Thermal photons and dielectron continuum

Ju Hwan Kang

February 25-27, 2010

HIM at Yongpyong

Outline

- Thermal photons: Most of slides are from Akiba's recent talk at APS
- Dielectron continuum: From arXiv:0706.3034 & arXiv:0912.0244
- Electron or virtual photon detection in ALICE

Press release

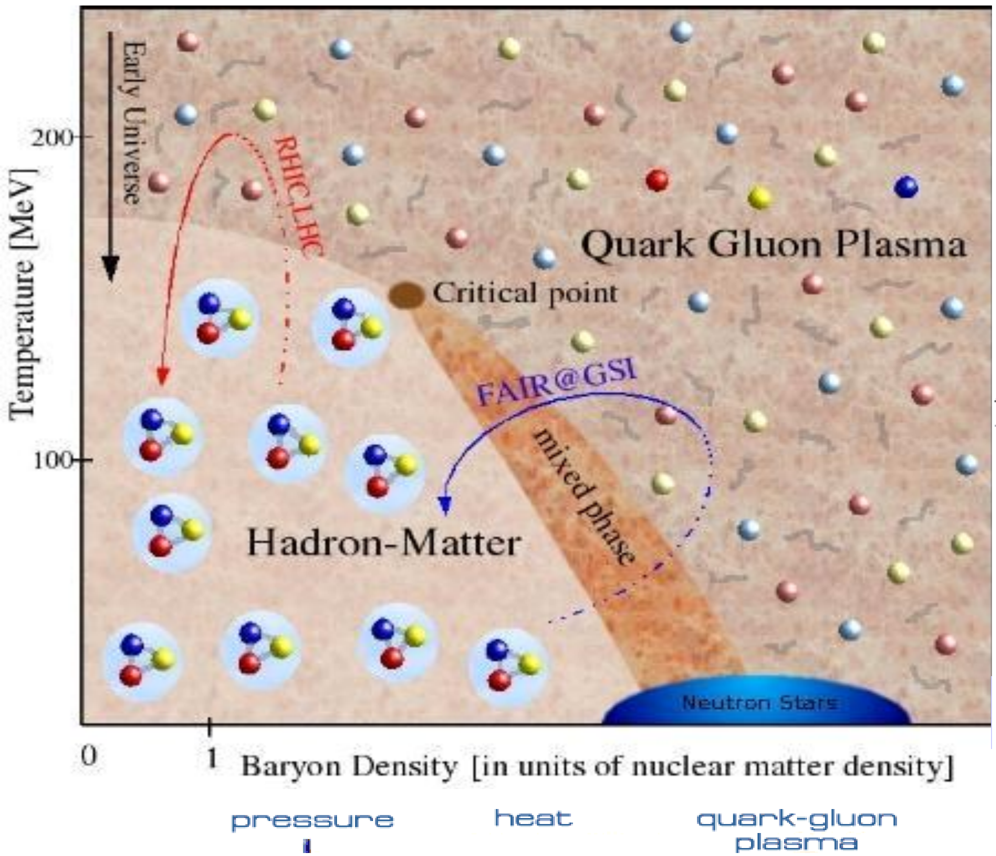
WHEN: Monday, February 15, 2010, 9:30 a.m.

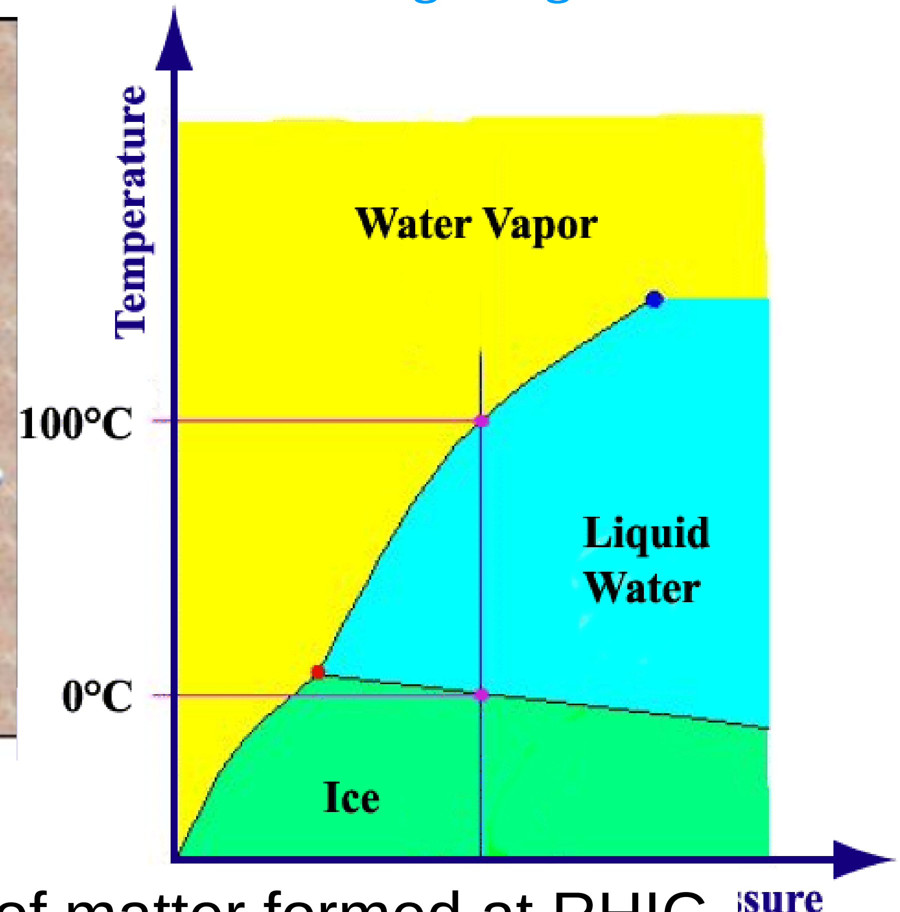
WHERE: The American Physical Society (APS) meeting, Marriott Wardman Park Hotel, Washington, D.C., Press Room/Briefing Room, Park Tower 8222

DETAILS: The Relativistic Heavy Ion Collider (RHIC) is a 2.4-mile-circumference particle accelerator/collider that has been operating at Brookhaven Lab since 2000, delivering collisions of heavy ions, protons, and other particles to an international team of physicists investigating the basic structure and fundamental forces of matter. In 2005, RHIC physicists announced that the matter created in RHIC's most energetic collisions behaves like a nearly "perfect“ liquid in that it has extraordinarily low viscosity, or resistance to flow. Since then, the scientists have been taking a closer look at this remarkable form of matter, which last existed some 13 billion years ago, a mere fraction of a second after the Big Bang. At this press event, scientists will present new findings, including the first measurement of temperature very early in the collision events, and their implications for the nature of this early-universe matter.

QCD Phase Transition

- The colliding nuclei at RHIC energies would melt from protons and neutrons into a collection of quarks and gluons
- Recreate the state of Universe a few microcse after the Big Bang

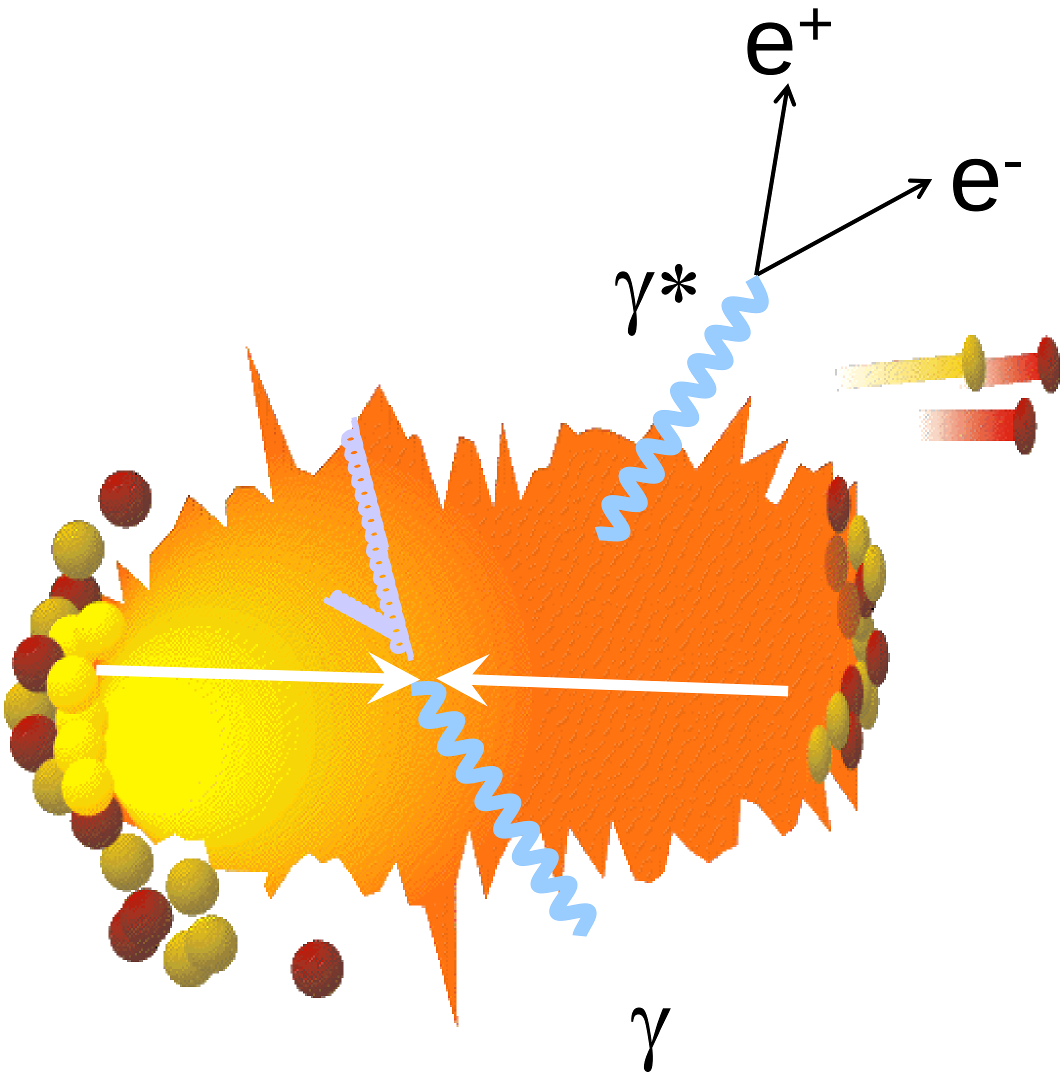




Measure the initial temperature of matter formed at RHIC

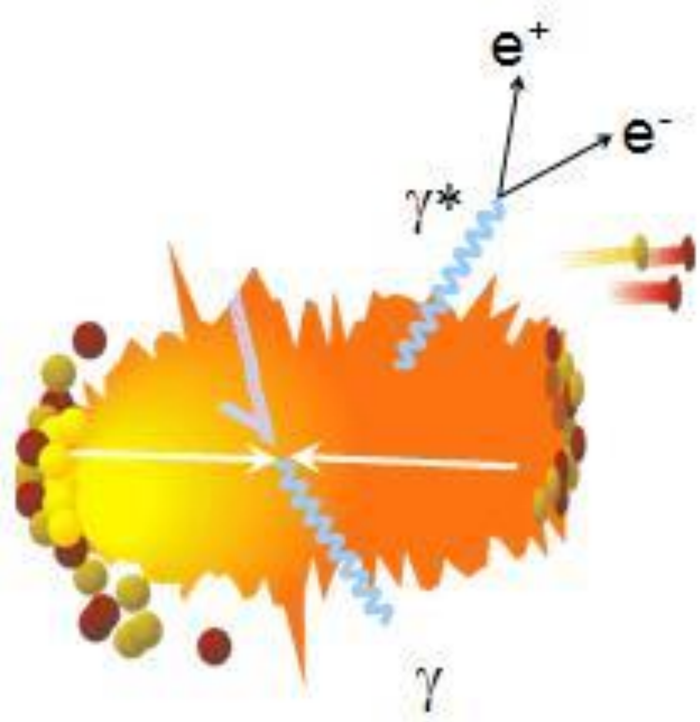
Is T_{init} higher than T_c ~ 170 MeV?

Electromagentic probes (photon and lepton pairs)



- Photons and lepton pairs are cleanest probes of the dense matter formed at RHIC
- These probes have little interaction with the matter so they carry information deep inside of the matter
  - Temperature?
  - Hadrons inside the matter?
  - Matter properties?

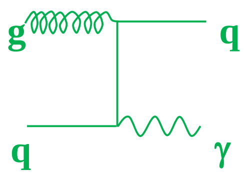
Thermal photon from hot matter



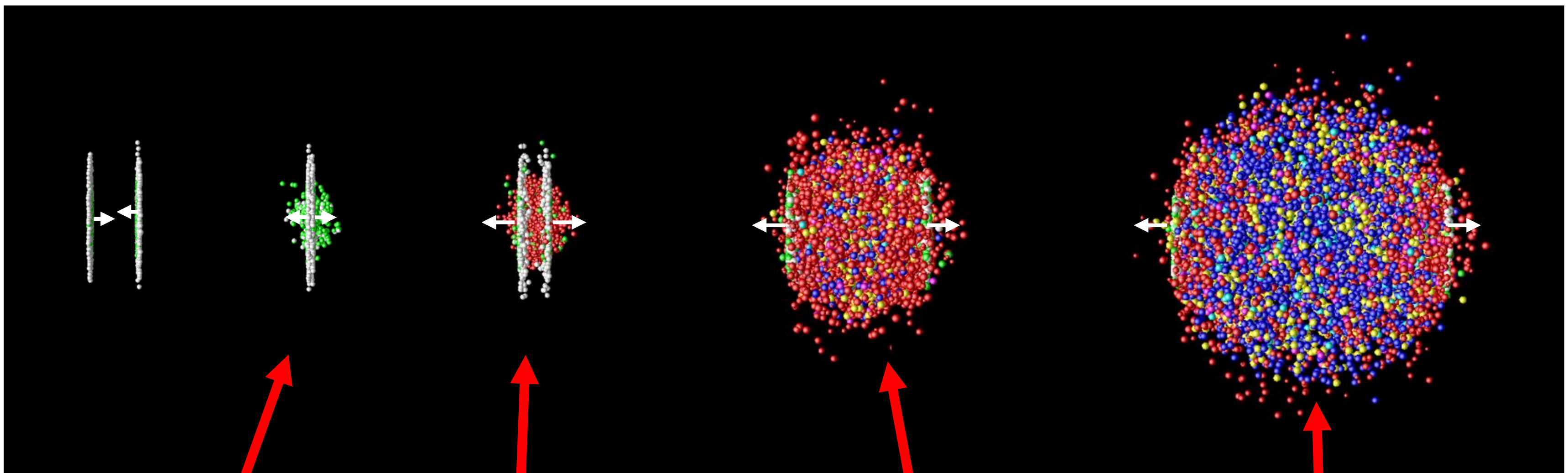
Hot matter emits thermal radiation

Temperature can be measured from the *emission spectrum*

Thermal photons in nucleus-nucleus collisions



Time →



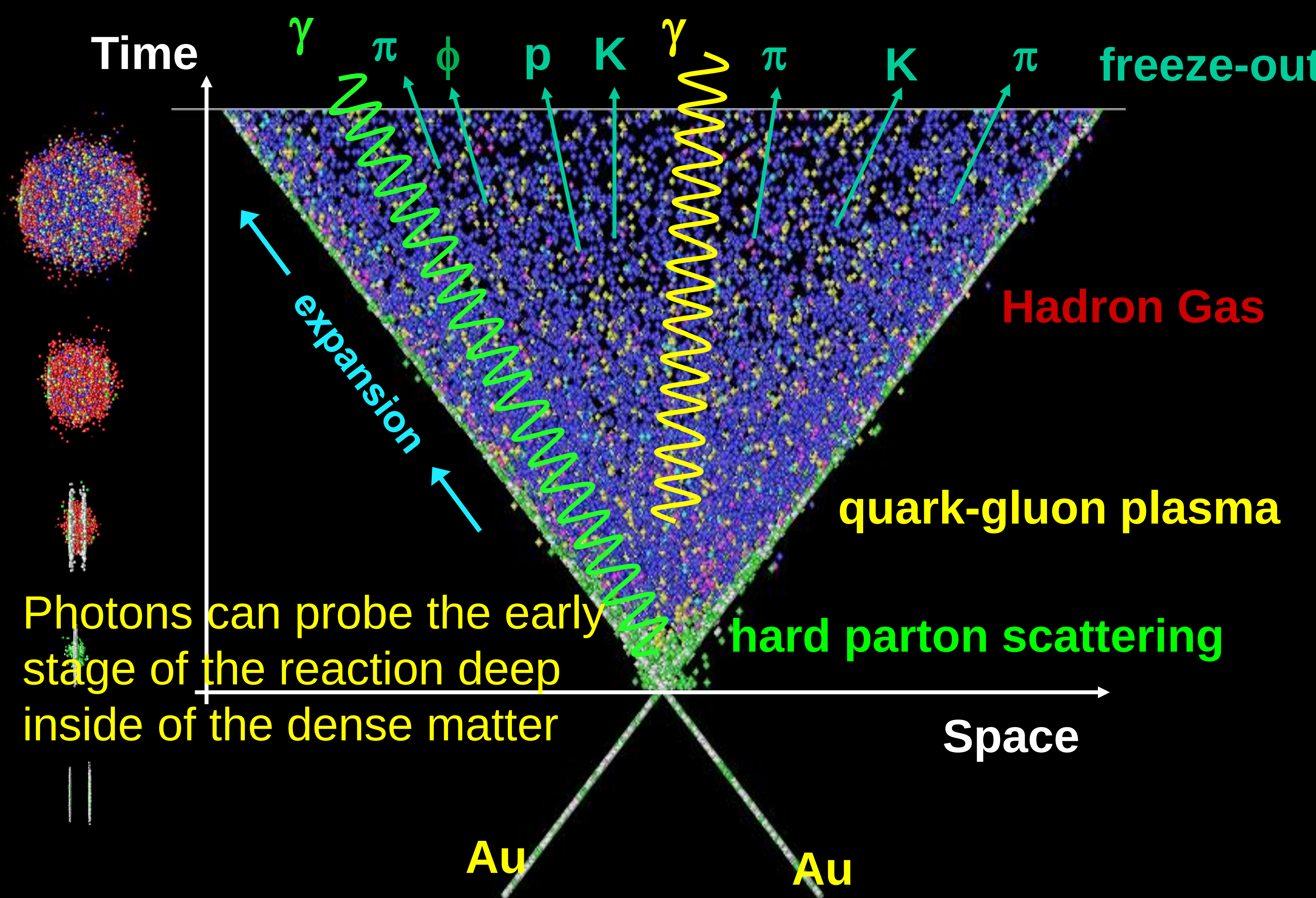
Initial hard parton-parton scatterings
(→ hard γ)

