Low Mass Dileptons: from the SPS to the LHC

Antonio URAS

ALICE Lyon group @ IPNL

cnrs advancing the frontiers

Probing the Strong Interaction at A Fixed Target ExpeRiment with the LHC beams

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Outline

- **Physics Motivations**
- **Second and Third generations of experiments at the SPS:**
  - Helios-3, CERES, NA38/50
  - NA60
- **STAR and PHENIX at the RHIC**
  - Top energy run
  - Beam Energy Scan
- **Low Mass Dileptons in ALICE at the LHC**
  - pp and p-Pb reference
  - Preliminary results in Pb-Pb

Dilepton Physics

Probing full evolution of collisions, with negligible final-state interactions

High Mass Region (M > 3 GeV/c²)

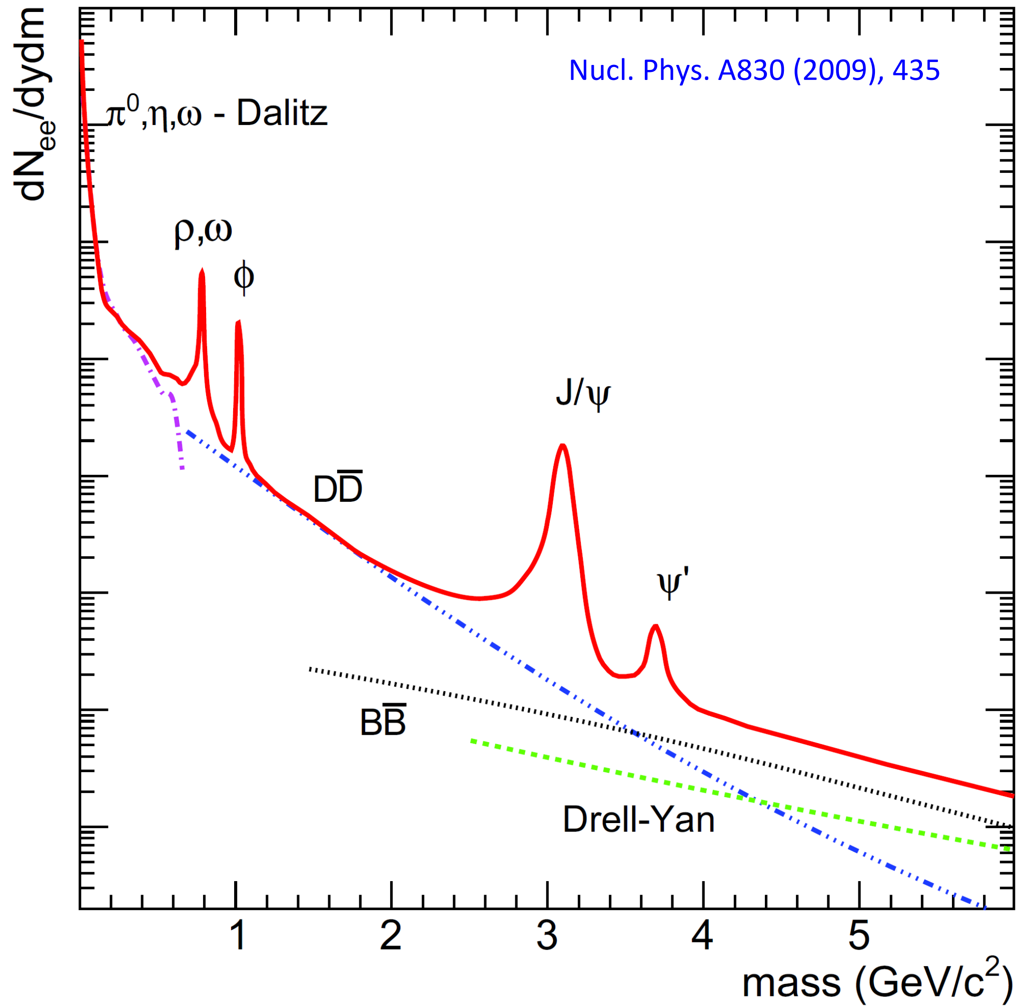
- Primordial emission, Drell-Yan
- Quarkonia and open heavy flavors (mostly beauty)

Intermediate Mass Region (1 < M < 3 GeV/c²)

- Thermal radiation from QGP
- Open heavy flavors (mostly charm)

Low Mass Region (M < 1 GeV/c²)

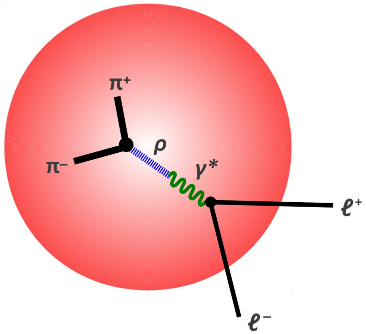
- Dalitz and 2-body decays of light narrow resonances (close to freeze-out)
- Thermal emission dominantly hadronic (from a hadron gas), mediated by the broad vector meson ρ in the form $\pi^+\pi^- \rightarrow \rho \rightarrow \ell^+\ell^-$



Low Mass Dileptons from QGP

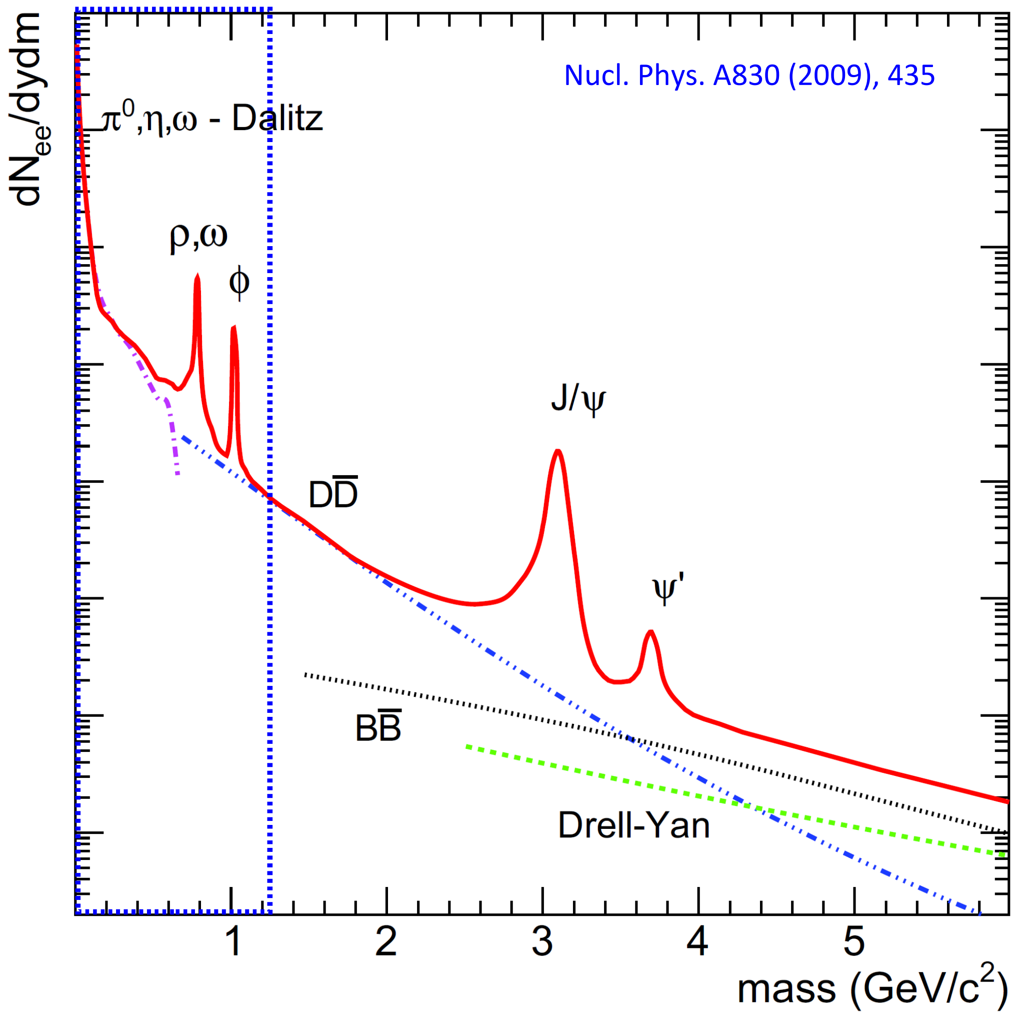
- **Ultimate goal:** inferring signatures of QCD phase transitions (chiral symmetry restoration and/or deconfinement)

- **A more imminent (and relatively easier) objective:** describing medium modifications of the vector mesons spectral function



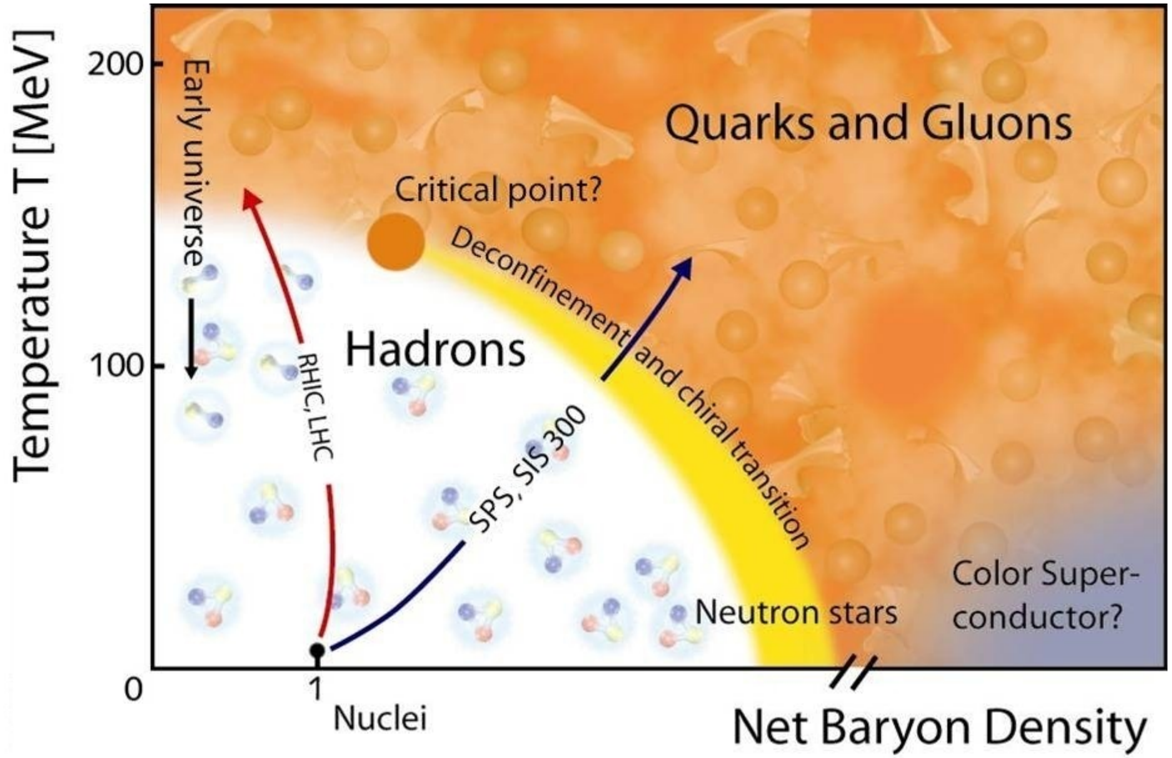
- **Also accessible: strangeness production via ϕ/ω ratio**. Strangeness enhancement historically predicted to be a signature for the presence of a QGP phase [Phys. Rev. Lett., 48:1066, 1982]

- **Measurements in pp and p-A collisions** → reference for interpreting heavy-ion data

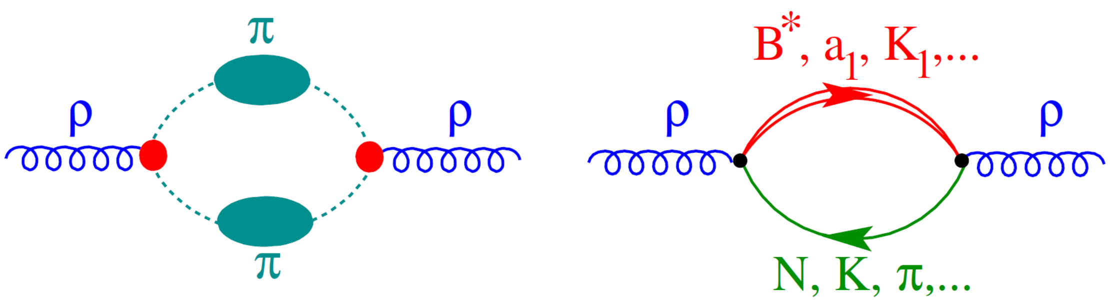


THE QCD Phase Diagram from the SPS to the LHC

Varying the collision energy $\rightarrow$ varying the initial temperature and the net baryon density on the QCD phase diagram



Warning: <u>total</u> baryon density also important in contributing to in-medium modifications of vector mesons line shapes $\rightarrow$ still relevant at RHIC and LHC where the net baryon density approaches zero



Hadronic Many-Body Theory for vector mesons

[Ko et al, Chanfray et al, Herrmann et al, Rapp et al, ...]

