直接生成光子測定の物理、現状、展望

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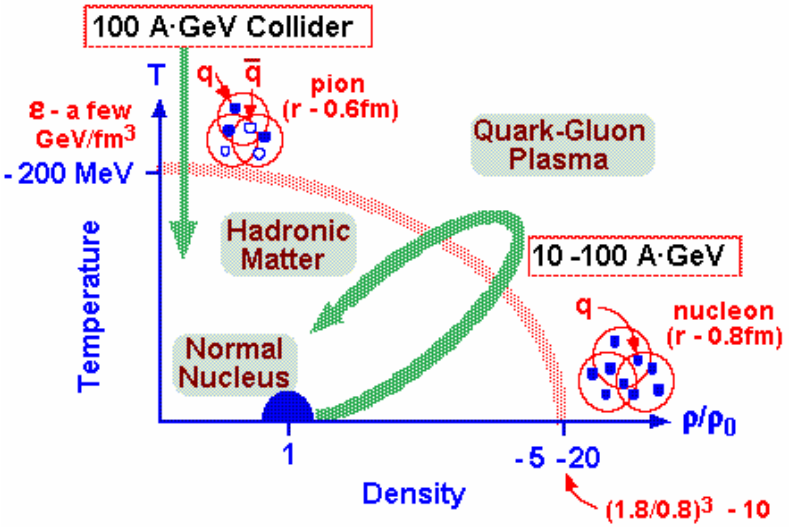
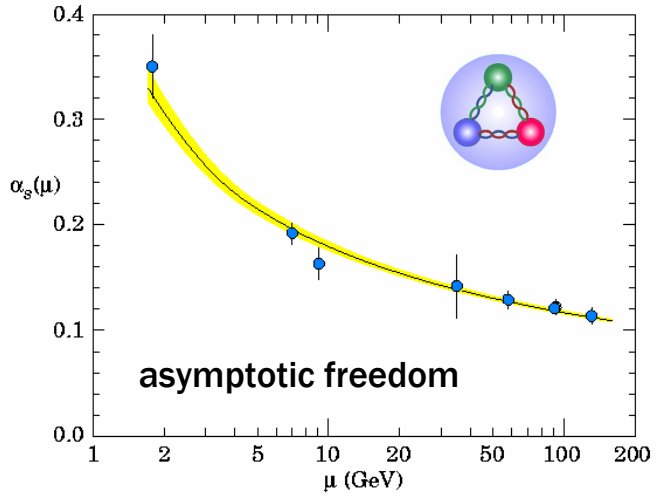
大阪大学核物理研究センター研究会
「高エネルギー重イオン実験の現象論的解析」

- Presentation Outline -

- physics goals of relativistic heavy ion programs
  - primary motivations for “QGP” physics
- experimental probes of deconfined partonic phase
  - initial parton scattering oriented *indirect* probes
  - thermal phase oriented *direct* probes
- status summary of new phase search
- physics via direct photons
  - prompt photon observation at RHIC/PHENIX
  - thermal photon prospects at RHIC and LHC/ALICE
- summary and concluding remarks

