Lepton and Photon Measurements at RHIC/PHENIX

大阪大学核物理研究センター研究会
「高エネルギー重イオン実験の現象論的解析」

2003 年 10 月 27－28 日
大阪大学核物理研究センター

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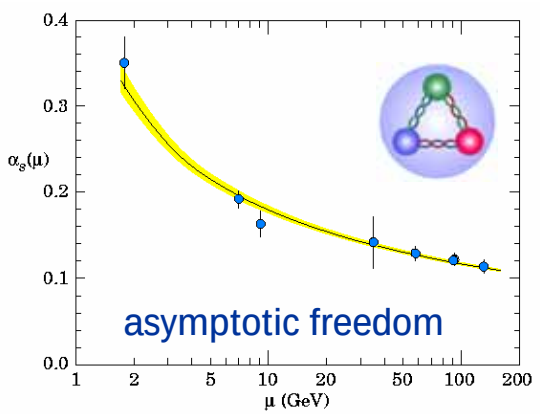
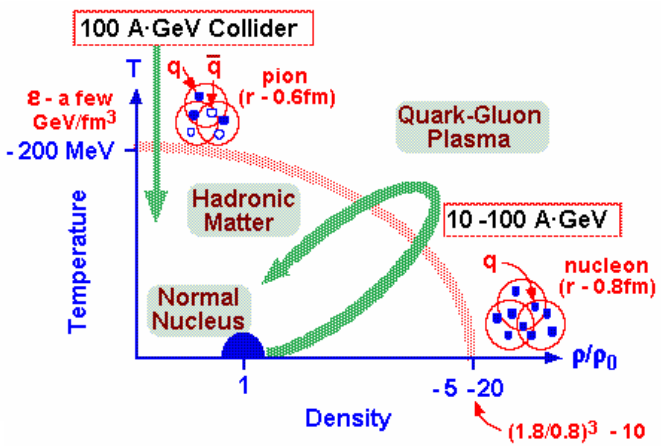
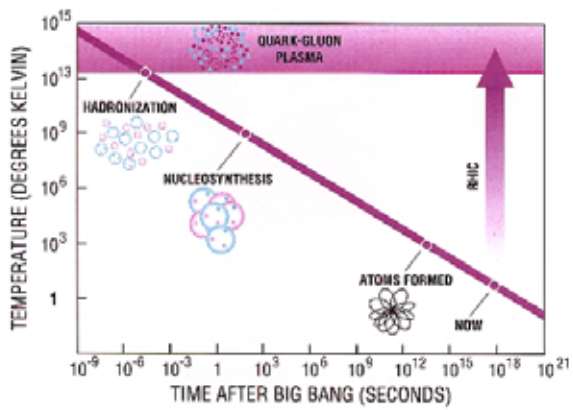
- Presentation Outline -

- physics via lepton/photon channels at RHIC
  - physics goals of relativistic heavy ion programs
  - lessons from SPS programs
- physics via lepton/photon channels at PHENIX
  - physics strategies and detectors
  - Au+Au/d+Au/p+p results from Runs 1-3
  - plans and expectations for Run 4 and beyond
    - heavy quark states for deconfinement
    - open heavy flavors for QCD dynamics
    - light vector mesons for chiral symmetry restoration
    - thermal dileptons for equation of state
    - direct photons for equation of state
- summary and concluding remarks

- Physics Goals of RHI Programs -







- QCD in extreme conditions and scales
  - high energy and/or nuclear density frontier
    - search for and characterize deconfined partonic phase
- Bevalac/SIS/AGS/SPS to RHIC/LHC
  - high density regime to high energy density regime
  - reproduction of universe a few μsec after big bang

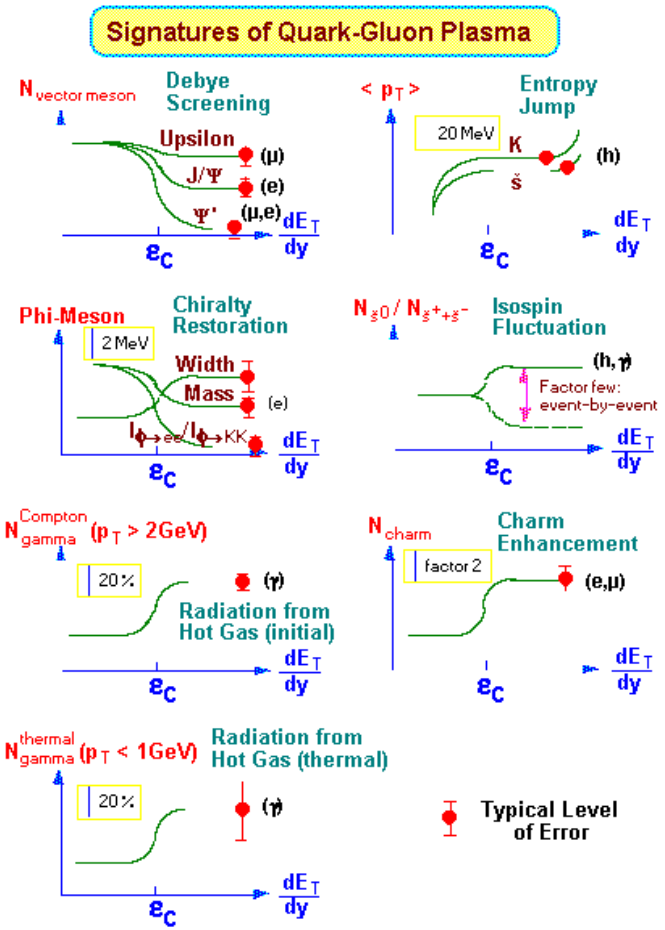
- Lessons from SPS Heavy Ion Programs -

- claim of QGP discovery by 7 experiments in 2000
- combination of signatures essential
  - hadrons to probe boundary conditions of dynamics
  - photons to trace evolution of system
  - leptons to probe early hot stage of interaction
- particular importance to probe early stages
  - J/Ψ “anomalous” suppression
    - NA50; Pb+Pb; color Debye screening ?
  - intermediate-mass dimuon enhancement
    - NA50; S+U, Pb+Pb; charm enhancement ?
  - low-mass dielectron enhancement
    - NA45 (CERES); S+Au, Pb+Au; ρ enhancement/melting ?

- Pioneering High Energy Nucl. Interaction Exp. -

- maximal set of probes and physics channels
  - photons/electrons/muons/hadrons
- high quality measurement
  - good particle identification
  - high resolution
  - wide kinematical coverage
- access to rare processes
  - high rate capability
  - selective multi-level triggering

- PHENIX Physics Strategies -

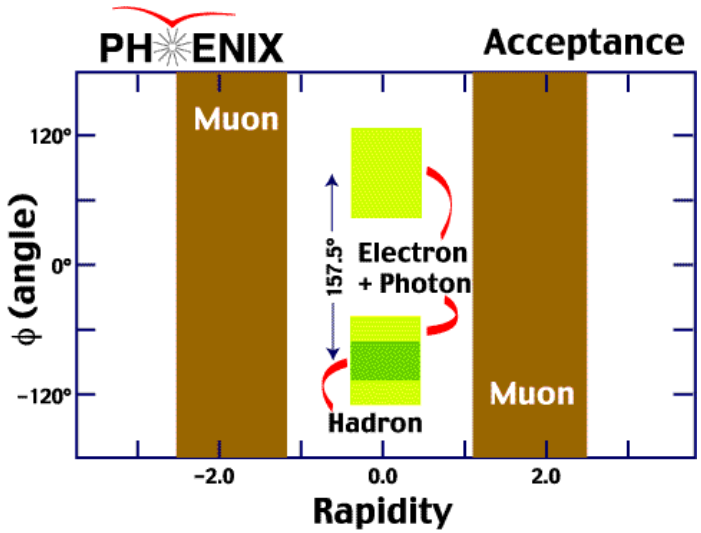


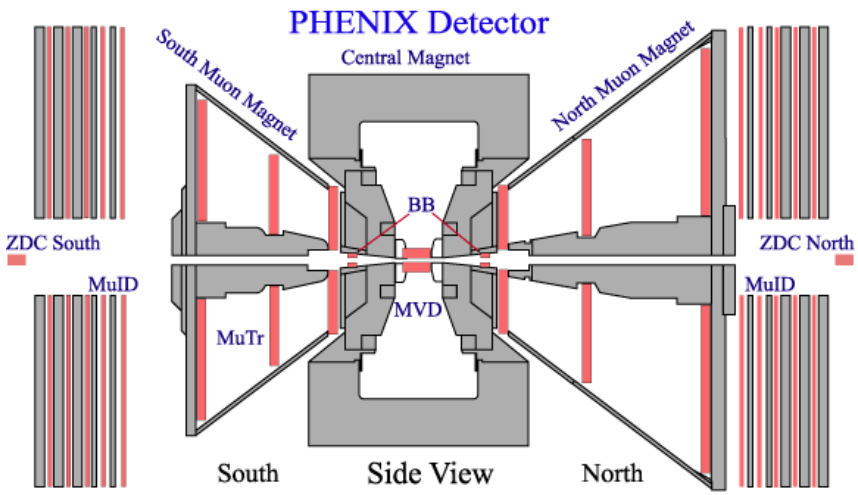
- various signatures; essentially all time scales
  - initial hard process
    - jets, high p_t hadrons/photons
  - deconfinement
    - heavy quark states
  - chiral symmetry restoration
    - light vector mesons, isospin fluctuations
  - thermalization
    - thermal photons/dileptons, open heavy flavors
  - hadronization
    - hadron spectra, strangeness, HBT interferometry
  - hydro-dynamics
    - transverse energy, *dN/dy*

