初期パートン衝突起源の現象と パートン非束縛系生成の予兆

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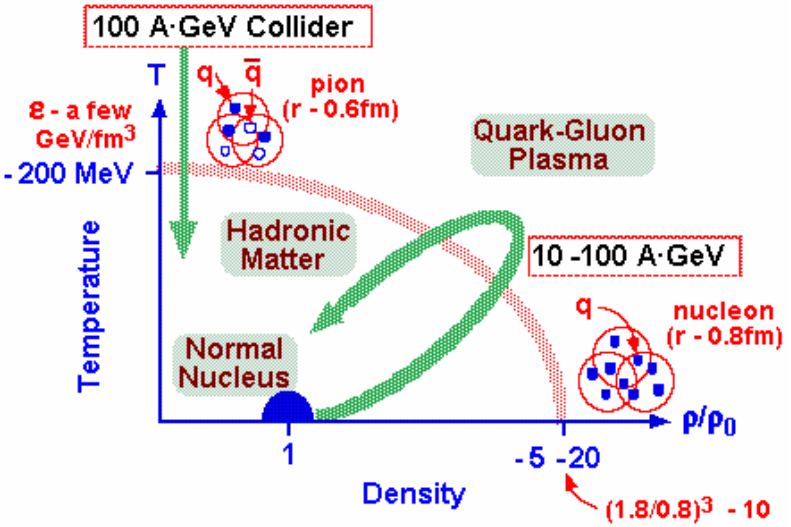
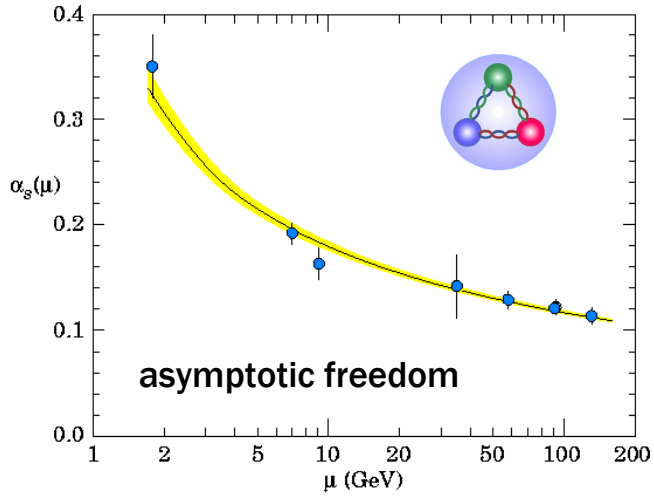
「超高温 QCD 研究の最前線」
於 高知大学

- Presentation Outline -

- experimental program overview
- experimental highlights at RHIC/PHENIX
  - initial phase oriented probes
    - jets/high p_t hadrons (production and subsequent suppression)
    - open heavy flavors (production and subsequent energy loss)
    - heavy quark states (production in color Debye screening)
    - direct photon (prompt production; observed !)
  - intermediate phase - quark dynamics (?)
  - final phase – hadronic observables
- prospects at RHIC/PHENIX and LHC/ALICE
- summary and concluding remarks

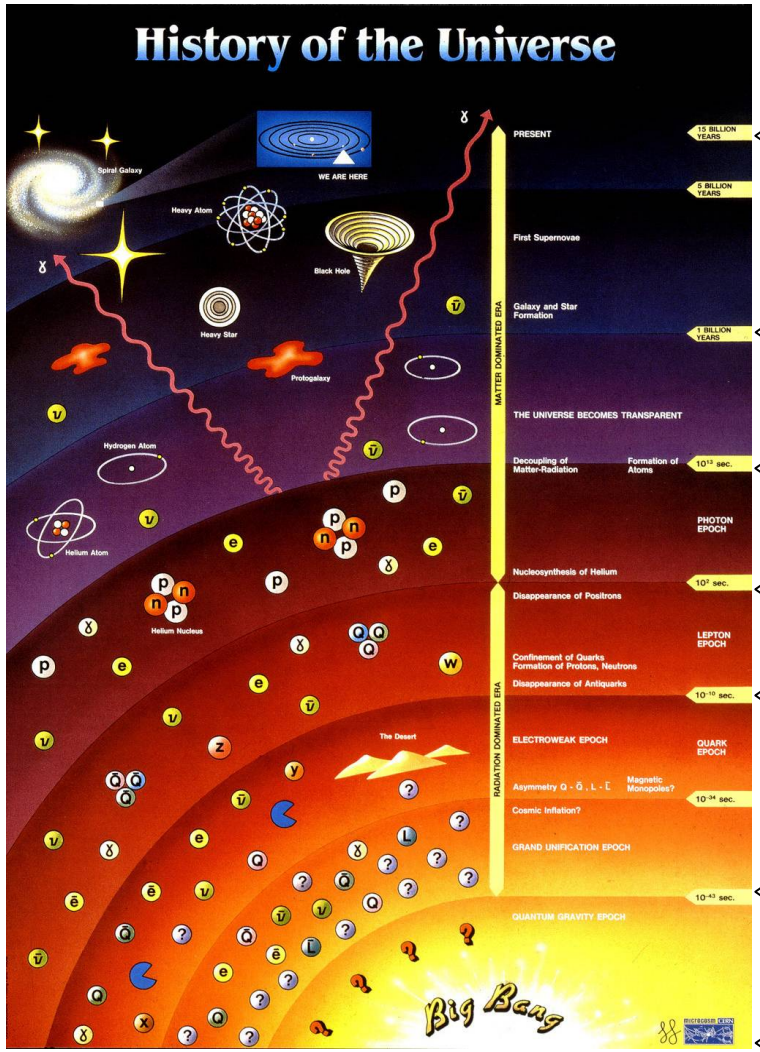
- Physics Goals of RHI Programs -



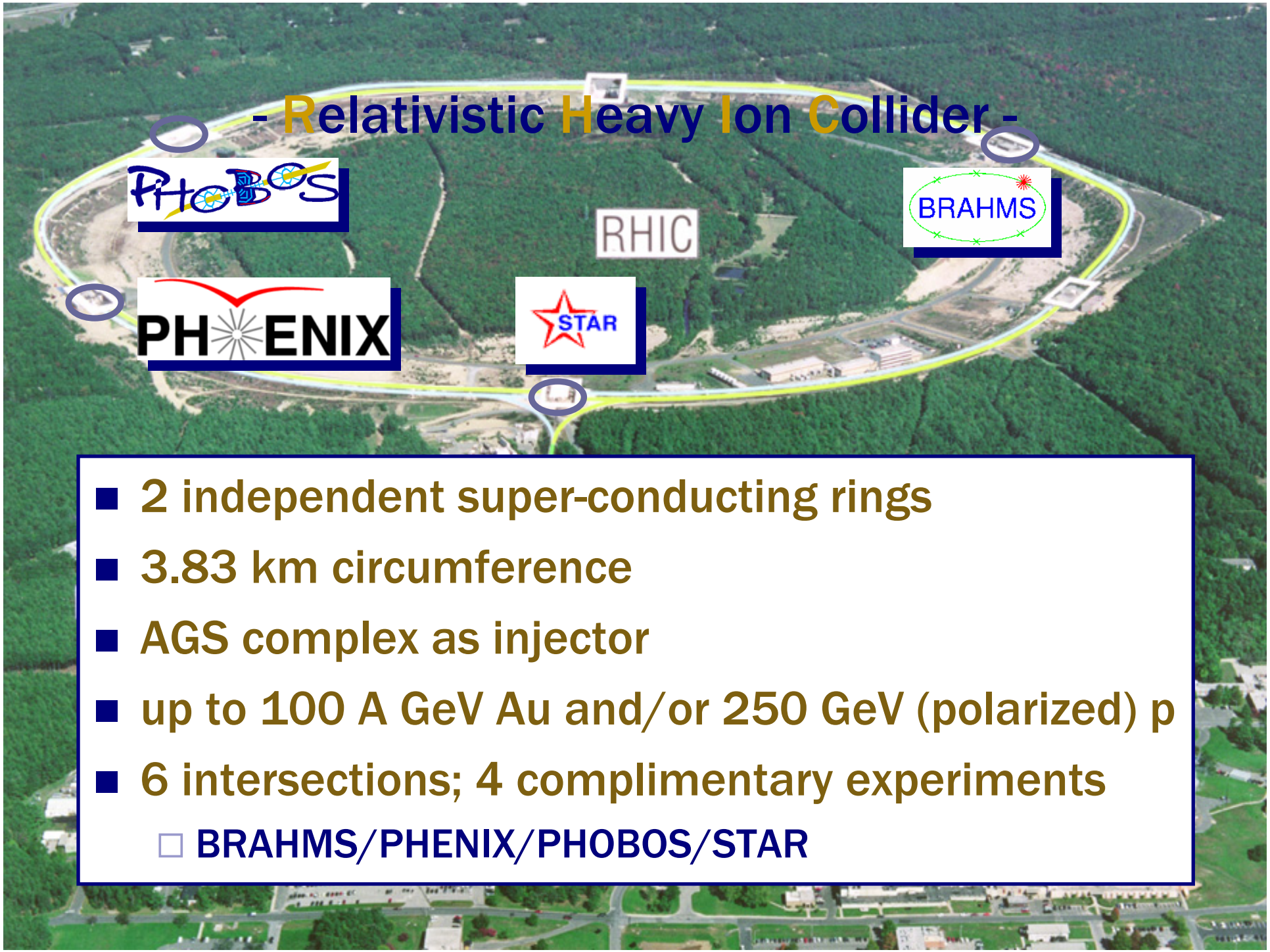


- QCD in extreme conditions and/or scales
  - high energy and/or nuclear density frontier
    - search for and characterize deconfined partonic phase
- Bevalac/SIS/AGS/SPS to RHIC/LHC
  - high density regime to high energy density regime
  - reproduction of universe a few μsec after big bang

- QCD in History of Universe -



15 by	birth of life: present
1 by	galaxy and star formation
10^{12} s	atom formation
10^{2} s	nucleo-synthesis
10^{-6} s	quark confinement anti-quark disappearance quark creation
10^{-35} s	inflationary era
0.00 s	big bang



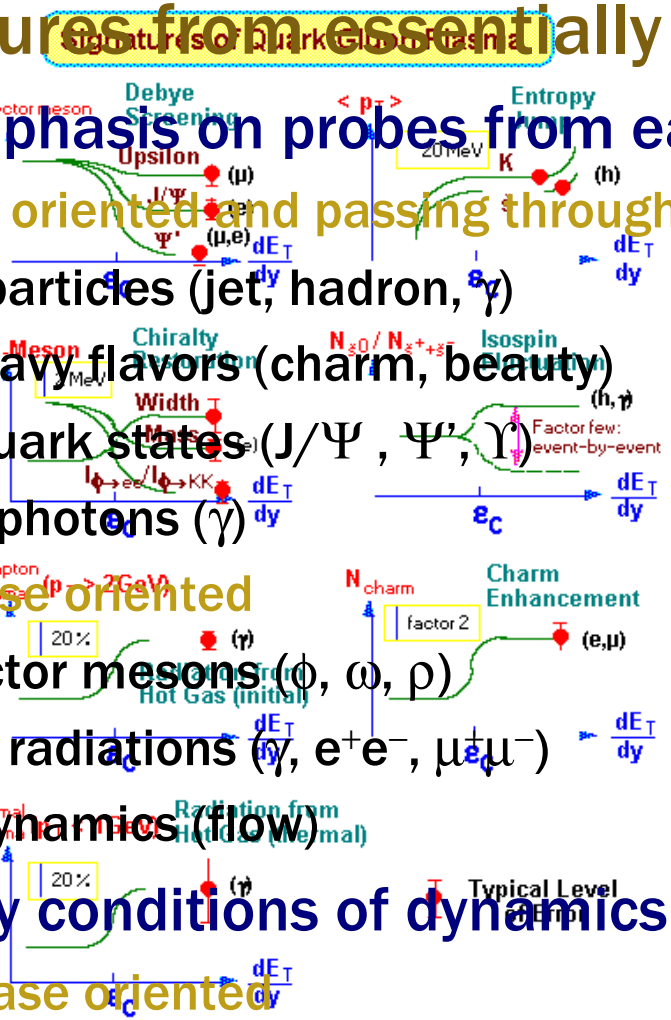
- 2 independent super-conducting rings
- 3.83 km circumference
- AGS complex as injector
- up to 100 A GeV Au and/or 250 GeV (polarized) p
- 6 intersections; 4 complimentary experiments
  - BRAHMS/PHENIX/PHOBOS/STAR

- Pioneering High Energy Nucl. Interaction Exp. -

- maximal set of probes and physics channels
  - photons/electrons/muons/hadrons
- high quality measurement
  - good particle identification
  - high 4-momentum resolution
  - wide kinematical coverage
- access to rare processes
  - high rate capability
  - selective multi-level triggering

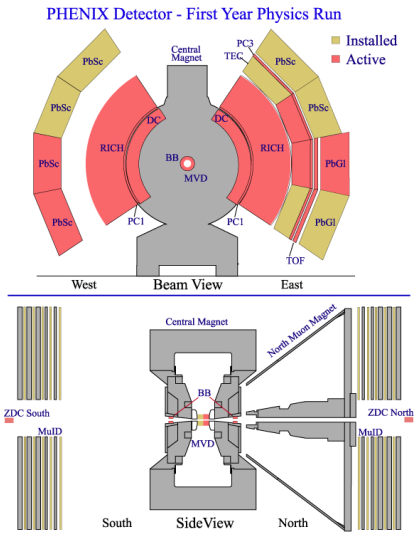
- PHENIX Physics Strategy -

- various signatures from essentially all time scales
  - particular emphasis on probes from early stages
    - initial phase oriented and passing through deconfined phase
      - high p_t particles (jet, hadron, γ)
      - open heavy flavors (charm, beauty)
      - heavy quark states (J/Ψ , Ψ', Υ)
      - prompt photons (γ)
    - thermal phase oriented
      - light vector mesons (ϕ, ω, ρ)
      - thermal radiations (γ, e^+e^-, $\mu^+\mu^-$)
      - quark dynamics (flow)
  - plus boundary conditions of dynamics
    - hadronic phase oriented

