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EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

Centrality Dependence of "Thermal" Radiation

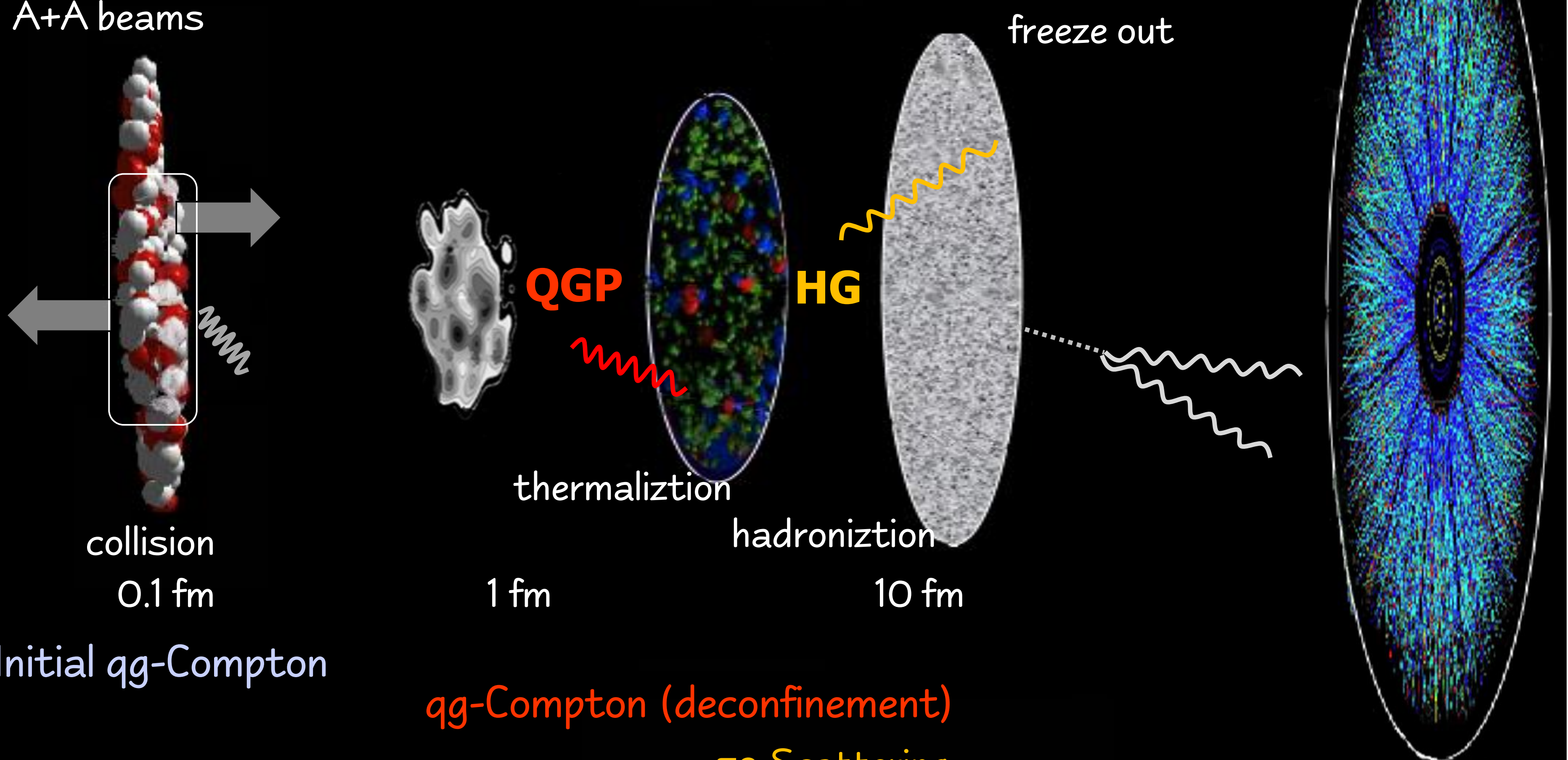
Axel Drees, Trento 2018, November 27, Italy

- **Introduction**
- **PHENIX analyses**
- **PHENIX: Photon Scaling with** $\frac{dN_{ch}}{d\eta}^{5/4}$
- **Review of Other Results**

Electromagnetic Radiation in A+A Collisions:

detector

Hubble expansion: T=300-160 160-110 110 MeV



Initial qg-Compton

qg-Compton (deconfinement)

πρ Scattering

Centrality dependence:

Hadron Decays

$\propto N_{coll}$ $\propto N_{ch}^{\alpha} \quad 1 < \alpha \leq 2$ $\propto N_{ch}$

Photon Measurements with PHENIX

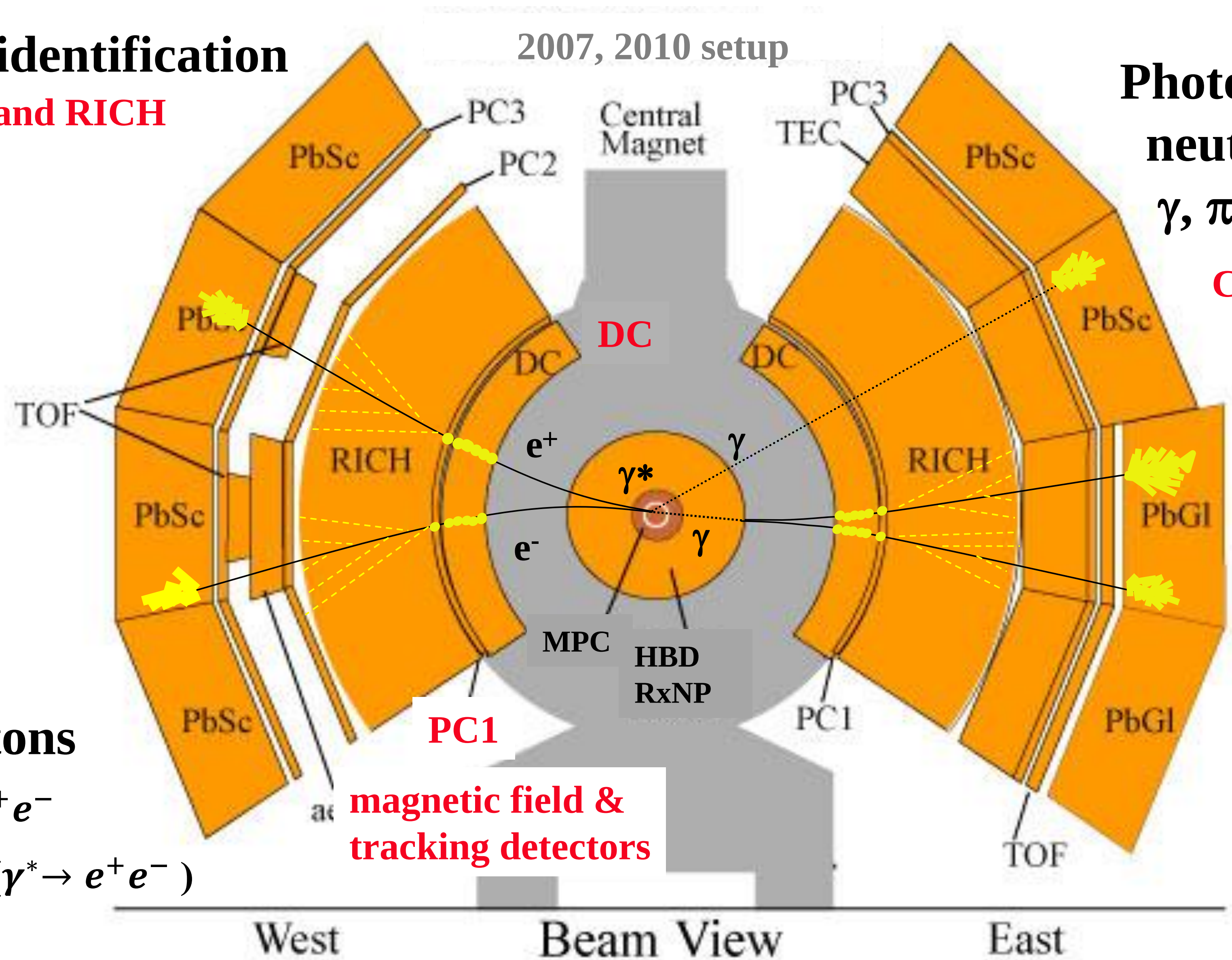
e⁺e⁻ identification

E/p and RICH

Photons, neutral pion

$\gamma, \pi^0 \rightarrow \gamma\,\gamma$

Calorimeter



Photons

$\gamma \rightarrow e^+e^-$

$\lim_{m_{ee}\rightarrow 0} (\gamma^* \rightarrow e^+e^-)$

PHENIX Low p_T Direct Photon Analyses

Low pt Direct Photon Spectra

Run	system	energy	type	Thesis			Publication
Run 2004/2005	Au+Au/p+p	200 GeV	γ^*	Dahms	SBU	2008	PRL 104 (2010) 132301
							PRC 81 (2010) 34911
Run 2006/2008	p+p/d+Au	200 GeV	γ^*	Yamaguchi	Tokyo	2011	PRC 87 (2013) 54907
Run 2007	Au+Au	200 GeV	$\gamma \rightarrow ee$	Petti	SBU	2013	PRC 91 (2015) 64904
Run 2010	Au+Au	200 GeV	$\gamma \rightarrow ee$	Bannier	SBU	2014	
Run 2004	Au+Au	200 GeV	γ	Gong	SBU	2014	-
Run 2005	Cu+Cu	200 GeV	γ^*	Hoshino	Hiroshima	2017	PRC 98 (2018) 54902
Run 2010	Au+Au	39/62 GeV	$\gamma \rightarrow ee$	Khachatryan	SBU	2015	arXiv:1804.04181
Run 2014/2015	Au+Au/p+Au	200 GeV	$\gamma \rightarrow ee$	Fan	SBU	est. 2019	

Low pt Direct Photon Azimuthal Anisotropy

Run	system	energy	type	Thesis			Publication
Run 2004	Au+Au	200 GeV	γ	Miki	Tsukuba	2009	PRL109 ((2012) 122302
Run 2010	Au+Au	200 GeV	$\gamma \rightarrow ee$	Bannier	SBU	2014	PRC 94 (2016) 64901
Run 2007	Au+Au	200 GeV	γ	Mizuno	Tsukuba	2015	
Run 2014	Au+Au	200 GeV	$\gamma \rightarrow ee$	Fan	SBU	est. 2019	

Well established data analysis
3 different methods, 9 theses, 8 publications

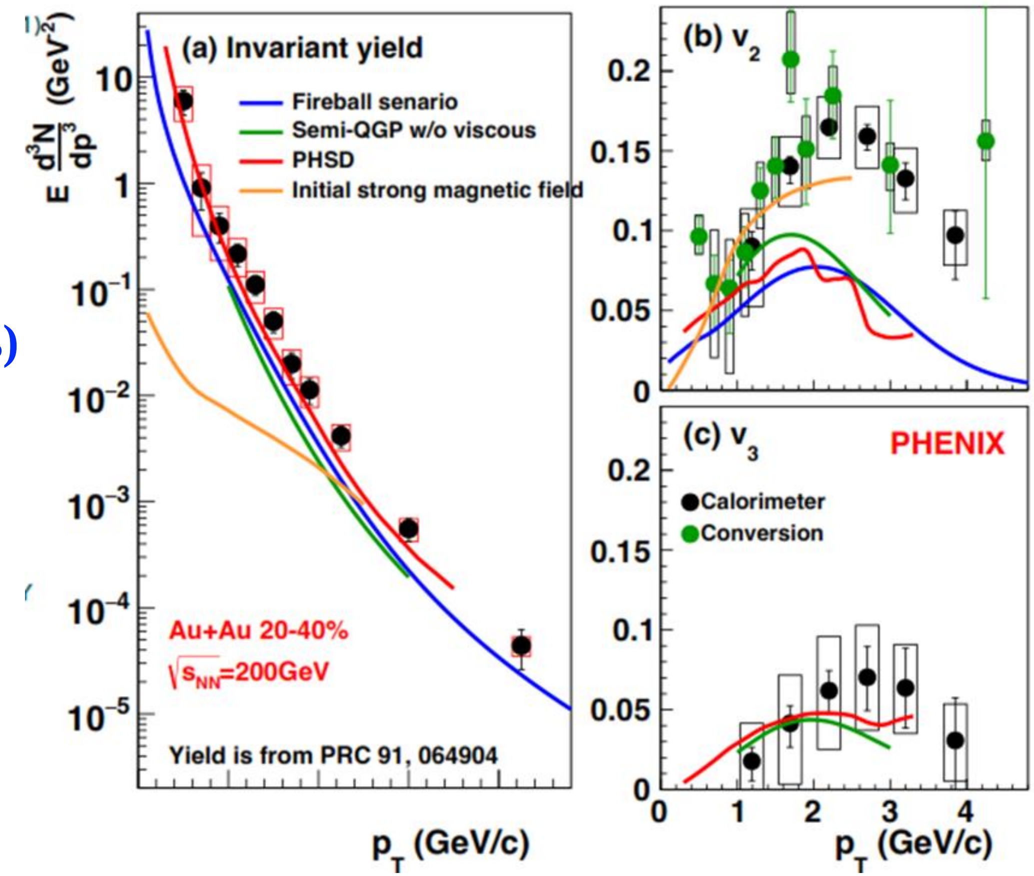
Current Status of PHENIX Results

"Direct Photon Puzzle"

tension between data and models*:

- **More traditional, large contribution from hadron gas**
  - Thermal rate in QGP & HG, with hydro (viscous/non viscous) or blastwave evolution
  - Microscopic transport (PHSD)
- **New early contributions**
  - Non-equilibrium effects (glasma, etc.)
  - Enhanced thermal emission in large B-fields
  - Modified formation time and initial conditions
- **New effects at phase boundary**
  - Extended emission
  - Emission at hadronization

