EM-Probes in High-Energy pp and AA Collisions

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Quark Confinement and the Hadron Spectrum 2016, Thessaloniki

Outline

- Introduction
- Prompt Photons
  - Saturation Signal
- Thermal Photons
  - Yield and Anisotropy
- Low-Mass Dileptons
- Conclusions

Electromagnetic Probes

- advantages:
  - elementary production processes well understood
    - reduce systematic uncertainty in interpretation
  - little modification in final state
    - probing early phases
- disadvantages:
  - small signal/large background

The Two Faces of Photons

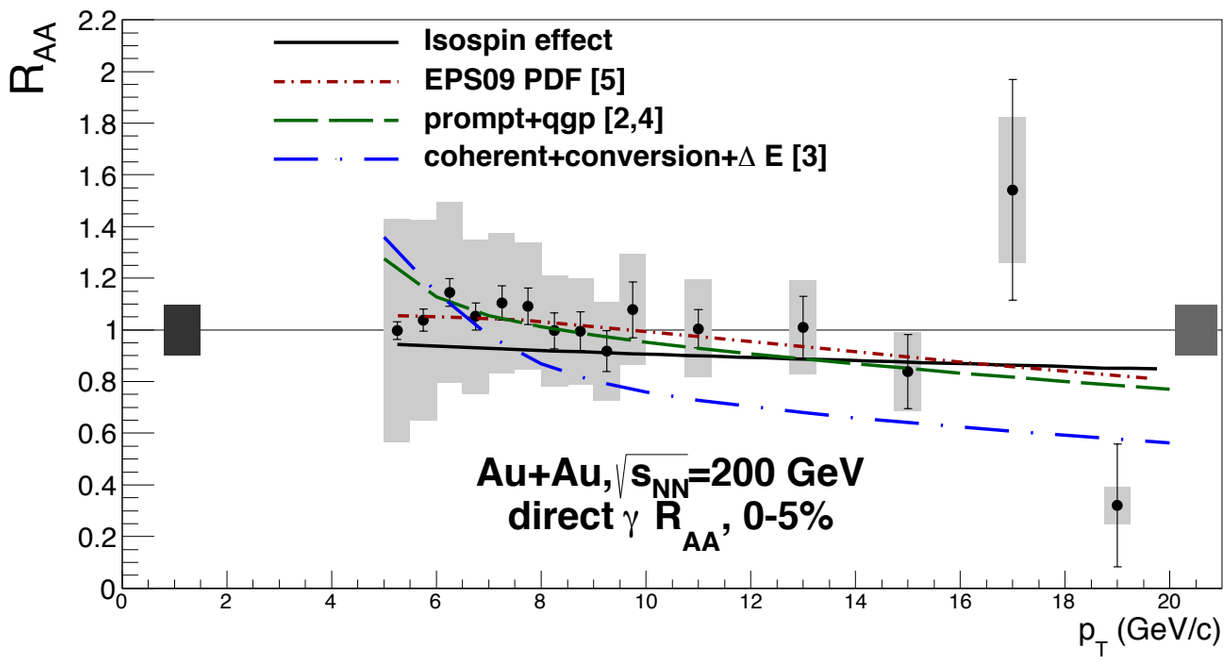
- prompt photons:
  - produced in hard scatterings
    - described by pQCD, dominate at high p_T
  - probing the initial state
    - nPDFs, saturation, …
- thermal photons:
  - thermal QCD (+hadrons)
    - good theoretical understanding, dominate at low p_T
  - em radiation from thermal system (QGP)
    - information on temperature from early phase

      … one of the holy grails of heavy-ion physics

Prompt Photons

Prompt Photons in AA

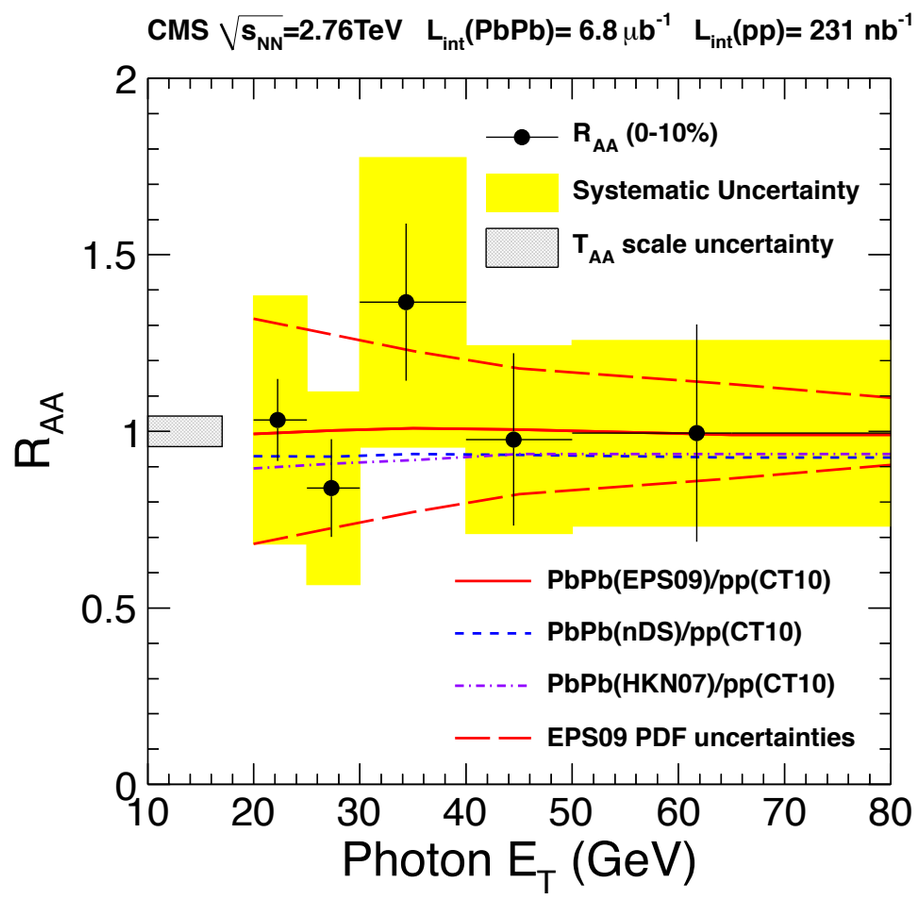
PHENIX, Phys. Rev. Lett.109:152302,2012



$$R_{AA} = \frac{dN/dp_T^2(AA)}{\langle N_{coll}\rangle \cdot dN/dp_T^2(pp)}$$

- compatible with N_{coll} scaling
- no strong nuclear effects expected
  - large p_T implies large Bjorken-x

