PHENIX: Current and Future

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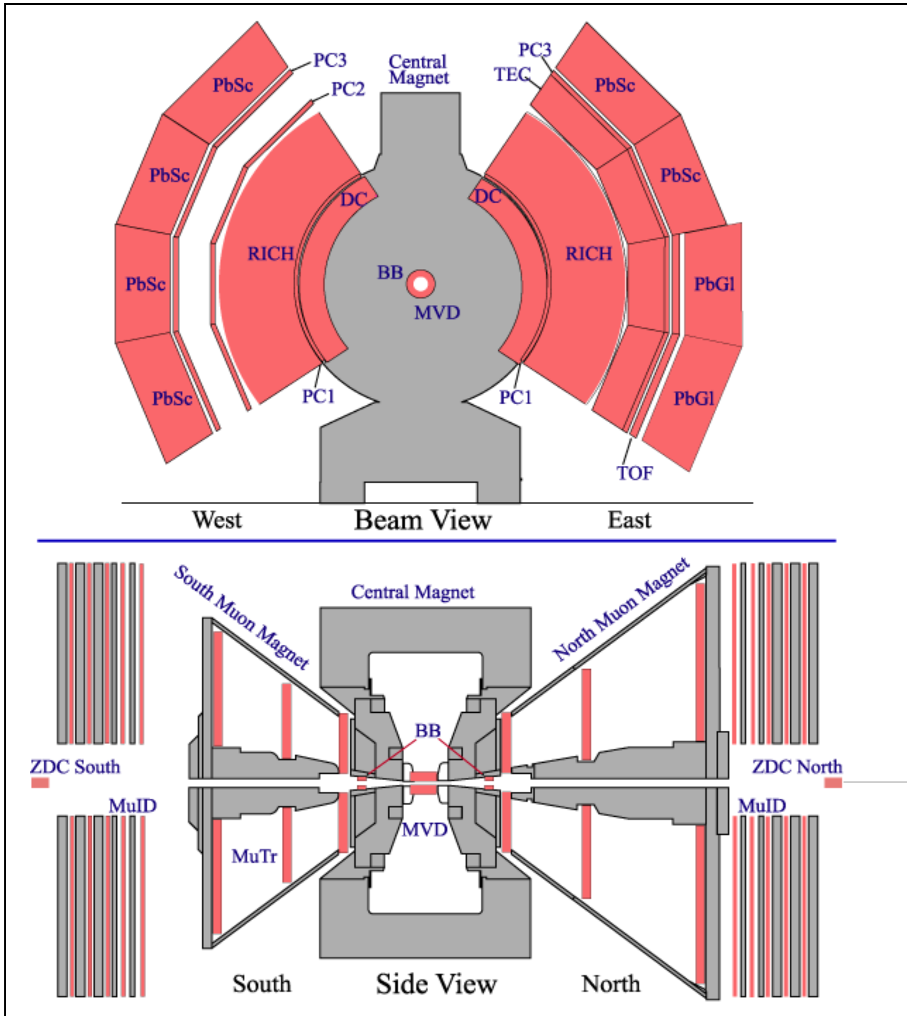
KIAS-APCTP Workshop
"Relativistic Heavy-Ion Collison : Present and Future"
2006-09 Heavy Ion Meeting (HIM 2006-09)

The PHENIX Detector

designed to measure rare probes:

Au-Au & p-p (spin)

+ high rate capability & granularity
+ good mass resolution and particle ID
- limited acceptance



- **2 central arms:** $|\eta|<0.38$ at $y=0$, $\Delta\phi = \pi$

  electrons, photons, hadrons
  - charmonium $J/\psi, \psi' \rightarrow e^+e^-$
  - vector meson $\rho, \omega, \phi \rightarrow e^+e^-$
  - high p_T pion □º –>©©
  - open charm, beauty ($D,B \rightarrow e$)

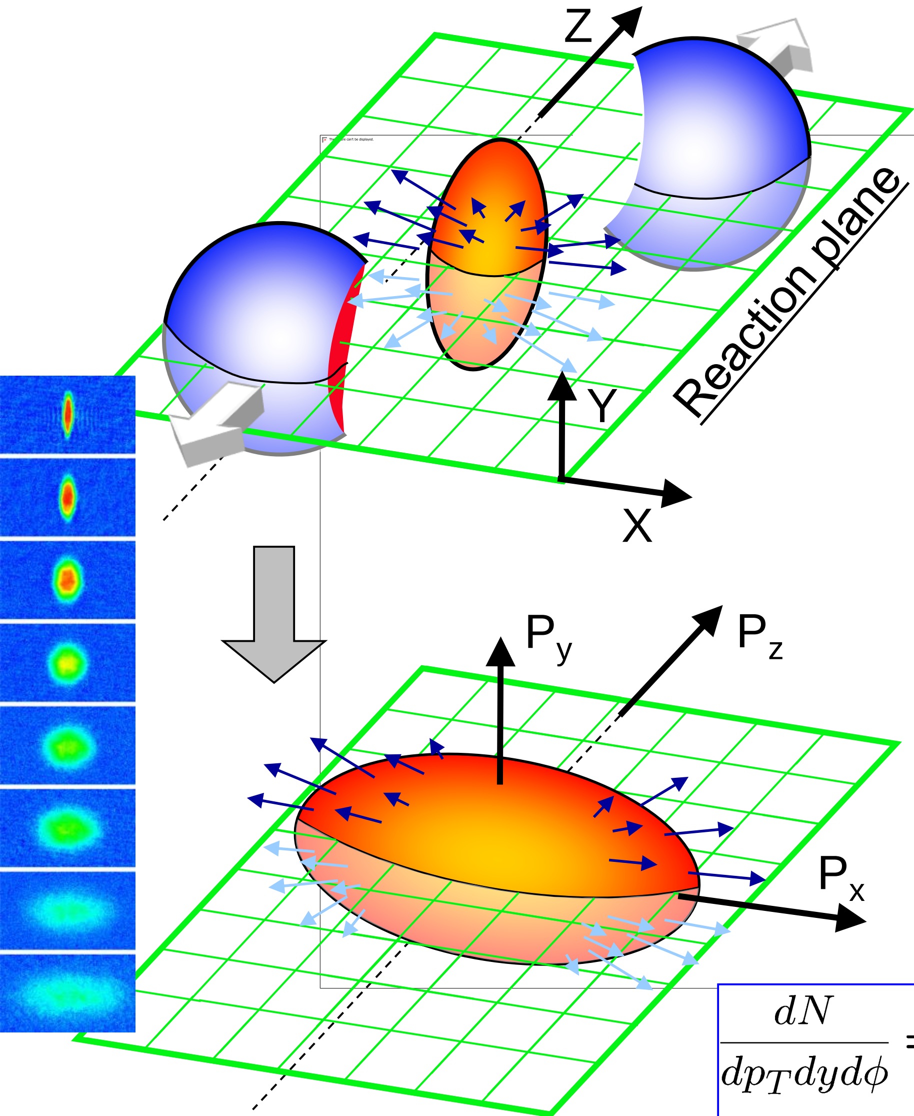
- **2 muon arms:** $1.2<|\eta|< 2.4$, $\Delta\phi = 2\pi$

  muons
  - "onium" $J/\psi, \psi', \Upsilon \rightarrow \mu^+\mu^-$
  - open charm, beauty ($D,B \rightarrow \mu$)

OUTLINE

- **Elliptic Flow**
  - Saturation of v_2
  - KE_T & n_{quark} scaling of v_2
- **High P_T suppression**
  - R_{AA} for hadron, photon, and heavy quark
- **J/Ψ suppression**
  - R_{dA} and R_{AA} for J/Ψ yield
- **PHENIX Upgrade**

Why Elliptic Flow ?



$$\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

- Elliptic flow is generated early when the system is asymmetric: sensitive to early dynamics
- Pressure gradient is largest in the shortest direction of the ellipsoid
- Spatial anisotropy is transformed into momentum anisotropy as the system expands
- Maximum (Minimum) number of particles at Φ=0,π (Φ=π/2,3π/2)
- Elliptic flow (v_2) is defined by the 2nd coefficient of Fourier expansion, having the period of π

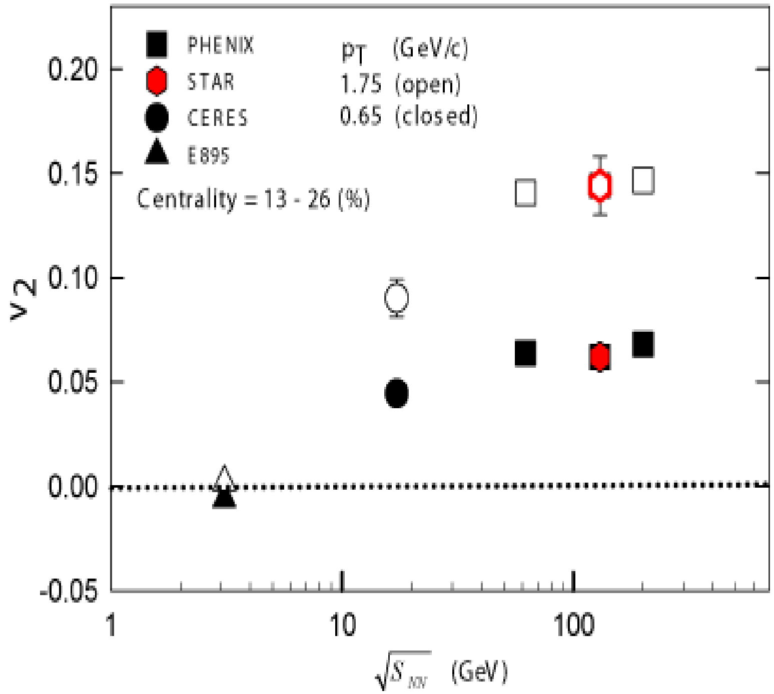
$$\frac{dN}{dp_T dy d\phi} = \frac{1}{2\pi}\frac{d^2N}{dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right)$$

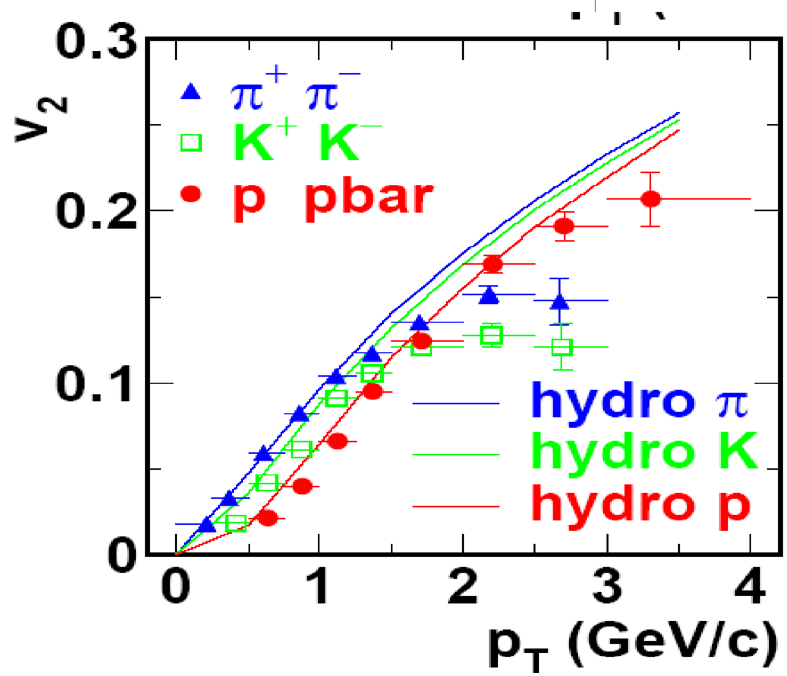
$$v_2 = \langle\cos(2\phi)\rangle$$

Saturation and Hydrodynamic description of v2

PRL 94, 232302 (2005)

PRL 91, 182301 (2003)



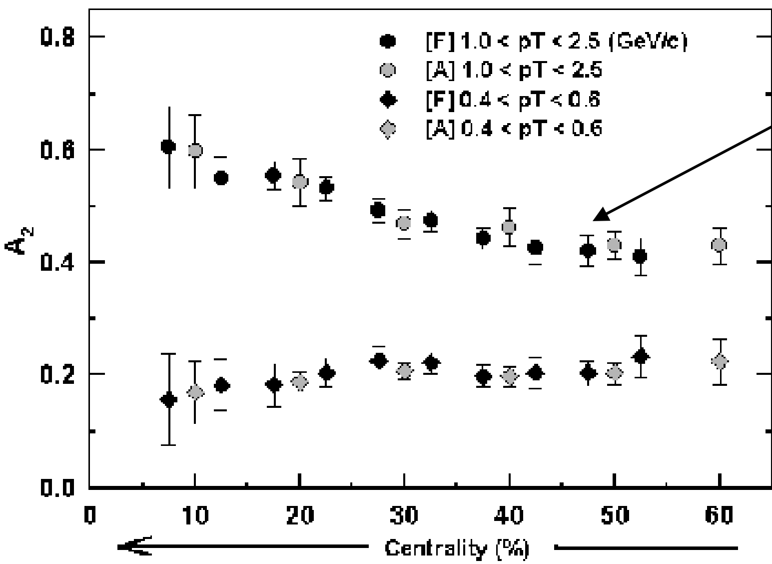


v_2 increases by ~50% from SPS to RHIC
Saturation at $\sqrt{\mathbf{s}}$ = 62.4 ~ 200 GeV
Larger pressure (gradients) at RHIC

Elliptic flow well described by hydrodynamic models up to p_T ~ 1.5 GeV/c

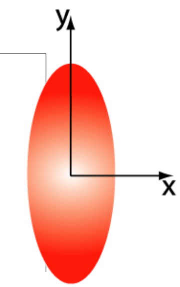
Scaling tests : eccentricity scaling

Au+Au √s = 130GeV



PRL 89, 212301 (2002)

$$A_2 = \frac{v_2}{\varepsilon}$$



$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

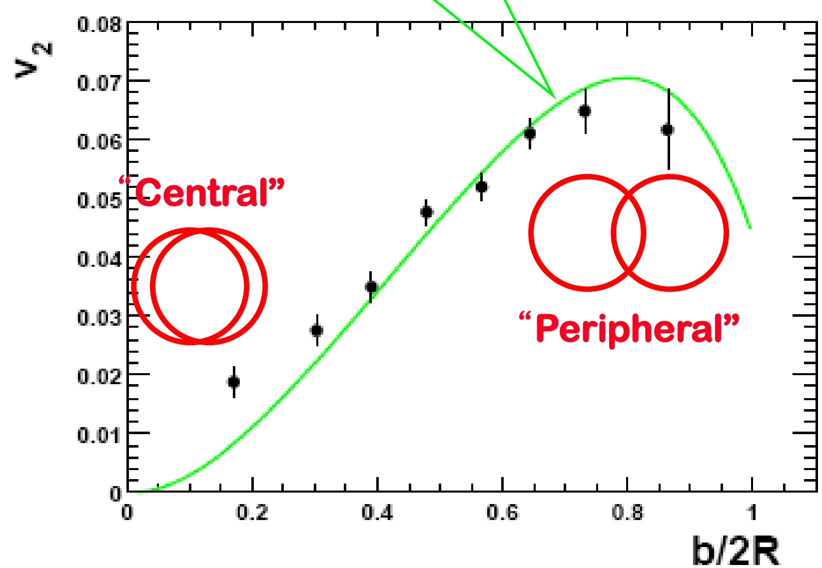
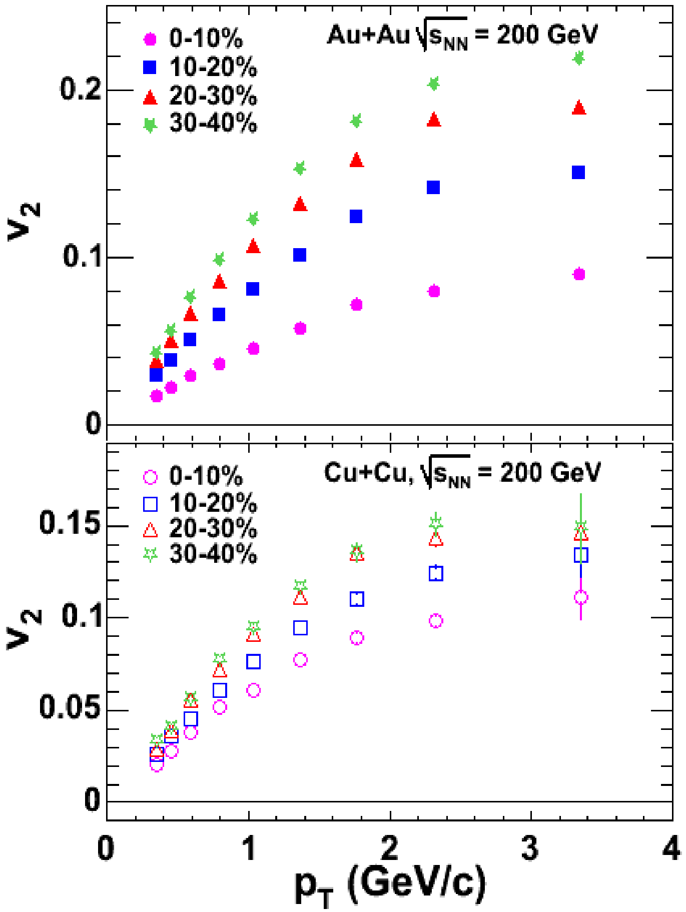


FIG. 3. Elliptic flow as a function of centrality defined from the fraction $\sigma_{top}/\sigma_{geo}$. The curve shows ϵ, the initial space eccentricity of the overlap region, multiplied by 0.16.