PHENIX: Phys. Rev. C94 (2016) 064901

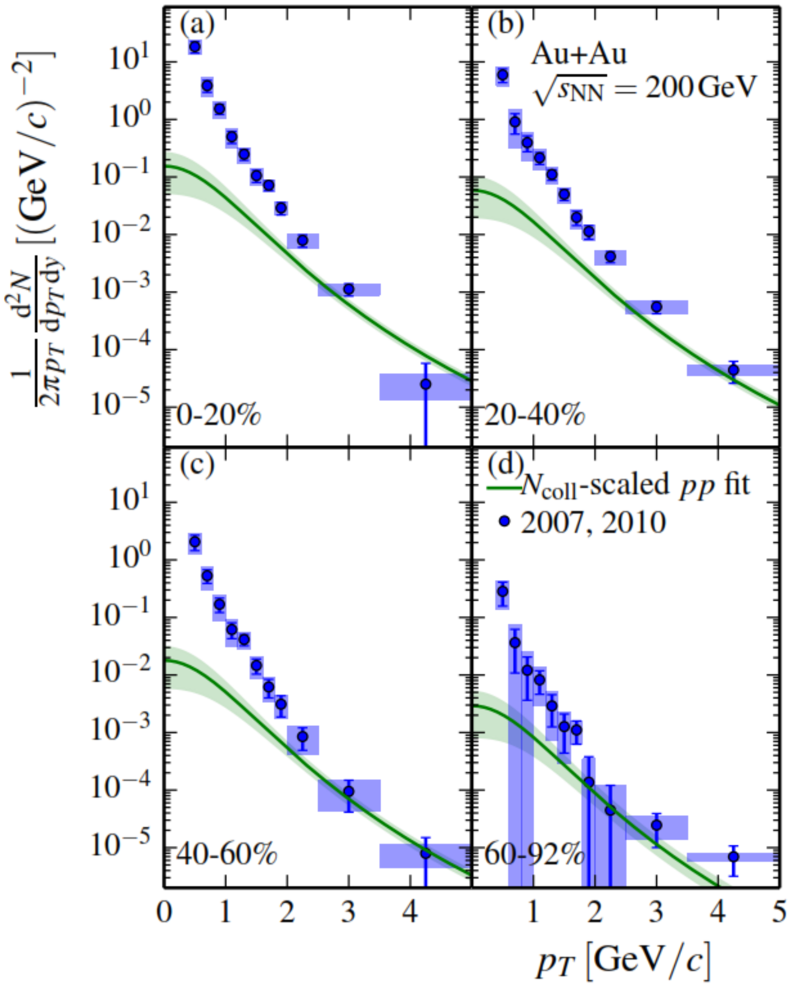


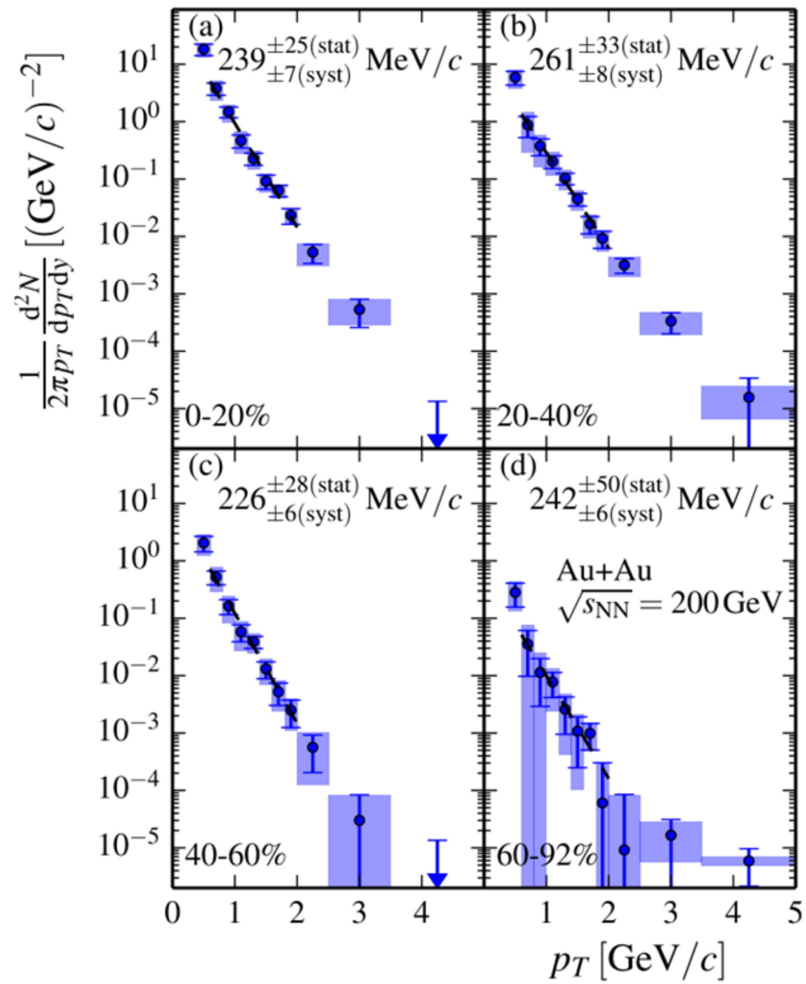
Large yield and v_n challenge understanding of sources, emission rates and space-time evolution

*list not complete

Centrality Dependence of Thermal Component

PHENIX: Phys. Rev. C91 (2015) 064904





Large direct photon excess

yield $\propto N_{part}^{1.38\pm0.3\pm0.07}$ with inv. slope T ~ 240 MeV

Centrality Dependence of Thermal Component

PHENIX: Phys. Rev. C91 (2015) 064904

p_T^{min} (GeV/c)	α	A
0.4	$1.36 \pm 0.08 \pm 0.08$	$(7.85 \pm 2.96 \pm 4.52) \times 10^{-3}$
0.6	$1.41 \pm 0.14 \pm 0.12$	$(2.20 \pm 1.54 \pm 1.64) \times 10^{-3}$
0.8	$1.42 \pm 0.07 \pm 0.11$	$(1.07 \pm 0.39 \pm 0.75) \times 10^{-3}$
1.0	$1.35 \pm 0.06 \pm 0.07$	$(7.70 \pm 2.32 \pm 4.37) \times 10^{-4}$
1.2	$1.36 \pm 0.09 \pm 0.07$	$(3.90 \pm 1.79 \pm 2.81) \times 10^{-4}$
1.4	$1.40 \pm 0.06 \pm 0.10$	$(1.63 \pm 0.47 \pm 1.11) \times 10^{-4}$

- **Centrality dependence Au+Au 200 GeV**

$$\frac{dN_\gamma}{dy} = A\, N_{part}^{\alpha}$$

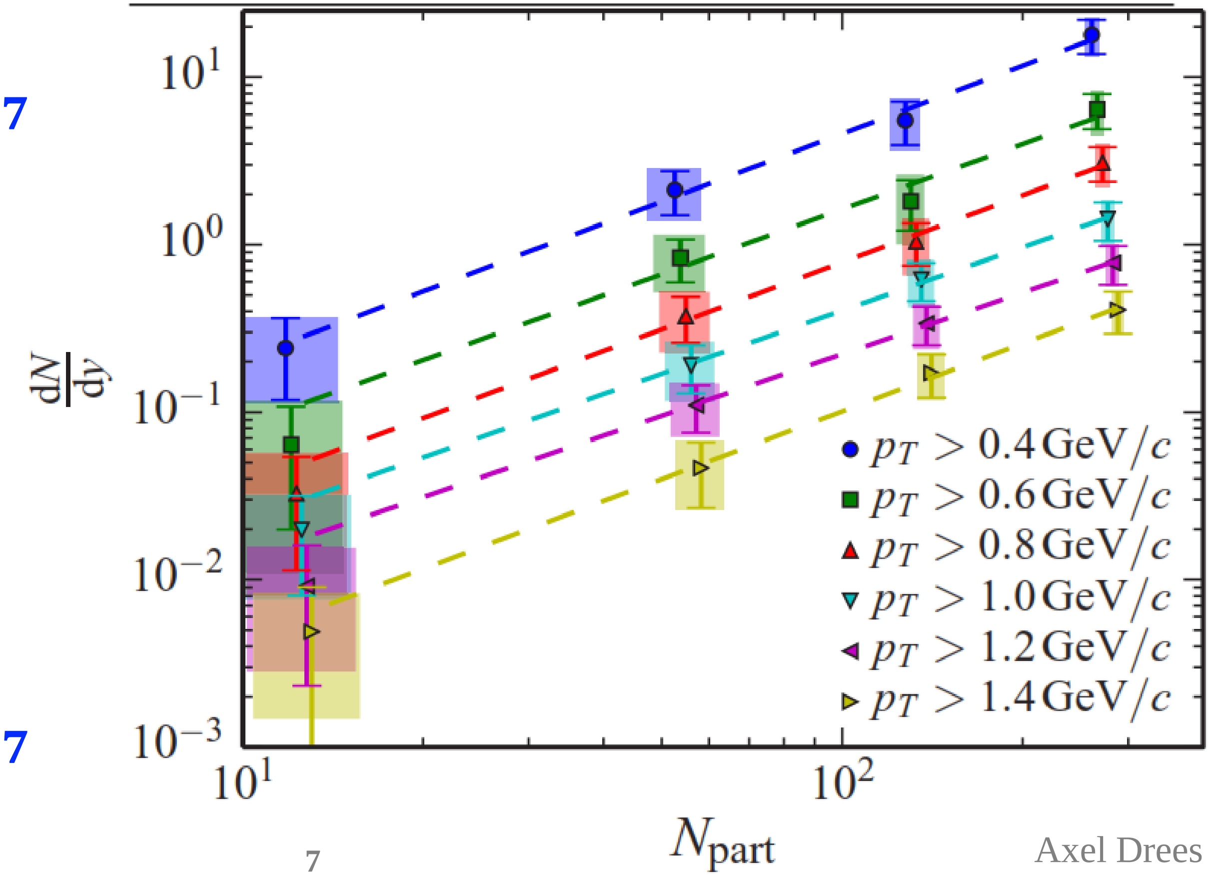
  - $\alpha = 1.38 \pm 0.03 \pm 0.7$
  - **independent of p_T**

- **At fixed √s:**

  - $N_{ch} \propto N_{qp} \sim N_{part}$

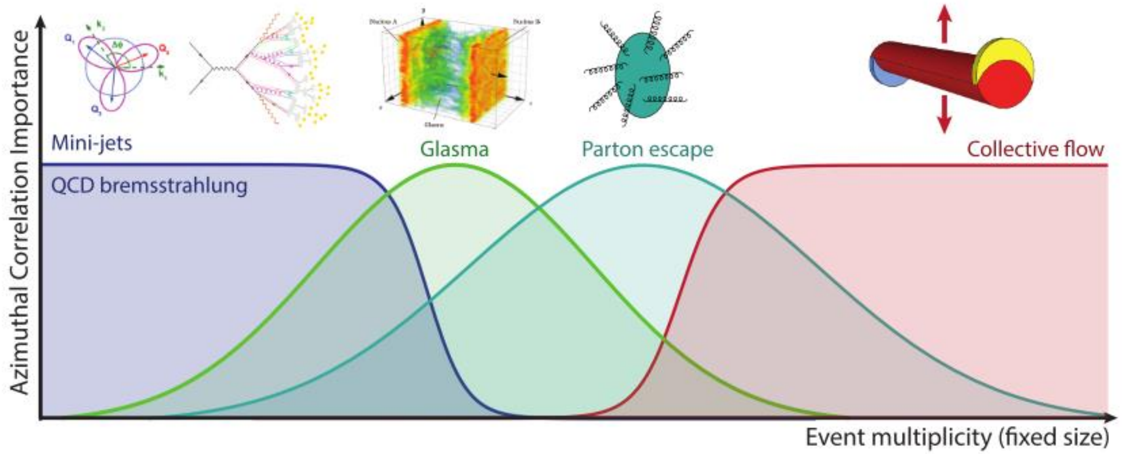
$$\frac{dN_\gamma}{dy} = A\, N_{qp}^{\beta}$$

  - $\beta = 1.27 \pm 0.03 \pm 0.7$

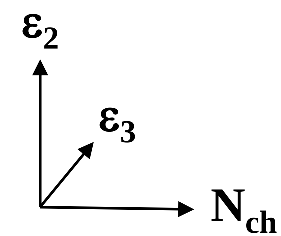


New Insight: Vary System Size and Geometry

M. Strickland: QM2018 arXiv:1807.07191



System size and geometry matter



- **Vary size & geometry through changing collision system, √s , centrality**
- **Measure system size via event multiplicity or $\frac{dN_{ch}}{d\eta}$ or similar**
  - **$\frac{dN_{ch}}{d\eta}$ is an experimental observable**
  - **at fixed √s $\frac{dN_{ch}}{d\eta} \sim N_{part} \sim$ Volume**
  - **Varying √s $\frac{dN_{ch}}{d\eta} \sim$ energy density x Volume**

Compare data as function of $\frac{dN_{ch}}{d\eta}$

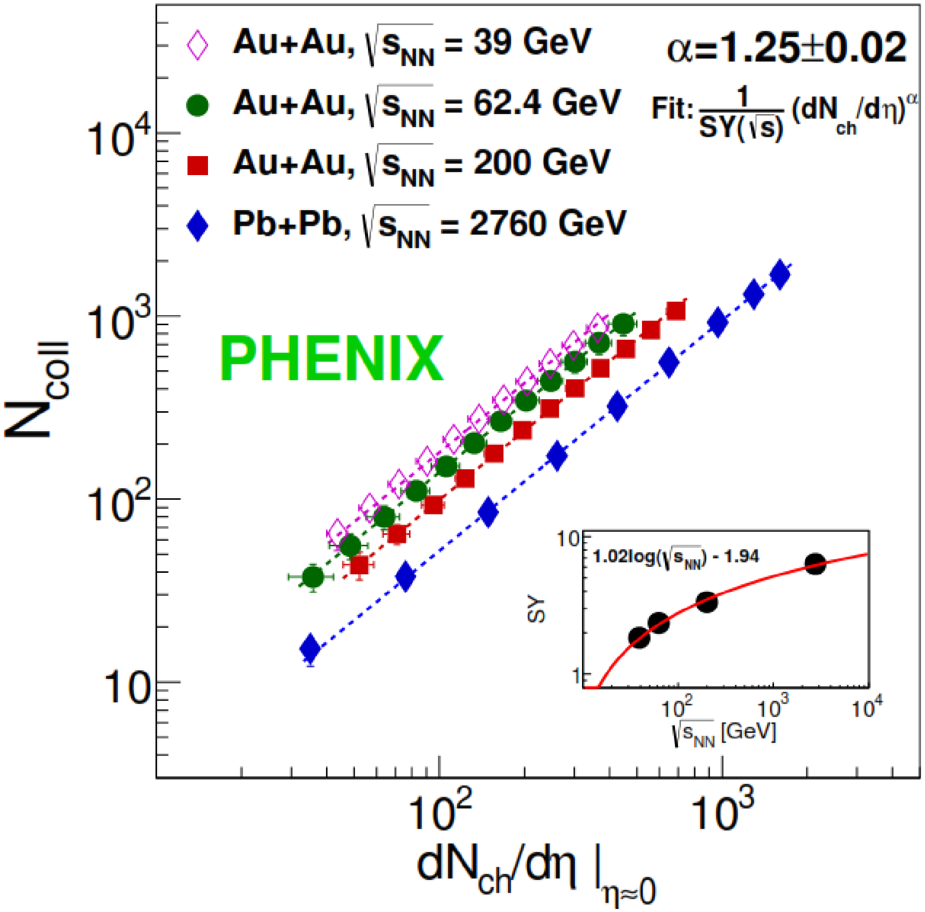
- **Available for direct γ analysis in PHENIX**
  - **200 GeV: Au+Au, Cu+Au, Cu+Cu, 3He+Au, d+Au, p+Au, p+p**
  - **200 – 62.4 – 39 GeV: Au+Au**

Compare Different Systems as function of System Size

- Compare different systems and energies using $\frac{dN_{ch}}{d\eta}$
  - Measure of energy deposited by incoming beams
- Discovery of scaling behavior
  - Connects bulk particle production and hard scattering processes

$$N_{\text{coll}} = \frac{1}{SY(\sqrt{s_{NN}})} \times \left(\frac{dN_{\text{ch}}}{d\eta}\right)^{\alpha}$$

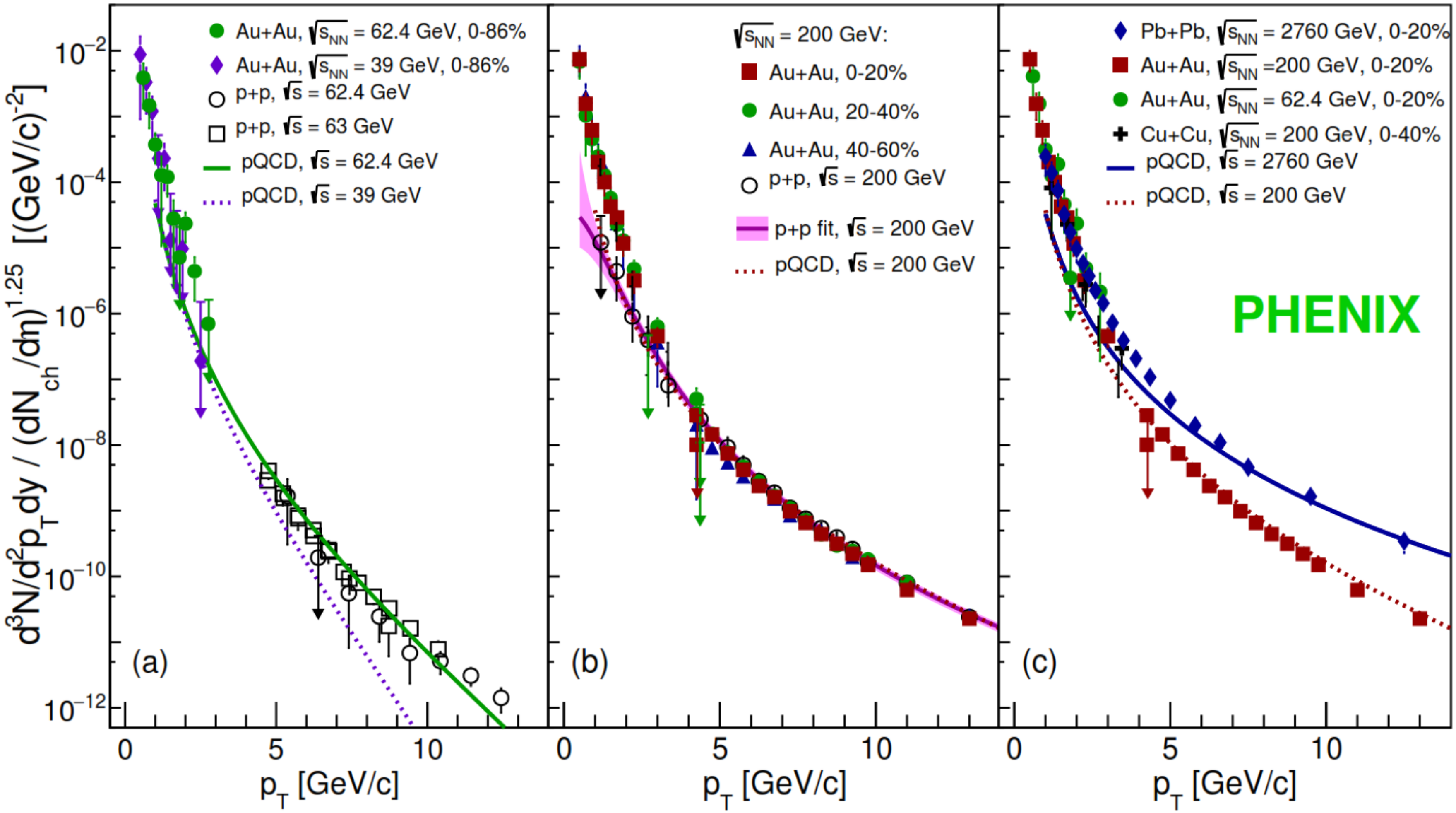
PHENIX: arXiv:1804.04181



What is the origin of this scaling?

