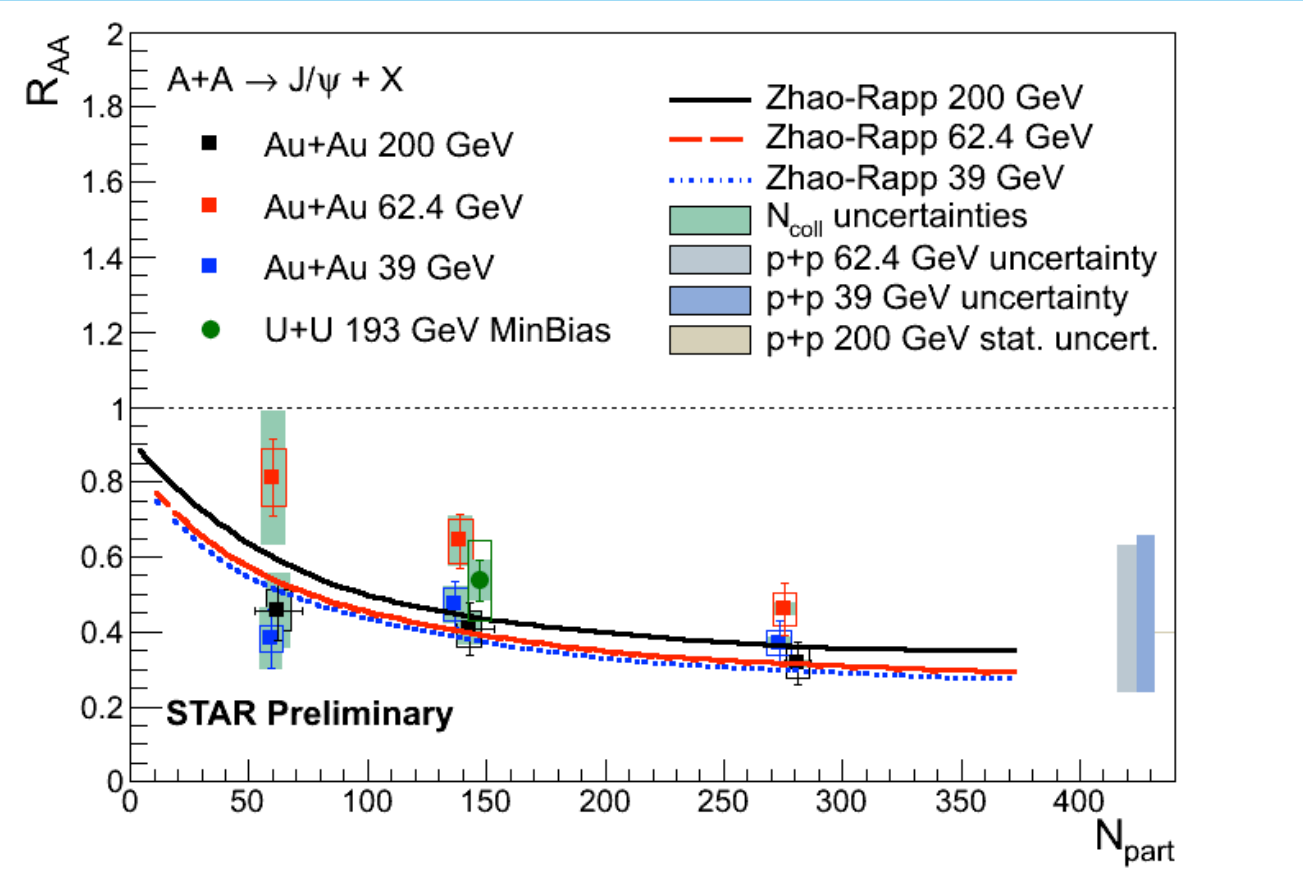
Needed developments

Review: S. Bass, QM2017,

current analysis focus was on the properties of bulk QCD matter and utilized only LHC data on soft hadrons. The analysis needs to be extended to:

- **include data from lower beam energies**
  - necessary for determination of the temperature and μ_B dependence of transport coefficients
- **include asymmetric collision systems (p+A, d+A, 3He+A, A+B)**
  - generate improved understanding of the initial state
- **include hard probes (jets and heavy quark observables)**
  - consistent determination of jet and heavy flavor transport coefficients
- **include other physics models**
  - analysis is model agnostic, allows for quantitative comparison among different models and verification/falsification of models/conceptual approaches

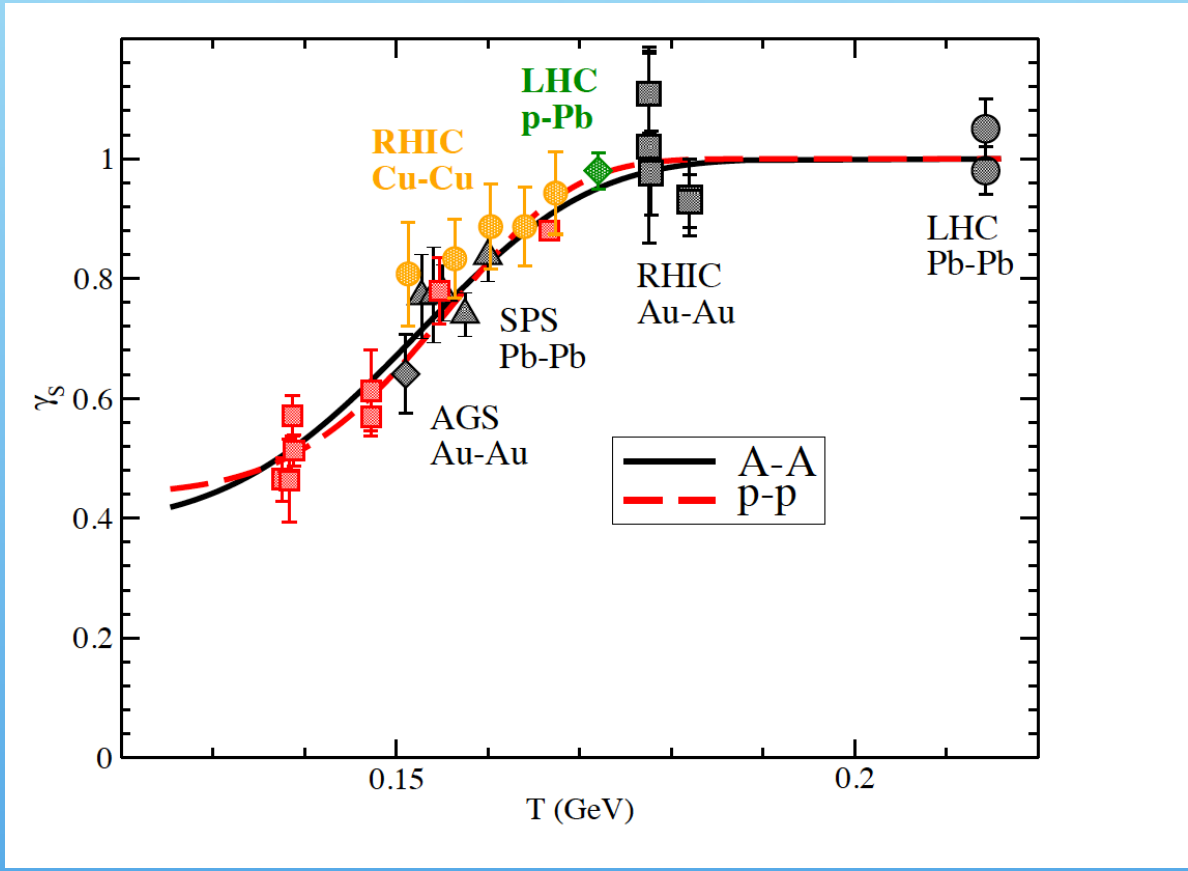
RHIC Beam Energy Scan:
At which energy does J/Psi suppression turn off?