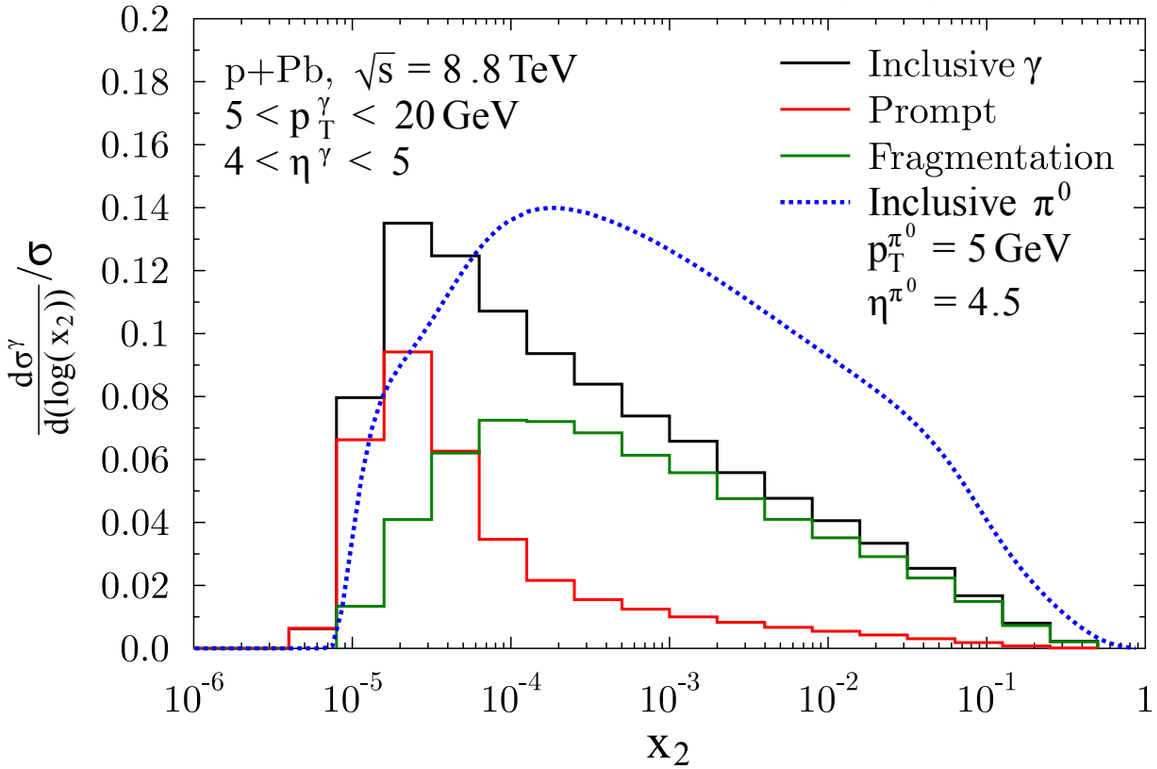
$$x \approx \frac{2p_T}{\sqrt{s}} > 0.01$$

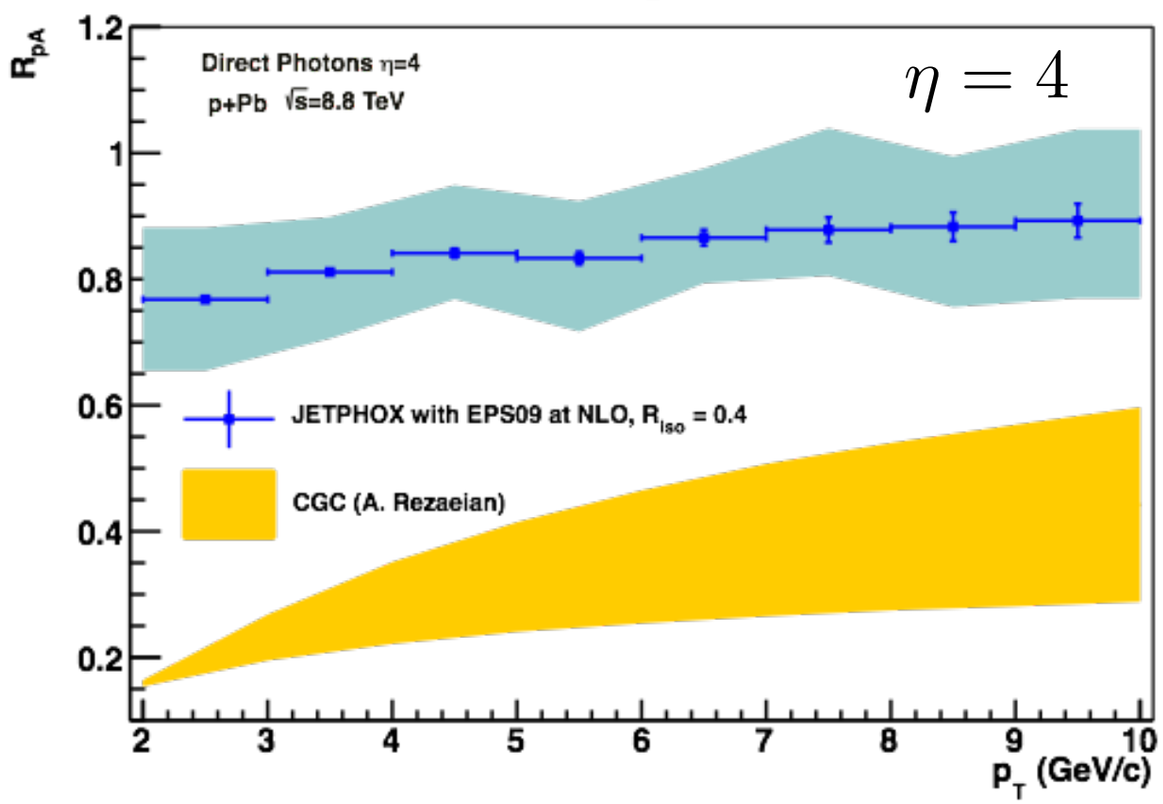


CMS, Physics Letters B, 710 (2012) 256–277

Nuclear Effects in pA at Forward Rapidity

NLO pQCD calculations with shadowing (EPS09)
Helenius, Eskola, Paukkunen, JHEP09 (2014) 138

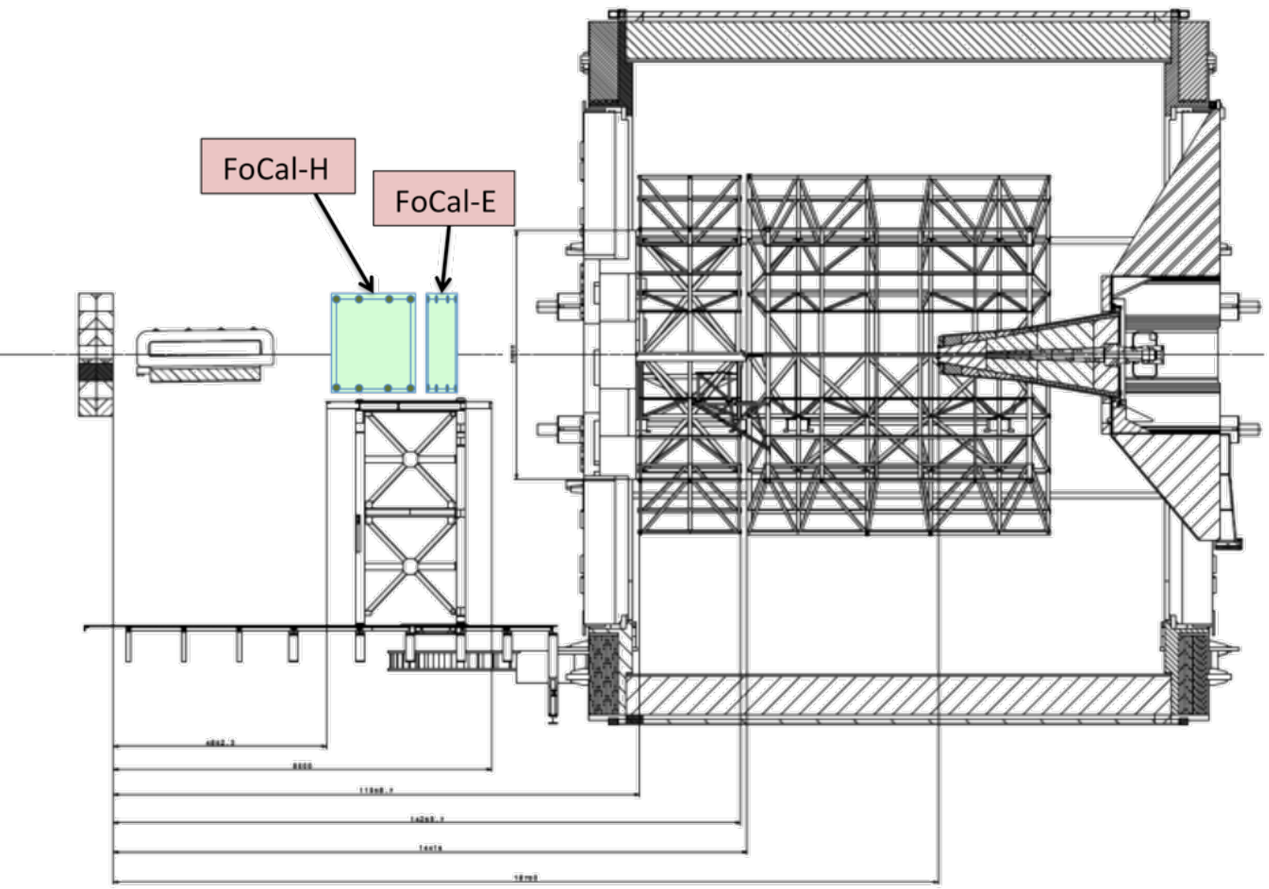




- good low-x sensitivity for direct photons at forward rapidity
- advantage over hadronic probes
  - no final state interaction
  - well-understood production process
  - well-defined kinematics

