Low-mass dileptons: A thermometer for the hottest stuff in the universe

– Torsten Dahms –
Excellence Cluster “Universe” - TU München

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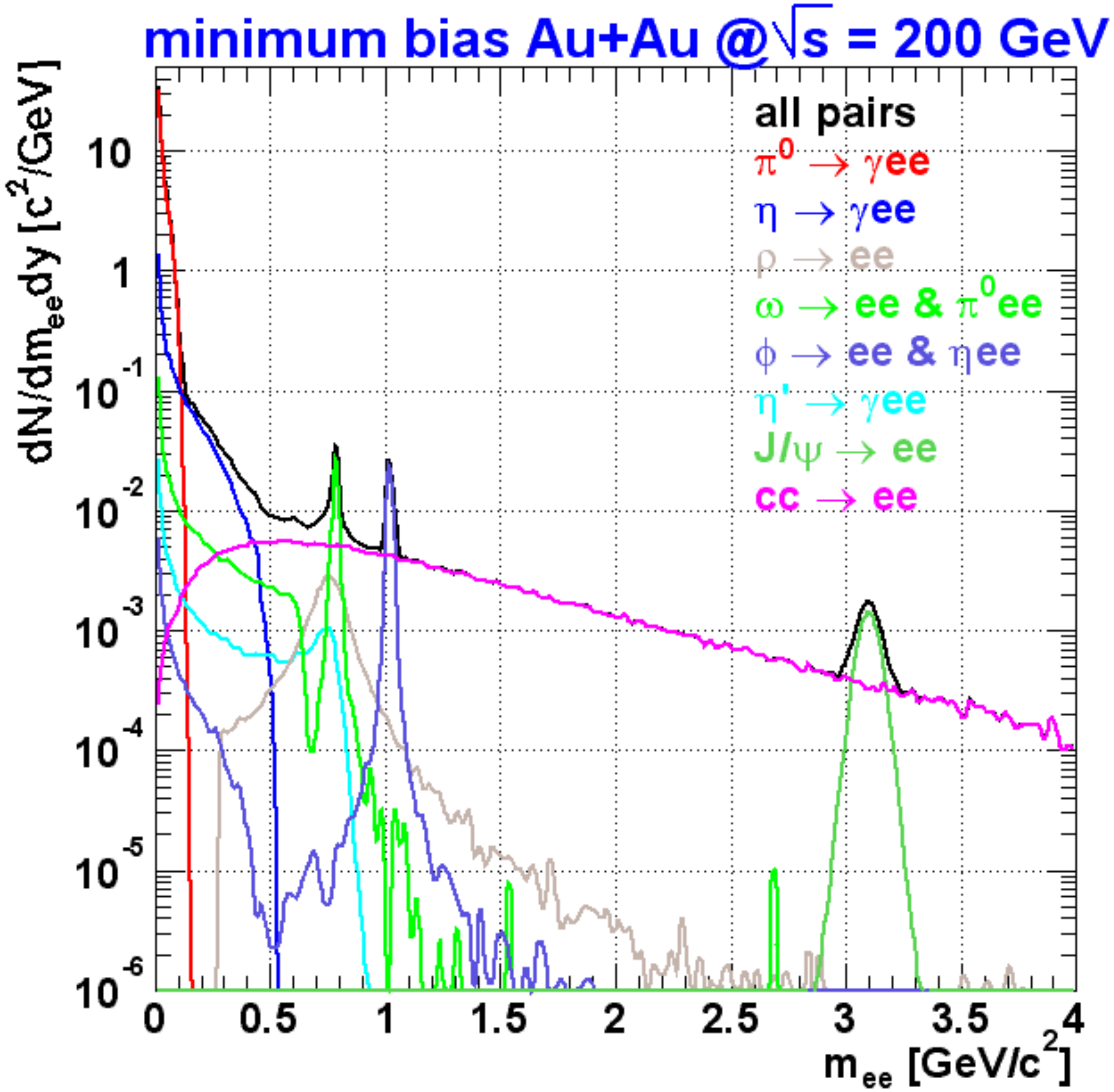
Excellence Cluster Universe

Technische Universität München

Properties of the QGP

- What is its temperature?
  - measure thermal photons
- Does it restore chiral symmetry?
  - modification of the vector mesons
- How does it affect heavy quarks?
  - modification of the intermediate mass region
- All these questions can be answered by measuring dileptons (e^+e^- or $\mu^+\mu^-$)
  - no strong final state interactions:
    - leave collision system unperturbed
    - emitted at all stages: need to disentangle contributions



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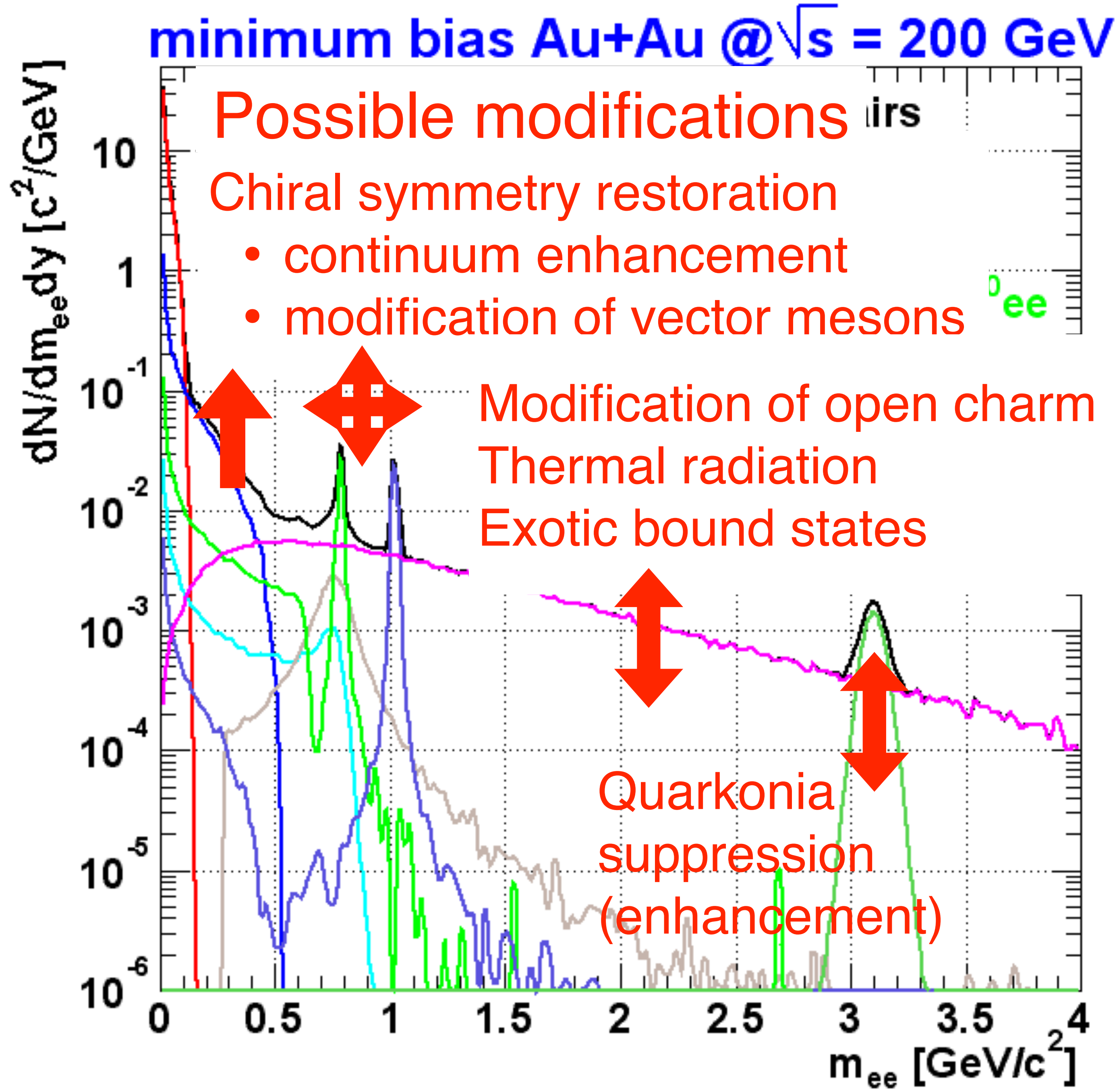
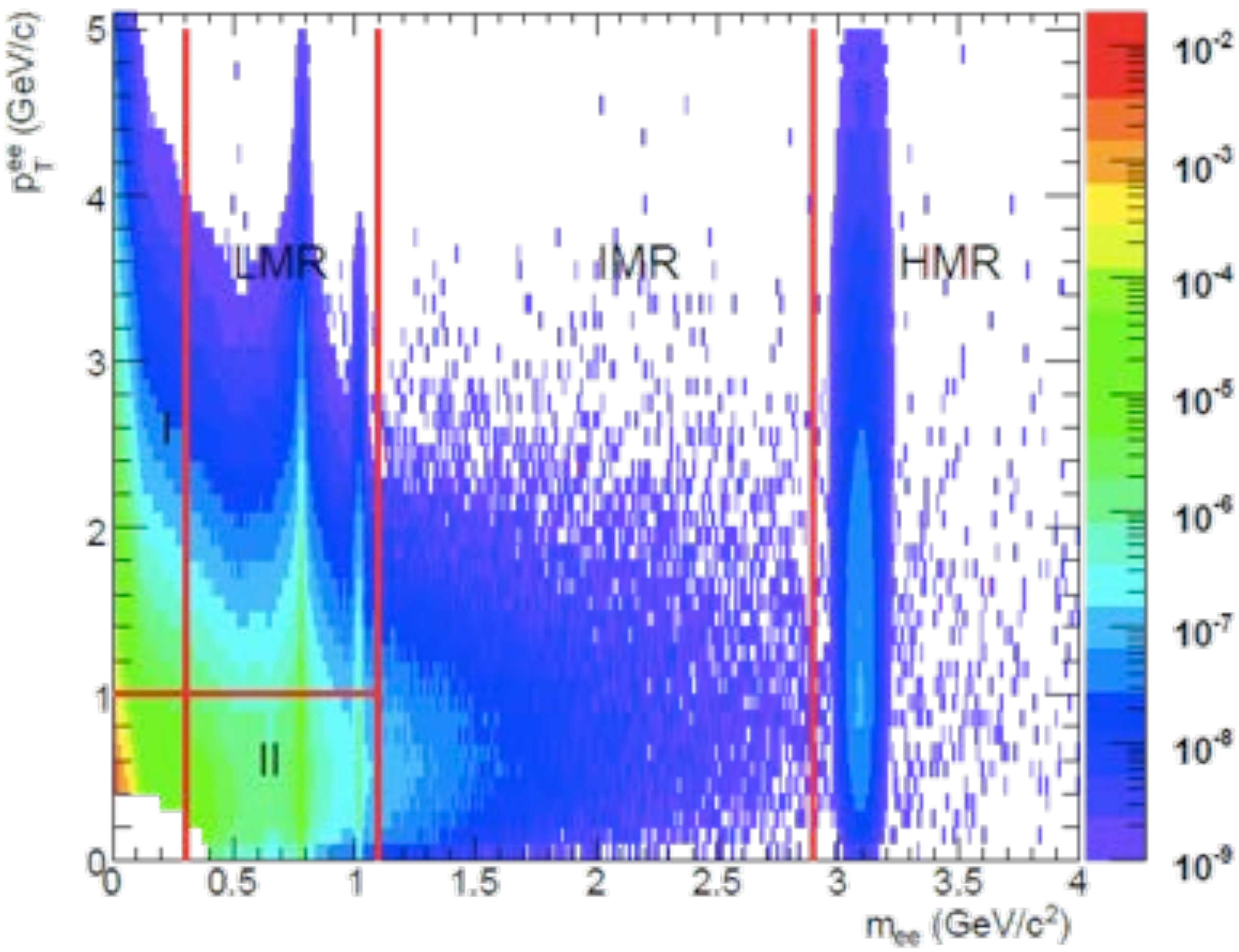


Dilepton Signals: p_T vs. mass



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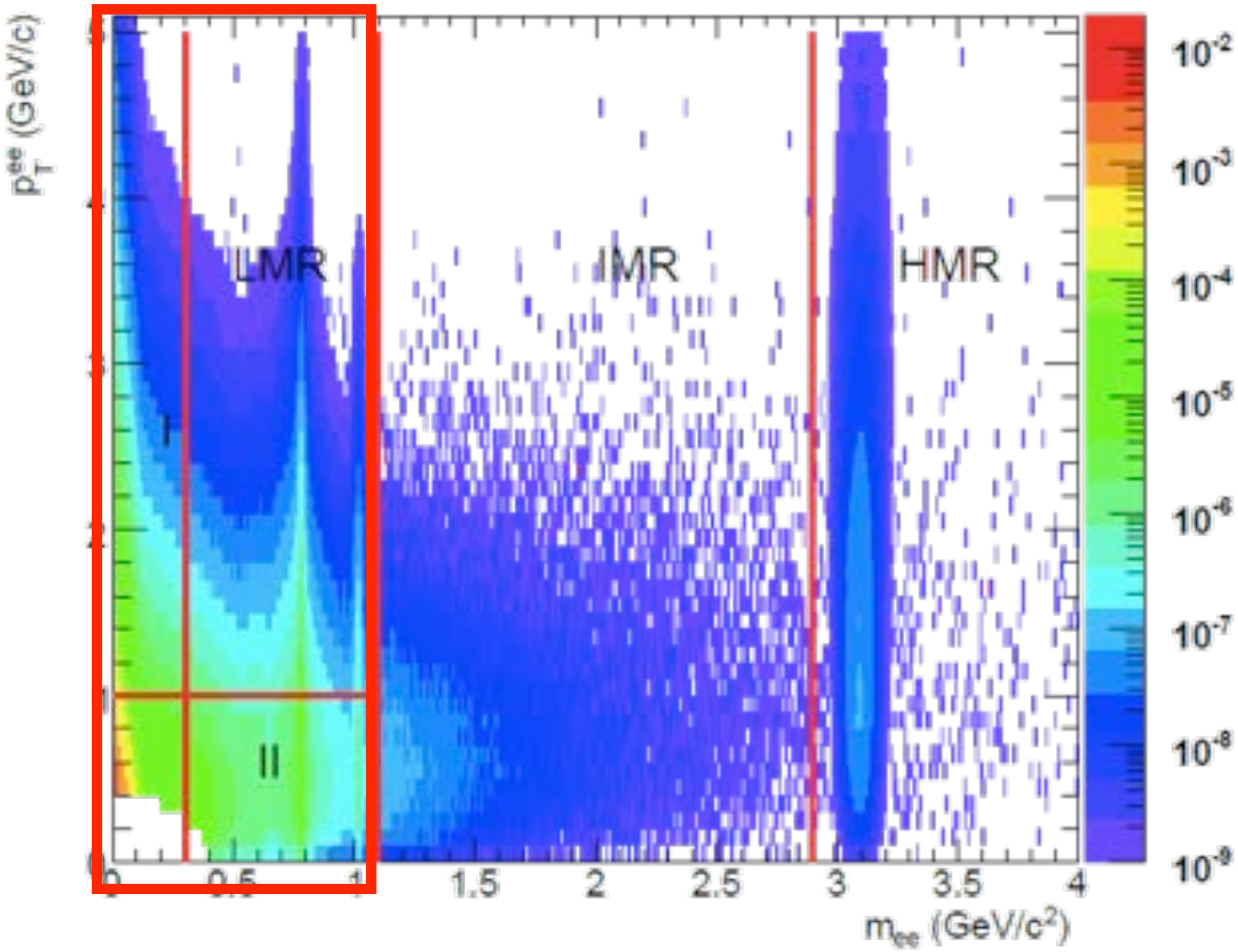

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  - Direct decays of vector mesons
  - In-medium decay of ρ mesons in the hadronic gas phase

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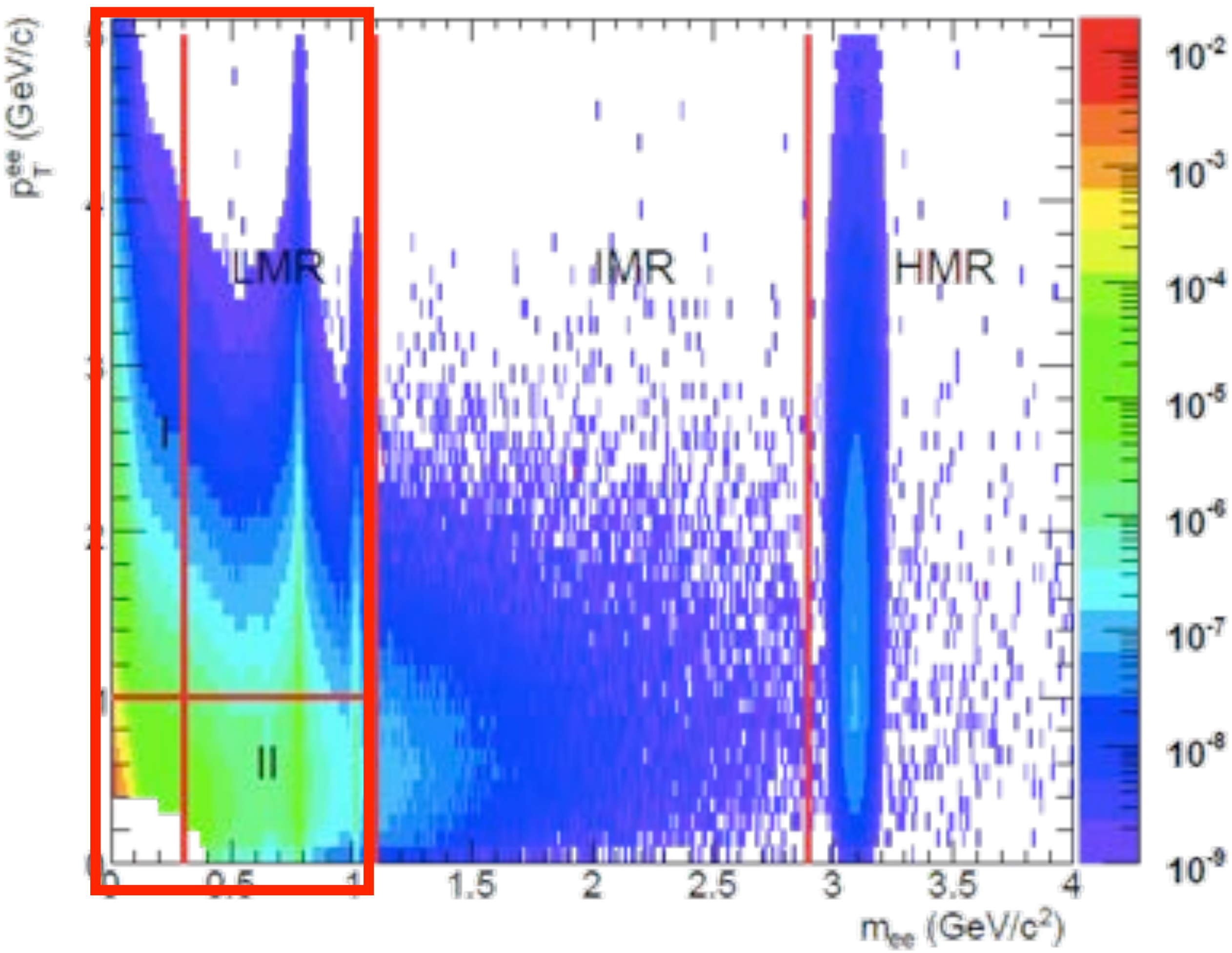

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  - LMR I ($p_T \gg m_{ee}$)
    quasi-real virtual photon region. Low mass pairs produced by higher order QED correction to the real photon emission
  - LMR II ($p_T < 1$ GeV)
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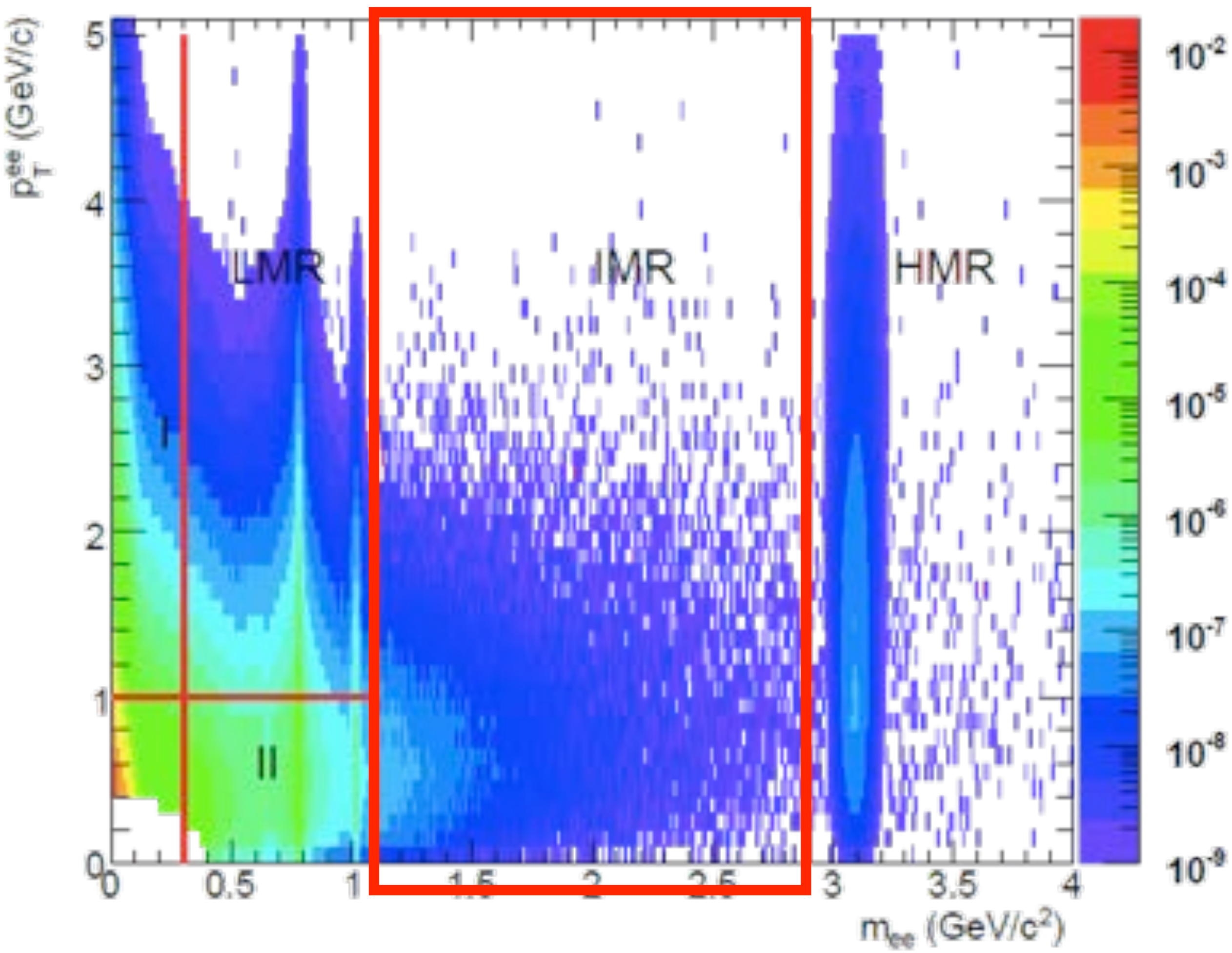

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  - Dileptons from the QGP

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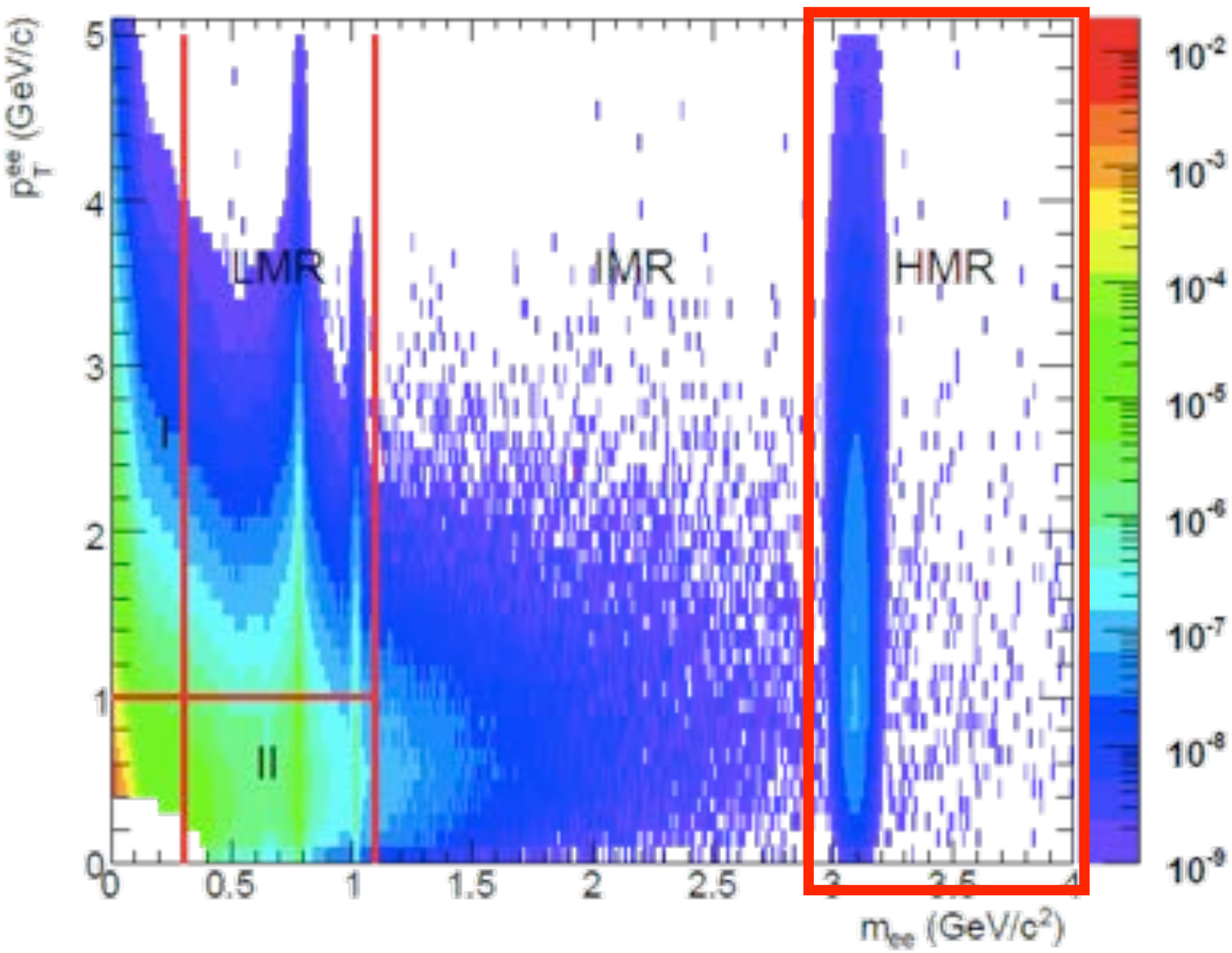

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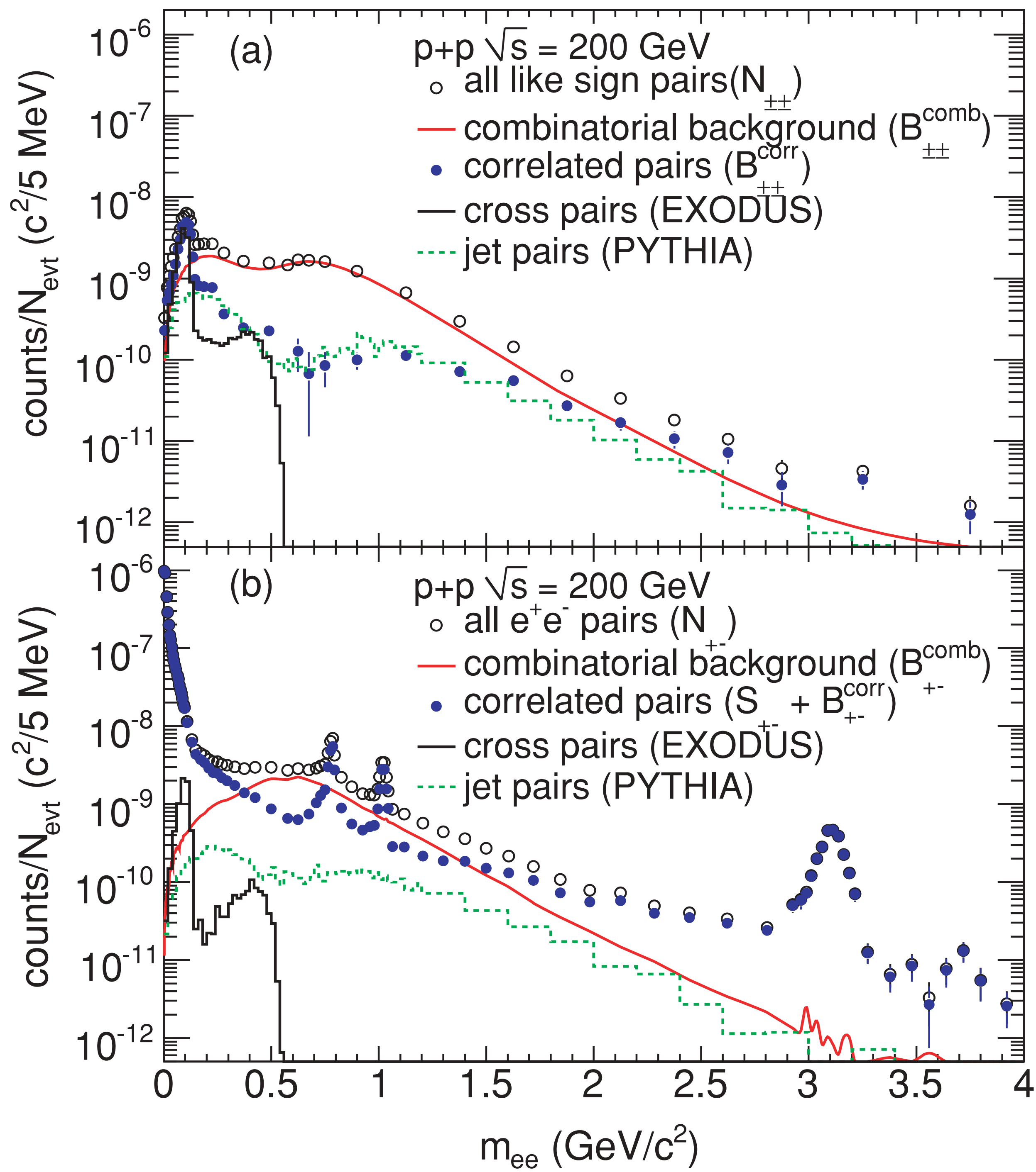
- High Mass Region: $m_{ee} > 2.9$ GeV/c^2
  - Dileptons from hard processes
    - Drell-Yan process
    - Correlated semi-leptonic decays of heavy quark pairs
    - Charmonium
    - Upsilon
  - HMR probe the initial stage
    - Little contribution from thermal radiation

Combinatorial and Correlated Background

- Same-sign spectrum contains all background sources



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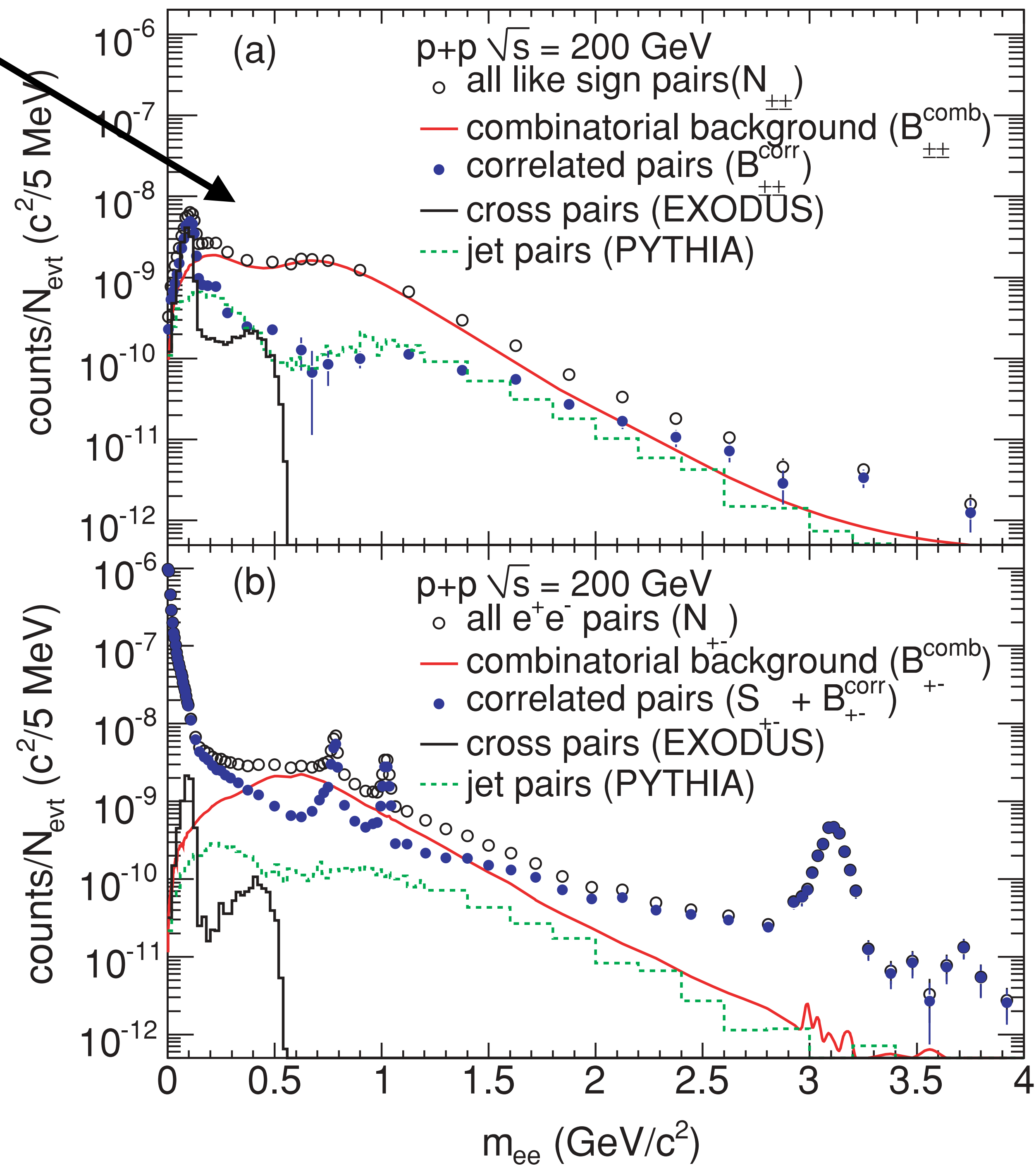

