# 25 Years of Dilepton Experiments

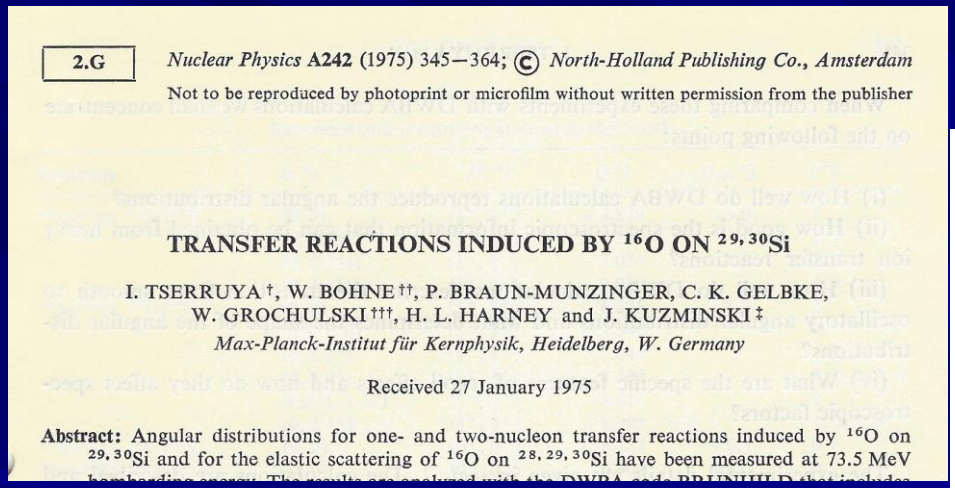
PBM Fest, August 25-26, 2016

Itzhak Tserruya

WEIZMANN INSTITUTE OF SCIENCE

# 42 years and looking forward

My first paper with PBM:
NP A242, 345 (1975)



2.G

*Nuclear Physics* **A242** (1975) 345—364; © *North-Holland Publishing Co., Amsterdam*



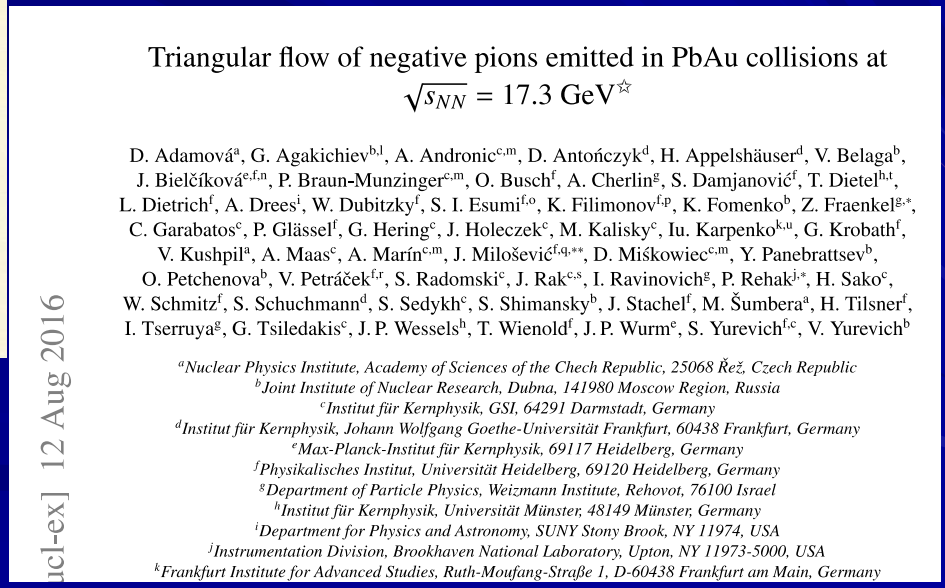
## TRANSFER REACTIONS INDUCED BY $^{16}$O ON $^{29,30}$Si

I. TSERRUYA †, W. BOHNE ††, P. BRAUN-MUNZINGER, C. K. GELBKE,
W. GROCHULSKI †††, H. L. HARNEY and J. KUZMINSKI ‡
*Max-Planck-Institut für Kernphysik, Heidelberg, W. Germany*

Received 27 January 1975

**Abstract:** Angular distributions for one- and two-nucleon transfer reactions induced by $^{16}$O on $^{29,30}$Si and for the elastic scattering of $^{16}$O on $^{28,29,30}$Si have been measured at 73.5 MeV

Our last paper posted to
the arXiv on April 2016



Triangular flow of negative pions emitted in PbAu collisions at $\sqrt{s_{NN}} = 17.3$ GeV☆

D. Adamová[a], G. Agakichiev[b,l], A. Andronic[c,m], D. Antończyk[d], H. Appelshäuser[d], V. Belaga[b], J. Bielčíková[e,f,n], P. Braun-Munzinger[c,m], O. Busch[f], A. Cherlin[g], S. Damjanović[f], T. Dietel[h,t], L. Dietrich[f], A. Drees[i], W. Dubitzky[f], S. I. Esumi[f,o], K. Filimonov[f,p], K. Fomenko[b], Z. Fraenkel[g,*], C. Garabatos[c], P. Glässel[f], G. Hering[c], J. Holeczek[c], M. Kalisky[c], Iu. Karpenko[k,u], G. Krobath[f], V. Kushpil[a], A. Maas[c], A. Marín[c,m], J. Milošević[f,q,**], D. Miśkowiec[c,m], Y. Panebrattsev[b], O. Petchenova[b], V. Petráček[f,r], S. Radomski[c], J. Rak[c,s], I. Ravinovich[g], P. Rehak[j,*], H. Sako[c], W. Schmitz[f], S. Schuchmann[d], S. Sedykh[c], S. Shimansky[b], J. Stachel[f], M. Šumbera[a], H. Tilsner[f], I. Tserruya[g], G. Tsiledakis[c], J. P. Wessels[h], T. Wienold[f], J. P. Wurm[e], S. Yurevich[f,c], V. Yurevich[b]

[a]*Nuclear Physics Institute, Academy of Sciences of the Chech Republic, 25068 Řež, Czech Republic*
[b]*Joint Institute of Nuclear Research, Dubna, 141980 Moscow Region, Russia*
[c]*Institut für Kernphysik, GSI, 64291 Darmstadt, Germany*
[d]*Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, 60438 Frankfurt, Germany*
[e]*Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*
[f]*Physikalisches Institut, Universität Heidelberg, 69120 Heidelberg, Germany*
[g]*Department of Particle Physics, Weizmann Institute, Rehovot, 76100 Israel*
[h]*Institut für Kernphysik, Universität Münster, 48149 Münster, Germany*
[i]*Department for Physics and Astronomy, SUNY Stony Brook, NY 11974, USA*
[j]*Instrumentation Division, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*
[k]*Frankfurt Institute for Advanced Studies, Ruth-Moufang-Straße 1, D-60438 Frankfurt am Main, Germany*

# Outline

- Introduction
  - Chiral symmetry restoration
  - Thermal radiation
- SPS
- RHIC
- Prospects at low and high energies
- Summary

# Introduction

# Motivation

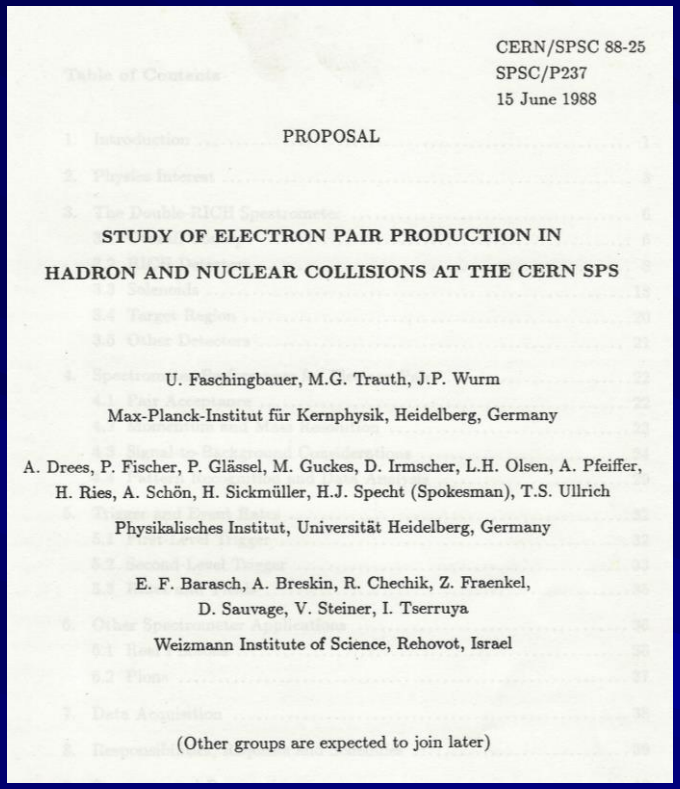
- Dileptons ($e^+e^-$, $\mu^+\mu^-$) are sensitive probes of the QGP and in particular of *Chiral Symmetry Restoration*

- *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: $q\bar{q} \longrightarrow$ ©* $\longrightarrow l^+l^-$

HG: □⁺□⁻ $\longrightarrow \rangle \longrightarrow$ ©* $\longrightarrow l^+l^-$

# CERES proposals



CERN/SPSC 88-25
SPSC/P237
15 June 1988

PROPOSAL

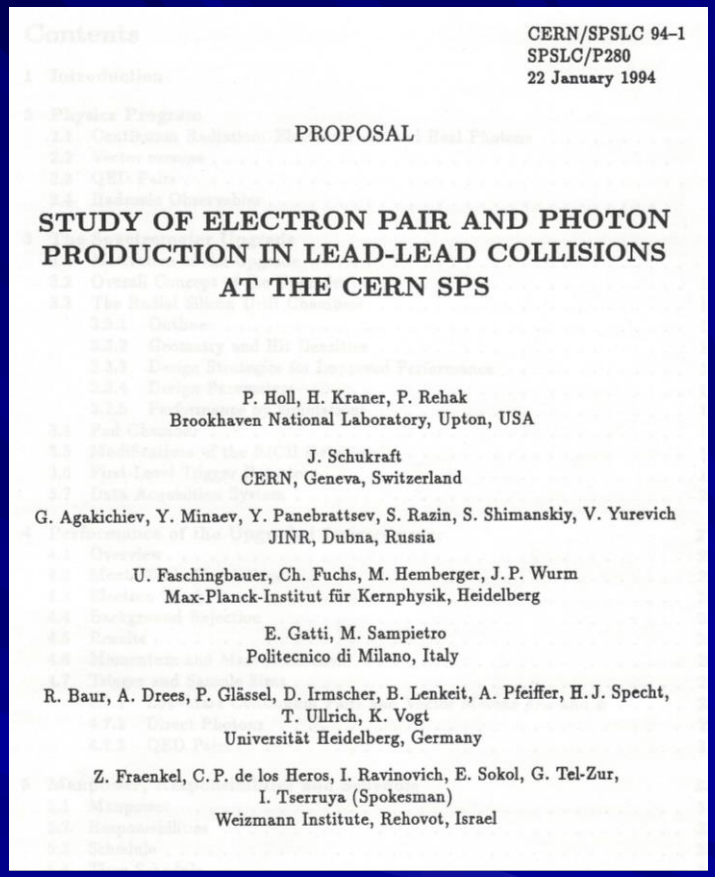
**STUDY OF ELECTRON PAIR PRODUCTION IN HADRON AND NUCLEAR COLLISIONS AT THE CERN SPS**

U. Faschingbauer, M.G. Trauth, J.P. Wurm
Max-Planck-Institut für Kernphysik, Heidelberg, Germany

A. Drees, P. Fischer, P. Glässel, M. Guckes, D. Irmscher, L.H. Olsen, A. Pfeiffer, H. Ries, A. Schön, H. Sickmüller, H.J. Specht (Spokesman), T.S. Ullrich
Physikalisches Institut, Universität Heidelberg, Germany

E. F. Barasch, A. Breskin, R. Chechik, Z. Fraenkel, D. Sauvage, V. Steiner, I. Tserruya
Weizmann Institute of Science, Rehovot, Israel

(Other groups are expected to join later)



