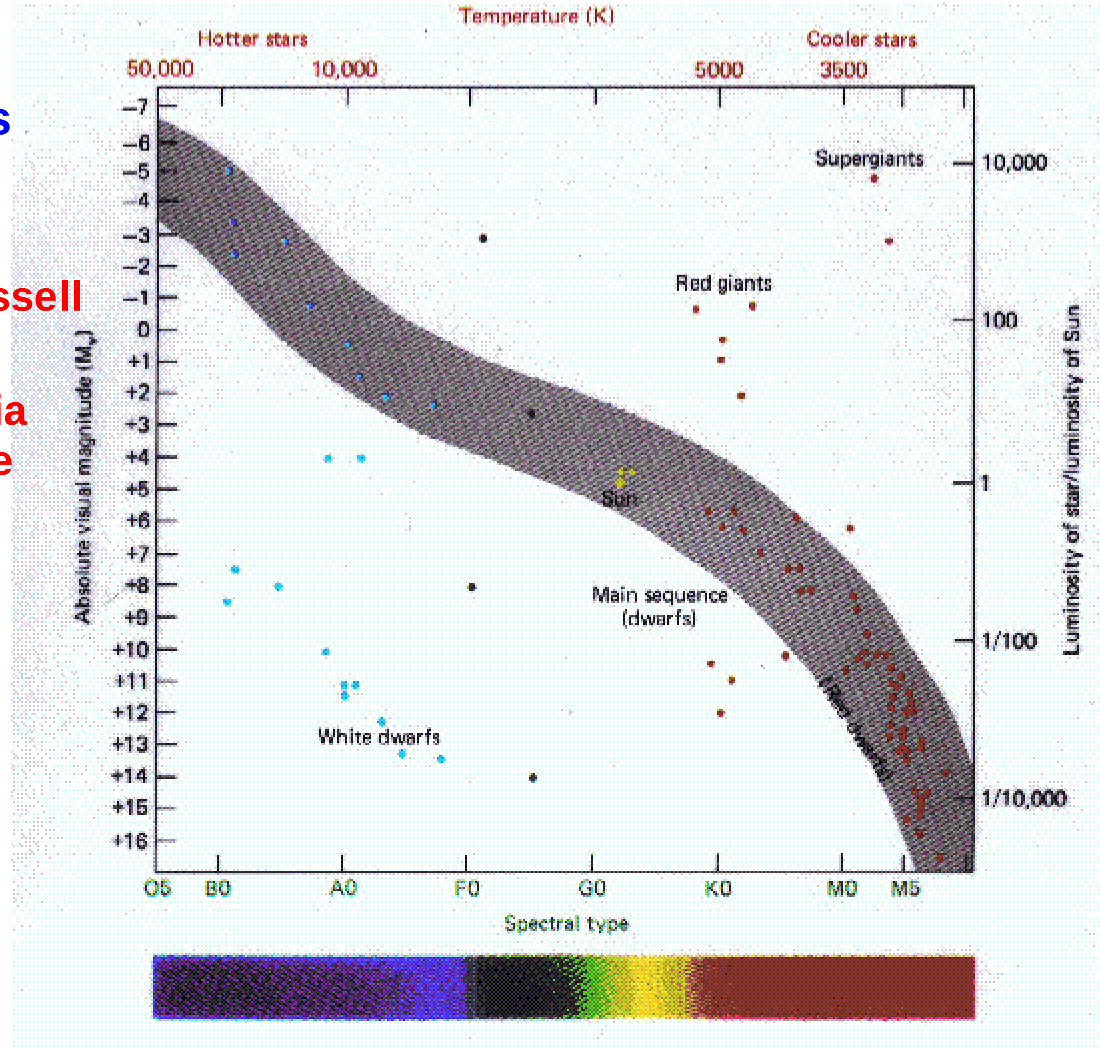
The Charm of PHENIX

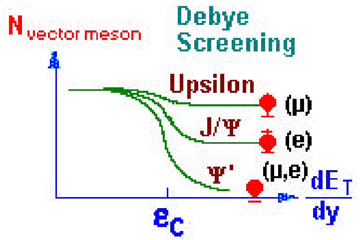
W.A. Zajc
Columbia University

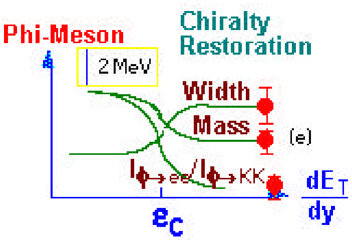
PHENIX

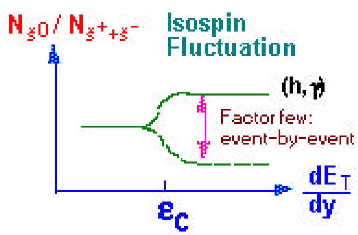
Studying Complex Phenomena

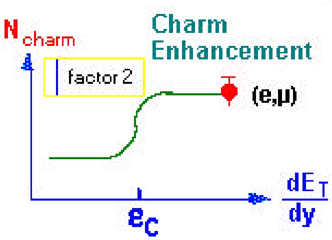
- **Ample historical evidence for categorizing complex physics through correlation of observables**
  - For example, Hertzprung-Russell in astronomy
  - PHENIX will approach QGP via as many channels as possible

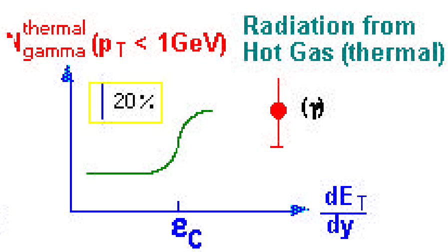












PHENIX Approach to QGP Detection

1. Deconfinement

R(Υ) ~ 0.13 fm < R(J/Ψ) ~ 0.29 fm < R(Υ ') ~ 0.56 fm

➪ Electrons, Muons

2. Chiral Symmetry Restoration

Mass, width, branching ratio of Φ to e^+e^-, K^+K^- with δM < 5 Mev:

➪ Electrons, Muons, Charged Hadrons

Baryon susceptibility, color fluctuations, anti-baryon production:

➪ Charged hadrons

DCC's, Isospin fluctuations:

➪ Photons, Charged Hadrons

3. Thermal Radiation of Hot Gas

Prompt γ, Prompt γ* to e^+e^-, $\mu^+\mu^-$:

➪ Photons, Electrons, Muons

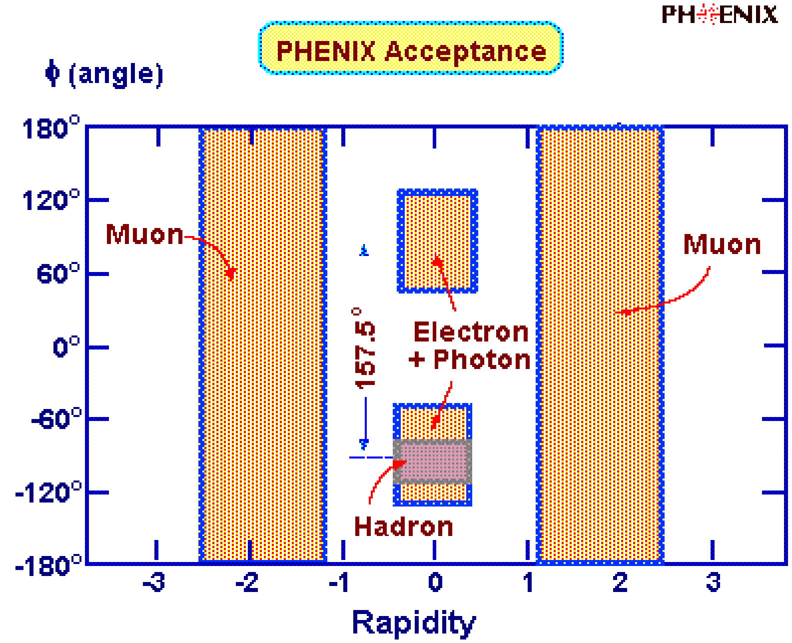
4. Strangeness and Charm Production

Production of K^+, K^- mesons:

➪ Hadrons

Production of Φ, J/Ψ, D mesons:

➪ Electrons, Muons



5. Jet Quenching

High pT jet via leading particle spectra:

➪ Hadrons, Photons

6. Space-Time Evolution

HBT Correlations of $\pi^\pm \pi^\pm$, $K^\pm K^\pm$:

➪ Hadrons

Summary: Electrons, Muons, Photons, Charged Hadrons

Measuring all Timescales

- PHENIX can and will do this.
  - Early timescales in collision typically probed by “hard processes”.
  - “Hard”
    - ➡ high momentum transfer
    - ➡ rare
    - ➡ luminosity limited
- Run-1 (Summer 2000):
  - < ~1 mb^{-1} recorded
  - ~5M “minimum bias” events
- Run-2 (2001-2)
  - ~24 mb^{-1} recorded
  - ~200M events “sampled”

Timescale	Probe	Available Run-1?	Available Run-2?
Initial Collision	*Hard Scattering*		
	Single "jet" via leading particle	Yes	Yes
	photon + "jet"	No	Yes?
Deconfinement	*High-Mass Vector Mesons*		
	J/Y, Y' screening	No	Observation
	U (non)screening	No	No
Chiral Restoration	*Low-Mass Vector Mesons*		
	r, w, f mass, width	No	Yes?
	f branching ratios	No	Yes?
QGP Thermalization	*Photons*		
	p^0, h, h'	p^0 only	Yes
	continuum direct; very soft	No	Yes
QGP Thermalization	*Dileptons*		
	non-resonant: 1-3 GeV	No	Yes?
	soft continuum, <1 GeV	No	No
QGP Thermalization	*Heavy Quark Production*		
	open charm	No	No
	open charm via single lepton	Yes	Yes
Hadronization	*Hadrons*		
	HBT Interferometry, p/K	Yes	Yes
	strangeness production: K, f	Yes	Yes
	spectra of identified hadrons	Yes	Yes
Hydrodynamics	*Global Variables*		
	E_T, dN/dy	Yes	Yes

Topic 1

- **Measurement of charm yields via inclusive electron production**
  - **"Open charm" appears in D mesons**
  - **D mesons decay semi-leptonically and make electrons**
  - **Can the electron spectrum be related back to charm production?**

- **To be answered in**

  "*Measurement of transverse momentum distribution of electrons in Au-Au Collisions at sqrt(s) = 130 GeV*", K. Adcox et al, available ~2-3 weeks.