- PHENIX Outstanding Features -

- unique emphasis on penetrating probes
  - the lepton/photon experiment at RHIC
    - used to be... PHoton Electron Nuclear Interaction eXp.
    - then... Photon Hadron Electron Nuclear Interaction eXp.
    - then maybe... Photon Hadron Electron muoN Integrated eXp.
    - and now... Pioneering High Energy Nuclear Interaction eXp.
  - the rare-process experiment at RHIC
- access to most promising physics probes
  - probes of early stages (deconfinement/chirality/EoS)
    - heavy quark states (J/Ψ , Ψ', Υ)
    - open heavy flavors (charm, beauty)
    - light vector mesons (ϕ, ω, ρ)
    - thermal dileptons (e^+e^-, $\mu^+\mu^-$)
    - direct photons (γ)

- PHENIX Detector Configuration -

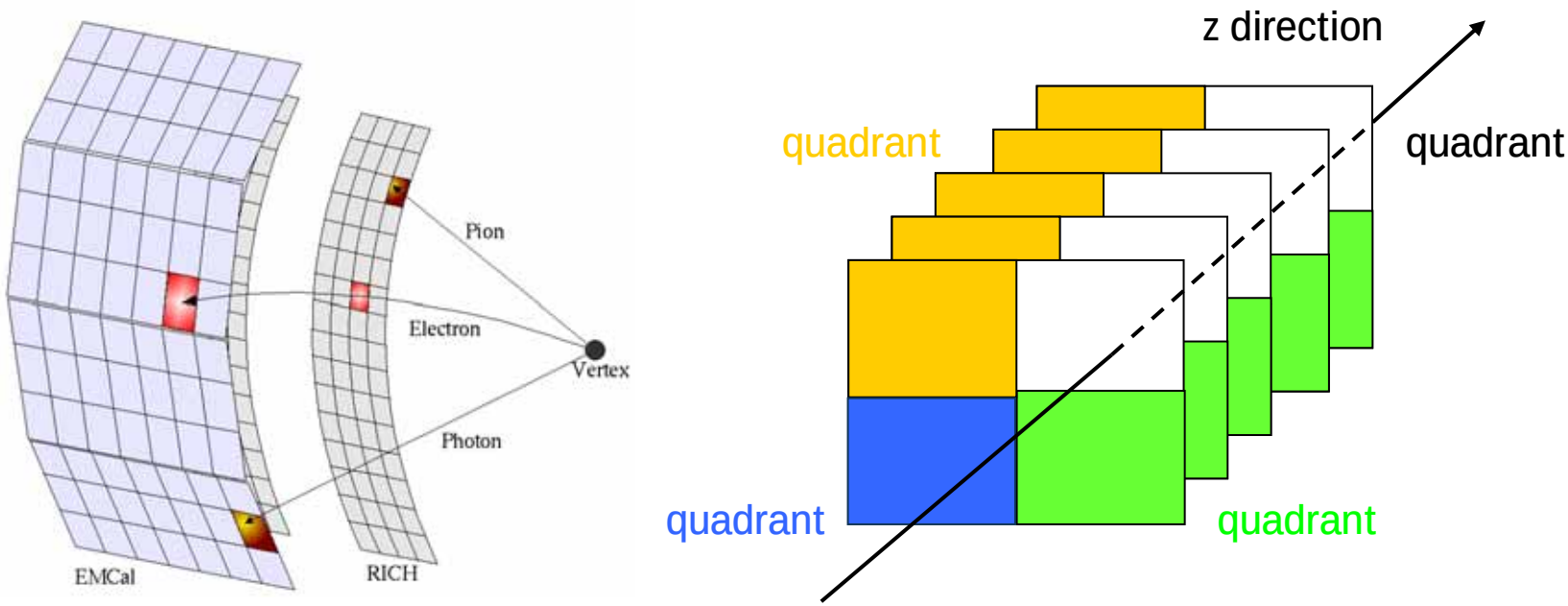




- central photon/electron/hadron arms
  - tracking chambers + EMCal/RICH/ToF
- forward muon arms
  - tracking chambers + muon identifiers
- global event characterization detectors
  - beam-beam counters, zero-degree calorimeters, ...

- PHENIX Lepton/Photon Triggers -

- real-time electron trigger with RICH and EMCal
- real-time muon trigger with μID
- real-time photon trigger with EMCal



concepts of PHENIX electron/muon triggers

- PHENIX Publication Status -

- published/accepted(/submitted) papers so far
  - Au+Au at $\sqrt{s_{NN}}$ = 130 GeV
    - global: E_t, multiplicity, p_t and E_t fluctuations, charge fluctuation
    - hadrons: identified charged, quenching, Λ, flow, HBT
    - leptons: single electron
  - Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
    - global: (p_t fluctuation)
    - hadrons: neutral pion, identified charged, proton scaling, elliptic flow, (quenching)
    - leptons: J/Ψ
  - p+p at $\sqrt{s}$ = 200 GeV
    - hadrons: neutral pion
    - leptons: J/Ψ
  - d+Au at $\sqrt{s_{NN}}$ = 200 GeV
    - hadrons: no quenching

- PHENIX Lepton/Photon Physics Status -

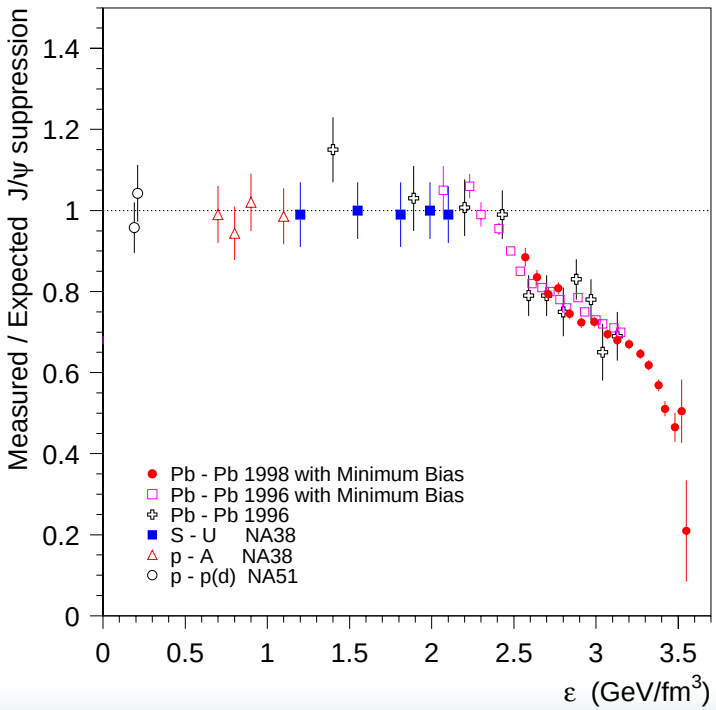
- PHENIX publications mostly on hadrons so far
- lepton/photon measurement baseline established; analyses in progress on many topics
  - a few first publications
  - preliminary presentations at, *e.g.*, JPS/APS meetings
  - new results coming soon at, *e.g.*, QM'04
- high-luminosity high-statistics run approaching
  - run 4 (2003-2004) to be long full-energy Au+Au run
    - accelerator commissioning from Nov.24, 2003; first collision expected on Dec.12, 2003; physics run planned from Jan.5, 2004
    - 300 μb^{-1} integrated luminosity anticipated to be delivered
  - PHENIX DAQ upgraded for higher data rate

