Happy Birthday Reinhardt !

Thank you for your Enthusiasm and your Guidance !

Heavy Ion Physics at RHIC

Subatech

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UNIVERSITÉ DE NANTES

1 November 2018, Frankfurt on Main, Germany

Outline

I Introduction

II Accelerator facilities and experiments

III Selected physics results :

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

IV Conclusions

I Introduction

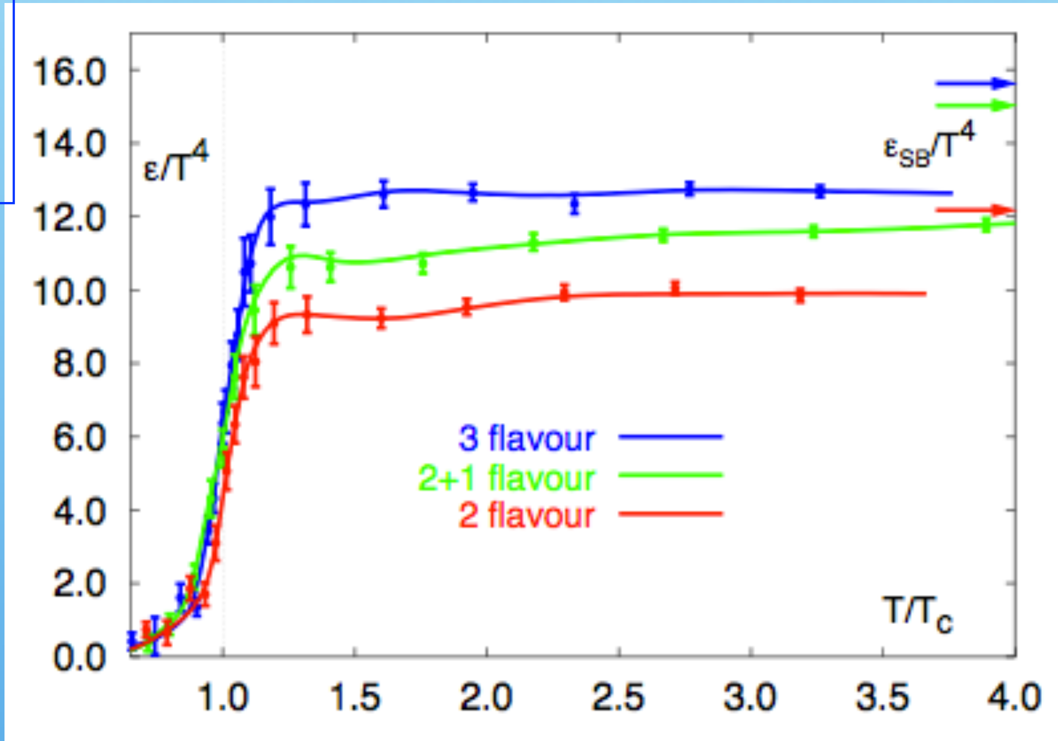
The QCD phase transition between hadronic and partonic phase

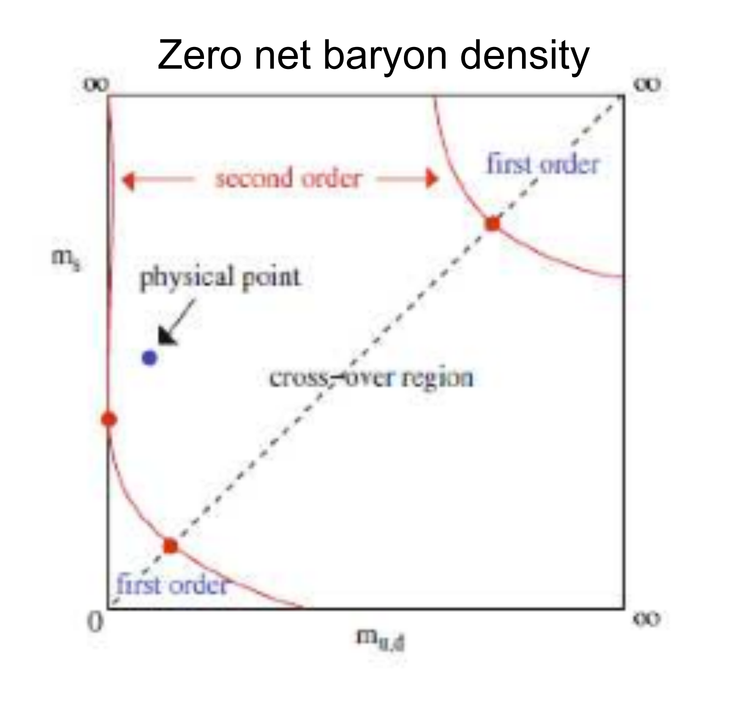
QCD on the lattice predicts a cross over at zero net baryon density with critical temperature Tc~154+-9 MeV (2014), critical energy density ~0.6 GeV/fm^3

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

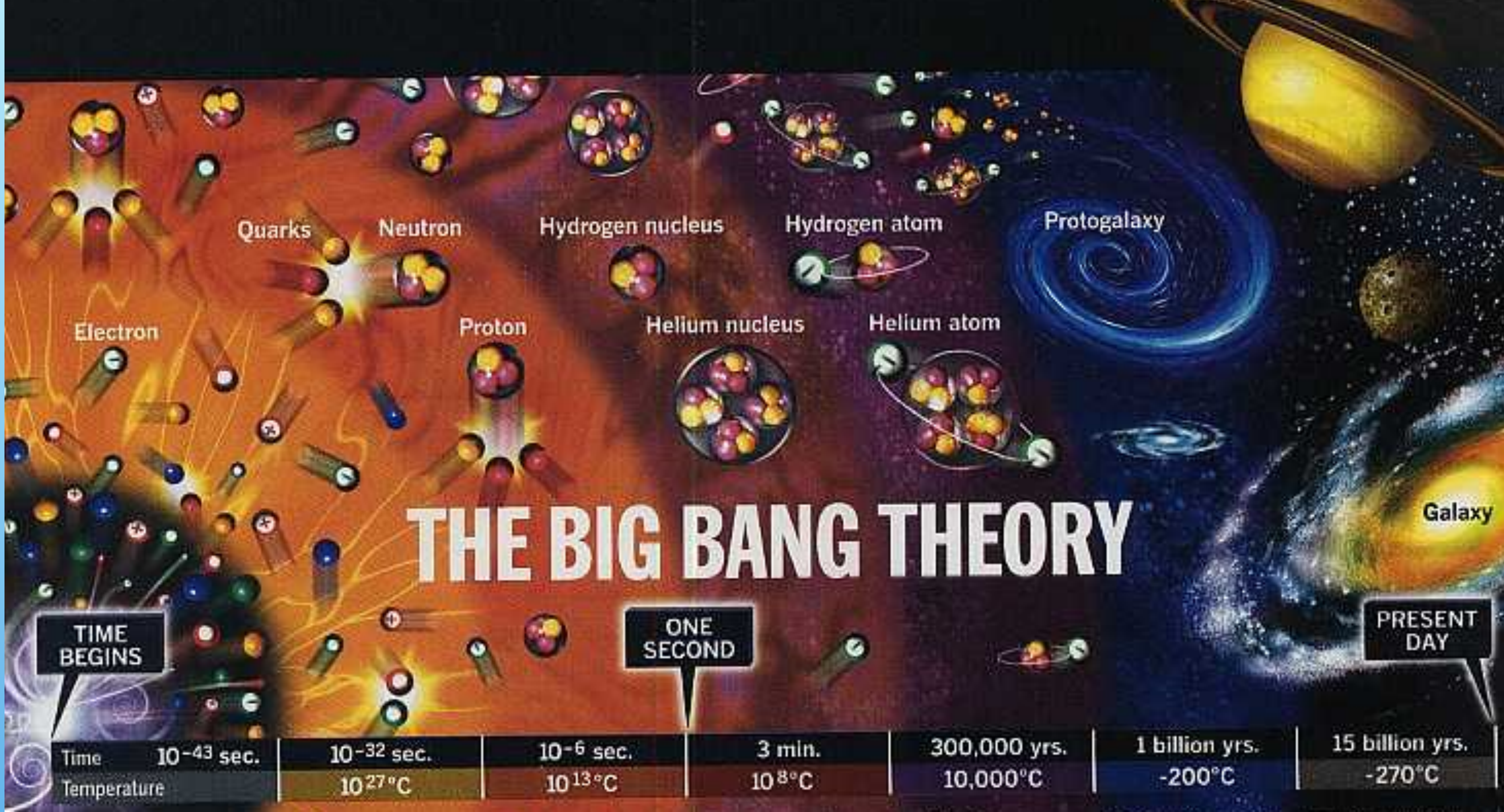
Zero net baryon density

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

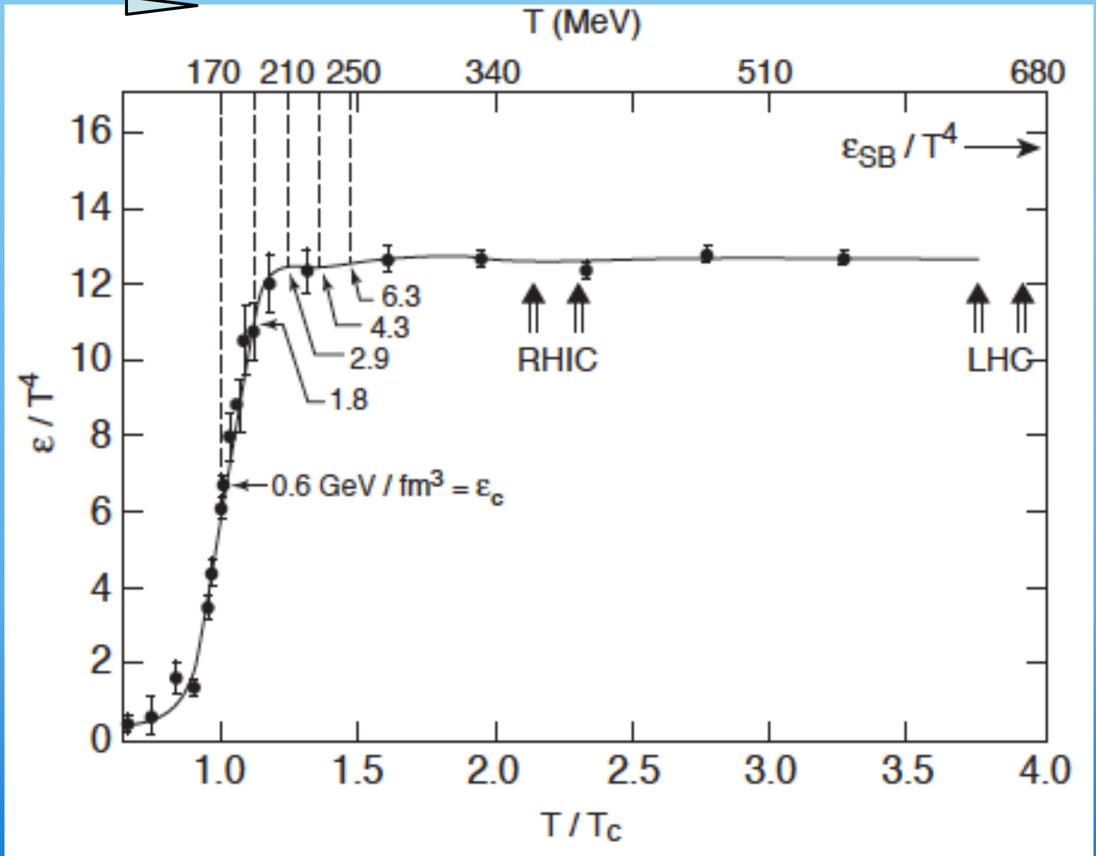
CERN, LHC (2009-)

BNL, RHIC (2000-)

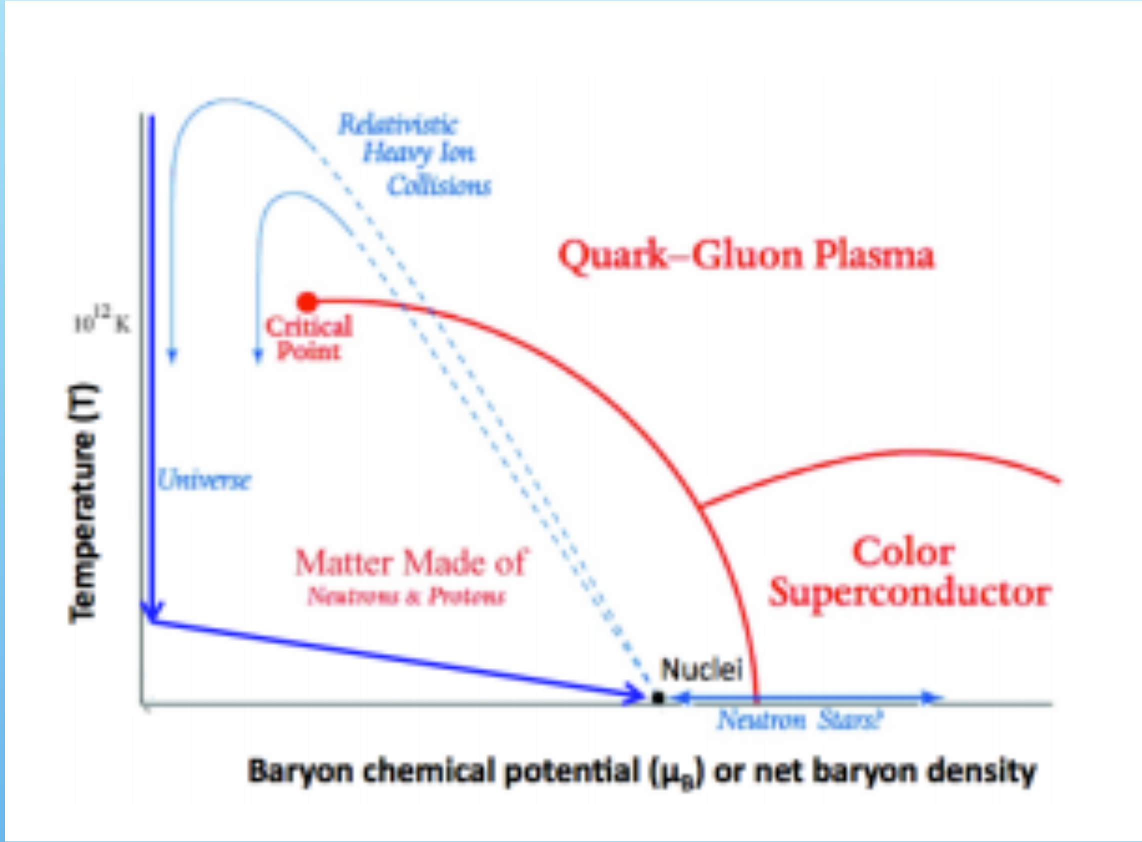
CERN, SPS (1988-)

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

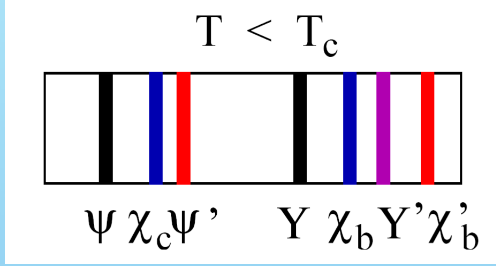
Direct photons from QGP → T(QGP)
Strangeness enhancement (Mueller, Rafelski 1981) → K/pi
U,d,s yields for T(freeze out) or pT slopes (Van Hove, H Stoecker et al) → plateau vs energy at Tc → e_init(crit), sqrt(s)("crit")
Multiquark states from QGP (Greiner et al) → 'small QGP-lumps'
Critical fluctuations 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

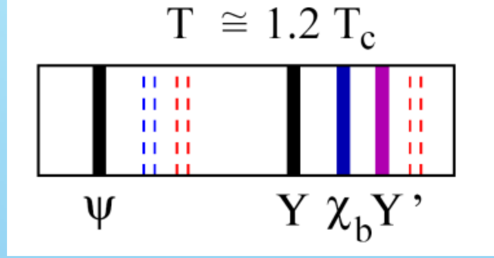
--> Goal is to achieve a combination of many signatures

But: discovery of "signatures" is not that simple

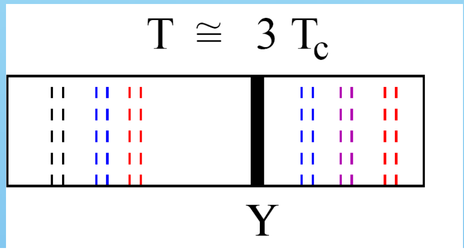
"Take a look at this everyone - it just could be the signature we've been looking for!"

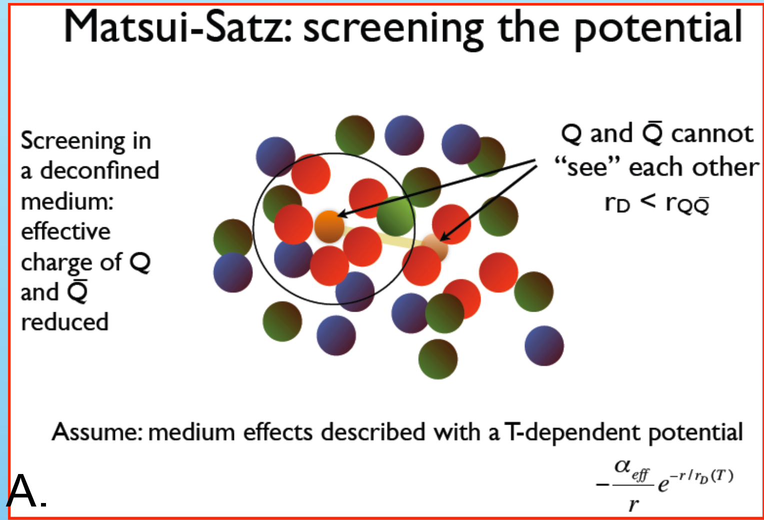
Quarkonia suppression as QGP signature



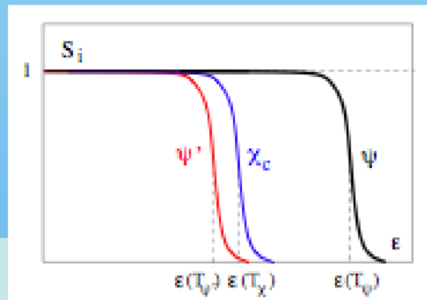


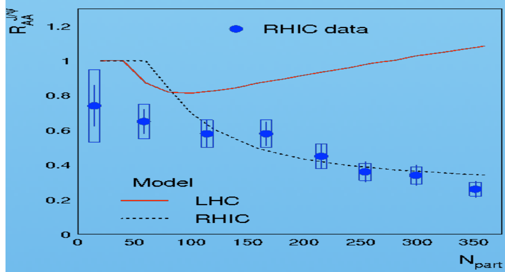
H. Satz, Nucl. Phys. A (783): 249-260(2007)





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

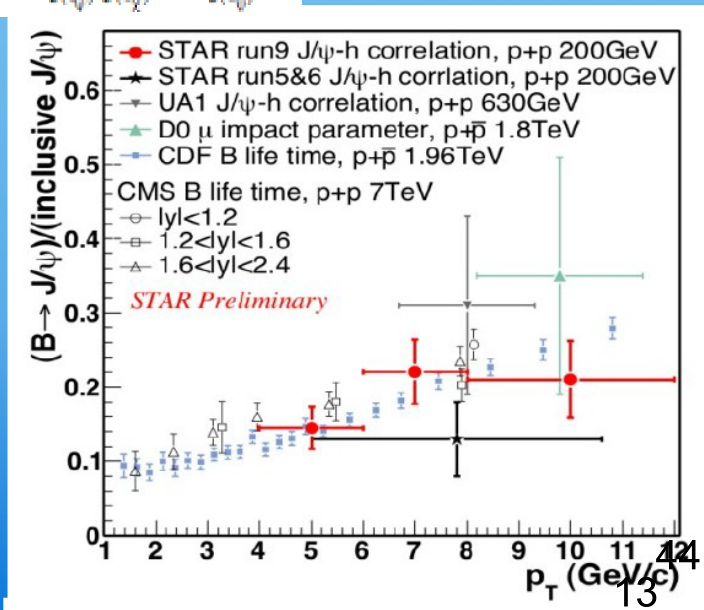




Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

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.



Historical result: Quarkonia suppression at CERN SPS

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

Evidence for QGP at CERN, till 2000 :

ccbar suppression

Strangeness enhancement

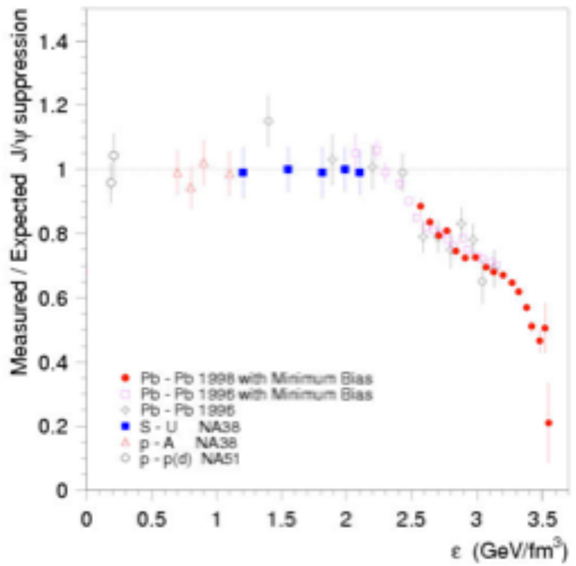
T(chem. freee out) ~ T (critical

Direct gammas consistent with T > Tcritical

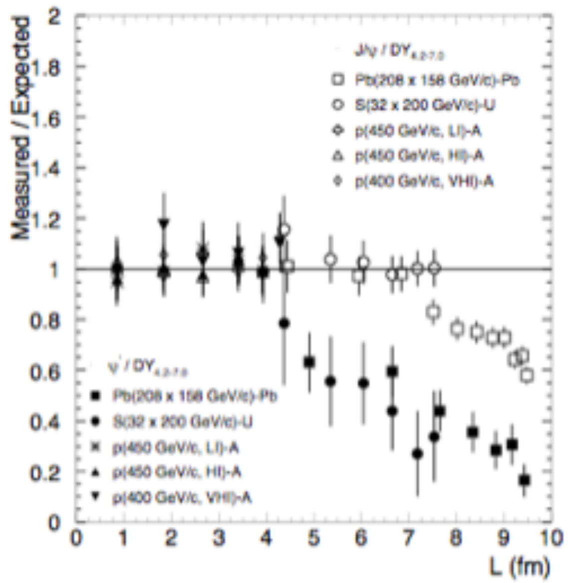
and other results

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

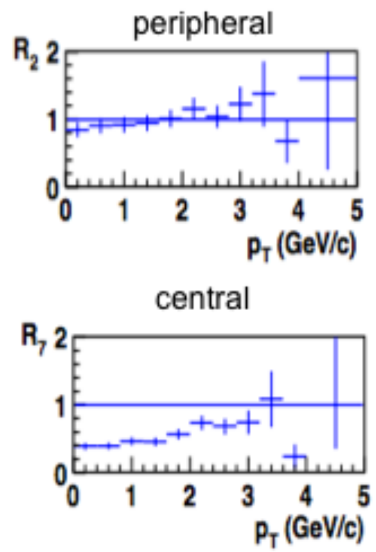
NA50, Phys Lett B 477 (2000) 28



Eur Phys J C 49 (2007) 559



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



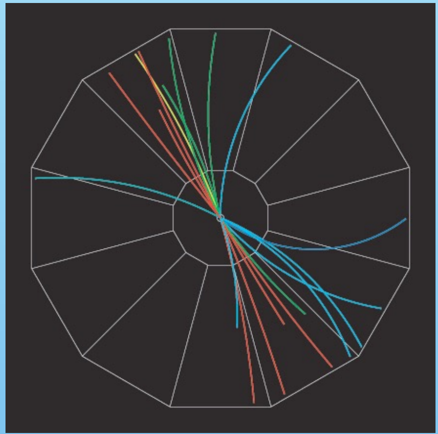
A Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004

*** 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**

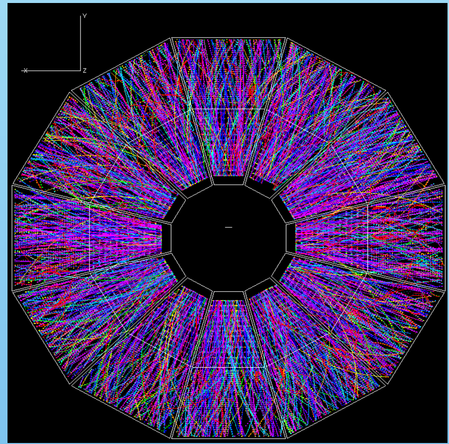
CERN press release 2000

Jet quenching as QGP signature

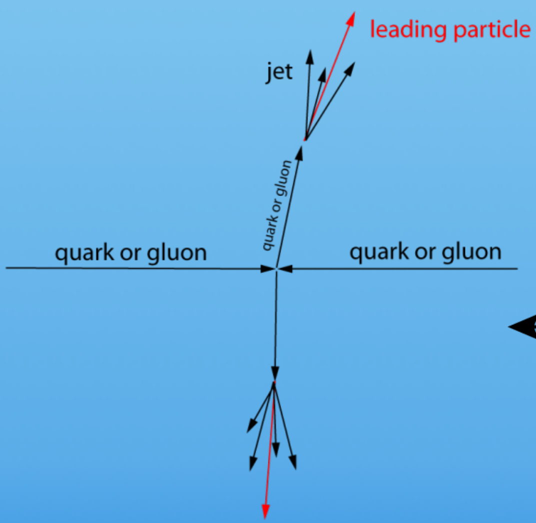
p+p Collision

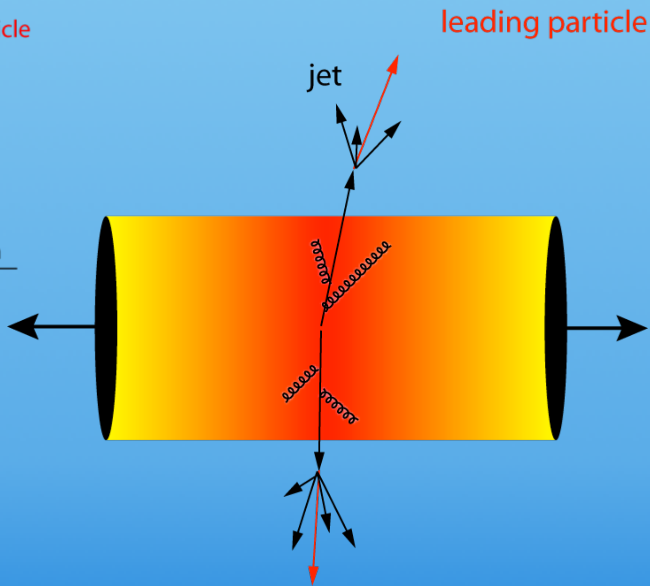


Au+Au Collision

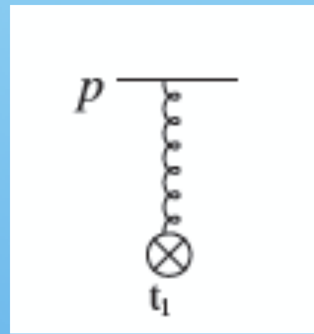


Partons interact with the medium and loose energy through eg gluon radiation

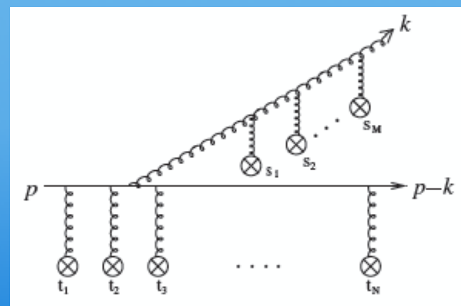




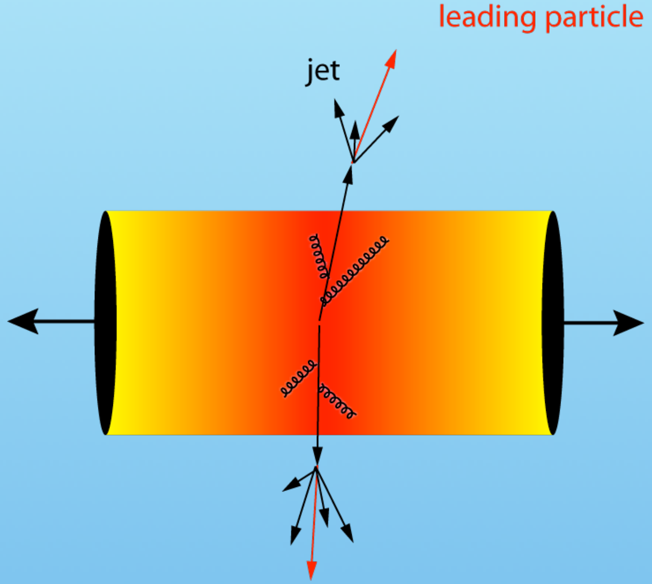
Collisional "elastic" energy loss: elastic interaction with the medium



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



Jet quenching

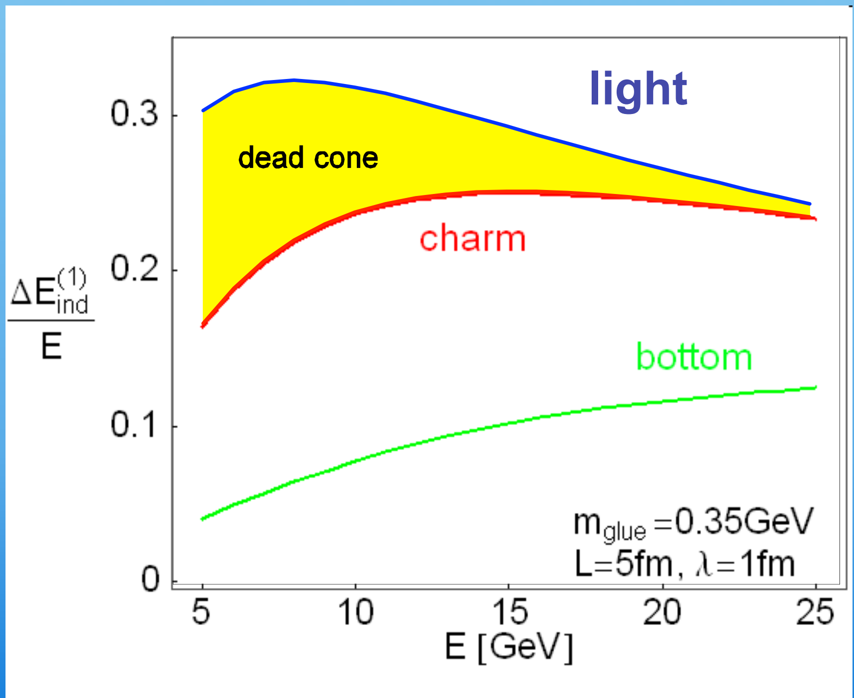


"The nuclear modification factor" R_{AA}

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: $R_{AA} < 1$

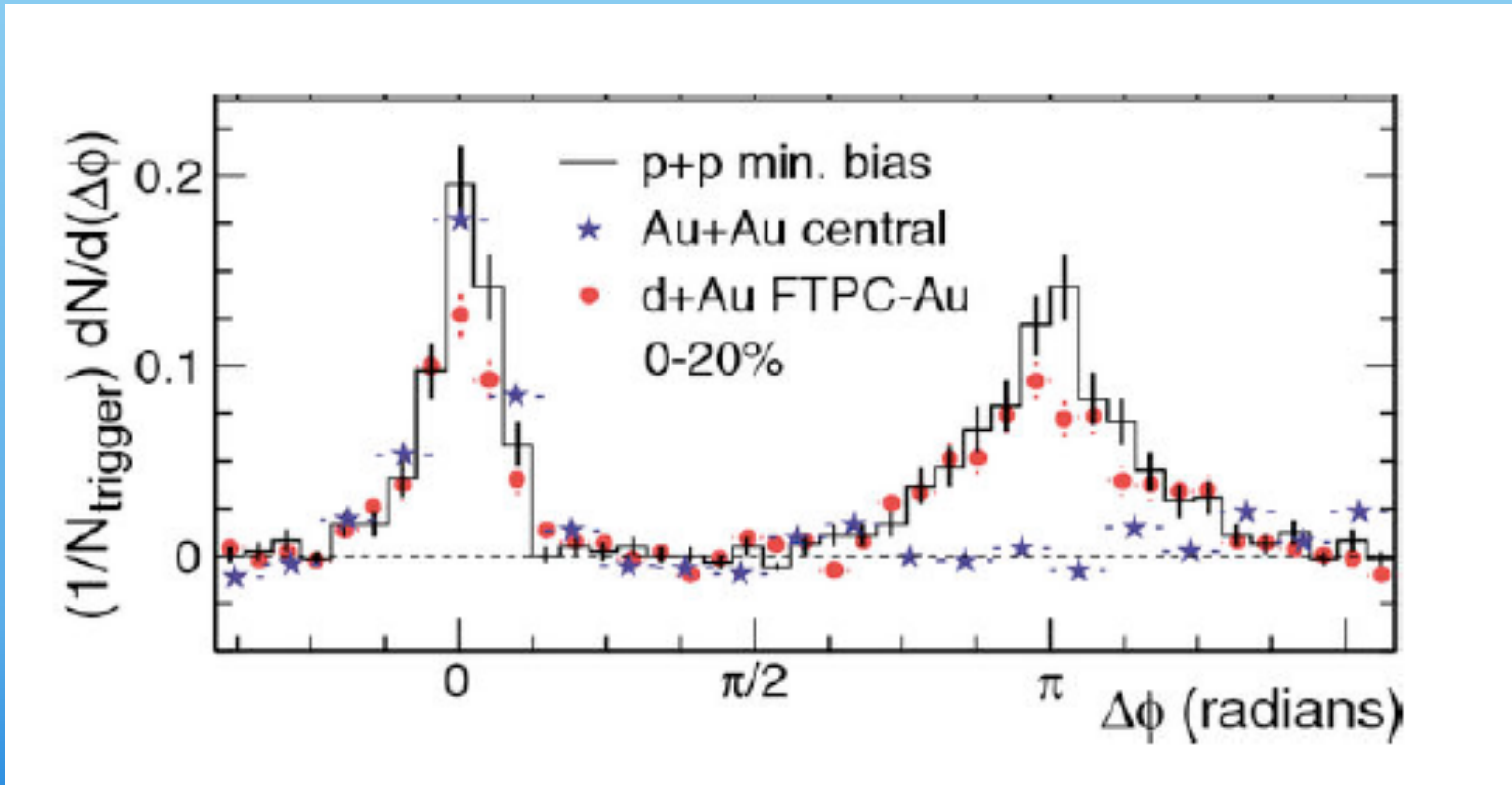
Quarks are expected to exhibit different radiative energy loss depending on their mass (**D.Kharzeev et al. Phys Letter B. 519:1999**)

M.Djordjevic PRL 94 (2004)

Historical result: Discovery of jet quenching at RHIC (2003)

Discovery of strongly interacting QGP :
RHIC white papers for the 4 RHIC experiments: 2005

STAR Phys. Rev. Lett. 91, 072304 (2003), nucl-ex/0306024.



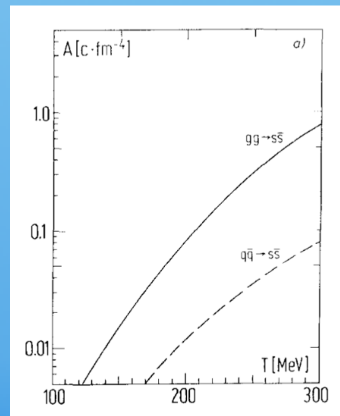
Dihadron correlations for pT(trig)=(4,6 GeV) and pT(associated)=(2 GeV,pT(trig))

Strangeness Enhancement as QGP signature

Initial idea introduced by J Rafelski:
First mentioned in:
J Rafelski, R Hagedorn, Ref TH.2969-CERN, 1980 :
Strangeness enhancement and Strange Antibaryons are discussed as signature for Quark Gluon Plasma formatio

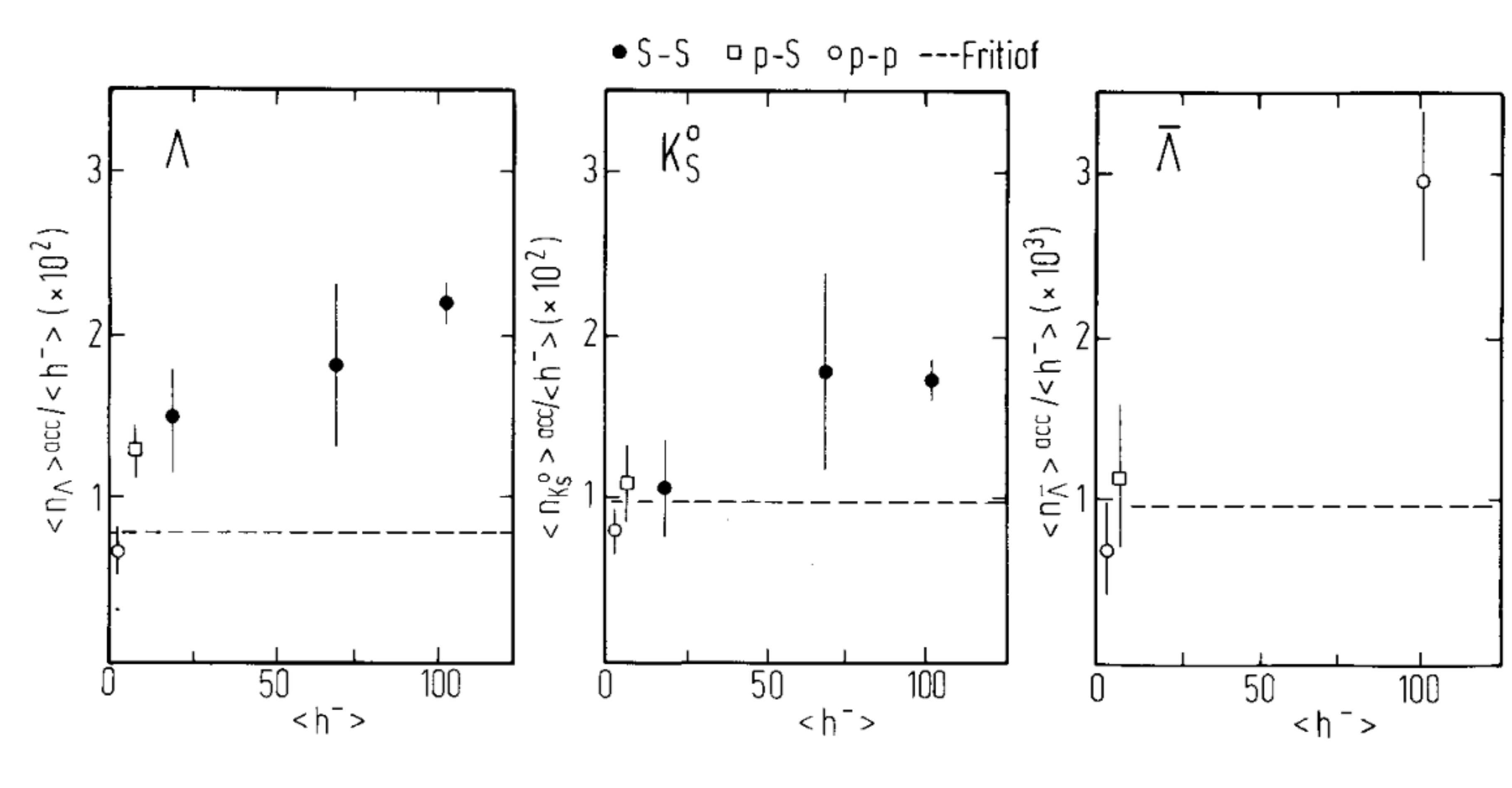
P. Koch, B. Muller and J. Rafelski, Phys. Rept. 142 (1986) 167.

