Heavy Ion Collisions at RHIC

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Recent Developments in High Energy Physics and Cosmology

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Outline

I Introduction

II Accelerator facilities and experiments

III Selected physics results :

1. Direct photons
2. Collectivity, flow, vorticity, strangeness
3. Jet quenching
4. Quarkonia suppression
5. Future perspectives

IV Conclusions

I Introduction

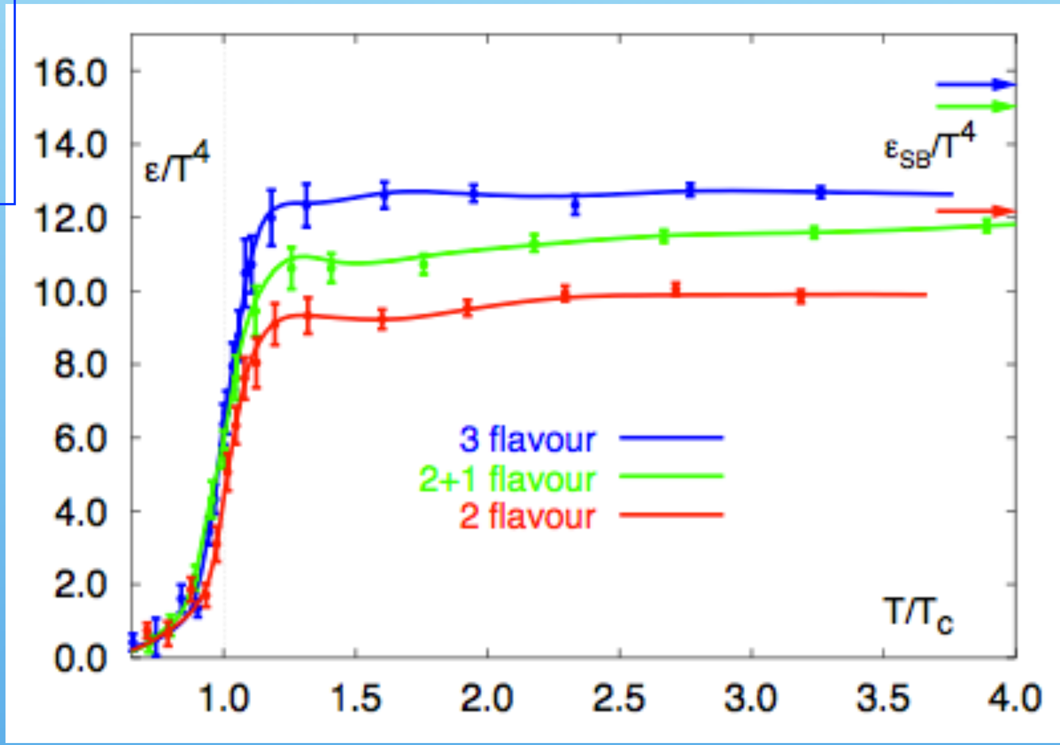
The QCD phase transition between hadronic and partonic phase

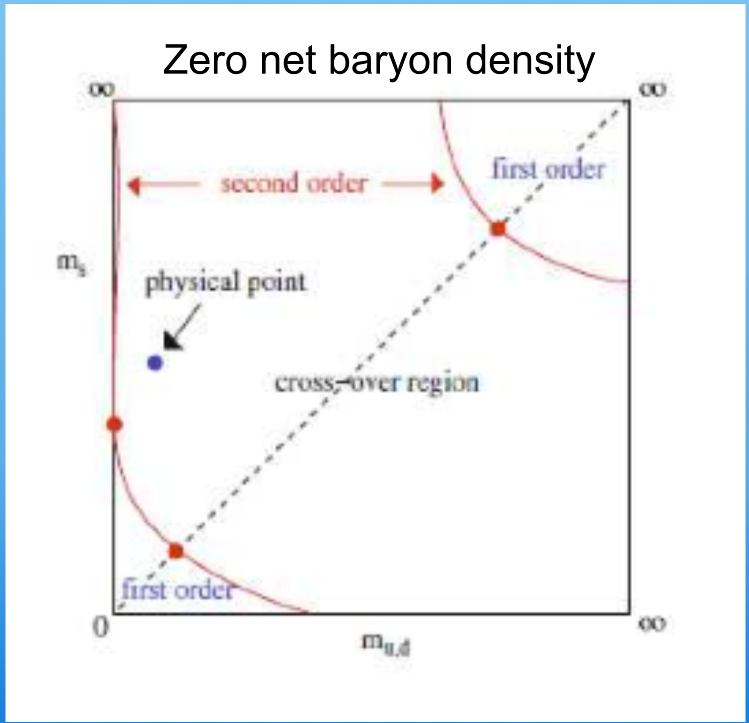
QCD on the lattice predicts a cross over at zero net baryon density with critical temperature Tc~154+-9 MeV (2014), critical energy density ~0.6 GeV/fm^3

(Nuclear Density: rho=0.15 GeV/fm^3
Density inside Nucleon: rho=0.5 GeV/fm^3)

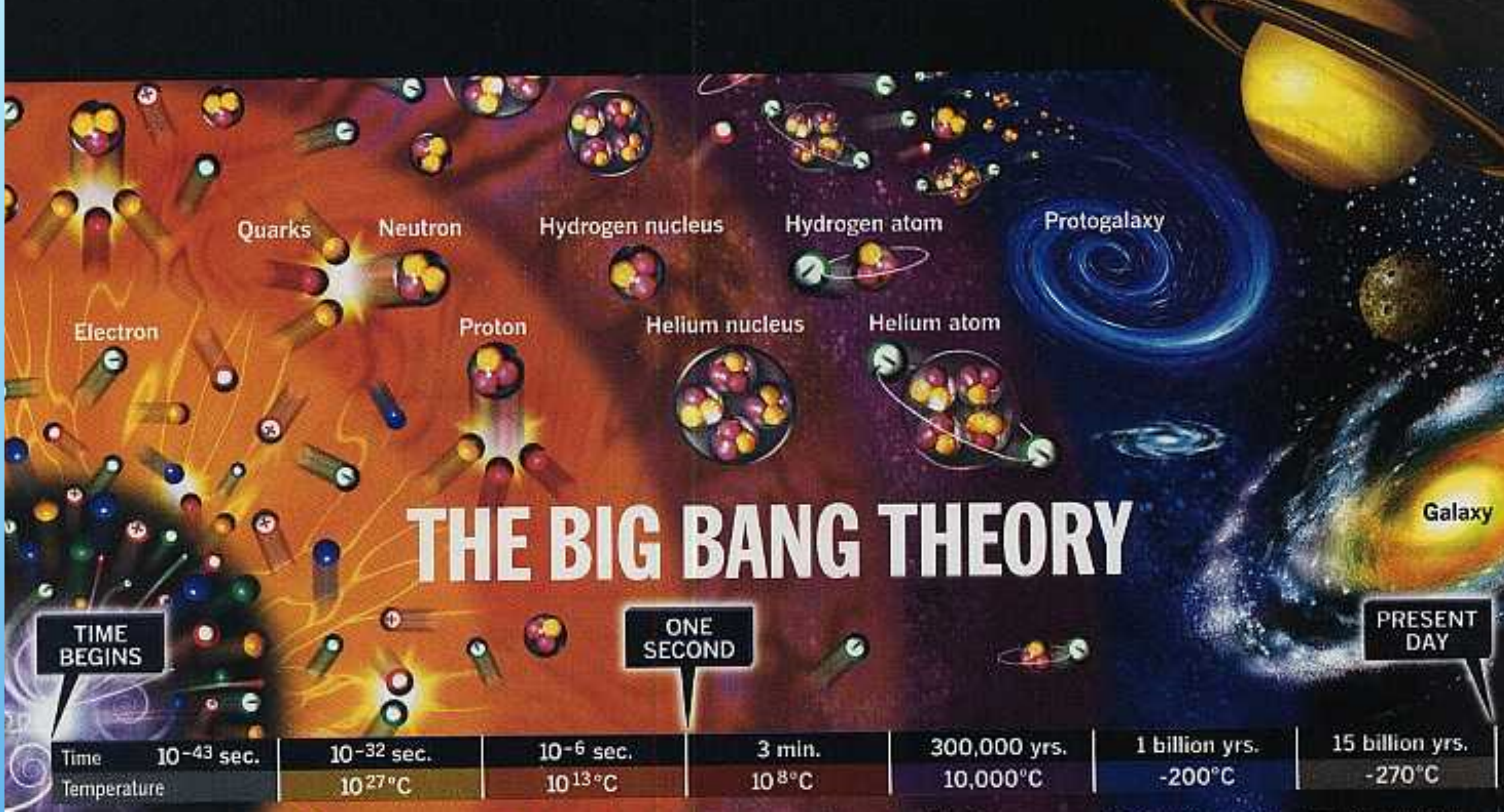
Zero net baryon density

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





The order of the transition depends on the parton masses. A cross over is expected by Lattice QCD for the physical point (for the physical u,d,s masses).



The transition from quarks and gluons to hadrons is believed that took place few 10-6 sec after the Big Bang.
The QCD phase transition is the only phase transition of the early universe that can be reproduced in the Lab today since Tcritical is about 200 MeV

Reach of accelerators in terms of initial Temperature

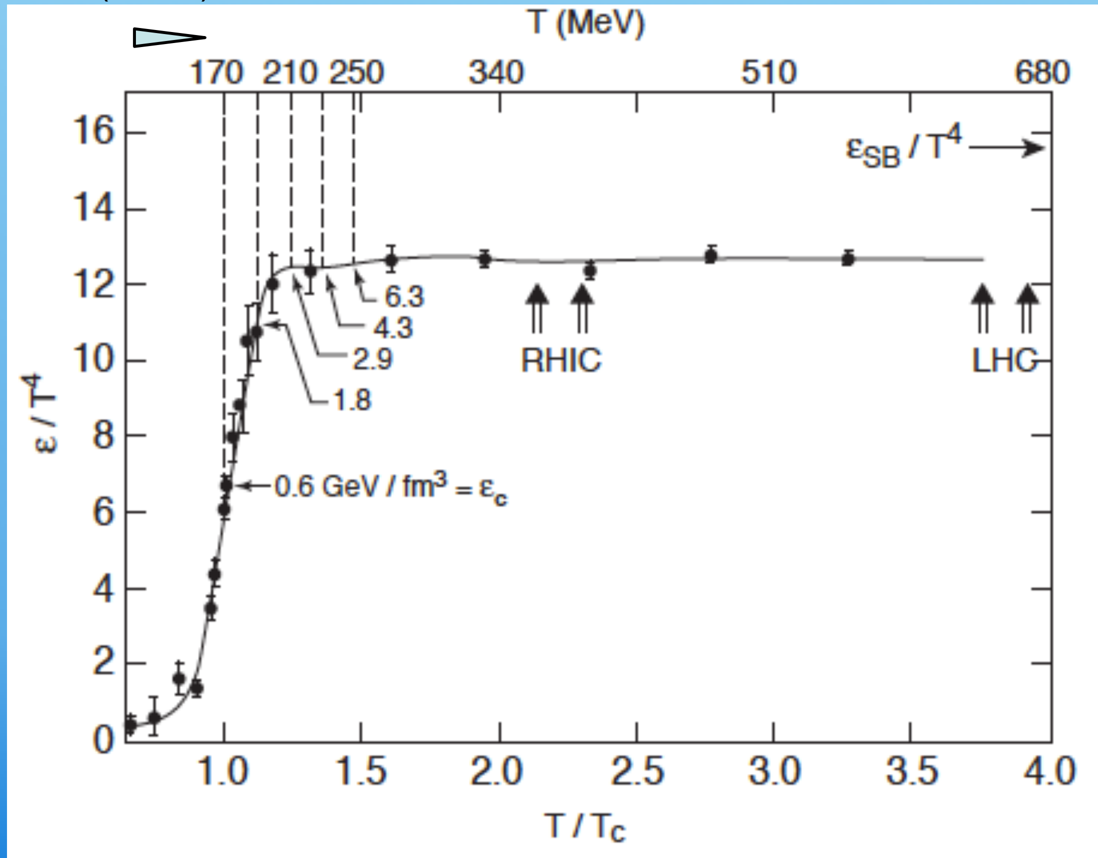
CERN, LHC (2009-)

BNL, RHIC (2000-)

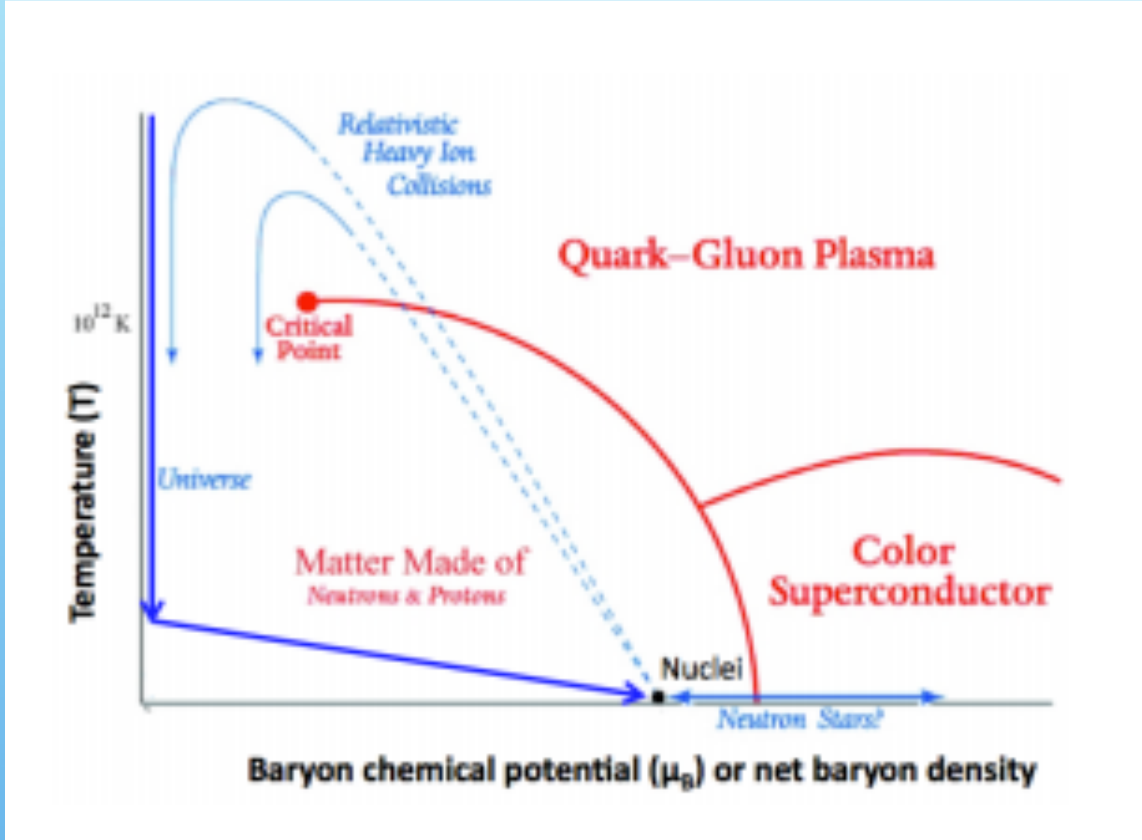
CERN, SPS (1988-)

BNL, AGS (1986-)

U. Heinz, 0009170.pdf



The expected QCD phase diagram



Ph. Rosnet,1510.04200

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).

Signatures of the Quark Gluon Plasma

Direct photons from QGP → T(QGP)

Strangeness enhancement (Mueller, Rafelski 1981) → K/pi

U,d,s yields for T(freeze out) or pT slopes (Van Hove, H Stoecker et al) → plateau vs energy at Tc → e_init(crit), sqrt(s)("crit")

Multiquark states from QGP (Greiner et al) → 'small QGP-lumps'

Critical fluctuations near the critical point, Tc → K/pi, <pT>, etc

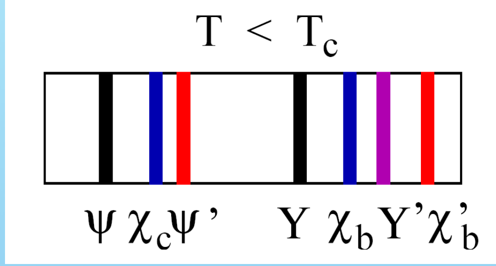
Hadronic mass/width changes (Pisarski 1982) → rho etc

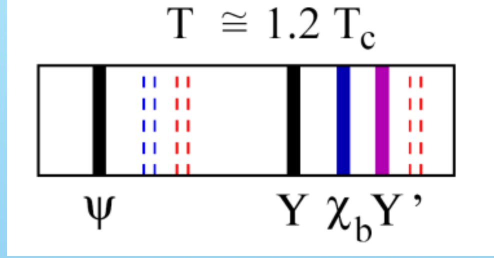
Charmonia suppression (Satz, Matsui 1987) → T(dissociation) of ccbar, bbbar

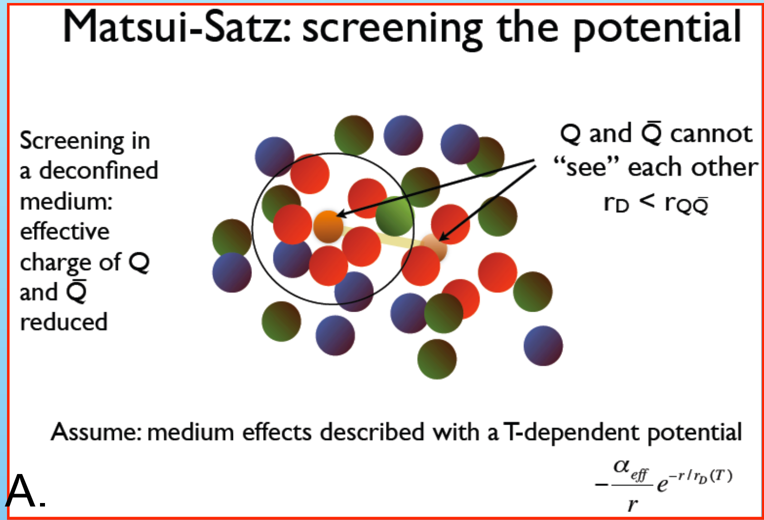
Jet quenching (J D Bjorken 1982) → medium density

--> Goal is to achieve a combination of many signatures

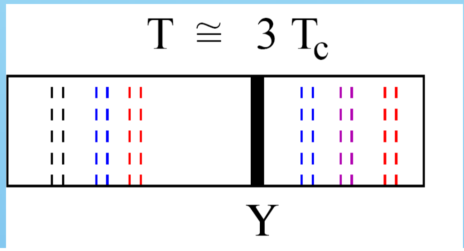
Quarkonia suppression as QGP signature



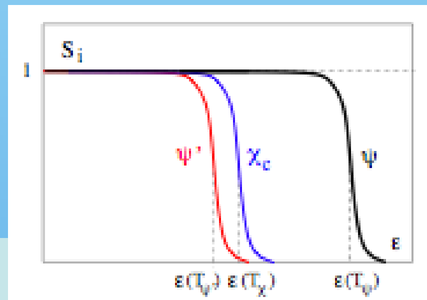


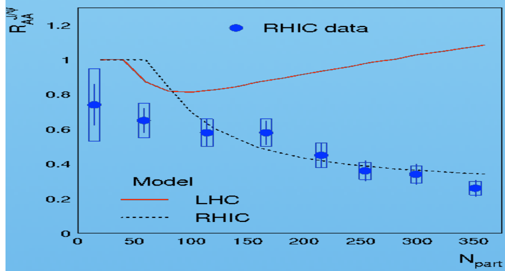


H. Satz, Nucl. Phys. A (783): 249-260(2007)



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

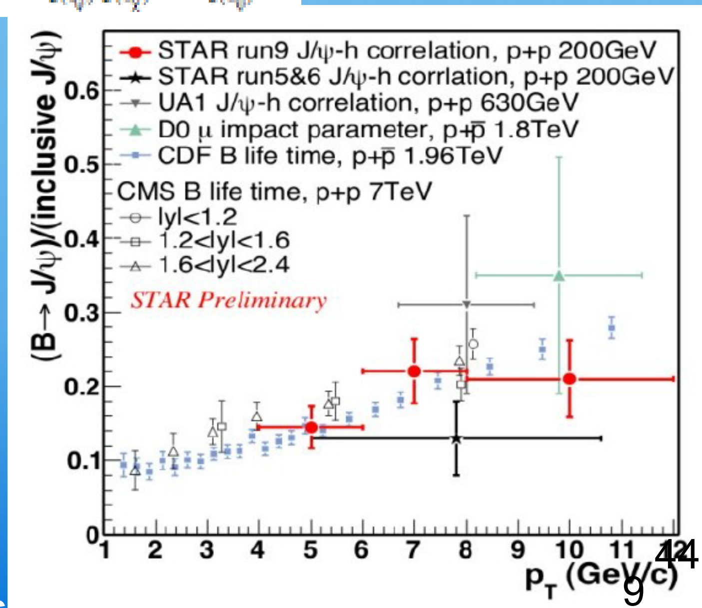




Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

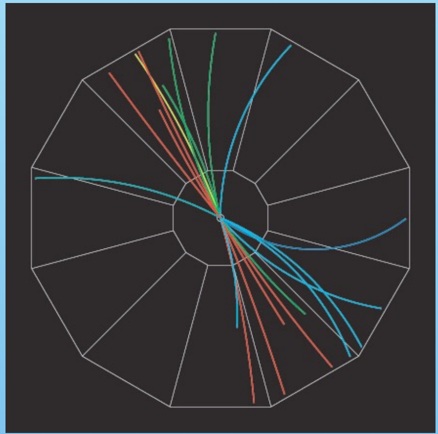
Many effects play a role like dissociation in QGP, cold matter absorption, recombination/ coalescence from c, cbar, feeding, eg B mesons carry 10-25% of charmonia yields (B->J/Psi from J/Psi-h correlation STAR measurement)

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

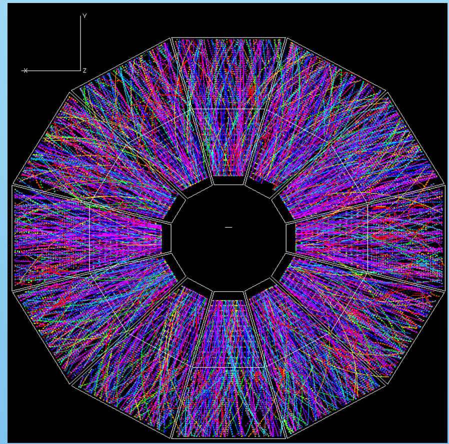


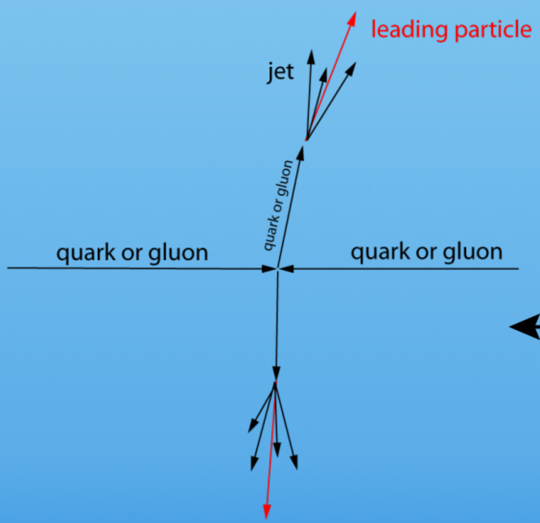
Jet quenching as QGP signature

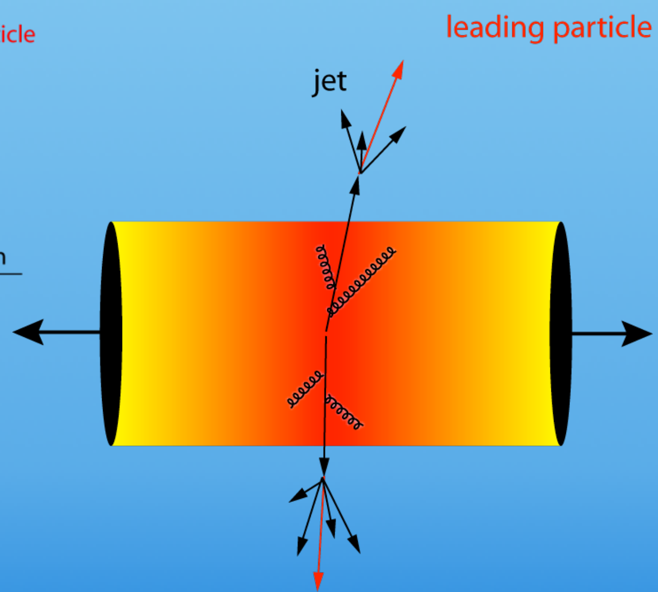
p+p Collision



Au+Au Collision

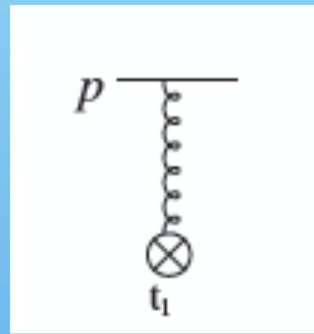




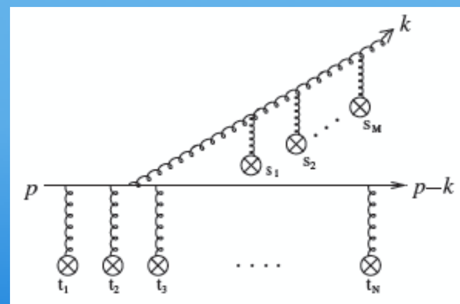


Partons interact with the medium and loose energy through eg gluon radiation

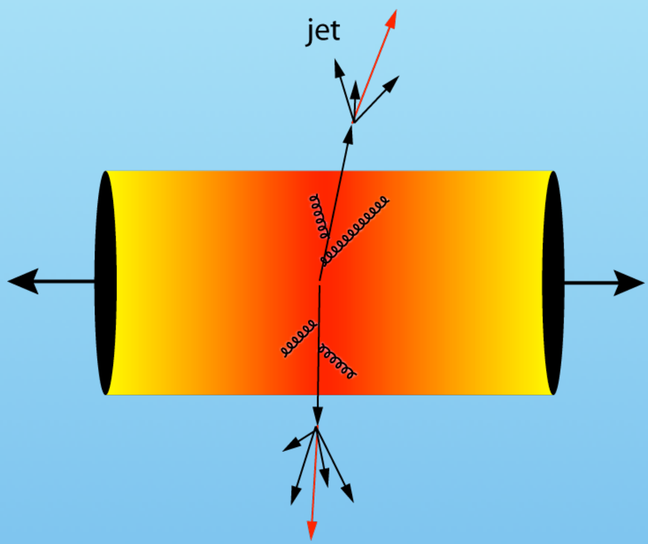
Collisional "elastic" energy loss: elastic interaction with the medium



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



Jet quenching

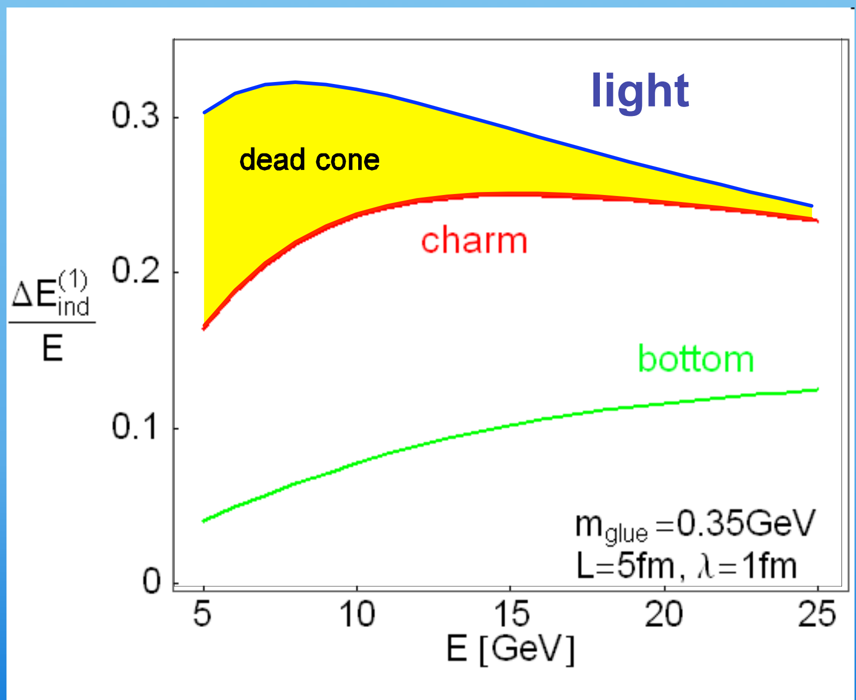


"The nuclear modification factor" R_{AA}

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

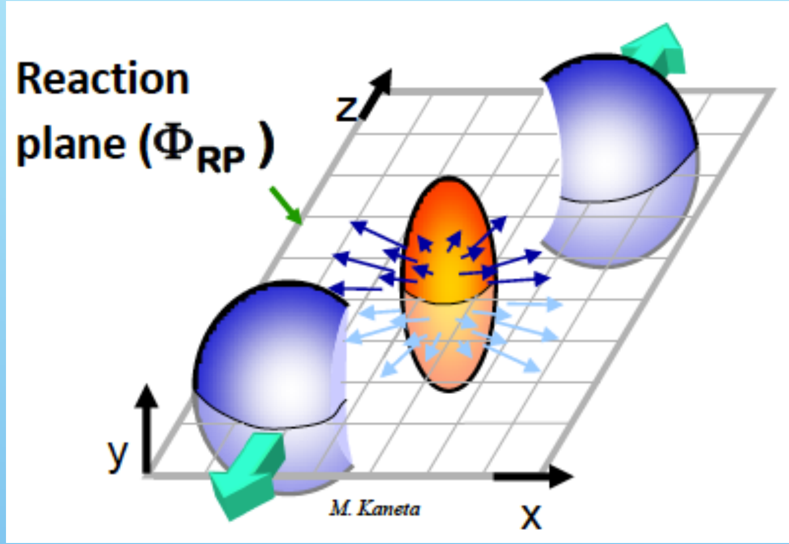


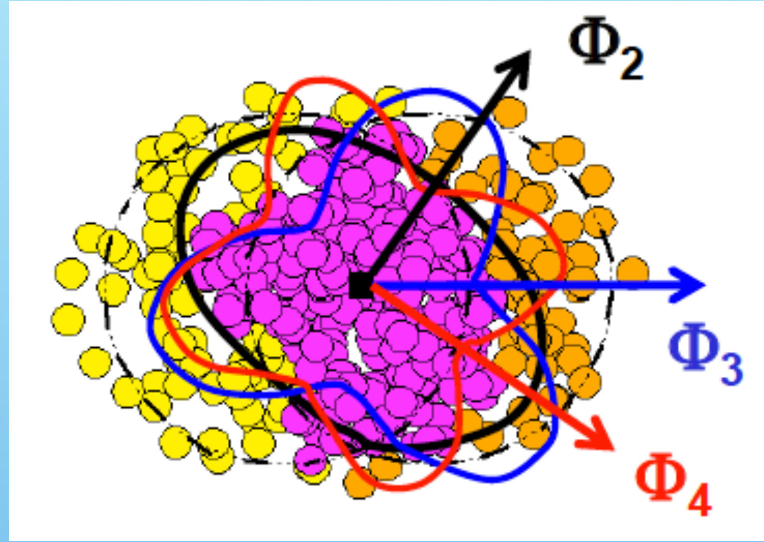
Suppression of jets in AuAu: $R_{AA} < 1$

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

M.Djordjevic PRL 94 (2004)

Flow coefficients v_n, n=1,2,3..





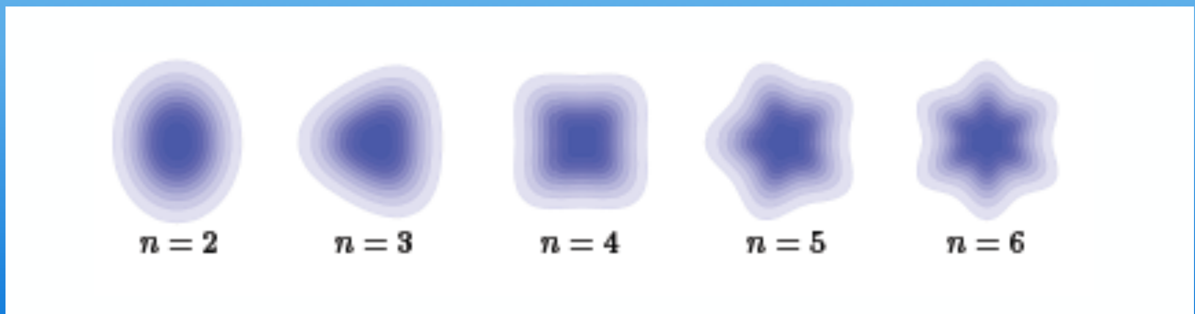
Matter in the overlapp area of two colliding nuclei gets compressed and heated

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, ...)

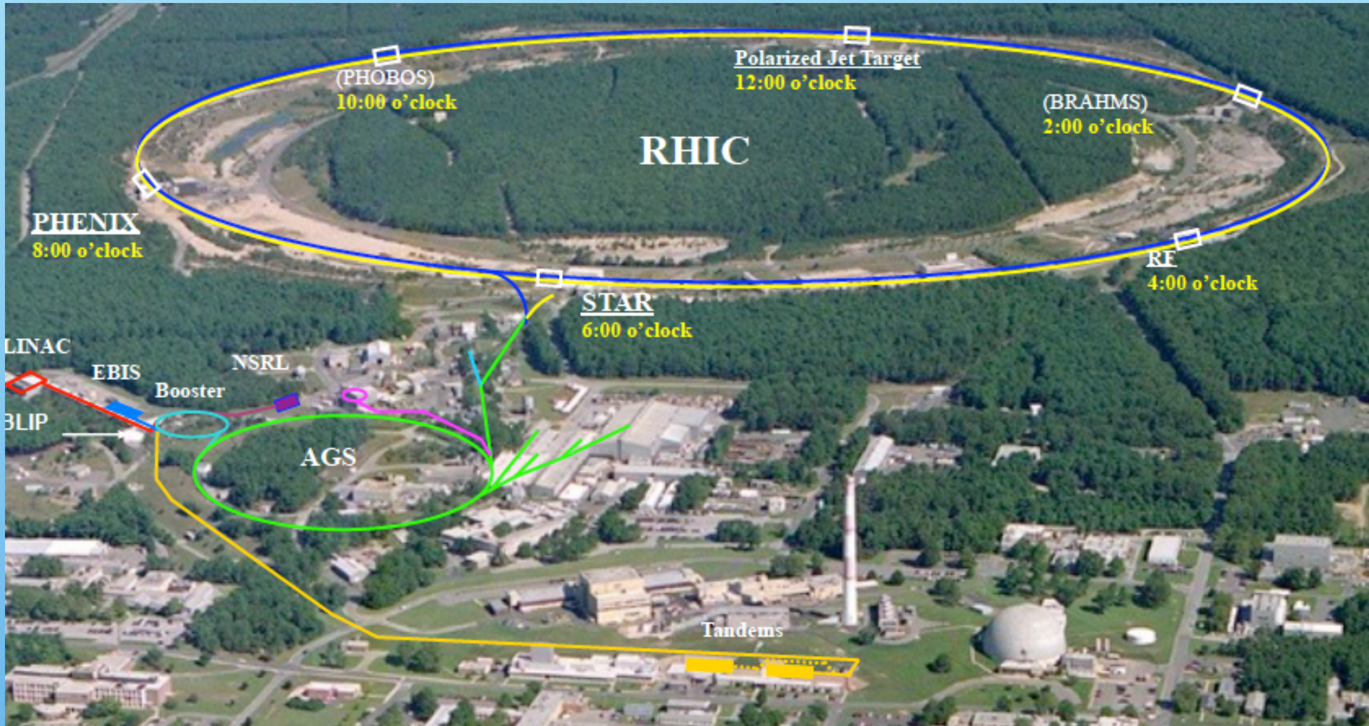


Higher harmonics

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 15 years 2000-2015

4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

Still runing: STAR

Still analysing data:
PHENIX

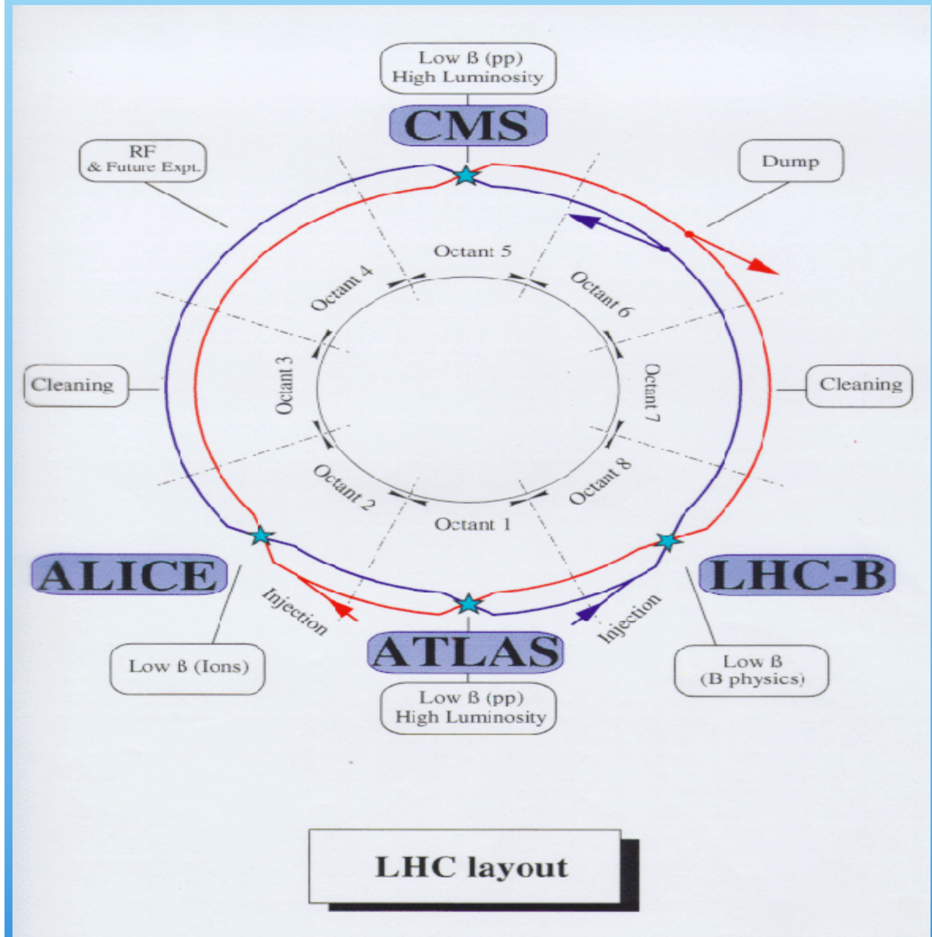
Colliding systems:

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

Energies A+A :

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

Large Hadron Collider (LHC) at CERN



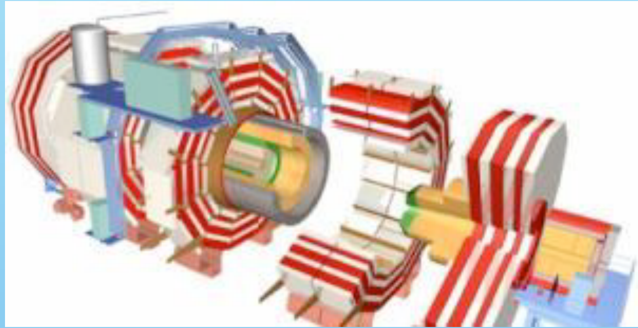
run-1 (2009-13) : p+p √sNN =0.9, 2.76, 7, 8 TeV, p+Pb √sNN =5.02 TeV, Pb+Pb at √sNN =2.76 TeV

run-2 (2015-18) : p+p √sNN = 5.02, 13 TeV p+Pb 5.02, 8.16 TeV Pb+Pb at √sNN =5.02 TeV

Current Experiments with Heavy Ion program

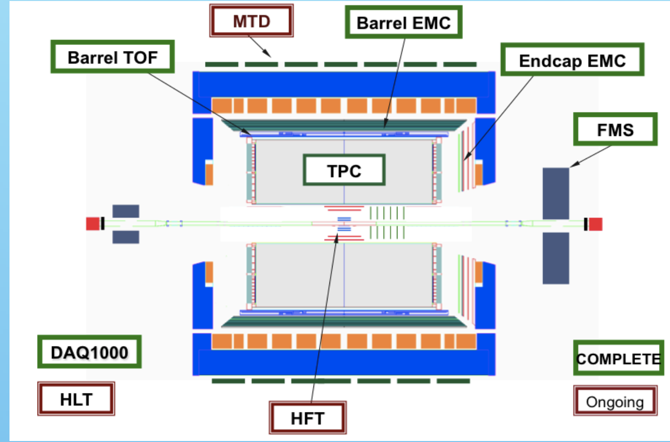
LHC

CMS

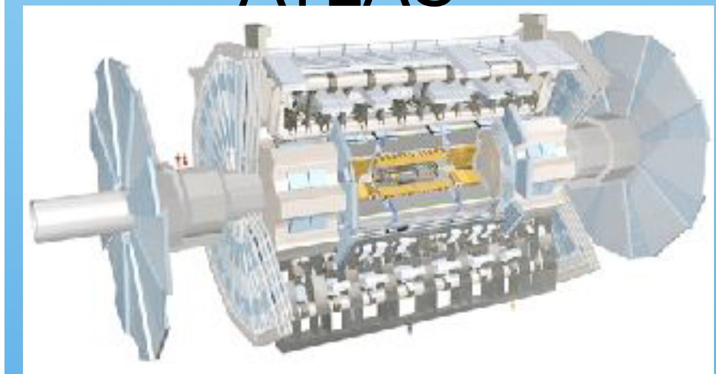


LHCb

STAR at RHIC

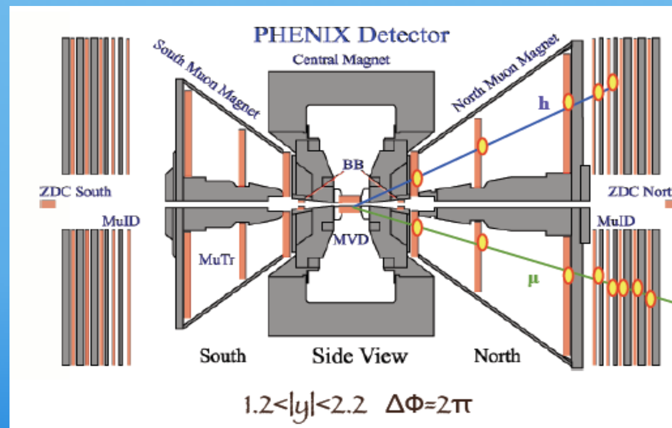


ATLAS

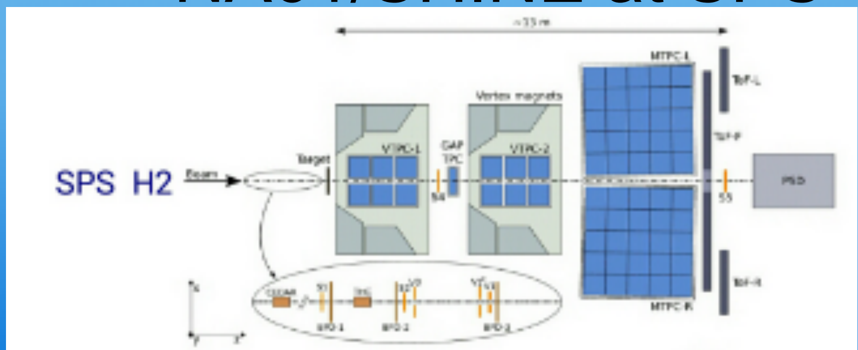


ALICE

PHENIX at RHIC



NA61/SHINE at SPS

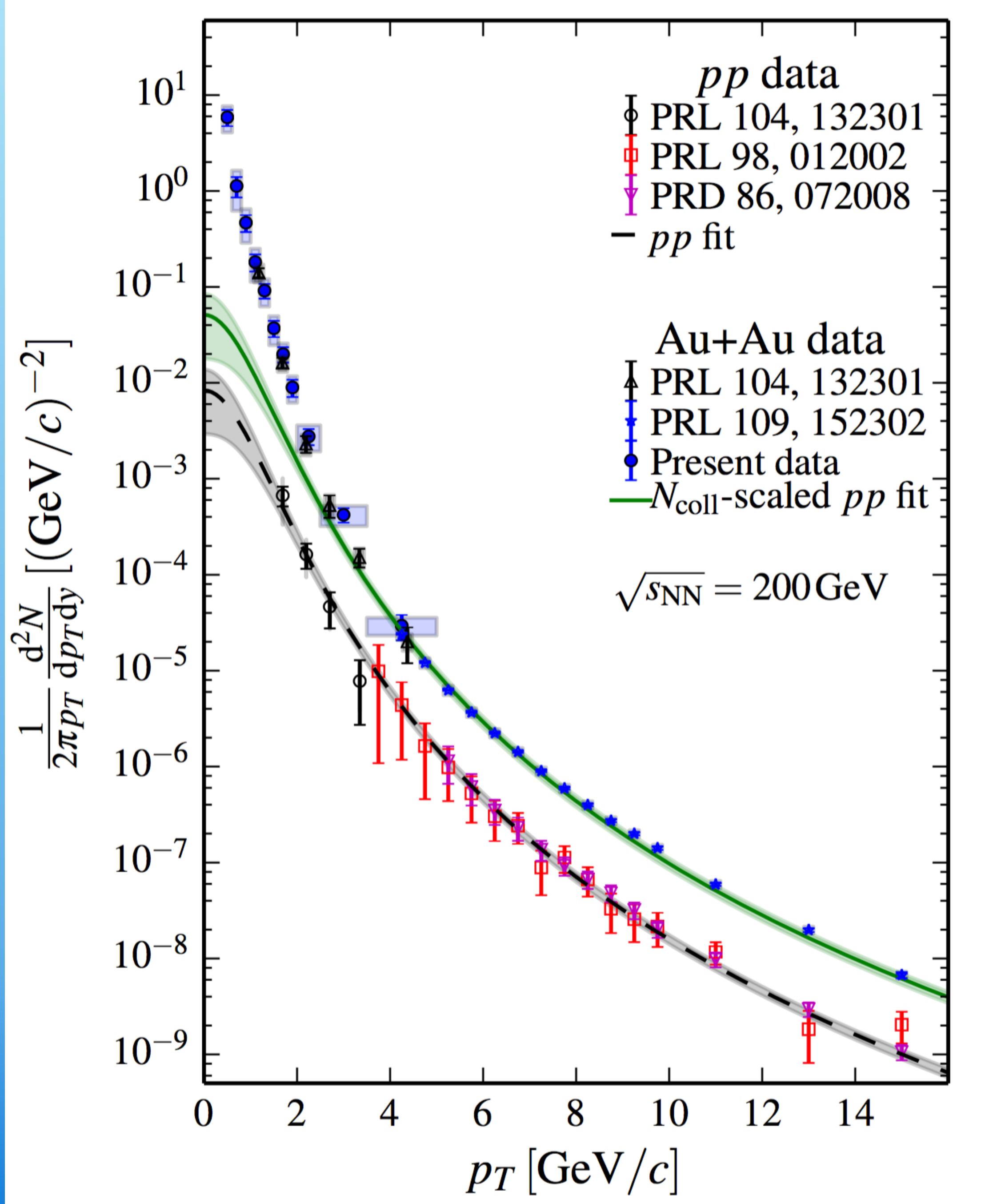


III Selected physics results:

1. Direct photons

Wenqing Fan, ICNFP2017

PHENIX AuAu 200 GeV

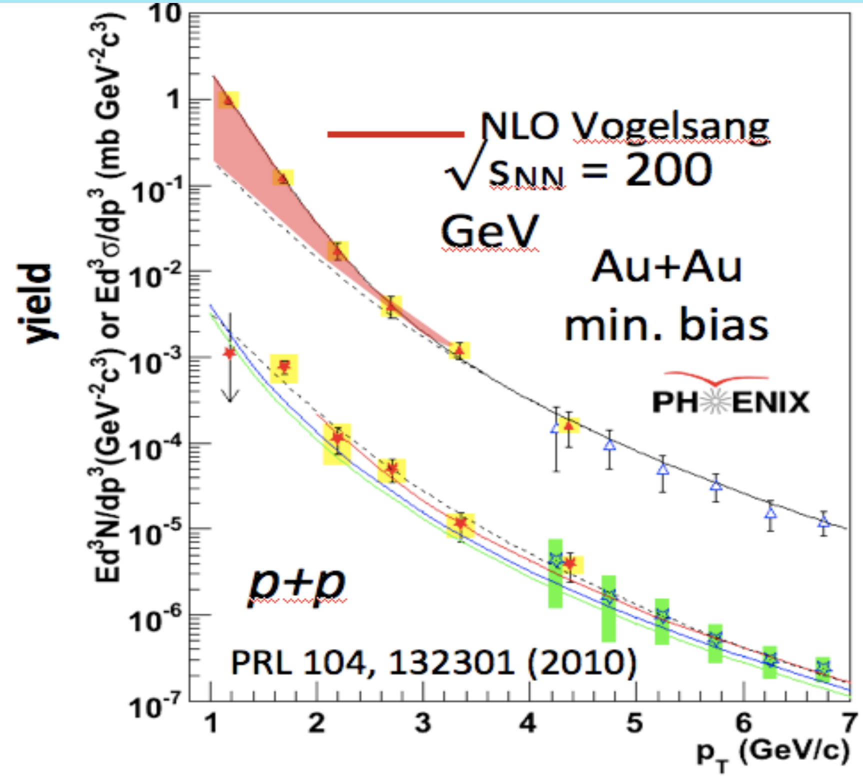


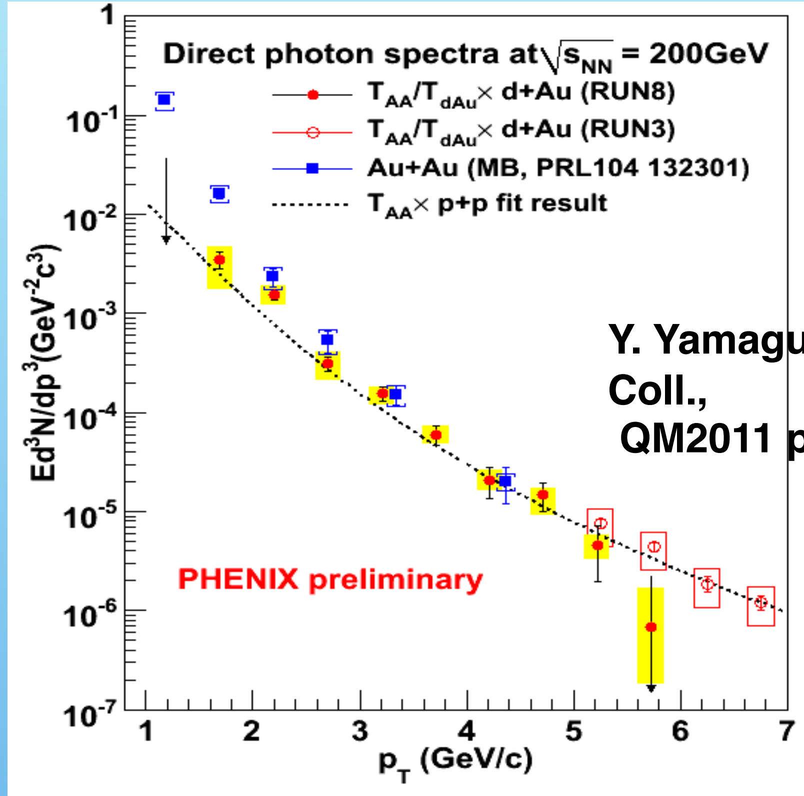
Different method: Measuring gammas via external conversions in detector material

AuAu at low pT : nearly exponential shape : T(eff) 240 MeV > T_c

AuAu follows nr of collision scaling above pT 4 GeV like p+p

RHIC PHENIX: Direct photon excess in min bias Au+Au at





Y. Yamaguchi, PHENIX Coll., QM2011 poster

Confirmed also with other measurement method : PHENIX 1405.3940, published in PRC 91 (2015) 064904

Direct photons in p+p described by NLO

Direct photon excess in min. bias Au+Au at 200 GeV over p+p at 200 GeV below pT ~2.5 GeV

Exponential spectrum in Au+Au - consistent with thermal below pT ~2.5 GeV with inverse slope 220 ± 20 MeV -->
T(init) from hydrodynamic models : 300-600 MeV, depending on thermalization time

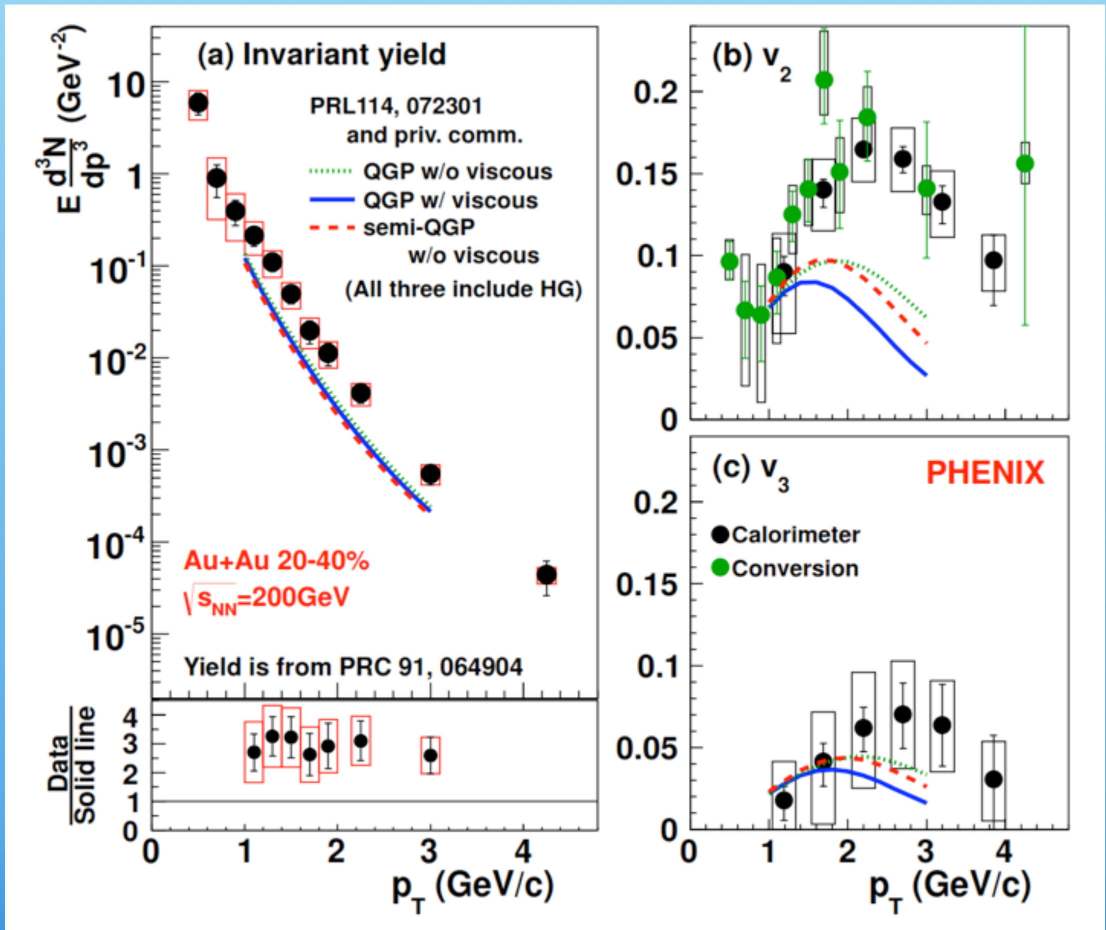
Critical d+Au check : No exponential excess in d+Au

Direct thermal photons were firmly established for the first time at RHIC

Direct photons also flow

Example: viscous hydro + thermal emission

PHENIX: Phys. Rev. C 91 064904 (2015)
and 1405.3940

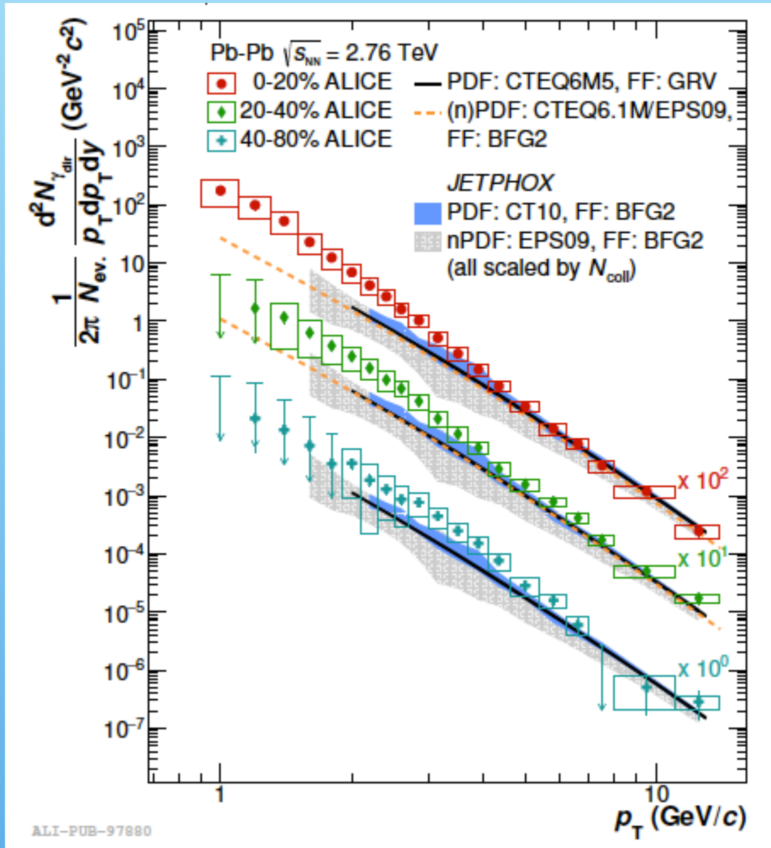


Thermal direct photons with large flow v2, v3: challenge for models

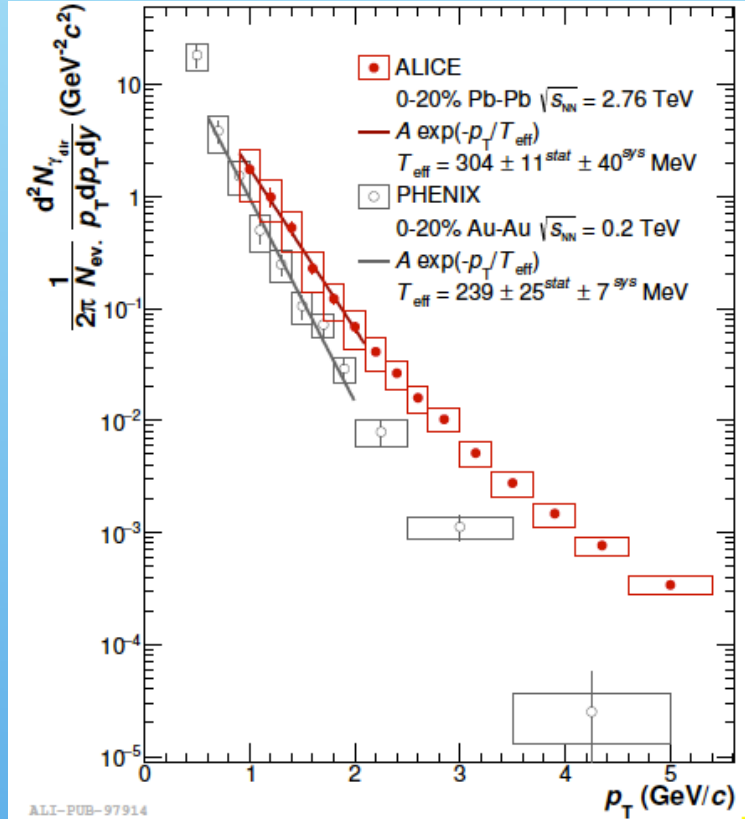
ALICE direct photons

ALICE:1509.07324

ALICE: different centralities



ALICE vs PHENIX

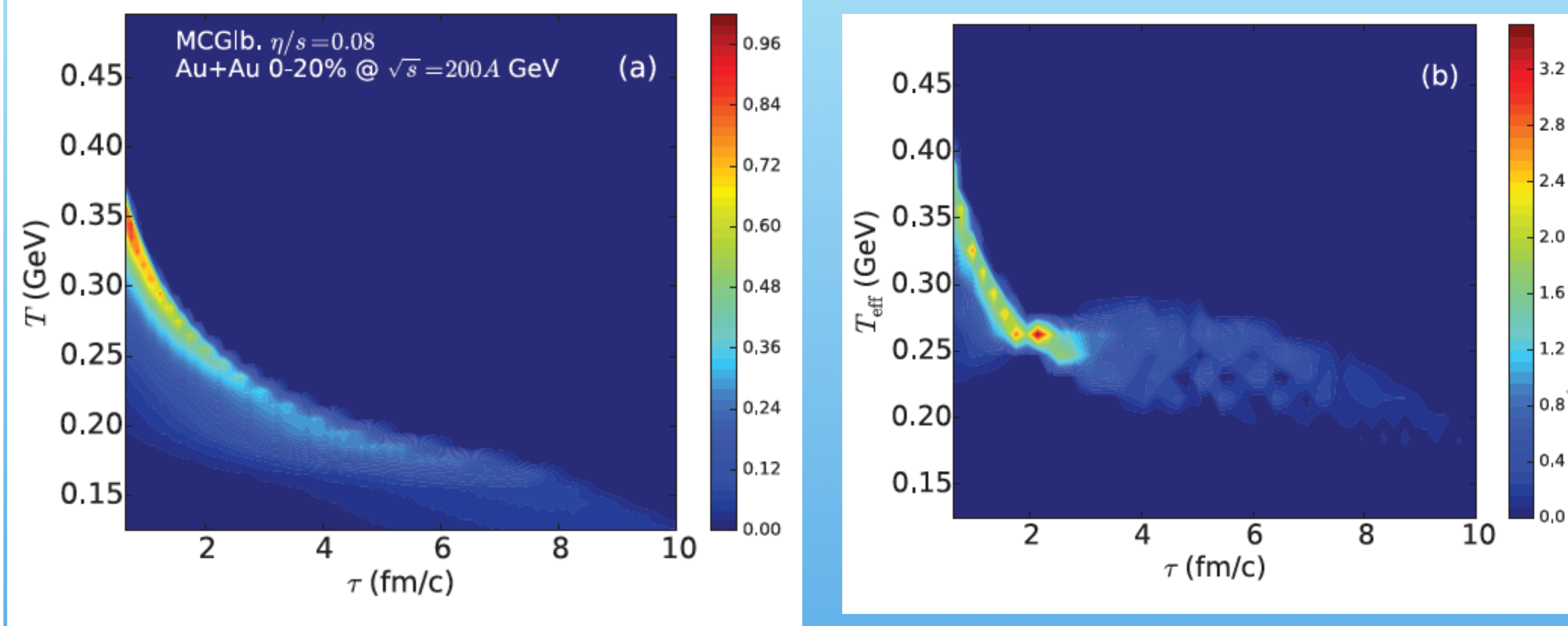


- 2.6σ excess in low p_T in 0–20% central
- T_{eff} = 304±11±40 MeV (30% larger than at RHIC)

T(dir. phot.) at RHIC and LHC is > than critical Tcrit~154 MeV
The real initial T of the source is higher than the measured T

RHIC
Theory on direct photons

C. Gale et al, 1308.2440

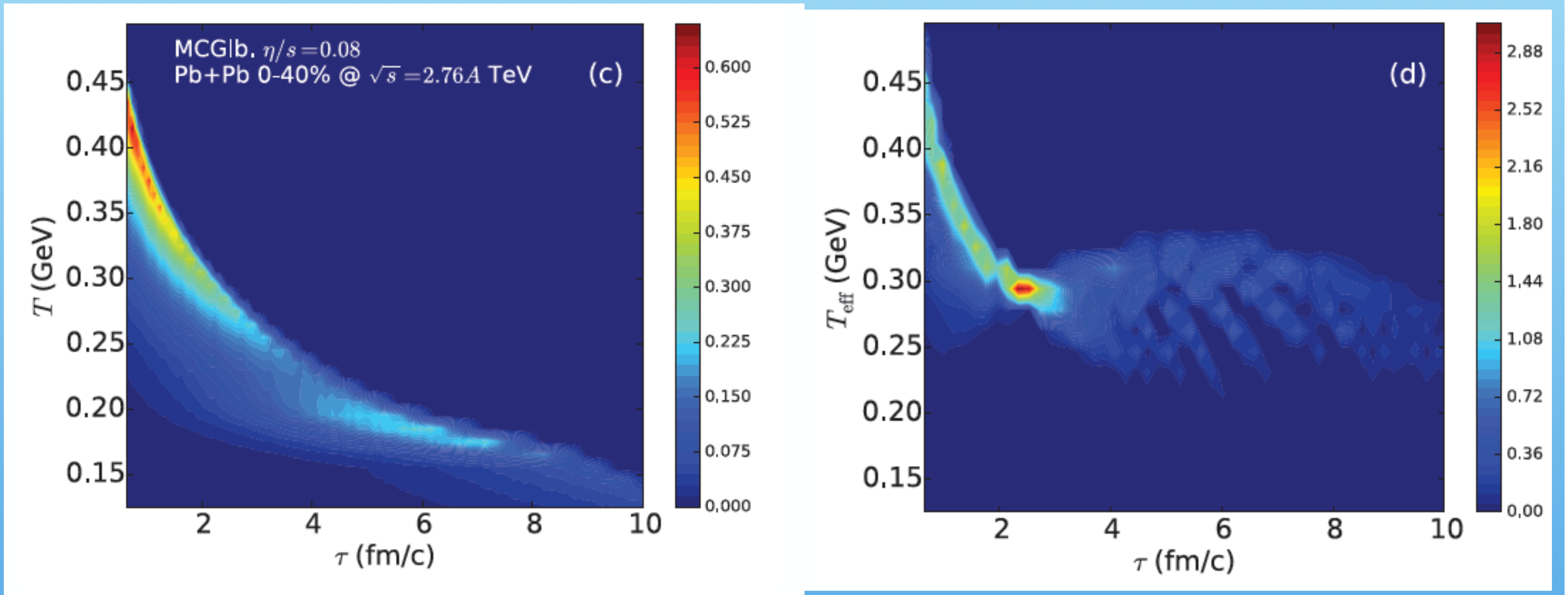


The 3rd dimension in these plots is cross section of photons

$$\frac{dN^{\gamma} / dydTd\tau}{dN^{\gamma} / dy}$$

LHC

Theory on direct photons



C. Gale et al, 1308.2440

Photons as a thermometer

range of photon emission	fraction of total photon yield	
	AuAu@RHIC 0-20% centr.	PbPb@LHC 0-40% centr.
T = 120-165 MeV	17%	15%
T = 165-250 MeV	62%	53%
T > 250 MeV	21%	32%
$\tau = 0.6 - 2.0\,\mathrm{fm/c}$	28.5%	26%
$\tau > 2.0\,\mathrm{fm/c}$	71.5%	74%

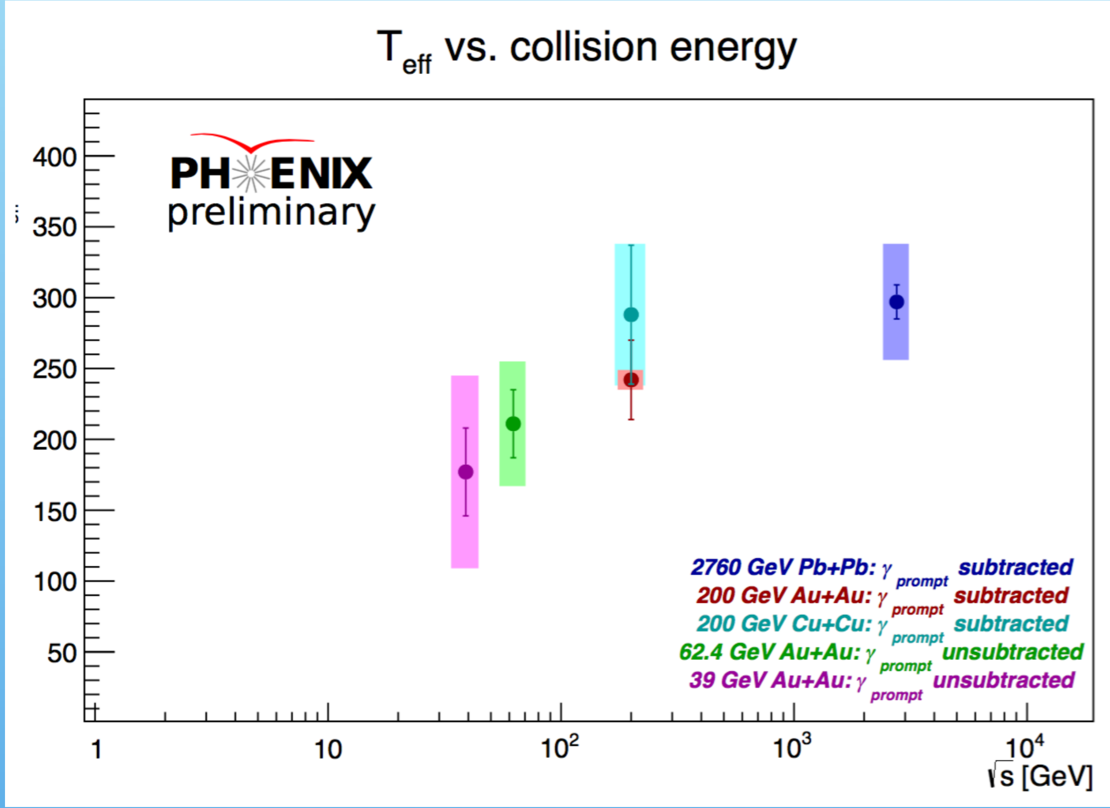
C. Gale et al, 1308.2440

*** Most photons at RHIC and LHC are emitted from time near Tc**
*** Their effective temperature is enhanced by strong radial flow (effective temperature of hadrons decaying into photons are above Tc due to mass dependence of radial flow).**
*** However a very high temperature early initial collision stage is required to generate this radial flow**

Conclusions:
*** Photons can be used as a thermometer**
*** T>Tc is reached**
*** More model calculations needed to fit the data and extract the T(init)**

Latest results from RHIC Beam Energy Scan: direct photons

effective T(from direct photons)



PHENIX, Dheepali Sharma
QM2017

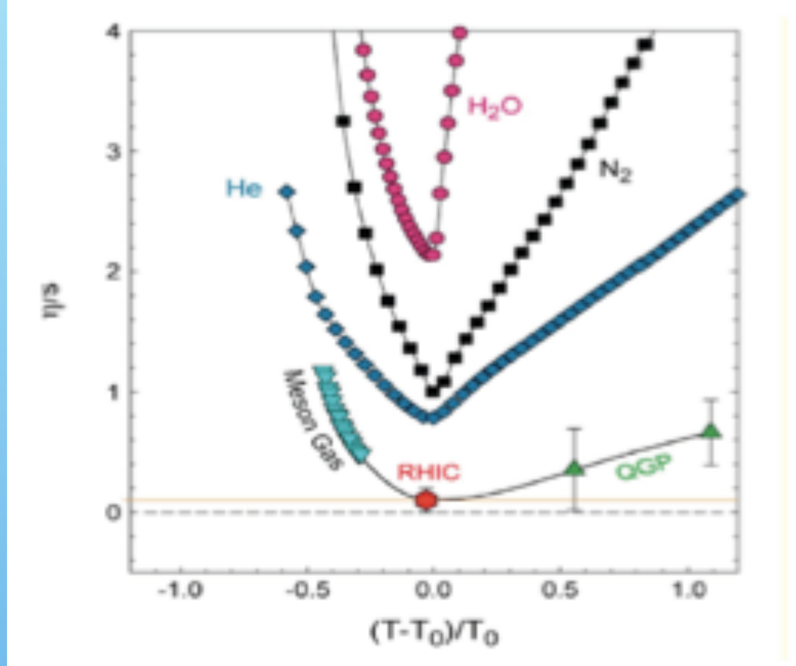
3. Collectivity, Flow, Strangeness

Flow and shear viscosity

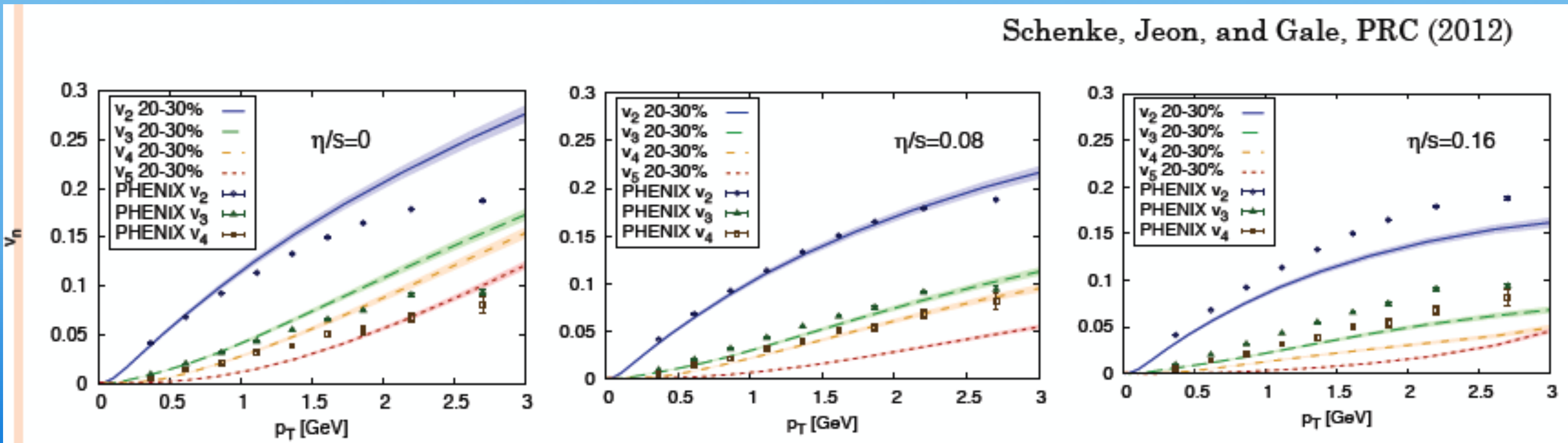
- 2003: discovery at RHIC of large flow and first extraction of shear viscosity -> RHIC white papers

- QGP : a perfect liquid

- strongly interacting QGP



PHENIX

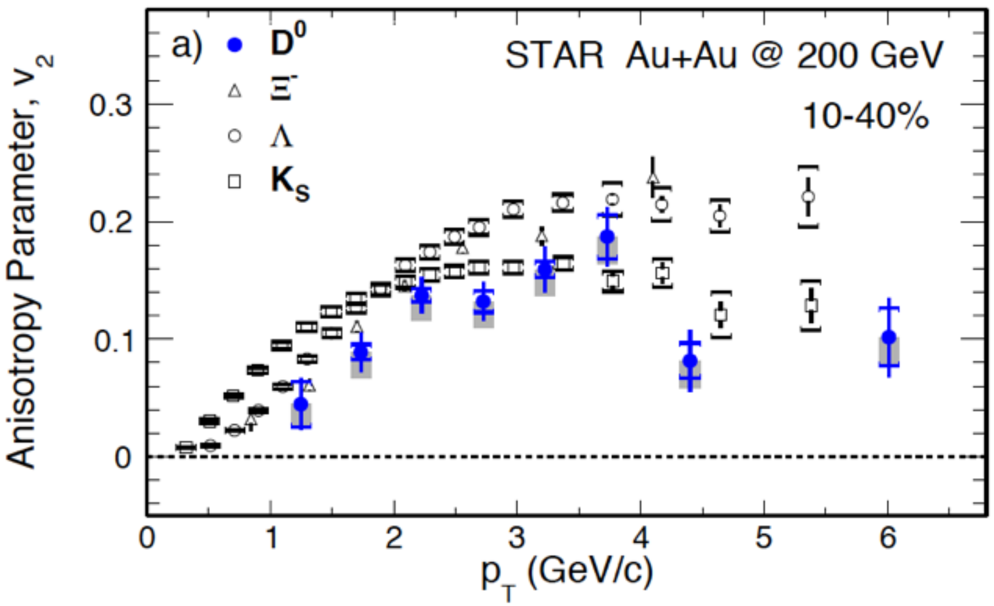


Strangeness and charm v2

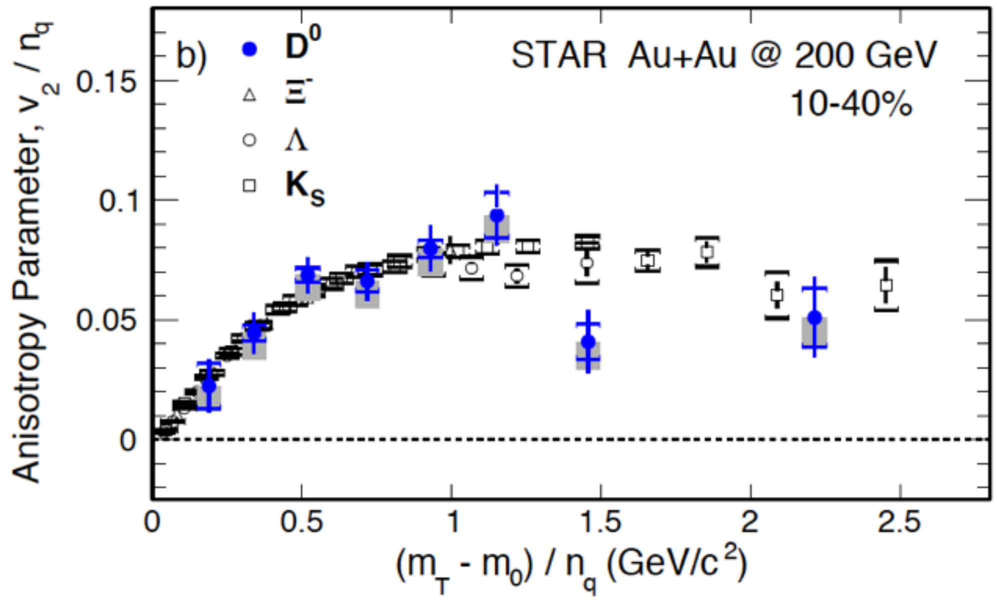
STAR New D0 v2 from STAR Heavy Flavor Tracker

1701.06060, STAR

Mass ordering



NCQ scaling

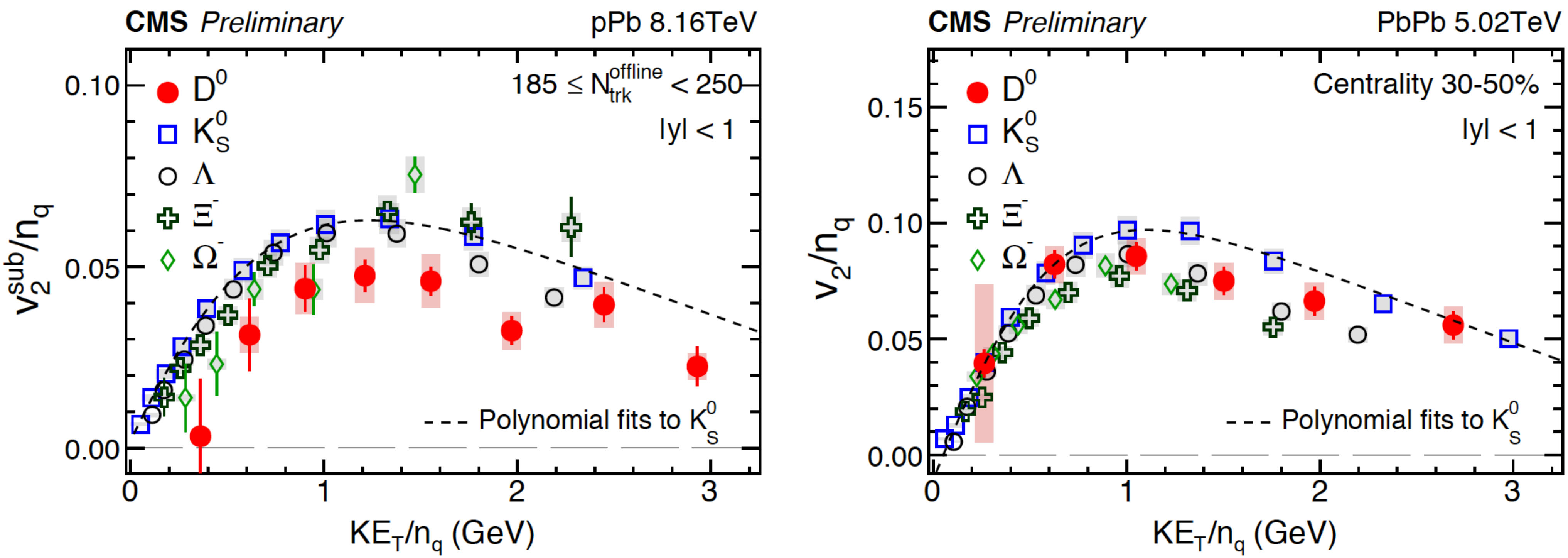


v2 of D0 in Au+Au follows Number-of-Constituent-Quarks scaling of other hadrons

-> Evidence for thermalization of u,d,s,c mesons

CMS D0 and strange particles in pPb, PbPb

CMS 1705.01974

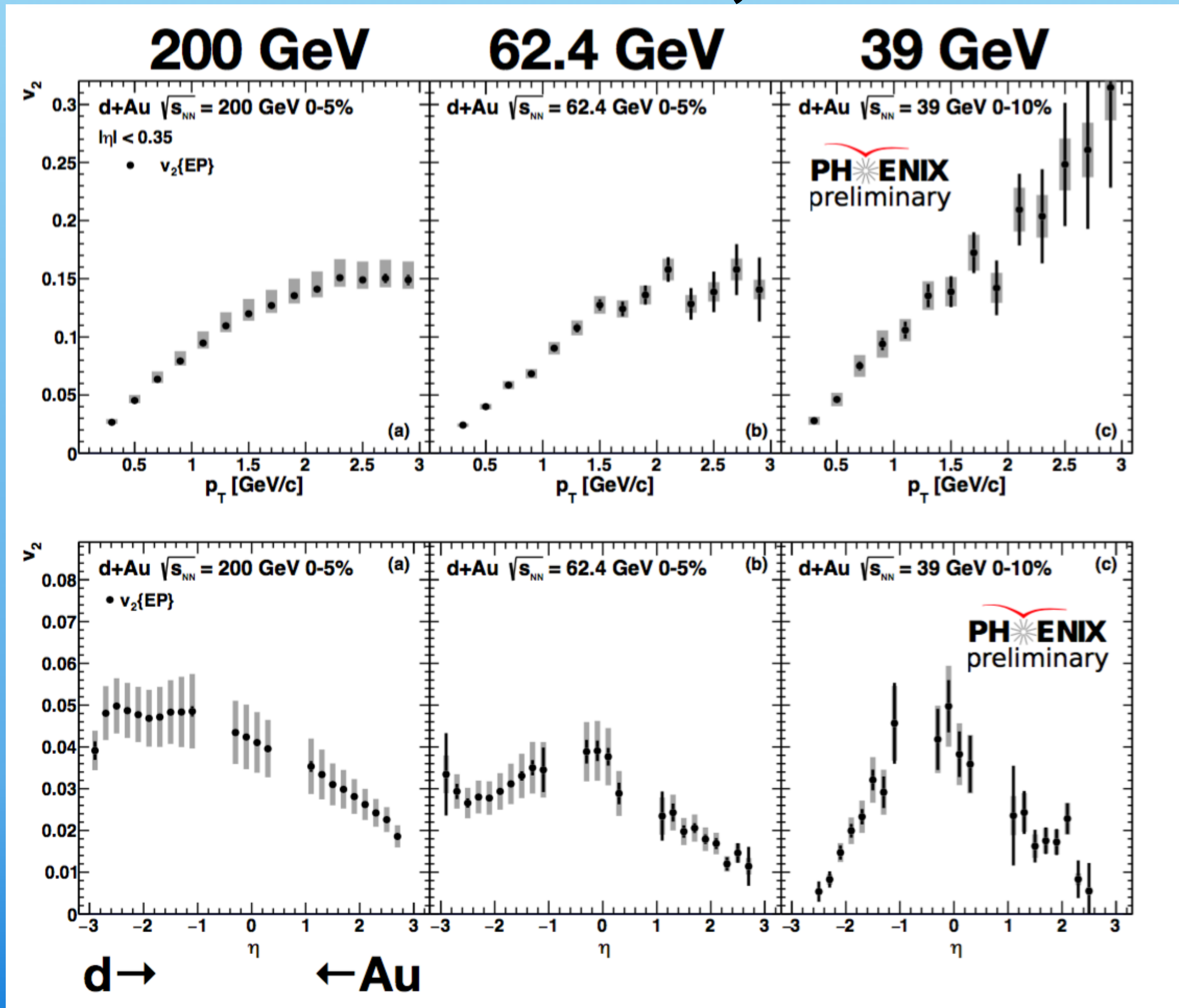


Left, pPb at high mult: v2/nq of strange particles tend to lie on a universal curve below 1.5 GeV, while D0 fall below indicating weaker collective behaviour for charm quarks

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

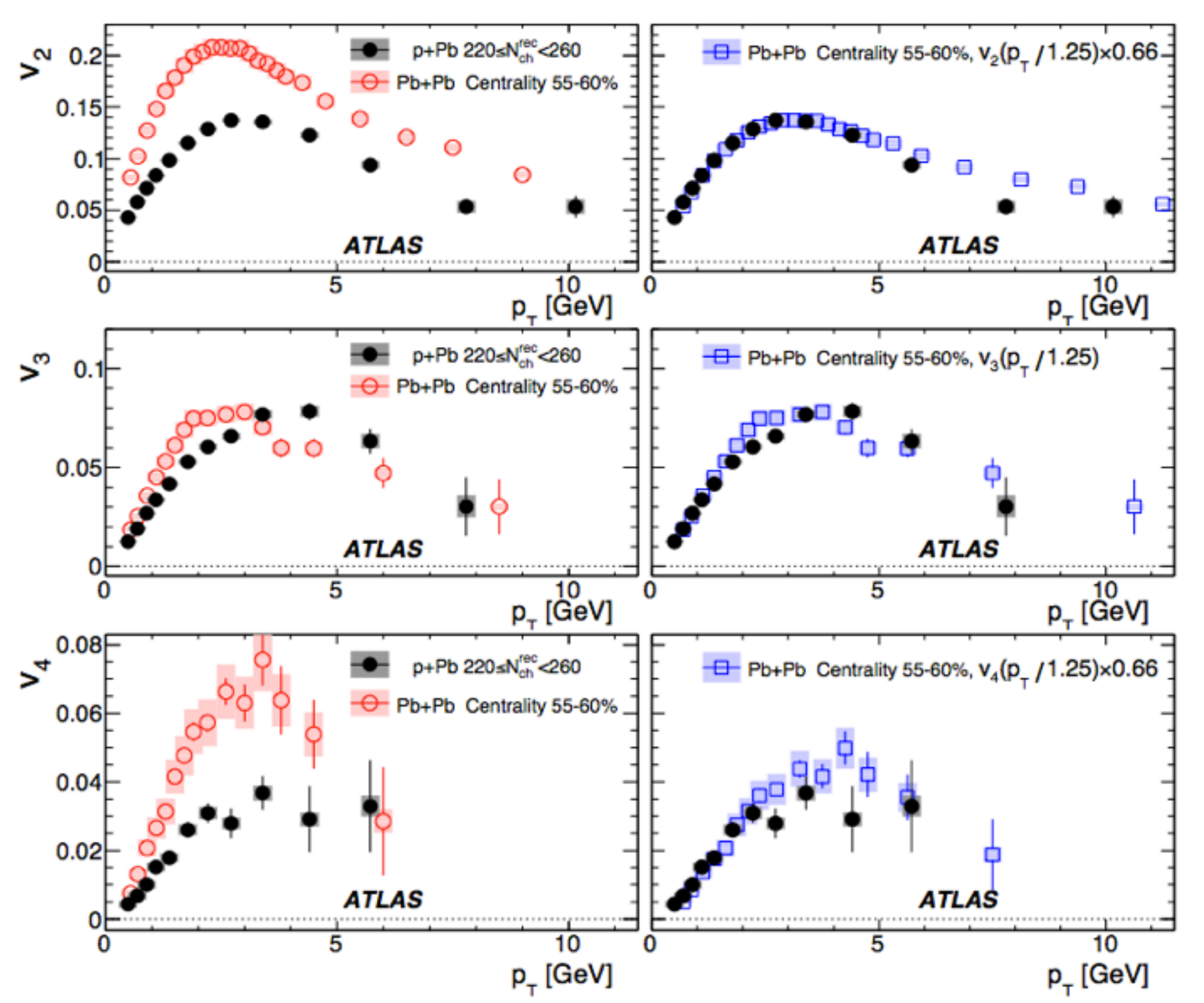
Small Systems

v2, v3 observed also in small systems: PHENIX, d+Au



PHENIX, J. Velkovska, QM2017

Large flow observed in p+Pb collisions at sqrt(s)=5.02 TeV



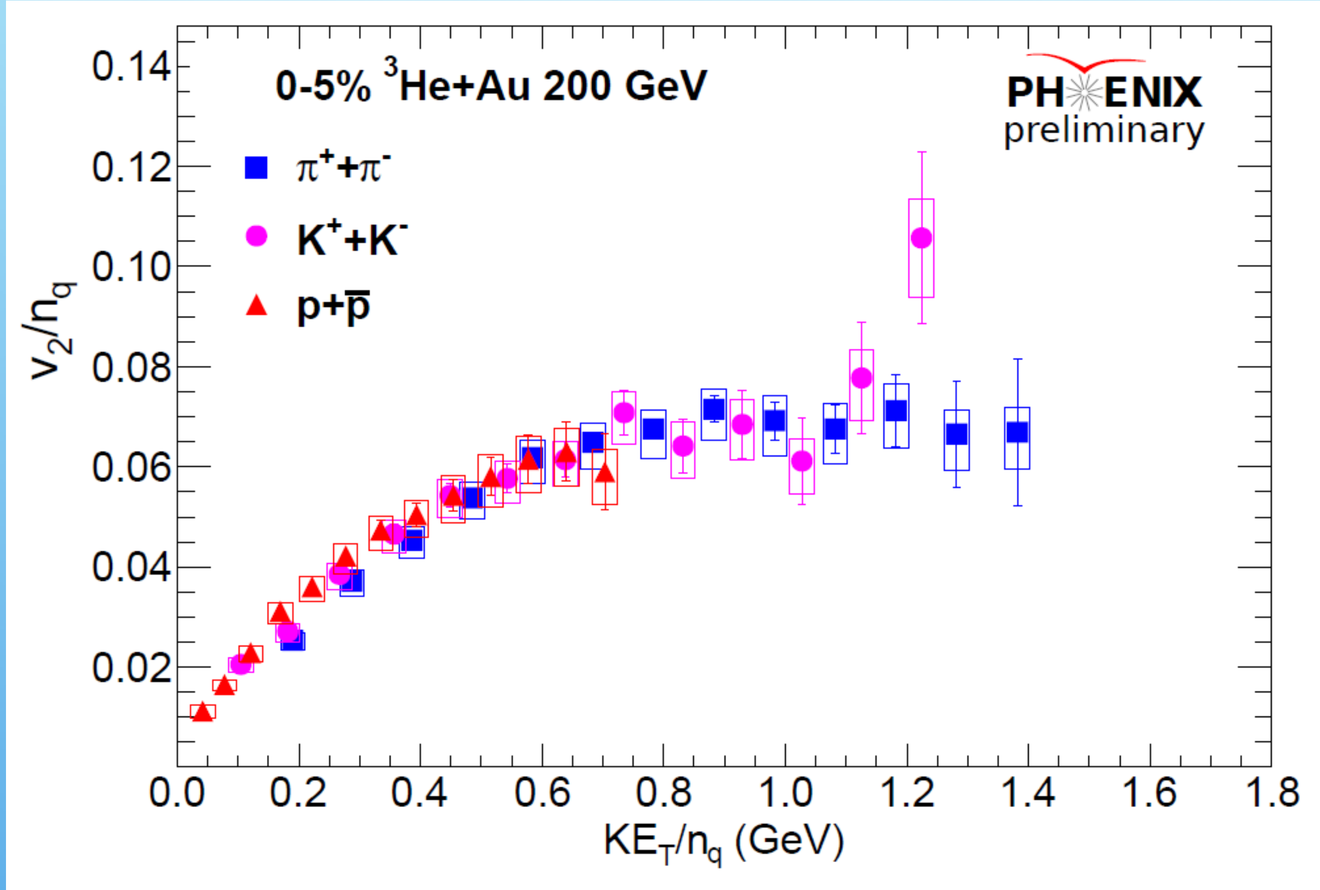
Results from ATLAS 1409.1792

After applying scale factor of 1.25 accounting for the difference in mean pT of pPb and PbPb as proposed by Basar and Teaney :

The shape of the v_n distributions in pPb and PbPb are found to be similar

Evidence for collectivity in p+Pb ?

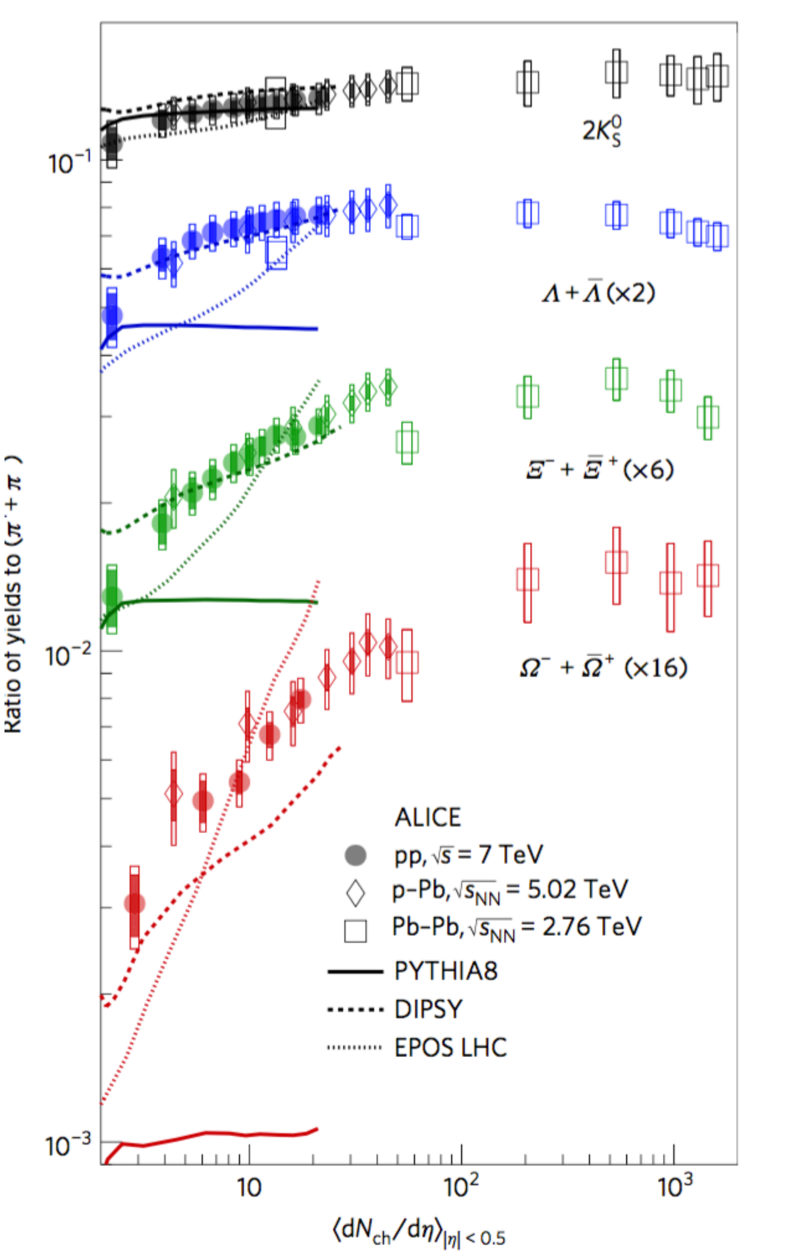
Number of quark scaling in 3He+Au



S Huang, STAR, QM15

The familiar behavior of number of quark scaling observed in Au+Au collisions is also seen in the small ^{3}He+Au system

ALICE



The novel measurement of ALICE: consistent strangeness enhancement in pp, pPb and PbPb collisions which depends on strangeness content and cannot be reproduced by models at same time as p/pi ratio

Adds to previous measurements showing QGP signatures in small systems. These new measurements at LHC point towards possible formation of QGP matter at high Temperature and density also in small collisions systems.

