

# Electromagnetic & Weak Probes: experimental overview

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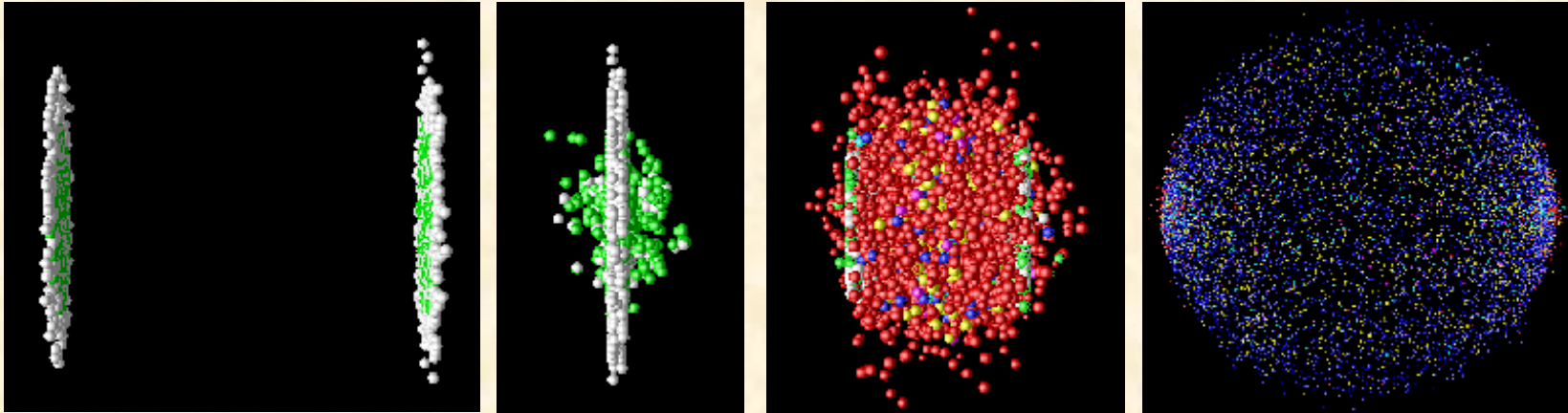


RICE UNIVERSITY

# Probing Strongly Interacting Matter

## ➤ General appeal of EM/weak probes:

- produced in by various ways throughout the system's evolution
- colorless objects  $\therefore$  no coupling to strongly interacting matter



## • Hard Processes

- $W^\pm$  and Z production
- prompt photons

## • Soft Processes

- di-leptons
- thermal photons

## ➤ Access to initial conditions, (early) system evolution

- tag jets
- measure effective temperature
- test chiral symmetry restoration
- test QED

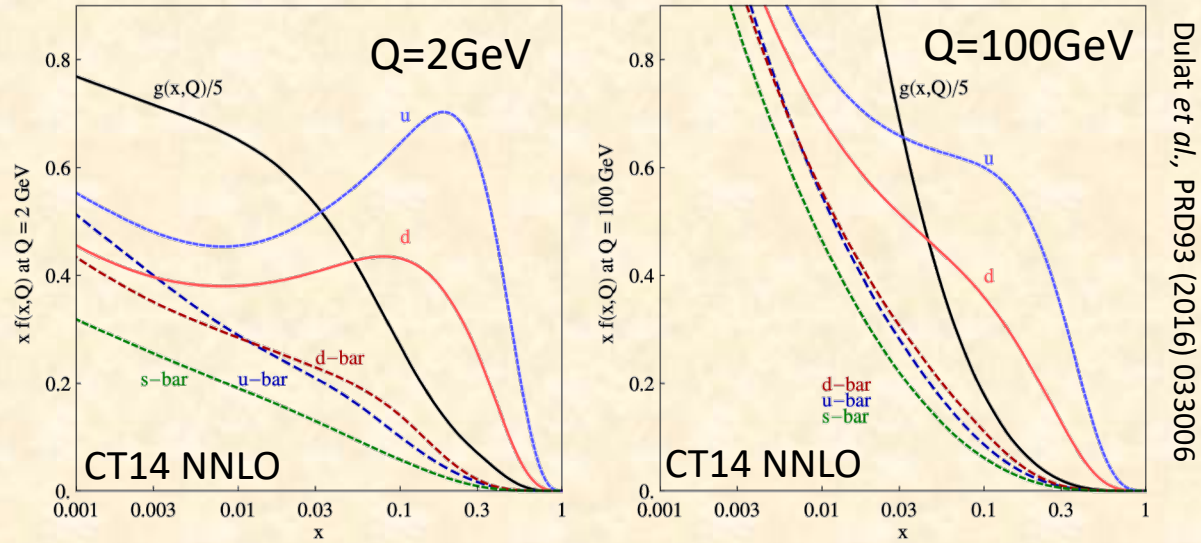


# Experimental Landscape

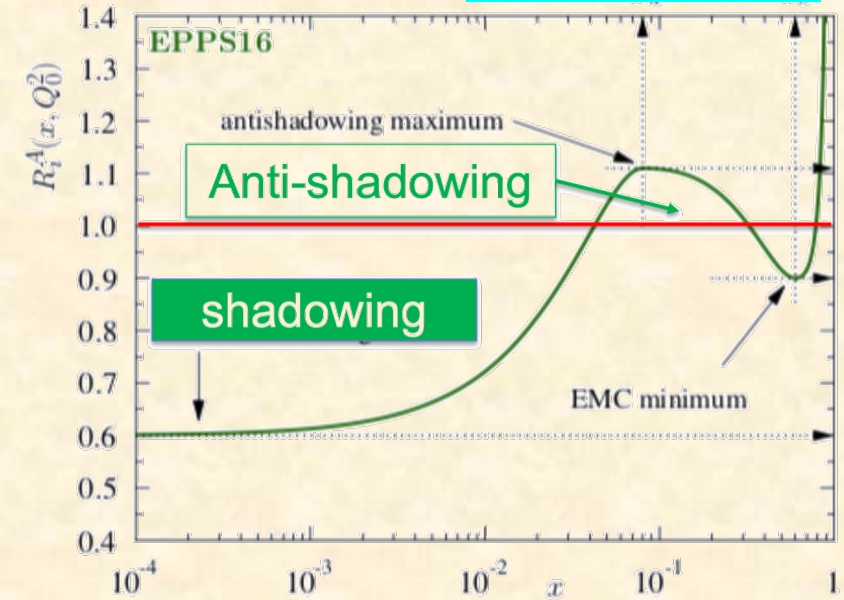
- Facilities and experiments spanning  
~4 orders of magnitude in beam energies
- Many collisions systems
  - p+p, p+Au, p+Pb, ..., Cu+Cu, ..., In+In, ..., Au+Au, Pb+Pb
- Centrality/multiplicity ranges  
from UPC to central A+A, and high-multiplicity p+p
- Experimental access from direct and virtual photons,  
to massive vector bosons



# Weak Probes: Constraining Nuclear PDFs



Hyunchul Kim, talk #495



- PDFs give probability at a given scale  $Q^2$  for finding a parton with momentum fraction  $x$  within **proton**
- nPDFs reflect parton distributions in **bound nucleus**

$$f_i^{P/A}(x, Q^2) \equiv \underbrace{R_i^A(x, Q^2)}_{\text{nuclear modification}} \underbrace{f_i^P(x, Q^2)}_{\text{free proton baseline}}$$

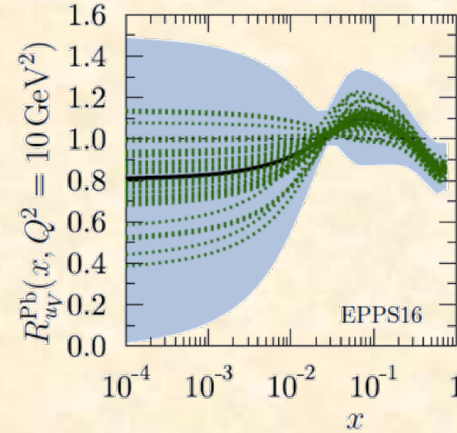
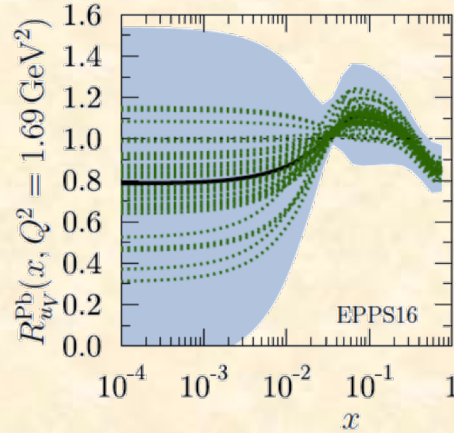


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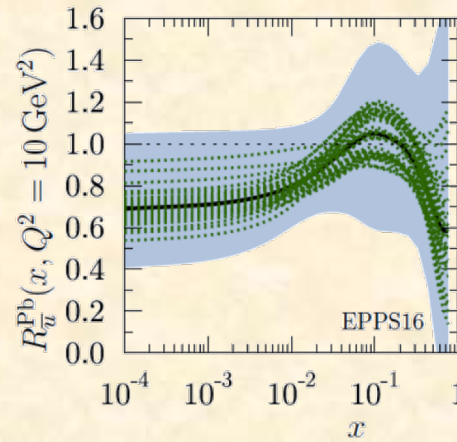
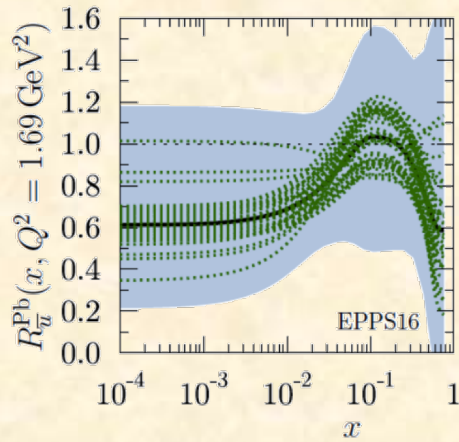
# Constraining Nuclear PDFs