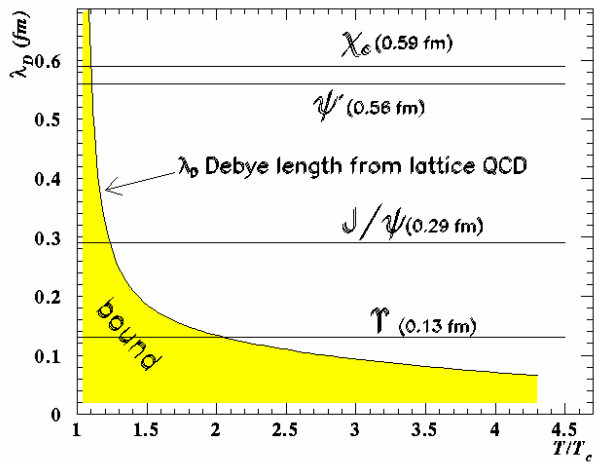
- Heavy Quark States at RHIC/PHENIX -

- anticipated probes of deconfined partonic phase
- systematic studies to overcome uncertainties
  - baseline p+p/p(d)+A measurements
  - $\sqrt{s_{NN}}$, rapidity, p_t dependences
    - PHENIX central and forward arms
      - regions with different energy densities
  - J/Ψ and Υ families
    - J/Ψ, Ψ', Υ(1S), Υ(2S+3S)
  - reference channels
    - continuum dileptons (charm, Drell Yan), single leptons (charm), single photons
  - high-statistics analyses
    - detailed centrality dependence
    - feed down effect, *e.g.* $p+p \rightarrow \chi_c \rightarrow J/\Psi + \gamma$

- Heavy Quark States at $\sqrt{s_{NN}}$ = 17.3 GeV -

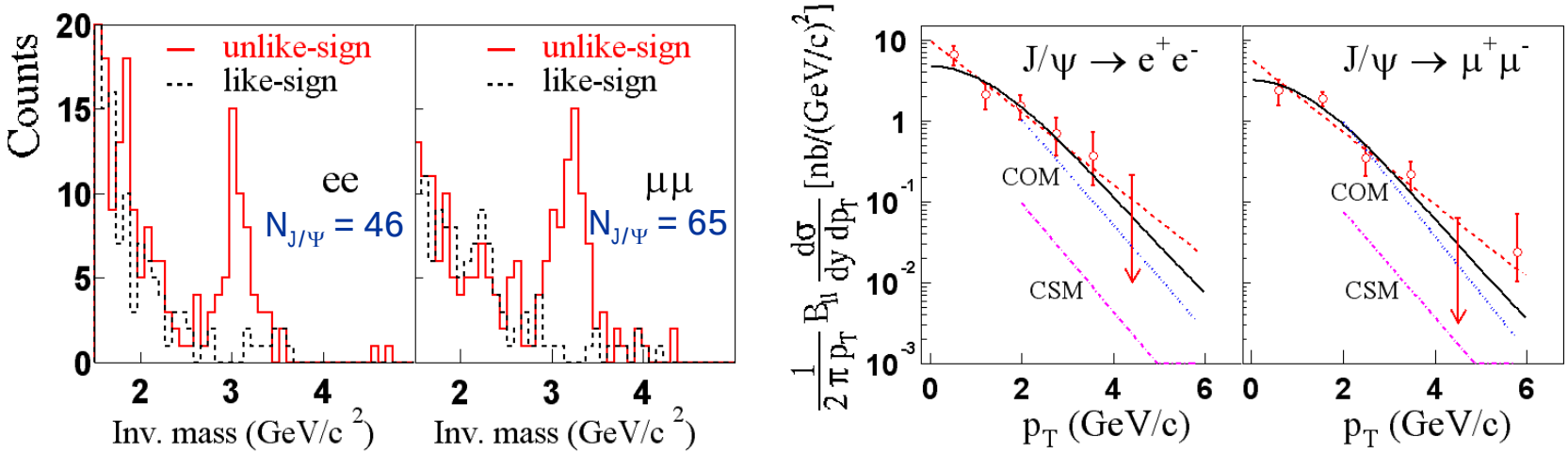
- SPS NA50, Pb+Pb
  - strong suppression of Ψ'
  - two-step J/Ψ behavior due to χ_c and J/Ψ dissolution ?





Pb+Pb→J/Ψ+X at $\sqrt{s_{NN}}$ = 17.3 GeV
NA50 PLB477, 28 (2000)

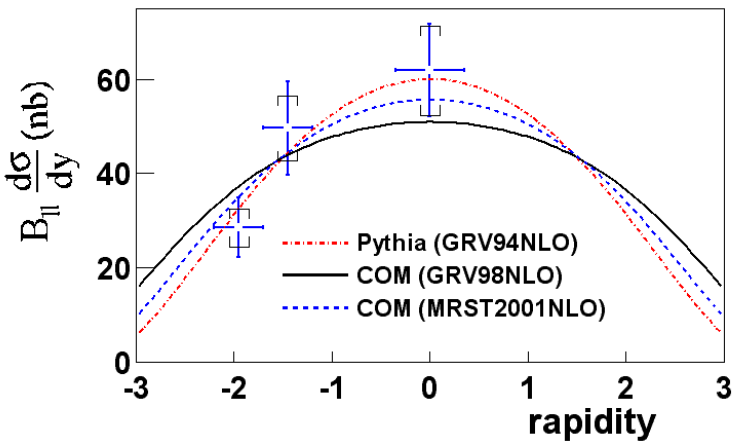
- J/Ψ Baseline: p+p -

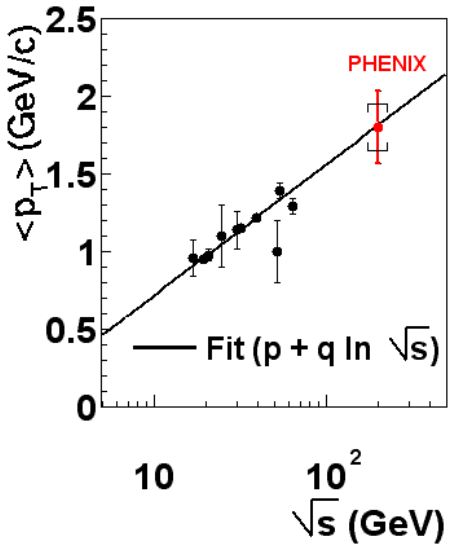


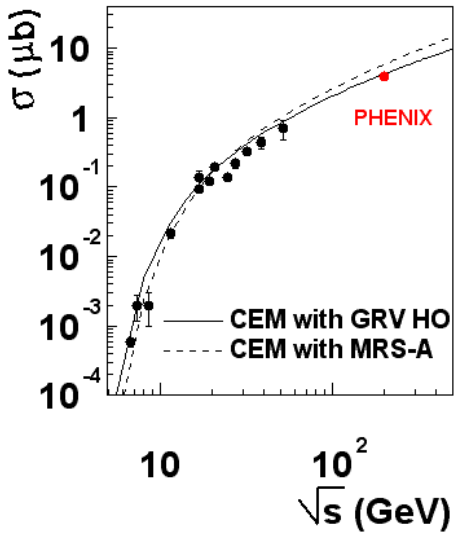
p+p→J/Ψ+X at $\sqrt{s_{NN}}$ = 200 GeV
nucl-ex/0307019; submitted to PRL

- clear J/Ψ signals in both central and forward arms
  - expected mass resolutions
  - mean transverse momentum:
    1.80 ± 0.23 (stat.) ± 0.16 (sys.) GeV/*c*
  - integrated cross section:
    3.99 ± 0.61 (stat.) ± 0.58 (sys.) ± 0.40 (abs.) μb

- Comparison with Models and Previous Data -



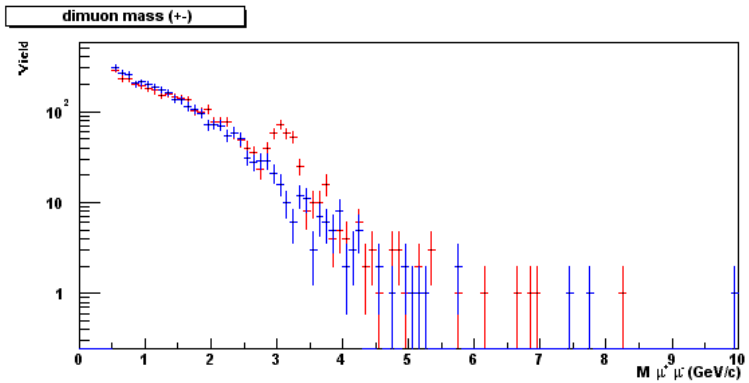




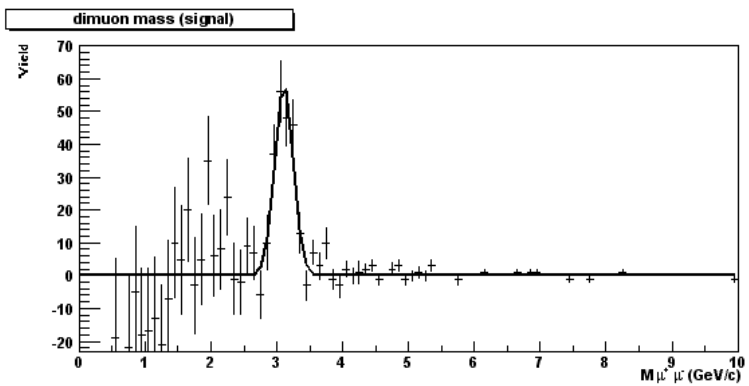
p+p→J/Ψ+X at $\sqrt{s_{NN}}$ = 200 GeV
nucl-ex/0307019; submitted to PRL