Thermalized medium (QGP!?),
$T_0 > T_c$,
$T_c \approx$ 170 - 190 MeV
(→ thermal γ)

Phase transition QGP → hadron gas

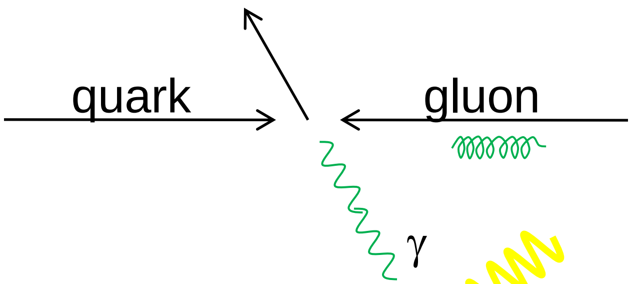
Freeze-out

Photon Probe of Nuclear Collisions

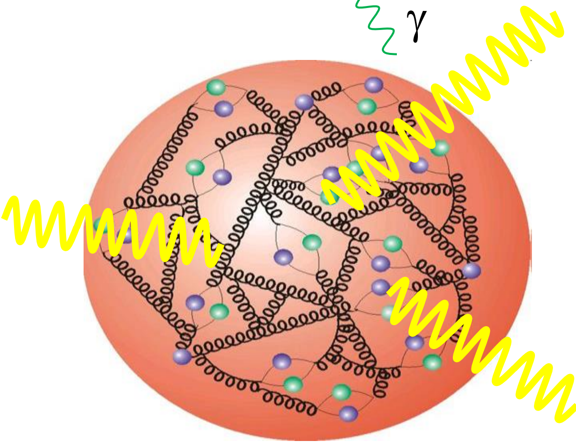


Photons can probe the early stage of the reaction deep inside of the dense matter

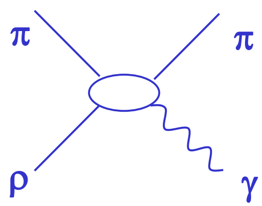
Many source of photons



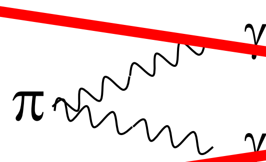
pQCD direct photons from initial *hard scattering* of quarks and gluons



Thermal photons from hot *quark gluon plasma*



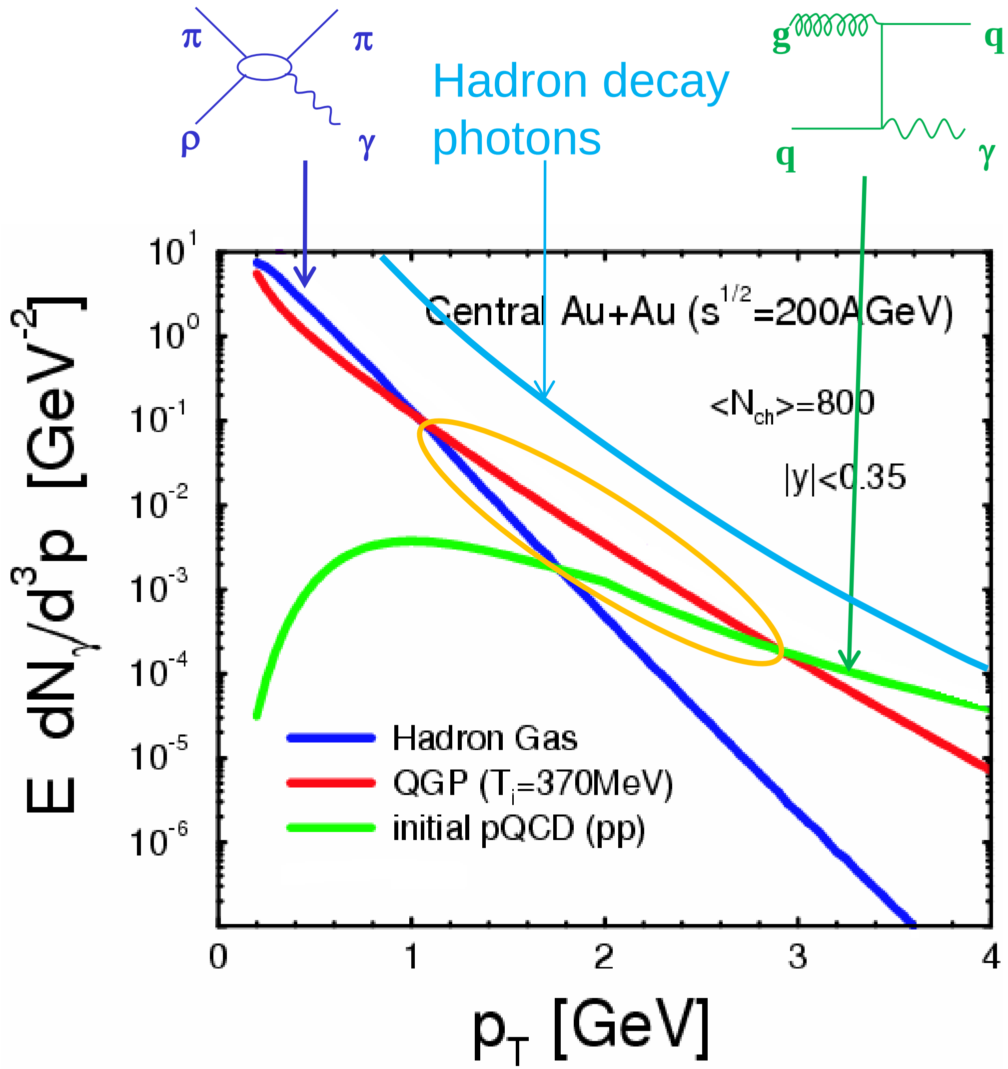
Thermal photons from *hadron gas* after hadronization



background

Decay Photons from hadrons (π^0, η, etc)

Thermal photons (theory prediction)

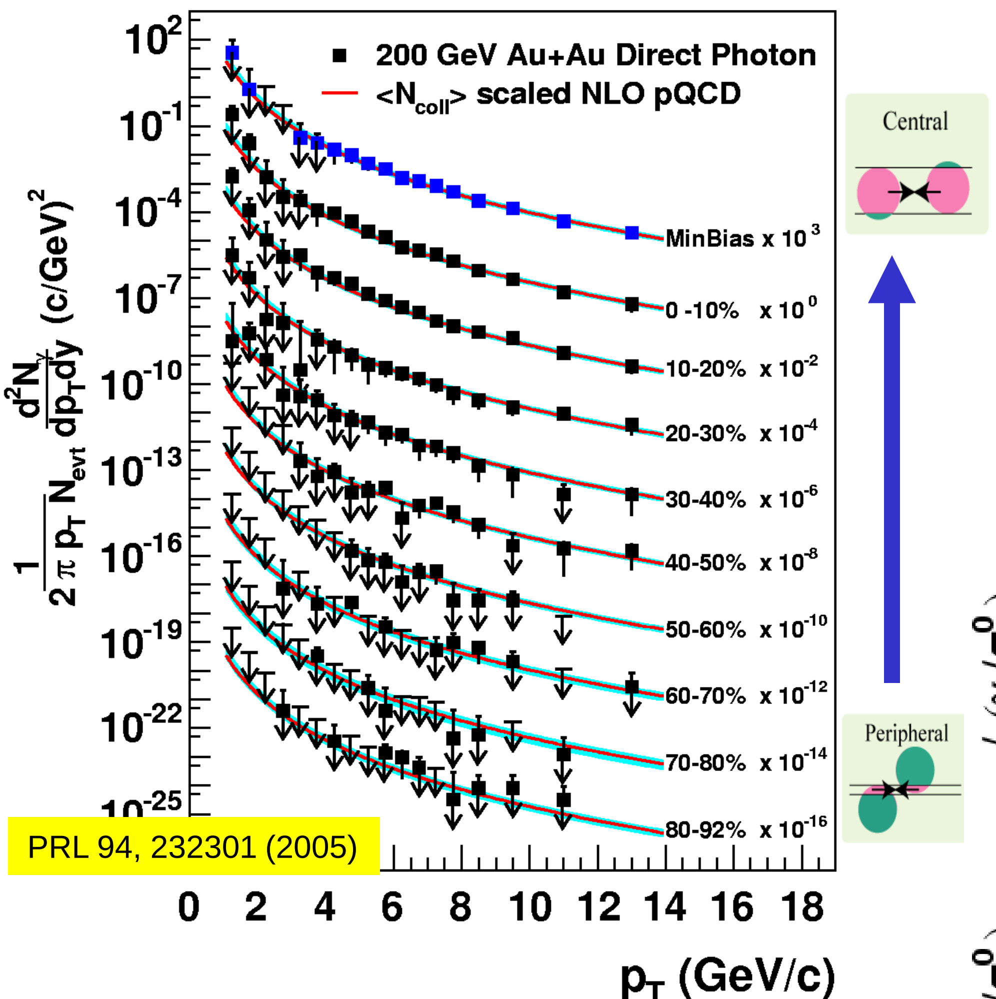


S.Turbide *et al* PRC 69 014903

- High p_T (p_T>3 GeV/c) pQCD photon
- Low p_T (p_T<1 GeV/c) photons from hadronic Gas
- Themal photons from QGP is the dominant source of direct photons for $1<p_T<3$ GeV/c
- Recently, other sources, such as jet-medium interaction are discussed
- Measurement is difficult since the expected signal is only 1/10 of photons from hadron decays

Direct Photons in Au+Au

Blue line: N_{coll} scaled p+p cross-section

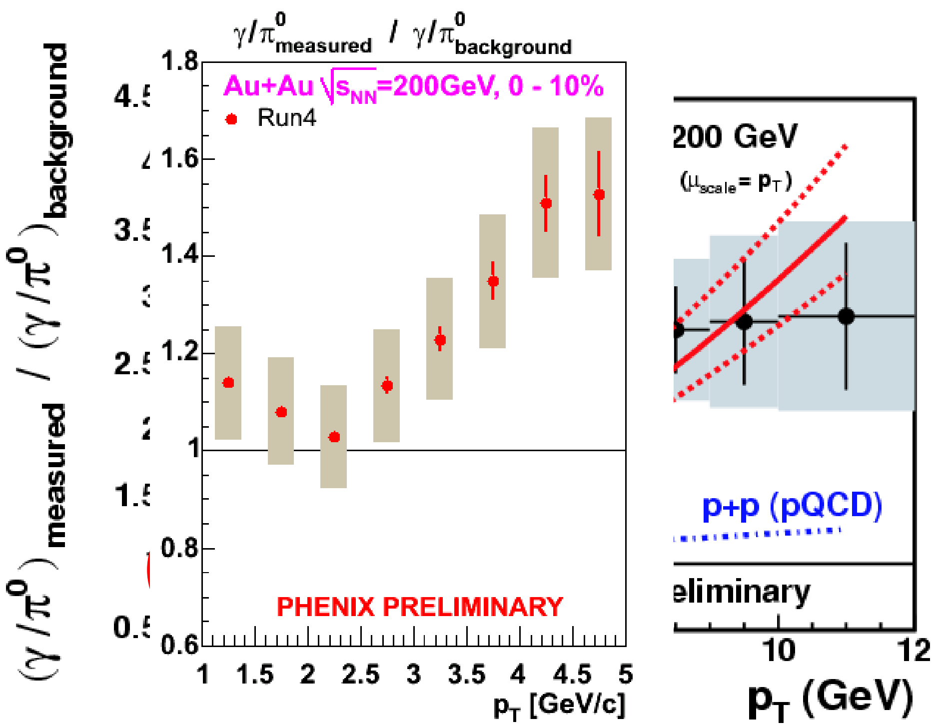


PRL 94, 232301 (2005)

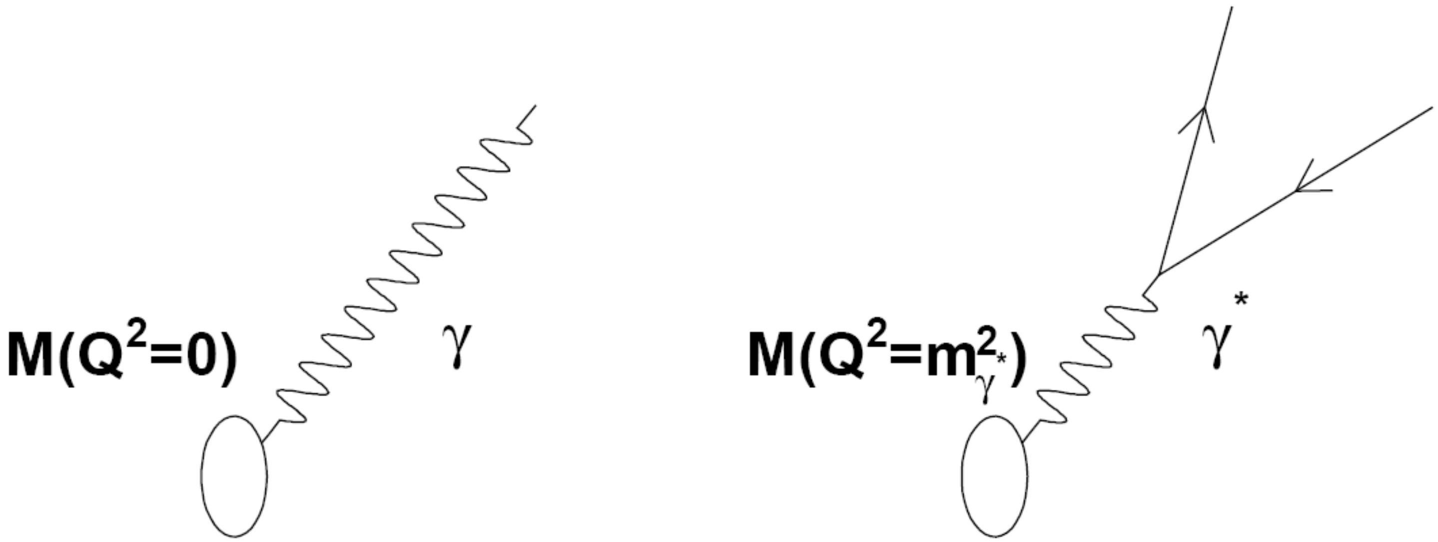
Au+Au data consistent with pQCD calculation scaled by N_{coll}

Direct photon is measured as "excess" above hadron decay photons

Measurement at low p_T difficult since the yield of thermal photons is only 1/10 of that of hadron decay photons



Alternative method - measure virtual photon



- Source of real photon should also be able to emit virtual photon
- At m→0, the yield of virtual photons is the same as real photon

→ Real photon yield can be measured from virtual photon yield, which is observed as low mass e^+e^- pairs

- Advantage: hadron decay background can be substantially reduced. For $m>m_\pi$, π^0 decay photons (~80% of background) are removed

→ S/B is improved by a factor of five

- Other advantages: photon ID, energy resolution, etc

Relation between dilepton and virtual photon

e.g. Rapp, Wambach Adv.Nucl.Phys 25 (2000)

Emission rate of (virtual) photon

$$q_0 \frac{dR_{\gamma^*}}{d^3q} = -\frac{\alpha}{2\pi^2} \mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T) f^B(q_0,T).$$

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

EM correlator
Matter property

Boltzmann factor
temperature

Emission rate of dilepton

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2} \mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T) f^B(q_0,T)$$

$$L(M) = \sqrt{1-\frac{4m_l^2}{M^2}}(1+\frac{2m_l^2}{M^2})$$

Relation between them

Prob. $\gamma^* \rightarrow l^+l^-$

$$q_0 \frac{dR_{ll}}{dM^2 d^3q} = \frac{1}{2}\frac{dR}{d^4q} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2} q_0 \frac{dR_{\gamma^*}}{d^3q}$$