CERN/SPSLC 94-1
SPSLC/P280
22 January 1994

PROPOSAL

**STUDY OF ELECTRON PAIR AND PHOTON PRODUCTION IN LEAD-LEAD COLLISIONS AT THE CERN SPS**

P. Holl, H. Kraner, P. Rehak
Brookhaven National Laboratory, Upton, USA

J. Schukraft
CERN, Geneva, Switzerland

G. Agakichiev, Y. Minaev, Y. Panebrattsev, S. Razin, S. Shimanskiy, V. Yurevich
JINR, Dubna, Russia

U. Faschingbauer, Ch. Fuchs, M. Hemberger, J.P. Wurm
Max-Planck-Institut für Kernphysik, Heidelberg

E. Gatti, M. Sampietro
Politecnico di Milano, Italy

R. Baur, A. Drees, P. Glässel, D. Irmscher, B. Lenkeit, A. Pfeiffer, H.J. Specht, T. Ullrich, K. Vogt
Universität Heidelberg, Germany

Z. Fraenkel, C.P. de los Heros, I. Ravinovich, E. Sokol, G. Tel-Zur, I. Tserruya (Spokesman)
Weizmann Institute, Rehovot, Israel

Main emphasis on both proposals: “study the pair continuum in the invariant mass region from 100 MeV/$c^2$ to beyond 3 GeV/$c^2$”

“in-medium” modification did not exist in the jargon at the time we proposed the CERES experiment

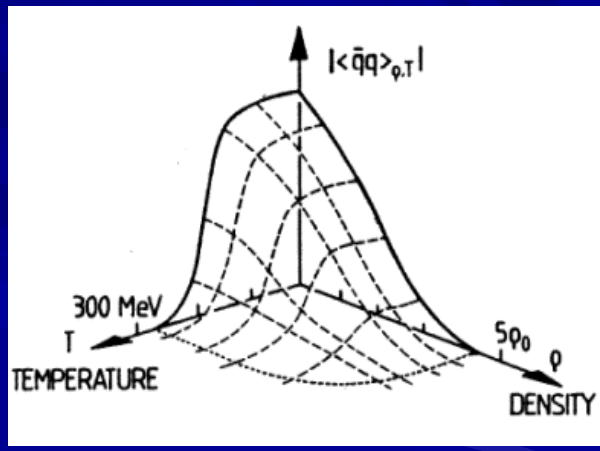
# Chiral Symmetry Restoration

- Chiral symmetry is explicitly and spontaneously broken.
- The spontaneous breaking is marked by a non-zero value of an order parameter, the quark condensate:

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

- Numerical calculations of QCD on the lattice show that at high temperatures ($T>T_C$) or high baryon densities ($\rho>\rho_C$), the quark condensate vanishes:

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




Chiral symmetry (approximately) restored
Chiral partners (e.g. ρ and $a_1$) become degenerate

How is the degeneracy of the chiral partners achieved?

How is the quark condensate linked to hadron properties (mass and width)?

# Dilepton Experiments

## Nuclear Collisions

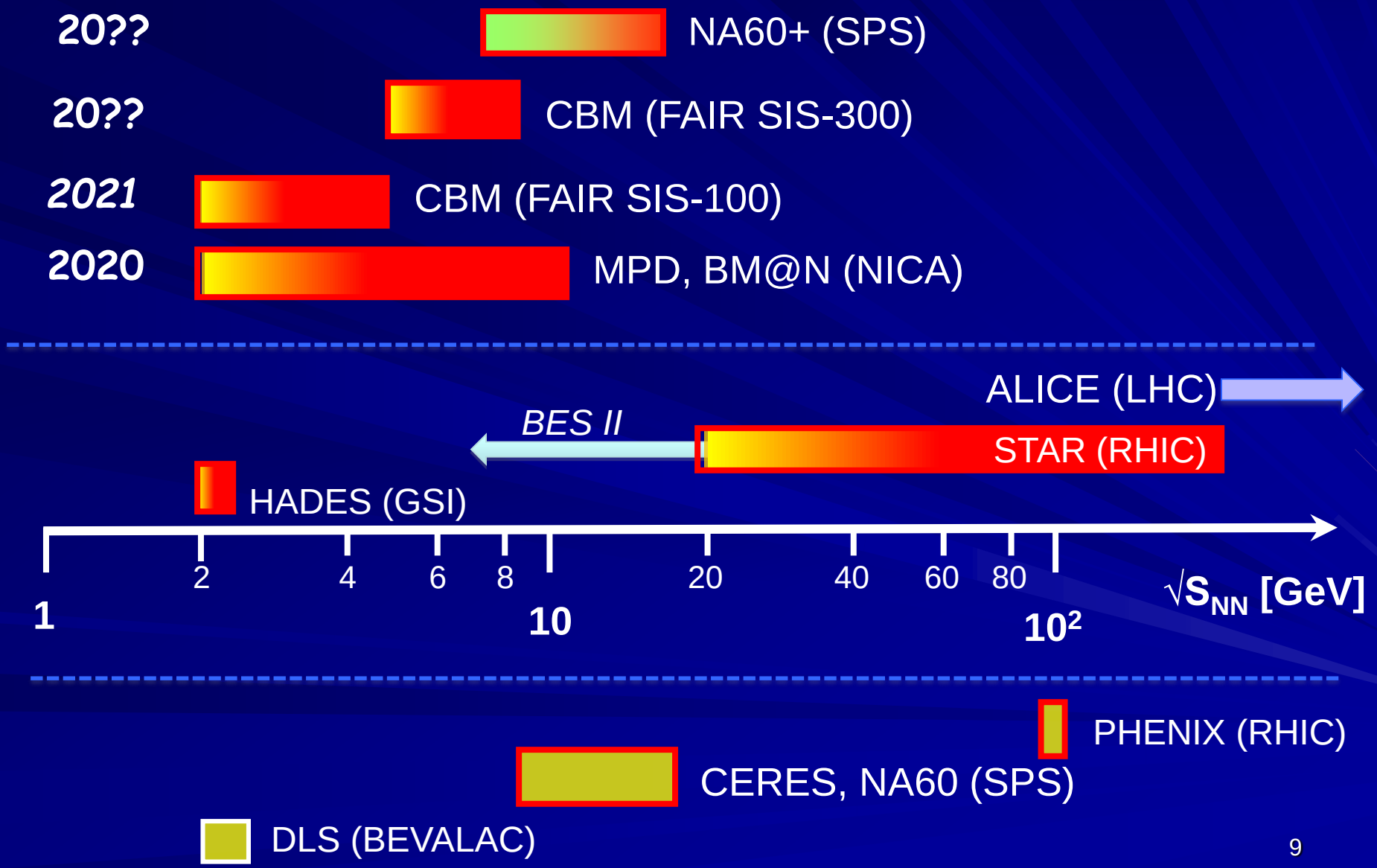
- CERES
- DLS
- HELIOS
- NA38/50
- NA60
- PHENIX
- ALICE
- HADES
- STAR
- BM@N
- CBM
- NA60+
- MPD

## Elementary Reactions

- CLAS
- CBELSA/TAPS
- KEK E235
- TAGX
- JPARC – E16

Completed
Runnning
Future

# Dilepton experiments – energy map



# SPS

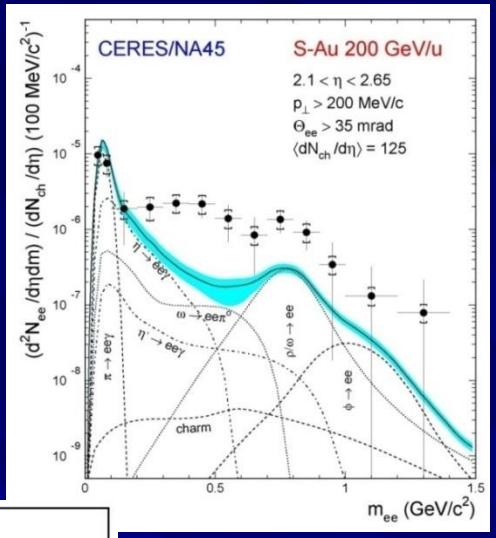
CERES – low masses

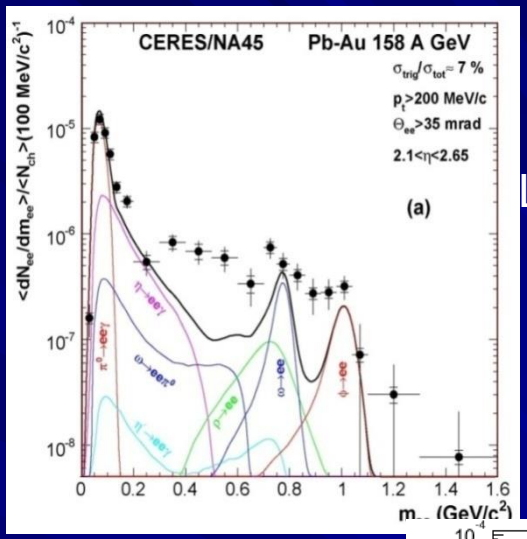
NA60 – low and intermediate masses

# CERES Pioneering Dilepton Results

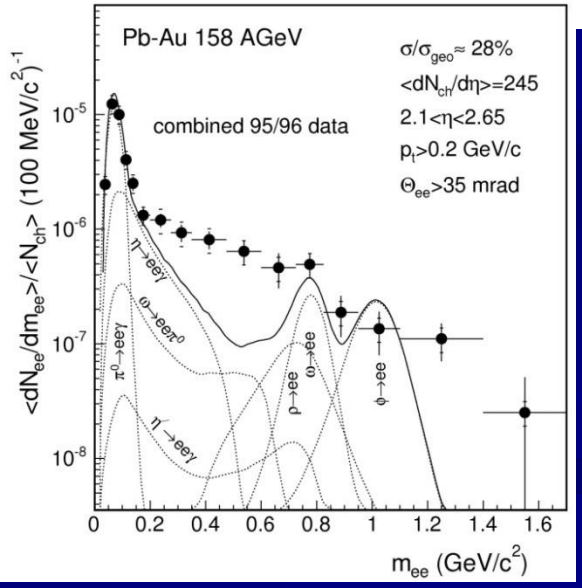
First CERES result
PRL 75, 1272 (1995)

(renowned paper: 566 citations)



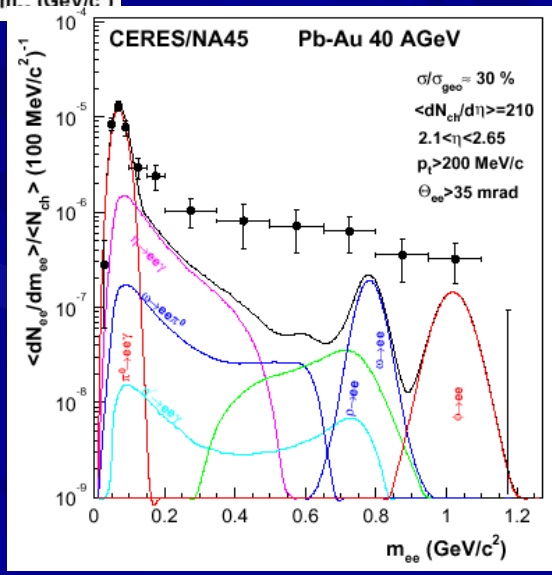

Last dilepton result
PLB 666, 425 (2008)