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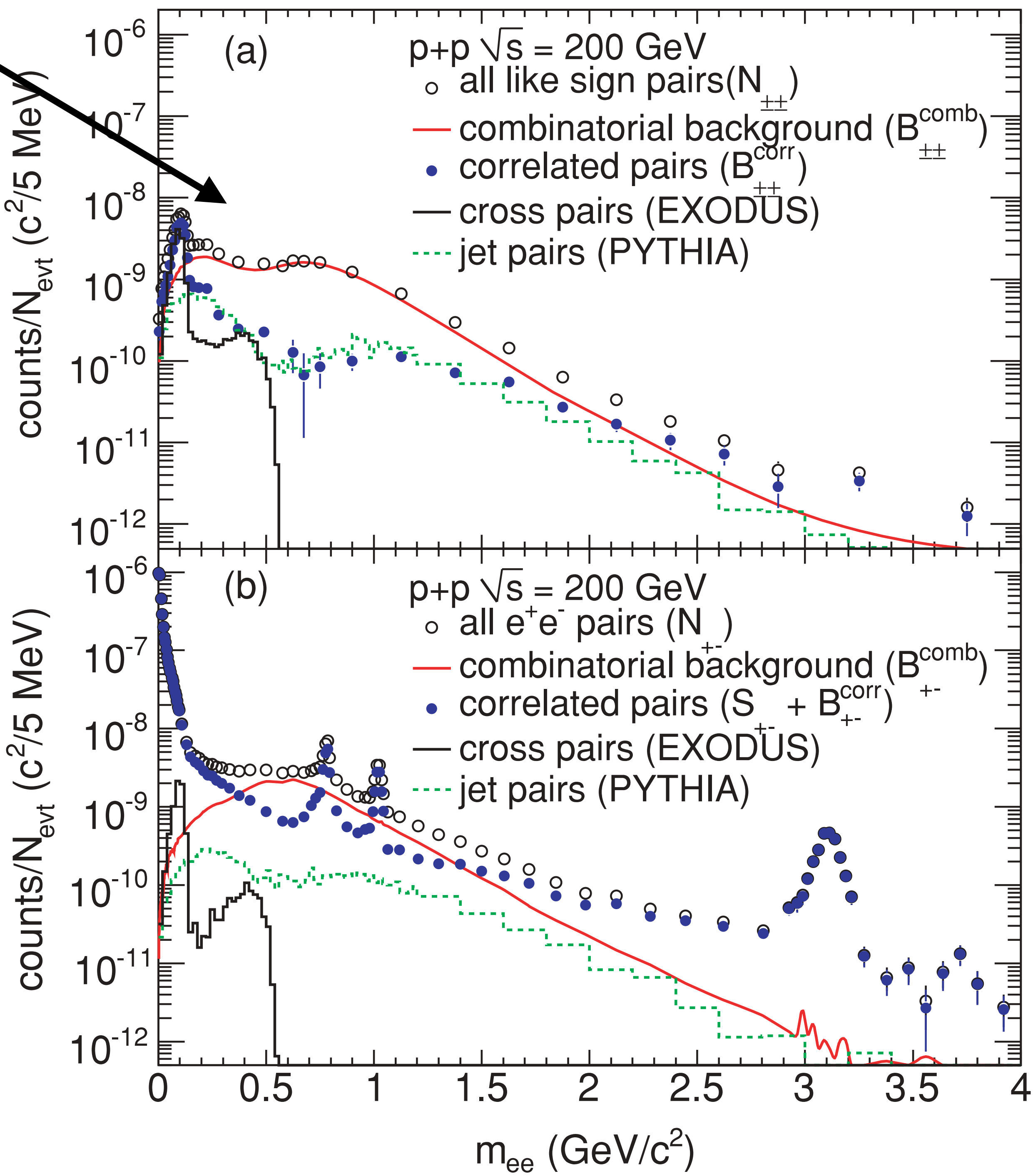

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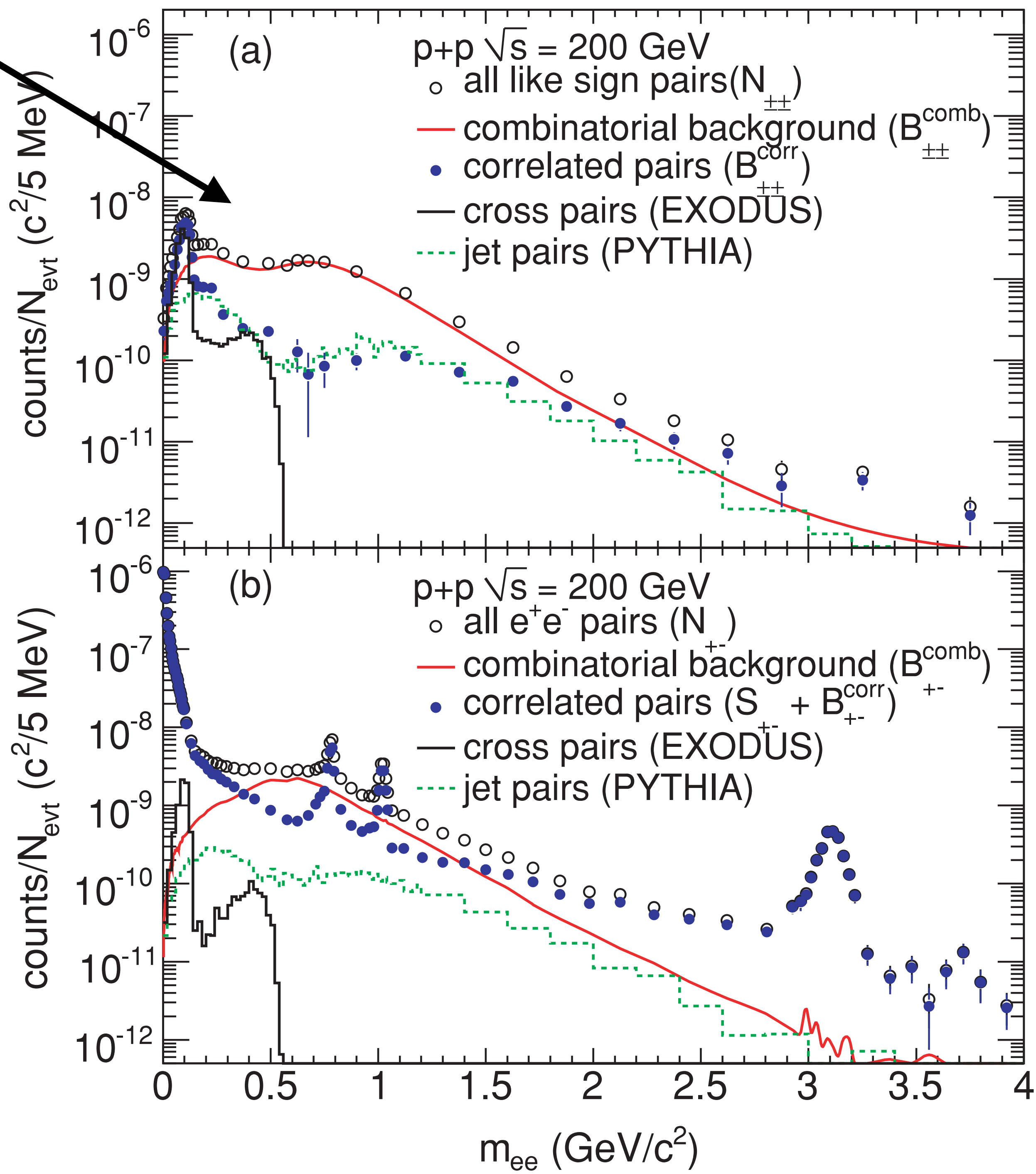

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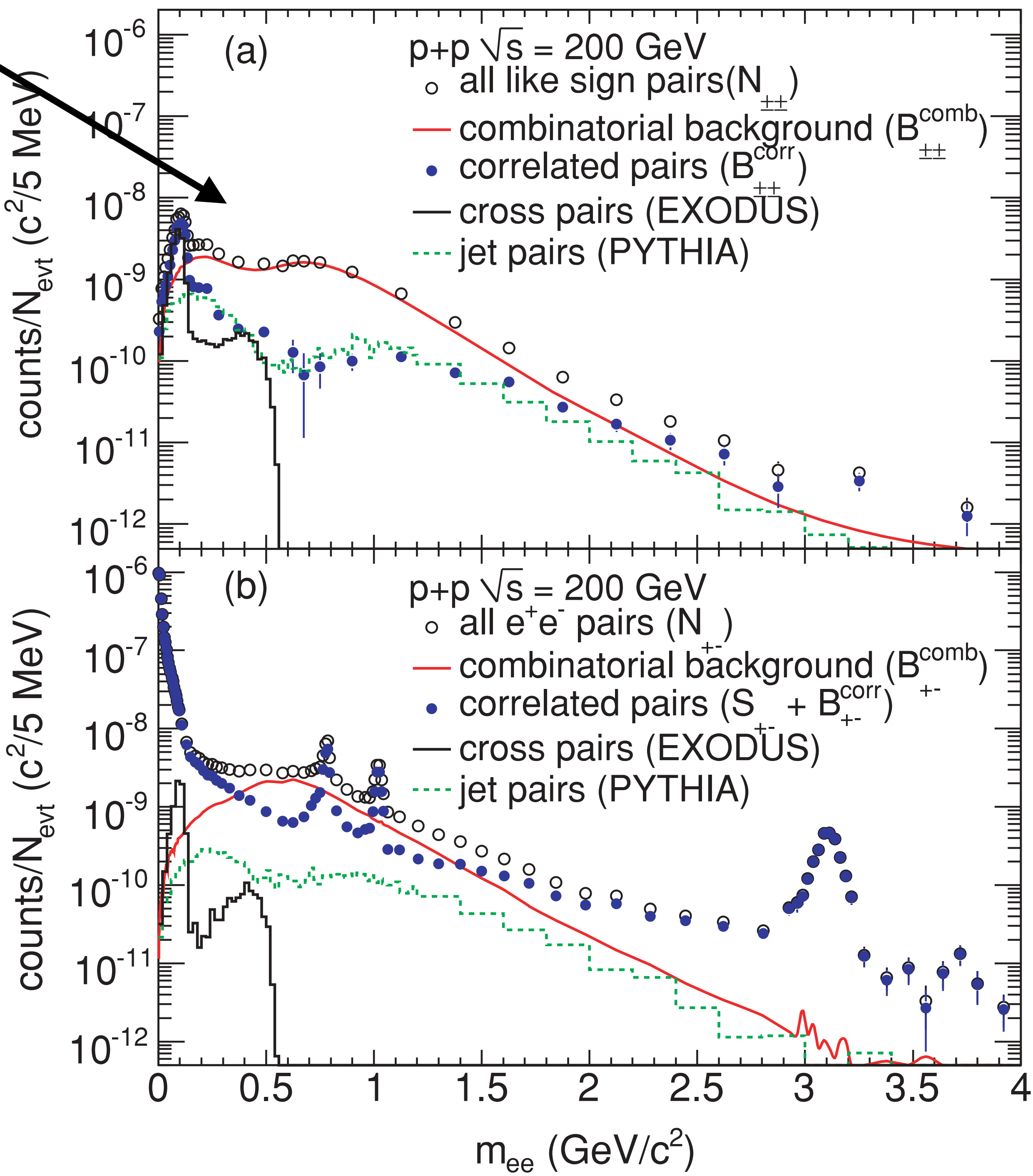

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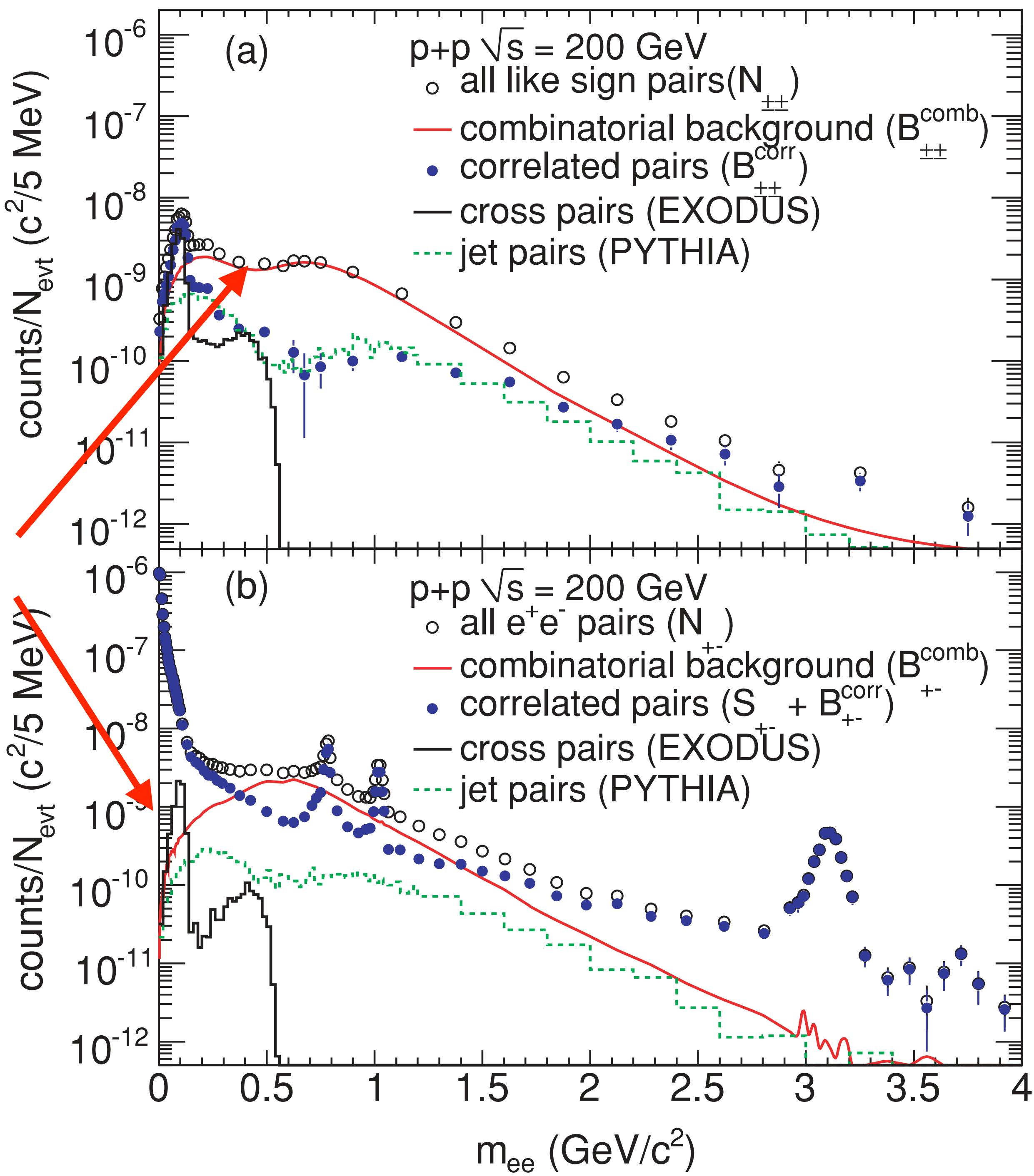
  - statistics only limited by memory



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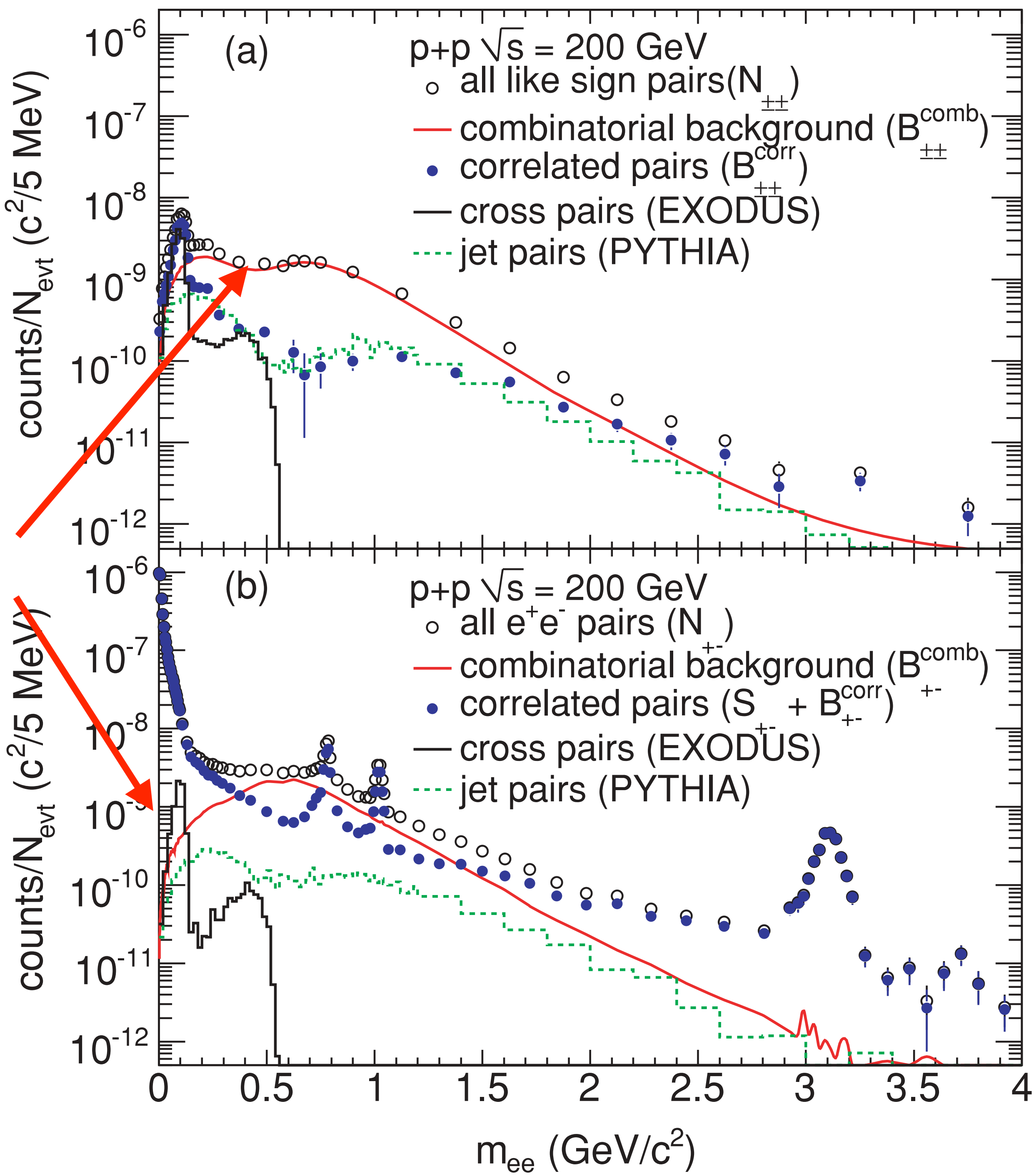

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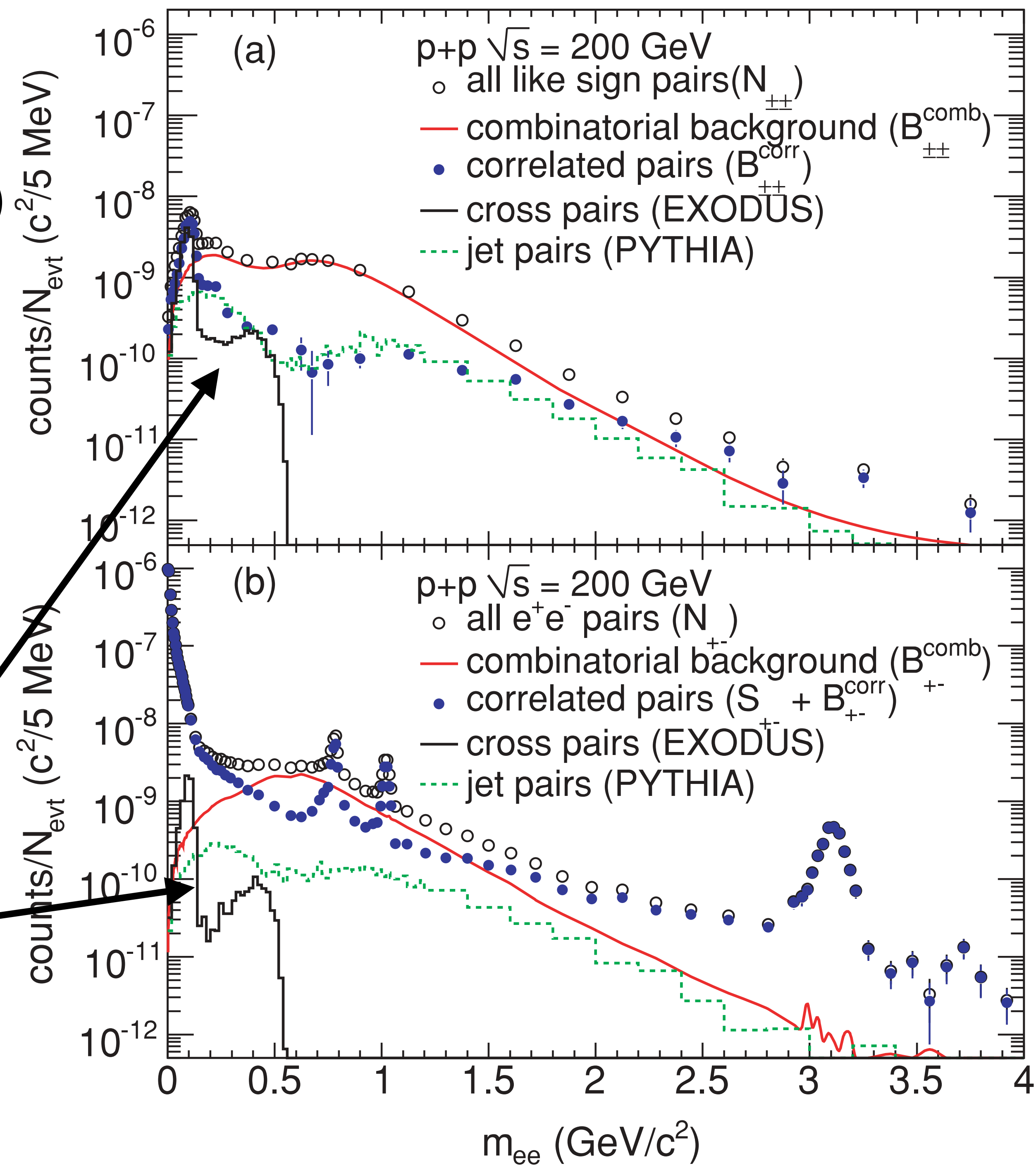

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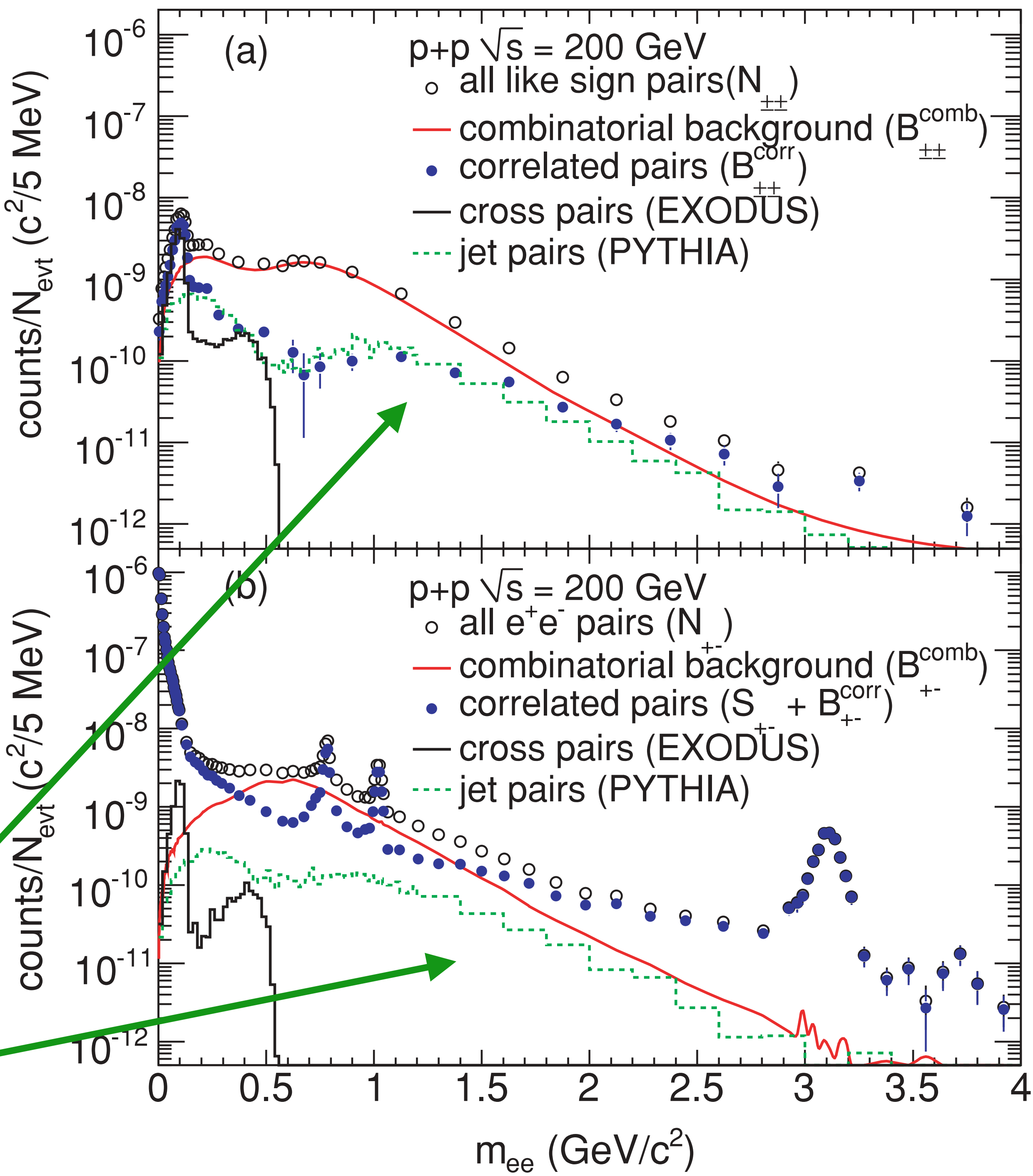

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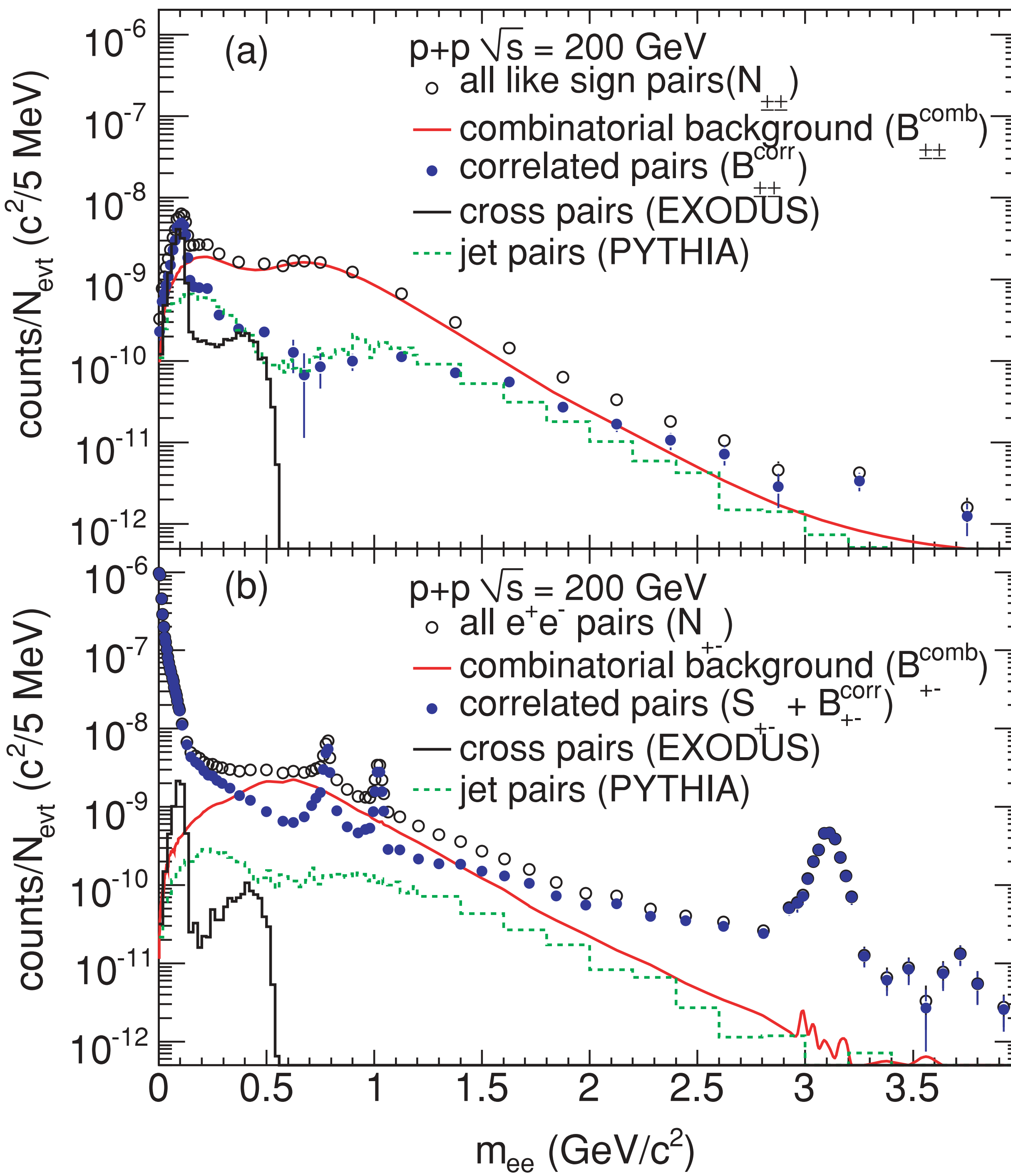
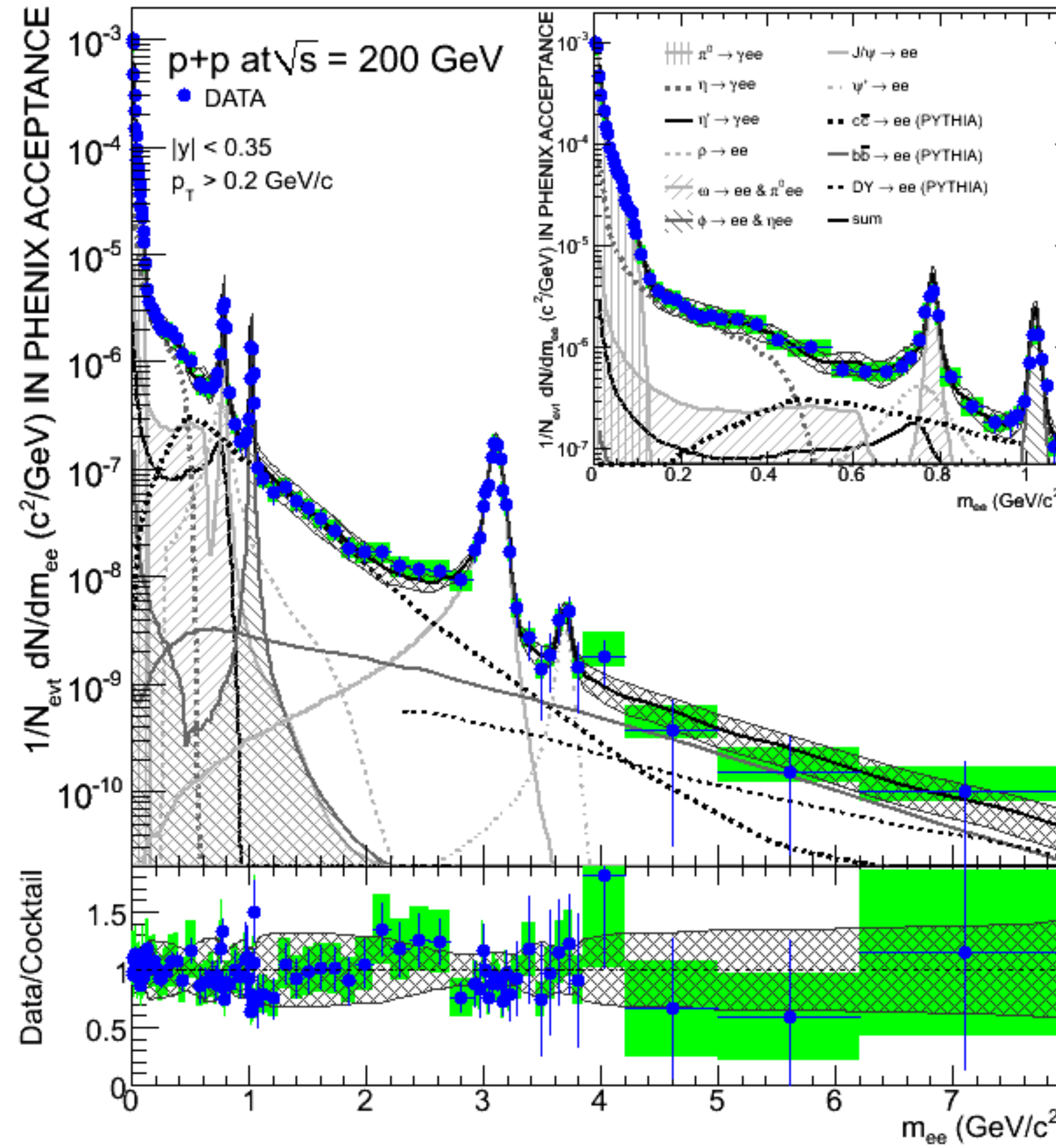
➡ normalized to same-sign data and use same normalization for opposite-sign background



p+p at $\sqrt{s}$ = 200 GeV

PHENIX, PLB 670 (2009) 313

- Data absolutely normalized
- Excellent agreement with cocktail
  - Filtered in PHENIX acceptance



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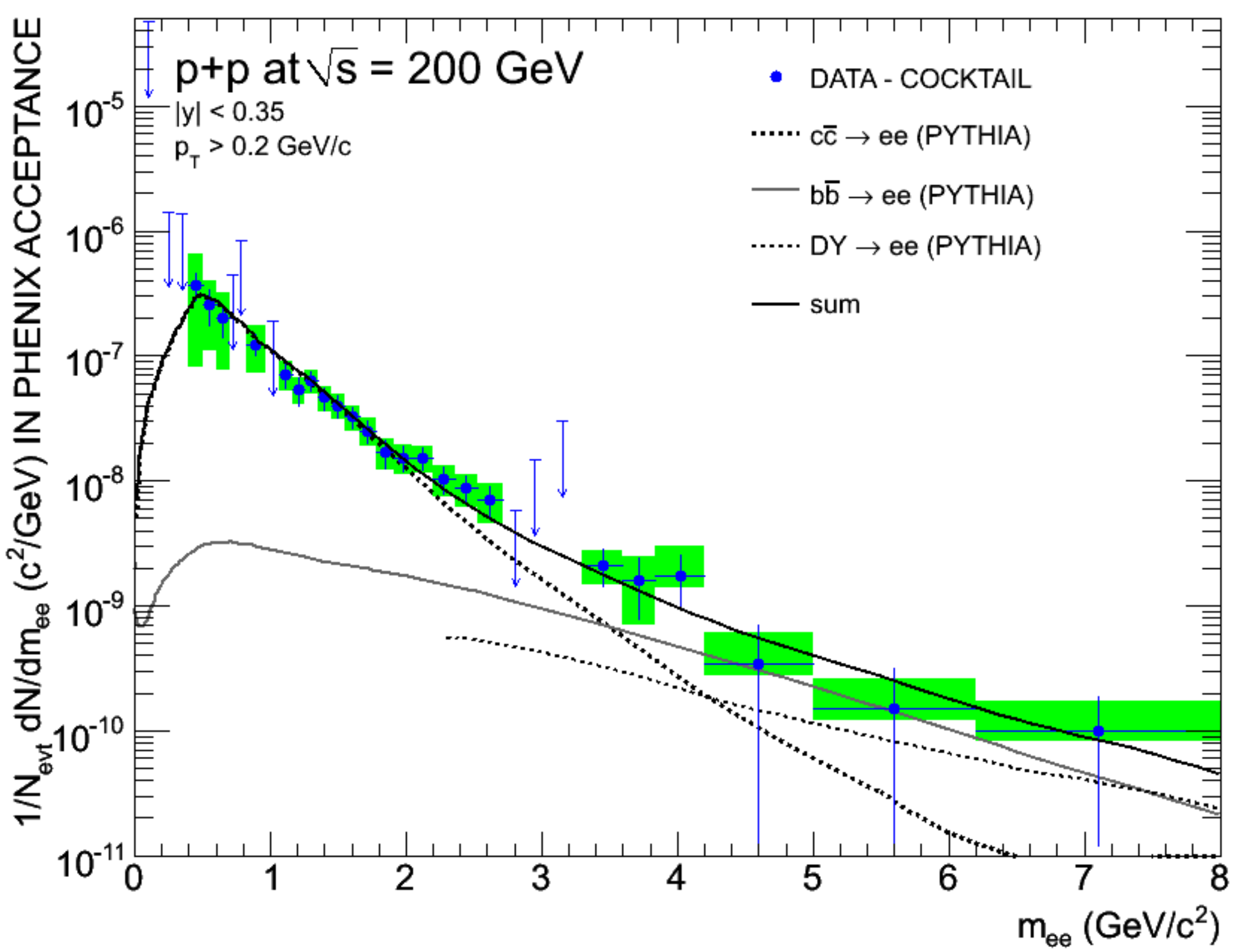

