Di-lepton production at top RHIC beam energy

Jaakko Manninen[1]

[1] Justus-Liebig Universität Gießen

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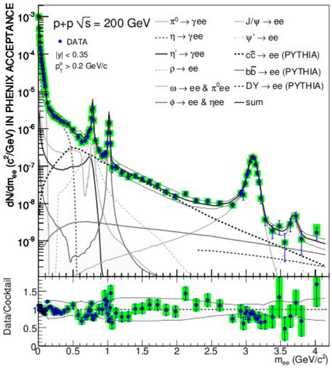
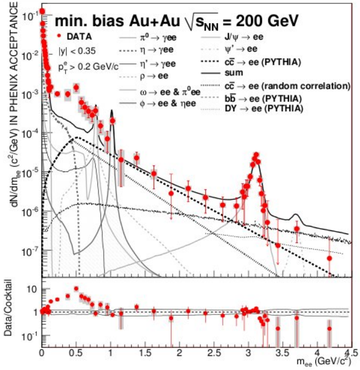
Outline

Motivation





Phys.Lett.B670:313-320,2009 arXiv:0706.3034,arXiv:0912.0244

- Invariant mass spectrum of $e^- e^+$ pairs can be understood very well within hadronic scenarios.
- Large excess in LMR in (semi)central Au-Au collisions

Introducing a new SHM event generator

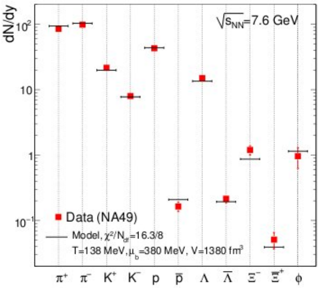
- Independent Monte-Carlo implementation in FORTRAN77
- (almost) compatible with PYTHIA: easy comparison
- Boltzmann statistics only
  $\longrightarrow$ multiplicity distributions Poissonian
- Choose thermal parameters, calculate (once) $\langle N_j \rangle$ as usual
- Sample for each event N_i:s from Poisson with $\langle N_j \rangle$
- Sample N_i hadrons for each event $\longrightarrow$ distributions
- So far GCE only, easy to switch to CE
- Similar, yet more versatile code: PLUTO (root)

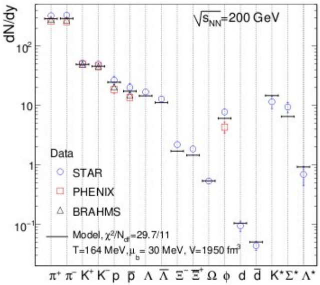
$$\langle N_j \rangle = \frac{(2J_j + 1)V}{(2\pi)^3} \int \int \left[\gamma_S^{-n_s} \mathrm{e}^{\sqrt{\mathrm{p}^2 + m_j^2}/T - \boldsymbol{\mu} \cdot \mathbf{q}_j / T} \right]^{-1} \times SF(m) d^3\mathrm{p} d\mathrm{m}$$

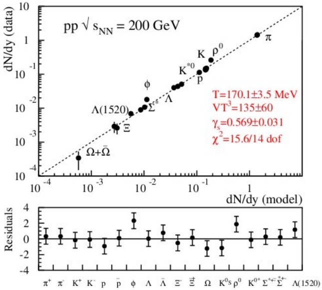
Many new features compared to (my) earlier works

- Spectral functions
  - Relativistic Breit-Wigner used for resonances
  - Can be replaced easily with any spectral function
  - Normalization and integration limits evaluated iteratively taking into account the spectral functions of all daughters in the whole decay chain
  - Further "rationalized" (do not sample epsilon tails)
- Mass dependent partial widths (branching ratios)
  - Implemented in detail for channels involving e^+e^-
  - Energy threshold effects for bulk resonance production
- Dalitz decays, 3, 4, (5) body decays
- Non-isotropic decay matrix elements (in construction)
- All distributions are histogrammed and (nicely) organized $\rightarrow \approx$ 2000 1D histograms to look at
- For fluctuation/correlation analyses NTUPLES should be used

Statistical hadronization: counting the number of hadrons







↑

arXiv:0901.2909v2

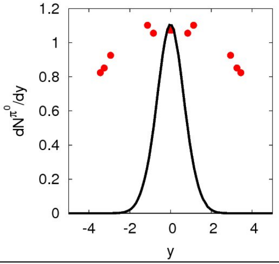
← arXiv:0911.3026

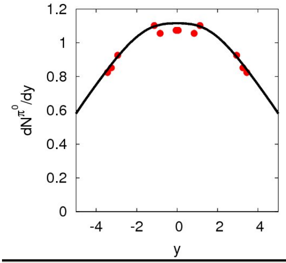
All light (uds) hadron yields can be describe in all collision systems