➤ nPDFs need more experimental datasets

$u$  quark

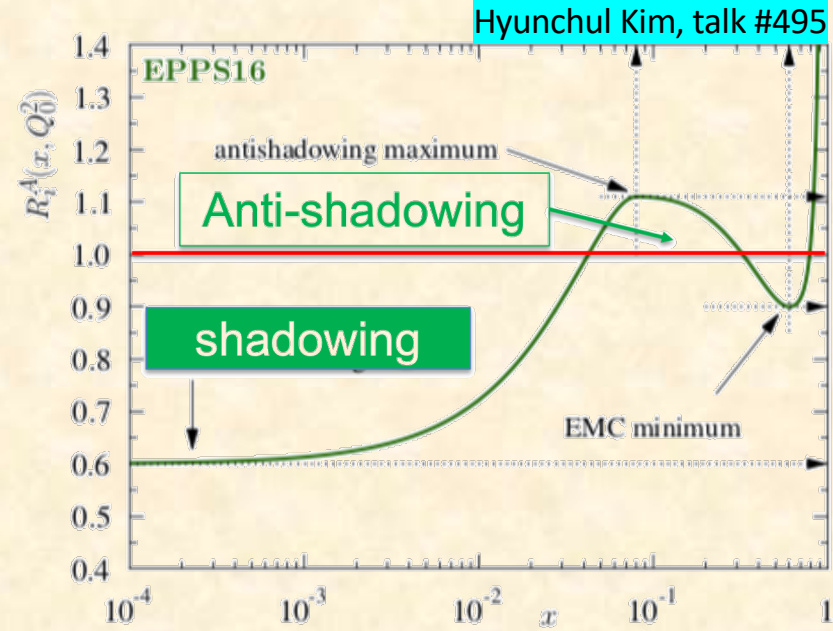


$\bar{u}$  quark



$Q^2=1.69\text{GeV}^2$

$Q^2=10\text{GeV}^2$



W in 8.16 TeV pPb

Z in 5.02 TeV pPb

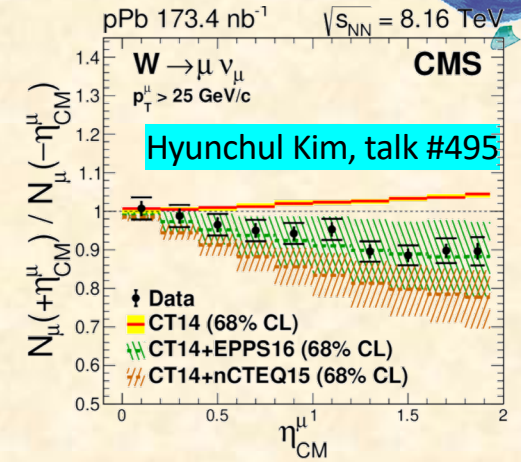
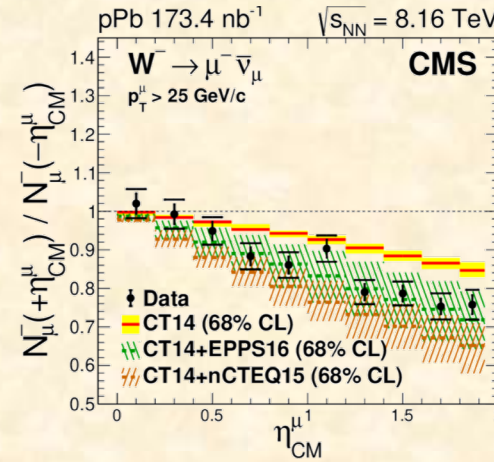
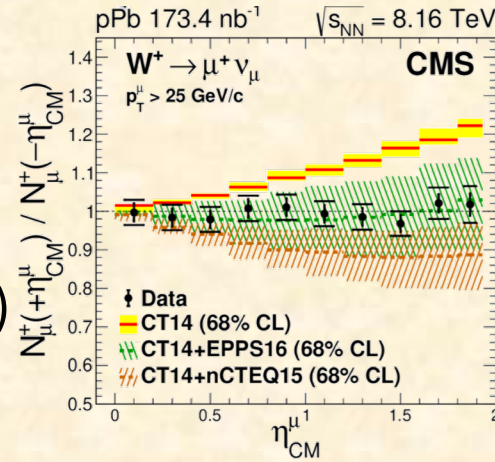
Drell-Yan in 8.16 TeV pPb



# Recent results from p+Pb (1)

## [CMS, p+Pb $\sqrt{s}=8.16$ TeV]

- $R_{FB}$  of W bosons
  - 5x more statistics than 5.02TeV
  - compare backward region (Pb-going) to forward region (p-going)
- Drell-Yan results for  $\sqrt{s}=8.16$  TeV
  - work in progress
  - $10.5 < M_{DY} < 20$  GeV/c<sup>2</sup>
  - allow for wider range in x



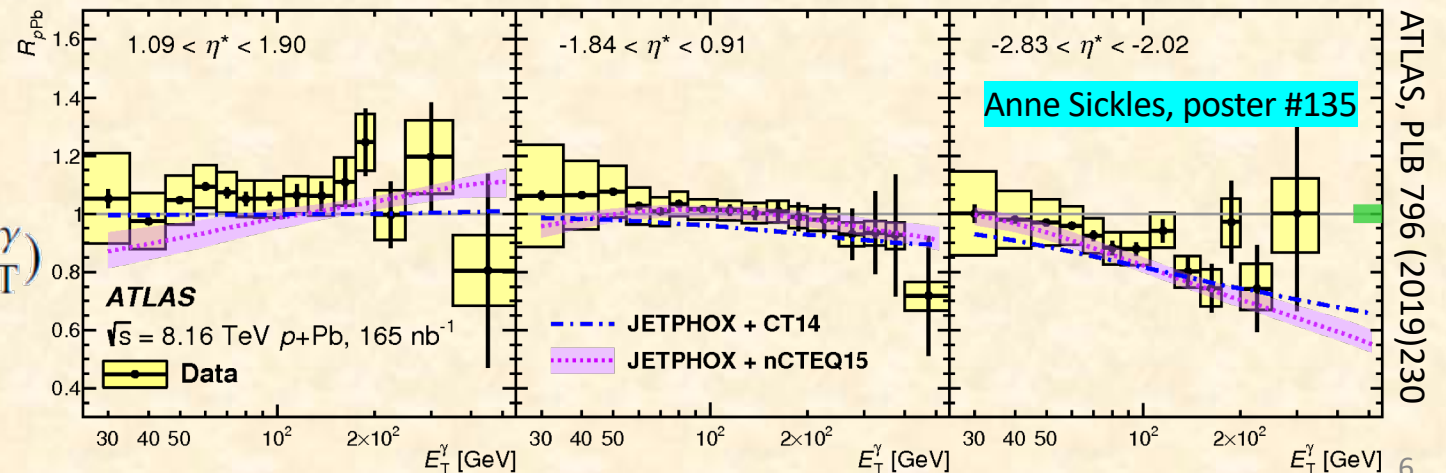
- ✓ nPDFs favored over CT14 PDF
- ✓ consistent with published results from Z boson at 5.02TeV
- experimental uncertainties smaller than model uncertainties

## [ATLAS, p+Pb $\sqrt{s}=8.16$ TeV]

- Prompt photons in p+Pb
  - instead of  $R_{FB}$  use

$$R_{pPb} = (d\sigma^{p+Pb \rightarrow \gamma+X} / dE_T^\gamma) / (A \cdot d\sigma^{pp \rightarrow \gamma+X} / dE_T^\gamma)$$

- small affects from nPDF confirmed for CT14+EPPS16 and nCTEQ15





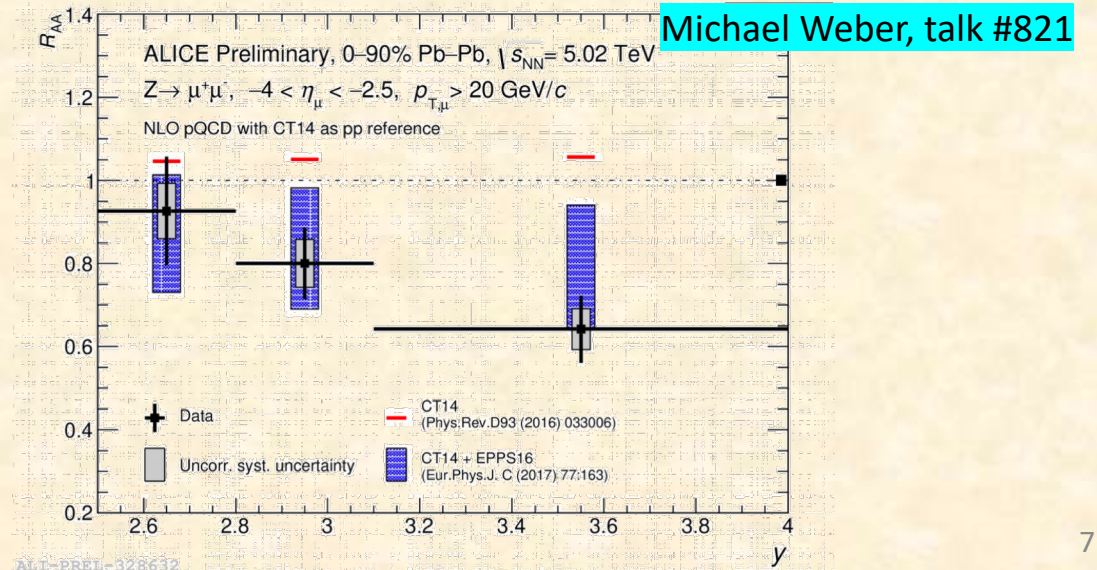
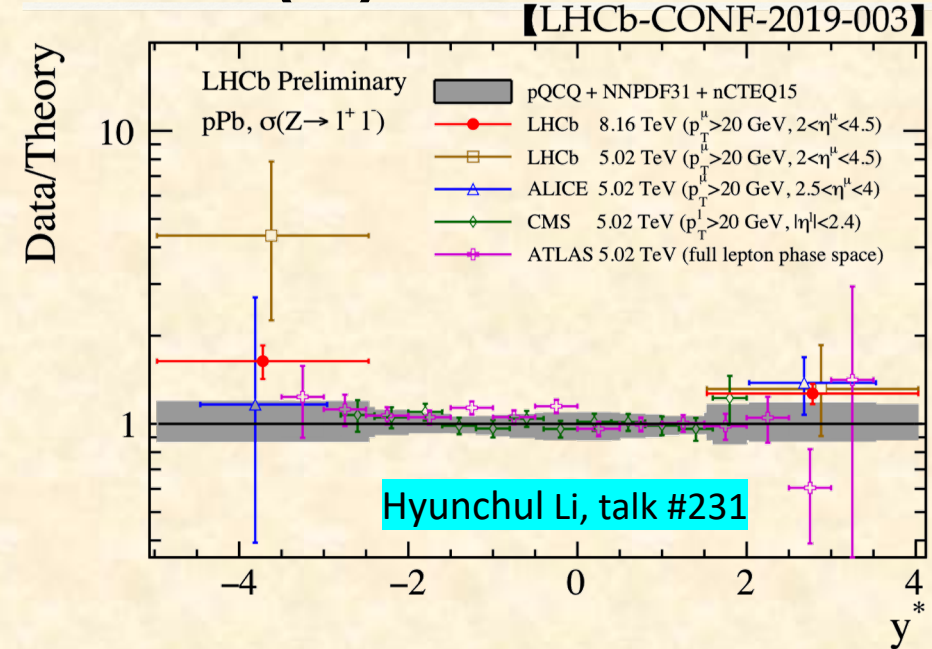
# Recent results from p+Pb and Pb+Pb (2)