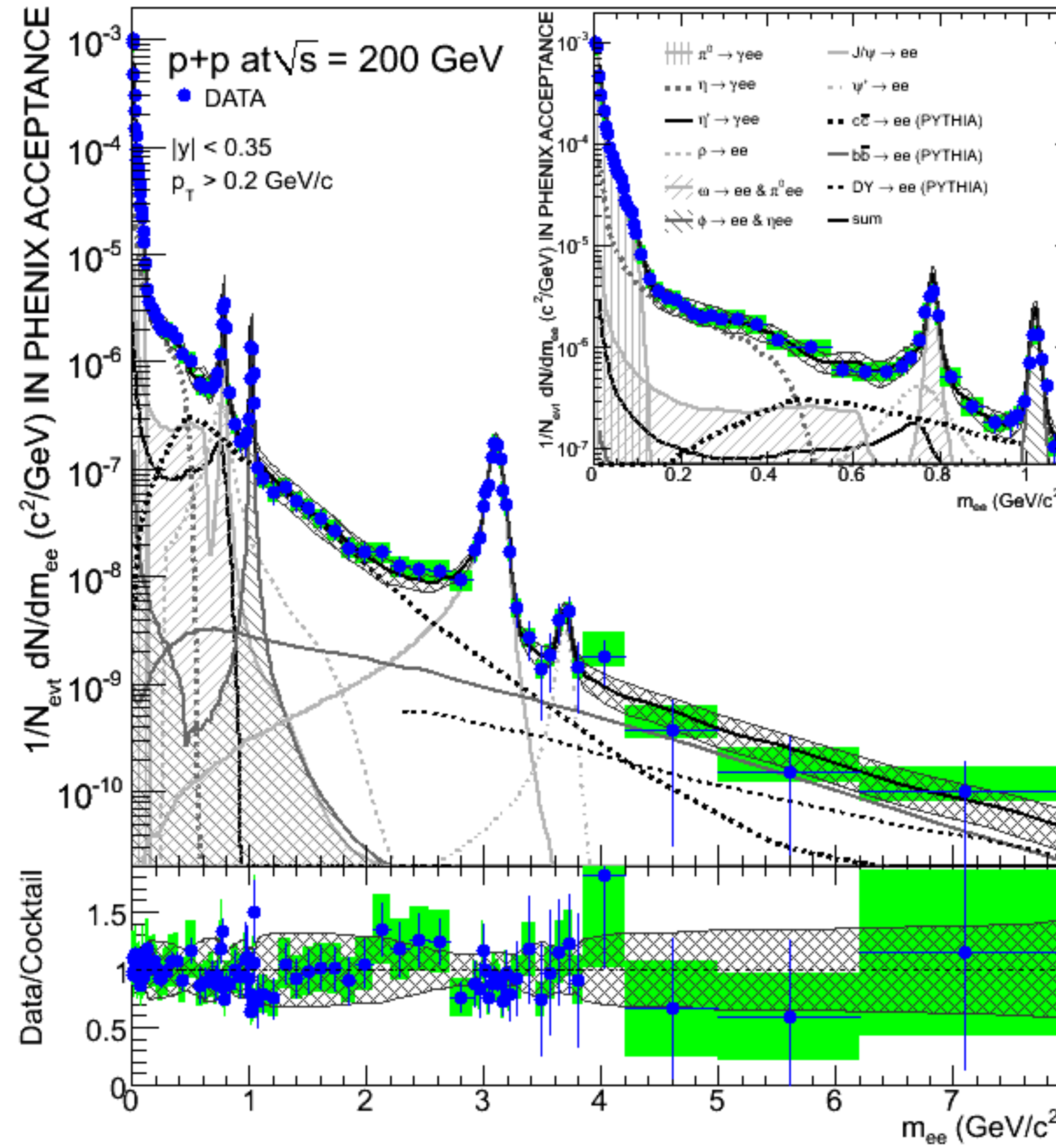

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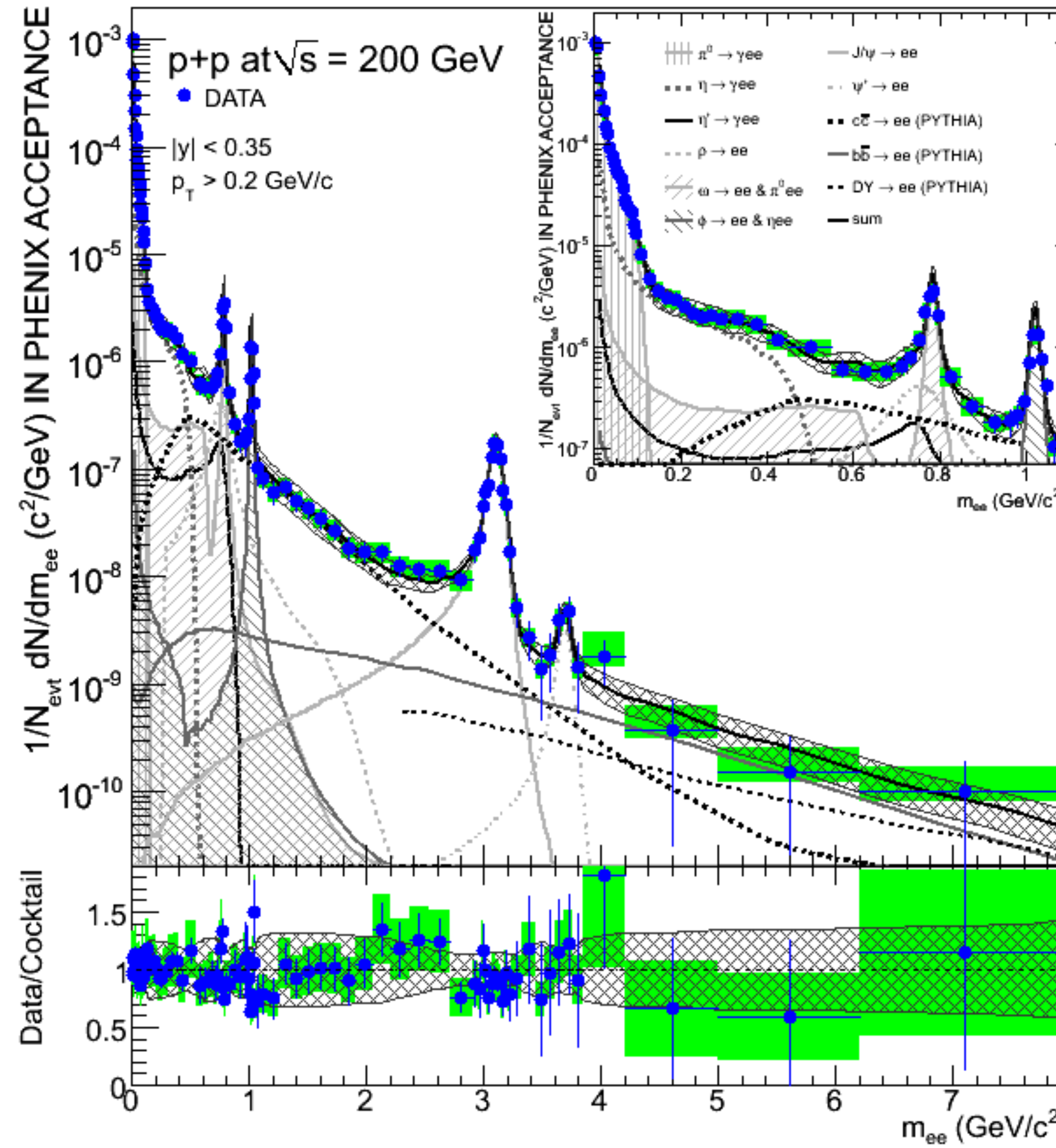
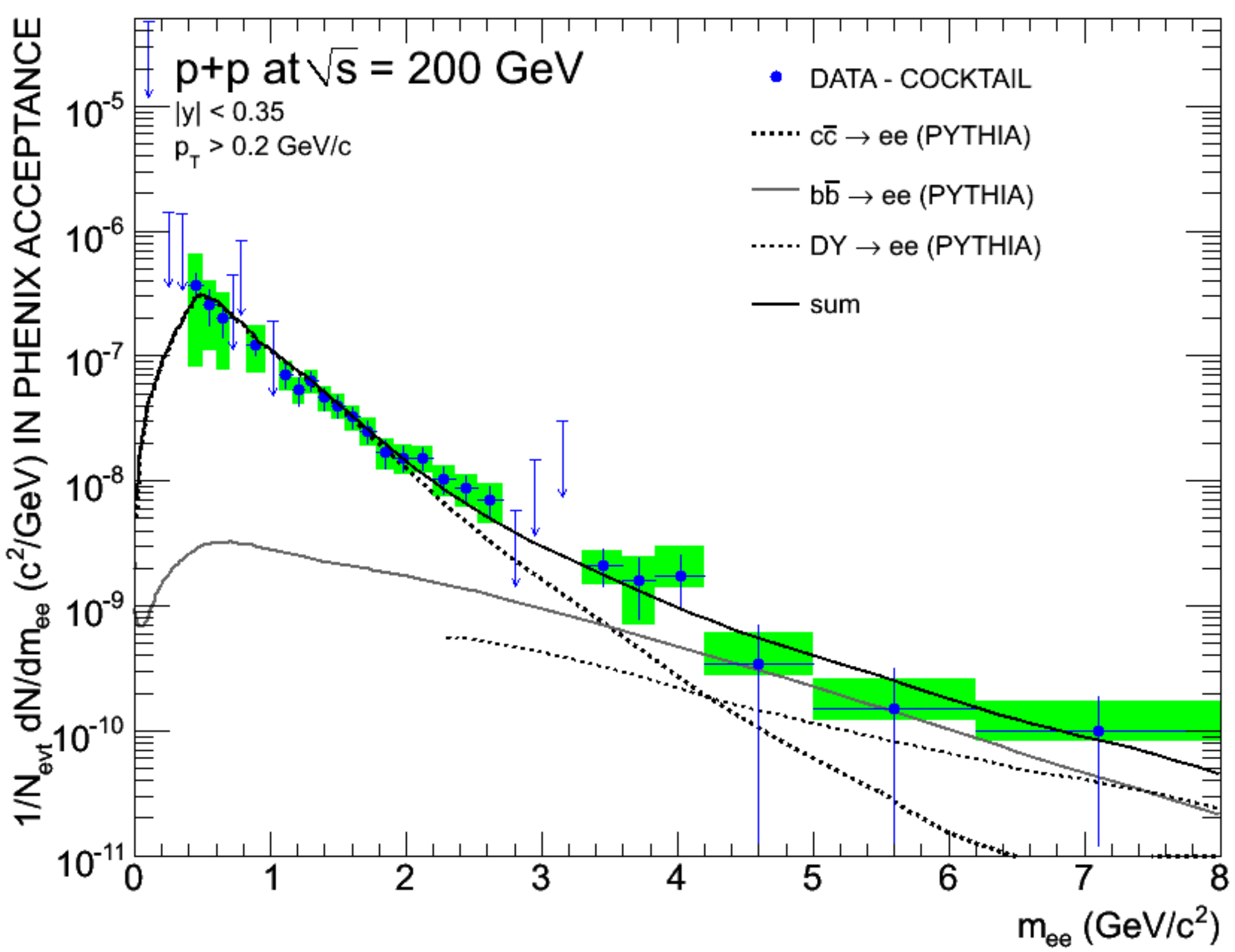




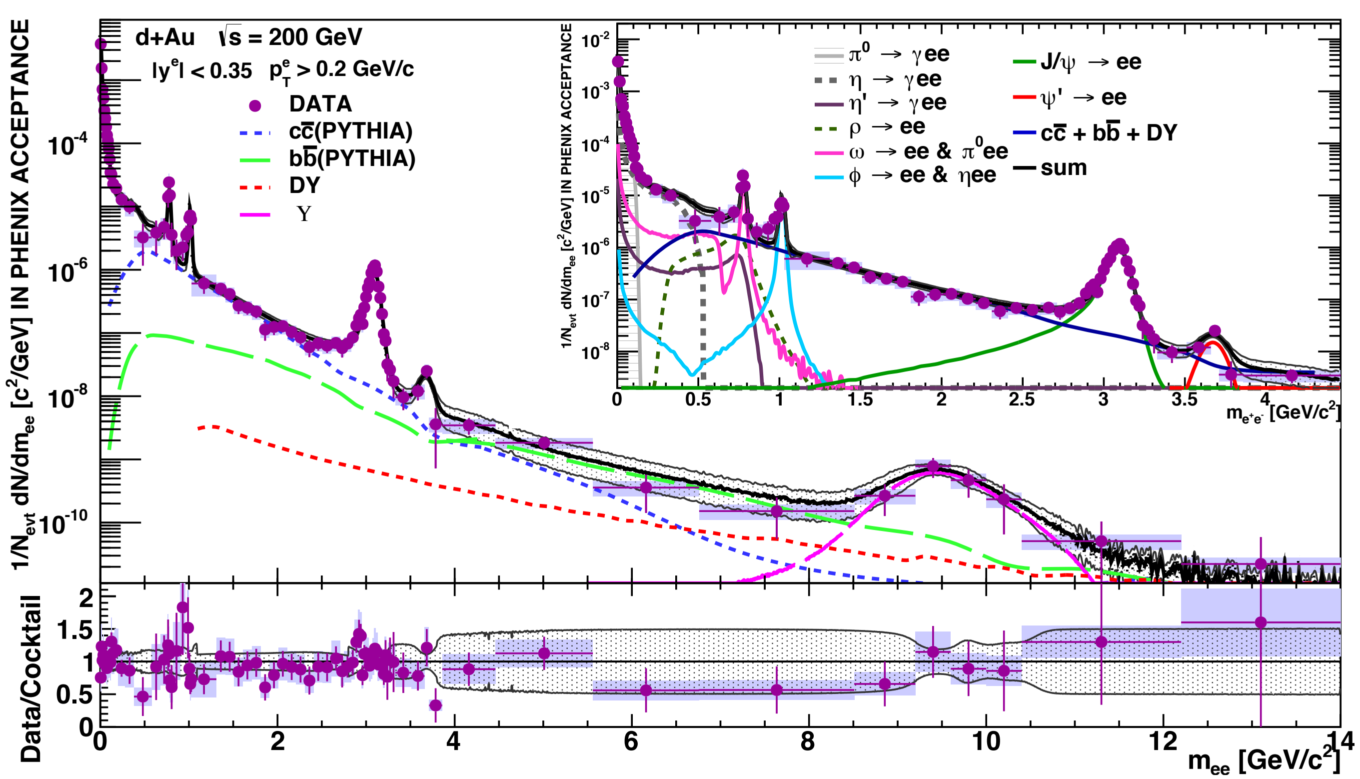
$$\sigma_{c\bar{c}} = 518 \pm 47(\mathrm{stat}) \pm 135(\mathrm{syst}) \pm 200(\mathrm{model})\ \mu\mathrm{b}$$

$$\sigma_{b\bar{b}} = 3.9 \pm 2.4(\mathrm{stat})^{+3}_{-2}(\mathrm{syst})\ \mu\mathrm{b}$$

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

- Data consistent with cocktail
  - No significant cold nuclear matter effects

PHENIX, PRC 91 (2015) 014907



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

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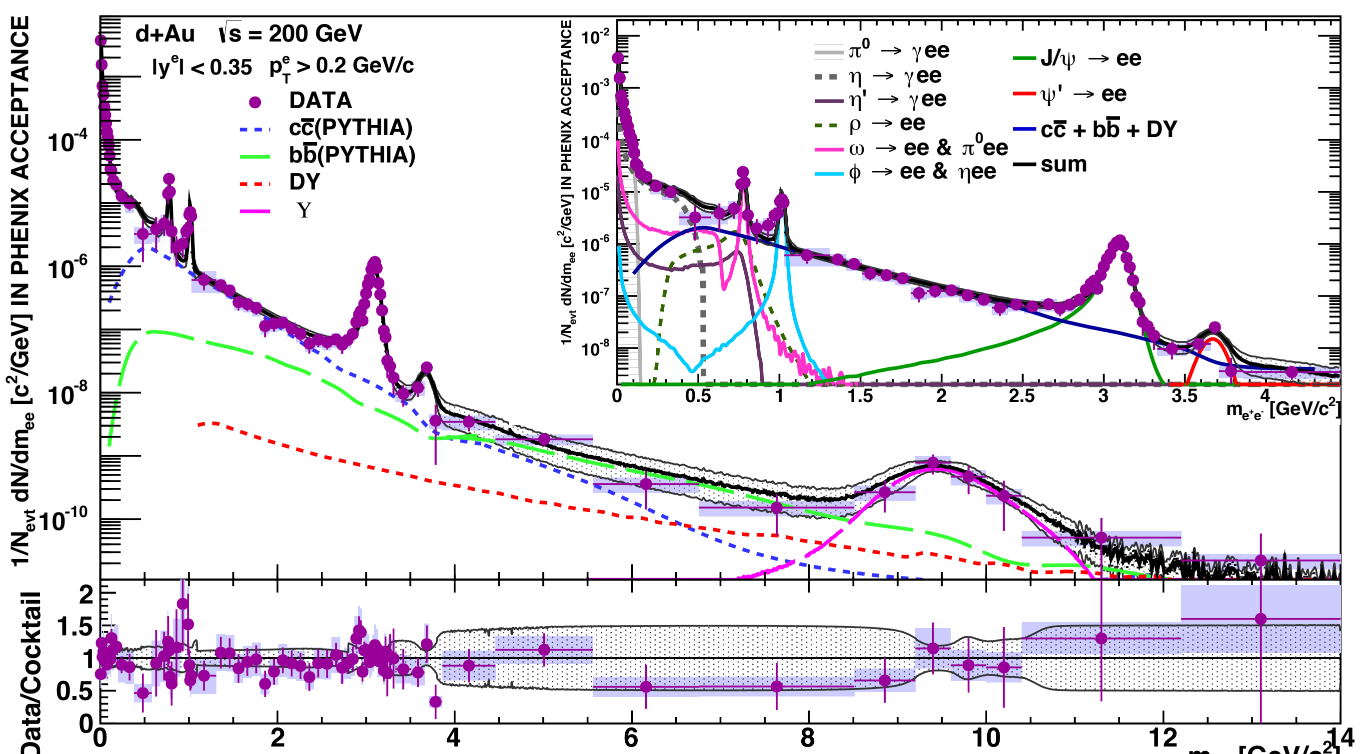
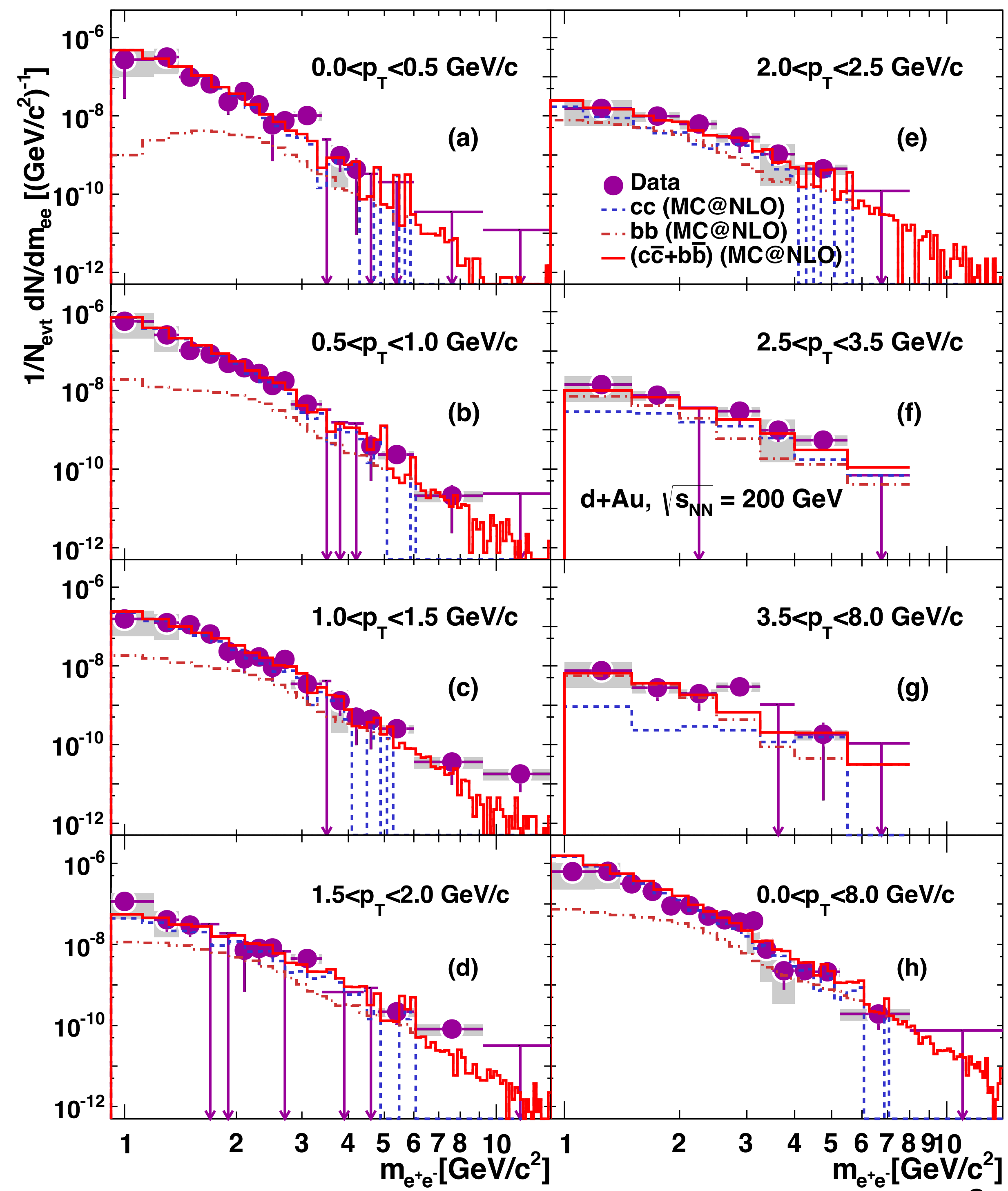
- Extract beauty from fit in mass & p_T
  - σ_{bb}^{NN} = 3.4 ± 0.8 (stat) ± 1.1 (syst) ± 0.11 (model) μb

PHENIX, PRC 91 (2015) 014907





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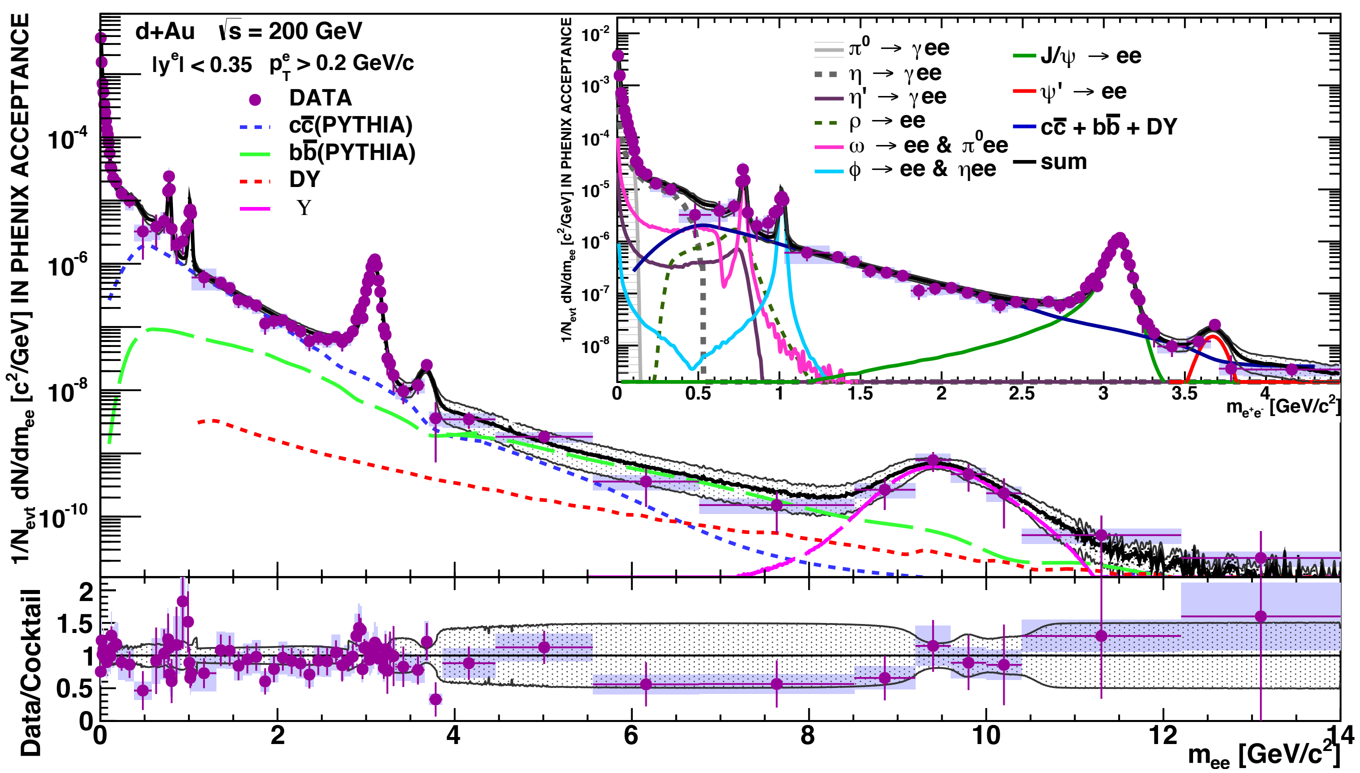
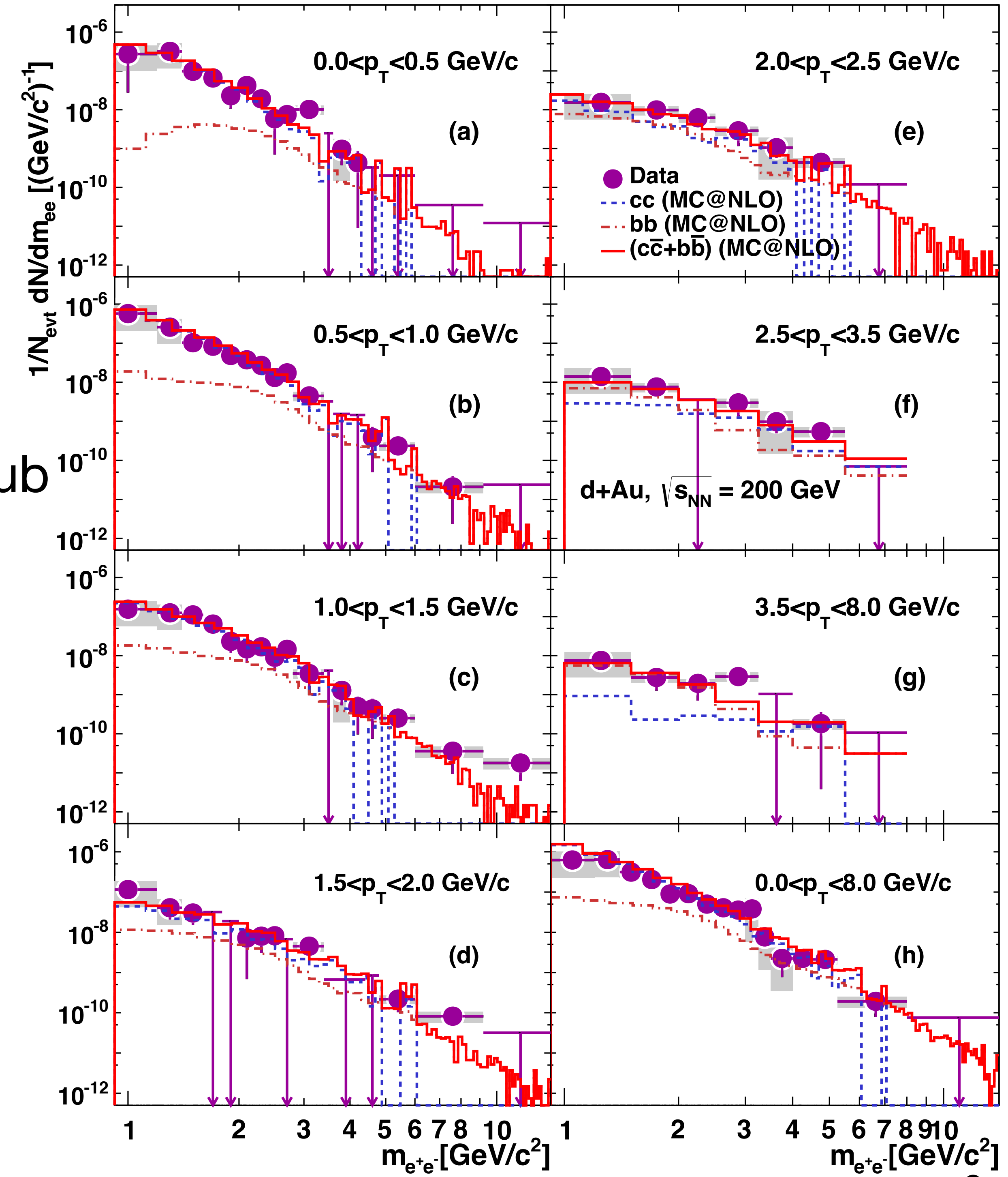
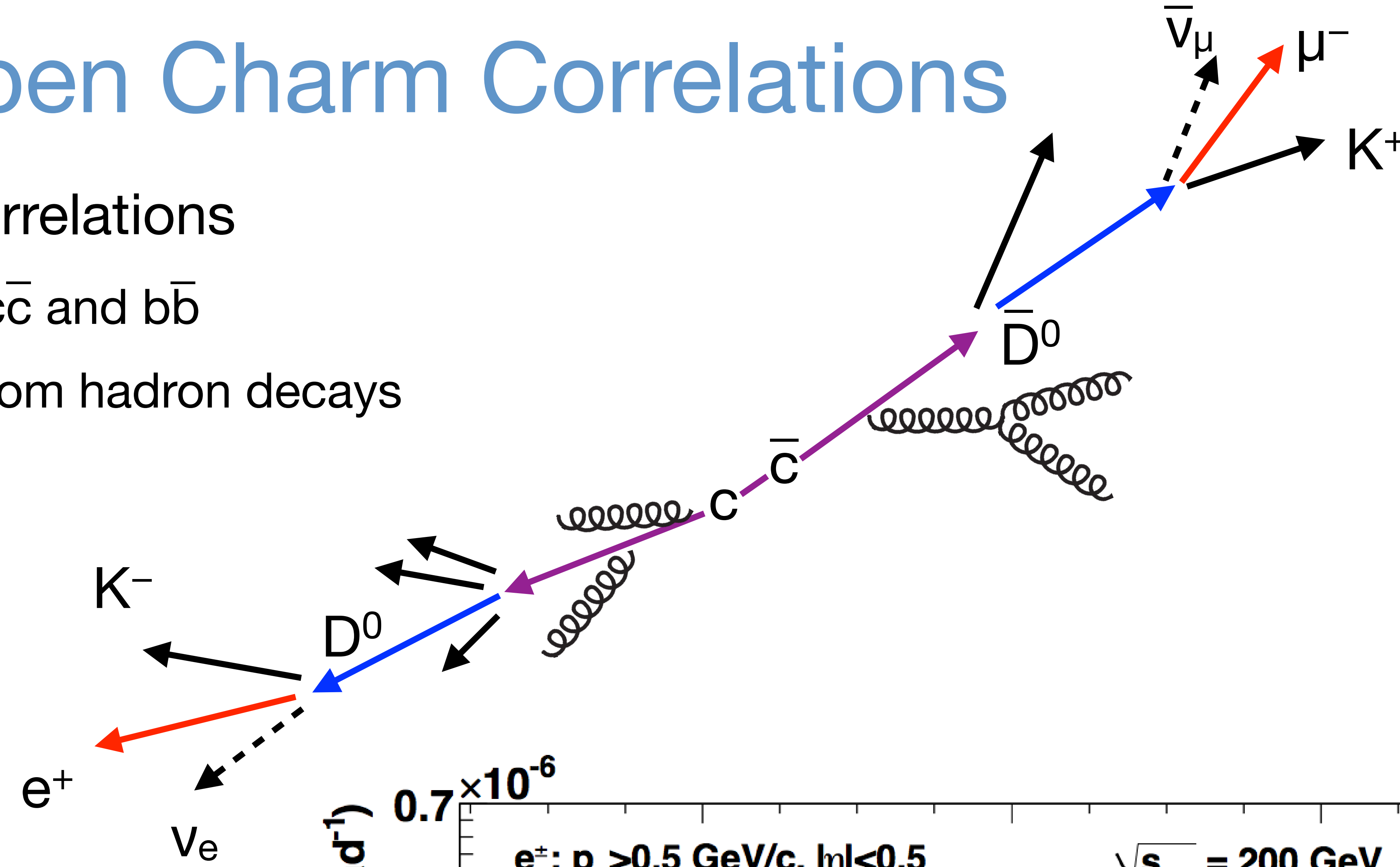
  - σ_{bb}^{NN} = 3.4 ± 0.8 (stat) ± 1.1 (syst) ± 0.11 (model) μb
- Charm very model dependent!
  - PYTHIA: σ_{cc}^{NN} = 385±34(stat)±119(syst) μb
  - MC@NLO: σ_{cc}^{NN} = 958±96(stat)±335(syst) μb