Use Francesco's fit parameters, no fine tuning (besides normalization)

Limited acceptance: spectra need corrections

- In full acceptance, no problems (Lorentz invariance)
- PHENIX: $|y| < 0.35$; $p_T^{e^i} > 0.2$ GeV
- Beam direction trivial
  - Projectile/Target dynamics spread the thermal distribution rapidity
  - Approximate "boost-invariance"
  - Random (Gaussian) boosts along z-axis

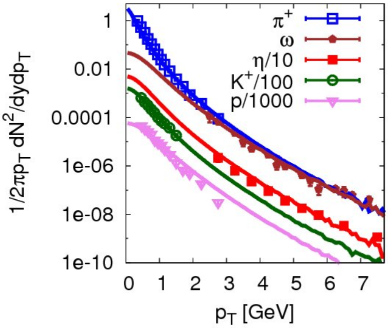


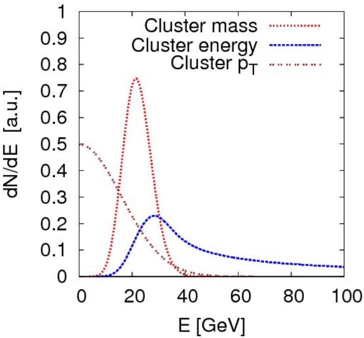


Boosts do not change the invariant mass of the di-lepton pair

Transverse direction: from Gaussian to power law

- Transverse direction: too many hadrons at low p_T
- $\rightarrow$too few $e^- e^+$ at low $M_{e^+ e^-}$
- Imitate transverse flow with Gaussian for the clusters's momenta
- Dynamics seem irrelevant: just a single huge cluster
- Clusters' p_T distribution Gaussian with $\mu = 0$, $\sigma =$16GeV





Transverse direction: from Gaussian to power law

- Transverse direction: too many hadrons at low p_T
- $\rightarrow$too few e^-e^+ at low $M_{e^+e^-}$
- Emulate transverse flow with Gaussian for the clusters's momenta
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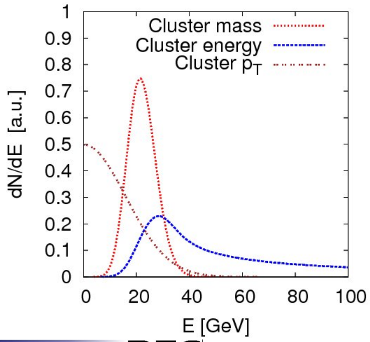
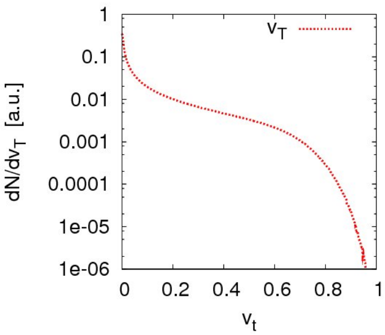




Di-electrons in the low invariant mass region ($m_{e^+e^-} < m_\phi$)

Di-leptons come from everywhere

- Any neutral hadron/resonance can decay $X \to \mathrm{e}^+\mathrm{e}^-$
- Anything that can decay $X \to \gamma\gamma$, can decay $X \to \gamma\mathrm{e}^+\mathrm{e}^-$ (also $X \to \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-$)
- Anything that can decay $X \to \gamma$h, can decay $X \to \mathrm{e}^+\mathrm{e}^-$h

But the branching ratios are usually extremely small and mostly only upper limits are known

In general (and very roughly) internal conversion $\gamma \to \mathrm{e}^+\mathrm{e}^-$ reduces the probability by a factor of 1/100

Which channels are dominant depends on the thermal state of the system At RHIC: emission from neutral mesons overwhelming