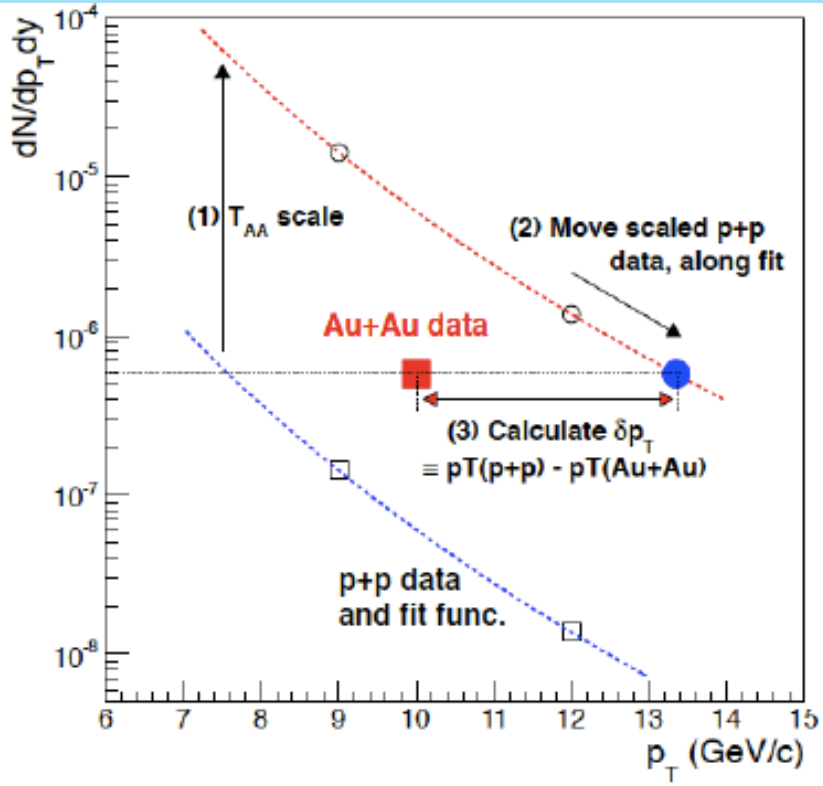
Color Evaporation Model (CEM) estimate for p+p reference used for 39, 62 GeV
R_{AA} in U+U 193 GeV is consistent within errors with Au+Au 200 GeV
R_{AA} of J/Psi is suppressed in similar way at 39, 62 and 200 GeV

Strangeness suppression near Tc

P. Castorina, S Plumari, H Satz, 1709.02706

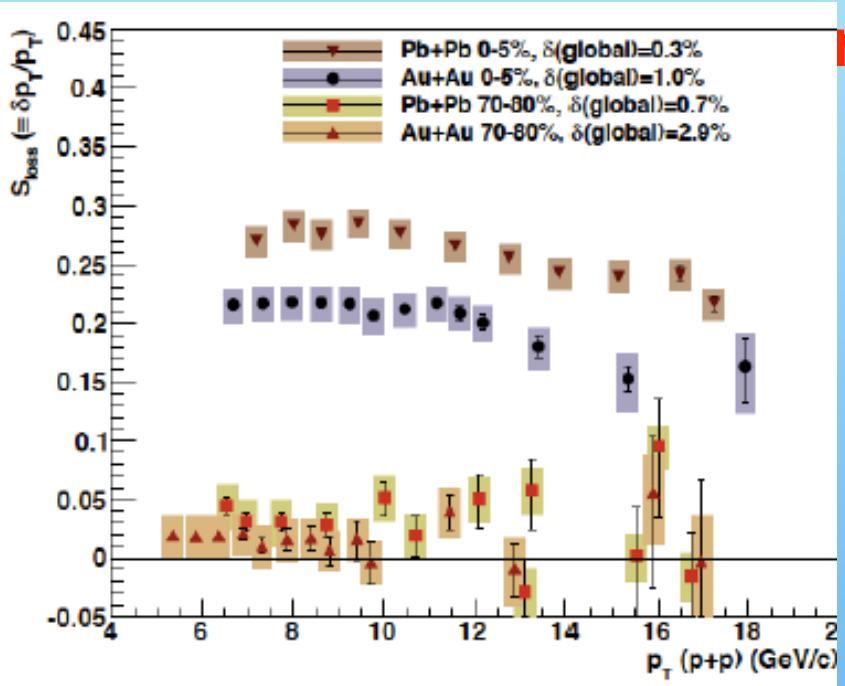


Gamma_s becomes 1 near T_c



Measure fractional momentum loss instead of RAA

arXiv 1208.2254



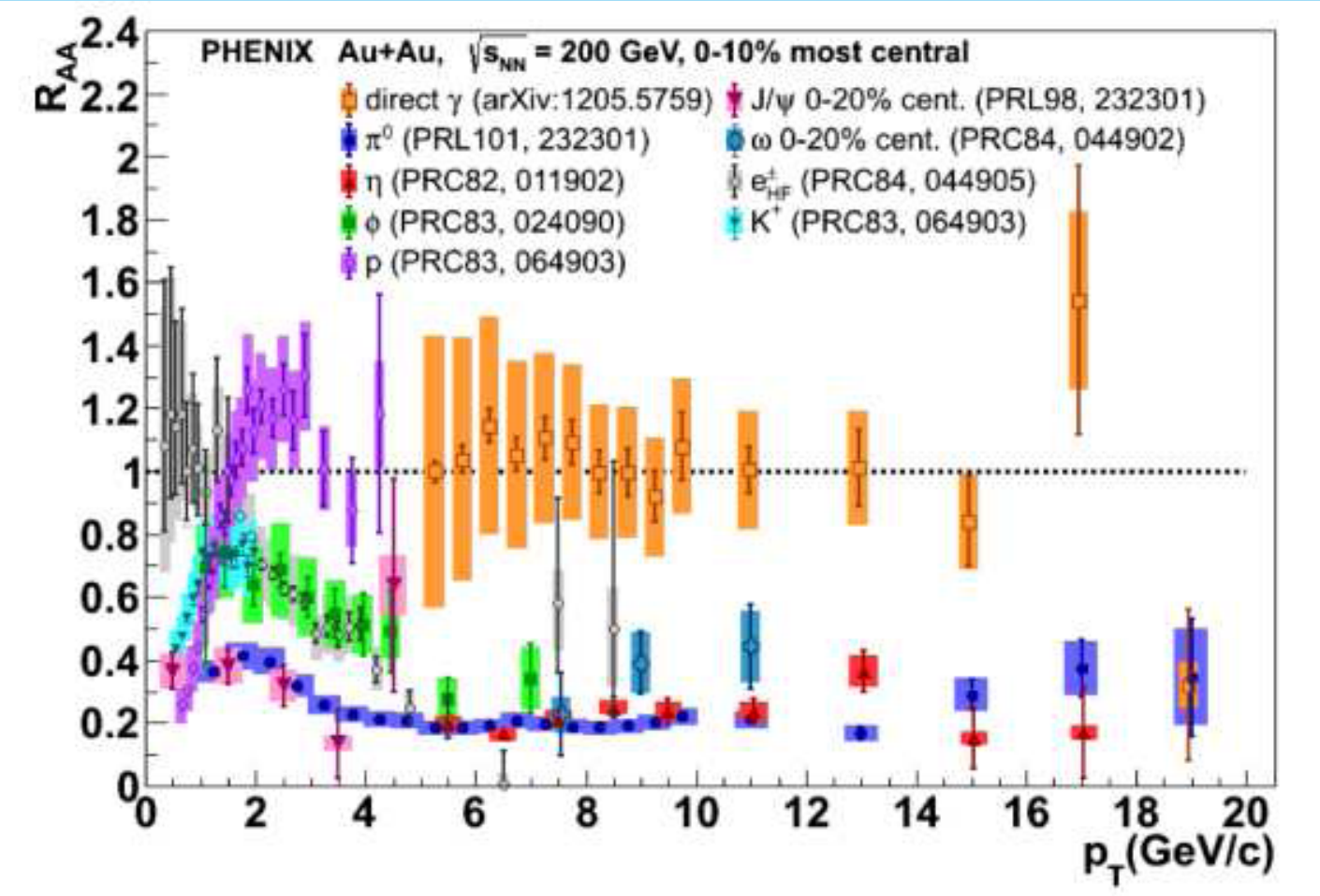
- Different dpT/pt for RHIC and LHC, for same RAA
- dpt/pt is 25% higher for ALICE
- dpt/pt decreases slightly with increasing pt (where rise of RAA occurs)