## [LHCb, p+Pb $\sqrt{s}=8.16$ TeV]

- Z bosons
  - 20x more statistics than results from 5 TeV
  - compatible with 5 TeV
- Measured  $R_{FB}$  compatible with EPPS16 and CTEQ15 predictions
  - $R_{FB}^{2.5 < |\eta| < 4.0} = 1.28 \pm 0.14(\text{stat}) \pm 0.14(\text{sys}) \pm 0.05(\text{lumi})$
  - NNPDF3.1 :  $1.59 \pm 0.01(\text{num}) \pm 0.05(\text{PDF})$
  - NNPDF3.1+EPPS16 :  $1.45 \pm 0.01(\text{num}) \pm 0.27(\text{PDF})$
  - NNPDF3.1+nCTEQ15 :  $1.44 \pm 0.01(\text{num}) \pm 0.20(\text{PDF})$

## [ALICE, Pb+Pb $\sqrt{s_{NN}}=5.02$ TeV]

- Z bosons in Pb+Pb
  - improved statistical precision
- in agreement with CT14+EPPS16





# Direct Photons

status updates on a number of analyses

- p+p at  $\sqrt{s}=13\text{TeV}$  [ALICE]

Ran Xu, poster #399

- measuring isolated direct photons out to very large  $p_T \sim 200 \text{ GeV}/c$

- p+p and p+Au at  $\sqrt{s}=200\text{GeV}$  [PHENIX]

Gabor David #755 & Zhandong Sun #632

- includes re-analysis of  $\pi^0$  in order to test applicability of Glauber model to  $p_T \sim 17\text{GeV}/c$

- Pb+Pb at  $\sqrt{s_{NN}}=5.02\text{TeV}$  [ALICE]

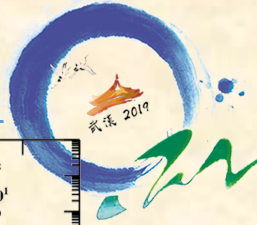
Daiki Sekihata #315

- virtual direct photons from the 2018 high statistics run
- 9x more central data



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# Direct Photon Puzzle

- Large yields
  - suggestive of large T
  - early stage
- Large flow
  - collective flow needs to build up
  - late stage
- Challenge to theoretically reconcile

- STAR: no large yields
- ALICE: large uncertainties in Pb+Pb
  - ∴ puzzle is not significant at  $\sqrt{s_{NN}}=2.76\text{TeV}$

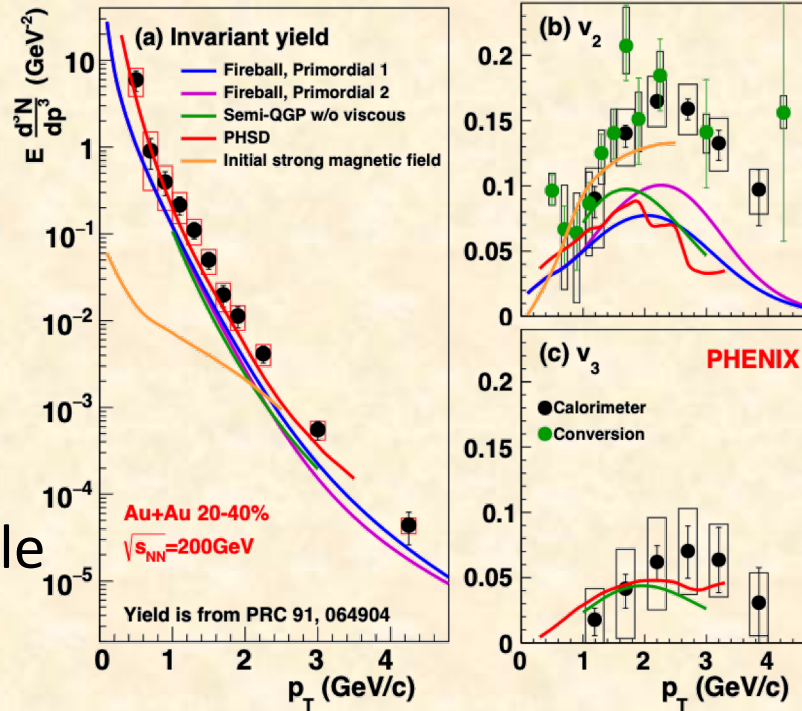
## ➤ Improved quality by ALICE on $\eta/\pi^0$

Mike Sas, talk #247

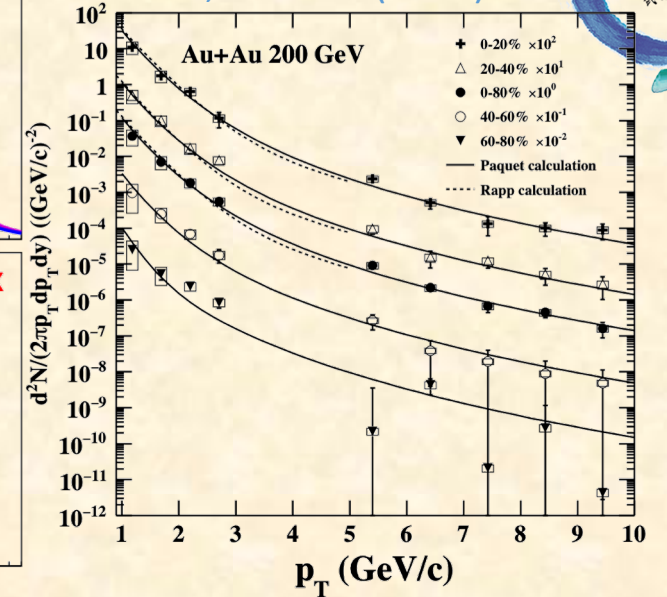
- $\pi^0$  down to  $p_T=0.4\text{GeV}/c$
- $\eta$  down to  $p_T=0.8\text{GeV}/c$

## ❖ New data from PHENIX ...

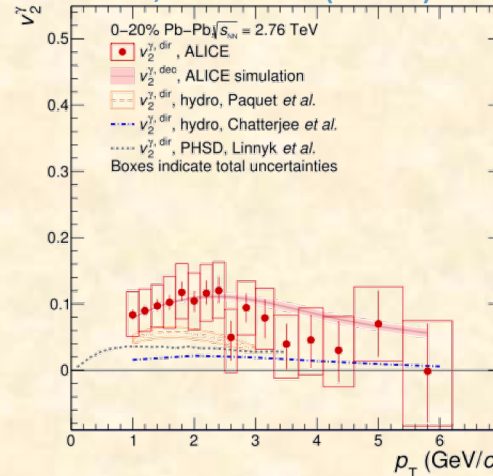
PHENIX, PRC 94 (2016) 064901



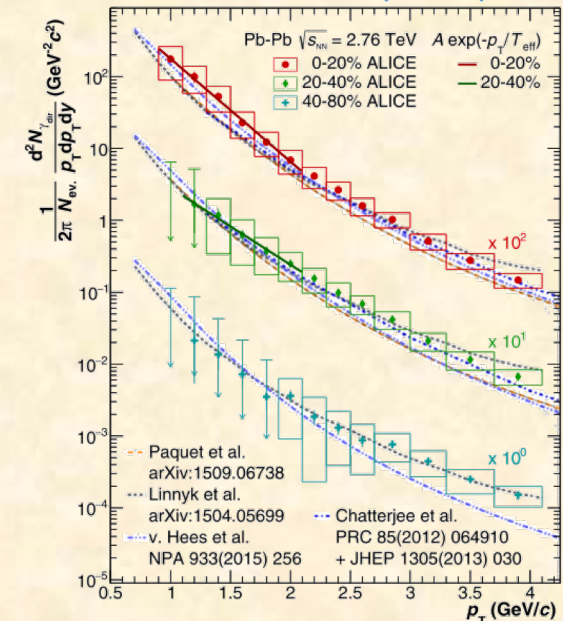
STAR, PLB 770 (2017) 451



ALICE, PLB 789 (2019) 308



ALICE, PLB 754 (2016) 23





# New Results on $R_\gamma$ in Au+Au at $\sqrt{s_{NN}}=200$ GeV

## ➤ New measurements from PHENIX

- 2014 data set (red symbols)
- based external conversion, 10x statistics
- double tagging ratio to reduce systematics:

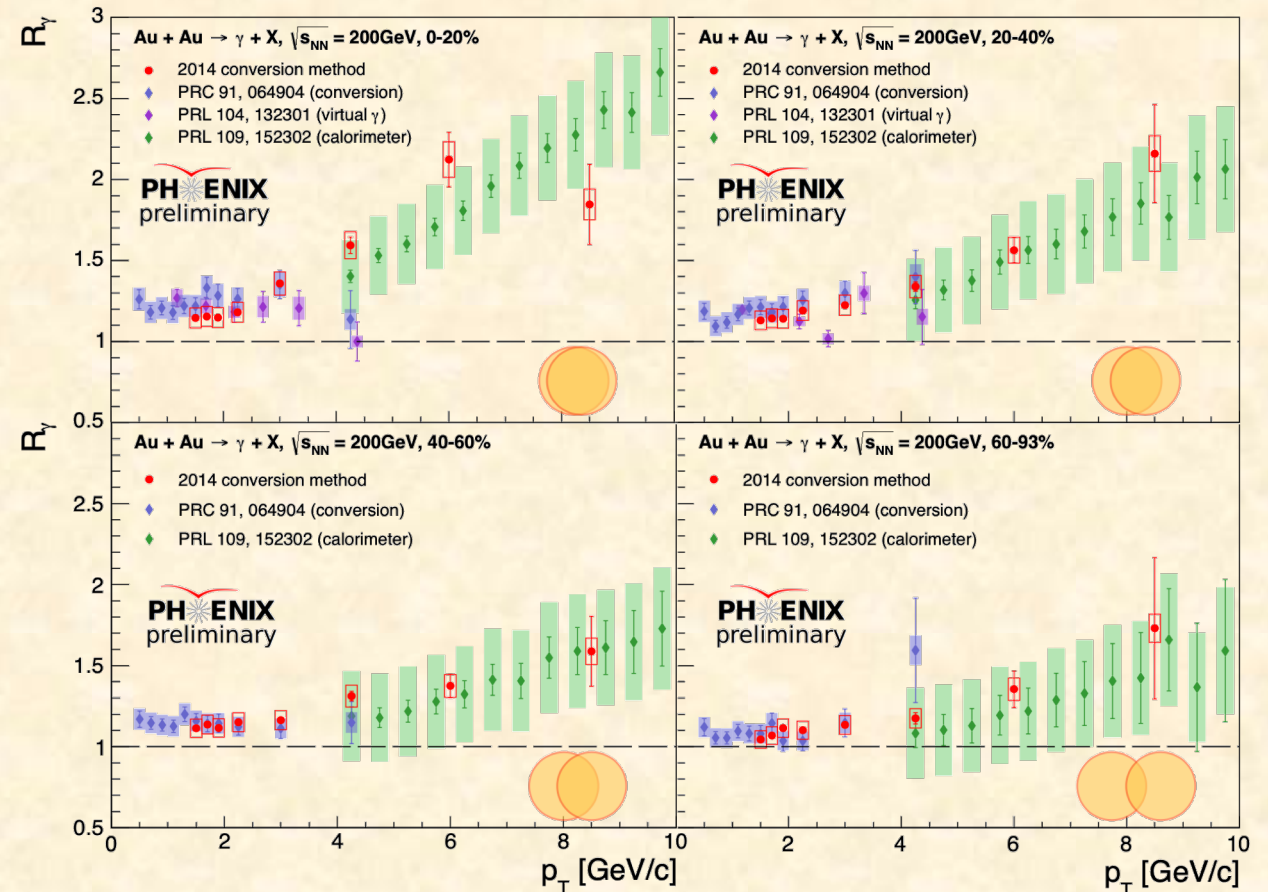
$$R_\gamma(p_T) = \left( \frac{N_\gamma^{incl}}{N_\gamma^{\pi^0}} \right)_{data} / \left( \frac{\gamma^{hadron}}{\gamma^{\pi^0}} \right)_{sim}$$

## • consistent with published results from

- conversion method (blue, 2007+2010)
- virtual- $\gamma$  method (purple, 2004+2005)
- calorimeter method (green, 2004)

## ➤ Extract $\gamma^{dir} = (R_\gamma - 1)\gamma^{hadron}$

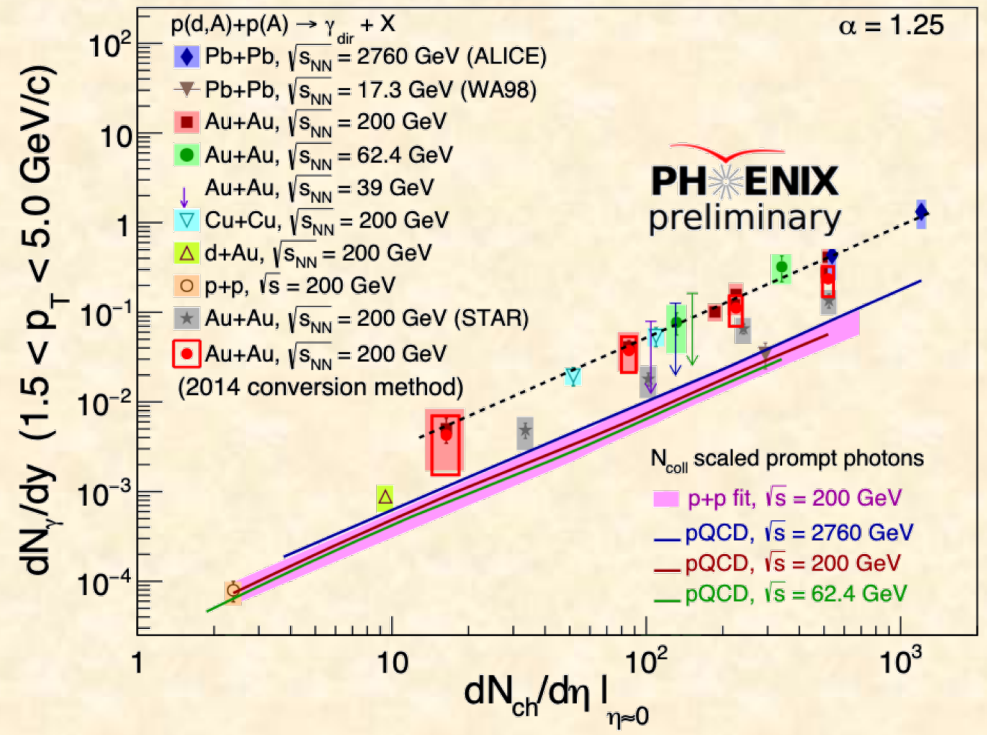
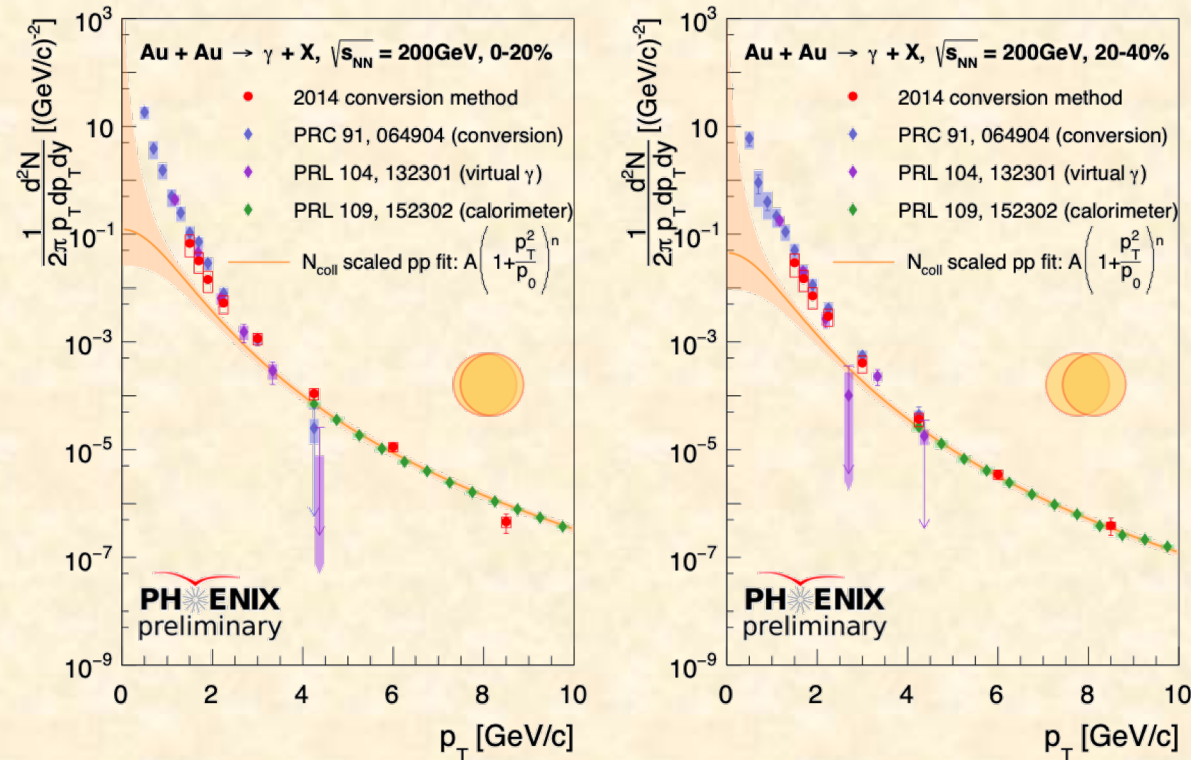
Wenqing Fan, talk #623





Wenqing Fan, talk #623

# Direct Photon Yields and Scaling



- Clear enhancement below 3 GeV/c<sup>2</sup> in central
  - persists in semi-peripheral
- At high p<sub>T</sub> consistent with N<sub>coll</sub>-scaled p+p result
- Consistent with observed scaling behavior

- STAR data appears to show similar scaling
  - but at lower rates
- Look into including BES-2 data from STAR?