Comment from ALICE paper:

"The remarkable similarity of strange particle production in pp, p–Pb and Pb–Pb collisions adds to previous measurements in pp, whch also exhibit characteristic features known from high-energy heavy-ion collisions and are understood to be connected to the formation of a deconfined QCD phase at high temperature and energy density.

QGP formation also in small systems?

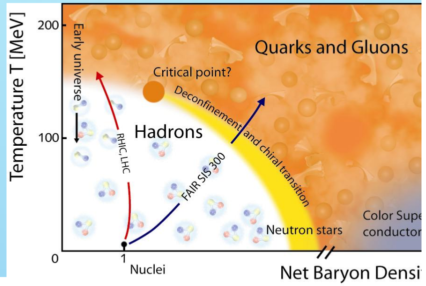
Do small QGP droplet form in p+p, p+A?

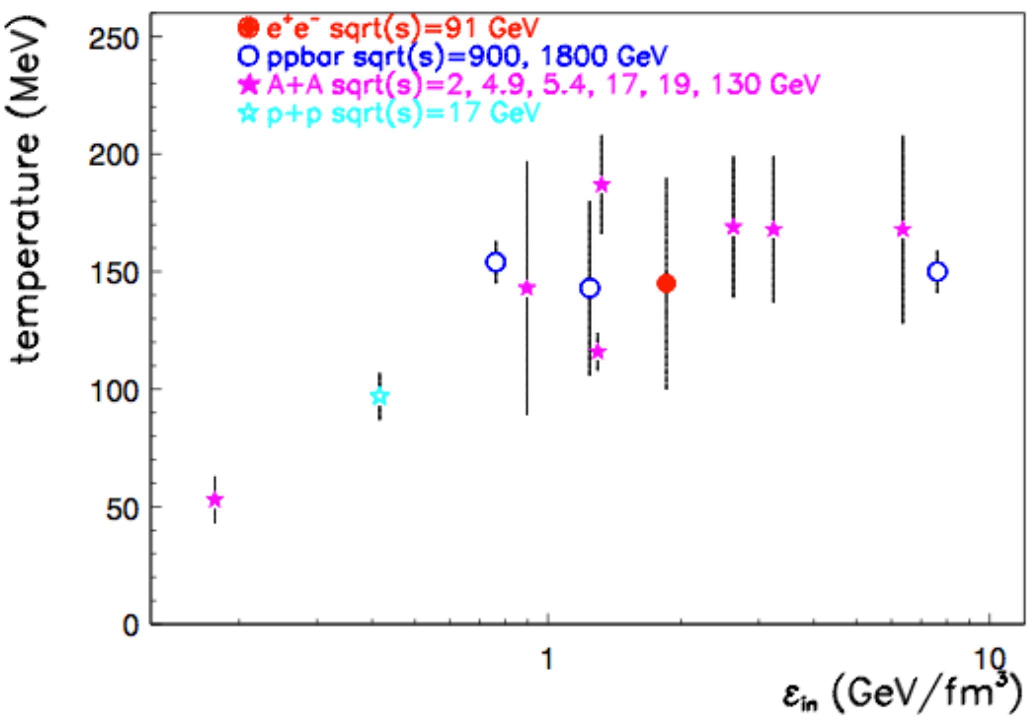
Till few years ago, p+p, p+A in the heavy ion community were assumed to be QGP-free systems by definiton to which people compared A+A to find the QGP

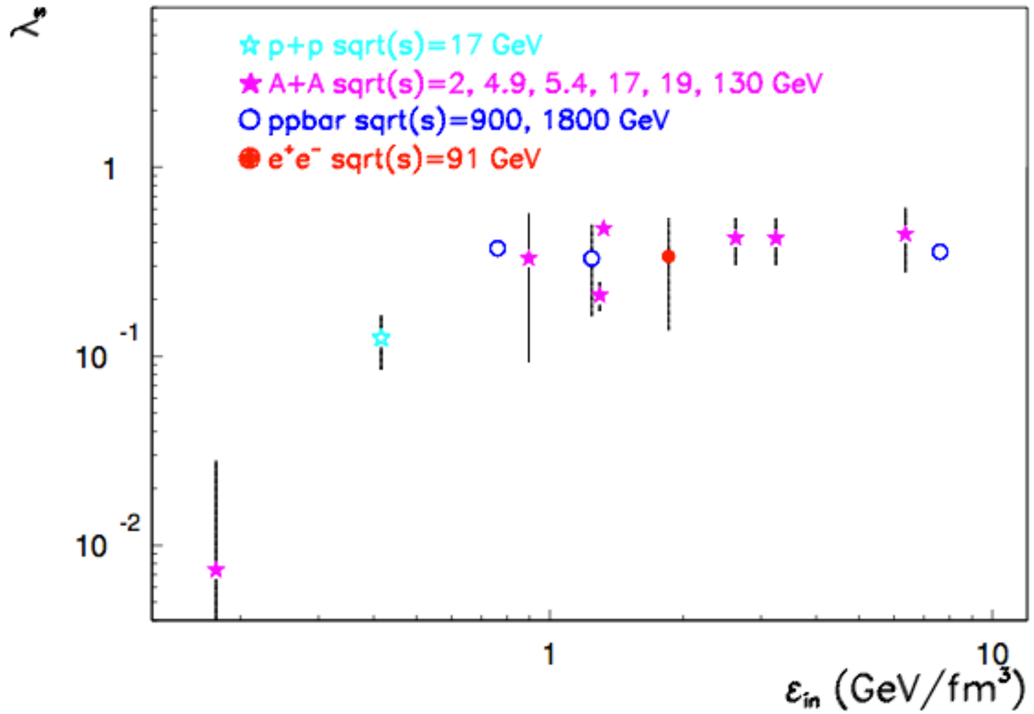
New data on collectivity seen in p+A, p+p prompt the idea that QGP may form in p+p, p+A ?

S.K. P. Minkowski, 2001 New J. Phys. 3, 4:
proposed the universality of QGP phase transition in p+p, p+A, A+A appearing above a critical energy density.

Universality of the QCD phase transition in p+p, p+A, A+A







S.K., P. Minkowski, 2001 New J. Phys. 3 4

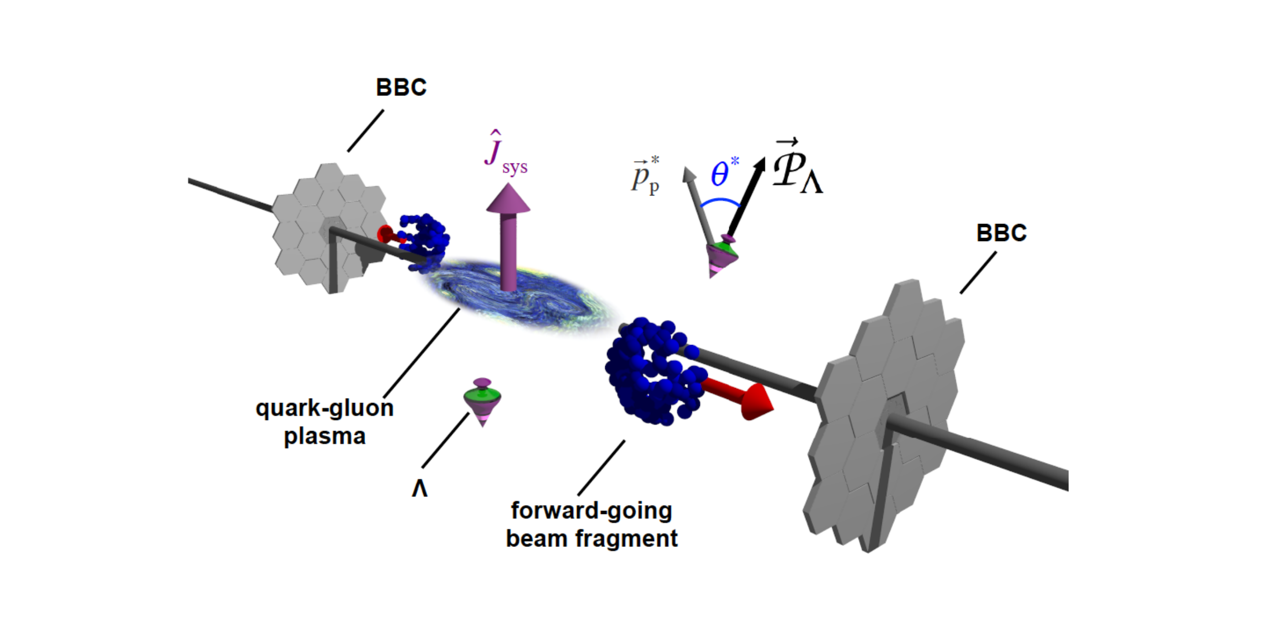
Key idea: extrapolate to muB=0
Consequences:
-> Universality of onset of phase transition near ~0.8 GeV/fm^3
-> Universality of onset of saturation of strangeness suppression factor

Differences of AA, pp, pA dissappear at high enough initial energy density and at same mu_B

First measurement of the Vorticity of QGP

First Vorticity measurement in AuAu 200 GeV 20-50% centrality

STAR, Nature, 2017, 1701.06657



Average vorticity points towards the direction of the angular momentum J(sys) of the collision.

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right).$$

H: Lambda/Anti-Lambda

P_H : Lambda/AntiL polarizatin vector in the hyperon rest frame

decay parameter $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$

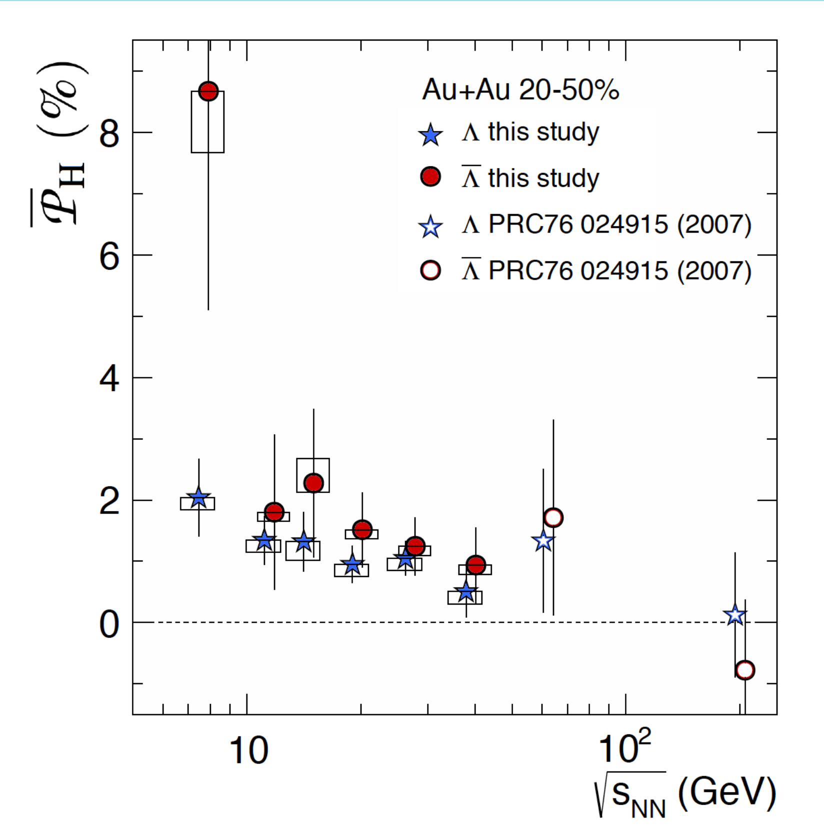
Average projection of the Polarization on J(sys) is extracted:

$$\overline{\mathcal{P}}_H \equiv \langle \vec{\mathcal{P}}_H \cdot \hat{J}_{sys} \rangle = \frac{8}{\pi\alpha_H} \frac{\left\langle \cos\left(\phi_p^* - \phi_{\hat{J}_{sys}}\right) \right\rangle}{R_{EP}^{(1)}},$$

noted here as "global polarization"

sQGP vorticity measured to be maximal

P_H: average polarization with
H: Lambda or Antilambda



STAR, Nature, 2017, 1701.06657

Measurement of vorticity in Au+Au collisions with 20-50% centrality via the average polarization of Lambda and Antilambda.

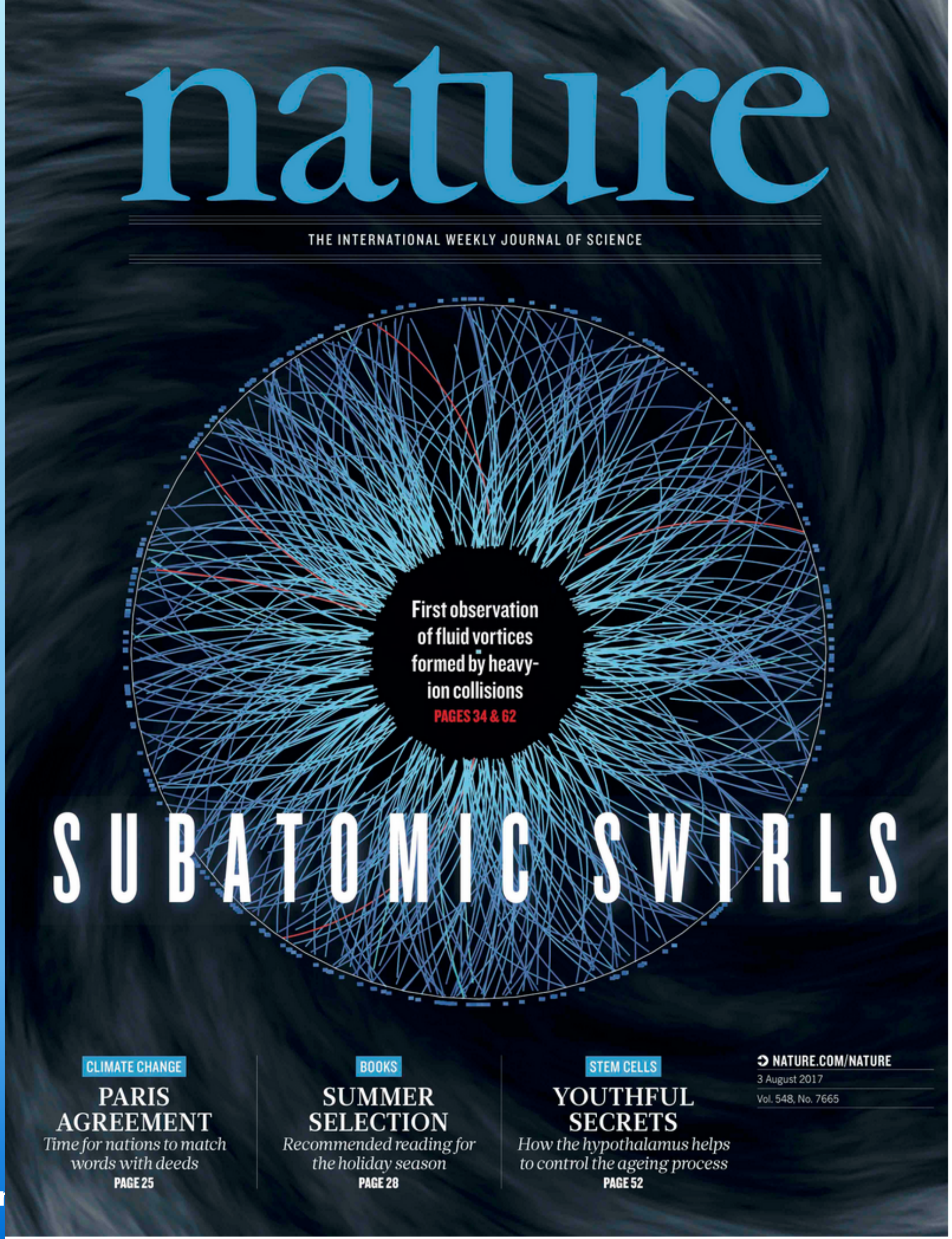
Fluid vorticity can be calculated using the hydrodynamic relation (Becatini et al 1610.02506.)

$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'} \right) / \hbar,$$

With T the temperature. The vorticity found is
omega = (9+-1) 10ˆ21 s-1
with an additional systematic error of a factor of 2 which by far surpasses the vorticity of all known fluids

For example solar subsurface flow has omega= 10-7 s-1, and superfluid nanodroplets omega=10ˆ7 s-1

*** The Quark Gluon Plasma produced in heavy ion collisions is**
- **hotter**
- **least viscous**
- **and has larger vorticity,**
  from all fluids ever produced in the laboratory !

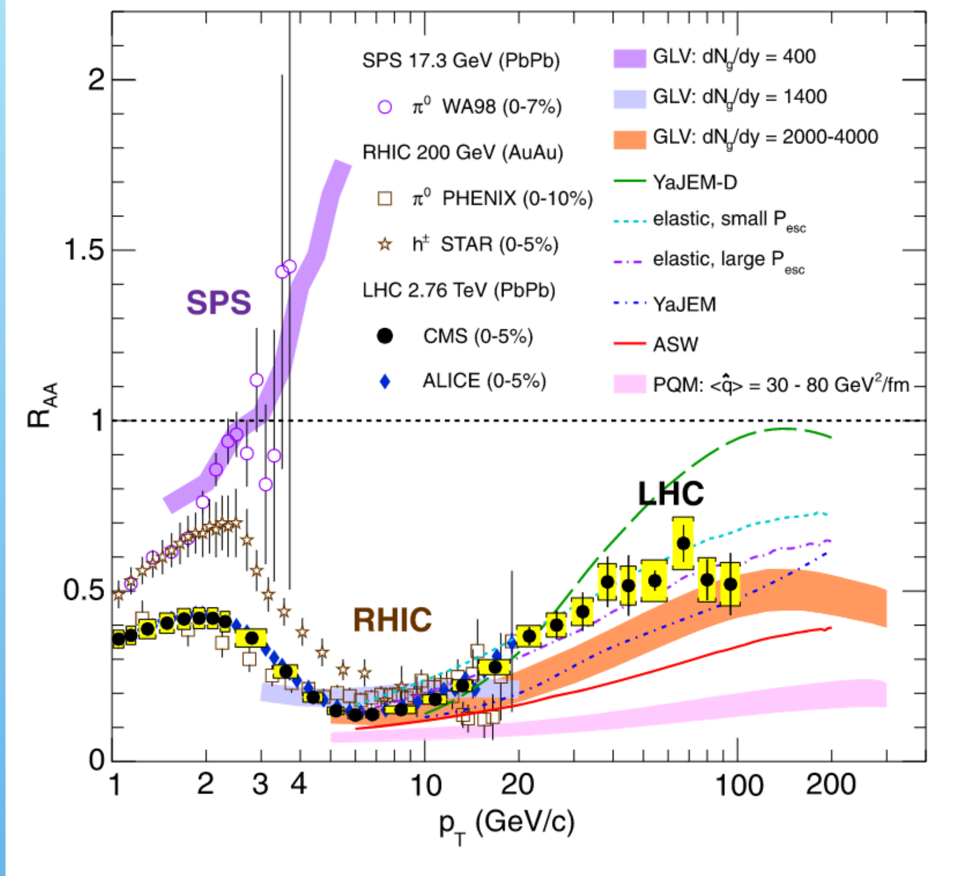

nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
First observation of fluid vortices formed by heavy-ion collisions
PAGES 34 & 62
SUBATOMIC SWIRLS
CLIMATE CHANGE
PARIS AGREEMENT
Time for nations to match words with deeds
PAGE 25
BOOKS
SUMMER SELECTION
Recommended reading for the holiday season
PAGE 28
STEM CELLS
YOUTHFUL SECRETS
How the hypothalamus helps to control the ageing process
PAGE 52
NATURE.COM/NATURE
3 August 2017
Vol. 548, No. 7665

4. Jet quenching

Single hadrons

Jet quenching hadrons
Collision energy dependence

CMS, EPJC (2012) 72:1945



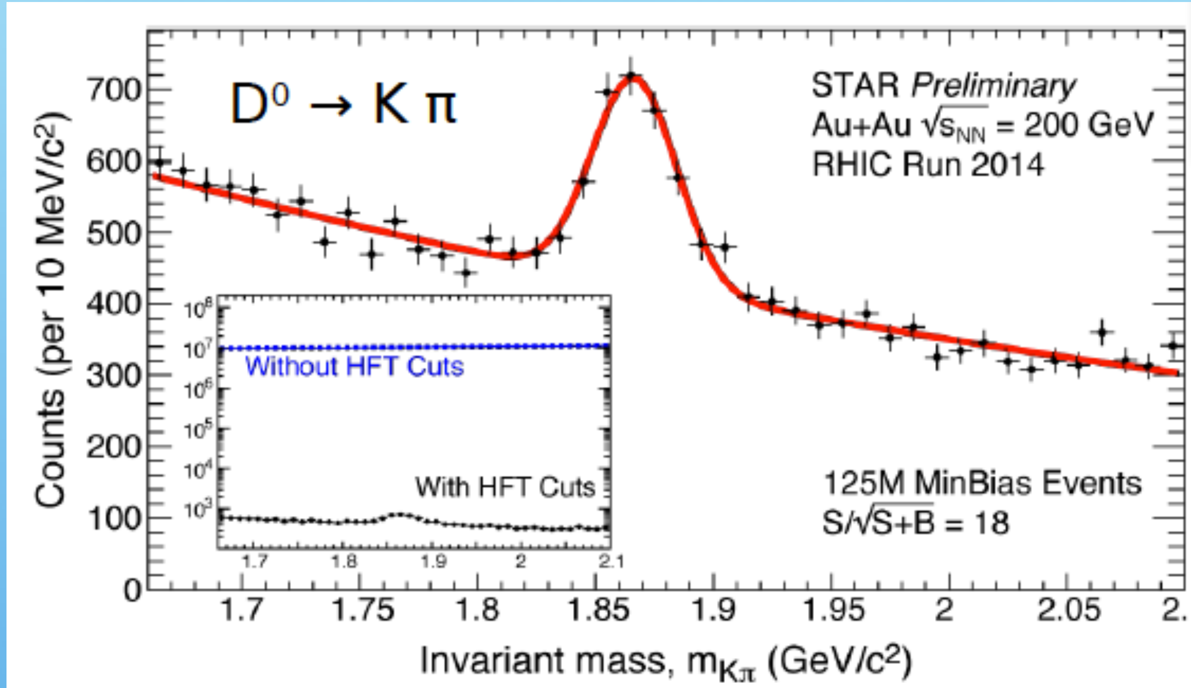
RAA compared to models for energy loss allows for an estimate of gluon density dN/dy(gluon)
Here as an example we get (GLV model):

- **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

Secondary vertex reconstruction of D mesons with HFT

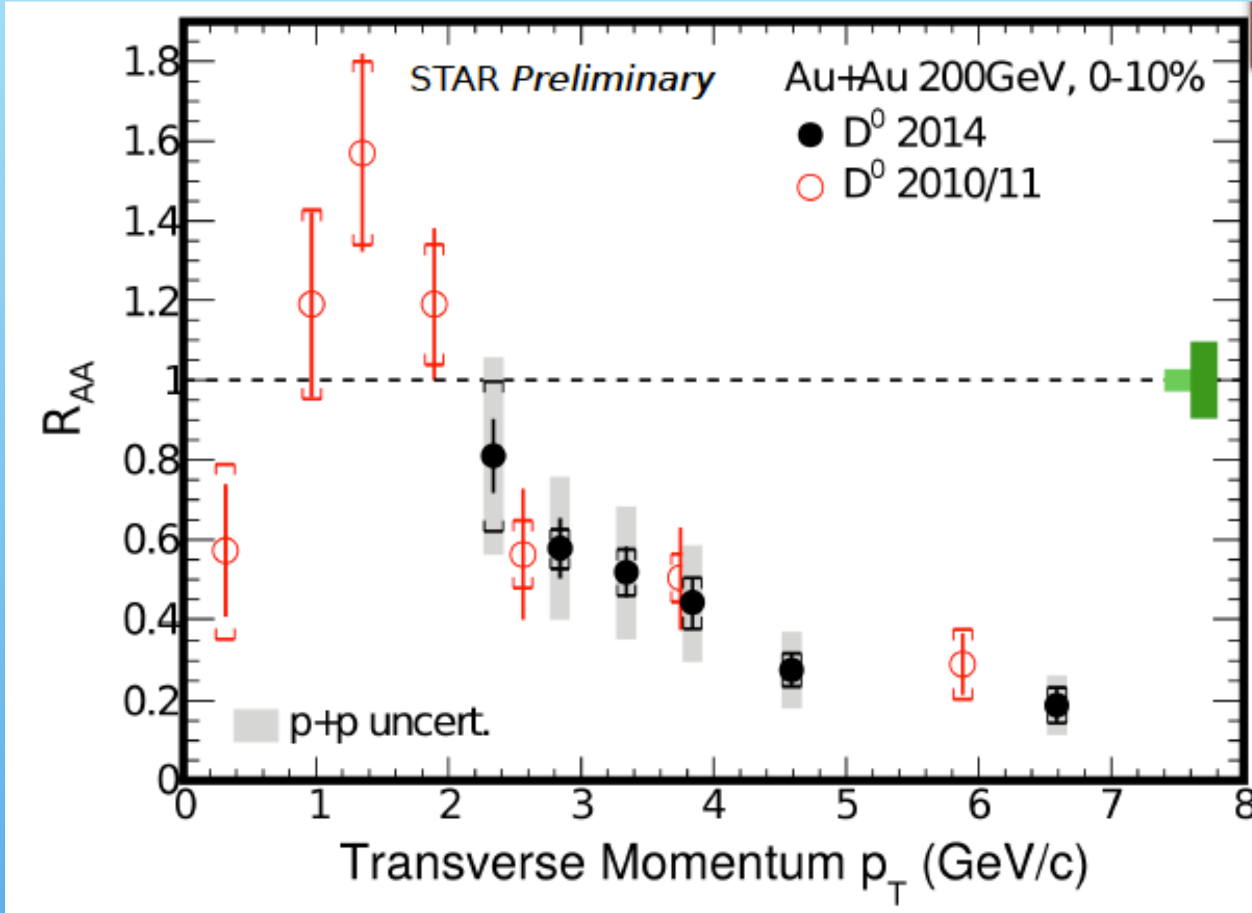
Heavy Flavor Tracker started taking data in run-14



STAR, QM15

~ 4 orders of magnitude reduction of combinatorial background

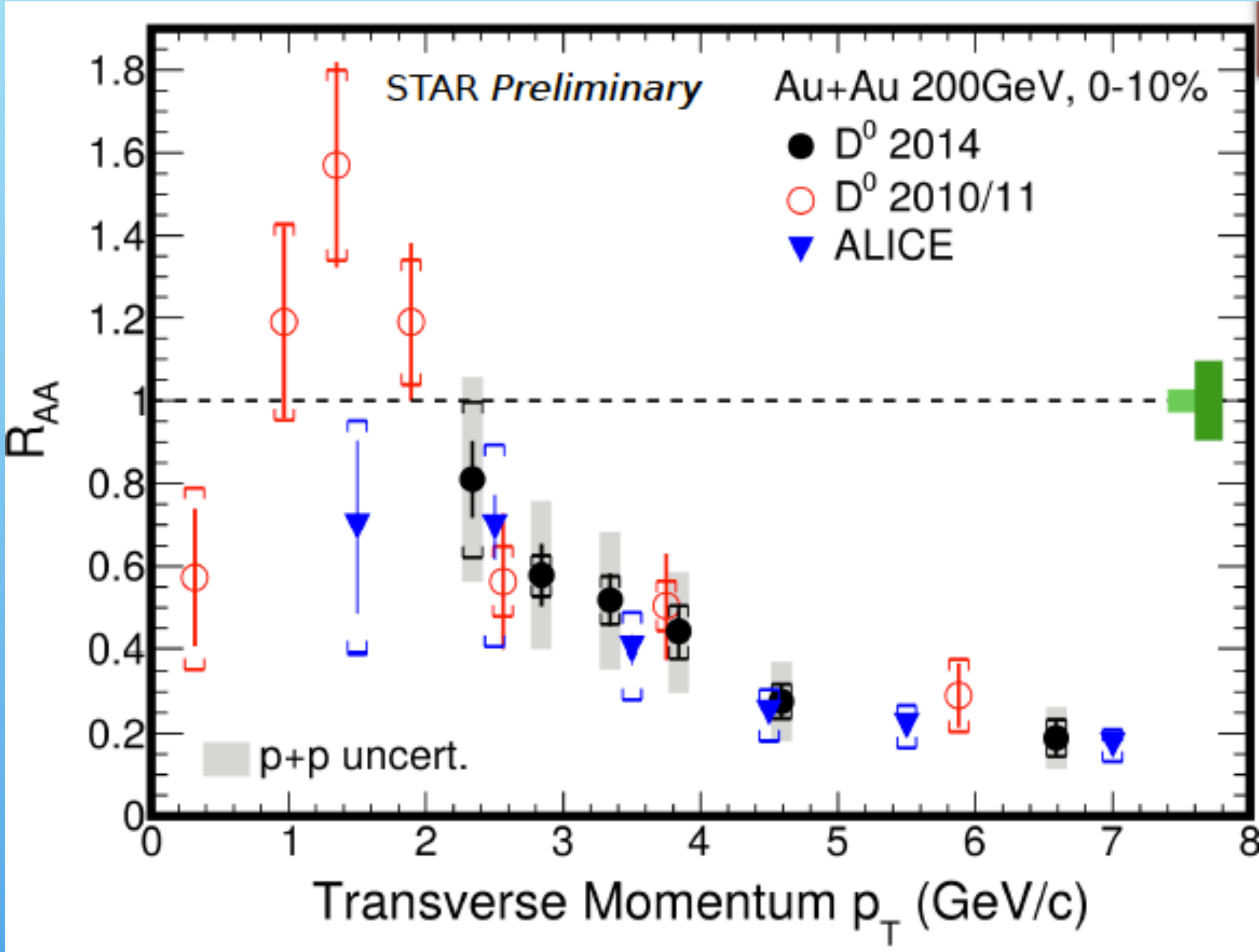
D0 nuclear modification factor in Au+Au 200 GeV from HFT



STAR, QM15

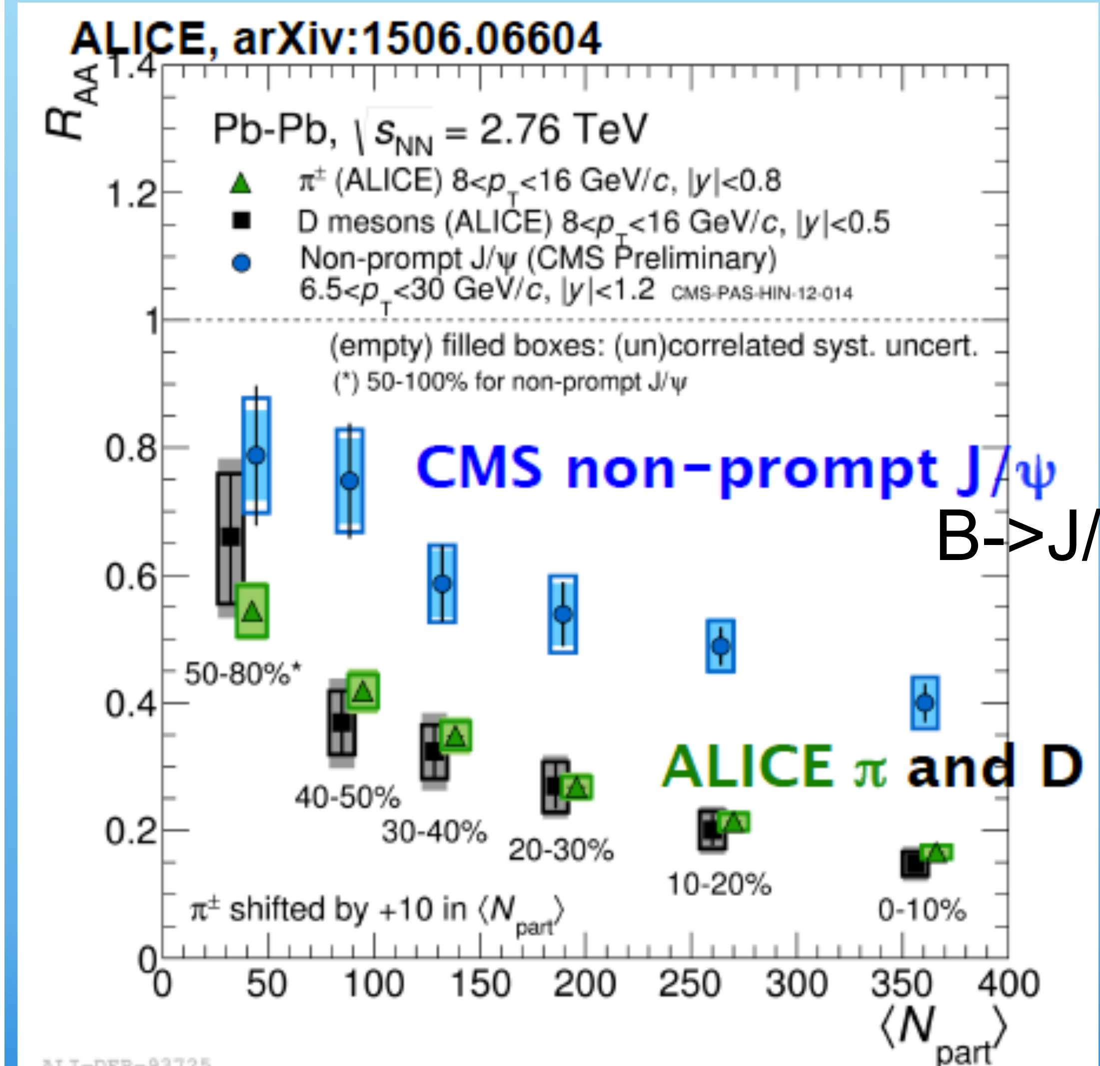
Suppression of D0 at high pT
Enhancement of D0 at pT<2 GeV/c pointing to charm coalescence with a flowing medium

Comparison RHIC to LHC



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

RAA of open charm and beauty at the LHC



B->J/Psi

ALICE, QM2015

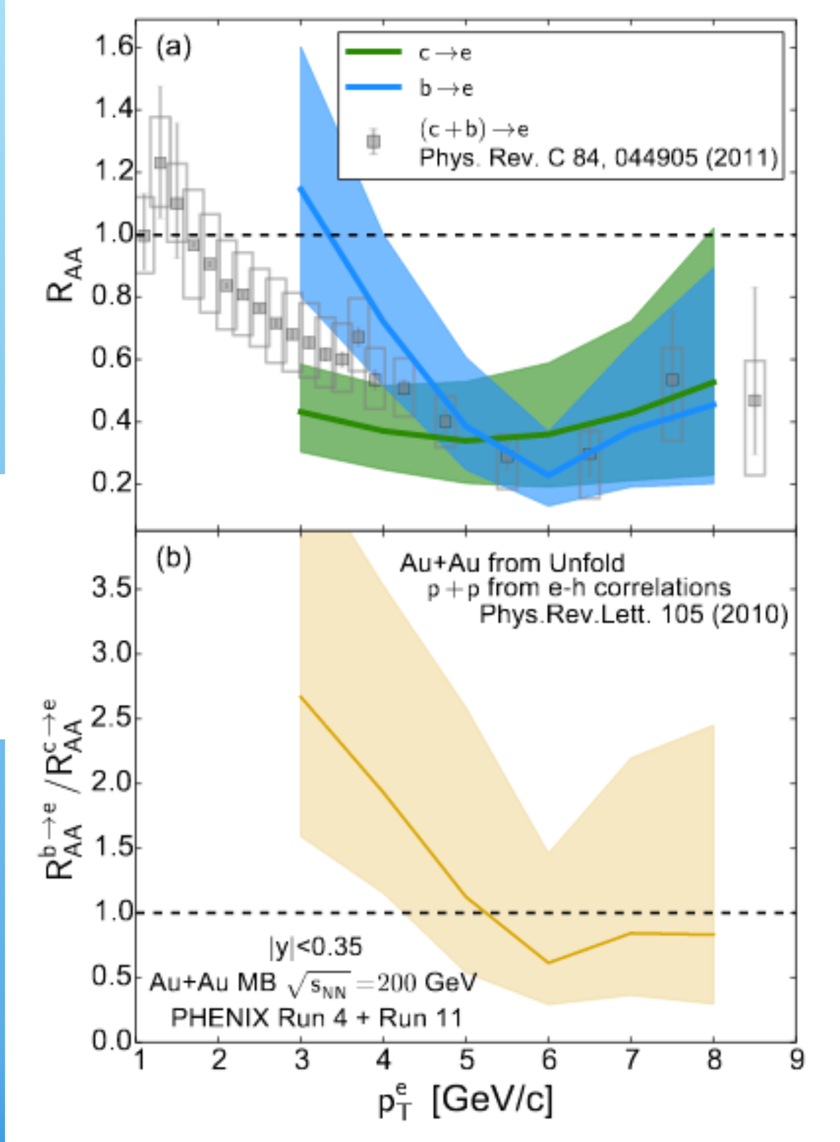
Pb+Pb ALICE, CMS:

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)

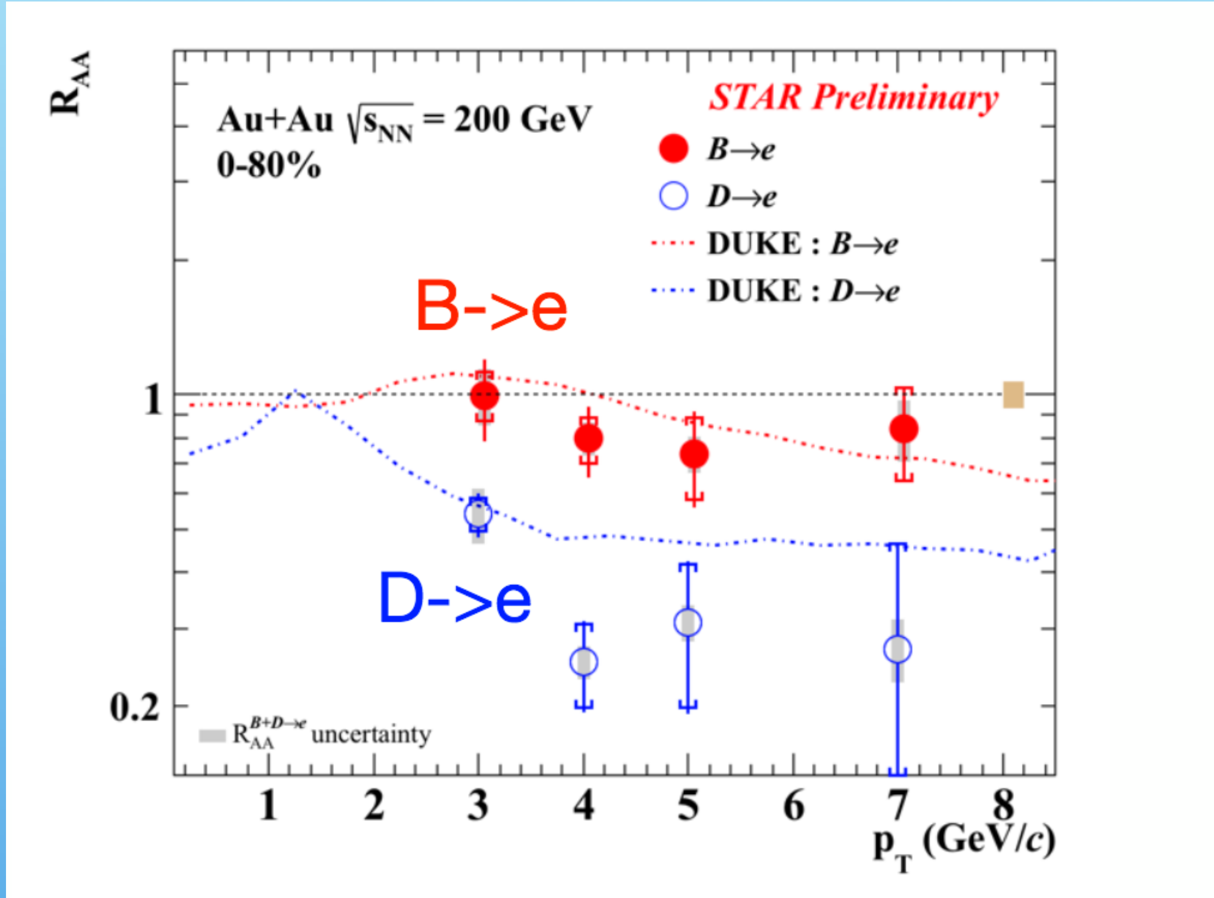
RAA of Charm and Beauty in min. bias Au+Au at 200 GeV

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

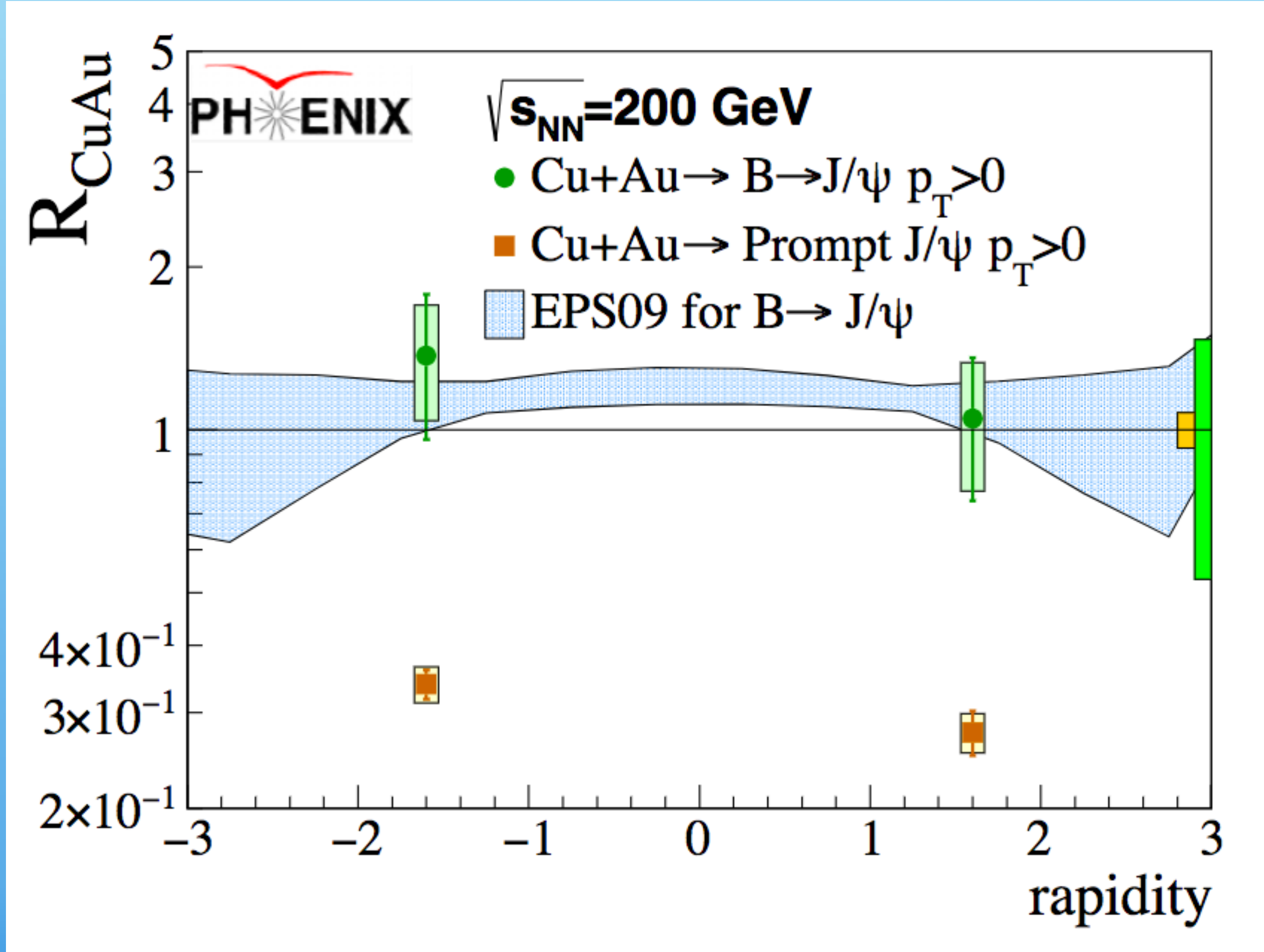


Li Yi, STAR coll.
Santa Fe work.
Jan 2018

*** Using the new STAR HFT silicon tracker with excellent resolution (high precision measurement coming)**

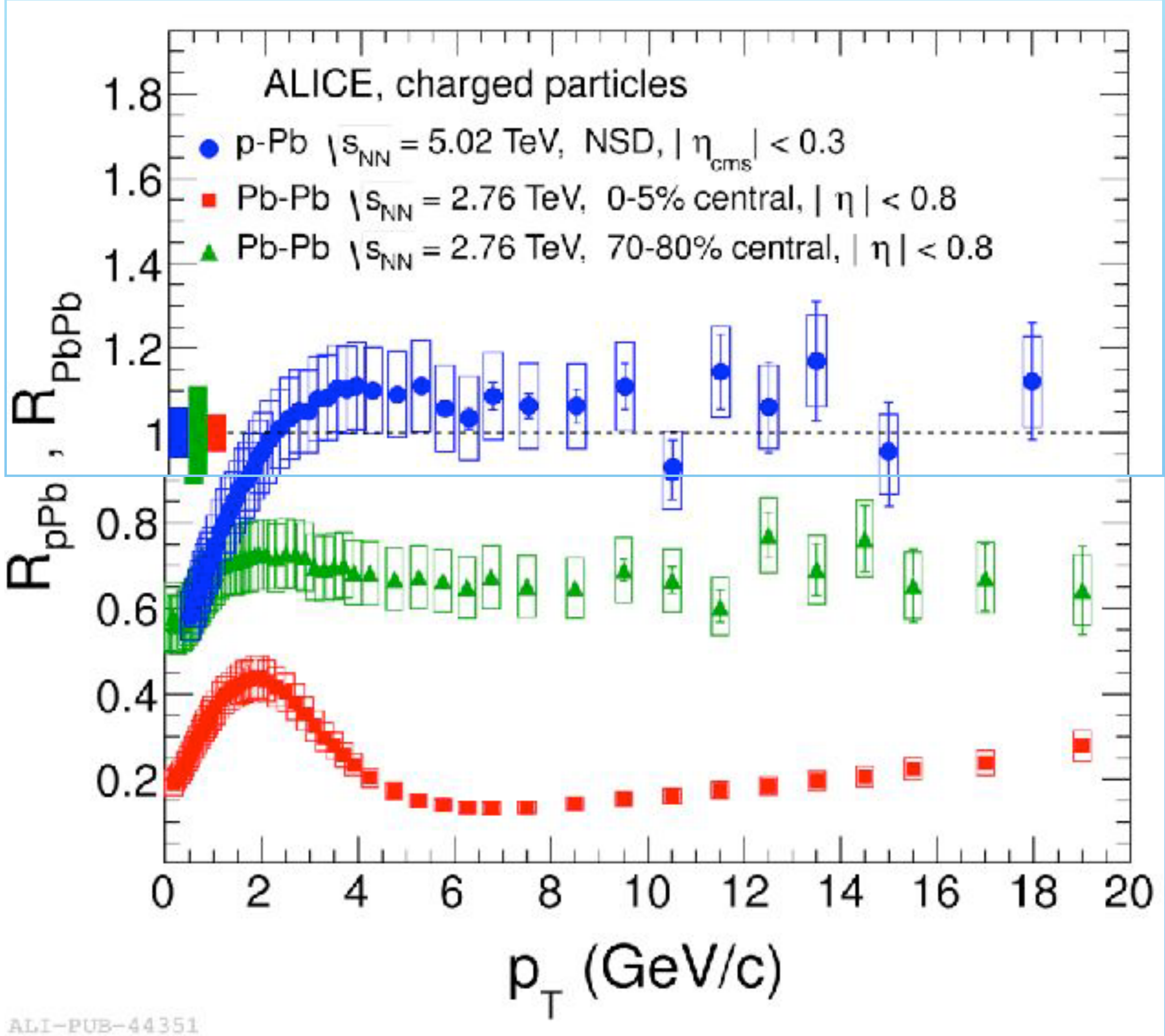
*** Electrons from B quark are less suppressed than electrons from D**

