Di-electron Measurements in Beam Energy Scan Phase 2

Frank Geurts

Rice University

Electromagnetic Radiation from Hot and Dense Nuclear Matter
ECT*, Trento, Nov. 26 – 30, 2018

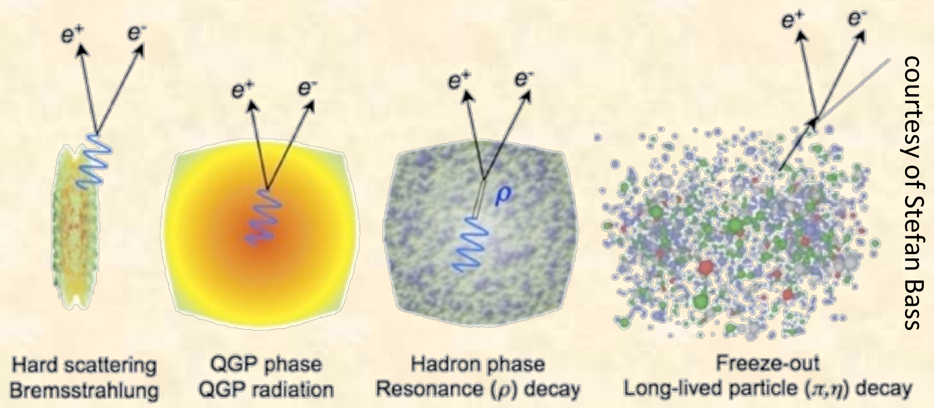
U.S. DEPARTMENT OF ENERGY | Office of Science

RICE

Outline

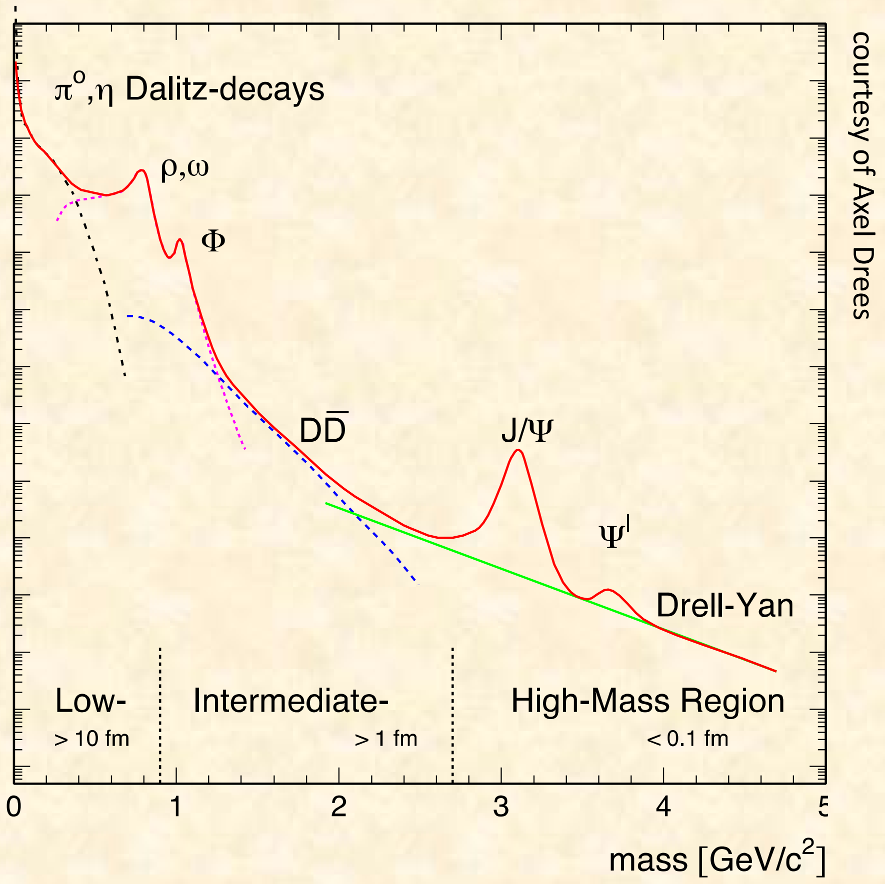
- Motivation
- Tying SPS to RHIC
  - dielectron spectra from Beam Energy Scan Phase I
- Towards Systematic Scan
  - recent runs
  - recent RHIC detector upgrades
  - preparations BES Phase 2
- Revisiting RHIC top energy
  - STAR 2021+
- Summary

Dilepton Physics



<u>Dileptons are excellent penetrating probes</u>

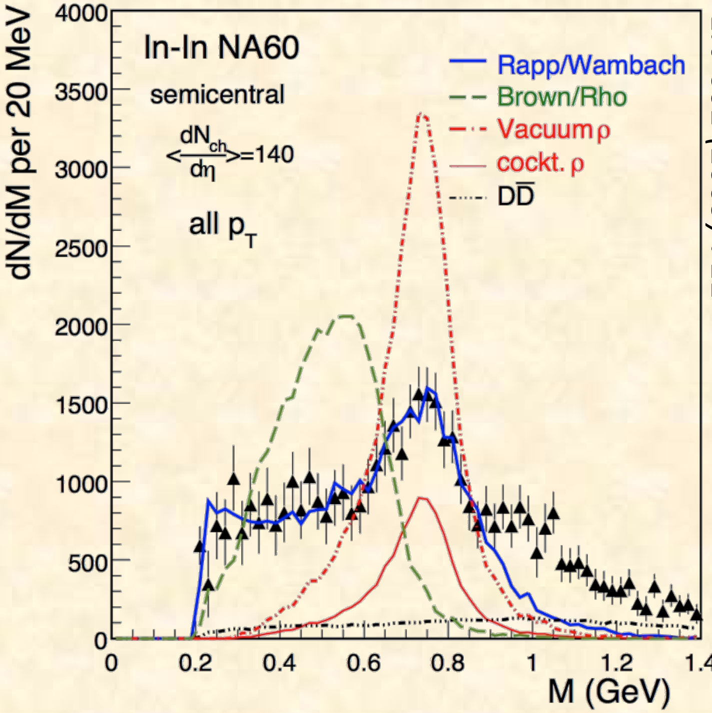
- very low cross-section with QCD medium
- created throughout evolution of system



- High Mass Range (HMR)
  - $M_{ee} > 3$ GeV/c^2
  - primordial emission, Drell-Yan
  - Heavy quarkonia: J/ψ and ϒ suppression
- Intermediate Mass Range (IMR)
  - $1.1 < M_{ee} < 3$ GeV/c^2
  - QGP thermal radiation
  - Semi-leptonic decay of correlated charm: heavy-flavor modification
- Low Mass Range (LMR)
  - $M_{ee} < 1.1$ GeV/c^2
  - in-medium modification of vector mesons
  - fireball lifetime measurement

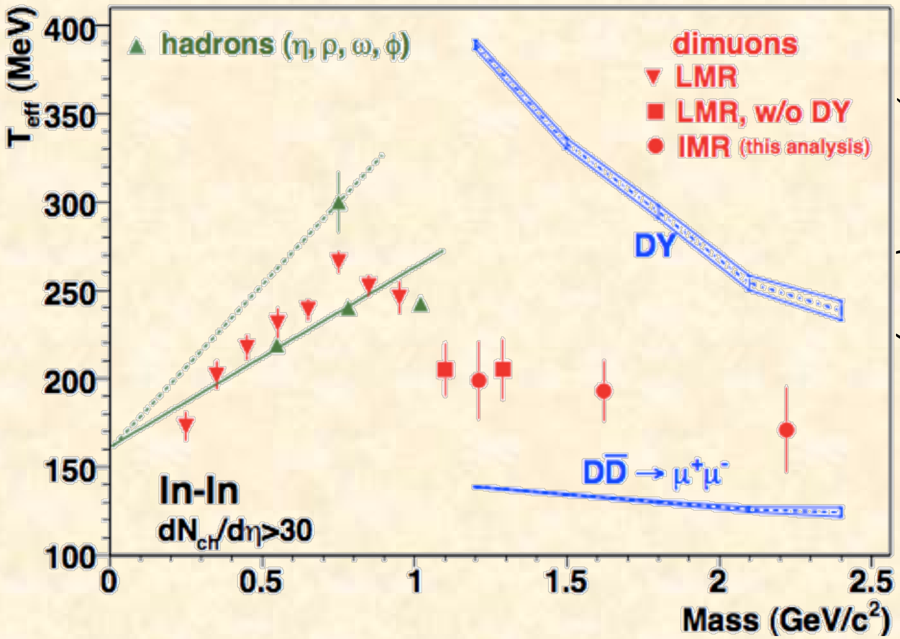
What have we learned from SPS?

PRL 96 (2006) 162302



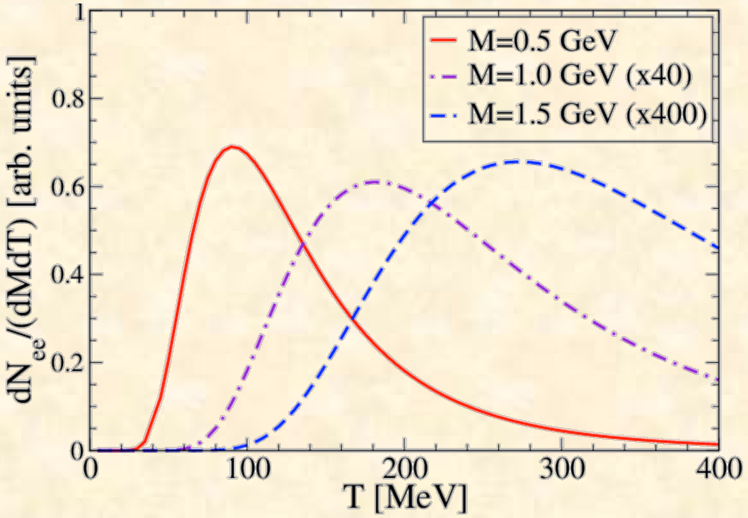
EPJ C61 (2009) 711

PRL 100 (2008) 022302



NA60, EPJ C 59 (2009) 607

Temperature Profile of Dilepton Yields



Rapp, Acta Phys. Pol. B42 (2011) 2823

Precise dimuon mass spectrum

- favors ρ broadening through interactions with hadronic medium

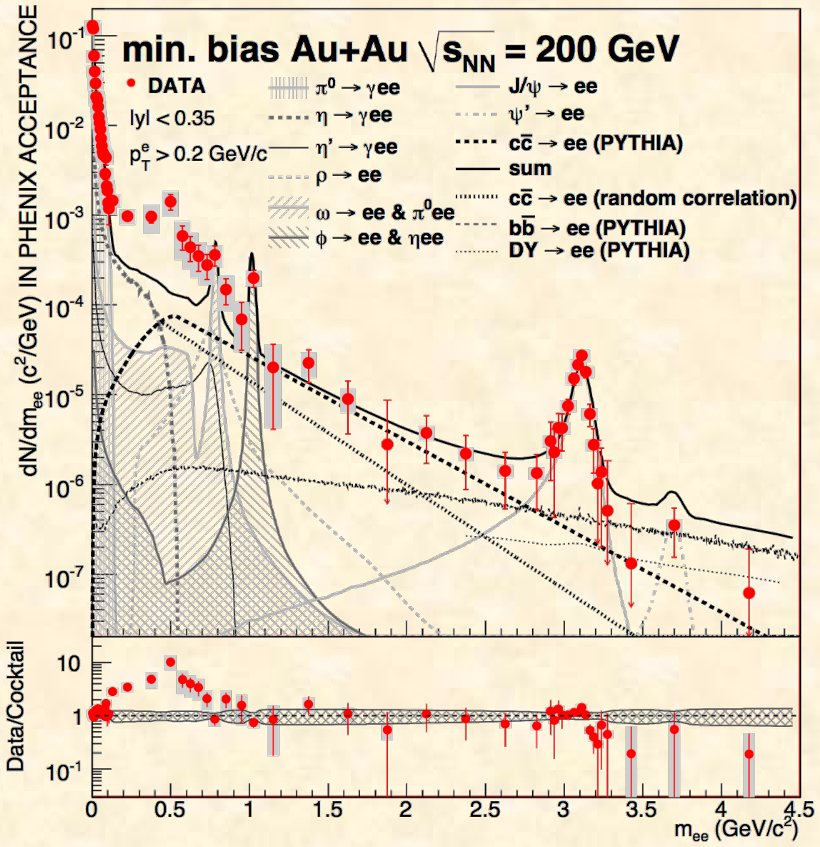
Inverse slope parameter from m_T distributions

- IMR: no indication of mass dependence
- indicative of thermal radiation from partonic medium, T=205 ± 12 MeV

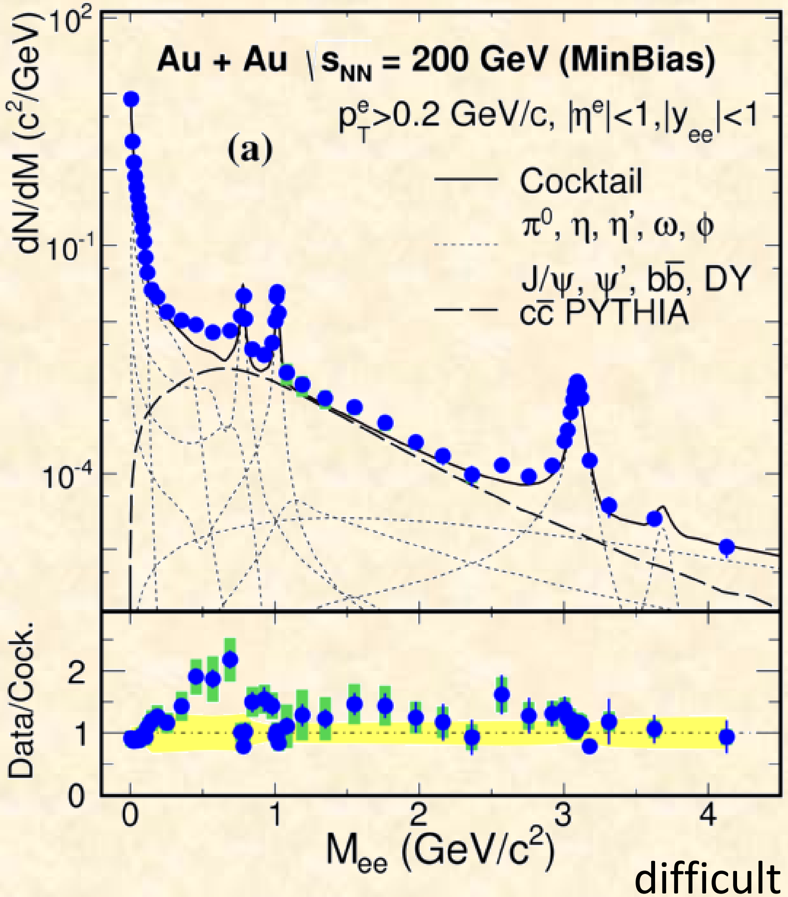
What did we learn from Au+Au@200GeV at RHIC?

PHENIX :: Run 4 - PRC 81 (2010) 034911
STAR :: Run 10 - PRL 113 (2014) 022301; Run 10+11 - PRC 92 (2015) 024912

PHENIX



STAR



Low Mass Range:

- ➢ enhancement

  when compared to cocktail (w/o ρ)

✗ Large quantitative differences in low-mass , low-p_T region

Intermediate Mass Range:

within errors consistent with cocktail

- ➢ dominated by correlated charm contributions
- ➢ thermal QGP radiation
- ➢ modification of charm?

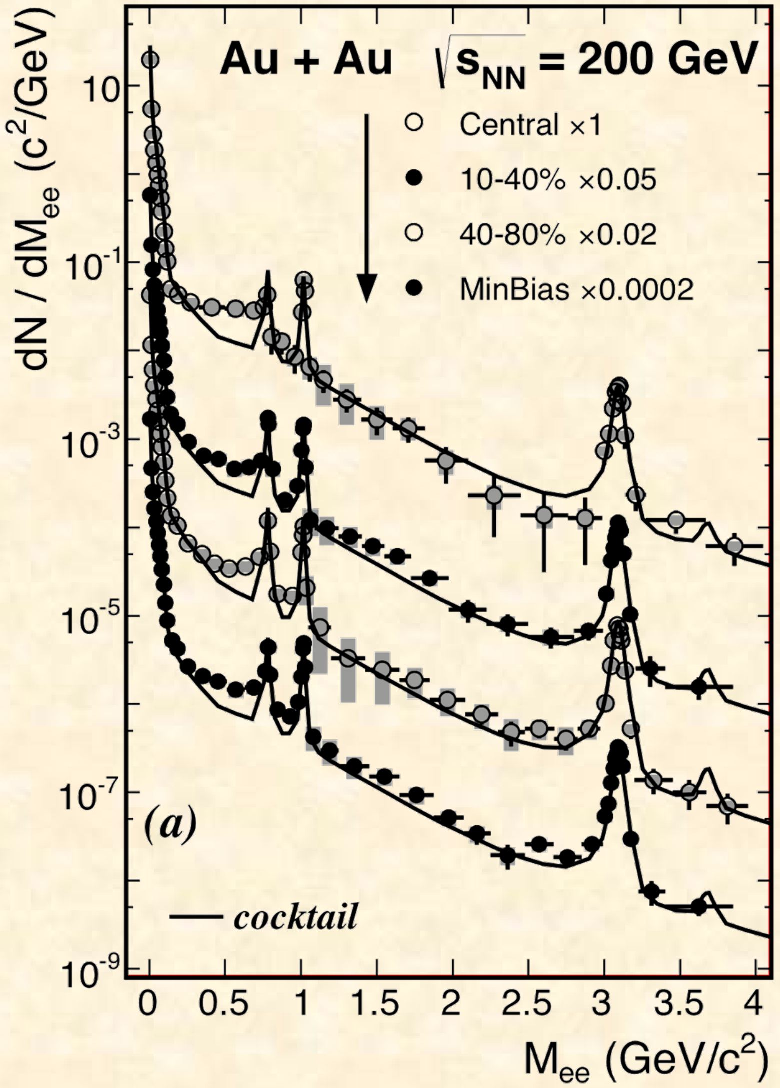
difficult to disentangle

✓ RHIC Runs-14/16 focus on heavy-flavor

LMR enhancement: Agreement between PHENIX & STAR

✓STAR

PRC 92 (2015) 024912



Enhancement factors (in MB)

PHENIX (PYTHIA):

2.3 ± 0.4(stat) ± 0.3(syst) ± 0.2(model)

PHENIX (MC@NLO)

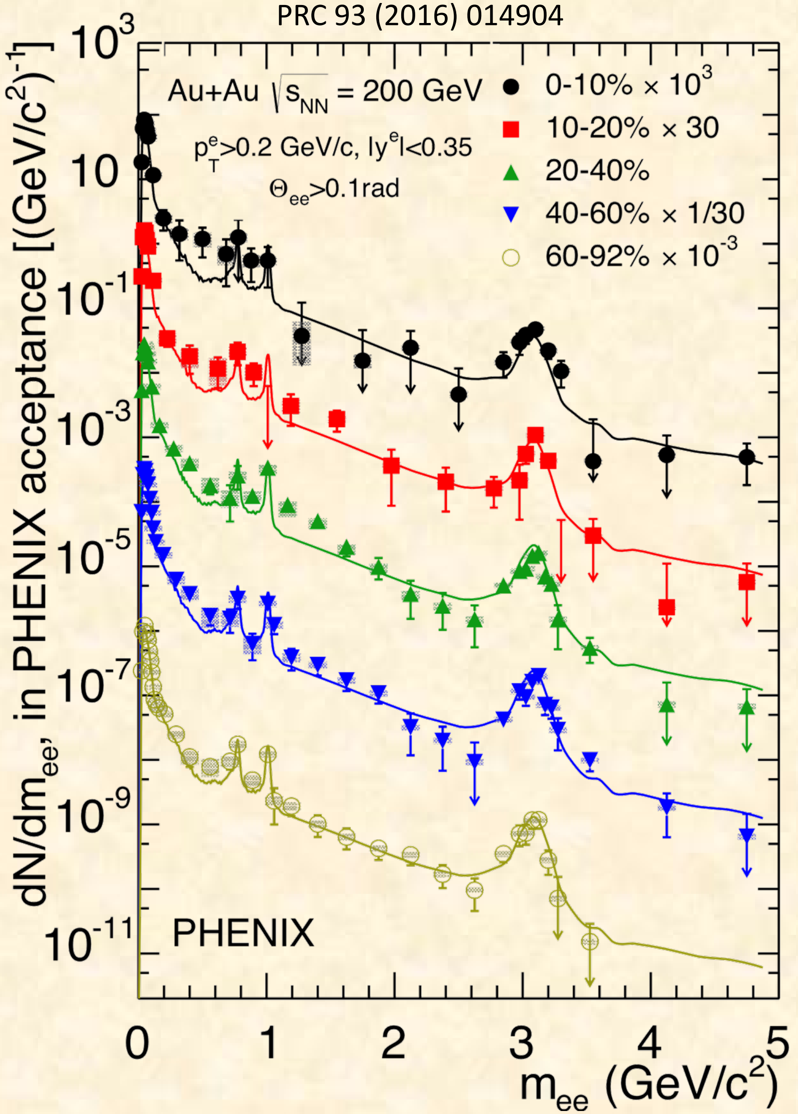
1.7 ± 0.3(stat) ± 0.3(syst) ± 0.2(model)

STAR (PYTHIA†) :

1.76 ± 0.06(stat) ± 0.26(sys) ± 0.29(cockt.)

