Selected results from the STAR experiment

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for the STAR collaboration

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in Prague

Primordial QCD Matter in LHC Era, 2/13/2013 Cairo,Egypt

Outline

- Introduction
  - RHIC, STAR
  - properties of QCD matter
- RHIC Beam Energy Scan
  - selected results
- Heavy Flavor production
  - open charm
  - quarkonia
- STAR near term upgrades
- Anti-He^4 at RHIC
- Conclusions

Properties of nuclear matter

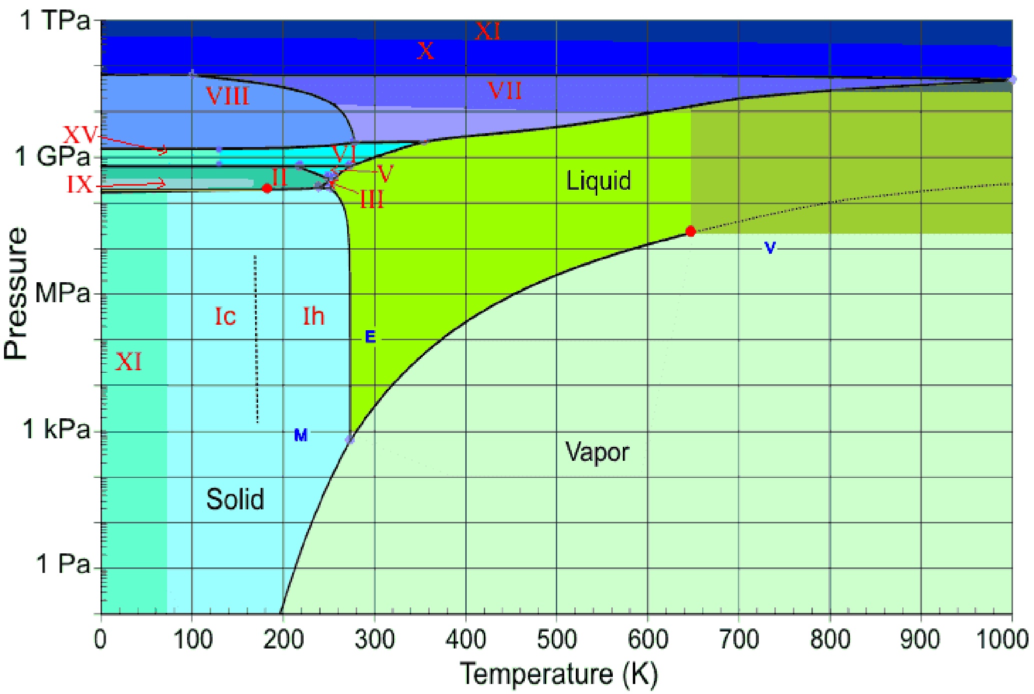
Quantum chromodynamics (QCD)

- fundamental description of strong interaction
- extensively tested in the perturbative regime
- **little is known about soft regime and emergent phenomena**

Analogy with solid state physics

- QED – fundamental theory
- Rich, dynamically generated, set of phenomena
  - *Example: water*

    15 phase, 16 triple points, 2 critical points



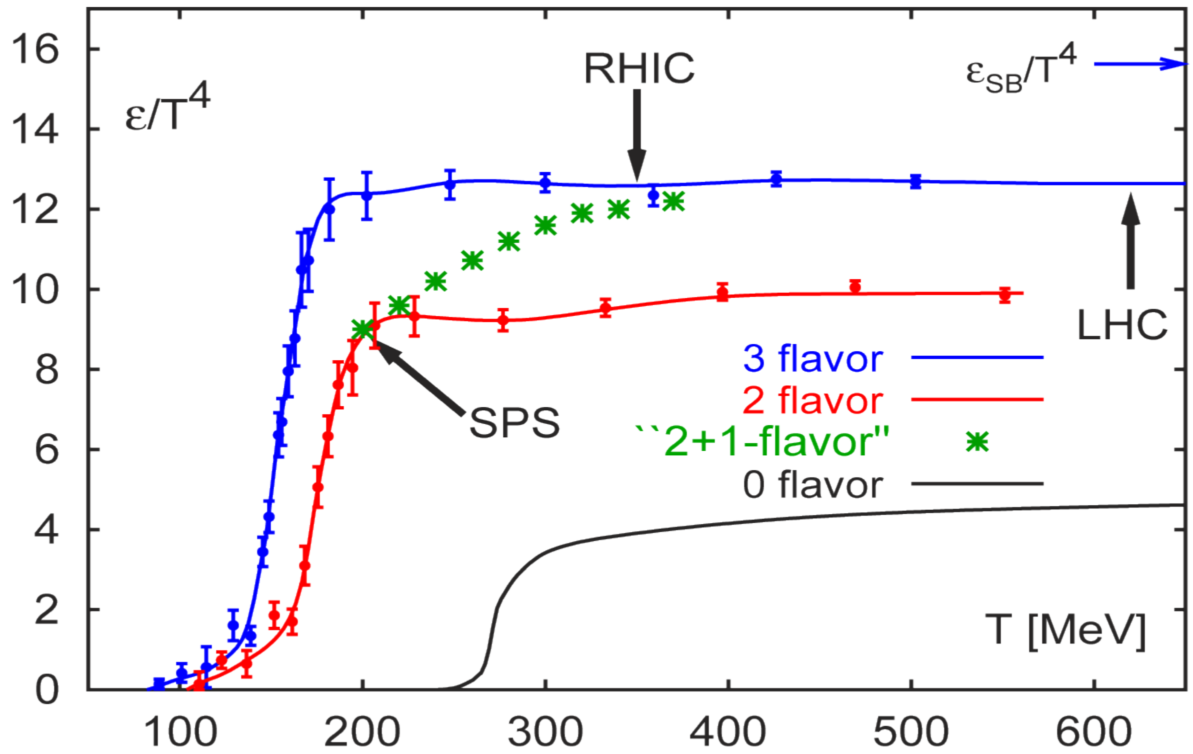
Phase transition

Lattice QCD calculations:

- critical energy density

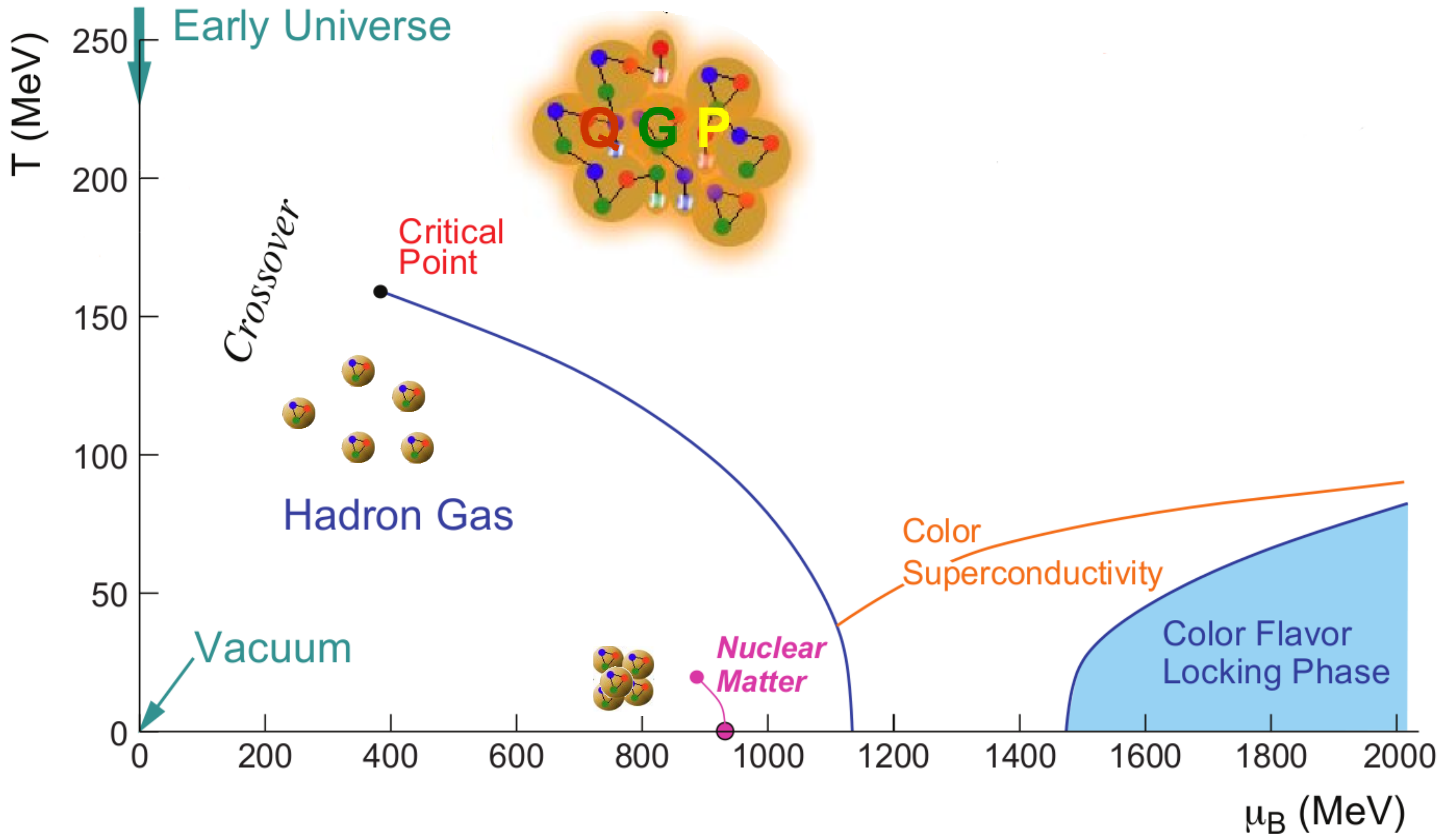
$$\epsilon_c \approx 1\ GeV/fm^3$$
$$T_c \approx 175\ MeV$$

- predict smooth cross-over at large T and μ_B=0.
- at high T reaching 80 % of non-interacting gas limit
- remaining interaction- change of initial expectation of perfect gas to (strongly) interacting liquid (sQGP)

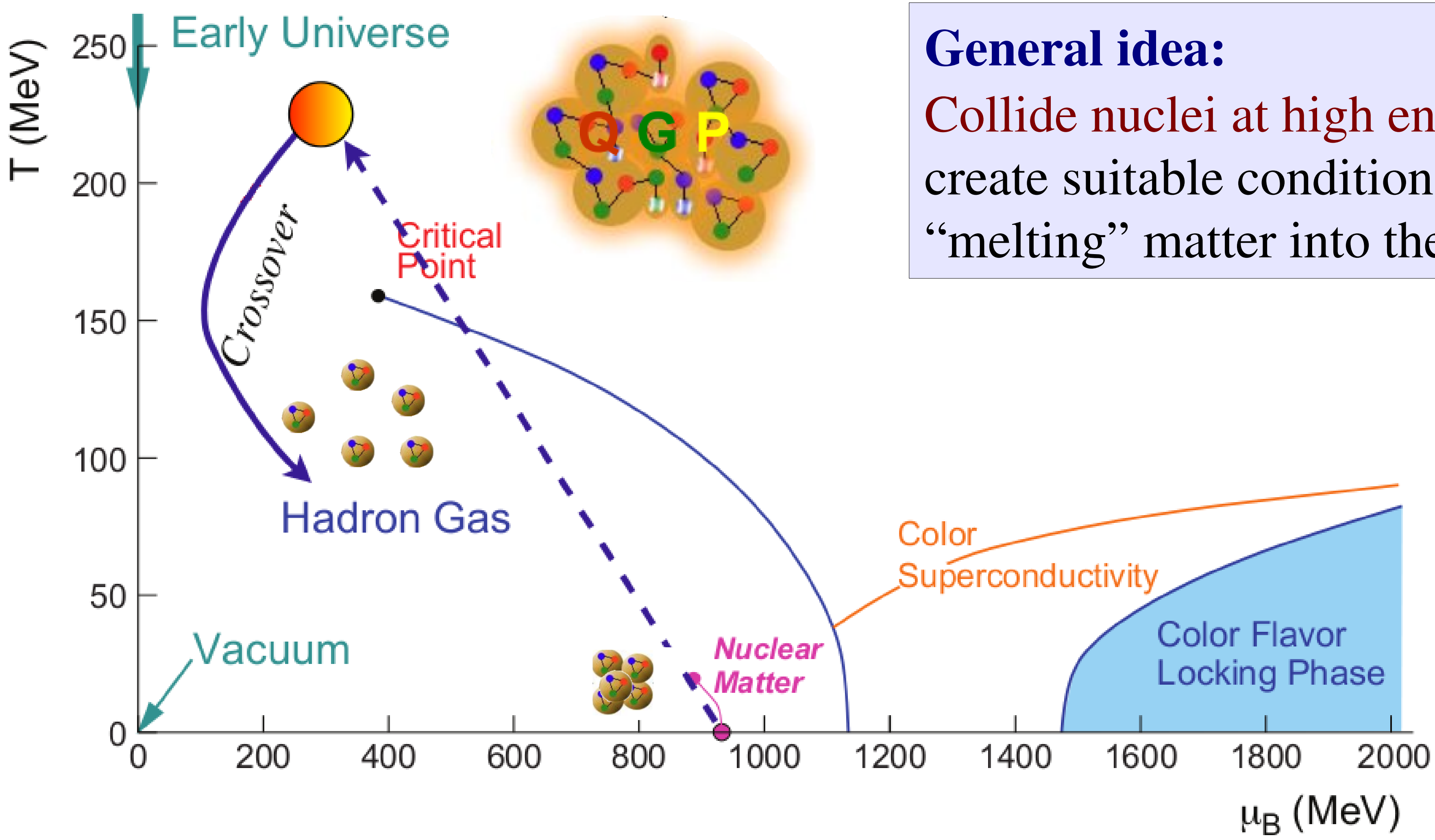


F. Karsch, et al.
Nucl. Phys. B605 (2001) 579

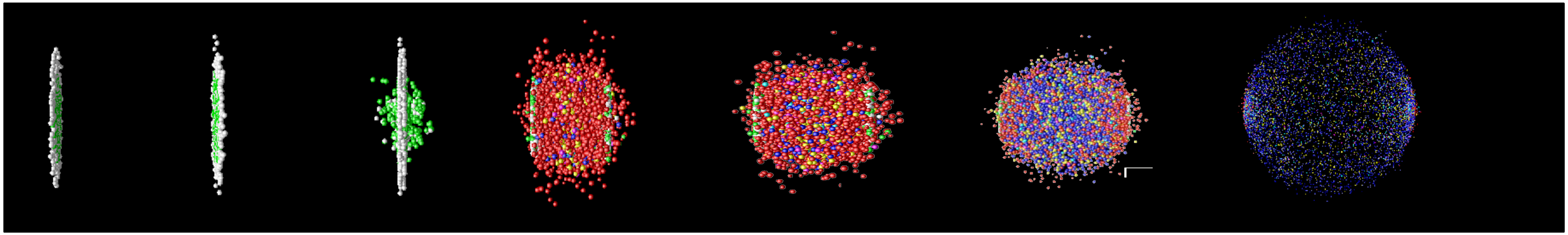
QCD phase diagram



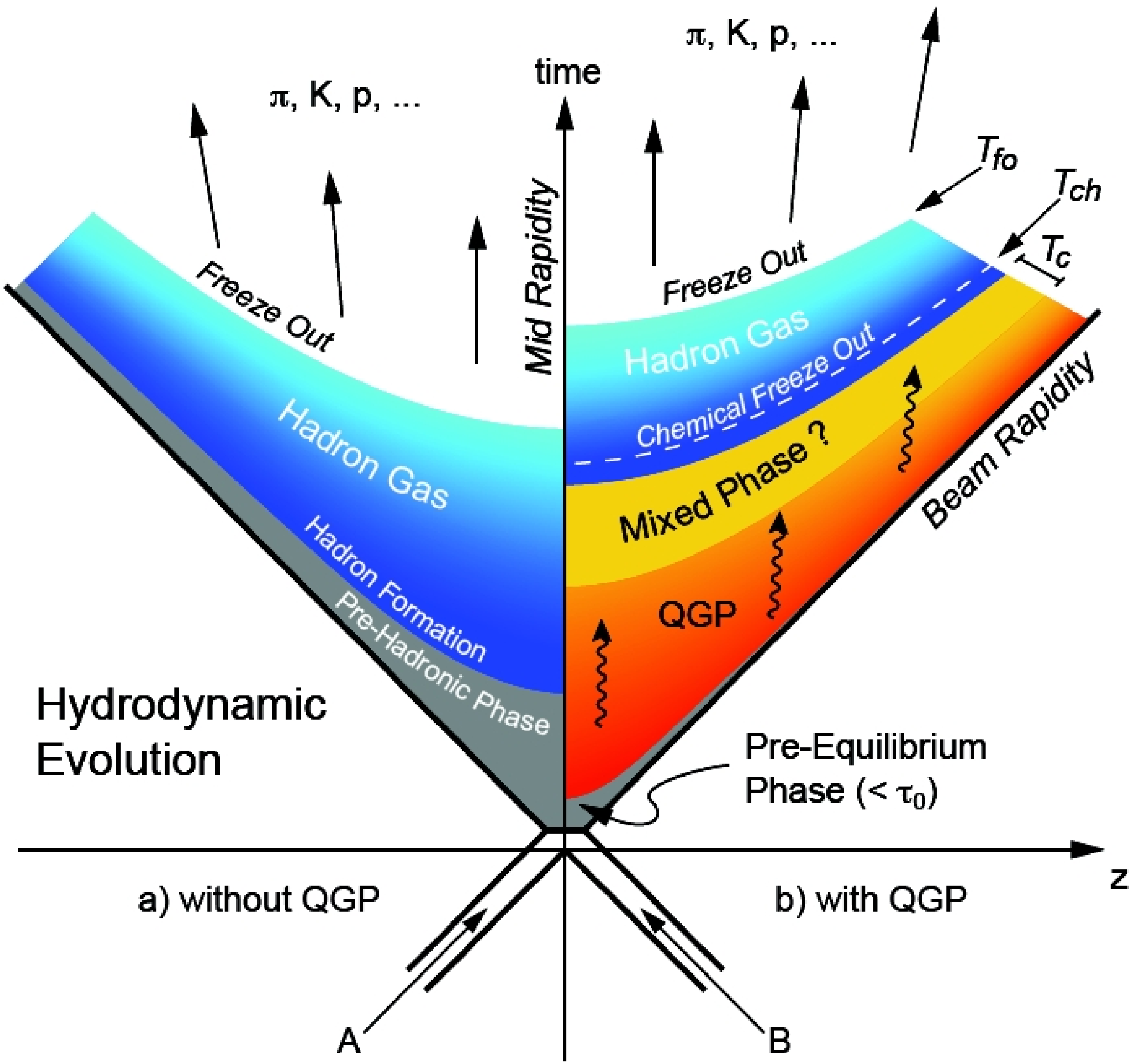
QCD phase diagram

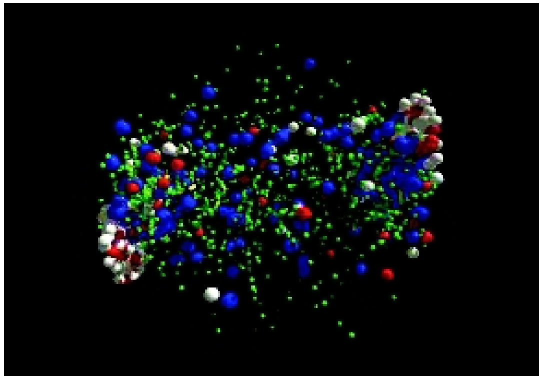


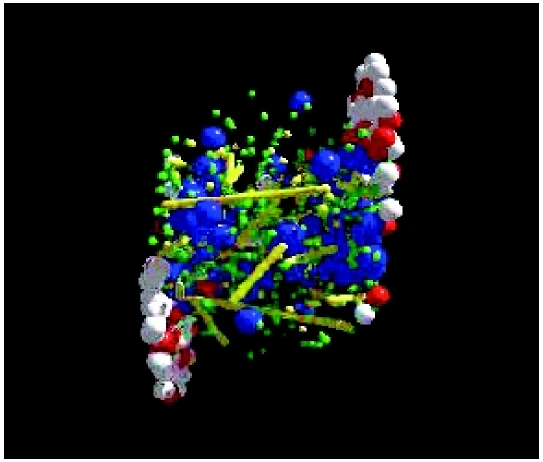
General idea:
Collide nuclei at high energy to create suitable conditions for "melting" matter into the QGP

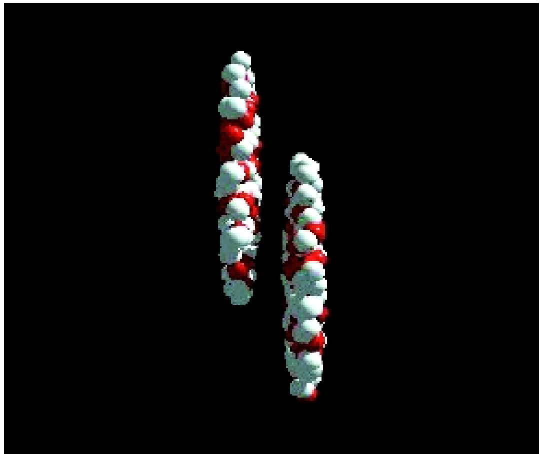


Collision evolution



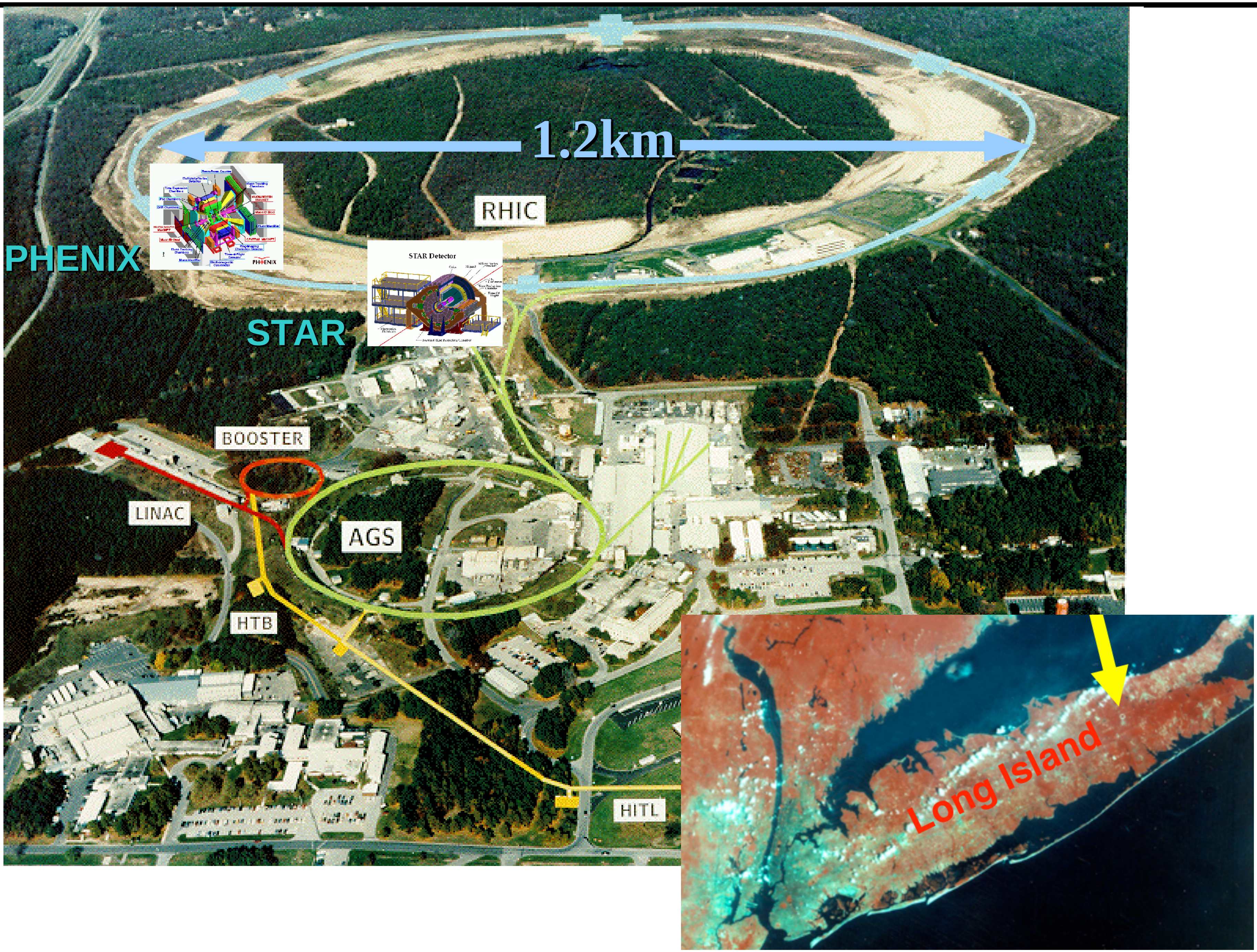




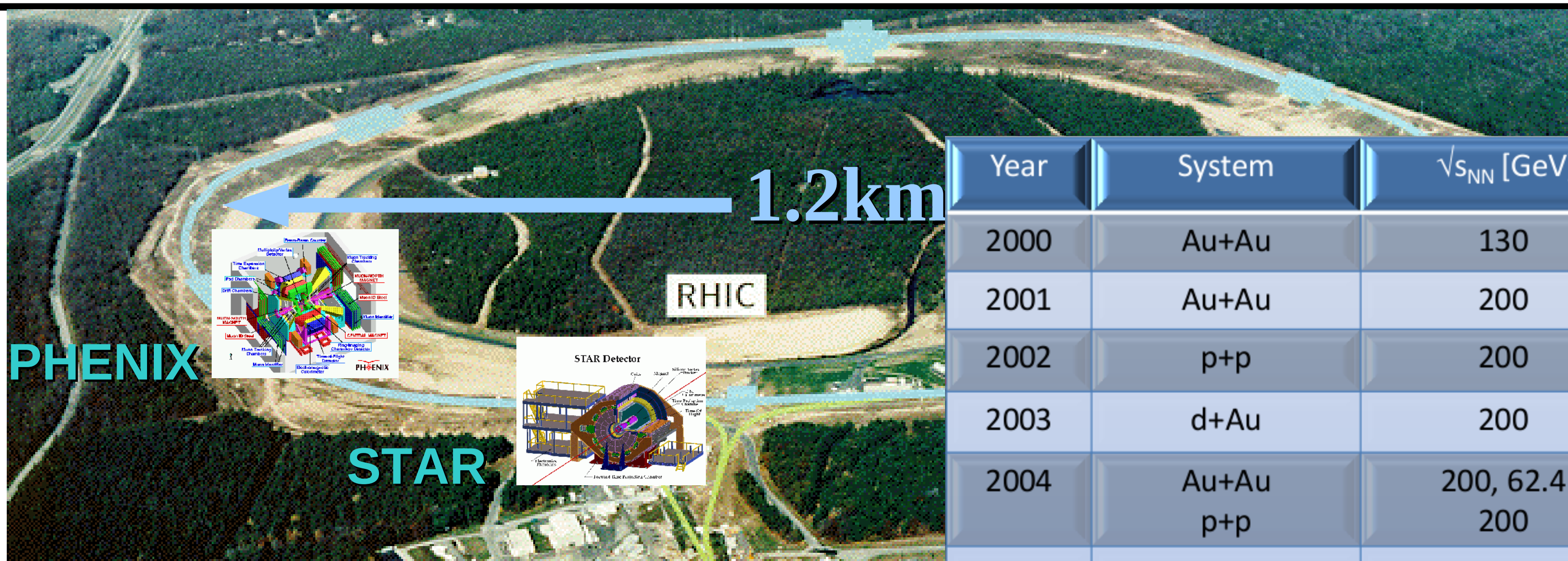


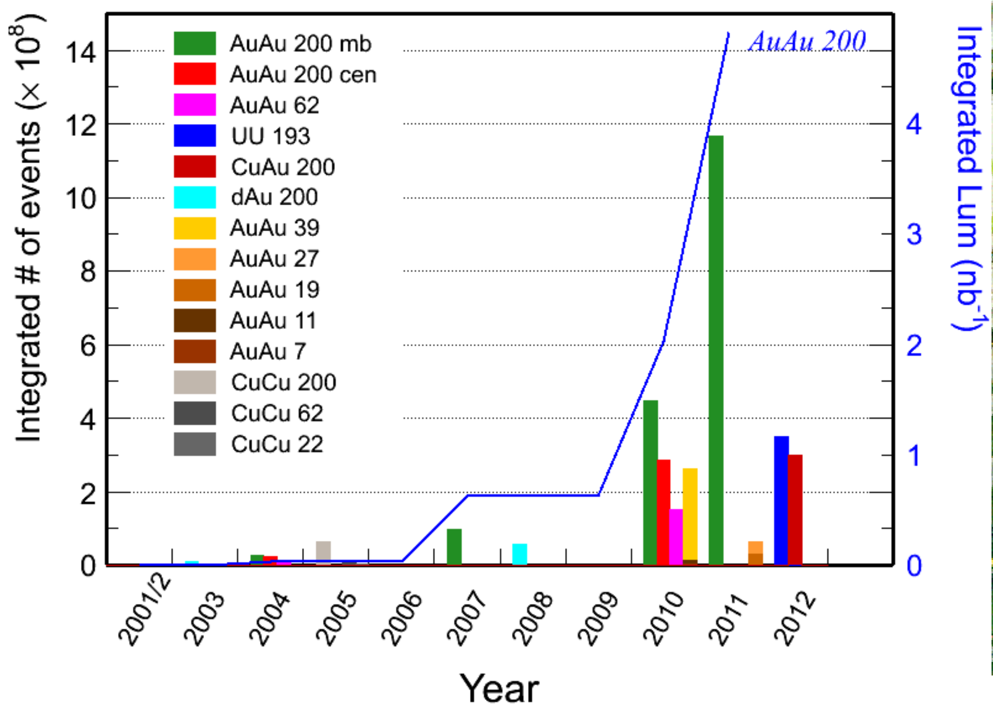
Chemical freeze-out (Tch) inelastic collisions cease
Kinetic freeze-out (Tfo < Tch) elastic collisions cease