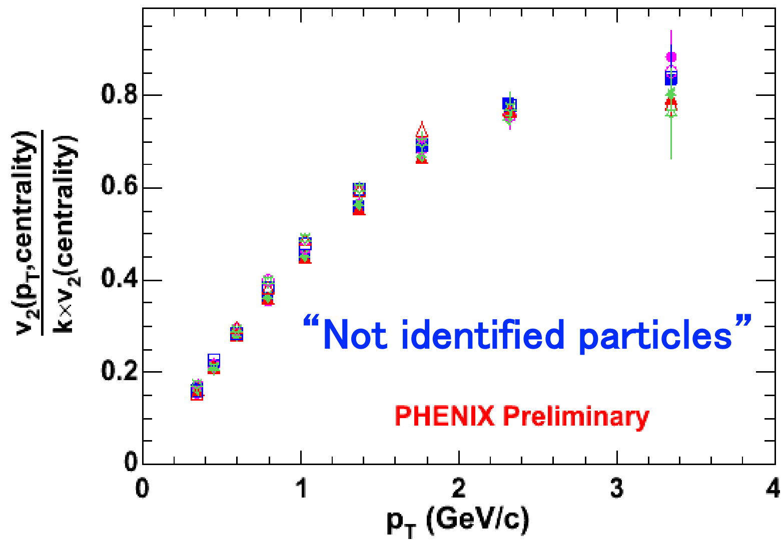
Ideal hydrodynamics is scale invariant. Hence, v_2 should be independent of system size if ideal hydro applies

pairs from a common range (Fixed-pt), and from a fixed pt and outside this range (Assorted-pt)

Eccentricity scaling and system size



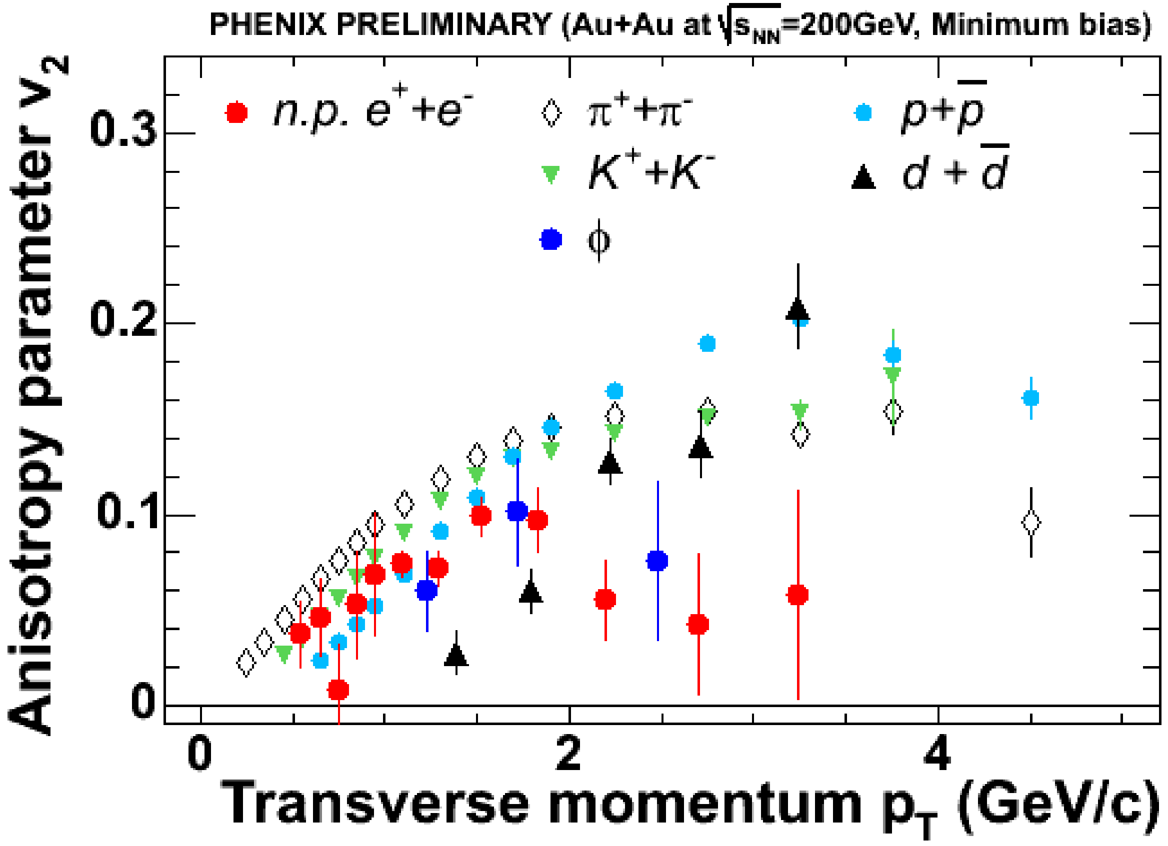
Nucl-ex/060833



For the v_2 integrated over p_t,
hydrodynamic model predicts : $\varepsilon = k v_2$
ε from Glauber model : $k=3.1$

- v_2 scales with eccentricity across system size (Au+Au, Cu+Cu)
- Indicates high degree of thermalization of the matter at RHIC

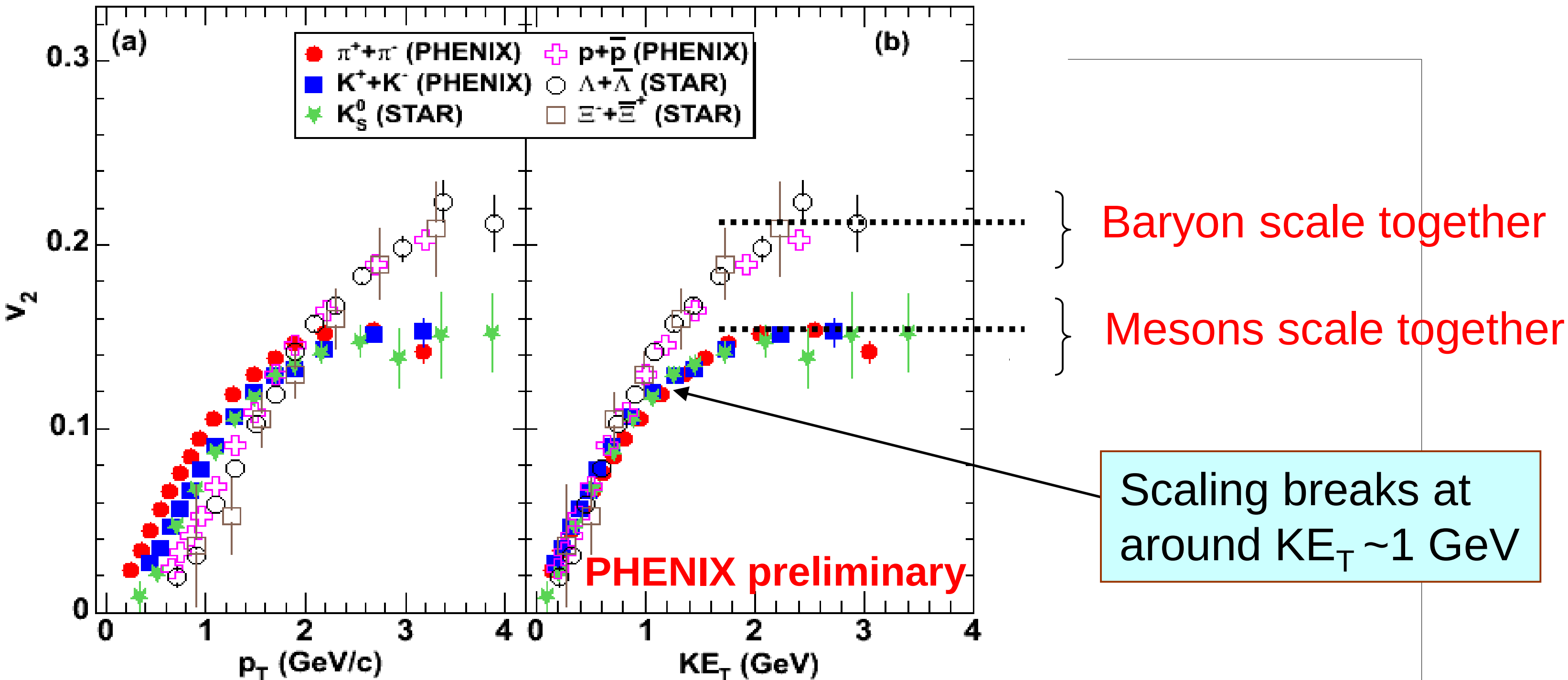
v2 of identified particles in PHENIX



Significant elliptic flow observed for all identified particles

Transverse kinetic energy as a scaling variable

Min. bias Au+Au



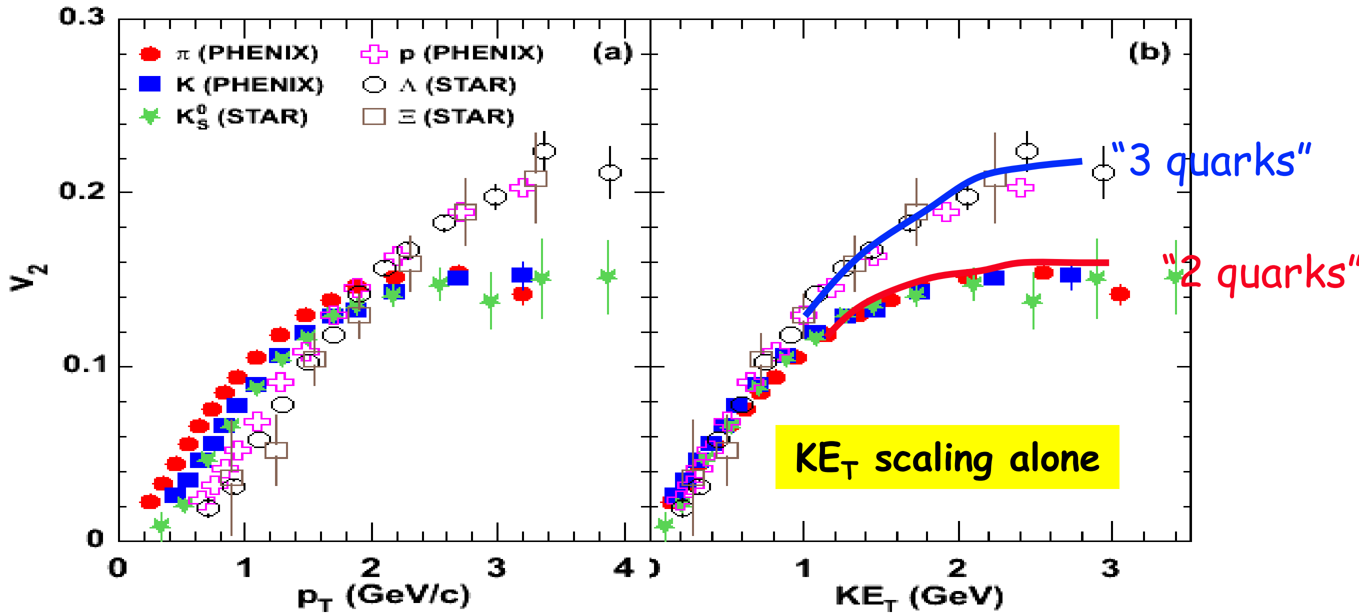
- Pressure gradients convert some work into kinetic energy
- Hence, KE_T is a natural variable to use for testing hydrodynamic behavior
- Very good scaling of v_2 with KE_T seen for $KE_T \leq 1$ GeV
- Two separate branches appear for mesons and baryons at $KE_T > 1$ GeV
- Hint of quark degrees of freedom due to partonic flow

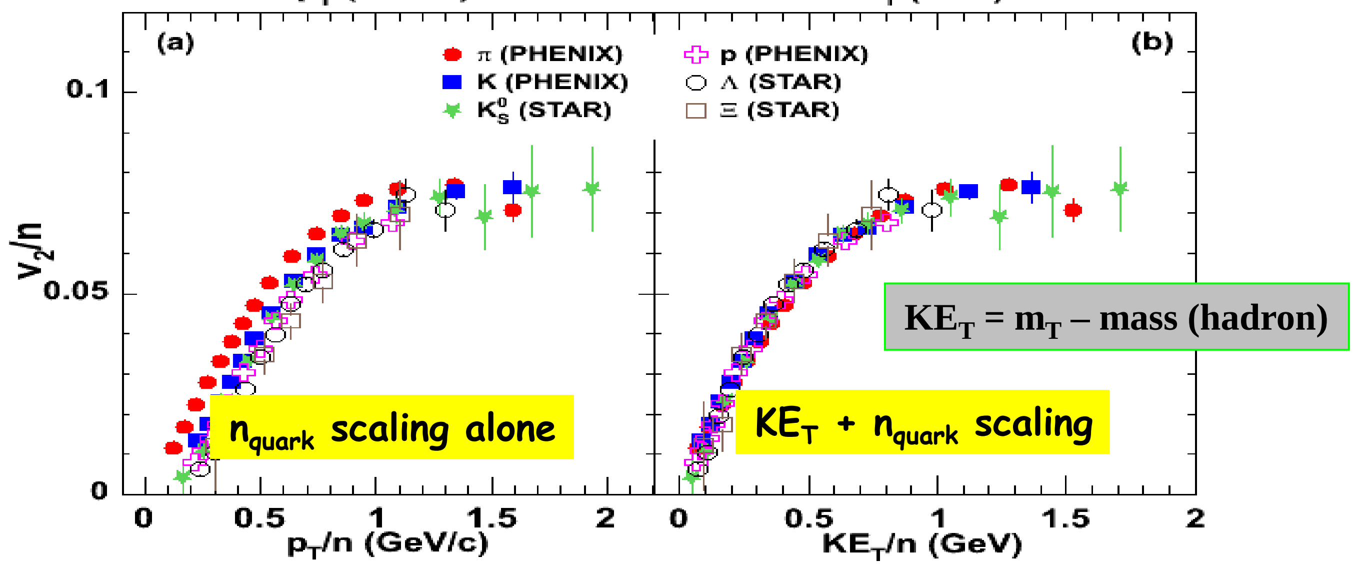
KE_T & n_{quark} scaling of v_2

Min. bias Au+Au

Nucl-ex/060833

Quark coalescence:
$v_2^{hadron}(p_T) \approx n \times v_2^{quark}(p_T/n)$

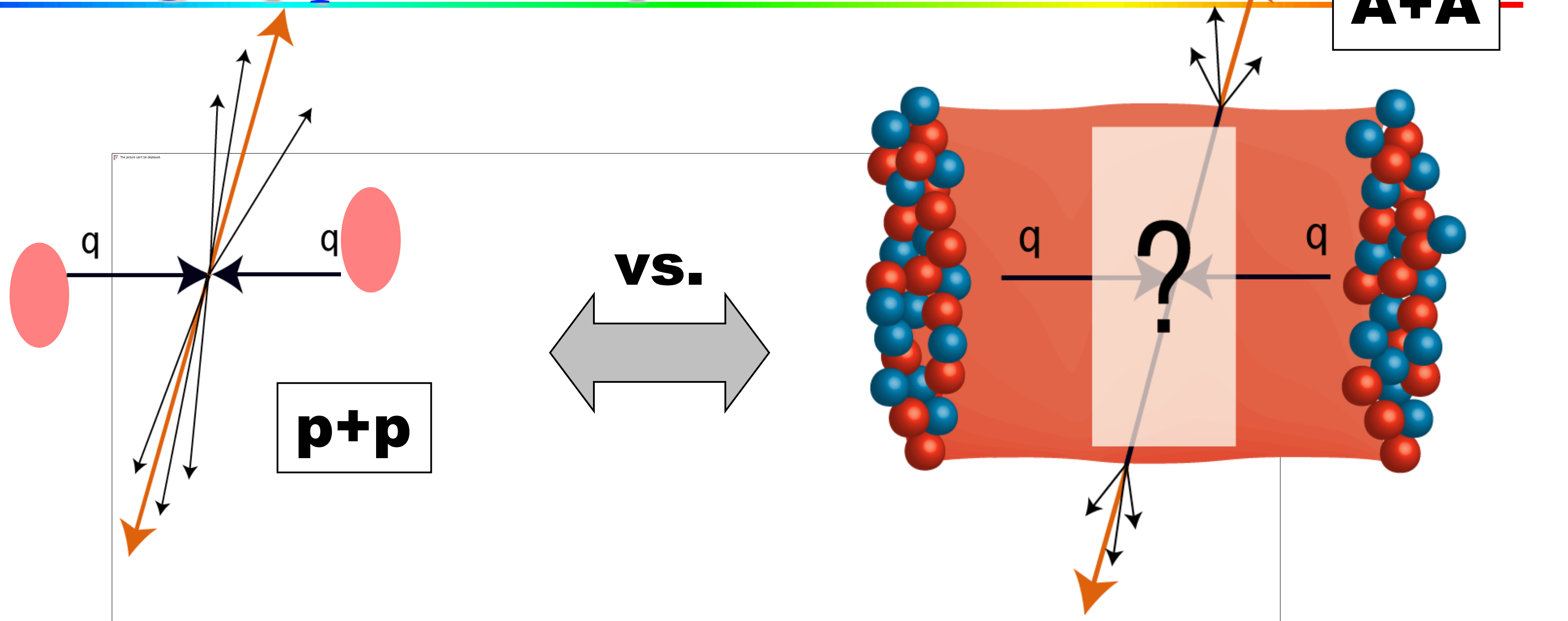




Summary: Elliptic Flow

- Charged hadron v_2 increases by ~50% from SPS to RHIC and saturates at $\sqrt{s}$ = 62.4 ~ 200 GeV
- v_2 scales with eccentricity across system size, independent of system size and centrality, indicating high degree of thermalization at RHIC
- PHENIX has measured the v_2 of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$ in detail, as well as v_2 of Φ and deuteron
- Parton number scaling appears to be better described by KE_T/n than p_T/n
- The observation of the scaling with KE_T/n needs to be better understood and could be served as input to model comparisons