2nd and 3rd generations of experiments at the SPS

Prologue: before Heavy-Ions

- **Interest in lepton-pair production in high-energy collisions** dates back to the '70s, triggered by the detection of Drell-Yan process and the J/ψ

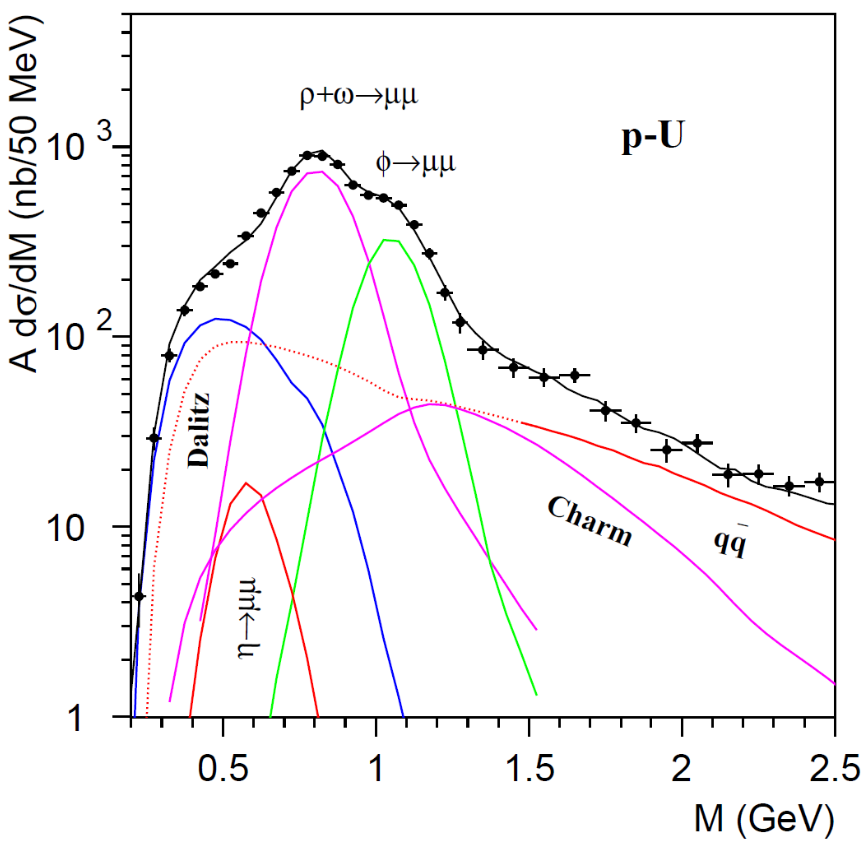
- **The flood of experimental findings also involved the Low Mass Region (below 1 GeV/c²)** where data were compared to a "hadronic-decay cocktail" containing all contributions known at that time

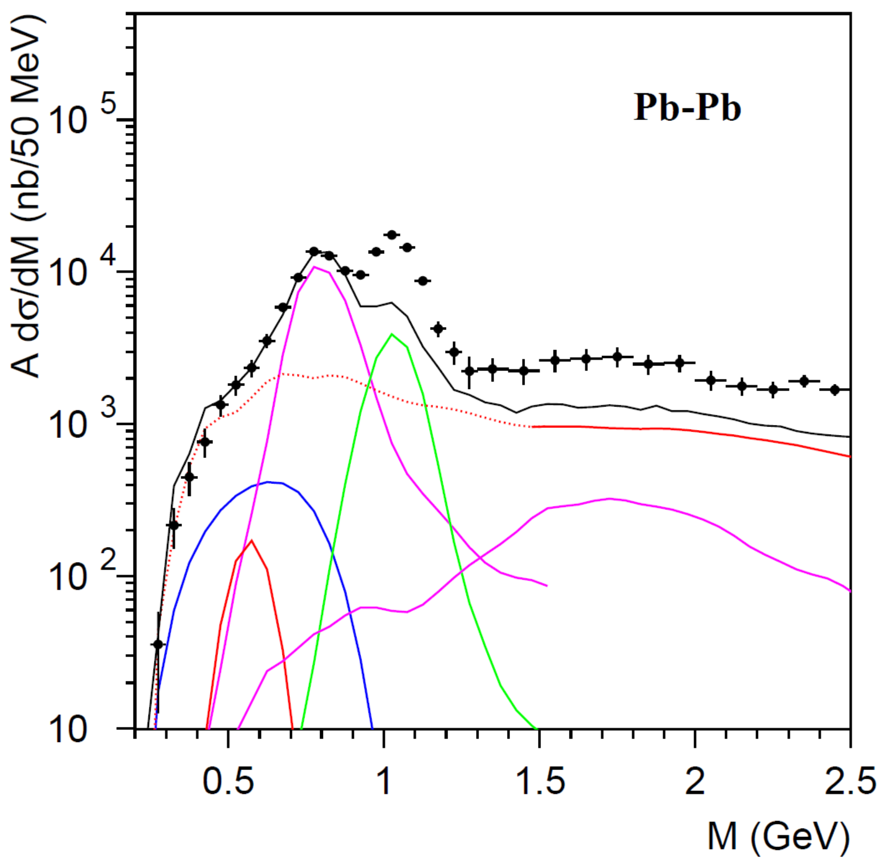
- **An excess of lepton pairs above the known sources was indeed found**. It was finally recognized as due to a severe underestimation of the η Dalitz contributions, but... in the meantime, these dubious pp results had relevant consequences:
    - Bjorken and Weisberg proposed for the first time **partons produced in the collisions** to be a potential, further source of continuum lepton pairs especially at low masses
    - Shuryak proposed the production of deconfined partons in thermal equilibrium during the collisions and phrased the terms **"Quark Gluon Plasma"** and **"Thermal Radiation"**
    - **In the mid-80s, the SPS started its heavy-ion program...**

Low Mass Dimuons in NA38 and NA50

- **No excess in p-U collisions** w.r.t. the Hadronic Cocktail
- **Strangeness enhancement in Pb-Pb**, addressed via ϕ/ω measurement
- **No sensitivity to any low mass excess** due to the limited acceptance (detector optimized for J/ψ studies)

Eur. Phys. J. C 13, 69-78 (2000)

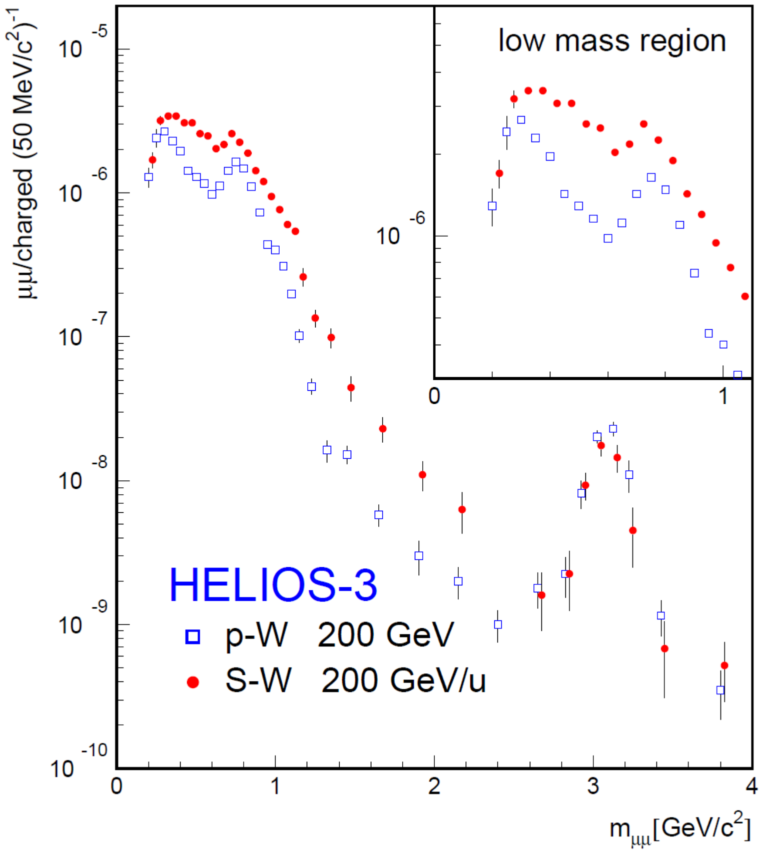




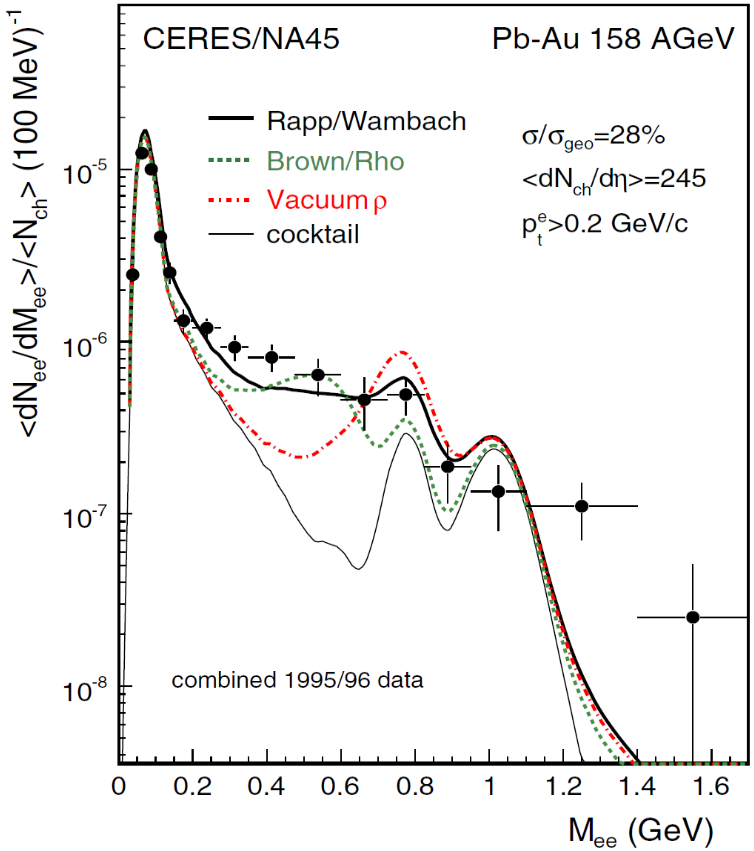
Low Mass Dileptons in Helios-3 and CERES

- **Helios-3 (NA34-3): dimuon excess in S-W w.r.t. p-W**
- **CERES (NA45): dielectron excess in Pb-Au w.r.t. Hadronic Cocktail.**
  First theoretical attempts to explain the excess on the basis of in-medium effects. Mass shift and Broadening scenarios could not be discriminated because of the limited data quality

Nucl. Phys. A 590, 93c-102c (1995)



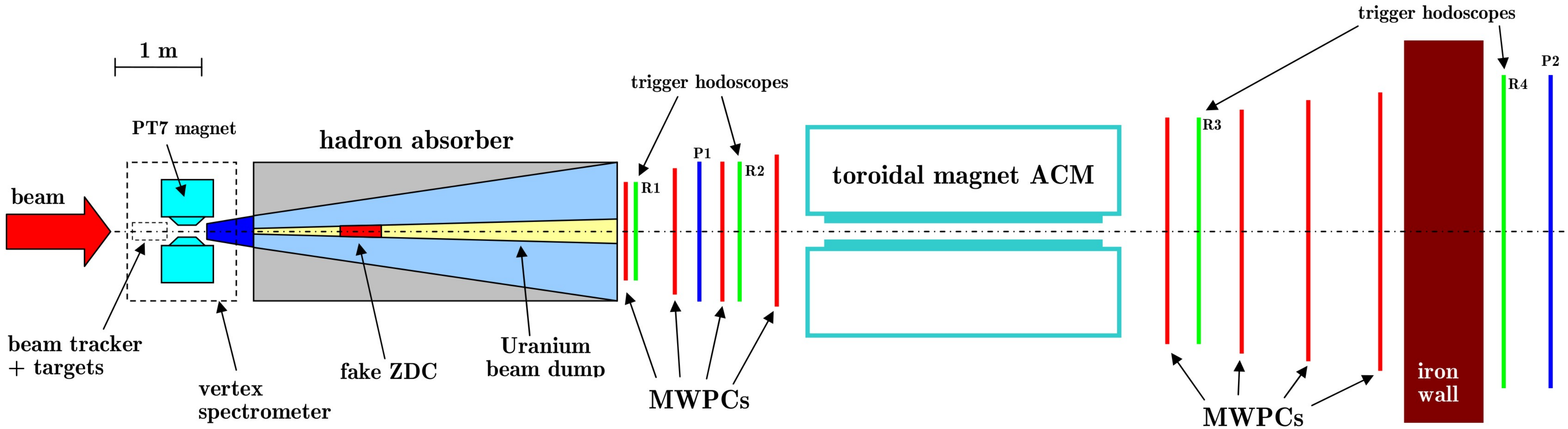
Eur. Phys. J. C 41, 475–513 (2005)



Status before NA60:

- Vacuum ρ unable to describe Low-Mass dileptons in Heavy-Ion data
- Various scenarios for in-medium modifications:
  - decrease of ρ mass (Brown-Rho), mass expected to scale with $\langle q\bar{q} \rangle$ condensate
  - broadening of ρ spectral function (Rapp-Wambach) due to hadronic (including baryons) scattering

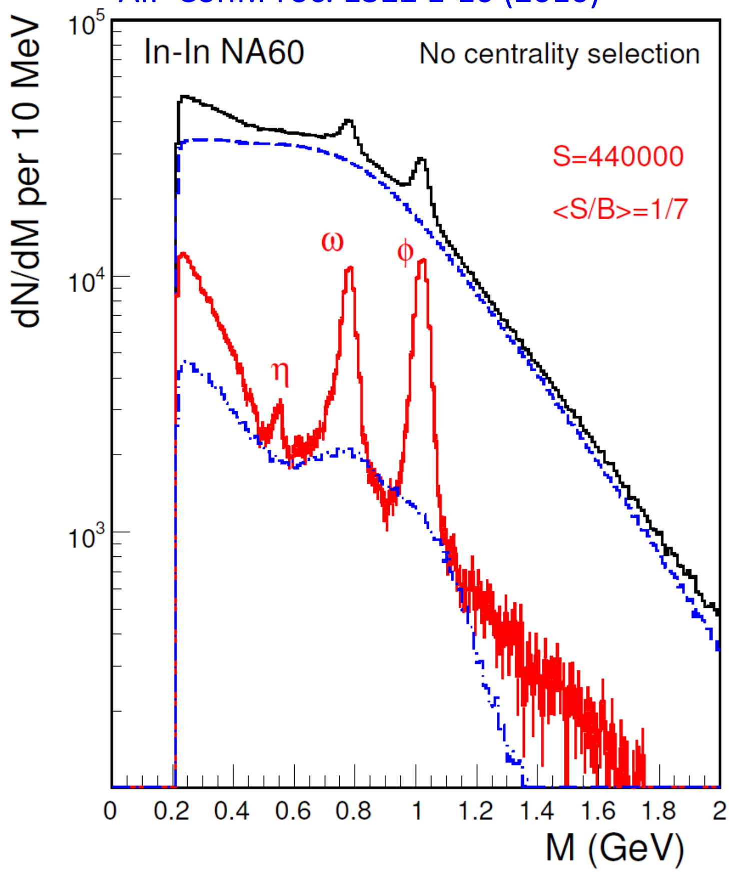
Both scenarios rely on high-baryon densities, both showed good agreement with existing 158 and 40 AGeV data (CERES)