Relativistic Heavy Ion Collider



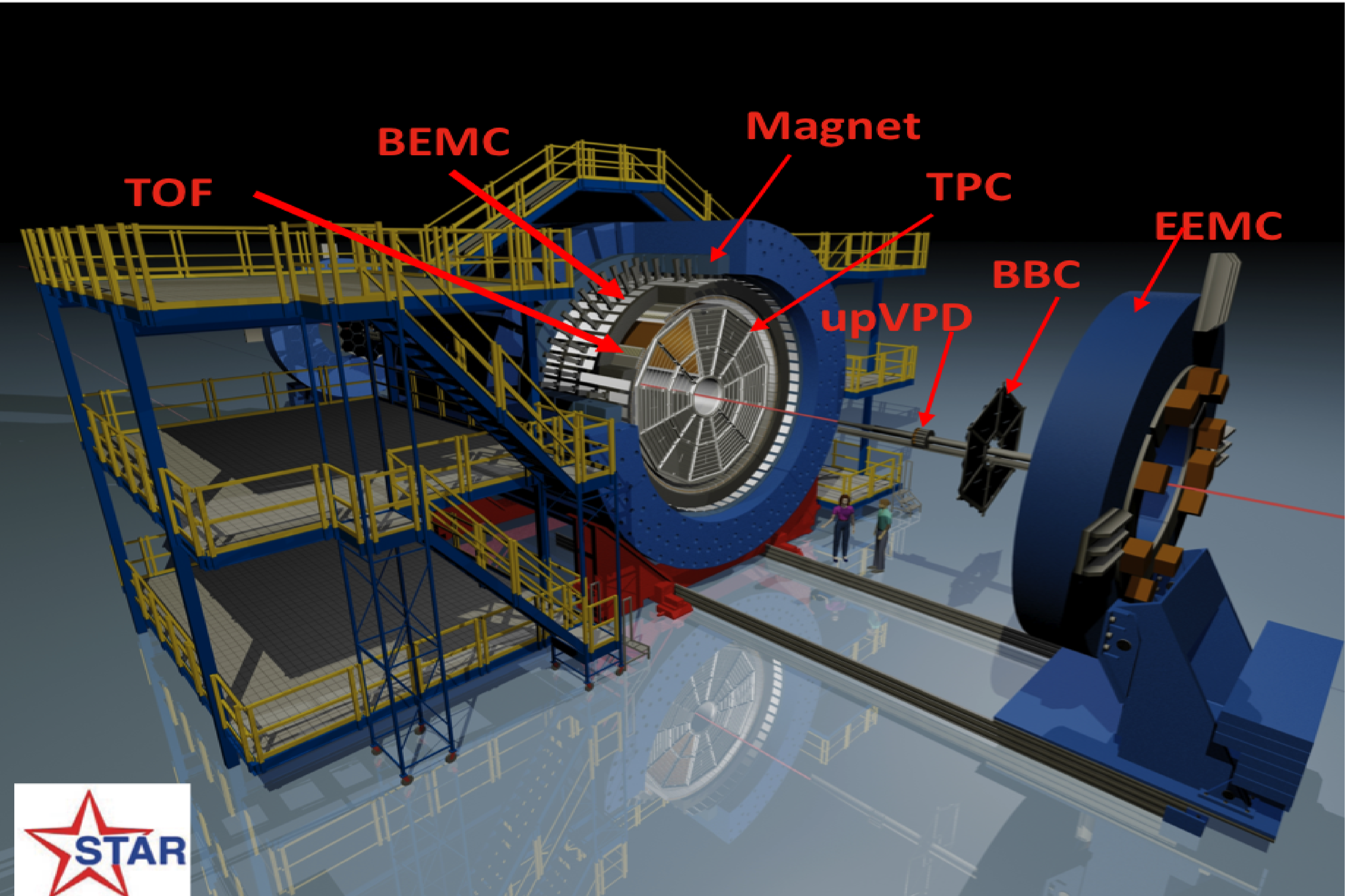
Relativistic Heavy Ion Collider



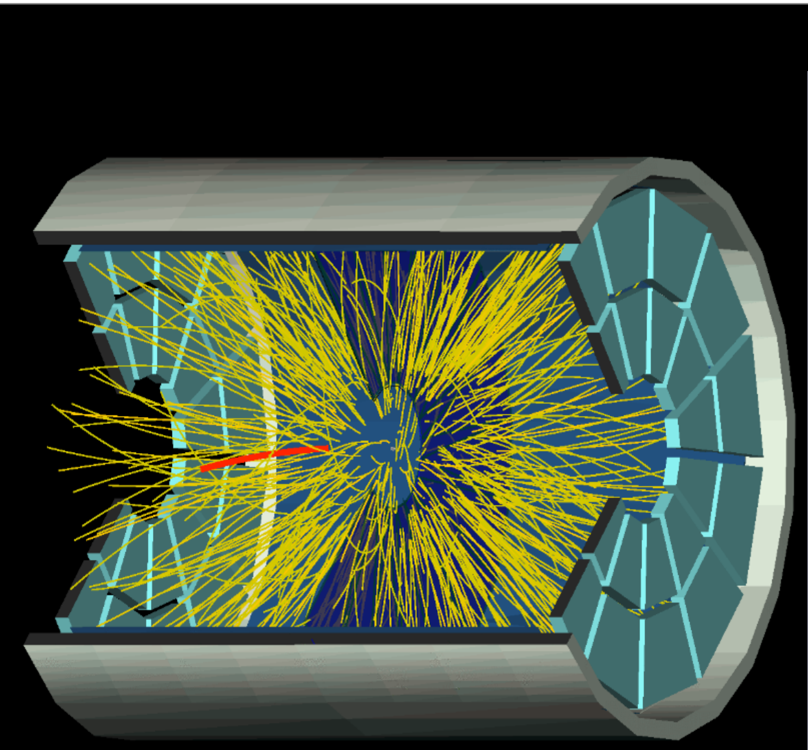


Year	System	$\sqrt{s_{NN}}$ [GeV]
2000	Au+Au	130
2001	Au+Au	200
2002	p+p	200
2003	d+Au	200
2004	Au+Au p+p	200, 62.4 200
2005	Cu+Cu	200, 62.4, 22
2006	p+p	62.4, 200, 500
2007	Au+Au	200
2008	d+Au p+p Au+Au	200 200 9.2
2009	p+p	200, 500
2010	Au+Au	200, 62.4, 39, 11.5, 7.7
2011	Au+Au p+p	200,19.6,27 500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

STAR experiment



TPC and TOF



Time Projection Chamber (TPC):

charged particle tracking

2π coverage in $|\eta|<1.3$

dE/dx PID: π /K separation up to $p_T \sim 0.6$ GeV/c

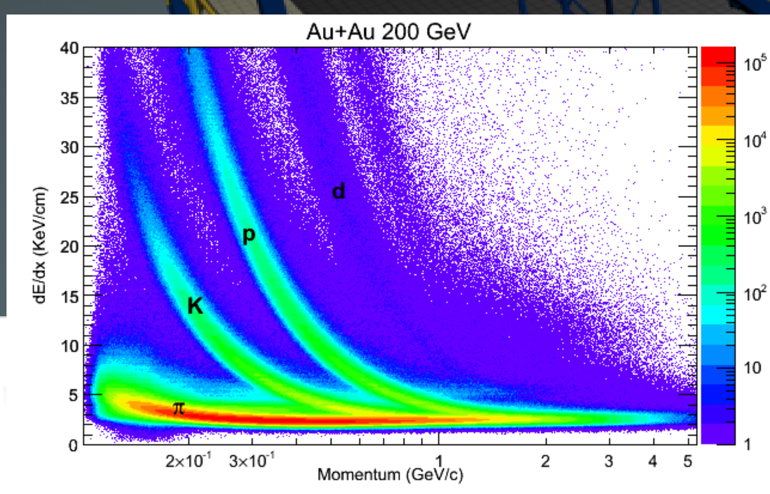
Time Of Flight (TOF):

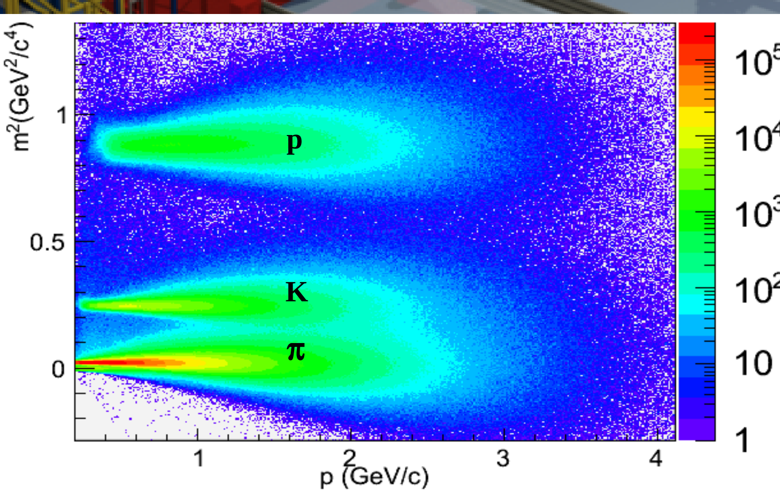
Timing resolution <100ps

$1/\beta$ PID

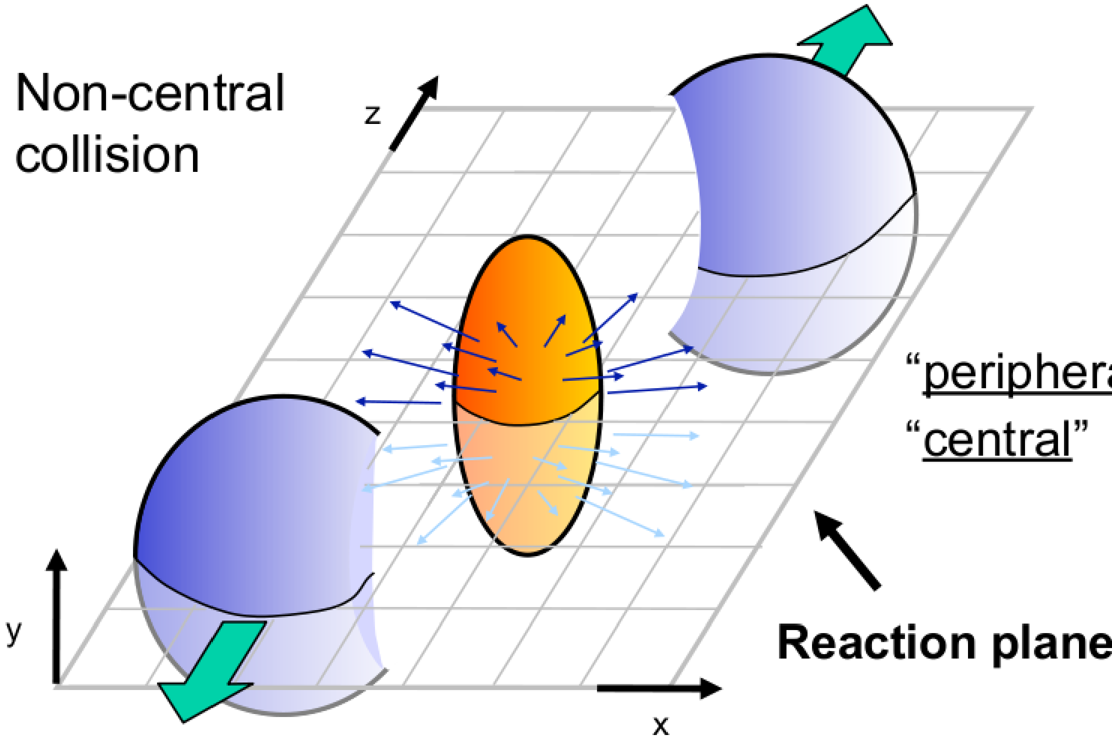
TOF + TPC :

π /K: $p_T \sim 1.6$ GeV/c and proton $p_T \sim 3.0$ GeV/c

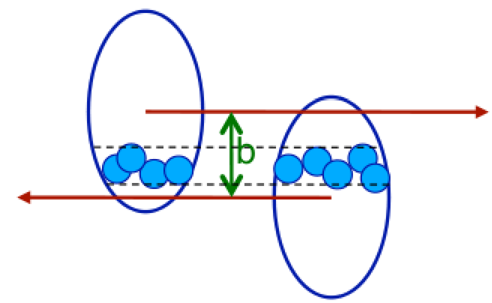




Collision geometry



"peripheral" collision ($b \sim b_{max}$)
"central" collision ($b \sim 0$)

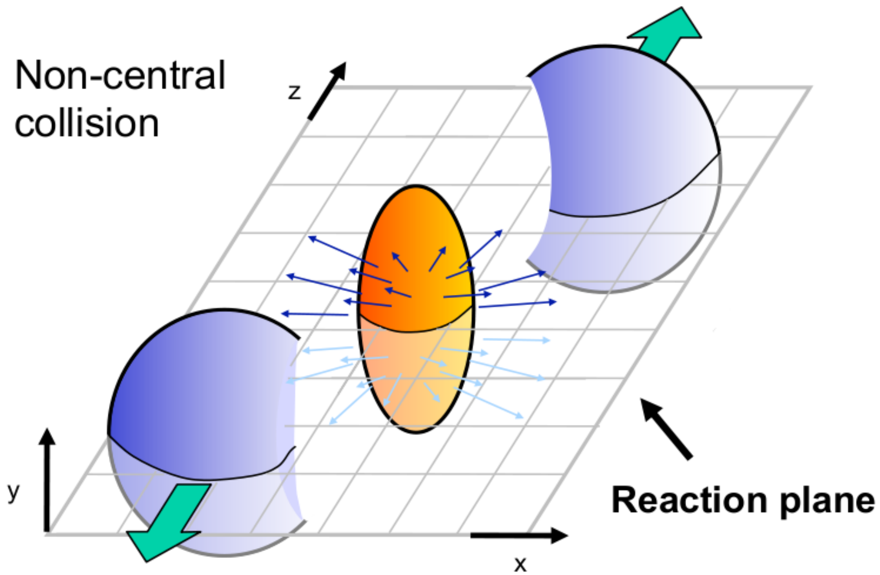


Number of participants (**N_{part}**):
number of incoming nucleons in the overlap region

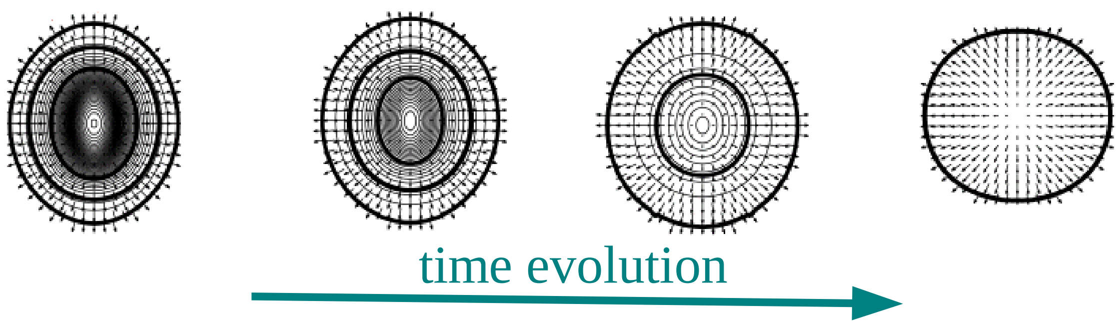
Number of binary collisions (**N_{bin}** or **N_{coll}**):
number of equivalent inelastic nucleon-nucleon collisions

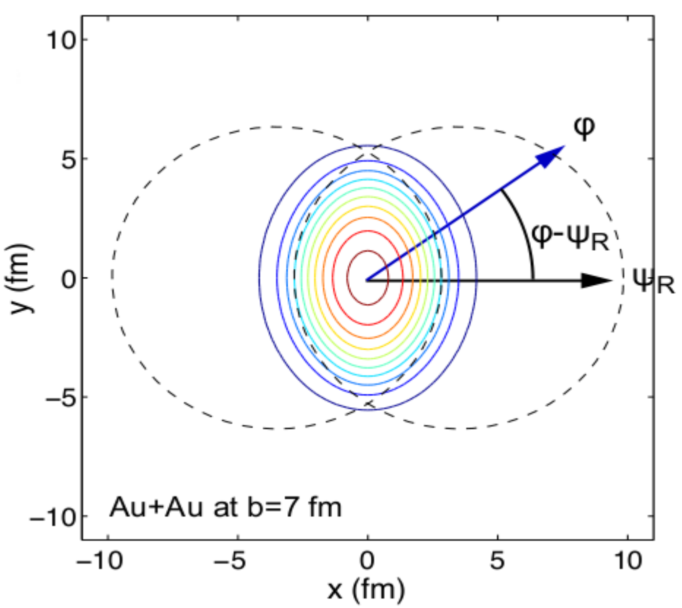
Derived from multiplicity information and a simple version of Glauber theory

Elliptic flow



- initial spacial anisotropy
- interactions and time evolution
- final momentum anisotropy
- sensitive to thermalization, EOS and early pressure

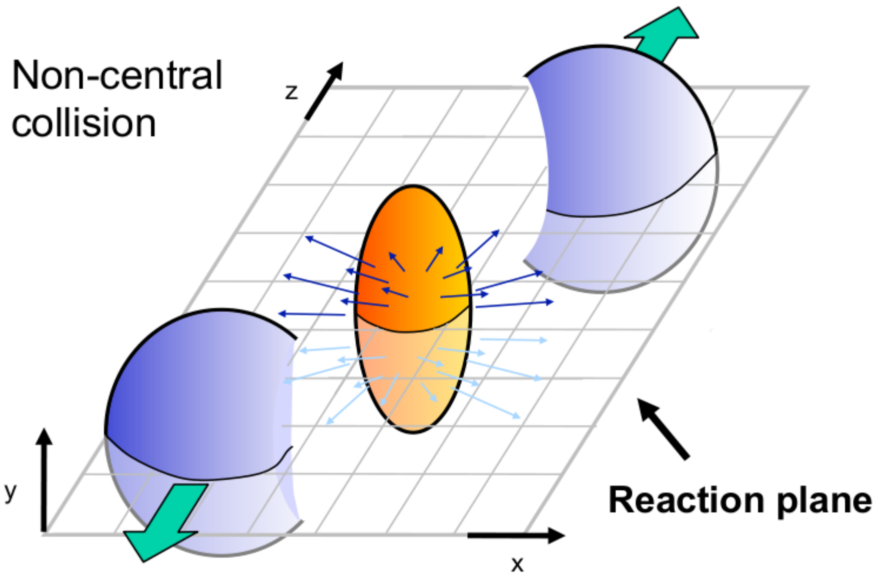


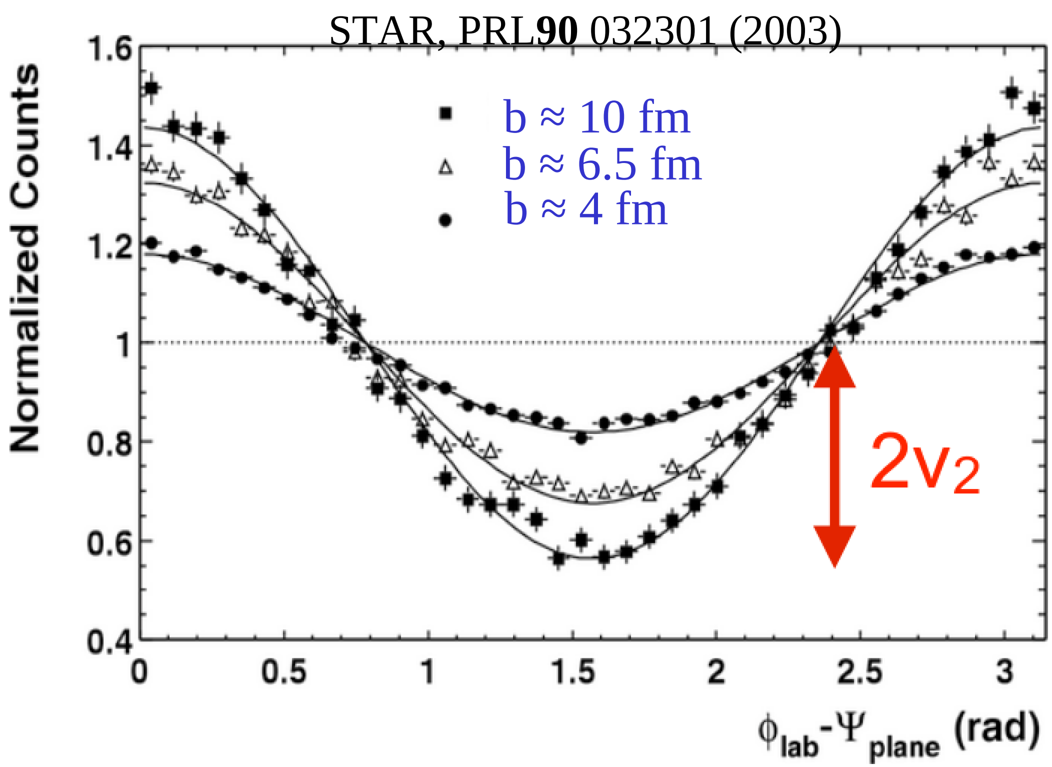


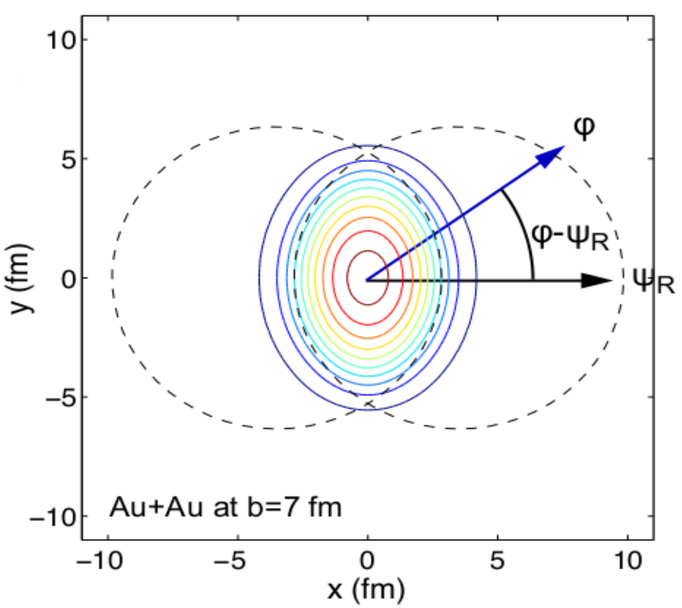
$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

$$v_2 = \langle \cos[2(\varphi - \psi_R)] \rangle$$

Elliptic flow







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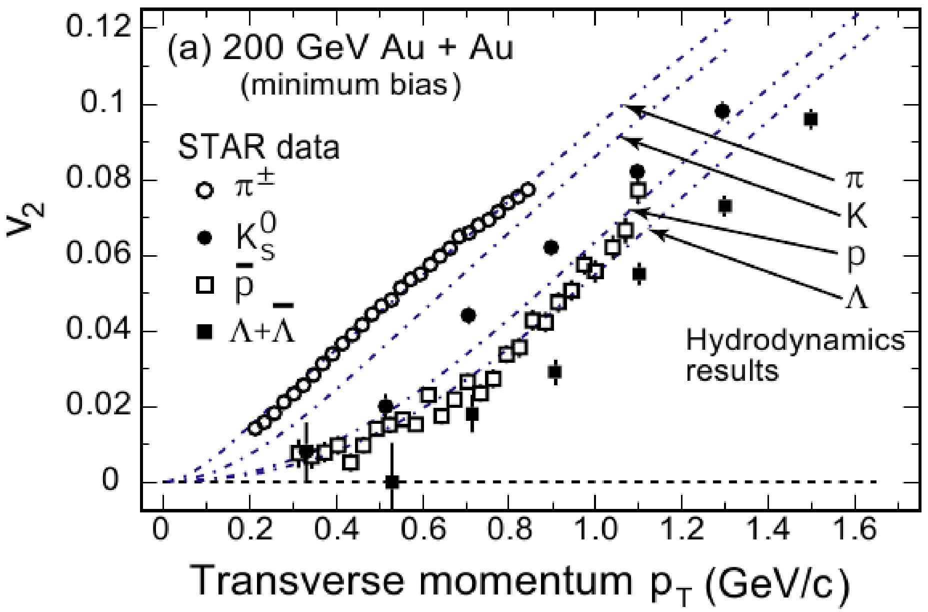
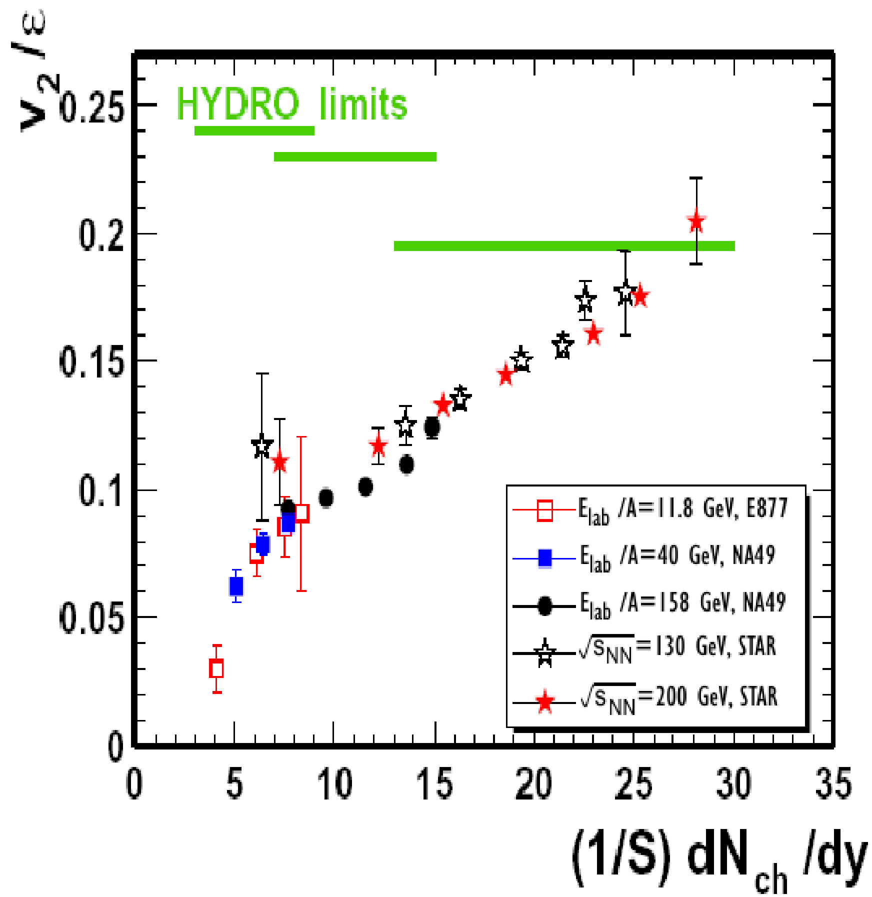
Elliptic flow at RHIC



Nucl.Phys. A757 (2005) 102-183

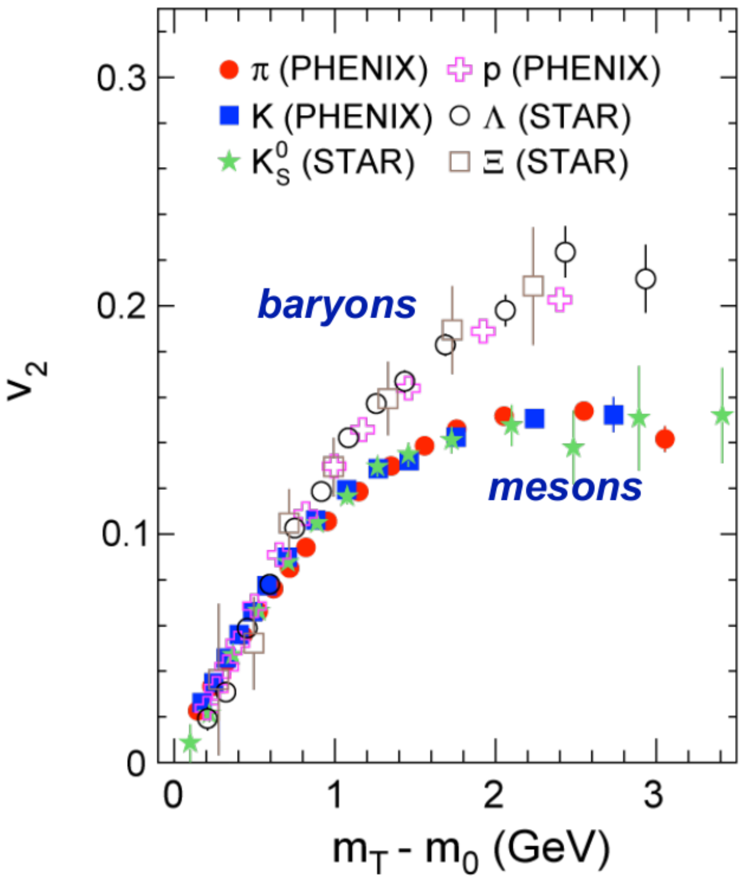
- Large v_2 compared to SPS
- Fine structure” v_2(pT) for different mass particles



- Includes strange particles
- **Close to perfect hydro predictions**

Partonic collectivity

Is v_2 generated on hadronic or partonic level?

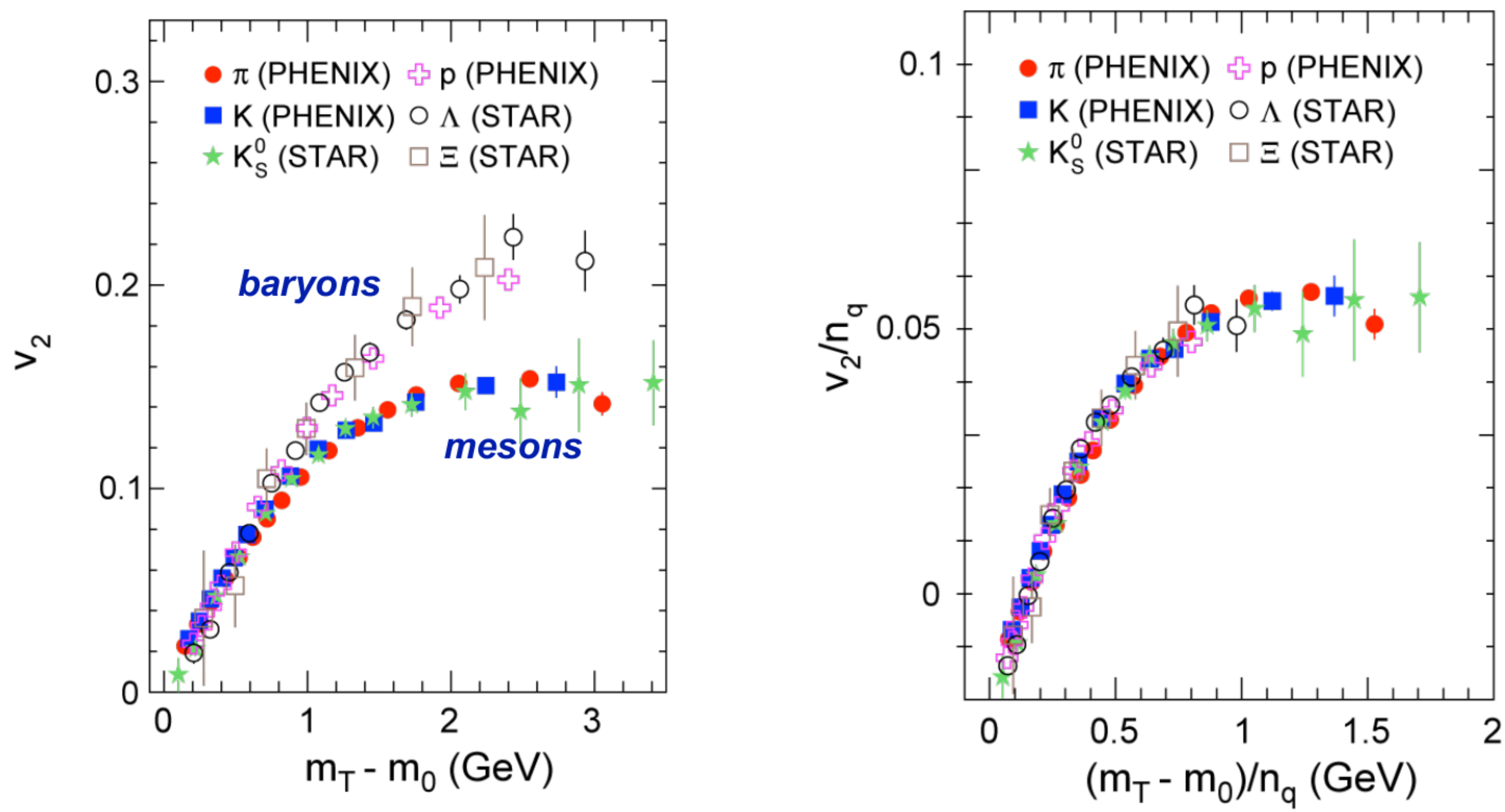


STAR: PRL ***95****, 122301 (2005)*
PHENIX: PRL ***98****, 162301 (2007)*

Partonic collectivity

Is v_2 generated on hadronic or partonic level?