High-p_T as hard probe of the medium

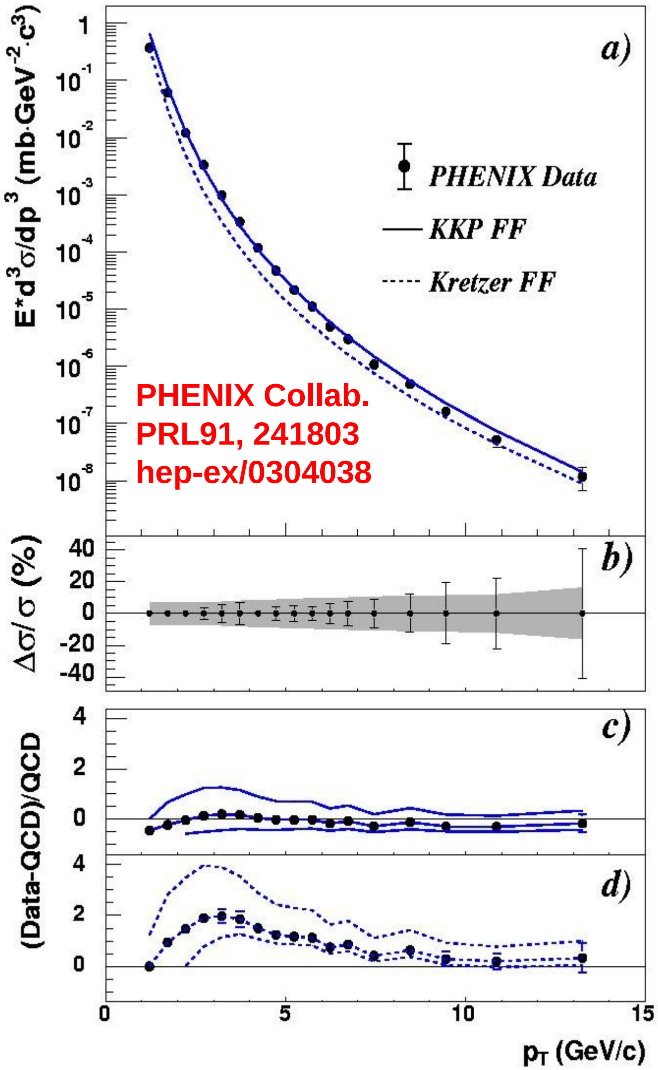


- Hard-scattering cross-section is large in high energy collisions
- Initial yields and p_T distributions can be predicted from p+p measurements + pQCD + collision geometry + cold (initial) nuclear effects
  - Critical to perform measurements in reference p+p and p(d)+A systems
- Observed deviations from reference measurements can be attributed to the medium

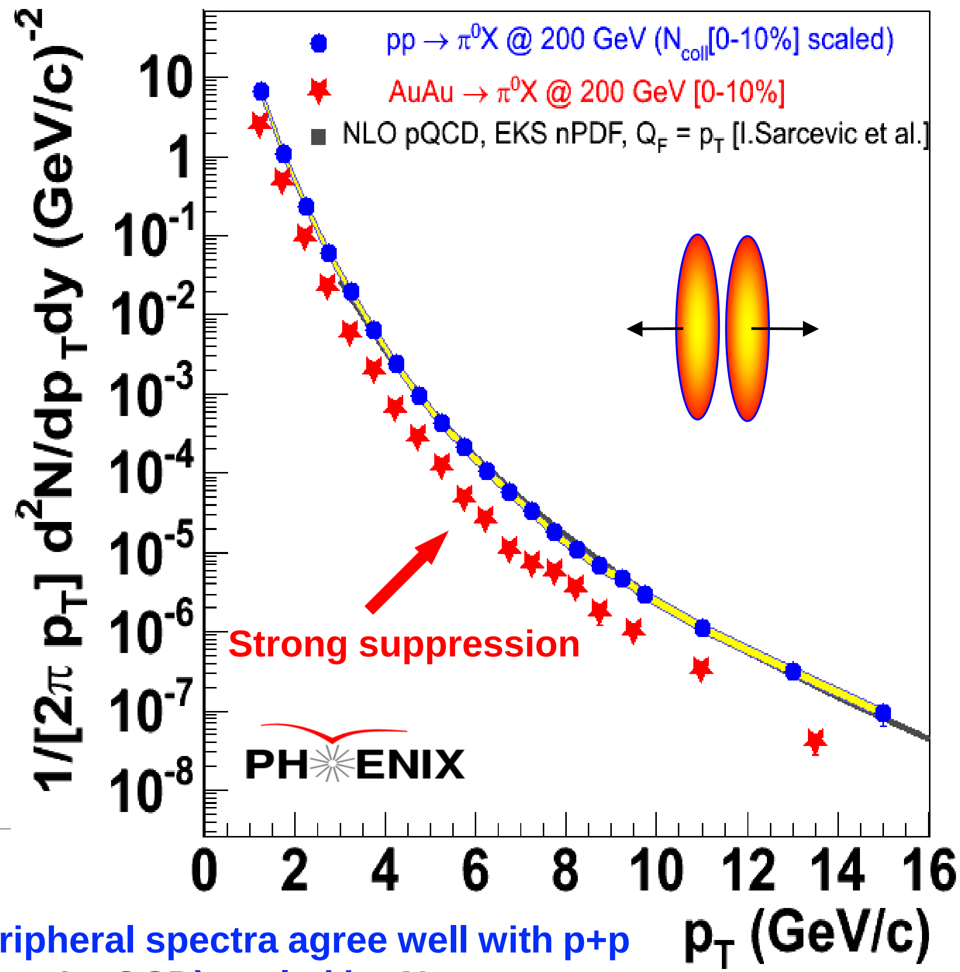
Do we observe hard-scattering?

Single-particle spectrum and QCD predictions

$p+p \rightarrow \pi^0+X$



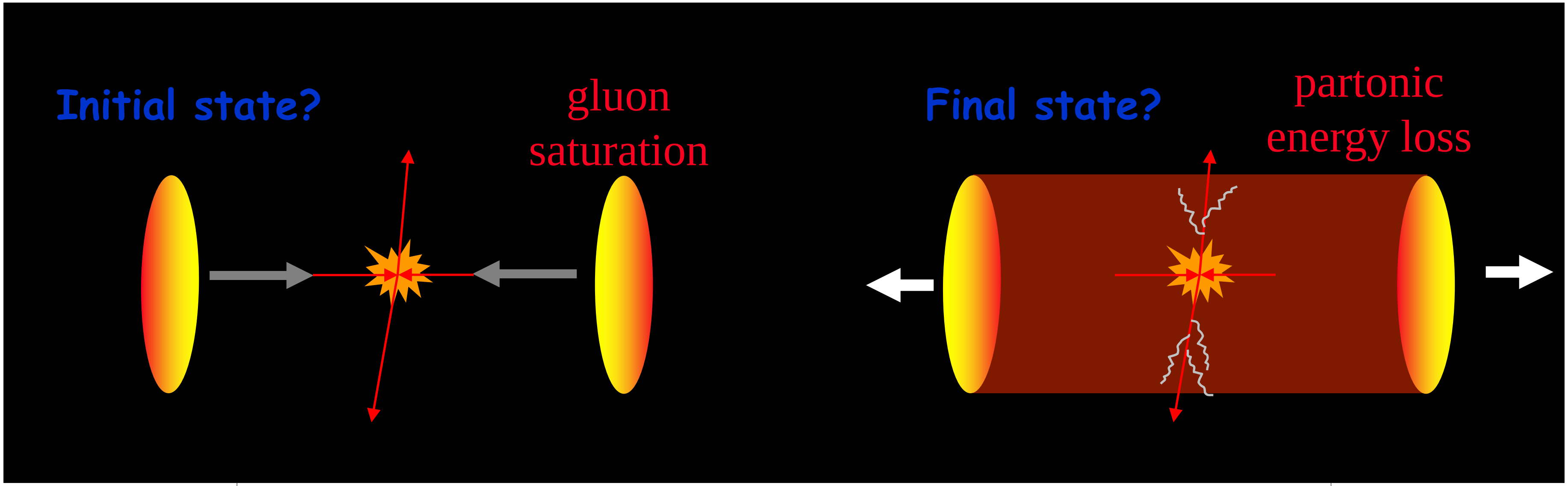
$Au+Au \rightarrow \pi^0 + X$ (central)



Peripheral spectra agree well with p+p (data & pQCD) scaled by N_{coll}

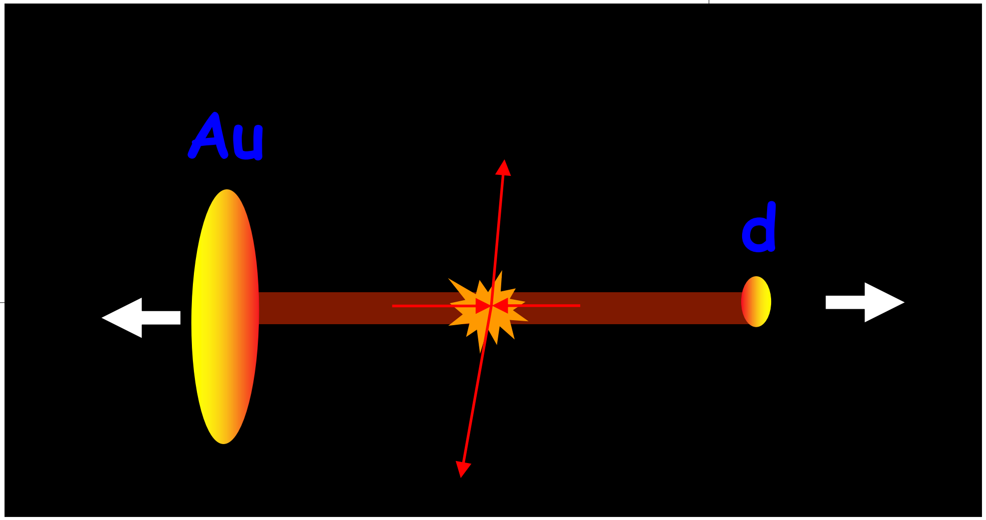
Central data exhibits suppression: R_{AA}= red/blue < 1

Is suppression an initial or final state effect?

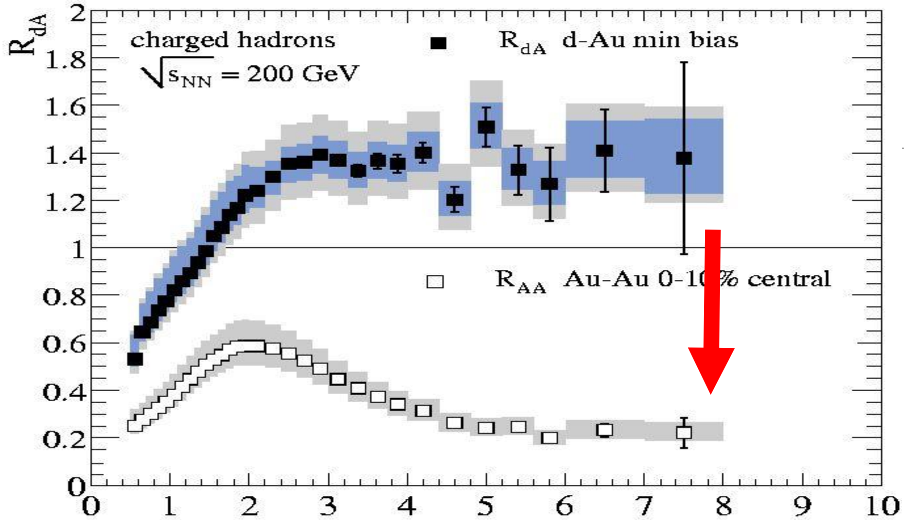


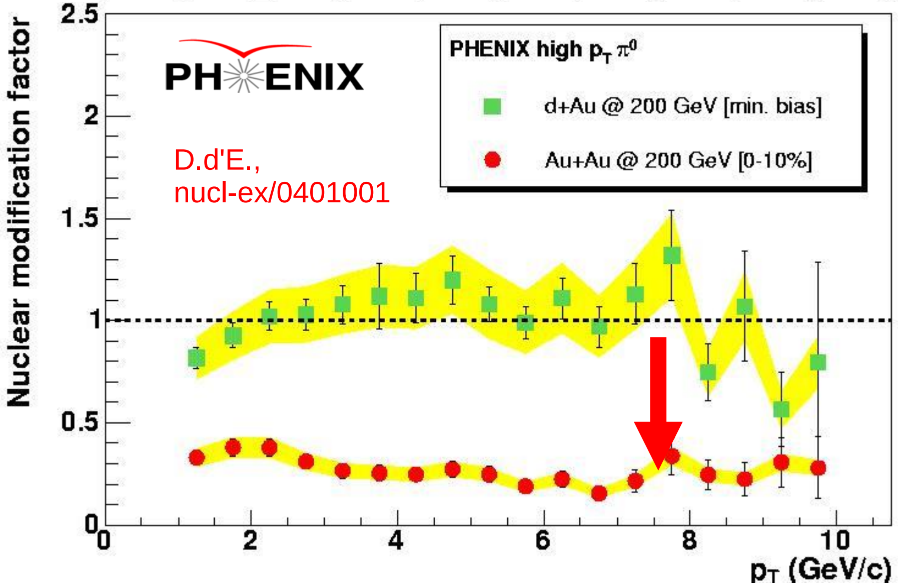
How to discriminate?
- Turn off final state

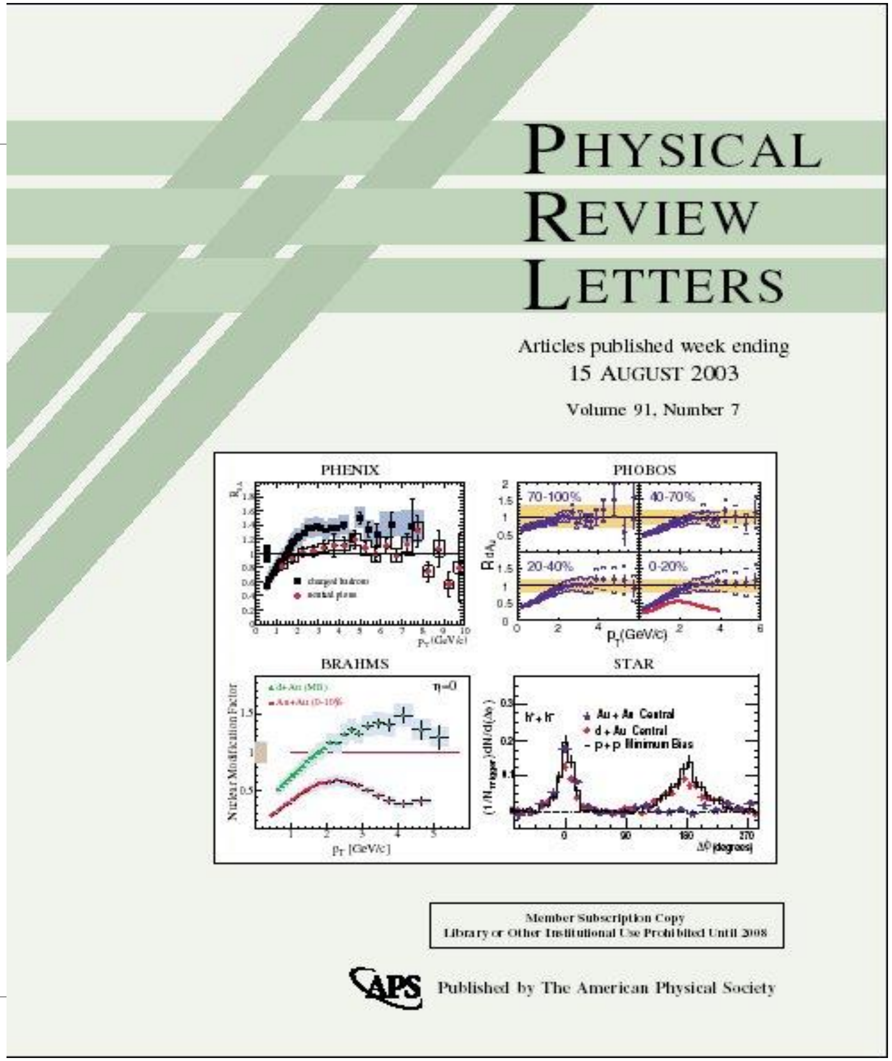
⇒ d+Au collisions



Absence of suppression in d+Au





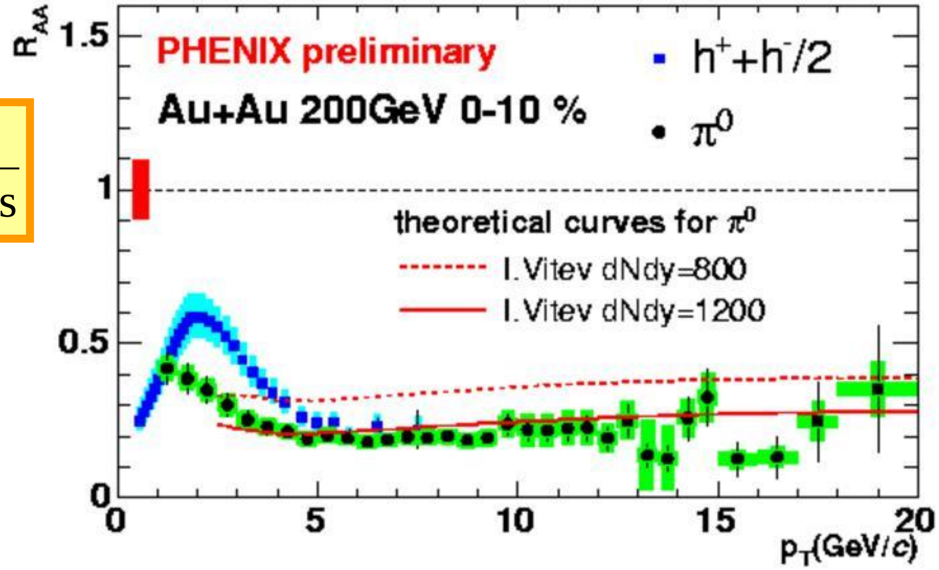


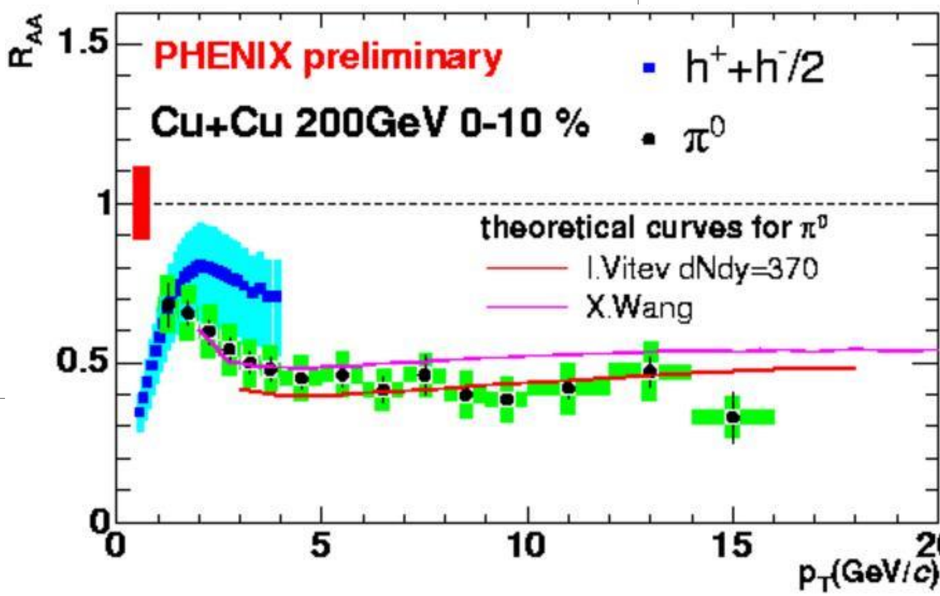
High p_T suppression in central Au+Au due to final-state effects (absent in d+Au), indicating jet-quenching in QGP.

