NEW PHENIX DIELECTRON RESULTS IN AU+AU COLLISIONS

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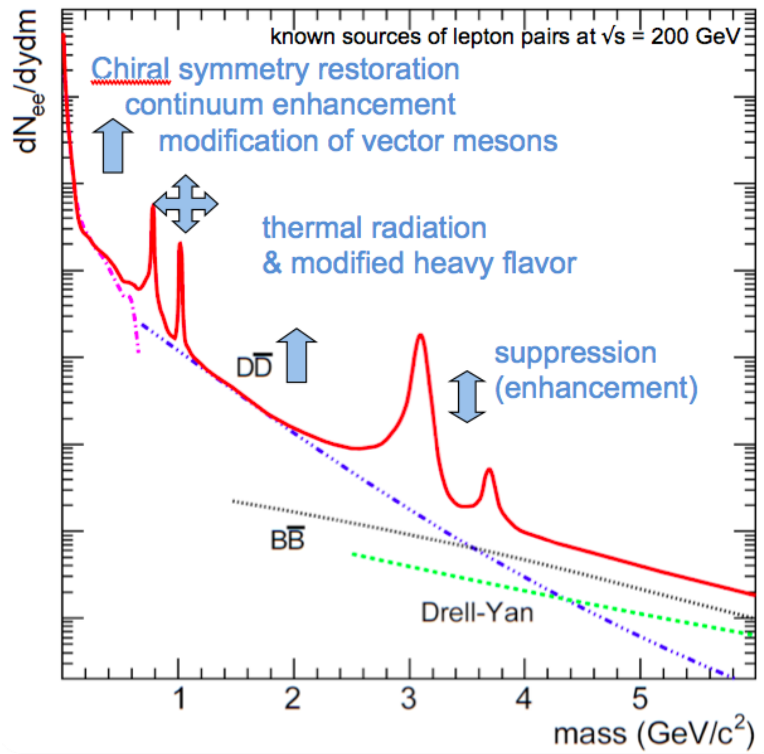
Outline

- Introduction
- The Hadron Blind Detector
- Analysis
  - Electron identification
  - Background subtraction
  - Cocktail of hadronic sources
- Results
- Comparison to model
- Summary

Dileptons

Known sources of dielectrons at $\sqrt{s_{NN}} = 200\,\text{GeV}$

- Dalitz decays of π^0, η, η', ω
- Direct decays of ρ, ω, ϕ
- Charm (beauty) production
- Drell-Yan



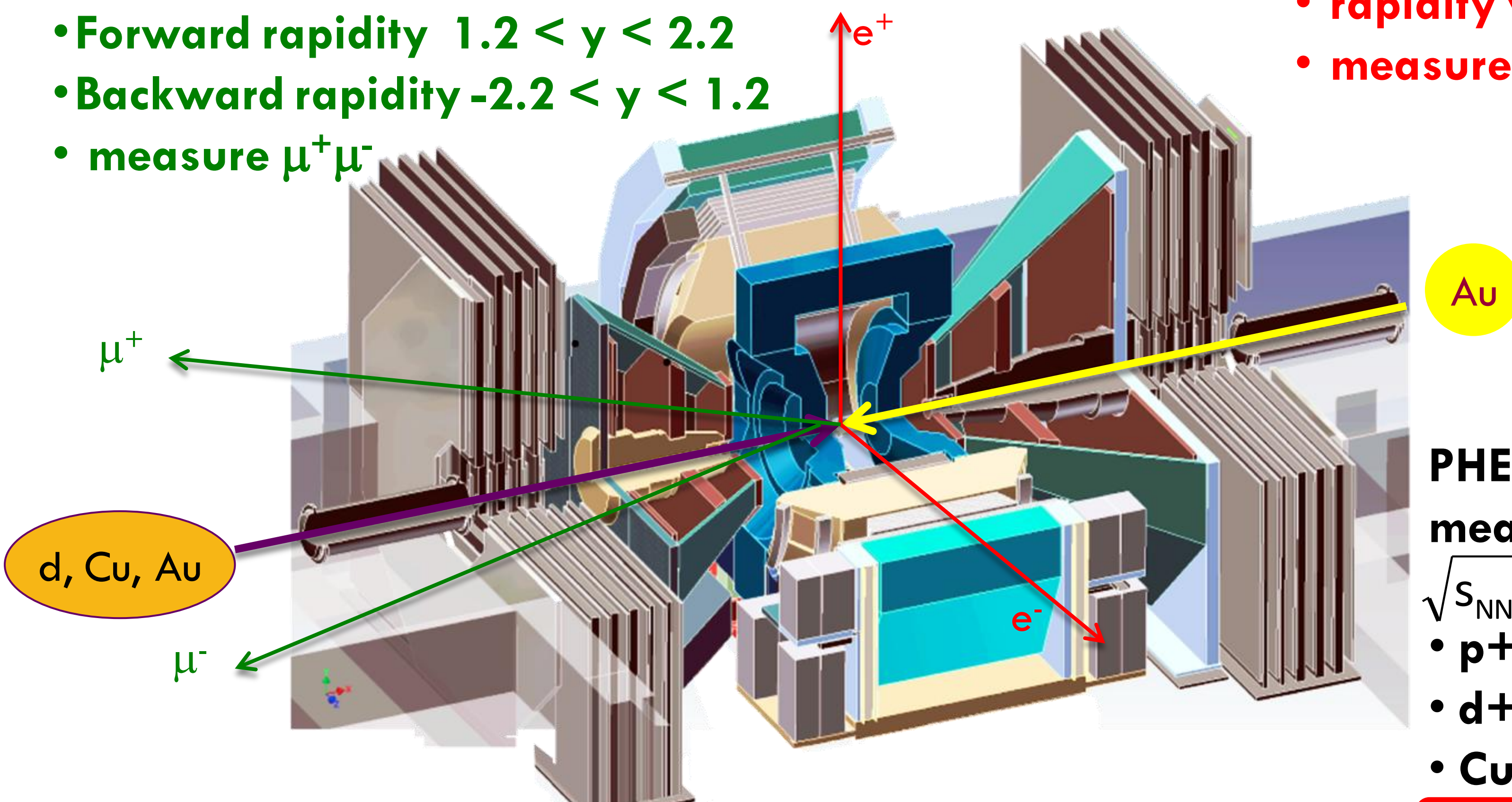
- **Modifications to the dilepton spectrum due to the QCD phase transition:**
  - Change in the spectral shape of light vector mesons related to chiral symmetry restoration
  - Continuum enhancement related to QGP thermal radiation
  - Medium effects on hard probes - Heavy flavor energy loss

Base-line measurements: p+p and d+Au

Dileptons in PHENIX

Muon Arms:
- **Forward rapidity 1.2 < y < 2.2**
- **Backward rapidity -2.2 < y < 1.2**
- **measure $\mu^+\mu^-$**

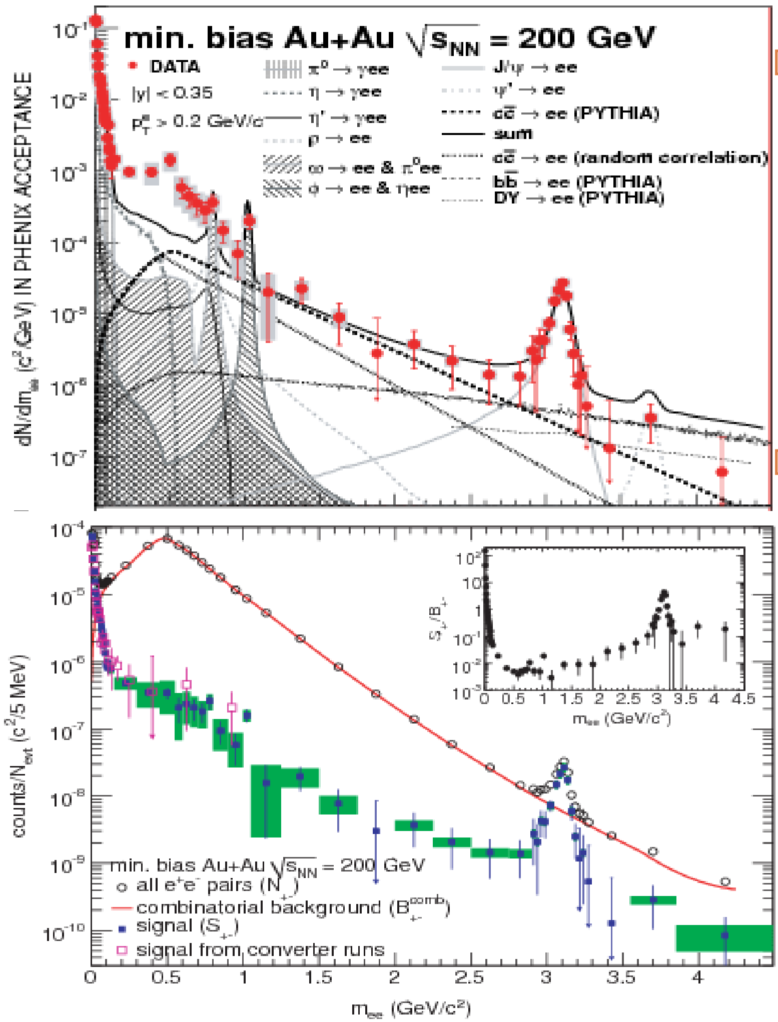
Central Arms:
- **rapidity y<|0.35|**
- **measure e^+e^-**



PHENIX dielectron measurements at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$:
- **p+p**
- **d+Au**
- **Cu+Cu**
- **Au+Au**

PHENIX dielectrons in Au+Au (2004 measurement)

PRC 81, 034911(2010)



- In RHIC Run-4 PHENIX observed a large e^+e^- enhancement in the low mass region
  - Could not be explained by the models
  - S/B background ratio ~1/200 in Min.Bias
  - Hadron contamination ~25% in Min. Bias
- STAR observed much smaller enhancement (RHIC Run-10) PRL113 022301 (2014)
- A new PHENIX measurement in RHIC Run-10 with the Hadron Blind Detector to:
  - Reduce the hadron contamination
  - Improve the signal sensitivity

