Heavy Ion Physics

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Outline

LECTURE II

- Dileptons
  - Motivation
  - Challenges of measurement
  - SPS results: CERES, NA60
  - RHIC results: PHENIX, STAR
  - Prospects

- Energy loss
  - Single hadrons high p_T suppression
  - Jet quenching
  - The golden channels

Summary

Dileptons

Motivation

Motivation

- 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 dilepton 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 $q\bar{q} \longrightarrow \gamma^* \longrightarrow l^+l^-$

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

Chirality

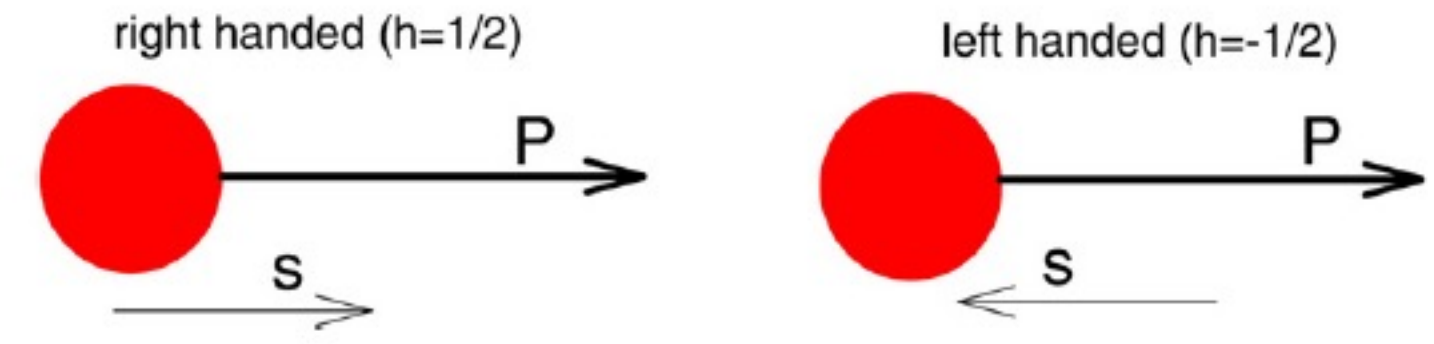
What is chirality?

- Comes from the greek word "$\chi\varepsilon\iota\rho$" 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).



- For massive particles, chirality is not conserved.

QCD and explicit chiral symmetry breaking

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

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

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.

In the chiral limit:
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
Constituent quark masses

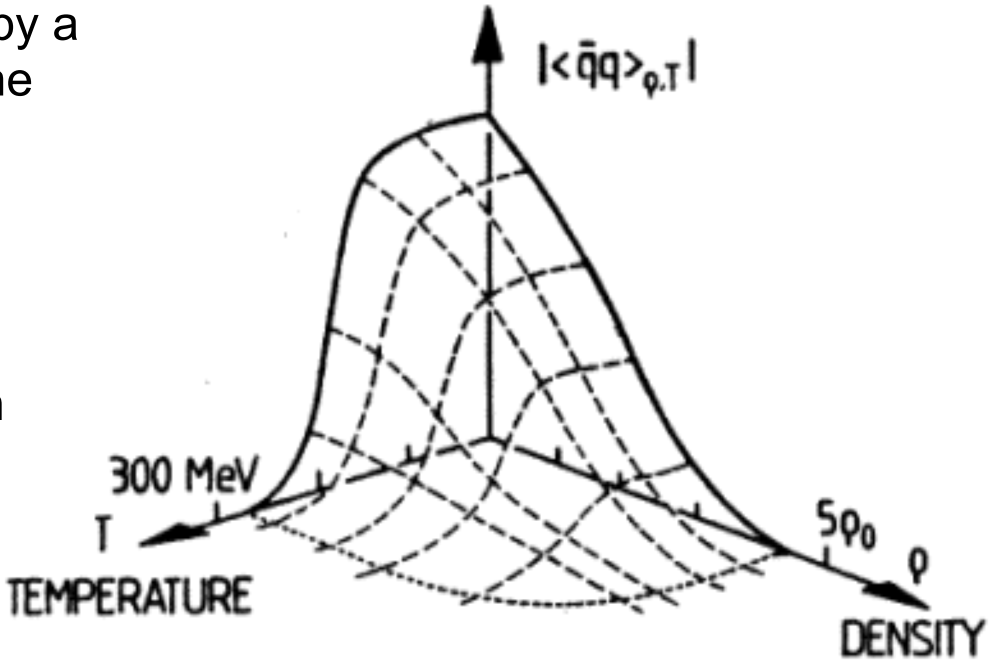
Chiral Symmetry Restoration

- 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 T ($T>T_C$) or high baryon densities ($\rho>\rho_C$), the quark condensate vanishes:

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



constituent mass → current mass
chiral symmetry (approximately) restored
Chiral partners (e.g. ρ and a_1) become degenerate
Coincides with the deconfinement phase transition?

- How is the quark condensate linked to the hadron properties (mass and width)? How is the degeneracy of the chiral partners achieved?

ρ – a_1

If CS is restored the masses of the a_1 and ρ mesons should become equal.

Problem: very hard to measure the a_1 meson

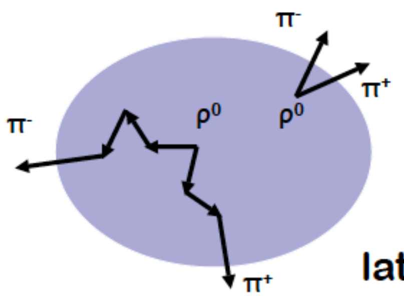
$a_1(1260)$ DECAY MODES

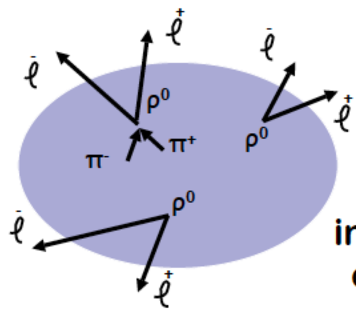
	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-\pi^0$	
Γ_2	$\pi^0\pi^0\pi^0$	
Γ_3	$(\rho\pi)_{S-\text{wave}}$	seen
Γ_4	$(\rho\pi)_{D-\text{wave}}$	seen
Γ_5	$(\rho(1450)\pi)_{S-\text{wave}}$	seen
Γ_6	$(\rho(1450)\pi)_{D-\text{wave}}$	seen
Γ_7	$\sigma\pi$	seen
Γ_8	$f_0(980)\pi$	not seen
Γ_9	$f_0(1370)\pi$	seen
Γ_{10}	$f_2(1270)\pi$	seen
Γ_{11}	$K\overline{K}^*(892)+$ c.c.	seen
Γ_{12}	$\pi\gamma$	seen

Experimental efforts focused on the ρ meson

$\rho \to e^+e^-$ decay and CSR

- $\rho \to \pi^+\pi^-$ BR ~100% $\rho \to e^+e^-$ BR = 4.7 10^{-5}





- 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**

short lifetime compared to the medium lifetime ($\tau \approx$ 10 fm/c)

can decay and be regenerated in the medium

Advantages and Chellenges

- 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

- Emitted by a variety of sources all along the history of the collision
  → need a very good understanding of all these sources to disentangle the interesting ones.

The double challenge

1. Experimental challenge

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

  hadron decays (m>150 MeV/c^2 p_T > 200 MeV/c) ~ 10^{-6} / π^0

- in the presence of hundreds of charged particles

  central mid-rapidity Au-Au collision at RHIC ($dN_{ch}/d\eta$) 650

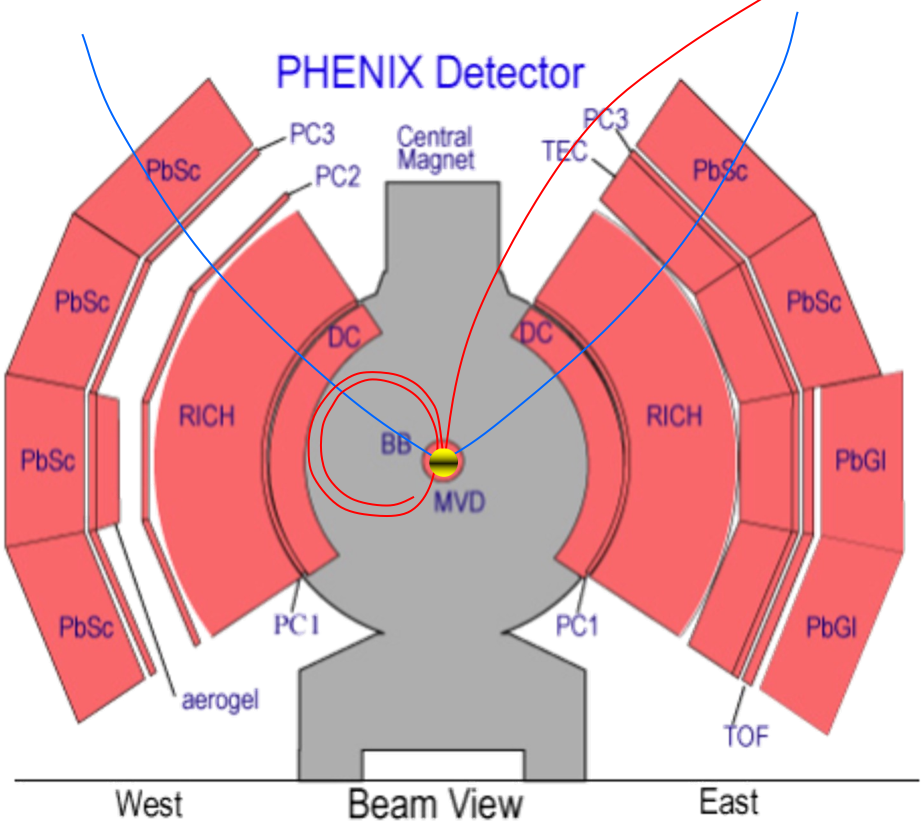
- and several pairs per event from trivial origin

  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



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

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 = 1/200 has the same relative statistical error as 25 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 ΔS/S is ~50% (assuming S/B=1/200). Even in an infinite statistics measurement the systematic uncertainty will be very large.

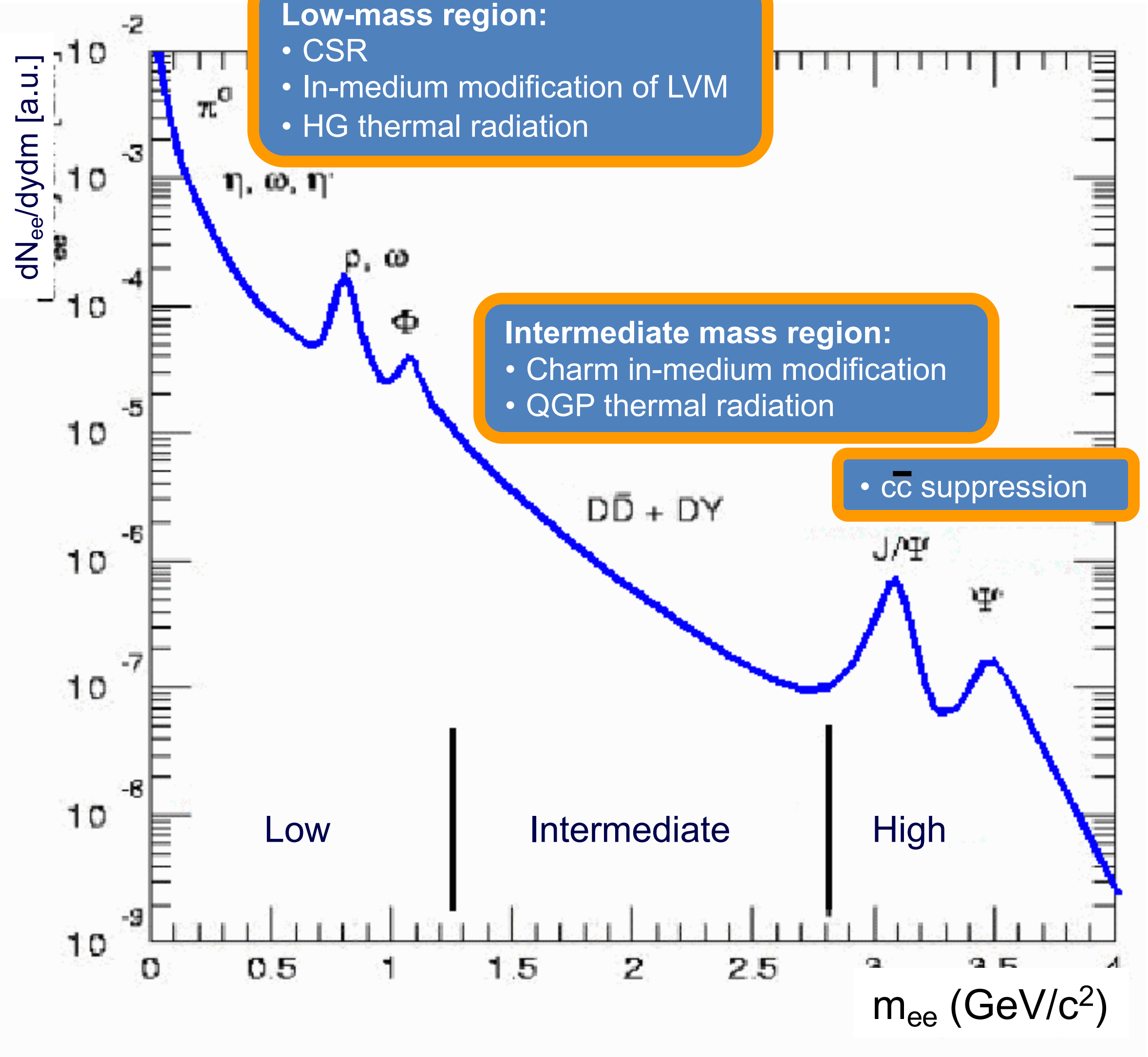
The double challenge

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

Schematic dilepton spectrum



Low-mass region:
- CSR
- In-medium modification of LVM
- HG thermal radiation

Intermediate mass region:
- Charm in-medium modification
- QGP thermal radiation

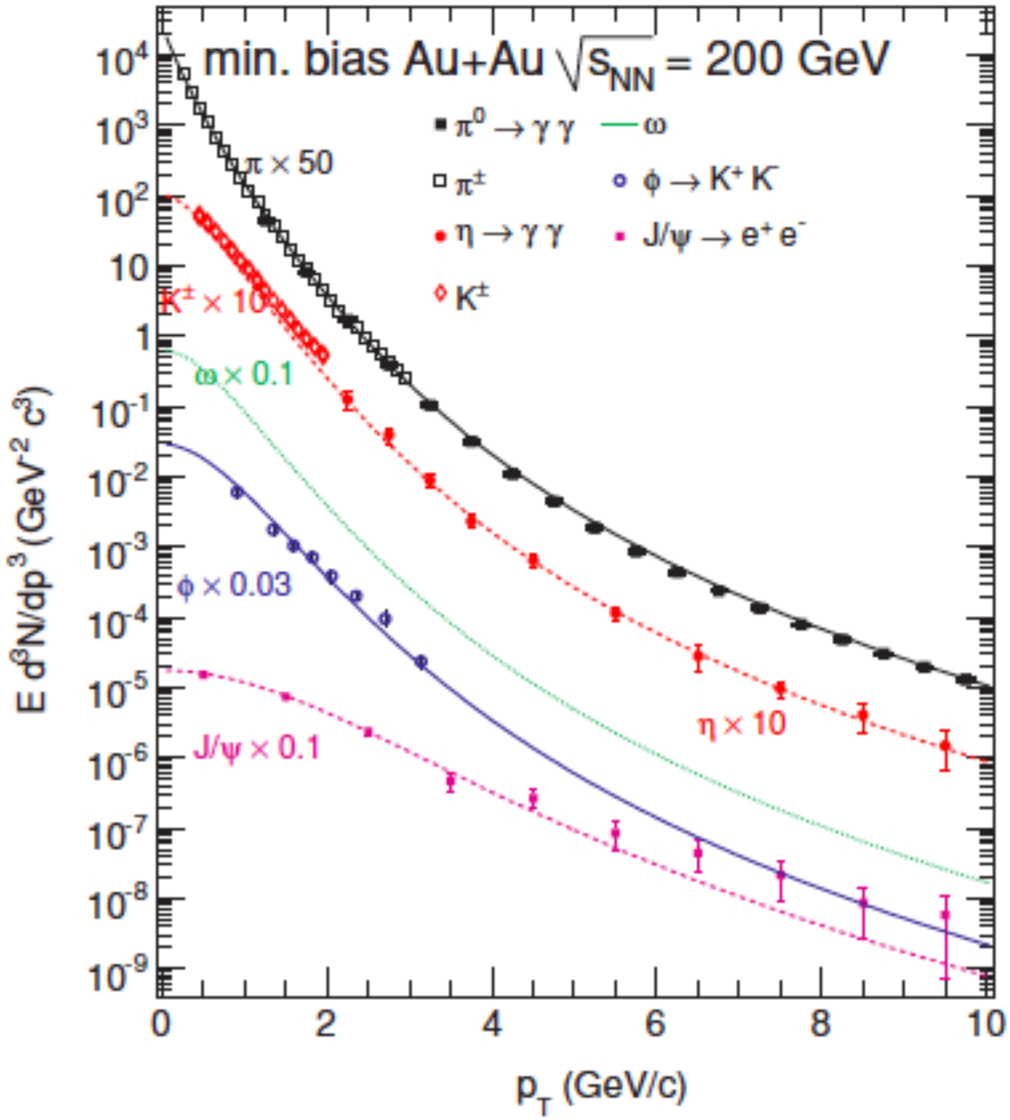
- $c\bar{c}$ suppression

- New physics expected in heavy ion collisions

Au+Au Cocktail

Cocktail of known sources:

- Dalitz decays:
  $\pi^0,\eta,\eta' \longrightarrow e^+e^-\gamma$
  $\omega \longrightarrow \pi^0 e^+e^-$
- Resonance decays:
  $\rho, \omega, \varphi \longrightarrow e^+e^-$
- Semi-leptonic decays of HF:
  cc, bb $\longrightarrow e^+e^-$

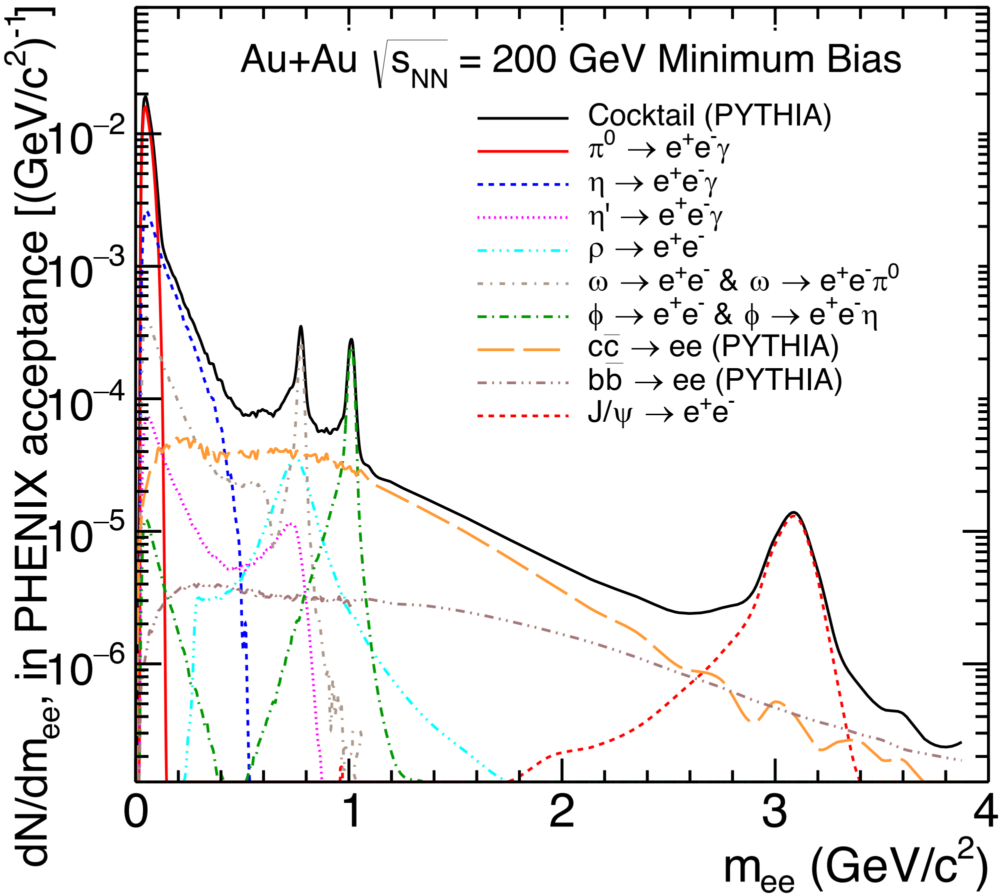


- π^0 and charged π data fit to a modified Hagedorn function:

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

- 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}

Au+Au Cocktail



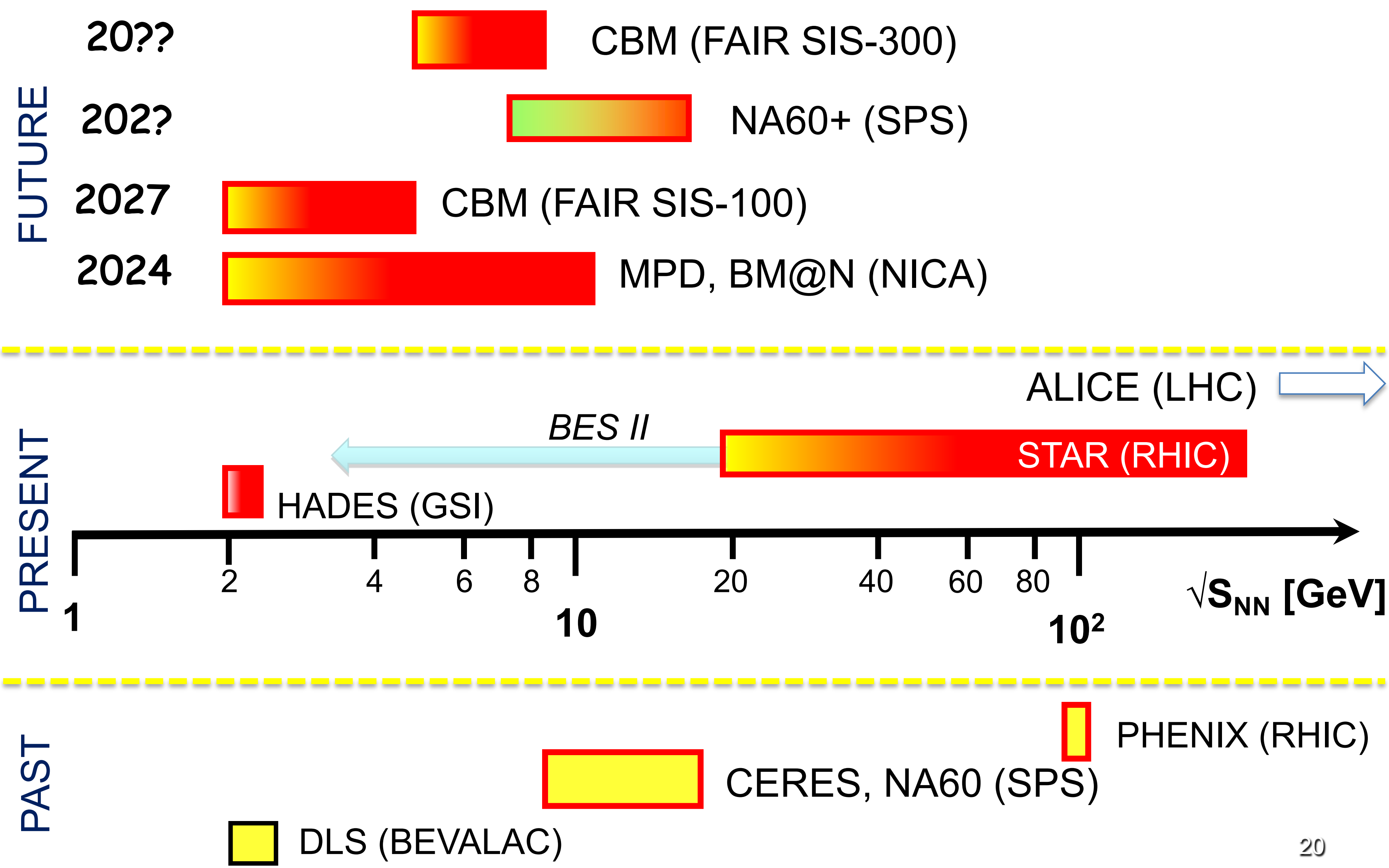
Cocktail of known sources:

- Dalitz decays:
  $\pi^0, \eta, \eta' \longrightarrow e^+e^-\gamma$
  $\omega \longrightarrow \pi^0 e^+e^-$
- Resonance decays:
  $\rho, \omega, \varphi \longrightarrow e^+e^-$
- Semi-leptonic decays of HF:
  $c\bar{c}, b\bar{b} \longrightarrow e^+e^-$

- Sources independently measured in AA collisions
- If not, use m_T scaling or scale from pp collisions

Dilepton Experiments

Dilepton experiments



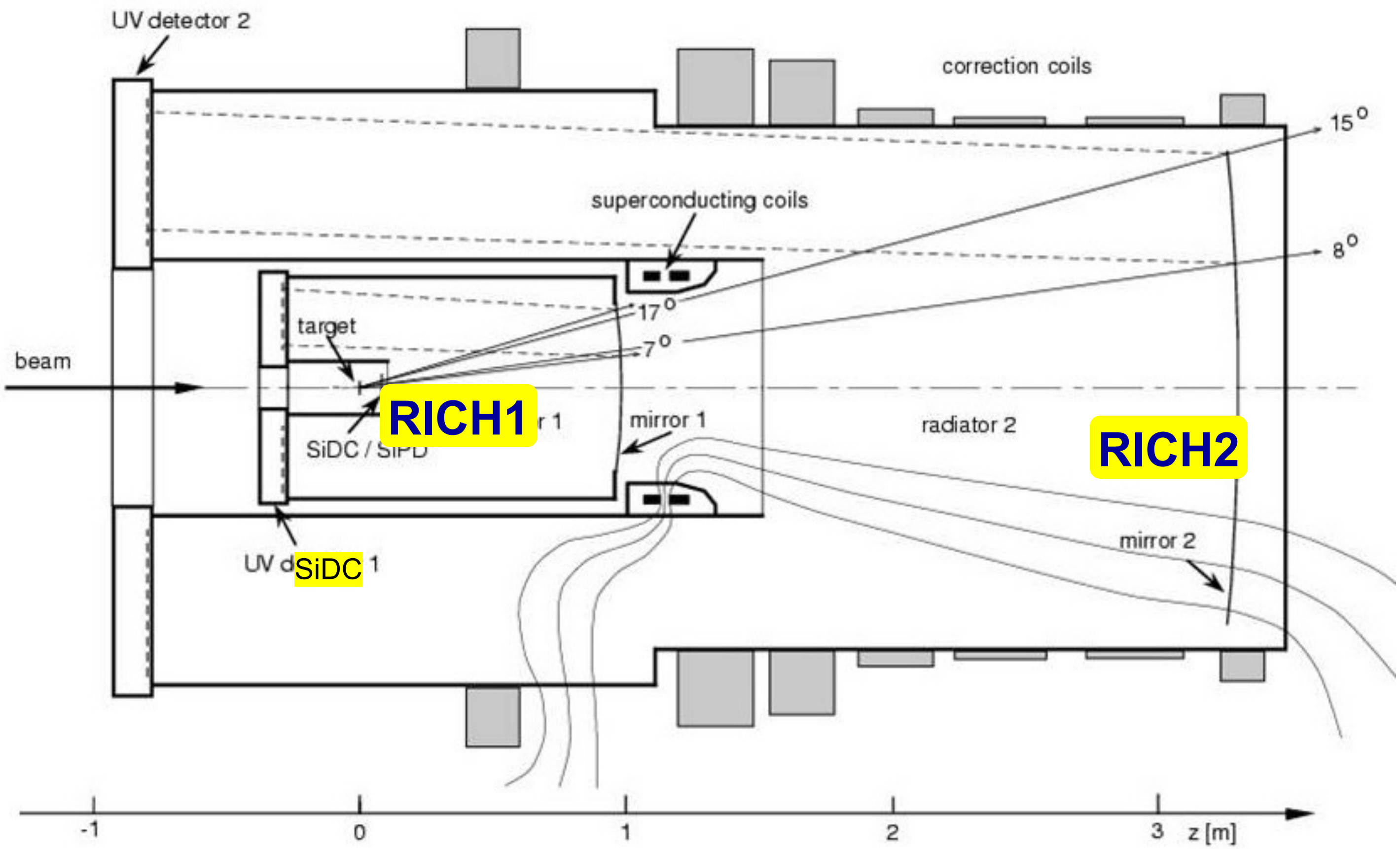
SPS results:

CERES – low masses

NA60 – low and intermediate masses

CERES – NA45

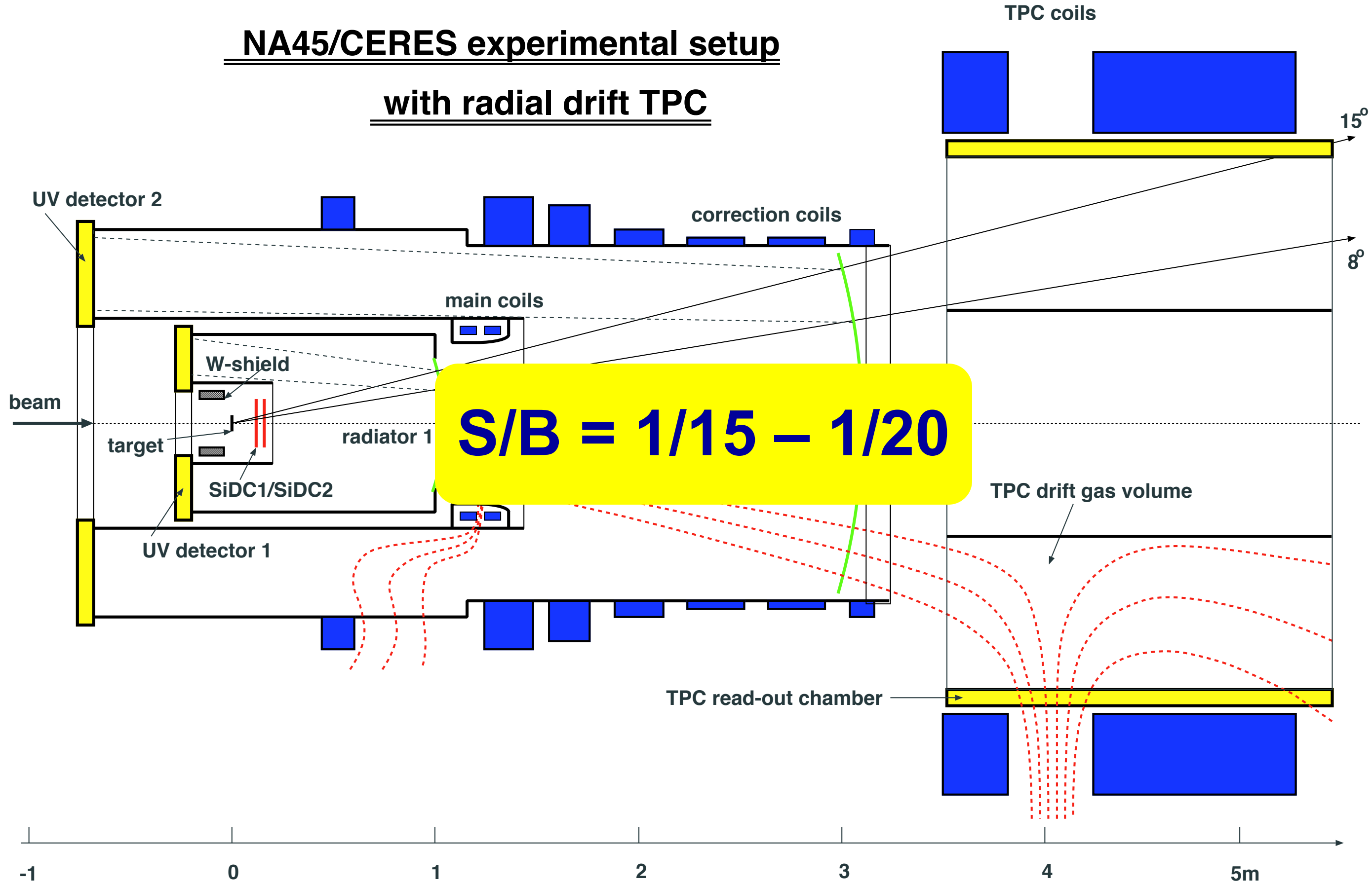
Original setup (1992) – minimal configuration, no particle tracking
double RICH spectrometer, for eid and CB rejection



- Field free region in RICH-1 (allows rejection of close pairs)
- Field lines in RICH-2 pointing to the target (parallel to particle trajectory)
- Detectors upstream of target (not traversed by the large flux of forward-going charged particles

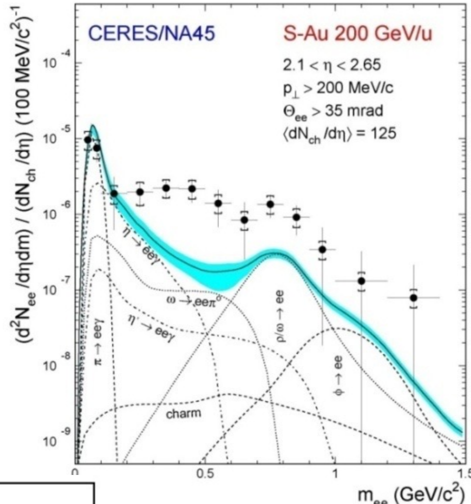
CERES – NA45

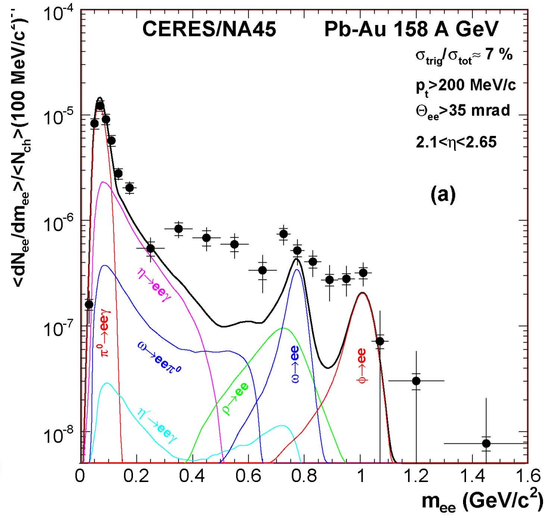
2000 setup – tracking: doublet of SiDC – RICH1 – RICH2 – TPC
improved momentum and mass resolutions
eid: double RICH, rejection RICH1 and SiDC



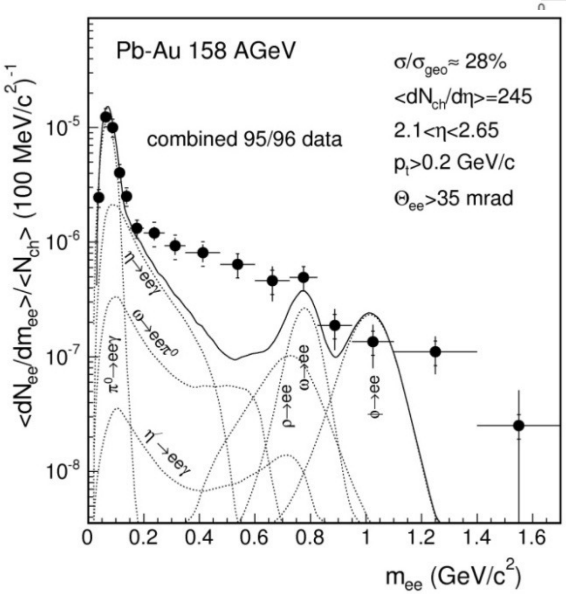
CERES Pioneering Results (I)

First CERES result
PRL 75, (1995) 1272





Last CERES result
PLB 666 (2008) 425

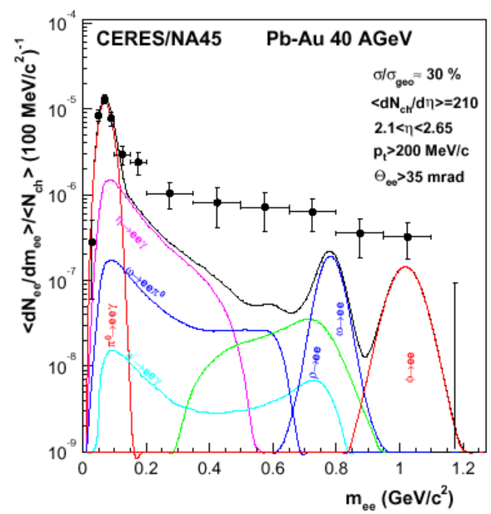


EPJ C41 (2005) 475

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

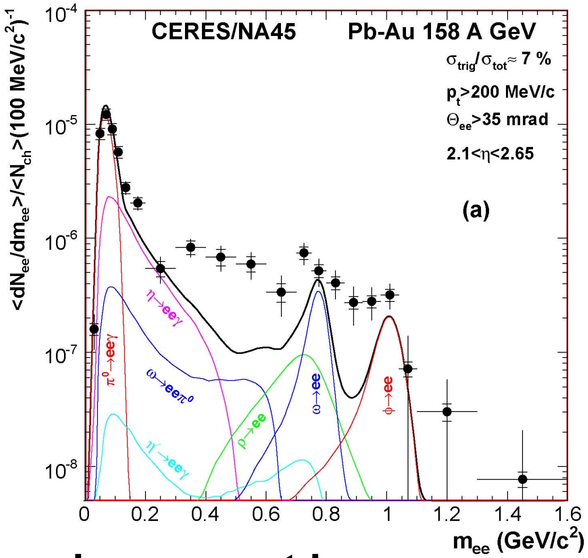
- **Doublet of SiDC close to vertex**
- **Radial TPC upgrade downstream of double RICH spectrometer**

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



PRL 91 (2003) 042301

CERES Pioneering Results (II)



Last CERES result (2000 Pb run)

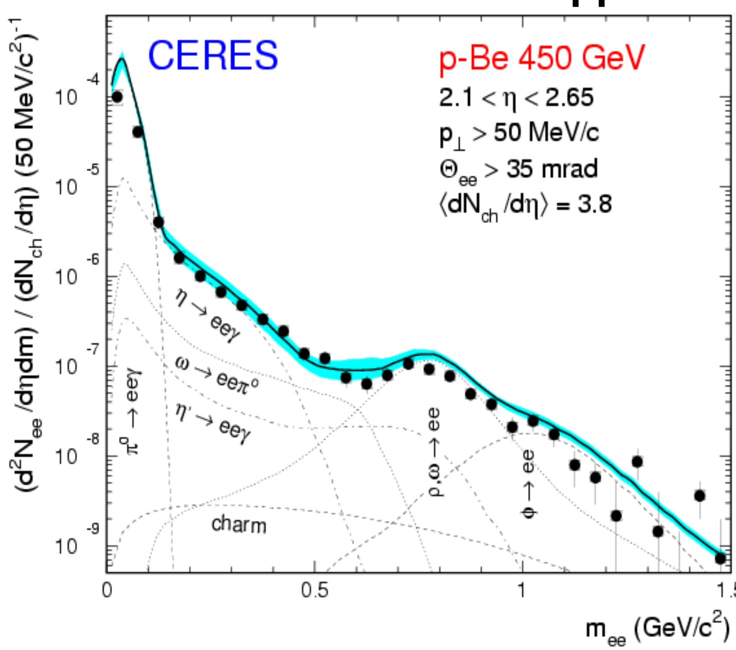
PLB 666(2008) 425

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

Enhancement factor (0.2 <m < 1.1 GeV/c²):

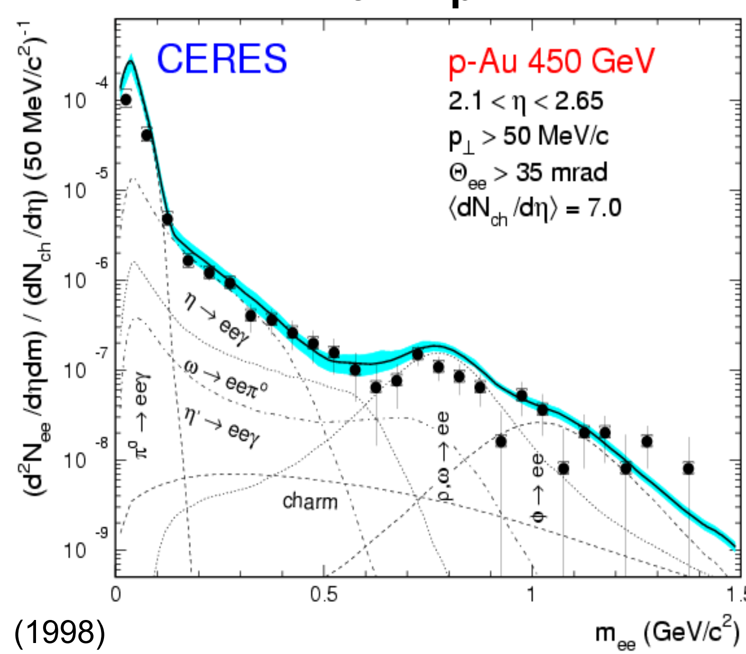
2.45 ± 0.21 (stat) ± 0.35 (syst) ± 0.58 (decays)

No enhancement in pp



EPJ C4, 231 (1998)

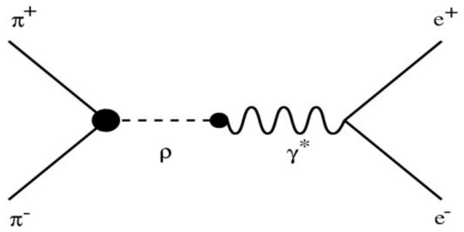
nor in pA



- Interpretation (s)?

Dropping Mass or Broadening (I) ?

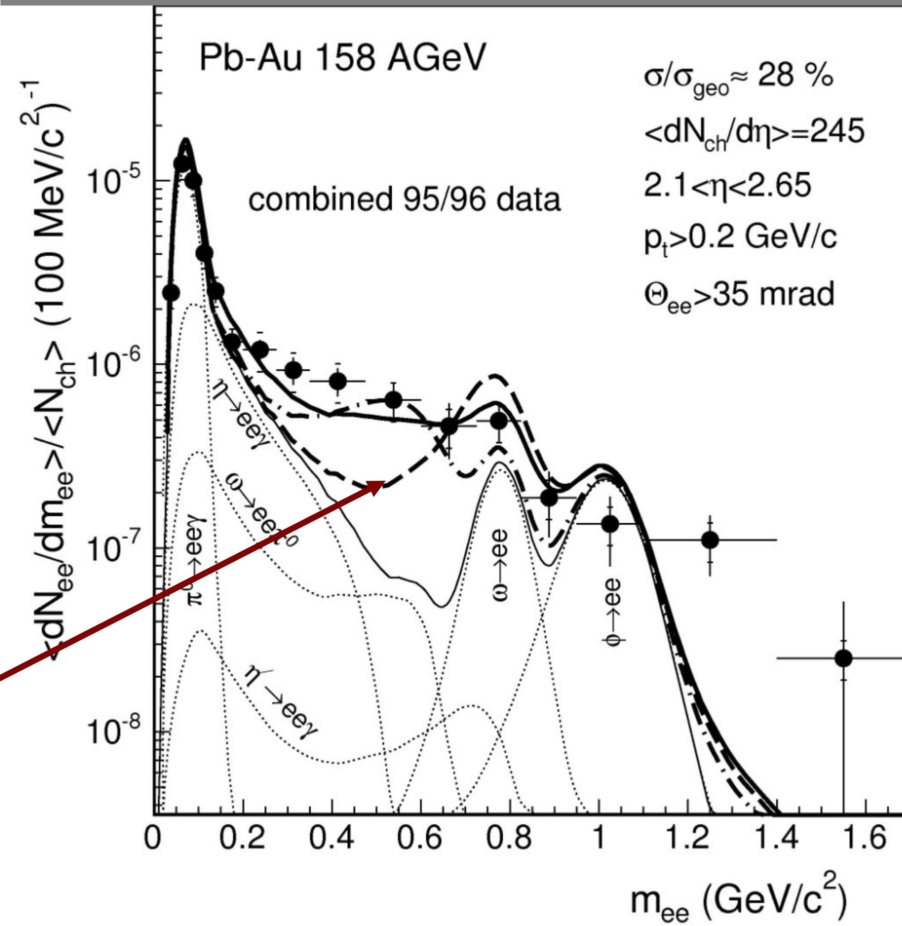
* Invoke new source not present in pp or pA collisions:



thermal radiation from HG

* vacuum ρ not enough to reproduce data

CERES Pb-Au 158 A GeV 95/96 data



EPJ C41 (2005) 475

In-medium modification of the ρ meson

Dropping mass

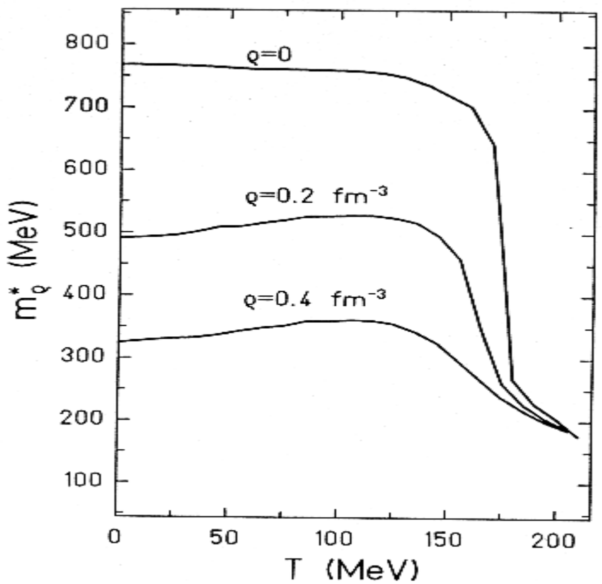
Brown-Rho conjecture that links hadron masses to the quark condensate. Effective QCD Lagrangian, quarks are the relevant d.o.f.

