Dileptons in heavy-ion collisions: Experiment

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Lectures Outline

- Lecture 1
  - Motivation and experimental challenge

- Lecture 2
  - Review of experiments and results (I)
    - DLS, HADES
    - CERES, NA60

- Lecture 3
  - Review of experimental results (II)
    - PHENIX, STAR
  - Outlook

Lectrure 1 - outline

- Motivation – dileptons and the QGP
- Chirality, chiral symmetry breaking and chiral symmetry restoration
- *The* experimental challenge: combinatorial background

- Motivation

Motivation (I)

- The Quark Gluon Plasma created in relativistic heavy ion collisions is characterized by two fundamental properties:
  - Deconfinement
  - Chiral Symmetry Restoration

- Virtual photons i.e. dileptons (e^+e^-, $\mu^+\mu^-$) are sensitive probes of both properties and in particular lepton pairs are unique probes of CSR.

- Thermal radiation emitted in the form of real photons or virtual photons (dileptons) provides a direct fingerprint of the matter formed (QGP and HG) and ~~a~~ measurement of its temperature.

QGP $qq \longrightarrow \gamma^* \longrightarrow l^+l^-$

HG $\pi^+\pi^- \longrightarrow \rho \longrightarrow \gamma^* \longrightarrow l^+l^-$

Advantages of dileptons

- no final state interaction: large mfp compared to the size of the system. Once produced they leave the fireball without any further interaction

  → carry direct information from place of production to detectors

- Production rate strongly increasing function of T and density

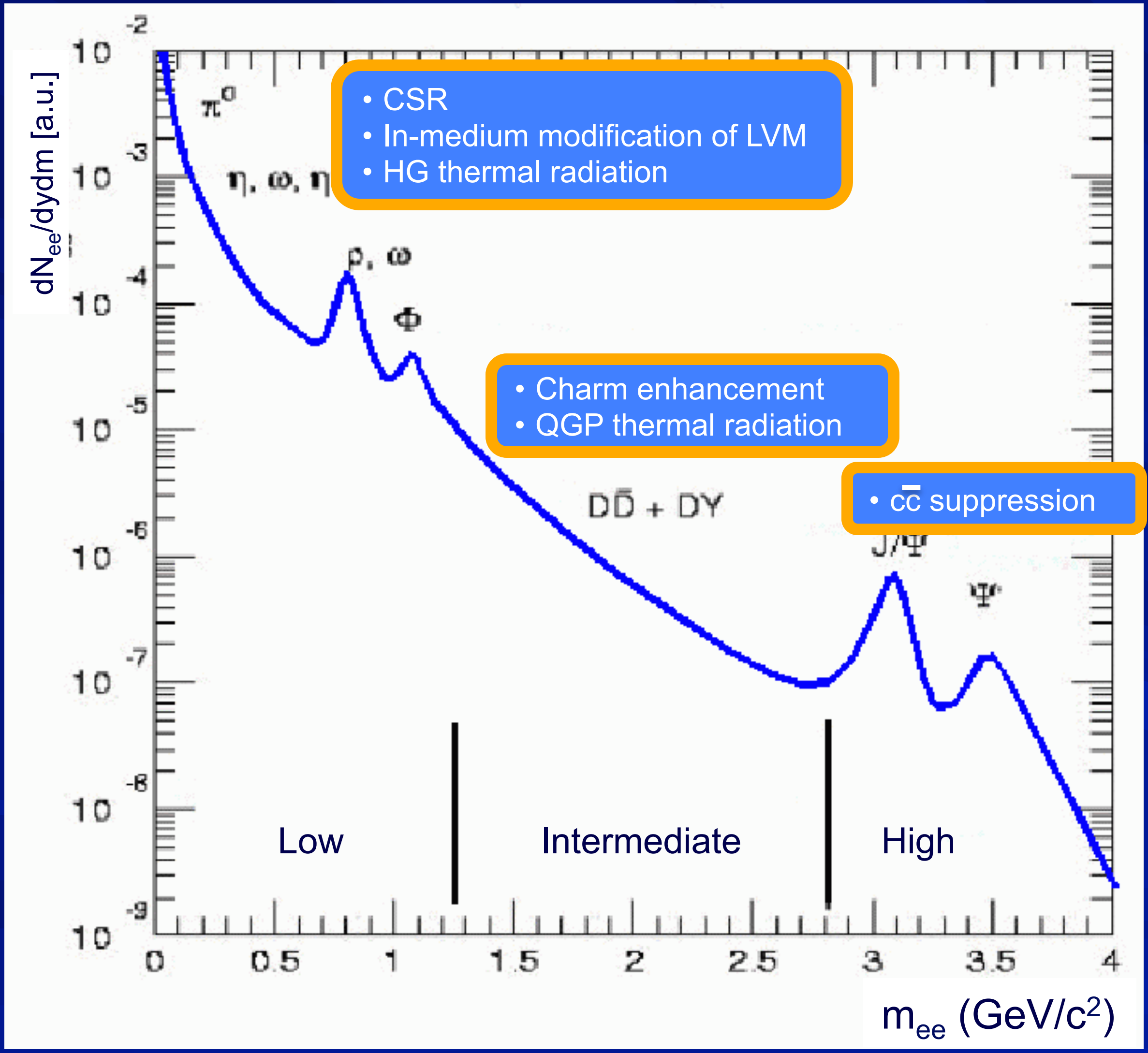
  → most abundantly produced at the early stage of the collisions

- …But very difficult measurements

  large combinatorial background

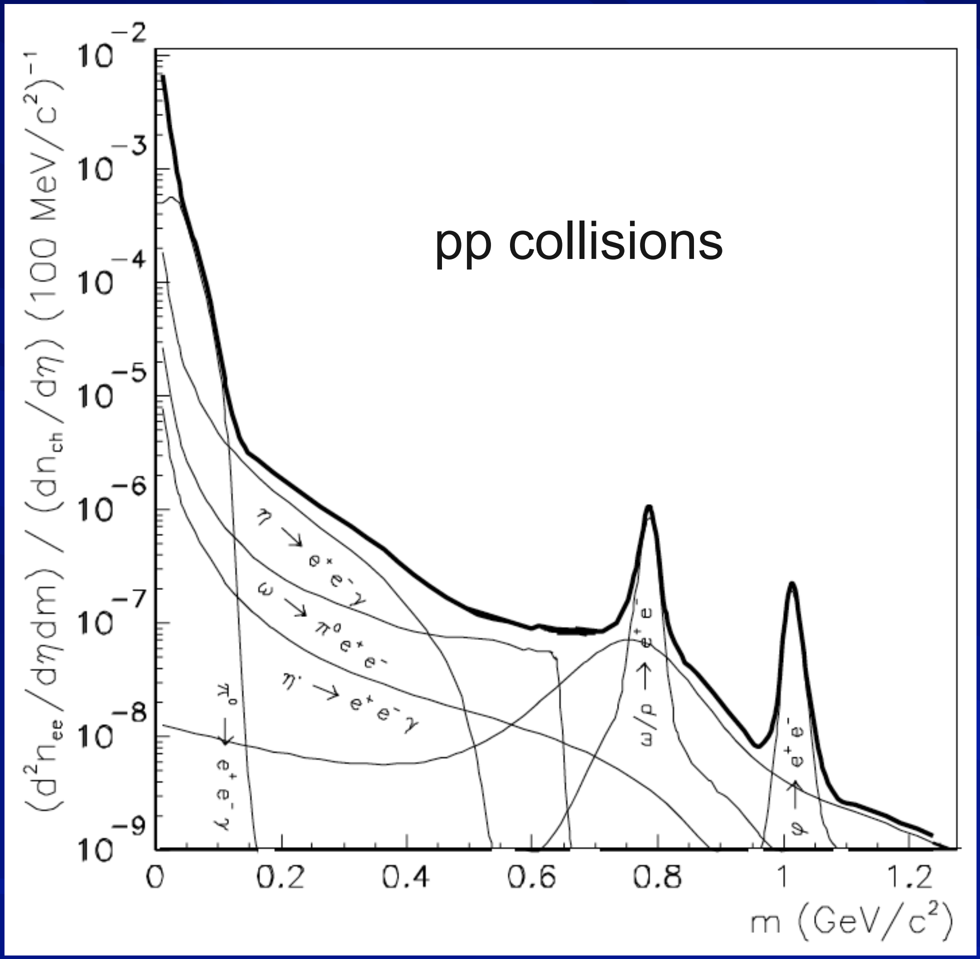
- What have we learned in almost 20 years of dilepton measurements?

Schematic Dilepton Spectrum



- New physics expected in heavy ion collisions

e^+e^- low-mass cocktail



The cocktail of known sources:

- Dalitz decays:
  $\pi^0,\eta,\eta' \longrightarrow e^+e^-\gamma$
  $\omega \longrightarrow \pi^0 e^+e^-$
- Resonance decays:
  $\rho, \omega, \phi \longrightarrow e^+e^-$

- Sources should be independently measured in AA collisions
- Scaling from pp collisions

Chirality

Two fundamental properties of the QGP:
- Deconfinement
- Chiral symmetry restoration

What is chirality?

- Comes from the greek word "χειρ" meaning hand
- An object or a system has ***chirality*** if it differs from its mirror image.

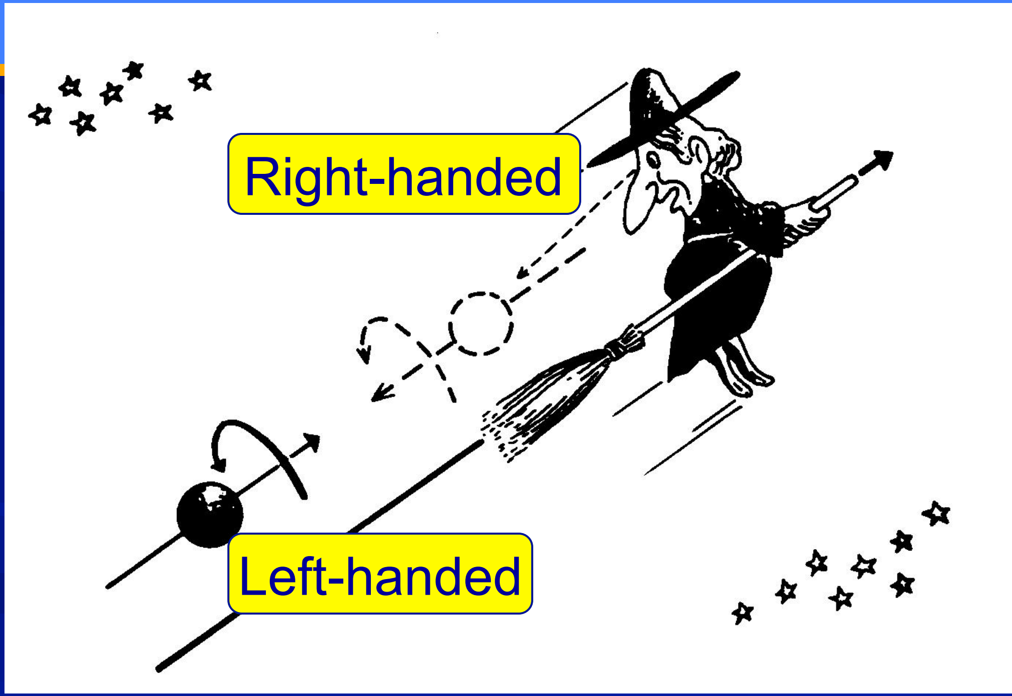
Such objects then come in two forms, L and R, which are mirror images of each other.

Simple definition:

- the chirality of a particle is determined by the projection of its spin along its momentum direction (this is in fact the definition of helicity. In the high energy limit chirality ≈ helicity)

Chiral Symmetry

❖ If a particle has mass both right- and left-handed components must exist. The reason is that massive particles travel slower than the speed of light and a particle that appears left-handed in a particular reference frame will look right-handed from a reference frame moving faster than the particle → ***chirality is not conserved***



QCD and explict chiral symmetry breaking

➢ QCD, the theory of the strong interaction, is encoded in a one line Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F^{\alpha}_{\mu\nu} F^{\mu\nu}_{\alpha} - \sum_n \bar{\psi}_n \gamma^\mu [\partial_\mu - i g A^\alpha_\mu t_\alpha]\psi_n - \sum_n m_n \bar{\psi}_n \psi_n$$

Free gluon field

q interaction with gluon field

Free quarks of mass m_n at rest

➢ The mass term $m_n \psi_n \psi_n$ ***explicitly*** breaks the chiral symmetry of the QCD Lagrangian

Spontaneous Chiral Symmetry Breaking

- Chiral limit: $m_u = m_d = m_s = 0$
  In this idealized world, the interactions quark-gluon conserve the quark chirality. (left–handed u,d,s, quarks remain left-handed forever).

Chiral symmetry of QCD means:
all states have a chiral partner with opposite parity and equal mass

m_u and m_d are so small ($m_u \approx 4$ MeV $m_d \approx 7$ MeV) that our world should be very close to the chiral limit

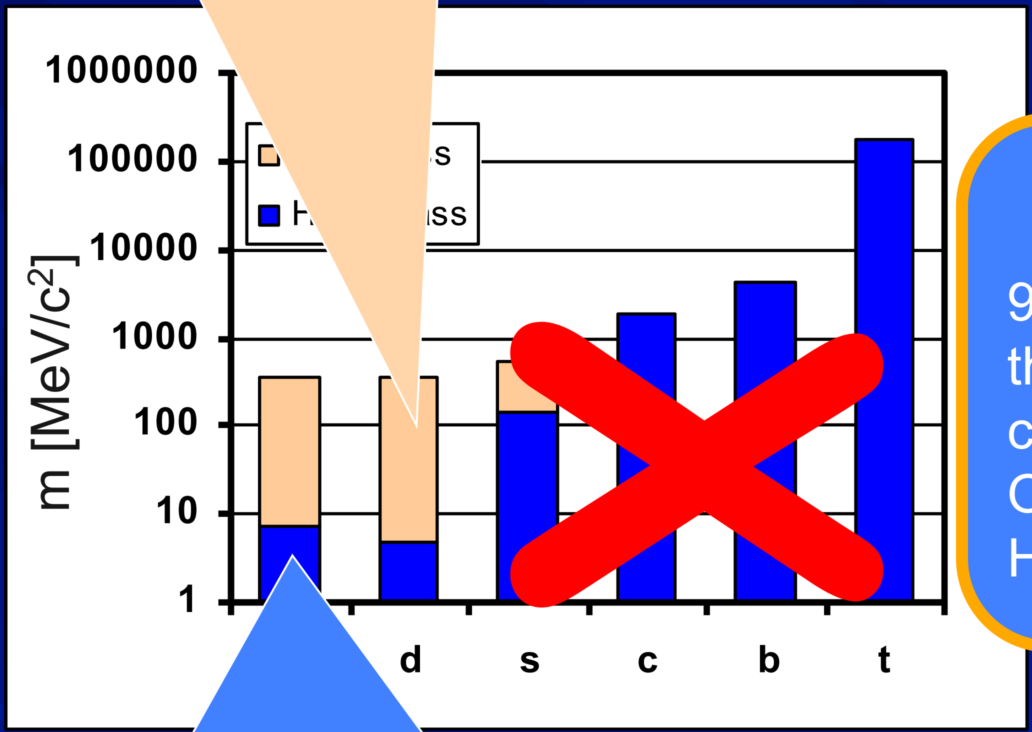
- In reality:
- ρ ($J^P = 1^-$) m=770 MeV chiral partner a_1 ($J^P = 1^+$) m=1250 MeV → $\Delta \approx 500$ MeV
- For the nucleons the splitting is even larger:
  N ($1/2^+$) m=940 MeV chiral partner N^* ($1/2^-$) m=1535 MeV → $\Delta \approx 600$ MeV
- The differences are too large to be explained by the small current quark masses

Chiral symmetry is spontaneously (≡ dynamically) broken in nature
Quarks have large “effective” mass $m_u \approx m_d \approx 1/3 m_N \approx 300$ MeV/c^2
Contitutent quark masses

Origin of mass

Constituent quark masses generated by spontaneous chiral symmetry breaking

proton = uud   neutron = udd
$m_{nucleon} \approx 1$ GeV



Origin of (our) mass:

95% of the (visible) mass is due to the spontaneous breaking of the chiral symmetry.
Only 5% of the mass is due to the Higgs field.

Current quark masses generated by spontaneous symmetry breaking (Higgs field)

current quark masses:
$m_u \approx 4$ MeV $m_d \approx 7$ MeV

Chiral Symmetry Restoration

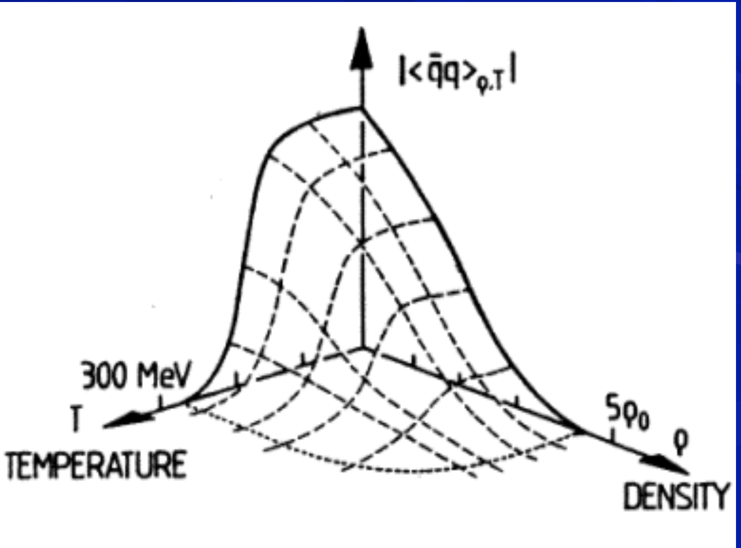
- Spontaneous breaking of a symmetry is marked by:
  * a non-zero order parameter, the quark condensate in the case of QCD:

$$< \bar{q}q > \approx 250 MeV^3$$

- Many models link the hadron masses to the quark condensate.

- At high temperatures ($T>T_C$) or high baryon densities ($\rho>\rho_C$), numerical QCD calculations on the lattice predict that the quark condensate vanishes:

$$\langle \bar{q}q \rangle \rightarrow 0$$



constituent mass → current mass
chiral symmetry (approximately) restored

- Low-mass dileptons and chiral symmetry restoration

How does CSR manifest itself ?

- What happens when chiral symmetry is restored?

Meson properties (m,Γ) expected to be modified but how?

- Is there an explicit connection between the spectral properties of hadrons (masses,widths) and the value of the chiral condensate $\langle q\bar{q} \rangle$?
- From the QCD Lagrangian, the only requirement is that parity doublets should be degenerate in mass.
  - how is the degeneracy of chiral partners realized ?
  - do the masses drop to zero?
  - do the widths increase (melting resonances)?

All good questions but no formal answer.
First hints of an answer provided recently.

Low-mass dileptons and CSR

- Low-mass dileptons are the best probes to look for CSR effects:
  - * **Large mfp:** → no final state interaction

  carry information from place of creation to detectors.

	m [MeV]	Γ_{tot} [MeV]	τ [fm/c]
ρ	770	150	1.3
ω	782	8.6	23
ϕ	1020	4.4	44

❖ **Best candidate: the ρ-meson**

It has a short lifetime compared to the medium lifetime ($\tau \approx$ 10 fm/c) and can decay and can be regenerated in the medium

- **ϕ meson:** a special probe for CSR, long lifetime but m(Φ) ≈ 2 m(K)

  simultaneous measurement of $\phi \to e^+ e^-$ and $\phi \to K^+ K^-$ could be a powerful tool to evidence in-medium effects.

- Challenge of the measurement

The Double Challenge

1. Experimental challenge

- Need to detect a very weak source of e^+e^- pairs

hadron decays (m>150 MeV/c² p_T > 200 MeV/c) ~ 10^{-6} / π^0

- in the presence of hundreds of charged particles

central Au-Au collision 250

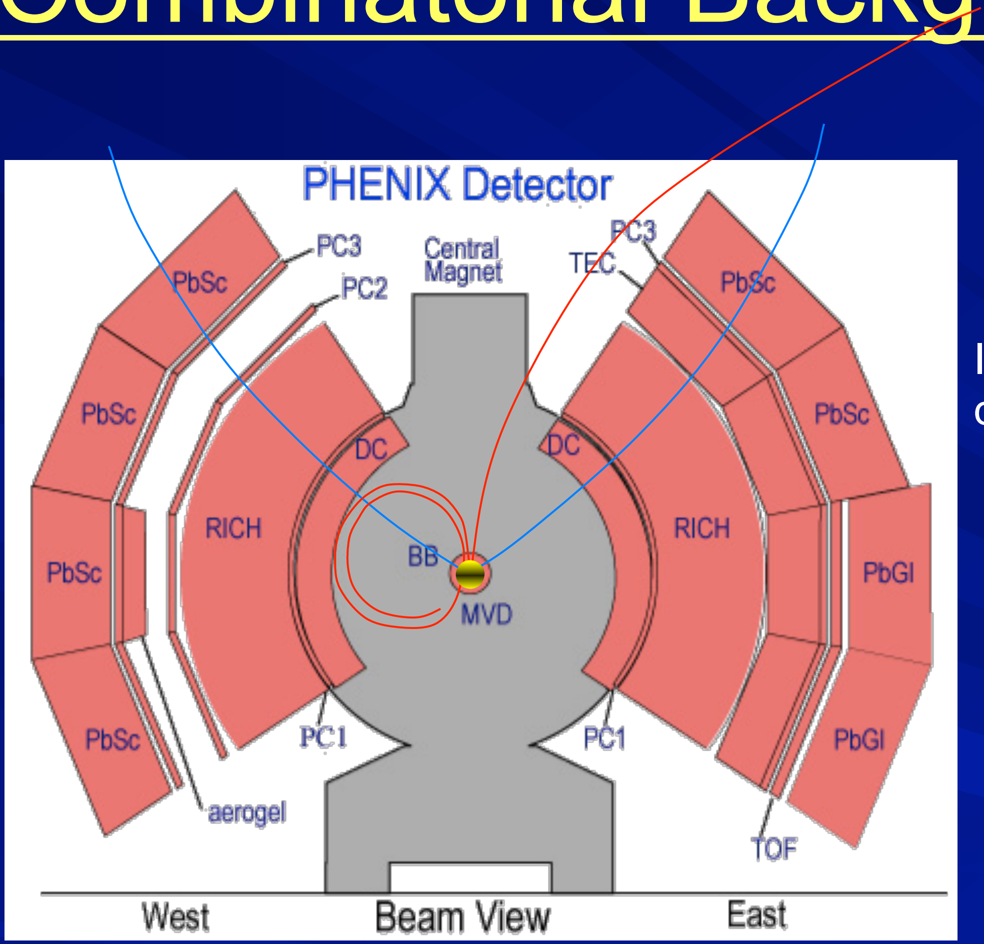
- and several pairs per event from trivial origin

π^o Dalitz decays ~ 10^{-2} / π^0

\+ γ conversions (assume 1% radiation length) 2 . 10^{-2} / π^0

huge combinatorial background $\propto (dN_{ch} / dy)^2$

Combinatorial Background in PHENIX



It often happens that only one electron is detected and the other is lost due to:

- limited geometrical acceptance
- low p_T particle curling in the magnetic field
- particle not reconstructed

Since the origin of each track is unknown, must pair all electrons with all positrons in the same event

→ Signal (S) and combinatorial Background (B)
B must be subtracted using a mixed event technique or using the like sign spectrum

Magnitude of the problem

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

- ‘Single’ e-tracks/evt in the two central arms:

$$N_e = (dN/d\eta)_{\pi^o} * BR * acc * f(p_T \geq 200)$$

Dalitz + conv

350   2 (0.012+0.01)   ½ 0.7   0.32 = 1.7 tracks/evt

- Combinatorial Background:

B = $1/2 \, . \, 1/2 \, N_e^2$ = 0.7 pairs/evt

- Cocktail Signal (m>150, p_T>200):   S = 4 * 10^{-4} pairs/evt

- Cocktail Signal to Background: S/B ≈ 1 / 2000

Consequences of poor S/B ratio

- The signal is obtained by subtracting the combinatorial background (estimated by the like-sign pair yield or a mixed event technique) from the total unlike sign yield:

$$S = U - B$$

- The ***statistical error*** of S is not dictated by the magnitude of S but by the magnitude of the background. In the case S<<B

$$\Delta S \approx \sqrt{2B}$$

- It is useful to consider the *"background free equivalent"* signal, i.e. the signal with the same relative error as in a situation of zero background:

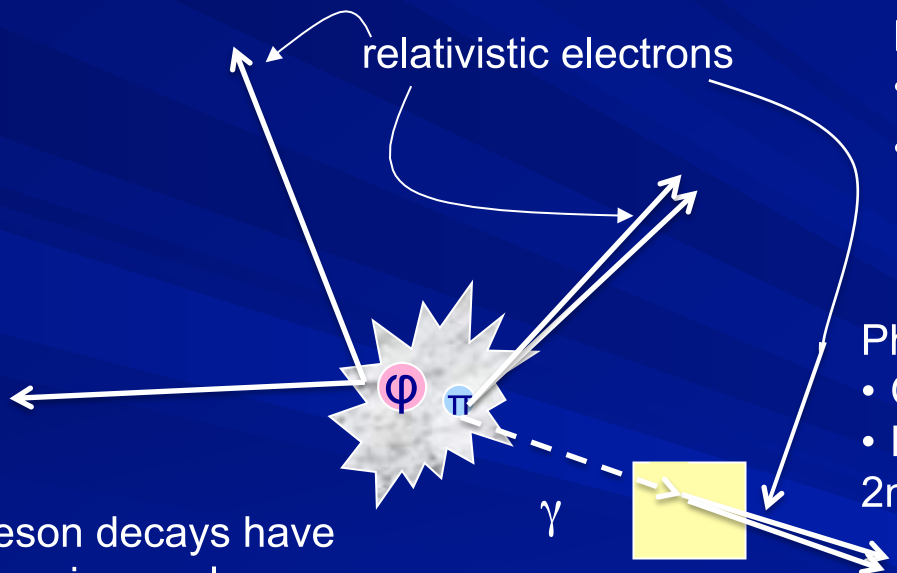
$$S_{bfe} = S^2 / 2B$$

A signal $S = 10^4$ pairs measured with a S/B = 1/250 has the same relative statistical error as 20 pairs measured in free background conditions.

- The ***systematic uncertainty*** in S is dominated by the systematic uncertainty in B. Even if the event mixing technique is mastered to a fantastic precision of ±0.25%, the resulting systematic uncertainty in S is a factor of ~5 (assuming S/B=1/2000). Even in an infinite statistics measurement the systematic uncertainty will be huge.

Separating Signal from Background (I)

$$m_{ee} = [2\, p_1 p_2\, (1-\cos\theta)]^{1/2}$$



Pion Dalitz decays:
- Small opening angle
- Pair mass peaked around $2m_e$

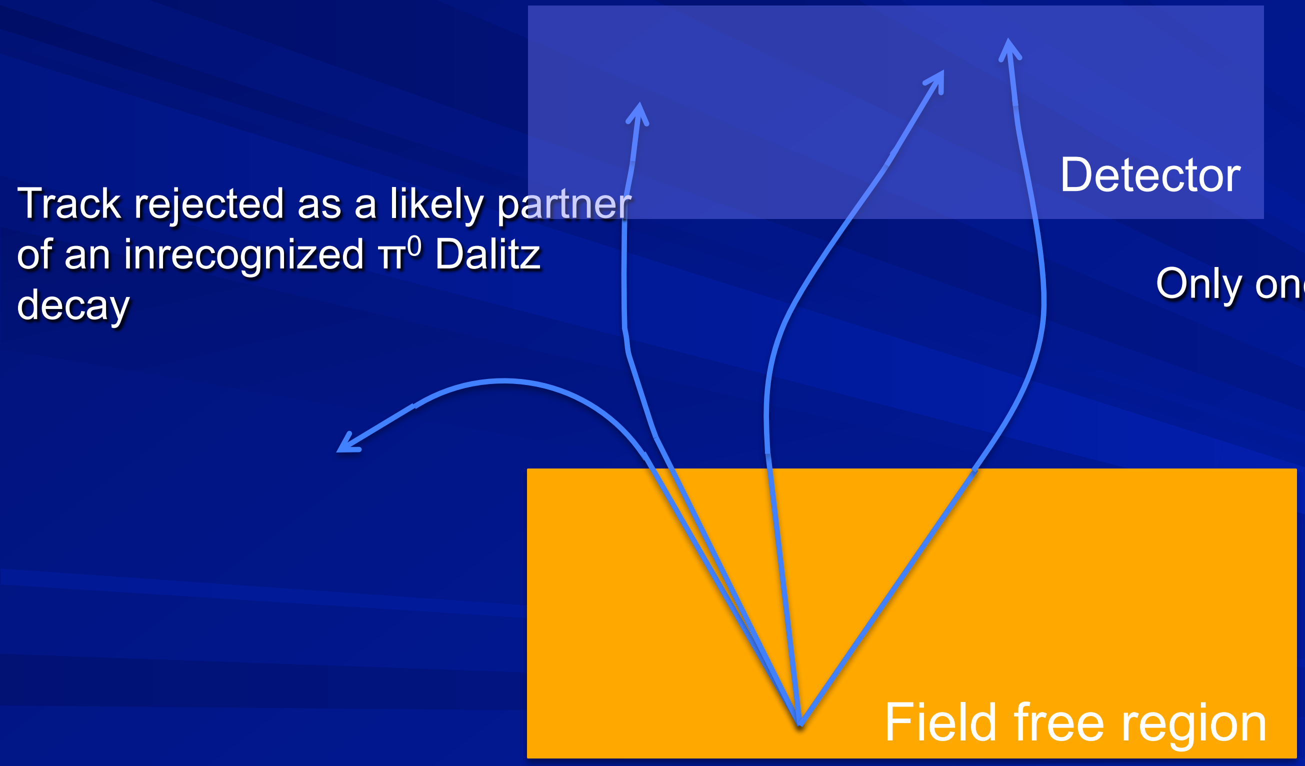
Photon conversion:
- Opening angle ~0
- Pair mass tightly peaked around $2m_e$

Heavier meson decays have large opening angles

Opening angle can be used to identify conversion and Dalitz decays

Separating Signal from Background (II)

- Need a field free region to preserve the original direction of the electron and positron tracks.
- Need a detector with eid capability inside the field free region to detect the partner of a close pair where only one of the two tracks is reconstructed.