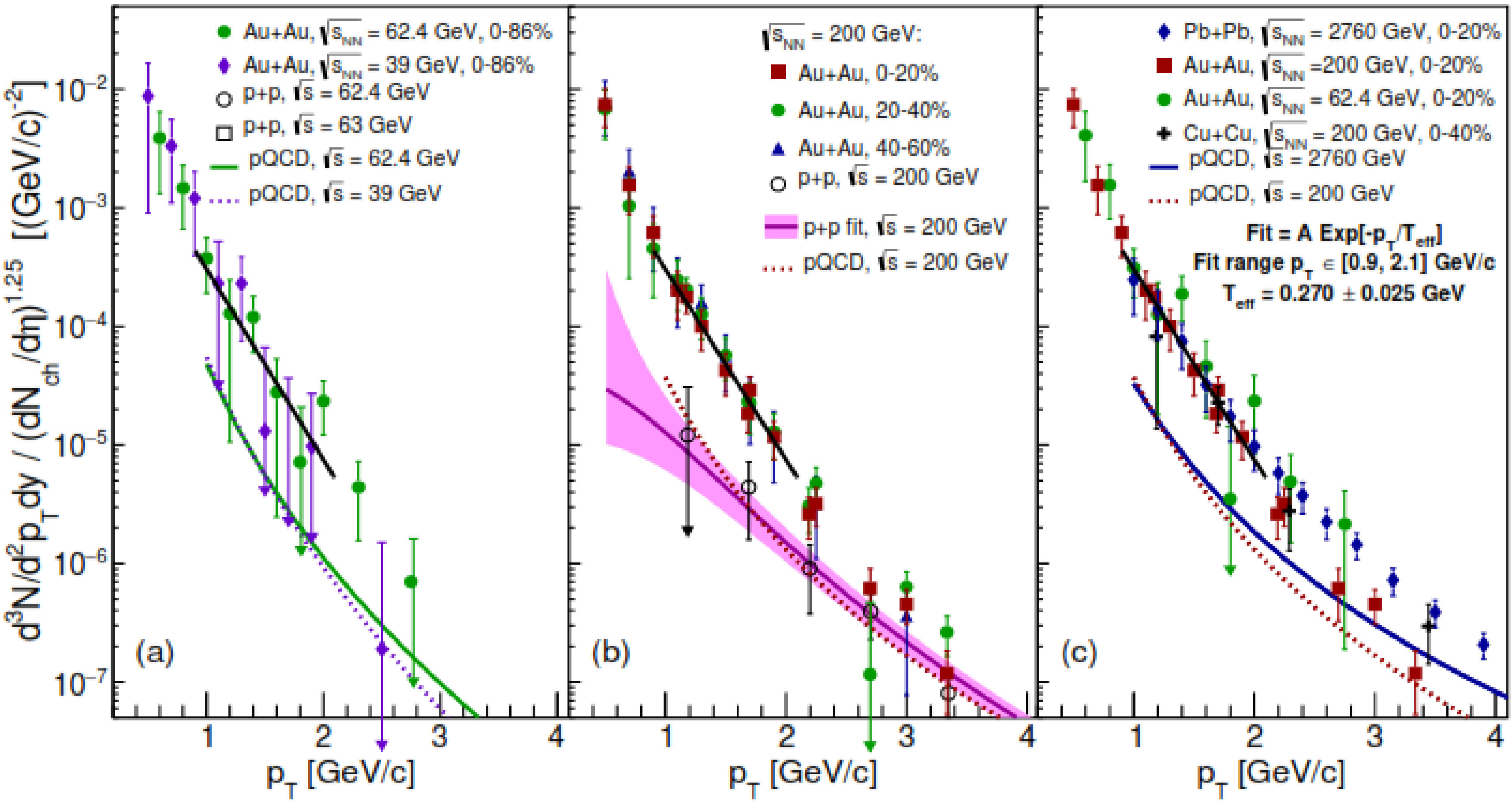
Comparison of Different Collision Systems

PHENIX: arXiv:1804.04181 *ALICE: Phys. Lett. B 754 (2016) 235*



Similar thermal photon yield when scaled with $\frac{dN_{ch}}{d\eta}^{1.25}$
independent of energy, centrality, or system size

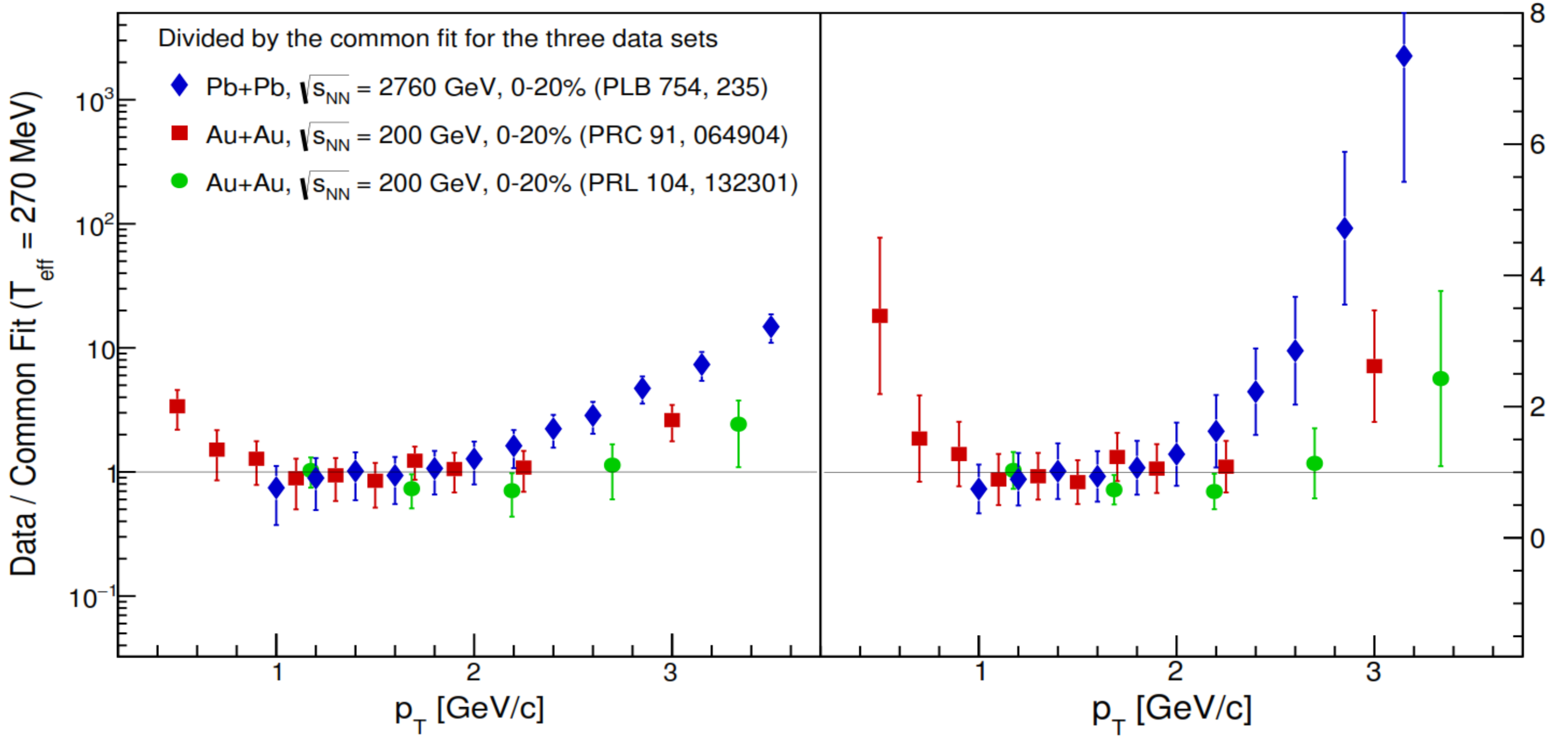
Focus on low p_T Region



- **Similar inverse slope**
  - T_{eff} ~ 270 MeV for all spectra 0.9 < pT < 2.1 GeV/c
  - Independent of centrality and √s from 39 to 2760 GeV

Scaled Spectra Divided by Common Fit

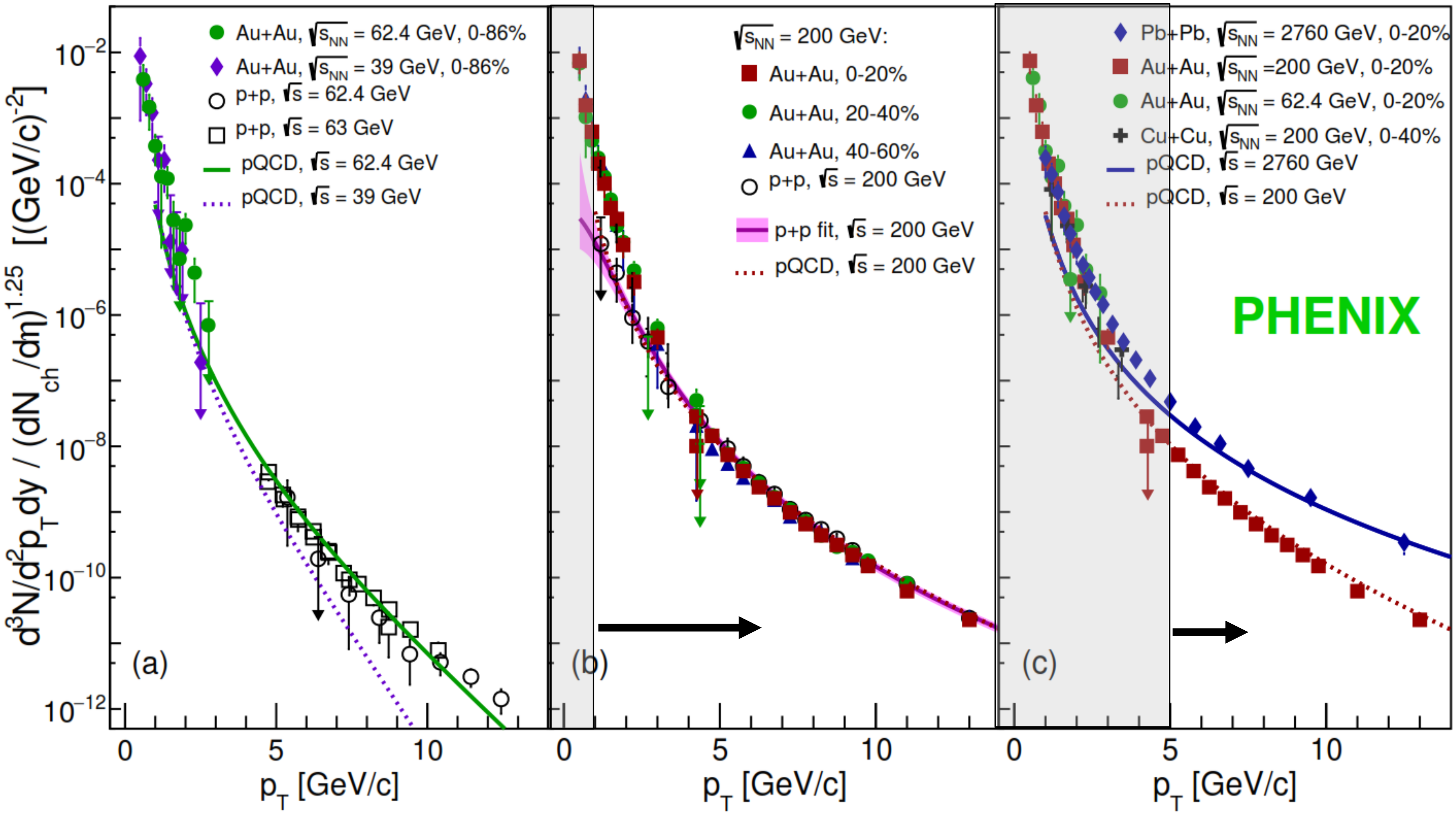
- **Data normalized to common fit 0.9 < p_T < 2.1 GeV**



- **Data similar in overlap region below 2 GeV**
- **Data not truly exponential**
- **For p_T > 2.5 GeV developing √s dependence**