- signals expected at low-intermediate p_T
- two scenarios:
  - little suppression from EPS09 shadowing
  - strong suppression in direct γ R_{pA} for saturation/CGC
- forward direct photons at LHC as signal for gluon saturation

FoCal Upgrade Proposal in ALICE



electromagnetic calorimeter for γ and π^0 measurement

\+ hadronic calorimeter for isolation and jet measurement

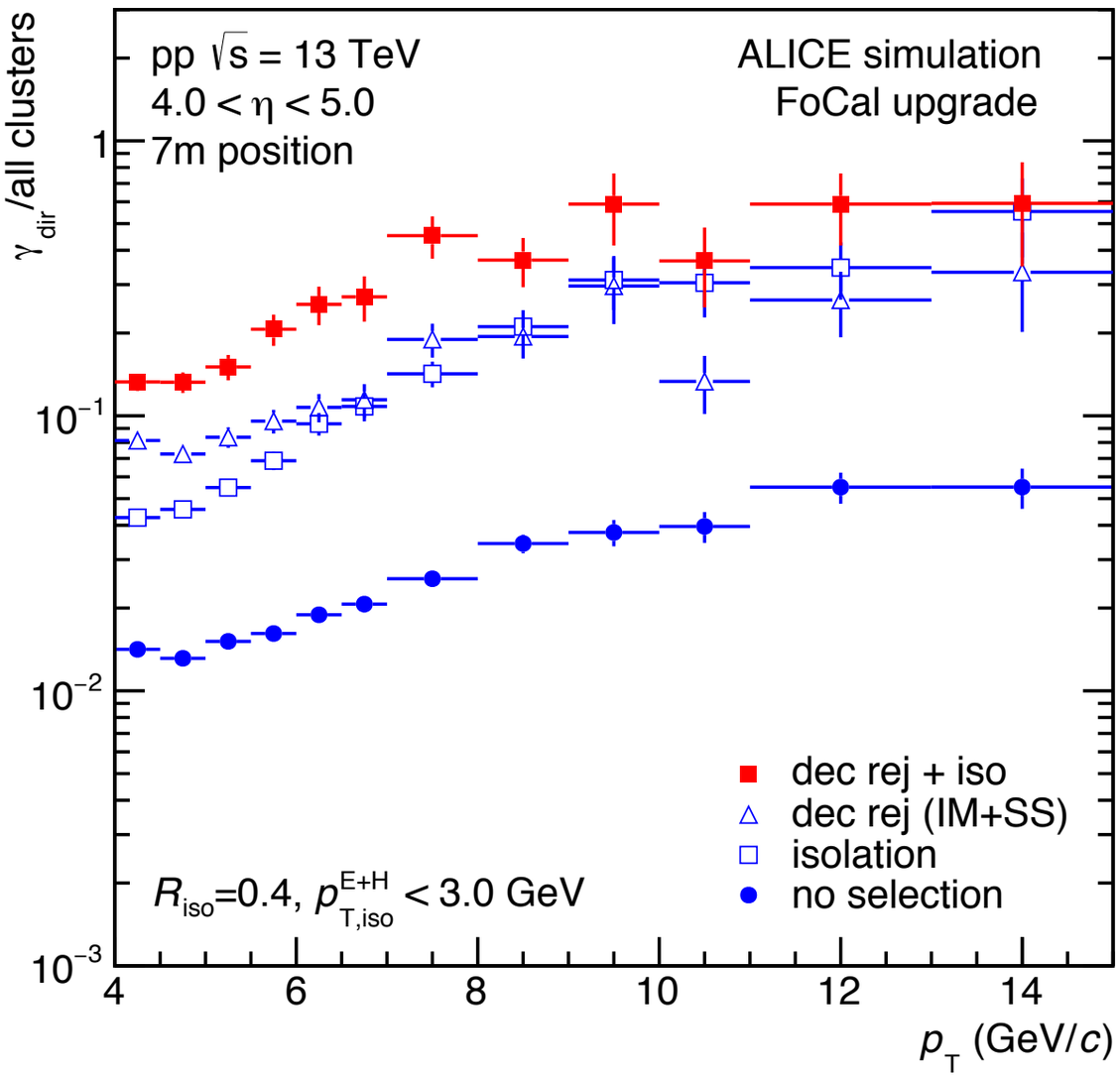
baseline scenario:
at $z \approx 7$m (outside magnet)
$3.3 < \eta < 5.3$

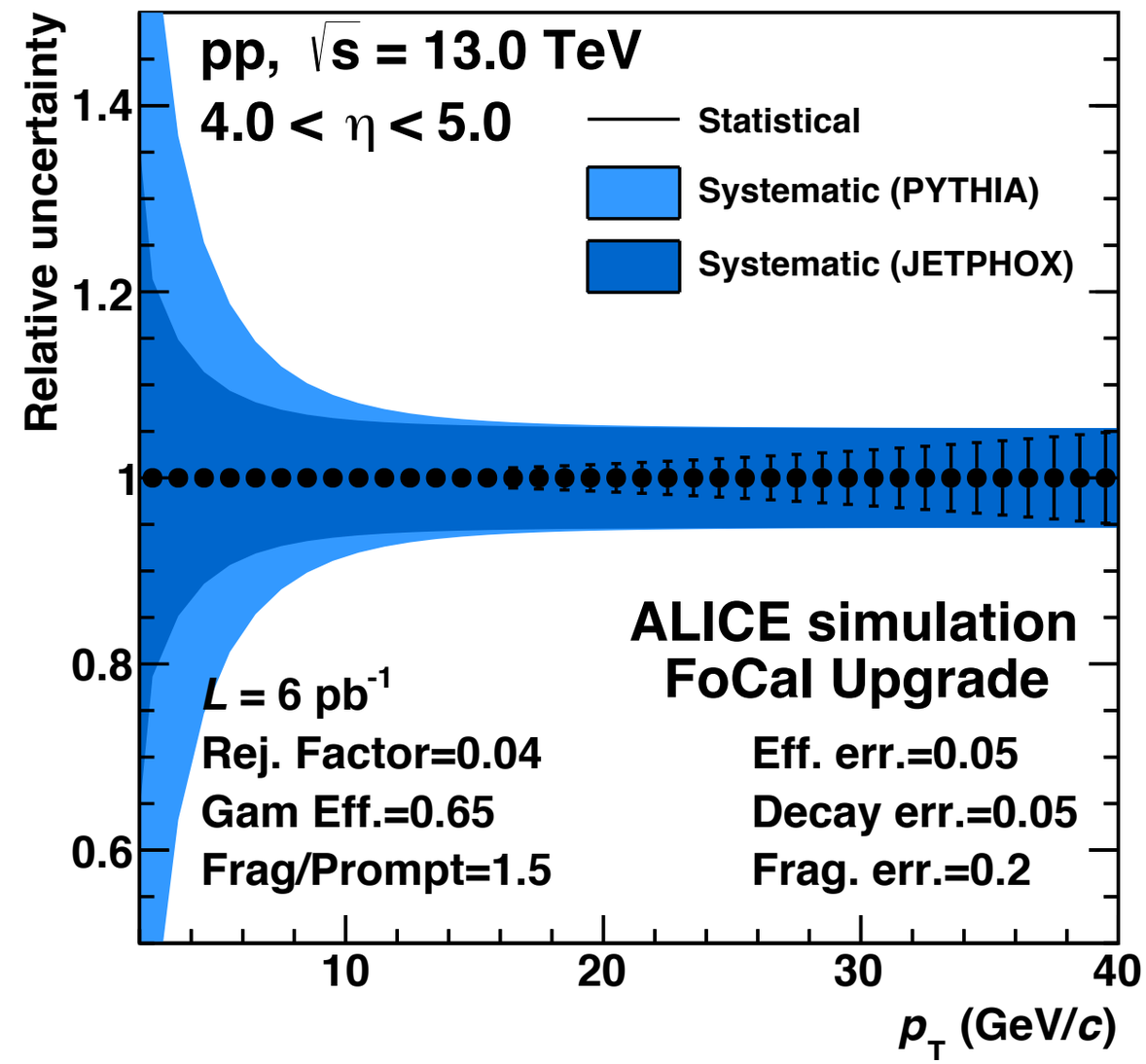
discussed for possible installation in LS3 (≈2024)