Dilepton

$q_0/dM^2 = q_0/2MdM = 1/2dq_0$

virtual photon

Universal factor describing the decay of the virtual photon into an e+e− pair. Exact to first order in the electromagnetic coupling

Virtual photon emission rate can be determined from dilepton emission rate

$$q_0 \frac{dn_{\gamma^*}}{d^3q} \simeq \frac{3\pi}{\alpha} M^2 q_0 \frac{dn_{ll}}{d^3q dM^2}$$

$$= \frac{3\pi}{2\alpha} M q_0 \frac{dn_{ll}}{d^3q dM}.$$

$L(M) = \sqrt{1-\frac{4m_l^2}{M^2}}(1+\frac{2m_l^2}{M^2}) \rightarrow 1$ for $m_e \ll M$

No diff. between γ & γ* if M=0

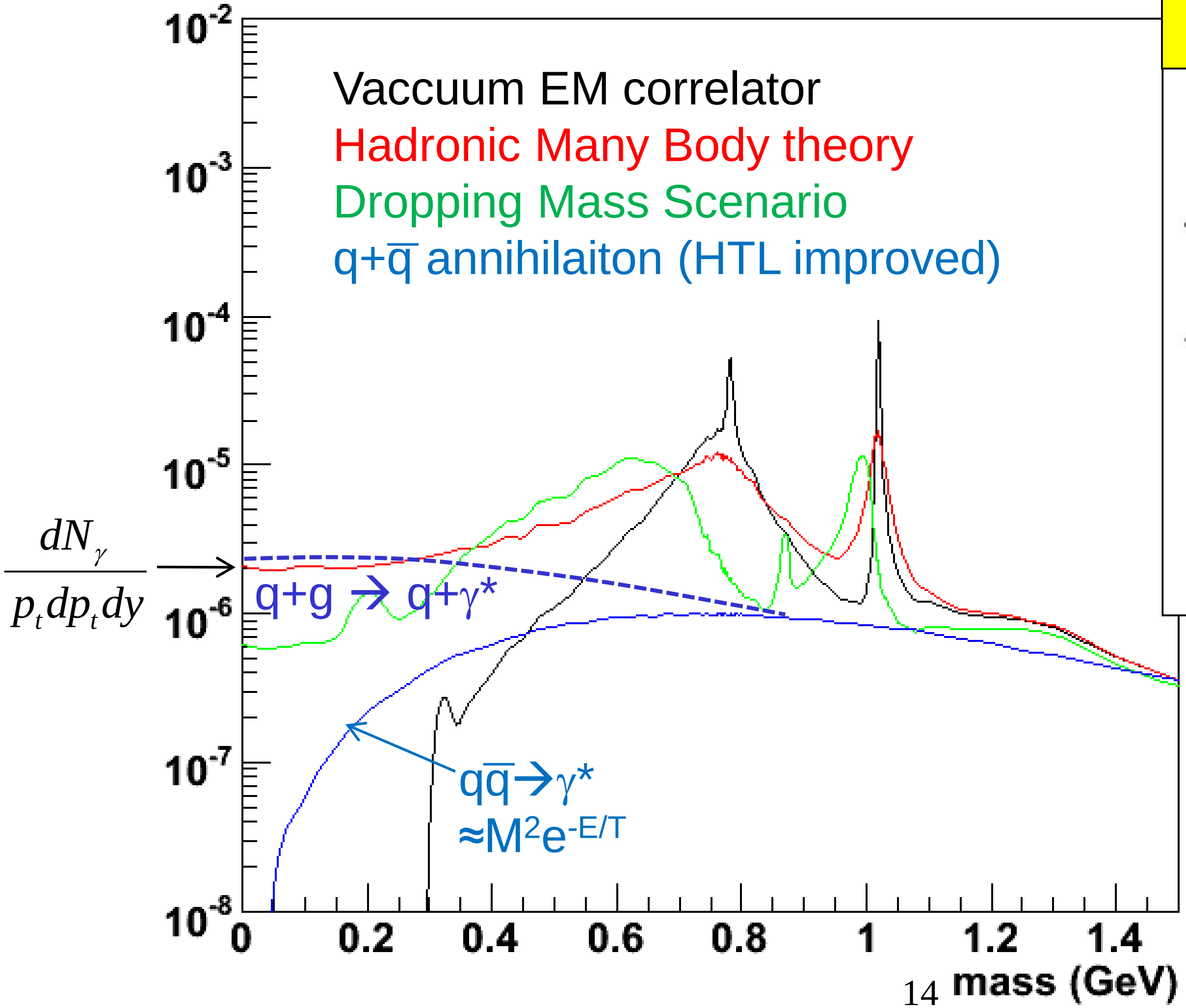
$M \times dN_{ee}/dM$ gives virtual photon yield

For M→0, n_γ^* → n_γ(real); real photon emission rate can also be determined

Theory prediction of (Virtual) photon emission

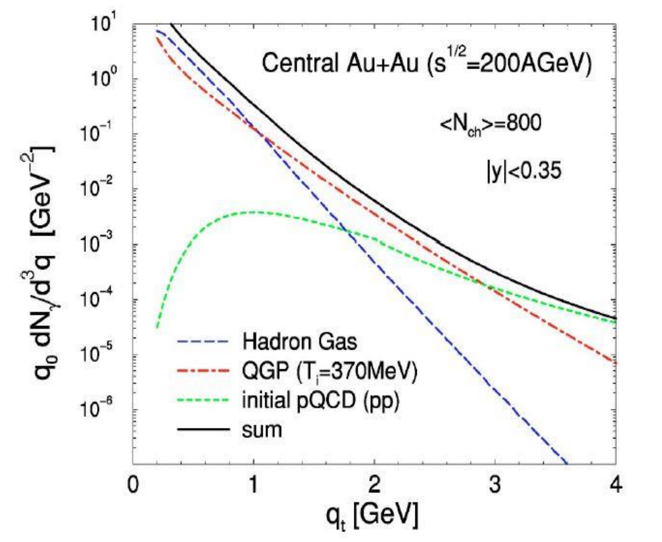
$$M \times \frac{dN_{ee}}{p_t dp_t dM dy} \propto \frac{dN_{\gamma^*}}{p_t dp_t dy}$$ at y=0, pt=1.025 GeV/c

Theory calculation by Ralf Rapp



Real photon yield

Turbide, Rapp, Gale PRC69,014903(2004)



q+g→q+γ* is not in the calculation; it should be similar size as HMBT at this p_T

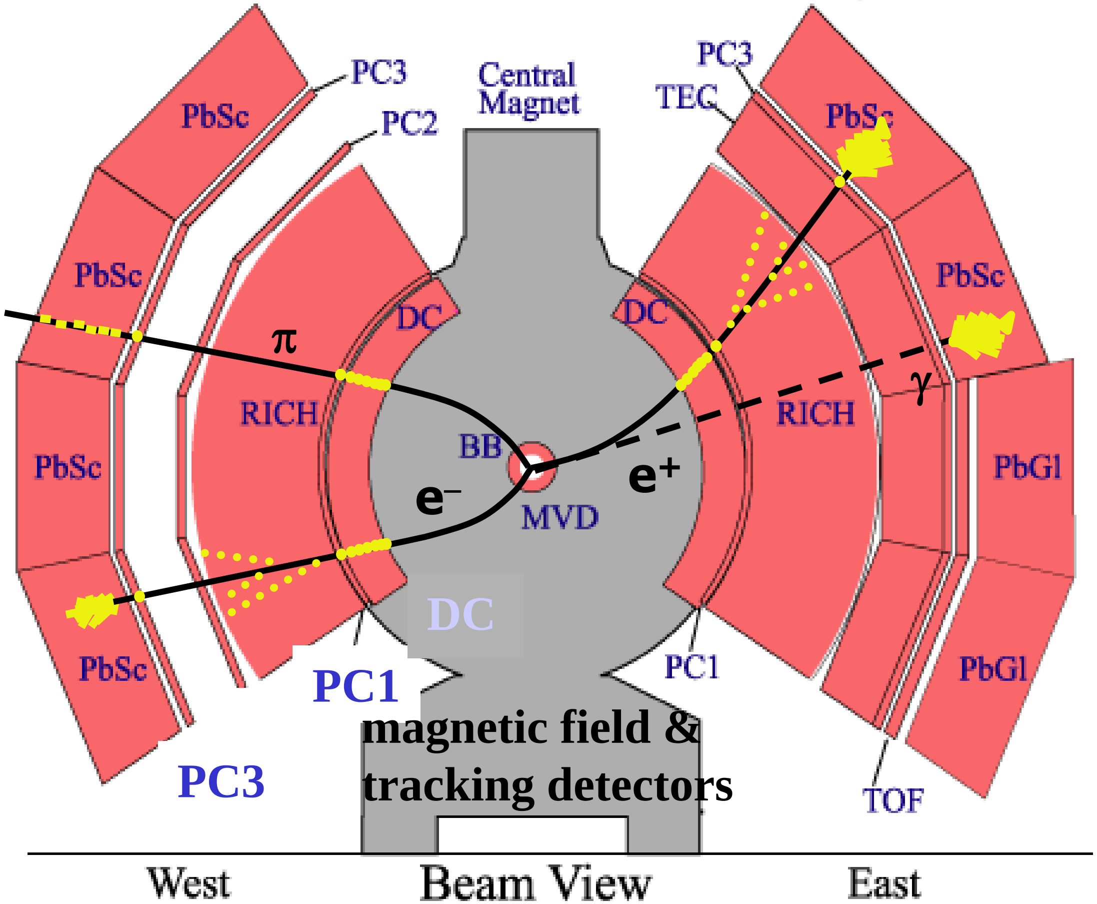
Electron pair measurement in PHENIX

designed to measure rare probes:

Au-Au & p-p spin

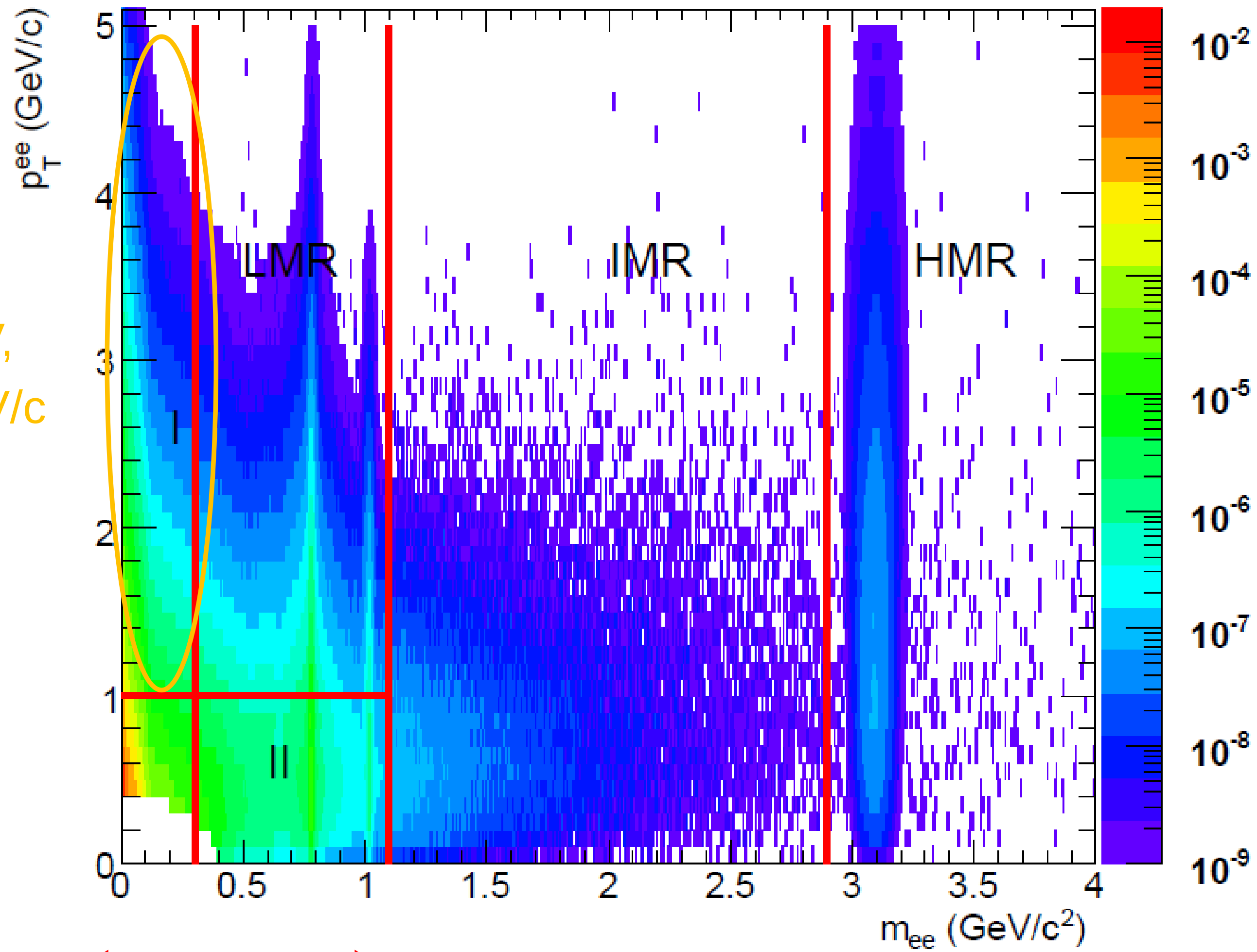
- **+ high rate capability & granularity**
- **+ good mass resolution and particle ID**
- **- limited acceptance**

- 2 central arms:
  electrons, photons, hadrons
  - charmonium J/ψ, ψ' -> e^+e^-
  - vector meson r, w, φ -> e^+e^-
  - high p_T π^o, π^+, π^-
  - direct photons
  - open charm
  - hadron physics



LMR-I = quasi-real virtual photon

m<300 MeV,
$1<p_T<5$ GeV/c



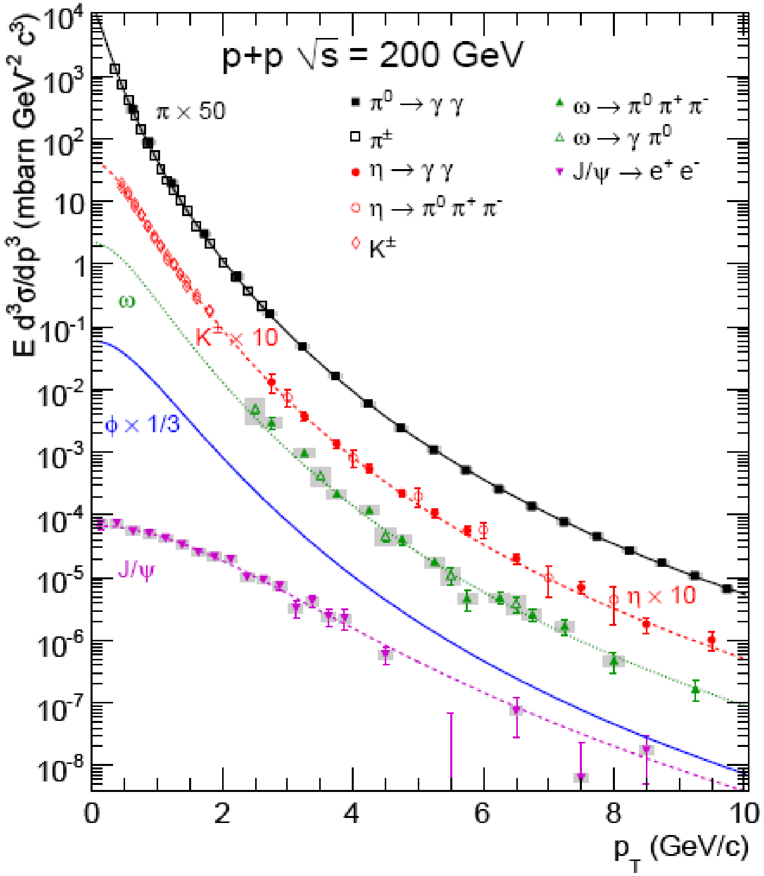
Dilepton spectrum as a function of m_ee & pT from a simulation of hadron decays.