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



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

ALICE p+Pb and Pb+Pb data at LHC



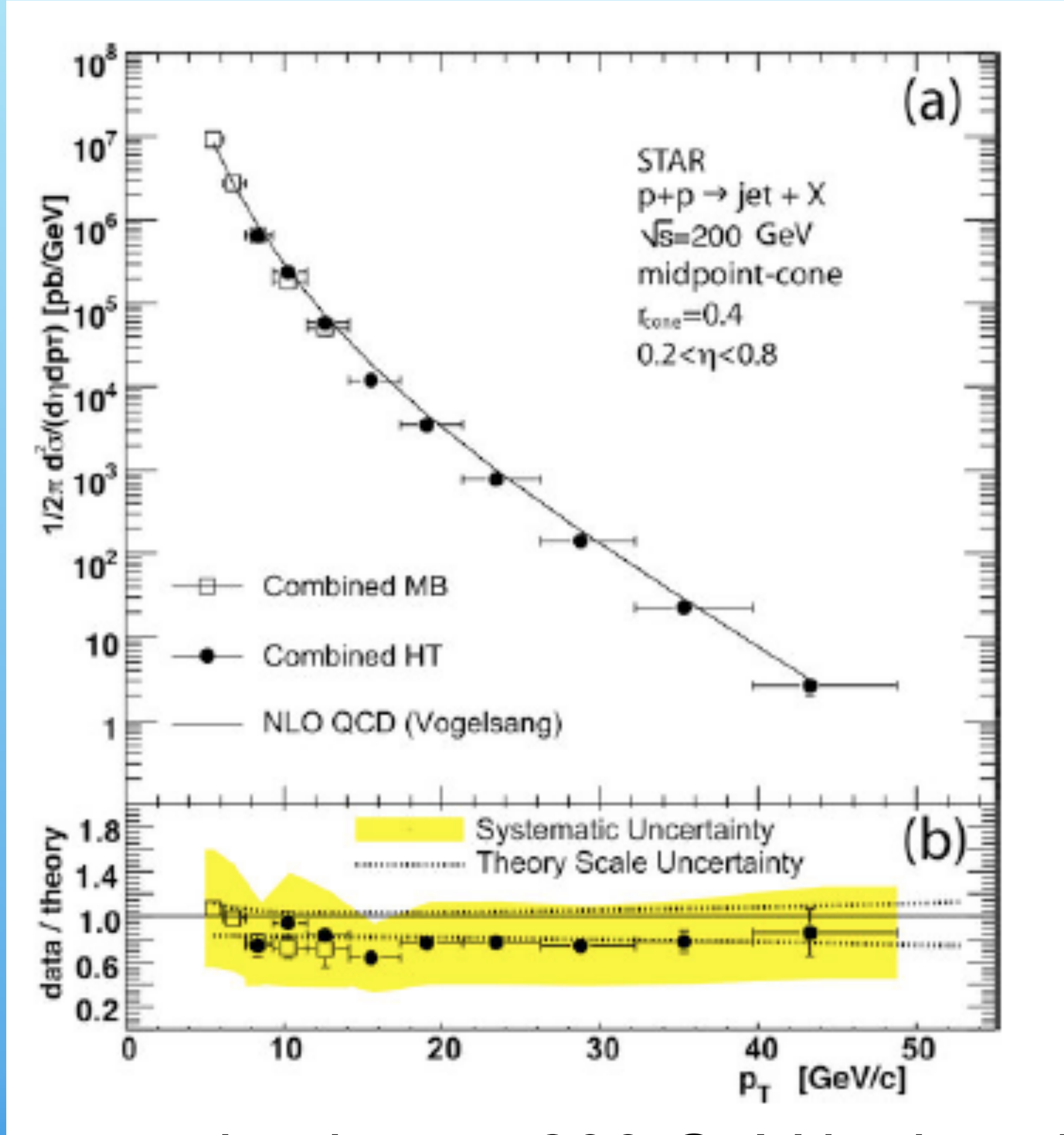
R(pPb) for charged particles is compatible with 1 at hight pT

No jet quenching in p+Pb

The jet quenching seen in Pb+Pb is not due to cold nuclear matter effects

Reconstructed jets

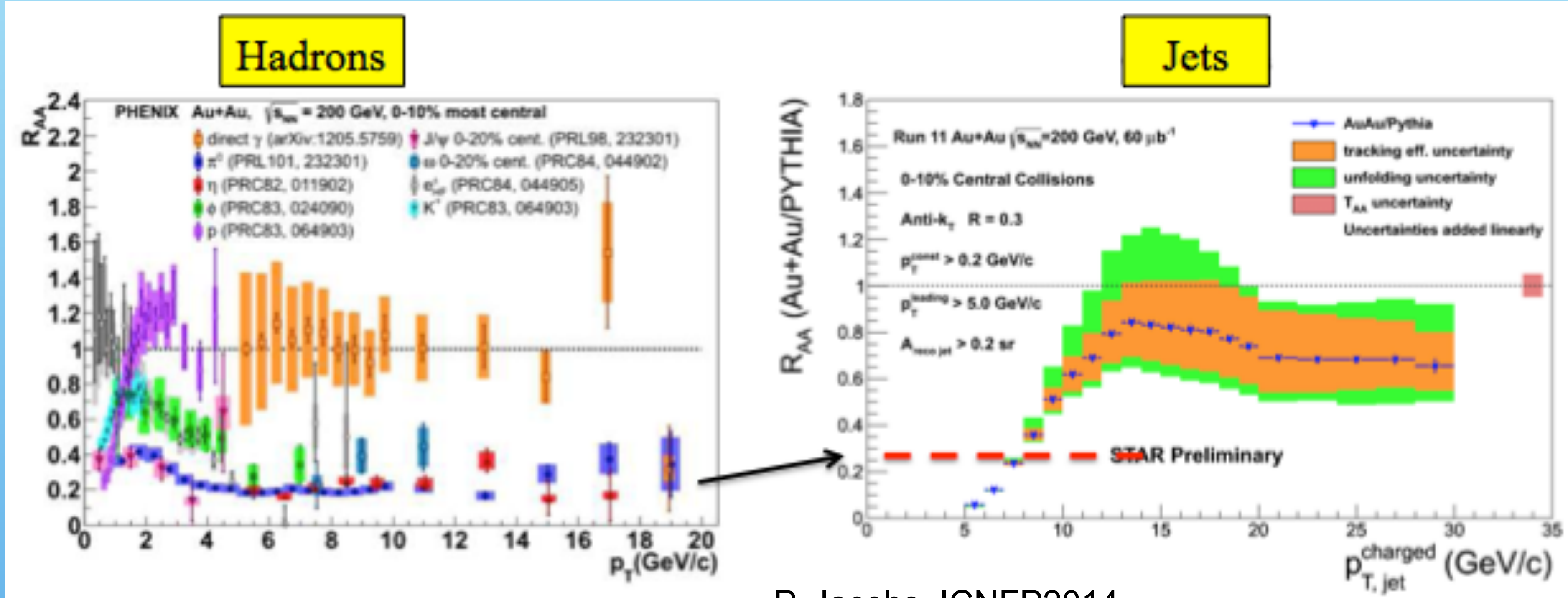
Jet cross section in p+p 200 GeV RHIC



STAR, Phys. Rev. Lett. 97, 252001 (2006), hep-ex/0608030.

The jet cross section in p+p 200 GeV is described by NLO pQCD over seven orders of magnitude

Hadron vs jet suppression



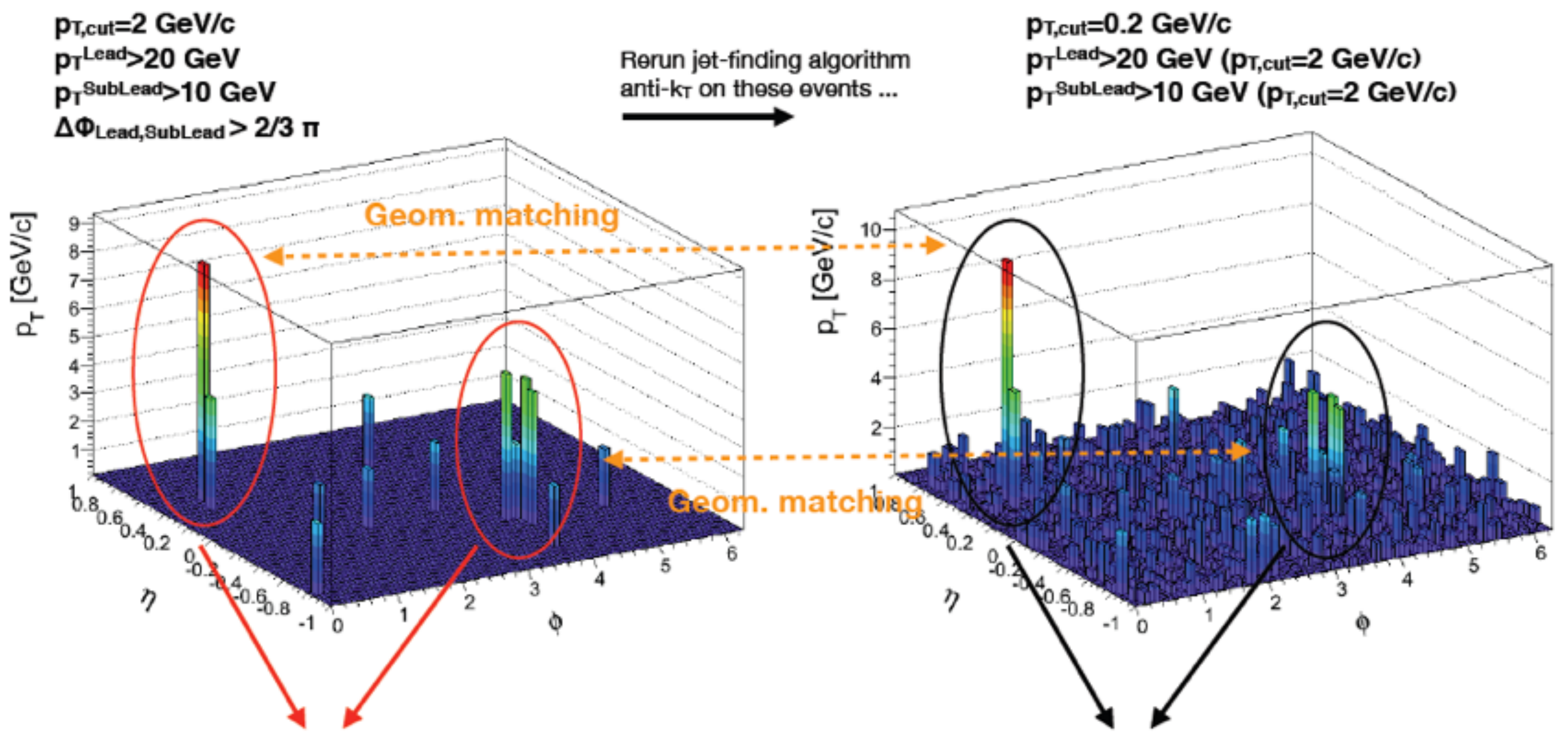
P. Jacobs, ICNFP2014

Jets are less suppressed than hadrons at RHIC, while in LHC they are suppressed the same.
Less out of cone radiation at RHIC?

Dijets

Dijet imbalance in STAR: A_J

STAR, PRL 119, 062301 (2017)



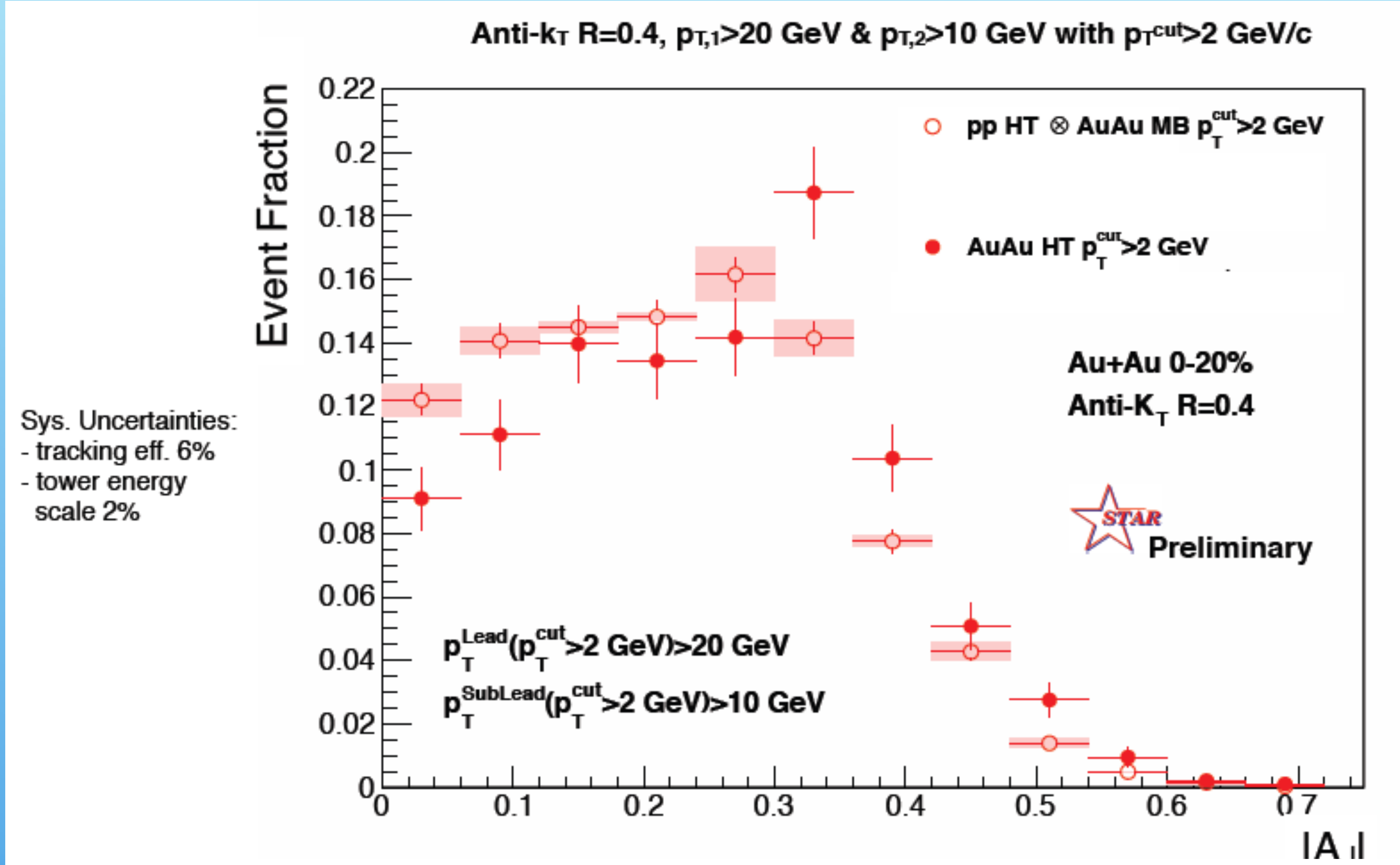
Calculate A_j with constituent $p_{T,cut}$>2 GeV/c

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \qquad p_T = p_T^{rec} - \rho \times A$$

Calculate "matched" $|A_j|$ with constituent $p_{T,cut}$>0.2 GeV/c.

J. Putschke, STAR, QM14

STAR, Dijet imbalance Au+Au 0-20% R=0.4

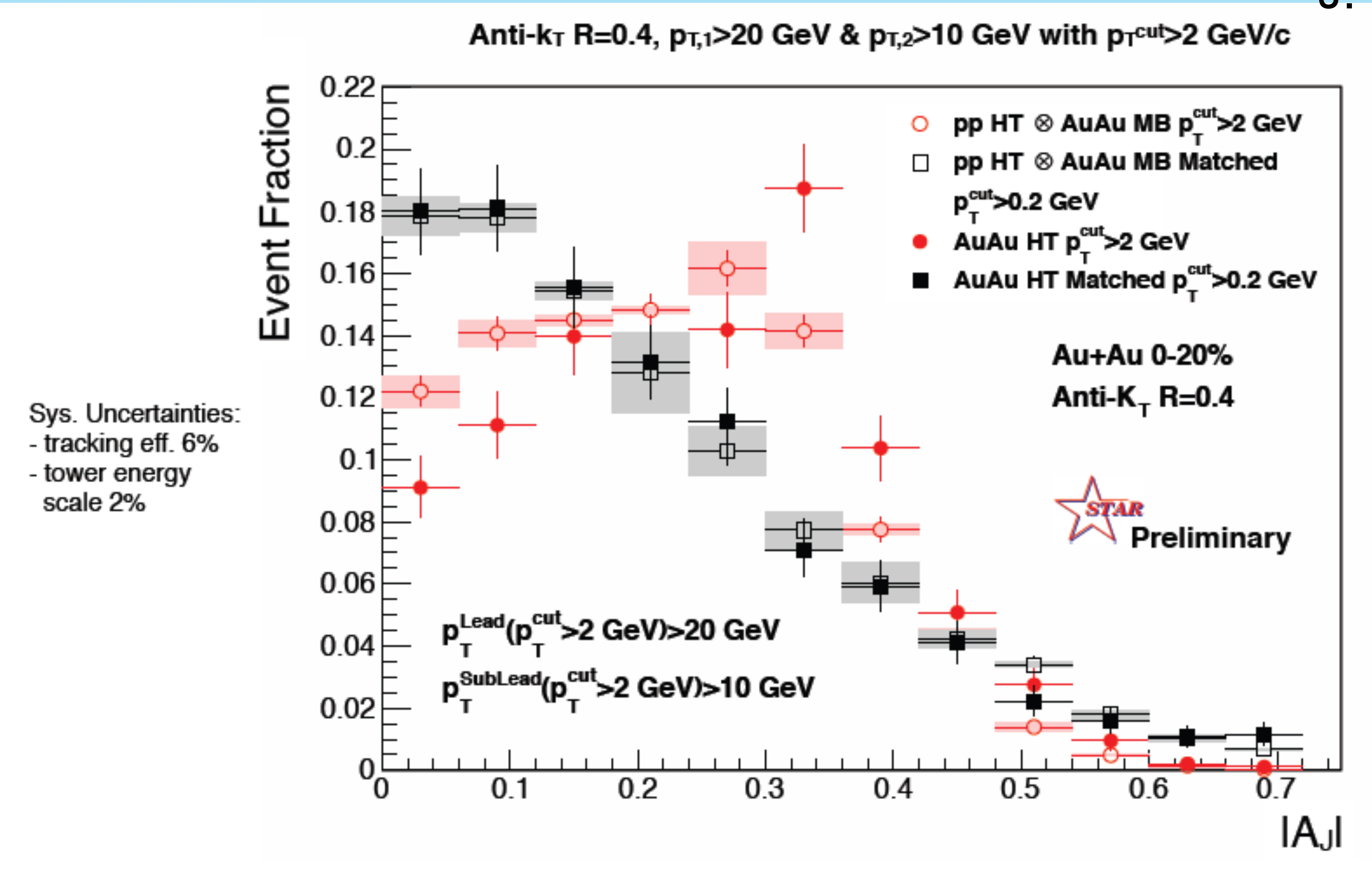


Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

J. Putschke, STAR, QM14

STAR, Dijet imbalance Au+Au 0-20% R=0.4

J. Putschke, STAR, QM



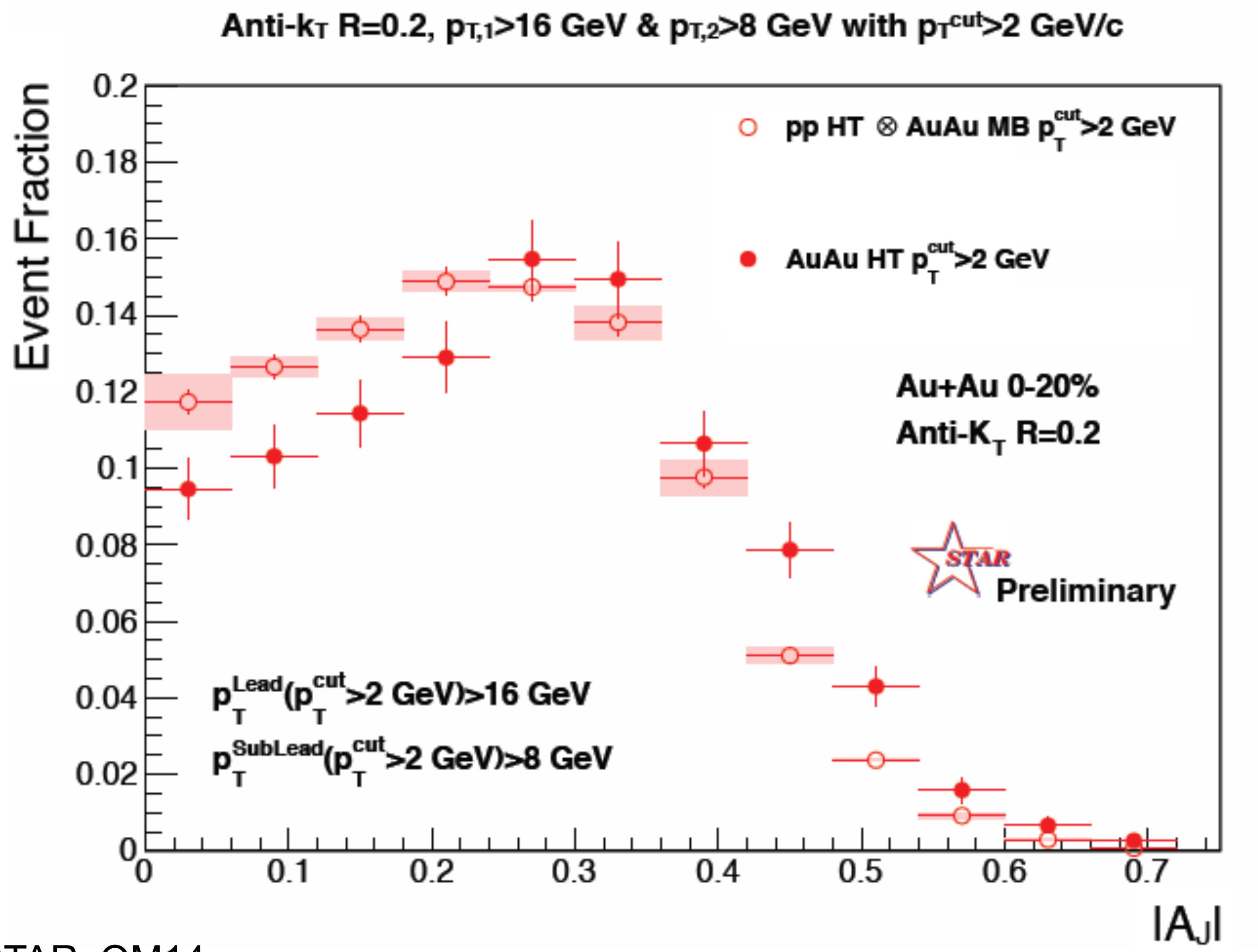
Red: ptcut>2 GeV
Grey: pTcut > 0.2 GeV (matched)

Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

Quenched jet energy is recovered at low pT within a cone of R=0.4

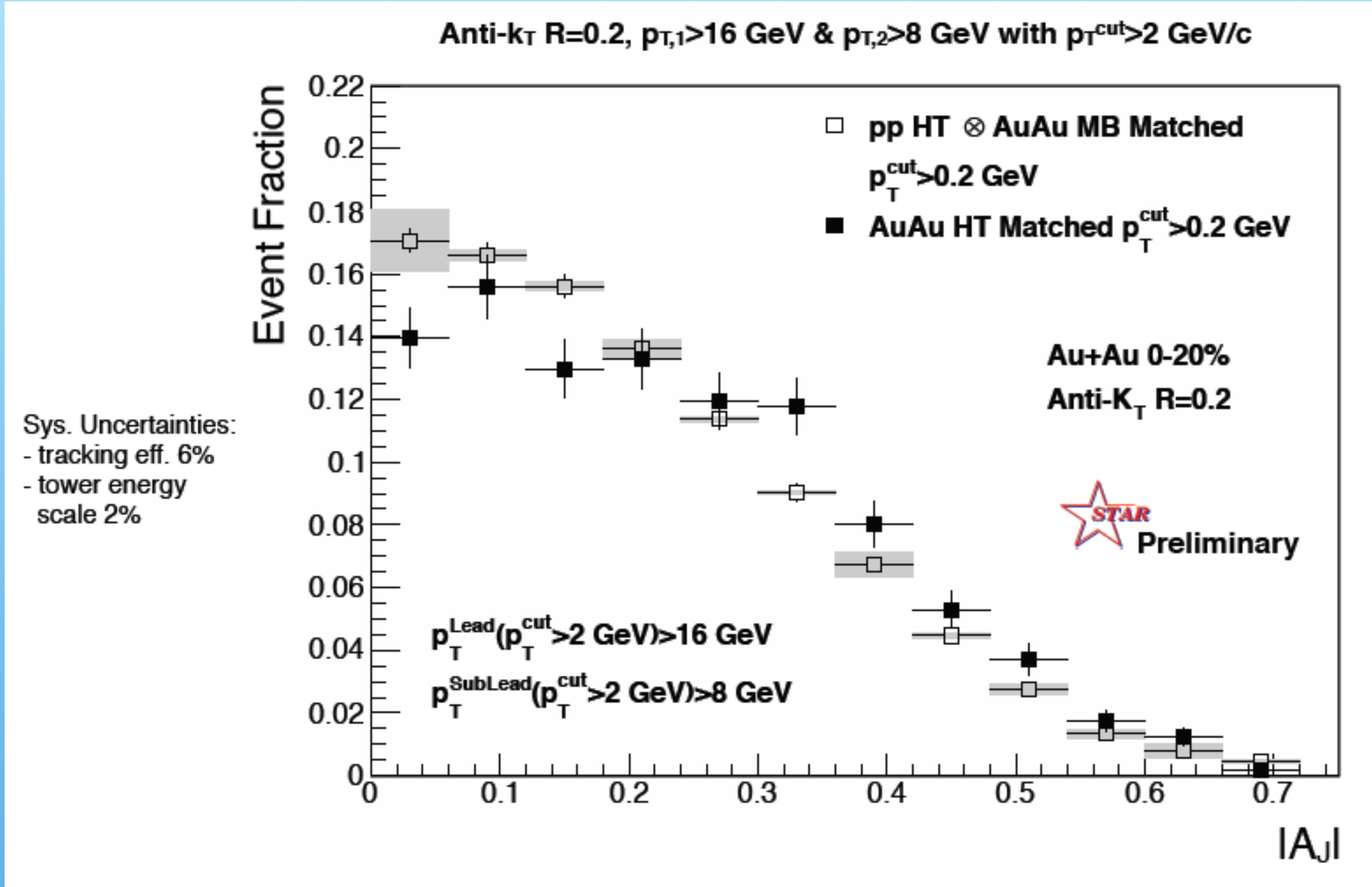
Dijet imbalance with R=0.2



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

J. Putschke, STAR, QM14

Dijet imbalance with R=0.2, matched

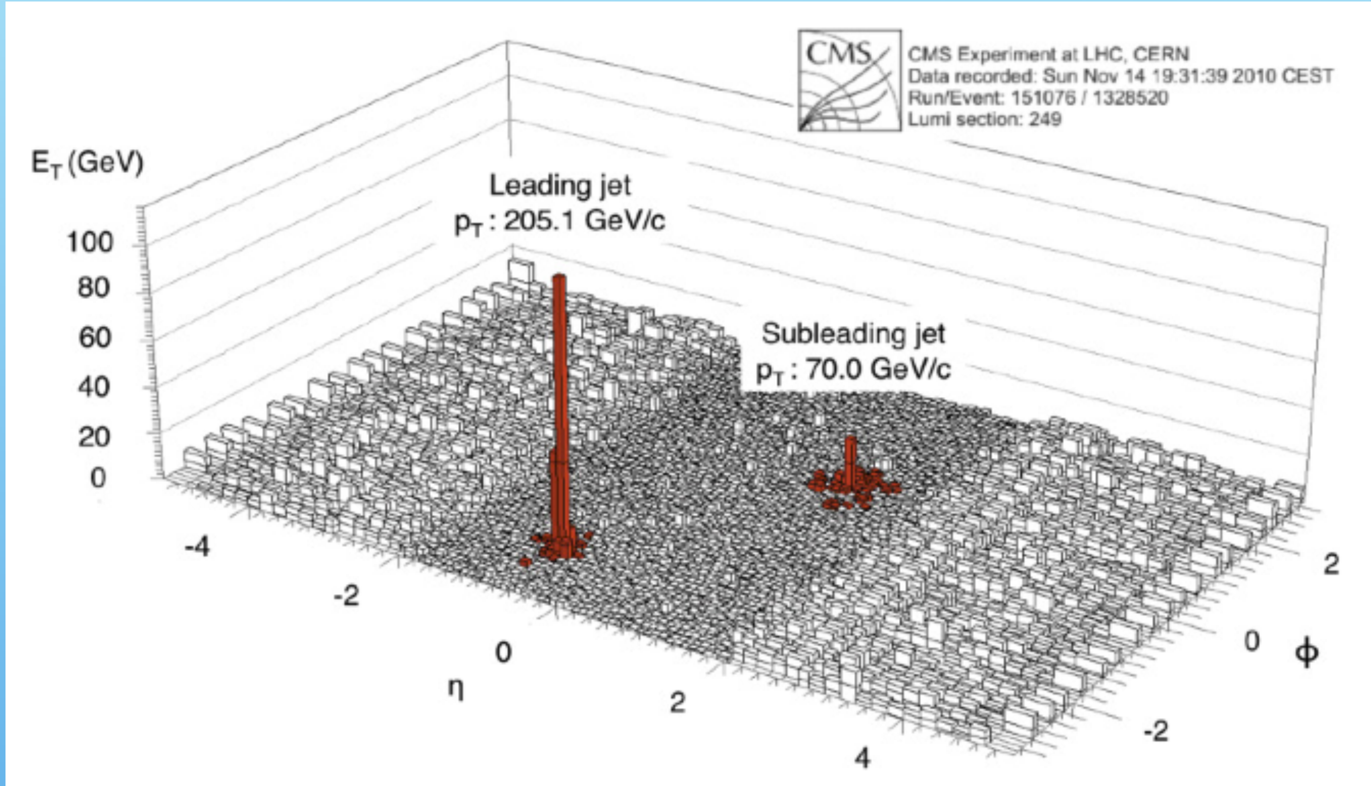


Matched Au+Au $A_J \neq$ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

J. Putschke, STAR, QM14

At RHIC the lost energy seem to reside inside a cone of R=0.4

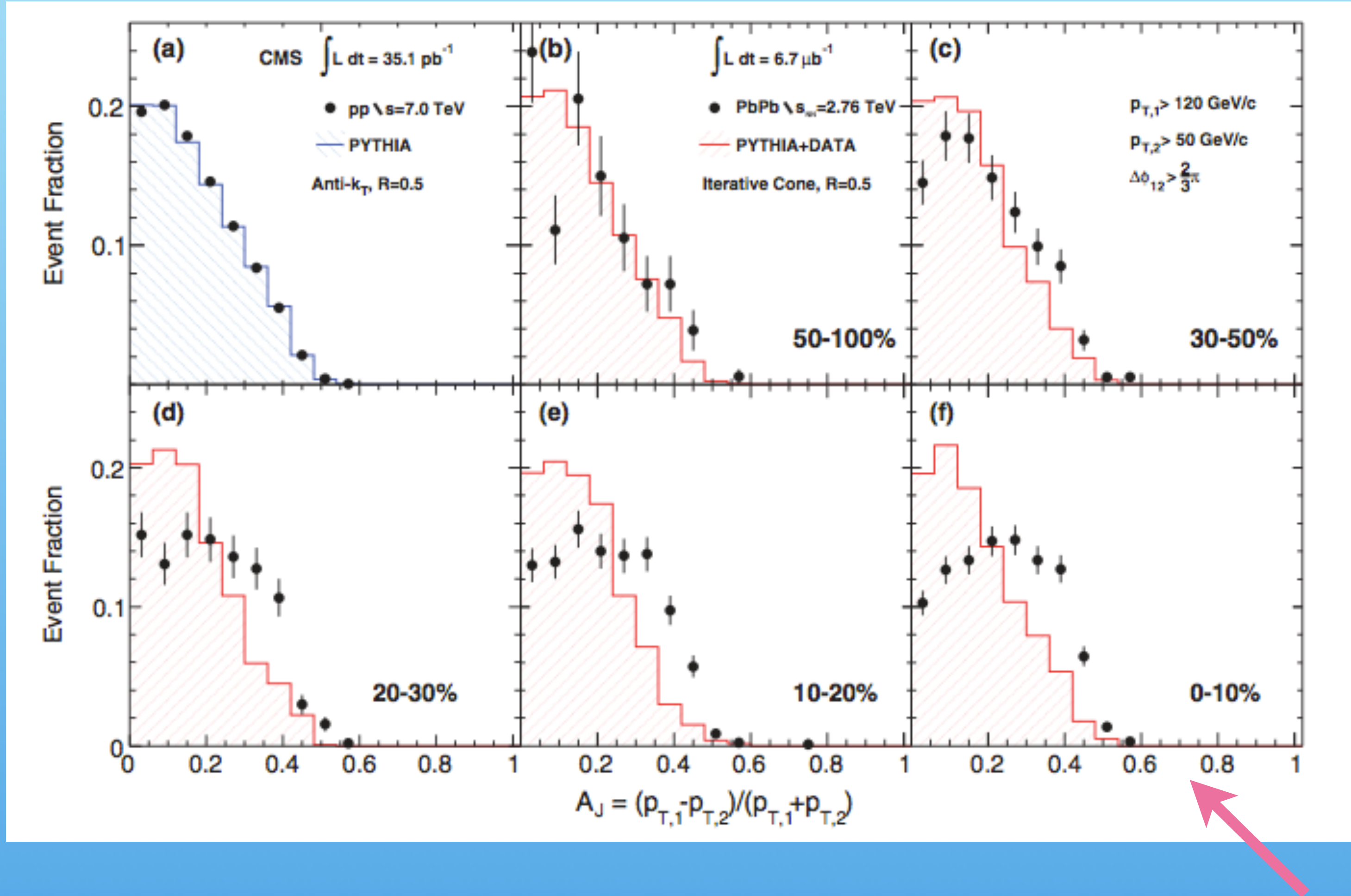
Comparison to LHC: first LHC results



Asymmetry parameter AJ defined to characterize dijet balance (or imbalance):

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}},$$

Jet quenching via dijet imbalance



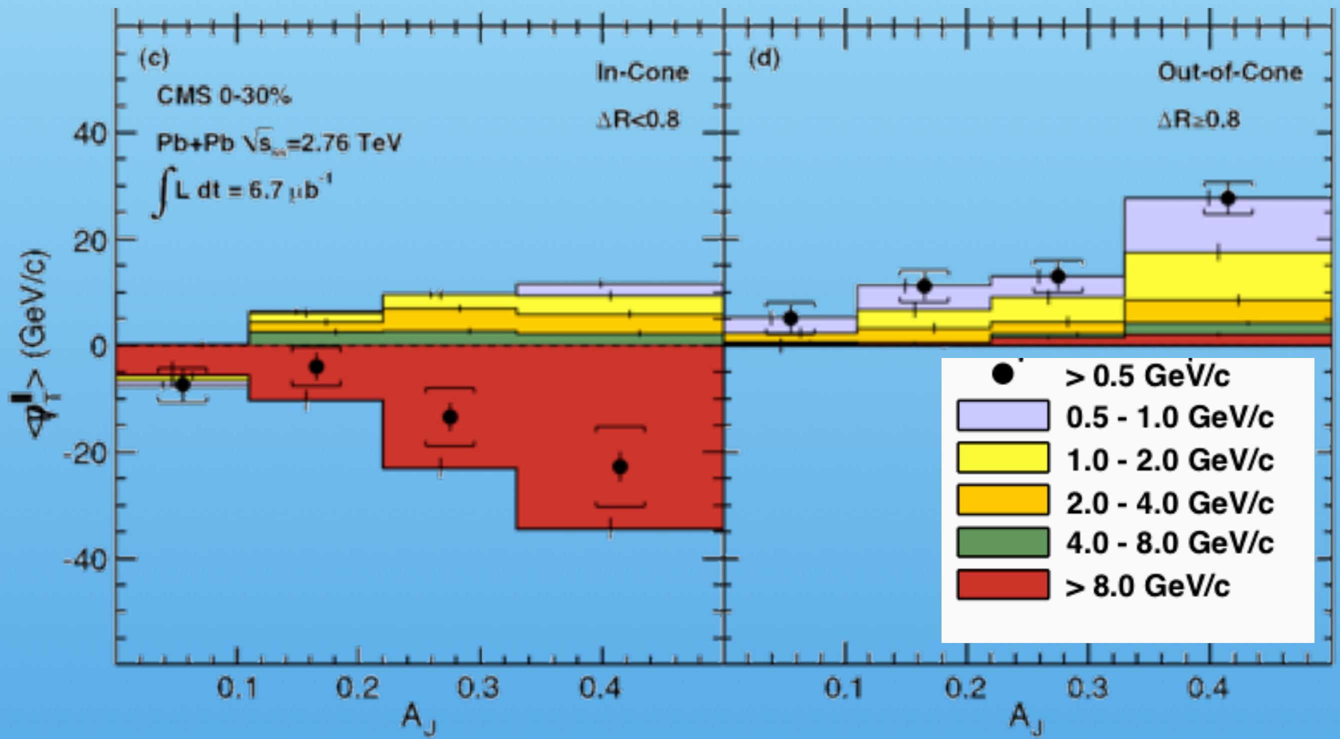
Observation of highly unbalanced dijet events in central PbPb collisions -> evidence for energy loss in medium or "jet quenching"

Where did the lost energy go?

CMS: Look at track-jet correlations

-> RHIC and LHC differ: **in LHC lost energy is moved from large to small PT and from small to large angles namely outside the leading and subleading jets cones.**

CMS, PRC 84 (2011) 024906



Color decoherence can lead to large angle emission

N. Armesto et al, 1207.0984
K. Tywokiuk et al 1401.8293

Colored bands show contribution to pT for five pT ranges

Dijet balance (or imbalance) characterization:

$$A = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$$

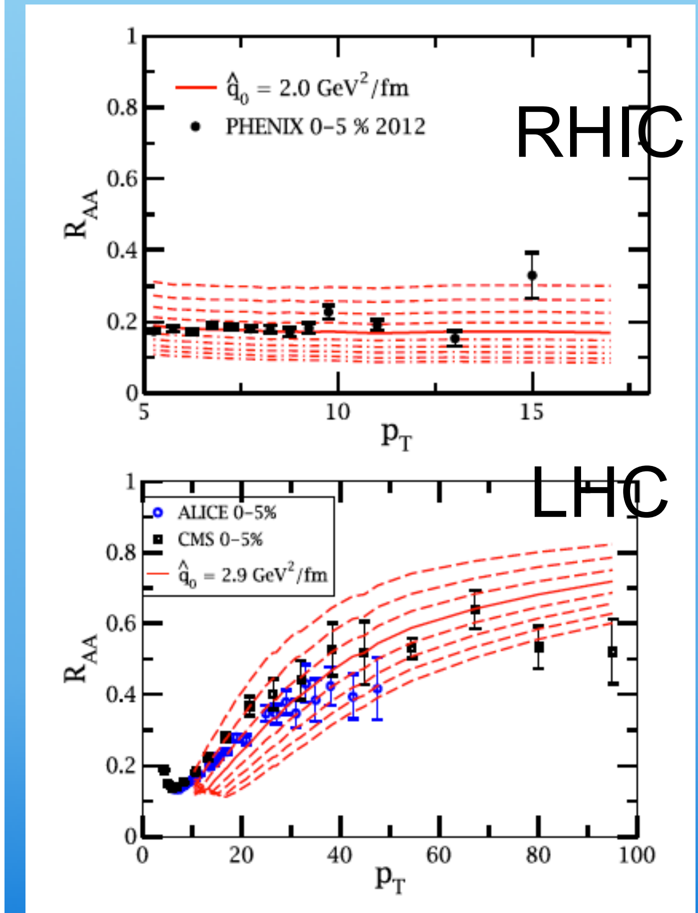
Jet transport coefficient at RHIC and LHC

Extracting jet transport coefficient from data and models at RHIC and LHC

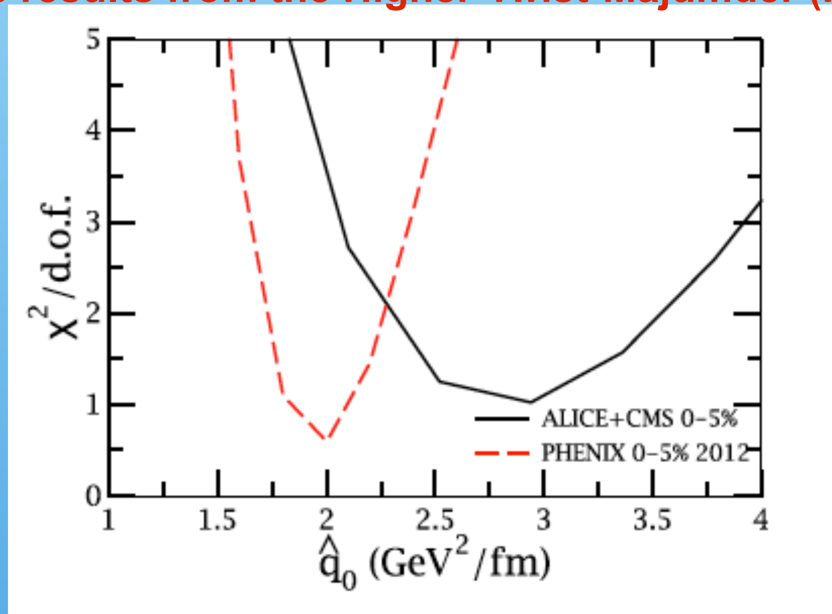
In last years the JET collaboration of groups using different models has made an important step forward evaluating for the first time q-hut with a fit to both RHIC and LHC and reaching a good agreement of all models while fiting the experimental data at RHIC and LHC.
Models: GLV-CUJET, HT-M, HT-BW, MARTINI and McGill-AMY. GLV and its recent CUJET implementation.
Jet transport coefficient for a jet initiated by a light quark considered (10 GeV jet assumed).
For the QGP medium viscous hydrodynamics (VISH2+1) is employed (Ohio State group).

Karen M. Burke,[1] Alessandro Buzzatti,[2,3] Ningbo Chang,[4,5] Charles Gale,[6] Miklos Gyulassy,[3] Ulrich Heinz,[7] Sangyong Jeon,[6] Abhijit Majumder,[1] Berndt Müller,[8] Guang-You Qin,[5,1] Björn Schenke,[8] Chun Shen,[7] Xin-Nian Wang,[5,2] Jiechen Xu,[3] Clint Young,[9] and Hanzhong Zhang[5]

K. Burke et al, JET collaboration, 1312.5003



Example results from the Higher-Twist-Majumder (HT-M) model



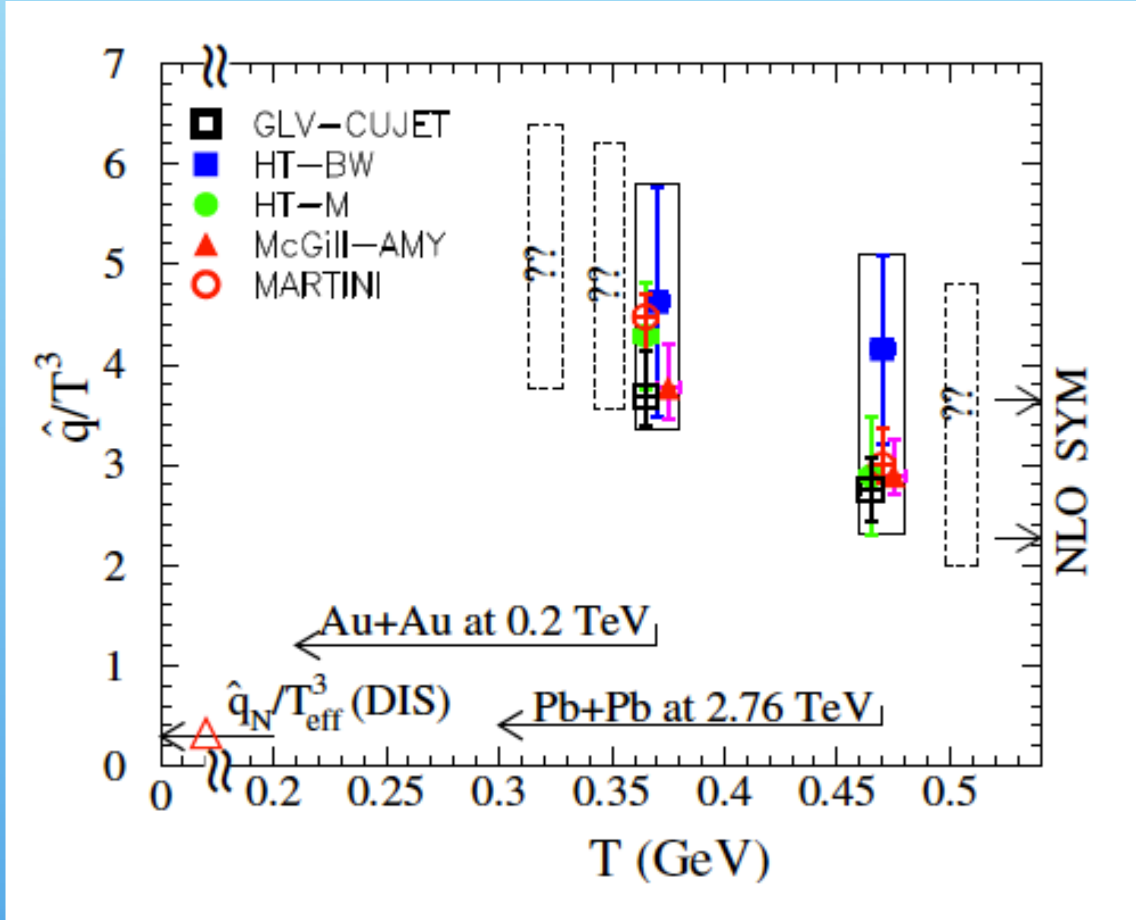
Dedx(radiative)~ q-hut

Example of fit to pi0 in central 0-5% Au+Au and Pb+Pb for the Higher-Twist-Majumder (HT-M) model.

The model calculates the medium modified fragmentation function including multiple induced gluon emission.