The Double Challenge

2. Analysis challenge

Electron pairs are emitted through the whole history of the collision (from the QGP phase, mixed phase, HG phase and after freeze-out)

- need to disentangle the different sources.
- need excellent reference pp and dA data.
- need independent information about the known sources in nuclear collisions

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Lecture II

Review of experiments and results (I)

DLS, HADES

CERES, NA60

Low-mass dilepton experiments

Nuclear Collisions

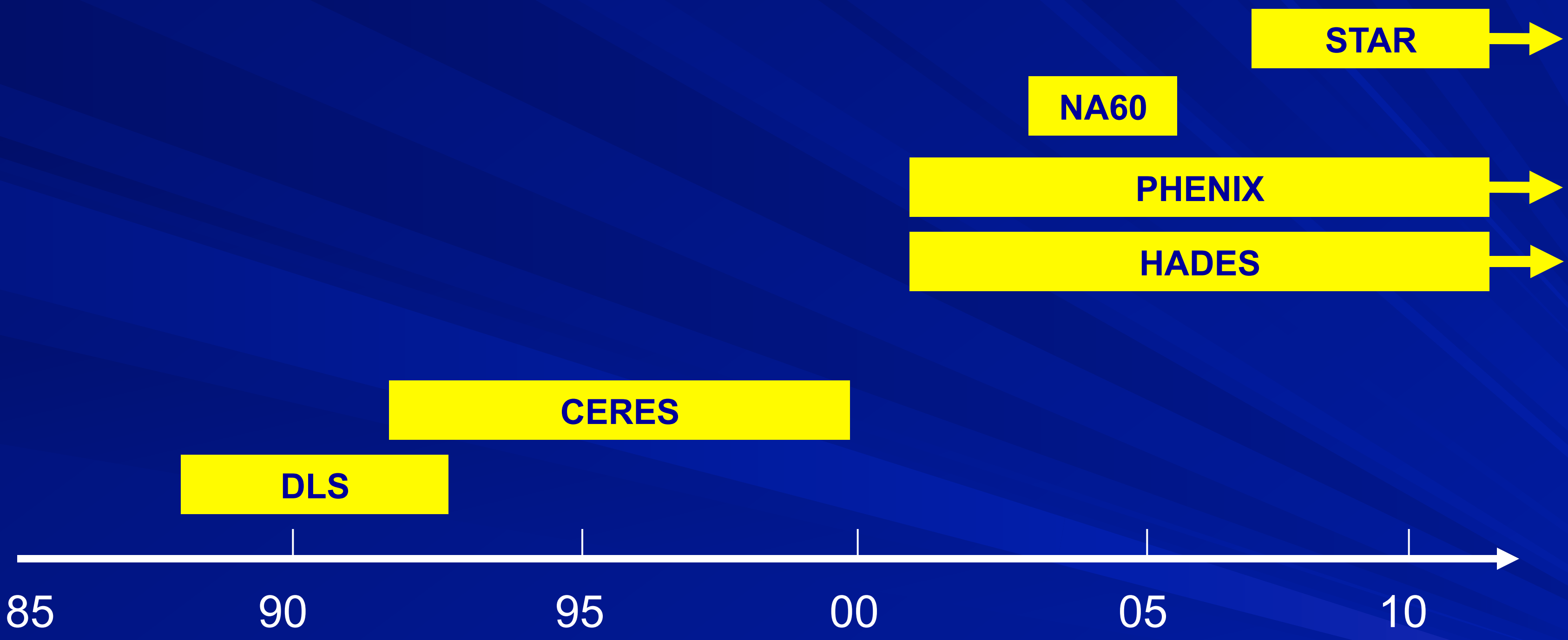
- ALICE
- CBM
- CERES
- DLS
- HADES
- HELIOS
- MPD
- NA38/50
- NA60
- PHENIX
- STAR

Elementary Reactions

- CLAS
- CBELSA/TAPS
- KEK E235
- TAGX

Low-Mass Dileptons at a Glance:

Time Scale



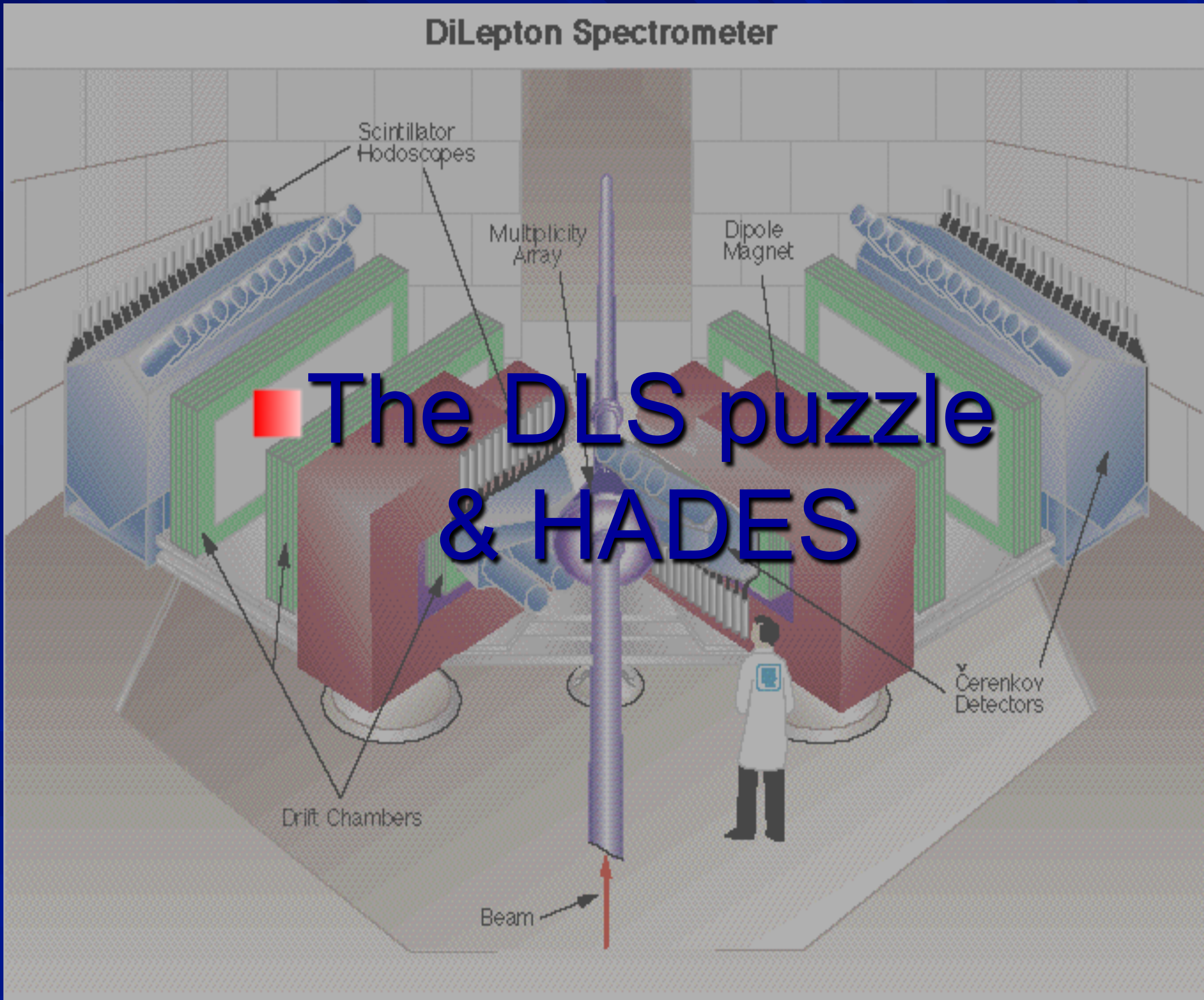
= Period of data taking

Low-Mass Dileptons at a Glance:

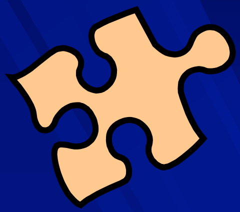
Energy Scale

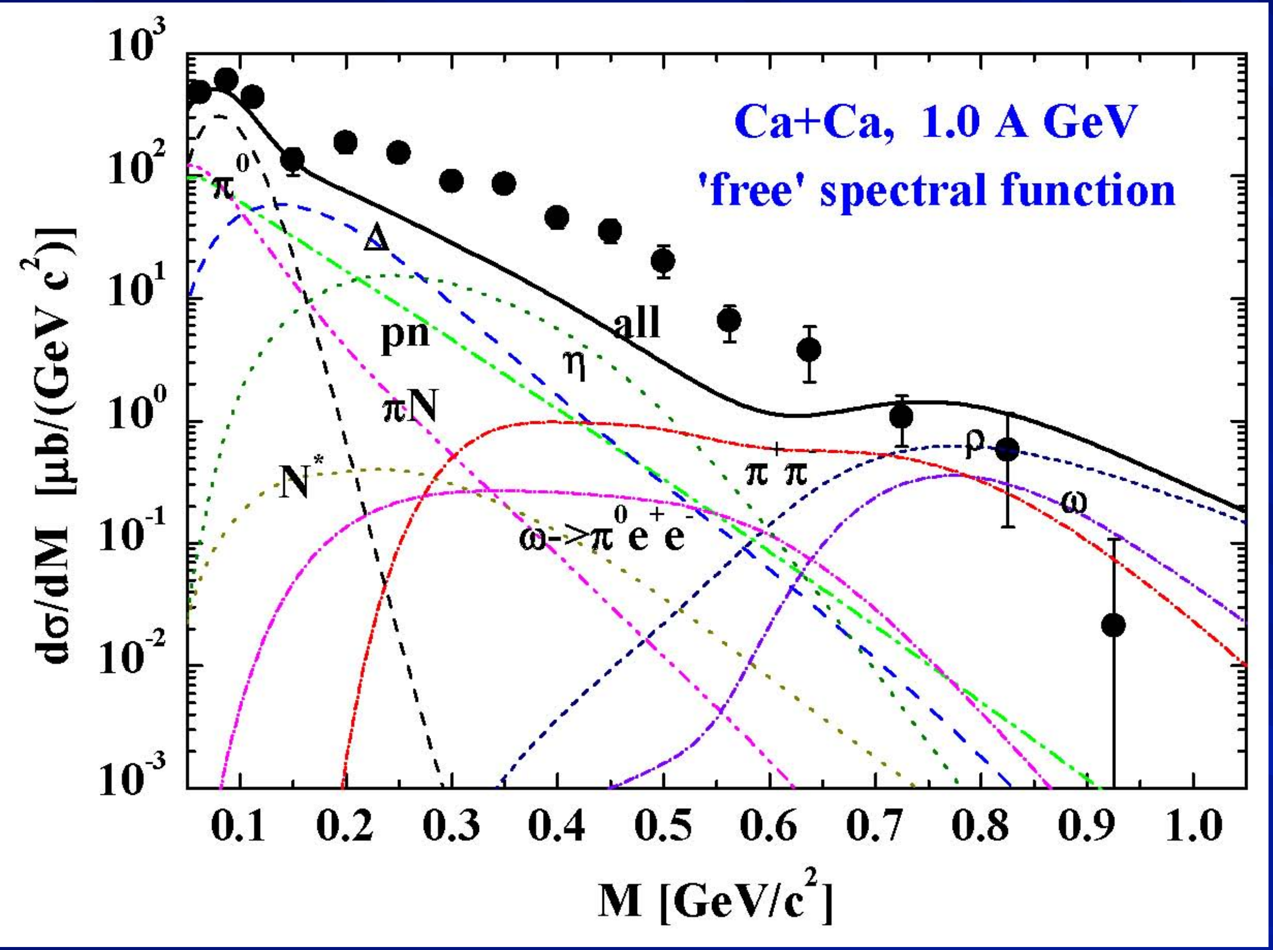
- Low-energies: DLS and HADES

The DLS puzzle & HADES



DLS "puzzle"



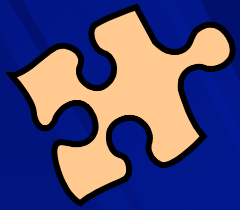


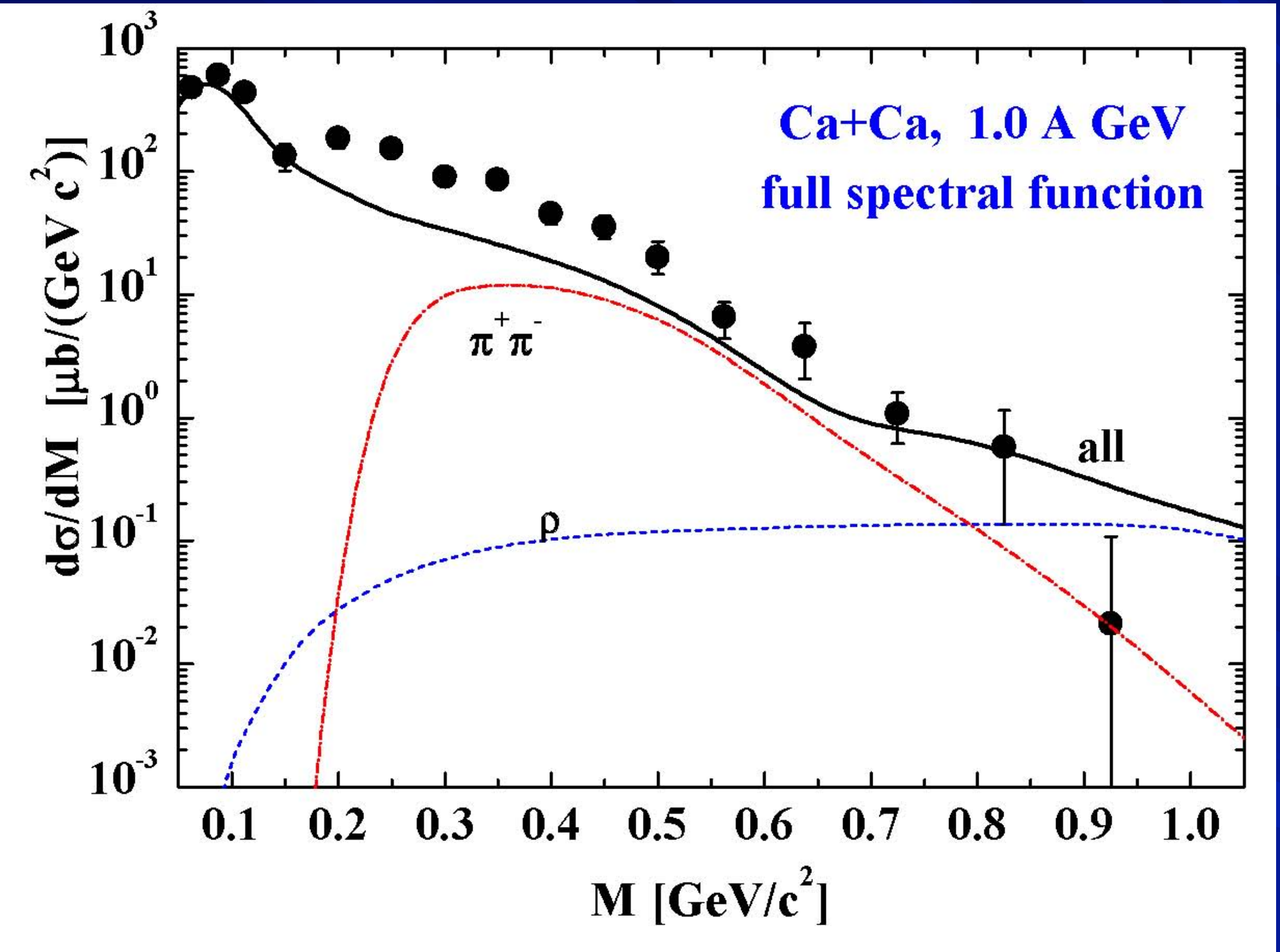
DLS data: Porter et al., PRL 79, 1229 (1997)

Calculations: Bratkovskaya et al., NP A634, 168 (1998)

Strong enhancement over hadronic cocktail with "free" ρ spectral function

DLS "puzzle"





DLS data: Porter et al., PRL 79, 1229 (1997)

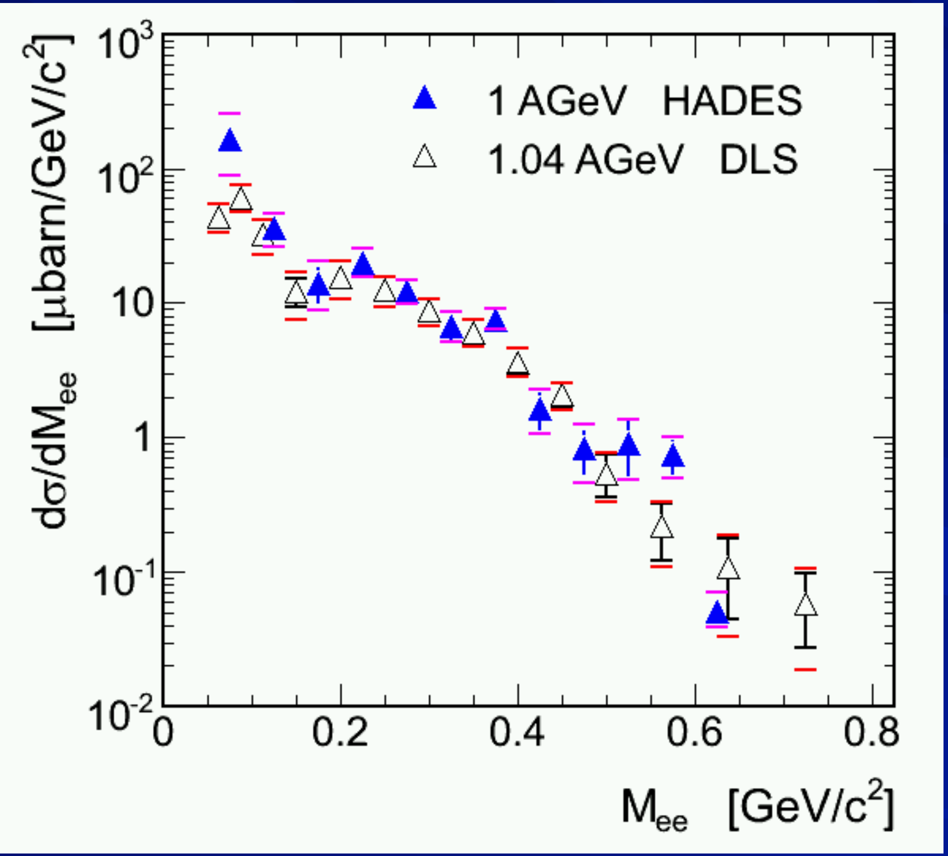
Calculations: Bratkovskaya et al., NP A634, 168 (1998)

- Enhancement not described by in-medium ρ spectral function
- All other attempts to reproduce the DLS results failed
- Main motivation for the HADES experiment

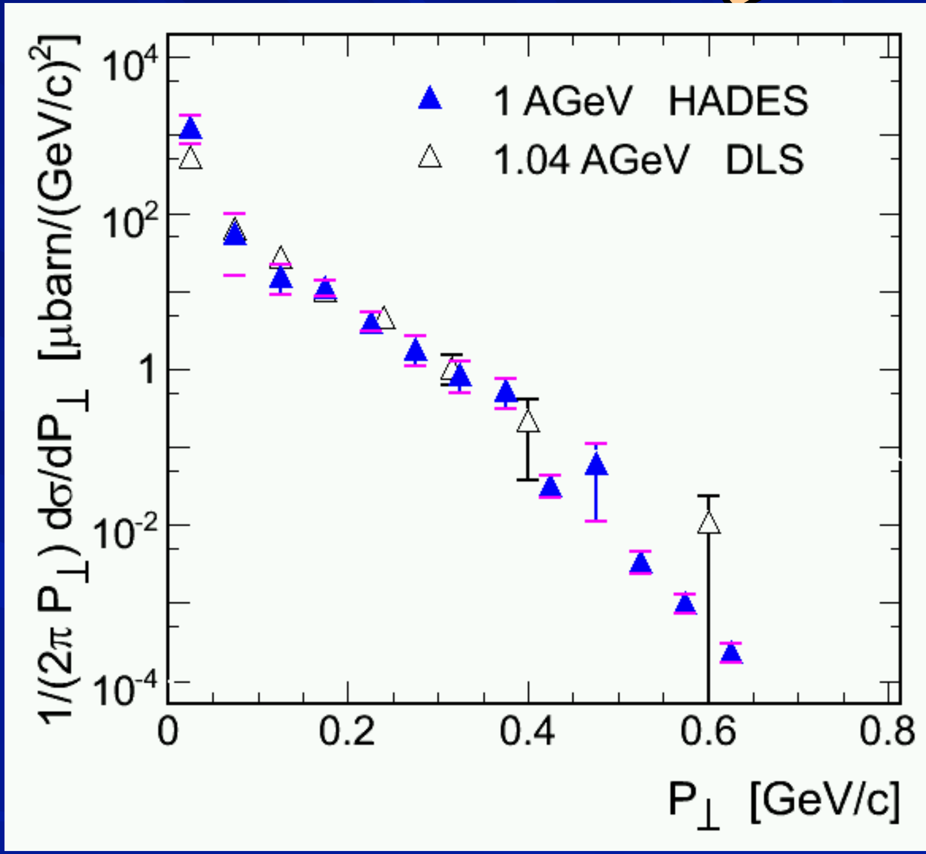
HADES confirms the DLS results

C + C

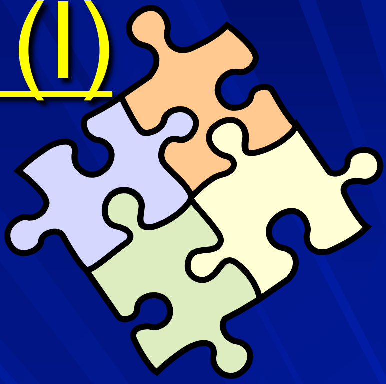
Mass distribution



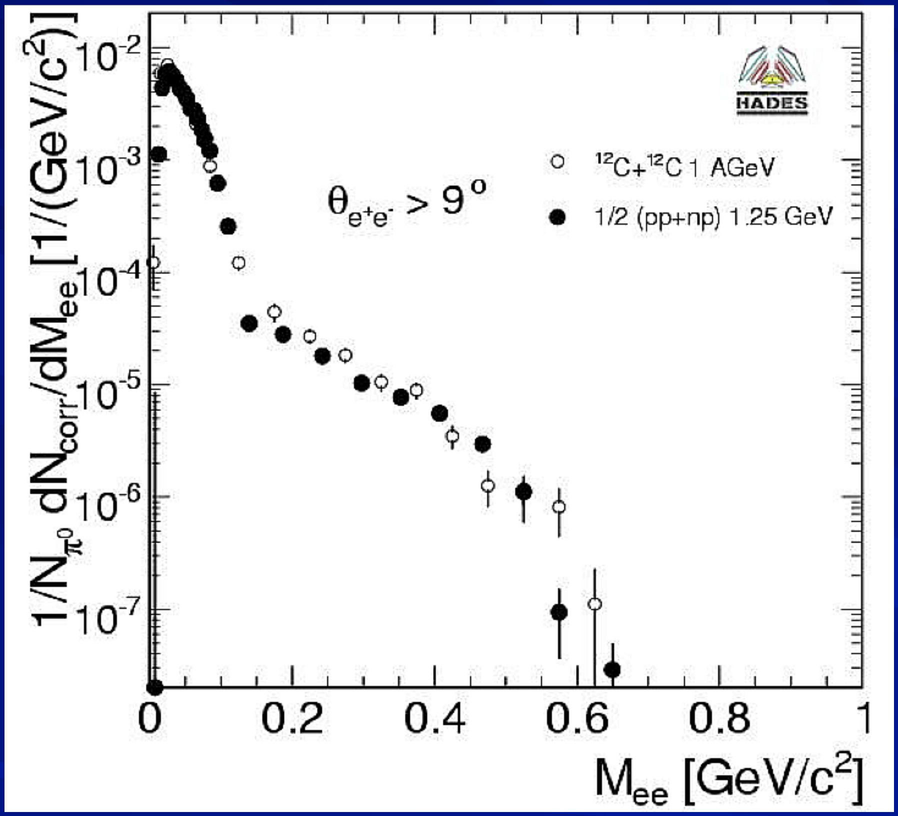
p_T distribution



Putting the puzzle together (I)



C+C @ 1 AGeV – pp & pd @ 1.25 GeV



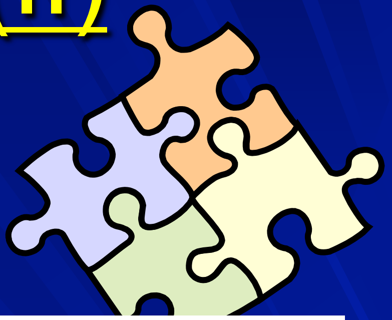
- **Spectra normalized to π^0 measured in C+C and NN**

C+C @ 1 AGeV:
$\langle M_\pi \rangle / A_{part}$ = 0.06 ± 0.07

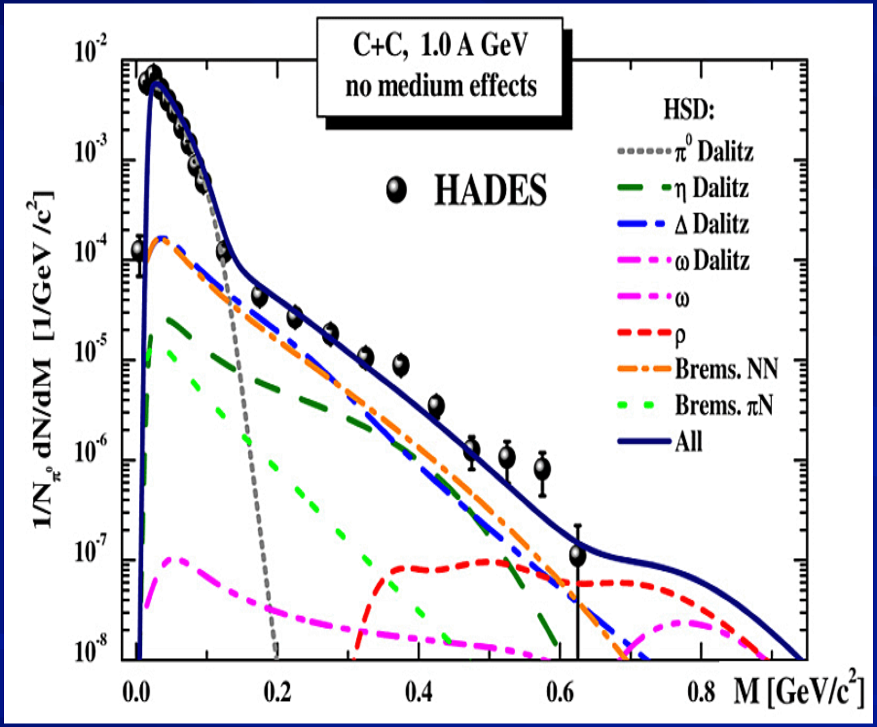
N+N @ 1.25 GeV (using pp and pd measurements)
$\langle M_\pi^{NN} \rangle / A_{part}$ = 1/4(pp+2pn+nn)/2
= 1/2(pp+pn) = 0.076±0.015

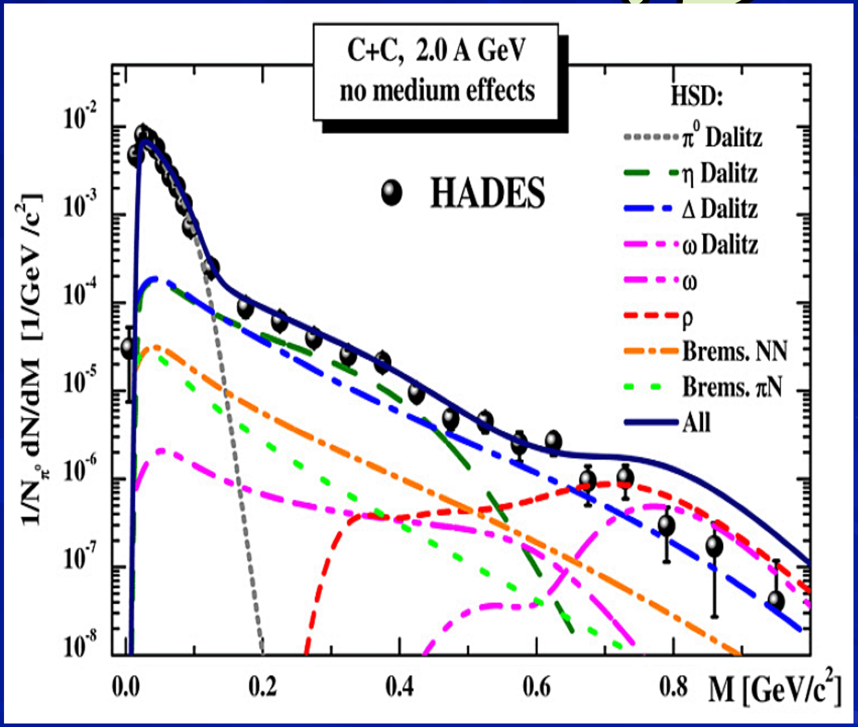
Dielectron spectrum from C+C consistent with superposition of NN collisions!
No compelling evidence for in-medium effects in C+C

Putting the puzzle together (II)



Recent transport calculations:
enhanced NN bremsstrahlung , in line with recent OBE calculations
HSD: Bratkovskaya et al. NPA 807214 (2008)

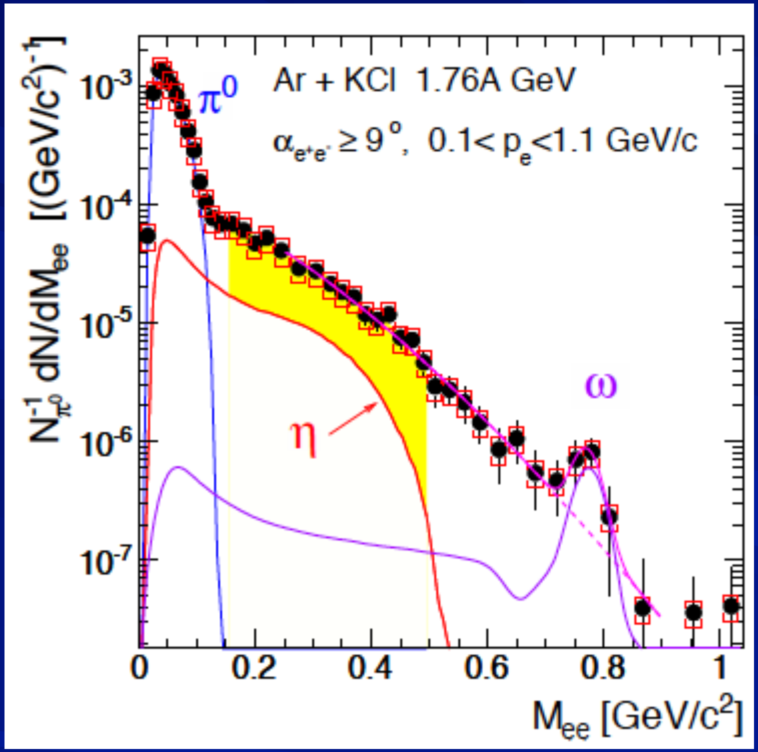


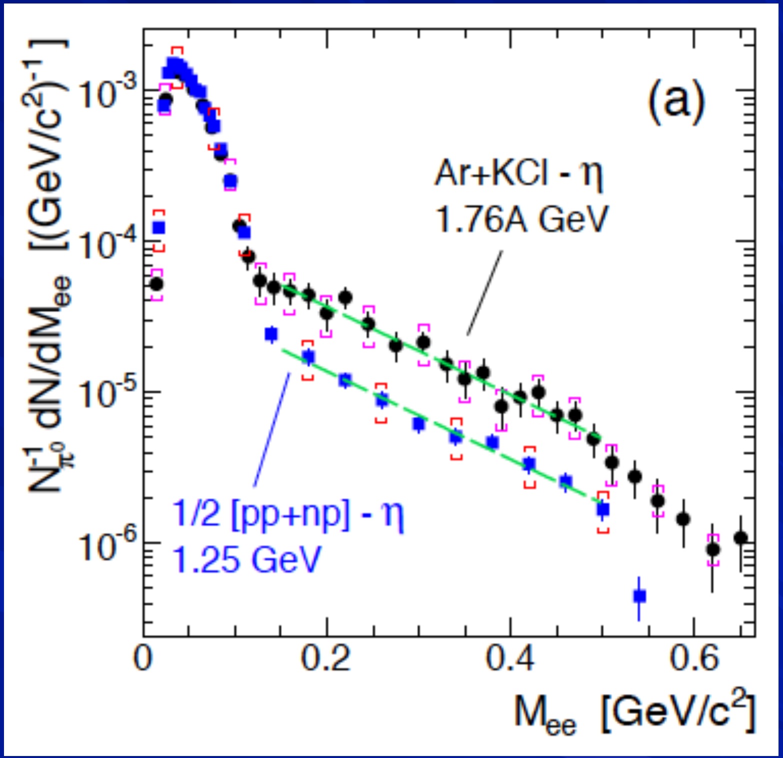


The DLS puzzle seems to be reduced to an understanting of the elementary contributions to NN reactions.