The main background in PHENIX

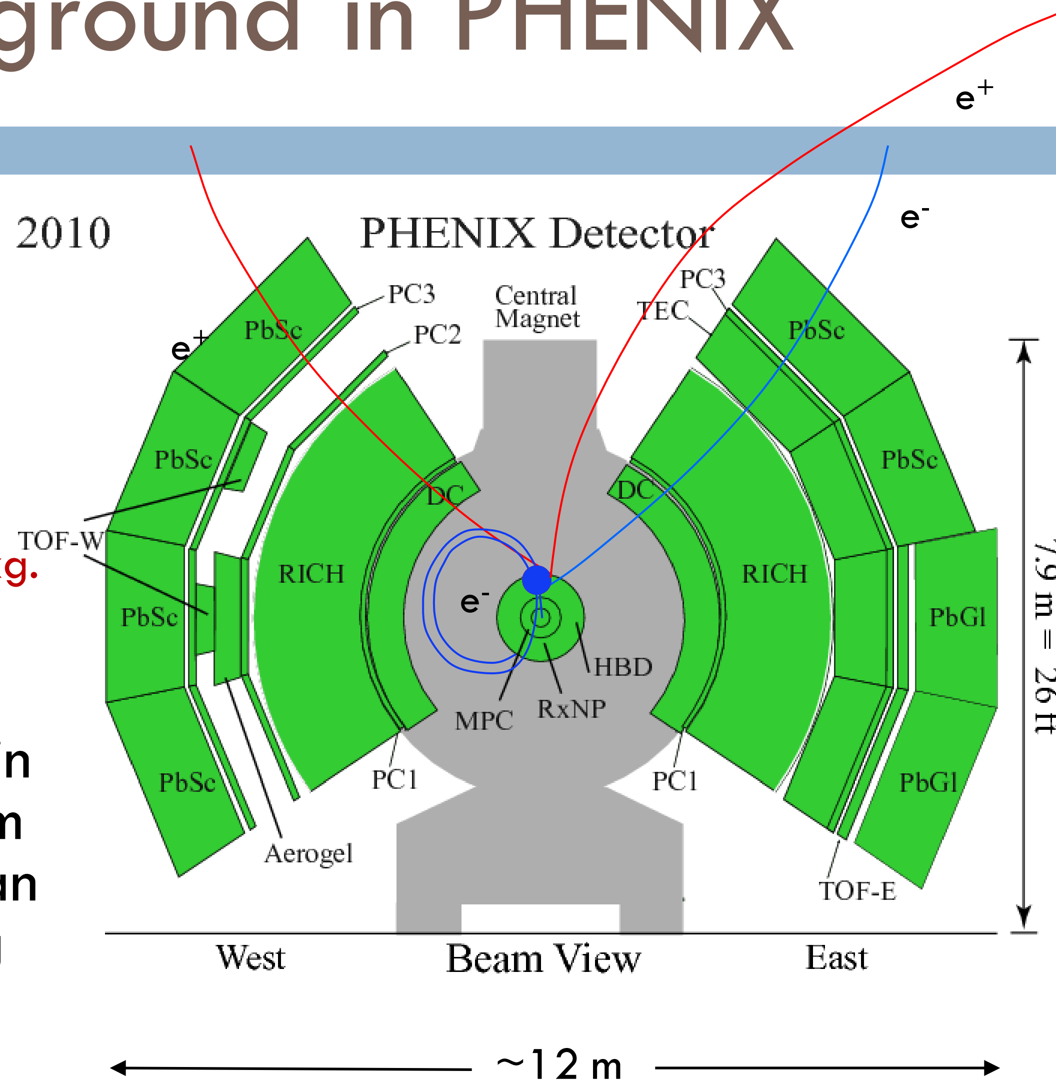
- The main sources of the <u>combinatorial background</u>:

$$\pi^0 \rightarrow \gamma\,\gamma \rightarrow \gamma\, e^+\, e^-$$

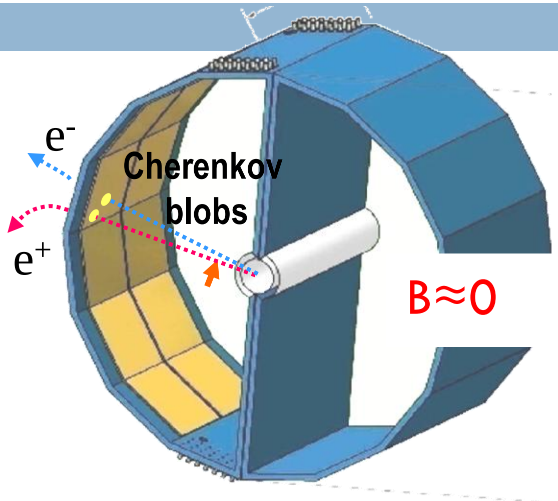
$$\pi^0 \rightarrow \gamma\, e^+\, e^-$$

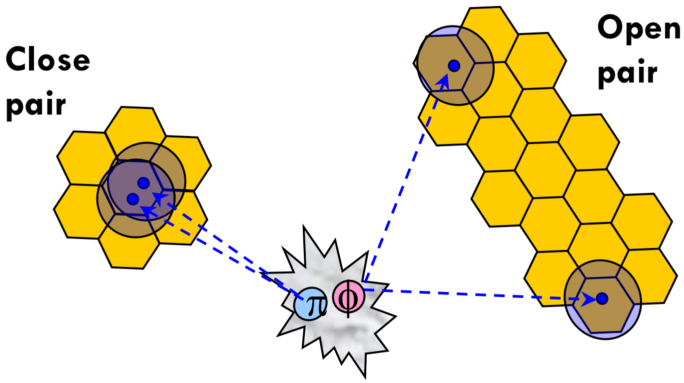
comb. backg. pair

- The magnetic field bends e^+e^- in opposite directions, one of them can go out of acceptance or can spiral not reaching the tracking detectors

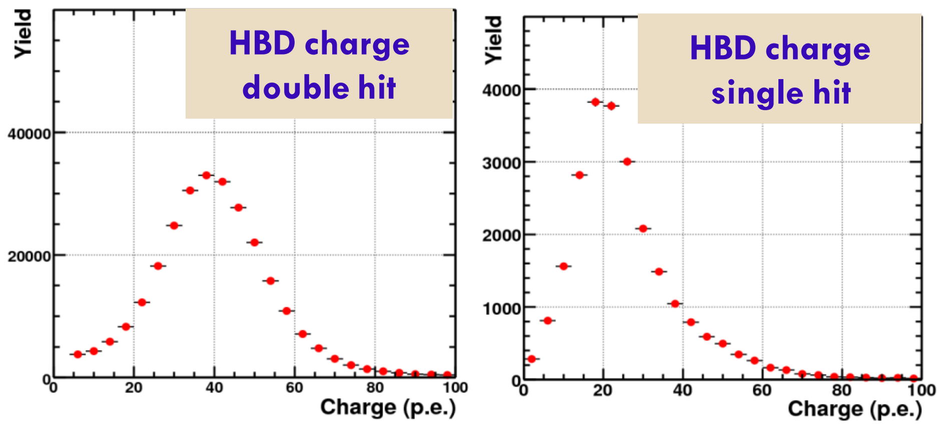


The Hadron Blind Detector





- Cherenkov detector using GEMs with CsI photocathode and CF_4 in a windowless configuration
  - Provides hadron rejection
  - Adds to eID capabilites
  - Suppresses bckg. e^+e^- pairs from π^0 Dalitz and γ conversions by their opening angle
  - Operates in magnetic field free region



NIM A646, 35-58 (2011)

Analysis

Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
RHIC Run-10

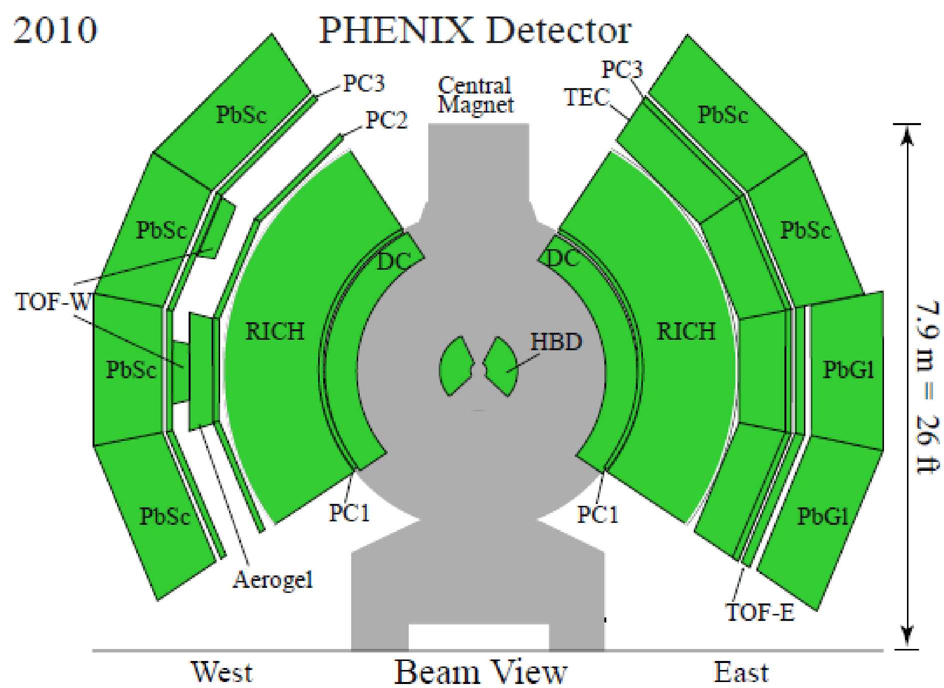
Electron identification

Background subtraction

Cocktail of hadronic sources

Electron identification with neural networks

- RICH
- EMCAL
- HBD
- TOF
  - EMCAL
  - TOFE



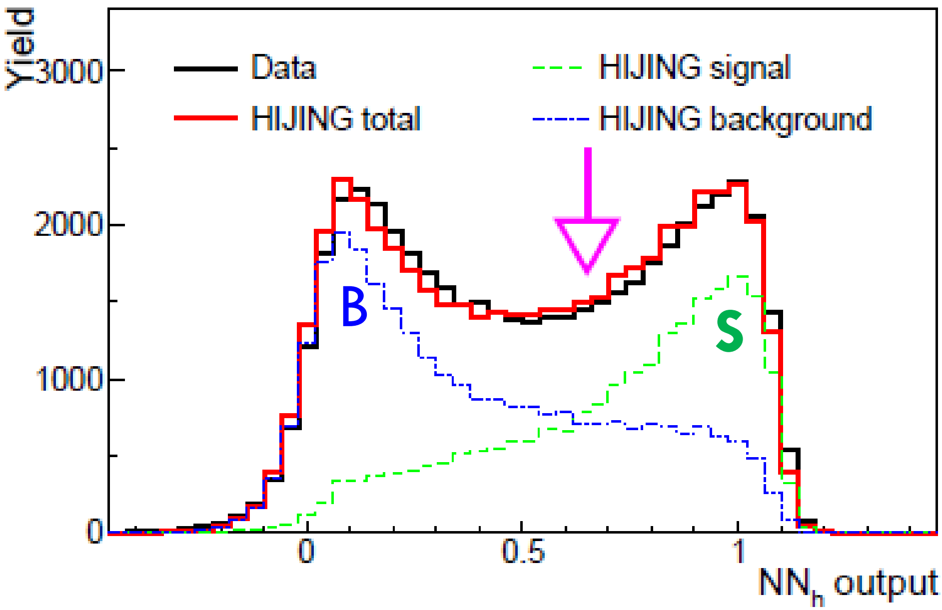
Electron identification with neural networks