Fract. momentum loss : dpt(LHC) ~ 1.25 dpt(RHIC)
Charged multiplicity: dN/dy(LHC) ~ 2.2 dN/dy(RHIC)

M. Tannenbaum and PHENIX collaboration

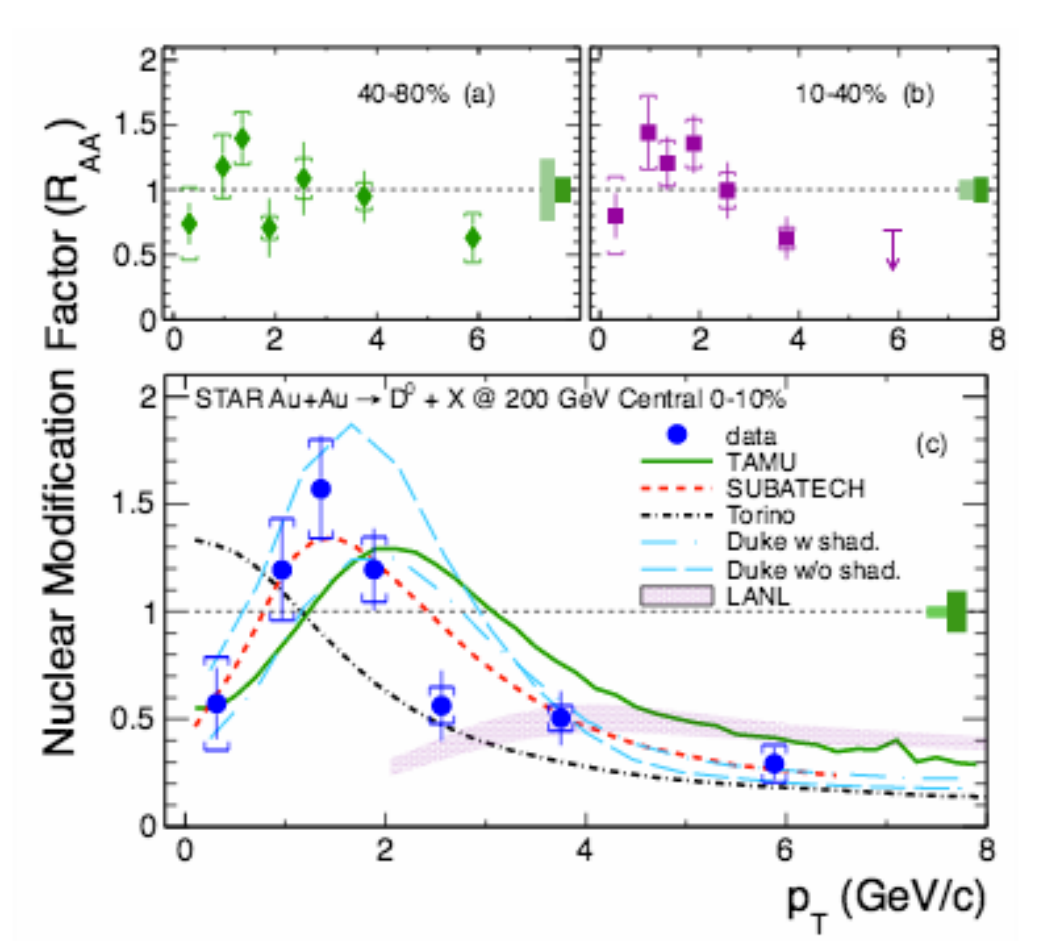
-> Interaction region at LHC less opaque to hard partons than RHIC