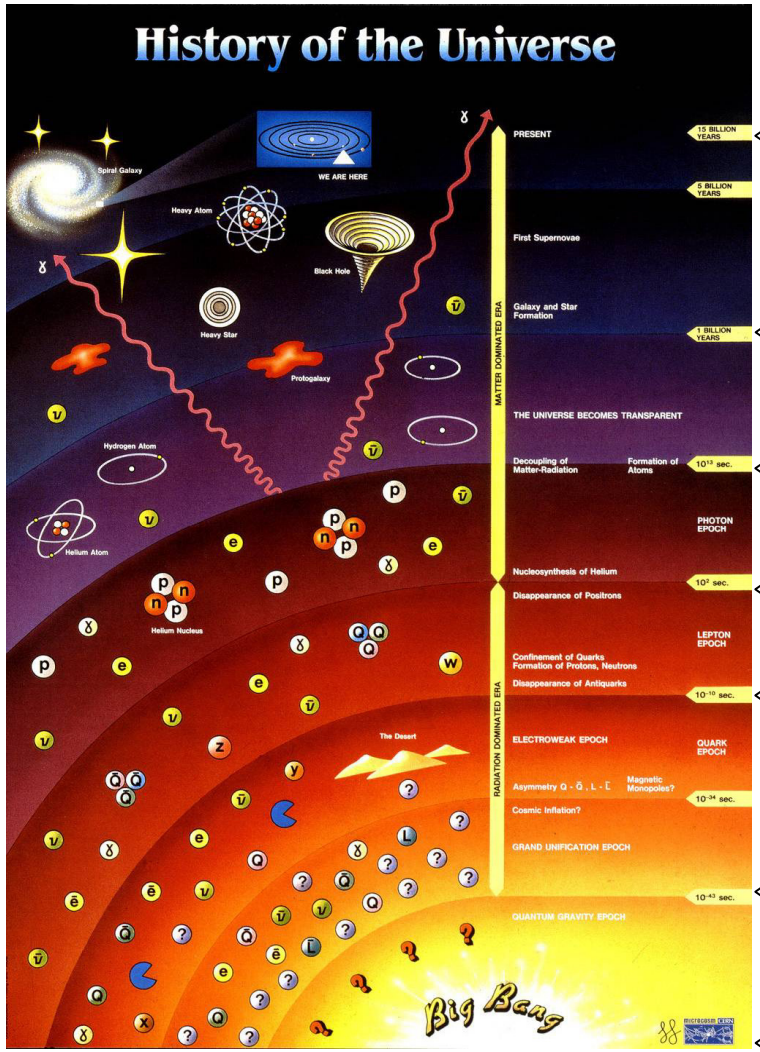
- Physics Goals of RHI Programs -





- 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

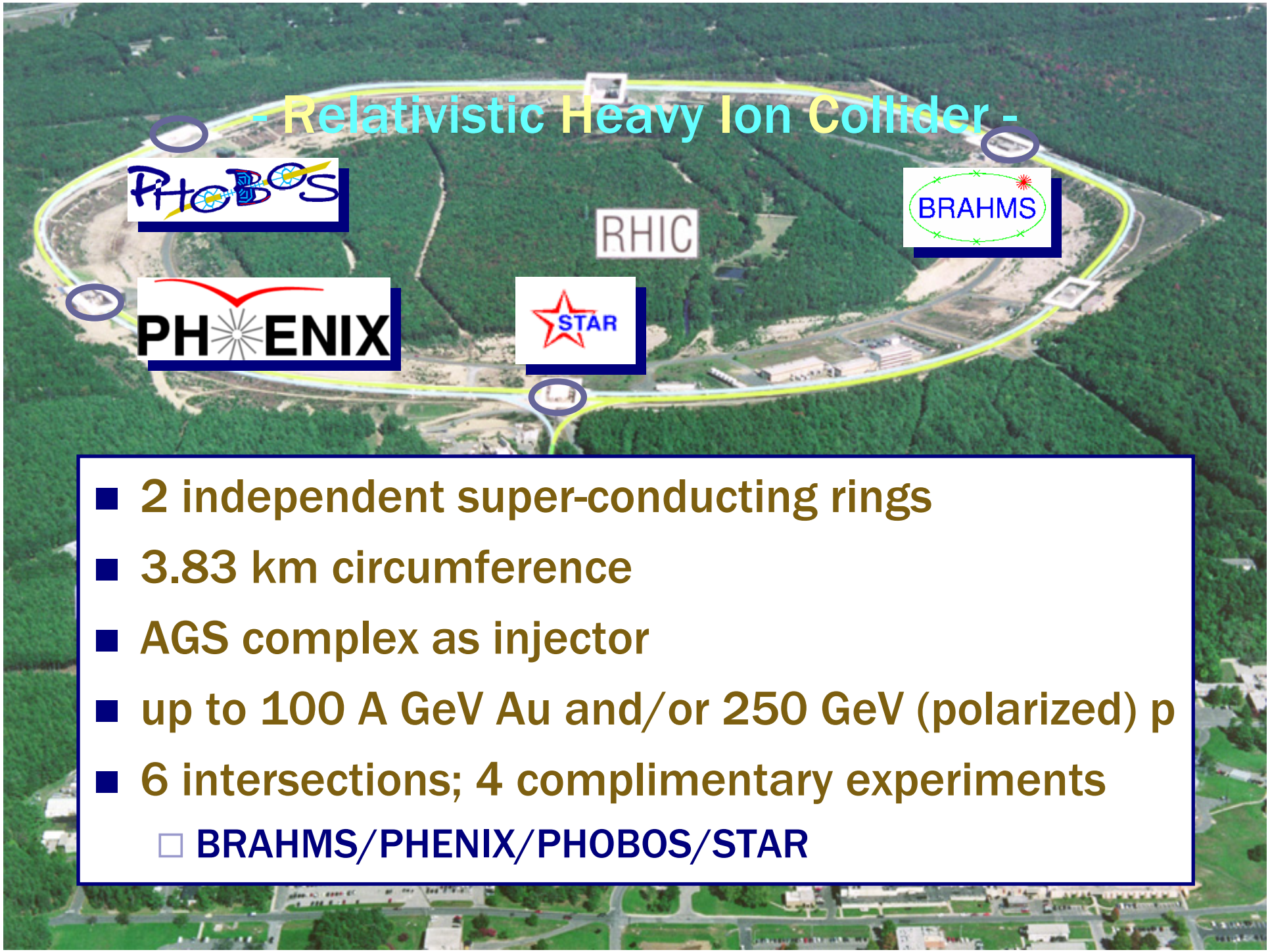
- QCD in History of Universe -



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

- Primary Motivations for “QGP” Physics -

- search for deconfined partonic phase
  - believed as state of matter in very early universe
  - predicted by solid-state analogies and (lattice) QCD
    - no matter if strongly interacting or not
  - RHIC’s accomplishments *much better* than Columbus’
- its characterization, once found
  - quantitative property investigation
  - RHIC undoubtedly strong leadoff
  - LHC (QGP factory ?) even more promising



- 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

広島大学

PHENIX

12 countries; 58 institutions; 480 participants
(as of January, 2004)

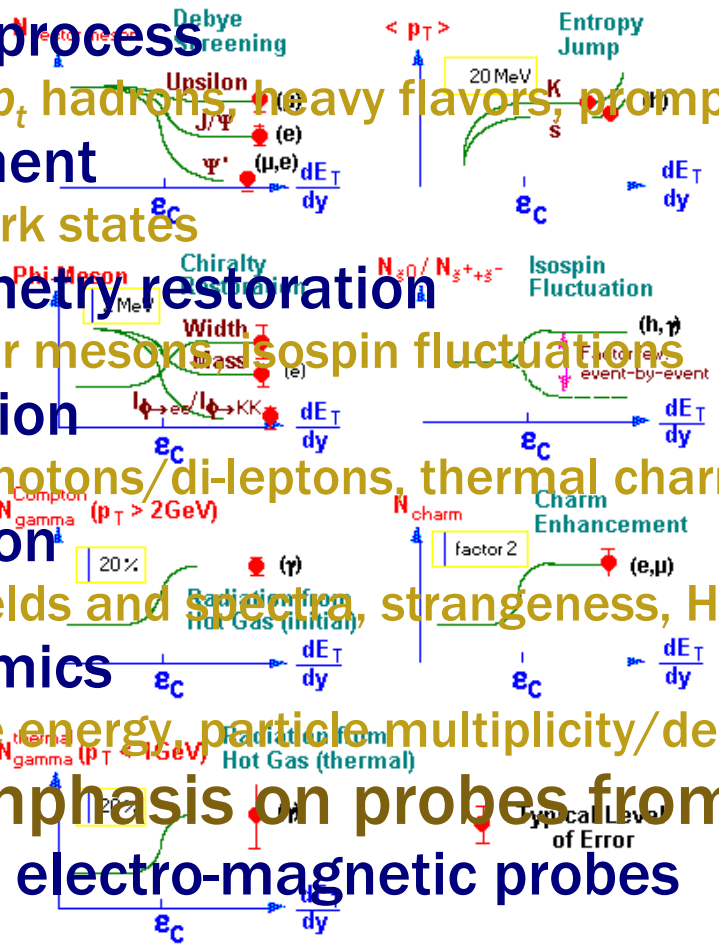
Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	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
	Rikkyo University, Tokyo, Japan
	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
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
	Florida Technical University, Melbourne, 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

- 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
  - initial hard process
    - jets, high p_t hadrons, heavy flavors, prompt photons
  - deconfinement
    - heavy quark states
  - chiral symmetry restoration
    - light vector mesons, isospin fluctuations
  - thermalization
    - thermal photons/di-leptons, thermal charm, partonic flow
  - hadronization
    - hadron yields and spectra, strangeness, HBT interferometry
  - hydro-dynamics
    - transverse energy, particle multiplicity/density
- particular emphasis on probes from early stages
  - penetrating electro-magnetic probes

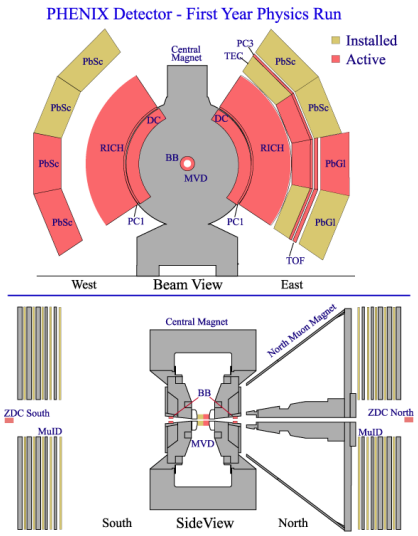


- Probes of Deconfined Partonic Phase -

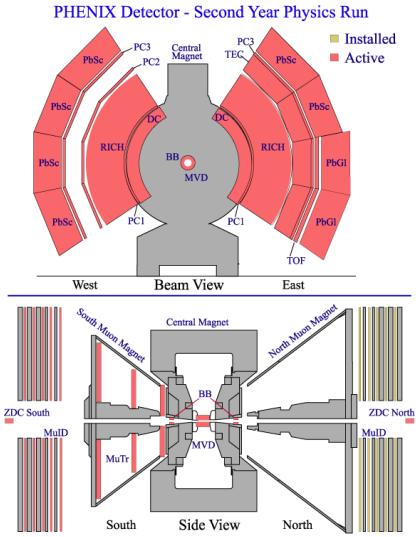
- initial parton scattering oriented *indirect* probes
  - achievements and near-term prospects at RHIC/PHENIX
    - jets/high p_t hadrons (production and subsequent suppression)
    - open heavy flavors (production and subsequent energy loss)
    - heavy quark states (production in color Debye screening)
    - prompt photons (production; observed !)
- thermal phase oriented *direct* probes
  - *ditto* + not-so-long-term-any-more prospects at LHC/ALICE
    - light vector mesons (chiral properties)
    - thermal photons (thermal properties)
    - thermal di-leptons (virtual photons) (thermal properties)
    - hadronic flow (parton dynamics)