HADES – heavier system

arXiv:1103.0876

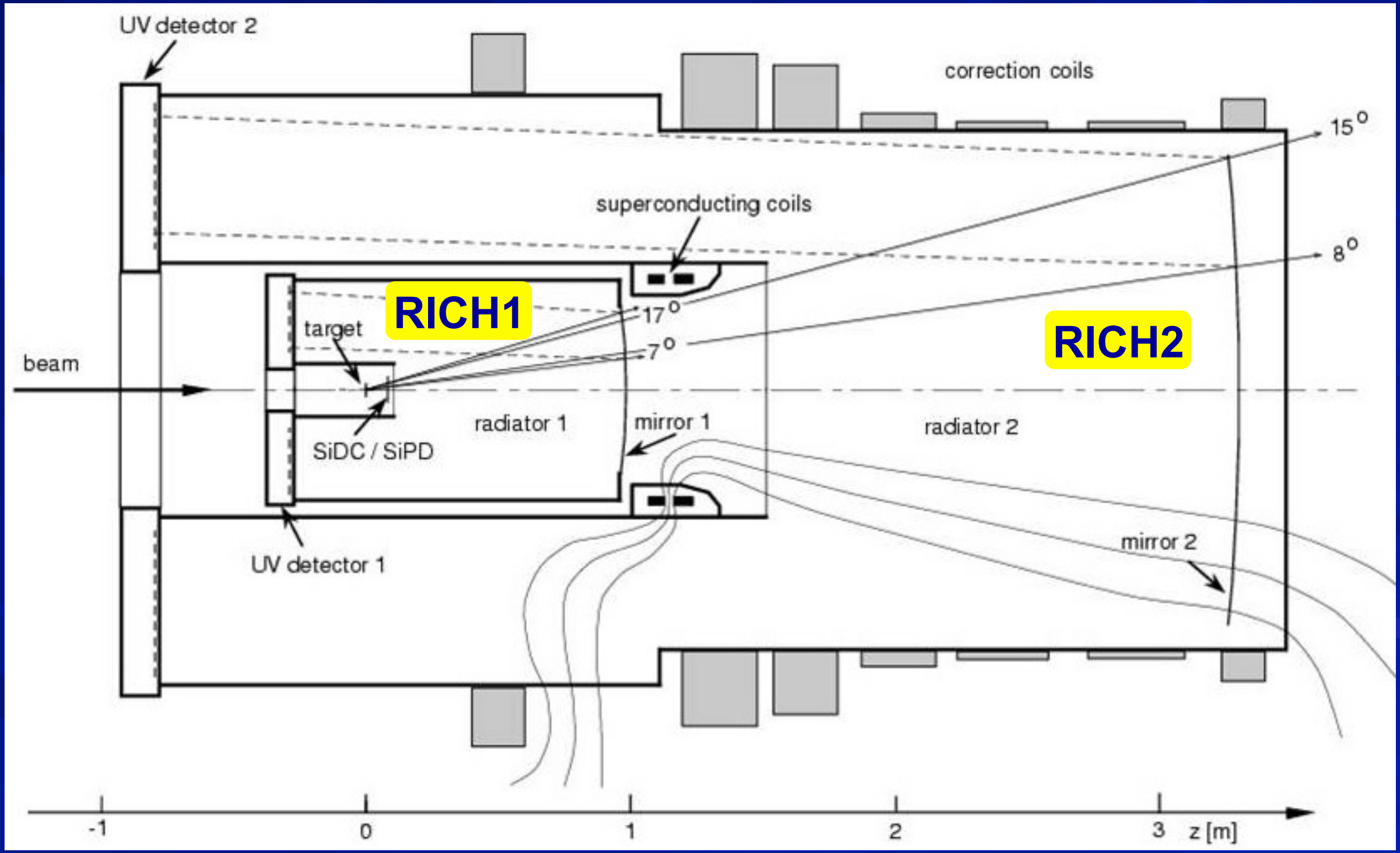




- Strong enhancement of the pair yield over the expected reference spectrum, above the π^0
- No mere superposition of elementary pp and np collisions

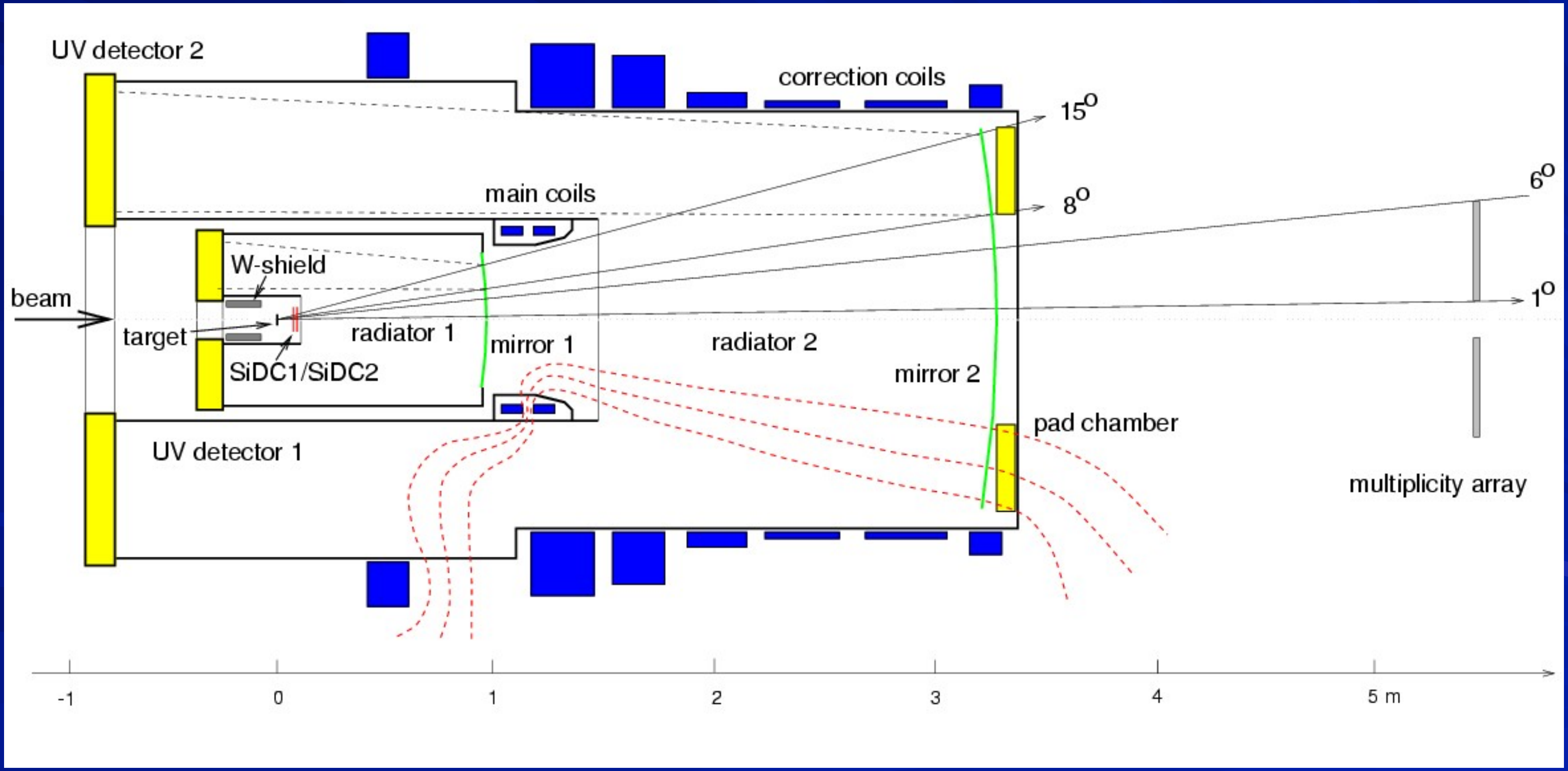
CERES

1992 setup – minimal configuration, no particle tracking
double RICH spectrometer, for eid and rejection



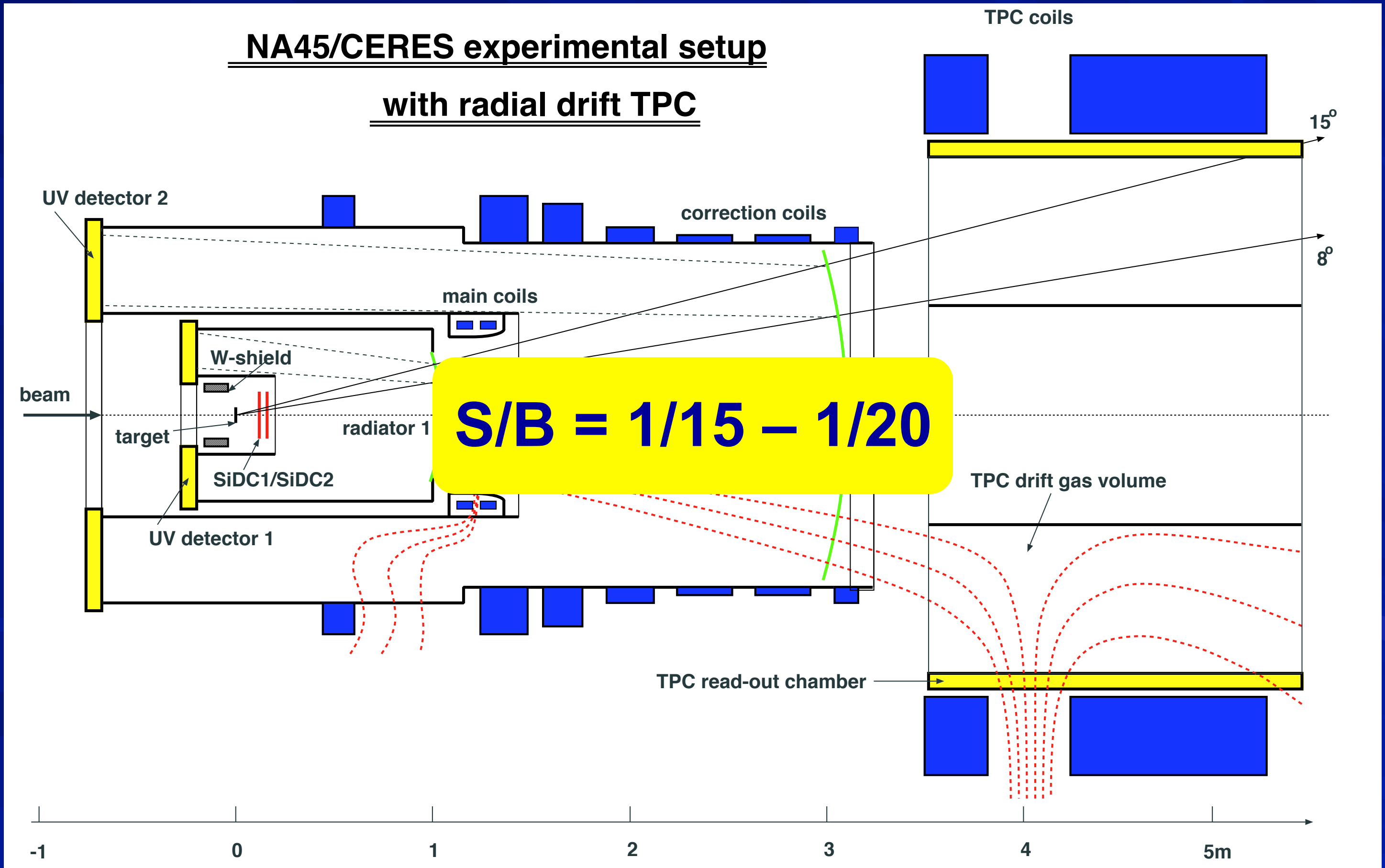
CERES

1995 setup – tracking: doublet of SiDC – RICH1 – RICH2 - PC
eid: double RICH, rejection RICH1 and SiDC



CERES

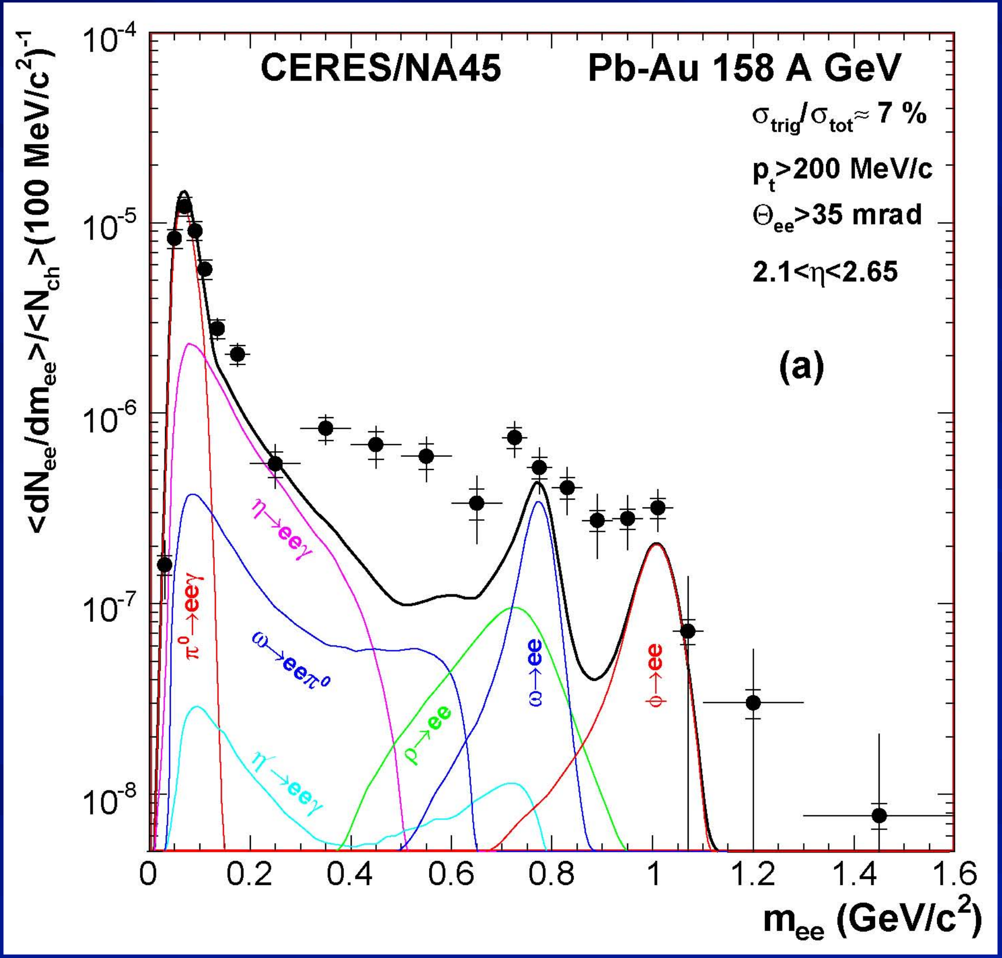
2000 setup – tracking: doublet of SiDC – RICH1 – RICH2 – TPC
improved momentum and mass resolutions
eid: double RICH, rejection RICH1 and SiDC



S/B = 1/15 – 1/20

CERES Pioneering Results (I)

Strong enhancement of low-mass e^+e^- pairs (wrt to expected yield from known sources)



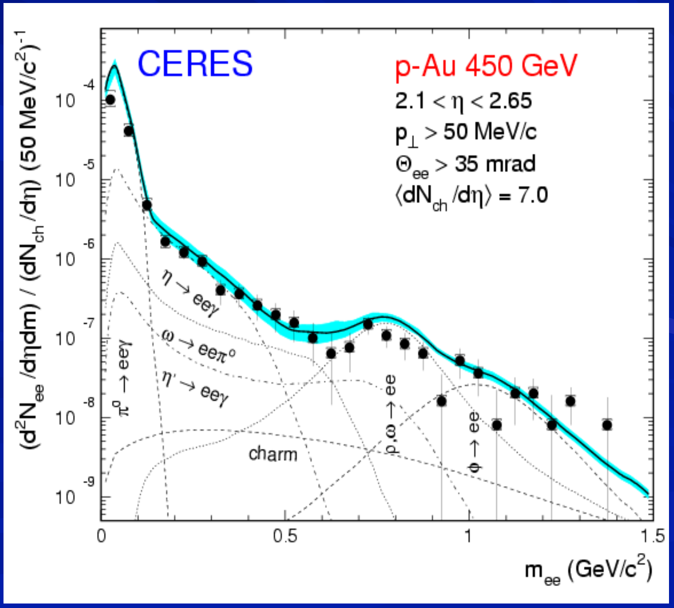
Last CERES result

2000 Pb run PLB 666(2008) 425

Enhancement factor (0.2 <m < 1.1 GeV/c^2):

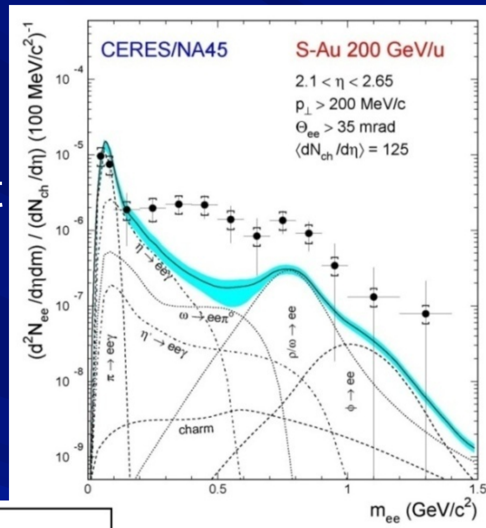
2.45 ± 0.21 (stat) ± 0.35 (syst) ± 0.58 (decays)

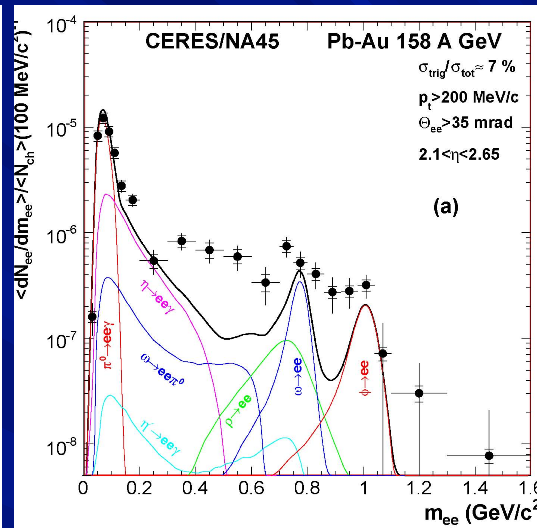
No enhancement in pp nor in pA



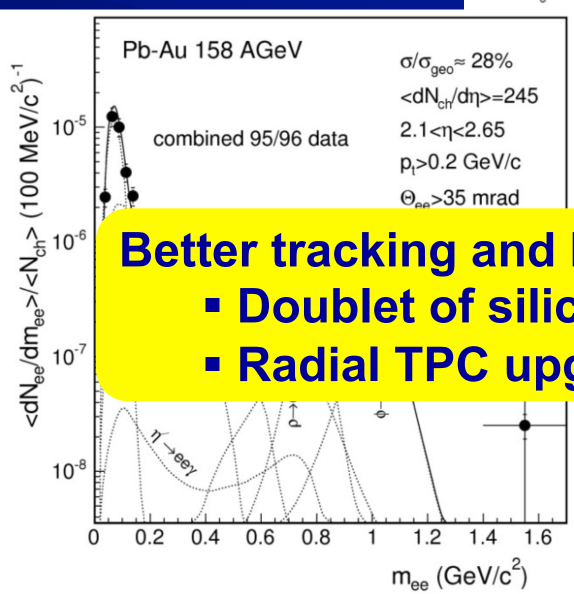
CERES Pioneering Results (II)

First CERES result
PRL 75, (1995) 1272

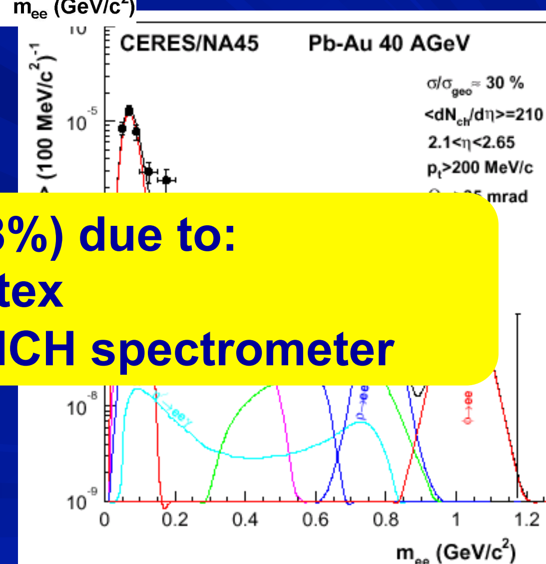




Last CERES result
PLB 666 (2008) 425



Strong enhancement



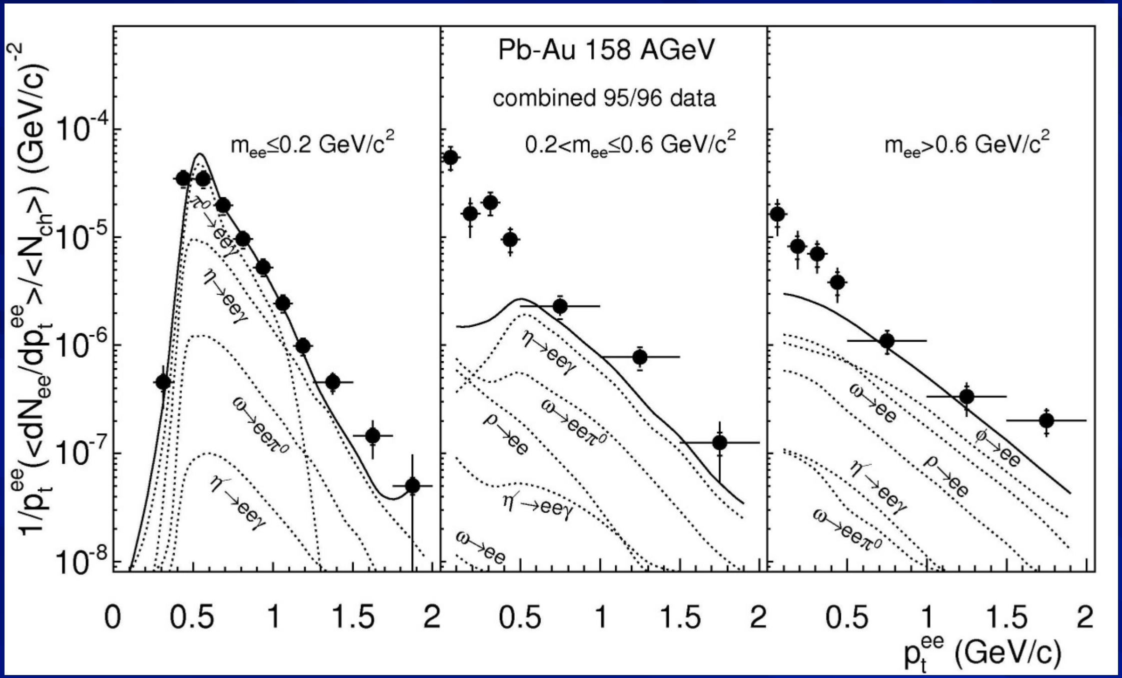
Better tracking and better mass resolution ($\Delta m/m = 3.8\%$) due to:

- **Doublet of silicon drift chambers close to the vertex**
- **Radial TPC upgrade downstream of the double RICH spectrometer**

Eur. Phys J. C41 (2005) 475

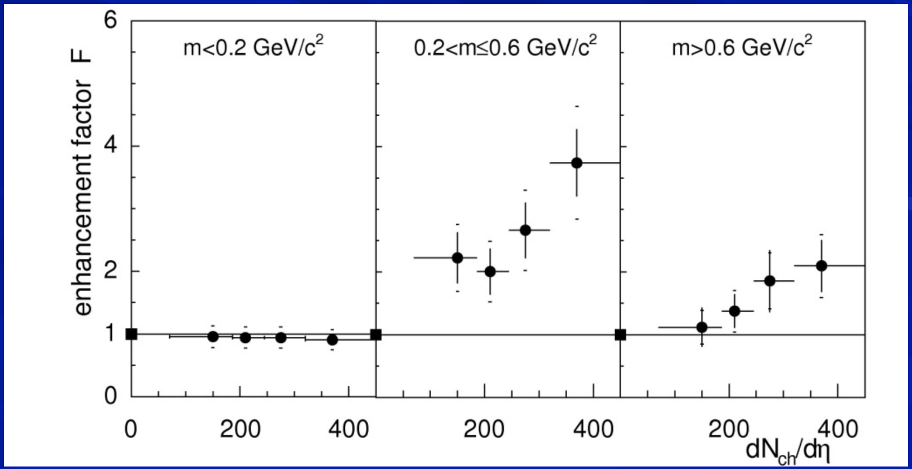
PRL 91 (2003) 042301

p_T and Multiplicity Dependencies



Enhancement is mainly at low p_T

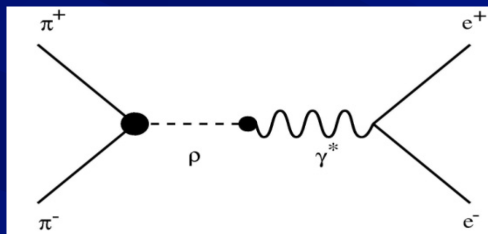
Increases faster than linearly with multiplicity



- Interpretation (s)?

Dropping Mass or Broadening (I) ?

* Interpretations invoke:
$\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-$



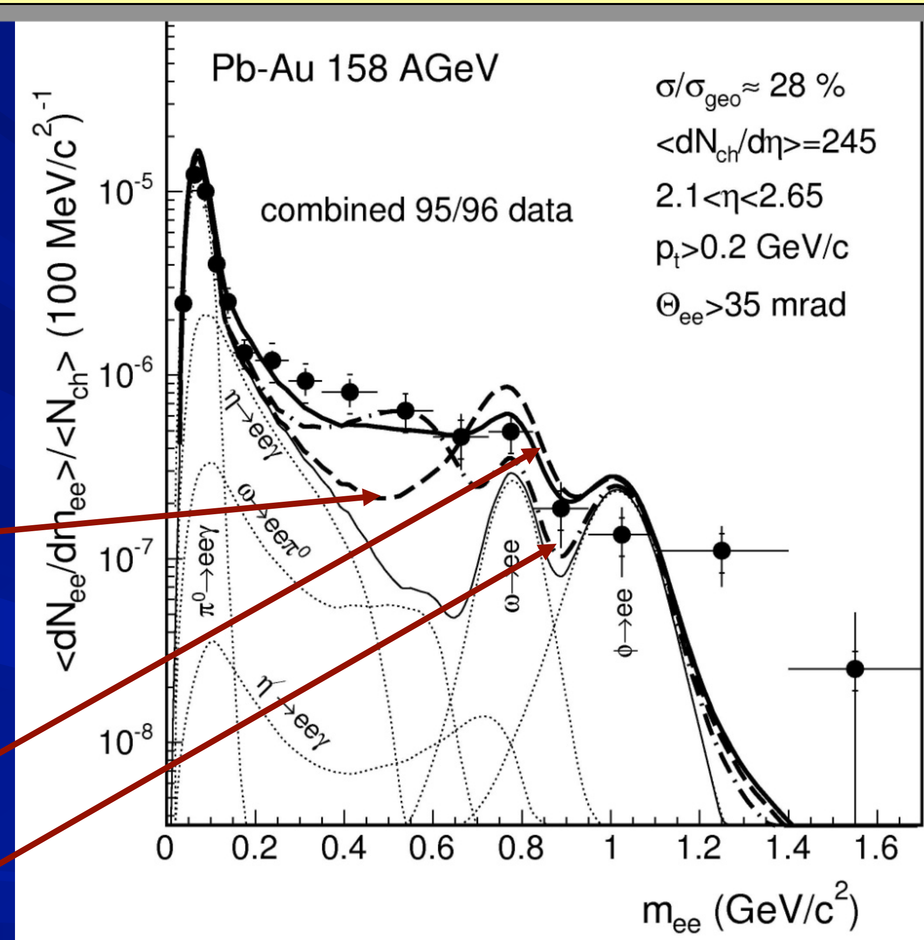
thermal radiation from HG

* vacuum ρ not enough to reproduce data

* in-medium modifications of ρ:

- broadening ρ spectral shape (Rapp and Wambach)
- dropping ρ meson mass (Brown et al)

CERES Pb-Au 158 A GeV 95/96 data



Dropping Mass

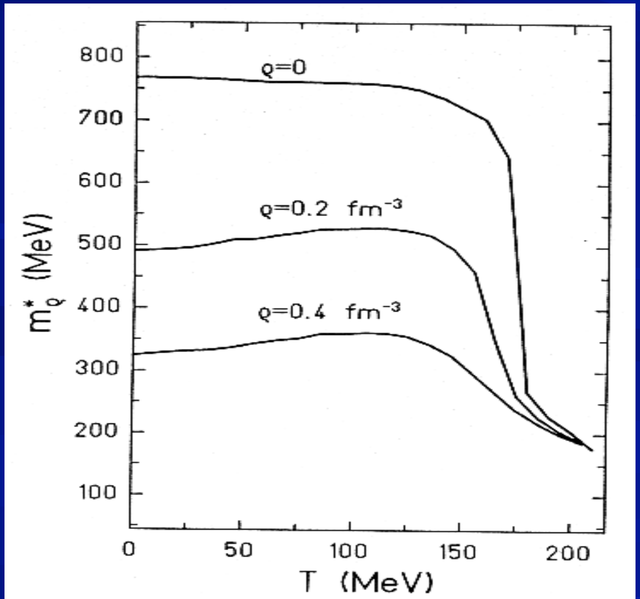
Brown-Rho conjecture that links hadron masses to the quark condensate. Effective QCD Lagrangian, quarks are the relevant d.o.f.

Brown-Rho scaling PRL 66, (1991) 2720

$$\frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \approx \left(\frac{<\bar{q}q>_{\rho^*}}{<\bar{q}q>_0} \right)^{1/3} = 1 - 0.26\,\frac{\rho^*}{\rho_0}$$

$$= 1 - 0.16\,\frac{\rho^*}{\rho_0}$$

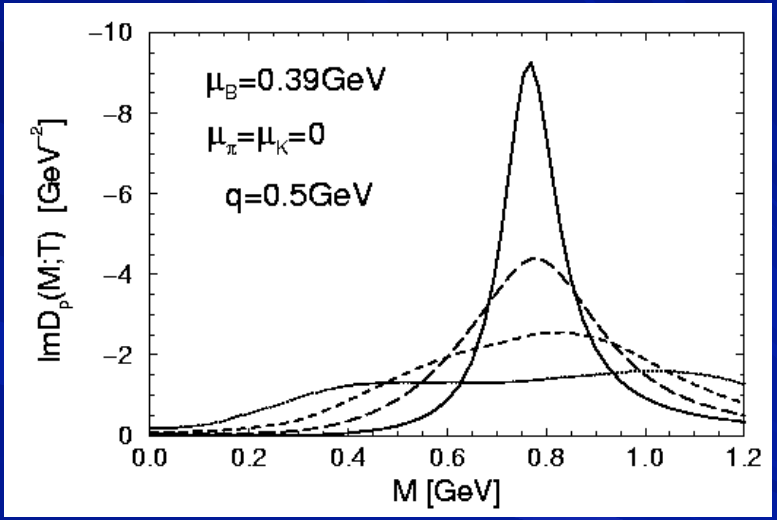
Hatsuda & Lee PR C42, (1992) R34



Broadening

Rapp & Wambach et al

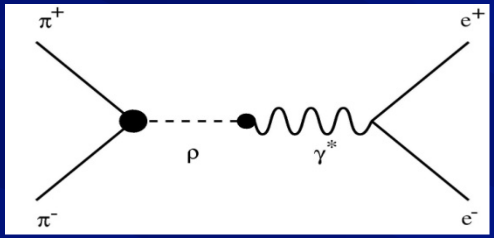
ρ-meson scatters off particles in the high density medium → collision broadening.
Pure hadronic model



At SPS both the mass drop and the broadening of the ρ-meson are due to the high baryon density.

