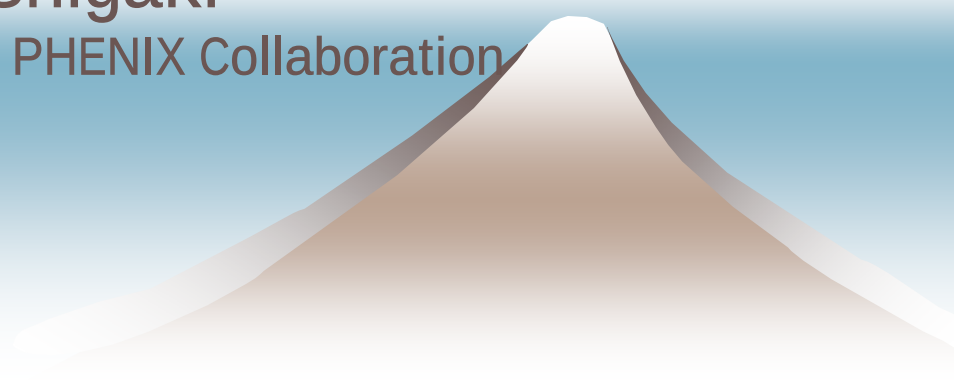
Experimental Highlights in Recent/Future Relativistic Heavy-Ion Programs

Symposium and Workshop on the QGP and HI Physics at RHIC and LHC
on
July 25, 2003
at
University of Tokyo

Kenta Shigaki
Hiroshima University / PHENIX Collaboration



- Outline -

- achievements at RHIC
  - Au+Au, d+Au and p+p up to $\sqrt{s_{NN}}$ = 200 GeV
    - hadron suppression at high p_t (jet quenching)
    - modification of angular correlations
- ongoing and near-future programs at RHIC
  - high statistics Au+Au (and p+p)
    - heavy quark states (color Debye screening)
    - low-mass dileptons (chiral restoration)
    - direct photons (thermal radiation)
  - more systematics with A and energy scans
- future programs at LHC
  - expectations and ongoing activities

- Disclaimer -

- focus on PHENIX and (a very limited part of) ALICE
  - cannot cover all RHIC and LHC programs in 45 minutes
- focus on data presentation
  - theoretical pictures better handled by audiences

- Relativistic Heavy Ion Collider -

- 2 independent super-conducting rings
- 3.83 km circumference
- up to 100 A GeV Au and/or 250 GeV (polarized) p
- 6 intersections
- 4 experiments
  - BRAHMS/PHENIX/PHOBOS/STAR

- Pioneering High Energy Nucl. Interaction Exp. -

- sensitive to maximal set of probes
  - photons/electrons/ muons/hadrons
- access to essentially all time scales
- high rate capability and multi-level selective triggering
  - rare processes

- PHENIX Worldwide -

PHENIX

Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
	SUBATECH, Ecòle des Mines at Nantes, Nantes
Germany	University of Münster, Münster
Hungary	Central Research Institute for Physics (KFKI), Budapest
	Debrecen University, Debrecen
	Eötvös Loránd University (ELTE), Budapest
India	Banaras Hindu University, Banaras
	Bhabha Atomic Research Centre, Bombay
Israel	Weizmann Institute, Rehovot
Japan	Center for Nuclear Study, University of Tokyo, Tokyo
	Hiroshima University, Higashi-Hiroshima
	KEK, Institute for High Energy Physics, Tsukuba
	Kyoto University, Kyoto
	Nagasaki Institute of Applied Science, Nagasaki
	RIKEN, Institute for Physical and Chemical Research, Wako
	RIKEN-BNL Research Center, Upton, NY
	University of Tokyo, Bunkyo-ku, Tokyo
	Tokyo Institute of Technology, Tokyo
	University of Tsukuba, Tsukuba
	Waseda University, Tokyo
S. Korea	Cyclotron Application Laboratory, KAERI, Seoul
	Kangnung National University, Kangnung
	Korea University, Seoul
	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
Russia	Institute of High Energy Physics, Protovino
	Joint Institute for Nuclear Research, Dubna
	Kurchatov Institute, Moscow
	PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund

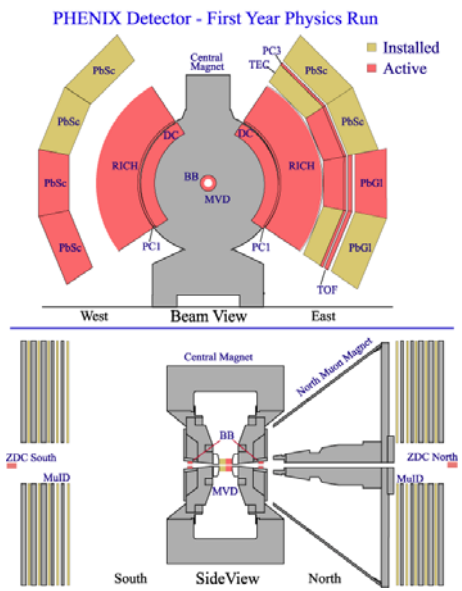
12 Countries; 57 Institutions; 460 Participants*

USA	Abilene Christian University, Abilene, TX
	Brookhaven National Laboratory, Upton, NY
	University of California - Riverside, Riverside, CA
	University of Colorado, Boulder, CO
	Columbia University, Nevis Laboratories, Irvington, NY
	Florida State University, Tallahassee, FL
	Georgia State University, Atlanta, GA
	University of Illinois Urbana Champaign, Urbana-Champaign, IL
	Iowa State University and Ames Laboratory, Ames, IA
	Los Alamos National Laboratory, Los Alamos, NM
	Lawrence Livermore National Laboratory, Livermore, CA
	University of New Mexico, Albuquerque, NM
	New Mexico State University, Las Cruces, NM
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

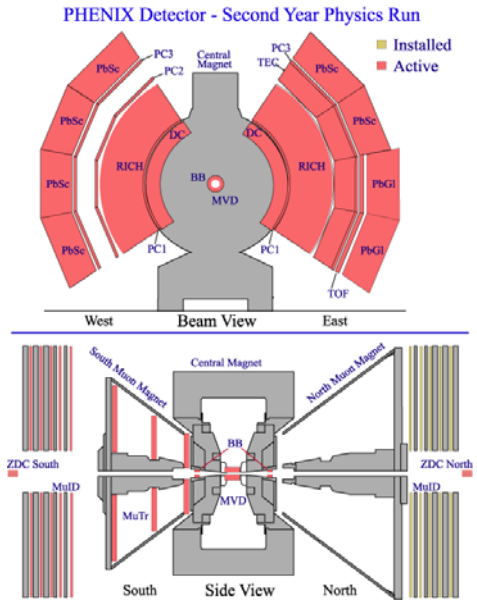
*as of July 2002

- RHIC/PHENIX Run History -

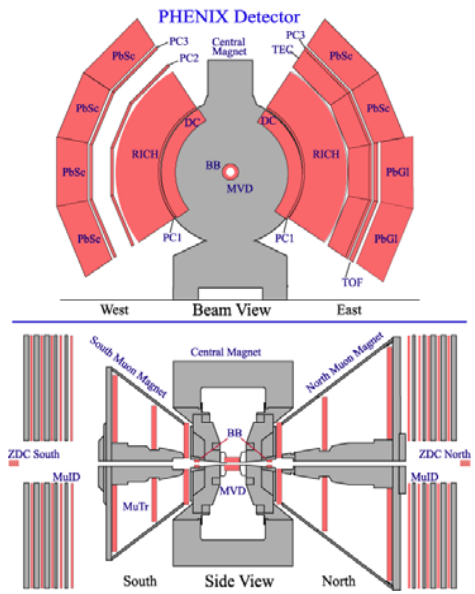
2000



2001/2002



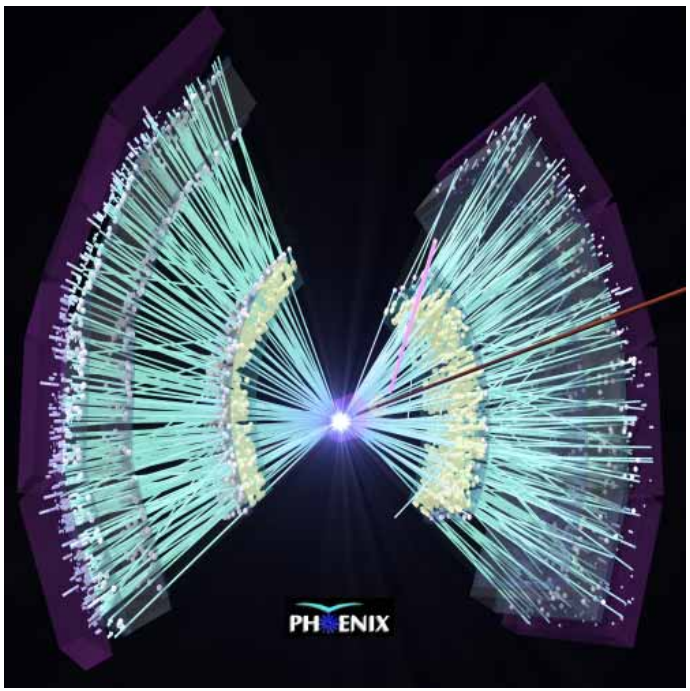
2002/2003



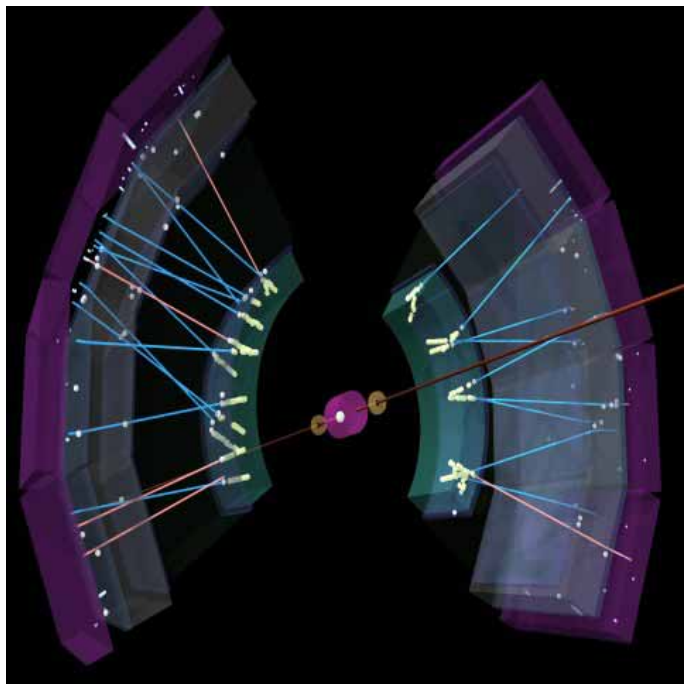
run	year	species	$\sqrt{s_{NN}}$	$\int Ldt$
01	2000	Au+Au	130 GeV	1 mb^{-1}
02	2001/02	Au+Au	200 GeV	24 mb^{-1}
		p+p	200 GeV	0.15 pb^{-1}
03	2002/03	d+Au	200 GeV	2.74 nb^{-1}
		p+p	200 GeV	0.35 pb^{-1}

- Collisions as Seen by PHENIX Central Arms -

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV



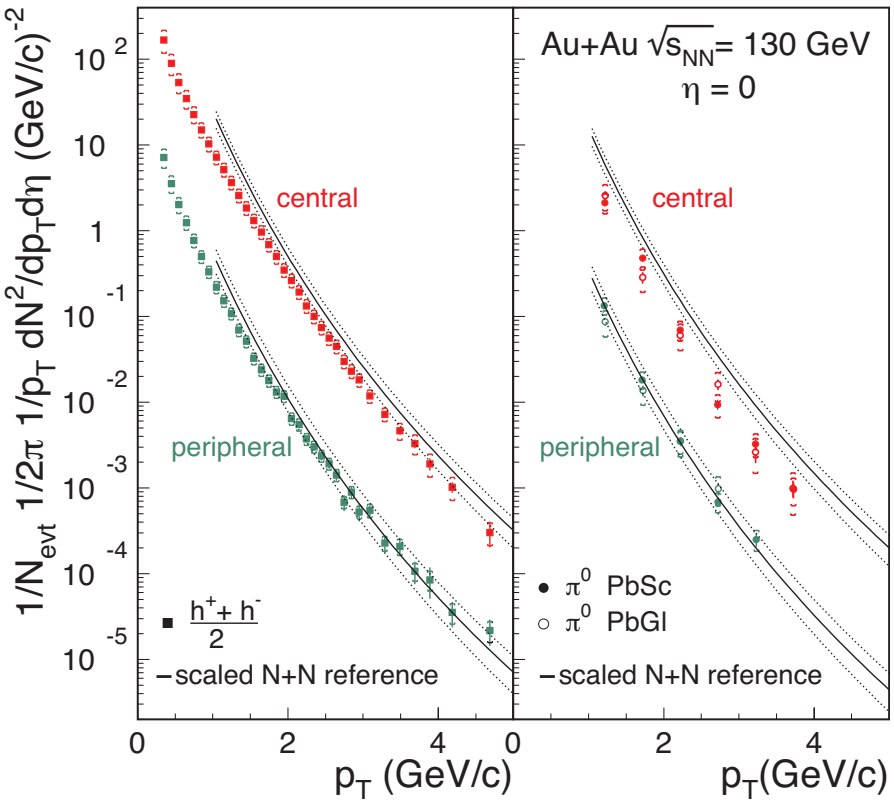
d+Au at $\sqrt{s_{NN}}$ = 200 GeV



- ~ 5000 charged particles produced in a central Au+Au collision at $\sqrt{s_{NN}}$ = 200 GeV

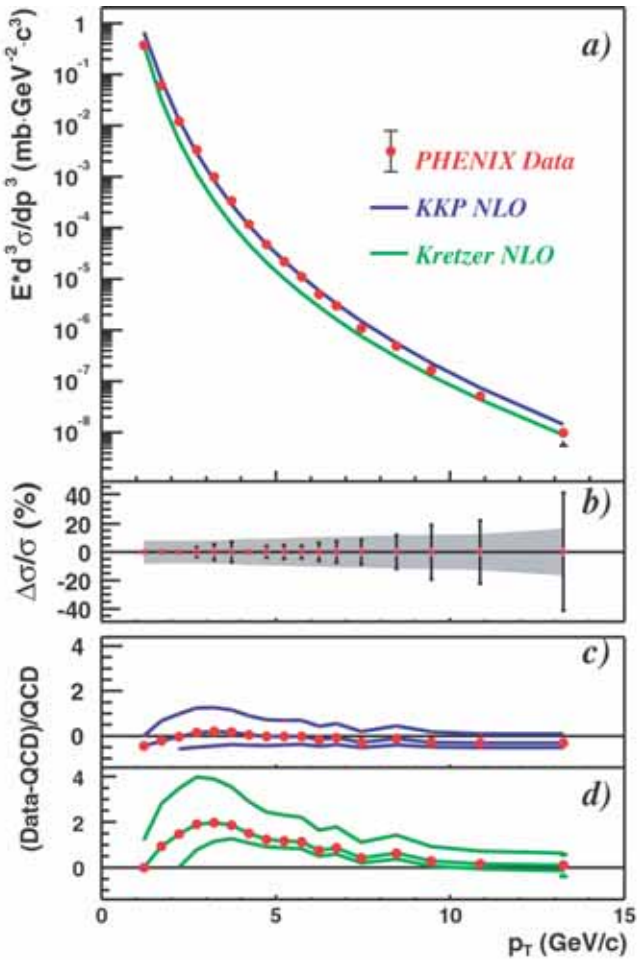
- High p_t Hadron Results in RHIC Year-1 -

- measurements up to 4-5 GeV/c in p_t
  - charged hadrons and neutral pions
- nominally expected from hard scattering
  - binary collision scaling extrapolated from UA1 data



- Hard Scattering as Probe of Medium -

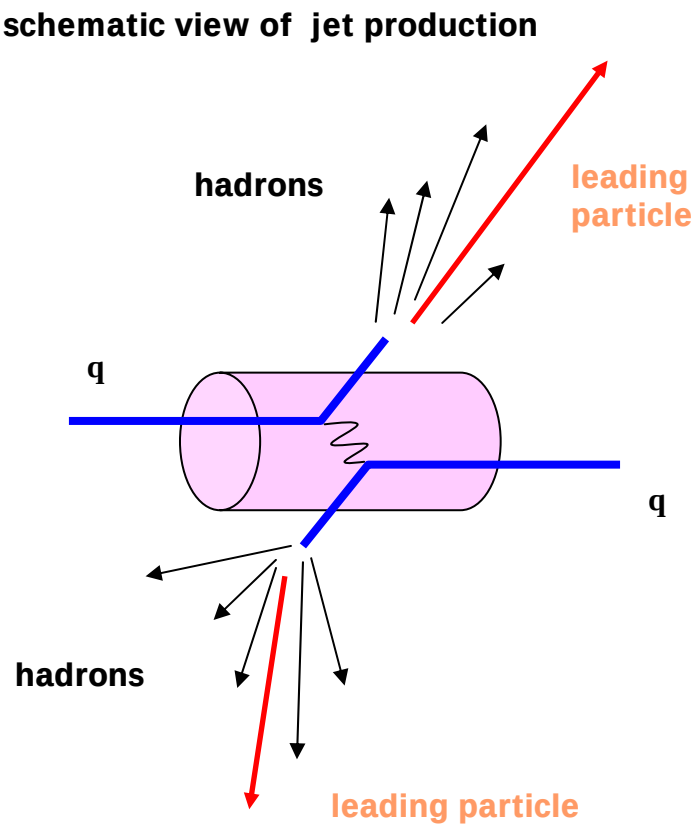
- different mechanisms for different regions
  - soft production
    - responsible at low p_t
    - thermally shaped
  - hard scattering
    - responsible at high p_t
    - probe of medium
    - well calibrated