- RHIC/PHENIX Run History -

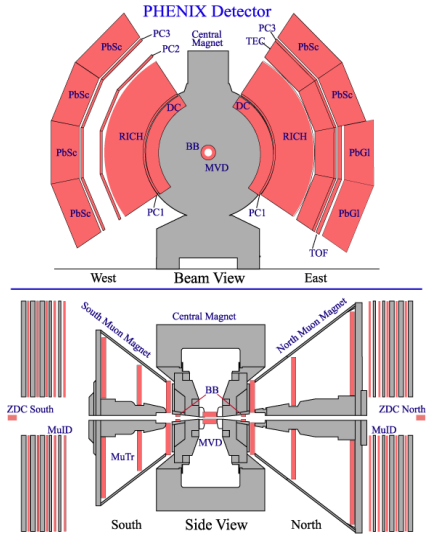
2000



2001/2002



since 2002/2003

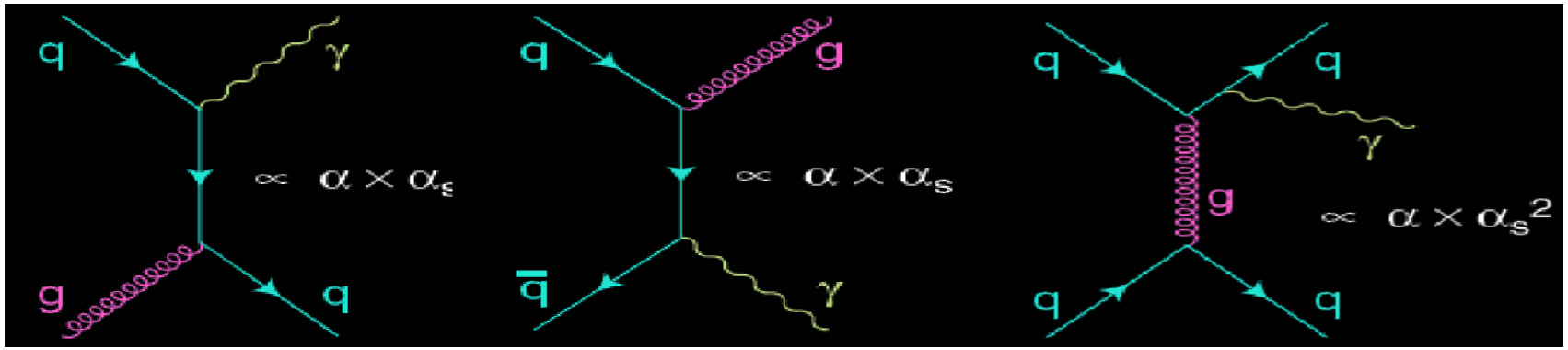


run	year	species	$\sqrt{s_{NN}}$	$\int Ldt$
01	2000	Au+Au	130 GeV	1 μb^{-1}
02	2001/02	Au+Au	200 GeV	24 μb^{-1}
		p+p	200 GeV	150 nb^{-1}
03	2002/03	d+Au	200 GeV	2.74 nb^{-1}
		p+p	200 GeV	350 nb^{-1}
04	2003/04	Au+Au	200 GeV	240 μb^{-1}
		Au+Au	62 GeV	9 μb^{-1}
		p+p	200 GeV	350 nb^{-1}

- Status Summary of New Phase Search -

- jet quenching (parton energy loss) established
  - 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”
  - further tests (jet tomography) in progress
    - quantitative understanding
    - quark mass dependences (open heavy flavor spectra)
    - jet energy redistribution
- apparent quark number scaling in hadronic flow
  - possible signature of partonic thermalization
- more evidences anticipated (and coming)

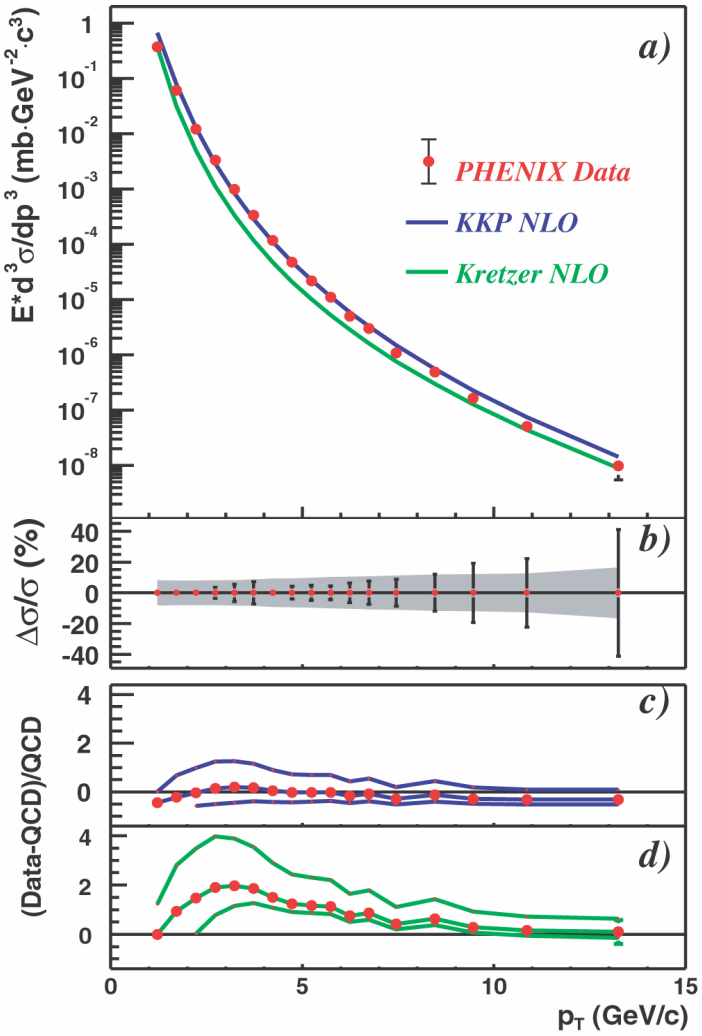
- Physics via Prompt Direct Photons -



- 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 -

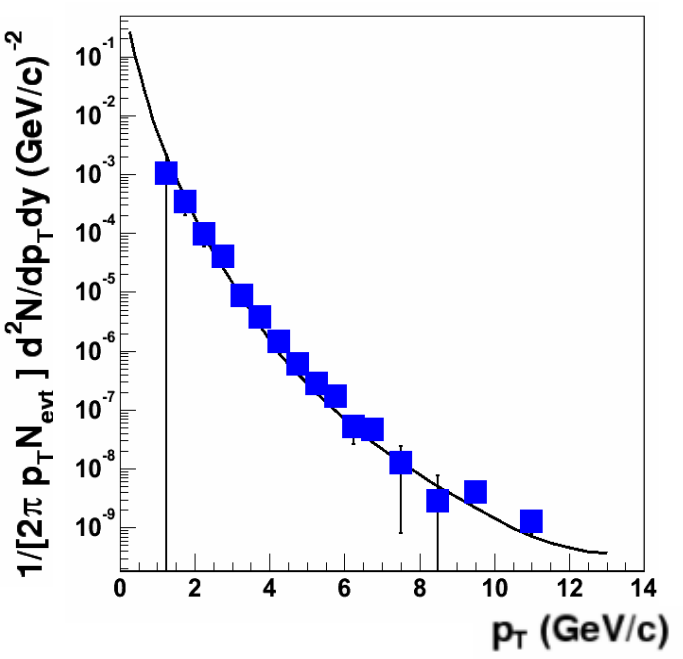
- evaluated based on measured hadron spectra
  - $\pi^0 \rightarrow 2\,\gamma$ most significant
  - first baseline: π^0 in p+p
    - available up to p_t ~ 12 GeV/c
    - agreement with NLO pQCD
      - no intrinsic k_t included
  - π^0 in Au+Au also measured



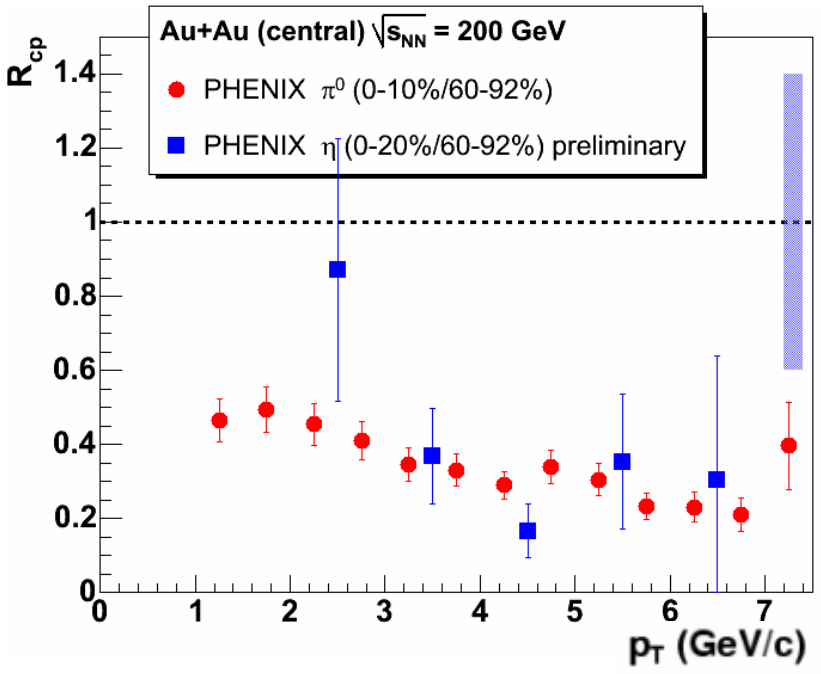
p+p→π^0+X at $\sqrt{s}$ = 200 GeV
PHENIX PRL 91, 241803 (2003)

- Other Hadronic Contributions: η, η', ω -

- based on measured π^0 and m_t scaling assumption
  - η in p+p consistent with m_t scaling
  - (η/π^0 in Au+Au consistent as in p+p)