- RICH
- EMCAL
- HBD
- TOF
  - EMCAL
  - TOFE

Total 14
eID parameters:

- Use as inputs to **neural networks**
- NNs trained and monitored by simulations
- **Achieve electron sample purity for all centralities ≥95%**

Example NN output for 0-10% centrality



Analysis

Electron identification

Background subtraction

Cocktail of hadronic sources

Background subtraction

Strategy – subtract component by component:

- Traditional approach:

  Total BG = mixed BG } **combinatorial**

  + jet pairs
  + cross-pairs } **correlated**

  → could not reproduce the shape of the like-sign foreground

  → essential elements missing

Background subtraction

Strategy – subtract component by component:

- Traditional approach:

  Total BG = mixed BG } combinatorial

  + jet pairs

  + cross-pairs } correlated

  → could not reproduce the shape of the like-sign foreground

  → essential elements missing

- New approach:

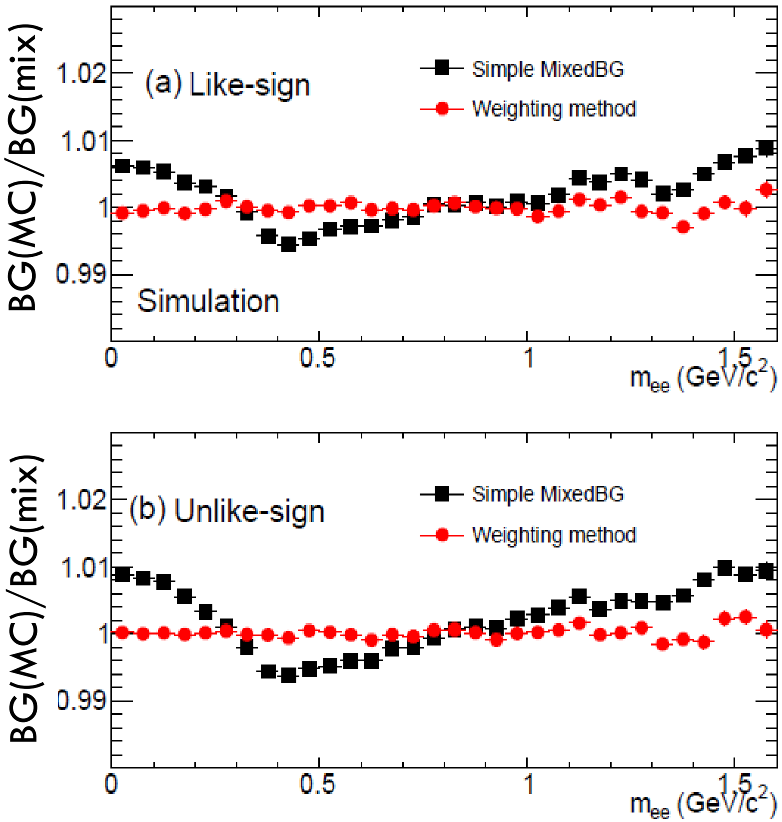
  Total BG = mixed BG with flow modulation } combinatorial

  + jet pairs

  + cross-pairs

  + e-h pairs } correlated

Mixed background with flow modulation



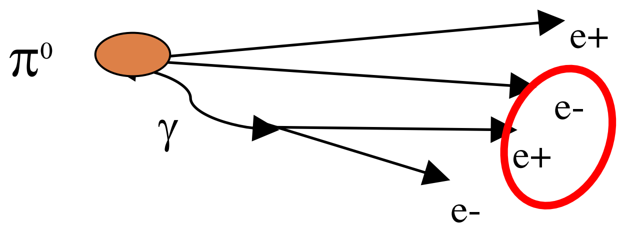
arXiv:1509.04667

- Flow distorts the shape of the combina-torial background
- To correct for the flow effect, each mixed BG pair is weighted by an analytic factor:

  $w(\Delta\varphi) = 1 + 2\, v_2(p_{T,1})\, v_2(p_{T,2})\, \cos(2\Delta\varphi)$

  - Inclusive single electron v_2 from the data
- The approach is verified by the simulation (plots on the left)
- The weighting method reproduces correctly the combinatorial background shape

Cross-pairs and jet pairs



- Simulated with EXODUS:
  $\pi^0 \rightarrow e^+e^-\gamma$, $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow e^+e^-\gamma$, $\eta \rightarrow \gamma\gamma$
- Normalization: **absolute**
  - π^0 and η measured by PHENIX

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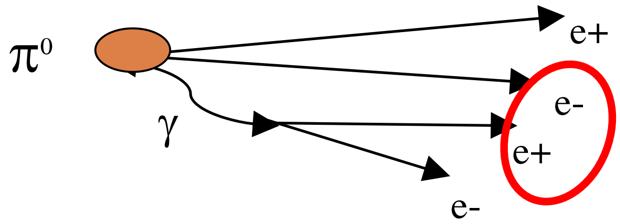

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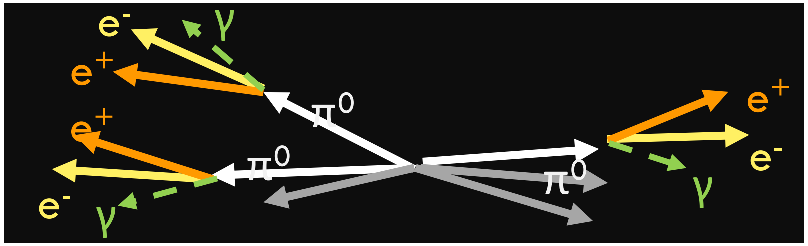
- Normalization: **absolute**
  - π^0 and η measured by PHENIX

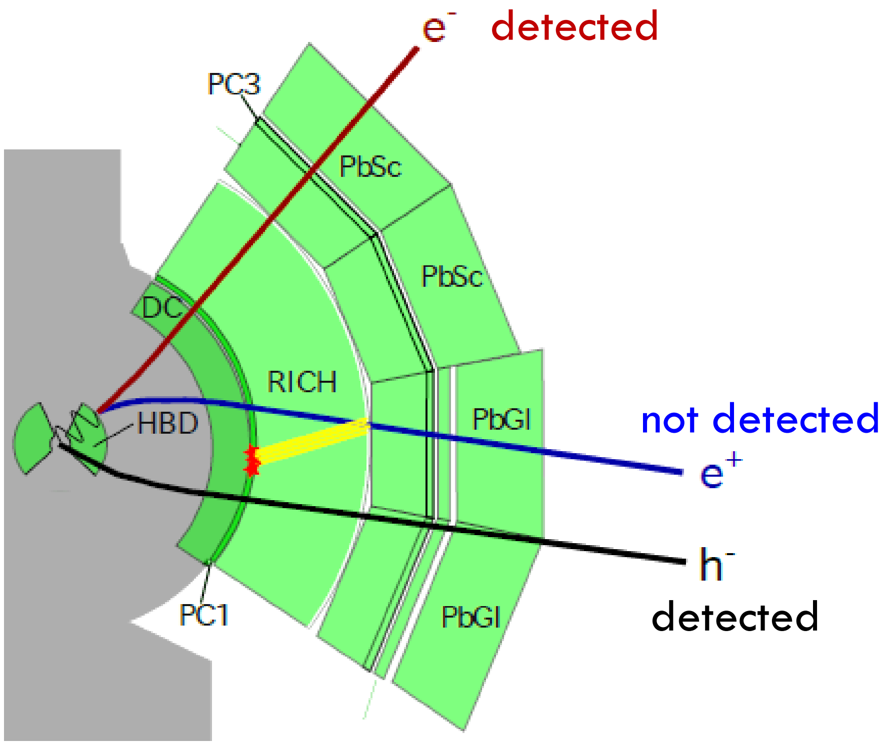
- Simulated with PYTHIA (p+p jets)
- Normalization: **absolute**
  - Each ee pair scaled by:

    $\mathbf{N_{coll} * R_{AA}(p_T^a) * I_{AA}(p_T^b, \Delta\phi)}$

    - p_T and $\Delta\phi$ refer to primary particles
    - a – the particle with the higher p_T, b – the particle with the lower p_T
    - R_{AA} and I_{AA} from PHENIX measurements



e-h pairs



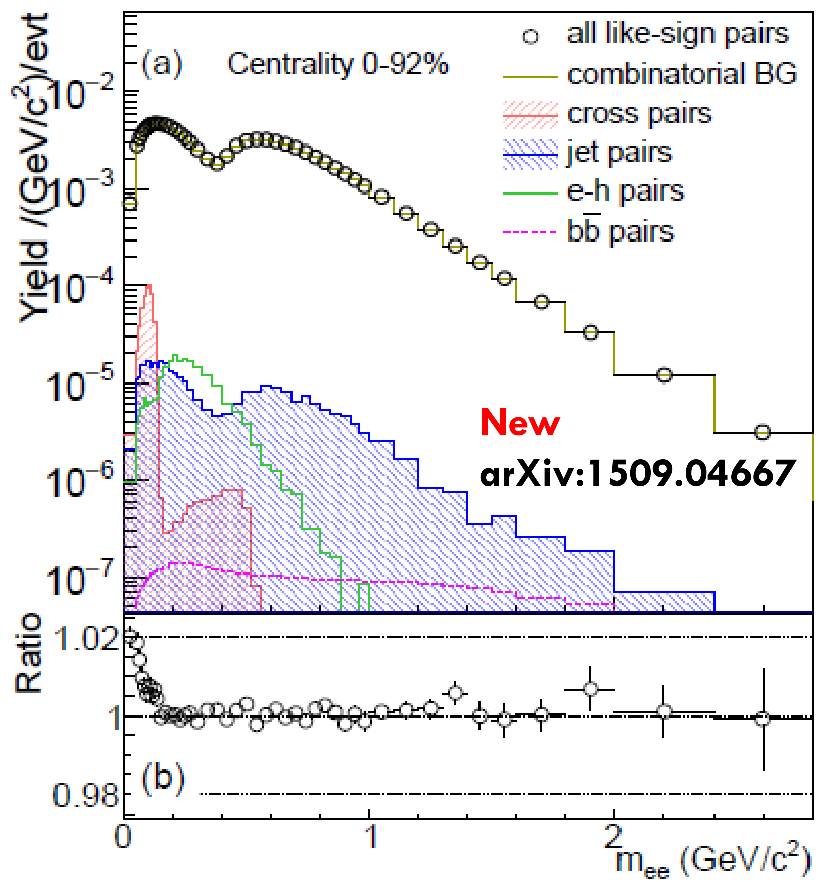
- RICH spherical mirror causes hit sharing of parallel tracks
- Direct e-h correlations, e.g. e^+h^-, can be detected by hit proximity and rejected
- Indirect correlations, e.g. e^-h^- cannot be detected → they are simulated and subtracted
- Normalization: **absolute** using PHENIX dN/dy of pions