✓PHENIX

PRC 93 (2016) 014904



LMR enhancement: Model Comparisons

✓STAR

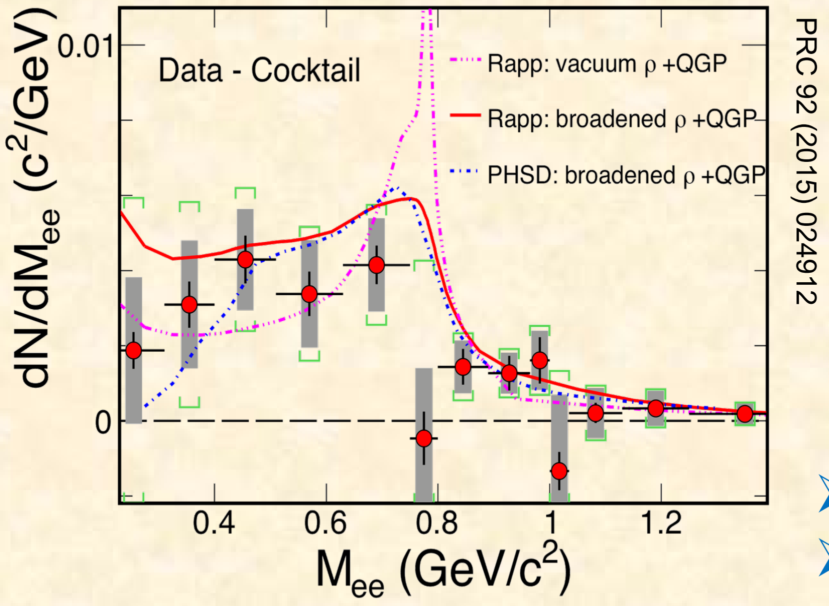


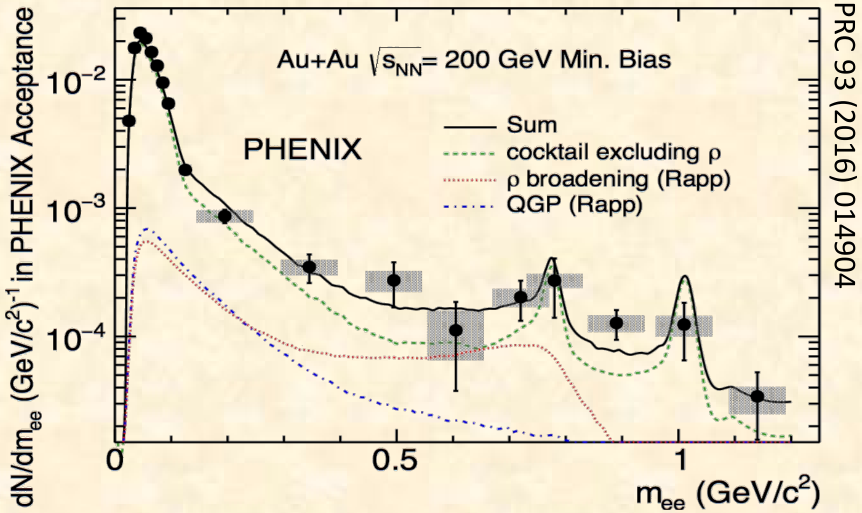
TABLE VIII. Reduced χ^2 for model calculations compared to the excess data in the invariant-mass region of 0.3–1.0 GeV/c^2.

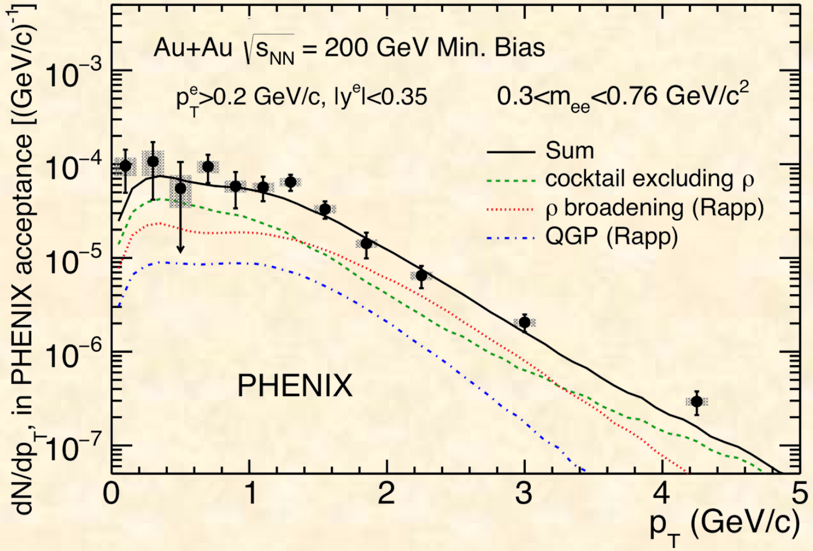
Model	χ^2/ndf	p value
Rapp: vacuum ρ + QGP	41.3/8	2.4×10^{-7}
Rapp: broadened ρ + QGP	8.0/8	0.32
PHSD: broadened ρ + QGP	16.5/8	0.040

R. Rapp,PRC 63 (2001) 054907
O. Linnyk et al., PRC 85 024910 (2012)

- Data does not support vacuum ρ
- Within uncertainties agreement between experiment and theory

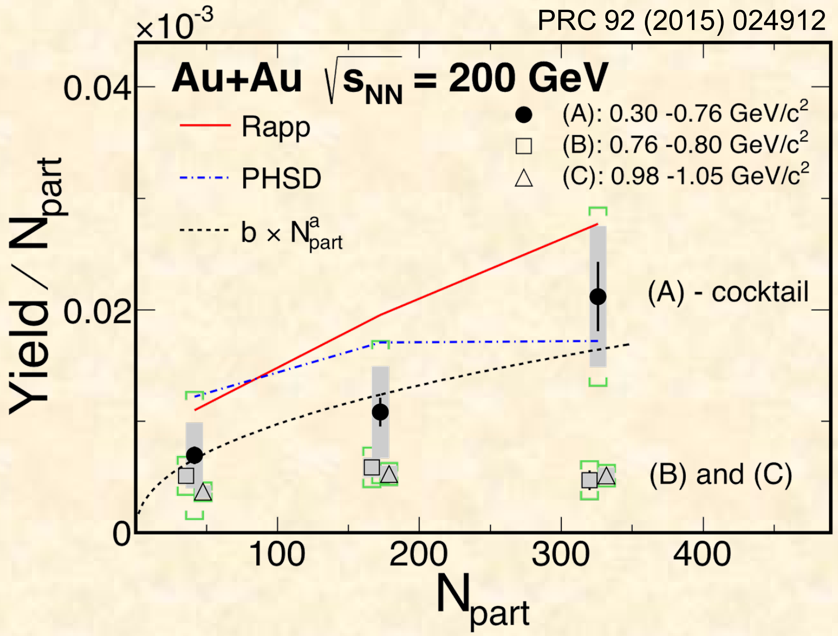
✓PHENIX



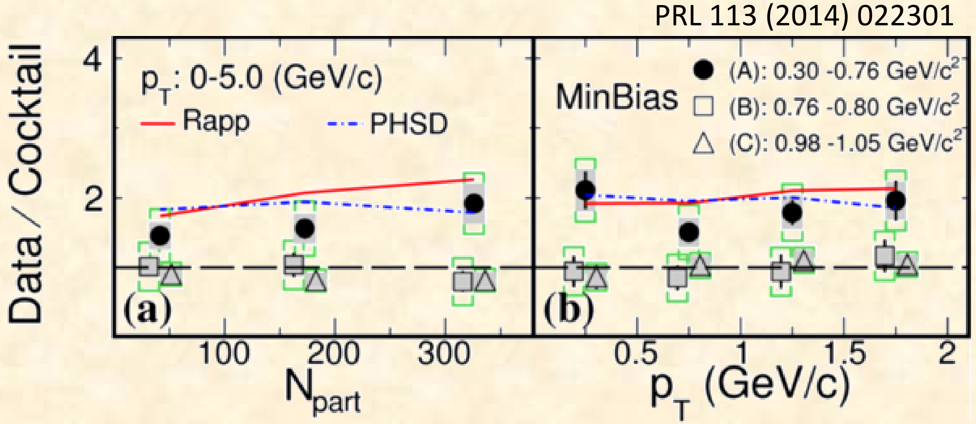


LMR enhancement: Model Comparisons

✓ STAR

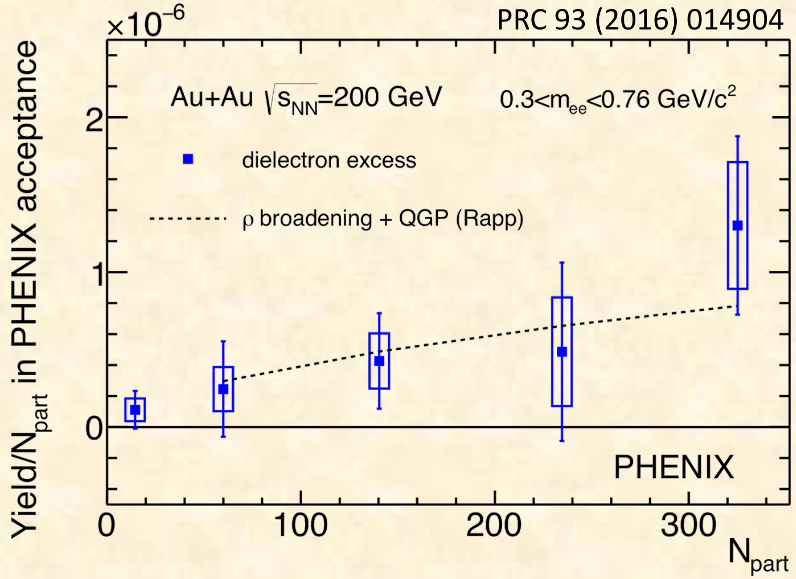


A: ρ-like 0.30 - 0.76 GeV/c²
B: ω-like 0.76 - 0.80 GeV/c²
C: φ-like 0.98 - 1.05 GeV/c²



Run 10 only
PRL 113 022301

✓ PHENIX



$$Y \propto (dN_{ch}/dy)^a$$

- STAR: a = 1.44 ± 0.10
- PHENIX: consistent with a ~ 1.43
- Rapp: a = 1.45 (~10% error)

Dielectron Production in U+U at 193GeV

Expect energy density to be higher by 20% than that in Au+Au at 200GeV

- longer life time of the medium?
- Higher excess yields in low mass range?

Significant enhancement w.r.t. cocktail in ρ range

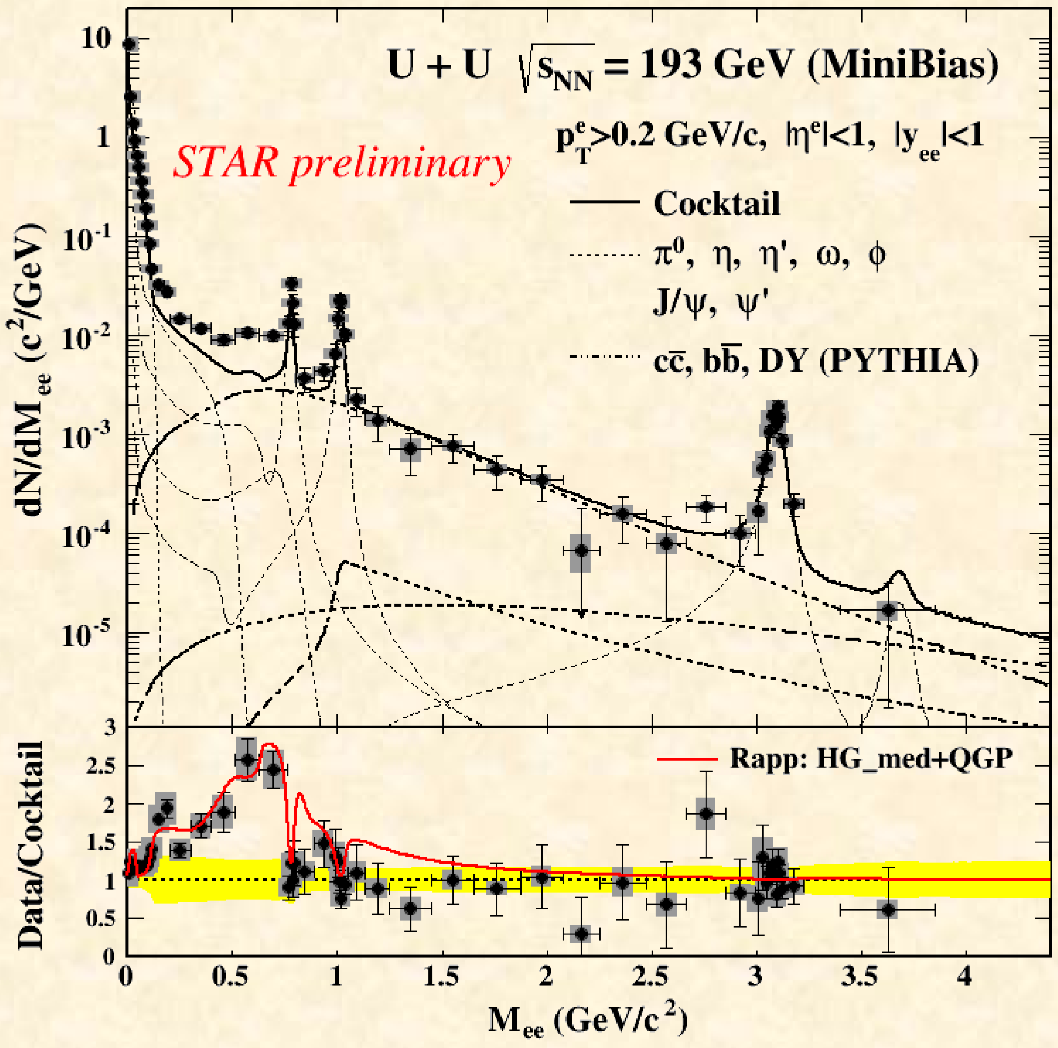
- 2.1 ± 0.1 (stat) ± 0.2 (syst) ± 0.3 (cocktail)
  - for $300 < M_{ee} < 760$ MeV/c^2
- Significant charm contribution in this range: 48.5%
  - σ_{cc}=797 μb, σ_{bb}=3.7 μb, σ_{DY}=42nb
- Model comparison again show good agreement

Model simulation:

R. Rapp – Adv. High energy Phys. (2013) 148253

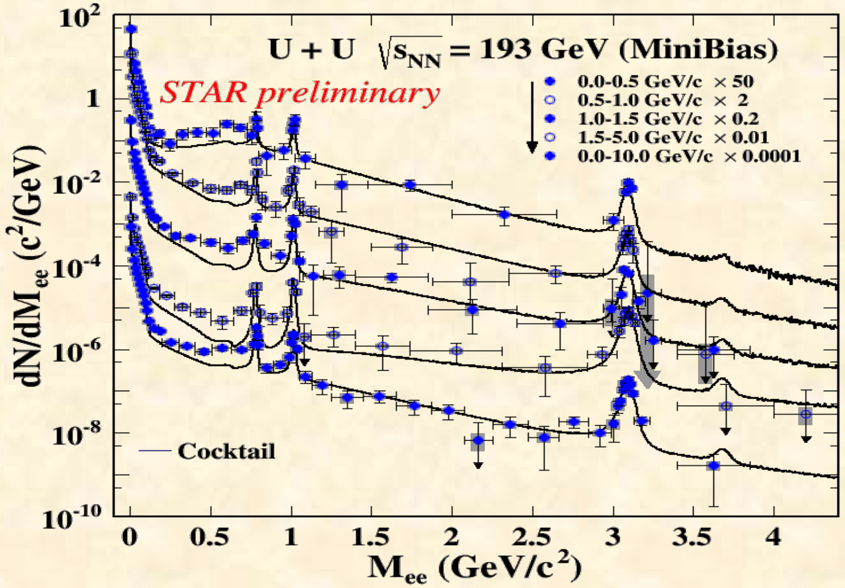
Cocktail simulations:

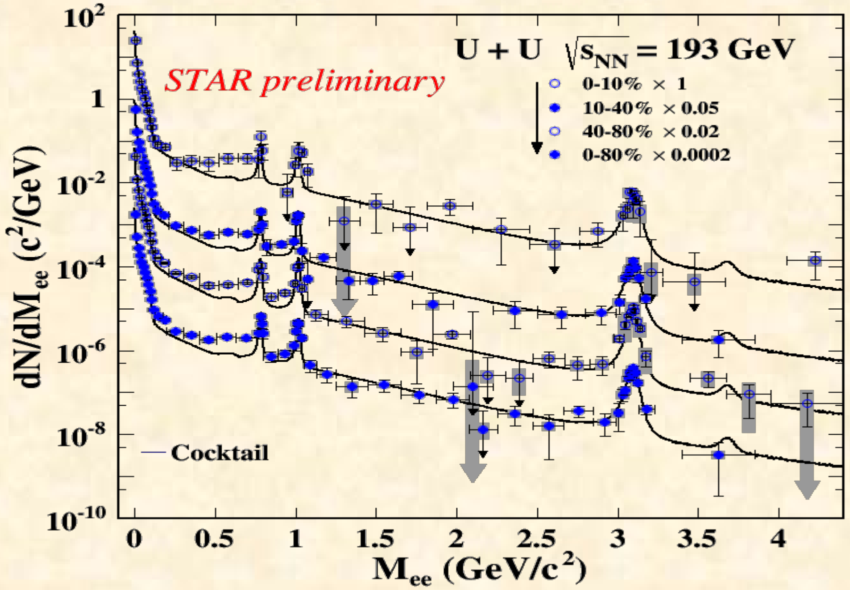
STAR, PRC 92 (2015) 024912

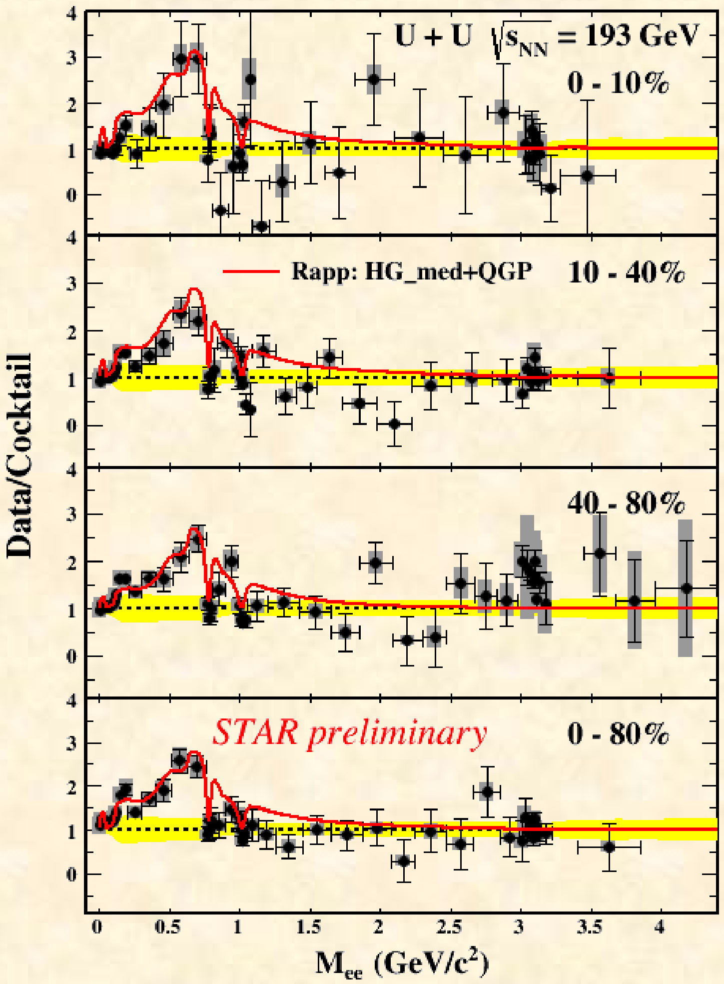


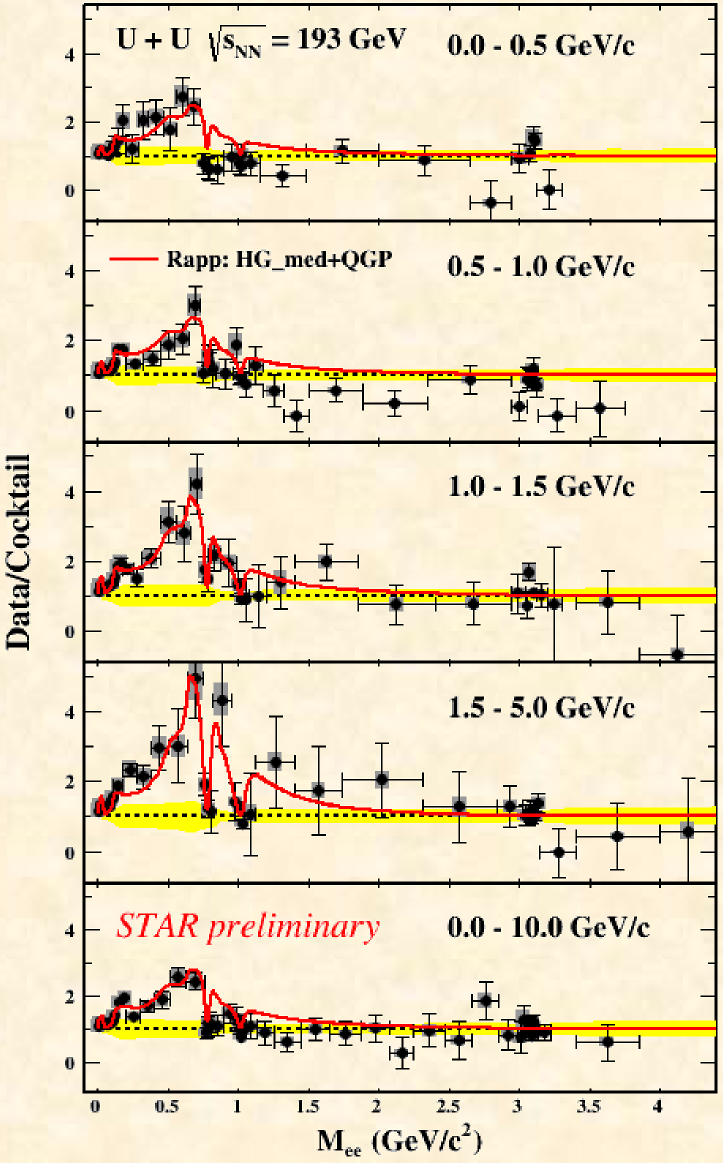
Shuai Yang, QM2015

U+U@193GeV: Centrality and p_T Differentials



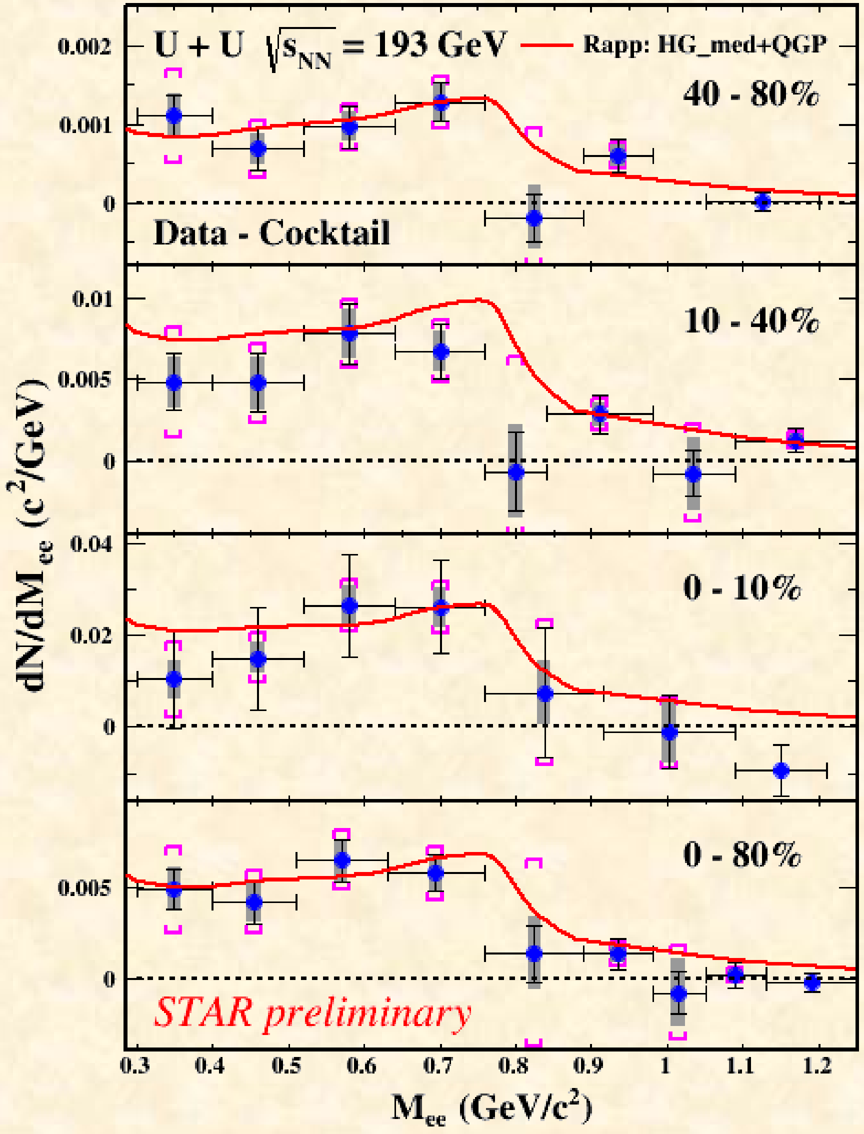


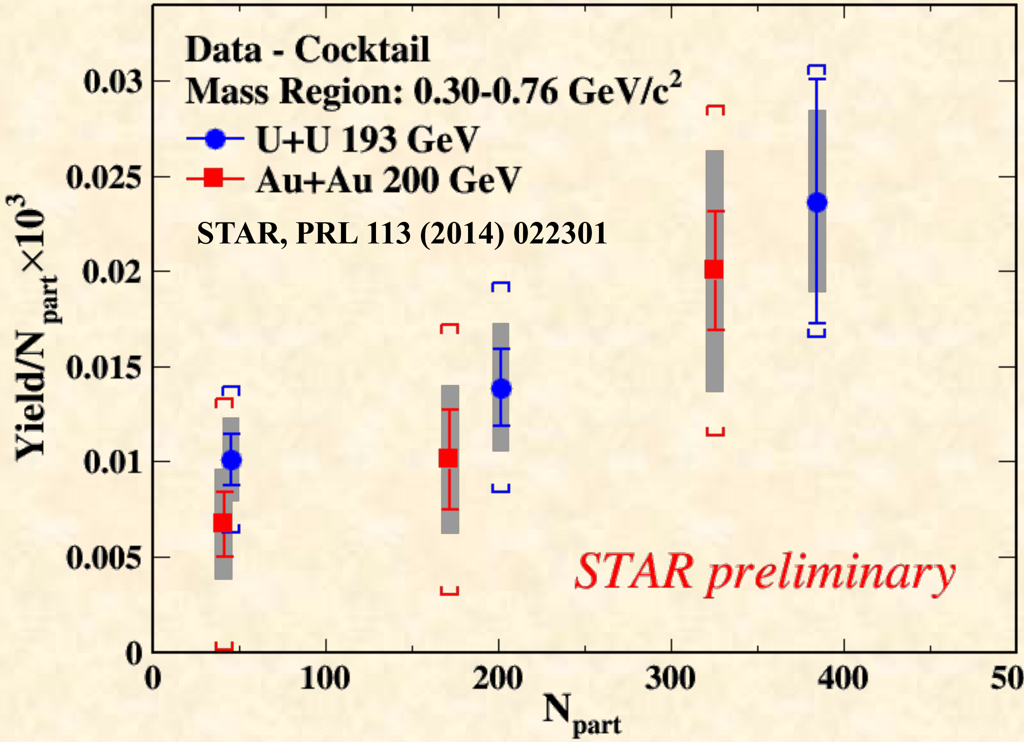




Shuai Yang, QM2015

U+U@193GeV: Excess Spectrum





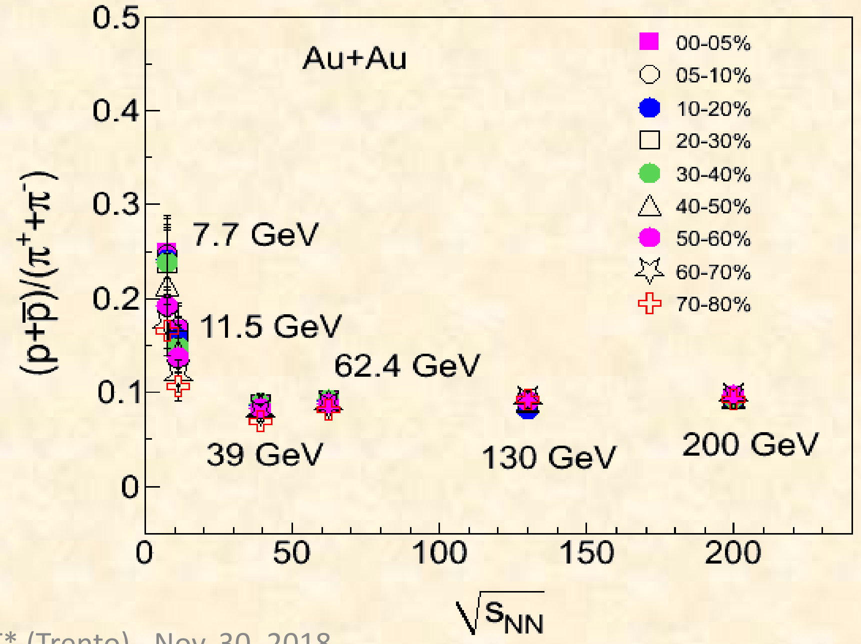
Shuai Yang, QM2015

- Observe excess yield in ρ-like mass region
- Model calculation consistently describes low-mass range
  - N_{part} scaling similar to that in Au+Au

Dielectron Production at lower $\sqrt{s_{NN}}$

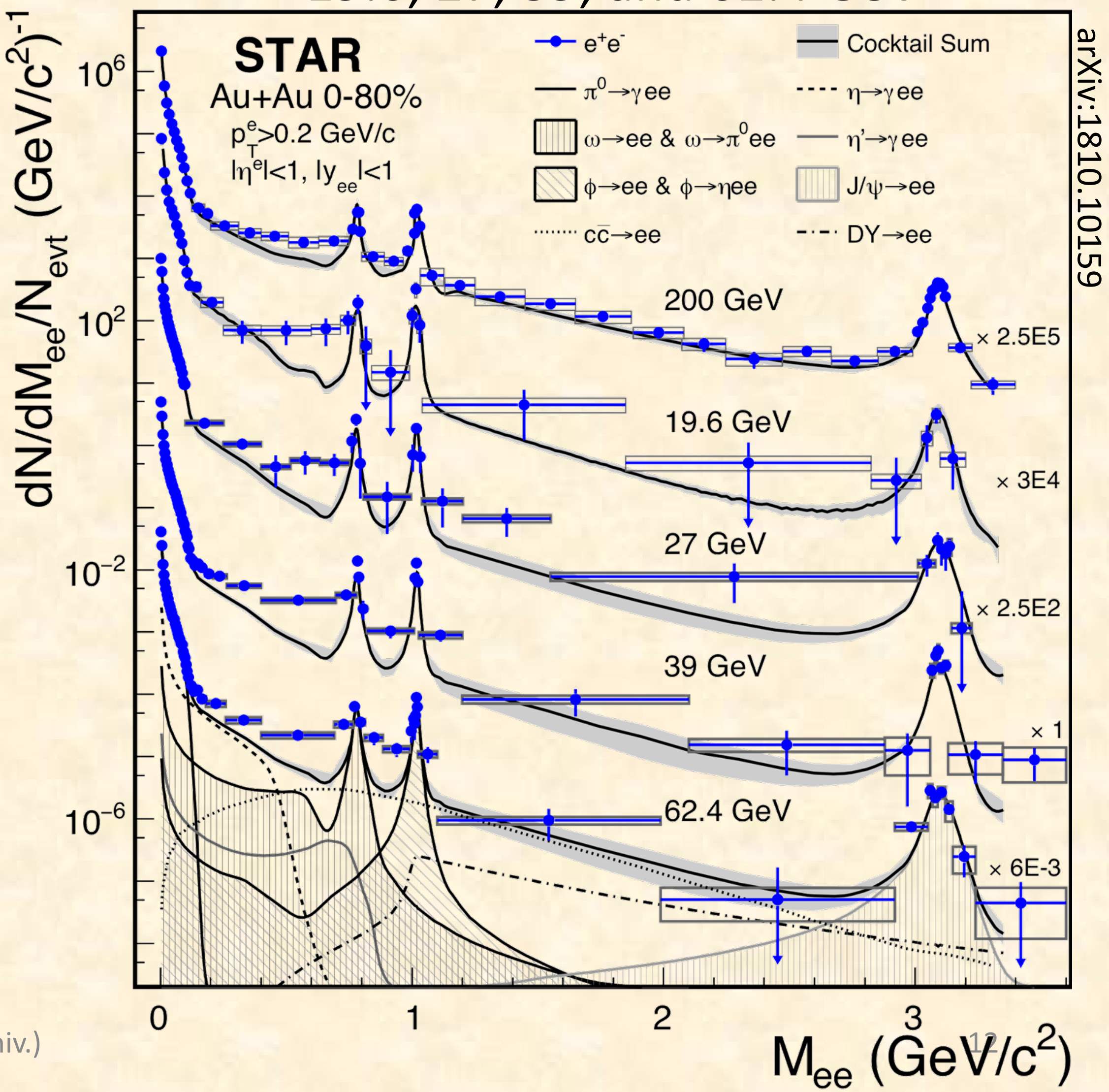
Observed low-mass enhancement at top RHIC energy
- in-medium modification effects?
- indication of chiral symmetry restoration?

Explore low-mass range down to SPS energies
- change initial conditions, net-baryon density
- total-baryon density ~constant
- possible enhancement, consistent model description?

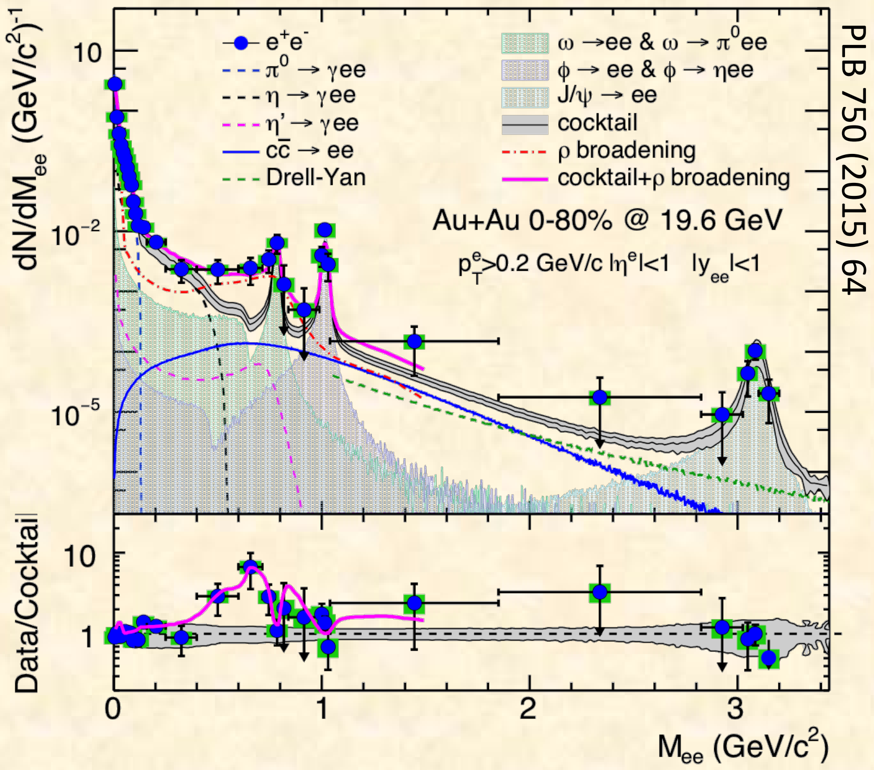


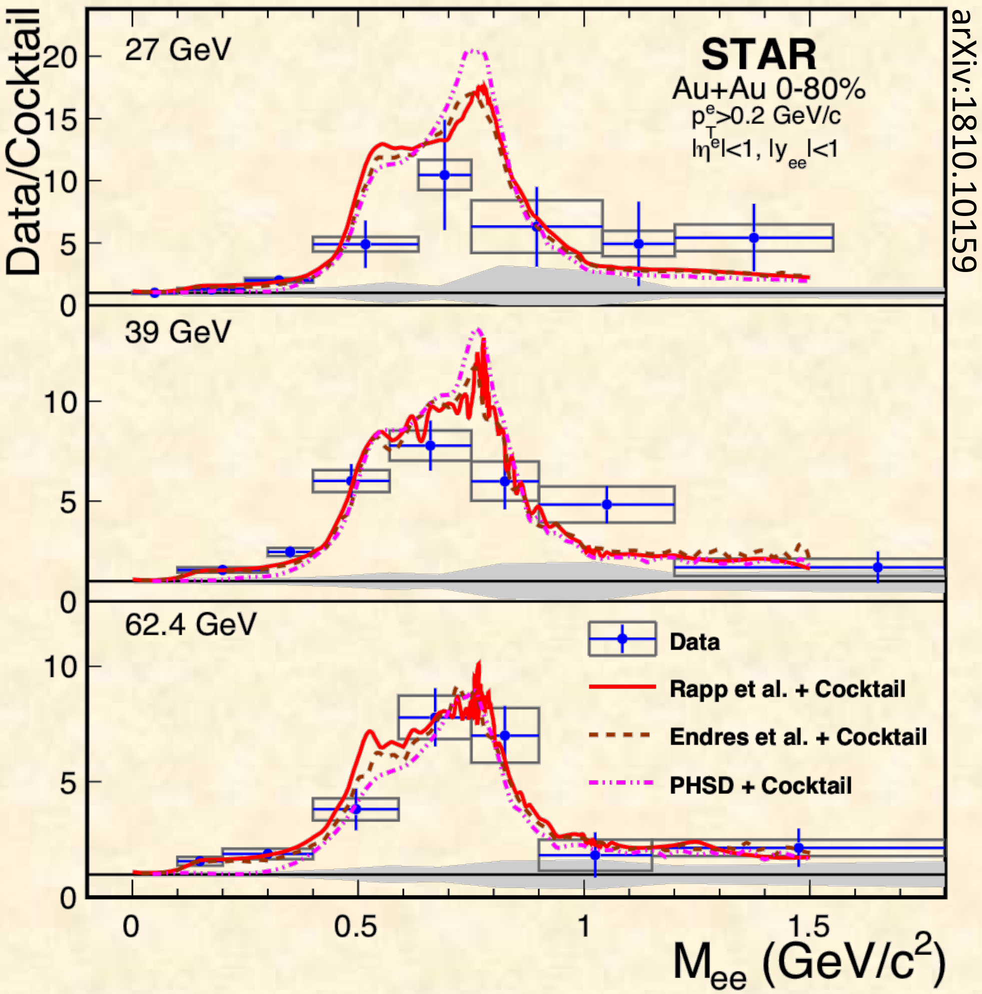
RHIC Beam Energy Scan Dielectrons

2010 – 2011 Au+Au at
19.6, 27, 39, and 62.4 GeV



Compare to Theory: In-Medium ρ





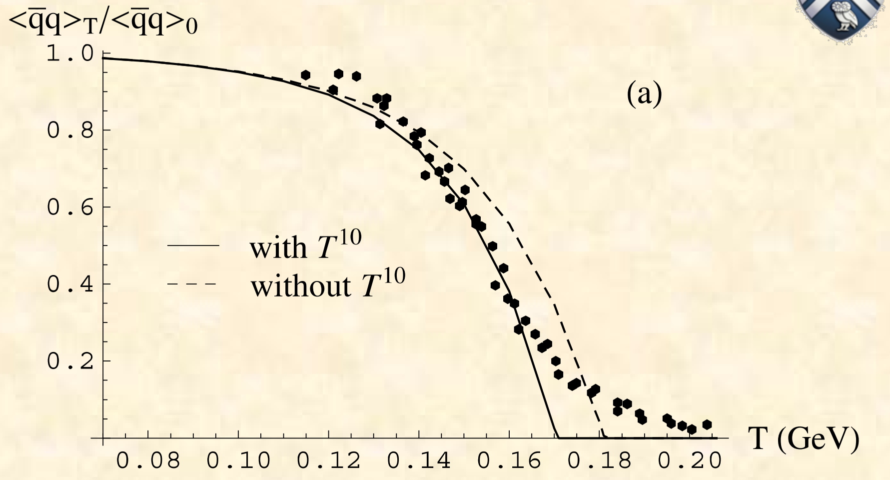
- ➢ Sustained low-mass excess radiation
  - ➢ top RHIC down to SPS energies
- ➢ Robust theoretical description
  - – black dotted curve: cocktail + in-medium ρ (Rapp)
- ➢ Consistent with in-medium ρ broadening
  - – expected to depend on total baryon density

Hohler & Rapp: "Is ρ-meson melting compatible with chiral restoration? "

A Phenomenological Approach

Experiment: Strong evidence ρ meson "melts"