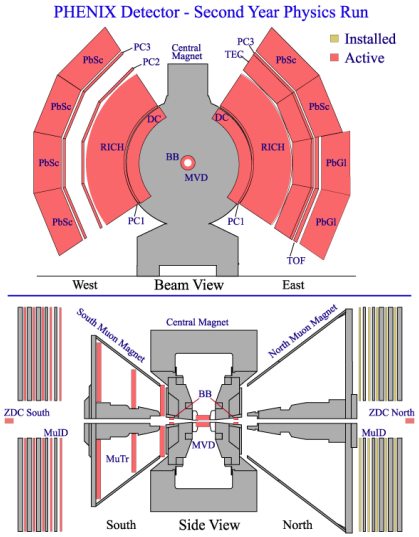


- RHIC/PHENIX Run History -

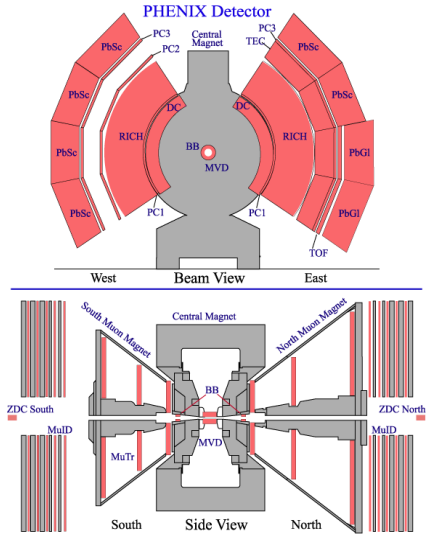
2000



2001/2002



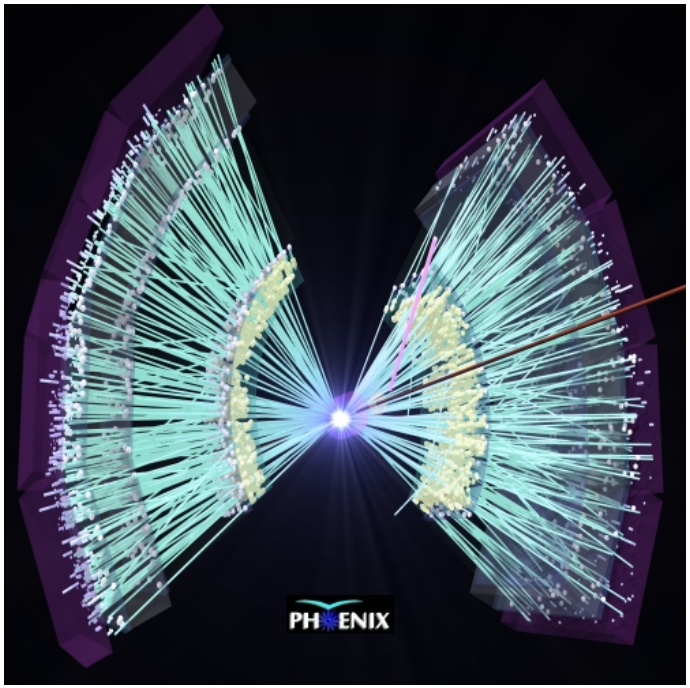
since 2002/2003



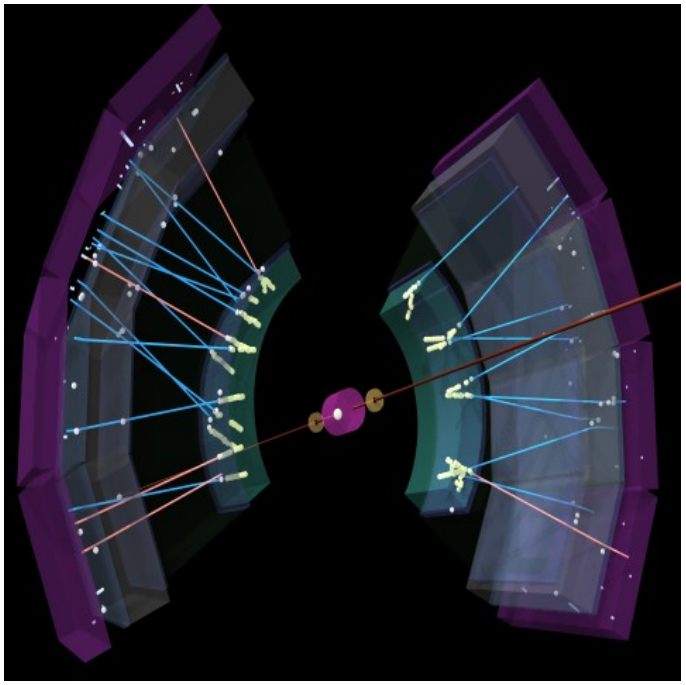
run	year	species	$\sqrt{s_{NN}}$	$\int Ldt$
01	2000	Au+Au	130 GeV	1 μb^{-1}
02	2001/02	Au+Au	200 GeV	24 μb^{-1}
		p+p	200 GeV	150 nb^{-1}
03	2002/03	d+Au	200 GeV	2.74 nb^{-1}
		p+p	200 GeV	350 nb^{-1}
04	2003/04	Au+Au	200 GeV	240 μb^{-1}
		Au+Au	62 GeV	9 μb^{-1}
		p+p	200 GeV	350 nb^{-1}

- Collisions as Seen by PHENIX Central Arms -

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



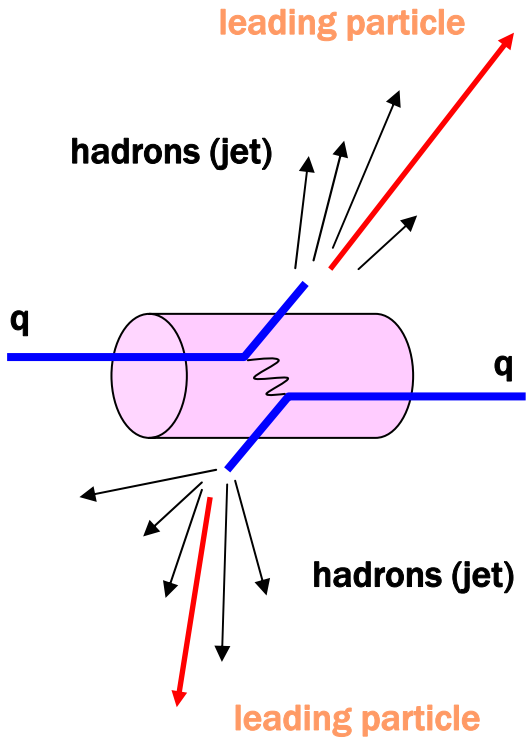
d+Au at $\sqrt{s_{NN}}$ = 200 GeV



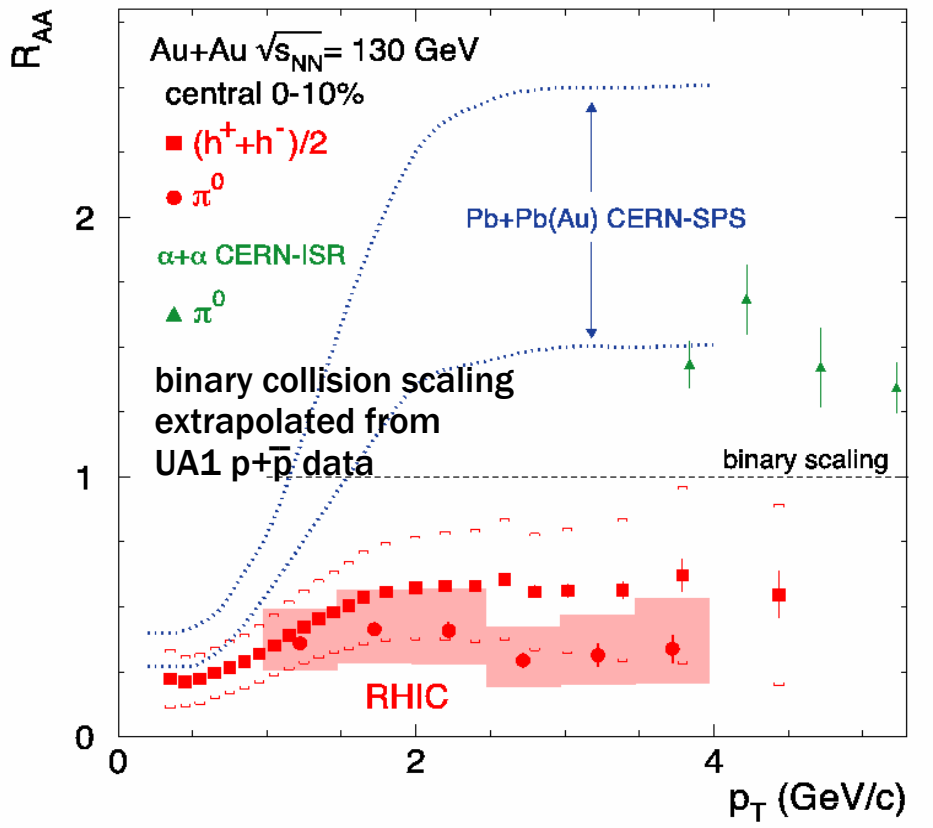
- ~ 5,000 charged particles produced in a central Au+Au collision at $\sqrt{s_{NN}}$ = 200 GeV
  - only few of them carrying early stage information

- Physics via Jets and High p_t Particles -

- responsible particle production mechanisms
  - soft production at low p_t
    - thermally shaped
  - hard scattering at high p_t
    - binary collision scaling expected
    - well calibrated probe of medium
- hard probes of partonic matter
  - energy loss of scattered partons
    - suppression of jets/high p_t hadrons
    - modification of angular correlation
  - modification of fragmentation
    - changes of particle composition



- RHIC Year 1: Discovery -

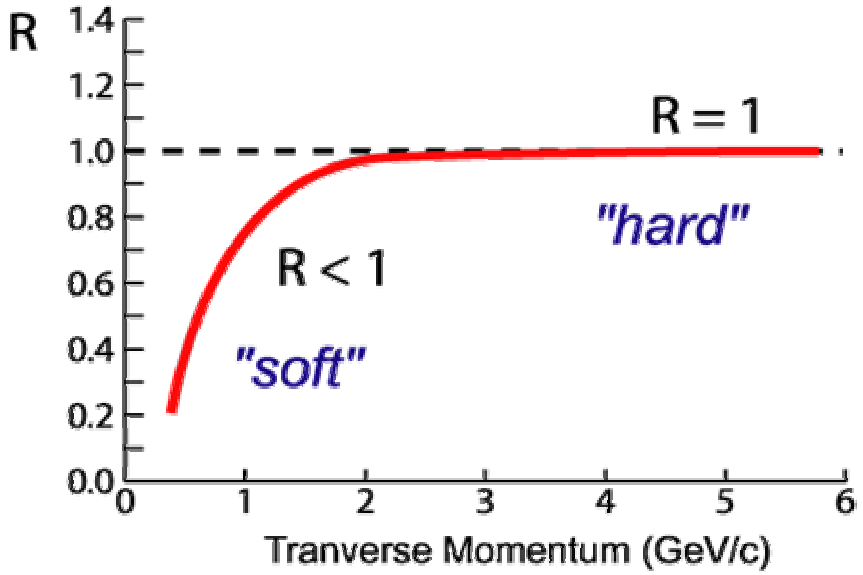


Au+Au at $\sqrt{s_{NN}}$ = 130 GeV
PHENIX PRL 88, 022301 (2002)

- high p_t hadron suppression in central Au+Au

- Nuclear Modification Factor R_{AB} -

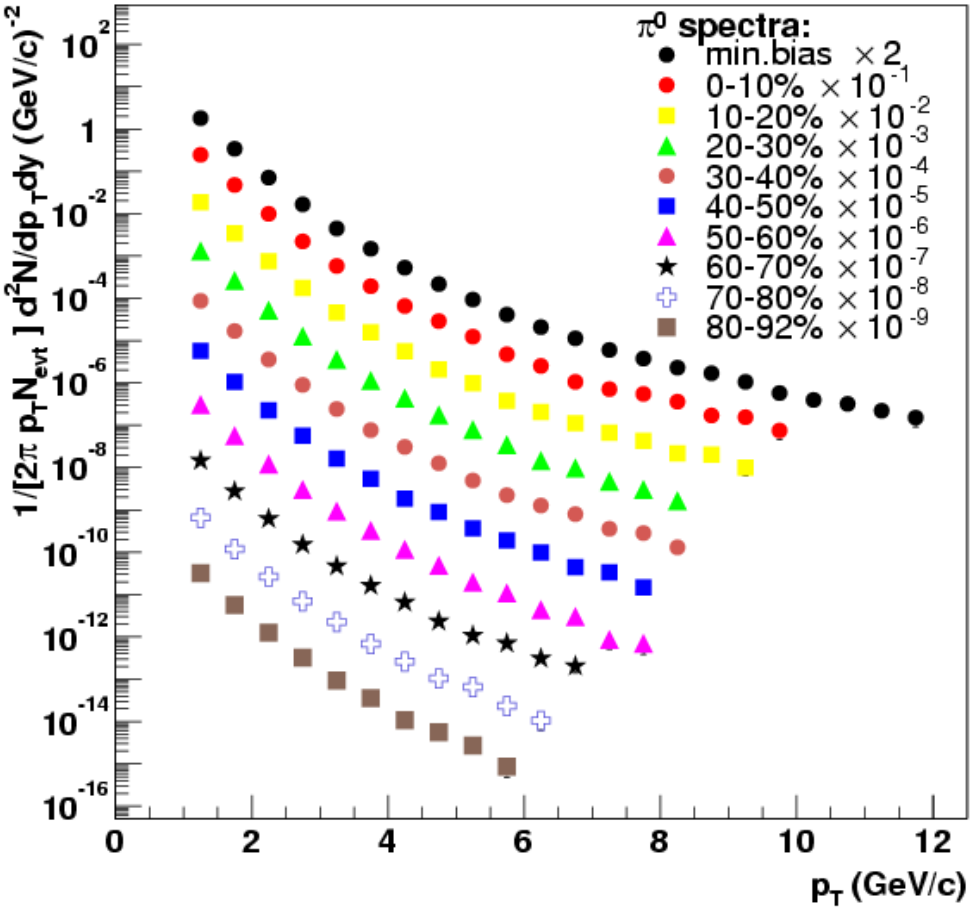
$$R_{AB} = \frac{\mathrm{d}N_{\mathrm{AB}} / \mathrm{d}p_T \mathrm{d}y}{\langle N_{coll} \rangle / \sigma_{\mathrm{NN}}^{\mathrm{inel}} \cdot \mathrm{d}\sigma_{\mathrm{pp}} / \mathrm{d}p_T \mathrm{d}y}$$