# Dilepton Measurements

New results over a wide range of energies

- ALICE
  - p+p, p+Pb, and Pb+Pb at  $\sqrt{s_{NN}} = 5.02\text{TeV}$
  - p+p at  $\sqrt{s} = 13\text{TeV}$  (low B-field)
- STAR
  - Au+Au at  $\sqrt{s_{NN}} = 27, 54, \text{ and } 200\text{ GeV}$
- HADES
  - Au+Au at  $\sqrt{s_{NN}} = 2.4\text{GeV}$
  - Ag+Ag at  $\sqrt{s_{NN}} = 2.6\text{GeV}$
  - $\pi+p \rightarrow e^+e^-n$  at  $\sqrt{s_{NN}} = 1.49\text{GeV}$





# HADES: Thermal Dielectrons at $\sqrt{s_{NN}} = 2.42 \text{ GeV}$

- Strong broadening of in-medium  $\rho$  spectral function
- Enable measurement of fireball temperature

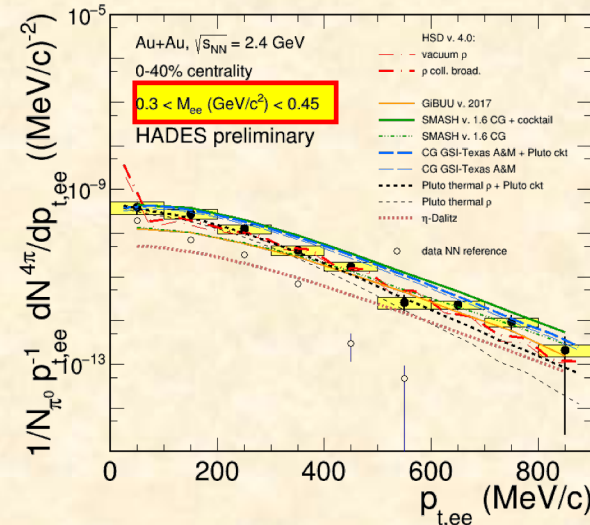
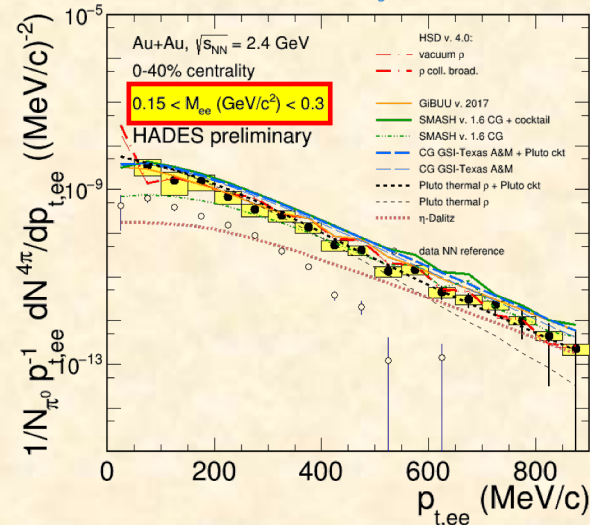
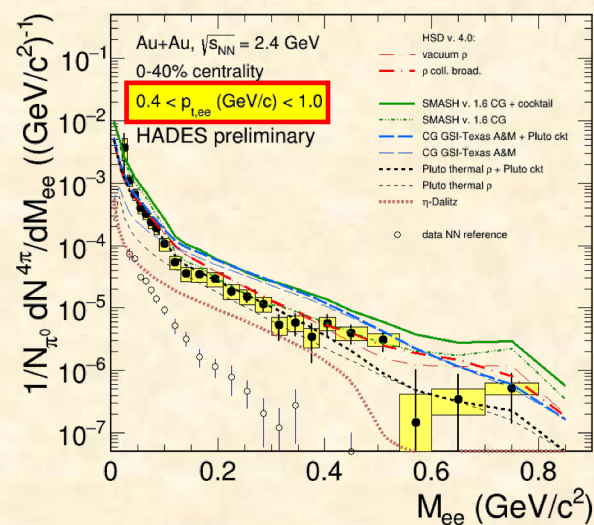
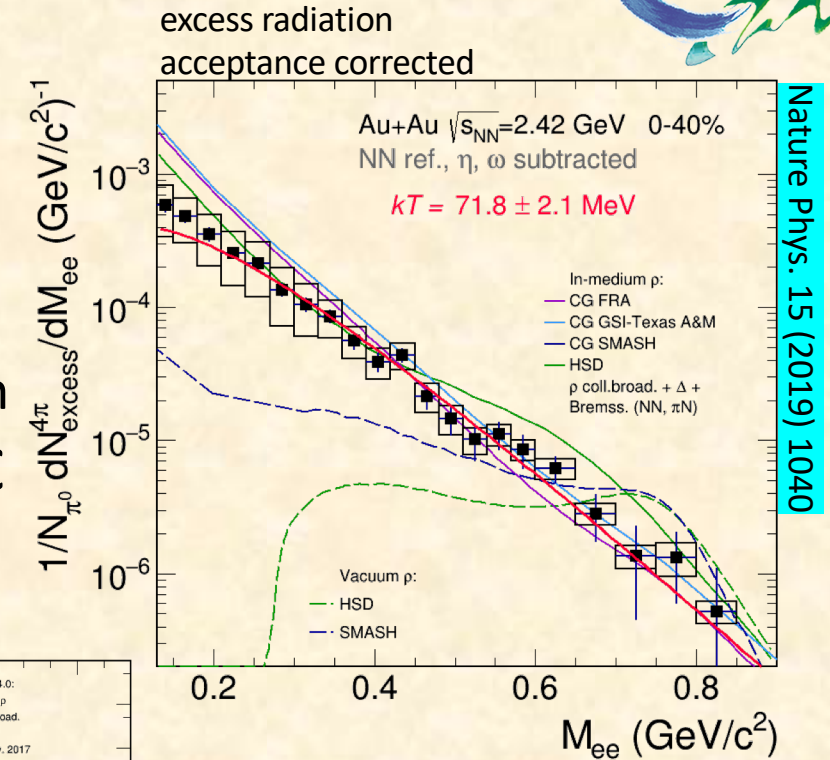
$$\langle T_{\text{fireball}} \rangle = 72 \pm 2 \text{ MeV}$$

## ➤ Thermal rates work at low energies

- folded over coarse-grained transport models medium evolution

## ➤ Supports baryon-driven medium effects at SPS and RHIC (LHC)

- New differentials with sensitivity to model details



Szymon Harabasz, talk #765



Florian Seck, talk #287  
 Zhen Wang, poster #329  
 Zaochen Ye, poster #387

# STAR $e^+e^-$ : from $\sqrt{s_{NN}} = 27, 54, \text{ and } 200 \text{ GeV}$

New high-statistics data sets: 10x more data

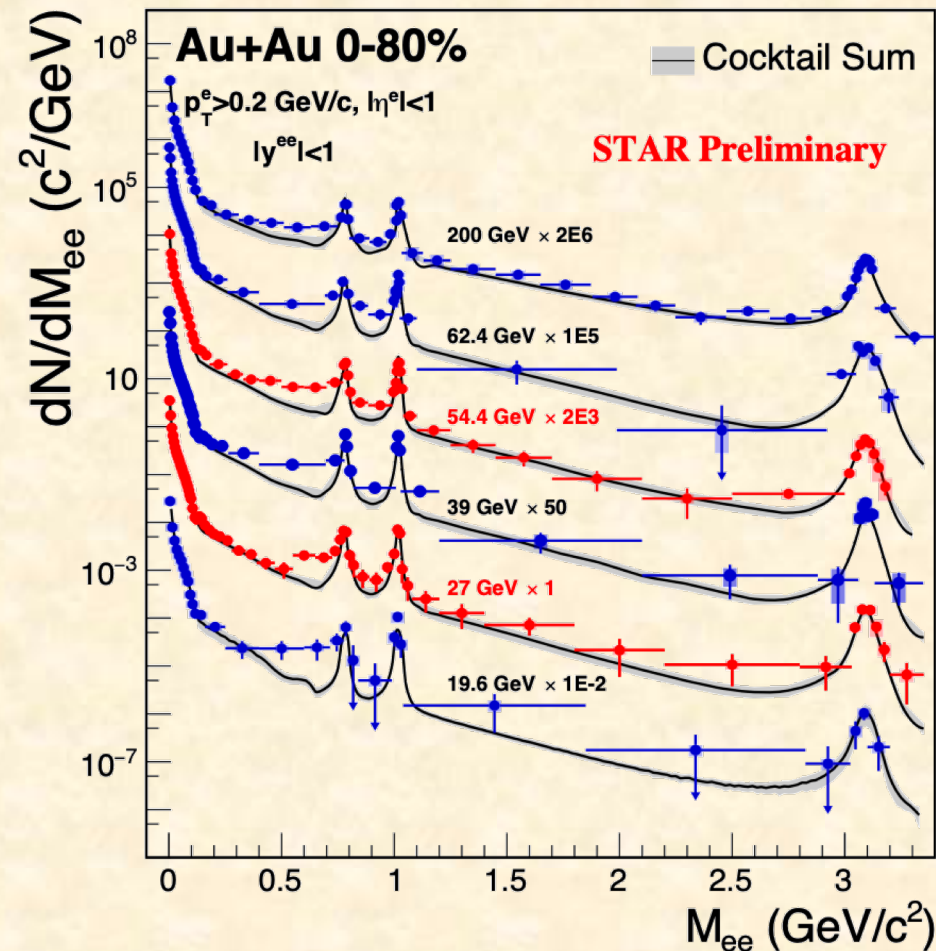
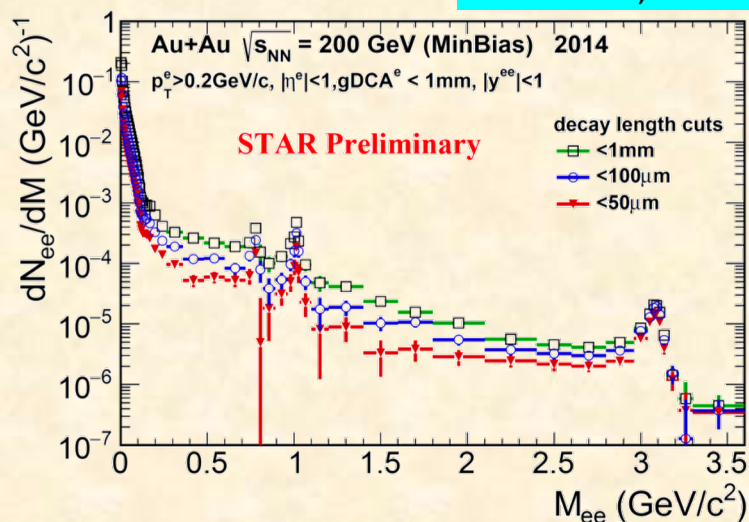
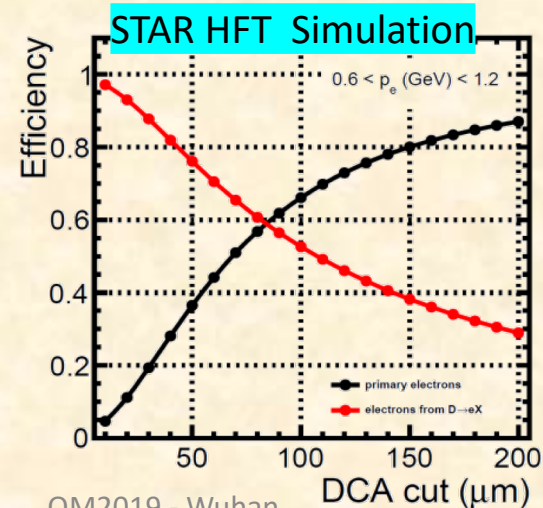
- constrain cocktail by direct  $\omega$  and  $\phi$  measurements
- allow for multi-differentials
- enable virtual direct  $\gamma$  measurements