Strangeness enhancement in QGP is expected due to
* The dominance of the gluonic production channel for strangeness in the QGP
* High gluon density in the QGP
* To the mass of the s quark being similar to the critical temperature T for the QCD phase transition
* Strangeness in QGP reach equilibrium values
* Effect expected to be more pronounced for strange antibaryons



Historical result: Observation of ssbar enhancement in SPS at CERN

NA35, Zeitschrift für Physik C Particles and Fields, June 1990, Volume 48, Issue 2, pp 191–200



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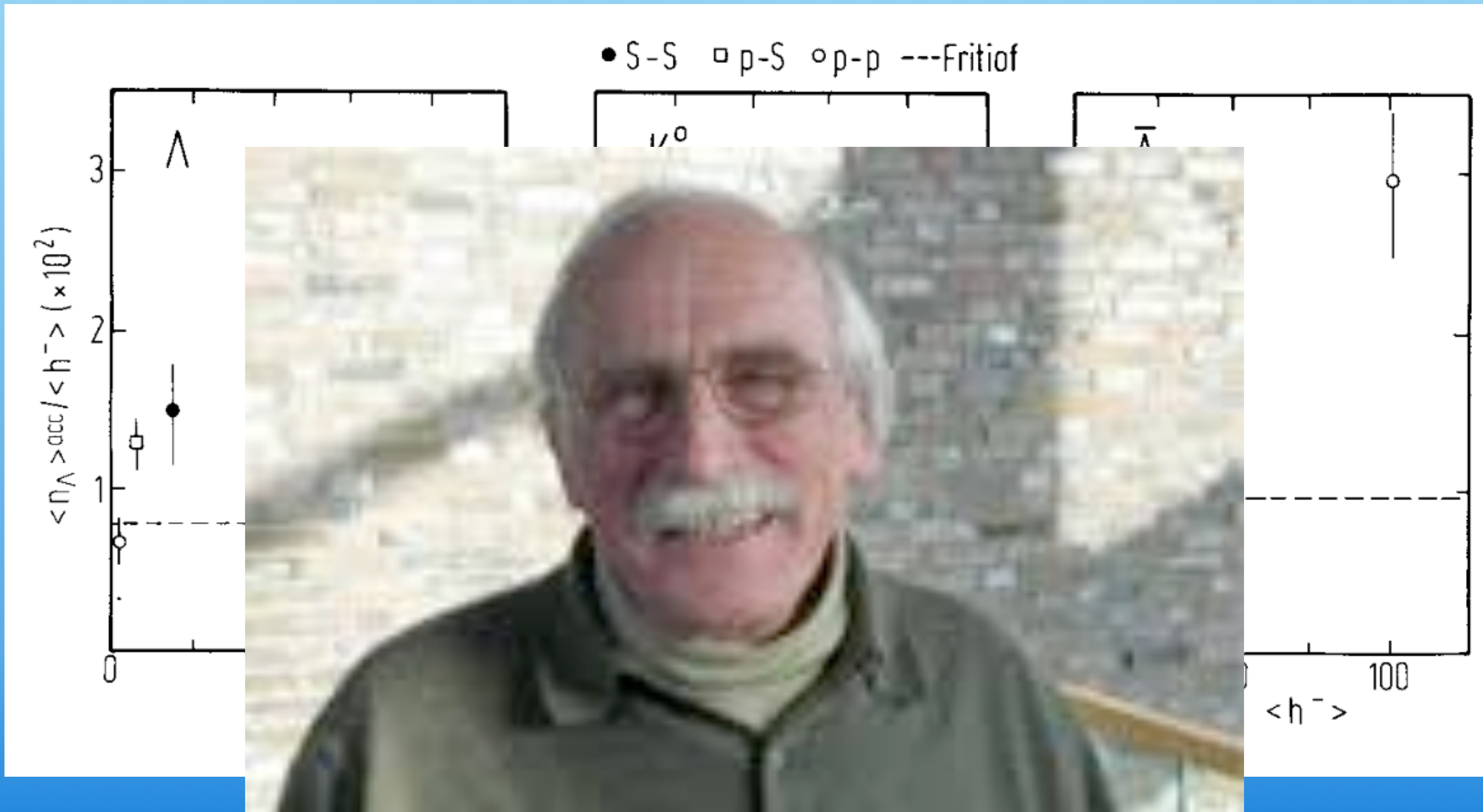
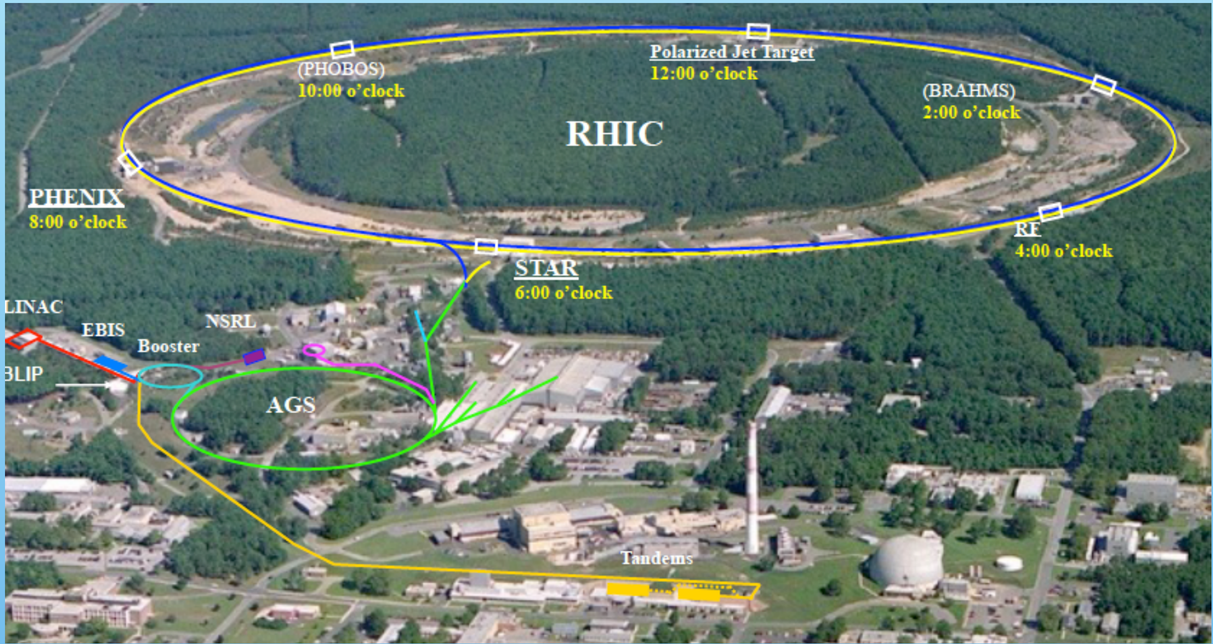
NA35, Zeitschrift für Physik C Particles and Fields, June 1990, Volume 48, Issue 2, pp 191–200



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

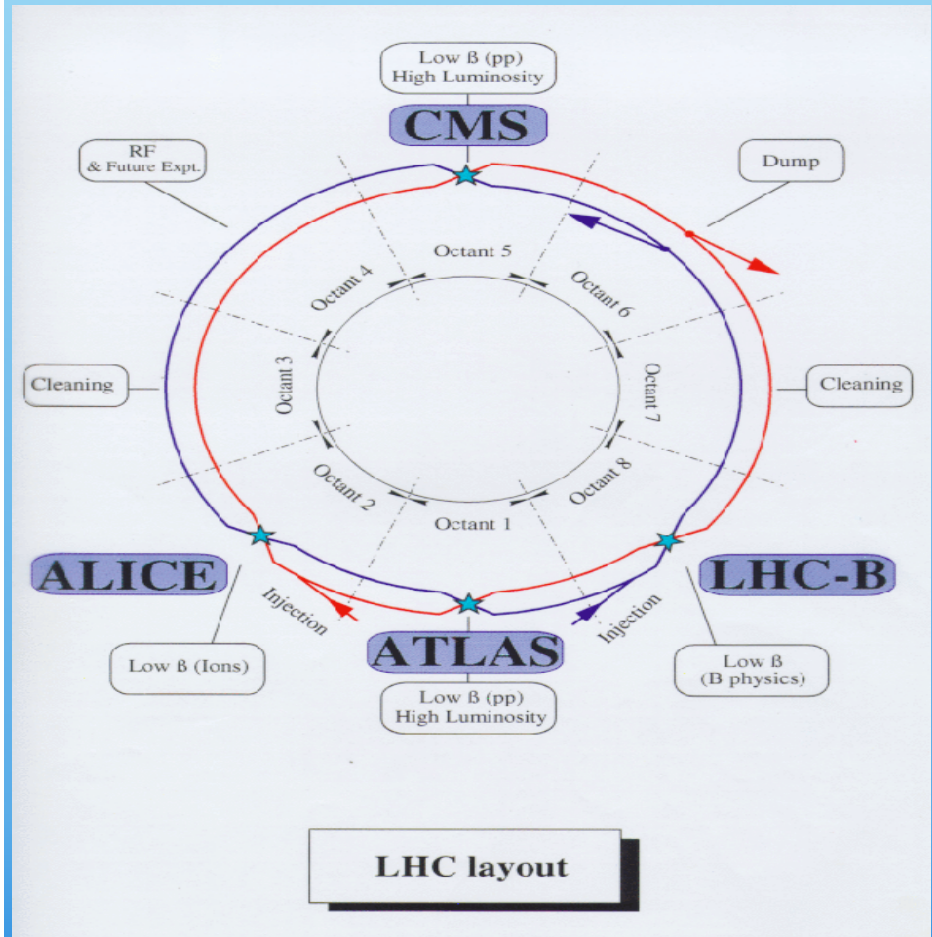
Main colliding systems:

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



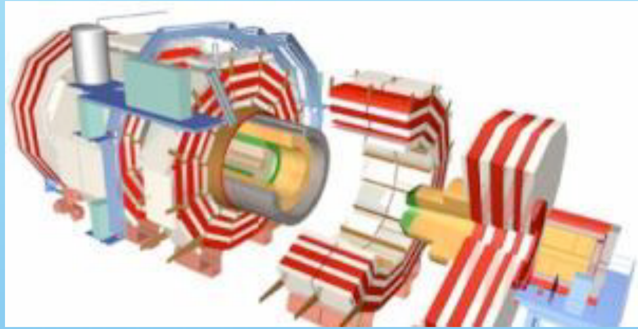
run-1 (2009-13) : p+p $\sqrt{s_{NN}}$ =0.9, 2.76, 7, 8 TeV, p+Pb $\sqrt{s_{NN}}$ =5.02 TeV, Pb+Pb at $\sqrt{s_{NN}}$ =2.76 TeV

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

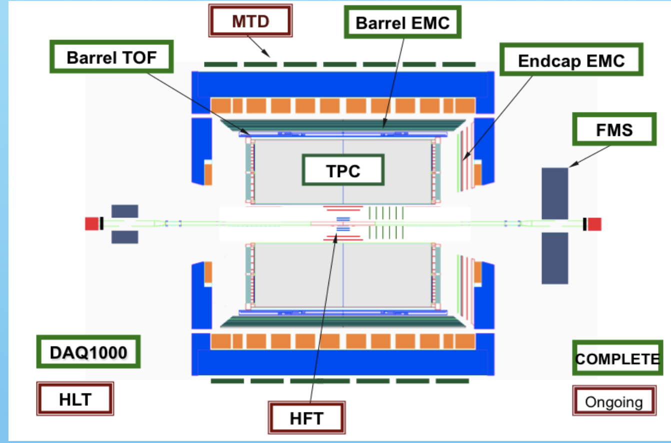
LHC

CMS

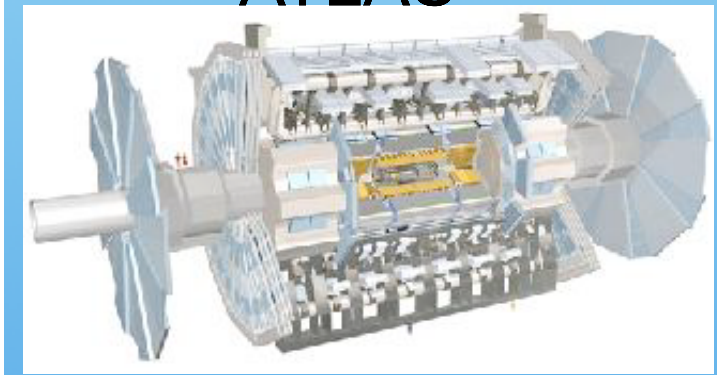


LHCb

STAR at RHIC

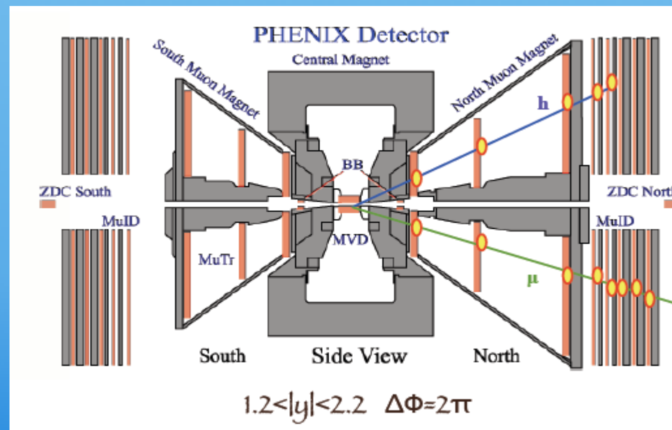


ATLAS

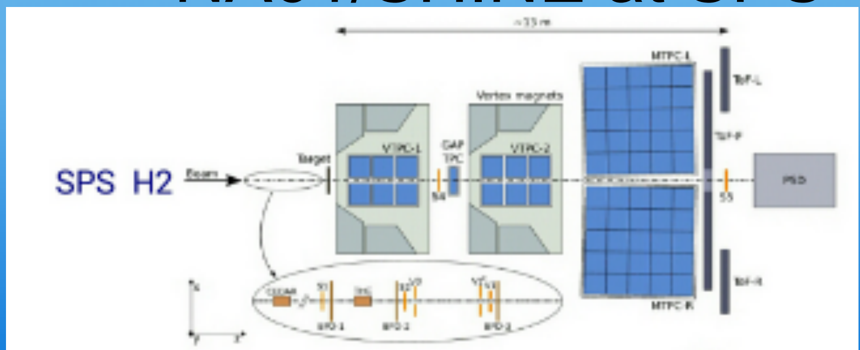


ALICE

PHENIX at RHIC



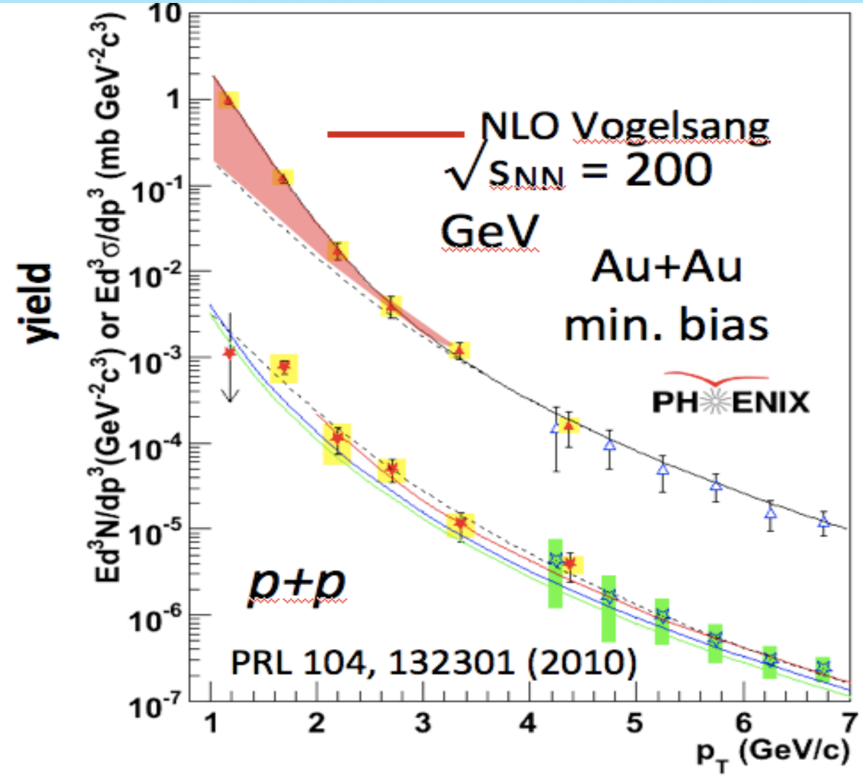
NA61/SHINE at SPS

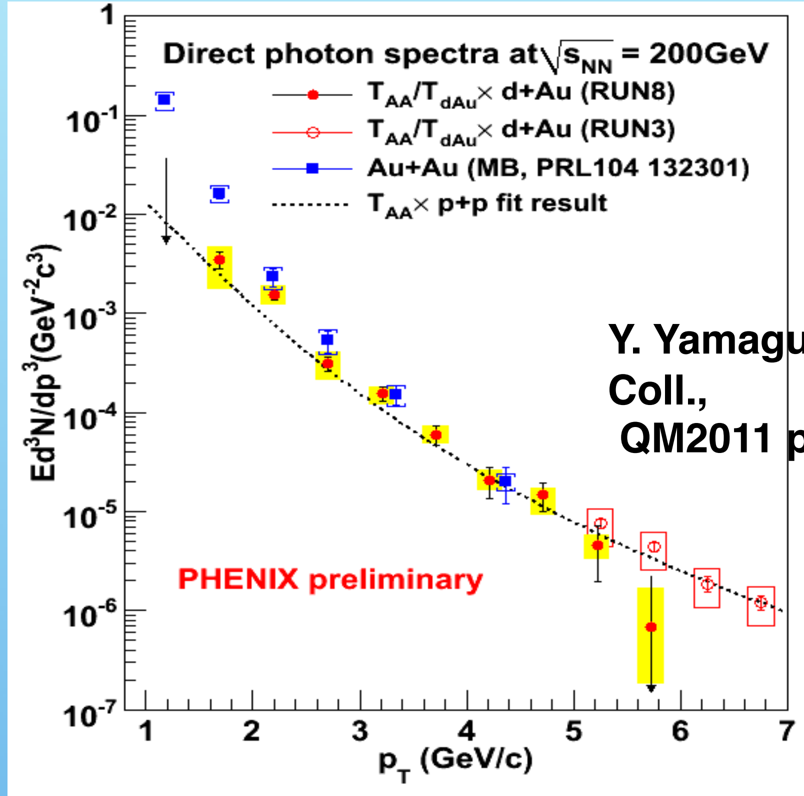


III Selected physics results:

1. Direct photons

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

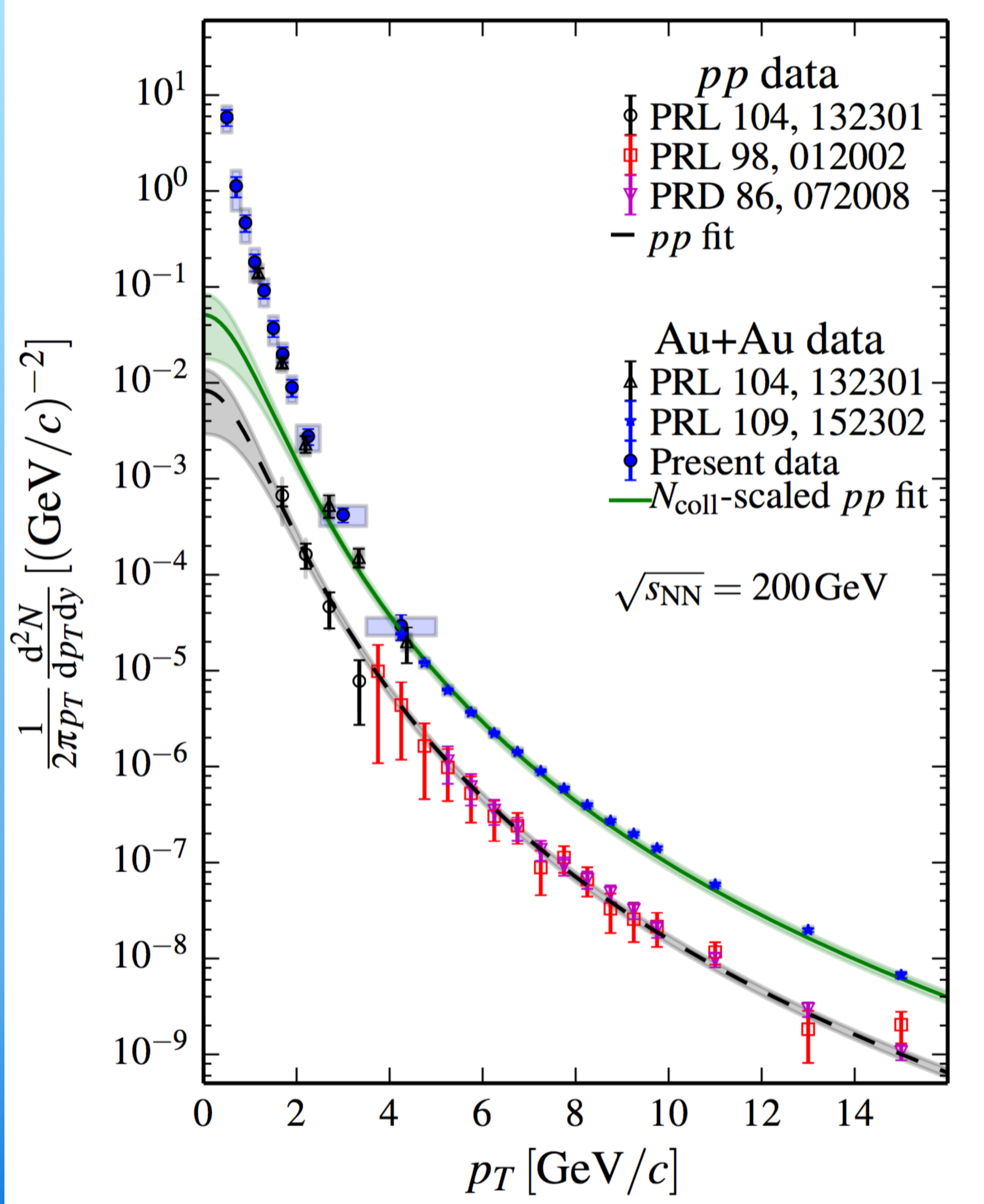
Exponential spectrum in Au+Au - consistent with thermal below pT ~2.5 GeV with inverse slope 220 ± 20 MeV -->
T(init) from hydrodynamic models : 300-600 MeV, depending on thermalization time

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

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

Wenqing Fan, ICNFP2017

PHENIX AuAu 200 GeV



Different method: Measuring gammas via external conversions in detector material

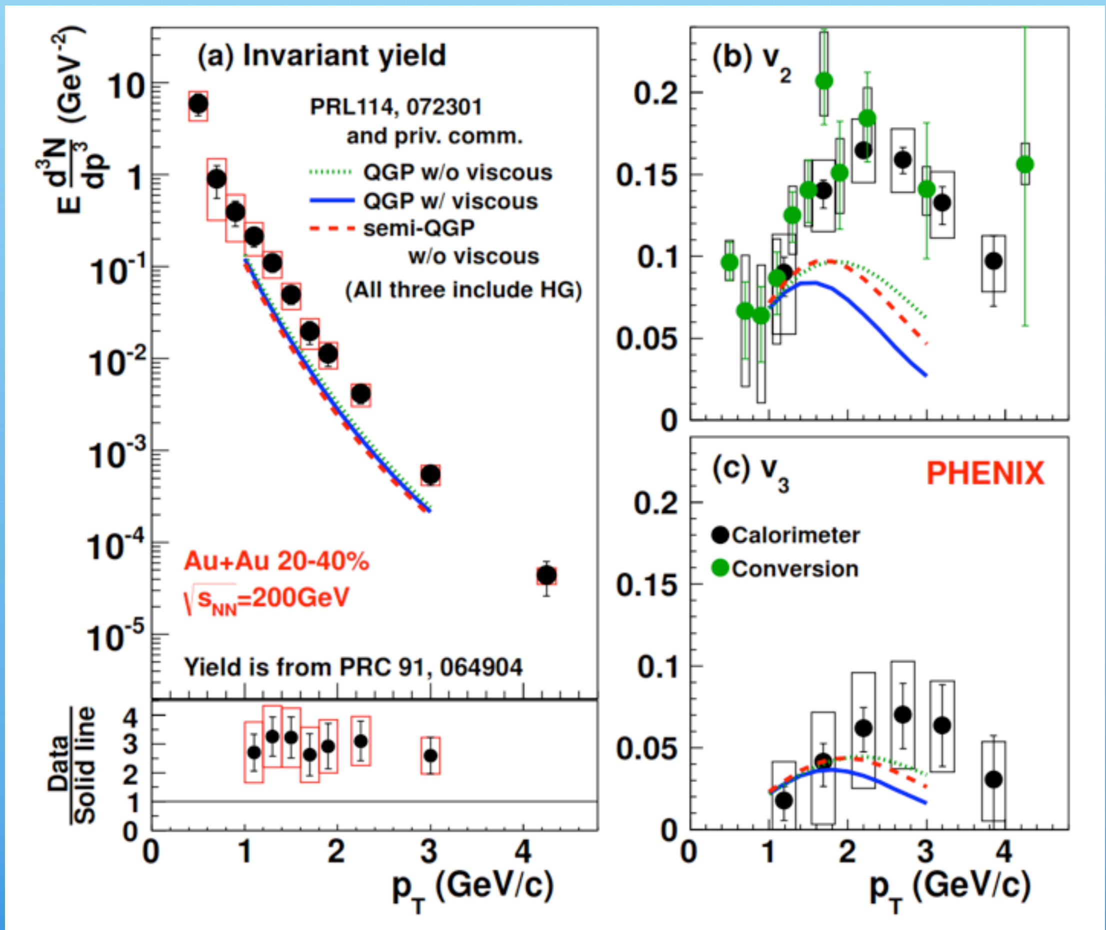
AuAu at low pT :
nearly exponential shape
T(eff) 240 MeV > T_c

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

Direct photons also flow

Example: viscous hydro + thermal emission

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

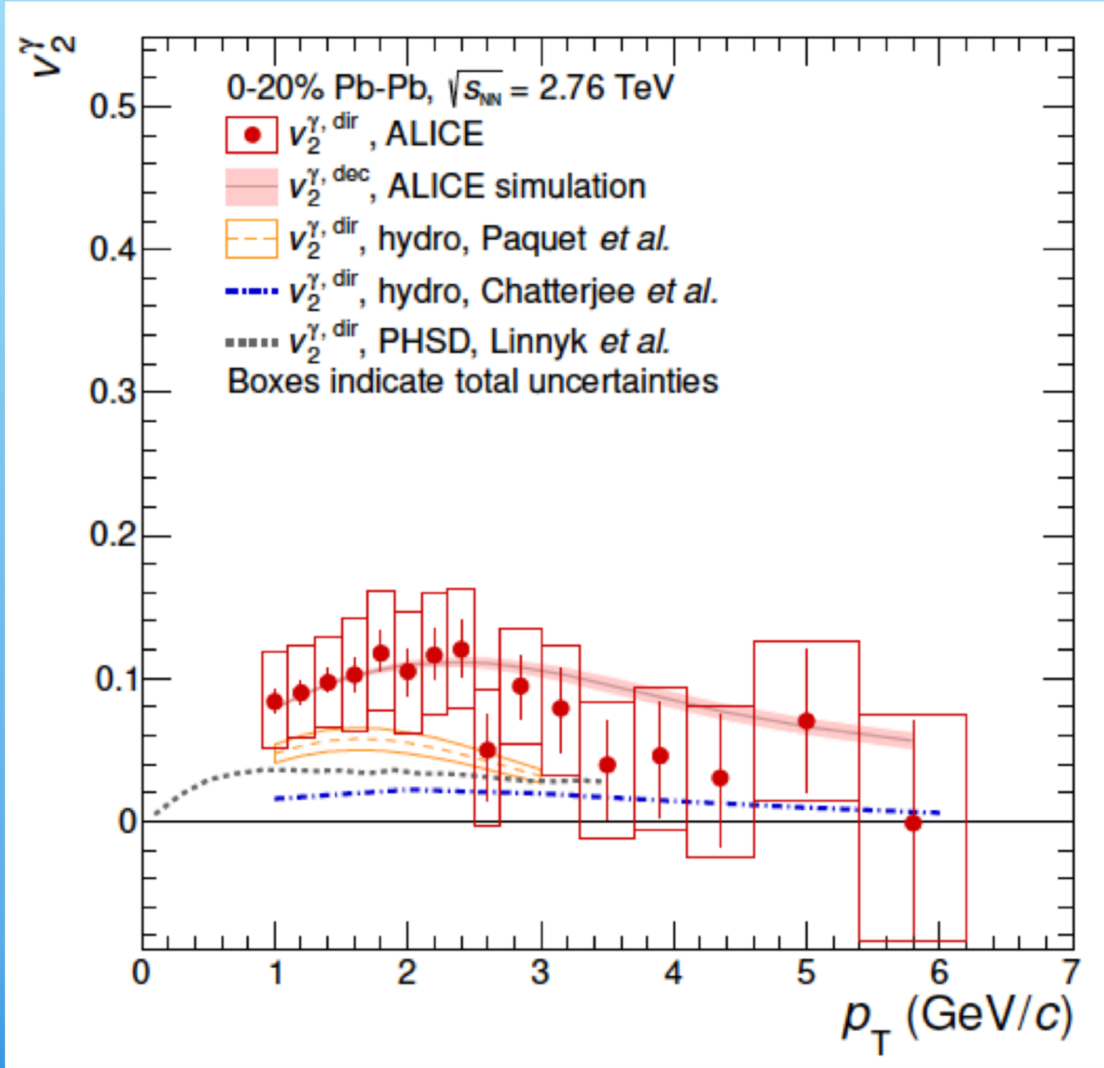


Thermal direct photons with large flow v2, v3: challenge for models

Direct photon elliptic flow in ALICE

arXiv:1805.04403

and QM2018



→ Non-zero $v_2^{\gamma,dir}$ observed for low momenta direct photons and of similar magnitude as at RHIC.

→ Flow signal is close to the expected flow for decay photons.

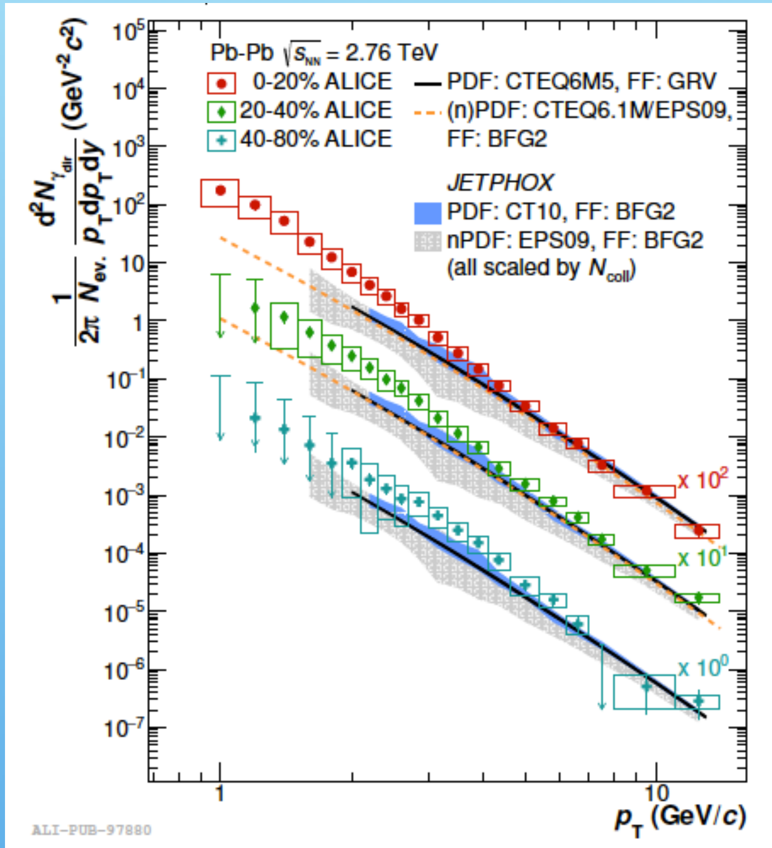
→ 1.4σ significance for hypothesis $v_2^{\gamma,dir} = 0$ for $0.9 < p_T < 2.1$ GeV/c.

→ Transport and hydrodynamic models predict a smaller direct photon flow, but are consistent with the data.

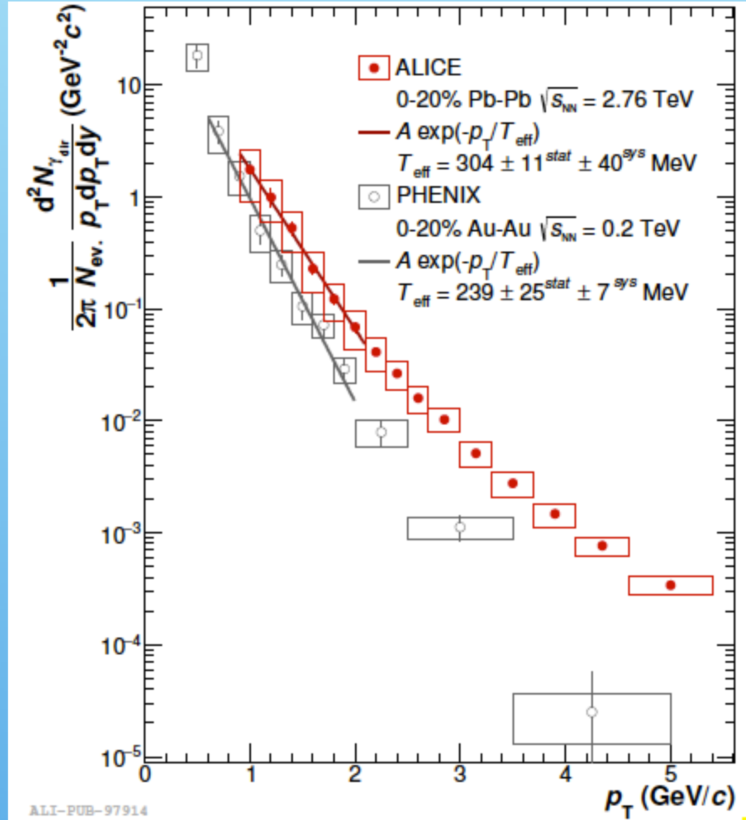
ALICE direct photons

ALICE:1509.07324

ALICE: different centralities



ALICE vs PHENIX

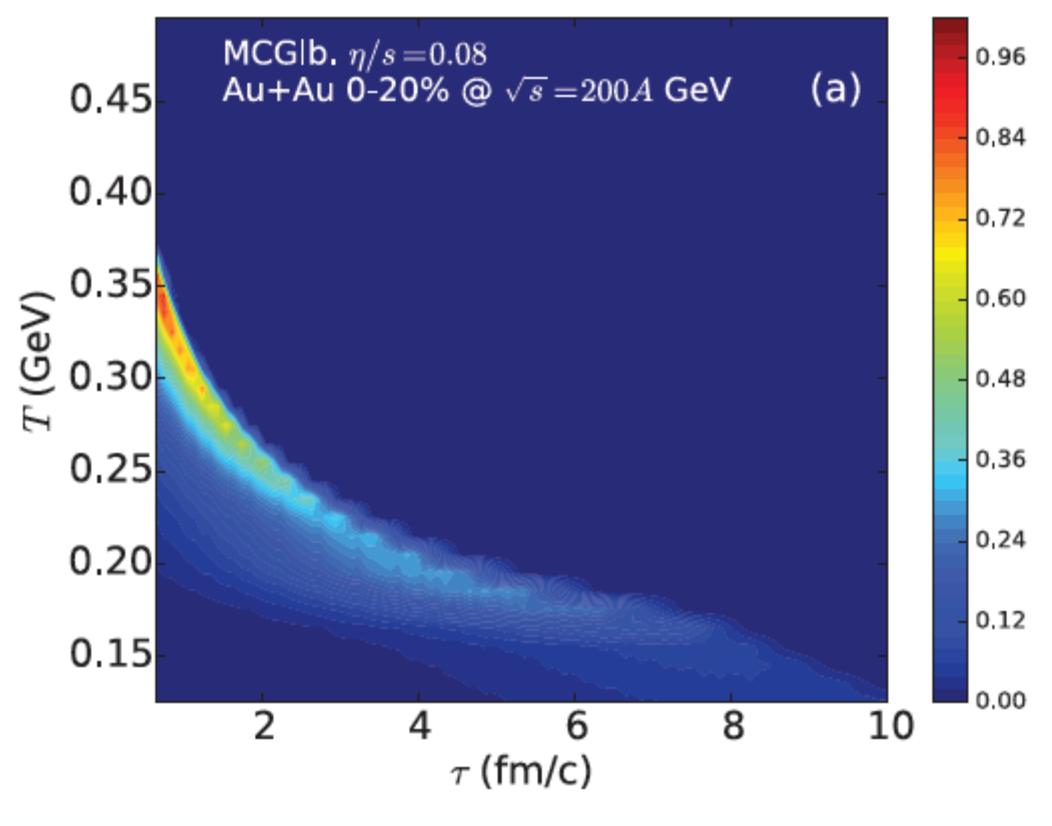


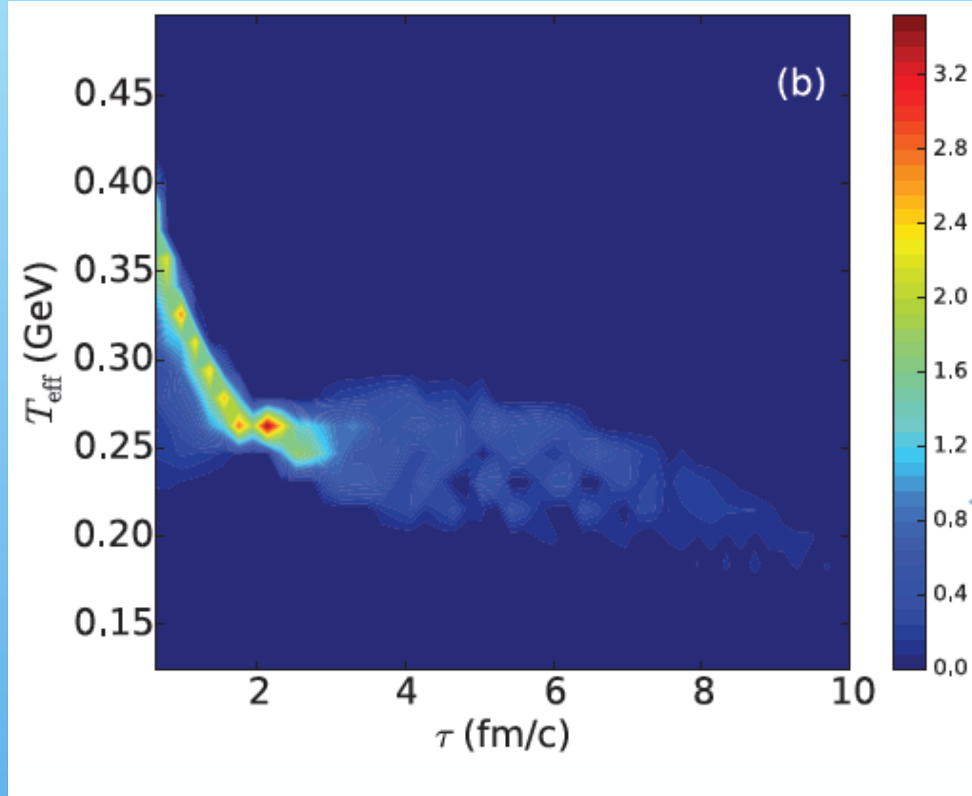
- 2.6σ excess in low p_T in 0–20% central
- T_{eff} = 304±11±40 MeV (30% larger than at RHIC)

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



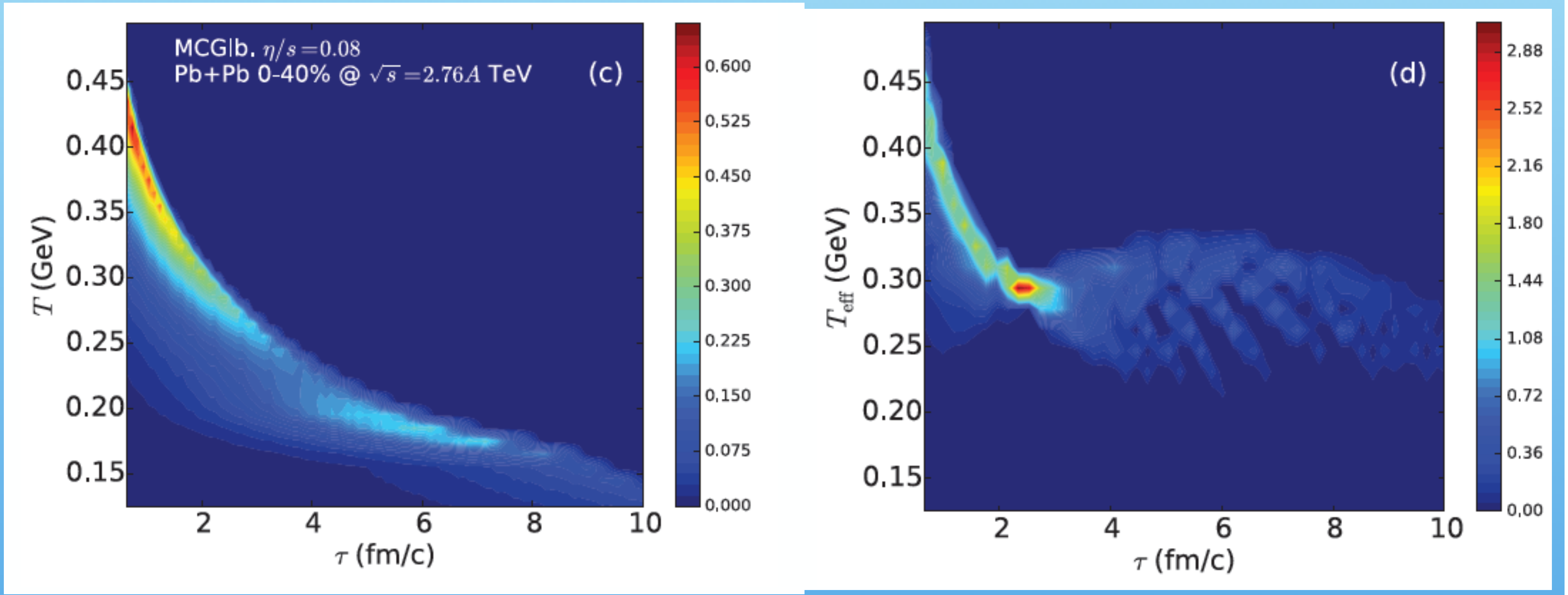


The 3rd dimension in these plots is cross section of photons

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

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.
$T = 120\text{-}165\,\mathrm{MeV}$	17%	15%
$T = 165\text{-}250\,\mathrm{MeV}$	62%	53%
$T > 250\,\mathrm{MeV}$	21%	32%
$\tau = 0.6 - 2.0\,\mathrm{fm/c}$	28.5%	26%
$\tau > 2.0\,\mathrm{fm/c}$	71.5%	74%

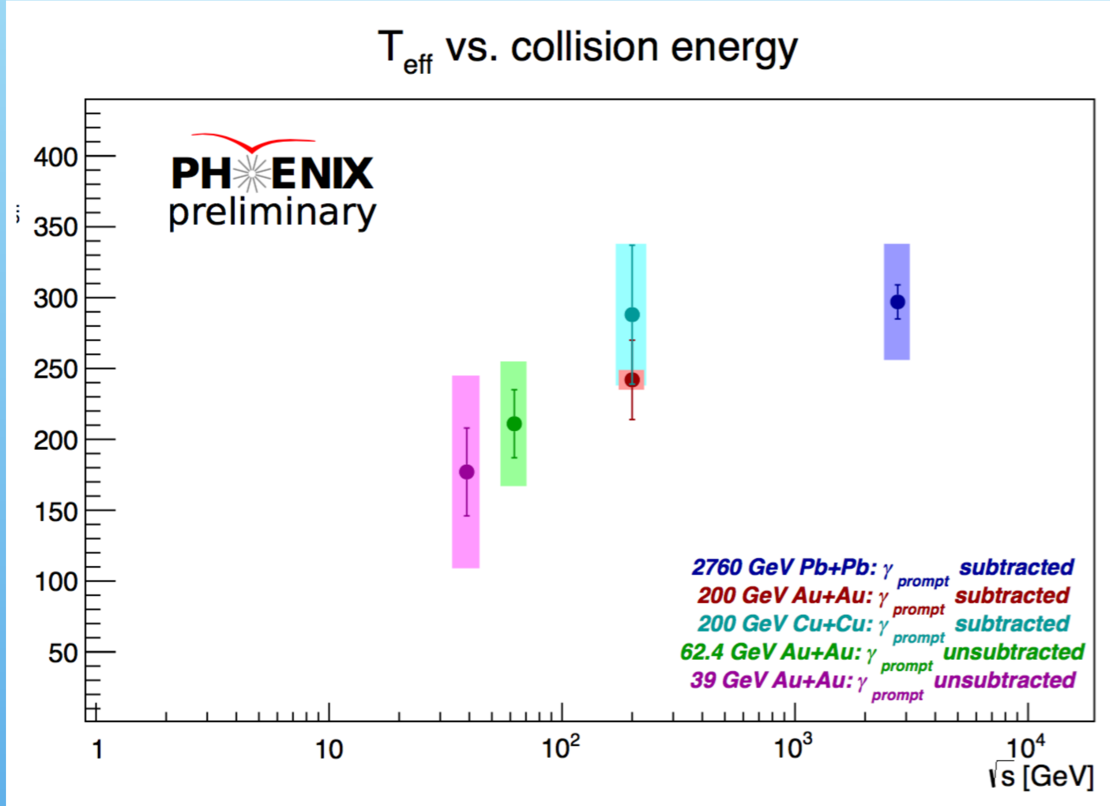
C. Gale et al, 1308.2440

*** 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)**

Results from RHIC Beam Energy Scan: direct photons

effective T(from direct photons)



PHENIX, Dheepali Sharma QM2017

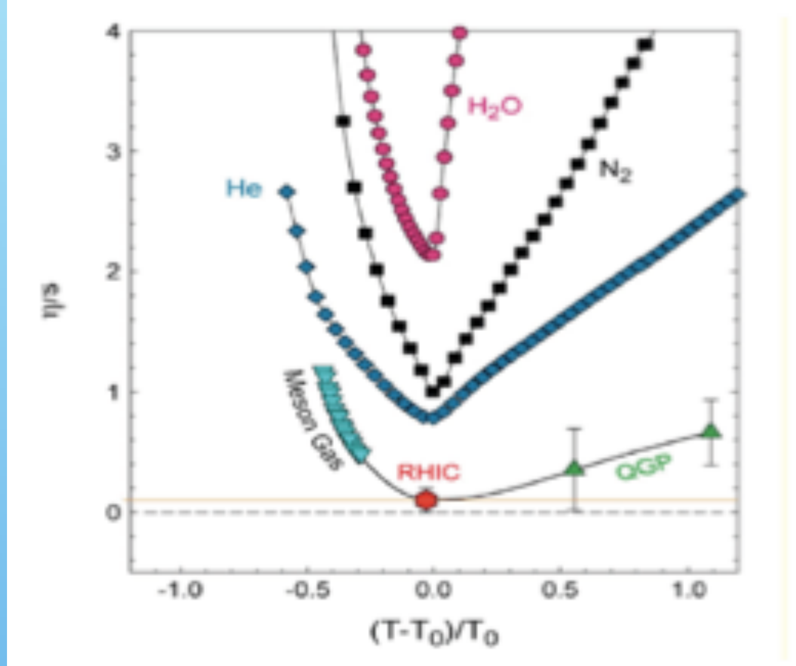
2. Collectivity, Flow, Strangeness

Flow and shear viscosity

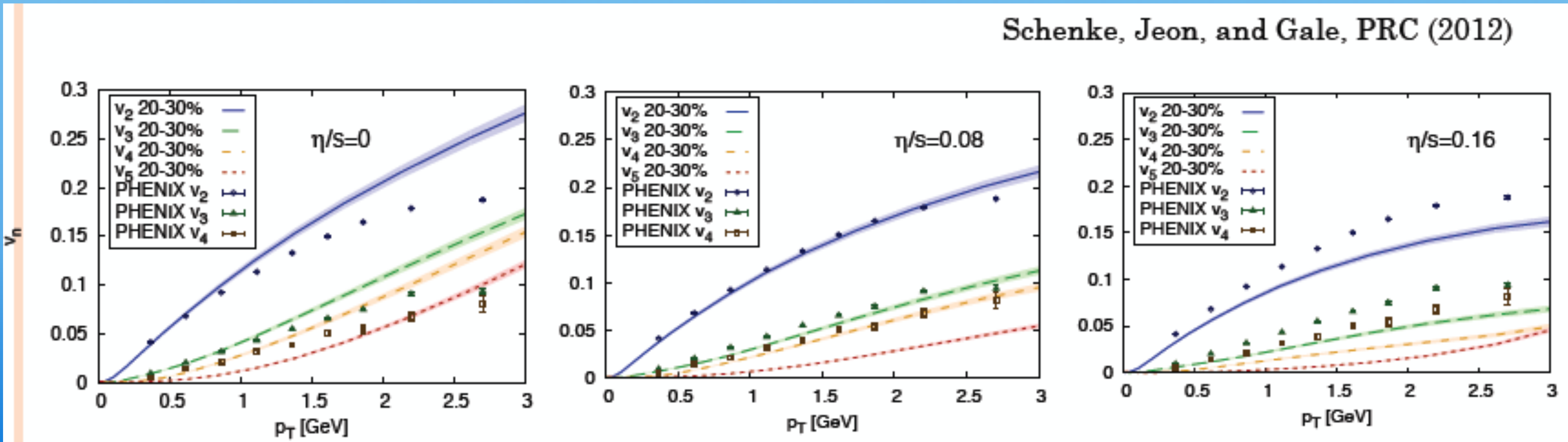
- 2003: discovery at RHIC of large flow and first extraction of shear viscosity -> RHIC white papers