Event mixing: study **correlated** pairs only

Relevant channels at RHIC

Hadron	direct	Dalitz	other
π^0	-	$\pi^0 \to \gamma\, e^+e^-$	-
η^0	-	$\eta^0 \to \gamma\, e^+e^-$	$\eta^0 \to \pi^+\pi^- e^+e^-$
η'	-	$\eta' \to \gamma\, e^+e^-$	$\eta' \to \pi^+\pi^- e^+e^-$
ρ^0	$\rho^0 \to e^+e^-$	-	-
ω^0	$\omega^0 \to e^+e^-$	-	$\omega^0 \to \pi^0\, e^+e^-$
ϕ^0	$\phi^0 \to e^+e^-$	-	$\phi^0 \to \eta\, e^+e^-$
J/ψ	$J/\psi \to e^+e^-$	$J/\psi \to \gamma\, e^+e^-$	
ψ'	$\psi' \to e^+e^-$	$\psi' \to \gamma\, e^+e^-$	-
D mesons	-	-	$D^\pm \to e^\pm \nu_e + X$

Table: List of decay channels relevant for di-electron production in $p+p$ collisions at $\sqrt{s}$=200 GeV. For $D^\pm$ mesons, 11 semileptonic (electron(positron) + anti-neutrino(neutrino) + 1 or 2 light hadrons) decay channels are considered. For the neutral (D^0 and $\bar{D}^0$) mesons and $D_s^\pm$, there are 7 and 5 semileptonic decay channels, respectively, taken into account

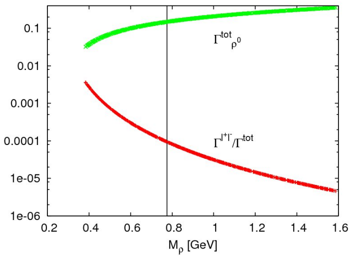
Details are important for the di-lepton sources

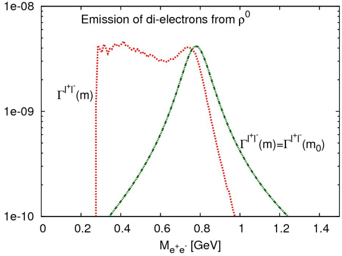
Example ρ^0 direct decay

$$\text{Partial width}: \quad \Gamma^{V\to l^+l^-}(m) = \frac{m_0^3}{m^3}\Gamma^{V\to l^+l^-}(m_0)$$

$$\text{Total width}: \quad \Gamma^{tot}(m) \approx \Gamma^{\rho\to\pi\pi}(m) = \Gamma^0 \frac{m_0^2}{m^2}\left(\frac{\sqrt{m^2-4m_\pi^2}}{\sqrt{m_0^2-4m_\pi^2}}\right)^3$$

$$\text{Branching fraction}(\rho^0 \to e^+e^-) = \frac{\Gamma^{V\to l^+l^-}(m)}{\Gamma^{tot}(m)}$$





Dalitz decays

(light) vector mesons

$$\frac{d\Gamma(X \to \gamma\, l^+ l^-)}{dm} = \frac{\Gamma(X \to l^+ l^-)}{m} \frac{4\alpha}{3\pi} \sqrt{1 - \frac{4m_l^2}{m^2}}$$
$$\times \left(1 + \frac{2m_l^2}{m^2}\right)\left(1 - \frac{m^2}{m_X^2}\right)^3 |F^{X\to\gamma\gamma}(m)|^2$$

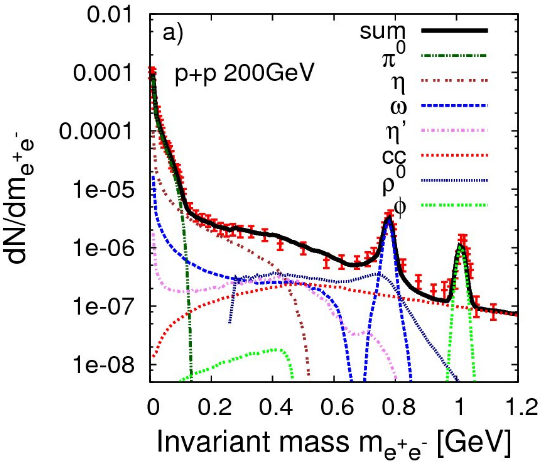
Form factors have been studied extensively:

- vector meson dominance model
- or fits to data

Charmonium decays:

$$\frac{d\Gamma(X \to l^+ l^- \gamma)}{dm} = \frac{\alpha}{\pi} \frac{2m}{M_X^2 - m^2} \left(1 + \frac{m^4}{M_X^4}\right)$$
$$\times \left(\ln \frac{1+r}{1-r} - r\right) \Gamma_0(X \to l^+ l^-)$$