Integrated Direct Photon Yield

PHENIX: arXiv:1804.04181



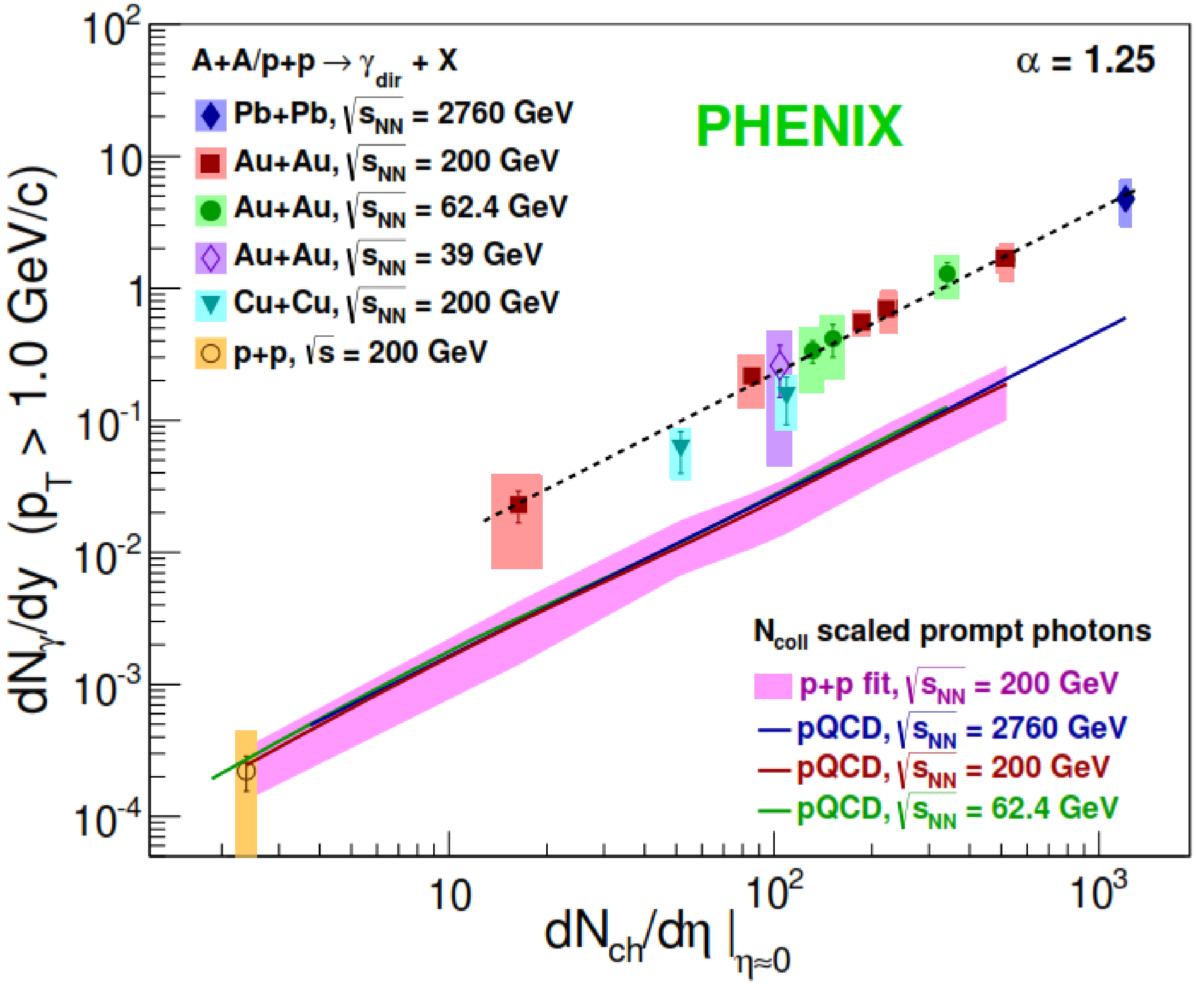
p_T > 1 GeV
"thermal" region

p_T > 5 GeV
"hard scattering" region

Integrated "Thermal" Photon Yield

PHENIX: arXiv:1804.04181

ALICE: arXiv:1804.04181



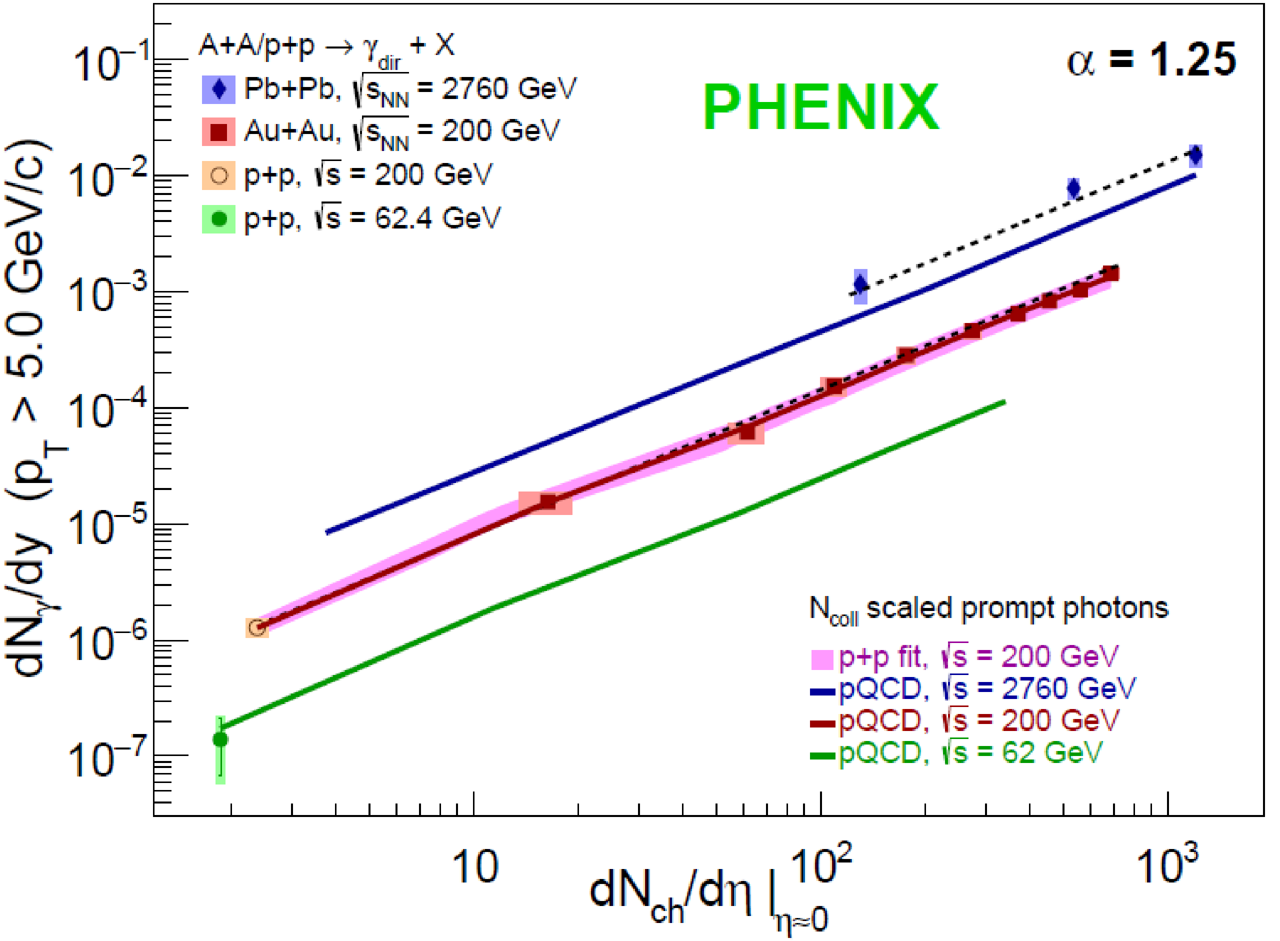
Universal scaling behavior!

Source of thermal photons must be similar!

Ncoll x pQCD and Ncoll x p+p follow same scaling at 0.1 of yield

Integrated Photon Yield $p_T > 5$ GeV/c

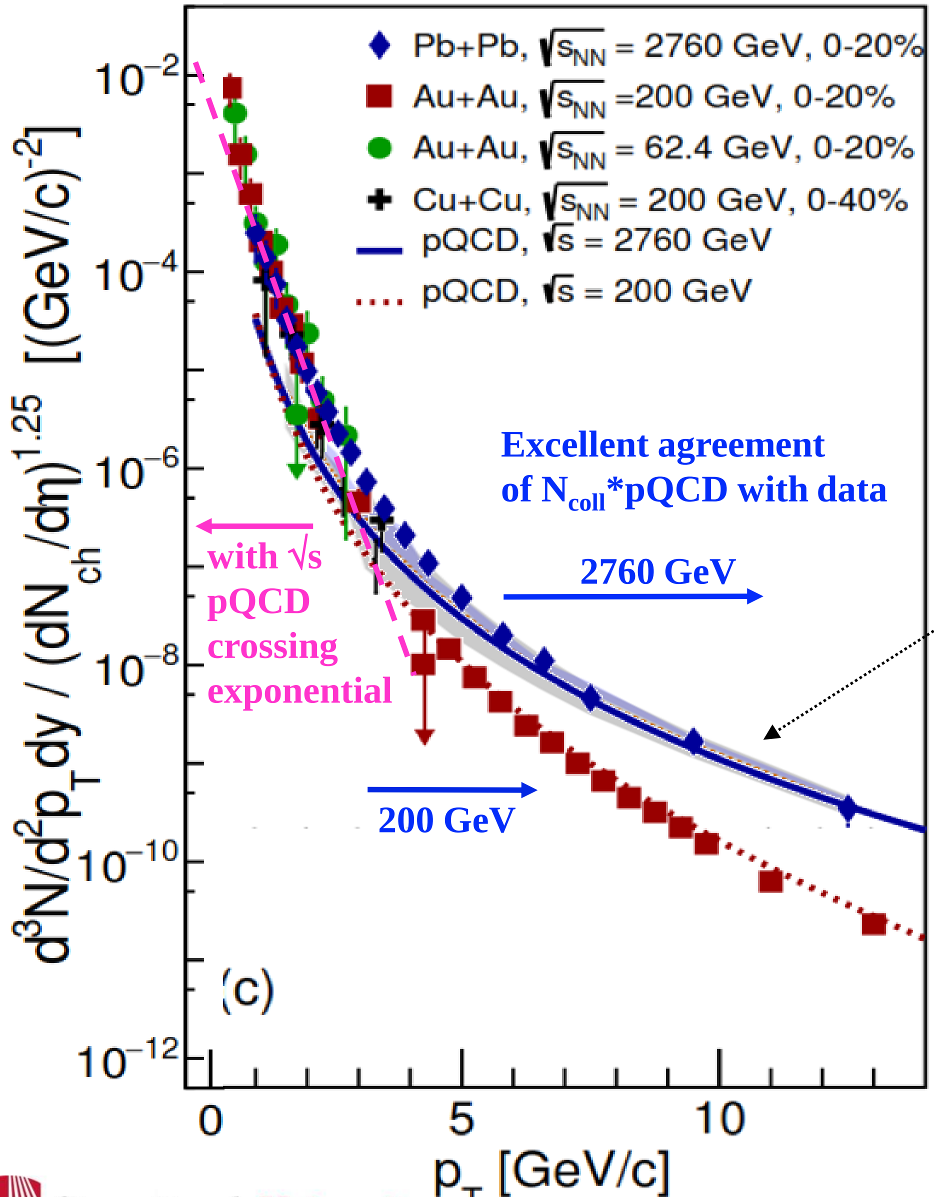
PHENIX: arXiv:1804.04181



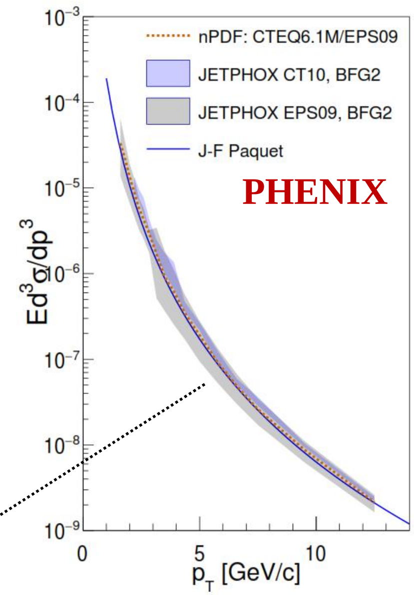
Au+Au at 200 GeV consistent with Ncoll x p+p and Ncoll + pQCD

Pb+Pb same scaling but 30% above Ncoll x pQCD p+p

Comment on p_T > 5 GeV ALICE data



Systematic uncertainty of
pQCD calculation

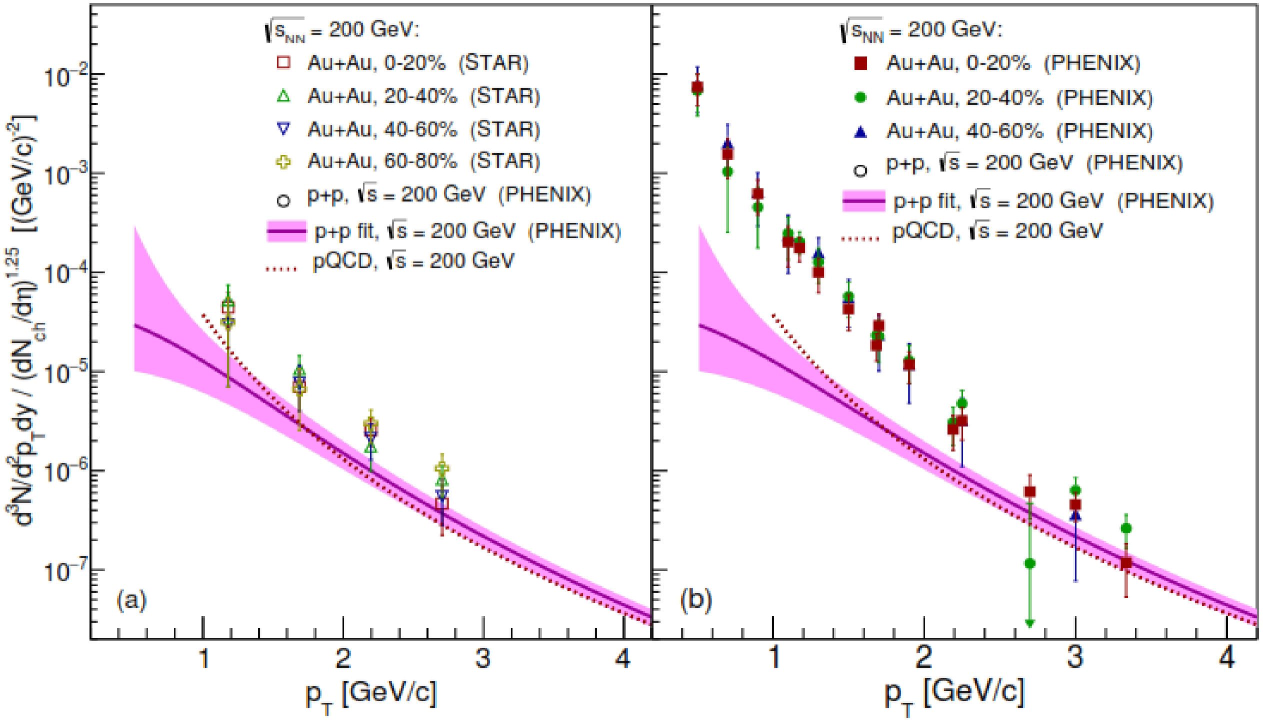


scale uncertainties
PDF uncertainties

- Comparison Data to N_{coll} * pQCD
  - Agreement moves higher p_T with increasing √s
  - Exponential + pQCD would move to lower p_T with increasing √s
  - Significant if scale uncertainties dominate pQCD uncertainties

PHENIX – STAR Direct Photon Comparison

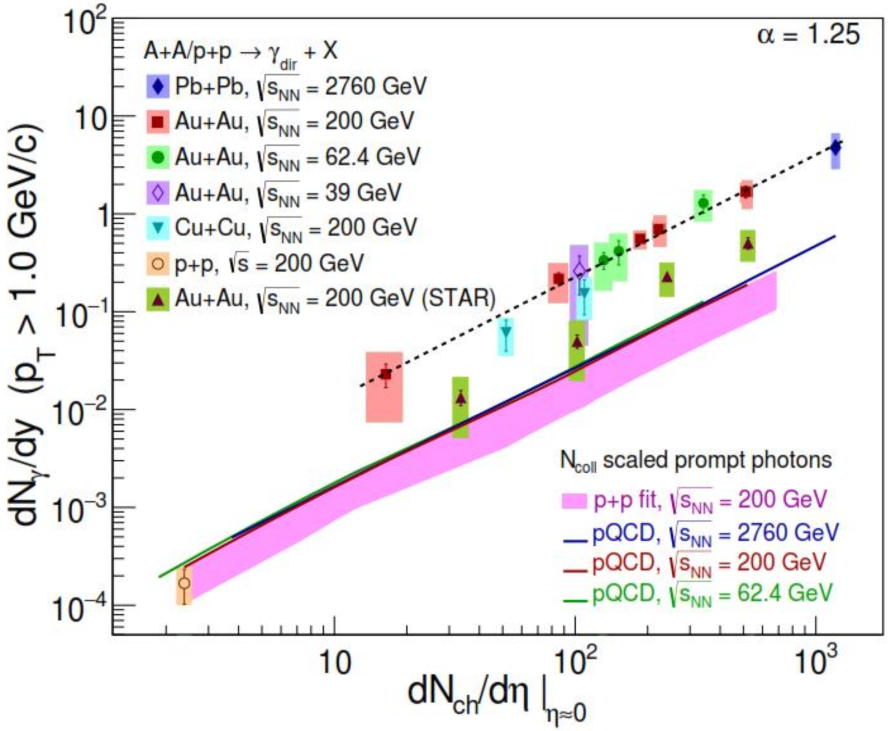
PHENIX $\gamma \rightarrow e^+e^-$: Phys. Rev. C91 (2015) 064904
STAR: Phys. Lett. B770 (2017) 451 *γ^*: Phys. Rev. Lett. 104 (2010) 132301*