Jet quenching of light hadrons at RHIC

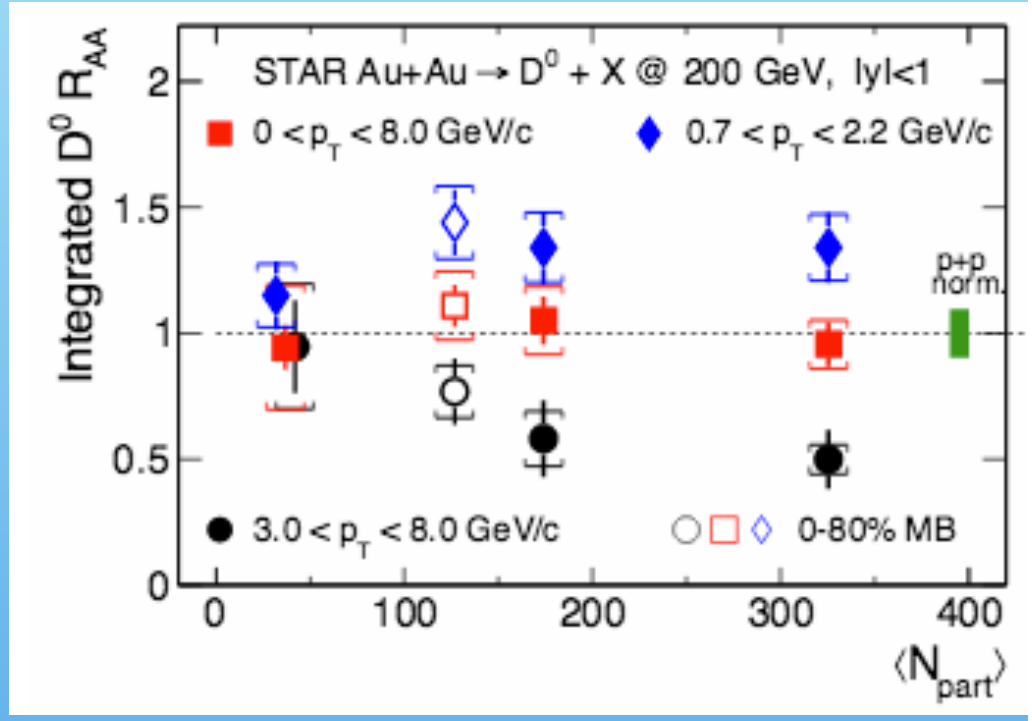


*** Light hadrons are quenched**
*** Photons are not quenched**

STAR R_{AA} of D_0 in Au+Au 200 GeV



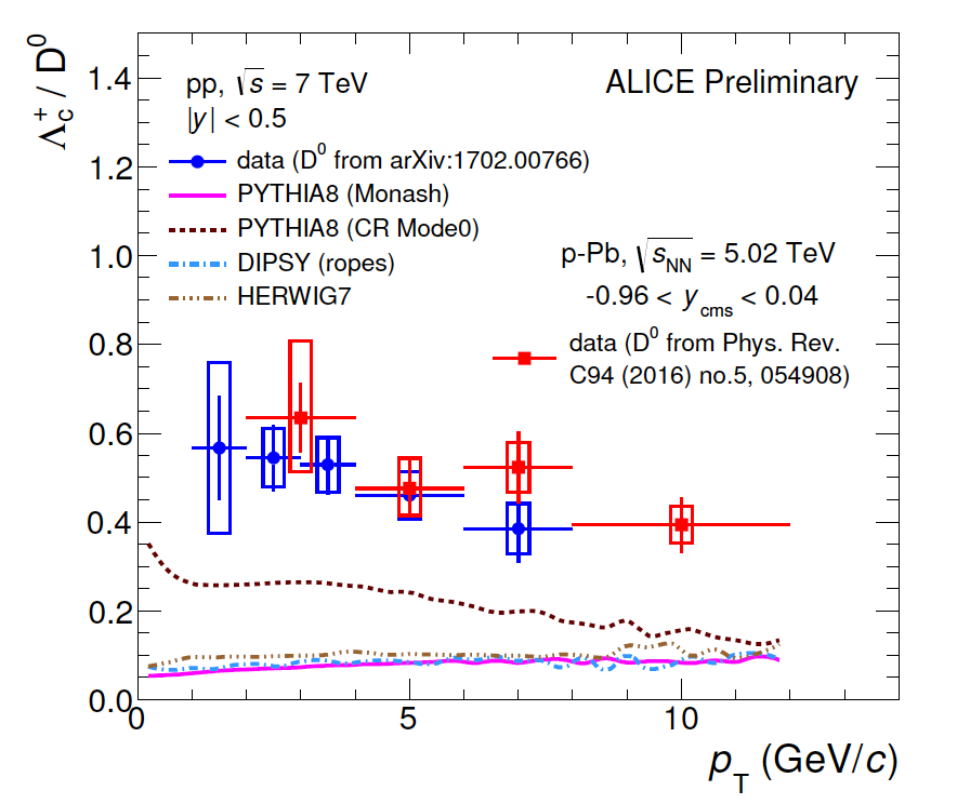
STAR: Phys. Rev. Lett. **113** (2014) 142301 and 1404.6185

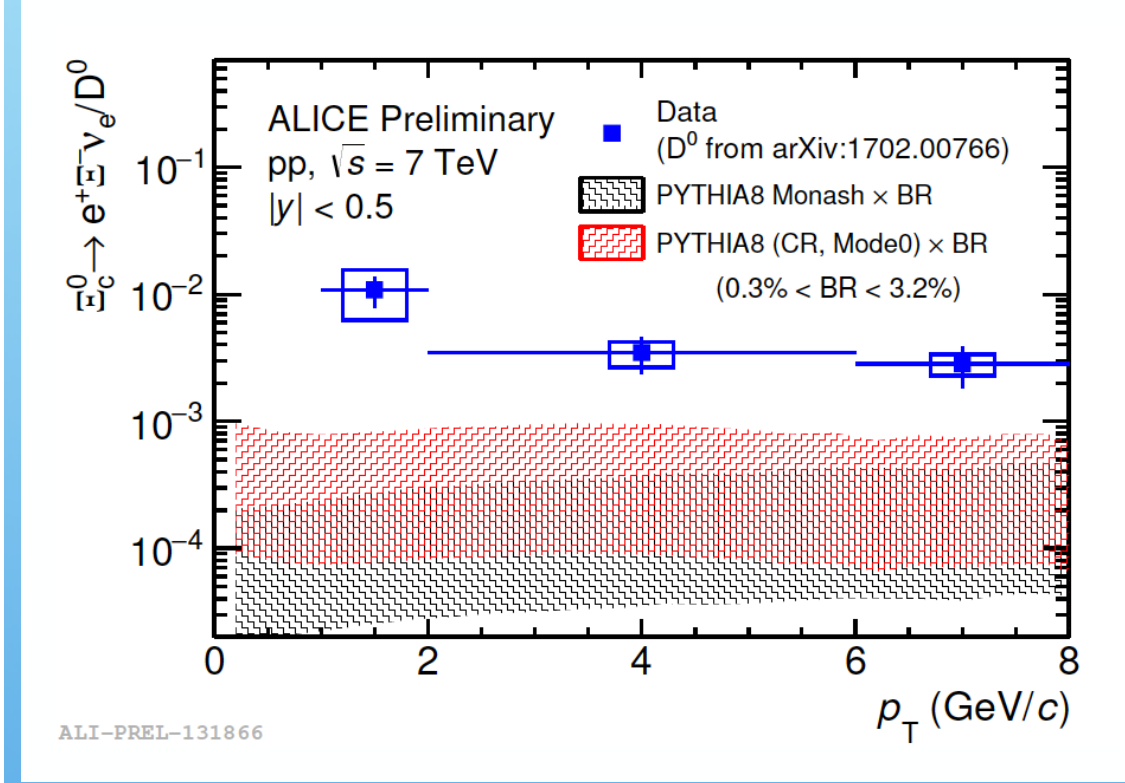


R_{AA} of D_0 at high p_T:

- **RAA D0 suppression in central Au+Au 200 GeV**
- **suppression at high p_T similar to pions**
- **Enhancement at pT~0.7-2 GeV (described eg by models with charm quark coalescence with light quarks)**