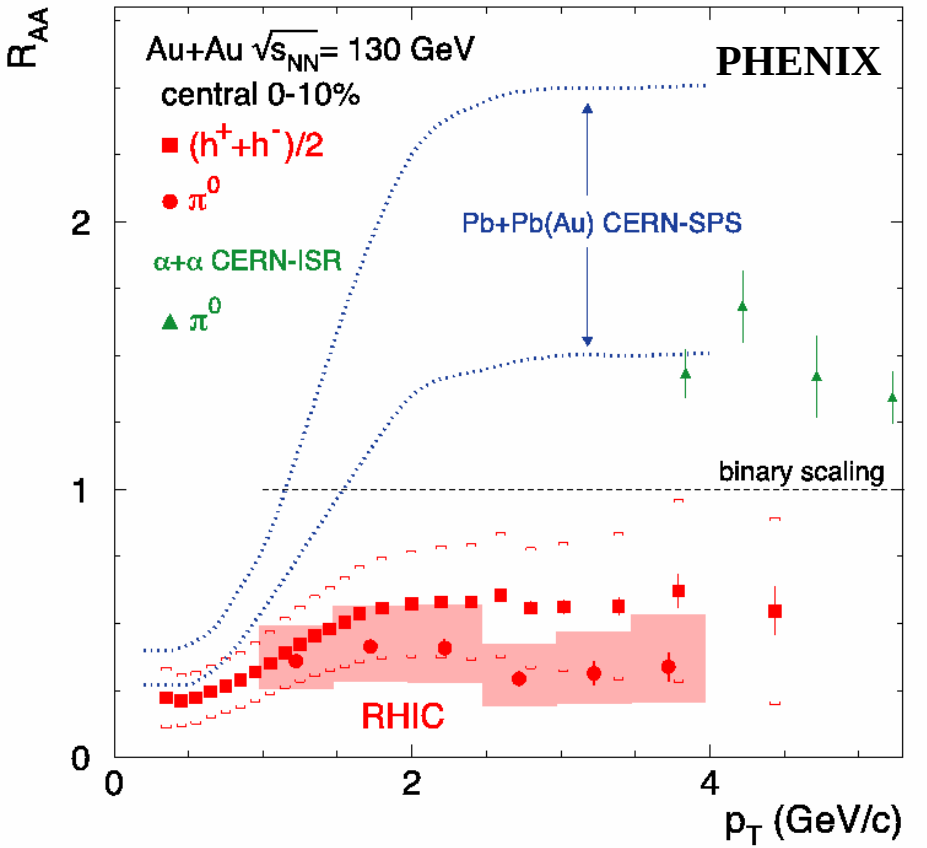
$p+p \rightarrow \pi^0+X$
hep-ex/0304038

- Probes of Partonic Matter -

- energy loss of scattered partons
  - suppression of high p_t hadrons and jets
  - modification of angular correlation
- modification of fragmentation process
  - changes of particle composition



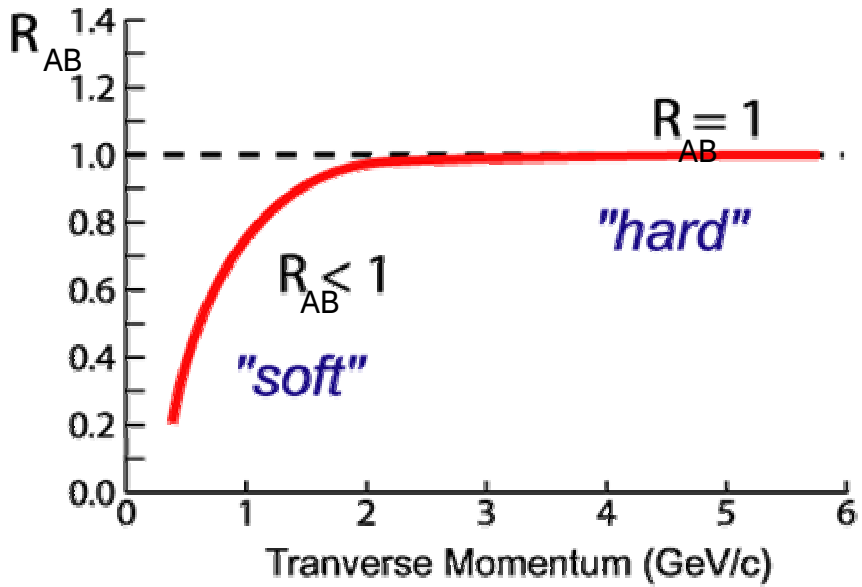
- Discovery of High p_t Hadron Suppression -



- suppression observed in central Au+Au collisions
  - scattered parton interaction in dense medium ?

- Nuclear Modification Factor R_{AB} -

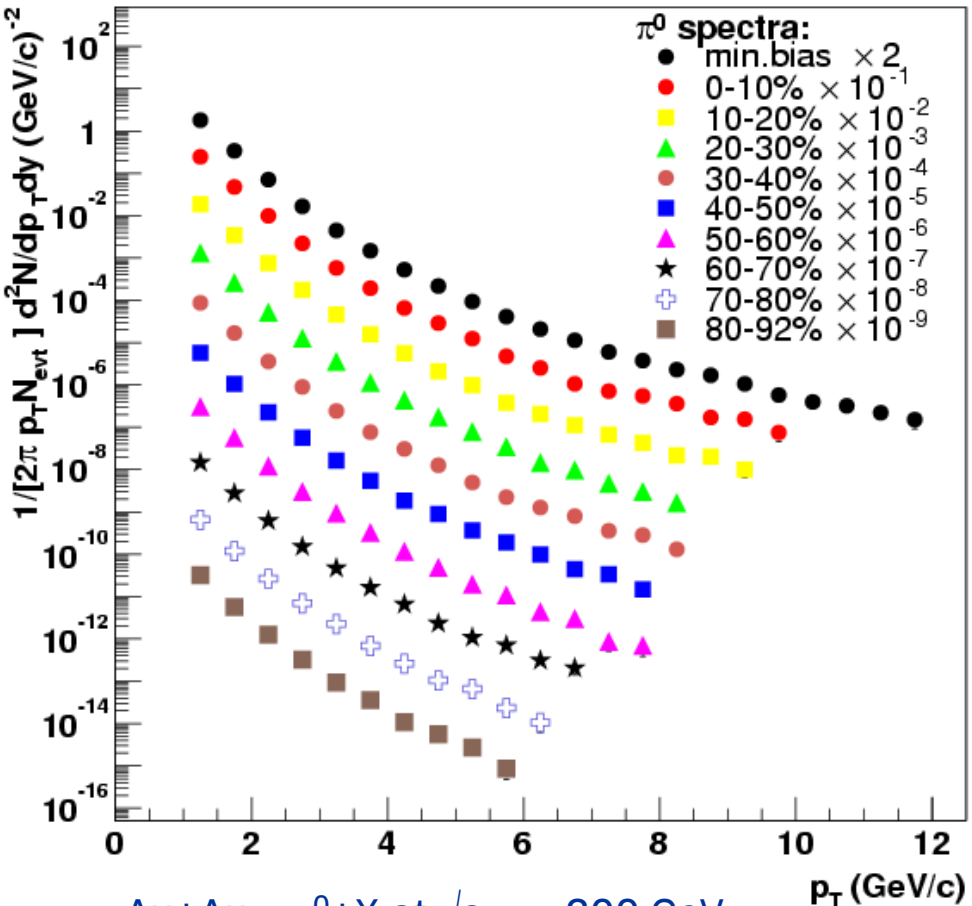
$$R_{AB} = \frac{\mathbf{d}N_{\mathbf{AB}} / \mathbf{d}p_T\mathbf{d}y}{\langle N_{coll} \rangle / \sigma_{\mathbf{NN}}^{\mathbf{inel}} \cdot \mathbf{d}\sigma_{\mathbf{pp}} / \mathbf{d}p_T\mathbf{d}y}$$



- in absence of nuclear effects
  - $R_{AB} < 1$ at low p_t (soft physics regime)
  - $R_{AB} = 1$ at high p_t (hard scattering regime)
- "suppression" (enhancement, *e.g.* Cronin effect)
  - $R_{AB} < 1$ (> 1) at high p_t

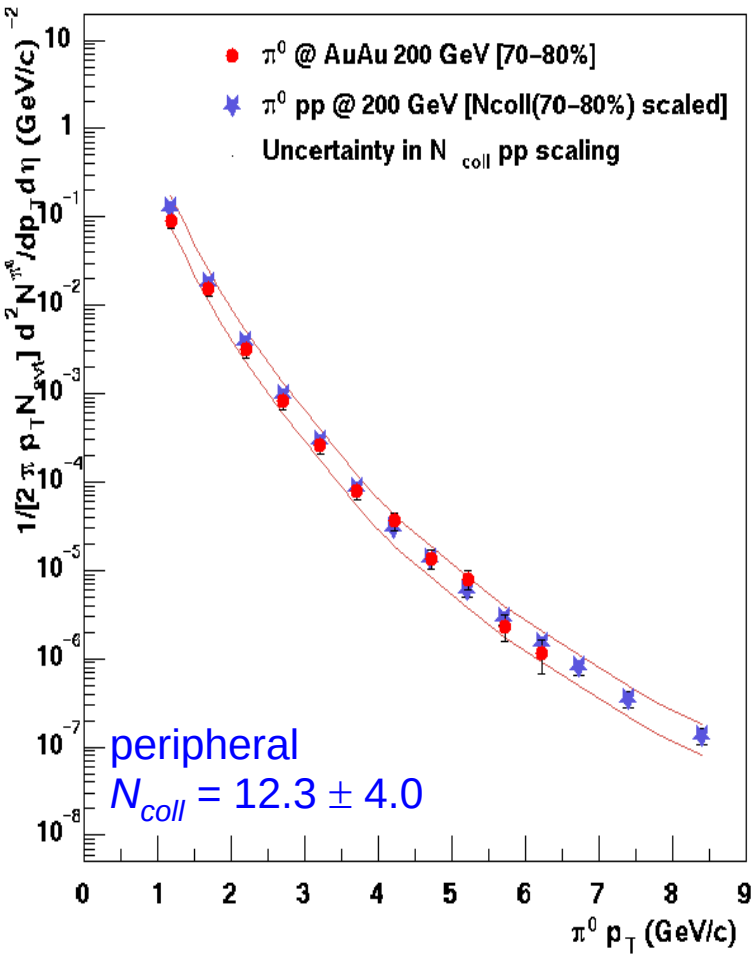
- Achievements in RHIC Year-2 -

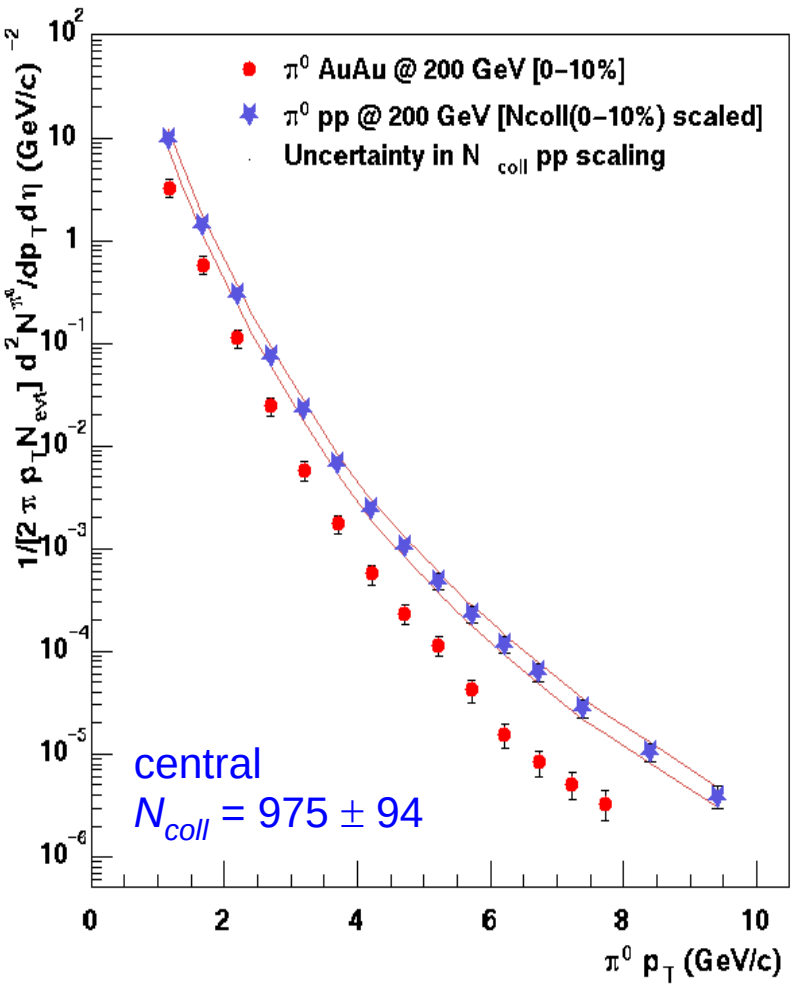
- RHIC at full energy
  - $\sqrt{s_{NN}}$ = 200 GeV
- higher statistics
  - charged and neutral hadrons to higher p_t
- reference p+p data



Au+Au→π^0+X at $\sqrt{s_{NN}}$ = 200 GeV
nucl-ex/0304022, submitted to PRL

- Neutral Pion Production at $\sqrt{s_{NN}}$ = 200 GeV -





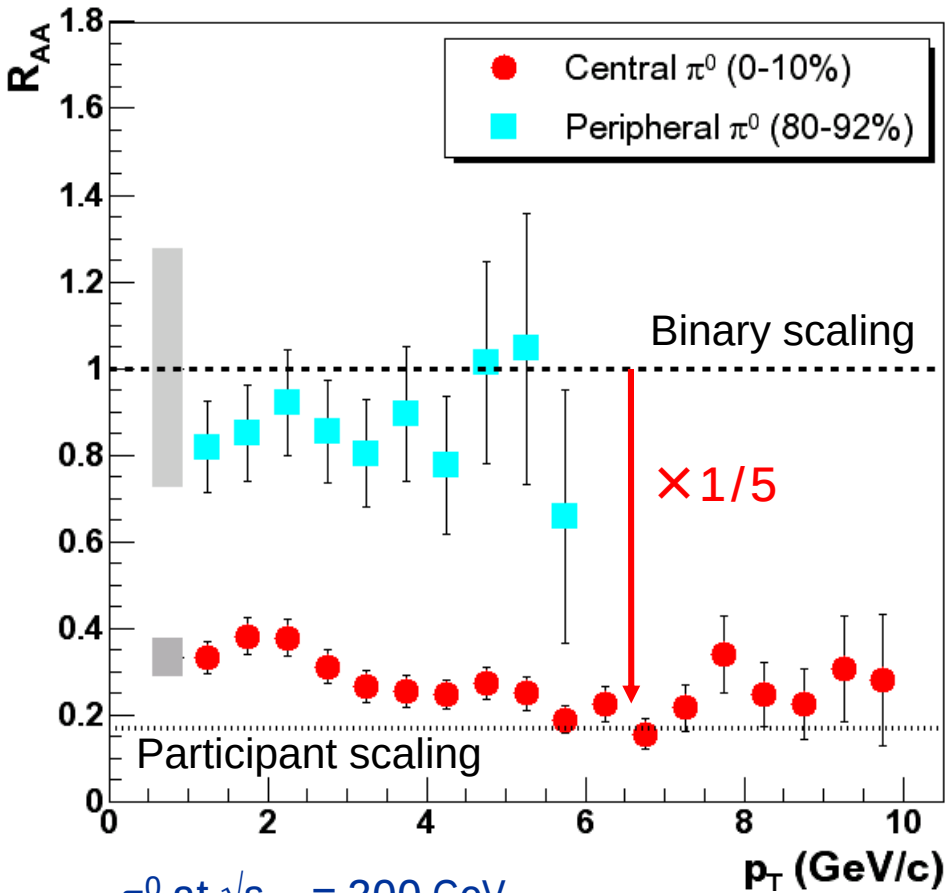
- binary scaling not in central Au+Au

- Neutral Pion Production in p+p and Au+Au -

- reference p+p data with same detector

$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$

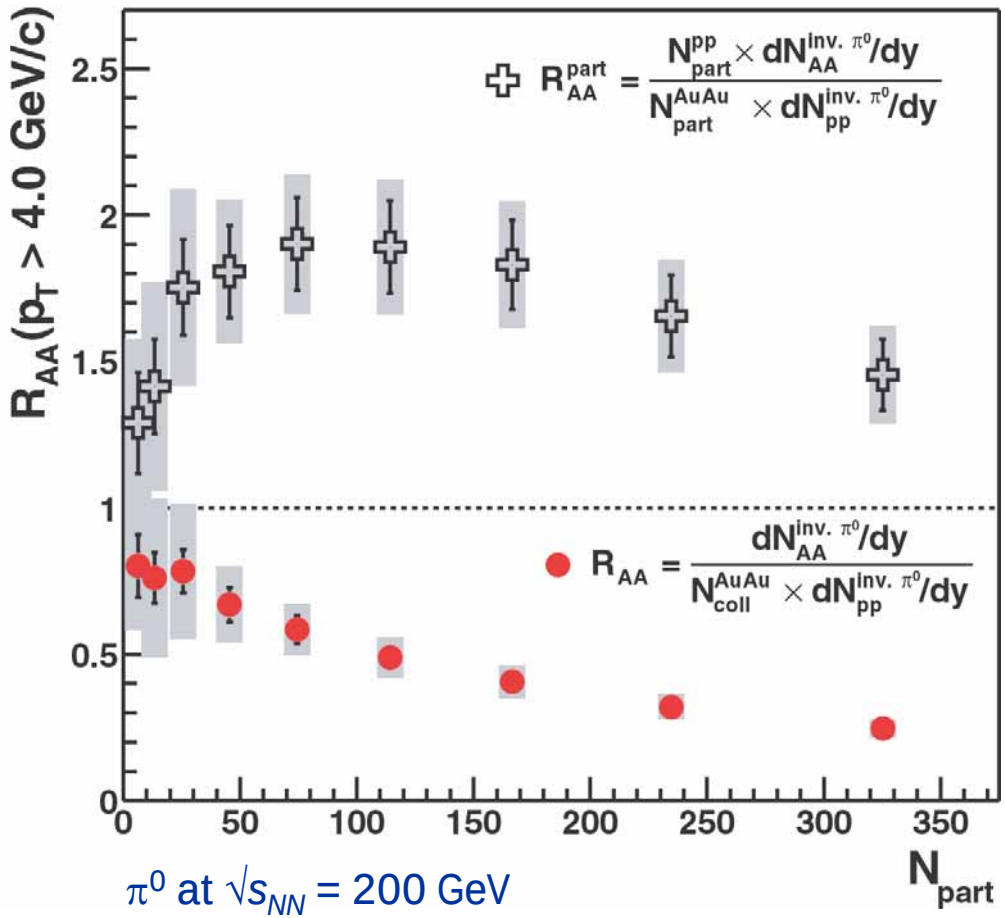
- binary scaling in peripheral Au+Au
- suppression factor
  ~ 5 in central Au+Au