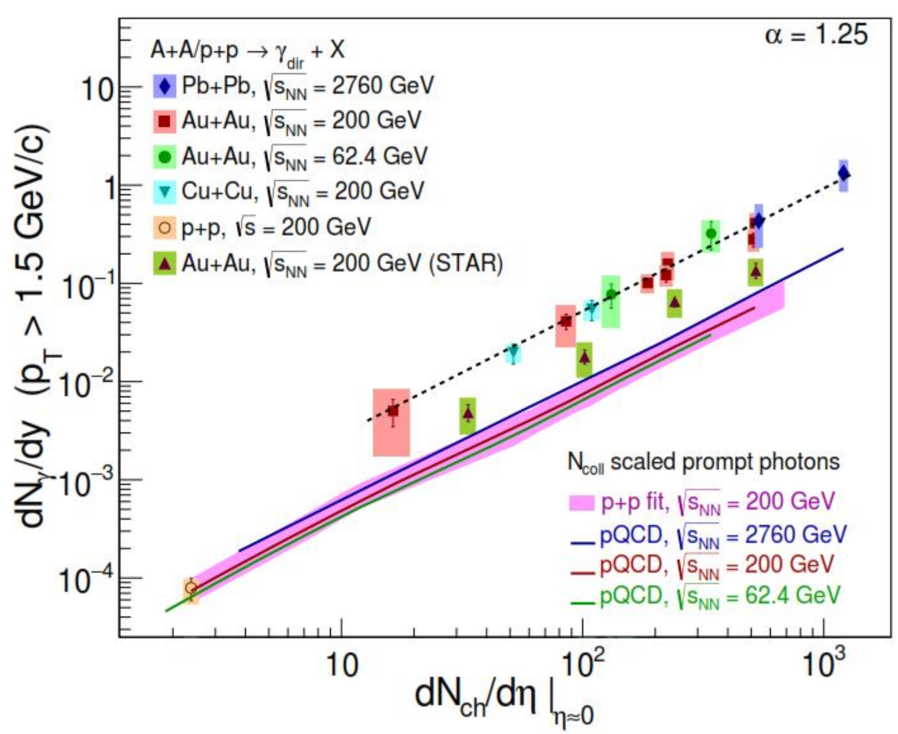


- **PHENIX data consistent between independent analyses**
- **STAR data significantly lower than PHENIX data**
  - **STAR assume a <u>smaller</u> η yield than PHENIX**
  - **Using PHENIX η yield will reduce STAR direct photon yield further**
- **Discrepancy not (yet) resolved**

Direct Photon Centrality Dependence

- **Comparison STAR – PHENIX - ALICE**





Survey of System Size Dependence of Direct Radiation

- **Direct Photon Data**
  - PHENIX
  - ALICE

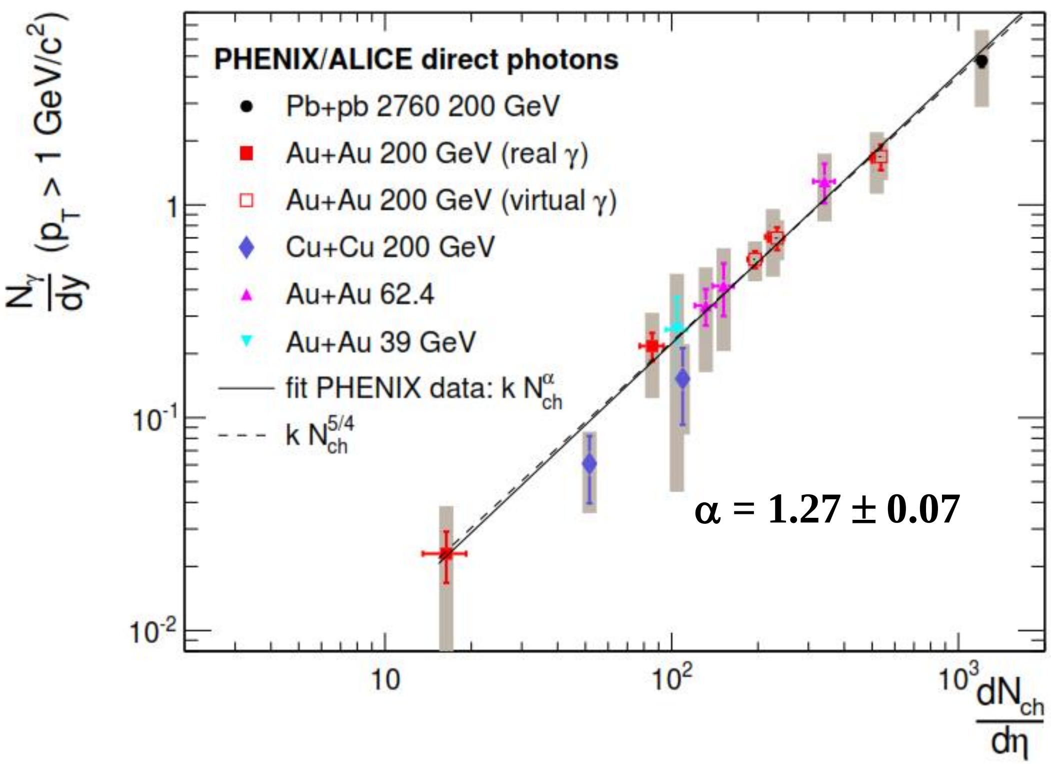
$$\frac{dN_\gamma}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha}$$

- **Dilepton Enhancement**
  - STAR
  - CERES
  - NA38/NA50
  - NA60

Direct photons follow

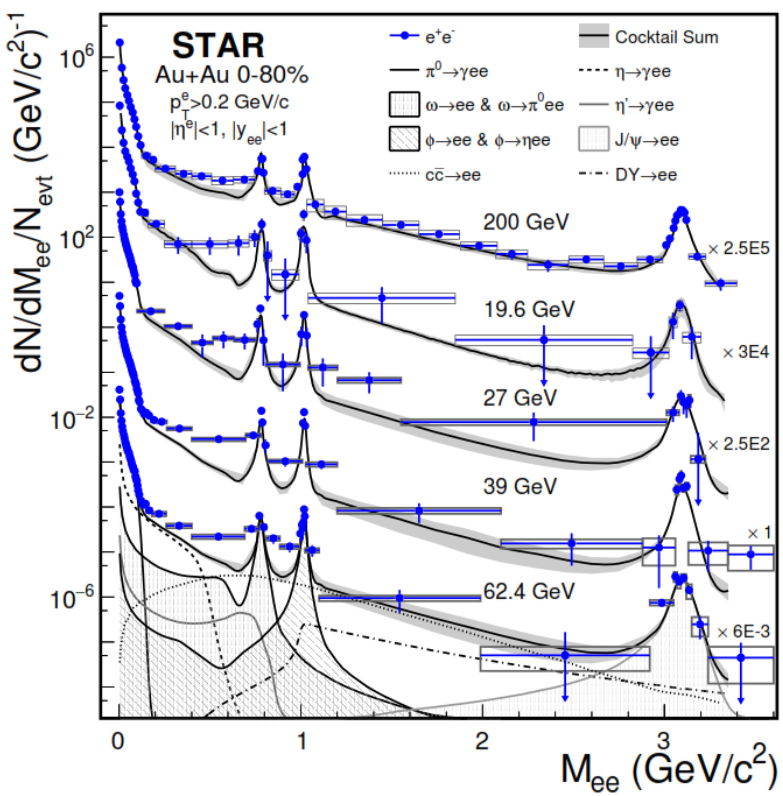
$$\frac{dN_\gamma}{dy} \sim k\left(\frac{dN_{ch}}{d\eta}\right)^{5/4}$$

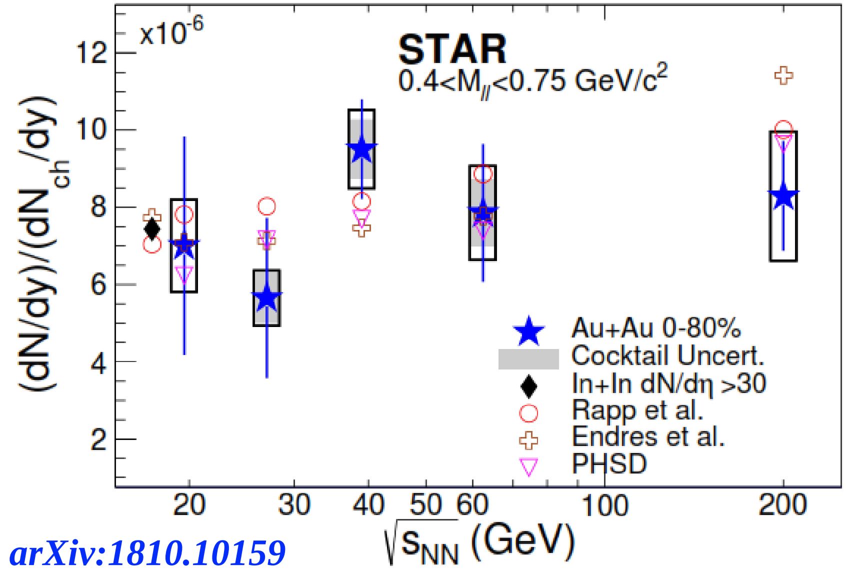
scaling with √s and centrality



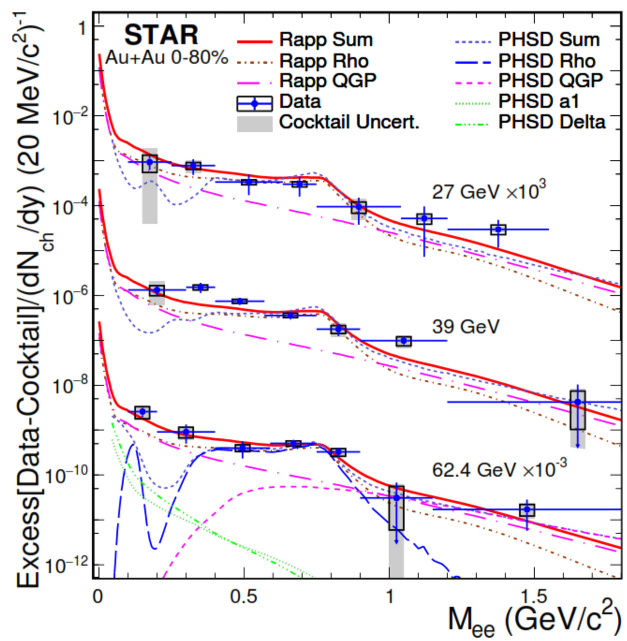
STAR Dileptons

- **Dileptons form beam energy scan**
  - Au+Au collisions
  - √s = 19.6, 27, 39, 62.4 and 200 GeV
  - Fully corrected dilepton excess
  - √s dependence as Excess/$\frac{dN_{ch}}{d\eta}$



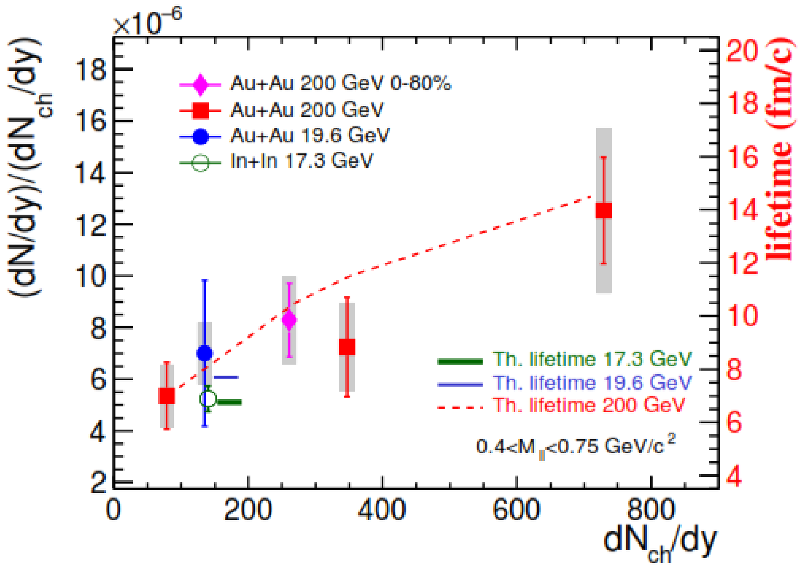


STAR: arXiv:1810.10159



STAR Dileptons

STAR: Phys.Lett. B750 (2015) 64-71



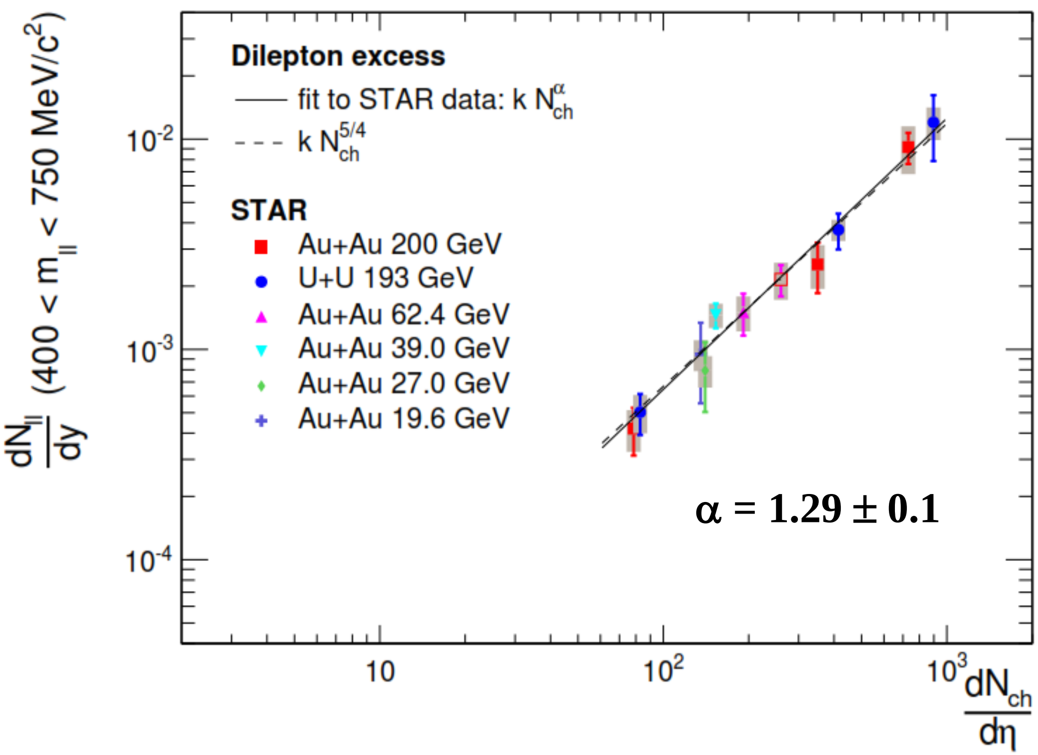
STAR dileptons follow

$$\frac{dN_{ll}}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{5/4}$$

scaling with √s and centrality

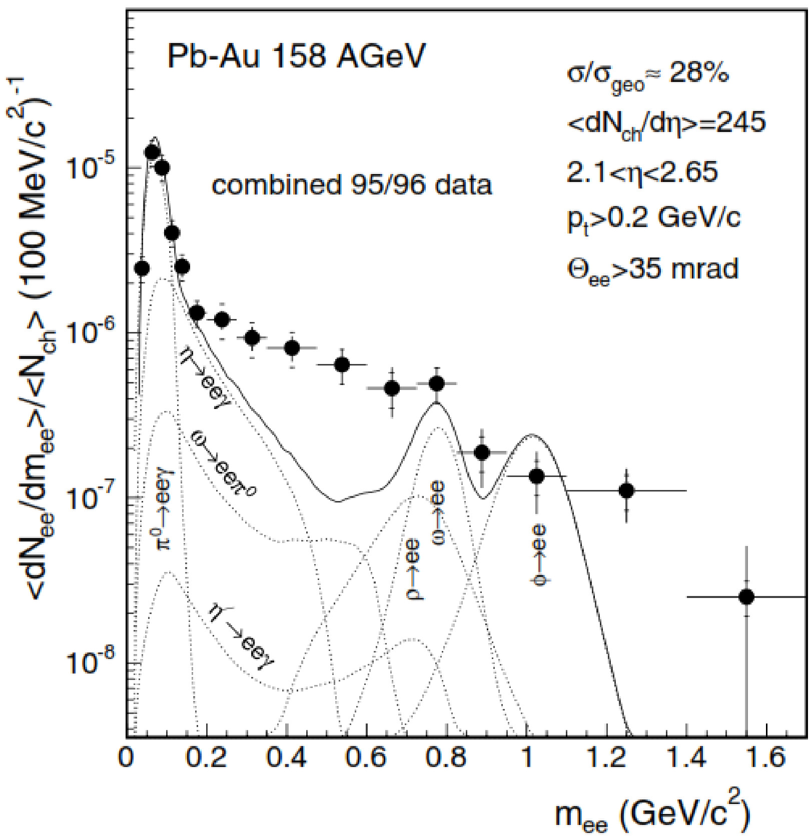
- **Dileptons centrality dependence**
  - **Au+Au at 200 GeV**
  - **U+U at 193 GeV**

$$\frac{dN_{ll}}{dy} = \left[\left(\frac{dN_{ll}}{dy}\right)\Big/\left(\frac{N_{ch}}{d\eta}\right)\right] \times \left(\frac{N_{ch}}{d\eta}\right)$$