ALICE new data on charmed baryons



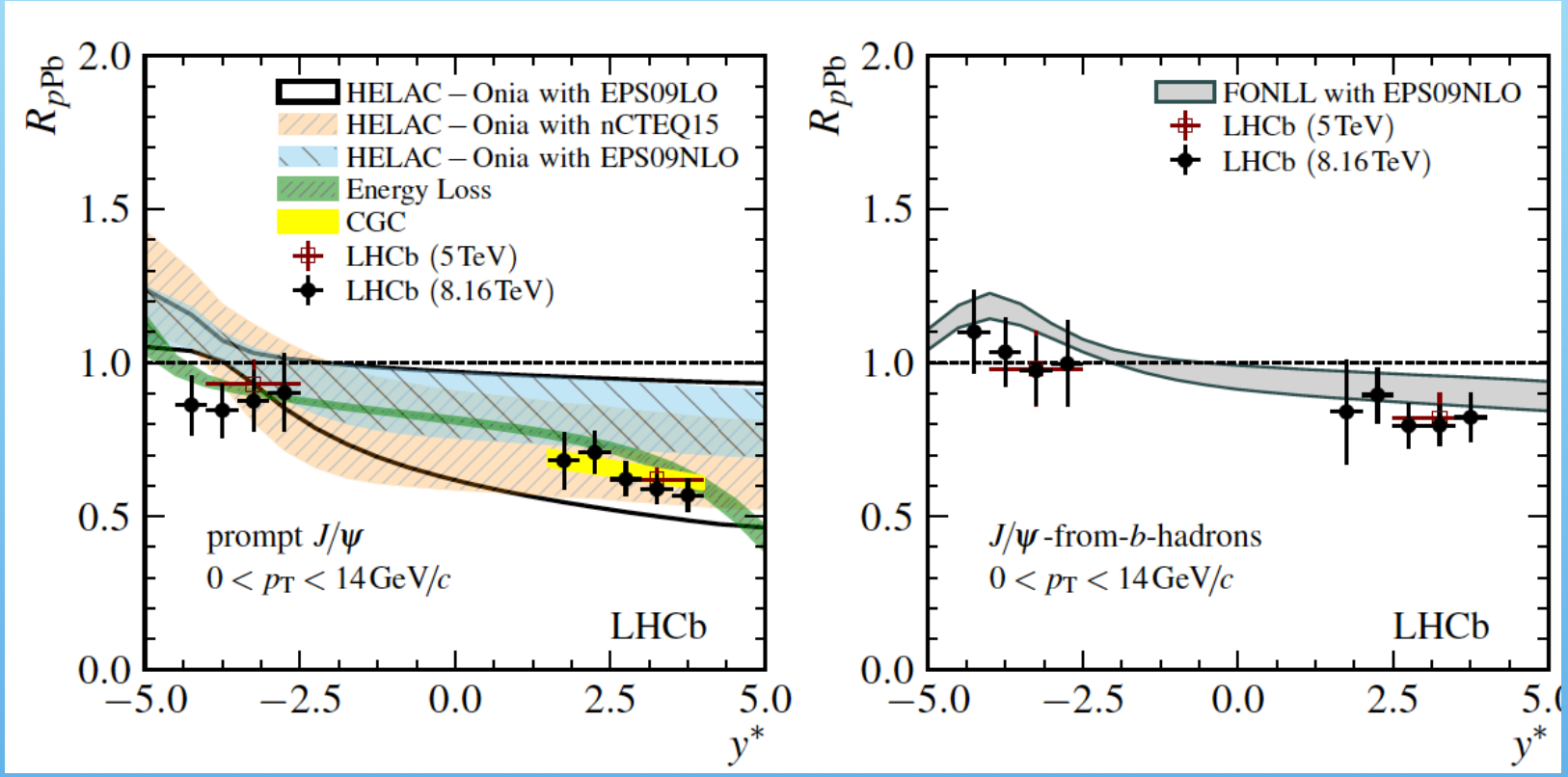


T Dahms, ICNFP

* New charmed baryon measurements from ALICE
* Charmed baryon to meson ratios are not well described by event generators