- good agreement with
  - lower $\sqrt{s}$ data and phenomenological extrapolation
  - color evaporation model

- More J/Ψ Baseline: d+Au -



opposite-sign pairs
same-sign pair background

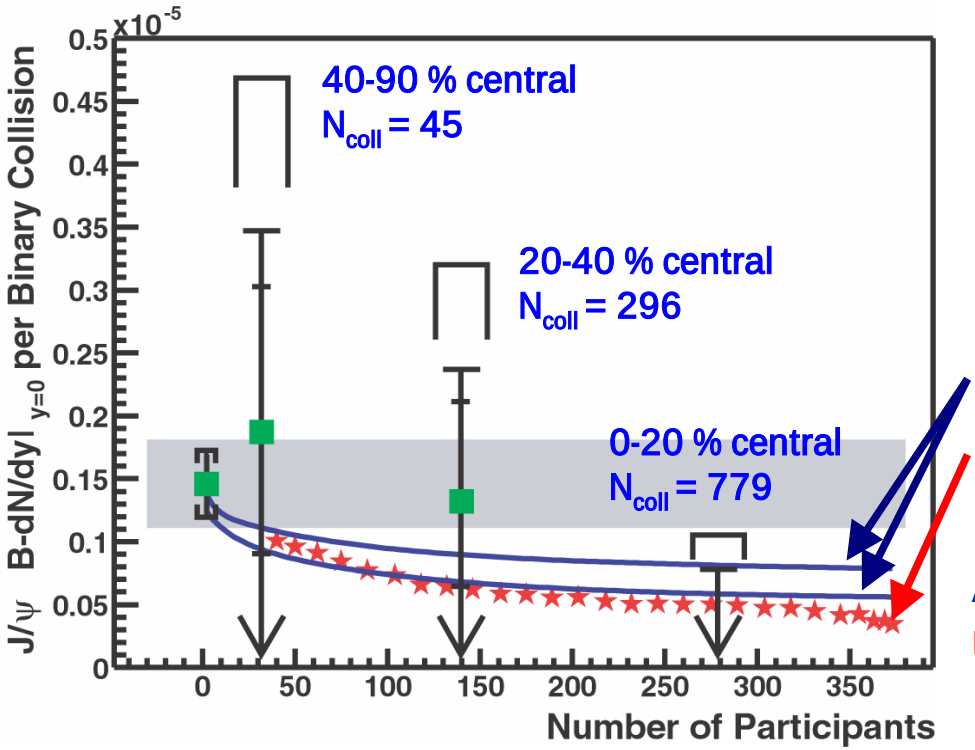


~ 211 J/Ψ's
mass: 3.11 ±0 .02 GeV
width: 143 ± 14 MeV

$d+Au \rightarrow J/\Psi \rightarrow \mu^+ \mu^-$ at $\sqrt{s_{NN}}$ = 200 GeV

- analysis in progress
  - only ~ 1/3 of d+Au data shown here

- J/Ψ: Run 2 Au+Au -



normal nuclear absorption

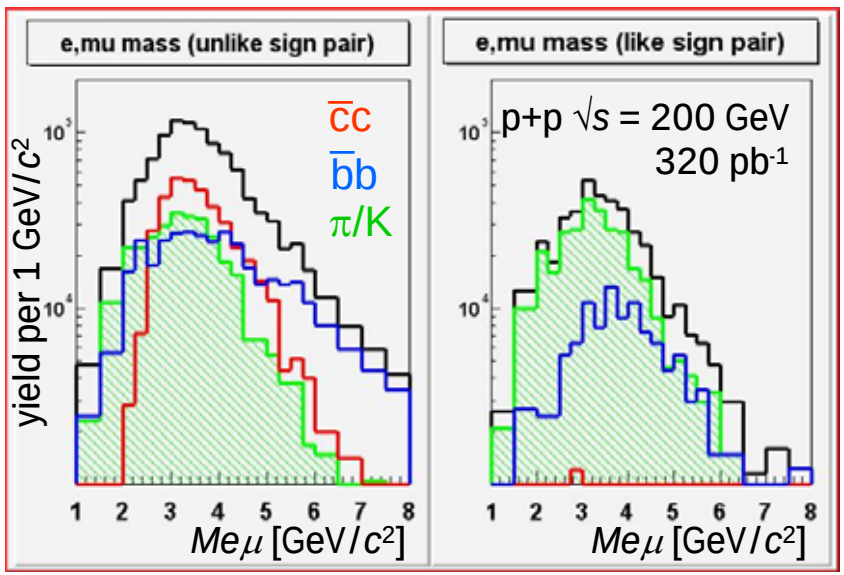
SPS NA50 normalized to p+p point

Au+Au→J/Ψ→e⁺e⁻ at $\sqrt{s_{NN}}$ = 200 GeV
nucl-ex/0305030; accepted for PRC

- not much statistics, but
  - binary scaling disfavored
  - inconsistent with enhancement scenarios
    - *e.g.* coalescence model, *cf.* PRC 63, 054905 (2001)

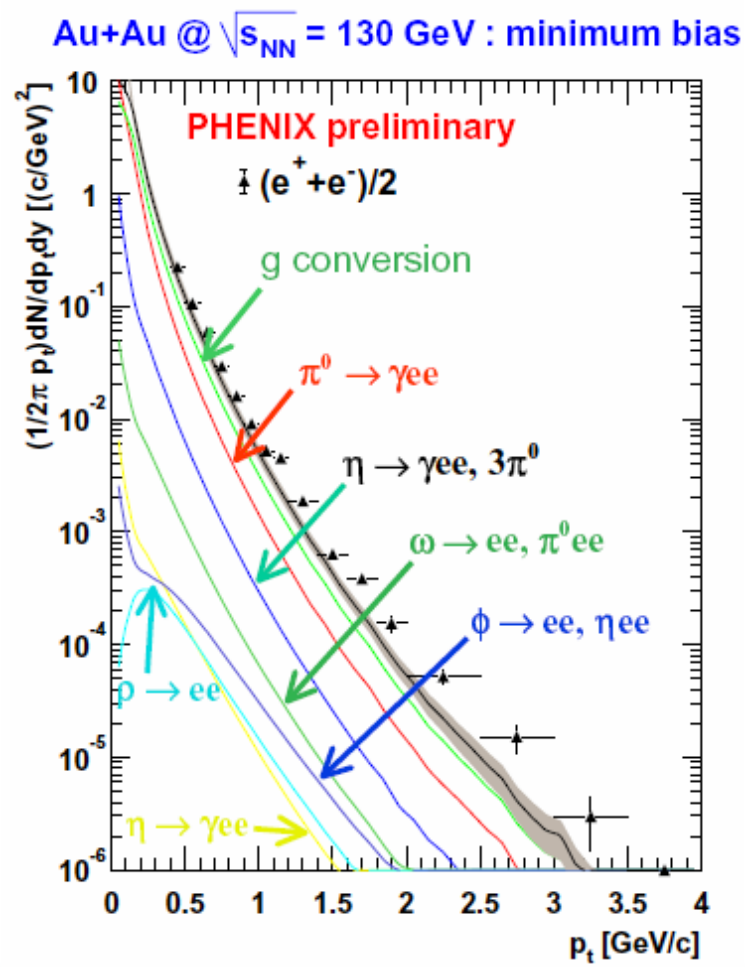
- Open Heavy Flavors at RHIC/PHENIX -

- valuable probes of QCD dynamics in early stages
  - thermal charm production
  - quark energy loss
  - reference of heavy quark states and continuum dileptons
- observables include:
  - high p_t leptons
  - high-mass dileptons
  - e-μ coincidence



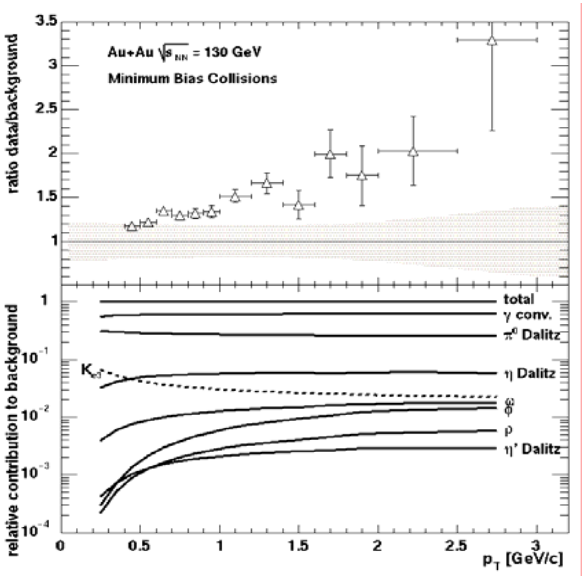
- Open Heavy Flavors via Single Electrons -