Strong enhancement of low-mass $e^+e^-$ pairs in all A-A systems studied

First evidence of thermal radiation from the HG

□⁺□⁻ → 〉 → ©* → $e^+e^-$

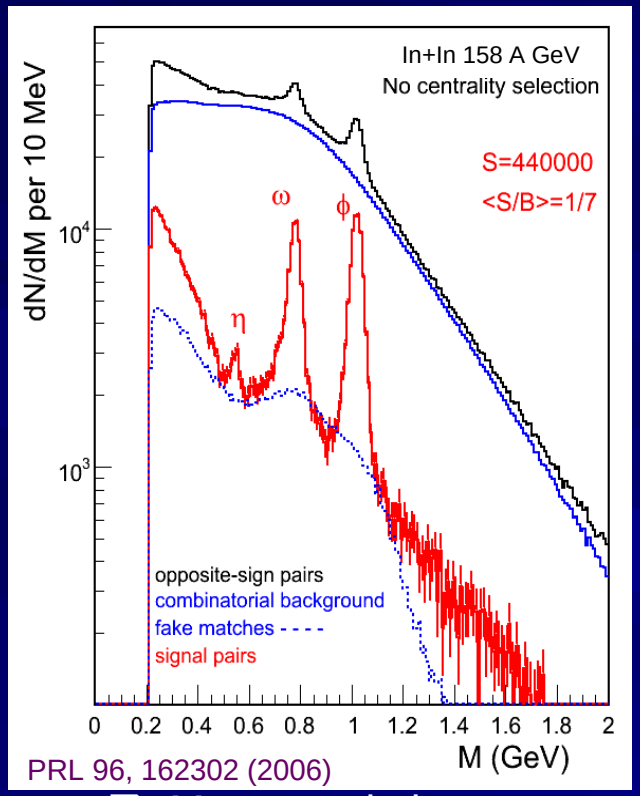



Eur. Phys J. C41, 475 (2005)

PRL 91, 042301 (2003)

# NA60 Low-mass dimuons

**Superb data!**

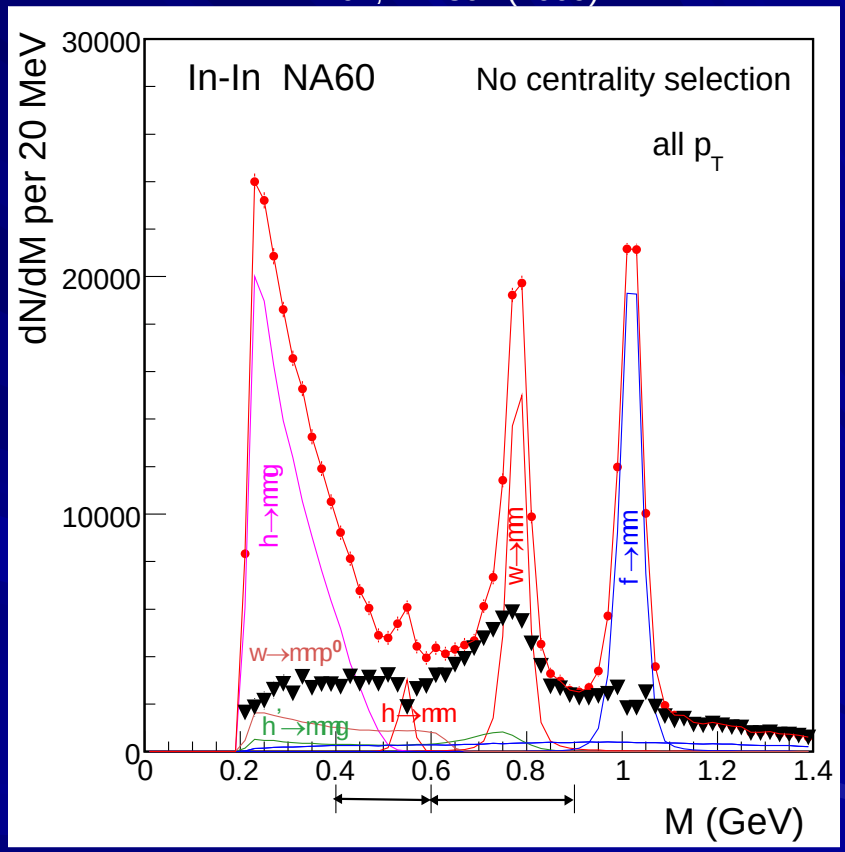



PRL 96, 162302 (2006)

- Mass resolution:
  23 MeV at the ϕ position
- S/B = 1/7

- NA60 excess

PRL 102, 222301 (2009)

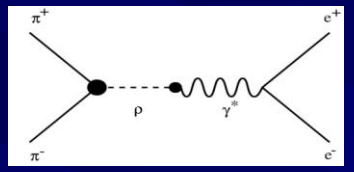



✓***confirm and consistent with CERES***
✓**rising with centrality**
✓**more pronounced at low pT**

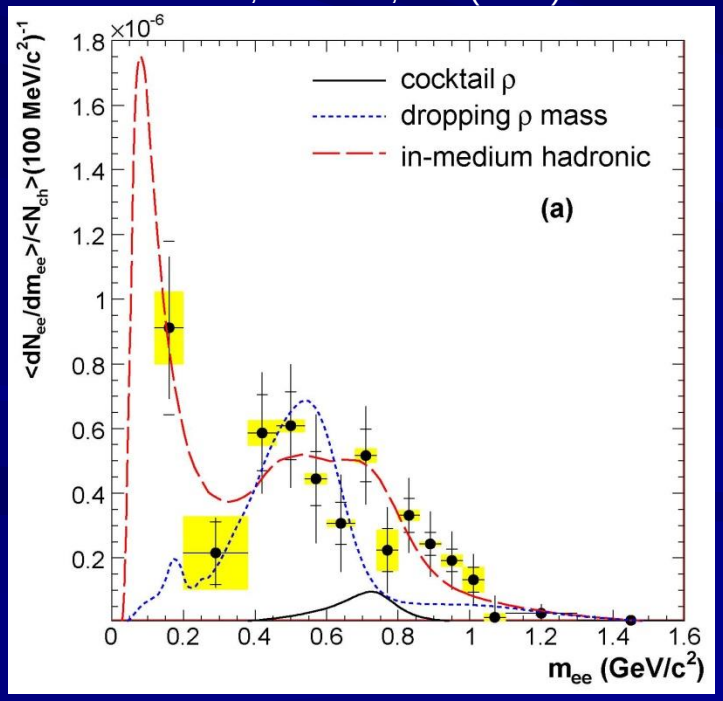
# Low-mass dileptons and CSR

* Interpretation: Thermal radiation from HG

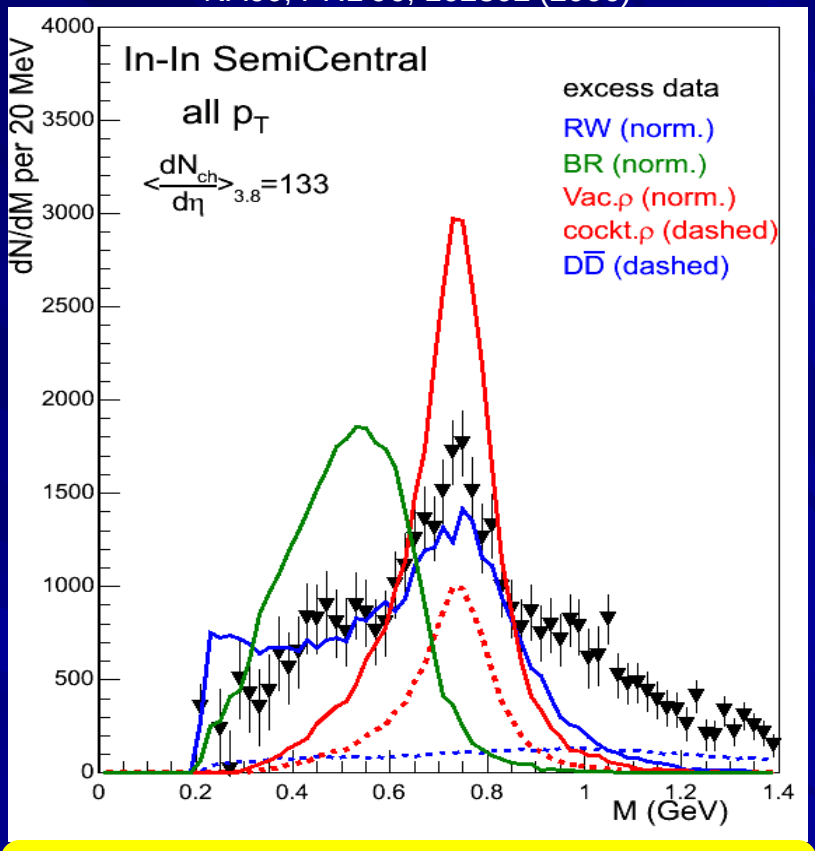
$\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-$




CERES, PLB 666, 425 (2008)



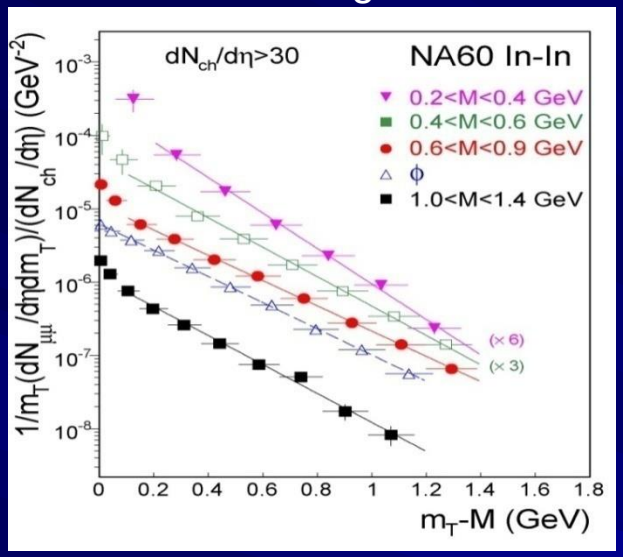

NA60, PRL 96, 162302 (2006)



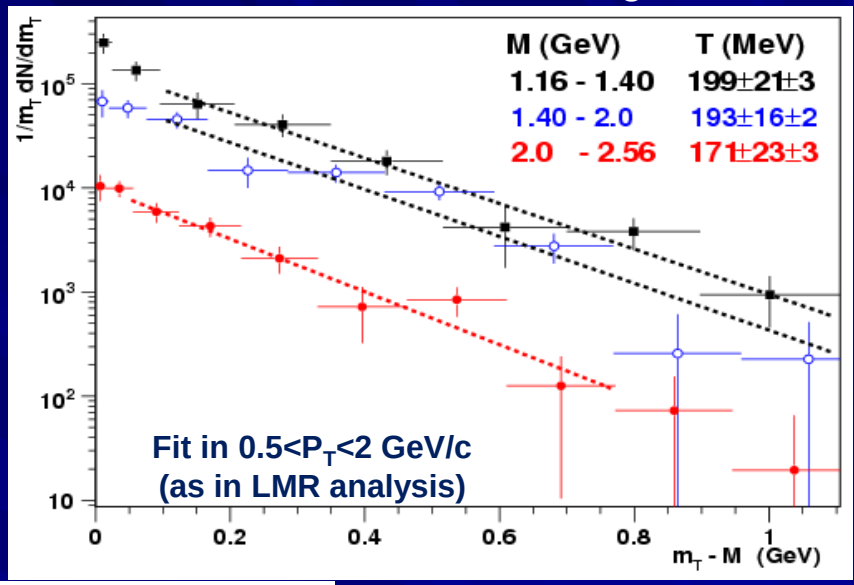

- ❑ **Excess shape in agreement with broadening of the ρ (Rapp-Wambach)**
- ❑ **Mass shift of the ρ (Brown-Rho) ruled out**
- ❑ **Melting of the ρ**

# $p_T$ distributions

Low-mass region

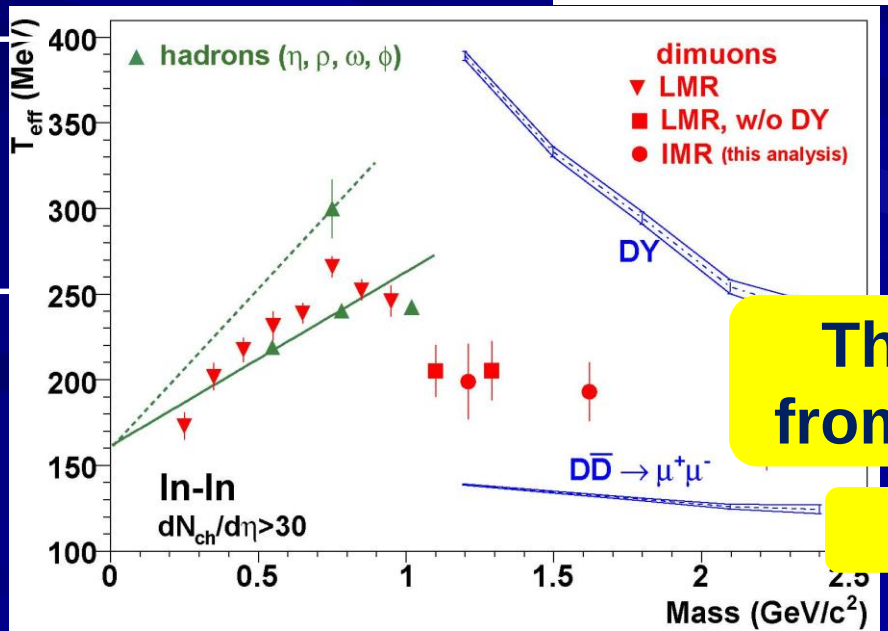



Intermediate mass region




- $m_T$ spectra exponential
- inverse slopes depend on mass.