Mixed background normalization

- Like-sign mixed BG normalization:
  - $FG_{++} = Cross_{++} + Jet_{++} + e\text{-}h_{++} + bb_{++} + \mathbf{nf_{++}} * mixBG_{++}$
  - $FG_{--} = Cross_{--} + Jet_{--} + e\text{-}h_{--} + bb_{--} + \mathbf{nf_{--}} * mixBG_{--}$
- All correlated components calculated on absulute terms
- $\mathbf{nf_{++}}$ and $\mathbf{nf_{--}}$ are determined as the fit parameters in the pair opening angle ($\Delta\phi_0$) region where the correlated backgrounds are smallest
- Unlike-sign normalization: $\mathbf{nf}_{+-} = \sqrt{\mathbf{nf}_{++} \cdot \mathbf{nf}_{--}}$

Quantitative understanding of the background

- Understanding of the background verified by the **like-sign** spectra
  - Correlated components absolutely normalized
  - Combinatorial background - mixed background with flow modulation
- The ratio of the like-sign foreground to total background, for m_{ee}>0.15 is **flat at 1**
- **Excellent quantitative understanding of the background**



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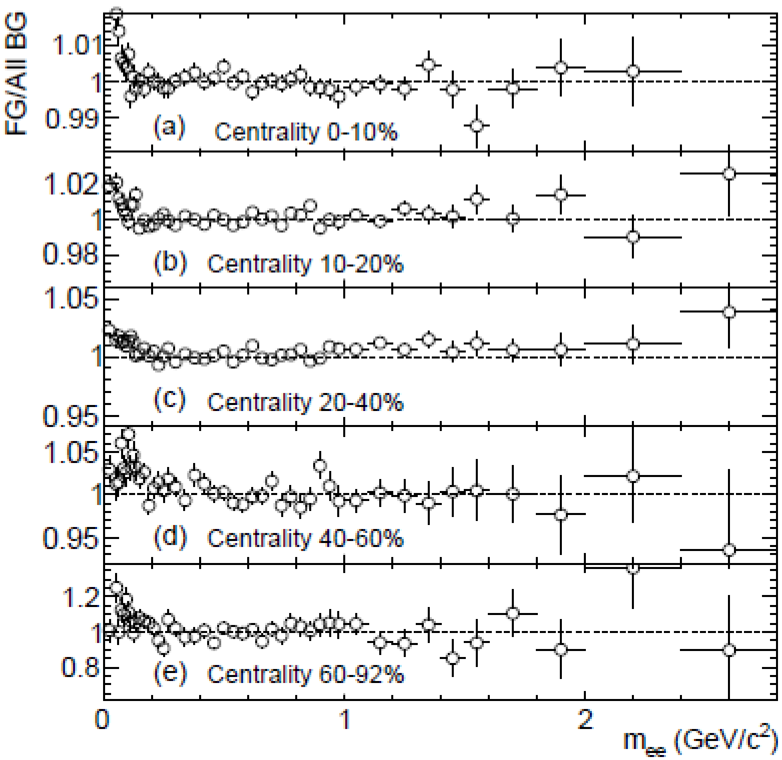
arXiv:1509.04667



Analysis

Electron identification

Background subtraction

Cocktail of hadronic sources

Cocktail of hadronic sources

- Dielectron and Dalitz decay of mesons simulated with EXODUS
  - π^0 parametrized using modified Haggedorn function
  - Other mesons(η, ω, ρ, ϕ, J/Ψ): use m_T scaling for the shape and meson to π^0 ratio at high p_T for absolute normalization

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- Semileptonic decays of open heavy flavor (c,b) simulated with PYTHIA and MC@NLO
  - Uncertainty in the charm cross-section and shape - PHENIX PRC 91, 014907 (2015)

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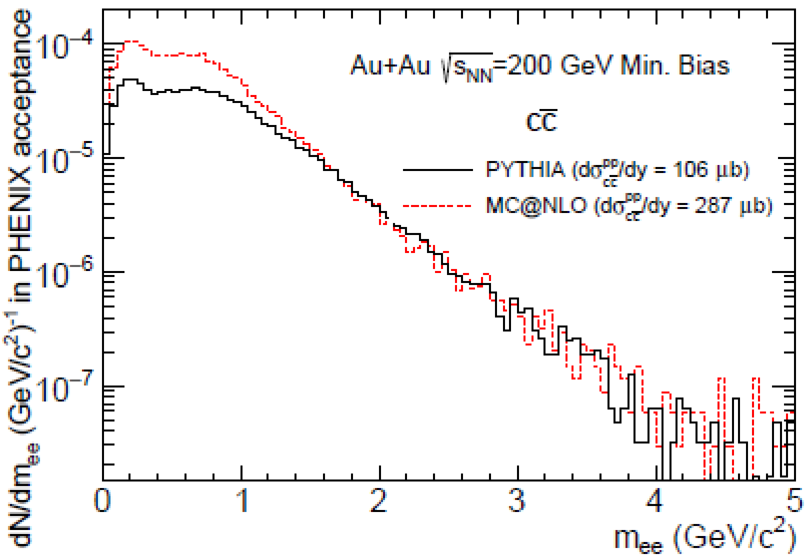

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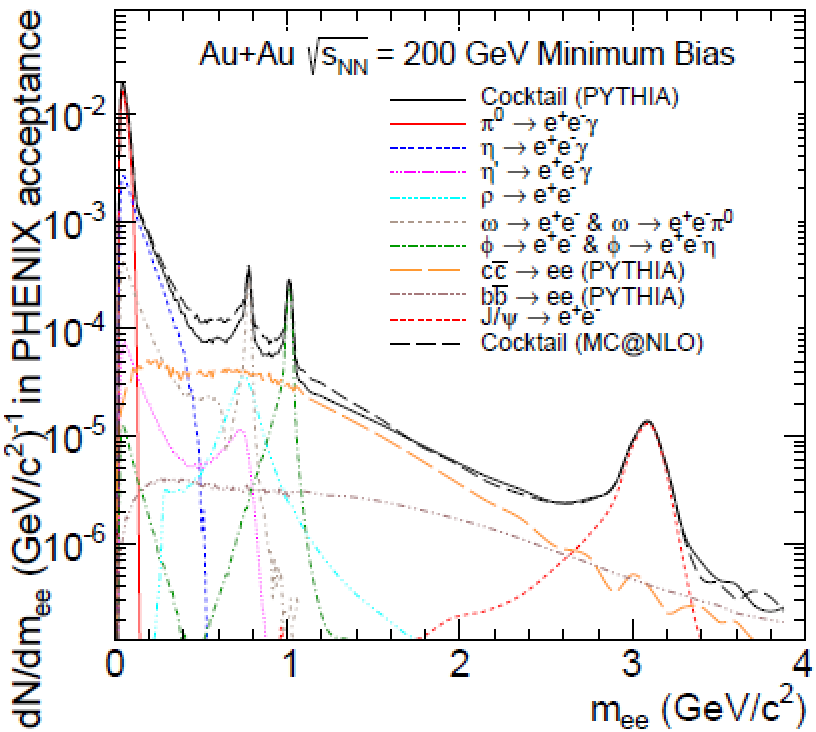
  → **PYTHIA cocktail** and **MC@NLO cocktail**
- Normalization
  - In m_{ee}<0.1 GeV/c^2 and p_T/m_{ee}>5
  - Normalize to measured $\pi^0 + \eta +$ direct γ

arXiv:1509.04667

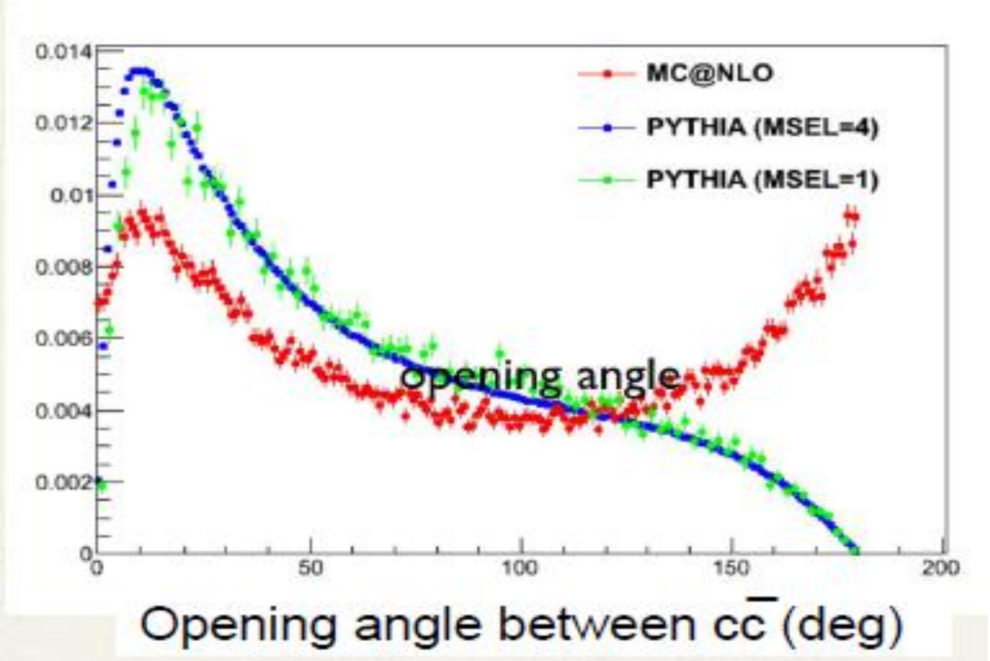


Simulating charm contributions

- Uncertainty in the cross-section and shape depending on MC@NLO or PYTHIA:
  - The cross-sections extracted from fit to dielectrons in d+Au in the *intermediate mass region* – both models decribe the data well (PRC 91, 014907 (2015))

• The two models differ in extrapolation to lower invariant masses caused by their different charm p_t and opening angle distributions