- 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

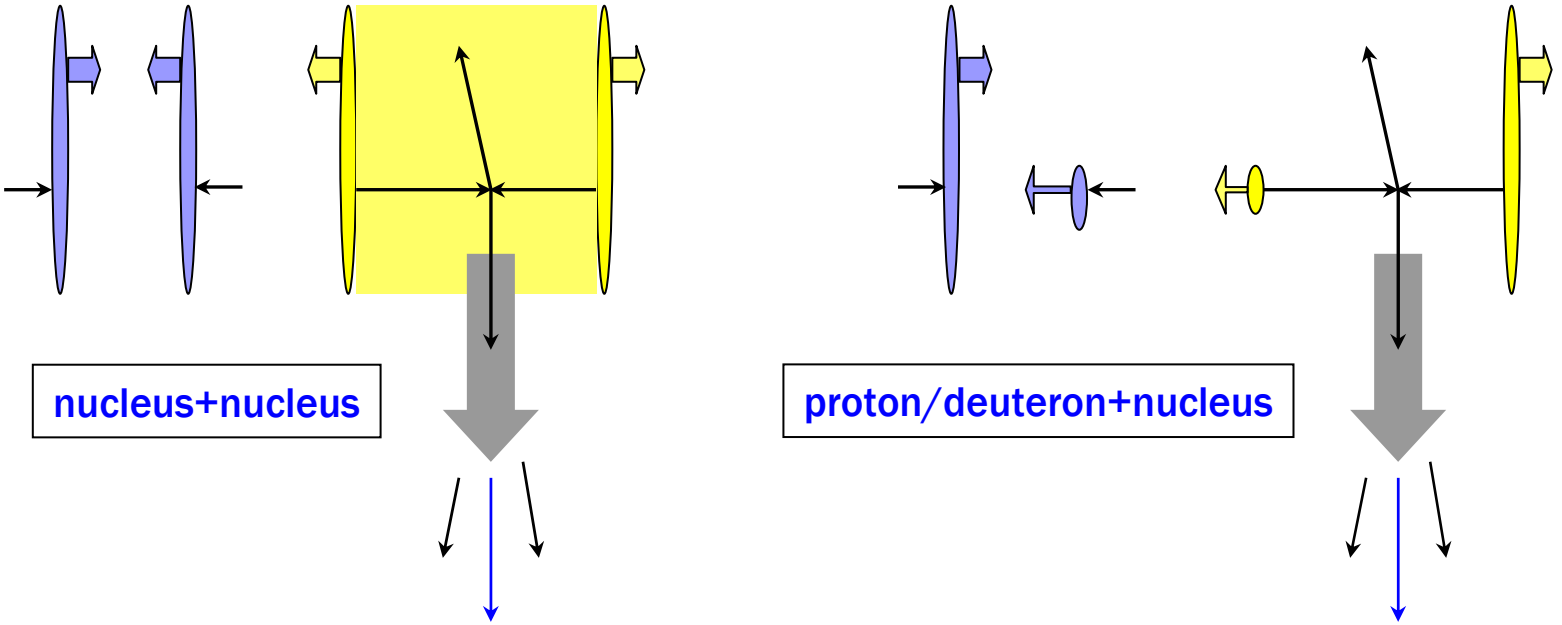
- RHIC Year 2: Improvement -

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



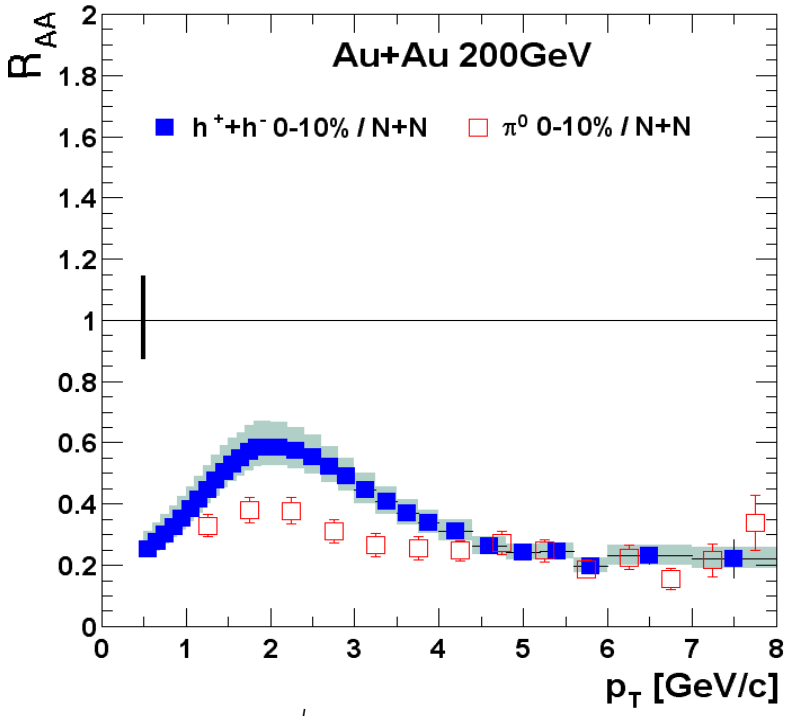
Au+Au→π^0+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX PRL 91, 072301 (2003)

- RHIC Year 3: Control -

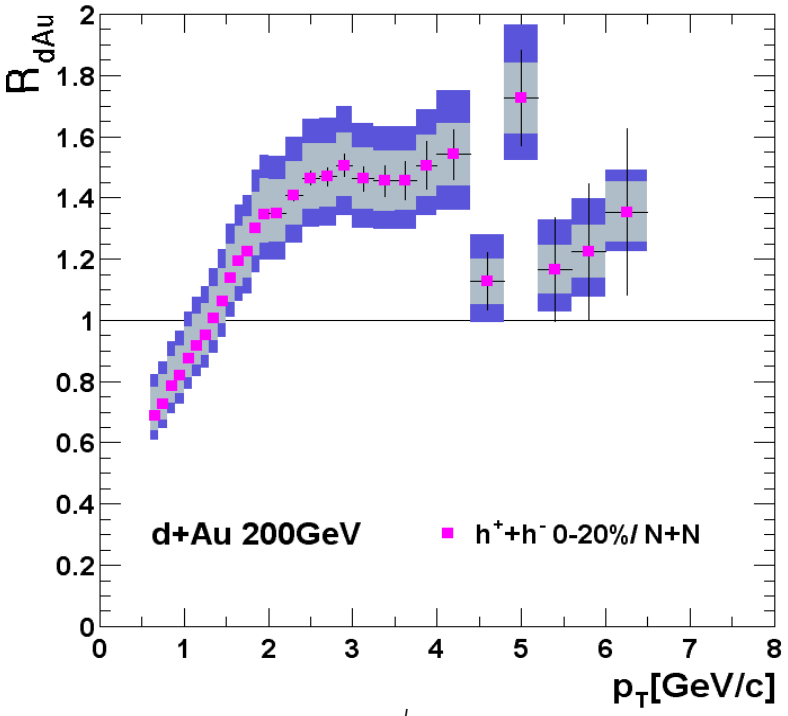


- cold nuclear matter effects quantified
- “initial” and “final” state effects distinguished
  - “initial/final” with respect to “initial” partonic collisions
  - “less jets created” versus “jets quenched”

- Contrary Behavior in Au+Au and d+Au -



Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX *cf.* PRL 91, 072303 (2003)



d+Au→$h^{\pm}$+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX *cf.* PRL 91, 072303 (2003)

- clearly different and opposite centrality evolution
- final state jet quenching in central Au+Au

- Jet Quenching Observation -

- most prominent signature of new phase of matter
  - hot and dense matter with strong final state effects
    - most likely what has been called “quark gluon plasma”
- (light) quark energy loss in final states
  - dominated by Bremsstrahlung, *i.e.* gluon radiation
- further tests (jet tomography)
  - quantitative understanding
    - gluon density and temperature
  - jet energy redistribution
  - open heavy flavor spectra
    - less energy loss with heavier flavors ?

- Physics via Open Heavy Flavors -

- valuable probes of QCD dynamics in early stages
  - production primarily via gluon-gluon fusion
    - initial gluon density
  - reference of heavy quark states + continuum di-leptons
  - energy loss via gluon radiation
    - *cf.* jet quenching via lighter quark energy loss
  - additional thermal charm production
    - equation of state in thermal phase

Classic production diagrams

The heavy-flavor production diagrams shown below are taken from
E. Norrbin and T. Sjostrand, Eur. Phys. J. C17 (2000) 137.

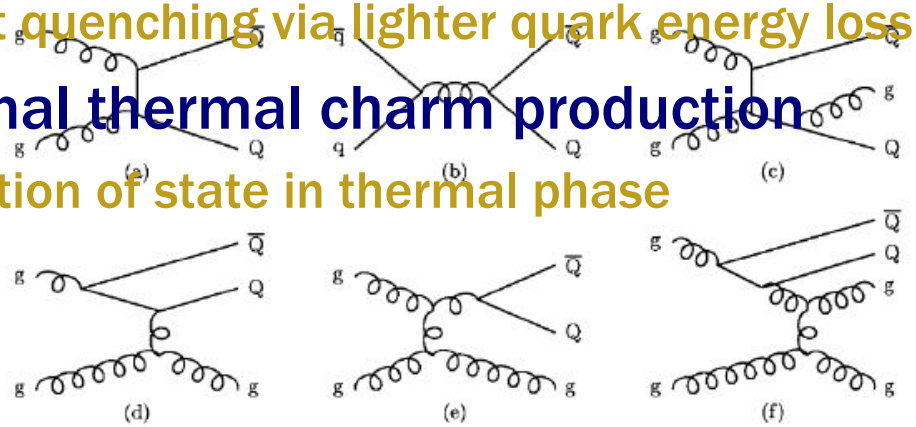
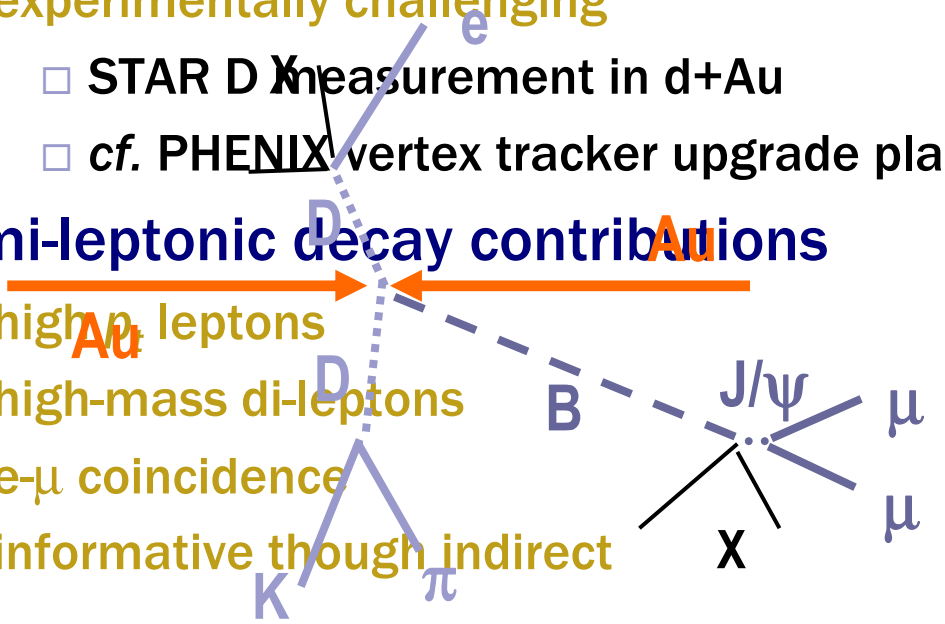


Fig. 1a–f. Examples of heavy-flavor production diagrams. a,b Leading order. c Pair creation (with gluon emission). d Flavor excitation. e Gluon splitting. f Events classified as gluon splitting but of flavor-excitation character

The mechanisms can be separated into three categories: **pair creation** (a, b, c), **flavor excitation** (d, f) and **gluon splitting** (e). Gluon splitting is a final state effect.

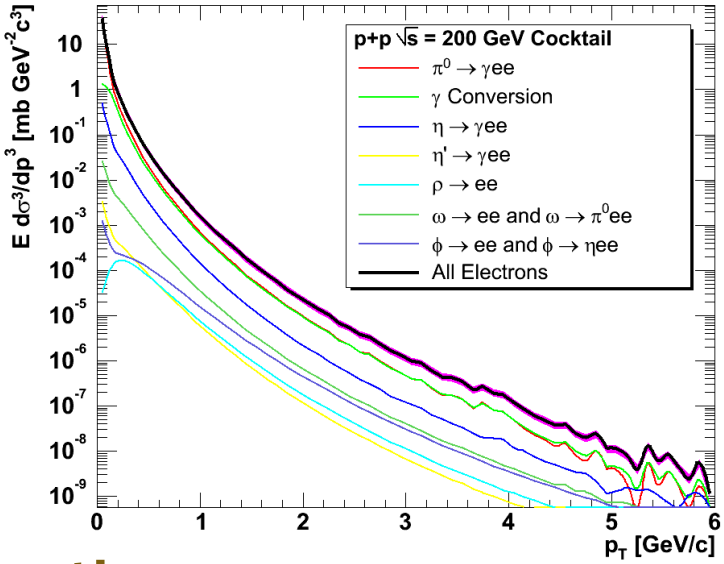
- Open Heavy Flavors at RHIC/PHENIX -

- charm/beauty meson observables include:
  - direct decay reconstruction
    - e.g. $D^0 \rightarrow K^- + \pi^+$, $B \rightarrow J/\Psi + X$
    - experimentally challenging
      - STAR D $\rightarrow$ K measurement in d+Au
      - *cf.* PHENIX vertex tracker upgrade plan
  - semi-leptonic decay contributions
    - high-p_T leptons
    - high-mass di-leptons
    - e-μ coincidence
    - informative though indirect



- Open Heavy Flavors via Single Electrons -

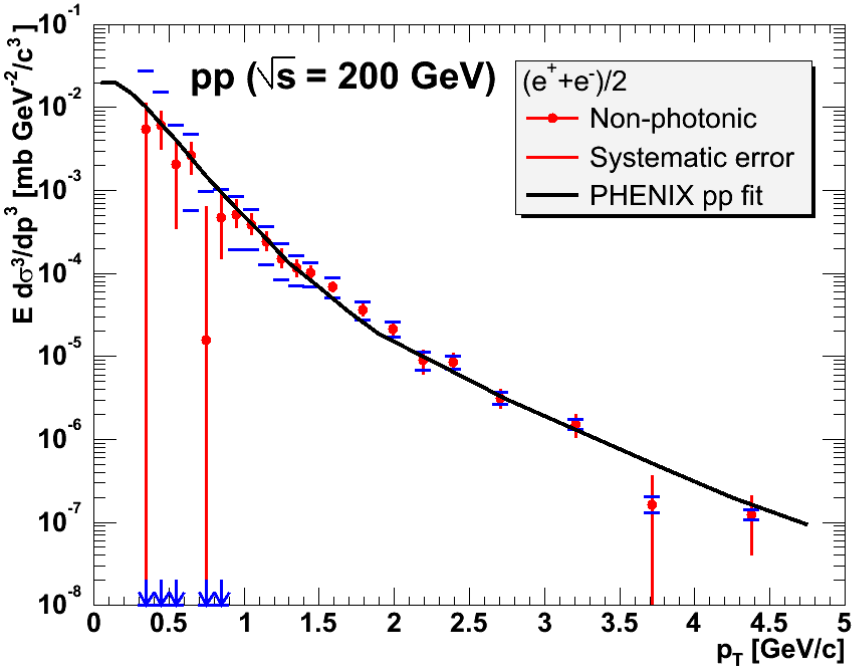
- "background" electron sources
  - photon conversion
  - Dalitz decay of
    π^0, η^0, η', ϕ, ω
  - di-electron decay of
    ϕ, ω, ρ
  - weak decay of K's



