Heavy Flavor Era at RHIC

Barbara Trzeciak

Czech Technical University in Prague

Faculty of Nuclear Sciences and Physical Engineering

european social fund in the czech republic

EUROPEAN UNION

MINISTRY OF EDUCATION, YOUTH AND SPORTS

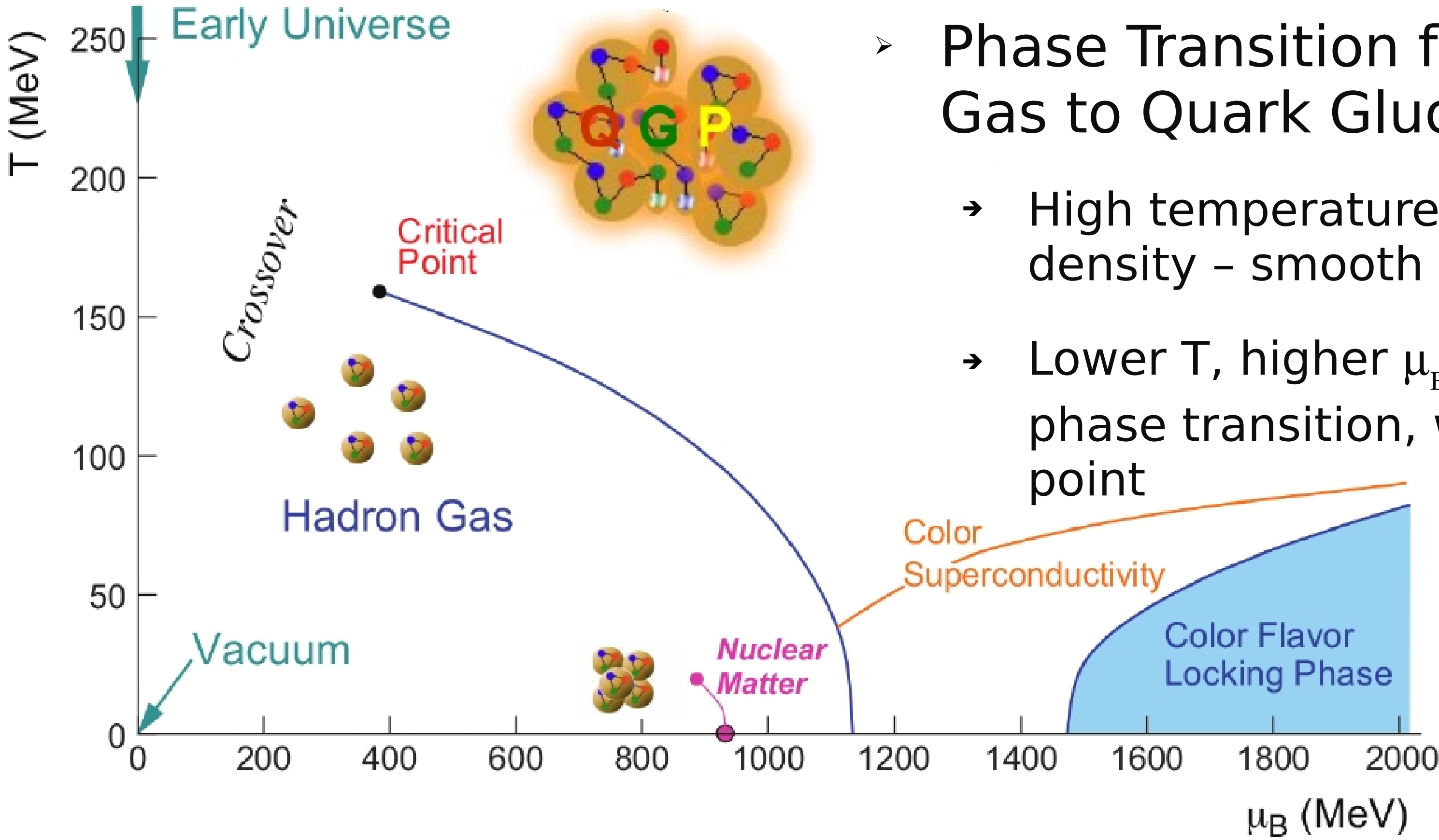
OP Education for Competitiveness

INVESTMENTS IN EDUCATION DEVELOPMENT

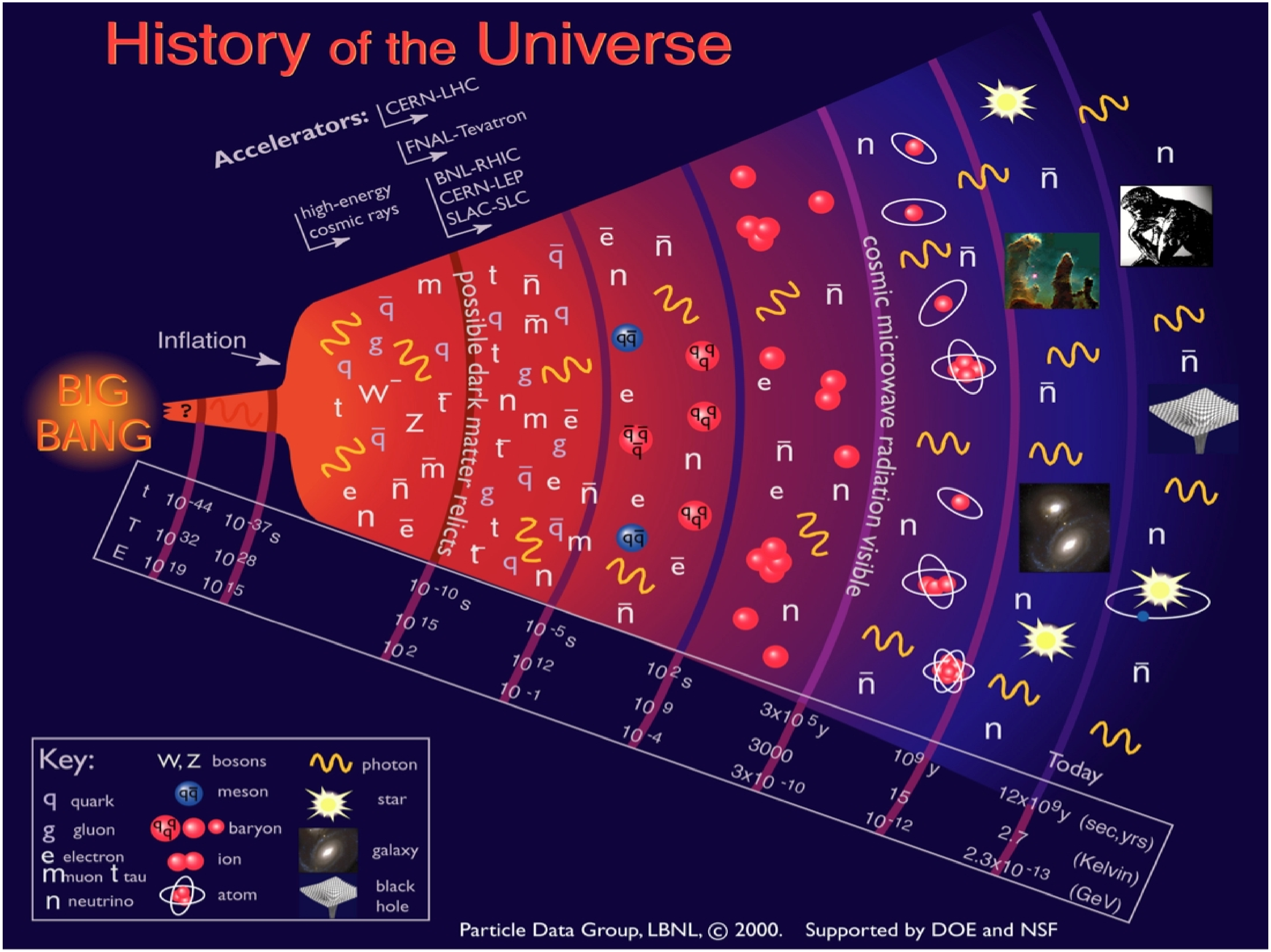
Properties of Nuclear Matter

- Quantum Chromodynamics (QCD) – fundamental description of strong interactions

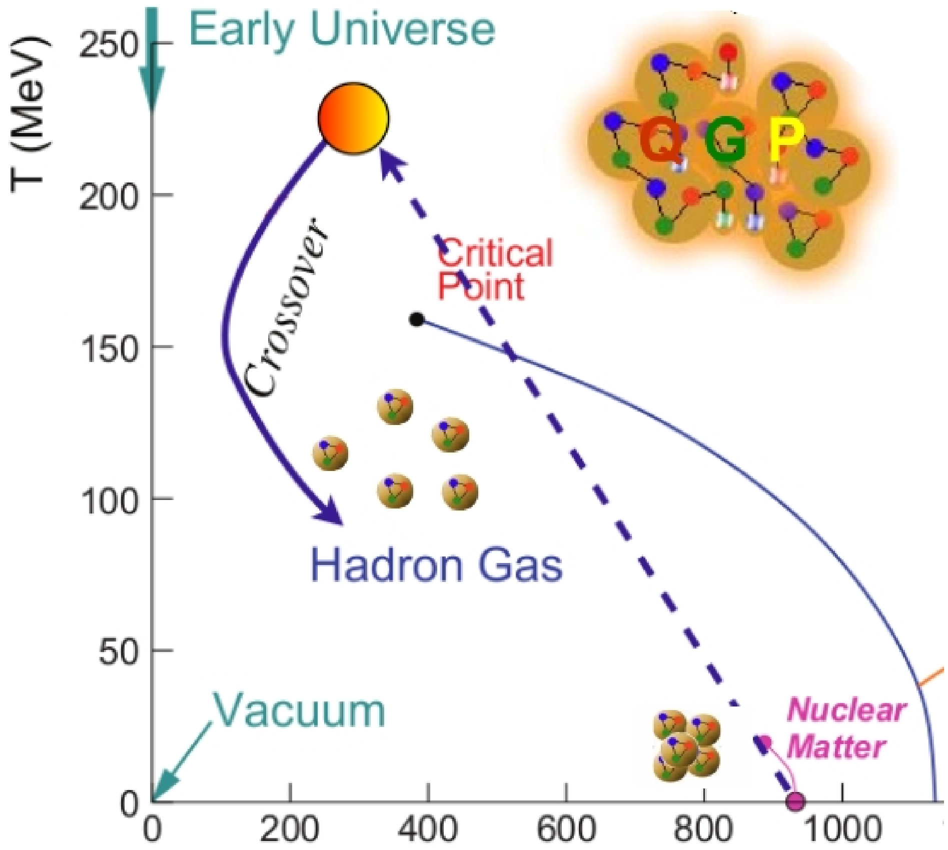
QCD Phase Diagram



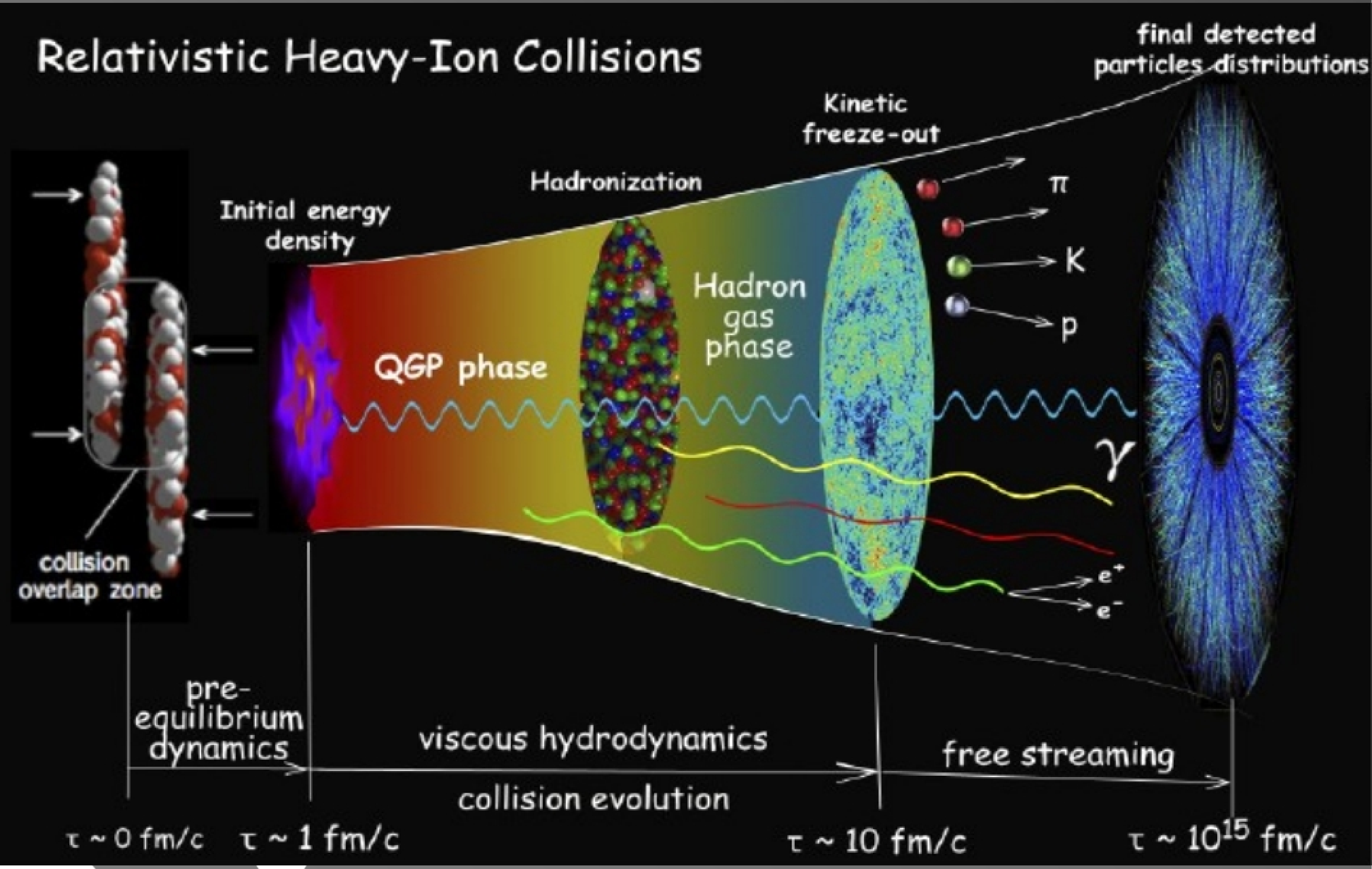
- Phase Transition from Hadron Gas to Quark Gluon Plasma
  - High temperature, low baryon density – smooth crossover
  - Lower T, higher μ_B – 1st order phase transition, with a critical point


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

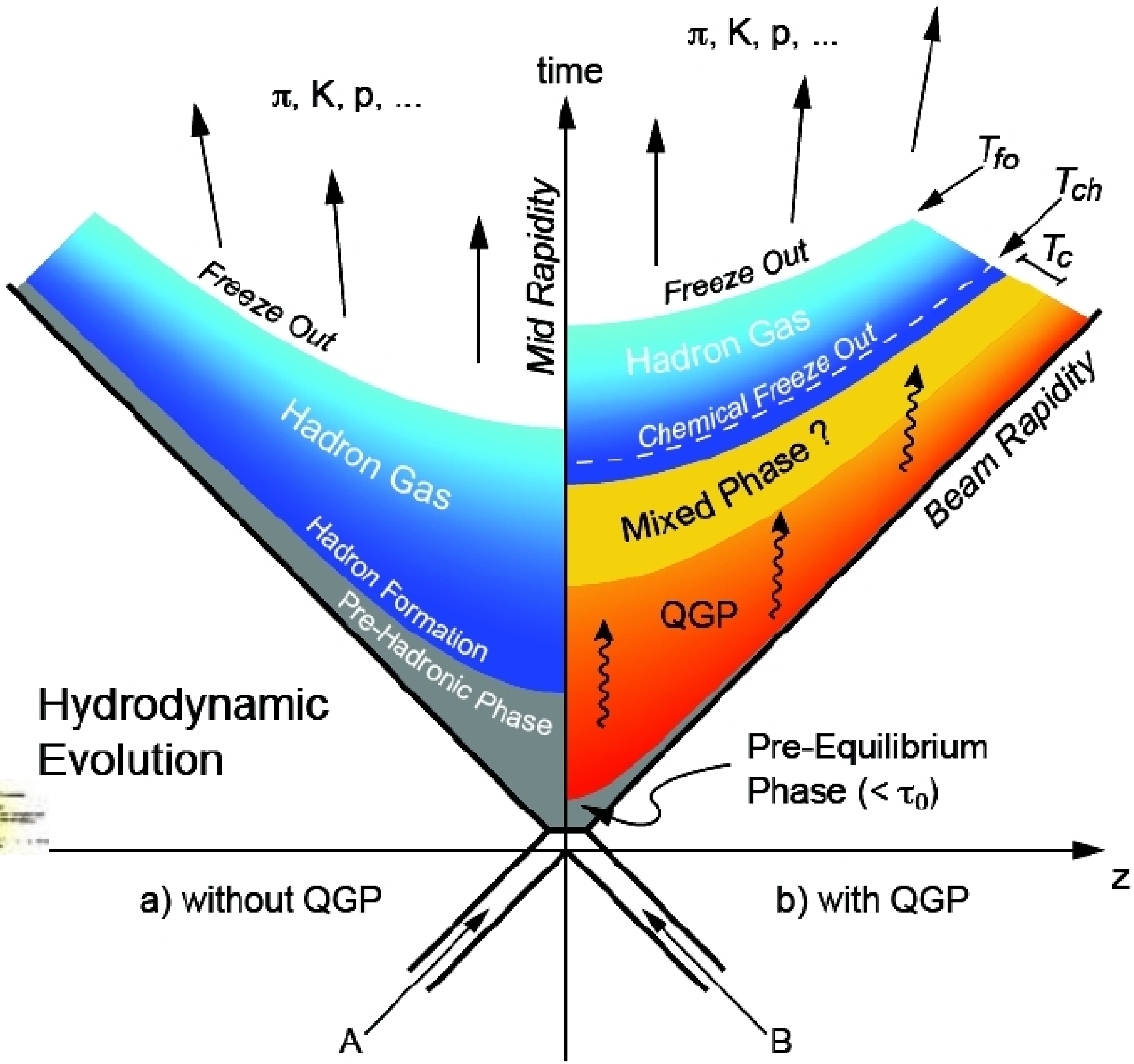
Create Quark Gluon Plasma in a laboratory

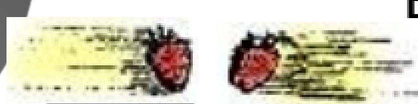


Create Quark Gluon Plasma in a laboratory

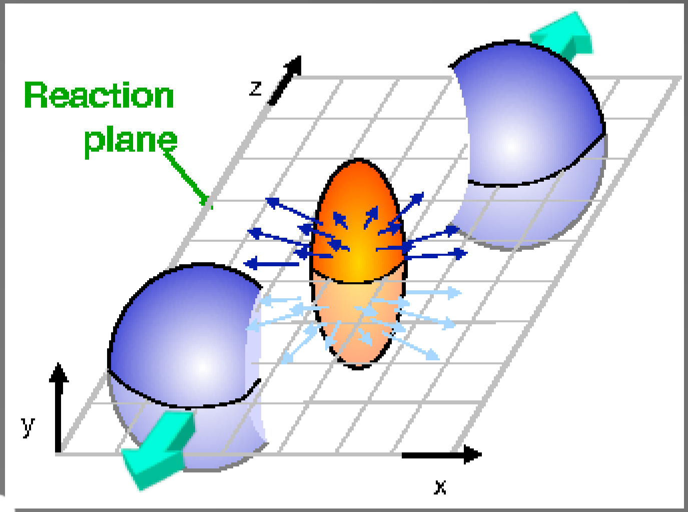

Relativistic Heavy-Ion Collisions
final detected particles distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e^+
e^-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^{15} fm/c

Collision evolution





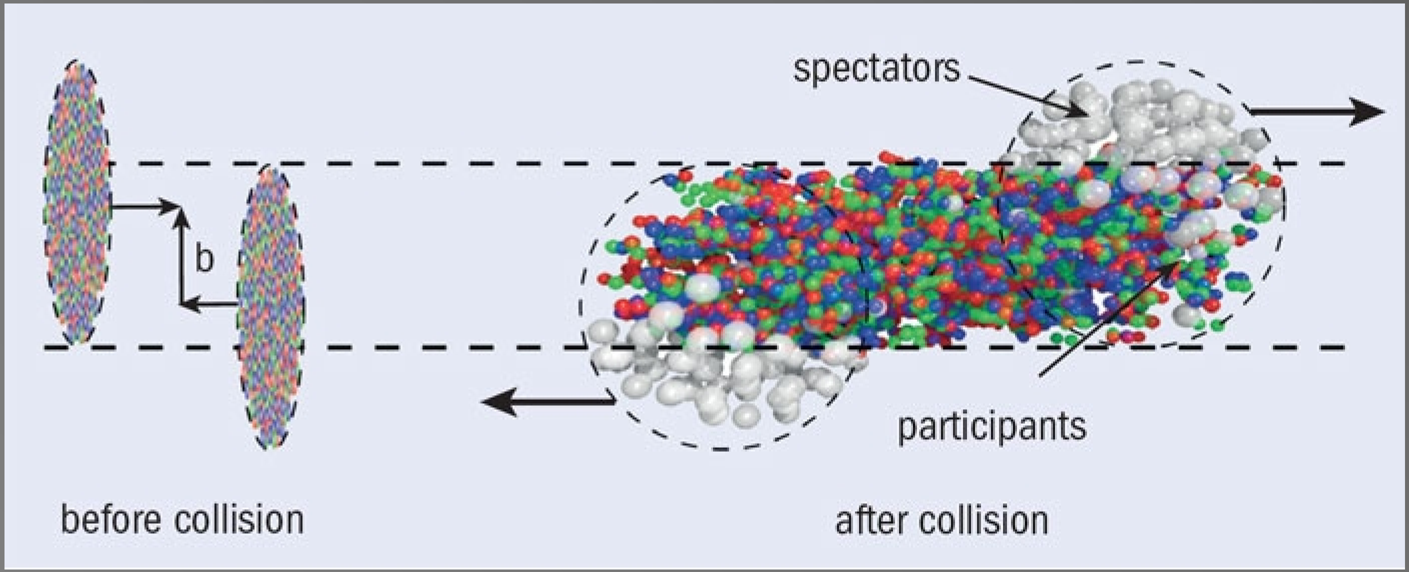
Collision geometry



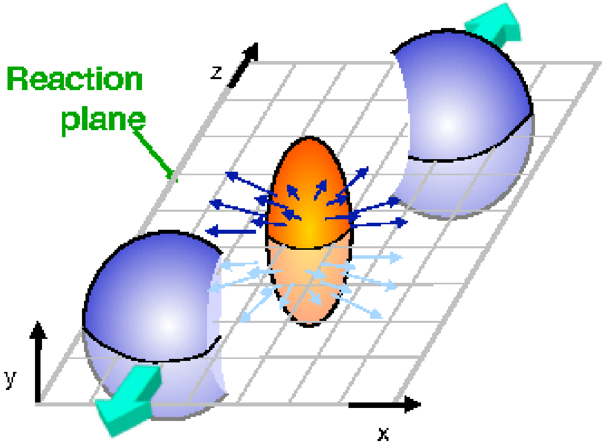
- Central collisions: $b \sim 0$
- Peripheral: $b \sim b_{max}$

- Number of participants (N_{part}): number of incoming nucleons in the overlap region
- Number of binary collisions (N_{bin}): number of inelastic nucleon-nucleon collisions