• The difference is more significant in Au+Au collisions where cc and bb contributions scale with N_{coll} while the other contributions scale with N_{part}



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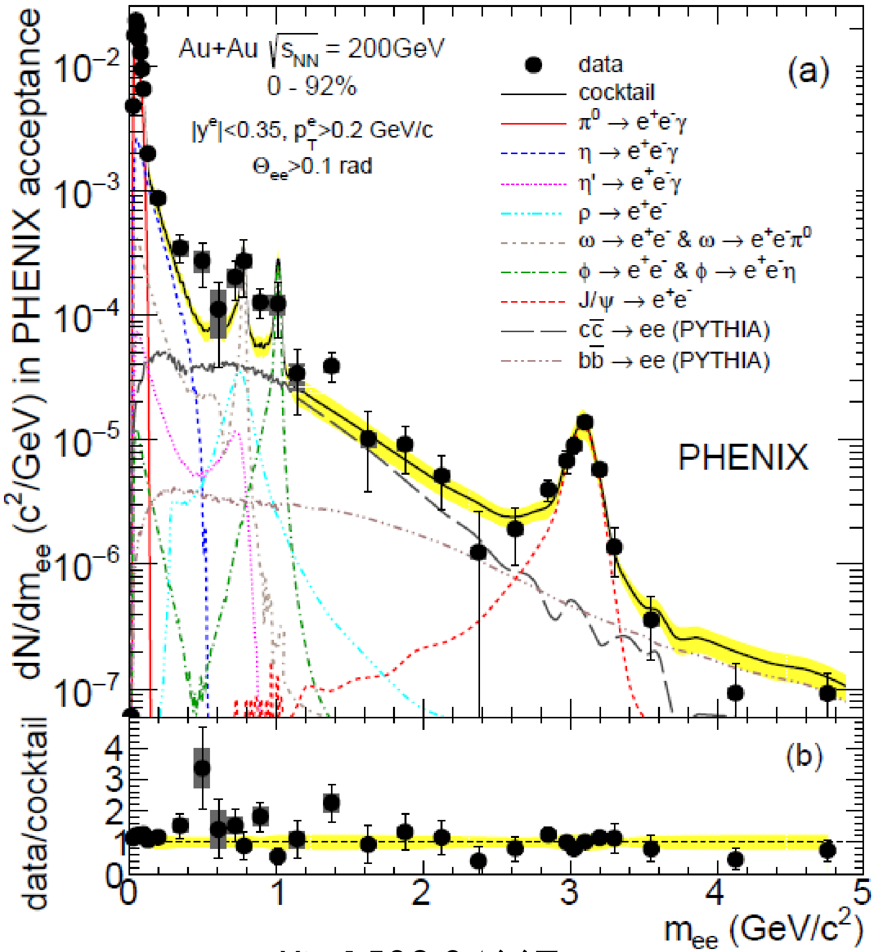
Results

Invariant mass spectra

Minimum bias



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Invariant mass spectra

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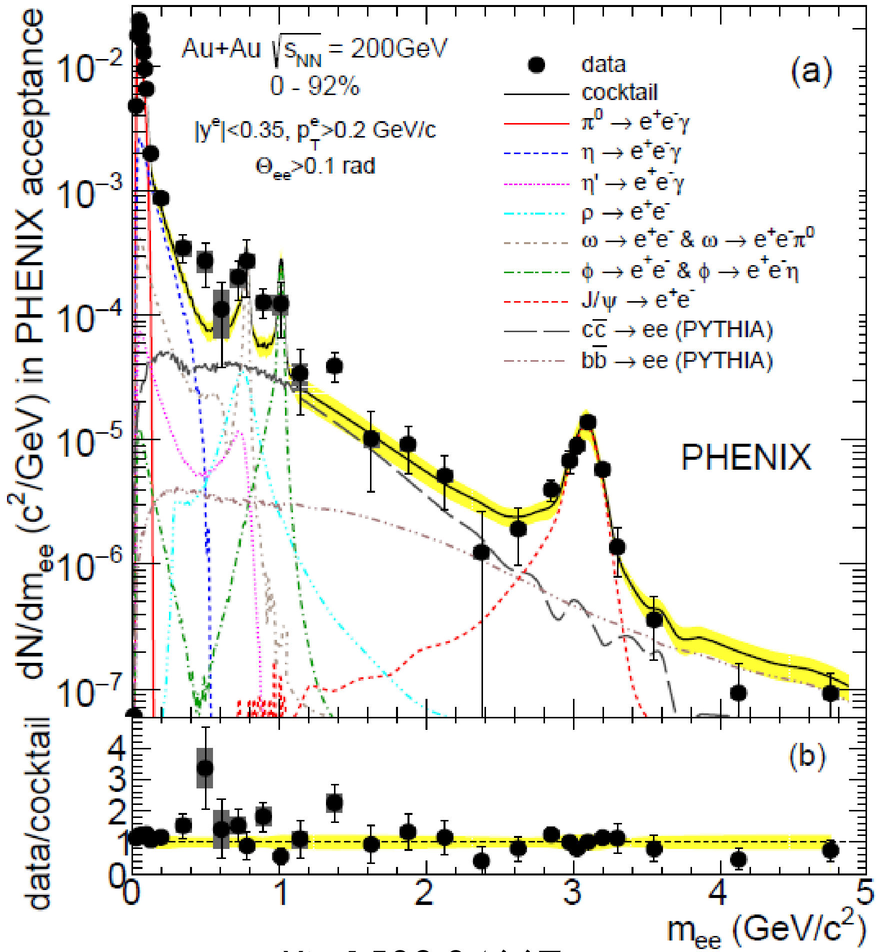

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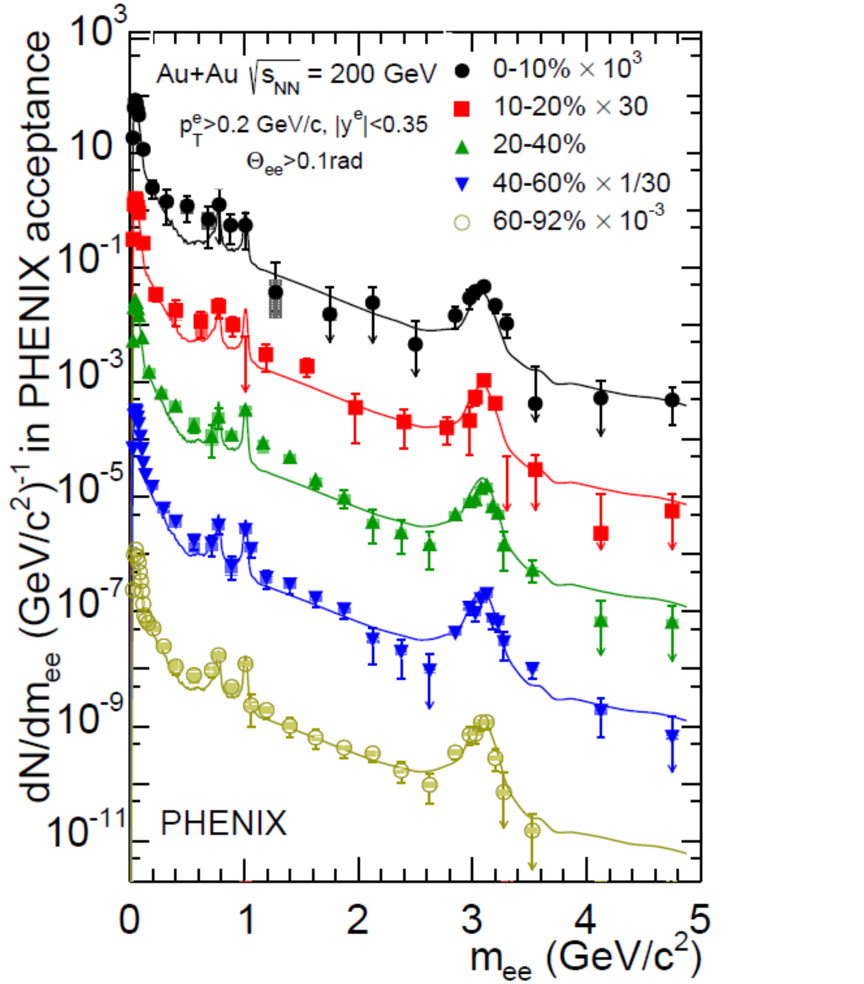
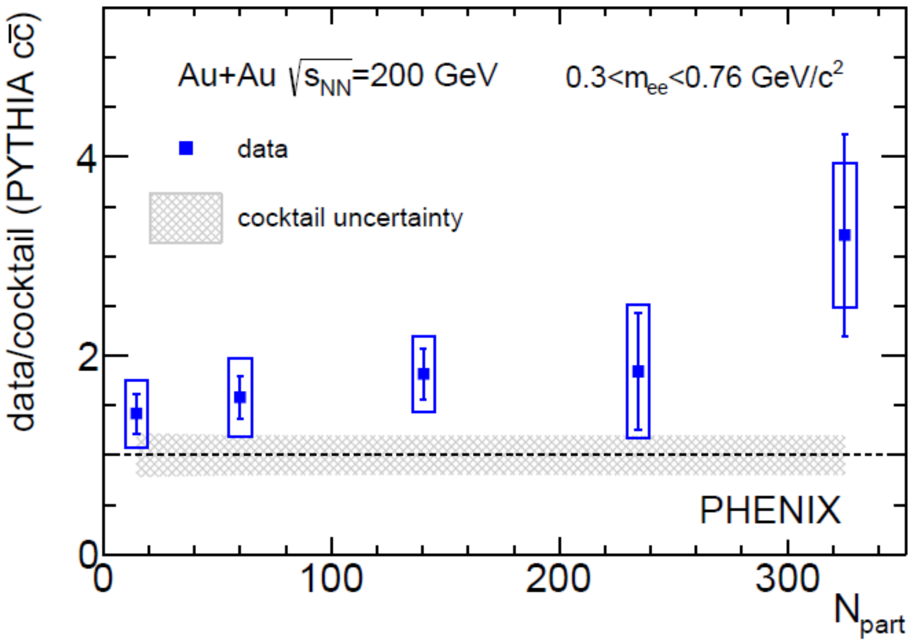
Centrality dependence



Integrated yields (LMR)