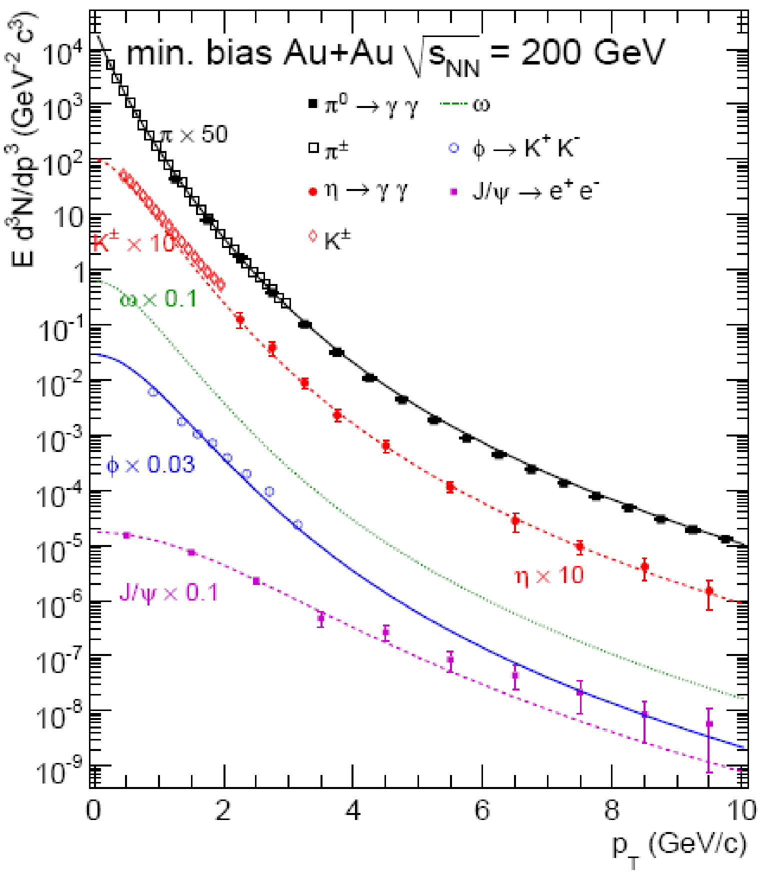
○**LMR I** ($p_T >> m_{ee}$)

quasi-real virtual photon region. Low mass pairs produced by higher order QED correction to the real photon emission

LMR II : dilepton production is expected to be dominated by the hadronic gas phase (mass modification?)

Input hadron spectra for cocktail

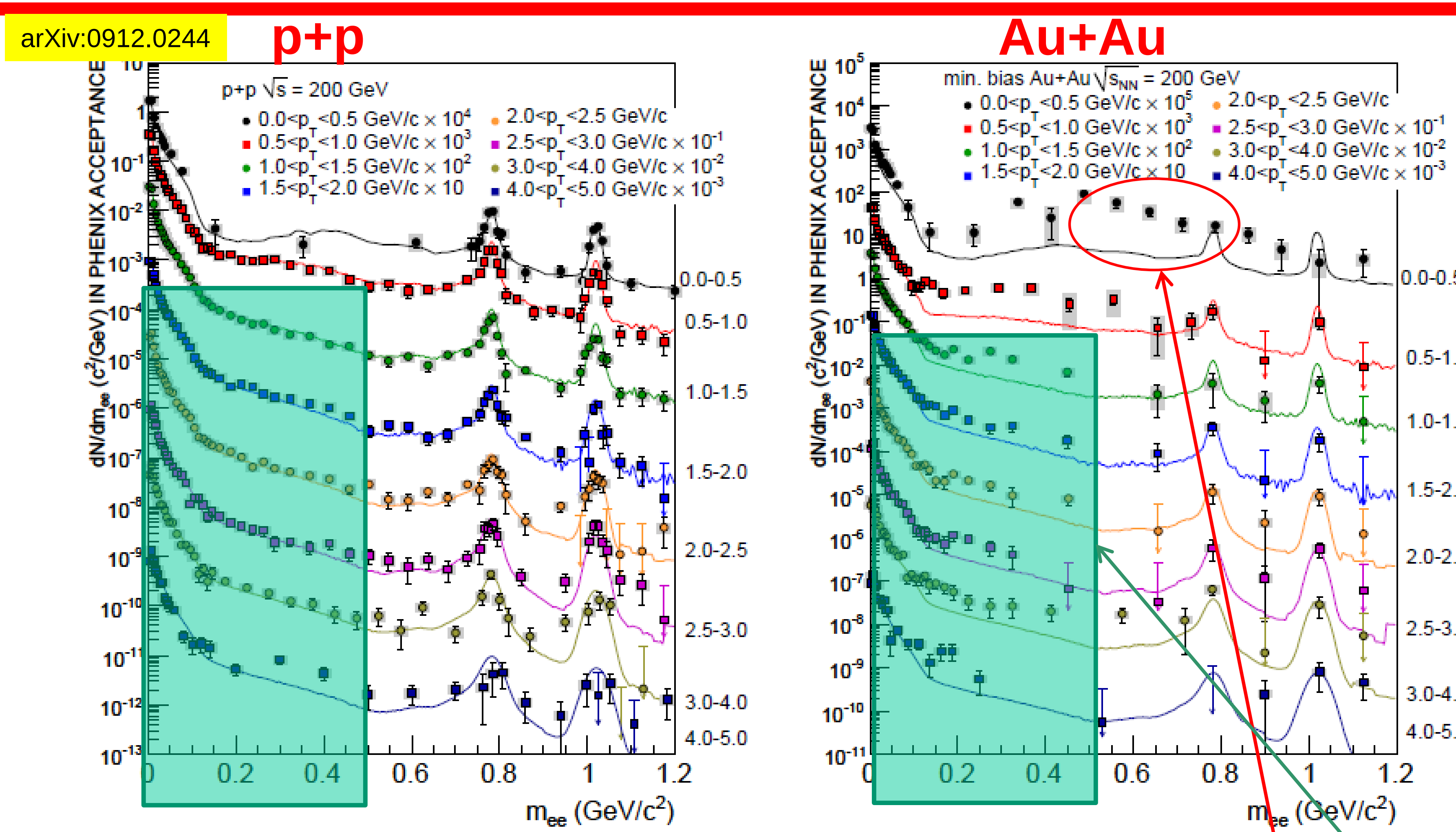




$$E\frac{d^3\sigma}{dp^3} = A(e^{-(ap_T+bp_T^2)} + p_T/p_0)^{-n}$$

Fitting with a modified Hagedorn function for pion, for all other mesons assume m_T scaling by replacing p_T by $\sqrt{m^2 - m_\pi^2 + (p_T/c)^2}$

e^+e^- mass spectra in p_T slices



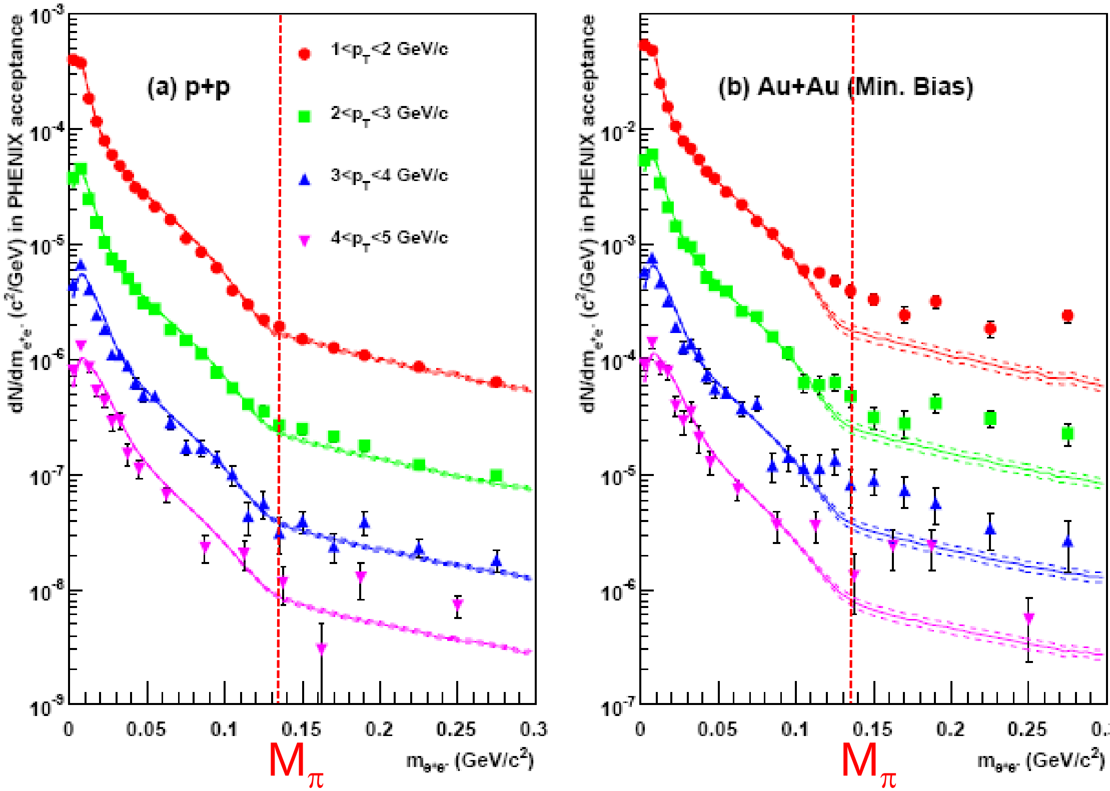
- p+p in agreement with cocktail
- Au+Au low mass enhancement concentrated at low p_T

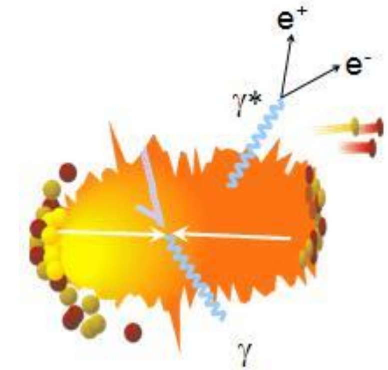
Excess has a similar shape to the cocktail and the level of the excess is approximately constant.

Enhancement of almost real photon

arXiv:0804.4168

pp   Au+Au (MB)





1 < p_T < 2 GeV

2 < p_T < 3 GeV

3 < p_T < 4 GeV

4 < p_T < 5 GeV

Low mass e^+e^- pairs (m<300 MeV) for $1<p_T<5$ GeV/c

p+p:

- Good agreement of p+p data and hadronic decay cocktail
- Small excess above m_π at large m_{ee} and high p_T

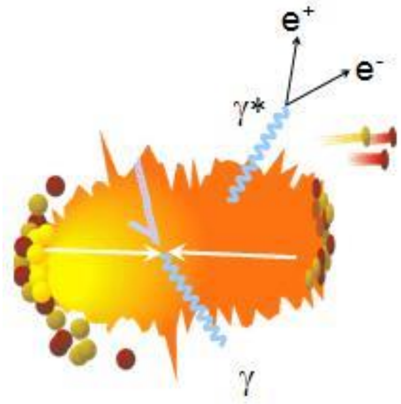
Au+Au:

- Clear enhancement visible above m_π =135 MeV for all p_T

Excess → Emission of almost real photon

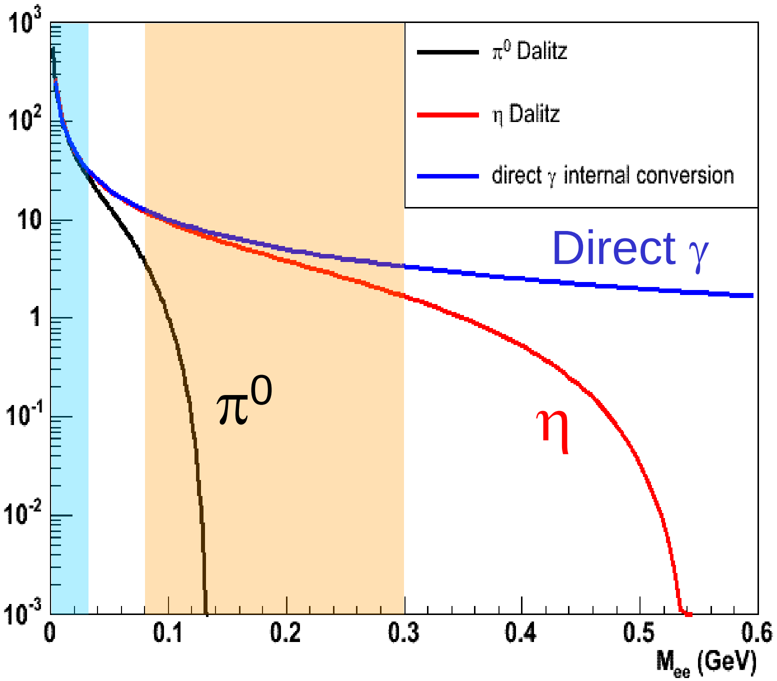
Virtual Photon Measurement

Any source of real γ can emit γ^* with very low mass.
Relation between the γ^* yield and real photon yield is known.



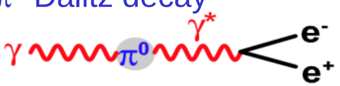
$$\frac{d^2N}{dM_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}S(M_{ee},p_t)dN_\gamma$$

Process dependent factor $S(M_{ee},p_t) \equiv \frac{dN_{\gamma^*}}{dN_\gamma}$



- Case of hadrons (π^0, η) (Kroll-Wada)

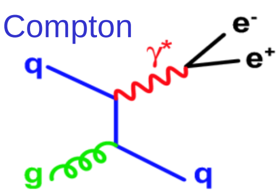
$$S = \left|F\left(M_{ee}^2\right)\right|^2\left(1-\frac{M_{ee}^2}{M_{hadron}^2}\right)^3$$



$S = 0$ at $M_{ee} > M_{hadron}$

- Case of direct γ^*

If $p_T^2 >> M_{ee}^2$ $S = 1$



- For $m > m_\pi$, π^0 background (~80% of background) is removed

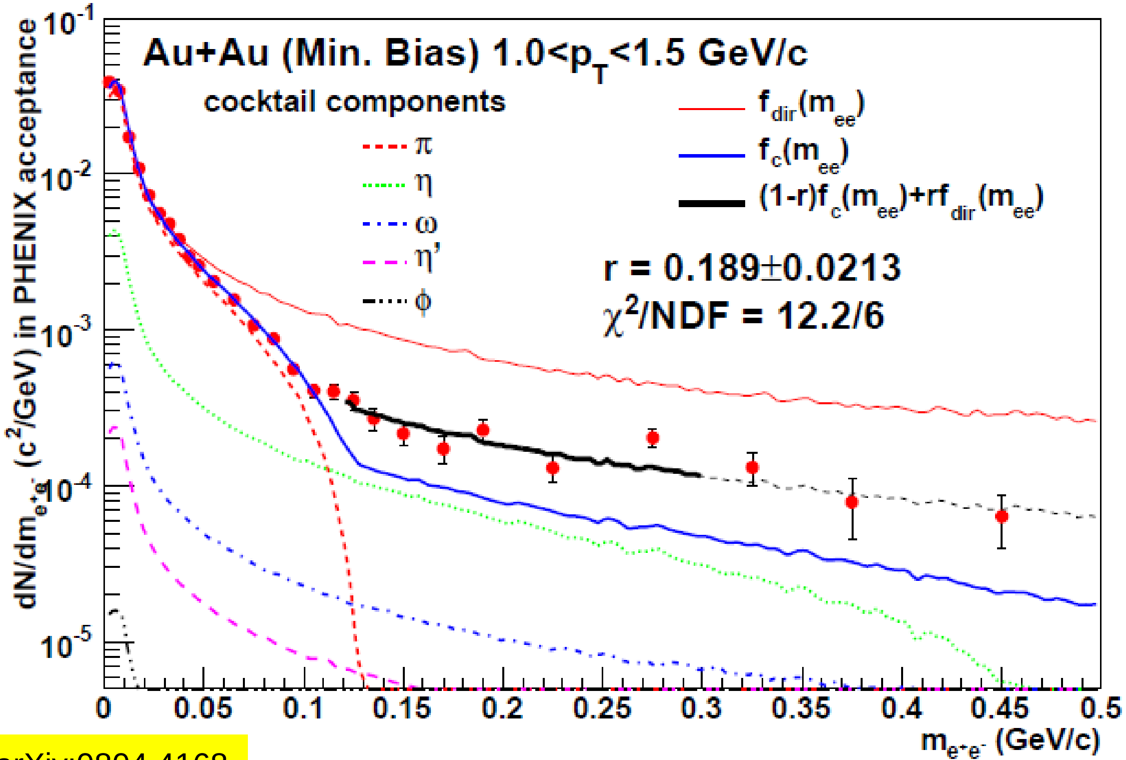
→ S/B is improved by a factor of five

Extraction of the direct γ signal

$$f(m_{ee}) = (1 - r) \cdot f_{cocktail}(m_{ee}) + r \cdot f_{direct}(m_{ee})$$

r = direct γ^*/inclusive γ^*

f_{direct} : direct photon shape with S = 1



- Interpret deviation from hadronic cocktail (π, η, ω, η', ϕ) as signal from virtual direct photons
- Fit in 120-300MeV/c^2 (insensitive to π^0 yield)