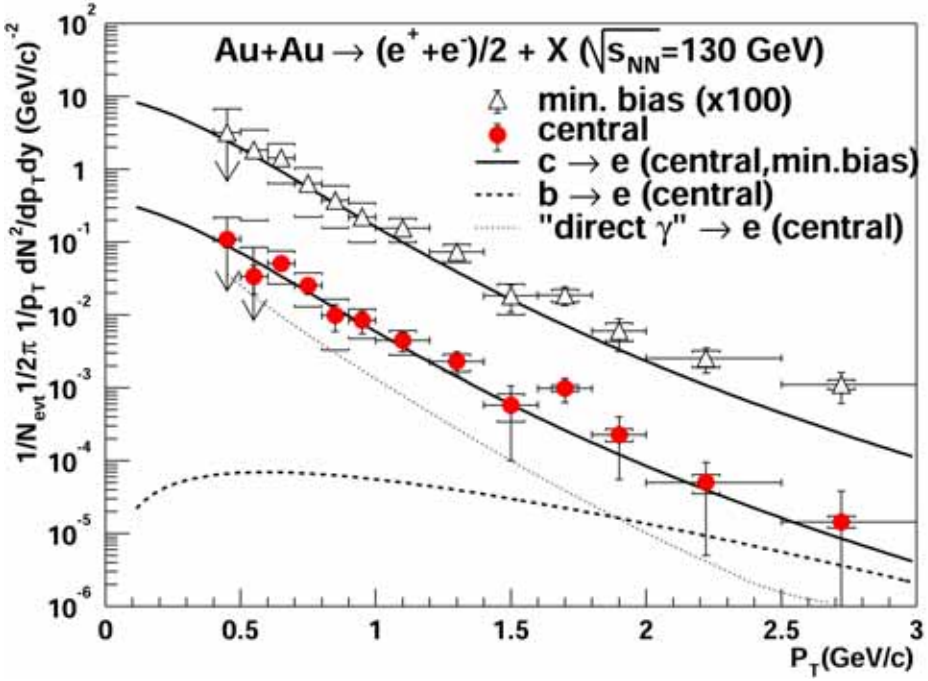
- inclusive electrons dominated by photon conversions and hadron Dalitz decays
- excess from cocktail attributed to charm



Au+Au→$e^{\pm}$+X at $\sqrt{s_{NN}}$ = 130 GeV
cf. PHENIX PRL88, 192303 (2002)

- Non-Photonic (Heavy Flavor) Electrons -

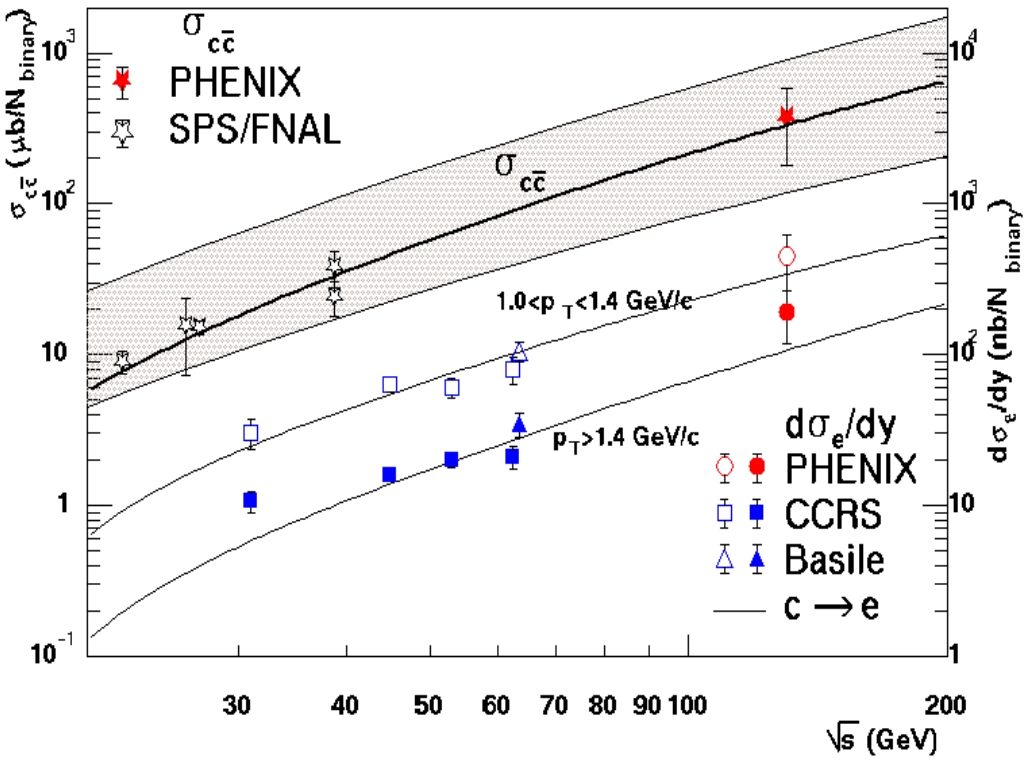




Au+Au→$e^{\pm}$ at $\sqrt{s_{NN}}$ = 130 GeV
PHENIX PRL88, 192303 (2002)

- agreement with PYTHIA with binary scaling
  - both in minimum-bias and central Au+Au
    - no high p_t suppression observed (!)

- Comparison with Models and Previous Data -

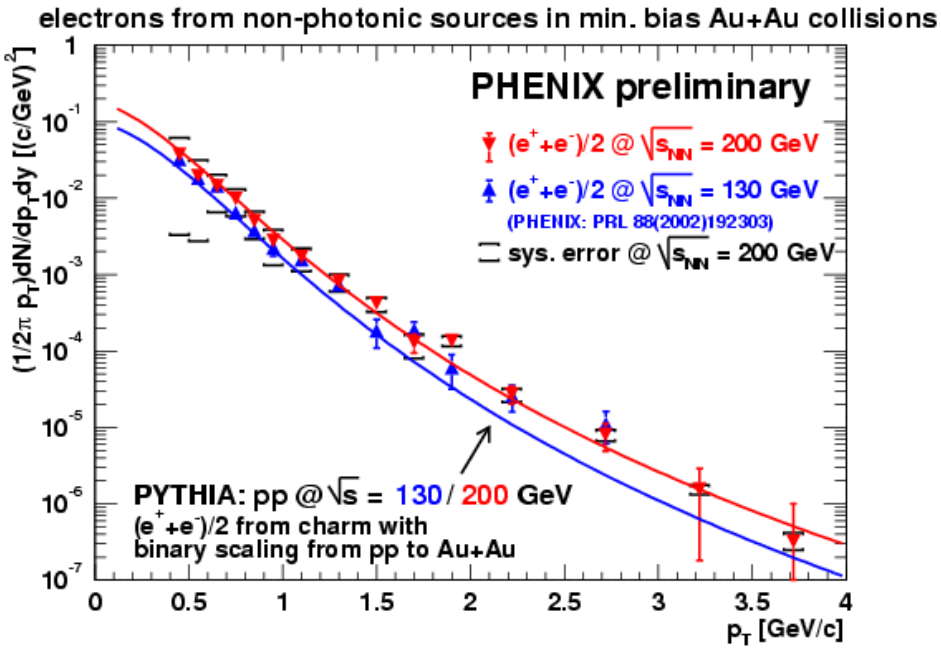


solid curves: PYTHIA
shaded band: NLO pQCD

Au+Au→$e^{\pm}$ at $\sqrt{s_{NN}}$ = 130 GeV
PHENIX PRL88, 192303 (2002)

- consistent with $\sqrt{s}$ systematics and binary scaling
  - within large systematic uncertainties

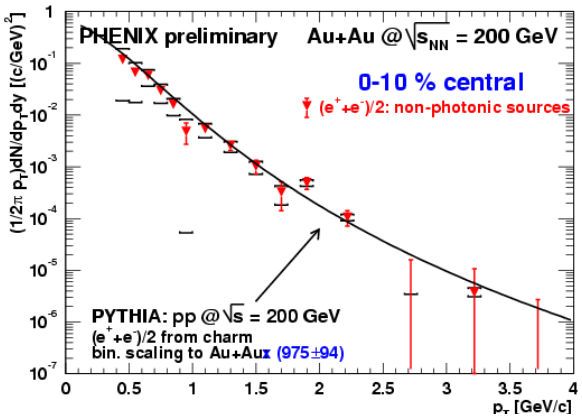
- Converter Analysis of Open Heavy Flavors -