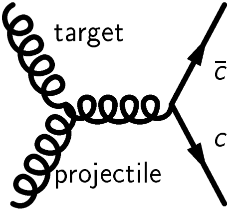
Invariant mass spectrum in LMR in p+p $\sqrt{s_{NN}}$=200 GeV



LMR can be understood well within the simple model

Contribution from charmed hadron decays

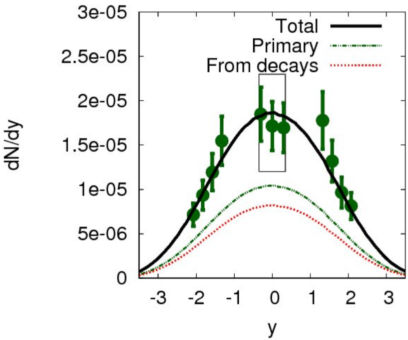
- $m_{e^+e^-} \in [m_\phi; m_{J/\psi}]$ dominated by D meson decays
- $m_{e^+e^-} \approx 3$ GeV dominated by charmonia decays
- SHM does not describe the charmed hadron yields
- Take $\sigma^{pp}_{J/\psi} = 3\mu b$ from experiment and assume
-
  - All $c\bar{c}$ due to $g + g \to g \to c\bar{c}$
  - NNLO gluon PDF:s
  - Limiting fragmentation
- $\to \frac{dN}{dy}$ of $c\bar{c}$



$$xg(x) \sim x^a(1-x)^b(1+\gamma_1\sqrt{x}+\gamma_2 x) \quad \text{with}$$
$$a = -0.118 \quad b = 9.6 \quad \gamma_1 = -3.83 \quad \text{and} \quad \gamma_2 = 8.4$$

Charmed rapidity distributions in $p + p$ collisions

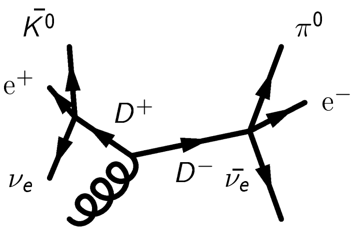
- Modified BGK model arXiv:0911.4775
  - $y_{cm} = \text{atanh}(\frac{x_1 - x_2}{x_1 + x_2})$
  - Probability to find parton along the rapidity axis is defined by a triangle whose maximum is at y_{cm} and goes to zero at $y = \text{asinh}(x_1\sqrt{s}/2m_{\text{N}})$ and $y = -\text{asinh}(x_2\sqrt{s}/2m_{\text{N}})$.

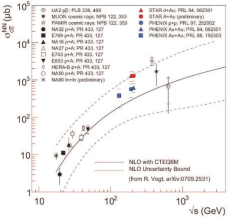


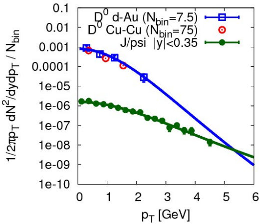
- dN/dy of J/ψ
- Assume the same model describes all charmed rapidity distributions
- Conversion $\sigma_{tot} \leftrightarrow \frac{d\sigma}{dy}_{y\approx 0}$

Contribution from open charm

- p_T spectrum is irrelevant for hadrons with m >0.6 GeV in the PHENIX acceptance
- Exception is the "dilepton continuum" from D meson decays

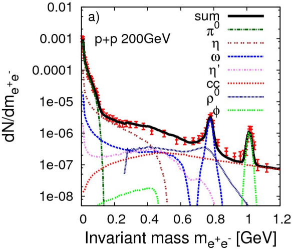


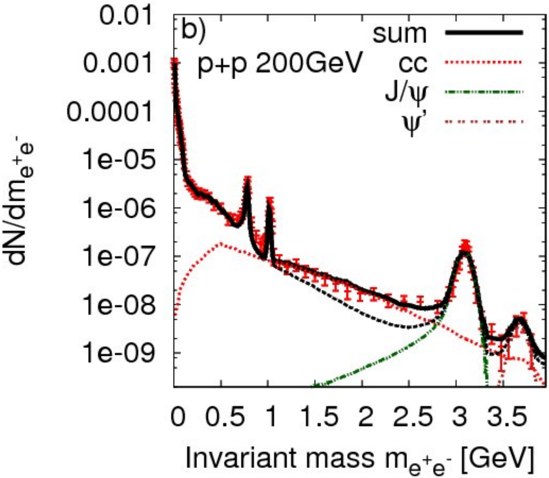




- p_T spectrum and angular correlations among the D mesons affect the $m_{e^+e^-}$
- Fit dN/dp_T to $d + Au$ data
- Assume exact back-to-back correlations in the CM frame
- Total cross section $\sigma_{c\bar{c}} = 485\mu b$