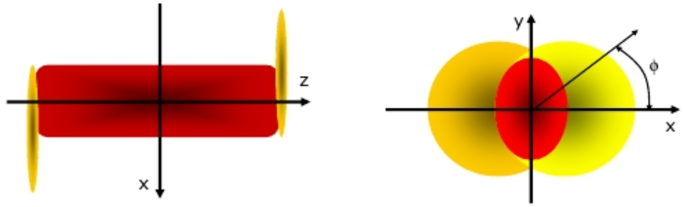
Non-central collision



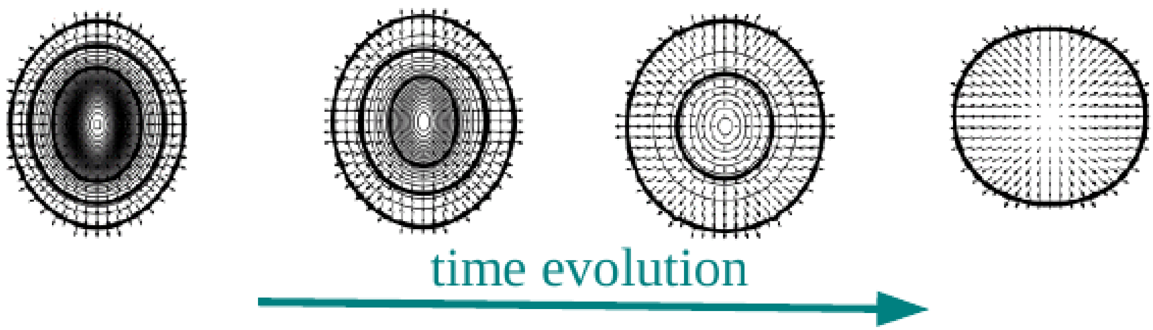
Elliptic flow

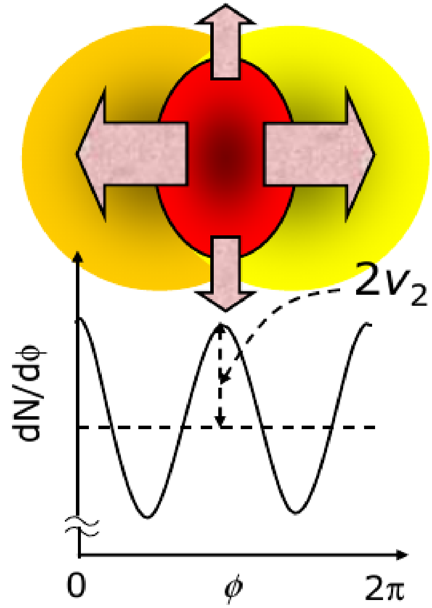


- Initial spacial anisotropy



- Final momentum anisotropy

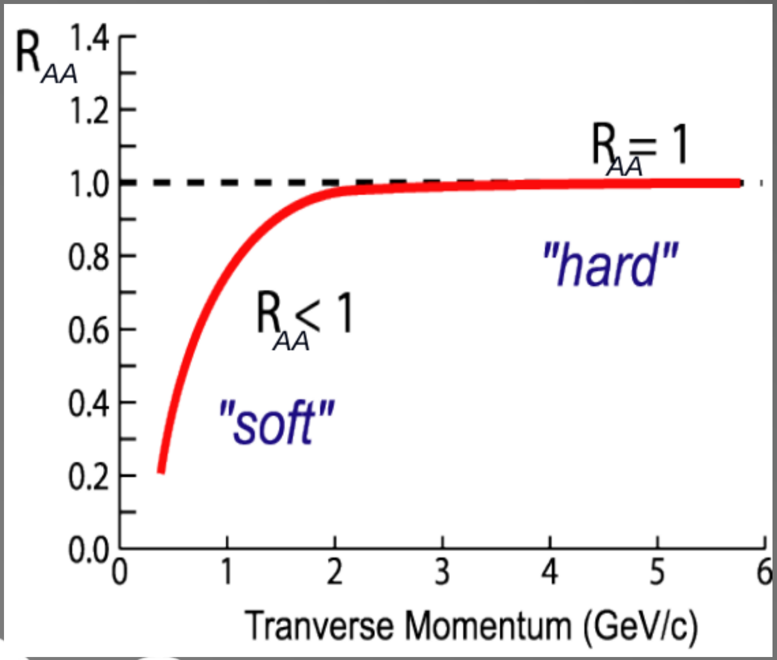




Azimuthal momentum distribution expanded into Fourier series:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \cdots\right]$$

Nuclear modification factor

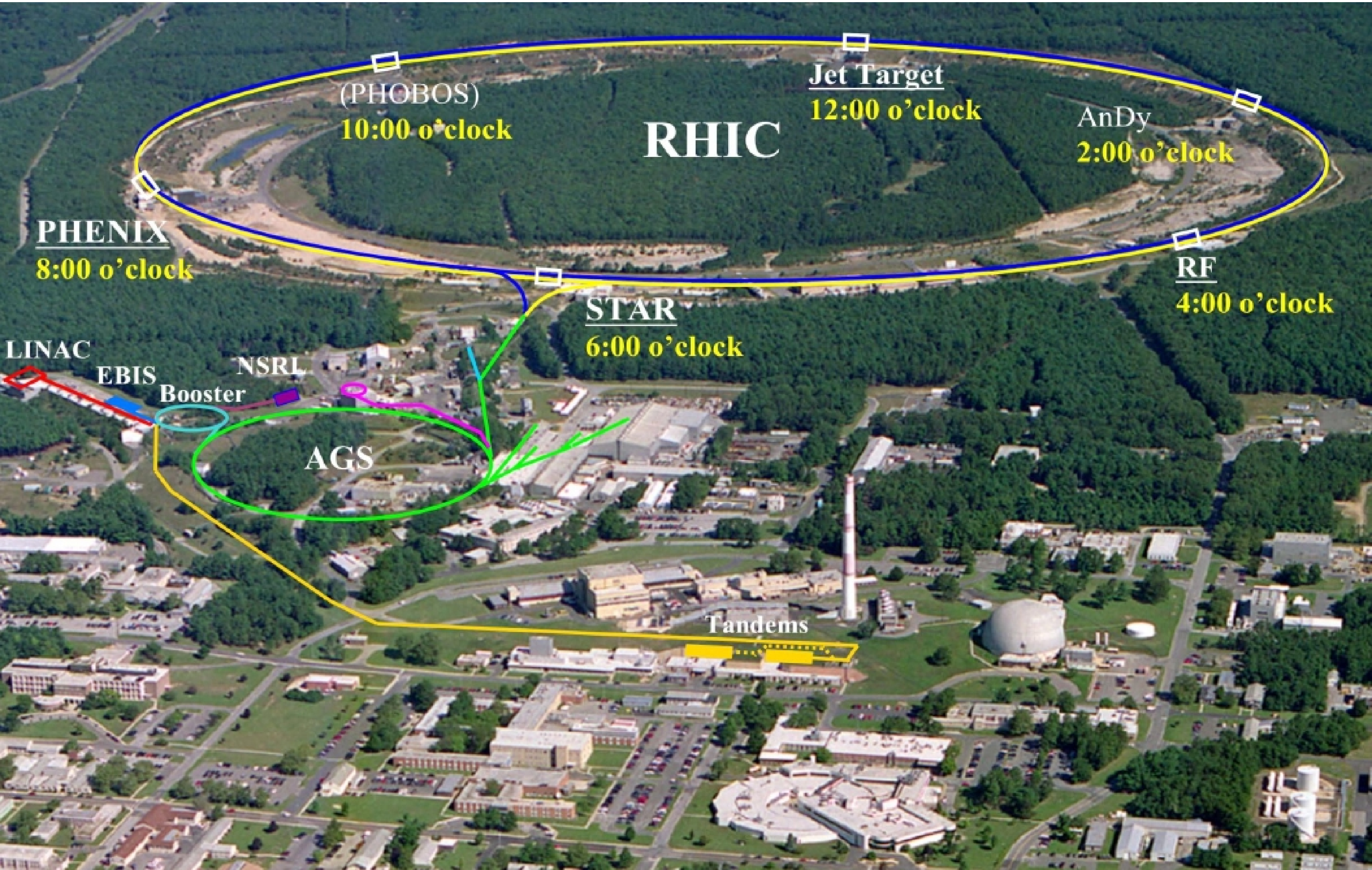


Particle production in A+A compare to p+p

$$R_{AA}(p_T) = \frac{\mathrm{Yield}_{AA}(p_T)}{\langle Nbin \rangle_{AA} \mathrm{Yield}_{pp}(p_T)}$$

- No medium effect:
  - $R_{AA} < 1$ in regime of soft physics
  - $R_{AA} = 1$ at high p_T – hard scattering dominates – A+A superposition of p+p
- Suppression:
  - $R_{AA} < 1$ at high p_T

Relativistic Heavy Ion Collider



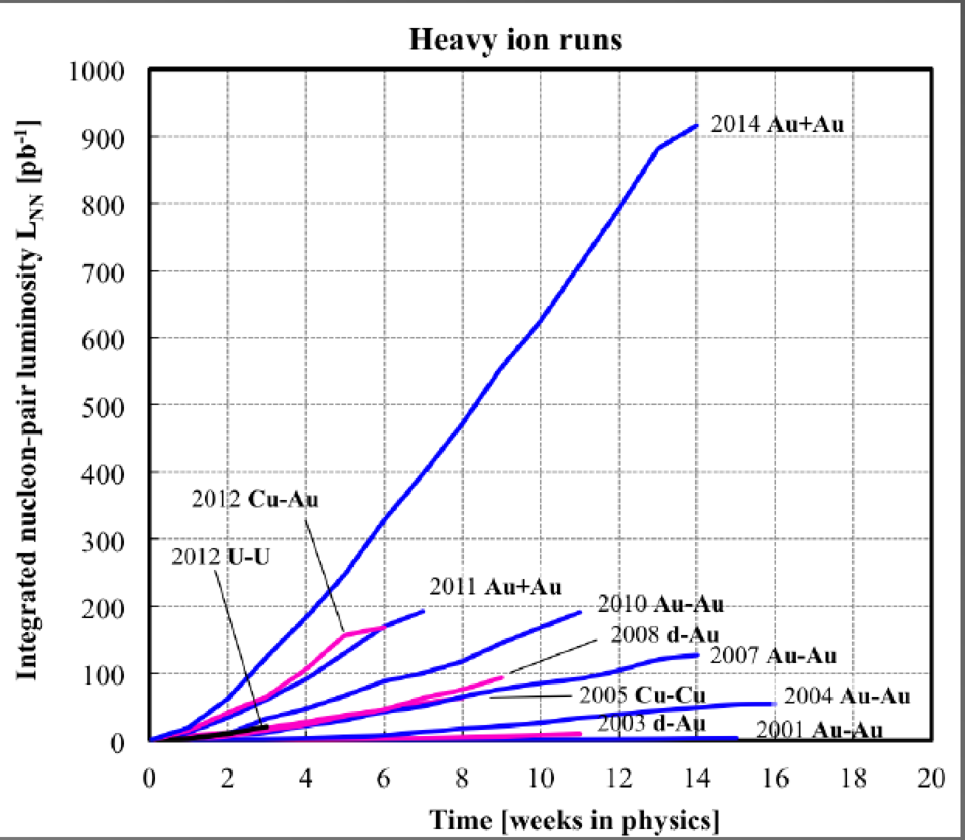
Relativistic Heavy Ion Collider

RHIC Heavy Ion Collisions

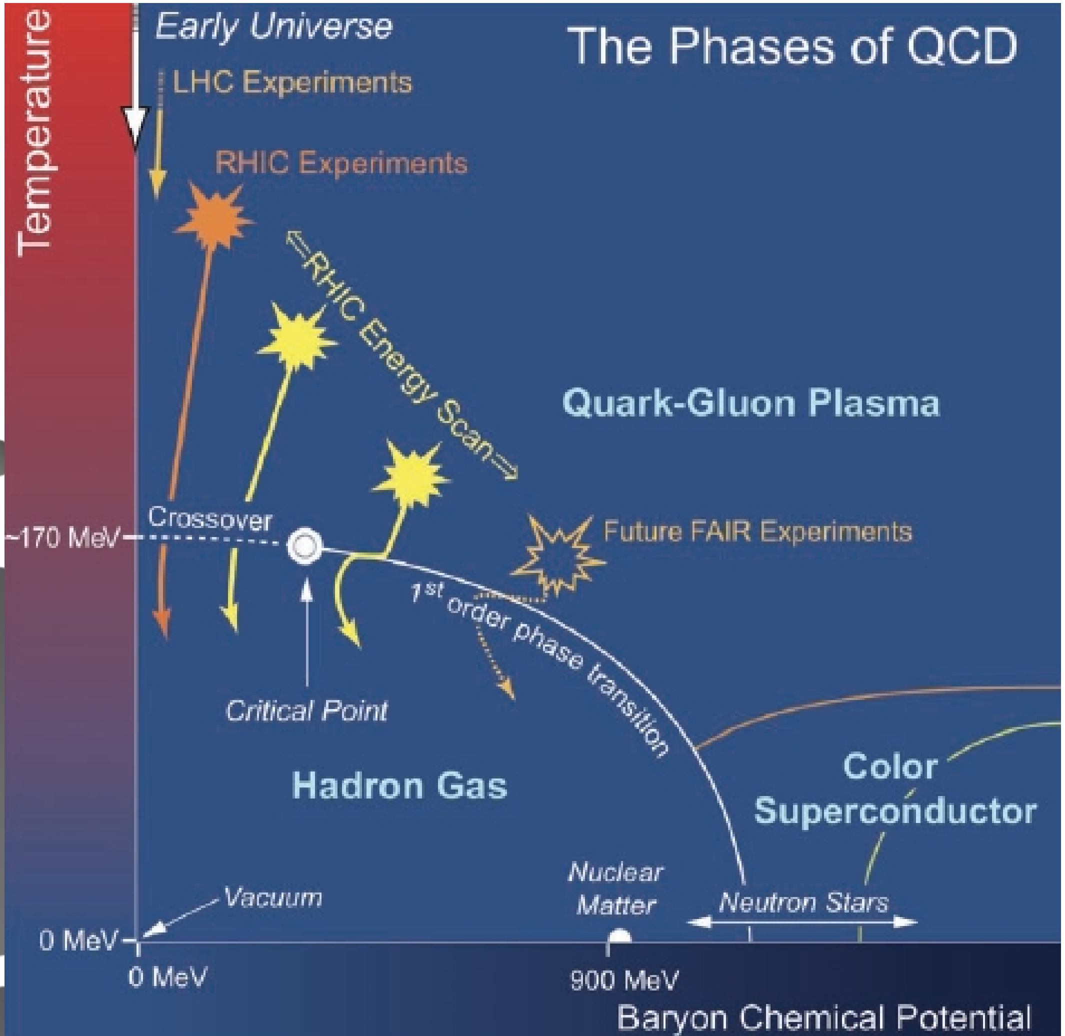
- Different species at different CMS energies

Year	System	$\sqrt{s_{NN}}$ [GeV]
2000	Au+Au	130
2001	Au+Au	200
2002	p+p	200
2003	d+Au	200
2004	Au+Au p+p	200, 62.4 200
2005	Cu+Cu	200, 62.4, 22
2006	p+p	62.4, 200, 500
2007	Au+Au	200
2008	d+Au p+p Au+Au	200 200 9.2
2009	p+p	200, 500
2010	Au+Au	200, 62.4, 39, 11.5, 7.7
2011	Au+Au p+p	200,19.6,27 500
2012	U+U Cu+Au p+p	193 200 200,510
2013	p+p	254.9
2014	Au+Au He+Au	7.3, 100 100

- More data each year



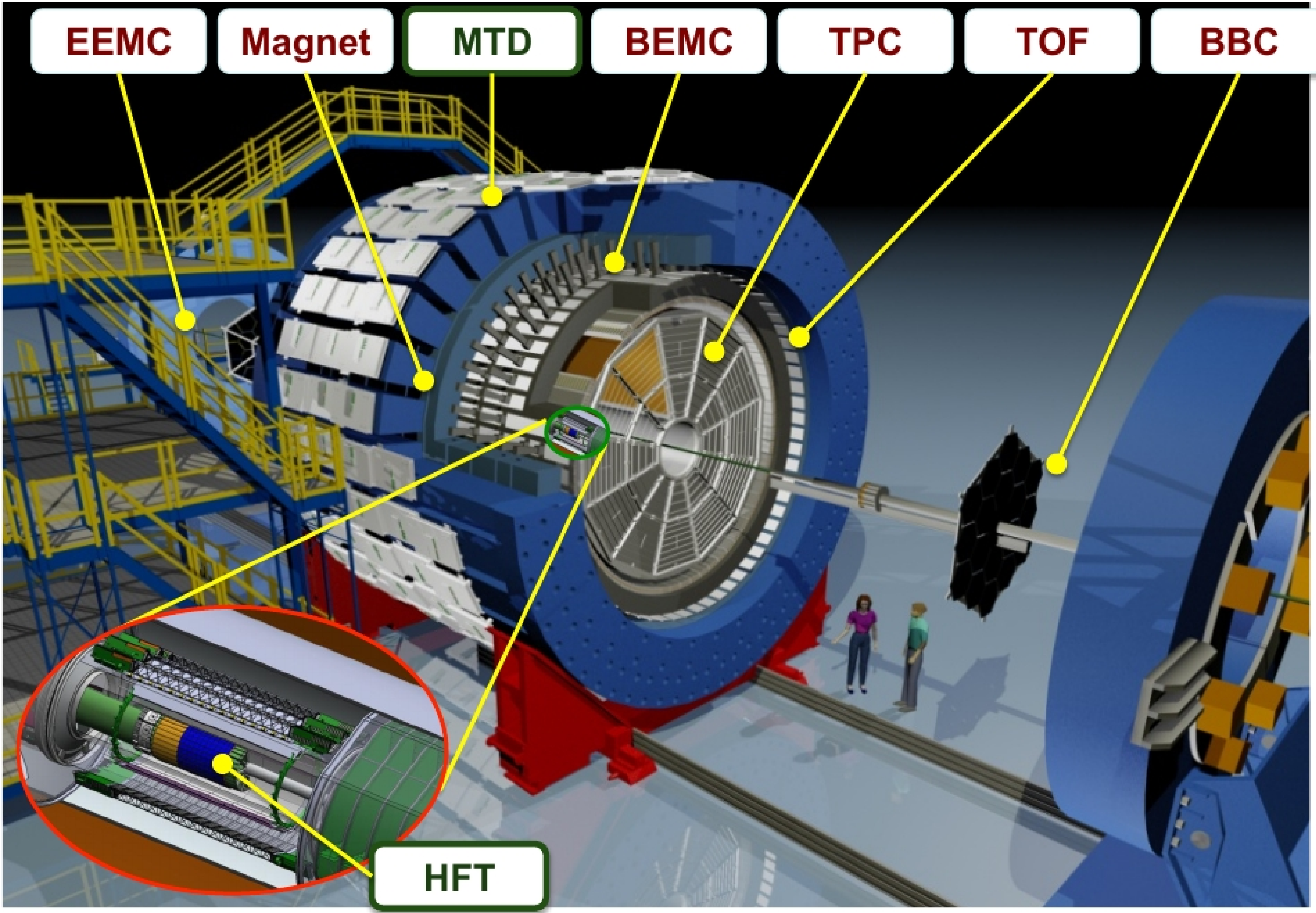
Understanding QCD Phase Diagram



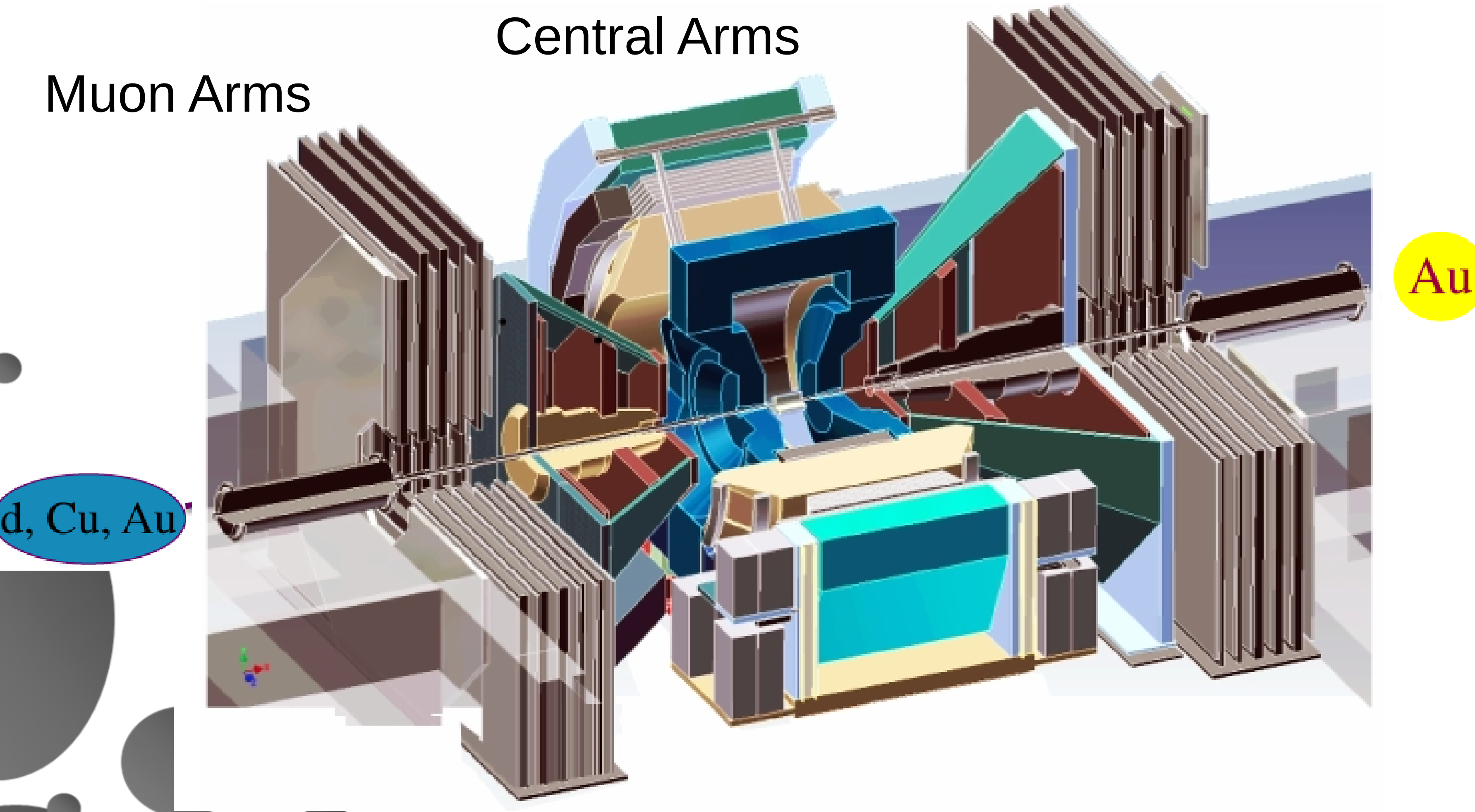
- Top RHIC energies
  - Hot and dense sQGP
  - Initial conditions
- Beam Energy Scan at RHIC
  - Study QCD phase structure
    - Phase boundary
    - QCD Critical point