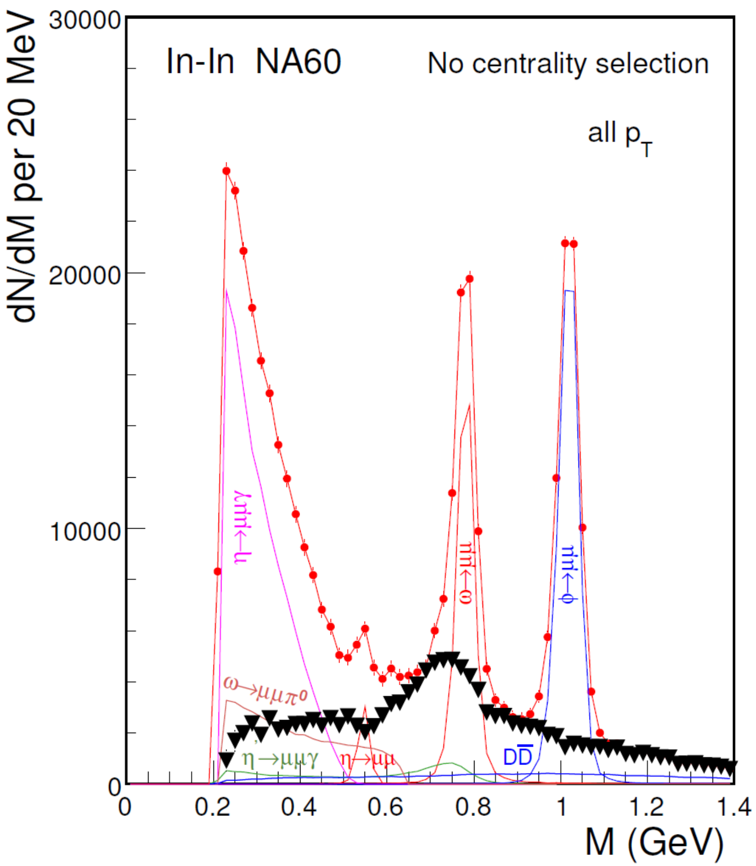


Low Mass Dimuons in NA60 (II)

- NA60 data raised the experimental precision to an unprecedented level, issuing serious challenges to theoretical models
- Excess is isolated without any *a priori* assumption on its characteristics

AIP Conf.Proc. 1322 1-10 (2010)





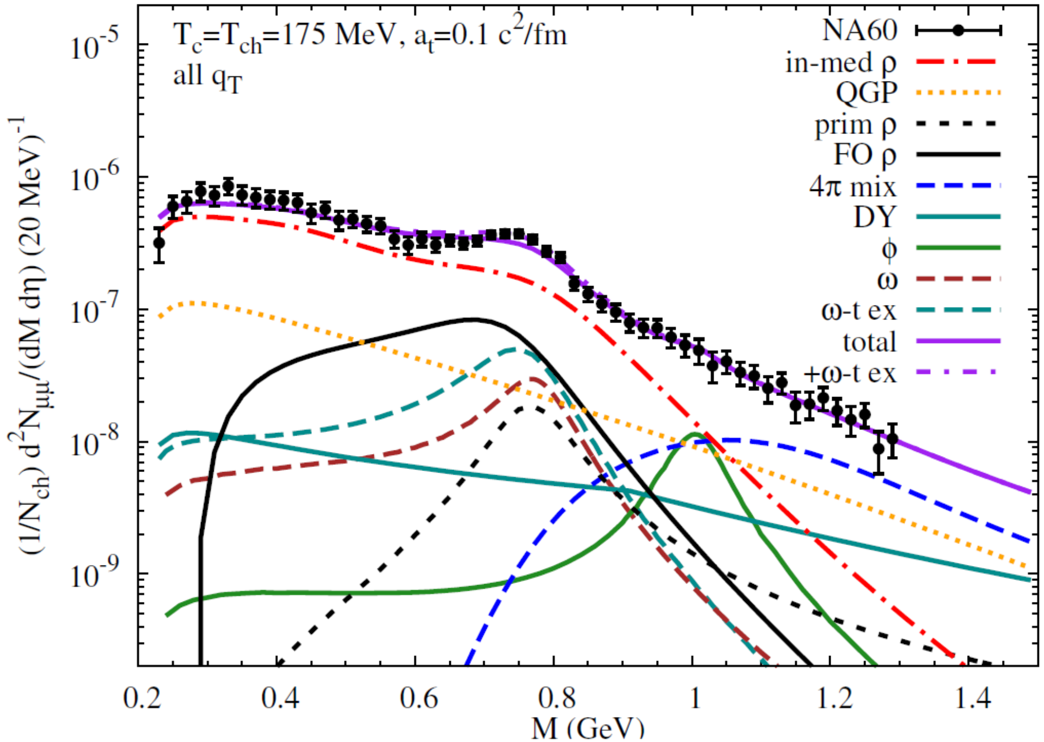
Key points of NA60:

- Dimuons allow higher luminosities than dielectrons
- Double, independent tracking: excellent mass resolution and background rejection
- Acceptance down to zero p_T for low masses

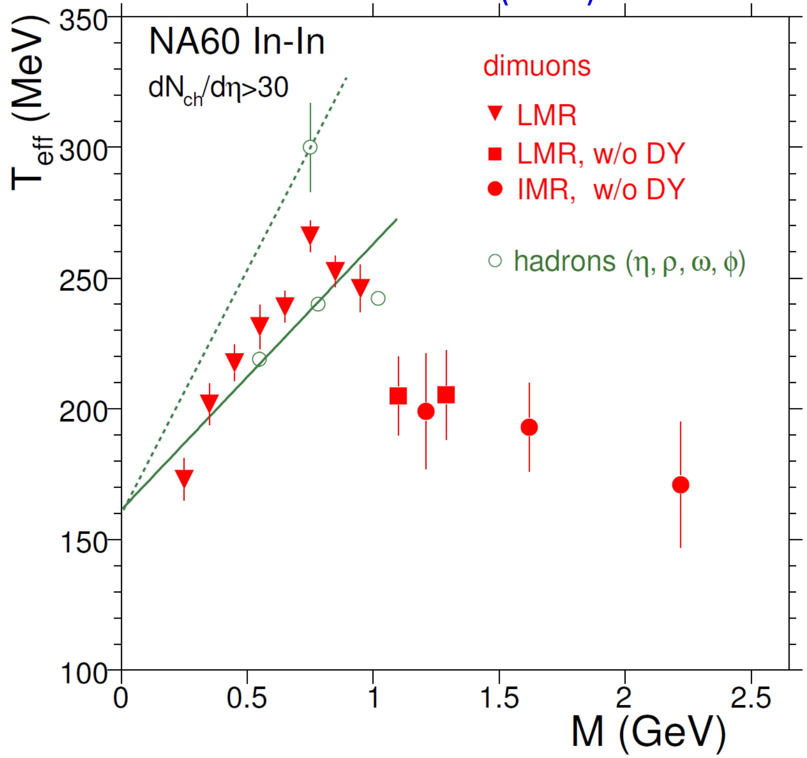
Low Mass Dimuons in NA60 (III)

- **Excess at low mass spectacularly well described by thermal models.** E.g. the one by Rapp & Hees (broadened ρ + QGP + multi-hadron annihilations)
- Purely exponential m_T distributions: at low masses the T parameter monotonically rises up to the nominal pole of the ρ meson: **radial flow of a "hadron-like" dilepton source**

PoS CPOD2013 008 (2013)



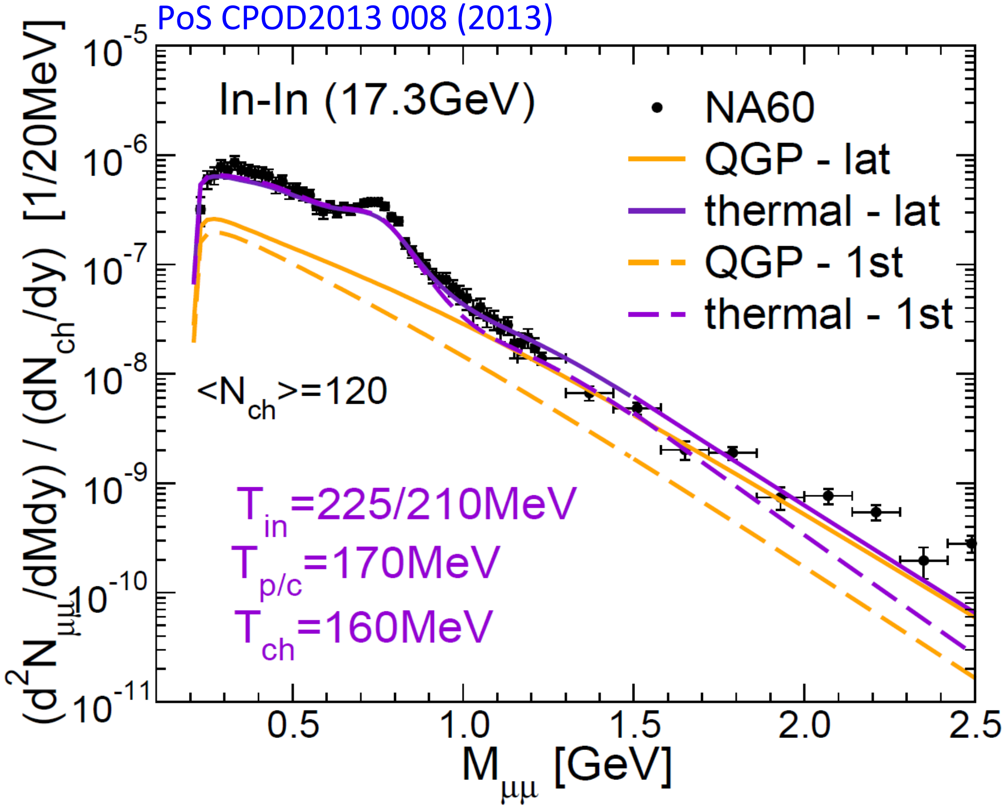
AIP Conf.Proc. 1322 1-10 (2010)



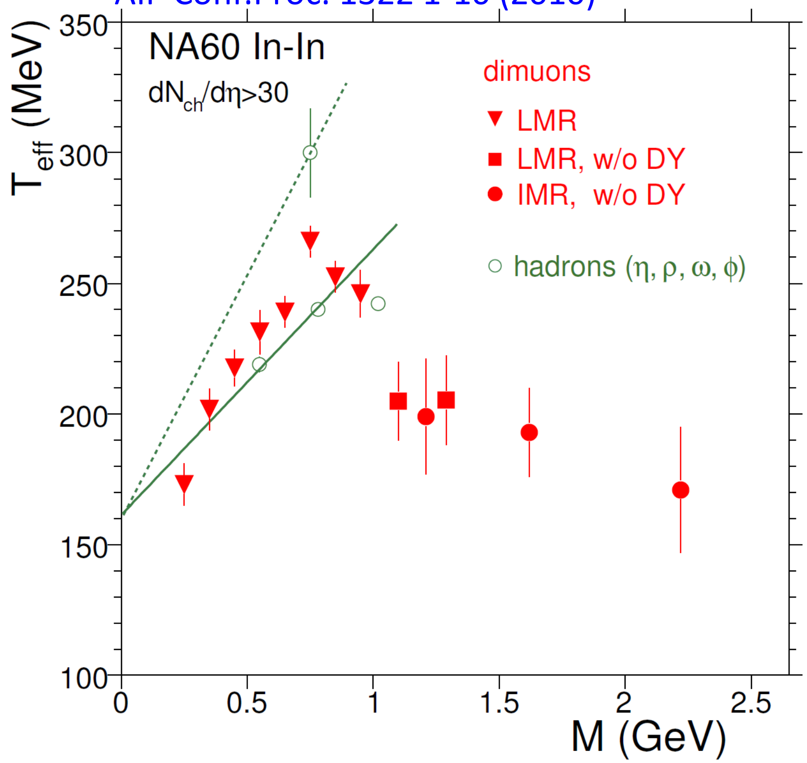
(Not-so)-Low Mass Dimuons in NA60 (IV)

- **Planck-like (nearly exponential) shape of intermediate masses.** Exponential m_T spectra with $T \approx 200$ MeV, basically flat vs mass: temperature sensibly larger than T_c suggests primordial (partonic) emission source
- **Intermediate mass region is thus maximally sensitive to the QGP:** possibility to extract the (average) fireball lifetime and study the EoS varying the baryon density

PoS CPOD2013 008 (2013)



AIP Conf.Proc. 1322 1-10 (2010)



Low Mass Dimuons in NA60 (V)

Other results from the Low Mass Region, not shown in this presentation:

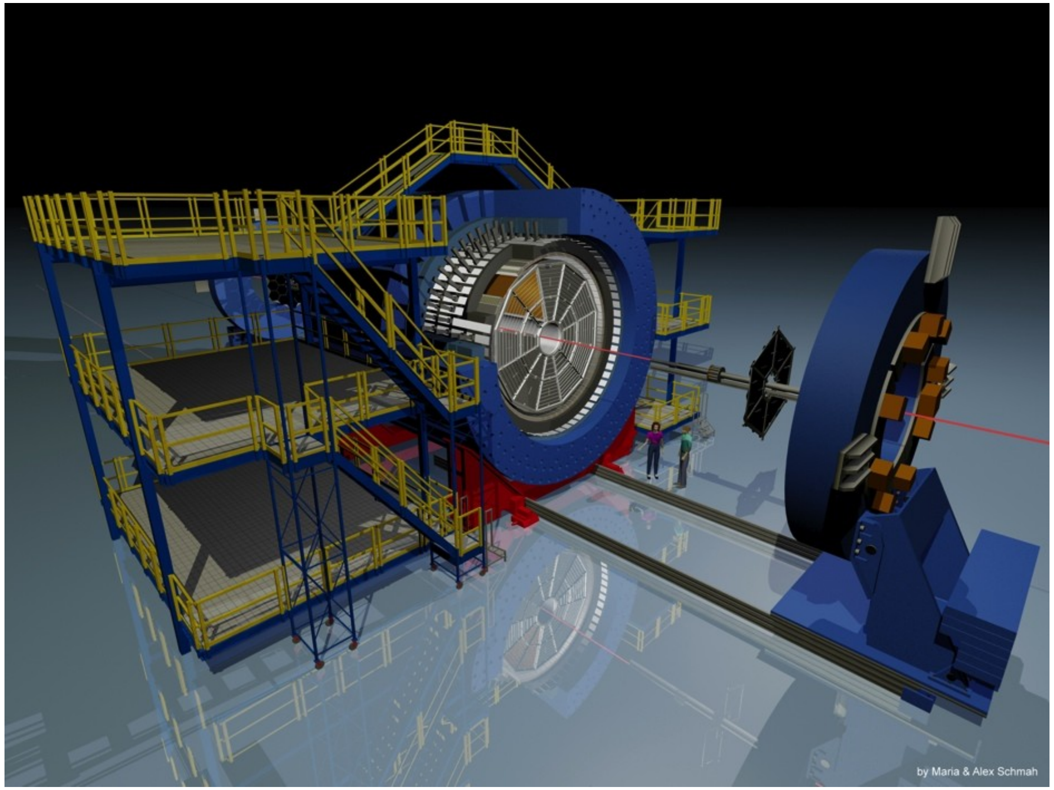
- **Angular distributions for excess dilepton:** structure function parameters λ, μ, ν compatible with zero confirm the thermal emission from a randomized system
- **Precision study of the ϕ meson** in the μμ channel. Extraction of ϕ signal in the KK channel: direct comparison of leptonic and hadronic decay channels
- **Precision study of ρ line shape in cold nuclear matter** and first measurement of the Boltzmann factor. **Precision measurement of the Dalitz decay form factors** for the η and ω mesons
- Low mass neutral meson production in p-A collisions