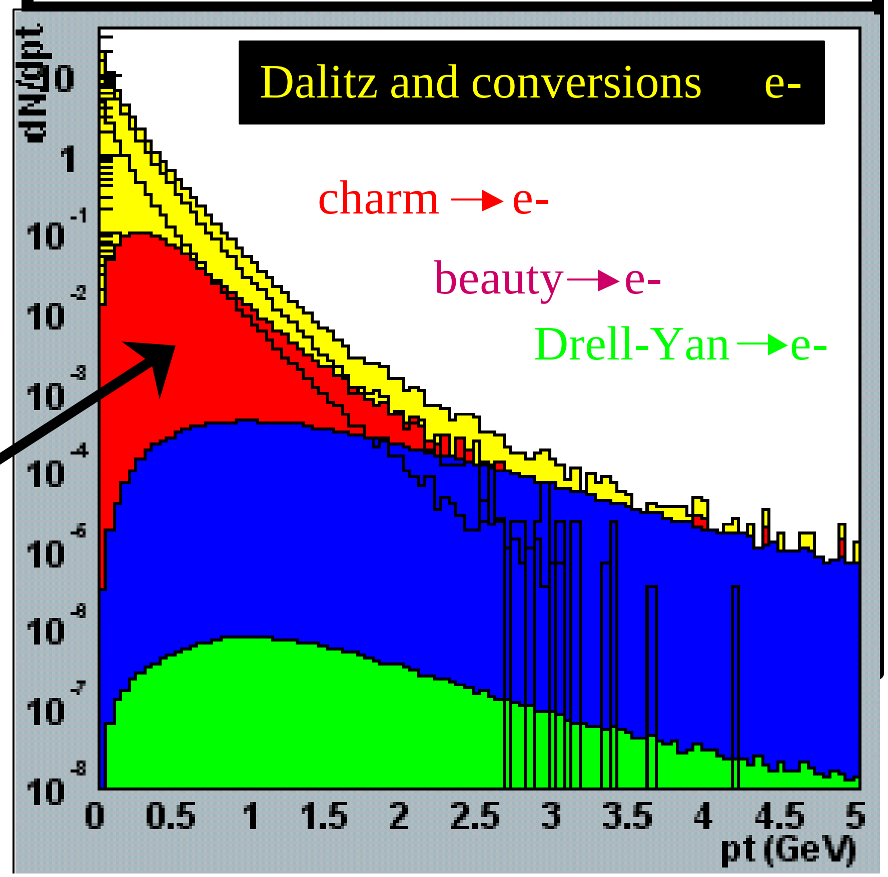
Charm Physics (1)

- **Increased understanding of open charm significance**
  - Saturation of u,d,s abundances important in establishing thermal properties of system
  - Chemical equilibrium ➡ no further information on *dynamics*
  - Charm (probably) does not chemically equilibrate
    - ➡ Important probe of early dynamics
  - Important complement to charmonium measurements
- **Major interest in pursuit of "open charm" as a plasma diagnostic**
  - Currently only modest capabilities via measurement of high p_T leptons
  - ➡ Important to extend with *direct* detection via displaced vertices

$D^0 \rightarrow K^- \pi^+$ $D^0 = (c\bar{u})$

$D^0 \rightarrow K^- e^+ \nu_e$

$D^0 \rightarrow K^- \mu^+ \nu_\mu$



Study by Mickey Chiu, J. Nagle

Approach

- Measure the spectrum of electrons
  - Track charged particles
  - Reject the overwhelming background of charged hadrons
- Identify and quantify "trivial" sources of electrons:

"Dalitz" decays: BR: 1.2% $\pi^0 \rightarrow e^+e^- \gamma$

Dominant decay: BR: 98.8% $\pi^0 \rightarrow \gamma\gamma$

"Conversions" ~ mass in aperture $\rightarrow e^+e^-$

~ 2 x Dalitz for PHENIX

~80% of background electrons from these p^0 contributions

Additional ~20% from similar decays of h's

- Subtract "trivial" sources from measured electron spectrum
- Remainder = charm decays(?)

Expected Situation

- *First* required step:

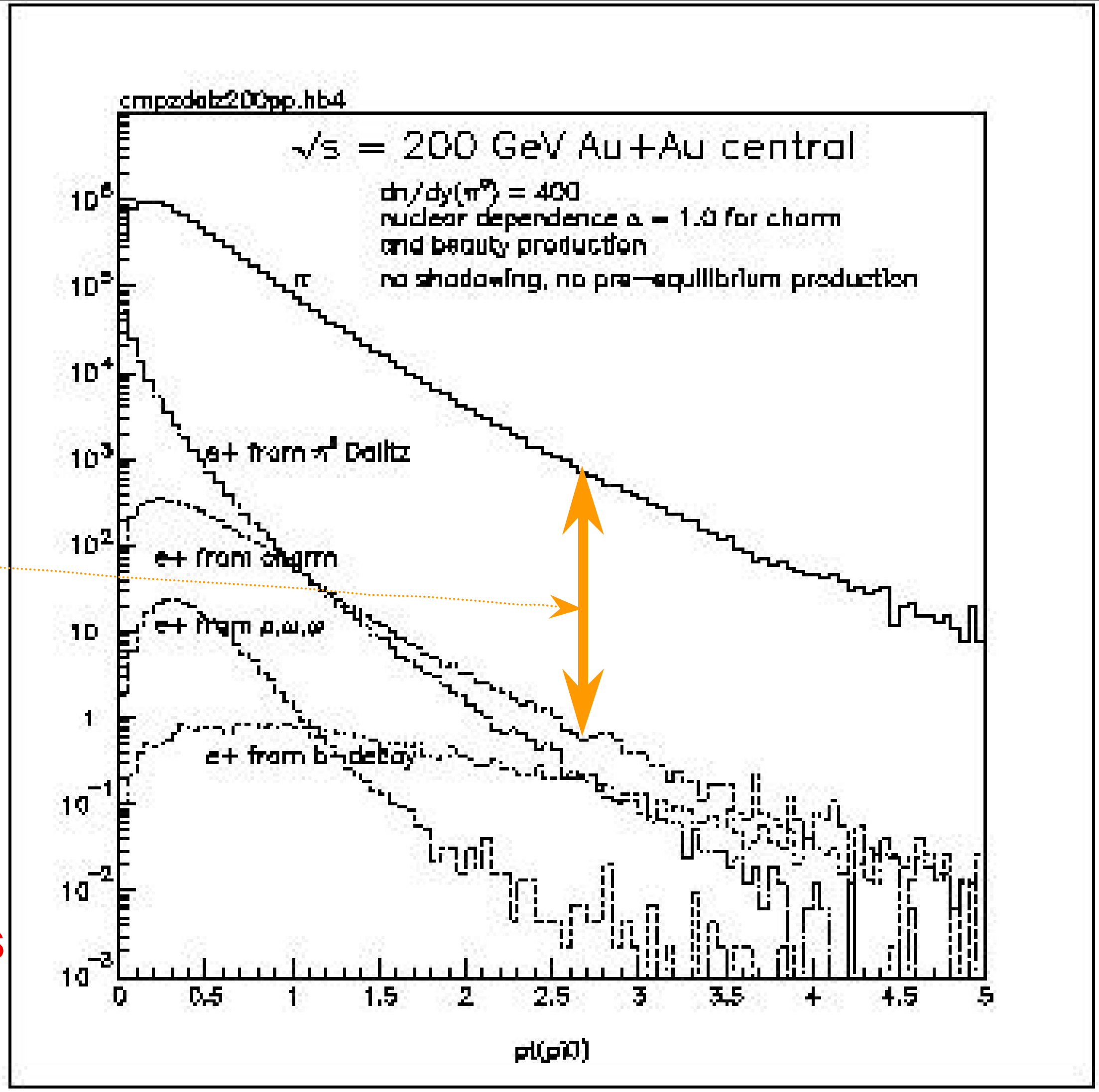
  Be able to cleanly separate electrons from pions at the level of 10^{-3} or greater

- *(Zero-th required step)* :

  Minimize mass in aperture, that is,

  do NOT allow photons from $\mathbf{p}^0$ **g g**

  to convert to electrons

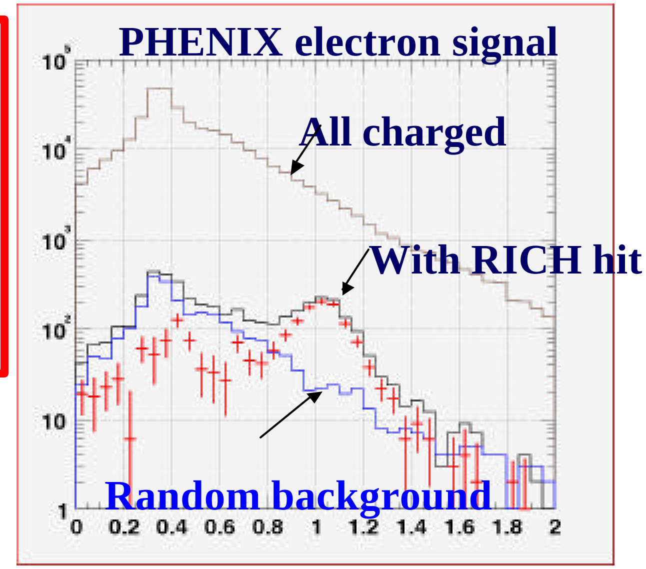


- *Then*

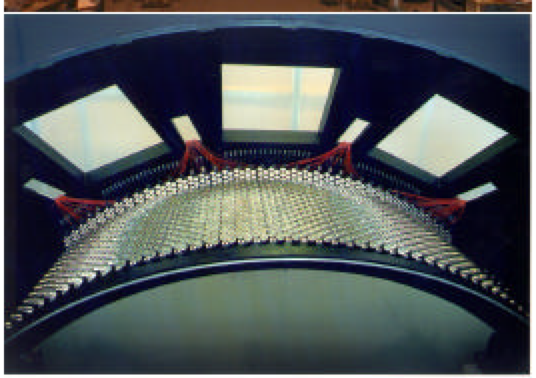
  Remove "trivial" sources of electrons

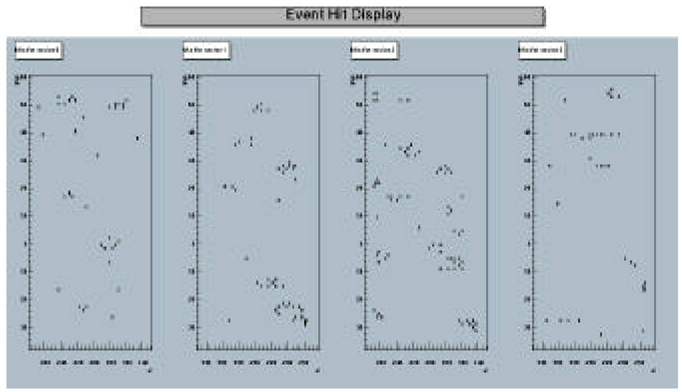
Ring Imaging Cerenkov Detector

- Gas radiator CO_2 , e/π separation for p < 5 GeV/c
- 5120 PMTs sensitive to single photoelectrons, σ_t < 1 ns
- Ring resolution ~1° in both Φ and η