π^0 at $\sqrt{s_{NN}}$ = 200 GeV
nucl-ex/0304022, submitted to PRL

- Centrality Dependence of Pion Suppression -

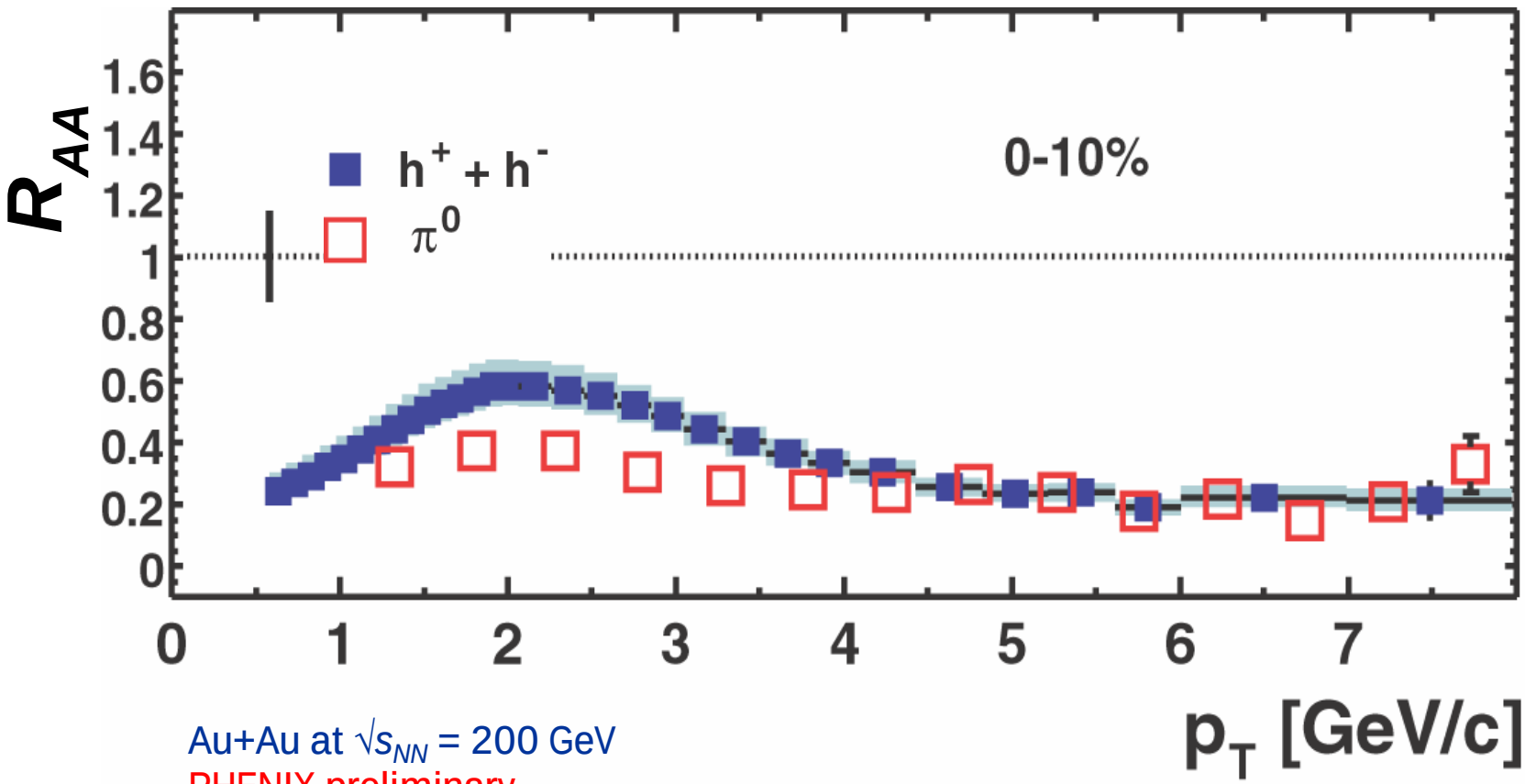
- smooth increase of suppression with centrality
- neither binary or participant scaling



π^0 at $\sqrt{s_{NN}}$ = 200 GeV

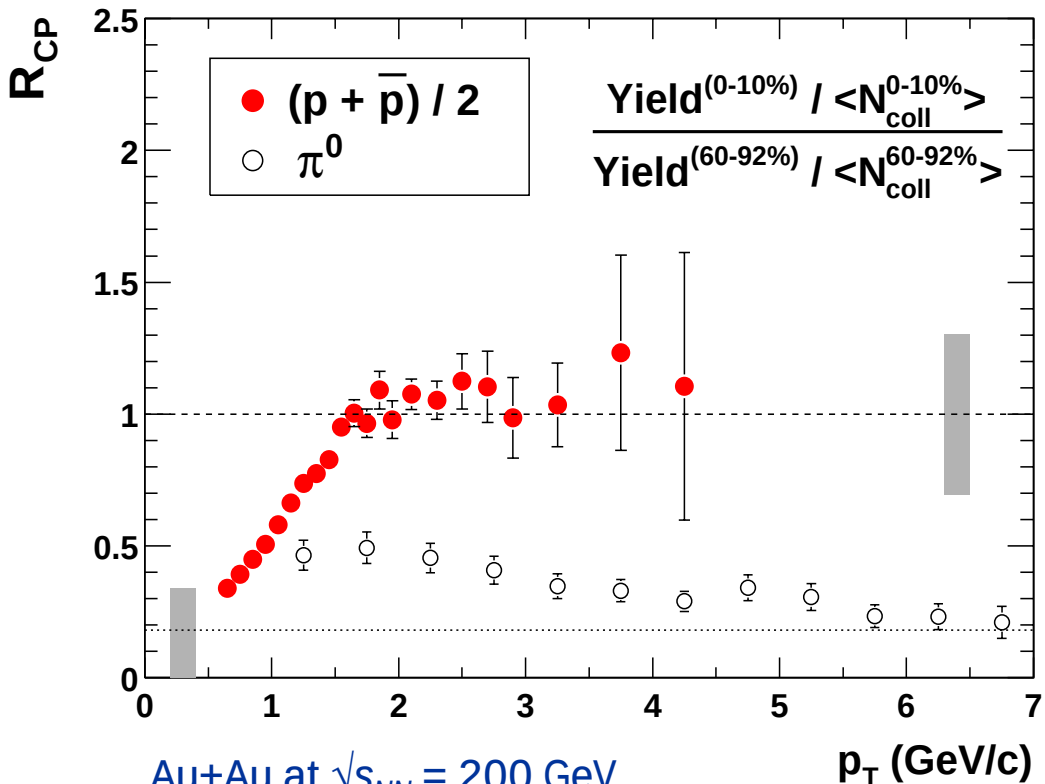
nucl-ex/0304022, submitted to PRL

- Centrality Dependence of High p_t Suppression -



- Particle Dependence of High p_t Suppression -

- no apparent proton suppression for 2-4 GeV/c in p_t
  - different production mechanism ?

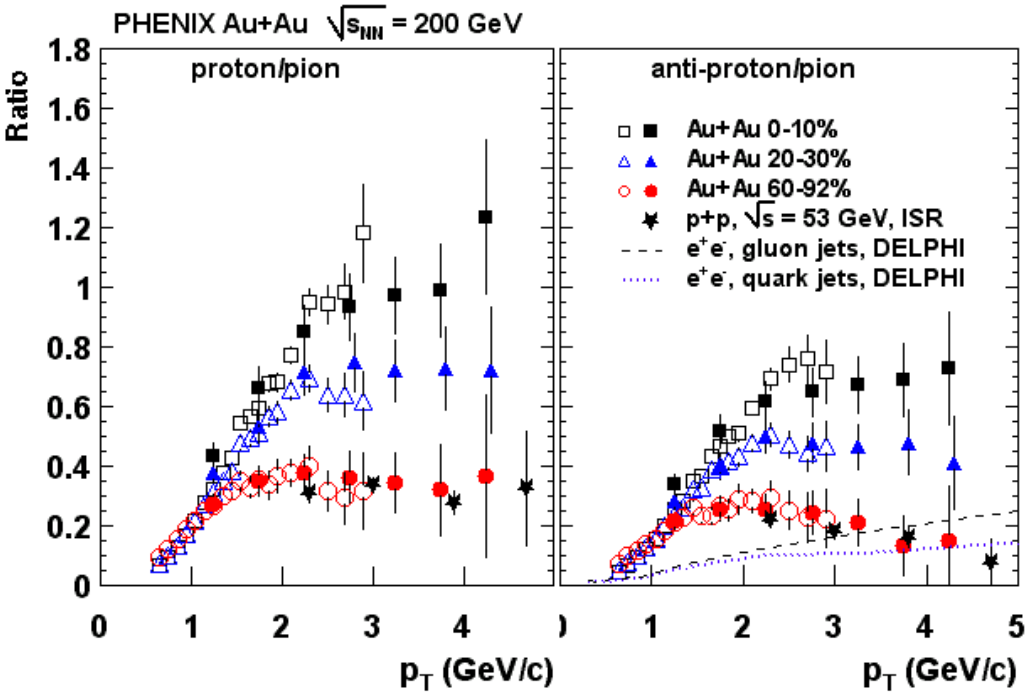


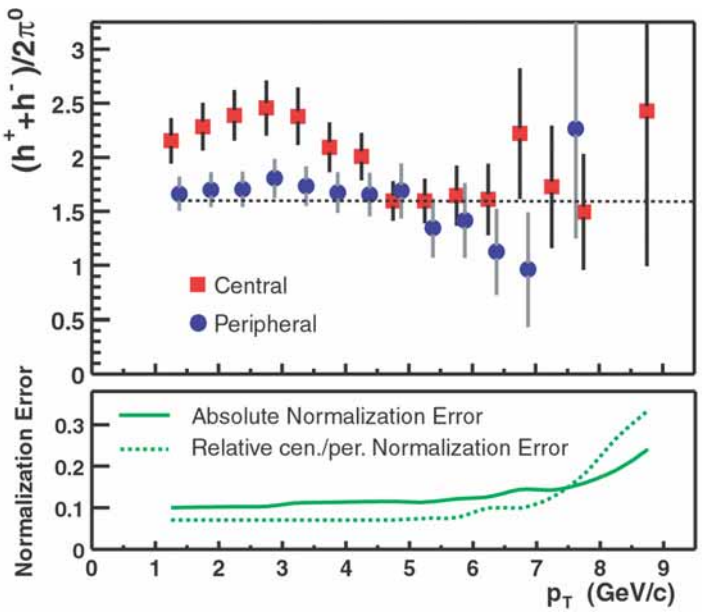
Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

nucl-ex/0305036, submitted to PRL

- Particle Composition at High p_t -

- $p/\pi < 0.25$ expected from jet fragmentation
- observed $p/\pi \sim 0.4$ in peripheral, ~ 1 in central
  - protons from non-fragmentation sources ?



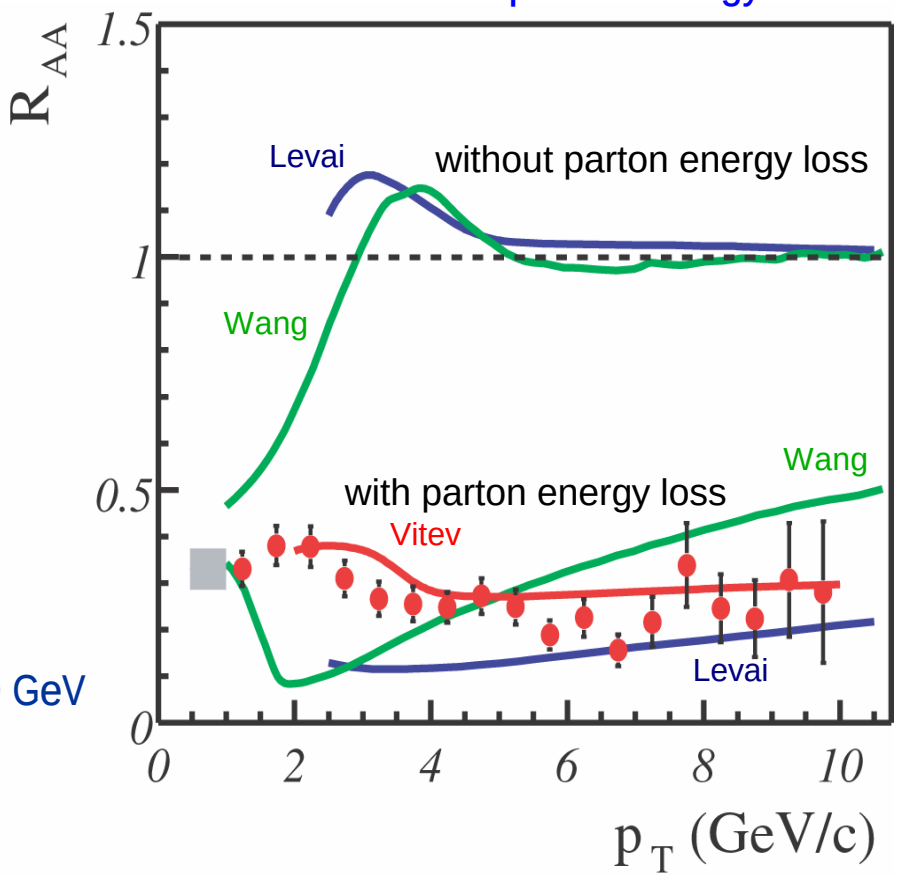


Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
nucl-ex/0305036, submitted to PRL

- Jet Quenching ? -

- pion suppression reproduced by models with parton energy loss
- other explanations not ruled out (at this stage)

comparison with model calculations with and without parton energy loss



Au+Au→π^0+X at $\sqrt{s_{NN}}$ = 200 GeV

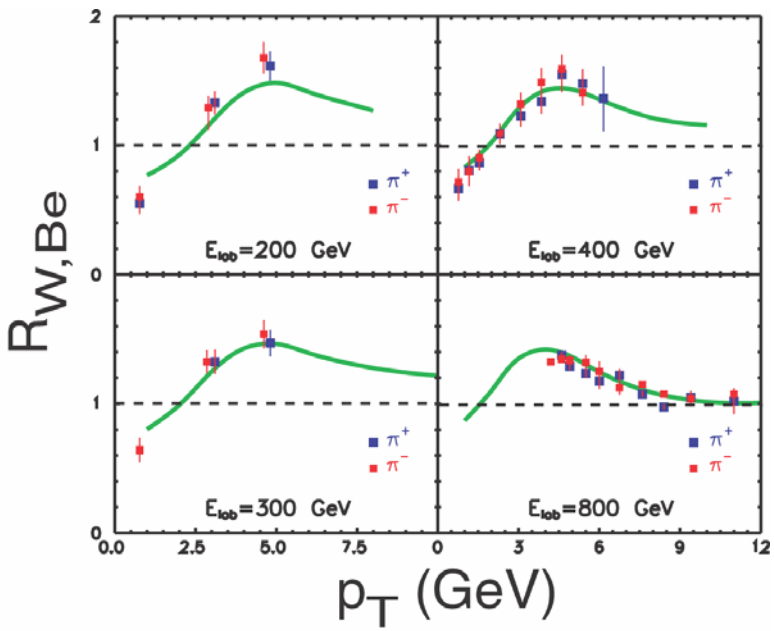
- Origin of Suppression ? -

- initial state effects
  - gluon saturation (color glass condensate)
    - property of nuclear wave function
    - suppression predicted also in p/d+Au
  - shadowing
  - (Cronin effect)
- final state effects
  - parton energy loss (jet quenching)
    - related to medium density
    - no suppression predicted in p/d+Au
  - hadronic absorption
  - parton recombination