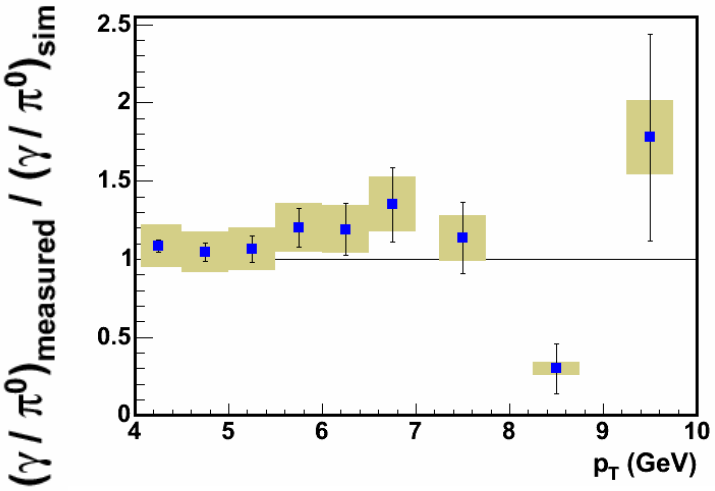
p+p→η+X at $\sqrt{s}$ = 200 GeV
PHENIX preliminary



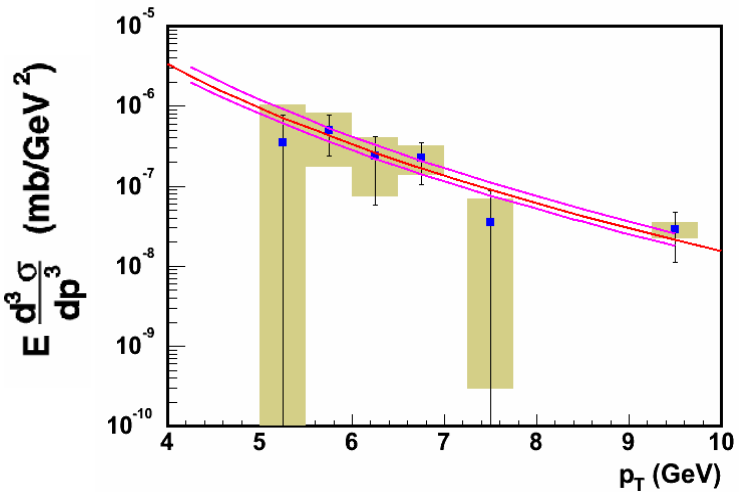
Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary

- 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



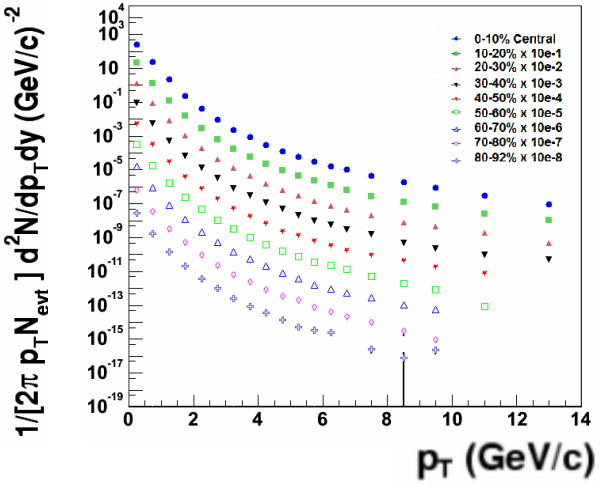
p+p→γ+X at $\sqrt{s}$ = 200 GeV
PHENIX preliminary



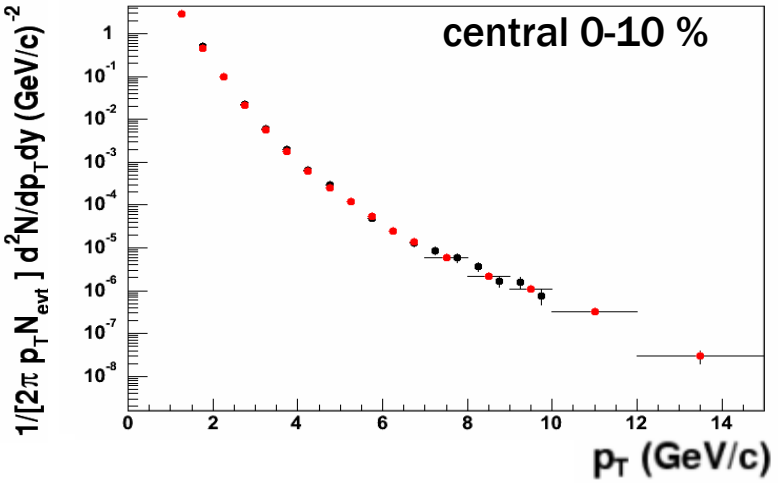
p+p→γ+X at $\sqrt{s}$ = 200 GeV
PHENIX preliminary
cf. W.Vogelsang JHEP 9903, 025 (1999)

- 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
  - *e.g.* photon identification