STAR and PHENIX at the RHIC

The STAR and PHENIX Detectors

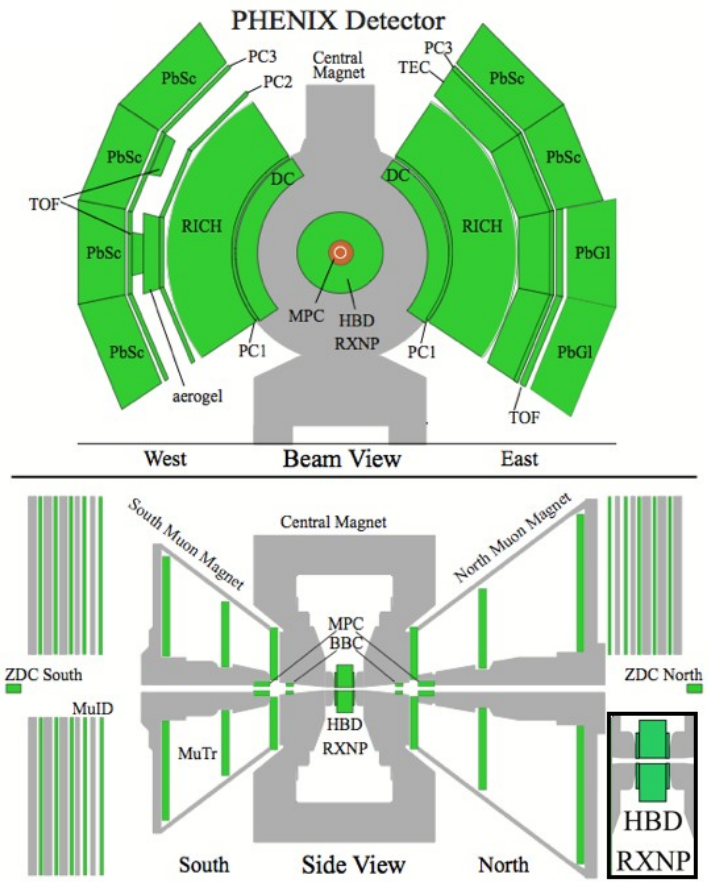
- **STAR:**

  Electron tracking and identification with TPC + TOF in $0 < \phi < 2\pi$, $|\eta|<0.9$ (electron purity at least 95% in Au+Au)



- **PHENIX:**

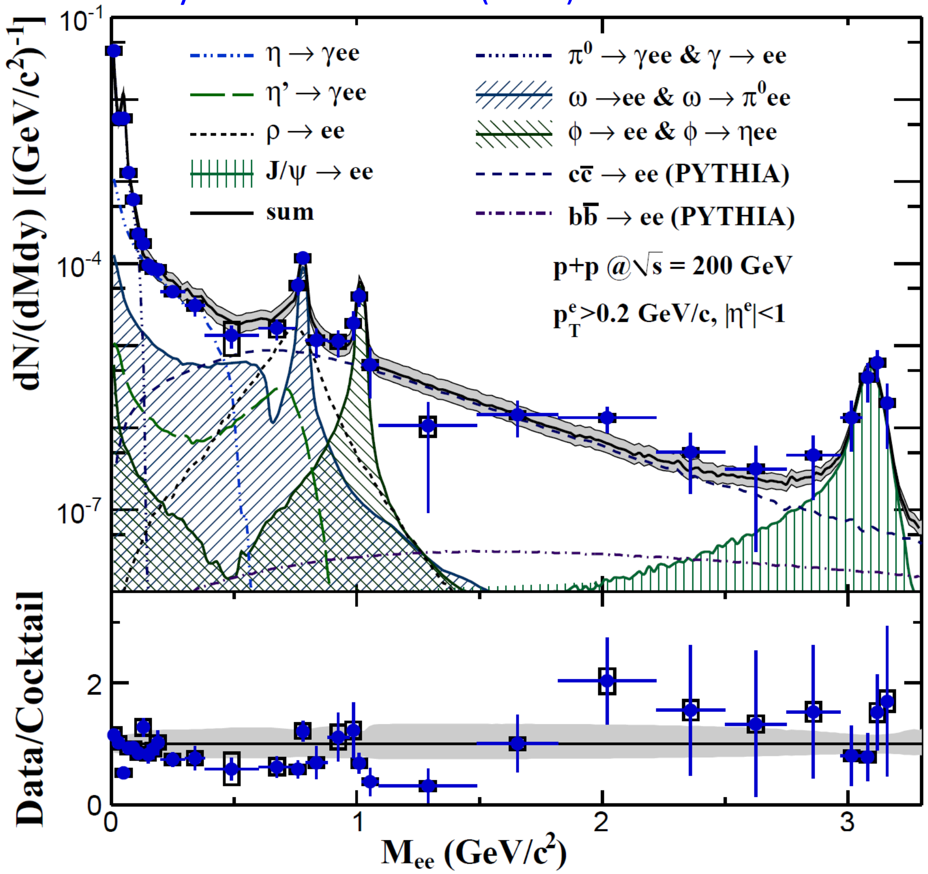
  Electron tracking and identification with Drift + MWPC + RICH in two arms each covering $\pi/2$ in azimuth and $|\eta|<0.35$



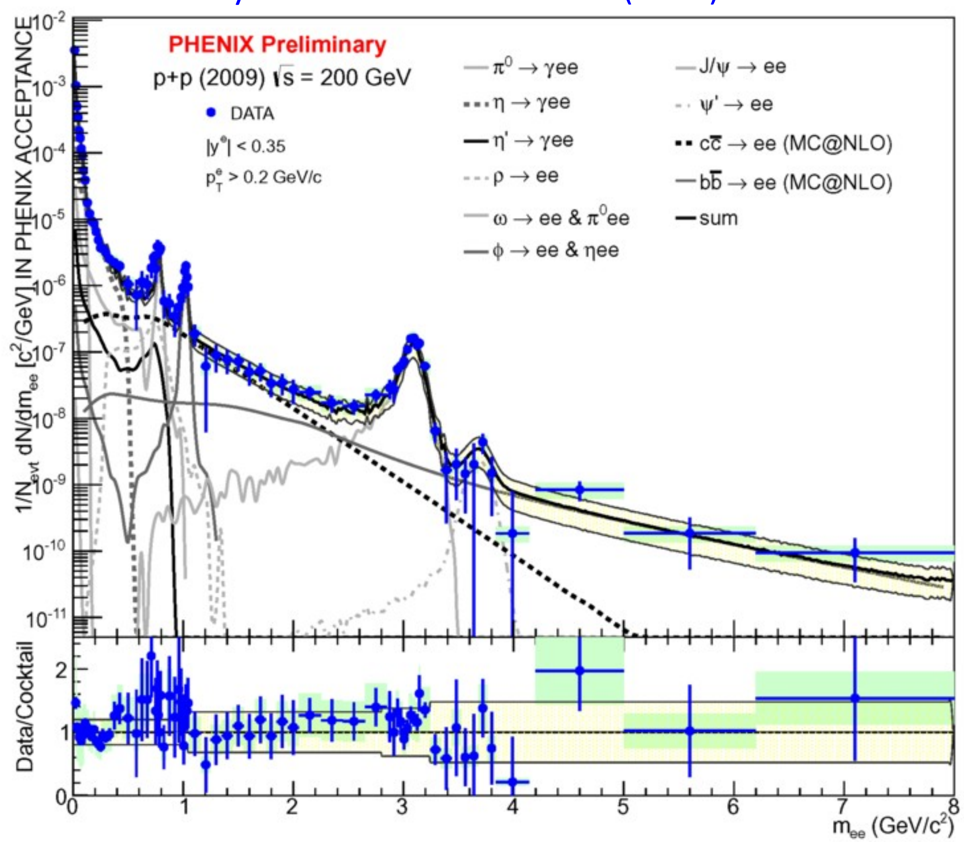
Reference in pp

- **In pp collisions, agreement is observed both in STAR and PHENIX** between the measured yields and the expected yields from a range of hadronic decays, heavy-flavor decays, and Drell-Yan production
- **Baseline** for the measurements of any excess in Heavy-Ion collisions

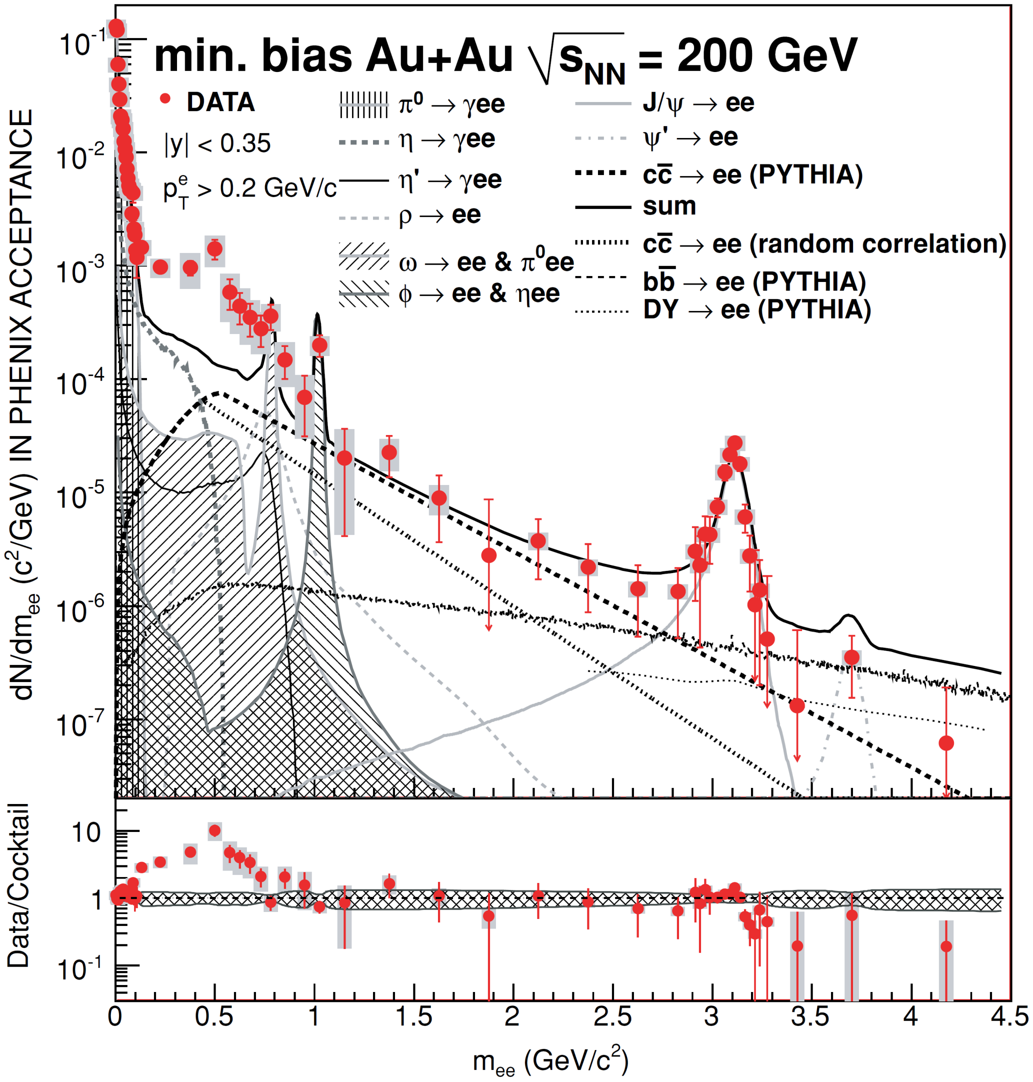
Phys.Rev. C86 024906 (2012)



Nucl. Phys. A 904–905 225c–232c (2013)



Phys. Rev. C 81, 034911 (2010)



PHENIX excess at low masses:

- Increasing rapidly with centrality
- Concentrated at low p_T (p_T < 1 GeV/c)
- Cannot be reconciled within any of the theoretical models proposed