→ So far: 7.7, 11.5, 14.5, 19.6, 27, 39 GeV
→ BES-II: focus on energies < 20 GeV

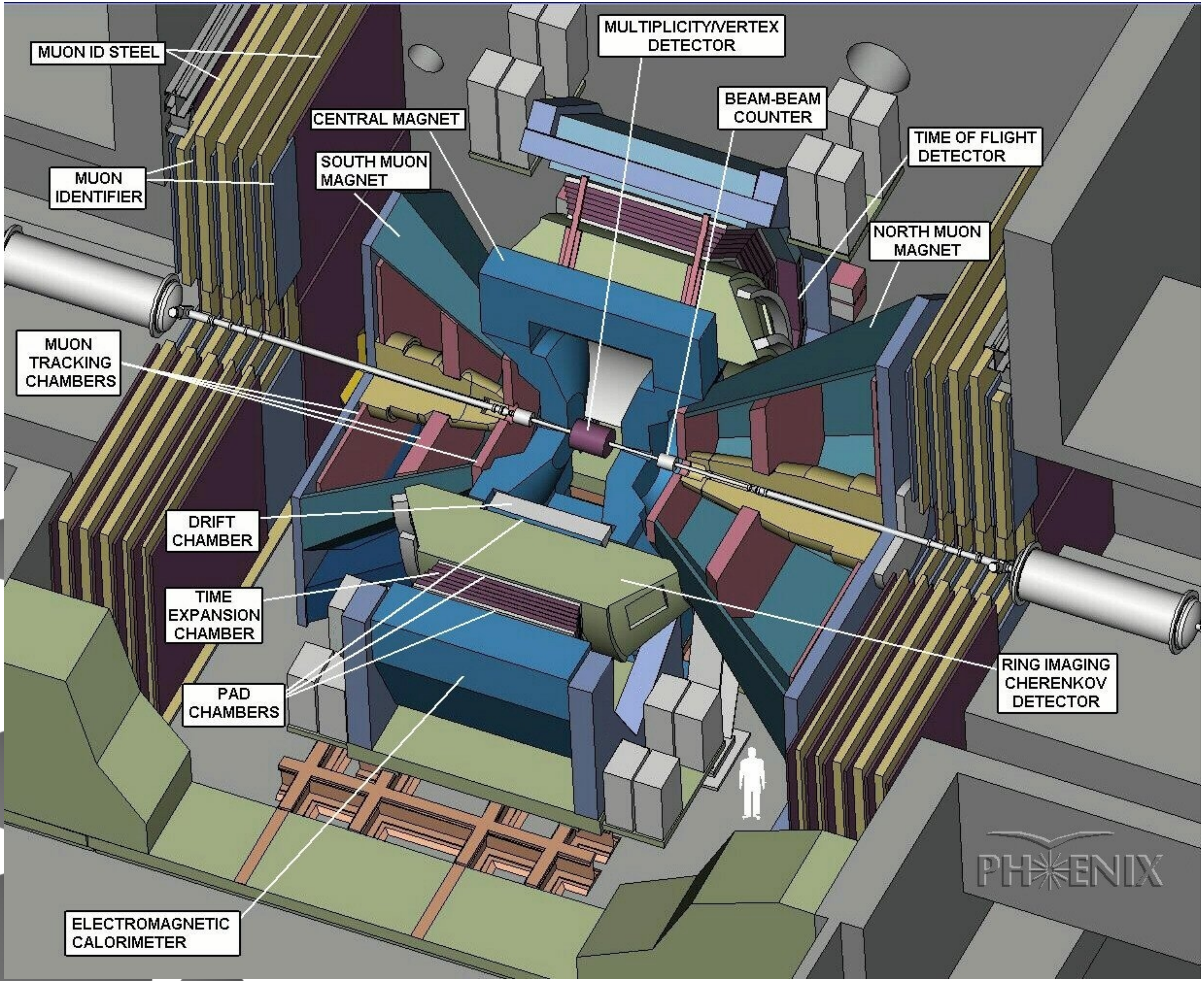
STAR Detector



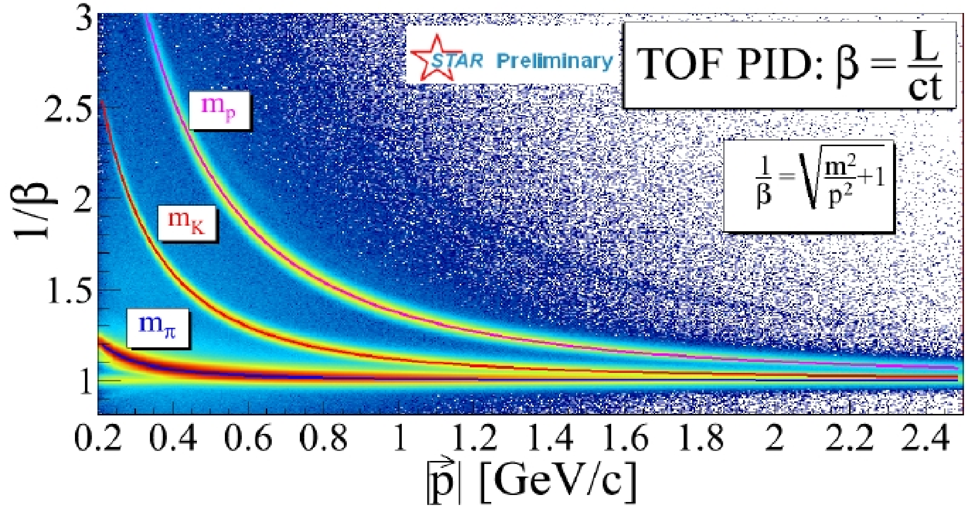
PHENIX Detector

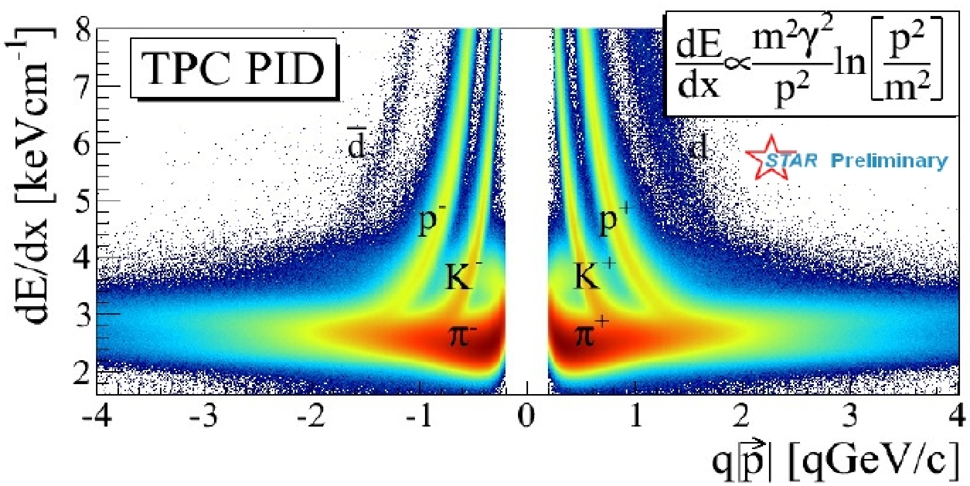


PHENIX Detector

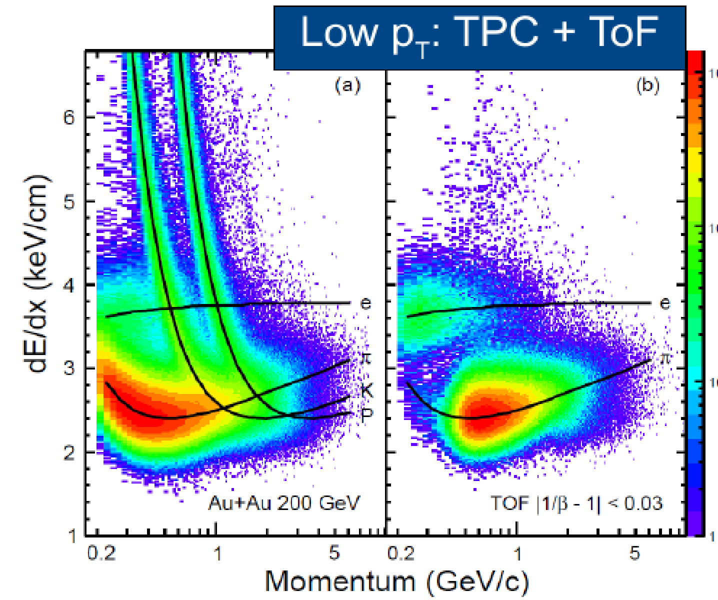


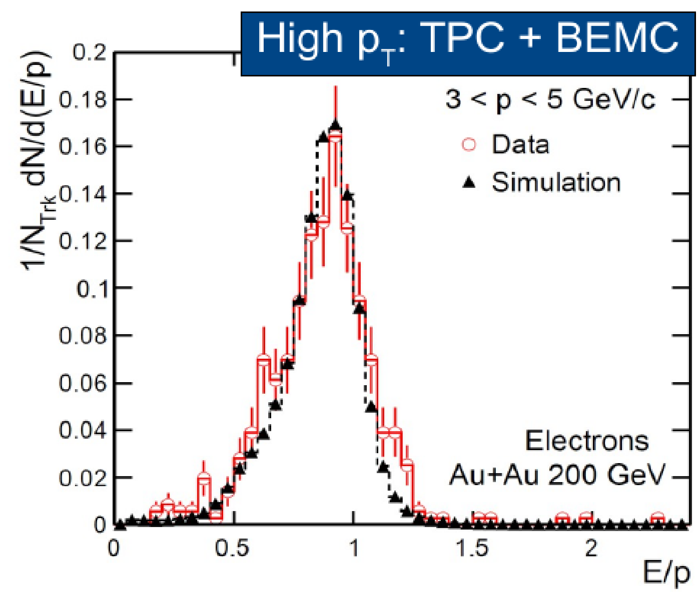
Particle identification





Electron Identification



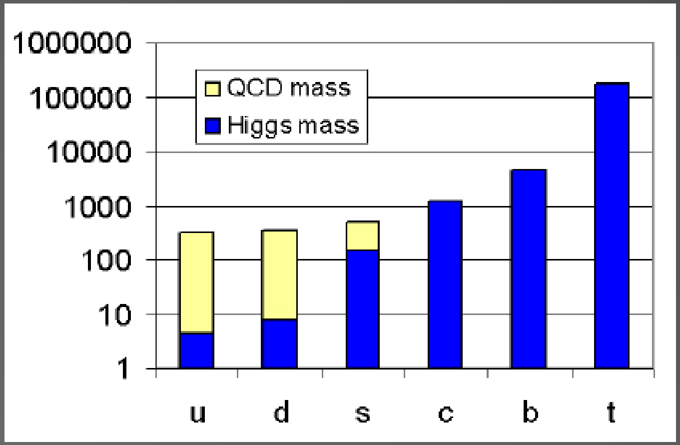


Heavy Flavor Physics

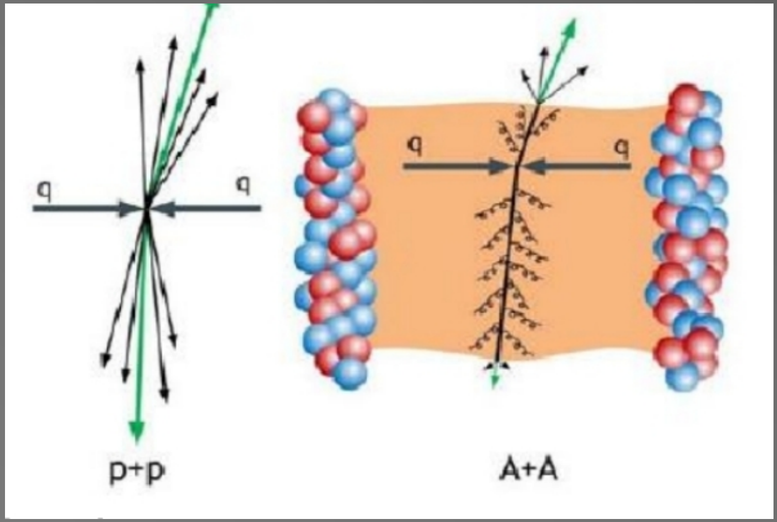
Why heavy flavor

Why heavy flavor

- Unique QGP probes
  - Produced in initial, hard scattering, stage of the collisions
  - Masses external to QCD
  - Sensitive to initial gluon density and distribution

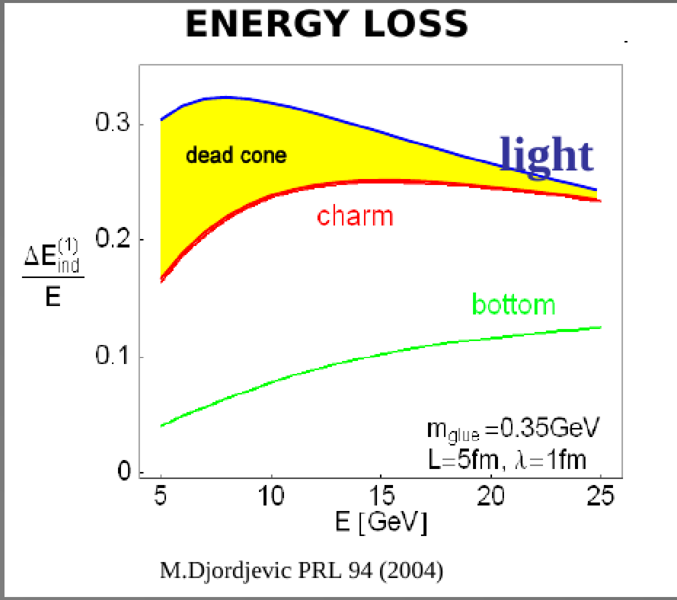


  - Interact with the medium differently from light quarks



Why heavy flavor

- Production and elliptic flow sensitive to dynamics of the medium – degree of the medium thermalization
- Parton energy loss mechanism
  - Medium induced gluon radiation



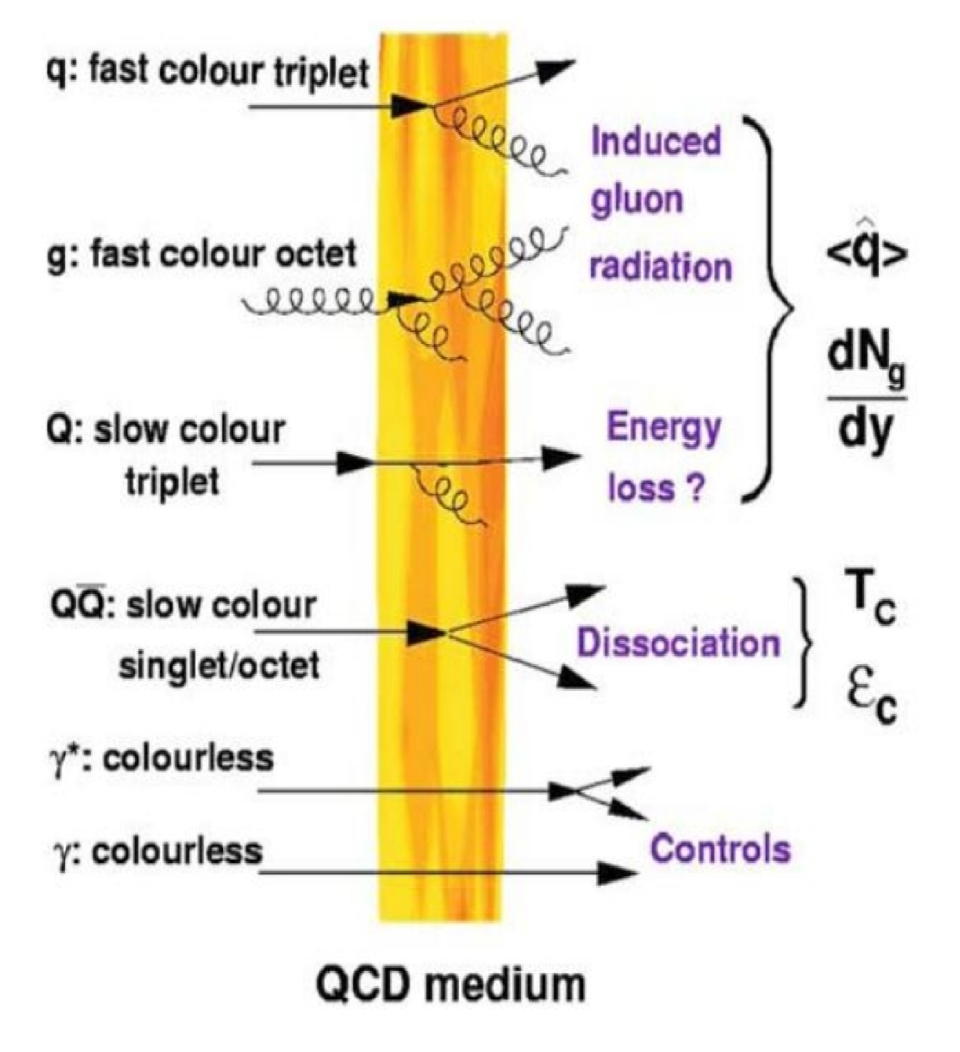
- Dead cone effect – reduction of emission probability in particle direction

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b ?$$

Energy loss

$$\Delta E = \Delta E_{coll} + \Delta E_{rad}$$

- Collisional energy loss – elastic scattering with the medium constituents (low momenta)
- Radiative energy loss – inelastic scattering (high momenta)

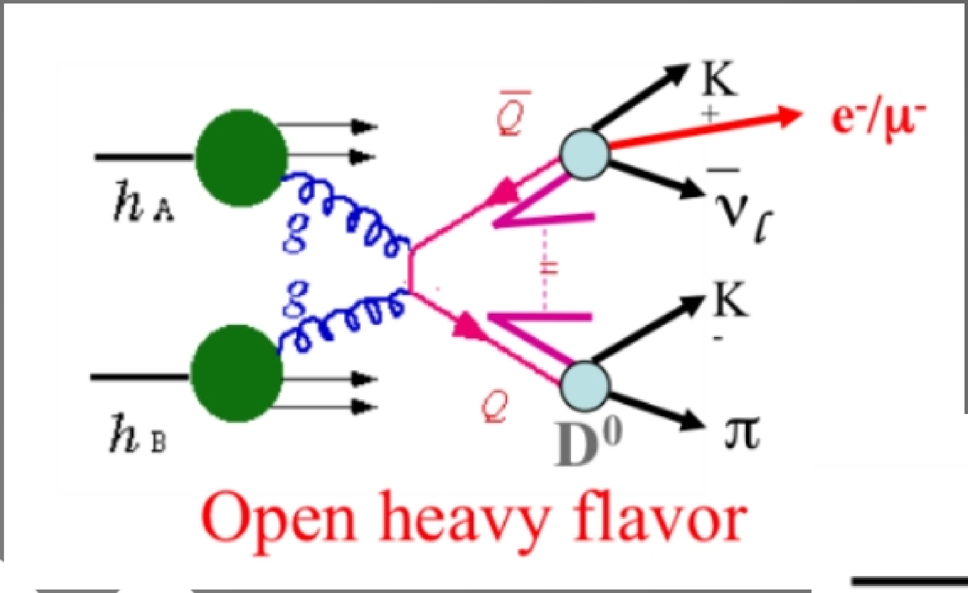


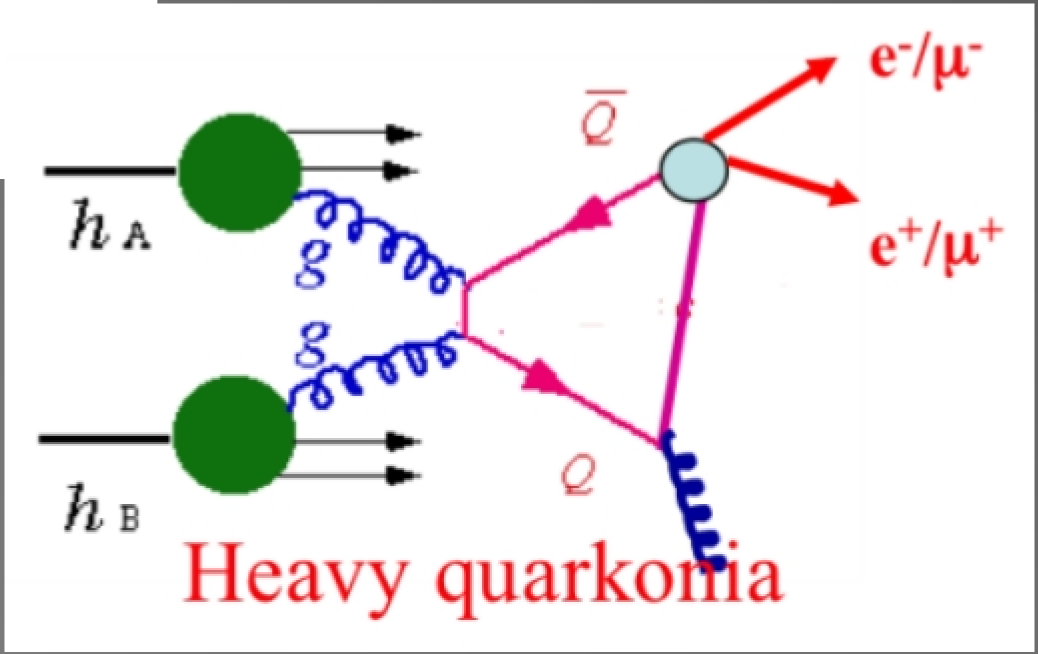
Heavy Flavor Physics at RHIC

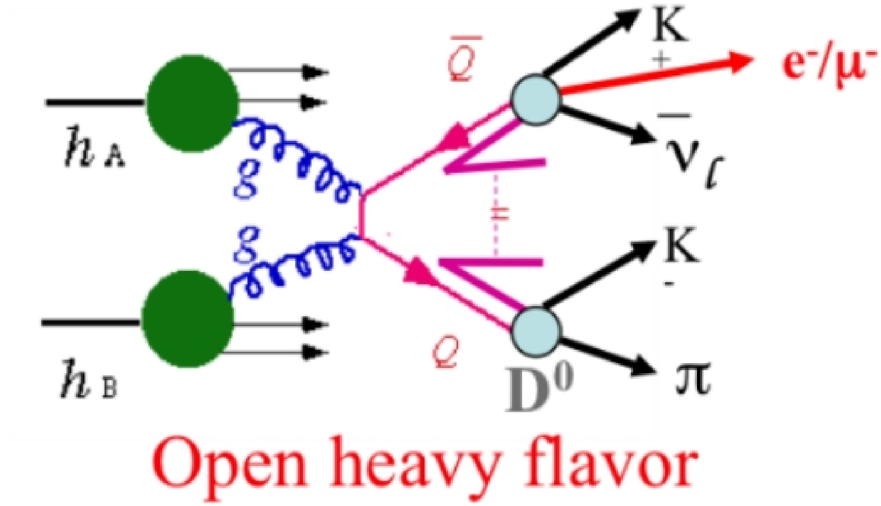
Selected A+A results

Heavy Flavor Physics at RHIC

Open Heavy Flavor and Quarkonia







Open Heavy Flavor

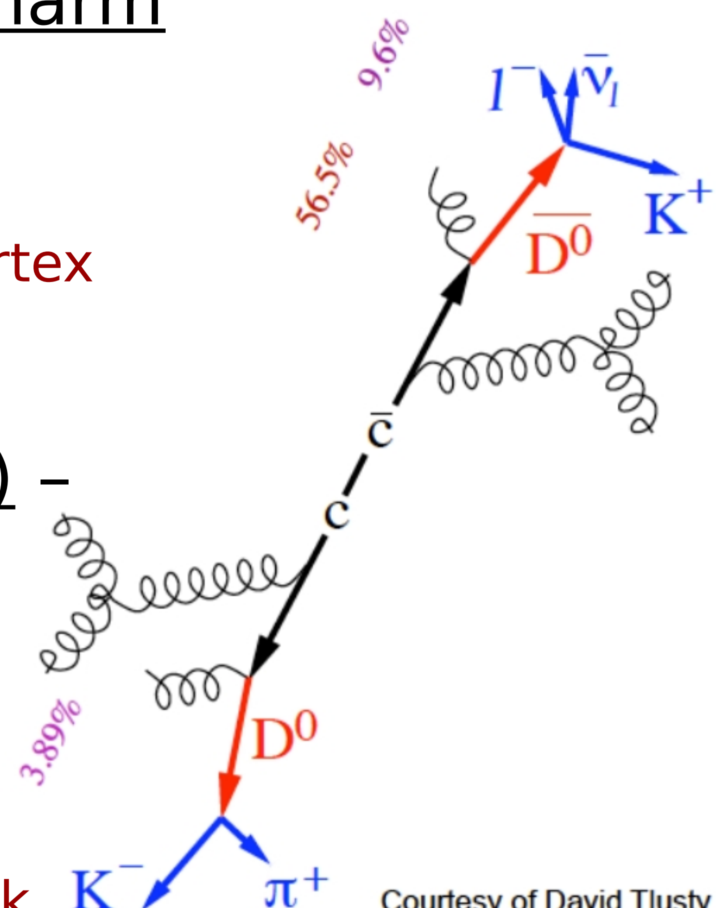
Open Heavy Flavor

➔ Direct reconstruction of open charm

- ✔ direct access to heavy quark kinematics
- ✗ high statistics compete with large combinatorial background w/o good vertex resolution
- ✗ difficult to trigger

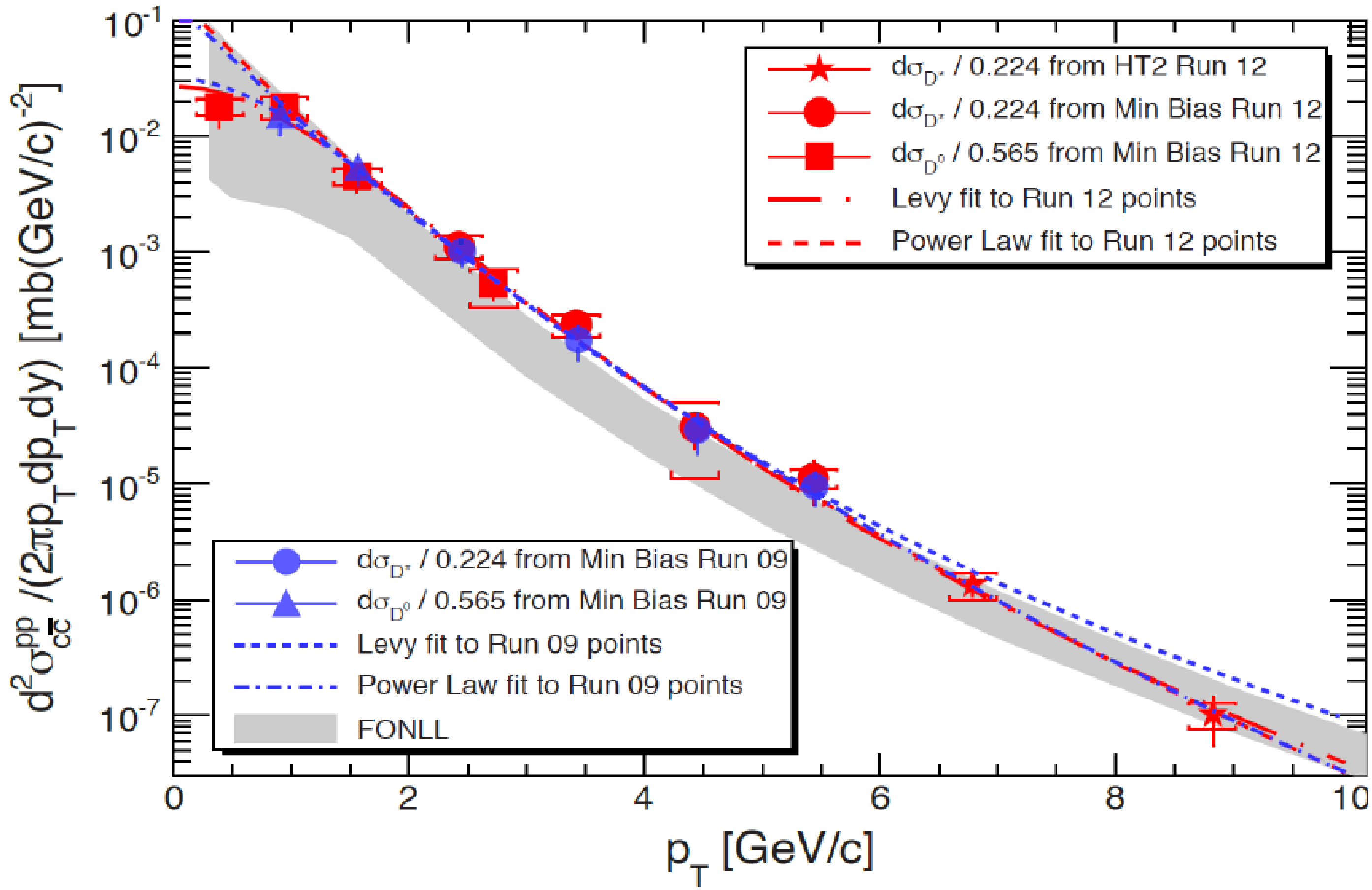
➔ Non-photonic electrons (NPE) – *electrons from semi-leptonic HF hadron decays*