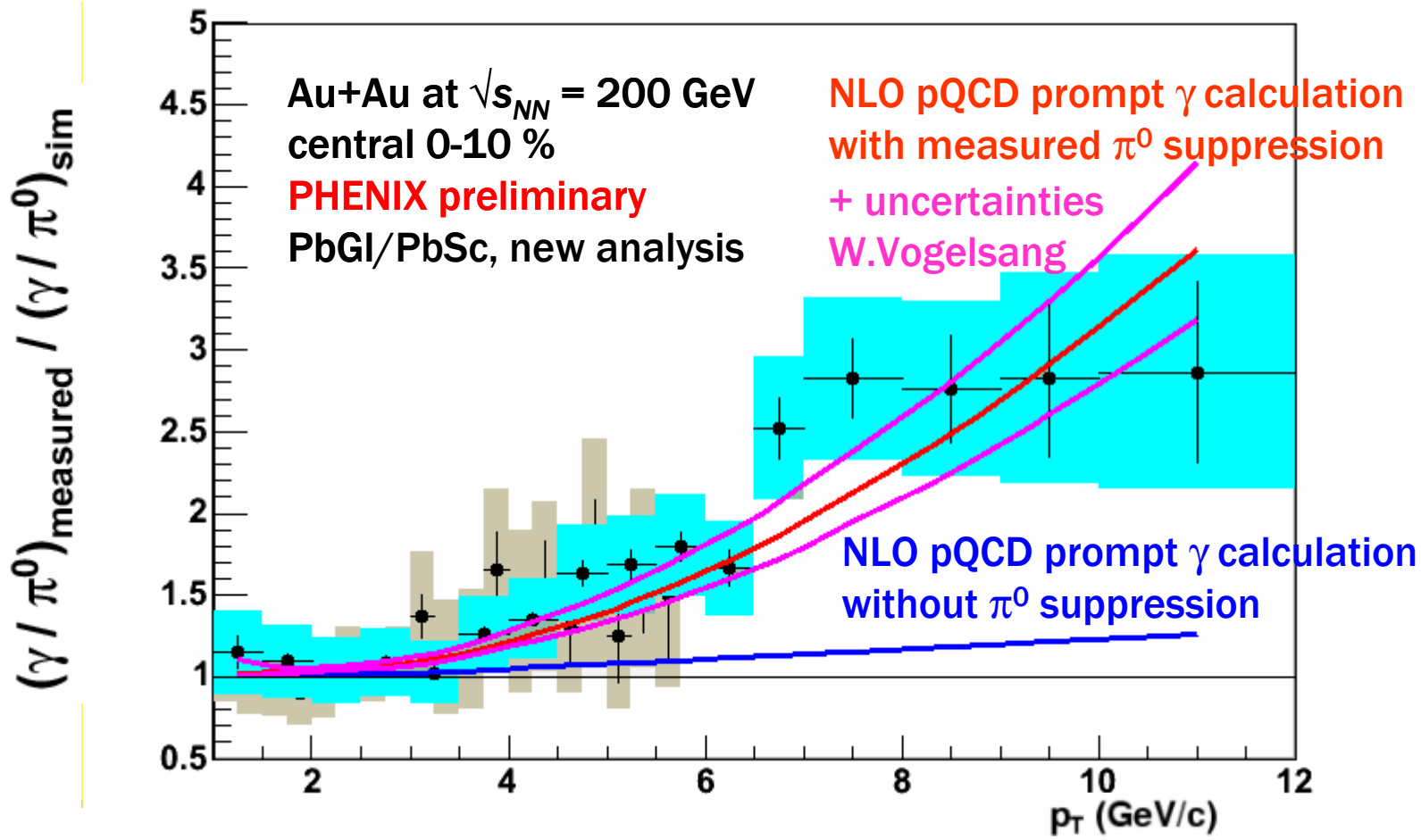


Au+Au→γ+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX preliminary



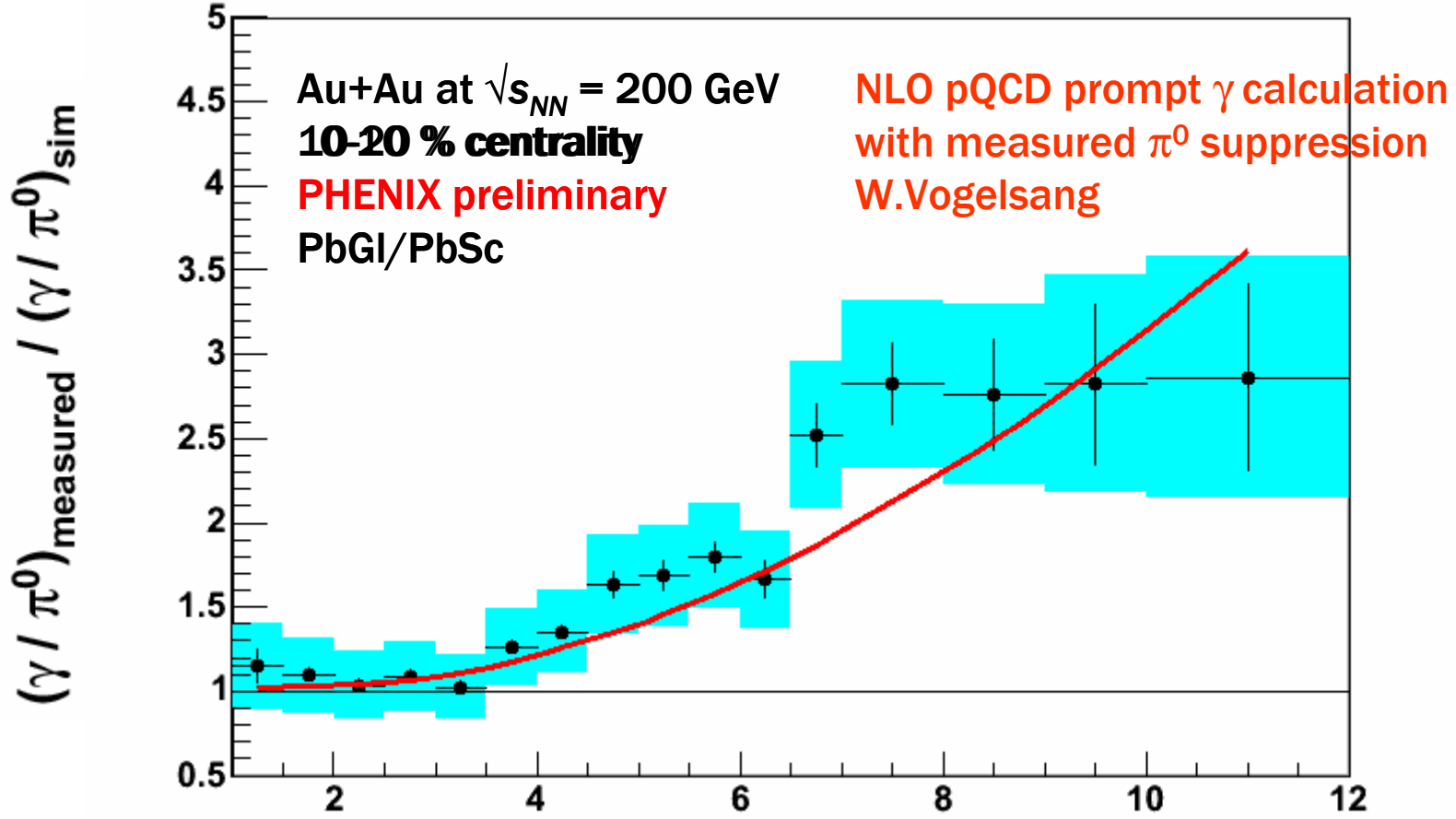
Au+Au→π^0+X at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX PRL 91, 072301 (2003)
PHENIX preliminary

- Photon "Excess" in Central Au+Au -



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

- Photon "Excess" Centrality Dependence -



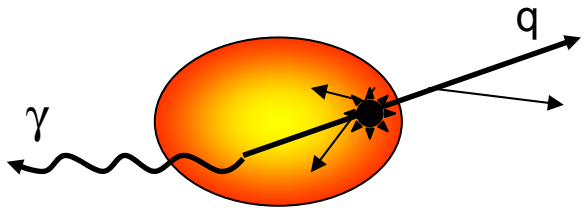
$$[\gamma/\pi^0]_{measured}/[\gamma/\pi^0]_{background} = \gamma_{measured}/\gamma_{background}$$

- 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
  - *ditto* for extra direct photons from parton energy loss

- More Physics via Prompt Photons -

- photon-jet correlation
  - better sensitivity than single photons to:
    - photons from *normal* prompt production
      - gluon compton scattering
      - annihilation
      - bremsstrahlung
    - *extra* photons from parton energy loss



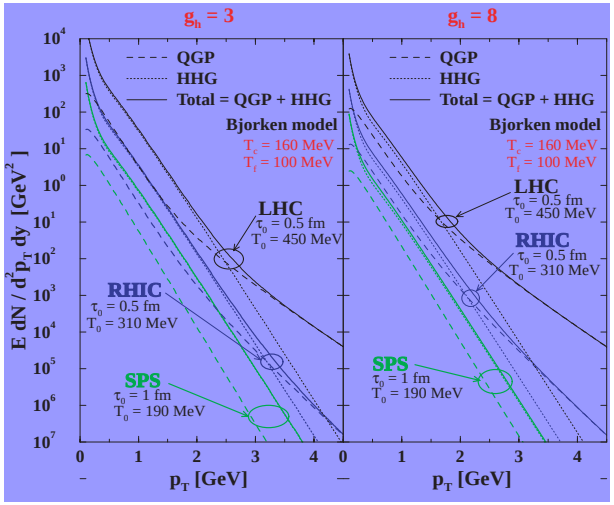
  - higher statistics required
    - high statistics (run 4) Au+Au data under work
- photon HBT correlation
  - finer granule electromagnetic calorimeter required
    - ALICE-PHOS at RHIC ?

- Physics via Thermal Photons -

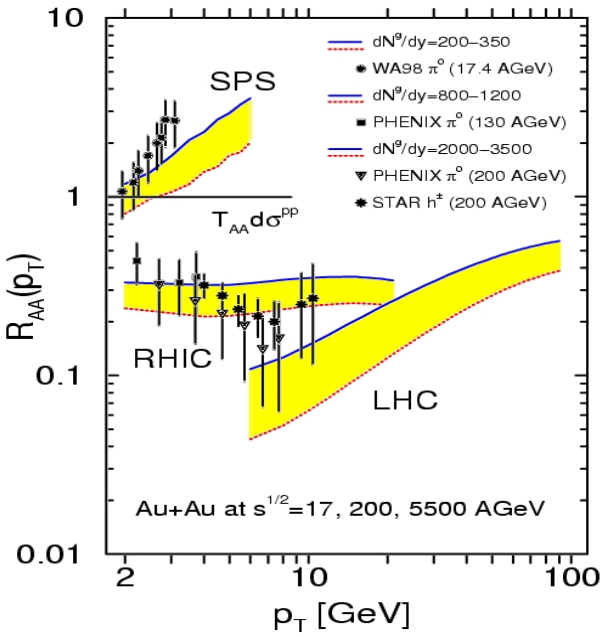
- direct probe of thermal phase
  - direct proof of partonic thermalization
  - precious means to measure achieved temperature
- *cf.* thermal di-leptons
  - (another) experimental challenge
    - possible mass window at 1 - 2 GeV/c^2 at RHIC
    - prime goal of PHENIX future upgrade
- *cf.* probes of chiral symmetry restoration
  - light vector mesons (ϕ, ω, ρ)
    - analyses in progress on Au+Au/d+Au/p+p data
    - *ref.* presentation by T.Hachiya