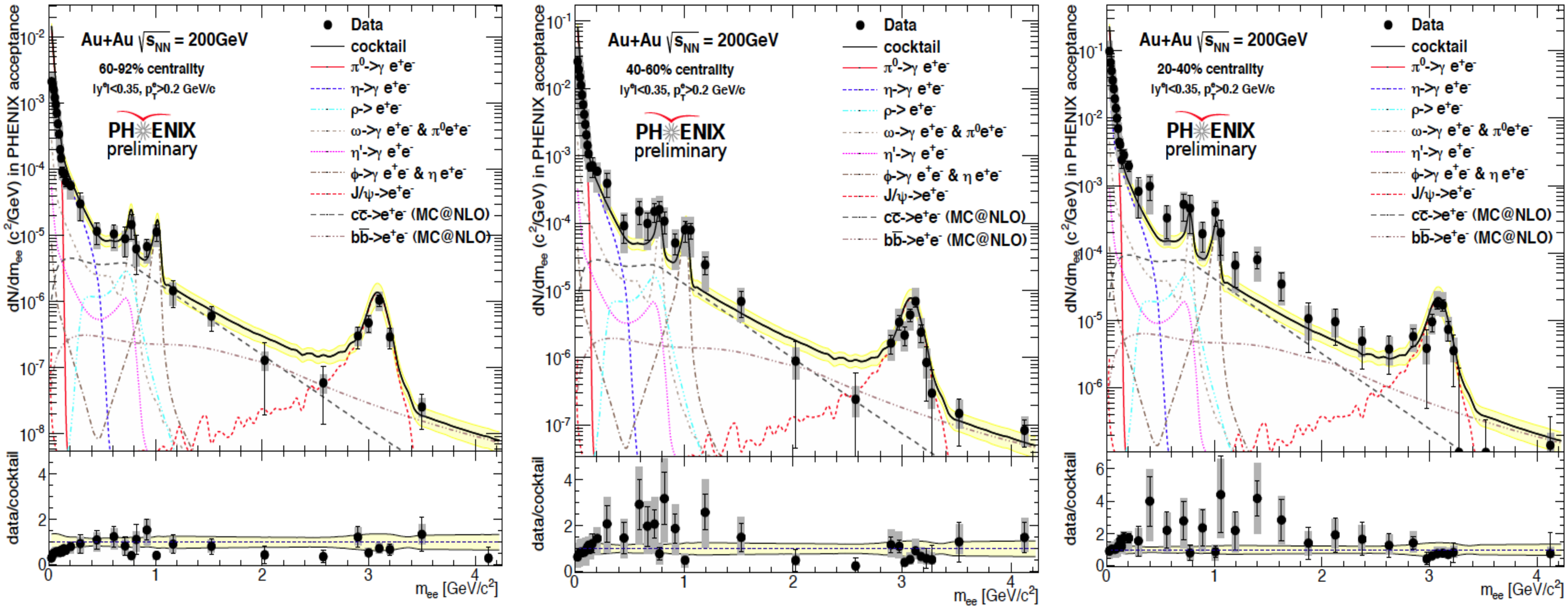
However: measurement affected by very small signal-to-background ratio (the bulk of the background in this mass region comes from pairs of electrons that are from different π^0 ancestors)

New data taking in 2009/10 with the Hadron Blind Detector, with an improvement of the S/B by a factor ~5

Dielectrons in Au-Au from PHENIX: $\sqrt{s_{NN}}$ = 200 GeV

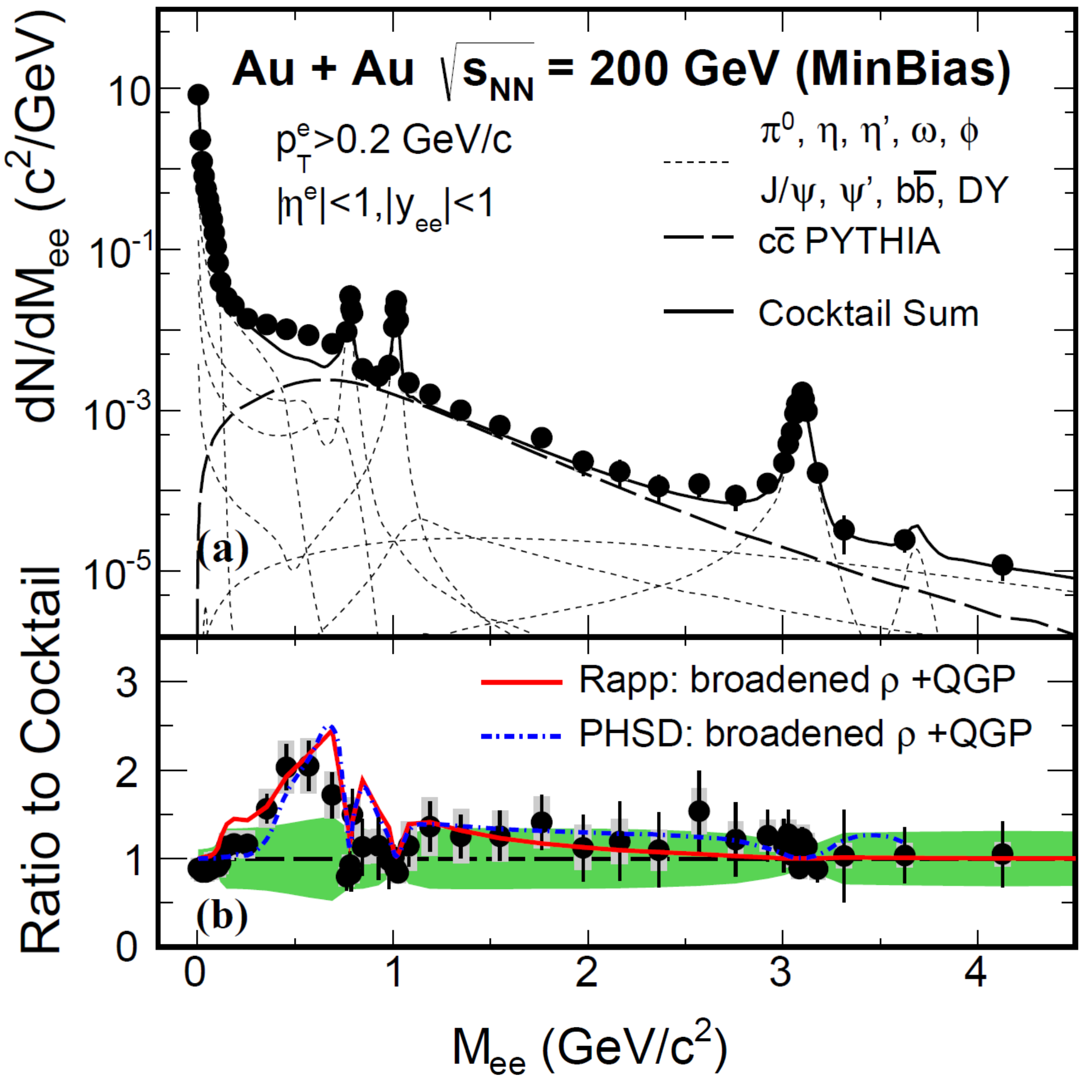
- **Results of HBD analysis in (0-10%) and (10-20%) centrality classes not yet available**
- Preliminary results with the HBD for the available centrality classes are **consistent** with the ones from the previous analysis
- **Waiting for the HBD results** in the two most central classes...

Nucl. Phys. A 904–905 225c–232c (2013)



Dielectrons in Au-Au from STAR: $\sqrt{s_{NN}}$ = 200 GeV

arXiv:1312.7397 (28 Dic. 2013)

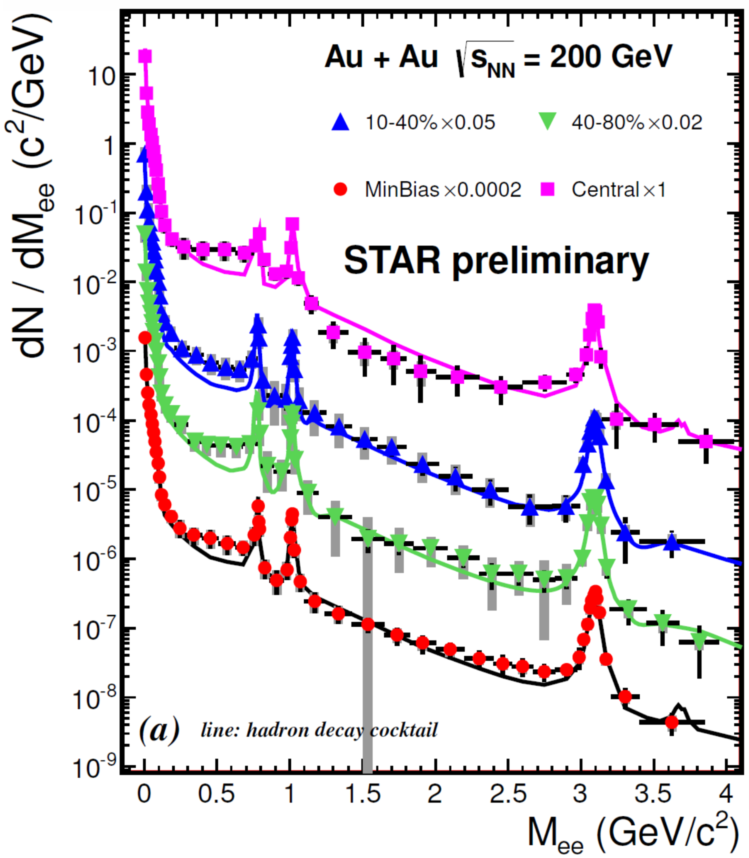


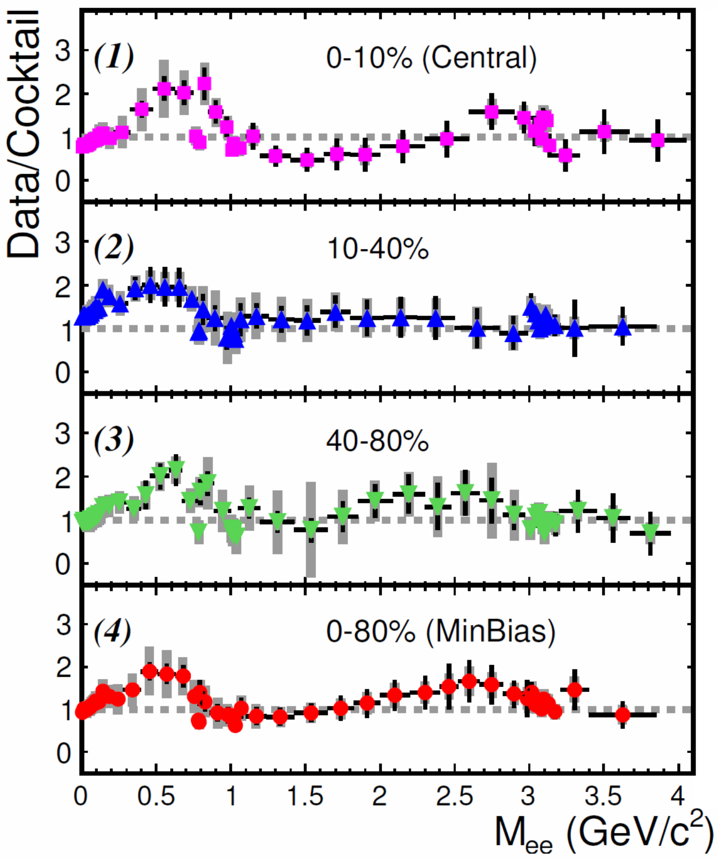
- **Excess measured by STAR** is significantly lower than the one from PHENIX
- Both **effective many-body calculation** (Rapp et al.) with microscopic transport model and **Parton-Hadron String Dynamics** (Linnyk et al.) satisfactorily describe the shape and magnitude of the LMR enhancement. They already described SPS data
- **Both models fail to reproduce the dielectron enhancement reported by PHENIX**

Dielectrons in Au-Au from STAR: $\sqrt{s_{NN}}$ = 200 GeV

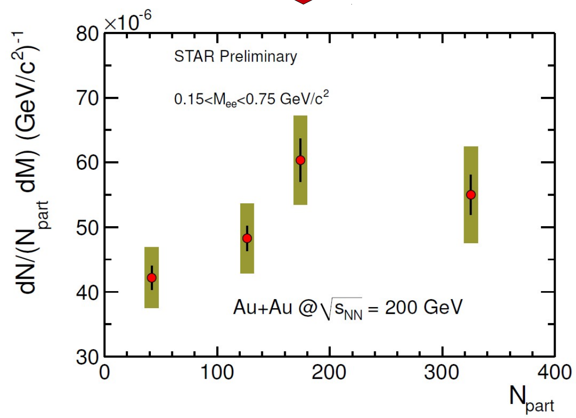
- **LMR enhancement in centrality classes**
- Very little centrality dependence of the observed excess

Nucl. Phys. A 904–905 (2013) 217c–224c





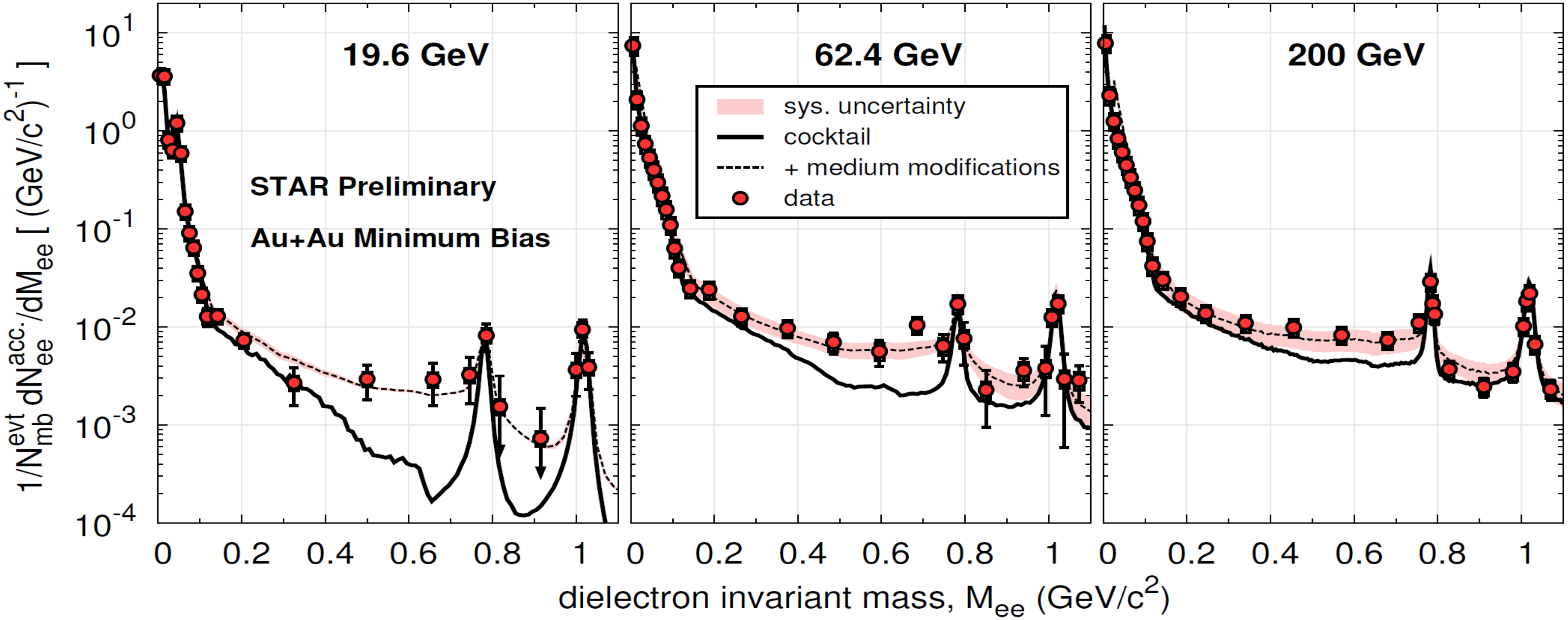
- A comparison of the dilepton yield in 0.15 < M < 0.75 GeV/c² scaled to the number of participants appears to indicate an increase of the LMR enhancement with increasing centrality