- ✔ higher branching ratio
- ✔ easy to trigger
- ✗ indirect access to heavy quark kinematics
- ✗ contribution from c and b



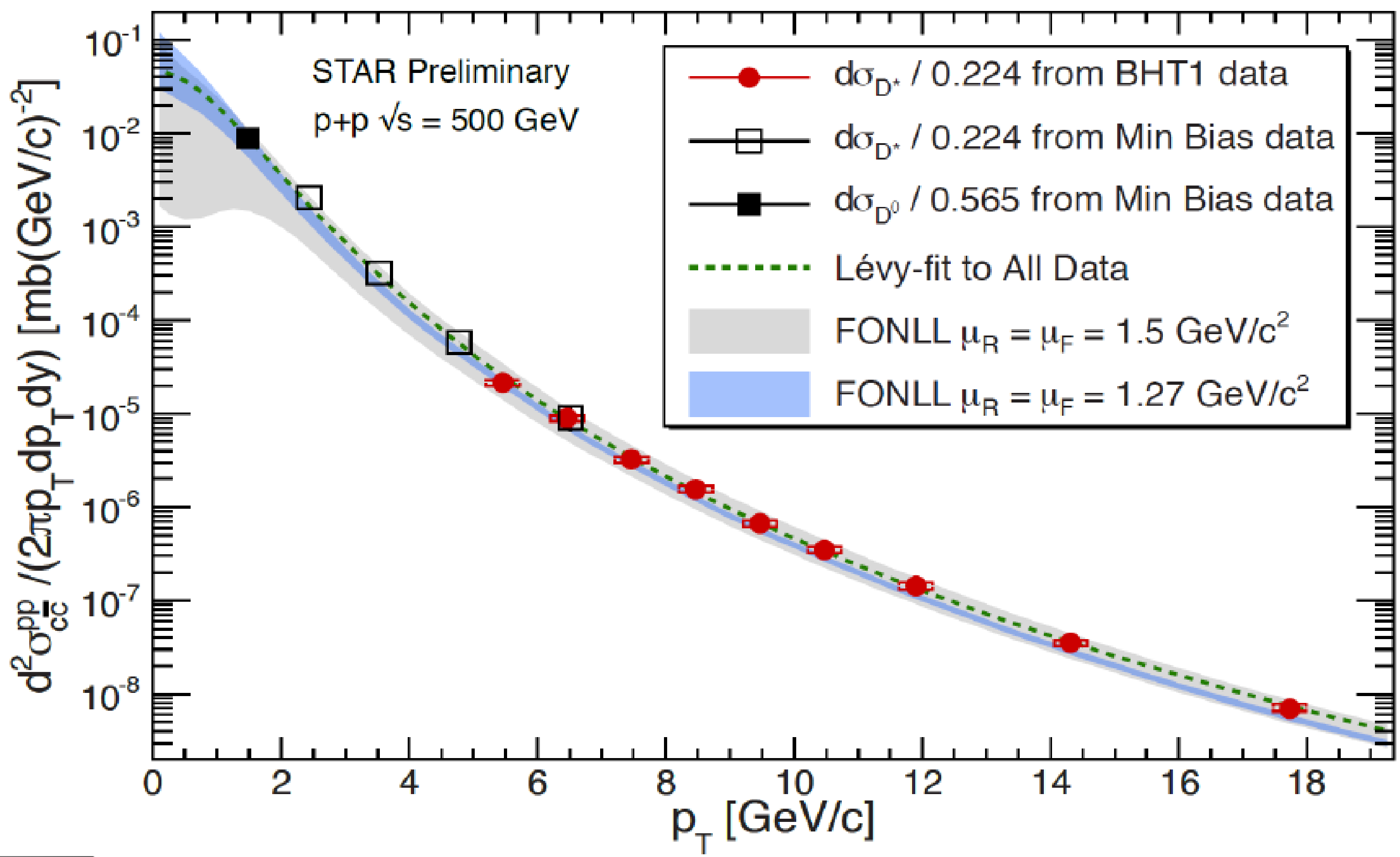
Courtesy of David Tlusty

D p_T spectra in p+p 200 GeV



➔Agreement with theoretical calculations

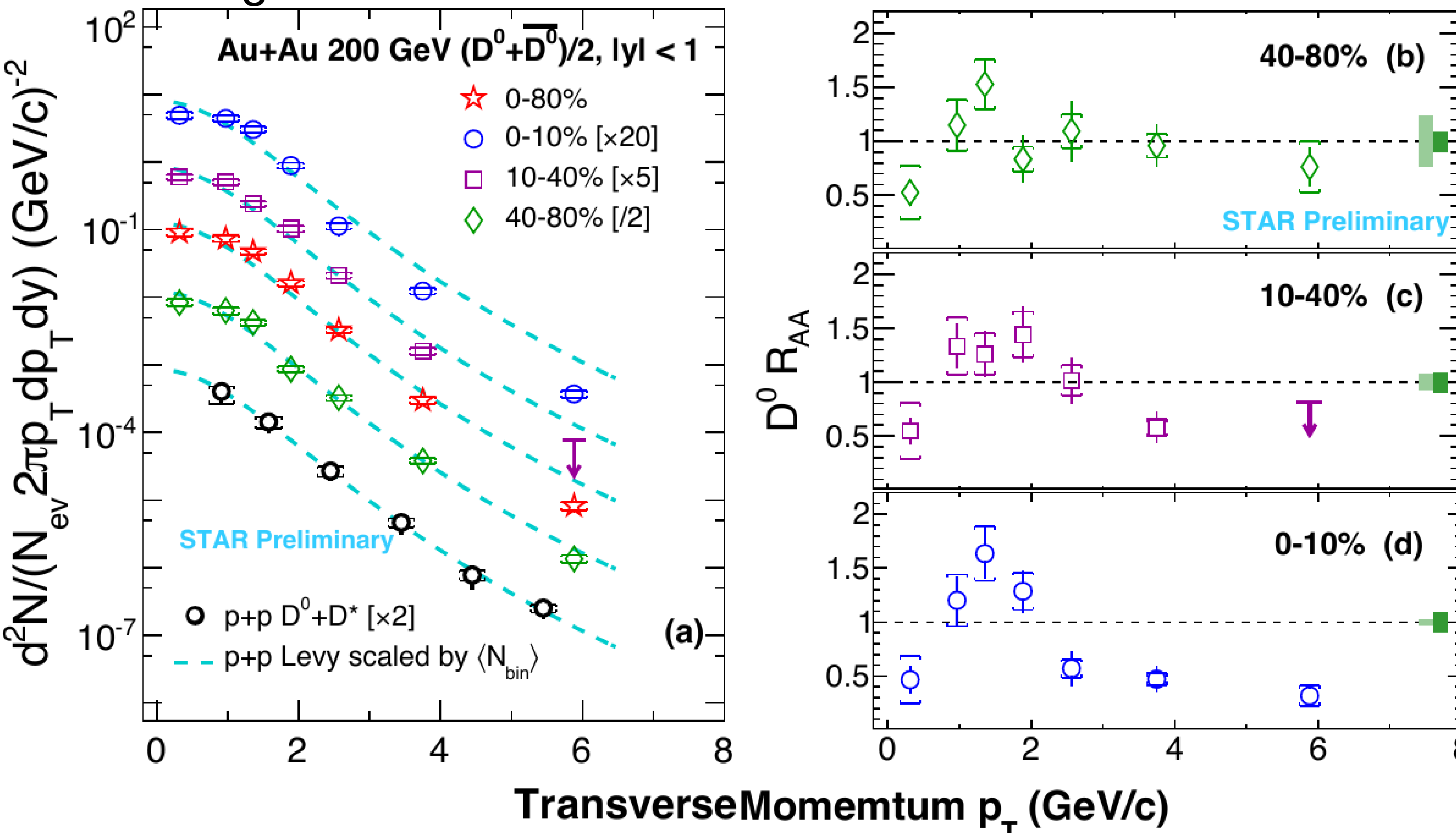
D p_T spectra in p+p 500 GeV



➔Agreement with theoretical calculations

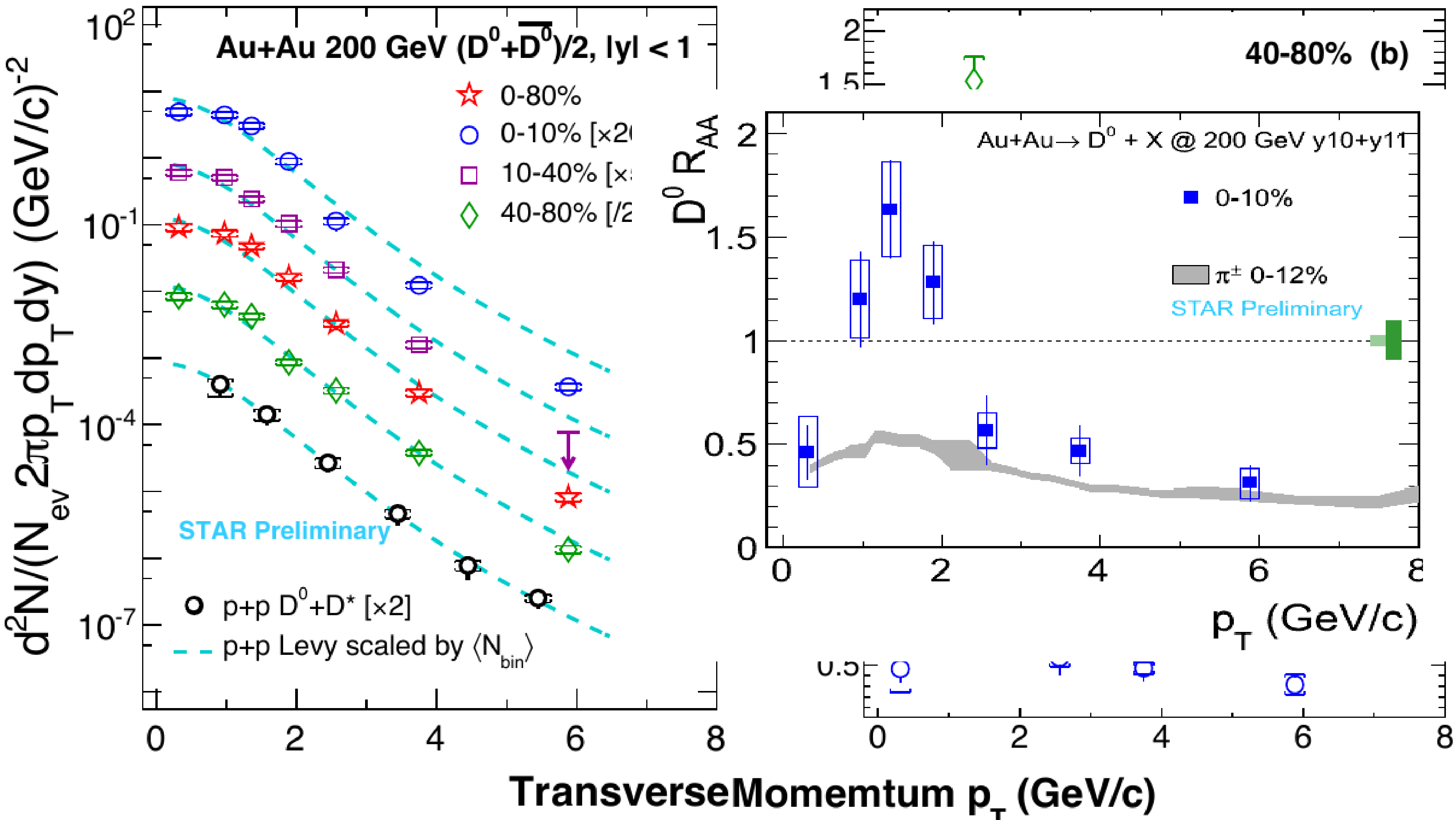
D in Au+Au 200 GeV

- ✓ In central collisions strong suppression at high p_T – strong charm-medium interaction



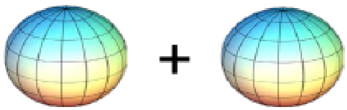
D in Au+Au 200 GeV

- ✓ Similar suppression to light hadrons



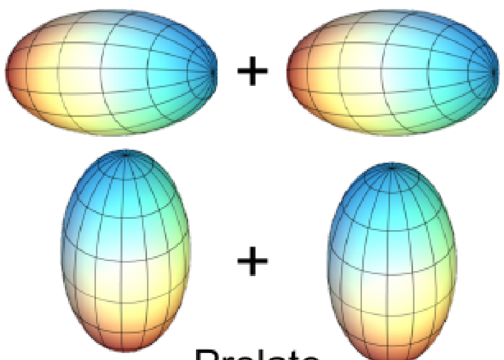
U+U Collisions

Au+Au Collisions



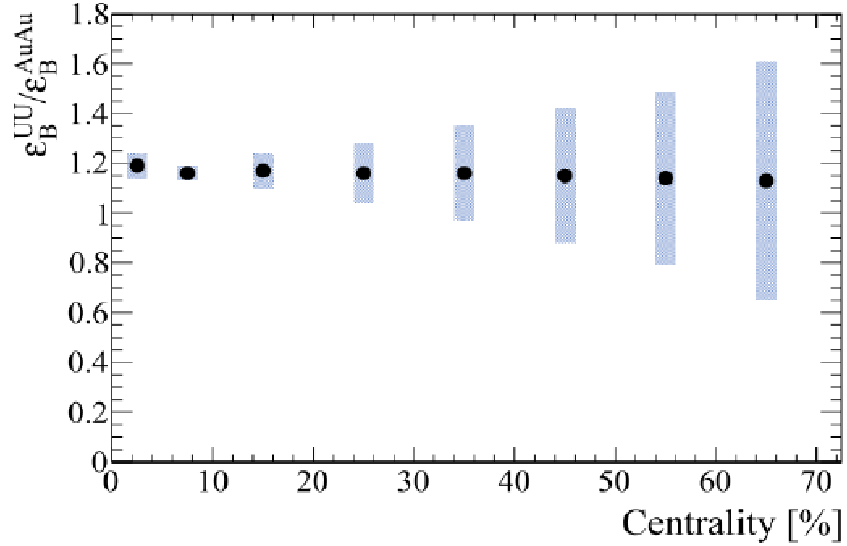
Oblate

U+U Collisions



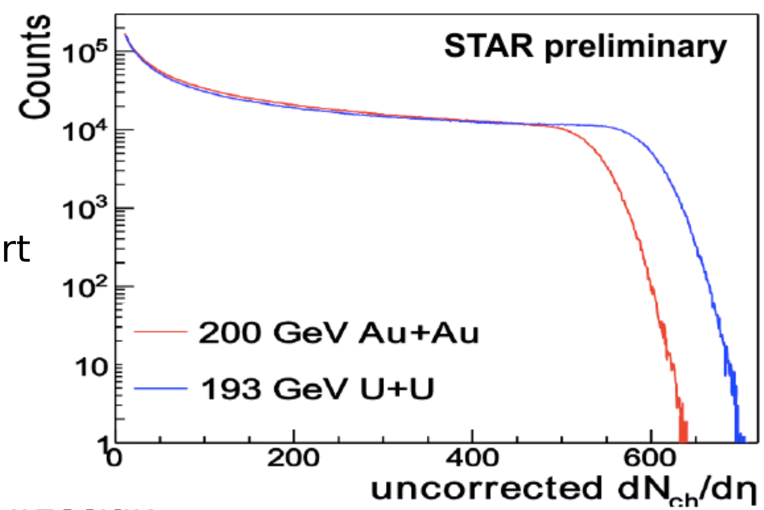
Prolate

Higher energy density



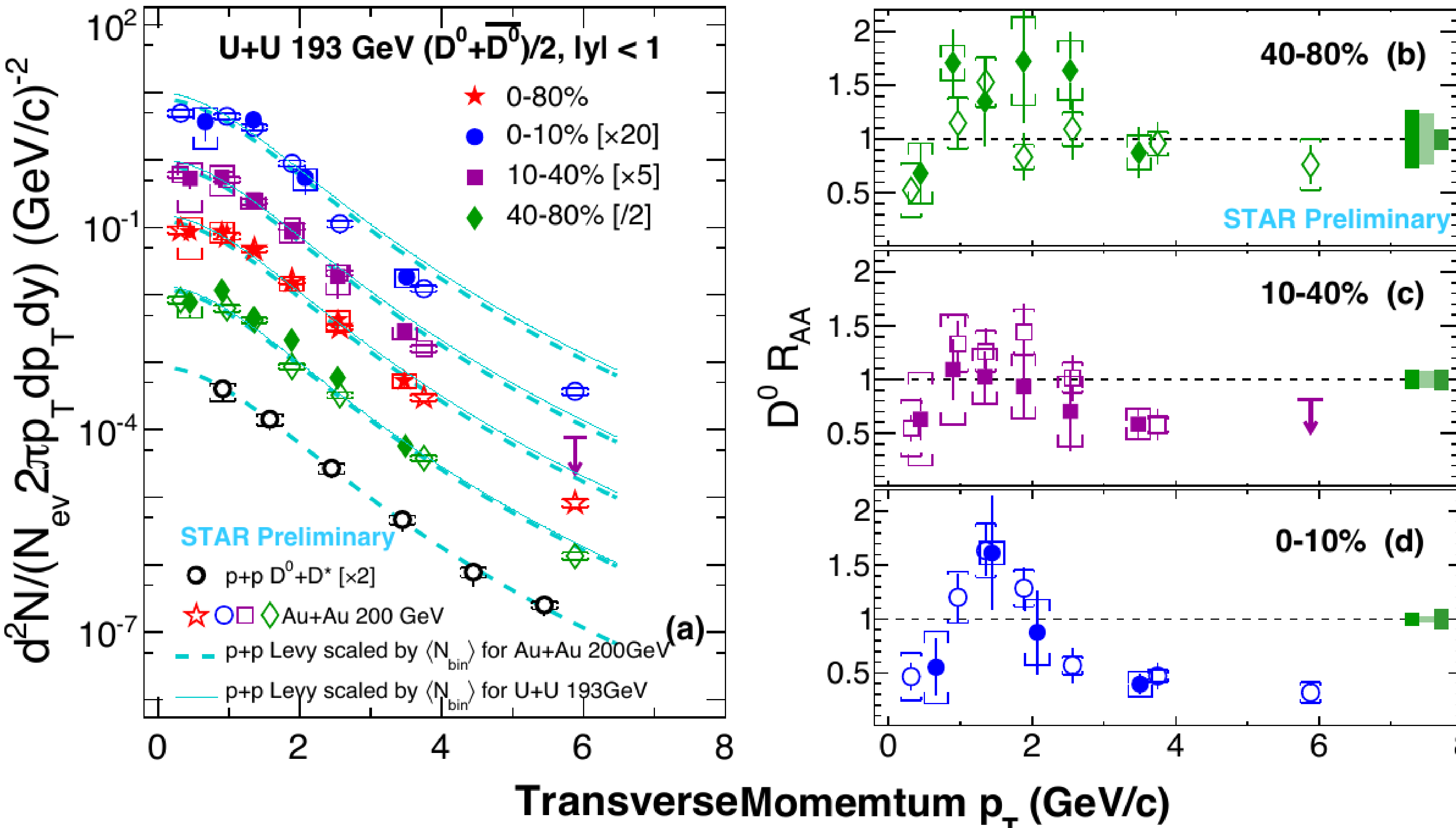
Kikola, Odyniec, Vogt, Phys. Rev. C 84, 054907

Higher N_{part}

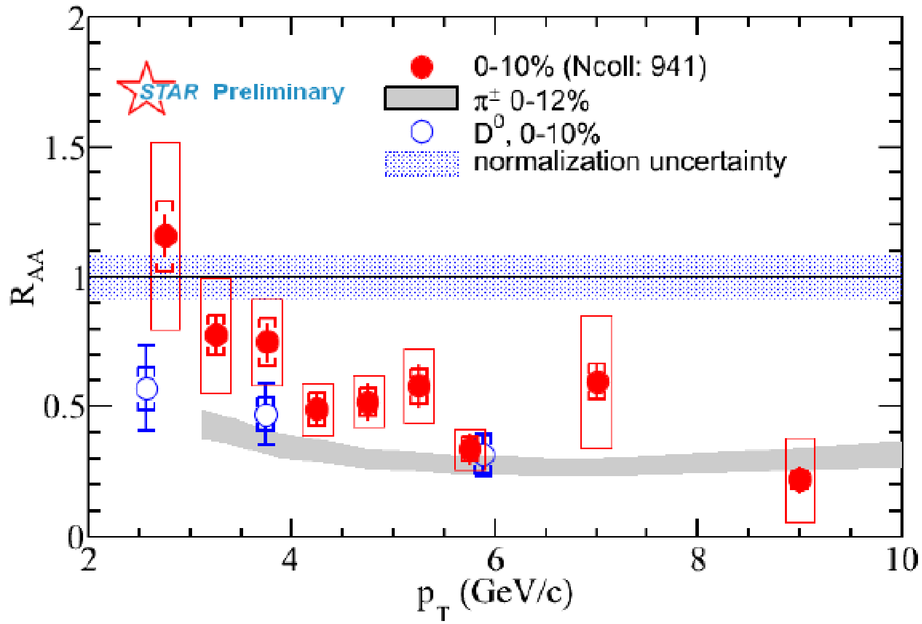


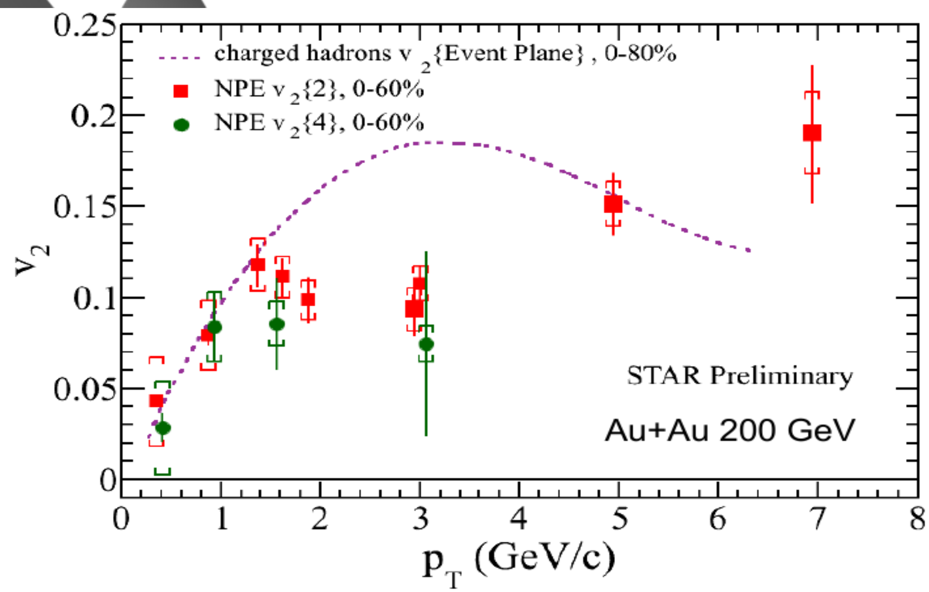
D in U+U 193 GeV

✓ Similar behavior in U+U and Au+Au



NPE in Au+Au 200 GeV



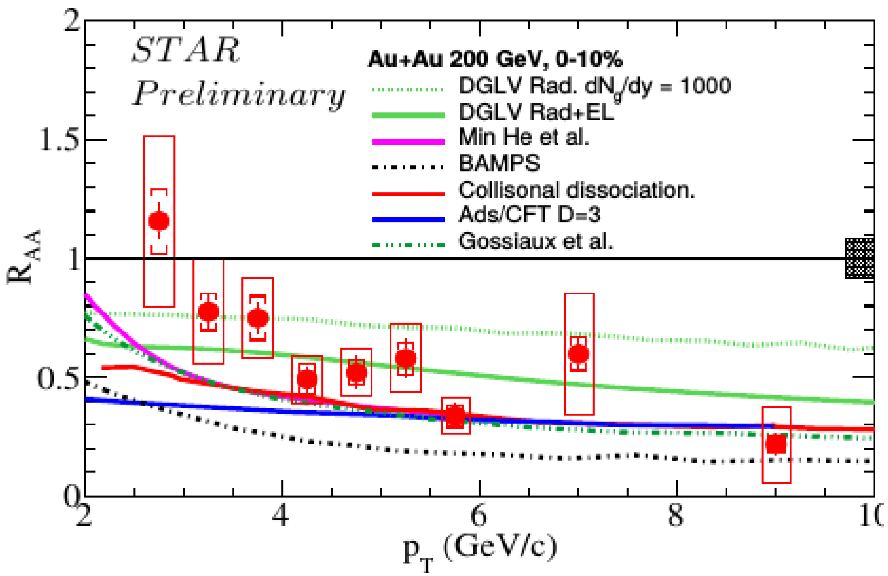


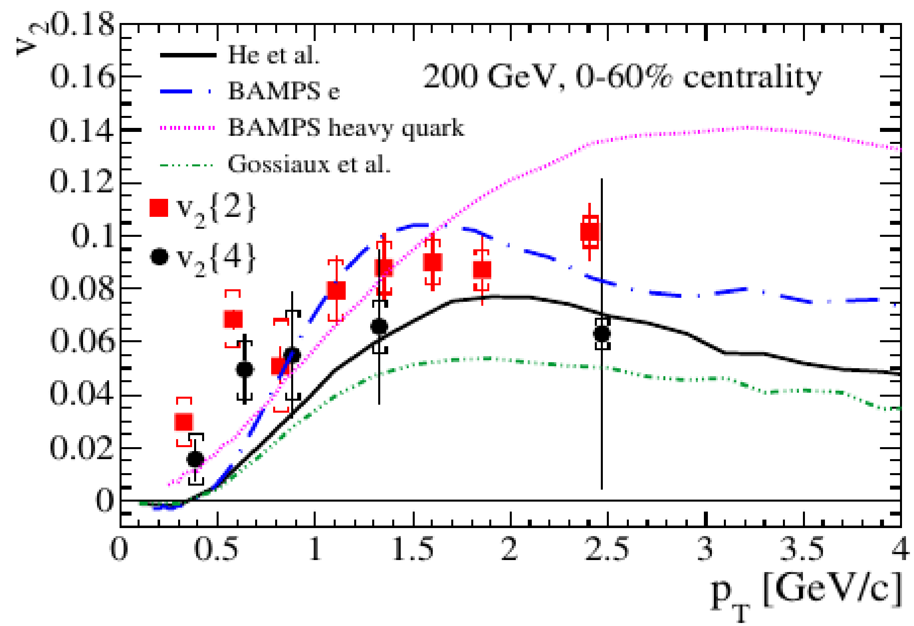
- ✓ Strong suppression at high p_T
  - Similar to D^0 mesons and light hadrons suppression