Scaling by number of constituent quarks

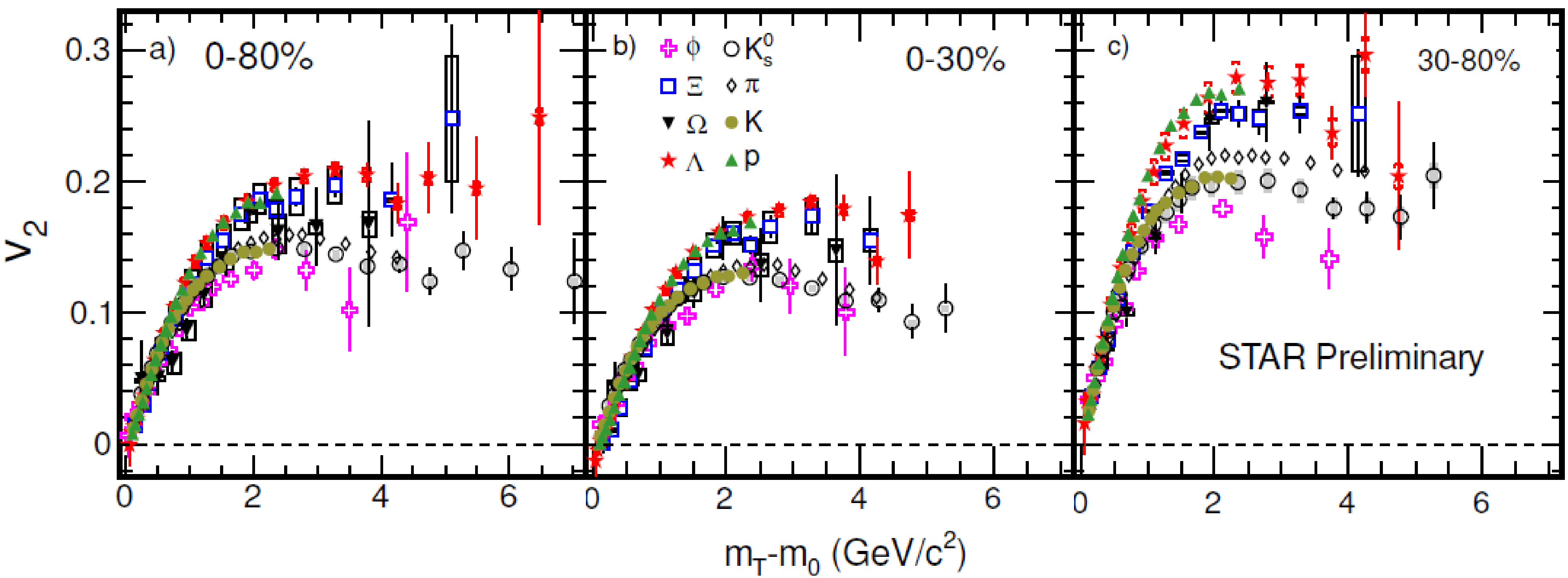


STAR: PRL ***95****, 122301 (2005)*
PHENIX: PRL ***98****, 162301 (2007)*

v_2 from Au+Au 200GeV

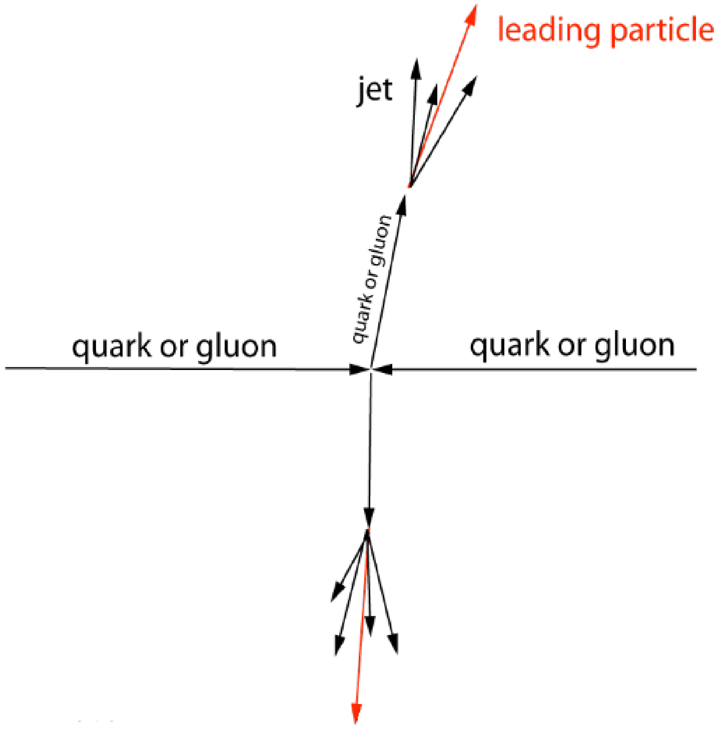
High precision result from 200 GeV for Au+Au

- including strange and multistrange particles
- central collision – clear baryon/meson splitting at medium p_T
- key role of ϕ – heavy meson
  - partonic collectivity confirmation
- flow of heavy quarks? (charm, bottom)- check of thermalization



High p_T probes

- **Study interaction of created matter with passing particle**
- high p_T partons created at initial stage - pQCD



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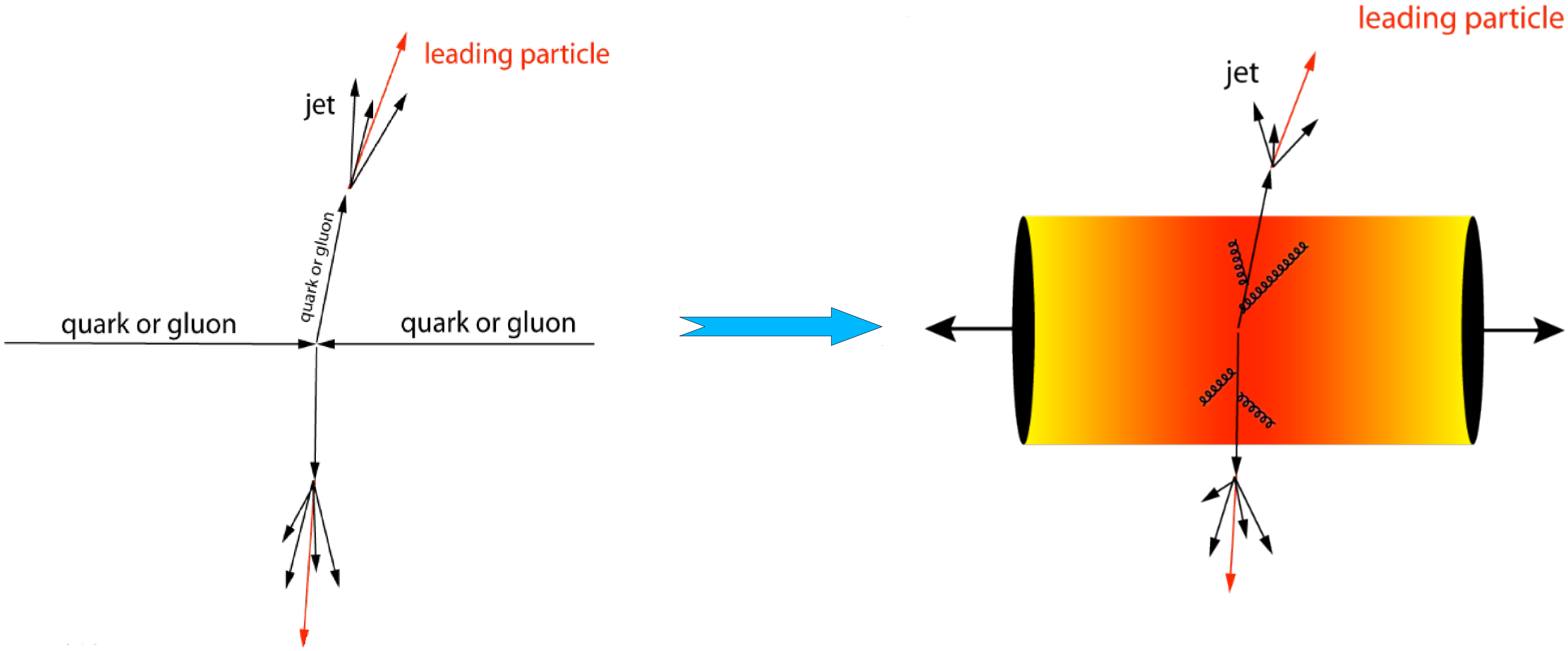
- control over cold matter effects via d+Au



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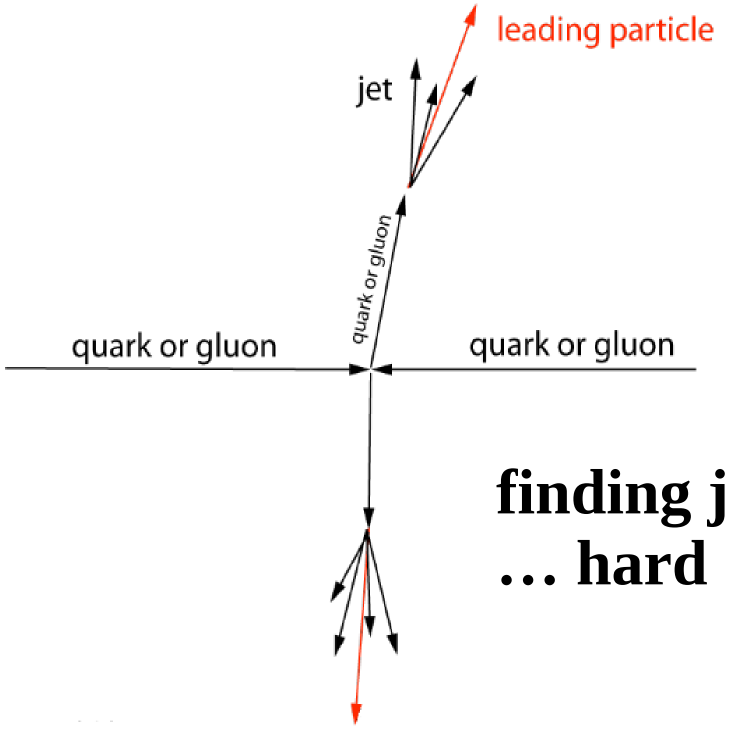
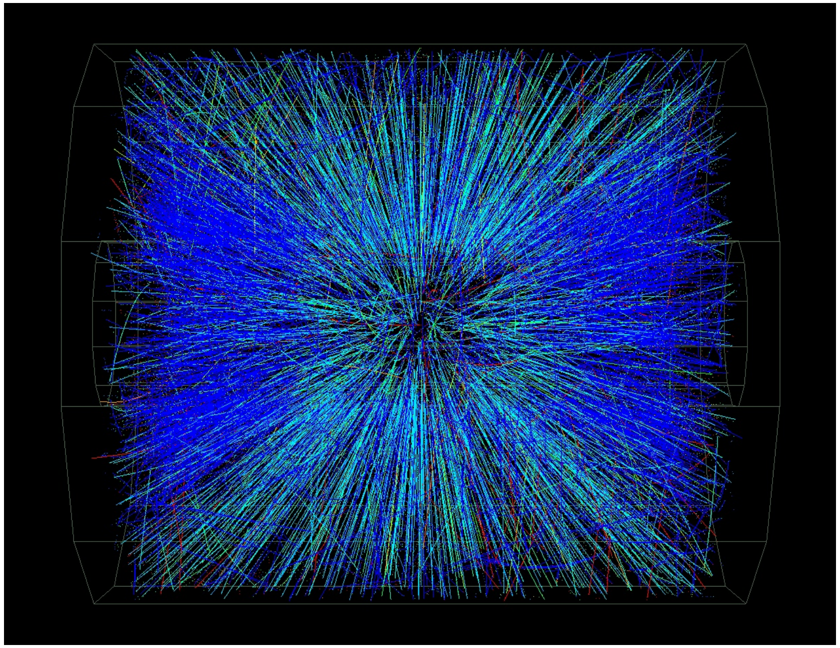


finding jet in this ?
… hard

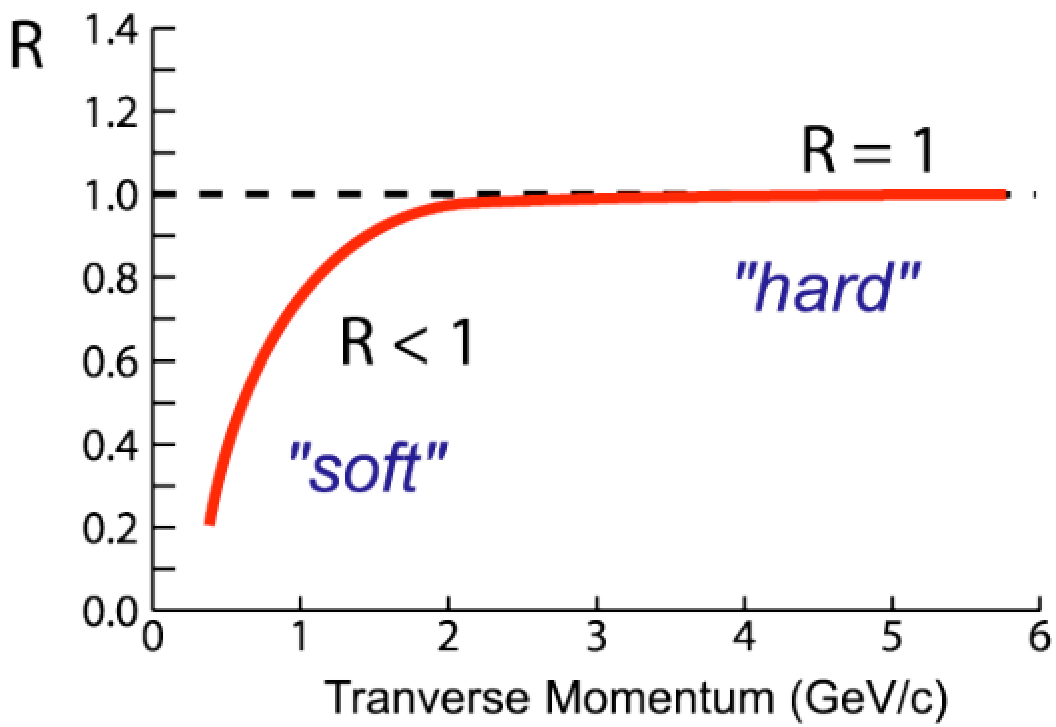


Nuclear modification factor

comparing particle production to p+p

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

Average number of p-p collision in A-A collision



Region of interest: $p_T \gtrsim 5$ GeV

No effect:

R=1 at high p_T

A+A similar to p+p superposition

Suppresion:

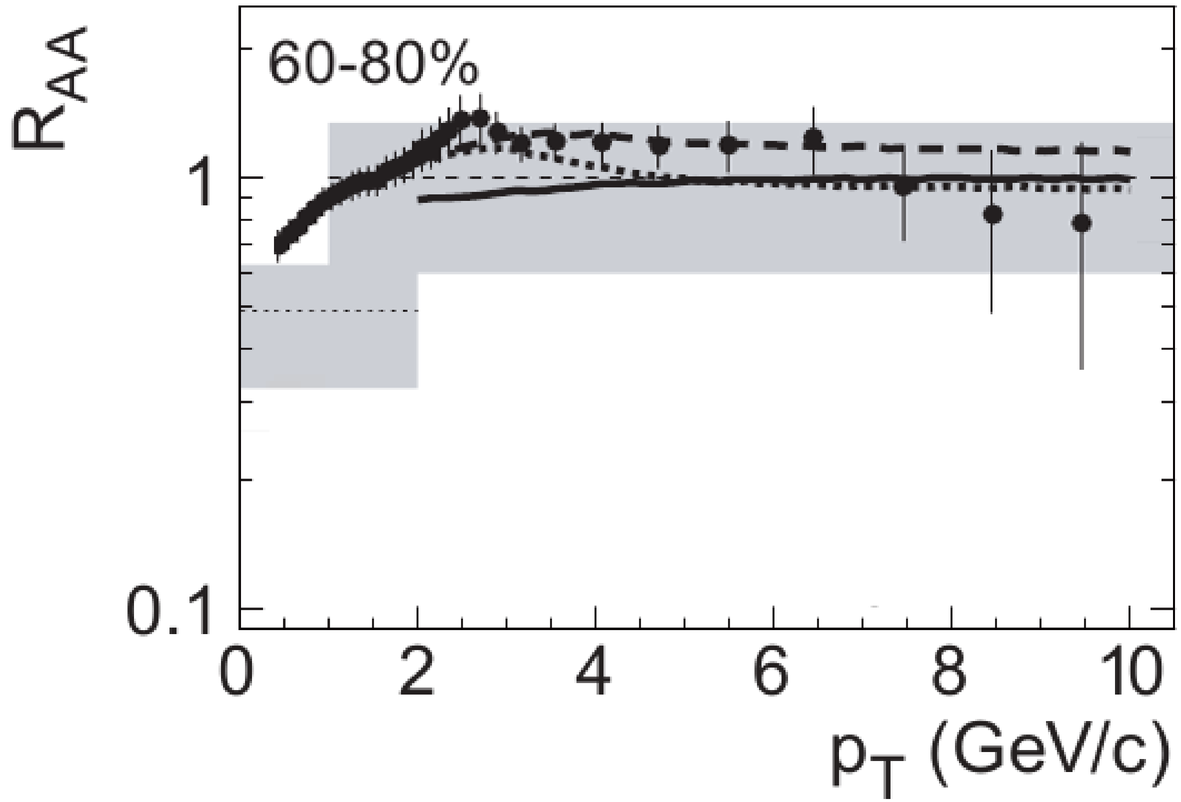
R<1 at high p_T

R_{AA} in Au+Au 200GeV

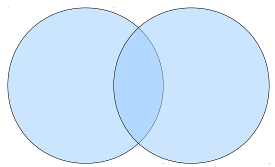
$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle Nbin \rangle_{AA} \text{Yield}_{pp}(p_T)}$$

observed R_{AA} at RHIC:

- no suppression in peripheral collisions



collision geometry:



Phys.Rev.Lett.91:172302,2003

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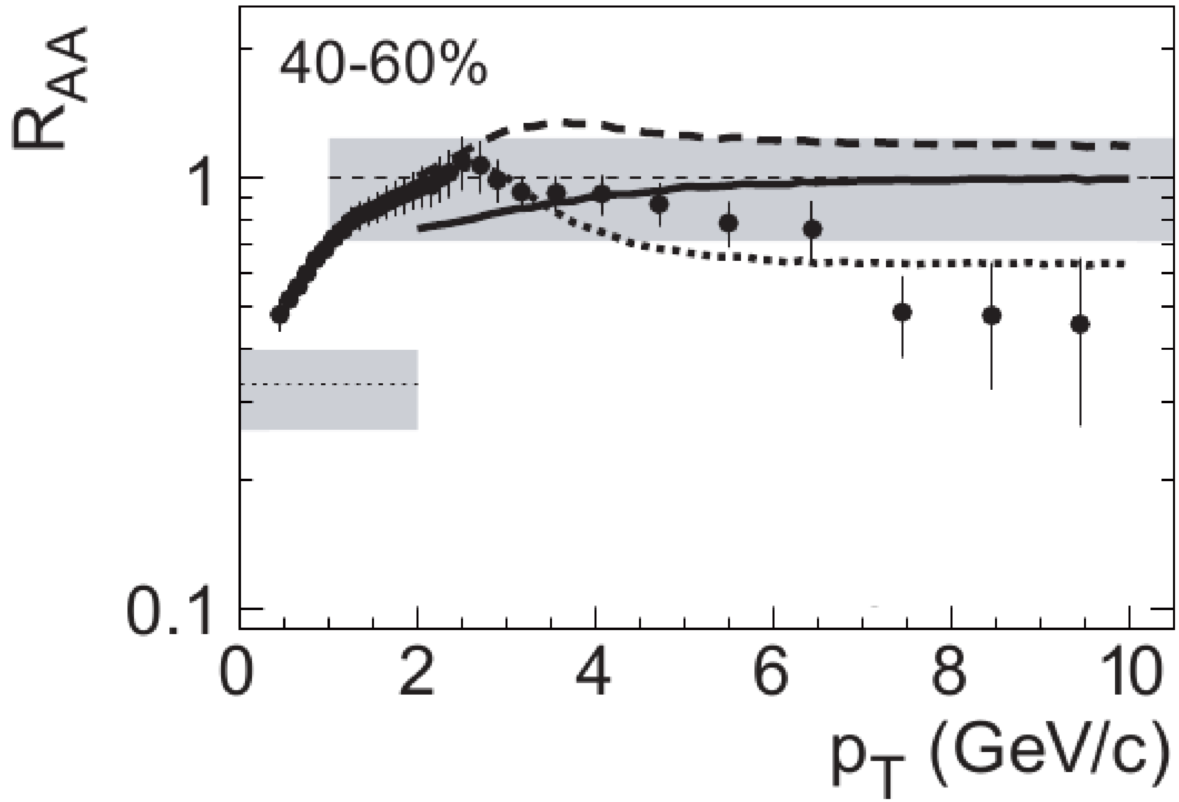

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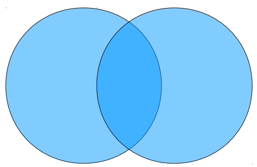

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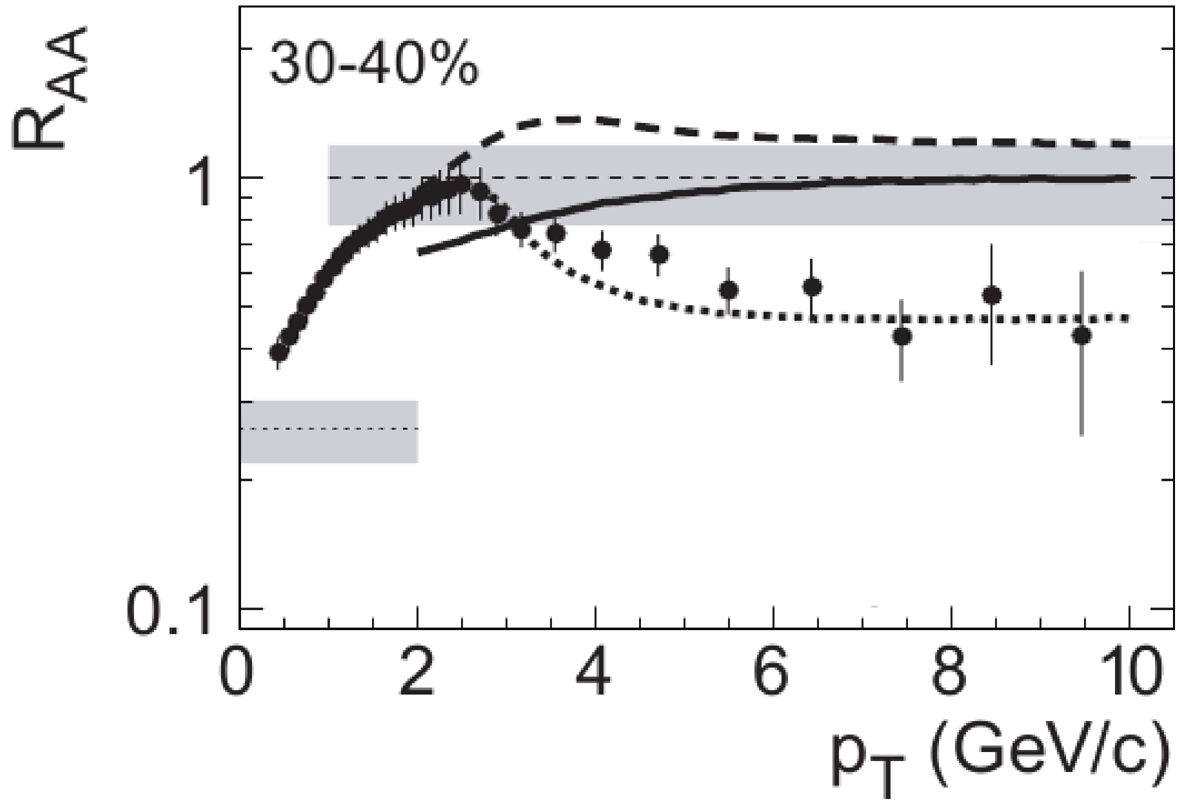

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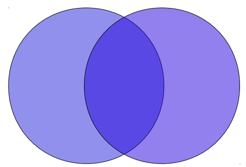

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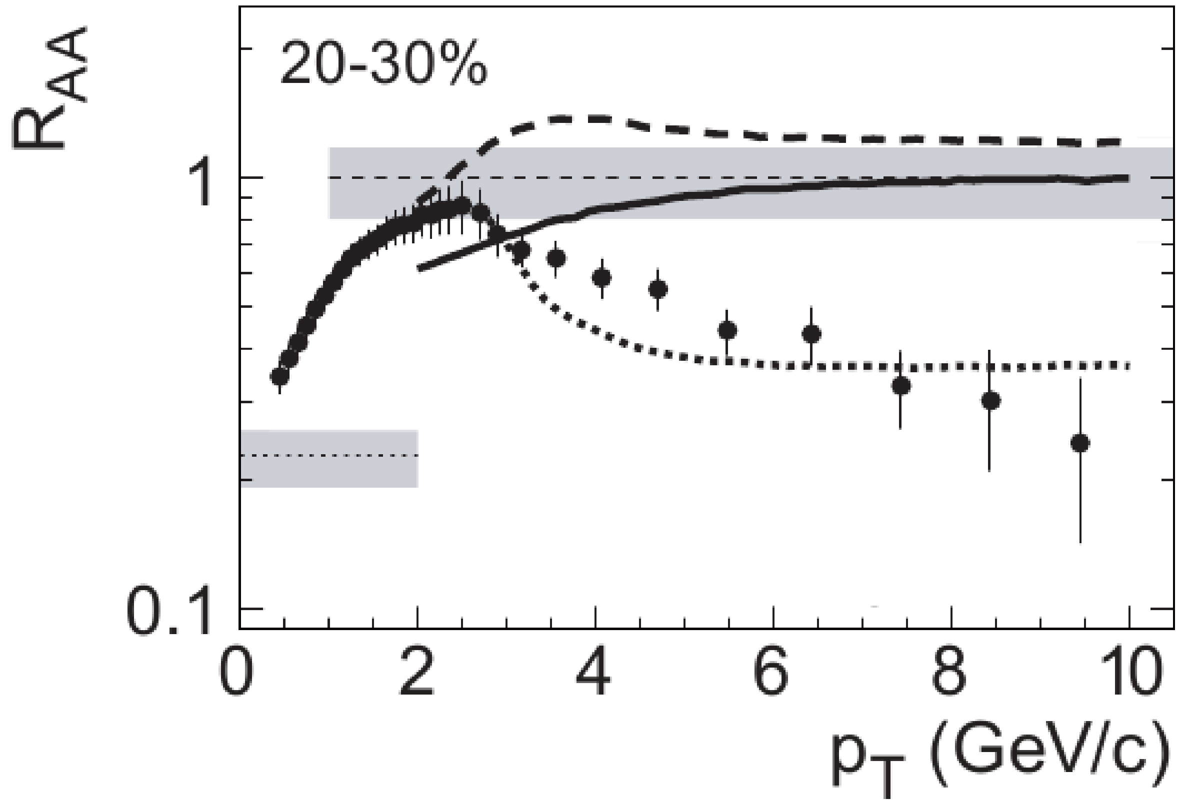

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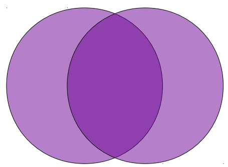

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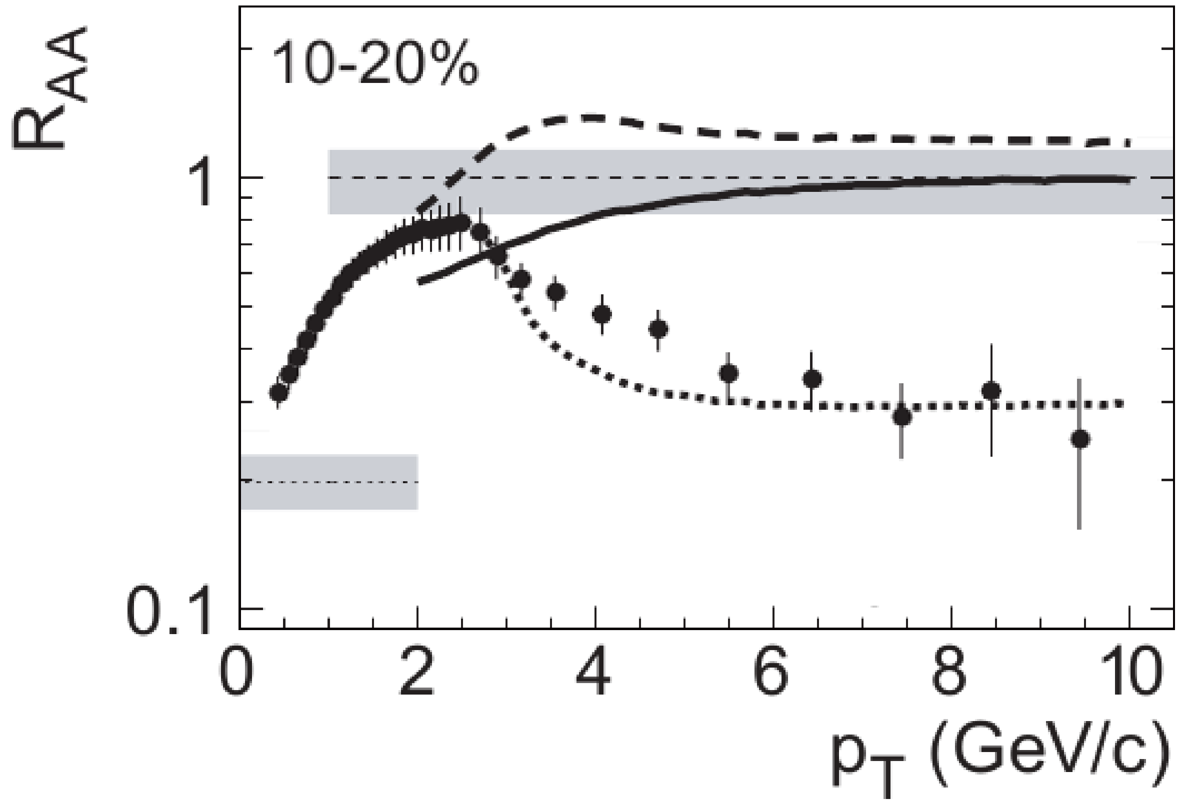

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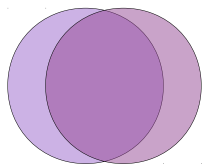

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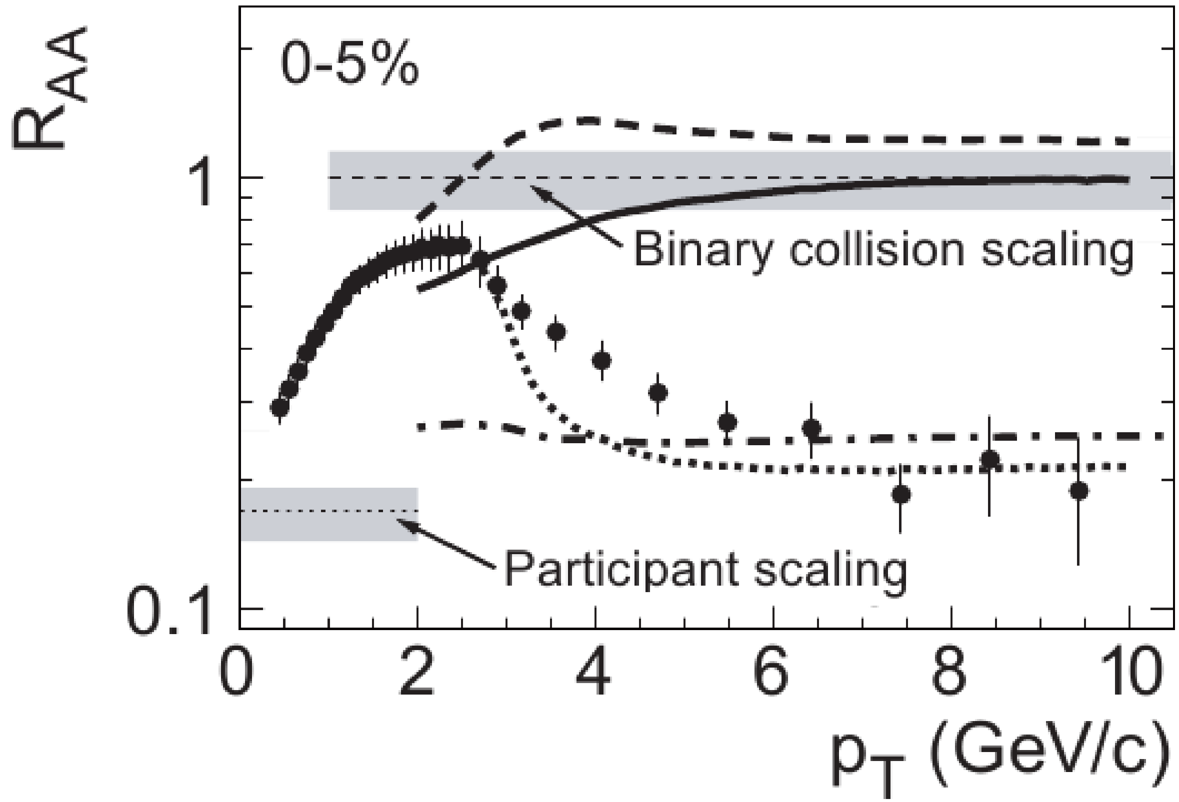
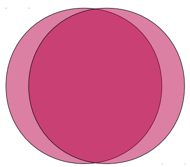
observed R_{AA} at RHIC:

- no suppression in peripheral collisions
- large suppression in central collision - factor ~ 5



collision geometry:



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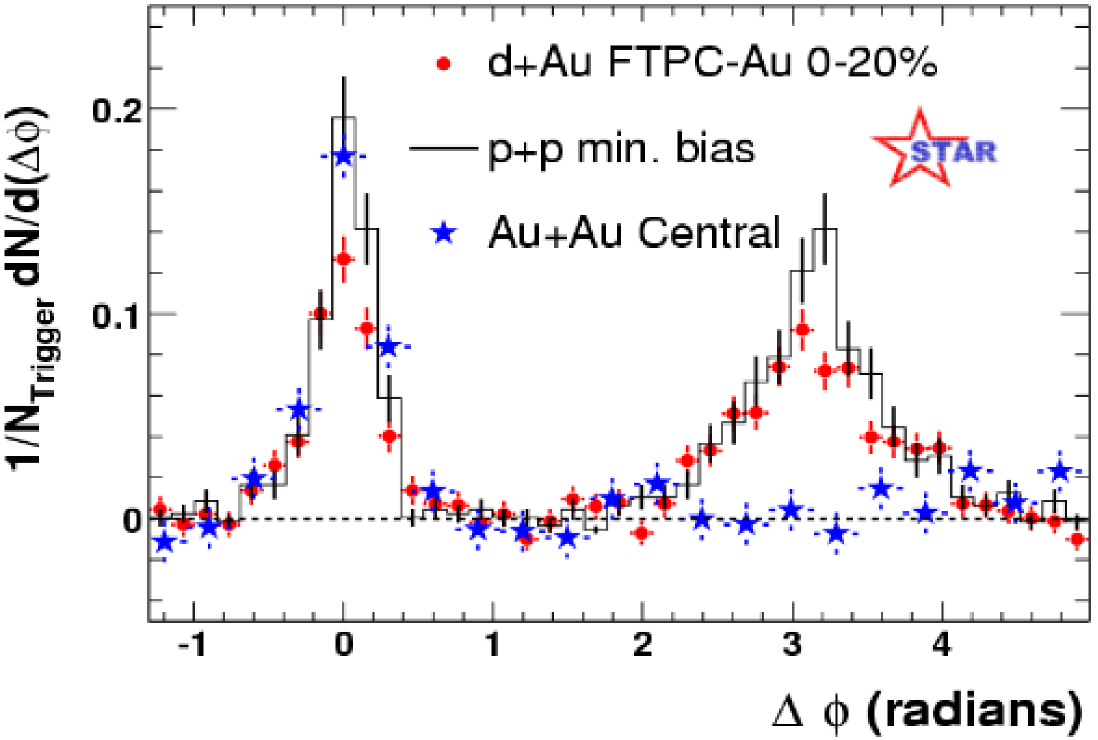
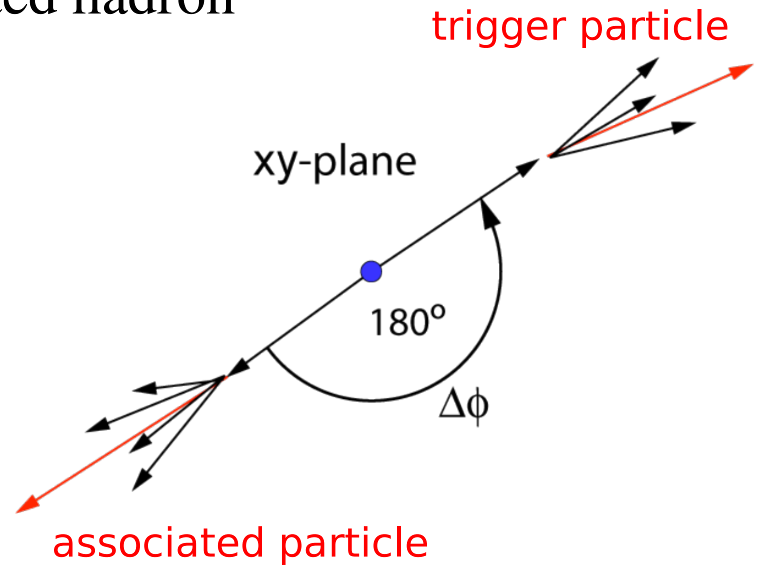
Dihadron correlations

Different way of looking at jet quenching

- angular correlation between leading and associated hadron

trigger: $4 < p_T(\mathrm{trig}) < 6$ GeV
associated: $2 < p_T < p_T(\mathrm{trig})$





STAR, PRL 90(2003) 082302

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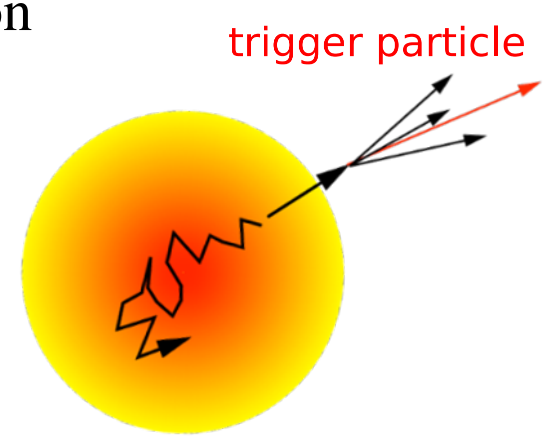

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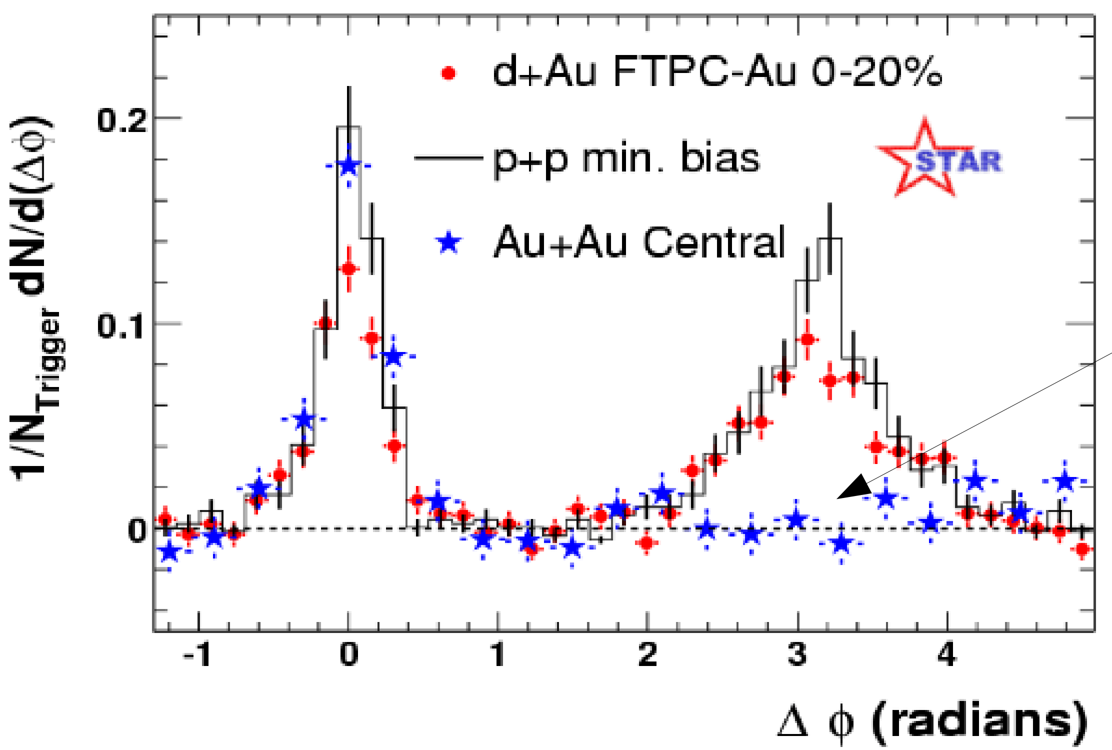


Disappearance of awayside correlation in Au+Au

- Partner in hard scatter is absorbed in the dense medium

STAR, PRL 90(2003) 082302

Summary: 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

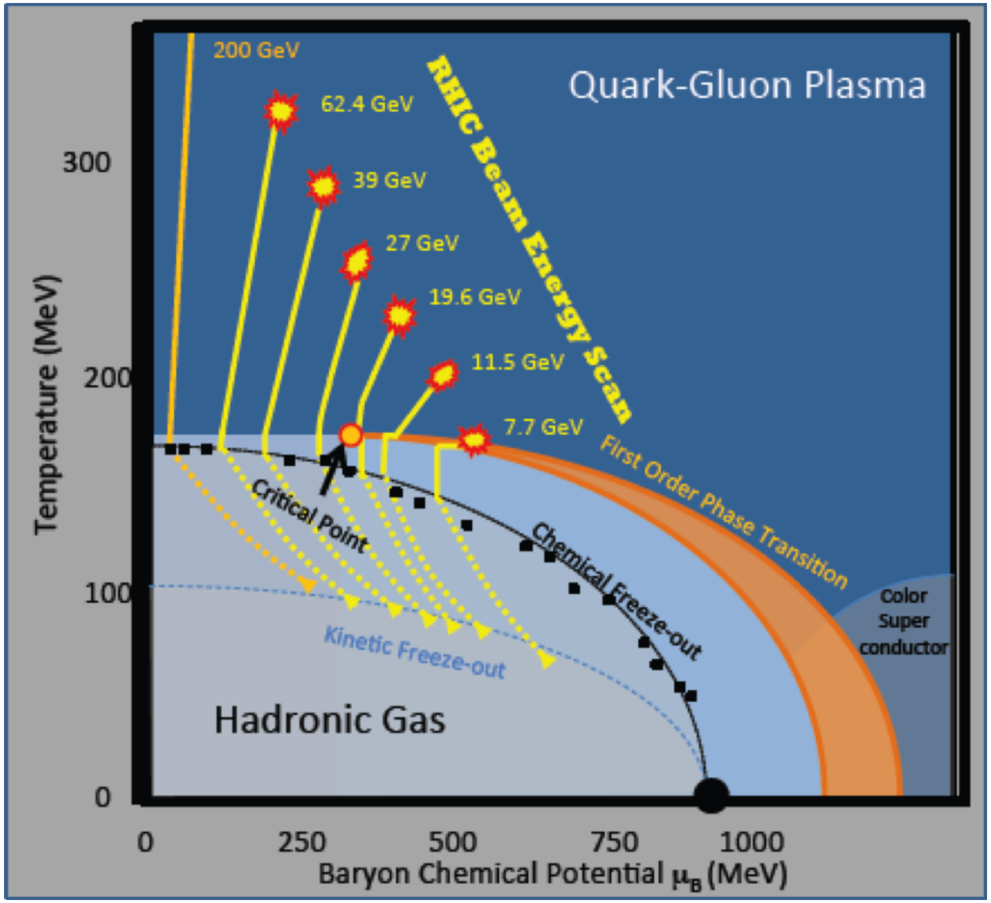
- Dominates over fragmentation at medium p_T

Paradigm shift:

non-interacting gas => strongly coupled QGP (sQGP)

RHIC Beam Energy Scan

Beam Energy Scan



arXiv:1007.2613

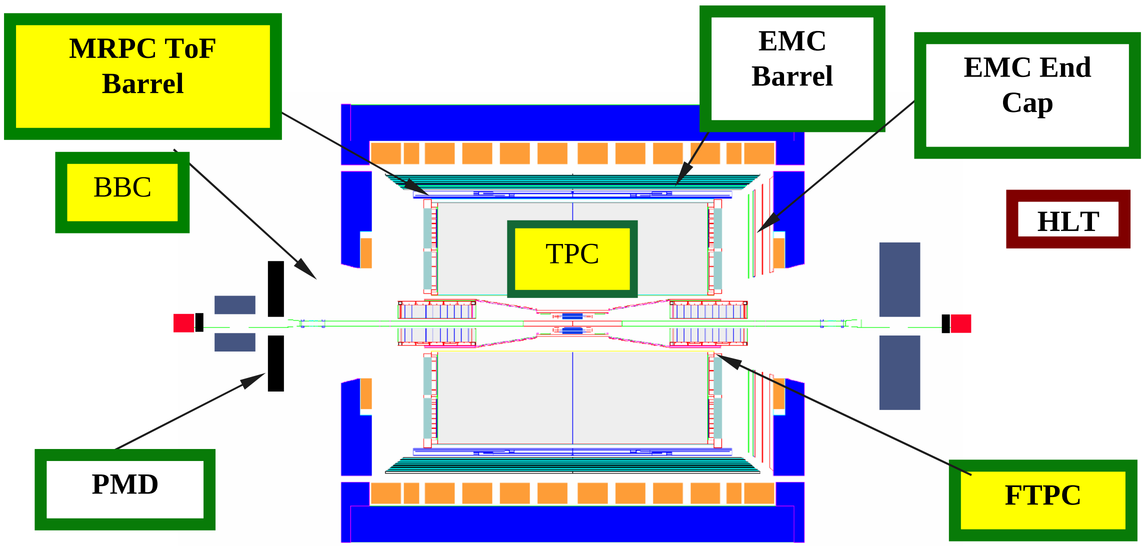
Main goal

- Study the **QCD phase diagram**:
- Search for the signals of **possible phase boundary**
- Search for the possible **QCD critical point**

BES Phase-I

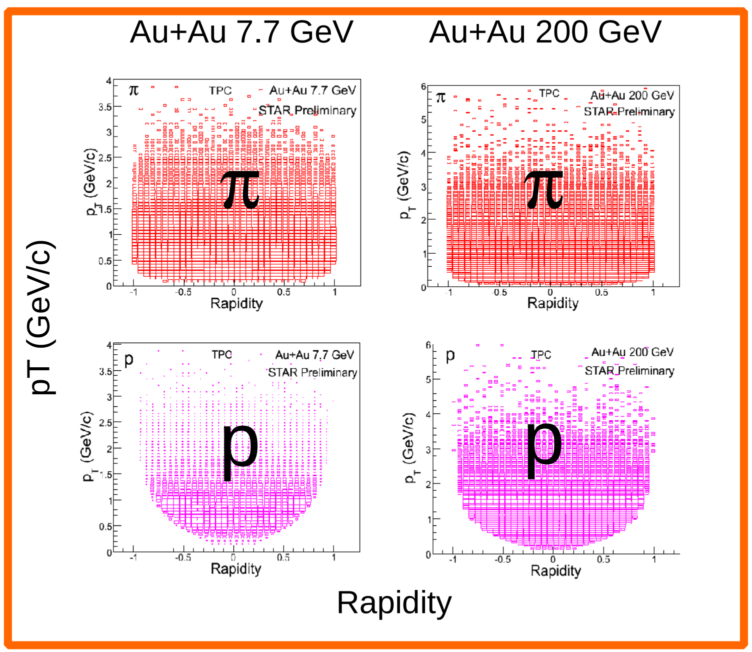
Year	$\sqrt{s_{NN}}$ (GeV)	Events (10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5

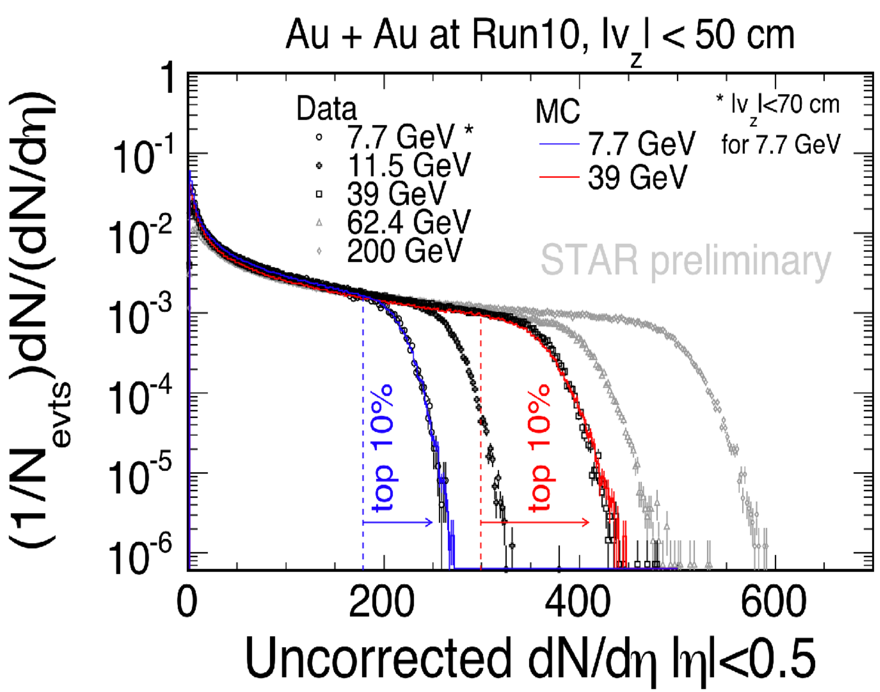
STAR – uniform acceptance



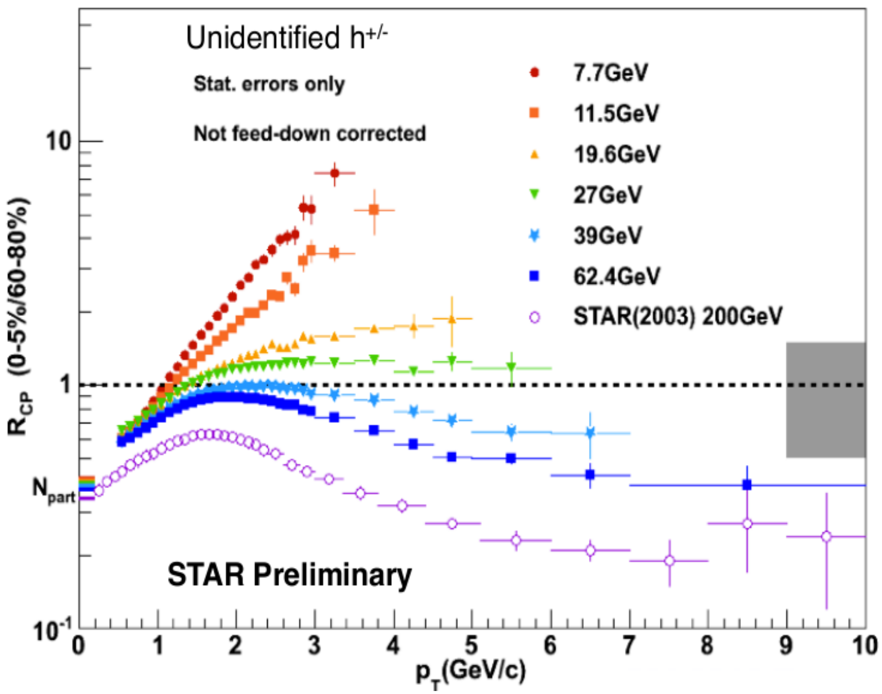
Coverage:
$0 < \phi < 2\pi$
$|\eta| < 1.0$

Uniform acceptance:
All energies and particles





Disappearance of R_{CP} suppression



$$R_{CP} = \frac{d^2 N dp_T d\eta / \langle N_{bin} \rangle (central)}{d^2 N dp_T d\eta / \langle N_{bin} \rangle (peripheral)}$$

- R_{CP} suppression NOT seen at lower energies!
- **The QGP signature turned off?**
- Relative contribution of soft physics and hard scattering

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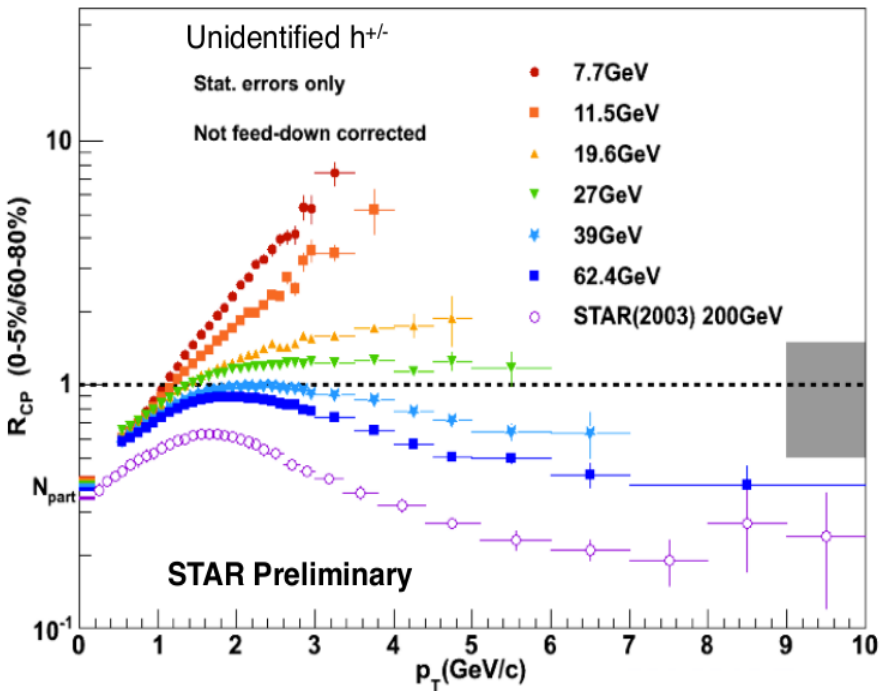

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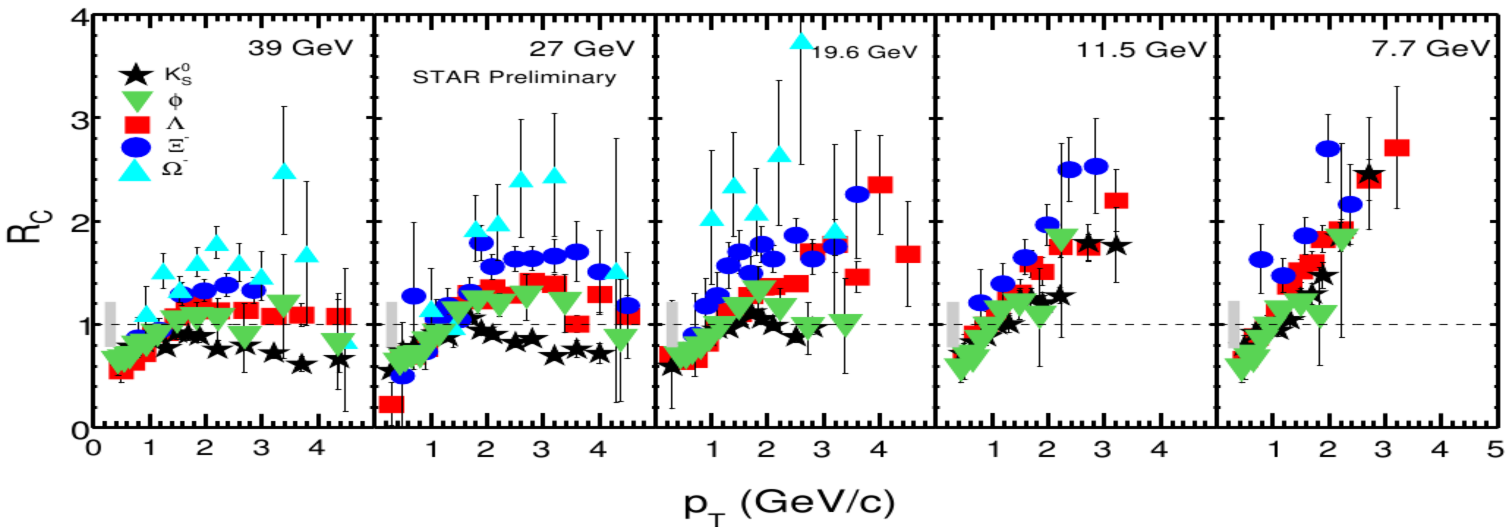
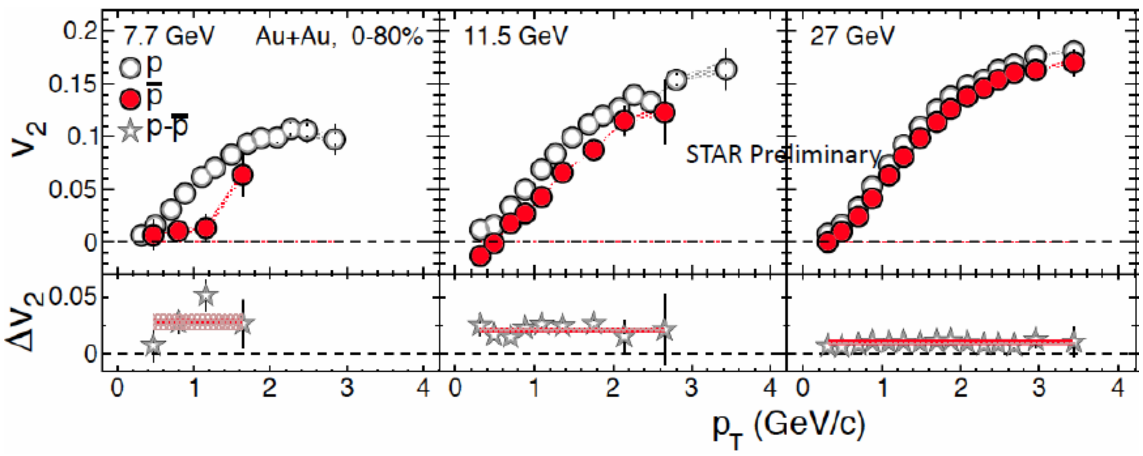
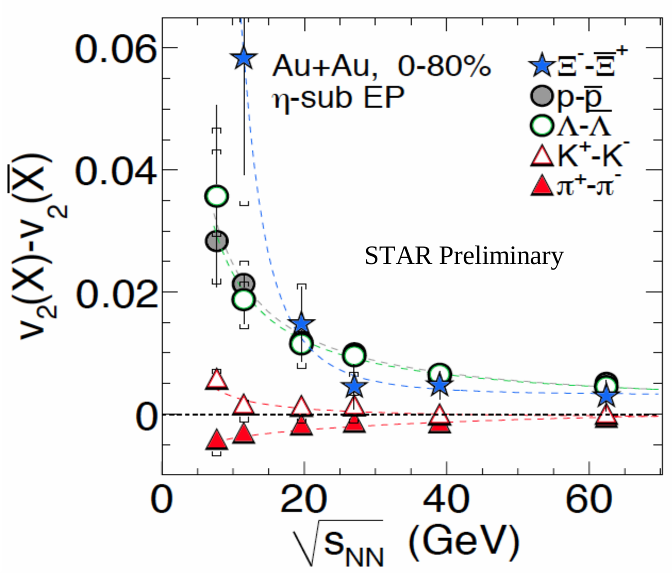


Evolution of v_2 and NCQ scaling

NCQ scaling of v_2 is interpreted as a sign of partonic collectivity.





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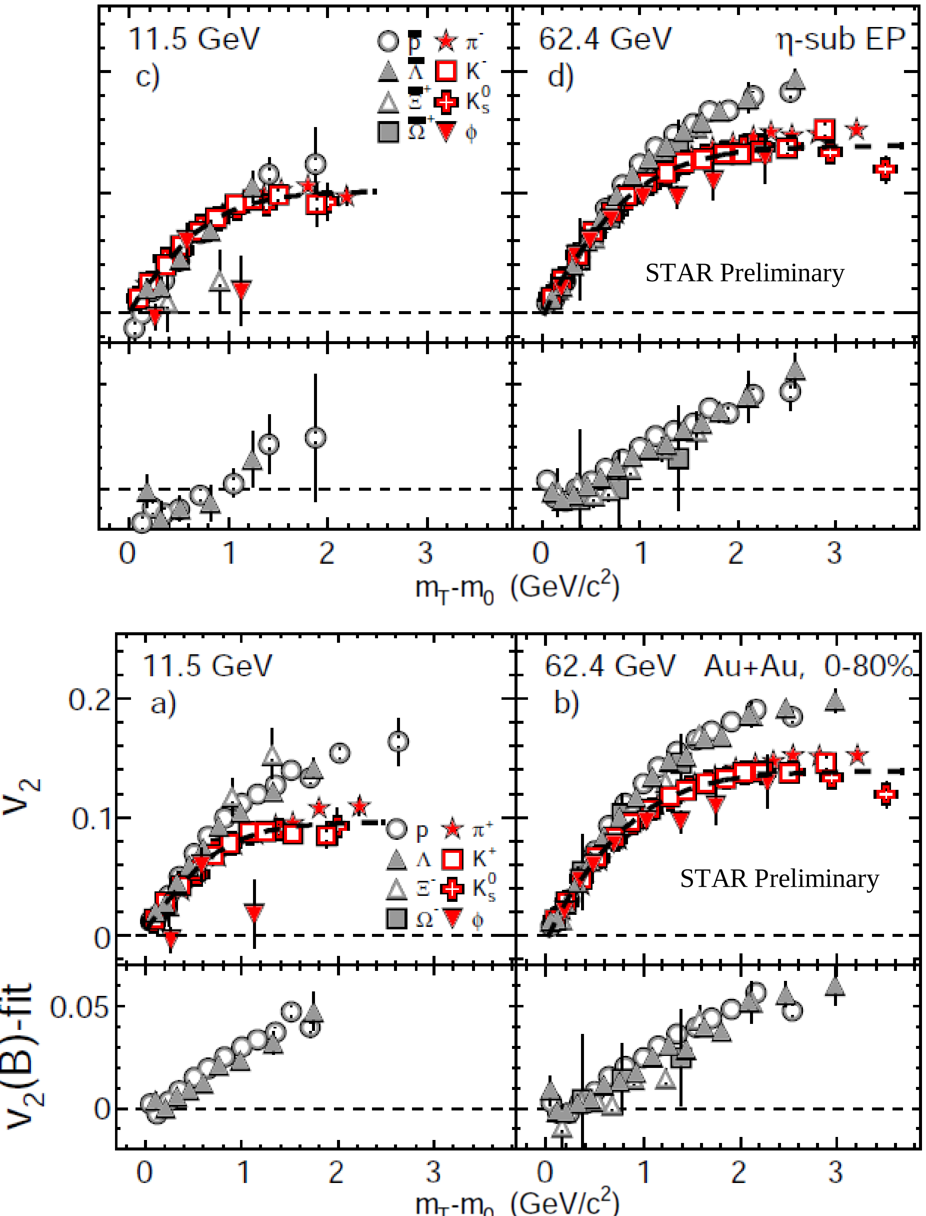