- QGP : a perfect liquid

- strongly interacting QGP



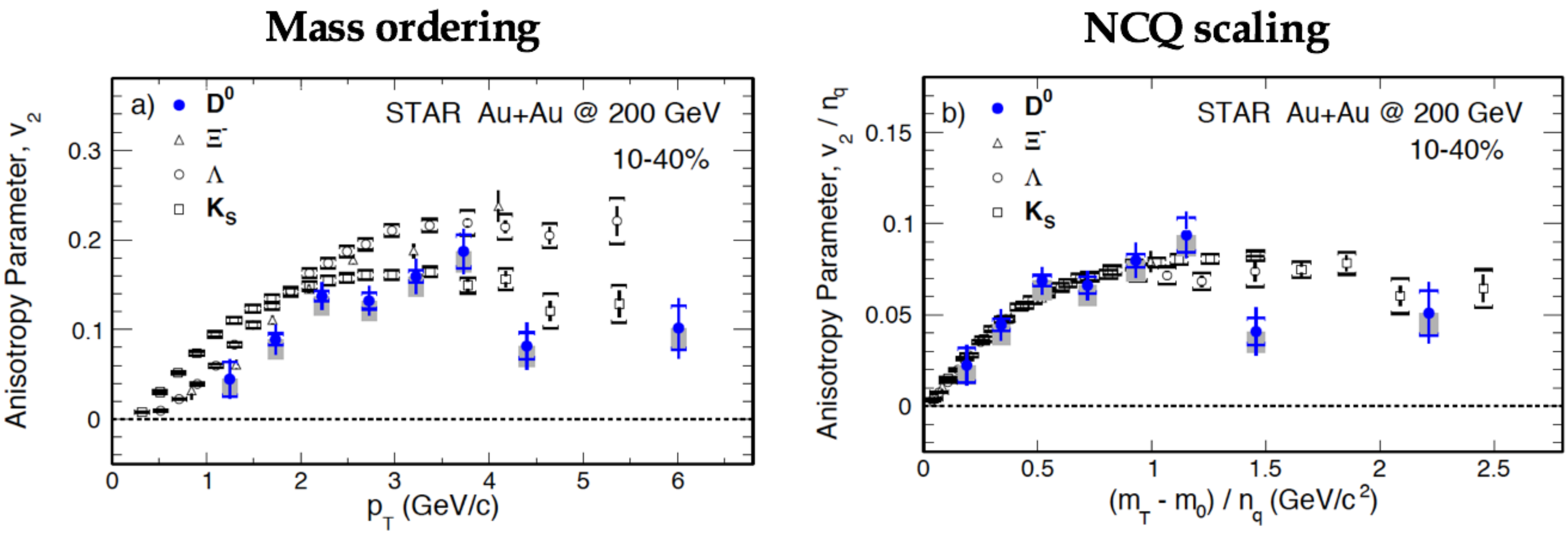
PHENIX



Strangeness and charm v2

STAR New D0 v2 from STAR Heavy Flavor Tracker

1701.06060, STAR

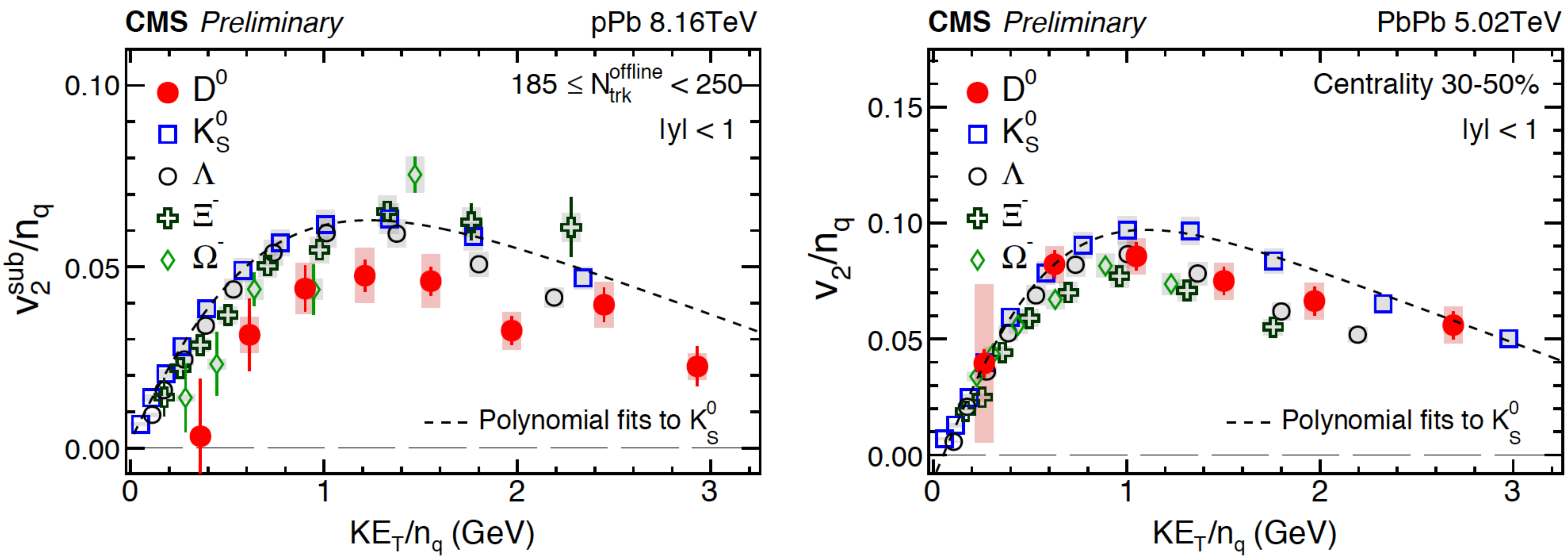


v2 of D0 in Au+Au follows Number-of-Constituent-Quarks scaling of other hadrons
-> Evidence for thermalization of u,d,s,c mesons

Small Systems

CMS D0 and strange particles in pPb, PbPb

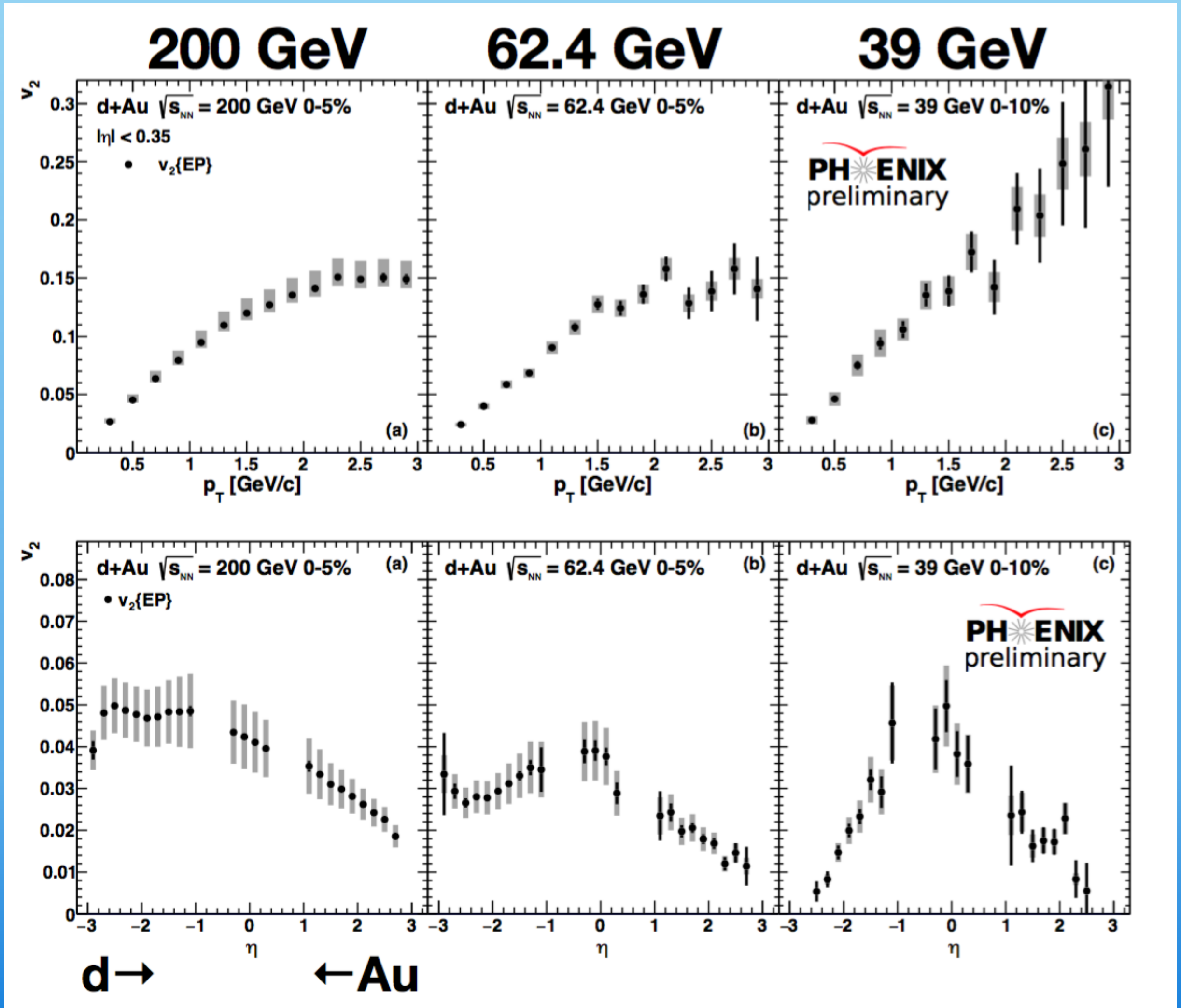
CMS 1705.01974



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

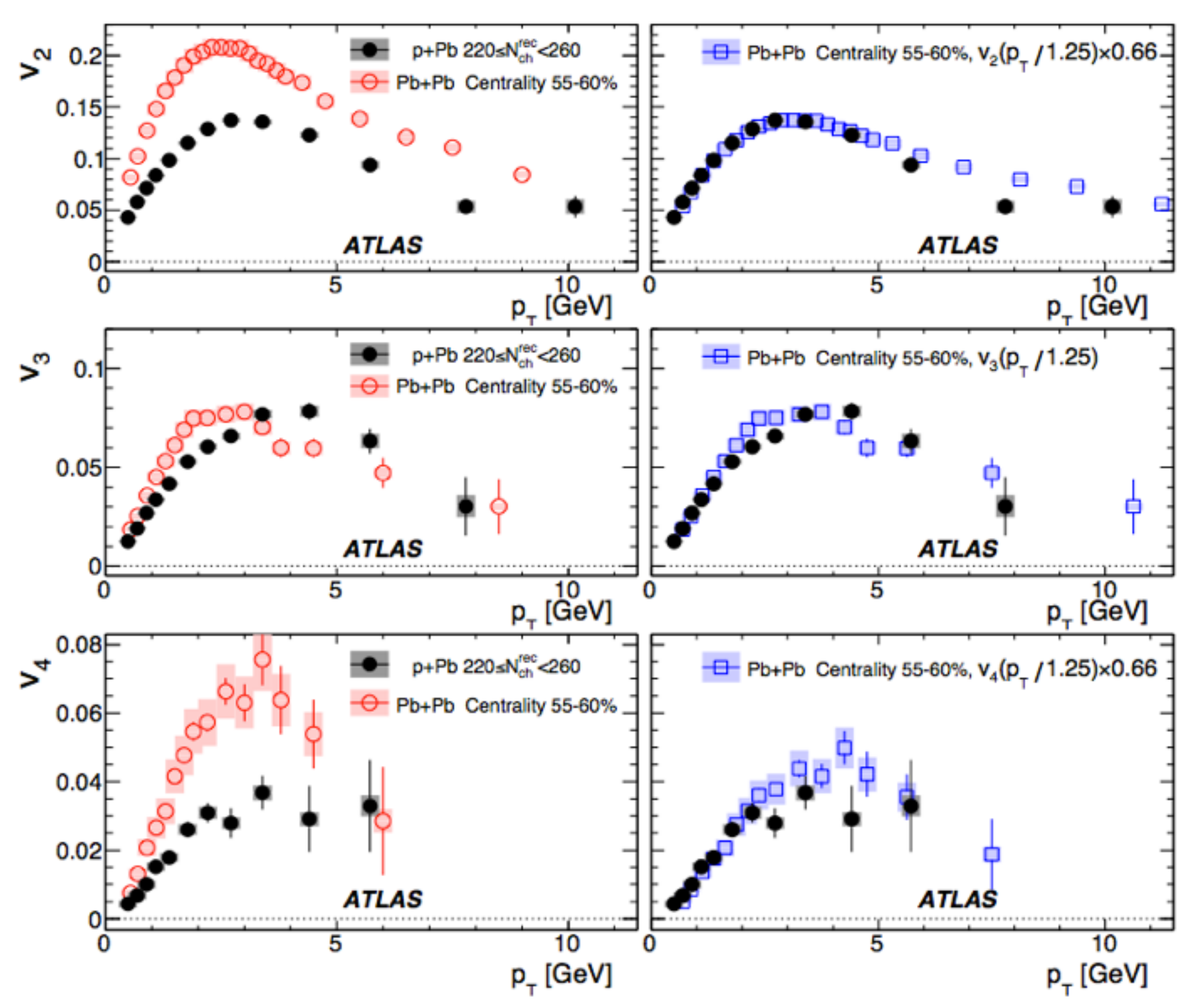
Right, PbPb semiperiph.: v2/nq of strange particles and D0 tend to lie on a universal curve below 1.0 GeV, indicating strong collective behaviour of D0 similar to the bulk of QGP medium

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



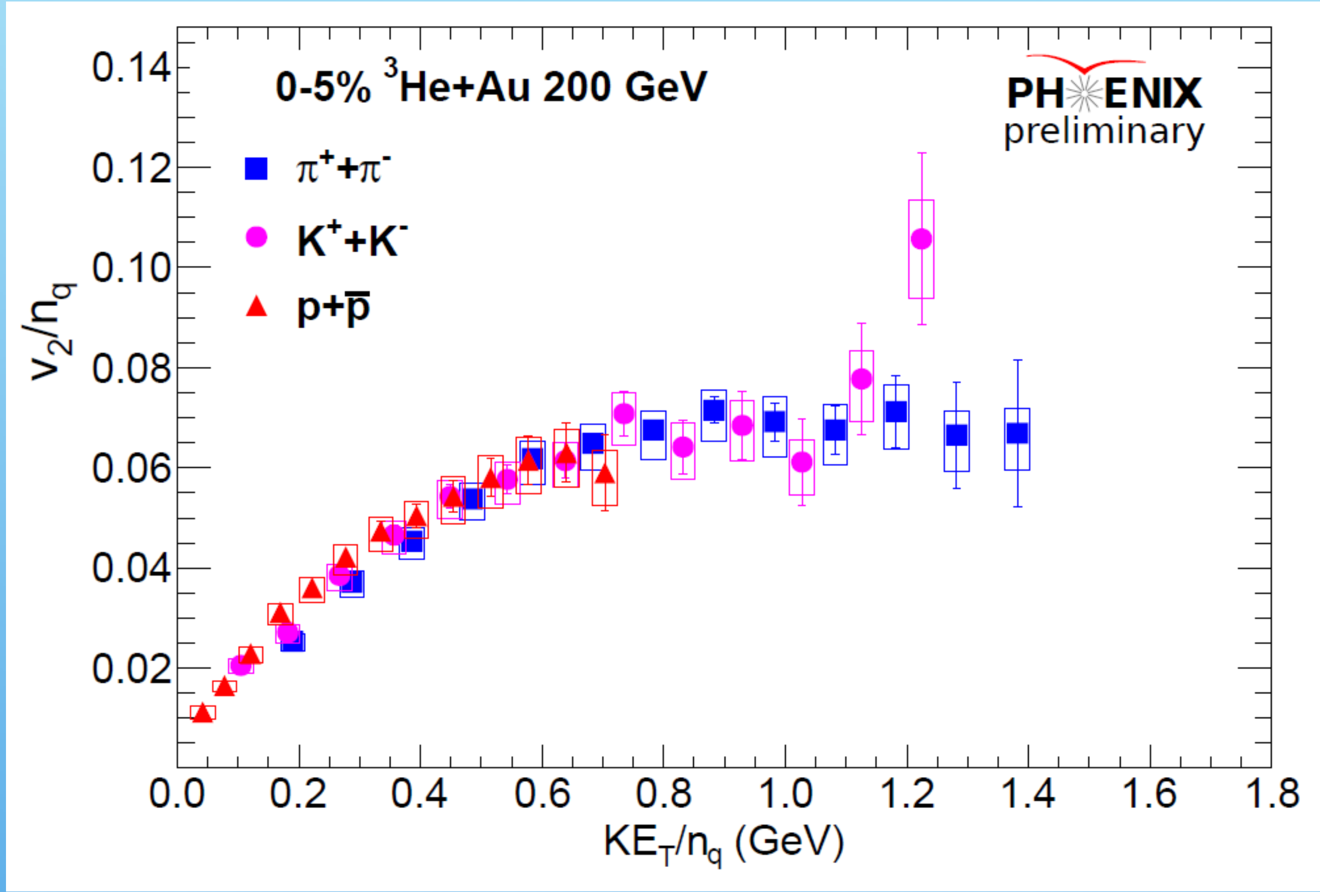
Results from ATLAS 1409.1792

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



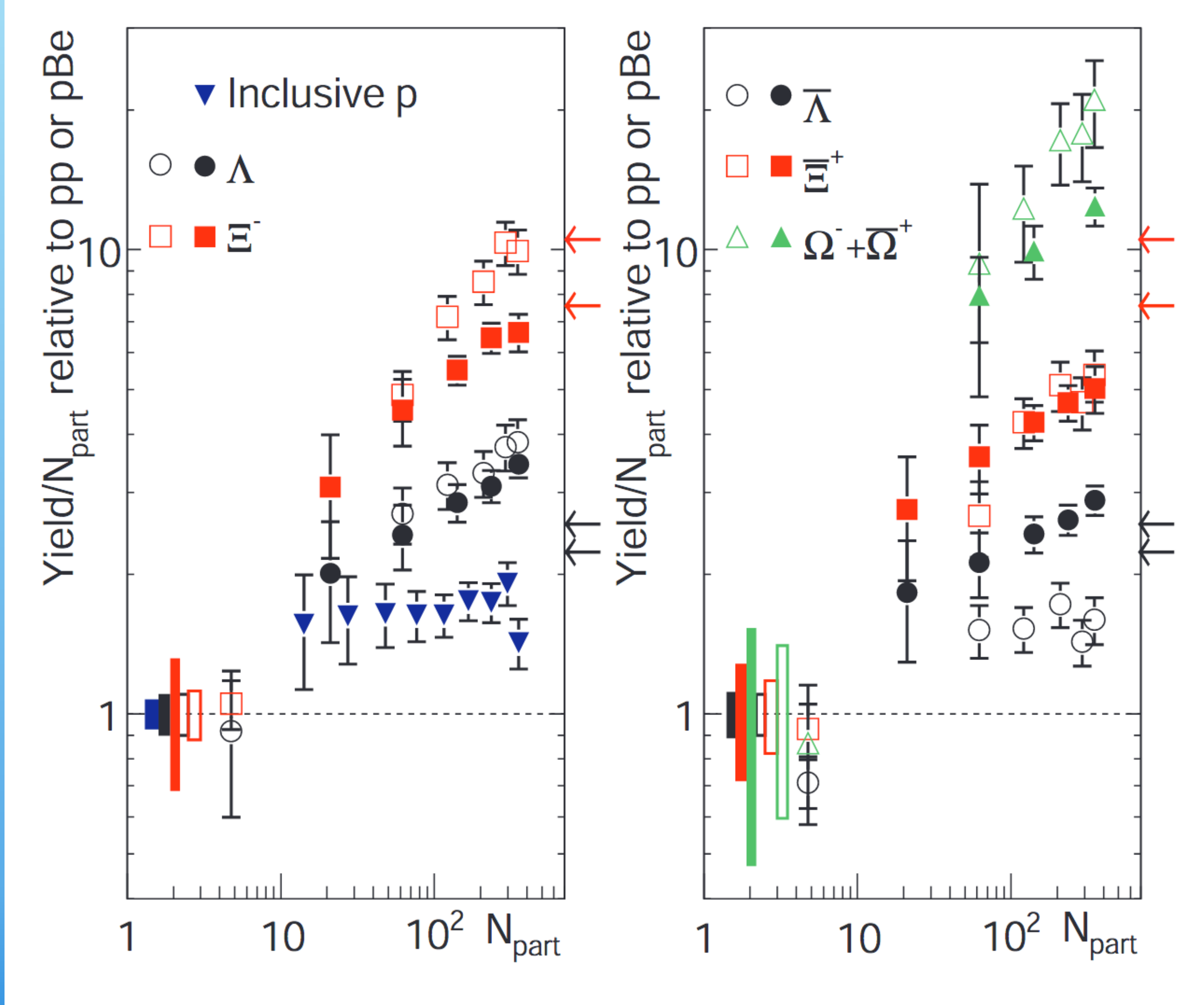
S Huang, STAR, QM15

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

Strangeness enhancement

Strange particle enhancement in AuAu 200 GeV STAR (AA) / (pp or pBe)

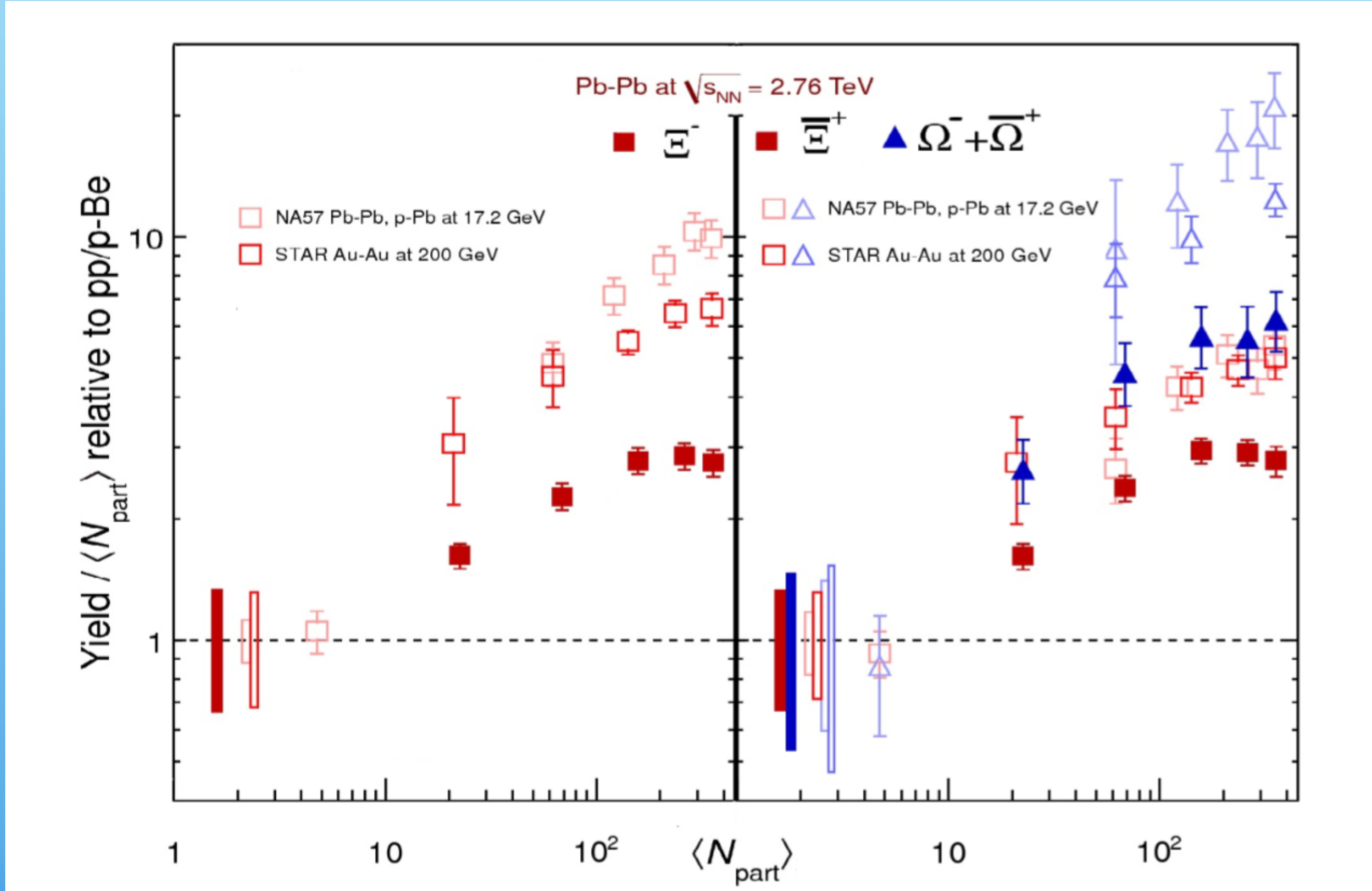
STAR, https://arxiv.org/pdf/0705.2511.pdf



STAR (solid marks) vs SPS PbPb sqrt(s)=17.3 GeV (open marks)

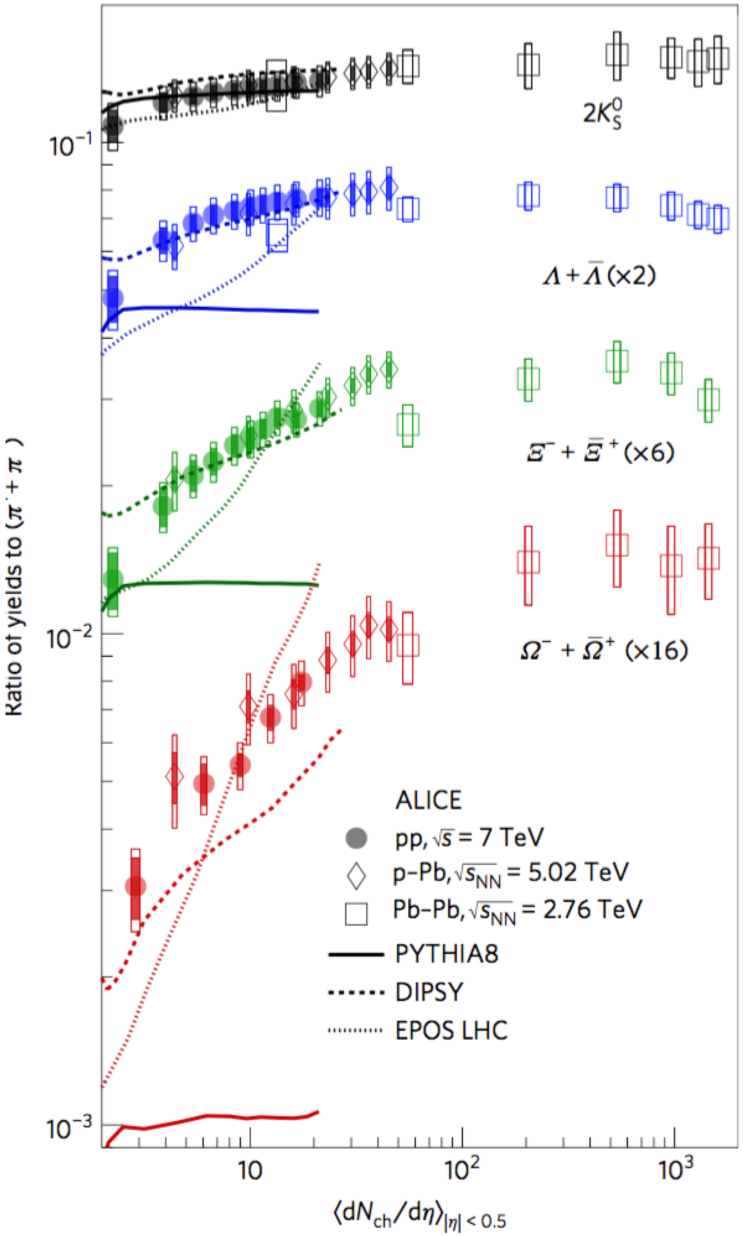
Strangeness enhancement in LHC, RHIC, SPS

ALICE, Phys. Lett. B 728 (2014) 216,



Strangeness enhancement gets smaller as collision energy increases here from SPS 17 GeV -> RHIC 200 GeV -> LHC 2.76 TeV

ALICE strangeness



PbPb 2.76 TeV, p+p 7 TeV, p+Pb 5.02 TeV

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

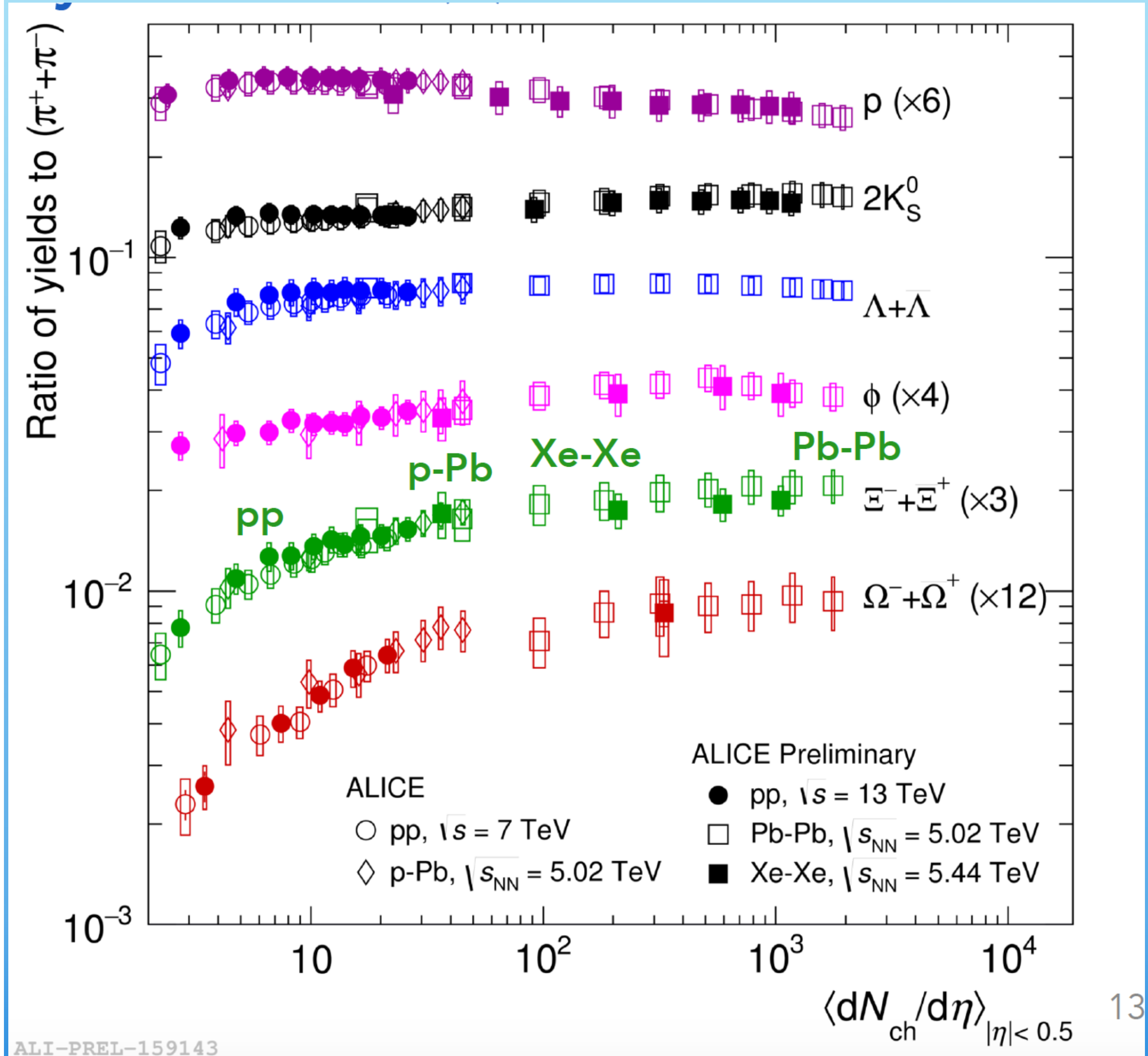
Adds to previous measurements showing QGP signatures in small systems. These new measurements at LHC point towards possible formation of QGP matter at high Temperature and density also in small collisions systems.

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?

Strangeness in Xe+Xe ALICE



ALICE Collab. QM2018

Same picture with new data from Xe+Xe 5.44 TeV and p+p sqrt(s)=13 TeV

p+Pb 5.02 TeV
Pb+Pb=5.02 TeV
Xe+Xe 5.44 TeV

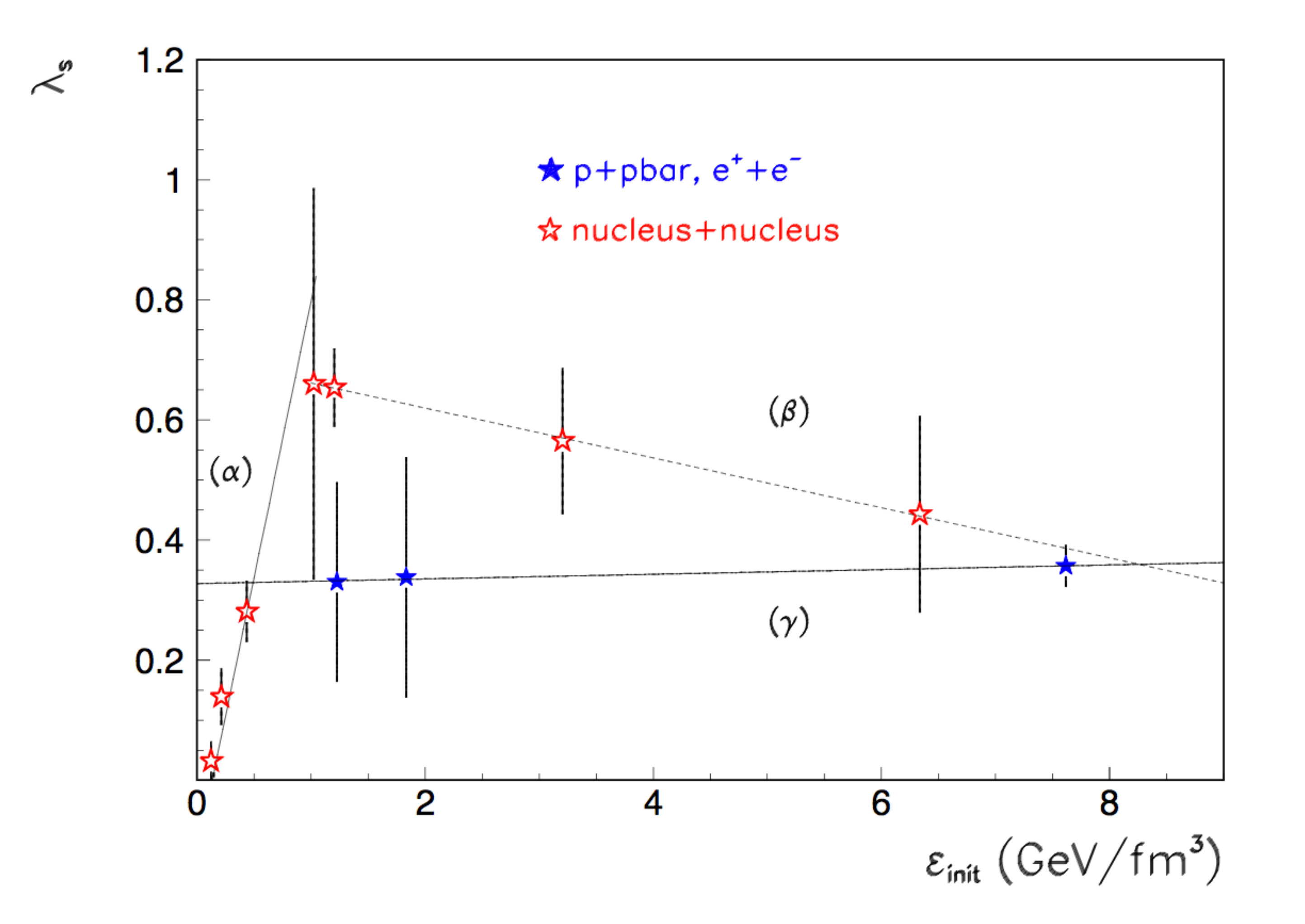
Do small QGP droplet form in p+p, p+A?

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 for the first time the universality of QGP phase transition in p+p, p+A, A+A appearing above a critical energy density.

Maximum of strangeness suppression factor



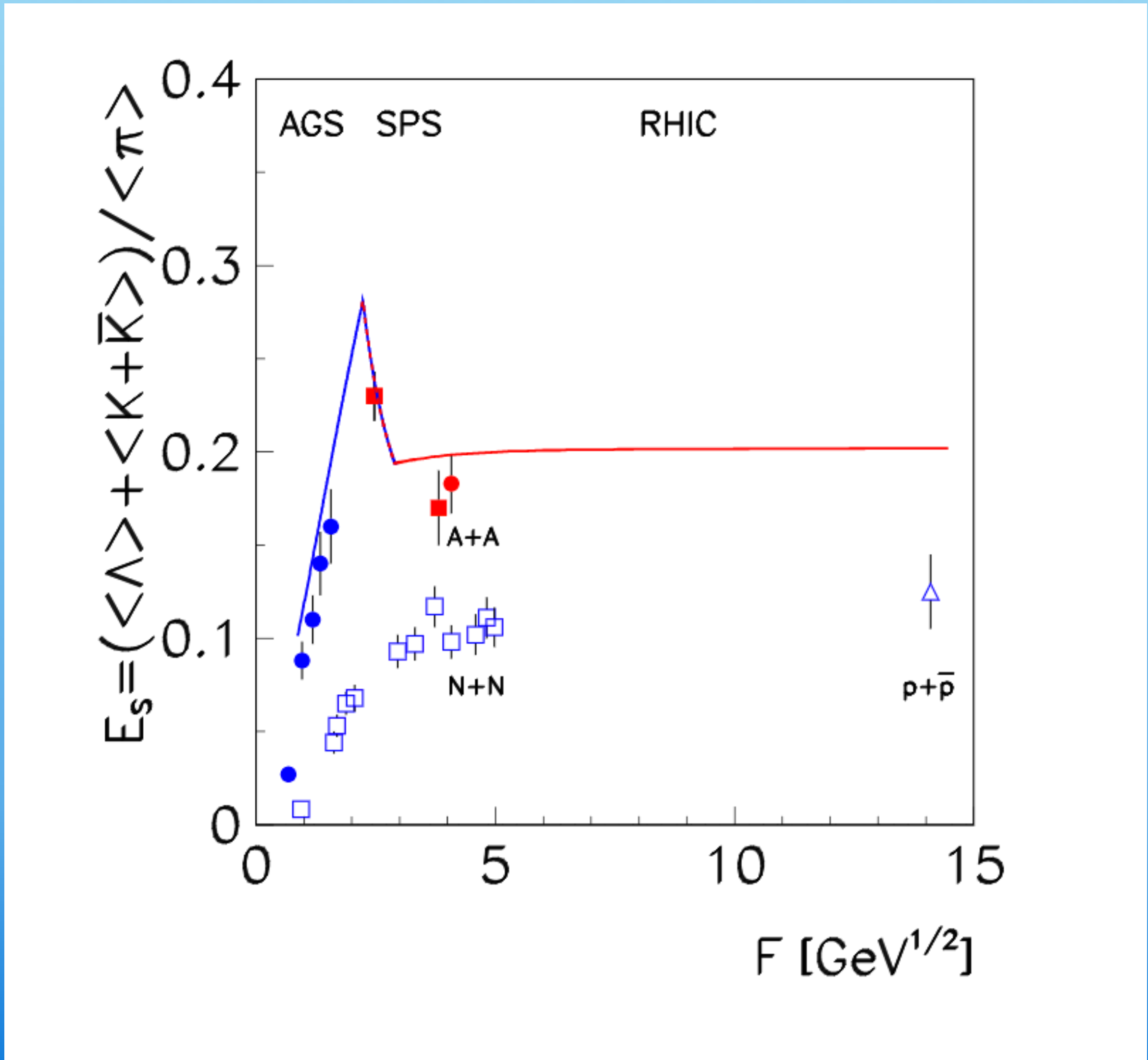
Maximum of λs occurs at or below initial energy density of 1 GeV/fm^3 (red points)

The maximum is not seen in p+pbar and e+e- collisions

S.K., Eur.Phys.J. C21 (2001) 545-555

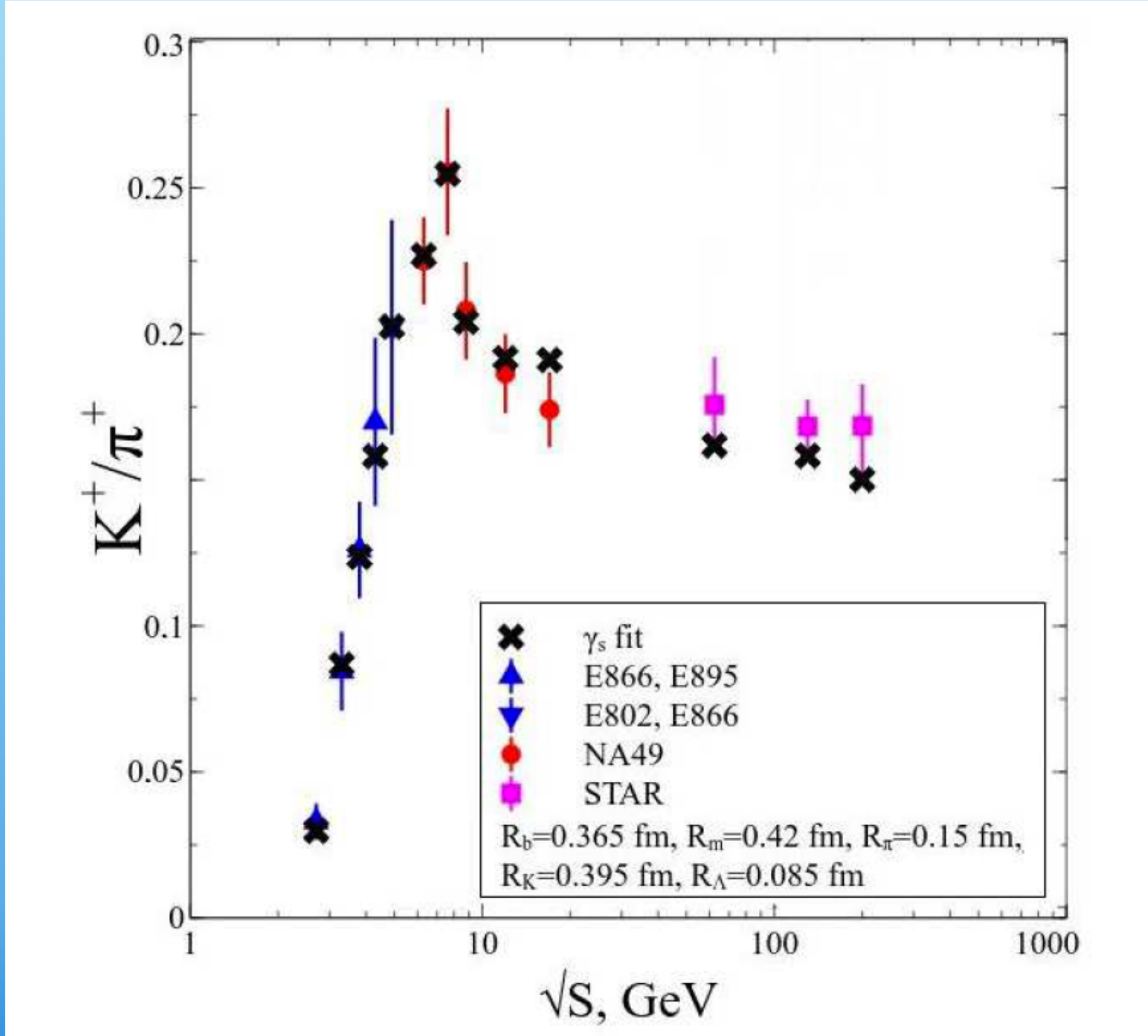
Historical plot: Energy dependence of s/q
The "Horn"

M. Gorenstein, M. Gazdzicki, Acta Phys. Pol. B 30, (1999) 2705.



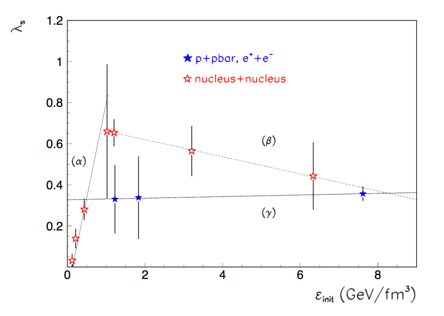
"Horn" proposed as signature for the QCD phase transition occuring nearby !