Brown-Rho scaling PRL 66, (1991) 2720

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

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

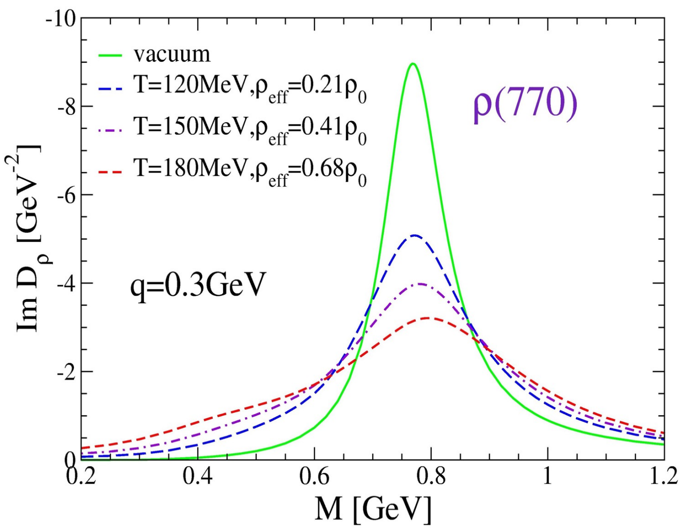
Hatsuda & Lee PR C46, (1992) R34



Broadening

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

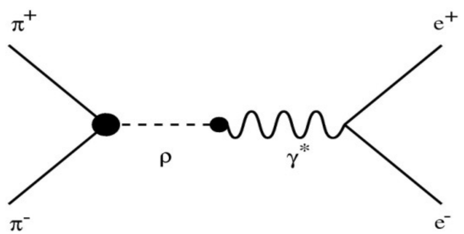
ρ-meson scatters off baryons in the high density medium → collision broadening.



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

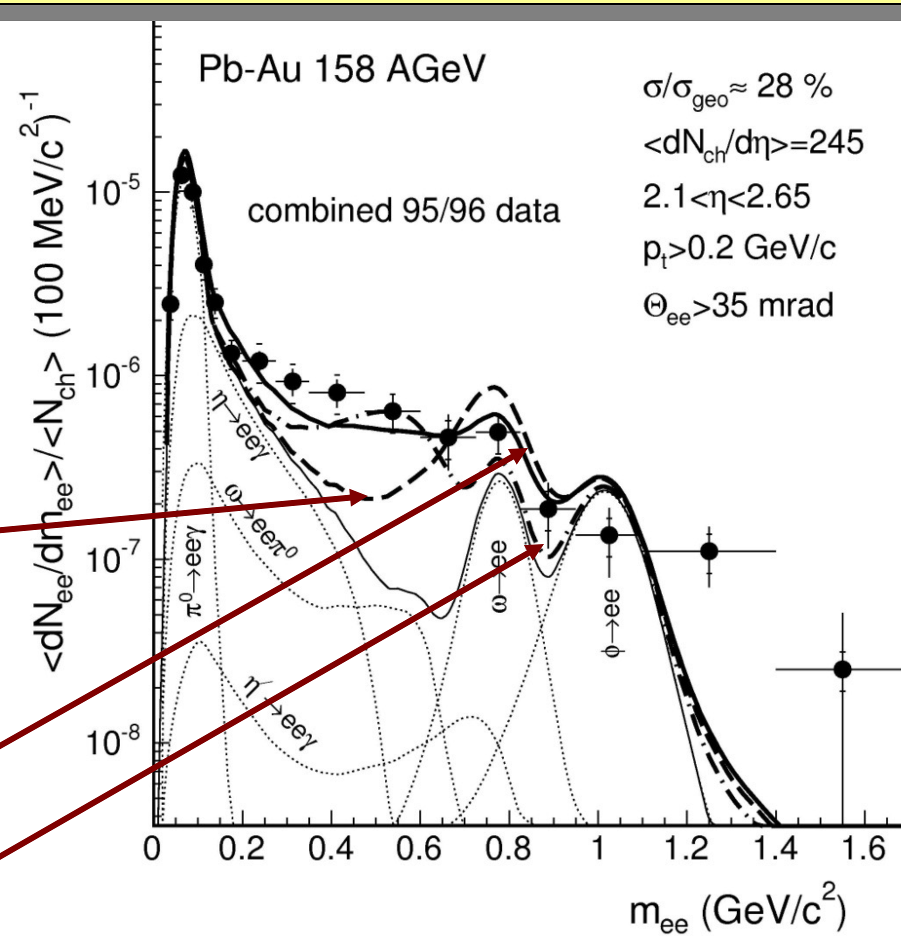


thermal radiation from HG

* 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



EPJ C41 (2005) 475

Dropping Mass or Broadening (II) ?

* Interpretations invoke:
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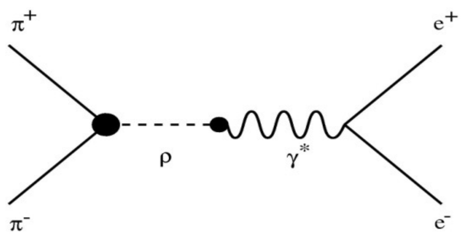

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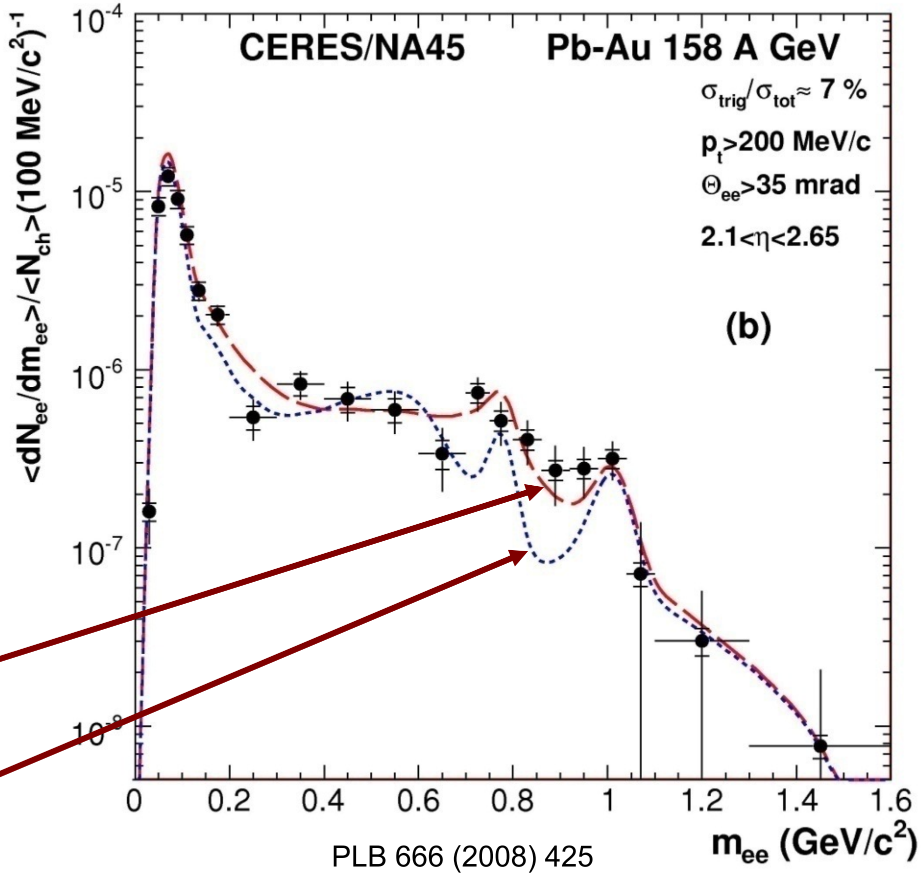
CERES Pb-A 158 A GeV 2000 data

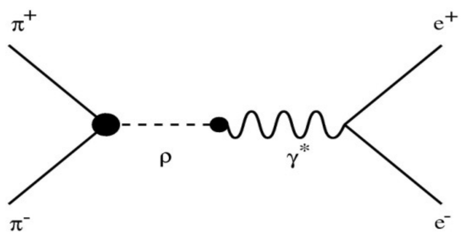


PLB 666 (2008) 425

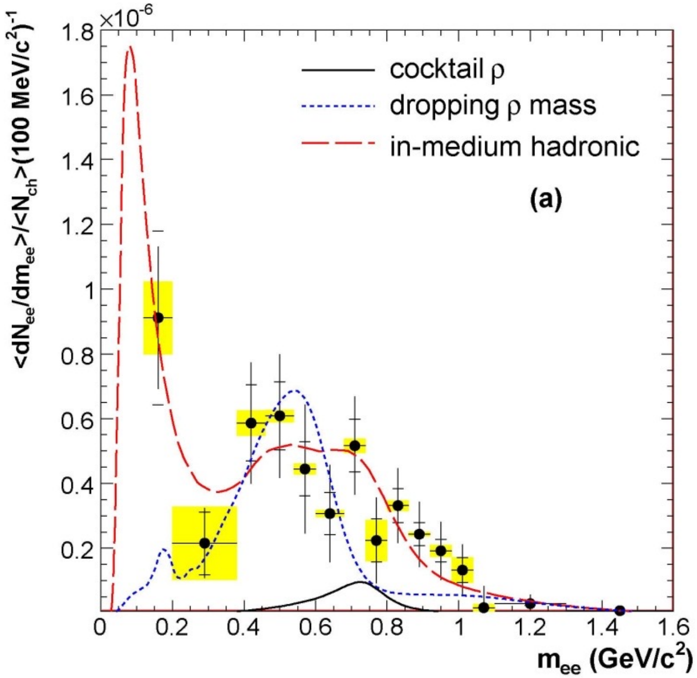
Data favor the broadening scenario.

Dropping Mass or Broadening (III) ?

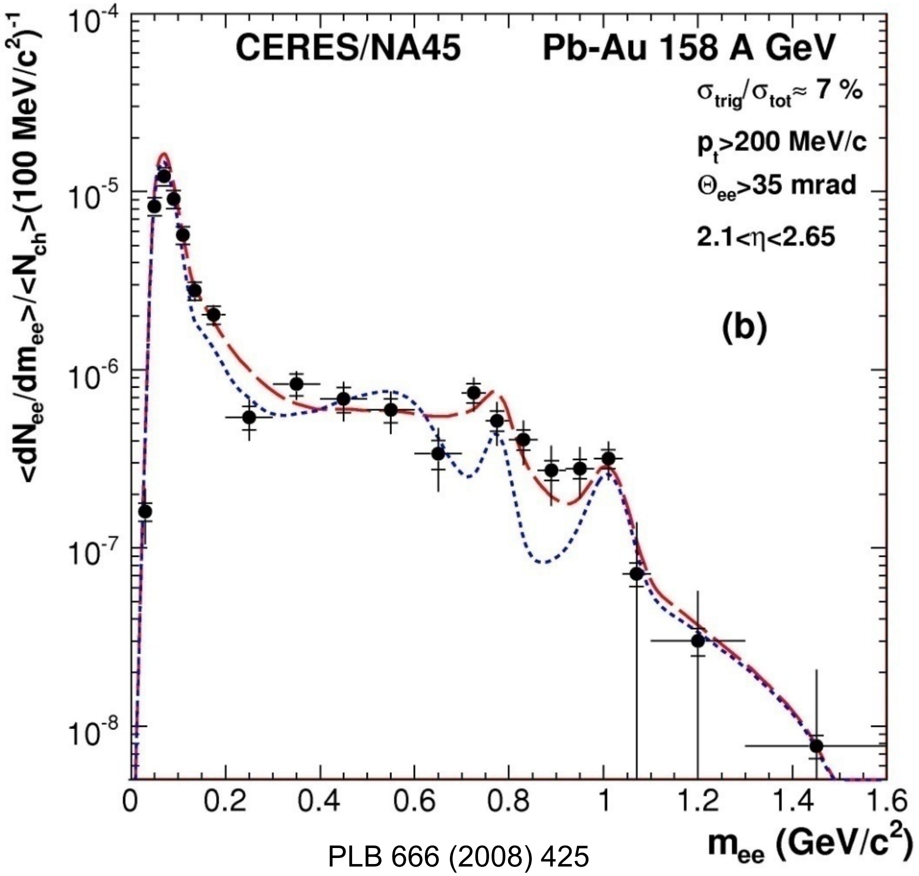
* Interpretations invoke:
  $\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-$



thermal radiation from HG



CERES Pb-A 158 A GeV 2000 data

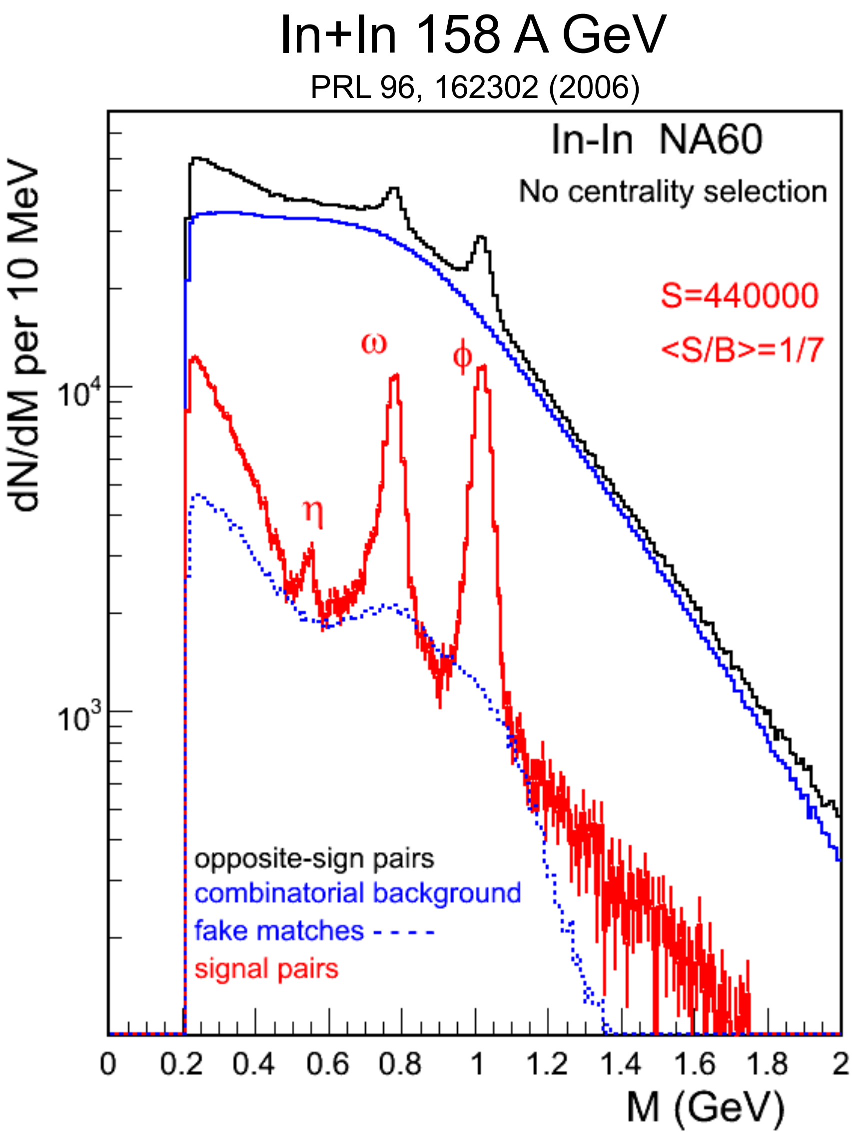


PLB 666 (2008) 425

Data favor the broadening scenario.

NA60 – low masses

NA60 low-mass dimuons



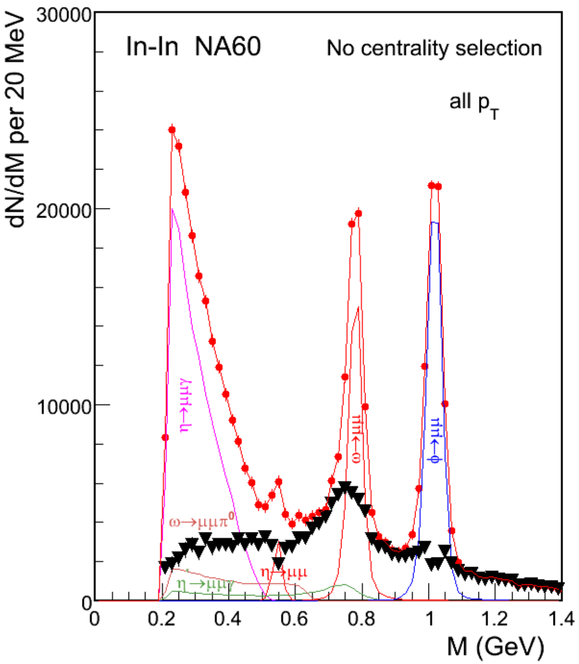
Superb data!!!

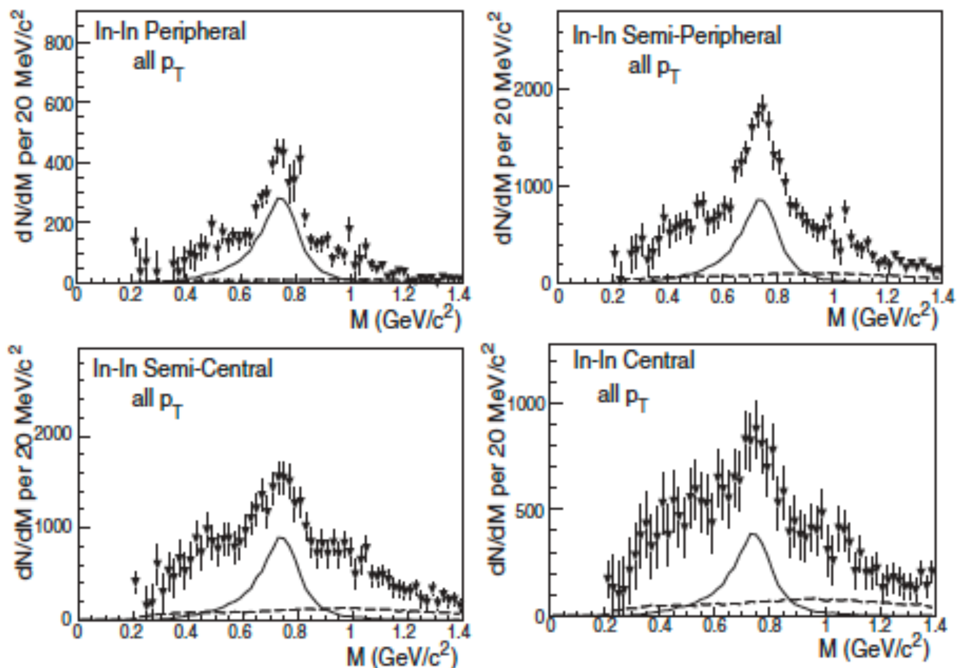
- Mass resolution: 23 MeV at the ϕ position
- S/B = 1/7
- ω, ϕ and even η peaks clearly visible in dimuon channel

PRL 96, 162302 (2006)

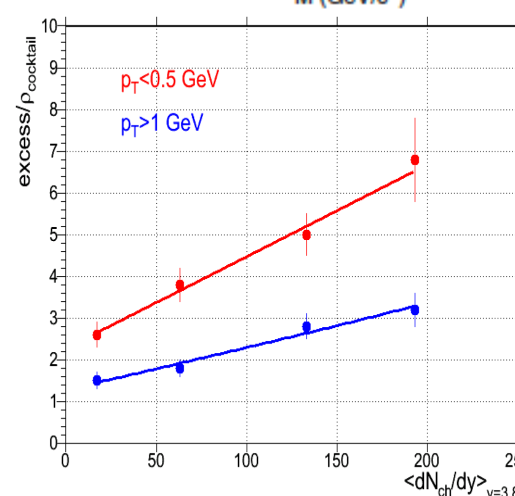
Low-mass excess

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

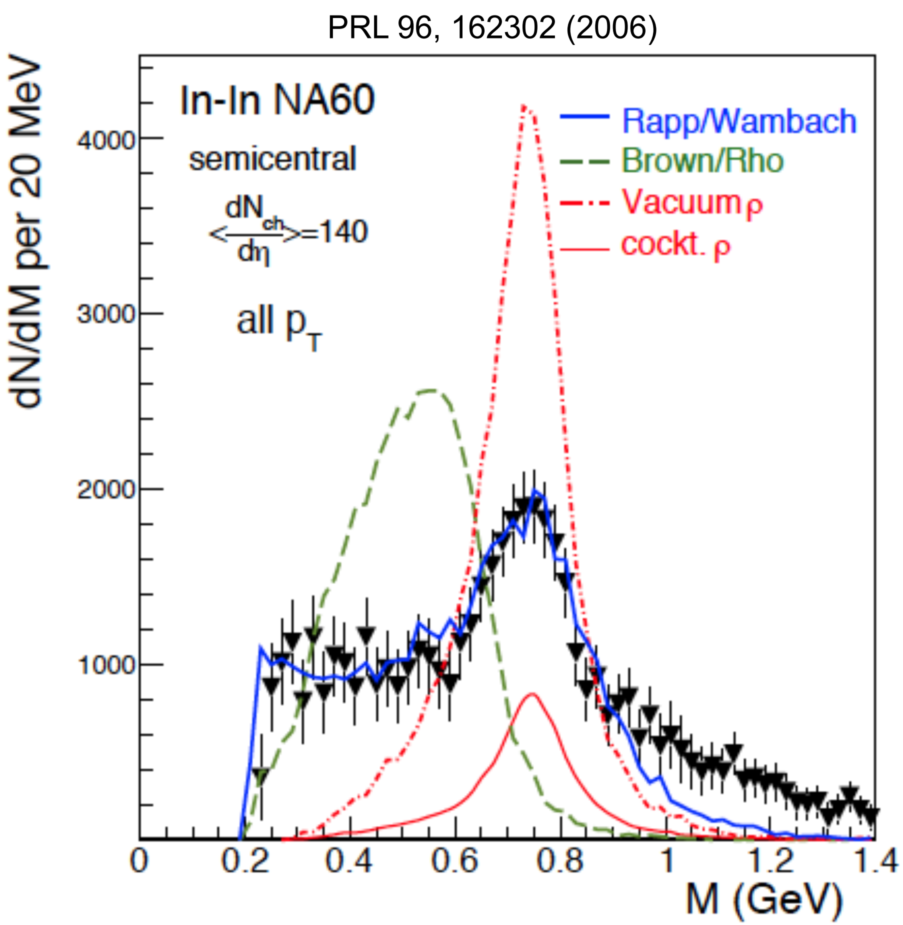




- **Confirms and consistent with CERES results**
- **Rises and broadens with centrality**
- **More pronounced at low p_T**



NA60 low-mass dimuons excess



- ❑ **Isolate excess by subtracting the cocktail (without the ρ) from the data**
- ❑ **Excess shape consistent with broadening of the ρ (Rapp-Wambach)**
- ❑ **Dropping mass of the ρ (Brown-Rho) ruled out**
  - Conclusions valid also as a function of p_T
- ❑ **Is this telling us something about CSR?**

NA60 – intermediate masses

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

NA50 IMR results

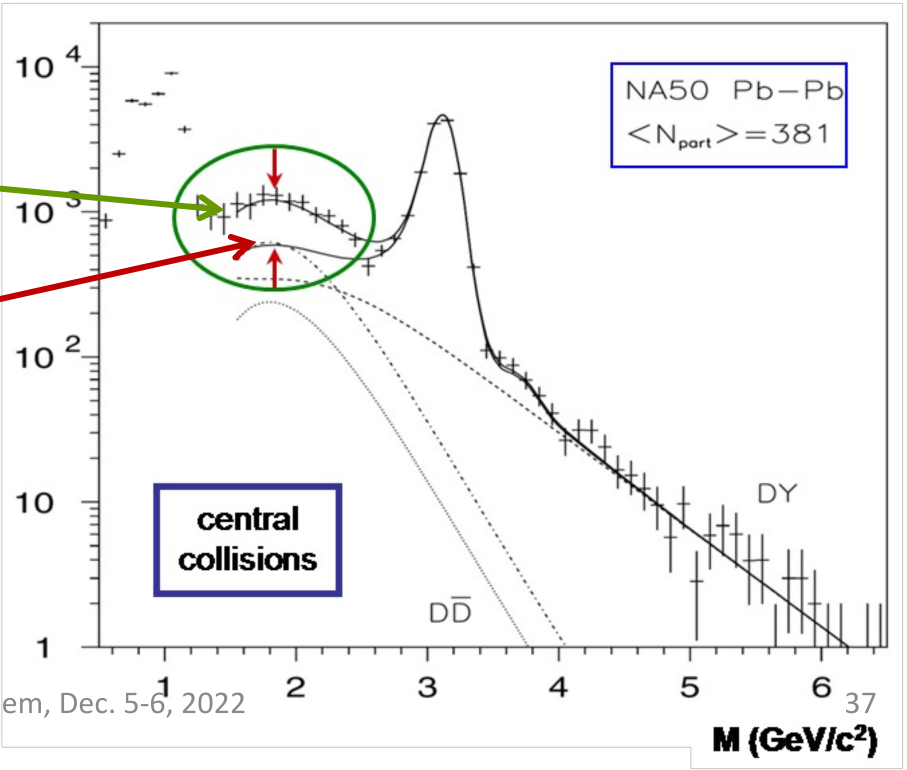
- Drell-Yan and Open Charm are the main contributions in the IMR
- p-A is well described by the sum of these two contributions (obtained from Pythia)
- The yield observed in heavy-ion collisions exceeds the sum of DY and OC decays, extrapolated from the p-A data.
- The excess has mass and p_T shapes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

EPJ C14, 443 (2000)

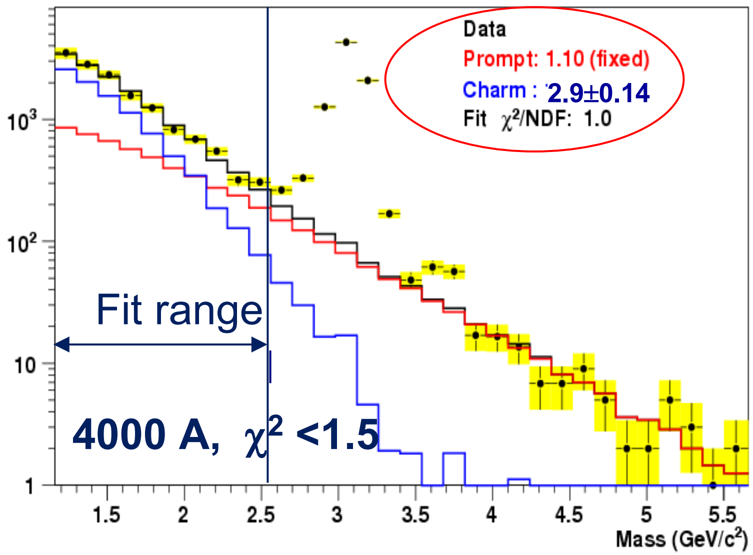
Drell Yan + 3.6 x Open charm

Drell Yan + Open charm

charm enhancement?