- a preview of expected precision for BES-2 energies  $\sqrt{s_{NN}} = 7.7 - 19.6 \text{ GeV}$

## • STAR's large Run-14 200GeV includes HFT

- increase in conversion background
- use **decay topology** to increase sensitivity to the thermal radiation in the IMR
- next: apply to Run-16 200GeV dataset

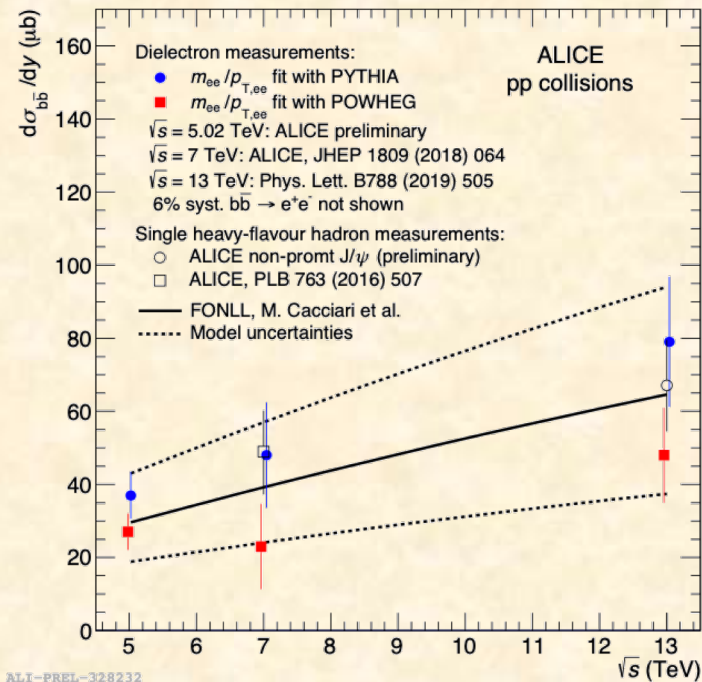
Florian Seck, talk #287



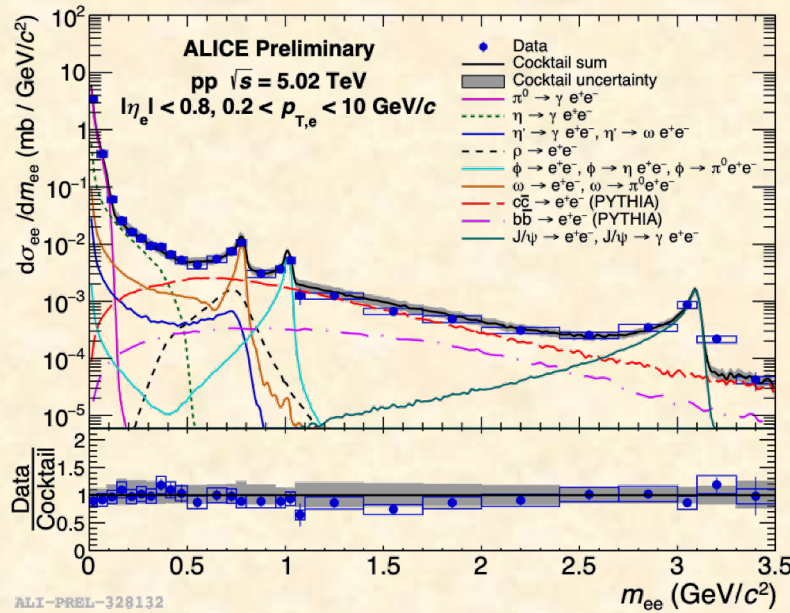


# ALICE $e^+e^-$ : p+p, p+Pb at $\sqrt{s}_{NN} = 5.02\text{TeV}$

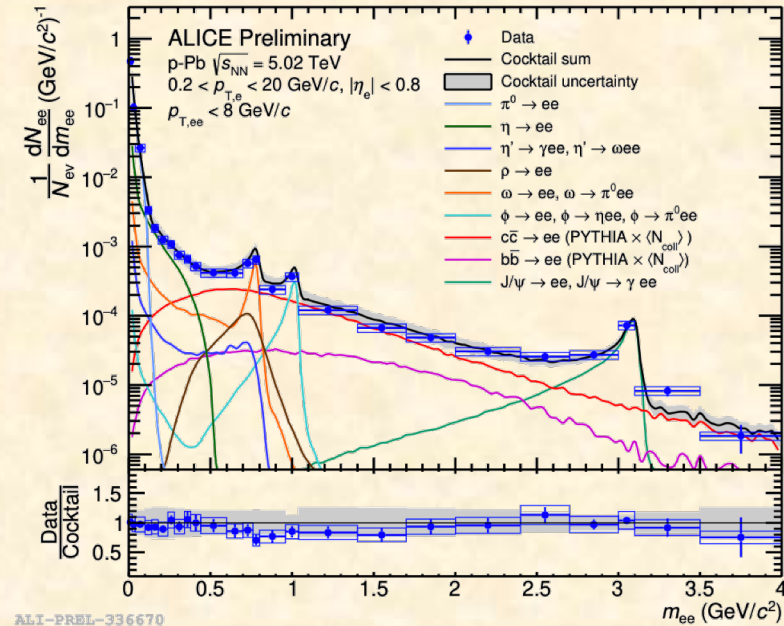
- New results for p+p and p+Pb
  - 2016 data set
- Extract  $d\sigma_{c\bar{c}}/dy$  and  $d\sigma_{b\bar{b}}/dy$ 
  - consistent with HF cross sections



Leonhardt Viebach, poster #319



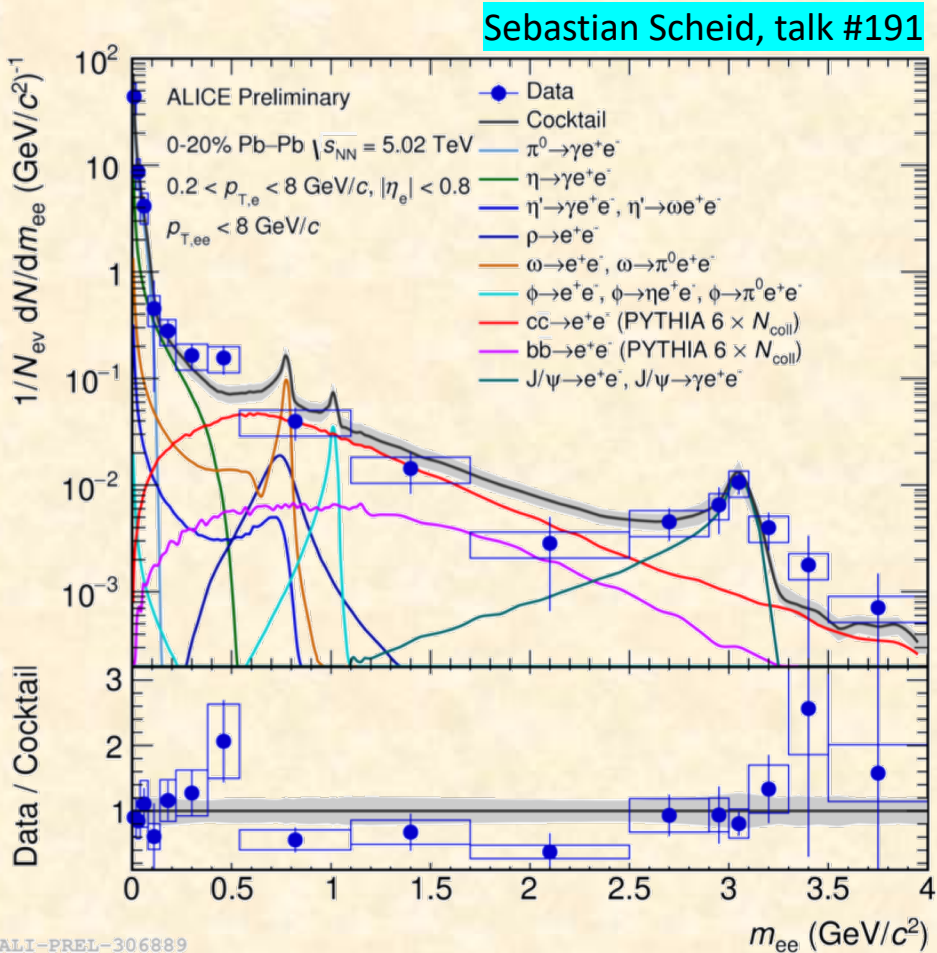
Aaron Capon, poster #808



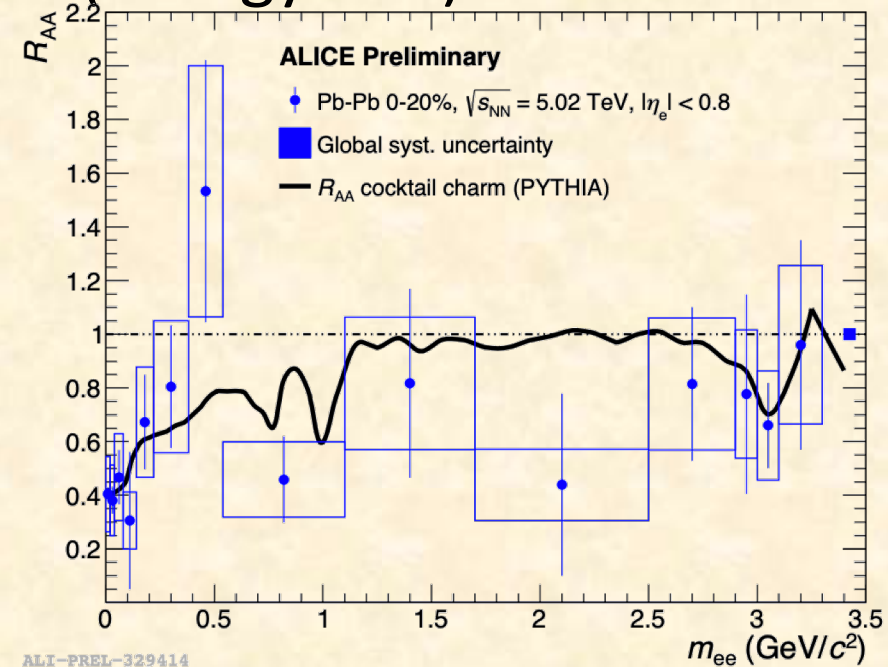


# ALICE $e^+e^-$ : Pb+Pb at $\sqrt{s_{NN}} = 5.02\text{TeV}$

➤ hint of LMR enhancement



- Suppression below IMR vacuum baseline
- Complex interplay between initial and final state (energy loss) effects



Can we disentangle thermal radiation from HF sources?