- Thermal Photon Status and Prospects -

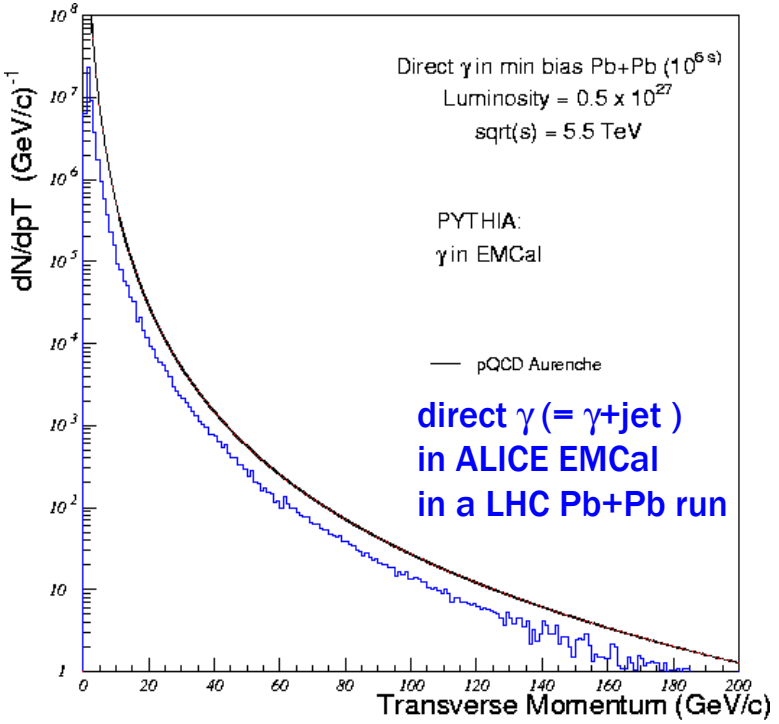
- experimental challenge due to limited S/B ratio
  - severe decay and prompt photon background
  - possible p_t window at 3 - 4 GeV/c at RHIC ?
- (partly) unexplored even after RHIC ?
  - odds-on physics channel at LHC
    - deconfined partonic phase contribution dominance expected



- Direct (Prompt + Thermal) Photons at LHC -



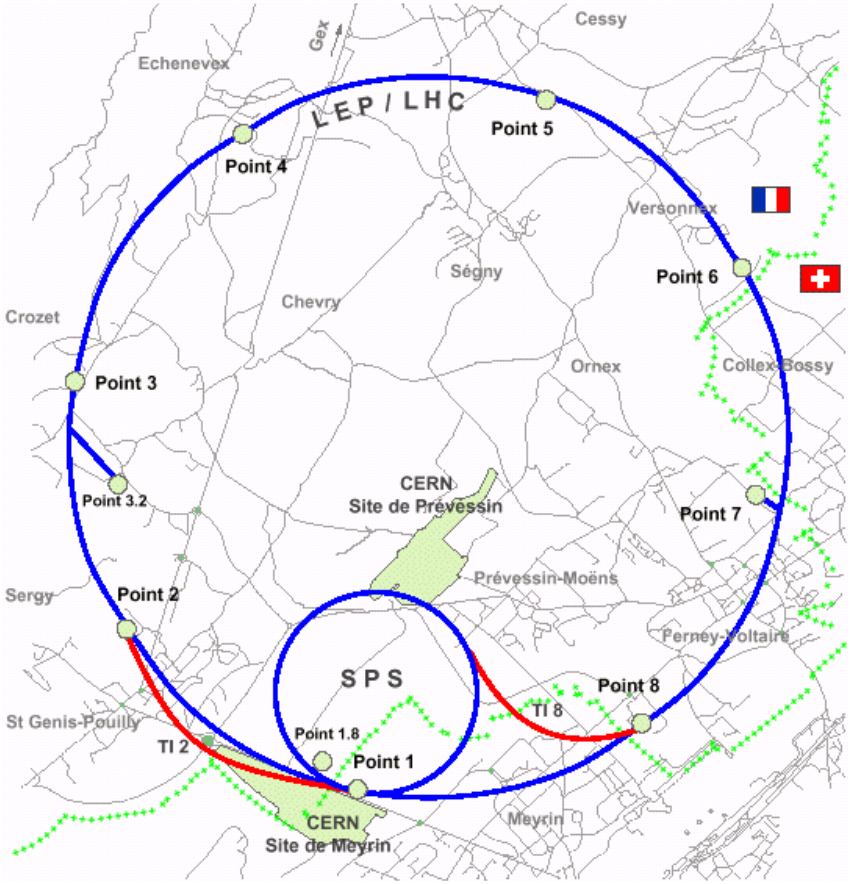
I.Vitev, M.Gyulassy
PRL 89, 252301 (2002)



- 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 -

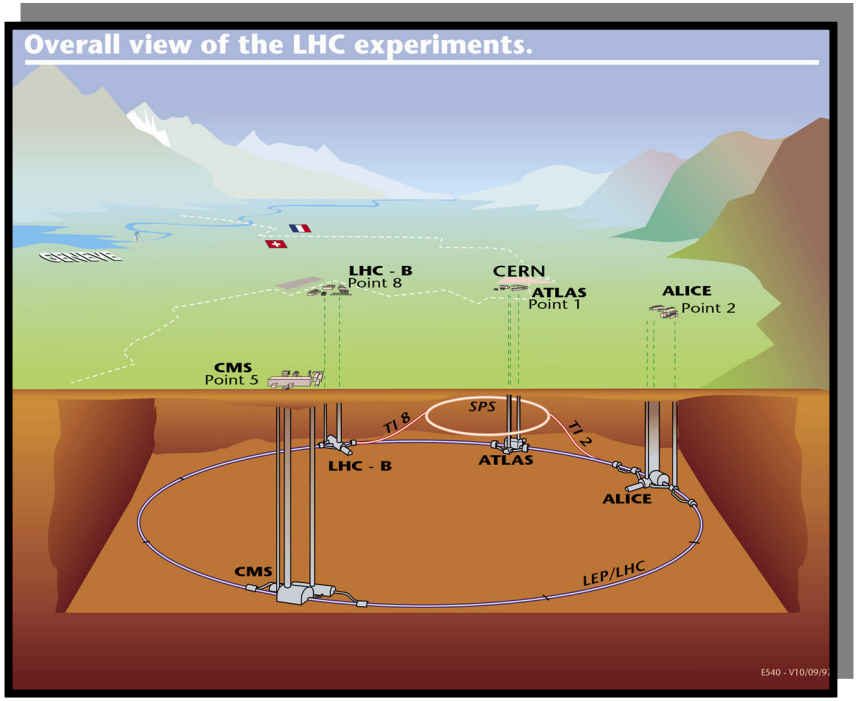
- next generation relativistic hadron collider
  - former LEP tunnel
  - 27 km circumference
  - up to 2.8 A TeV Pb
- heavy ion physics goals
  - to settle QCD phase transition search
  - deconfined partonic matter characterization
    - QGP factory ?



- LHC Status and Plan -

- accelerator + detectors 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 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} $cm^{-2}s^{-1}$