NA60: IMR excess is a prompt source



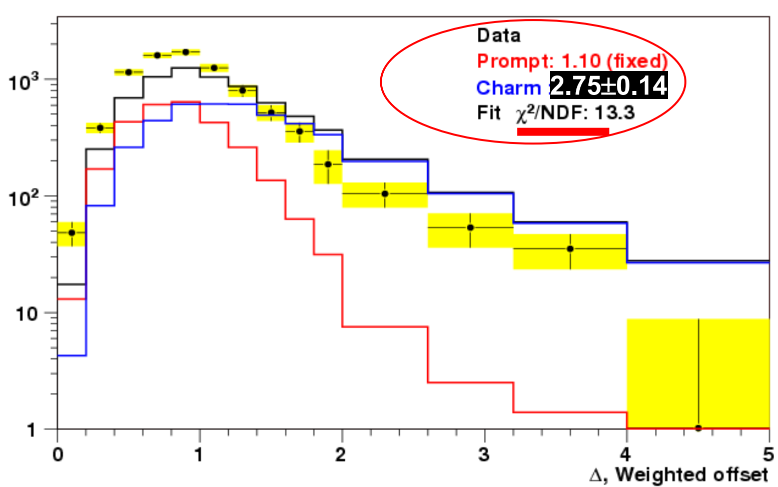
EPJ C59, 07 (2009)

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

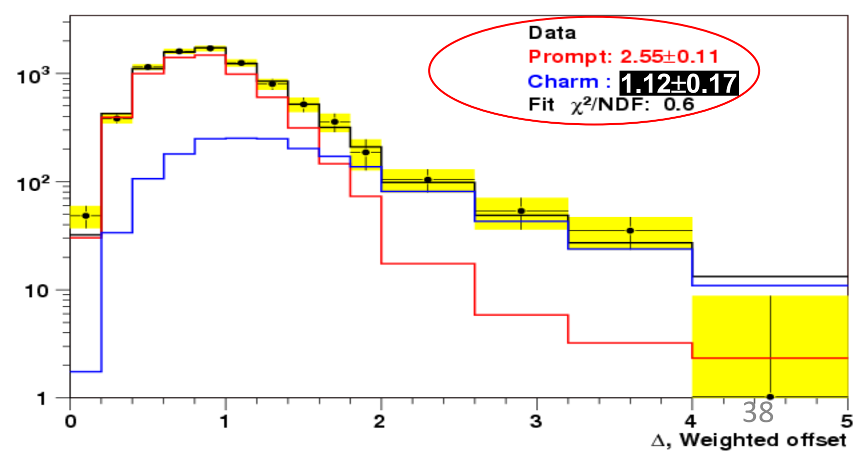
In agreement with NA50

… But the offset distribution (displaced vertex) is not compatible with this assumption.
Take offset shape of prompt source from muons from phi and J/psi decays.
Take offset shape of non-prompt source from simulated open charm decays.

Fixed prompt and fit non-prompt (open charm)

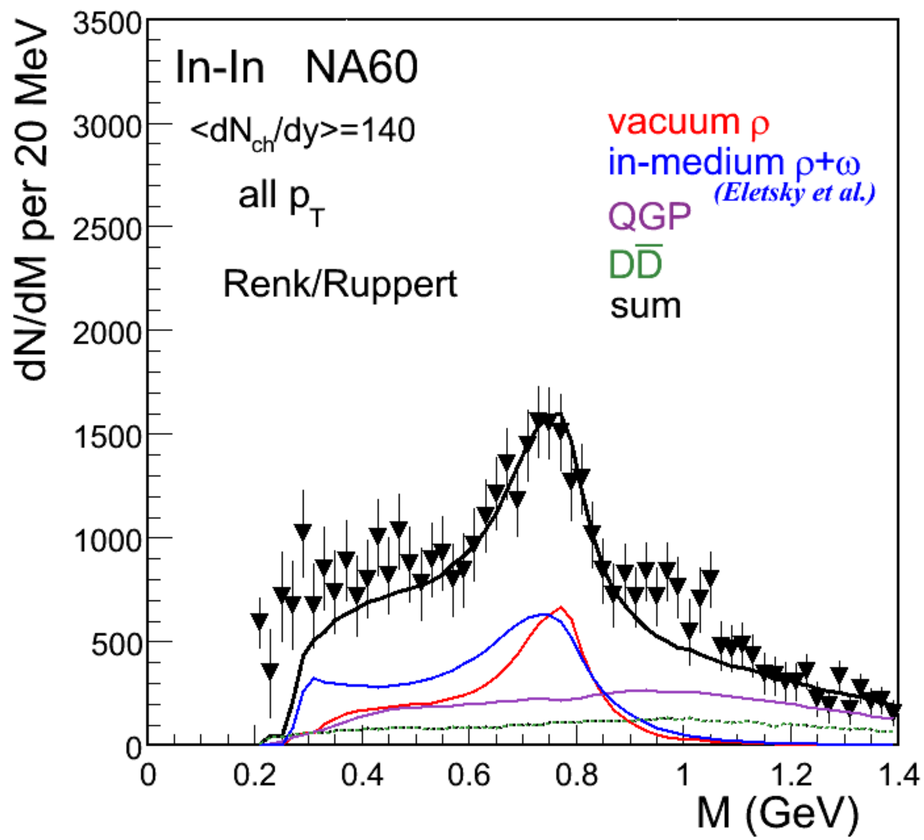


Fit prompt and non-prompt (open charm)



Origin of IMR excess

Renk/Ruppert, PRL 100,162301 (2008)

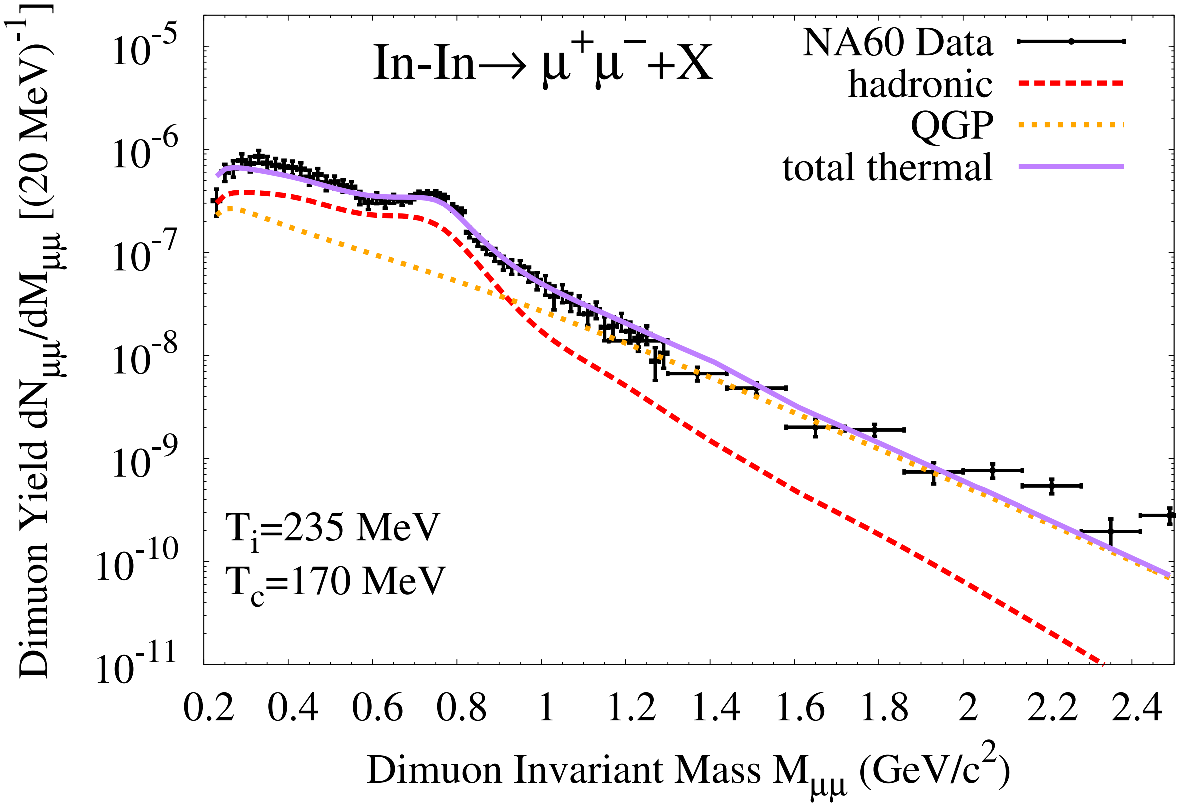


Dominant process in mass region m > 1 GeV/c^2:

$q\bar{q}$ annihilation

Acceptance corrected invariant mass spectrum

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 results

PHENIX, 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

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

- At SPS energies, the ρ-meson broadening, that explains both the CERES and NA60 data, relies on a high baryon density.

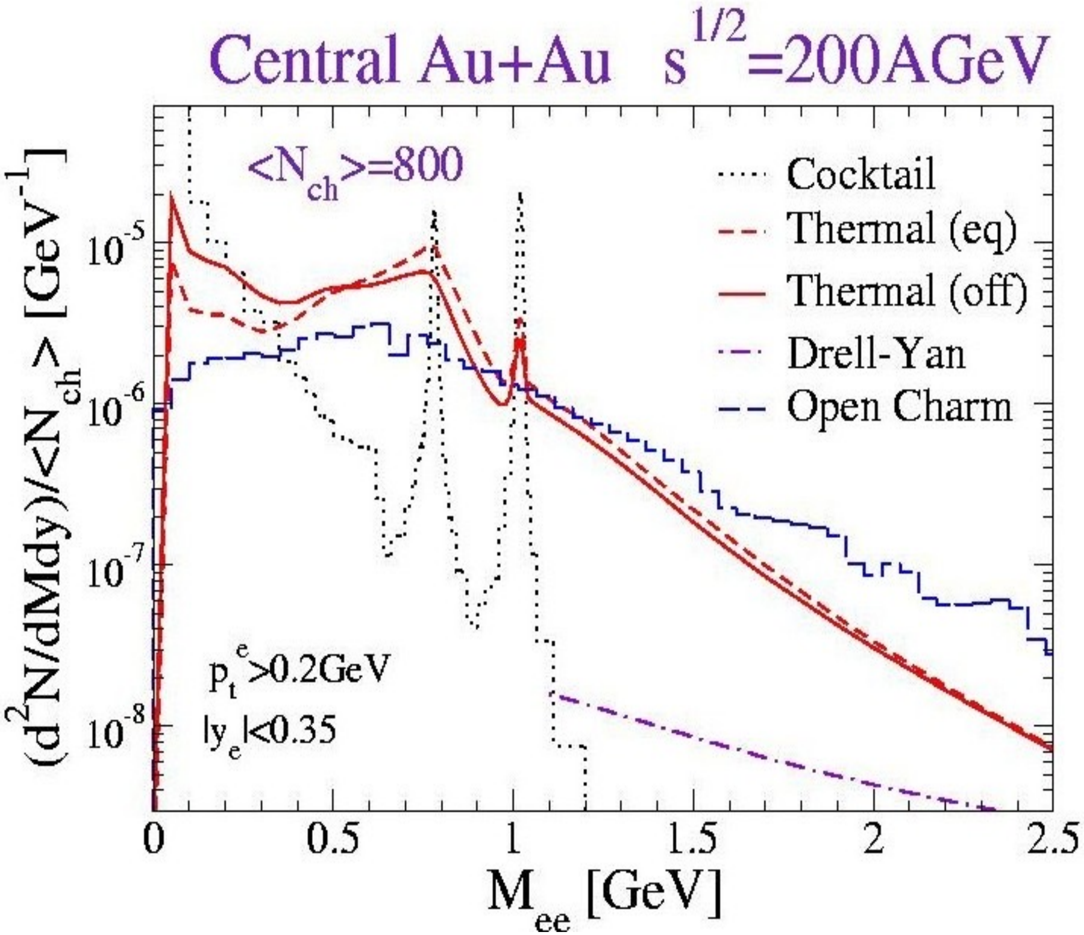
- Baryon density at RHIC?

	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

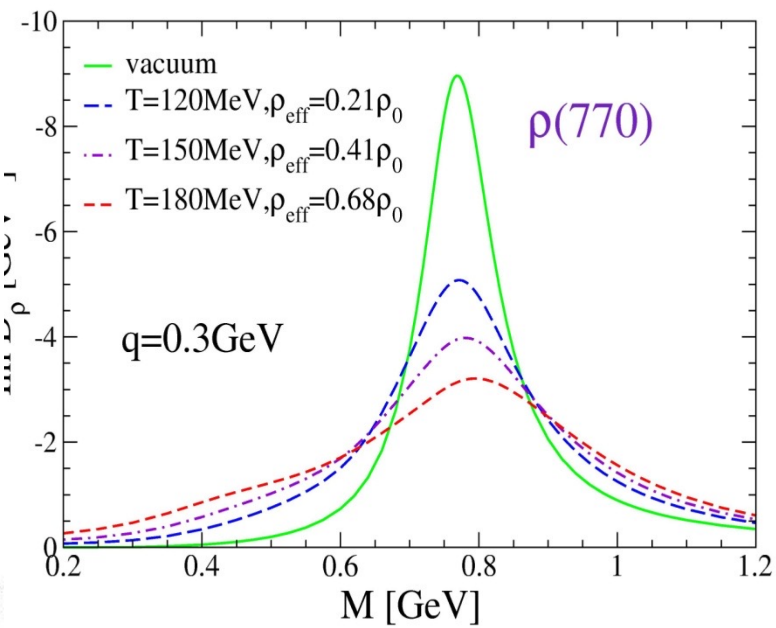
- Baryon density is almost the same at RHIC and SPS

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

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



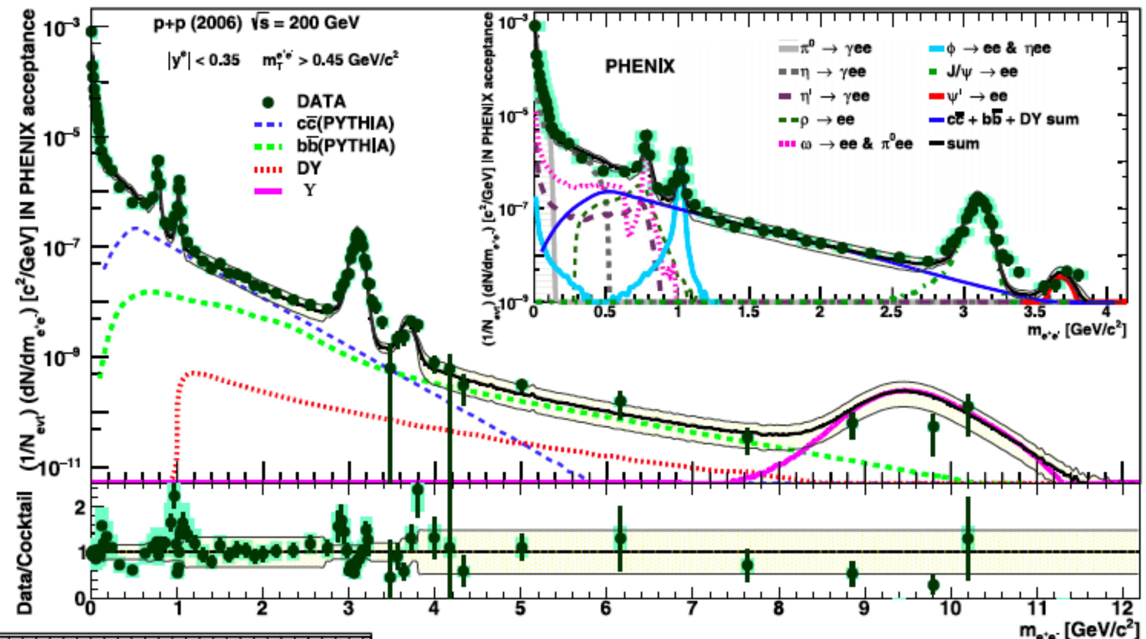
R. Rapp nucl-th/0204003



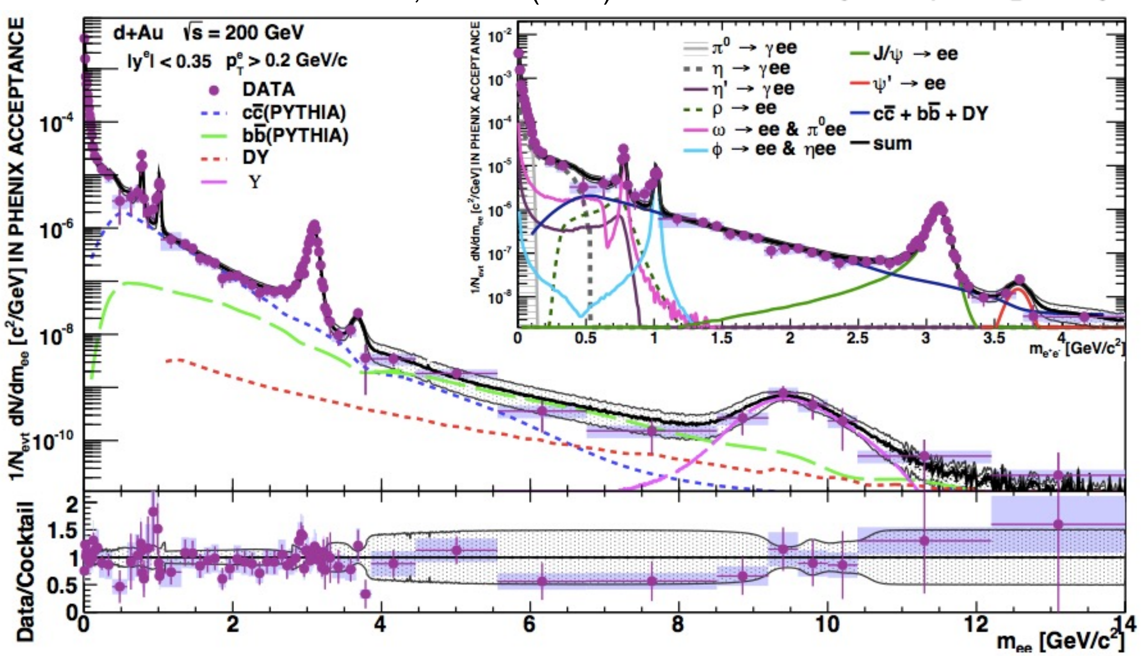
- ❑ **Enhancement of low-mass pairs persists at RHIC**
- ❑ **Open charm contribution becomes significant**

Dileptons in PHENIX: p+p and d+Au

PRC 96, 024907 (2017)
PLB 670, 313 (2009)



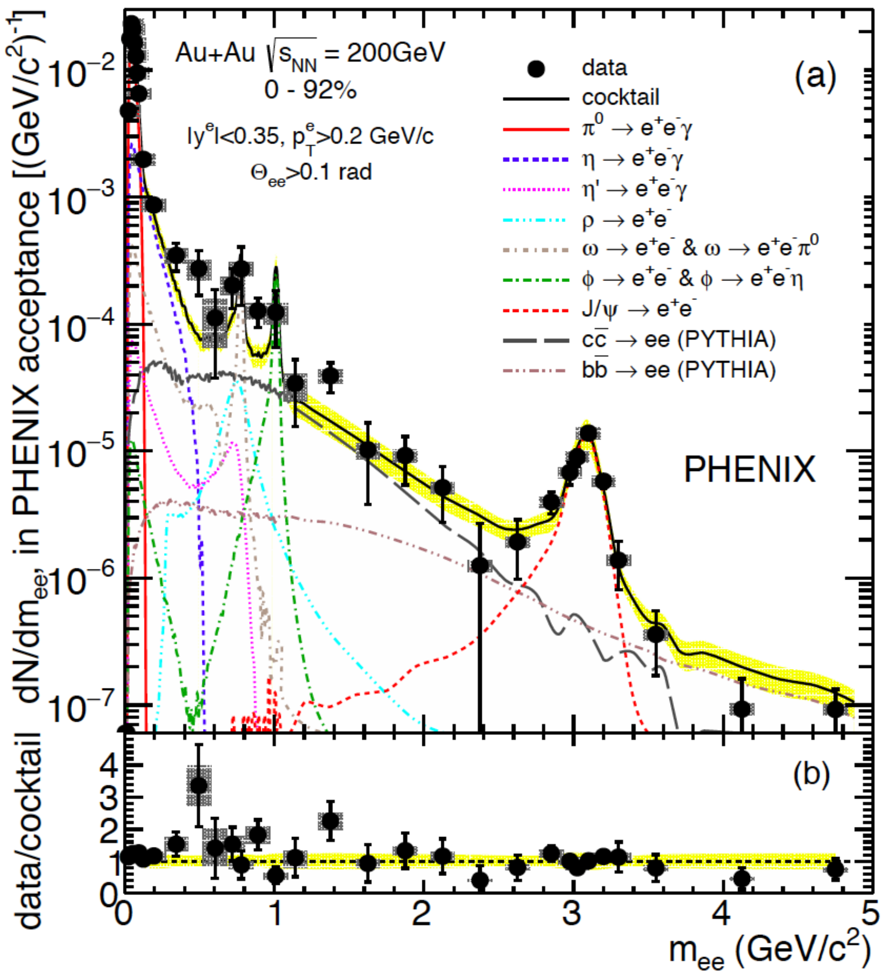
PRC 91, 014907 (2015)