- Input
  - vector SF (ρ meson) from phenomenological model, verified against experimental data
  - T dependence of the condensate: from LQCD
- QCD sum rules
  - constrain vector/axial-vector SFs individually
- Weinberg sum rules
  - difference between vector & axial-vector SFs
- Output …

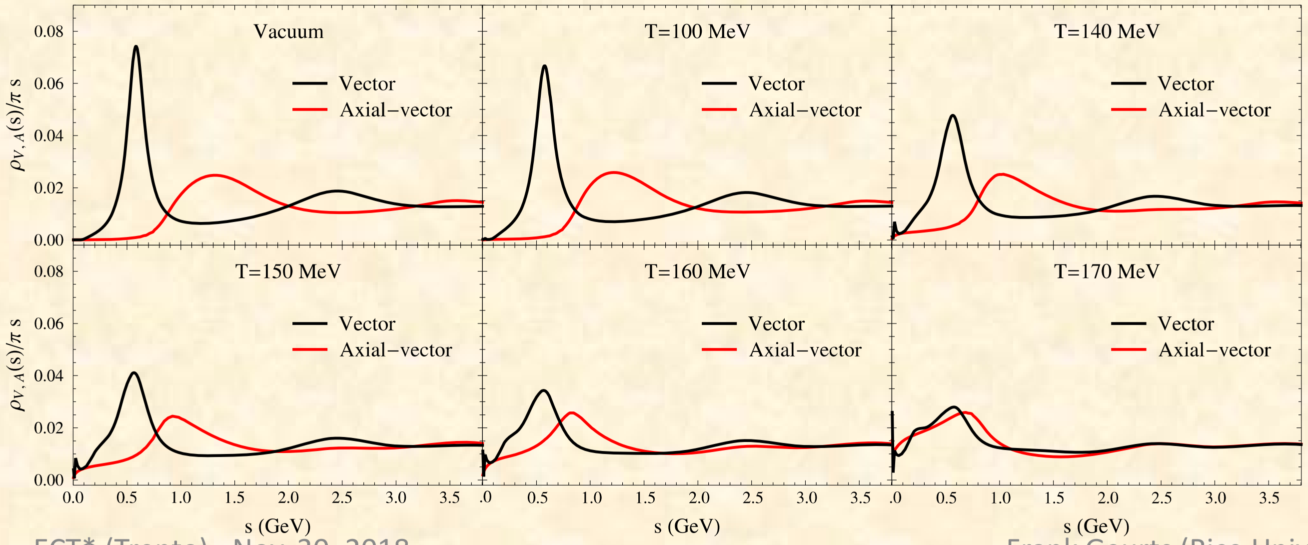


$$\frac{1}{M^2}\int ds \frac{\rho_{V/A}(s)}{s} e^{-s/M^2} = \sum_n C_n \langle O_n \rangle$$

$$\int ds (\rho_V - \rho_A) s^n = f_n$$

Quantitatively compatible with (approach to) chiral restoration

Hohler, Rapp *PLB 731 (2014) 103*



But, still need microscopic calculations of $a_1(1260)$ … (Massive Yang-Mills)

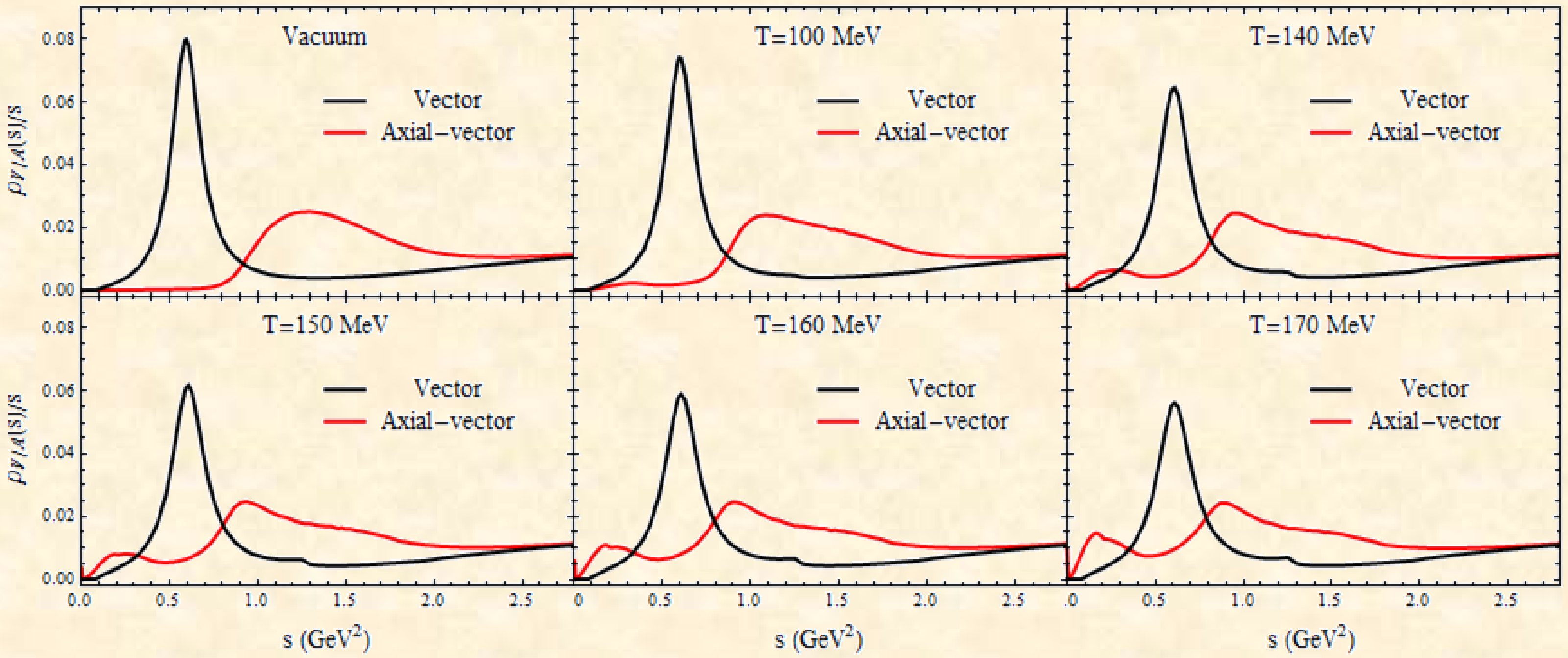
Effective Chiral Lagrangian

Gauge ρ and a_1 into chiral pion Lagrangian

Hohler & Rapp, PRD 89, 125013 (2014)

- Massive Yang-Mills in hot pion gas

  starting point for evaluation of chiral restoration in medium



Rapp, HardProbes 2015

- Supports "burning" of chiral-mass splitting as a mechanism for chiral restoration

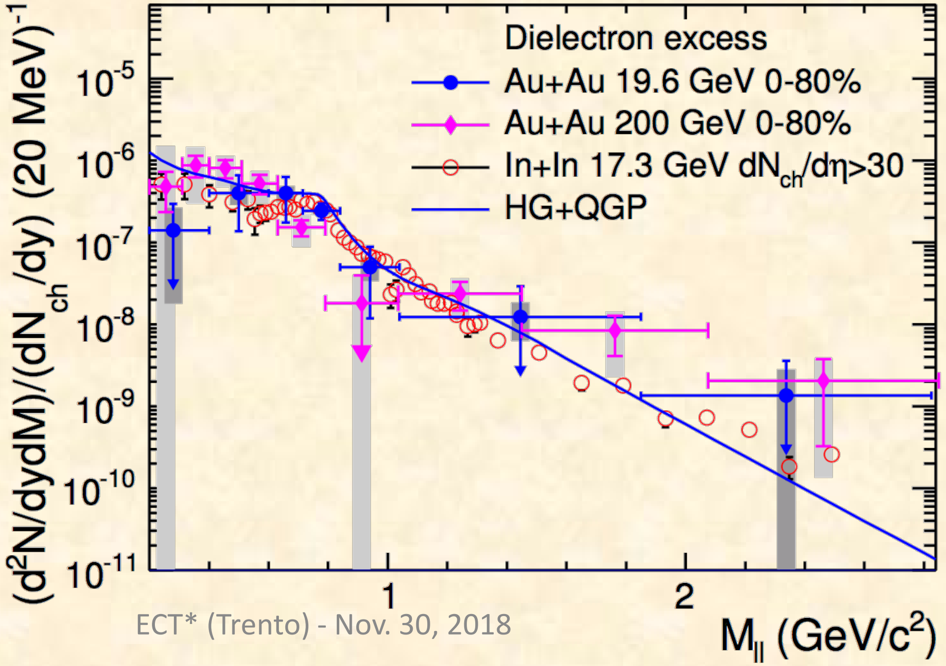
– "The implementation of the here constructed axial-vector spectral function into hadronic matter can thus serve as a quantitative framework to establish the long-sought connection to chiral symmetry restoration. "

Acceptance-Corrected Excess Spectra

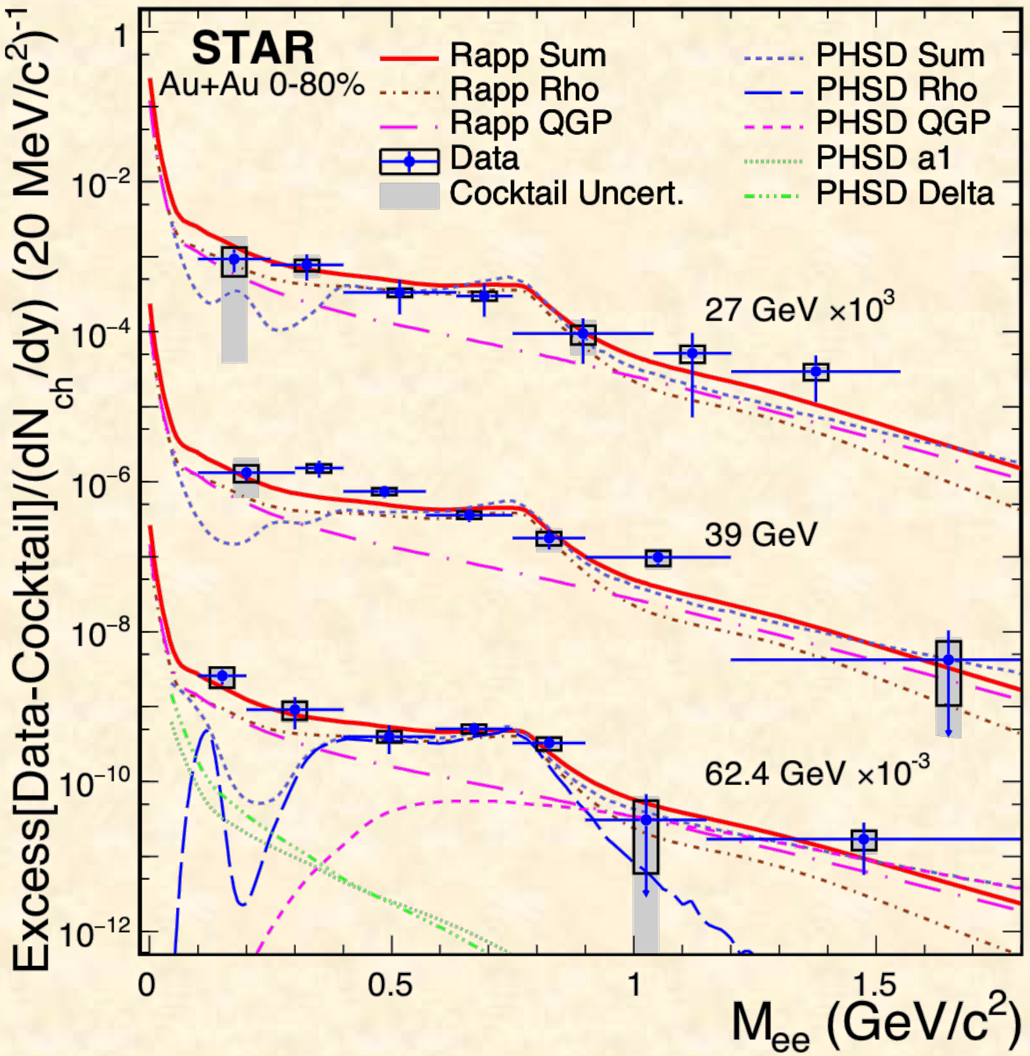
STAR-acceptance corrected excess spectra

- Au+Au at 19.6 and 200 GeV
- normalized to $(dN_{ch}/dy)_{y=0}$
- 17.3 GeV (NA60) and 19.6 GeV consistent

Acceptance-corrected spectra for BES energies at 27, 39, and 62 GeV



STAR, PLB 750 (2015) 64

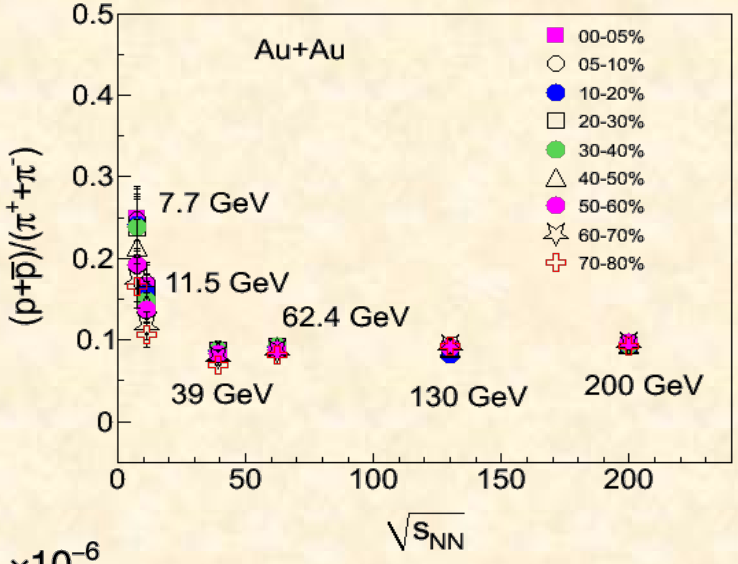


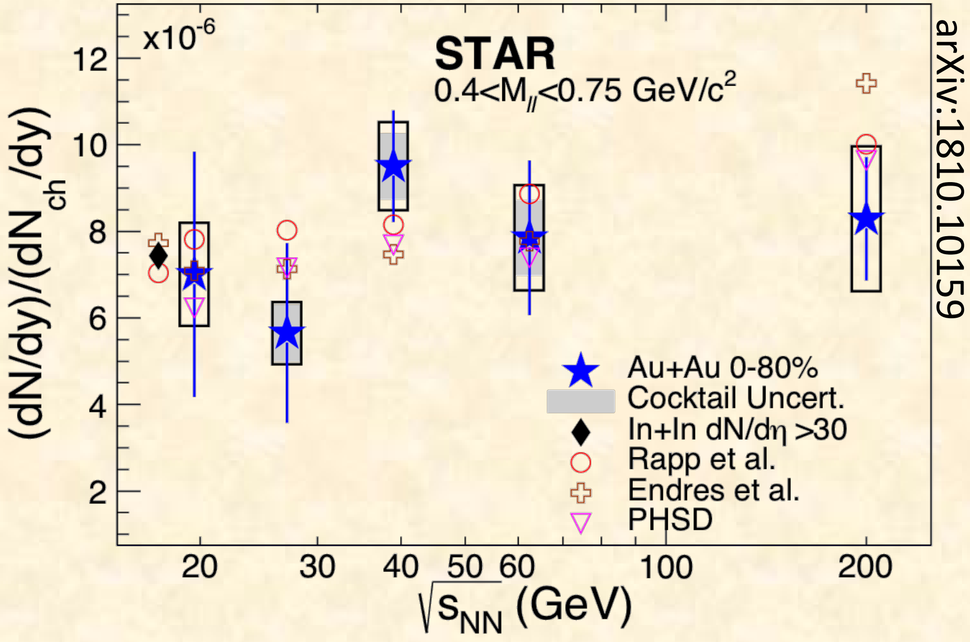
arXiv:1810.10159

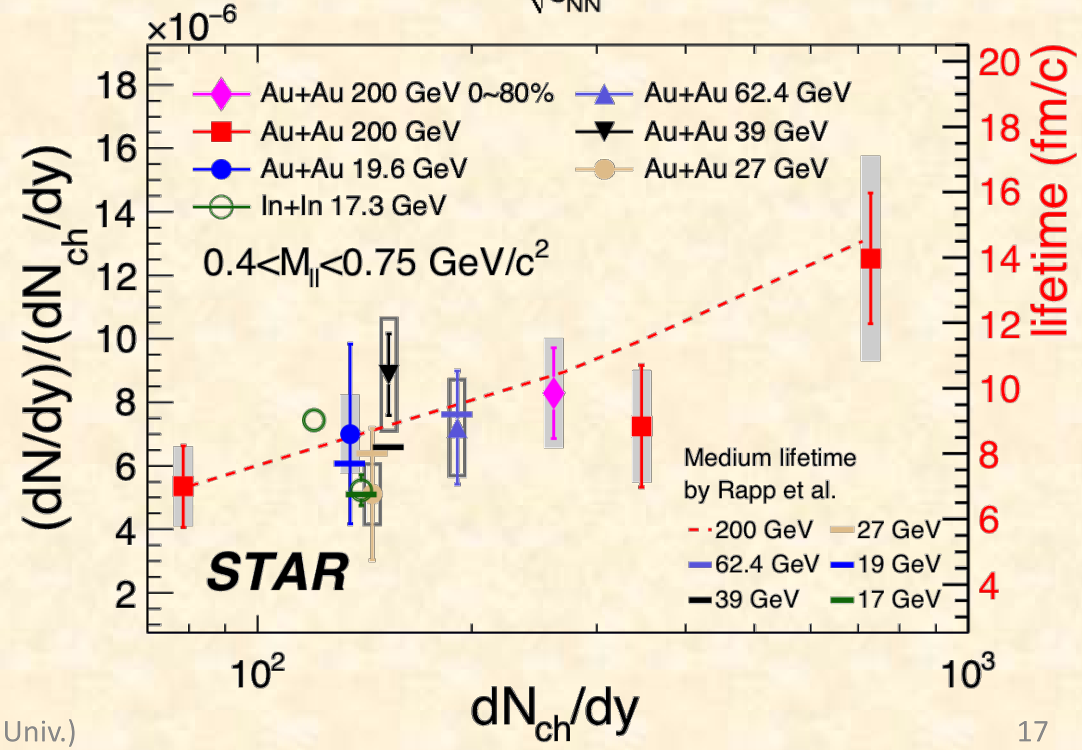
➢ **Acceptance-corrected excess mass spectra well described by broadened ρ SF**

Excitation Functions: Normalized Yields

- ➢ Normalized excess yields in LMR proportional to medium life time (QGP+HG) for $\sqrt{s_{NN}}$=17.3–200 GeV
  - – Nearly constant total baryon density
  - – Emission rates dominated around T_C
- • Yields in Au+Au@200GeV
  - – observe increase from peripheral to central