  → Radial Flow




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

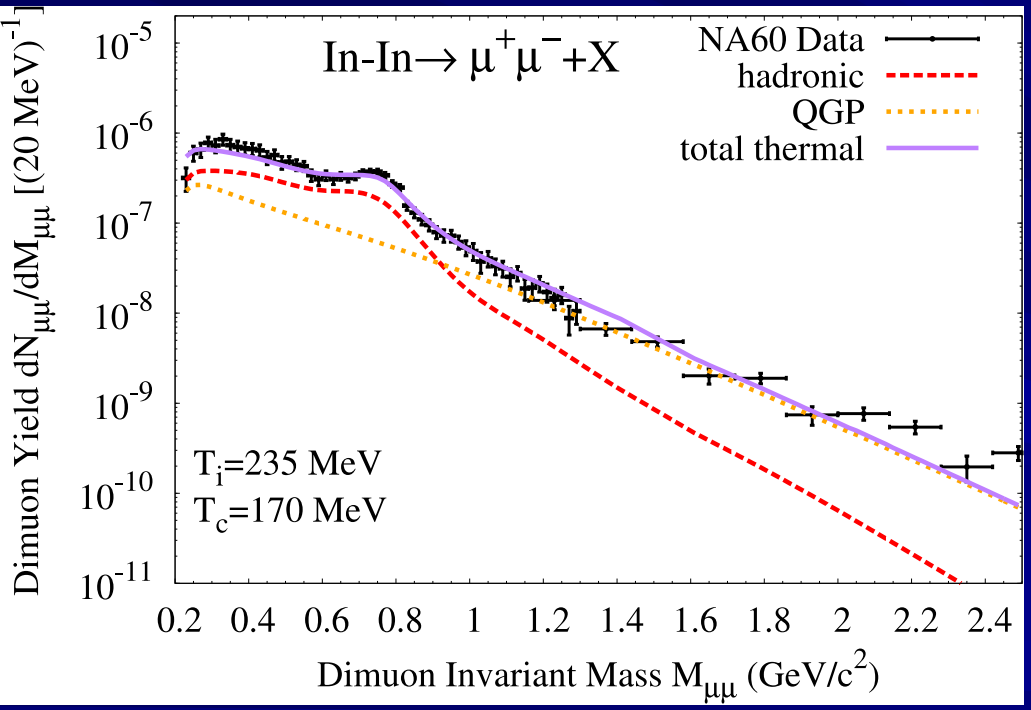
**Thermal radiation from partonic phase**

**Elliptic flow?**

# Acceptance corrected invariant mass spectrum

NA60 excess corrected for acceptance in m - $p_T$

Rapp and Hees PLB 753, 586 (2016)




- LMR:
  - Thermal radiation from HG
    $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$
  - Resonances melt as the system approaches CSR?
- IMR:
  - Thermal radiation from QGP
    $q\bar{q} \rightarrow \mu^+\mu^-$

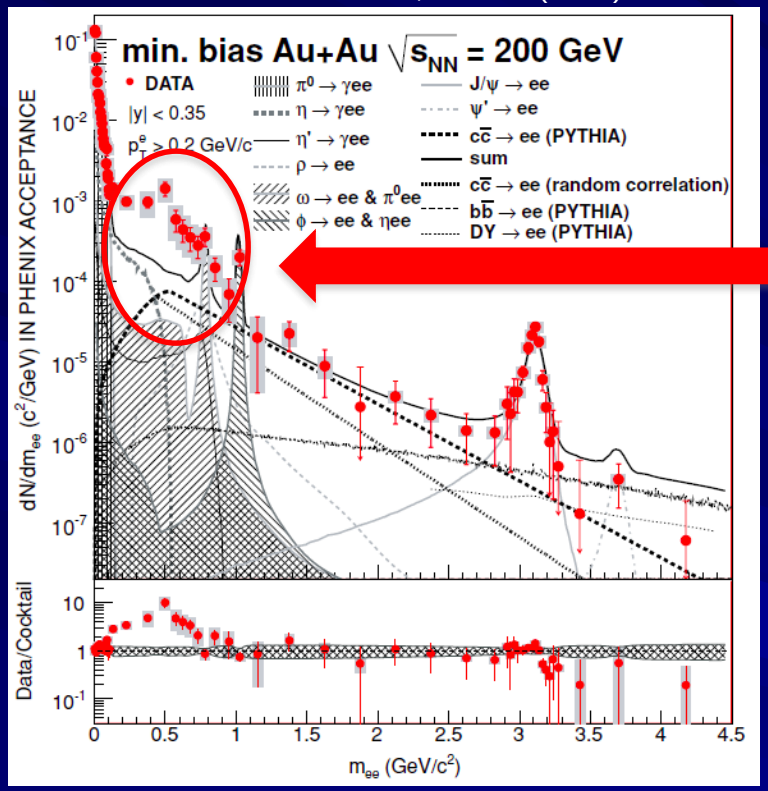
# RHIC

## PHENIX and STAR

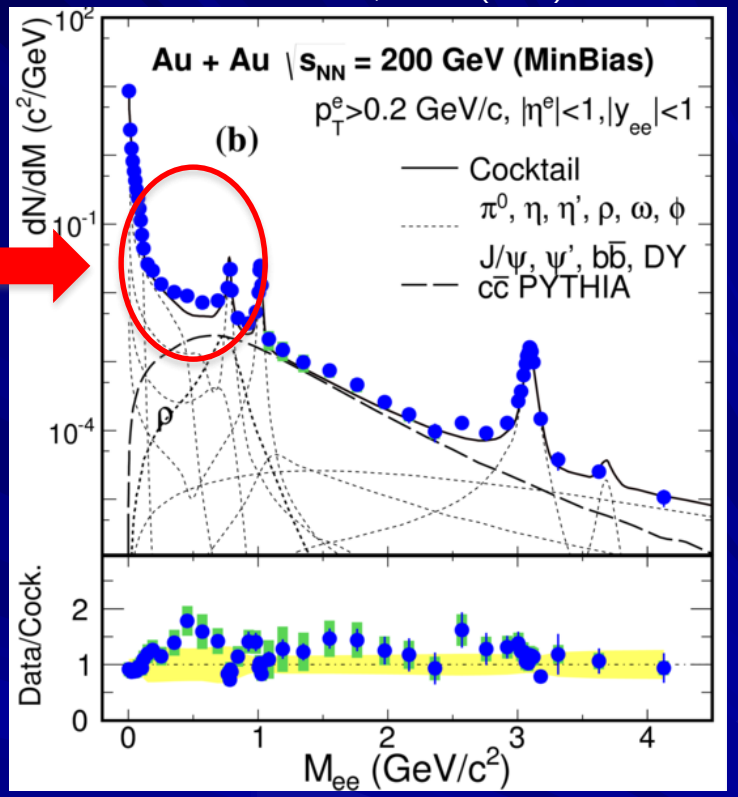
PHENIX: p+p, d+Au and Au+Au at 200 Gev
STAR: p+p and Au+Au at 200 GeV
BES Au+Au at 62.4, 39, 27 and 19.6 GeV

# PHENIX vs. STAR

PHENIX PRC 81, 034911 (2010)




STAR PRL 113, 22301 (2014)



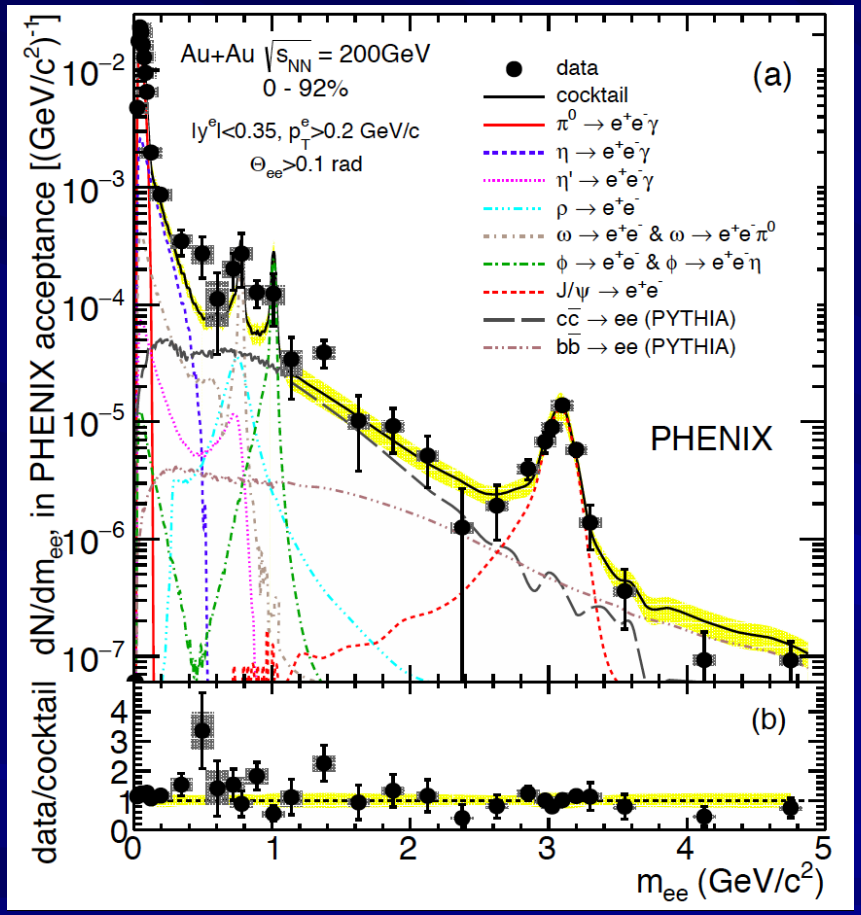

Enhancement factor in $0.15<M_{ee}<0.75$ Gev/$c^2$

| | Minimum Bias | Central collisions |
|---|---|---|
| PHENIX | 4.7 ± 0.4 ± 1.5 | 7.6 ± 0.5 ± 1.3 |
| STAR | 1.40 ± 0.06 ± 0.38 | 1.54 ± 0.09 ± 0.45 |

Large quantitative differences

# Last PHENIX results

PRC 93, 014904 (2016)




- HBD upgrade:
  - Improved hadron rejection: 30% → 5%
  - Improved signal sensitivity
- New improved analysis
  - Neural network for e-id
  - Flow modulation incorporated in the mixed event using an exact analytical method
  - Absolutely normalized correlated BG