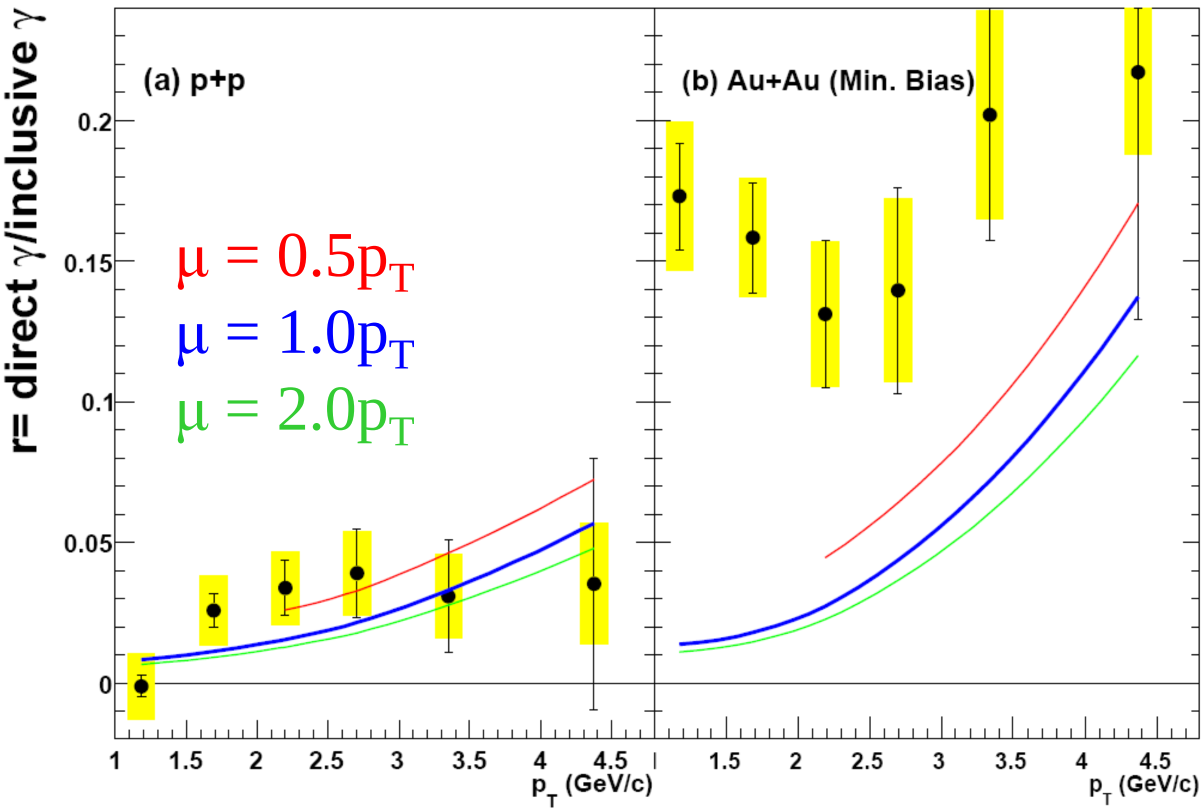
arXiv:0804.4168
arXiv:0912.0244

A. Adare et al., PRL accepted

Fraction of direct photons

arXiv:0804.4168
arXiv:0912.0244

p+p Au+Au (MB)



NLO pQCD calculation by Werner Vogelsang

- Fraction of direct photons
- Compared to direct photons from pQCD

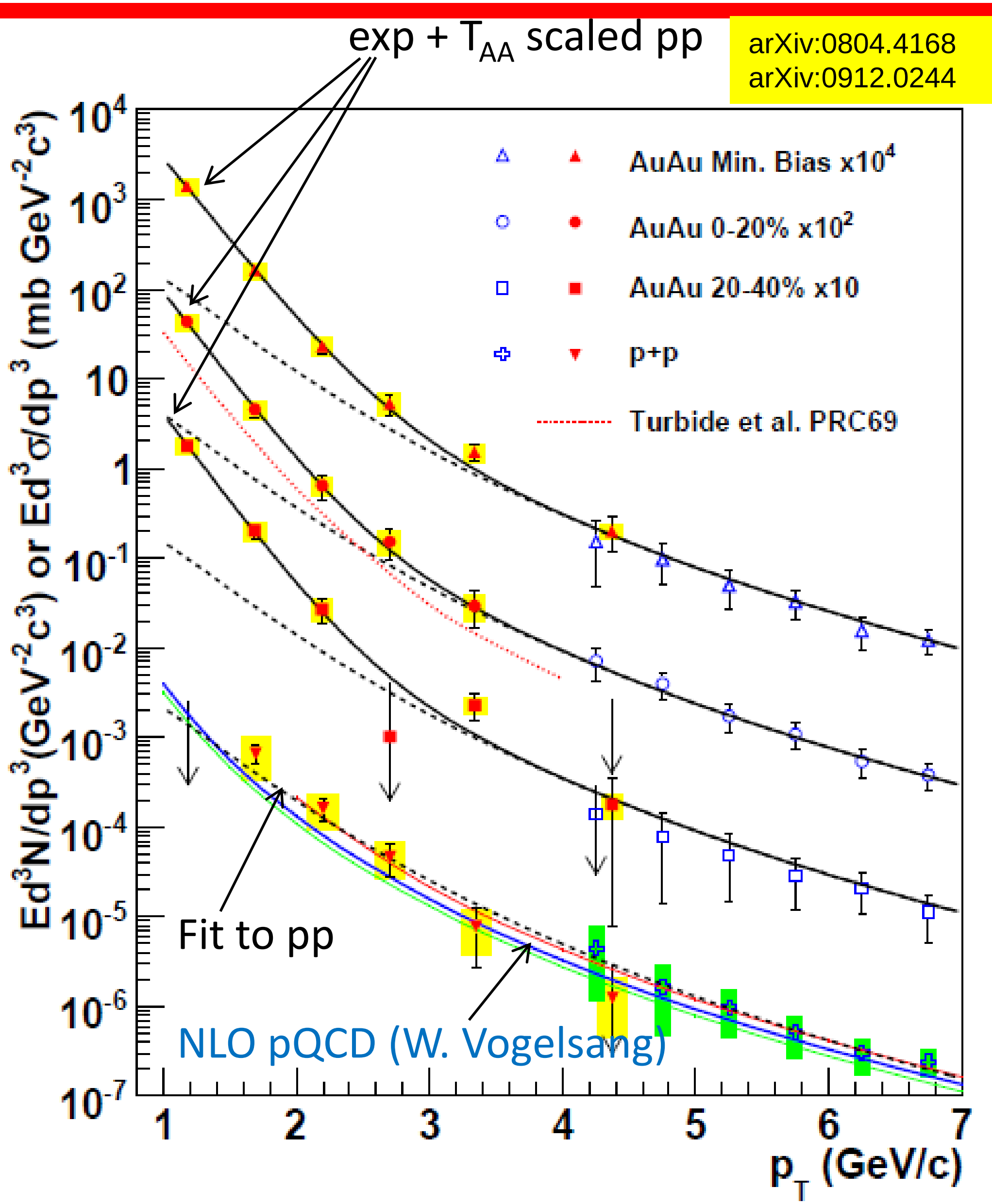
p+p

- Consistent with NLO pQCD

Au+Au

- Clear excess above pQCD

Direct photon spectra



- Direct photon measurements
  - real (p_T>4GeV)
  - virtual ($1<p_T<5$GeV)
- pQCD consistent with p+p down to p_T=1GeV/c
- Au+Au data are above N_{coll} scaled p+p for p_T < 2.5 GeV/c
- Au+Au = scaled p+p + exp: $T_{ave} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV

The dotted (red) curve near the 0–20% centrality data is a theory calculation by Turbide, Rapp, Gale, PRC 69, 014903 (2004).

Summary of the fit

TABLE I: Summary of the fits. The first and second errors are statistical and systematic, respectively.

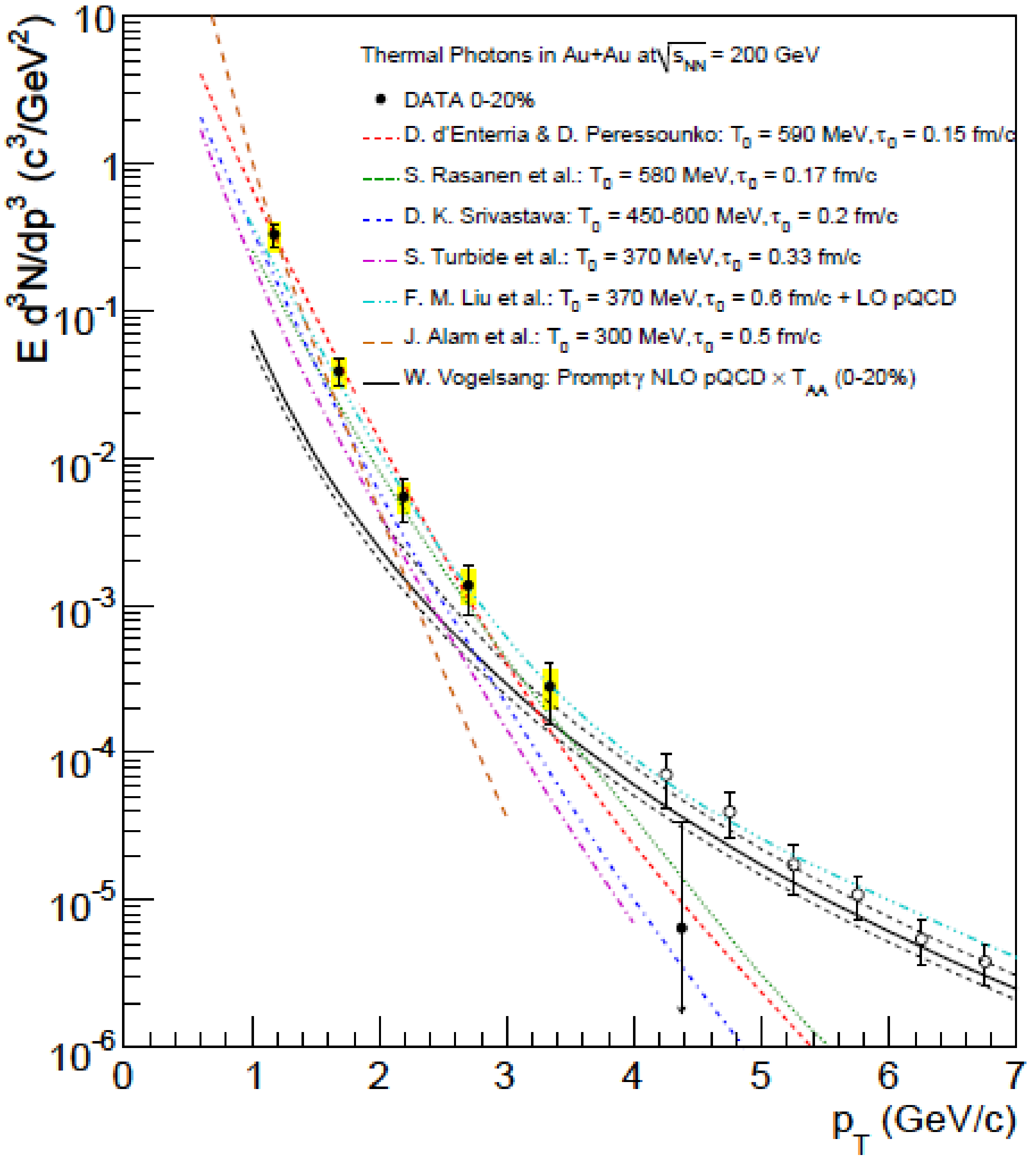
centrality	$dN/dy(p_T > 1\text{GeV}/c)$	T(MeV)	χ^2/DOF
0-20%	$1.50 \pm 0.23 \pm 0.35$	$221 \pm 19 \pm 19$	$4.7/4$
20-40%	$0.65 \pm 0.08 \pm 0.15$	$217 \pm 18 \pm 16$	$5.0/3$
Min. Bias	$0.49 \pm 0.05 \pm 0.11$	$233 \pm 14 \pm 19$	$3.2/4$

- Significant yield of the exponential component (excess over the scaled p+p)
- The inverse slope T_{AuAu} = 221±19±19 MeV (>T_c ~ 170 MeV)
  - p+p fit funciton: $A_{pp}(1+p_t^2/b)^{-n}$
  - If power-law fit ($\propto p_T^{-n}$) is used for the p+p spectrum, T_{AuAu} = 240±21 MeV

A is converted to dN/dy for pT > 1GeV/c

$$(Ae^{-p_T/T} + T_{AA} \times A_{pp}(1 + p_T^2/b)^{-n})$$

Theory comparison



Hydrodynamical models are compared with the data

D.d'Enterria &D.Peressounko

T=590MeV, τ_0=0.15fm/c

S. Rasanen et al.

T=580MeV, τ_0=0.17fm/c

D. K. Srivastava

T=450-600MeV, τ_0=0.2fm/c

S. Turbide et al.

T=370MeV, τ_0=0.33fm/c

J. Alam et al.

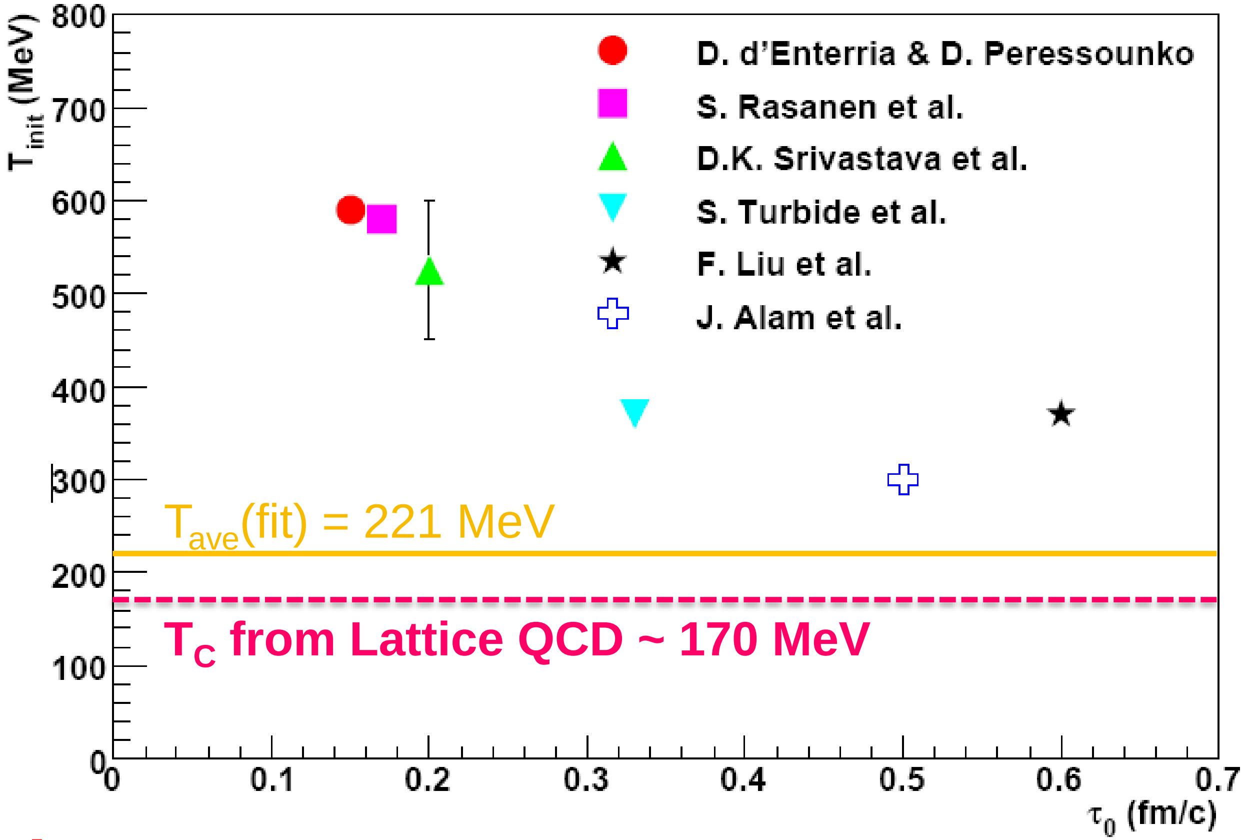
T=300MeV, τ_0=0.5fm/c

F.M. Liu et al.