➤ topological separation ...





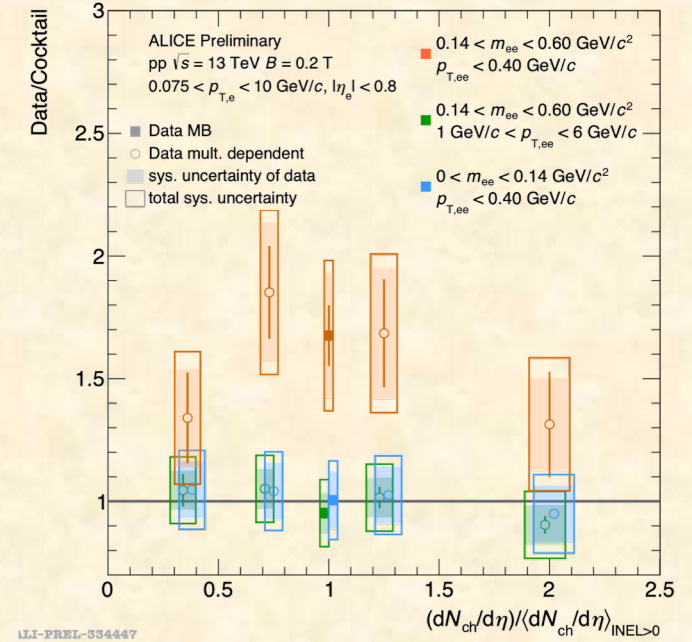
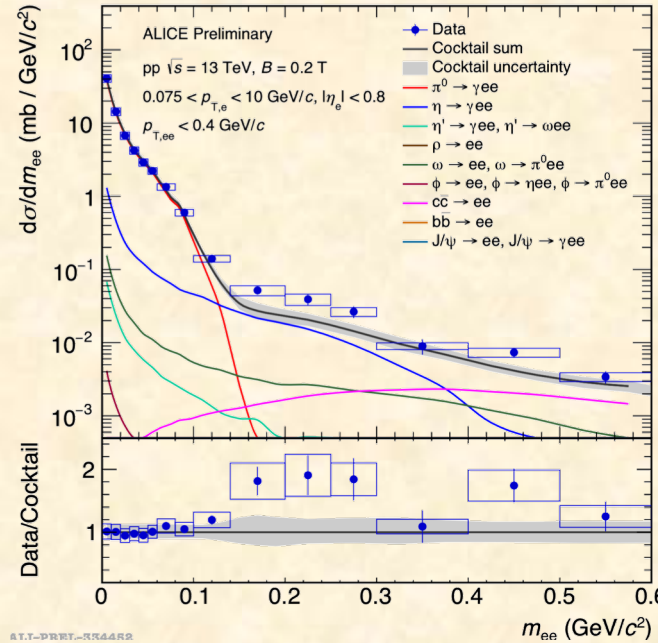
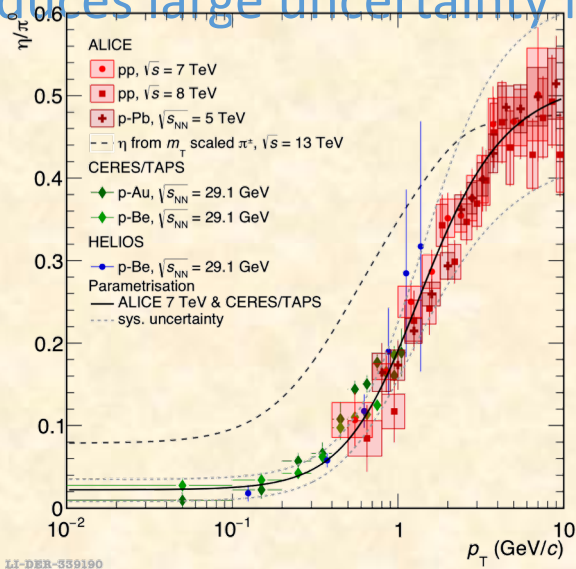
# ALICE: soft dielectrons in 13TeV p+p

First reported by the Axial Field Spectrometer collaboration  
at ISR in p+p@63GeV

ALICE:

- low B-field p+p data (2018)
  - low- $p_T$  reach to 75MeV/c for electrons
- new parametrization of  $\eta$  meson
  - reduces large uncertainty in cocktail

Sebastian Scheid, talk #191



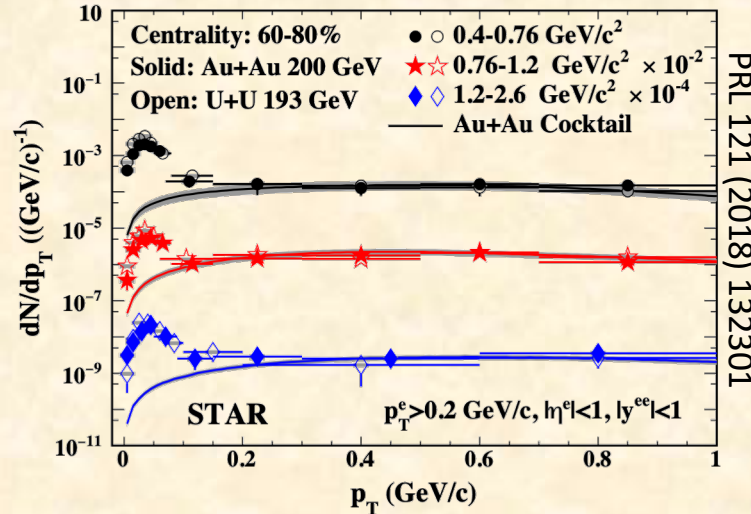
➤ consistently over cocktail in  $\eta$ -mass range and  $p_{T,ee} < 0.4 \text{ GeV}/c$

- consistent with cocktail for
  - low  $p_T \pi^0$
  - higher  $p_T \eta$
- linear scaling with multiplicity (?)

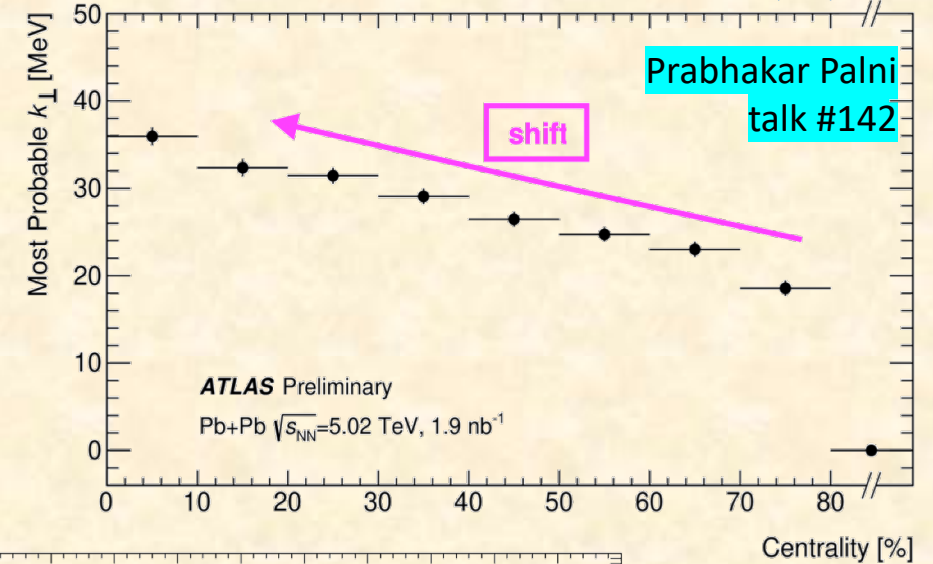


# Photo-production with nuclear overlap

Coherent  $\gamma$ -N and  $\gamma$ - $\gamma$  interactions conventionally studied in UPC interactions.

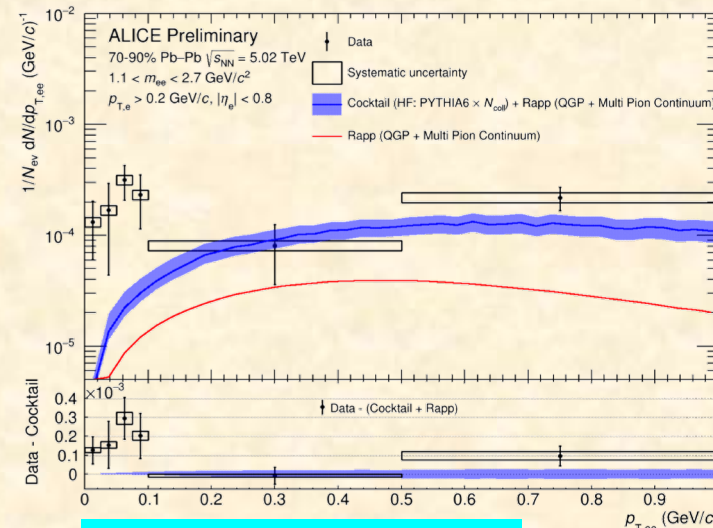


## Clear centrality dependence of $\langle k_T \rangle$



Low  $p_T$  dilepton excess in hadronic heavy ion collisions?