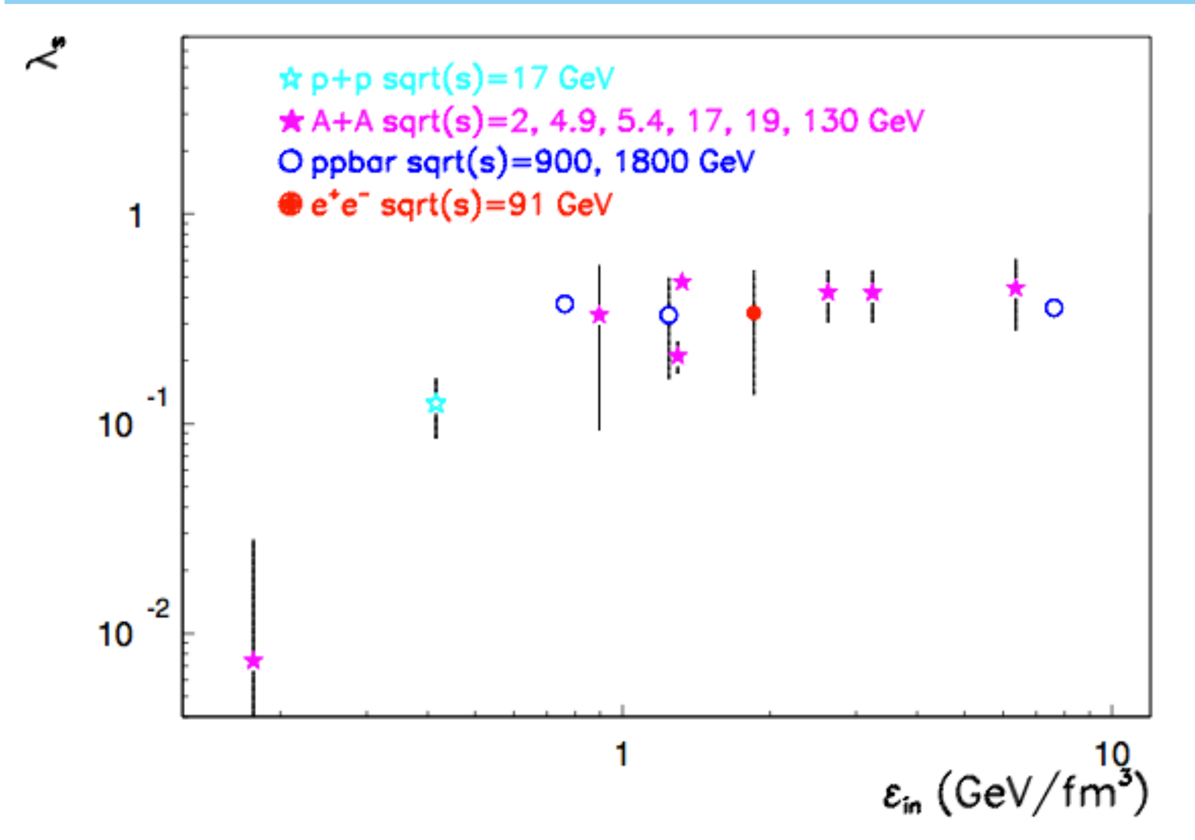
Maximum seen in the K/pi collision energy dependence



V Sagun et al, EPJA (2018) 54; 100

The maximum dissappears at muB=0





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

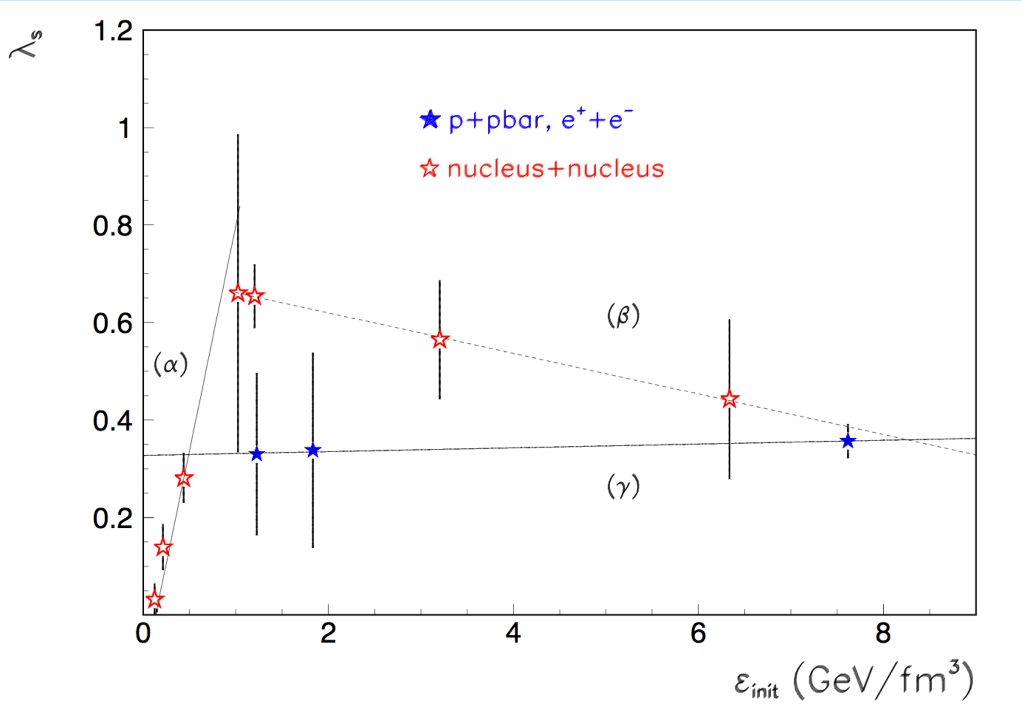
After extrapolating all points to muB=0 the maximum of λs dissappear
This suggest that the maximum is entirely due to the finite values of mu_B

After eliminating the effect of having different mu_B for each point, small and large systems universally agree and depend only on initial Bjorken energy density reached in the collision

The onset of saturation reveals the onset of the QCD phase transition (Van Hove's signature)

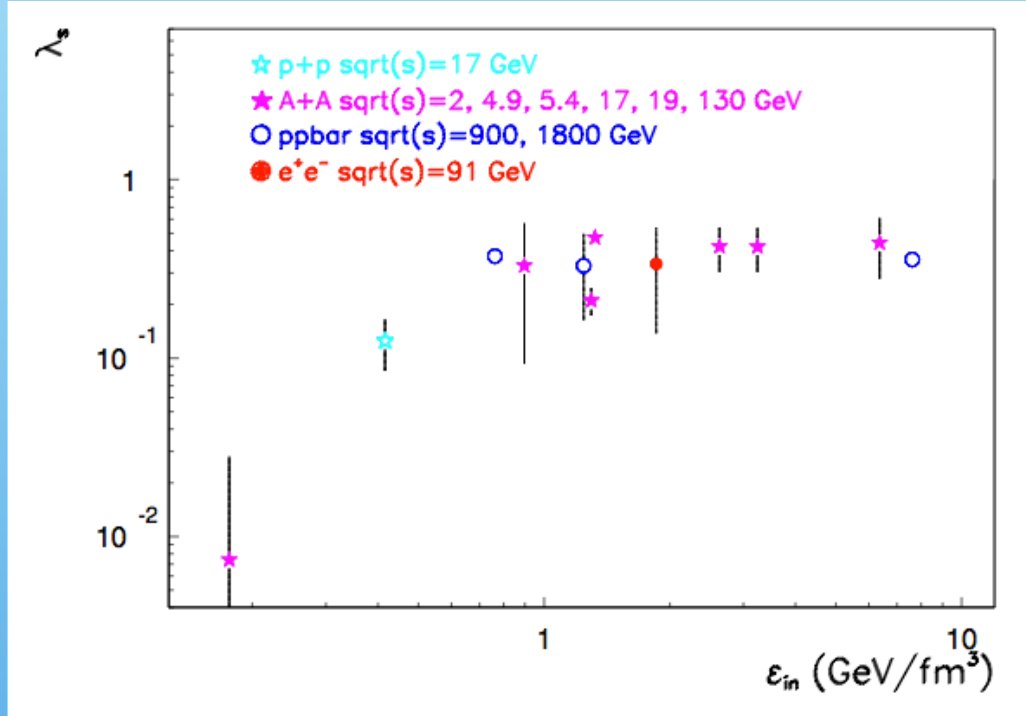
Dissapearance of "maximum " at muB=0 in A+A

Mu_b non-zero



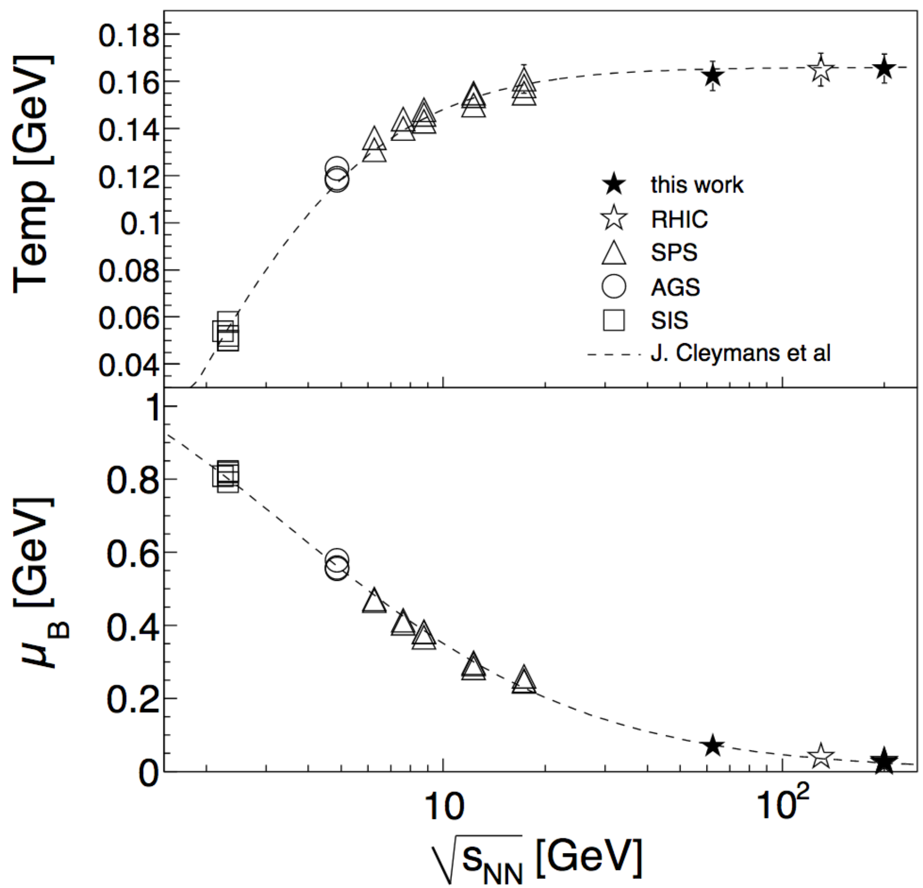
S.K. Eur Phys J C 21 (2001) 545

Mu_b zero



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

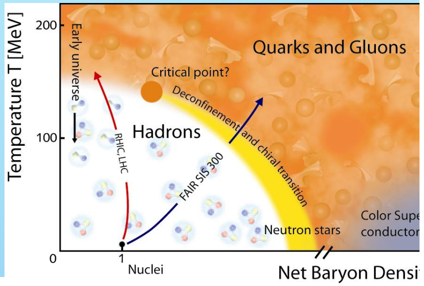
Temperature and baryochemical potential collision energy dependence in A+A

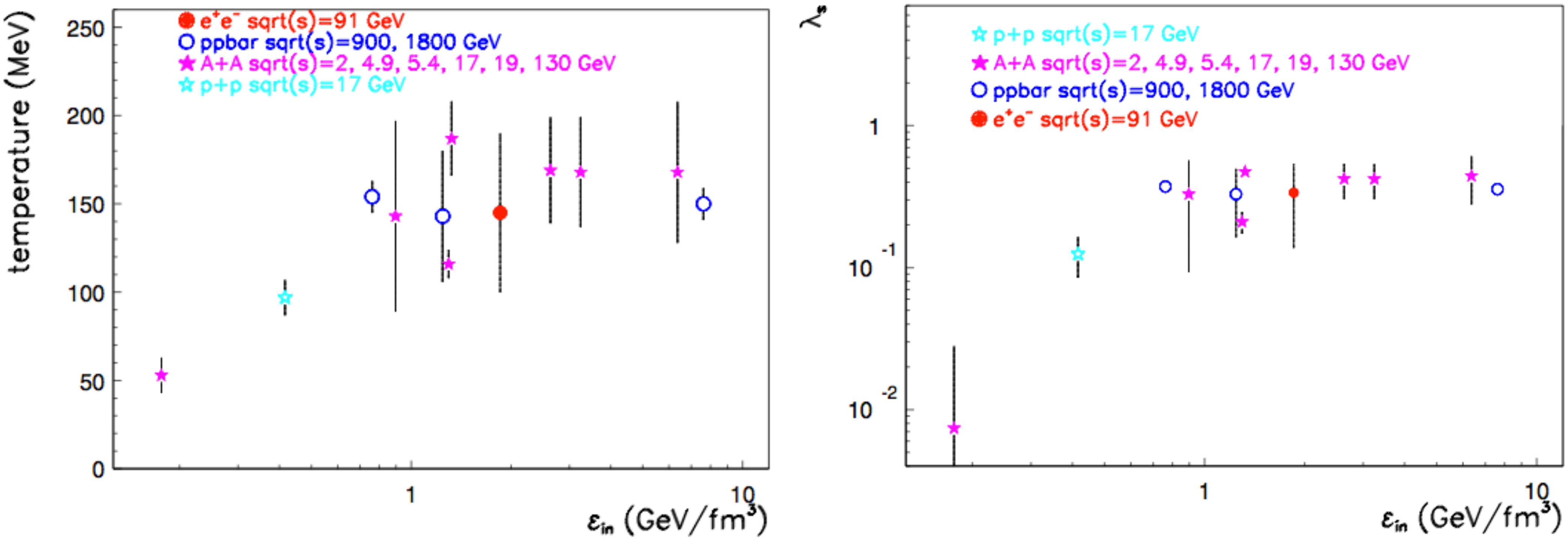


STAR

https://arxiv.org/pdf/1010.0142.pdf

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

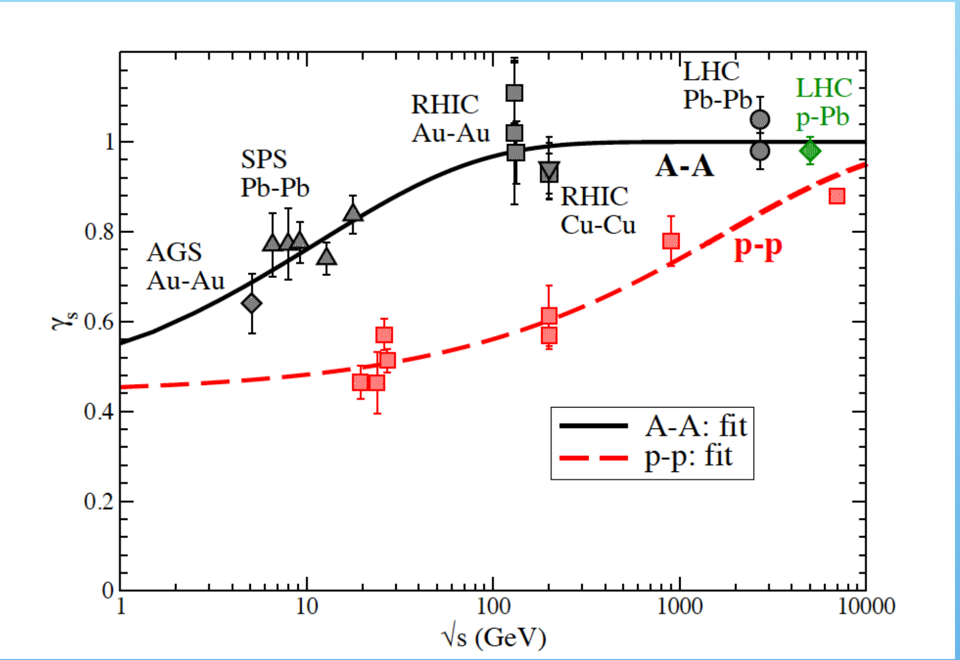
Consequences:

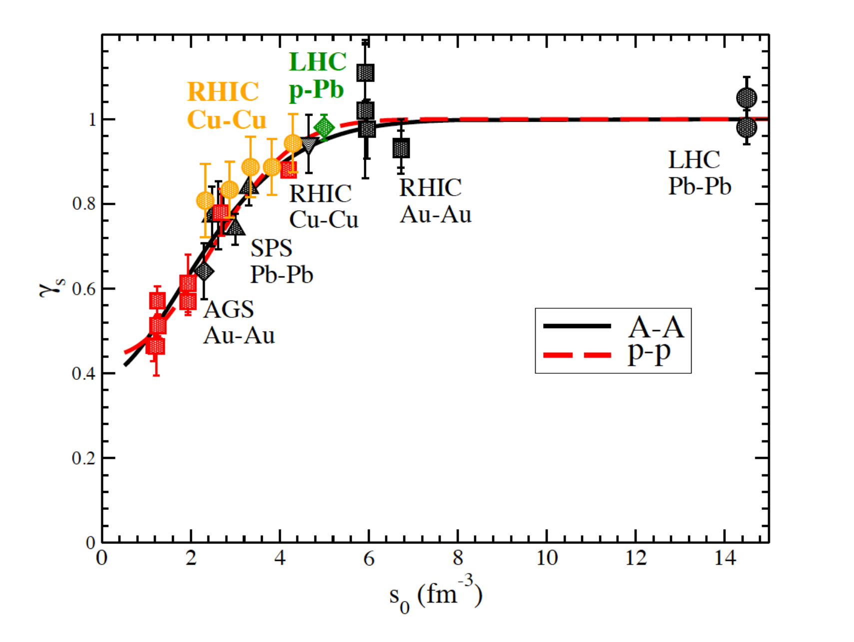
-> Universality of onset of phase transition near ~0.8 GeV/fm^3

-> Universality of onset of saturation of strangeness suppression factor

Universal Strangeness Production

results from F Becattini et al P. Castorina, S Plumari, H Satz, 1709.02706





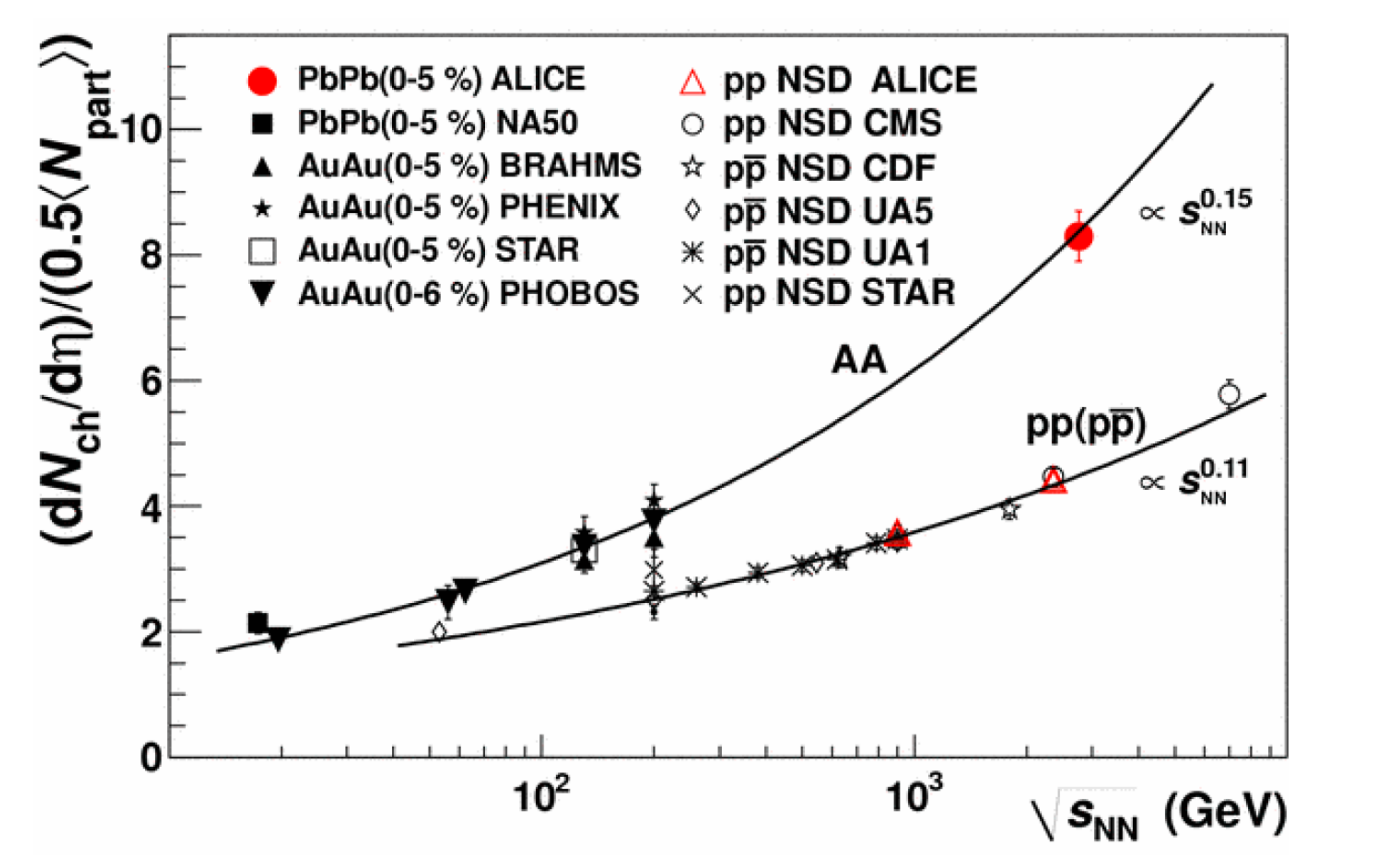
s_0 initial entropy density calculated using the Bjorken relation

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

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

P Castorina - H Satz

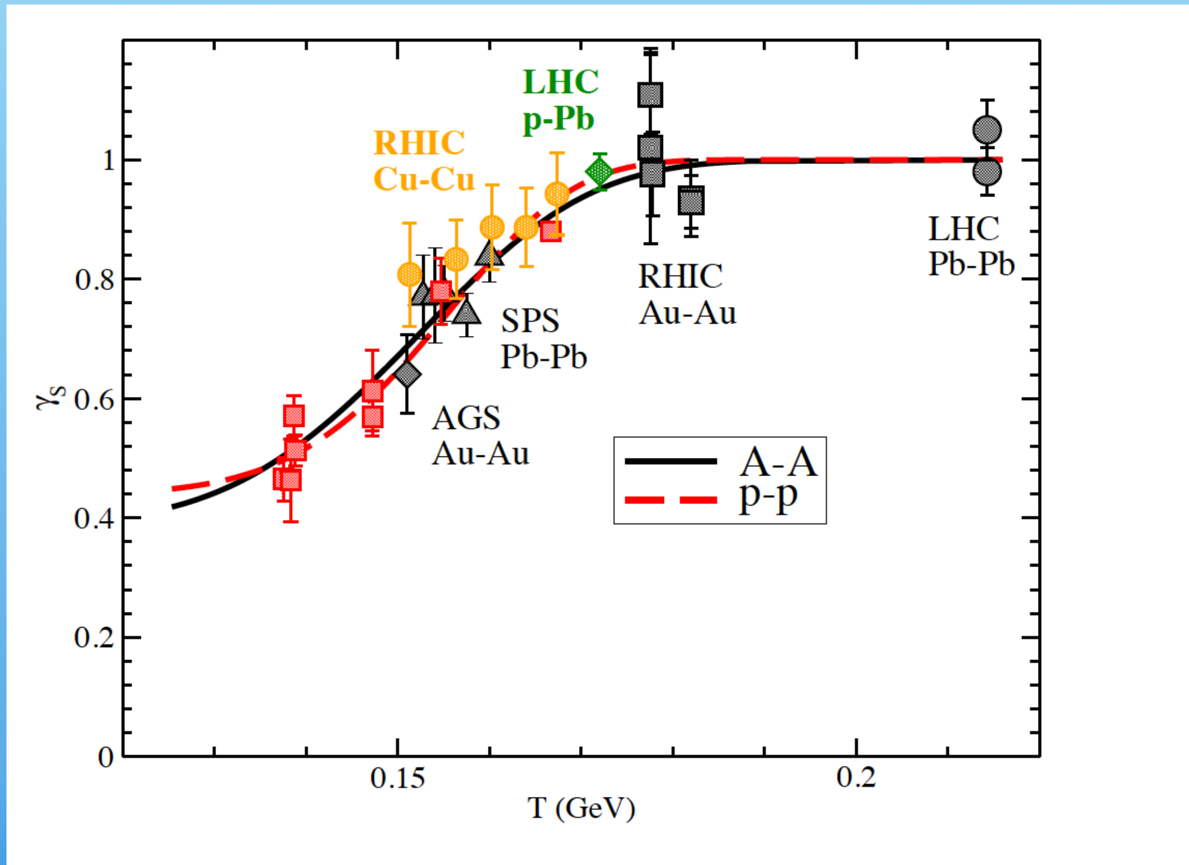
K. Aamodt et al. (ALICE Coll.), Phys. Rev. Lett. 105 (2010) 252301.



They calculate the initial entropy density using a parametrization of data from above figure and the Bjorken formula

Strangeness suppression is happening only below Tc

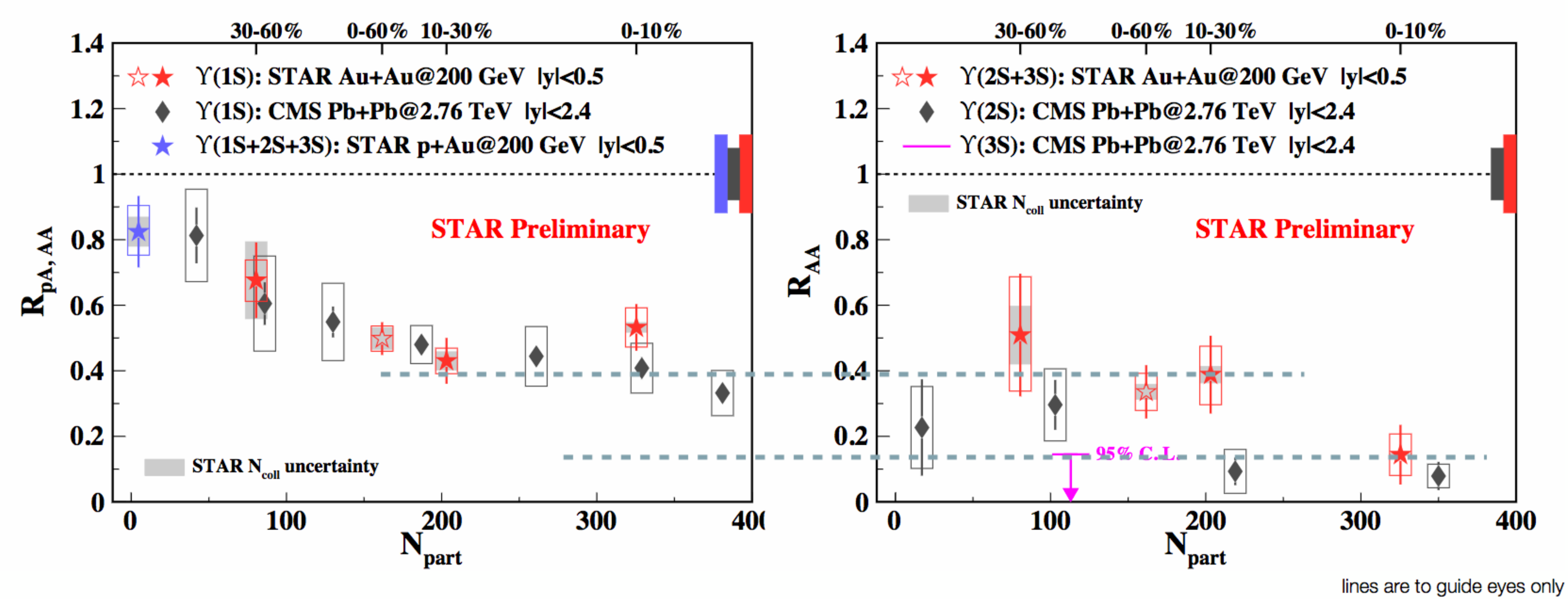
P. Castorina, S Plumari, H Satz, 1709.02706



Gamma_s becomes 1 near T_c

5. Quarkonia suppression

ϒ Suppression in Au+Au Collisions



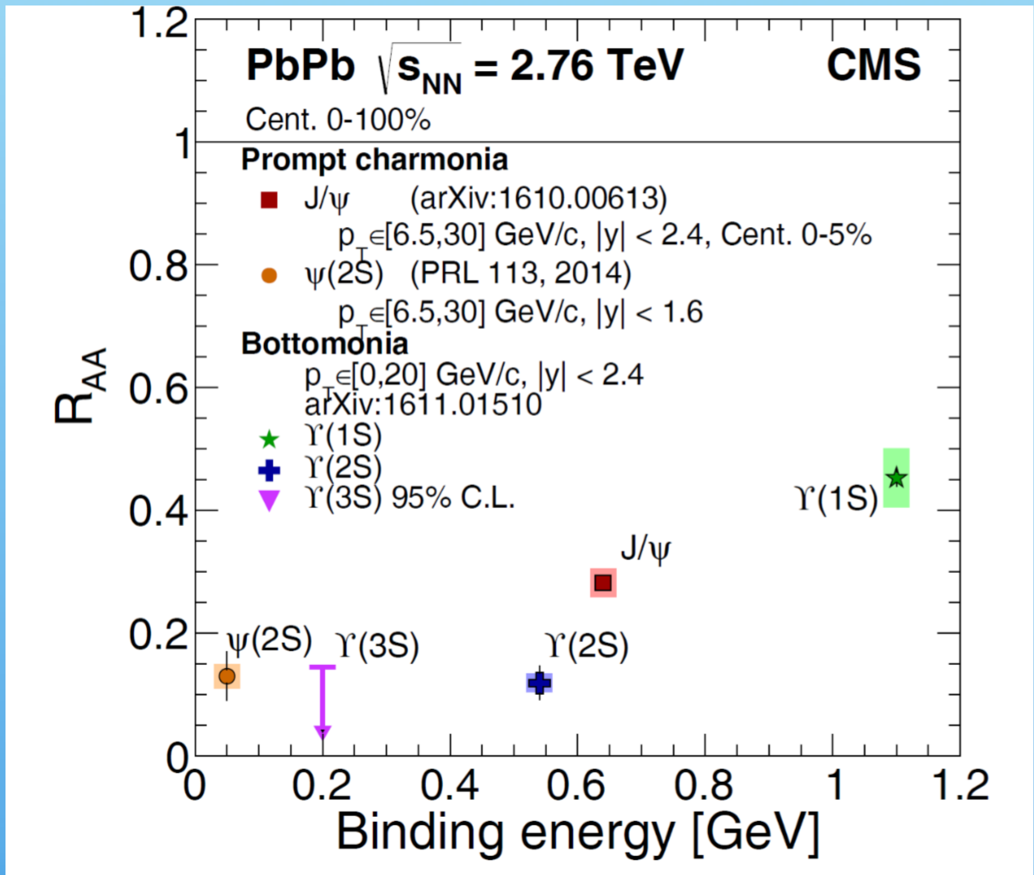
Sequential melting observed at both RHIC and LHC energies

CMS, PLB 770 (2017) 357

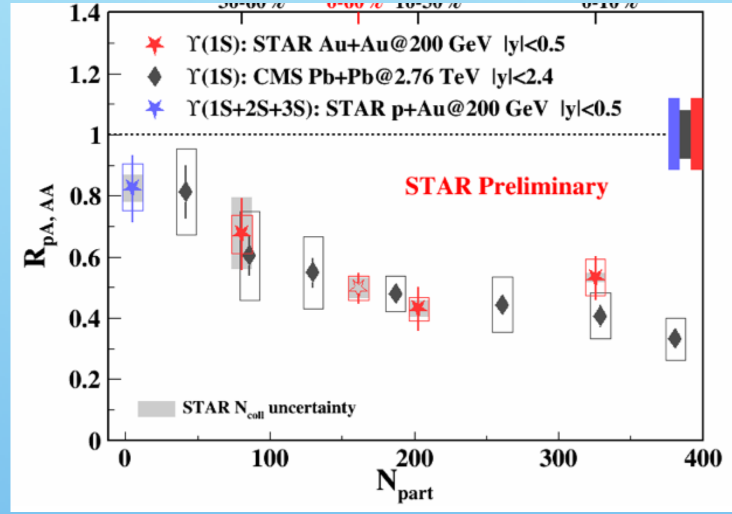
Li Yi (STAR coll.) Santa Fe 2018

Hierarchy of quarkonia suppression has been observed at RHIC and LHC

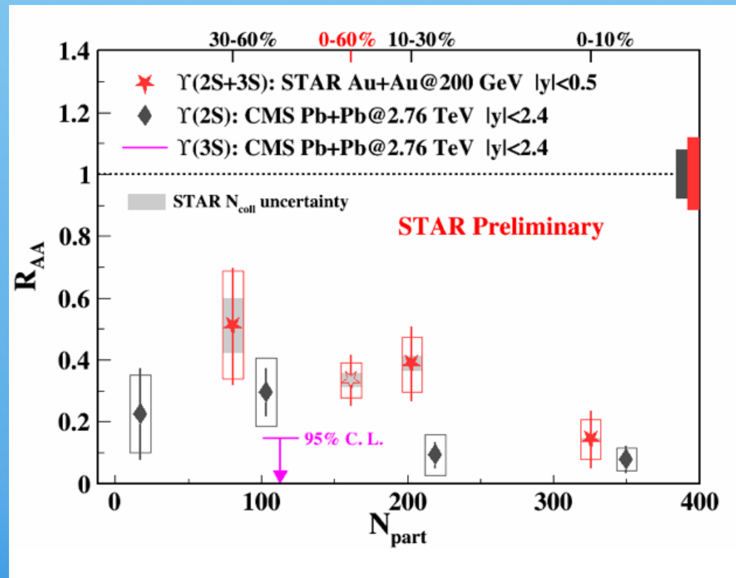
STAR, Z. Ye, QM2017



Y(1S)



Y(2S+3S)

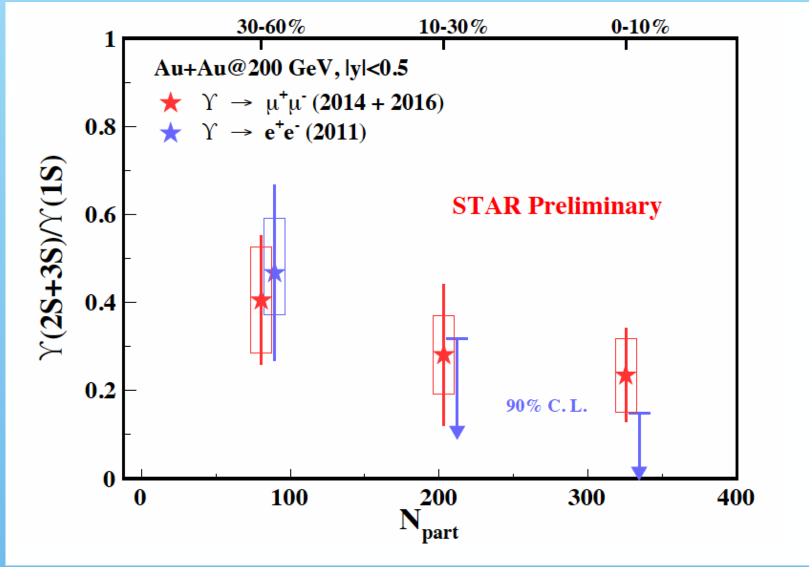


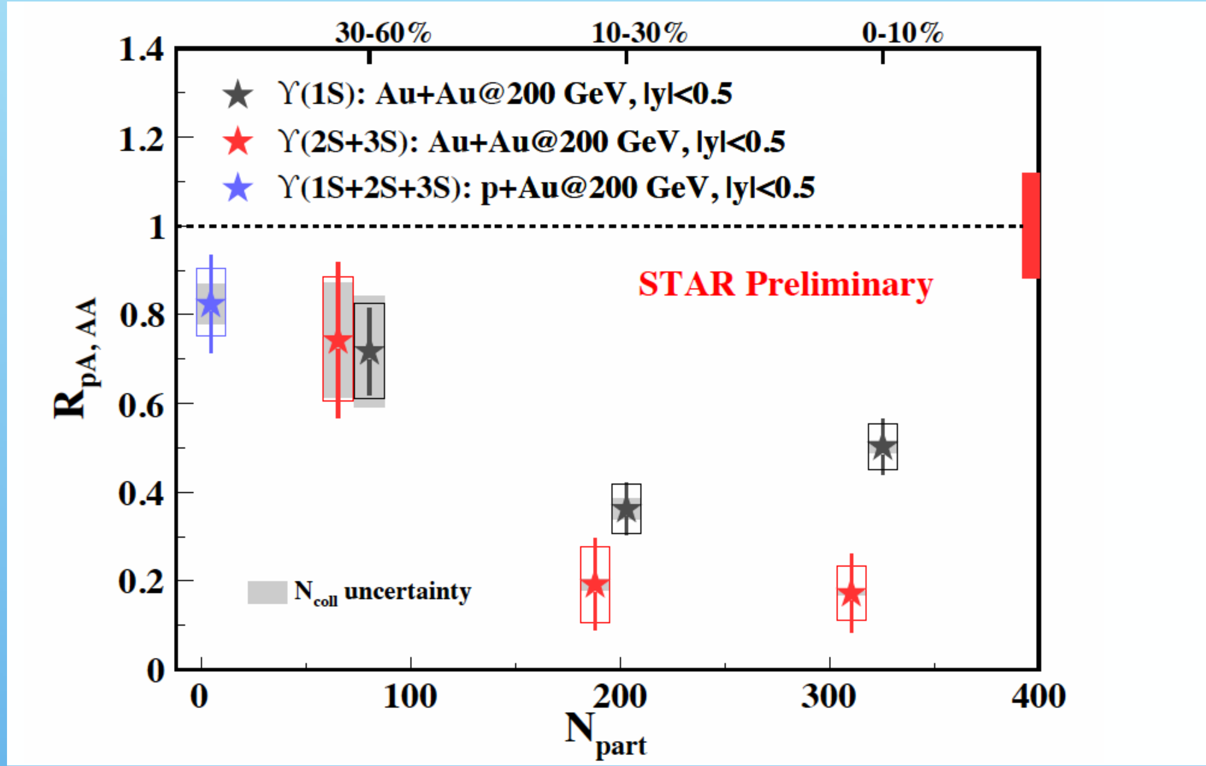
In central collisions Y(2S+3S) more suppressed than Y(1S)

Upsilon

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

Υ->e+e- vs Υ->mu+mu-





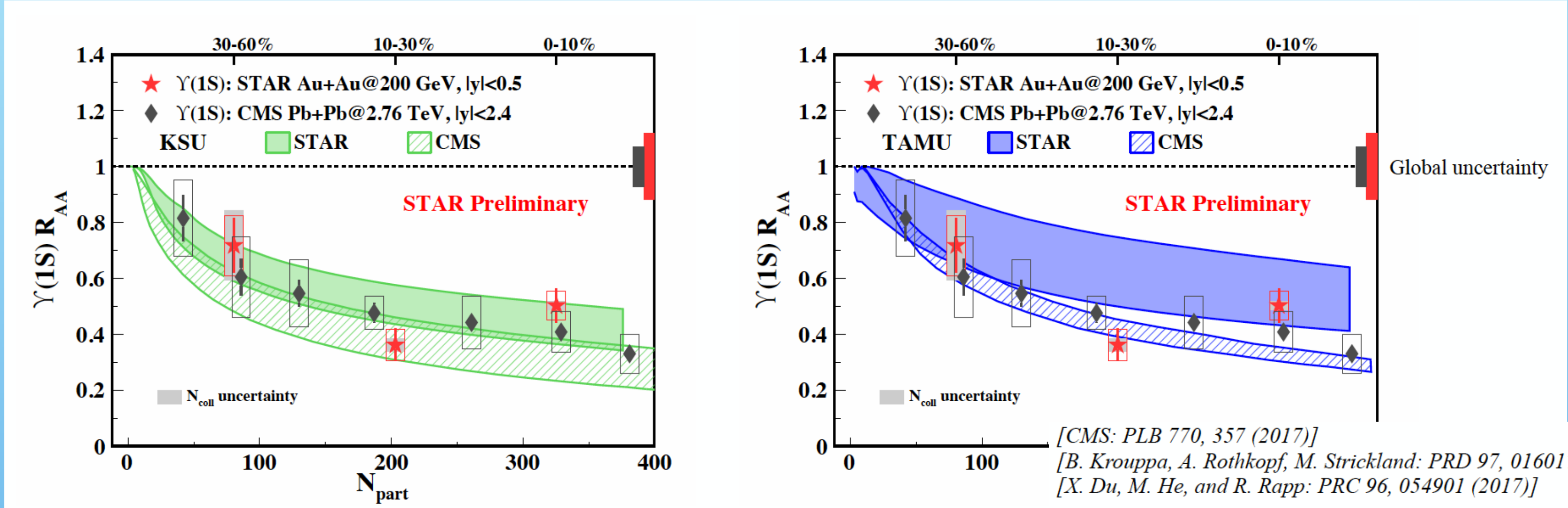
Υ-> $\mu^+\mu^-$ with the Muon Telescope Detector (MTD):
Less Bremstrahlung allows to separate the Υ(1S) from Υ(2S+3S)

Υ(2S+3S) more suppressed than Υ(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 Υ(1S): STAR vs LHC vs models



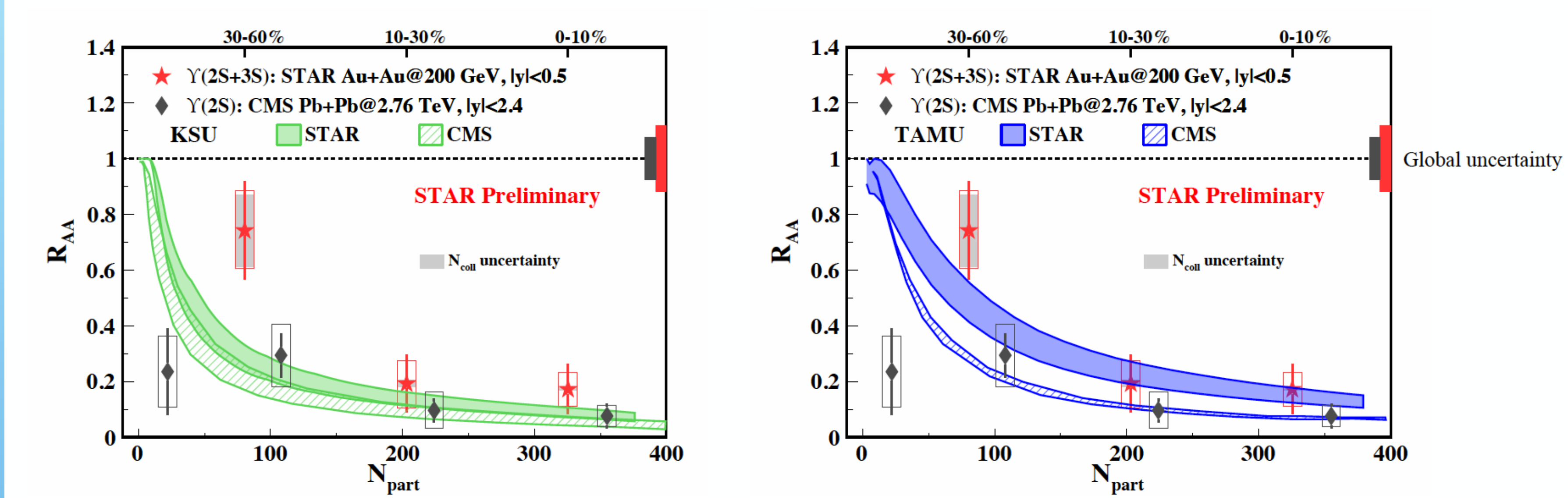
[CMS: PLB 770, 357 (2017)]
[B. Krouppa, A. Rothkopf, M. Strickland: PRD 97, 016017 (2018)]
[X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)]

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

Upsilon Υ(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%)