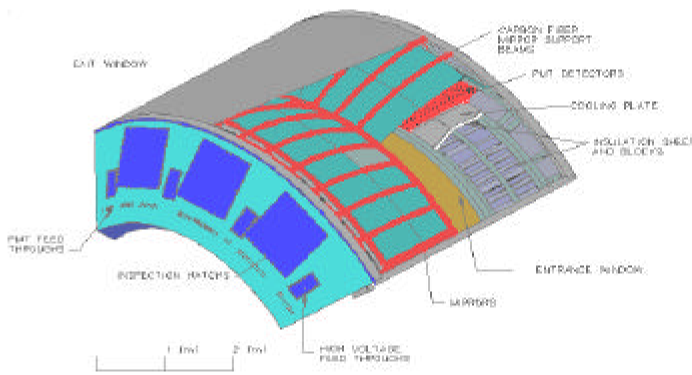


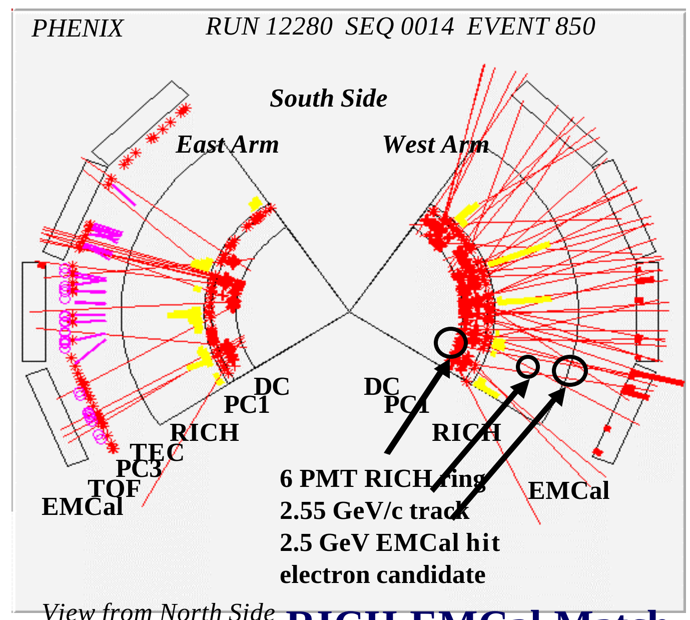
E/p ratio :RICH-EMCal





Rings in RICH from Central Au-Au collision

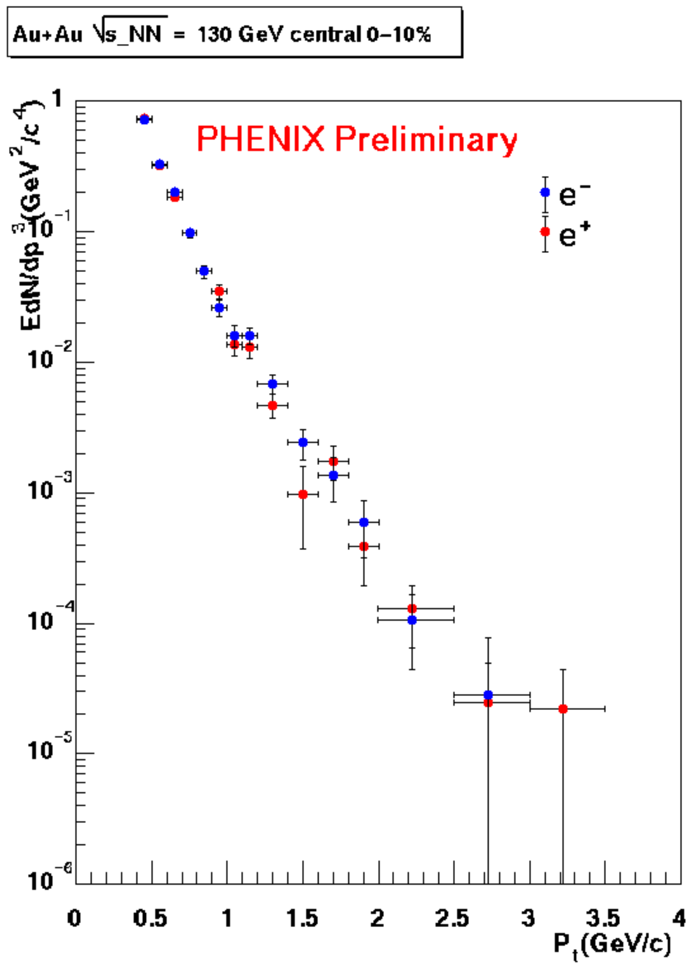


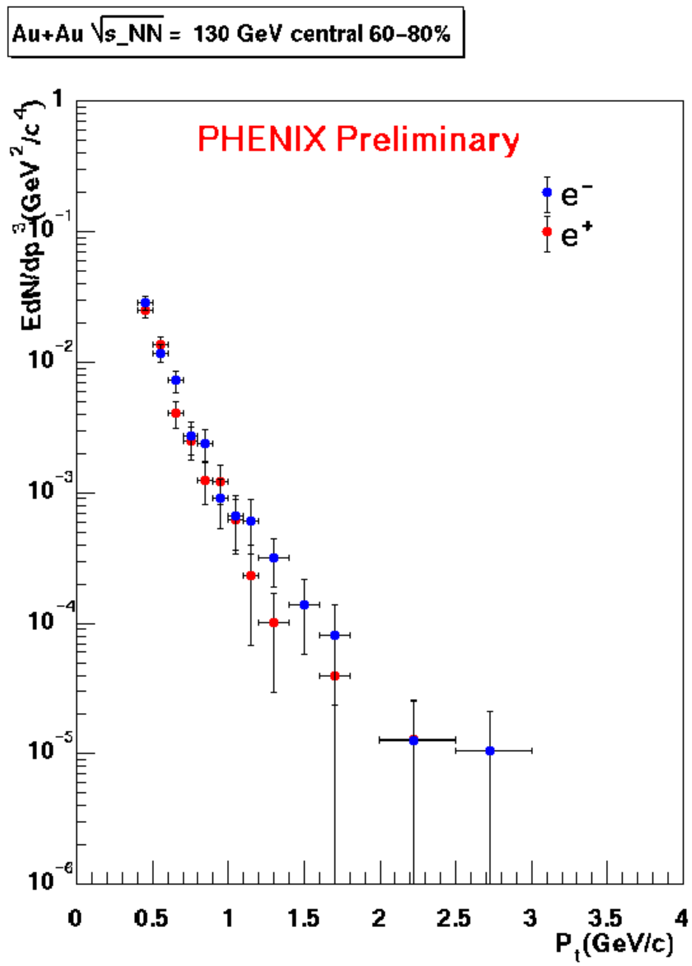


RICH-EMCal Match

Measured Electron Spectra

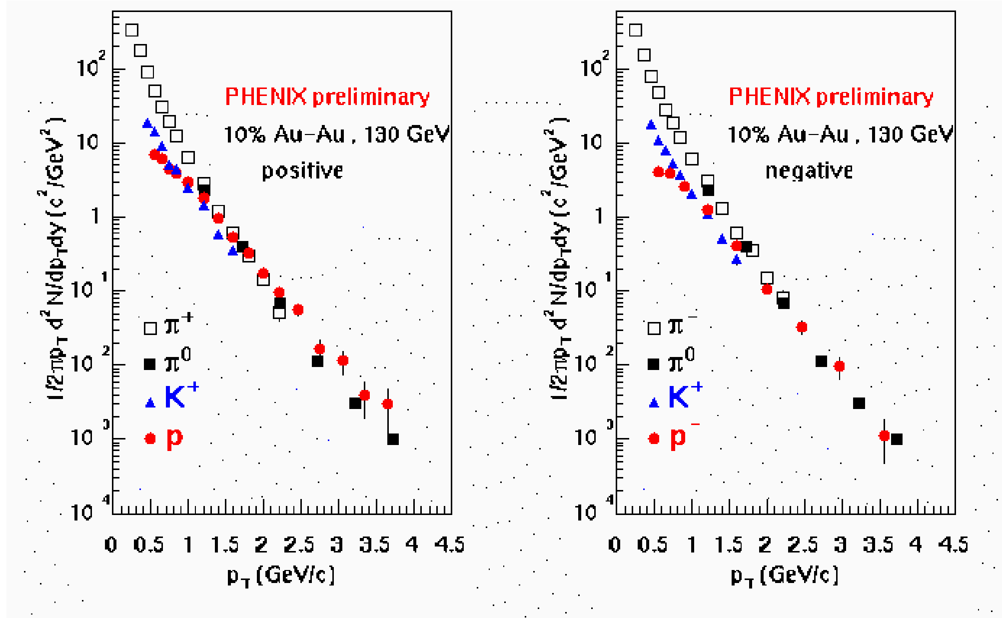
- These are inclusive distributions
- ➡ Now must remove the “trivial” sources of electrons

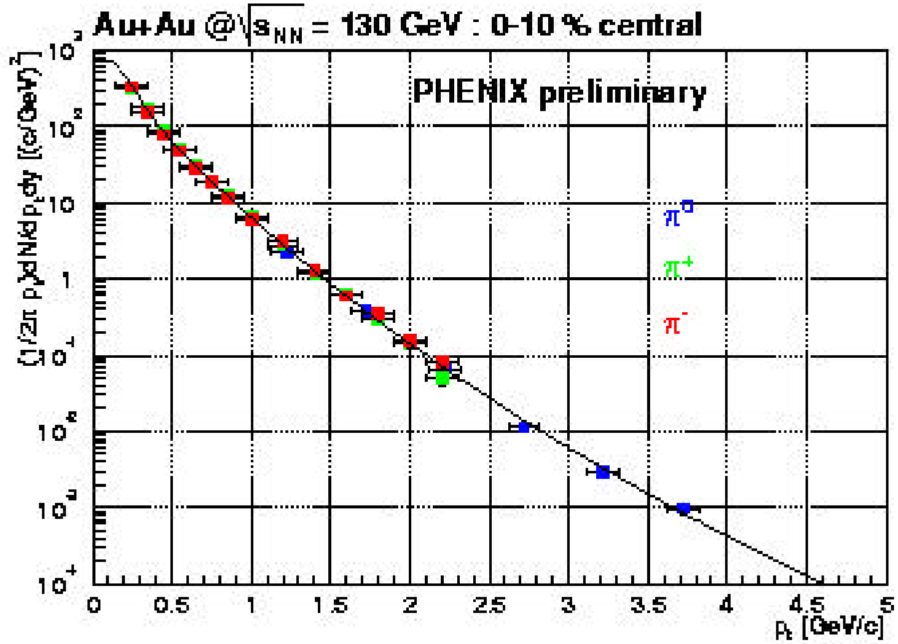




Input to background

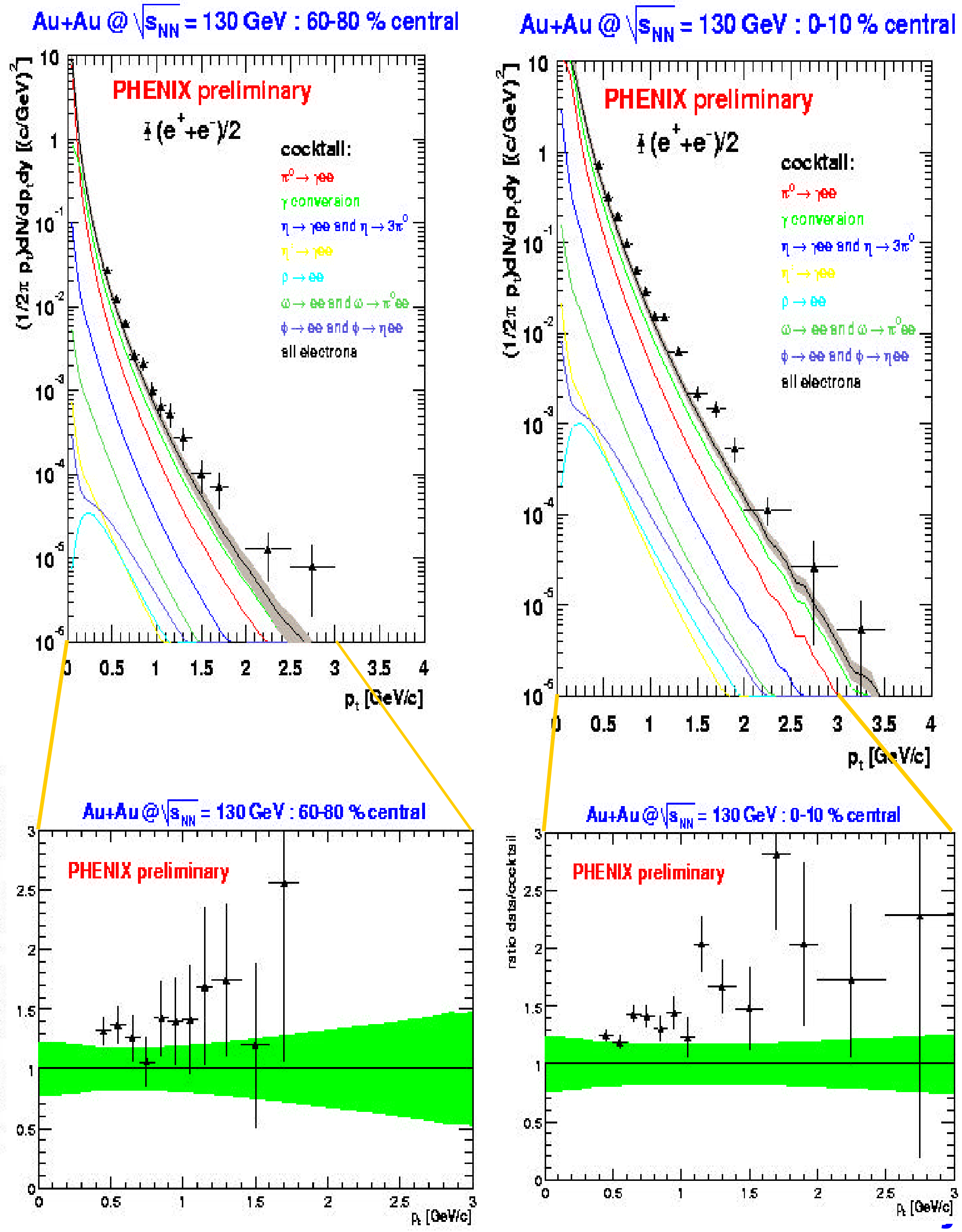
- Use simultaneous fit to the measured p^+, p^o, p^- spectra
- Estimate h's
  - Yields from $h/p^0 = 0.55$ from ISR, SPS, FNAL data
  - Spectrum from m_T scaling
  - Systematic errors from varying assumptions on yields and spectral shape
- Conversions known from
  - Simulations
  - (Ultimately) measurements