Modeling $R_{AA}(p_T)$ of Au+Au and Cu+Cu

$$R_{AA}(p_T) = \frac{\text{Measured yield in A + A}}{\text{Expectation for indep. N + N scatterings}}$$

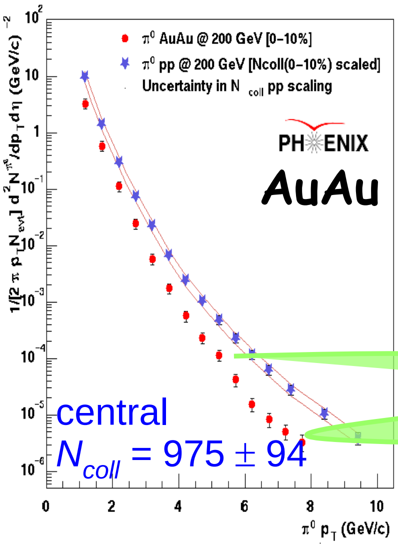
- R_{AA} for central Au+Au
  - Suppression strong and nearly constant up to 20 GeV/c
  - Consistent with $dN_g/dy \sim 1200$
- R_{AA} for central Cu+Cu
  - Also suppressed to high-p_T
  - Consistent with $dN_g/dy \sim 370$

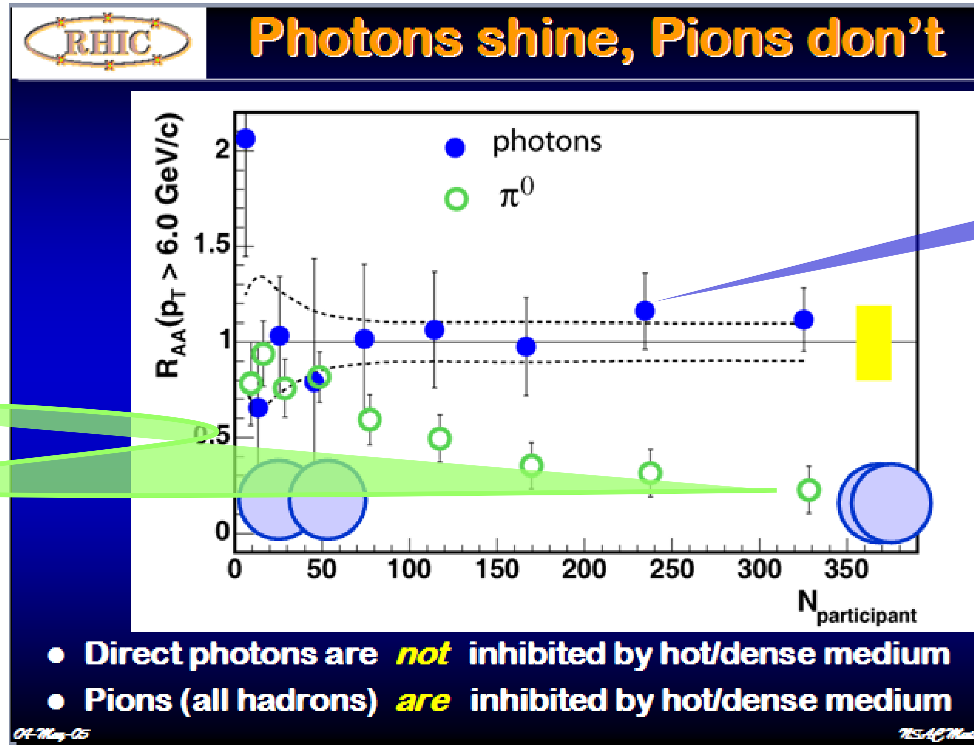




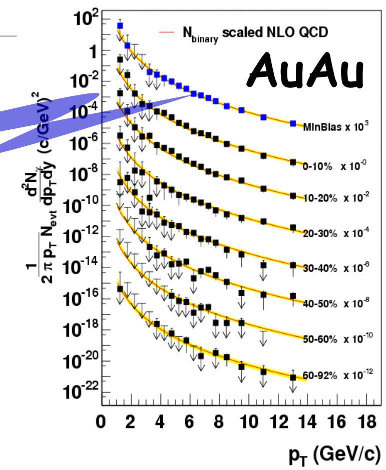
Direct Photons vs hadrons

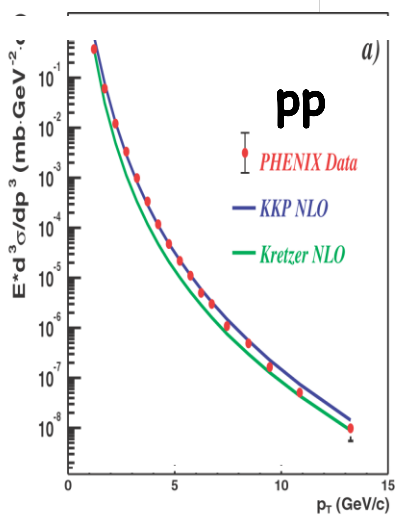
π^0

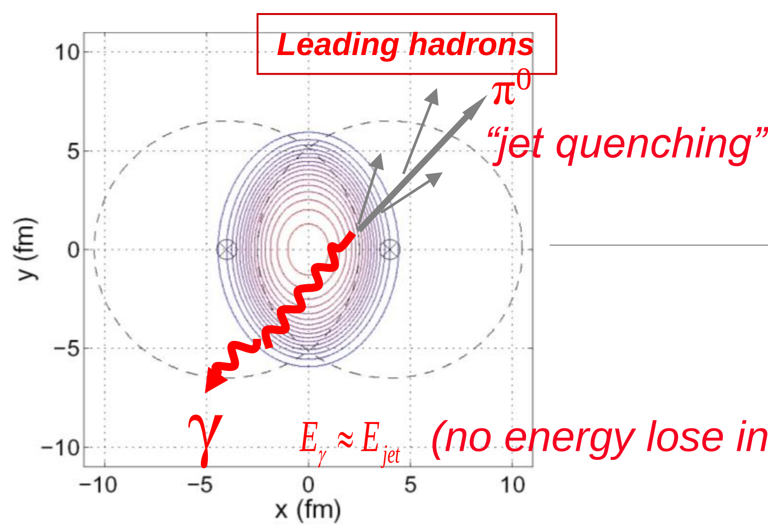




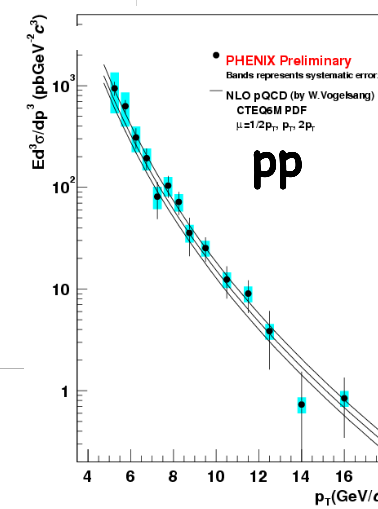
direct γ





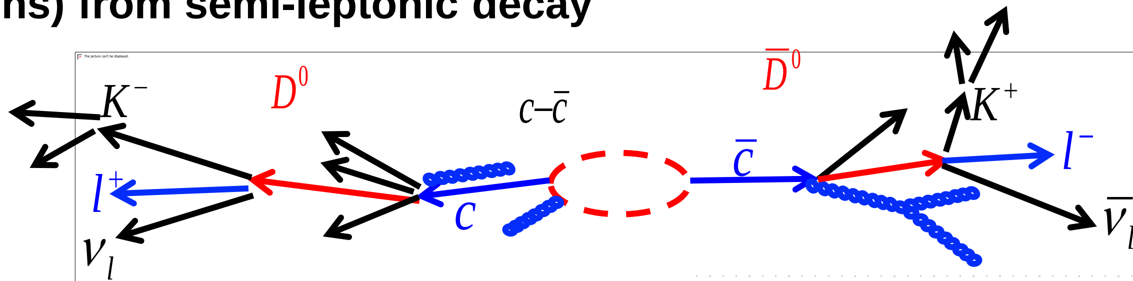


$E_\gamma \approx E_{jet}$ (no energy lose in QCD matter)

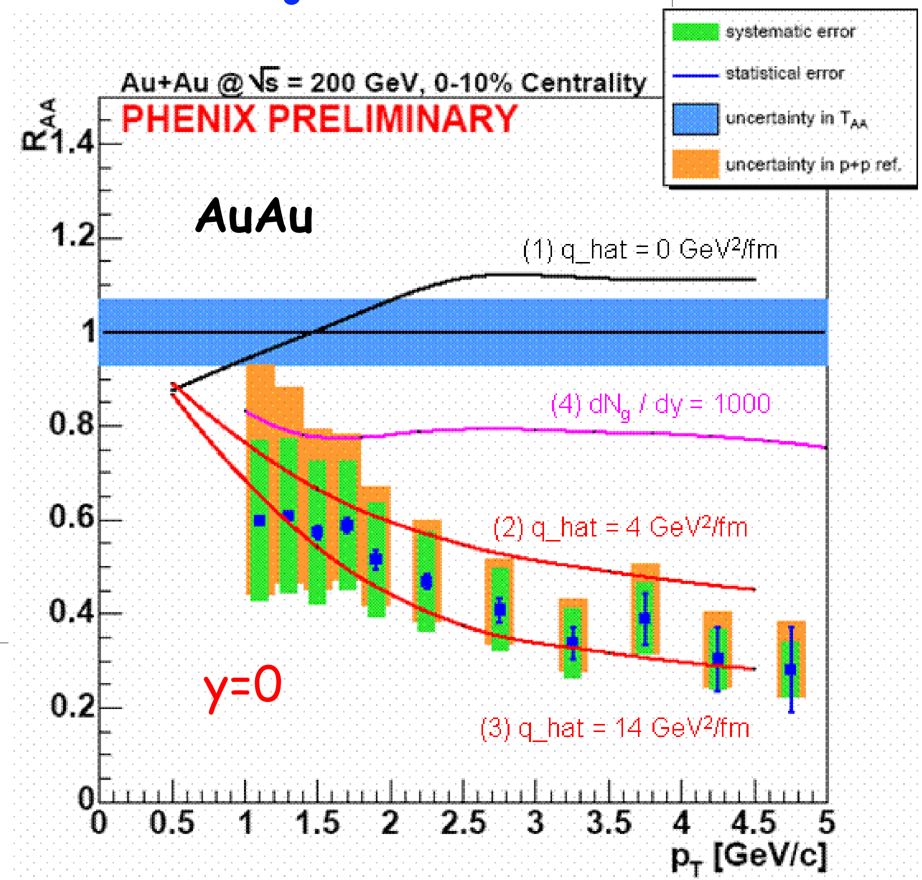


Heavy Quark Energy Loss

Heavy-quark energy loss can be studied by detecting single leptons (electrons or muons) from semi-leptonic decay



The data suggest large c-quark-medium cross section; evidence for strongly coupled QGP?



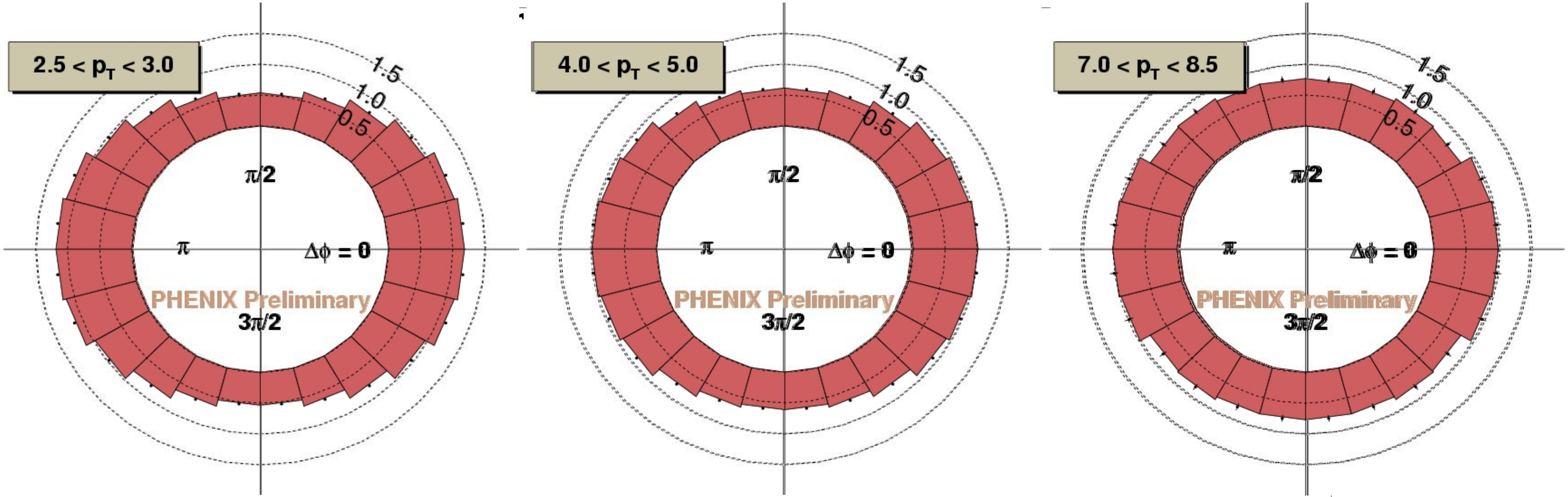
Theory curves at right:

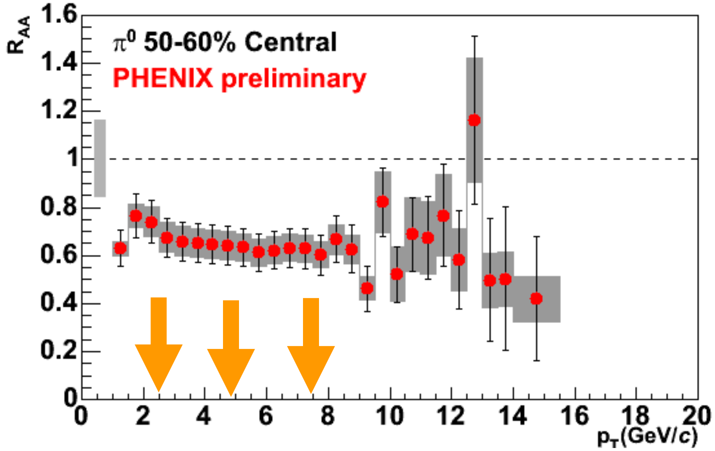
(1-3) from N. Armesto, *et al.*, PRD 71, 054027

(4) from M. Djordjevic, M. Gyullasy, S.Wicks, PRL 94, 112301

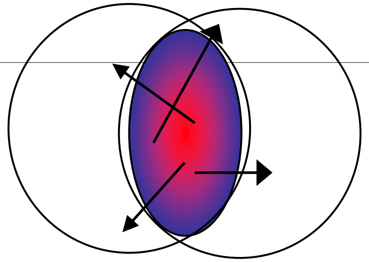
R_{AA} as function of angle wrt Reaction Plane

$R_{AA}(\Delta\phi, p_T)$ plotted in polar coords (folded to 2π) D. Winter: CIPANP 2006