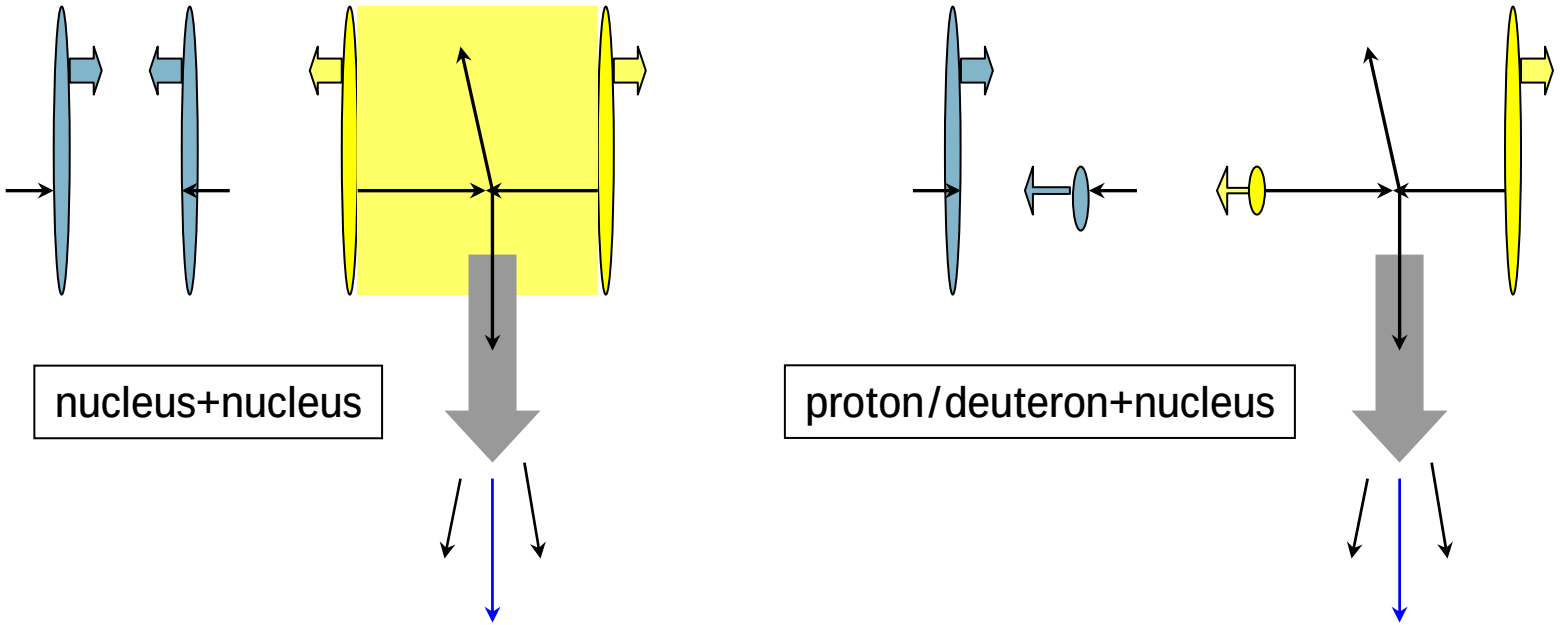
- Other Candidates: Initial State Effects -

- not related to properties of hot and dense matter
- several candidates leading to $R_{AA} \neq 1$ at high p_t:
  - Cronin effect (↑)
    - initial state multiple soft scattering
  - shadowing (↓)
    - modification of nuclear structure functions
  - color glass condensate (↓)
    - gluon saturation

Cronin effect observed in fixed target experiments

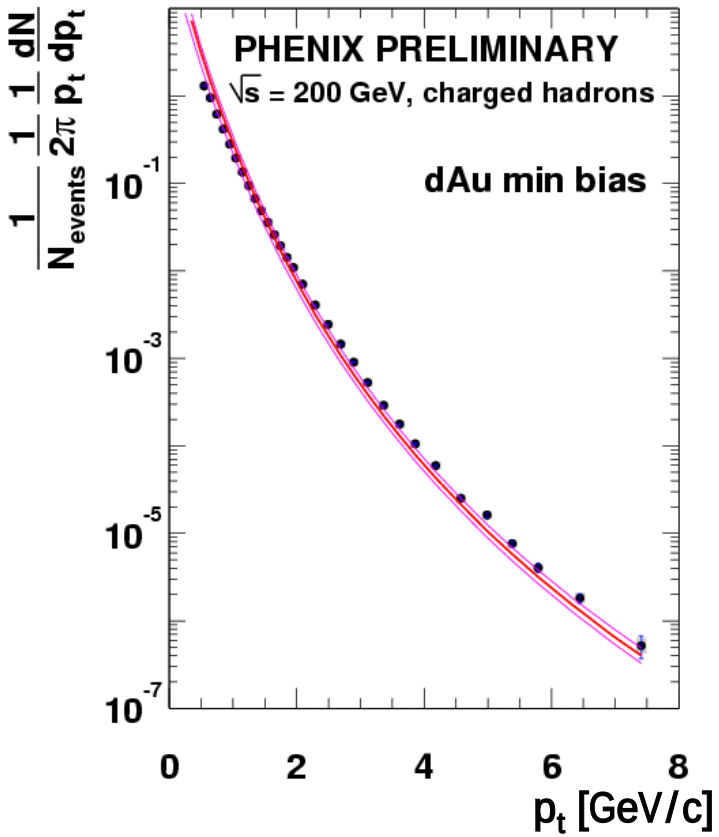


- Control Experiment: d+Au -

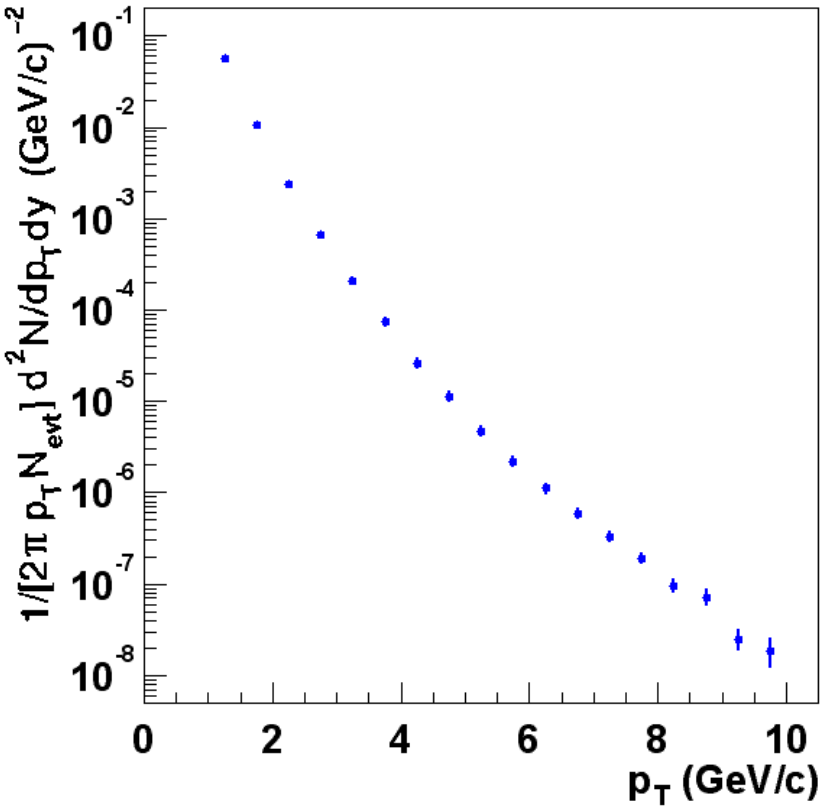


- quantify cold nuclear matter effects
- distinguish initial and final state effects
  - less jets created (color glass condensate) or quenched

- Hadron Production in d+Au at $\sqrt{s_{NN}}$ = 200 GeV -



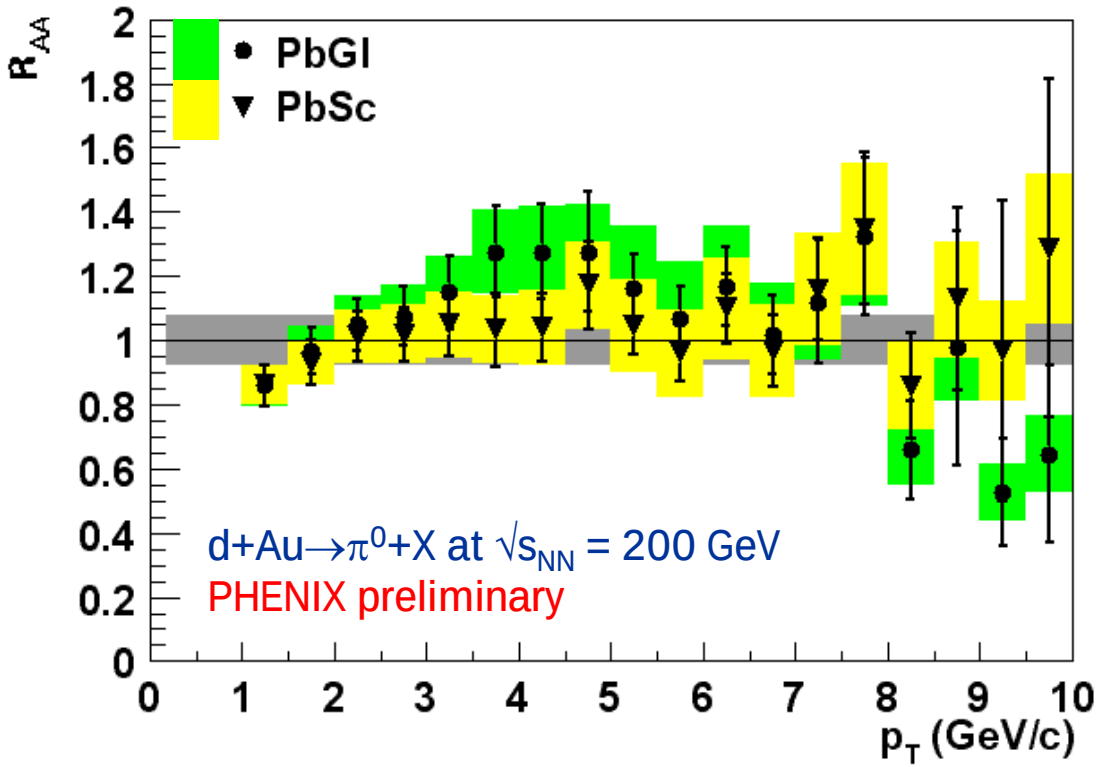
d+Au→$h^{\pm}$+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary



d+Au→π^0+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary

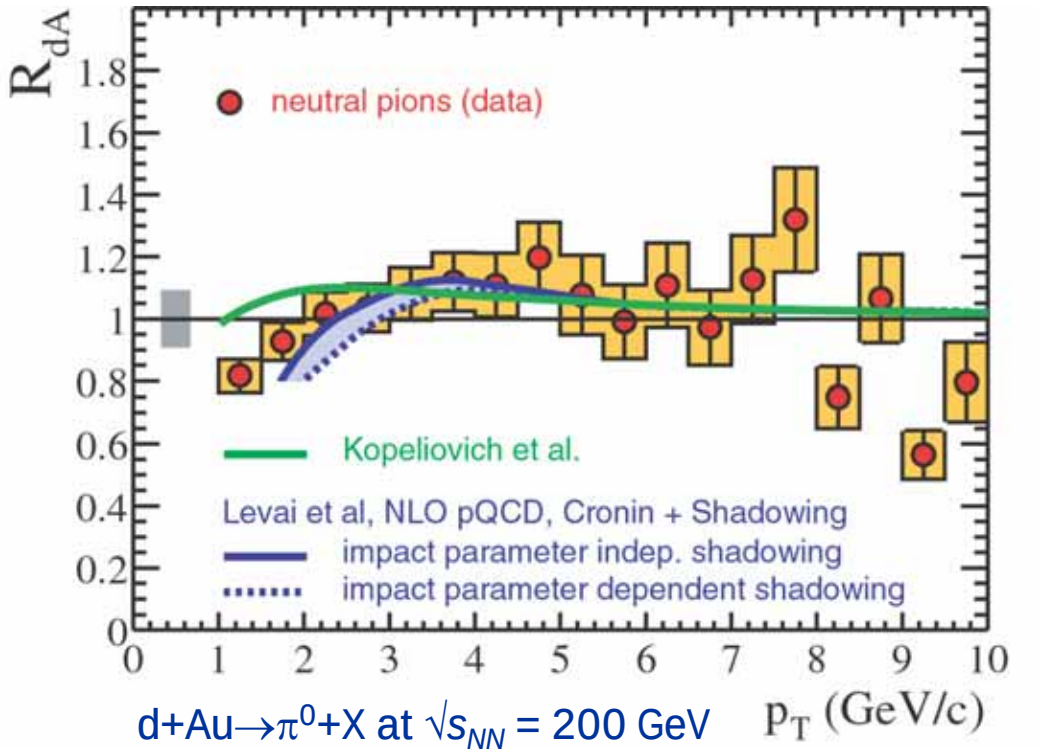
- Neutral Pion R_{dAu} -

- neutral pions measured in independent detectors
  - agreement within systematic error



- no suppression relative to binary scaling

- Neutral Pion Data and pQCD -



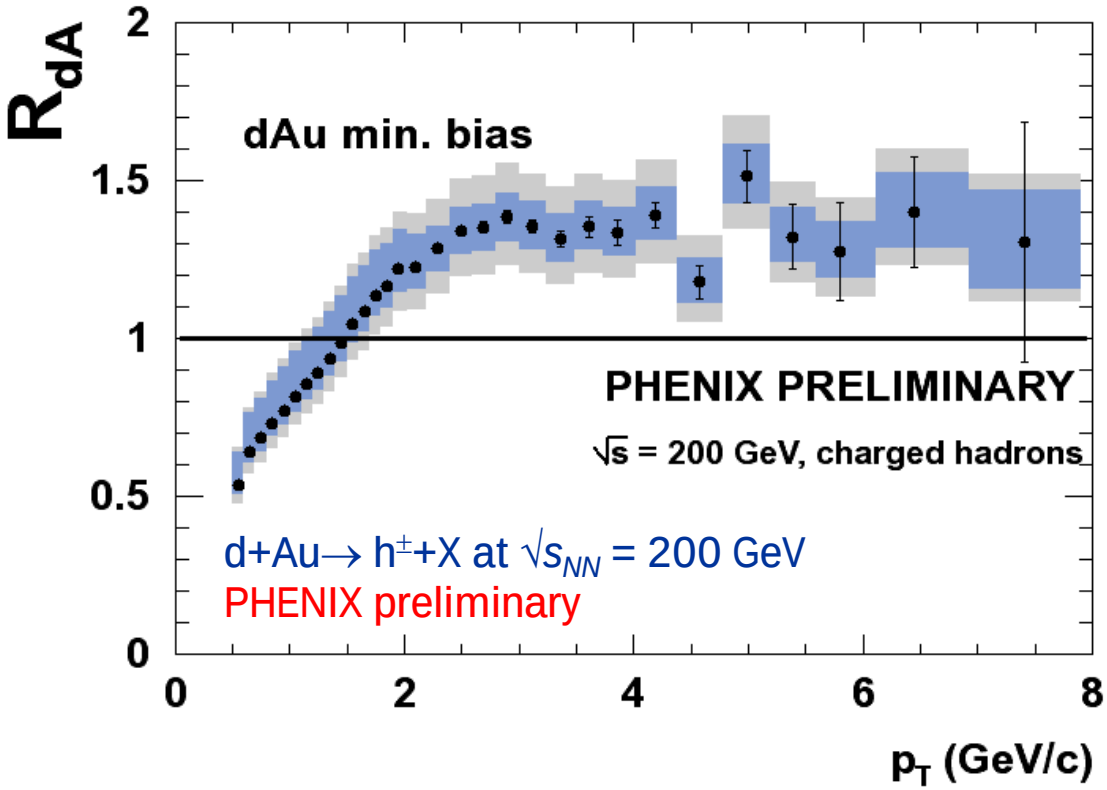
d+Au→π^0+X at $\sqrt{s_{NN}}$ = 200 GeV

Levai *et al.* nucl-th/0306019

Kopeliovich *et al.* PRL 88, 232303 (2002)