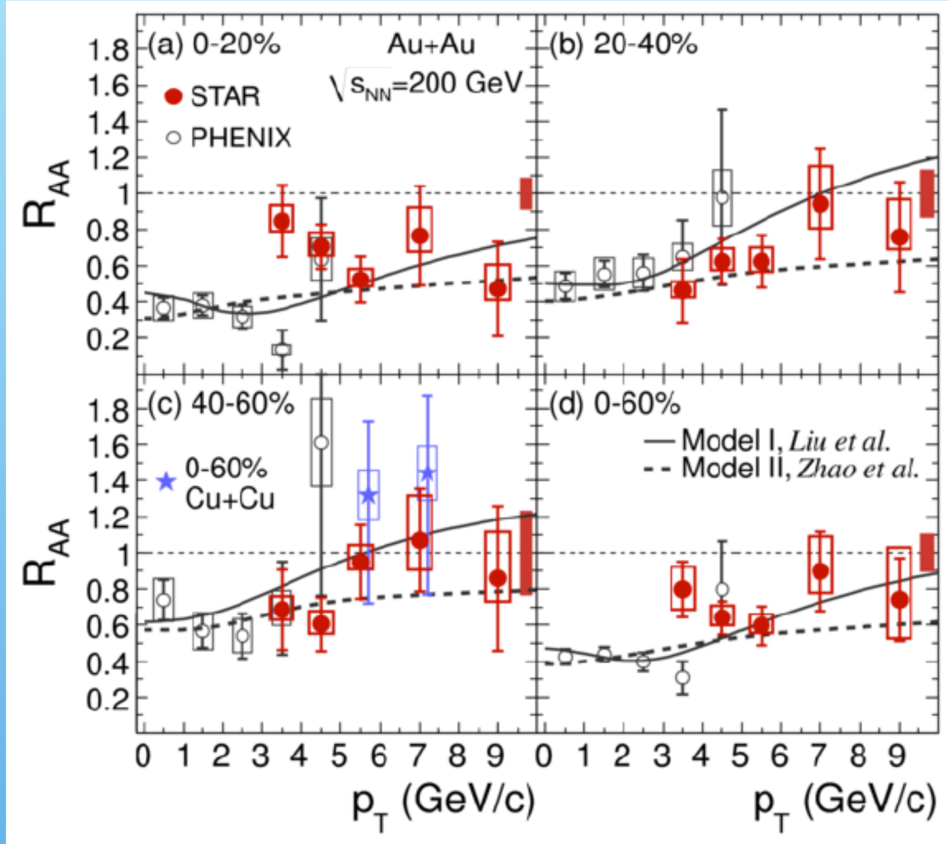
[CMS: PLB 770, 357 (2017)]
[B. Krouppa, A. Rothkopf, M. Strickland: PRD 97, 016017 (2018)]
[X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)]

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

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

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 suppressed at all p_T's for most central events

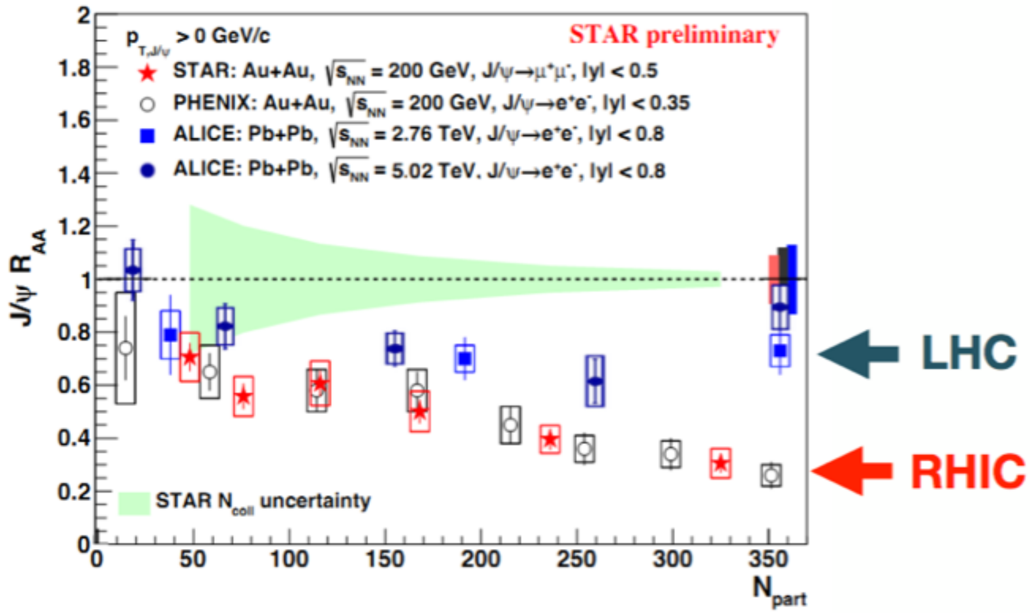
- R_{AA} of J/Psi is systematically larger for higher p_T. Low pT J/Psi is more suppressed

J/ψ Suppression in Au+Au Collisions

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

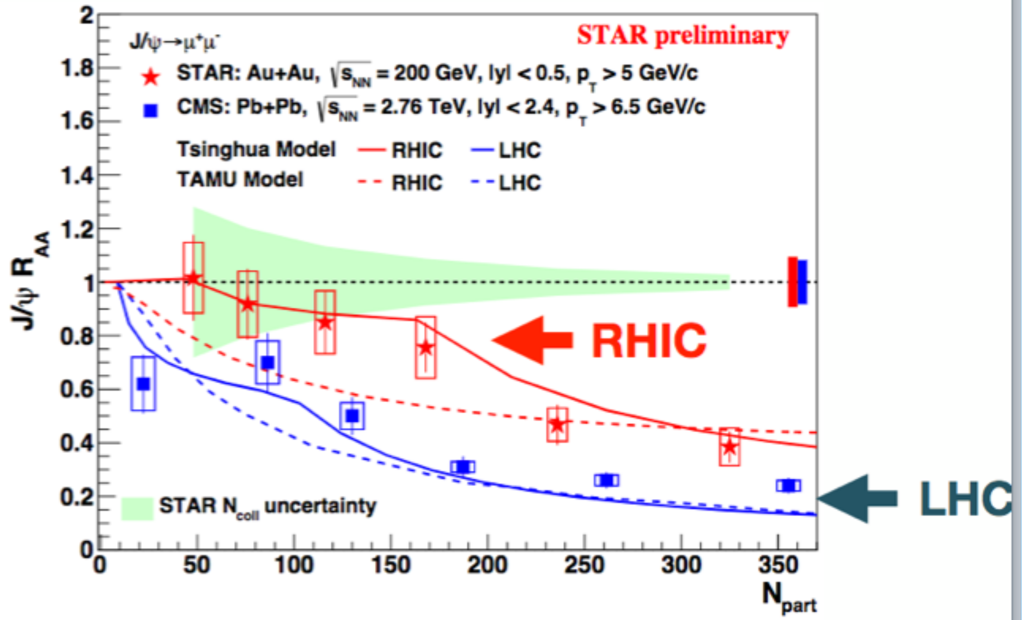
CMS: EPJC77(2017) 252
Tsinghua at RHIC: PLB **678** (2009) 72
Tsinghua at LHC: PRC **89** (2014) 054911
TAMU at RHIC: PRC **82** (2010) 064905
TAMU at LHC: NPA **859** (2011) 114

Low p_T J/ψ in central collisions:



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

High p_T J/ψ in all centralities:



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

Li Yi (STAR coll.) Santa Fe 2018

J/Psi recombination at LHC ?

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)

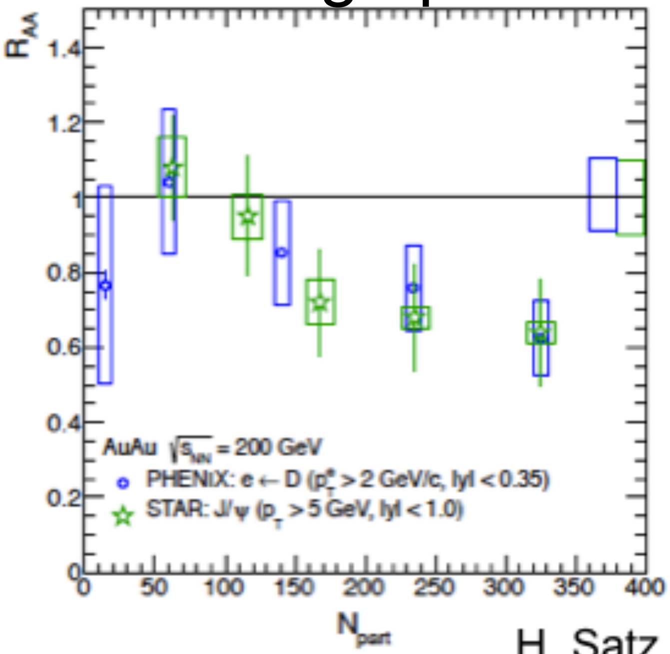
3. (J/Psi AA/pp) / (open charm AA/pp) :
RAA(J/Psi) / RAA(open charm)

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

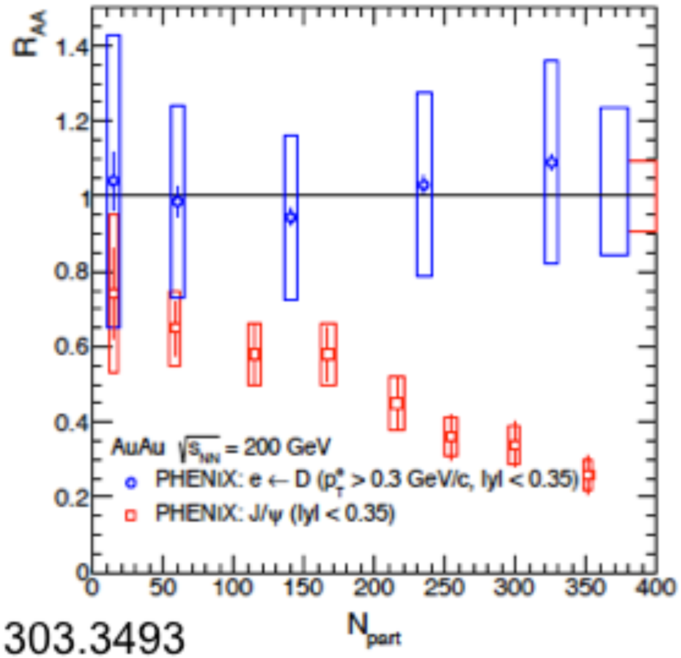
Very different conclusions can be drown depending on normalization

J/Psi compared to open charm - RHIC

High pT



Low Pt

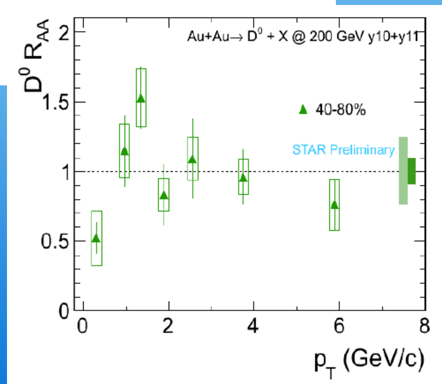


H. Satz, arXiv 1303.3493

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)

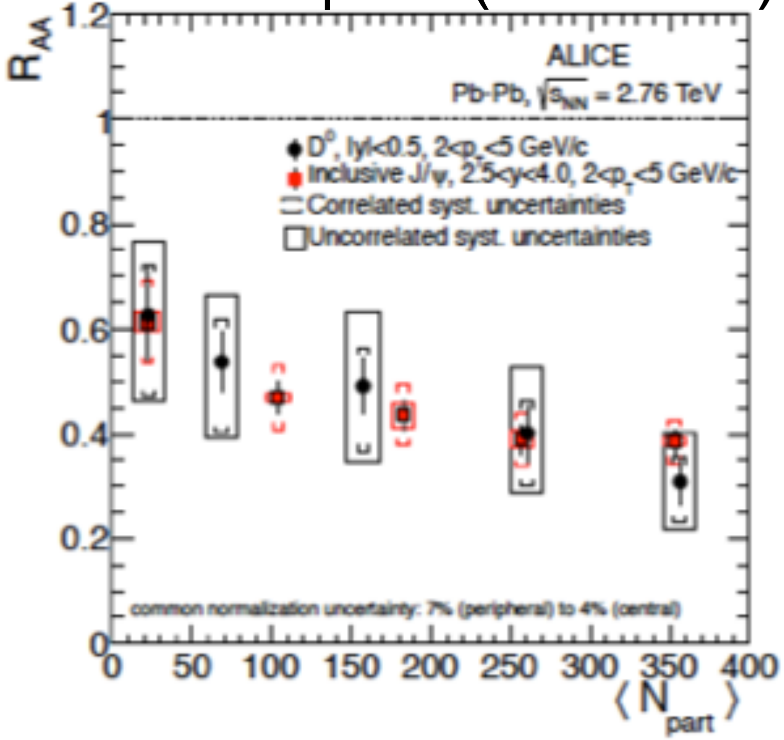
Low Pt * J/Psi seems to be **significantly suppressed** with respect to open charm at low pT in central Au+Au events (same acceptance here)

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

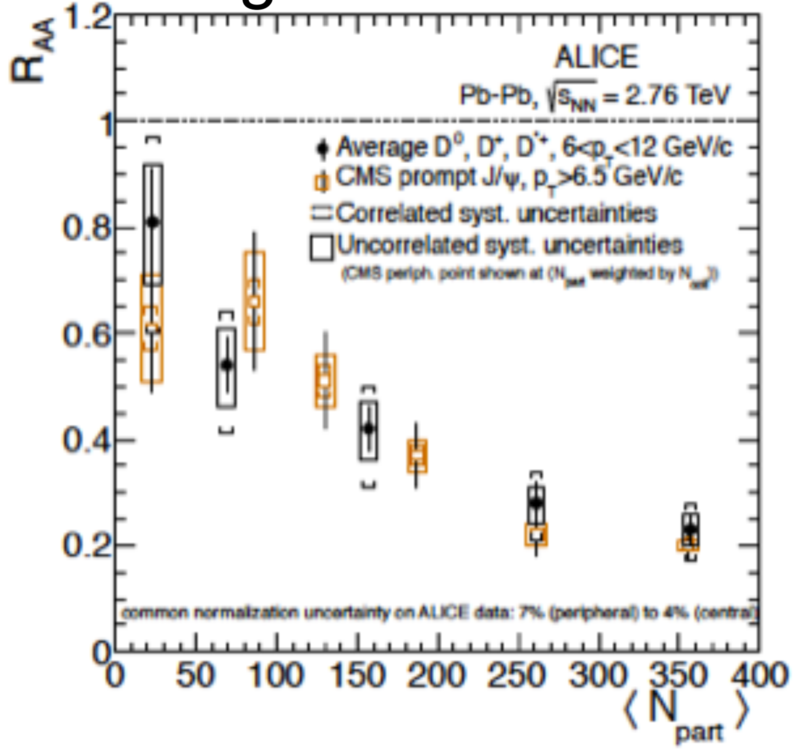


J/Psi compared to open charm - LHC

"Low|" Pt (2-5 GeV)



High Pt> 6.5 GeV

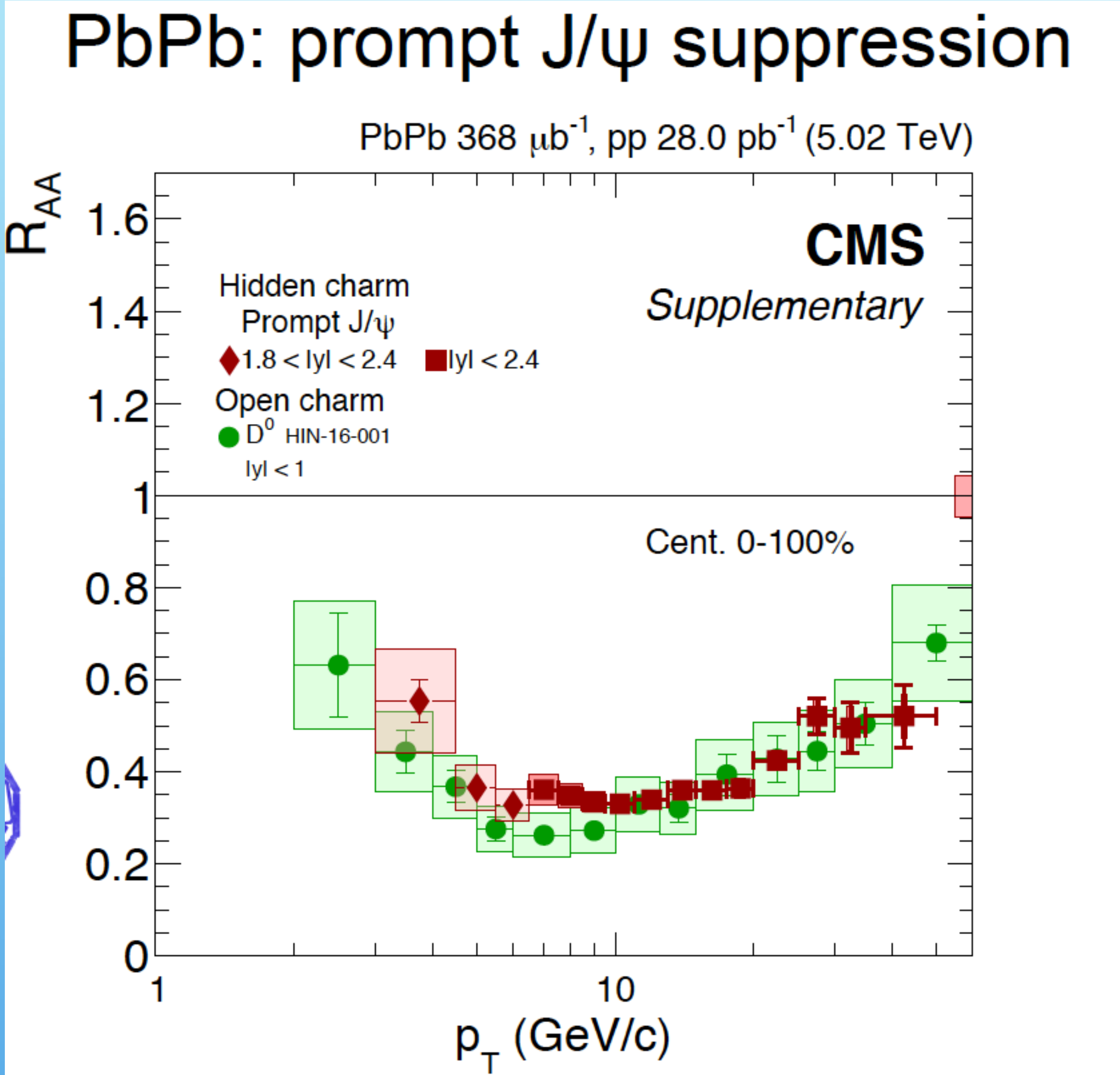


H. Satz, arXiv 1303.3493

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

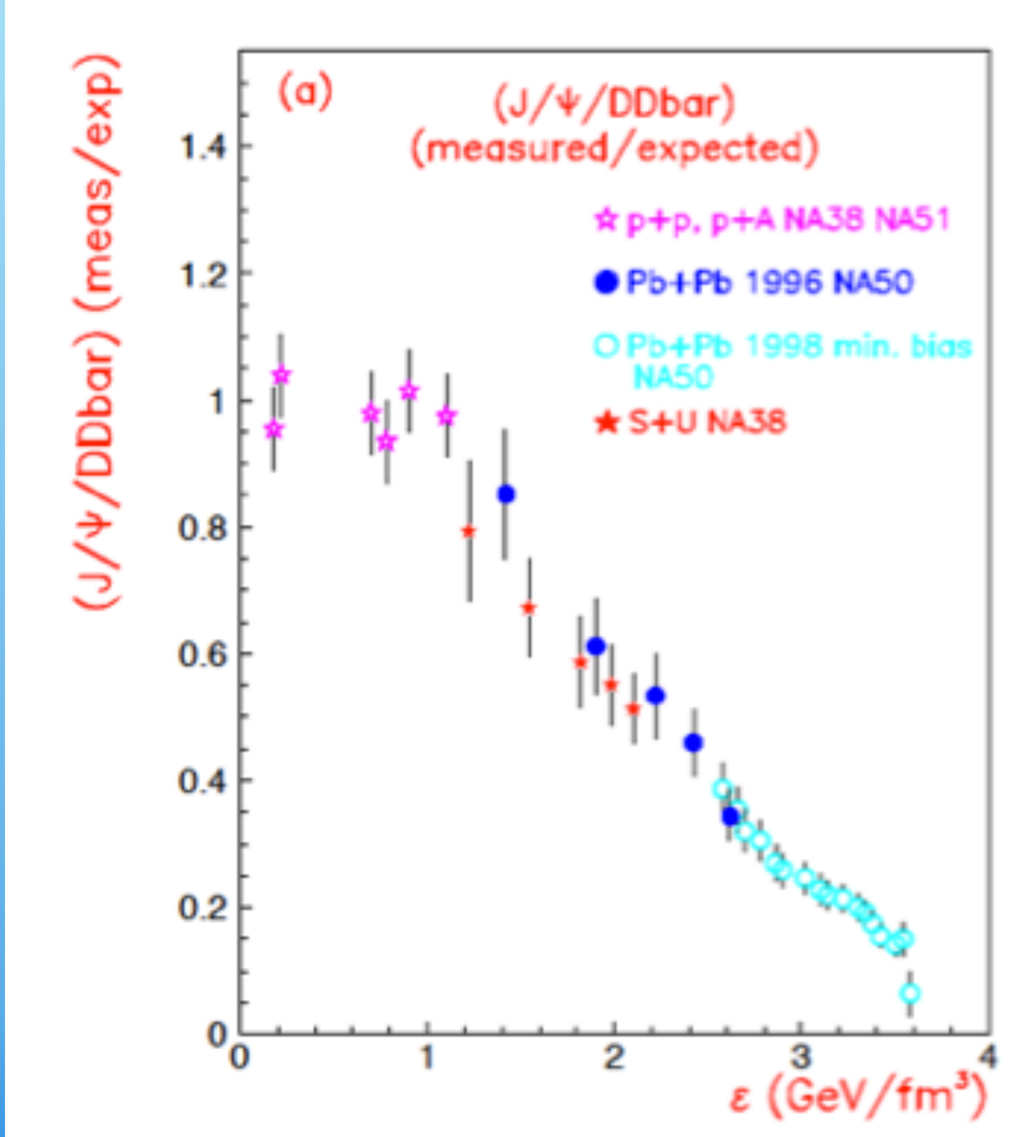
However experiments should compare more precisely within exactly same acceptance (here different y) and at low pT too

J/Psi vs D0 (CMS)



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

First study of J/Psi/D0 suppression versus ε(init,Bjorken): Measured ratio of J/Psi to D mesons at SPS



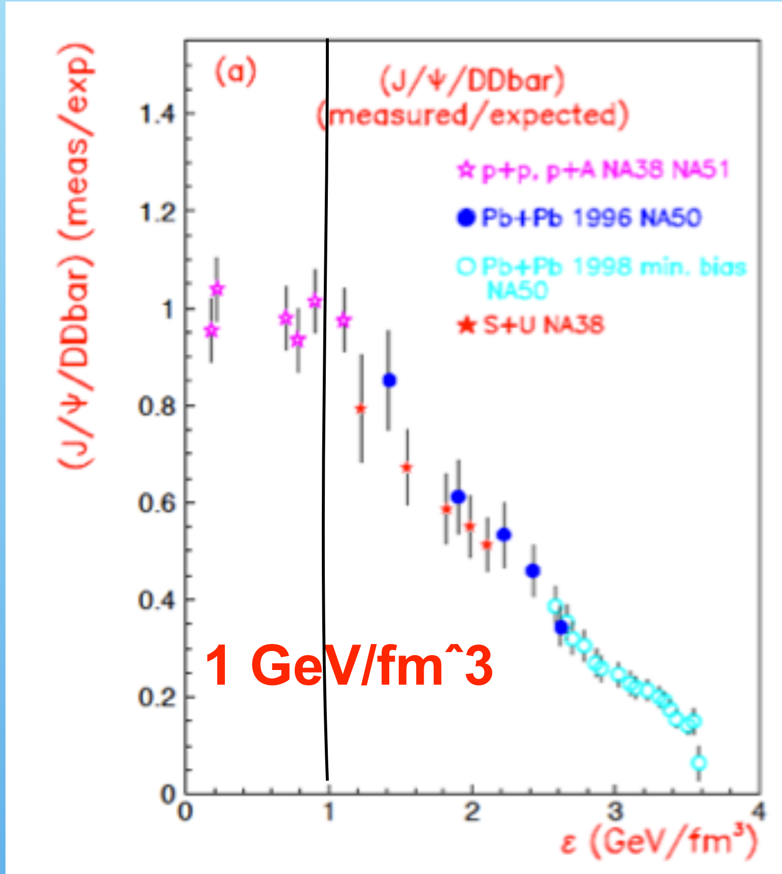
Open charm measured by dimuons in region 1.6-2.5 GeV

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

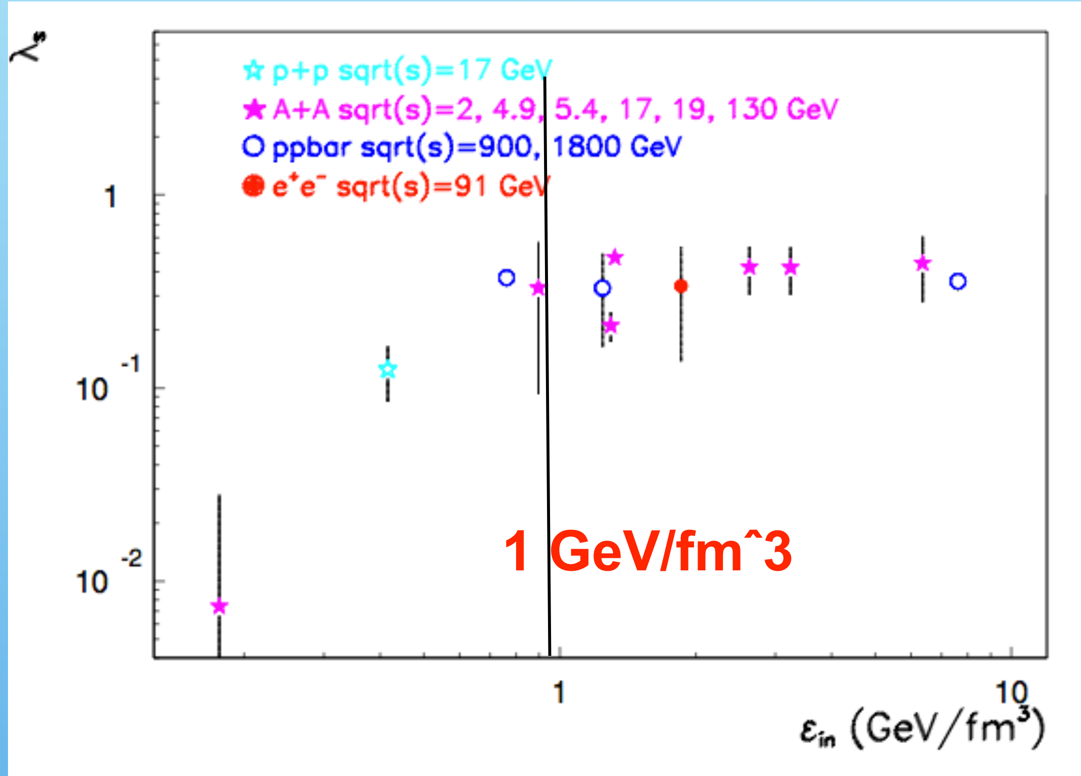
Need open charm measurements at low energy to understand quarkonia onset of suppression

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

First comparison of J/Psi/D suppression and ssbar enhancement versus ε(init,Bjorken):



S.K. New J. of Phys. vol. 3 (2001)

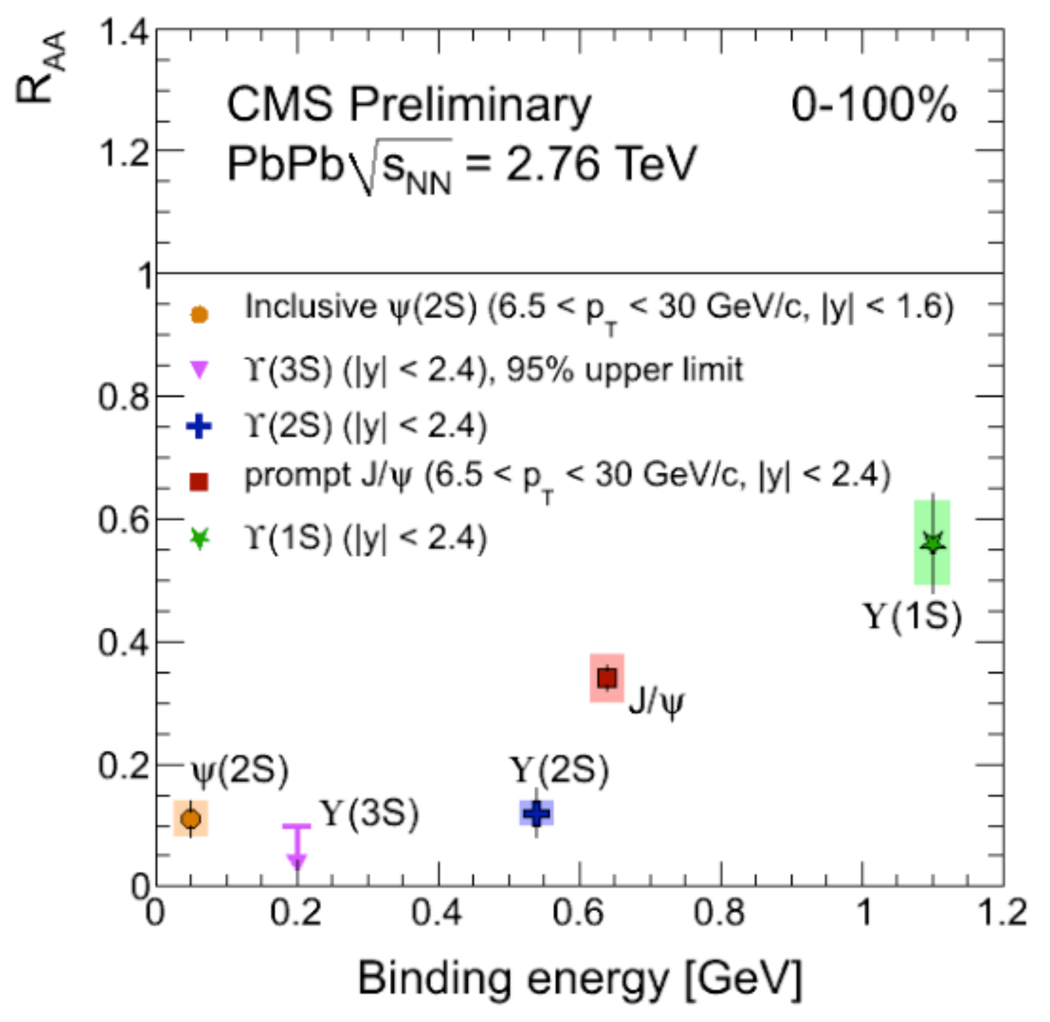


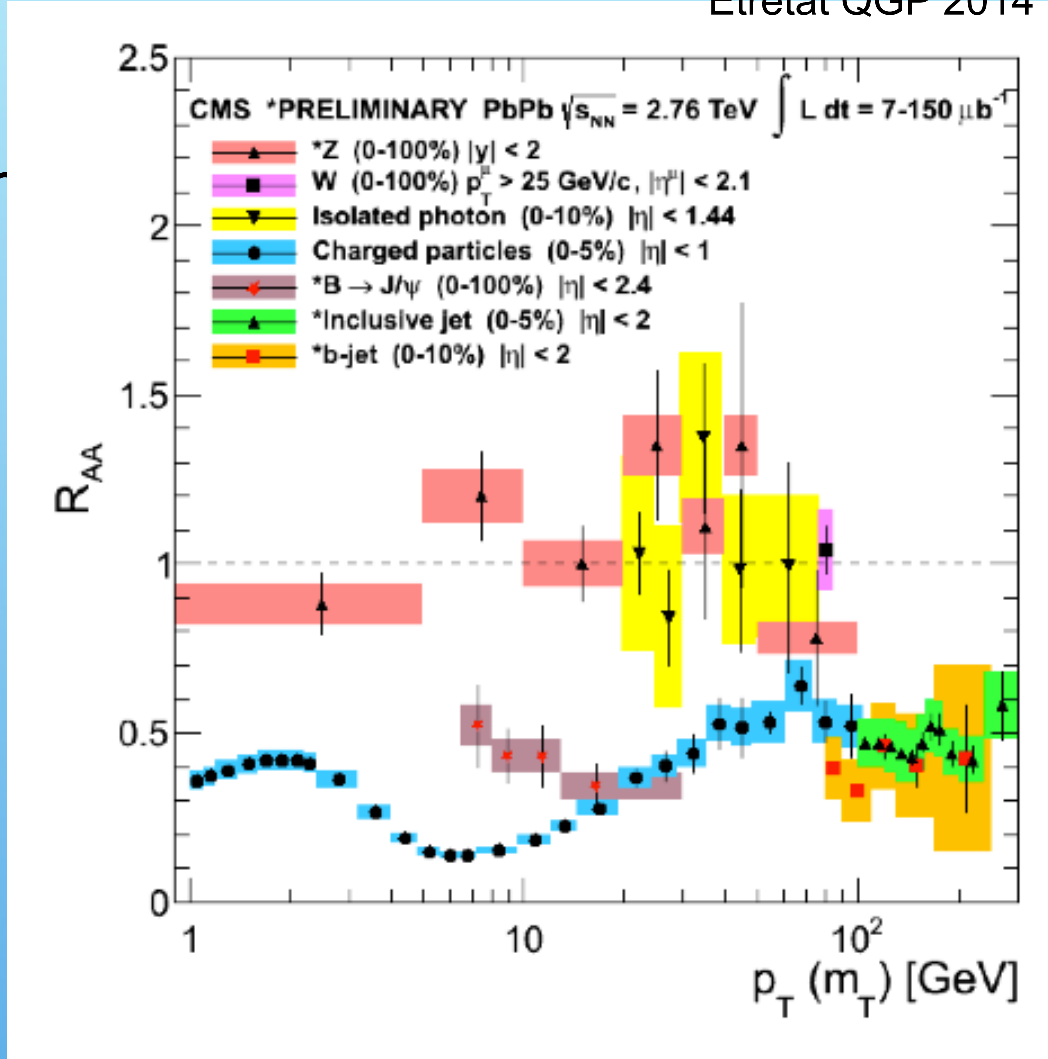
S.K. P. Minkowski, New J. of Phys (2001) 3 4

When J/Psi suppression is quantified by J/Psi/(open charm) onset of J/Psi suppression is 1 GeV/fm^3, and coincides with the onset of strangeness enhancement

Beauty

M. Jo et al CMS, Etretat QGP 2014





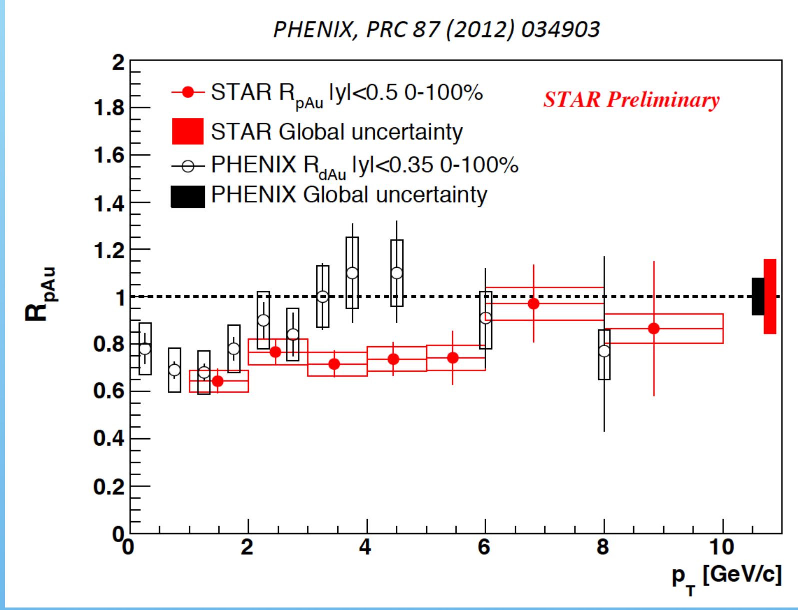
Y(1S) in PbPb seem less suppressed than open beauty in PbPb (needs better stat) if so -> no Y(1S) suppression

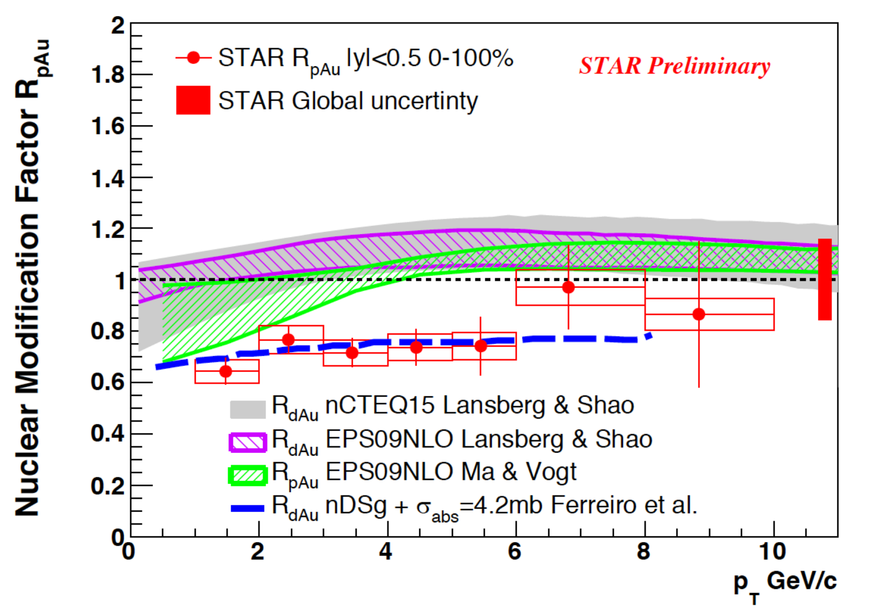
Y(2S), Y(3S) in PbPb seem more suppressed than open beauty in PbPb -> compatible with Y(2S) and Y(3S) suppression

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

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





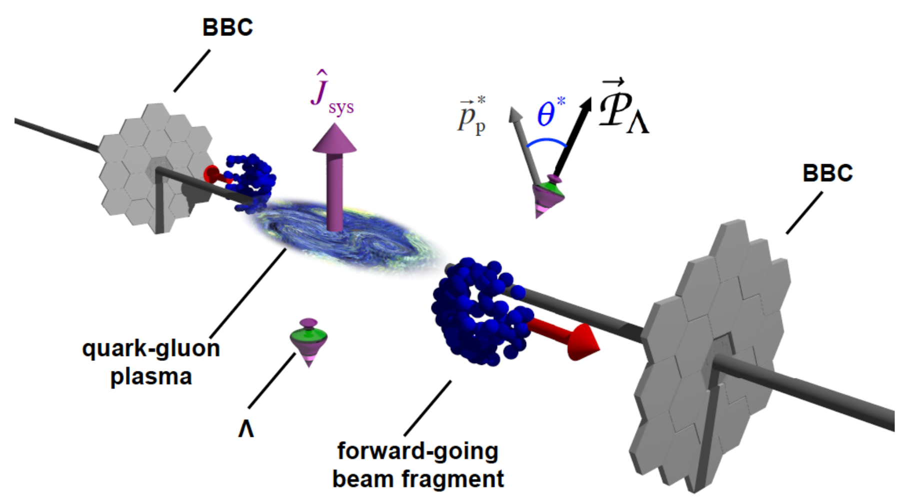
- R_{pAu} is consistent with R_{dAu} within uncertainty
  - There seems to be tension at $3< p_T <5$ GeV/c with 1.4σ significance
- Suggests similar CNM effects in these collision systems

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

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

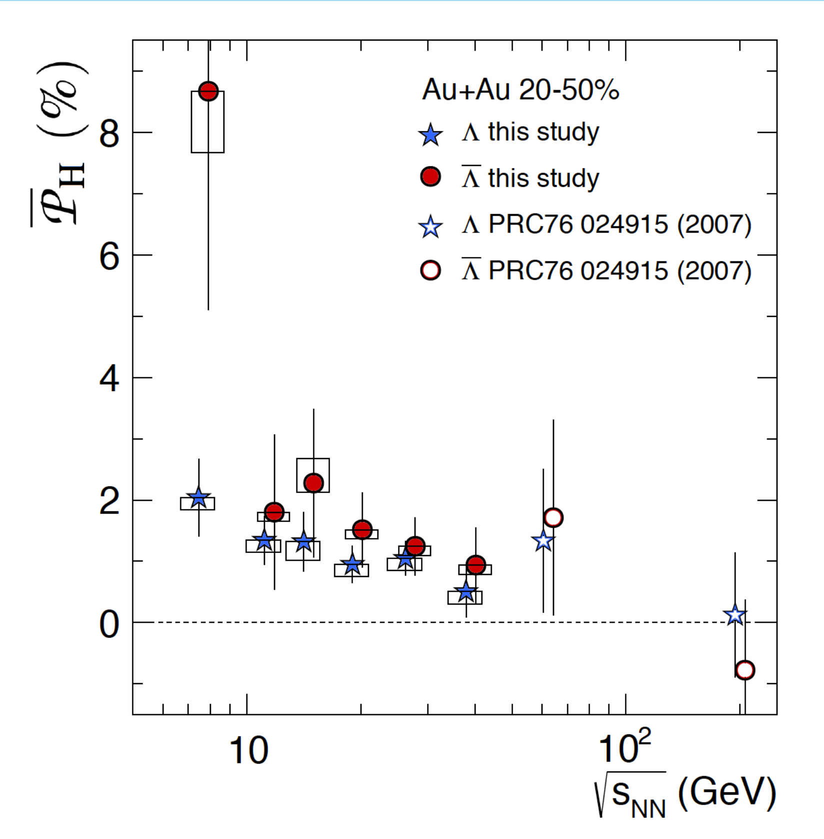
Average projection of the Polarization on J(sys) is extracted:

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

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

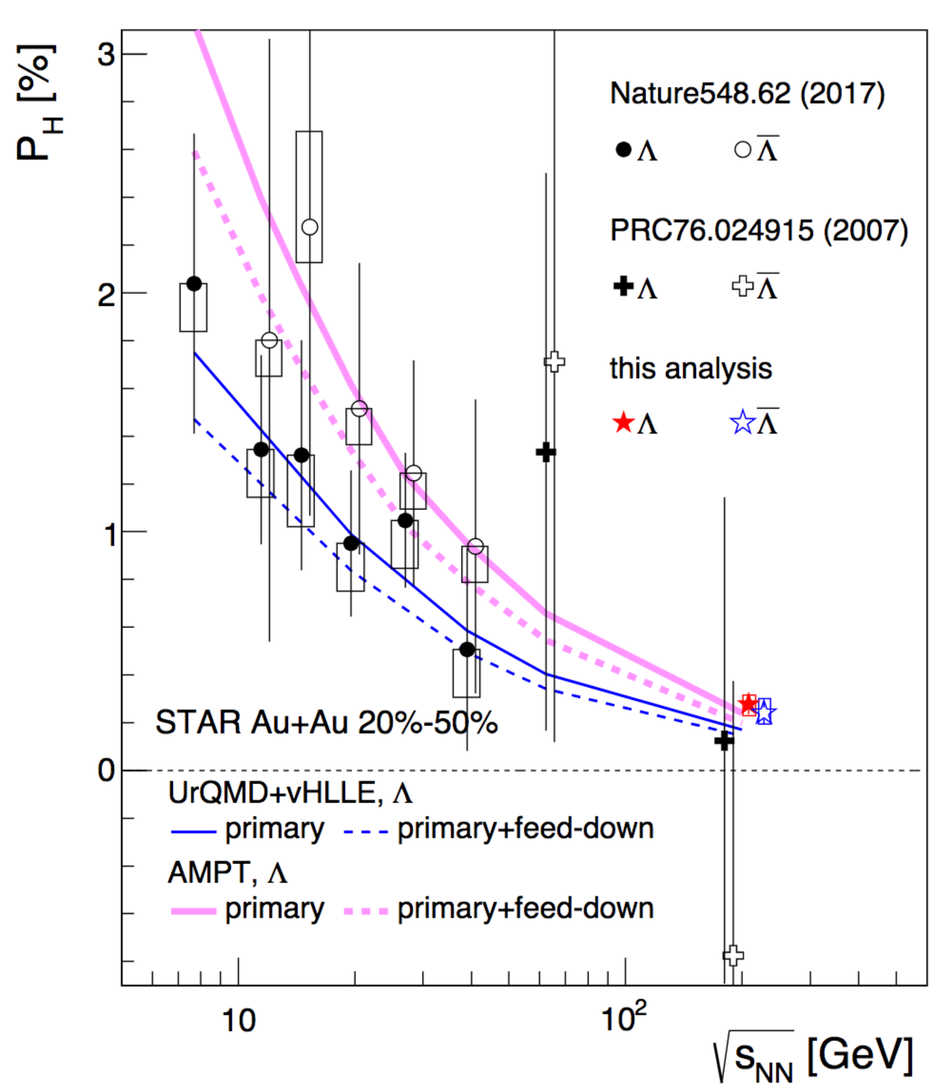
For example solar subsurface flow has omega= 10-7 s-1, and superfluid nanodroplets omega=10ˆ7 s-1