CERES e^+e^- Pair Enhancement

CERES/NA45 Eur.Phys.J. C41 (2005) 475

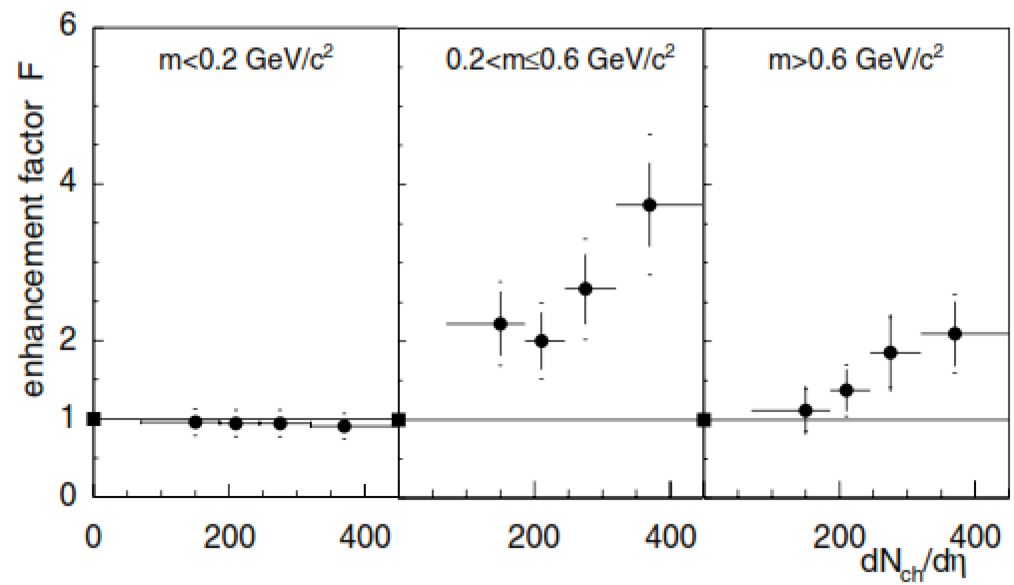


- **Large low mass e^+e^- pair enhancement**
  - **$0.2 < m < 0.6$ GeV/c2:**

$$\sum\left(\frac{dN_{ee}}{dm}\right)^{data} = F\sum\left(\frac{dN_{ee}}{dm}\right)^{cocktail}$$

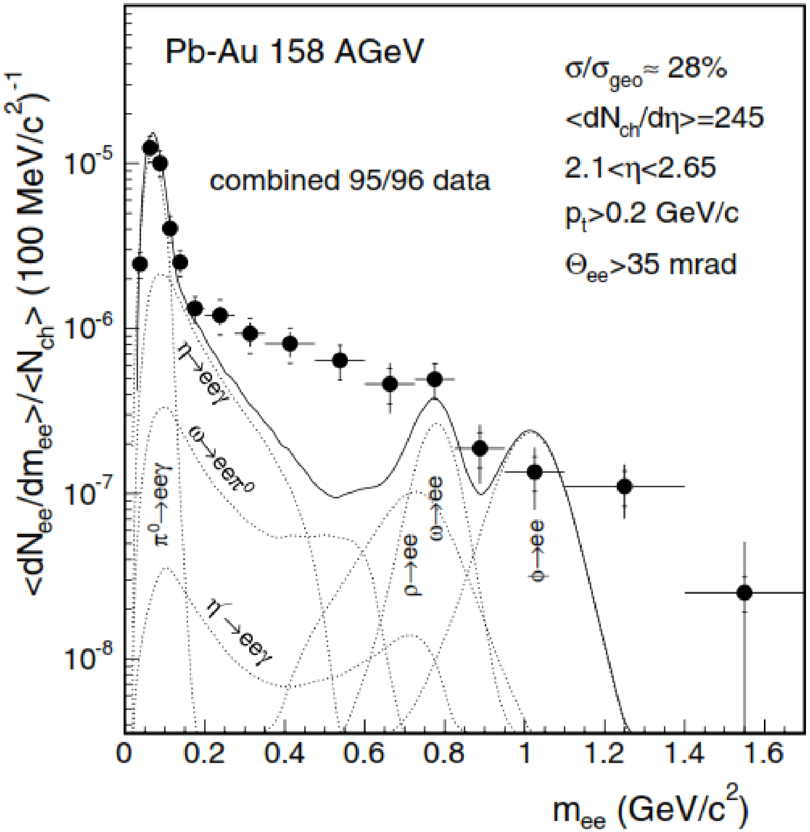
$$F = 2.73 \pm 0.25\,(stat) \pm 1.0\,(sys)$$

  - **F has a significant $\frac{dN_{ch}}{d\eta}$ dependence**



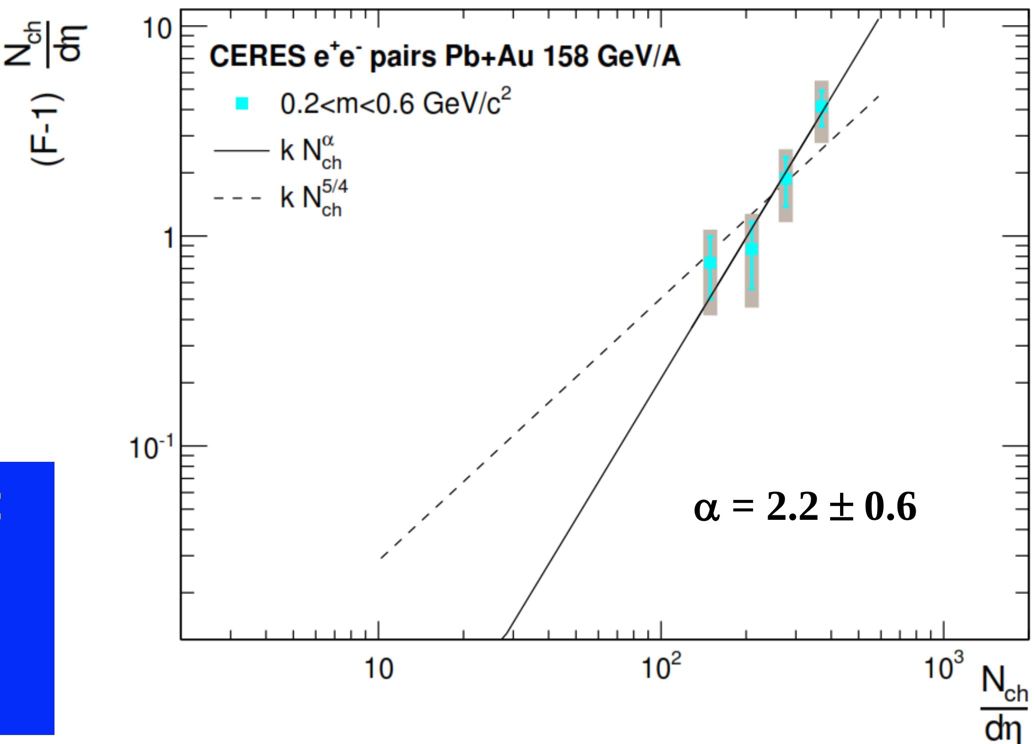
CERES e^+e^- Pair Enhancement

CERES/NA45 Eur.Phys.J. C41 (2005) 475



- **Large low mass e^+e^- pair enhancement**
  - **$0.2 < m < 0.6$ GeV/c2**
  - **Convert $F\left(\frac{dN_{ch}}{d\eta}\right)$ to excess yield**

$$N_{ee}^{excess} = (F-1)\frac{N_{ee}^{cocktail}}{\langle N_{ch}\rangle} \propto (F-1)\frac{dN_{ch}}{d\eta}$$



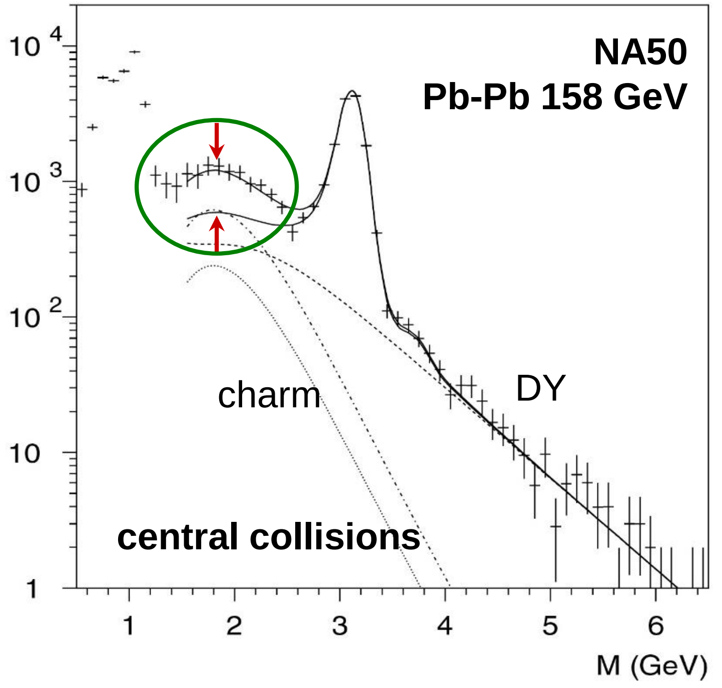
CERES dileptons consistent

$$\frac{dN_{ll}}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha}$$

with $\alpha > 5/4$

NA35/NA50 Dimuon Enhancement

NA38/NA50 Eur.Phys.J. C14 (2000) 443

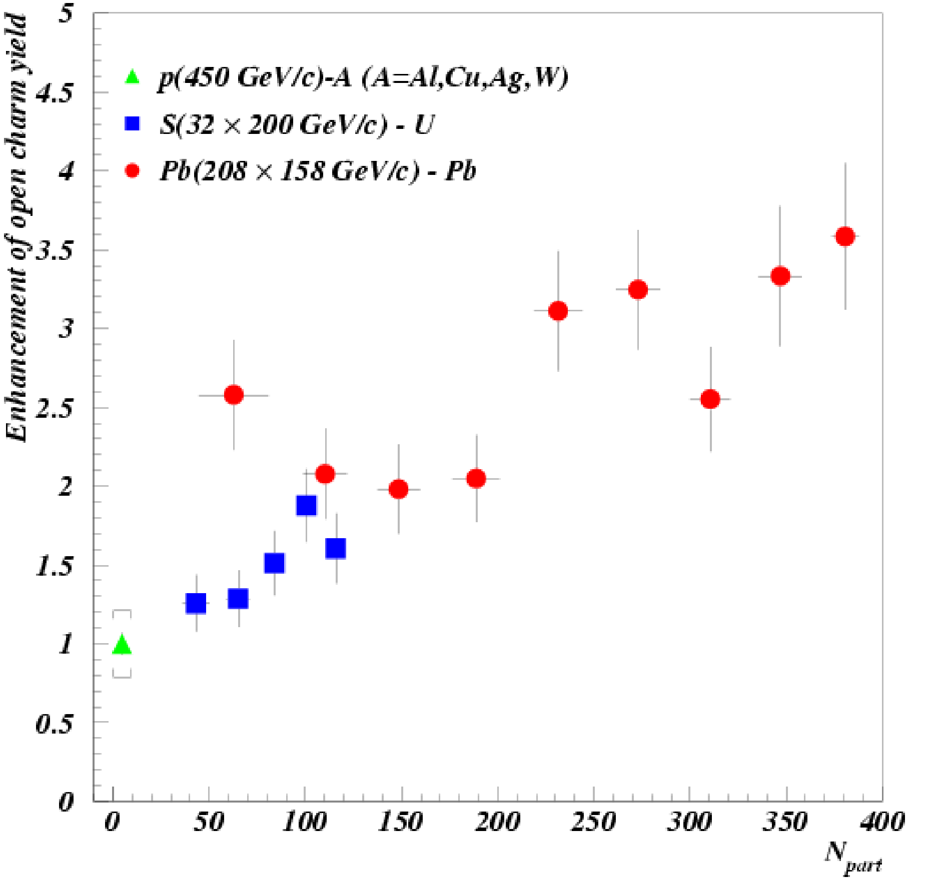


E : Enhancement of open charm

$$N_{\mu\mu} = N_{DY} + E\, N_{DD}^{exp.}$$

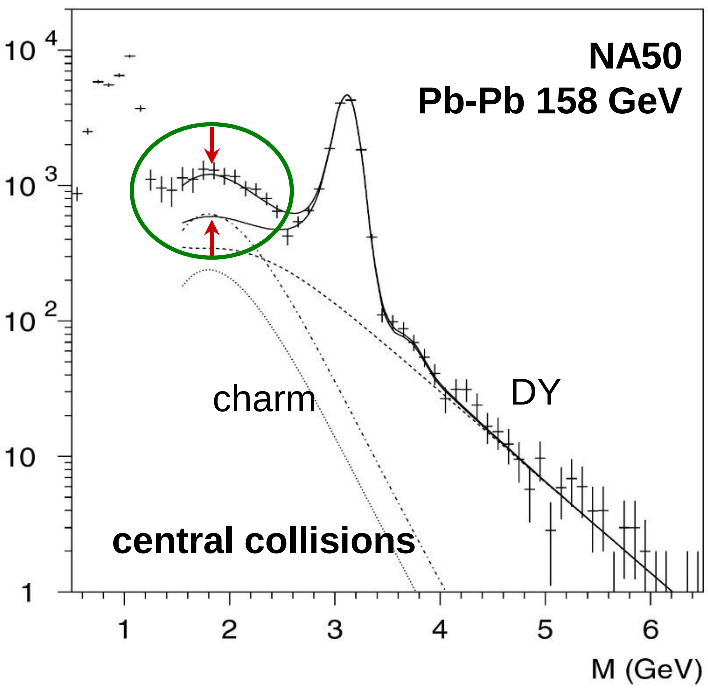
$$N_{\mu\mu} = \left(N_{DY}^{pp} + E\, N_{DD}^{pp}\right) N_{coll}$$

- **Intermediate mass dimuon enhancement**
  - **Discovered by NA38/NA50**
  - **Originally interpreted as charm enhancement**
  - **Established as thermal dimuons from QGP by NA60 using vertex detectors**