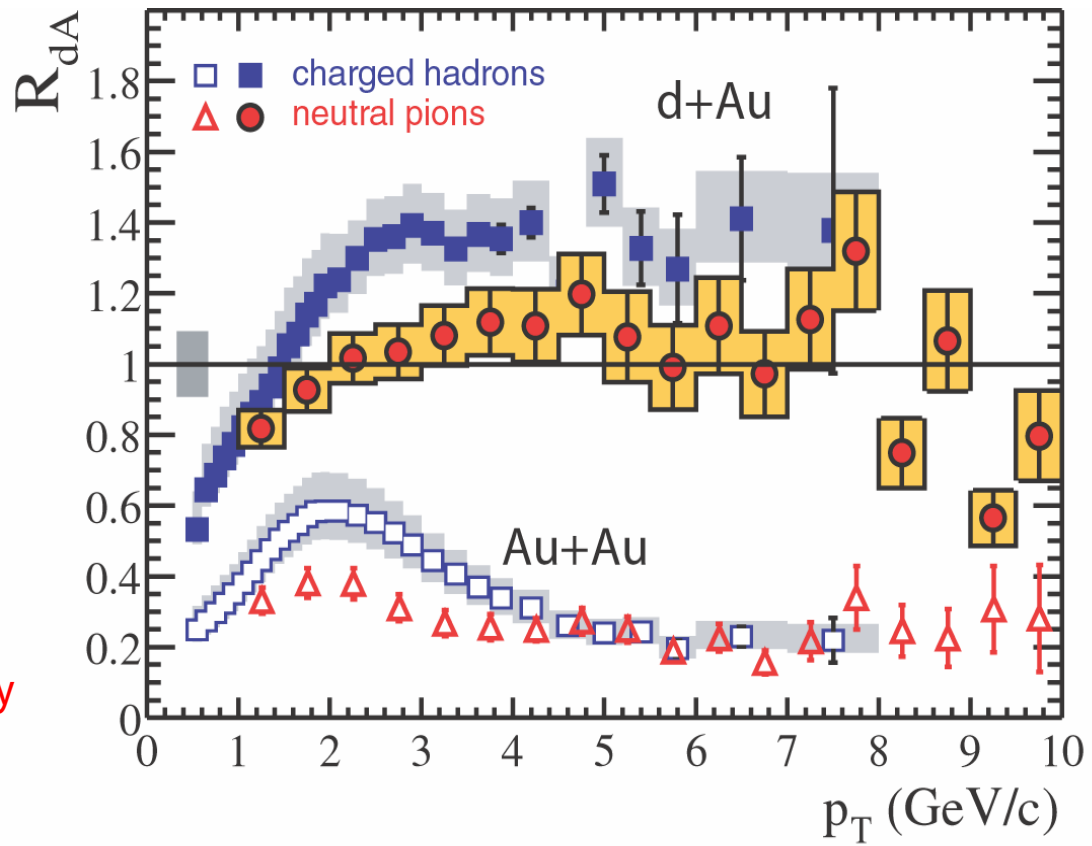
- data reproduced by NLO pQCD + phenomenology

- Charged Hadron R_{dAu} -



- Cronin type enhancement relative to binary scaling

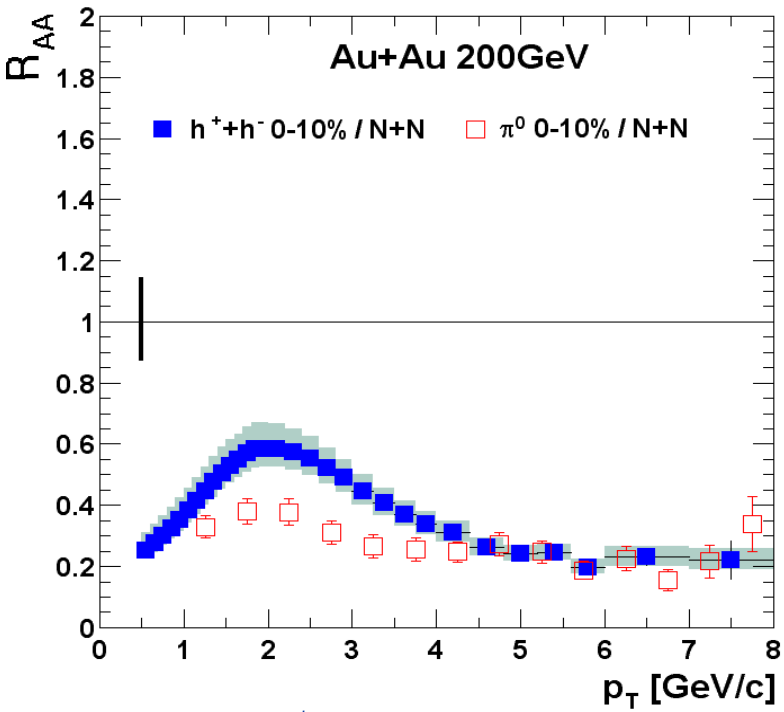
- Comparison between Au+Au and d+Au -



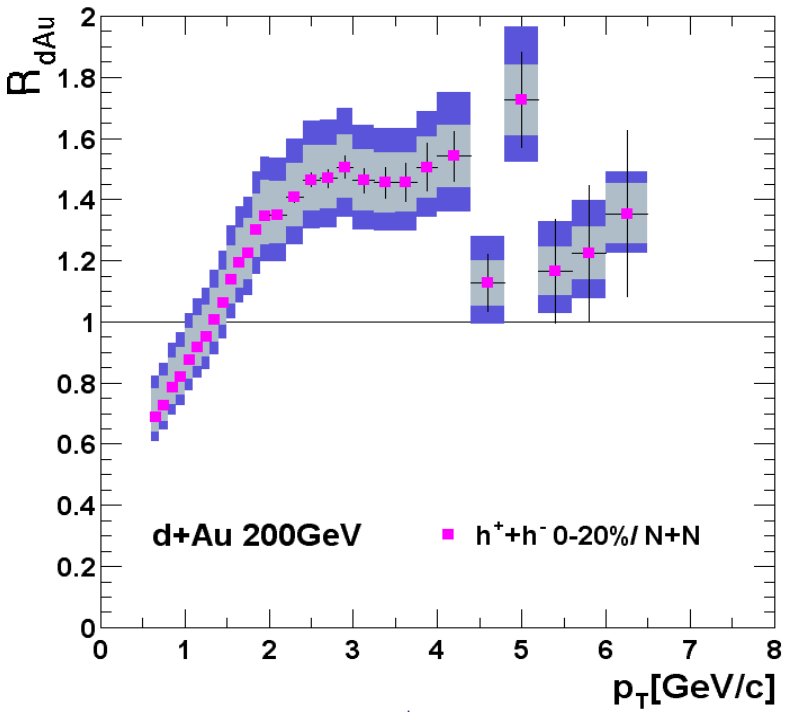
$\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary

- no suppression in d+Au
- initial state effects ruled out as explanation

- Centrality Dependence of R_{AuAu} and R_{dAu} -



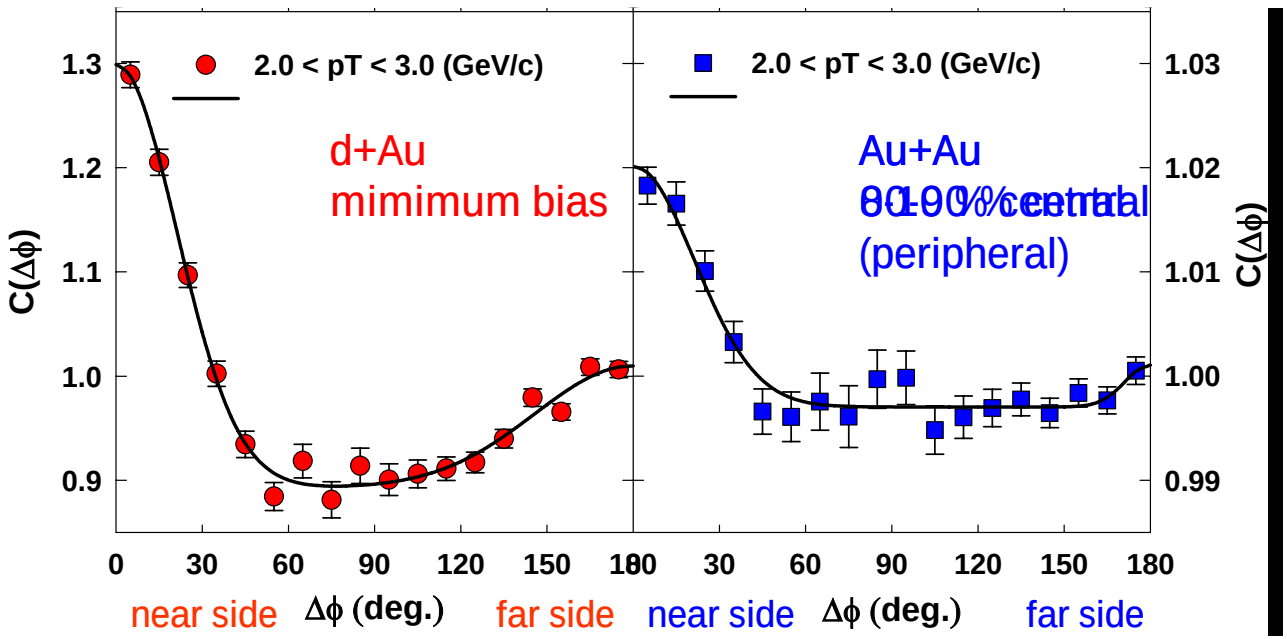
Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary

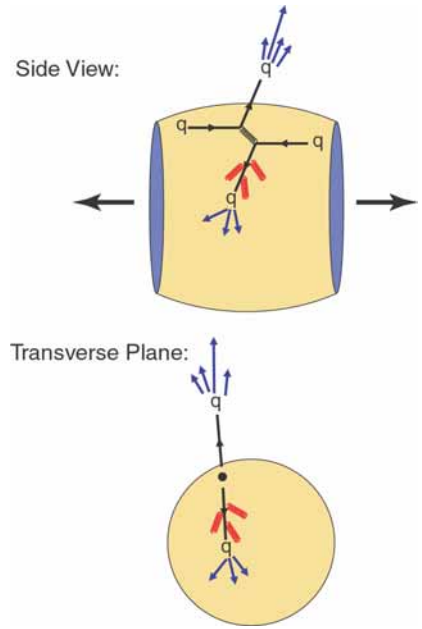


d+Au→$h^{\pm}$+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary

- clearly different and opposite centrality evolution
- final state jet quenching

- Jet Correlation -



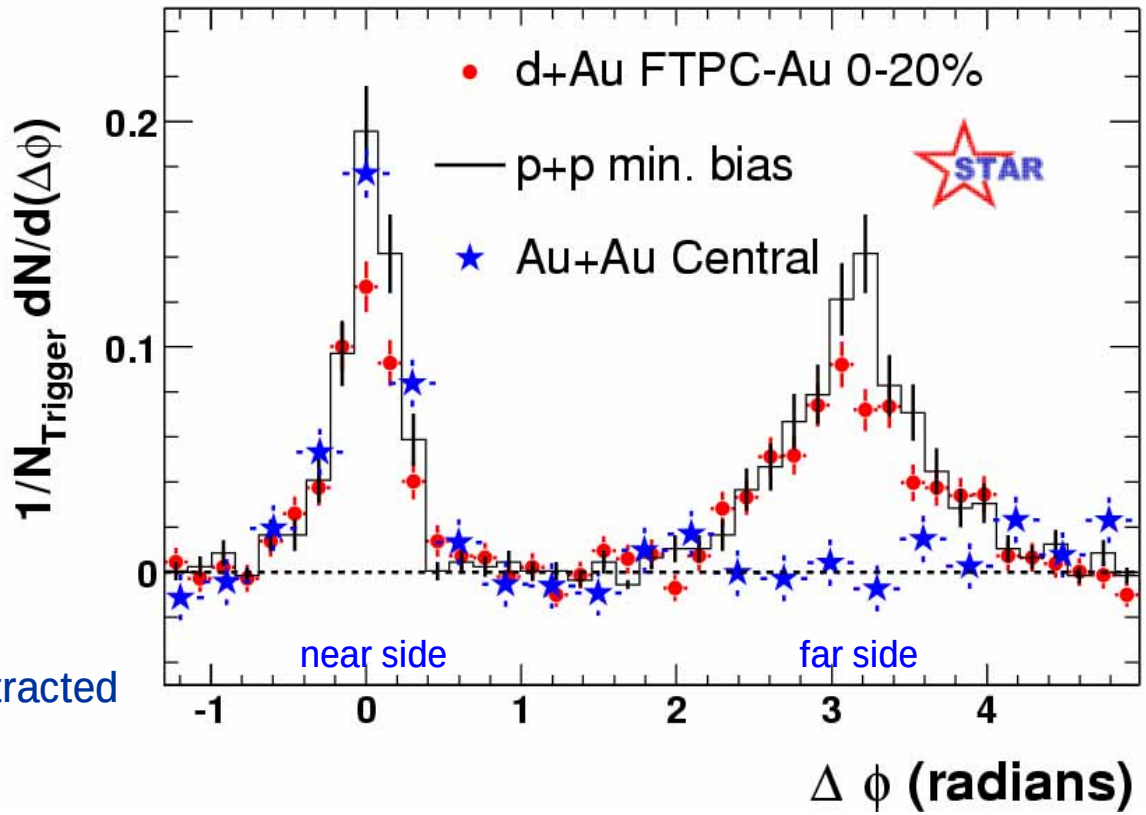


d+Au at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary

- peripheral Au+Au similar to d+Au
- disappearance of far-side jet in central Au+Au

- Jet Correlation in STAR -



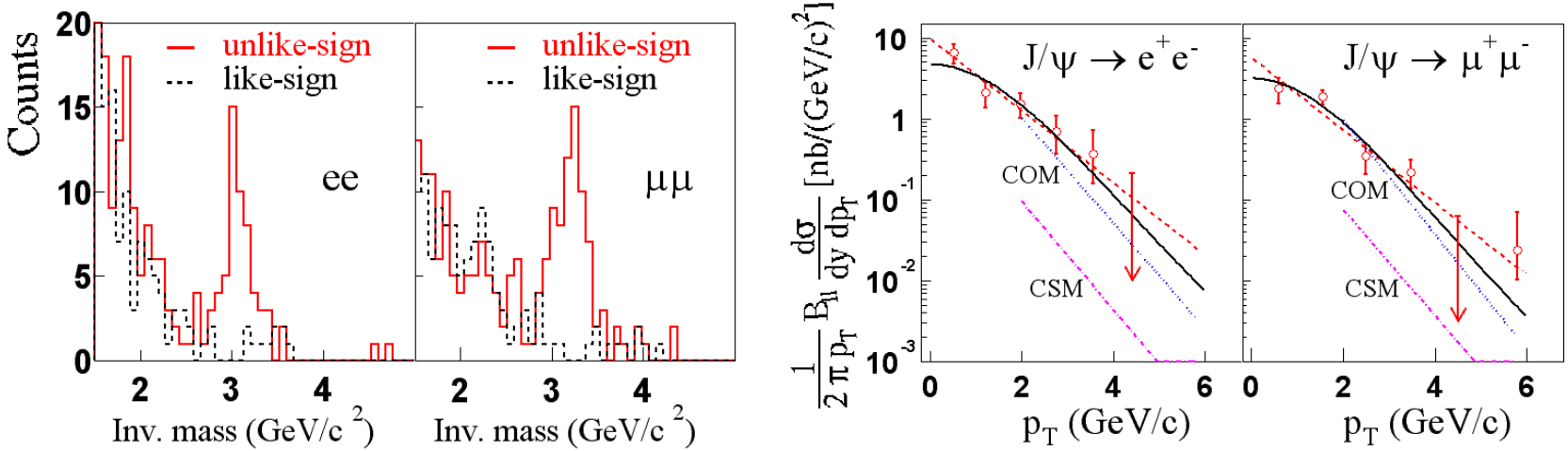
$\sqrt{s_{NN}}$ = 200 GeV
pedestal and flow subtracted

- back-to-back correlation suppressed in central Au+Au

- Where are We ? What is Next ? -

- quark-gluon plasma discovered ?
  - “it’s a quark-gluon plasma. period.” (M.Gyulassy)
  - maybe premature to claim triumph
- further insights expected via rare processes
  - probe of deconfinement
    - heavy quark states: J/Ψ, Ψ’
  - penetrating probes of medium
    - dileptons: e^+e^-, $\mu^+\mu^-$
    - direct photons
- these measurements planned in next Au+Au run