- Mass spectrum measured from m=0 up to m~10 GeV/c²
- Very well understood in terms of:
  - hadron cocktail at low masses
  - heavy flavor + DY at high masses using PYTHIA

Dileptons in PHENIX: Au+Au

PRC 93, 014904 (2016)



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

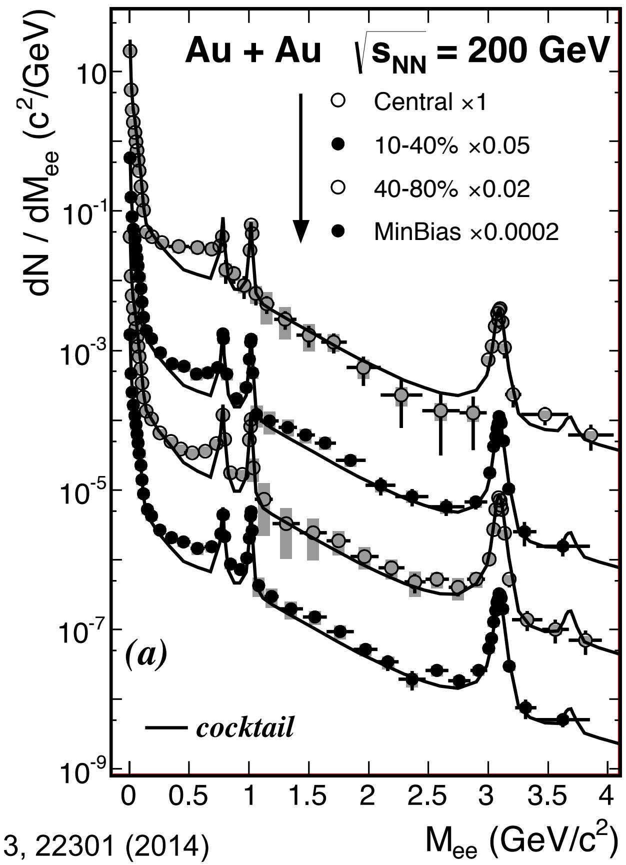
MB Enhancement factor

Data/Cocktail ±stat ±syst ±model m=0.3 – 0. 76 (GeV/c²)
2.3 ± 0.4 ± 0.4 ± 0.2

Consistent with STAR results

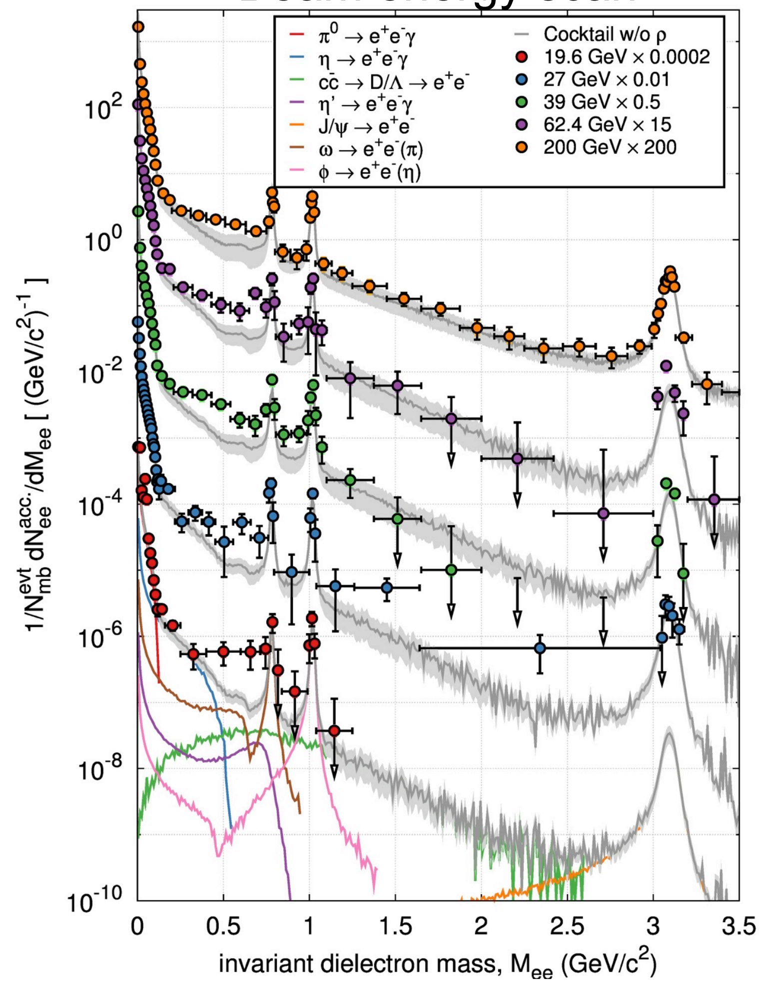
Dileptons in STAR: Au+Au

Centrality dependence



PRL 113, 22301 (2014)
PRC 92, 24912 (2015)

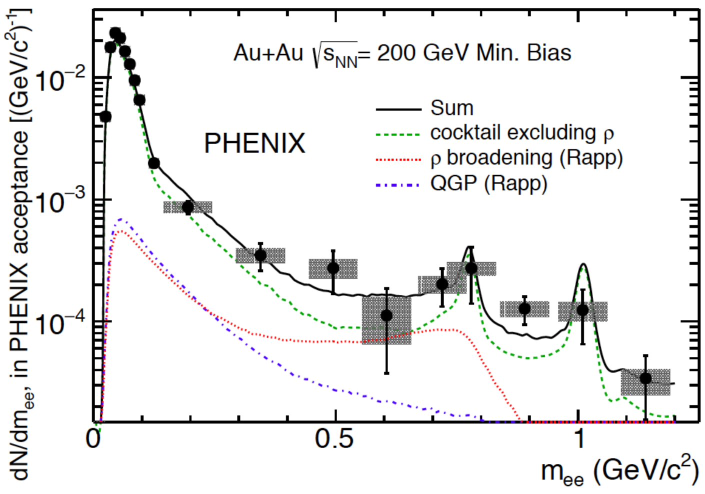
Beam energy scan

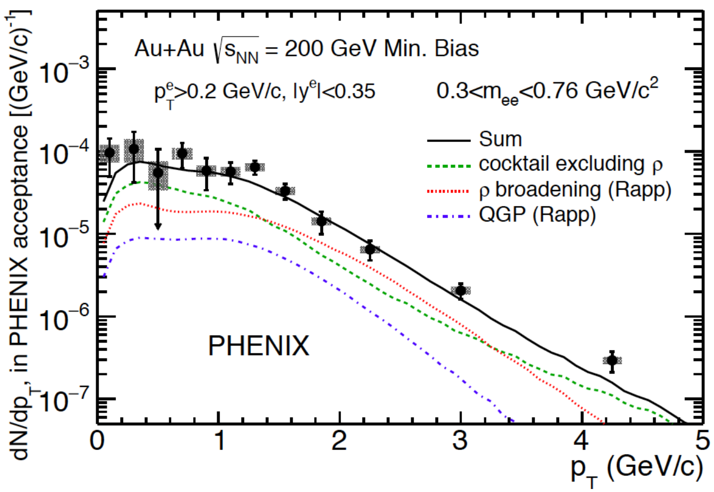


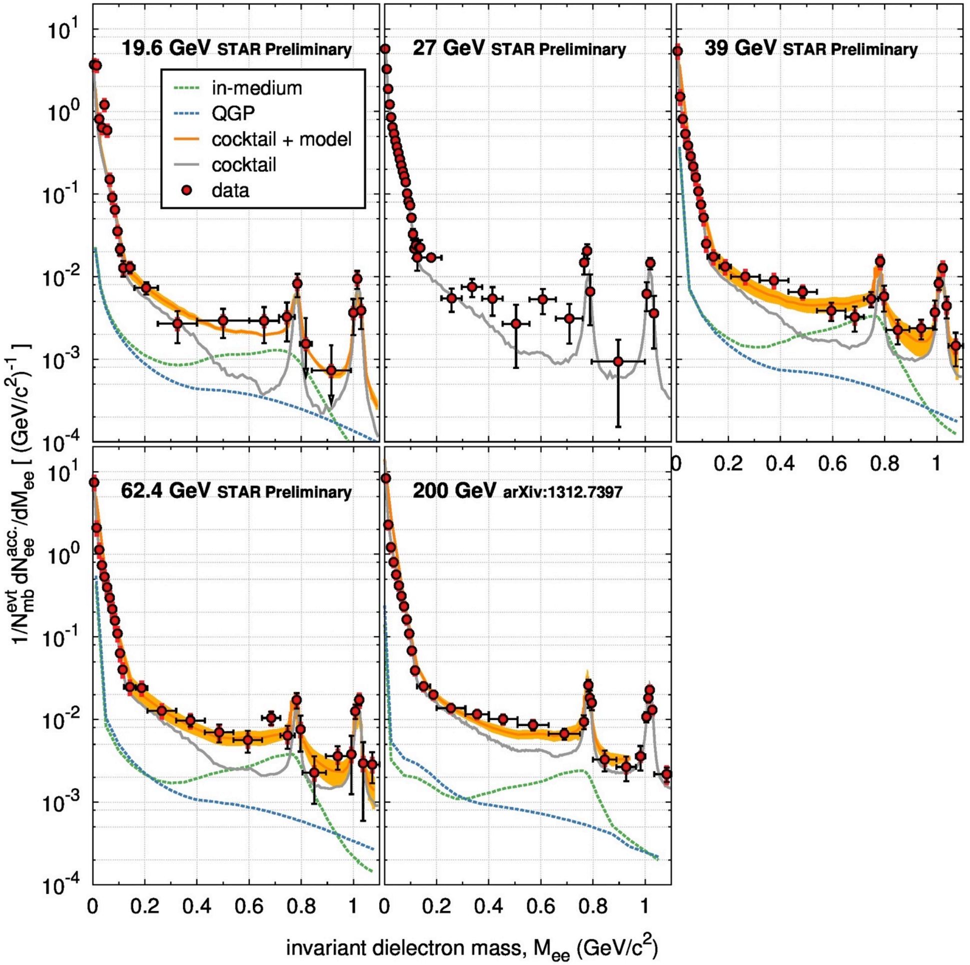
- LMR: clear enhancement wrt to cocktail
  small centrality dependence
  observed at all energies down to 19.6 GeV

- IMR: no clear picture

Comparison to Rapp model





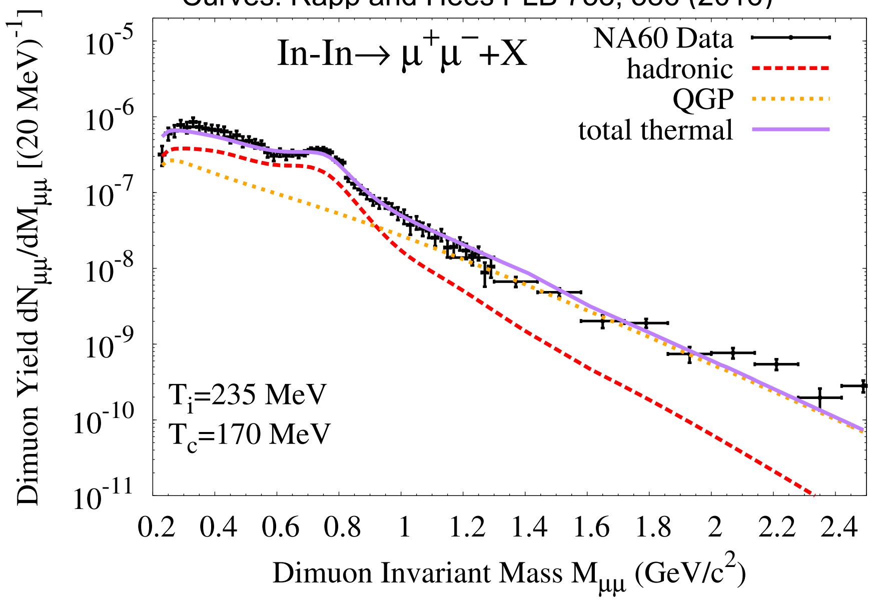


Same model that describes the SPS data reproduces the dilepton excess all the way up to top RHIC energy

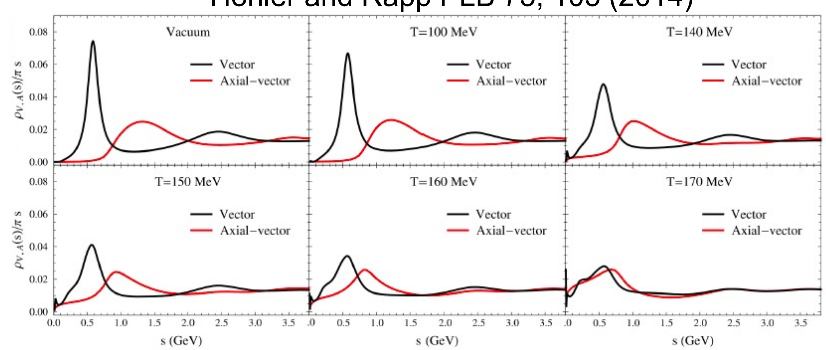
Dilepton measurements - Summary

- All HI systems at all energies studied show an excess of dileptons wrt to hadronic sources
- Excess consistently reproduced by microscopic many body model (Rapp et al.)
- LMR:
  - Thermal radiation from HG
    $\pi^+\pi^- \to \rho \to \mu^+\mu^-$
  - Tracks the medium lifetime
- IMR:
  - Thermal radiation from QGP
    $q\bar{q} \to \mu^+\mu^-$
  - Provides a measurement of <T>
- Emerging picture for the realization of CSR: the ρ meson broadens in the medium, the a_1 mass drops and becomes degenerate with the ρ.

NA60 data: Eur. Phys. J. C61, 711 (2009)
Curves: Rapp and Hees PLB 753, 586 (2016)



Hohler and Rapp PLB 73, 103 (2014)

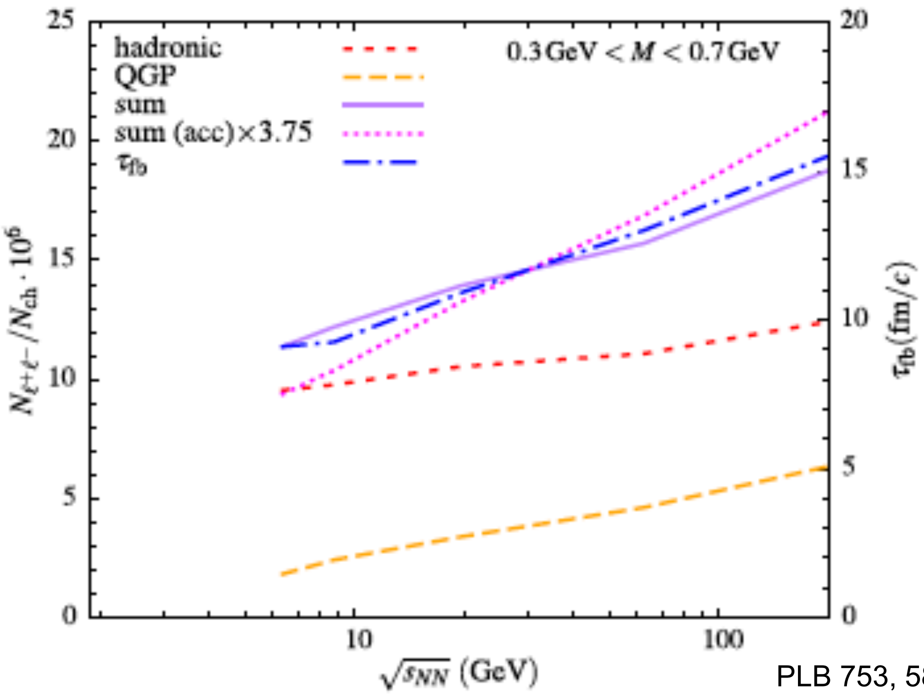


- Effects exclusively observed in AA collisions

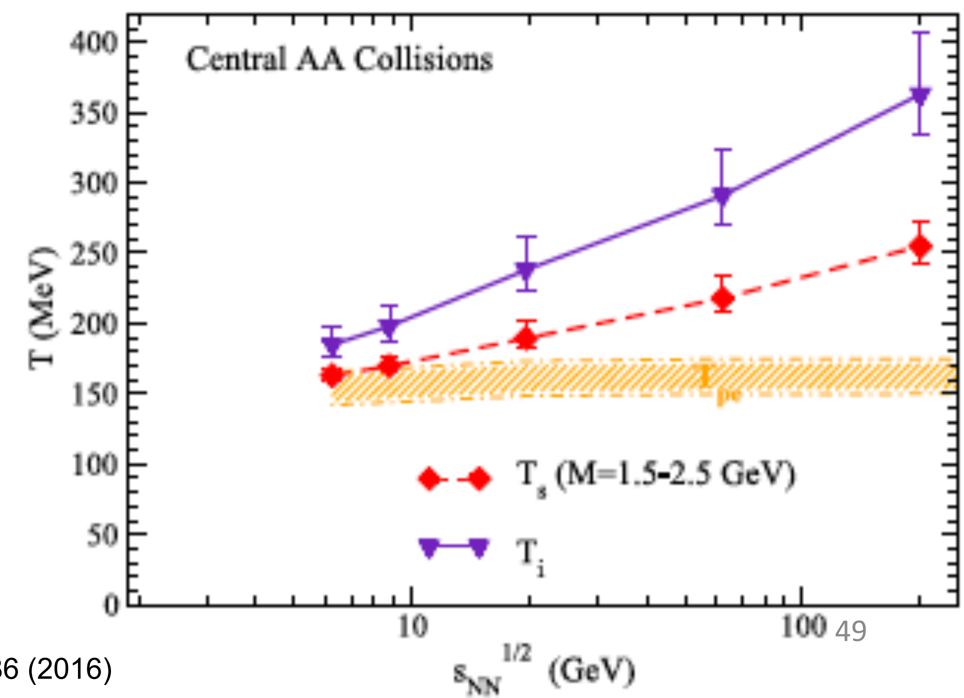
Prospects

- Onset of deconfinement? Onset of CSR? Energy scan of dilepton excess
  - Integrated yield in the LMR tracks the fireball lifetime
  - Inverse slope of the mass spectrum in the IMR provides a measurement of <T>
    First order phase transition?
  - Thermal radiation down to $\sqrt{s_{NN}}$ – 6 GeV ?

LMR as chronometer



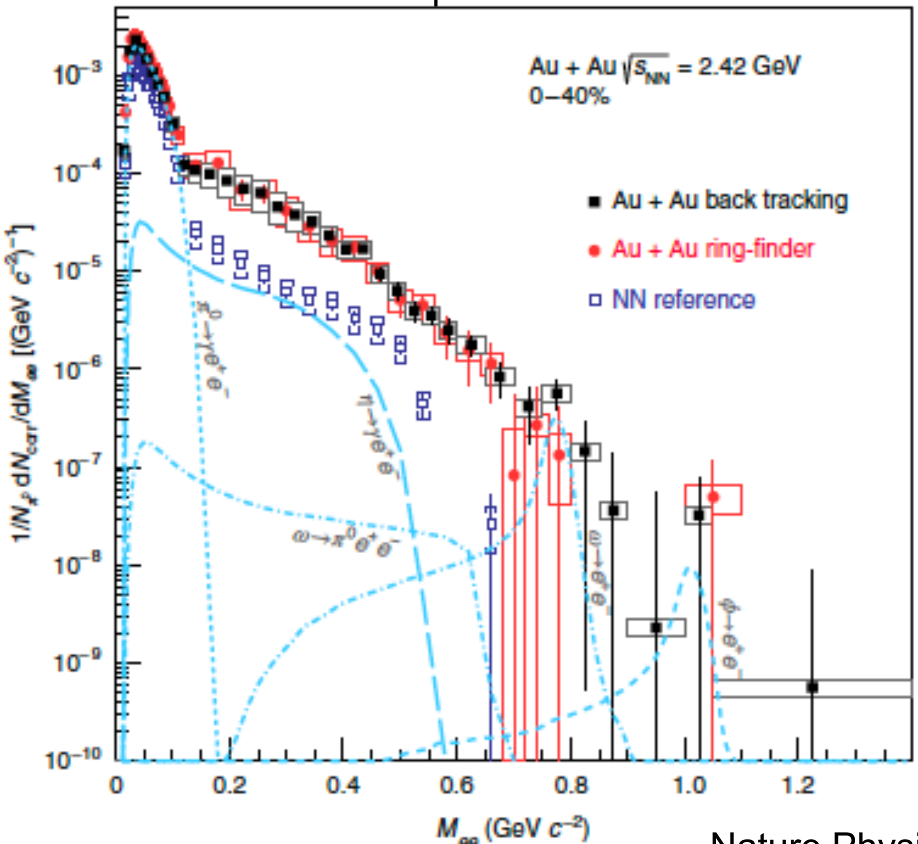
IMR as thermometer



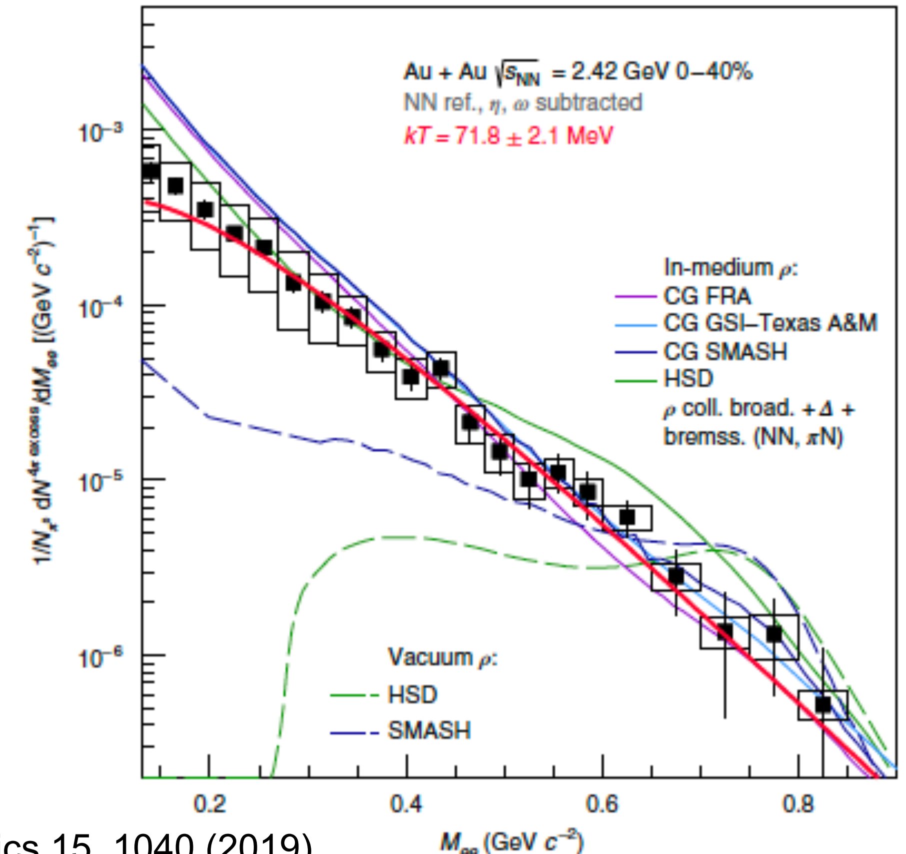
PLB 753, 586 (2016)