STAR Results In Au-Au: Beam Energy Scan

- Systematic study of excess establishing **consistency with previous SPS results**
- **Strongly broadened ρ spectral function plus QGP and Hadron Gas contributions,** already working at the SPS energy, describe the data up to top RHIC energy
- **Universal emission source**, with hadronic medium effects depending upon the **total** baryon density

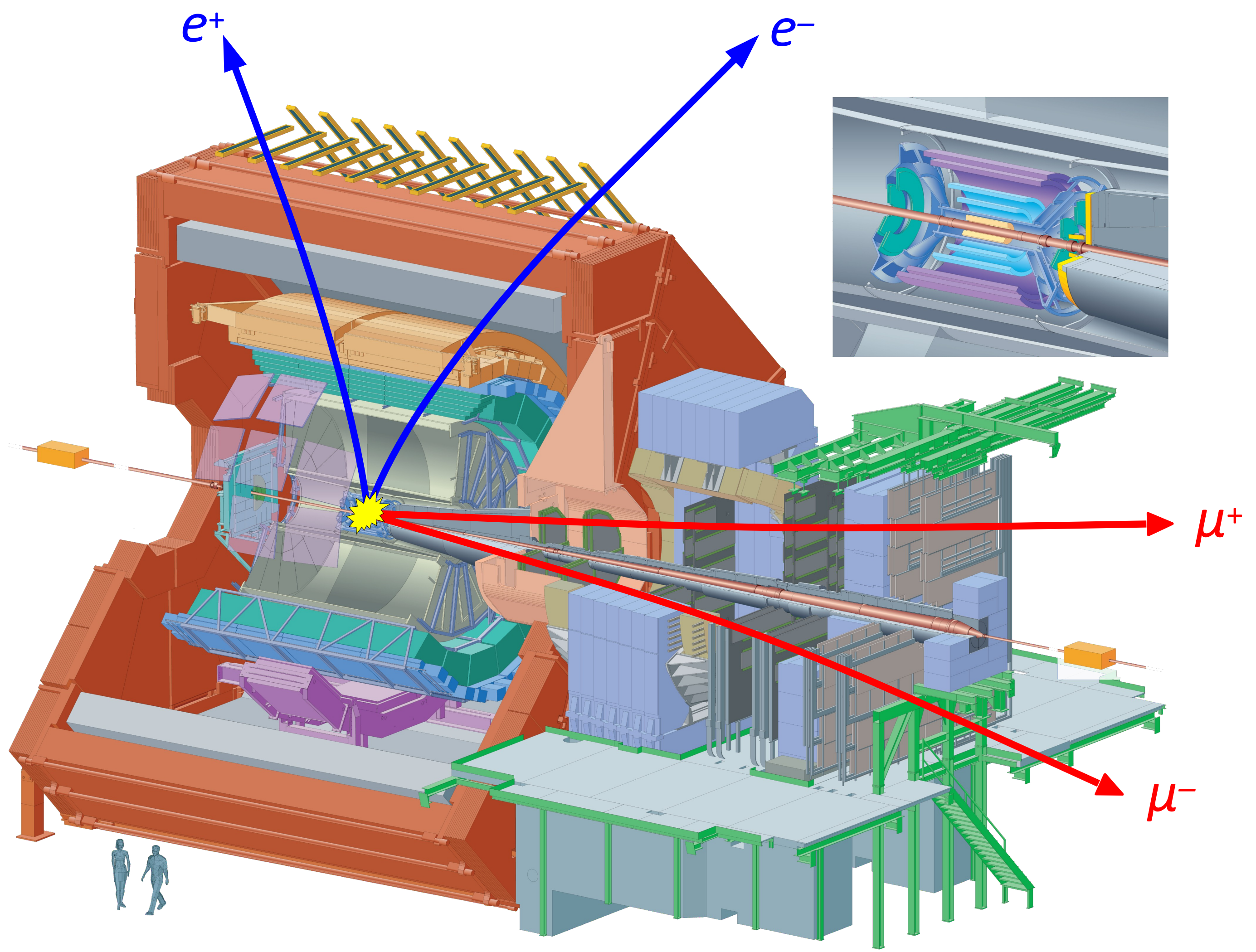
Nucl. Phys. A 904–905 (2013) 217c–224c



Low Mass Dileptons in ALICE at the LHC

The ALICE Apparatus

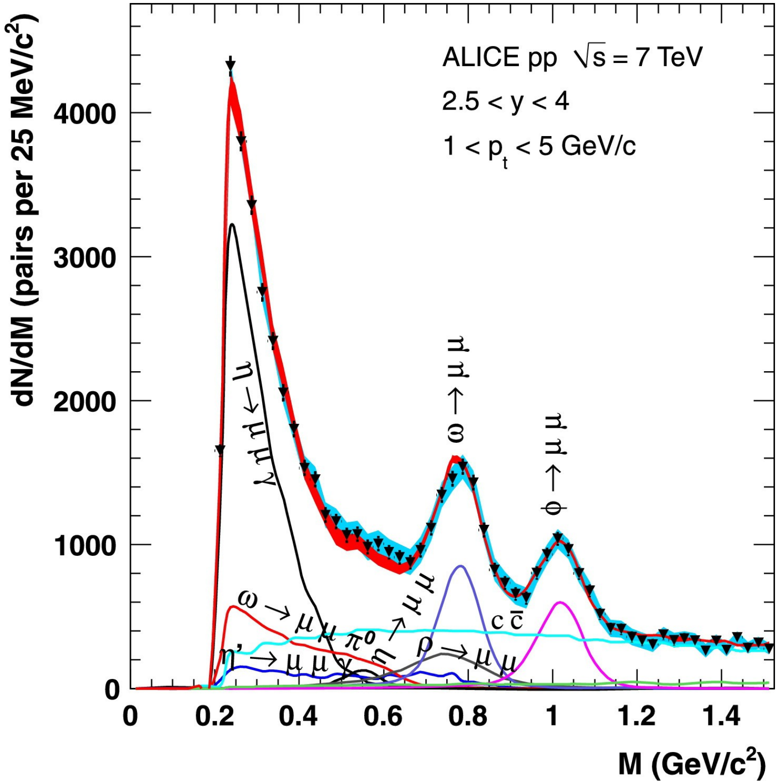
- **Dimuons** $\rightarrow$ **$2.5 < \eta < 4$**
  Muon Arm: MWPC Tracking Chambers + RPC Muon Trigger
- **Dielectrons** $\rightarrow$ **$|\eta| < 0.9$**
  Central Barrel: Si Inner Tracking System + Time Projection Chamber + Time Of Flight

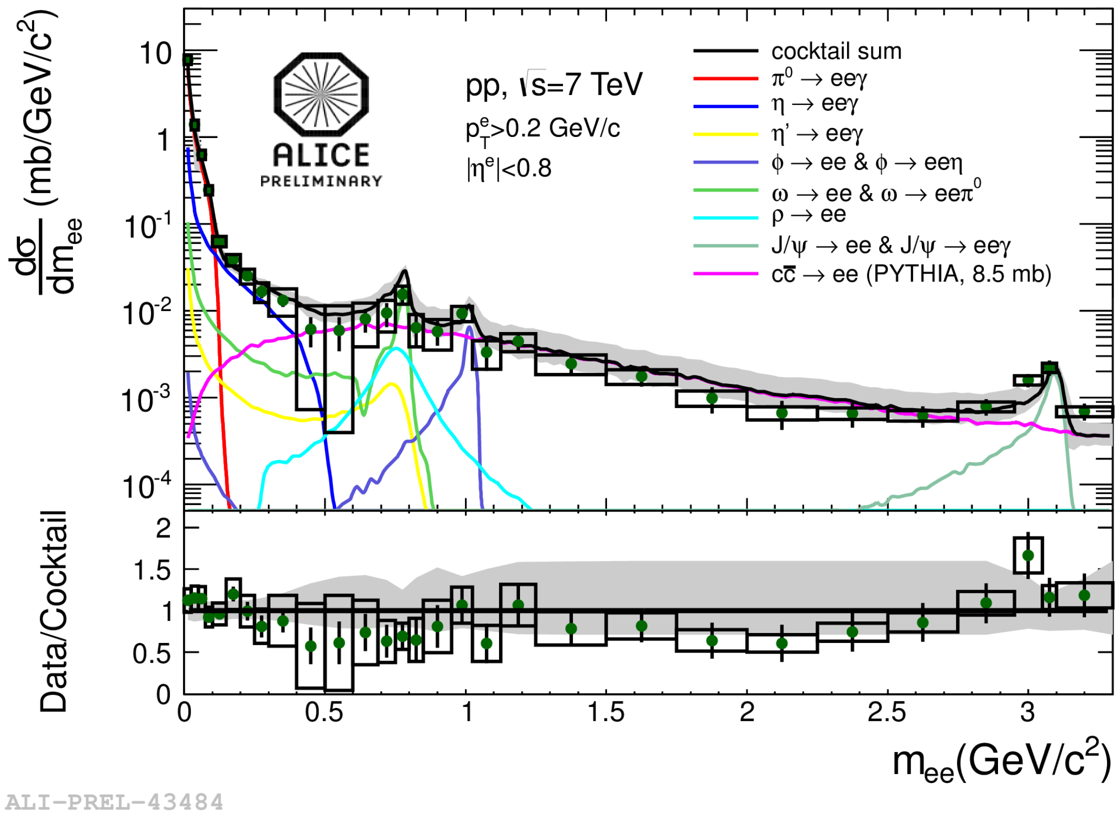


- pp collisions at **2.76 TeV** and **7 TeV**
- Pb-Pb collisions at **2.76 TeV** per nucleon pair
- p-Pb and Pb-p collisions at **5.02 TeV** per nucleon pair

- Low Mass Dimuon and Dielectron spectra at 7 TeV: **good agreement between signal and MC sources**
- **Data at 2.76 TeV also agree with MC**, with larger uncertainties due to the smaller data sample

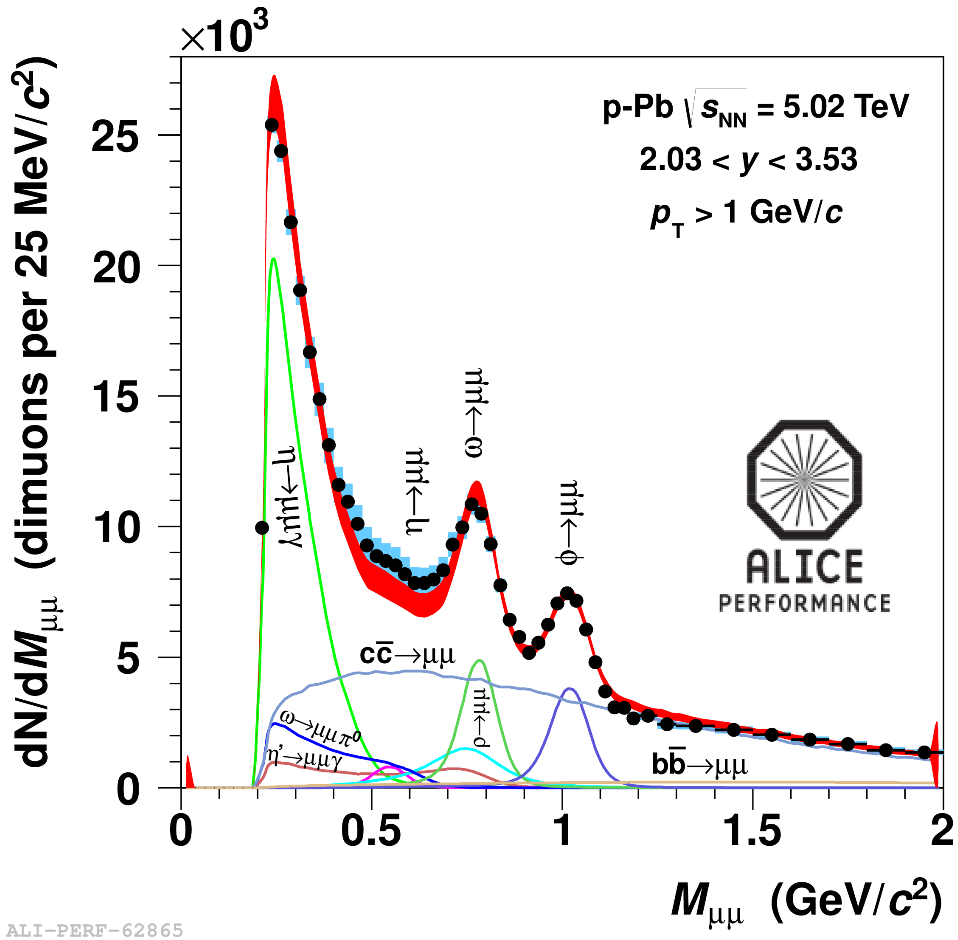
Phys. Lett. B 710 557–568 (2012)