- main challenge:
  separate γ/π^0 at high energy
- need small Molière radius, high-granularity read-out
  - Si-W calorimeter, granularity ≈ 1mm^2

- R&D ongoing
- achieved with proof-of-principle prototype:
  - $R_M \approx 11$mm
  - shower position resolution $\sigma_x < 40\mu$m

FoCal Upgrade – Direct γ Performance in pp





after combined rejection:
direct photon/all > 0.1
for p_T > 4 GeV/c

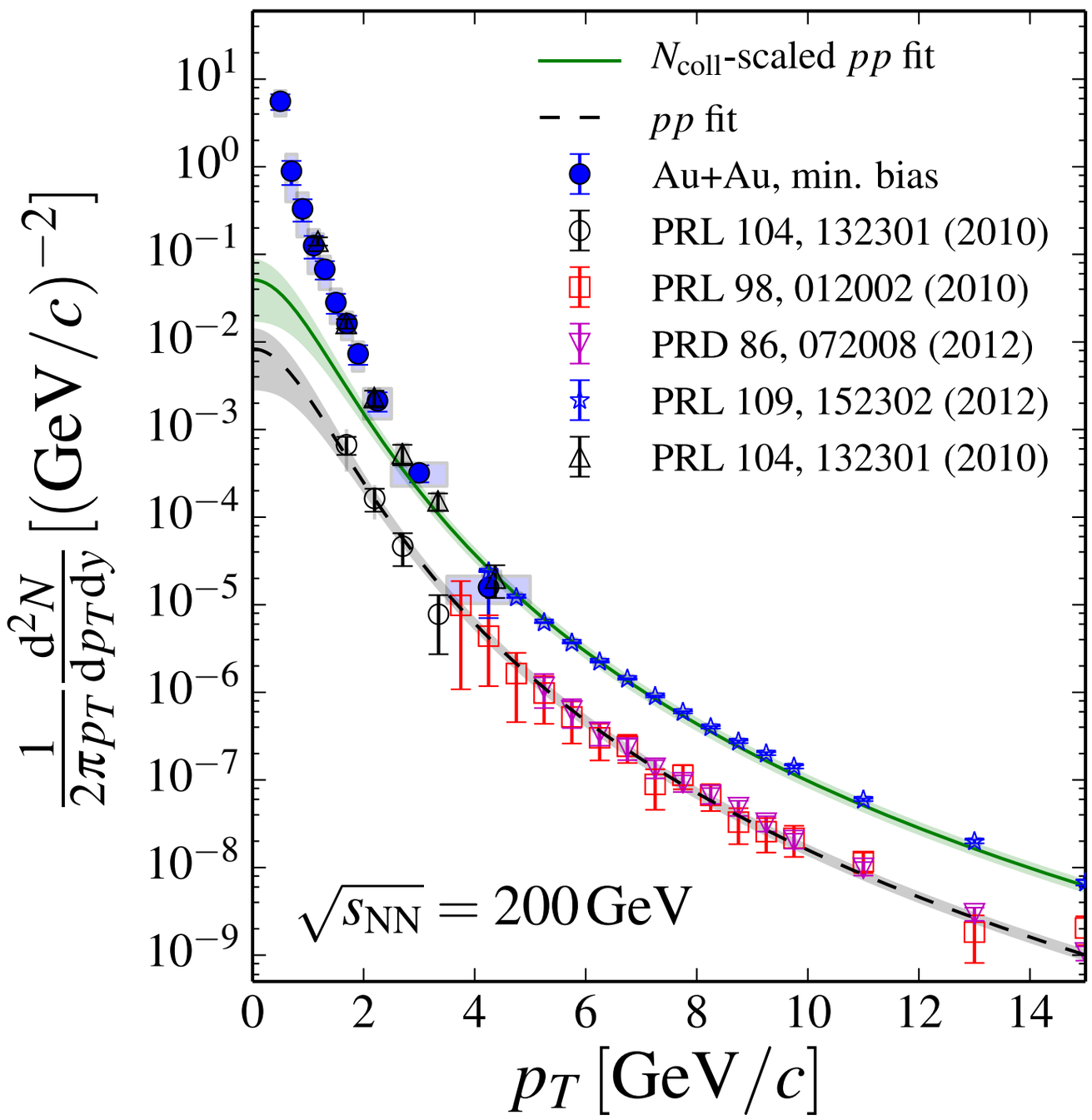
20-40% uncertainty
at p_T = 4 GeV/c
decreases with increasing p_T

Thermal Photons

Direct Photons in Au-Au 200 GeV (PHENIX)

- advanced measurements from PHENIX combining:
  - calorimetry
  - low-mass virtual photons
  - photon conversions
- shape in pp and Au–Au at high pT very similar
  - unmodified pQCD
- excess at low pT beyond extrapolation of pp data
  - thermal photons
  - uncertainty of extrapolation?