- heavy flavor electron extraction
  - hadron cocktail method
  - photon converter method
    - *ref.* M.Togawa, F.Kajihara, T.Tabaru, 29a SH-12/13/14

- Open Heavy Flavor in p+p at $\sqrt{s}$ = 200 GeV -

- fit with PYTHIA + 2 free parameters
  - PYTHIA “standard” parameter set
  - charm and beauty cross sections tuned
    - $\sigma_{cc} = 709 \pm 85\ (\text{stat})\ ^{+332}_{-281}\ (\text{sys})\ \mu\text{b}$

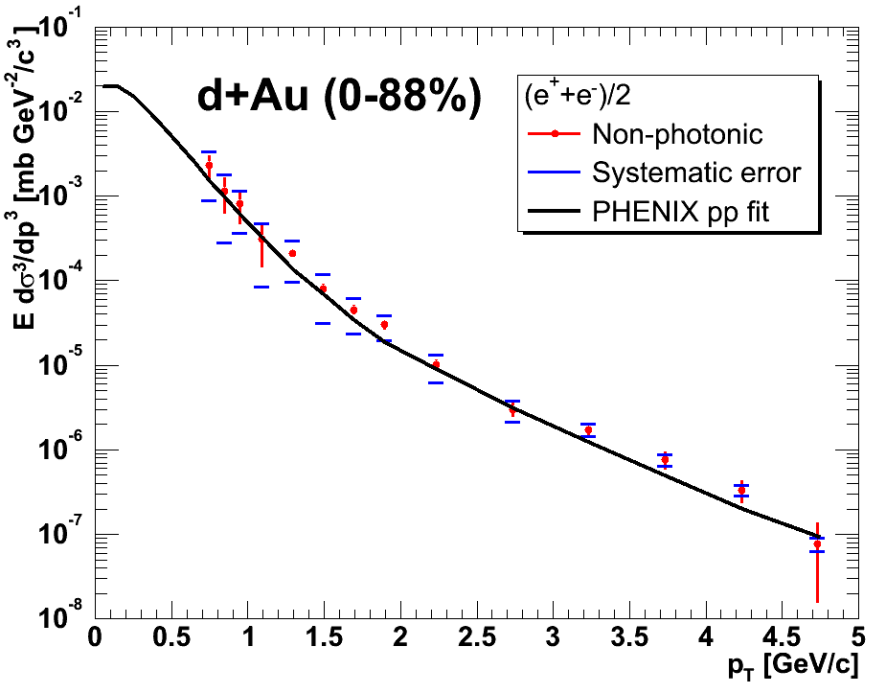


p+p→$e^{\pm}$ at $\sqrt{s}$ = 200 GeV

cf. PHENIX PRL88, 192303 (2002)

- Open Heavy Flavors in d+Au -

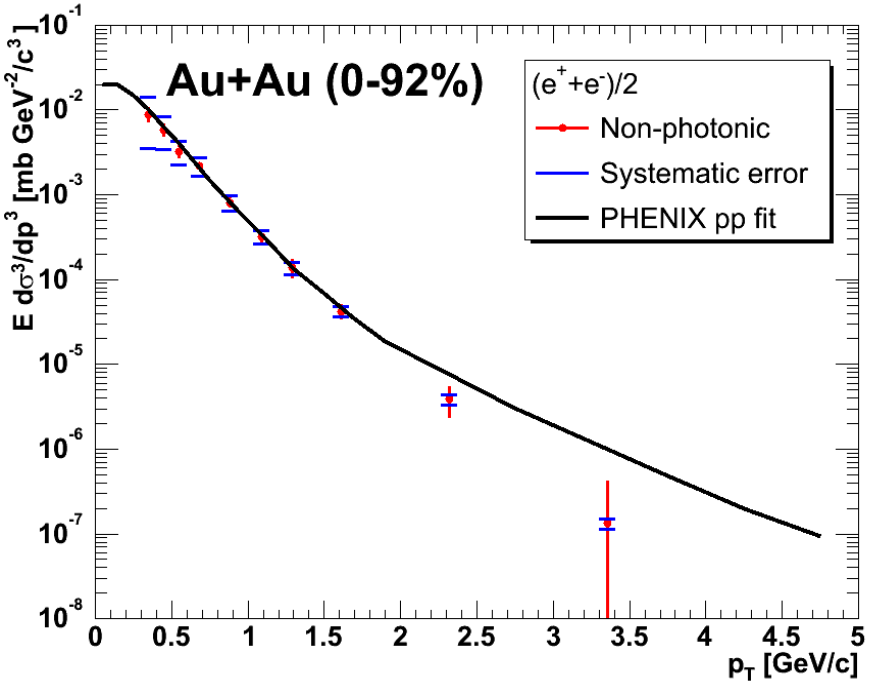
- non-photonic electron spectrum in d+Au
  - photon converter method
  - scaled with number of binary nucleon-nucleon collisions
  - good agreement with p+p data



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

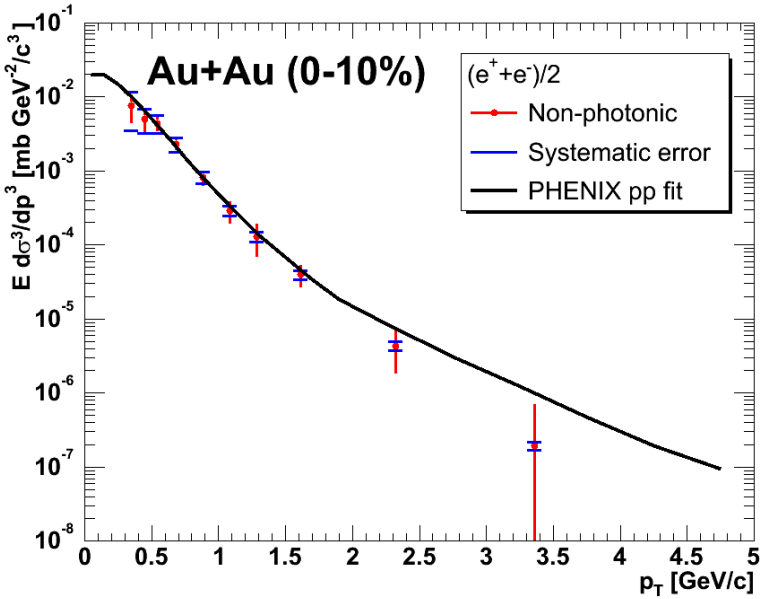
- Open Heavy Flavors in Au+Au -

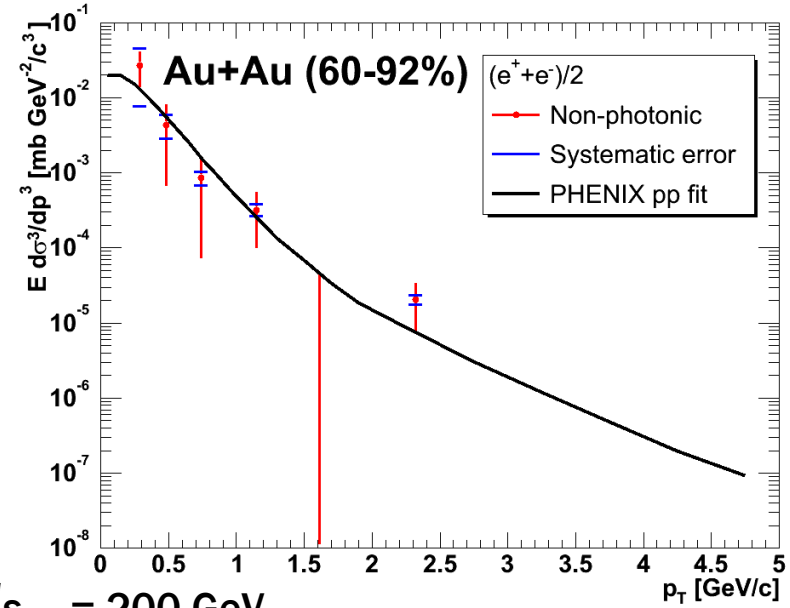
- non-photonic electron spectrum in Au+Au
  - photon converter method
  - scaled with number of binary nucleon-nucleon collisions
  - good agreement with p+p data at least at low p_t



Au+Au→$e^{\pm}$ at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX submitted to PRL

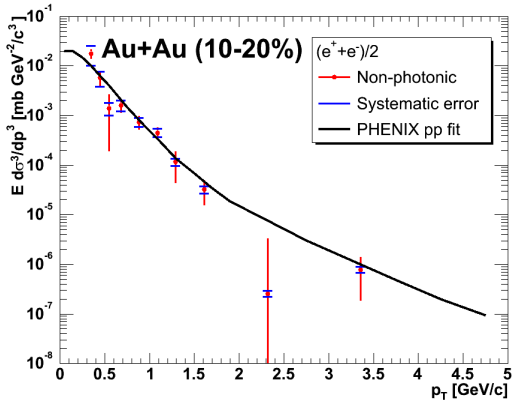
- Centrality (In)dependence in Au+Au -

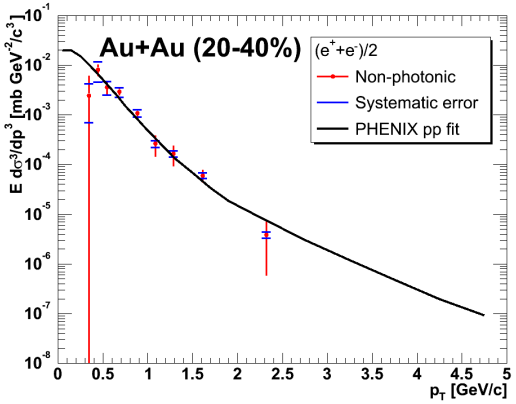


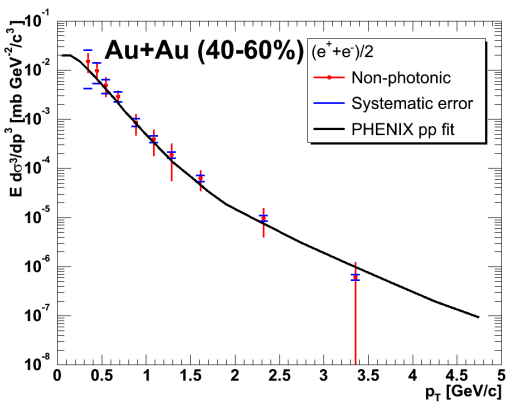


Au+Au→e± at $\sqrt{s_{NN}}$ = 200 GeV

PHENIX submitted to PRL



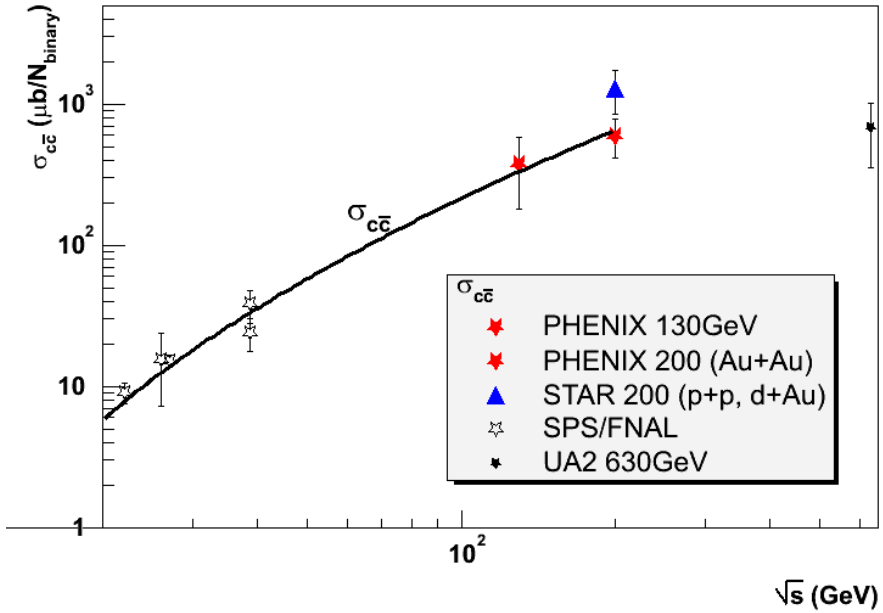




- Charm (Non-)Quenching ? -

- no indication of ***strong*** charm energy loss
  - *cf.* jet quenching with lighter quarks
- higher p_t interesting; analyses in progress
  - hadron cocktail method on Au+Au data
  - high statistics Au+Au data (run 4)
  - single $\mu^{\pm}$ in forward arms
- promising probe of created fireball state

- Charm Production Cross Section -

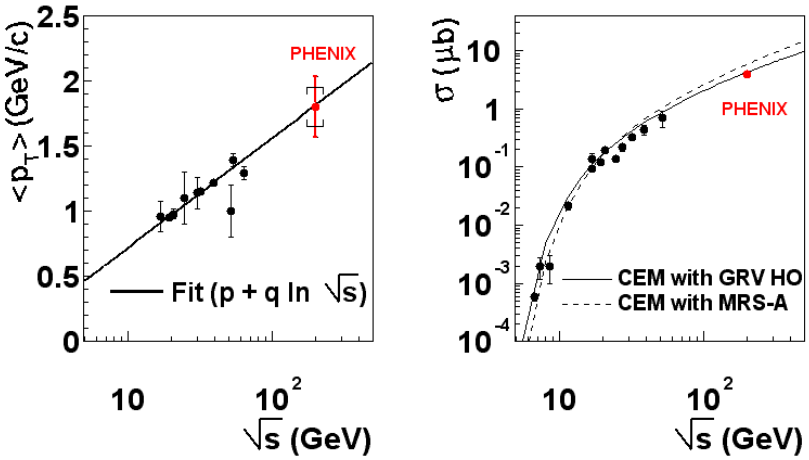


- consistent with $\sqrt{s}$ systematics and binary scaling
  - agreement with NLO pQCD within systematic errors
    - $\sigma_{cc} = 420 \pm 33$ (stat) ± 250 (sys) μb at $\sqrt{s_{NN}} = 130$ GeV
    - $\sigma_{cc} = 622 \pm 57$ (stat) ± 160 (sys) μb in $\sqrt{s_{NN}} = 200$ GeV
  - direct reference for heavy quark states