LHCb J/Psi and B->J/Psi in p+Pb

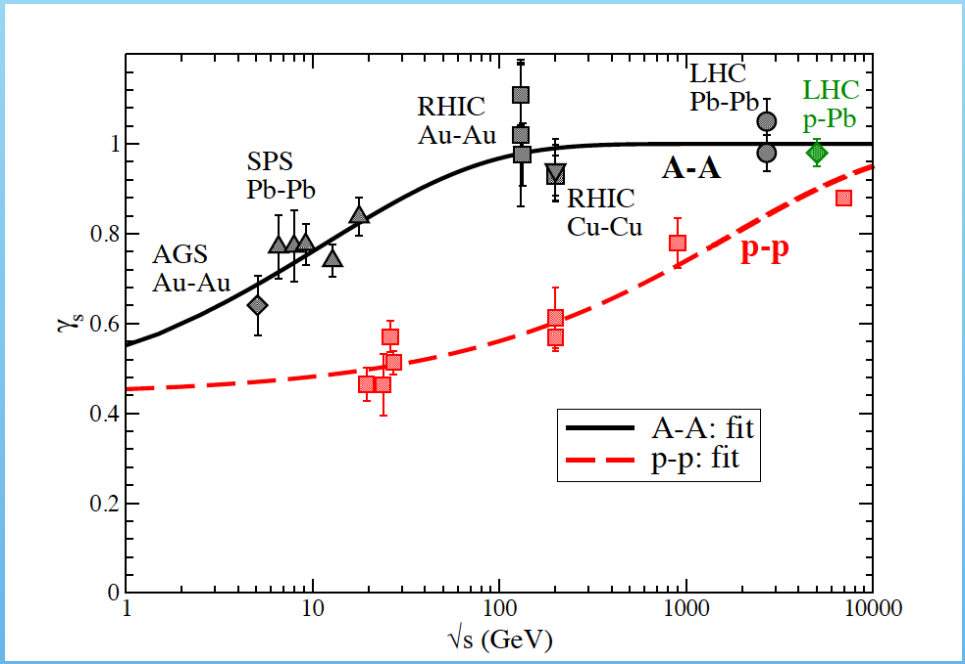
LHCb, 1706.07122

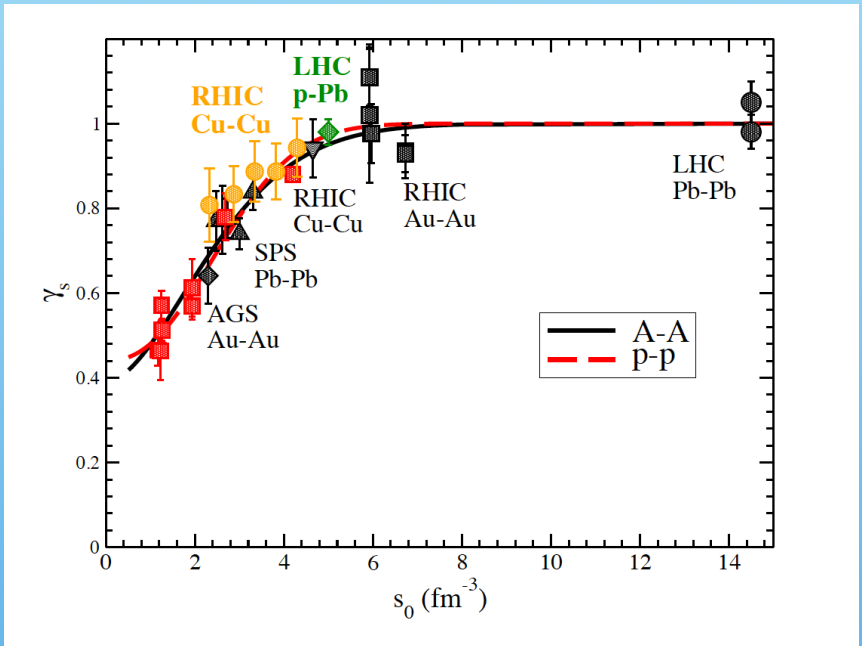


At backward rapidity prompt J/Psi not well described by models

Universal Strangeness Production

P. Castorina, S Plumari, H Satz, 1709.02706





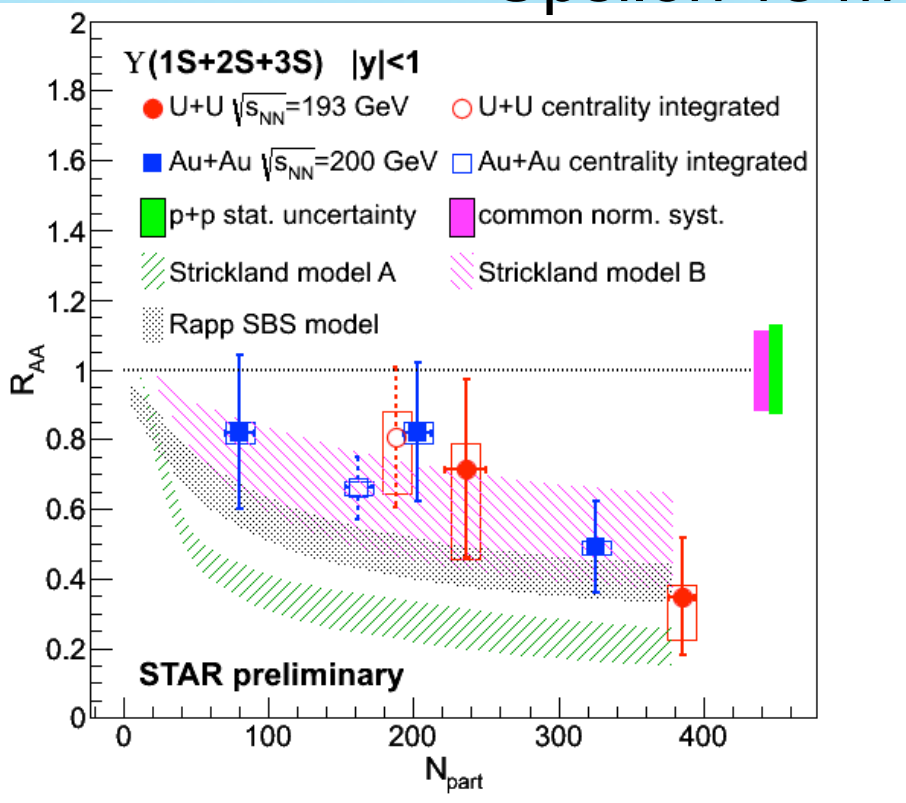
s_0 initial entropy density calculated using the Bjorken relation

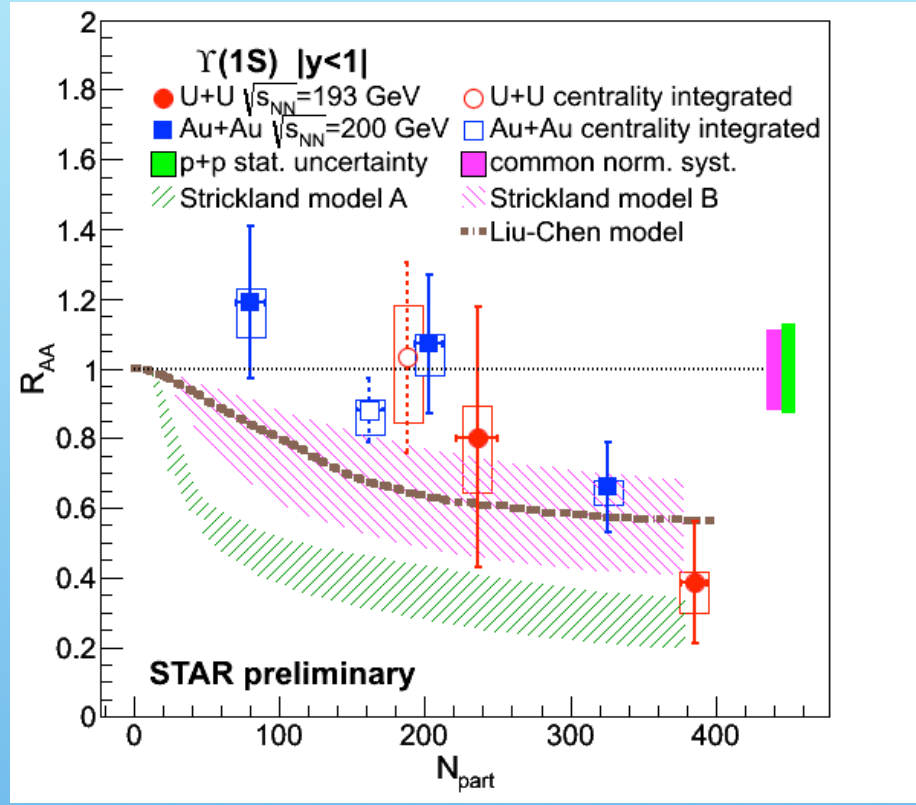
$$s_0\,\tau_0 \simeq \frac{1.5A^x}{\pi R_x^2}\left(\frac{dN}{dy}\right)^x_{y=0}, \quad \text{with } x \sim pp, pA, AA,$$

Gamma_s factor depends in universal way from s_0 for small and big systems

Gamma_s becomes 1 near T_c

Upsilon vs models at RHIC





*** Model of Strickland, Bazov (Nucl. Phys. A 879, 25 (2012))**
No Cold Nuclear Matter effects
T(initial)=428-443 MeV
Potential model A is based on heavy quark free energy (disfavored)
Potential model B is based on heavy quark internal energy

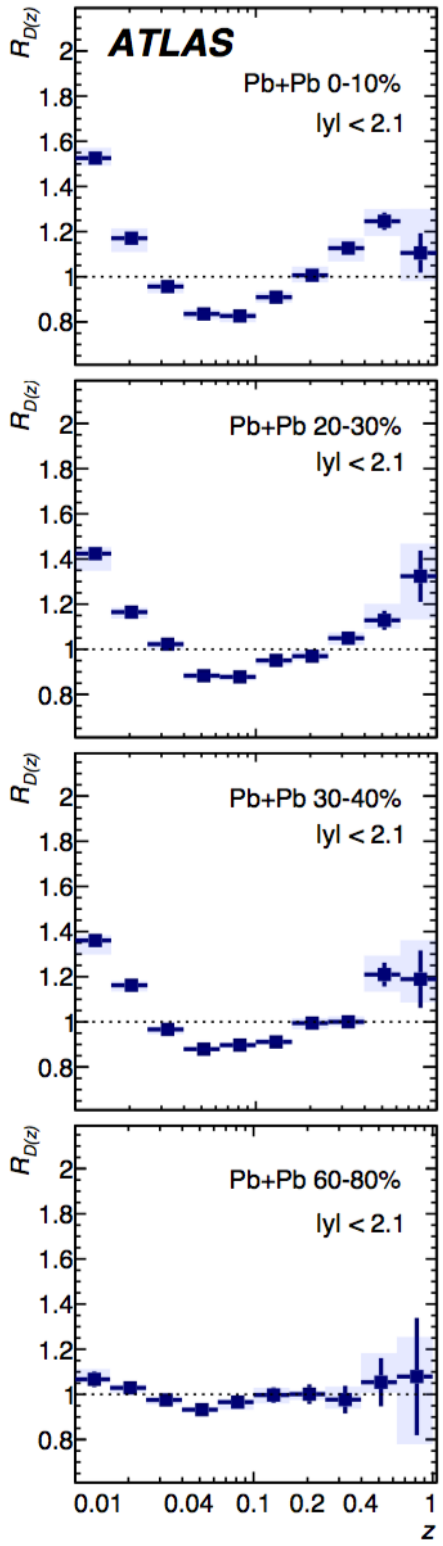
*** Model of Liu, Chen, Xu, Zhuang (Phys Lett B 697, 32 (2011)**
Potential model, no Cold Nuclear Matter effects. T= 340 MeV