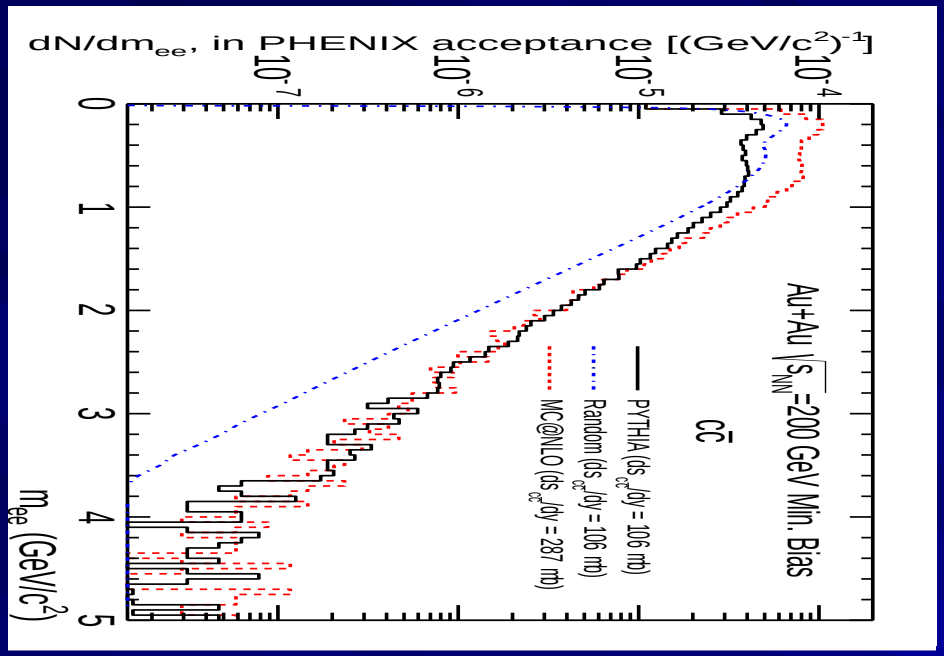
Minimum bias data/cocktail

| 0.3-0.76 (GeV/c²) | Data/cocktail ±stat ±syst ±model |
|---|---|
| PHENIX 2010 | $2.3 \pm 0.4 \pm 0.4 \pm 0.2$ (Pythia)<br>$1.7 \pm 0.3 \pm 0.3 \pm 0.2$ (MC@NLO) |
| STAR | $1.76 \pm 0.06 \pm 0.26 \pm 0.29$ |

PHENIX and STAR results are now consistent

# $c\bar{c}$ in cocktail

PHENIX, PRC 93, 014904 (2016)



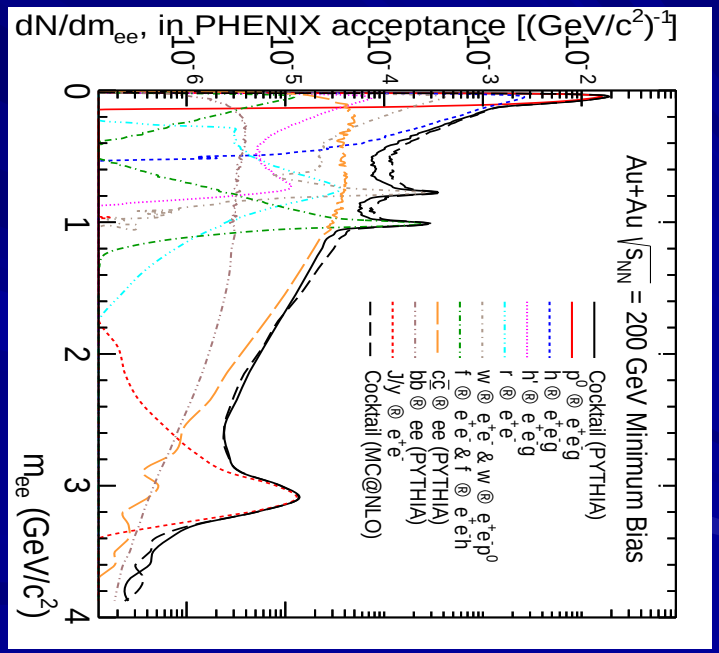

- c quarks suffer energy loss in the medium → effect on the $c\bar{c}$ correlation?
- Lack of appropriate modeling of $c\bar{c}$ correlation

- Cross section derived using IMR in d+Au collisions and extrapolating to m~0

→ uncertainty in cross section and shape

PHENIX, PRC 91, 014907 (2015)

| | $d\sigma_{c\bar{c}}^{pp}/dy$ (μb) |
|---|---|
| PYTHIA | $106 \pm 9^{stat} \pm 33^{syst}$ |
| MC@NLO | $287 \pm 29^{stat} \pm 100^{syst}$ |

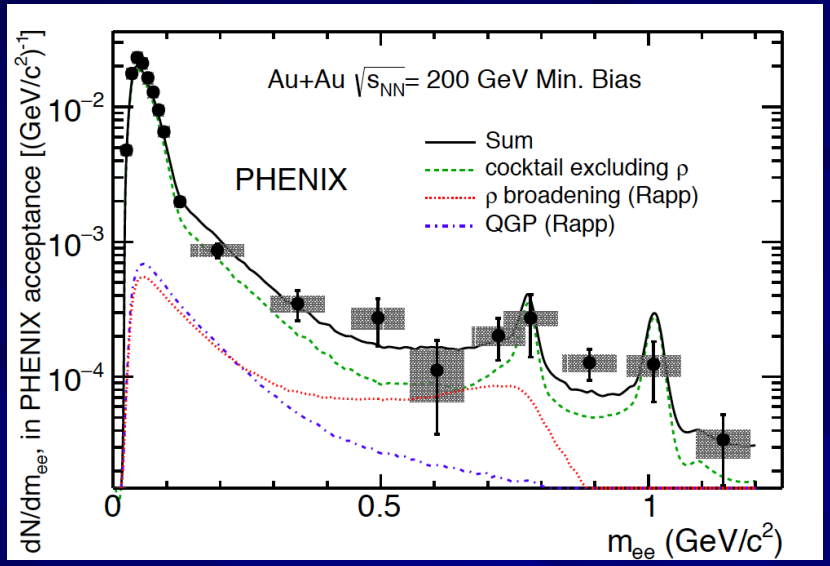


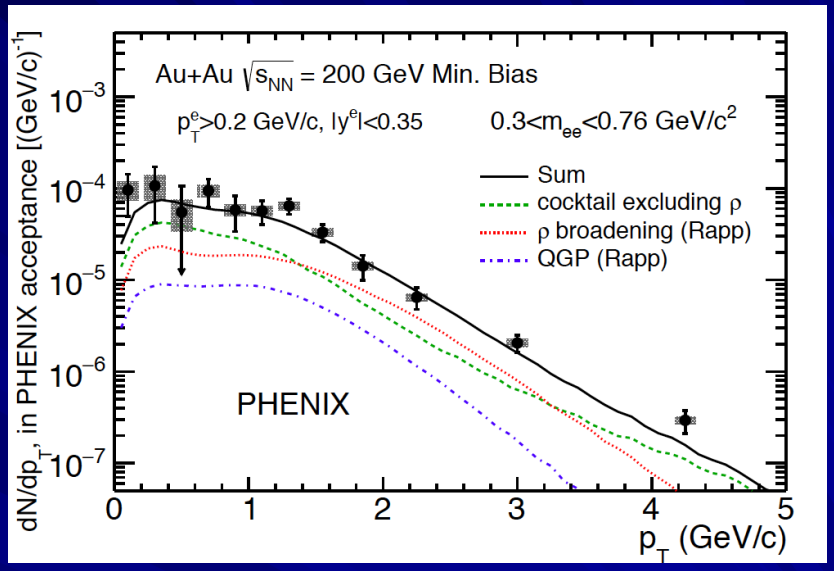

- Hadronic decays of D mesons

STAR, PRL 113, 22301 (2014)

dσ/dy = 171 ± 26 μb (PYTHIA)

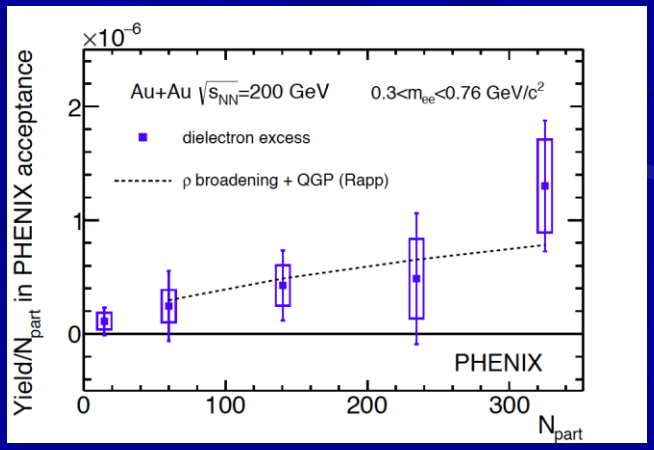
# Comparison to Rapp's model



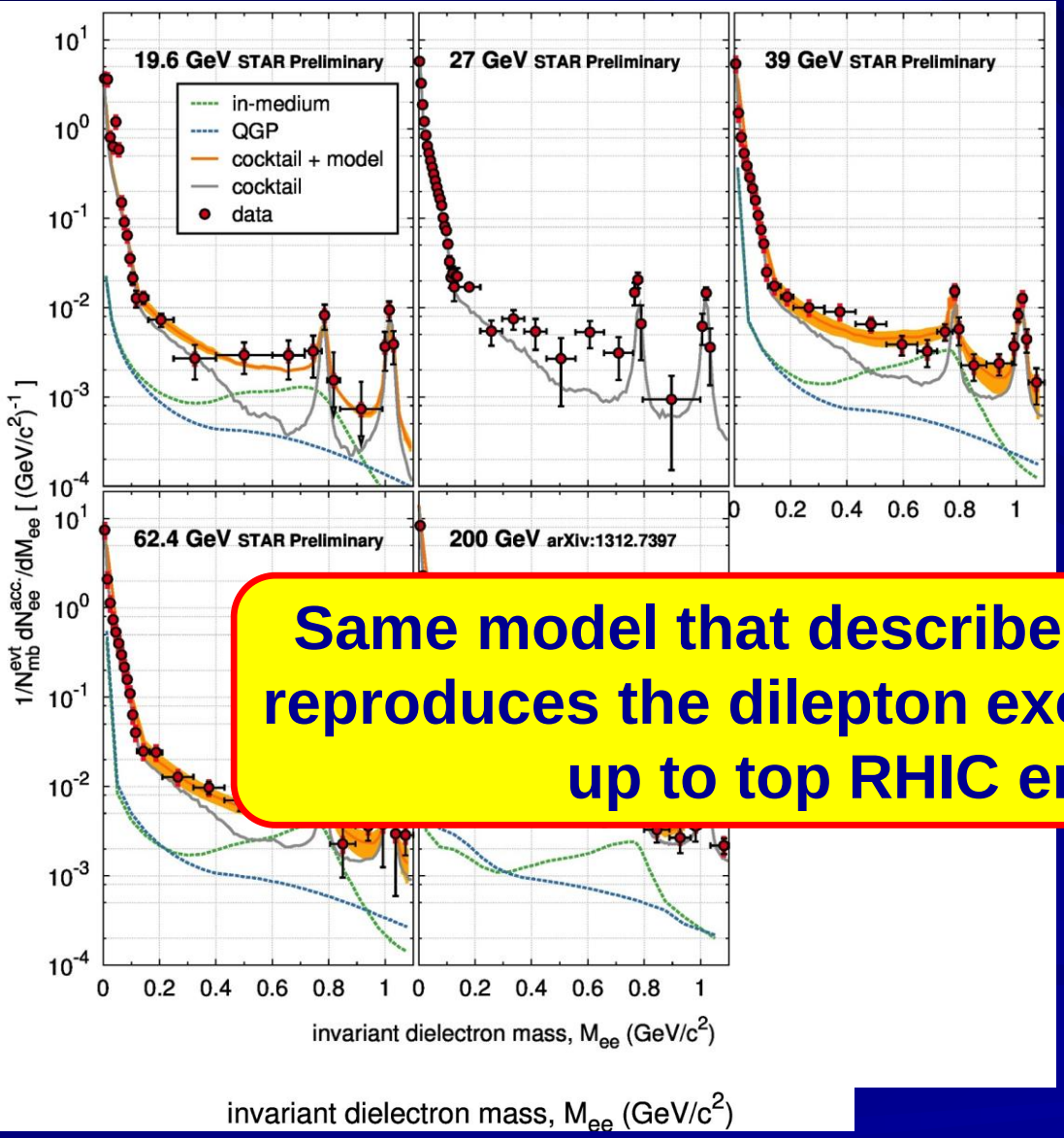




- Mass and $p_T$ dependencies of excess well reproduced by Rapp's model
- In-medium ρ broadening due to the scattering of the ρ off baryons in the HG
- Significant contribution from the QGP at low masses

Centrality dependence consistent with $N_{part}^{1.45}$ as predicted by model.