Invariant mass spectrum in in p+p $\sqrt{s_{NN}}$=200 GeV





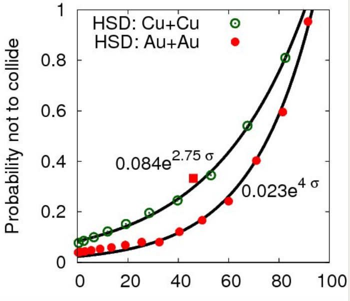
Look at the slope between ϕ and $J/\psi \longrightarrow$
Slope harder than in PYTHIA
(over-simplified picture?)

Random correlation picture dis-favored by the data (wrong slope)
Baseline to study heavy-ion collisions

Angular correlations of open charm in $A+A$ collisions

Open charm mesons are expected to interact in the hot and dense medium created in (central) $A+A$ collisions

- We study angular correlations in HIC in 3 distinct cases:
- $p+p$ correlations preserved
- random correlations
- "Realistic case": mixture of random and correlated emission, survival probability from HSD



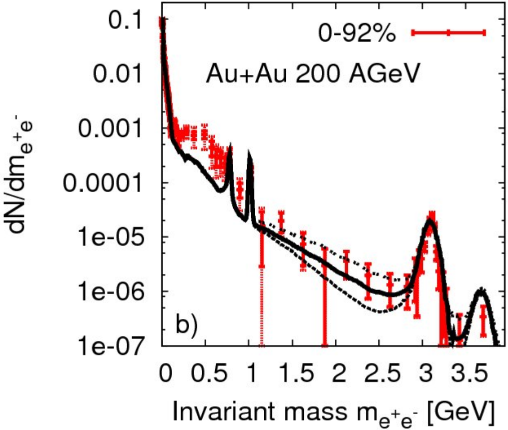
$$P_{surv} = P(D_{noco} \cap \bar{D}_{noco})$$

"Realistic case" could be further improved by transport simulation

Scaling from p+p to heavy-ion collisions (Min bias Au-Au)

$A + A$ and $p + p$ thermodynamically similar at RHIC (volume)

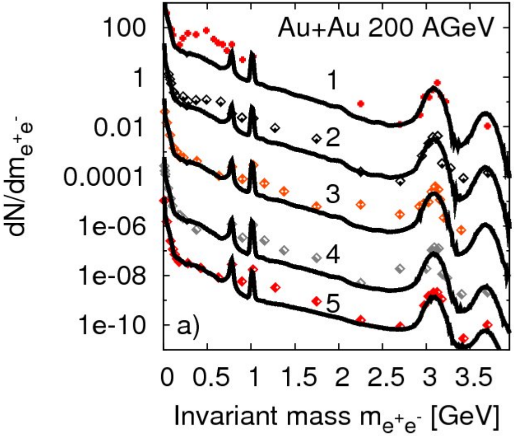
- Scale non-charmed hadron yields with $N_{\rm P}$ $(+\ \gamma_s = 1)$
- Scale charmed hadron yields with $N_{\rm bin}$ $(+\ R_{AA}^{J/\psi})$



- LMR Huge excess
- IMR slope (solid) between $p + p$ (top) and random correlation (bottom)

Closer look into the Au+Au data

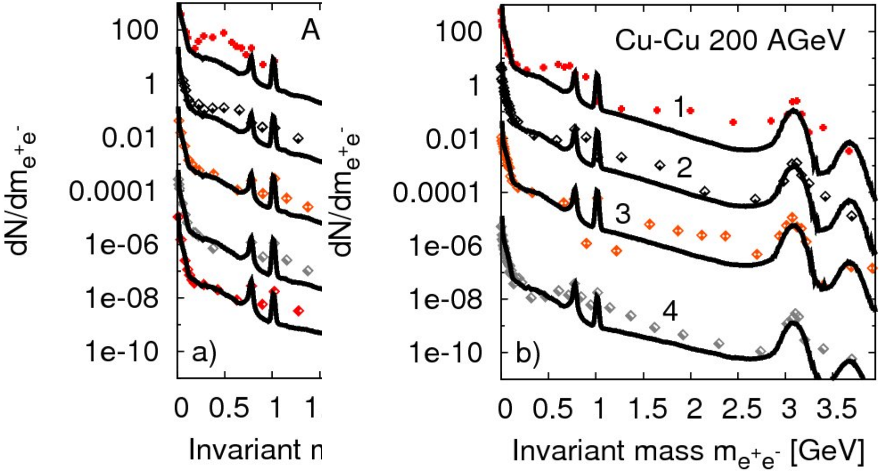
- Scale non-charmed hadron yields with N_{P} $(+\ \gamma_s)$
- Scale charmed hadron yields with N_{bin} $(+\ R_{AA}^{J/\psi})$