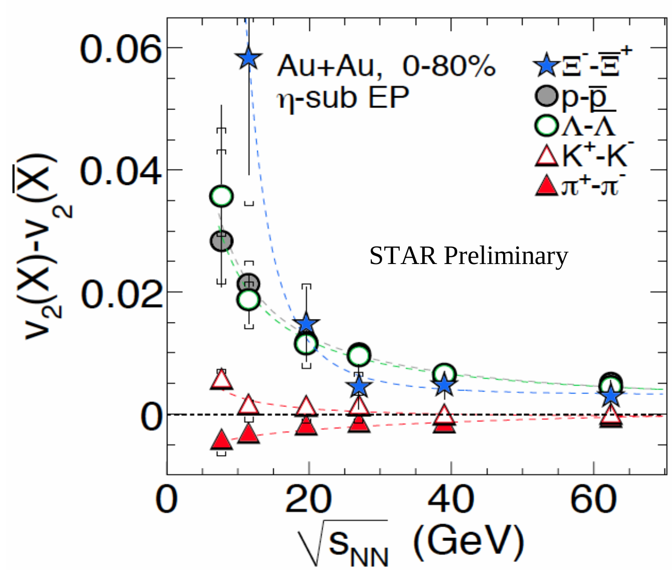

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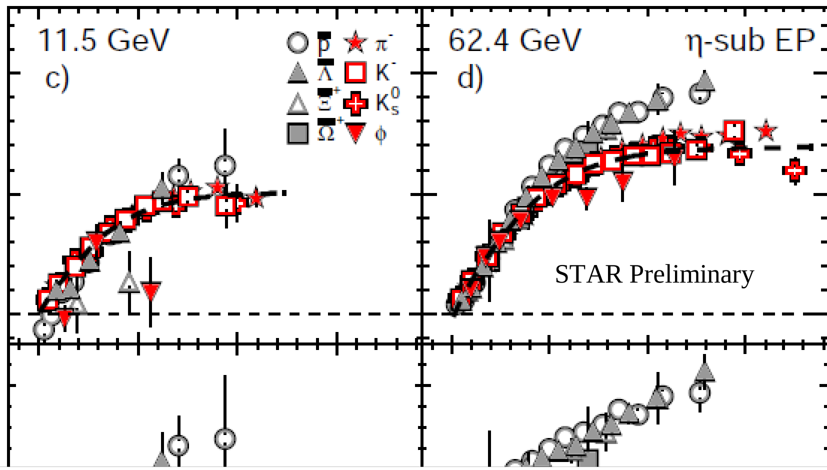
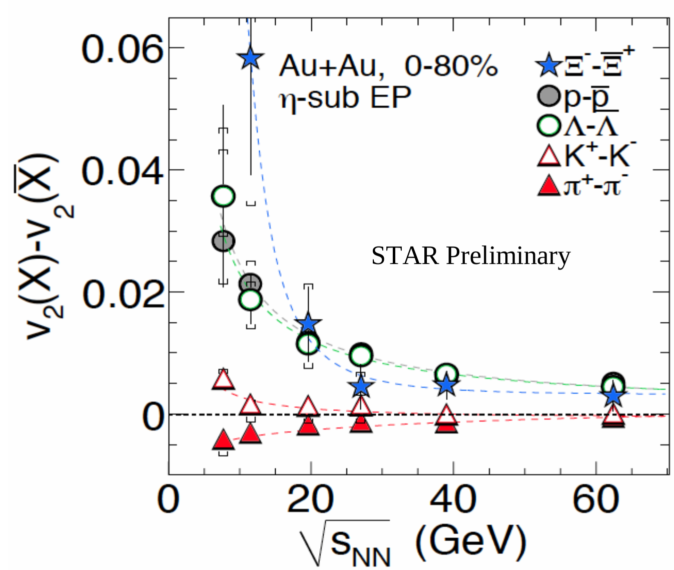
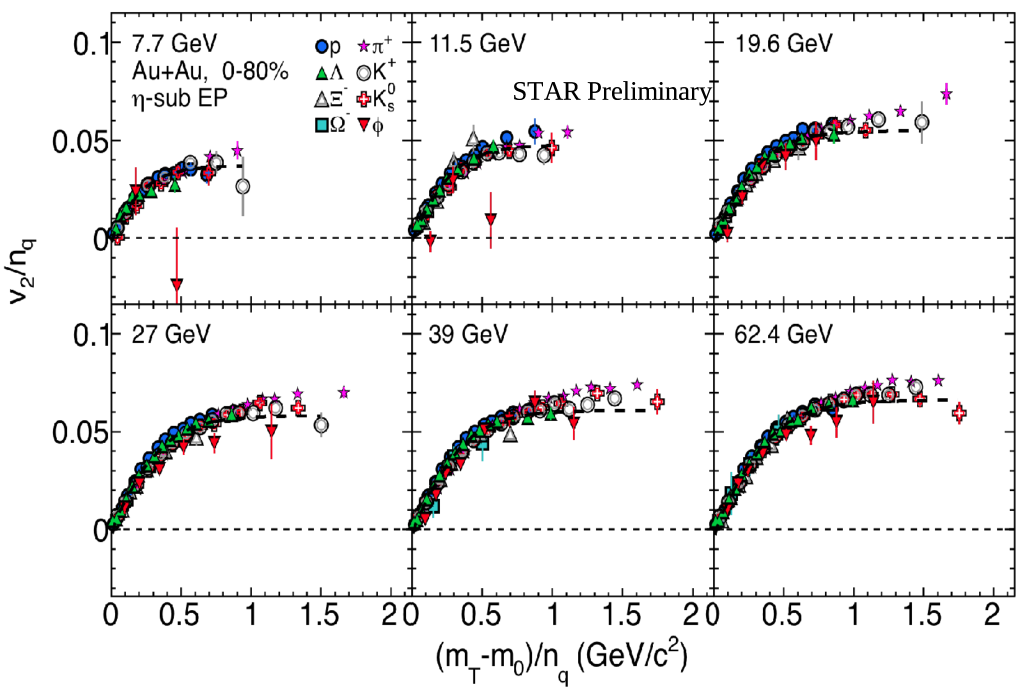
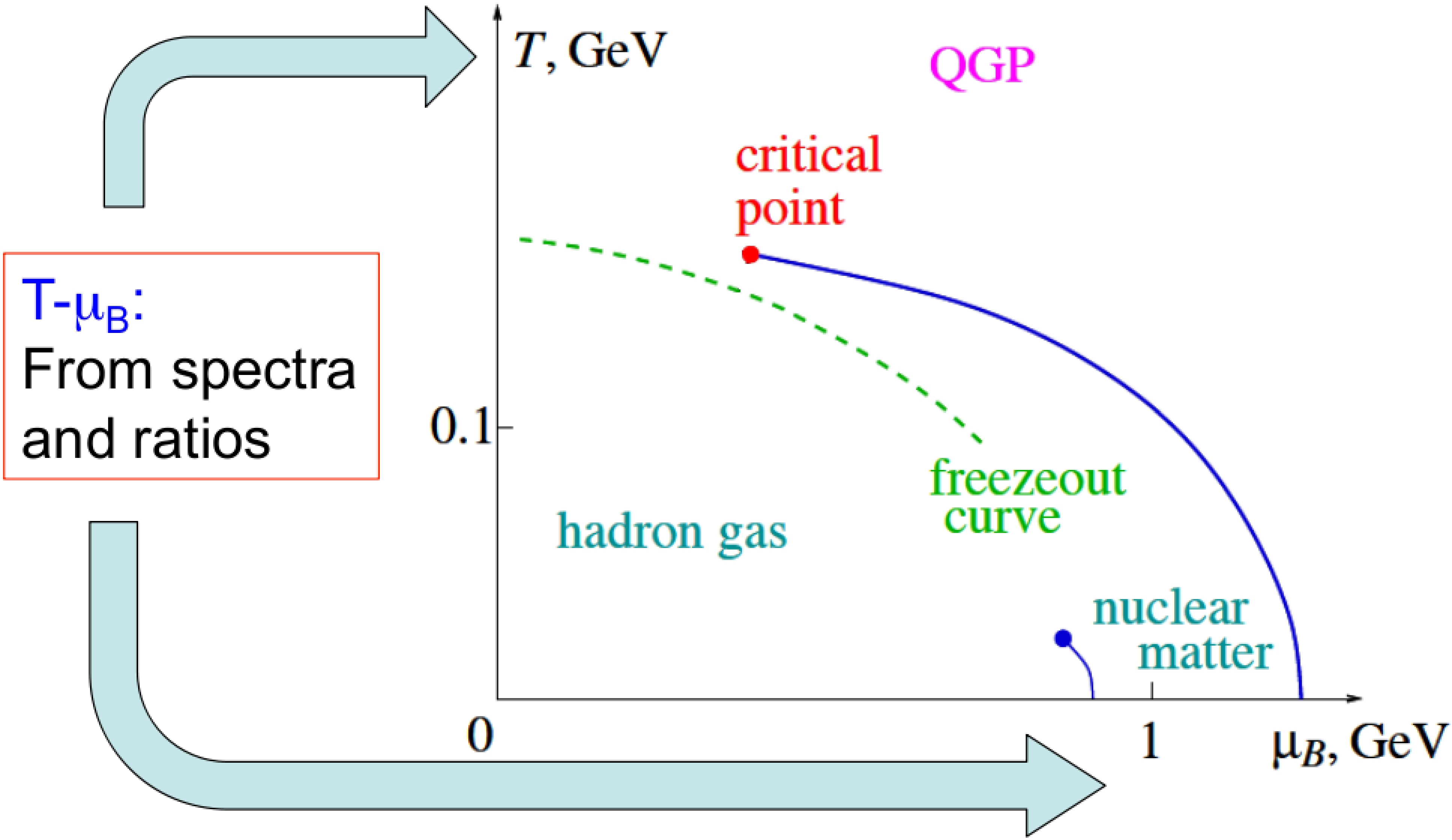






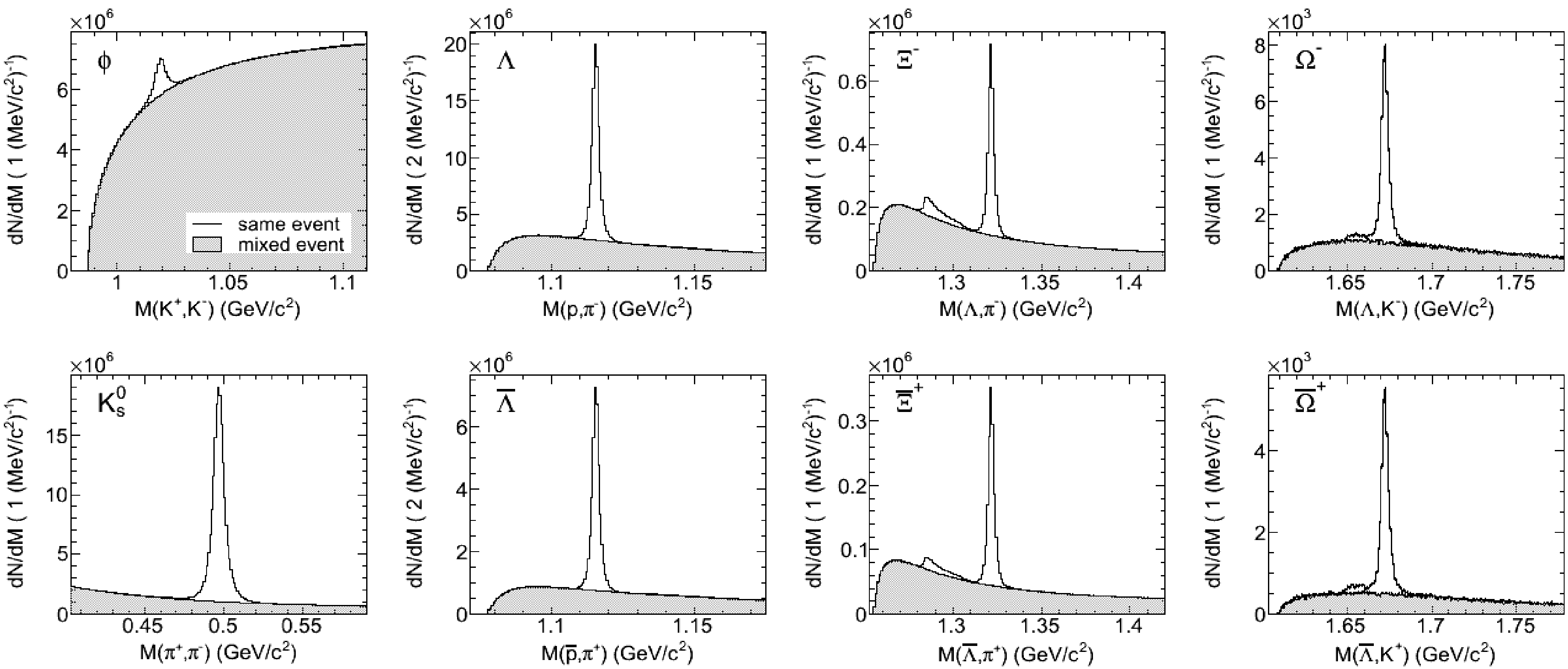
- New feature: Significant **difference between baryon-antibaryon v_2** at lower energies
- No clear baryon/meson grouping for anti-particles at <=11.5 GeV
- NCQ scaling holds separately for particles and antiparticles.
- ϕ-meson v_2 deviates (~2σ) from others for $\sqrt{s_{NN}} \leq 11.5$ GeV, more data needed

Mapping phase diagram

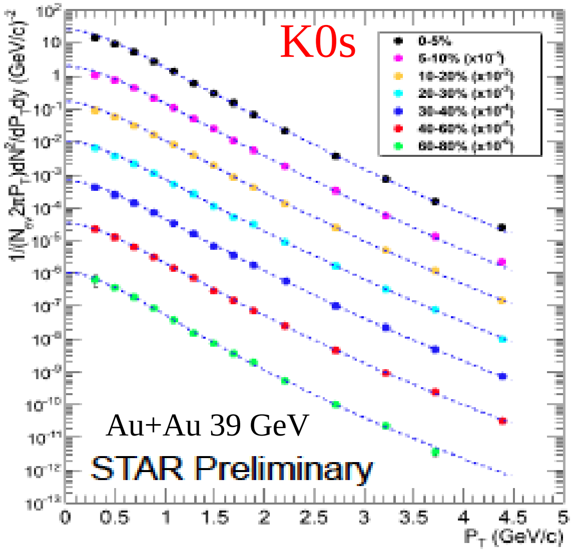


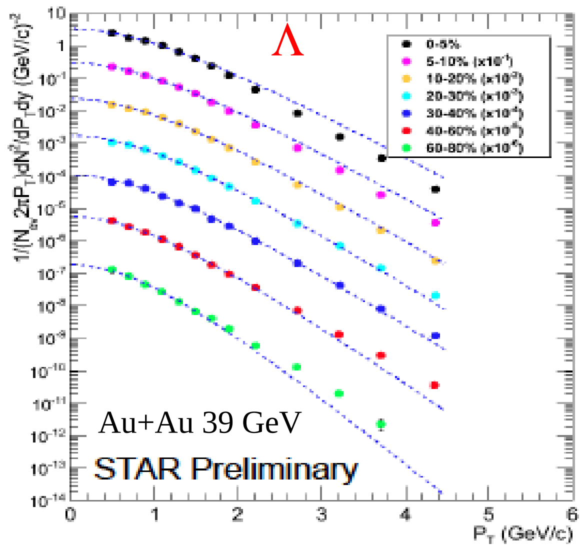
Strangeness reconstruction

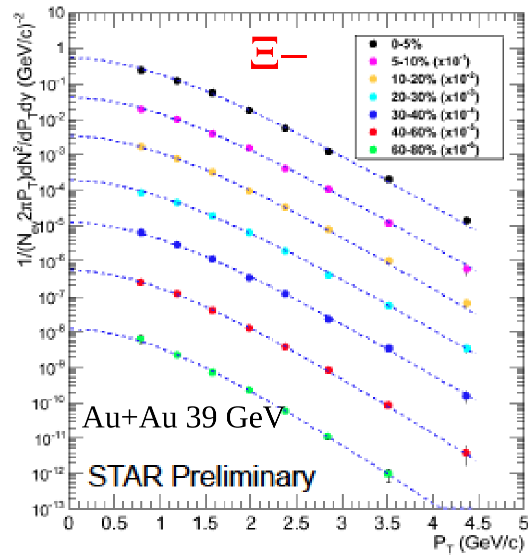
- STAR – excellent reconstruction capability
- PID (TPC+TOF): pion/kaon: p_T~1.6 GeV/c, proton p_T~3.0 GeV/c
- Strange hadrons: decay topology & invariant mass

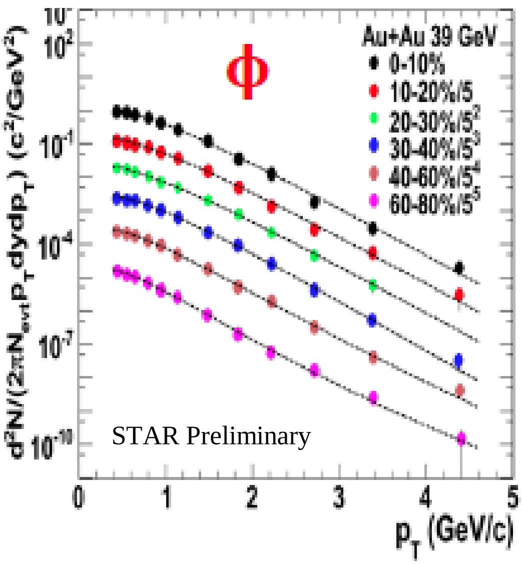


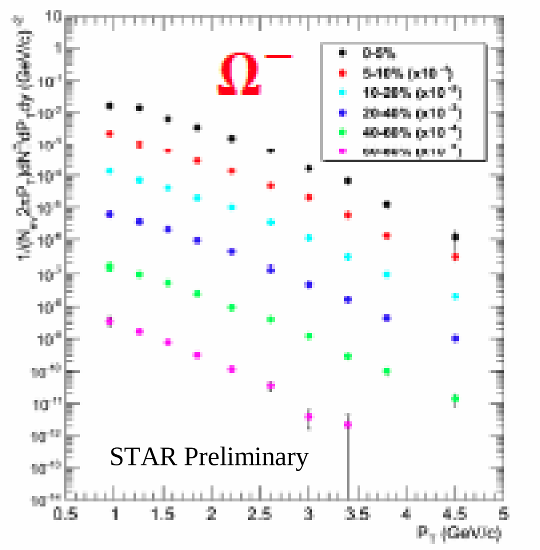
Strange particle spectra











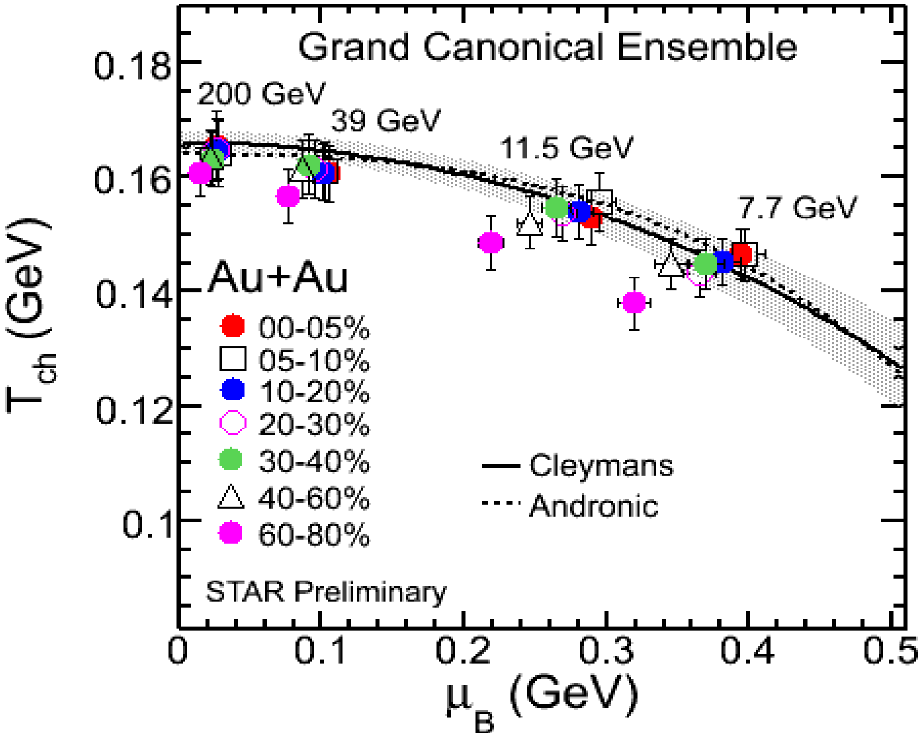
Extensive strange particle spectra measurements

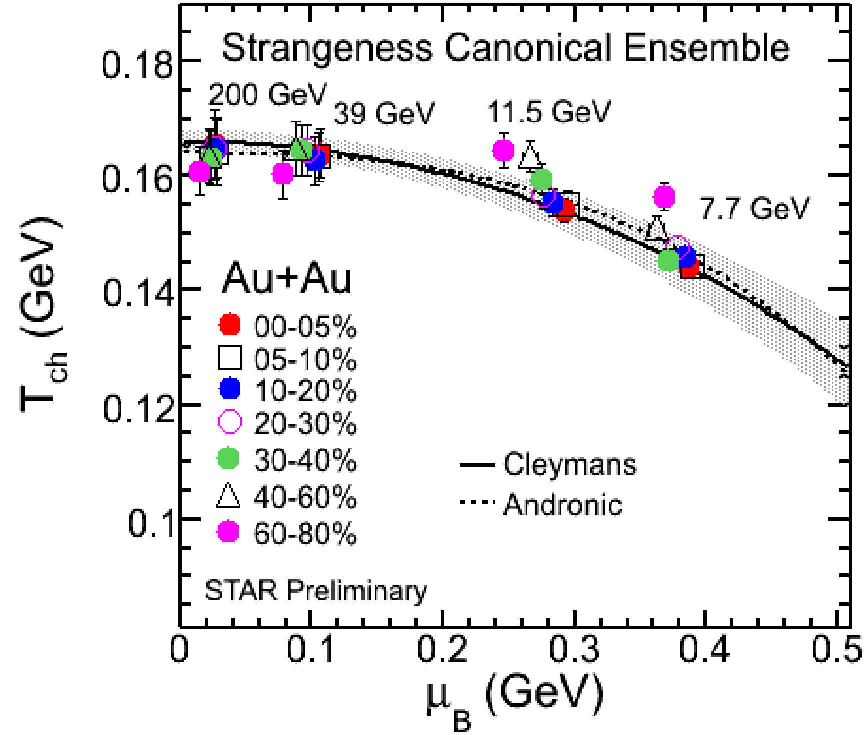
- ϕ, K0s: Levy function fit
- Λ, Ξ : Boltzmann fit
- Λ: feed-down corrected

Chemical freeze-out

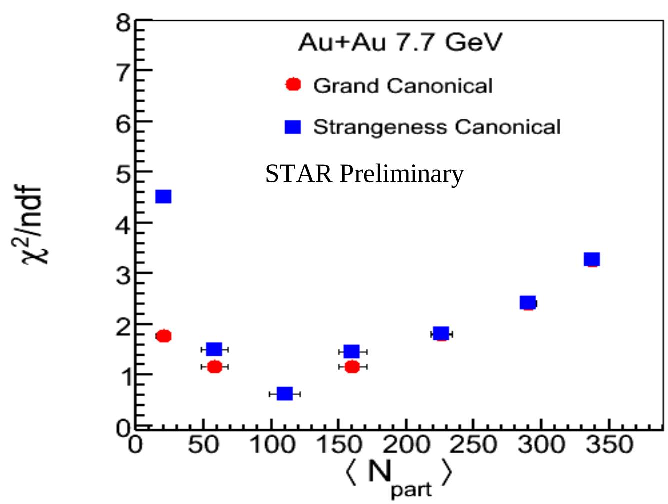
Particles used: π, K, p, Λ, K^0_S, Ξ

Andronic: NPA 834(2010) 237
Cleymans: PRC 73(2006) 034905.





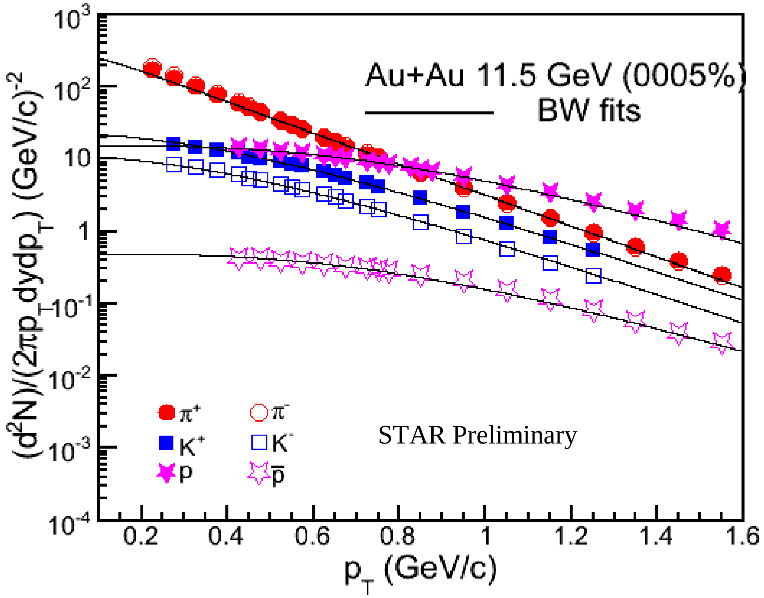
- Maping μ_B region from 20 to 400 MeV in the QCD phase diagram.
- **Centrality dependence of freeze-out** temperature with baryon chemical potential observed **at lower energies**.



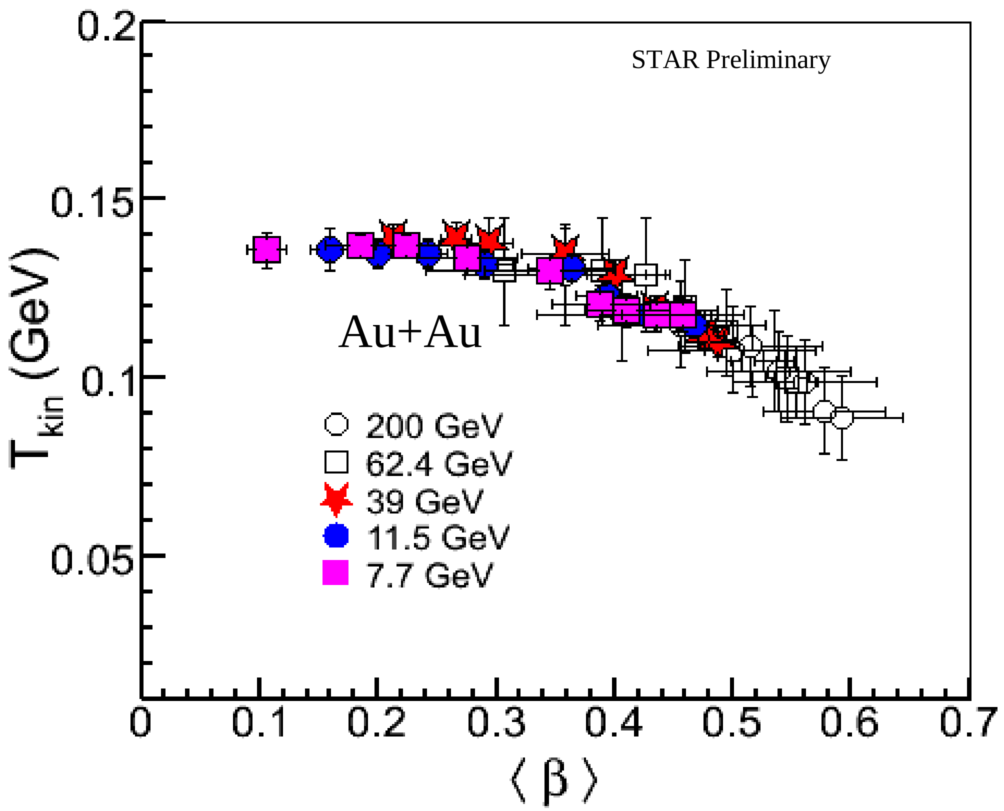
Kinetic freeze-out

Particles used: π,K,p

Blast Wave: T_{kin} and <β>



E. Schnedermann et al., Phys. Rev. C 48, 2462 (1993)



- Higher kinetic temperature corresponds to lower value of average flow velocity and vice-versa.
- All beam energies - the central collisions are characterized by a lower T_{kin} and larger <β>

Beam Energy Scan Summary

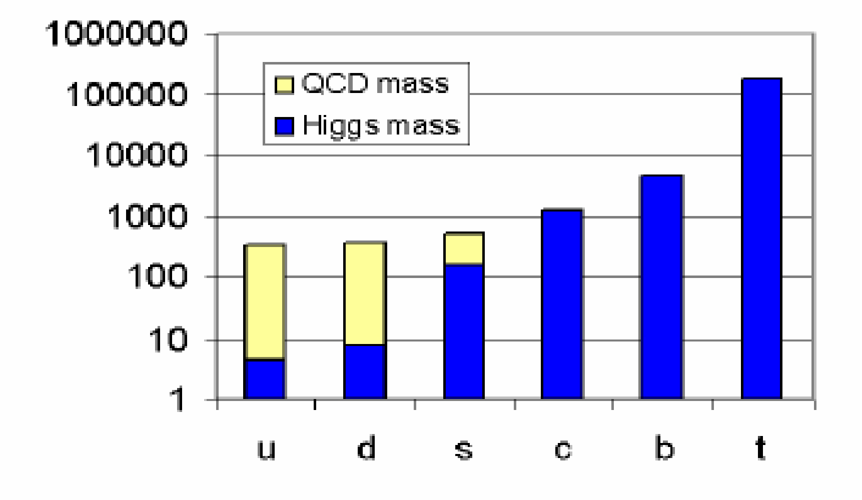
- **Very successful Beam Energy Scan program**
  - versatility of RHIC and STAR combination
- **Disappearance of QGP signatures at low energies**
  - Disappearance of R_{CP} suppression at lower energies.
  - Break down of v_2 NCQ scaling between particles and antiparticles.
- **Signatures of critical point / 1st order transition**
  - Not part of this talk
  - There are hints, but needs better statistics
- **Mapping of QCD phase diagram**
  - covers μ_B range from 20 - 400 MeV

Heavy Flavor Production

Heavy flavor physics at STAR

Why to use heavy quarks (c, b)

- Masses are only slightly modified by QCD.
- Sensitive to initial gluon density and gluon distribution.
  - Produced at initial collision stage



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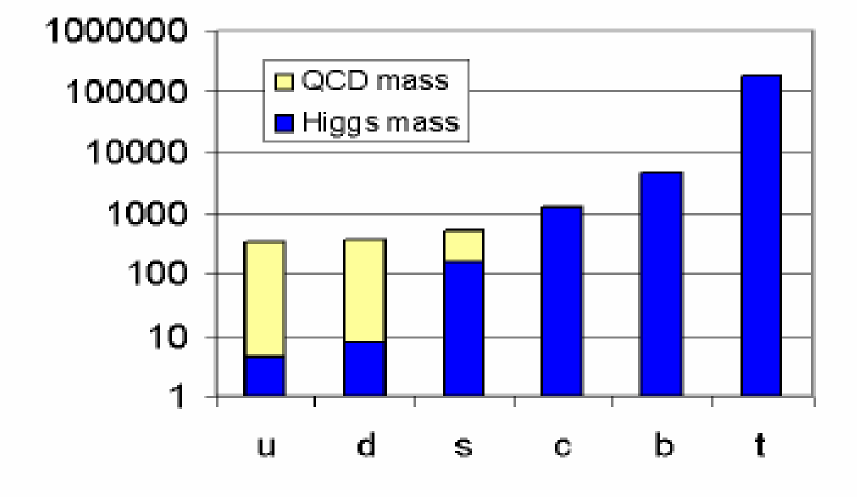
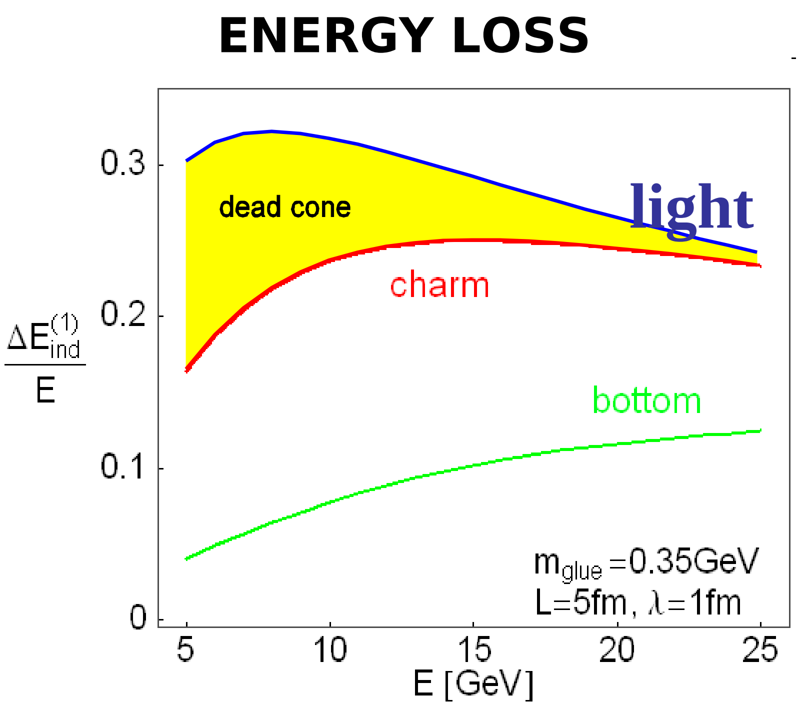


- Interact with the medium differently from light quarks.
- Suppression or enhancement pattern reveals critical features of the medium (temperature)
- Possible Cold Nuclear effects (CNM)