Dropping Mass or Broadening (I) ?

* Interpretations invoke:
  $\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-$

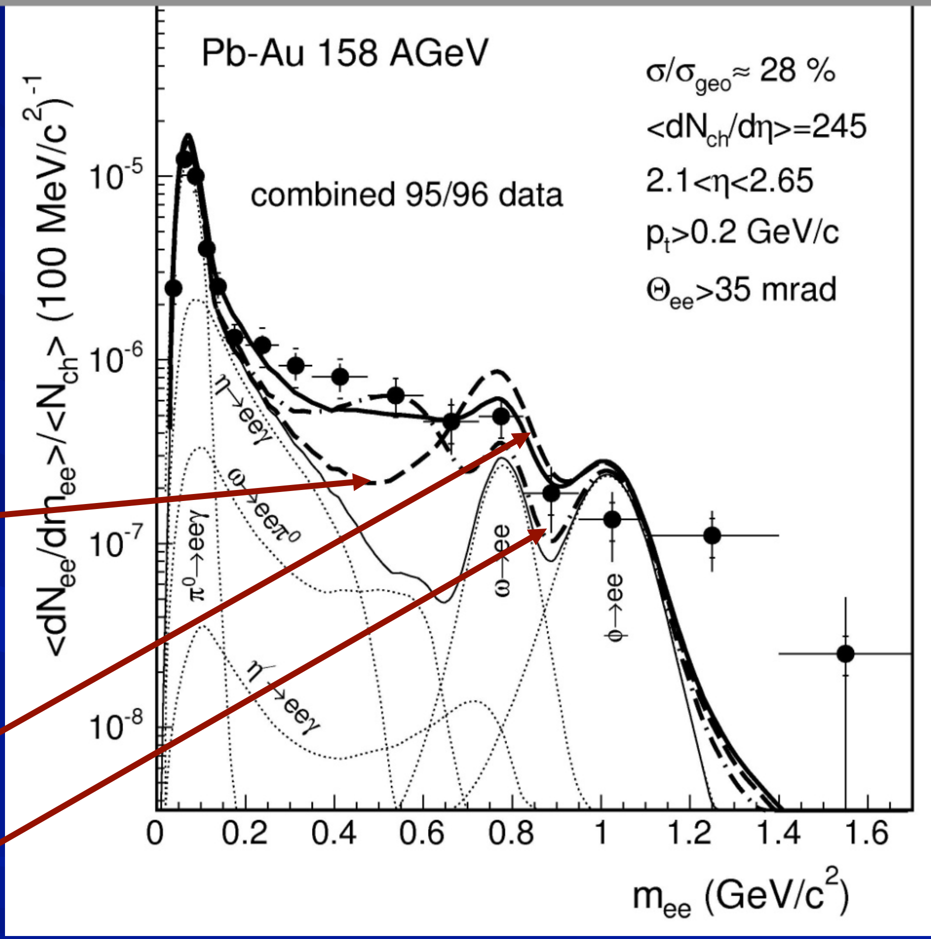


thermal radiation from HG

* vacuum ρ not enough to reproduce data

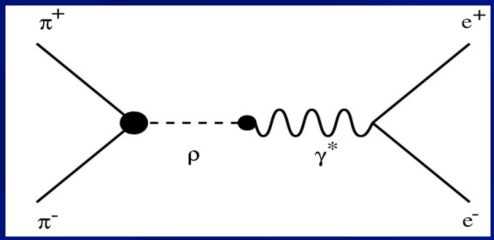
* in-medium modifications of ρ:
- broadening ρ spectral shape
  (Rapp and Wambach)
- dropping ρ meson mass
  (Brown et al)

CERES Pb-Au 158 A GeV 95/96 data



Dropping Mass or Broadening (II) ?

* Interpretations invoke:
  $\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-$



thermal radiation from HG

* vac … a

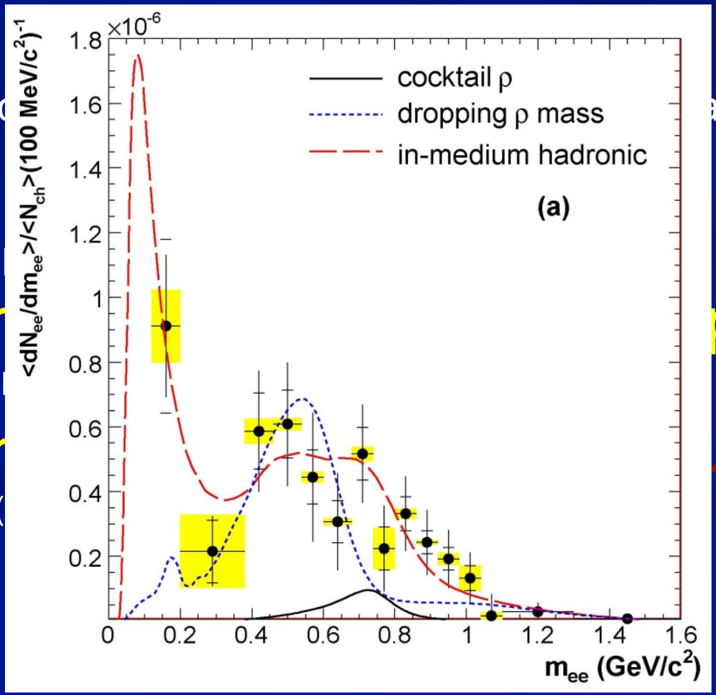
* in- …

❖ br … pe

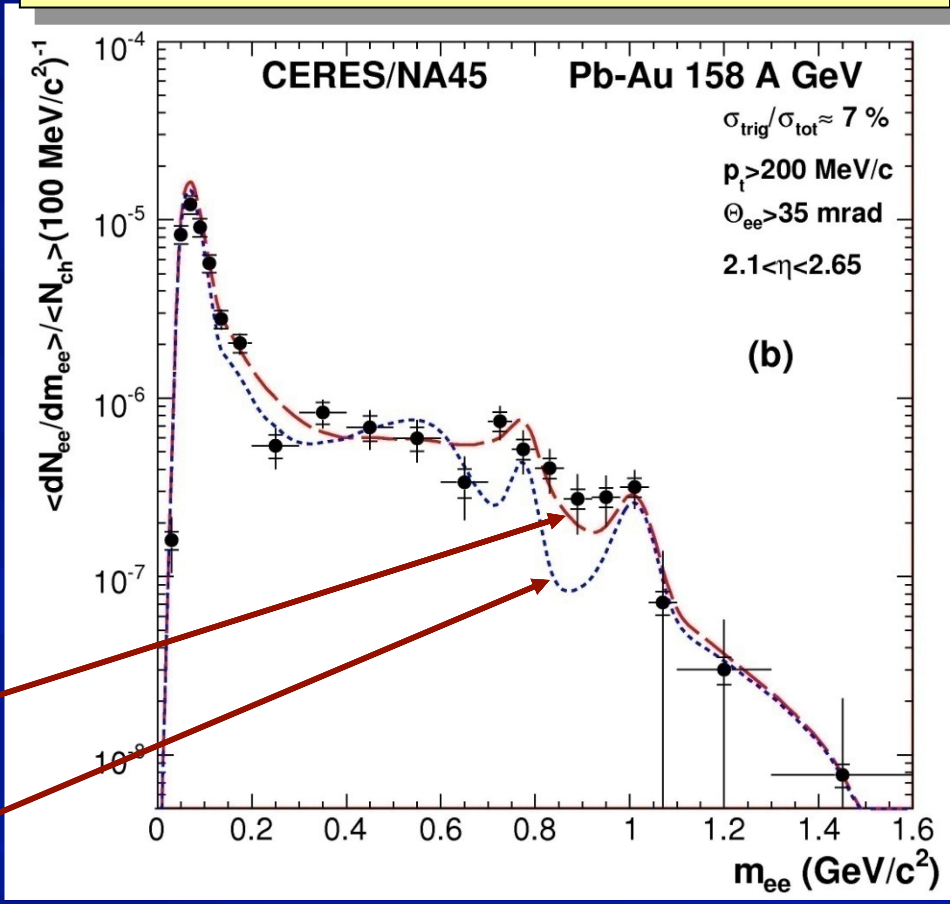
(Ra …

❖dr …

(…



CERES Pb-A 158 A GeV 2000 data

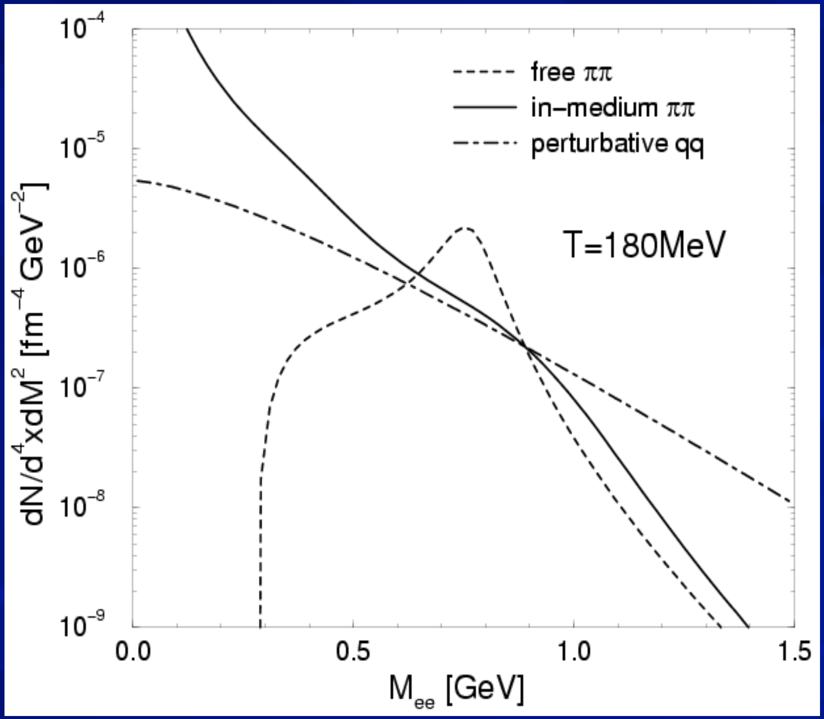


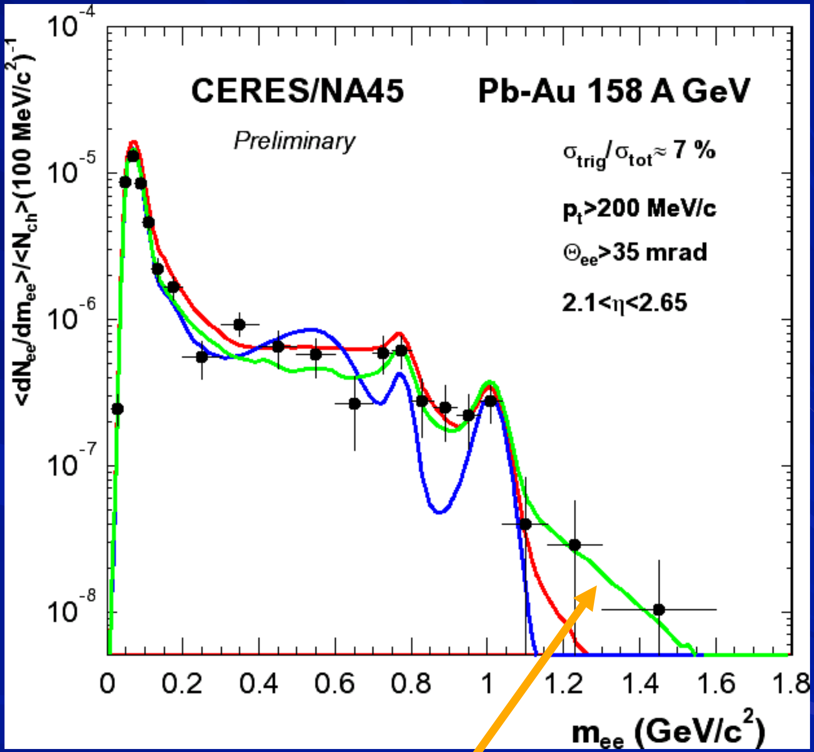
Data favor the broadening scenario.

Quark – Hadron Duality

R. Rapp

In-medium $\pi^+ \pi^-$ ann. rates $\approx$ perturbative qbarq ann. rates
quark – hadron duality down to m ~ 0.5 GeV/c^2



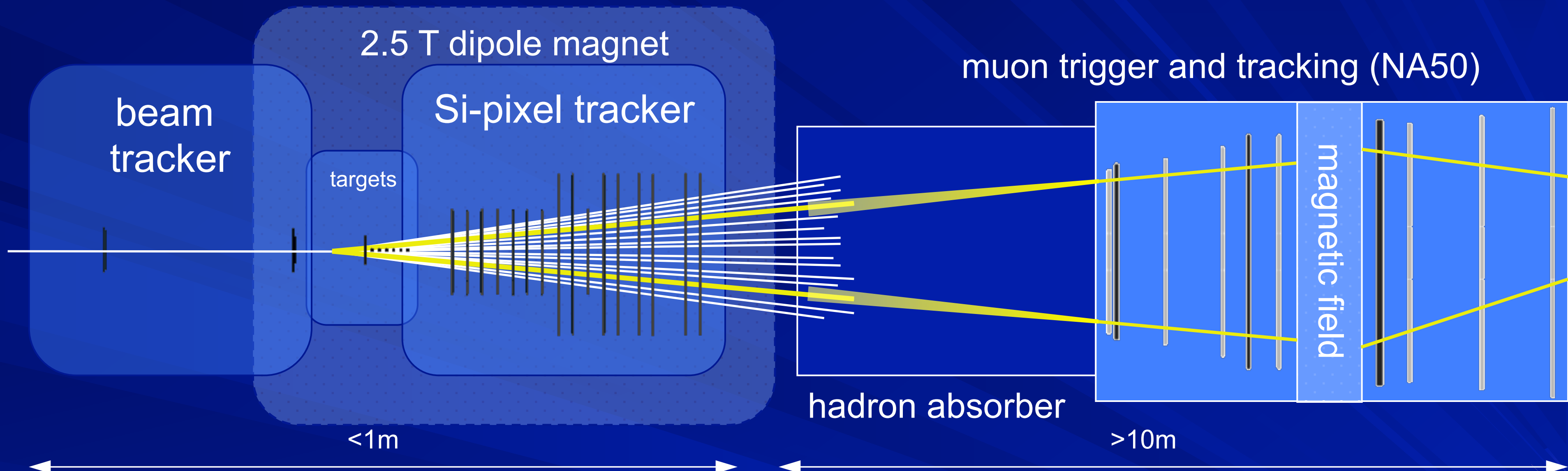


Kämpfer calculations: Thermal radiation from the plasma or just a parametrization of the e^+e^- yield inspired by quark-hadron duality?

- NA60

NA60 spectrometer

Based on the NA50 spectrometer with the addition of a Si tracker



Additional bend by the dipole field

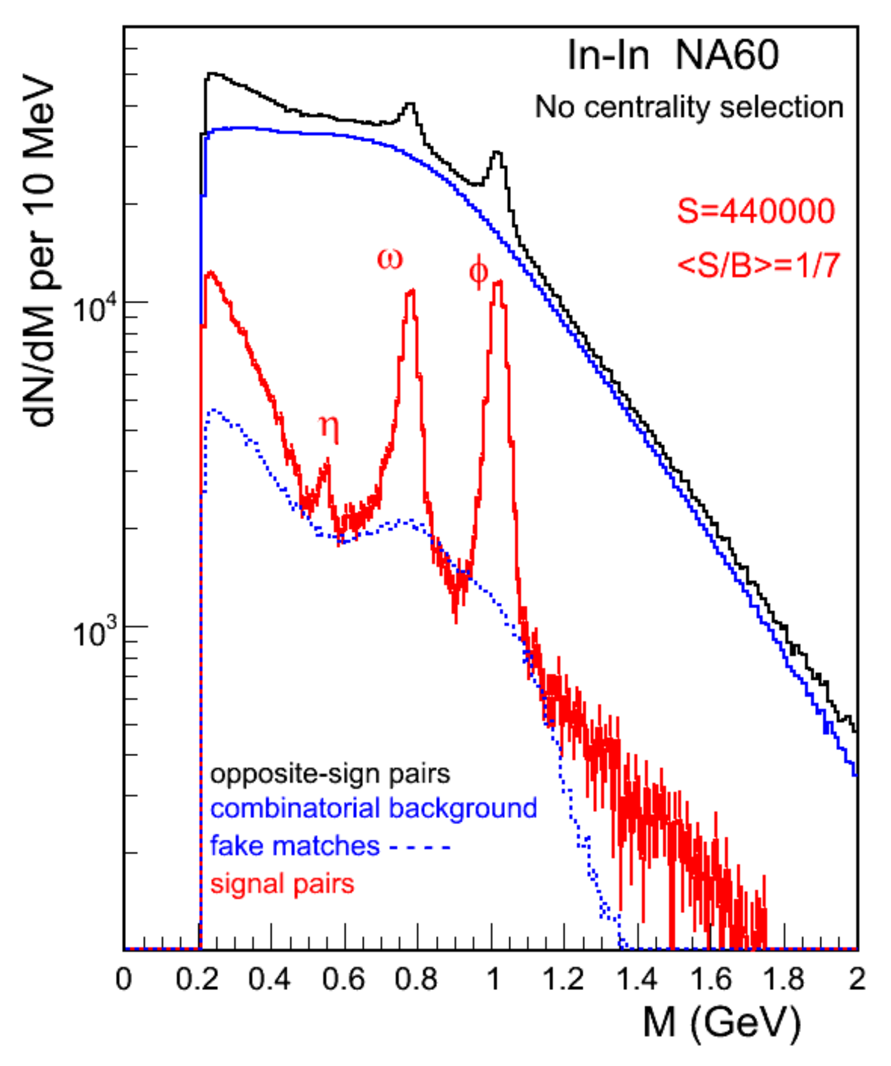
Track matching in coordinate and momentum space

- Improved dimuon mass resolution
- Distinguish prompt from decay dimuons

Dimuon coverage extended to low p_T

NA60 Low-mass dimuons

In+In 158 A GeV

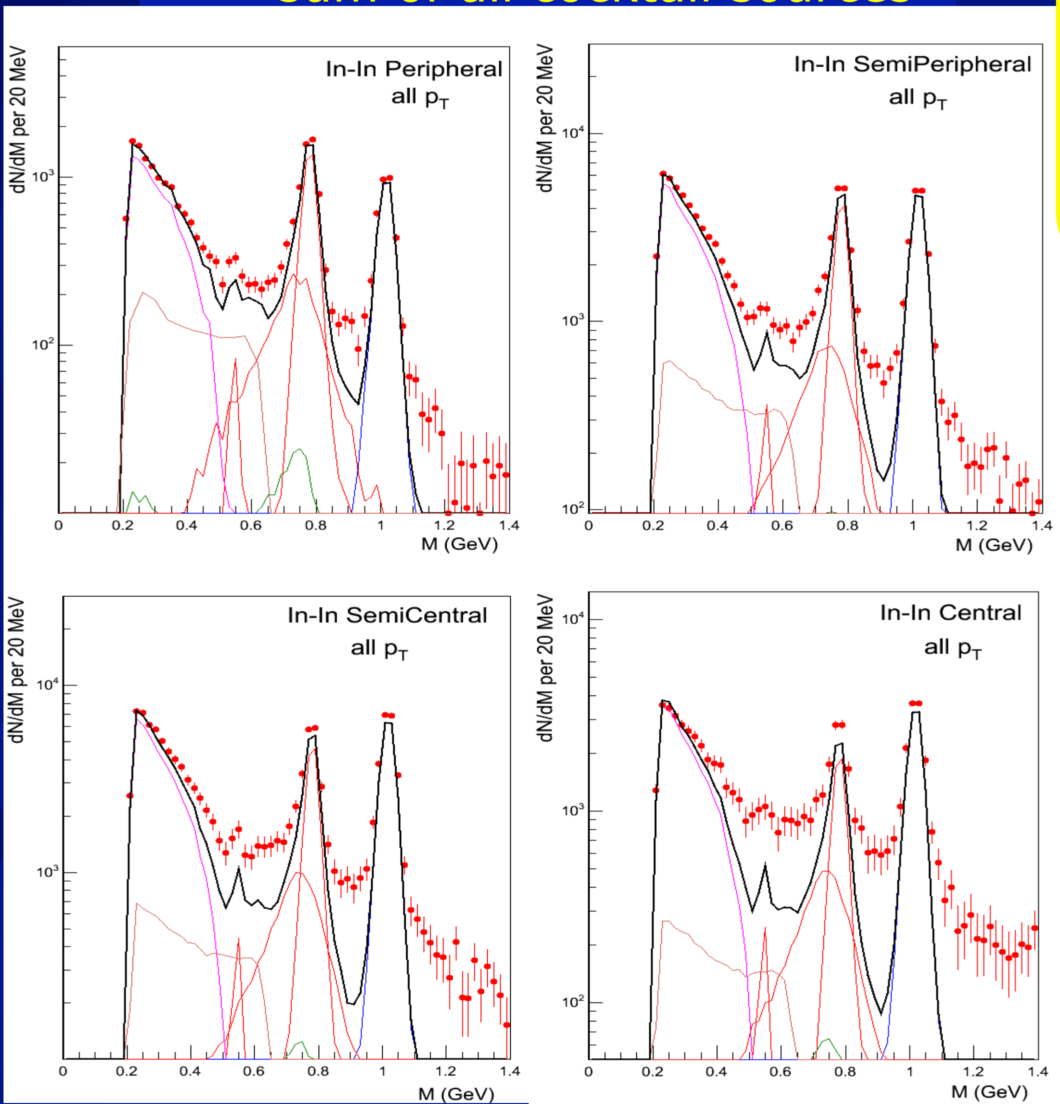


Superb data!!!

- Mass resolution: 23 MeV at the ϕ position
- S/B = 1/7
- ω, ϕ and even η peaks clearly visible in dimuon channel

Clear excess of low mass with centrality

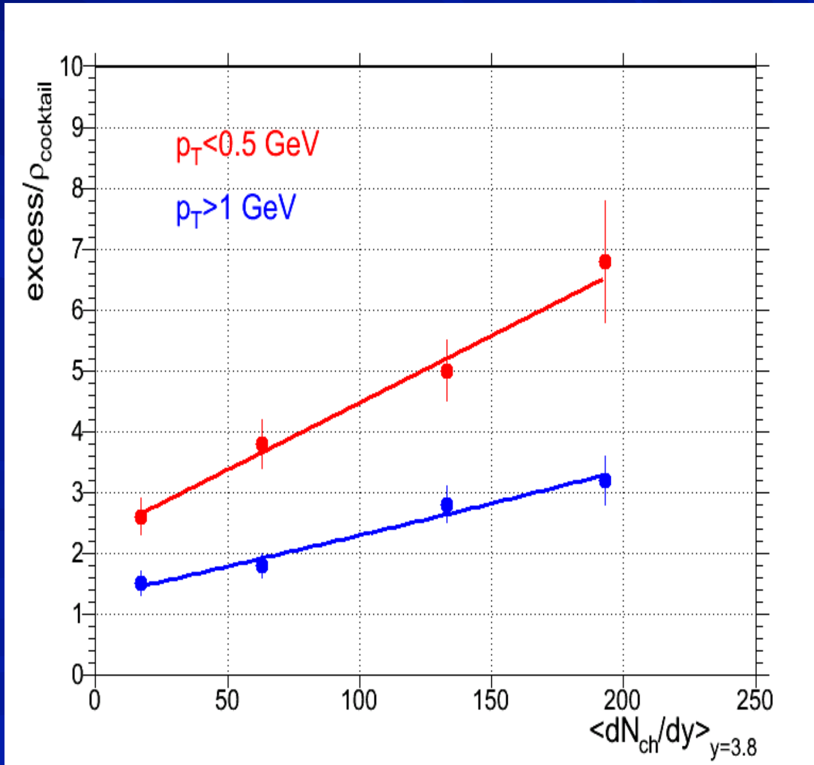
- NA60 data
- sum of all cocktail sources



✓ ***confirms and consistent with CERES results***

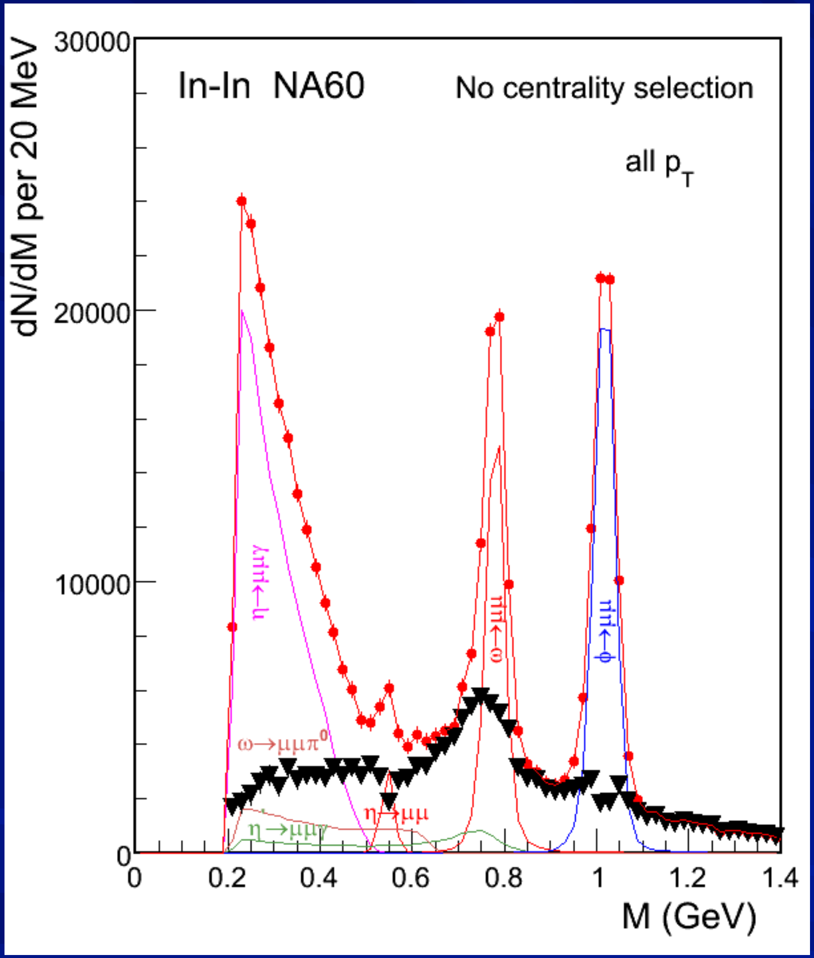
✓ **rising with centrality**

✓ **more pronounced at low pT**



Dimuon Excess

Phys. Rev. Lett. 96 (2006) 162302

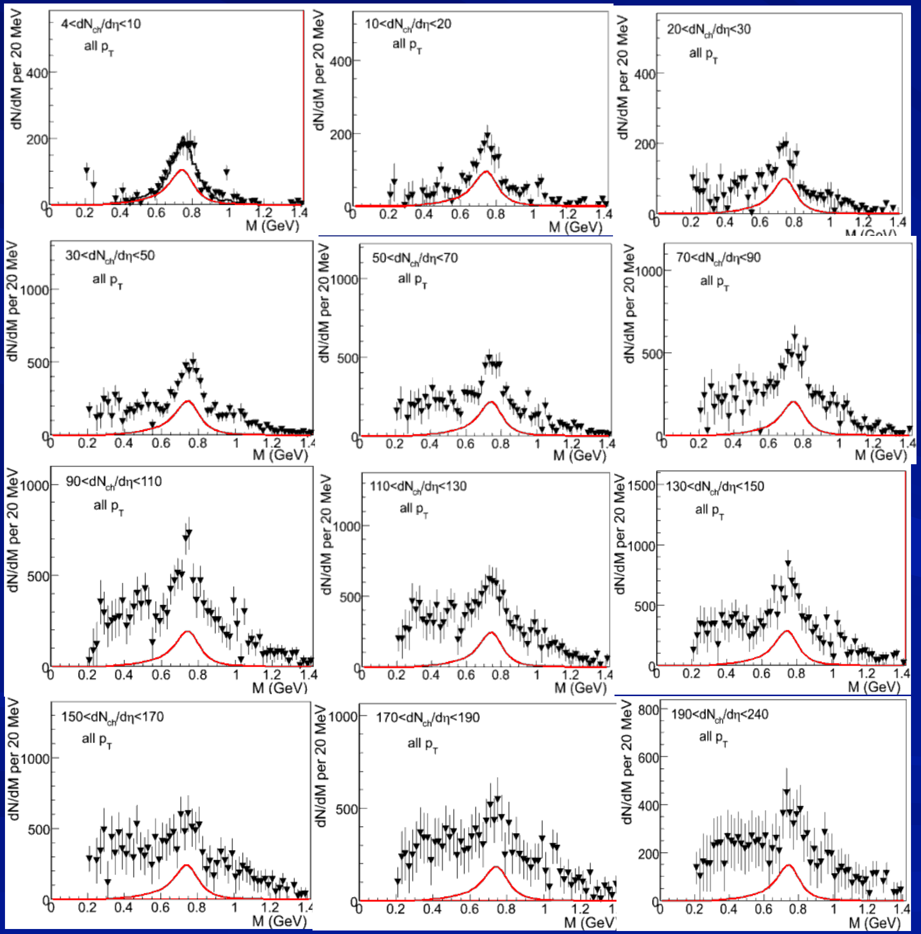


Dimuon excess isolated by subtracting the hadron cocktail (without the ρ)

Dimuon Excess

Dimuon excess isolated by subtracting the hadron cocktail (without the ρ)