Extracting jet transport coefficient from data and models at RHIC and LHC

Scaled jet transport parameter q-hut/T^3



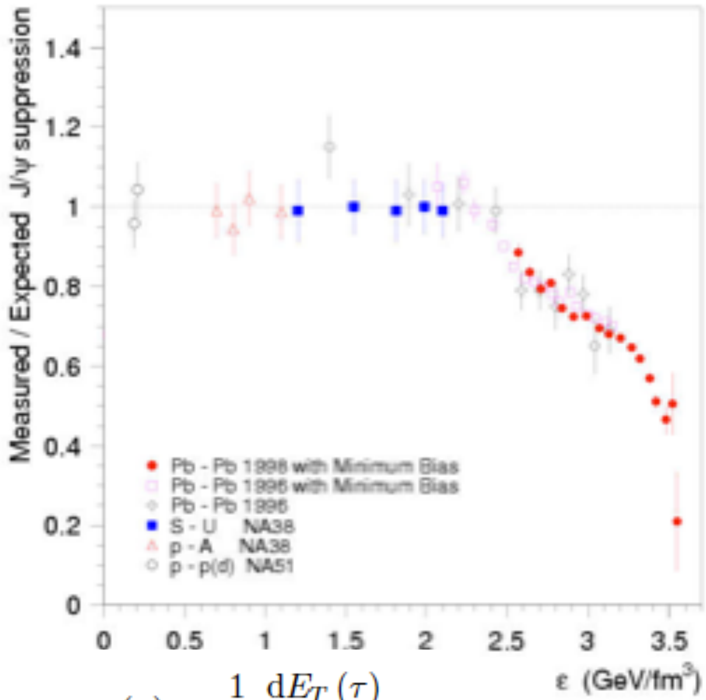
Dashed boxes show expected values for sqrt(s)=0.063, 0.130 and 5.5 TeV

Results from JET collaboration agree with results from AdS/CFT correspondance shown here with the arrows named NLO SYM

5. Quarkonia suppression

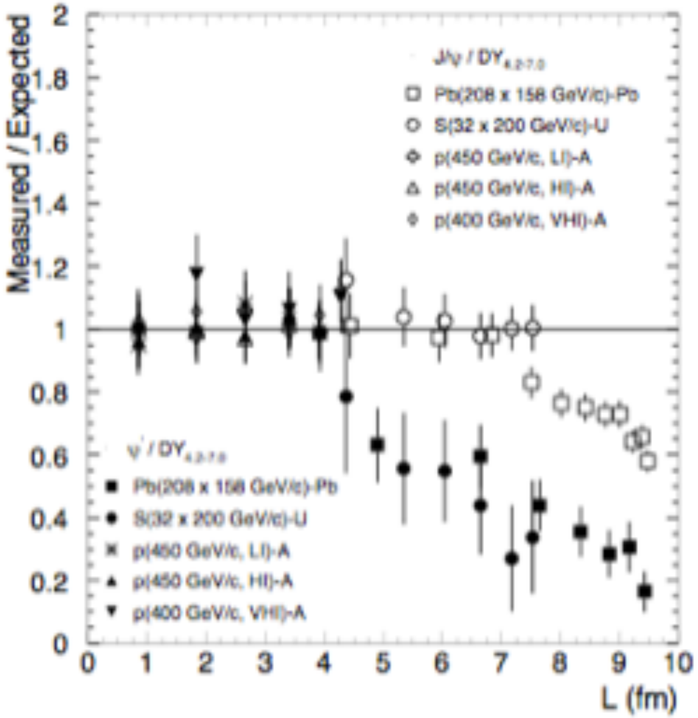
Sequential Psi prime and J/Psi suppression has been observed at CERN SPS Pb+Pb 158 A GeV

NA50, Phys Lett B 477 (2000) 28

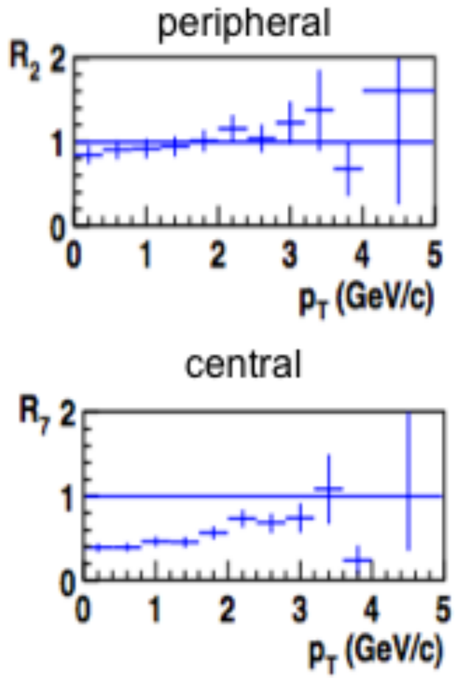


$$\varepsilon_{Bj}(\tau) = \frac{1}{A\tau}\frac{\mathrm{d}E_T(\tau)}{\mathrm{d}y},$$

Eur Phys J C 49 (2007) 559



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



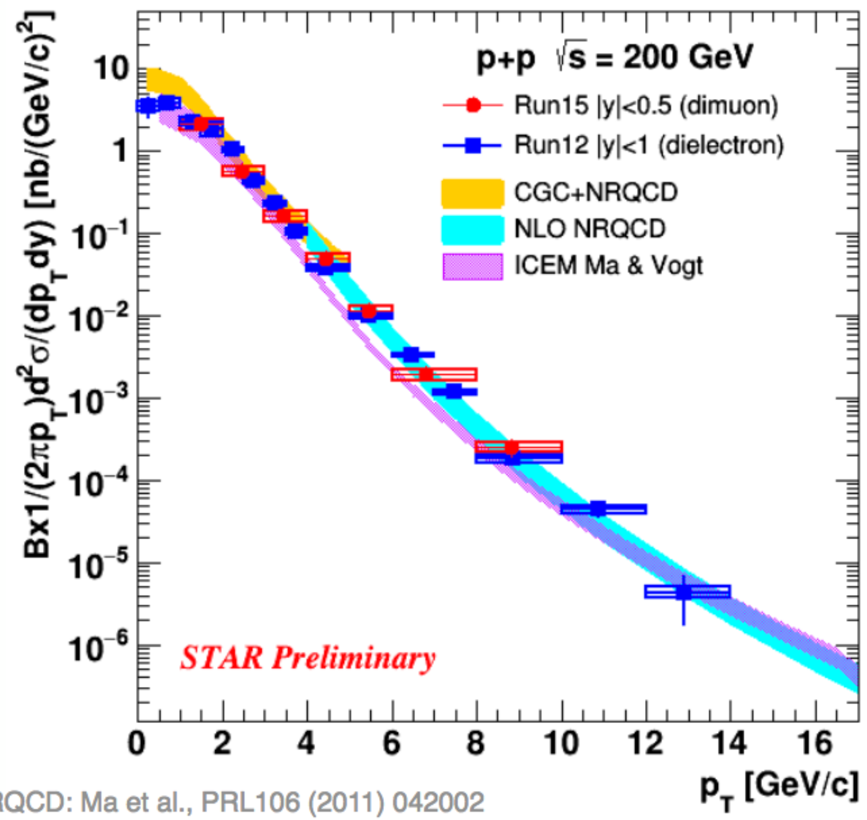
A Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004

- **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**

J/Psi in p+p coll at RHIC

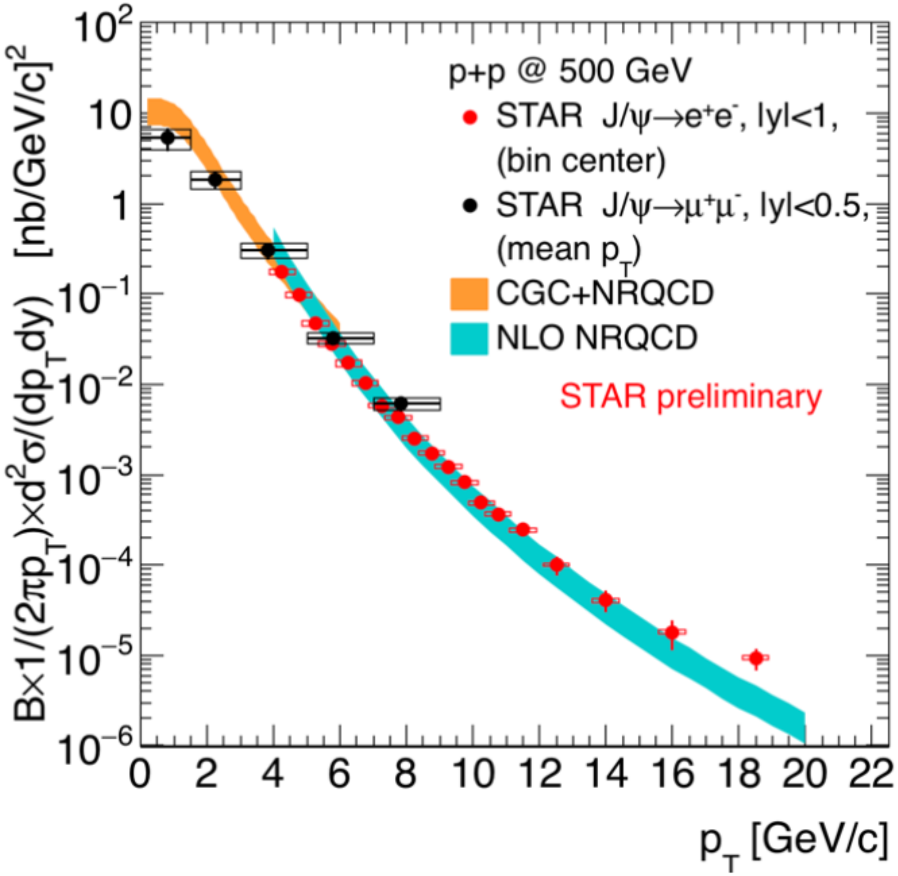
- CGC+NRQCD and NLO NRQCD (prompt) consistent with data (inclusive) at p+p @ 200 and 500 GeV

p+p@ 200 GeV



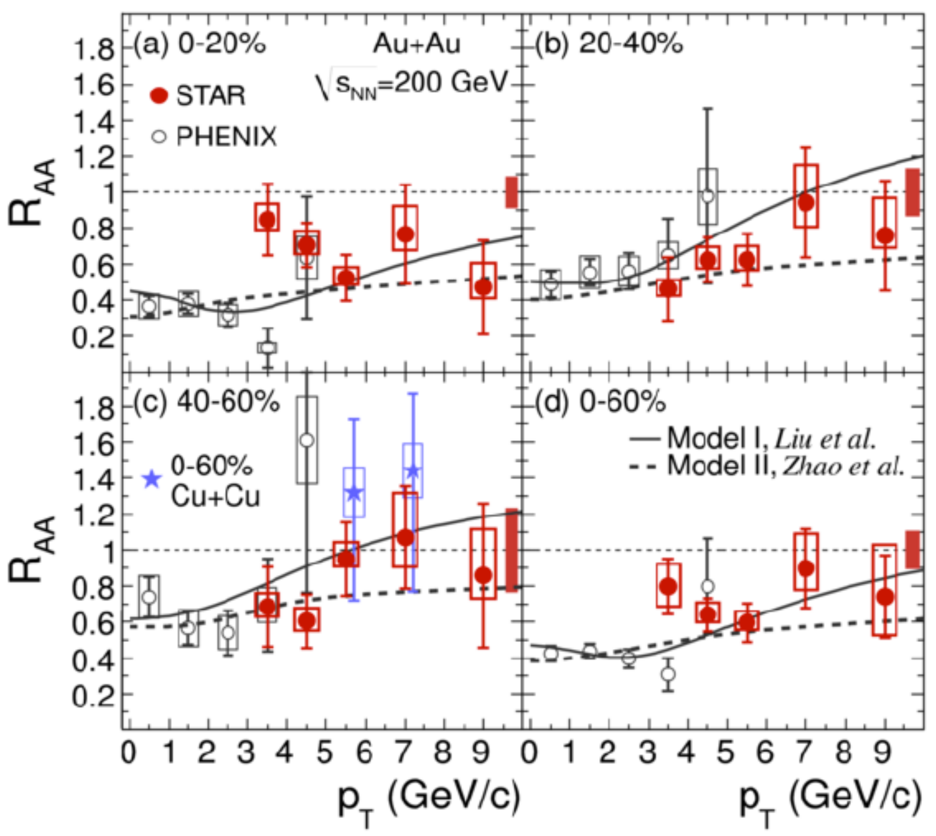
NLO NRQCD: Ma et al., PRL106 (2011) 042002
CGC+NRQCD: Ma, Venugopalan, PRL113 (2014) 192301

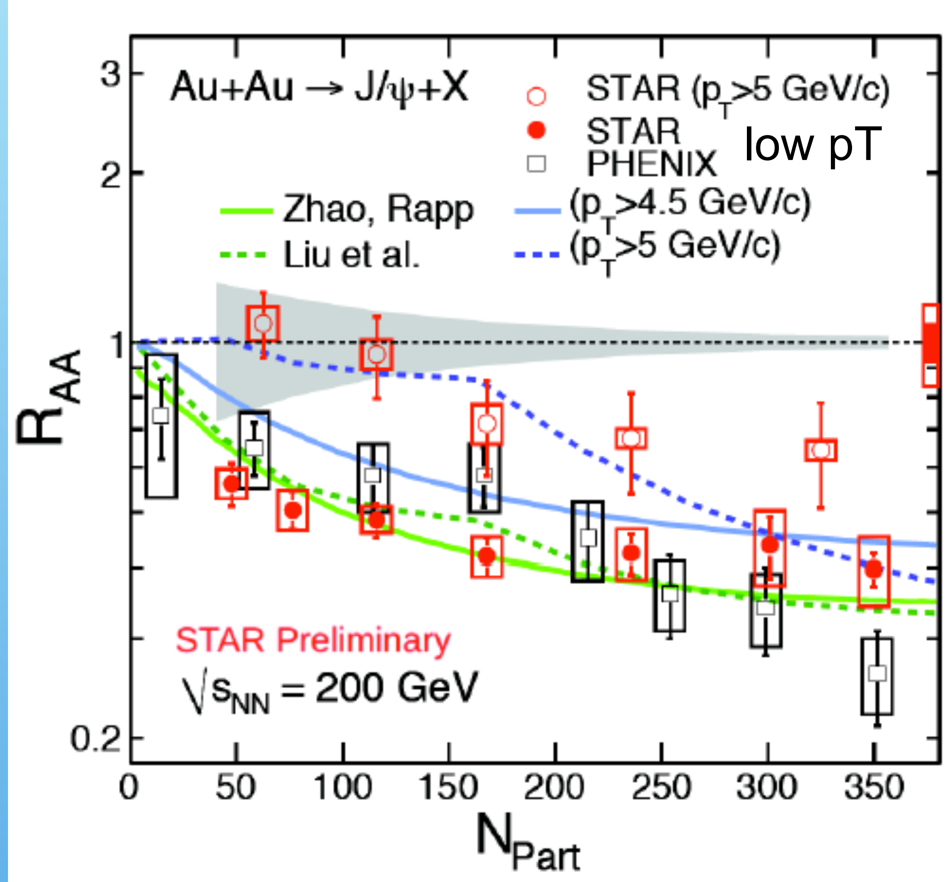
p+p@ 500 GeV



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

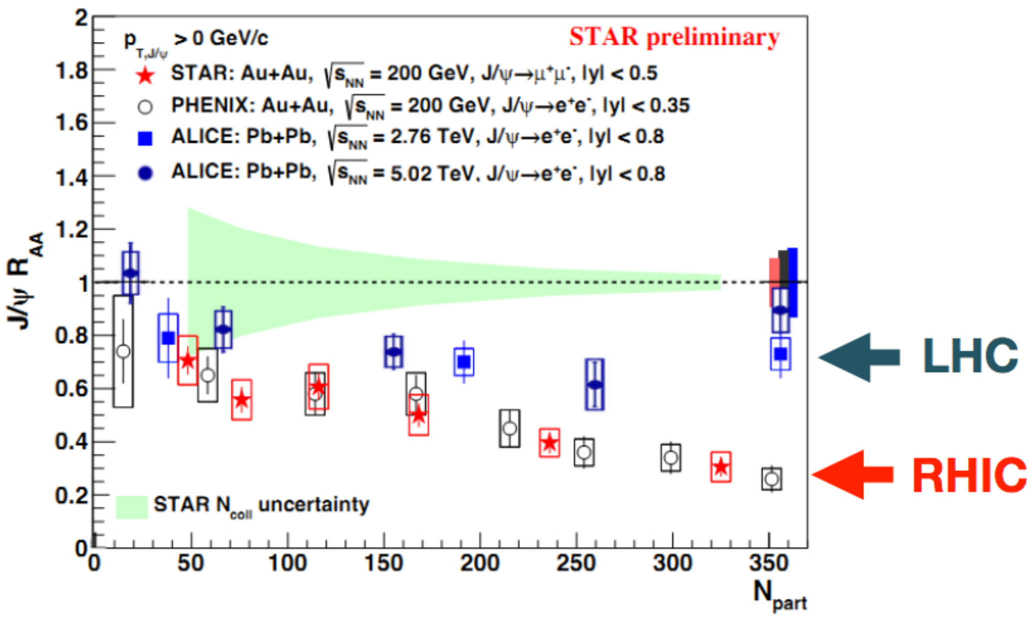
- R_{AA} of J/Psi is systematically larger for higher p_T. Low pT J/Psi is more suppressed

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

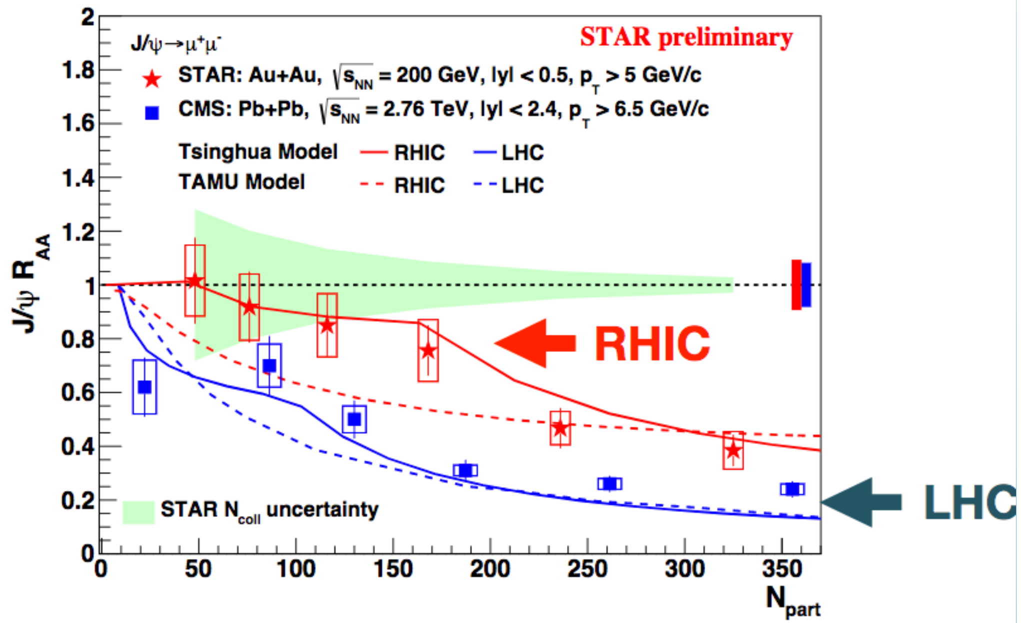
Low p_T J/ψ in central collisions:



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

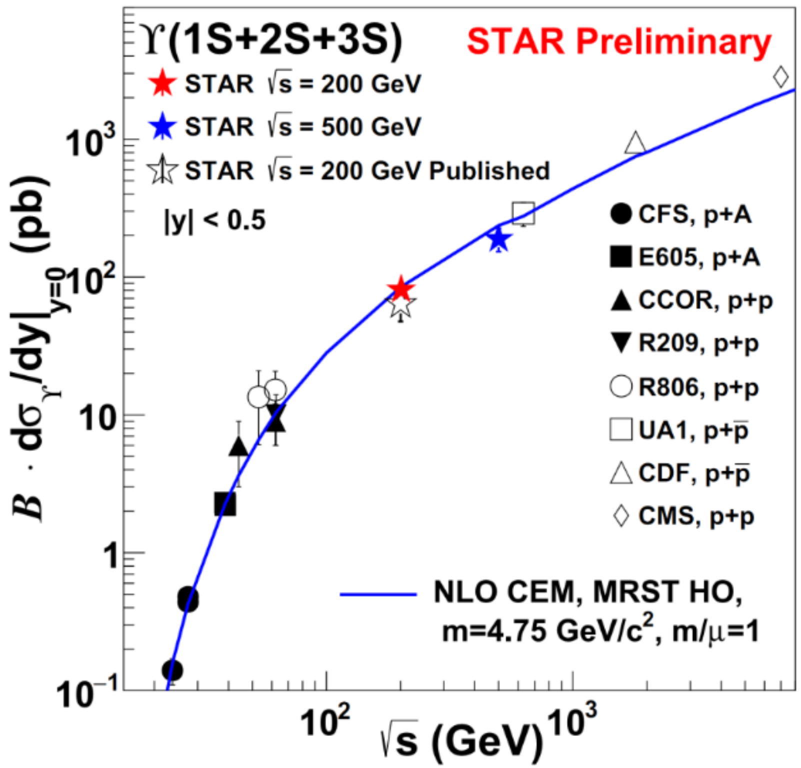
Li Yi (STAR coll.) Santa Fe 2018

Υ in p+p p+A

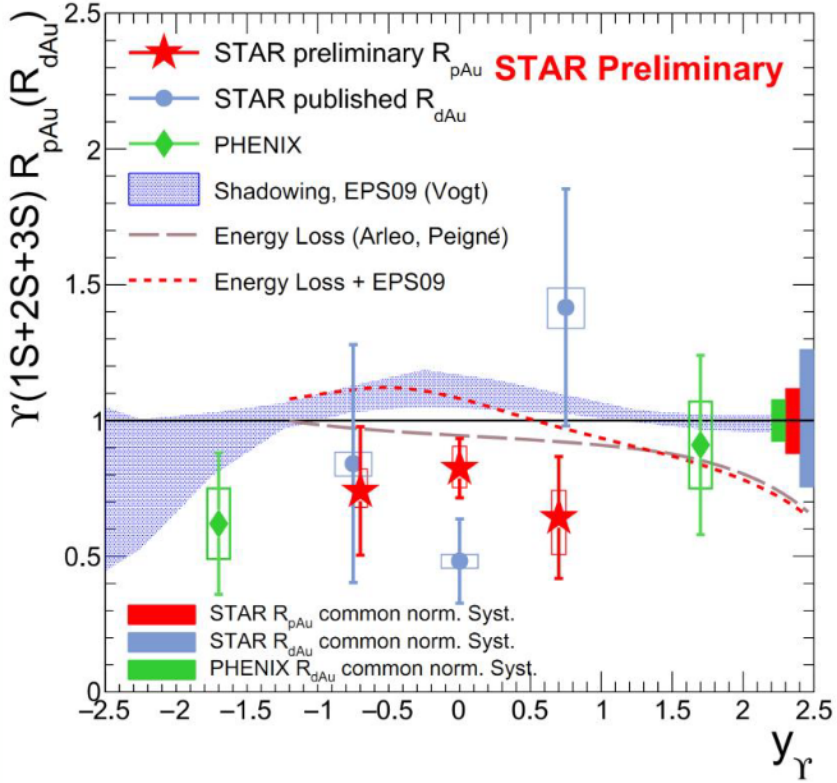
R. Vogt ,Phys. Rept. **462**(2008) 125

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



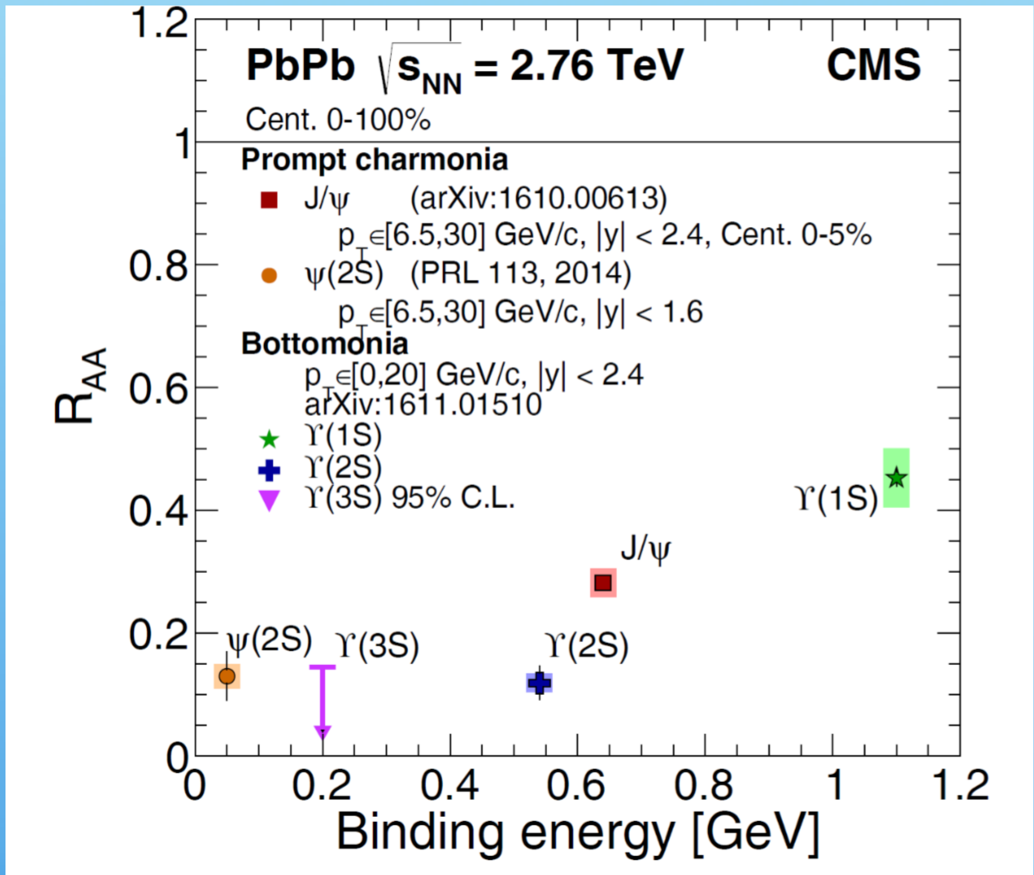
p+Au



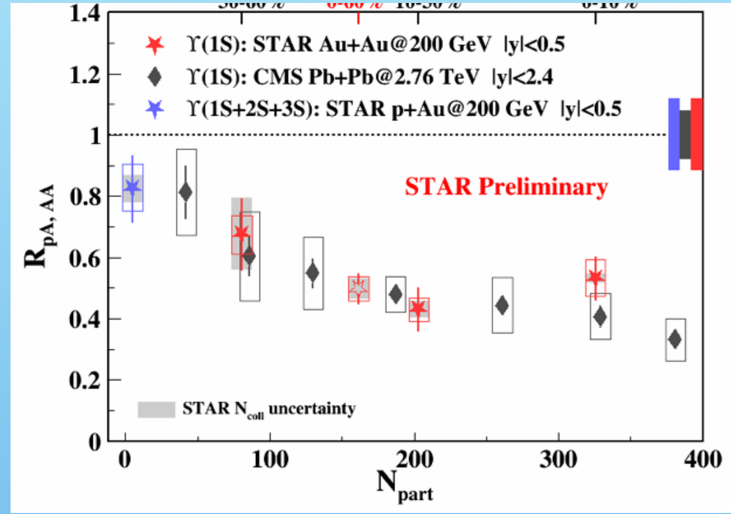
- Yields consistent with NLO model
- R_{pA} quantifies CNM effects

Hierarchy of quarkonia suppression has been observed at RHIC and LHC

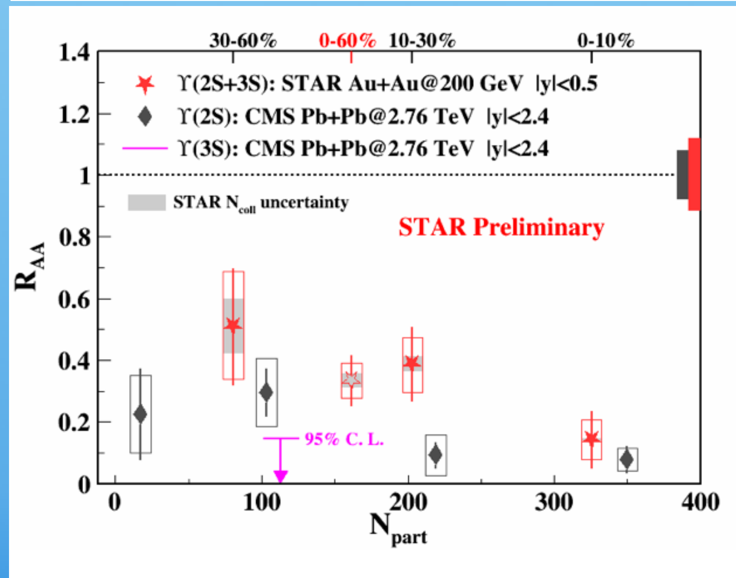
STAR, Z. Ye, QM2017



Y(1S)

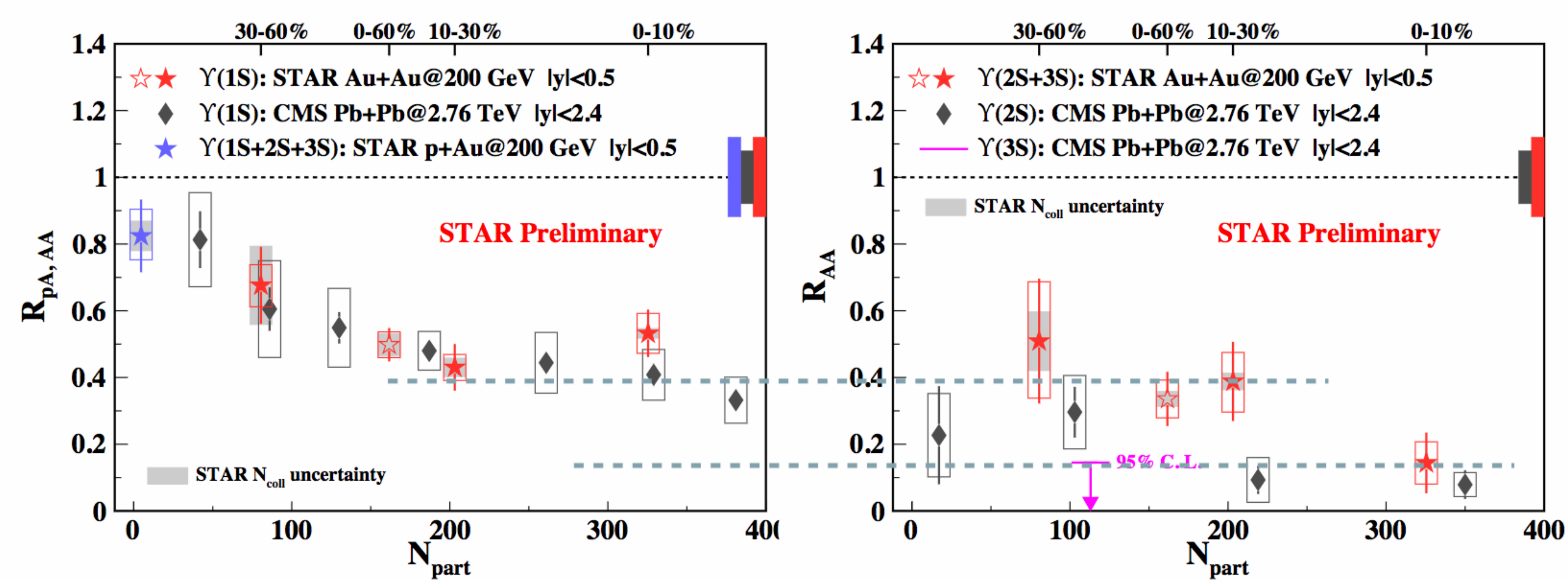


Y(2S+3S)



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

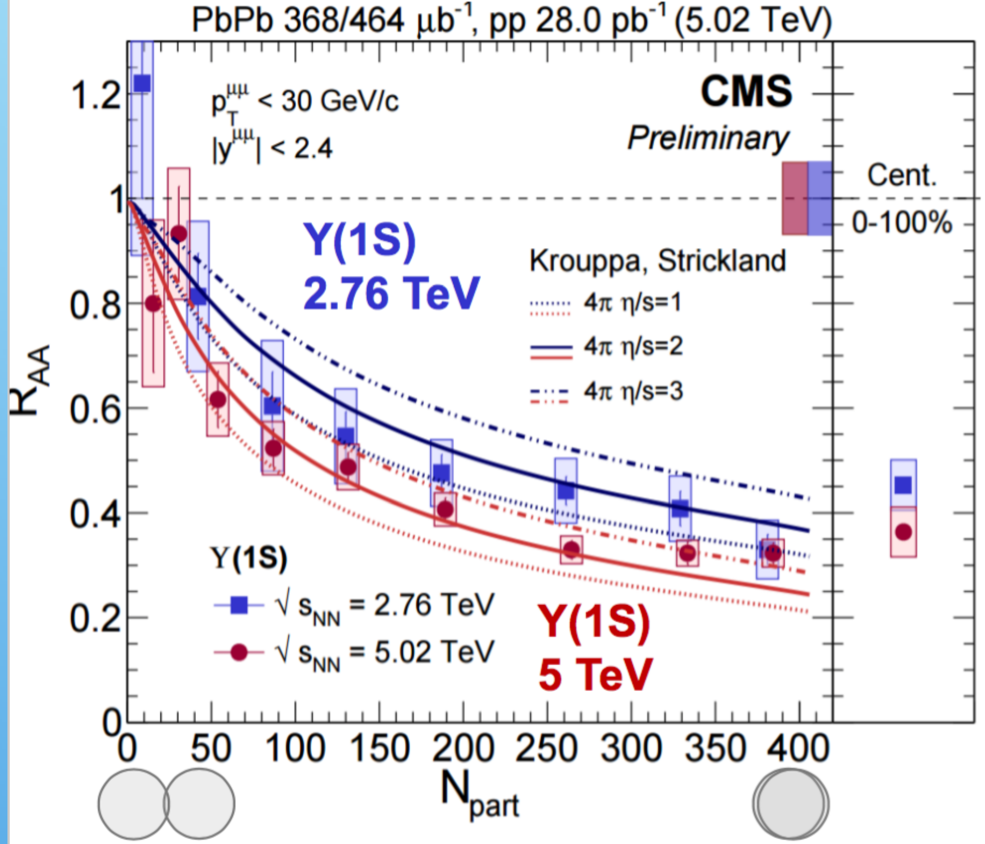
CMS, PLB 770 (2017) 357

Li Yi (STAR coll.) Santa Fe 2018

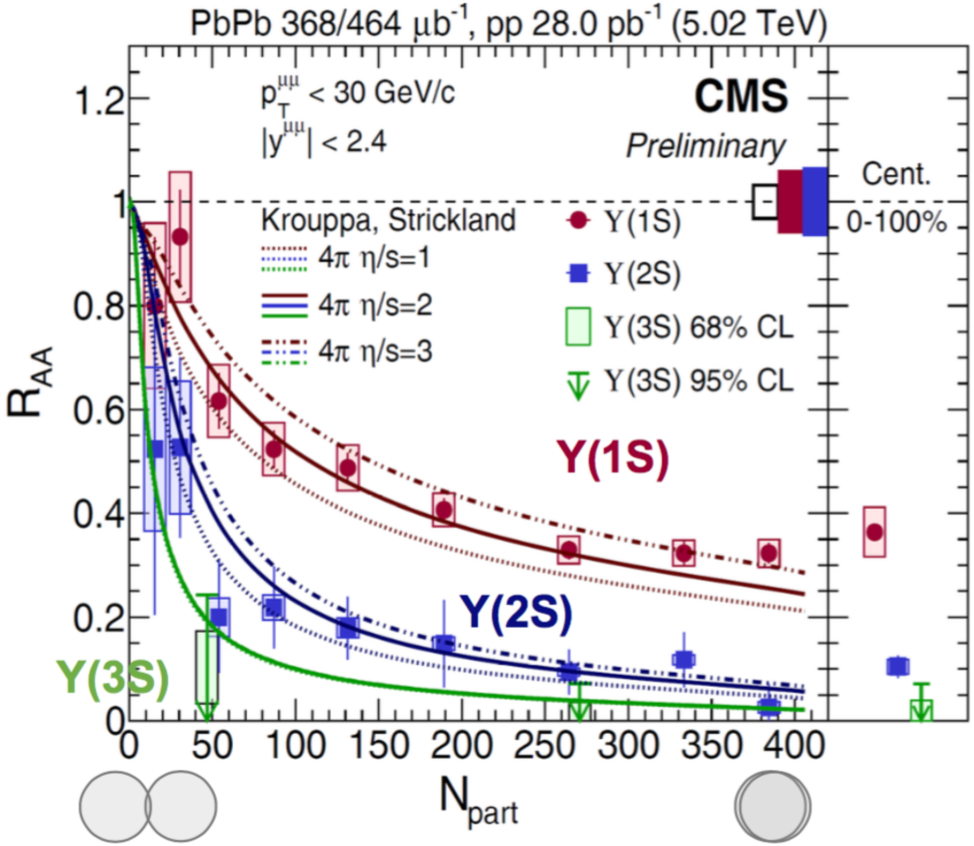
New: Quarkonia at 5 TeV PbPb

CMS,J. J. Lee, QM2017 Υ(1S) and Υ(2S)

Υ(1S) PbPb at 2.76 and 5 TeV



PbPb at 5 TeV

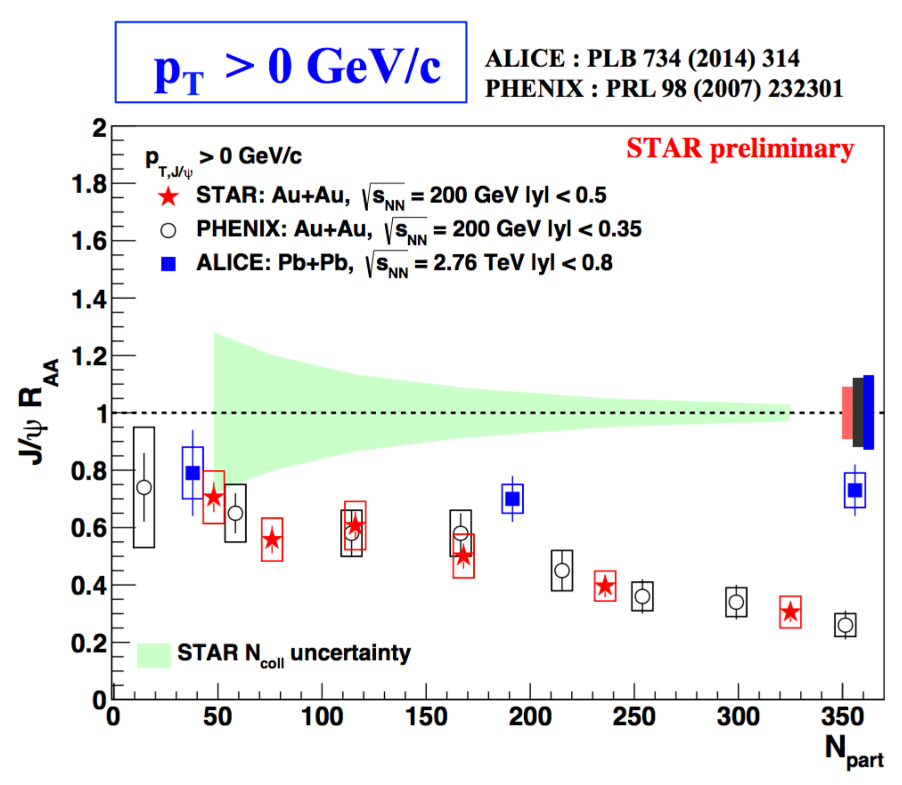


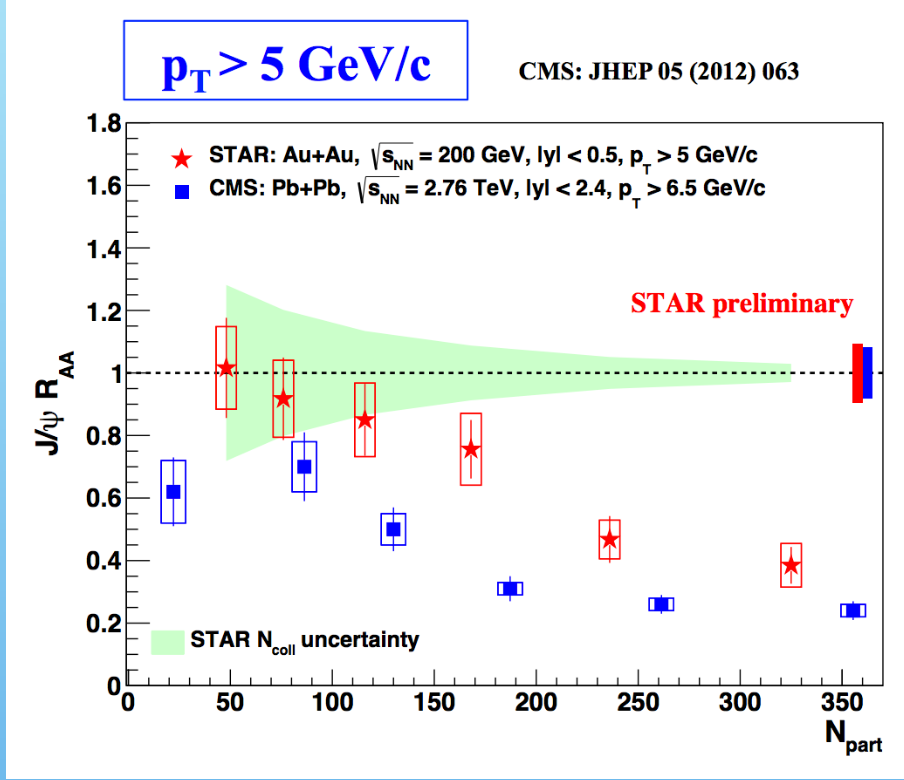
- Indication of larger suppression at 5 TeV
- Consistent with predictions from a **hotter** and **denser** medium

- Highest precision measurement
- Upsilon sequential suppression at 5 TeV
- Still no sign of Υ(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

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)

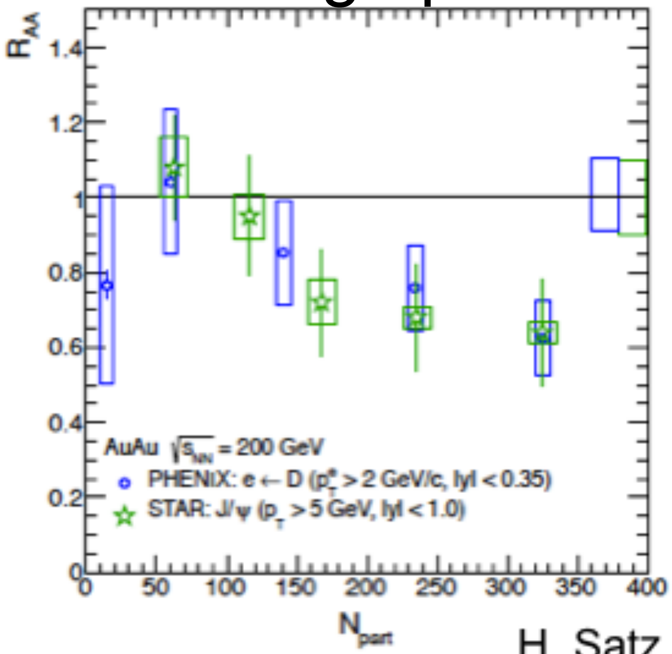
3. (J/Psi AA/pp) / (open charm AA/pp) :
RAA(J/Psi) / RAA(open charm)

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

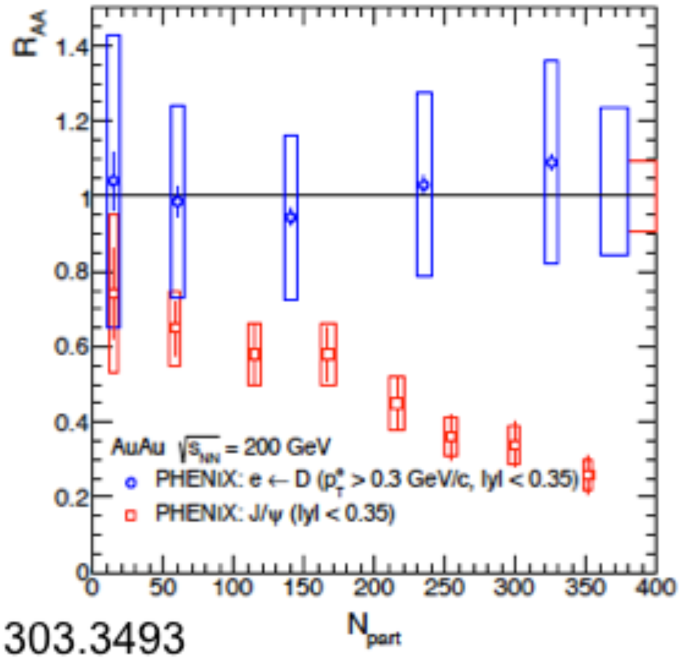
Very different conclusions can be drown depending on normalization

J/Psi compared to open charm - RHIC

High pT



Low Pt

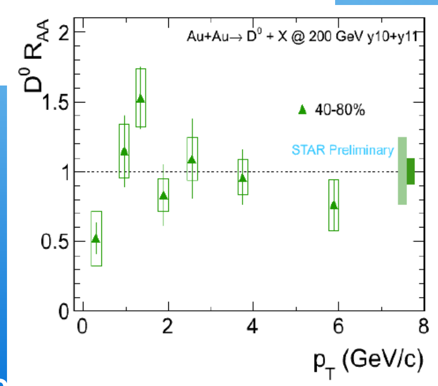


H. Satz, arXiv 1303.3493

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)

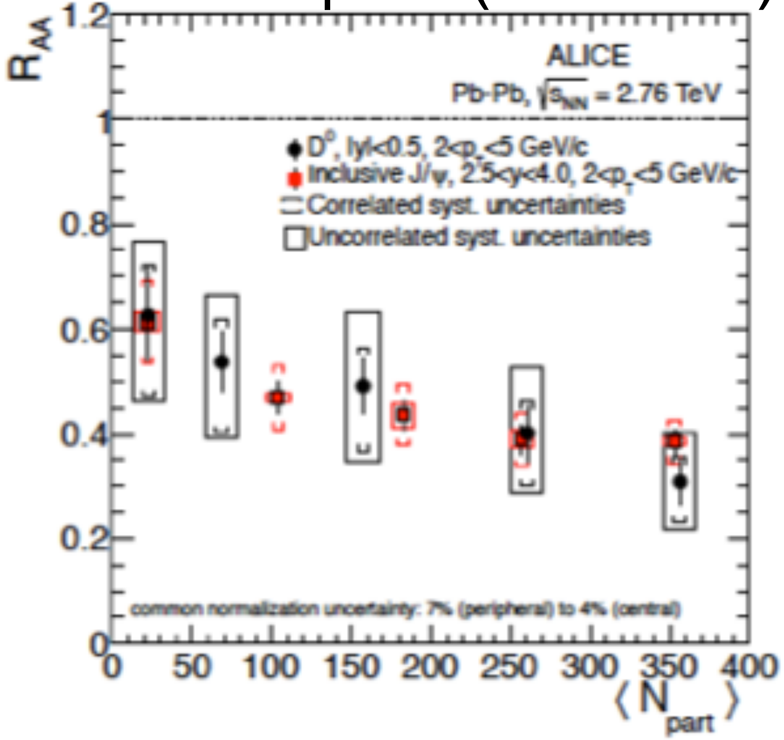
Low Pt — * J/Psi seems to be **significantly suppressed** with respect to open charm at low pT in central Au+Au events (same acceptance here)

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

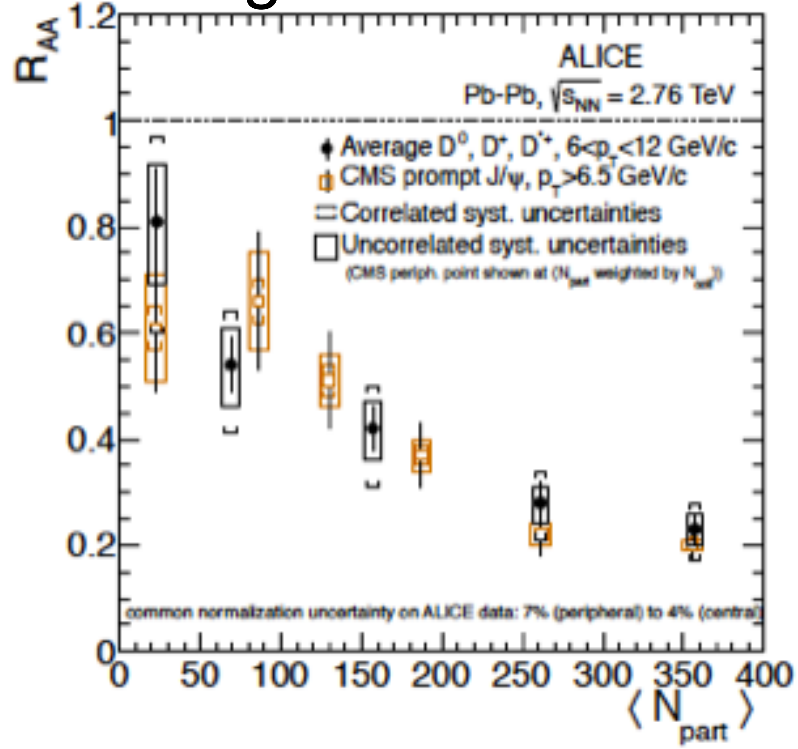


J/Psi compared to open charm - LHC

"Low|" Pt (2-5 GeV)