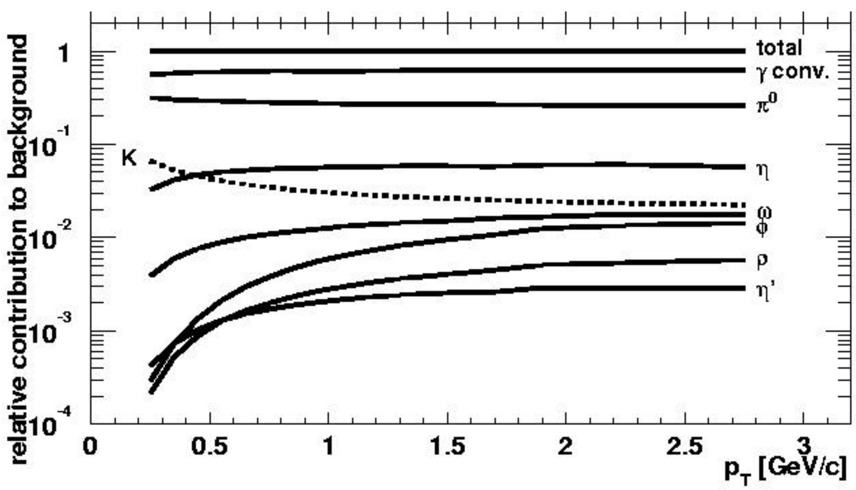




Background Subtraction

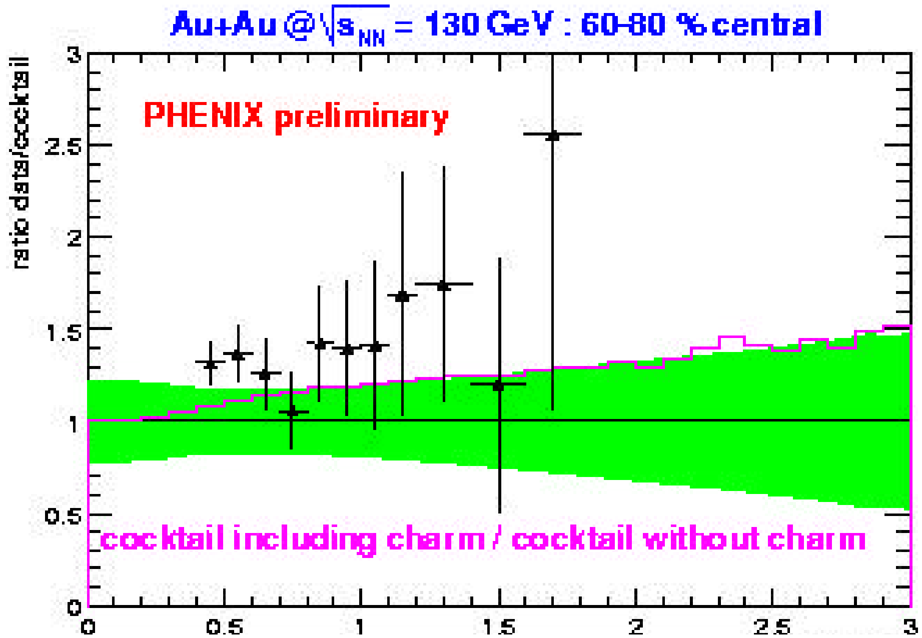
- After consideration of all known sources of electrons, there remains an excess for $p_T >$ ~1 GeV/c
- Is it consistent with “expected” charm yields?

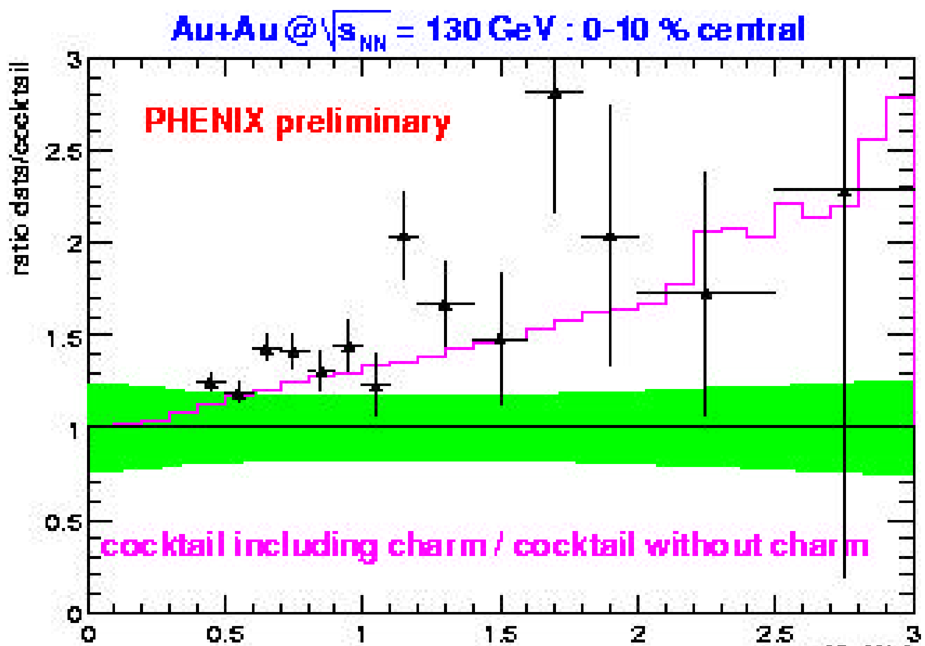




Comparison to PYTHIA

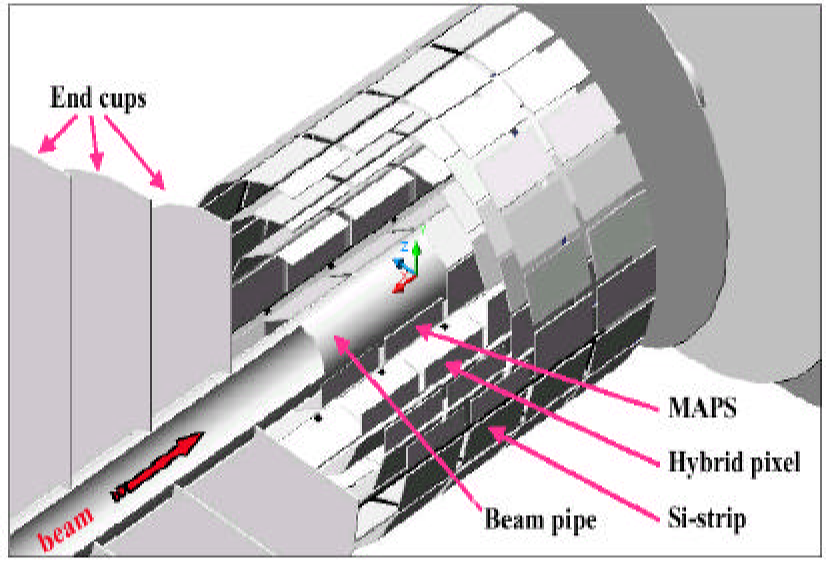
- **PYTHIA parameters tuned to fit all previous hadronic data on cross-sections and yields with**
  - M_c = 1.35 GeV/c
  - $<k_T^2>$ = $(1.5\ \mathrm{GeV/c})^2$
  - K = 3.5
  - ➡ s_{cc} = 330 mb for 130 GeV pp collisions
- **Scale to Au-Au assuming A^2 scaling:**
  - Min. bias: 420 ± 43 ± 250 mb
  - Central : 380 ± 60 ± 200 mb
  - ➡ Clearly need larger sample to better quantify
  - ➡ Look to Run-2

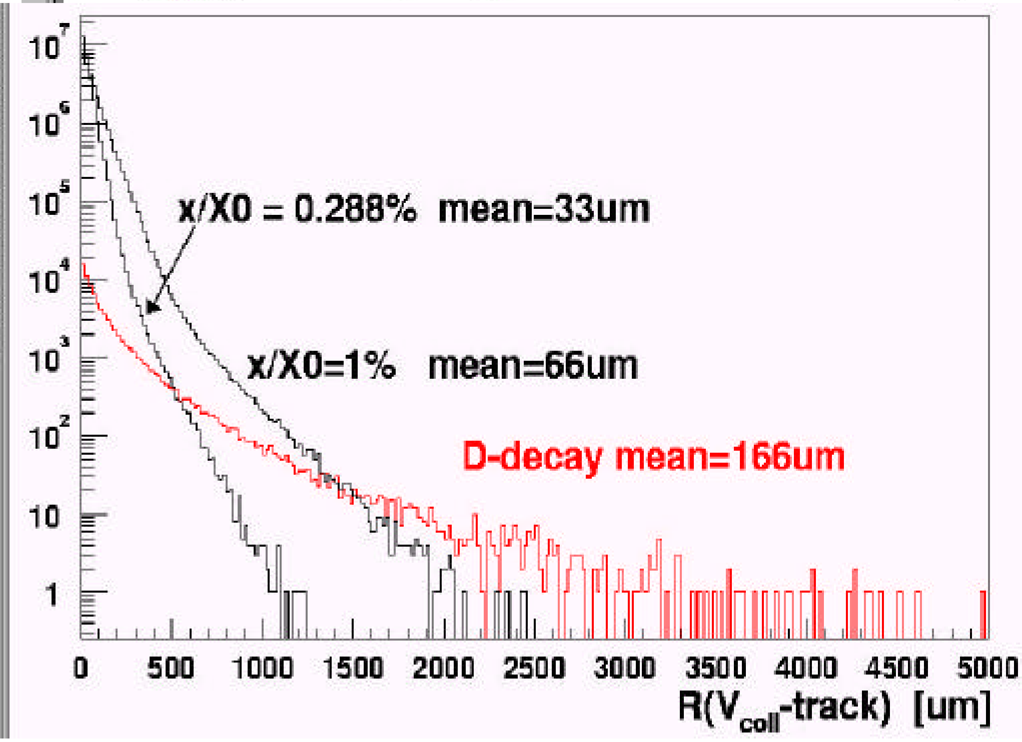




Beyond Run-2

- Ultimately want to detect open charm "directly" via displaced vertices
- Extremely challenging in high multiplicity heavy ion environment
- Development of required Si tracking for PHENIX well underway