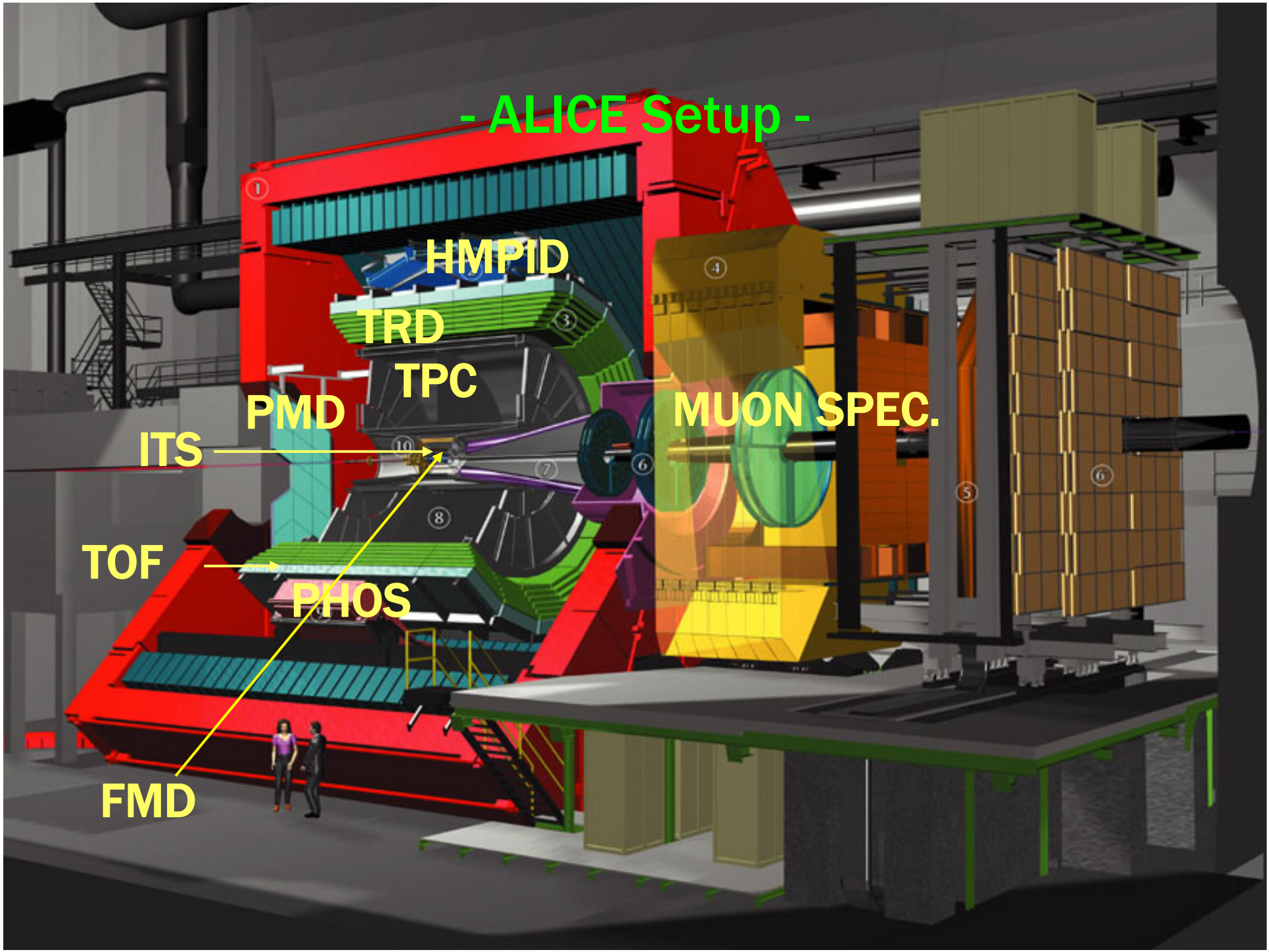
- LHC Experiments -



- 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 -

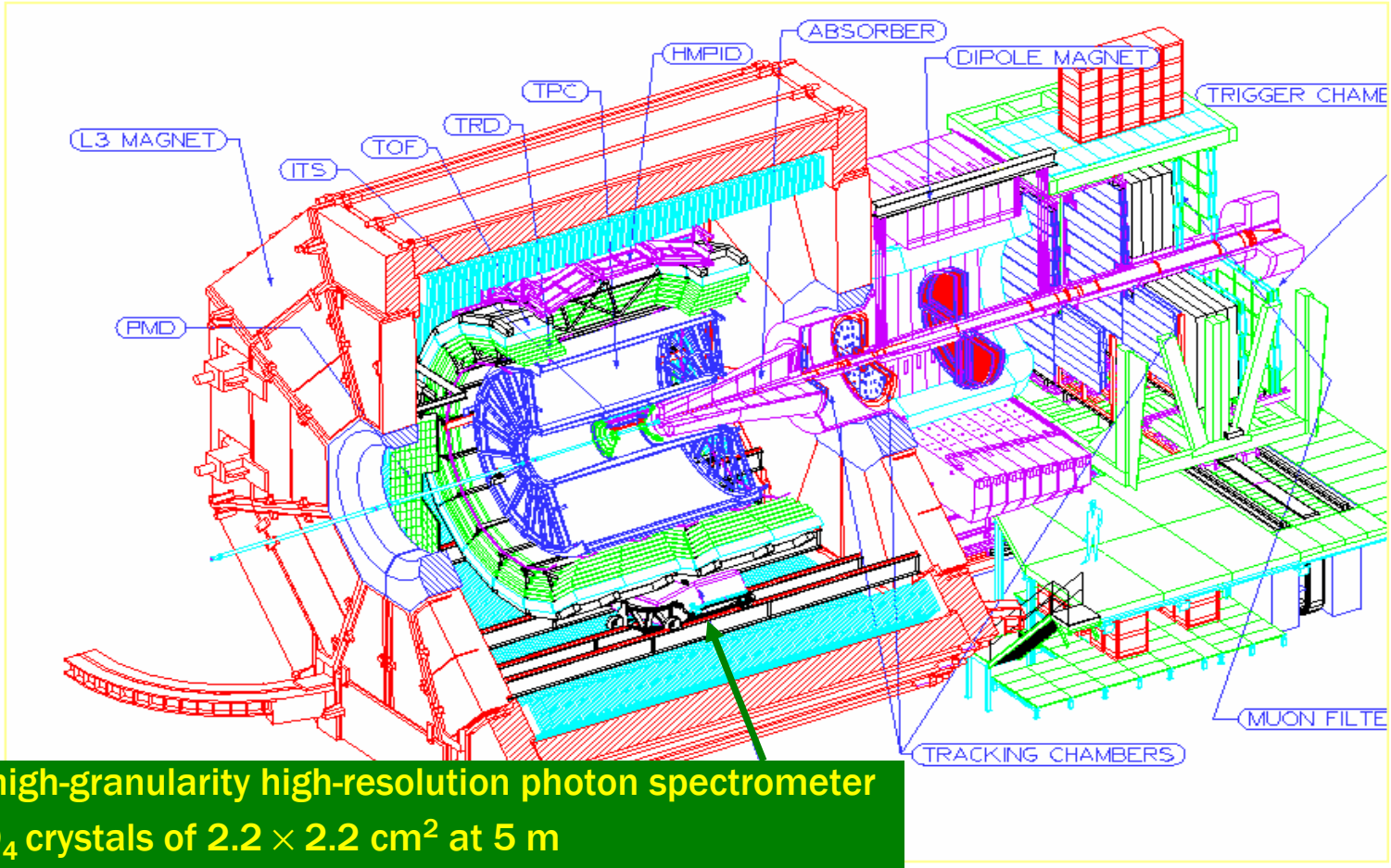
- to cover in single experiment what is by 4 at RHIC (and by several at SPS and AGS)
  - multiplicities; rapidity distributions; flows; particle spectra and ratios; jet quenching; di-leptons; direct photons; heavy flavors; fluctuations; correlations; ...
- versatility with variety of techniques
  - wide 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 in Japan -

- coherent destination after PHENIX
  - Hiroshima U. on photon spectrometer
    - primarily on readout
  - CNS U.Tokyo on transition radiation detector
    - primarily on readout
  - U.Tsukuba on transition radiation detector
    - primarily on mechanicals
- *associate collaboration since September, 2004*
  - activities continuing on more formal basis
- exploring for funding source(s)

- ALICE Photon Spectrometer -

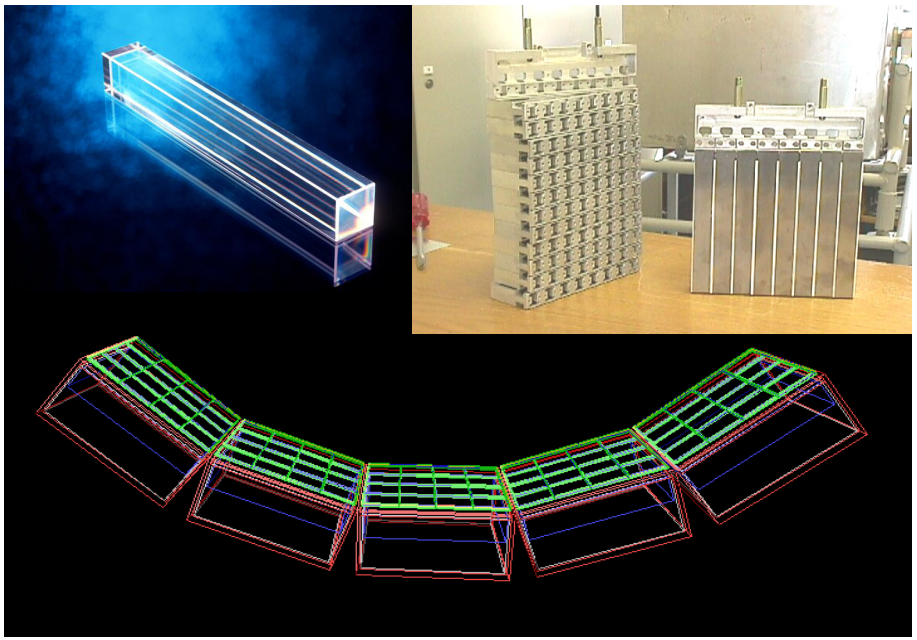


PHOS: high-granularity high-resolution photon spectrometer

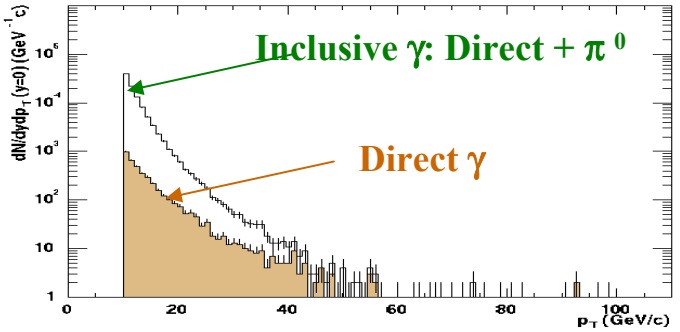
- $PbWO_4$ crystals of 2.2×2.2 cm^2 at 5 m
- $|\eta| < 0.5$, $\Delta\phi \sim 100$ degrees
- photons and neutral mesons
- γ-jet tagging