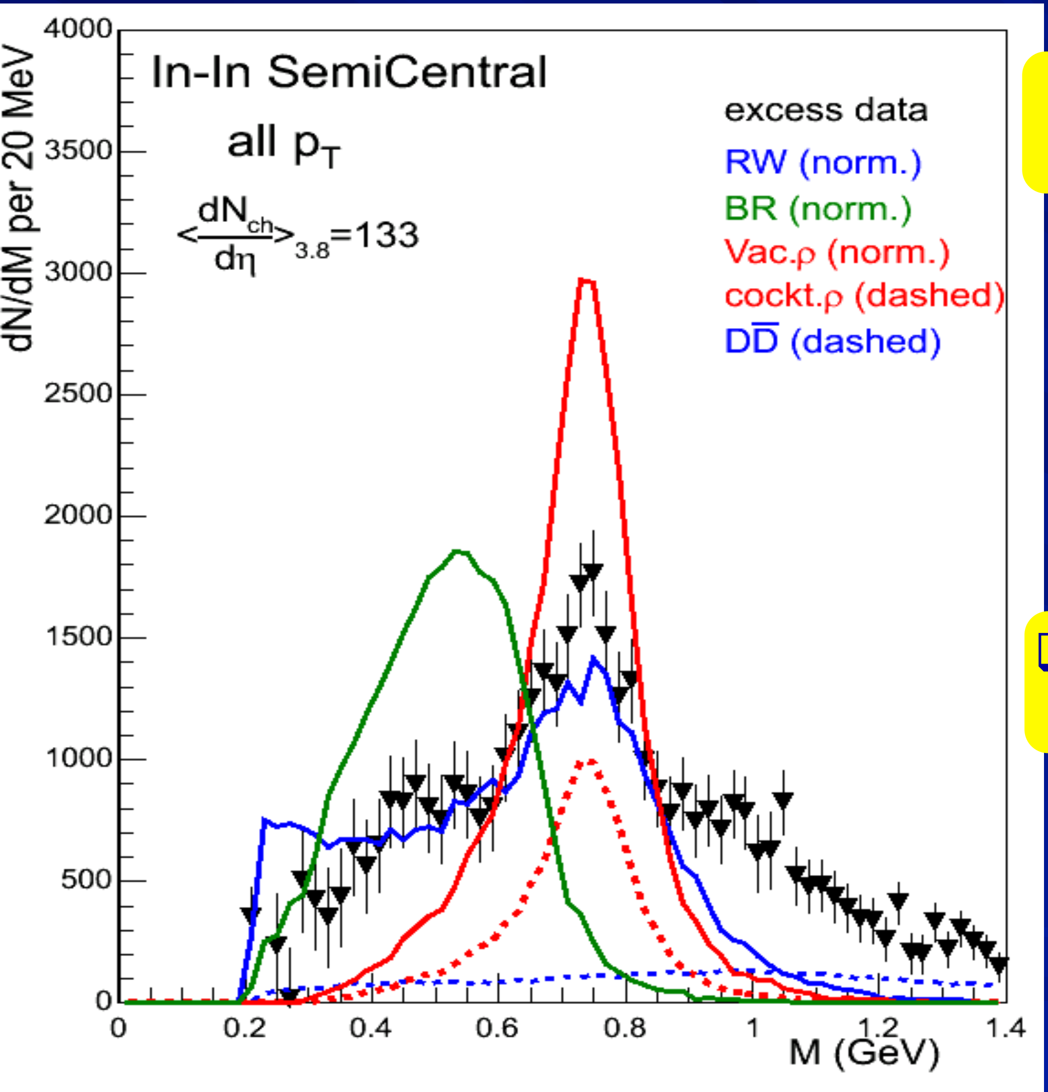
Eur.Phys.J.C 49 (2007) 235



Excess centered at the nominal ρ pole

Excess rises ad broadens with centrality

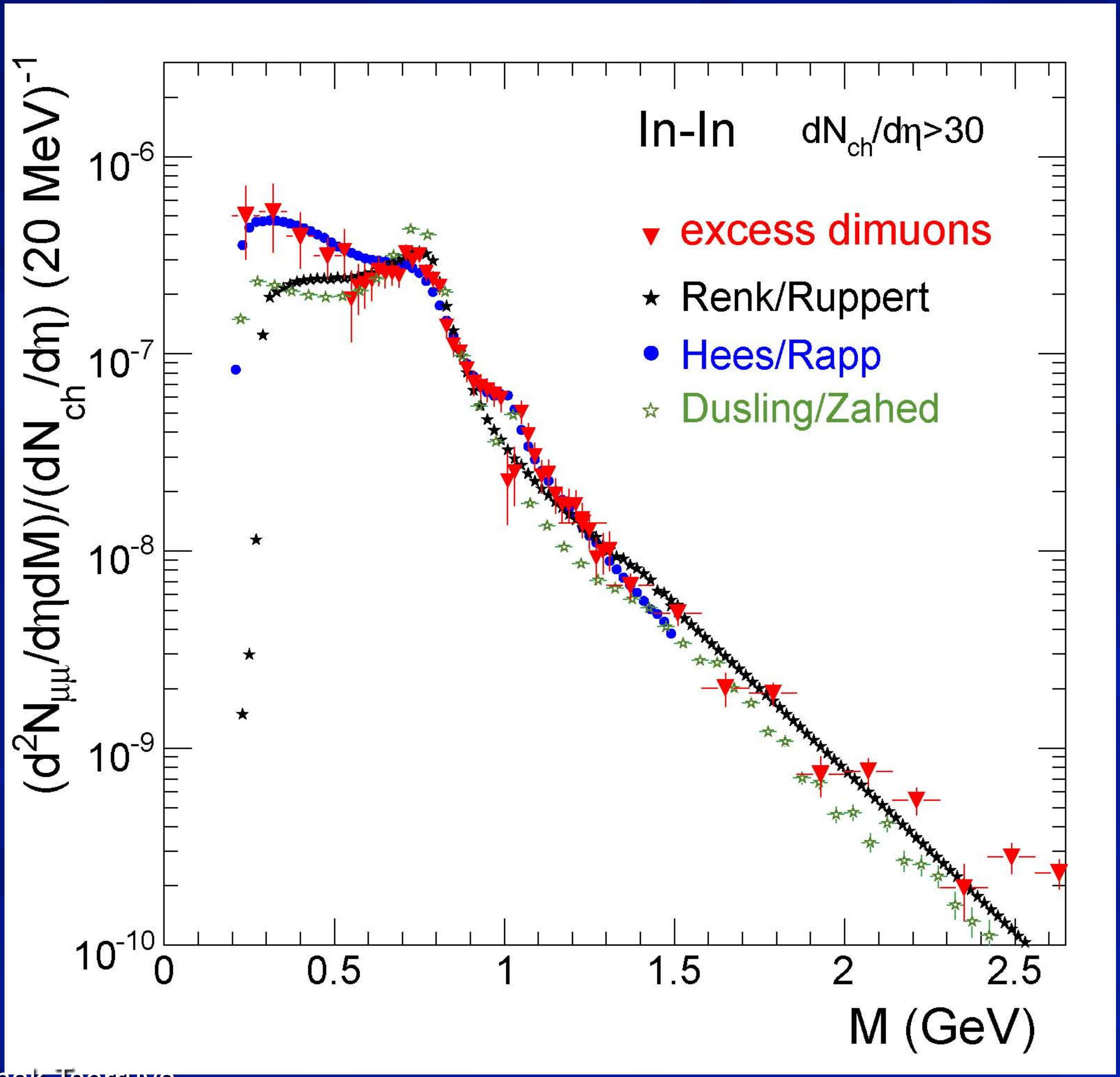
NA60 low mass: comparison with models



- **Subtract the cocktail (without the ρ) from the data**
- **Excess shape consistent with broadening of the ρ (Rapp-Wambach)**
- **Mass shift of the ρ (Brown-Rho) is ruled out**
  - Conclusions valid also as a function of p_T
- **Is this telling us something about CSR?**

- Theoretical yields normalized to data in the mass window $m_{\mu\mu}$ < 0.9 GeV
- All calculations for In-In by Rapp et al., for $\langle dN_{ch}/d\eta \rangle$ = 140

Acceptance corrected invariant mass spectrum



Mass spectrum corrected for acceptance in m - p_T

- SPS

Intermediate masses

(m = 1-3 GeV/c^2)

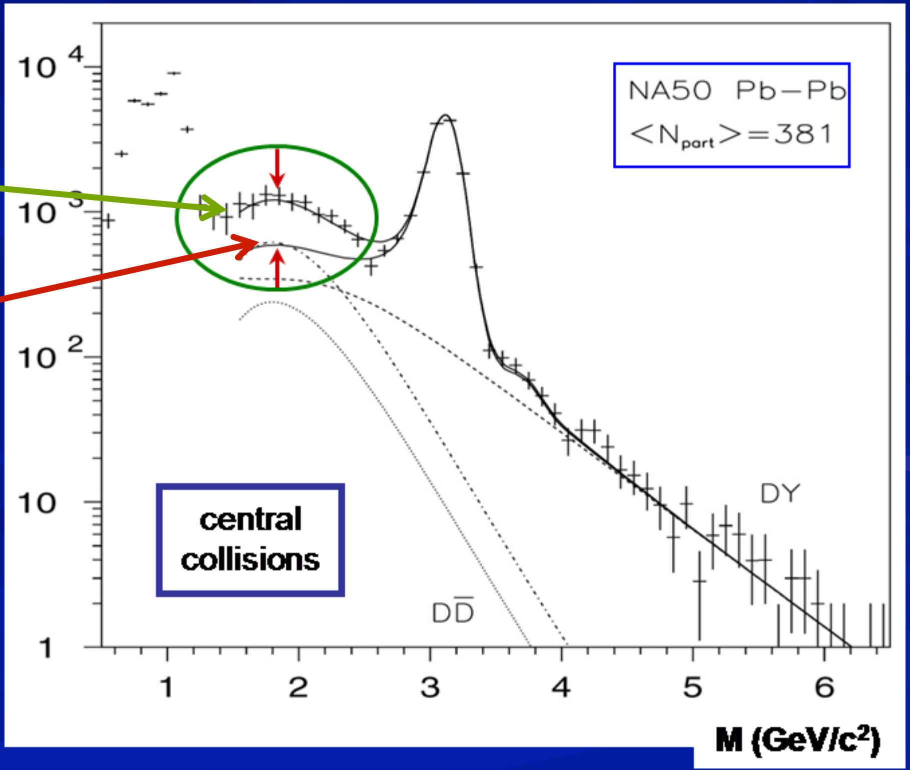
NA50 IMR Results

- Drell-Yan and Open Charm are the main contributions in the IMR
- p-A is well described by the sum of these two contributions (obtained from Pythia)
- The yield observed in heavy-ion collisions exceeds the sum of DY and OC decays, extrapolated from the p-A data.
- The excess has mass and p_T shapes similar to the contribution of the Open Charm (DY + 3.6OC nicely reproduces the data).

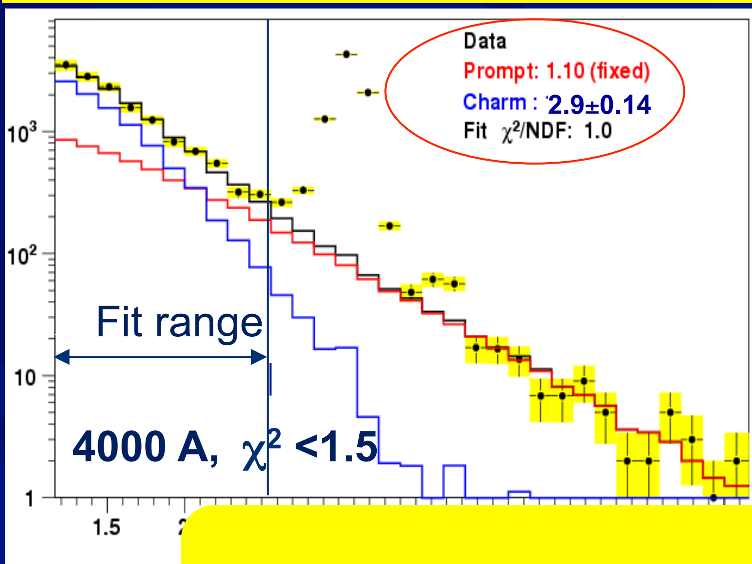
Drell Yan + 3.6 x Open charm

Drell Yan + Open charm

charm enhancement?



NA60: IMR excess in agreement with NA50



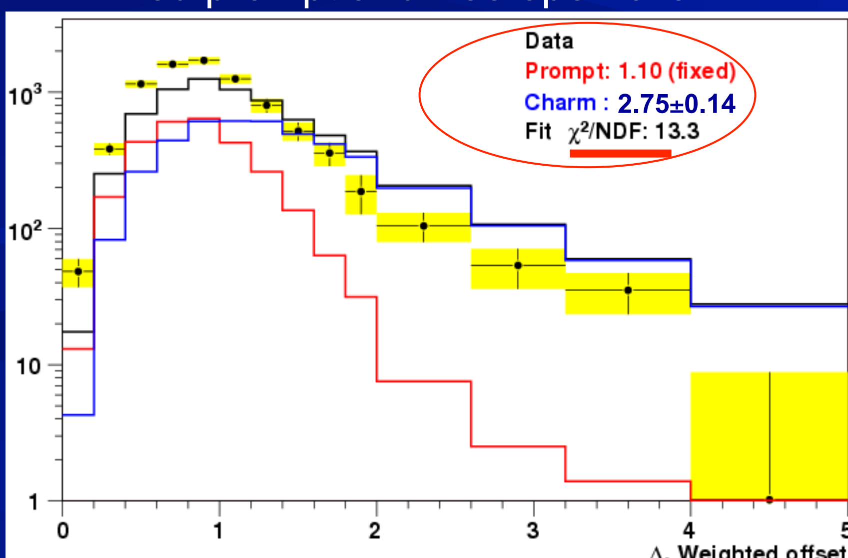
- IMR yield in In-In collisions enhanced compared to expected yield from DY and OC
- Can be fitted with fixed DY (within 10%) and OC enhanced by a factor of ~3

Full agreement with NA50

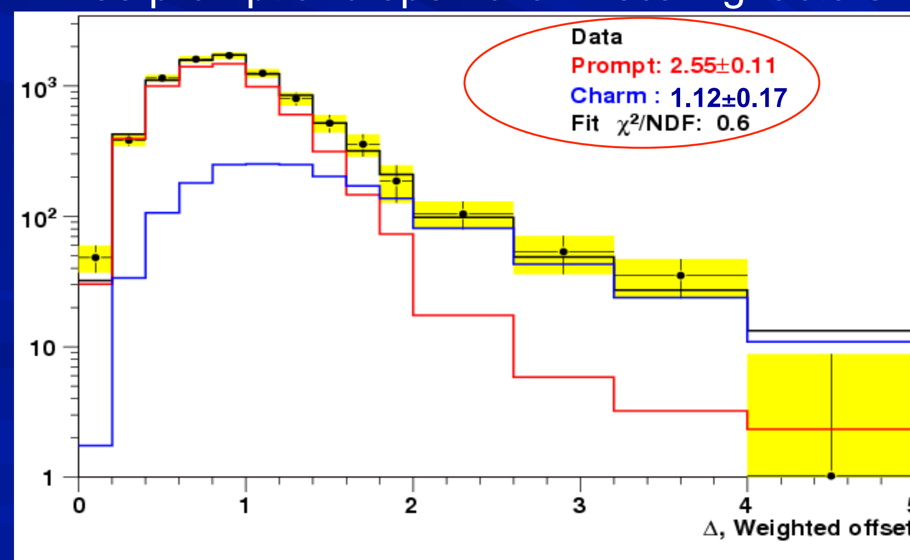
… But t

NA60:
IMR excess is a prompt source

Fixed prompt and free open charm

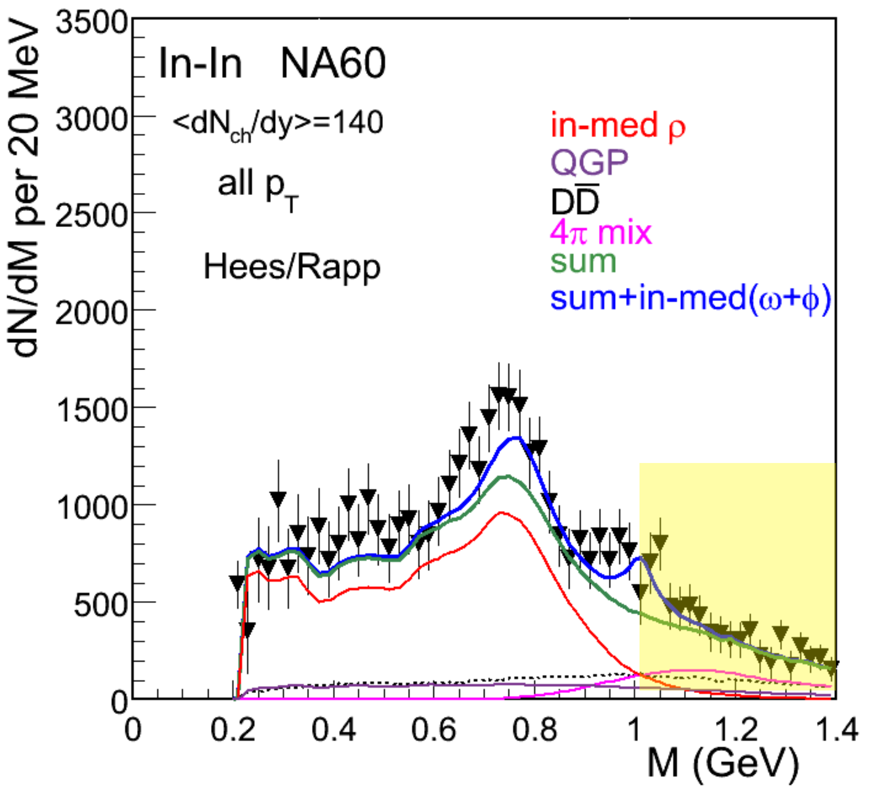


Free prompt and open charm scaling factors

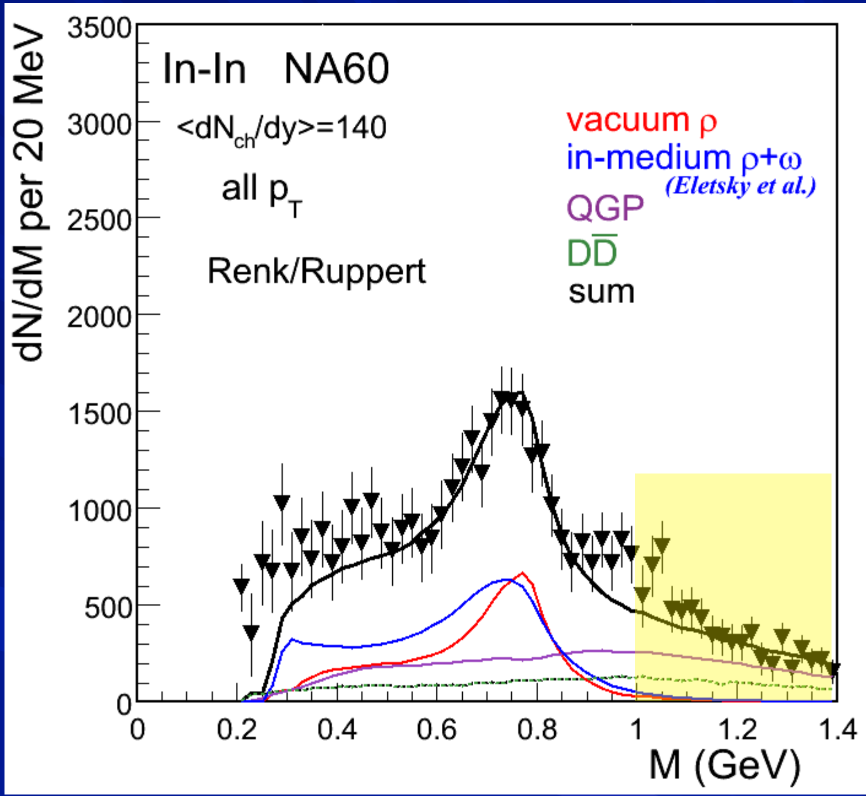


Origin of the IMR Excess

Hees/Rapp, PRL 97, 102301 (2006)



Renk/Ruppert, PRL 100,162301 (2008)



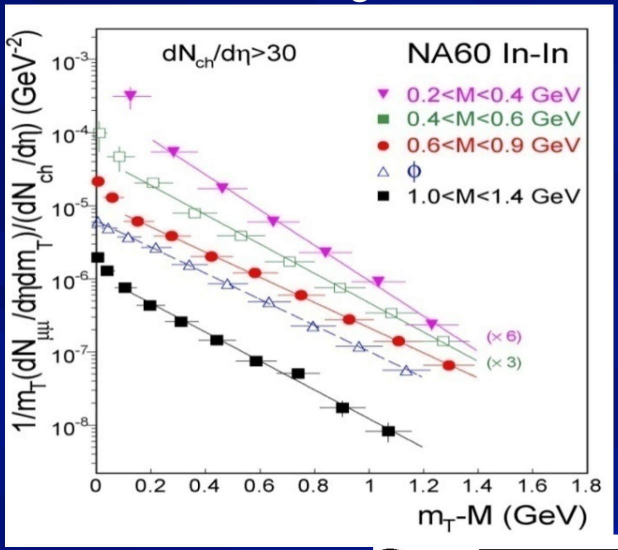
Dominant process in mass region m > 1 GeV/c^2:

hadronic processes, 4π … **partonic processes, qq annihilation**

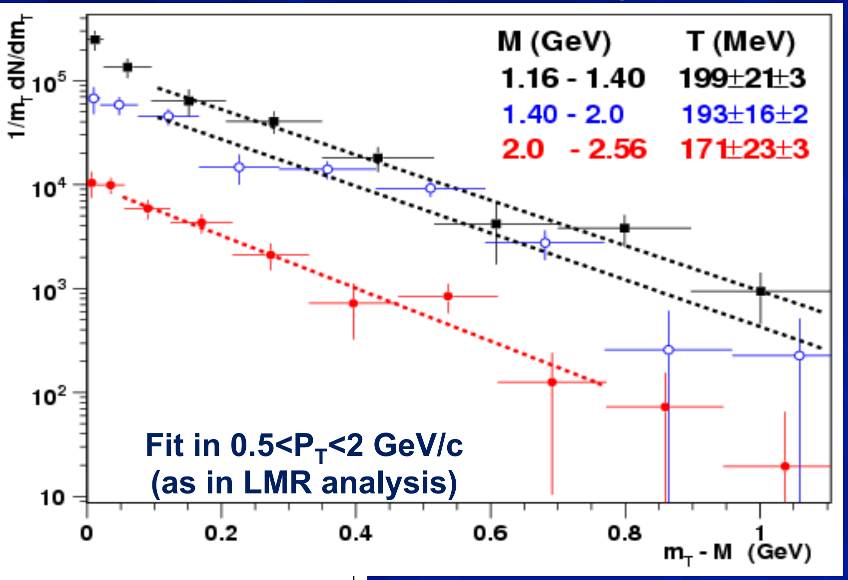
Quark-Hadron duality?

p_T distributions

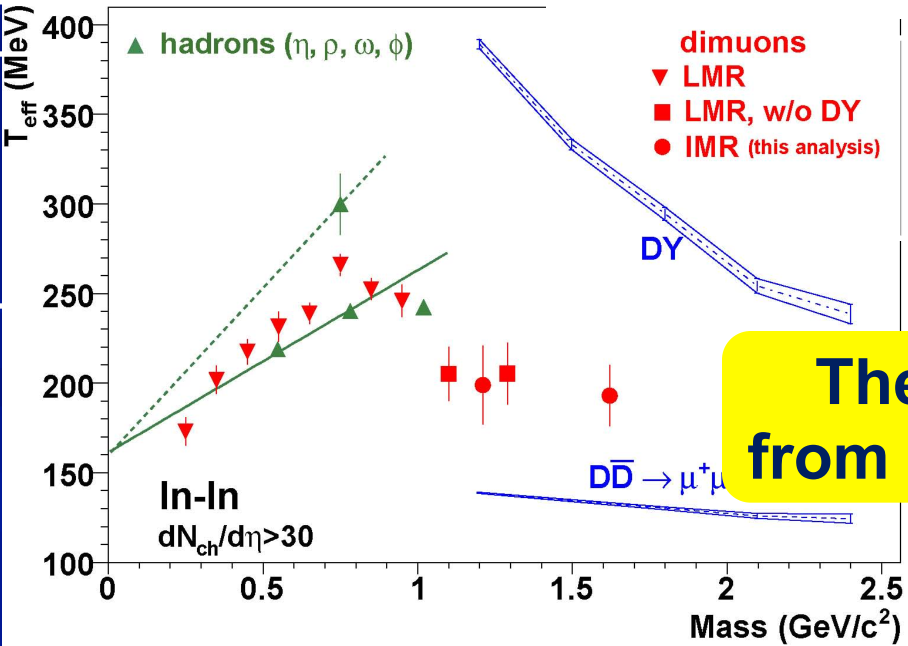
Low-mass region



Intermediate mass region



- m_T spectra exponential
- inverse slopes depend on mass.
  → Radial Flow



- m_T spectra exponential
- inverse slopes do not depend on mass.

Thermal radiation from partonic phase?

Dileptons in heavy-ion collisions: Experiment

HISS, JINR Dubna
September 4-6, 2012

Itzhak Tserruya

WEIZMANN INSTITUTE OF SCIENCE

Lecture III

Review of experiments and results (II)

PHENIX, STAR

- RHIC

Low-mass e^+e^- Pairs: Prospects at RHIC

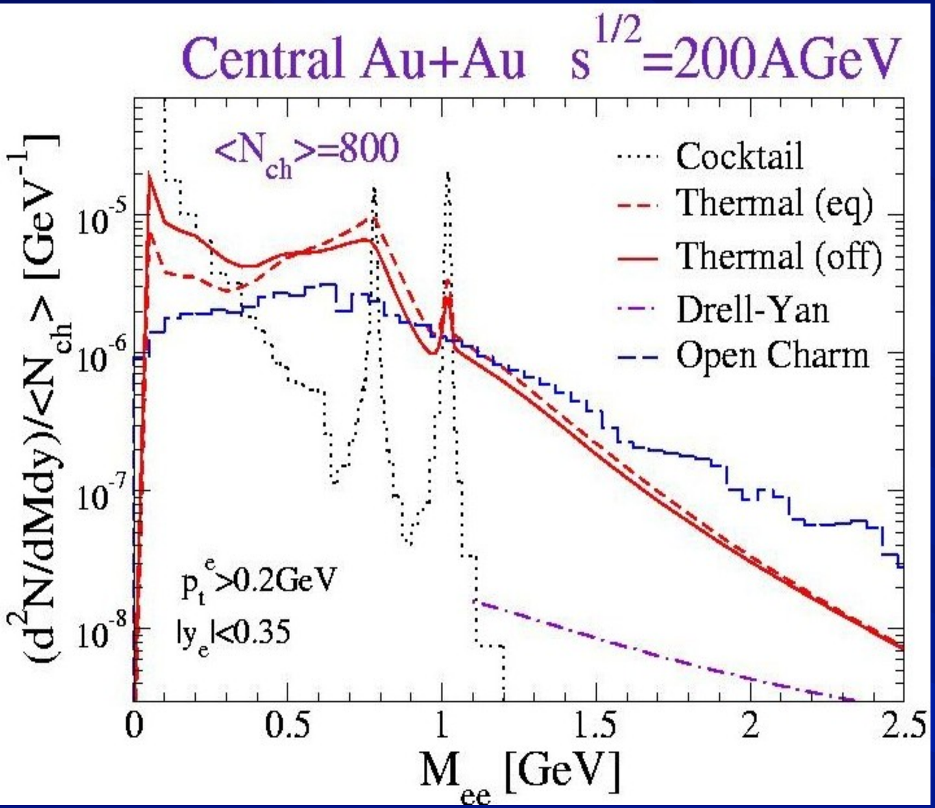
- At SPS energies, the ρ-meson broadening, that explains both the CERES and NA60 data, relies on a high baryon density.
- What can we expect at RHIC?