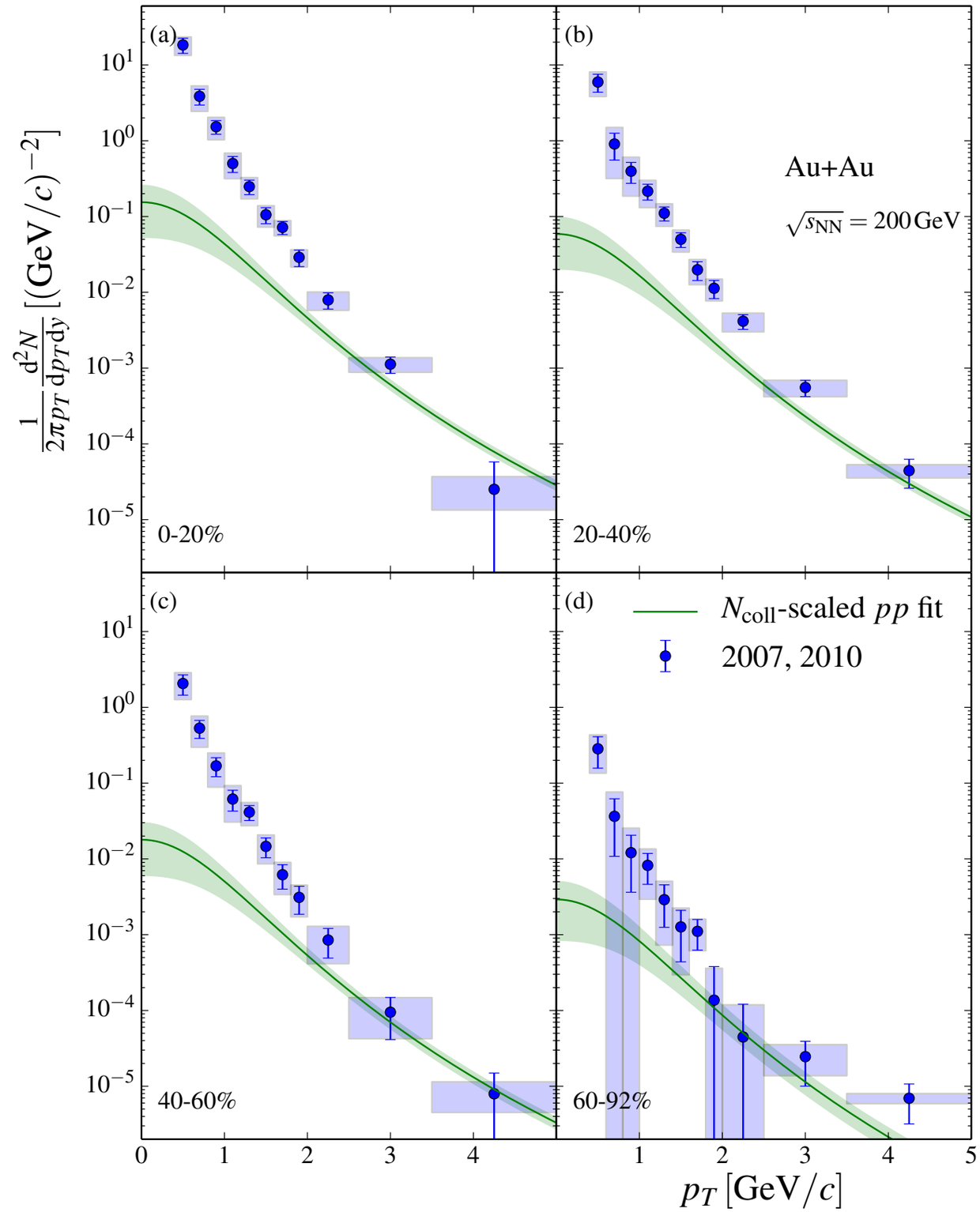
PHENIX, Phys. Rev. C 91(2015) 064904



Direct Photons in Au-Au 200 GeV (PHENIX)

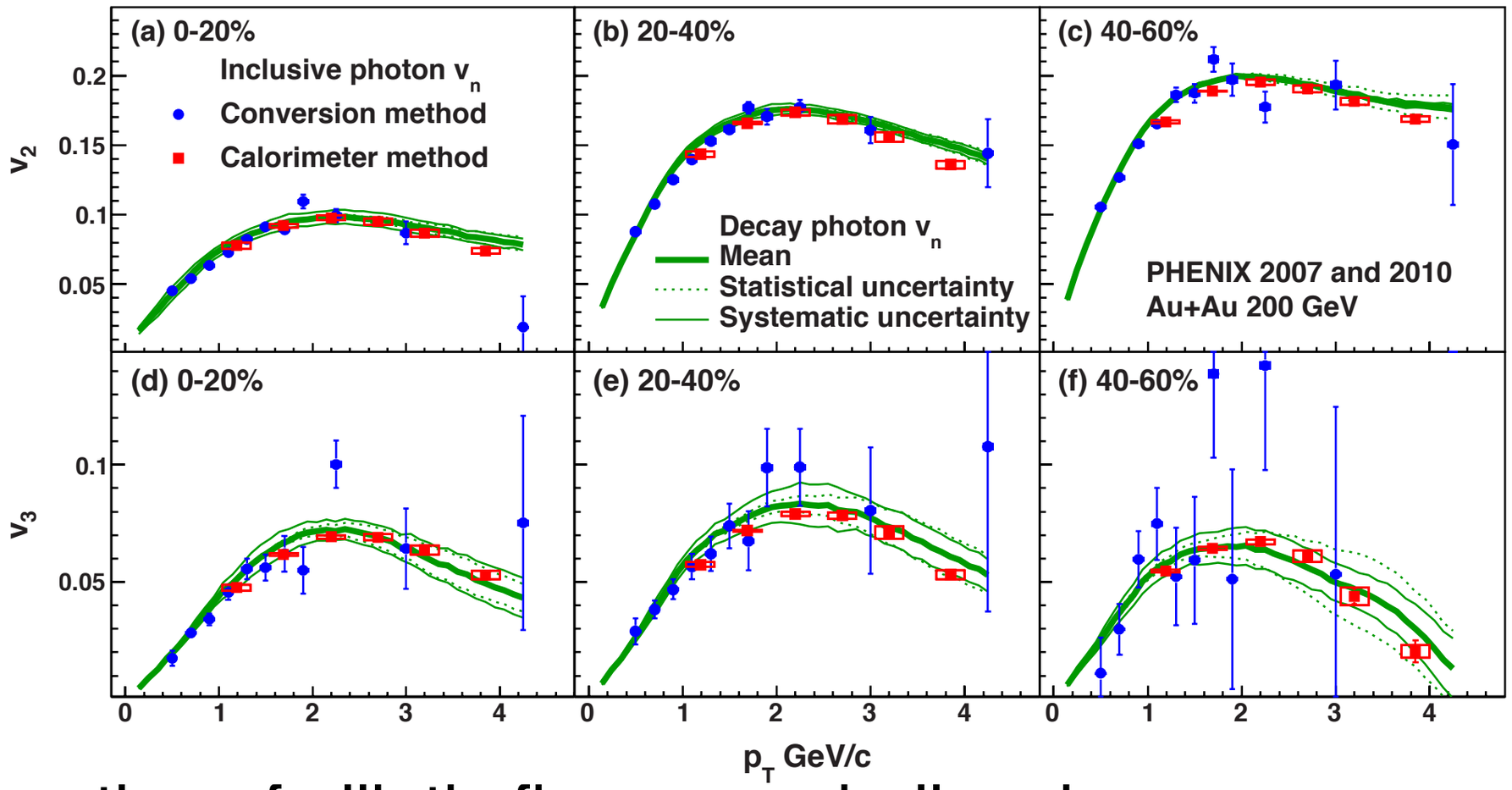
PHENIX, Phys. Rev. C 91(2015) 064904

- direct photons in Au–Au for different centralities
- compared to scaled pp-fit
  - question to theory: how well understood is low-pT non-thermal production?
- scaling assumption can be used to extract direct photon excess: thermal photons