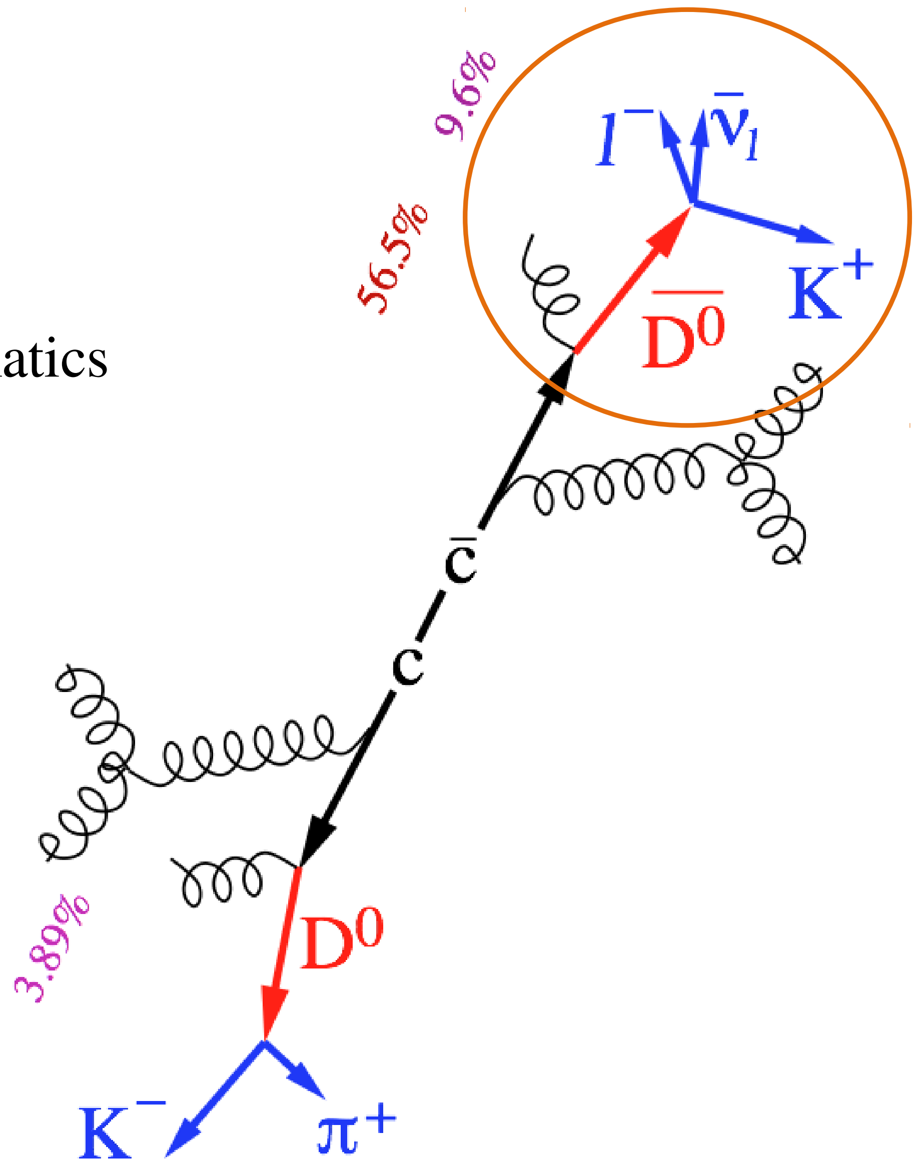


M.Djordjevic PRL 94 (2004)

Open heavy flavor production

Indirect: semi-leptonic decays

- \+ can be triggered easily (high p_T)
- \+ Higher branching ratio
- – Indirect access to the heavy quark kinematics
- – Mixing contribution from all charm and bottom hadron decays



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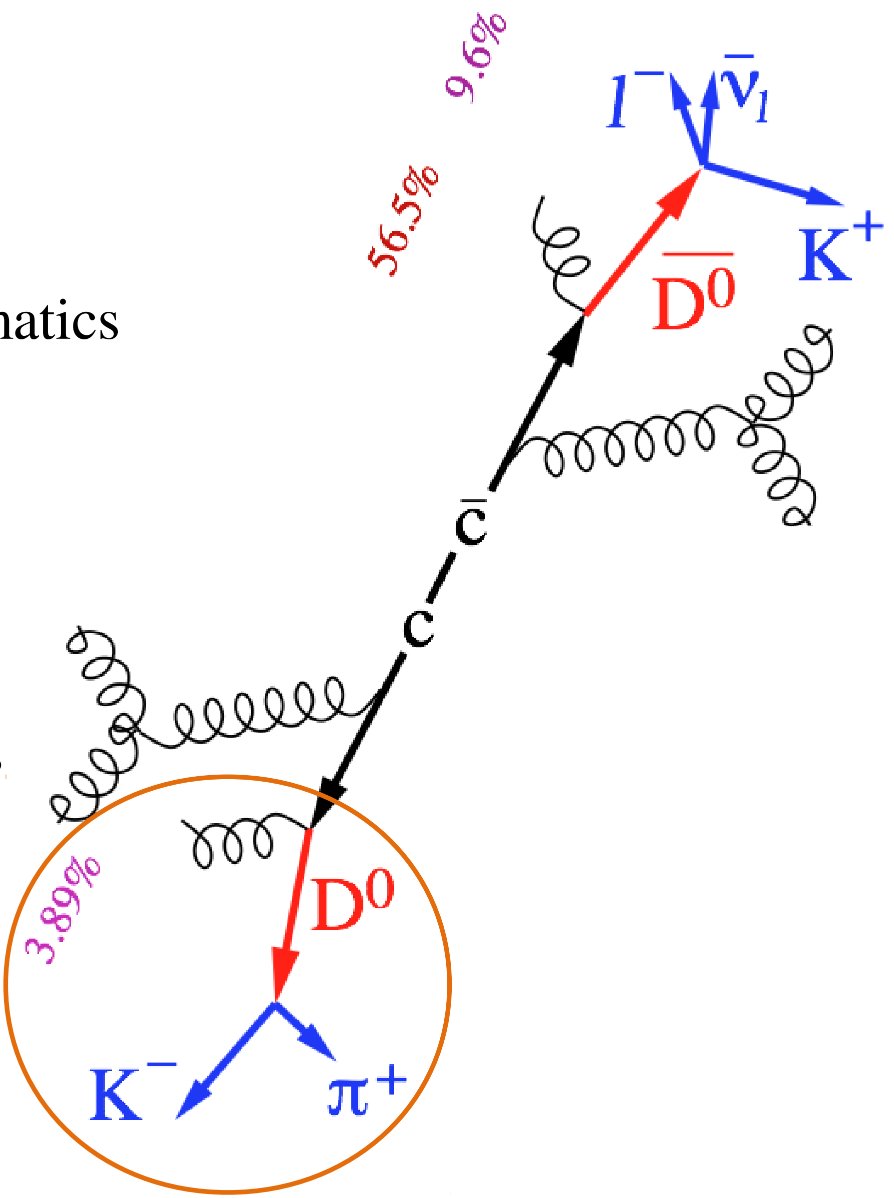
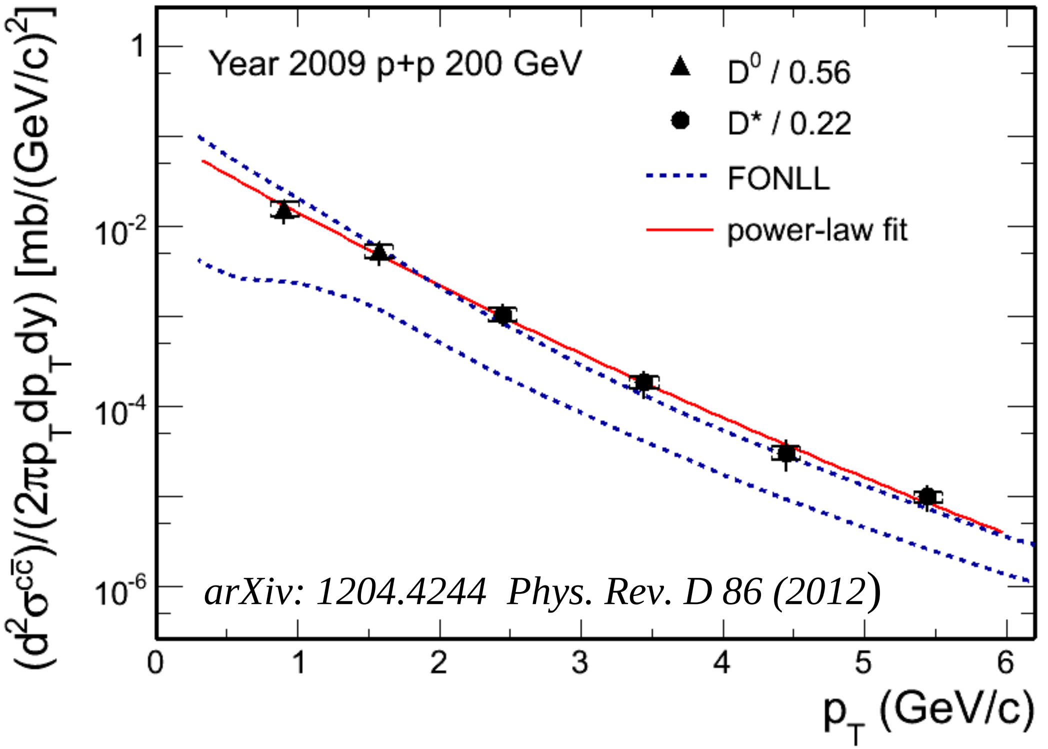
Direct reconstruction

- \+ direct access to heavy quark kinematics
- – hard to trigger
- – smaller branching ratio
- – large combinatorial background (need handle on decay vertex)



D^0 and D* p_T spectra in p+p

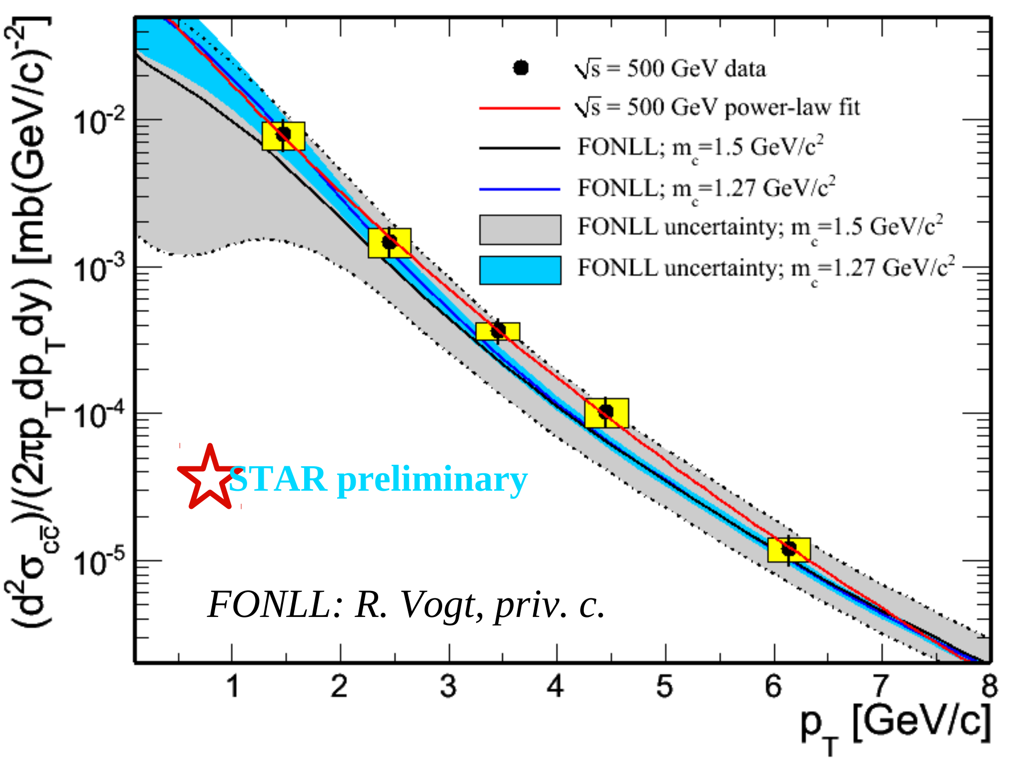


available data from p+p at $\sqrt{s}$=200 and 500 GeV

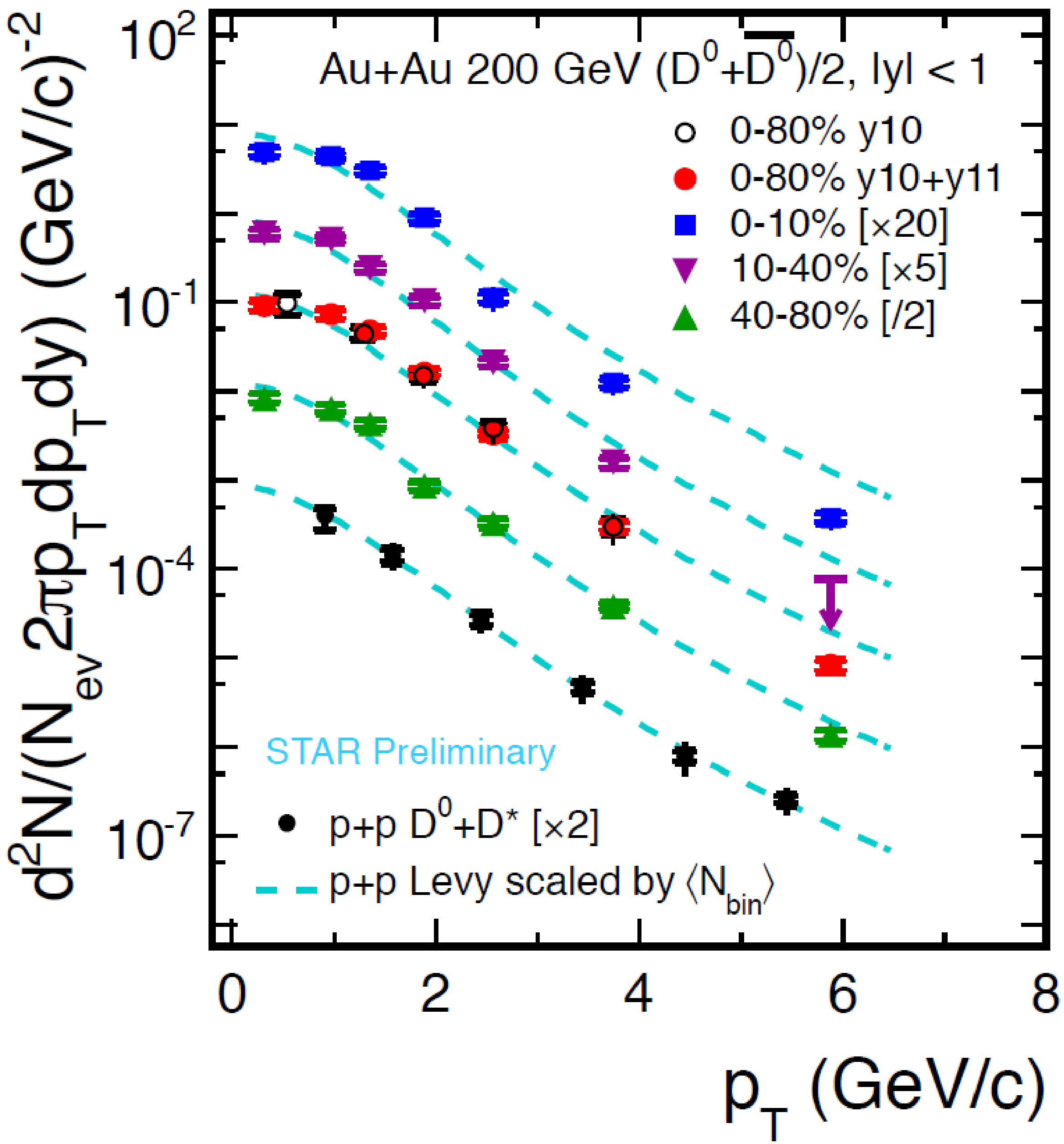
D^0 yields scaled by
$N_{cc} / N_{D0} = 1 / 0.56$

D* yields scaled by
$N_{cc} / N_{D*} = 1 / 0.22$

- **Both data sets are consistent with FONLL upper limit**
- Test of pQCD calculations
- Baseline of heavy ion measurements is under control



D^0 yield and R_{AA} in 200 GeV Au+Au



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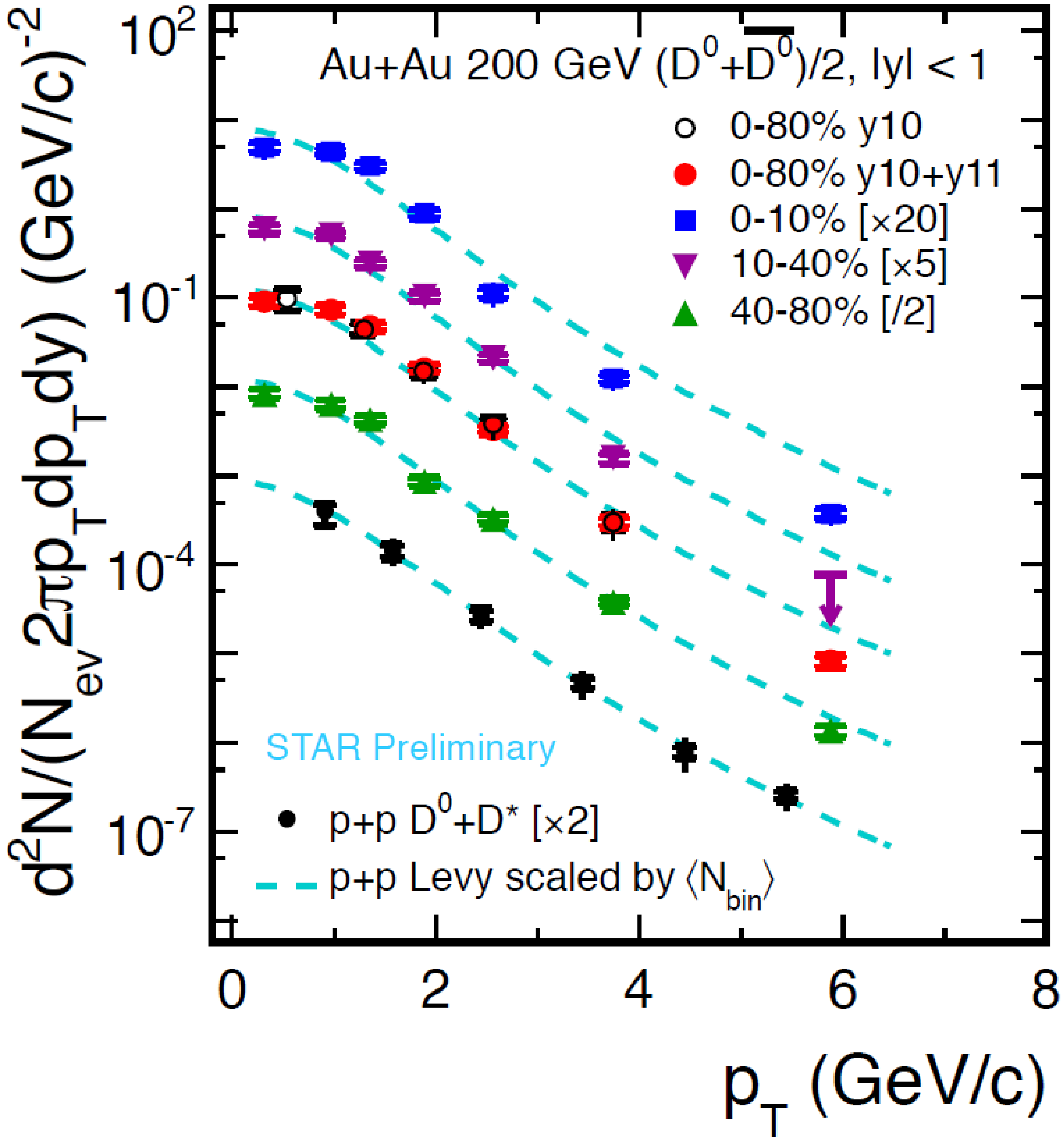

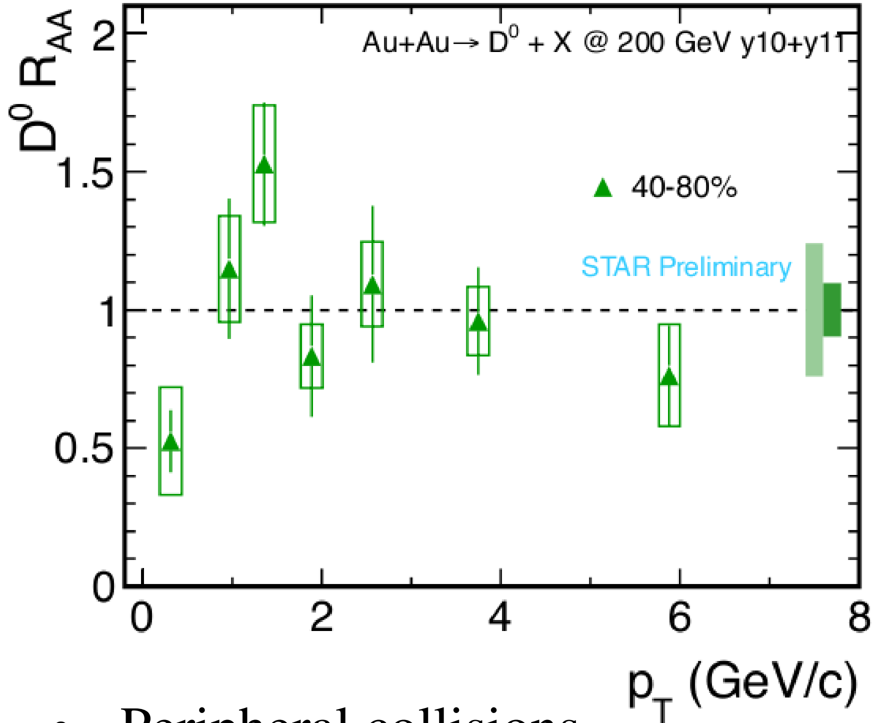

- Peripheral collisions
  - no suppression

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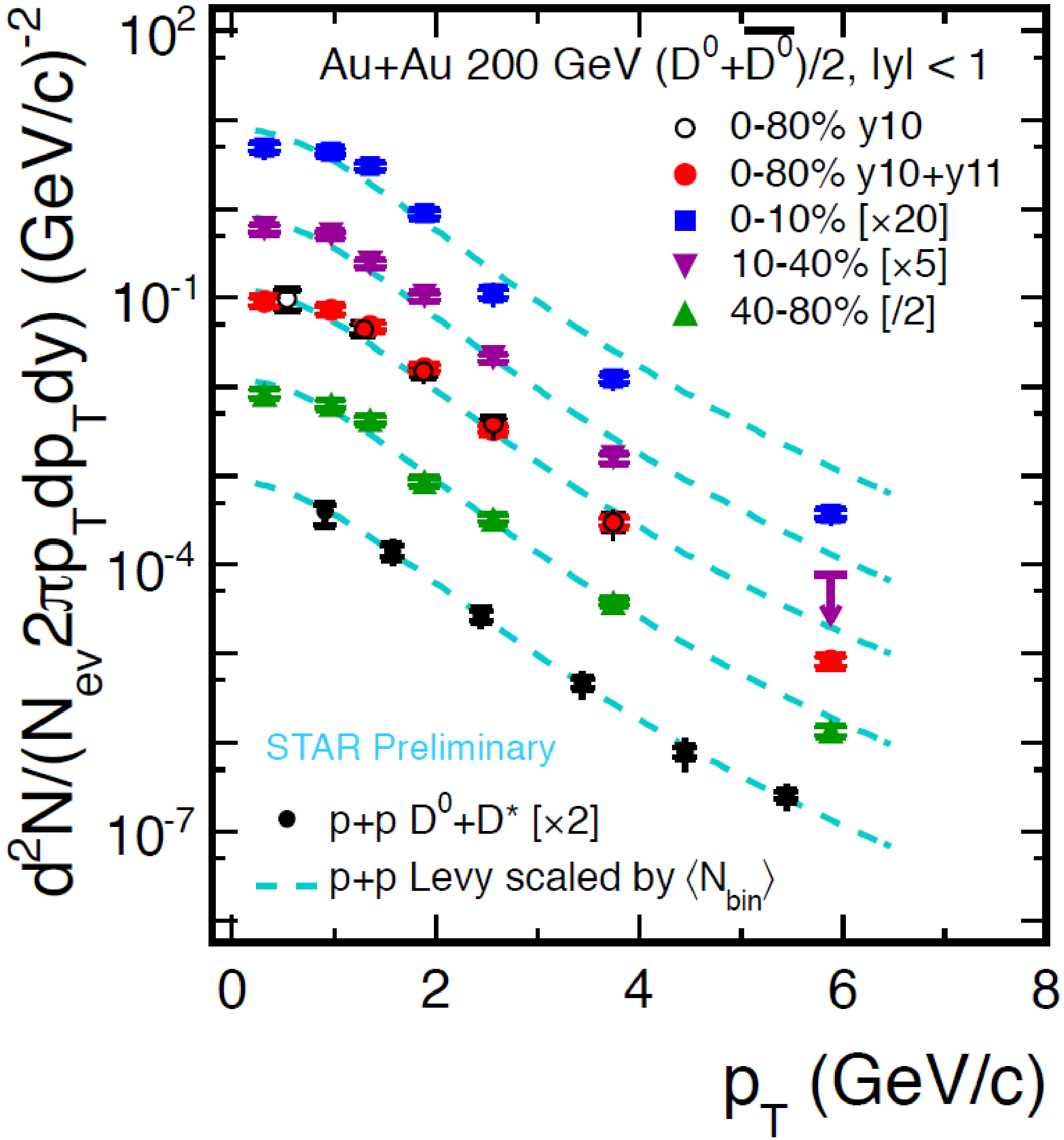

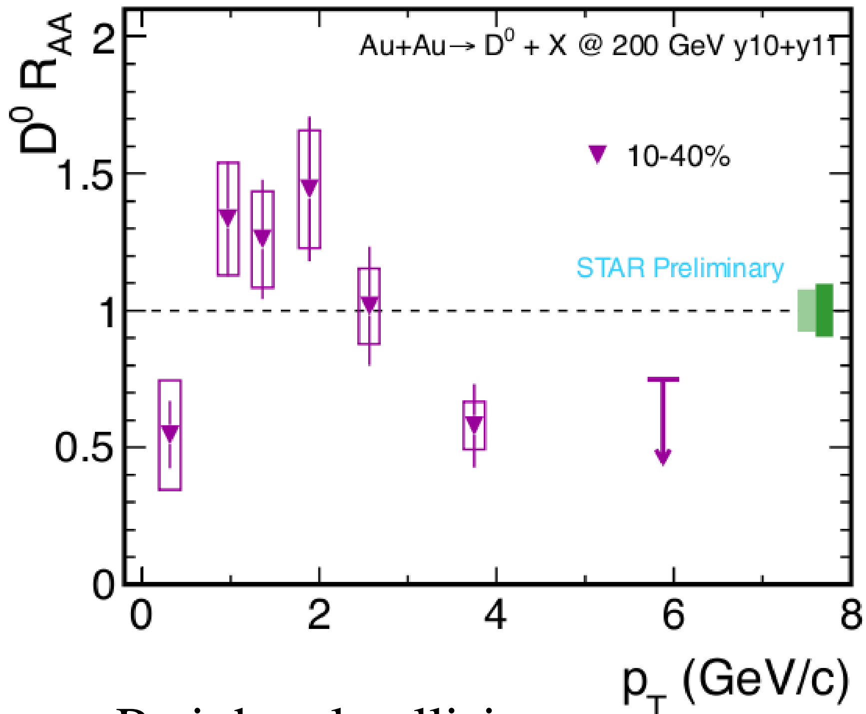

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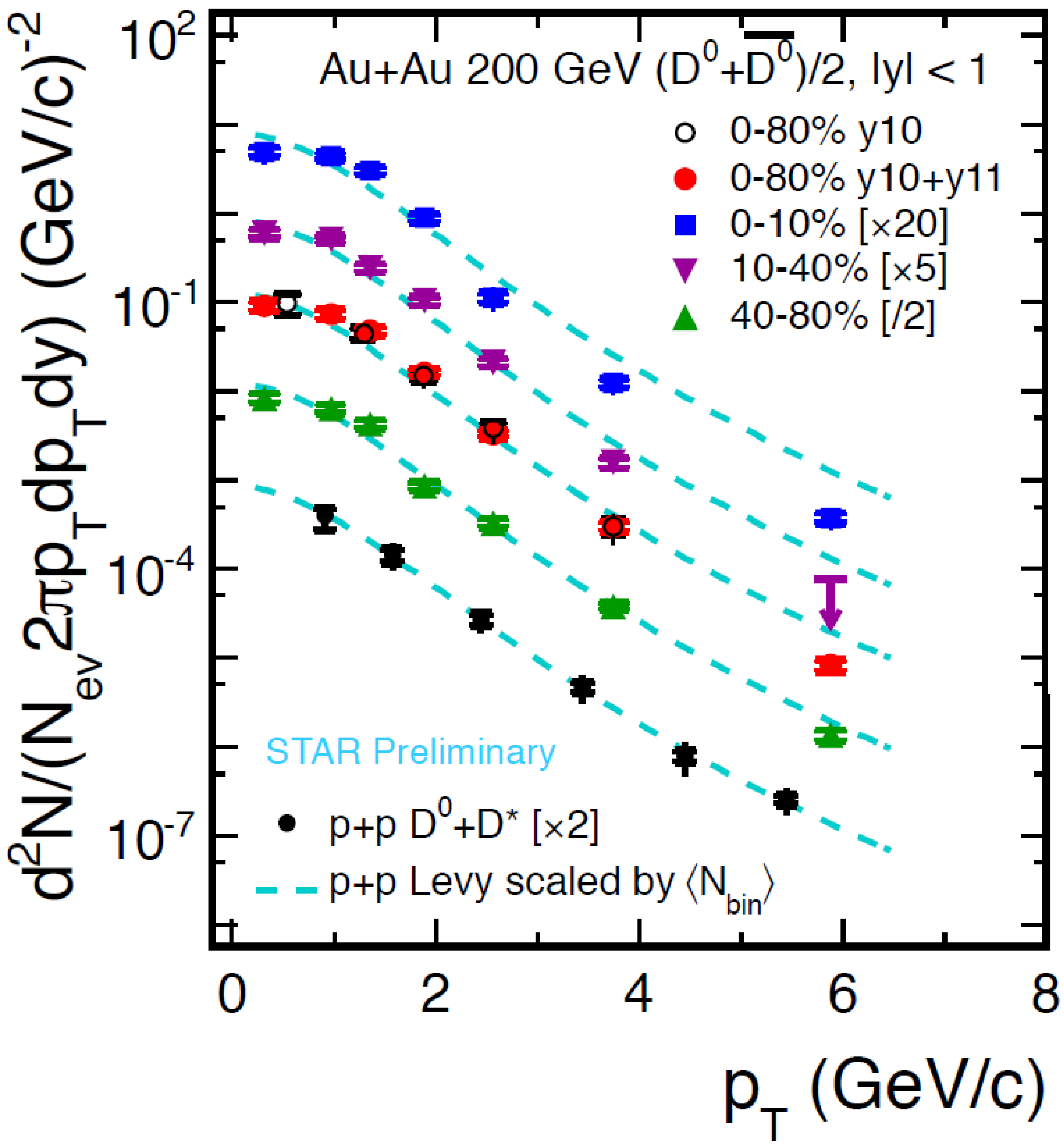
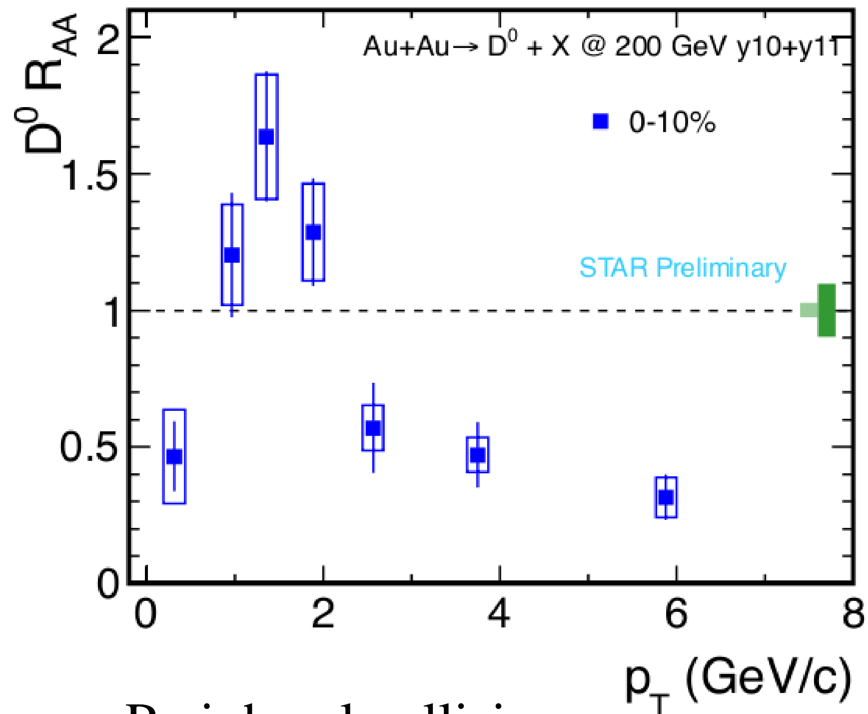
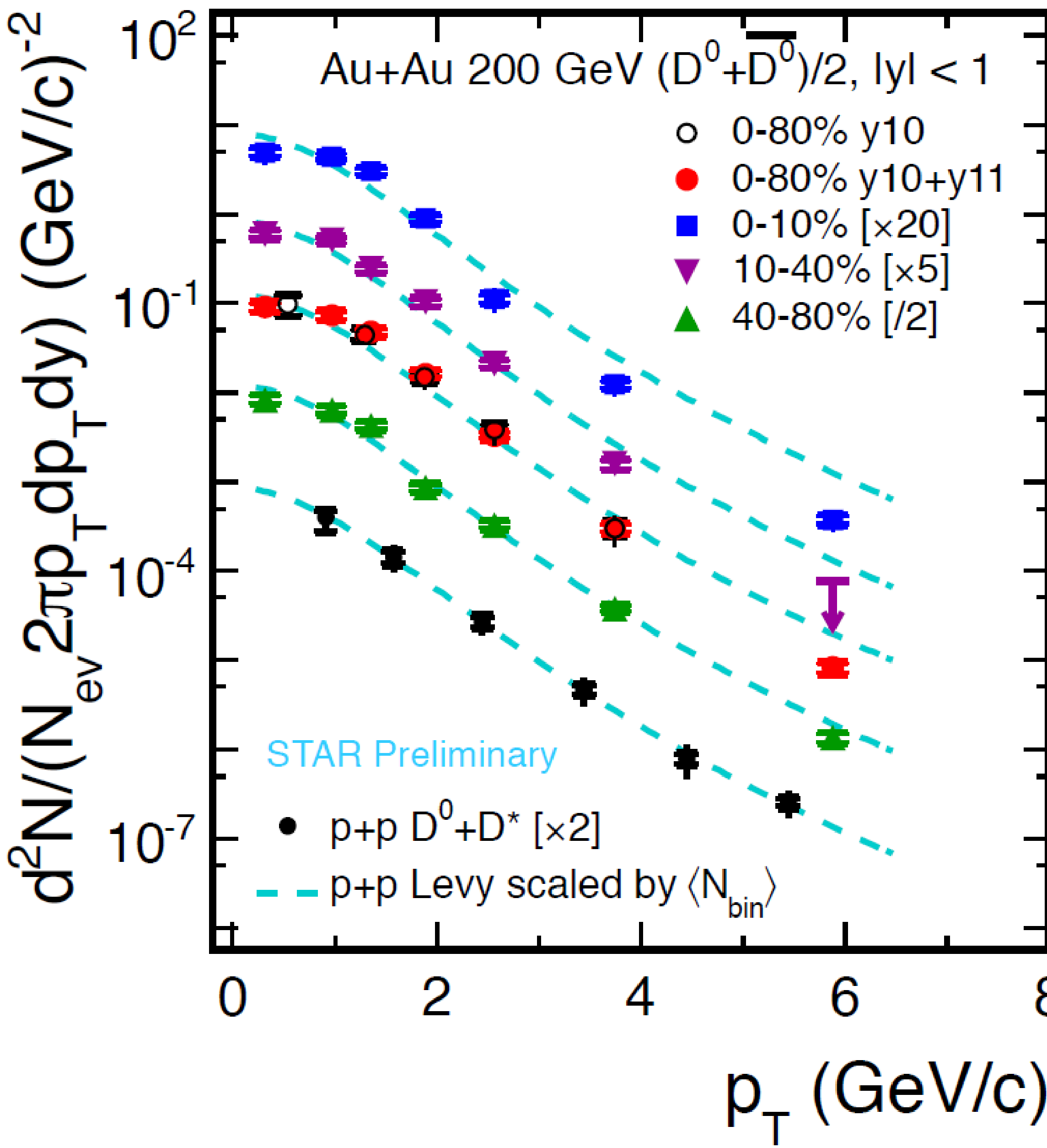
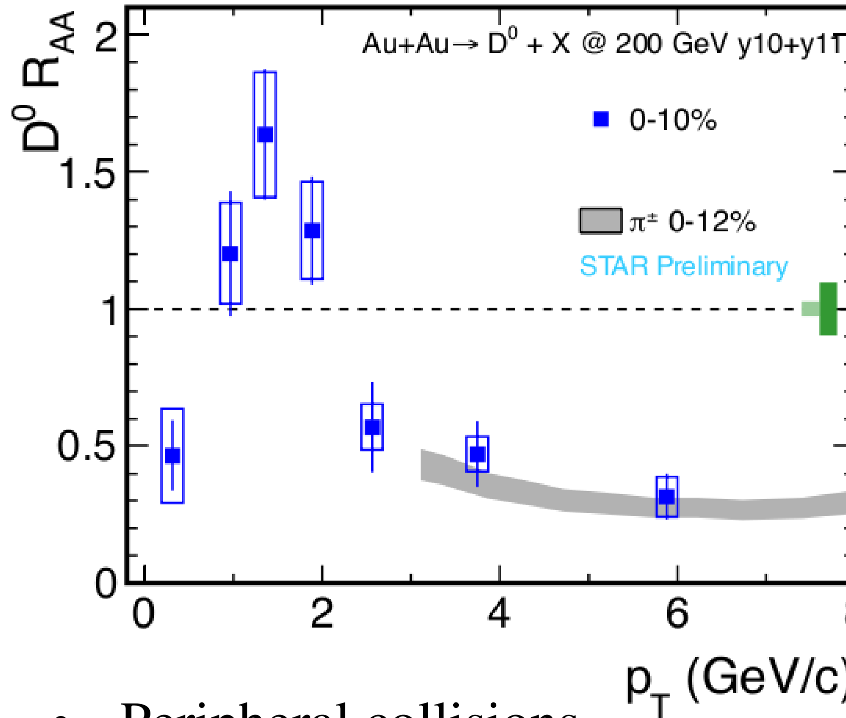