NPE includes both c and b

- ✓ Finite v_2 at low and intermediate p_T
- ➔ Suggests strong charm-medium interaction, but more precise measurements of D^0 v_2 are needed

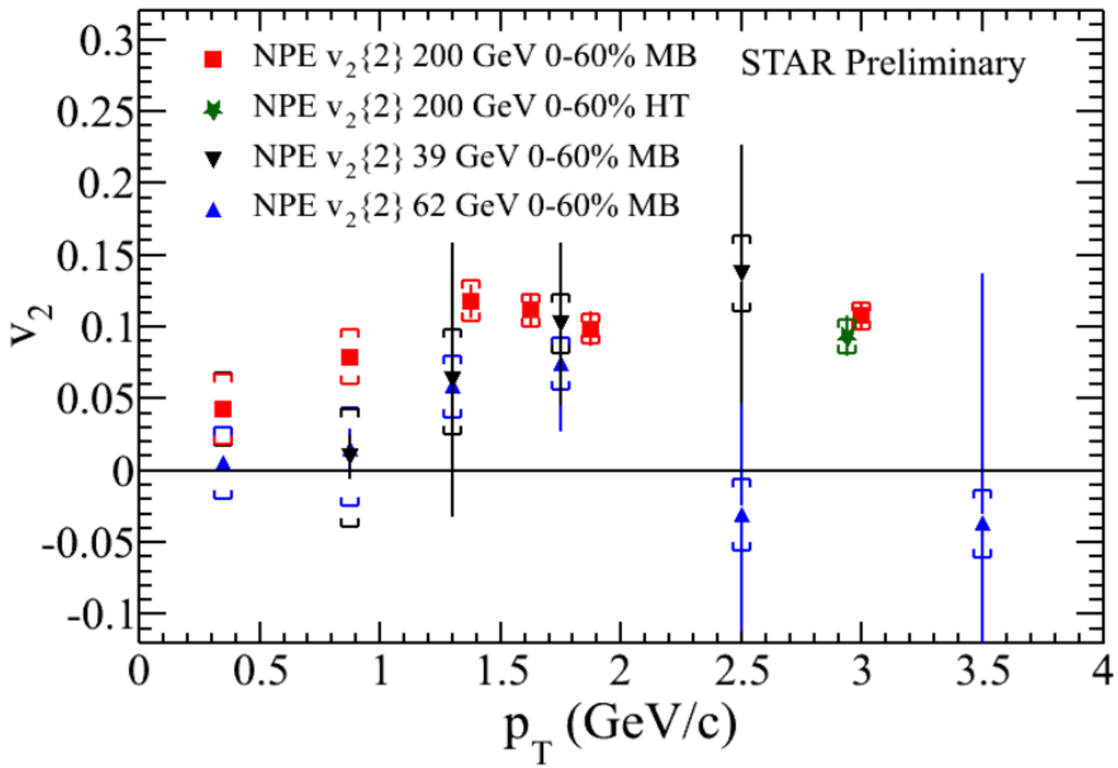
NPE in Au+Au 200 GeV





- ✓ Gluon radiation scenario alone fails to describe large NPE suppression
- ✓ No model can successfully explain the suppression and v_2 simultaneously

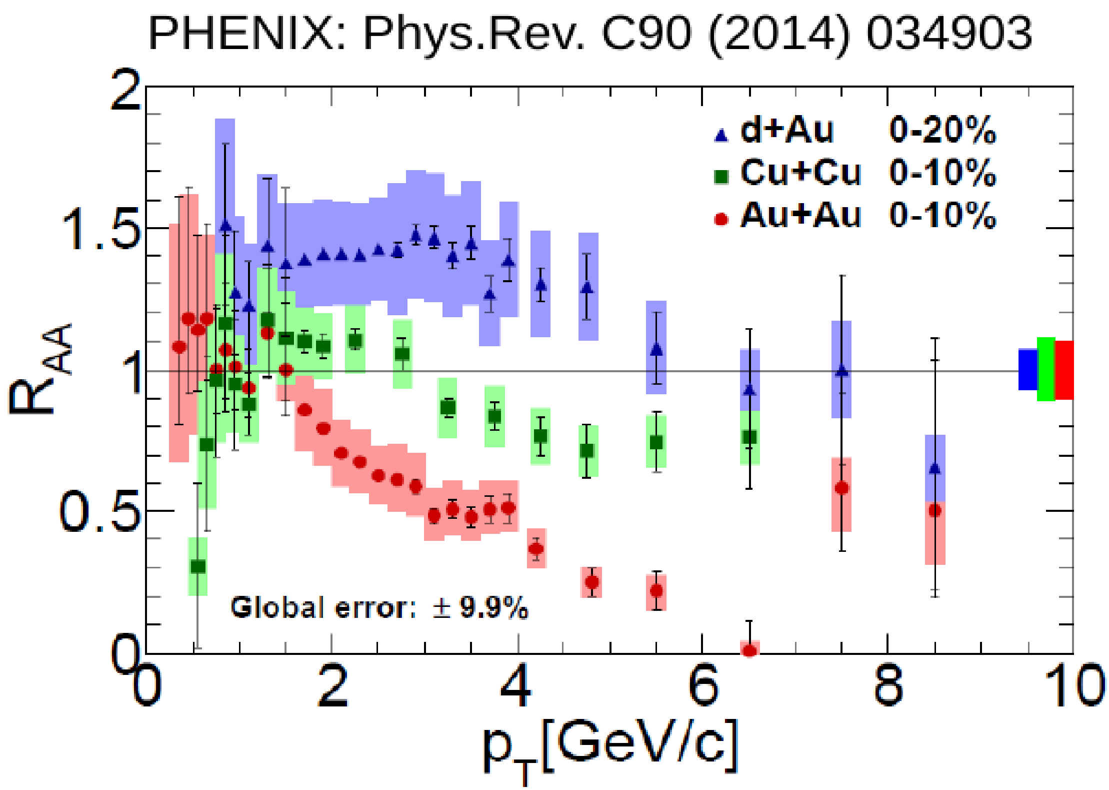
NPE v_2 – energy dependence



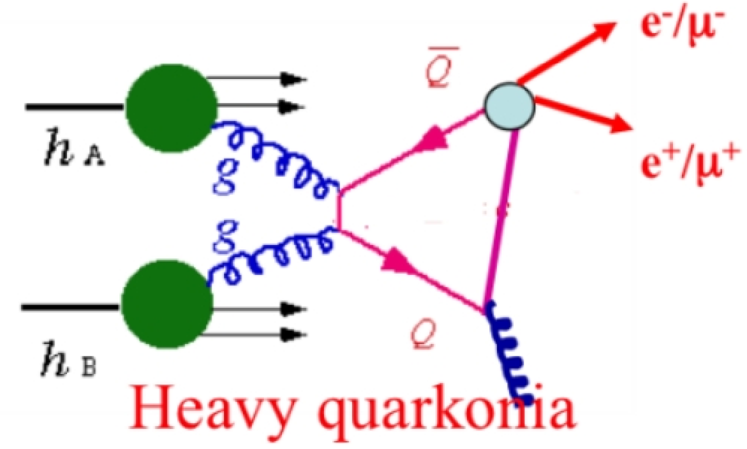
✓ At p_T < 1 GeV/c lower v_2 at 39 and 62.4 GeV compare to 200 GeV

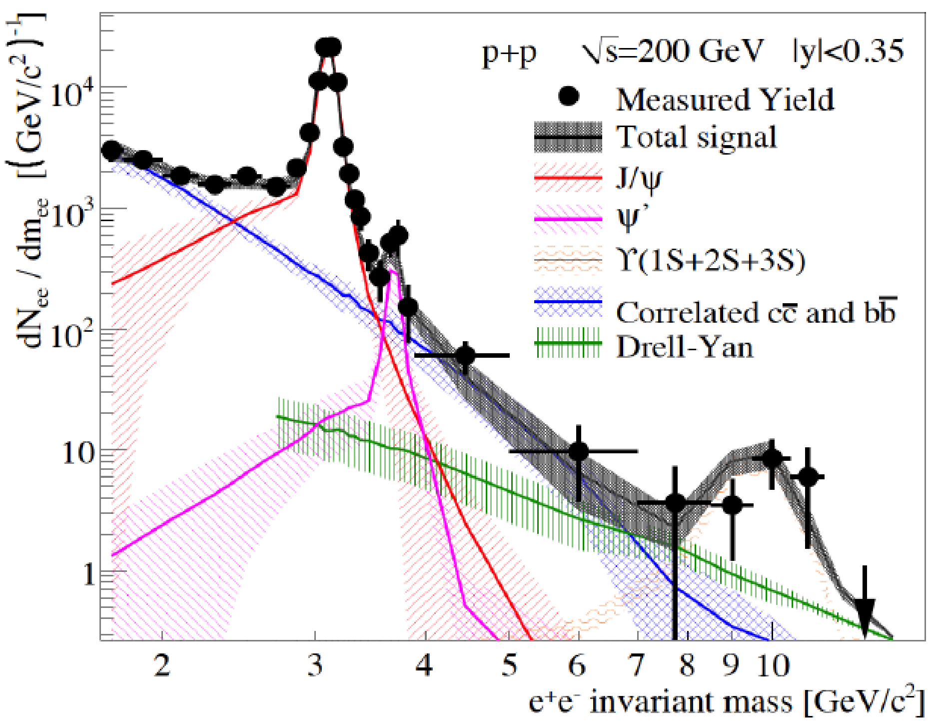
- Hint of a difference in the degree of charmed-medium interaction at lower energies

NPE in Au+Au and Cu+Cu 200 GeV



- ✓ d+Au – Cold Nuclear Matter (CNM) effects – *not related to hot and dense medium*
  - ✓ Au+Au – hot medium effects
  - ✓ Cu+Cu suppression between d+Au and Au+Au


e⁻/μ⁻
e⁺/μ⁺
h A
h B
g
g
Q
Heavy quarkonia


p+p √s=200 GeV |y|<0.35
Measured Yield
Total signal
J/ψ
ψ'
Υ(1S+2S+3S)
Correlated cc̄ and bb̄
Drell-Yan
dN_ee / dm_ee [(GeV/c²)⁻¹]
e⁺e⁻ invariant mass [GeV/c²]

Quarkonia

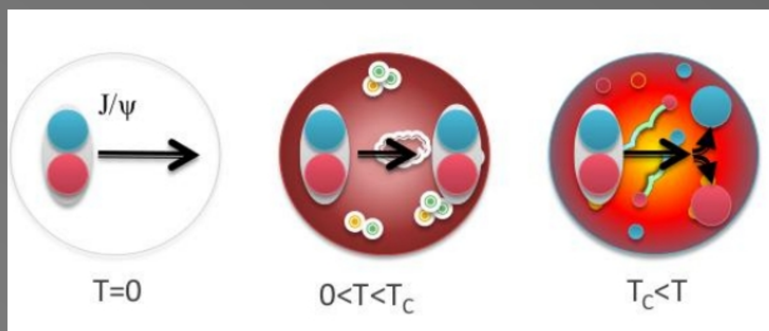
Why quarkonia

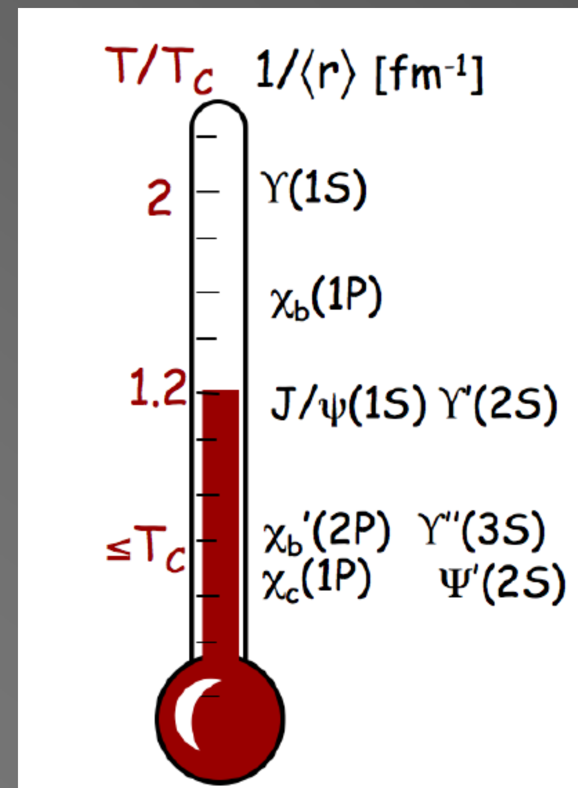
Charmonia: J/ψ, $\psi(2S)$, χ_C *Bottomonia*: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_B

J/ψ / $\Upsilon \rightarrow e^+ e^-$ ($\mu^+ \mu^-$)

First ideas:

- ***color screening*** - quarkonium suppression in QGP in heavy-ion collisions





- ✓ ***QGP thermometer*** - suppression of different states is determined by T and their binding energies

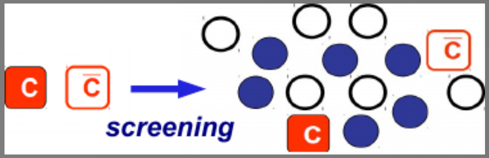
Screening radius:

$r_D(T) \propto 1/T$

Other effects

But there are additional complications:

- Still unclear ***production mechanism*** in elementary collisions
- ***Feed-down:***
  - prompt: *direct* J/ψ (*~60%*) + *feed down* from ψ(2S) and χ_C (~40%); non-prompt: B-mesons feed-down (up to 25% at 12 GeV/c, Phys. Lett. B722 (2013) 55)
- ***Cold Nuclear Matter (CNM) effects*** - nuclear (anti-)shadowing, Cronin effect, nuclear absorption, …
- Other ***Hot Nuclear Matter effects*** - regeneration, …

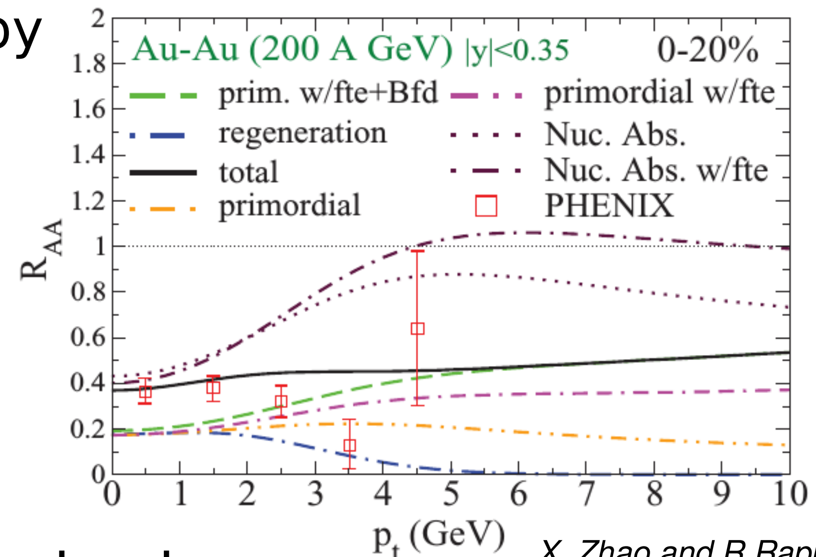


Strategy

- ***High-p_T J/ψ and ϒ – cleaner probes***

  - High-p_T J/ψ - almost not affected by CNM effects and recombination
  - ϒ - negligible co-mover absorption and recombination

    at RHIC: σ_{cc} ~800μb >> σ_{bb} ~(1-2)μb

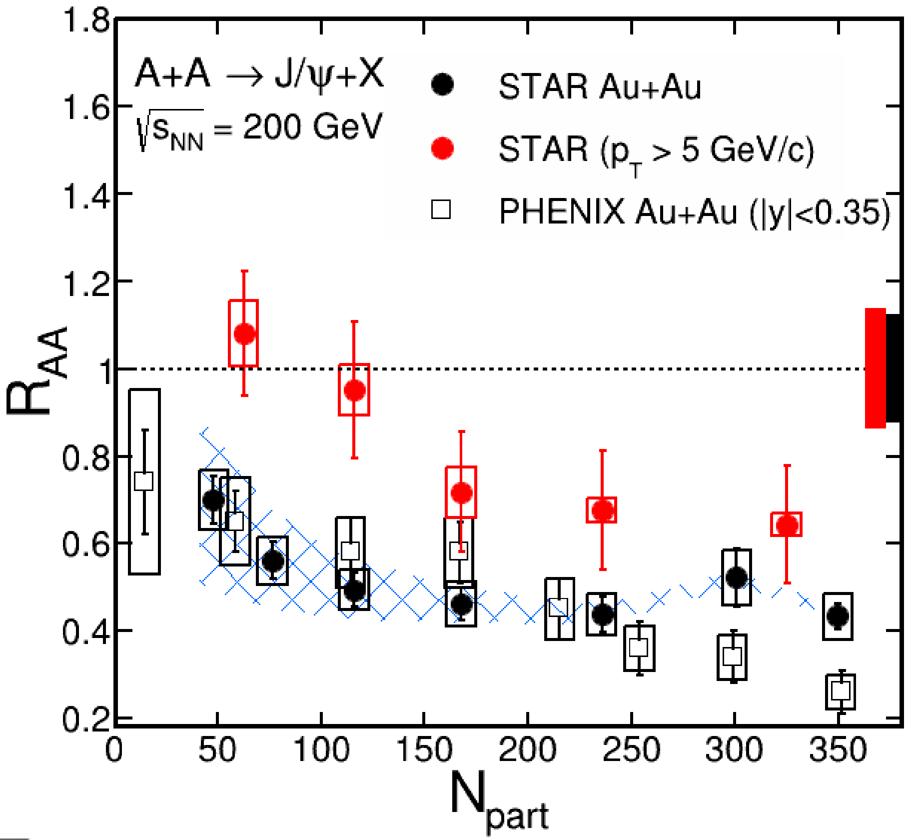


X .Zhao and R.Rapp, P
Rev. C82, 064905 (20

  - Energy dependence of quarkonium production - varying relative contributions

    - ***Measure quarkonia at different colliding systems and energies, in different kinematic regions***

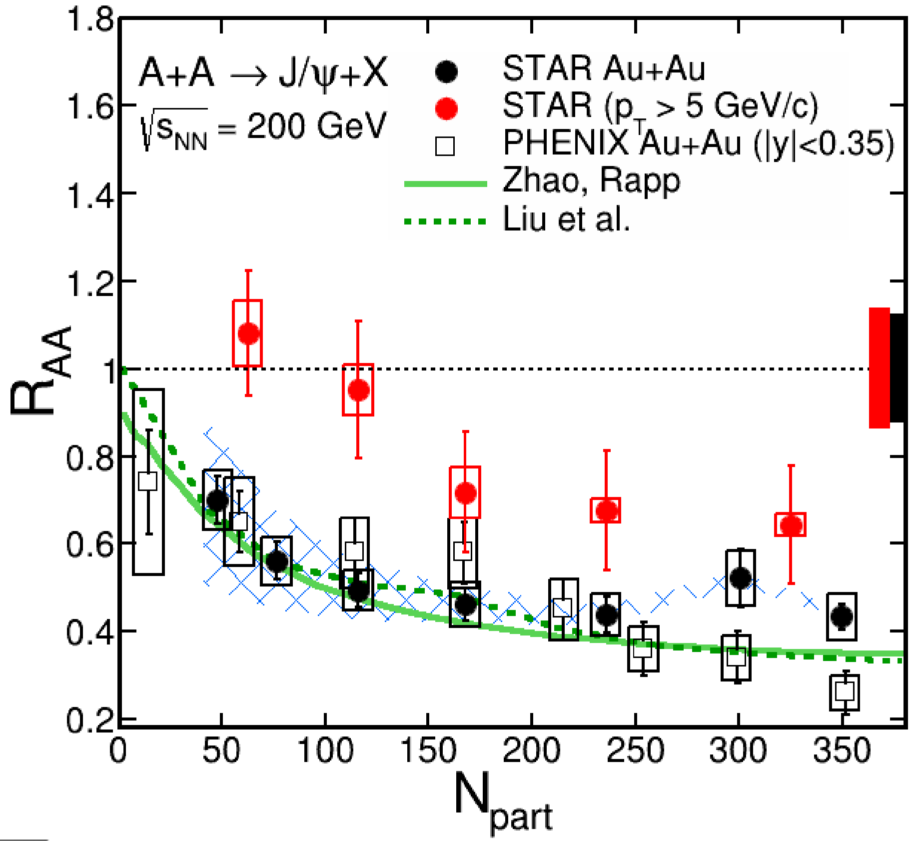
J/ψ in Au+Au 200 GeV



- ✓ Suppression increases with collision centrality
- ✓ High-p_T R_{AA} is systematically higher
  - J/ψ at high-p_T almost not affected by CNM effects and recombination
- ✓ High-p_T J/ψ suppressed in central collisions
  - → QGP effects

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{A+A}}{dN/dy^{p+p}}$$

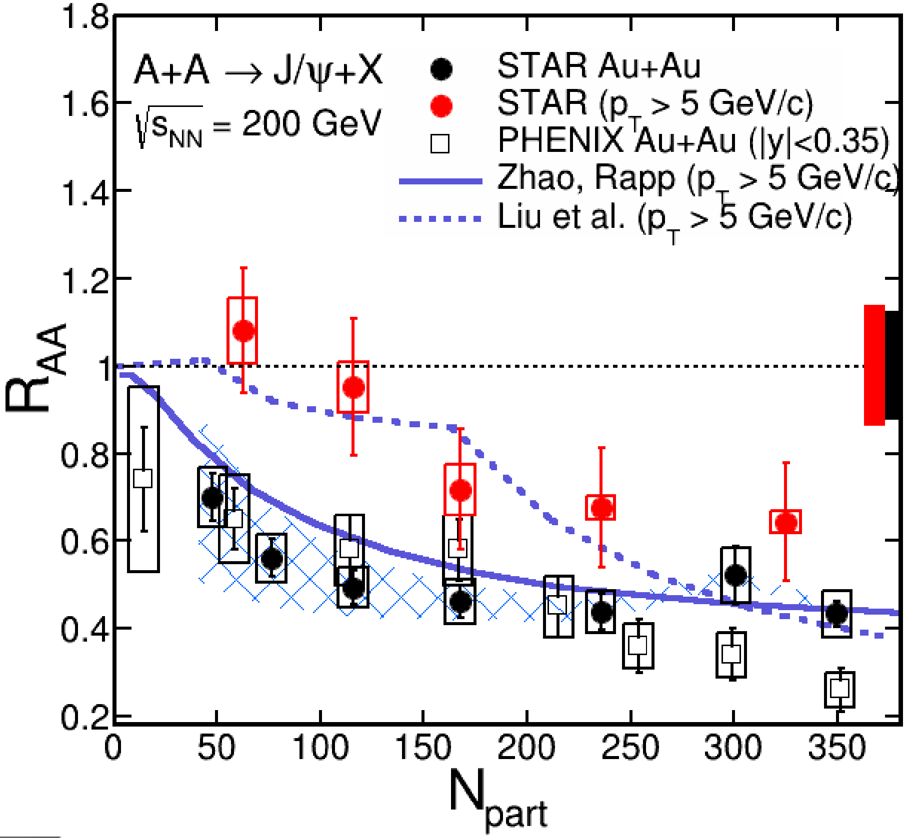
J/ψ in Au+Au 200 GeV



- Suppression increases with collision centrality
- High-p_T R_{AA} is systematically higher
- High-p_T J/ψ suppressed in central collisions
  - → QGP effects
- Models of *Zhao et al.* and *Liu et al.*: direct J/ψ production with color screening + recombination