NA35/NA50 Dimuon Enhancement

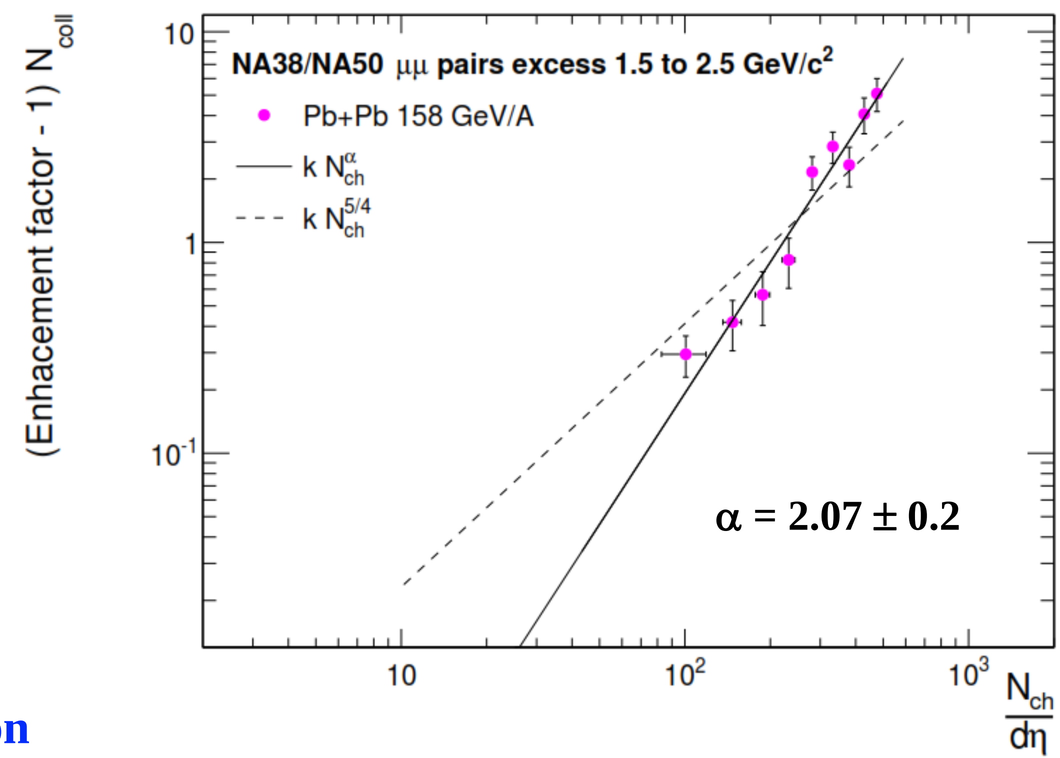
NA38/NA50 Eur.Phys.J. C14 (2000) 443



- **Intermediate mass dimuon enhancement**
  - **Assume: Enhancement – 1 ~ Direct Yield**

$$N_{thermal} = (E-1)\ N_{DD}^{pp}\ N_{coll}$$

  - **Assume ε×A independent of source**



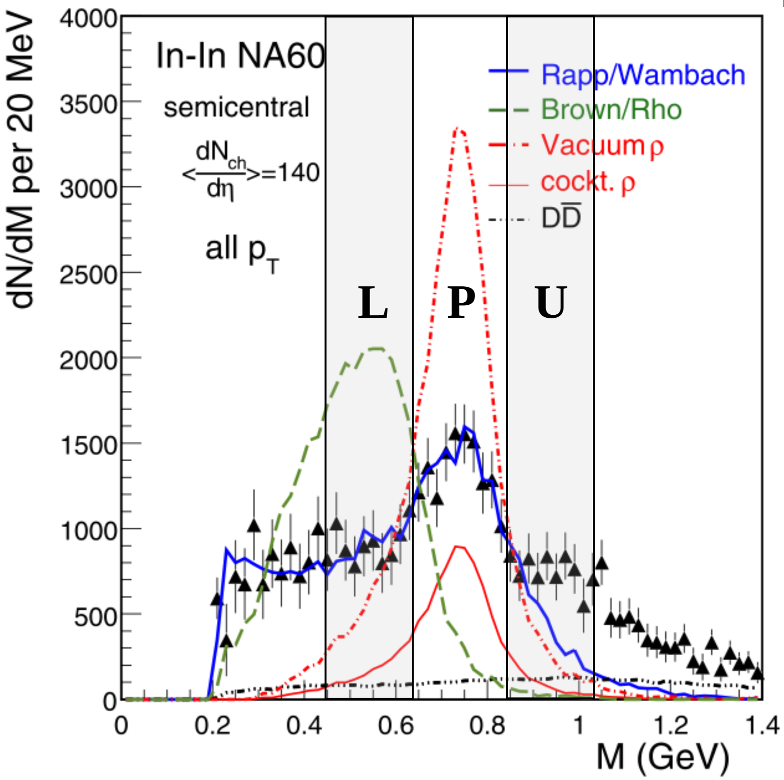
- **Reverse engineer $\frac{dN_{ch}}{d\eta}$**
  - ***NA50: PLB 530 (2002) 43:***

$$\frac{dN_{ch}}{d\eta} \sim 1.23\ N_{part}$$

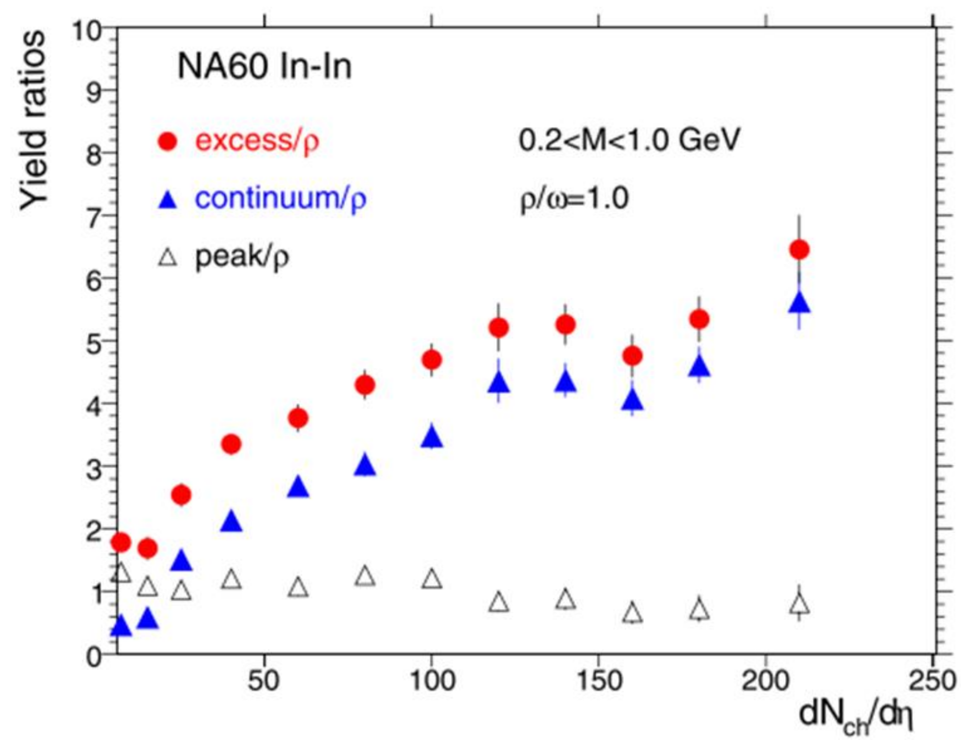
  - **Small non linear correction**

NA60 Excess Dimuons

NA60: Eur.Phys.J. C61 (2009) 711

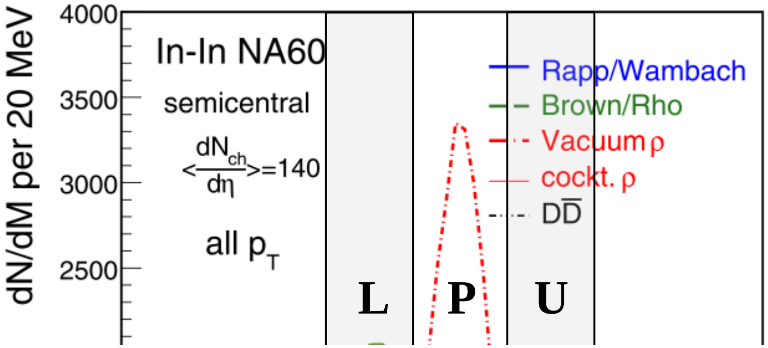


- **Dimuon excess – uncorrected for acceptance**
  - **Isolate ρ-peak and continuum region using side bands**
  - **Normalize to expected ρ yield (∝ $dN_{ch}/d\eta$)**



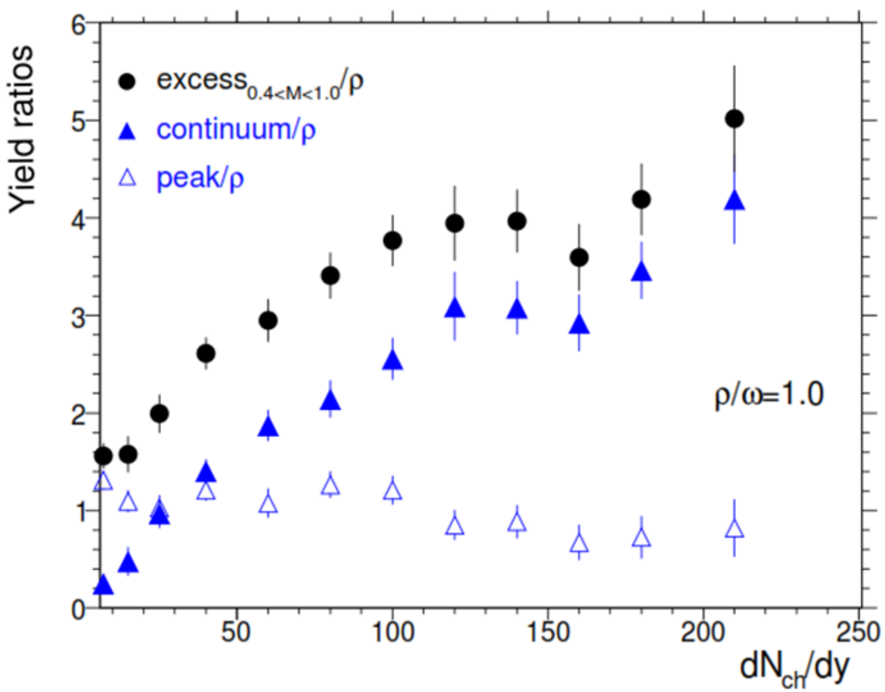
NA60 Excess Dimuons

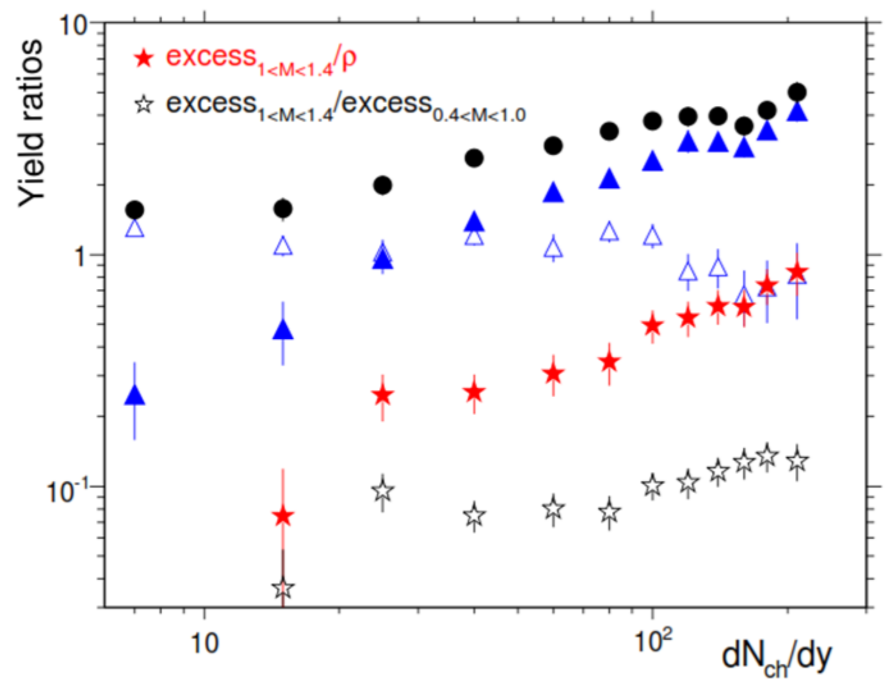
NA60: Eur.Phys.J. C61 (2009) 711



- **Dimuon excess – uncorrected for acceptance**
  - **Isolate ρ-peak and continuum region using side bands**
  - **Normalize to expected ρ yield (∝ $dN_{ch}/d\eta$)**

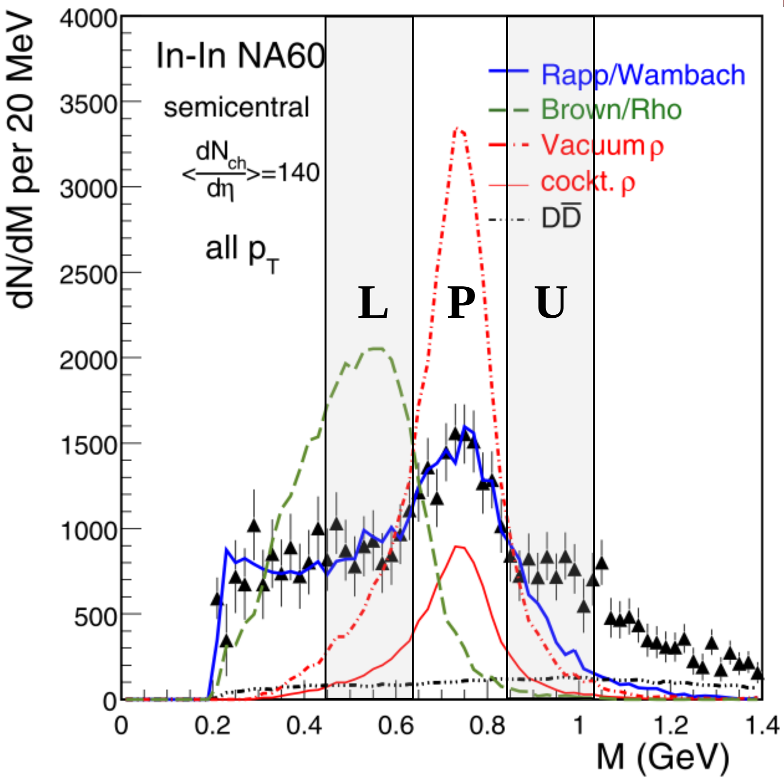
NA60 (QM2008): J.Phys. G35 (2008) 104036





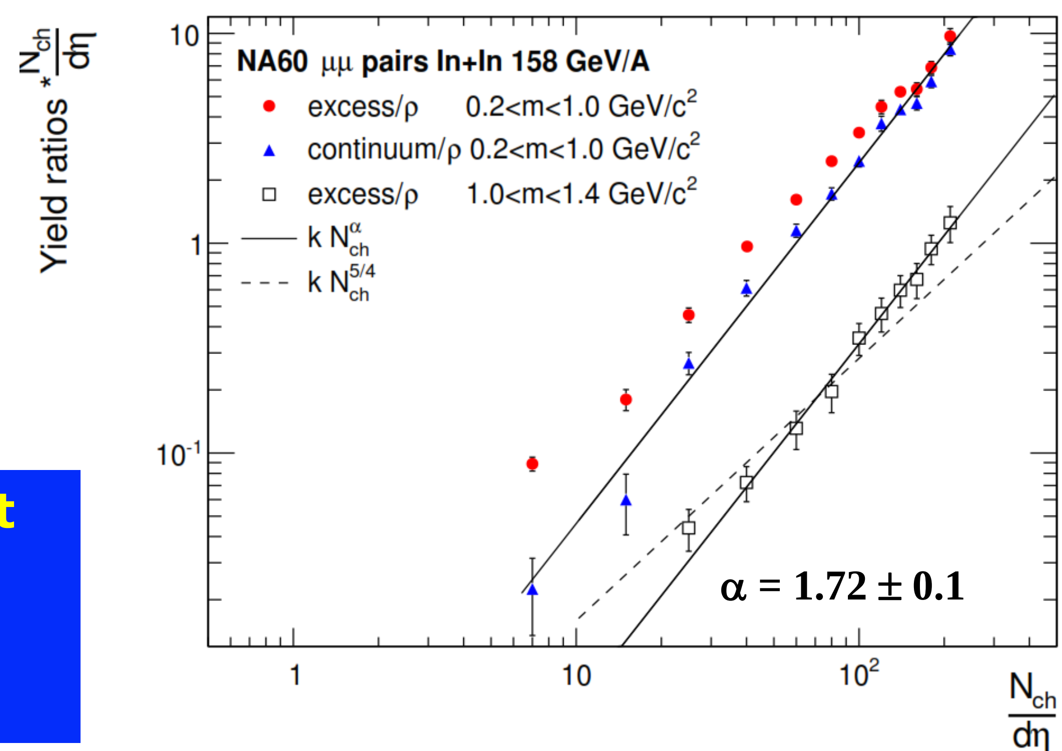
NA60 Excess Dimuons

NA60: Eur.Phys. J. C 61 (2009) 711



- **Dimuon excess – uncorrected for acceptance**
  - **Isolate ρ-peak and continuum region using side bands**
  - **Normalize to expected ρ yield (∝ $dN_{ch}/d\eta$)**