For peripheral collisions;
more energy lose at $\Delta\phi=\pi/2$ than $\Delta\phi=0$



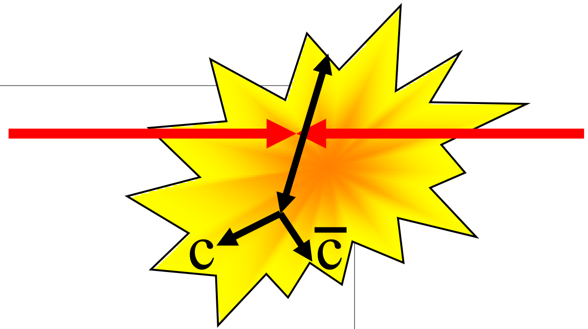
$$\Delta E \propto L^2$$

Summary: High P_T suppression

- Strong (R_{AA} ~ 0.2) high p_T suppression of π_0 up to 20 GeV for central Au+Au
- Absence of the high p_T suppression for d+Au, indicating high p_T suppression in central Au+Au is due to final-state effects
- As expected, no high p_T suppression for photons which does not lose energy in the QCD medium
- The data suggest large heavy-quark energy loss; evidence for strongly coupled QGP (sQGP) ?
- Reaction plane dependence for peripheral collisions; more energy lose at $\Delta\Phi=\pi/2$ (longer axis) than $\Delta\Phi=0$

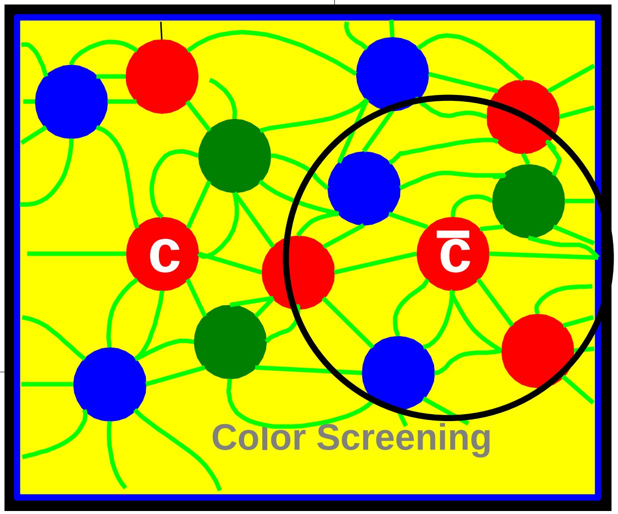
Quarkonia in the Medium

- Quarkonia Production
  hard scattering processes result in the production of heavy quark pairs that interact with the collision medium



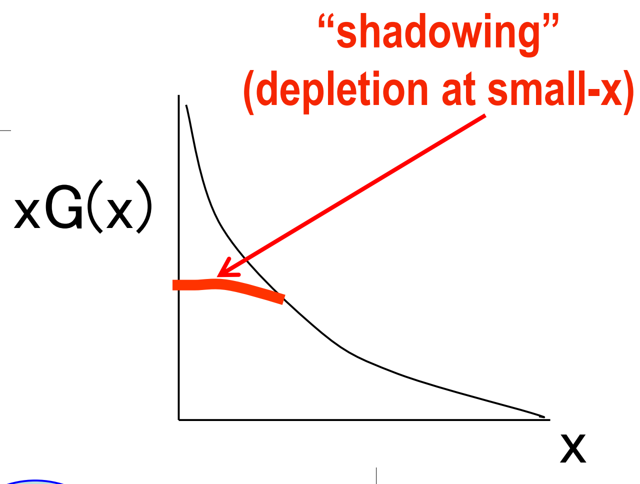
- In medium interactions convey information about the fundamental properties of the medium itself

- Competing effects are predicted for J/ψ production
  - J/ψ color screening:
    Suppression of J/ψ yield with increasing collision centrality
  - J/ψ recombination:
    Increased J/ψ yield with increasing collision centrality
    Narrowed J/ψ rapidity and p_T distributions with increasing centrality
  - Shadowing, Heavy quark energy loss, Normal nuclear absorption, etc



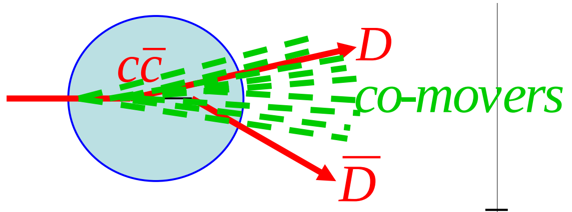
Studying J/Ψ suppression

Sensitive to **initial state effects** such as:
shadowing (depletion of low-momentum partons in nuclei) and anti-shadowing



and **final state effects** such as:

- normal nuclear absorption
- interaction with comovers
- recombination of charm quarks.



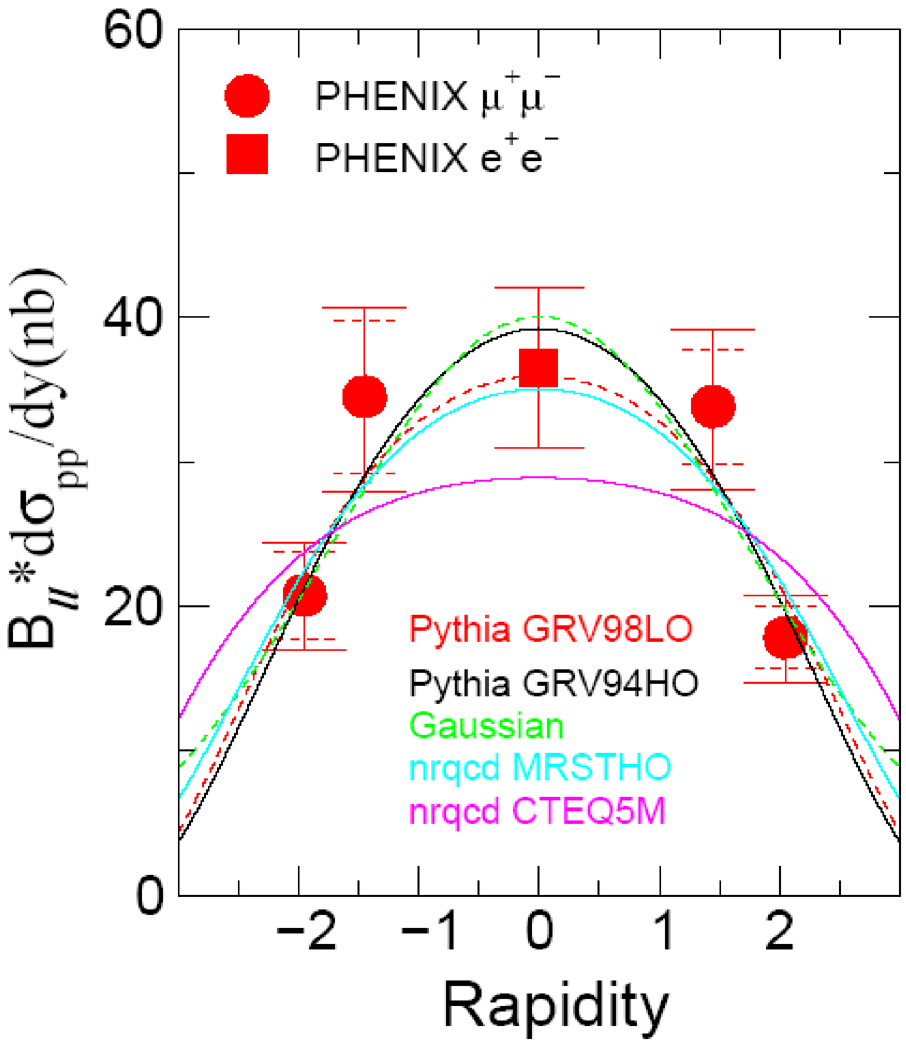
Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)

Studying J/Ψ suppression requires

- good p+p reference for baseline
- test experiment using pA (or dA) to control cold nuclear matter effects
- correct extrapolation from dA to AA

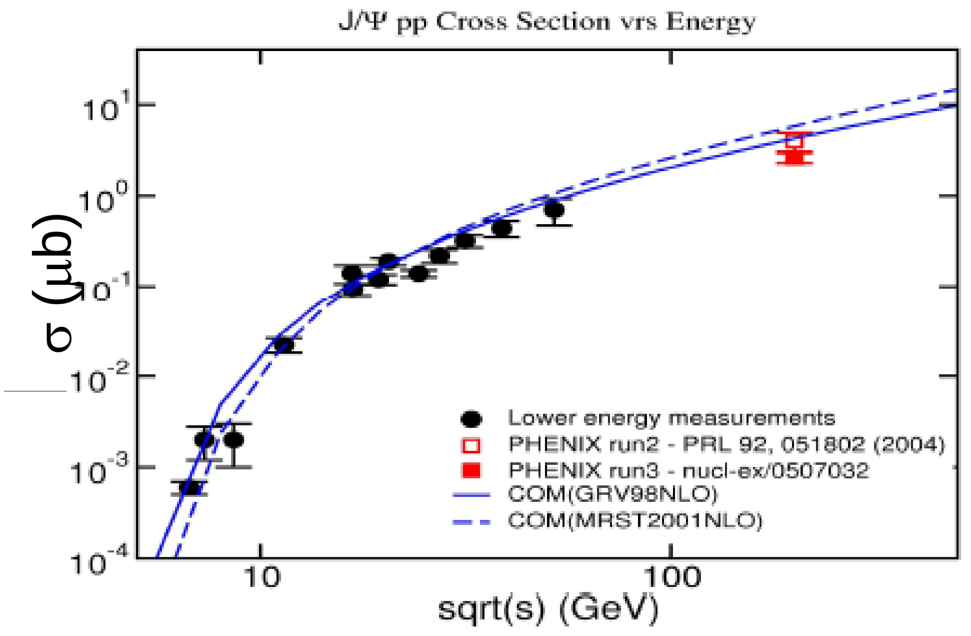
J/Ψ yield for P+P collisions

PHENIX PRL96 (2006) 012304



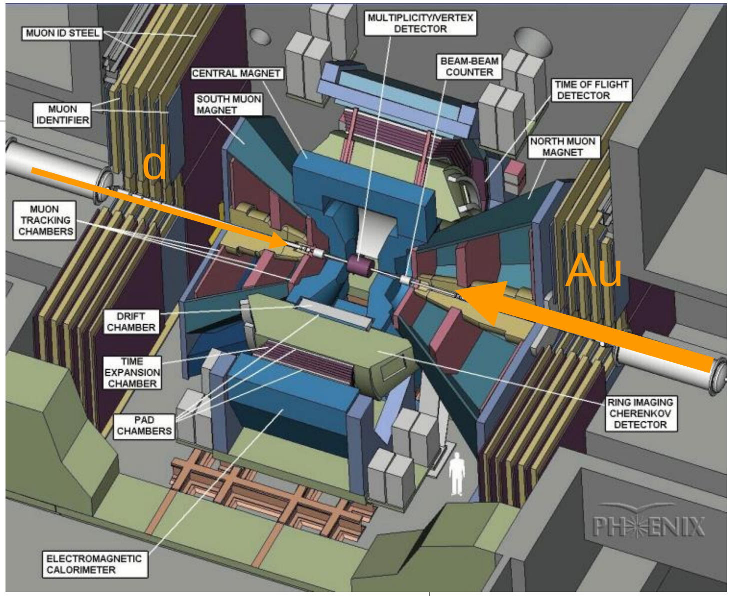
$\sigma(pp \rightarrow J/\Psi) = 2.61 \pm 0.20 \pm 0.26 \mu b$

Lineshape obtained from PYTHIA using different parton distribution functions.



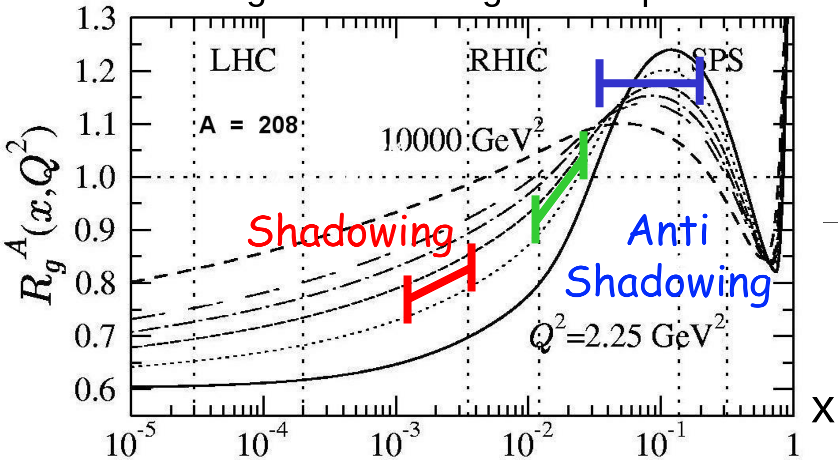
Initial State Effects (Shadowing)

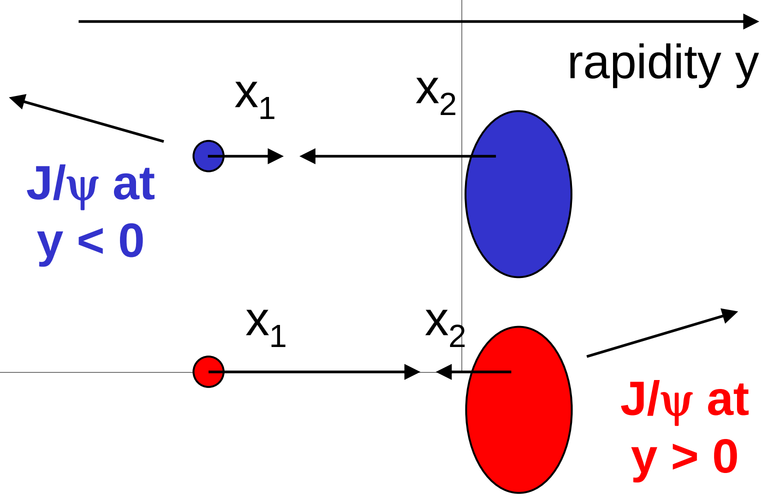
- In PHENIX, J/ψ mostly produced by gluon fusion, so sensitive to gluon pdf (Shadowing, anti-shadowing)
- Three rapidity ranges probe different momentum fraction of Au partons
  - South ($y < -1.2$) : large x_2 (in gold) ~ 0.090
  - Central ($y \sim 0$) : intermediate x_2 ~ 0.020
  - North ($y > 1.2$) : small x_2 (in gold) ~ 0.003



An example of gluon shadowing prediction

gluons in Pb / gluons in p





Eskola, Kolhinen, Vogt
NPA696 (2001) 729

R_{dAu} as a function of rapidity

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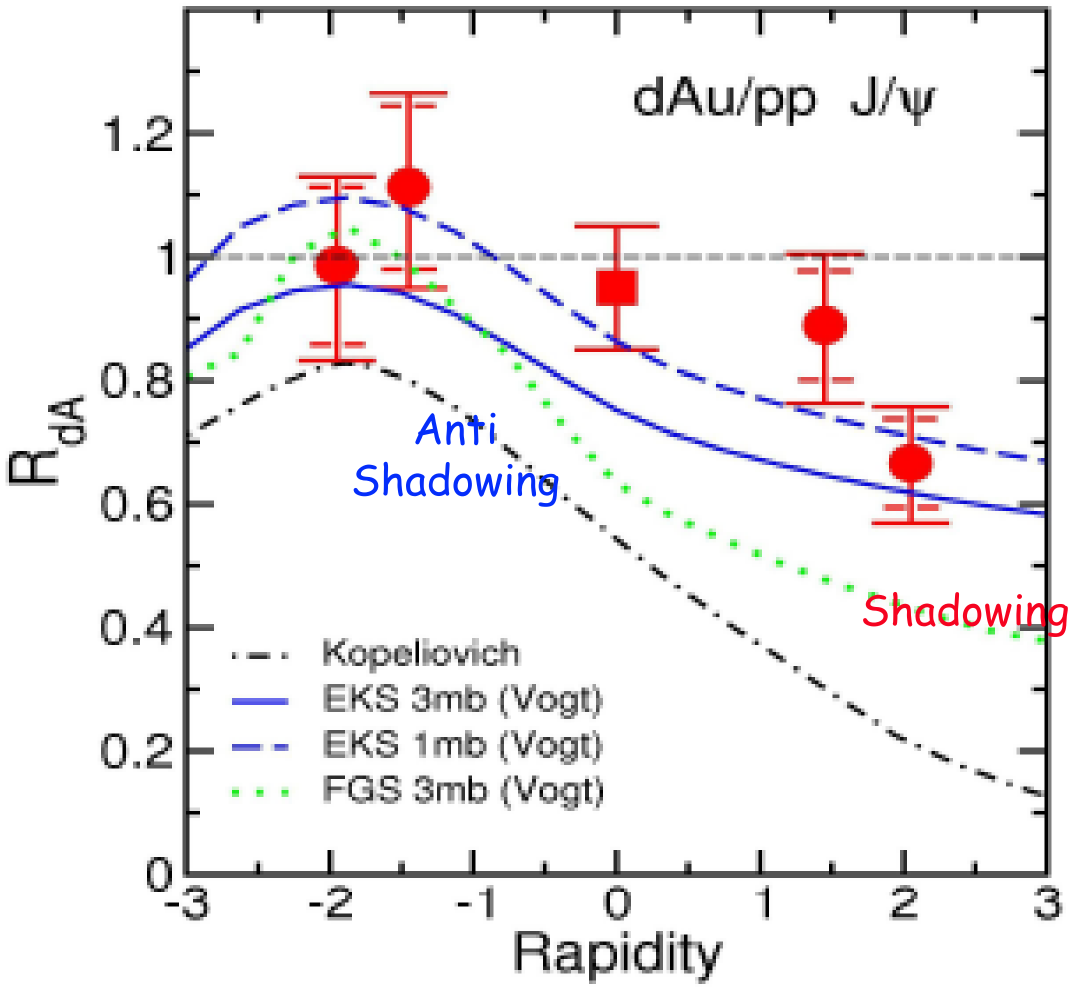