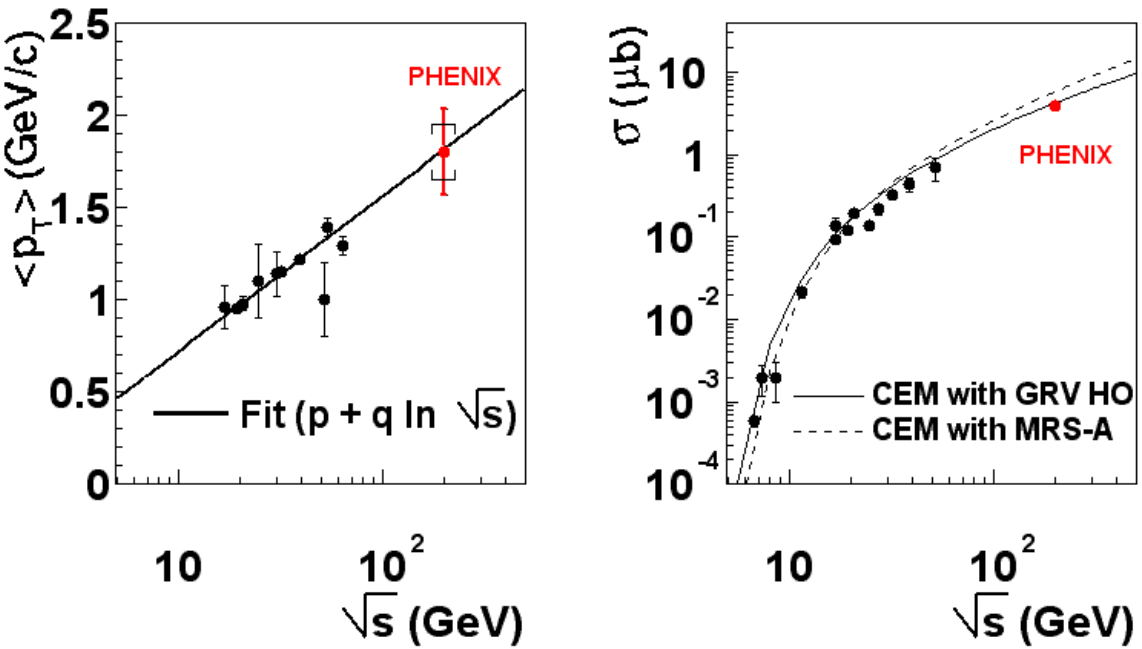
- J/Ψ Measurement Baseline Established -



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

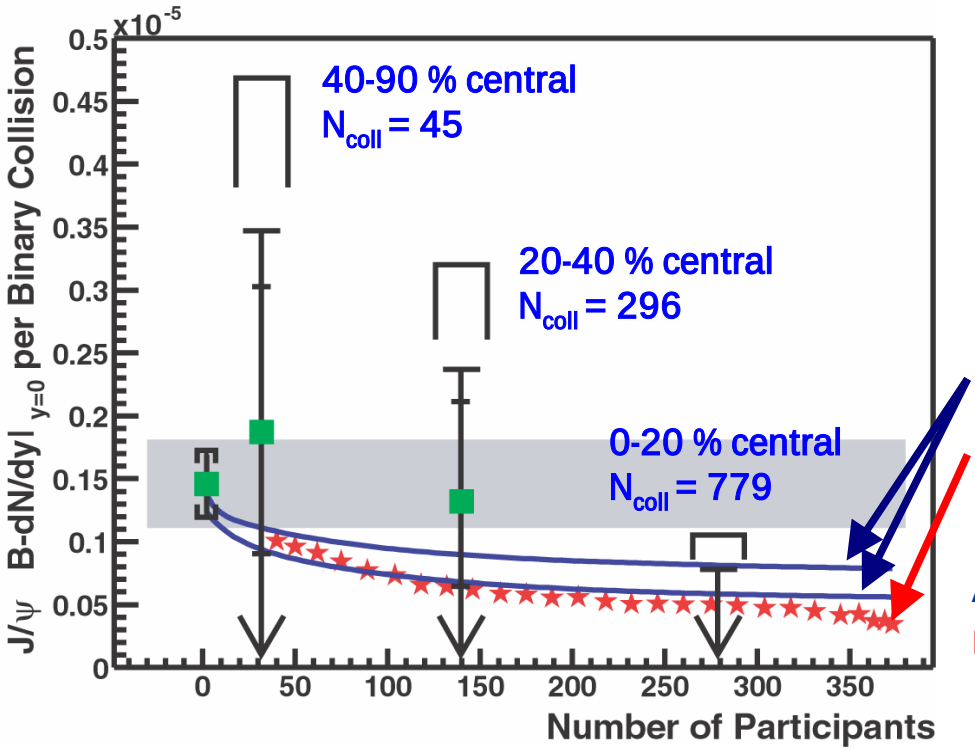
- J/Ψ Comparison with Previous Data -



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

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

- J/Ψ Measurement So Far -



normal nuclear absorption

SPS NA50 normalized to p+p point

Au+Au→J/Ψ→e⁺e⁻ at $\sqrt{s_{NN}}$ = 200 GeV

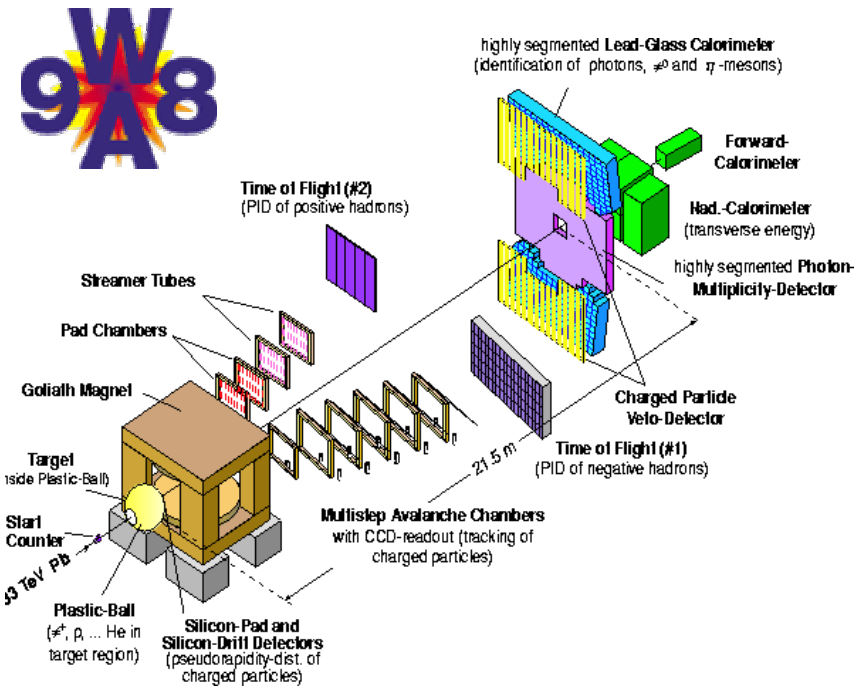
nucl-ex/0305030, submitted to PRC

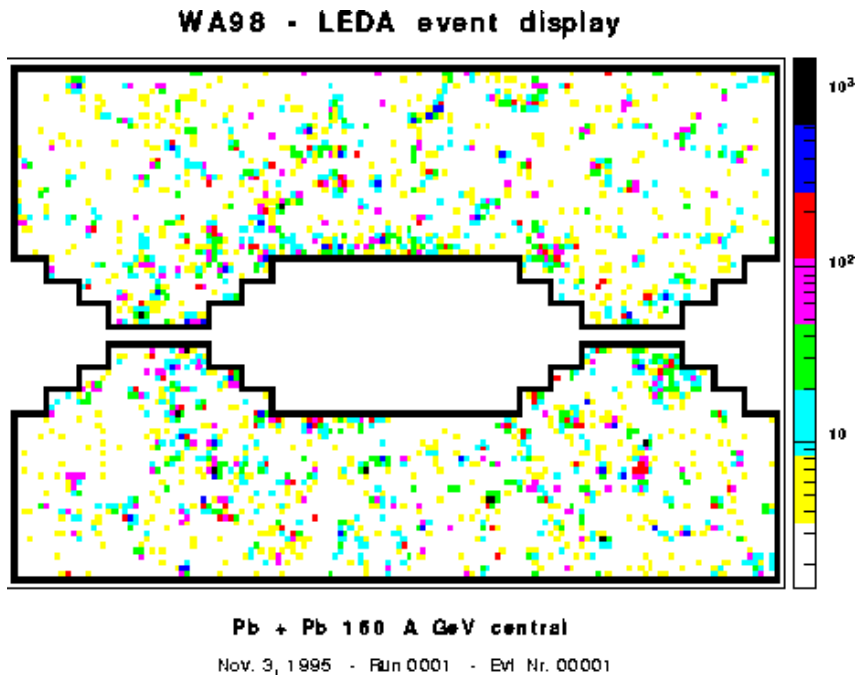
- not much statistics, but
  - binary scaling disfavored
  - inconsistent with enhancement scenarios
    - *e.g.* coalescence models

- Photon and Neutral Meson Measurements -

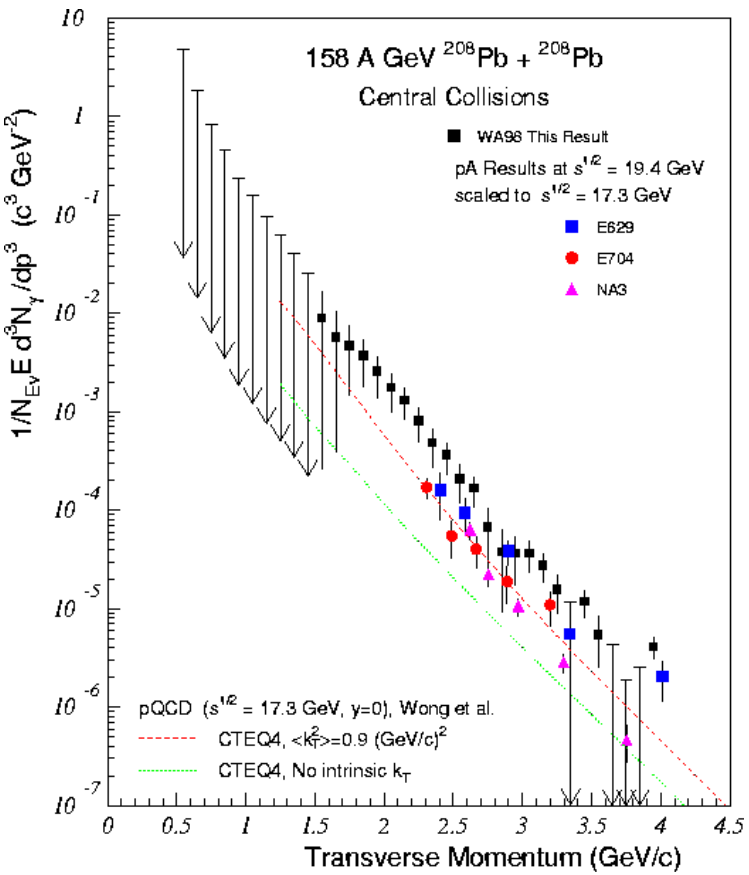
- photons sensitive to
  - initial parton distribution
    - initial k_t, k_t broadening (↑)
    - shadowing, saturation (↓)
  - final state parton/hadron rescattering
    - thermal radiation, jet/parton radiation (↑)
- neutral pions additionally sensitive to
  - final state effects, *e.g.*
    - k_t broadening (↑)
    - absorption, jet/parton energy loss (↓)
- experimental virtues
  - photons and neutral mesons measured in same detector
  - particle identification to very high p_t
- vital to distinguish initial/final state effects

- Photons and Neutral Mesons at SPS -





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



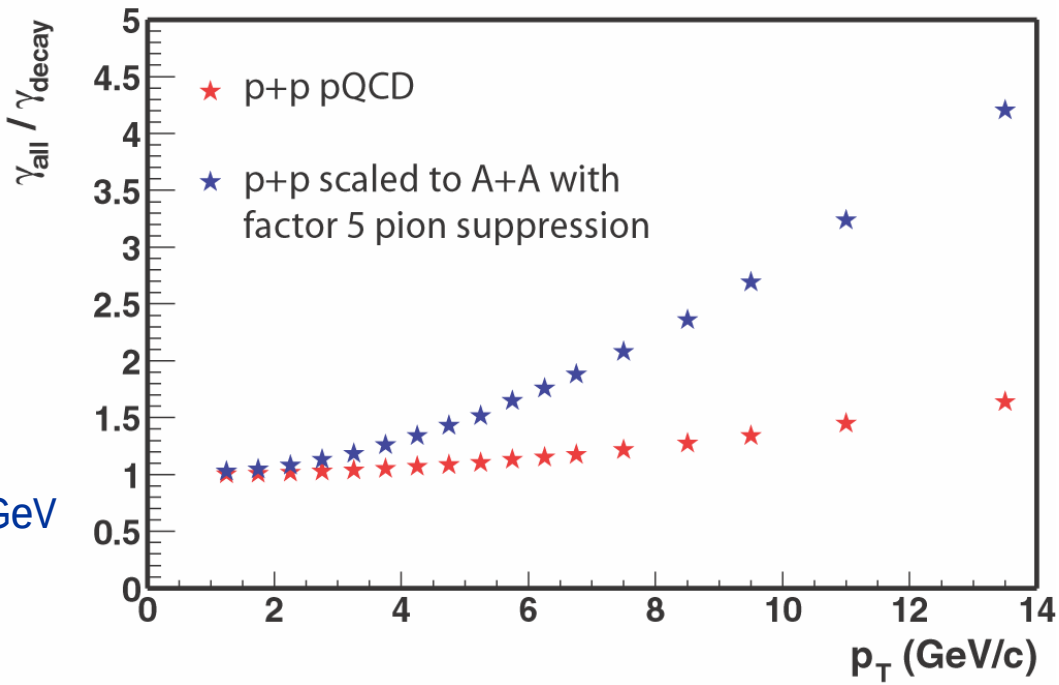
- SPS WA98, central Pb+Pb
- compared to p+A data
  - $\sqrt{s}$ scaling
  - binary collision scaling
- similar spectral shape
- p-induced reproduced by NLO pQCD + intrinsic k_t
- factor 2-3 enhancement in central Pb+Pb

Pb+Pb$\rightarrow\gamma$+X at $\sqrt{s_{NN}}$ = 17.3 GeV
WA98 nucl-ex/0006007, PRL 85 3595 (2000)

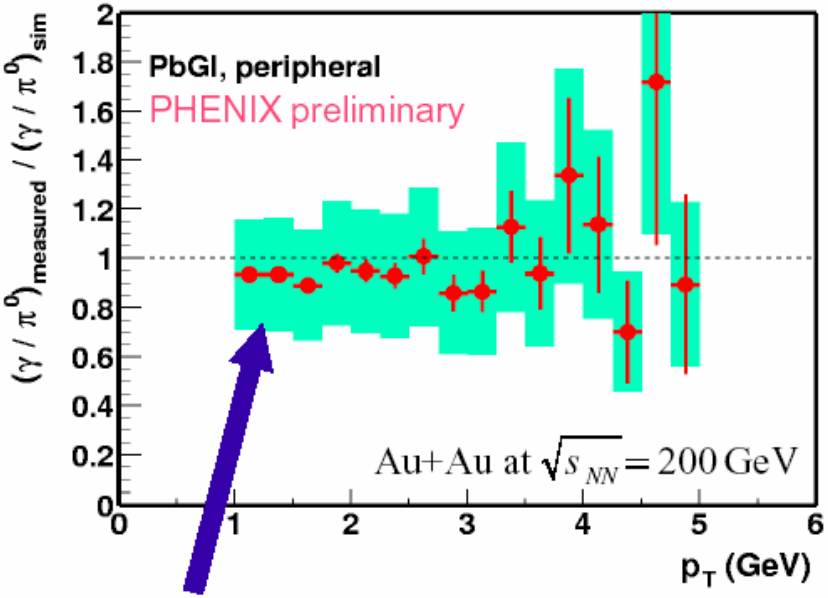
- pQCD Direct Photon Predictions for RHIC -

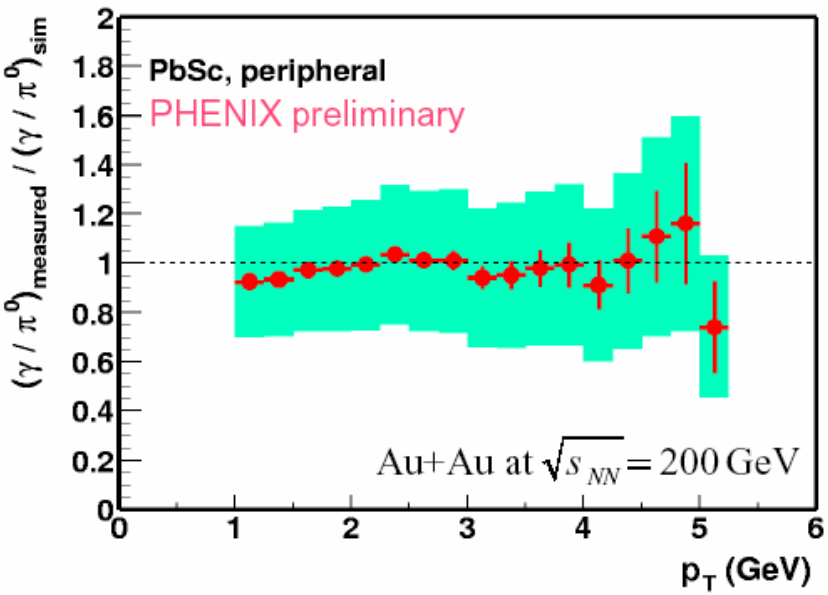
- large direct photon signal expected
  - (photons observed) / (photons from hadron decays)
  - except if photons also suppressed (initial state effect)