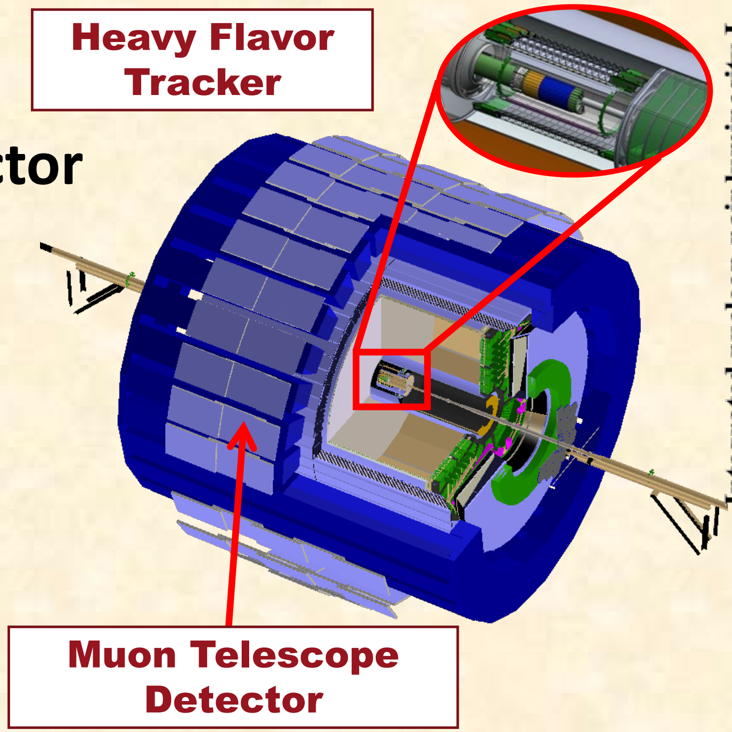




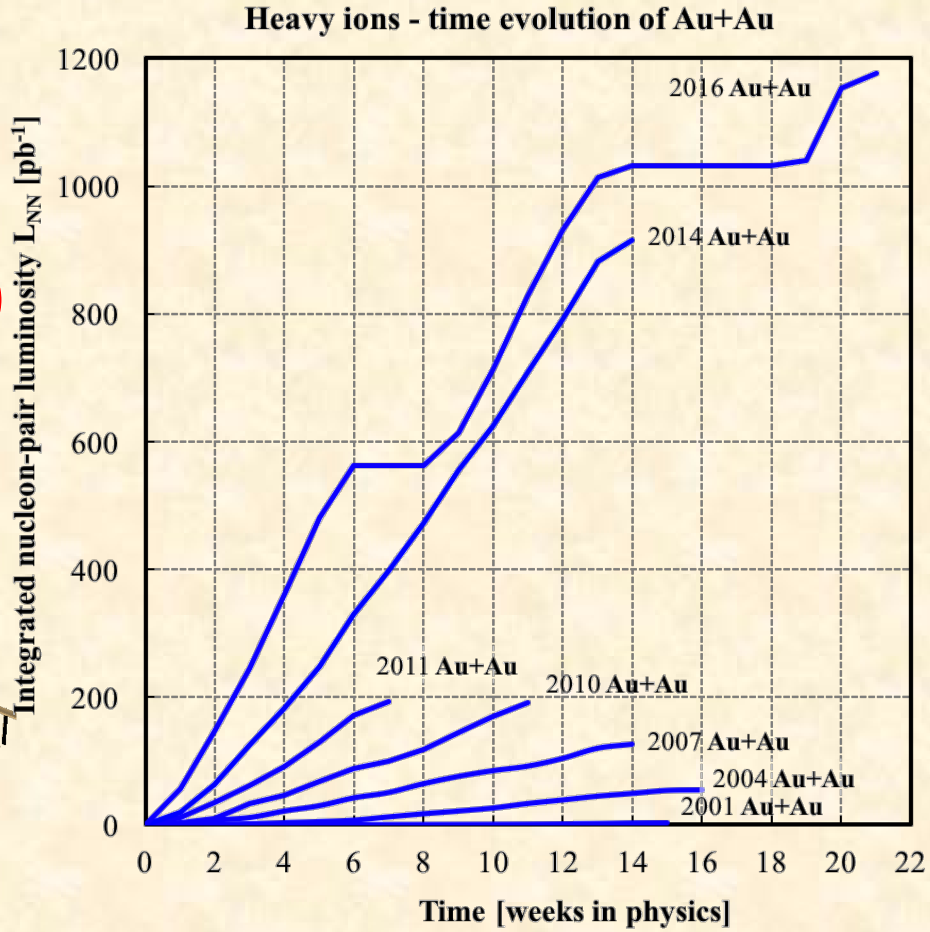
In+In@17.3 GeV: NA60, AIP Conf. Proc. 1322 (2010) 1

RHIC Program 2014-2016: Heavy Flavors

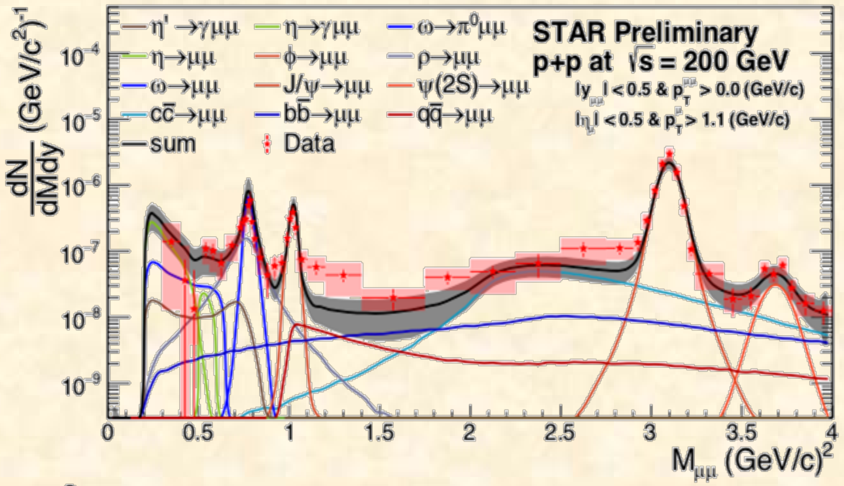
- RHIC upgrades
  - fully implemented stochastic cooling
- STAR upgrades
  - Heavy Flavor Tracker
  - ➢ **Muon Telescope Detector**

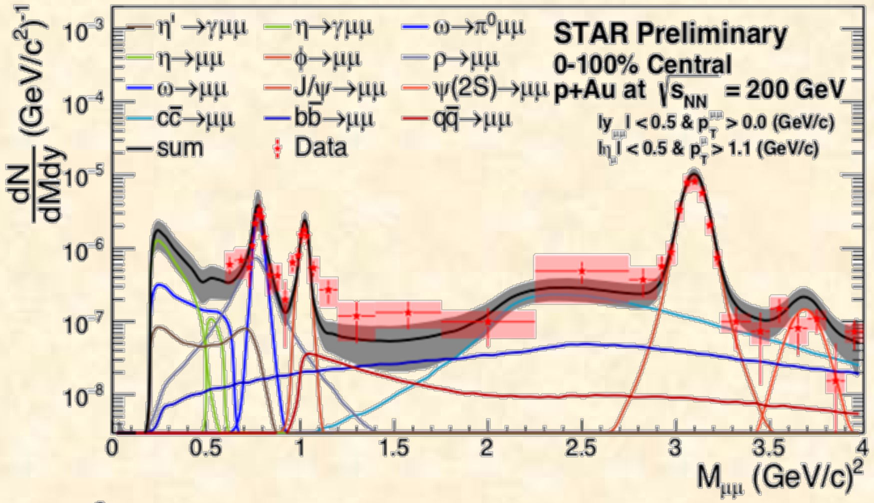


- 2014: Au+Au statistics
  - 200 GeV: 1.2B events
  - 14.6 GeV: 20M events
- 2015: p+p, p+Au, p+Al
- 2016: Au+Au (~10wks)
  - 200 GeV: 2B events

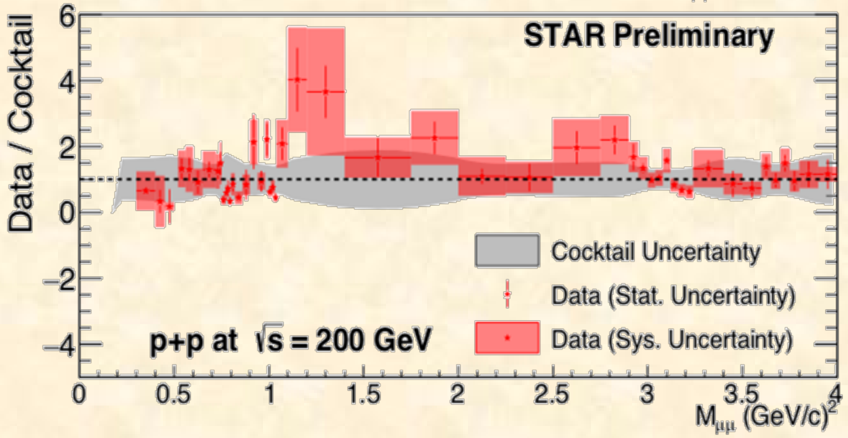


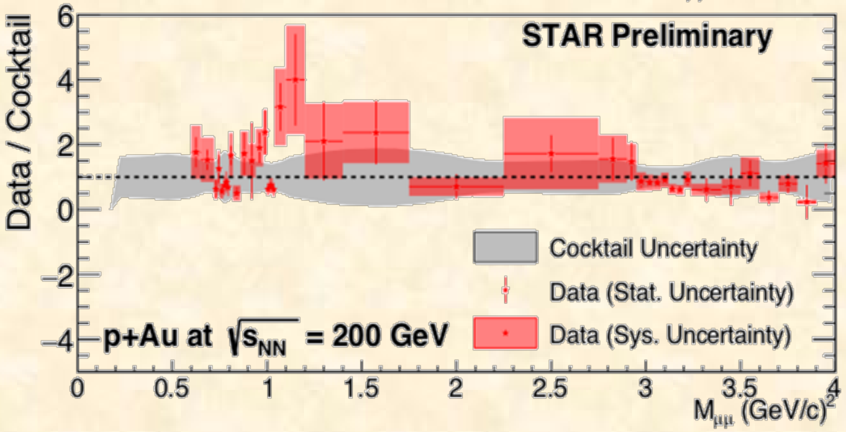
MTD Dilepton Physics



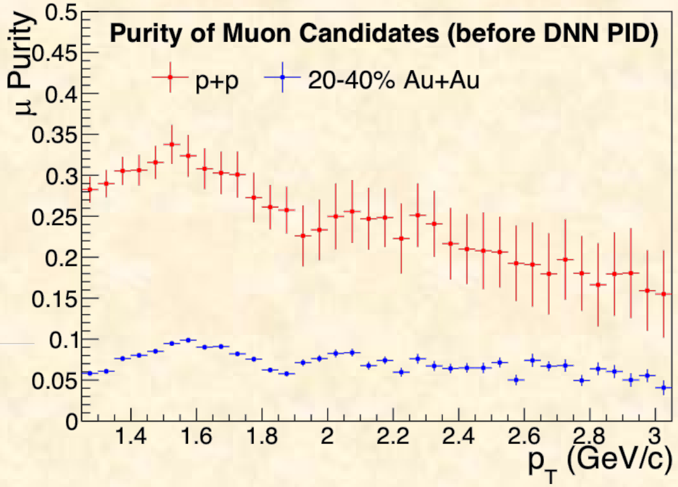


Brandenburg
HP 2018 (PhD thesis)





Muon purity estimate
(incl. secondaries)



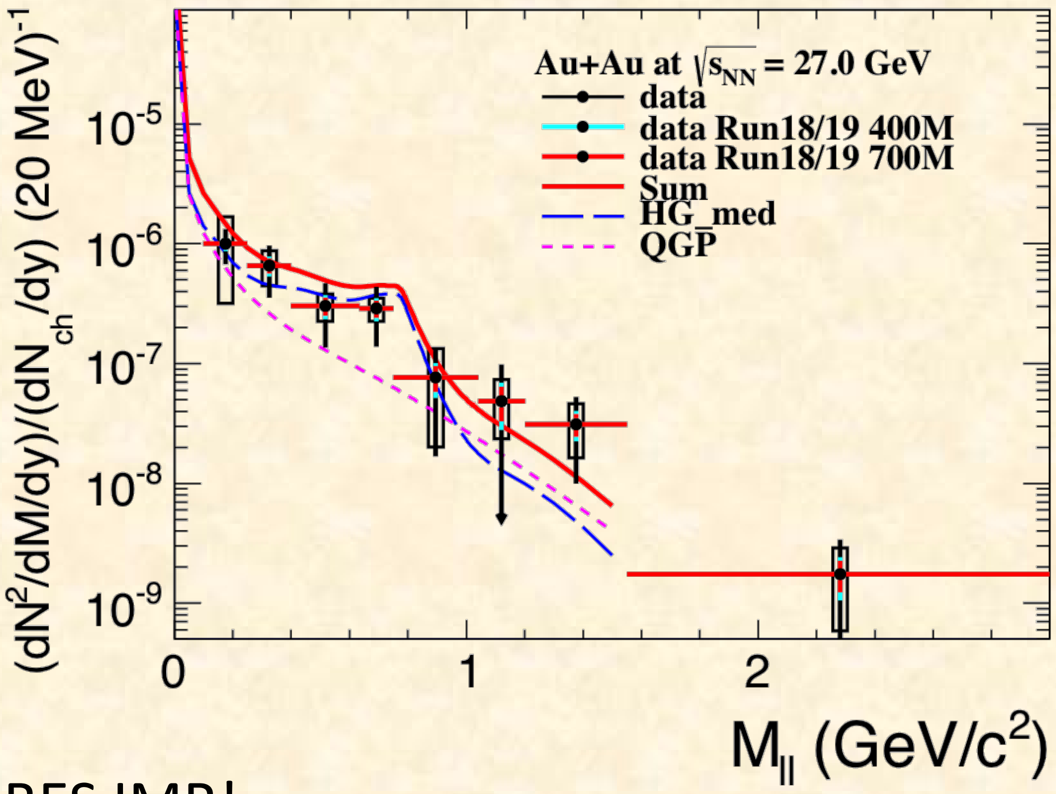
- Au+Au will be very difficult at best

New Datasets :: prospects

Run 17+: removal of HFT and restoration of old beam pipe

- Continue to take large data sets

STAR Beam Use Request 2017/2018 (SN670)



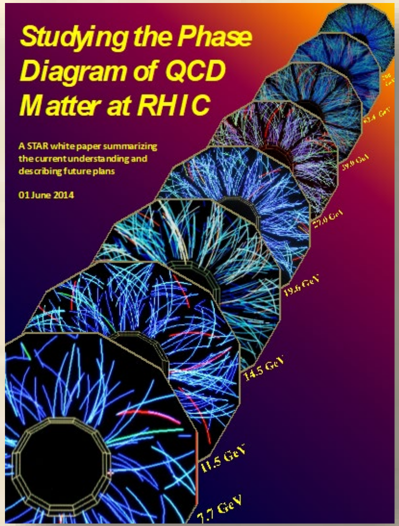
- Run 18 isobars (Ru+Ru and Zr+Zr): 3B events for each species
  - Dielecton analysis: virtual photon

- Data sets with large statistics to revisit BES IMR!
  - 1.5B events at 27GeV
  - 1.3B events at 54GeV

Beam Energy Scan Phase-II

Dedicated second phase of the BES program, proposed in 2014

STAR Note 598



STAR Beam Use Request 2019/2020 (SN696):

Table 8: Event statistics (in millions) needed in BES-II for various observables. This table updates estimates originally documented in Ref. [45].

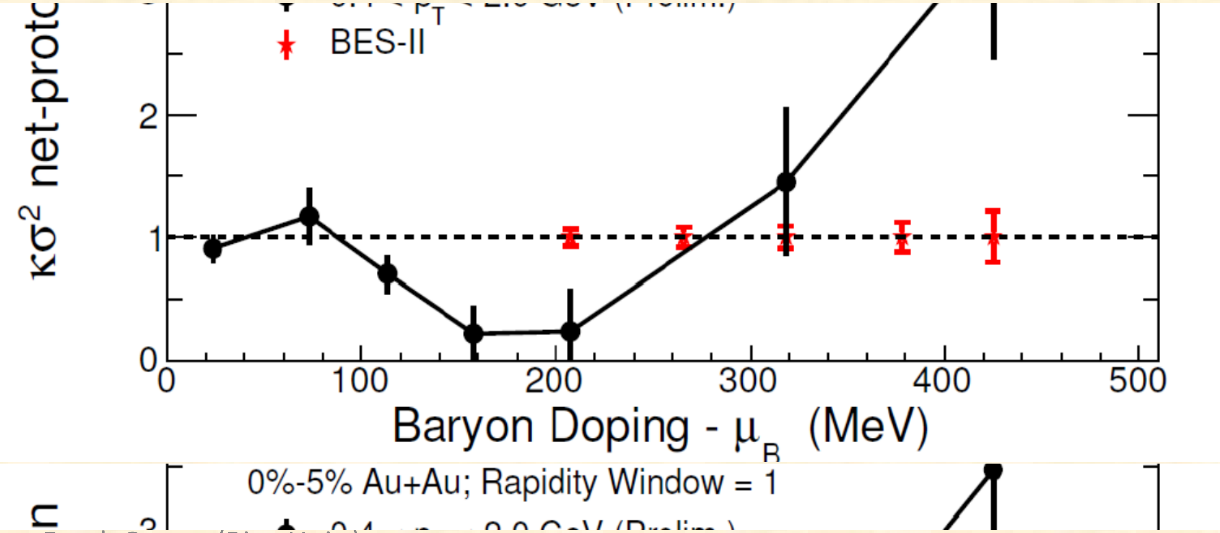
Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	-		160	125	92
Elliptic Flow (ϕ mesons)	80	120	160	160	320
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	20	30	35	45	50
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	70	85	100	170	340
Dileptons	100	160	230	300	400
$>5\sigma$ Magnetic Field Significance	50	80	110	150	200
Required Number of Events	100	160	230	300	400

Strong endorsement by NSAC

Long Range Plan 2015:

- ➢ *"Trends and features in BES-I data provide compelling motivation for […] experimental measurements with higher statistical precision from BES-II"*

http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

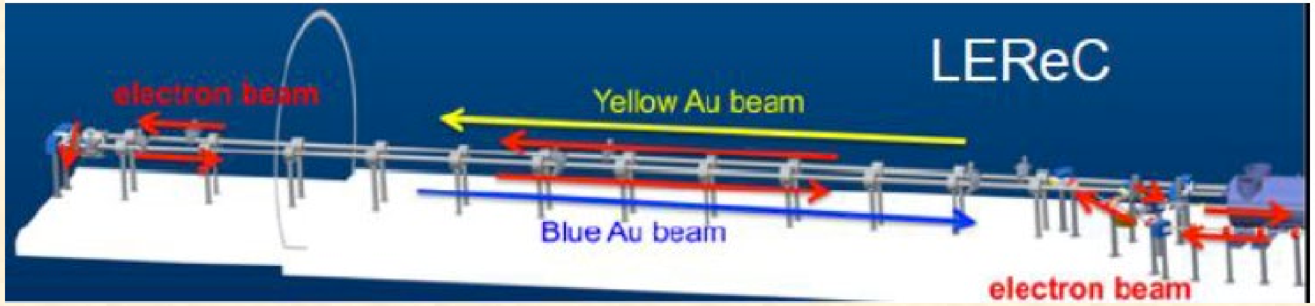


Low Energy RHIC Electron Cooling

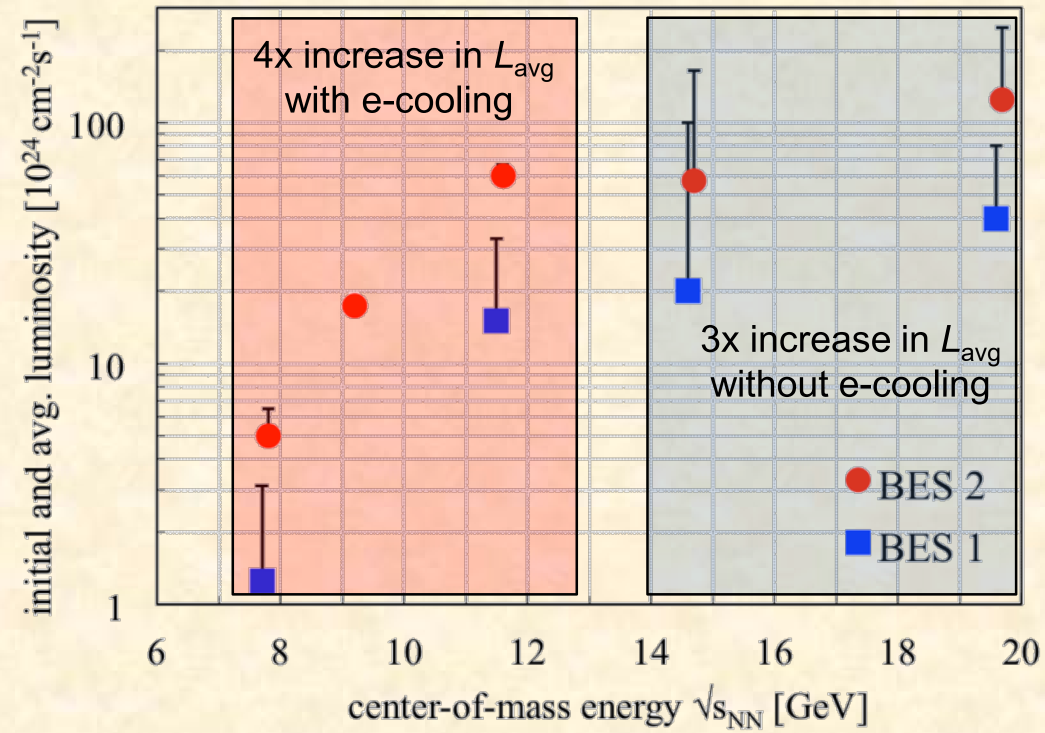
Improve luminosity for low energy beams:

- 2019 (w/o e-cooling): ~3× for $\sqrt{s_{NN}}$=14.5 and 19.6 GeV
- 2020-2021 (with e-cooling): ~4× for $\sqrt{s_{NN}}$=7.7, 9.1, and 11.5 GeV

➢ *e*-Cooling: a critical machine upgrade



Increased luminosity



2018 BNL NPP Adv. Committee Report:

3.1 RHIC Run 19

The PAC recommends for Run 19:

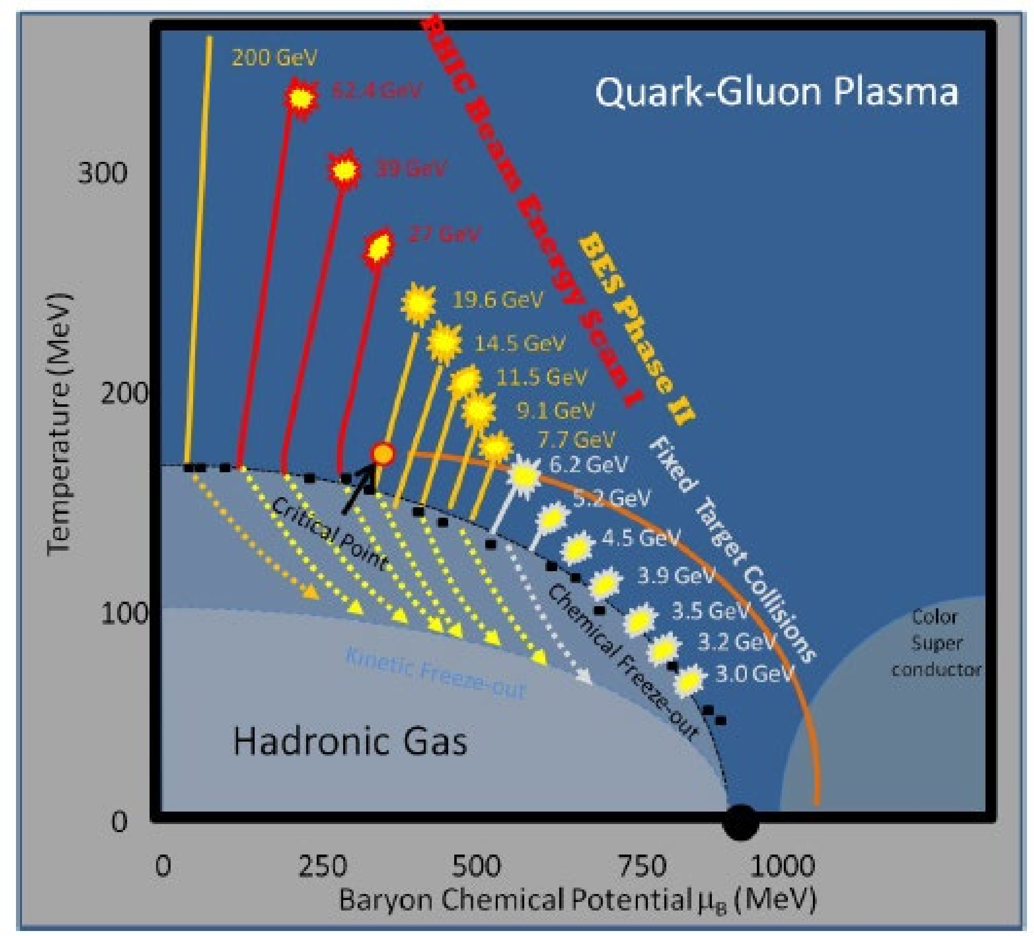
- Commissioning of LEReC for beams that yield Au+Au collisions with $\sqrt{s_{NN}}$ = 7.7 GeV and, if possible, also for beams that yield Au+Au collisions with $\sqrt{s_{NN}}$ = 9.1 GeV.
- The highest priority for data acquisition in Run 19 is Au+Au collider runs at $\sqrt{s_{NN}}$ = 19.6 and 14.5 GeV accumulating at least 400M and 300M minimum bias events respectively. This will begin the BES II program by acquiring the full data sets needed for all analyses proposed at these two highest BES energies, where LEReC is not needed.