# STAR beam energy scan




- Systematic study of the dielectron continuum at:

  19.6, 27, 39, 62.4 and 200 GeV

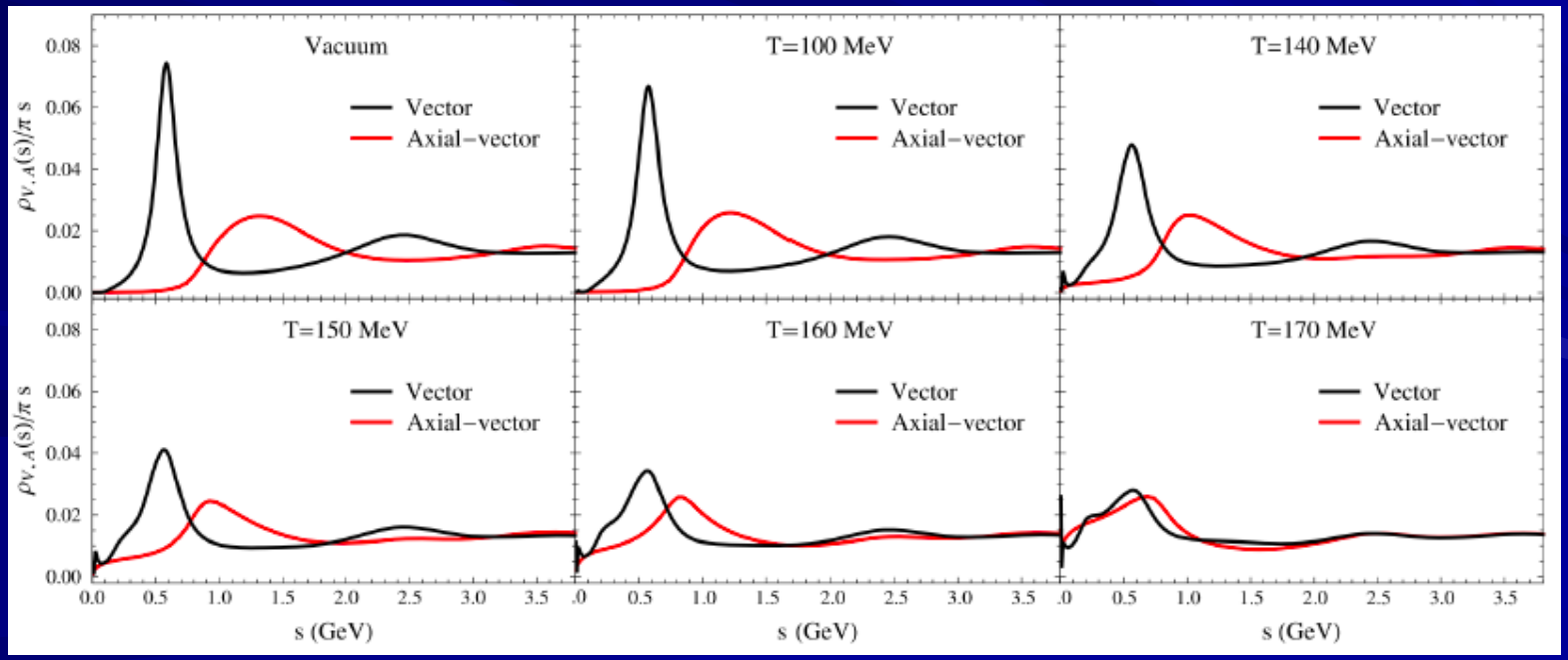
- Low mass excess observed at all energies

  are

**Same model that describes the SPS data reproduces the dilepton excess all the way up to top RHIC energy**

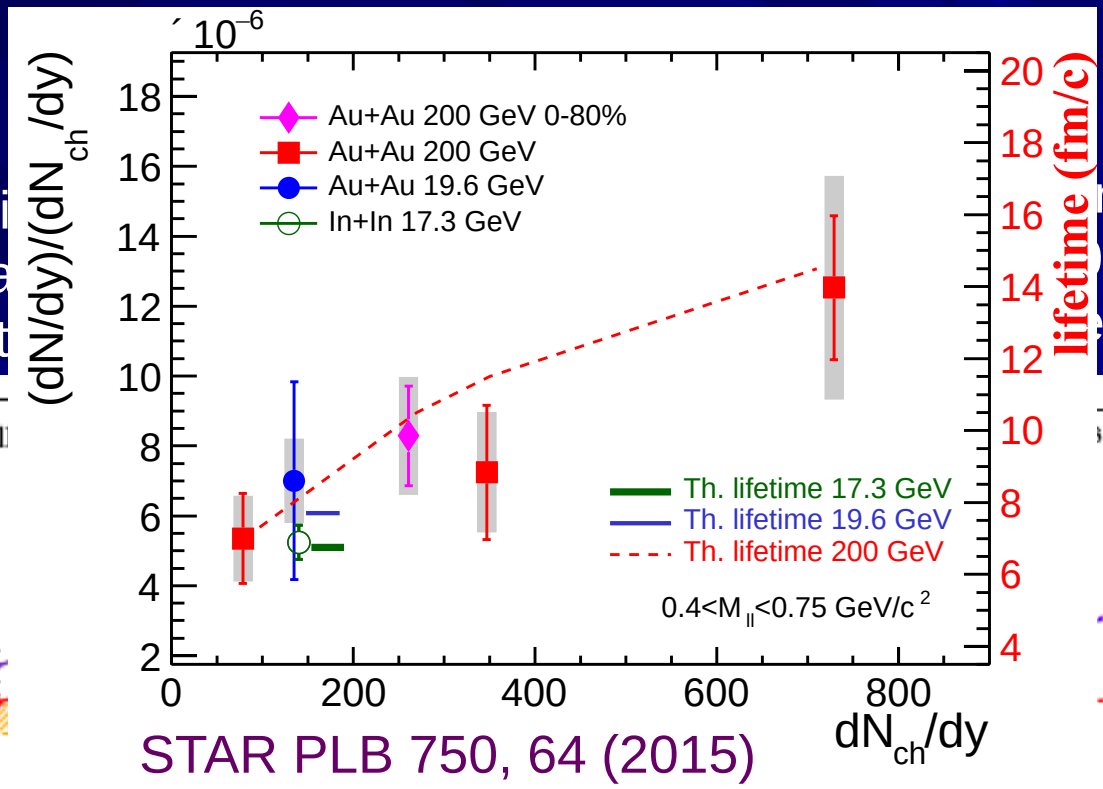
# Connection with CSR?

- In-medium broadening of the ρ meson (mainly by scattering off baryons) explains the dilepton excess in the LMR – The ρ meson *"melts"* in the high density medium.
- Is this connected to CSR? The measurement of the chiral partner $a_1$ is very difficult
- Recent calculations by Hohler and Rapp (PLB 731 (2014) 103) show that ρ and $a_1$ become degenerate at high temperatures: the ρ broadens as T increases, whereas $a_1$ mass drops and the spectral shapes of ρ and $a_1$ coincide at high T.

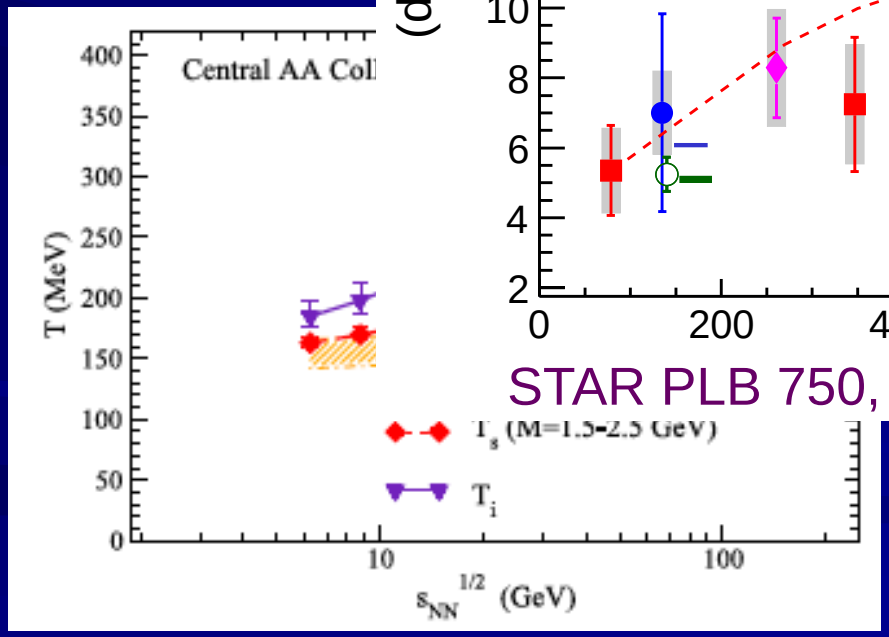


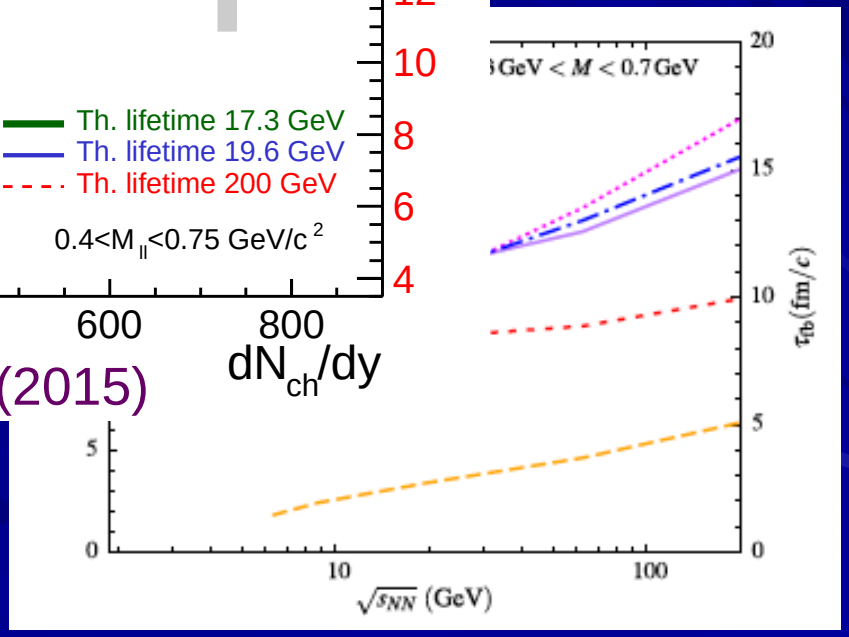
# IMR as thermometer and LMR as chronometer

T given by i … n integrated in
the accepta … .7 GeV/c²
mass spect … time quite well