$$N_{thermal} = \frac{excess}{\rho}\frac{dN_{ch}}{d\eta}$$



NA60 dileptons consistent

$$\frac{dN_{ll}}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha}$$

with α > 5/4

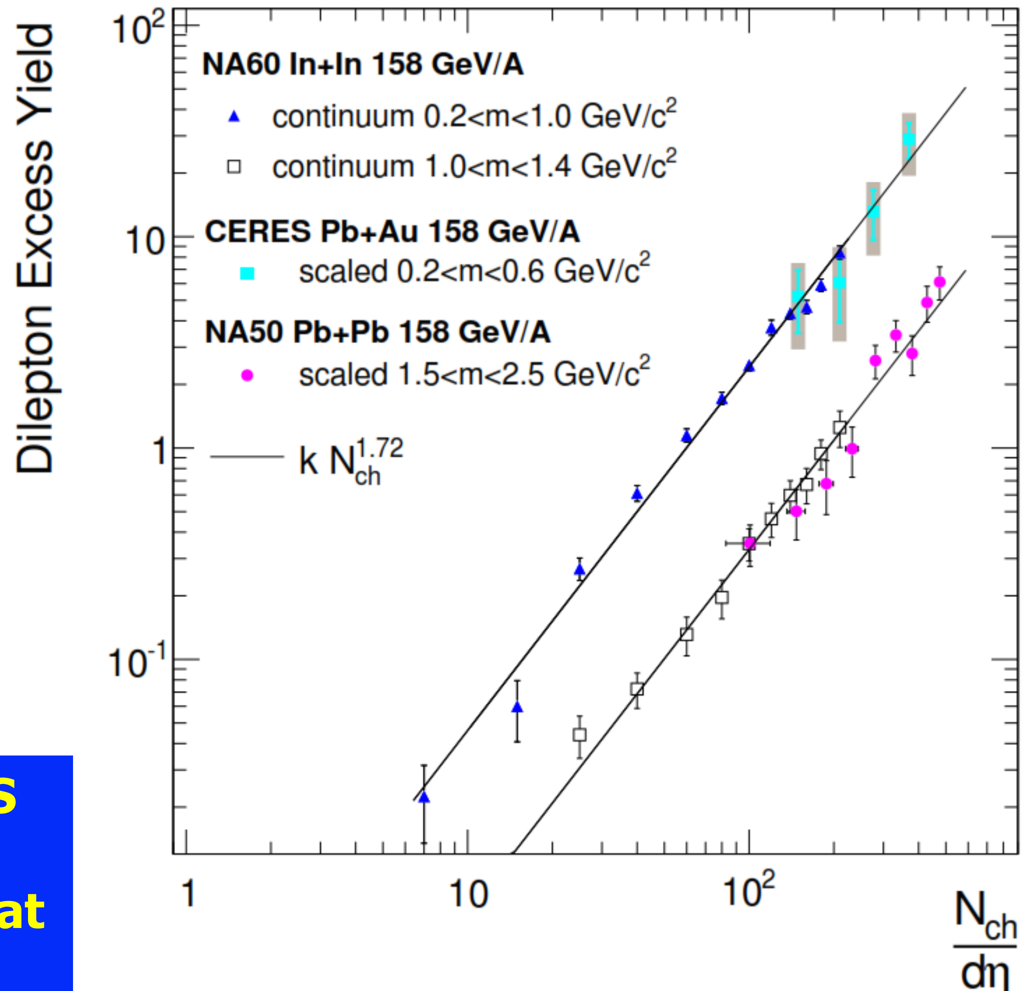
Compilation of SPS Results

- **Dilepton Continuum Excess at SPS**
  - **NA60, NA50, CERES data give consistent picture**
  - **Common Centrality Dependence above and below ρ meson**

$$\frac{dN_{ll}}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha}$$

$$\alpha \sim 1.72$$

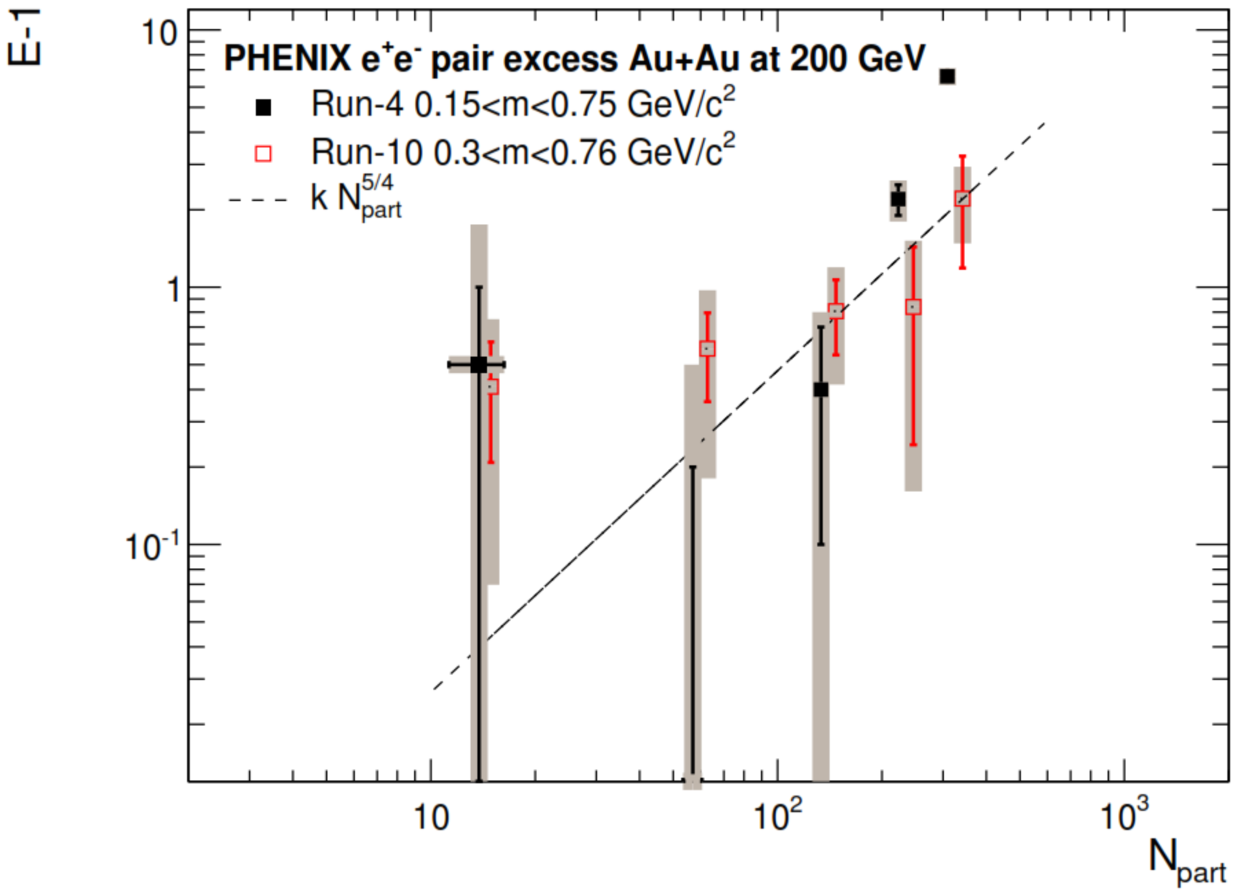
  - **Possible substructure**



Centrality dependence at SPS similar but different from √s and centrality dependence at higher energies

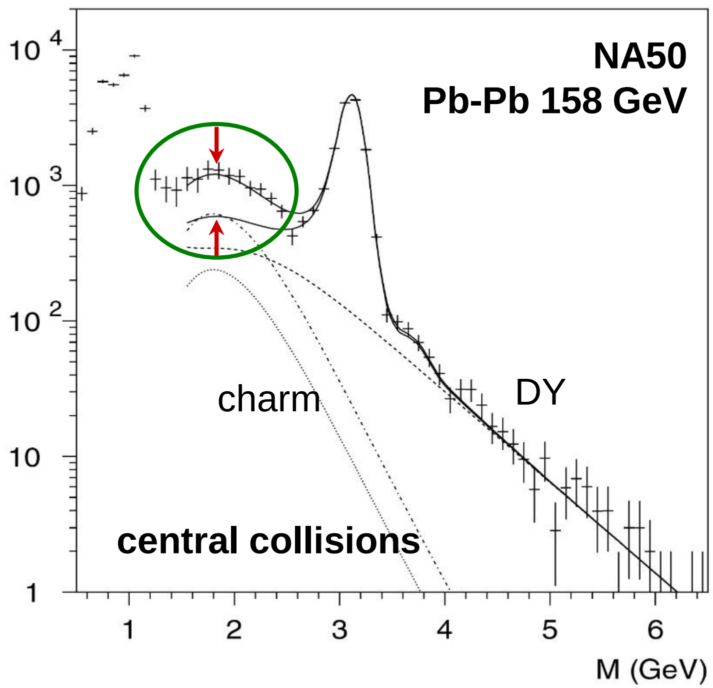
Backup

PHENIX Dileptons



NA35/NA50 Dimuon Enhancement

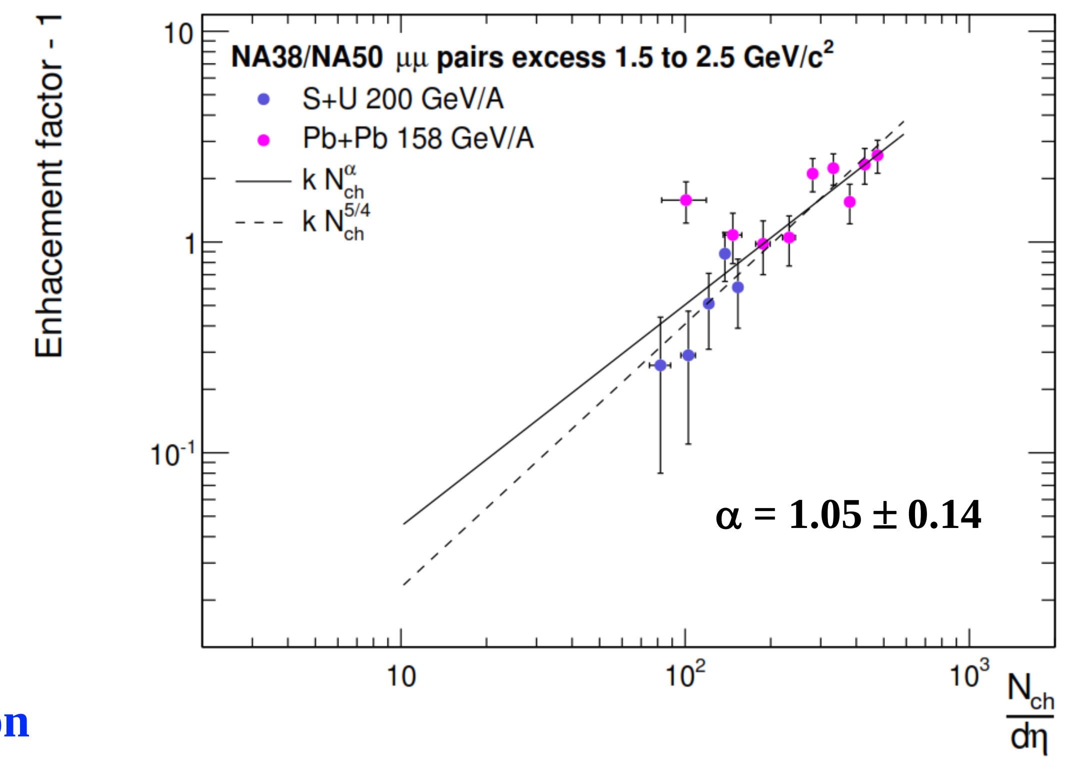
NA38/NA50 Eur.Phys.J. C14 (2000) 443



- **Intermediate mass dimuon enhancement**
  - **Assume: Enhancement – 1 ~ Direct Yield**

$$N_{thermal} = (E-1)\, N_{DD}^{exp.}$$

  - **Not corrected for N_{coll}**
  - **Assume ε×A independent of source**

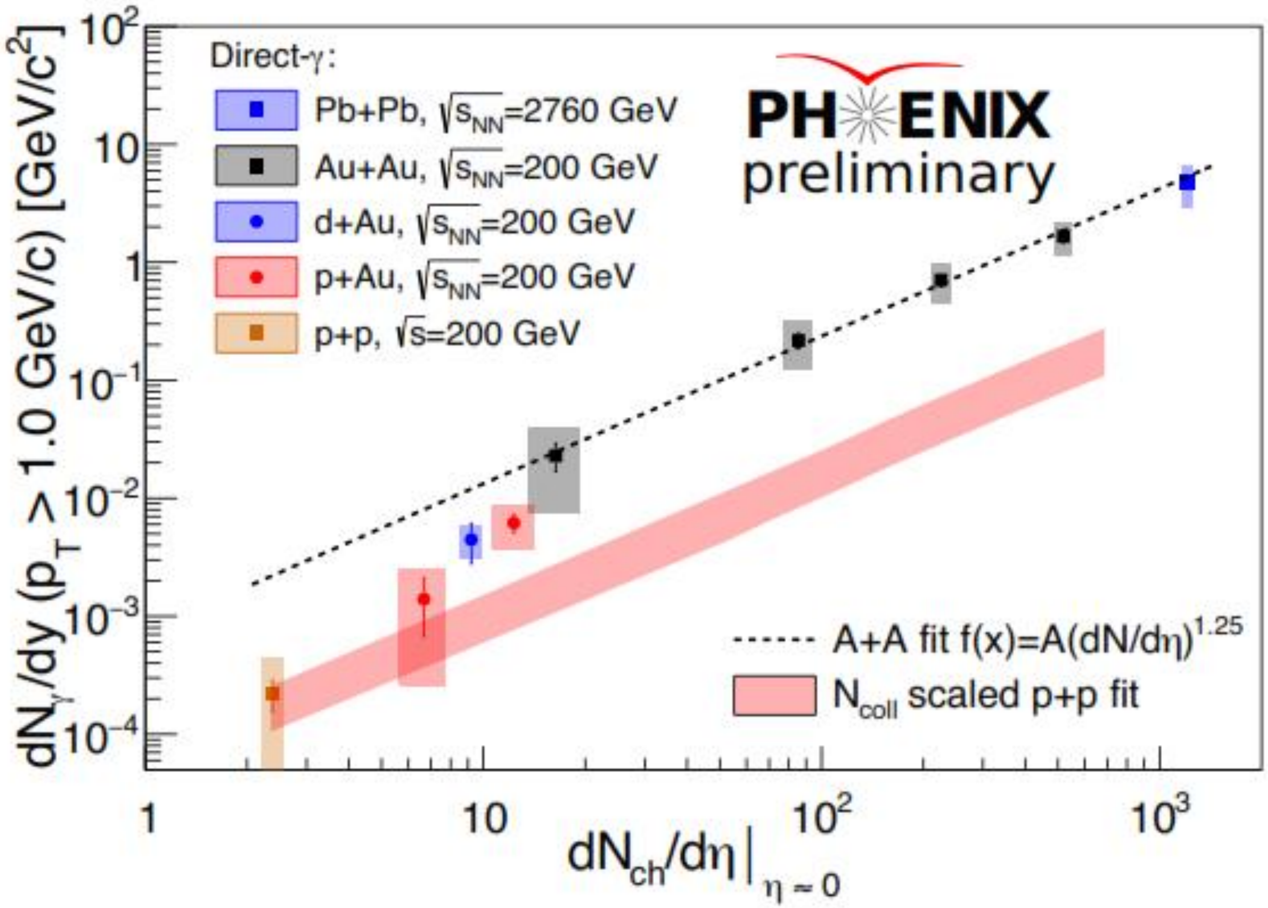


- **Reverse engineer $\frac{dN_{ch}}{d\eta}$**
  - ***NA50: PLB 530 (2002) 43:***

$$\frac{dN_{ch}}{d\eta} \sim 1.23\, N_{part}$$

  - **Small non linear correction**

First Results From p/d-Au Collisions



Onset of thermal radiation at $\frac{dN_{ch}}{d\eta} \sim 10$?

First evidence for threshold of QGP production!