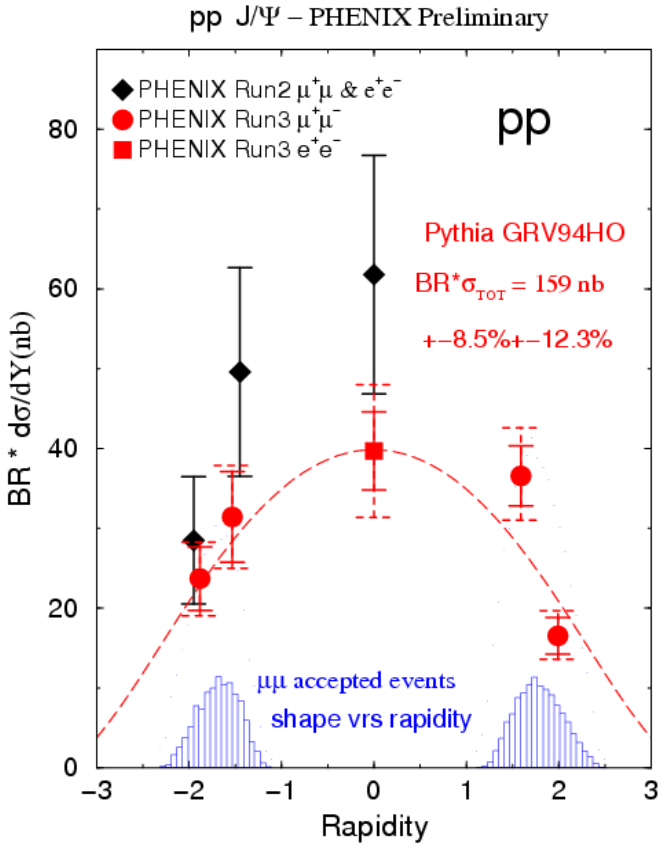
- Physics via Heavy Quark States -

- anticipated probes of deconfined partonic phase
- systematic studies required against uncertainties
  - p+p/p(d)+A/A+A, $\sqrt{s_{NN}}$, rapidity, p_t dependences
  - initial state reference channels
    - open heavy flavors (single leptons, continuum di-leptons)
    - Drell-Yan (continuum di-leptons)
    - prompt γ (single photons)
  - J/Ψ and Υ families
    - J/Ψ, Ψ', Υ(1S), Υ(2S+3S)
  - more systematics (only with high statistics data)
    - detailed centrality dependence
    - feed down effect, *e.g.* p+p $\rightarrow \chi_c \rightarrow$ J/$\Psi + \gamma$

- J/Ψ in p+p at √s = 200 GeV -



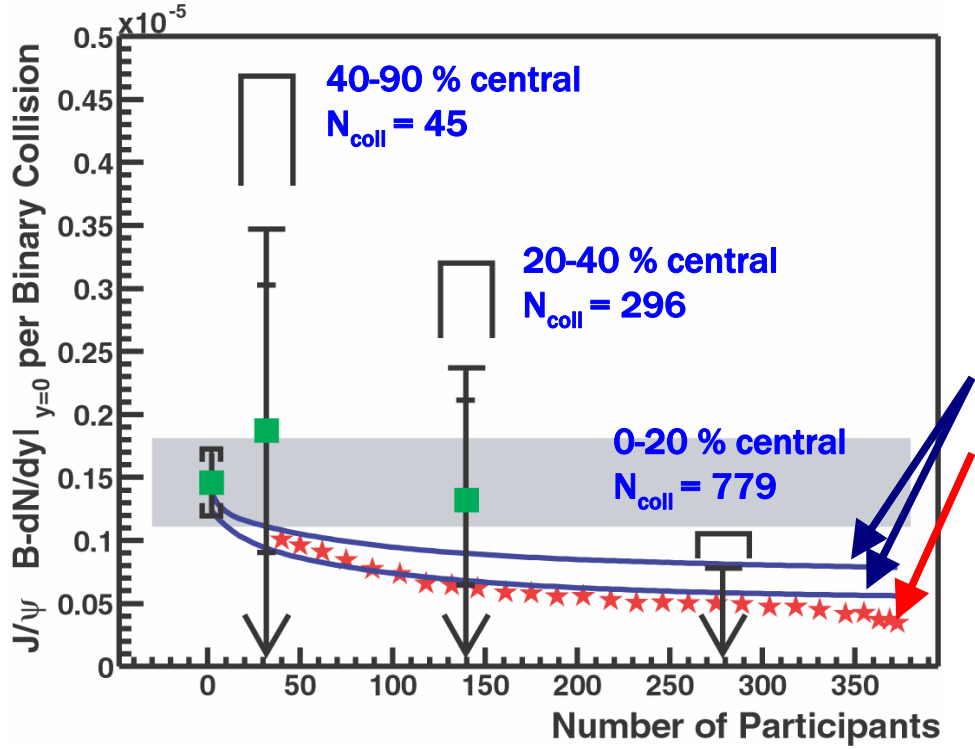
p+p→J/Ψ+X at √s = 200 GeV
PHENIX PRL 92, 051802 (2004)



p+p→J/Ψ+X at √s = 200 GeV
PHENIX preliminary

- good agreement with:
  - lower √s data and phenomenological extrapolation
  - color evaporation model

- J/Ψ in Au+Au Early Analysis (Run 2) -



normal nuclear absorption

SPS NA50 normalized to p+p point

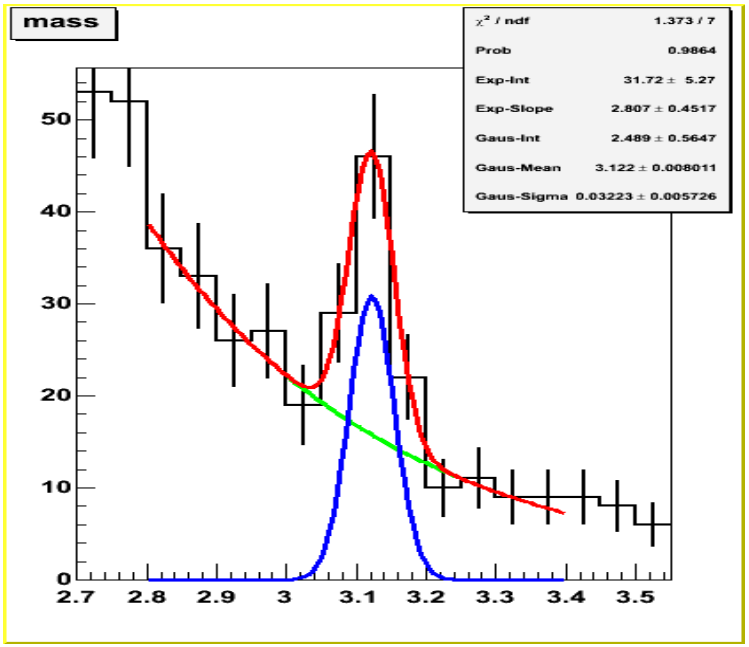
Au+Au→J/Ψ→e⁺e⁻ at $\sqrt{s_{NN}}$ = 200 GeV

PHENIX PRC 69, 014901 (2004)

- improved statistics needed (coming), but already:
  - inconsistent with enhancement scenarios
    - *e.g.* coalescence model, *cf.* PRC 63, 054905 (2001)

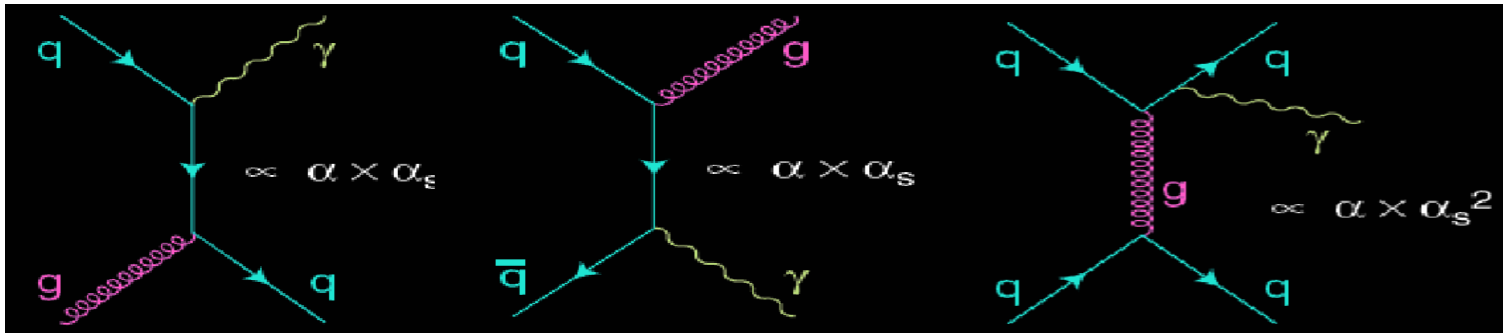
- J/Ψ in Au+Au Prospects (Run 4) -

- 240 μb^{-1} recorded with improved detectors
  - ~ 100 times more J/Ψ signals expected than in run 2
  - (massive) analysis started; first outputs available
    - *ref.* T.Gunji, 29a SH-11



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

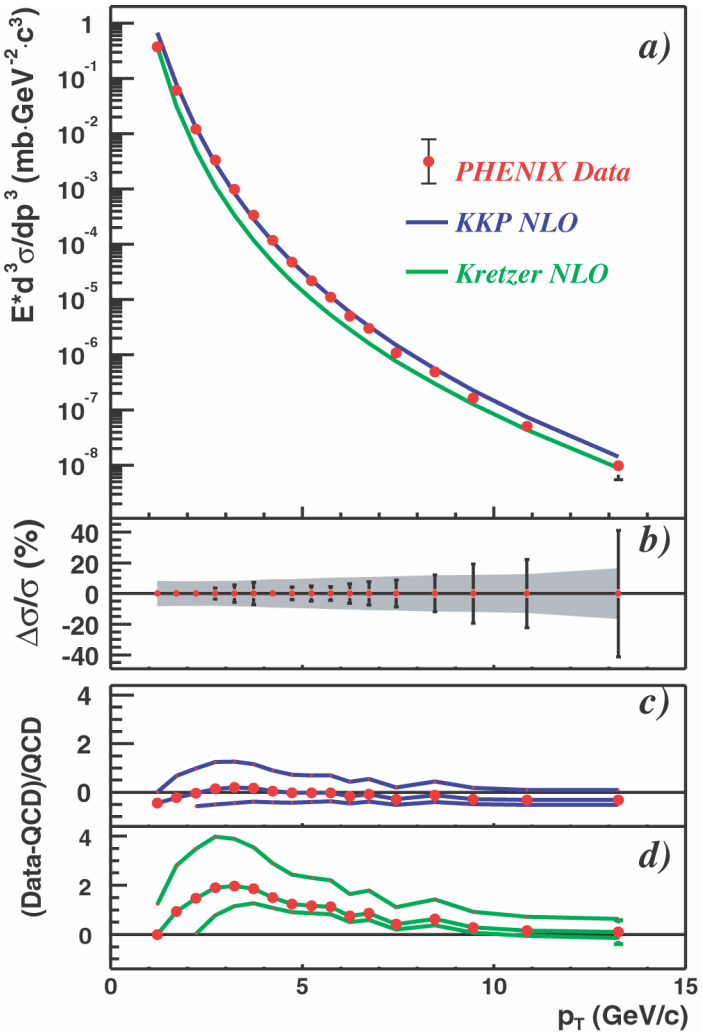
- Physics via Prompt Direct Photons -



- initial state parton distribution
  - excellent control for initial state modifications
    - gluon compton: half a di-“jet” without fragmentation
    - annihilation
    - Bremsstrahlung
- final state parton/jet radiation

- "Background" Hadronic Decay Photons -

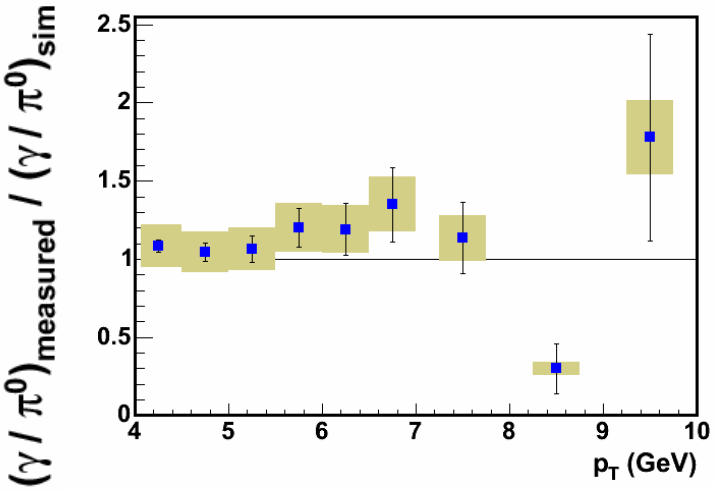
- evaluated based on measured hadron spectra
  - $\pi^0 \rightarrow 2\,\gamma$ most significant
  - first baseline: π^0 in p+p
    - available up to p_t ~ 12 GeV/c
    - agreement with NLO pQCD
      - no intrinsic k_t included
  - also η, η', ω, …
    - m_t scaling assumed



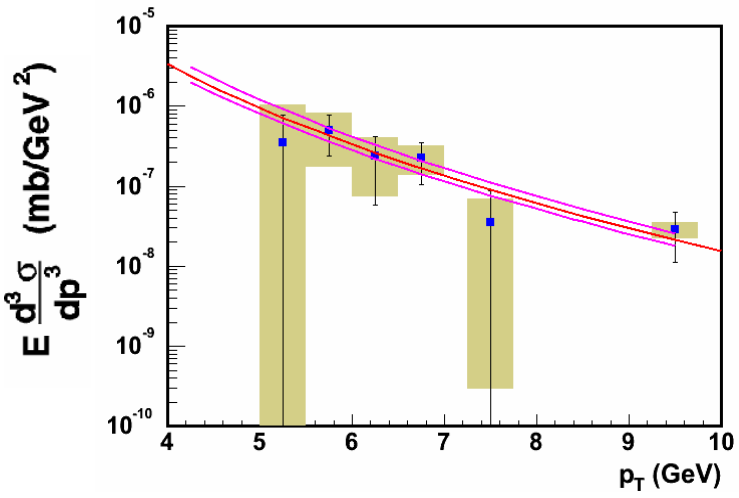
p+p→π^0+X
PHENIX PRL 91, 241803 (2003)