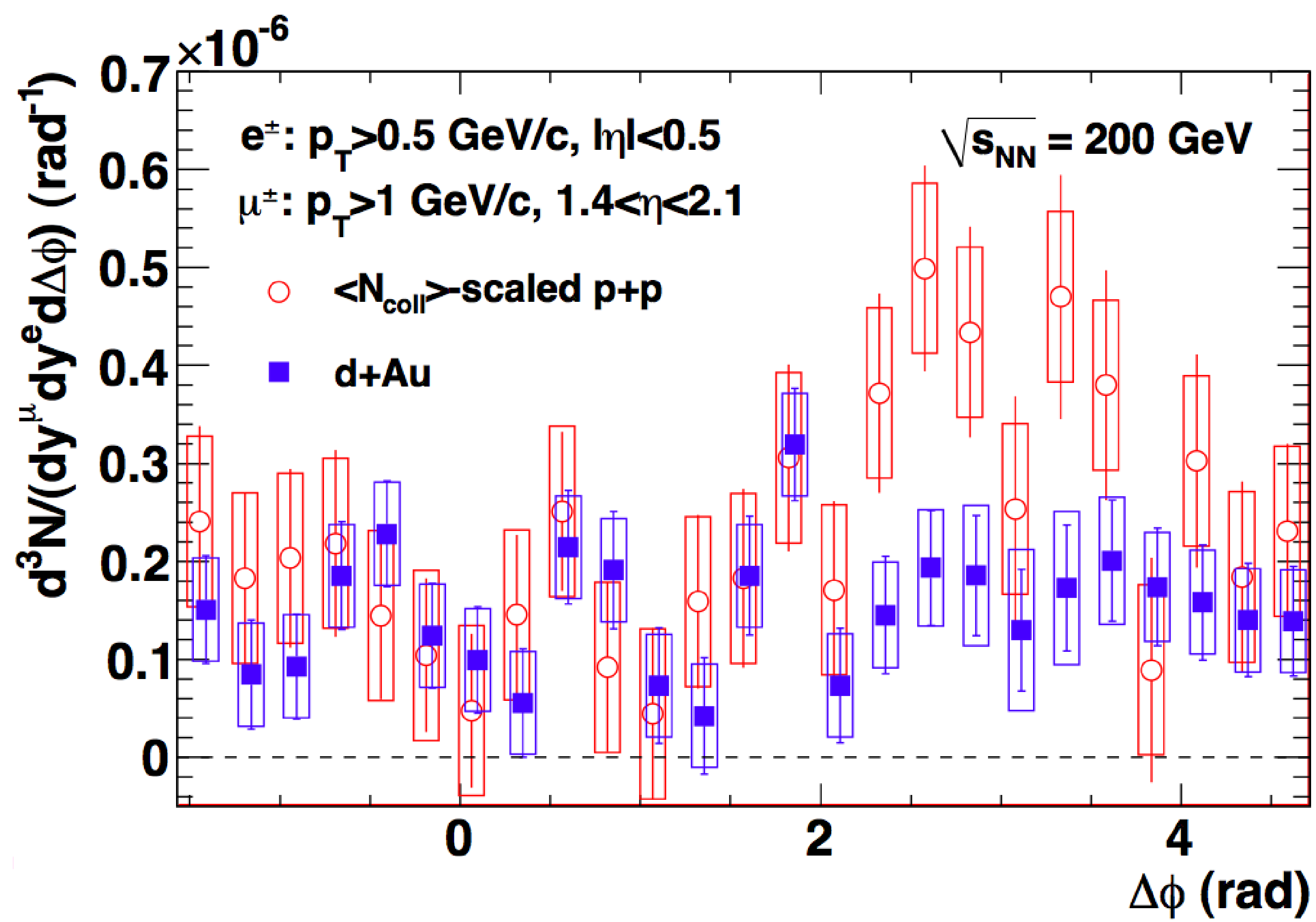


Open Charm Correlations

- Electron-muon correlations
  - Direct access to $c\bar{c}$ and $b\bar{b}$
  - No contribution from hadron decays



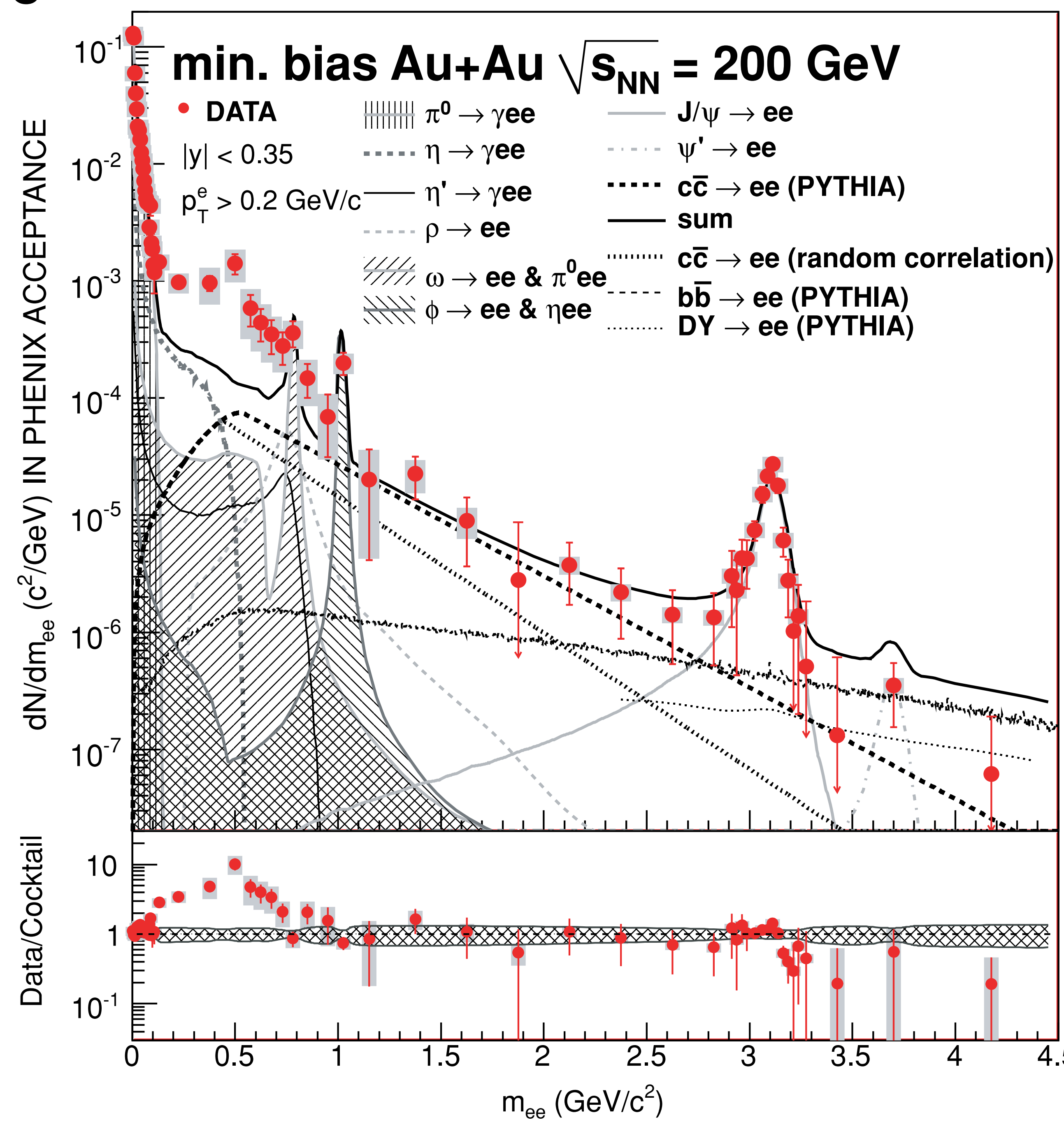
- Current measurement with rapidity gap
- Needs modelling to relate to midrapidity dielectron results



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

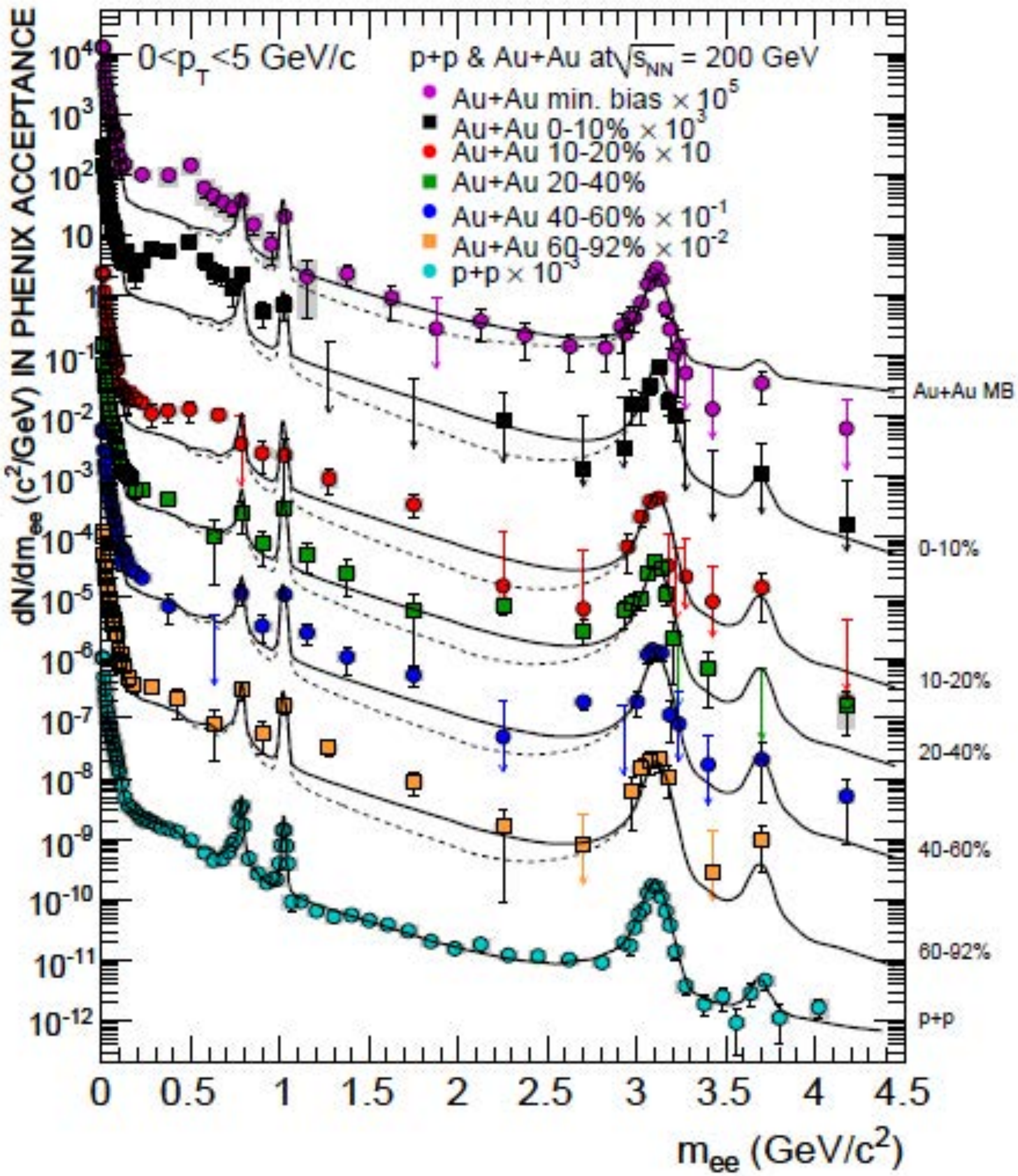
- Low Mass Region:
enhancement 150 < m_{ee} < 750 MeV/c^2
  - 4.7 ± 0.4(stat) ± 1.5(syst) ± 0.9(model)
- Intermediate Mass Region:
dominated by charm (N_{coll} × σ_{cc}^{NN})
  - Input: $d\sigma_{cc}^{NN}/dy$= 123±12±37μb
  - PYTHIA
  - Random $c\bar{c}$ correlation
- Single electron measurement:
  - High p_T suppression of charm
  - Charm flows
- Expected modifications in the pair invariant mass
  - random $c\bar{c}$ correlation?
- Room for thermal contribution?

PHENIX, PRC 81 (2010) 034911



Centrality Dependence

PHENIX, PRC 81 (2010) 034911



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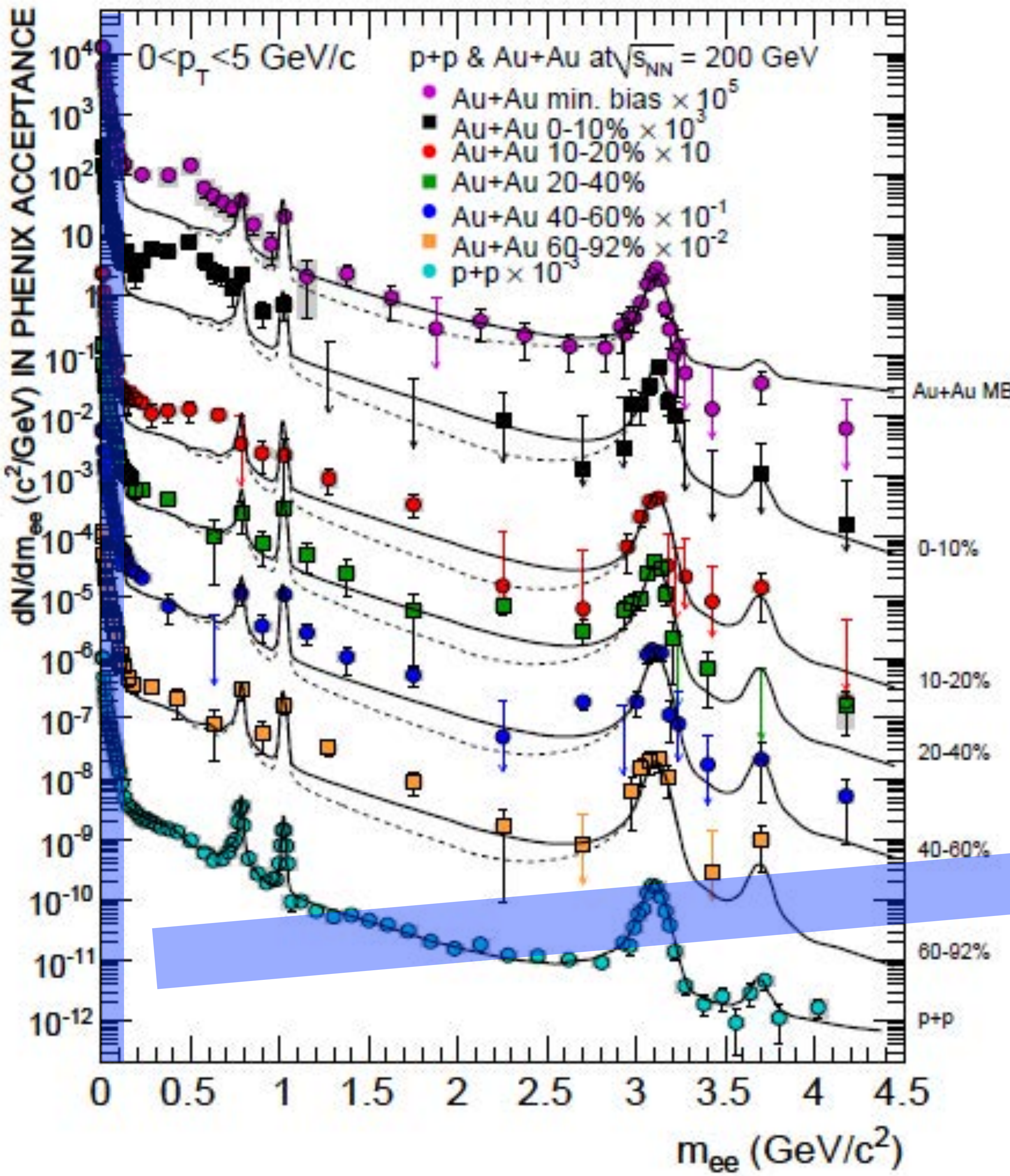

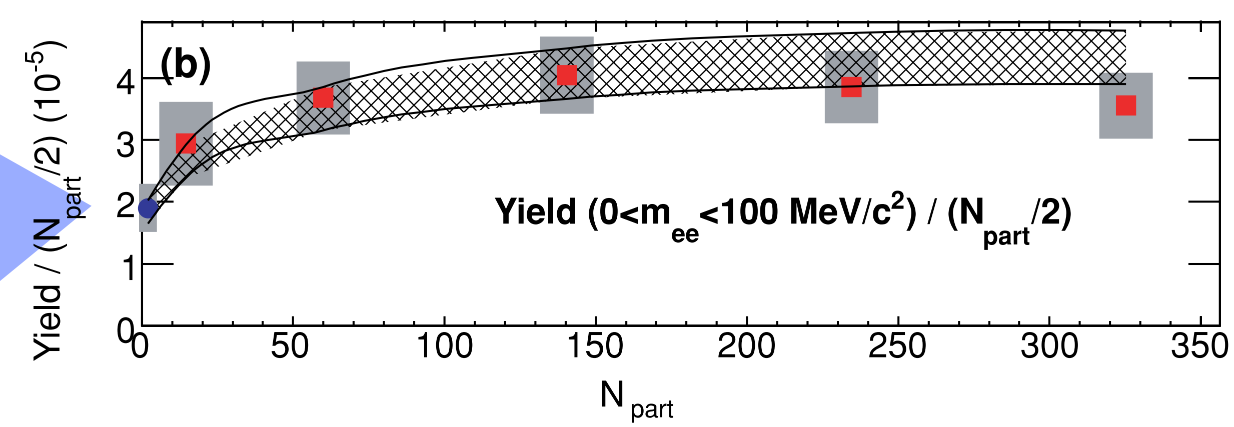

PHENIX

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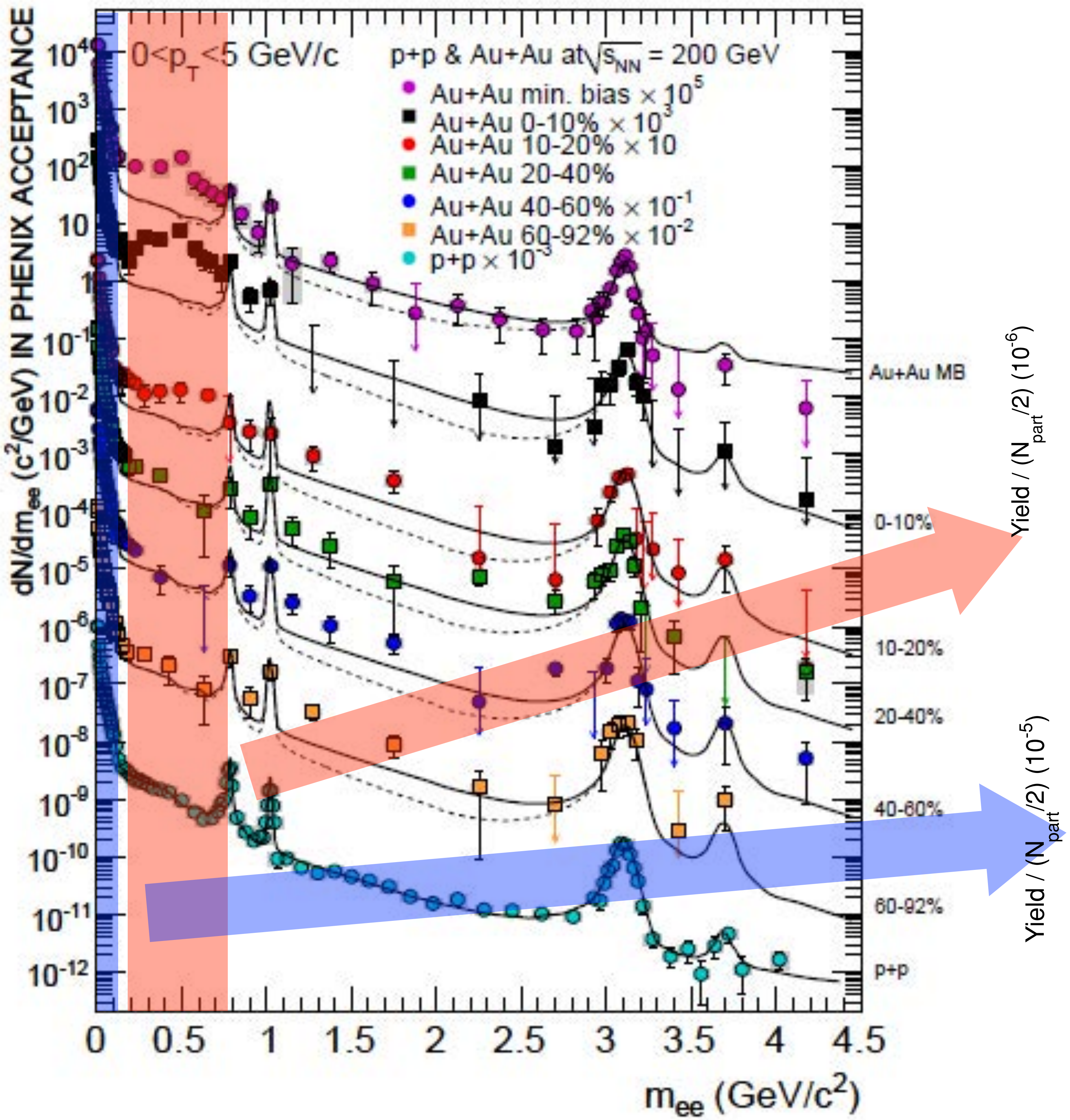

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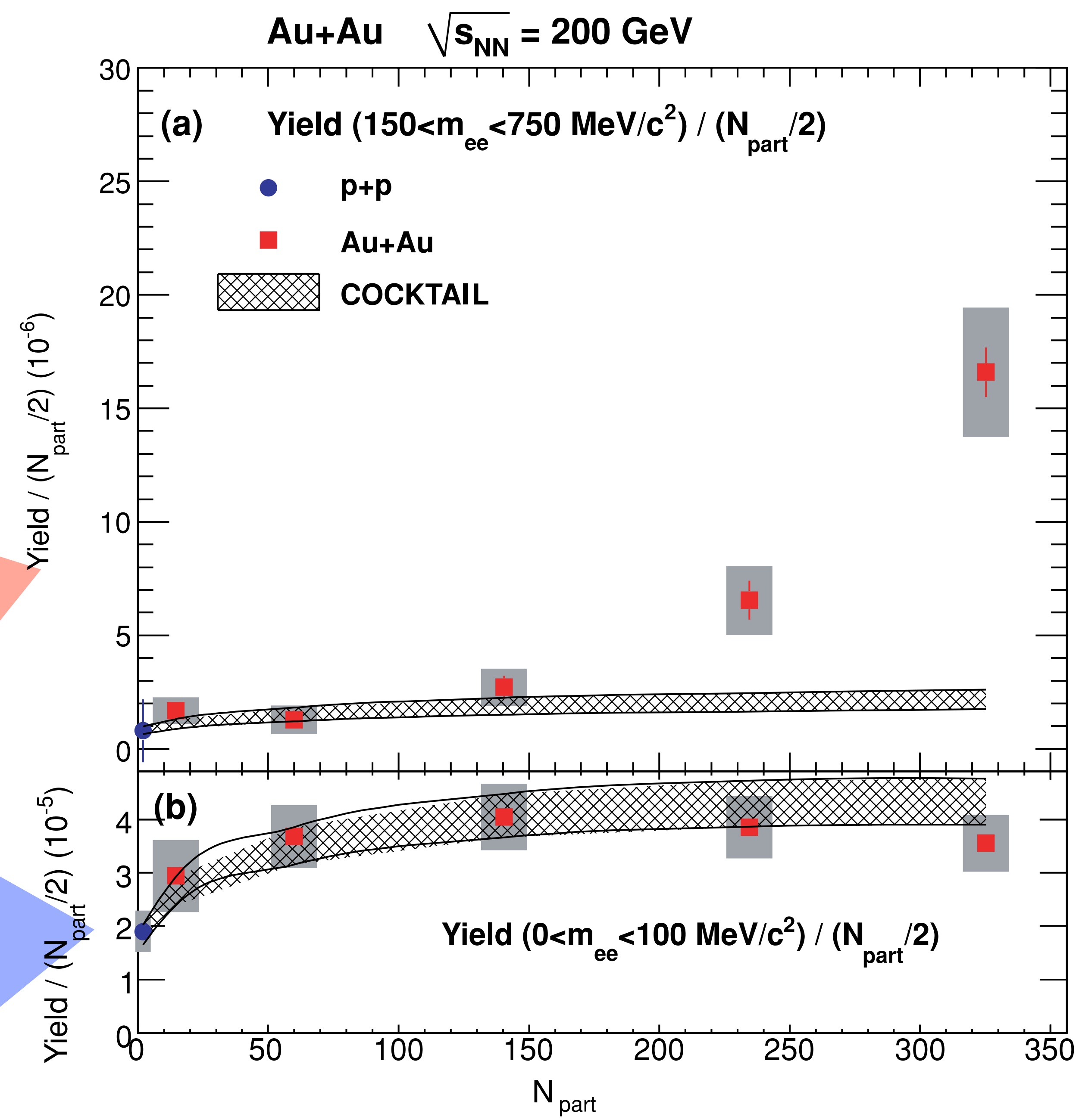
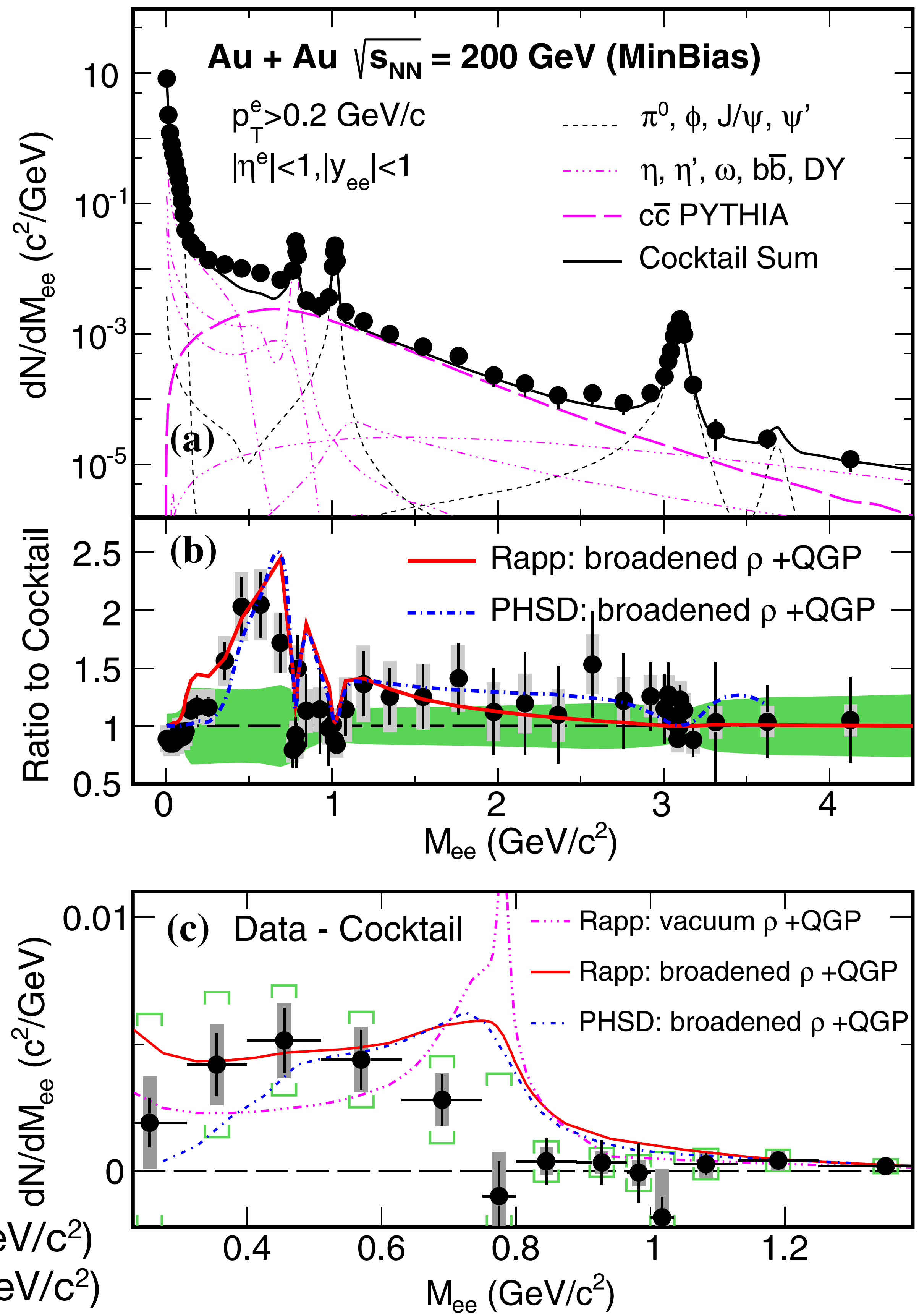
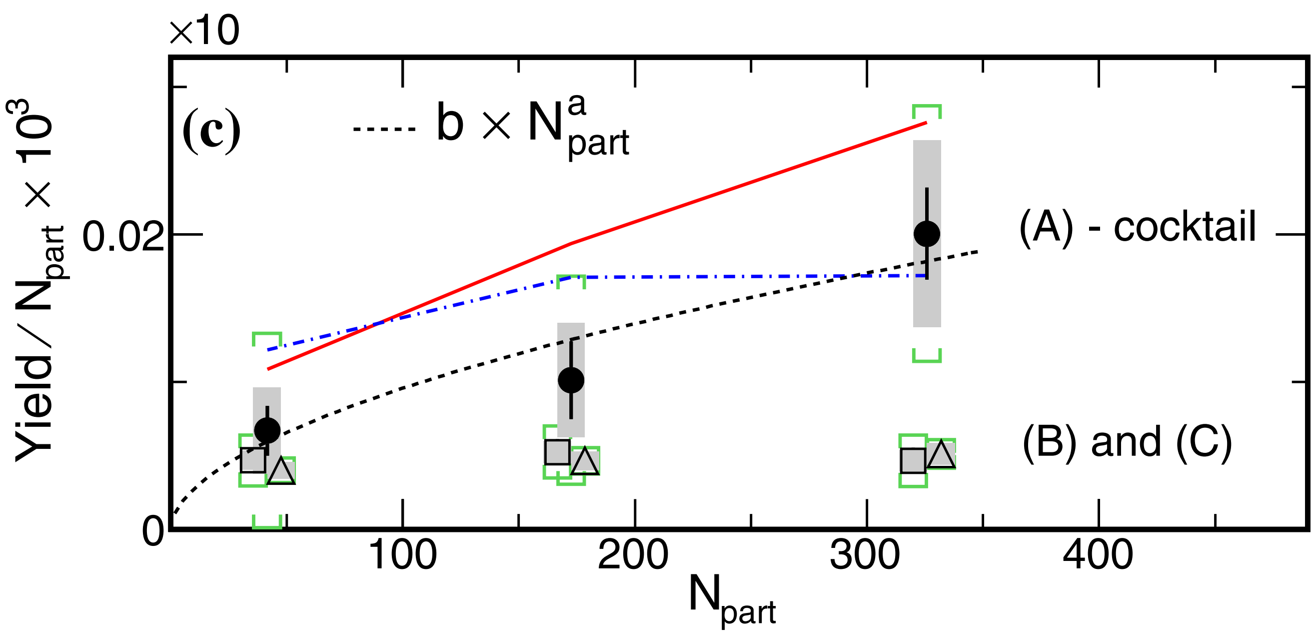


Waiting for HBD results?!