S18: HADES dileptons

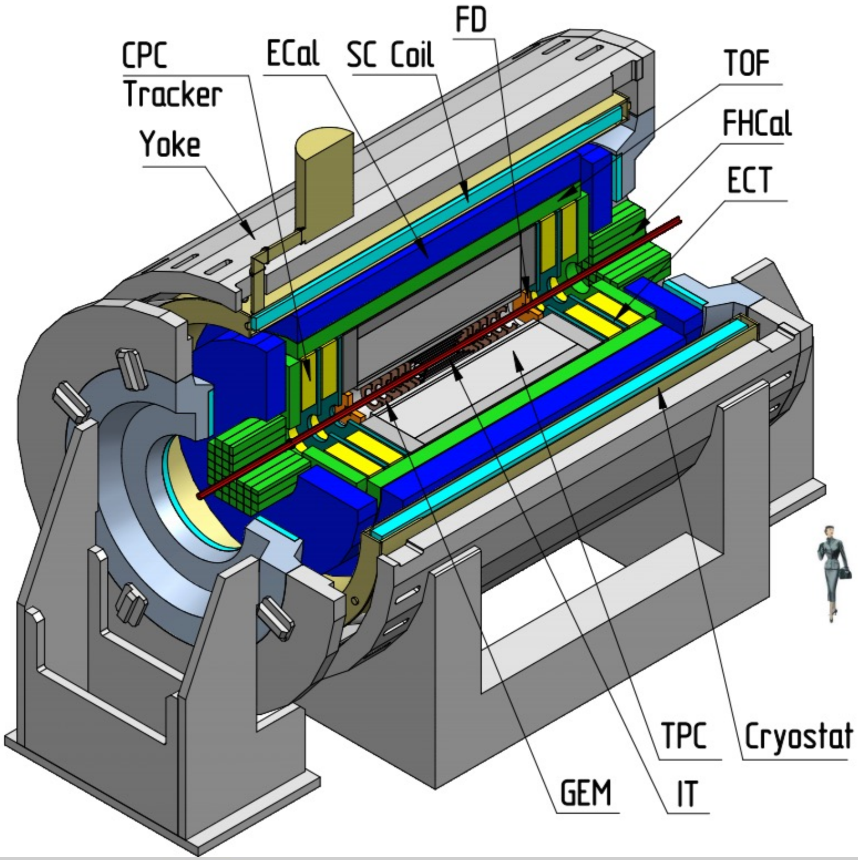
Measured invariant mass spectrum compared to expected sources



Acceptance corrected dilepton excess

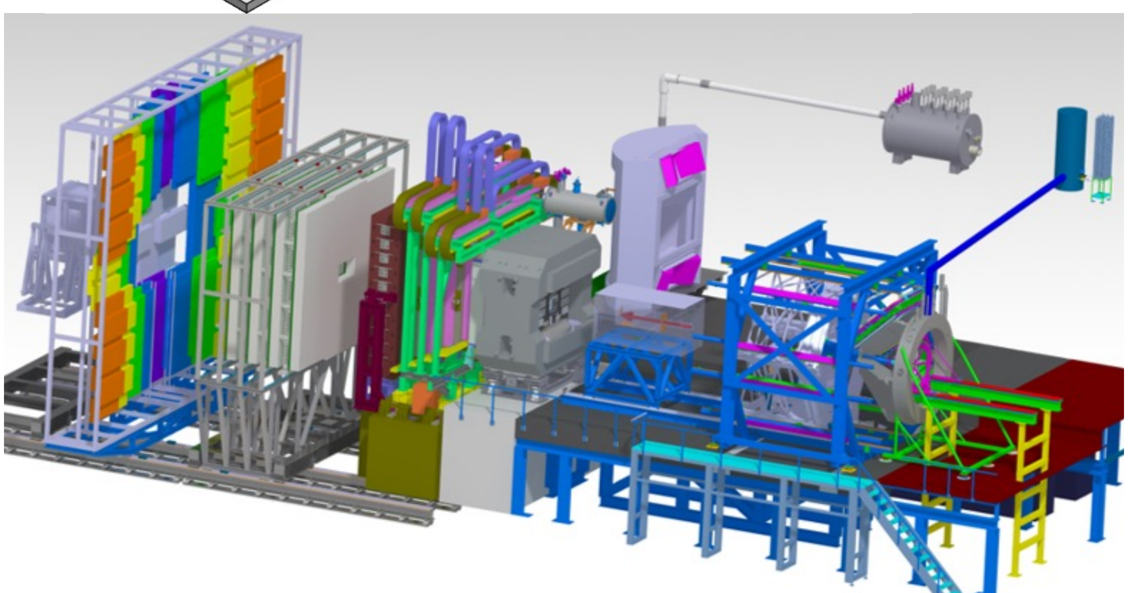


Nature Physics 15, 1040 (2019)



MPD at NICA

$\sqrt{s_{NN}}$ = 4 - 11 GeV
Expected to start operation in 2024



CBM @ FAIR

$\sqrt{s_{NN}}$ = 2 - 5 GeV
Expected to start operation in 2028?

Parton energy loss

An old prediction

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

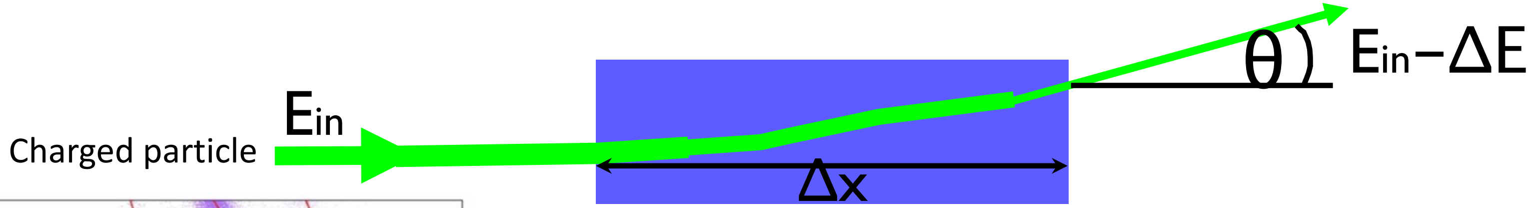
Abstract

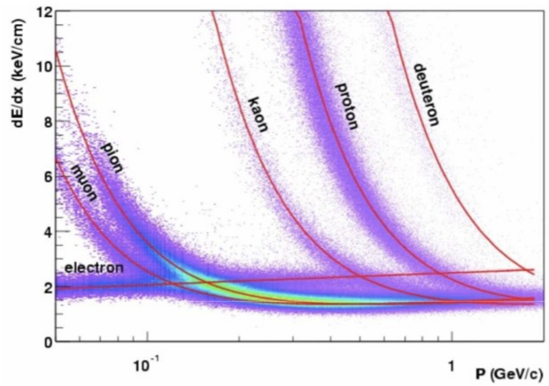
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

Motivation

Bethe Formula

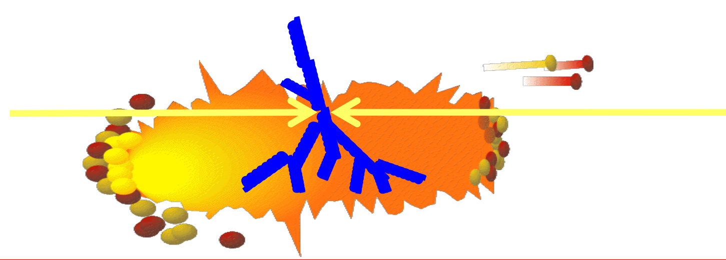
Energy loss of a charged particle in matter (QED)





$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

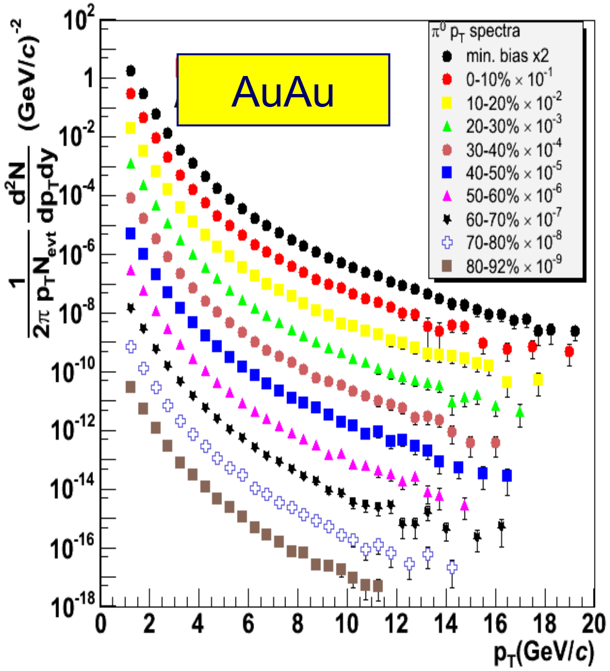
In the colored medium partons loose energy by radiating gluons and by collisions

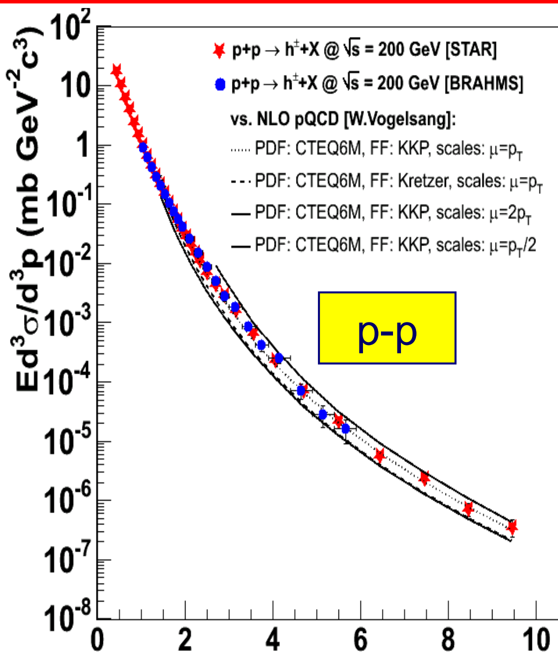


Goal: achieve same level of understanding for partons traversing strongly interacting matter (QCD)

- Single Hadrons - High p_T suppression R_{AA}

π^0 p_T spectra at $\sqrt{s_{NN}}$ = 200 GeV

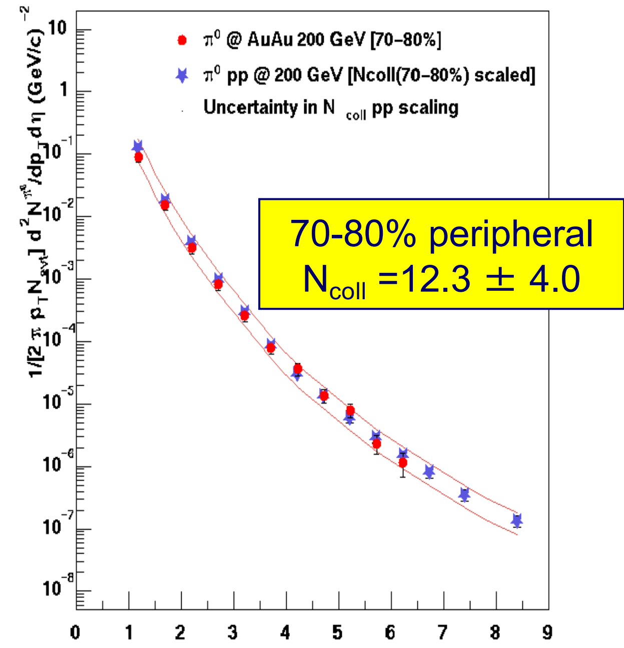


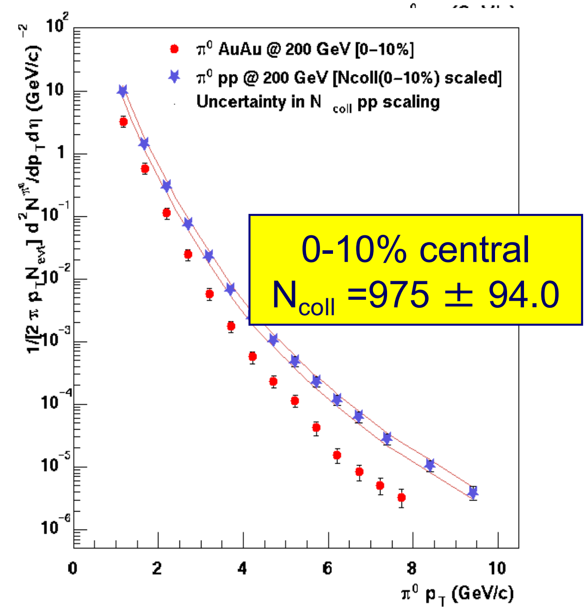


PHENIX PRL 91, 072301 (2003)

- Excellent agreement between measured π^0' s in p-p and π^0' s in *peripheral* Au-Au collisions scaled by the number of collisions over ~ 5 decades
- Central Au-Au collisions yield significantly suppressed relative to scaled p-p yield
- Quantify "effect" with nuclear modification factor

$$R_{AA}(p_t) = \frac{d^2N_{AA}/dp_T d\eta}{N_{coll} d^2N_{pp}/dp_T d\eta}$$





High p_T Suppression in Au-Au collisions !!

Major RHIC discovery

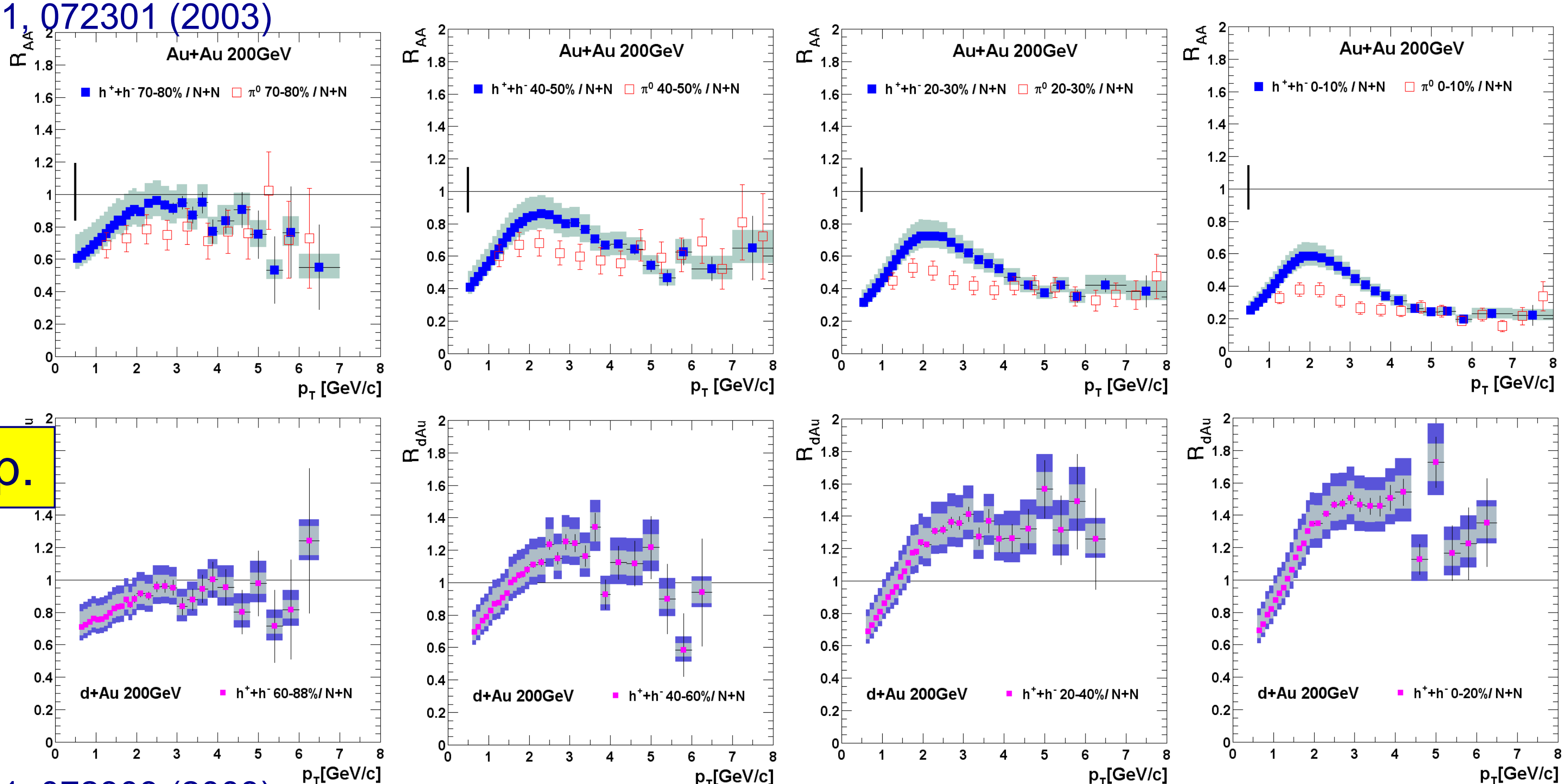
Peripheral → Central

PHENIX PRL 91, 072301 (2003)

AuAu

Control Exp.

dAu



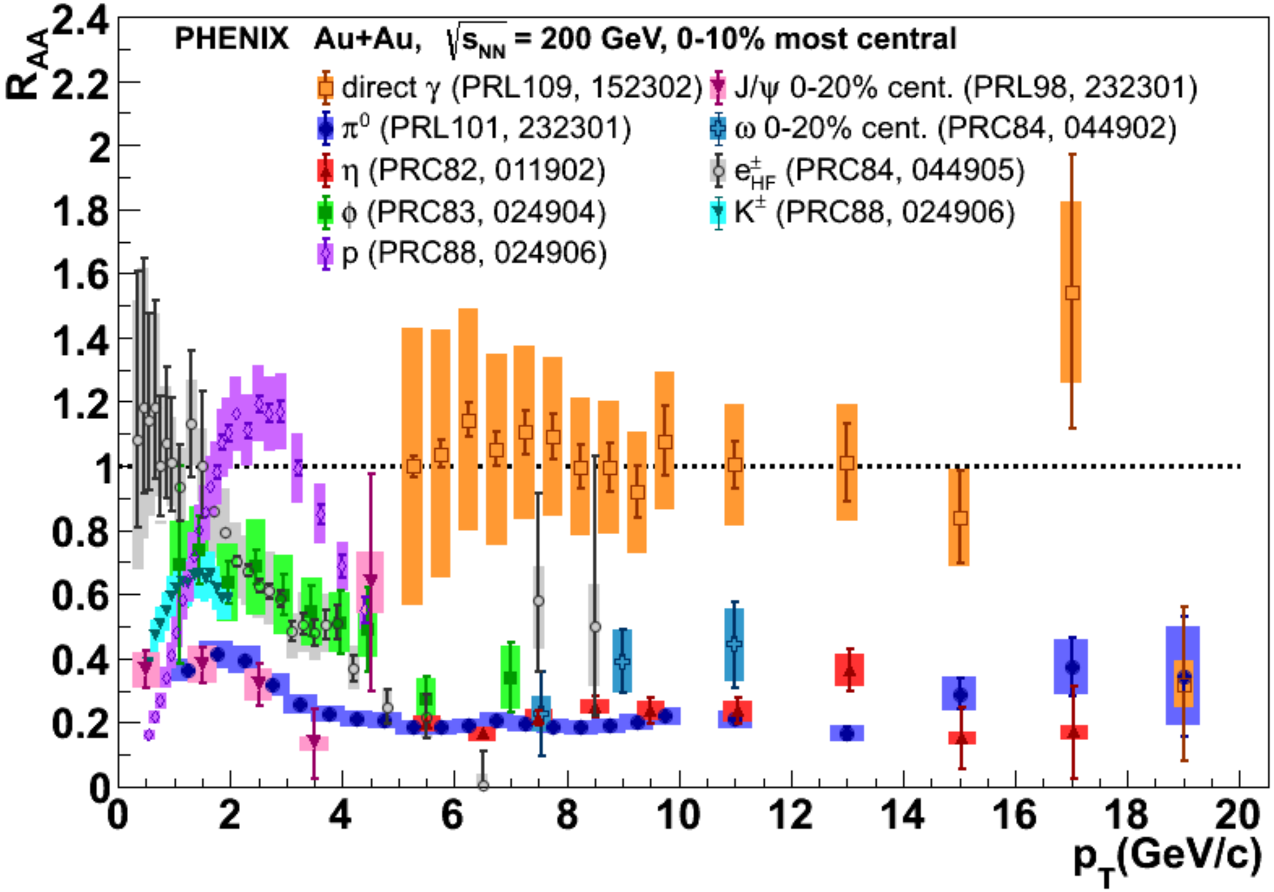
PHENIX PRL 91, 072303 (2003)

- AuAu:
  Peripheral collisions look like pp.
  Central collisions are strongly suppressed - Factor 5!

- dAu:
  No suppression
  but Cronin enhancement

Identified particles R_{AA}

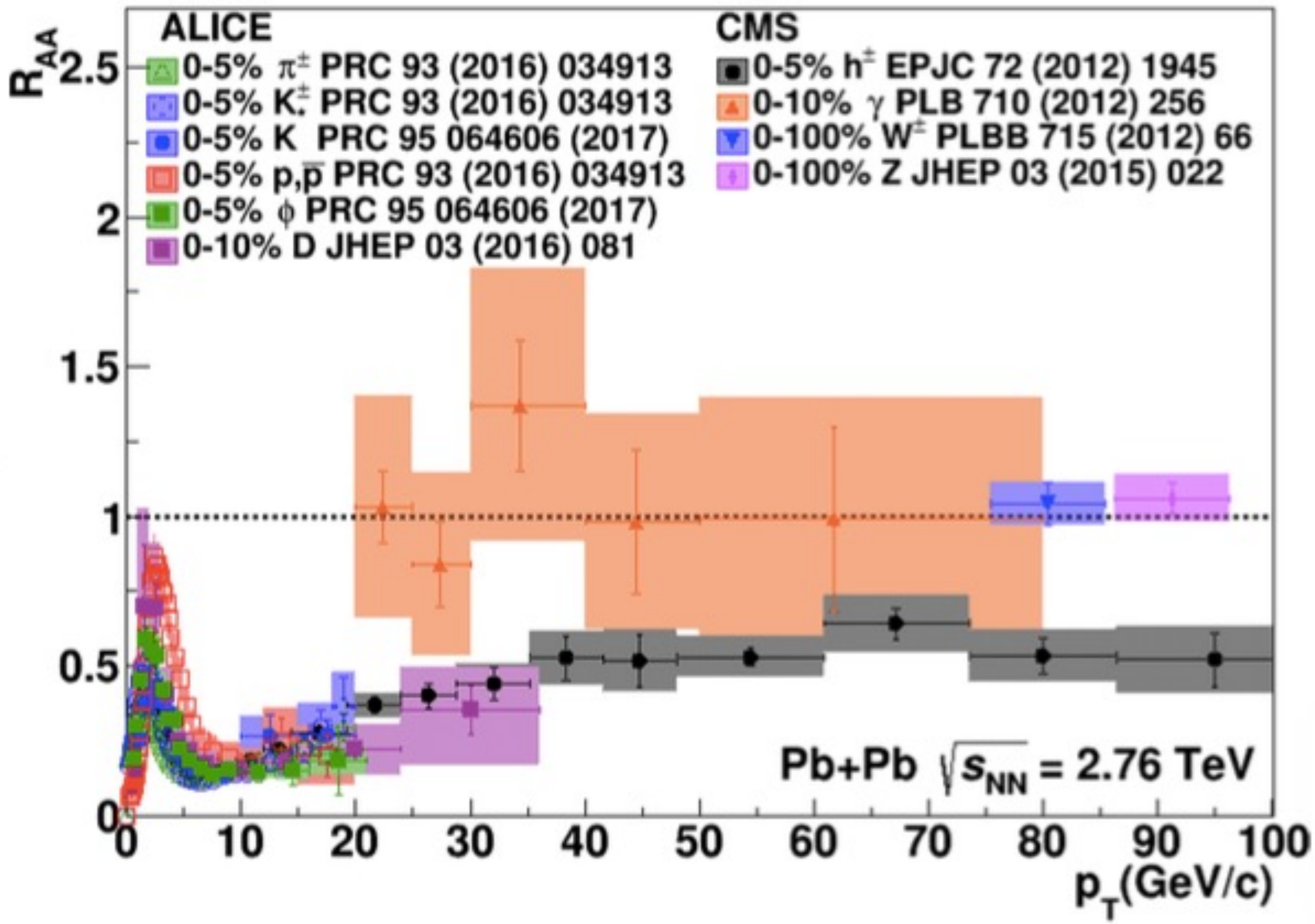
The PHENIX T-shirt plot



- High p_T : Same suppression level for all particles at p_T larger than ~7 GeV/c
- Low p_T: Hierarchy in the suppression pattern?