- Photon "Excess" in p+p at $\sqrt{s}$ = 200 GeV -

- "excess" ≡ "inclusive γ – decay γ" / "decay γ"
  - *i.e.* direct (= prompt + thermal) γ
- observed and agreed with NLO pQCD calculation
  - with CTEQ6 gluon PDF and different scale factors



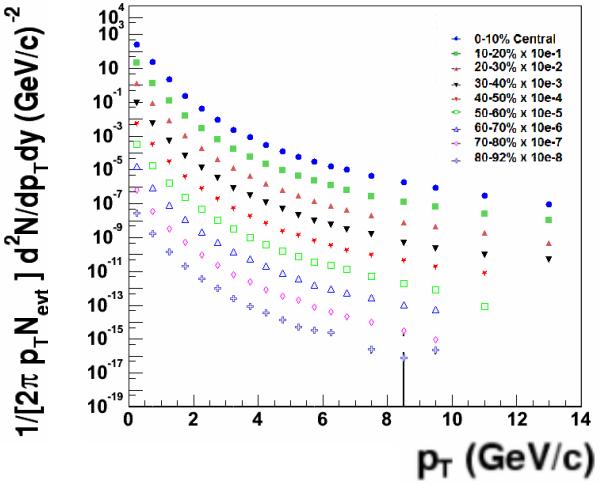
p+p→γ at $\sqrt{s}$ = 200 GeV
PHENIX preliminary



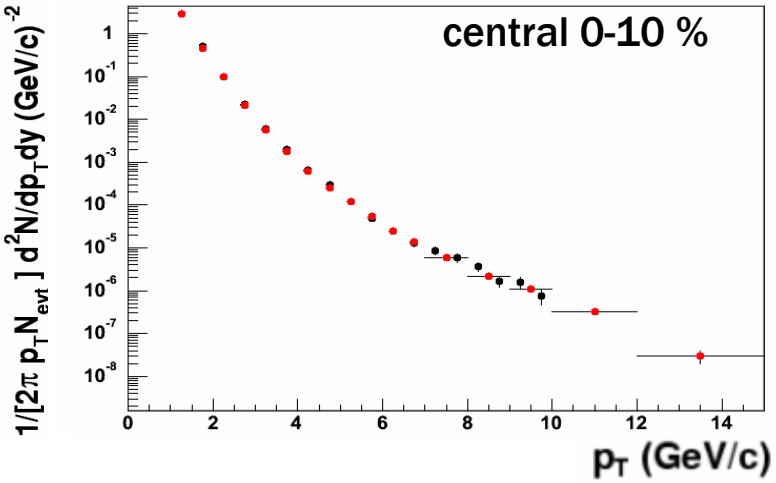
p+p→γ at $\sqrt{s}$ = 200 GeV
PHENIX preliminary
cf. W.Vogelsang JHEP 9903, 025 (1999)

- PHENIX Direct Photon Progress -

- Au+Au data with "second-level" selective trigger
  - π^0 spectrum up to p_t ~ 14 GeV/c
- improved analysis techniques
  - *ref.* K.Okada, T.Horaguchi/H.Torii, 27p SH-1/2 and T.Isobe, 29a SH-4

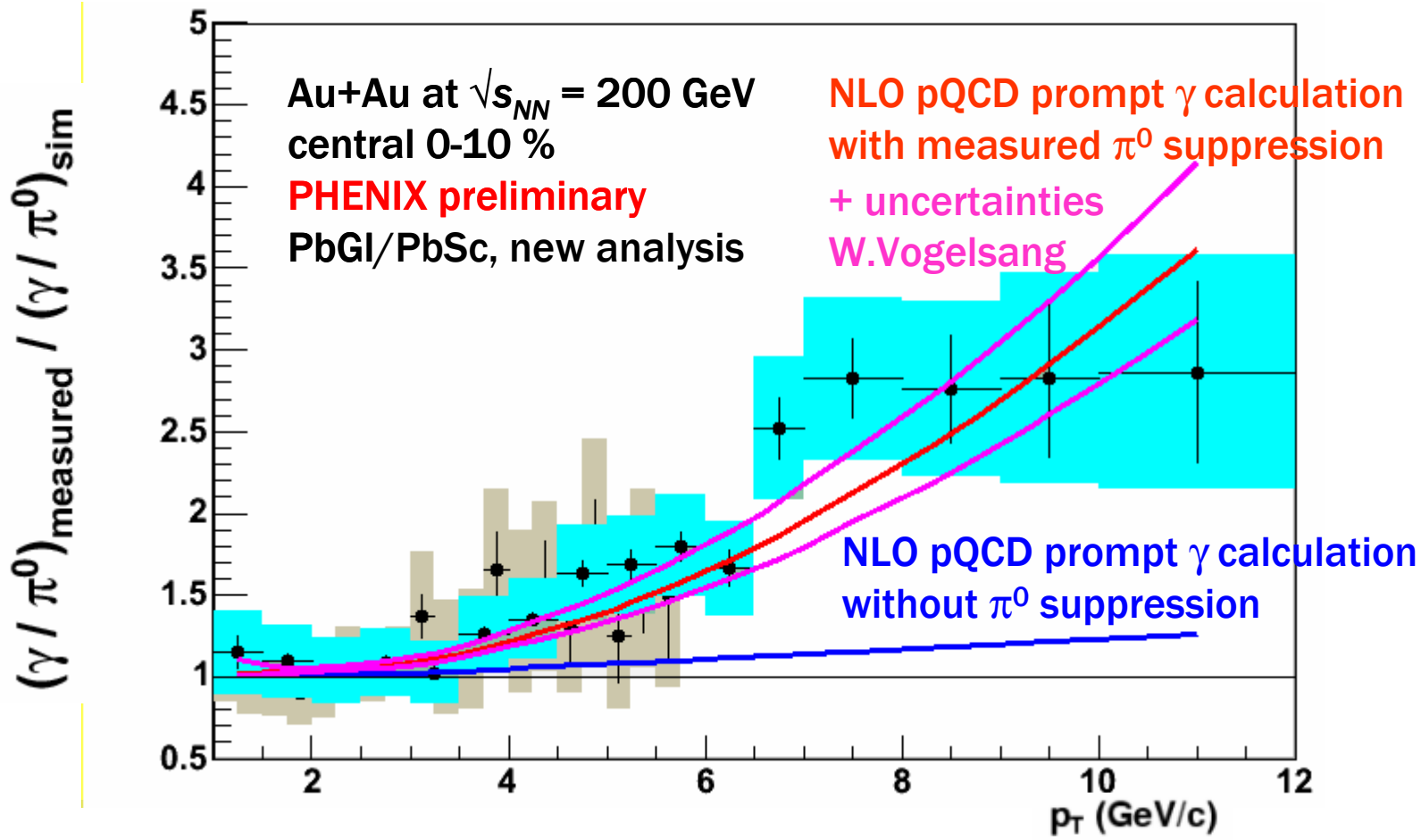


Au+Au→γ+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary



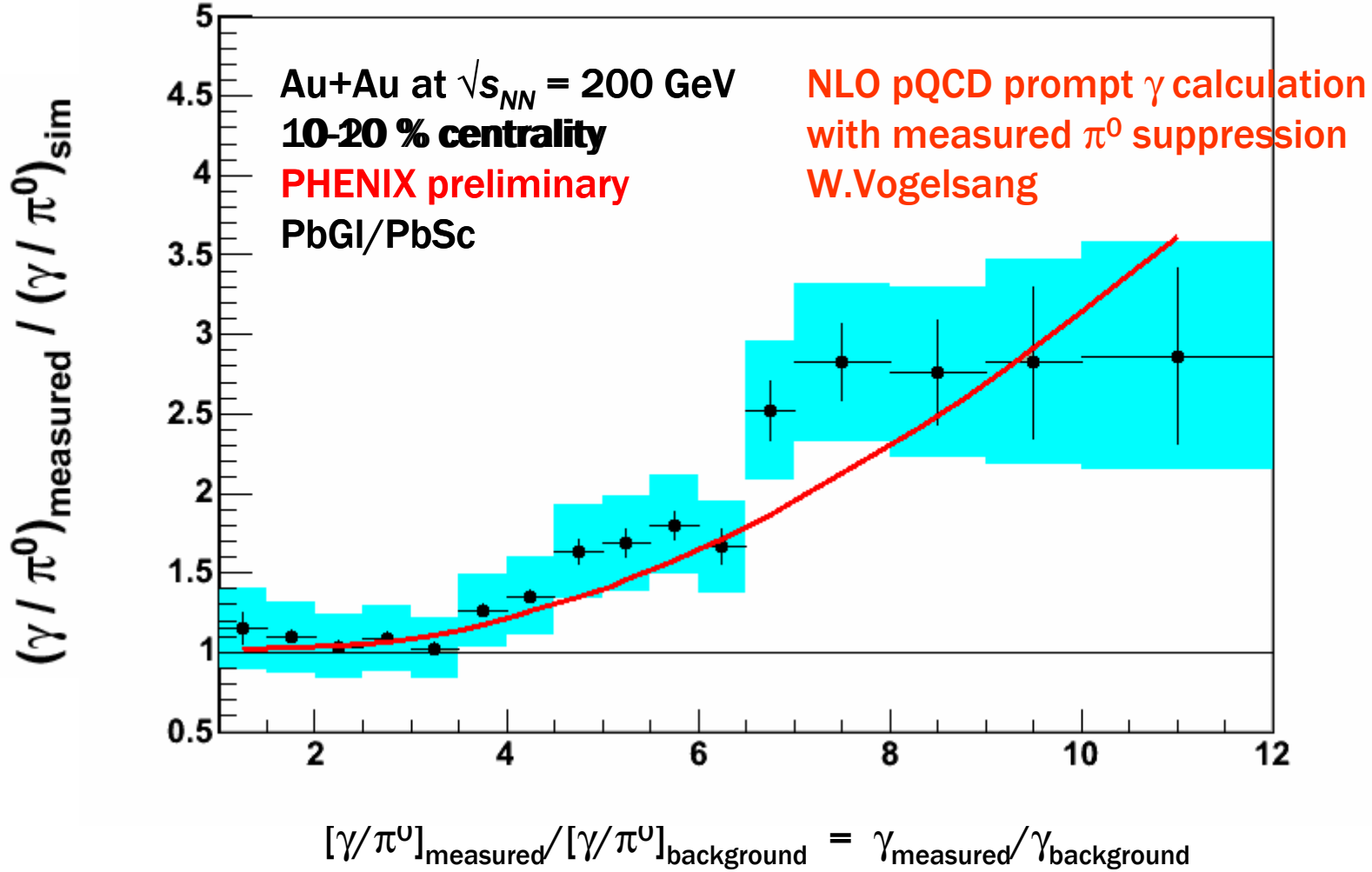
Au+Au→π^0+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX PRL 91, 072301 (2003)
PHENIX preliminary

- Photon “Excess” in Central Au+Au -



$$[\gamma/\pi^0]_{measured}/[\gamma/\pi^0]_{background} = \gamma_{measured}/\gamma_{background}$$

- Photon "Excess" Centrality Dependence -



$[\gamma/\pi^0]_{measured}/[\gamma/\pi^0]_{background} = \gamma_{measured}/\gamma_{background}$

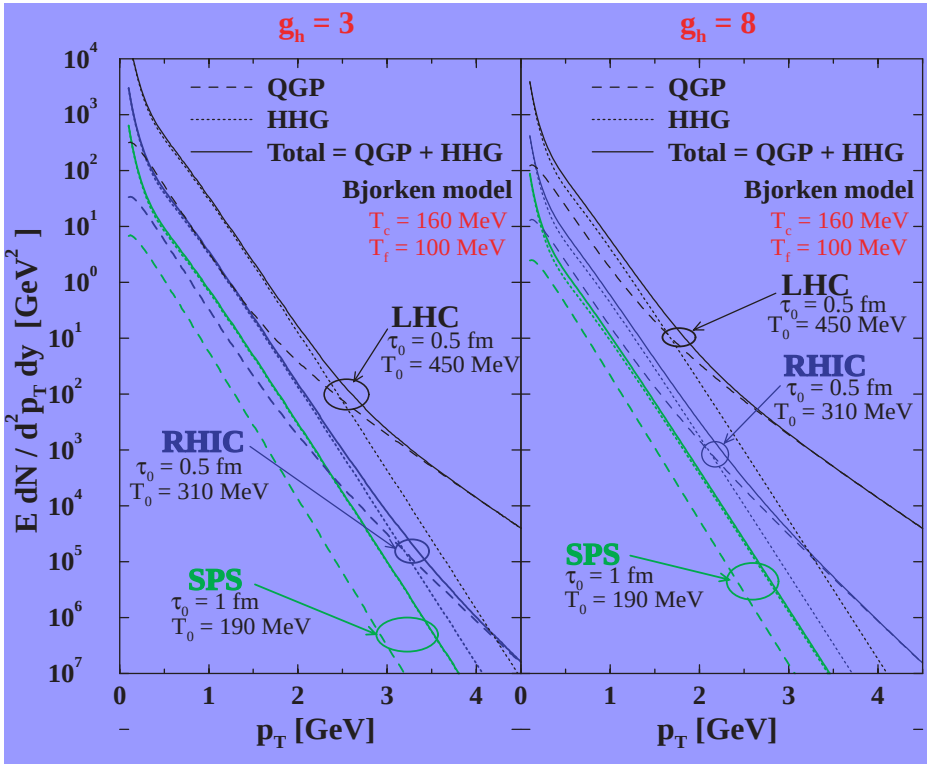
- Prompt Photon Observation -

- p+p result consistent with pQCD calculation
- photon “excess” observed in (central) Au+Au
  - more “excess” with increasing centrality
- Au+Au data consistent with
  - measured high p_t hadron (π^0) suppression
  - unsuppressed pQCD calculation with binary scaling
- physics + calibrator + sensitivity
  - no photon suppression; no initial process modification
  - control complement for very high p_t hadron suppression
  - vital baseline for thermal photon measurement