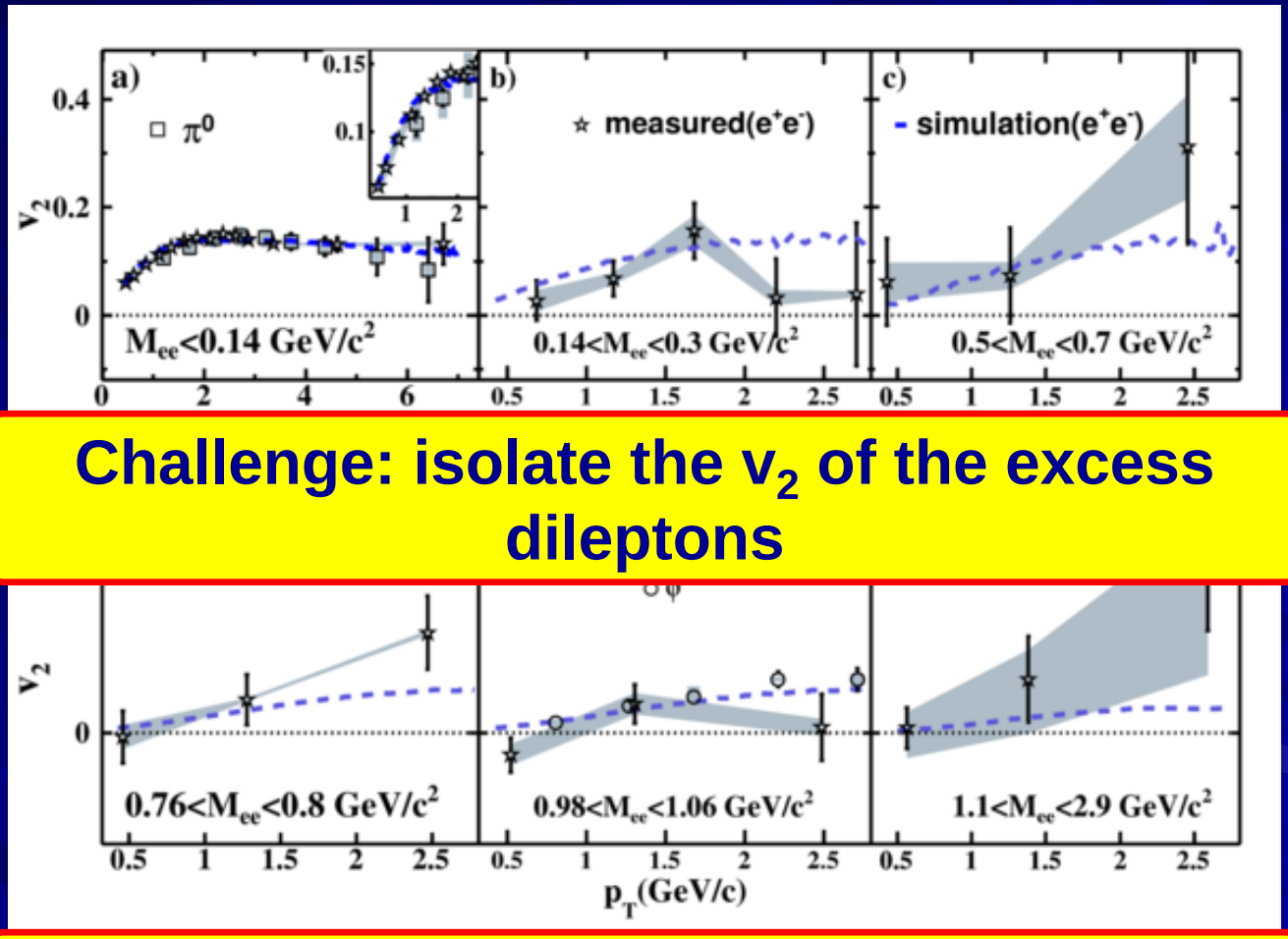

STAR PLB 750, 64 (2015)



# First results on Dielectron $v_2$

STAR PRC 90, 64904 (2014)

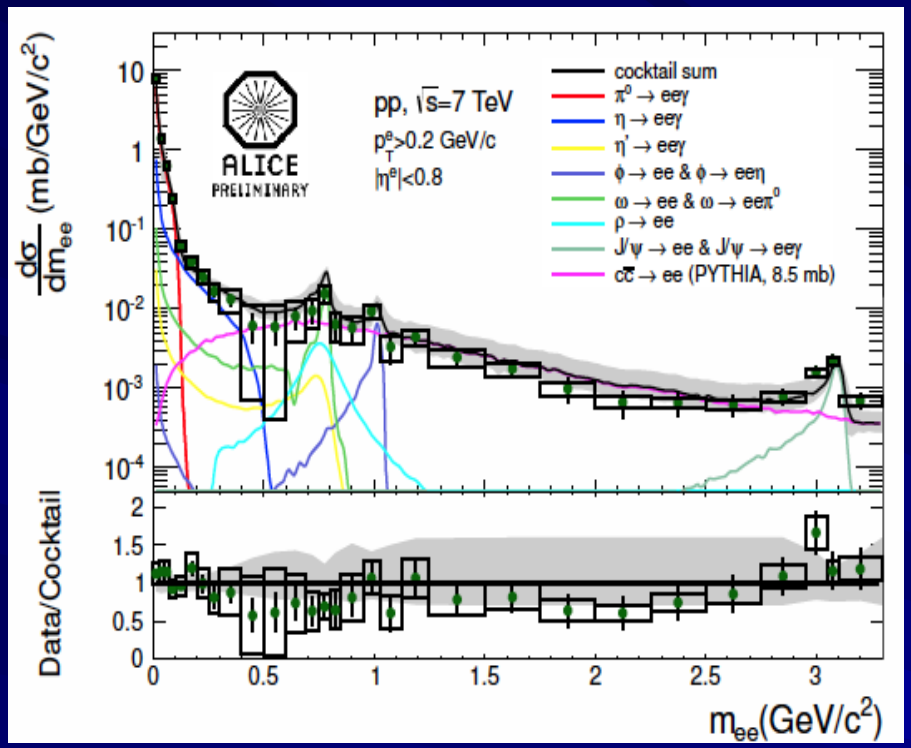


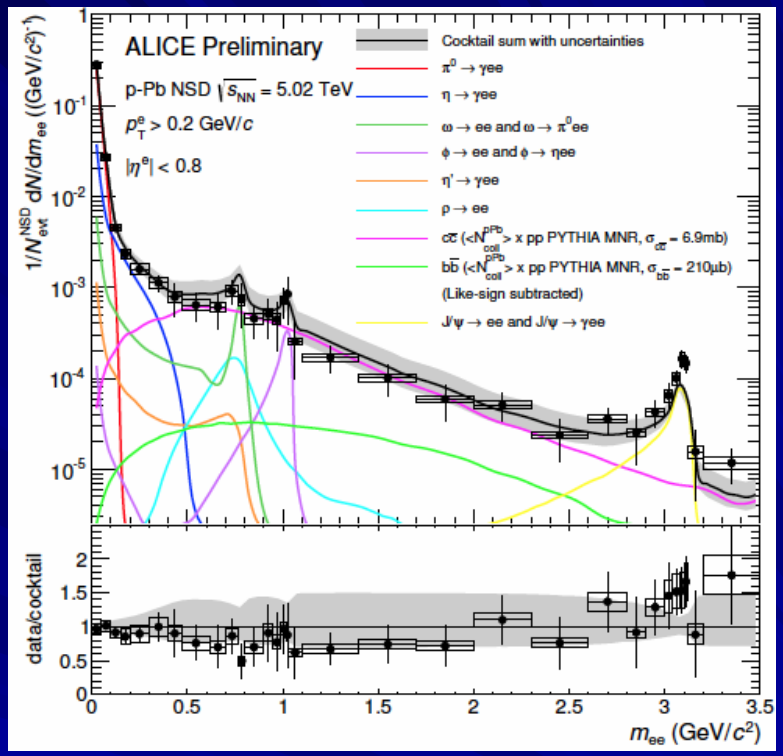

**Challenge: isolate the $v_2$ of the excess dileptons**

**Inclusive dielectron $v_2$ consistent with simulated $v_2$ from cocktail sources**

# LHC

# Dileptons in ALICE



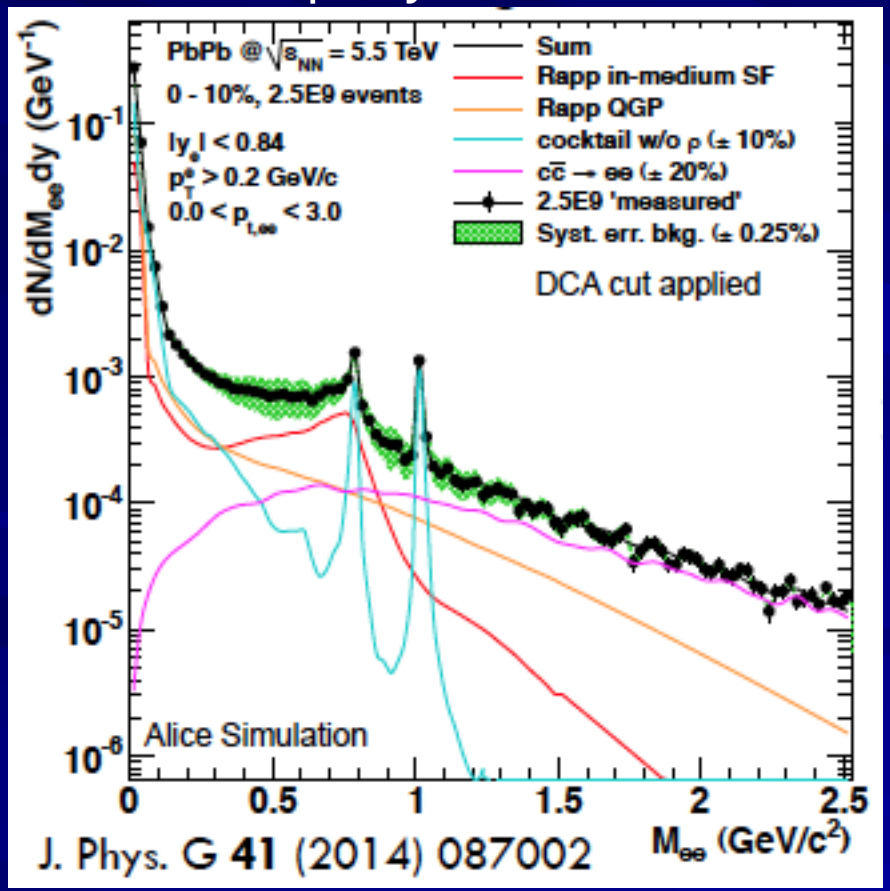




- **Cocktail consistent with data over the entire mass range up to m = 3.5 GeV/c², but systematic overprediction?**

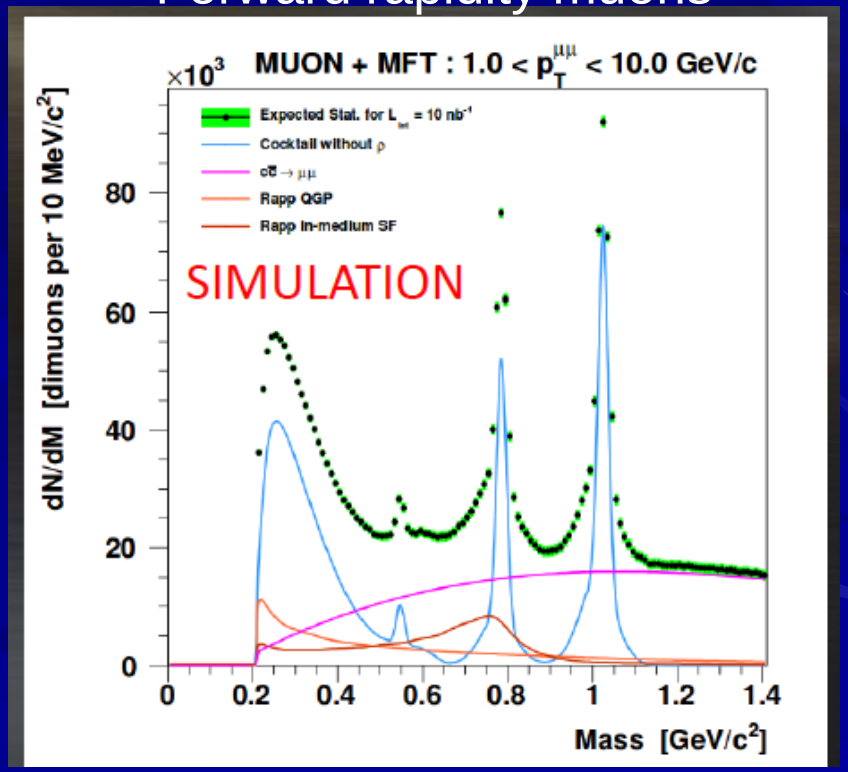
# ALICE Run-3 (>2020)

- New ITS systems (MAPS): veto $c\bar{c}$ contribution
- Replace TPC MWPC readout by GEMs: increase data taking rates up to x100 (50 KHz in Pb+Pb)
- Muon forward tracker: improve mass resolution