Low mass region

m_{ee} = 0.3-0.76 GeV/c^2



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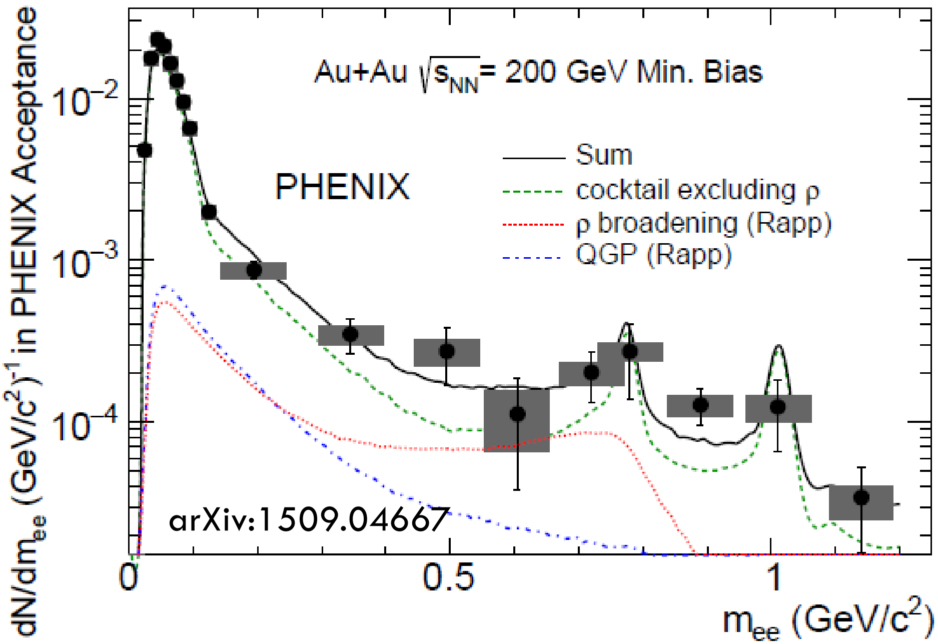
Data/cocktail in MB (±stat±syst± mod):

- ❑ Pythia: 2.3±0.4±0.4±0.2
- ❑ MC@NLO: 1.7±0.3±0.3±0.2

→ Compatible with STAR results: 1.76±0.06±0.26±0.33

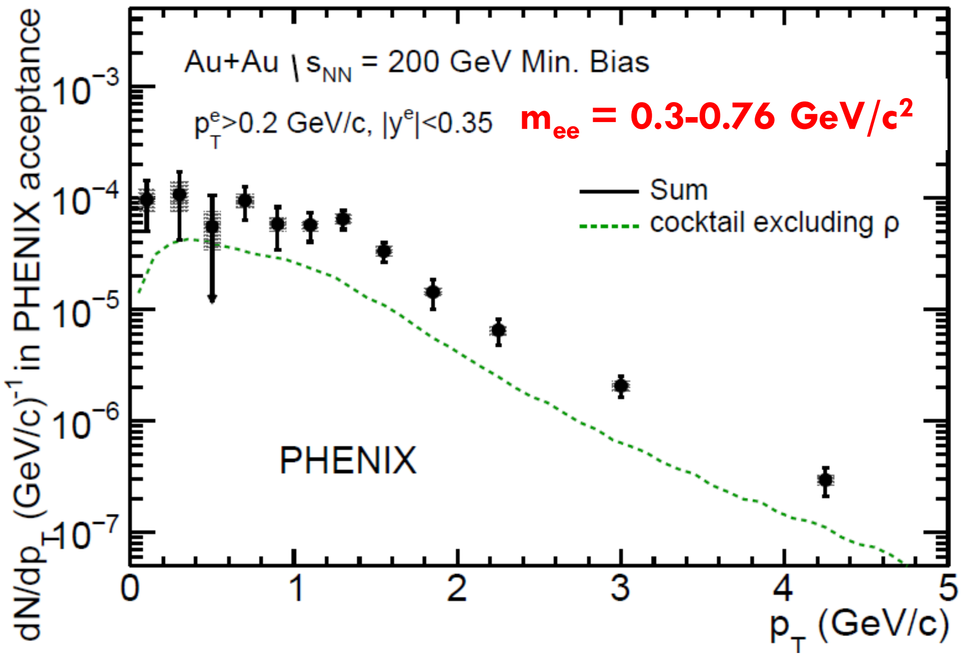
PRC92 (2015)024912

Comparison to model (Min. Bias)



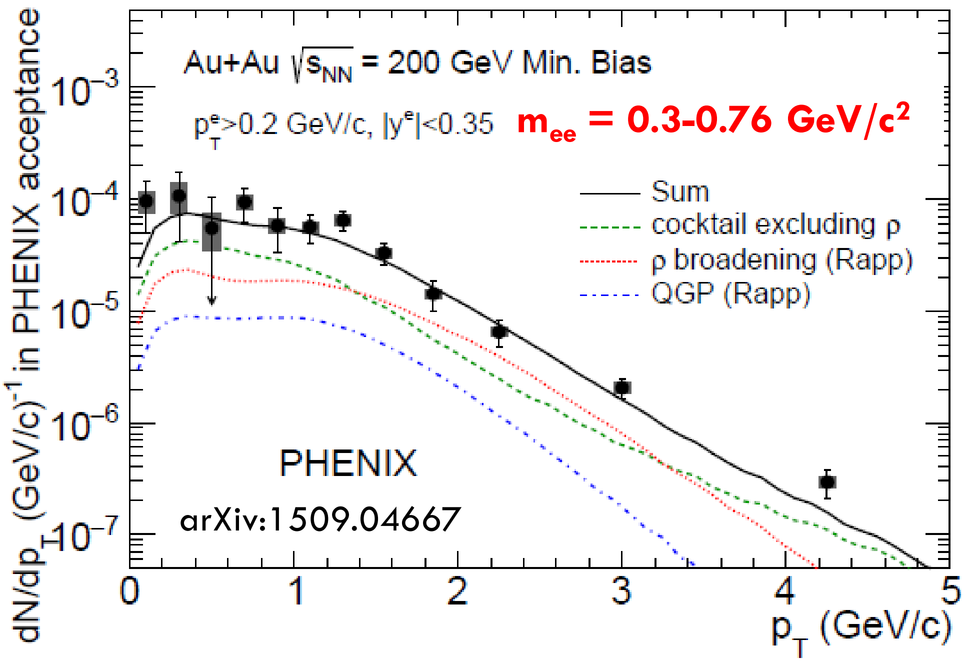
- Dielectron excess well described by the model (R. Rapp):
  - In-medium ρ broadening due to scatter off baryons in hadrons gas
  - Little contribution from the QGP

Invariant p_T (Min. Bias)



- Dielectron excess distributed over p_T

Comparison to model (Min. Bias)



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  - In-medium ρ broadening due to scatter off baryons in hadrons gas
  - Little contribution from the QGP

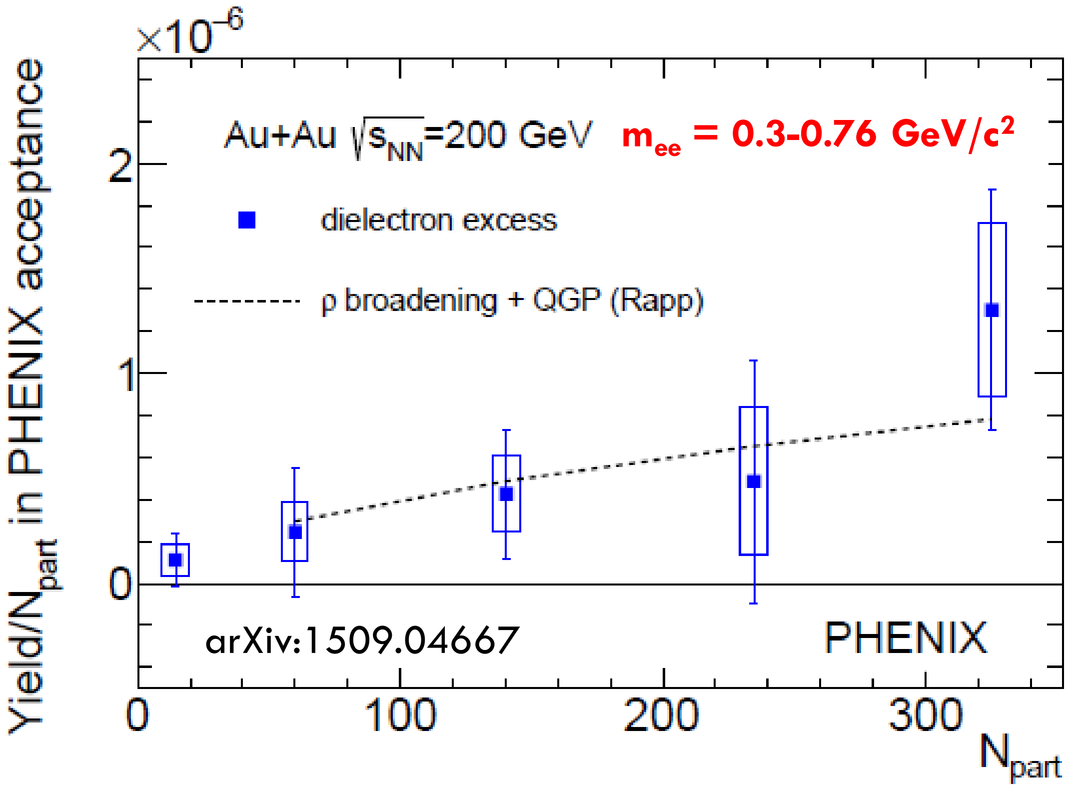
Comparison to model (centrality dependence)

- Centrality dependence of the model consistent with the data

Model yield scales with:

$(dN_{ch}/dy)^{1.45}$

(R. Rapp)



Integrated yields (IMR)

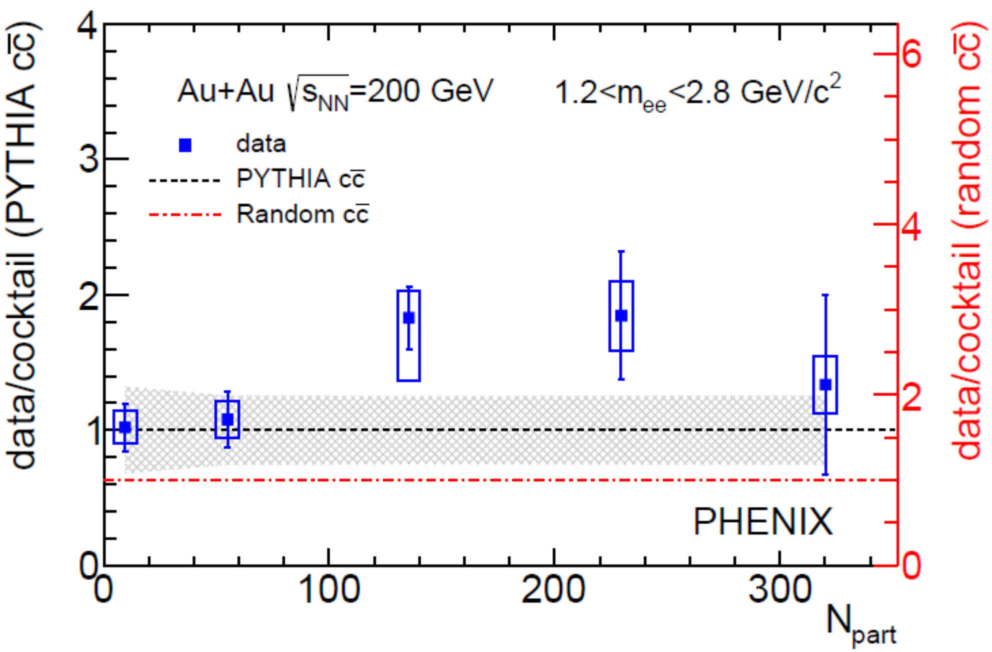
Intermediate mass region

m_{ee} = 1.2-2.8 GeV/c^2

Data/cocktail in MB (±stat±syst± mod):