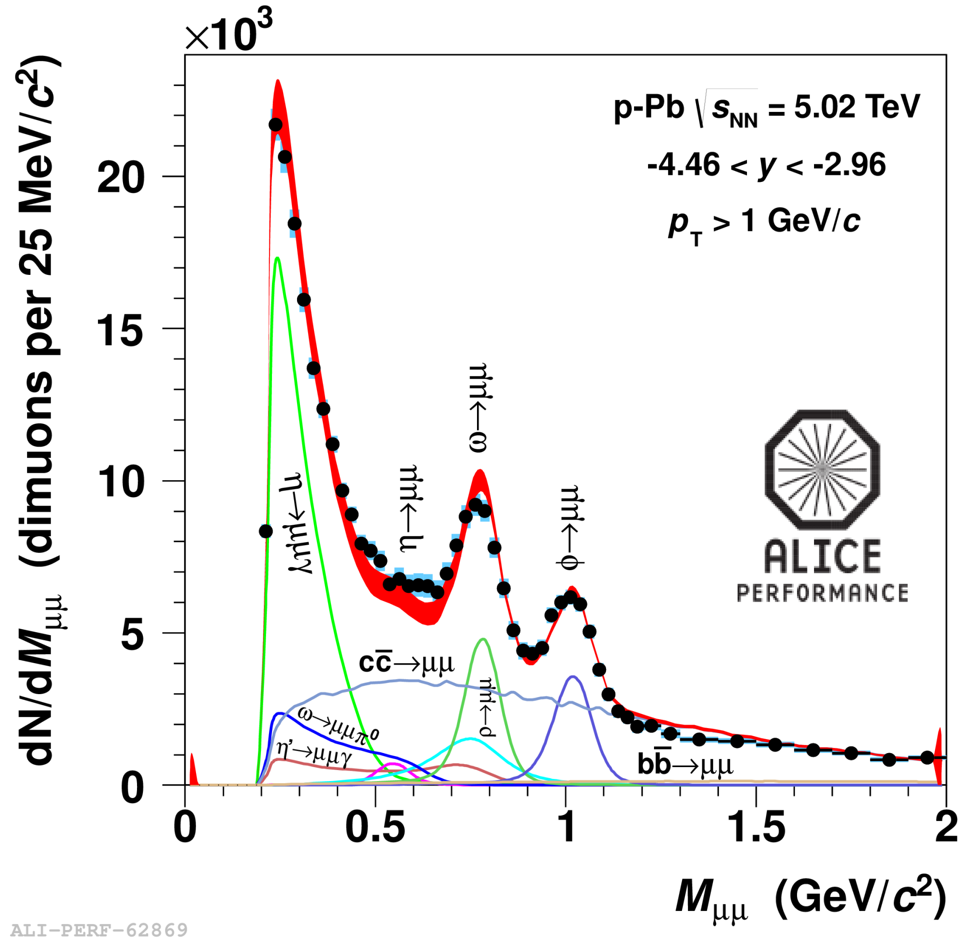




Results from Run 1: p-Pb Collisions

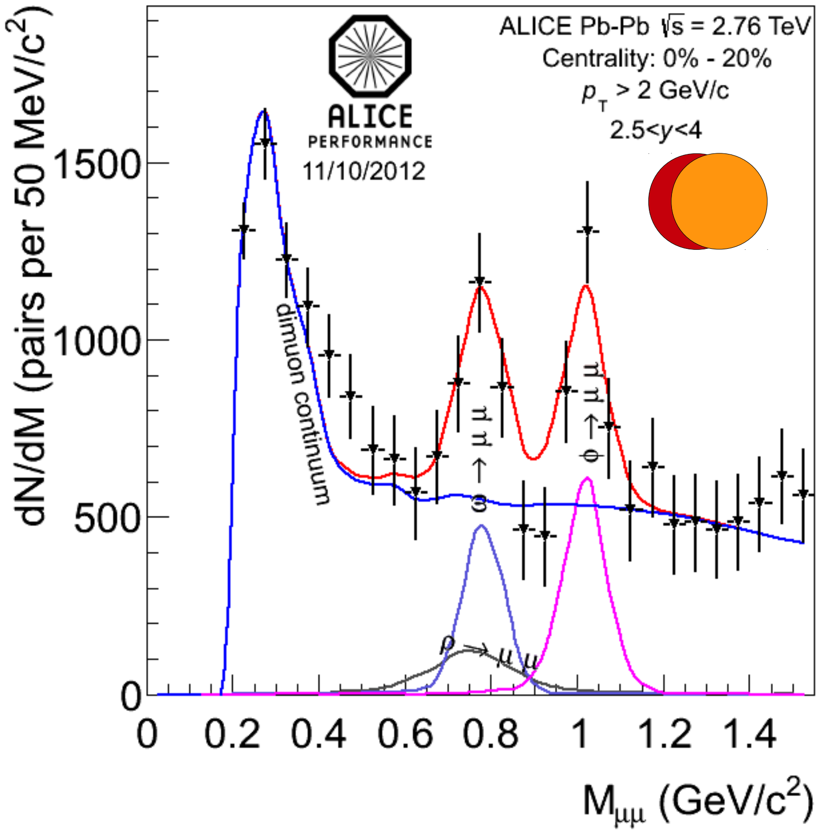
- **Preliminary results only available for the dimuon data**
- **Fair agreement** between data and hadronic cocktail + open heavy flavors
- **Various studies ongoing** both for resonances and continuum from open HF

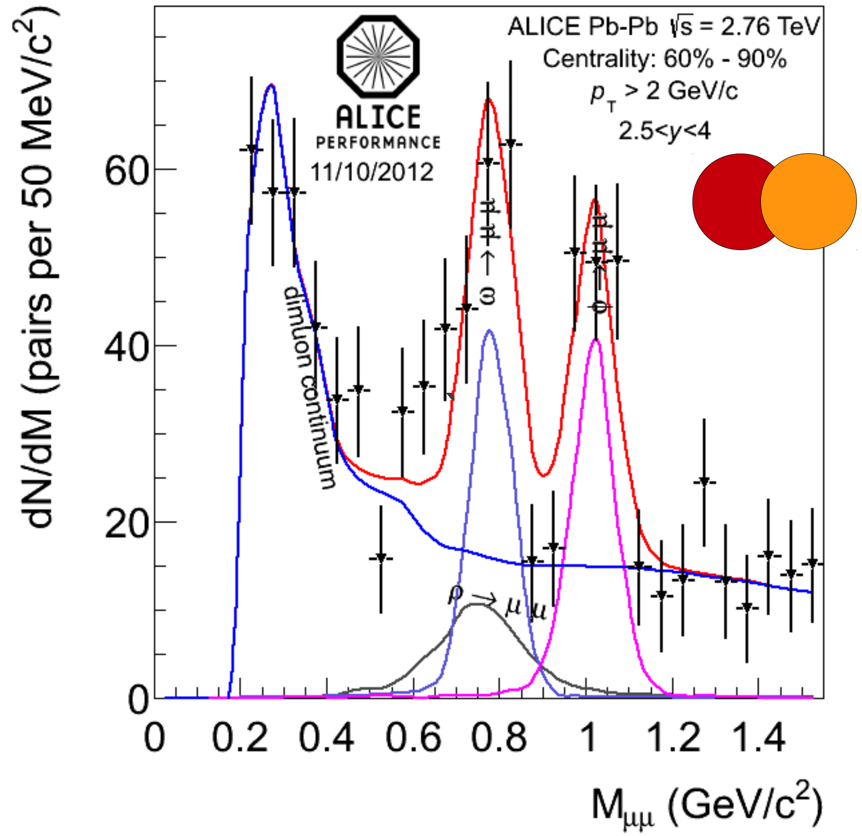




Results from Run 1: Pb-Pb Collisions

- **Dimuon signal fairly described** by vacuum ρ/ω and ϕ signals + continuum from open charm/beauty and Dalitz decays. Dielectron analysis ongoing
- **No precision study of the dimuon continuum** due to the large statistical uncertainties and the acceptance starting from $p_T(\mu\mu)$ ~2 GeV/c





Summary...

- **Low-mass dilepton physics spanned three orders of magnitude in the center of mass energy in 25 years**, going from *o*(20) GeV at the SPS to *o*(200) GeV at the RHIC to *o*(2000) GeV at the LHC

- **SPS experimental scenario is dominated by the high precision results of NA60** in the dimuon channel: first measurement of the in-medium ρ spectral function and of thermal radiation at intermediate masses

- **RHIC results on low-mass dielectrons** suffer from the luminosity limitations typical of colliders, and from some inconsistencies between the measurements in **STAR and PHENIX** in the most central Au-Au collisions. First results from the RHIC Beam Energy Scan program issued by STAR: **key point to link SPS and RHIC observations**

- **Low-mass dilepton measurement at the LHC**: a challenge with **ALICE** as the only competitor. Both dielectron (mid-rapidity) and dimuon (forward rapidity) channels began to produce results. Statistical uncertainties still dominate the measurements: waiting for LHC Run2 and the upgrade for Run3(-4-5)

… and Conclusions

PoS CPOD2013 008 (2013)

- **Electromagnetic radiation in heavy-ion collisions**, in the form of dilepton emission, continues to illuminate the properties of the formed medium
- Low-mass dilepton spectra and their interpretation are developing into a rather consistent picture, where the **melting of the ρ meson established at SPS,** thanks to the unprecedented precision of the NA60 data, seems to prevail also at RHIC
- The ρ melting is theoretically compatible with **chiral symmetry restoration** and suggestive for a **gradual change** in the effective degrees of freedom in the system (crossover more than 1st or 2nd order transition when going from confined to deconfined phase)
- Temperature slopes extracted from the invariant mass and m_T spectra suggest a **first evidence of observation of an electromagnetic thermal radiation from the QCD transition region**

Backup Slides

Physics Motivations

"For the ρ meson, the broadening amounts to a few hundred MeV at hadronic densities of $\rho_h = 0.2\ \mathrm{fm}^{-3}$, leading to its melting when extrapolated into the regime of the expected QCD phase boundary ($T \simeq 170\mathrm{MeV}$). The dissolution of the hadronic resonance structure suggests a change of the relevant degrees of freedom in the system, and thus may be interpreted as an indicator of deconfinement. Another issue is if and how these medium effects signal the restoration of the spontaneously broken chiral symmetry."

"Another issue is if and how these medium effects signal the restoration of the spontaneously broken chiral symmetry. This is quantified by Weinberg sum rules. Although we still do not have a proof of chiral restoration, a strongly broadened spectral function, as will be used in applications to dilepton data, is compatible with it. Another indication for this compatibility arises from the realization that the processes generating the ρ broadening (resonances and pion cloud modifications) find their counterparts in reducing the chiral."

PoS CPOD2013 008 (2013)

Why Dileptons?

photons: 1 variable: p_T

lepton pairs: 2 variables: M, p_T

relevant for thermal radiation:

pT sensitive to temperature and expansion velocity

M only sensitive to temperature (Lorentz invariant)

approximate mass spectrum (for flat spectral function, and interpreting T as the average temperature over the space-time evolution)

$$dN/dM \propto M^{3/2} \times \exp(-M/T)$$

⇒ 'Planck-like'

the only true (Lorentz invariant) thermometer of the field

systematic uncertainties:

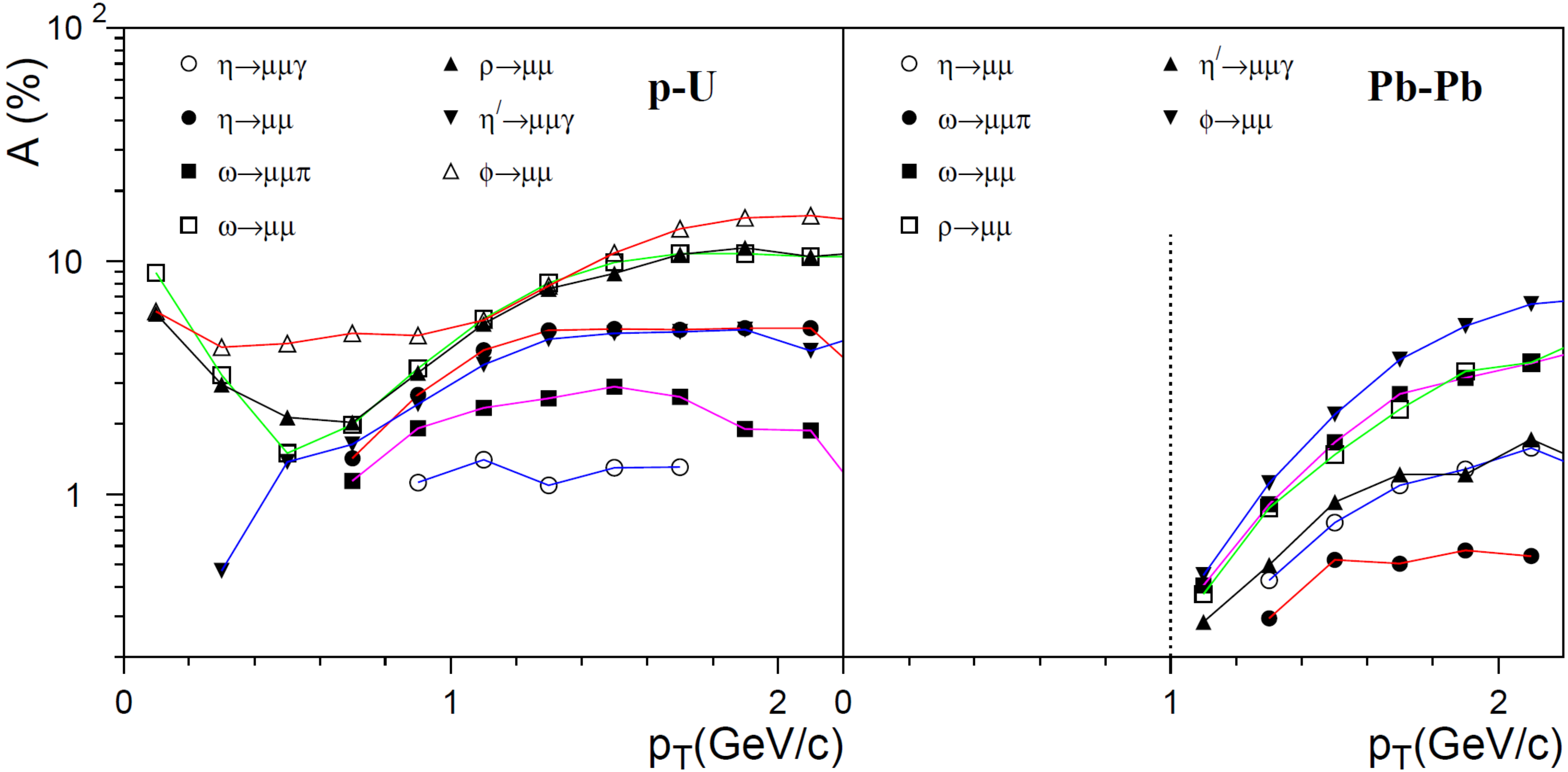
theory, from fits to RR and DZ: T =215 MeV; T1.2 GeV=205, T2.5 GeV = 225