T=370MeV, τ_0=0.6 fm/c

Hydrodynamical models are in qualitative agreement with the data

Initial temperature



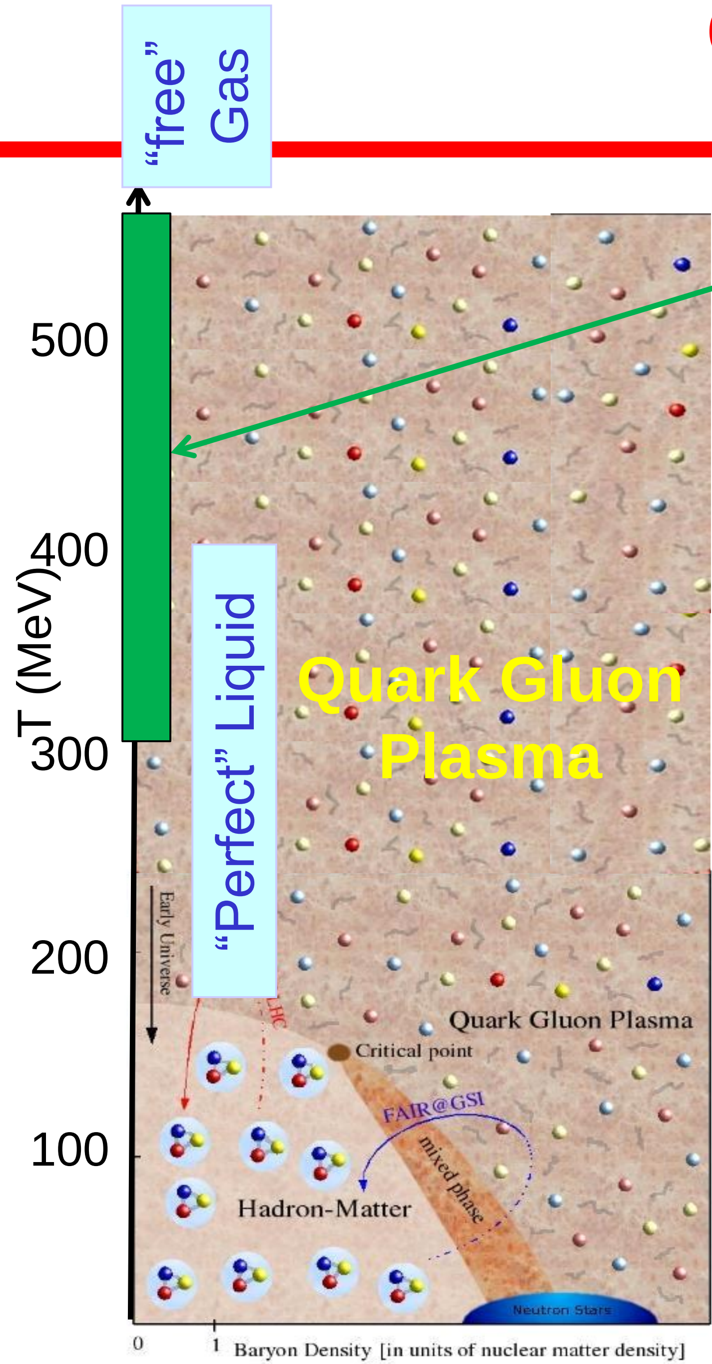
From data: $T_{ini} >$ Tave = 220 MeV

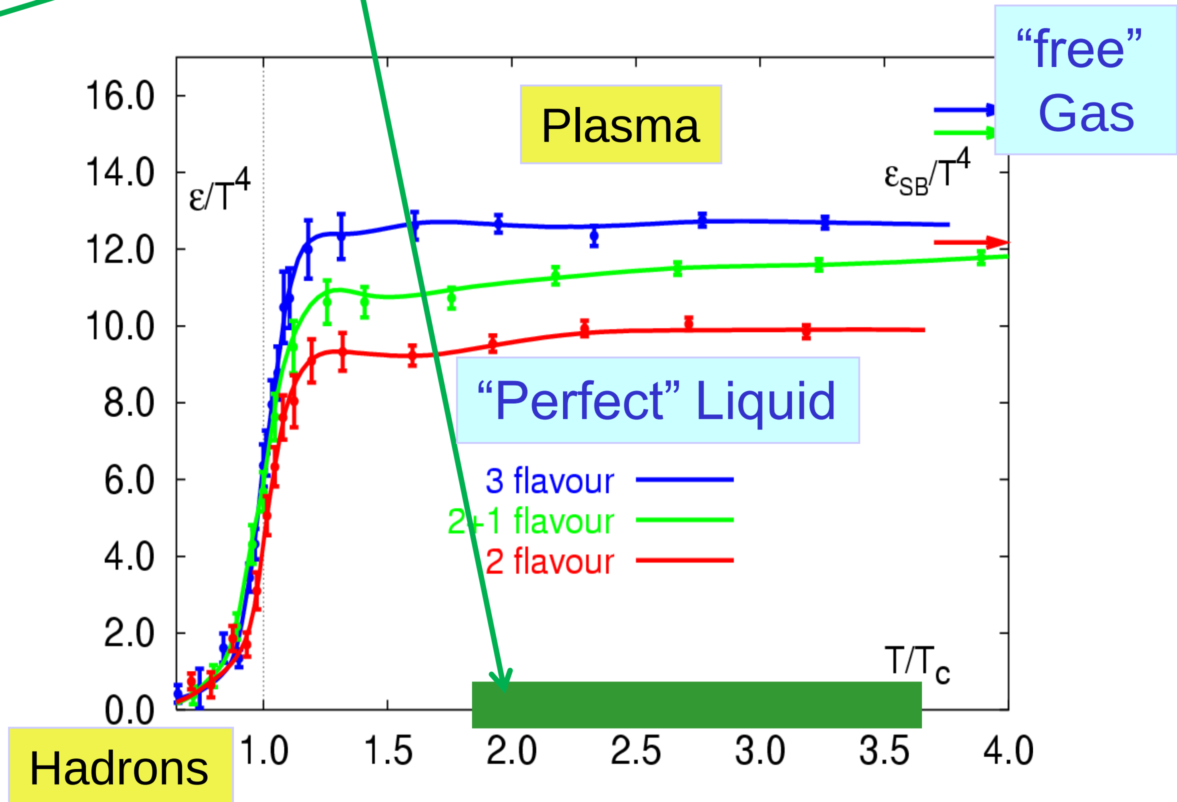
From models: T_{ini} = 300 to 600 MeV

τ_0 = 0.15 to 0.6 fm/c

Lattice QCD predicts a phase transition to quark gluon plasma at Tc ~ 170 MeV

On the Map





T_c ~ 170 MeV; ε ~ 1 GeV/fm^3

At these temperature, QGP is *"perfect" liquid.*

At higher temperature, it can become *"gas"*

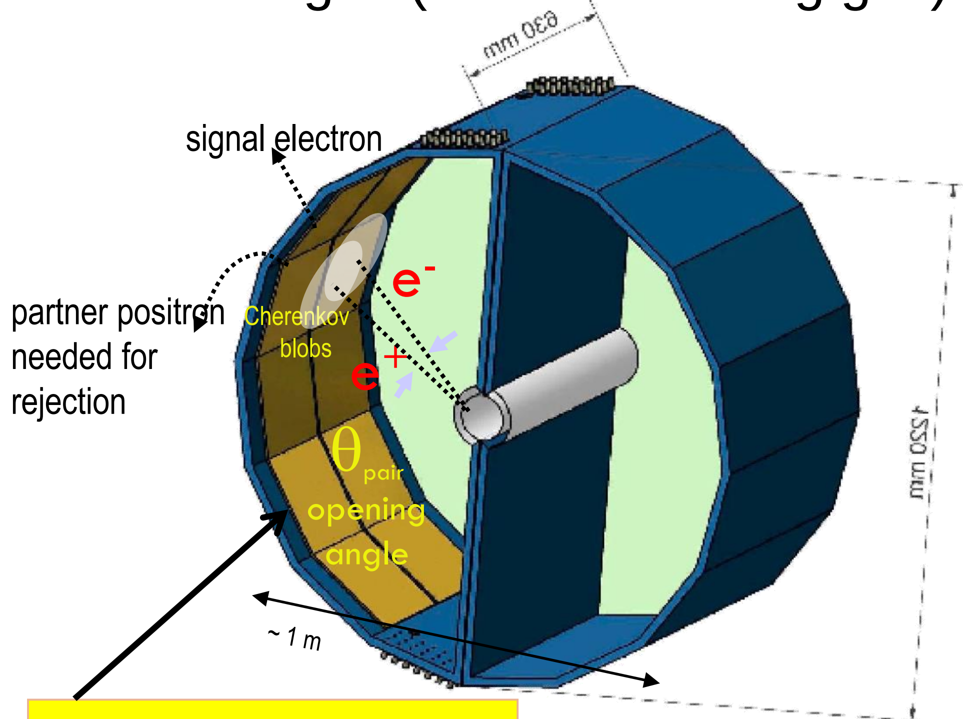
Outlook

A new detector, HBD, was installed in PHENIX.

HBD will greatly improve e+e- pair measurements, including the virtual photon analysis.

We are now taking Au+Au data with HBD in RUN10

HBD: novel windowless Cerenkov detector with CF4 gas (radiator/working gas)



CsI photocathode covering triple GEMs

Removes background e+e- pairs

Summary and conclusion

- We have measured e+e- pairs for m<300MeV and $1<p_T<5$ GeV/c
  - Excess above hadronic background is observed
  - Excess is much greater in Au+Au than in p+p
- Treating the excess as internal conversion of direct photons, the yield of direct photon is dedued.
- Direct photon yield in p+p is consistent with NLO pQCD
- Direct photon yield in Au+Au is much larger.
  - Spectrum shape above T_{AA} scaled pp is exponential, with inverse slope T=221 $\pm$19(stat)$\pm$19(sys) MeV
- Hydrodynamical models with T_{init}=300-600MeV at τ_0=0.6-0.15 fm/c are in qualitative agreement with the data.
- Lattice QCD predicts a phase transition to quark gluon plasma at $T_c \sim 170$ MeV

A Long Journey

- Au + Au and p+p collisions recorded during 2004 and 2005, respectively.
- "Enhanced production of direct photons in Au+Au collisions at sqrt(s_NN)=200 GeV and implications for the initial temperature"

  Preprint: arXiv:0804.4168

  Submitted: 2008-04-25
- Accepted by PRL on 27 Jan 2010 (comment by Babara: "I would like to add my congratulations on this excellent achievement! This is a seminal paper for the collaboration, with a very large impact - it already has 57 citations!"), needed 56 pages long arXiv:0912.0244 (2009-12-01)
- Presented at APS April meeting (February 13 - 17, 2010, Washington, DC)

Enhancement of the dielectron continuum in sqrt{s_NN} = 200 GeV Au+Au collisions

Preprint: arXiv:0706.3034
Submitted: 2007-06-21

Enhancement of the dielectron continuum

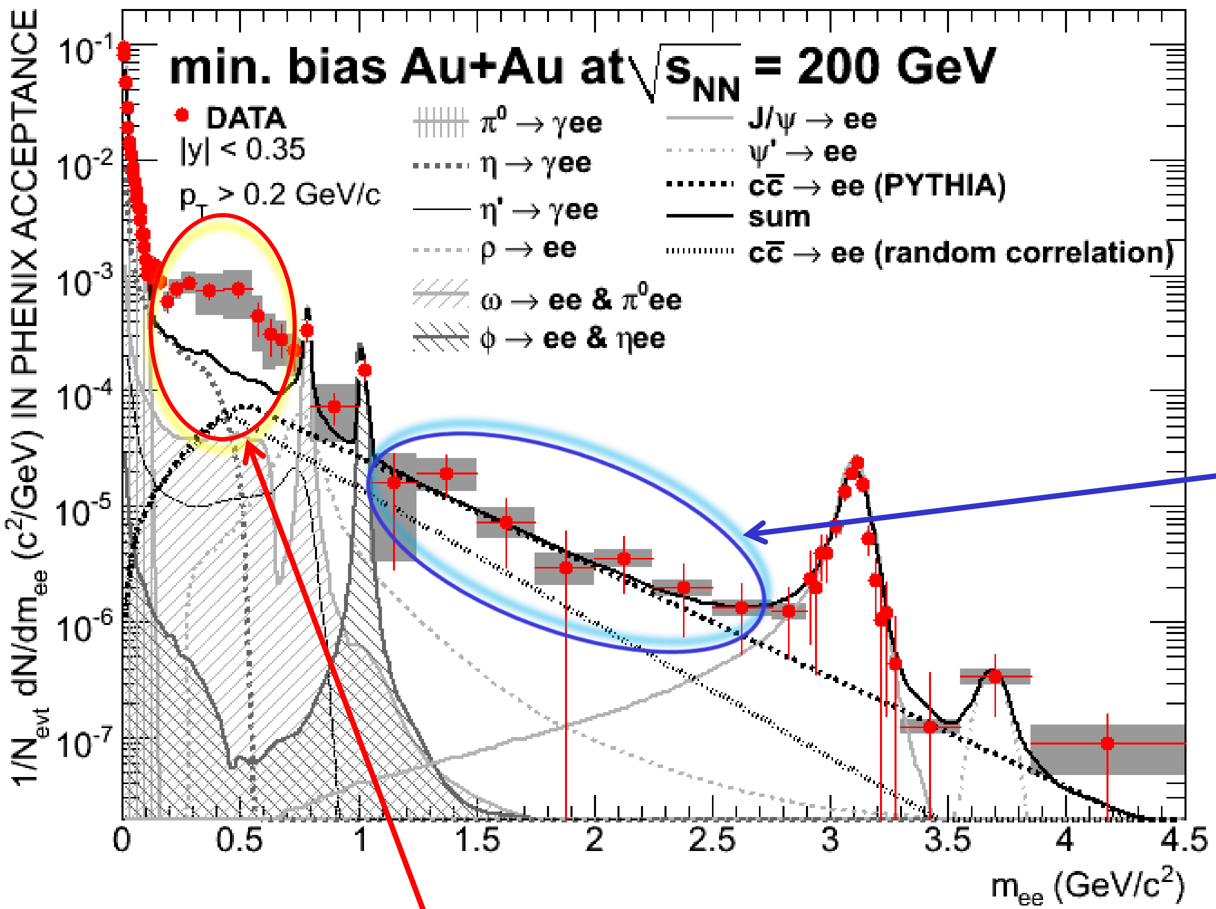
- Dilepton emission from the hot matter created at RHIC :
  - Thermal radiation
  - In-medium decays of mesons with short lifetimes, like the ρ meson, while their spectral functions may be strongly modified.

- Below the mass of the φ meson, these sources compete with a large contribution of e+e− pairs from :
  - Dalitz decays of pseudoscalar mesons (π^0, η, η′)
  - Decays of vector mesons (ρ, ω, φ)

Elimination of backgrounds

- Photon conversion minimized by a helium bag (~0.4% of a radiation length).
- Combinatorial background was removed with a mixed event technique.
- Elimination of unphysical correlations arising from overlapping tracks or hits.
- Background from photon conversions and cross pairs is removed with the cut on mass and opening angle.
- To check the background subtraction, some data with extra of 1.68% radiation length (X_0) to increase the background by factor of 2.5.

Enhancement of the dielectron continuum

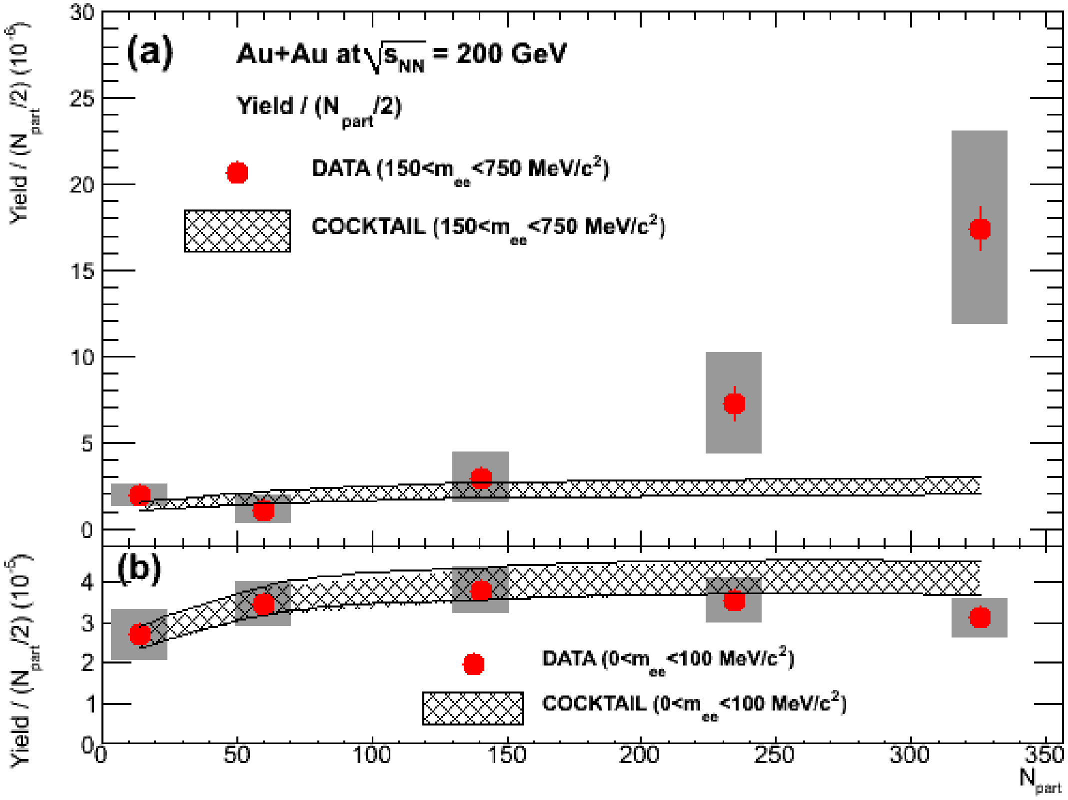


Cocktail of hadron decay contributions using PHENIX data for meson production and spectra.

Above the phi meson mass the data seem to be well described by the continuum calculation based on PYTHIA.

"Significant enhancement of the dielectron continuum in the mass range 150–750 MeV/c^2", factor of 3.4 $\pm$ 0.2(stat.) $\pm$ 1.3(syst.) $\pm$ 0.7(model).