Low Mass Dileptons from STAR

- STAR observes smaller enhancement than PHENIX
  - In better agreement with models that involve broadening of ρ spectral function
  - Caveat: 1.4x larger charm cross sections used in cocktail: $d\sigma/dy = 171 \pm 26\ \mu b$
  - Slower increase with centrality: $\text{Yield}/N_{part} \sim N_{part}^{0.54\pm0.18}$



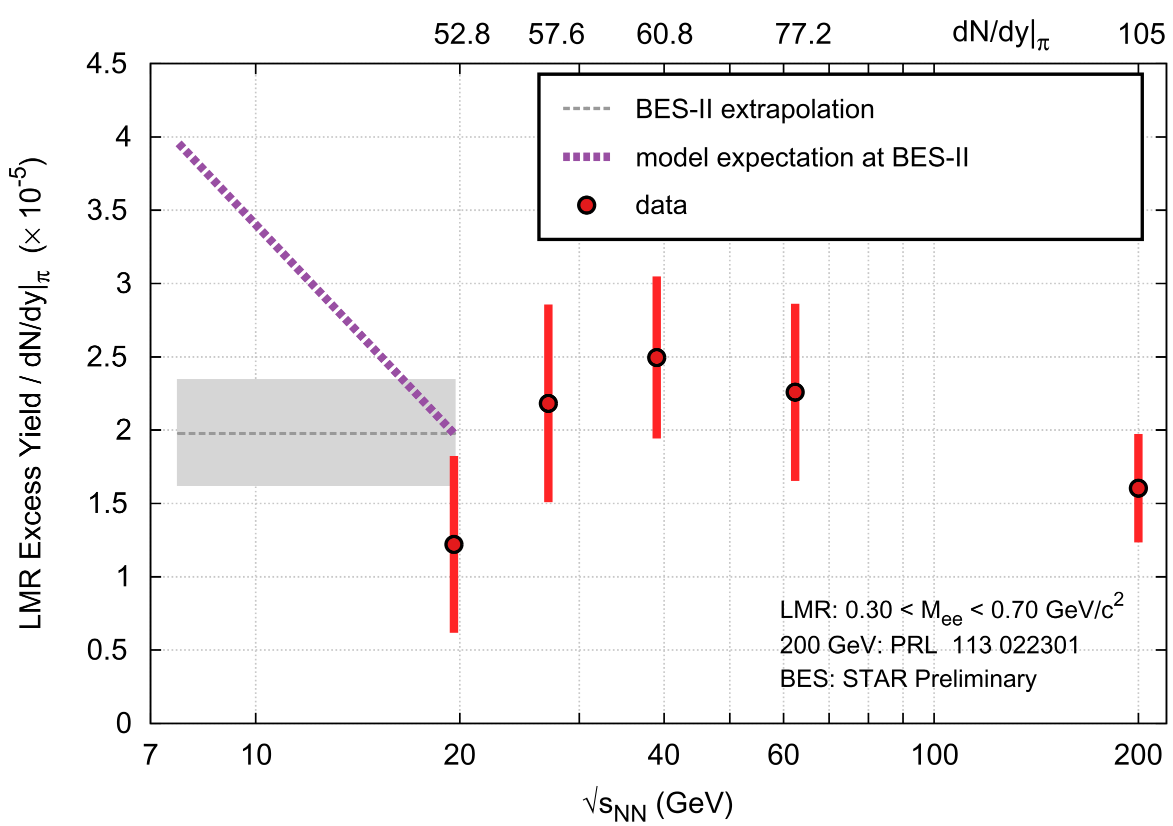


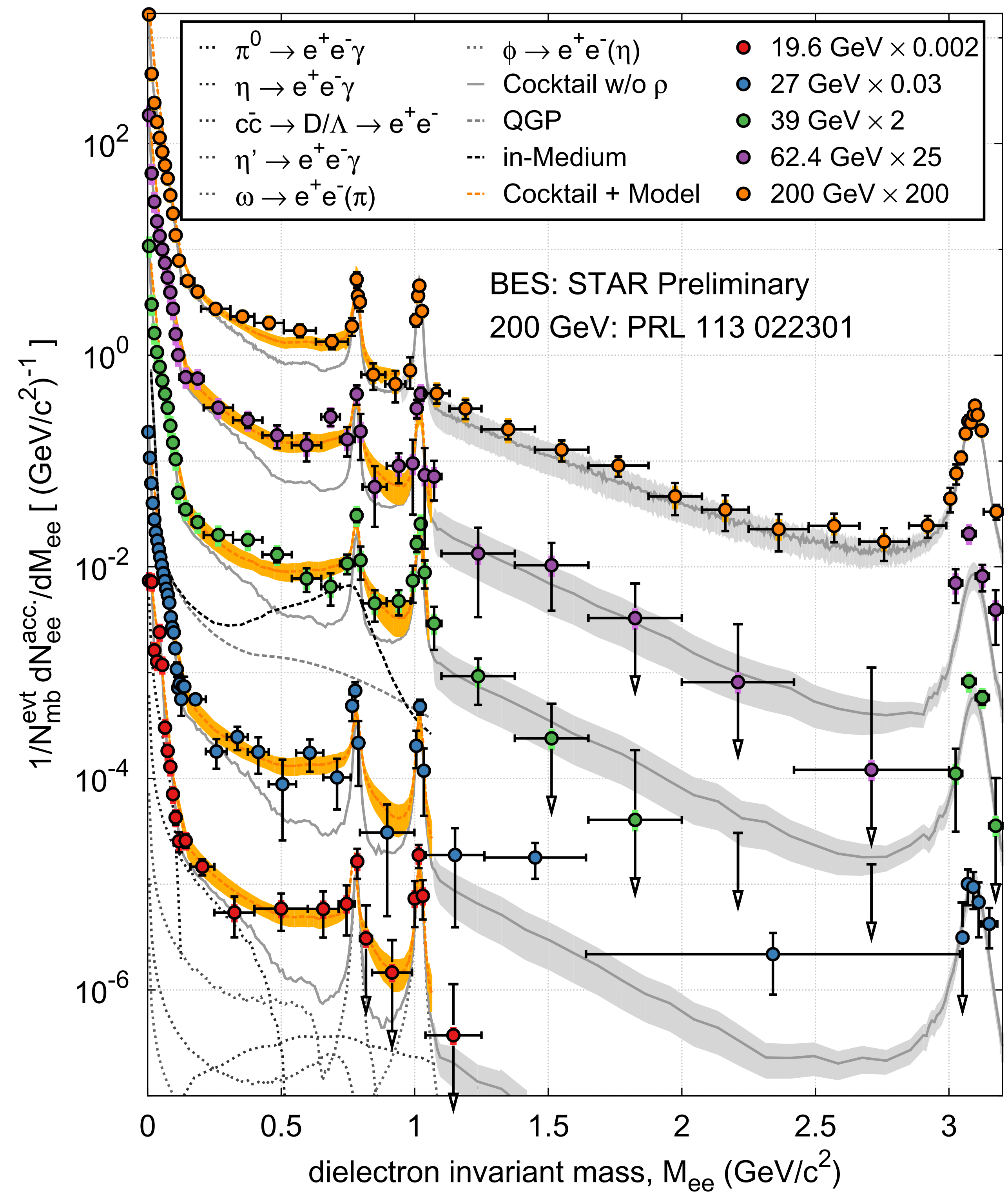
STAR, PRL 113 (2014) 022301

A: ρ-like (0.3–0.76 GeV/c^2)
B: ω-like (0.76–0.8 GeV/c^2)
C: ϕ-like (0.98–1.05 GeV/c^2)

Low Mass Dileptons: BES

- STAR measured low mass dileptons at five different $\sqrt{s_{NN}}$
  - no strong energy dependence of enhancement
  - total baryon density comparable at 20 and 200 GeV
    - increases only at even lower $\sqrt{s_{NN}}$

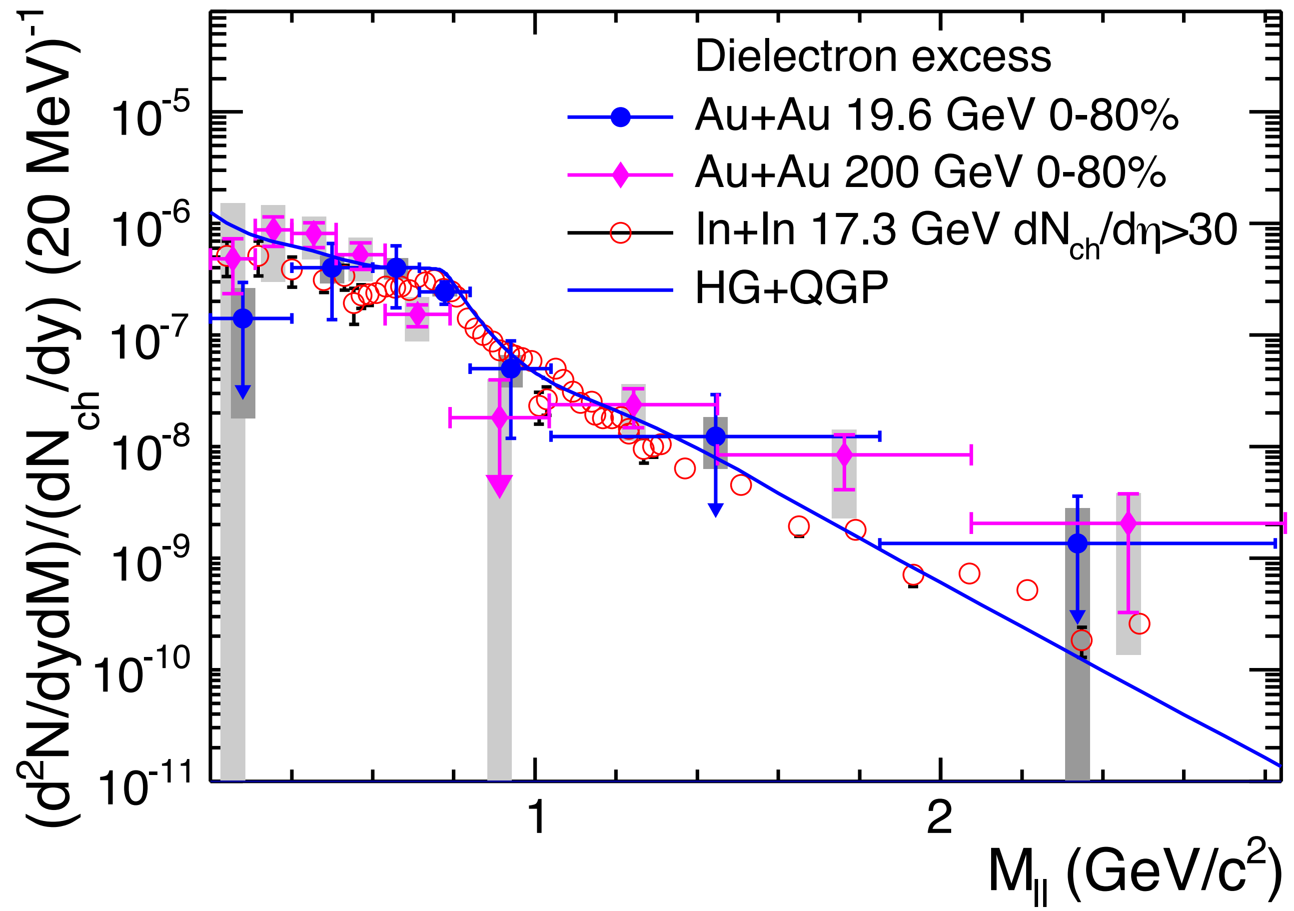


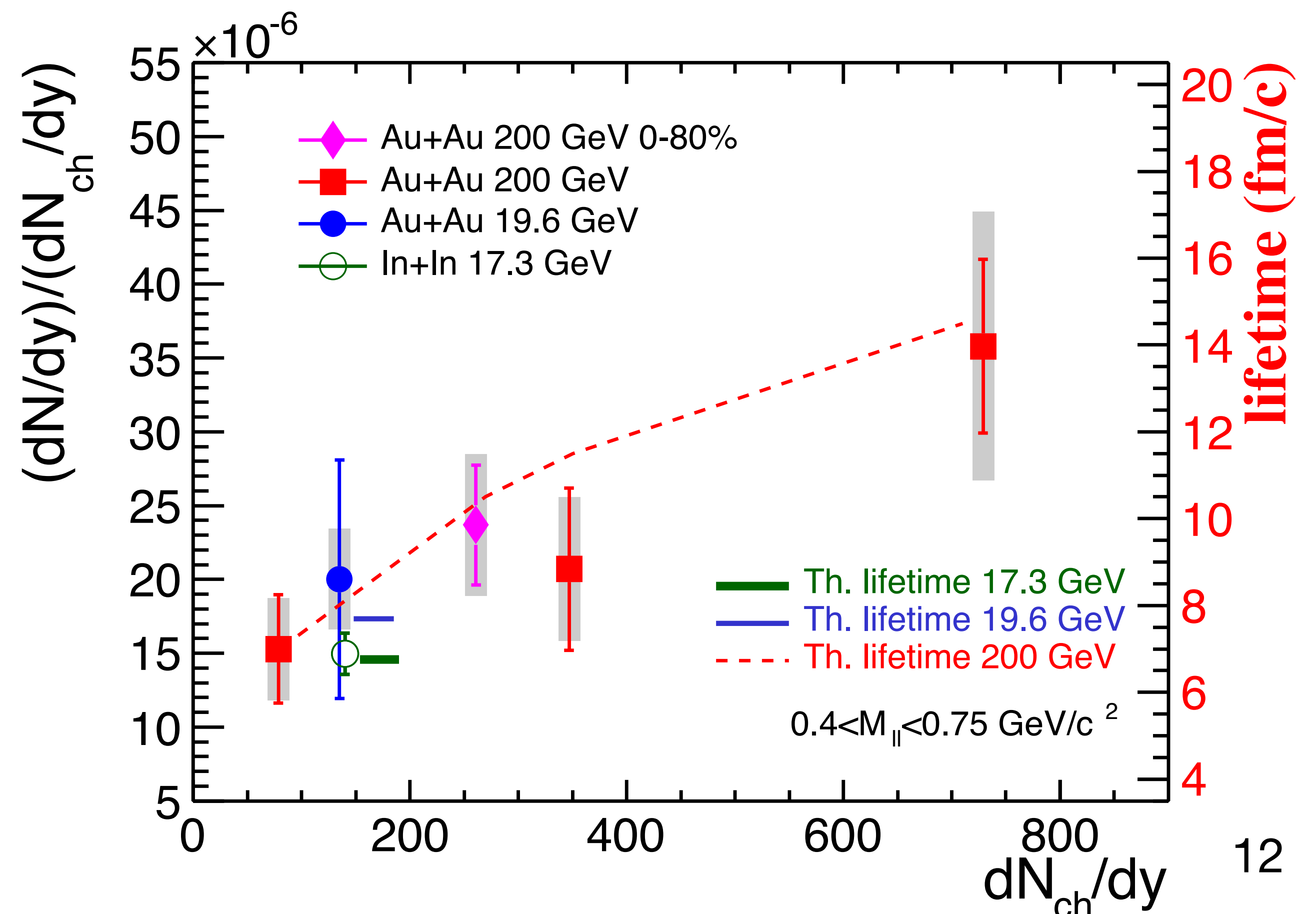


STAR, PRL 113 (2014) 022301
STAR (Preliminary)

Low Mass Dileptons: BES

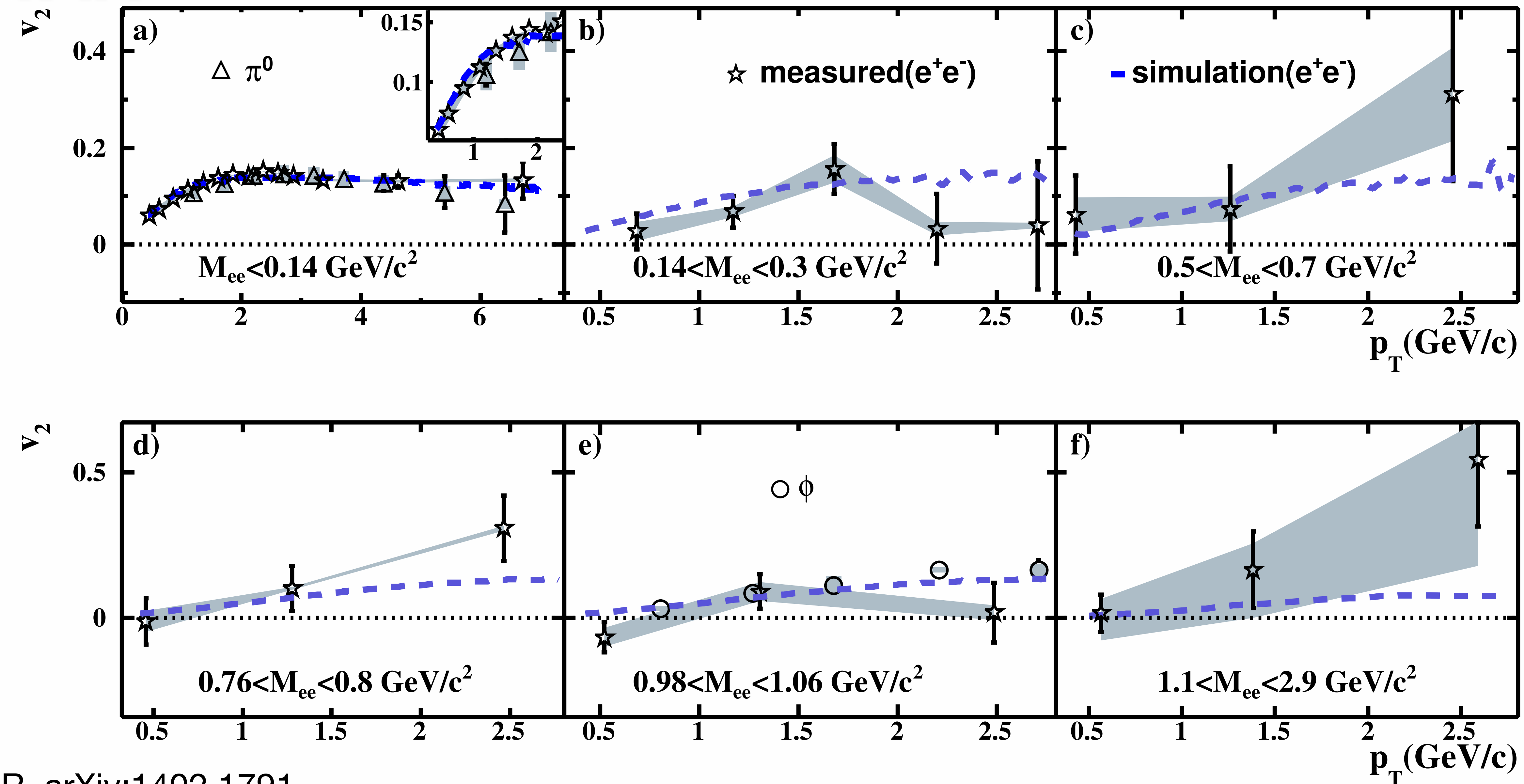
- Enhancement compared at 19.6 and 200 GeV
  - Fully acceptance corrected
- Spectrum at low energy consistent with NA60 result
- In contrast to NA60
  - did not separate prompt from non-prompt charm decay experimentally
  - subtracted charm and Drell-Yan with PYTHIA
- Indication of energy and centrality dependence of low mass enhancement
  - very similar total baryon density
  - sign of longer medium lifetime





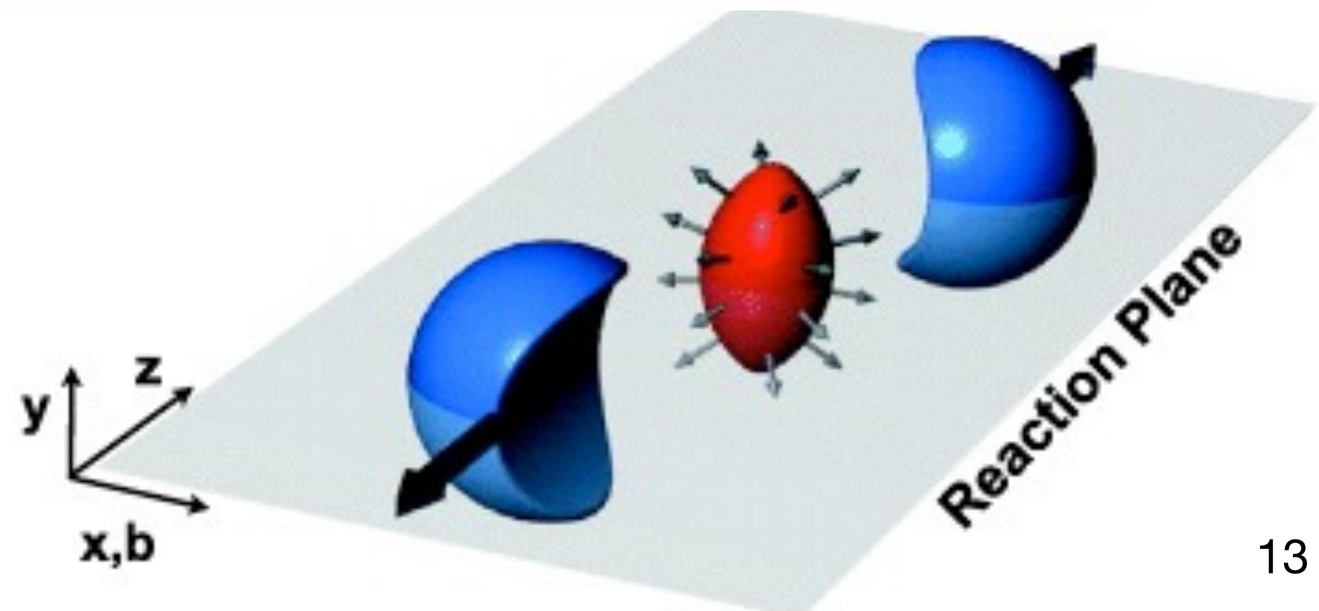
STAR, arXiv:1501.05341

Azimuthal Anisotropy



STAR, arXiv:1402.1791
(submitted to PRC)

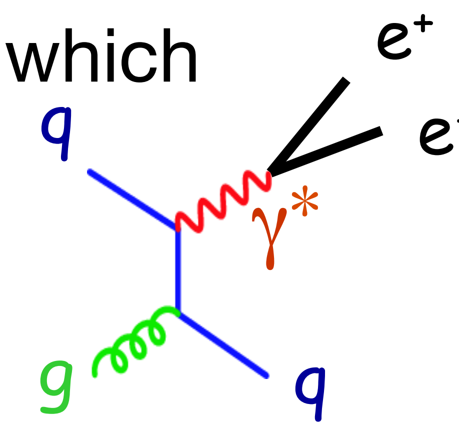
- Dielectron v_2 consistent with cocktail
- More data needed to extract v_2 of low mass enhancement



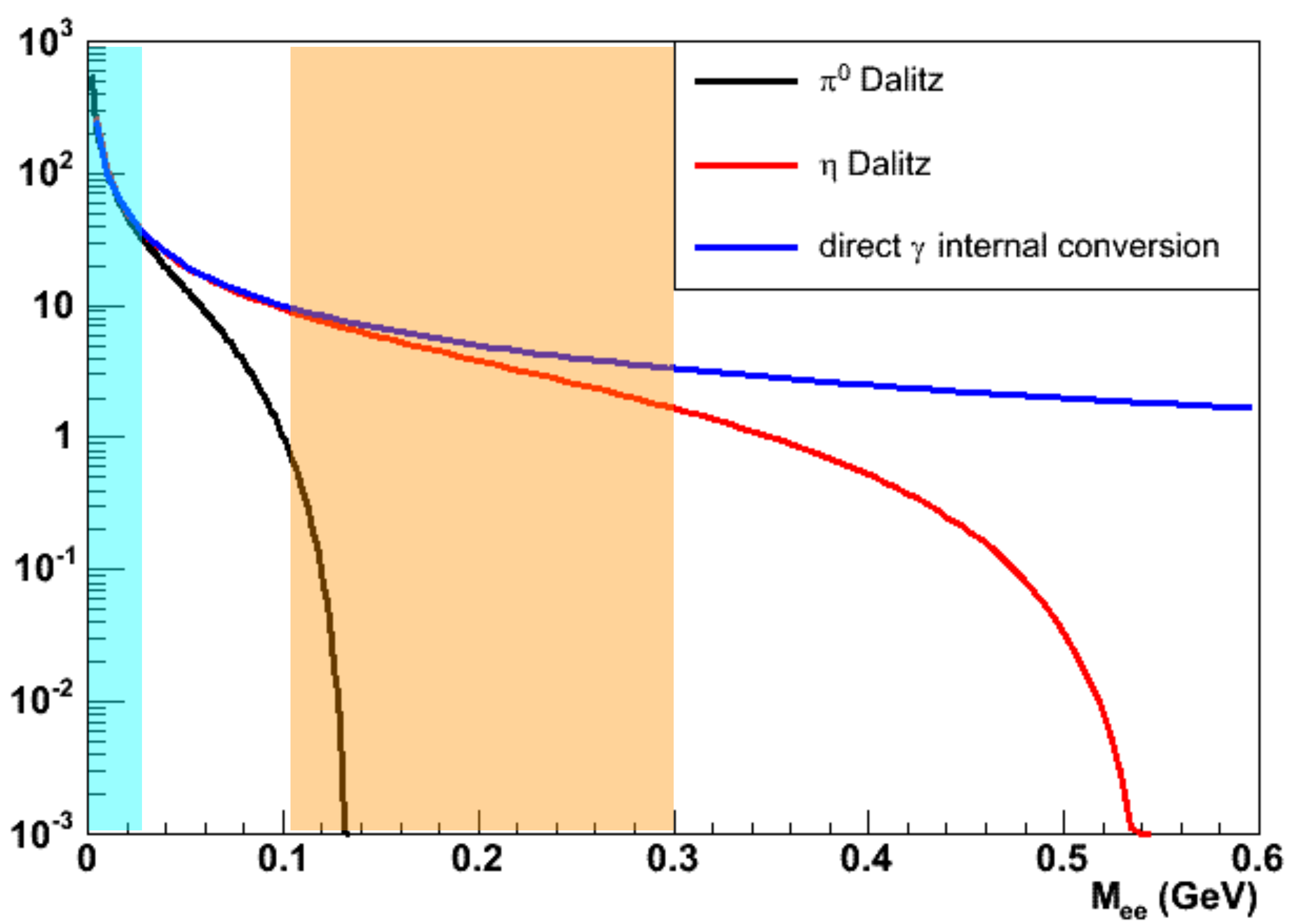
Virtual Photons

- Any source of real γ can emit γ* with very low mass
- If the Q^2 (= m^2) of virtual photon is sufficiently small, the source strength should be the same
- The ratio of real photon and quasi-real photon can be calculated by QED

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



Kroll-Wada equation: $$\frac{d^2N}{dM_{ee}dN_\gamma} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}S$$



- Case of Hadrons:

$$S = \left|F(M_{ee}^2)\right|^2\left(1-\frac{M_{ee}^2}{M_{\mathrm{hadron}}^2}\right)^3$$

  - obviously S = 0 at $M_{ee} > M_{hadron}$

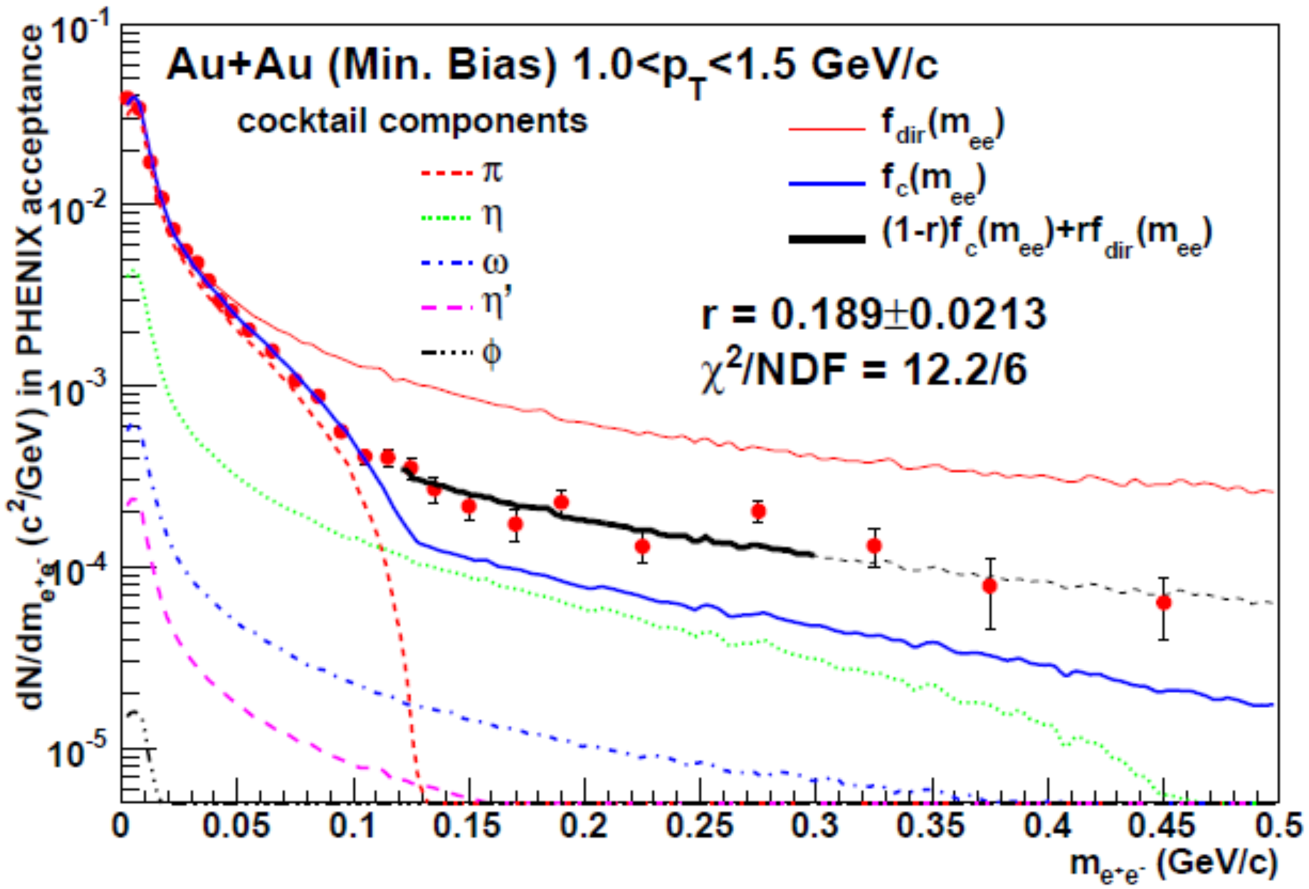
- Case of γ*:
  - if $p_T^2 \gg M_{ee}^2$: S = 1

- Possible to separate hadron decay components from real signal in the proper mass window

Fitting the direct γ* fraction

- r = direct γ*/inclusive γ*
  determined by fitting the following function for each p_T bin

$$f_{\text{data}}(M_{ee}) = (1-r)\cdot f_{\text{cocktail}}(M_{ee}) + r\cdot f_{\text{direct}}(M_{ee})$$



- f_{direct} given by Kroll-Wada formula with S = 1
- f_{cocktail} given by cocktail components
- Normalized to data for m < 30 MeV/c^2
- Fit in 120–300 MeV/c^2 (insensitive to π^0 yield)
- Assuming direct γ* mass shape: χ^2/NDF = 12.2/6

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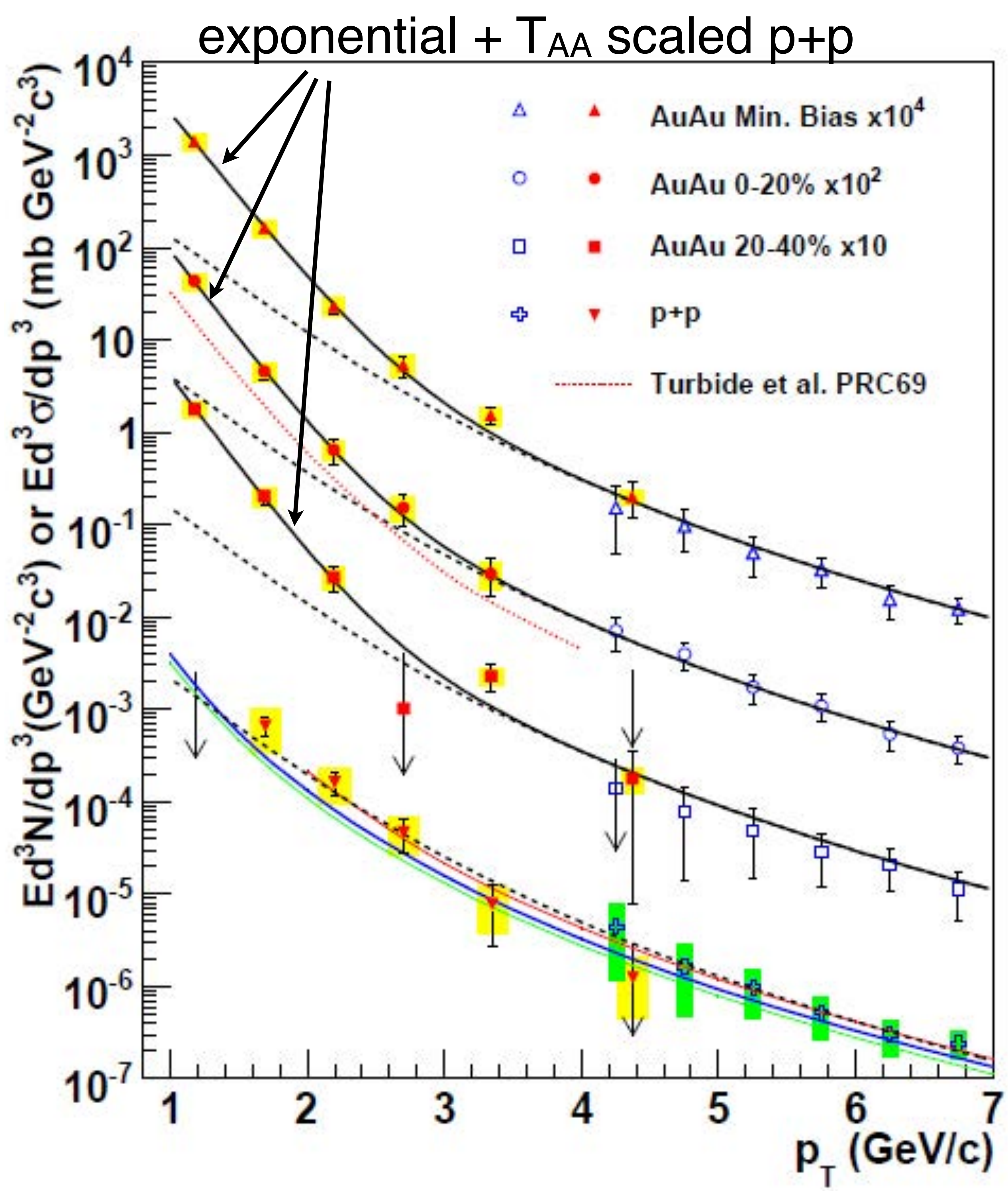
Thermal Photons

- Direct photon measurements
  - real (p_T > 4GeV)
  - virtual (1 < p_T < 4 GeV & m_{ee} < 300 MeV)
- p+p: good agreement with NLO pQCD down to p_T = 1 GeV/c
- Au+Au = pQCD + exponential
  - T_{ave} = 221 ± 19 (stat) ± 19 (syst) MeV
- In agreement with hydrodynamic models:
  - Assume formation of a hot QGP with: 300 MeV < T_{init} < 600 MeV 0.6 fm/c < τ_0 < 0.15 fm/c



well above the critical temperature of 170 MeV predicted by lattice QCD

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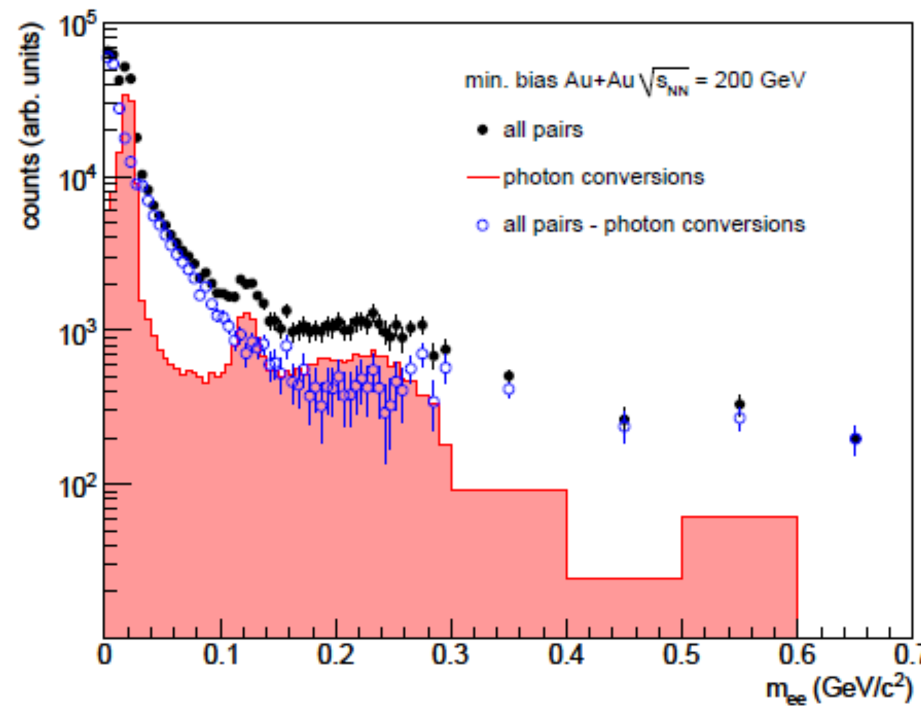
Internal vs. External Conversions

- Identify real photons via conversion pairs
- Tag photons from π^0 decays
  - look for an em. shower in the calorimeter and reconstruct $\gamma\gamma$ mass
  - conversion probability cancels



PHENIX, arXiv:1405.3940
(submitted to PRC)

PHENIX Internal vs. External Conversions

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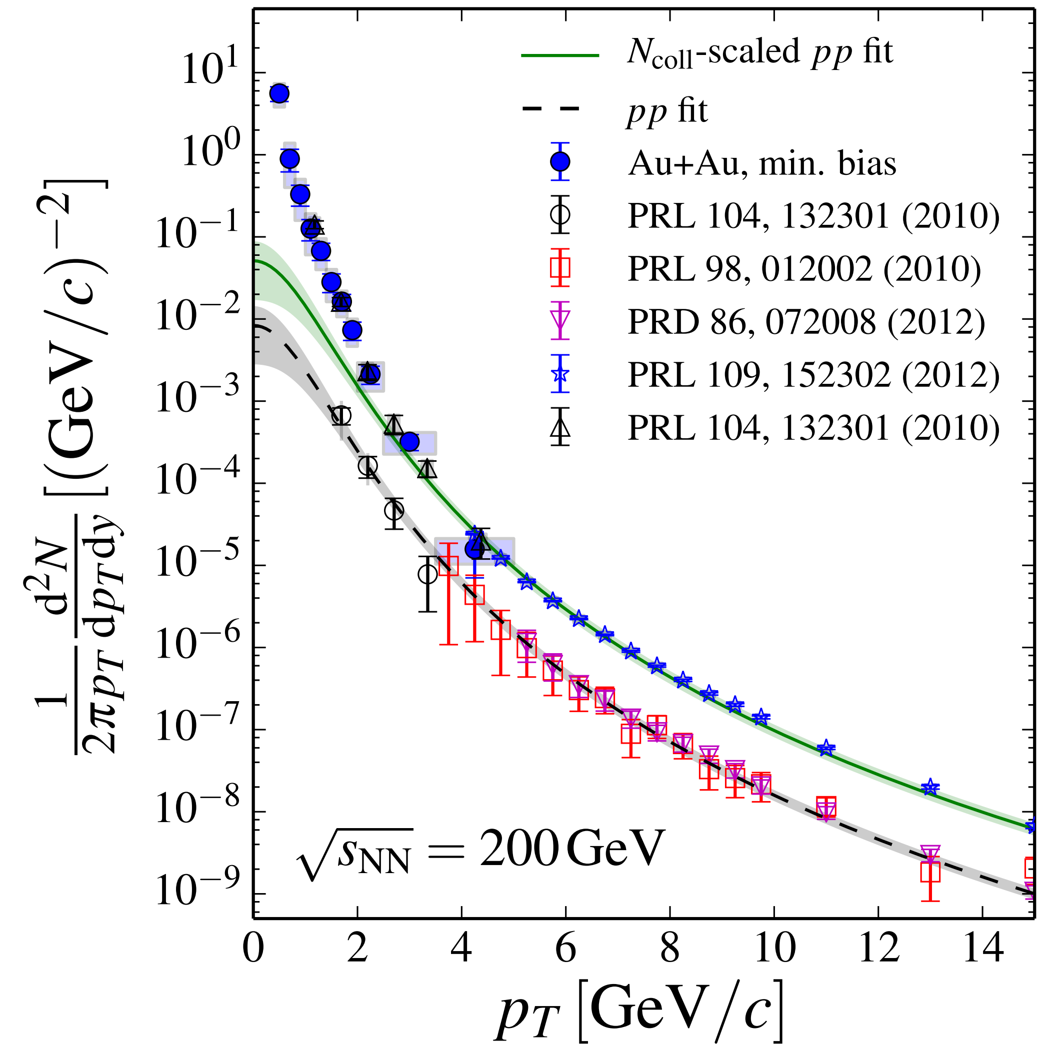
  - validates internal conversion method and extrapolation to m = 0