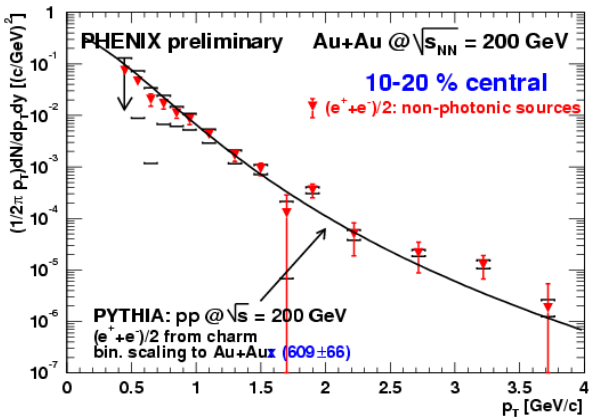


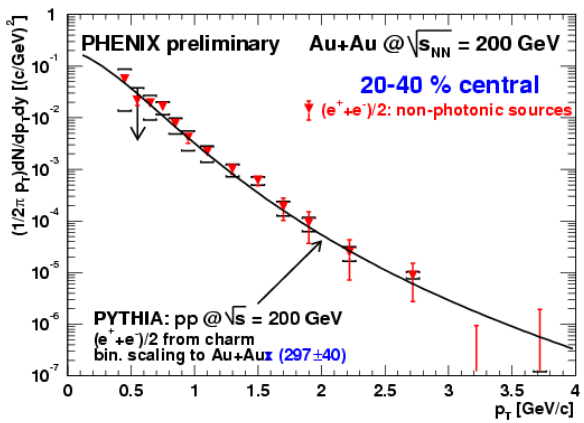
Au+Au→e±
PHENIX preliminary

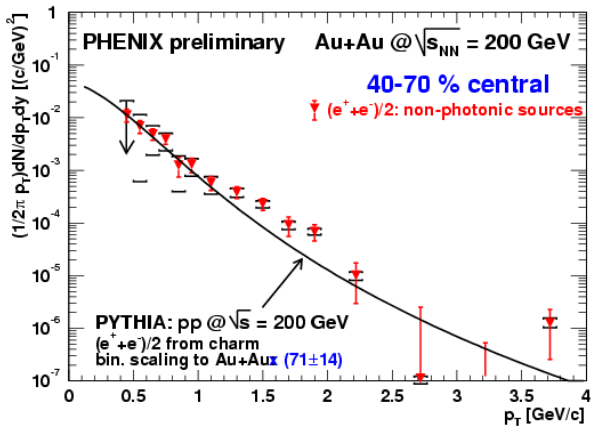
- photonic component subtracted from inclusive
  - real photon spectrum measured with photon converter
    - virtual-photon sources are also real-photon sources
- consistent with PYTHIA with binary scaling

- No Suppression Observed for Open Charms -









Au+Au→$e^{\pm}$
at $\sqrt{sNN}$ = 200 GeV
PHENIX preliminary

- consistent with PYTHIA in all centralities (!)

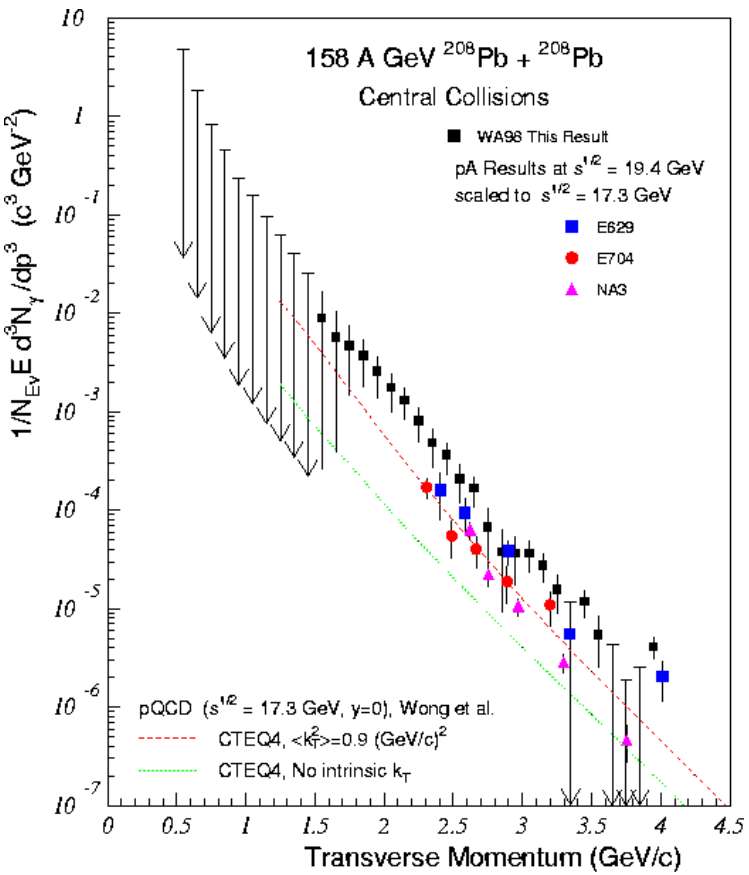
- More Lepton Channels at RHIC/PHENIX -

- light vector mesons (ϕ, ω, ρ)
  - probes of chiral symmetry restoration
    - changes in masses, widths, branching ratios
  - experimentally challenging due to limited S/B ratios
    - analyses in progress on Au+Au/d+Au/p+p data
    - material in central arm aperture reduced in Run 4
    - prime goal of PHENIX future upgrade
- thermal dileptons
  - possible mass window at 1-2 GeV/c^2
  - *cf.* direct photons
  - S/B ratio critical as with light vector mesons

- Direct Photons at RHIC/PHENIX -

- photons sensitive to
  - initial parton distribution
    - initial k_t (↑)
    - k_t broadening (↑)
    - shadowing (↓)
    - saturation (↓)
  - final state parton/hadron rescattering
    - thermal radiation (↑)
    - jet/parton radiation (↑)
- experimental virtues
  - particle identification to very high transverse momentum
  - photons and neutral mesons measured in same detector
    - neutral mesons additionally sensitive to final state effects
    - useful to distinguish initial/final state effects

- Direct Photon Observation at $\sqrt{s_{NN}}$ = 17.3 GeV -



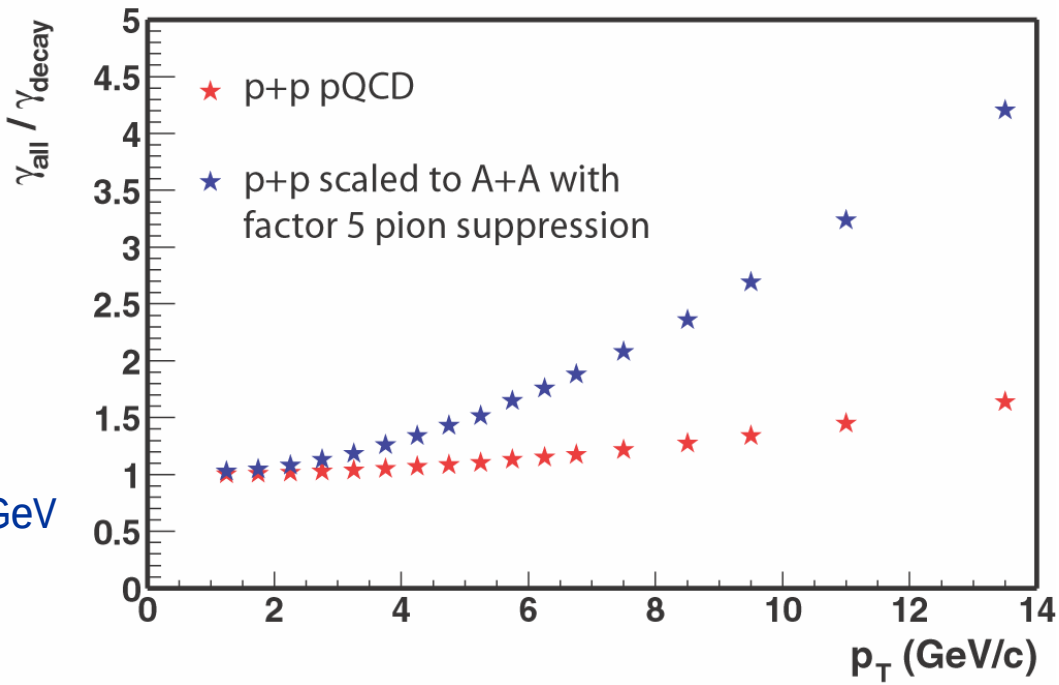
- SPS WA98, central Pb+Pb
- compared to p+A data
  - $\sqrt{s}$ and binary scaling
- similar spectral shape
- p-induced reproduced by NLO pQCD + intrinsic k_t
- factor 2-3 enhancement in central Pb+Pb

Pb+Pb$\rightarrow\gamma$+X at $\sqrt{s_{NN}}$ = 17.3 GeV
WA98 PRL 85, 3595 (2000)