Inclusive Photon Flow at RHIC

PHENIX, arXiv 1509.07758



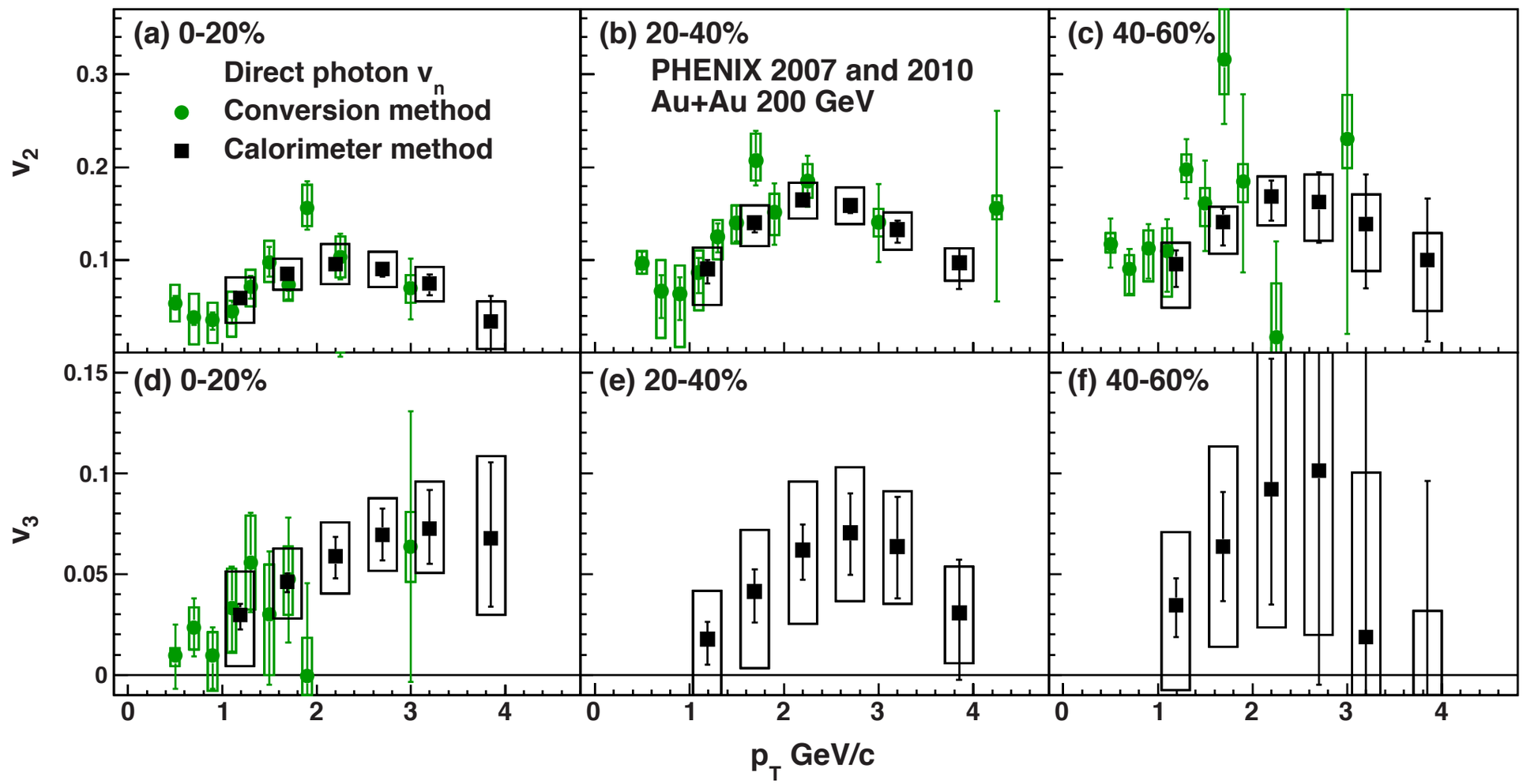
- extraction of elliptic flow very challenging
- subtraction of two similar numbers
  - flow of inclusive and decay photons

$$v_2^{\mathrm{dir}\,\gamma} = \frac{R_\gamma \cdot v_2^{\mathrm{incl}\,\gamma} - v_2^{\mathrm{dec}\,\gamma}}{R_\gamma - 1}$$

  - very sensitive to systematic errors for values of $R_\gamma \approx 1$

Direct Photon Flow at RHIC

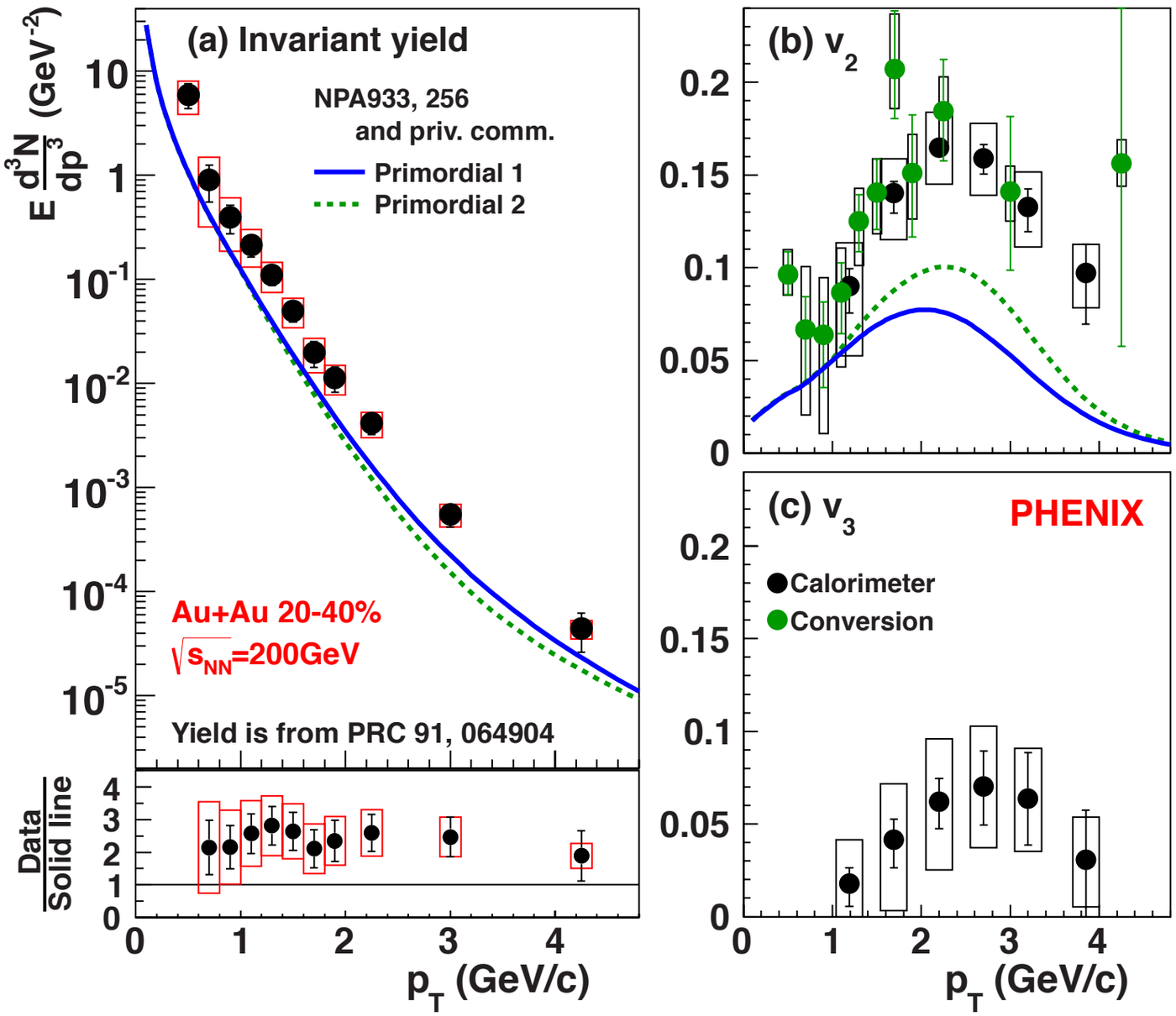
PHENIX, arXiv 1509.07758



- new final results: significant elliptic flow v_2 for direct photons
  - also v3 component
- difficult to describe theoretically