High Pt> 6.5 GeV

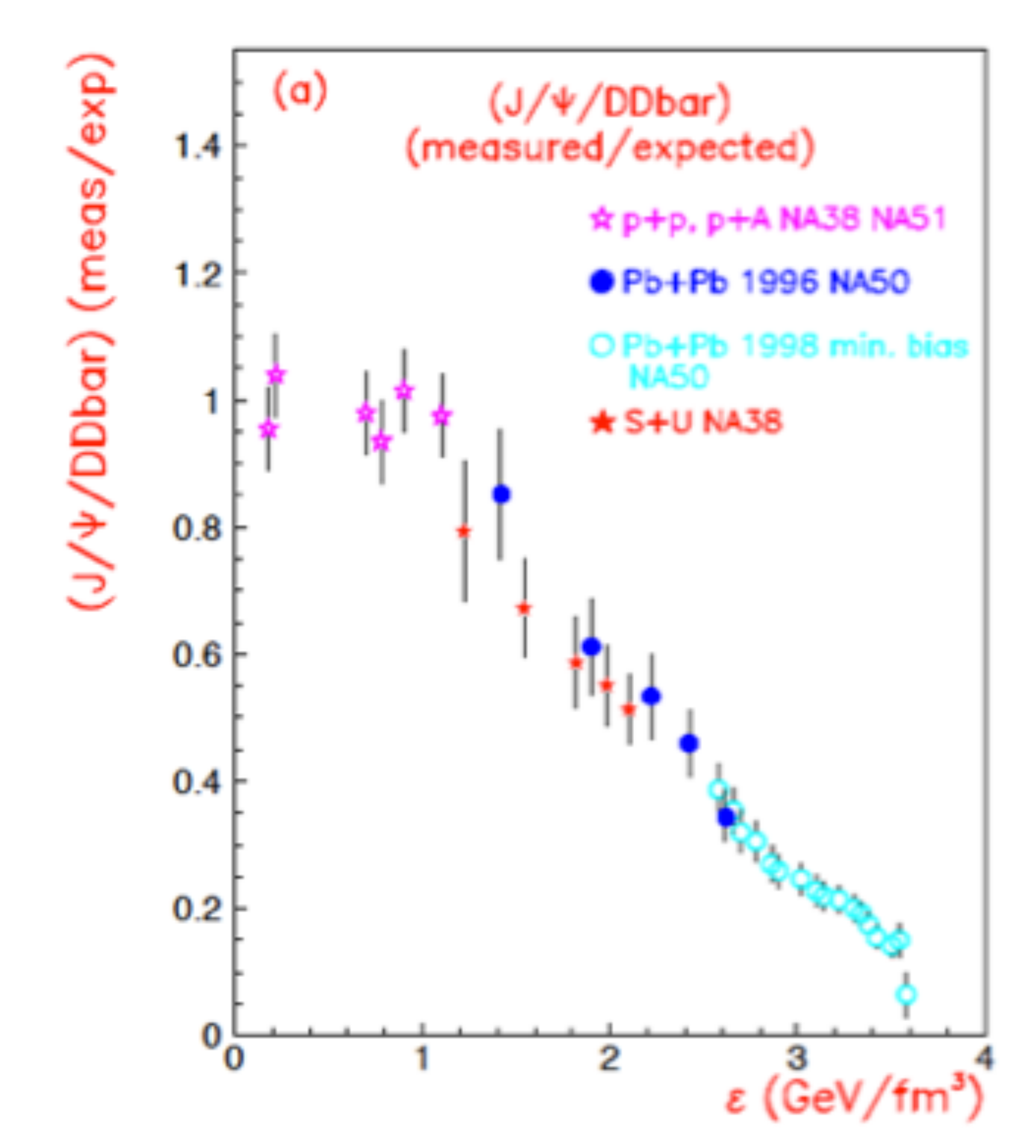


H. Satz, arXiv 1303.3493

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

Measured ratio of J/Psi to D mesons at SPS



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

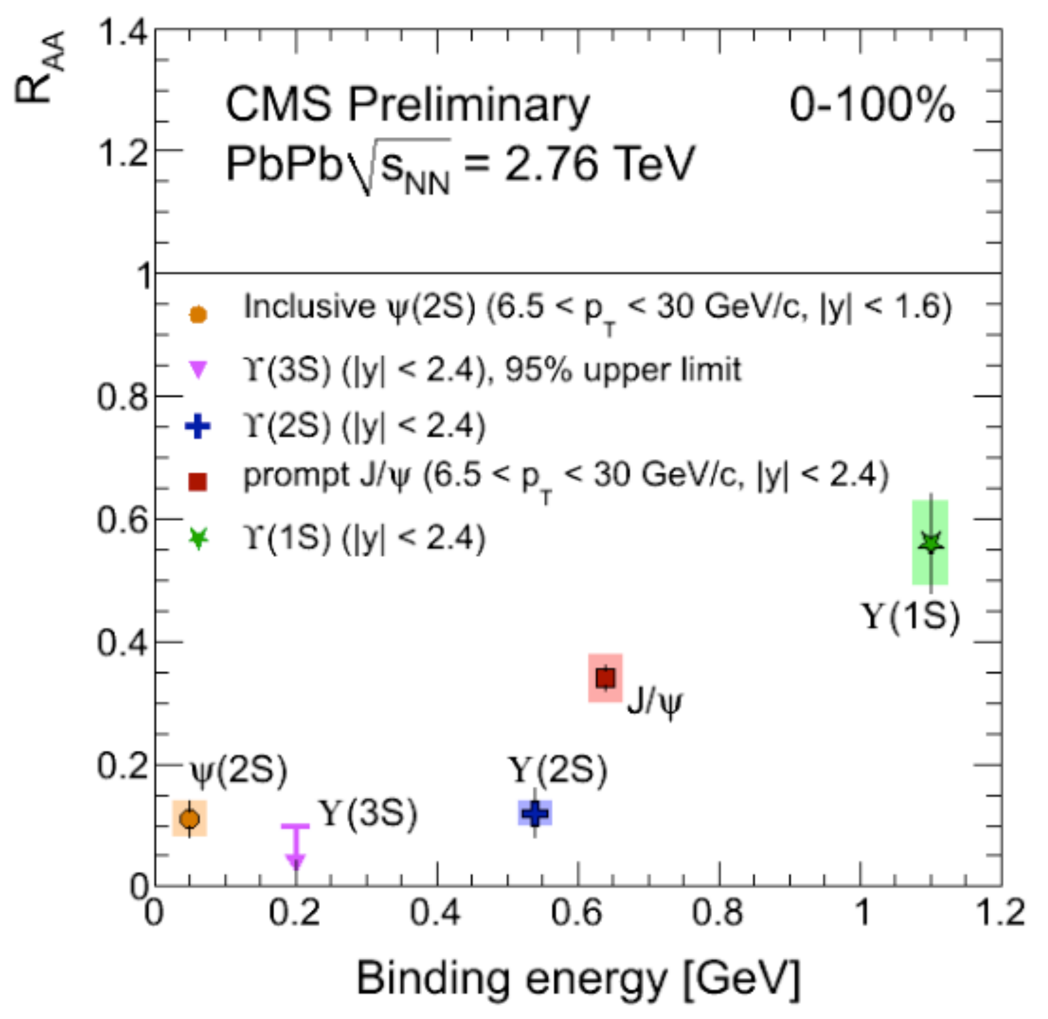
The J/Psi/(DDbar) estimate is suppressed at 1 GeV/fm^3 instead of 2.3 GeV/fmˆ3 and coincides with strangeness onset

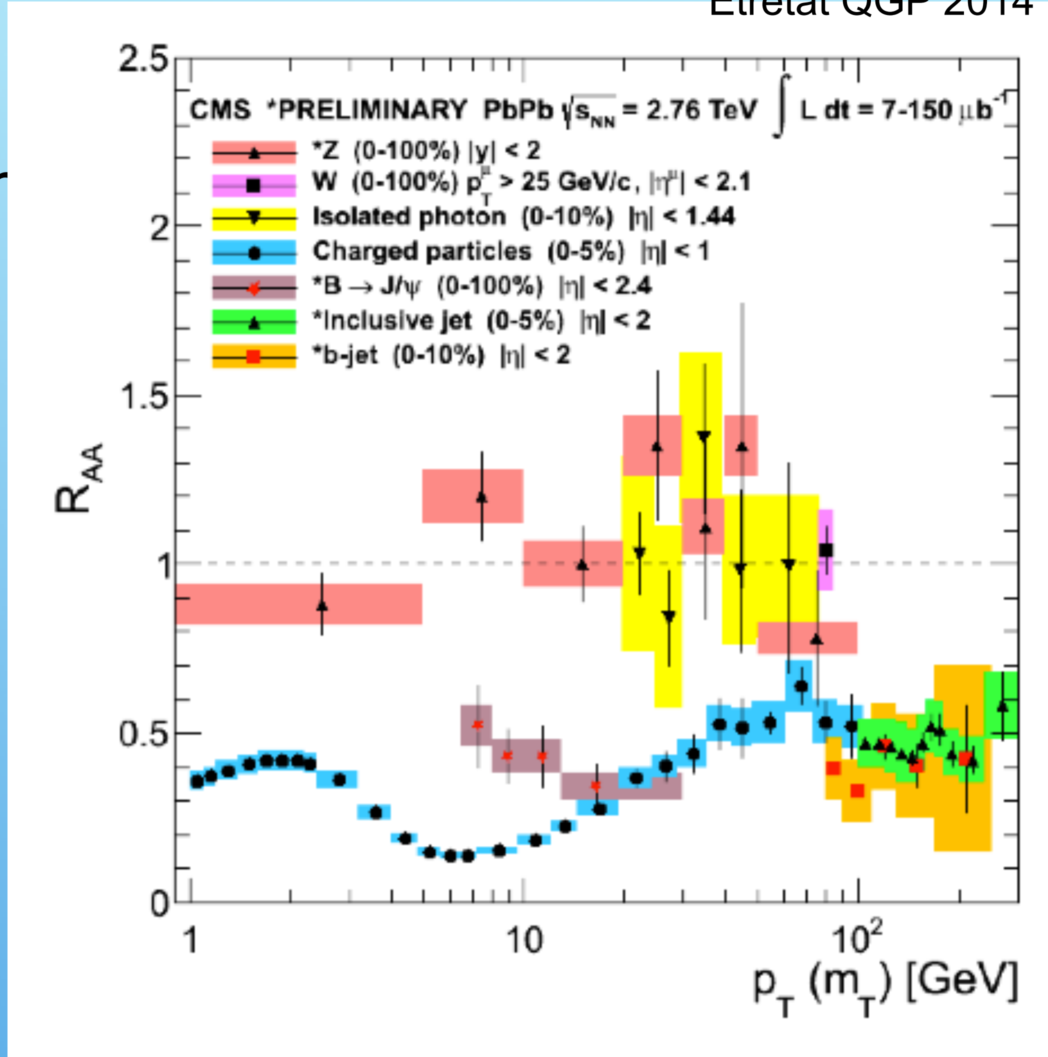
Need open charm measurements at low energy to understand quarkonia onset of suppression

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

Beauty

M. Jo et al CMS, Etretat QGP 2014



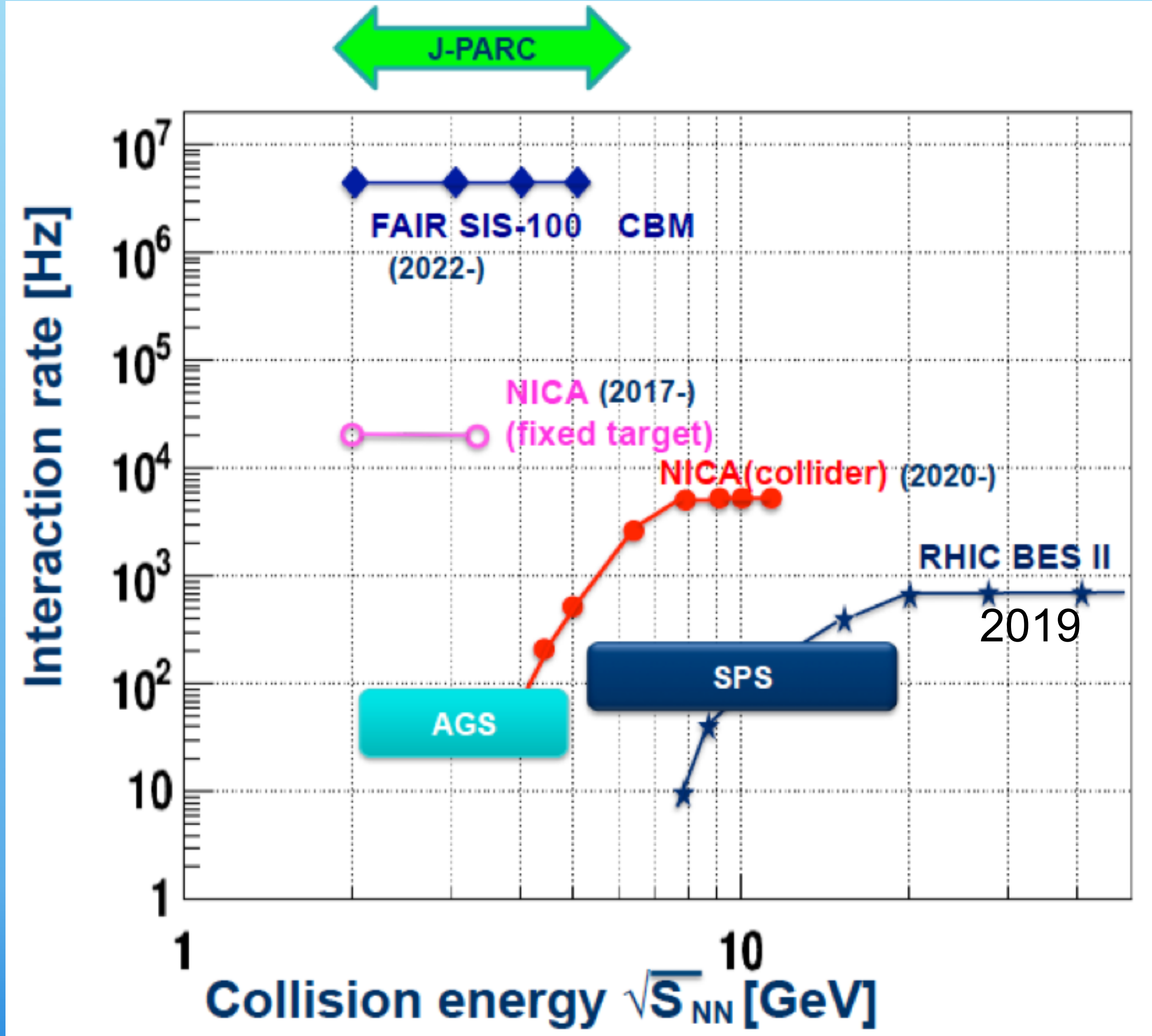


Y(1S) in PbPb seem less suppressed than open beauty in PbPb (needs better stat) if so -> no Y(1S) suppression

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

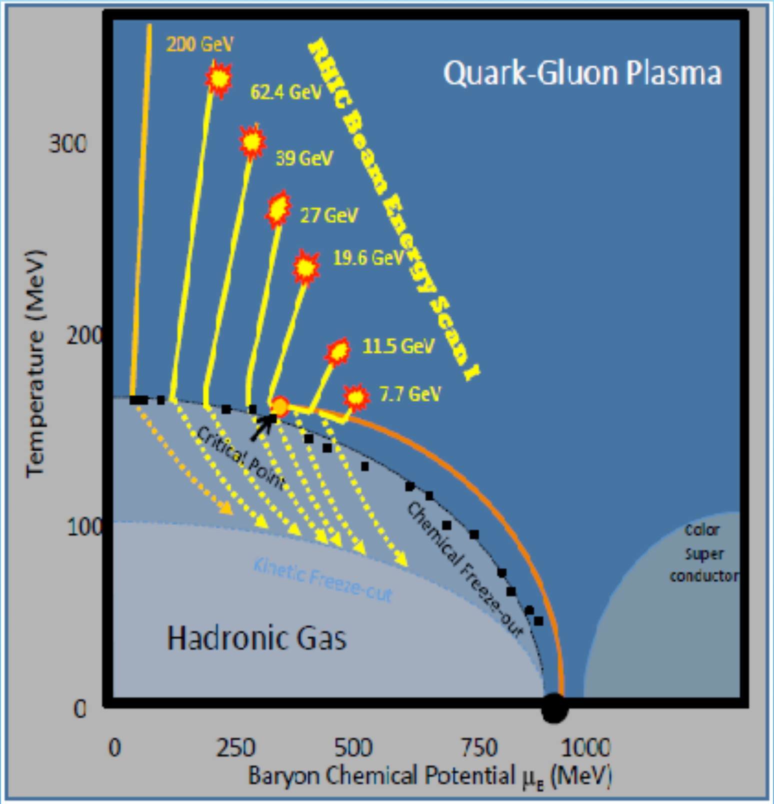
6. Future

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

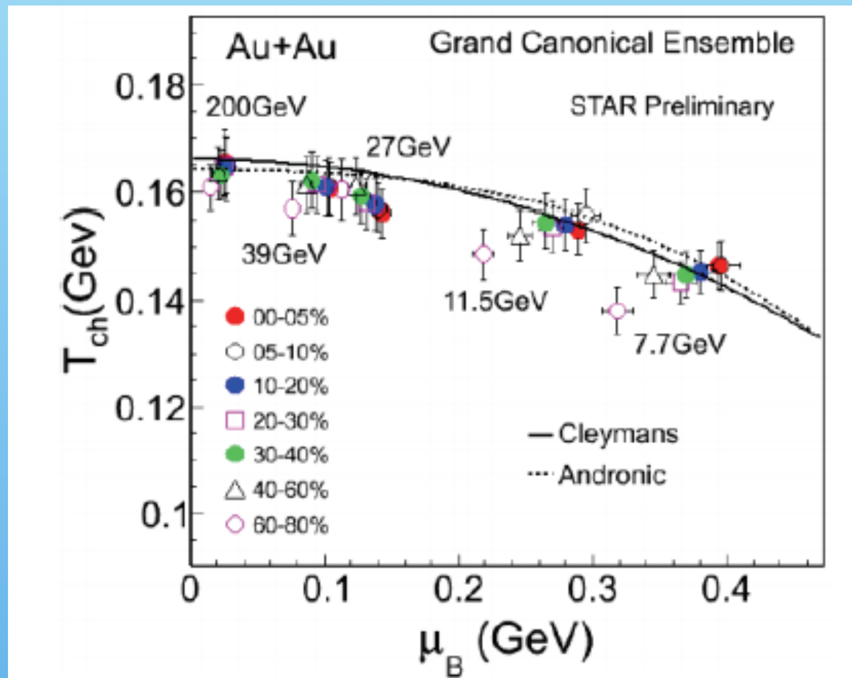


T. Sakaguchi, QM2017

Chemical freeze out temperature vs baryochemical potential



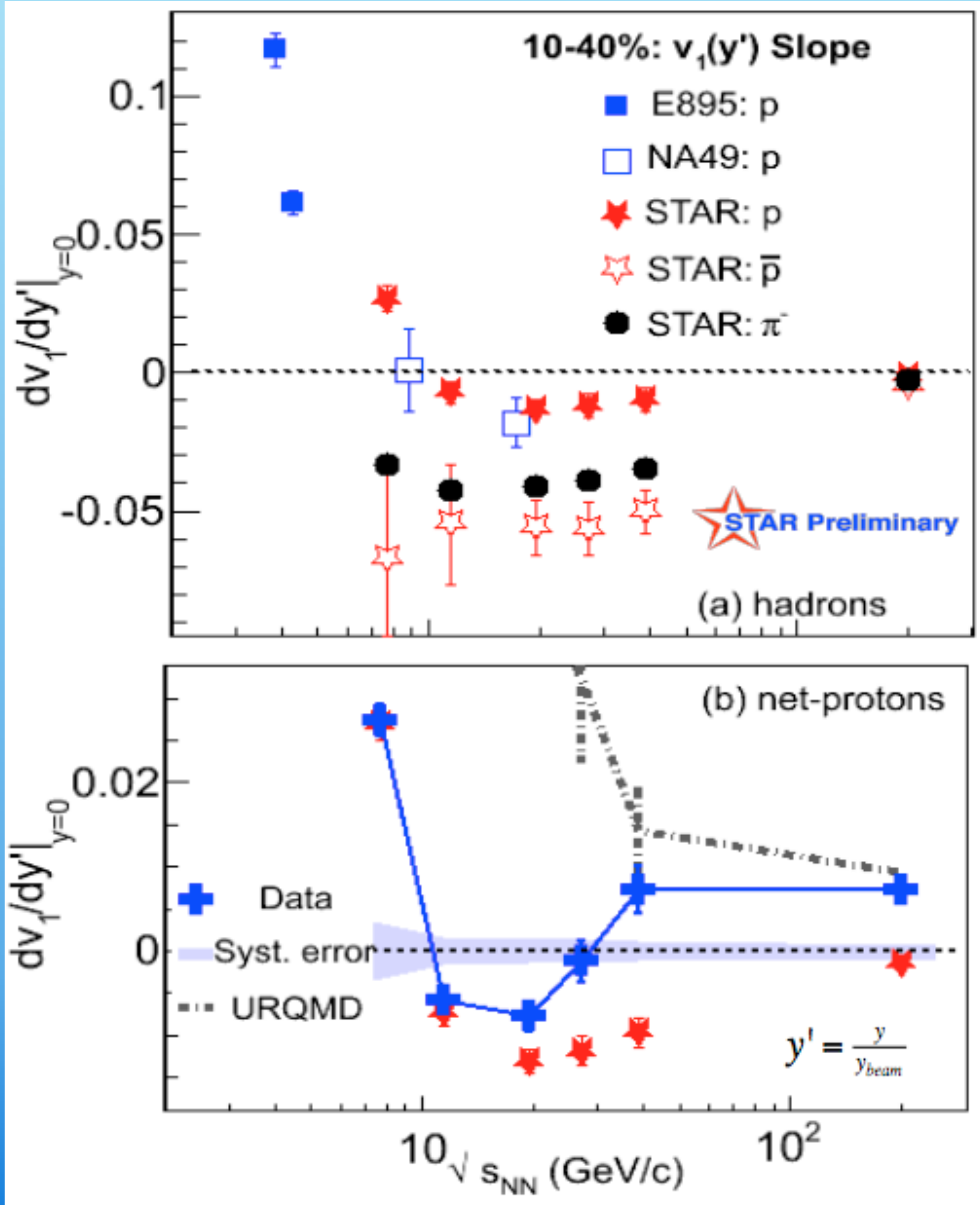
BES 1



Model used for particle ratio fits: THERMUS by J Cleymans et al

Grand canonical ensemble fits to particle ratios give consistent results for mid-central and central Au+Au collisions and disagree for peripheral collisions

Directed flow of protons BES 1



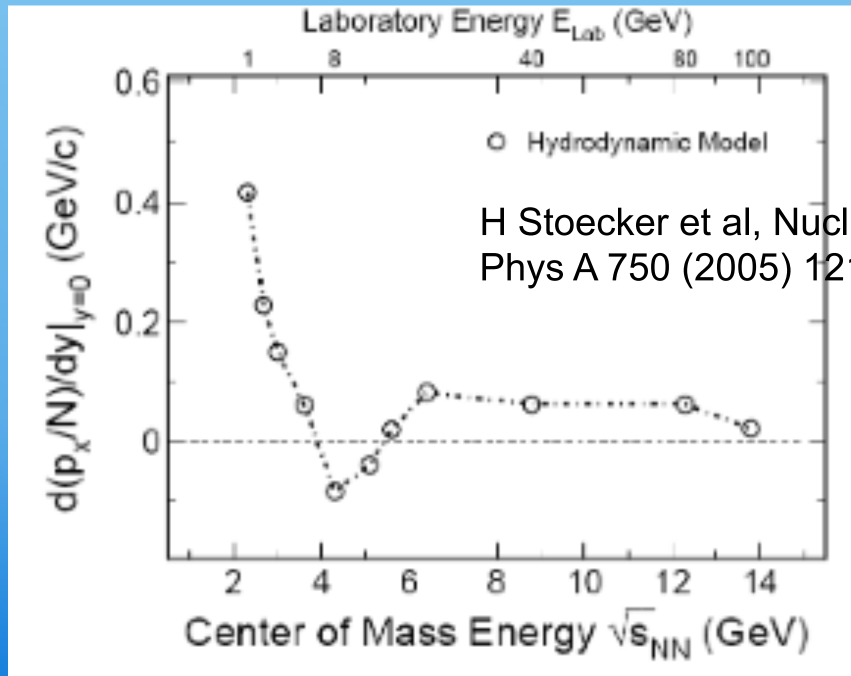
* Directed flow slope is sensitive to a 1st order transition

* STAR: v_1 slope changes sign from positive to negative between 7.7 and 11.5 GeV

Pions and antiprotons have always negative v1 slopes.

* Net-proton v_1 slope shows a minimum around 11.5-19.6 GeV

UrQMD model (model without phase transition) cannot explain the data



H Stoecker et al, Nucl Phys A 750 (2005) 121

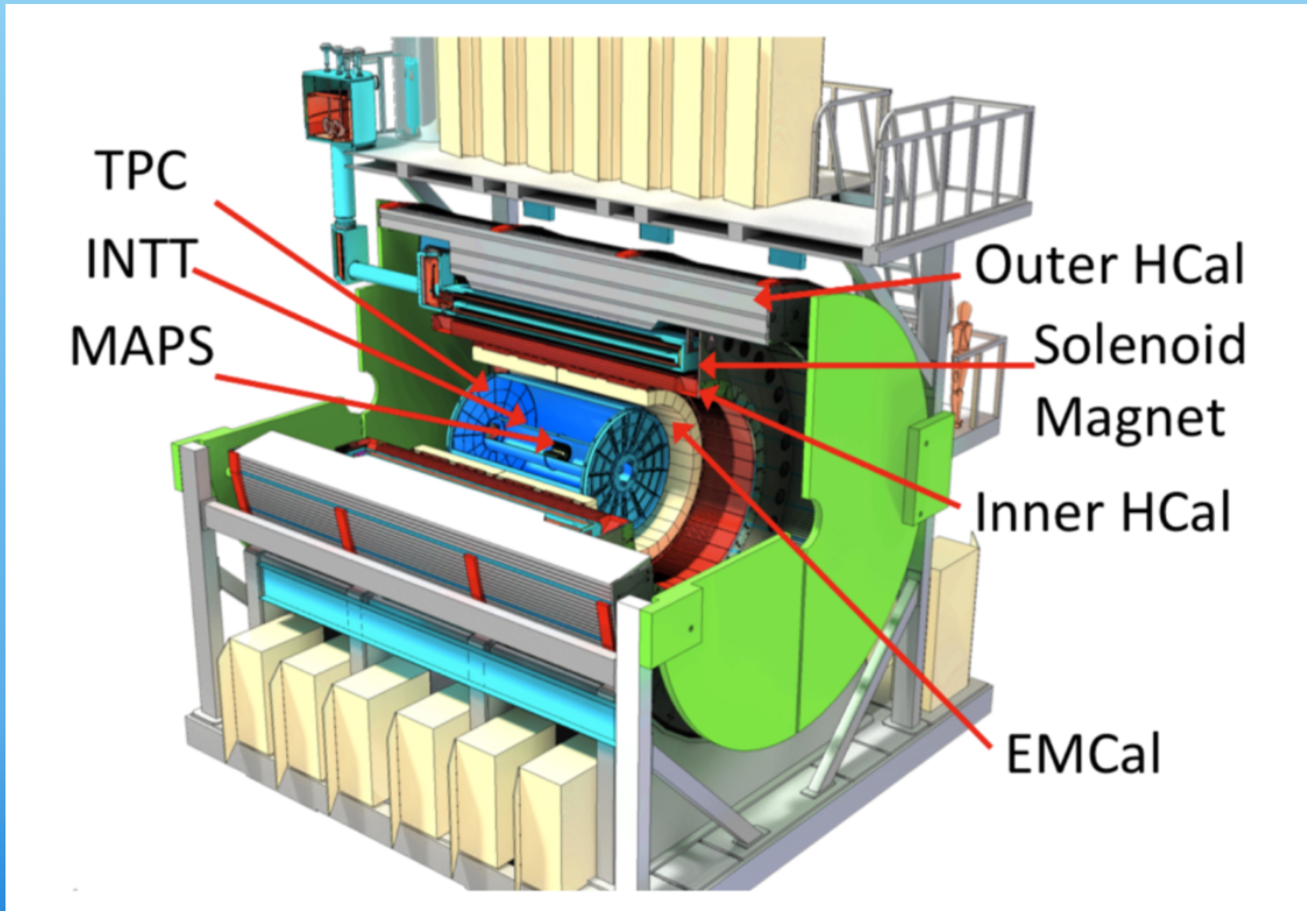
FiXed Target program energies

Collider Energy	Fixed-Target Energy	Single beam A GeV	Center-of-mass Rapidity	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	*721*

* STAR upgrades for BES-II and 2020+
* 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

IV Conclusions

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

- We have obtained first quantitative estimates for characteristics of sQGP, like its shear viscosity, temperature, density and energy density. The sQGP has a temperature more than 100000 the T of the core of the sun, has the smallest shear viscosity and the largest vorticity measured in fluids in the Lab.

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

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

- will allow to progress in significant way in the next decades.

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

https://indico.cern.ch/event/663474/overview

7th International Conference on New Frontiers in Physics

New Frontiers in Physics ICNFP 2018

4-12 July 2018,
Kolymbari, Crete, Greece
http://indico.cern.ch/event/icnfp2018

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High Energy Particle Physics

Heavy Ion Physics, Critical phenomena

Quantum Physics, Quantum Optics, Quantum Information

Cosmology, Astrophysics, Gravity, Mathematical physics

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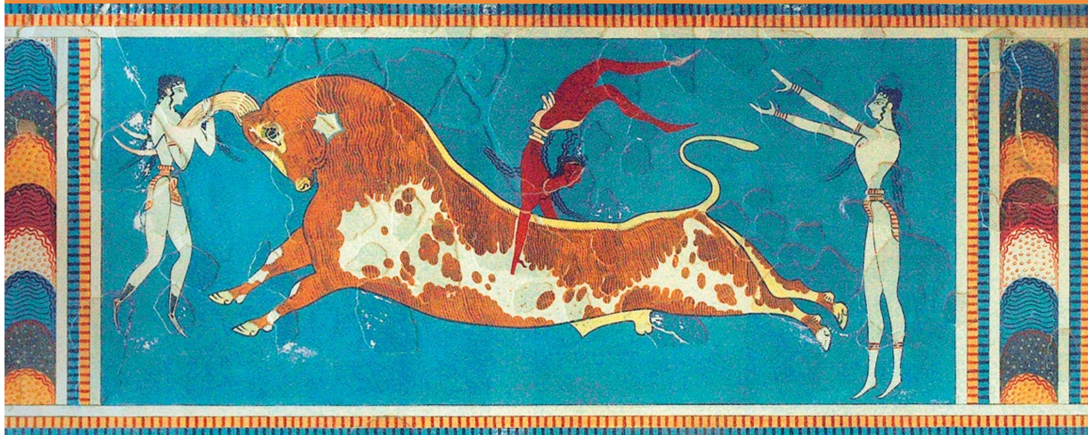


ICNFP 2018 conference
4-12 July 2018
Crete, Greece

You are warmly invited !

Backup slides

A view into the far Future : FCC

plot from M. Koratzinos, ICNFP2017

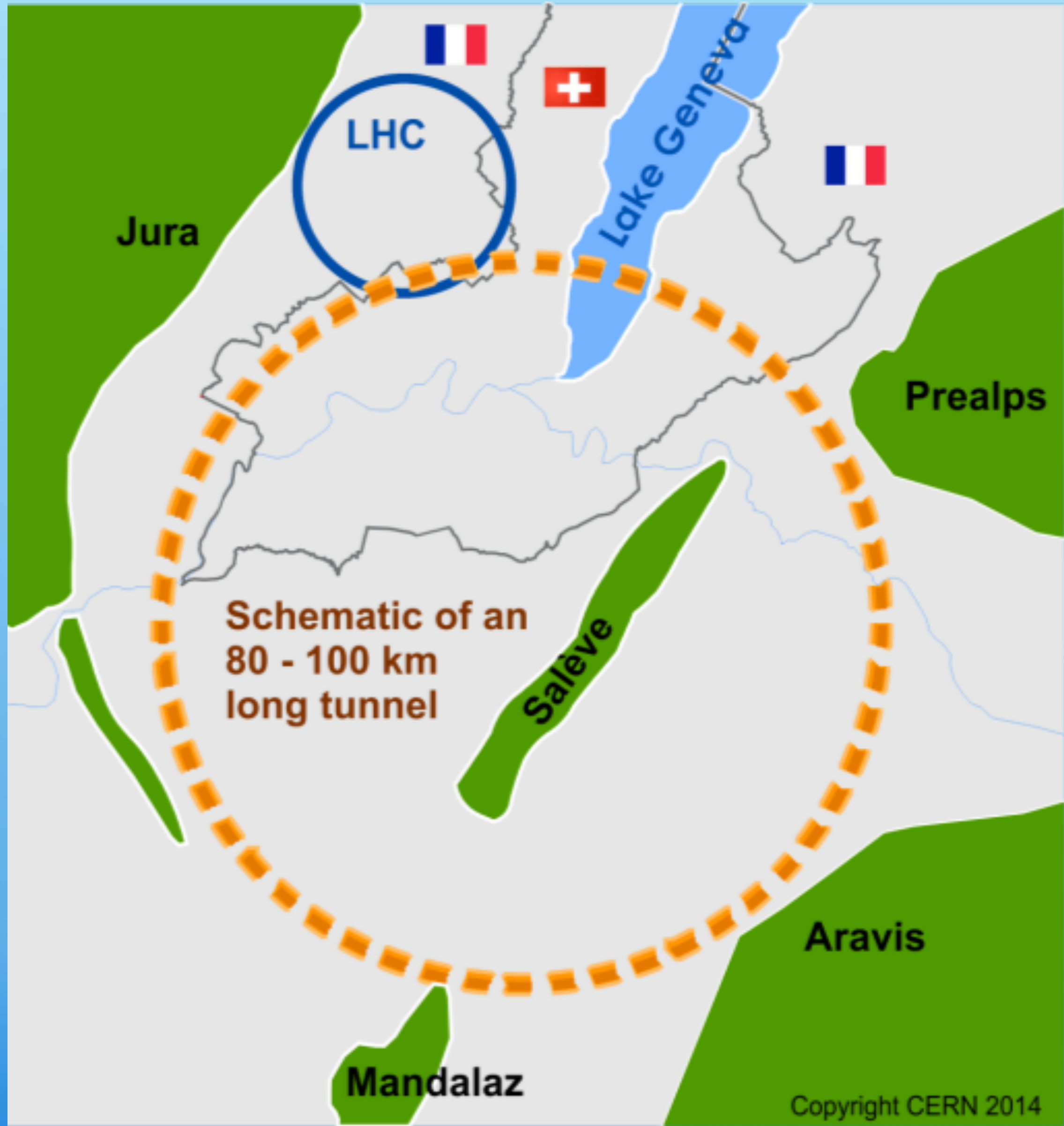
FCC: The Vision

~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

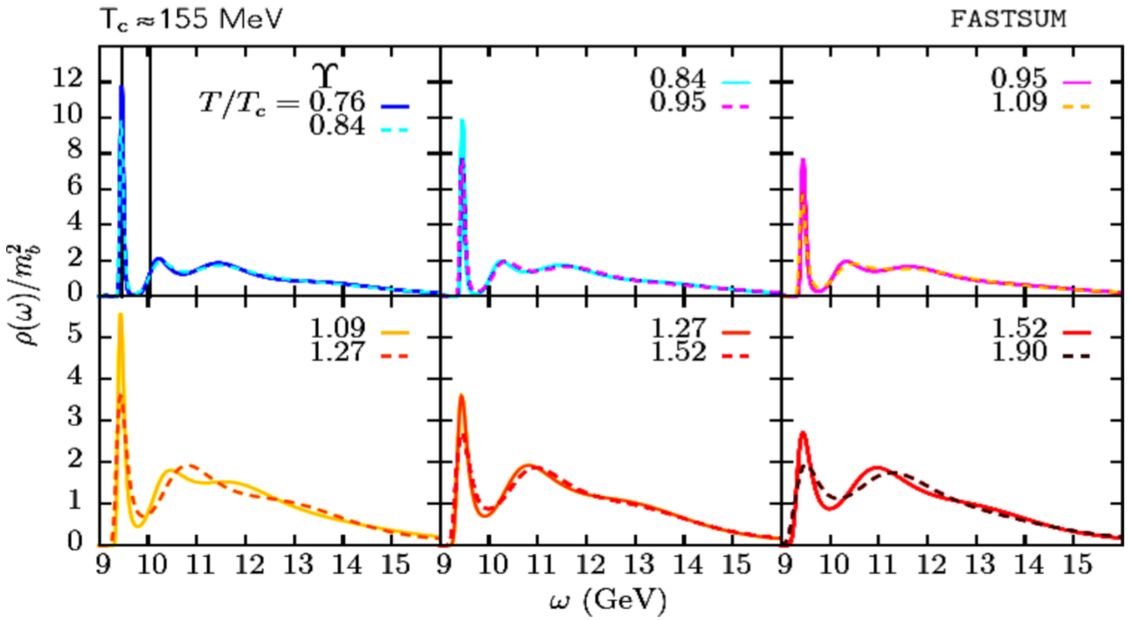


FCC quarkonia

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

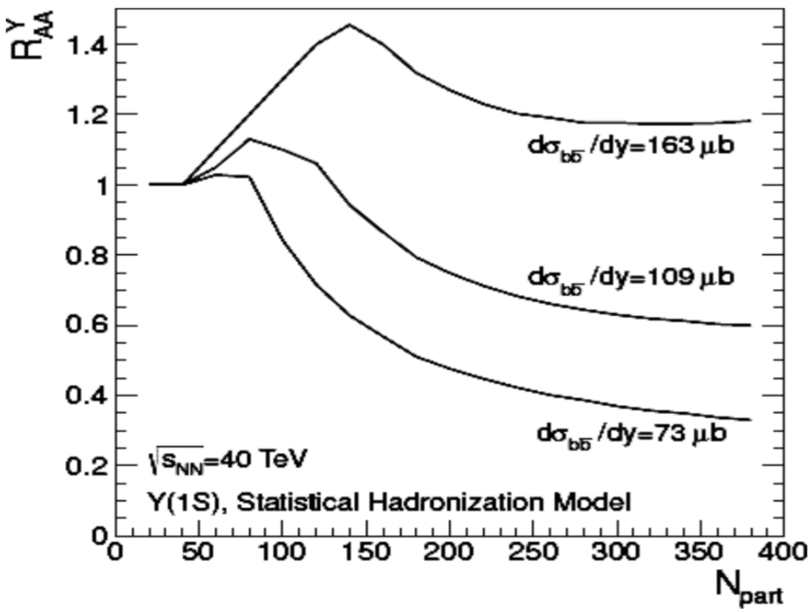
D. d Enterria, QM2017

- 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]

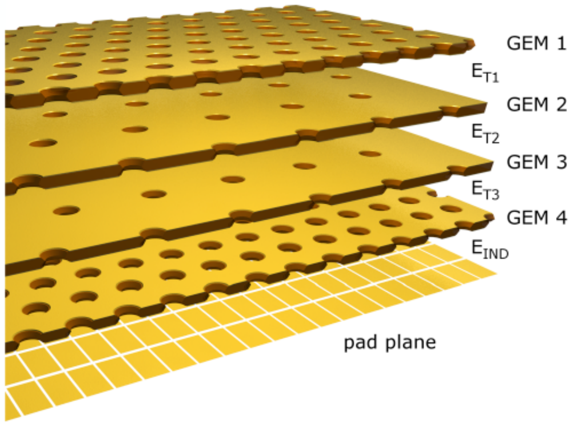
- Density of bbbar pairs large enough for Y(1S) recombination?

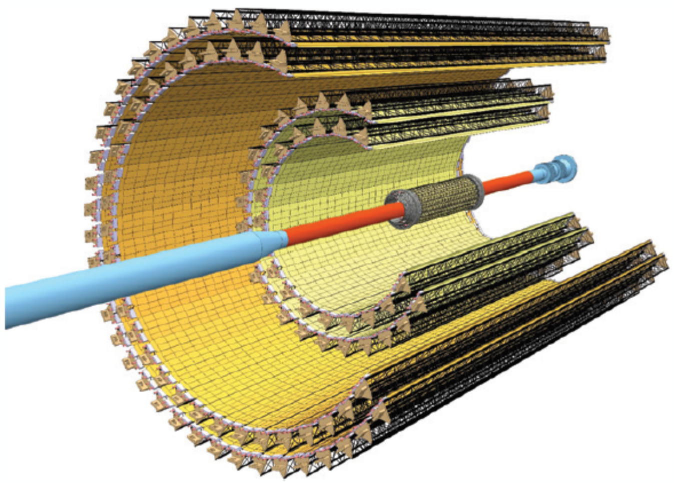


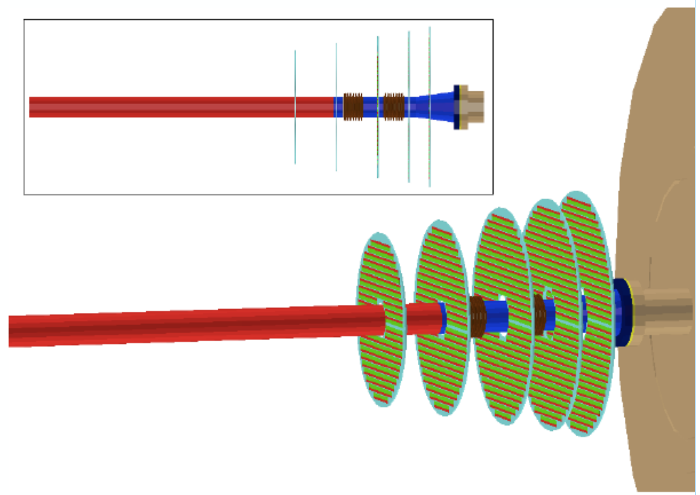
[A.Andronic, et al., JPG38 (2011) 124081]

LHC experimental upgrades

ALICE upgrades for run-3







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

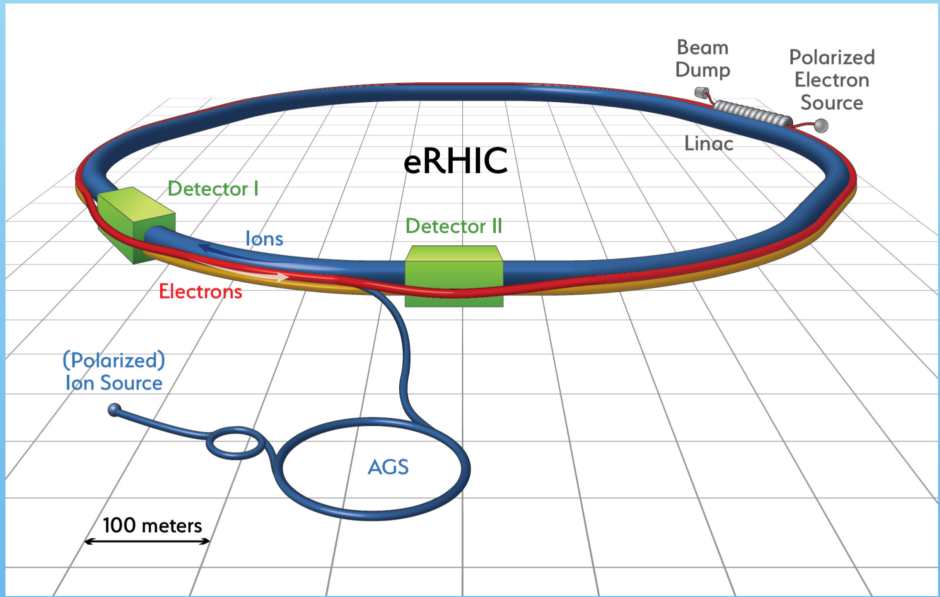
Beam Energy Scan Phase II

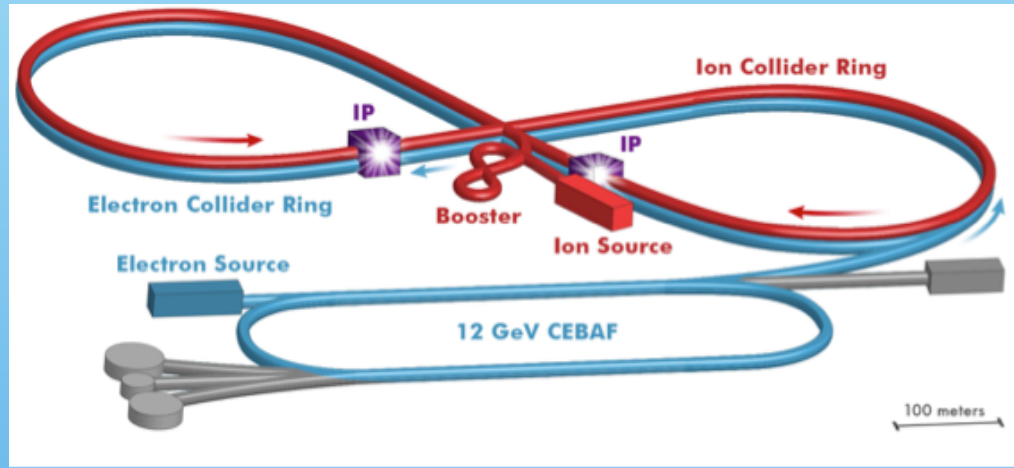
Collision Energies (GeV)	7.7	9.1	11.5	14.5	19.6	*Related to*
Chemical Potential (MeV)	420	370	315	260	205	
Observables	Millions of Events Needed					
R_{cp} up to p_T 5 GeV	N/A	N/A	160	125	92	*Turn-off of QGP signature*
Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400	
Local Parity Violation (CME)	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

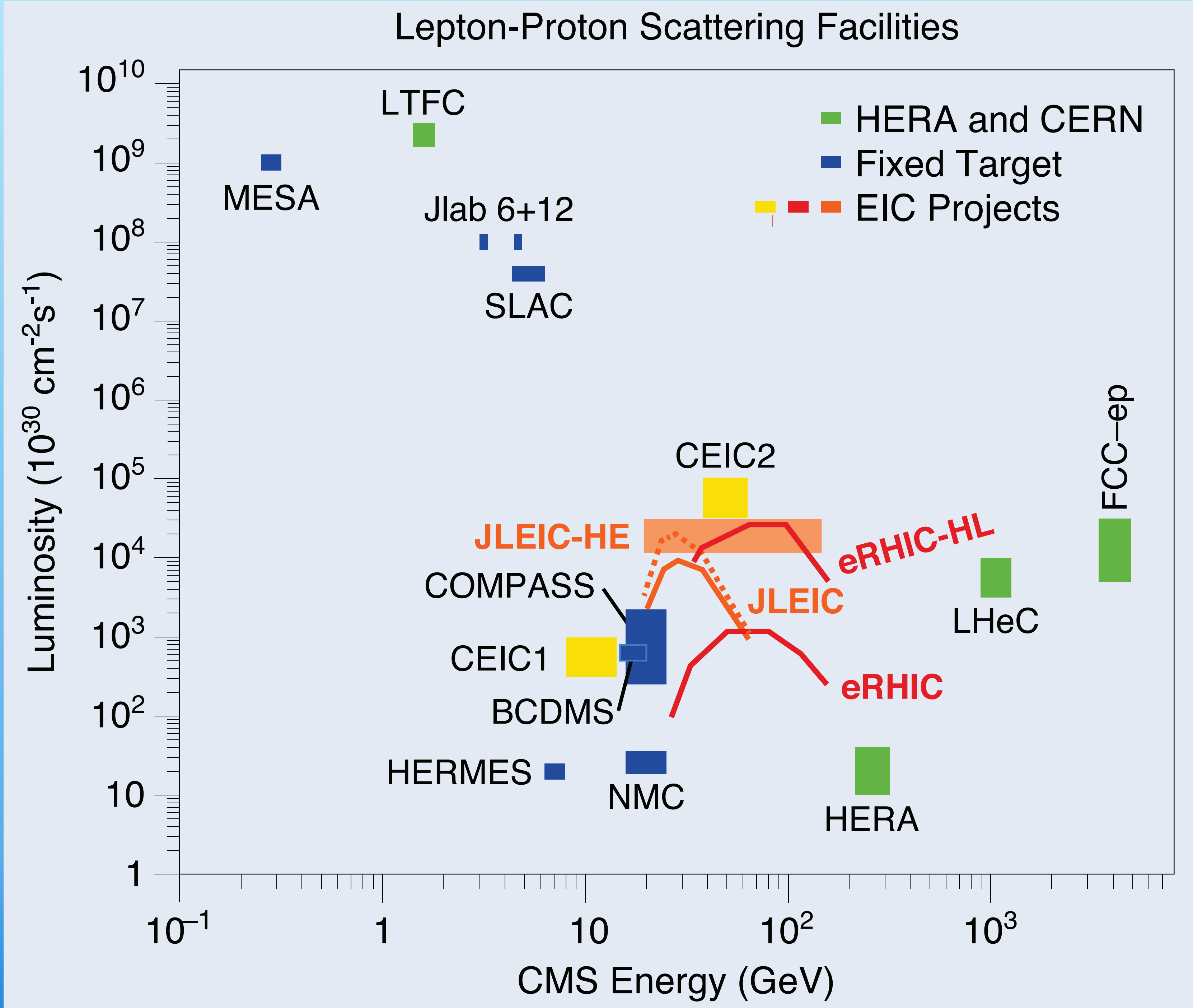




eRHIC	JLEIC
ep: $\sqrt{s}_{max}$= 140	ep: $\sqrt{s}_{max}$= 63
eAu: $\sqrt{s}_{max}$= 90	eAu: $\sqrt{s}_{max}$= 40

nuclei from deuterium to Uranium

E. Aschenauer, ICNFP2017



E. Aschenauer, ICNF2017

Example of results II:

EoS of QGP Matter

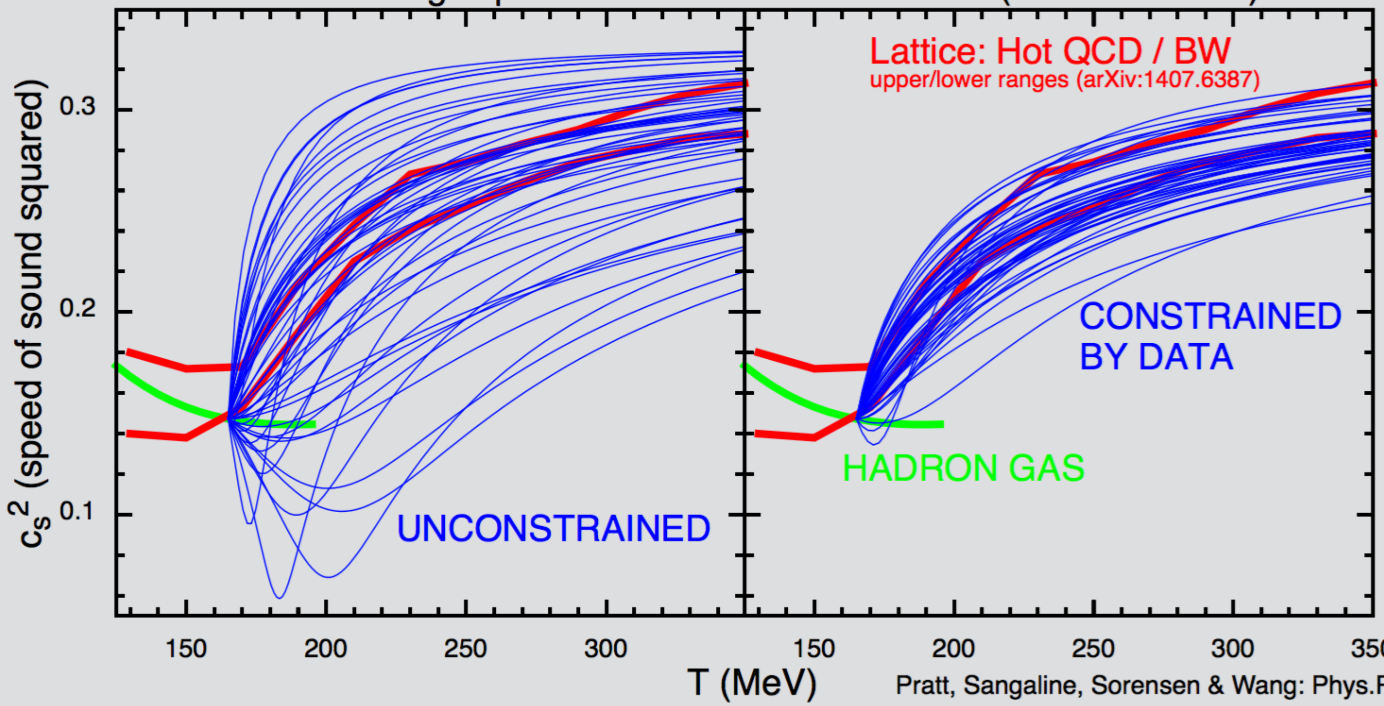
Example: determine the EoS of QGP matter from experimental measurements

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

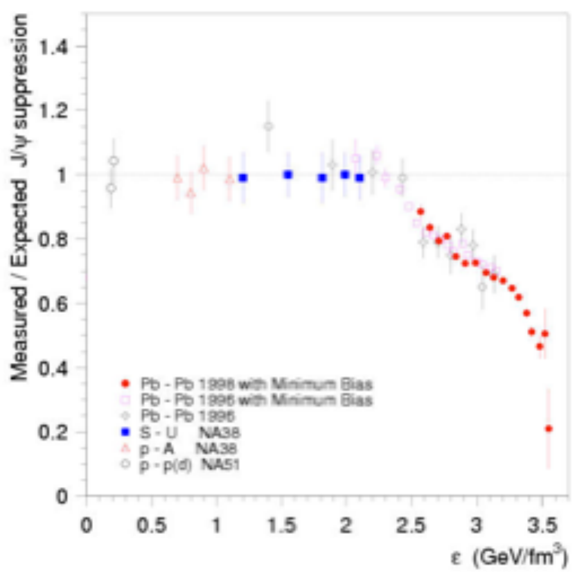
T(chem. freee out) ~ T (critical

Direct gammas consistent with T > Tcritical

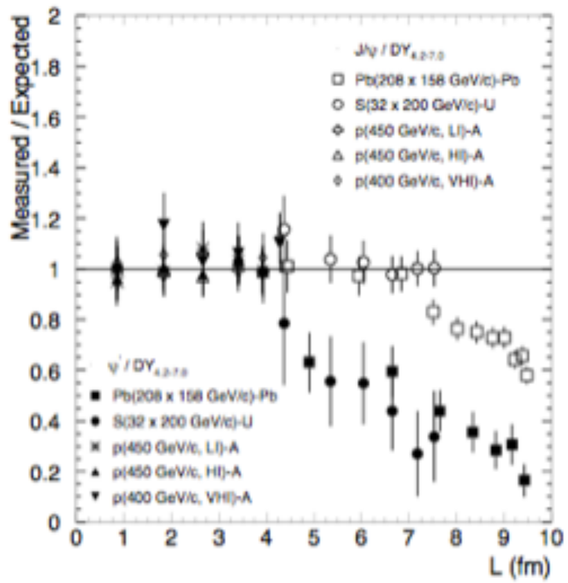
and other results

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

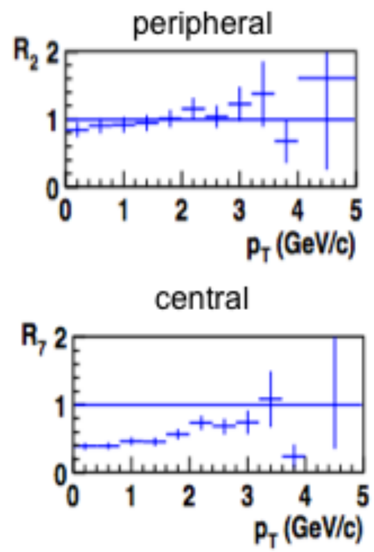
NA50, Phys Lett B 477 (2000) 28



Eur Phys J C 49 (2007) 559



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

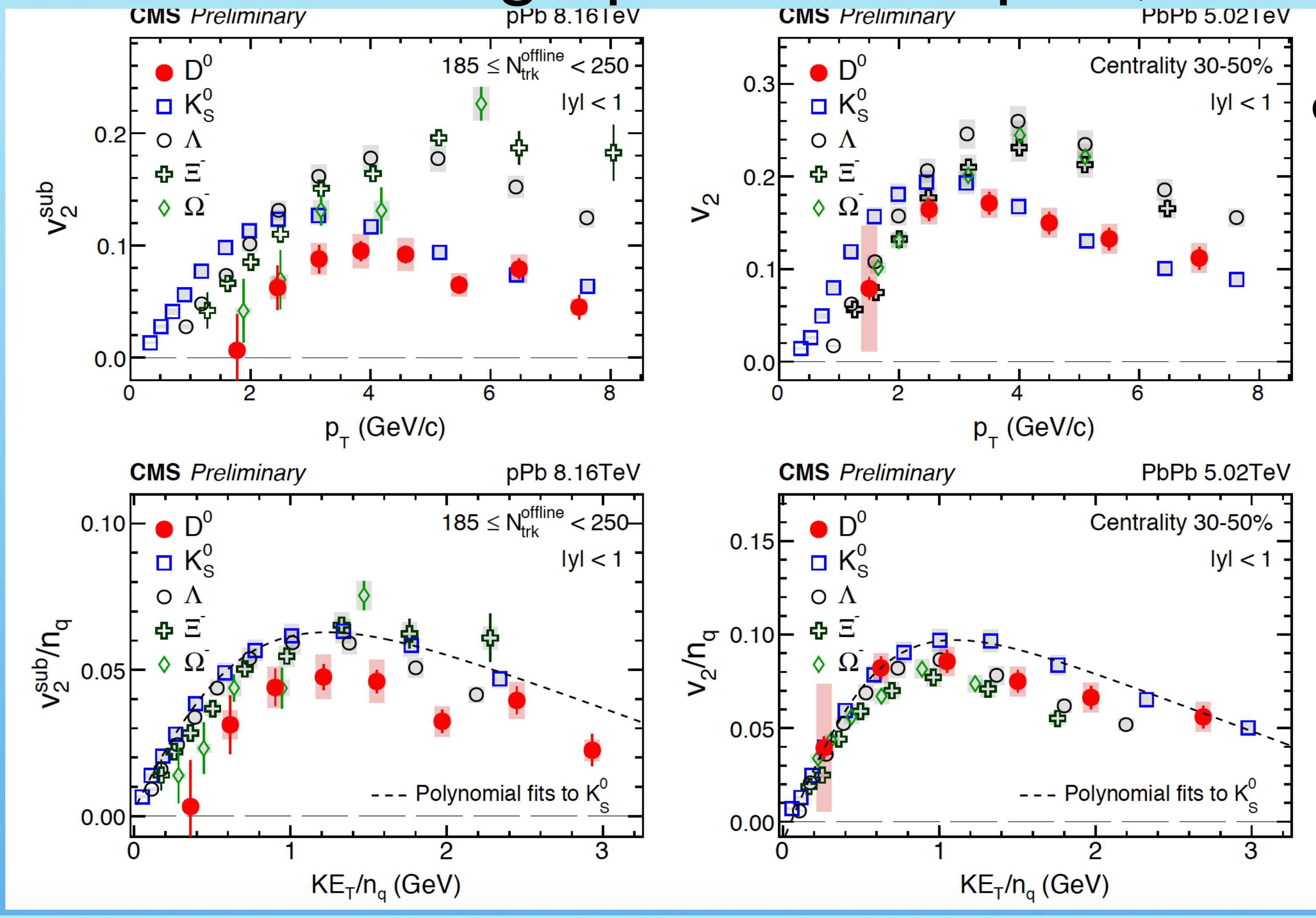


A Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004

* **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

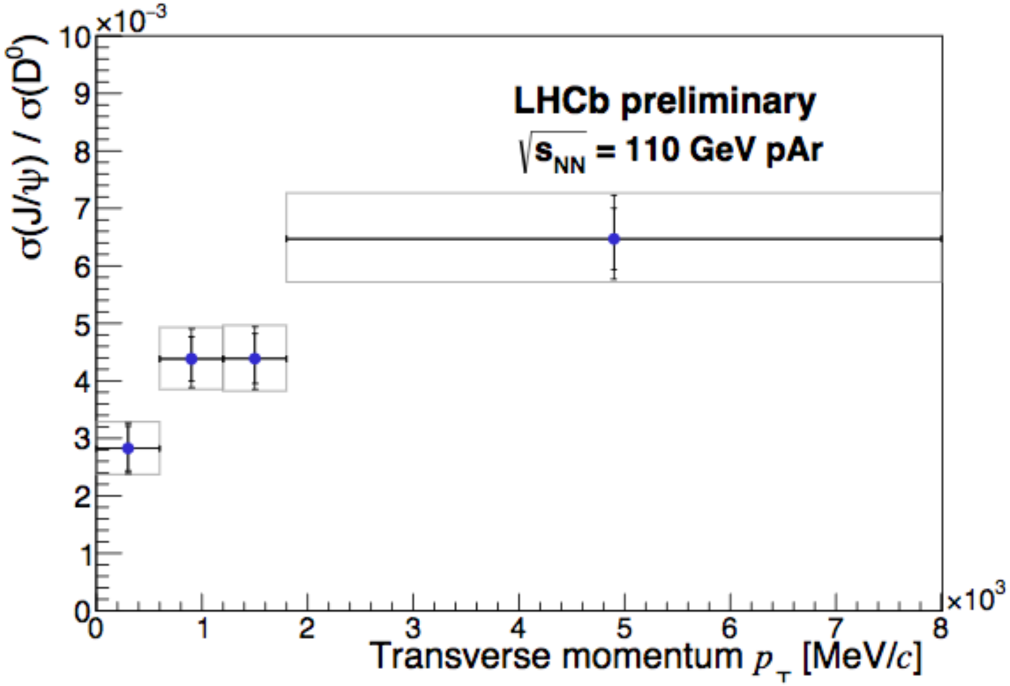


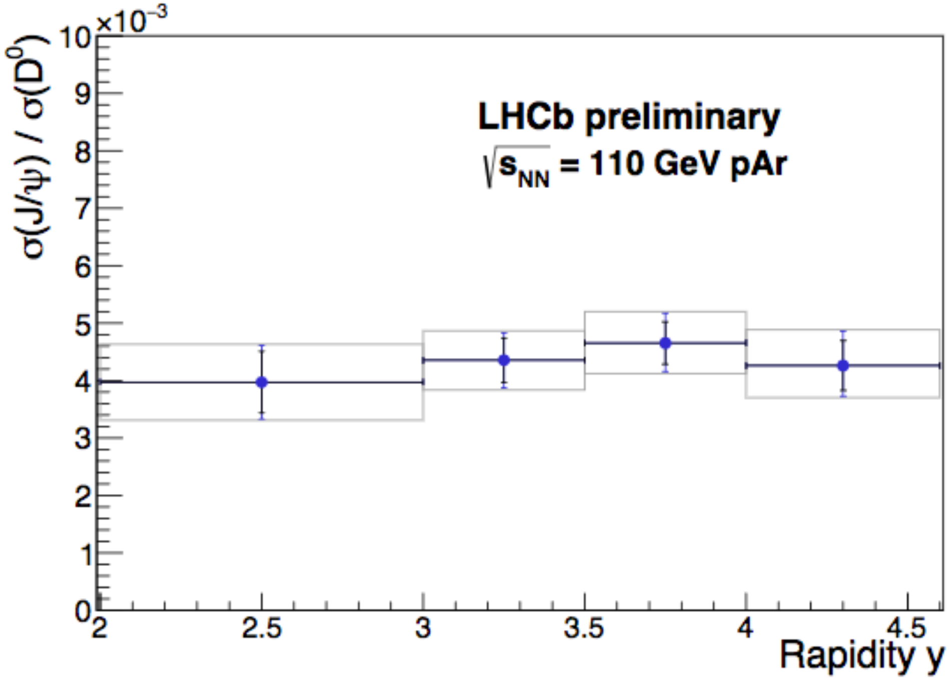
CMS 1705.01974

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

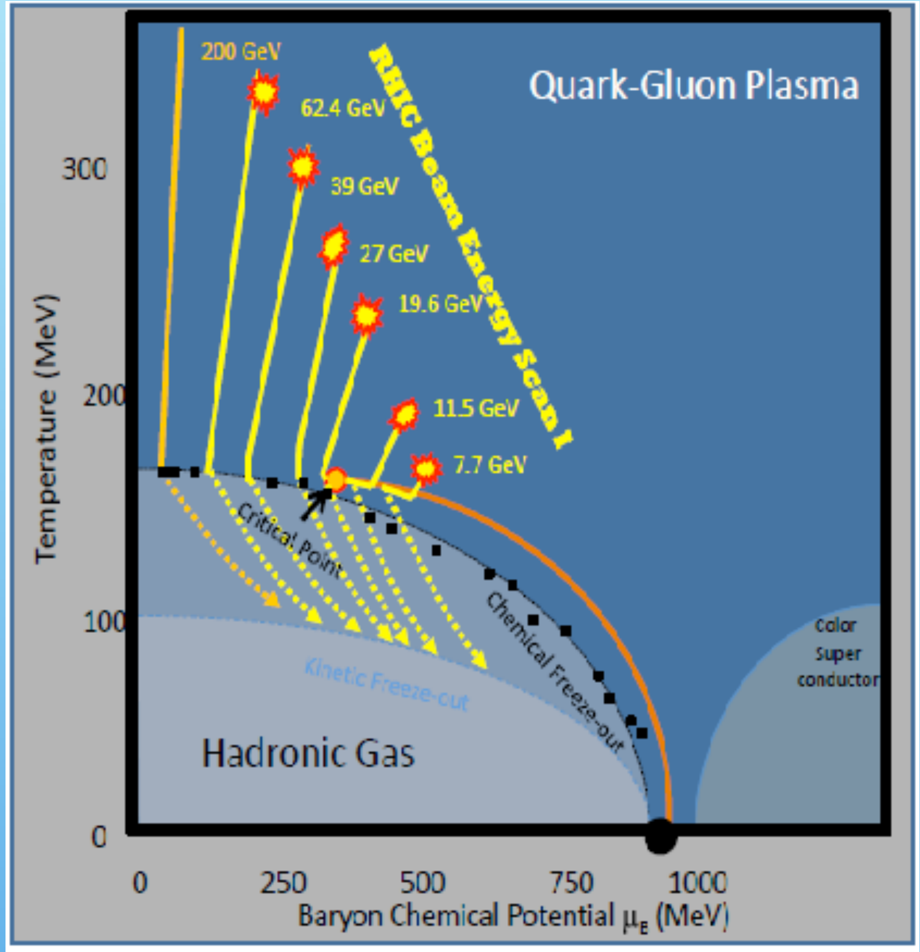
PbPb semiperiph.: v2/nq of strange particles and D0tend to lie on a universal curve below 1.0 GeV, indicating strong collective behaviour of D0 similar to the bulk of QGP medium

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





The expected QCD phase diagram



Phases of QCD Matter

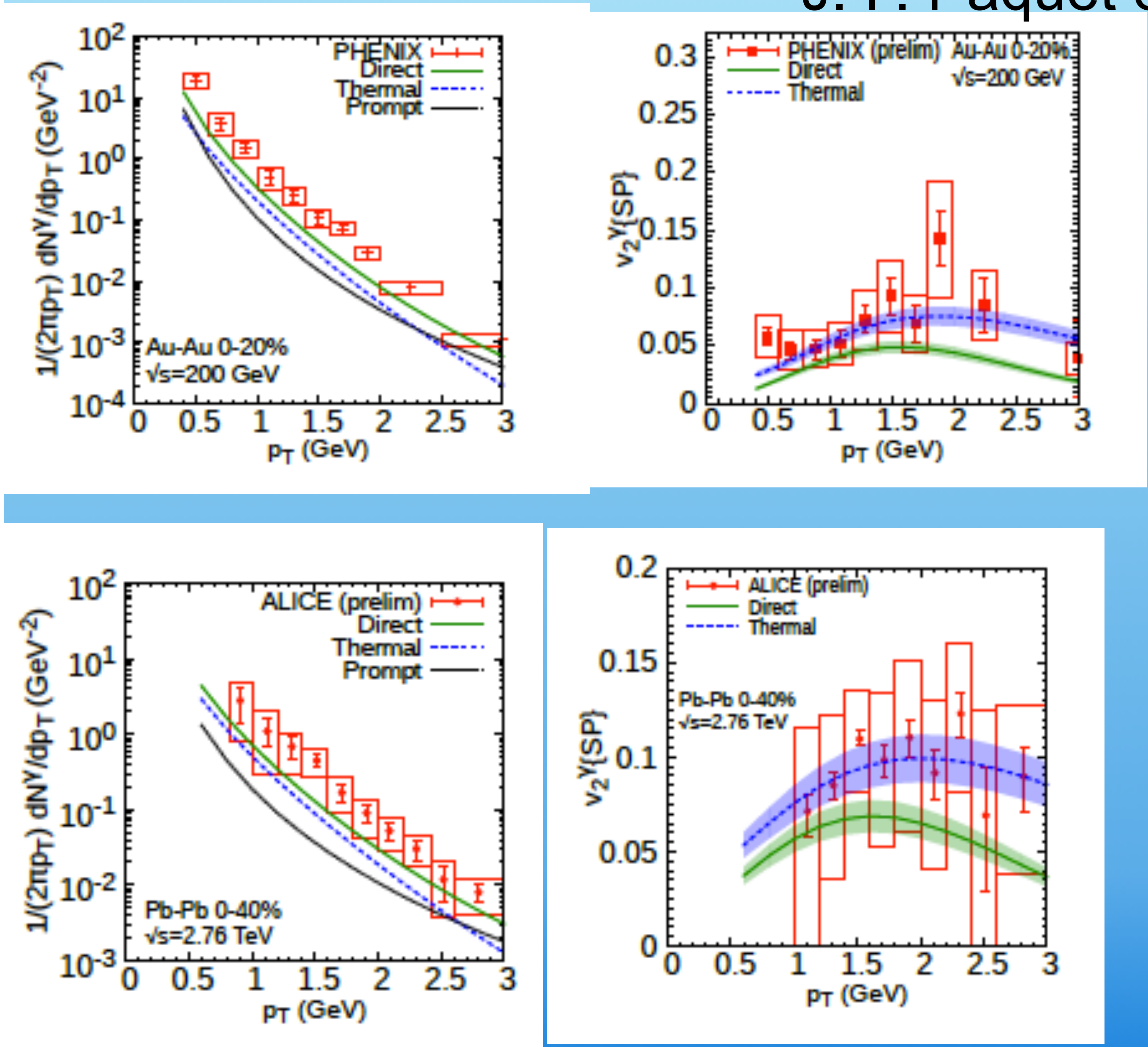
Areas of different net baryon densities and temperatures can be probed using different collision energies and nuclei.

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



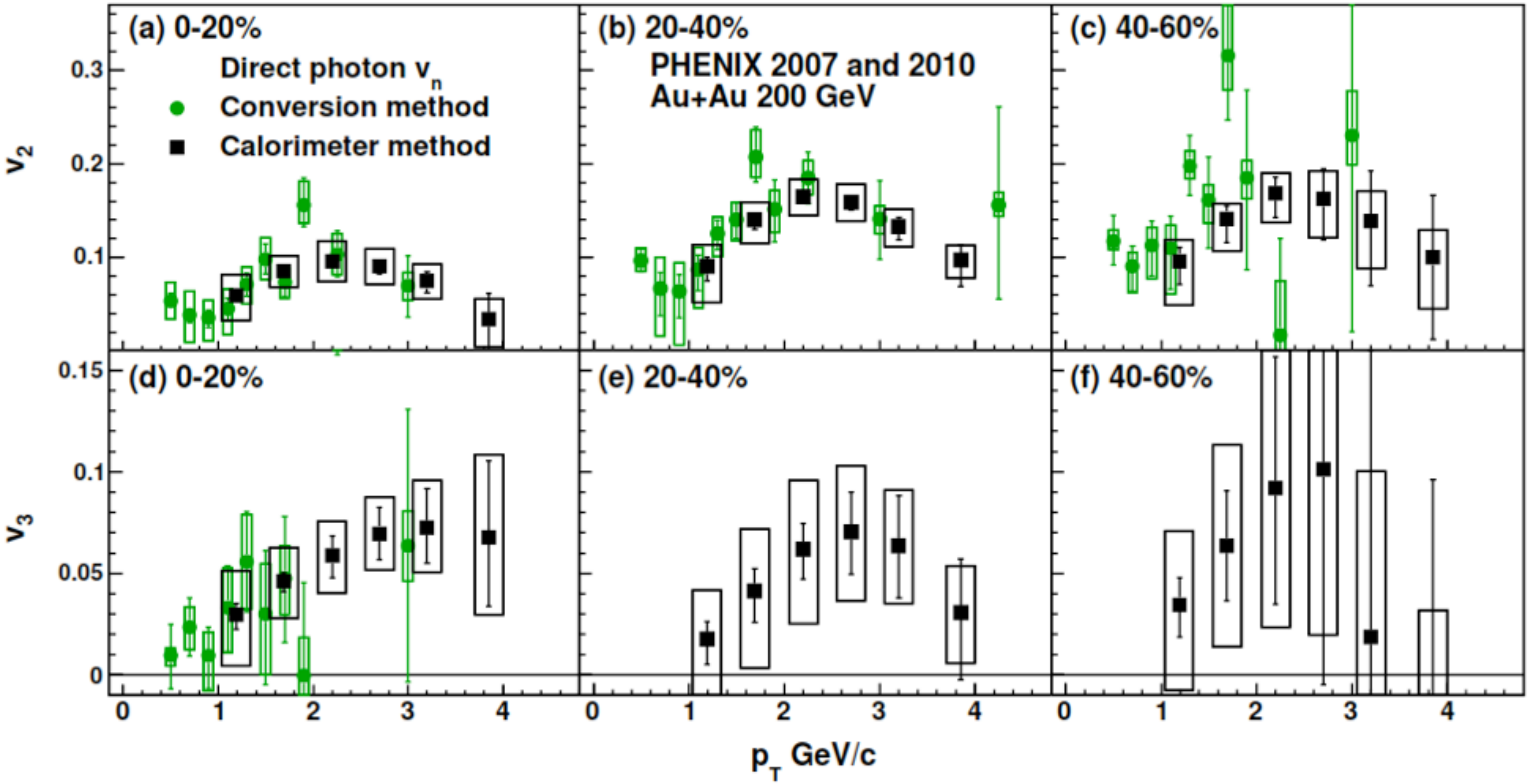
Difficult for models to describe both cross section and v2 flow of direct photons

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

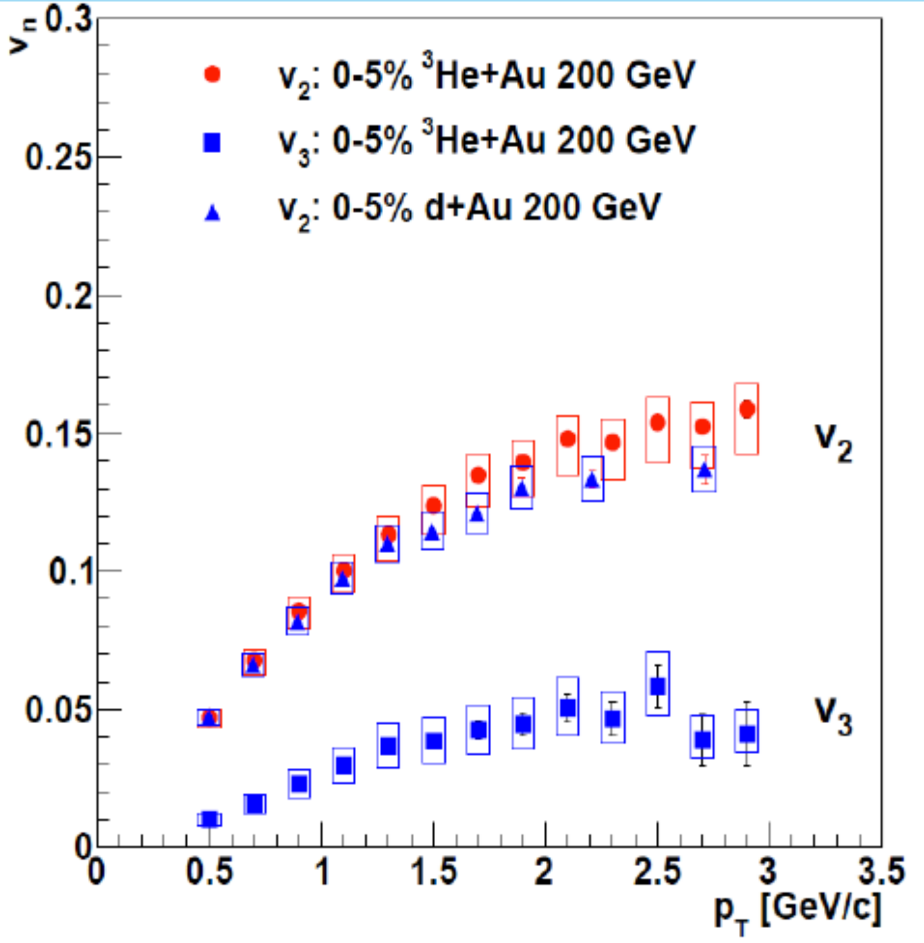
Anisotropic emission of direct photons

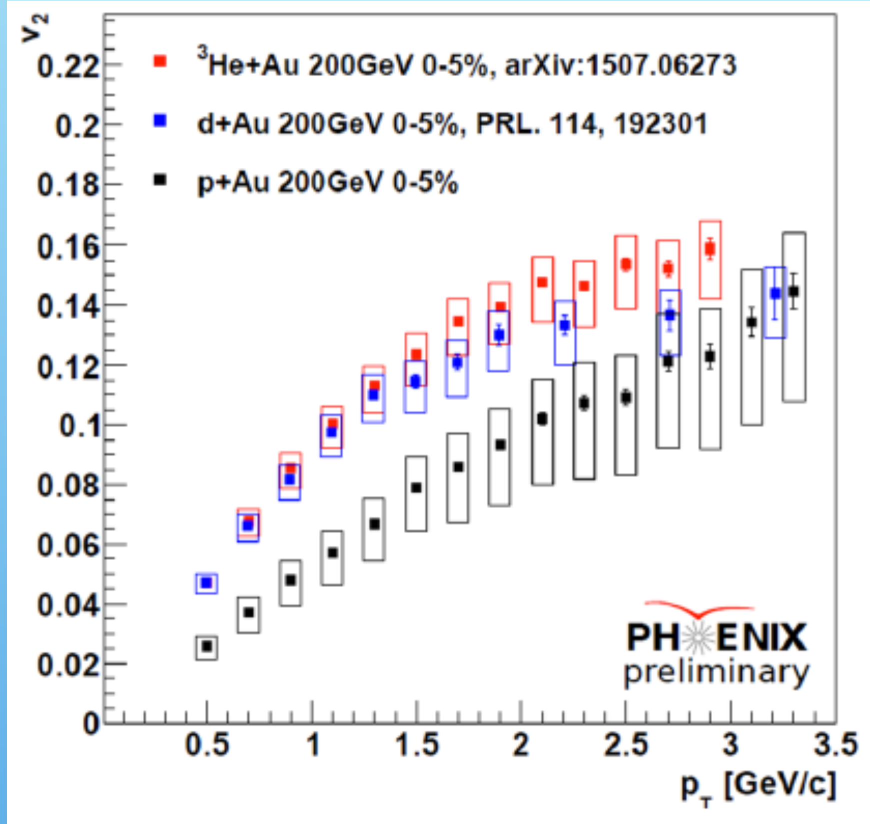


Large v_2 and v_3 of direct photons in Au+Au at 200 GeV studied vs pT and centrality

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

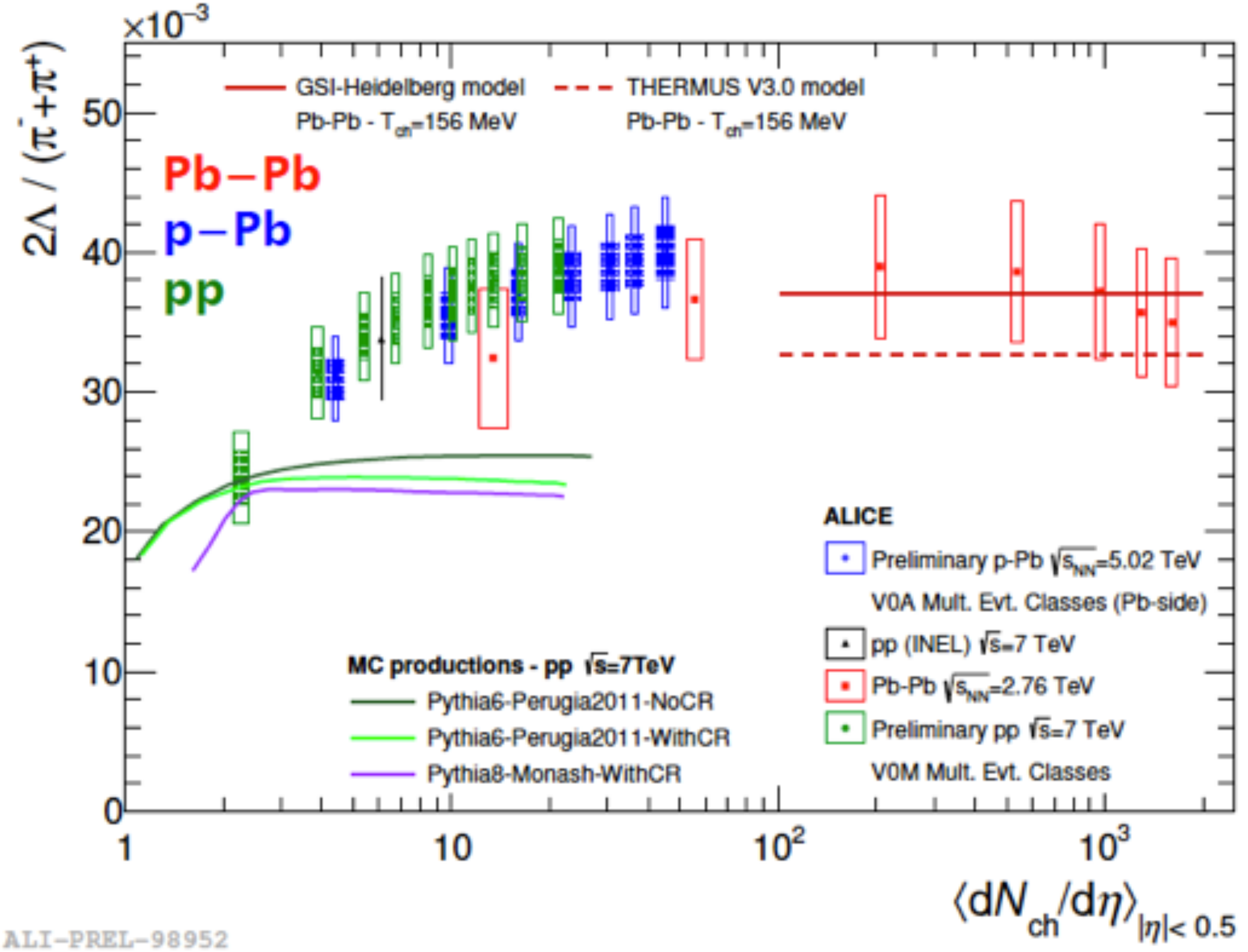
PHENIX 3HeAu: Phys. Rev. Lett. 115, 142301 (2015)
PHENIX dAu: Phys. Rev. Lett. 114, 192301 (2015)





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

Λ/π vs. $dN_{ch}/d\eta$

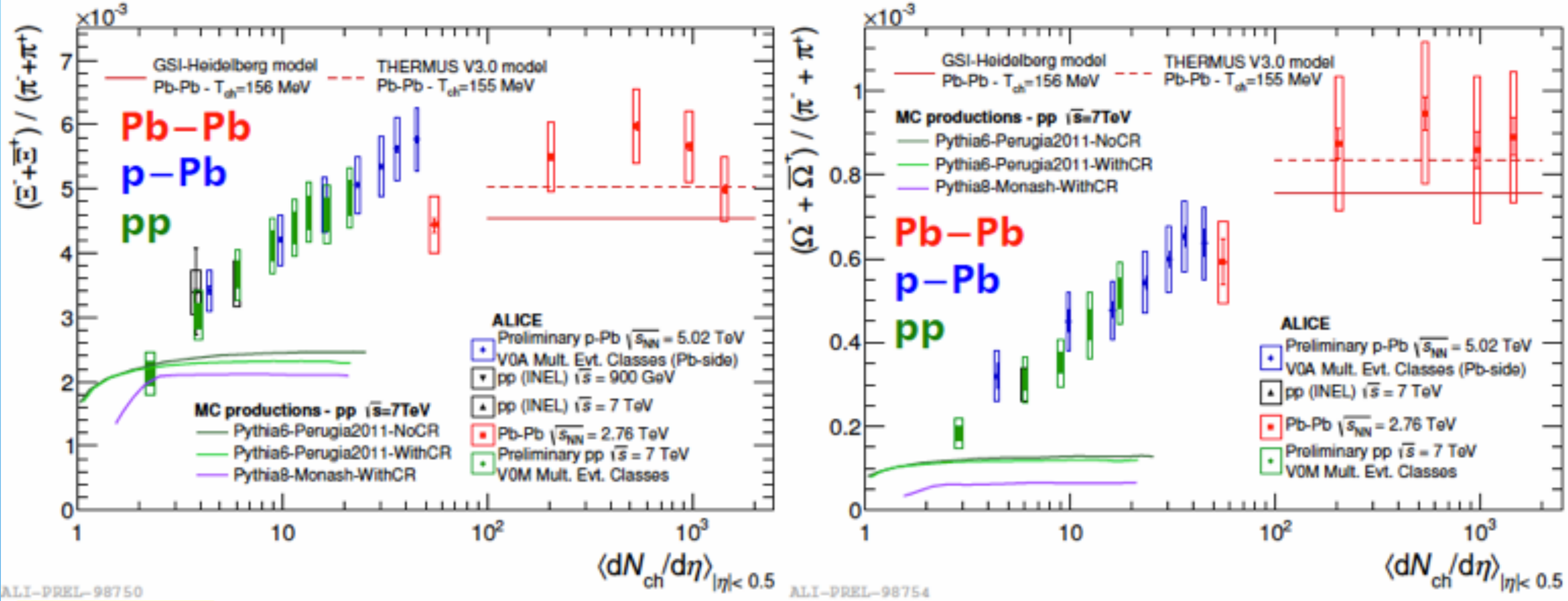


L. Bianchi
QM2015

- 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. $dN_{ch}/d\eta$

ALICE



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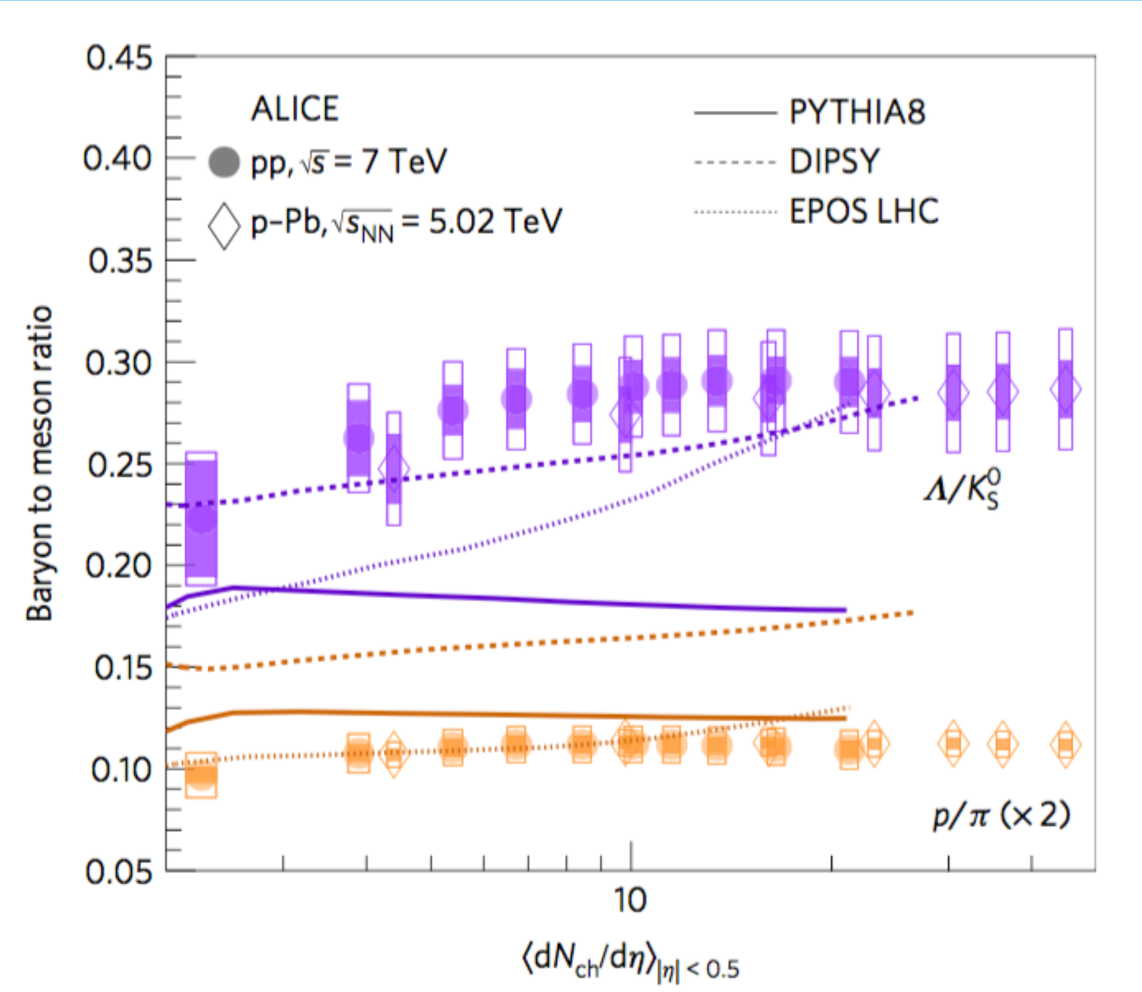
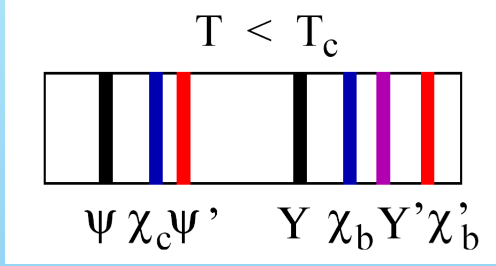


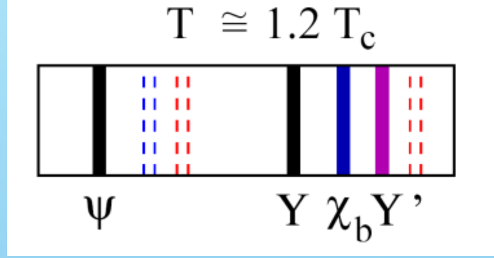
The ratios L/K0s and p/pi do not change significanctly with the charged multiplicity demonstrating that the observed enhancement of strange hadrons over pions is not due to the different hadron masses

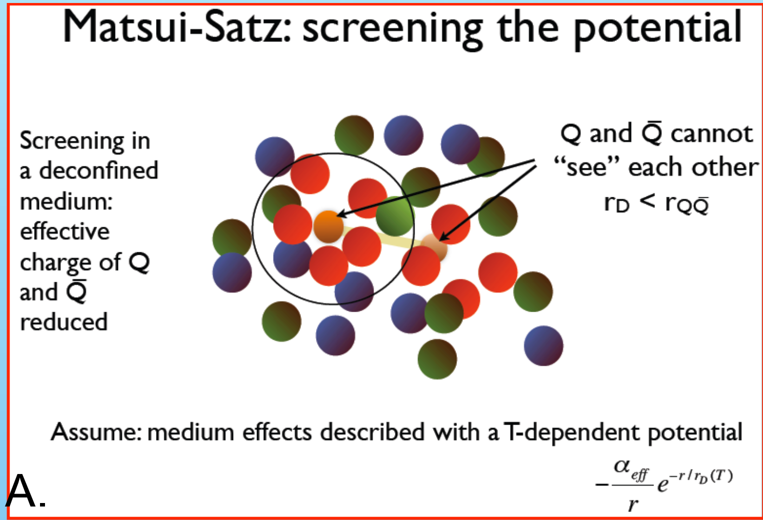
The models cannot reproduce simoultaneously the observation of strangeness enhancement over pions as a function of multiplicity and the constant p/pi ratio ve multiplicity.