- Photon Measurement in ALICE -

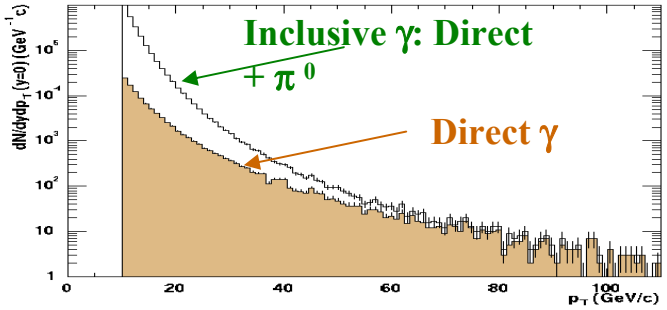
- photon spectrometer (PHOS)
  - high granularity high resolution $PbWO_4$ calorimeter
  - p_t up to ~ 100 GeV/c
    - photons and neutral mesons



without high p_t trigger

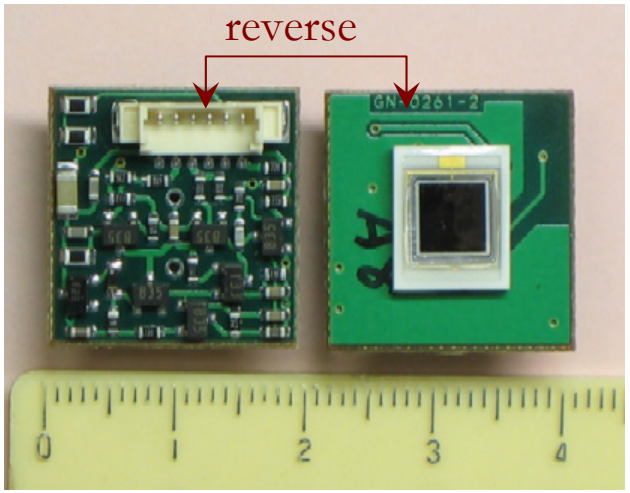


with high p_t trigger



- PHOS Activities at Hiroshima U. -

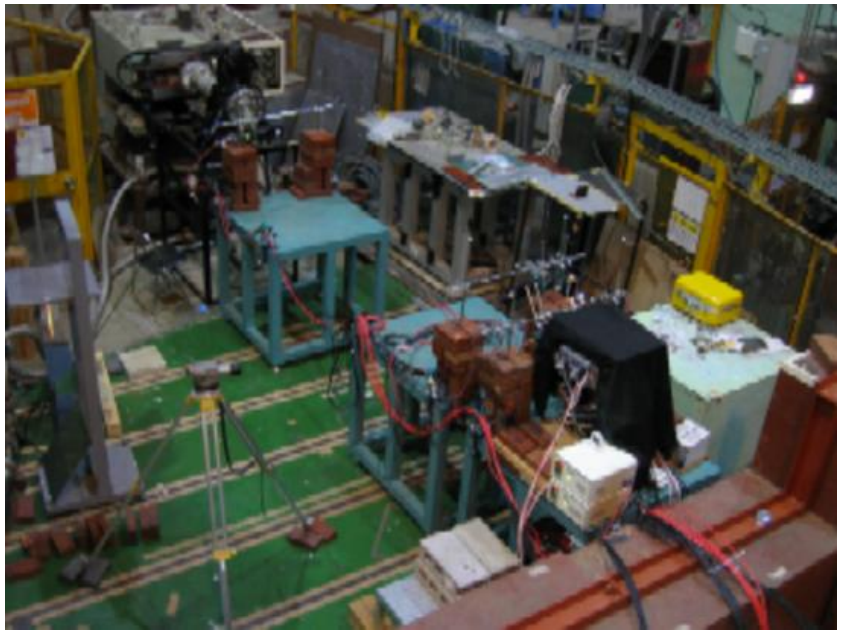
- avalanche photo-diode readout development
  - advantages over conventional PMT readout
    - magnetic field resistance
    - compactness
    - low power consumption
  - readout chain R&D completed; pre-production started
    - APD + pre-amplifiers + shaping amplifiers



- $PbWO_4$ crystal and PHOS prototype tests
  - at Hiroshima-REFER, KEK-PS, Tohoku-LNS
  - ~ 3 % /$\sqrt{E}$ [GeV] stochastic resolution achieved

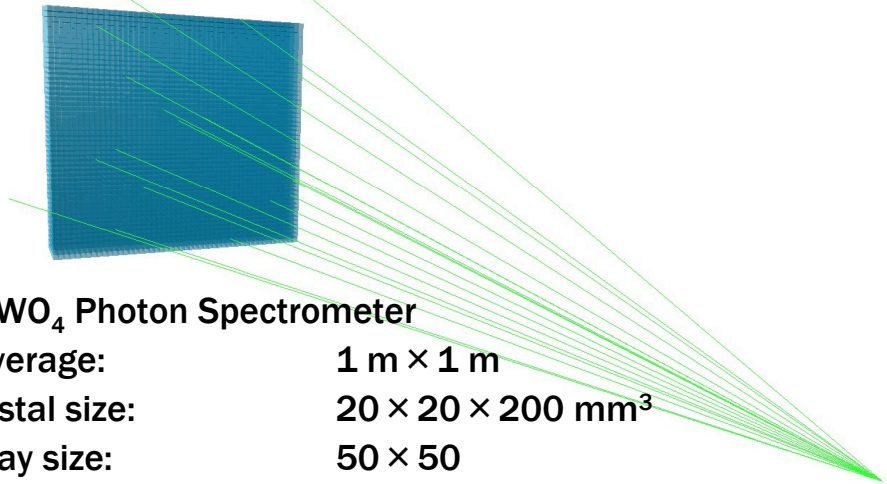
- KEK-PS T564 (16-23 June, 2004) -

- prototype with real ALICE-PHOS components
  - successful operation of APD readout with Peltier cooler
  - consistent results with CERN-PS/SPS beam tests



- Physics Chance Hunting -

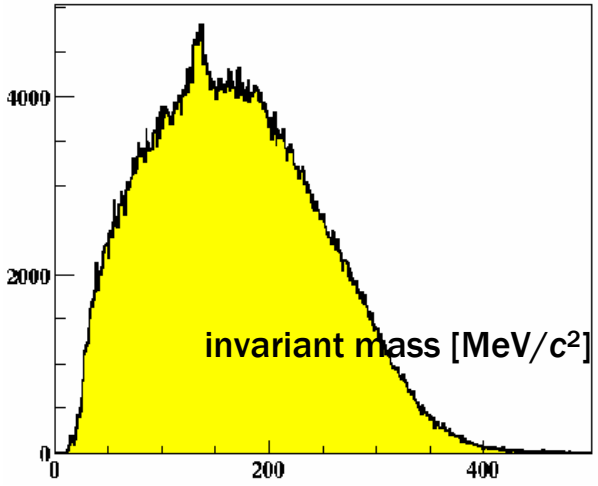
- $PbWO_4$ array (*e.g.* ALICE-PHOS) at RHIC ?
  - presently no fine granule electro-magnetic calorimeter
  - powerful tool for direct photons and di-photons
  - seeking for best experimental setup
  - shooting for RHIC runs in 2005 - 2007



$PbWO_4$ 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 Concluding Remarks -

- deconfined partonic phase *being* discovered
  - clear *manifests* of "quark gluon plasma"
  - more *evidences* anticipated (and coming)
    - high statistics Au+Au data (run 4) analyses in progress
- property investigation of "QGP" following
  - *direct* probes of thermal phase within reach
    - solid baseline for upcoming thermal photon measurement
      - prompt photon observation in Au+Au at RHIC/PHENIX (!)
    - high statistics Au+Au data in hand
    - RHIC/PHENIX upgrades under R&D/construction
    - LHC/ALICE starting in (only) 3 years
- photons at LHC/ALICE ~ electrons at RHIC/PHENIX