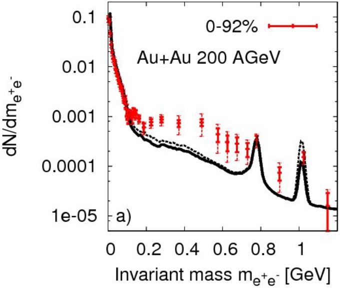
- (semi)Peripheral: LMR and IMR Ok
- (semi)Central: LMR Huge excess IMR near J/ψ ok
- Result of lots of re-shuffling: excess can not arise from the same components as in $p+p$ case

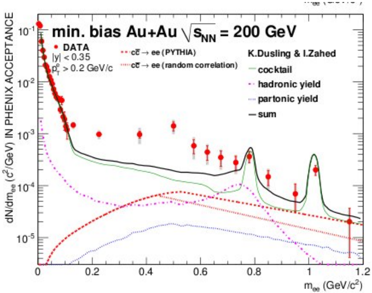
Preliminary Cu+Cu data/model comparison

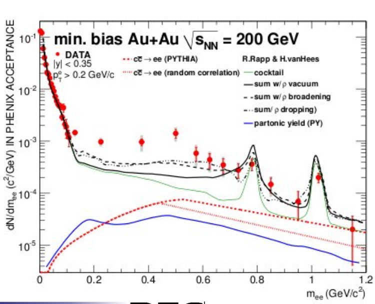
- Similar conclusions (as for Au+Au) hold also for Cu+Cu

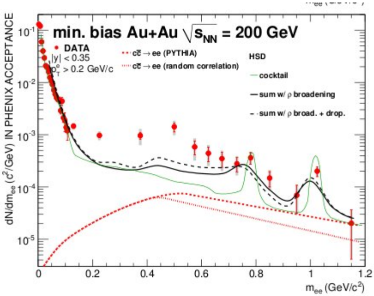


Comparison with other model calculations (Au+Au LMR)

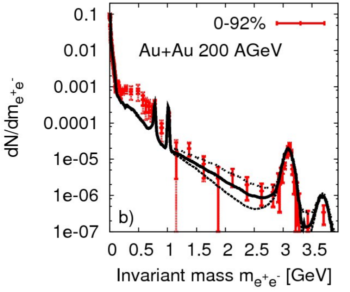


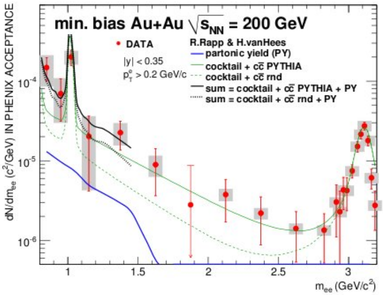


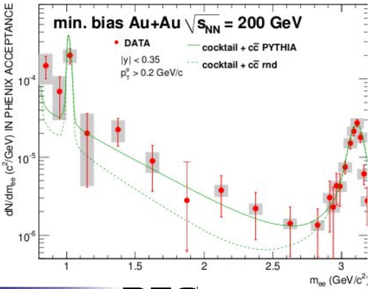


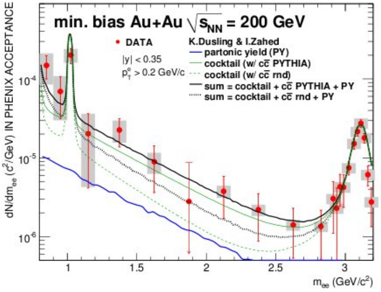


Comparison with other model calculations (Au+Au IMR)









Summary and outlook

Summary

- Experimental findings confirmed
- Qualitative agreement with more sophisticated calculations
- LMR excess does not seem to be originating from the components studied in this work
- Final errors are needed in order to draw (definitive) conclusions

Outlook

- Program is calibrated with the RHIC data now, repeat for LHC
- Compare with non-equilibrium calculations (p)HSD
- Thermal di-leptons?...