	SPS (Pb-Pb)	RHIC (Au-Au)
$dN(\bar{p})/dy$	6.2	20.1
Produced baryons ($\bar{p}$, p, $\bar{n}$, n)	24.8	80.4
$p - \bar{p}$	33.5	8.6
Participants nucleons $(p - \bar{p})A/Z$	85	21.4
Total baryon density	110	102

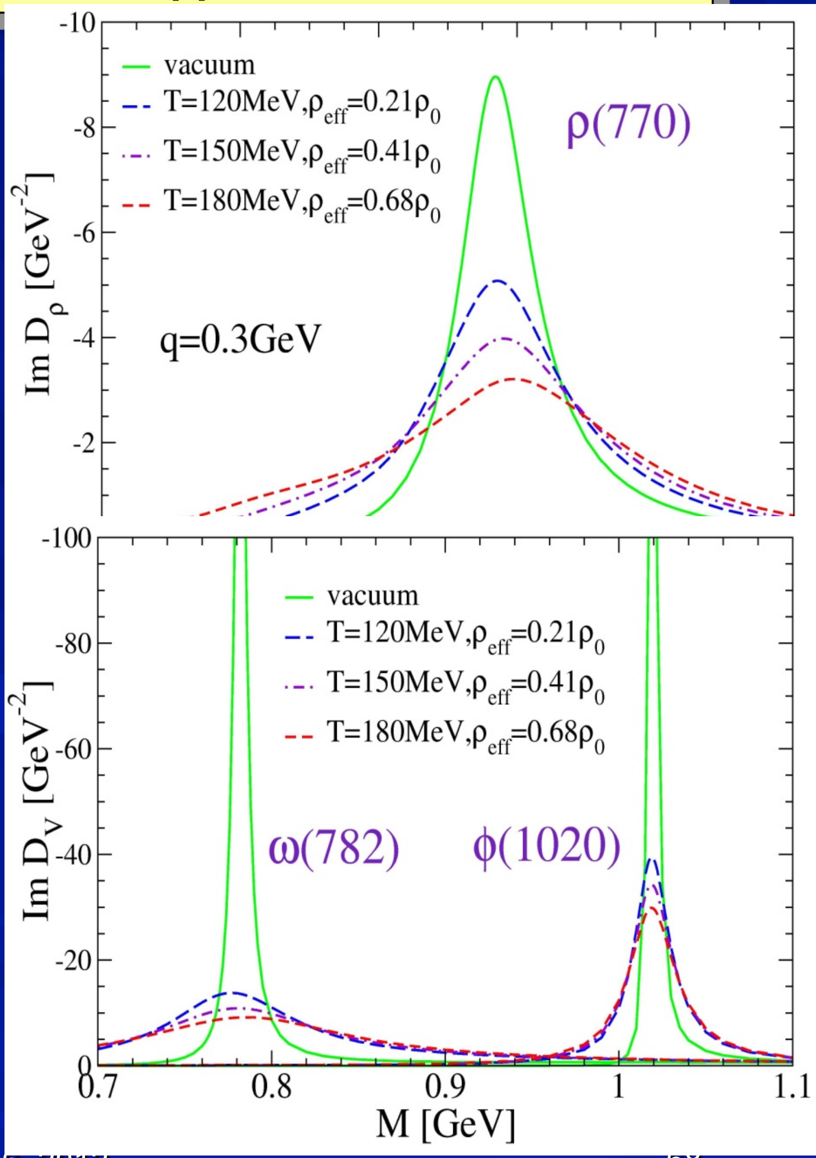
- Baryon density is almost the same at RHIC and SPS

(the decrease in the participating nucleons transported to mid-rapidity is accidentally compensated by the copious production of nucleon-antinucleon pairs)

Low-mass e^+e^- Pairs: Prospects at RHIC



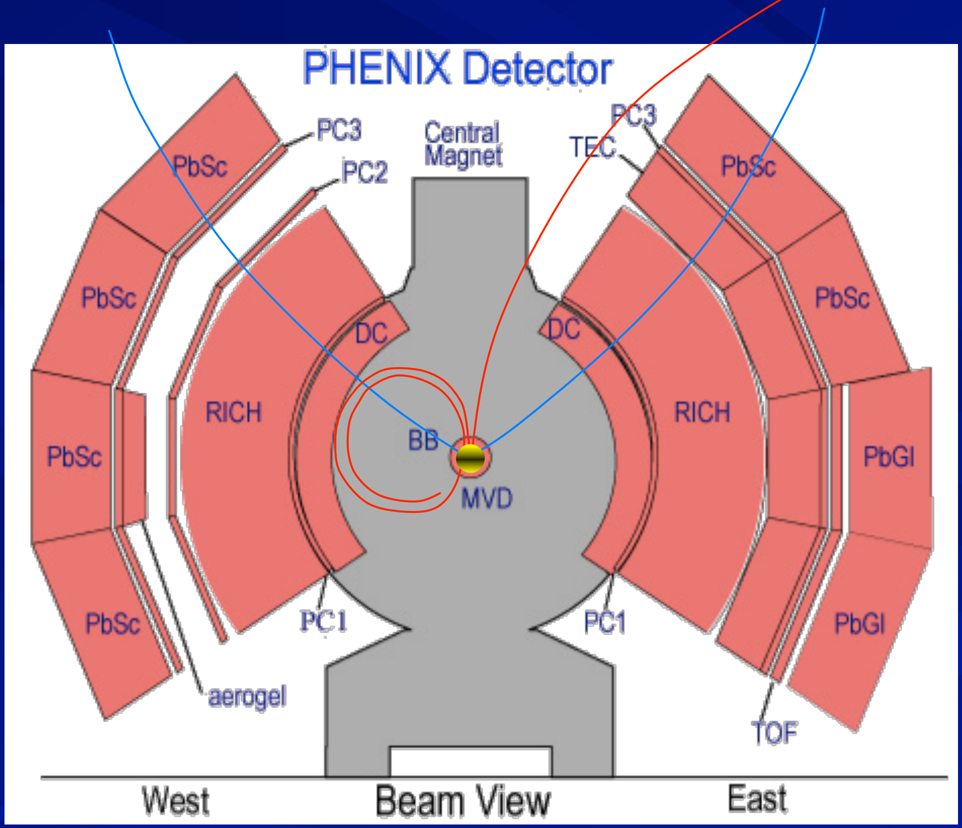
R. Rapp nucl-th/0204003



- **Strong enhancement of low-mass pairs persists at RHIC**
- **Open charm contribution becomes significant**

- Dileptons in PHENIX

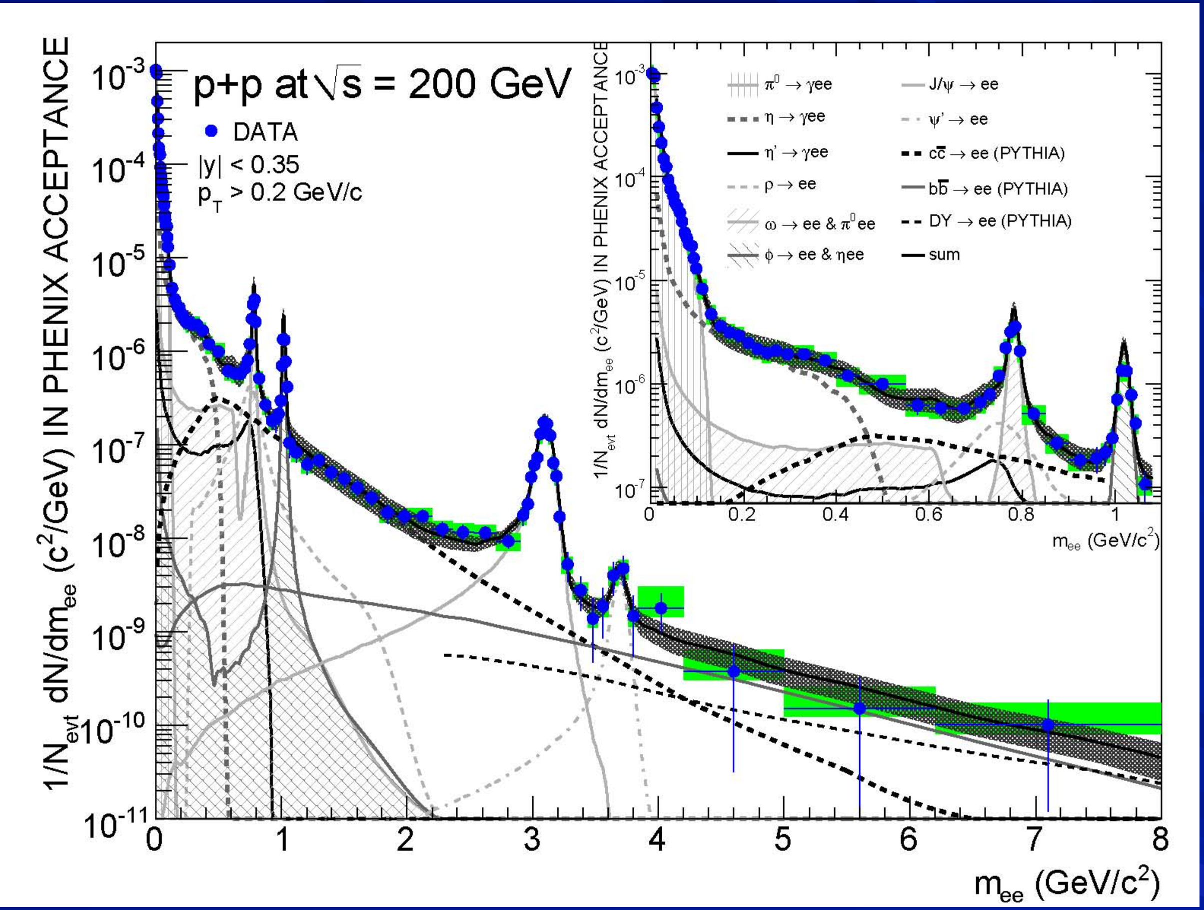
PHENIX central arm spectrometer



- Tracking: DC – PC1 – EmCal

  $\sigma(p_T)/p_T = 0.7\% \oplus 1\% p_T$
- Electron identification based on:
  - * RICH
  - * E/p
- No background rejection

Dileptons in PHENIX: p+p collisions



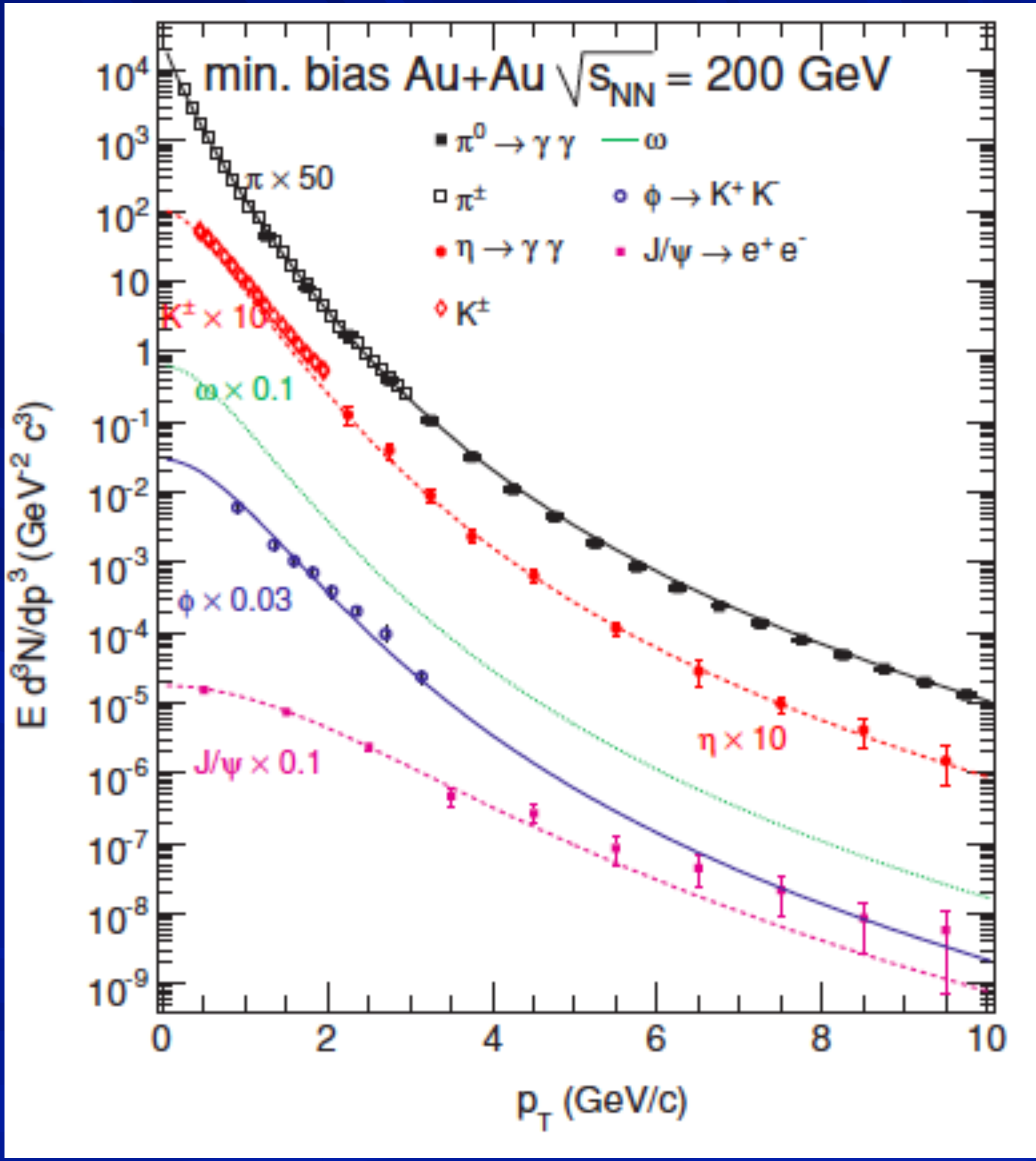
- ❑ Mass spectrum measured from m=0 up to m=8 GeV/c^2
- ❑ Very well understood in terms of:
  - ➢ hadron cocktail at low masses
  - ➢ heavy flavor + DY at high masses using PYTHIA

Au+Au Cocktail

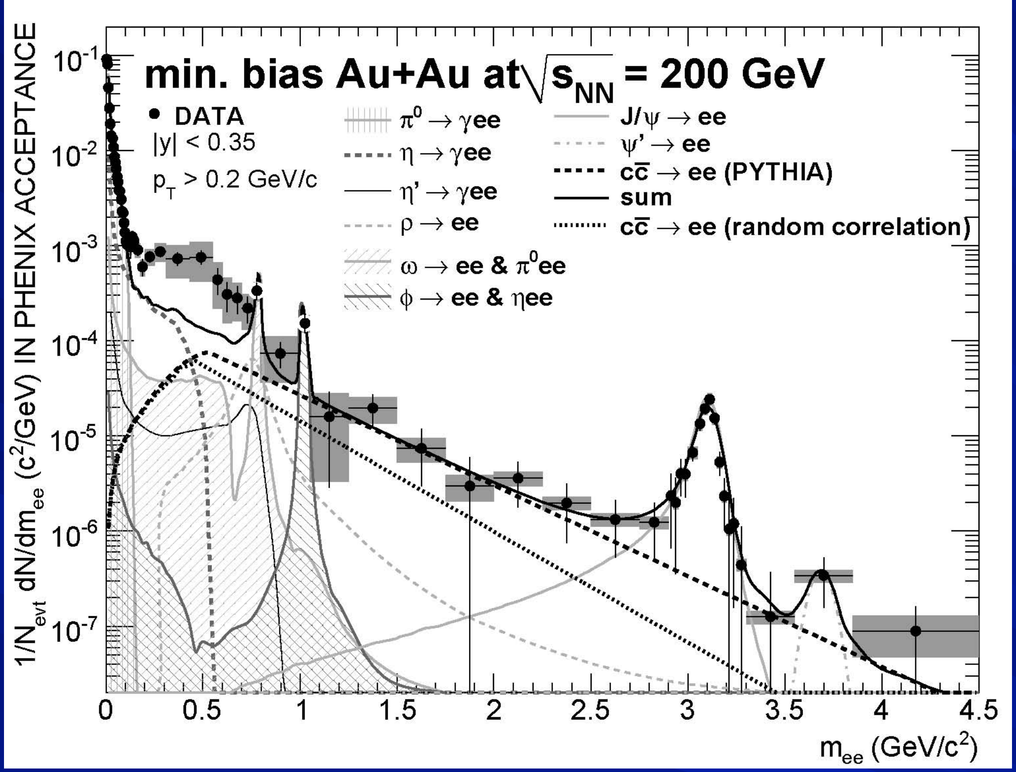
- π^0 and charged π data fit to a modified Hagedorn function:

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

- Use m_T scaling for shape of other hadrons, normalize to measured data
- Fits are done independently for each particle and each centrality
- Open heavy flavor (c,b) contributions determined using PYTHIA fitted to pp data and scaled to Au+Au with N_{coll}



Dileptons in PHENIX: Au+Au collisions

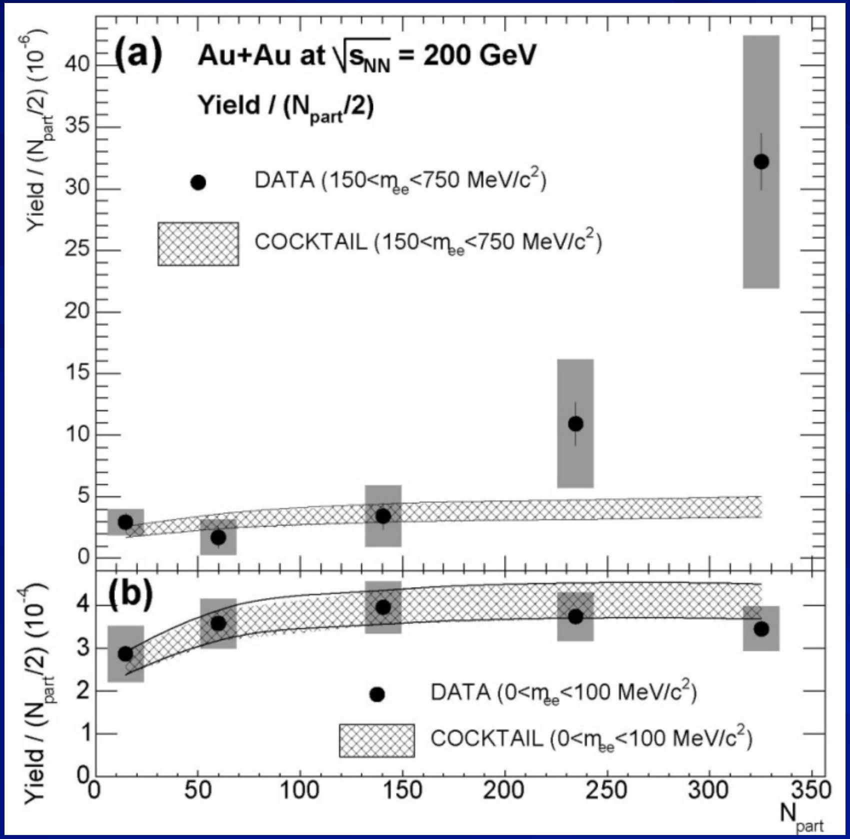


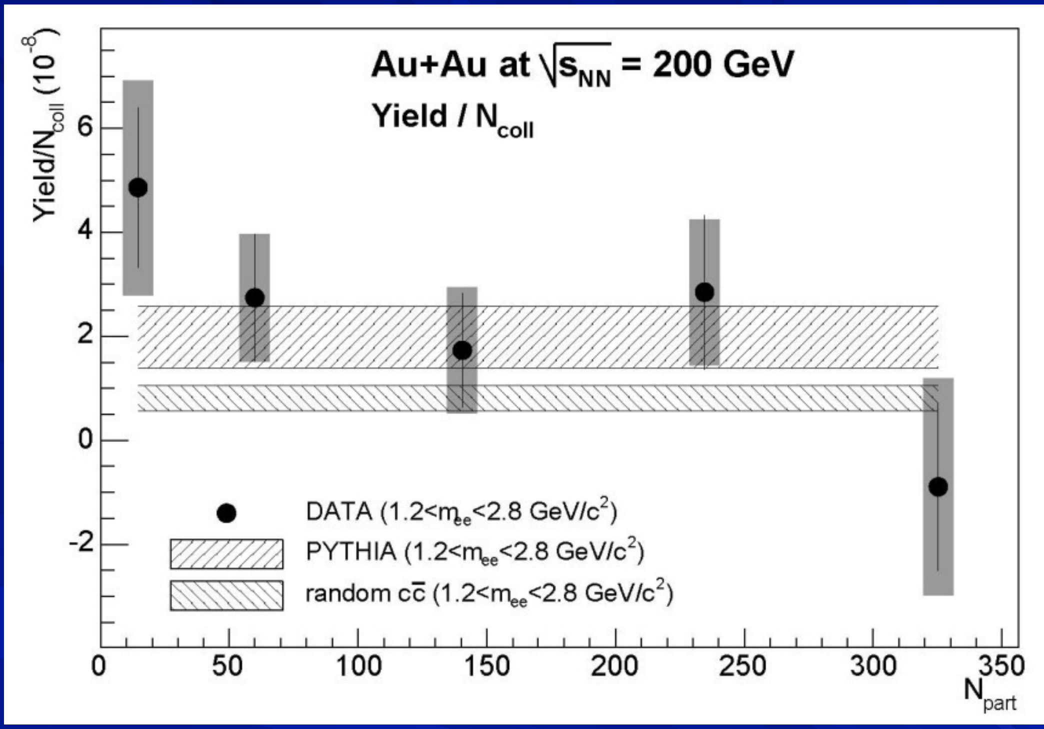
PRC 81, 034911 (2010)

In the LMR
S/B = 1/200

- LMR: Strong enhancement of e^+e^- pairs at m= 0.15 – 0.75 GeV/c^2.
  - min. bias 4.7 ± 0.4 (stat.) ±1.5 (syst.)
  - central collisions 7.6 ± 0.5 (stat.) ± 1.3 (syst.)
  - Enhancement down to very low masses
- IMR: surprising agreement with pp charm contribution scaled with N_{coll}

Dileptons in PHENIX: Au+Au collisions

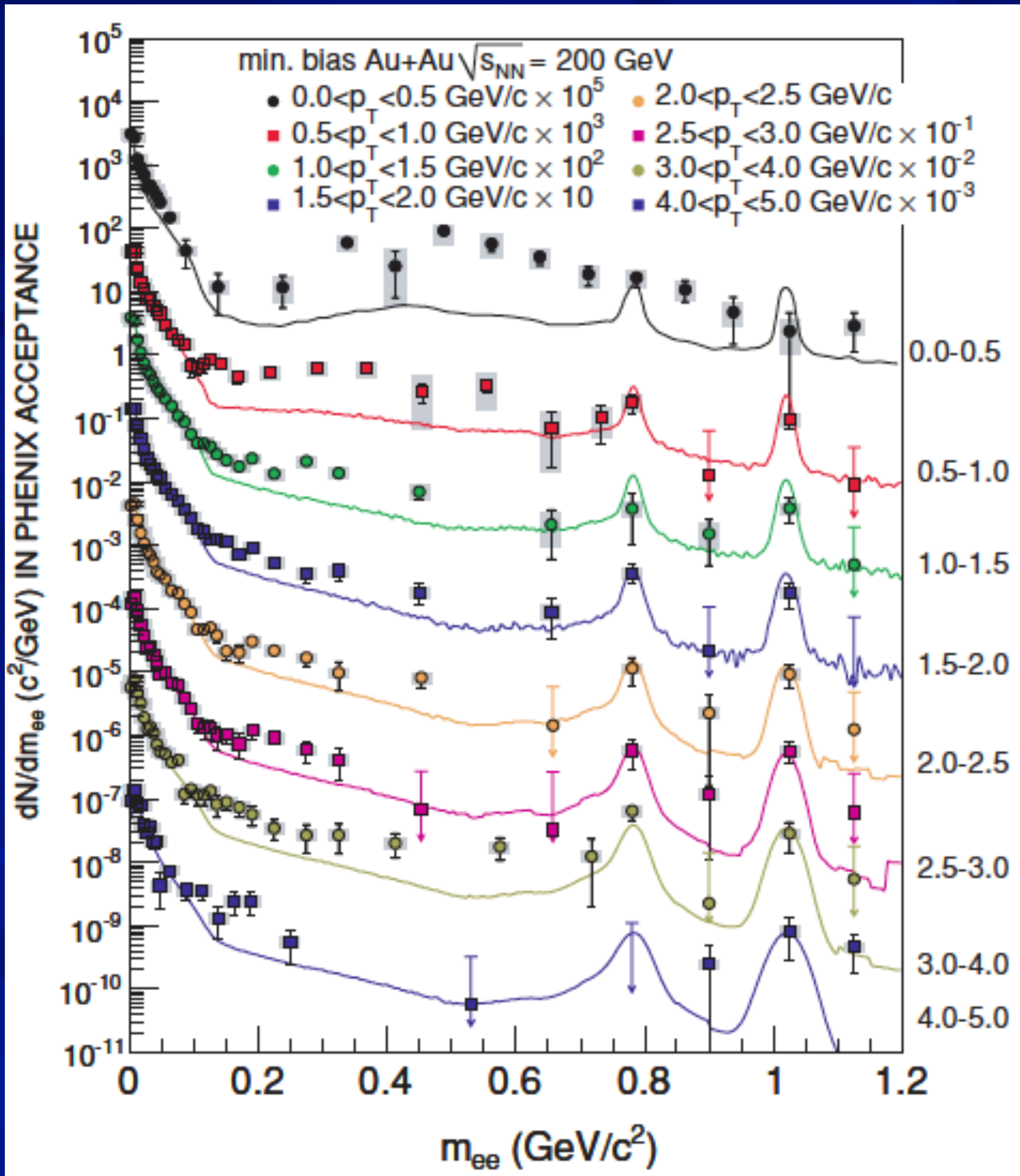




PRC 81, 034911 (2010)

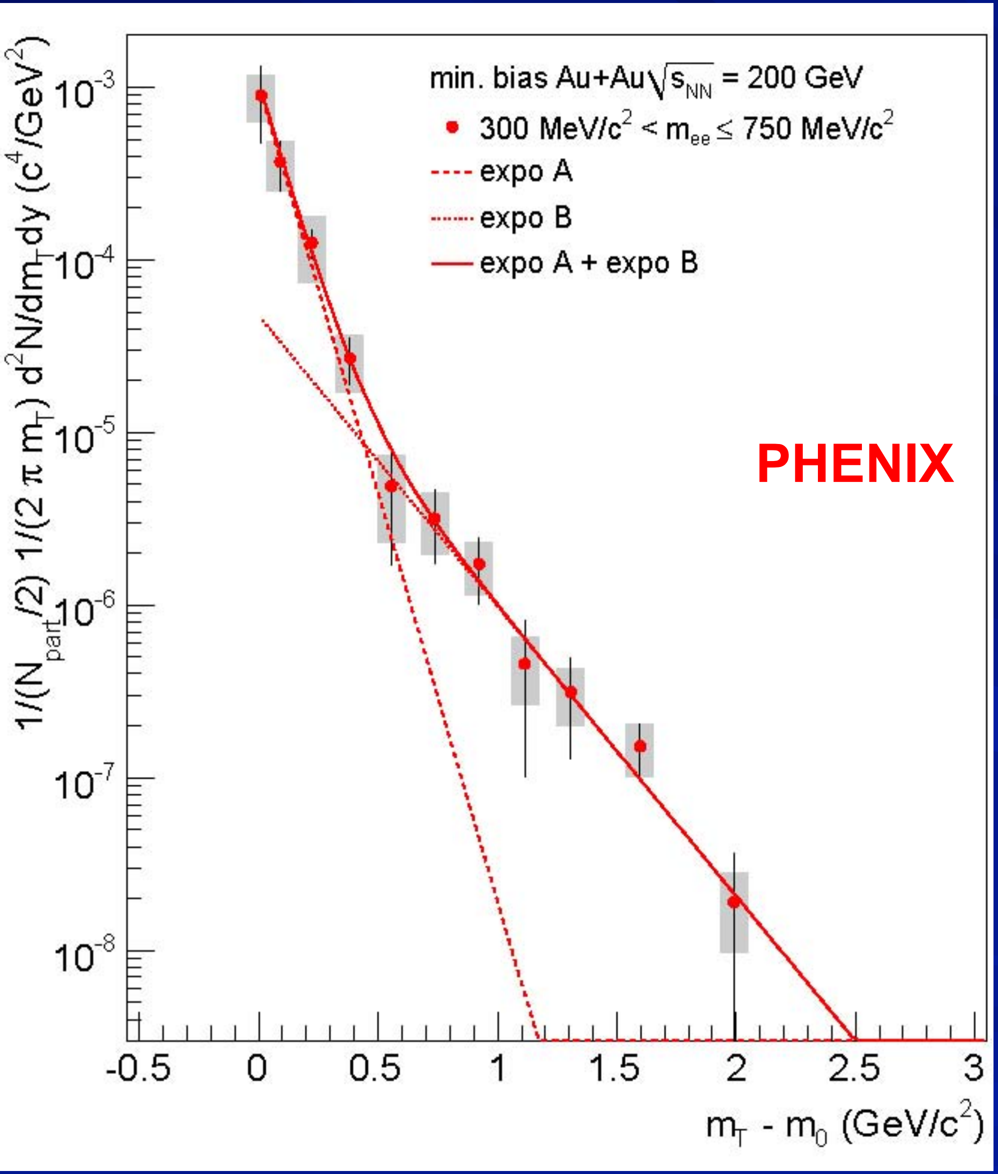
- Characteristic properties:
  - Enhancement concentrated in central collisions
  - No enhancement in the IMR

Low mass region: evolution with p_T



- Excess present at all pair p_T but more pronounced at low pair p_T

m_T distribution of low-mass excess



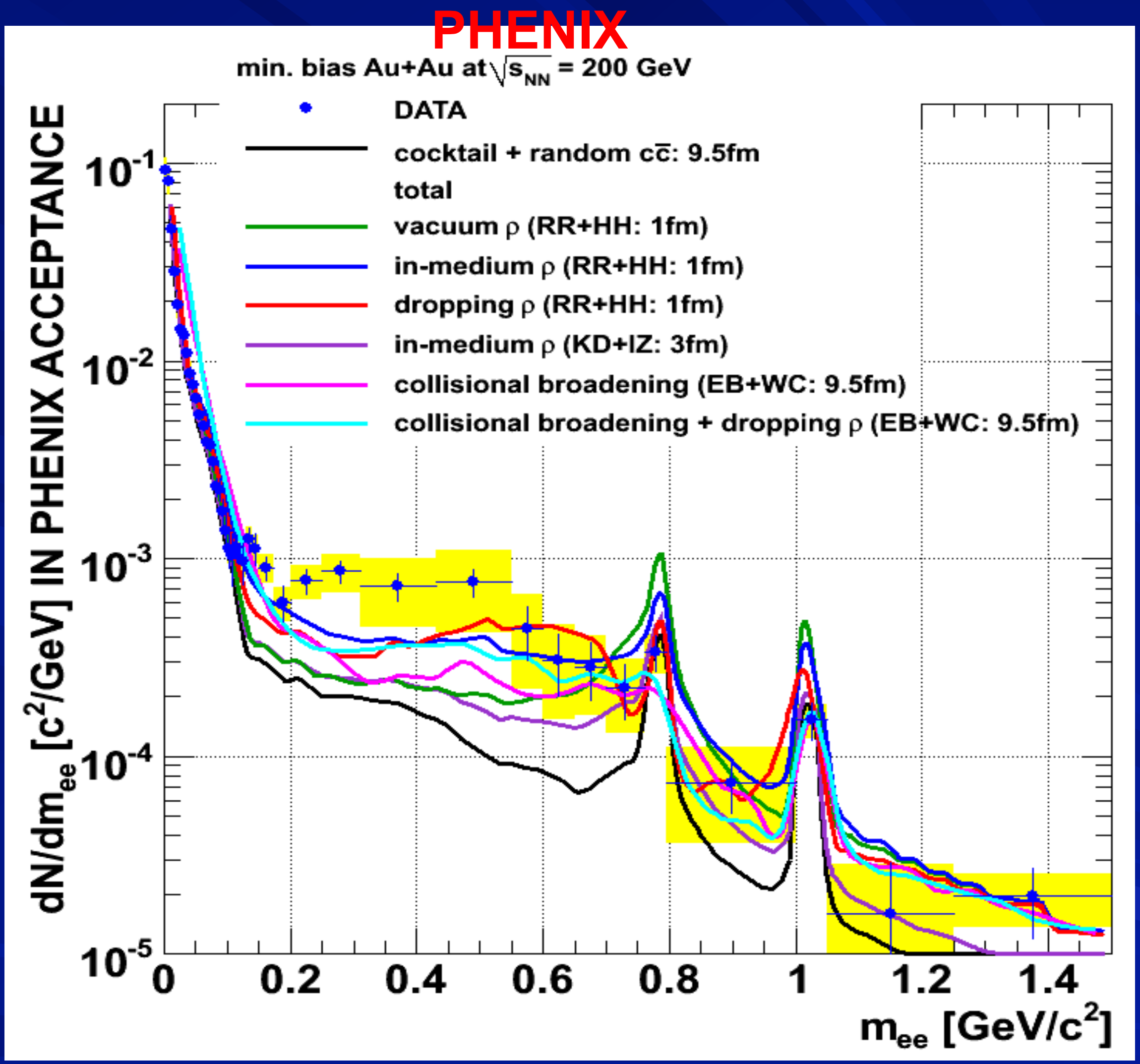
- Excess present at all pair p_T but is more pronounced at low pair p_T
- The excess m_T distribution exhibits two clear components
- It can be described by the sum of two exponential distributions with inverse slope parameters:

T1 = 92 ± 11.4^{stat} ± 8.4^{syst} MeV

T2 = 258.3 ± 37.3^{stat} ± 9.6^{syst} MeV

All this is very different from the SPS results

Comparison to theoretical models



All models and groups that successfully described the SPS data fail in describing the PHENIX results

- Dileptons in STAR

The STAR Detector

Large acceptance electron ID

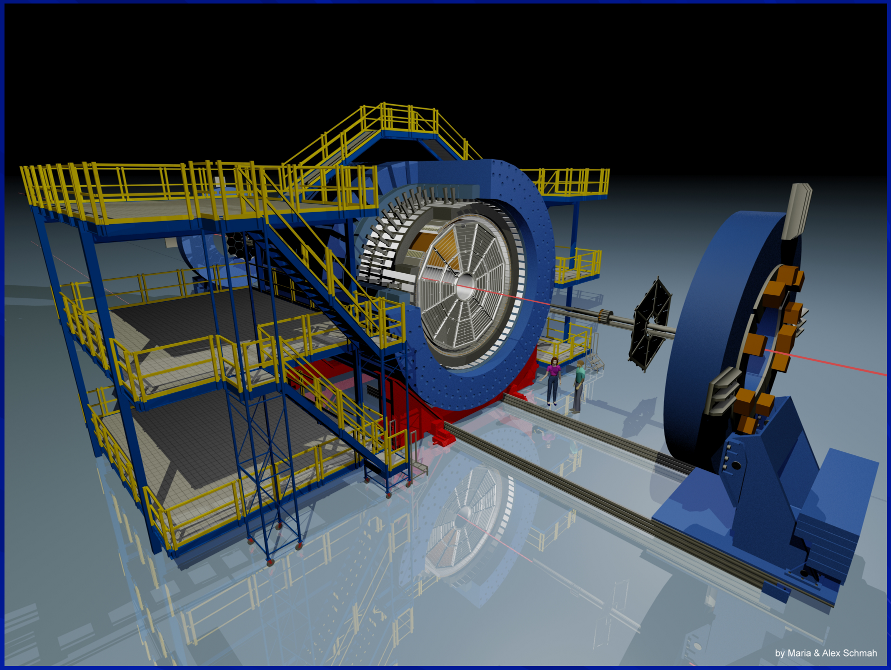
- Time Projection Chamber (dE/dx)