PHENIX

Topic 2

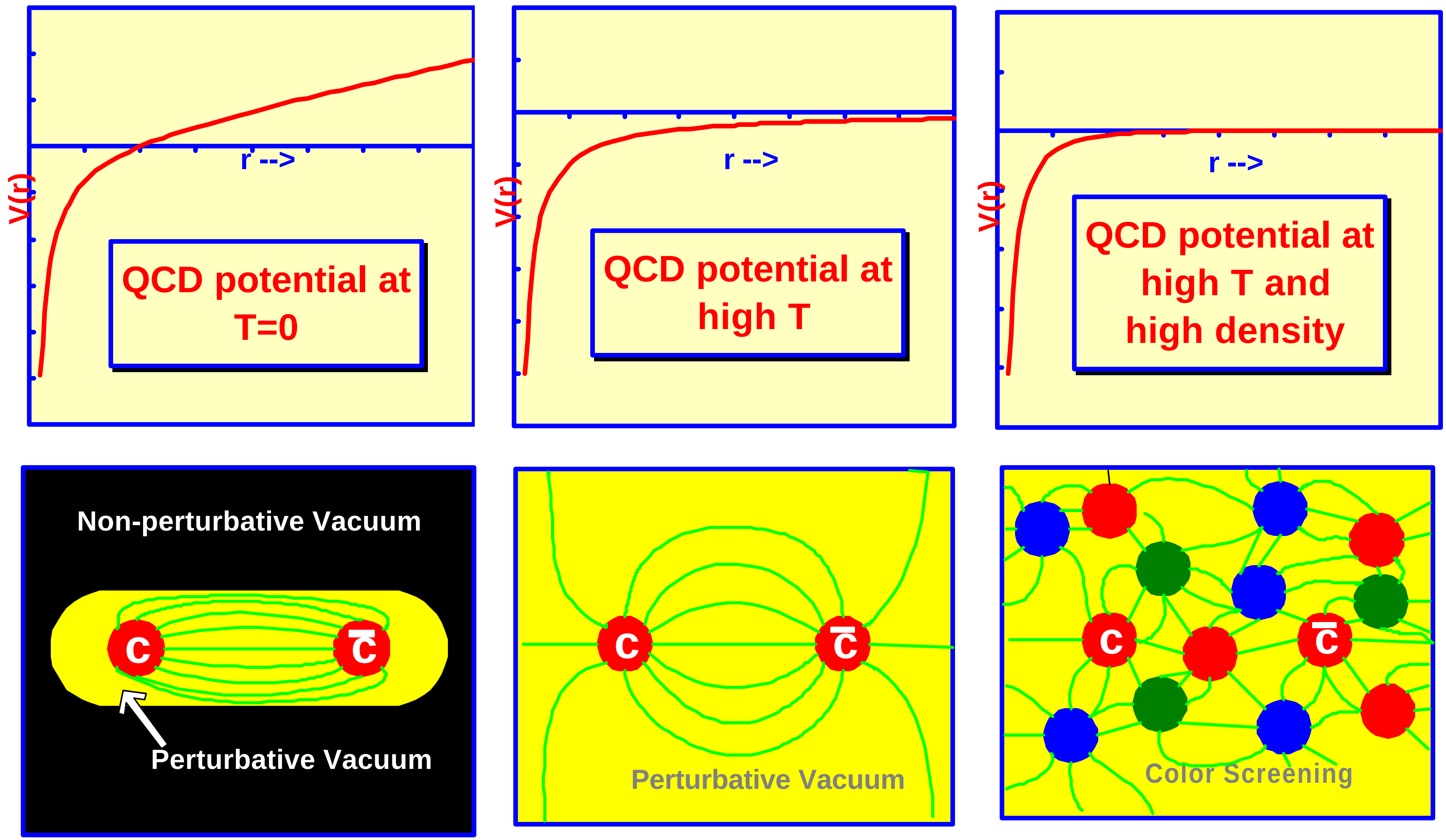
- **Charmonium production at RHIC**
  - **Is the J/Ψ suppressed? Enhanced?**
  - **How does the production depend on**
    - **Centrality?**
    - **Transverse Momentum?**

- **To be answered in**

"*Suppression/Production/Enhancement of J/Ψ mesons in Au-Au Collisions at sqrt(s) = 200 GeV*", S. Adler et al, available ~M-N years.

Screening by the QGP

In pictures:



Screening by the QGP

In first-order finger physics:

- Follow usual derivation of Debye screening

$$\nabla^2 f = 4pr = 4pn_o\left[e^{+ef/kT} - e^{-ef/kT}\right]$$

$$\approx 4pe^2\, 2n_o f / kT \equiv \frac{1}{l^2_D} f \quad \text{with} \quad l_D{}^2 \equiv \frac{kT}{2 \cdot 4pe^2 n_o}$$

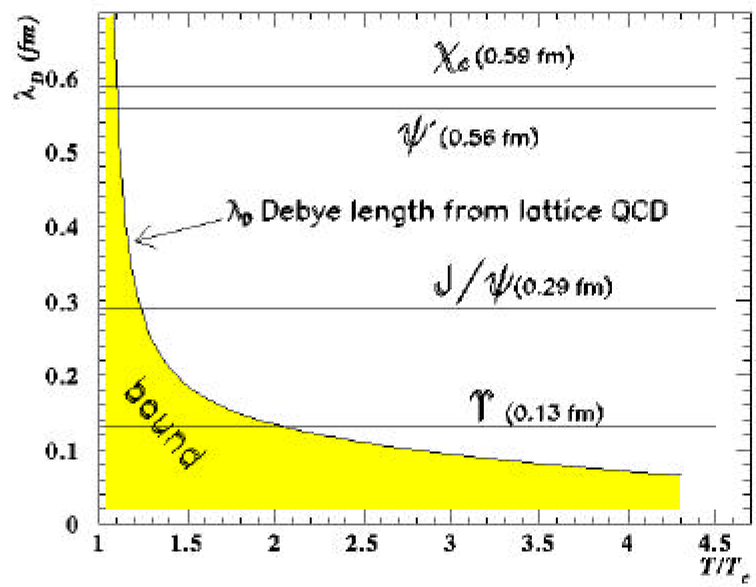
$$4pe^2 \rightarrow g^2 \sim 1$$

$$n_o = 3.6T^3 \equiv kT^3 \quad \text{(Stefan-Boltzman for QGP)}$$

$$T \approx 200 \text{ MeV}$$

$$\Rightarrow l_D = \frac{1}{\sqrt{2k}} \frac{1}{gT} \approx 0.4 \text{ fm}$$

- Hadrons with radii greater than ~ l_D will be dissolved
- Study "onium" bound states