- Peripheral collisions
  - no suppression
- Mid-peripheral, central
  - suppression at high p_T

D^0 yield and R_{AA} in 200 GeV Au+Au

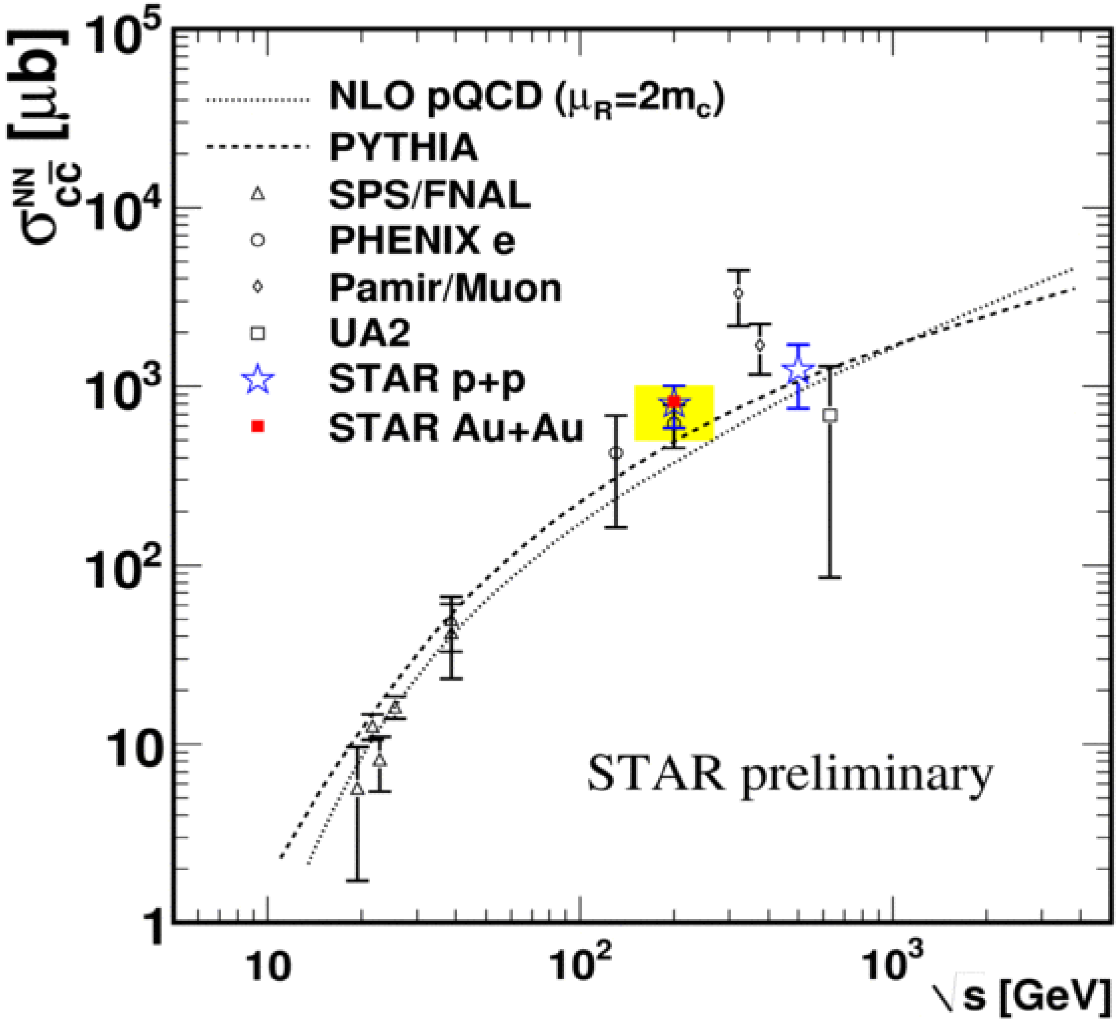




- Peripheral collisions
  - no suppression
- Mid-peripheral, central
  - suppression at high p_T
  - similar to light hadrons
  - enhancement at intermediate p_T
    - radial flow of light quarks
      coalescence with charm

Charm total cross-section

Extending to the full rapidity:



$$\sigma_{c\bar{c}} = F \left.\frac{\mathrm{d}N_{c\bar{c}}}{\mathrm{d}y}\right|_{y=0}$$

$$F \equiv \text{mid } y \rightarrow \text{full } y$$

500 GeV, F = 5.6

$$\sigma_{c\bar{c}} = 1215 \pm 482(\text{stat.}) \pm 409(\text{sys.})\ \mu\text{b}$$

200 GeV, F = 4.7

$$\sigma_{c\bar{c}} = 797 \pm 210(\text{stat.})\ ^{+208}_{-295}(\text{sys.})\ \mu\text{b}$$

Run2003 d+Au : D^0 + e

Run2009 p+p : D^0+ D*

Run 2010 & 2011 Au+Au: D^0

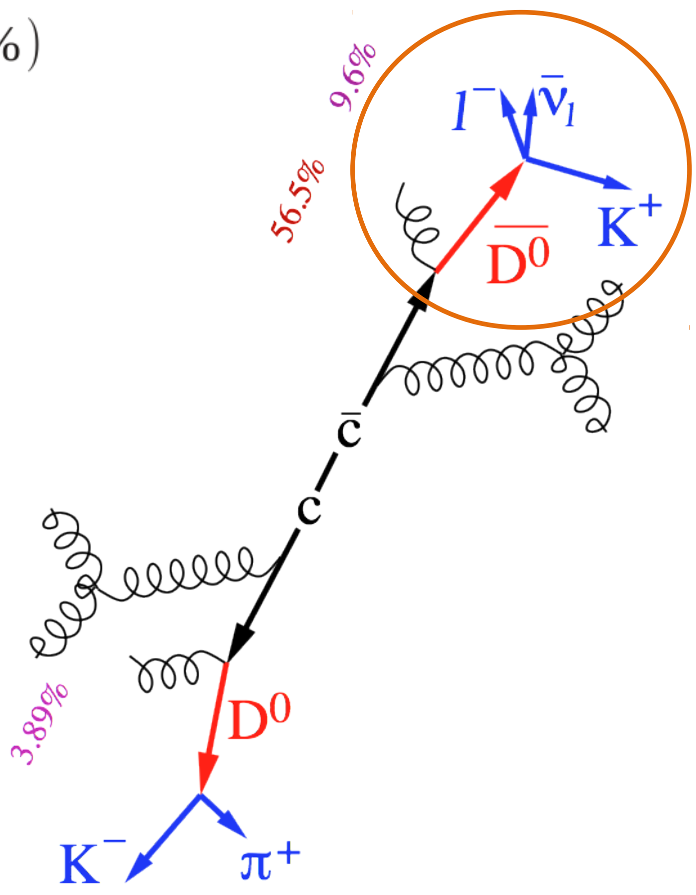
Charm cross-section follows the “world trend”

Non-photonic electrons(NPE)

NPE – proxy to heavy flavor production

- measure e± spectra from decays of heavy quarks

$b \to e^{\pm} + anything\,(10.86\%)$ $\qquad$ $c \to e^{\pm} + anything\,(9.6\%)$

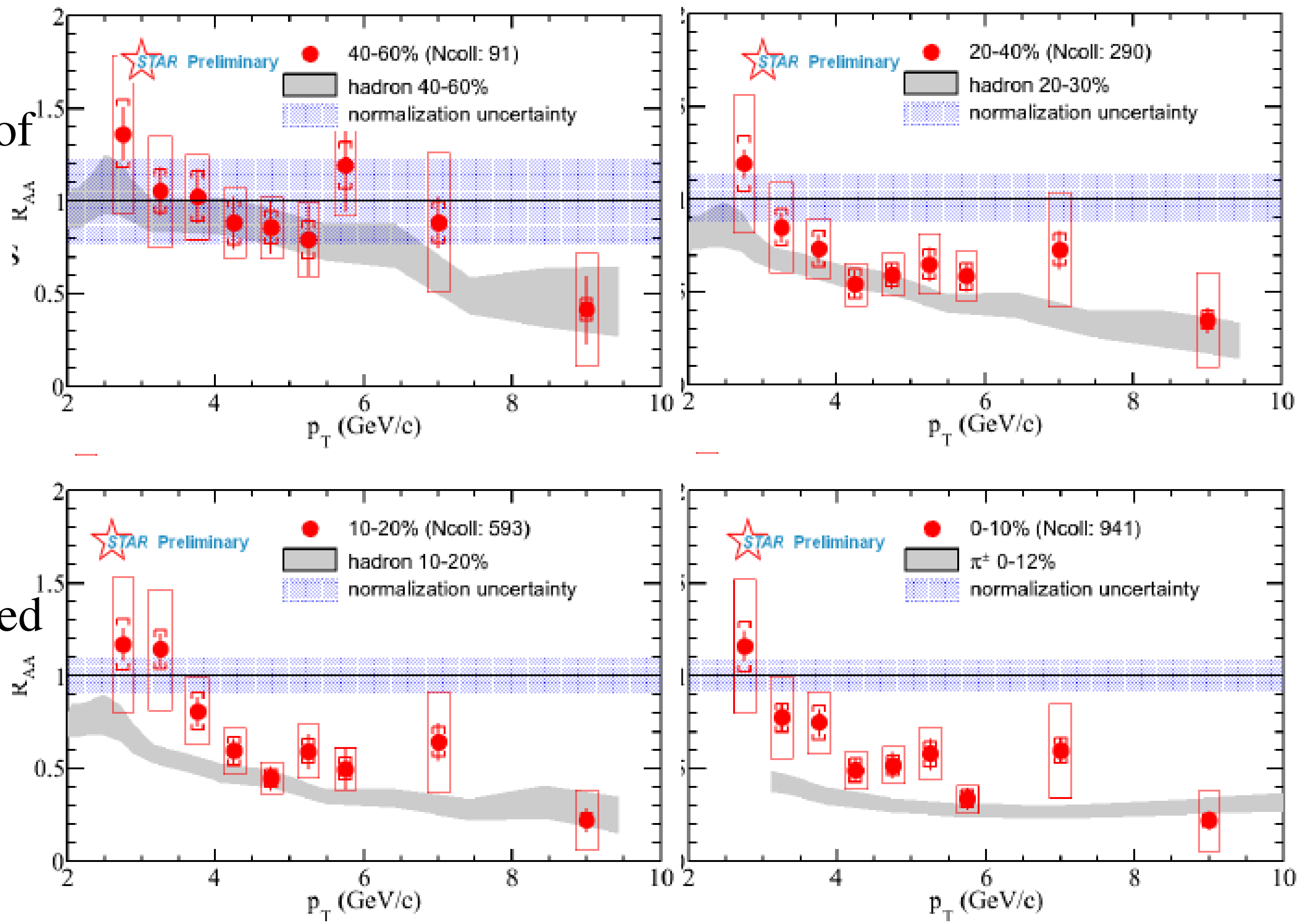


Main source of **backgrounds** comes from **photonic electrons**

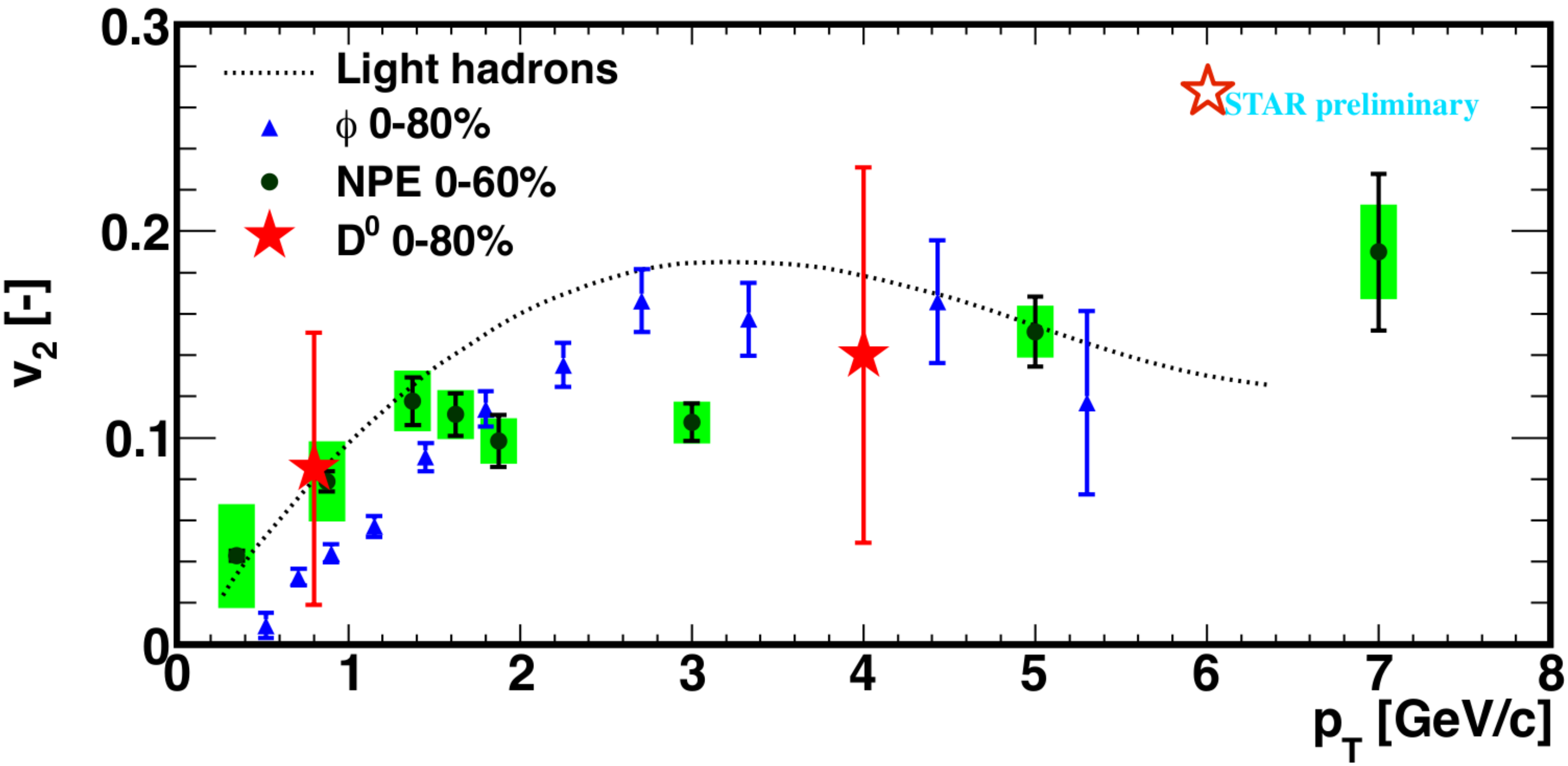
- Dalitz decay: $\pi^0 \to \gamma + e^+ + e^-$ (BR: ~1.2%)
- conversion electrons: $\gamma \to e^+ + e^-$
  - depends on the material budget

NPE in 200GeV Au+Au

- Strong suppression at high p_T.
- comparable to suppression of hadrons.
- Mixing of bottom/charm contributions .
- Cannot be explained by radiative energy loss only.
- R_{AA} uncertainty is dominated by p+p.
  - will improve with 2009+2012 large statistics data



Charm flow



- Finite v_2 at low p_T is an indication of strong charm- medium interaction.
- Consistent results from NPE and D^0
- Increase of v_2 at high p_T possibly due to jet correlation and pathlength dependence of energy loss.

Quarkonia production

Charmonia: J/ψ, ψ', χ_c Bottomia: Υ(1S,2S,3S), χ_b

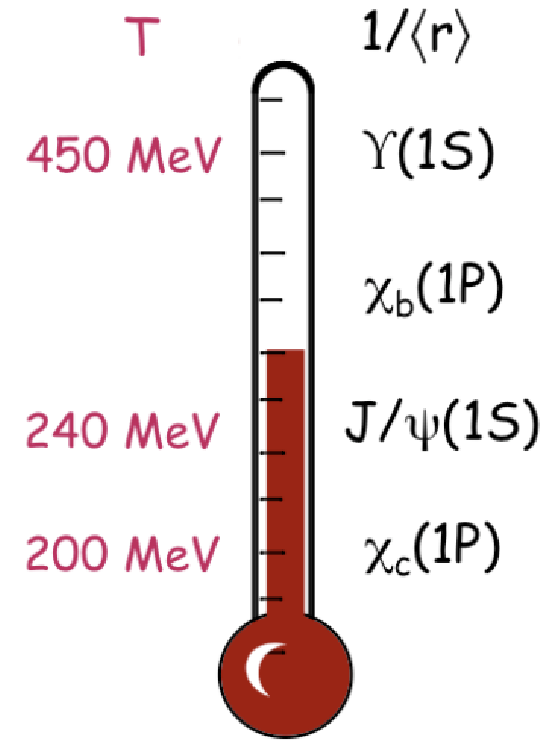
Expect a suppression of quarkonia in a QGP

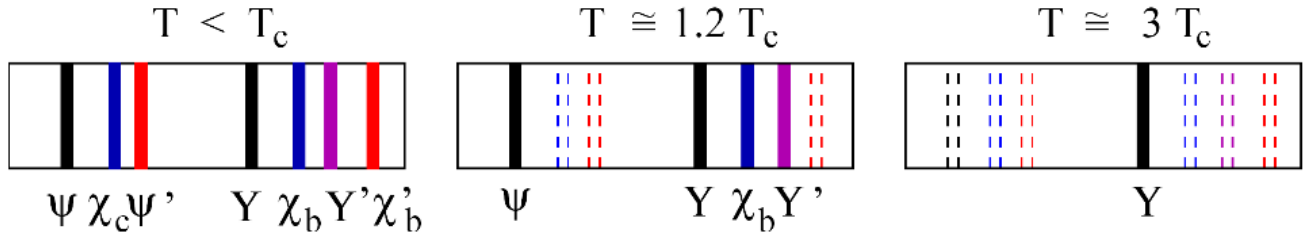
[T.Matsui and H. Satz, Phys Lett. B 178, 416 (1986).]

- color screening of heavy quark pair potential
- unique probe of deconfined medium

Sequential melting of different states

- melting depends on binding energy and T_C
- provides a thermometer of QGP
  [A .Mocsy, Eur. Phys. J. C61, 705-710 (2009)]

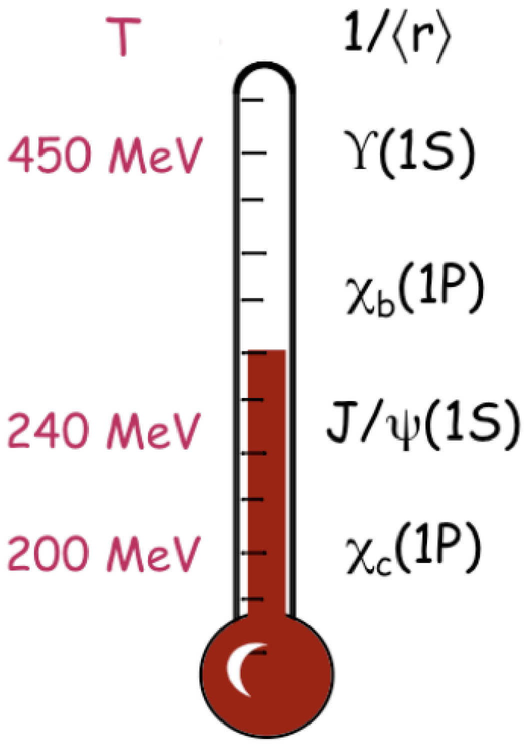




Quarkonia production

Other unknown effects

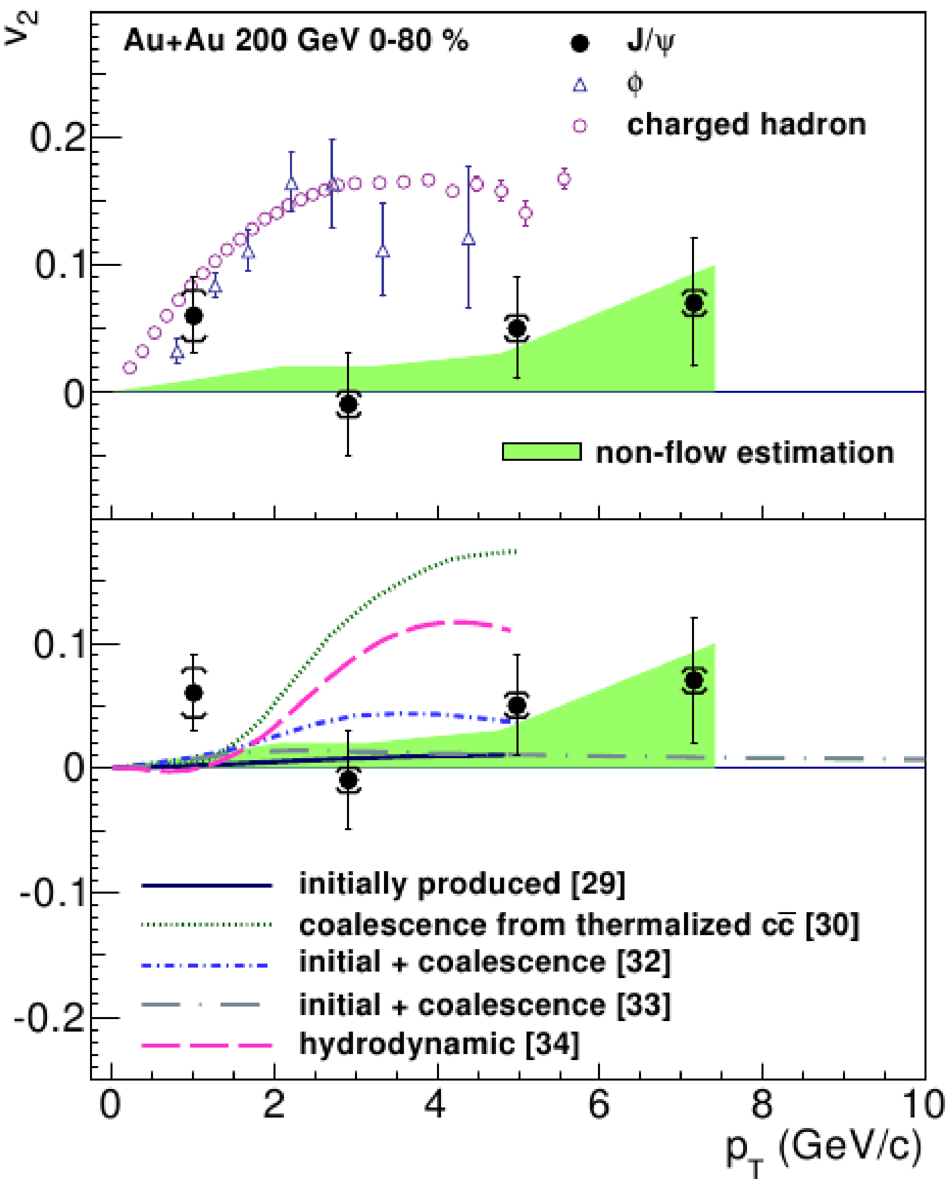
- **Production mechanism of quarkonia**
  - study p+p collision
- **Cold Nuclear matter effects**
  - nuclear shadowing, Cronin, nuclear absorption
  - study d+Au collision
- **Hot nuclear matter effects**
  - regeneration



Advantages of Υ

- negligible absorption and regeneration

Does J/ψ flow ?

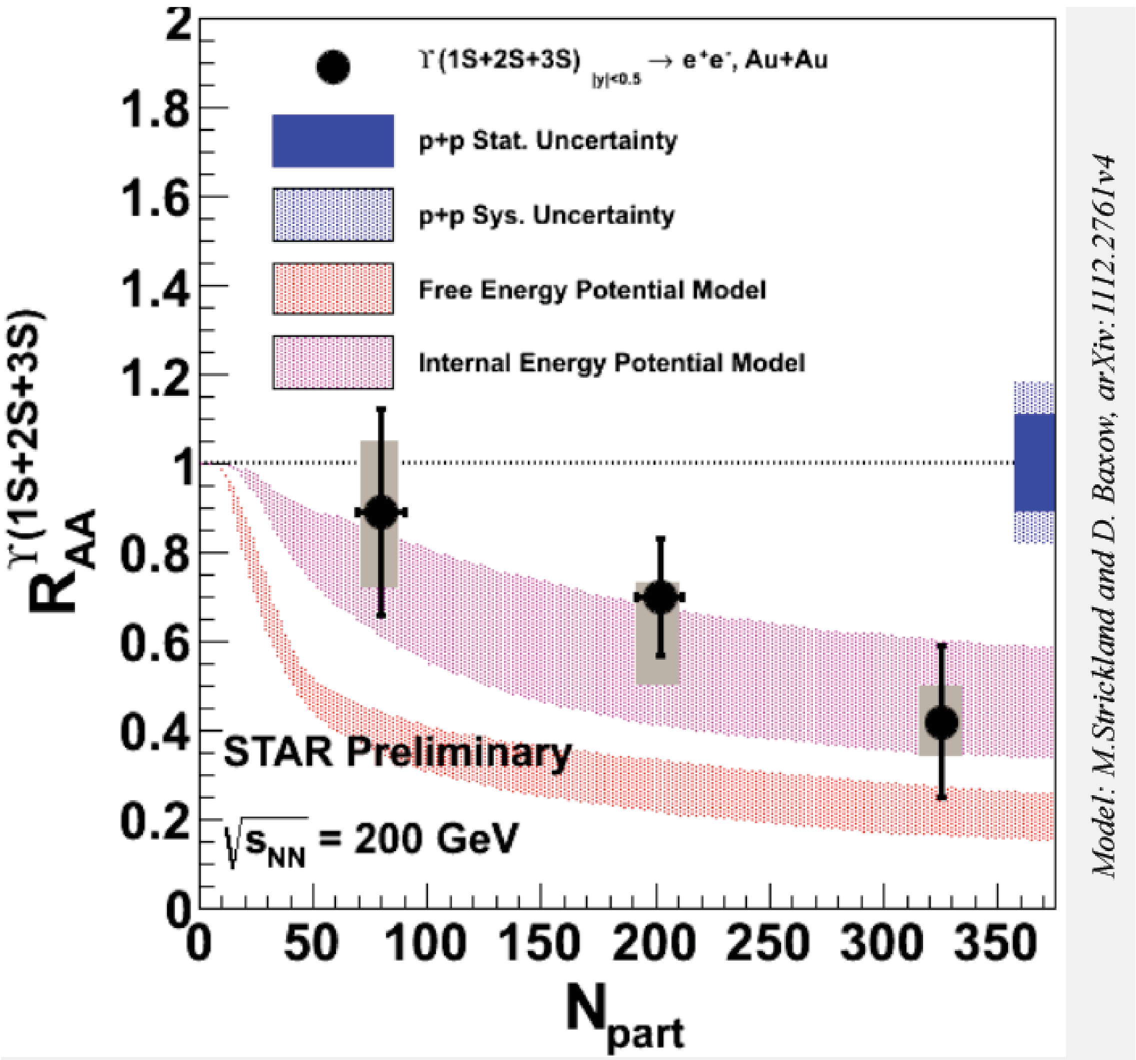


arXiv:1212.3304

- J/ψ from recombination of thermalized charm quarks is expected to acquire flow
- v_2 consistent with non-flow for $p_T > 2$GeV/c
- disfavors production by coalescence from thermalized quarks.