The centrality dependence of the yield



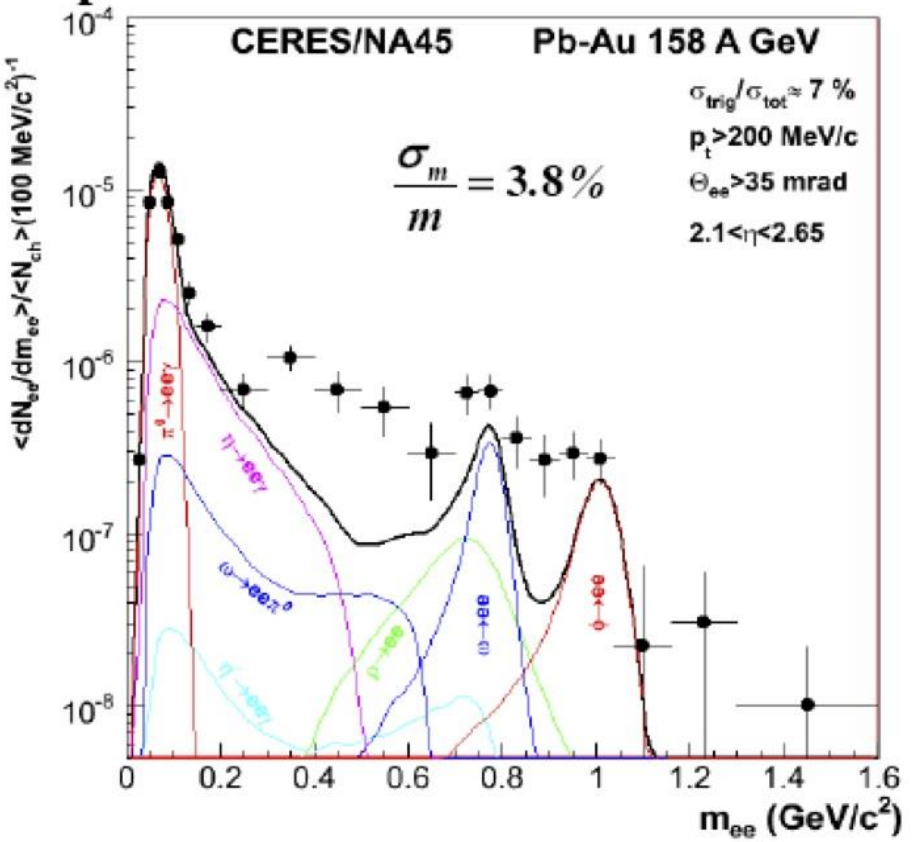
In the region 150–750 MeV/c^2: the yield divided by the number of participating nucleon pairs rises significantly compared to the expectation, reaching a factor of 7.7 ± 0.6(stat.) ± 2.5(syst.) ± 1.5(model) for most central collisions.

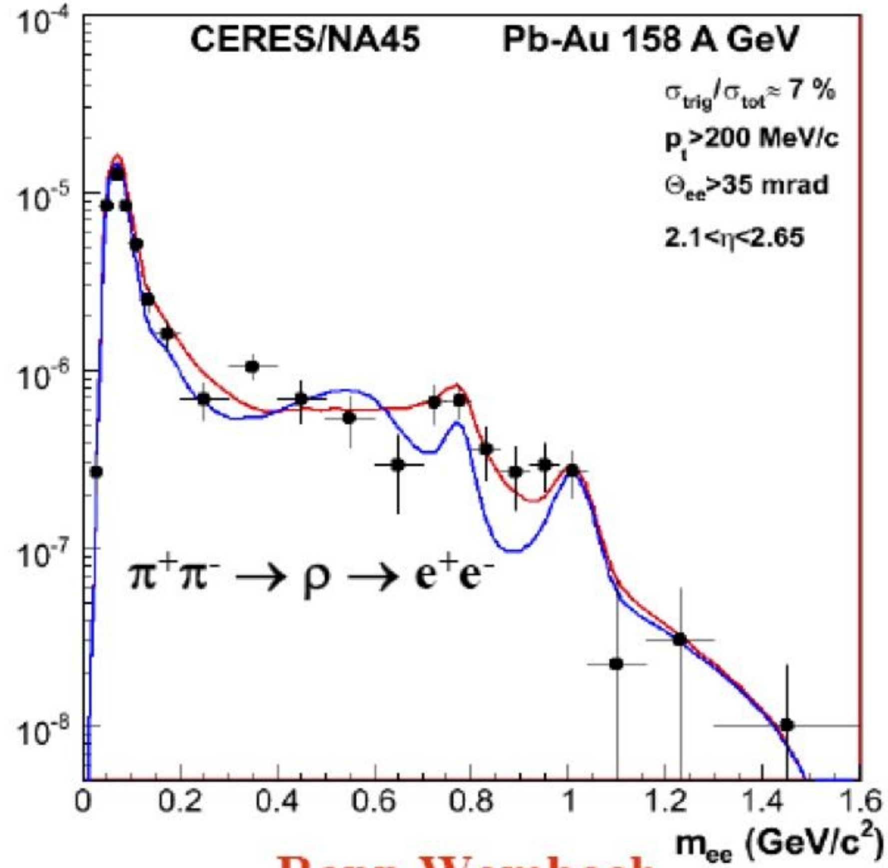
The yield below 100 MeV/c^2, which is dominated by low p_T pion decays, agrees with the expectation, i.e. is proportional to the pion yield.

The increase is qualitatively consistent with the conjecture that an in-medium enhancement of the dielectron continuum yield arises from scattering processes like ππ or $\bar{q}q$ annihilation, which would result in a yield rising faster than proportional to N_{part}.

Results from CERN

data in comparison to post freeze out hadronic cocktail



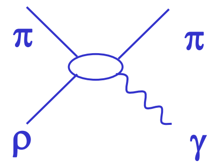


for $0.2 < m_{ee} < 1.1$ GeV/c^2
excess over hadronic decay contribution:
2.45 ± 0.30(stat) ± 0.38(syst) ± 0.74(decays)

Rapp Wambach broadened ρ spect. function

Brown Rho dropping ρ mass

Models



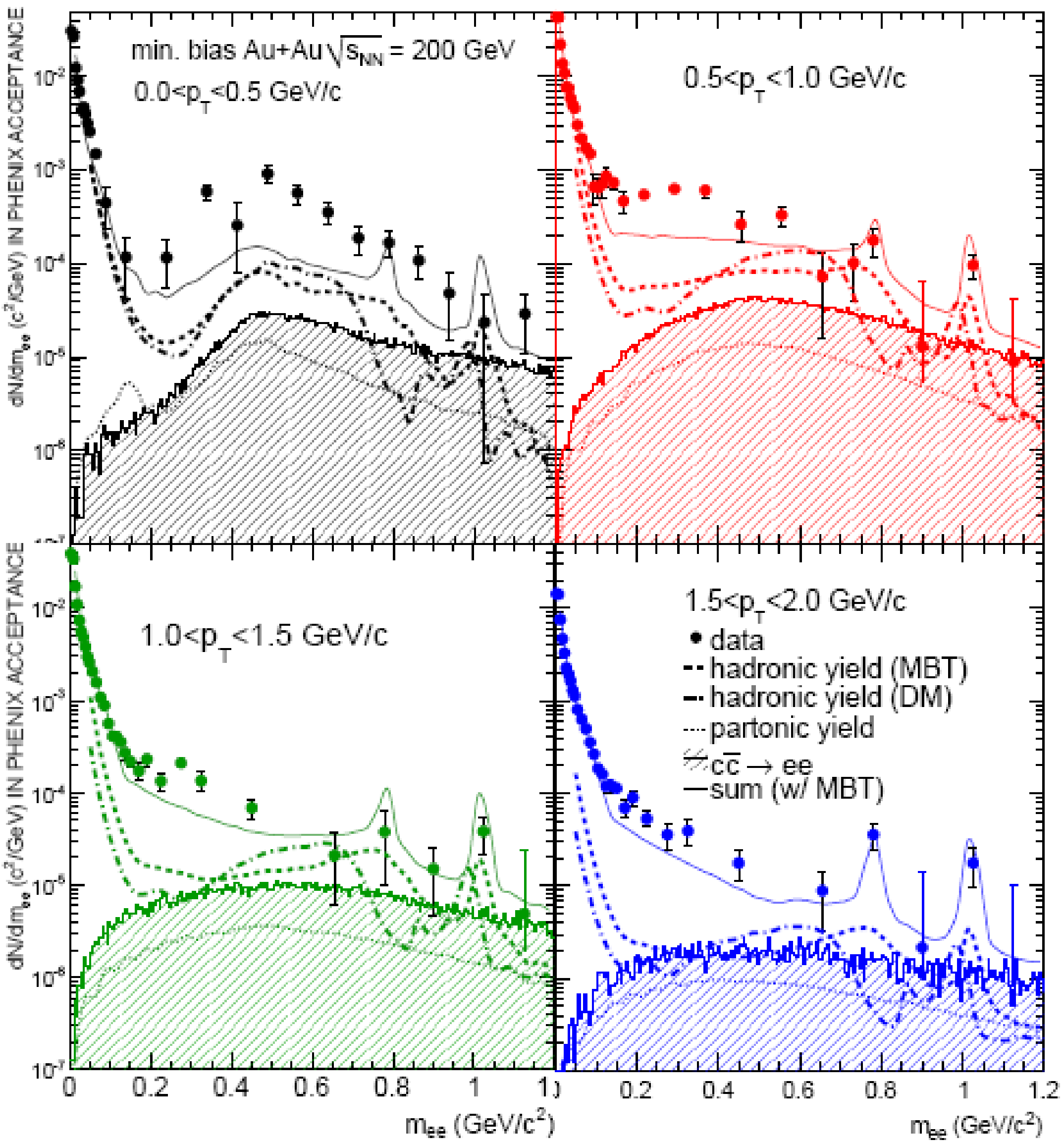
The models identified the pion annihilation process as the main source of thermal dileptons in the hadronic phase of the fireball, mediated by the intermediate meson, failed to describe the observed enhancement in the LMR at the SPS energy when vacuum properties of the ρ are used.
Suggesting that in-medium modifications of the ρ spectral function for the enhancement of dilepton yield.

Two different approaches:

- Dropping Mass scenario due to partial restoration of chiral symmetry.
  (G.E. Brown and M. Rho)

- Many-Body Interactions cause the broadening of the resonance, leading to enhancement of dilepton yield below ρ mass

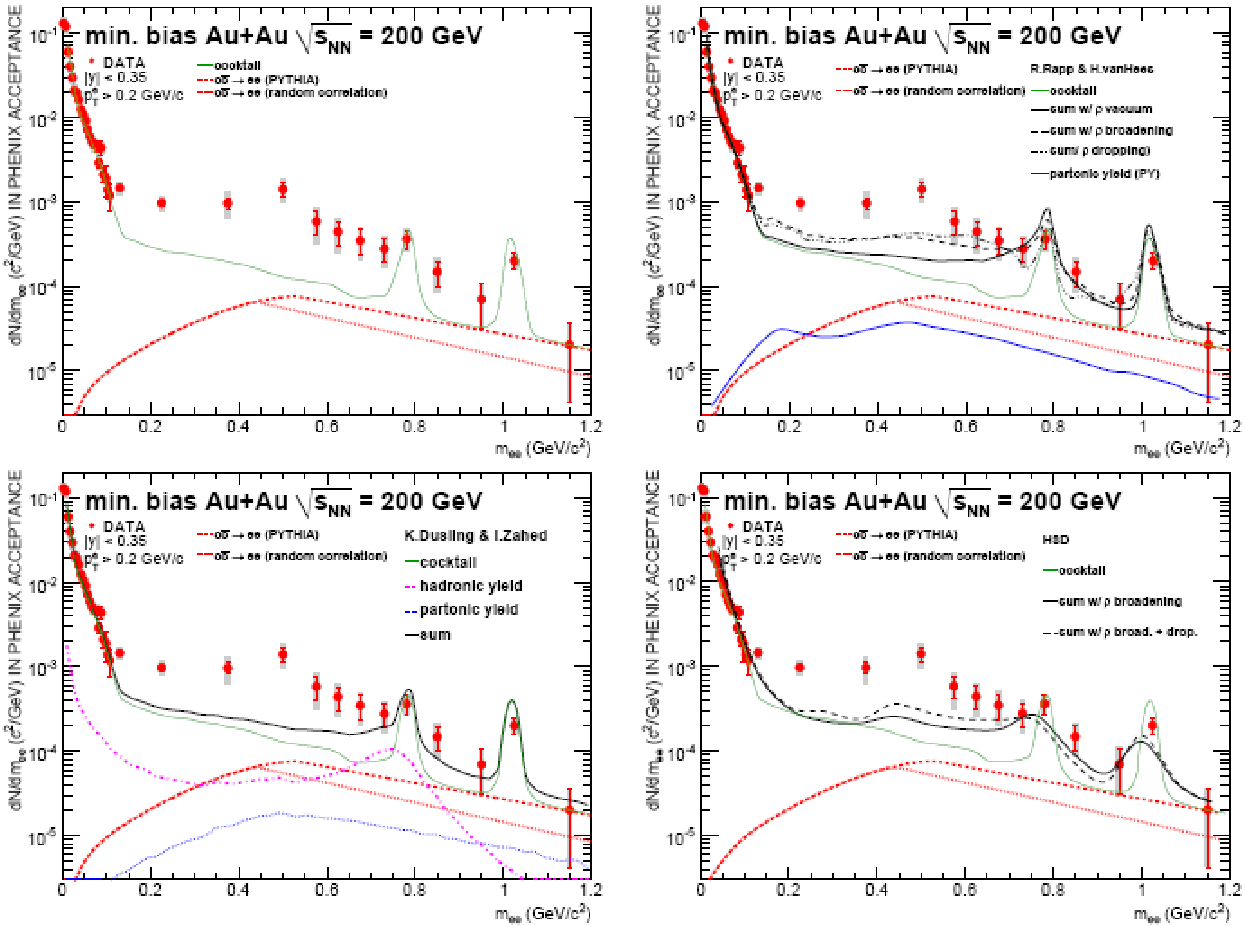
Different pT bins



Rapp and van Hees: separately showing the partonic and the hadronic yields and the different scenarios for the ρ spectral function, namely "Hadron Many Body Theory" (HMBT) and "Dropping Mass" (DM).

The calculations have been added to the cocktail of hadronic decays and charmed meson decays products.

Different Models



Data are also compared to,

TL: Sum of cocktail+charm

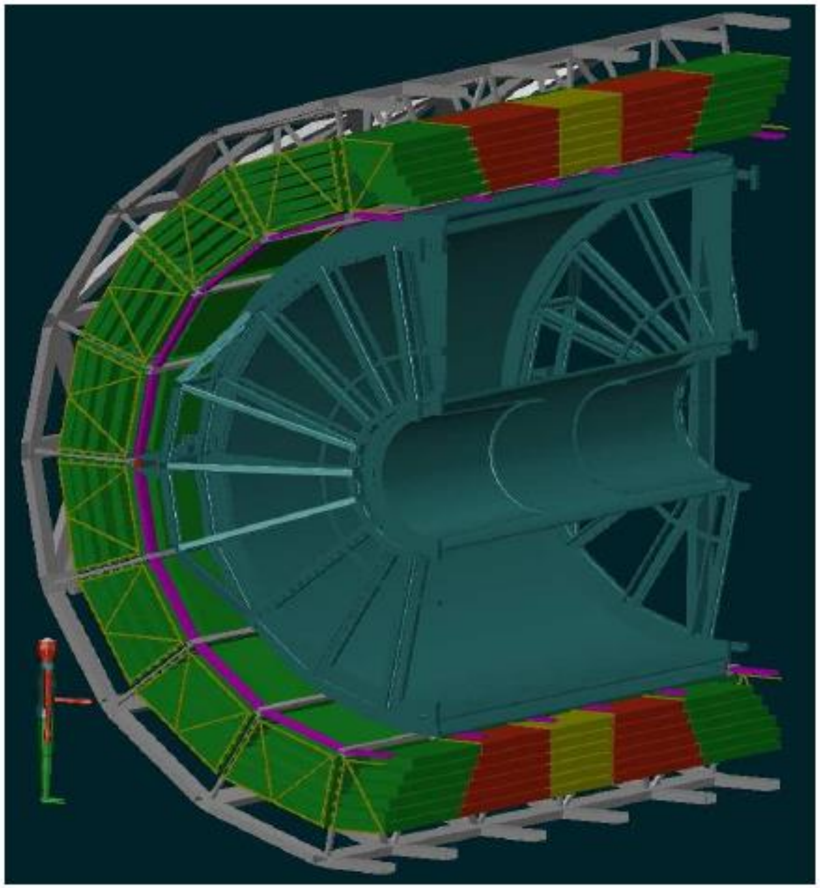
The sum of cocktail+charm and hadronic+partonic contributions from different models.