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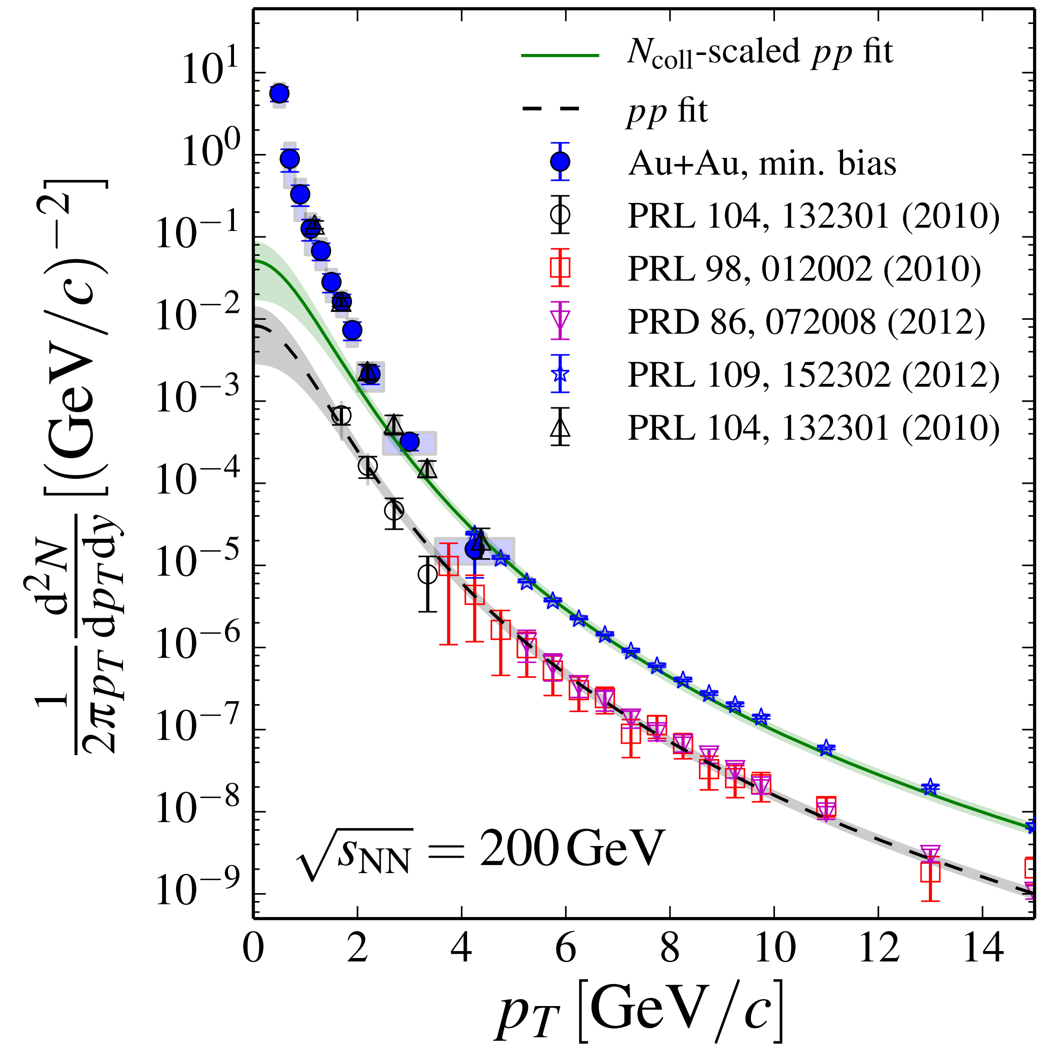
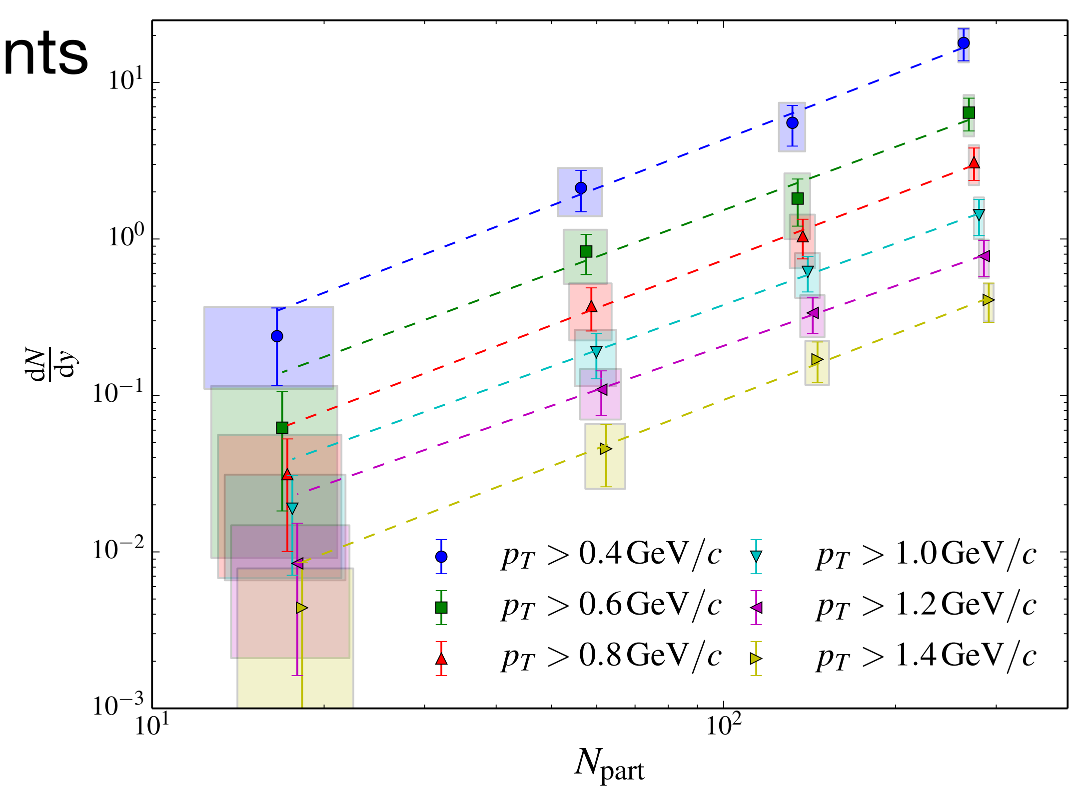
  - look for an em. shower in the calorimeter and reconstruct γγ mass
  - conversion probability cancels
- Matches result of internal conversions
  - validates internal conversion method and extrapolation to m = 0
- Excess scales with ~$N_{part}^{1.5}$
  - not an artefact of low p_T points

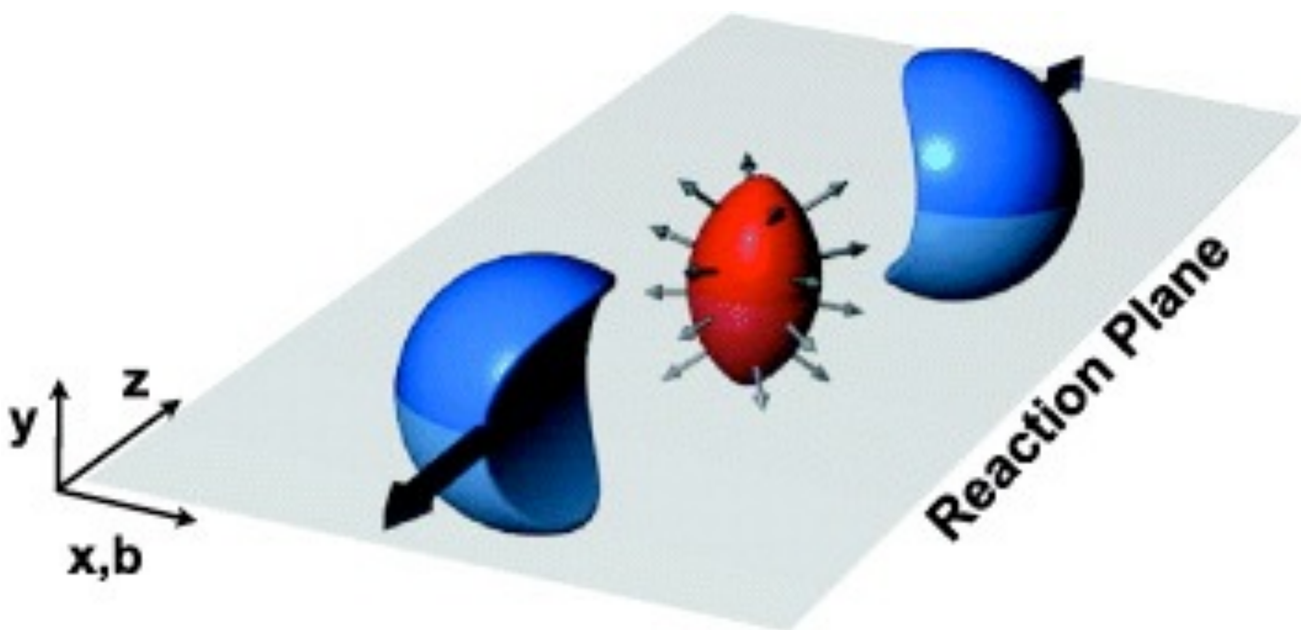




PHENIX, arXiv:1405.3940
(submitted to PRC)

Thermal Photon v_2

- Elliptic flow of direct photons at low p_T similar to π^0 flow
  - direct photons emitted from the late stage
  - hard to combine with large rates which suggest early emission from the hot phase



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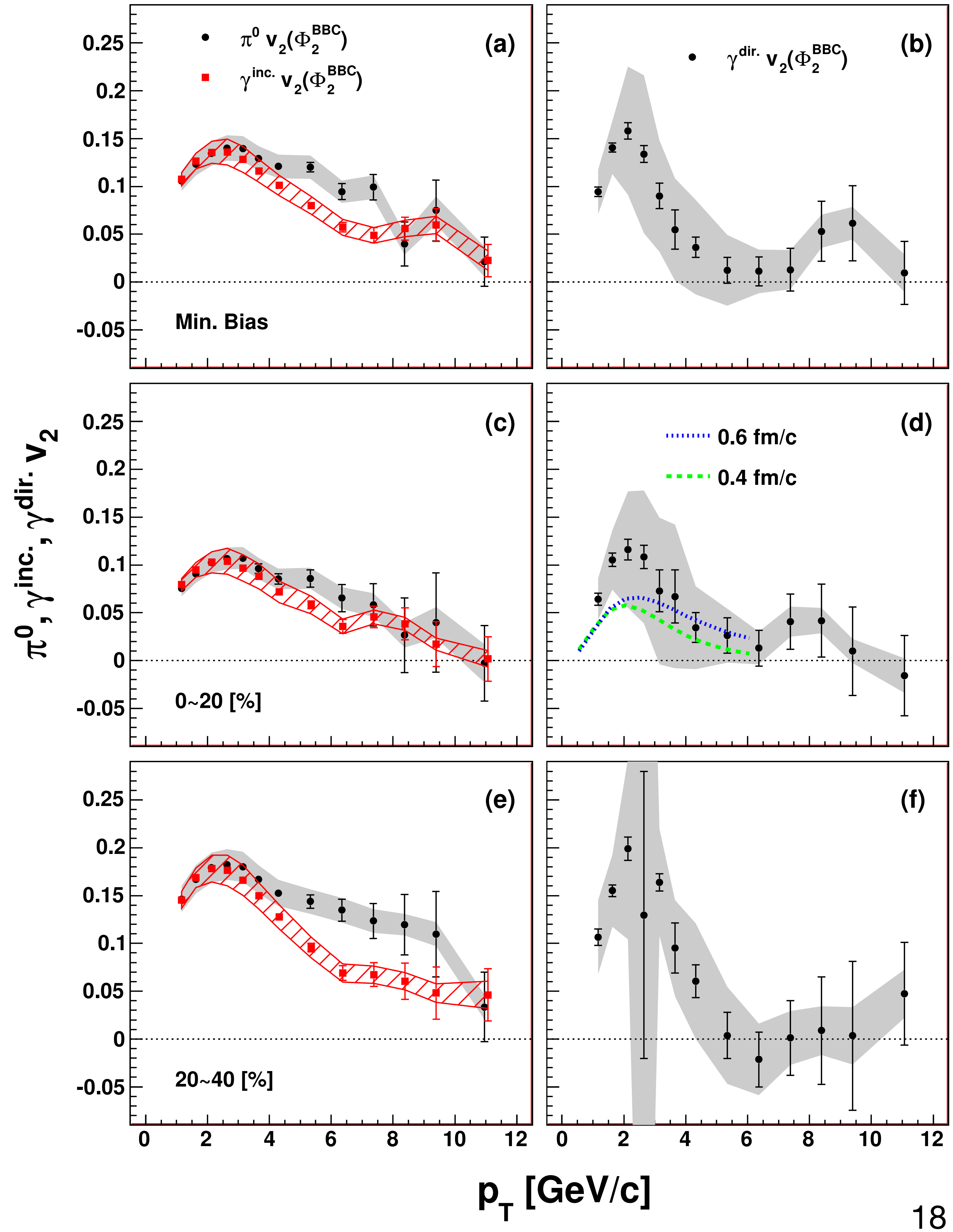
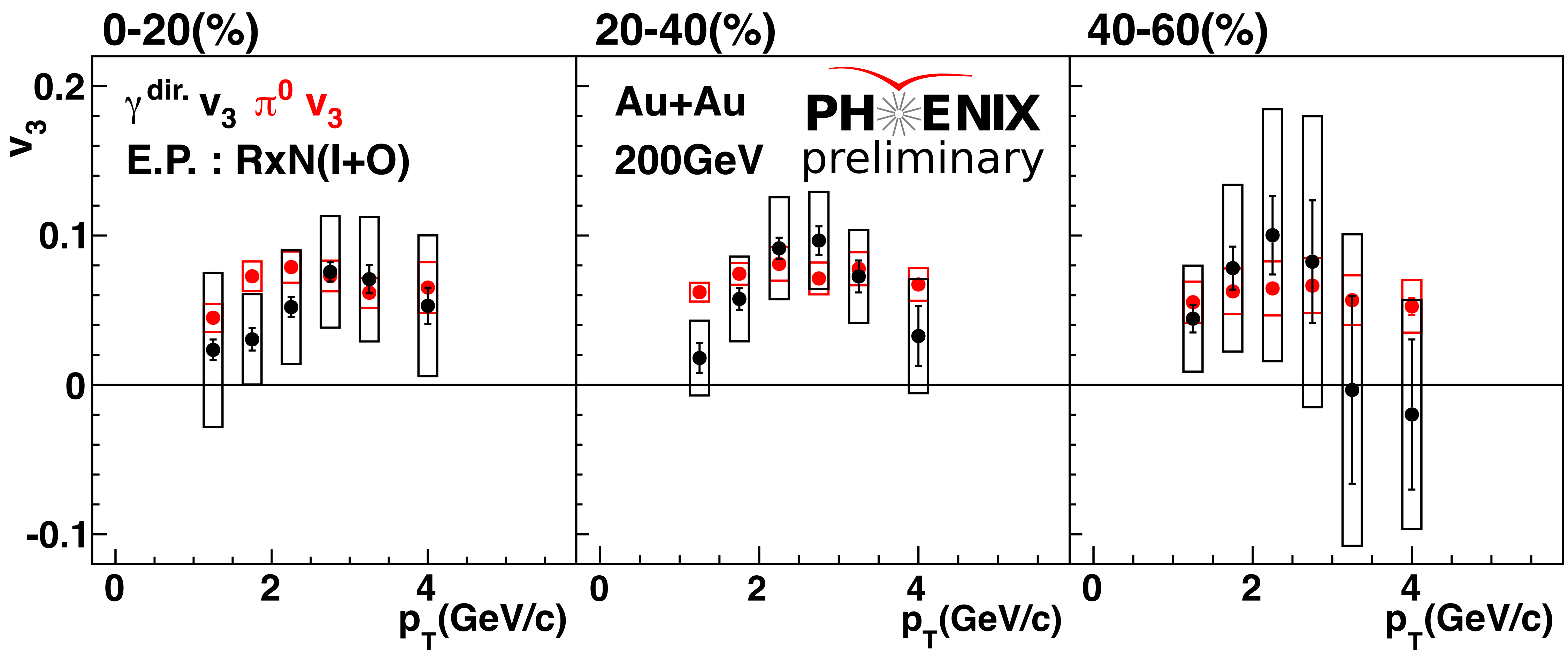


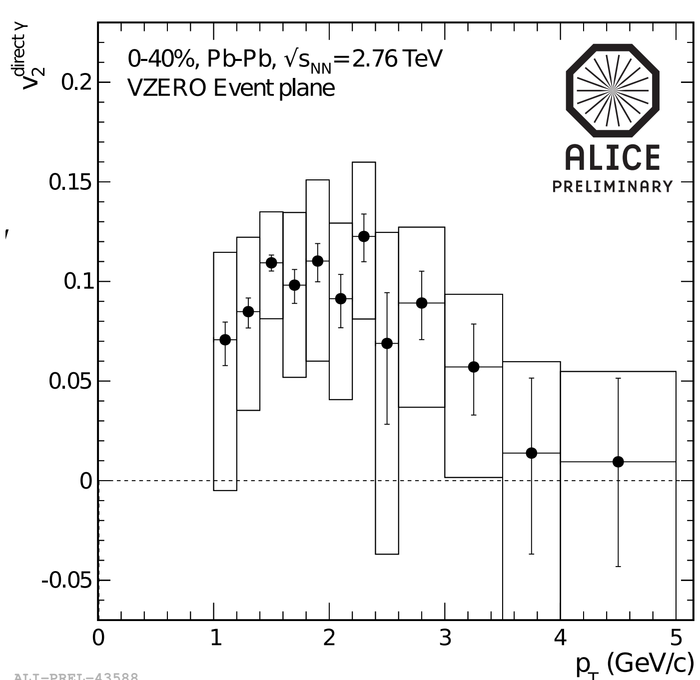
Thermal Photon v_3

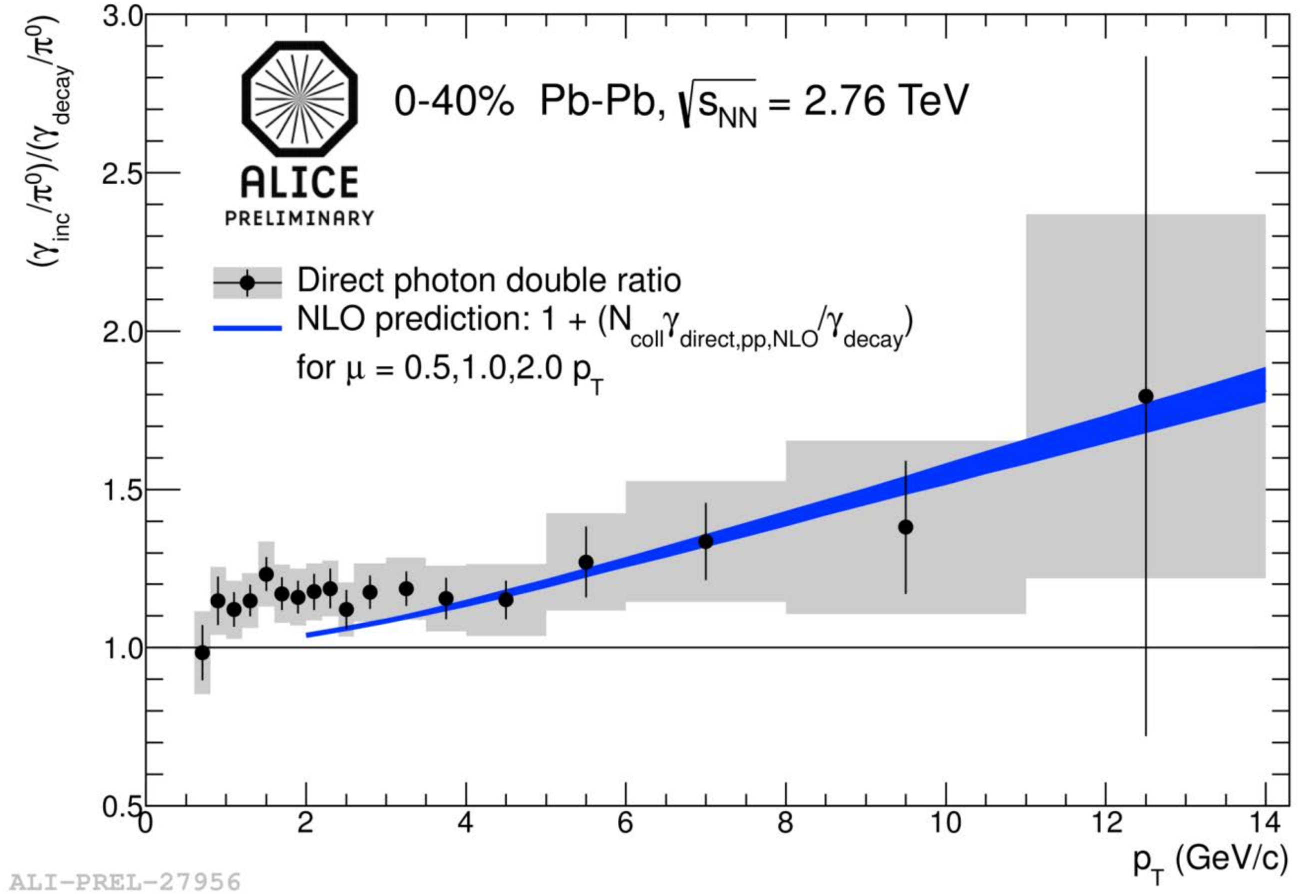


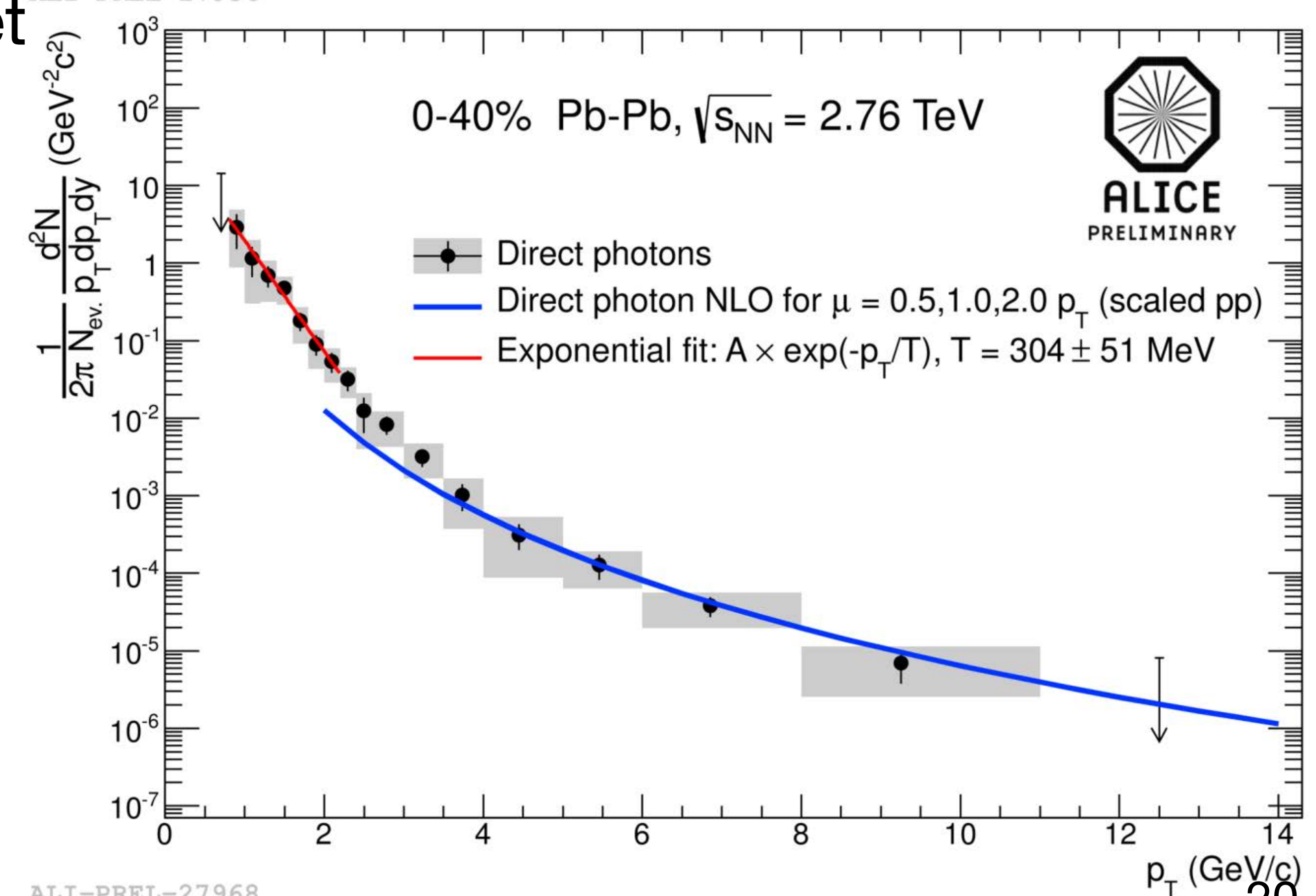
- Direct photons show also a v^3 similar to π^0
- Expect direct photon v_3 from fluctuations in the initial geometry
  - viscosity should reduce v_3

Thermal photons at the LHC?

- ALICE measured real photons via conversion pairs
- Observed excess above hadron decays
- However: needs comparison to pp!
  - crucial for the quantifying enhancement
- Large background from π^0 decays
  - Can be avoided by measuring virtual γ
- Large uncertainty due to material budget
  - Can be avoided by tagging method
- Similar flow as at RHIC

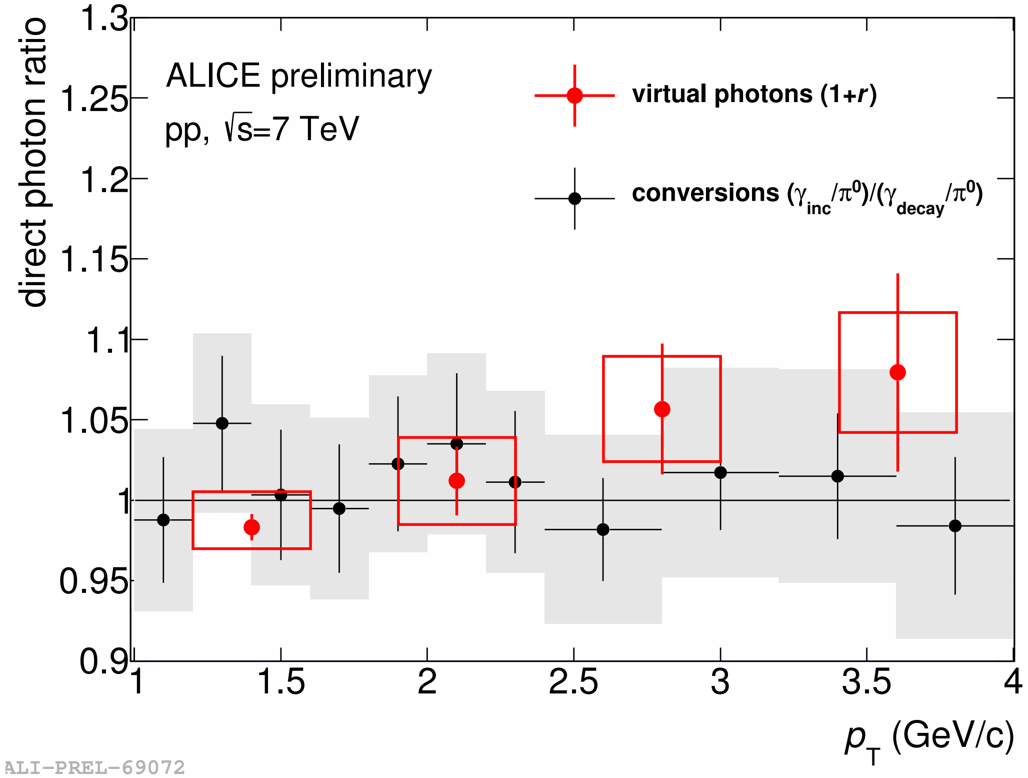




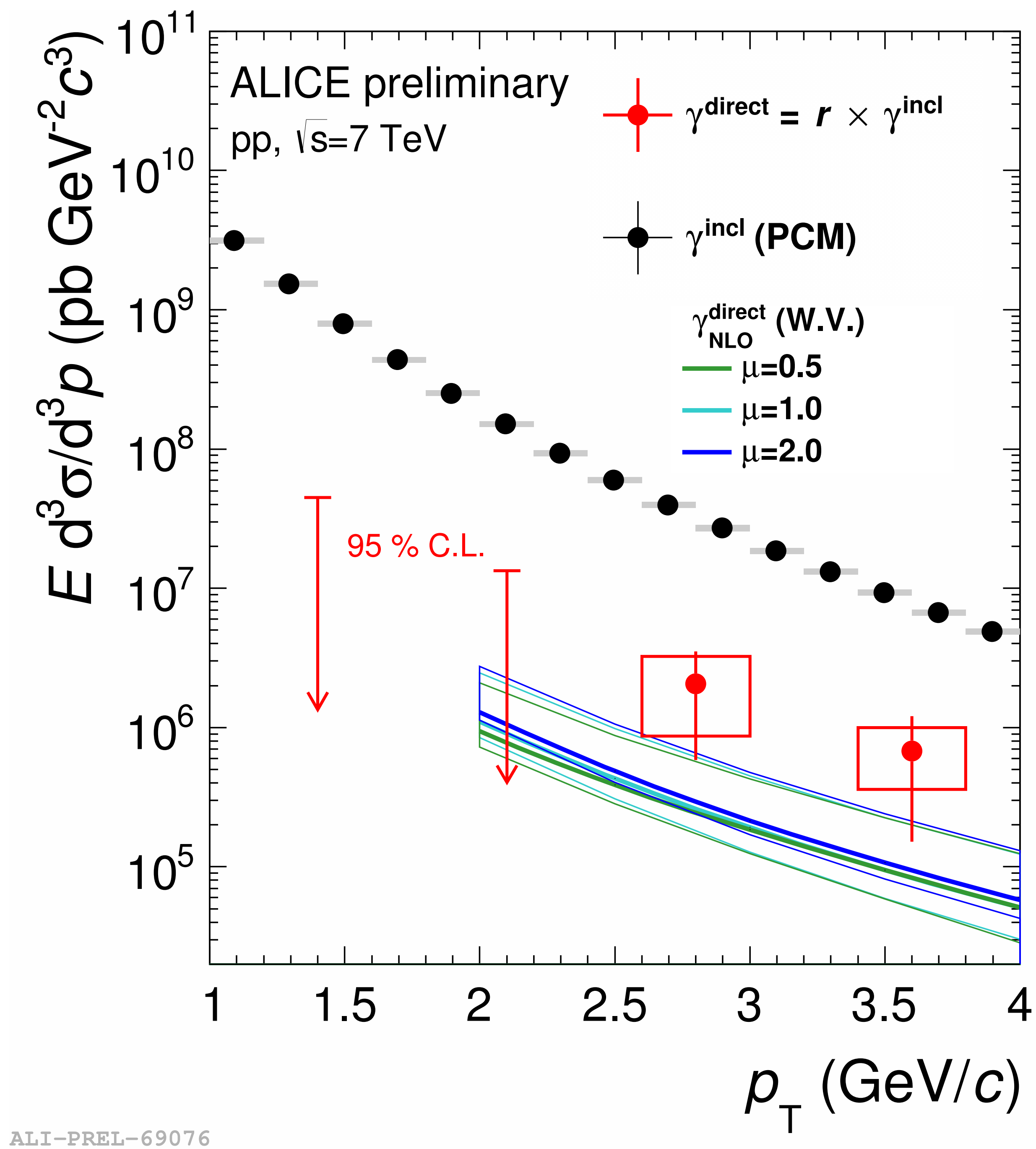


Direct Photons in p+p

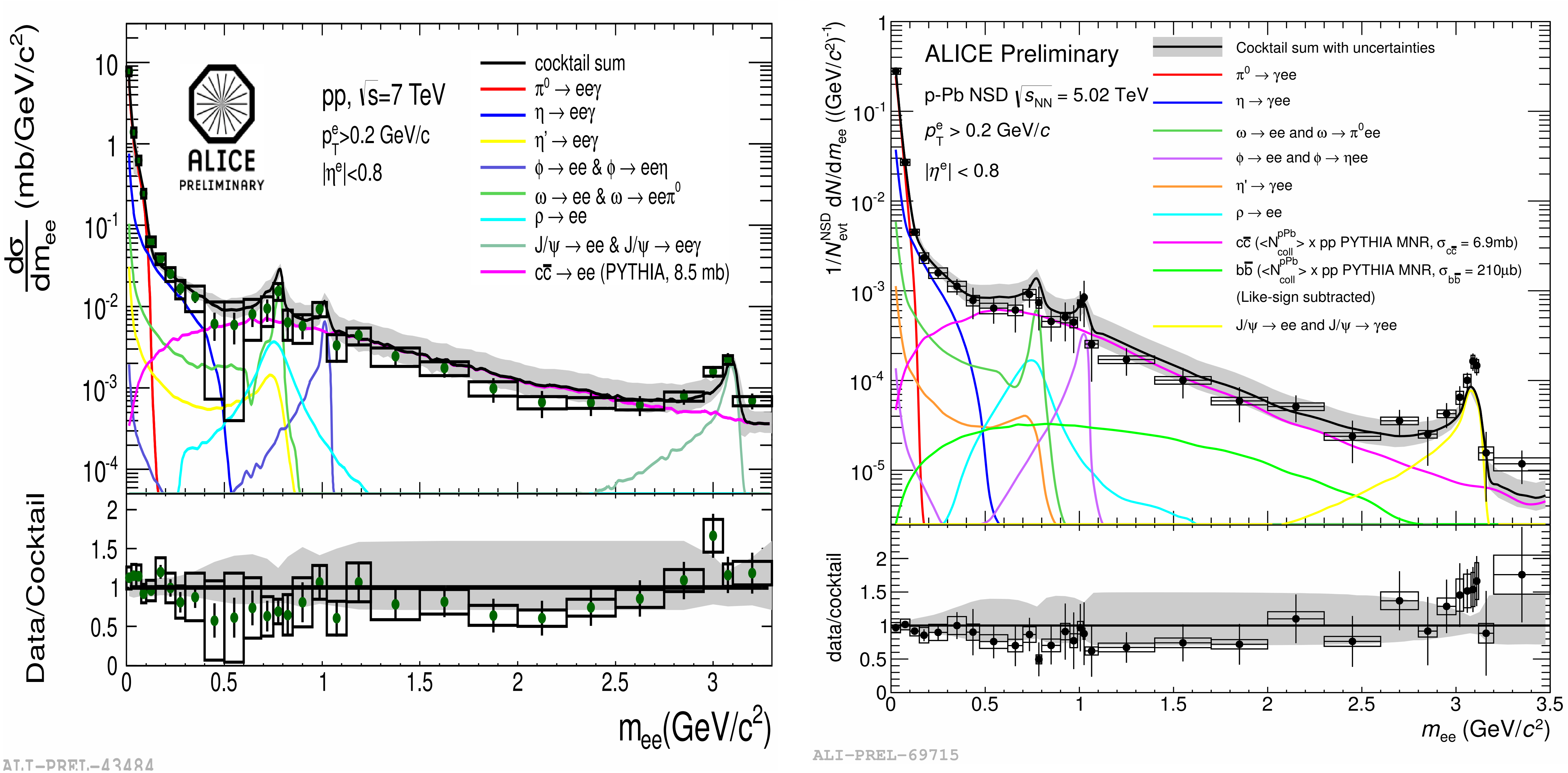
- Preliminary measurement of direct photon fraction in p+p at 7 TeV
  - via low mass dielectrons
  - observe hint of small signal