y<0 (deuteron side: S)
large x_{Au} (~0.09)
anti-shadowing region

y>0 (gold side: N)
small x_{Au} (~0.003)
shadowing region

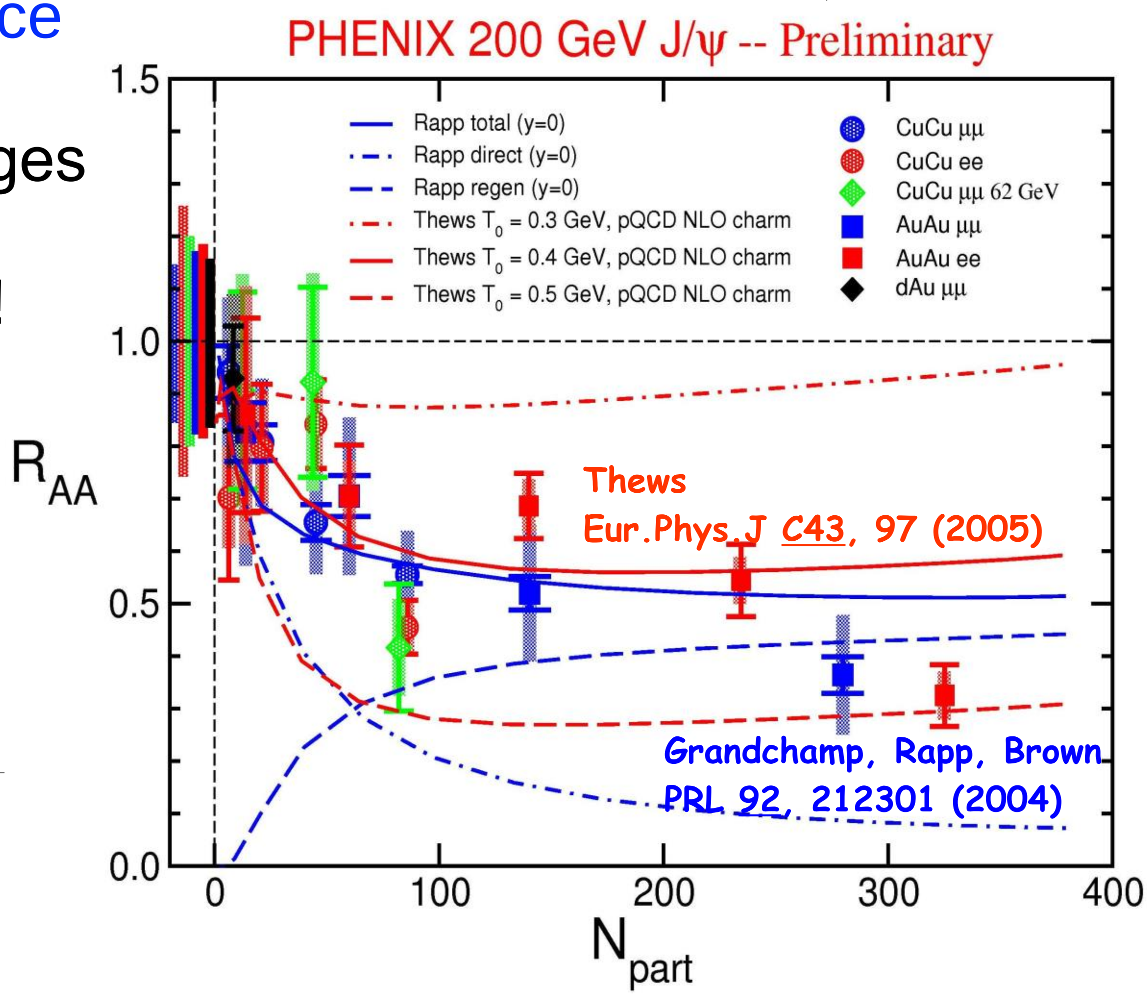
Compared to various parameterization for the nuclear shadowing + a nuclear absorption cross-section.

PHENIX, PRL96 (2006) 012304
Klein,Vogt, PRL91 (2003) 142301
Kopeliovich, NPA696 (2001) 669

R_{dA} vs y is consistent with EKS shadowing and a weak absorption (1-3mb)

J/Ψ Suppression (R_{AA}) and Models

In addition to the color screening, models with recombination/coalescence of single charm quarks forming J/Ψ's at later stages match the observed suppression much better!



Alternative explanations:

Sequential screening of the higher mass resonanses down to J/ψ, with J/ψ itself still not dissolved (recent lattice calculations give $T_{J/\psi}>2T_C$)

Karsch, Kharzeev, Satz, Phys. Lett. B637:75

Sequential Screening and Feed Down?

Sequential dissolution of the higher-mass resonances that feed-down to the J/ψ

Lattice calculations indicates that the charmonium ground state J/Ψ can survive in QGP up to $1.5T_C$ or more, while the excited states (χ_c, Ψ') are dissociated just above T_C

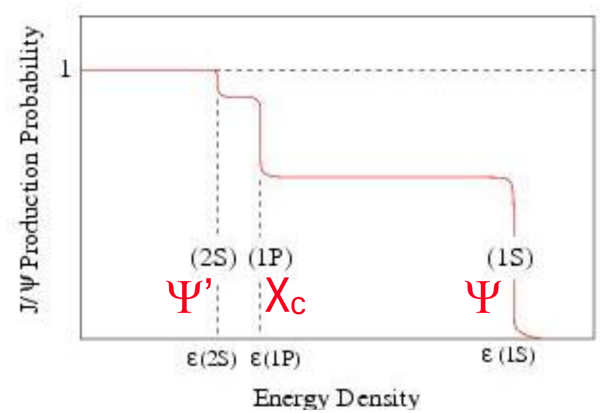
40% of J/Ψ come from Ψ' and χ_c decays

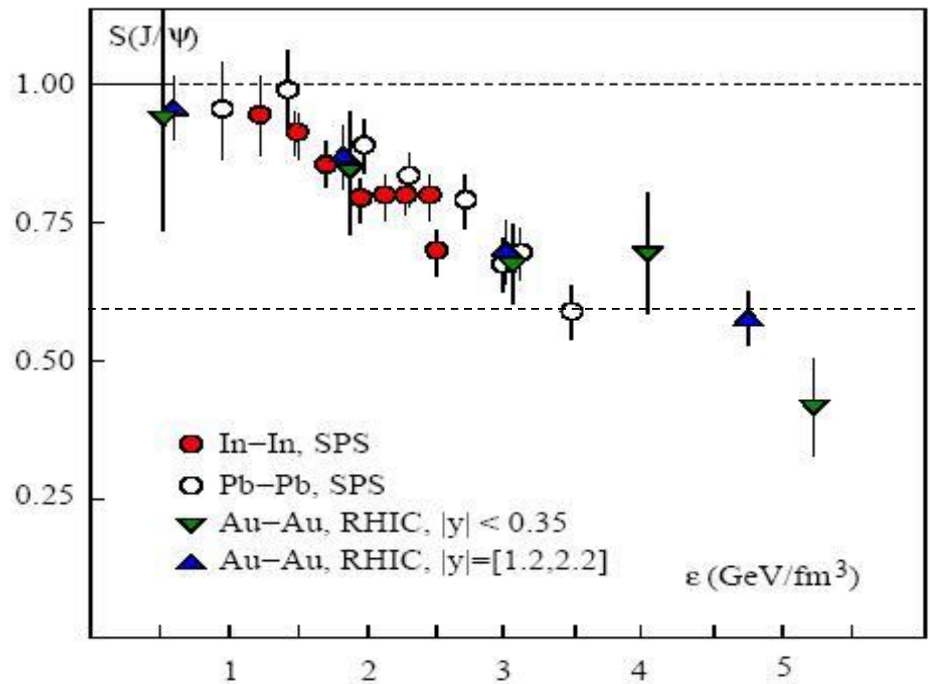
$J/\Psi \sim 0.6\ J/\Psi + 0.3\chi_c + 0.1\Psi'$

HERA-B exp. Phys. Lett. B 561(2003)

J/Ψ suppression pattern gives information of melting Ψ' and (or) χ_c ;

- $T_{diss}(\chi_c, \Psi') \sim T_c$ (dissolved)
- $T_{diss}(J/\Psi) \sim 2T_c$ (un-dissolved)
- $S(J/\Psi) = 0.6 + 0.4 * S(\chi_c, \Psi')$





Karsch, Kharzeev & Satz: PLB637(2006)75

Outlook: J/Ψ Suppression

Near future:

Final Run4 Au+Au results should be available for QM2006, with better control over systematic errors, and normalized to Run5 p+p.
Allow better measurements of R_{AA} vs rapidity and p_t

Future RHIC runs (PHENIX Beam Proposal):

Run7: high luminosity Au+Au (200GeV) and p+p
Run8: high luminosity d+Au (200GeV) and p+p
Run9: energy scan with Au+Au

Future measurements:

Need accurate open charm measurement (for coalescence models).
Ψ' and χ_c and Y would help too.
Need RHIC II and detector upgrades

Physics for PHENIX Upgrades

The capability of the following physics can be enhanced by detector upgrades

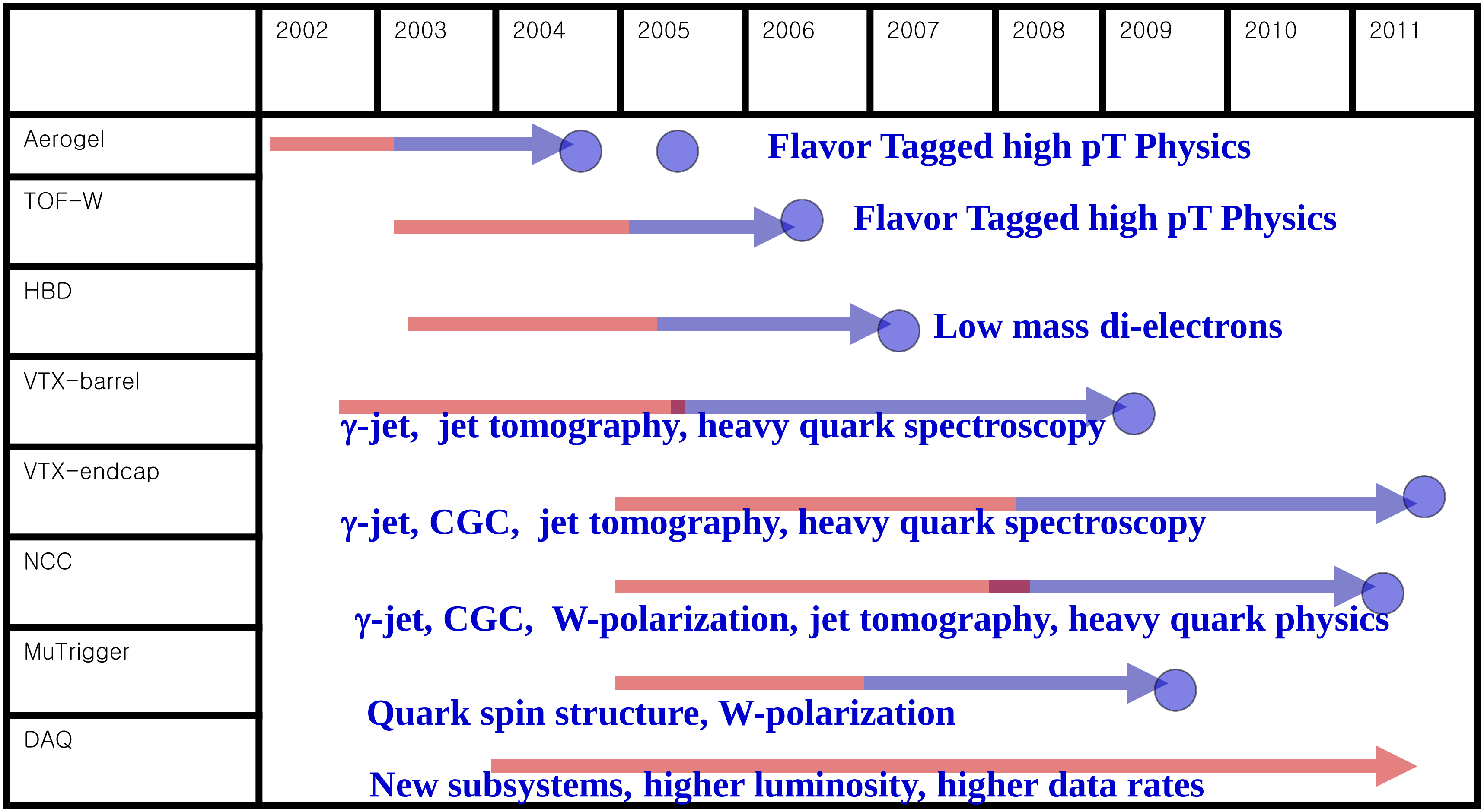
- High T QCD (AA, pA, and pp):
  - Electromagnetic radiation (e^+e^- pair continuum)
  - Heavy flavor (c- and b-production)
  - Jet tomography (high p_T PID, jet-jet and γ-jet)
  - Quarkonium (J/ψ, ψ' , χ_c and $\Upsilon(1s)$,$\Upsilon(2s)$,$\Upsilon(3s)$)

requires highest AA luminosity

- Spin structure of the nucleon:
  - Gluon spin structure $\Delta G/G$ (heavy flavor γ-jet correlations)
  - Quark spin structure $\Delta q/q$ (W-production for flavor decomposition)

- Low x phenomena
  - gluon saturation in nuclei (Color Glass Condensate)

PHENIX Upgrades Schedule



R&D Phase **Construction Phase** **Ready for Data**

AGEL + TOF-W

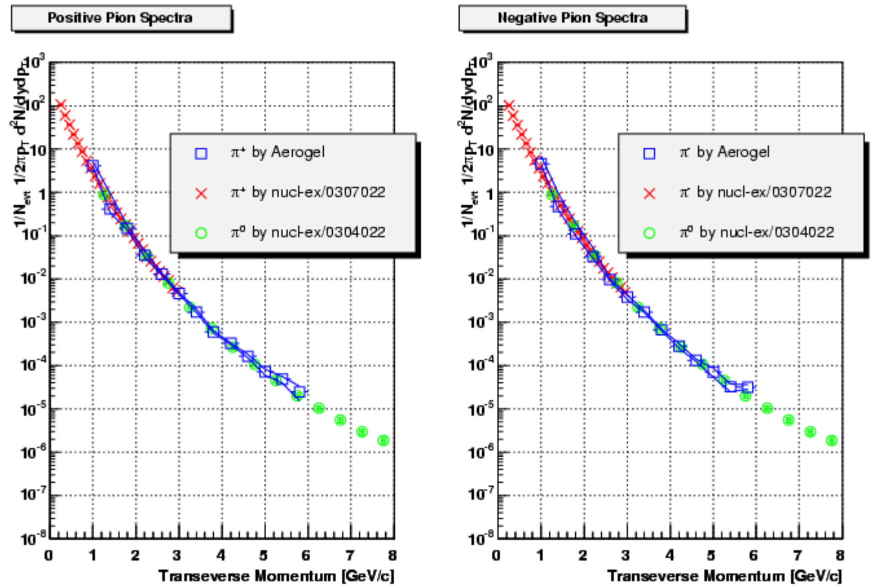
- “An aerogel and time-of-flight system to provide complete π/K/p separation for momenta up to ~10 GeV/c.”