  R_{AA}(baryons) > R_{AA}(strange mesons, e_{HF}) > R_{AA}(light quark mesons)

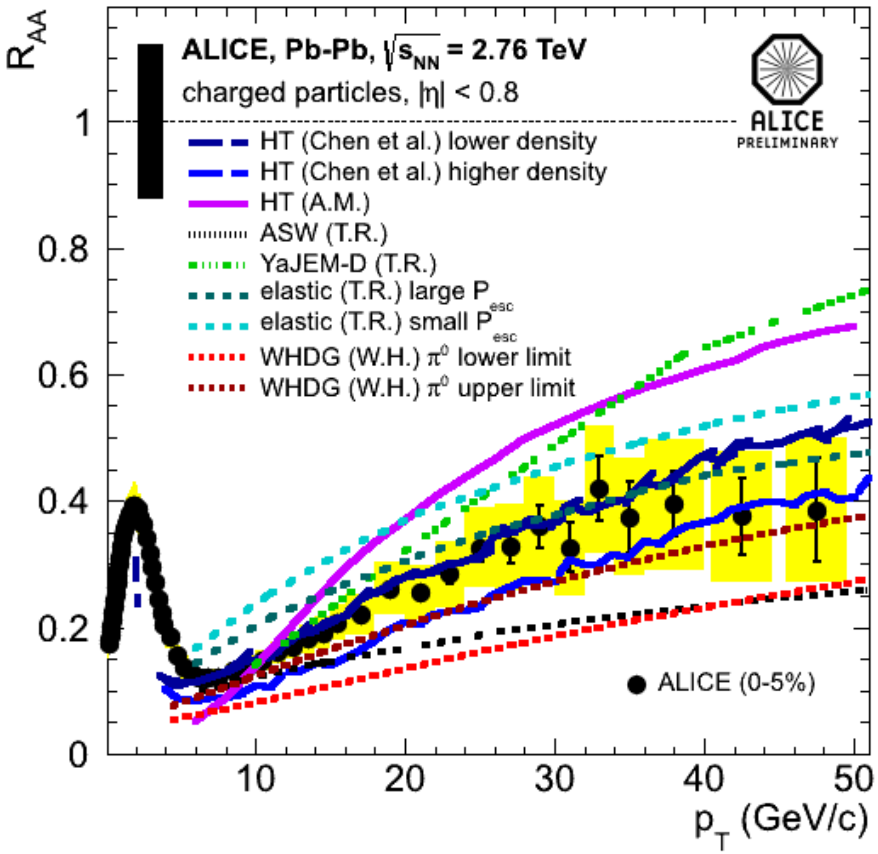
Also observed at LHC



- Extended to much higher p_T
- Electroweak probes give $R_{AA} = 1$

Comparison to theory

PLB 720, 52 (2013)



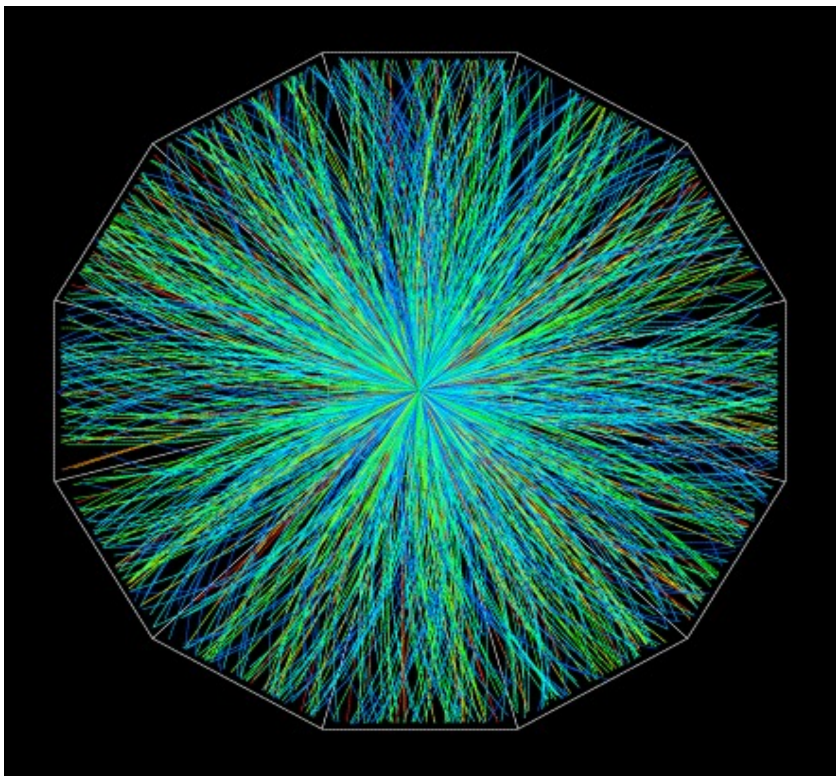
- Charged particle R_{AA} alone is not highly discriminating

Jet Quenching

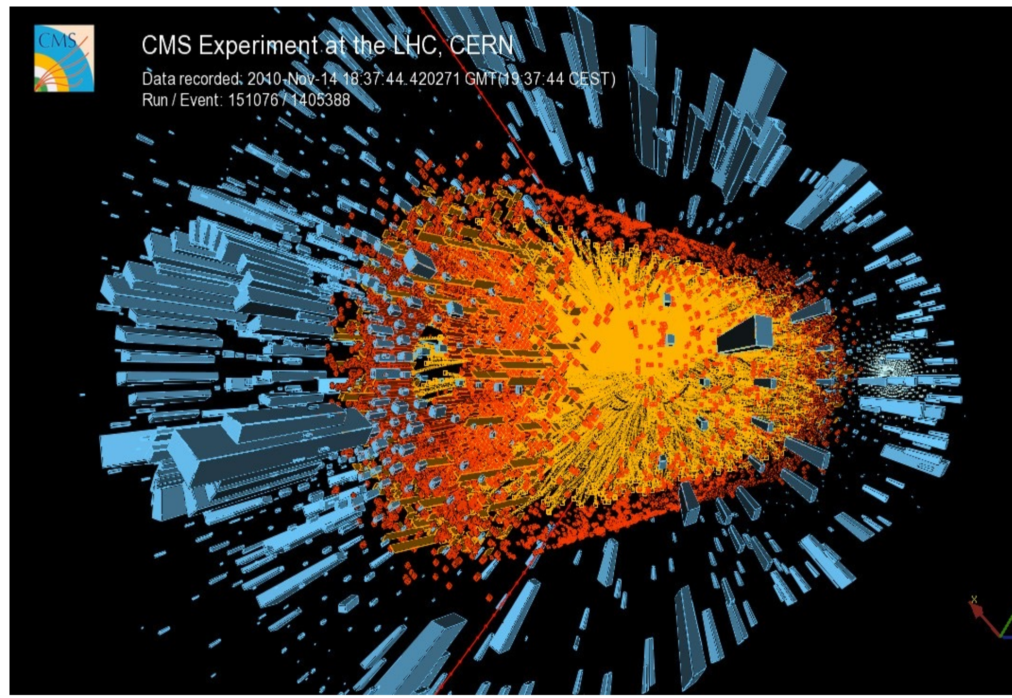
Spectacular events

Jet reconstruction in HI collisions?

STAR @ RHIC
Au+Au $\sqrt{s_{NN}}$ = 200 GeV/c



CMS @ LHC
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV/c

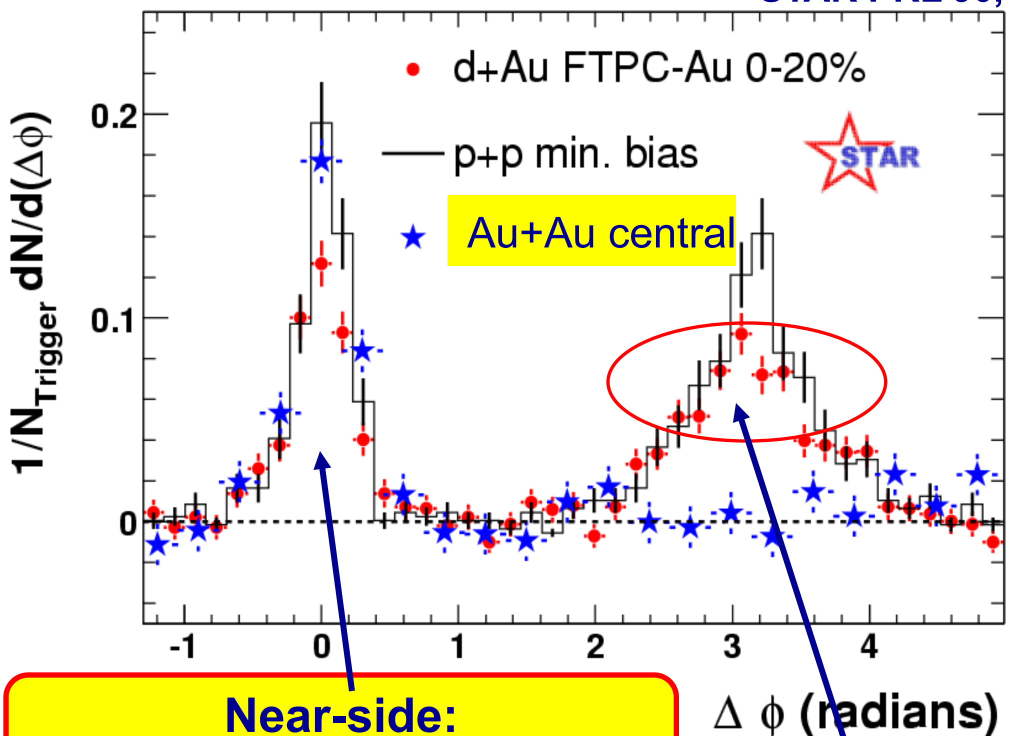


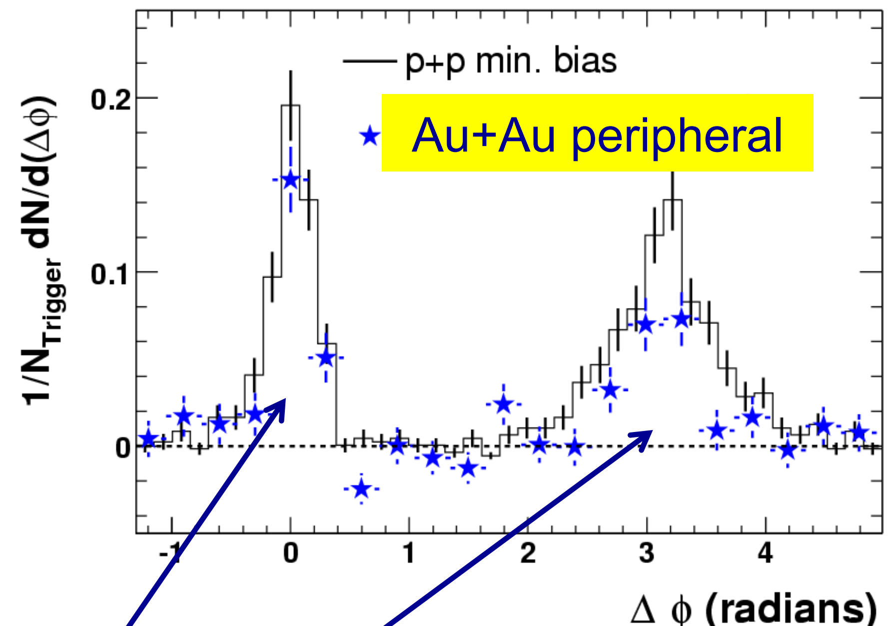
Jet quenching at RHIC

Azimuthal correlations in Au+Au

Trigger 4 < p_T < 6 GeV/c, associated particle p_T > 2 GeV/c

STAR PRL 90, 082302 (2003)





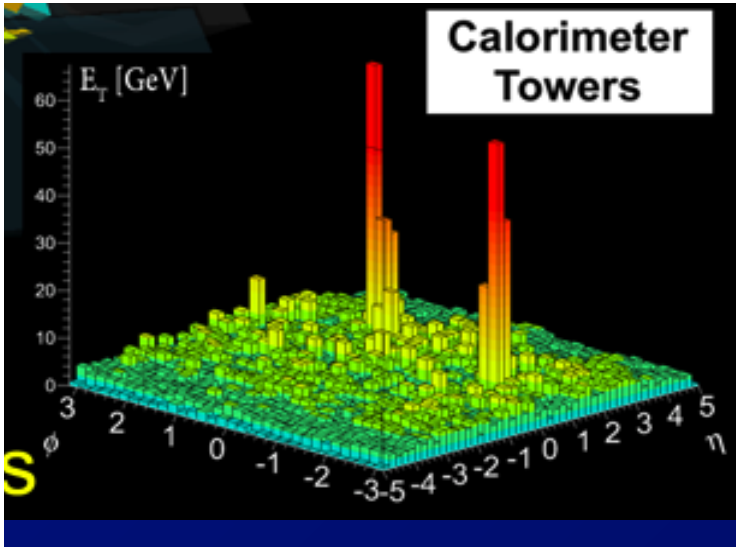
Near-side:
central AuAu similar to pp

Near and away side peaks similar in p+p and peripheral AuAu

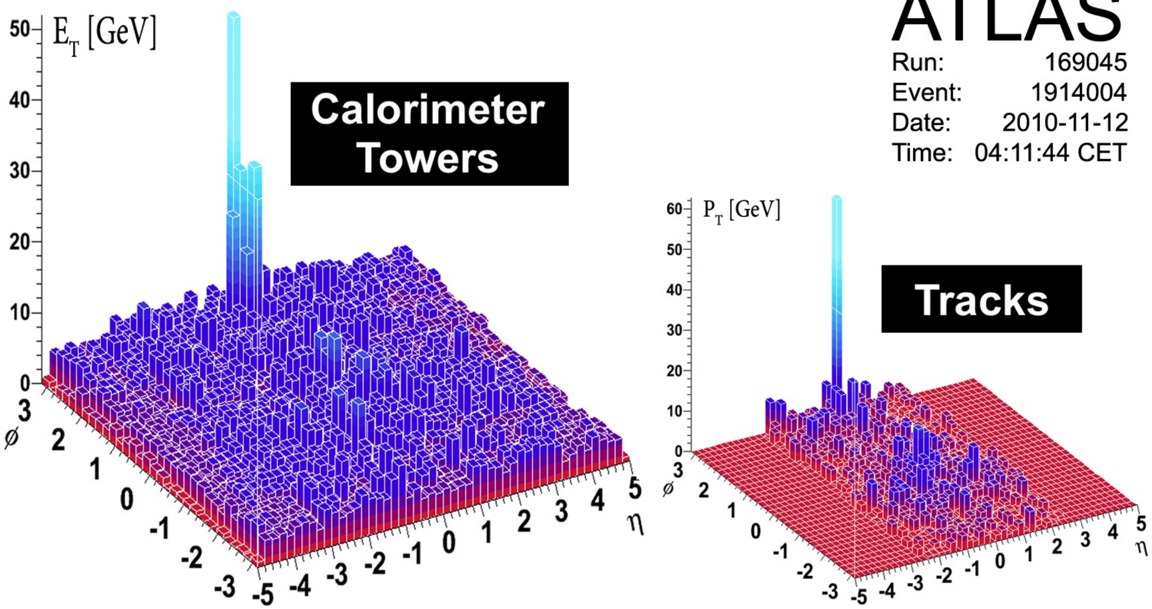
Away side:
Partner is *completely absorbed* in the dense medium in central AuAu
(Not a cold nuclear matter effect)

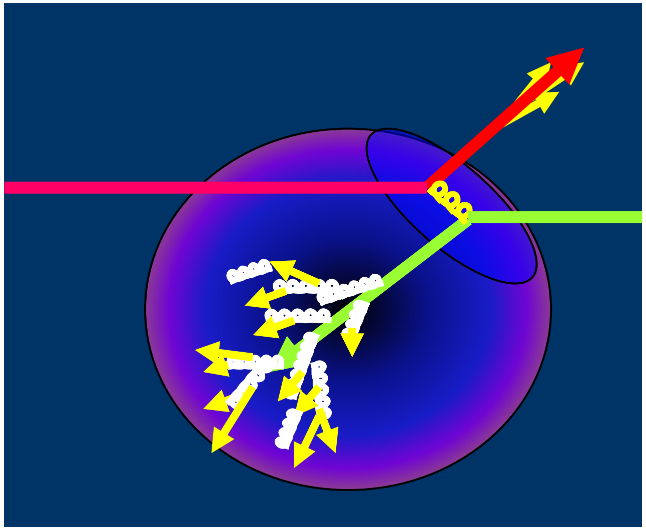
Jets at LHC

ATLAS: two jet event



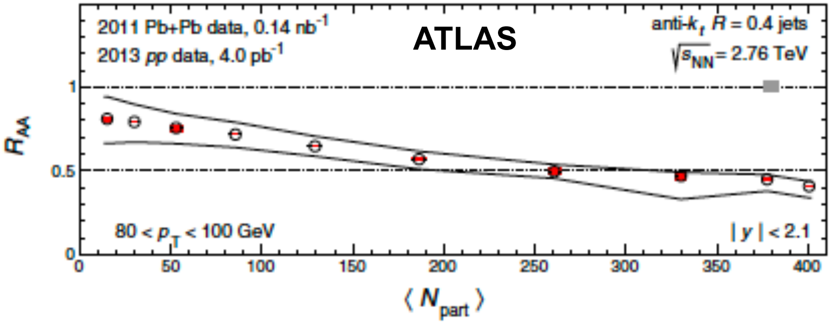
ATLAS: single jet event



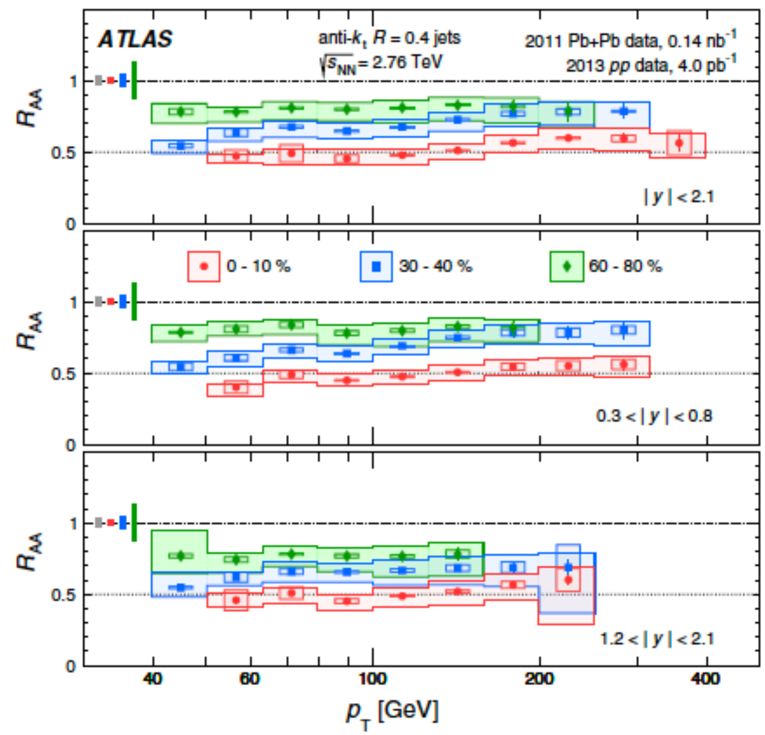


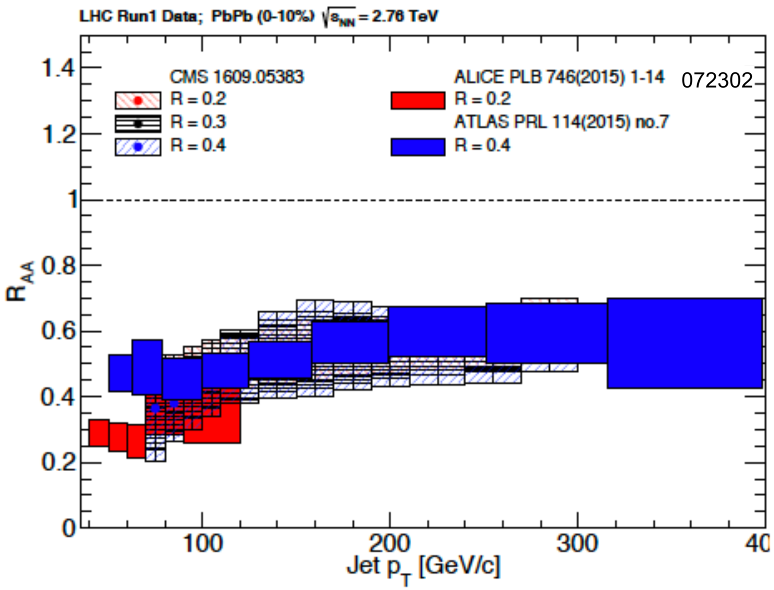
Medium is opaque

Jets - R_{AA}



PRL 114, 072302 (2015)