→ Both models describe the data well at low p_T

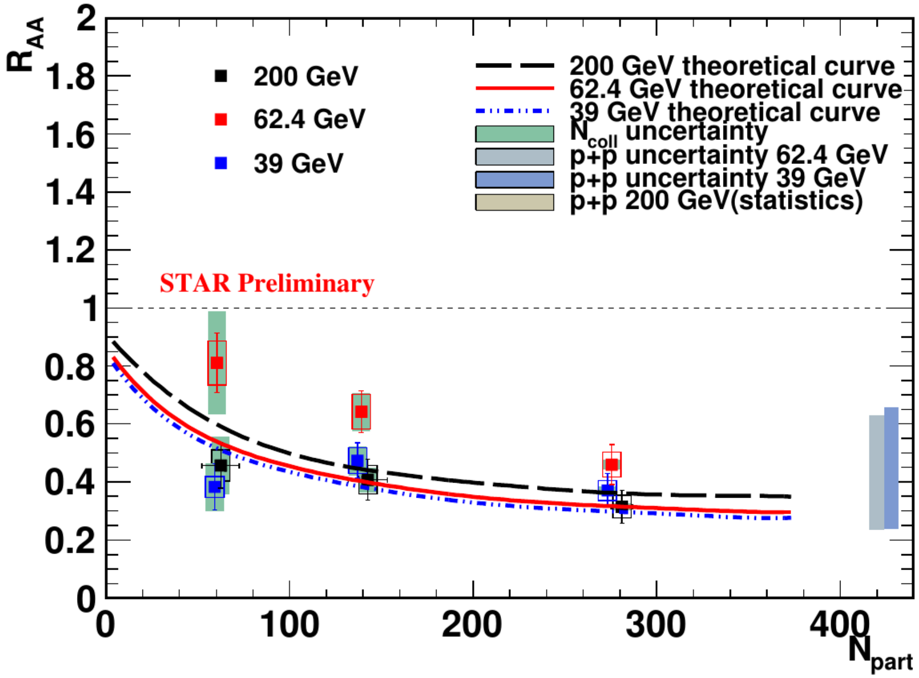
J/ψ in Au+Au 200 GeV

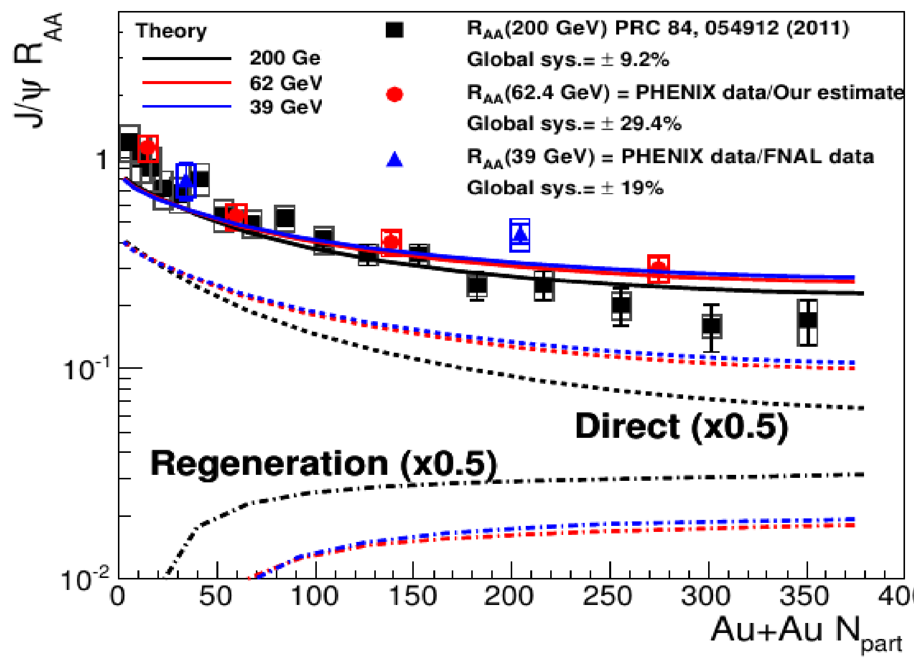


- ✓ Suppression increases with collision centrality
- High-p_T R_{AA} is systematically higher
- ✓ High-p_T J/ψ suppressed in central collisions
  - → QGP effects
- Models of *Zhao et al.* and *Liu et al.*: direct J/ψ production with color screening + recombination

→ At high p_T Liu *et al.* model describes the data well, while Zhao *et. al* model underpredicts the R_{AA}

Energy dependence of J/ψ

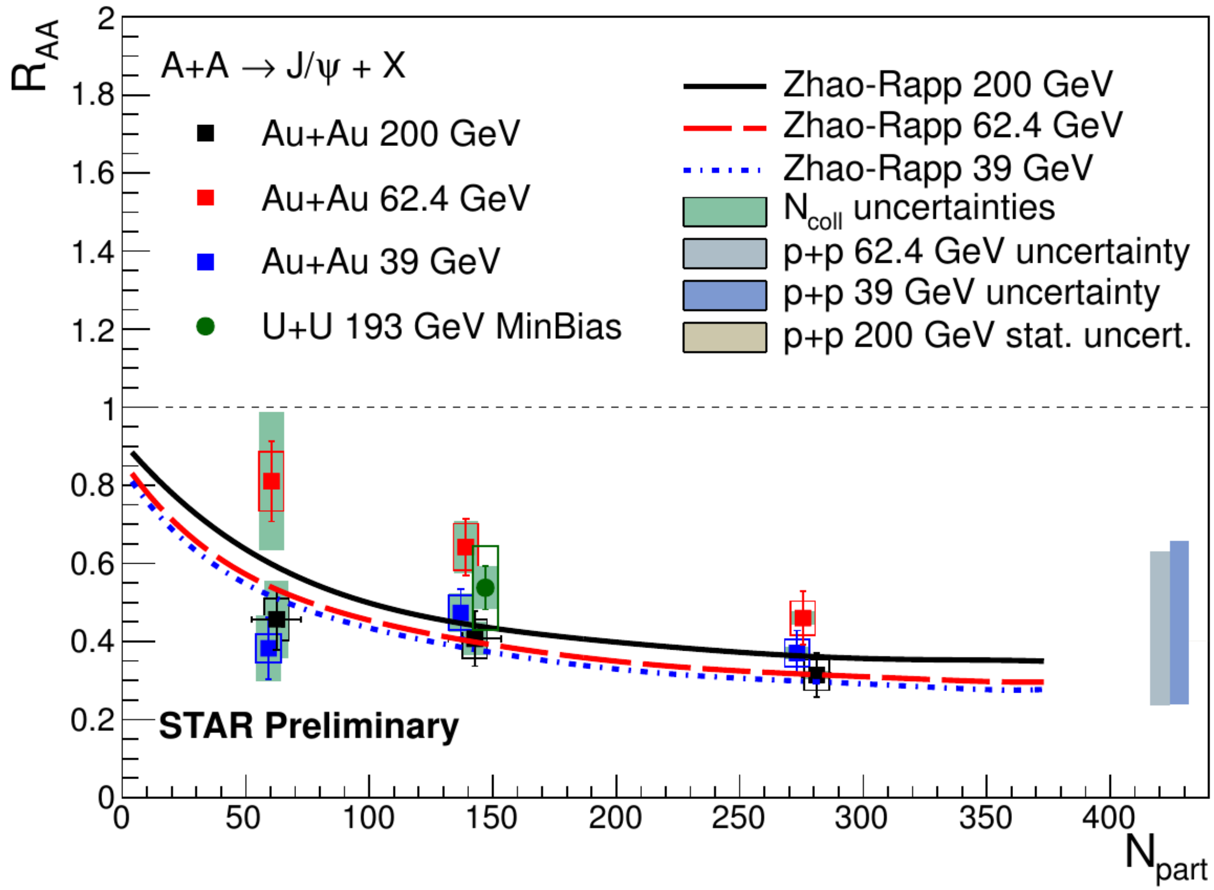




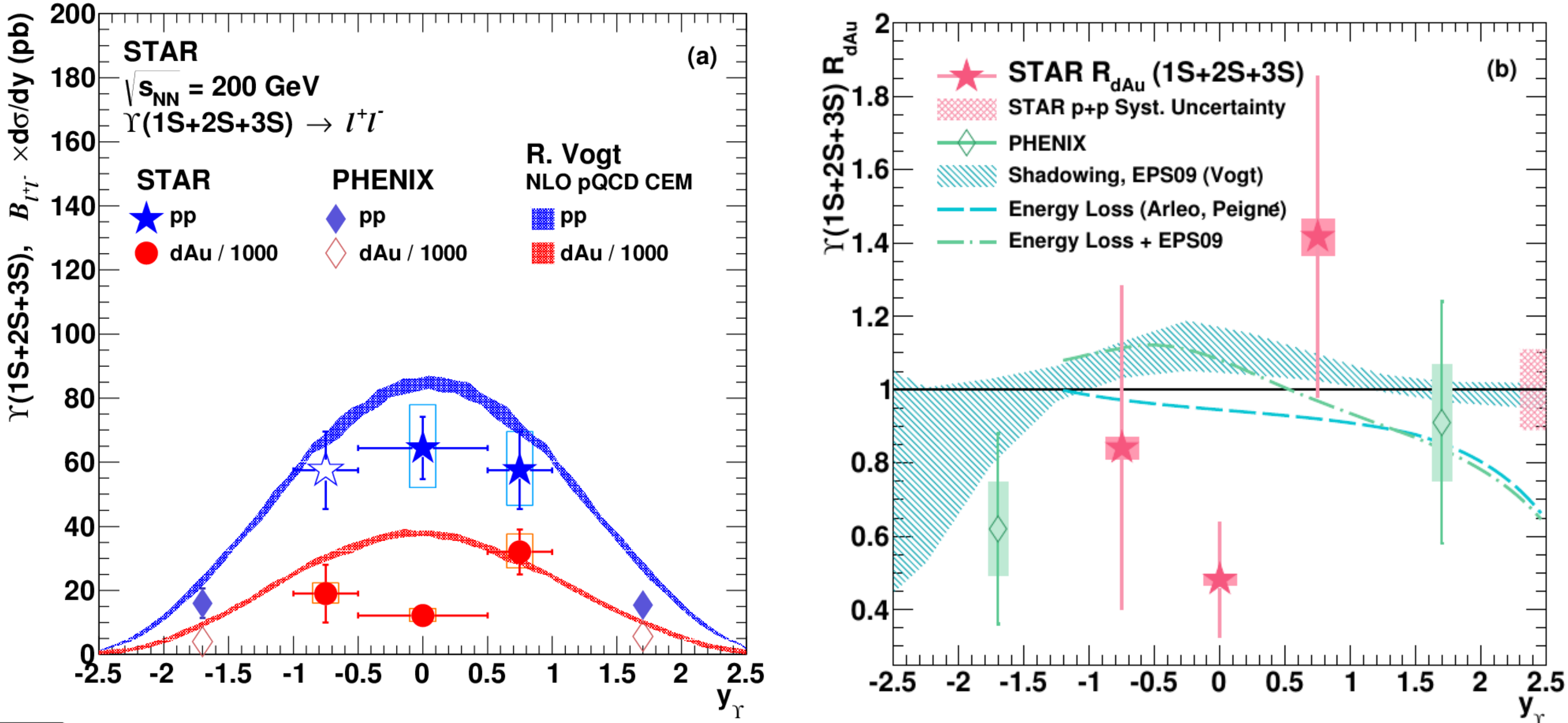
- ✓ Suppression observed for all energies: <u>200, 62.4 and 39 GeV,</u> similar trend in p_T
  - ➔ No strong energy dependence of J/ψ R_{AA}
  - ➔ Data agrees with the model prediction
    - *No p+p reference for 62.4 and 39 GeV - large uncertainties*

J/ψ in U+U 193 GeV

- Similar suppression pattern in U+U and Au+Au collisions, similar p_T trend

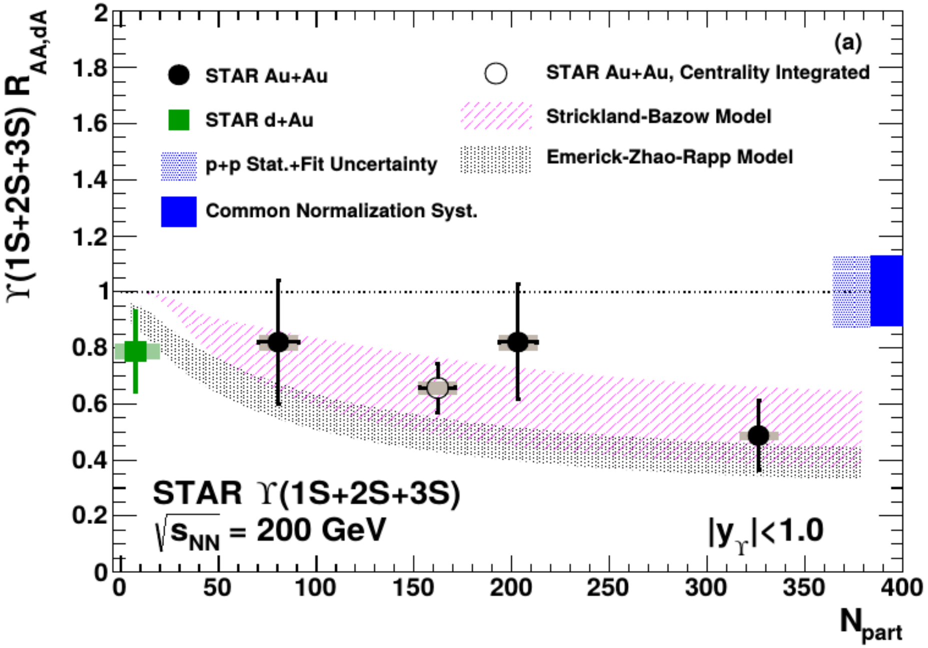


Υ in d+Au and Au+Au 200 GeV



- Agreement with models except y~0
  - Suppression at y~0, in addition to expected cold nuclear matter effects

ϒ Au+Au 200 GeV

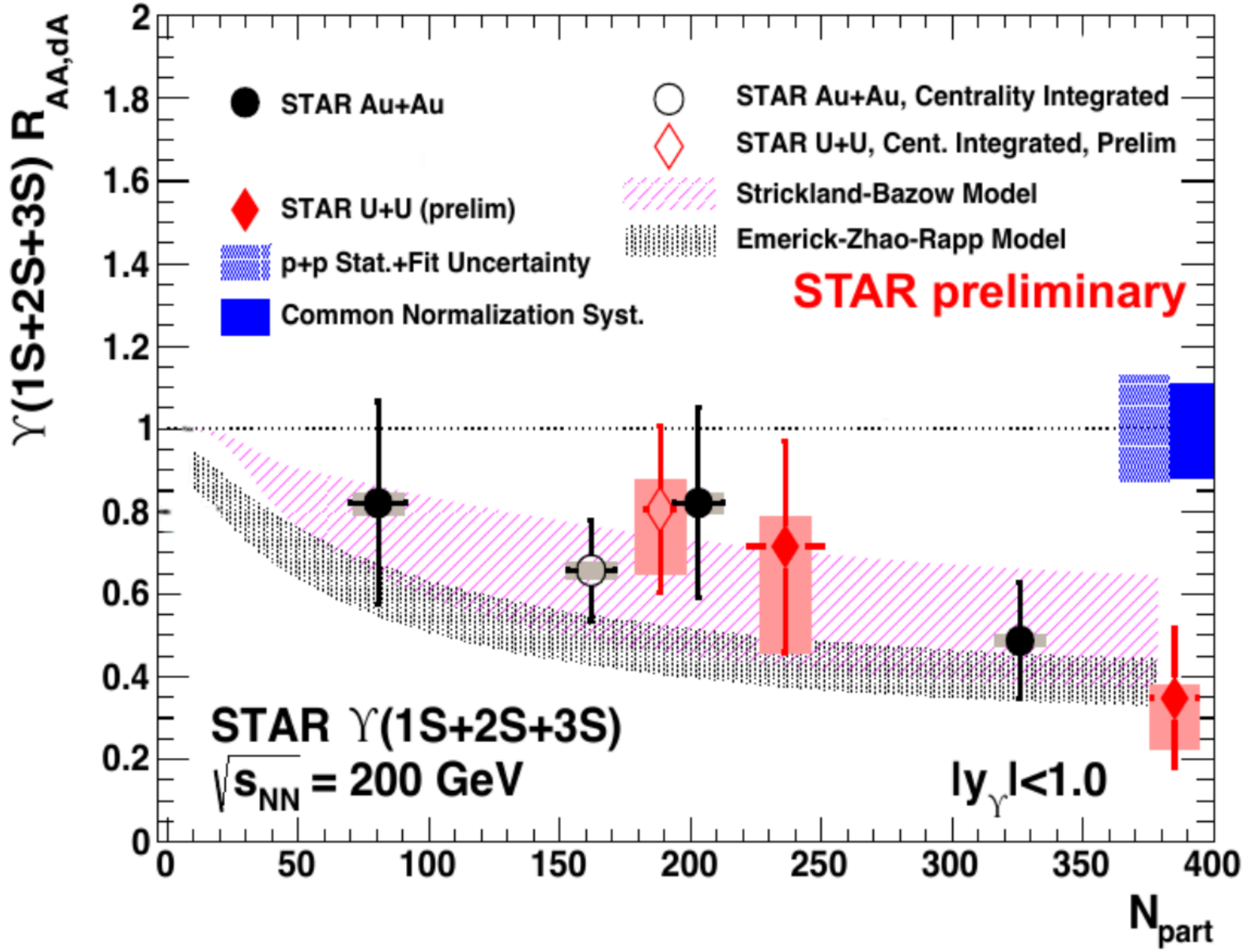


- ✓ Suppression increases with collision centrality
- ✓ Strong suppression in central collisions

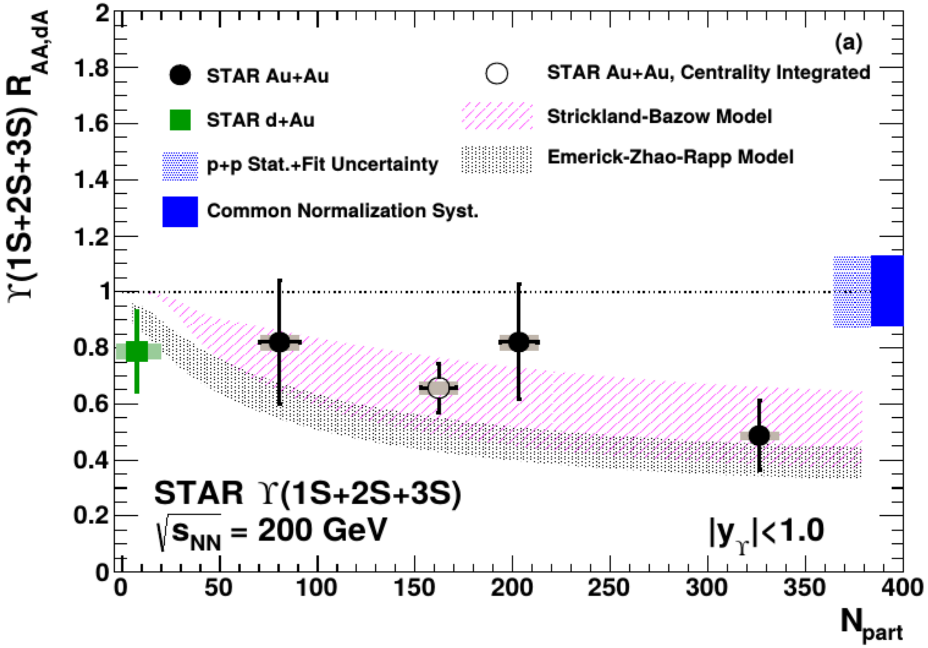
➔ Agreement with models that include presence of QGP

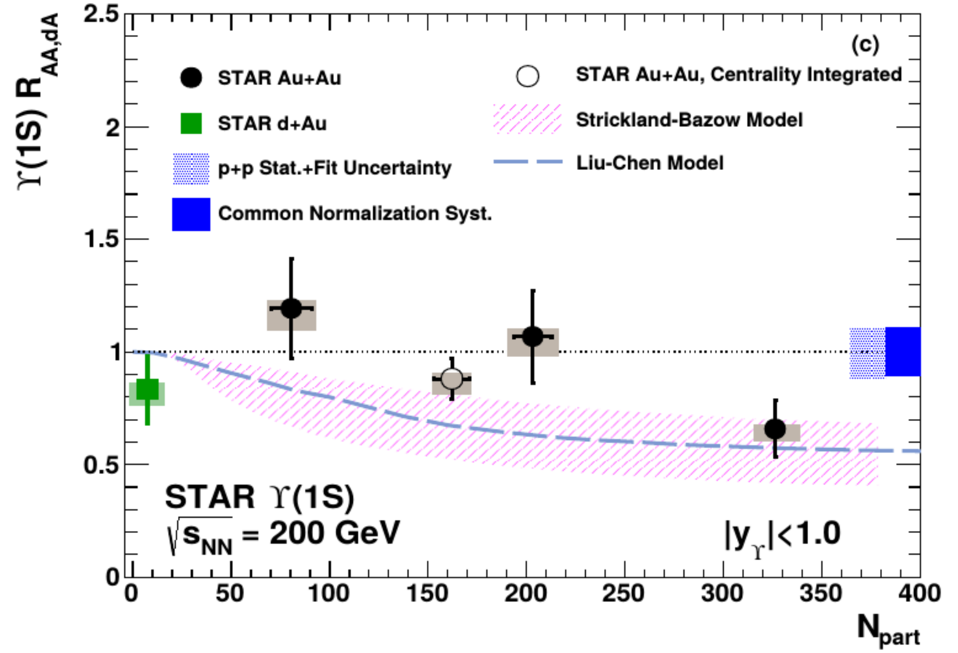
Υ U+U 193 GeV

- ✓ The same trend in Au+Au and U+U collisions



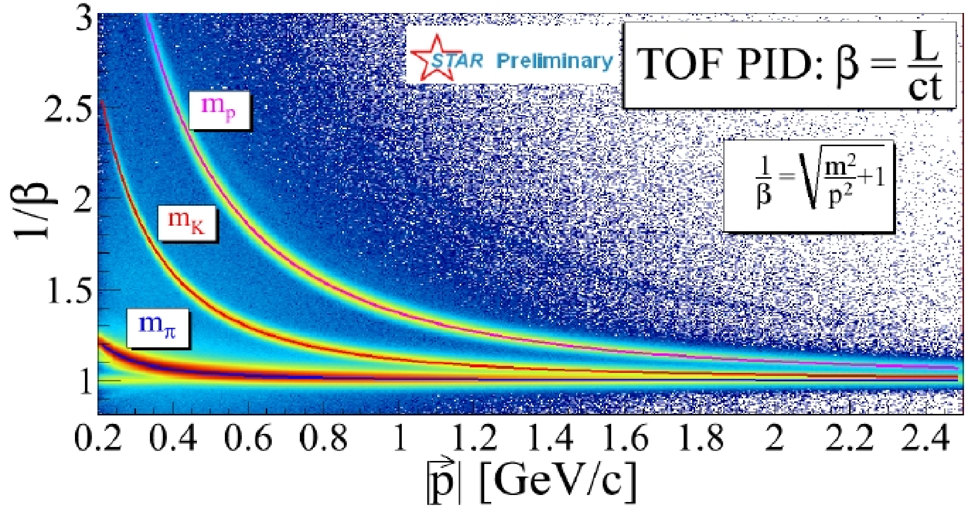
Suppression of different Υ states

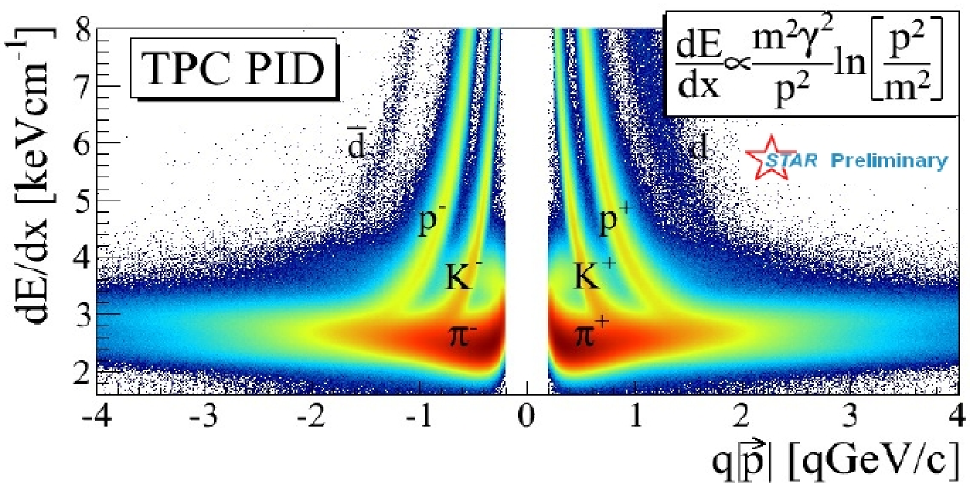




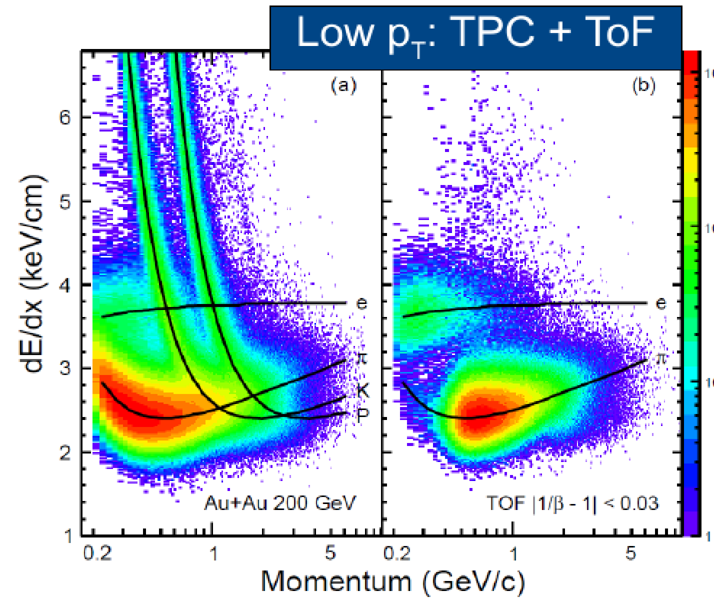
- Indication of complete Υ(2S+3S) suppression in central collisions
  - Sequential melting