- Extracted direct photon cross section consistent with NLO pQCD

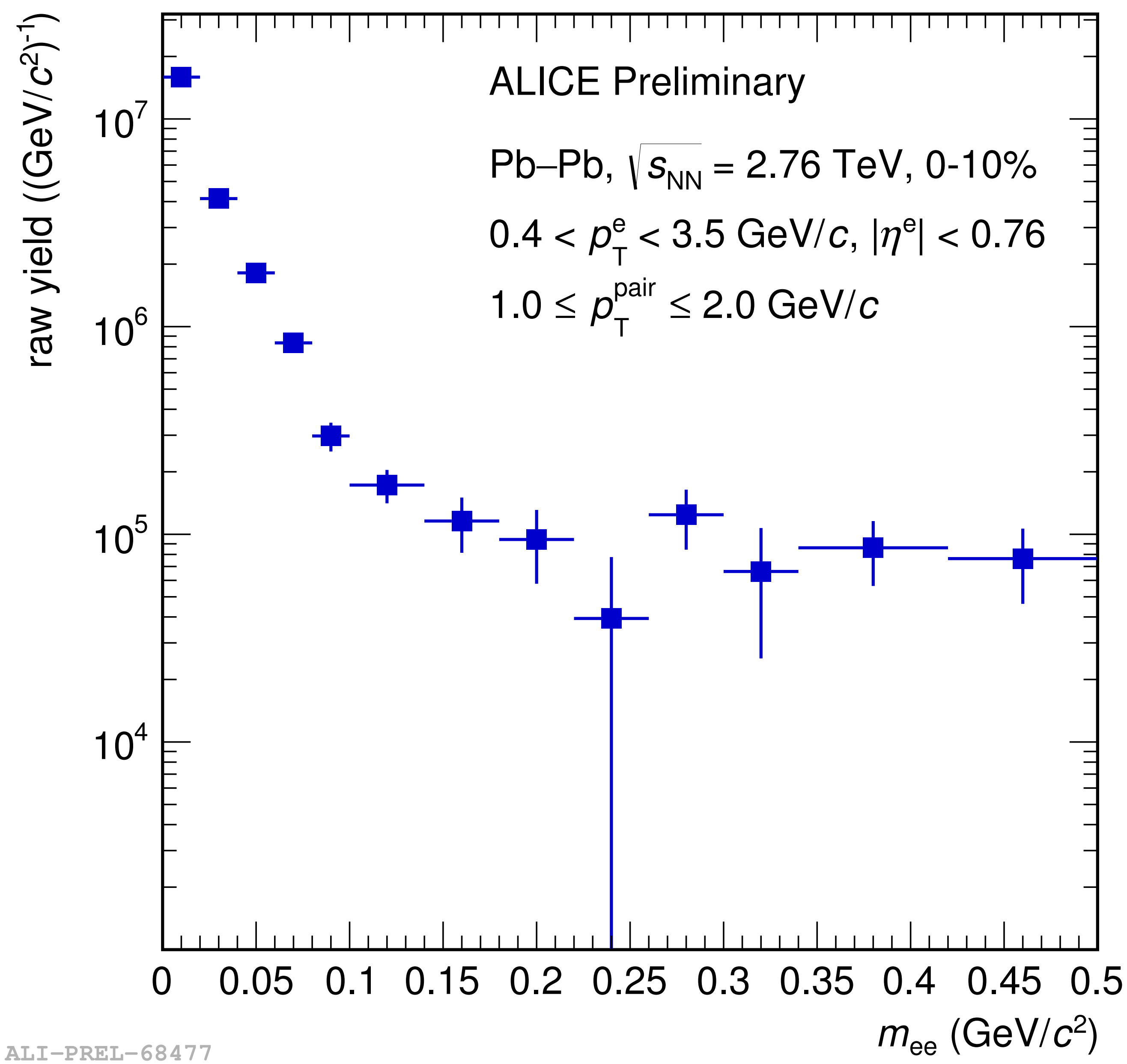


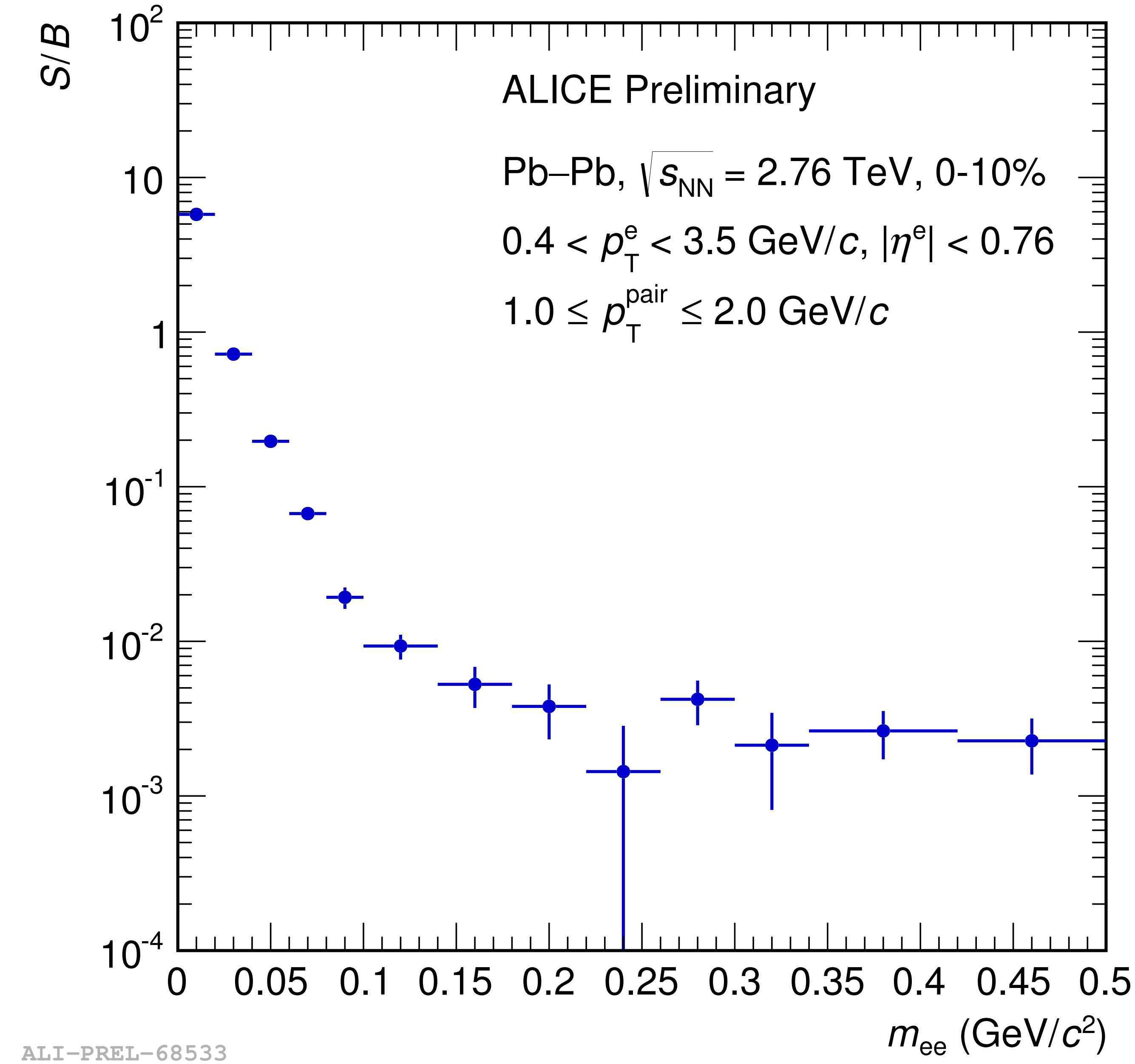
Low Mass Dileptons in ALICE



- Dielectron spectra in p+p and p+Pb consistent with hadron cocktail
- Big uncertainty on open charm cross section

Low Mass Dileptons in ALICE: Pb+Pb



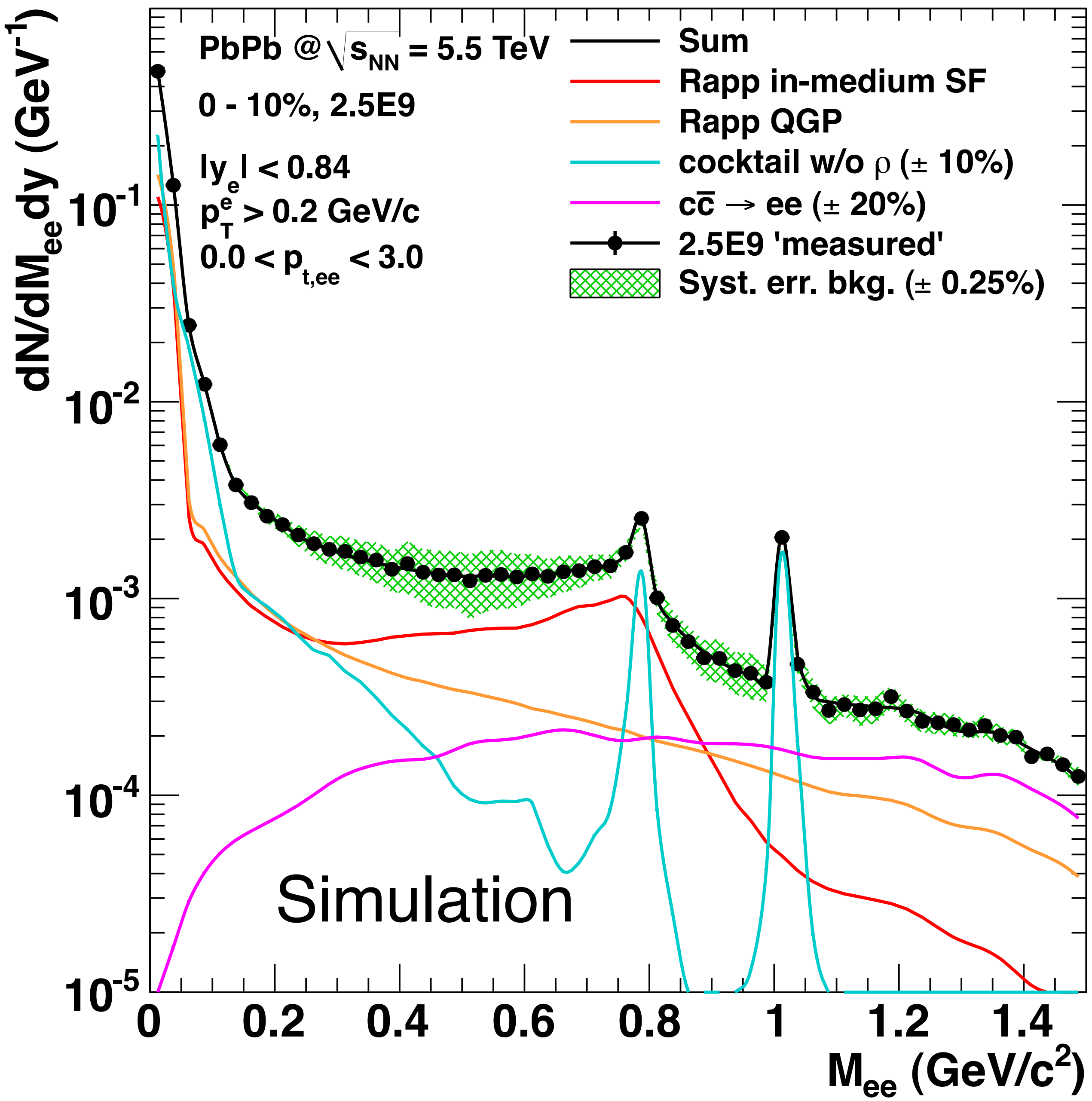


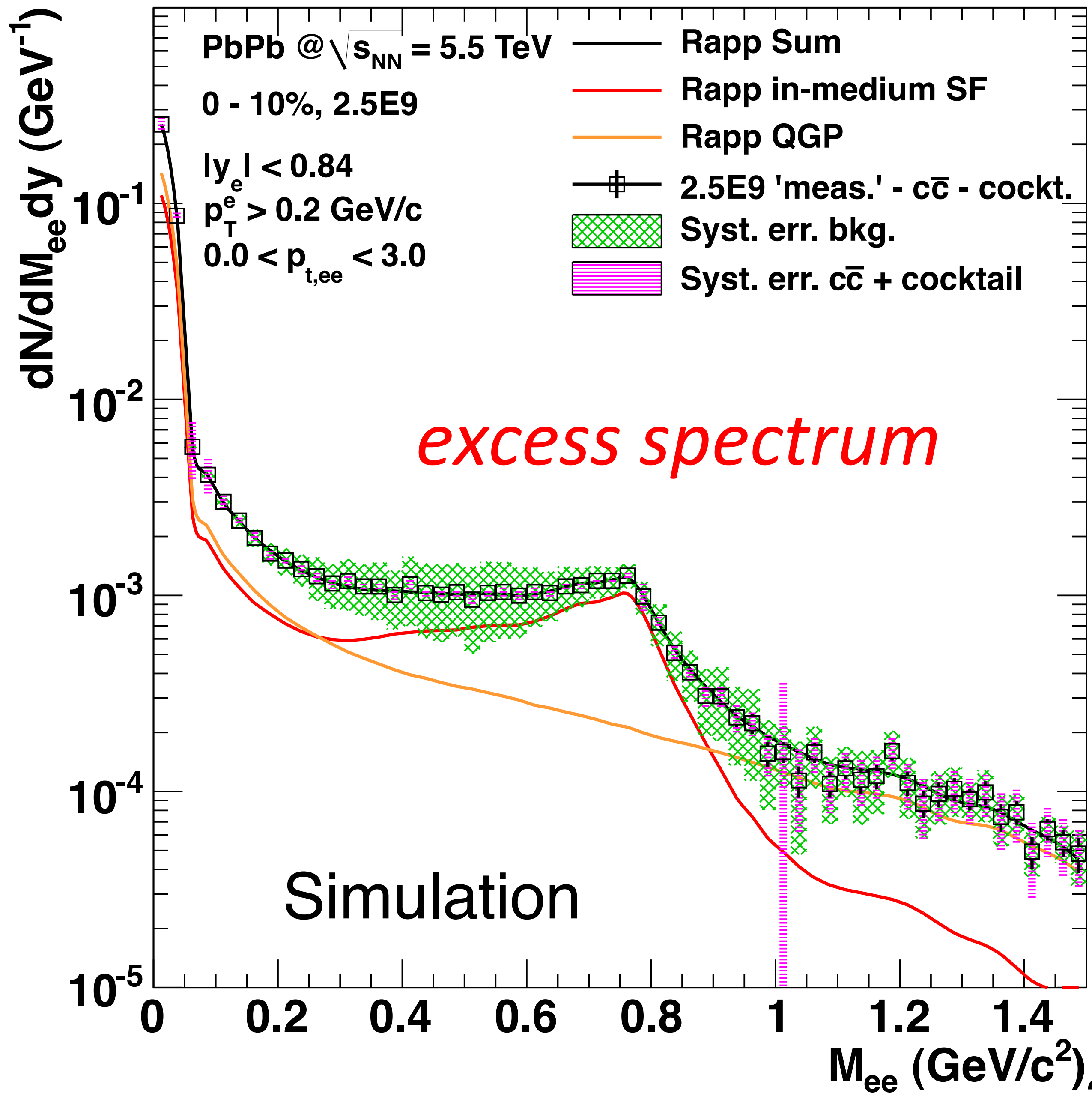
- S/B ratio of few ‰ at low p_T bin:
  - accurate combinatorial background evaluation needed
- Focus on virtual photon production

Low Mass Dileptons in ALICE: Future

- TPC and ITS upgrades:
  - allow high data rates
  - reduce charm background with dca cut
- Dedicated low B-field run (B=0.2 T)

2.5×10^9 events = “1 year” at 50 kHz





Summary

- EM probes ideal "penetrating probes" of dense partonic matter created at RHIC and the LHC
- Double differential measurement of dilepton emission rates can provide
  - Temperature of the matter
  - Medium modification of EM spectral function
- PHENIX and STAR measured dilepton continuum in p+p, d+Au and Au+Au:
  - In p+p and d+Au: good agreement between data and hadronic cocktail
    - measured charm and beauty cross section in IMR and HMR
  - In Au+Au: low p_T and low mass enhancement above hadronic cocktail
    - PHENIX data not reproduced by theoretical models
    - discrepancy to STAR measurement, which is well explained by models involving ρ broadening
  - In Au+Au: very low-mass enhancement for p_T>1 GeV/c
    - interpreted as thermal photons with inverse slope of ~220 MeV (initial T = 300–600 MeV)
    - strong elliptic flow in combination with large yields a challenge for theory
- At the LHC:
  - first performance studies from ALICE
  - need ITS and TPC upgrades for precise measurements (+ low B-field)

Backup

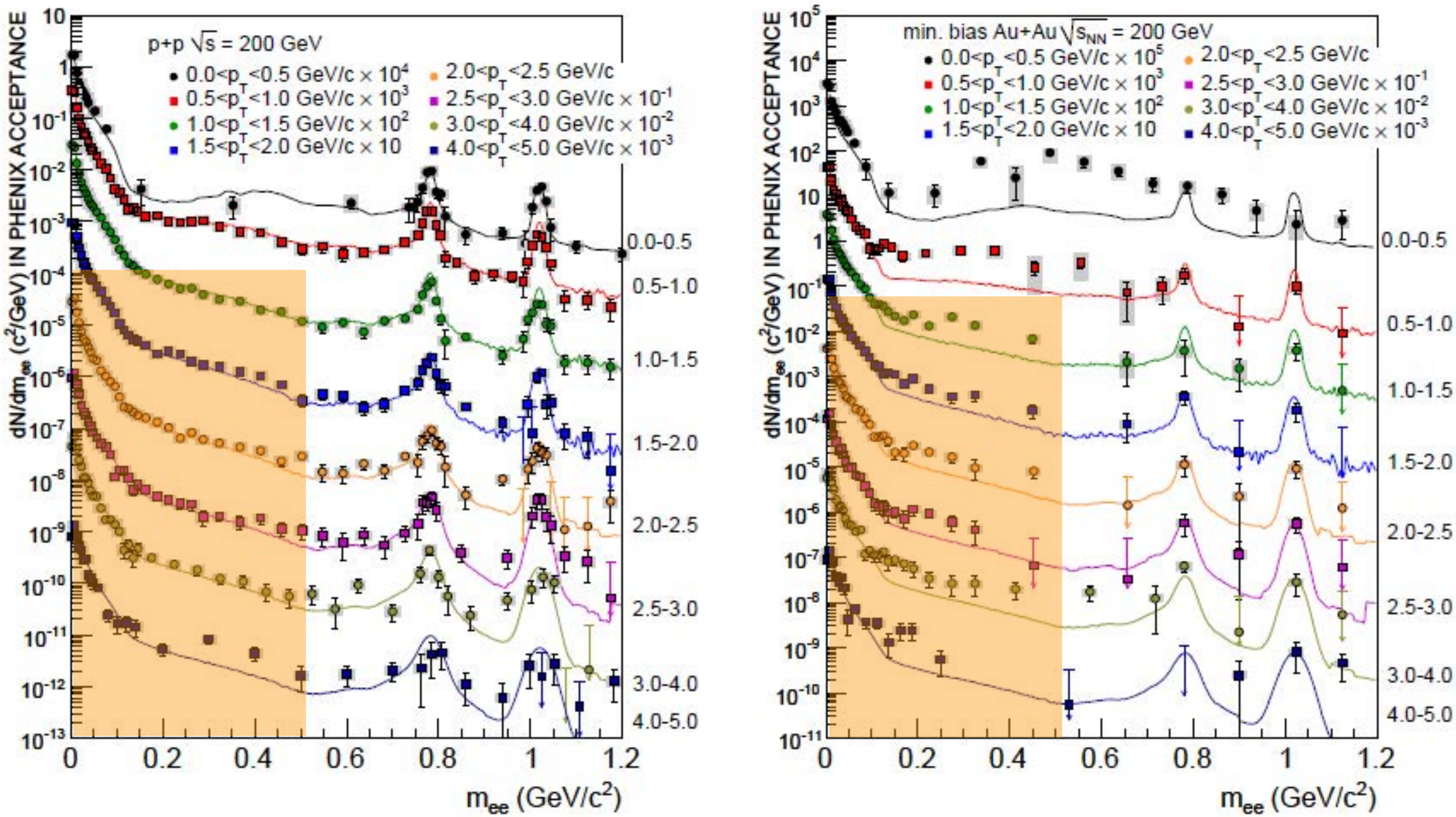
From SPS to RHIC

- 2 scenarios @ SPS profit from high baryon density
  - dropping ρ mass
  - broadening of ρ
- What to expect at RHIC?
  - increase of centre-of-mass per nucleon-nucleon pair from 17 to 200 GeV

	SPS (Pb+Pb)	RHIC (Au+Au)
$dN(\bar{p})/dy$	6.2	20.1
produced baryons (p, $\bar{p}$, n, $\bar{n}$)	24.8	80.4
$p - \bar{p}$	33.5	8.6
particpating nucleons $(p - \bar{p})A/Z$	85	21.4
total baryon number	110	102

- Baryon density: almost the same at SPS & RHIC (although the NET baryon density is not!)

Momentum Dependence



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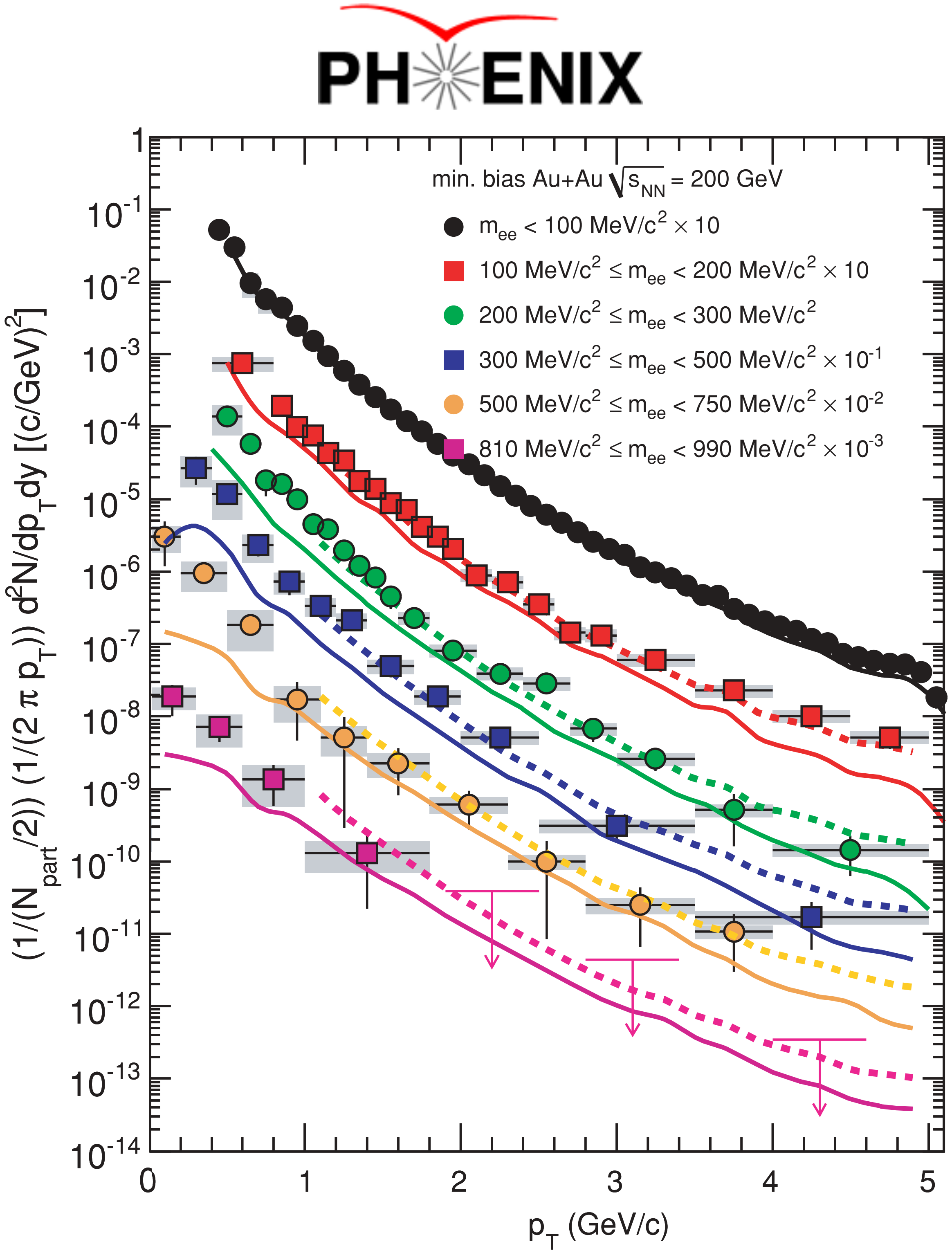
- p+p in agreement with cocktail
- Au+Au low mass enhancement concentrated at low p_T

Momentum Dependence: PHENIX vs. STAR



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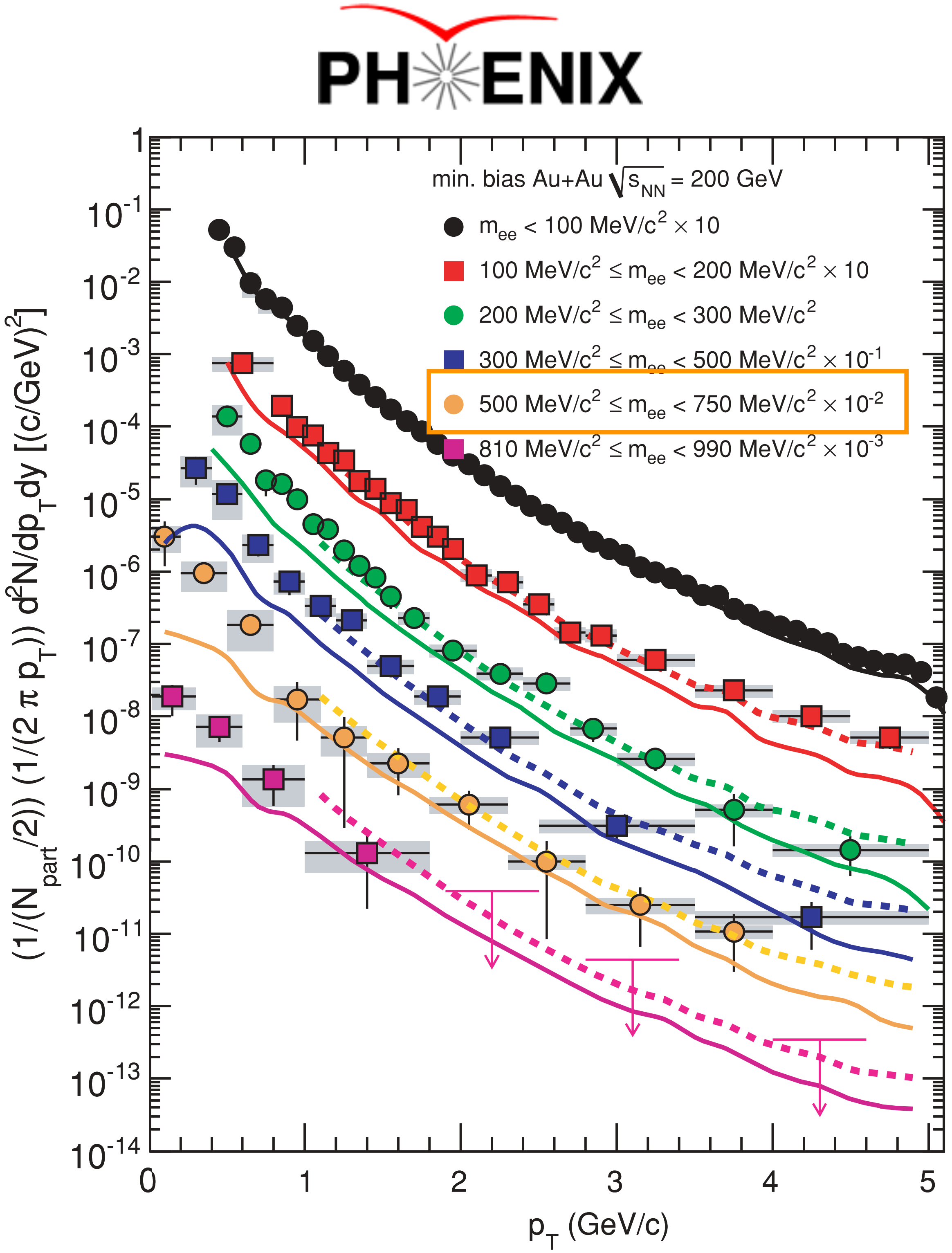
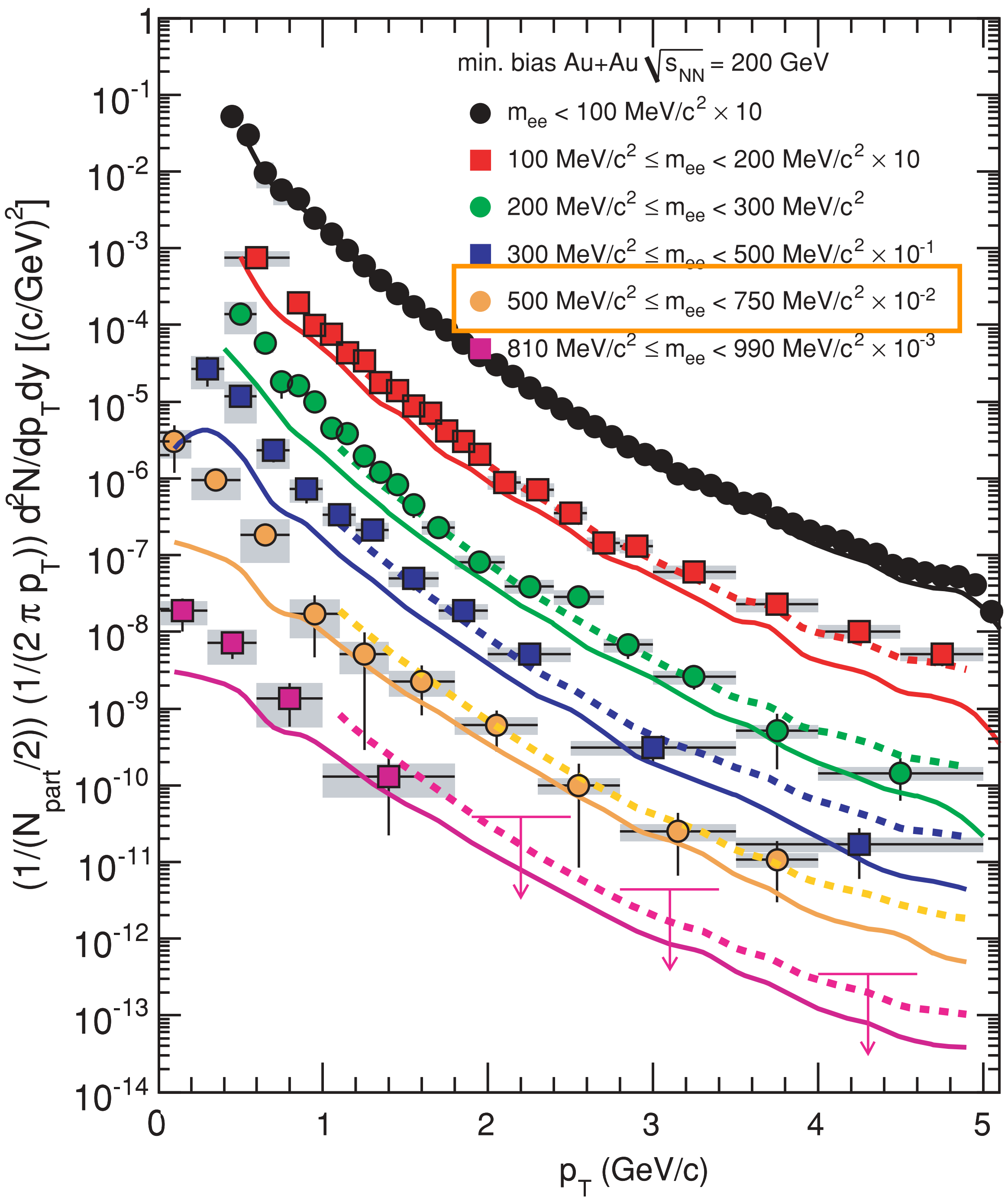
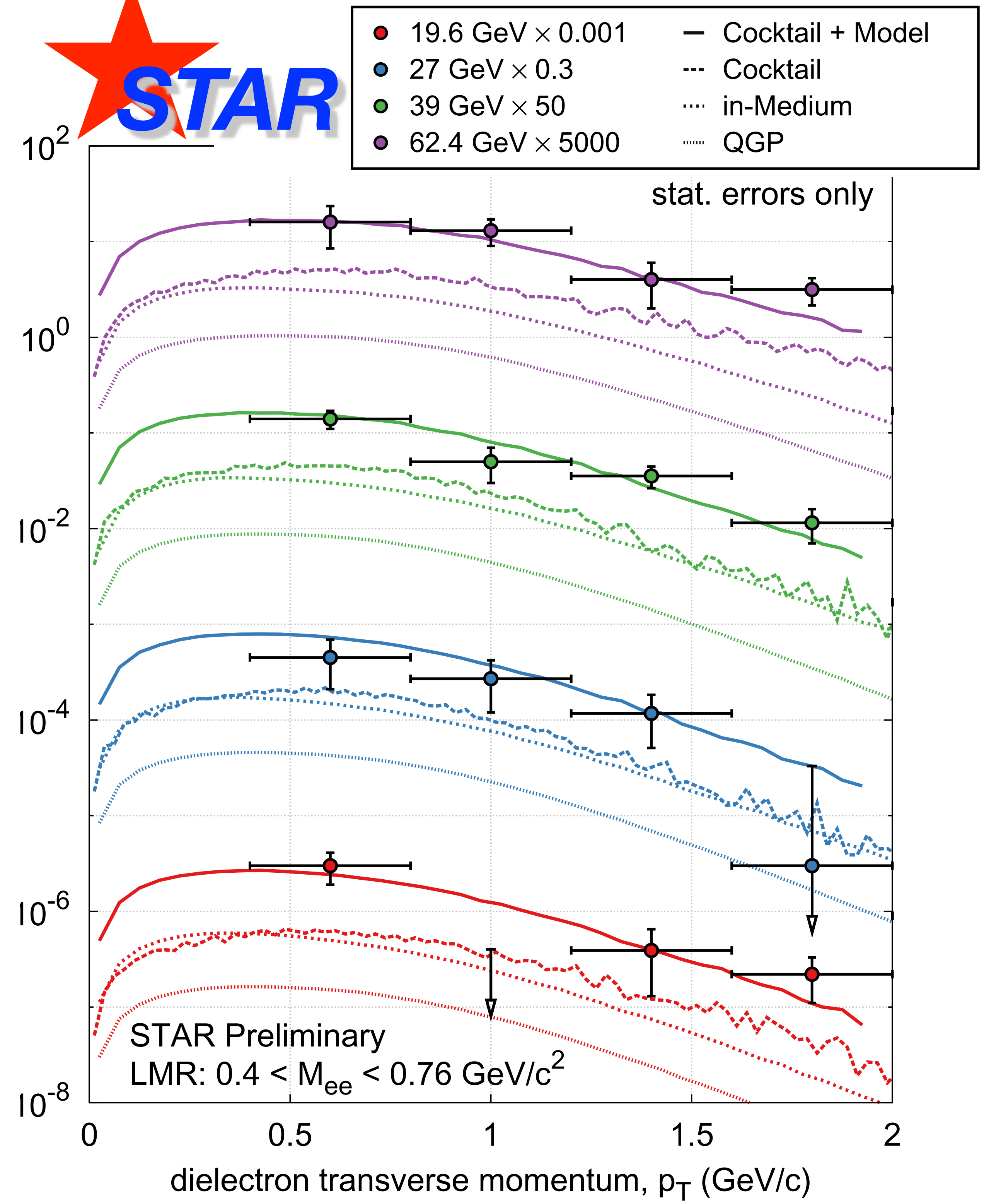
Momentum Dependence: PHENIX vs. STAR