- Project well underway
  - Aerogel completely installed

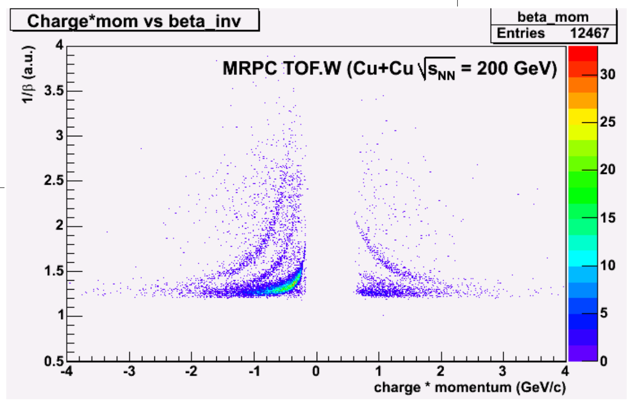
    First physics results now available
  - TOF-W (Multi-Resistive Plate Chamber)

    Prototypes tested in Run-5

    System will be installed in current shutdown

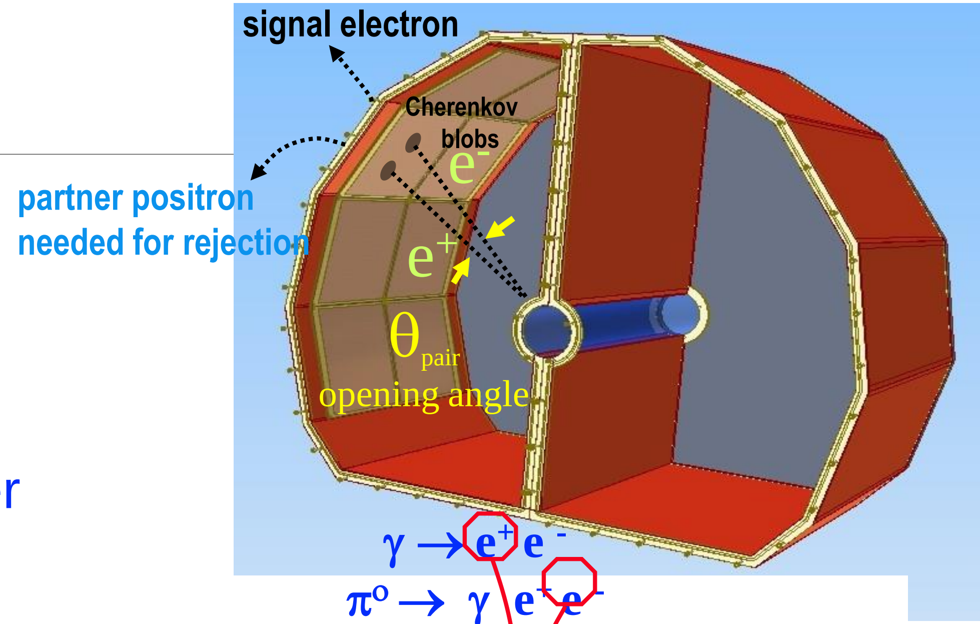


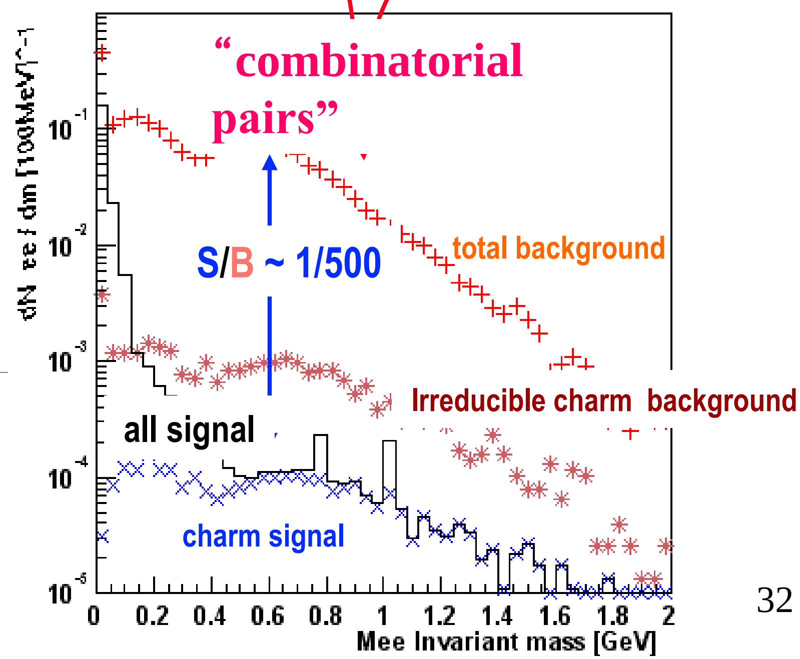
PHENIX Work in Progress



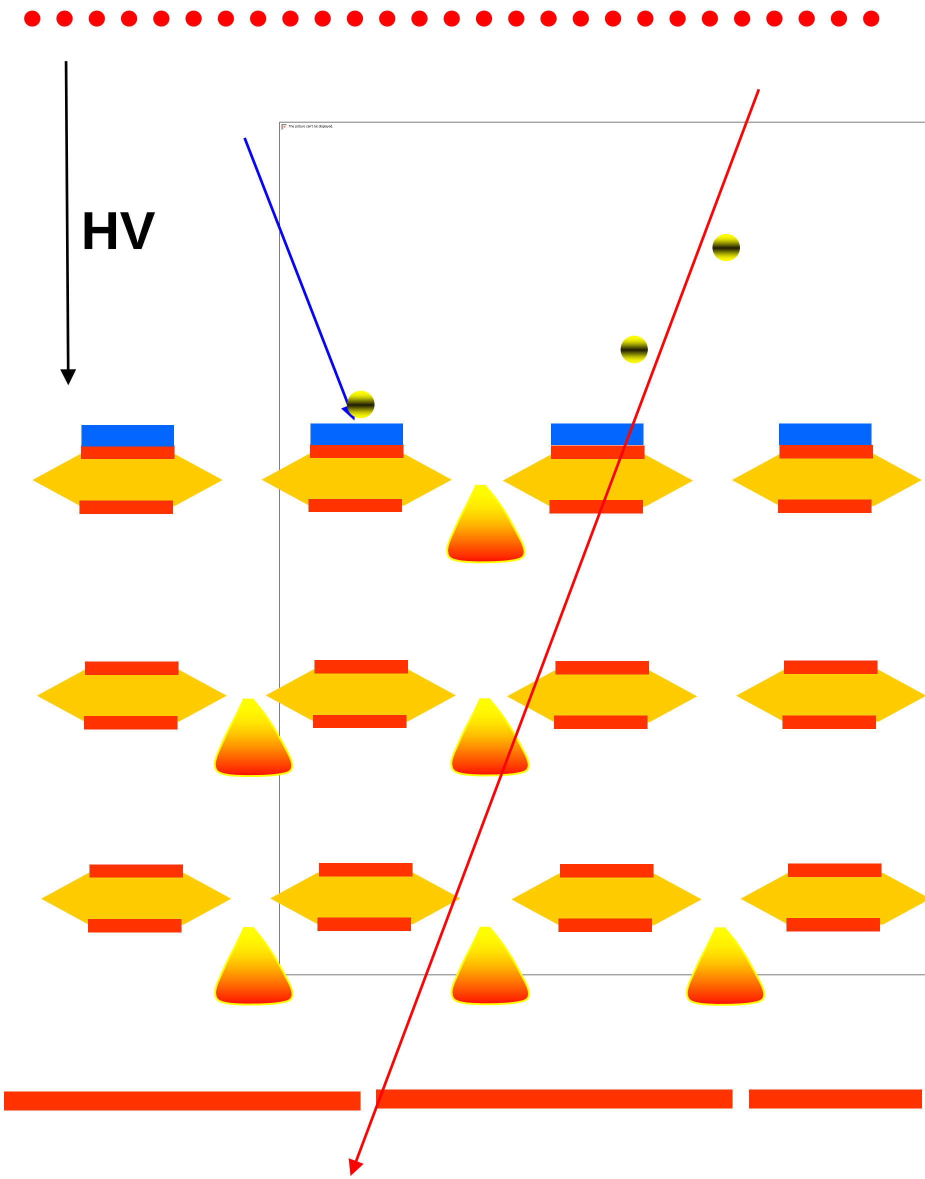
Hadron-Blind Detector (HBD)

- "HBD to detect and track electrons near the vertex."
- Dalitz rejection via opening angle
  - Identify electrons in field free region
  - Veto signal electrons with partner
- HBD: a novel detector concept:
  - CF4 Cherenkov detector
  - 50 cm radiator length
  - CsI reflective photocathode
  - Triple GEM with pad readout
- Construction/installation 2005/2006





The concept (HBD)



➢ Take a GEM (Gas Electron Mult.)

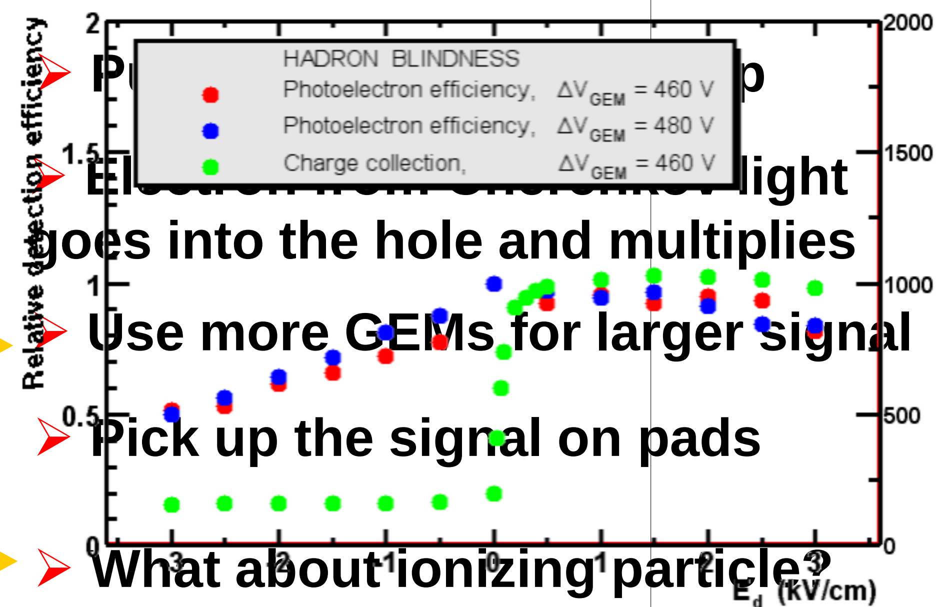
➢ Pu… p

➢ El… light goes into the hole and multiplies

➢ Use more GEMs for larger signal

➢ Pick up the signal on pads

➢ What about ionizing particle?

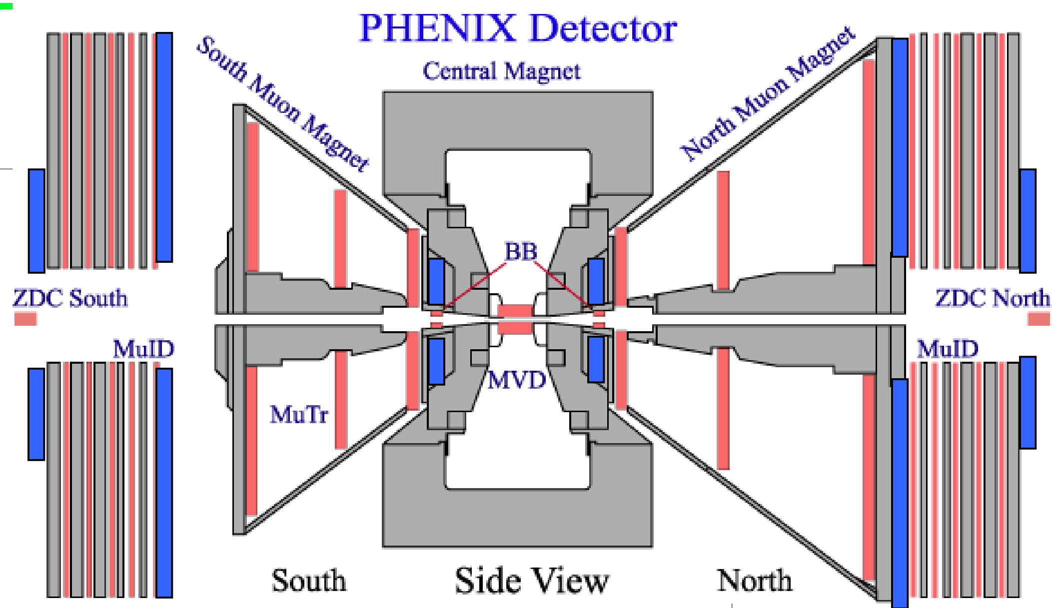


➢ Mesh with a reverse bias drifts ionization away from multiplication area

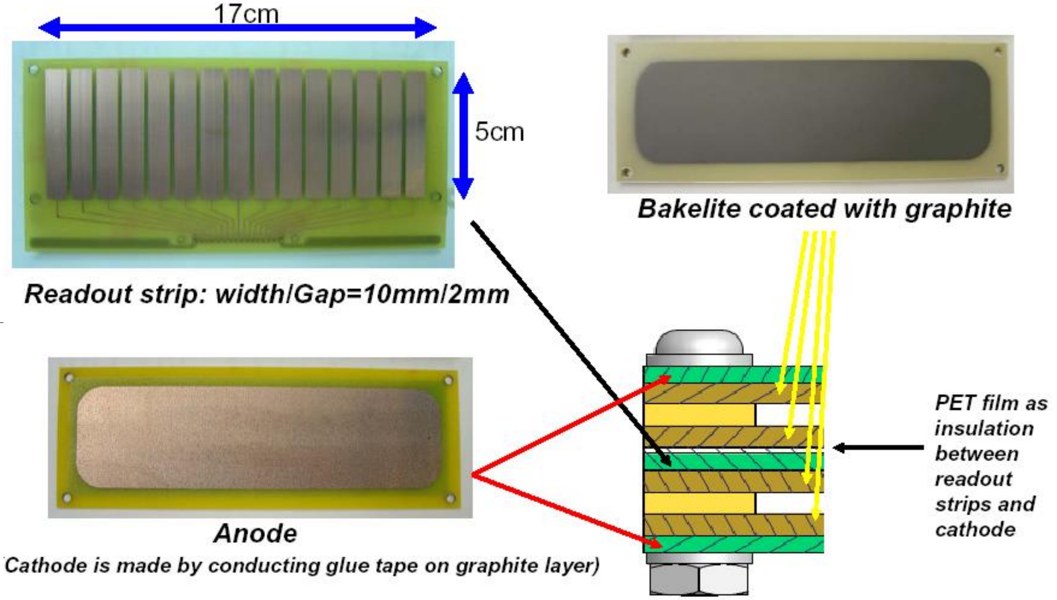
➢ **Sensitive to UV and blind to traversing ionizing particles**

Muon Trigger Upgrade

- "A muon trigger upgrade to preserve sensitivity at the highest projected RHIC luminosities."
- RHIC I Luminosities (2009-12):
  - Resistive Plate Chamber technology chosen by PHENIX
    - Cheap – wide coverage possible
    - 3-dim space point enhances pattern recognition
  - Two small prototypes successfully tested in Run05
- RHIC II Luminosities (2012+):
  - Fast read-out of muTr FEE

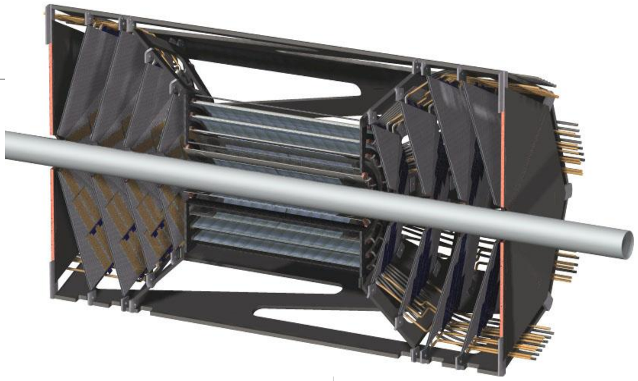


Trigger RPC Locations



Silicon Tracker

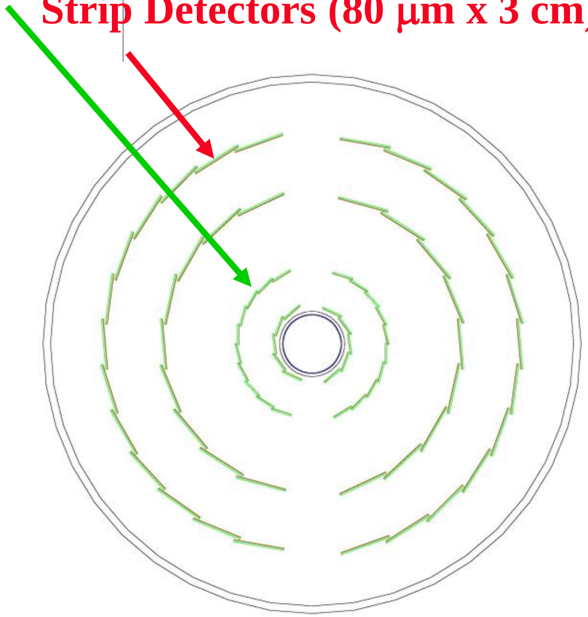
- "A vertex detector to detect displaced vertices from the decay of mesons containing charm or bottom quarks."

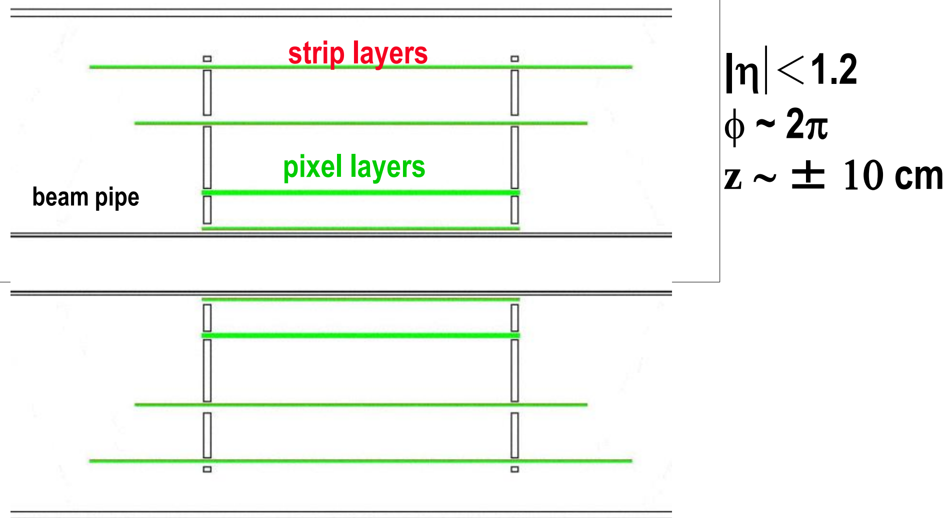


- Specifications (Barrel):
  - Large acceptance ($\Delta\phi \sim 2\pi$ and $|\eta| < 1.2$)
  - Displaced vertex measurement $\sigma < 40\ \mu m$
  - Charged particle tracking $\sigma_p/p \sim 5\%$ at high pT
  - Must work for both of AA and pp collisions.