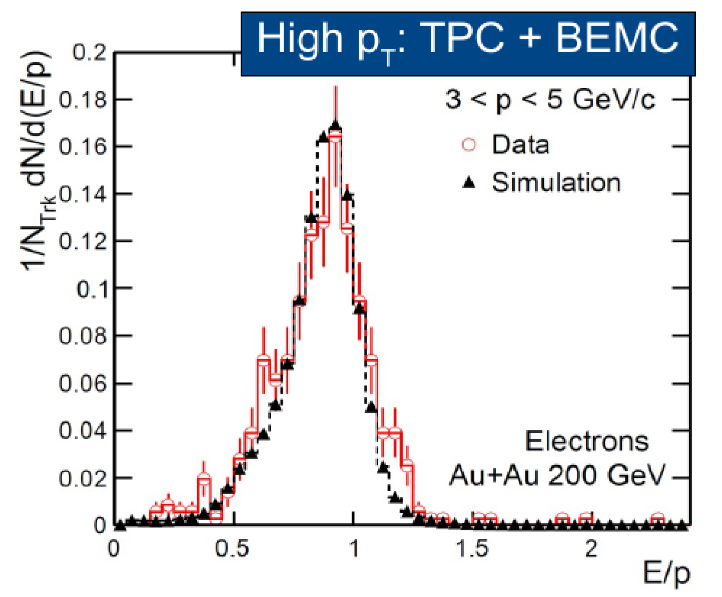
Particle identification





Electron Identification

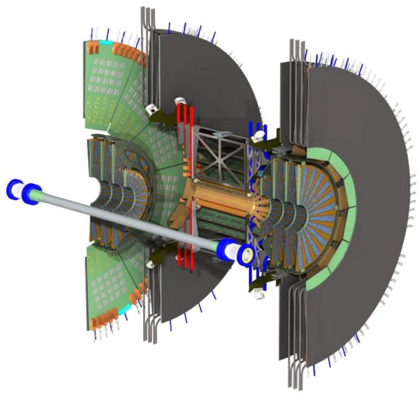




Upgrades

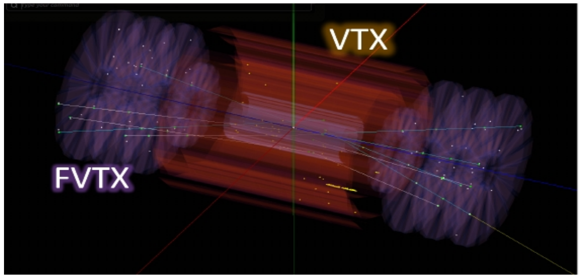
PHENIX Upgrade

Installed and taking data: FVTX



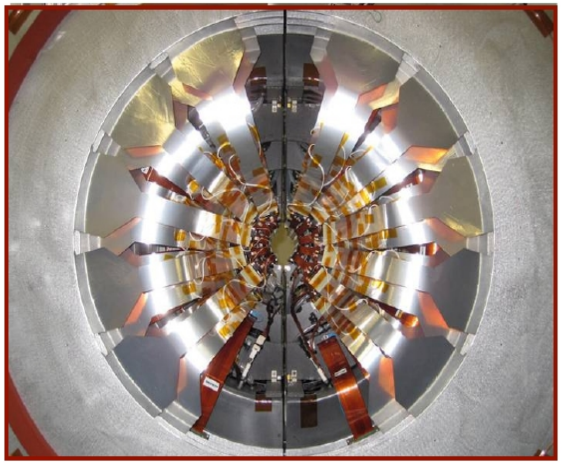
M.Durham - HP2013

Silicon detector for precision tracking at forward rapidity, covering PHENIX muon arms
-b/c muon separation
-ψ(2s) at forward rapidity
-Drell Yan dimuon production

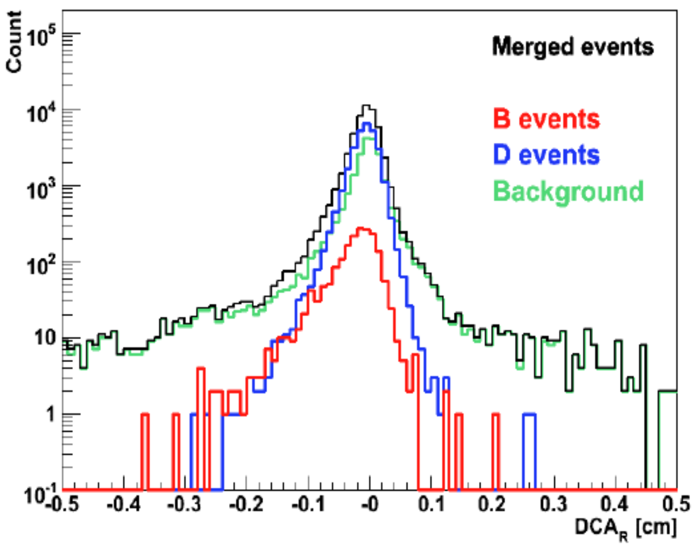


- VTX provides two new capabilities:
  1) Tag and reject conversion providing an independent measurement of photonic background
  2) Measure distance of closest approach to separate charm and bottom components of heavy flavor spectra

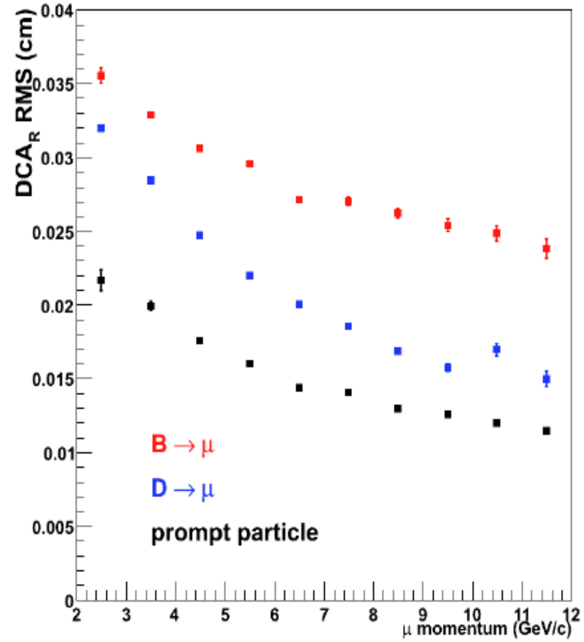
Front view of VTX



DCA_R for c/b separation



Simulated DCA_R for each process

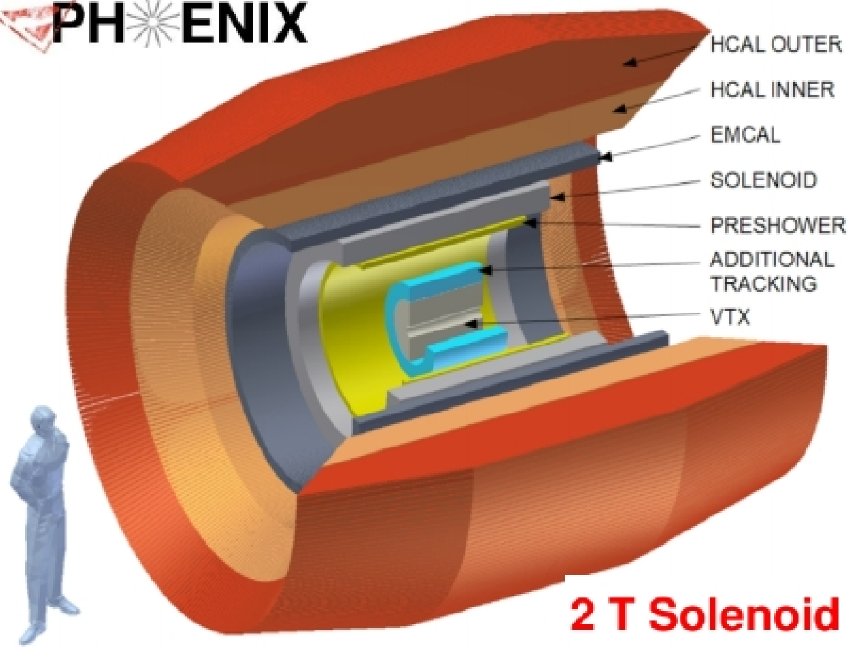


DCA_R vs momentum

Decay μs from D, B and hadrons have different DCA_R shapes in a given μ p_T bin.

-> Fit the shapes to data or cut out to reduce background keeping a specific window.

sPHENIX

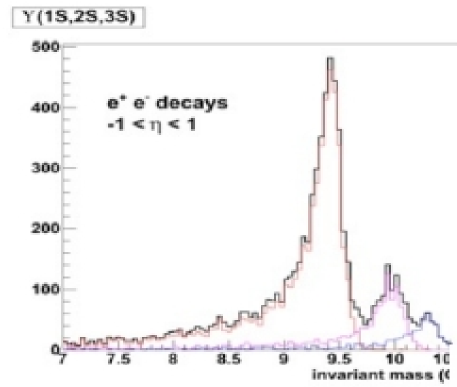


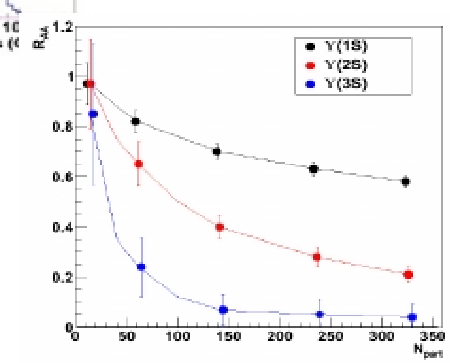
arXiv:1207.6378

- sPHENIX is a significant reworking of PHENIX

- The proposed large acceptance sPHENIX detector, which is designed as a jet detector, will also – with added tracking and electron ID, make good separated Upsilon measurements.

A.Frawley - HP2013

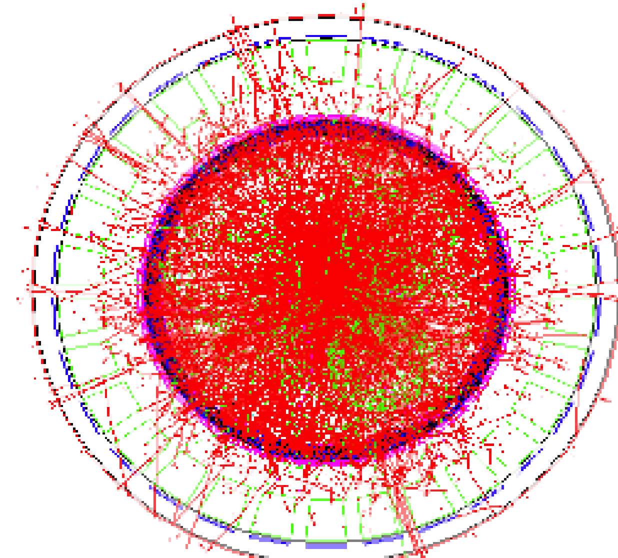




- interesting because of medium properties near T_C and because of complementarity with jet and quarkonia measurements from LHC

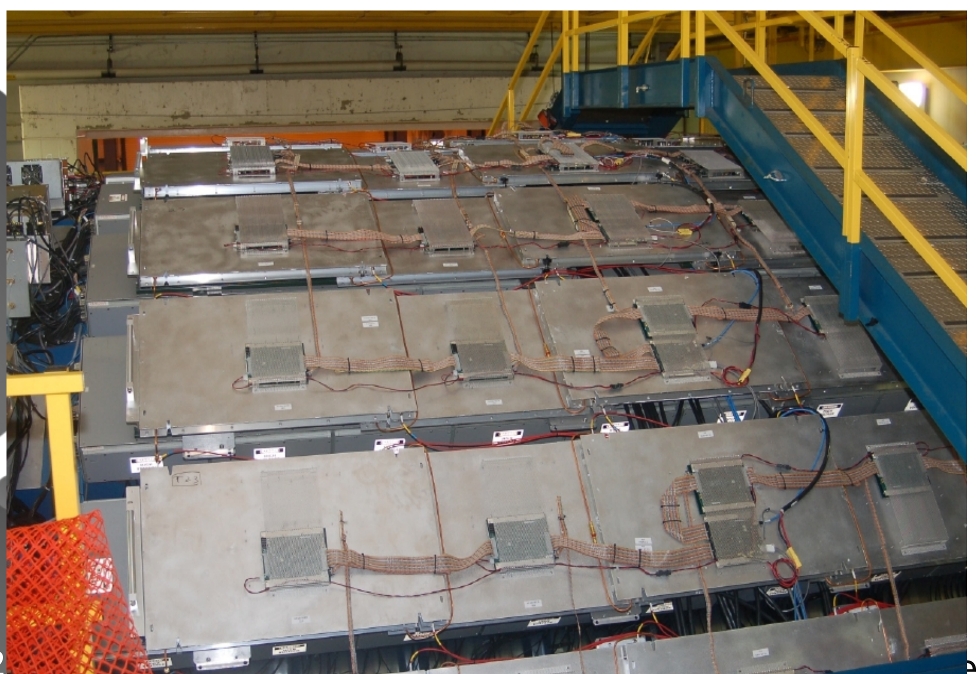
- additional tracking layers and EMCal pre-shower provide mass resolution and pion rejection to enable quarkonia program to augment STAR's and complement LHC

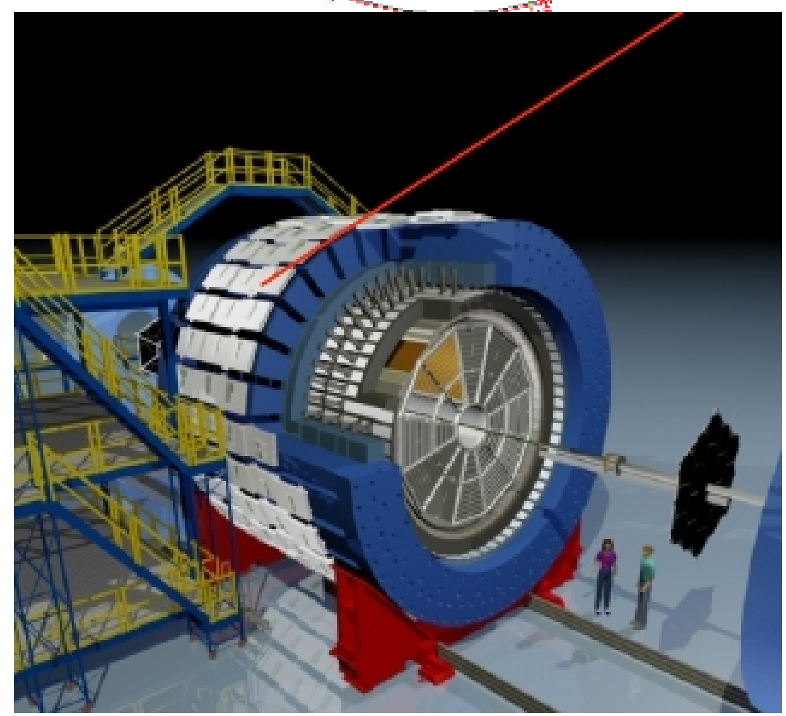
STAR Muon Telescope Detector



Accessing muons at mid-rapidity

- Multi-gap Resistive Plate Chamber (MRPC) - gas detector
- Acceptance: 45% at $|\eta| < 0.5$
- Long-MRPCs
- Electronics same as in STAR TOF

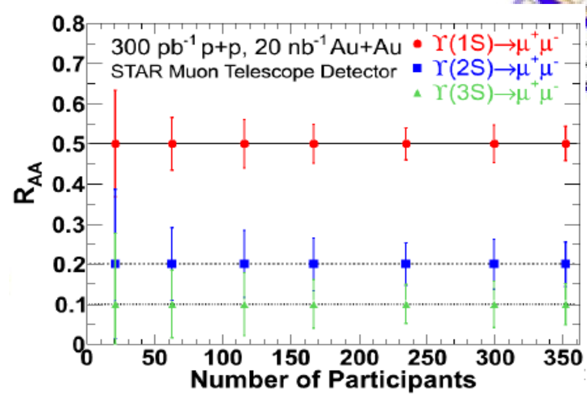


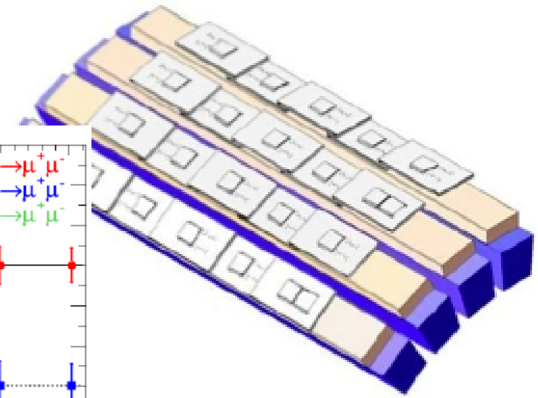


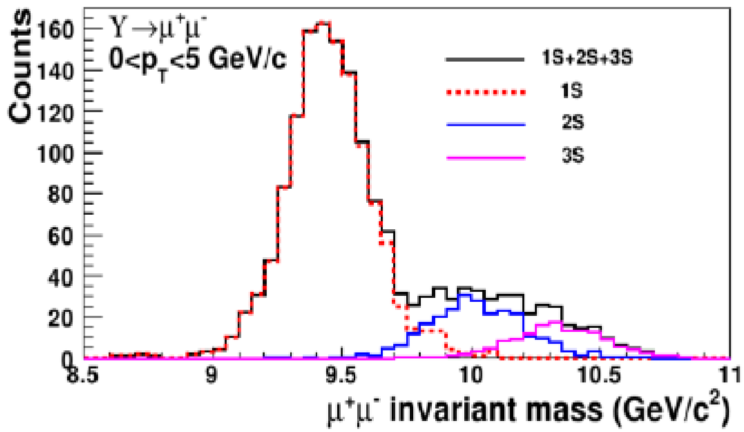
STAR Muon Telescope Detector

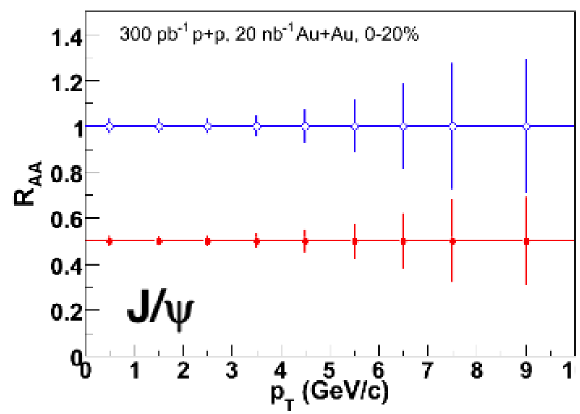
Accessing muons at mid-rapidity

- No γ conversion
- Much less Dalitz decay contribution
- Less affected by radiative looses in the materials







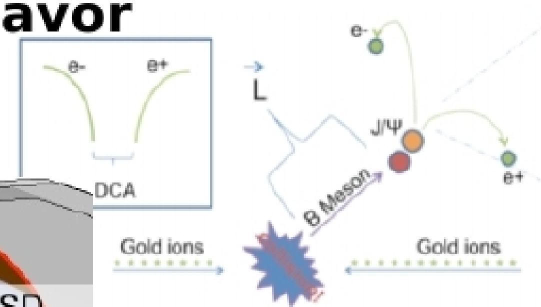


Fully installed in 2014

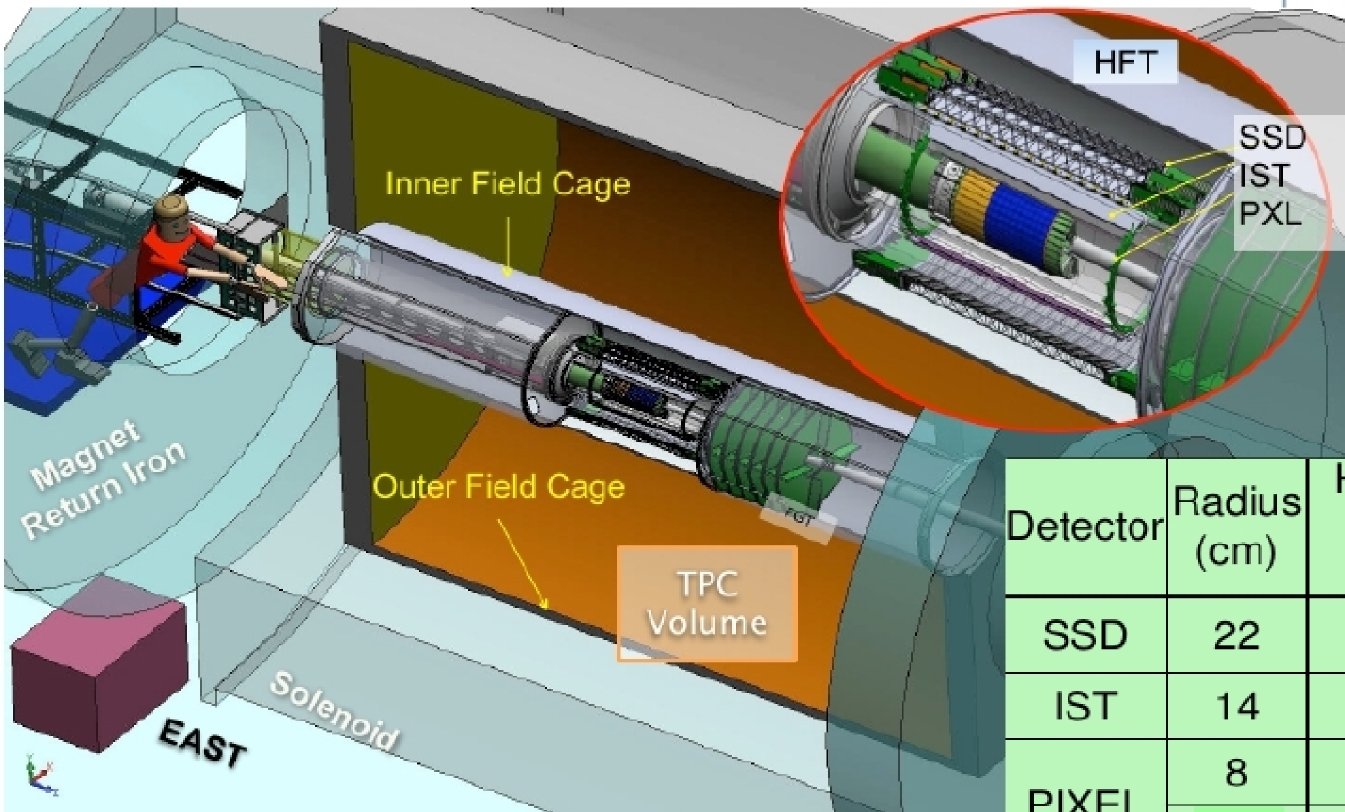
STAR Heavy Flavor Tracker

Precision vertex detector: **Open heavy flavor**

Non-prompt J/ψ: $B \rightarrow J/\psi + X$



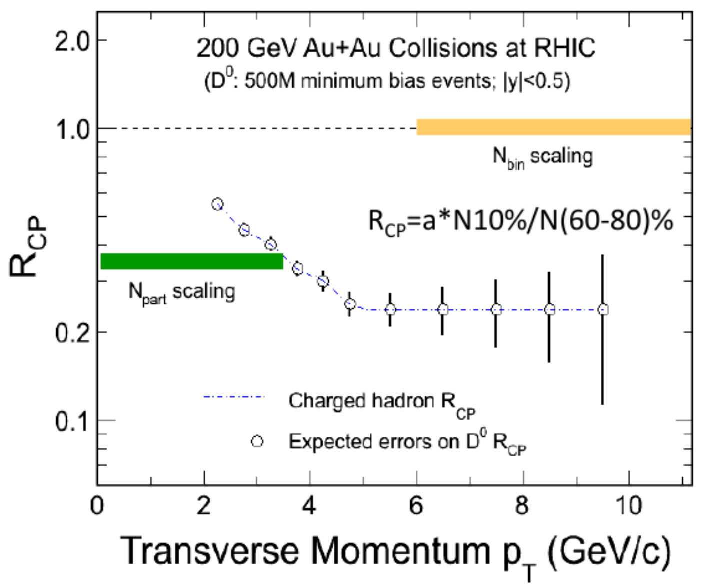
Direct topological reconstruction of deco vertex

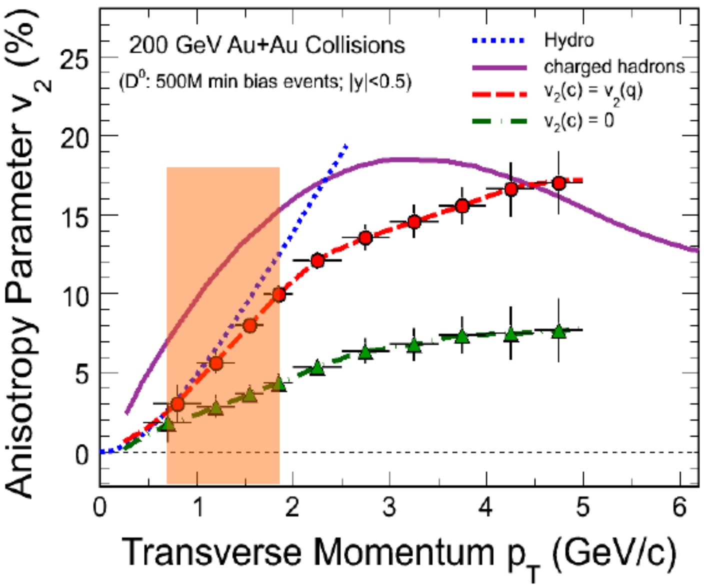


Detector	Radius (cm)	Hit Resolution R/φ - Z (μm - μm)	Radiation length
SSD	22	20 / 740	1% X_0
IST	14	170 / 1800	<1.5 %X_0
PIXEL	8	12/ 12	~0.4 %X_0
	2.7	12 / 12	~0.4% X_0

Fully installed in 2014

Statistical projection for next runs





Assuming D^0 R_{cp} distribution as charged hadron.