*** 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

New STAR results on global polarization of Lambda,Antilambda in Au+Au at 200 GeV

1805.04400



High precision measurement of a finite Lambda and Antilambda global polarization of the level of 0.1-0.5% (depending on centrality) in Au +Au at 200 GeV

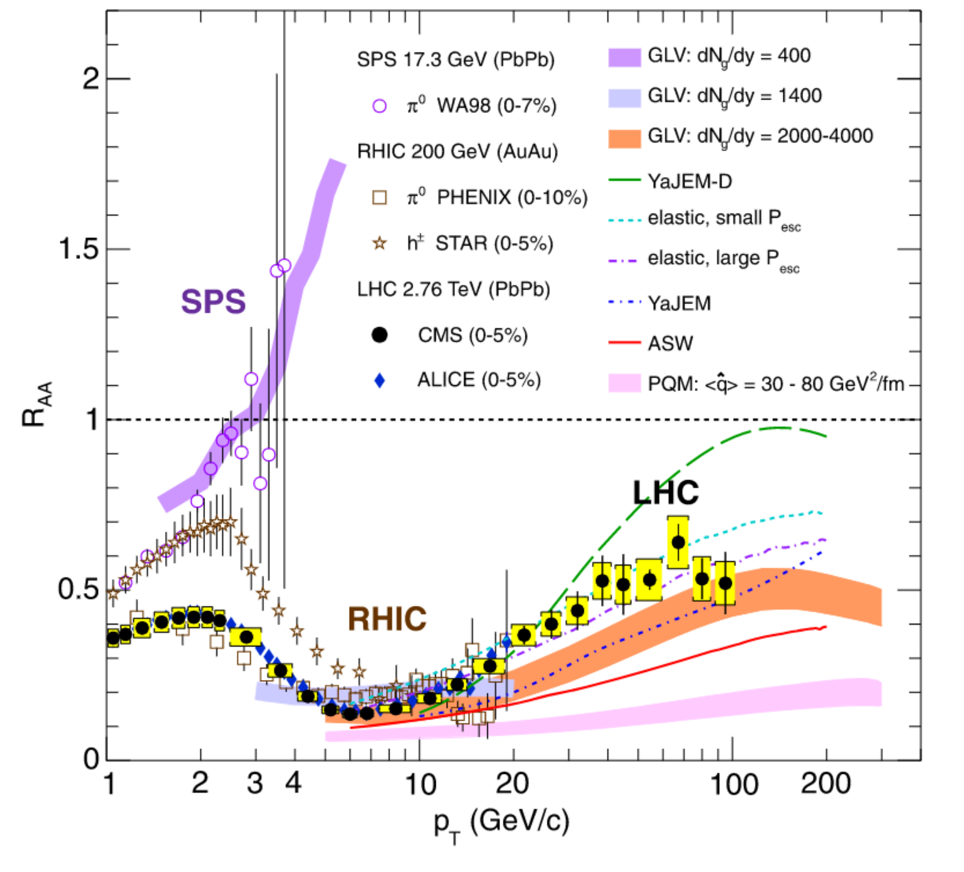
Global polarization increases with decreasing collision energy

4. Jet quenching

Single hadrons

Jet quenching hadrons
Collision energy dependence

CMS, EPJC (2012) 72:1945

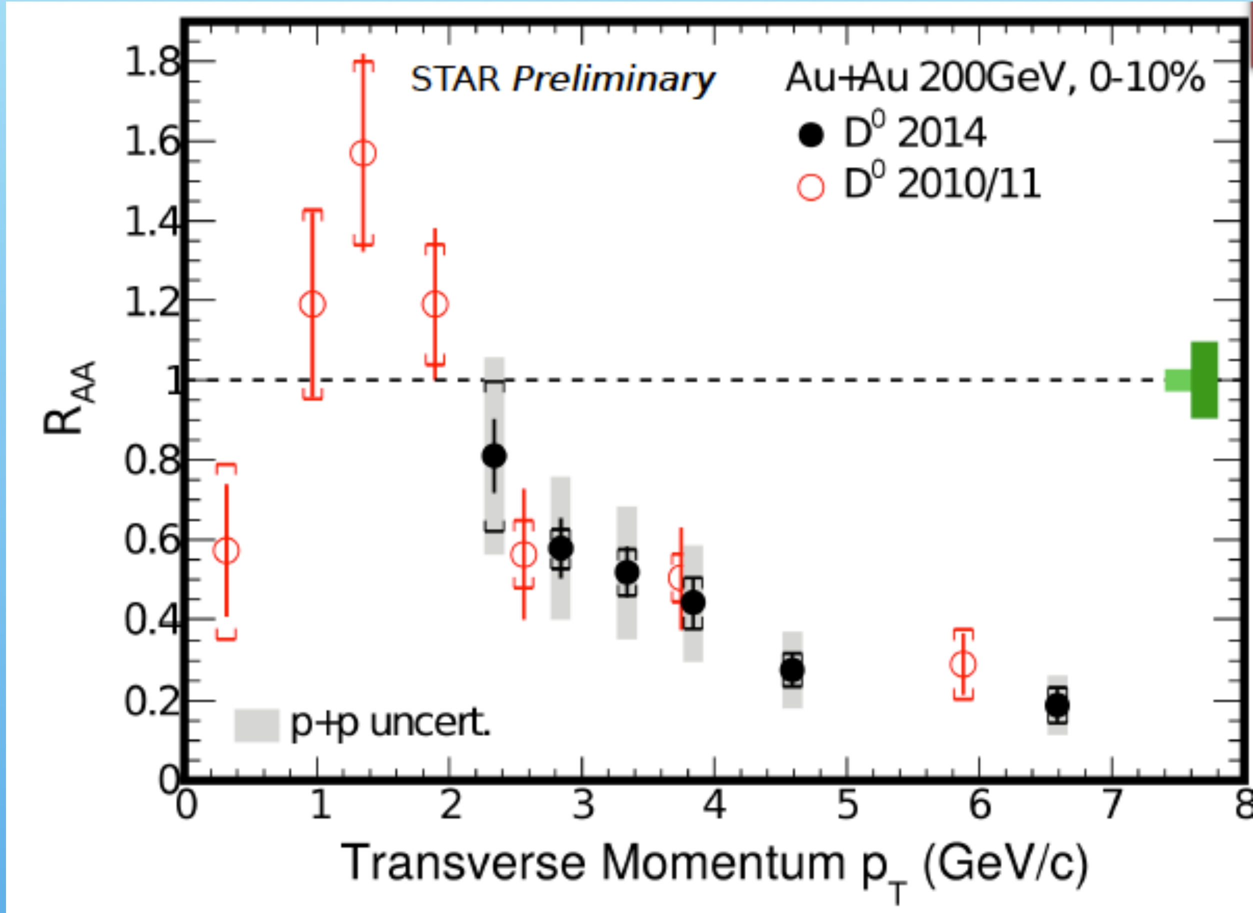


RAA compared to models for energy loss allows for an estimate of gluon density dN/dy(gluon)
Here as an example we get (GLV model):

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

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

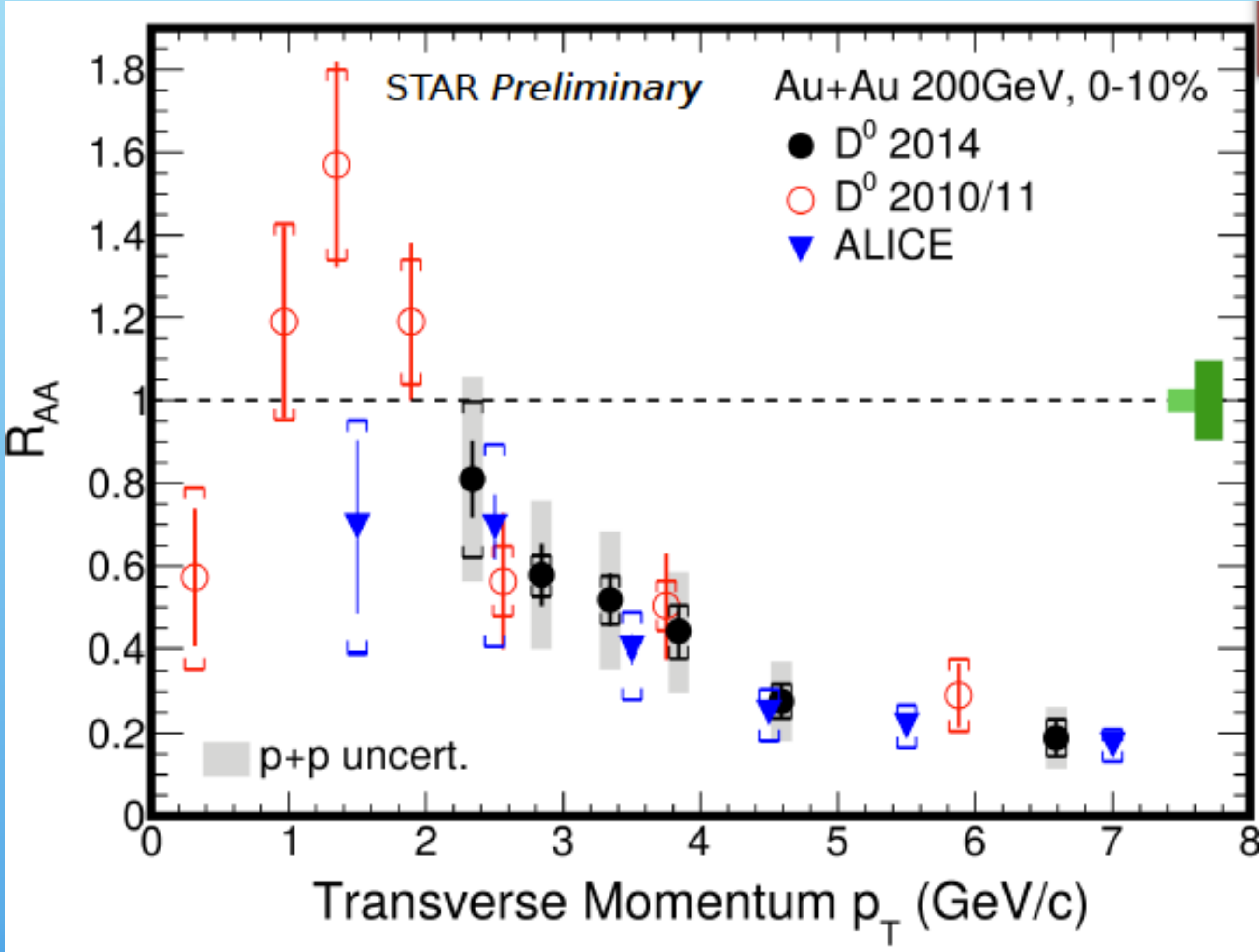


STAR, QM15

Suppression of D0 at high pT

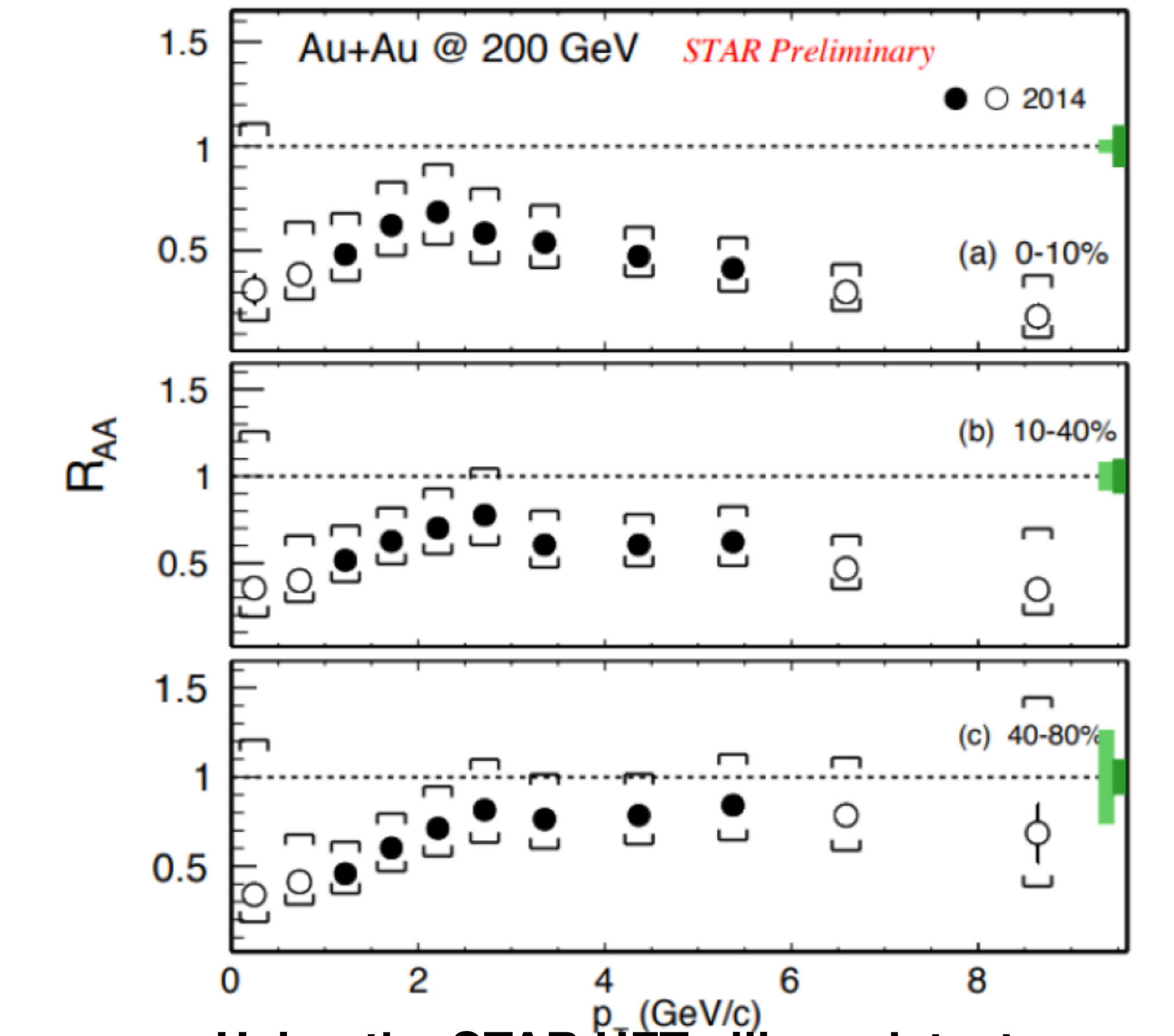
Enhancement of D0 at pT<2 GeV/c pointing to charm coalescence with a flowing medium

Comparison RHIC to LHC



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

D^0 R_{AA} suppression in Au+Au collisions at 200 GeV

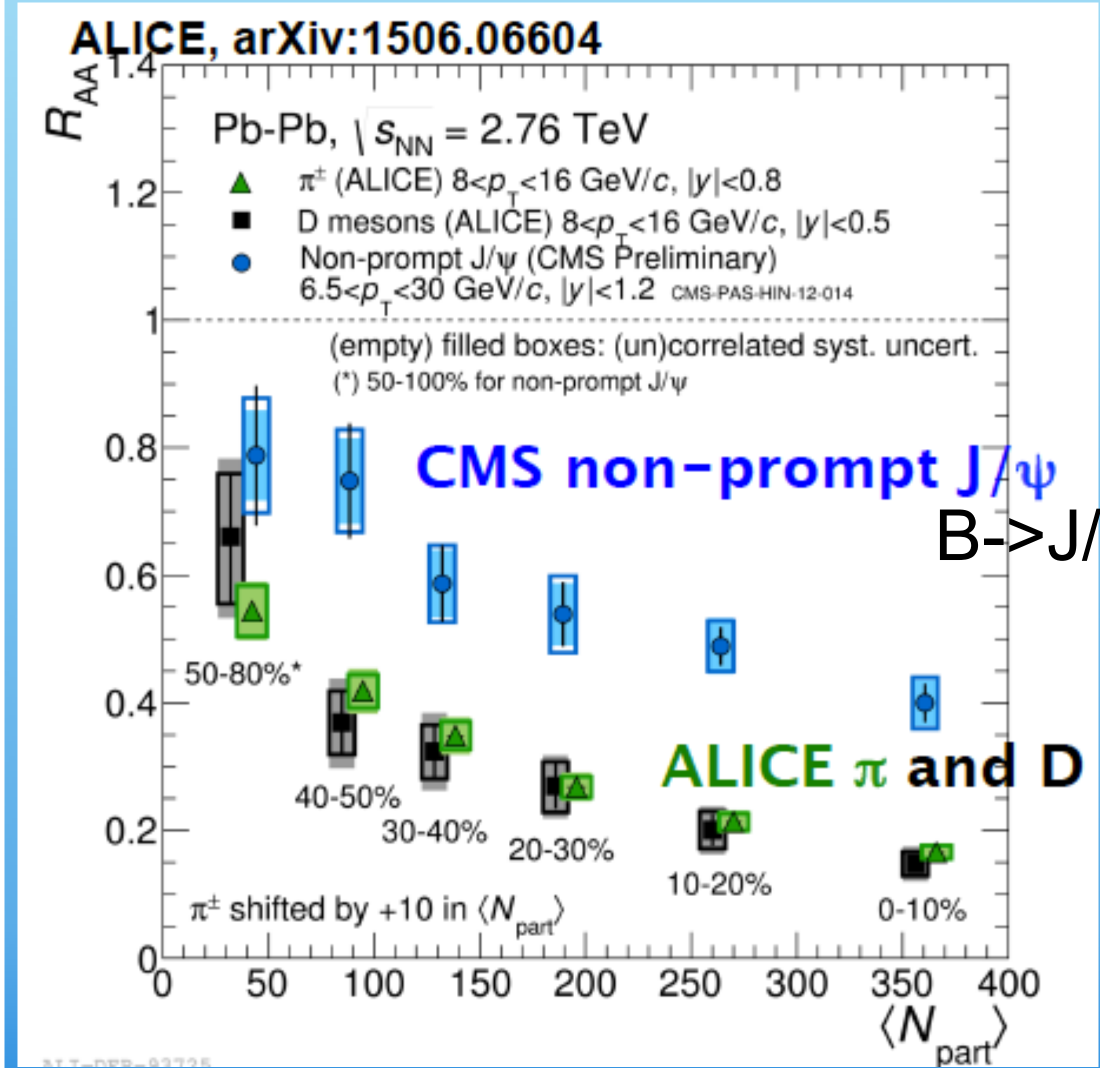


Using the STAR HFT silicon detector

D^0 at low p_T is suppressed without exhibiting significant centrality deendence

D^0 at high p_T in Au+Au collisions is more suppressed in central collisions

RAA of open charm and beauty at the LHC



B->J/Psi

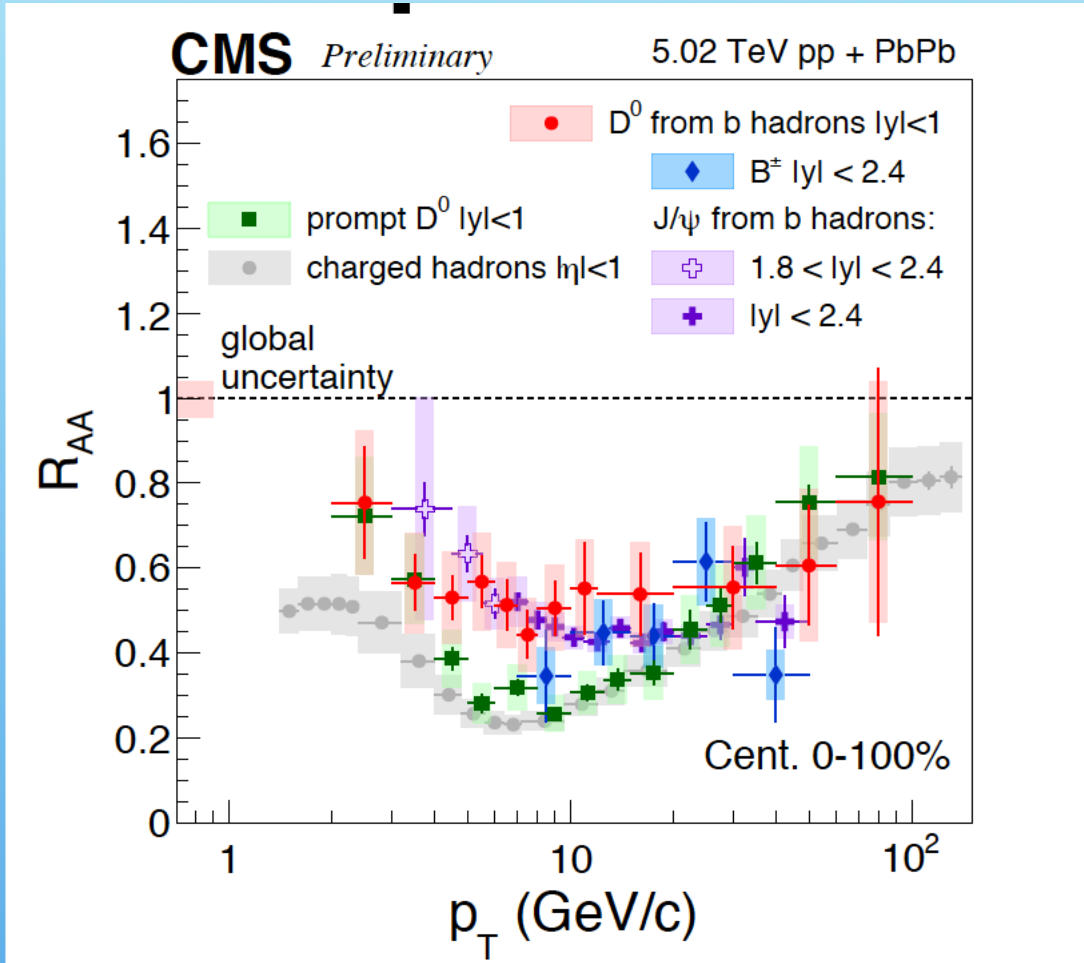
ALICE, QM2015

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)

CMS: non prompt D0 from b hadron



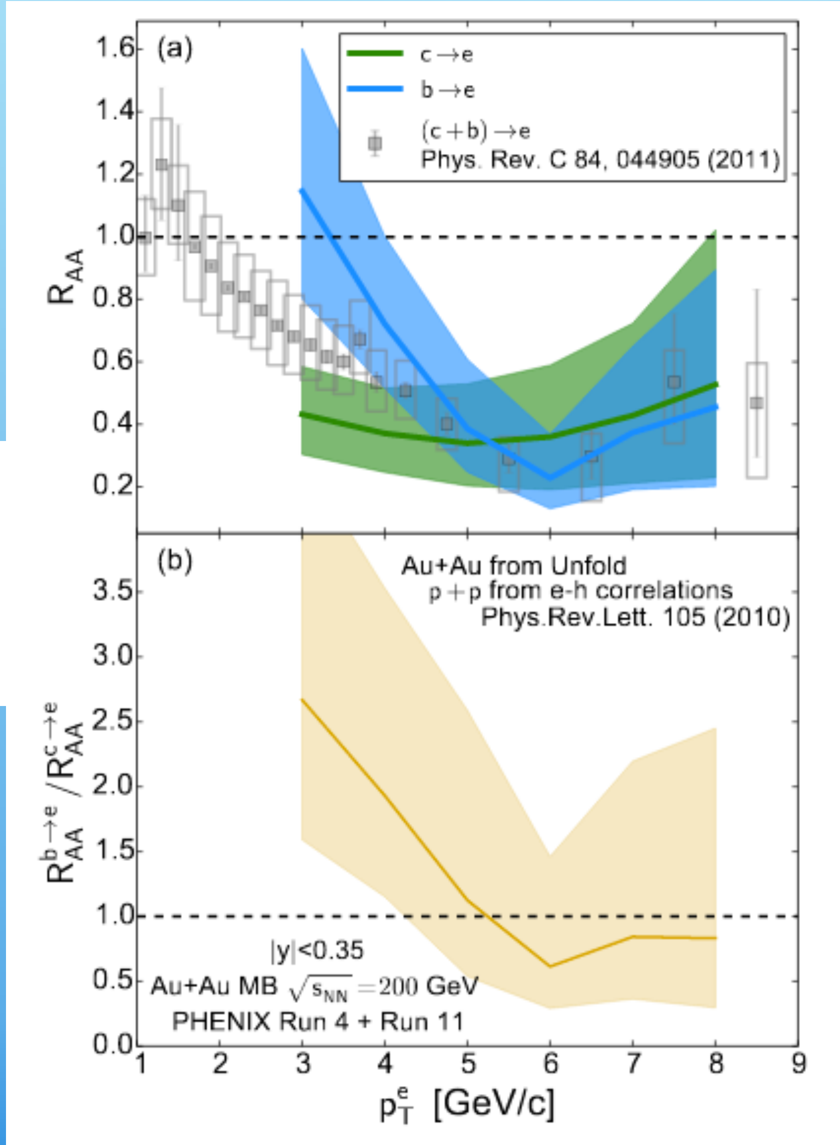
CMS Coll. QM2018

For $5<p_T<15$ GeV

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

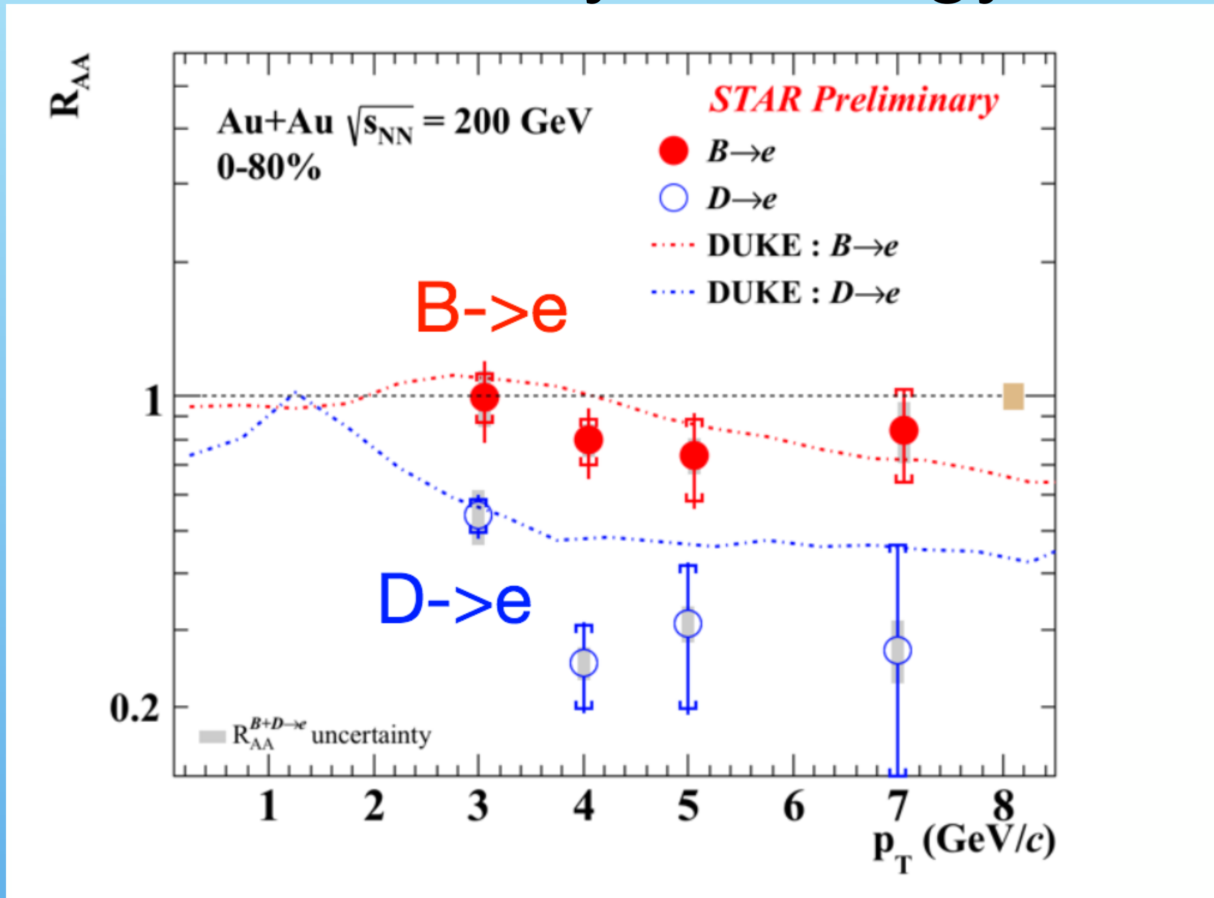
RAA of Charm and Beauty in min. bias Au+Au at 200 GeV

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

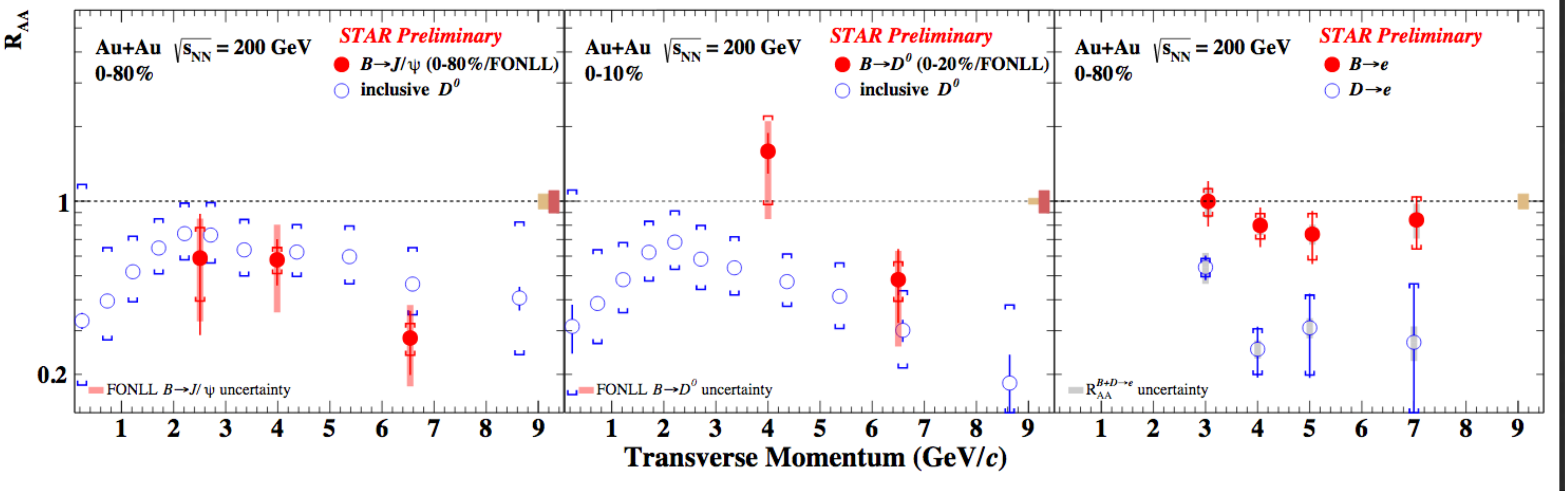


Li Yi, STAR coll.
Santa Fe work.
Jan 2018

- **Using the new STAR HFT silicon tracker with excellent resolution**
- **Electrons from B quark are less suppressed than electrons from D**

STAR B->J/Psi, B->D0, B->e in AuAu collisions 200 GeV

Xiaolong Chen, STAR Collaboration, Hard Probes 2018

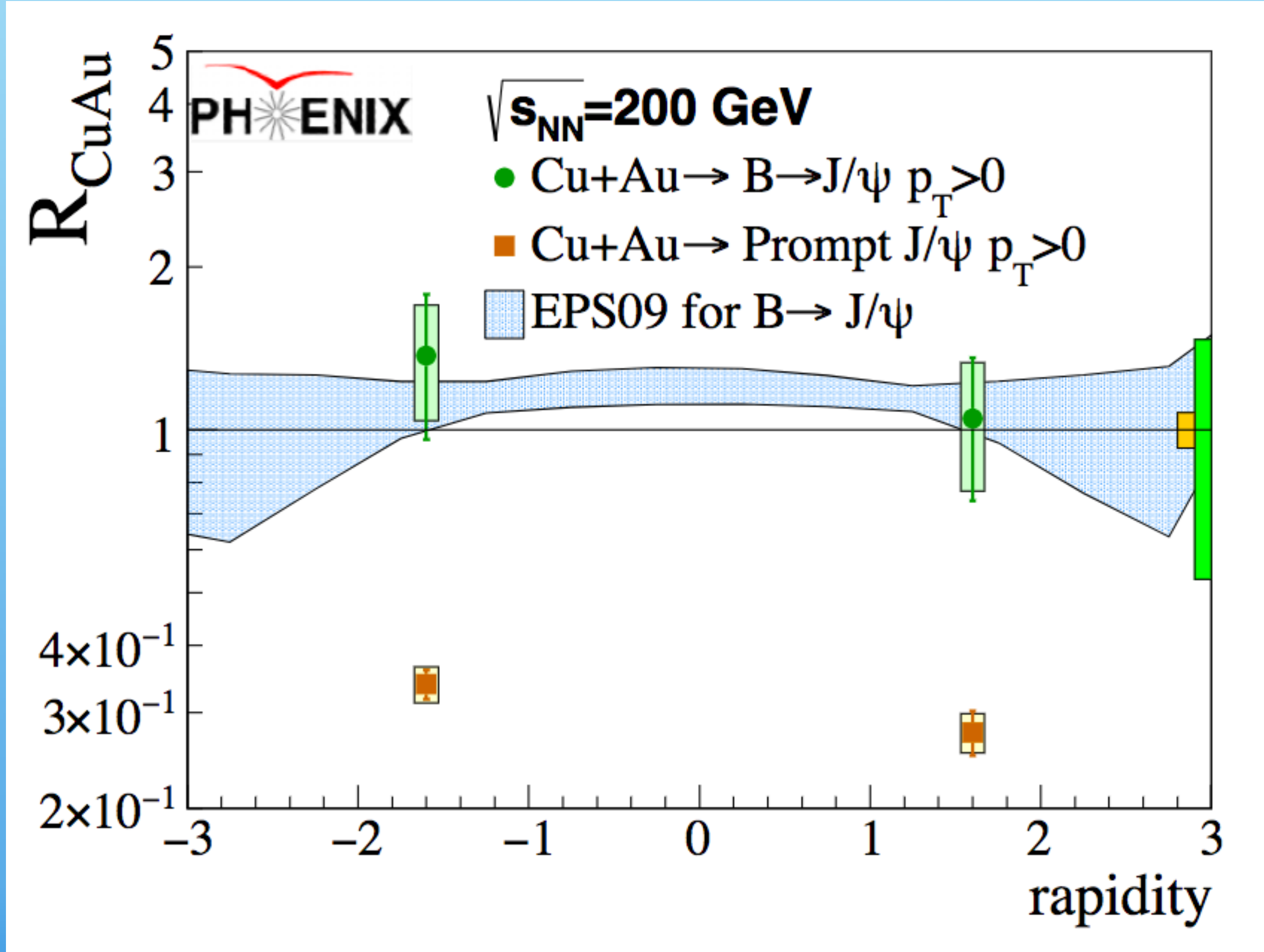


Measured open bottom hadron production via displaced J/ψ, D^0 and electron decay channels in 200 GeV Au+Au collisions

✓ Strong suppression for B → J/ψ and B → D^0 at high p_T

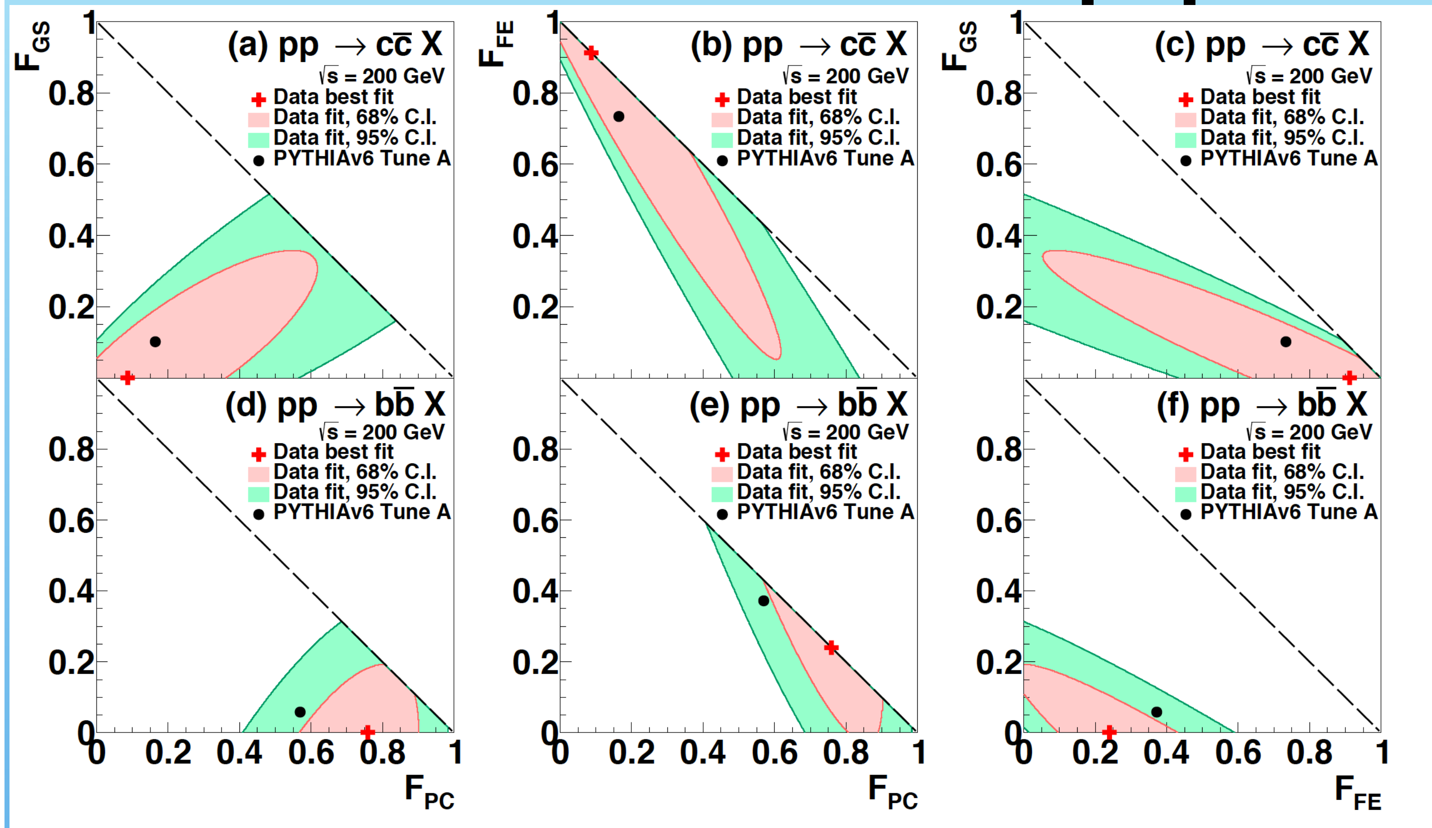
✓ Indication of less suppression for B → e than D → e (~2σ): consistent with $\Delta E_c > \Delta E_b$

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



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

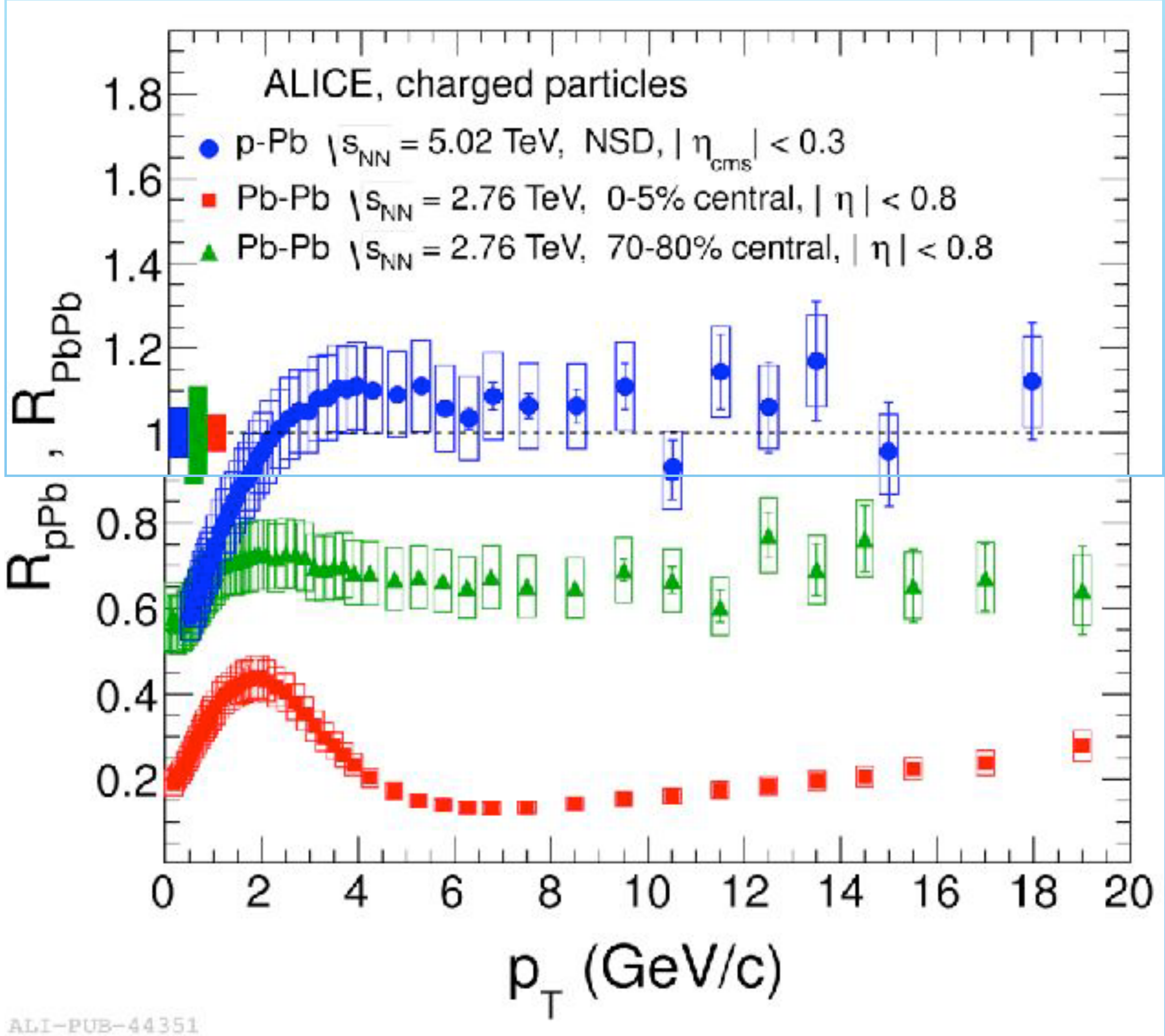
-Data are consistent with Pythia Tune A

(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**

ALICE p+Pb and Pb+Pb data at LHC



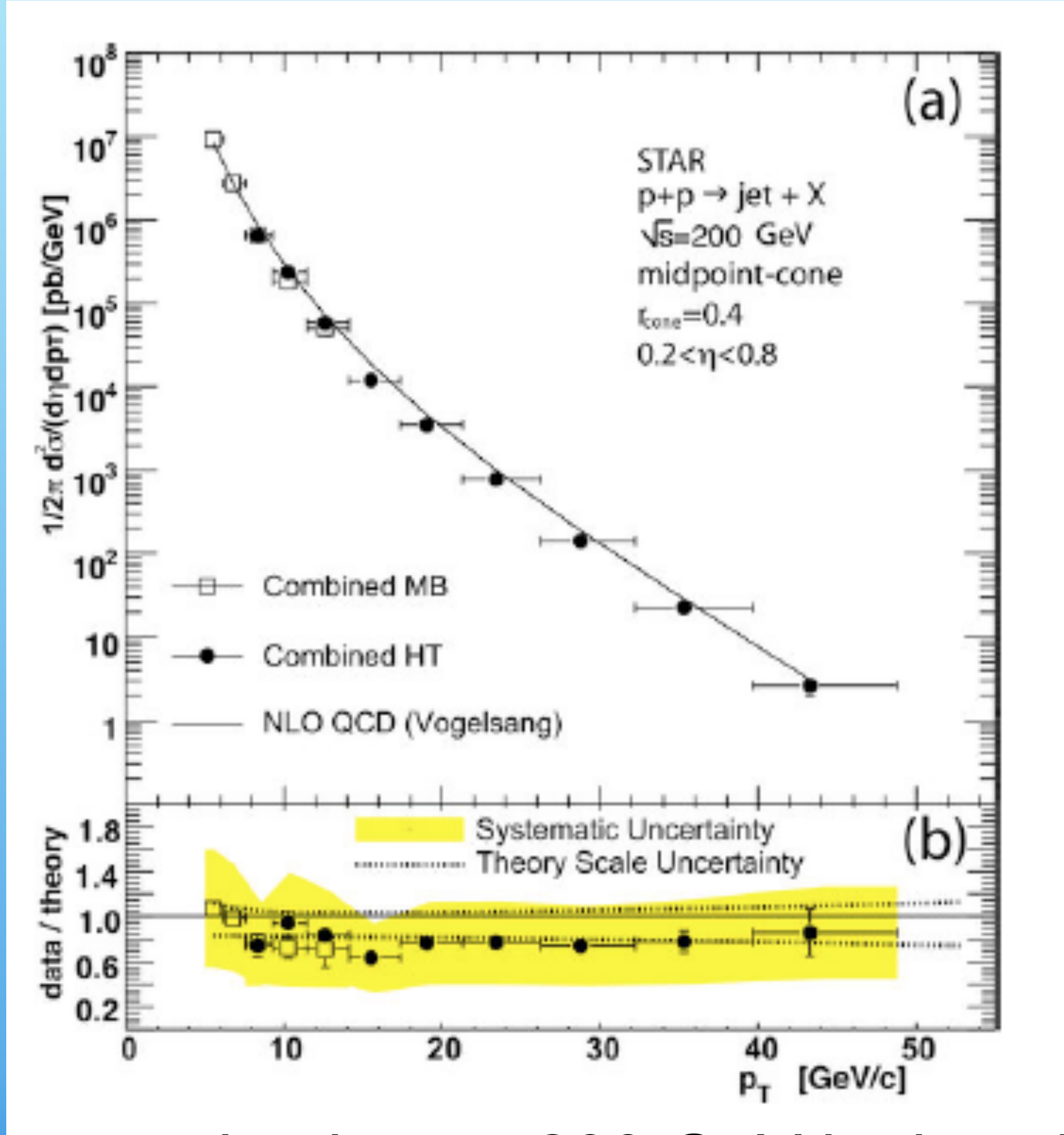
R(pPb) for charged particles is compatible with 1 at hight pT