ϒ measurement

- **ϒ considered cleaner probe**
  - negligible absorption and regeneration
- p+p year 2009- dedicated Upsilon trigger
- Au+Au year 2010 – three centrality bins
- **ϒ(1S+2S+3S) suppression observed**, increasing with centrality
- **Consistent** with prediction from a model requiring **strong 2S and complete 3S suppression.**



Heavy flavor summary

p+p reference data

- FONLL QCD describes the data rather well

Open charm

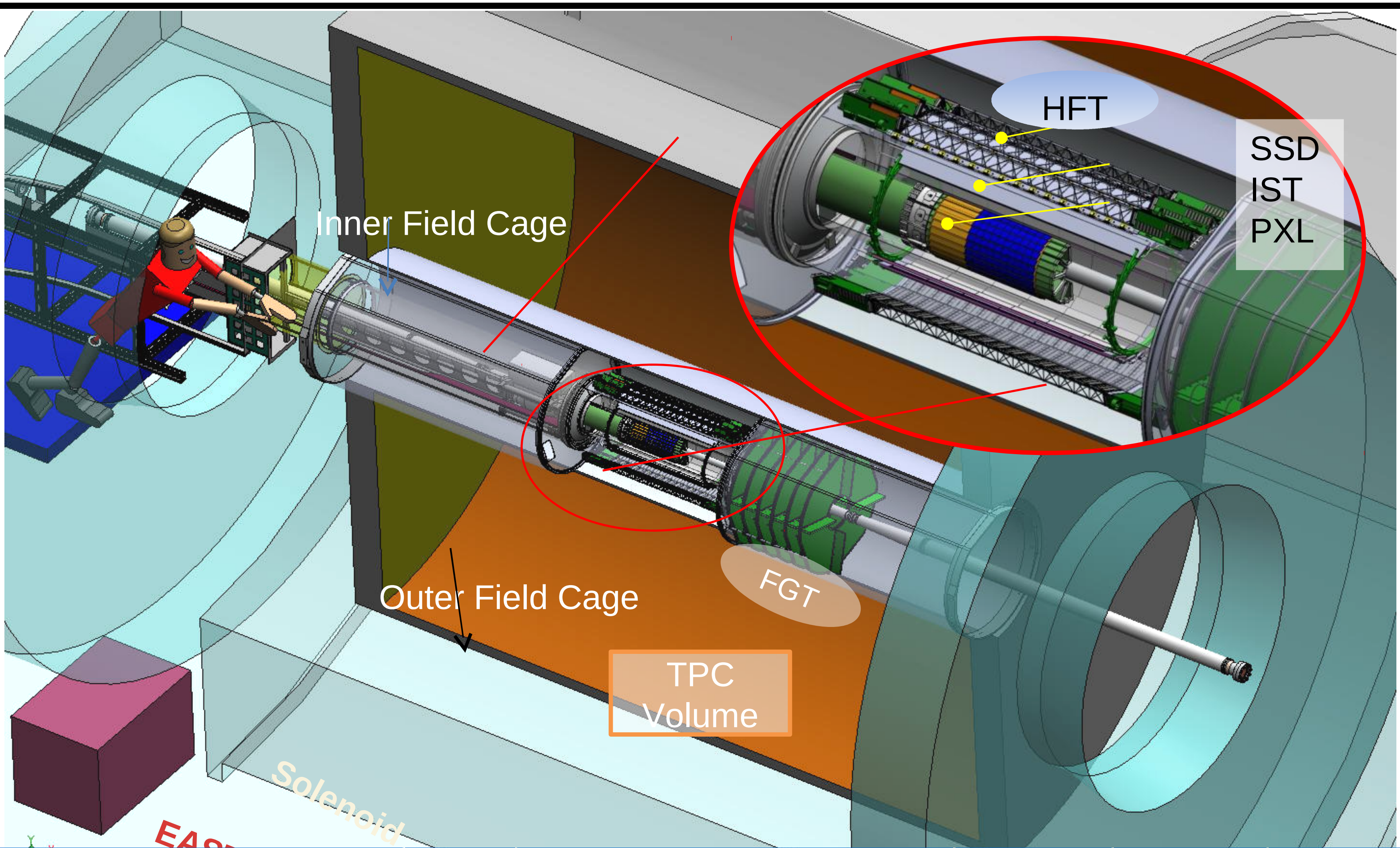
- Charm flows
  - significant v_2 for NPE, D^0 flow
- Significant suppression of NPE and D^0 at high p_T

Quarkonia

- From J/ψ – coalescence dominance is disfavored at high p_T
- Upsilon suppression
  - Consistent with full S3 and strong S2 melting

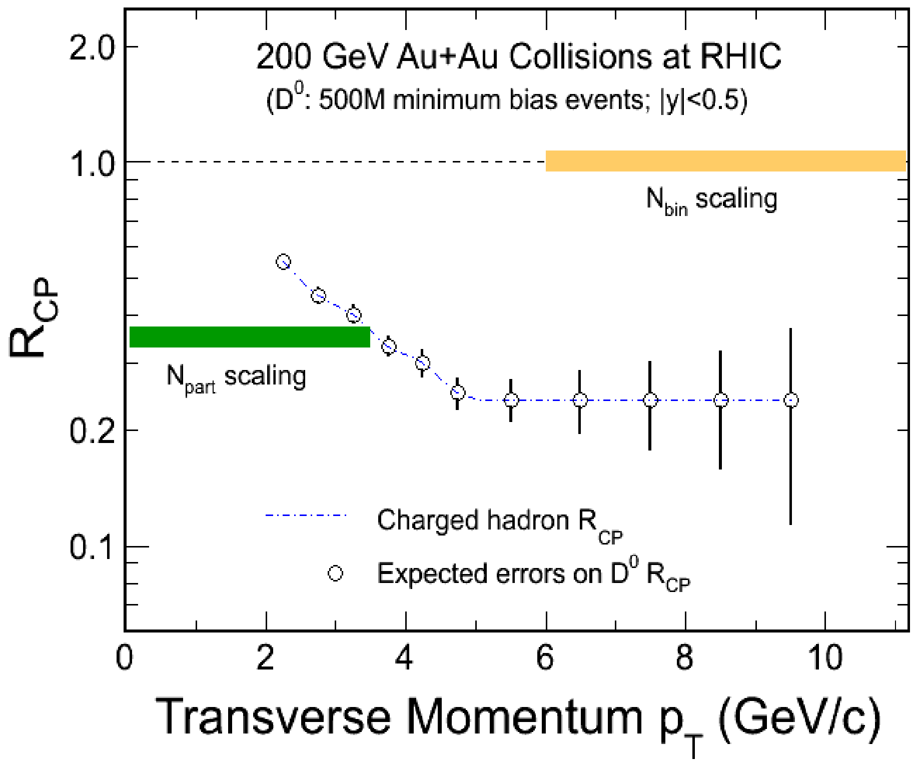
STAR near term upgrades

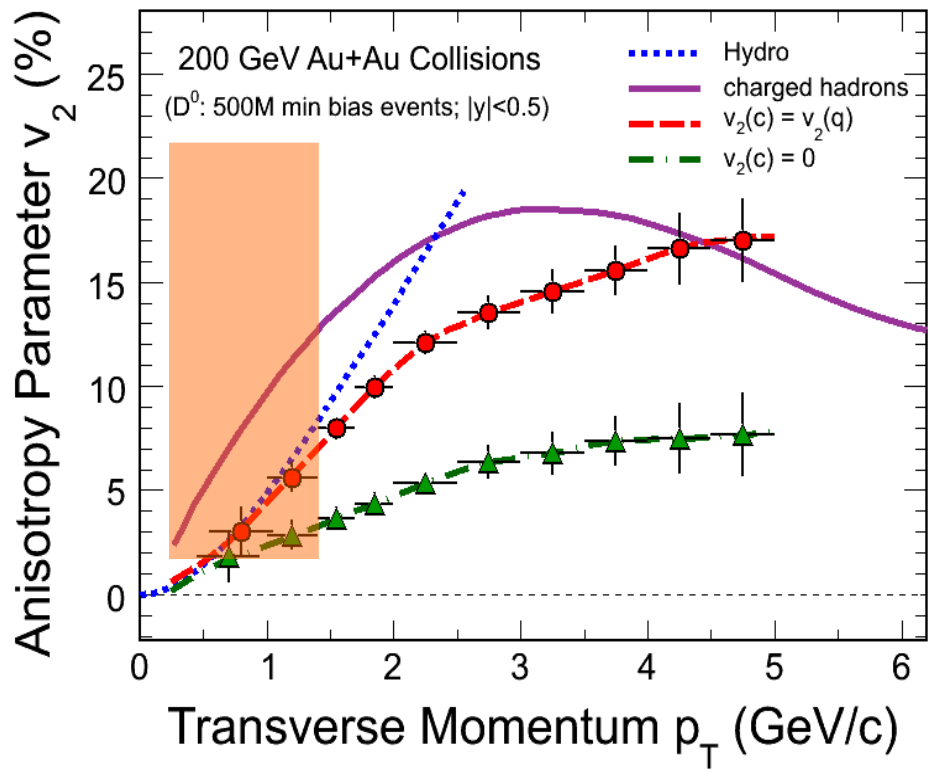
Heavy flavor tracker (HFT)



Sub detector	r (cm)	Sensitive units	$\sigma_{R-\varphi}$(μm)	σ_Z(μm)	X/X_0 (%)
Silicon Strip Detector	22	2 side strips with 95 μm pitch	20	740	1
Intermediate Silicon Tracker	14	500 μm x 1cm strips	170	1800	<1.5
PIXEL	2.5/8	18 μm pixel pitch	12	12	0.4/layer

Outlook for D^0 v_2 and R_{CP}





- Direct measurement of open-charm R_{CP} - **charm energy loss in QCD matter**
- Direct measurement of open-charm v_2 - **medium thermalization degree**
- Subtraction of charm component from NPE - **study bottom energy loss**

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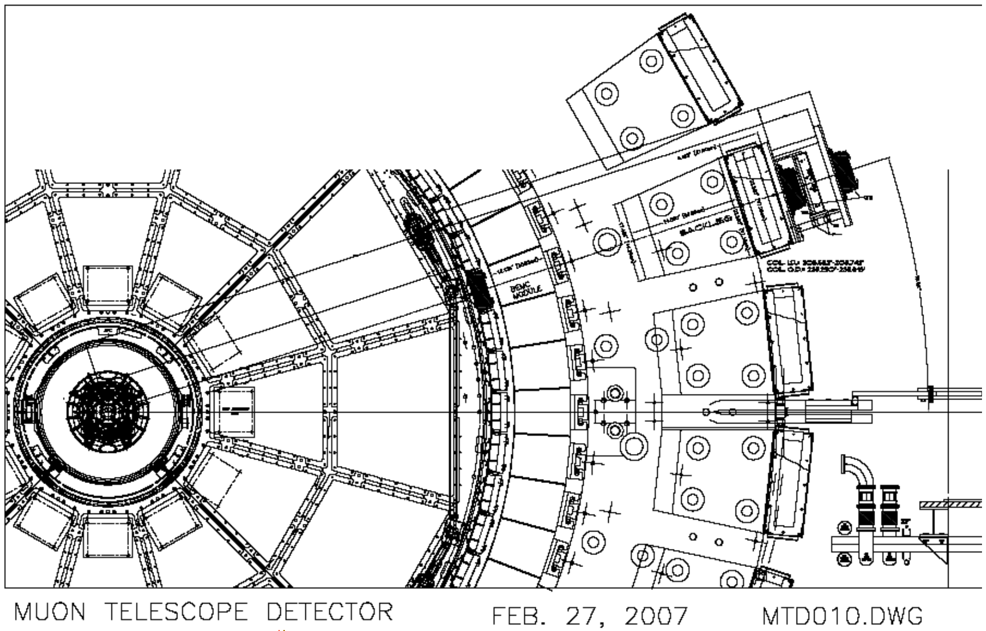
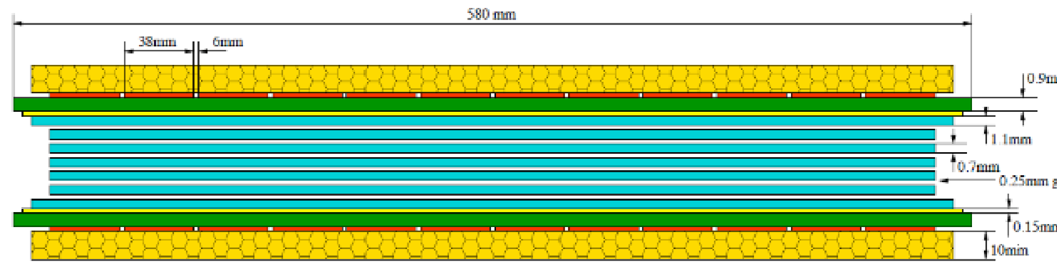
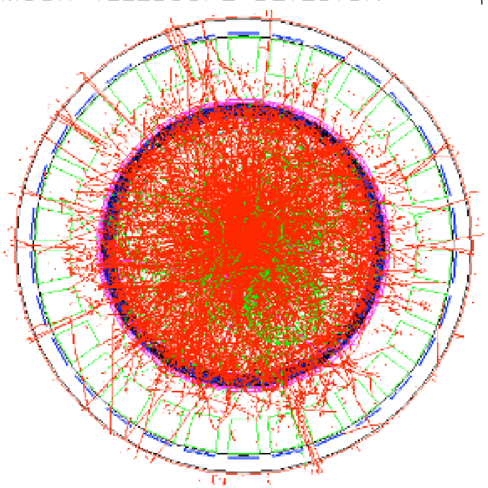
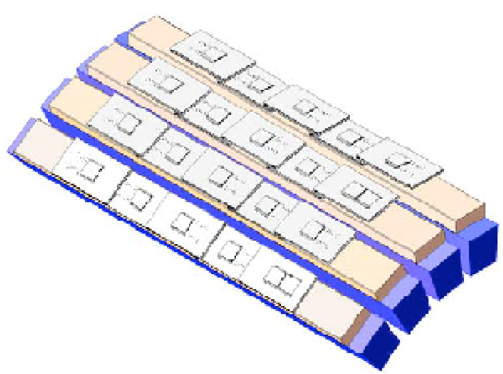
Muon Telescope Detector









Use the magnet steel as absorber and TPC for tracking.

Acceptance: $|\eta|<0.5$ and 45% in azimuth

118 modules, 1416 readout strips, 2832 readout channels

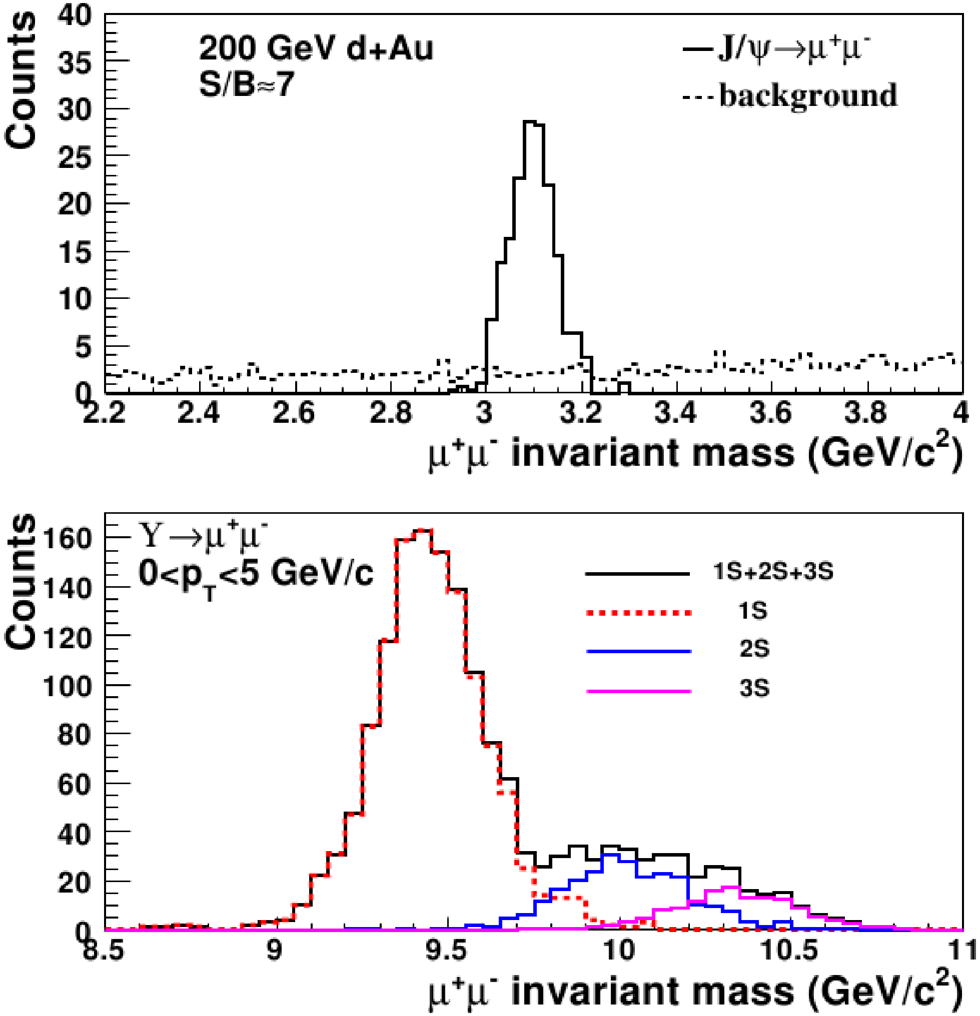
Long-MRPC detector technology,

HPTDC electronics (same as STAR-TOF)

Muon Telescope Detector

MTD will allow detection of

- di-muon pairs from QGP thermal radiation, quarkonia, light vector mesons, resonances in QGP, and Drell-Yan production
- single muons from the semi- leptonic decays of heavy flavor hadrons
- advantages over electrons: no γ conversion, much less Dalitz decay contribution
- trigger capability for low to high p_T J/ψ in central Au+Au collisions
- excellent mass resolution, separate different Upsilon states

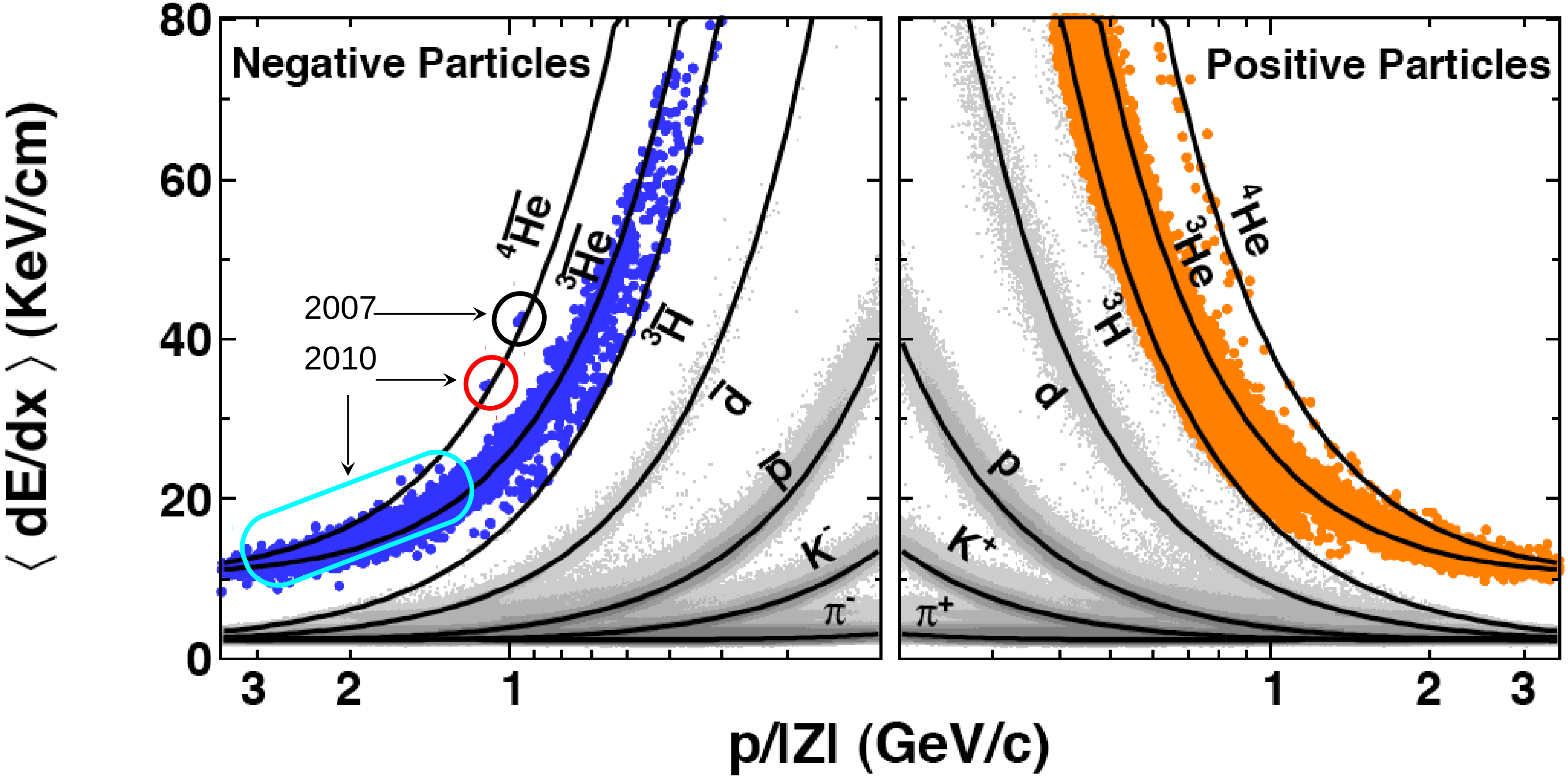


L. Ruan et al., Journal of Physics G: Nucl. Part. Phys. 36 (2009) 095001

Discovery of anti-He^4 at RHIC

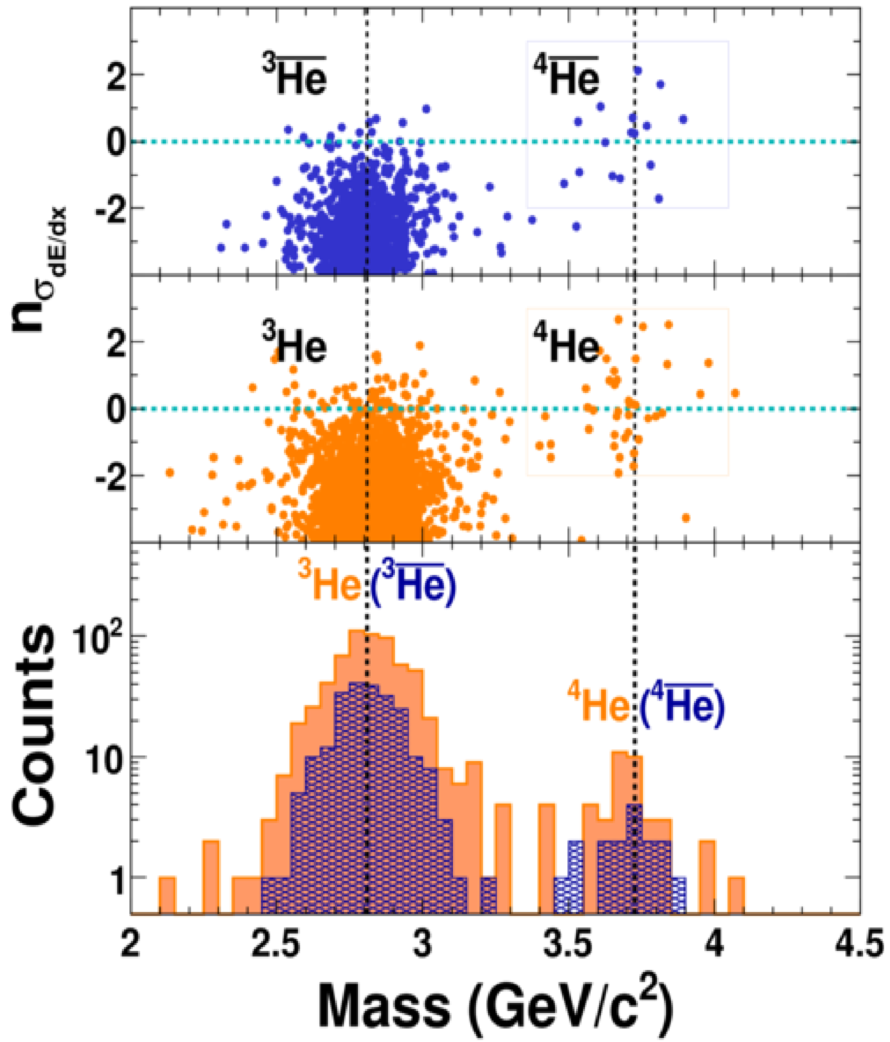
RHIC as an anti-matter machine

anti-He^4 identification in TPC



- **Level 3 trigger - tagging of events with tracks of |Z| = 2.**
- **In total one billion AuAu events sampled.**
- **dE/dx overlap at higher momentum, TOF information is needed**

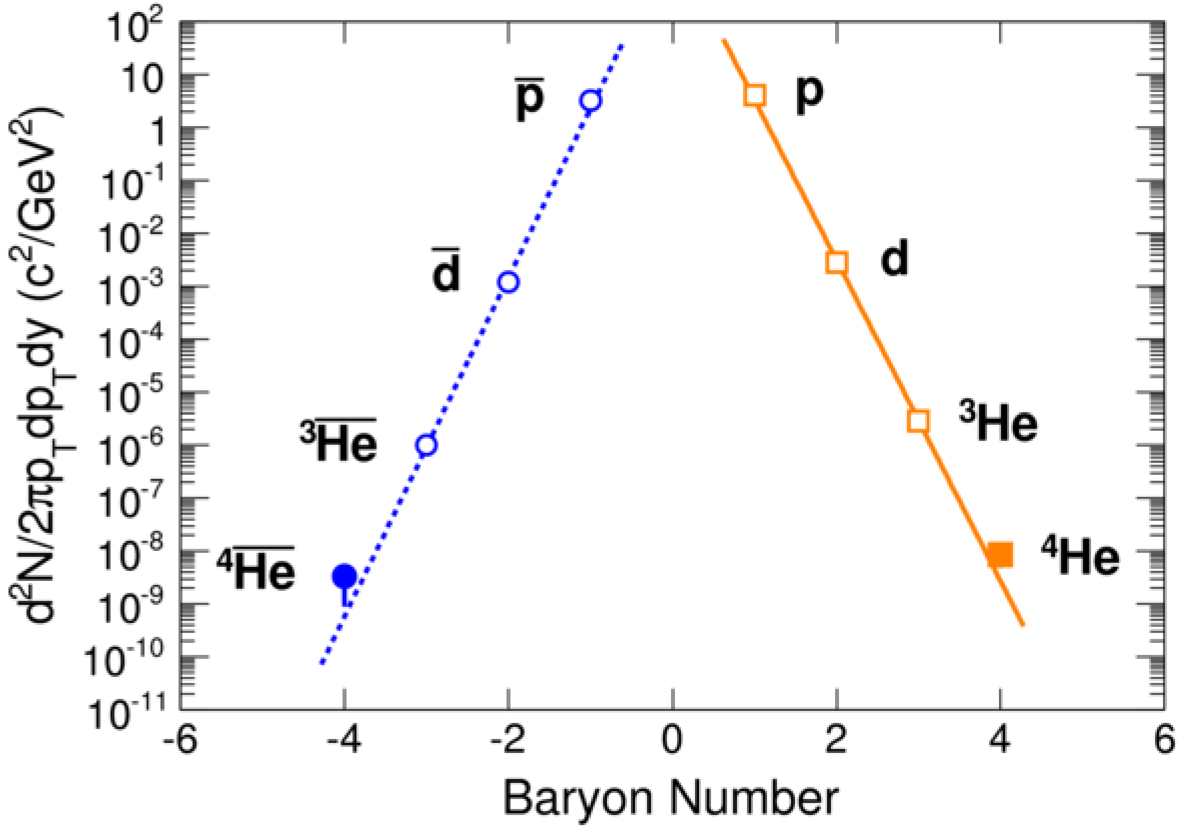
PID from TOF+TPC



18 counts in total

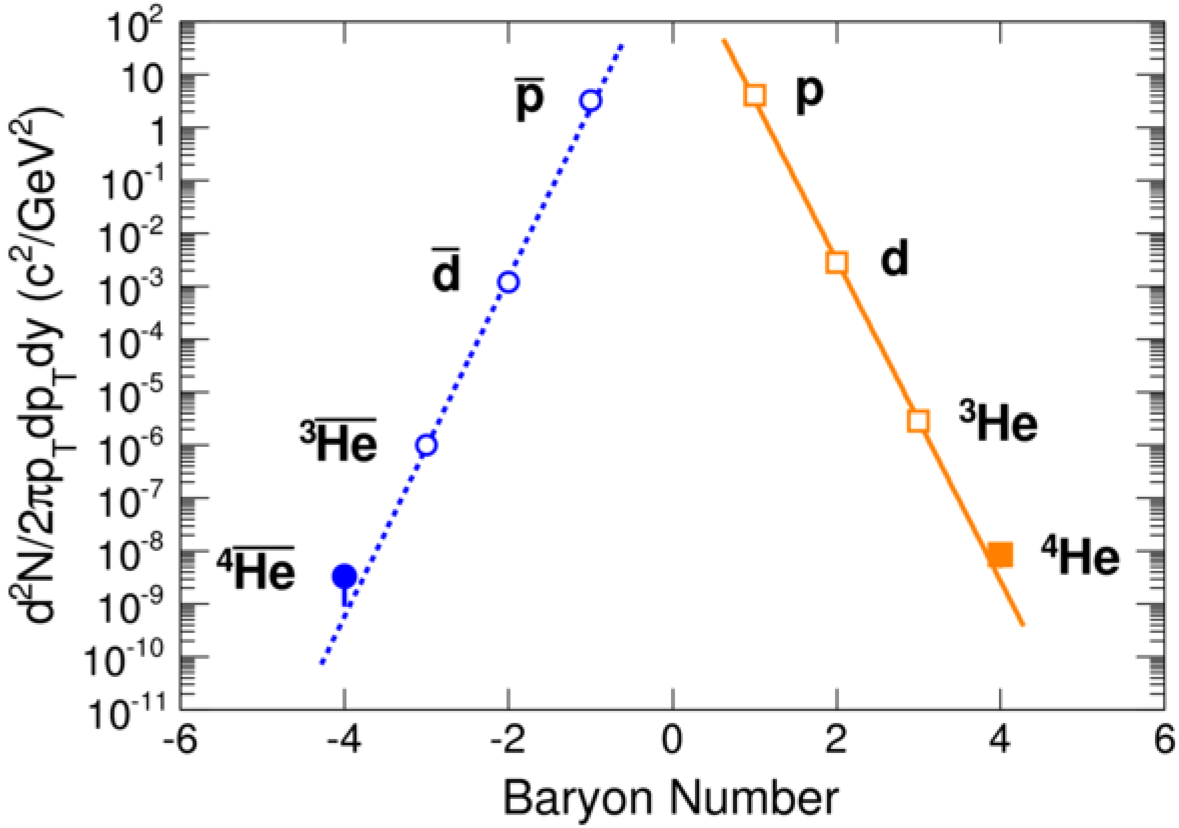
- **15 from 200 GeV AuAu in 2010**
  - **background ~ 1.4**
  - **probability of misidentification ~ 10^{-11}**
  - **significance > 6**
- **2 from 200 GeV AuAu in 2007**
- **1 from 62 GeV AuAu in 2010**

anti-He^4 yield



- Production rate reduces by a factor of $1.6x10^3$ ($1.1x10^3$) for each additional antinucleon (nucleon) added to the antinucleus (nucleus).
- Next stable are anti-^{6}Li and anti-^{6}He (suppression ~ 10^{-6}).
- anti-^{4}He **may remain the heaviest stable antimatter in the foreseeable future**.

anti-He^4 yield



- Point of reference for various searches for new phenomena in the cosmos.
- The production rate of ant-^{4}He in nuclear collisions is consistent with thermodynamic and coalescent nucleosynthesis models.
- If anti-α in the cosmos were from coalescence, the ratio of anti-α/α would be 10^{-16}. With a sensitivity of 10^{-9}, even a single anti-α count seen by the AMS experiment would be a strong evidence of anti-star.

Conclusions

Matter at the top RHIC collision energy

- strongly interacting almost perfect liquid - sQGP
  - collective behavior with partonic degrees of freedom

Successful completion of RHIC Beam Energy Scan

- observed that the QGP signatures disappear at lower energies,
- ongoing search for 1st order phase transition and critical point

Heavy flavor program

- rich collection of results and more will come with planned upgrades

STAR has entered the era of precision QCD measurements – lots of interesting results coming.

STAY TUNED....