- PHENIX: Au+Au low mass enhancement concentrated at low p_T

Momentum Dependence: PHENIX vs. STAR

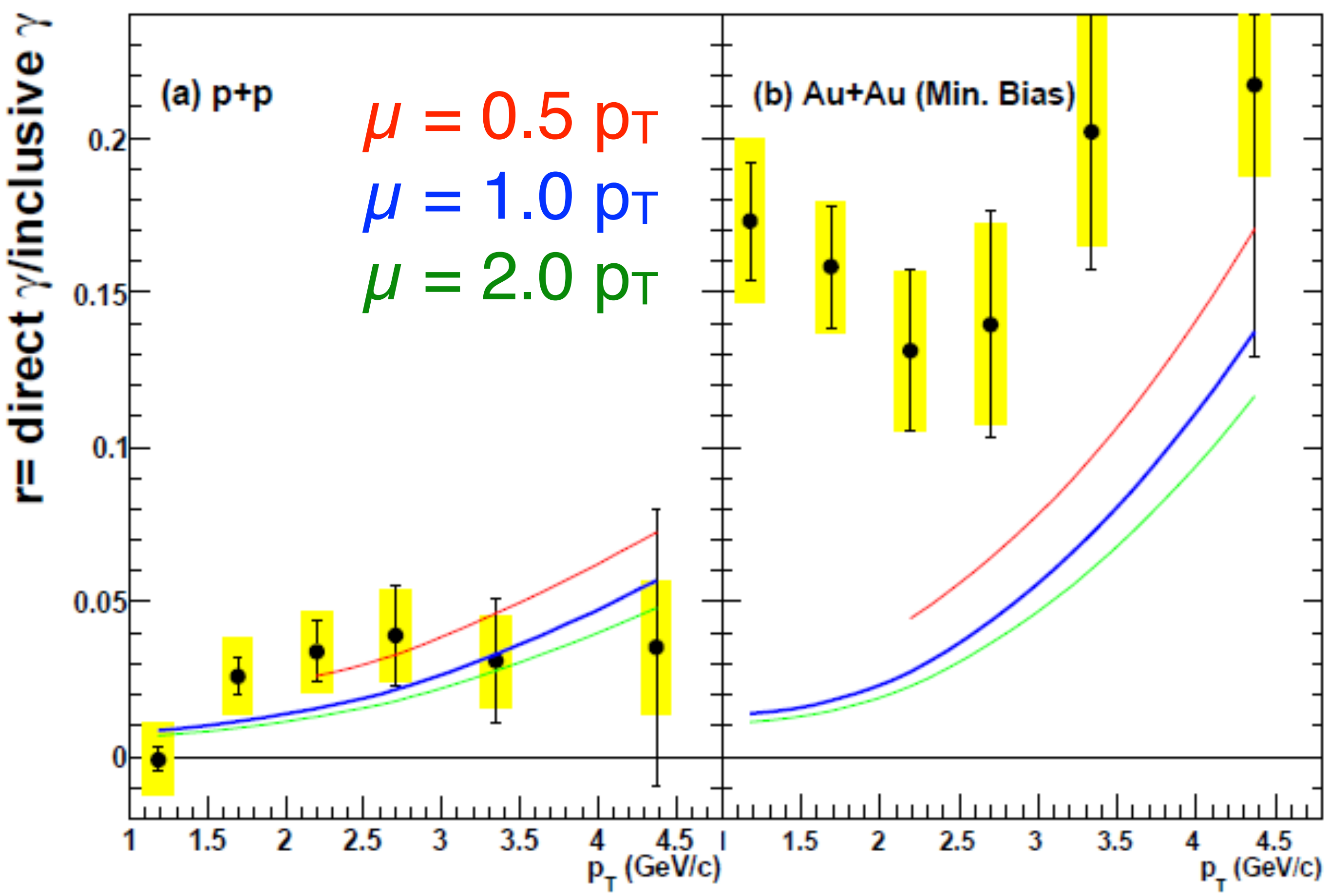




- PHENIX: Au+Au low mass enhancement concentrated at low p_T
- STAR: no p_T spectrum at $\sqrt{s_{NN}}$ = 200 GeV

Direct γ*/Inclusive γ*

p+p　　Au+Au



$$\frac{\gamma_{\text{direct}}}{\gamma_{\text{inclusive}}} = \frac{\gamma^*_{\text{direct}}}{\gamma^*_{\text{inclusive}}}$$

- Base line (curves):
  - NLO pQCD calculations with different theoretical scales done by W. Vogelsang
- p+p
  - Consistent with NLO pQCD
  - better agreement with small μ
- Au+Au
  - Clear enhancement above NLO pQCD

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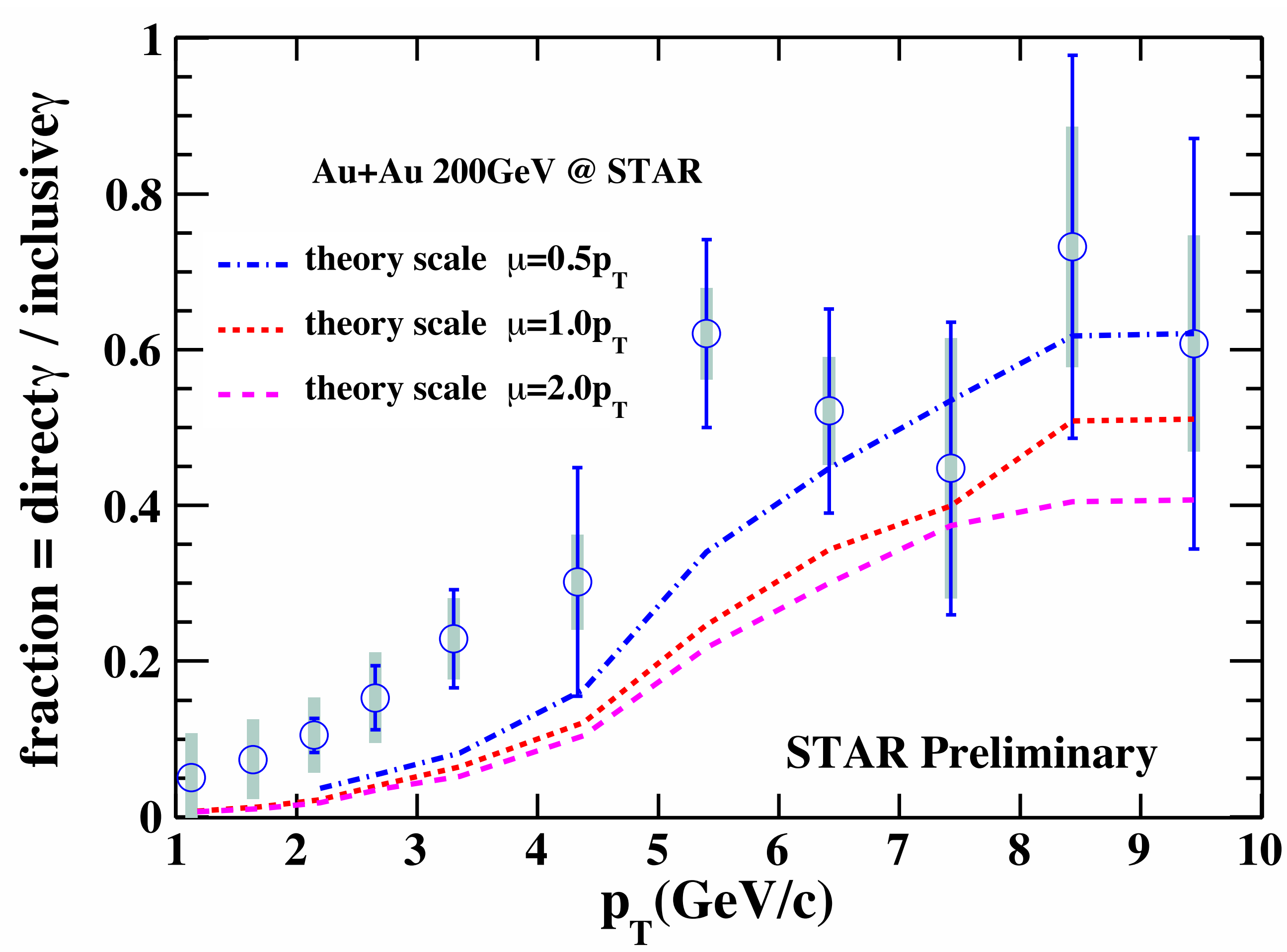
Direct γ*/Inclusive γ*



- Preliminary result by STAR
- Also sees enhancement above NLO pQCD at low pT

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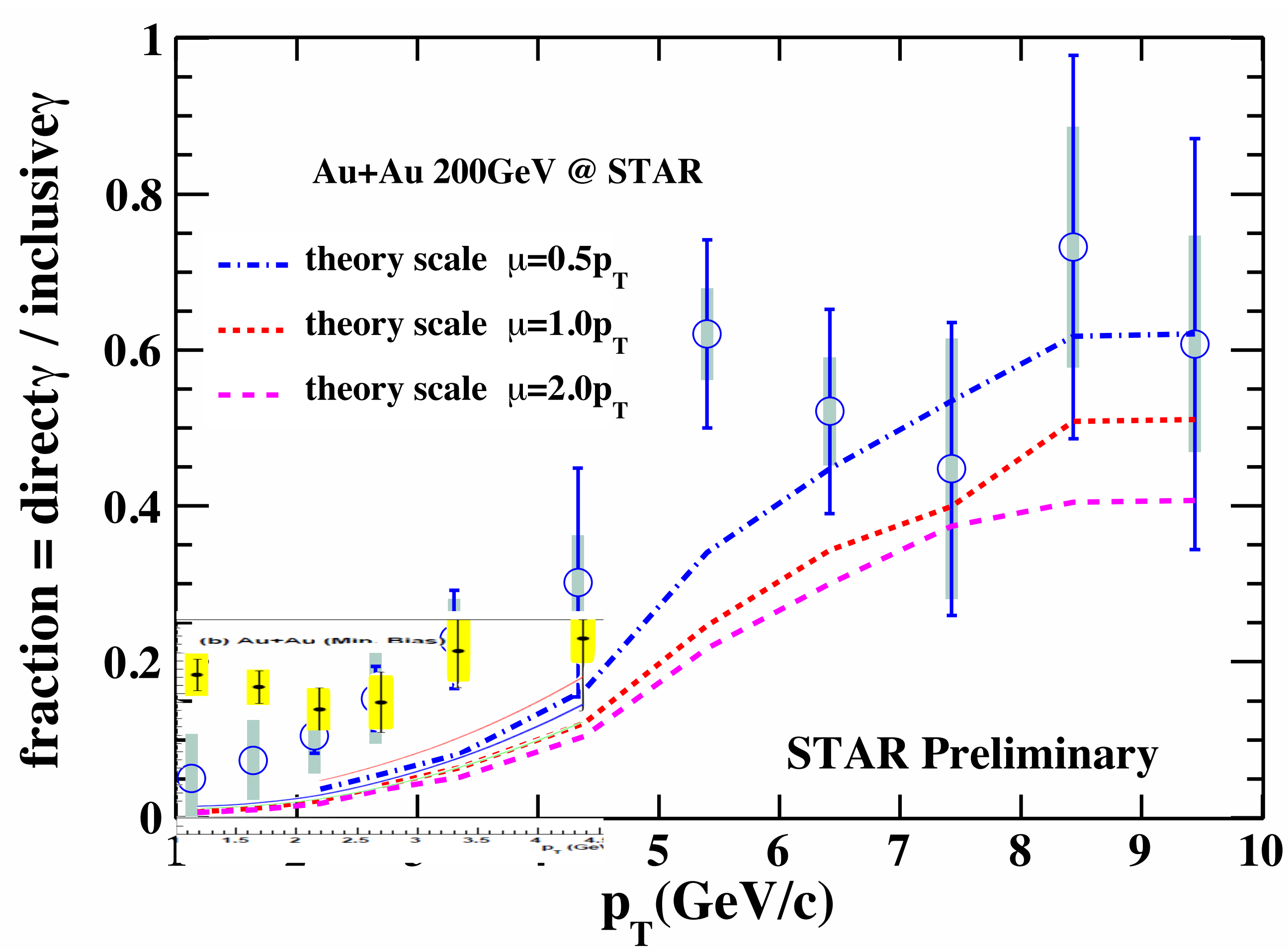

- Preliminary result by STAR
- Also sees enhancement above NLO pQCD at low pT
- Below 2 GeV/c:
  - smaller fraction than PHENIX?

Direct Photons: Model Comparison

- From data:
  Au+Au = pQCD + exponential
  - T_{ave} = 221 ± 19 (stat) ± 19 (syst) MeV
- Comparison to hydrodynamical models:
  - p_T < 3 GeV/c thermal contribution dominates over pQCD.
  - Assume formation of a hot QGP with:
    300 MeV < T_{init} < 600 MeV
    0.6 fm/c < τ_0 < 0.15 fm/c
  - Models reproduce the data within a factor of two

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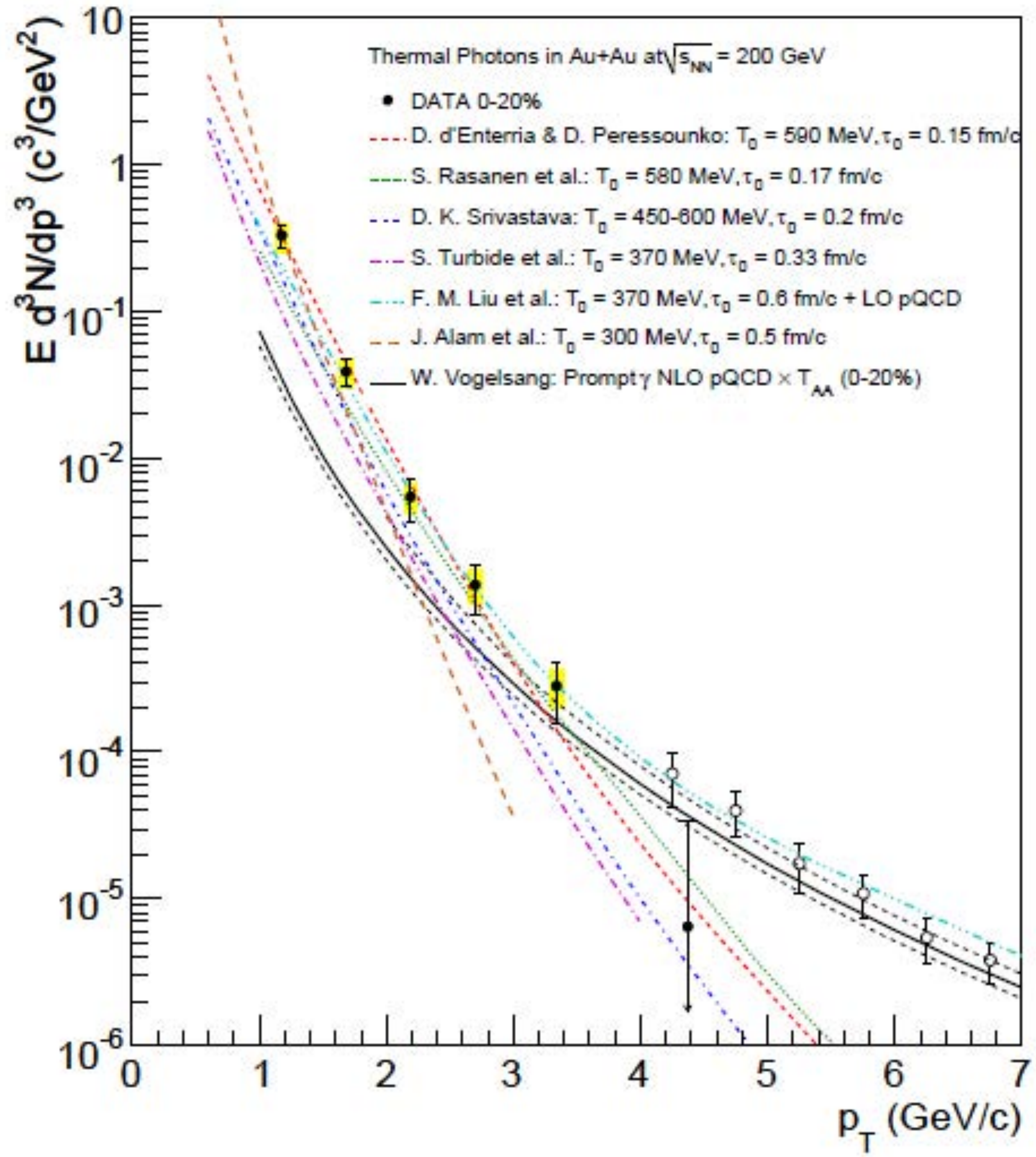
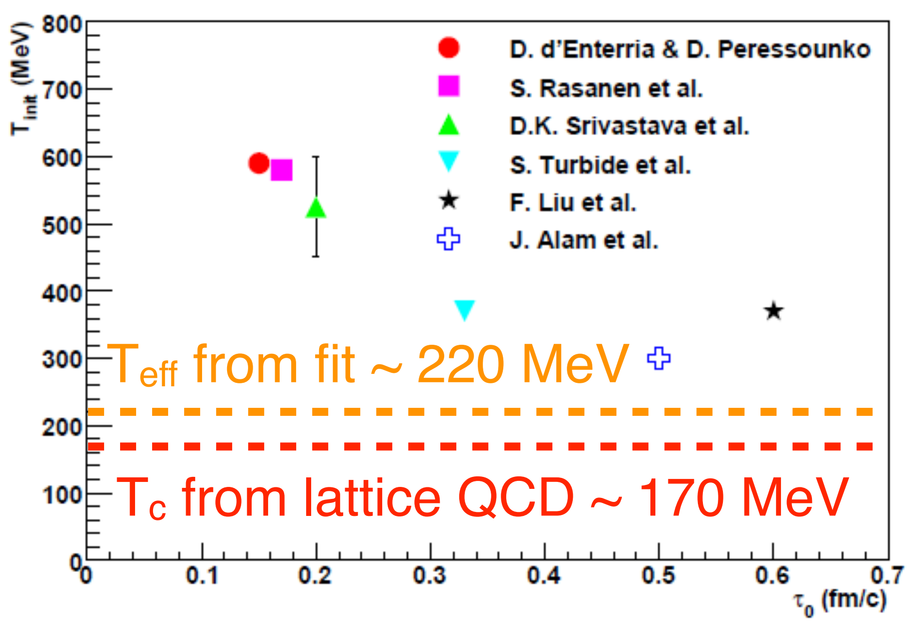
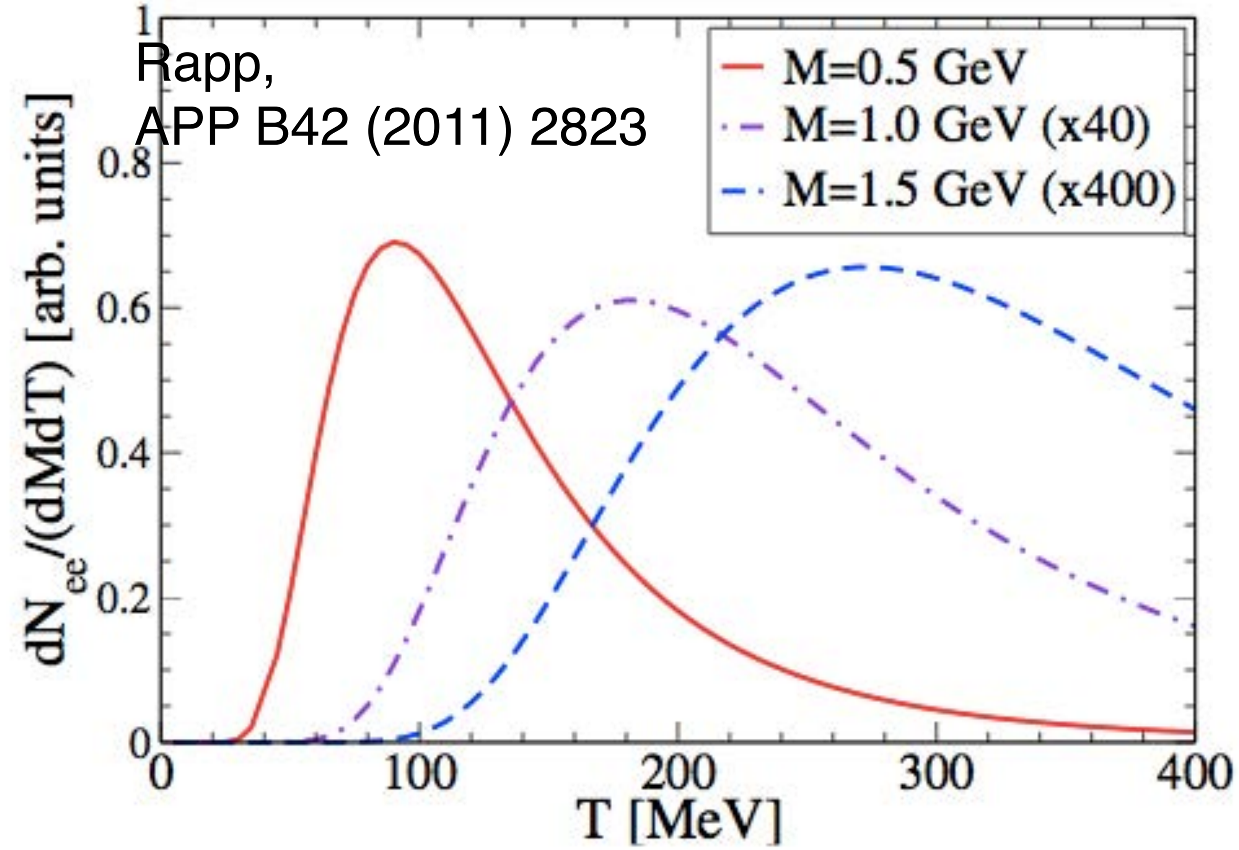
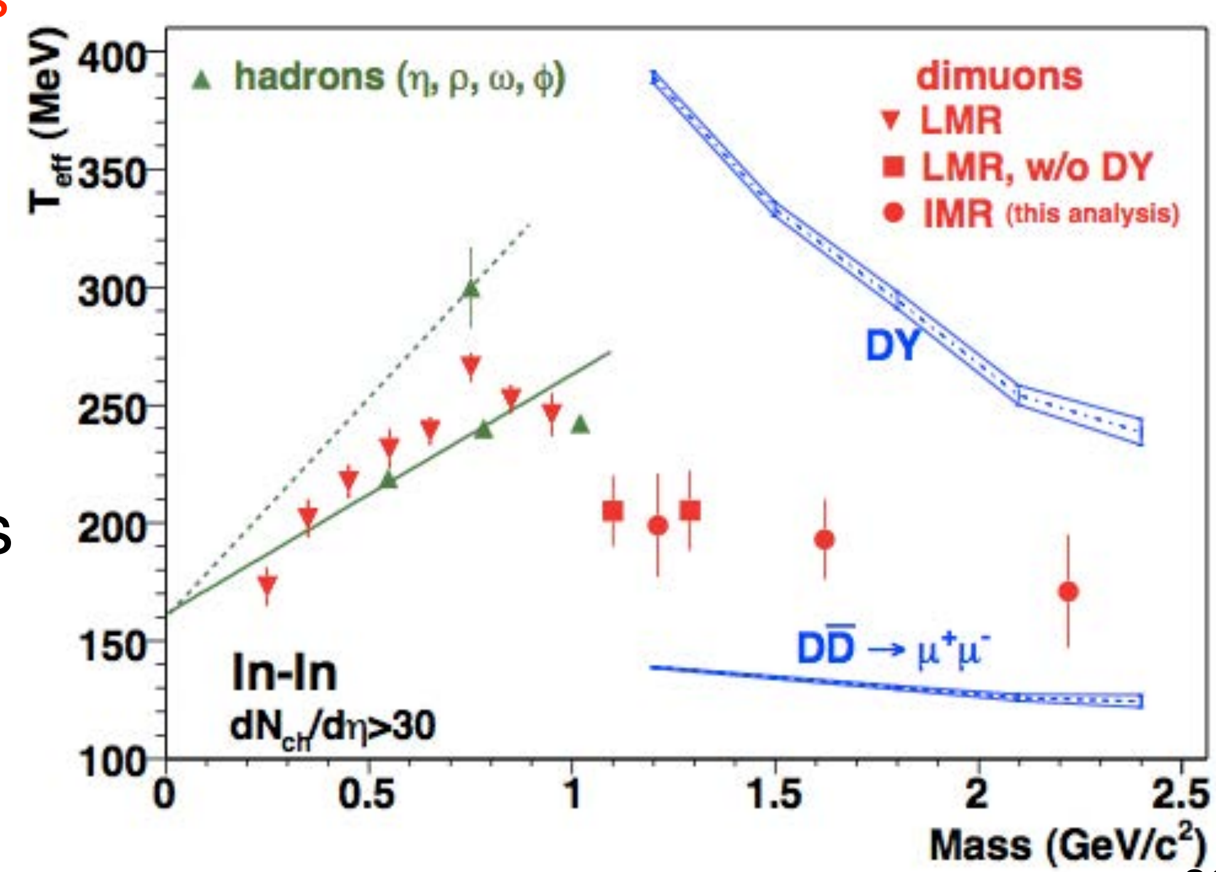




Temperature of the early QGP

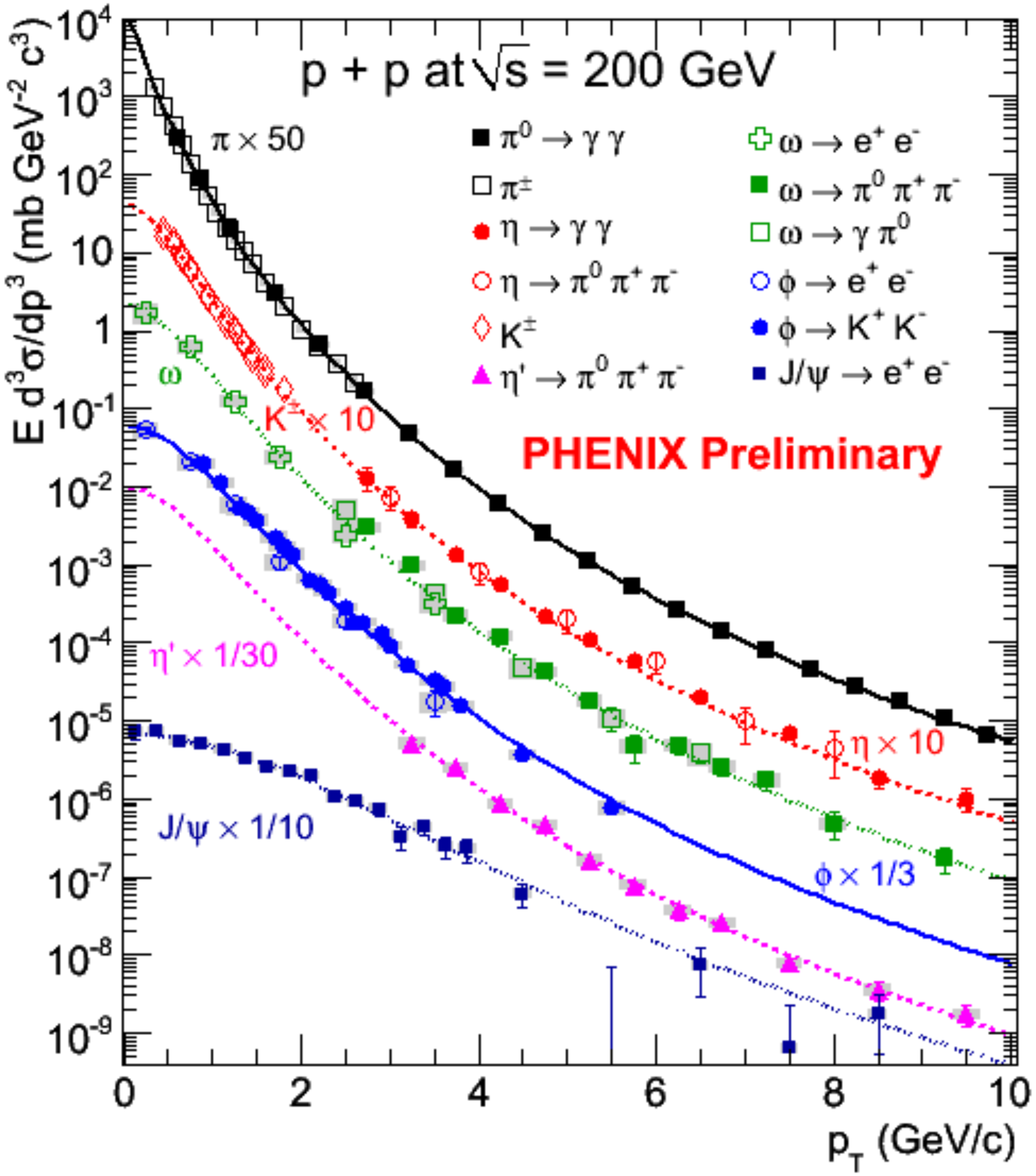
- Photons emitted during all stages of the medium evolution
  - measurement is always time integrated
- Low mass virtual photons:
  - Emission dominated by the hadronic phase
- How to measure "early temperature" from the partonic phase?
  - Intermediate mass (1–3GeV/c^2) provides another window to measure thermal dileptons
- NA60 at the SPS measured "prompt excess" above open charm continuum of possibly thermal origin
  - semileptonic charm decays = non-prompt
- At the LHC charm cross section 10^3 times higher than at the SPS!
  - Such measurement requires good vertexing resolution for lepton pairs





NA60, EPJ C 59 (2009) 607

Hadronic Cocktail

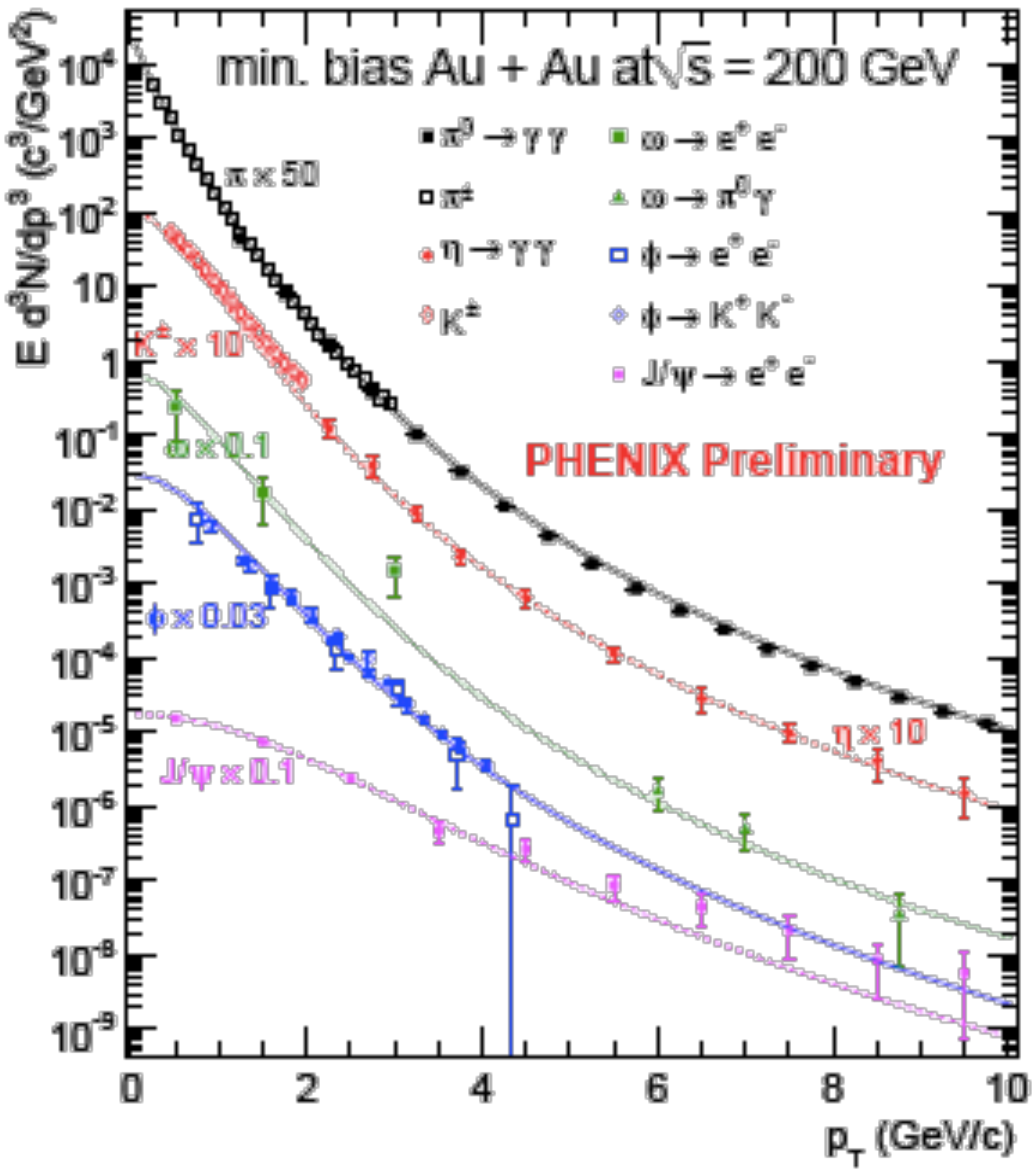


- Parameterization of PHENIX $\pi^{\pm}$, π^0 data ($\pi^0 = (\pi^+ + \pi^-)/2$)

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

- Other mesons: fit with m_T scaling of π^0
  $p_T \rightarrow \sqrt{(p_T^2 + m_{meson}^2 - m_\pi^2)}$
  fit the normalization constant
- All mesons m_T scale!
- Hadronic cocktail was well tuned to individually measured yield of mesons in PHENIX for both p+p and Au+Au collisions
- Mass distributions from hadron decays are simulated by Monte Carlo:
  π^0, η, η', ω, φ, ρ, J/ψ, ψ'
- Effects on real data are implemented

Hadronic Cocktail



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