Thermal Photons – Models 1

H.van Hees, M. He, R. Rapp, Nucl. Phys. A 933 (2015) 256

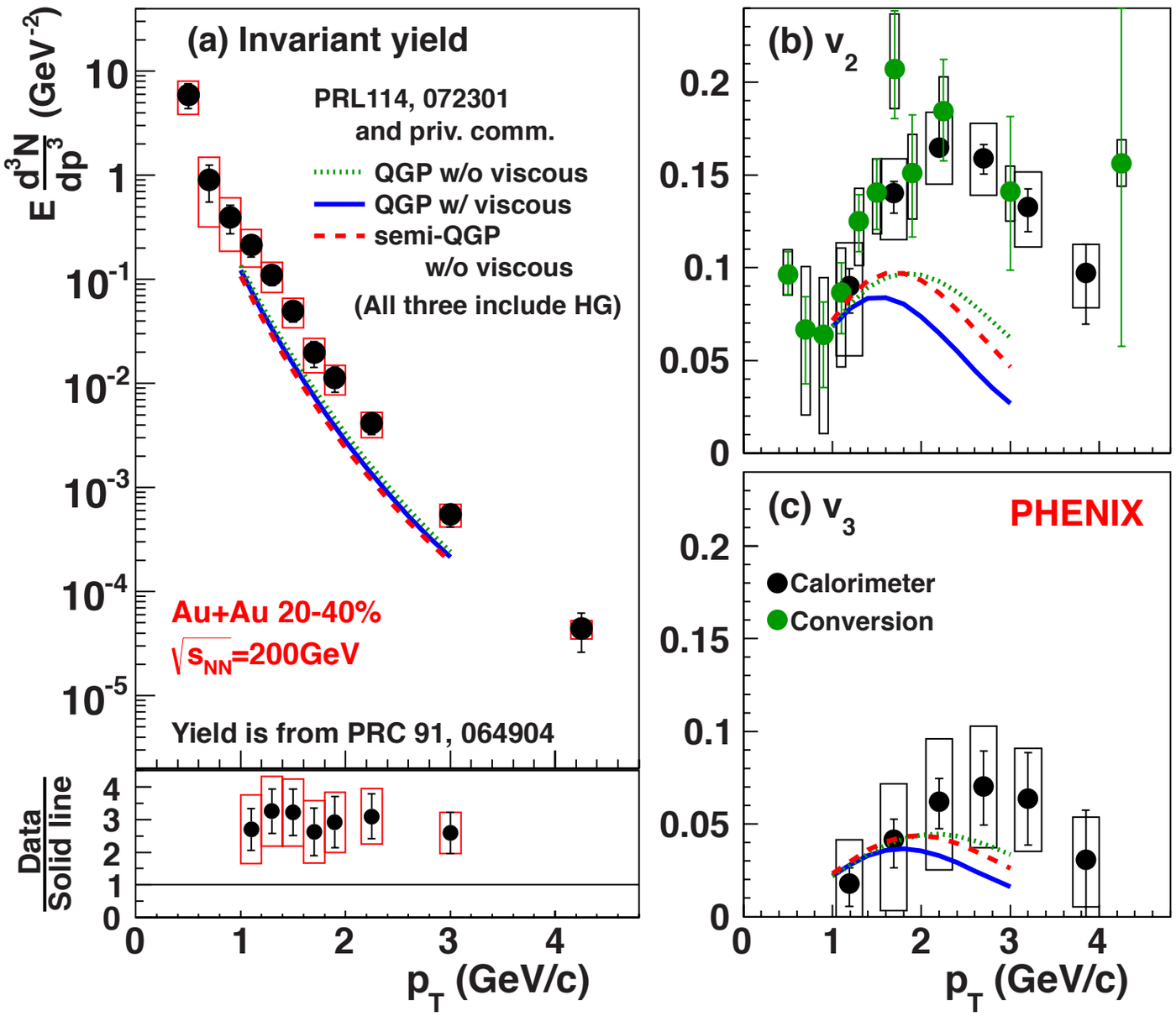


"fireball" model

- pQCD, QGP, HG
- ideal hydrodynamics
- initial transverse acceleration
- initial temperature
  T_0 = 350 MeV
- enhanced yields around T_c

Thermal Photons – Models 2

C. Gale, et al., Phys. Rev. Lett. **114** (2015) 072301

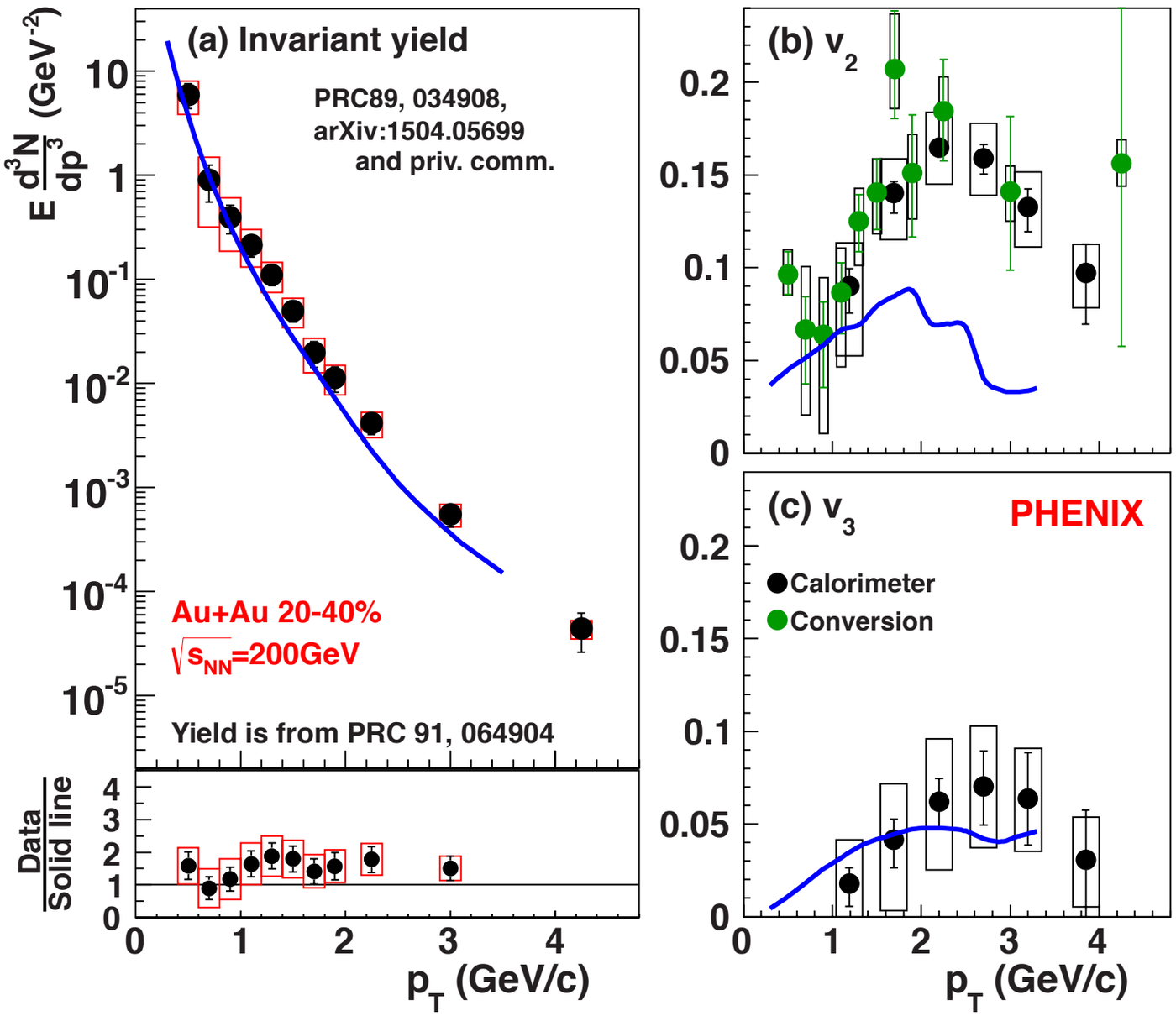


hydrodynamic model

- pQCD, QGP, HG
- different scenarios
  - ideal QGP
  - viscous QGP
  - ideal semi-QGP
- initial energy density $\varepsilon_0 \approx 40$ GeV/fm^3