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

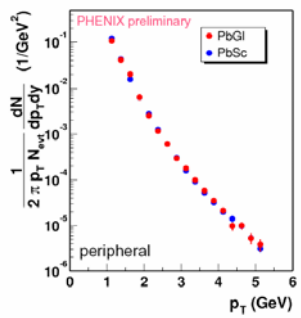


- Inclusive Photons in Peripheral Au+Au -



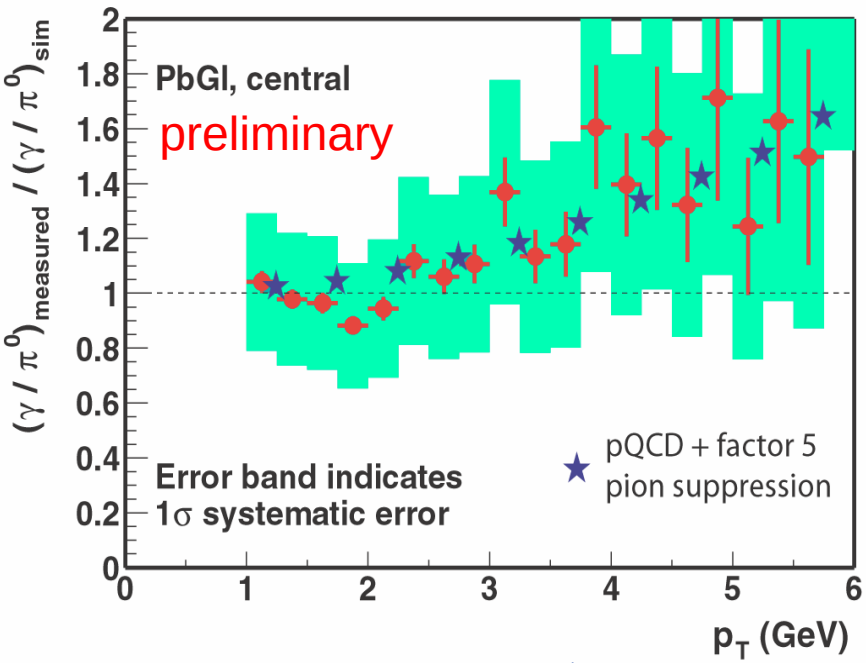


Boxes: 1σ systematic error



- two independent detectors consistent
- consistent with no photon excess in peripheral Au+Au
  - based on measured neutral pion spectrum

- Inclusive Photons in Central Au+Au -

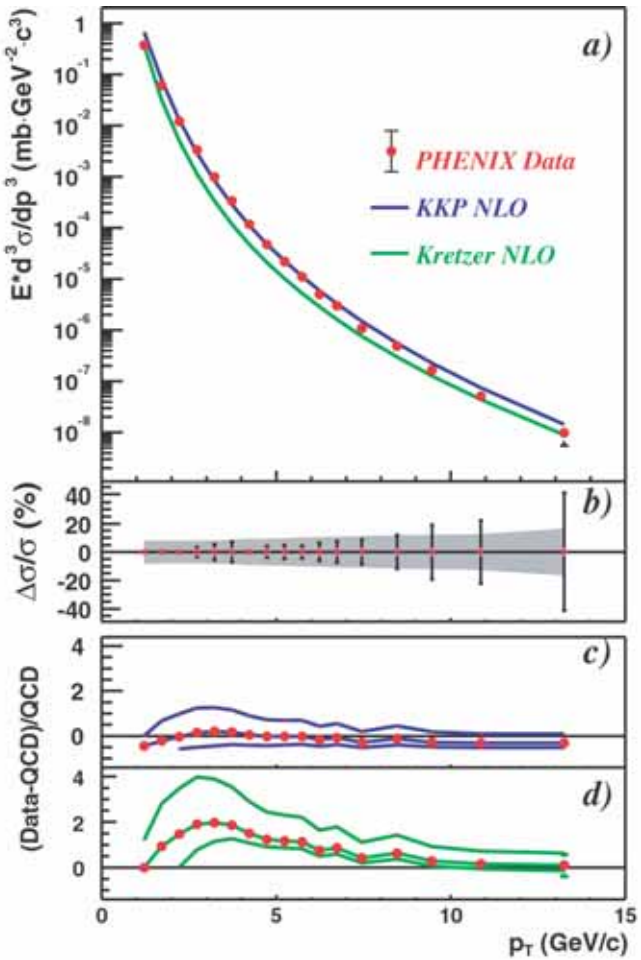


central Au+Au→γ+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary

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

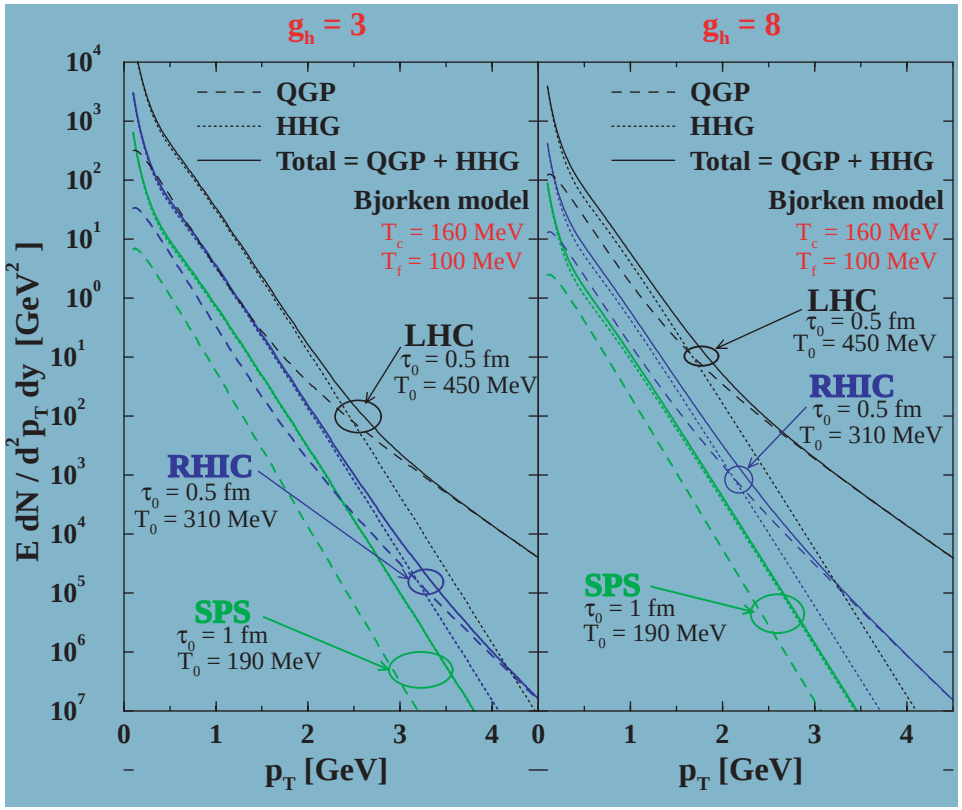
- Solid Basis of Direct Photon Measurement -

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



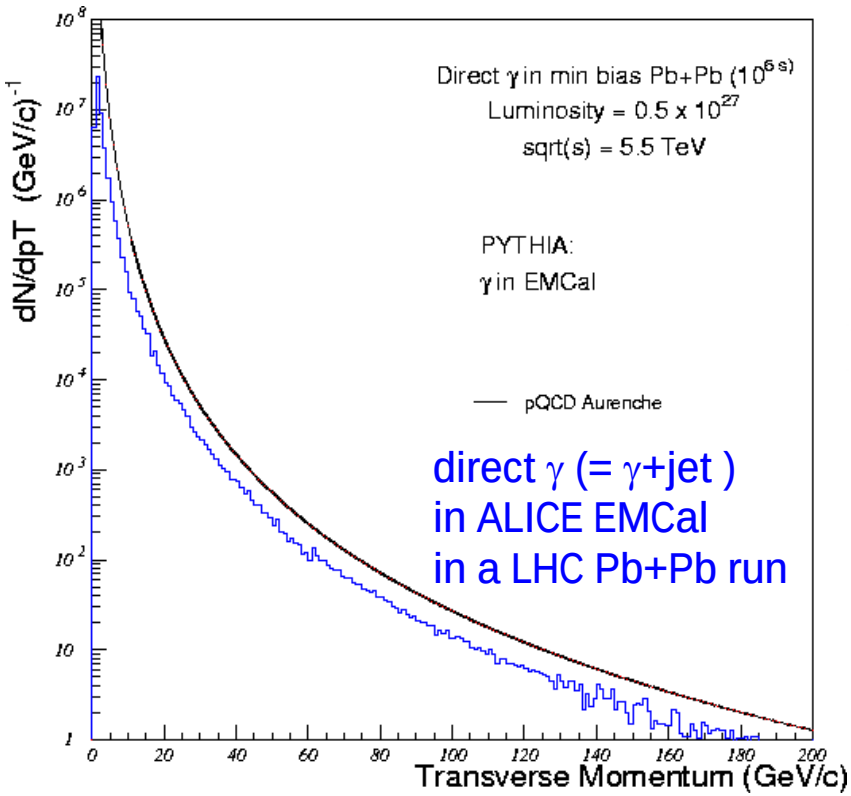
p+p→π^0+X
hep-ex/0304038

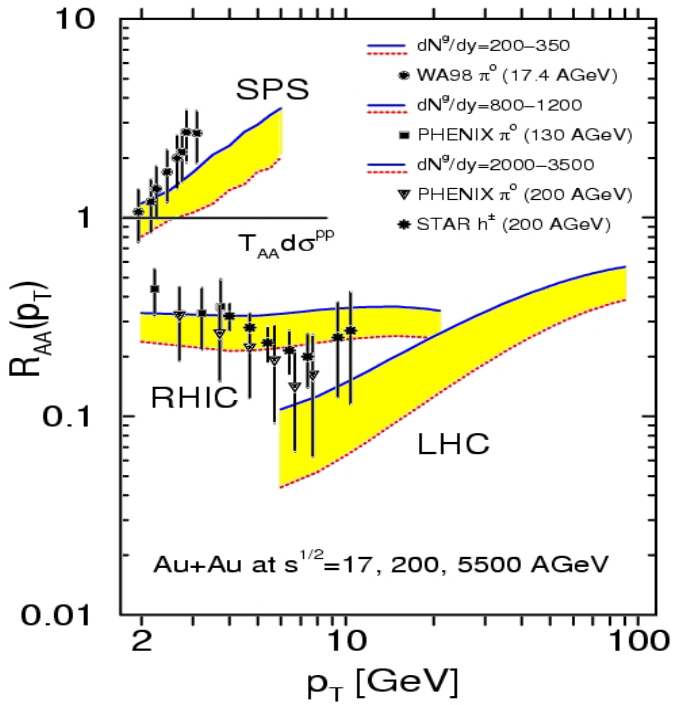
- Direct Photon Expectations at RHIC/LHC -



- QGP contribution dominates at > 2-3 GeV/*c* in p_t
- high p_t hadron suppression increases direct/decay

- Direct Photon and Neutral Mesons at LHC -





I.Vitev, M.Gyulassy
PRL 89, 252301 (2002)

- even more powerful probe at LHC
  - large direct photon rate up to ~ 100 GeV/*c*
  - large neutral meson suppression expected

- LHC Status and Plan -

- accelerator on its way
  - start-up in 2007 confirmed in June, 2003, CERN council
  - p+p commissioning in April 2007
  - heavy-ion pilot run by end of 2007
- wish list as of June 2002
  - initial few years
    - 2 - 3 years of Pb+Pb at $L \sim 10^{27}$ cm^{-2}s^{-1}
    - 1 year of p/d/α+Pb at $L \sim 10^{29}$ cm^{-2}s^{-1}
    - 1 year of light ions at $L \sim$ few 10^{27} - 10^{29} cm^{-2}s^{-1}

- ALICE Physics Goals and Strategies -

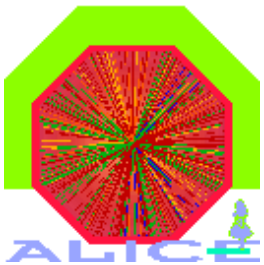
- to cover in single experiment what is by 4 at RHIC (and by several at SPS and AGS)
  - multiplicities; rapidity distributions; flows; particle spectra and ratios; jet quenching; dileptons; direct photons; heavy flavors; fluctuations; correlations; ...
- versatility with variety of techniques
  - wide acceptance and momentum coverage; accessibility to photons/electrons/muons/hadrons; excellent granularity; secondary vertex reconstruction capability; selective triggering; ...

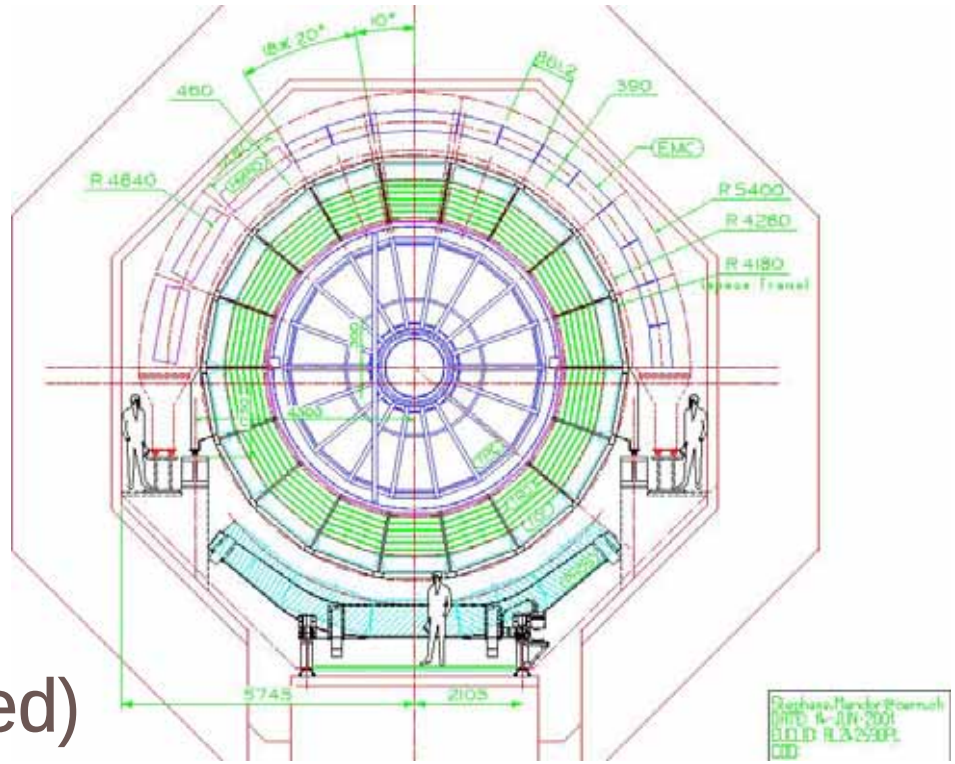

- ALICE Setup -
HMPID
TRD
TPC
PMD
MUON SPEC.
ITS
TOF
PHOS
FMD

- ALICE Status -

- in former LEP-L3 site
- L3 magnet modified
- muon magnet coming soon
- various detectors in R&D/testing/production

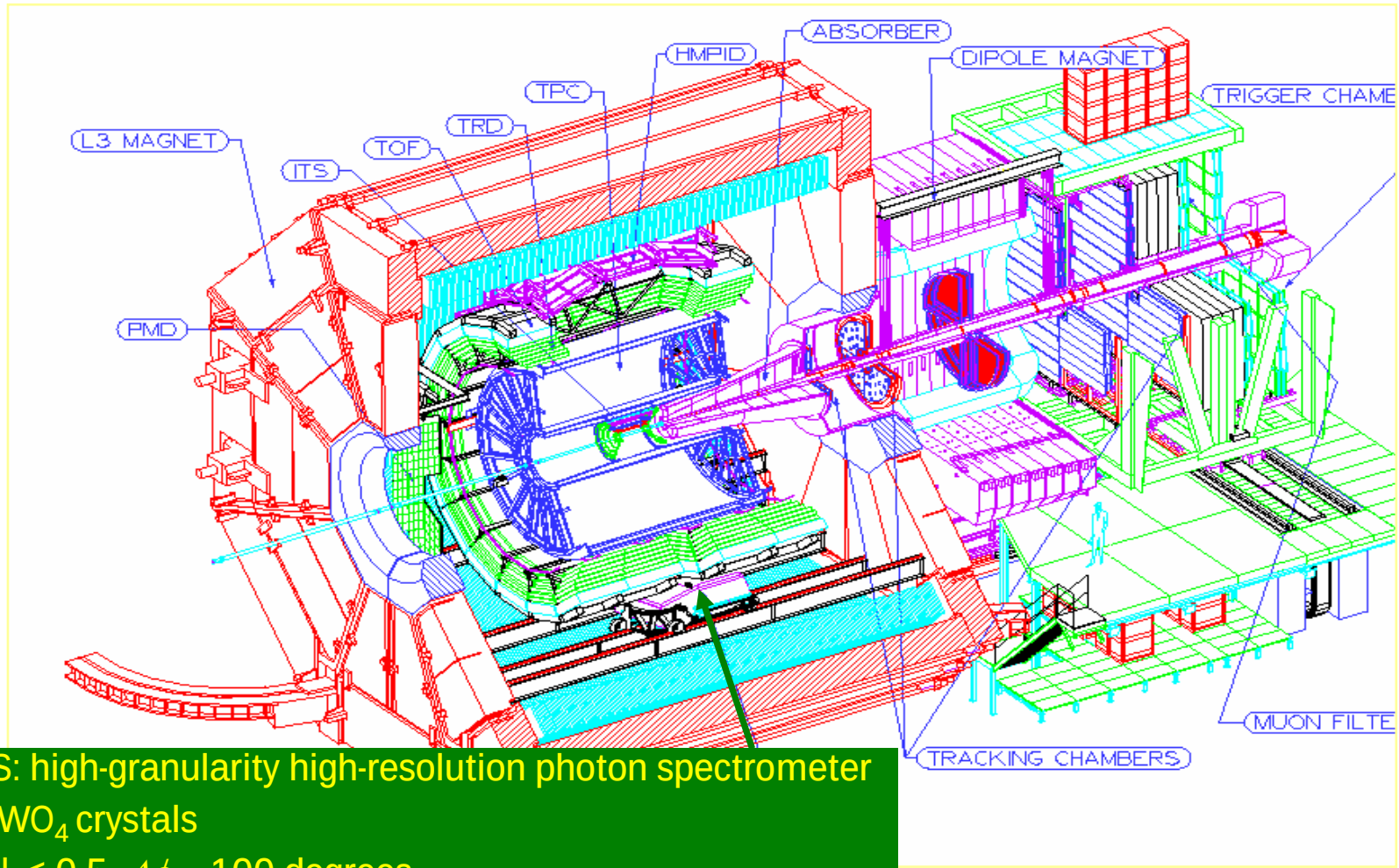
- Electro-Magnetic Calorimeter(s) in ALICE -