500M Au+Au m.b. events at 200 GeV.

- Charm R_{AA}

Energy loss mechanism!
Color charge effect!
Interaction with QCD matter!

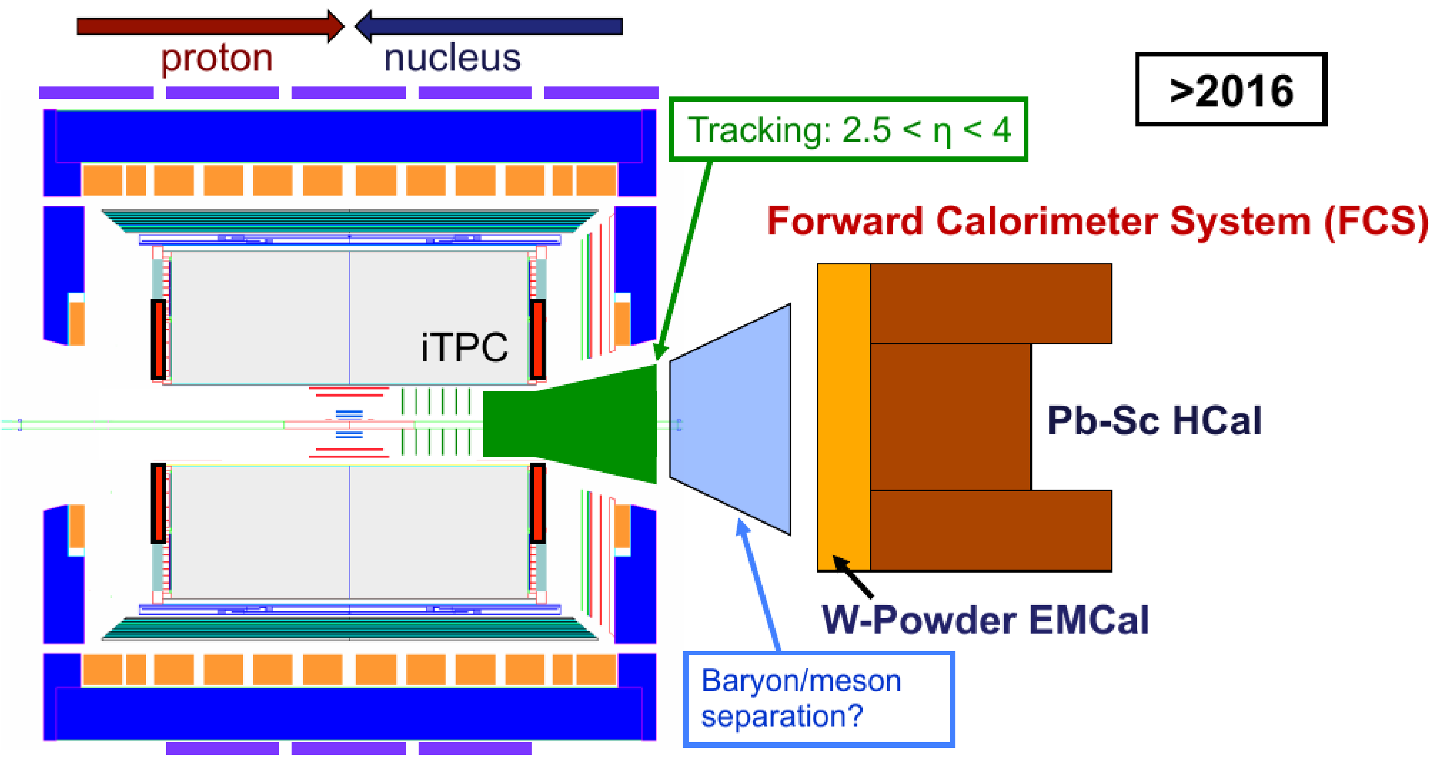
Assuming D^0 v_2 distribution from quark coalescence.

500M Au+Au m.b. events at 200 GeV.

- Charm v_2

Medium thermalization degree
Drag coefficients!

STAR Forward upgrade



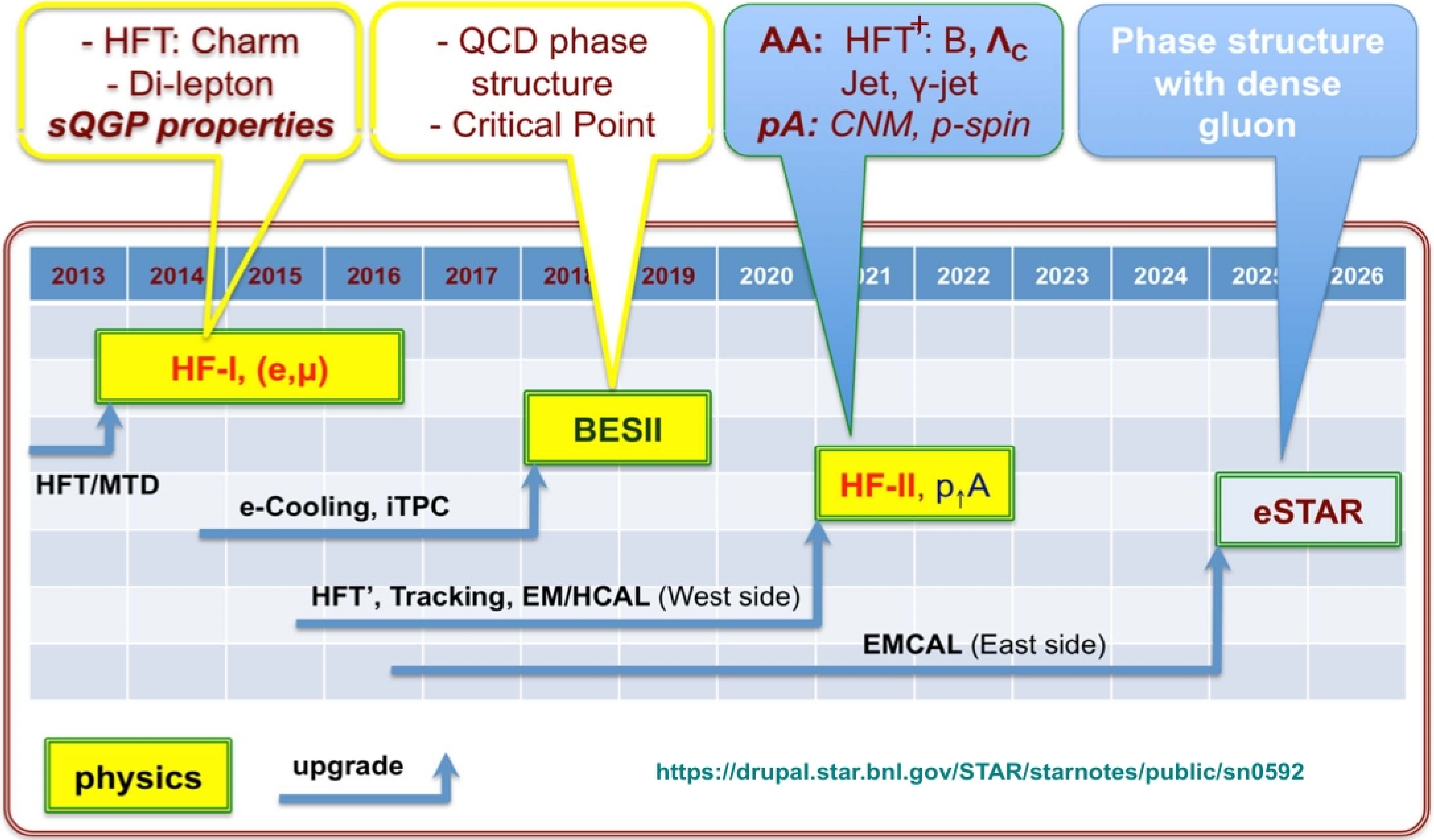
- **Forward instrumentation optimized for p+A and transverse spin physics**
  - **Charged-particle tracking**
  - ***e*/*h* and γ/π^0 discrimination**
  - **Baryon/meson separation**

RHIC schedule

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16			PHENIX MPC-EX Coherent e-cooling test
2017	No Run		Low energy e-cooling upgrade
2018-19	5-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR ITPC upgrade Partial commissioning of sPHENIX (in 2019)
2020	No Run		Complete sPHENIX installation STAR forward upgrades
2021-22	Long 200 GeV Au+Au with upgraded detectors p+p, p/d+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX
2023-24	No Runs		Transition to eRHIC

2015 p+p 200 GeV p+Au 200GeV
p+Si 200GeV
2016 Au+Au 200 GeV
p+p 500 GeV (or Au+Au and p+p 62 GeV)

STAR physics plan



Summary

- RHIC has perform many heavy flavor measurements, including open heavy flavor and quarkonia
- At different colliding energies and systems
- Indication of presence of hot and dense medium at top RHIC energies
    - ➔ RHIC Heavy Flavor Era has just started
        - With new upgrades - more precise measurements in next few years to further investigate medium properties
        - Crucial to separate charm and bottom and understand CNM effects from p+A

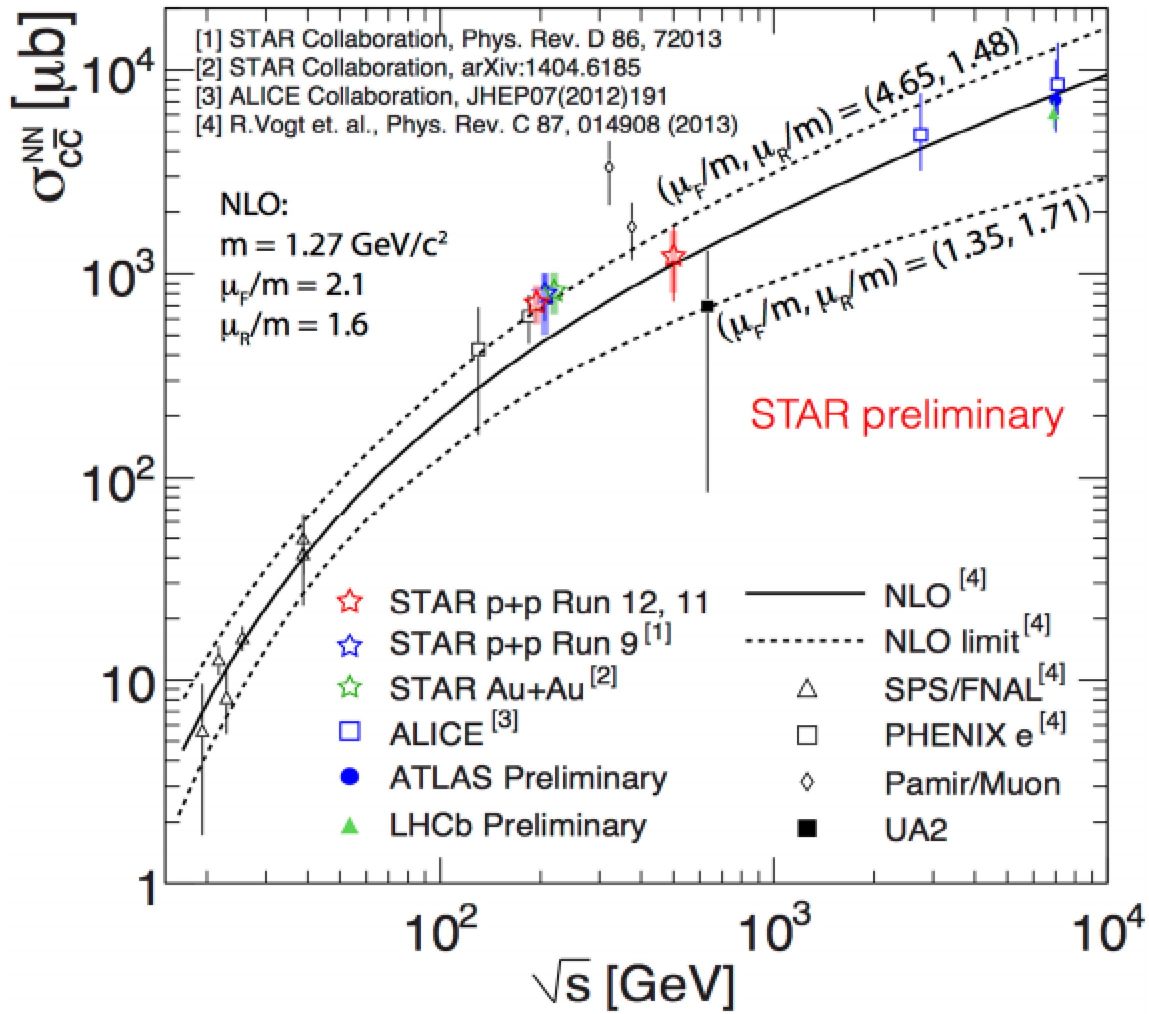
This work was supported by the European social fund within the framework of realizing the project „Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague", CZ.1.07/2.3.00/30.0034.

Backup

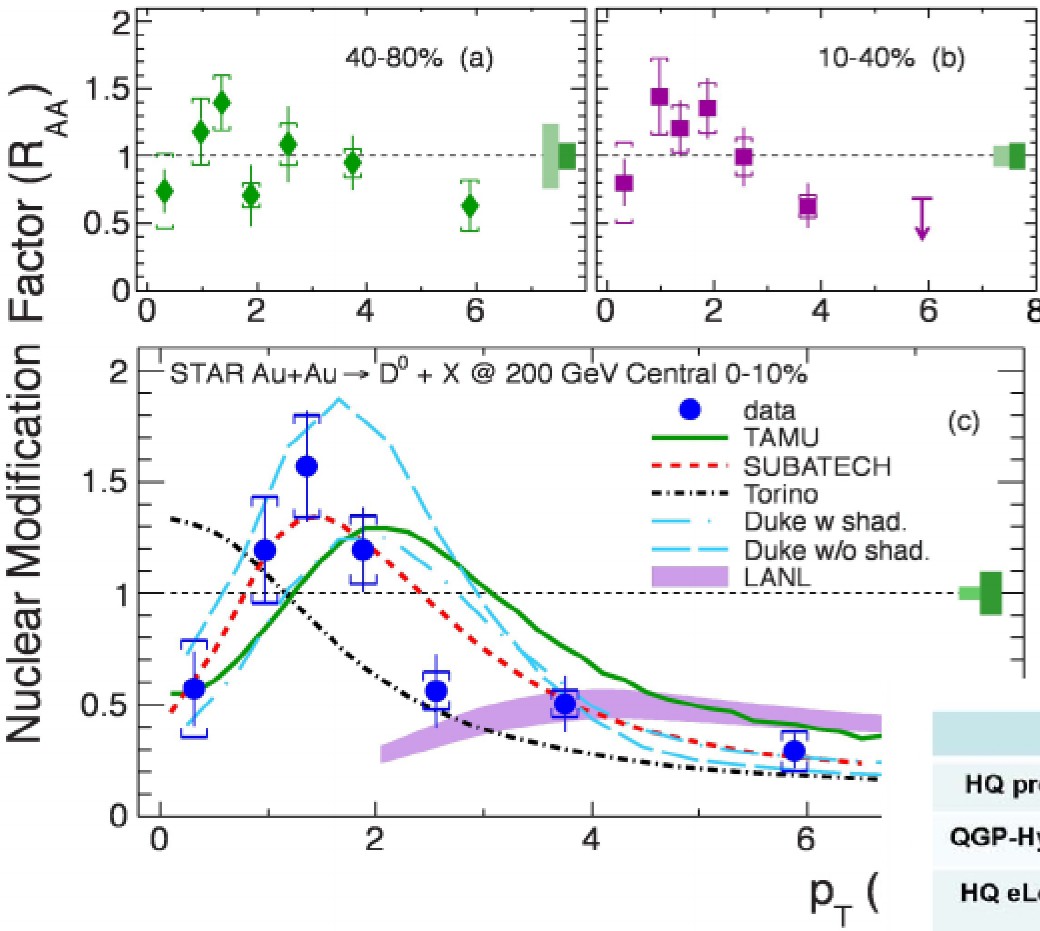
Matter at RHIC

- Strong elliptic flow
  - Collective flow of created matter
  - Constituent quark number degrees of freedom apparent in scaling laws of elliptic flow
- Jet quenching
  - Energy loss of high-p_T partons traversing the hot and dense matter
- Particle production through recombination/coalescence
  - Dominates over fragmentation at medium p_T
    - → noninteracting gas => strongly coupled QGP (sQGP)

Total charm cross section



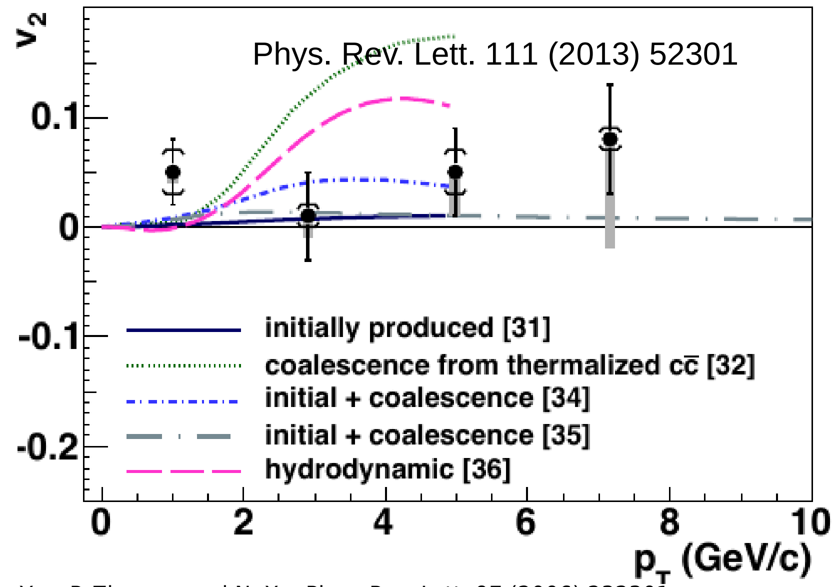
D in Au+Au 200 GeV vs models



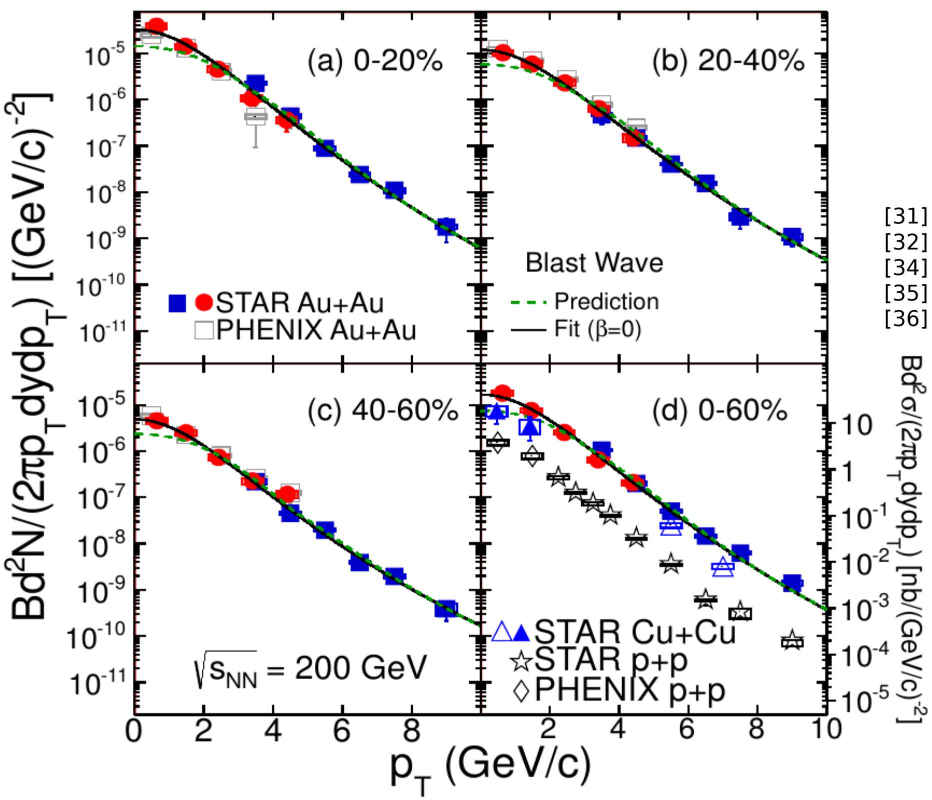
	TAMU	SUBATECH	Torino	Duke	LANL
HQ prod.	LO	FNOLL	NLO	LO	LO
QGP-Hydro	ideal	ideal	viscous	viscous	ideal
HQ eLoss	coll.	coll. +rad.	coll. +rad.	coll. +rad.	diss. +rad.
Coalescence	Yes	Yes	No	Yes	No
Cronin effect	Yes	Yes	No	No	Yes
Shadowing	No	No	Yes	Yes/No	Yes

J/ψ v_2 and p_T spectra

- ✓ J/ψ v_2 is consistent with zero at p_T > 2 GeV/c
  - ➔ Disfavors the model with J/ψ production via thermalized (anti-)charm coalescence



[31] L. Yan, P. Zhuang, and N. Xu, Phys. Rev. Lett. 97 (2006) 232301
[32] V. Greco, C.M. Ko, and R. Rapp, Phys. Lett. B 595 (2004) 202
[34] X. Zhao and R. Rapp, Phys. Lett. B 655 (2007) 126
[35] Y. Liu, N. Xu, and P. Zhuang, Nucl. Phys. A 834 (2010) 317c
[36] U. W. Heinz and C. Chen, private communication (2012)



- ✓ At low p_T J/ψ spectra softer than the *TBW* prediction from light hadron
  - ➔ small radial flow ?
  - ➔ regeneration at low p_T ?