- Pythia: 1.3±0.7±0.2±0.3
- Random cc: 2.5±0.5±0.3±0.3

→ Room for an additional thermal component within uncertainties



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Summary

- PHENIX provided a new measurement of dielectron invariant yields in Au+Au collisions at 200 GeV
- The new analysis with the HBD
  - Purity of the electron sample ≥95%
  - Background described qualitatively and quantitatively to an excellent level
  - Cocktail: uncertainty in the charm contribution (PYTHIA vs. MC@NLO)
- Results
  - LMR: enhancement consistent with in-medium rho broadening
  - IMR: room for a thermal source beyond the cocktail

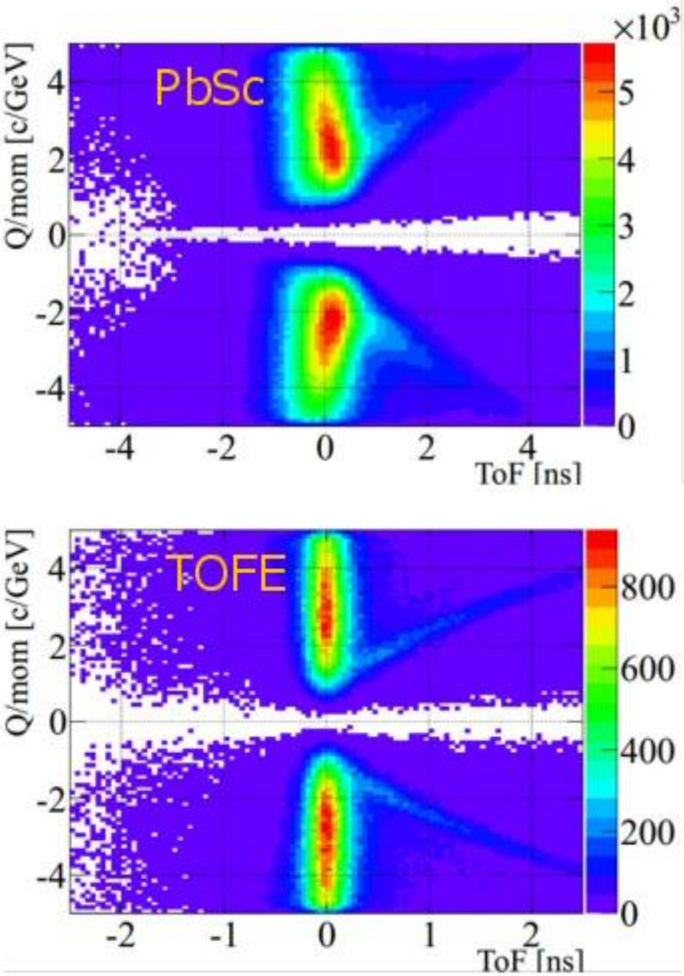
BACKUP

Comparison to previous PHENIX analysis

- **Hadron contamination:** was 30%, now 5% in MB
- **Signal sensitivity:** a factor of ~3.5 improvement in 0.15-0.75 GeV/c^2
- **Pair cuts:** now stronger pair cuts fully remove detector correlations
- **Flow:** now included in the shape of the mixed BG
- **e-h pairs:** now subtracted
- **Jets:** oposite jets component now explicitly subtracted
- **Background subtraction:** all correlated components calculated and subtracted on absoulte terms

PHENIX Time-of-flight

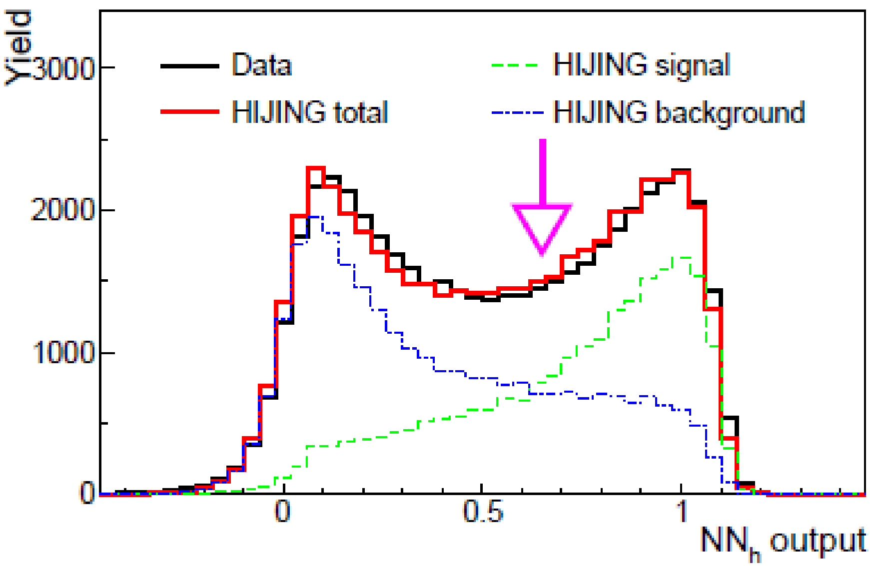
- Time-of-flight information implemented for improved hadron rejection
  - EMCal (PbSc)
    - 3/4 of acceptance
    - σ=450 ps
  - ToF East
    - ~ 1/8 of acceptance
    - σ=150 ps



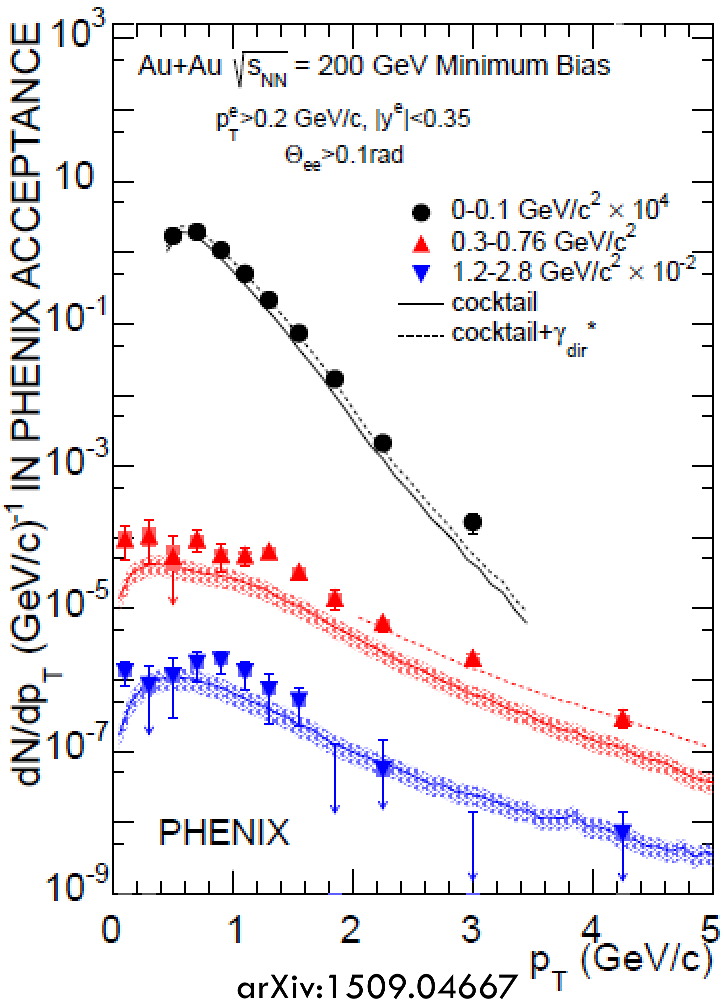
Electron identification with neural networks

- Use reconstructed parameters from RICH, EMCAL, HBD, ToF as NN inputs
- Train and monitor NNs using simulations
- Use separate neural networks for:
  - Hadron rejection
  - Conversion rejection
  - HBD double hit rejection
- **Achieve electron sample purity for all centralities ≥95%**
- Was ~70% in Run-4 with 1D eID cuts in MB collisions

Example: hadron rejection NN for 0-10% centrality



Dielectron invariant p_T (Min. Bias)



- Invariant p_T yield in m_{ee}:
  - 0 - 0.1 GeV/c²
  - 0.3 - 0.76 GeV/c²
  - 1.2 – 2.8 GeV/c²

Systematic uncertainties

- For Minium bias collisions

Component	Uncertainty
eID+occupancy	± 4%
Acceptance (time)	± 8%
Acceptance (data/MC)	± 4%
Combinat. backgr. (0-5 GeV/c^2)	± 25% (at 0.6 GeV/c^2)
Residual yield (0-0.08 GeV/c^2)	- 5% (at 0.08 GeV/c^2)
Residual yield (1-5 GeV/c^2)	- 15% (at 1.0 GeV/c^2)