- Physics via Thermal Photons -

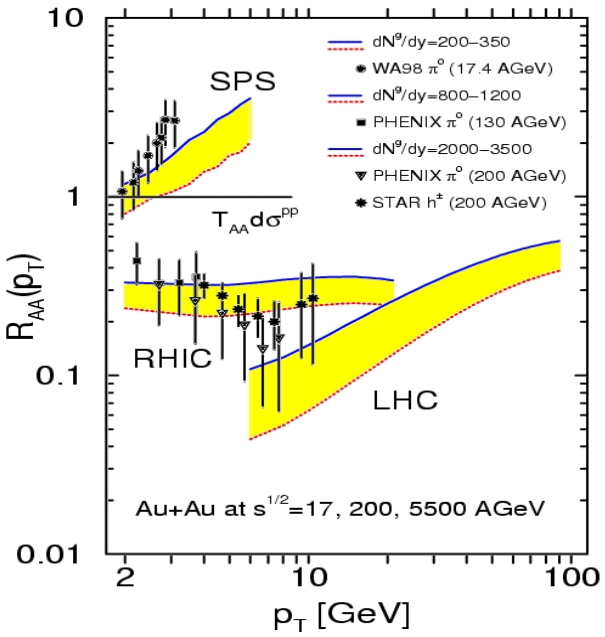
- direct probe of thermal phase
  - severe decay and prompt photon background
    - possible p_t window at 3-4 GeV/c at RHIC ?
  - *cf.* thermal di-leptons
    - possible mass window at 1-2 GeV/c^2 at RHIC
    - experimentally challenging due to limited S/B ratios
      - prime goal of PHENIX future upgrade
  - *cf.* light vector mesons (ϕ, ω, ρ)
    - probes of chiral symmetry restoration
      - changes in masses, widths, branching ratios
    - analyses in progress on Au+Au/d+Au/p+p data
    - *ref.* Y.Tsuchimoto/Y.Akiba, 29a SH-9

- Thermal Photon Expectations at RHIC/LHC -

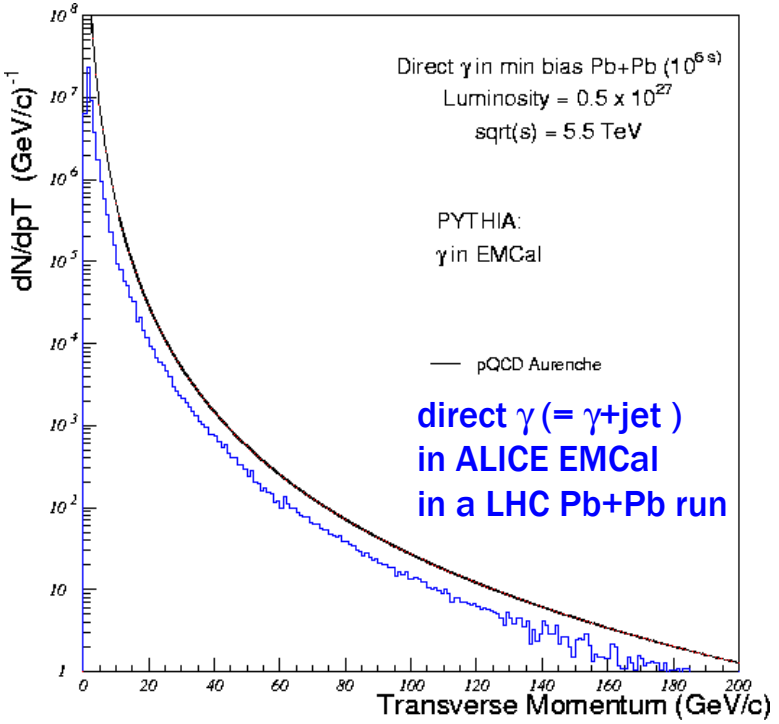


- may remain relatively unexplored even after RHIC
- “QGP” contribution dominance at LHC

- Direct (Prompt + Thermal) Photons at LHC -



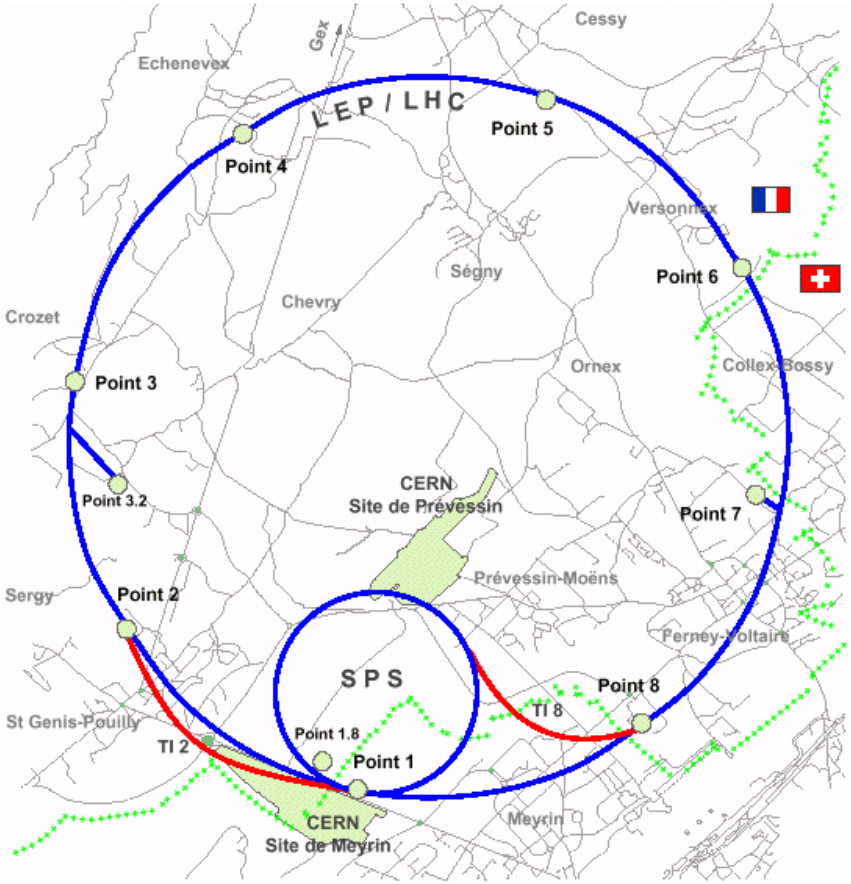
I.Vitev, M.Gyulassy
PRL 89, 252301 (2002)



- even more powerful probe at LHC
  - enhanced direct/decay ratio due to jet quenching
  - large prompt photon rate up to ~ 100 GeV/c

- CERN LHC -

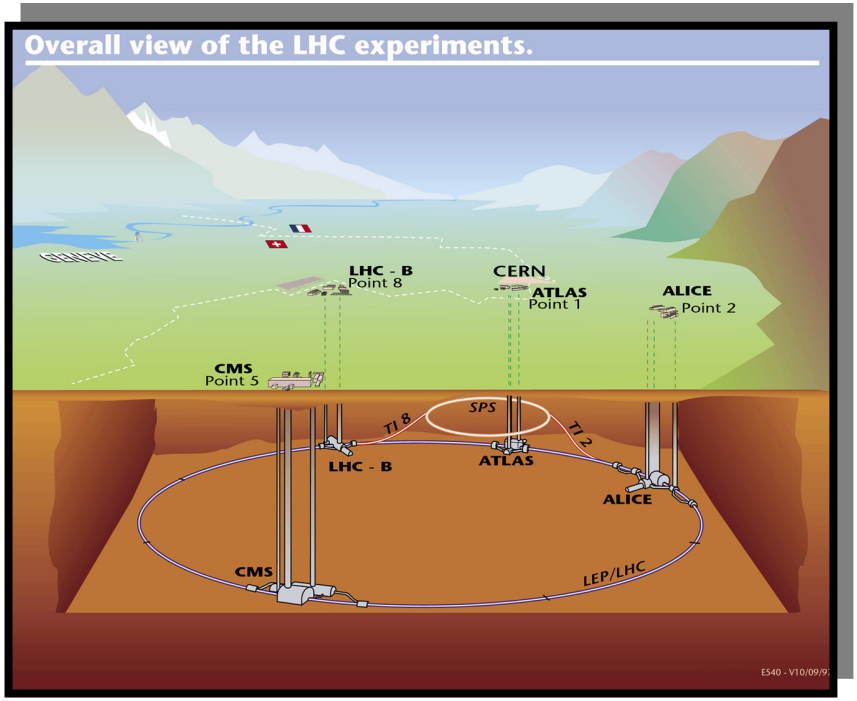
- next generation relativistic hadron collider
  - former LEP tunnel
  - 27 km circumference
  - up to 2.8 A TeV Pb
- heavy ion physics goals
  - to settle QCD phase transition search
  - deconfined partonic matter characterization
    - QGP factory ?



- LHC Status and Plan -

- accelerator steadily on its way
  - startup in 2007
    - confirmed in 2004 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
    - regular p+p runs at $\sqrt{s}$ = 14 TeV, L ~ 10^{29} and < 3×10^{30} $cm^{-2}s^{-1}$
    - 2 - 3 years of Pb+Pb at L ~ 10^{27} $cm^{-2}s^{-1}$
    - 1 year of p/d/α+Pb at L ~ 10^{29} $cm^{-2}s^{-1}$
    - 1 year of light ions at L ~ few 10^{27} - 10^{29} $cm^{-2}s^{-1}$