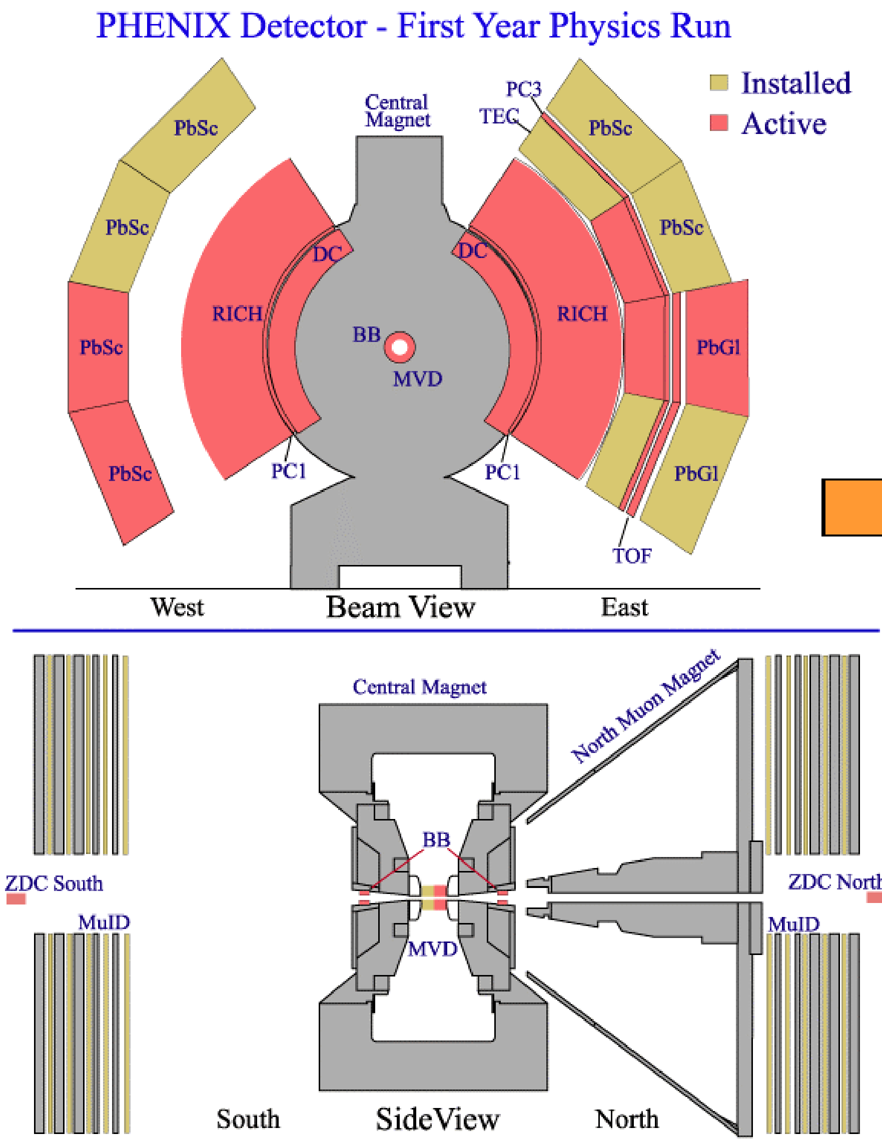
Run-2 Goals

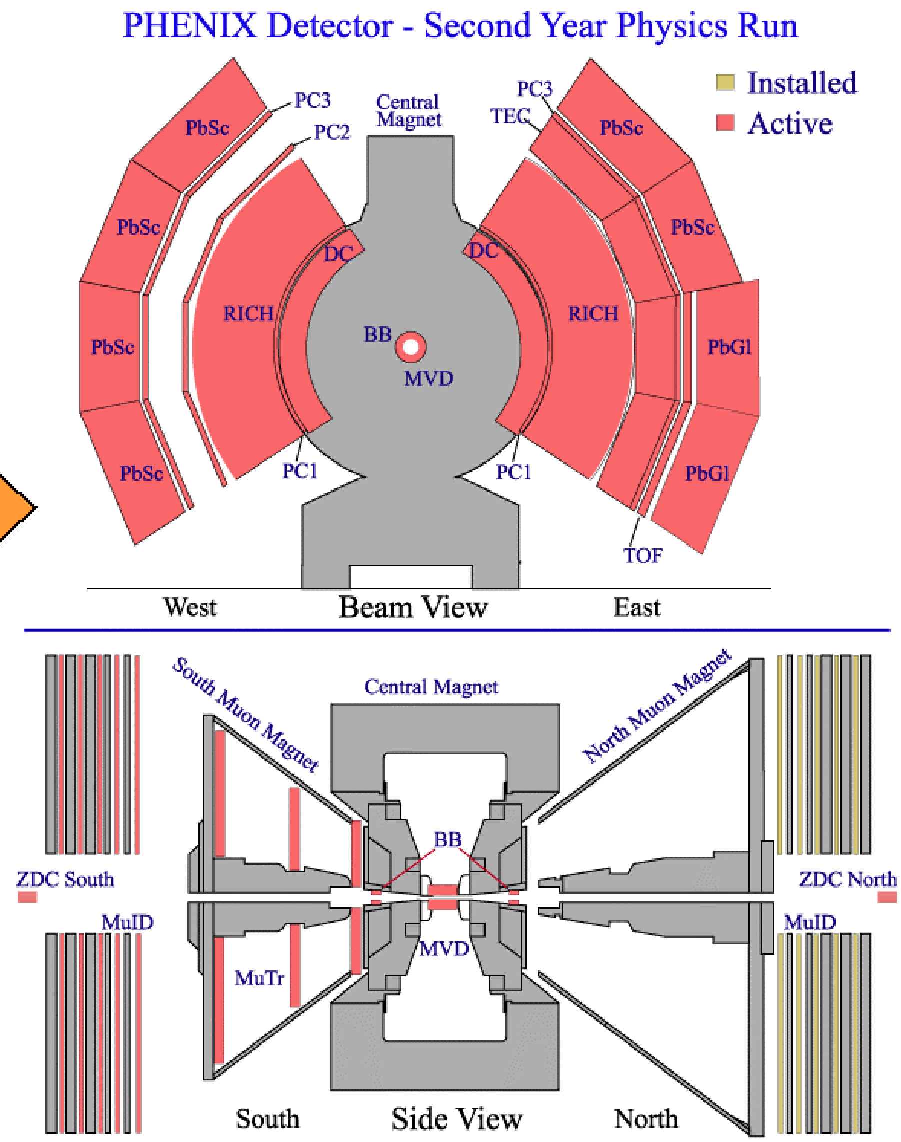
- Au-Au running
  - Achieve design values for
    - Energy (200 GeV)
    - Luminosity (2 x 10^{26} cm^{-2} s^{-1})
    - Interaction region (20 cm)
  - ~ 12 week physics run
  - ➡ ~ 100 x existing data sets from Run-1
- p-p running
  - Commission
    - proton collisions at 200 GeV (5 x 10^{30} cm^{-2} s^{-1})
    - Polarization for same (³ 50%)
  - ~ 5 weeks physics run

✖ (Additional ‘heavy ion’ running to be determined)

Run-2 Configuration

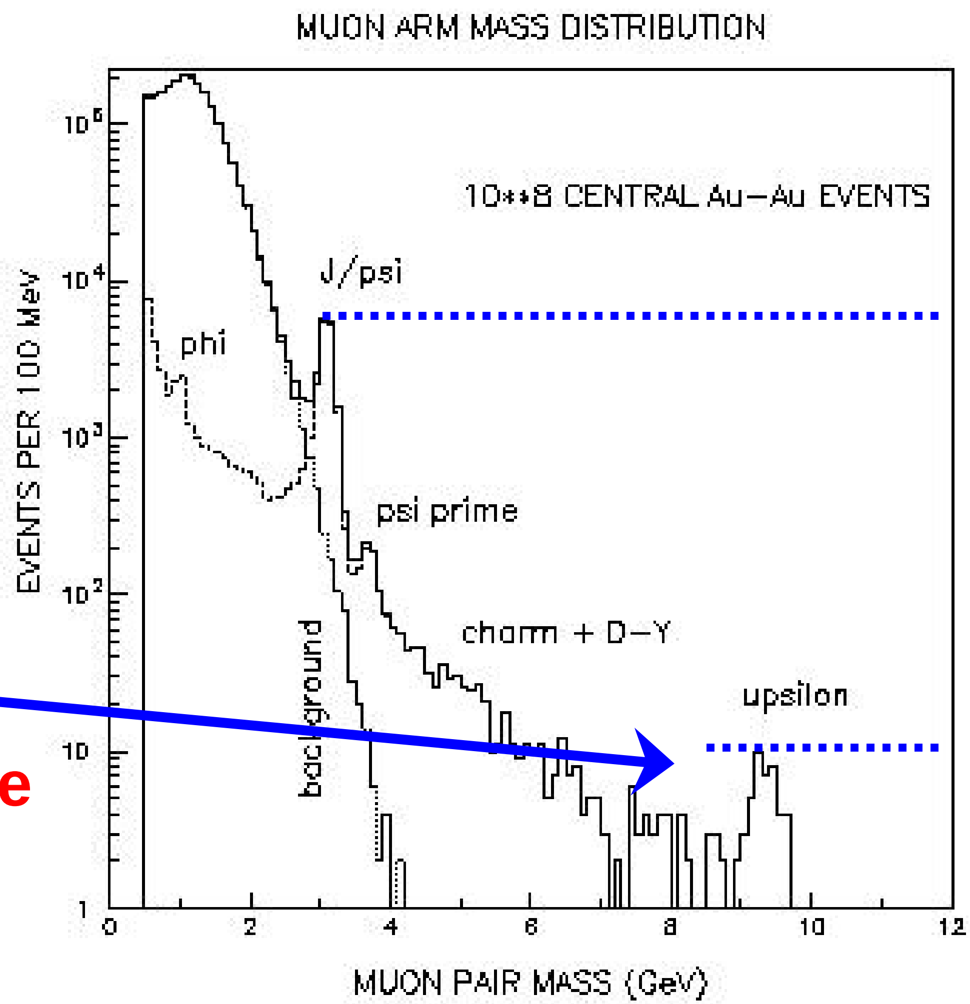
For 2001 Run:





Vector Meson Rates

- **10 weeks of Au-Au running at design luminosity:**
  - ➡ **30K J/Ψ 's**
  - ❑ **Enough for rough**
    - ◆ **centrality dependence**
    - ◆ **p_T spectra**
  - ❑ **But modest with respect to 500K J/Ψ 's in CERN Pb-Pb data set**
  - ❑ **x 4 luminosity growth produces 'CERN-like' production rate**



- **Upsilon rate ~ 10^{-3} J/Ψ**
  - ➡ **Major luminosity upgrade required to access this important physics**

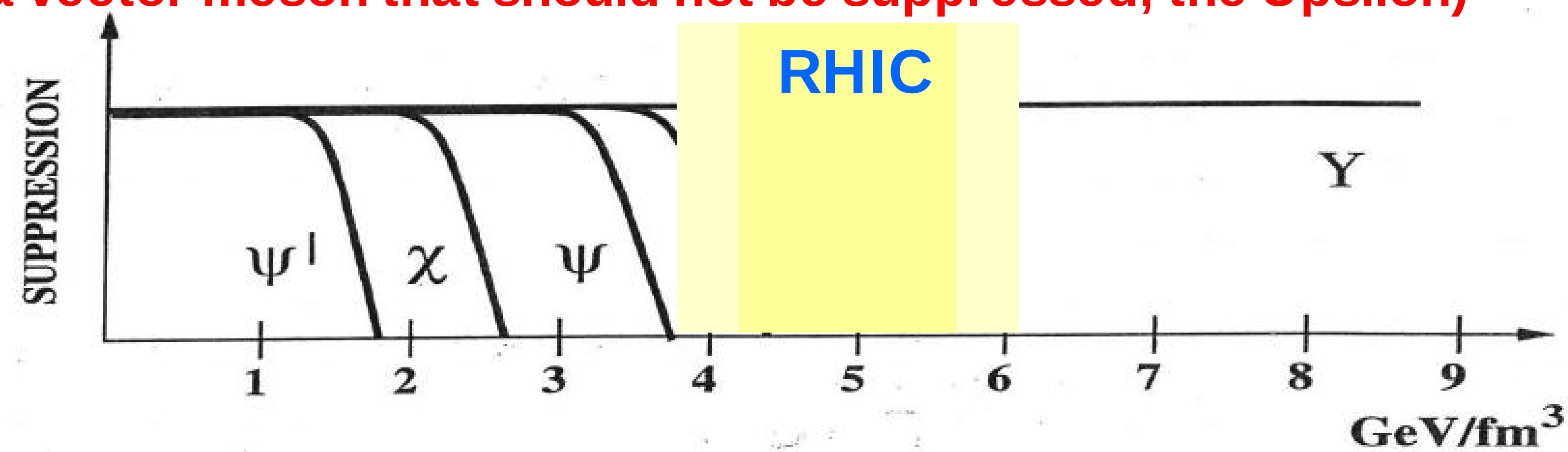
PHENIX

Control (1)

- **A plasma should exhibit a thermal (Debye) screening length $\lambda \sim 1/gT$**

Q. How to establish that the (to be observed) charmonium suppression pattern results from this mechanism?

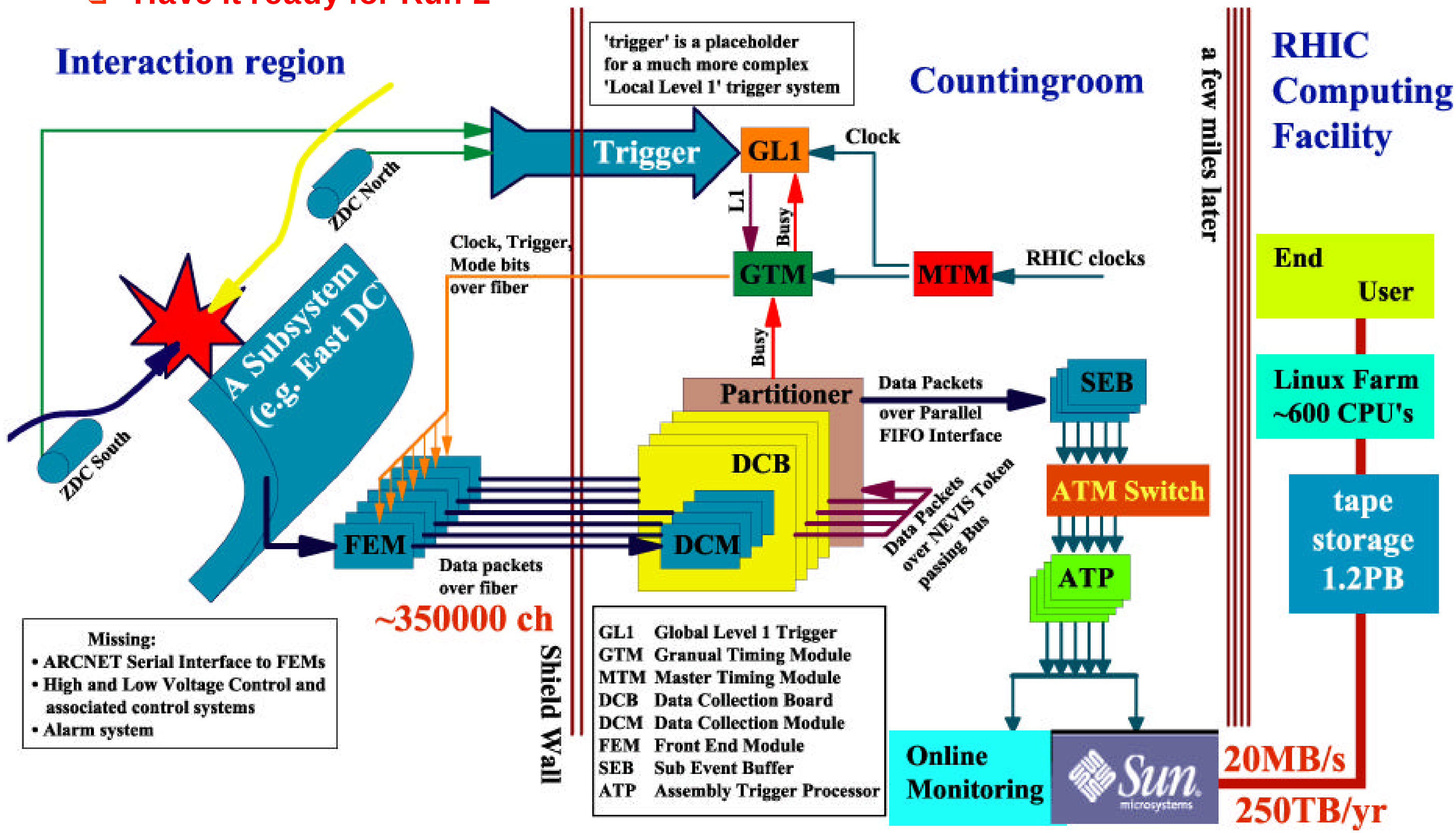
- **Answers:**
  - **Study vs. p_T**
  - **Study vs. centrality**
  - **Study in lighter systems**
  - **Study vs. a *control***
    (a vector meson that should not be suppressed, the Upsilon)