data: oversubtraction of DY by 20/30% ⇒ ΔT= -10/-20 MeV

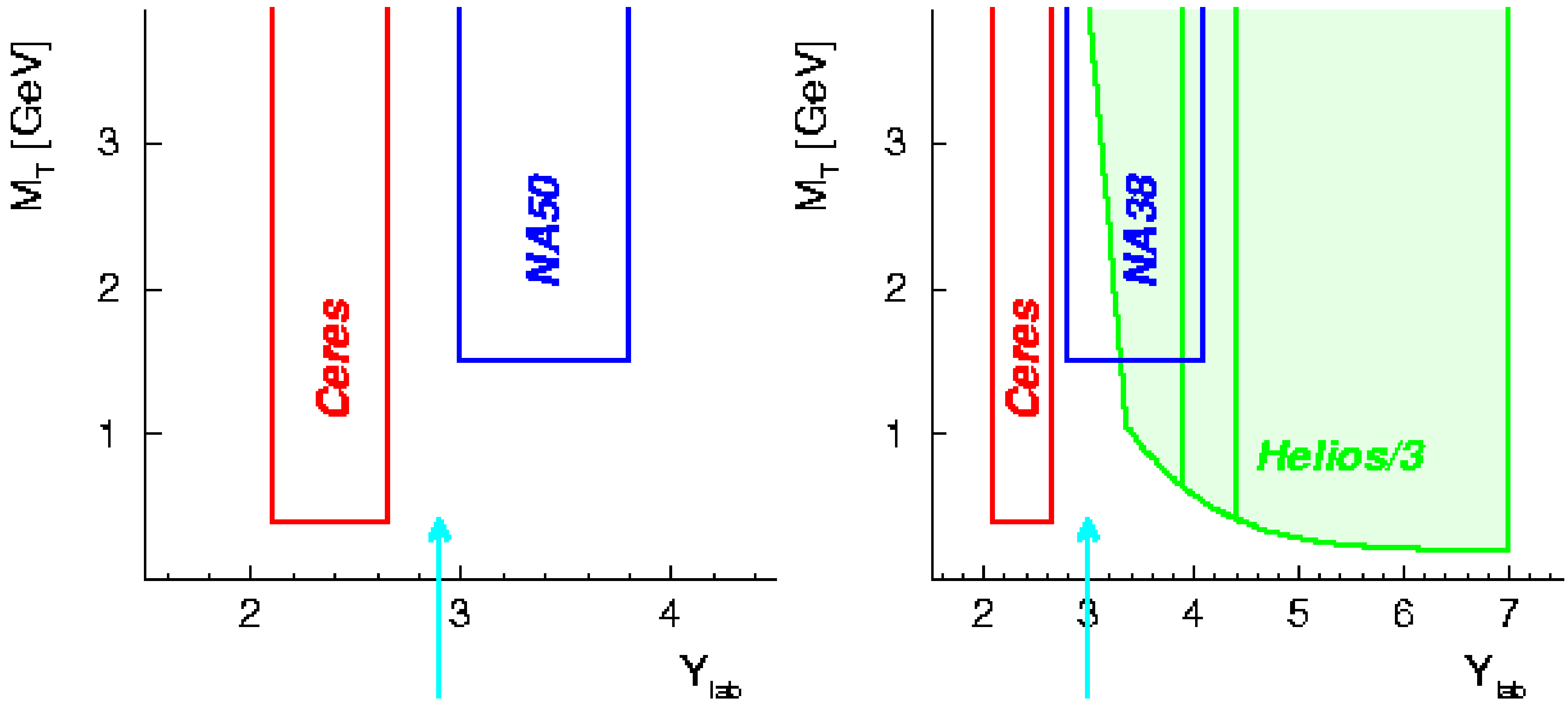
Low Mass Dimuons in NA38 and NA50

- Limited acceptance at low masses, especially in Pb-Pb

Eur. Phys. J. C 13, 69-78 (2000)



NA38, NA50, Helios-3 and CERES: Phase Space

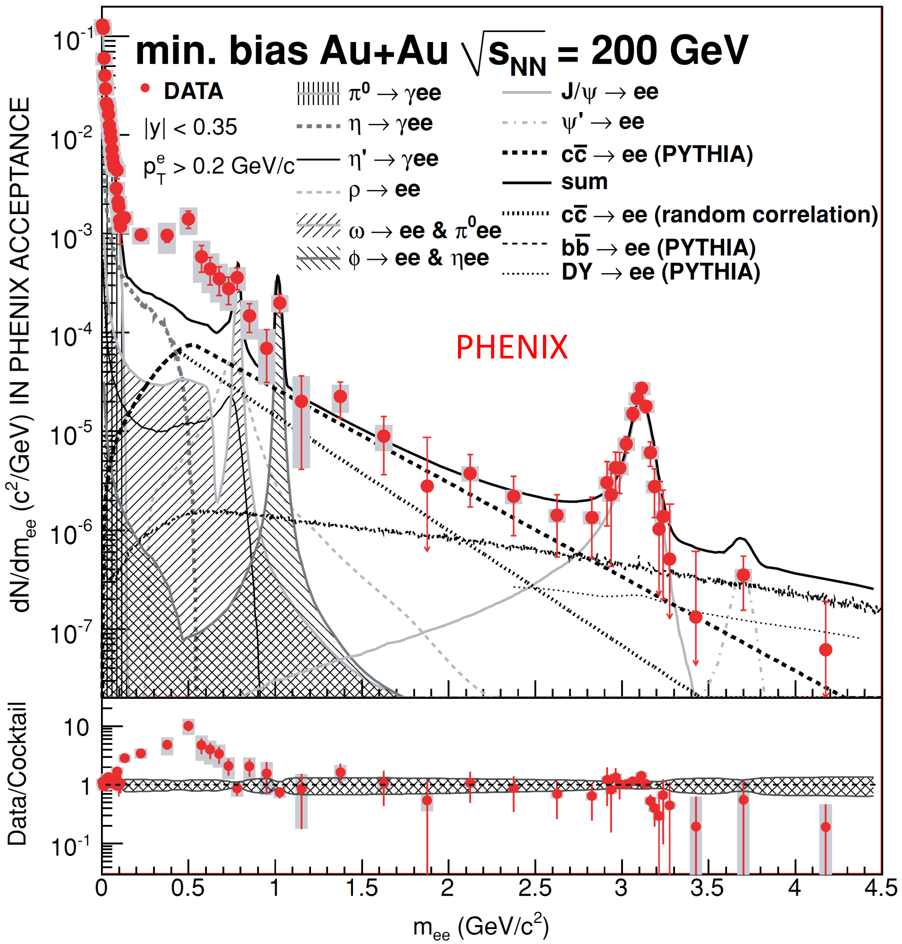


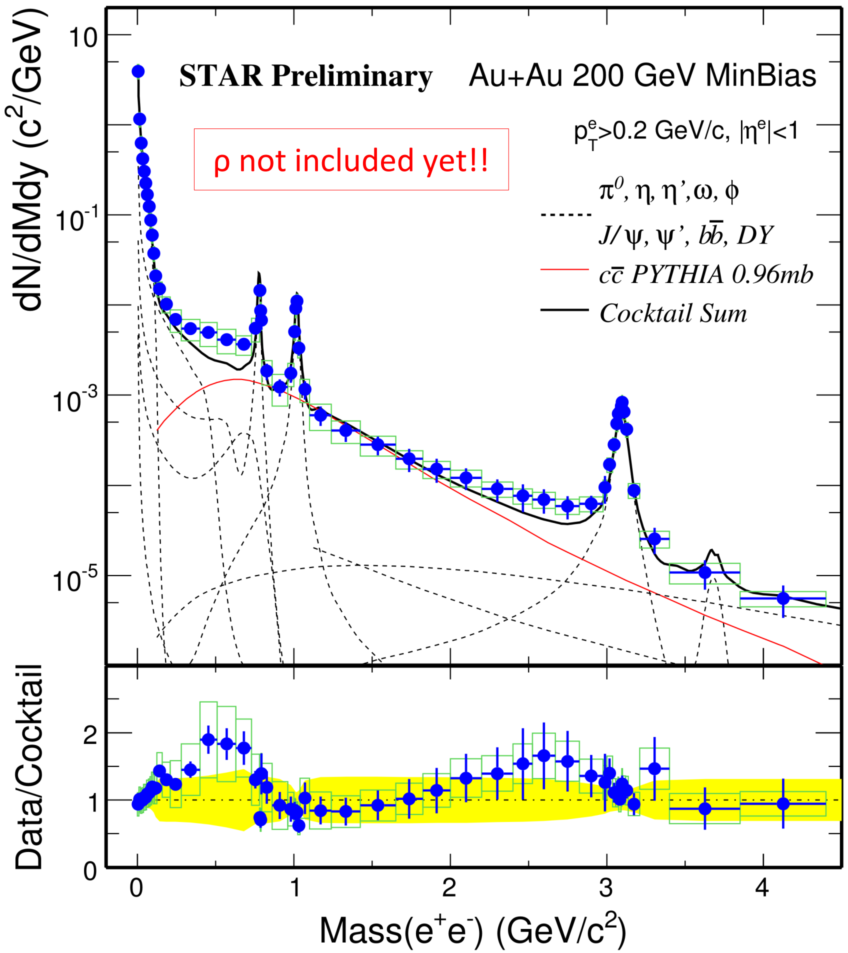
The RHIC Beam Energy Scan

sqrt (sNN) [GeV]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
200												
130												
62.4												
39												
27												
22.5												
19.6												
11.5										STAR only		
7.7												
5.0												Test run

Au+Au U+U Cu+Au Cu+Cu d+Au

Low Mass Dileptons from the QGP: RHIC (~200 GeV)

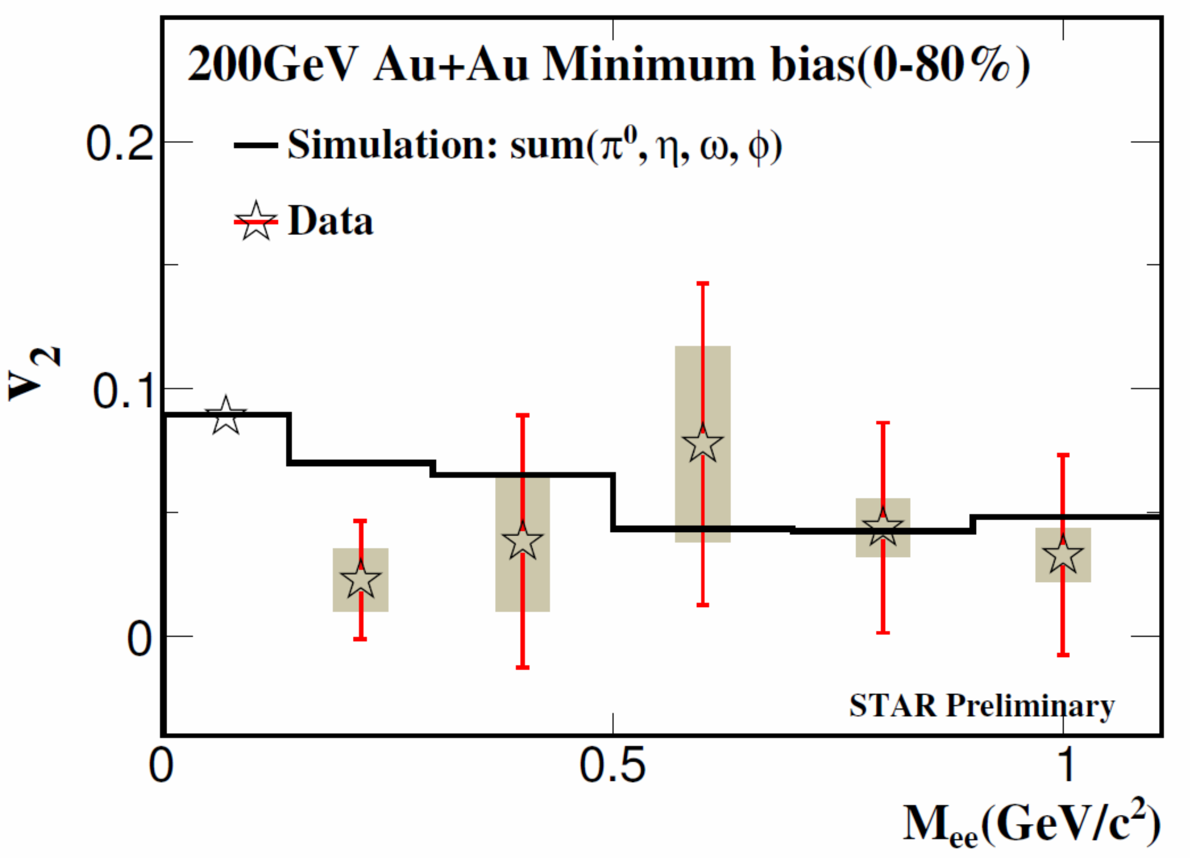




- **Au-Au minimum bias measurements:** strong excess at low masses for PHENIX after all expected sources are included

Low Mass Dielectrons from STAR: Elliptic Flow

- STAR dielectron elliptic-flow measurements in Au+Au collisions at sqrt(s) = 200 GeV as a function of the dielectron invariant mass



- The elliptic flow, v2, is calculated using the event-plane method in which the event plane has been reconstructed from TPC tracks
- The expected v2 from a cocktail simulation based on the contributions from π^0, η, ω, and ϕ mesons is within uncertainties consistent with the measurements

The HBD in Central Au-Au Collisions

In Au+Au collisions, the extraction of information from the HBD is complicated due to presence of scintillation light. This results in a significantly higher occupancy and a highly fluctuating background in the HBD pad readout, which becomes especially severe in the most central events.

To tackle this, two independent approaches were used to estimate the background around projections of candidate tracks with similar performance. The dielectron background subtraction is done in two steps. The first step involves subtracting the combinatoric background using mixed events. It is followed by the subtraction of an estimatation of the correlated backgrounds.

Combinatorial Background/Signal in Dilepton Exp.

Reference: hadron cocktail at masses of 0.5-0.6 GeV

Experiment	Centrality	Lepton flavor	B/S as meas. or simul.	B/S rescaled to dNch/dy=300
HADES-SIS100	semicentr	e+e-	20	60
CERES DR	semicentr	e+e-	80	100
CERES SR/TPC	central	e+e-	110	100
PHENIX with HBD	central	e+e-	250	100
PHENIX w/o HBD	central	e+e-	1300	600
STAR	central	e+e-	400	200
ALICE Upg ITS	central	e+e-	1200	200
CBM-SIS100	central	e+e-	80	100
CBM-SIS300	central	e+e-	100	100
NA60 (InIn)	semicentr	μ+μ-	35	80
NA60-like (20AGeV)	central	μ+μ-	90	110
CBM-SIS300	central	μ+μ-	600 (200)	600 (200)

data / simulations PbPb