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

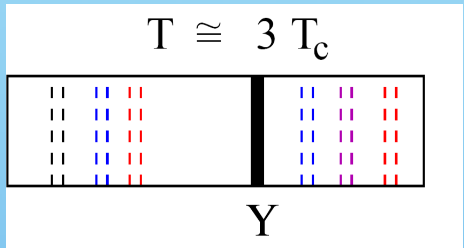
Quarkonia



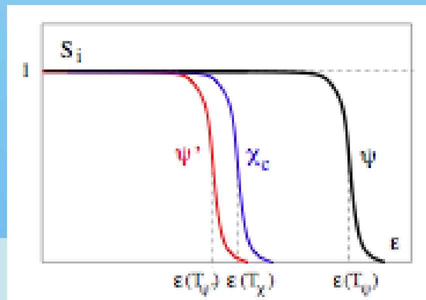


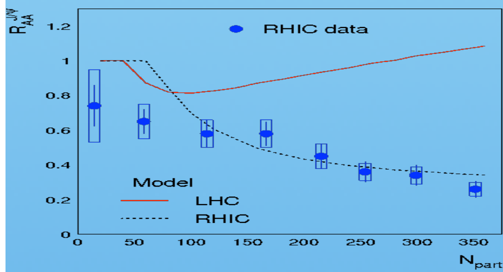


H. Satz, Nucl. Phys. A (783): 249-260(2007)



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

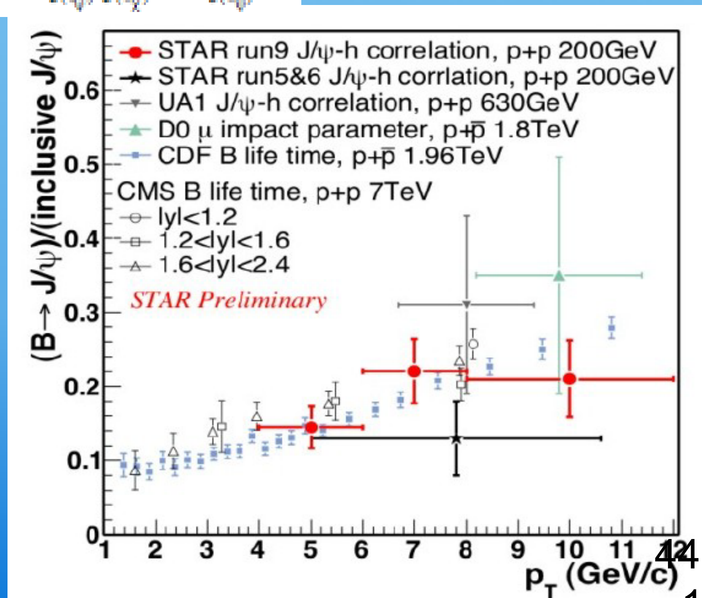




Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

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

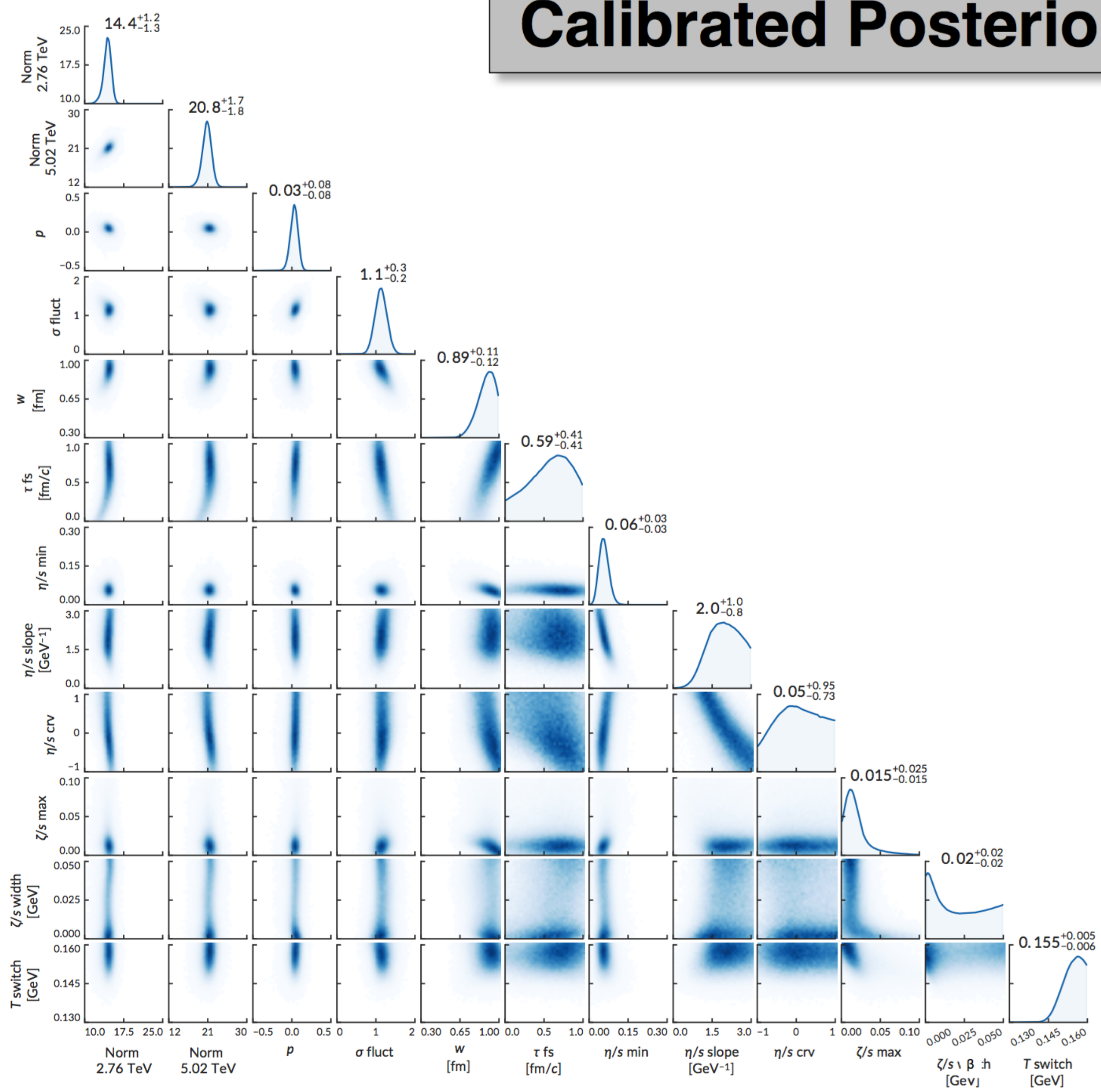
Multiple parameter estimation

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

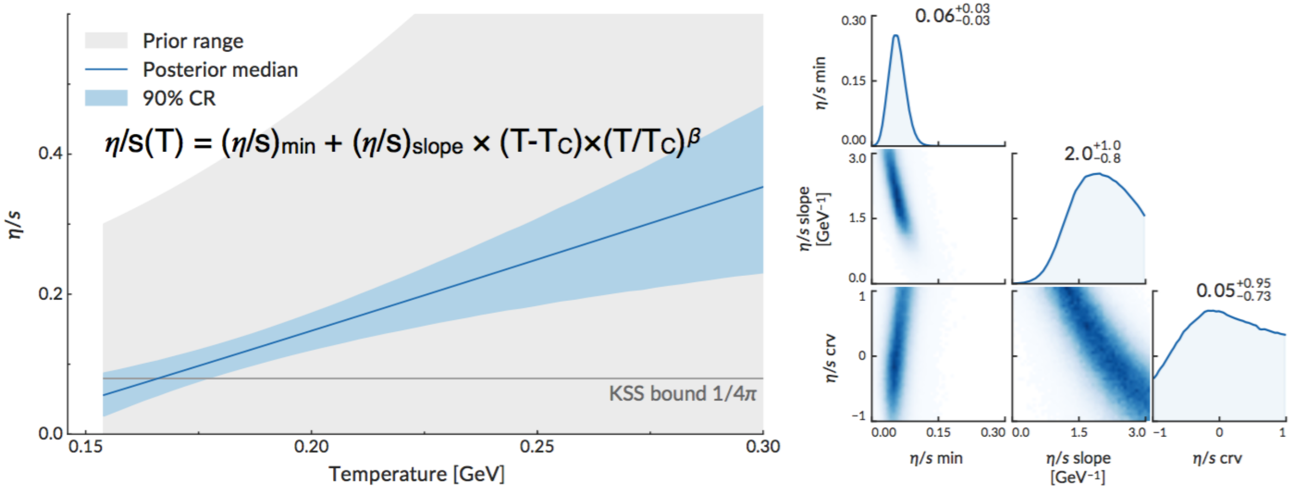
Example of results I: Review: S. Bass, QM2017,

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**

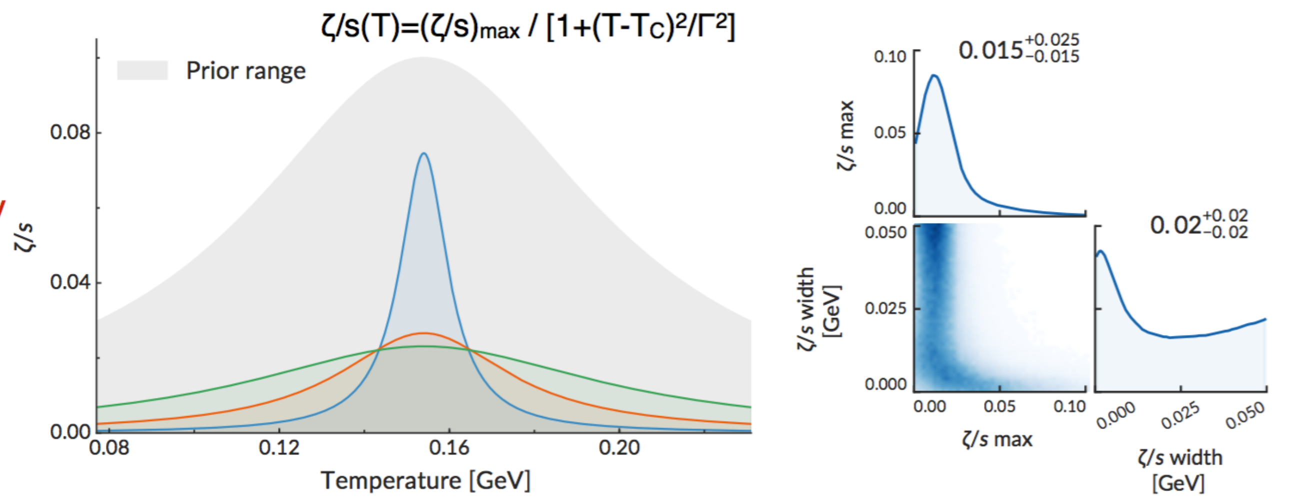


temperature dependent bulk viscosity:

- 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

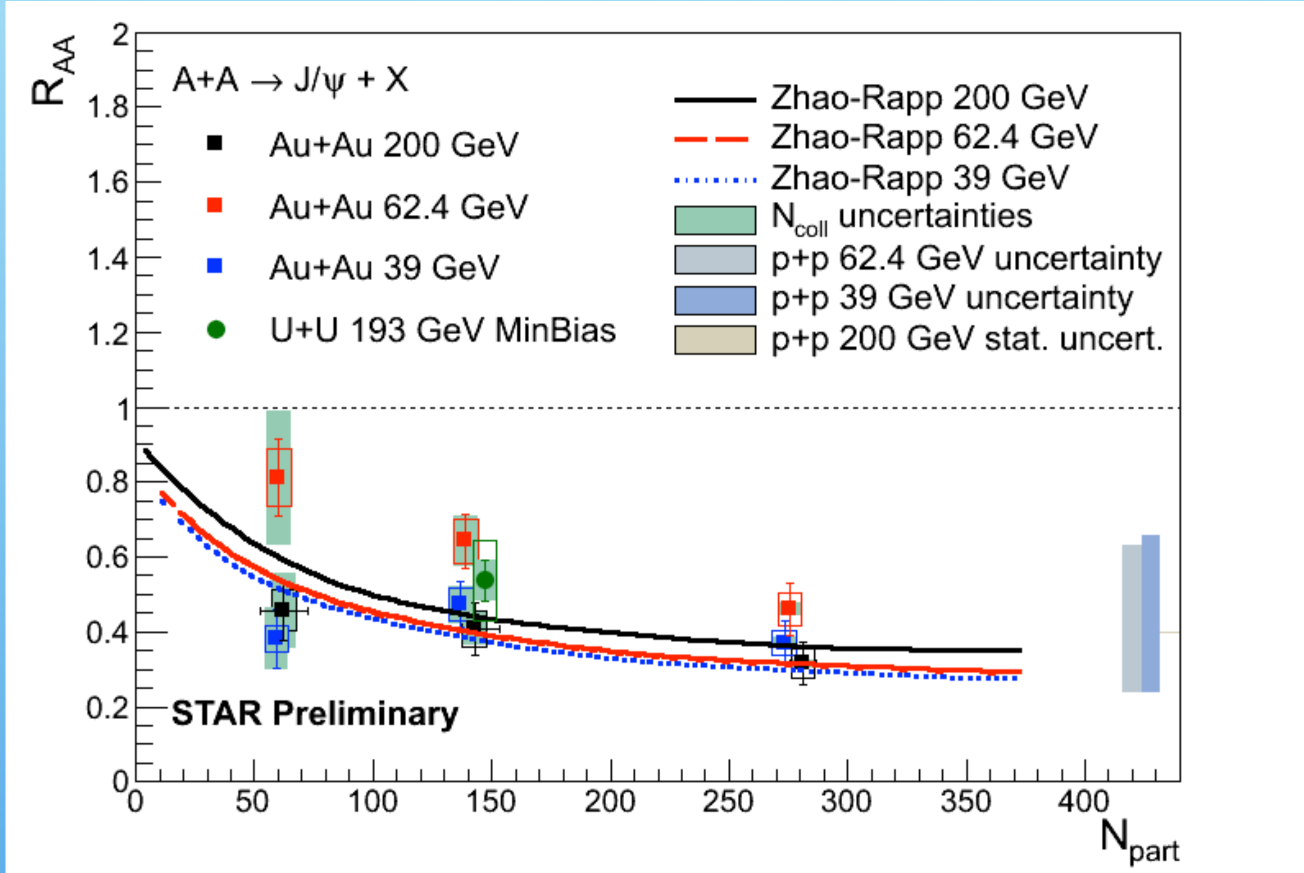
Review: S. Bass, QM2017,

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

JETSCAPE

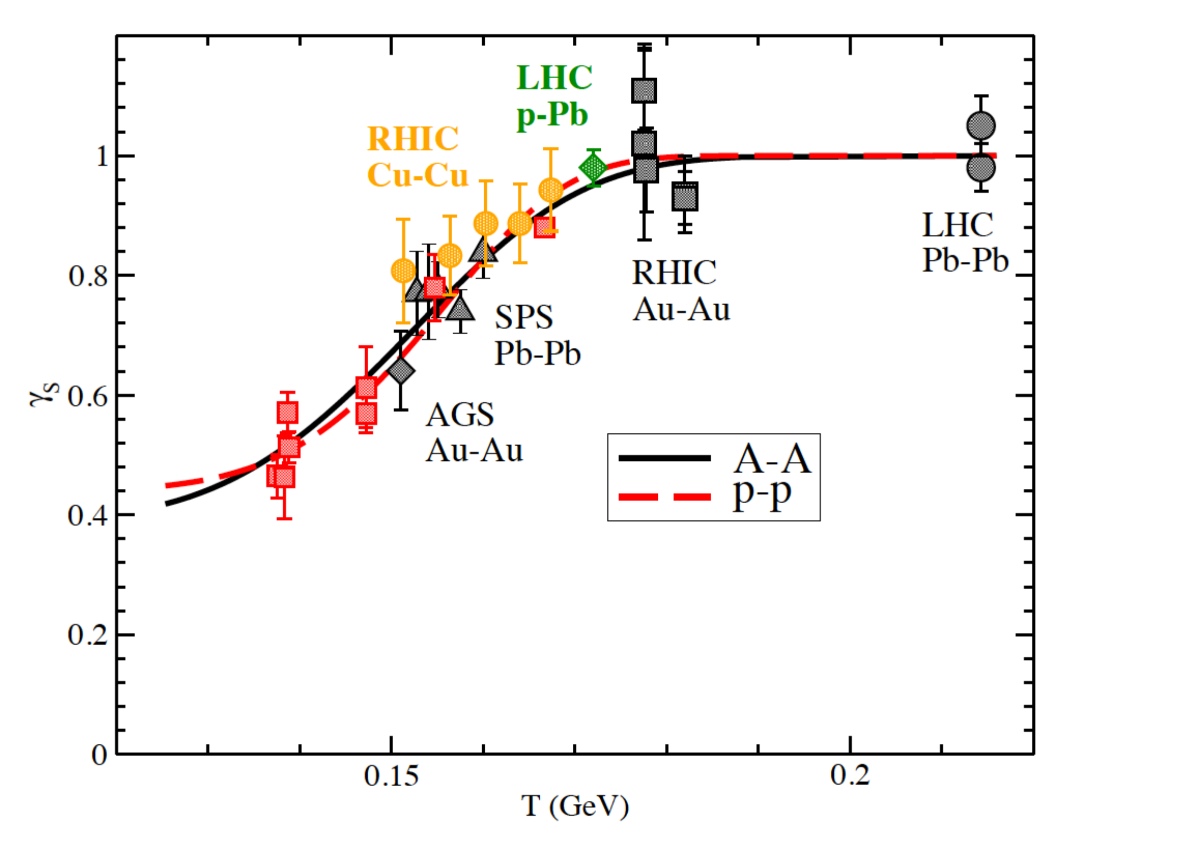
RHIC Beam Energy Scan:
At which energy does J/Psi suppression turn off?



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

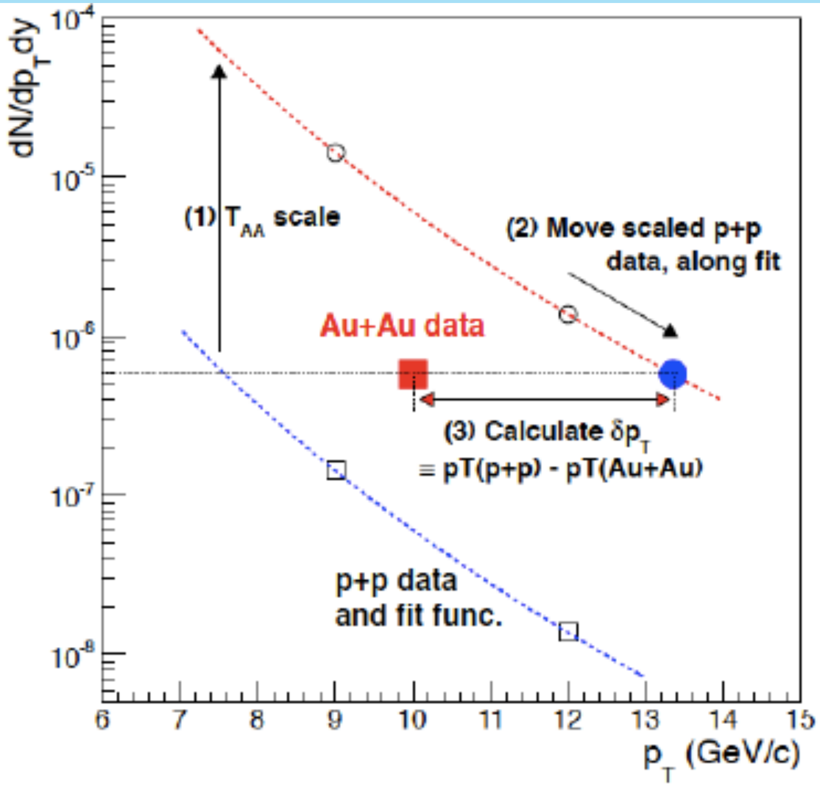
Strangeness suppression near Tc

P. Castorina, S Plumari, H Satz, 1709.02706



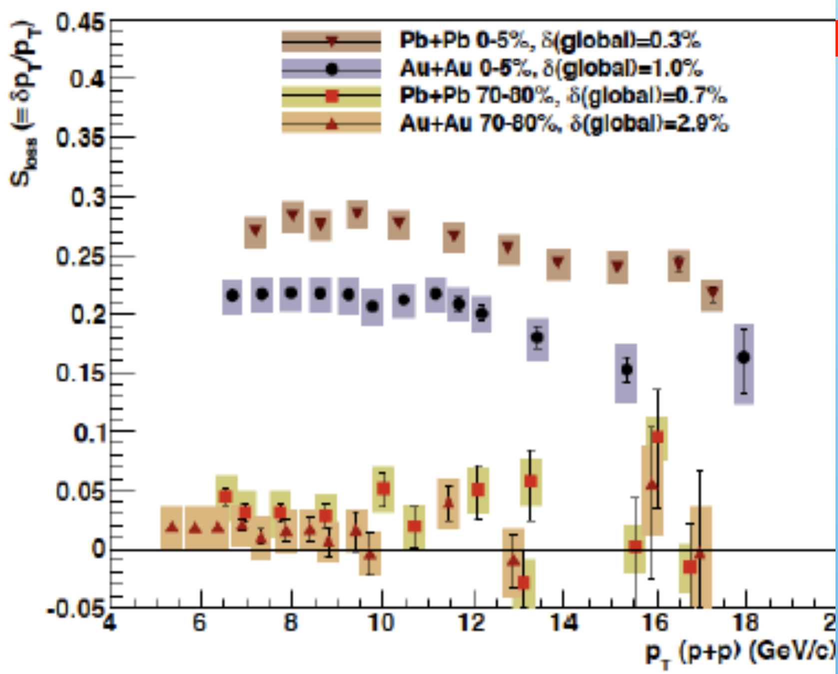
Gamma_s becomes 1 near T_c

nd



Measure fractional momentum loss instead of RAA

arXiv 1208.2254



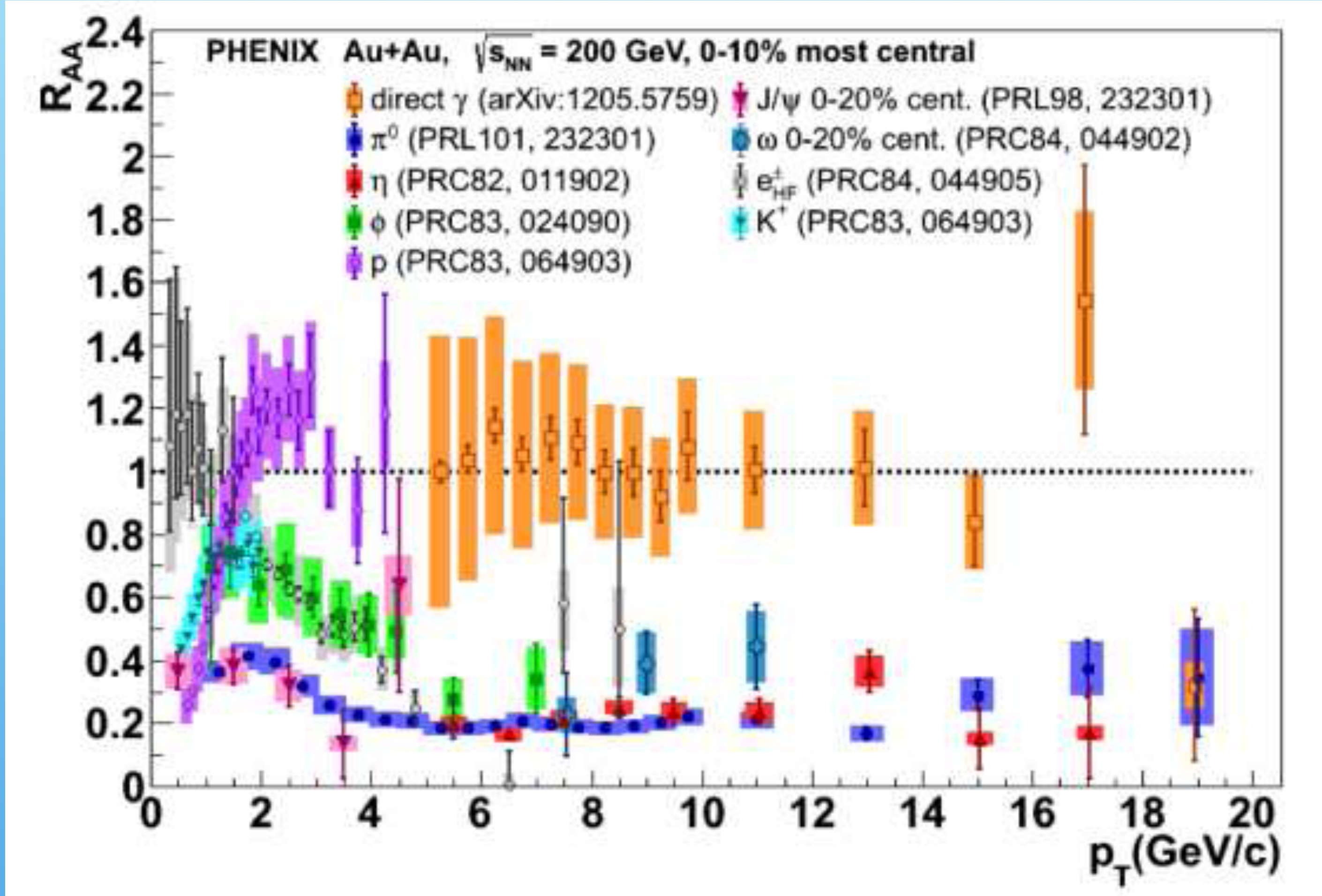
- Different dpT/pt for RHIC and LHC, for same RAA
- dpt/pt is 25% higher for ALICE
- dpt/pt decreases slightly with increasing pt (where rise of RAA occurs)

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

M. Tannenbaum and PHENIX collaboration

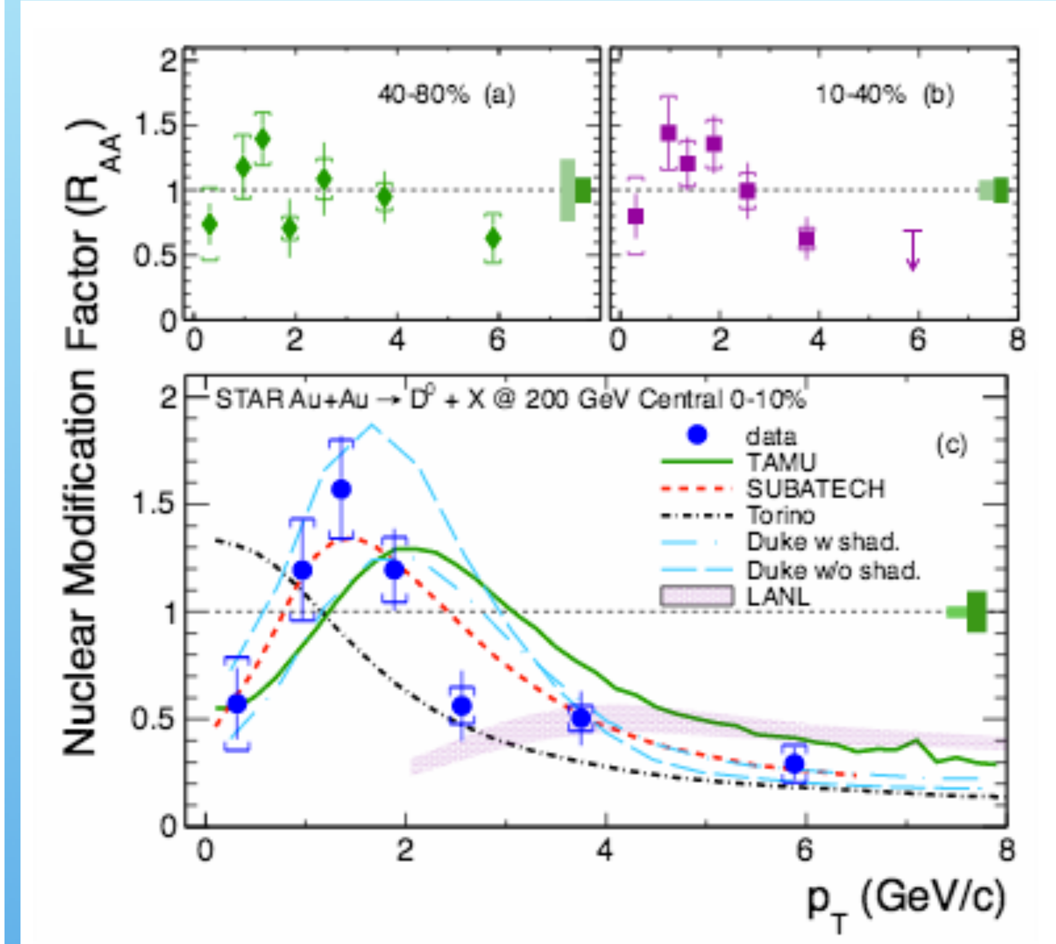
-> Interaction region at LHC less opaque to hard partons than RHIC

Jet quenching of light hadrons at RHIC

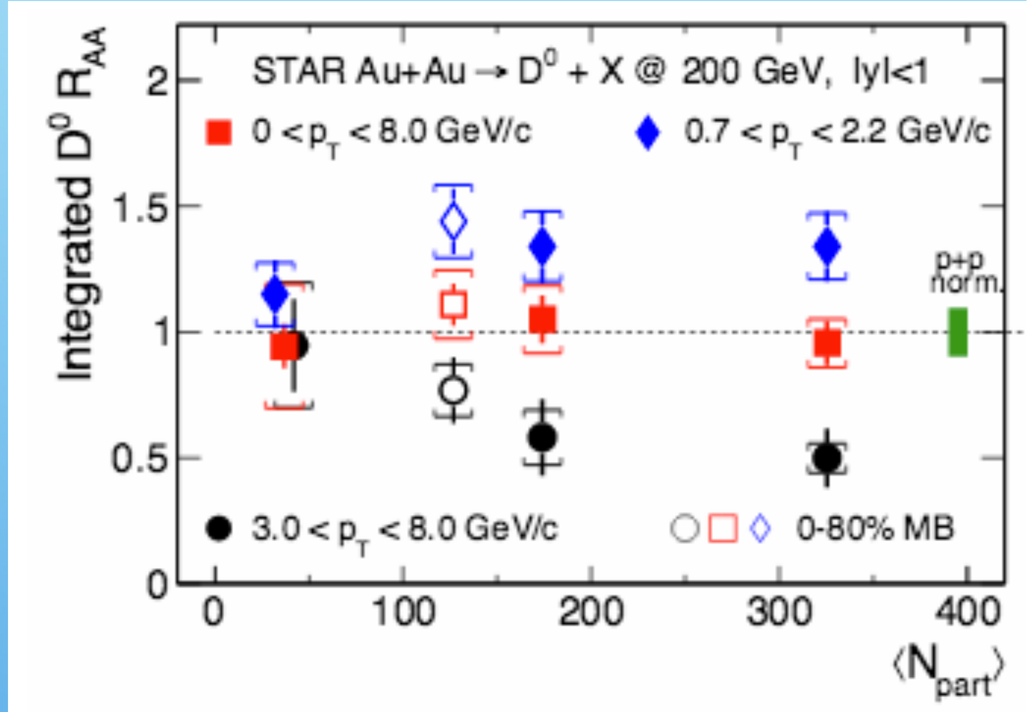


*** Light hadrons are quenched**
*** Photons are not quenched**

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



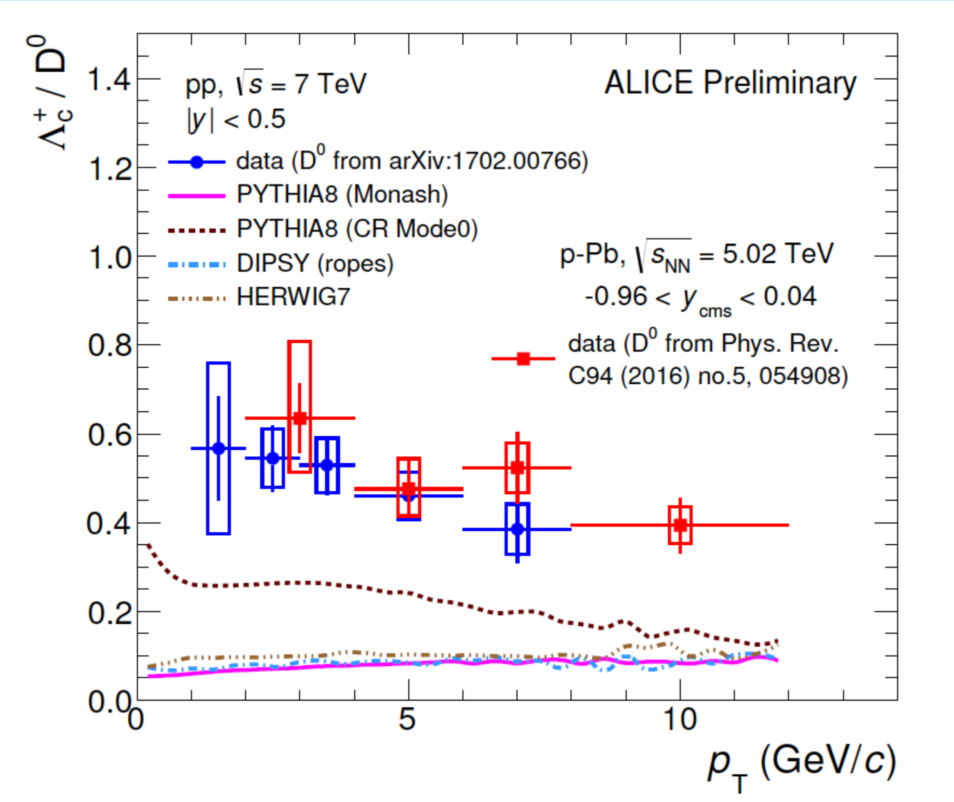
STAR: Phys. Rev. Lett. **113** (2014) 142301 and 1404.6185

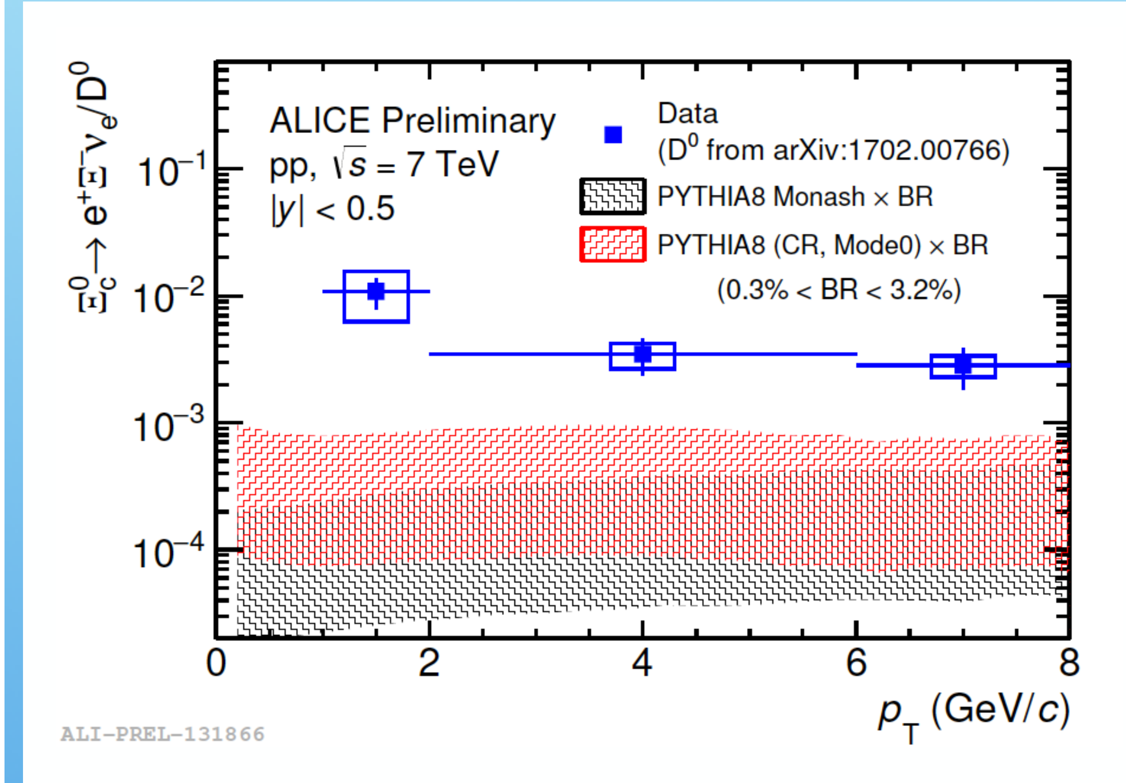


R_{AA} of D_0 at high p_T:

- 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



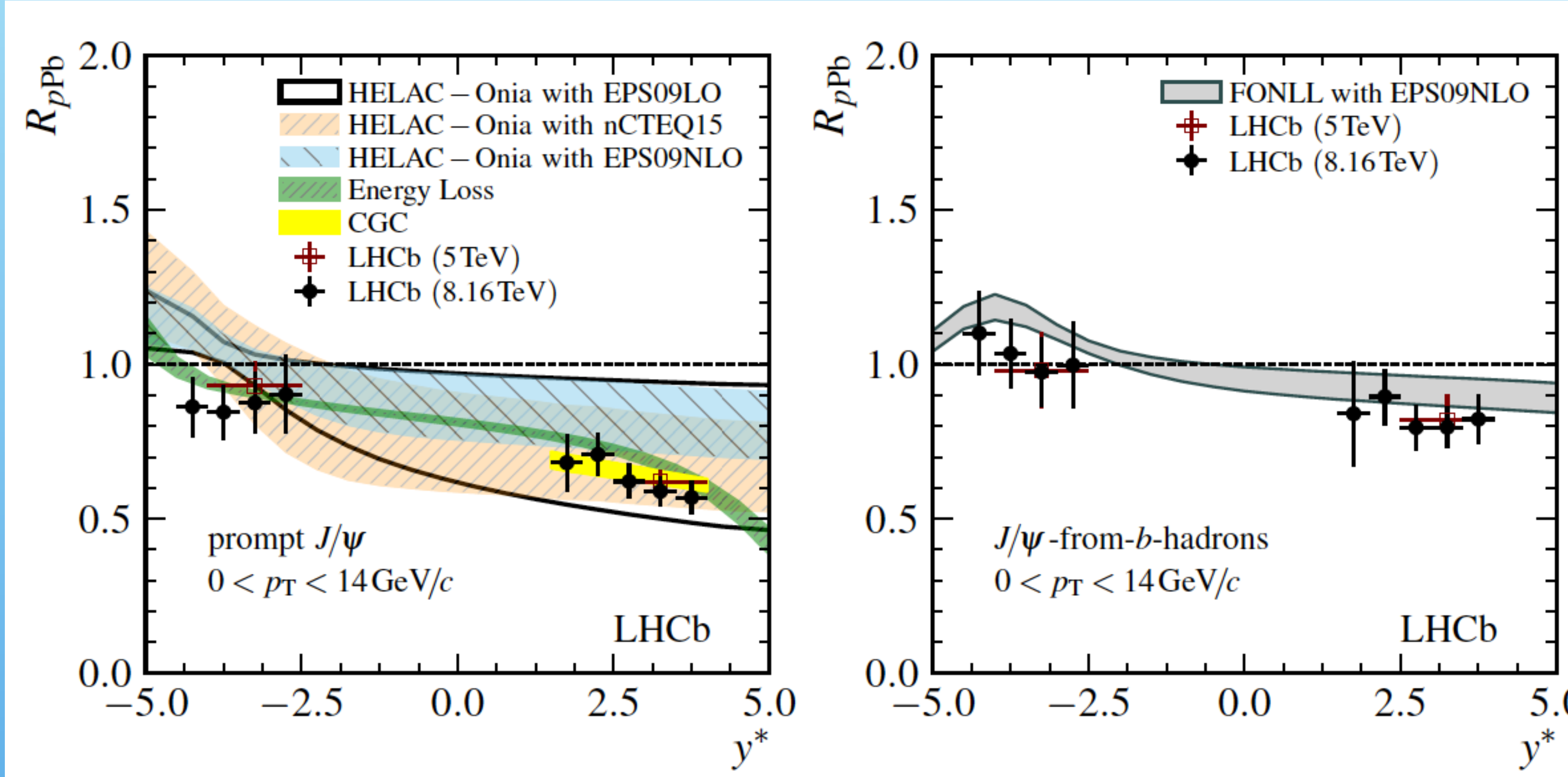


T Dahms, ICNFP

* 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

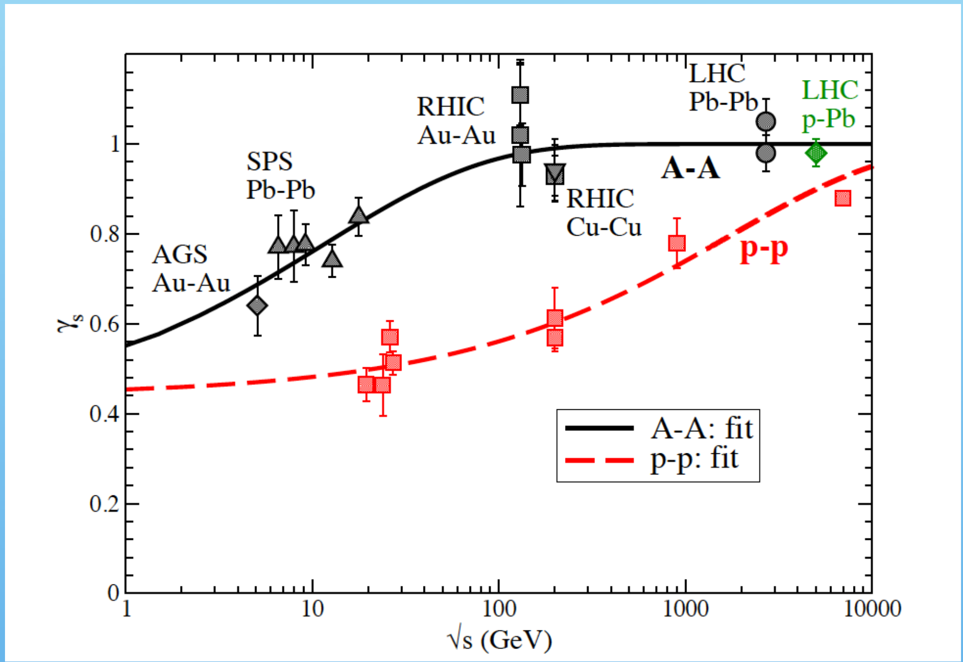
LHCb, 1706.07122

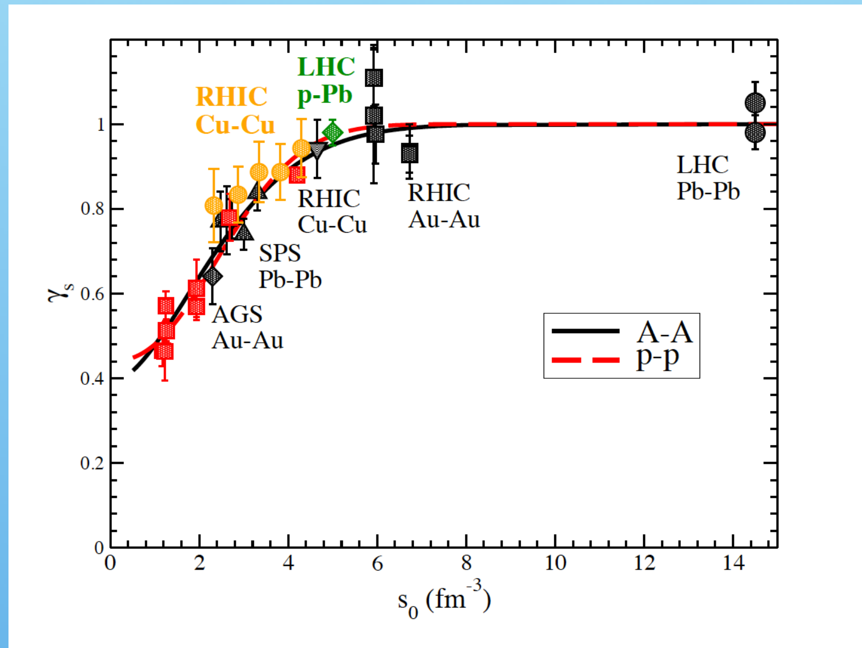


At backward rapidity prompt J/Psi not well described by models

Universal Strangeness Production

P. Castorina, S Plumari, H Satz, 1709.02706





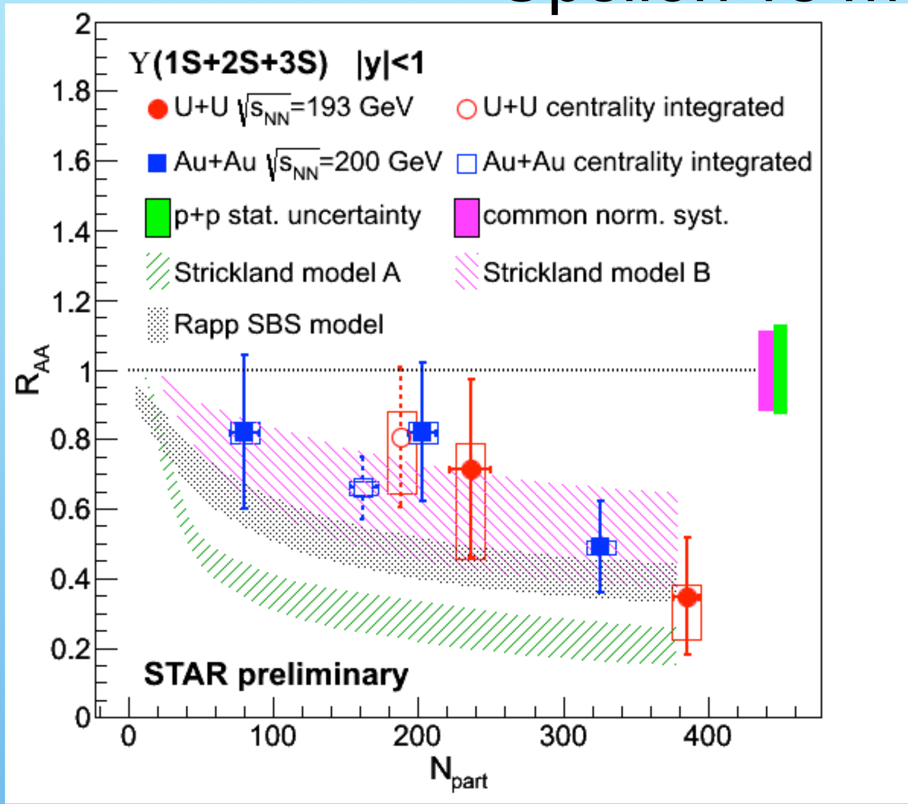
s_0 initial entropy density calculated using the Bjorken relation

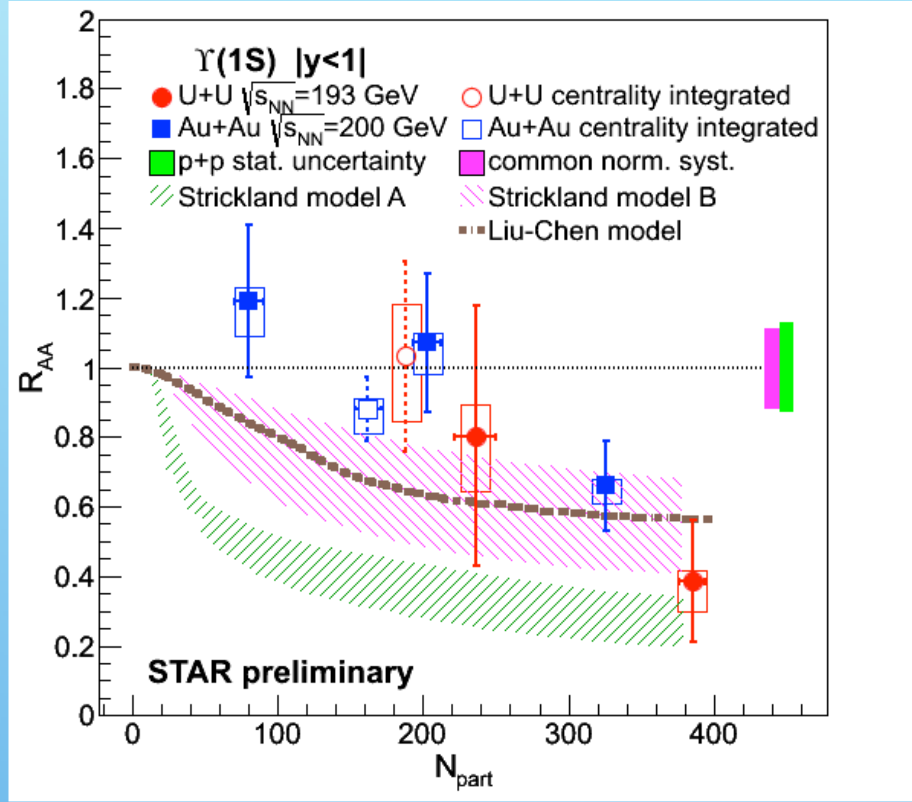
$$s_0\,\tau_0 \simeq \frac{1.5A^x}{\pi R_x^2}\left(\frac{dN}{dy}\right)^x_{y=0}, \quad \text{with } x \sim pp, pA, AA,$$

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

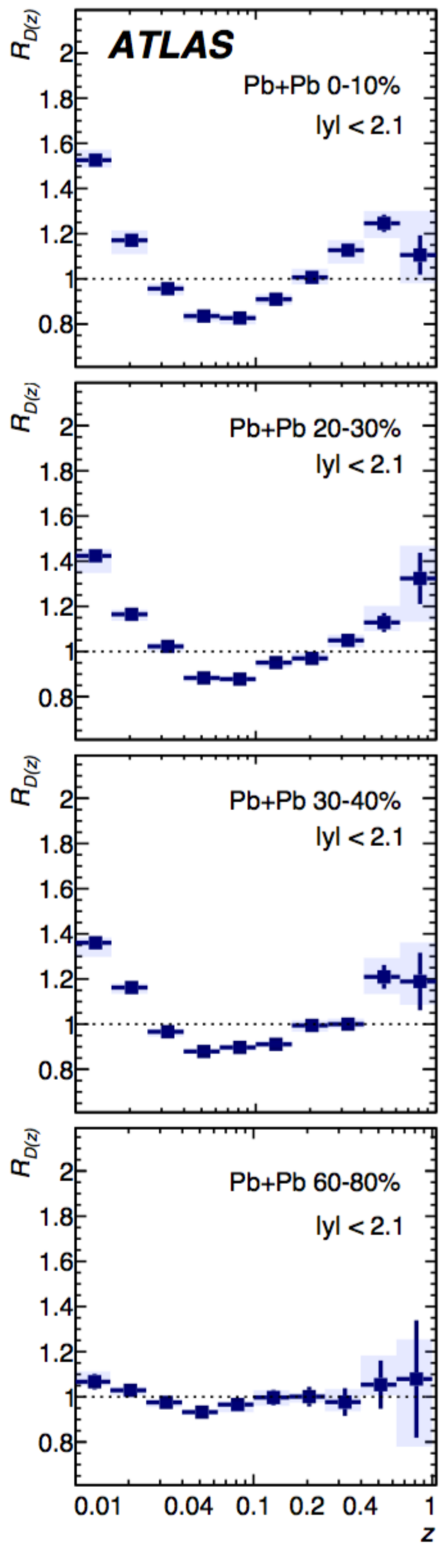
*** Model of Liu, Chen, Xu, Zhuang (Phys Lett B 697, 32 (2011))**
Potential model, no Cold Nuclear Matter effects. T= 340 MeV

*** 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

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

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

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