Run-2 DAQ and Trigger

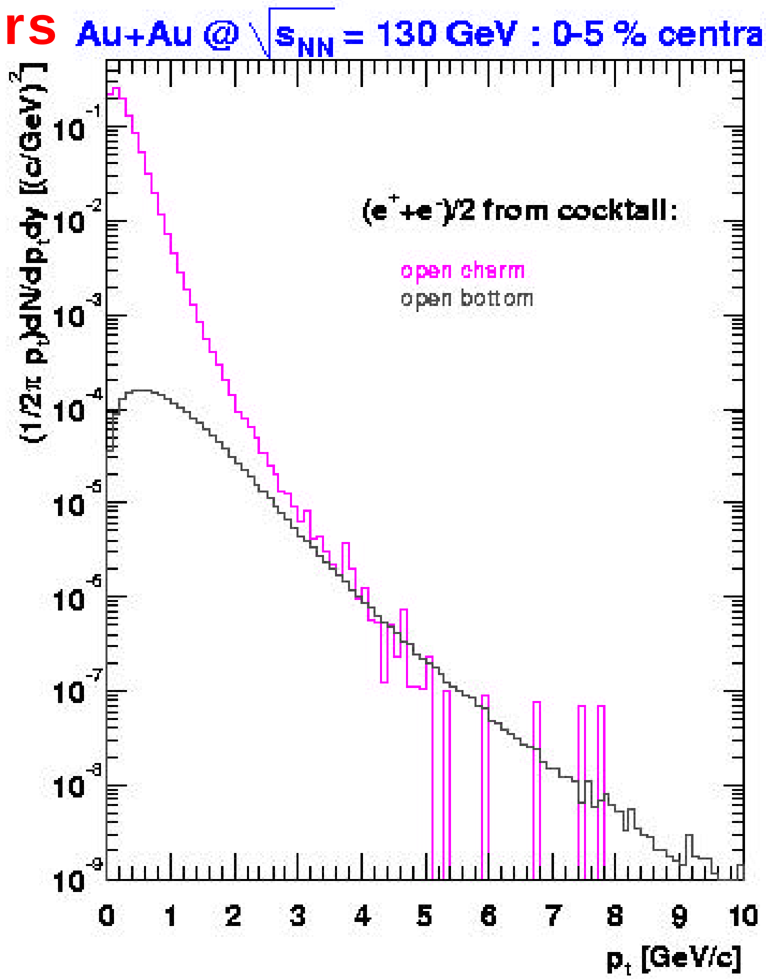
PHENIX has made a *major* effort to

- Design and build a system capable of extracting all physics at design luminosity
- Have it ready for Run-2



Run-2 DAQ and Trigger

- **High bandwidth + physics triggers**
  - ➡ **Able to use full luminosity of machine**
- **To date:**
  - **Implemented full set of Level-2 triggers**
    - Single muon
    - $J/\Psi \rightarrow \mu^+\mu^-$
    - $J/\Psi \rightarrow e^+e^-$
    - $\phi \rightarrow e^+e^-$ peripheral (40-100%)
    - High p_T
      - Photon (2.5-3.0 GeV/c cut)
      - Electron (2.5 GeV/c cut)
      - Charged (cut TBD)
    - e-μ coincidence
    - Coherent peripheral trigger
  - **DAQ Upgraded to**
    - ~30 Mb/s recording
    - ~150 events/sec



PHENIX Charmonium from Run-2?

- What will PHENIX have on J/Ψ for QM02?
- I don't know (today)
- Remarks:
  - RHIC did achieve (more than) design luminosity for Run-2 !!!
  - Note luminosity   Integrated Luminosity
  - PHENIX has <10% of our Run-2 goals for   L dt
  - Perhaps will have data on observation of J/Ψ
  - $(\text{Perhaps})^2$ yields cut on central vs. peripheral

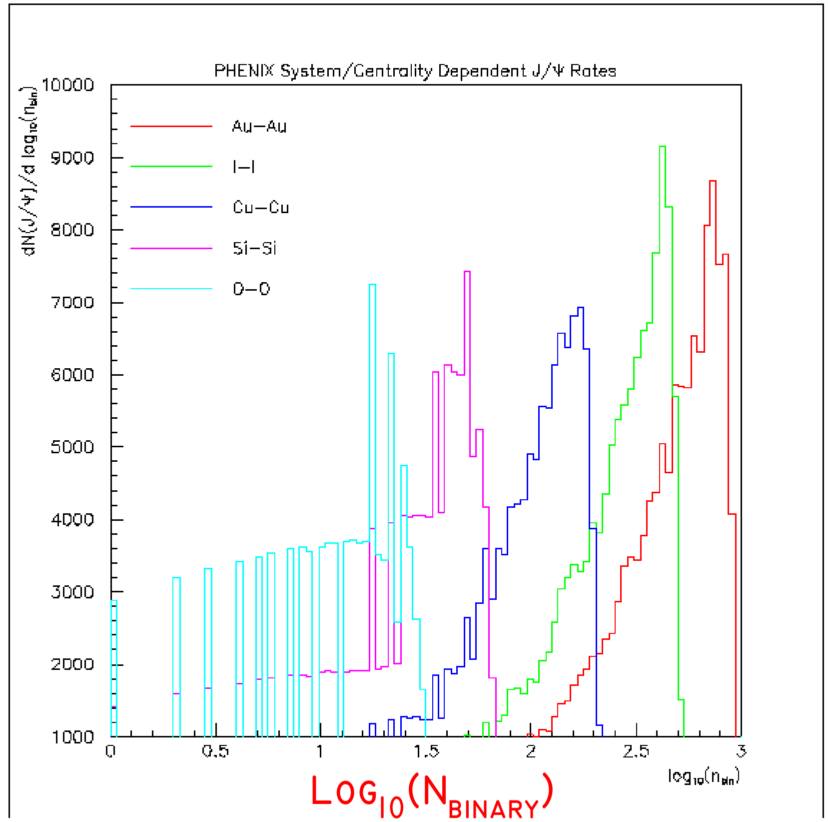
Looking Ahead

Run-3:

(Subject to the usual caveats about surprises and flexibility):

- **Heavy Ions**
  - Fully operational muon arm + new triggers
  - Full exploration of J/ϒ production versus "N_{binary}" ~ A(b)*A(b) via
    - A long run with Au-Au
    - A series of shorter light ion runs
- **p-A or d-A running**
- **Spin**

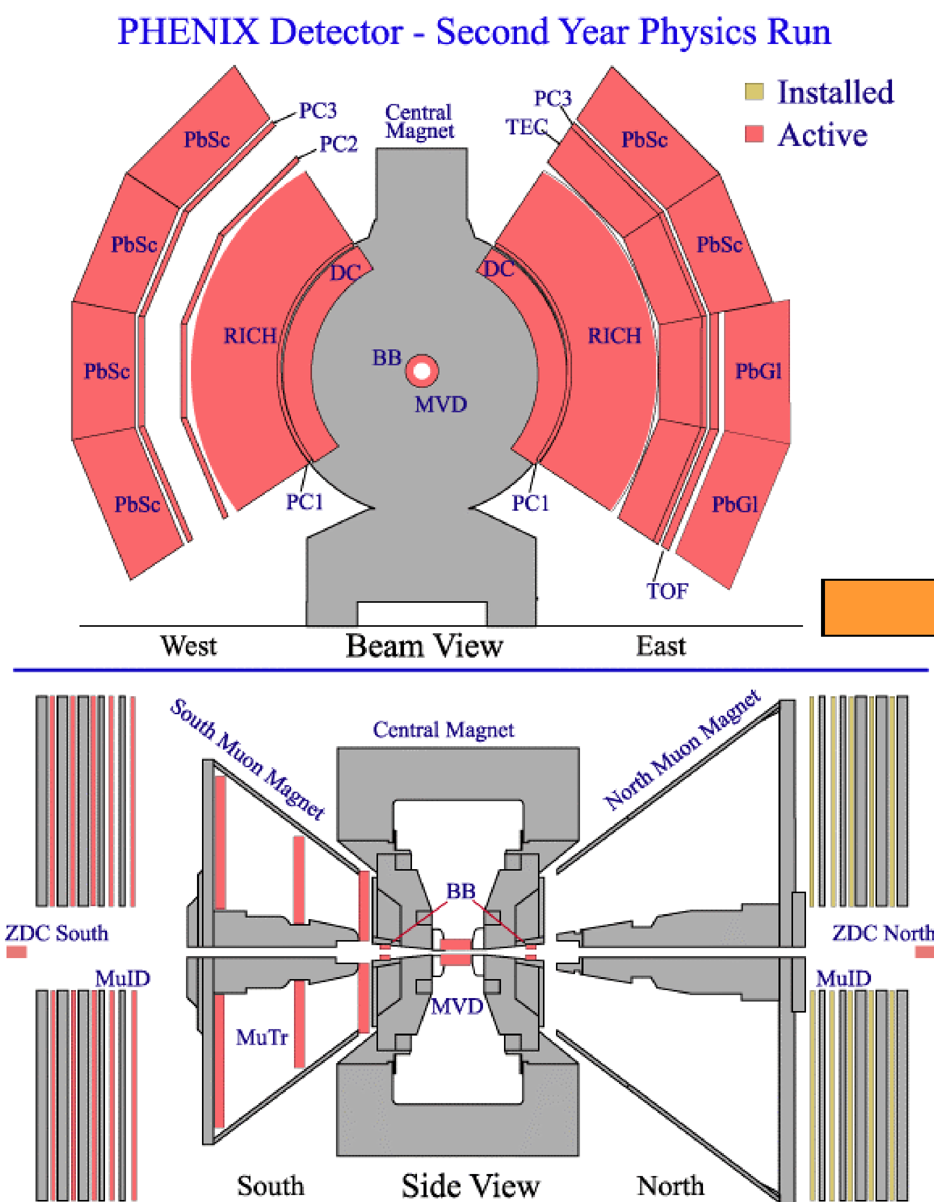
Continued running to accumulate 160 pb^{-1} at 200 GeV