*** Model of Emerick, Zhaon, Rapp (Eur. Phys. J A48, 72 (2012))**
Cold Nuclear Matter effects included

Y data in agreement with Y melting scenario

Modification in Jet fragmentation

ATLAS arXiv:1702.00674



Jet fragmentation function D(z)

z: longitudinal momentum fraction of a particle with respect to jet

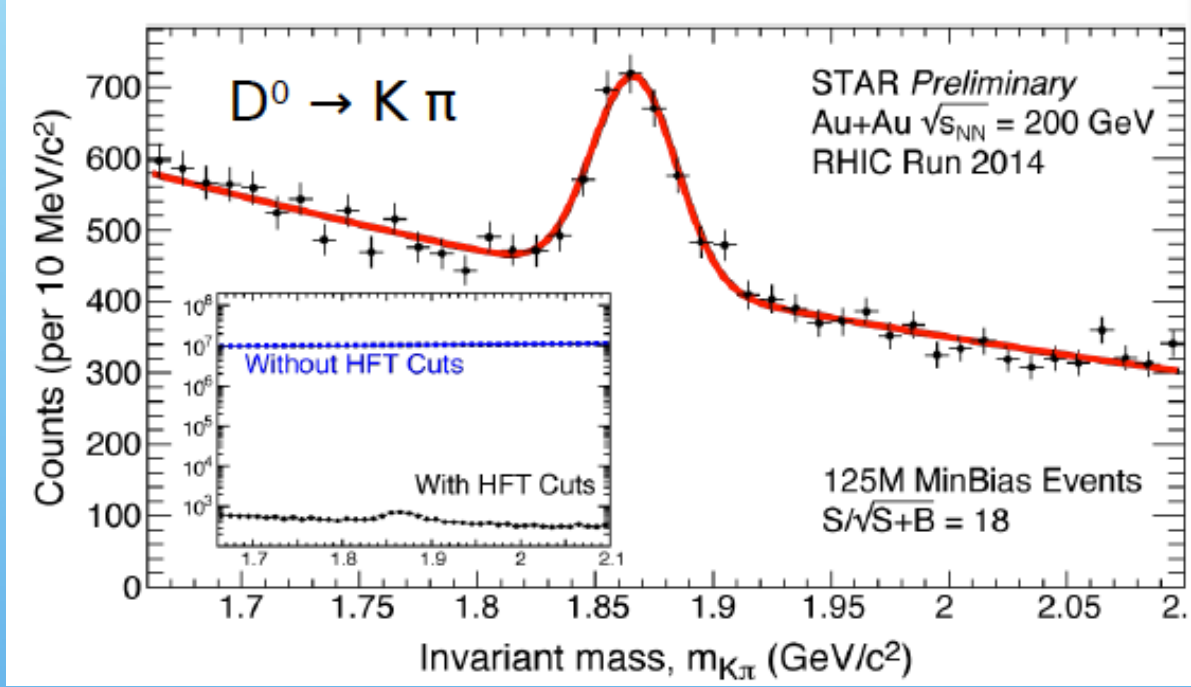
$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{\text{ch}}}{\mathrm{d}z},$$

$$R_{D(z)} = D(z)|_{\text{cent}} / D(z)|_{pp}$$

In central Pb+Pb:
Enhancement at low z
Suppression at z around 0.1
Enhancement at high z