No jet quenching in p+Pb

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

Reconstructed jets

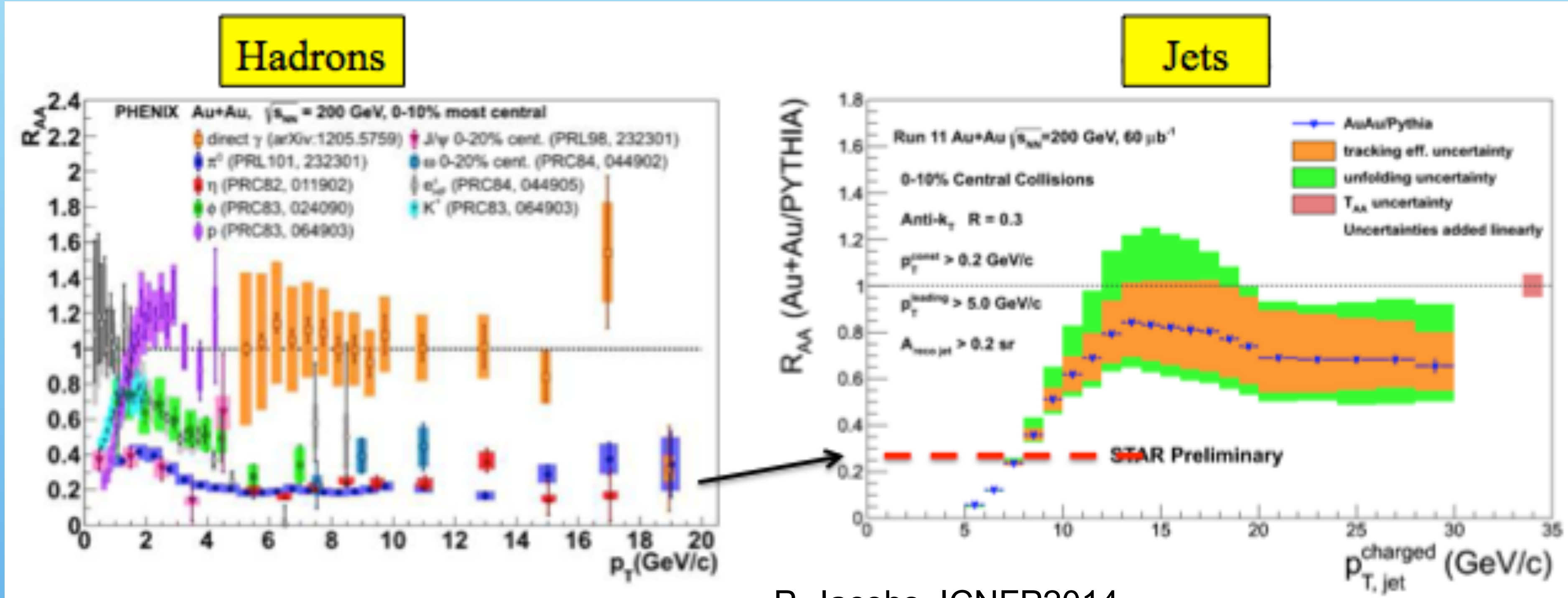
Jet cross section in p+p 200 GeV RHIC



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



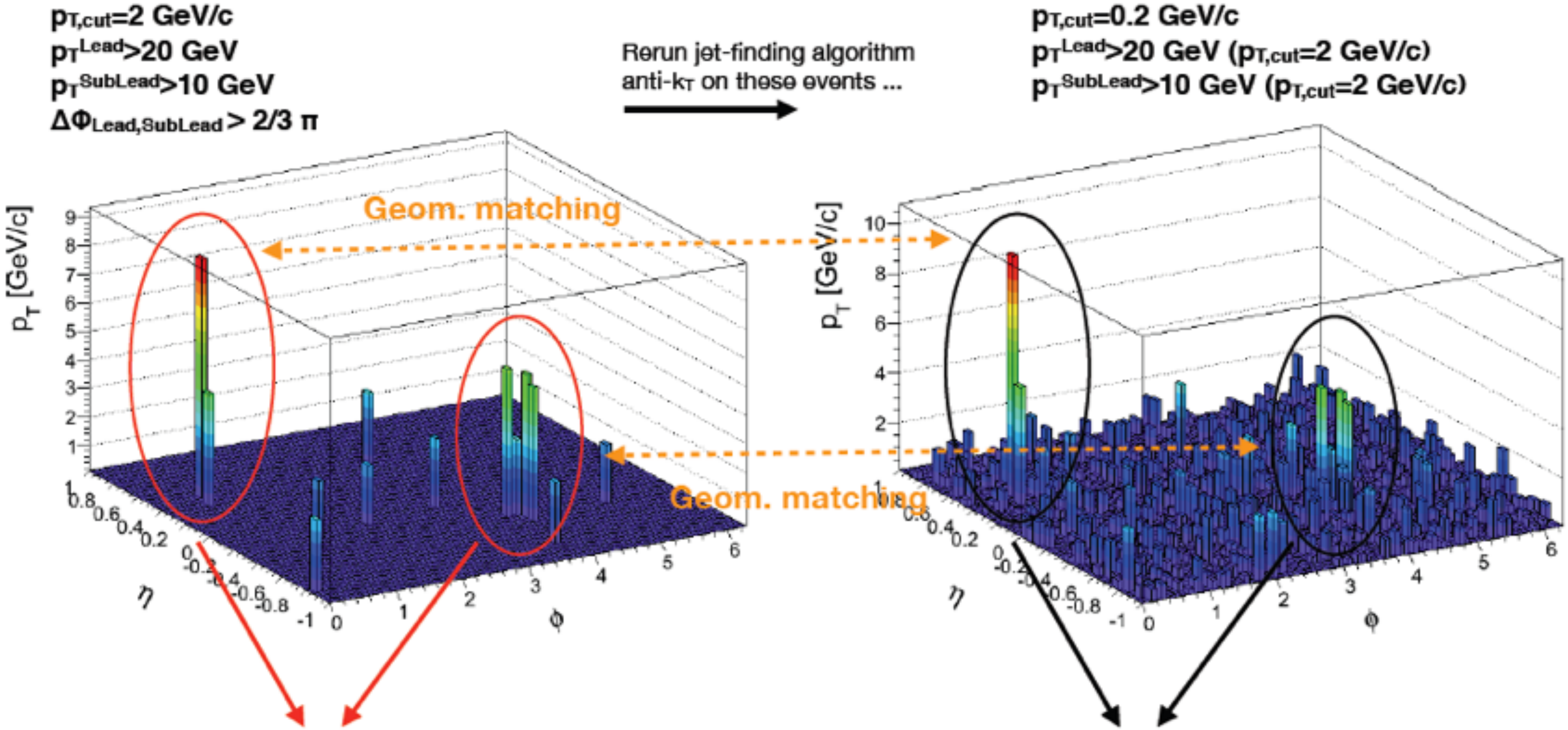
P. Jacobs, ICNFP2014

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)



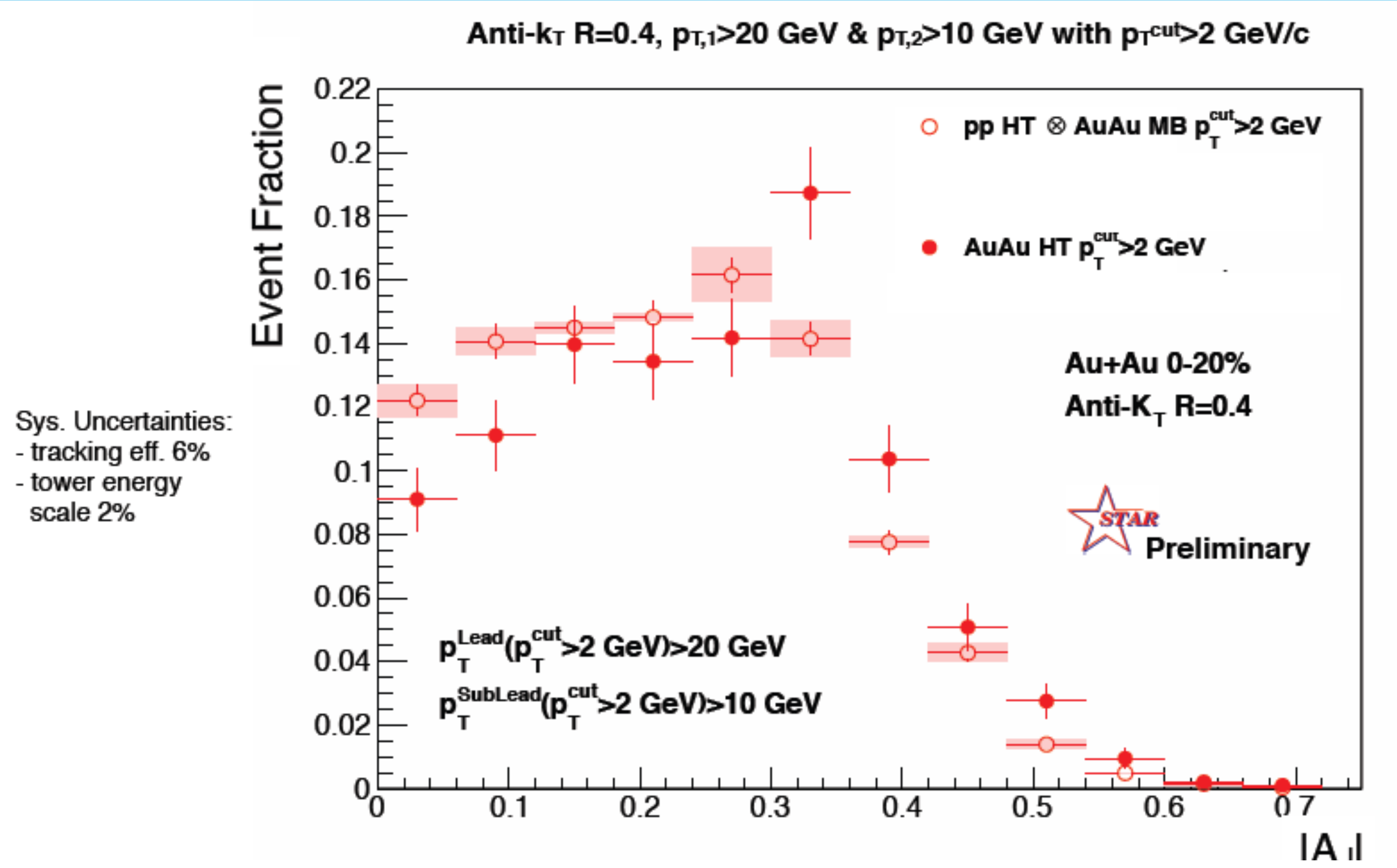
Calculate A_j with constituent $p_{T,cut}$>2 GeV/c

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

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

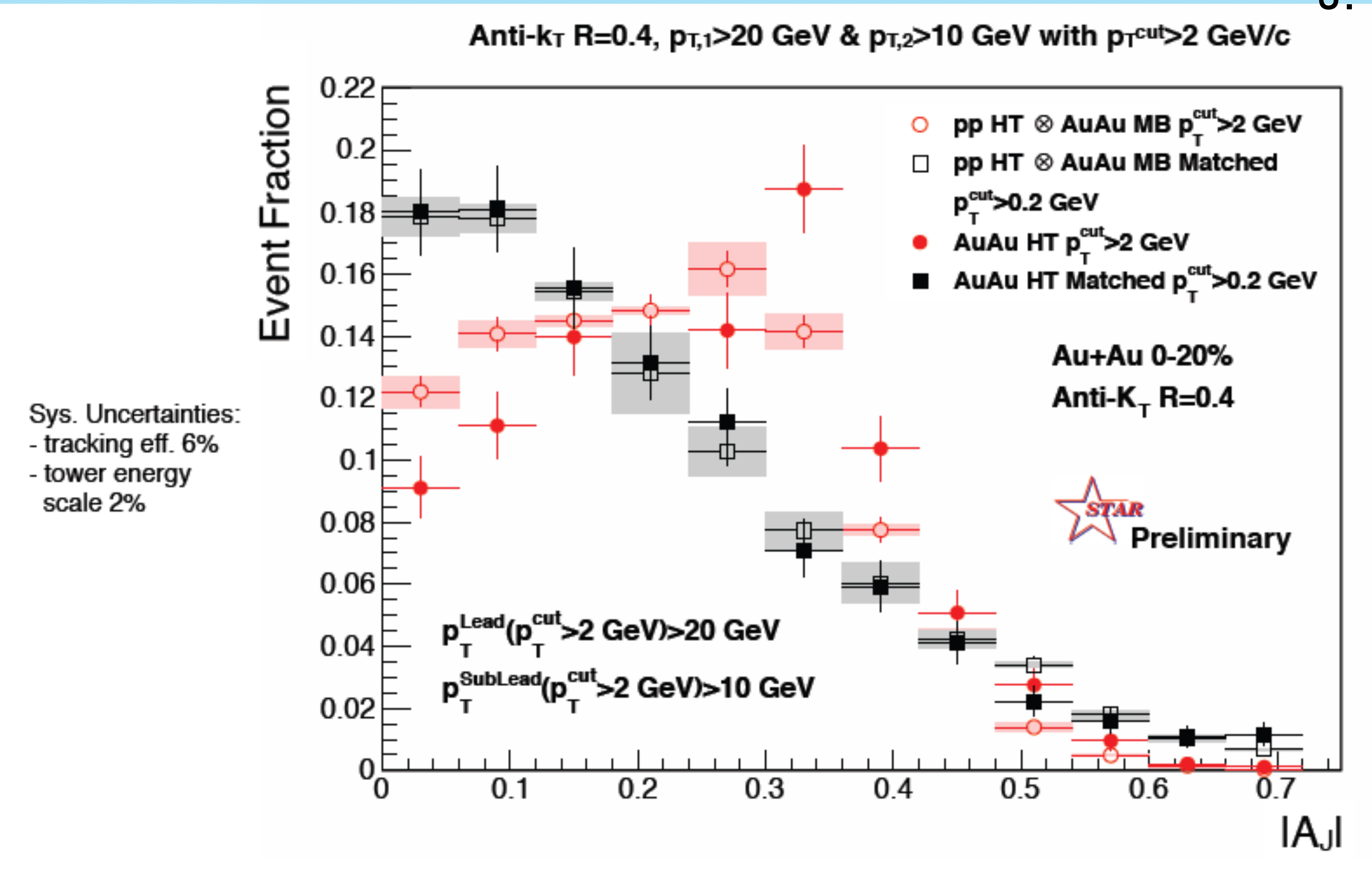


Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

J. Putschke, STAR, QM14

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

J. Putschke, STAR, QM



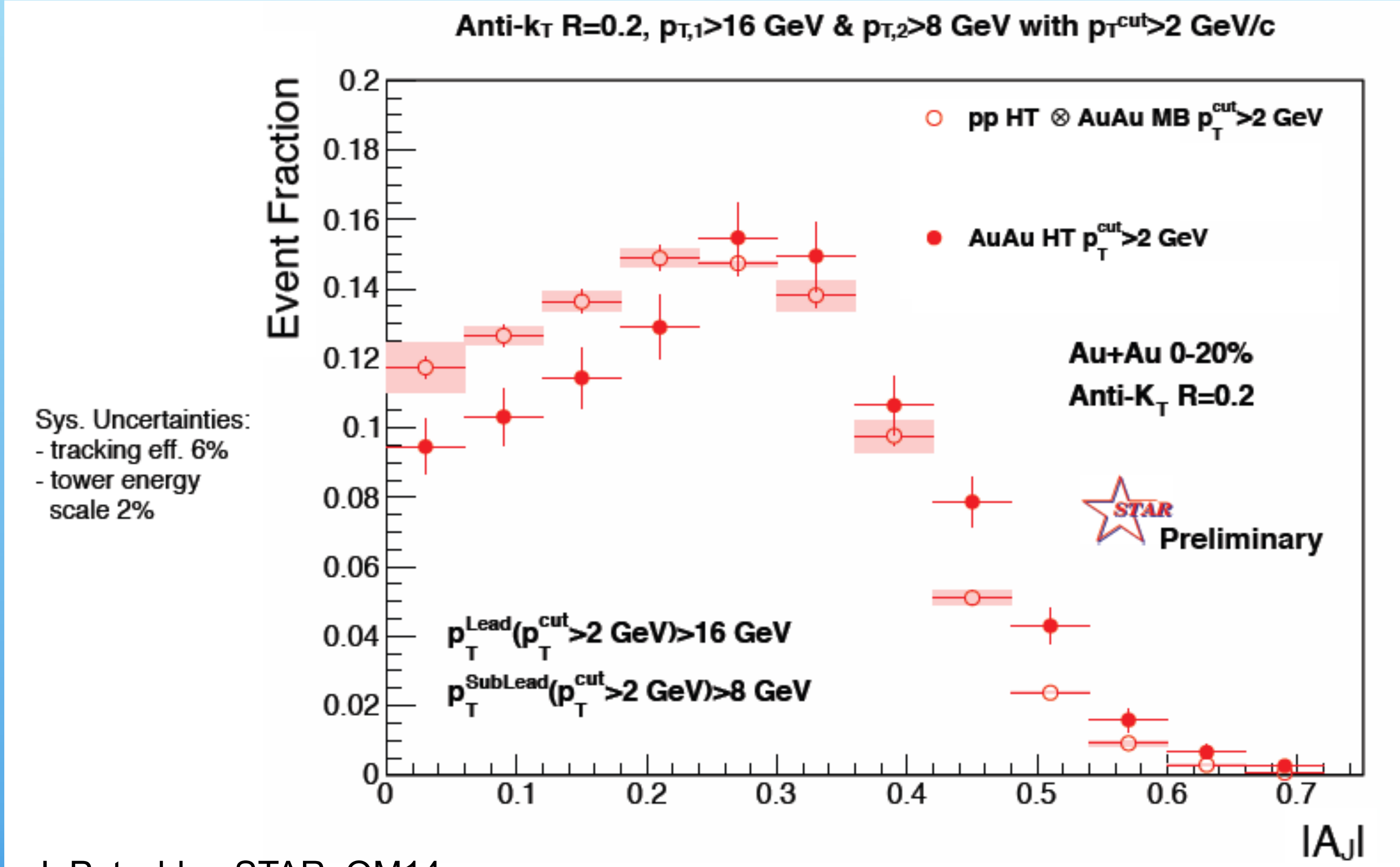
Red: ptcut>2 GeV
Grey: pTcut > 0.2 GeV (matched)

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)

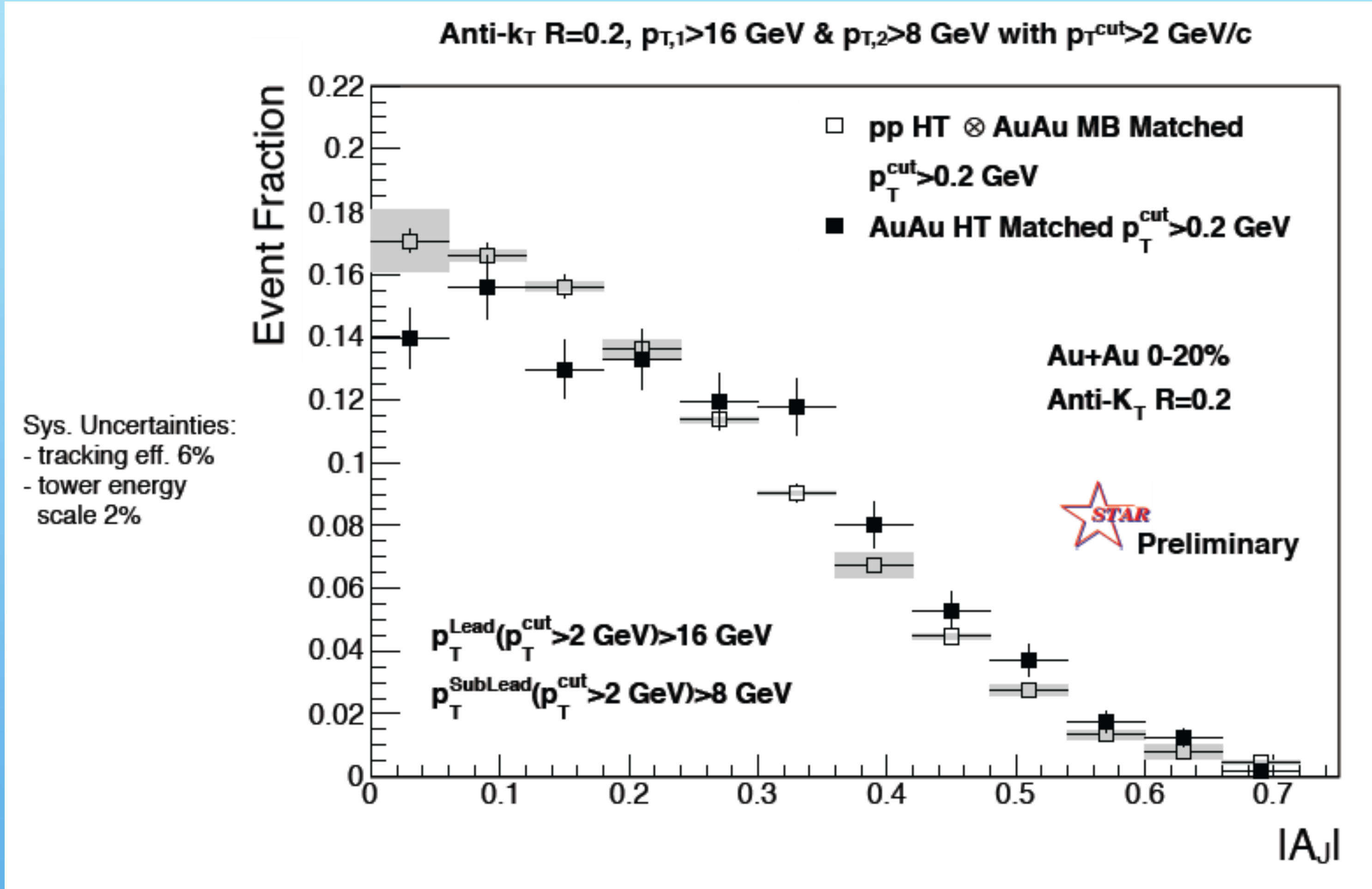
Quenched jet energy is recovered at low pT within a cone of R=0.4

Dijet imbalance with R=0.2



J. Putschke, STAR, QM14

Dijet imbalance with R=0.2, matched

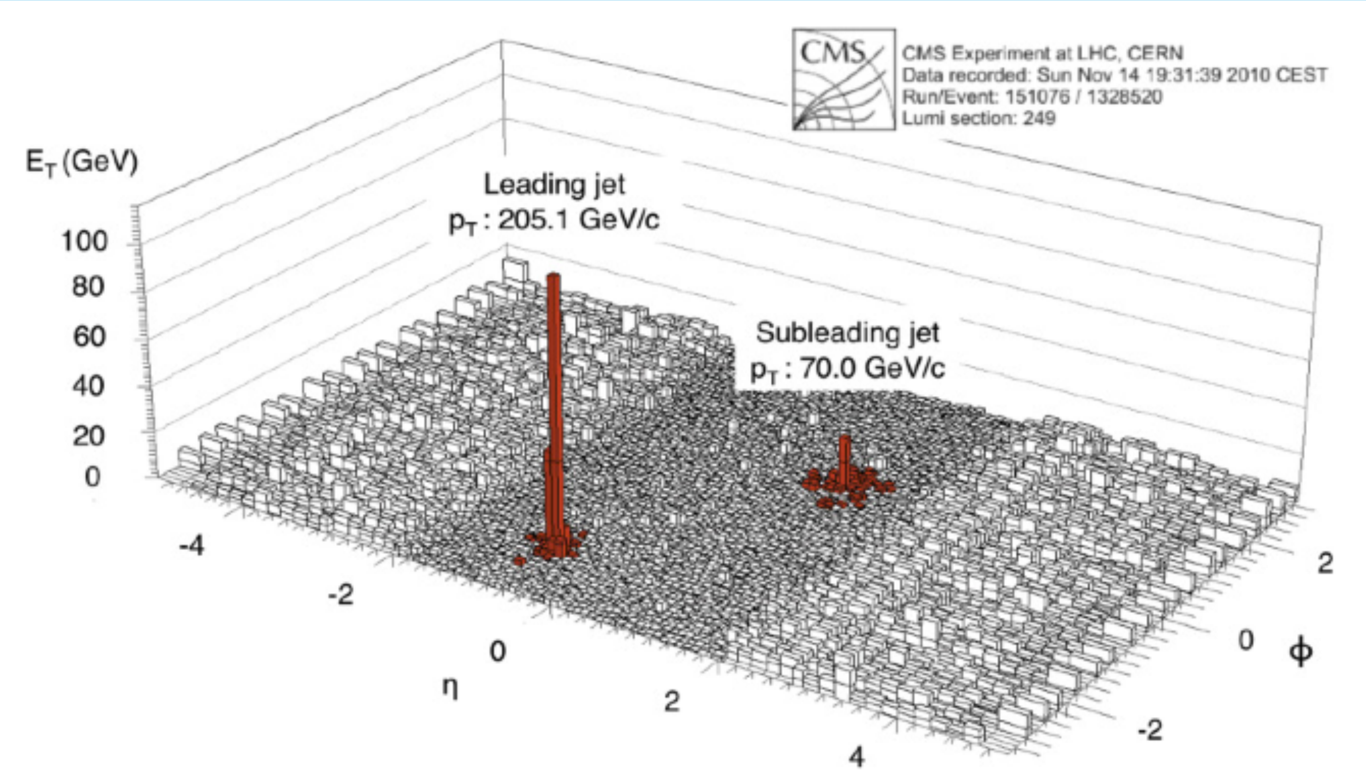


Matched Au+Au $A_J \neq$ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

J. Putschke, STAR, QM14

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

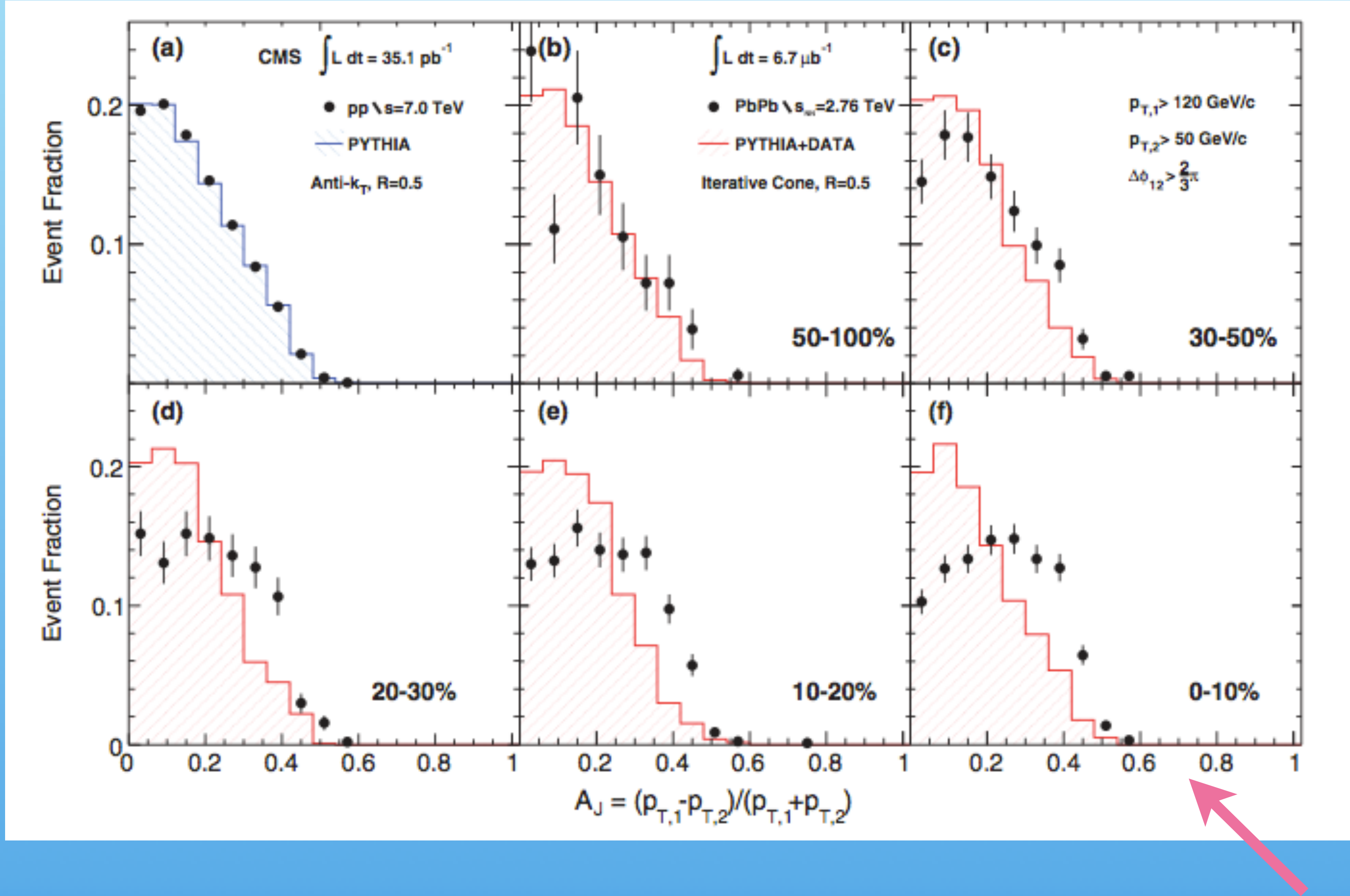
Comparison to LHC: first LHC results



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



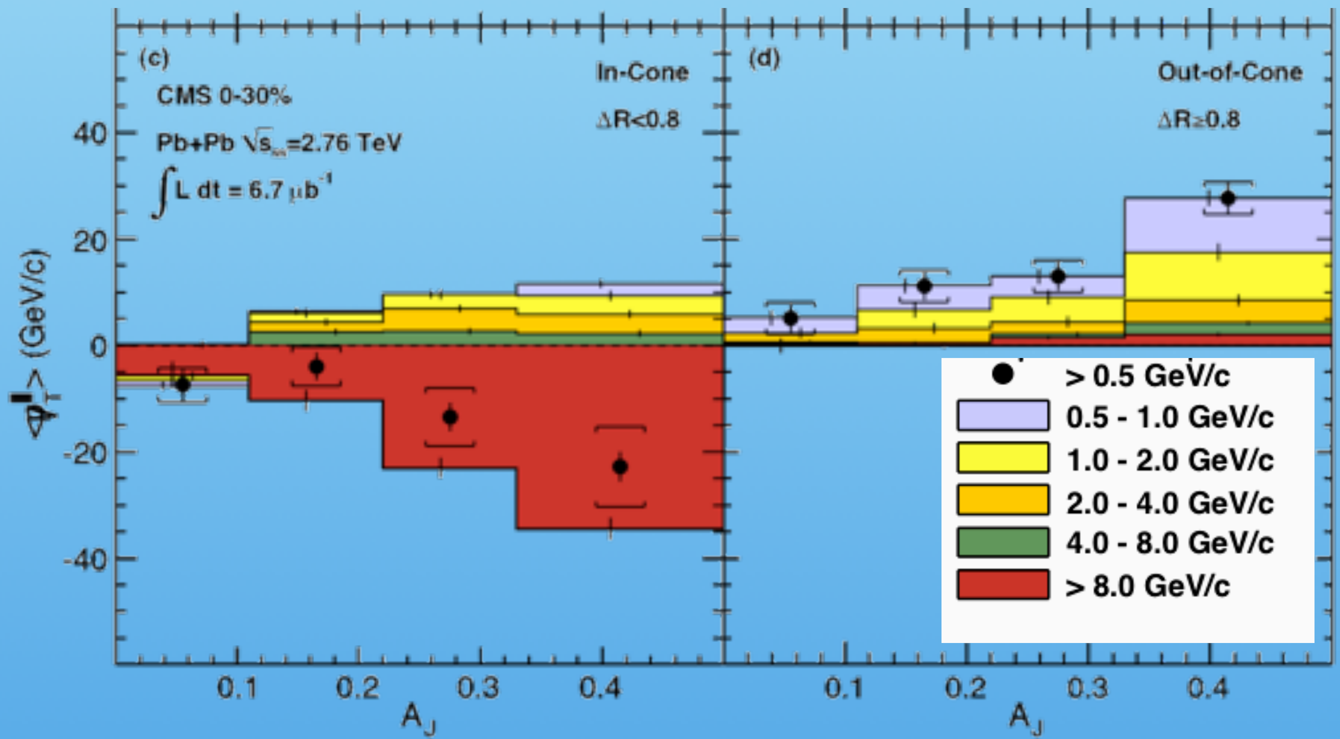
Observation of highly unbalanced dijet events in central PbPb collisions -> evidence for energy loss in medium or "jet quenching"

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

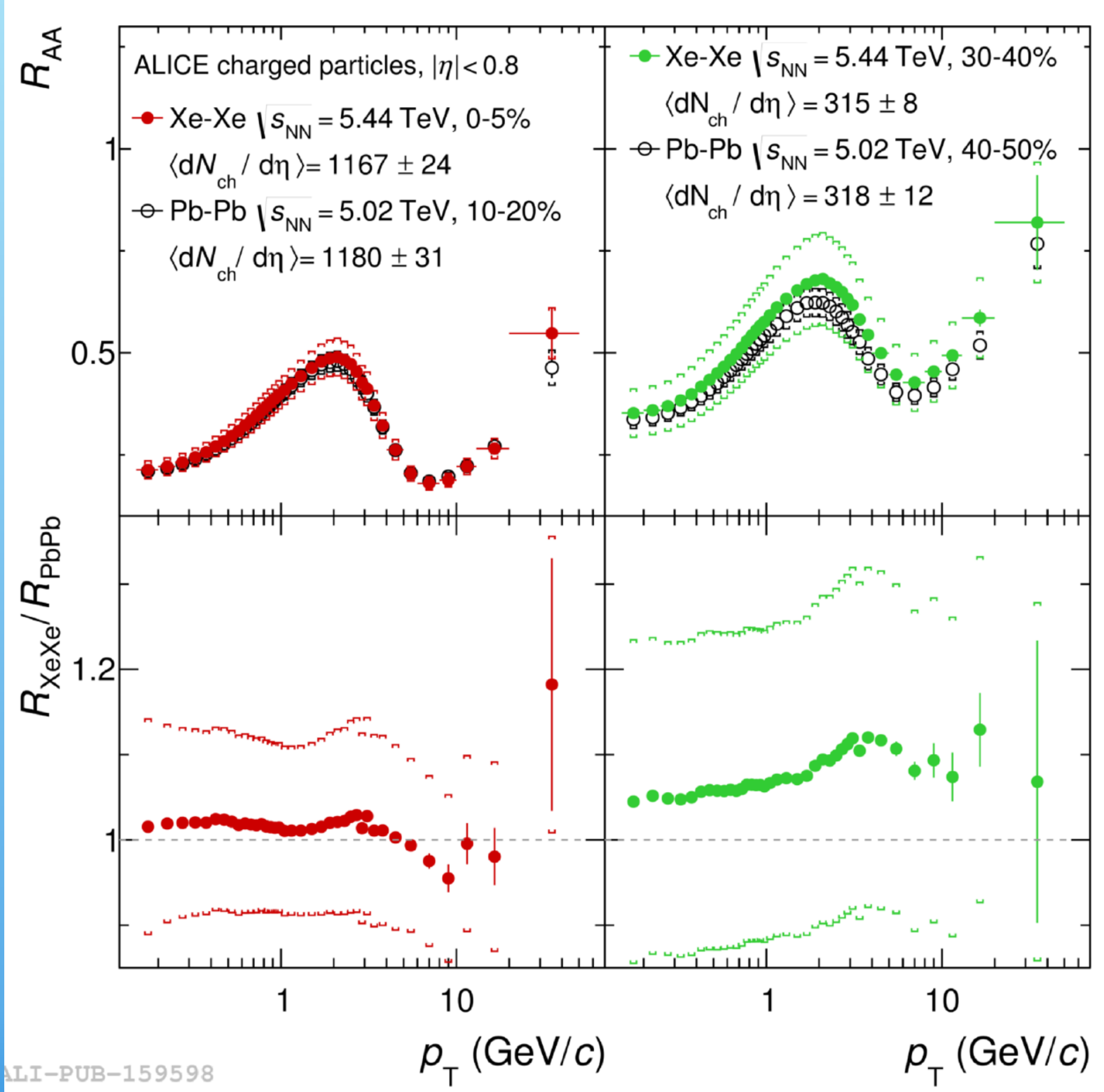
Dijet balance (or imbalance) characterization:

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

RAA in Xe+Xe at LHC

R_{AA} in central Xe-Xe collisions is similar to R_{AA} in Pb-Pb collisions at similar multiplicity.