- pQCD Direct Photon Predictions for RHIC -

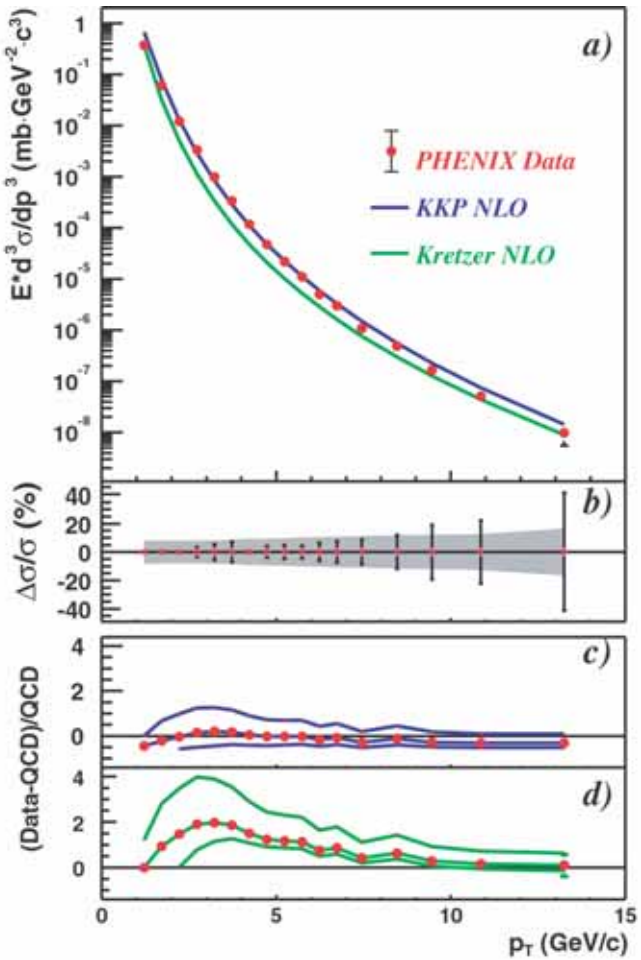
- large direct photon signal expected
  - (photons observed) / (photons from hadron decays)
  - except if photons also suppressed (initial state effect)

pQCD with jet quenching
p+p→γ+X at $\sqrt{s_{NN}}$ = 200 GeV
W.Vogelsang



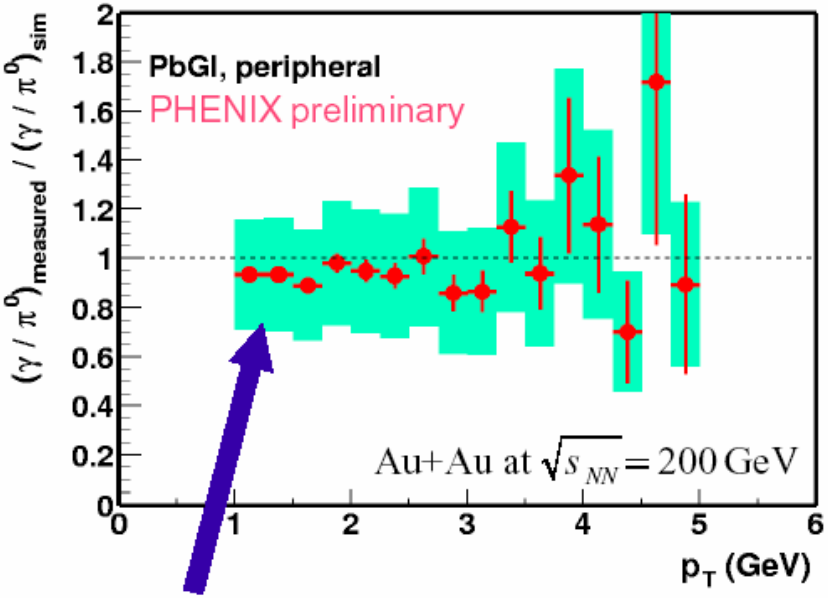
- Direct Photon Baseline -

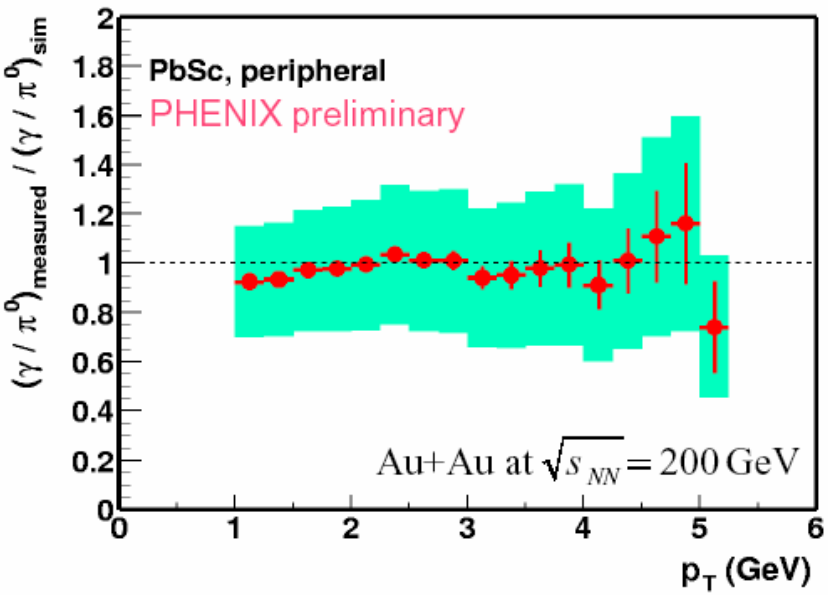
- p+p neutral pion spectra to high p_t ~ 12 GeV/c
- good agreement with NLO pQCD
  - no intrinsic k_t included



p+p→π^0+X
hep-ex/0304038; accepted for PRL

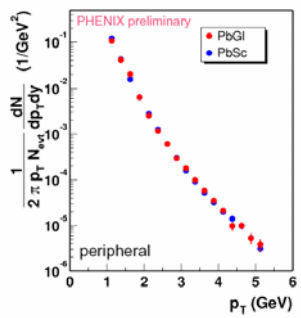
- Inclusive Photons: Peripheral Au+Au -



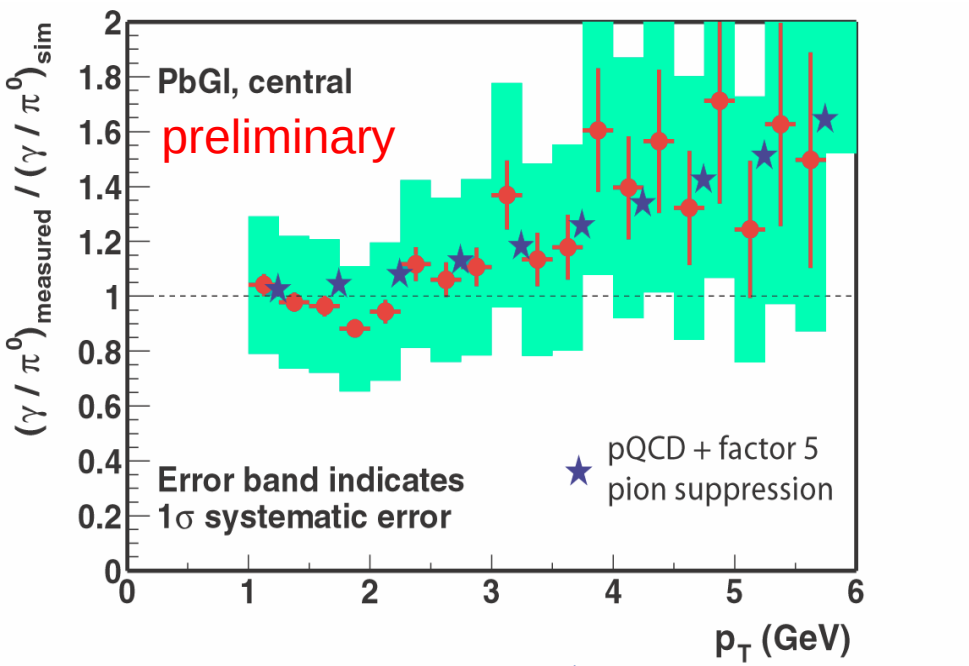


Boxes: 1σ systematic error

- two independent detectors consistent
- consistent with no photon excess
  - based on measured neutral pion spectrum