Secondary vertex reconstruction of D mesons with HFT

Heavy Flavor Tracker started taking data in run-14



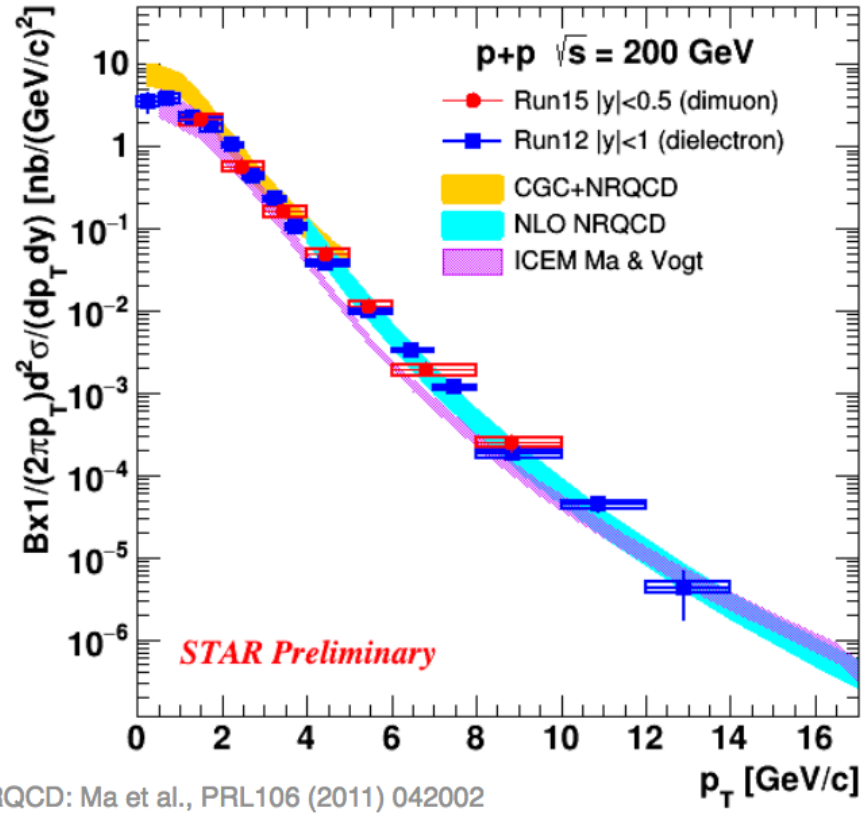
STAR, QM15

~ 4 orders of magnitude reduction of combinatorial background

J/Psi in p+p coll at RHIC

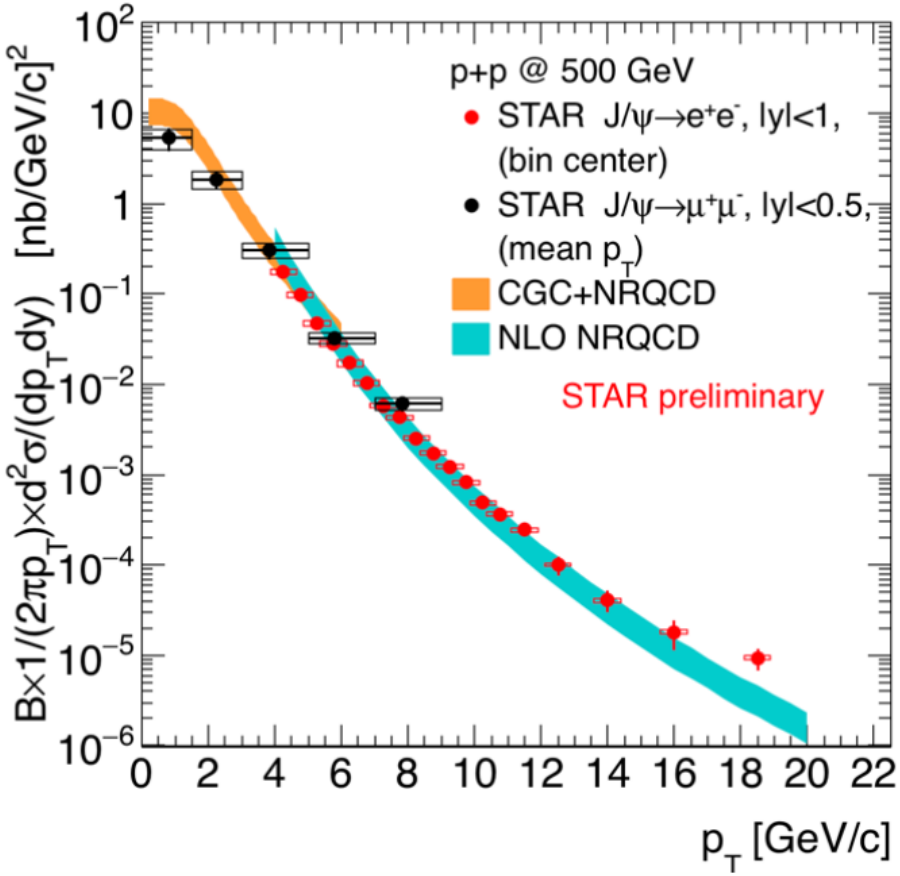
- CGC+NRQCD and NLO NRQCD (prompt) consistent with data (inclusive) at p+p @ 200 and 500 GeV

p+p@ 200 GeV



NLO NRQCD: Ma et al., PRL106 (2011) 042002
CGC+NRQCD: Ma, Venugopalan, PRL113 (2014) 192301

p+p@ 500 GeV



What is the right normalization for quarkonia ?

1. J/Psi AA/pp : RAA(J/Psi)

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

2. Jpsi AA/pA : RpA
(J/Psi AA measured)/(expected from pA) (NA50)
to subtract Cold Nuclear Matter effects (CNM)

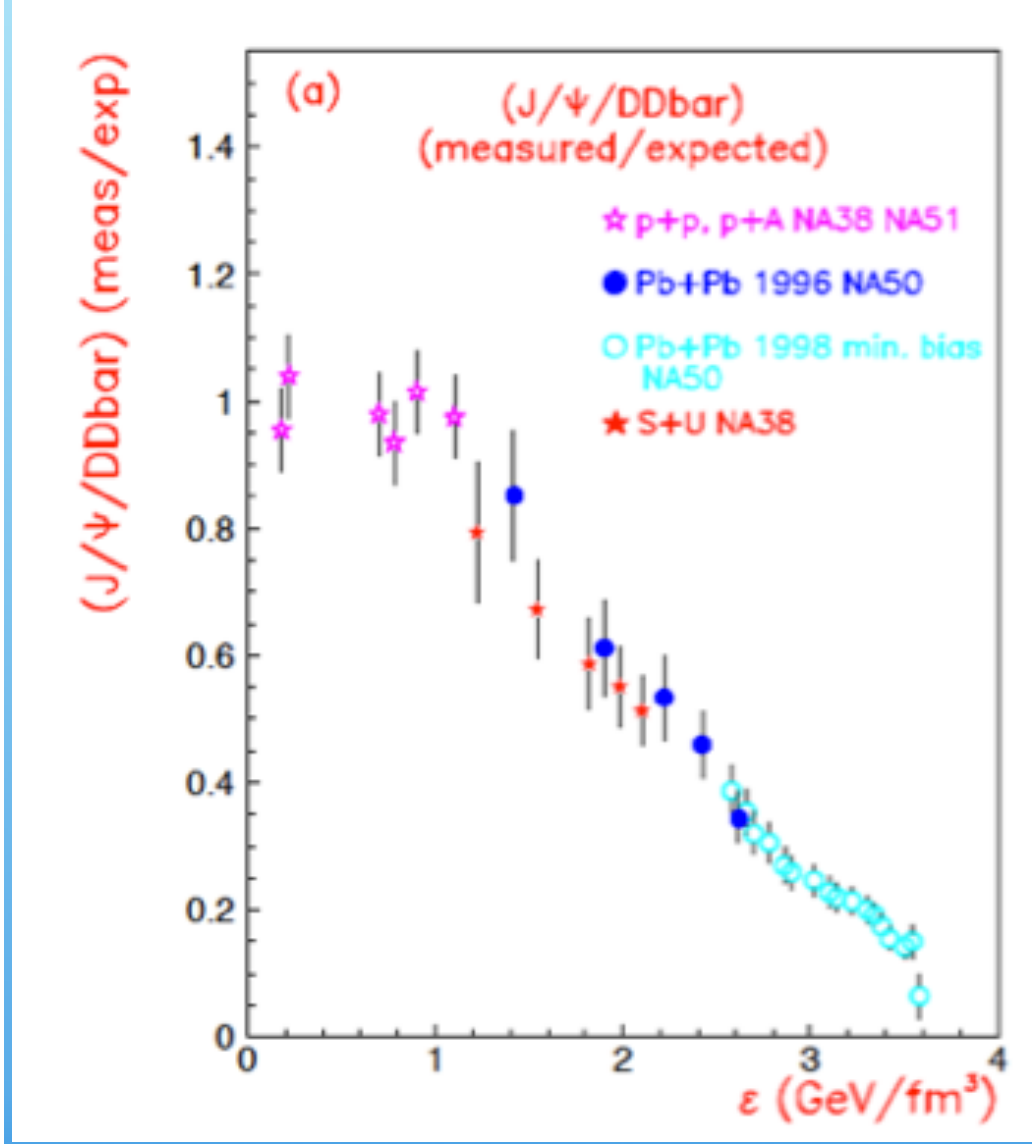
3. (J/Psi AA/pp) / (open charm AA/pp) :

RAA(J/Psi) / RAA(open charm)

4. (J/Psi AA/pA) / (open charm AA/pA):
(RpA (J/Psi))/ (RpA (open charm))

Very different conclusions can be drown depending on normalization

Measured ratio of J/Psi to D mesons at SPS



- **Open charm measured by dimuons in region 1.6-2.5 GeV**

The J/Psi/(DDbar) estimate is suppressed at 1 GeV/fm^3 instead of 2.3 GeV/fm^3 and coincides with strangeness saturation onset

Need open charm measurements at low energy to understand quarkonia onset of suppression

S.K., New J. of Physics, Vol. 3, (2001), 16, arXiv 0004138