3.2 RHIC Runs 20 and 21

The PAC recommends for Run 20 and (part of) Run 21:

- LEReC commissioning.
- The first priority for data acquisition in Run 20 and 21 is Au+Au collider runs with $\sqrt{s_{NN}}$ = 7.7, 9.1 and 11.5 GeV with a goal of accumulating at least 100M, 160M and 230M minimum bias events at these three energies, respectively. This program requires LEReC. Together with the data sets from Run 19, these data will enable analyses that will address the principal scientific goals of the BES II program.

BES II Fixed Target Mode



Extend energy range from 7.7 down to 3 GeV

- increase μ_B range from 420 MeV to 720MeV

Collider $\sqrt{s_{NN}}$	FXT $\sqrt{s_{NN}}$	Kinetic (AGeV)	Rapidity y_{CM}	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721

Expect 1-2 days dedicated beam time per energy
≈ 50M events/day

2018 BNL NPP Adv. Committee Report:

- The next priority for Run 19 is acquiring at least 100M events in fixed-target Au+Au collisions with $\sqrt{s_{NN}}$ = 3.9, 4.5 and 7.7 GeV, beginning the fixed-target component of the BES II program, thus extending its reach to lower energies and higher baryon density. The 7.7 GeV data set will later be particularly important, as it will allow direct comparison of measurements made in fixed-target runs and collider runs at the same $\sqrt{s_{NN}}$.

- The second priority for Run 20 and 21 is acquiring at least 100M events in fixed-target Au+Au collisions at $\sqrt{s_{NN}}$ = 3.0, 3.2, 3.5, 5.2 and 6.2 GeV, completing the fixed-target component of the BES II program and extending its reach to lower collision energies and higher baryon densities.

BES-2 Dileptons: 2019-2021

BES Phase 1: 19.6 – 200 GeV

- Dilepton emission dominant in T_C region and constant baryon density

➢ emission proportional to lifetime

BES Phase 2: 7.7 – 19.6 GeV

➢ Probe life time + baryon density dependence of the ρ spectral function

Close to CP, expect increase in correlation lengths. Critical slowing down?

Look for anomalous increase in the lifetime of the fireball

Down to FAIR energies

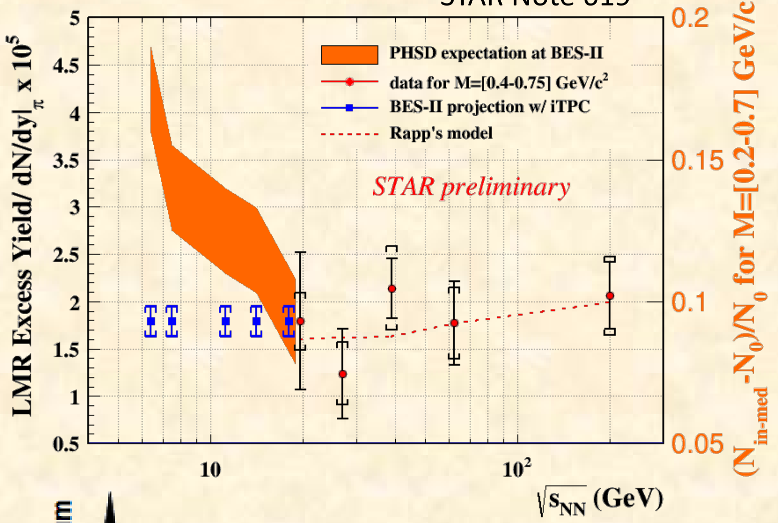
– CBM, HADES

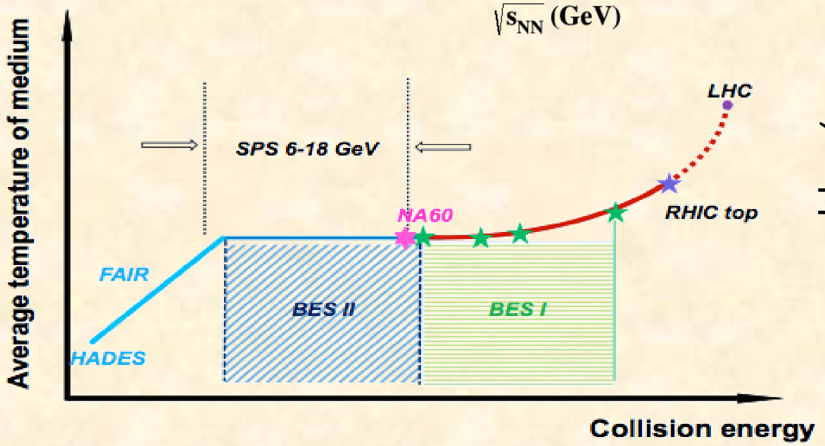
- probe lifetime, total baryon density, and temperature dependence

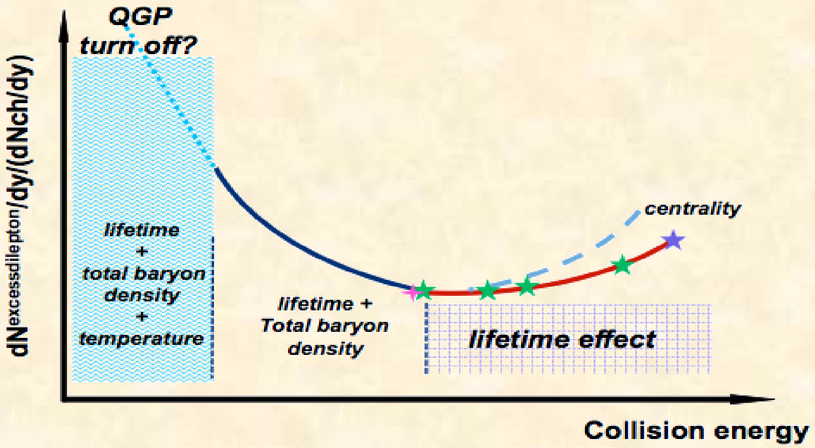
At SPS: proposed NA60+

- overlap with RHIC and FAIR

STAR Note 619

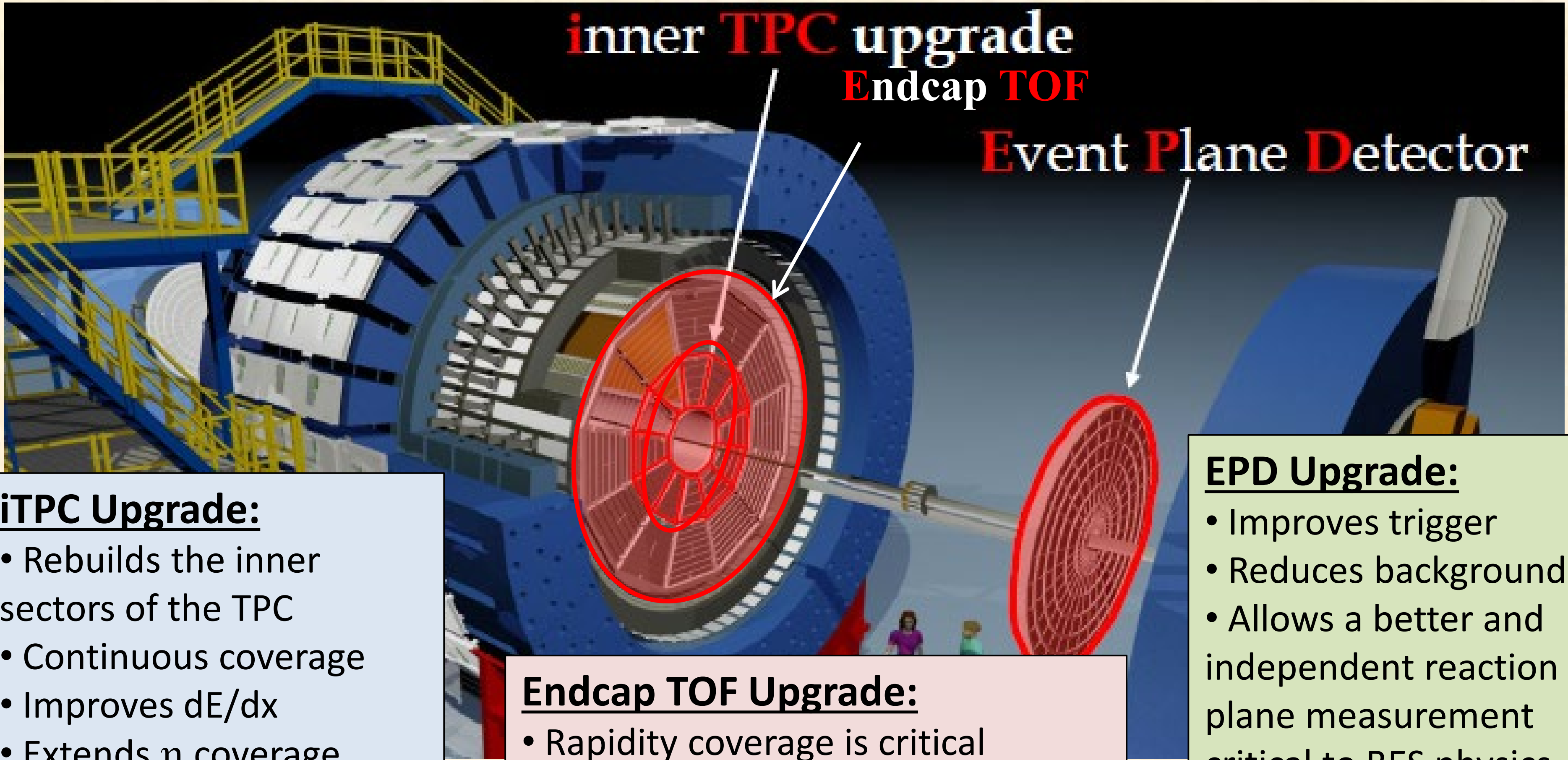






Ruan, Rapp – TPD'14

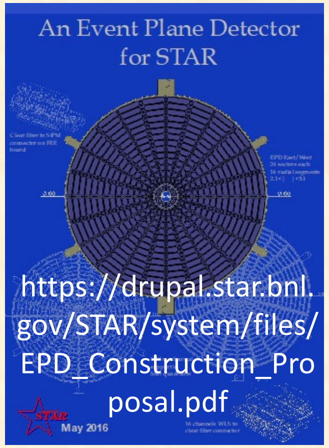
The STAR Upgrades for BES Phase II



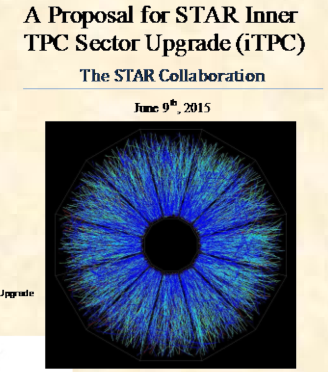
iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-off from 125 MeV/c to 60 MeV/c

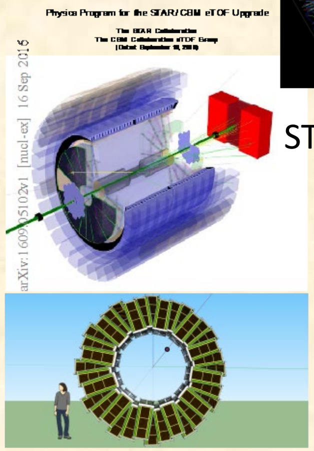
Endcap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1.1 to 1.5
- Improves the fixed target program
- Provided by CBM at FAIR

EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics



https://drupal.star.bnl.gov/STAR/system/files/EPD_Construction_Proposal.pdf

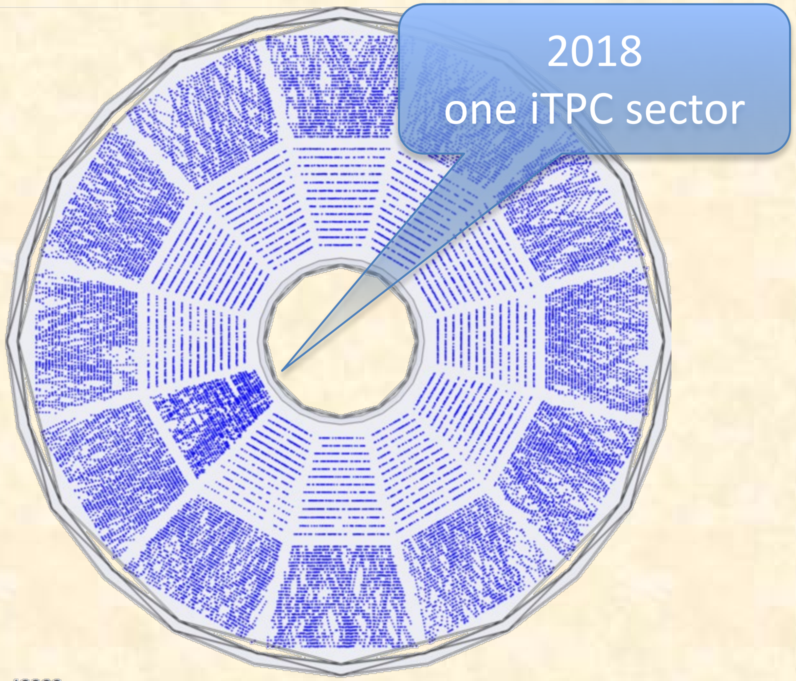


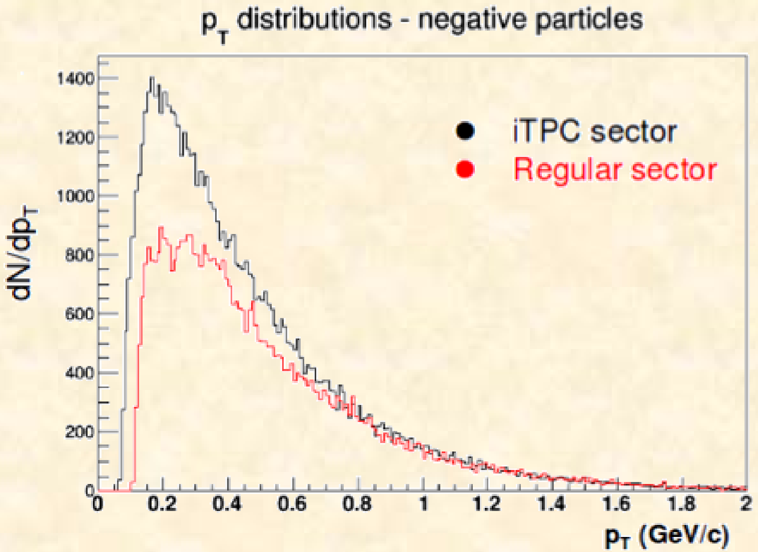


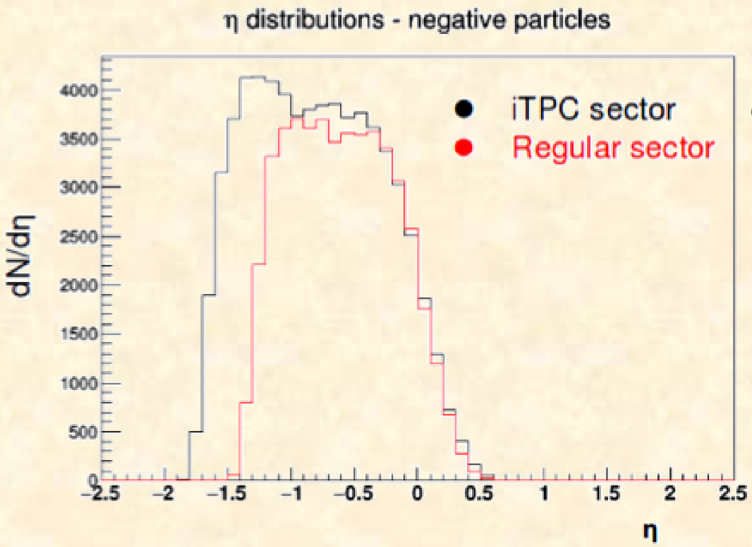
STAR Note 619

arXiv:1609.05102v1

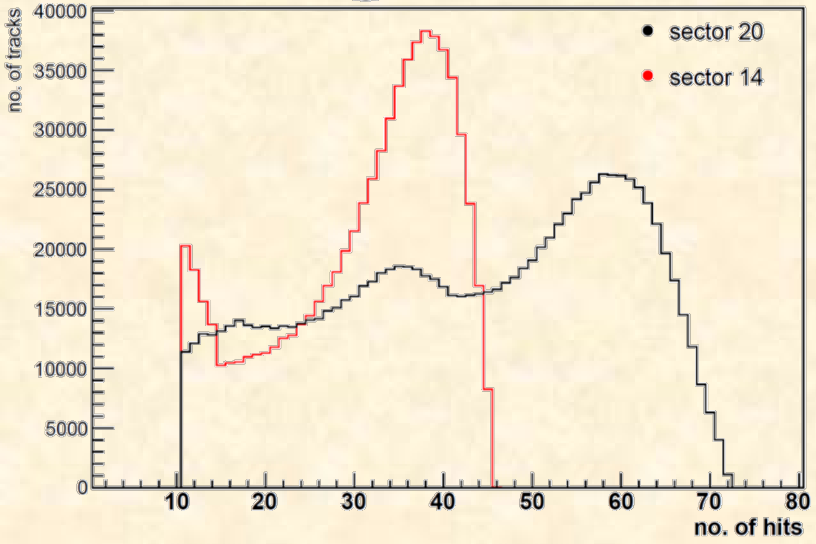
Detector Upgrades For BES 2 :: iTPC



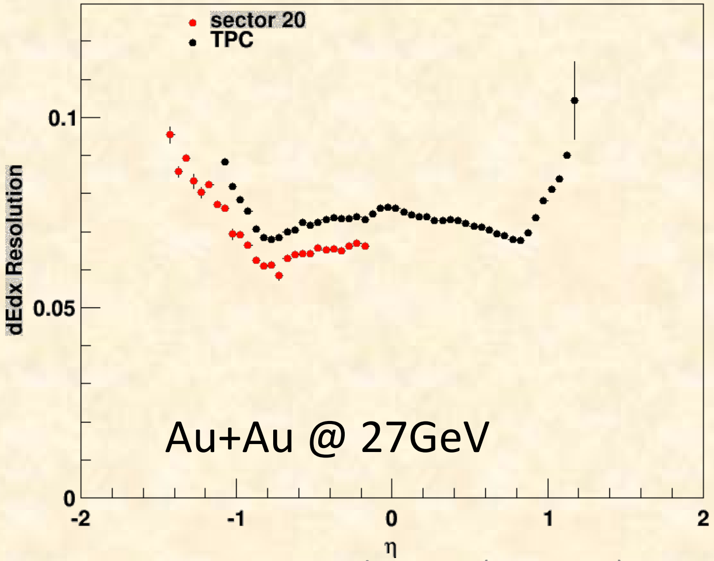




Nigmatkulov@ICPPA18



Videbæk@Annual iTPC Review (2018)