R_{AA} monotonically decreases with N_{part}

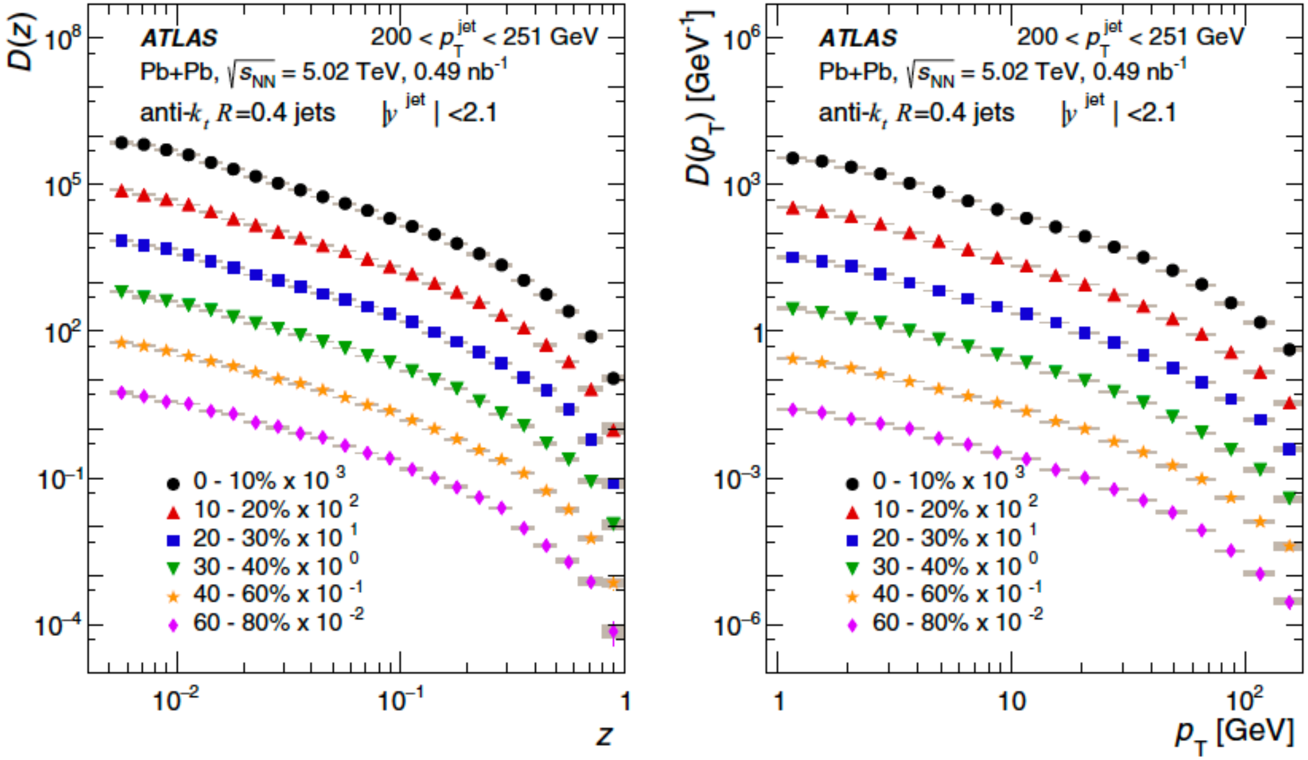
Jet yield suppressed in central collisions by about a factor of 2

Suppression level independent of jet energy

Suppression level independent of rapidity

Fragmentation Functions

PRC 98, 024908 (2018)



- Fragmentation function

$$D(p_T) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dp_T^{ch}}$$

$$D(z) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$

where z is the longitudinal momentum fraction:

$$z = \vec{p}_T \cdot \vec{p}_T^{\,jet} / |\vec{p}_T^{\,jet}|^2$$
$$= \frac{p_T}{p_T^{jet}} \cos \Delta R$$

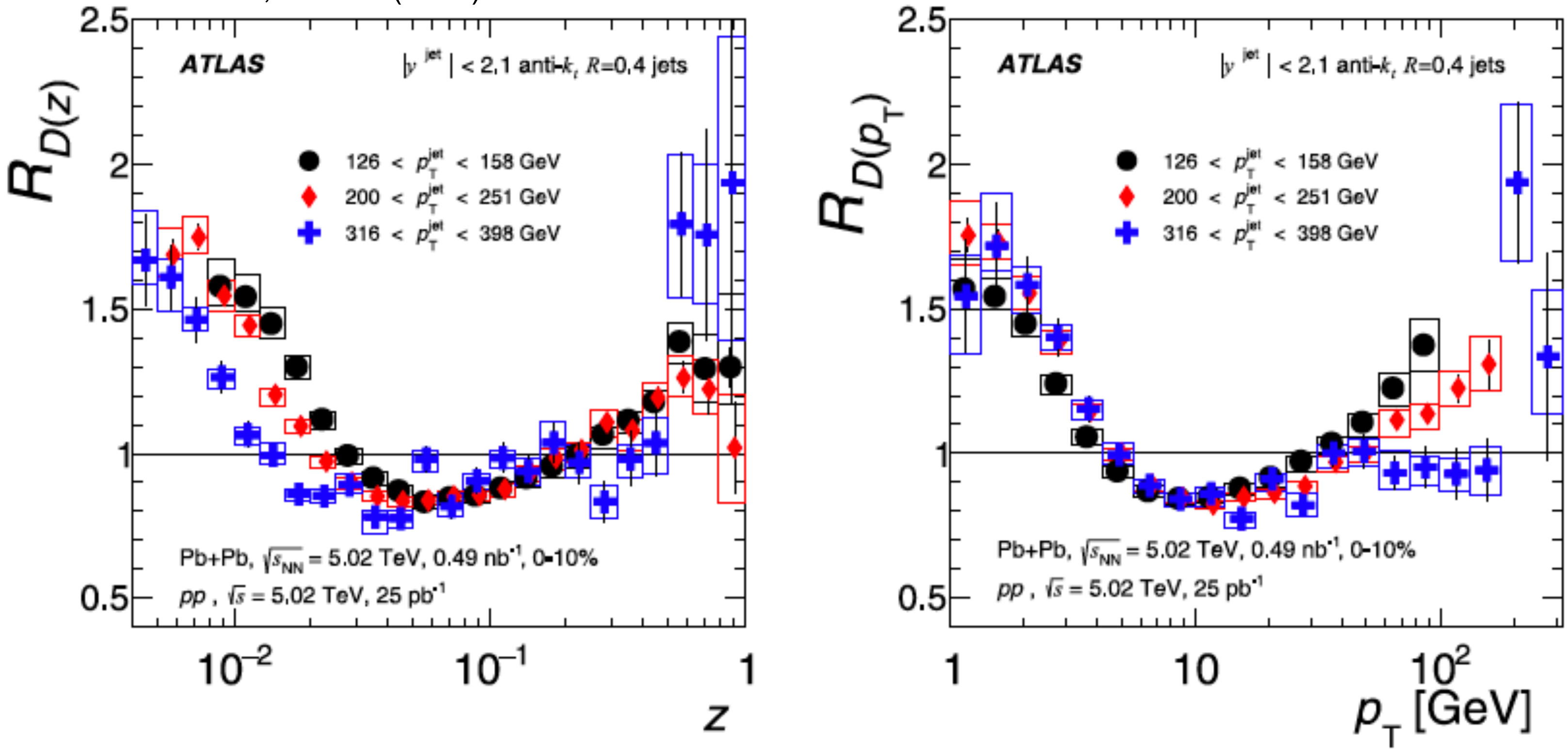
$$\Delta R = \cos\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- To quantify possible modifications of the fragmentation functions take the ratio to the same quantity in pp collisions:

$$R_{D(z)} = \frac{D(z)_{PbPb}}{D(z)_{pp}} \qquad R_{D(p_T)} = \frac{D(p_T)_{PbPb}}{D(p_T)_{pp}}$$

Modifications of Fragmentation Functions

PRC 98, 024908 (2018)



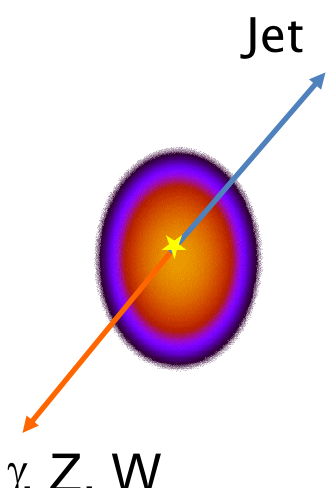
Significant modifications of the FF in central collisions:

- **Enhancement of soft fragment yield for p_T < 4 GeV**
- **Enhancement of hard fragments at z > 0.3**
- **Suppression between these two enhancements**

The golden channels:

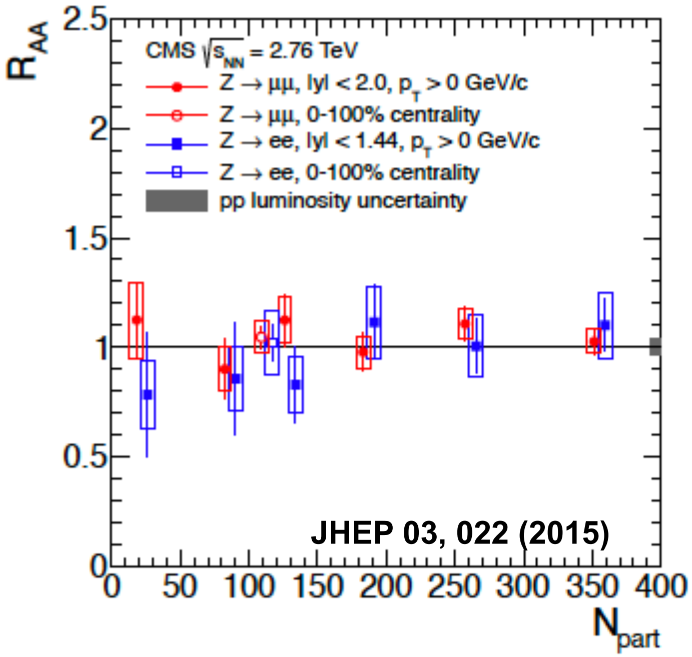
- Calibrated Probes:

  γ, Z, W – Jet



- γ, Z, W unmodified by the medium. Provide direct information about the initial parton energy
- γ measurements difficult due to large background
- Z, W are practically background free, but need high luminosity

Electroweak Probes

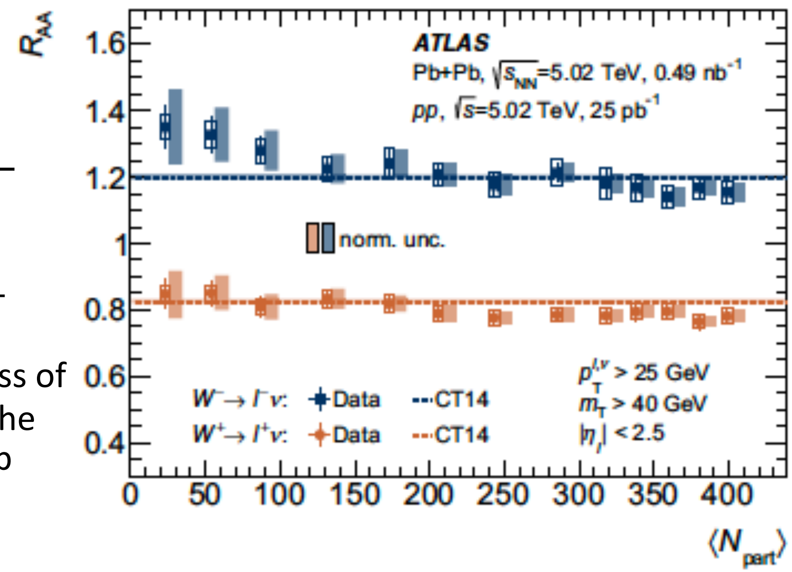


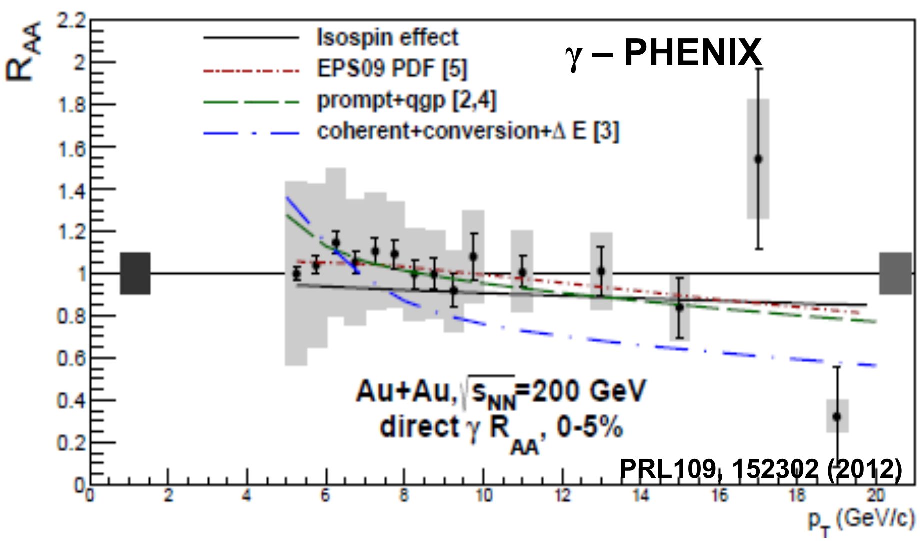
$$d + \bar{u} \rightarrow W^-$$

$$u + \bar{d} \rightarrow W^+$$

Isospin effect: excess of d quarks due to the excess of n in Pb

EPJ C79, 935 (2019)





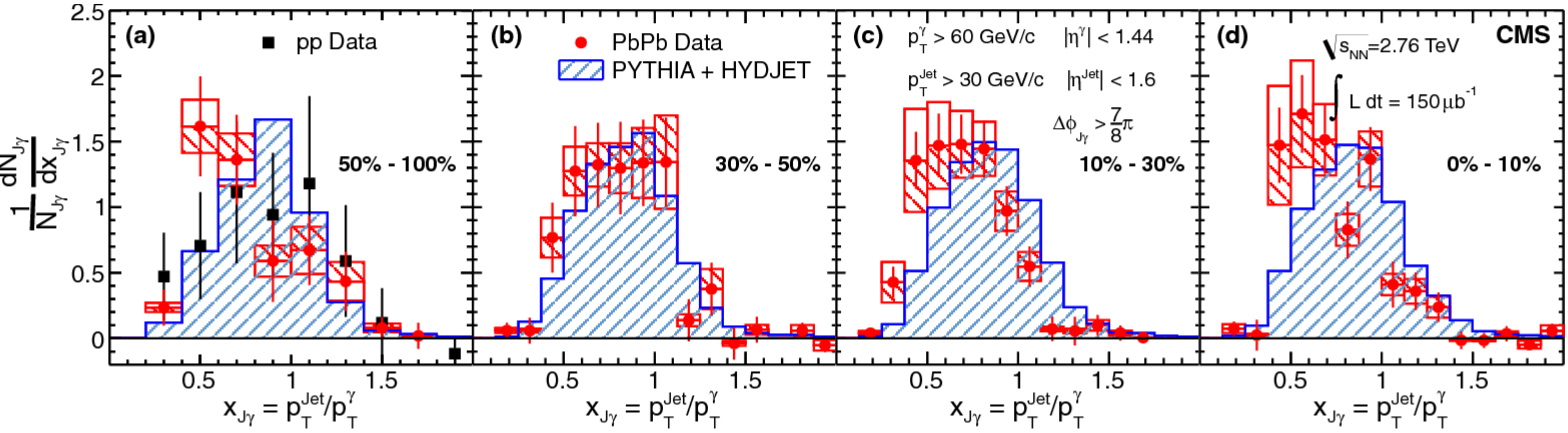
- Binary scaling

First measurements

γ-Jet Momentum Balance

$p_T^\gamma > 60$ GeV/c $|\eta| < 1.44$ $p_T^{Jet} > 30$ GeV/c $|\eta| < 1.6$

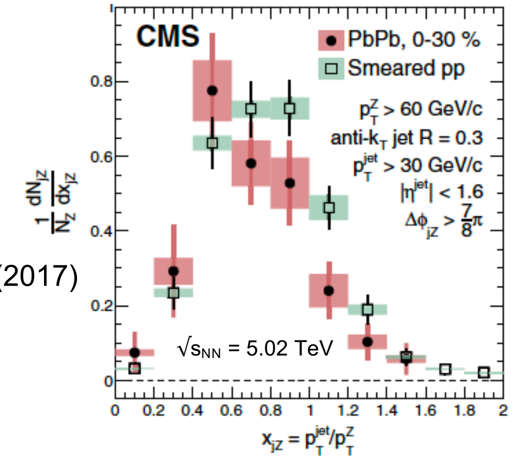
PLB 718, 3 (2013)



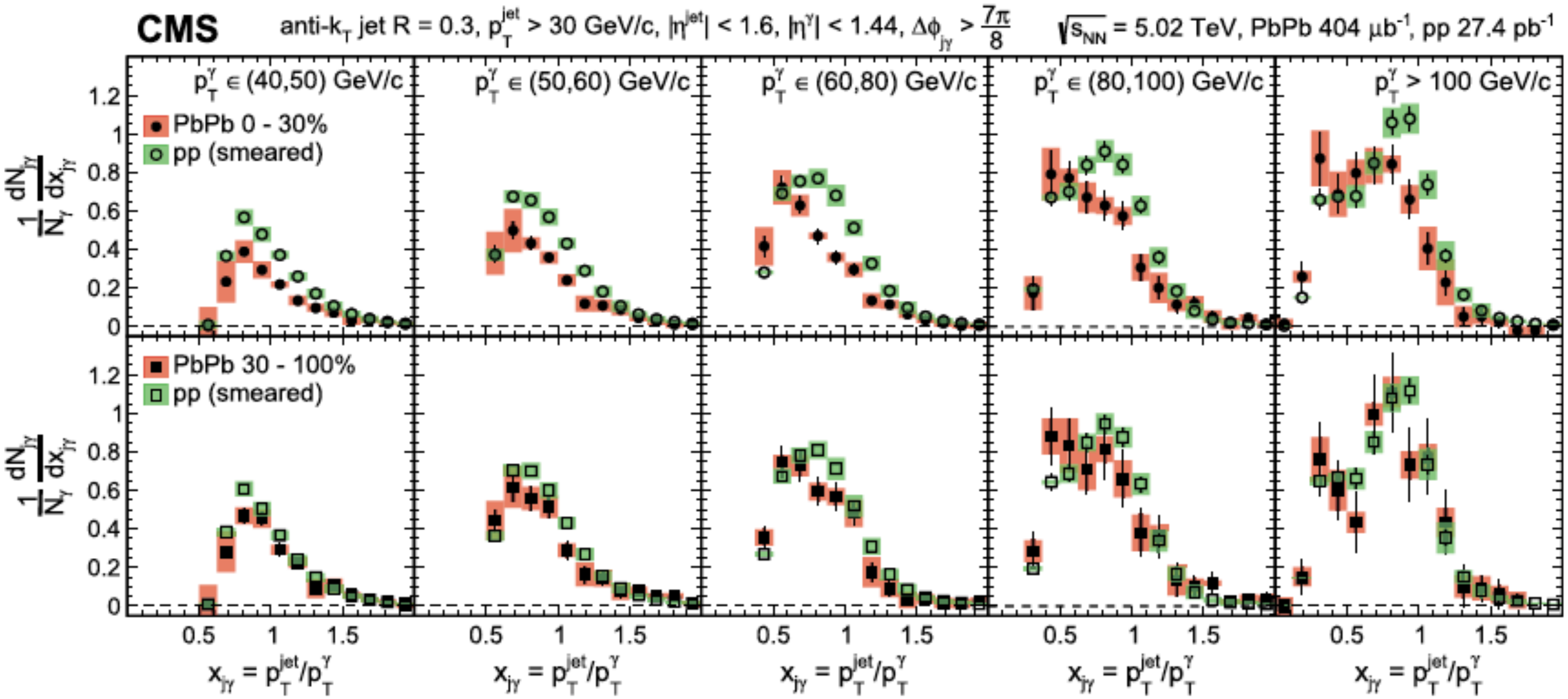
Z-Jet Momentum Balance

- Momentum ratio distribution shifts and decreases with centrality in γ-Jet
- Same trend in Z – jet but uncertainties too large.

PRL 119, 082301 (2017)



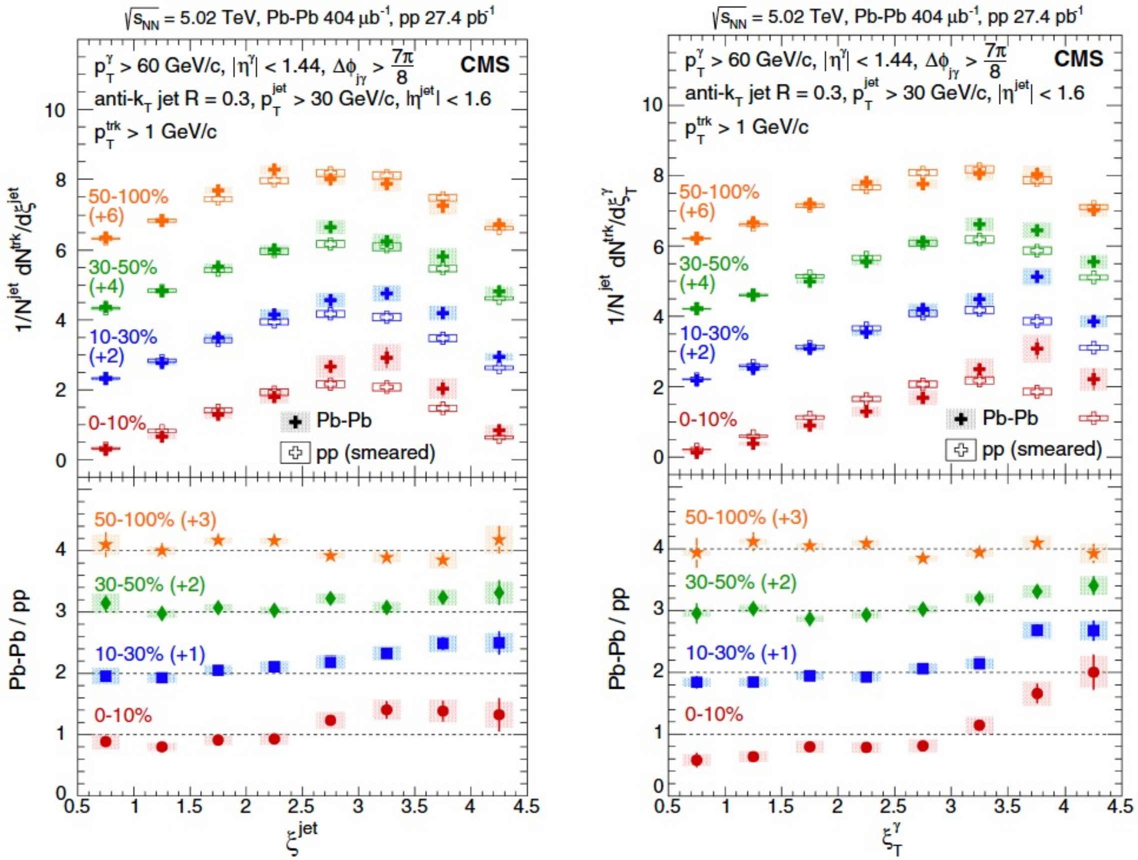
γ-Jet Momentum Balance



PLB 785, 14 (2018)

- Quantify the γ-jet p_T imbalance with the asymmetry ratio $x_{j\gamma} = p^{jet}_T/p^{\gamma}_T$
- Significant modifications (lower mean and smaller integral values) in 0-30% centrality PbPb collisions
- Much smaller modifications in the 30–100% centrality PbPb collisions.

γ-Jet Fragmentation Function



PRL 121, 242301 (2018)

$$\xi_T^\gamma = ln\,[-|\vec{p}_T^{\,\gamma}|^2/(\vec{p}_T^{\,trk}.\,\vec{p}_T^{\,\gamma})]$$

$$\xi^{jet} = ln\,[|p^{jet}|^2/(\vec{p}^{\,trk}.\,\vec{p}^{\,jet})]$$

N^{jet} number of γ-jet pairs

- For peripheral collisions, 50-100% centrality, Pb-Pb consistent with pp.
- In more central collisions:
  - Enhancement of the FF in Pb-Pb collisions with respect to the pp reference data for $\xi^{jet} > 2.5$ - 3 (low-p_T tracks)
  - Small suppression for $0.5 < \xi^{jet} < 2.5$ - 3 (high-p_T tracks).
  - Effects more pronounced in the ξ_T^γ distribution.

Unbiased characterization of the parton energy loss in the medium

Outlook

- At the high energy frontier (LHC and RHIC till 2025):
  - Focus the experimental efforts on precision measurements to characterize the properties of the QGP.

- At the low energy frontier (STAR-BESII, NICA and FAIR):
  - Explore the QCD phase diagram in the region of high baryon density
  - Search for the conjectured critical point and 1st order phase transition
  - Search for the onset of deconfinement and CSR phase transition(s).