The Cocktail

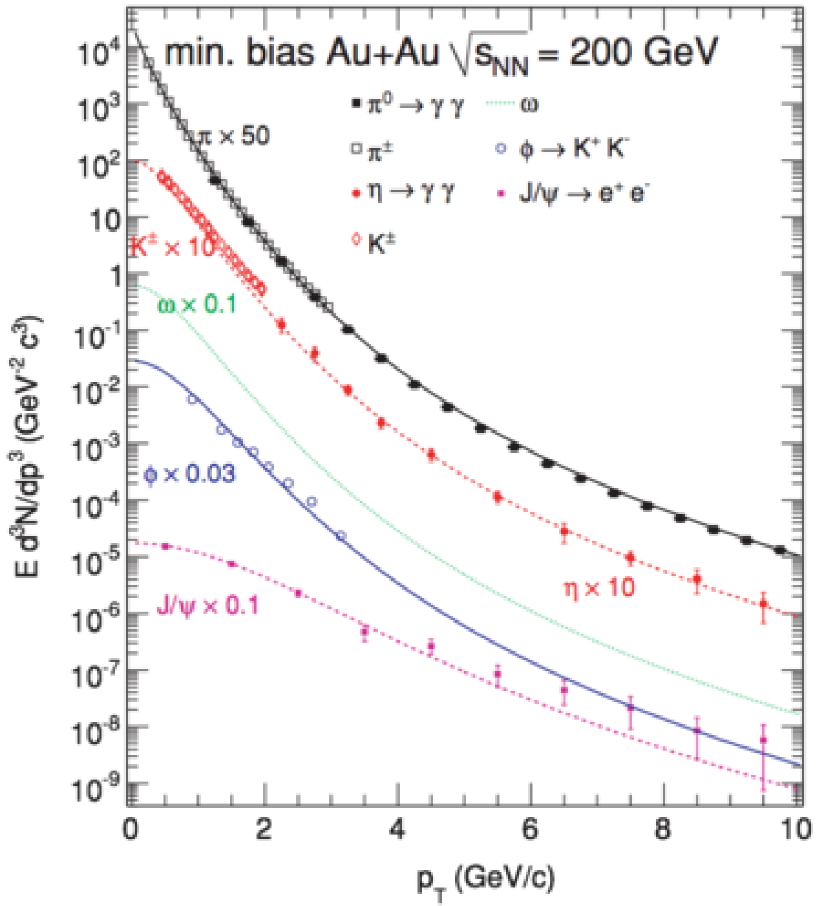
- Hadron decays simulated in EXODUS
- Fit π^0 and $\pi^{\pm}$ data p+p or Au+Au to modified Haggedorn function:

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

- for other mesons η, ω, ρ, ϕ, J/Ψ etc. use pion parametrization and replace:

$$p_T \rightarrow \sqrt{p_T^2 + m^2 - m_{\pi^0}^2}$$

- The absolute normalization of each meson provided by meson to π^0 ratio at high p_T
- Open heavy flavor (c,b) simulated with MC@NLO and PYTHIA
- The cocktail filtered through the PHENIX acceptance and smeared with detector resolution
- J/Ψ from full detector MC, normalization: pp yield scaled by N_{coll} * R_{aa}

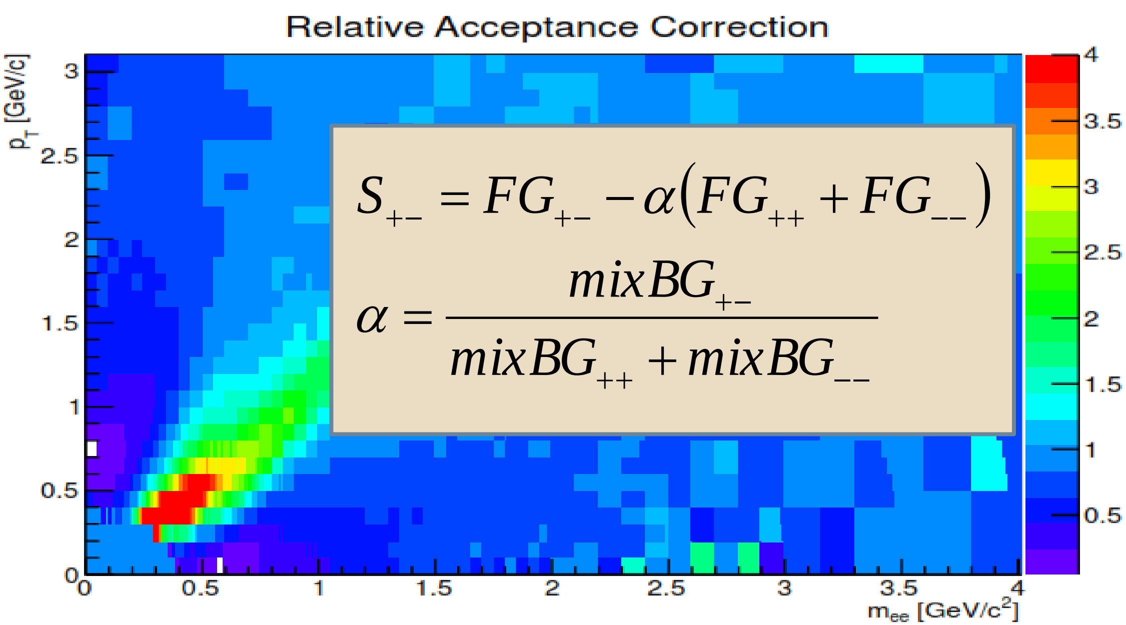


Relativistic Heavy Ion Collider

- Relativistic Heavy Ion Collider
- Circumference 3.8 km
- Two large experiments today: PHENIX and STAR
- Has collided various nuclei: p+p, p+Au, p+Al, d+Au, 3He+Au, Cu+Cu, Cu+Au, Au+Au, U+U
- Flexible in beam energy up to:
  - $\sqrt{s_{NN}}$=200 GeV, for Au+Au
  - $\sqrt{s}$=500 GeV, for p+p

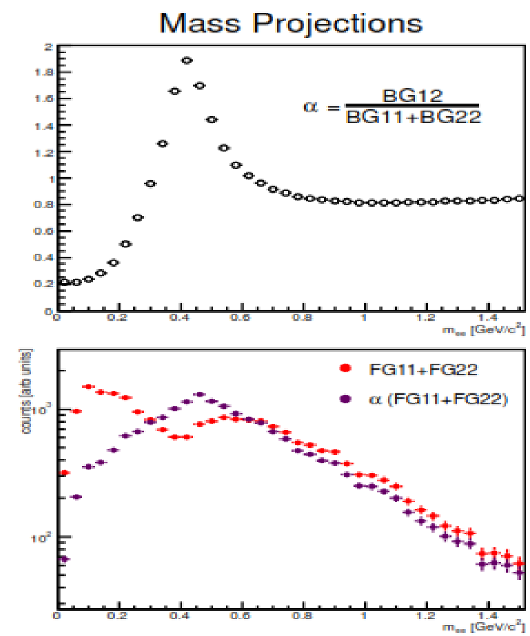
Like sign - background subtraction

- all bckg = relative acceptance corrected like-sign pairs



$$S_{+-} = FG_{+-} - \alpha\left(FG_{++} + FG_{--}\right)$$

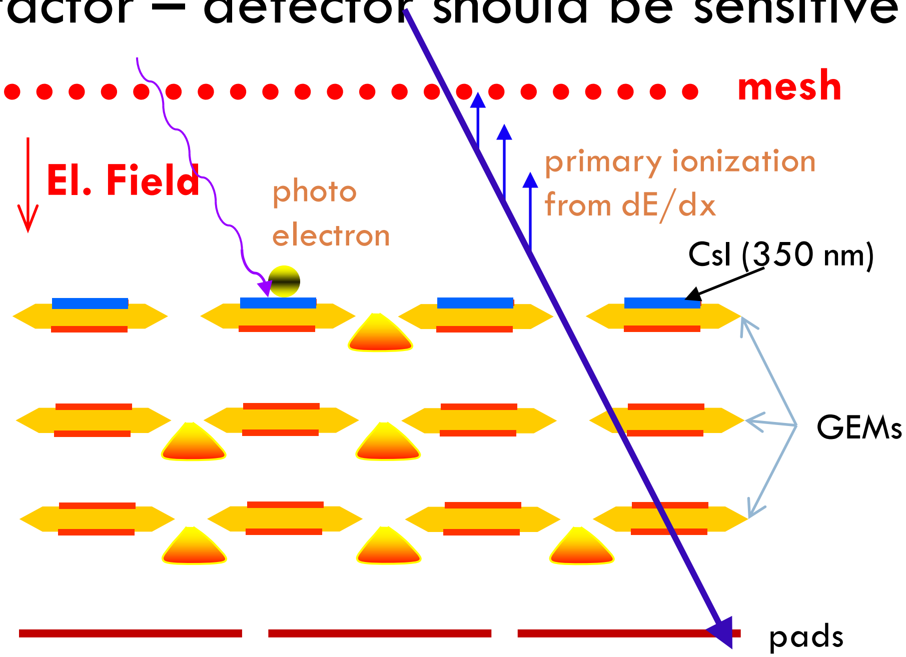
$$\alpha = \frac{mixBG_{+-}}{mixBG_{++} + mixBG_{--}}$$

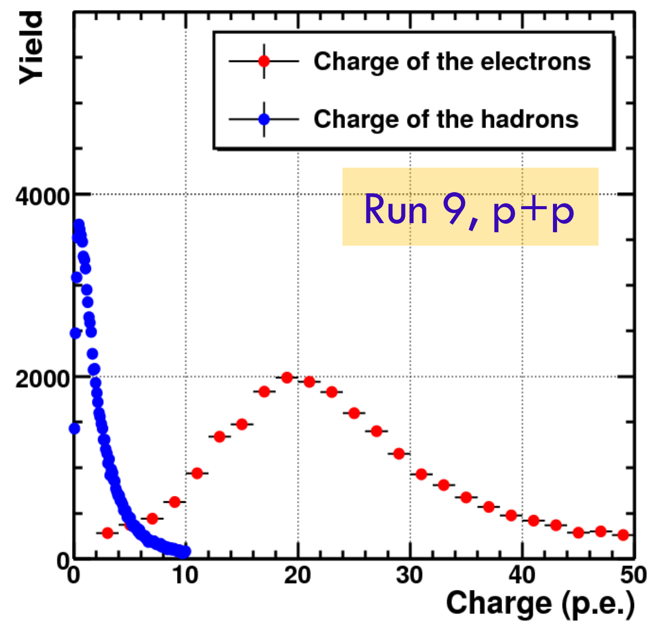


This method does not provide precision needed (~0.2%) for central Au+Au collisions → go to component by component cubtraction

The HBD: hadron blindness

- Hadron track multiplicity exceeds the electron multiplicity by a large factor – detector should be sensitive only to electrons





a. Cherenkov light is formed only by e^+ or e^-, threshold for π is 4 GeV/c
b. the detector is operated in reverse bias mode to repel the ionization charge from dE/dx

Parallel analysis

- Independent analysis to provide a consistency check
- Key differences are:
  - Different HBD reconstruction algorithm
  - eID with 1D cuts
  - Normalization of background components by simulateous fit to the like-sign spectra
- Features:
  - Electron purity ~ 85% in 0-10% cent.
  - Signal sensitivity in LMR ~0.5 compared to than the main analysis
- Result: consistent with the main analysis