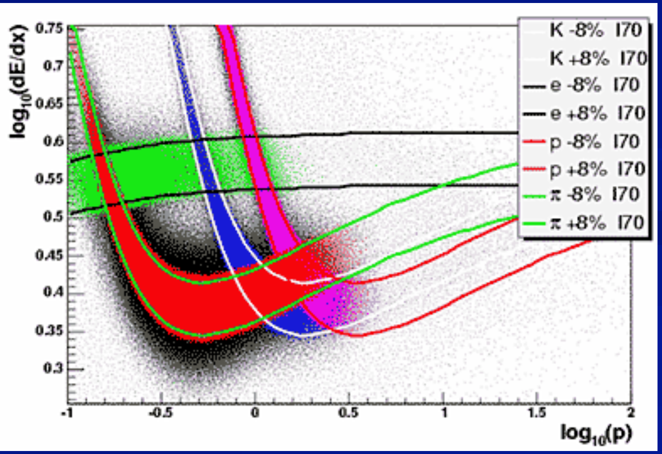
  $0<\phi<2\pi, |\eta|<1$

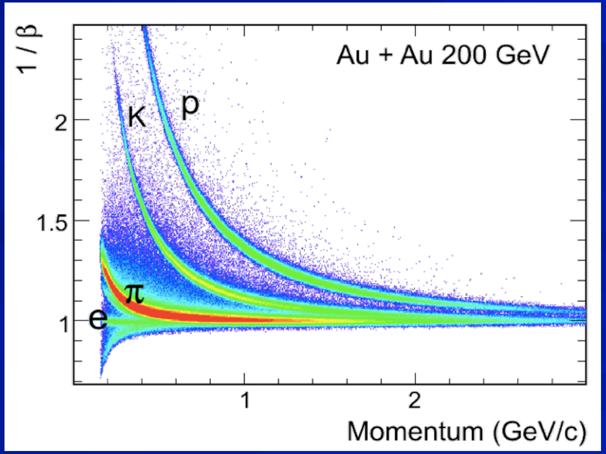
- Time-of-Flight detector (β)

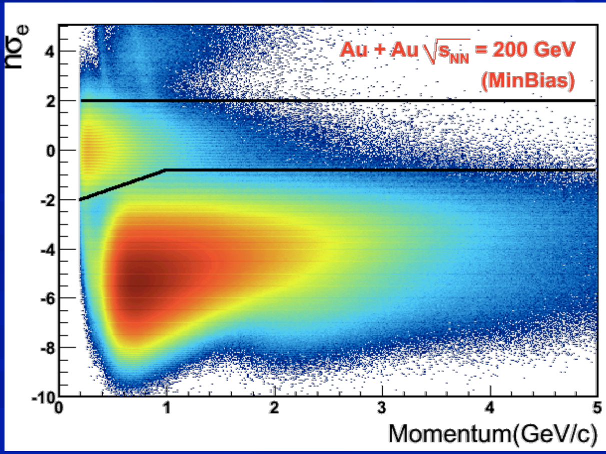
  $0<\phi<2\pi, |\eta|<0.9$

- Electromagnetic Calorimeter (E/p)
- Electron purity: central evts ~92%
- No rejection

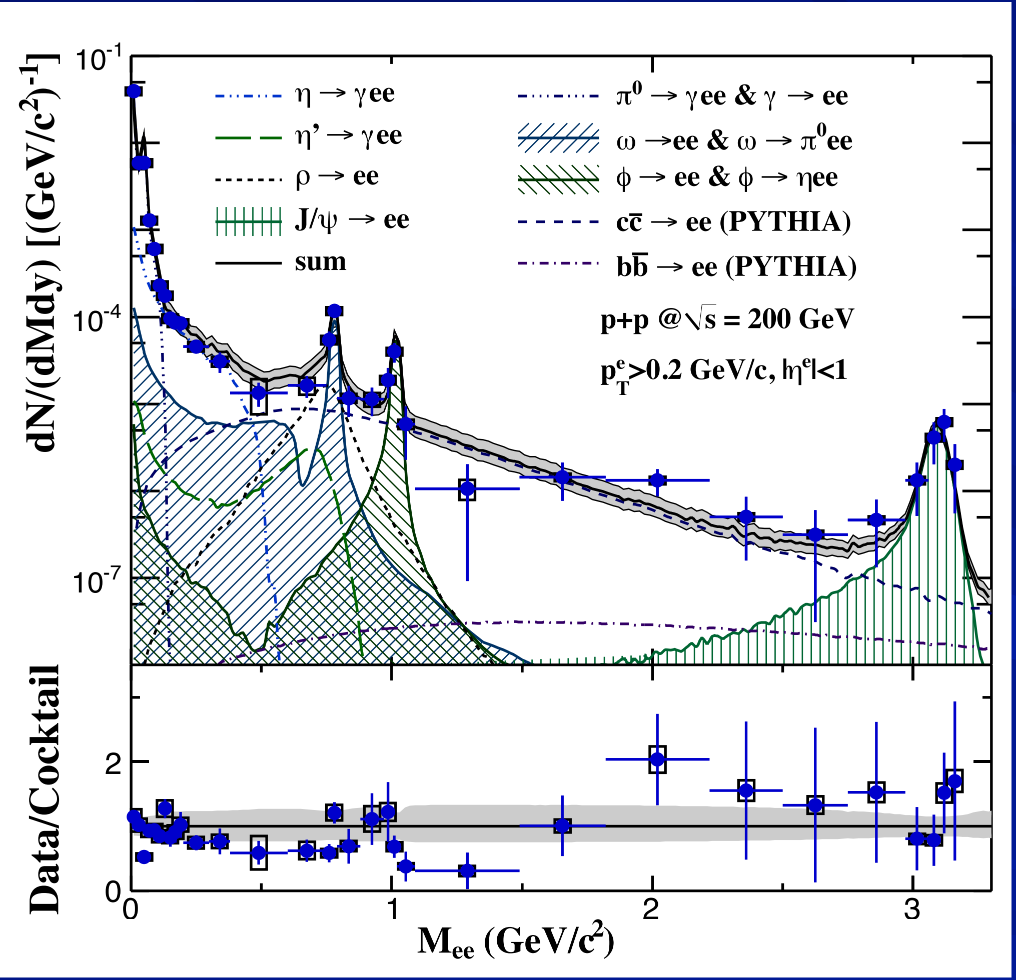








STAR p+p at 200 GeV



- Charm contribution dominates IMR
  - Cocktail uses the STAR charm cross-section

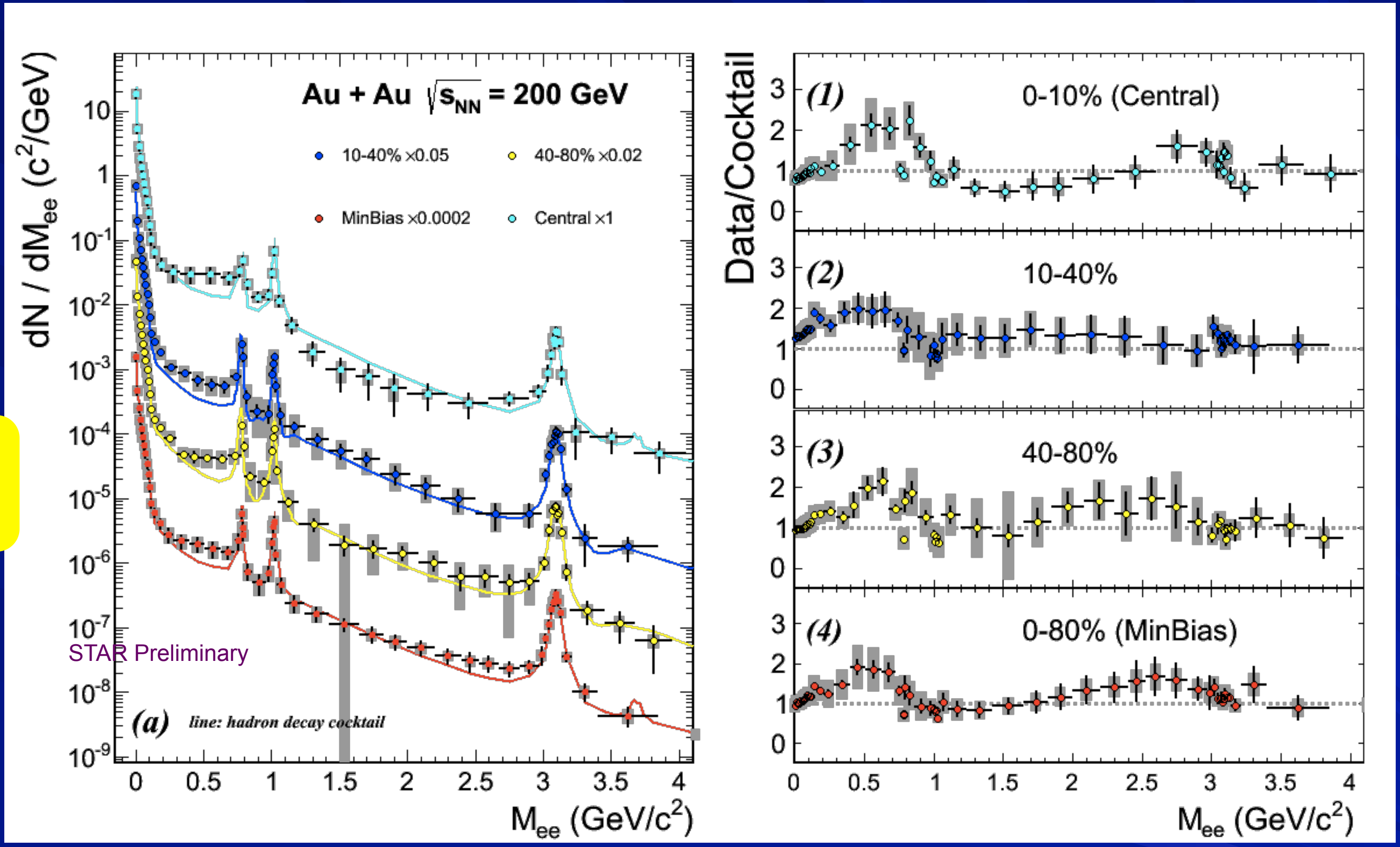
    Phys. Rev. Lett. 94 (2005) 062301

Uncertainties:

- vertical bars: statistical
- boxes: systematic
- grey band: cocktail simulation systematic
- not shown: 11% normalization

Data systematically below cocktail in the low-mass region!

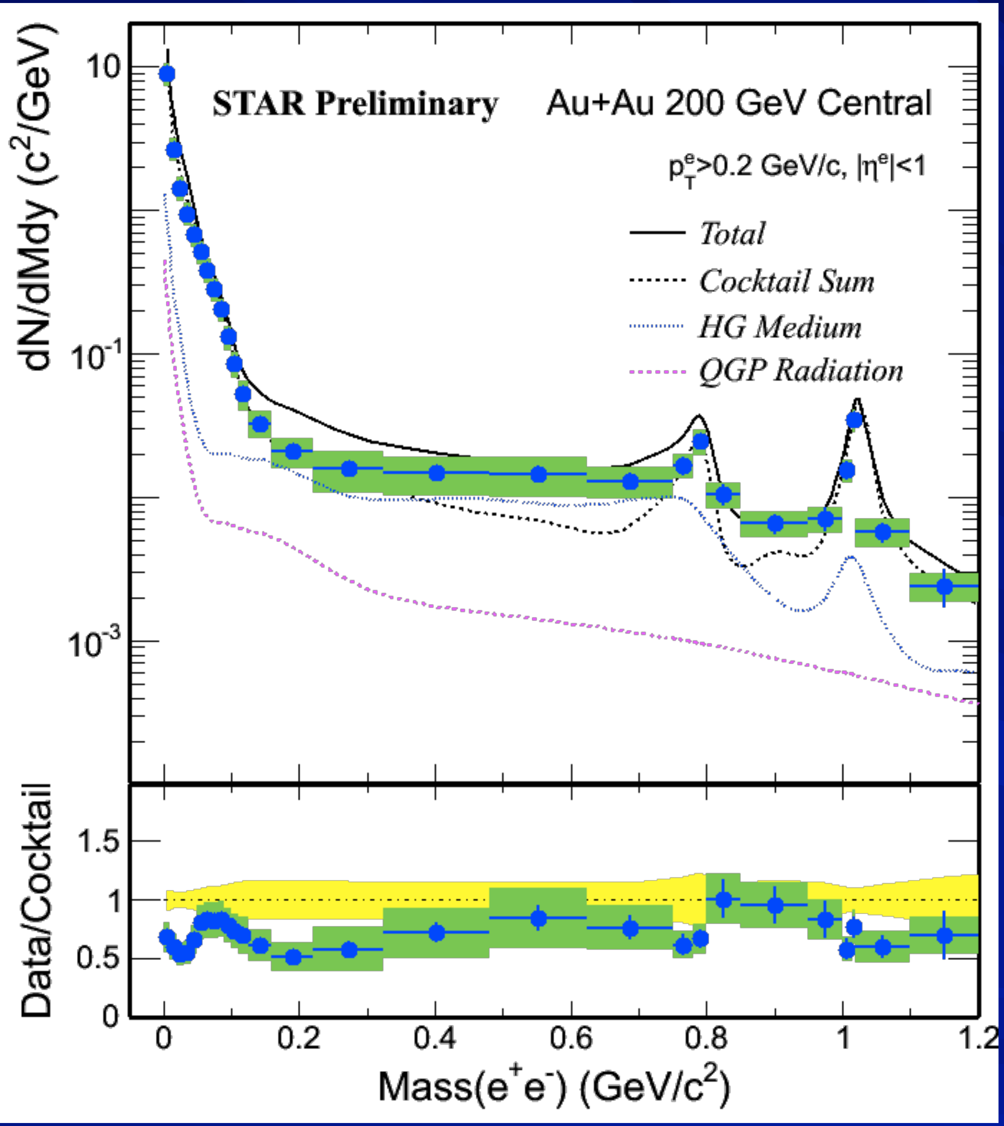
STAR Dileptons in Au+Au collisions



In the LMR
S/B = 1/200

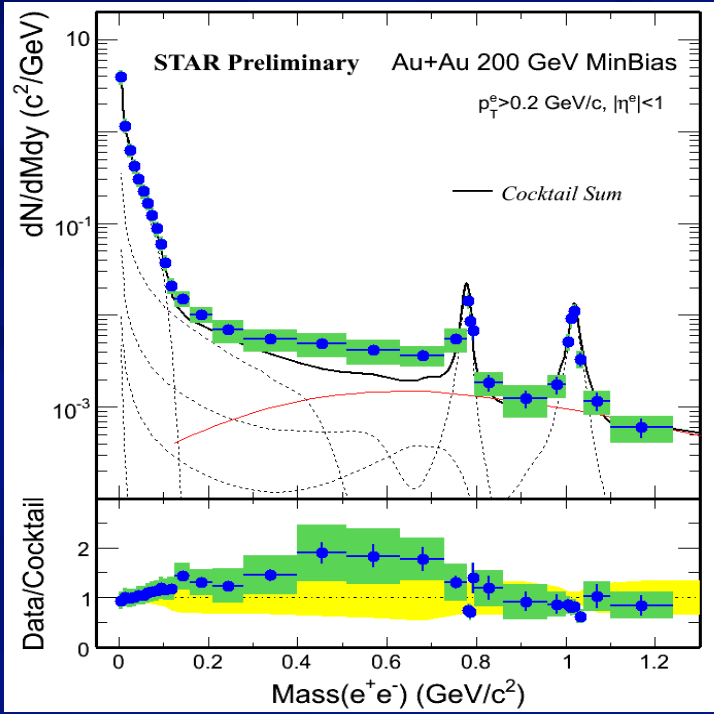
- LMR: enhancement wrt to cocktail
  little centrality dependence
- IMR: difficult to disentangle (modified) charm from thermal contributions

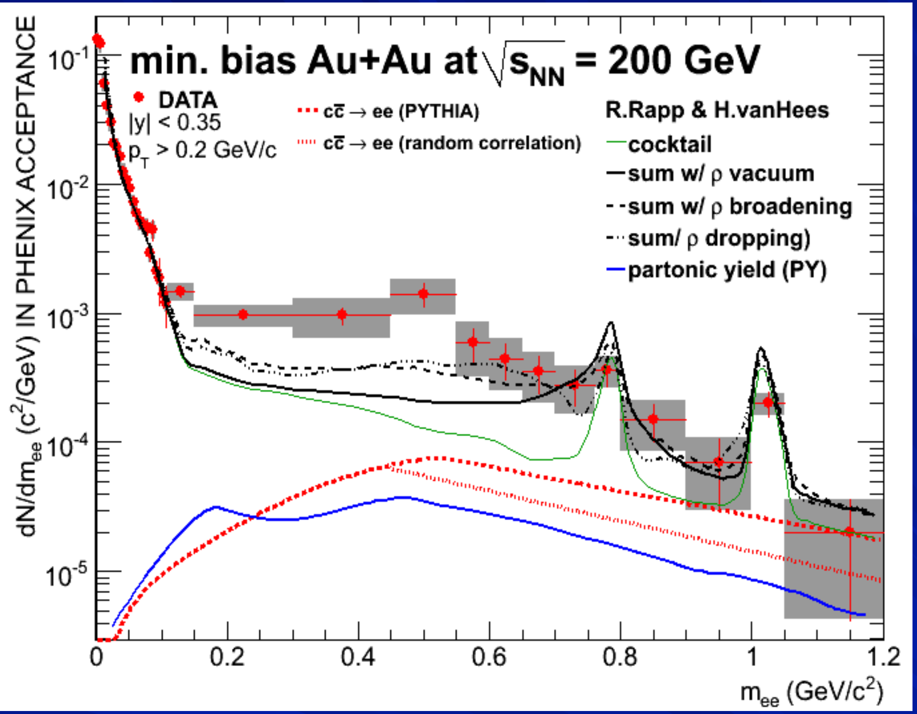
Compare to Rapp, Wambach, v. Hees



- STAR central 200 GeV Au+Au
- hadronic cocktail (STAR)
- Ralf Rapp (priv. comm. to STAR)
  Complete evolution (QGP+HG):
  cocktail + QGP + HG:
- Reasonable agreement with data

PHENIX vs. STAR





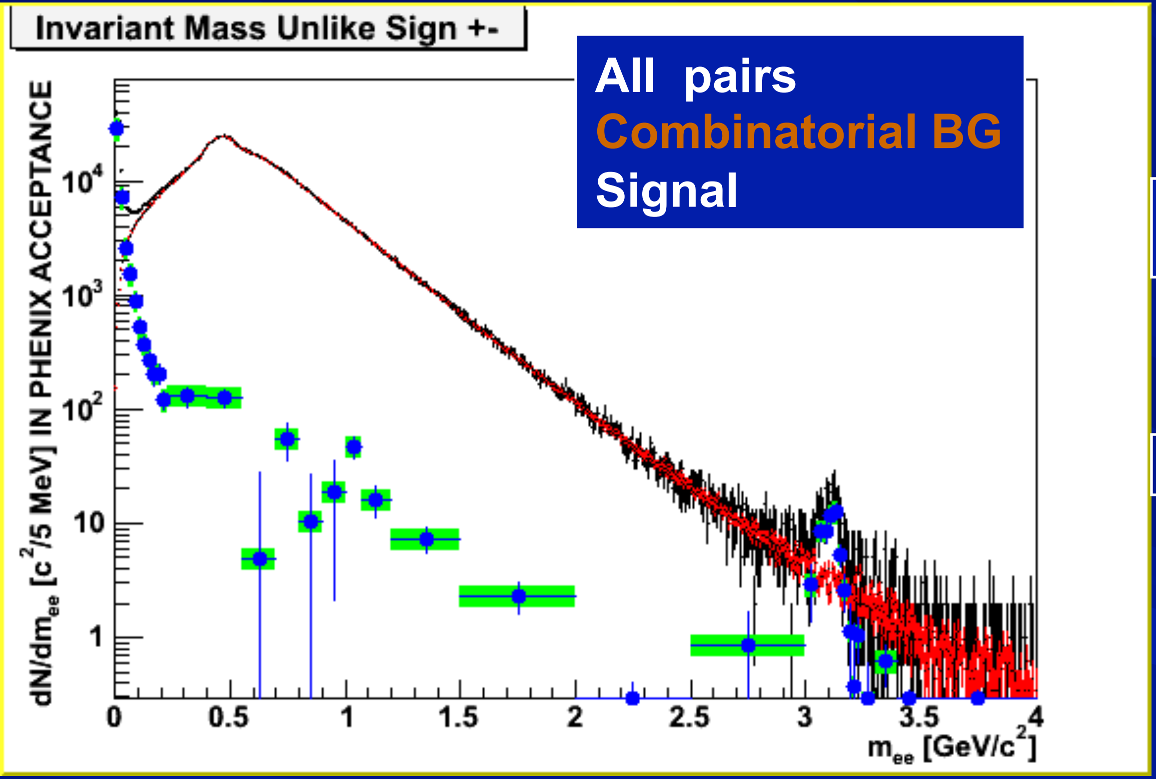
Enhancement factor in $0.15<M_{ee}<0.75$ Gev/c^2

	Minbias (value ± stat ± sys)	Central (value ± stat ± sys)
STAR	1.53 ± 0.07 ± 0.41 (w/o ρ) 1.40 ± 0.06 ± 0.38 (w/ ρ)	1.72 ± 0.10 ± 0.50 (w/o ρ) 1.54 ± 0.09 ± 0.45 (w/ ρ)
PHENIX	4.7 ± 0.4 ± 1.5	7.6 ± 0.5 ± 1.3
Difference	2.0 σ	4.2 σ

Dileptons in PHENIX: Au+Au collisions

Min bias Au+Au $\sqrt{s_{NN}}$ = 200 GeV
arXiv: 0706.3034 [nucl-ex]

Integral:180,000
above π^0:15,000

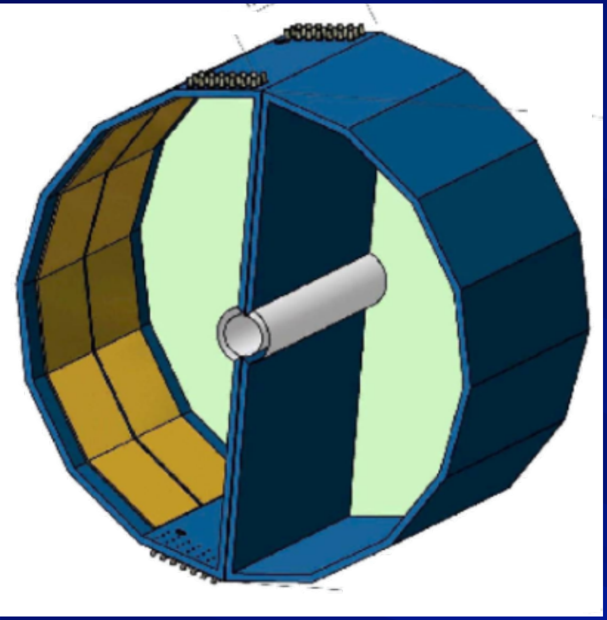


- BG determined by event mixing technique, normalized to like sign yield

- Green band: systematic error w/o error on CB

PHENIX has mastered the event mixing technique to unprecedented precision (±0.25%). But with a S/B ≈ 1/200 the *statistical significance is largely reduced* and the *systematic errors are large*
To improve the measurement PHENIX developed a Hadron Blind Detector

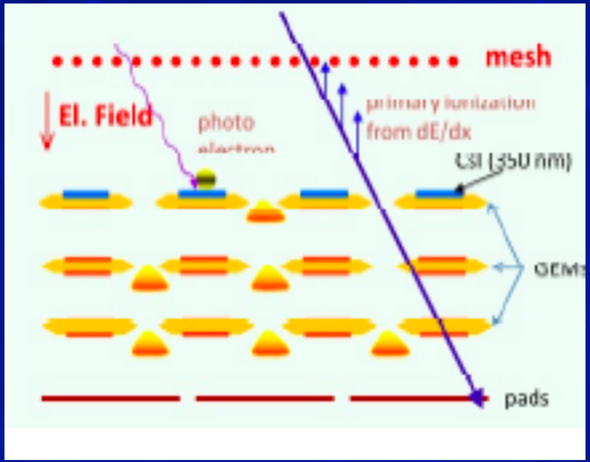
HBD performance



NIM A646, 35 (2011)

Windowless CF4 Cherenkov detector
GEM/CSI photo cathode readout
Operated in B-field free region

Goal: improve S/B by rejecting conversions and π^0 Dalitz decays

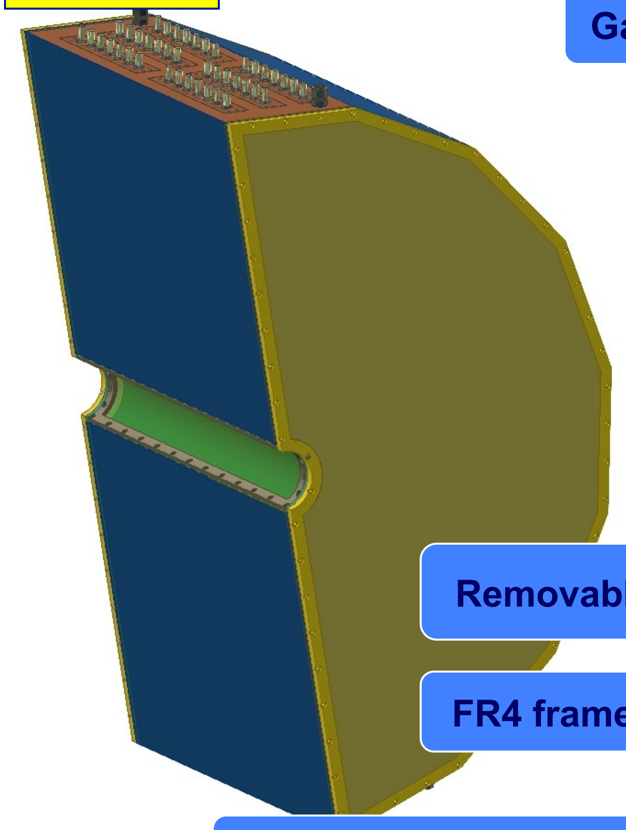


- Successfully operated:
  2009 p+p data
  2010 Au+Au data

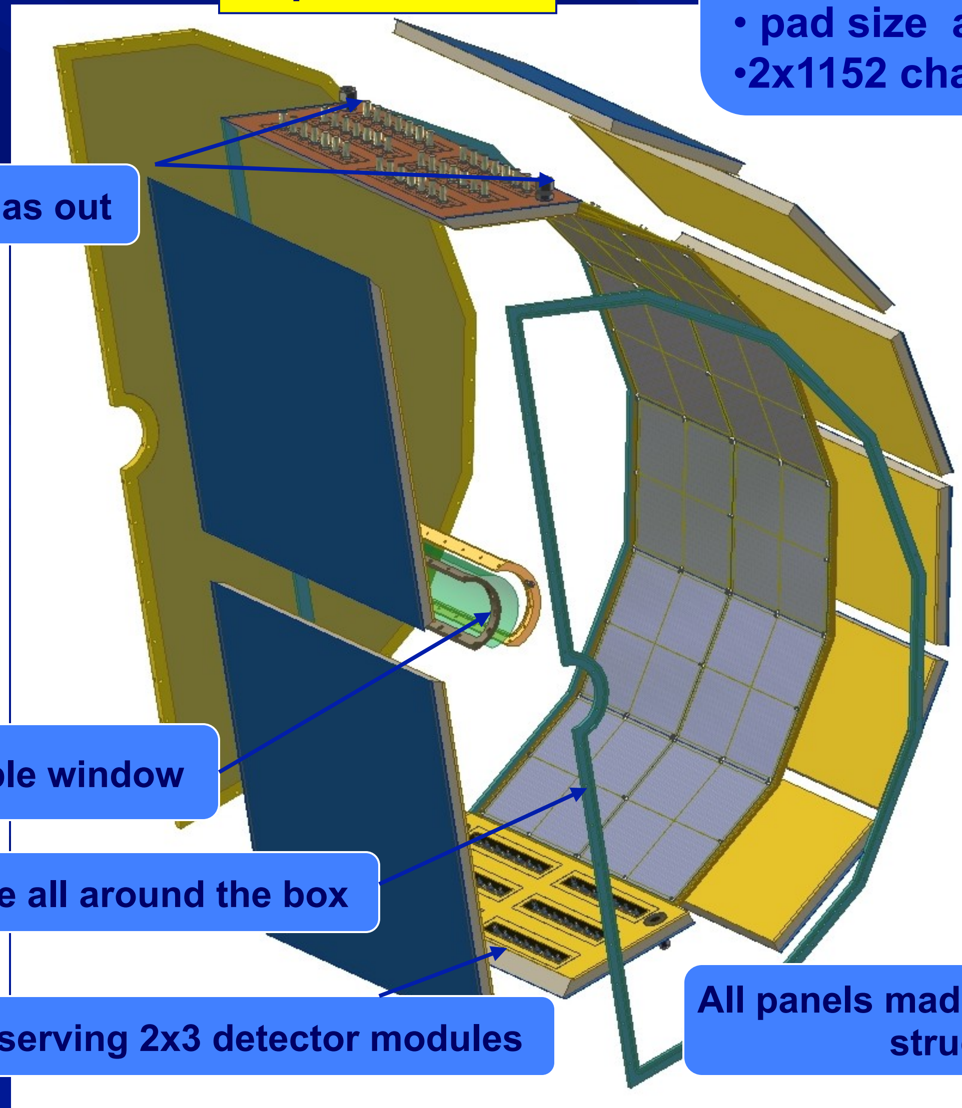
HBD design

- 24 detector modules [2 (arms) x 2 (z) x 6 (φ)]
- GEM size: 23 x 27 cm^2
- pad size a =15.1 mm
- 2x1152 channels

One arm

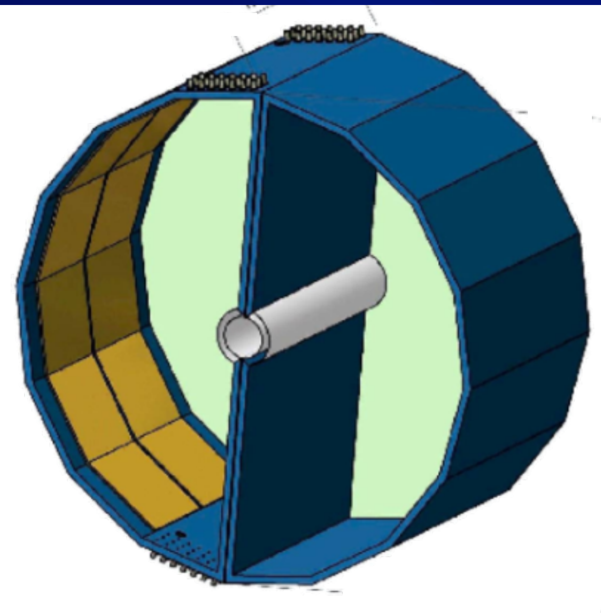


Exploded view



HBD performance

NIM A646, 35 (2011)