STAR's upgrade of the inner TPC sectors

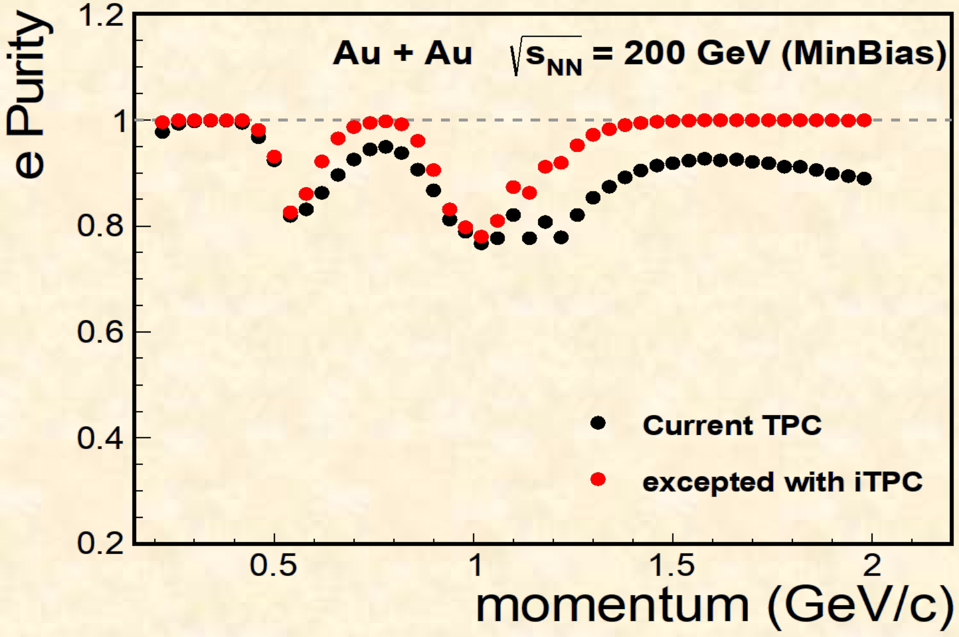
- p_T thresholds lowered
- increase in rapidity coverage
- dE/dx (PID) resolution improved

BES2 Dielectron Measurements

- iTPC upgrade is essential

Substantial improvement in purity of electron sample

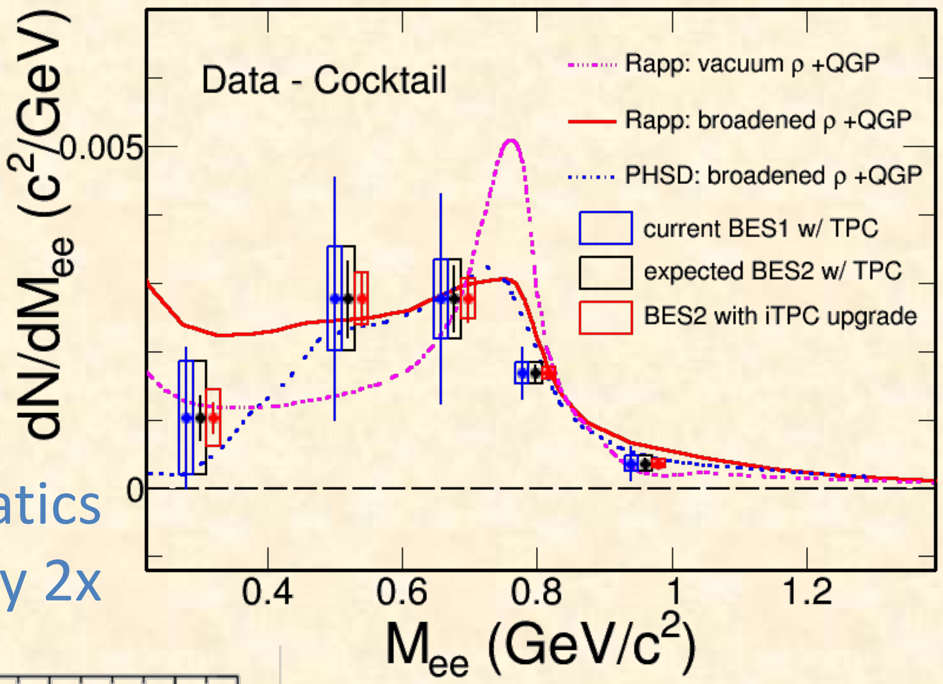
- reduction of hadron contamination

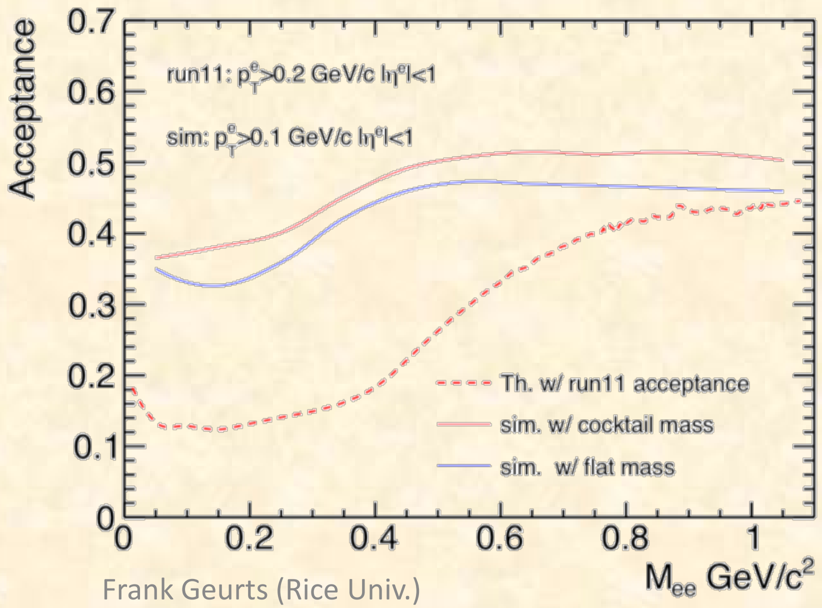


dominated by systematics

- expect reduction by 2x

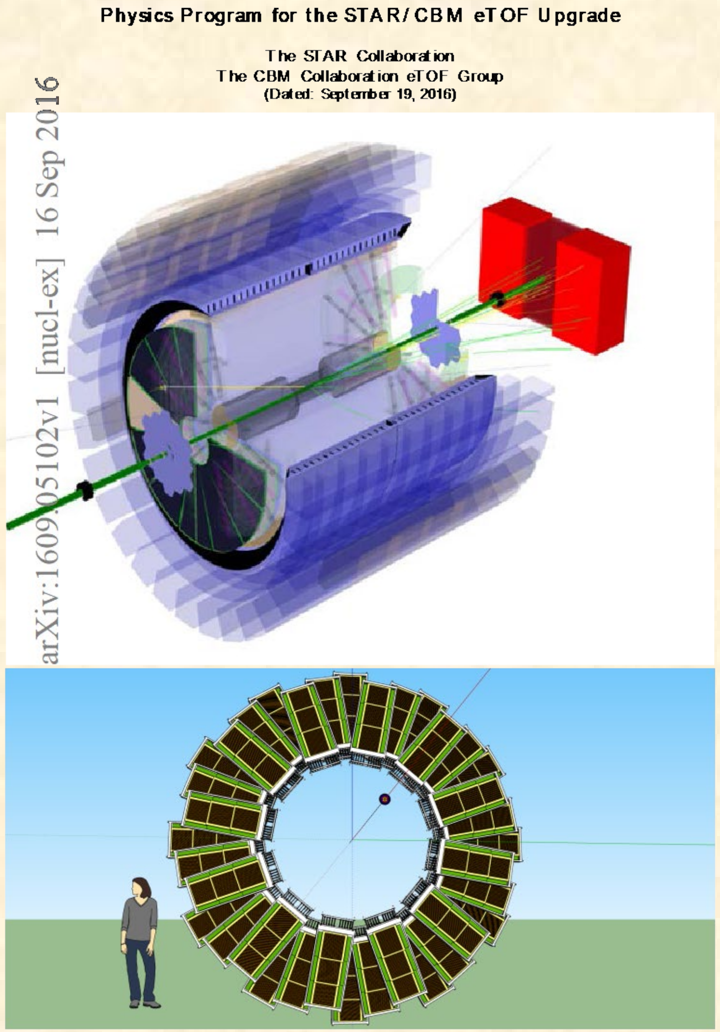
STAR Note 619





Expected dielectron excess spectrum in 19.6GeV in BES-II with and without iTPC upgrade

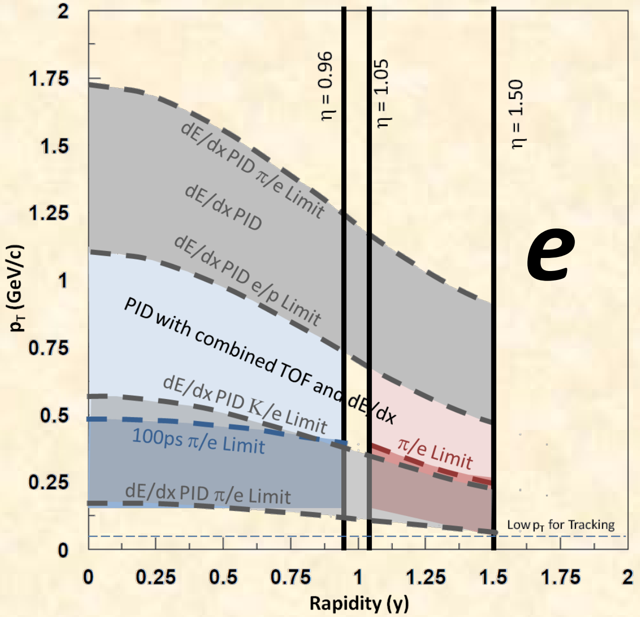
Detector Upgrades For BES 2 :: eTOF



STAR Note 0665
arXiv:1609.05102v1

CBM TOF installation at STAR (“FAIR Phase 0”)

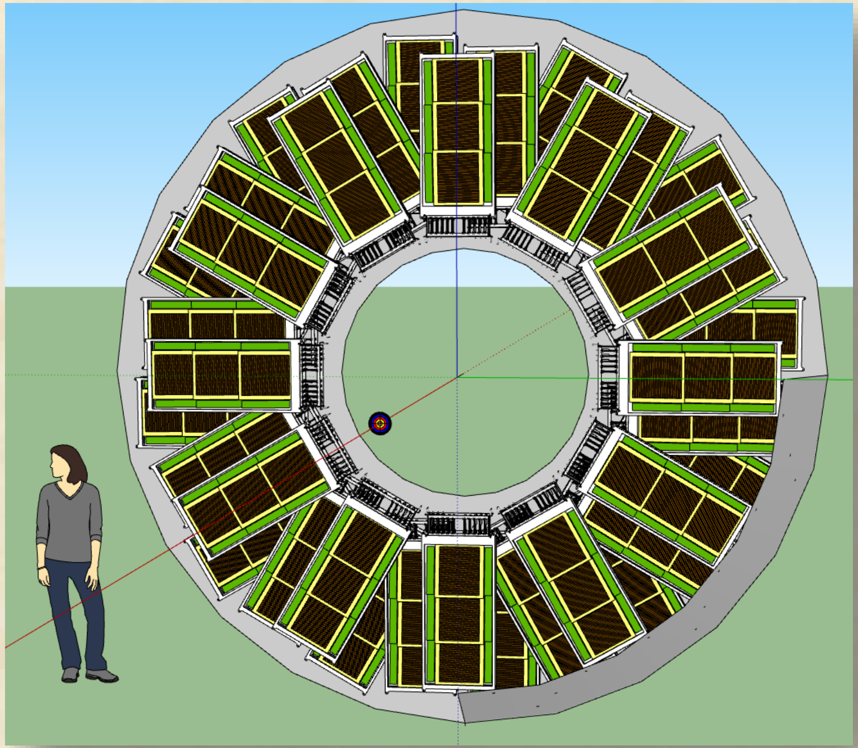
- mounted on east poletip
- increases PID rapidity coverage
  - ➢ taking advantage of large iTPC coverage



Dielectron measurements:
include rapidity differential

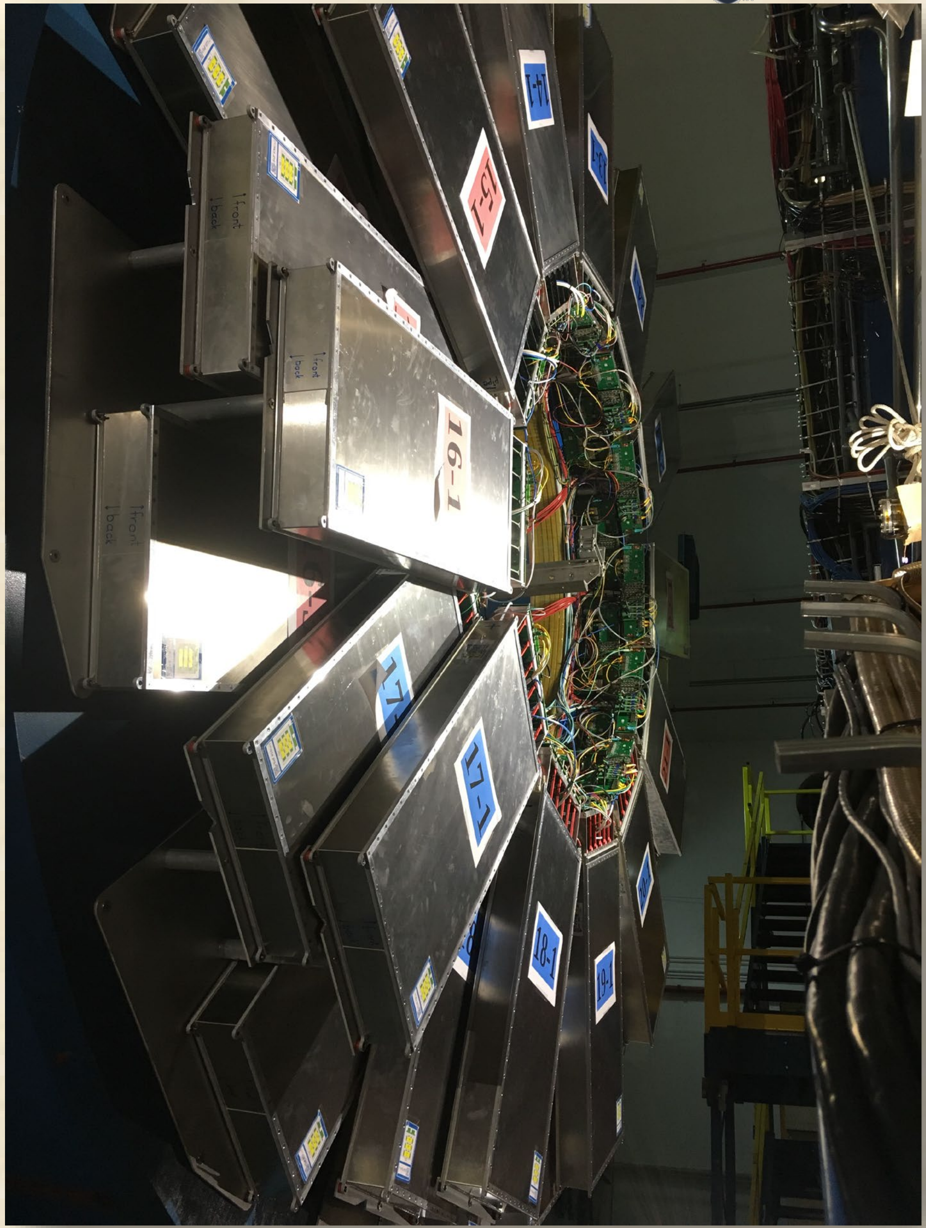
- LMR excess expected to depend on total baryon density
- π yields drop by a factor of two from y=0 to y=1.2 ❼“baryon density” drops by factor of two.
- analysis at y=1.2 is equivalent to lowering the beam energy

STAR/CBM eTOF "Wheel"



STAR Note 0665

Picture Credit: Ingo Deppner



… in numbers:

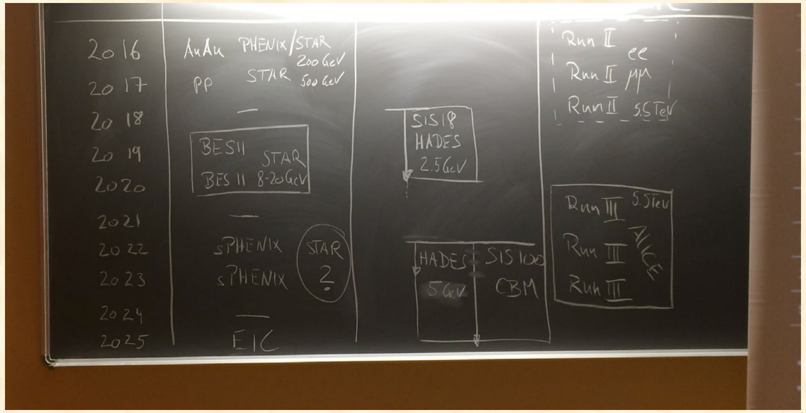
- 36 modules (= 108 MRPCs)

  CBM TOF involves 1,376 MRPCs
- 3 layers
- 6,912 channels

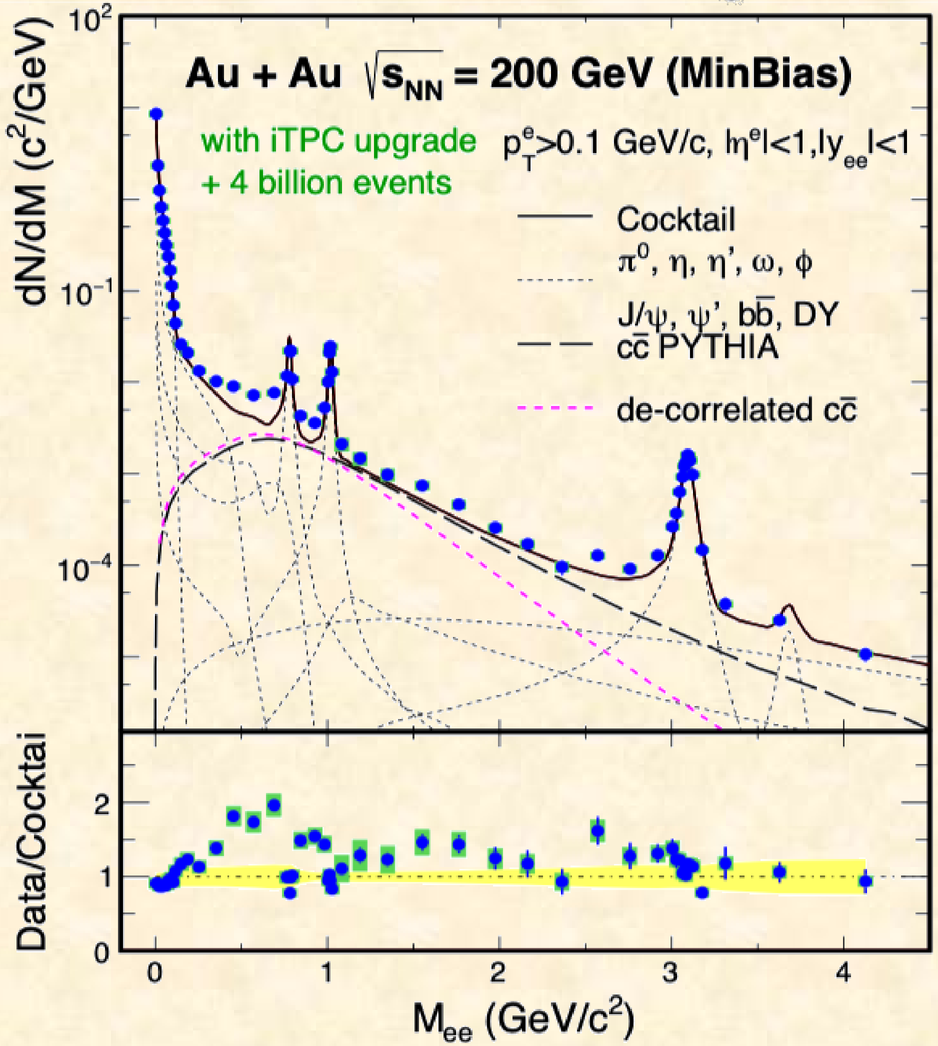
STARBTOF has 23,040 channels
(CBM plans on 100k channels)