- Inclusive Photons: Central Au+Au -



central Au+Au→γ+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary

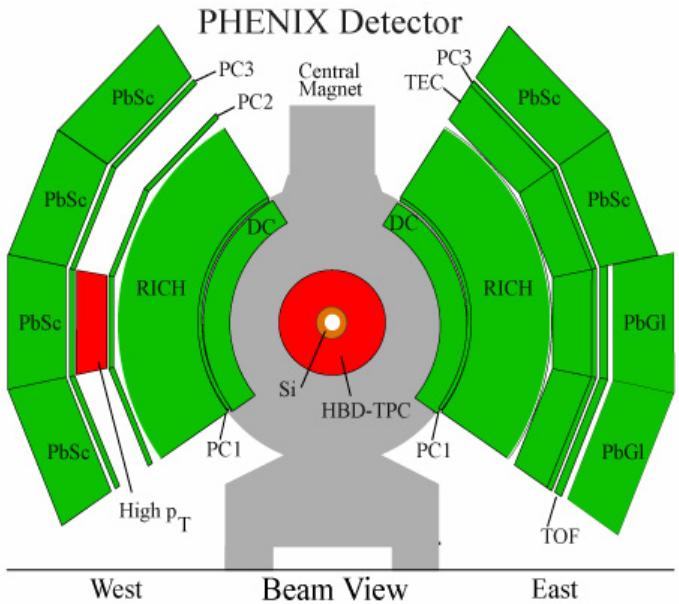
- no direct photon excess seen within errors
- systematic errors to be reduced in further analysis

- Summary as of October, 2003, and Outlook -

- hadrons (jets) exciting enough at RHIC
  - *cf.* precedent presentation by T.Chujo
  - "it's a quark-gluon plasma. period." (M.Gyulassy)
- further insights arriving via lepton/photon channels
  - penetrating probes of early stages
    - J/Ψ, Ψ', ϒ, charm, beauty, ϕ, ω, ρ , thermal e^+e^-, $\mu^+\mu^-$, direct γ
  - baseline established; already interesting clues
- coming high-statistics run(s) essential and exciting
  - run 4 (2003-2004) to be the rare-process run
  - stay tuned; more results appearing really soon
- ... plus upgrade plans and beyond

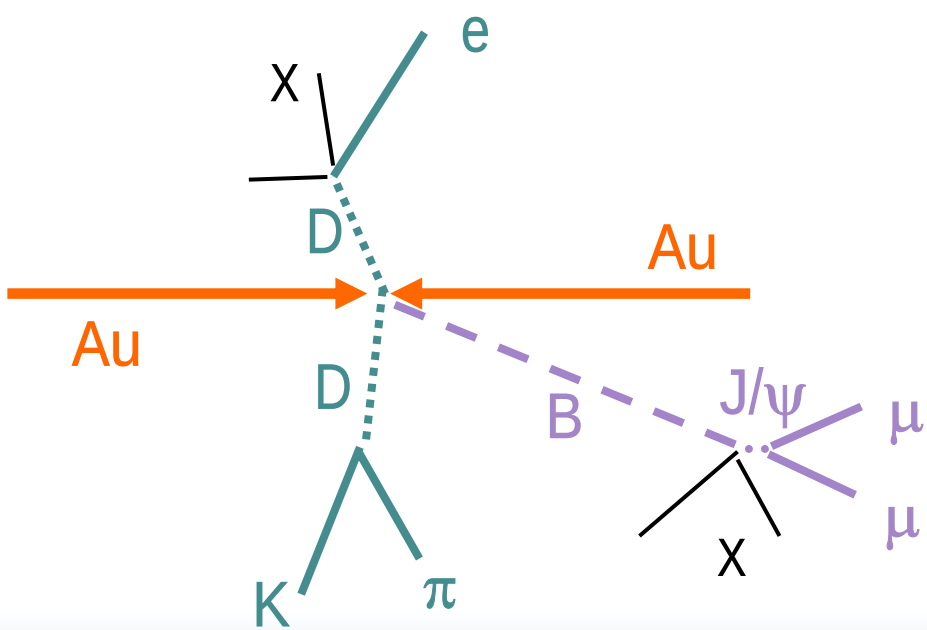
- Physics Programs with PHENIX Upgrades -

- high p_t identified hadrons
  - aerogel + ToF
- open charm and beauty
  - silicon vertex tracker
- low-mass dielectrons
  - hadron blind detector + TPC
- high p_t hadrons and jets
  - TPC + silicon vertex tracker
- high p_t muons (Υ, W)
  - enhanced muon trigger



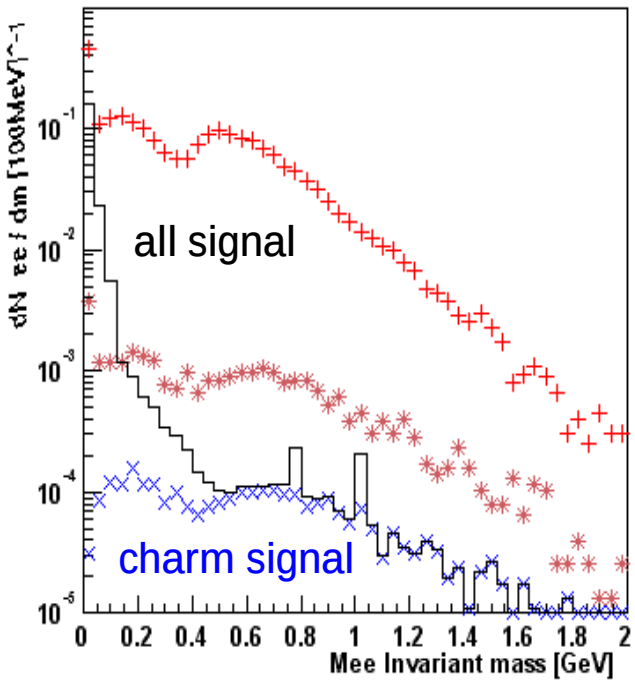
- Open Charm and Beauty with SVT -

- clean identification by decay vertex detection
  - beauty and low p_t charm via displaced $e^{\pm}$ and/or $\mu^{\pm}$
  - high p_t charm via $D \rightarrow \pi K$
  - beauty via displaced J/Ψ



- Low-Mass Dielectrons with HBD/TPC -

- charm S/B ratio to improve by > 20
  - by rejecting photon conversions and Dalitz decays
    - small opening-angle and/or mass dielectrons to be rejected



$\gamma \rightarrow e^+e^-$

$\pi^0 \rightarrow \gamma\, e^+e^-$

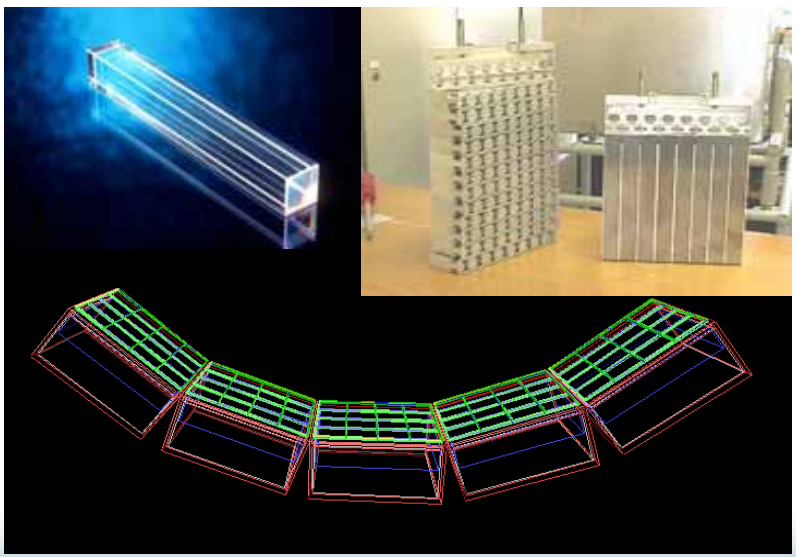
"combinatorial pairs"

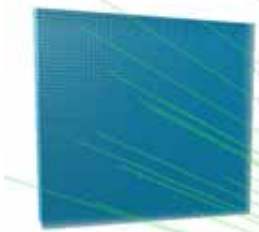
total background

irreducible charm background

- Fine-Granularity EM Calorimeter Option -

- *e.g.* ALICE photon spectrometer modules
  - high granularity and resolution with $PbWO_4$ crystals
  - must be powerful also at RHIC
    - direct photons
    - diphotons
- *n.b.* not presently in PHENIX future plan





possible $PbWO_4$ photon spectrometer at RHIC

coverage:	1 m × 1 m
crystal size:	20 × 20 × 200 mm^3
array size:	50 × 50
distance from IP:	3 m
η coverage:	$\pm$ 0.17

- (Real) Summary and Concluding Remarks -

- RHIC presenting rich harvest of physics
  - study of QCD in extreme conditions and scales
    - especially high energy density frontier
  - medium with strong final state effects formed in Au+Au
    - observed via hadron jet quenching and its absence in d+Au
- deeper insights coming via lepton/photon channels
  - most promising and unique to PHENIX
    - heavy quark states (J/Ψ, Ψ', Υ) for deconfinement
    - open heavy flavors (charm, beauty) for QCD dynamics
    - light vector mesons (ϕ, ω, ρ) for chiral symmetry restoration
    - thermal dileptons (e^+e^-, $\mu^+\mu^-$) for equation of state
    - direct photons (γ) for equation of state
- stay tuned; more results in near- and further-future
  - detector upgrades also under R&D/construction