ALICE Collab., QM2018



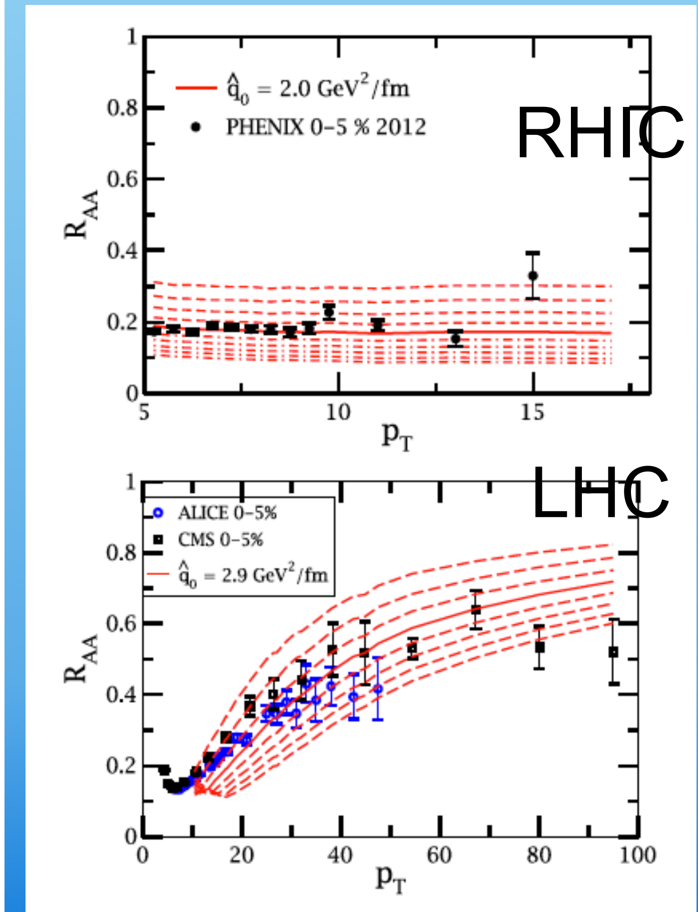
Jet transport coefficient at RHIC and LHC

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

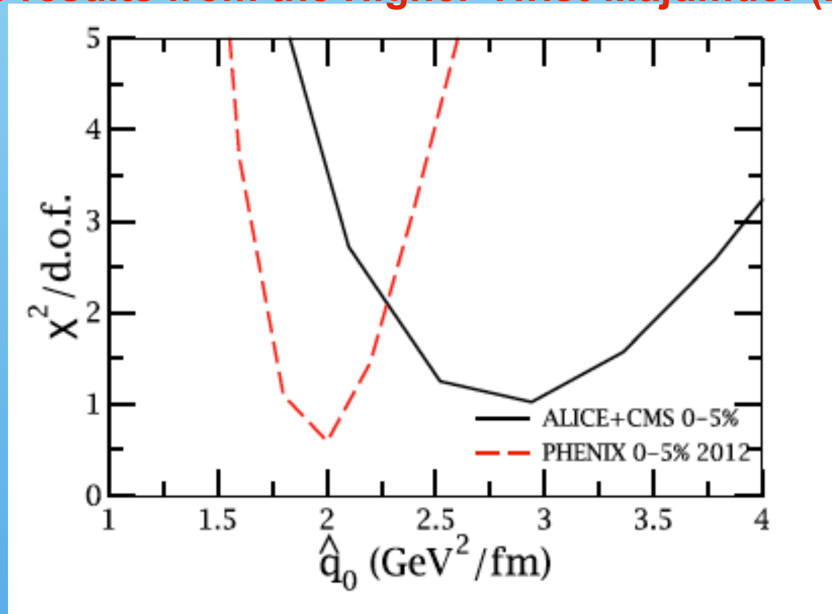
In last years the JET collaboration of groups using different models has made an important step forward evaluating for the first time q-hut with a fit to both RHIC and LHC and reaching a good agreement of all models while fiting the experimental data at RHIC and LHC.
Models: GLV-CUJET, HT-M, HT-BW, MARTINI 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



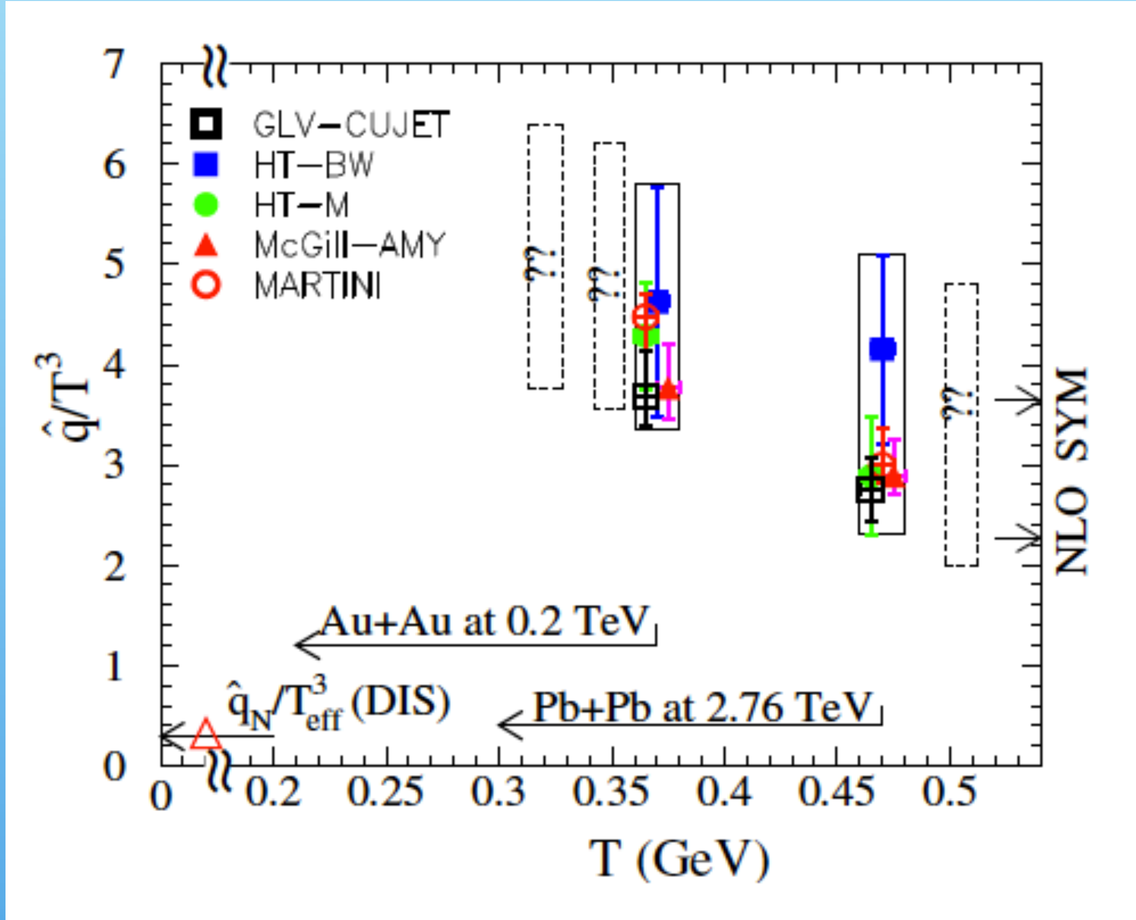
Dedx(radiative)~ q-hut

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



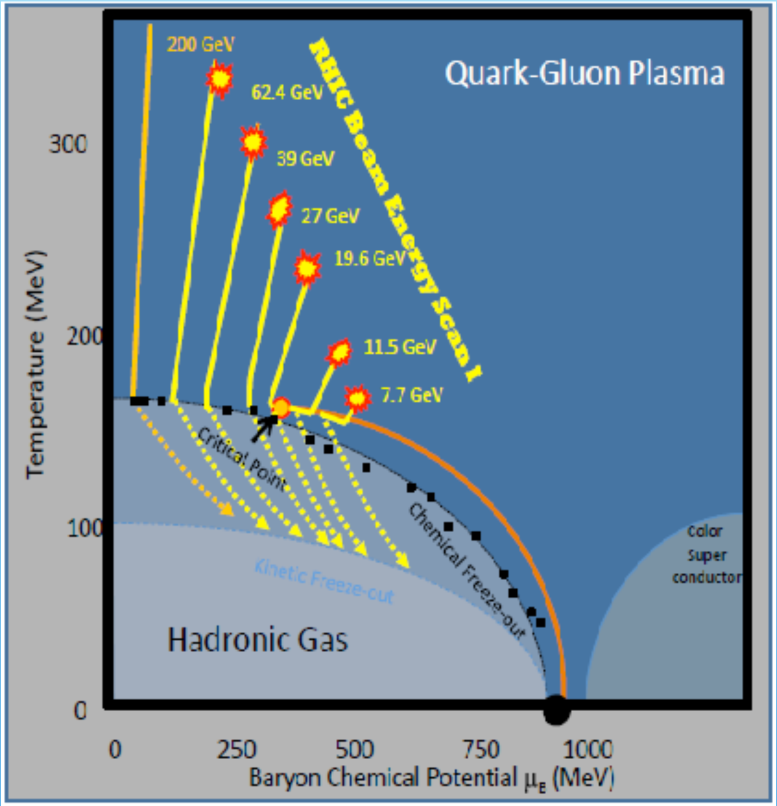
Dashed boxes show expected values for sqrt(s)=0.063, 0.130 and 5.5 TeV

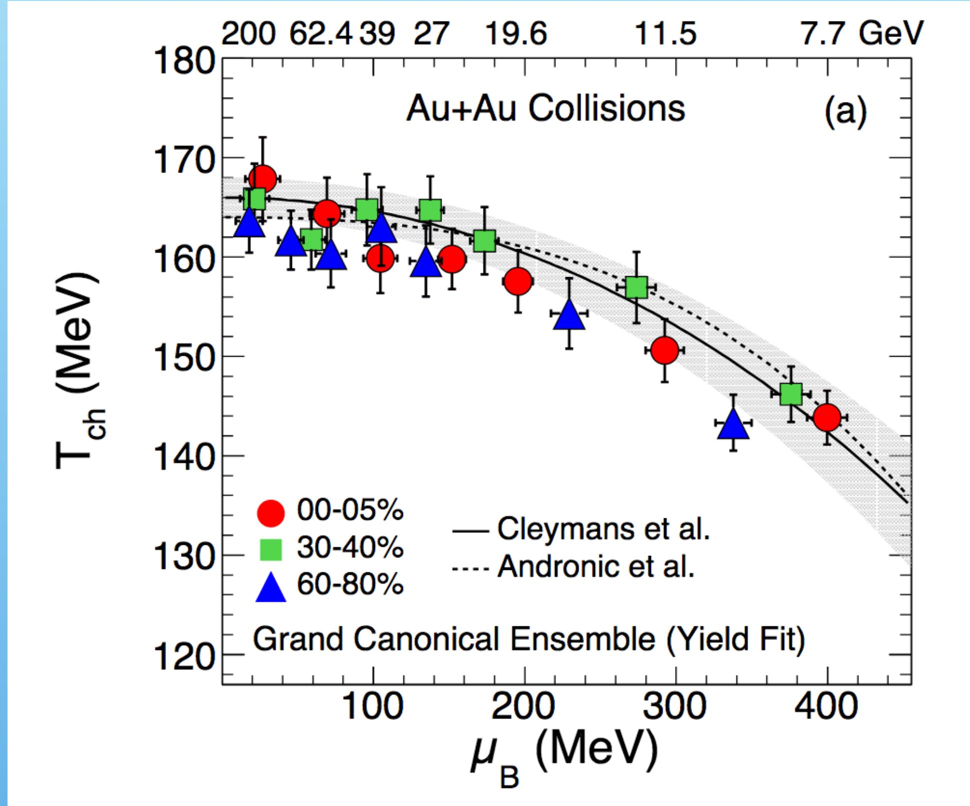
Results from JET collaboration agree with results from AdS/CFT correspondance shown here with the arrows named NLO SYM

5.Beam Energy Scan (BES) -1

Chemical freeze out temperature vs baryochemical potential

BES 1



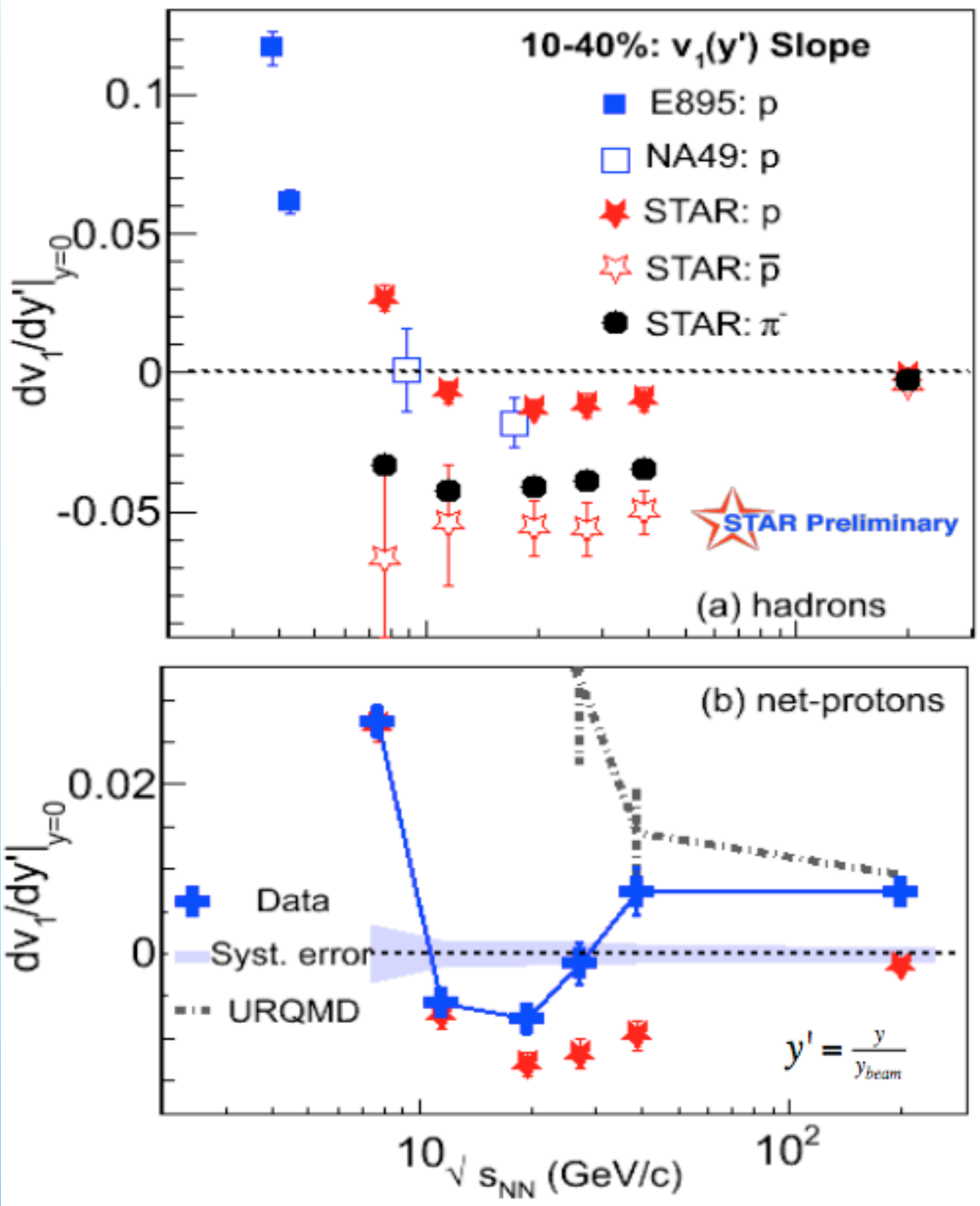


STAR, Phys.Rev. C96 (2017) no.4, 044904

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, unlike peripheral collisions

Directed flow of protons BES 1



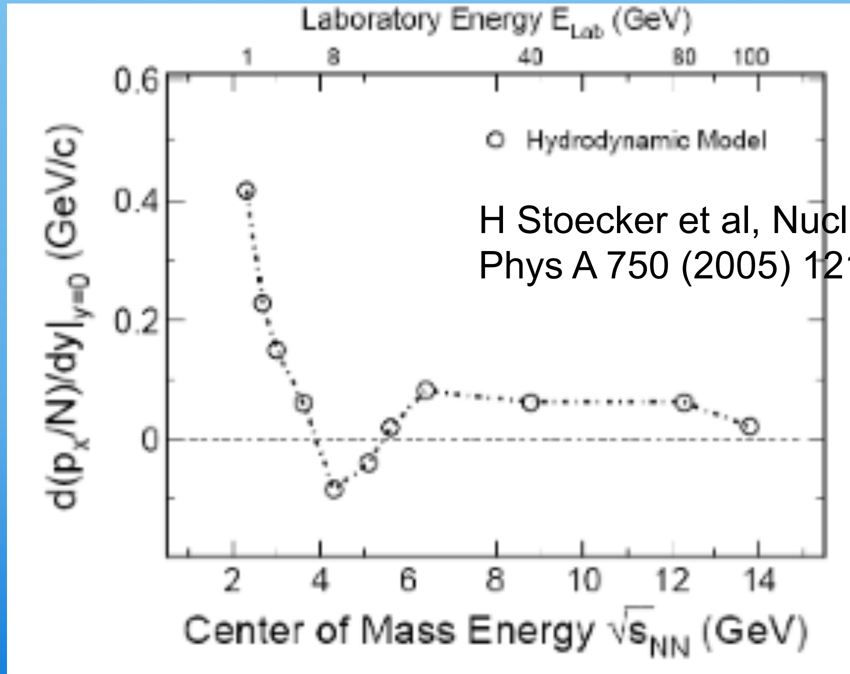
* Directed flow slope is sensitive to a 1st order transition

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

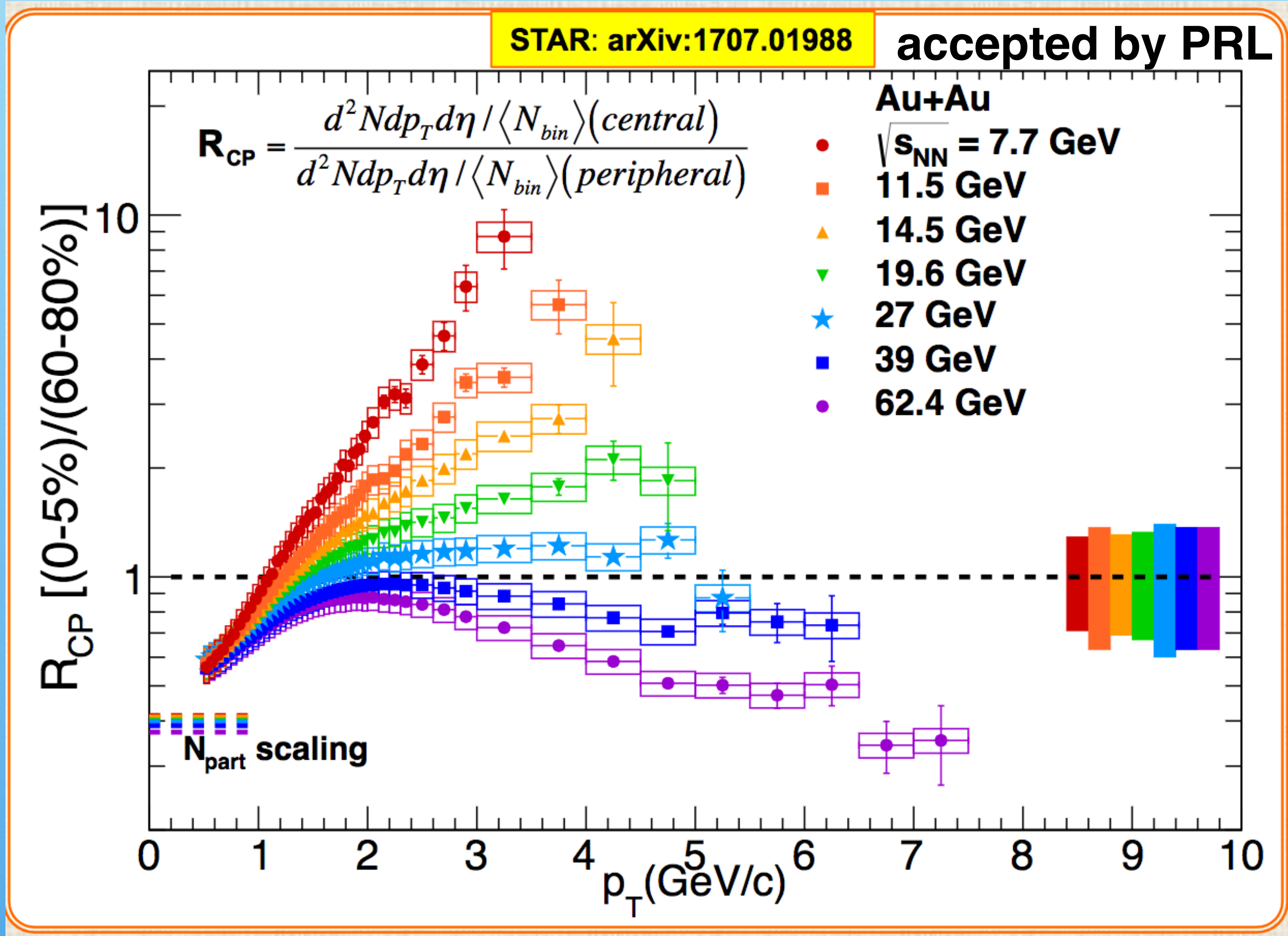
Pions and antiprotons have always negative v1 slopes.

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

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



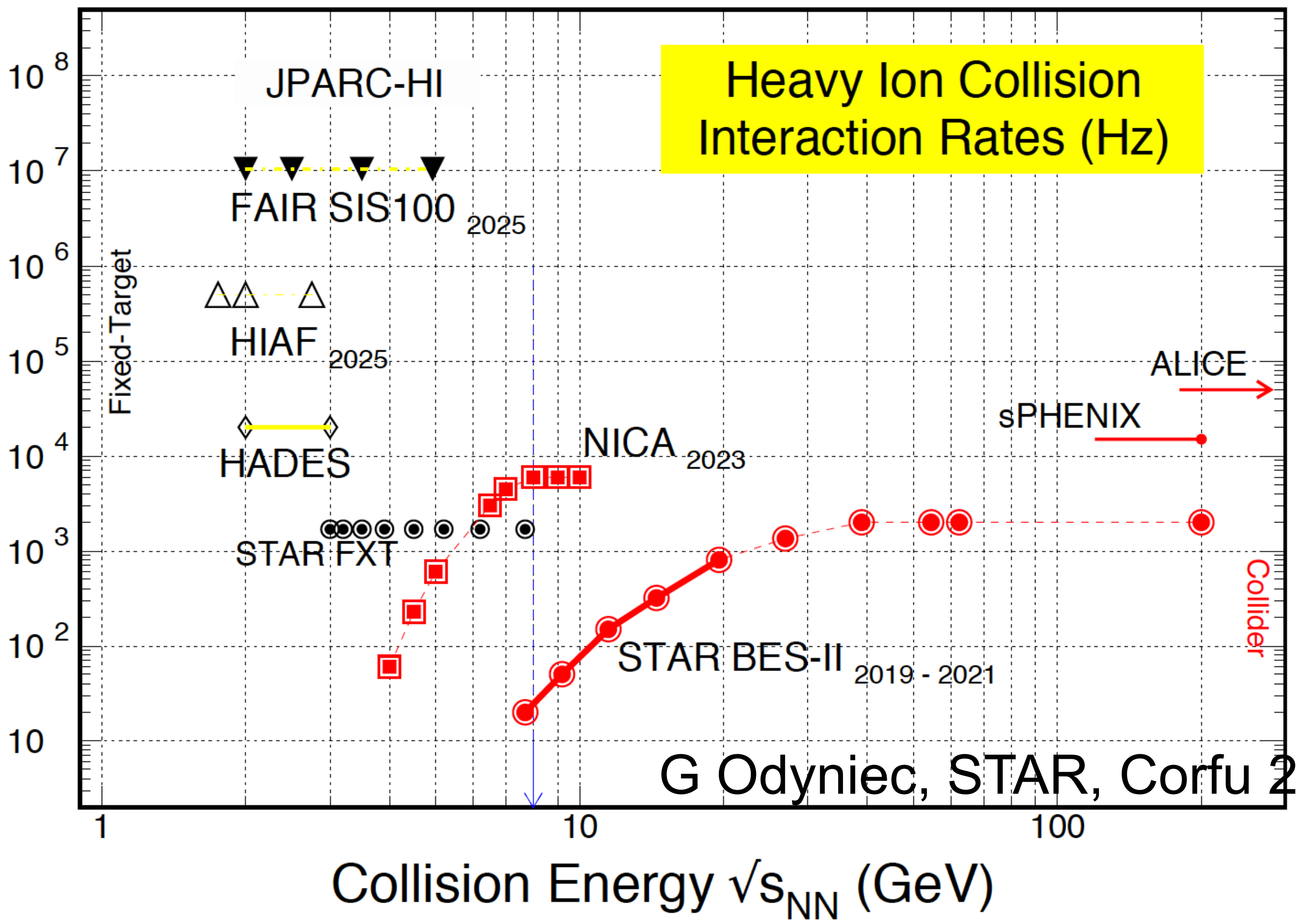
R_{CP} of charged hadrons vs



R_{CP} of charged hadrons becomes smaller than 1 at 39 GeV

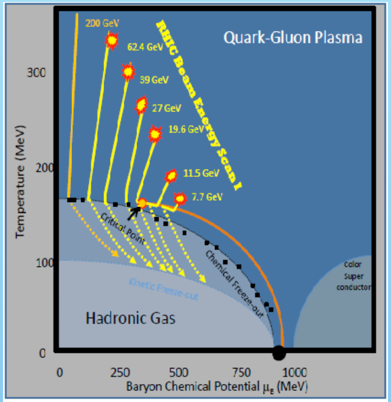
6. Future

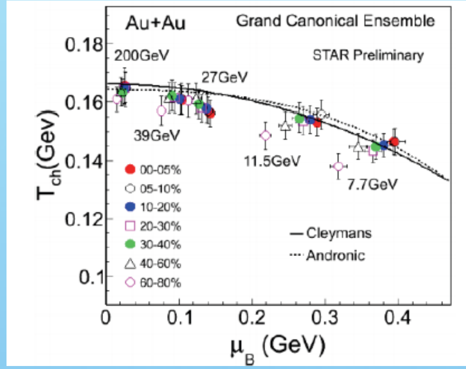
Energy scans with Heavy Ions
Future: BES-2, NICA, FAIR, HIAF, J-PARC



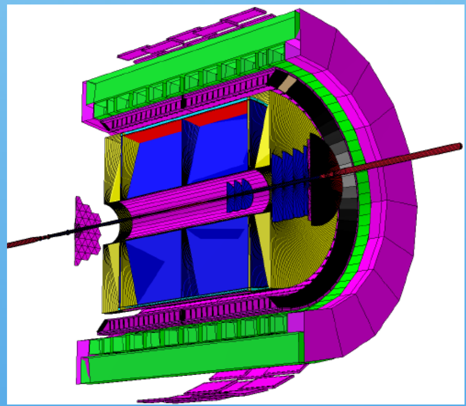
G Odyniec, STAR, Corfu 2018

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



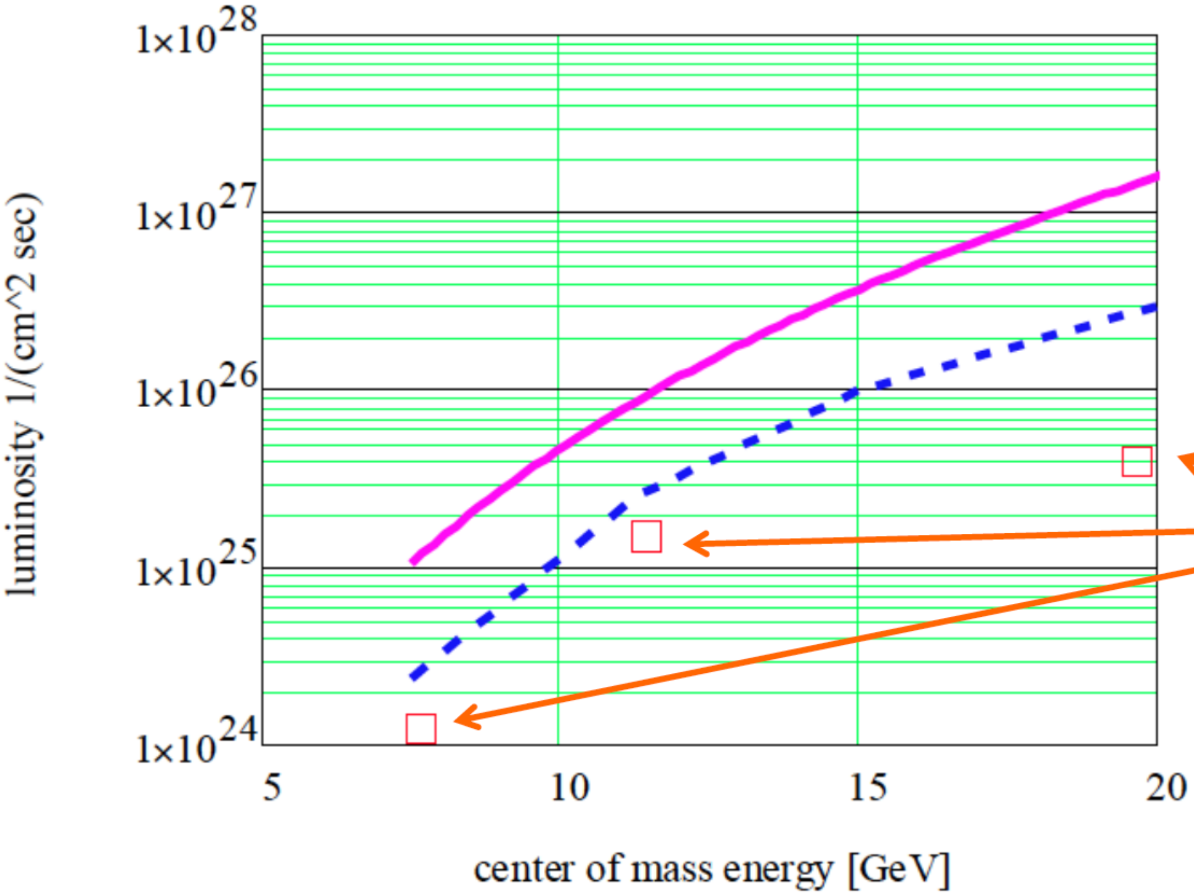
STAR forward rapidity program (2.5-eta-4): Hcal, Ecal, tracking (Silicon and sTGCs)
"Cold" QCD, Proton TMDs, gluon saturation
Test Electron Ion Colider (EIC) detector technologies
Milestone: 2021 p+p run and sPHENIX data taking 2022+
-> EIC

STAR goals BES-2

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

Luminosity improvements for BES-II



RHIC with e-cooling and long bunches (v_z = ± 1m)

Minimum projection (e-cooling only)

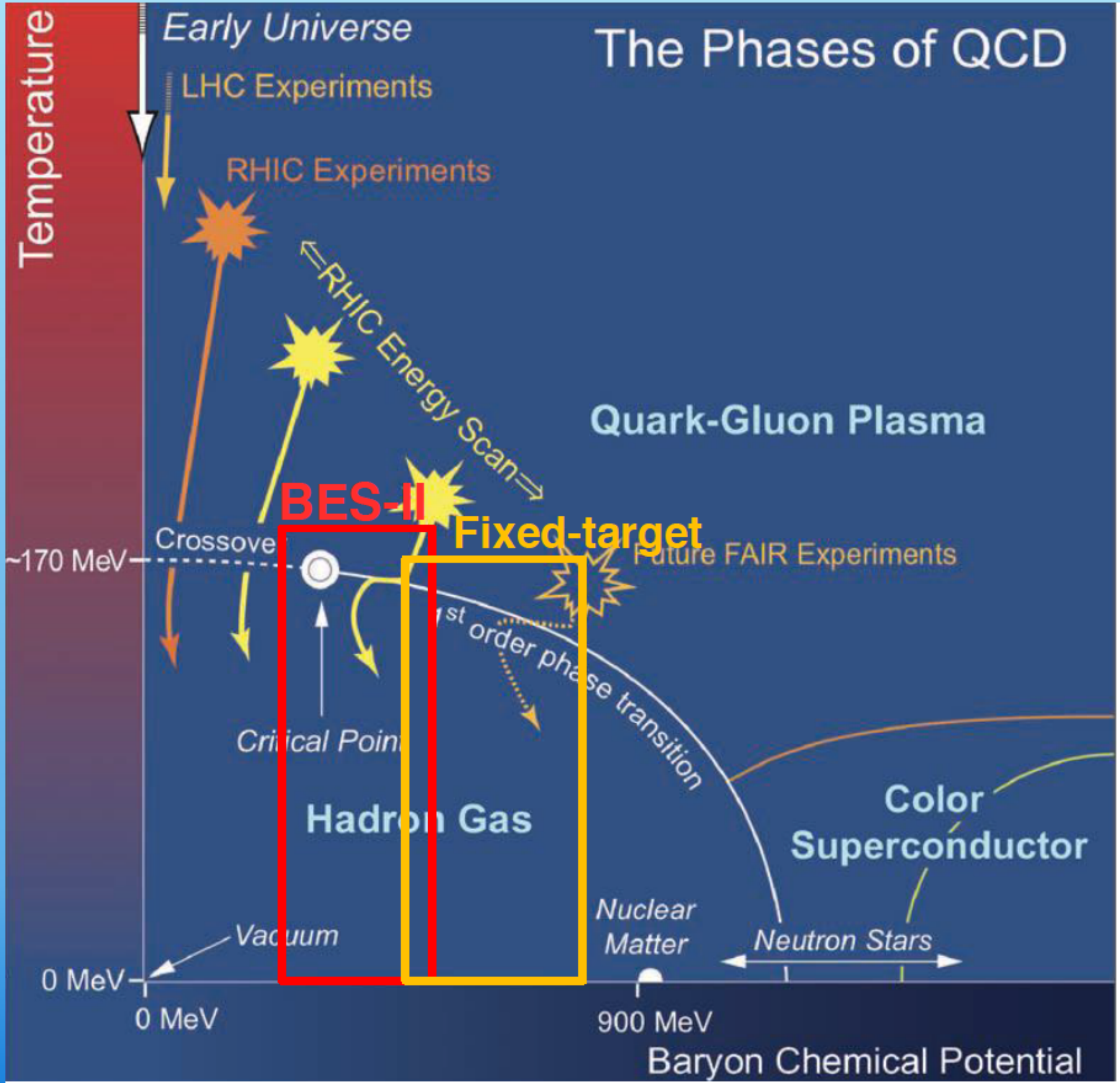
BES-I performance

Implementation:
2019 - $\sqrt{s_{NN}}$: 15 - 20 GeV
2020 - $\sqrt{s_{NN}}$: 7.7-11.5 GeV
2021 -

Electron cooling + longer beam bunches for BES-II provide factor 4-15 improvement in luminosity compared to BES-I
Every energy available with electron cooling

G Odyniec, STAR, Corfu 2018

BES II



Temperature
Early Universe
LHC Experiments
RHIC Experiments
The Phases of QCD
⇐RHIC Energy Scan⇒
Quark-Gluon Plasma
BES-II
Fixed-target
Future FAIR Experiments
~170 MeV
Crossove
1st order phase transition
Critical Poin
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Vacuum
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

Readiness of BES-II

3 year BES-II program 2019-2021 just starting

First BES-II run in 2019

run19: 19 and 14.5 GeV - will start from higher energies

run 20: 11.5, 9.1, 7.7 (part of) GeV - electron cooling available from 2020

run21: 7.7 GeV (finish)

STAR and STAR upgrades will be ready to take data on time

iTPC and eTOF installation will be completed before March 2019

EPD already installed and commissioned in 2018 run

STAR

BROOKHAVEN NATIONAL LABORATORY

Future of STAR at a glance:

STAR BES-2 2019-:

Avatar of FAIR-NICA physics

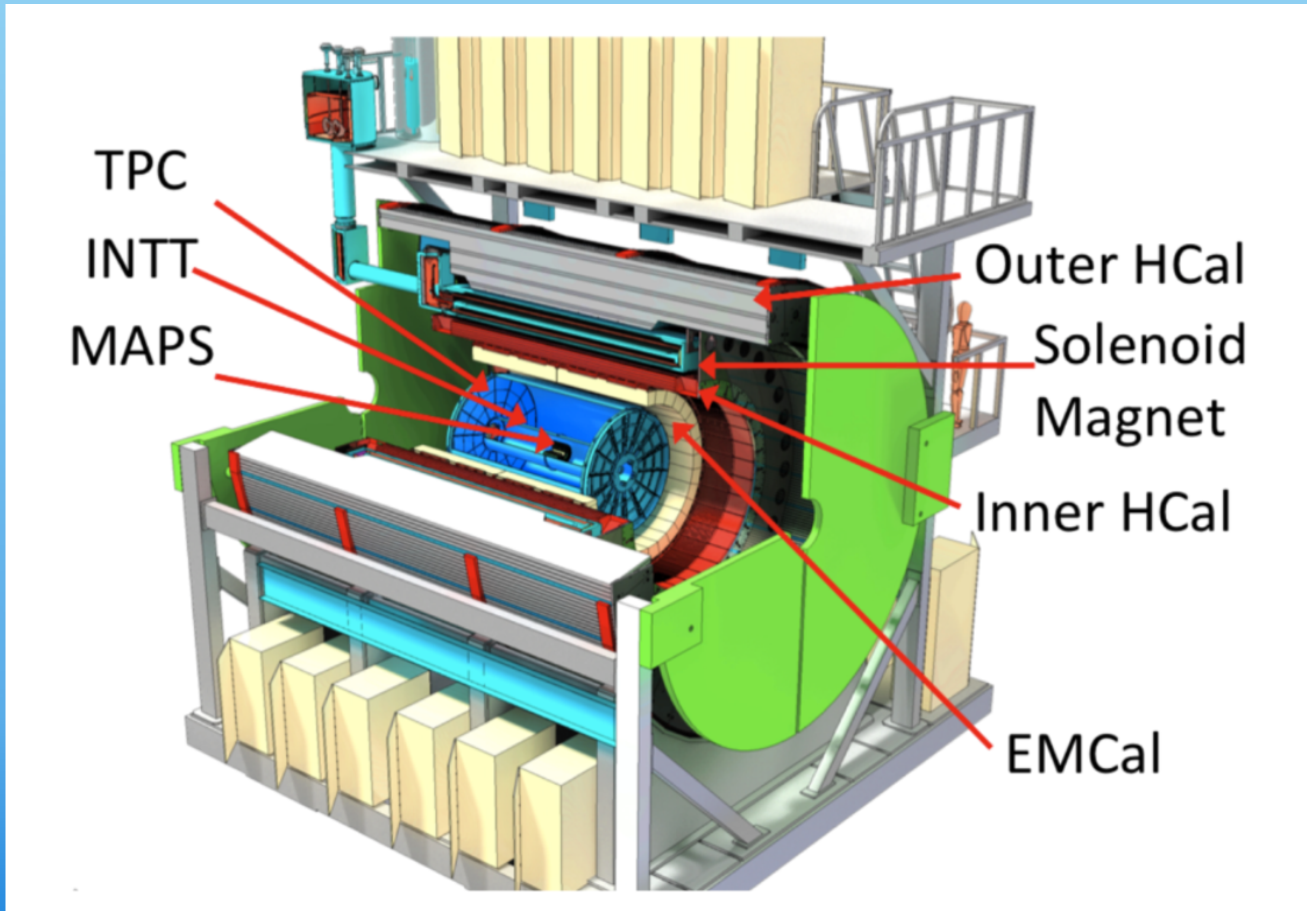
STAR and forward rapidity program 2021-:

Avatar of EIC physics (+10 years)

* 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

Universality and QGP signatures

If QGP forms in all collision systems that reach above critical energy density, still some QGP signatures may not show up in small systems.

For exampl volume in pp and pA at present collision energies may not be large enough for some signatures to develop (quarkonia suppression, jet quenching…)

What will be at the FCC?

IV Conclusions

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

- Some QGP signatures and collectivity are seen also in small systems p+p, p+A, small nuclei

Universality picture emerging

- Obtained quantitative estimates for characteristics of sQGP, like its shear viscosity, temperature, density and critical 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.

IV Conclusions

Focus of next years in many facilities:

Energy scans

- **RHIC BESII (2019-2020), sPHENIX (2020+), CERN SPS**
- **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 p+p at sqrt(s)=100 TeV, Pb+Pb at sqrt(s)=39 TeV.


Thank you very much

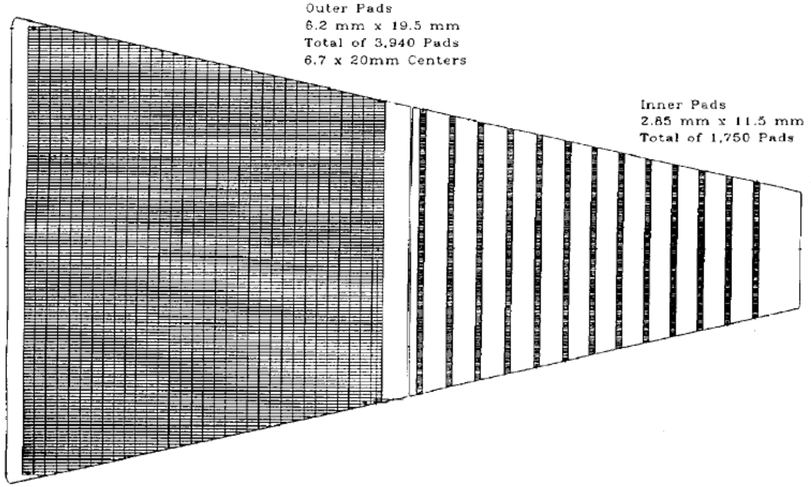
Happy Birthday Reinhardt !

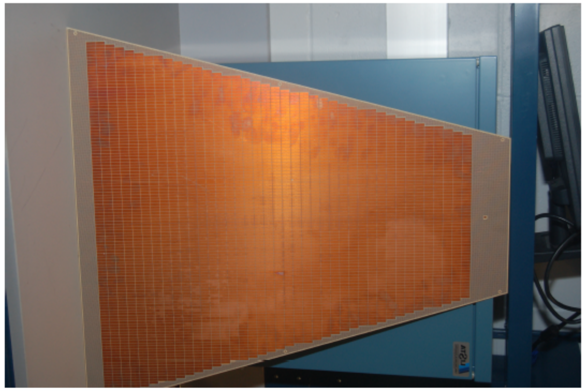
Reaching into the future

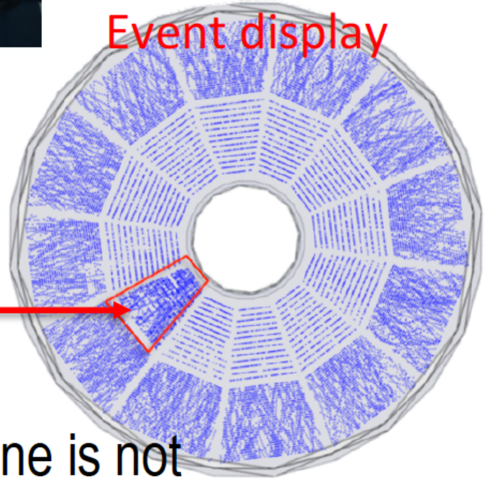
Backup slides

iTPC

Inner sectors upgrade







one sector has been installed in October 2017
data collected in 2018

The outer pad plane have continuous tracking… while the inner pad plane is not

- Increase the segmentation on the inner pad plane, new electronics for inner sectors
- Renew the inner sector wires which are showing signs of aging

Better momentum resolution, better dE/dx resolution, and improved acceptance at high η

Old: $-1 < \eta < 1$ New: $-1.5\ (-1.7) < \eta < 1.5 (1.7)$

Table 8: Event statistics (in millions) needed in BES-II for various observables. This table updat estimates originally documented in Ref. [45].

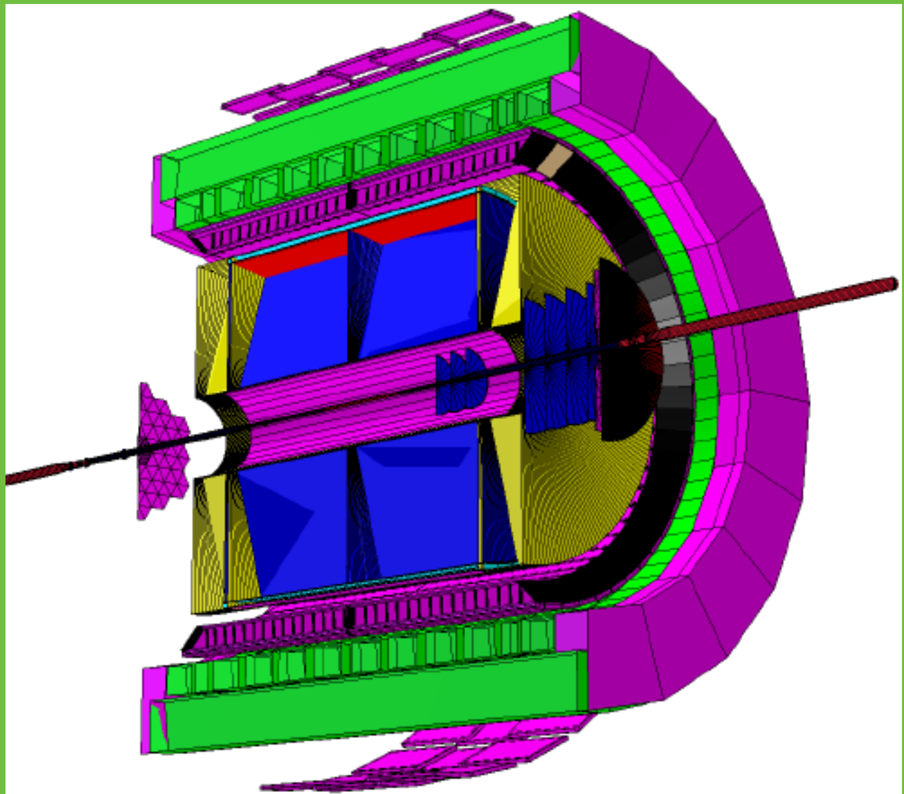
Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	-		160	125	92
Elliptic Flow (ϕ mesons)	80	120	160	160	320
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	20	30	35	45	50
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	70	85	100	170	340
Dileptons	100	160	230	300	400
$>5\sigma$ Magnetic Field Significance	50	80	110	150	200
Required Number of Events	100	160	230	300	400

+100M for each FXT energy

Typically factor 20 more than for BES-I

STAR BES-II goals

STAR forward rapidity program



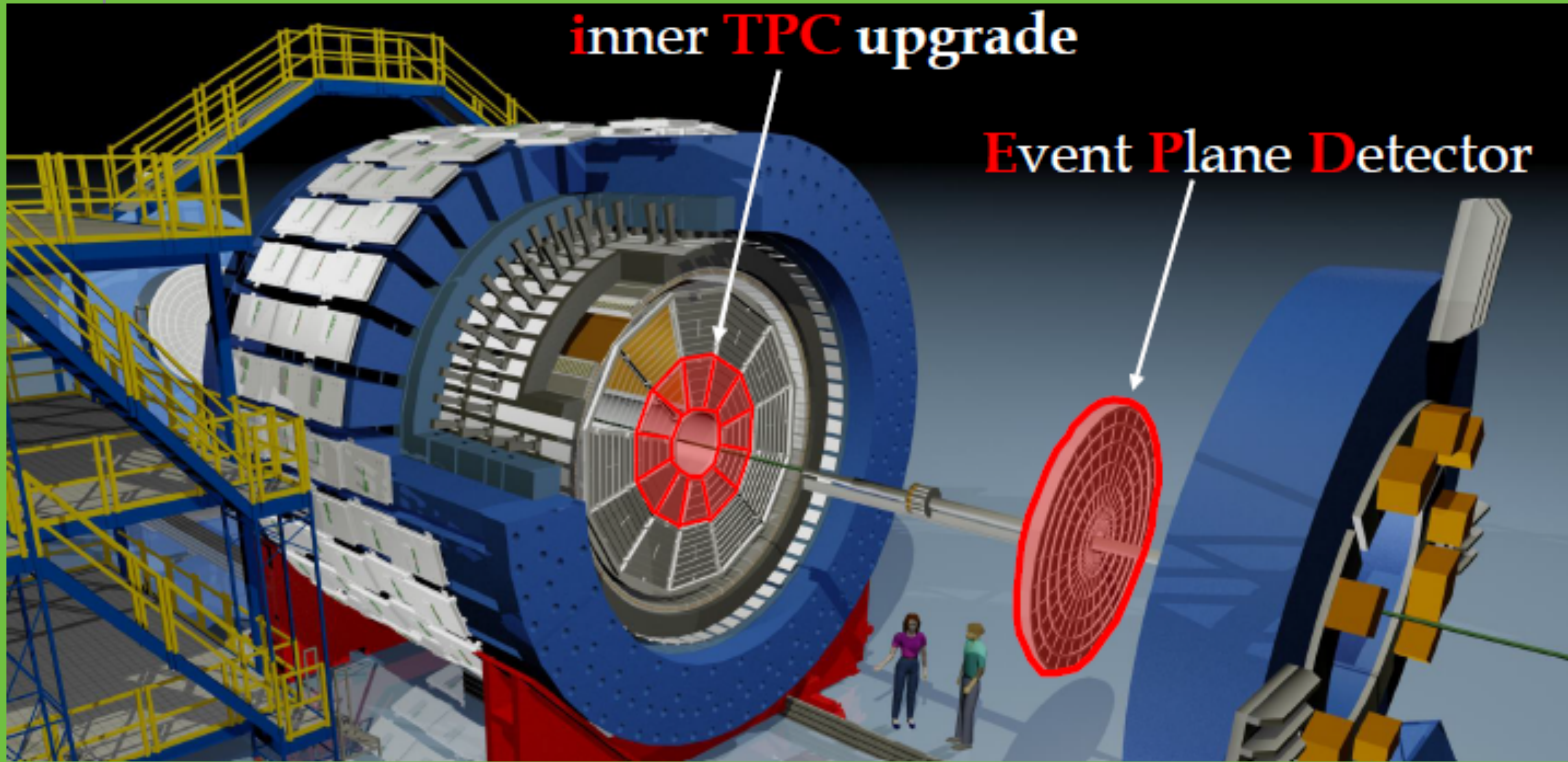
3 Silicon discs

4 Small-strip Thin Gap Chambers

ECal: use upgraded PHENIX PbSc calorimeter

HCal: Iron-scintillator

STAR upgrades



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