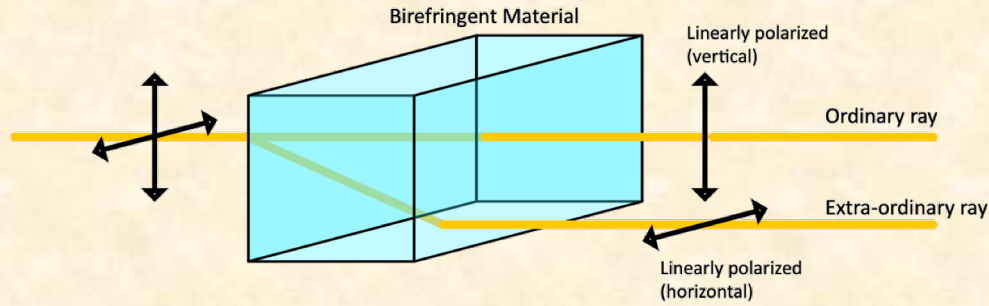
- **STAR**:  $e^+e^-$  excess in Au+Au and U+U at  $\sqrt{s_{NN}}=200$  GeV
  - investigating low- $p_T$   $\mu^+\mu^-$  for high  $M_{\mu\mu}$  Zhen Liu, poster#425
- **ATLAS**:  $\mu^+\mu^-$  in Pb+Pb at  $\sqrt{s_{NN}}=5.02$  TeV
  - 2015 data published PRL 121 (2018) 212301
  - new measurement combines 2015+2018 data
- **ALICE**:  $e^+e^-$  excess in Pb+Pb at  $\sqrt{s_{NN}}=5.02$  TeV
  - $3\sigma$  excess in IMR for 70-90% centrality class



Sebastian Scheid, talk #191

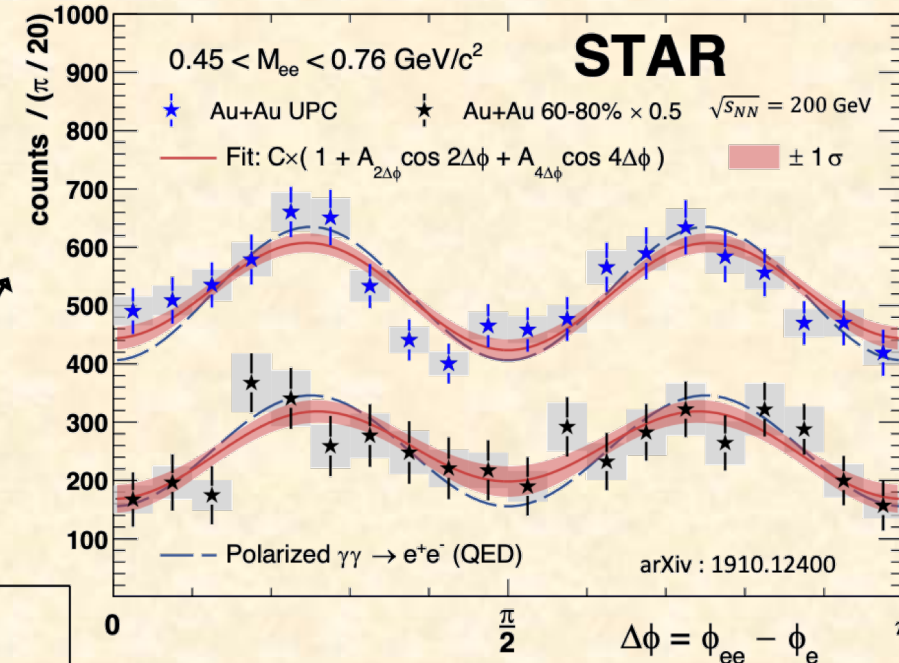
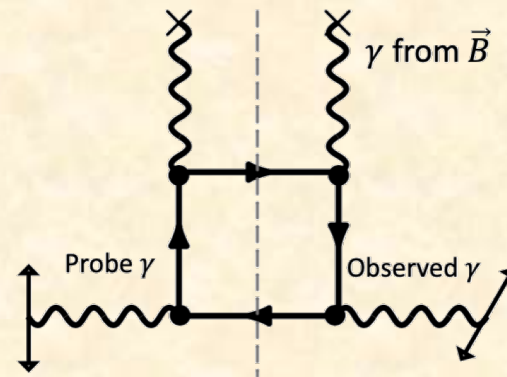


# Dielectrons to Map the $\vec{B}$ Field



Daniel Brandenburg, talk #646

- Birefringence of the QED vacuum observed for the first time
  - in UPC  $A_{4\Delta\phi}$  is at a  $6.7\sigma$  level
  - in peripheral events at  $\sim 4.5\sigma$

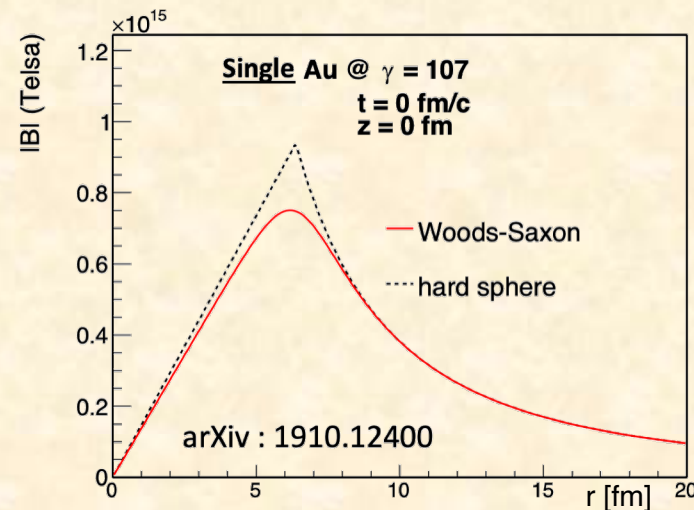


Potential application to peripheral (hadronic) interactions:

relate photon density to energy flux of EM fields

$$n \propto \vec{S} = \mu_0^{-1} \vec{E} \times \vec{B}$$

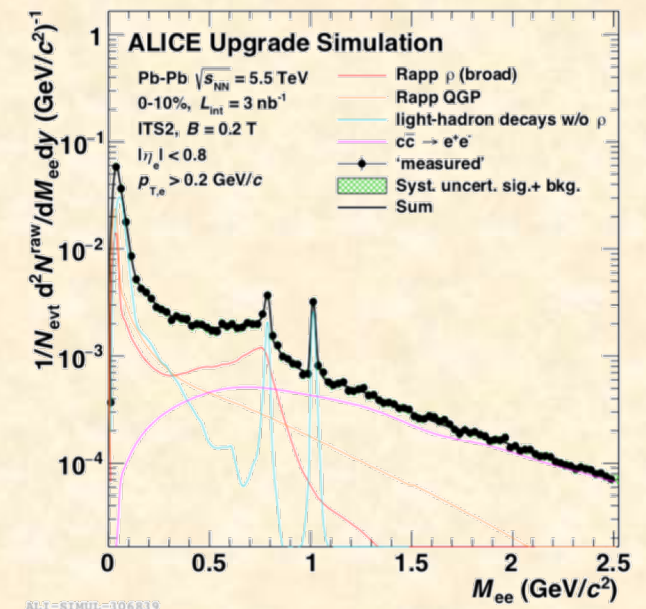
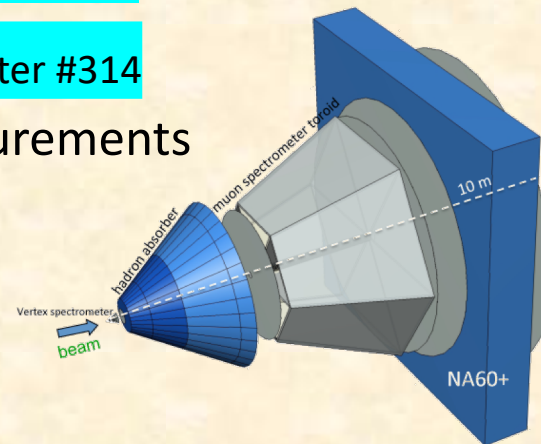
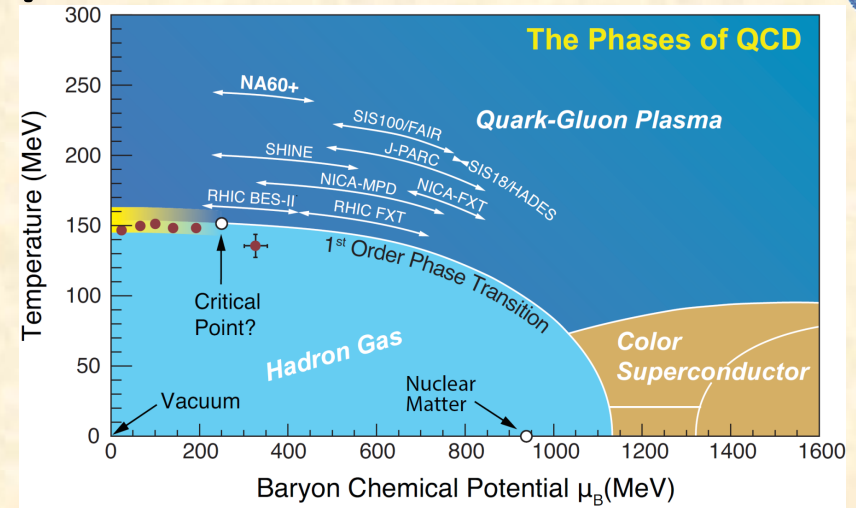
- report  $\vec{B}$  that matches measured cross section





# Near Future Experimental Landscape

- STAR BES-2 program 2019-2021 **Yi Yang, talk #388**
  - collider mode six energies between 7.7 – 19.6 GeV
  - event goals driven by dielectron program -> 10-15% significance in LMR/IMR
  - incl. CBM Fair Phase-0 program: endcap TOF
- ALICE Run 3 (2021+) **Sebastian Scheid, talk #191**
  - new ITS (resolution improvement 3-6x)
  - TPC readout upgrade (rate 100x)
  - dedicated dielectron runs with low B-field
- MPD ECAL installation (2020+) **Adam Kisiel, talk #457**
- NA60+. **Enrico Scomparin poster #314**
  - high precision, high statistics dimuon measurements
  - measure chiral  $\rho$ - $a_1$  mixing
  - discussion preparation of Lol





# My Summary

- EM/weak probes are the most versatile probes in heavy-ion collisions
  - nPDFs, QGP temperature, chiral symmetry restoration, lifetime, B-field
- Yes, there is still a photon puzzle
  - new data sets are collected and analyzed
  - improve  $\eta$  mesons at low  $p_T$
- Precision data is collected over almost 4 orders of magnitude
- New experiments and upgrades being proposed and/or readied

❖ **The future of weak and electromagnetic probes looks very bright**

# Thank you!