Hybrid Pixel Detectors (50 µm x 425 µm) at R ~ 2.5 & 5 cm

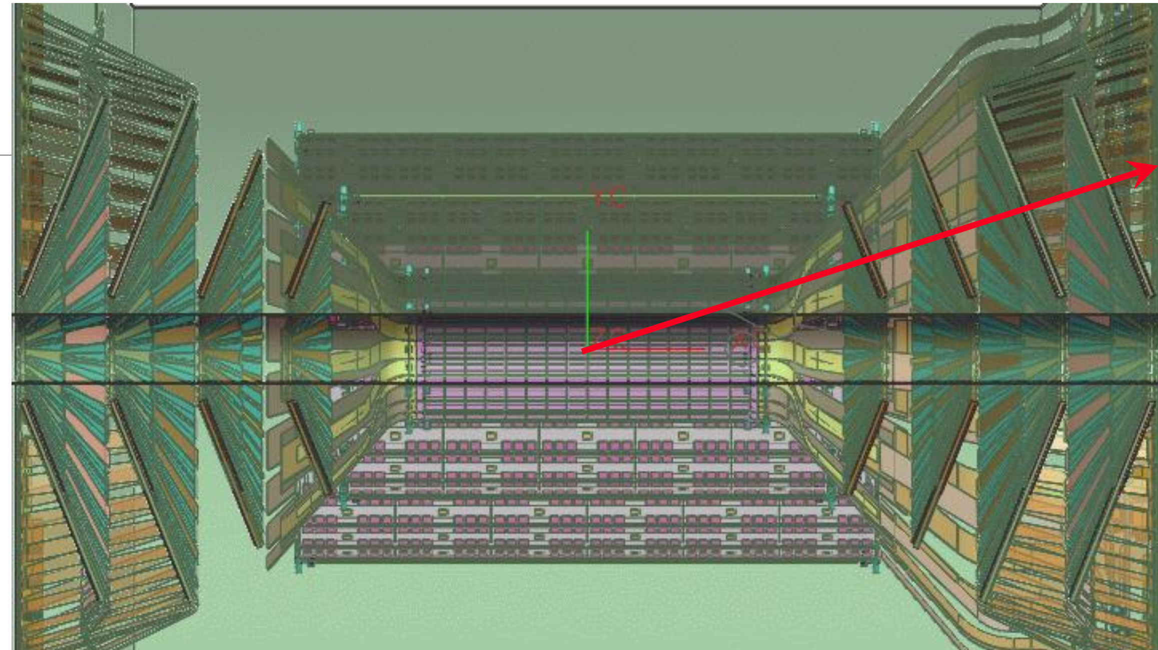
Strip Detectors (80 µm x 3 cm) at R ~ 10 & 14 cm

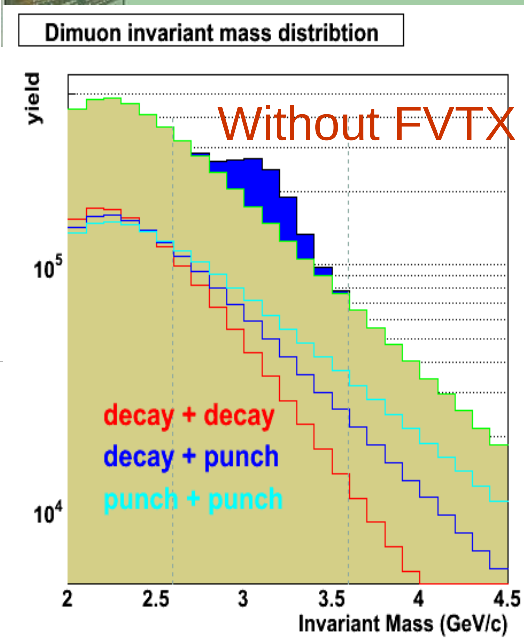


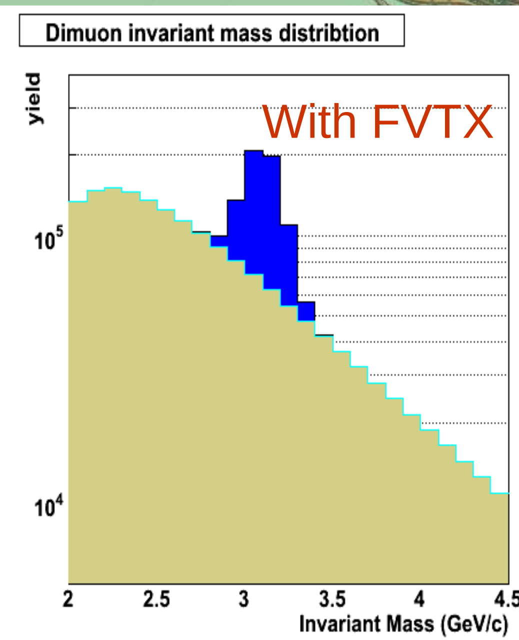


Forward Vertexing

- Baseline (Endcaps):
  - 4 layers
  - Tilted to make tracks ~normal-incidence
  - 50 μm radial pitch, 7.5° phi segmentation (2 – 13 mm)
  - Maximize z and r extent to give good resolution
  - 2*0.86M channels
- Scope
  - Recently favorably reviewed for FY08 start
  - Bootstrapped by LANL LDRD funds to construct one octant prototype







Nosecone Calorimeter (NCC)

- "A forward calorimeter to provide photon+jet studies over a wide kinematic range."

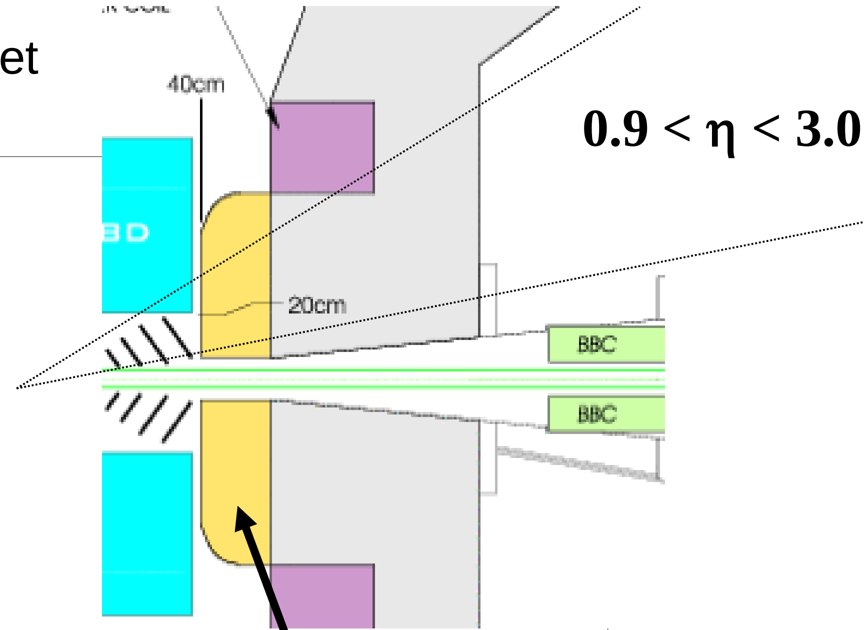
- Forward physics with PHENIX
  - Large acceptance calorimeter
  - EM calorimeter ~40 X/X_o
  - hadronic section (1.6 l/l_0)
  - Tungsten with Silicon readout

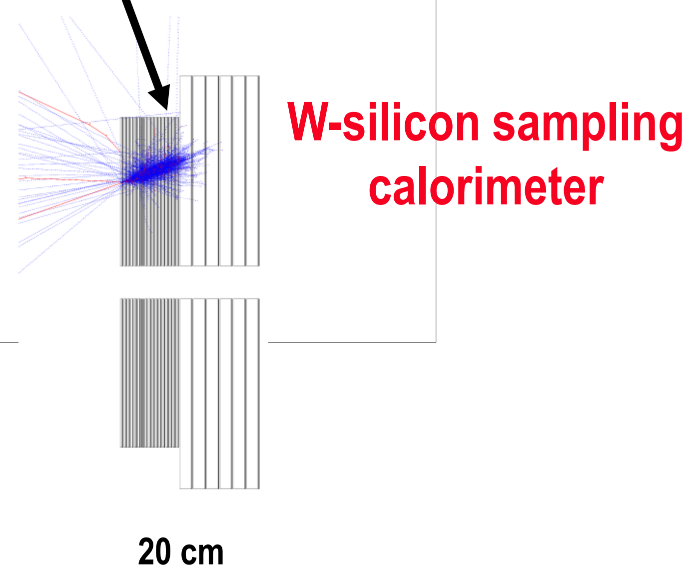
- Extended physics reach with NCC
  - Extended A-A program

    high p_T phenomena: π^0 and γ-jet

    $\chi_c \rightarrow J/\psi + \gamma$
  - Small x-physics in p-A

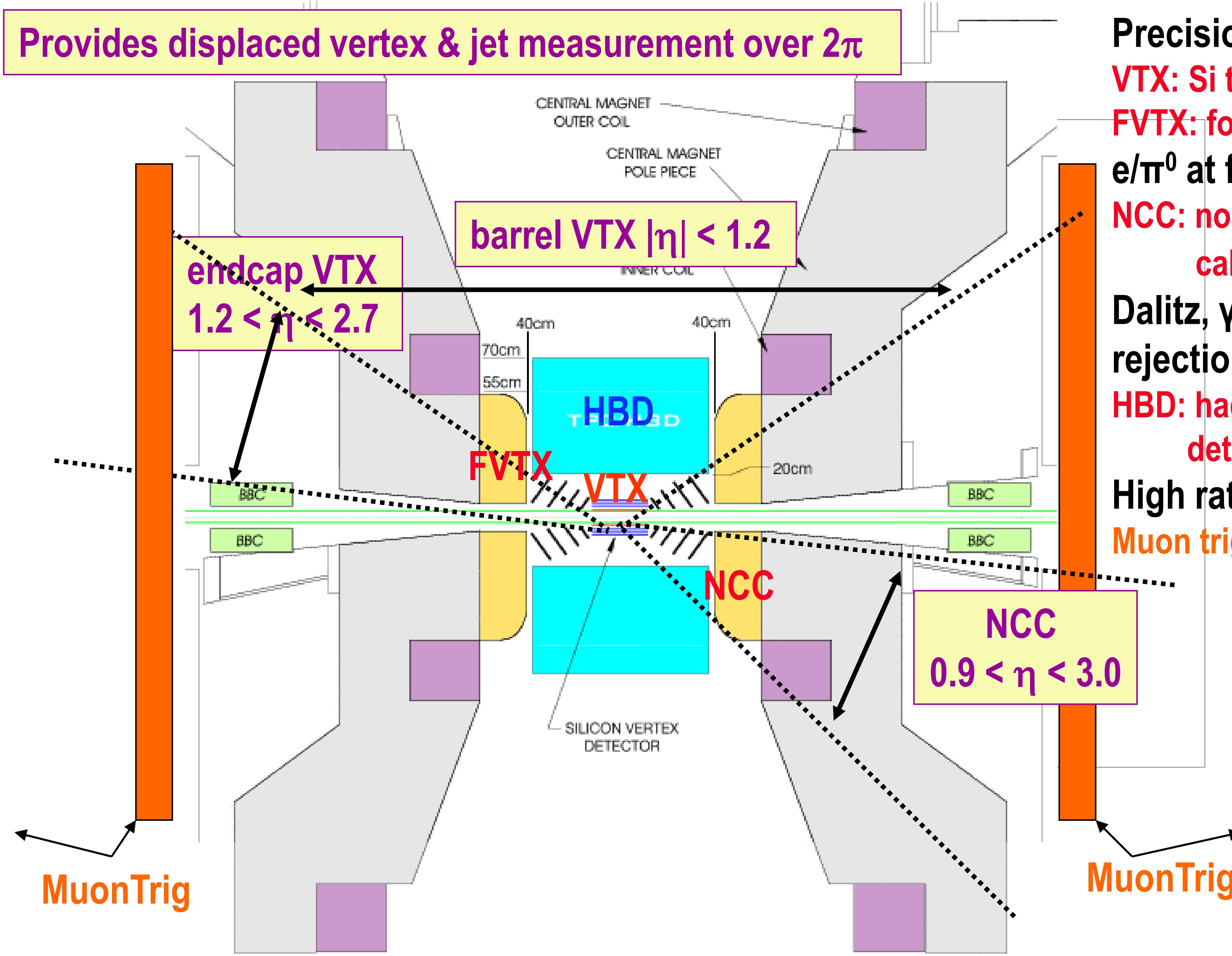
- Scope
  - Recently favorably reviewed for FY08 start
  - New groups (Moscow State, Czech groups, Korean groups) join R&D
  - Construction FY08 – FY10





PHENIX Upgrades Project

Provides displaced vertex & jet measurement over 2π



Precision vertex:

VTX: Si tracker

FVTX: forward Si

e/π^0 at forward y:

NCC: nose cone calorimeter

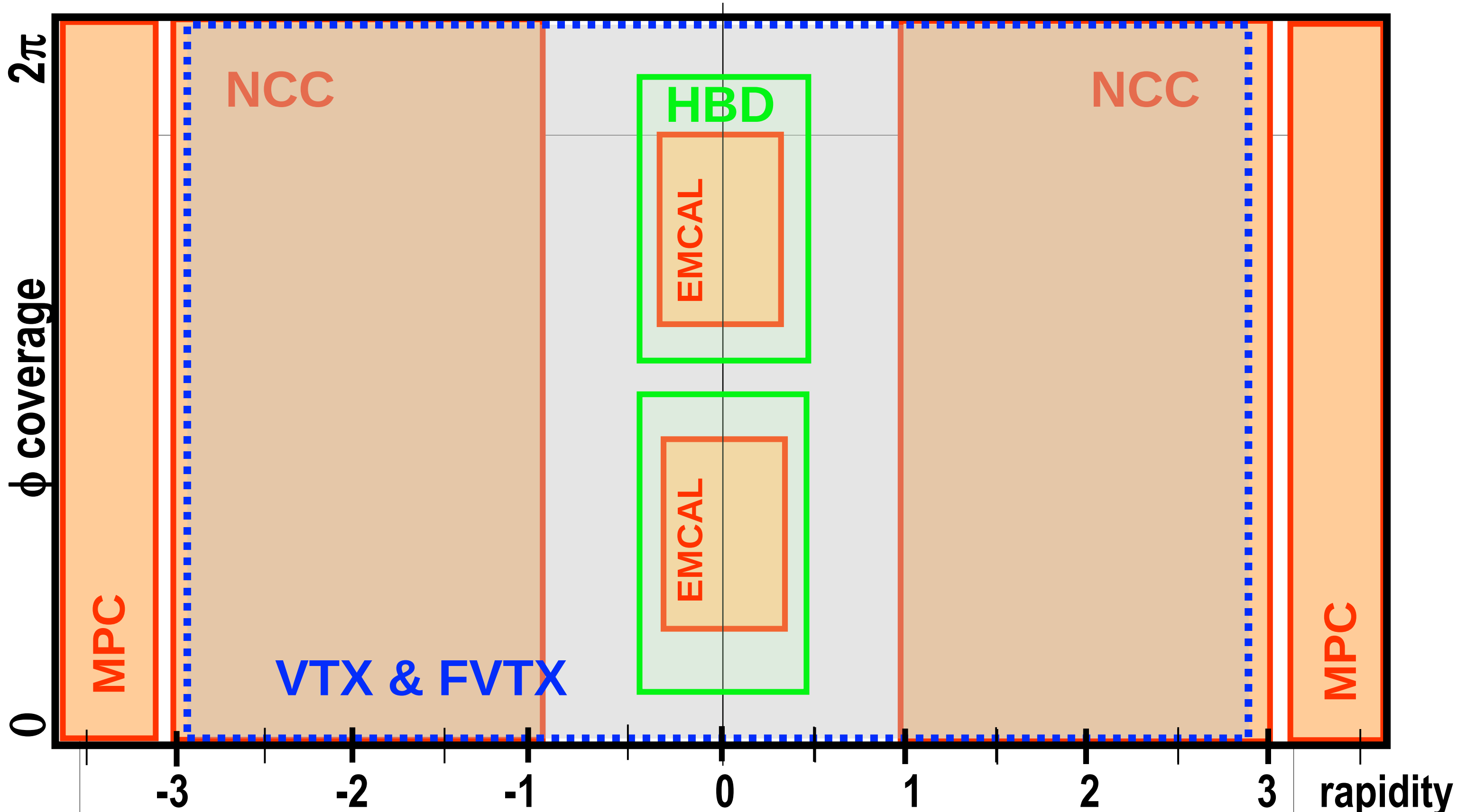
Dalitz, γ-conversion rejection:

HBD: hadron blind detector

High rate trigger:

Muon trigger

Future Acceptance



(i) π^0 and direct γ with combination of all electromagnetic calorimeters

(ii) heavy flavor with precision vertex tracking with silicon detectors

combine (i) & (ii) for jet tomography with γ-jet

(iii) low mass dilepton measurements with HBD + PHENIX central arms

PHENIX view of RHIC Upgrade

Near term: Base line | **Medium term: first upgrades** | **Long term: full detector and RHIC upgrades**

2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

Analysis of data on tape

Near term detector upgrades of PHENIX
TOF-W, HBD, VTX , μTrig

Commissioning

40x design luminosity for Au-Au via electron cooling

PHENIX upgrades

Long term upgrades
FVTX, NCC, …

RHIC luminosity upgrade

RHIC baseline program

- Au+Au ~ 250 μb^{-1} at 200 GeV
- Species scan at 200 GeV
- Au+Au energy scan
- Polarized protons $\geq$ 150 nb^{-1}

Extended program with 1st detector upgrades:

- Au+Au ~ 1.5 nb^{-1} at 200 GeV
- Polarized p at 500 GeV
- (start p+A program)

Full utilization of RHIC opportunities:

Studies of QGP with rare probes:
jet tomography, open flavor,
J/ψ, ψ', χc, $\Upsilon(1s)$, $\Upsilon(2s)$, $\Upsilon(3s)$

Complete spin physics program
p+A physics