- PHOS
  - high resolution
    - $PbWO_4$ crystals
  - high granularity
    - 2.2×2.2 cm^2 at 5 m
- EMCAL (being proposed)
  - large solid-angle
    - $|\eta| < 0.7$, $\Delta\phi \sim 120$ degrees
  - jets measurement together with TPC

- ALICE Photon Spectrometer -

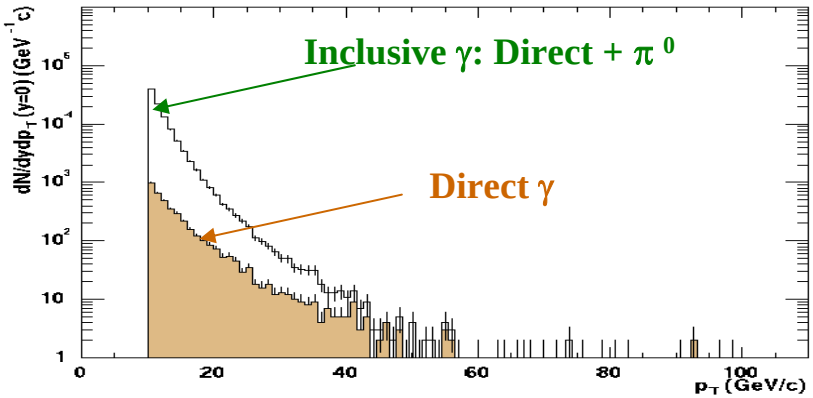


PHOS: high-granularity high-resolution photon spectrometer

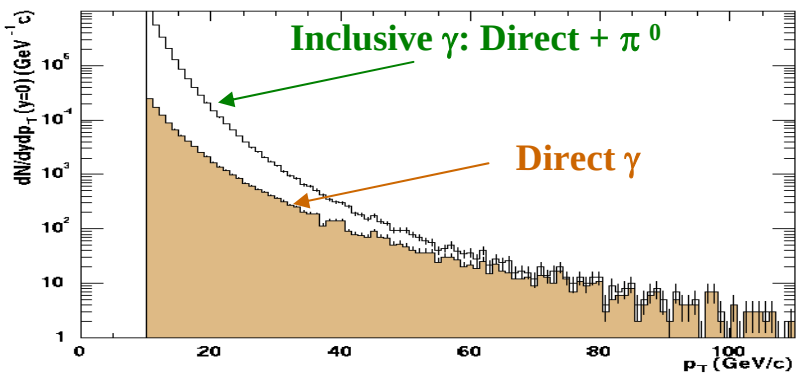
- $PbWO_4$ crystals
- $|\eta| < 0.5$, $\Delta\phi \sim 100$ degrees
- photons and neutral mesons
- γ-jet tagging

- Photon Measurement in ALICE -

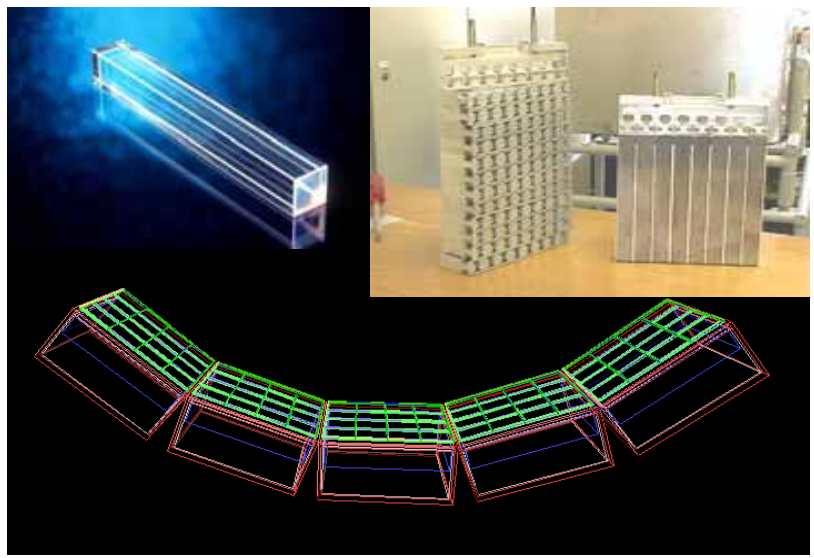
without high p_t trigger



with high p_t trigger



- photon and neutral mesons in p_t up to ~ 100 GeV/c

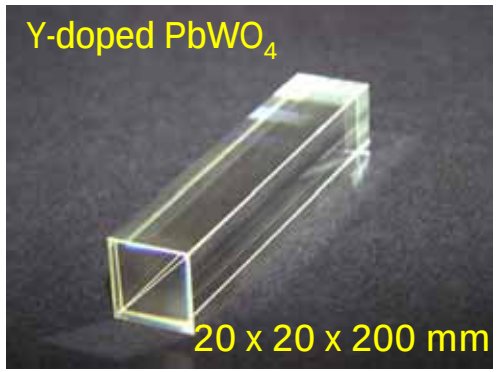


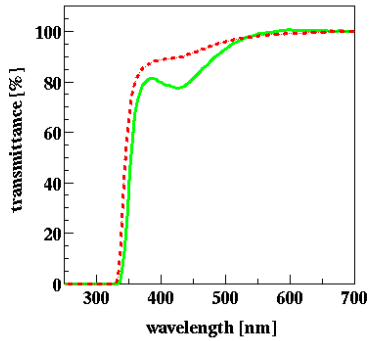
- PHOS Activities at Hiroshima -

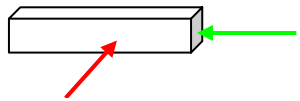
- Japanese $PbWO_4$ crystals tested as reference
  - at Hiroshima-REFER, KEK-PS, Tohoku-LNS
  - 2.50 % $/\sqrt{E}$ [GeV] $\oplus$ 1.25 % resolution achieved
- avalanche photodiode readout being tested
  - works in magnetic field; compact; low power
- preamplifiers and shapers under development
  - pre-production started

- Japanese $PbWO_4$ Crystal -

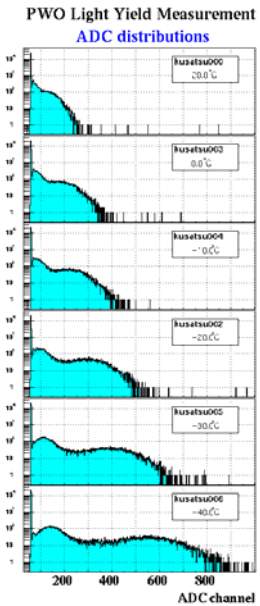
density 8.28 [g/cm³]
radiation length 0.89 [cm]
Moliere radius 2.2 [cm]
peak emission 420-440 [ns]
refractive index 2.3

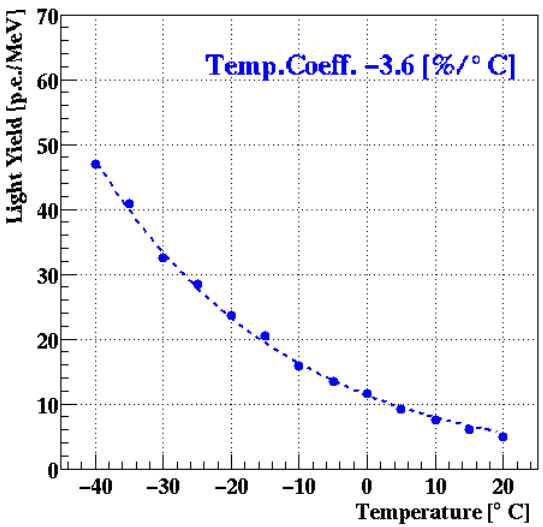




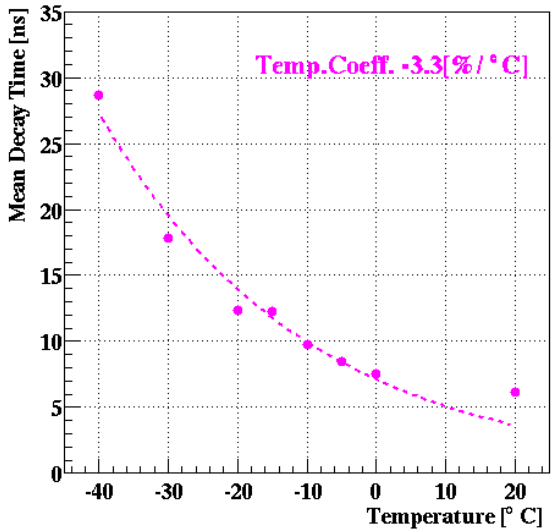


measured with
Hitachi U3010
spectrophotometer

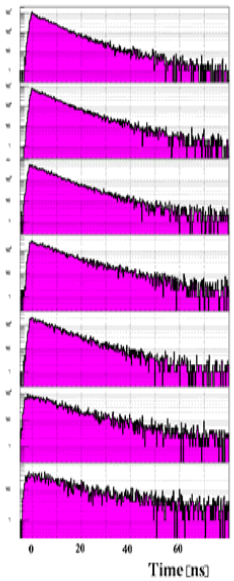




light yield

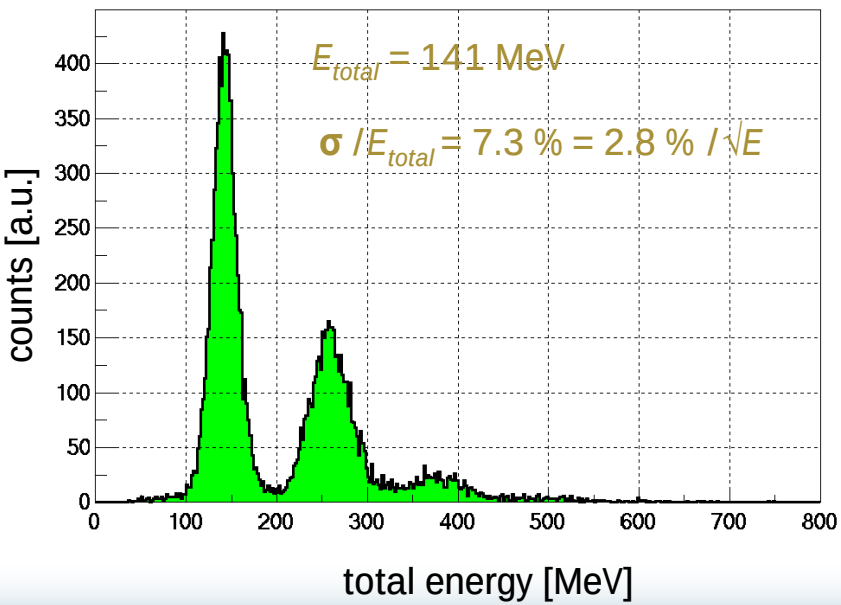


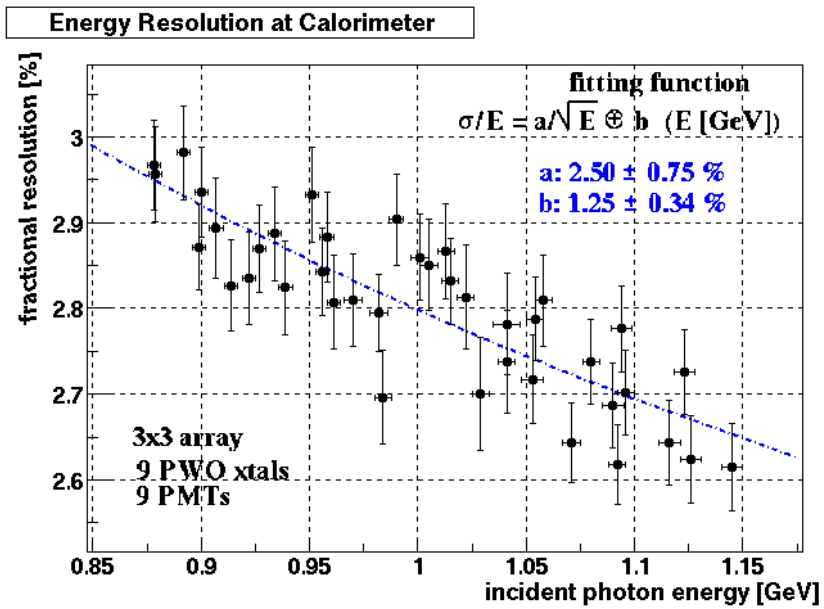
mean decay time



- $PbWO_4$ Performance Tests in Japan -

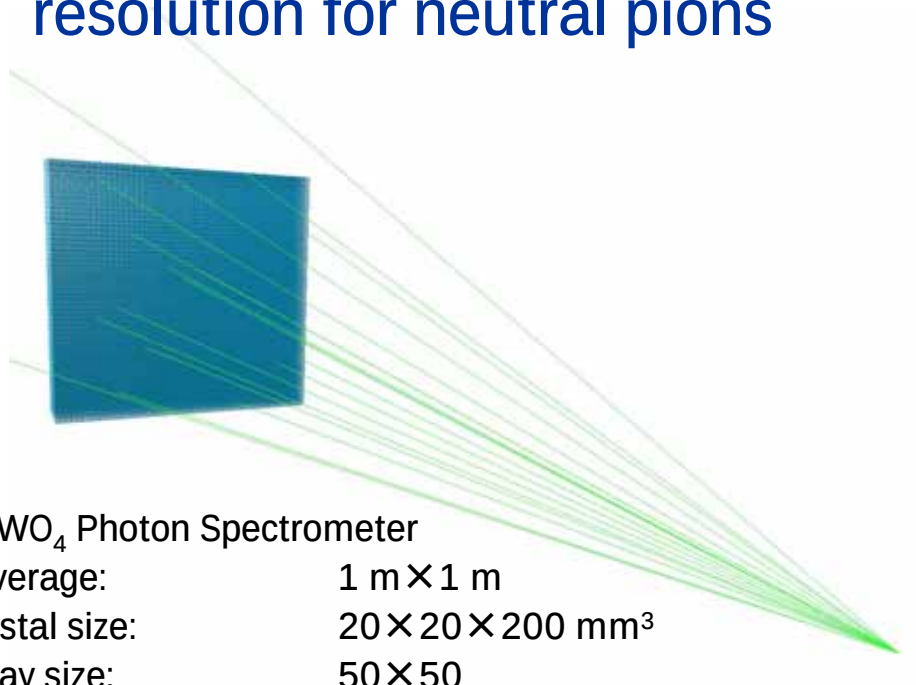
R.Kohara et al.





- Possibility at RHIC -

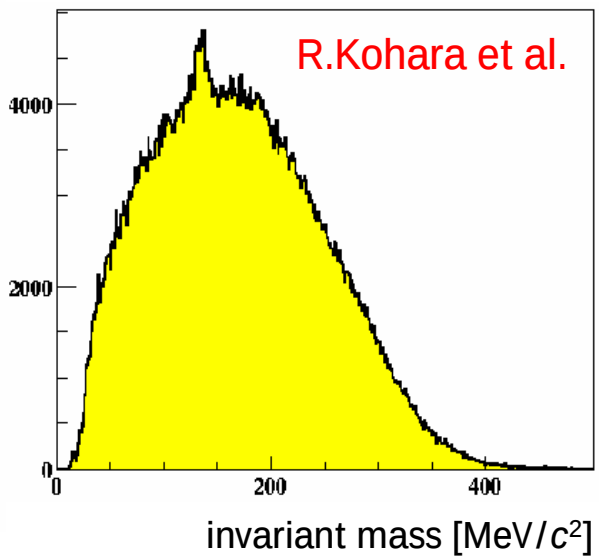
- $PbWO_4$ array at RHIC ?
  - no fine granule electro-magnetic calorimeter at RHIC
  - simulation under RHIC condition gives 3.2 % mass resolution for neutral pions



$PbWO_4$ Photon Spectrometer

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

GEANT4 simulation



- Summary and Conclusions -

- medium with strong final state effects formed in central Au+Au collisions at RHIC
  - observed via jet quenching and its absence in d+Au
  - can be quark-gluon plasma; not conclusive yet
- additional medium probes to be investigated soon
  - baseline established for J/Ψ measurement
  - light vector mesons also important
  - direct photons, unclear at SPS, will soar at RHIC/LHC
- RHIC presenting rich harvest; LHC getting ready
  - even more fruitful physics ahead of us