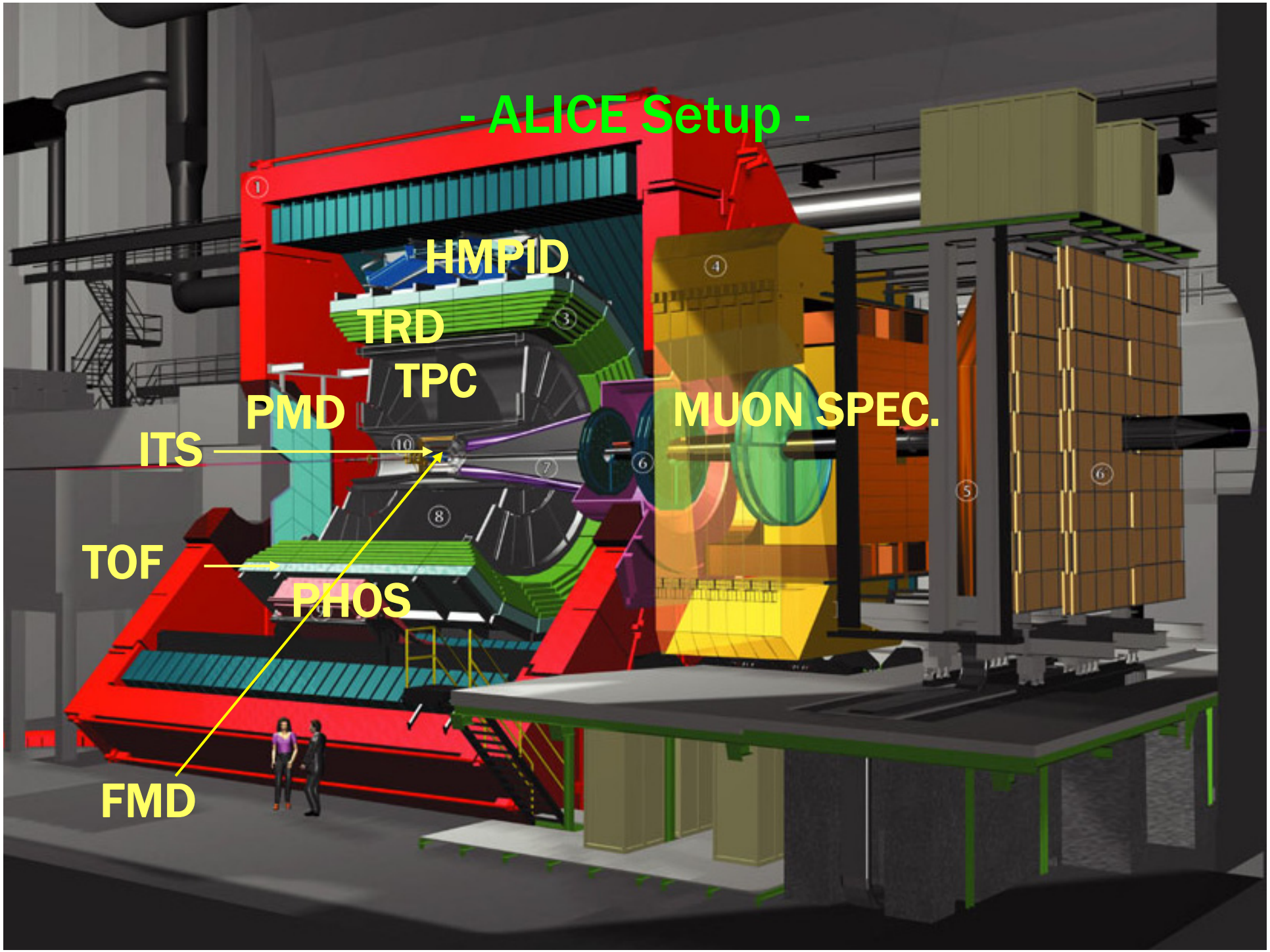
- LHC Experiments -



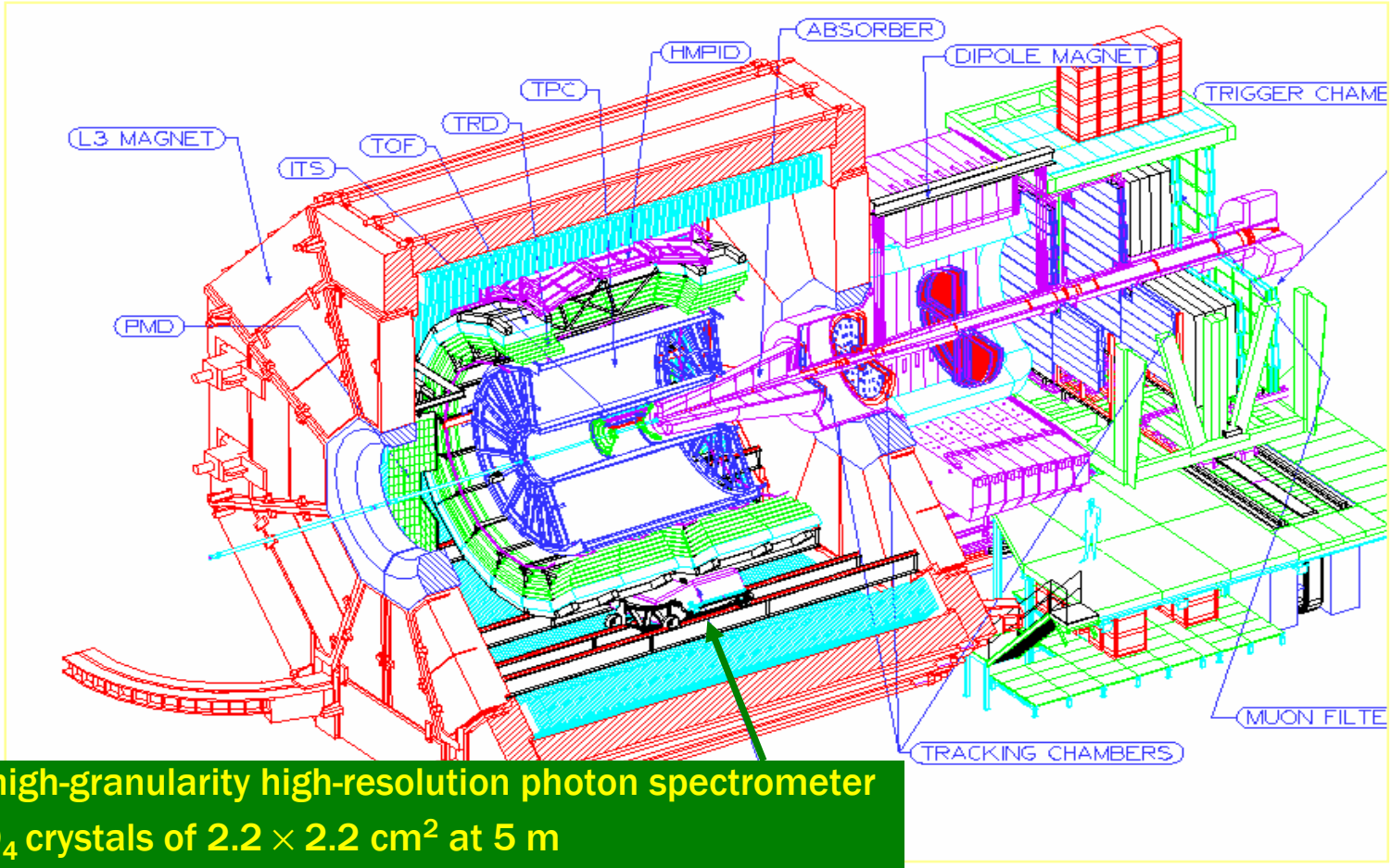
- 4 experiments; only 1 heavy ion dedicated
  - dedicated heavy ion experiment: ALICE
  - p+p experiment with heavy ion programs: CMS
  - p+p experiment considering heavy ion: ATLAS

- 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; di-leptons; 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
ITS
MUON SPEC.
TOF
PHOS
FMD

- ALICE Photon Spectrometer -

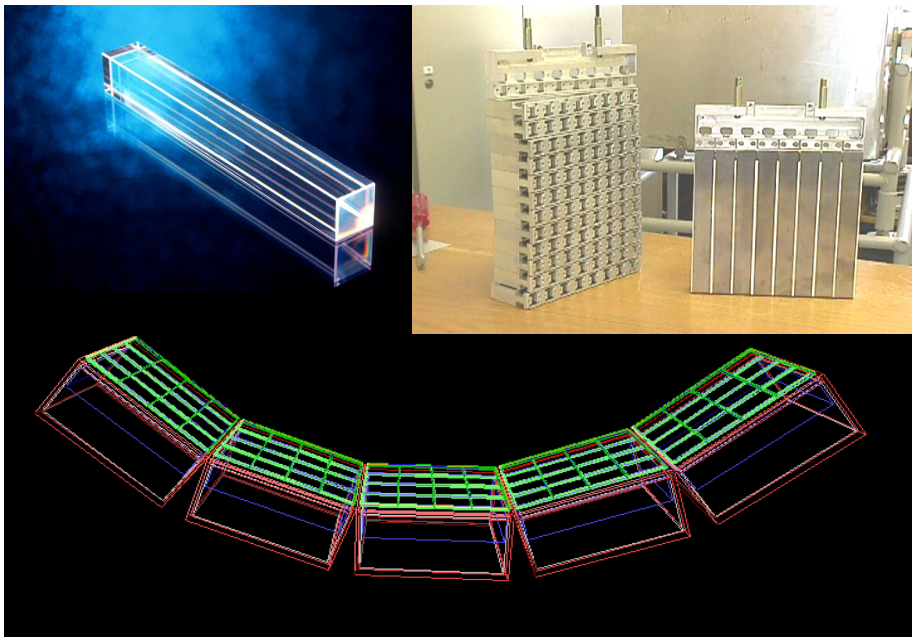


PHOS: high-granularity high-resolution photon spectrometer

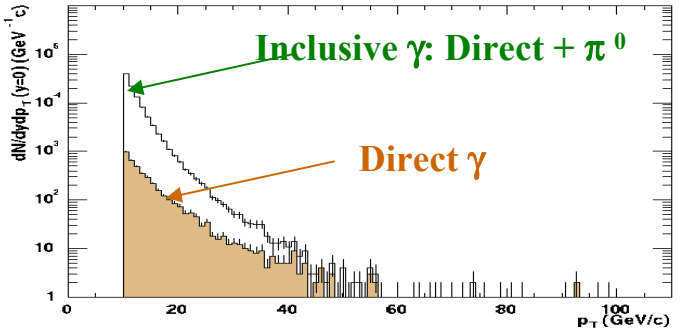
- $PbWO_4$ crystals of 2.2×2.2 cm^2 at 5 m
- $|\eta| < 0.5$, $\Delta\phi \sim 100$ degrees
- photons and neutral mesons
- γ-jet tagging

- Photon Measurement in ALICE -

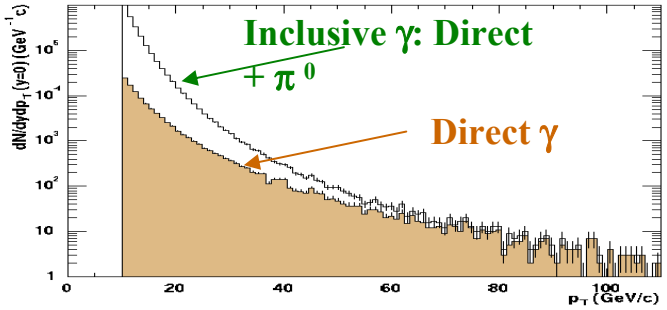
- photon spectrometer (PHOS)
  - high granularity high resolution $PbWO_4$ calorimeter
  - p_t up to ~ 100 GeV/c
    - photons and neutral mesons



without high p_t trigger



with high p_t trigger

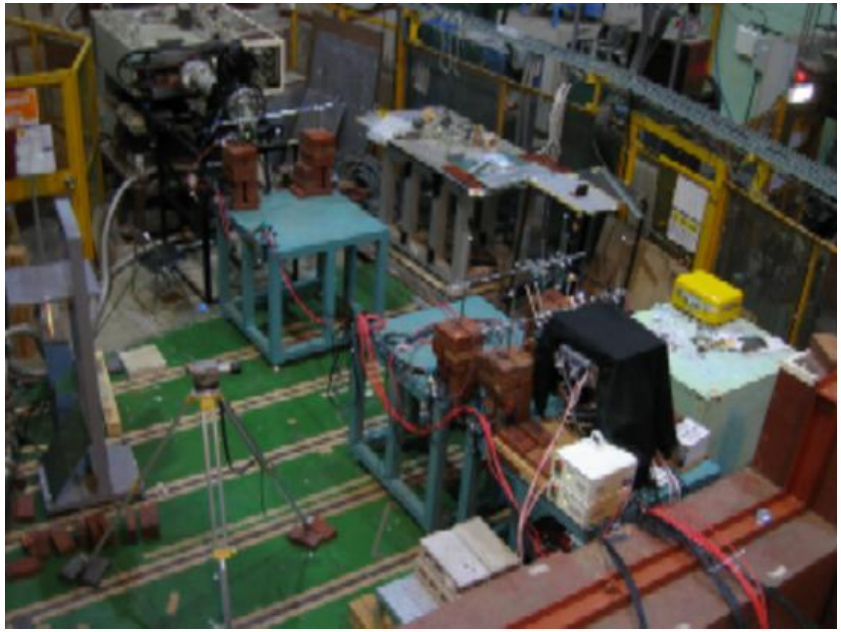


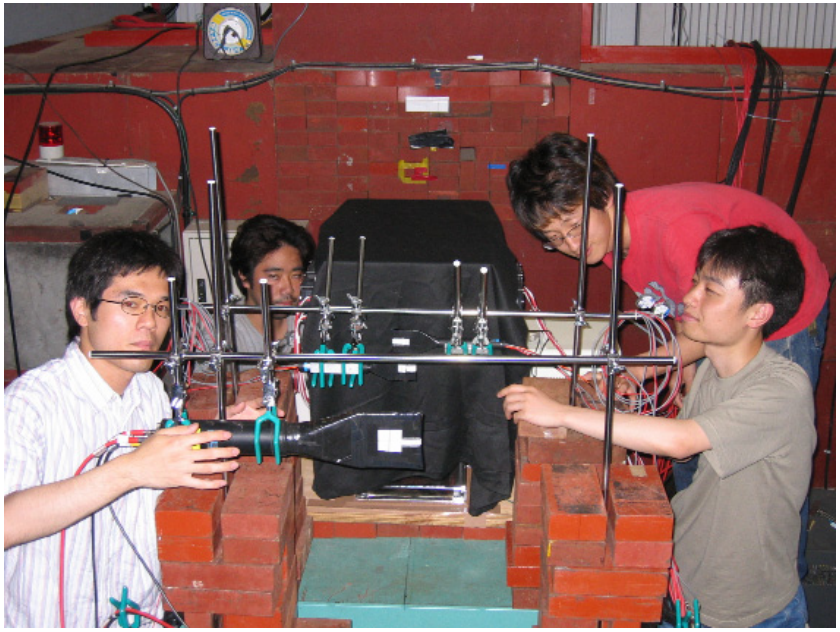
- PHOS Activities in Japan -

- avalanche photo-diode readout development
  - advantages over conventional PMT readout
    - magnetic field resistance
    - compactness
    - low power consumption
  - readout chain R&D completed; pre-production started
    - APD + pre-amplifiers + shaping amplifiers
- $PbWO_4$ crystal and PHOS prototype tests
  - at Hiroshima-REFER, KEK-PS, Tohoku-LNS
  - ~ 3 % /$\sqrt{E}$ [GeV] stochastic resolution achieved

- KEK-PS T564 (16-23 June, 2004) -

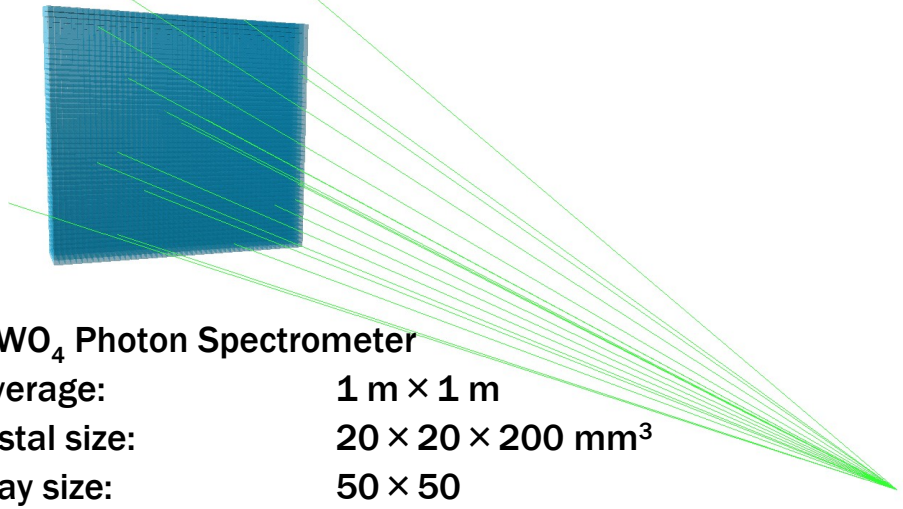
- prototype with real ALICE-PHOS components
  - successful operation of APD readout with Peltier cooler
  - consistent results with CERN-PS/SPS beam tests
    - *ref.* H.Sakata, 29p SA-16





- Physics Chance at RHIC -

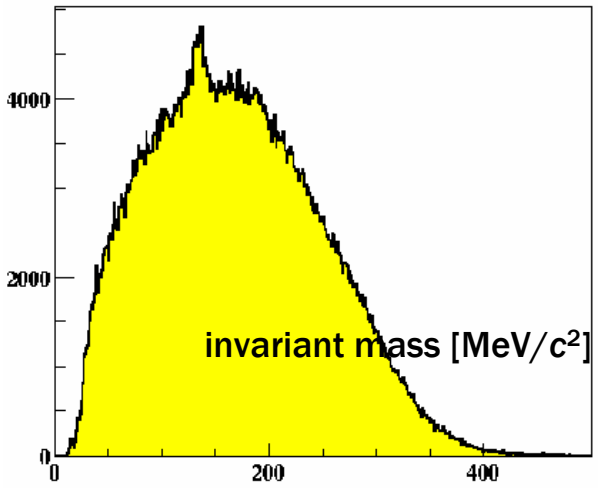
- $PbWO_4$ array (*e.g.* ALICE-PHOS) at RHIC ?
  - no fine granule electro-magnetic calorimeter present
  - powerful tool for direct photons and di-photons
  - *n.b.* not presently in PHENIX future plan



$PbWO_4$ 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 -

- more than enough RHIC/PHENIX experimental highlights for a talk (or even a half-day symposium)
  - jet (high p_t hadron) quenching established
    - beloved manifest of “quark gluon plasma”
  - open charm and beauty measurement blooming
    - further revealing state of fireball
  - heavy quark states (J/Ψ, Ψ’, ϒ) under eager look; light vector mesons (ϕ, ω, ρ), too
    - anticipated as another “proof” of deconfined partonic phase
    - high statistics Au+Au data (run 4) in hand
  - prompt photons observed in Au+Au at RHIC/PHENIX (!)
    - no suppression; no initial parton distribution modification
    - excellent reference for very high p_t hadron suppression
    - baseline for upcoming thermal photon measurement

- Concluding Remarks -

- RHIC/PHENIX presenting extremely rich harvest
- long awaited discovery *almost* in hand
  - hard process oriented probes having played major roles
    - e.g. first manifest of “QGP” via jet quenching
  - thermal phase oriented probes jumping in
    - direct probes of “QGP”
    - high statistics Au+Au data (run 4) analyses in progress
    - RHIC/PHENIX upgrades under R&D/construction
    - + LHC/ALICE starting in 3 years
- QCD at high energy density frontier into new stage
  - search for “quark gluon plasma” nearing its end
  - interesting “act 2” anticipated (and coming soon)