Mid-rapidity electrons




Forward rapidity muons



# Lower – energies:

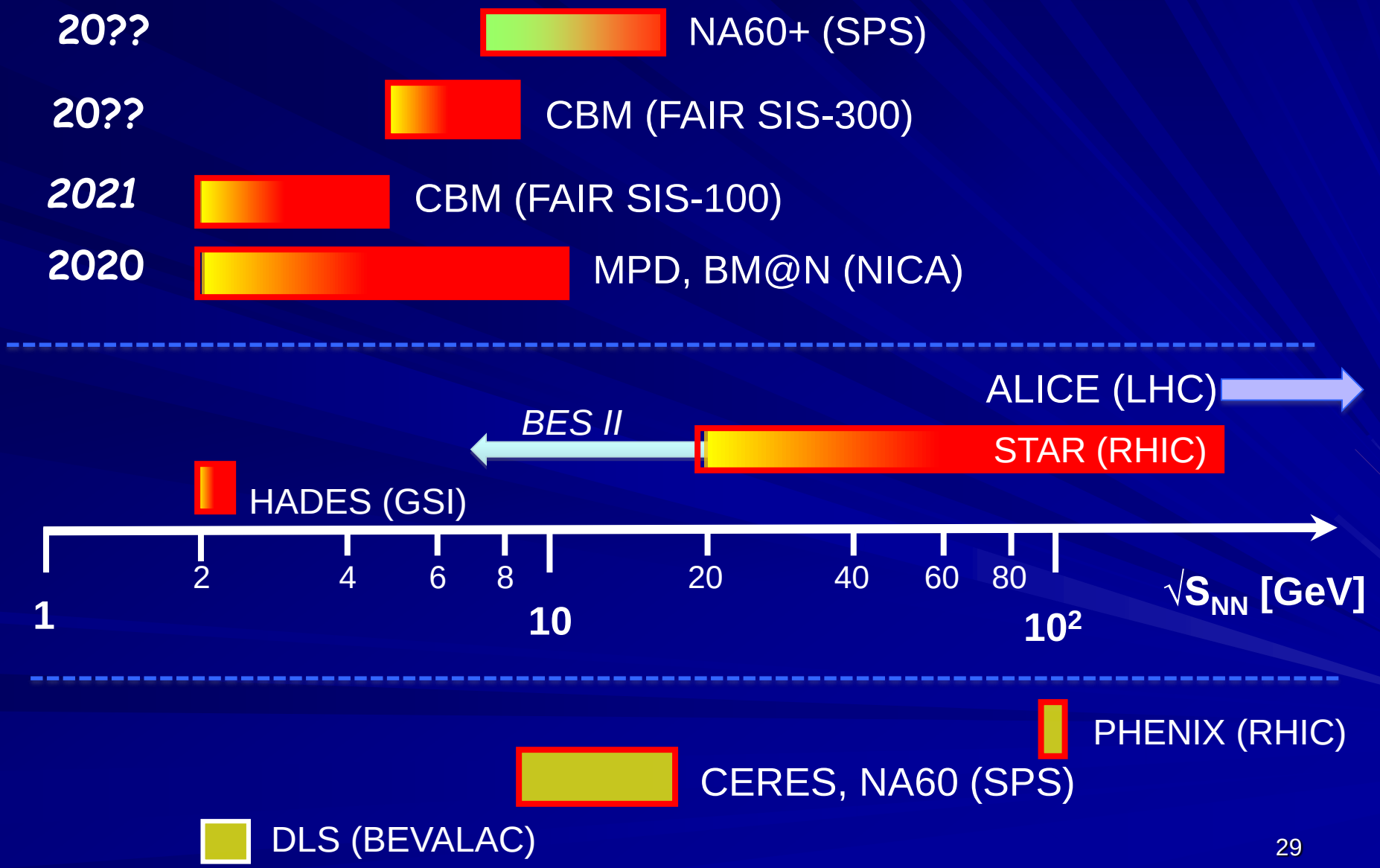
HADES at GSI
CBM at FAIR

MPD, BM@N at NICA

NA60+ at SPS

STAR – BES at RHIC

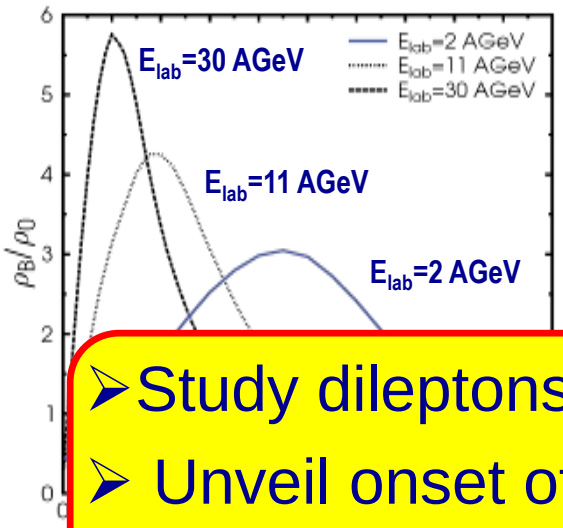
# Dilepton experiments – energy map



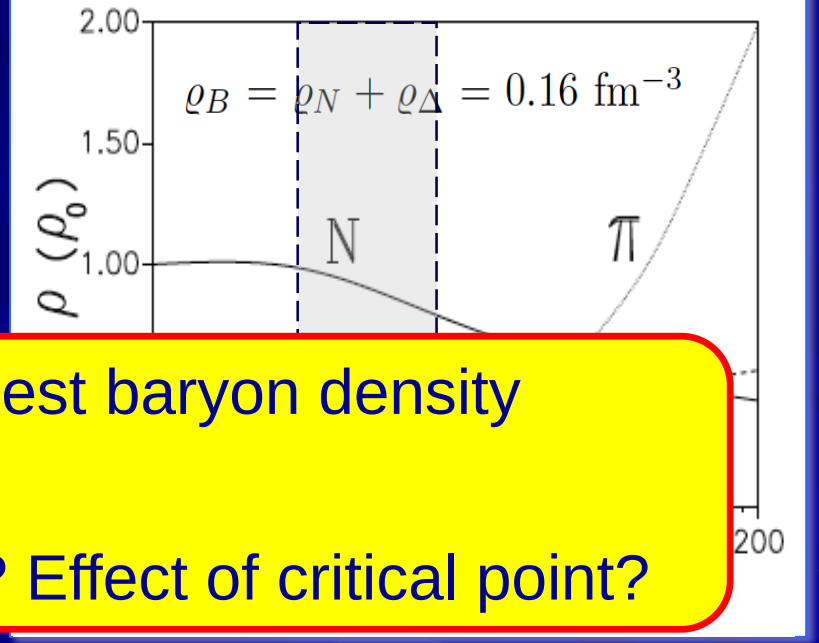
# Matter at low energy collisions

*Rapp, Wambach, Adv.Nucl.Phys. 25, 1 (2000)*

Evolution of average $\rho_B$




Composition of a hot $\pi\Delta N$ gas

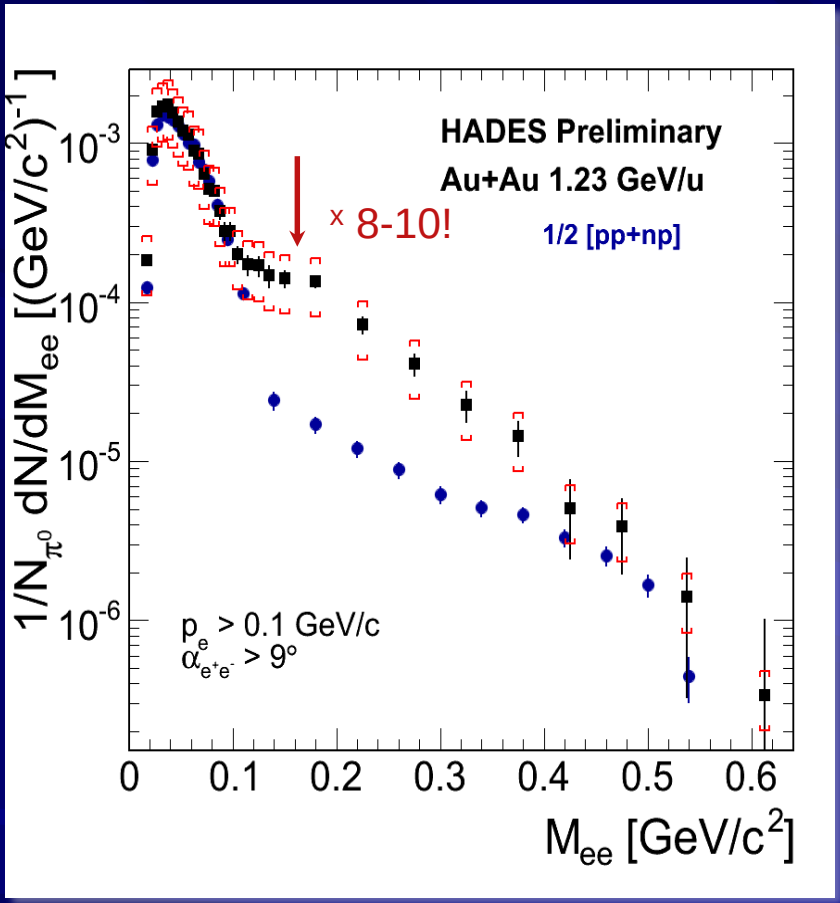



- Study dileptons under highest baryon density
- Unveil onset of excess?
- Onset of phase transition? Effect of critical point?

- Sizable densities 3-6 $\rho_0$
- T < 100 MeV
- Long lifetime

- Baryon dominated matter
- Very low pion density

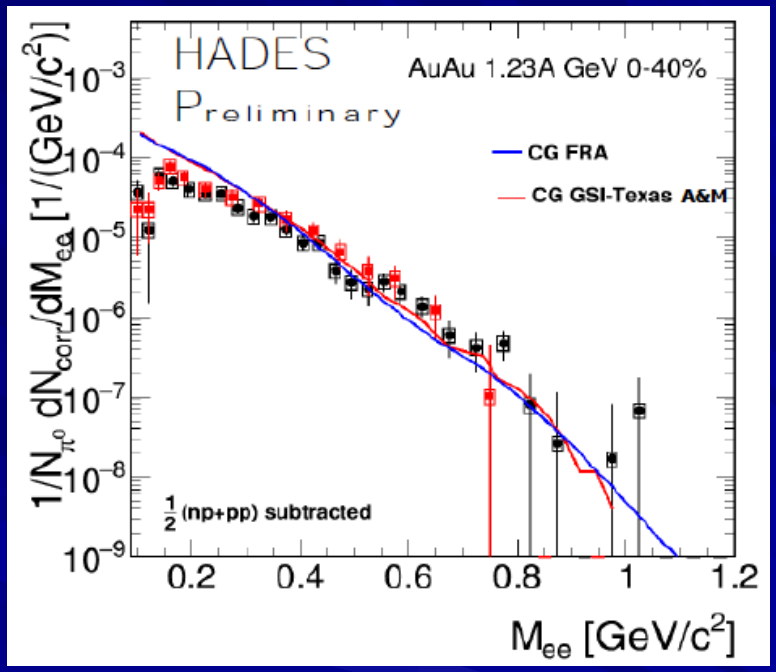
# Au+Au collisions at 1.23 AGeV




Coarse grained transport calculations:

CG Fra: PRC 92, 014911 (2015)

CG GSI-Texas A&M: Eur. Phys. J A52, 131 (2016)




- Main source of dileptons: N* decay

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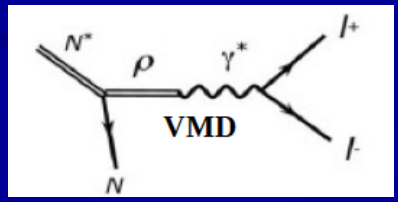
- Excess reasonably well explained by broadening of the ρ



# Summary

- All systems at all energies studied show an enhancement of dileptons.
- The same model explains the excess in the LMR from $\sqrt{s_{NN}}$ ~ 2.4 GeV all the way up to the top RHIC energy of 200 GeV. Emerging picture for the realization of CSR: the ρ meson melts (broadens) in the medium, the $a_1$ mass drops and becomes degenerate with the ρ.
- The thermal radiation from the HG dominates the dilepton excess in the LMR. Seem to track the medium lifetime.
- The thermal radiation from the QGP dominates the dilepton excess in the IMR. Provides a measurement of the average temperature of the medium in the QGP phase.
- Missing: precise measurements of IMR with vertex detector (veto $c\bar{c}$ contribution). $v_2$ measurements of the excess dileptons.
- Clear predictions at LHC energies to be tested by ALICE in the next few years.
- Very strong experimental program to study dileptons at low energies.

Happy birthday Peter