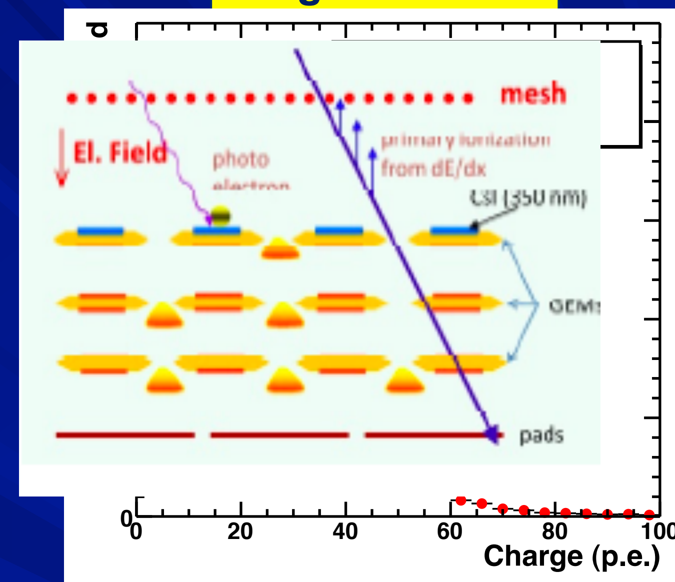


Windowless CF4 Cherenkov detector
GEM/CSI photo cathode readout
Operated in B-field free region

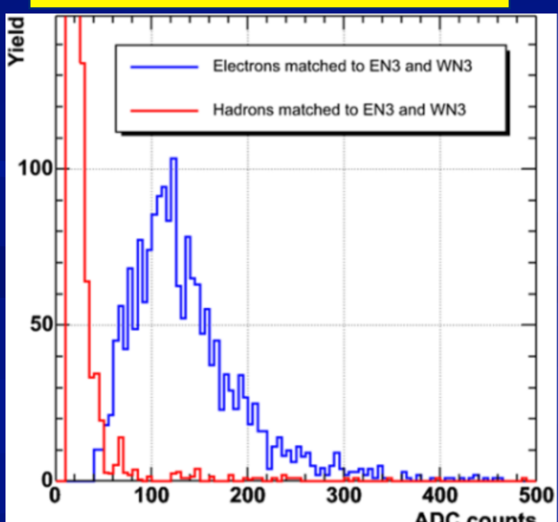
Goal: improve S/B by rejecting conversions and π^0 Dalitz decays

- Successfully operated:
  2009 p+p data
  2010 Au+Au data

Single electron

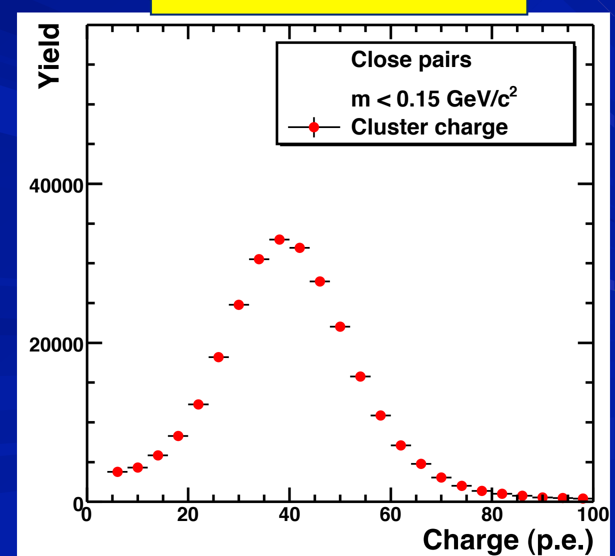


Hadron blindness
e-h separation

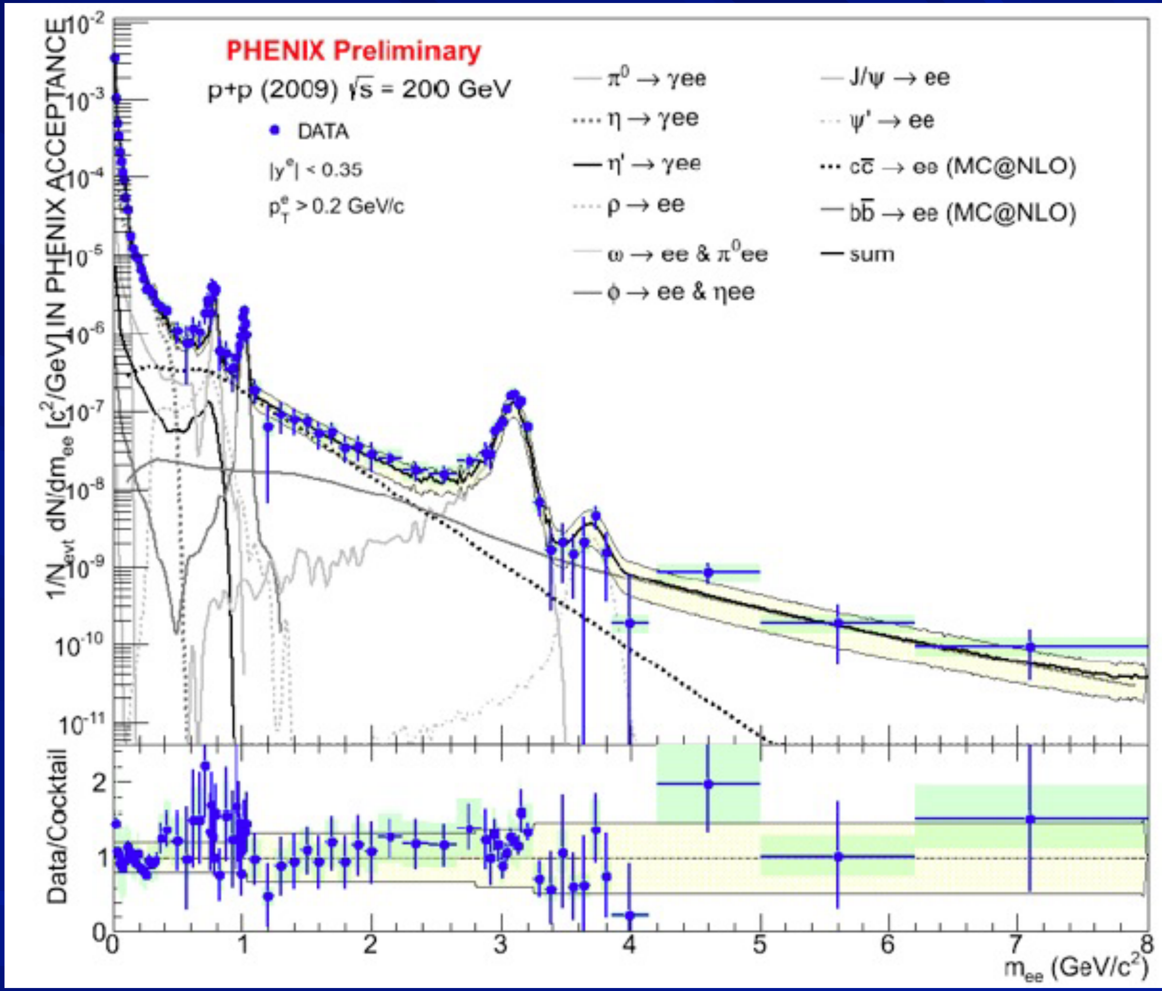


- Figure of merit: $N_0 = 322\ cm^{-1}$
- 20 p.e. for a single electron
- Preliminary results:
  S/B improvement of ~5 wrt previous results w/o HBD

Double electron

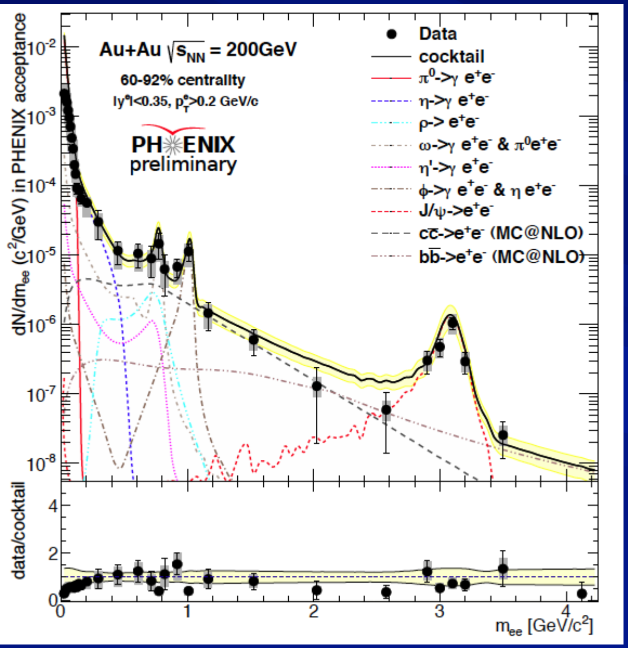


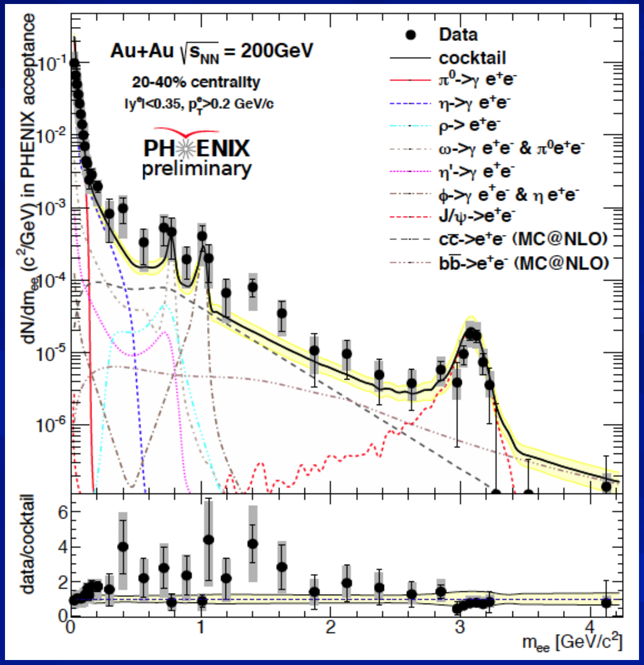
Run-9 p+p dileptons with the HBD

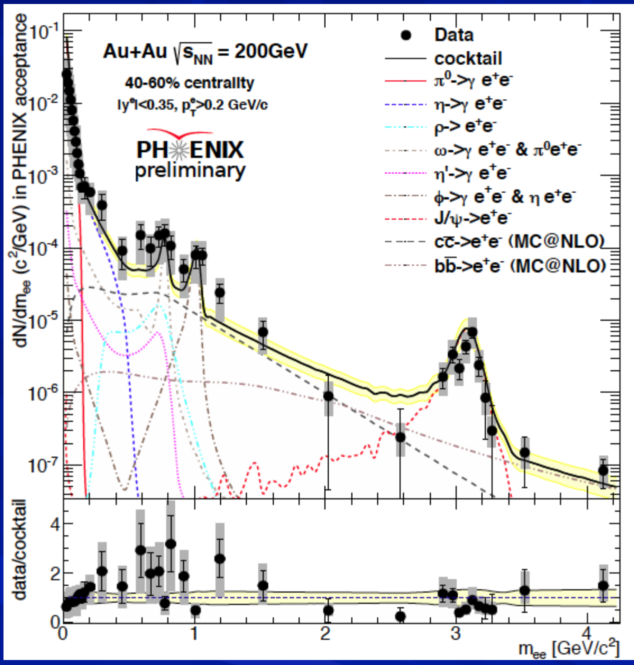


- Fully consistent with published result PR C81, 034911 (2010)
- Provide crucial proof of principle and testing ground for understanding the HBD

Run-10 Au+Au dileptons at $\sqrt{s_{NN}}$=200 GeV with the HBD

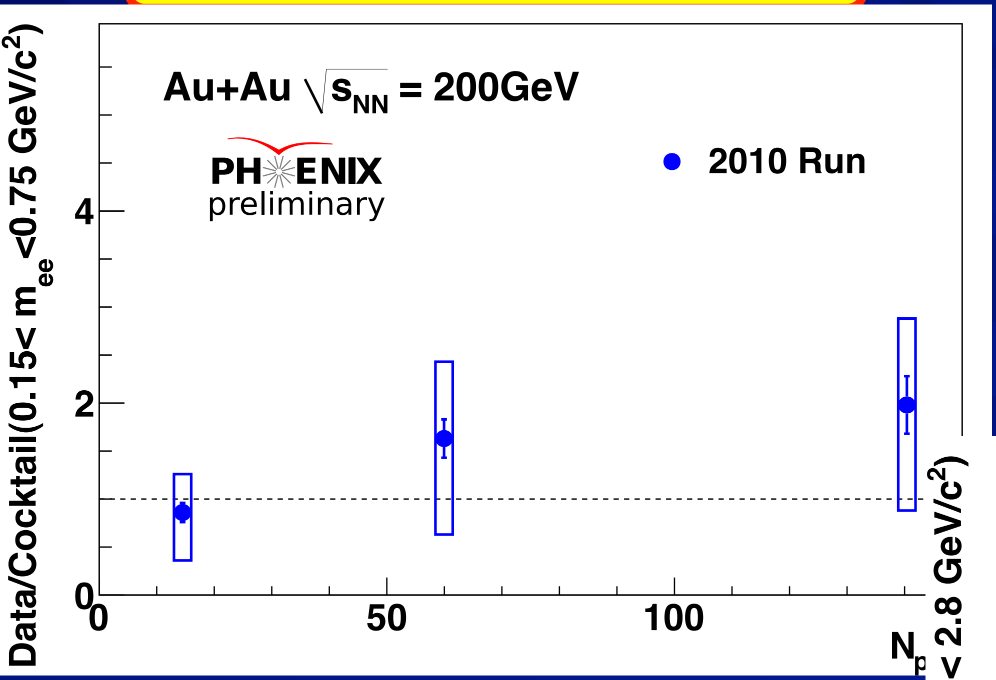






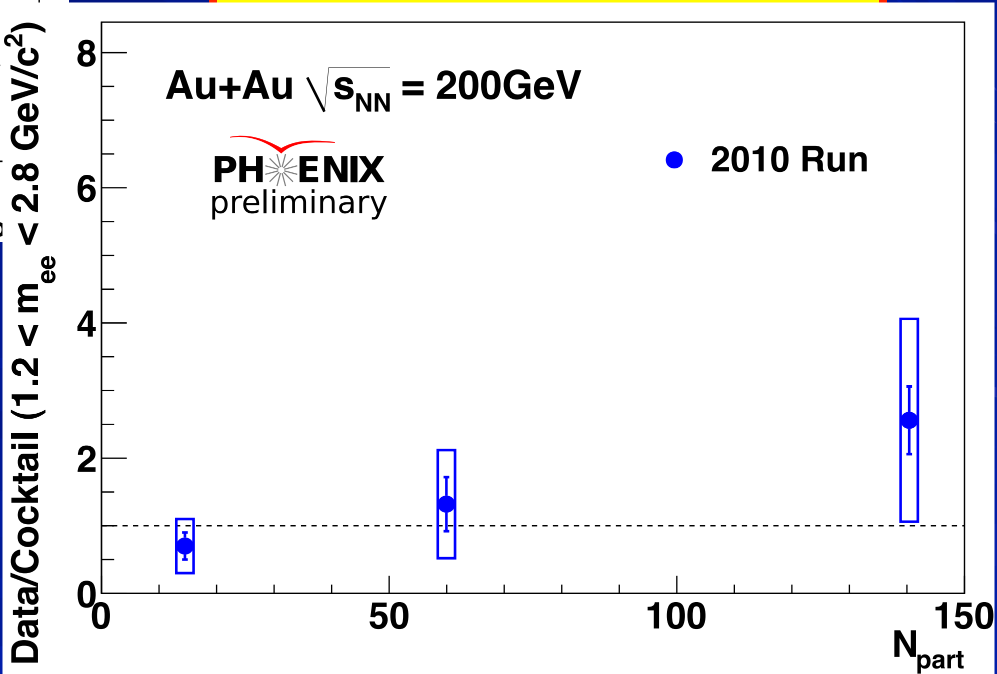
Run-10: Data/Cocktail

LMR (m = 0.15 – 0.75 GeV/c^2)



- Hint of enhancement for more central collisions
- Not conclusive given the present level of uncertainties

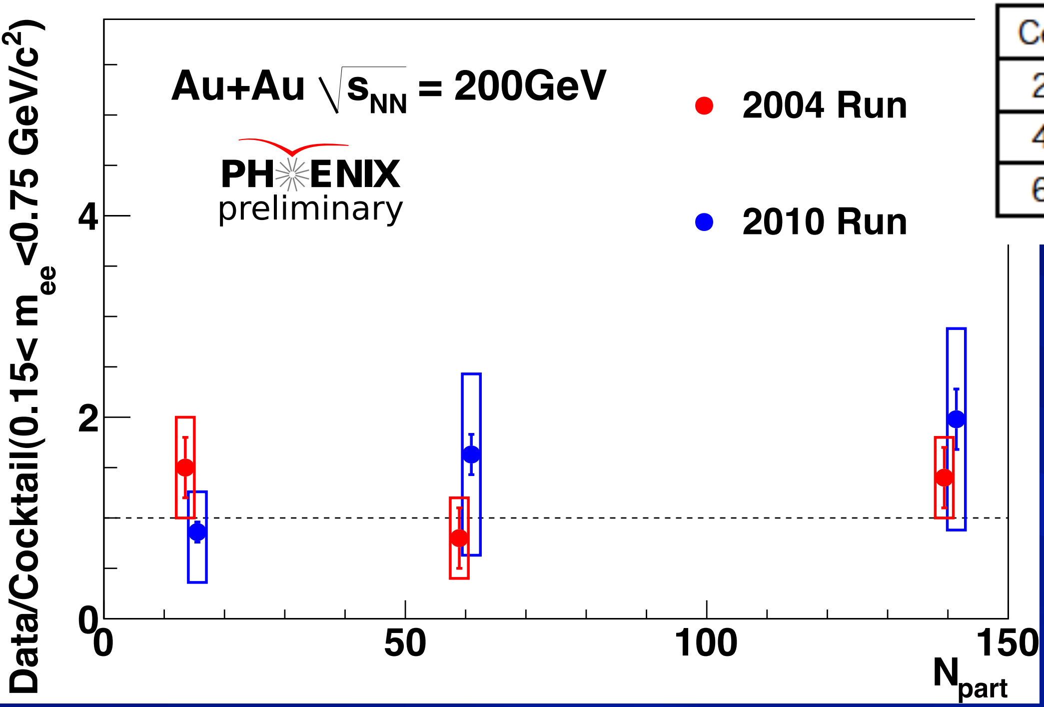
IMR (m = 1.2 – 2.8 GeV/c^2)



- Similar conclusions for the IMR

Comparison of run-10 to previous run-4 results

LMR (m = 0.15 – 0.75 GeV/c²)



Run 10 – Data/ cocktail

Centrality	Value	Stat	Syst(up)	Syst(dwn)
20-40%	1.98	0.3	0.9	1.1
40-60%	1.63	0.2	0.8	1.0
60-92%	0.86	0.1	0.4	0.5

Run 4 – Data/ cocktail

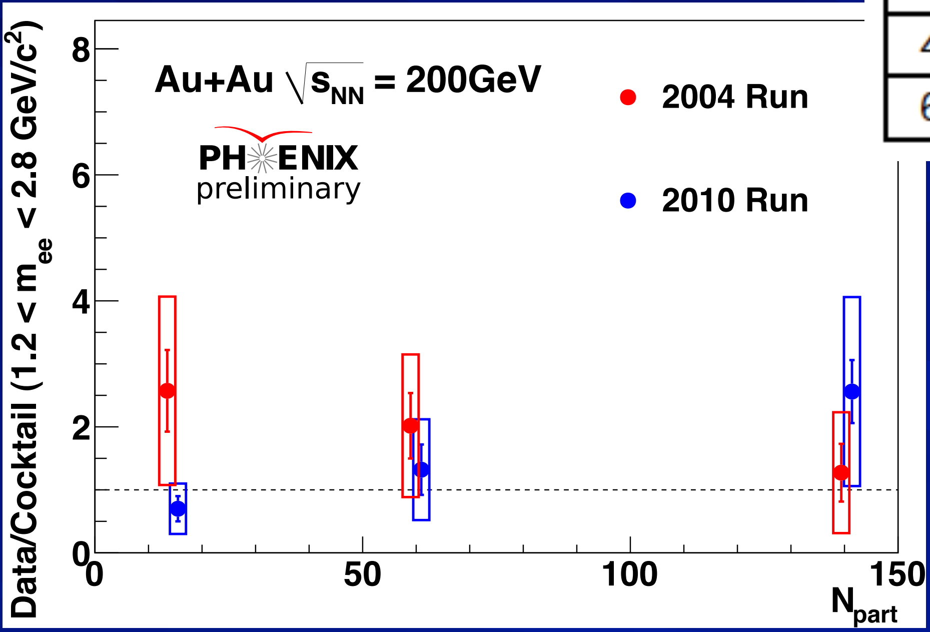
Phys Rev C81, 034911 (2010)

Centrality	Value	Stat	Syst	model
20-40%	1.4	0.3	0.4	0.3
40-60%	0.8	0.3	0.4	0.2
60-92%	1.5	0.3	0.5	0.3

Consistent results

Comparison of run-10 to previous run-4 results

IMR (m = 1.2 – 2.8 GeV/c^2)



Run 10 – Data/ cocktail

Centrality	Value	Stat	Syst(up)	Syst(dwn)
20-40%	2.56	0.5	1.5	1.5
40-60%	1.32	0.4	0.8	0.8
60-92%	0.70	0.2	0.4	0.4

Run 4 – Data/ cocktail
c,b yields based on MC@NLO
MC@NLO = PYTHIA * 1.16

Centrality	Value	Stat	Syst
20-40%	1.3	0.5	1.0
40-60%	2.0	0.5	1.1
60-92%	2.6	0.6	1.5

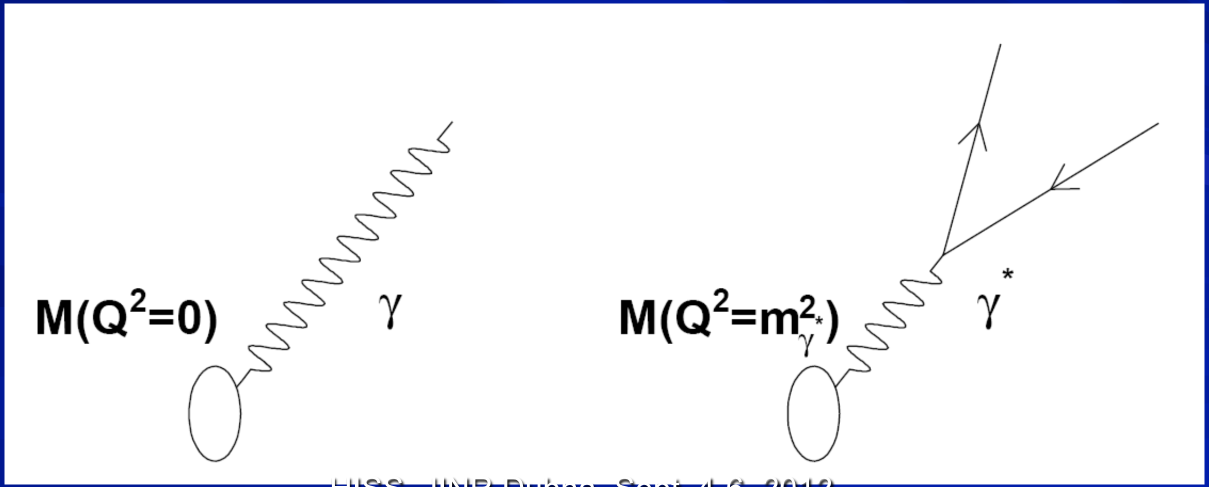
Consistent results

Thermal Radiation at RHIC

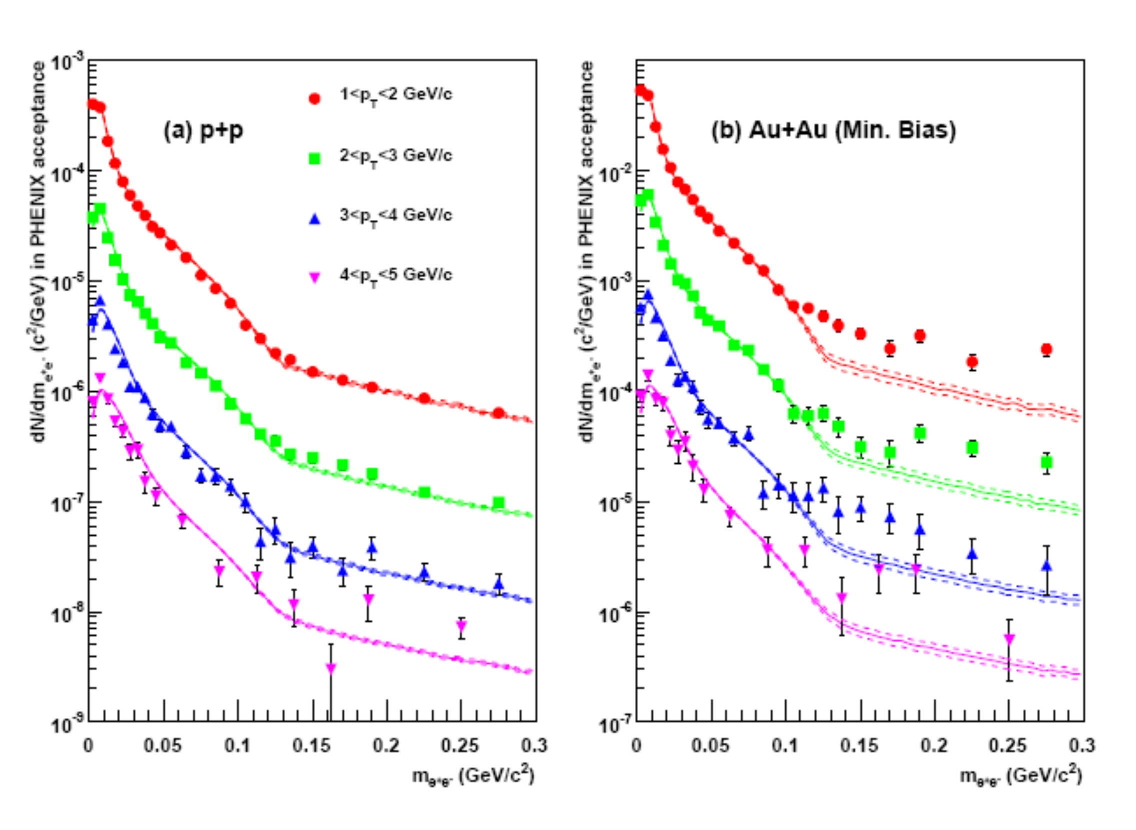
Thermal radiation at RHIC (I)

- Search for the thermal radiation in the dilepton spectrum
- Avoid the huge physics background inherent to a real photon measurement.
- Capitalize on the idea that every source of real photons should also emit virtual photons.
- At m→0, the yield of virtual photons is the same as real photon

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



Enhancement of (almost real photons) low-mass dileptons



Restricted kinematic window:
Low mass e^+e^- pairs
$m<300$MeV & $1<p_T<5$ GeV/c

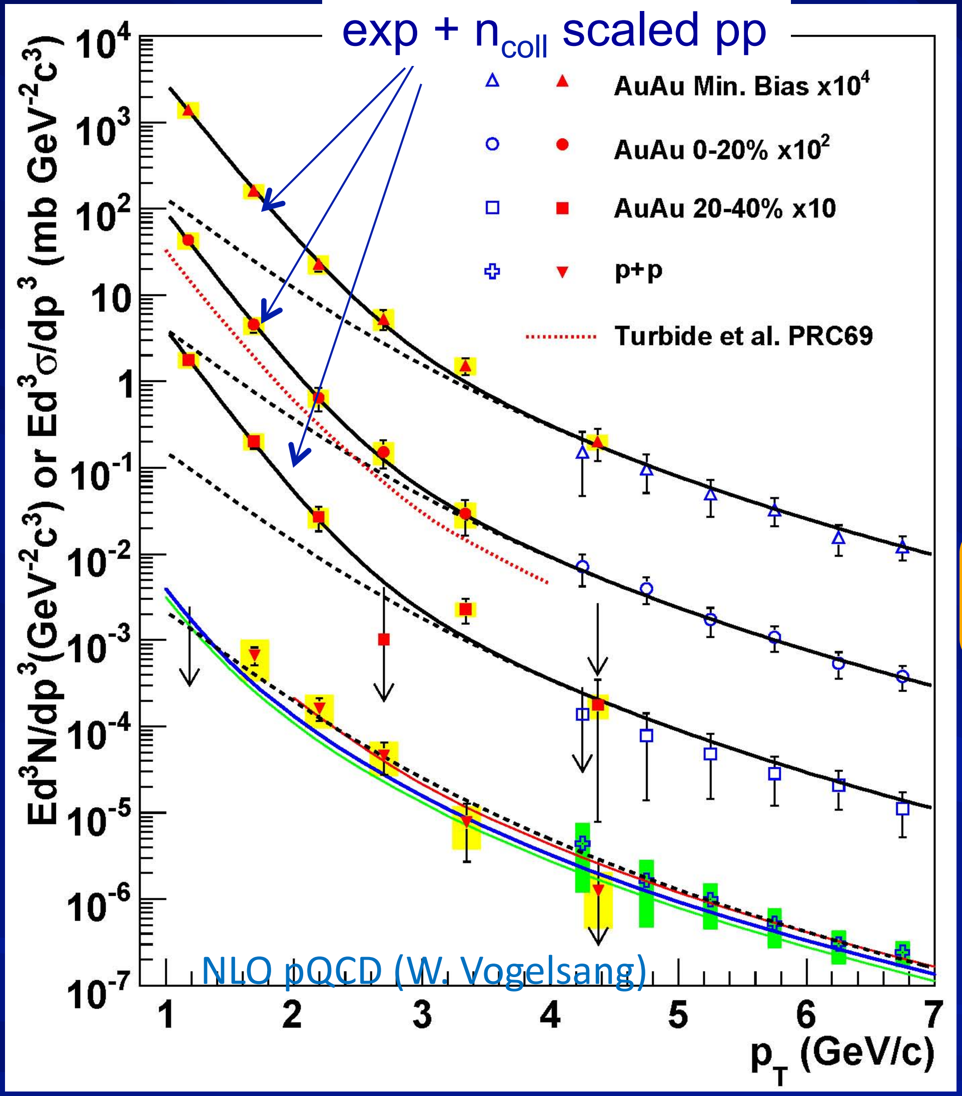
p+p:
- Good agreement of p+p data and hadronic decay cocktail
-

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

1 < p_T < 2 GeV
2 < p_T < 3 GeV
3 < p_T < 4 GeV
4 < p_T < 5 GeV

Excess → Emission of almost real photons

Thermal radiation from the QGP at RHIC



e^+e^- invariant mass excess:
- transformed into a spectrum of real photons under the assumption that the excess is entirely due to internal conversion of photons.
- compared to direct (real) photon measurement (p_T>4GeV)

Good agreement in range of overlap

- 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
- Fit Au+Au excess with exponential function + n_{coll} scaled p+p

$T_{ave} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV corresponds to
T_{ini} = 300 to 600 MeV, τ_0 = 0.15 to 0.6 fm/c

Summary

- Dileptons have provided interesting physics results at all energies.
- DLS puzzle solved in C+C. Dilepton spectrum understood as mere superposition of NN collisions. First results on heavier system show stron enhancement.
- Consistent and coherent picture from the SPS:
  - Low-mass pair enhancement: thermal radiation from the HG
  - Approach to CSR proceeds through broadening (melting) of the resonances
  - IMR enhancement: thermal radiation from partonic phase
- PHENIX results at RHIC very intriguing:
  - Strong enhancement of low-mass pairs down to very low masses
  - No enhancement in the IMR
  - Challenge for theoretical models
  - Diagreement with STAR results
  - Looking forward to more precise results with the HBD
- First measurement of thermal radiation at RHIC