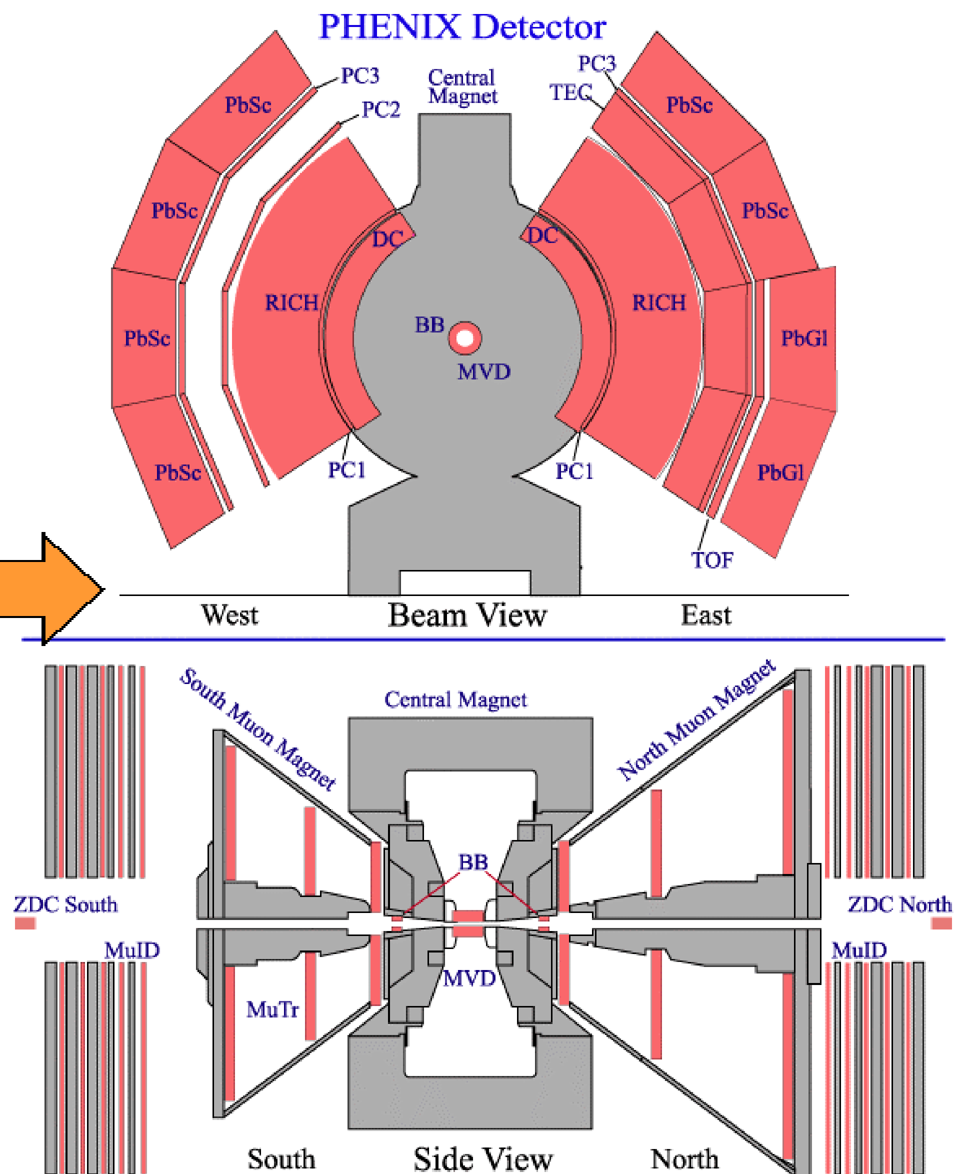


Species	Number of J/ϒ's (0.6 R.Y. - AuAu, 0.1 R.Y. - others)
OO	1.15E+05
SiSi	1.44E+05
CuCu	1.56E+05
II	1.73E+05
AuAu	1.79E+05

W.A. Zajc

Run-3 and Beyond





What's Left?

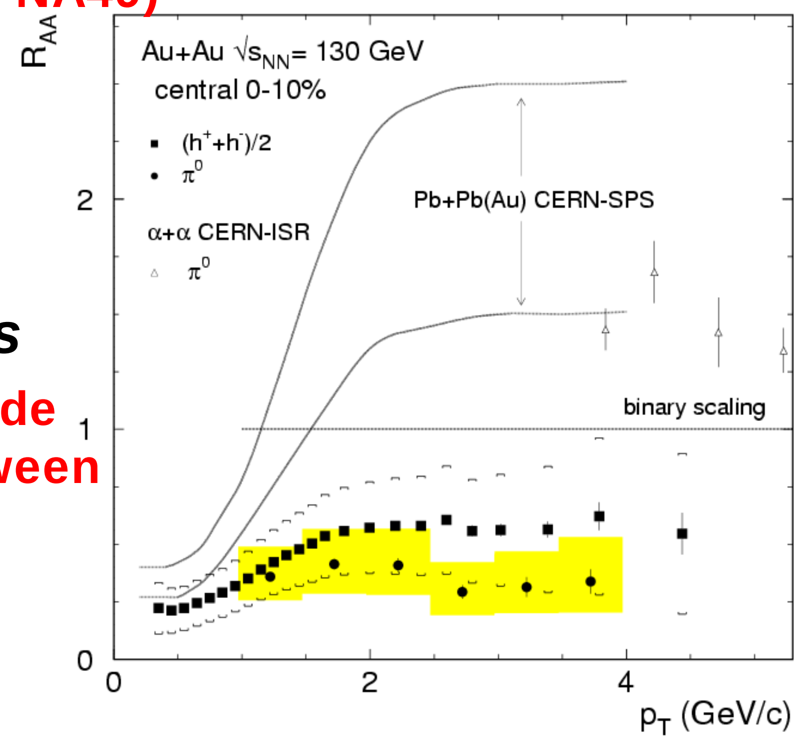
- **Most of the program:**
  - **Energy scans**
  - **Species scans**
  - **All the systematic studies required before laying claim to new physics**
  - **Vital spin program**
- ***Example* (A-A) program to do this:**
  - **Run-2:**
    - **Au+Au, crude p-p comparison run**
    - **First look at J/Υ production, high p_T**
    - **d-Au run?**
  - **Run-3:**
    - **High luminosity Au+Au (60%) of HI time**
    - **High luminosity light ions (40%) of HI time**
    - **Detailed examination of A*B scaling of J/Υ yield**
  - **Run-4:**
    - **p-d/p-p comparisons**
    - **Baseline data for rare processes**
  - **Run-5:**
    - **"Complete" p-A program with p-Au**
    - **Energy scans**
    - **Systematic mapping of parameter space**

PHENIX

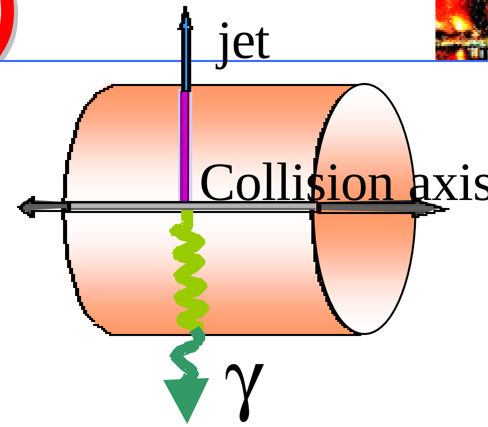
Why d-Au

- **General: Historically, p-A data has been essential in separating “mere” multi-particle effects from “genuine” heavy ion effects**
  - **Strangeness enhancement (e.g. E910, NA49)**
  - **Gluon shadowing (e.g. FNAL E866)**

- **Specific: The truly new result from Run-1 is**
  the suppression of high p_T hadrons
  - **A “proton”-nucleus data set will provide *the key information* to distinguish between effects in**
    - **cold nuclear matter**
    - **versus**
    - **hot (deconfined) nuclear matter**

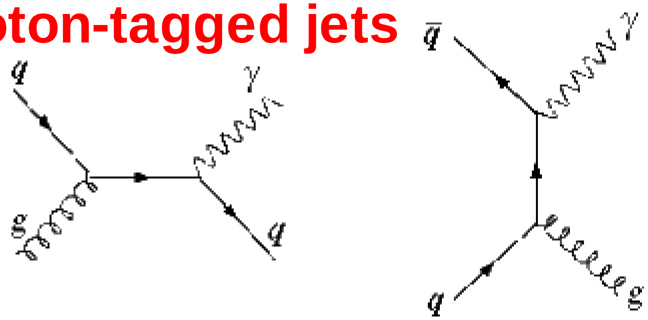


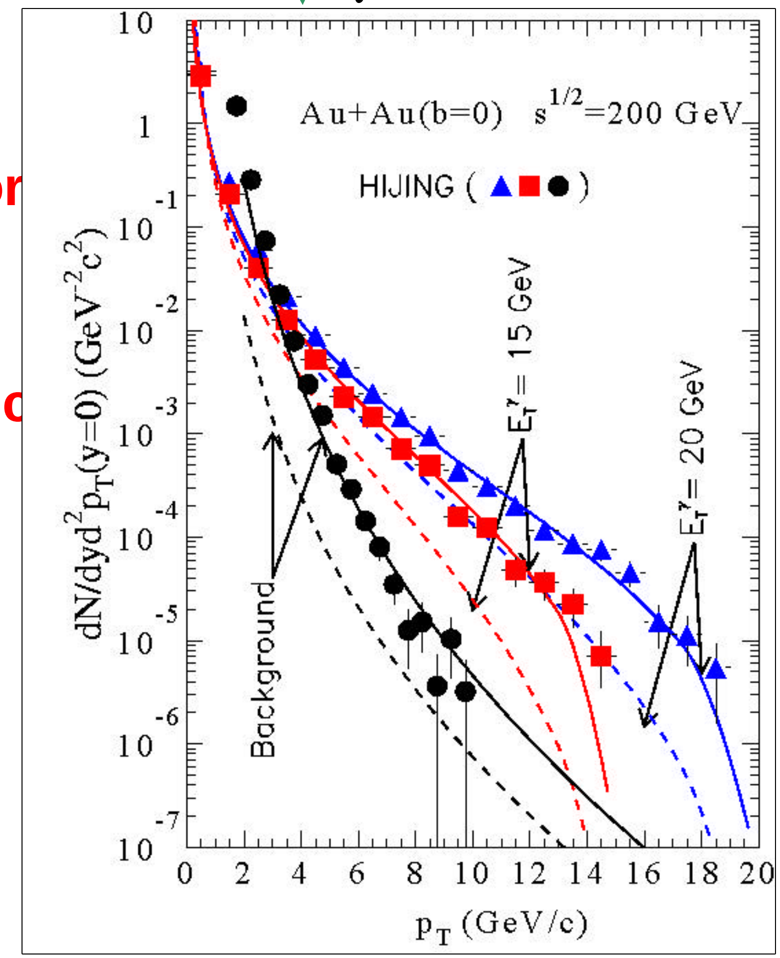
Control (2)



Q. How to establish the observed suppression at high p_T as a plasma effect?

- **Answers:**
  - **Study it out to highest possible transverse momenta**
  - **Study it as a function of flavor and/or color charge of probe**
  - ***Control* initial state geometry**
  - ***Control* initial state parton kinematics**
    - ➡ **photon-tagged jets**





- **RHIC: one 15 GeV photon / hour**

  (Central Au-Au into Dy = 1)

QGP Discovery

Q. How to categorize various approaches to QGP detection and characterization?

A?. "Factorization":

s(QGP) = s(INT) x *P*(formation) x *P*(probe)

s(INT) - geometry
P(formation) - unknown
P(probe) - below

	Common	Rare
Appearance	Strangeness Charged Pions Neutral Pions HBT Mass shifts Fluctuations in dn/dy	Direct Photons Thermal di-leptons Open Charm
Disappearance	Neutral Pions Charged Pions HBT F ® KK ? (jets)	J/Y (jets)

➡ Rare probes in disappearance mode will require concerted effort to establish by dependence on

- ✓ centrality
- ✓ E_{CM} (note advantage of collider)
- ✓ A,B
- ✓ p_T

Summary

- **PHENIX results on inclusive electron spectra provide first insights into charm production at RHIC.**

  (Note that this is from a very modest Run-1 data set.)

- **Prospects for**
  - **Greatly improved charm measurement from Run-2**
  - **Observation of charmonium yields from Run-2**

- **Much more to come from future runs via**
  - **Increasing integrated luminosity with existing apparatus**
  - **Upgrades for open charm detection**