Total depth ~36cm

STAR Dielectron Measurements :: Post BES2



3 yrs ago at
ECT* 2015 Workshop



Zhangbu Xu at CERN HI Town Hall (Oct.20, 2018):

Thermal Dilepton at Low and Intermediate Mass

iTPC upgrade essential

Mid-rapidity:

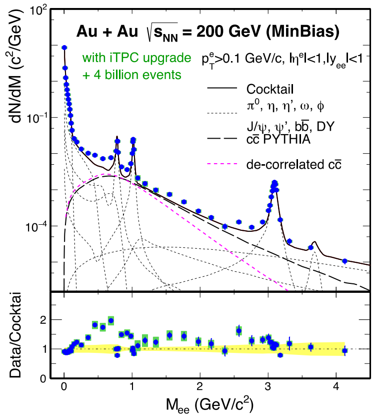
e^+e^- measurement at μ_B~0

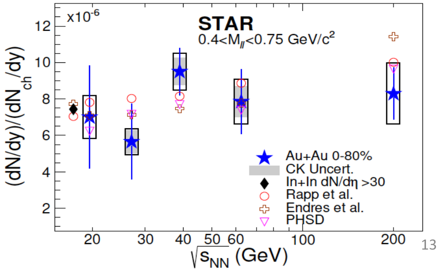
- Connection to chiral symmetry restoration
- Thermal radiation from QGP:

Low-mass di-lepton emission:
T, total baryon density, and life time; more importantly dynamics of approaching Chiral Symmetry

The slope T in IMR:
the true average temperature T of the medium.
(no blue shift by flow)

Improvement:
Factor 2 smaller systematic uncertainties
Factor 5.5 more statistics





Summary

- At SPS, NA60 and CERES demonstrated the physics potential of accurate dilepton measurements
- At RHIC, PHENIX & STAR both developed a strong dilepton program
  - BES phase-1 program has systematically tied top RHIC to top SPS energies
  - first dimuon mass spectra from STAR for p+p and p+Au

- Recent data sets will allow a revisit of the IMR for some of the BES-1 energies
  - at STAR: back to Run-10/11 material budget (HFT removed)
  - large 27 and 54 GeV datasets
  - isobar program provides large datasets for virtual photon, but also LMR/IMR dielectrons

- BES Phase 2 (2019-2021): systematic dilepton measurements down to $\sqrt{s_{NN}}$=7.7GeV
  - measure baryon density dependence
  - measure p_T slopes both in LMR and IMR
  - look for anomalous increases in yield, suggestive of a critical point
  - STAR detector upgrades in place to improve/expand its dielectron measurements
- STAR 2021+
  - take advantage of BES-2 detector upgrades
  - proposal for high-statistics revisit 200GeV

BACKUP

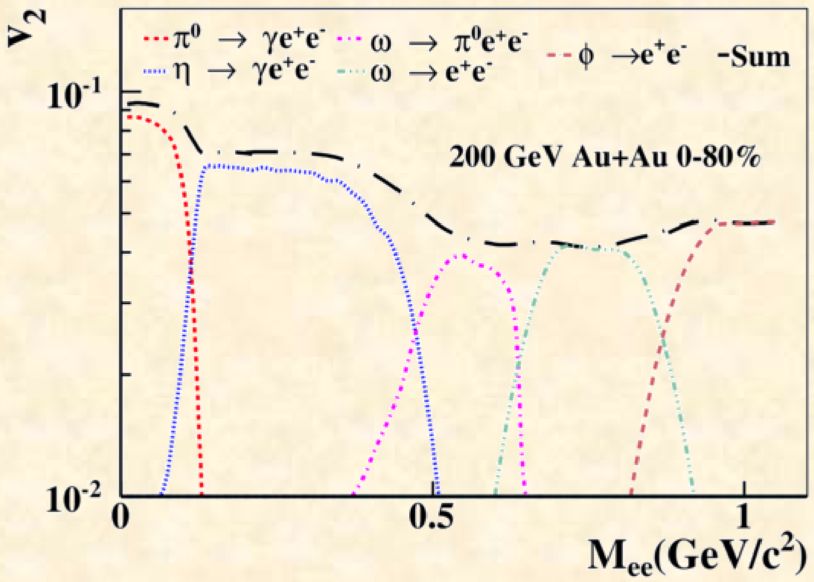
First Measurements of Dielectron v_2

STAR, PRC 90 (2014) 64904

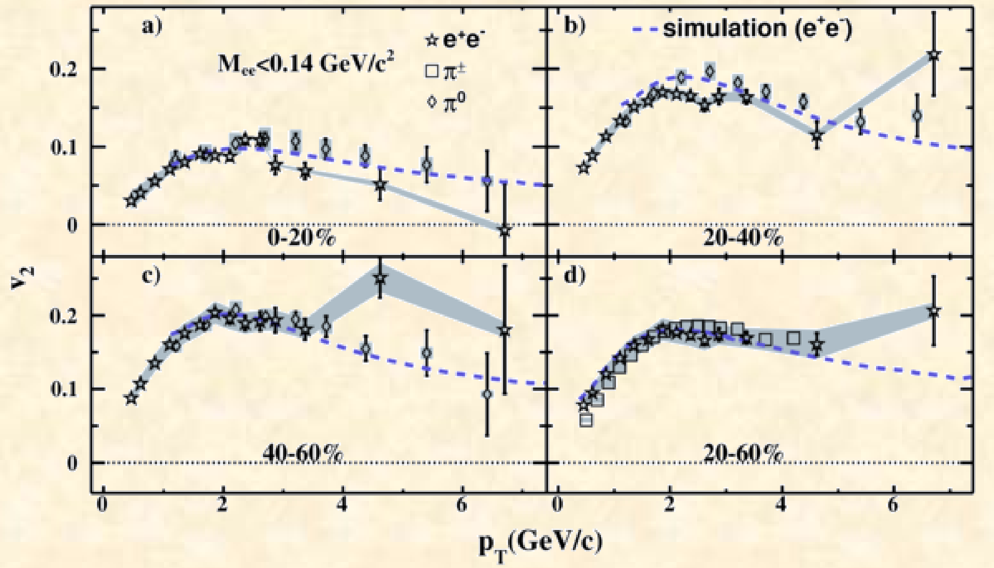
➢ Challenge: isolate v_2 of excess dielectrons

$$v_2^{\text{total}}(m_{ee}) = v_2^{\text{signal}}\left[\frac{N_S}{N_B+N_S}\right](m_{ee}) + v_2^{\text{background}}\left[1-\frac{N_S}{N_B+N_S}\right](m_{ee})$$

Cocktail simulations based on published light-hadron v_2 measurements



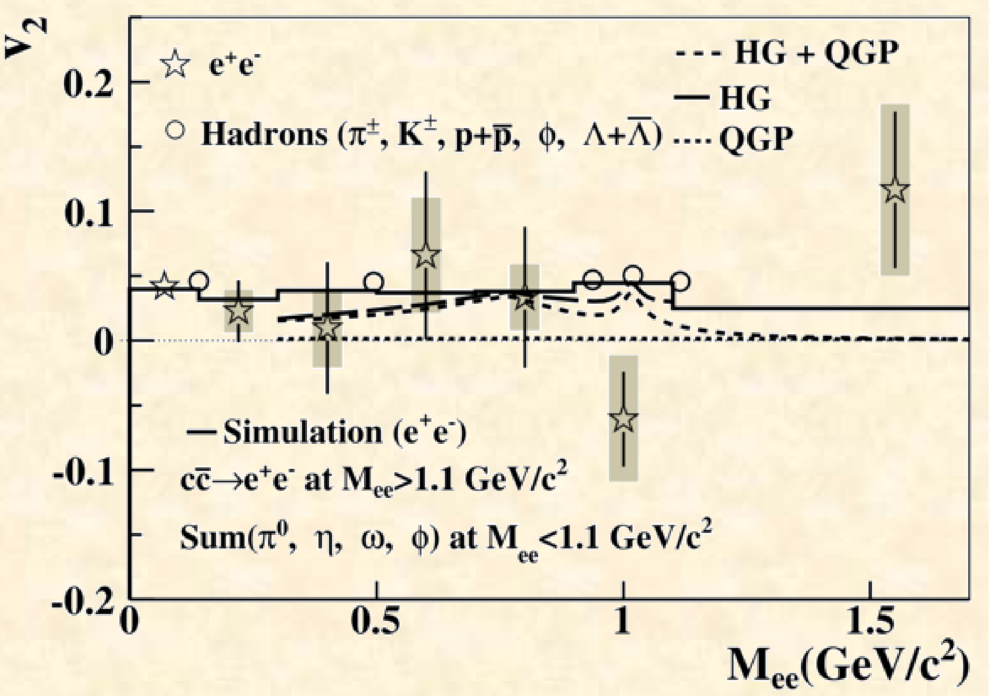
v_2 from π^0 Dalitz decay consistent with simulations based on published π^0 v_2



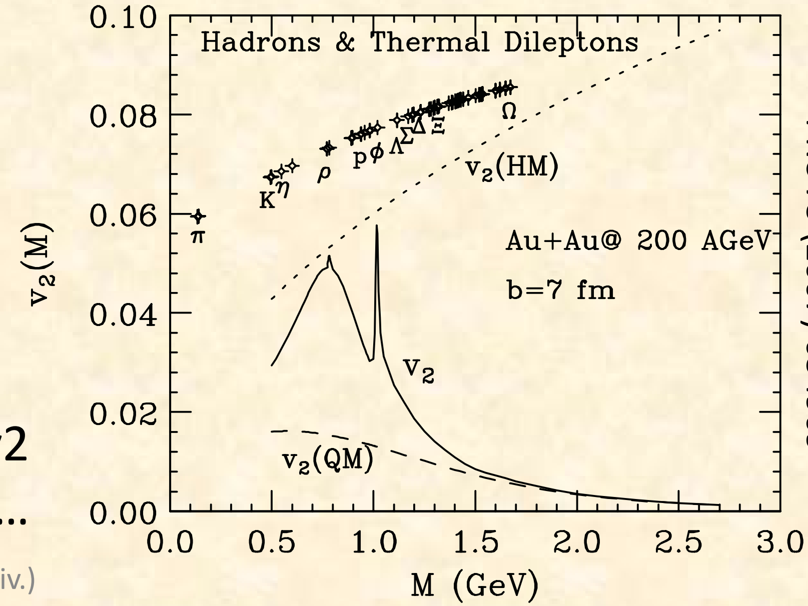
Proof-of-Principle Measurement

PRC 90 (2014) 64904

- based on combined Run 10 and 11 data (760M events)
- p_T integrated v_2 of dielectrons in STAR acceptance



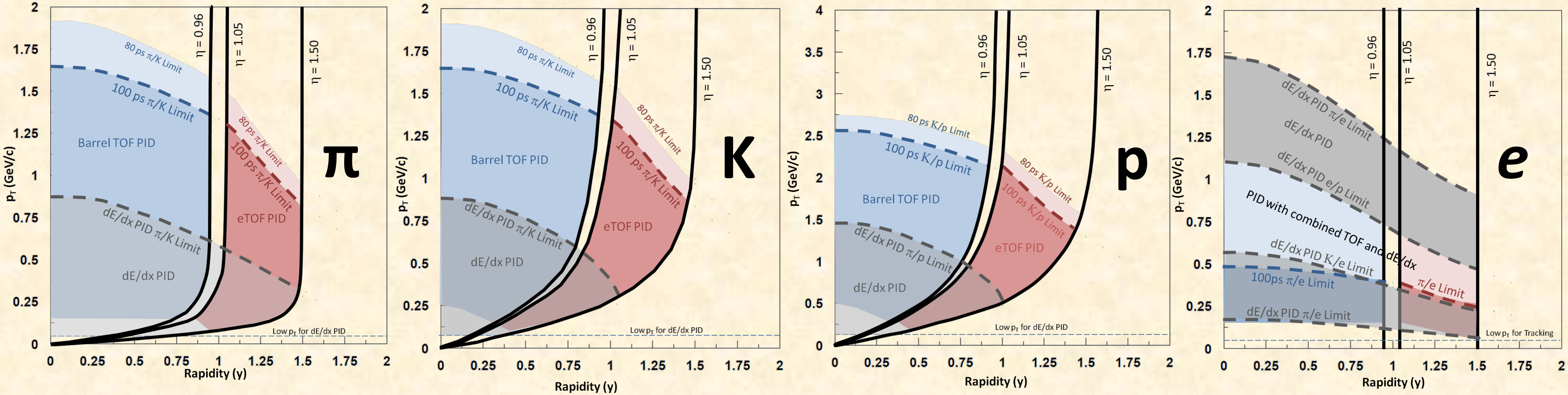
➢ Given the current precision: dielectron v_2 is consistent with cocktail simulations and measured hadron v_2



Chatterjee et al PRC 75 (2007) 054909

to distinguish between HG and QGP v2 need uncertainties < 4% …

STAR BES-2 TOF Acceptance: PID in Collider Mode

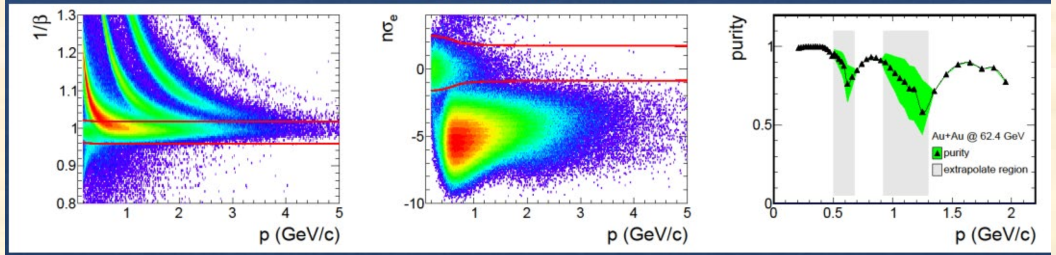


- Lower p_T limit – from track length of the TPC (multiple scattering);
  - for BTOF lower p_T limit from minimal track rigidity
- High p_T limit – from the TOF time resolution (σ_{TOF} = 100 and 80 ps ranges)

27 GeV – analysis details

Electron Identification

Au+Au @ $\sqrt{s_{NN}}$ = 62 GeV



- Uses the TOF's precise timing
  - Remove slower hadrons
  - Extends and improves the TPC's PID reach
- High-purity detection of electrons
  - Integrated purity > 95%

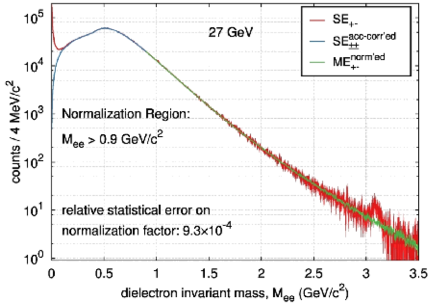
8

Background

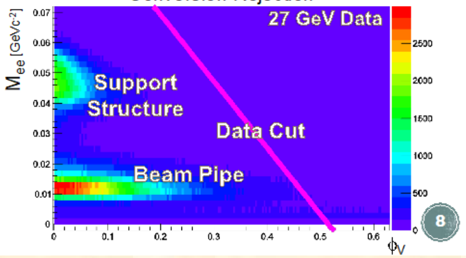
- Pair Background Sources
  - Combinatorial, Correlated, Conversion
- Like-Sign Same Event Method
  - Combine all like-sign pairs and average
  - Removes combinatorial & correlated
  - Acceptance correction w/ mixed event method

$$2\sqrt{SE_{++}SE_{--}}\,\frac{ME_{+-}}{2\sqrt{ME_{++}ME_{--}}}$$

- Unlike-Sign Mixed Event Method
  - Combine $e^{+/-}$ from different events w/ similar properties*
    - Z Vertex, Ref. Mult., and Event Plane Angle
    - Pools of 20 events
  - Removes combinatorial
- Conversion Rejection*
  - Selection based on pair's orientation in $\vec{B}$



Conversion Rejection



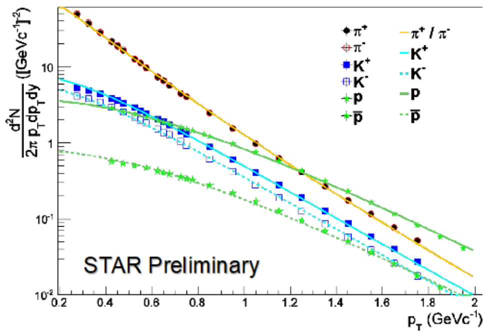
8

* Criteria vary for each $\sqrt{s_{NN}}$

Cocktail

- Contributions
  - π^0, η, η', ω, ϕ, J/ψ, cc [Note: no ρ]
- Input
  - Flat ϕ [0, 2π]
  - η [-1,1]
    - Flat for 39 & 62 GeV.
    - GENESIS for 19 & 27 GeV
  - p_T from Tsallis Blast Wave [TBW] fits
- Decay
  - Breit-Wigner/Kroll-Wada Formalism
- Yield
  - Meson-to-π^0 ratio from NA45 w/ $\pi^{+/-}$ dN/dy from STAR
- cc Contributions
  - PYTHIA; Scaled by N_{binary}

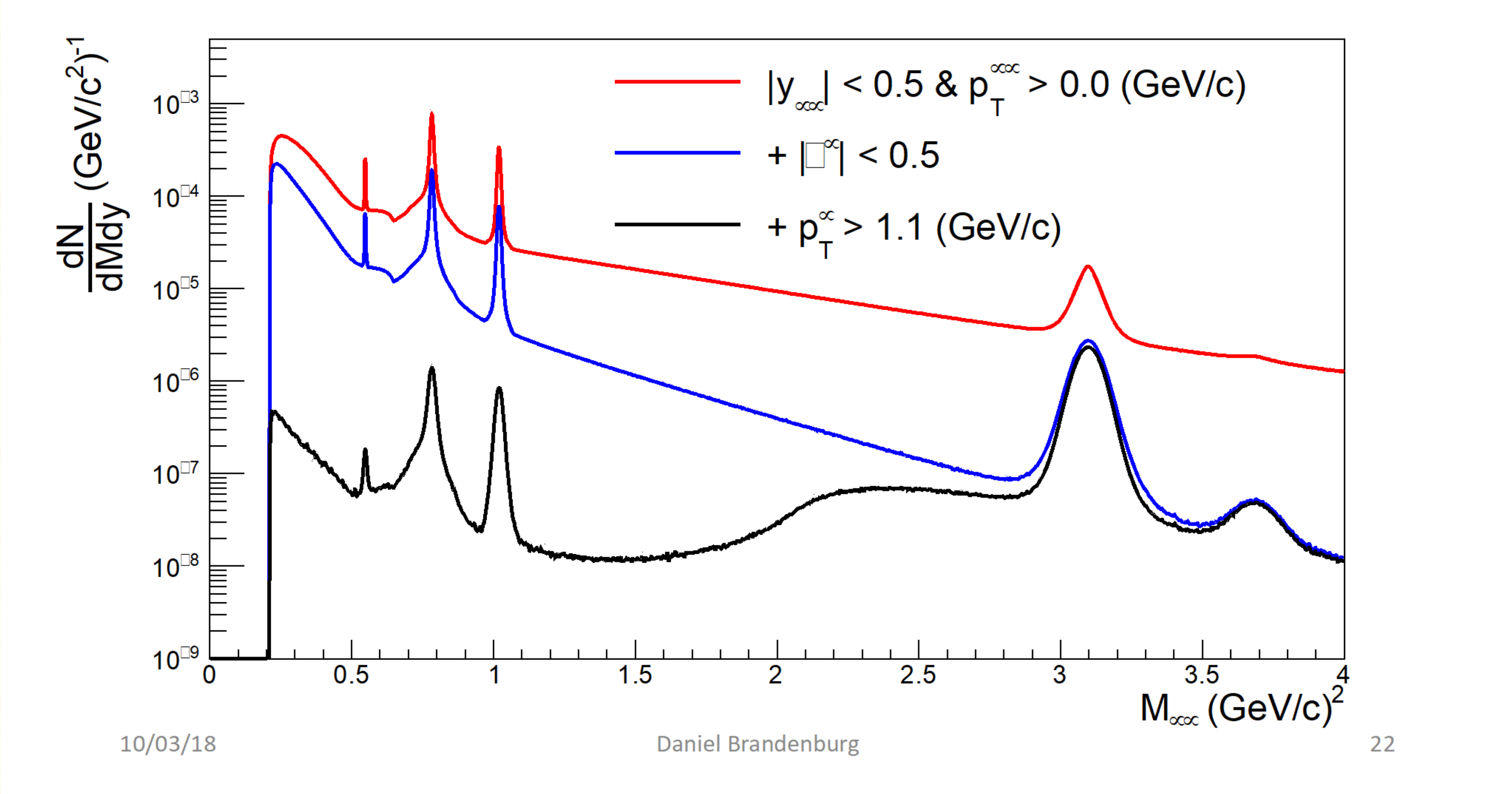
27 GeV TBW Fits



Meson	π^0	η	ω	ϕ	η'	J/ψ
Meson/π^0	1.0	0.085	0.069	0.018	0.078	6.2E-6

J.Butterworth : Rice University 8/20/2014 9

MTD Acceptance Effect on Cocktail



Brandenburg, HP2018