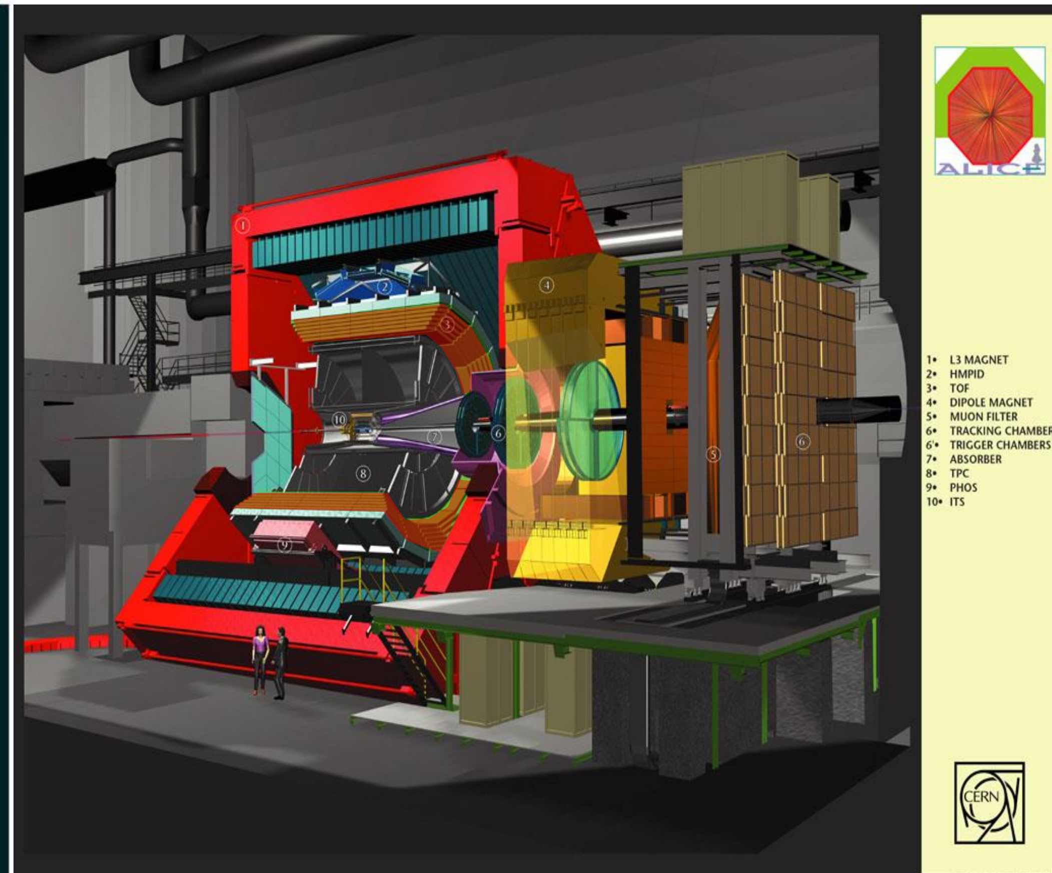
TR: Rapp. van Hees
BR: Dusling, Zahed
BL: Cassing, Bratkovskaya

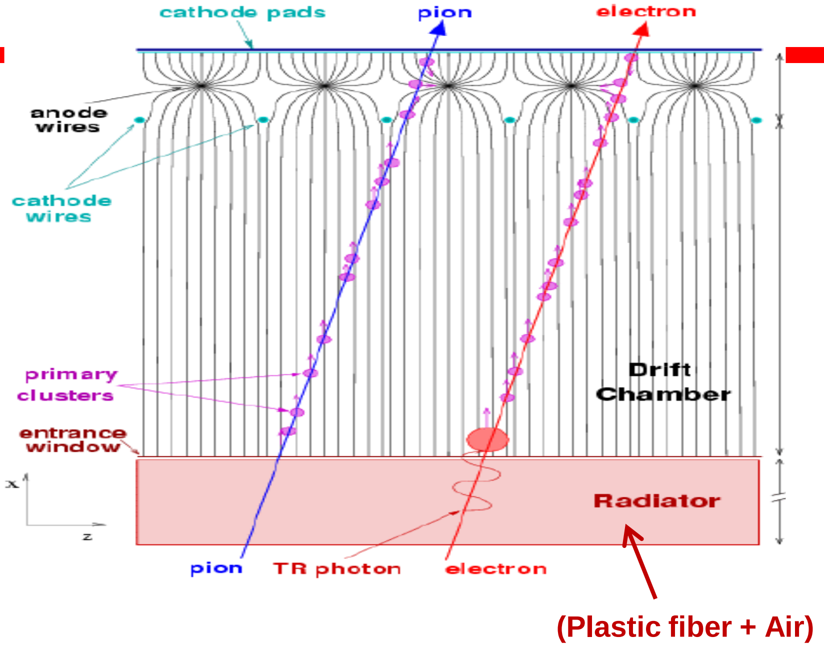
All of the models under predict the data for $0.2 < m_{ee} < 0.5$ GeV/c^2 by at least a factor of two.

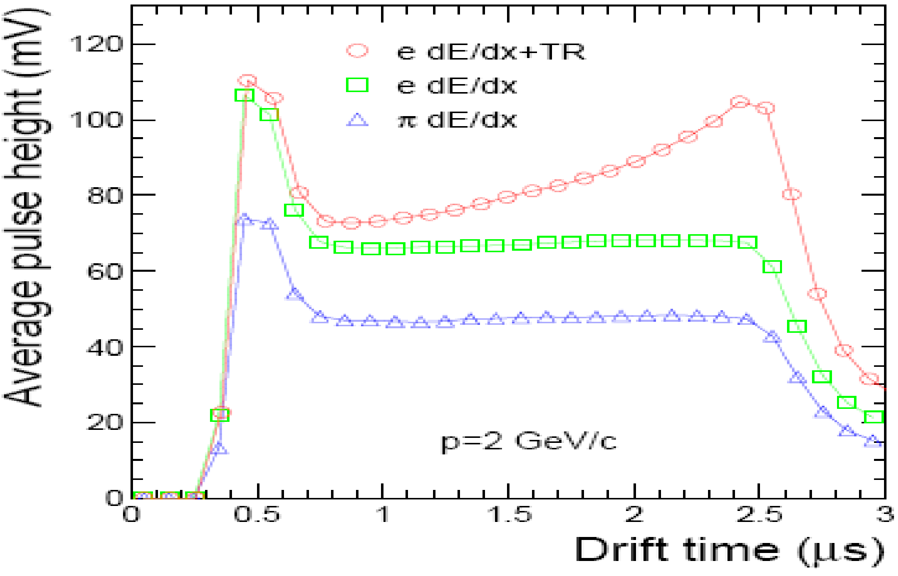
Electron measurement in ALICE using TRD (Transition radiation Detector)

TRD (Transition Radiation Detector)



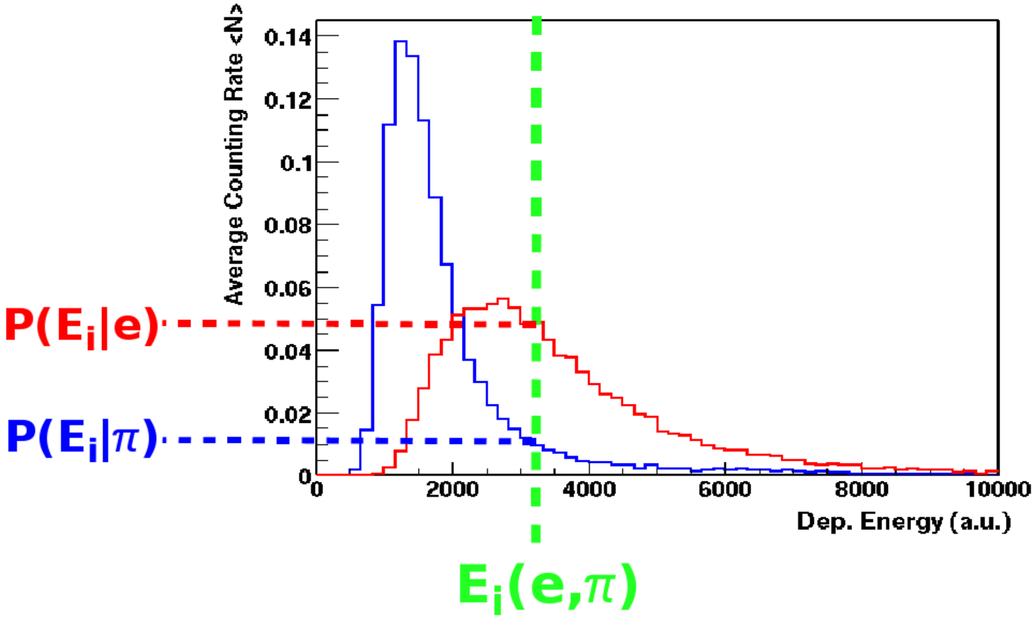






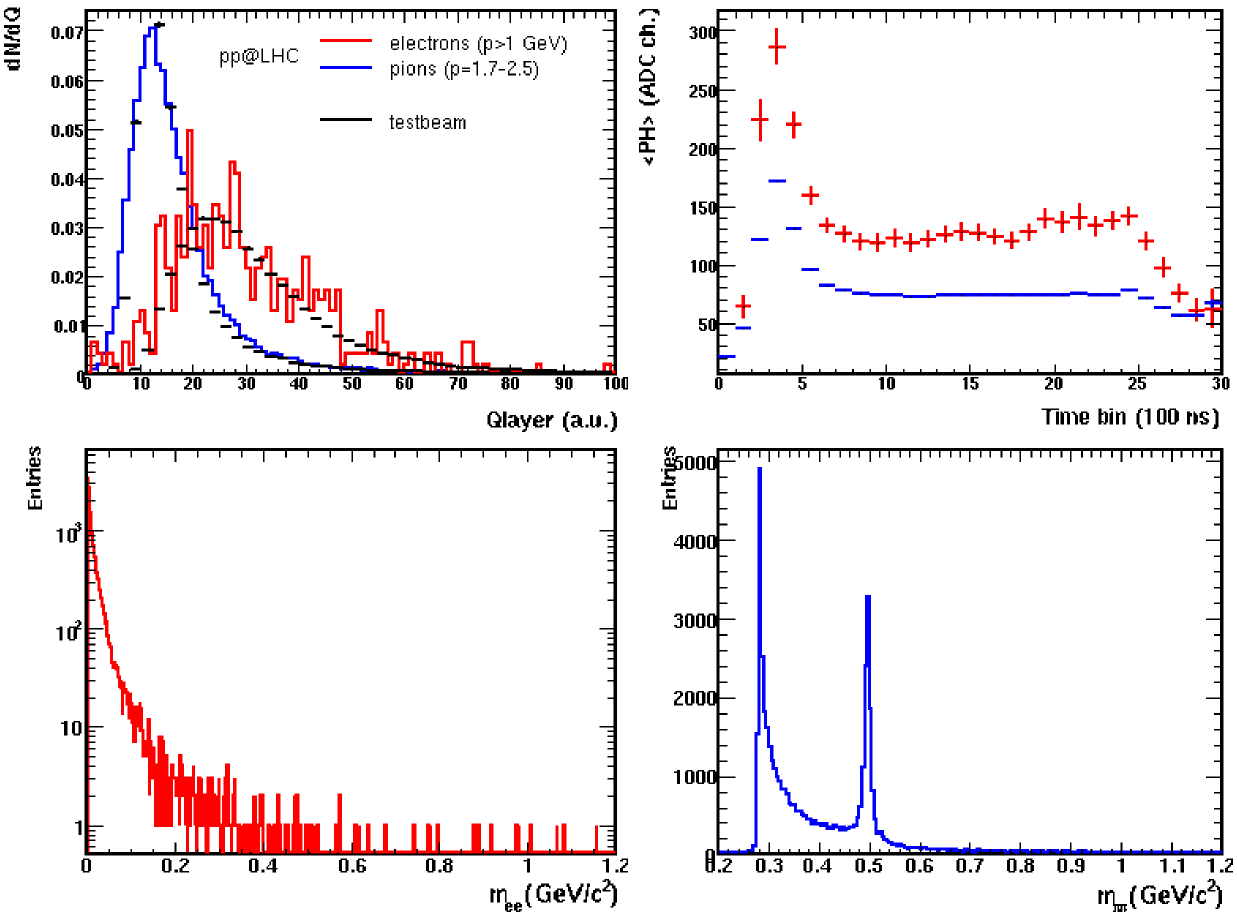
Transition radiation (TR) is produced if a highly relativistic (γ>900) particle traverses many boundaries between materials with different dielectric properties.

Electrons can be identified using
total deposited charge, and
signal intensity as function of drift time.

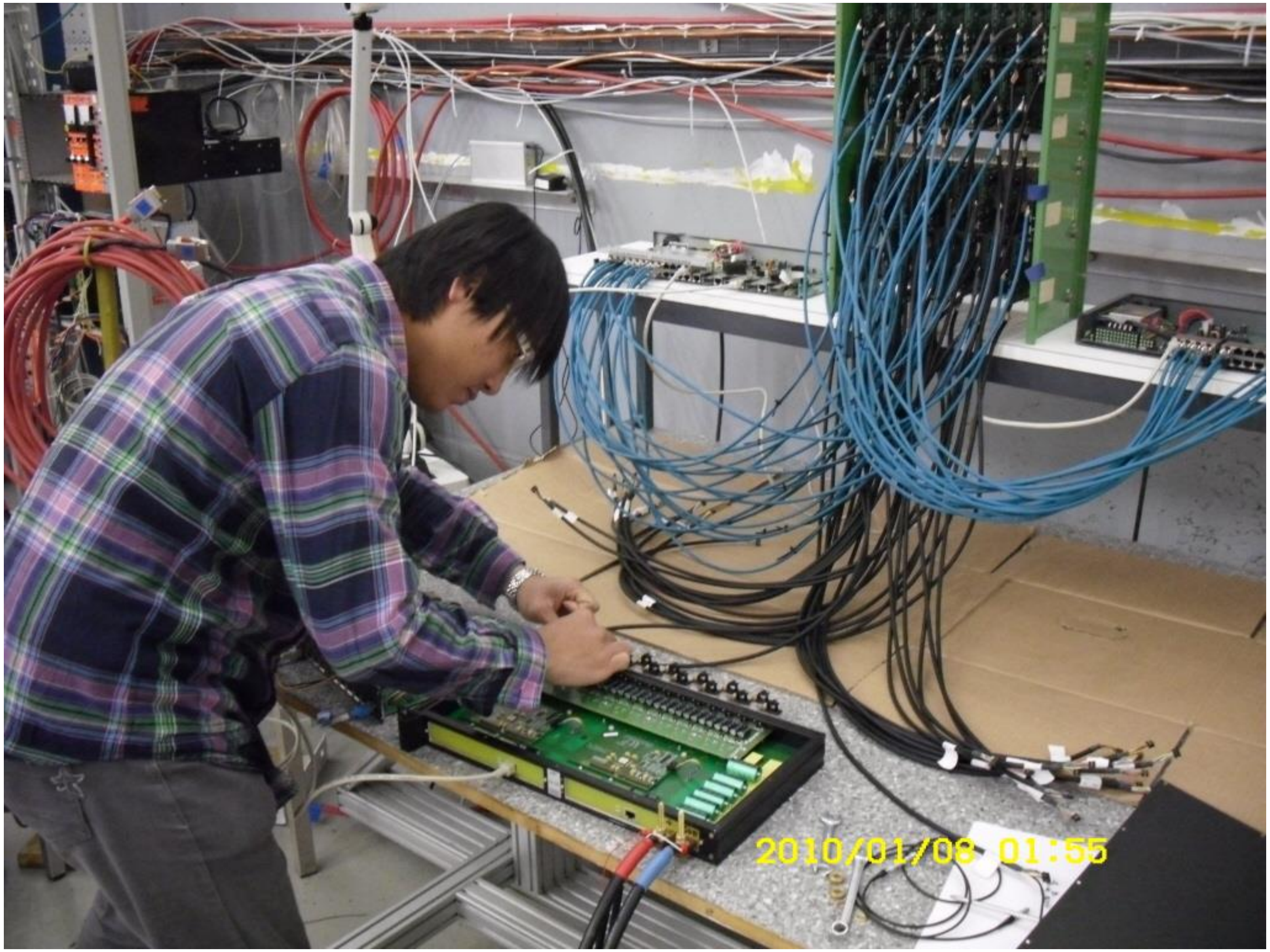


Electrons from real TRD data

Electrons are the conversions electrons (Minv<20 MeV/c^2) for pt>1 GeV/c,
pions not yet those form K0s, but selected with a bad cut in the TPC dE/dx



Student at CERN



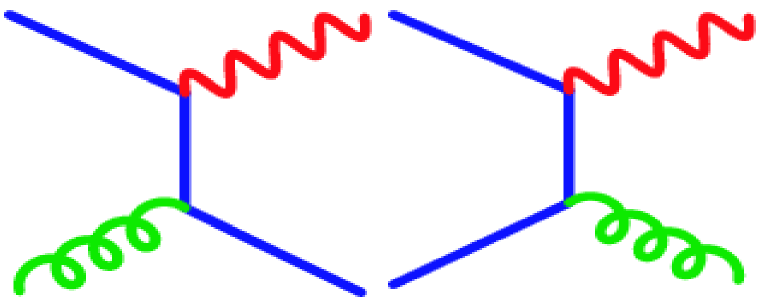
Participating in TRD integration and taking shift

Motivation for direct γ production in p+p

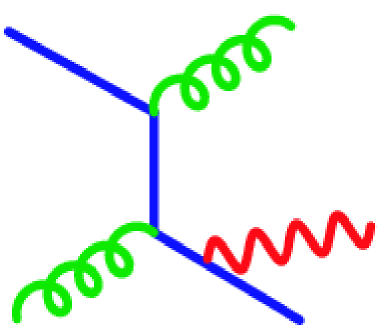
- Direct γ production in p+p

→ <u>One of the best known QCD process…</u>

Really?



→ Leading order diagram
in perturbation theory



Hard photon : Higher order pQCD
Soft photon : Initial/final radiation,
Fragmentation function