Thermal Photons – Models 3

O. Linnyk, W. Cassing, E. L. Bratkovskaya, Phys. Rev. C 89 (2014) 034908



microscopic transport model

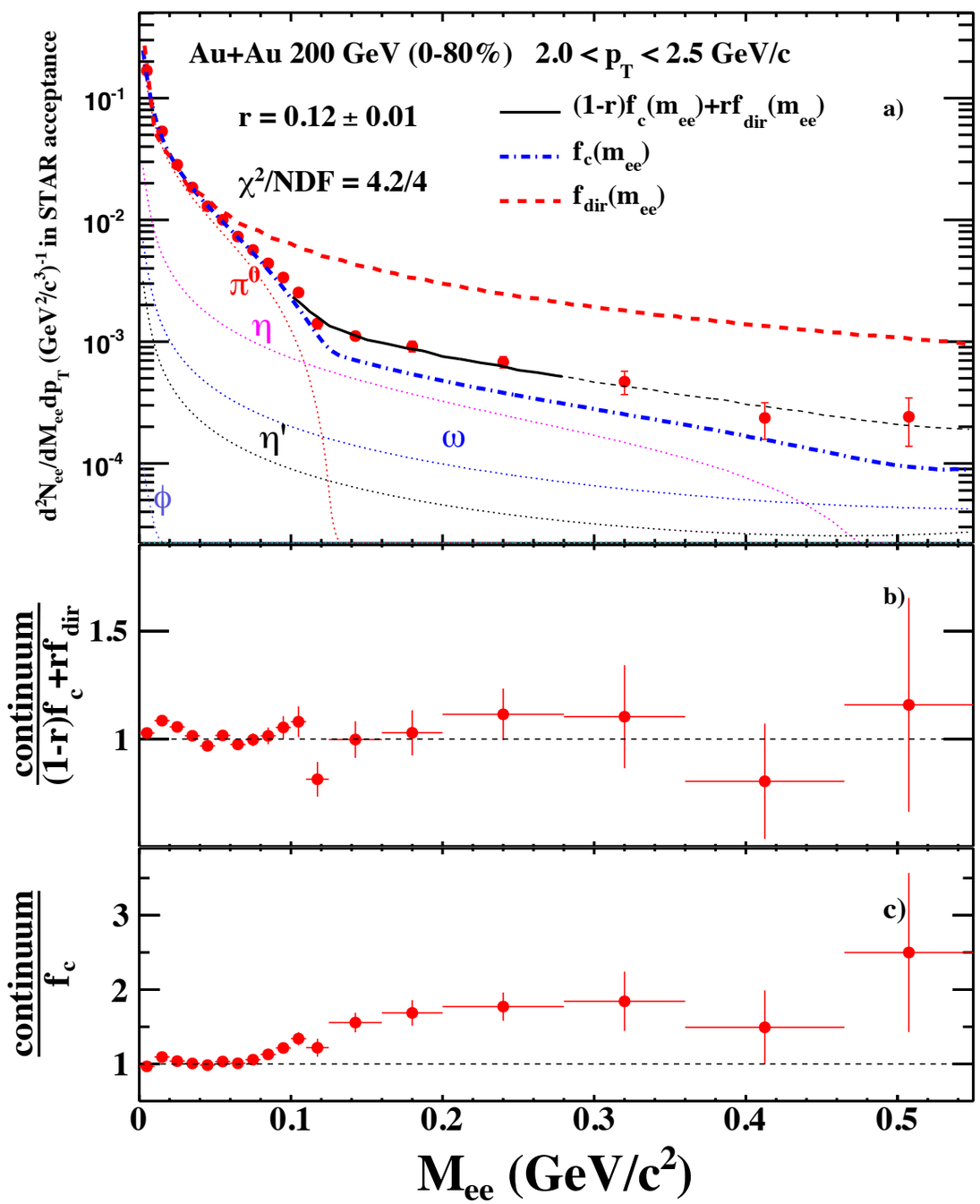
- pQCD, QGP, HG
- meson-meson and meson-baryon Bremsstrahlung

Direct photon puzzle: yield and elliptic flow cannot be described simultaneously

- large yield favours early production
- large anisotropy favours late production

New Results from STAR

STAR, arXiv 1607.01447



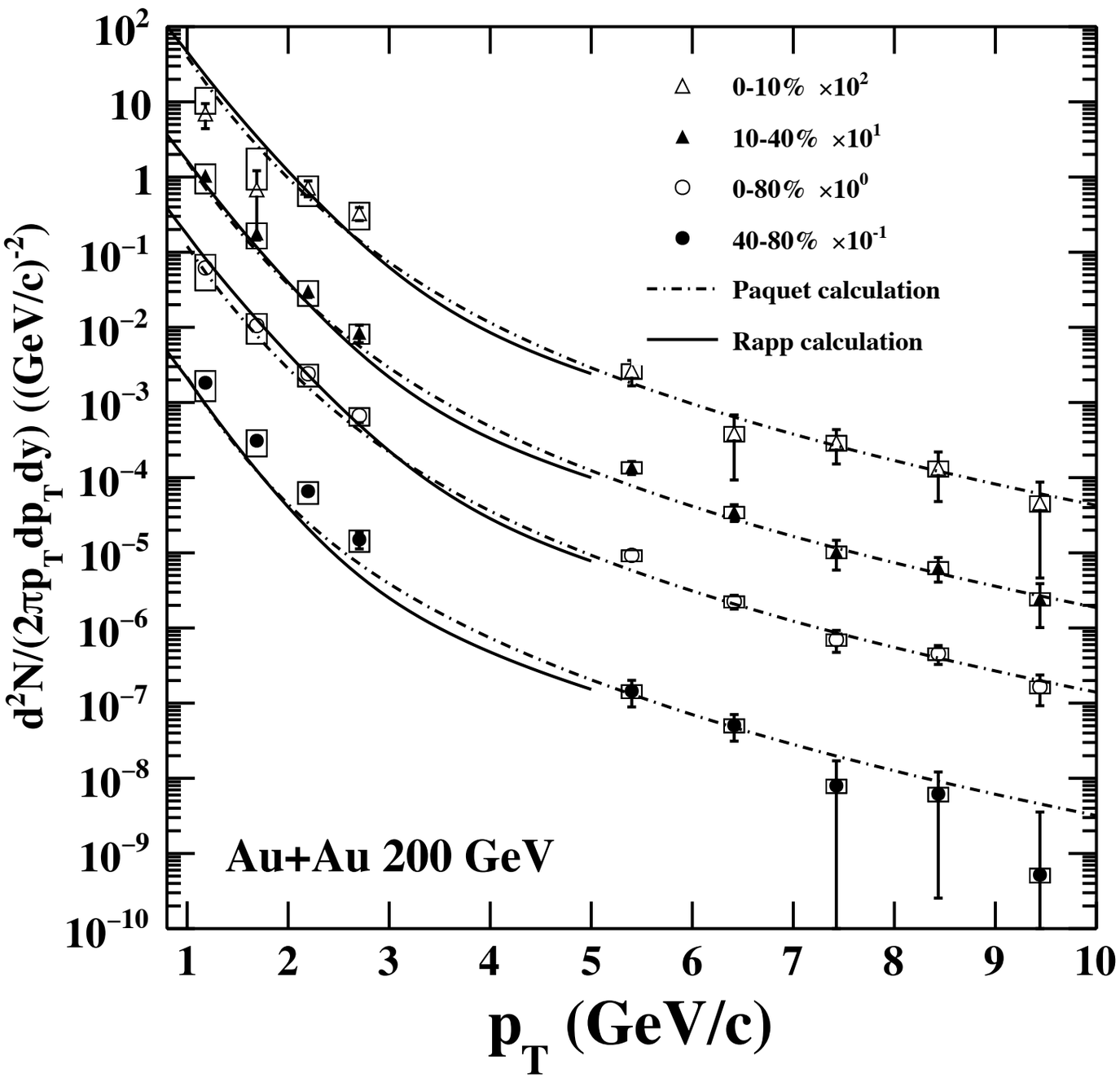
real photon measurement

via zero-mass virtual photons (e^+e^-)

- one of the methods also used by PHENIX (in addition to conversion and calorimetry)
- advantage: no π^0 decay background above m_π
- fit to well known functional shape (Kroll-Wada), extrapolate to m = 0
- fit to mass spectra in p_T-bins to obtain spectrum

New Results from STAR

STAR, arXiv 1607.01447



spectra for different centralities

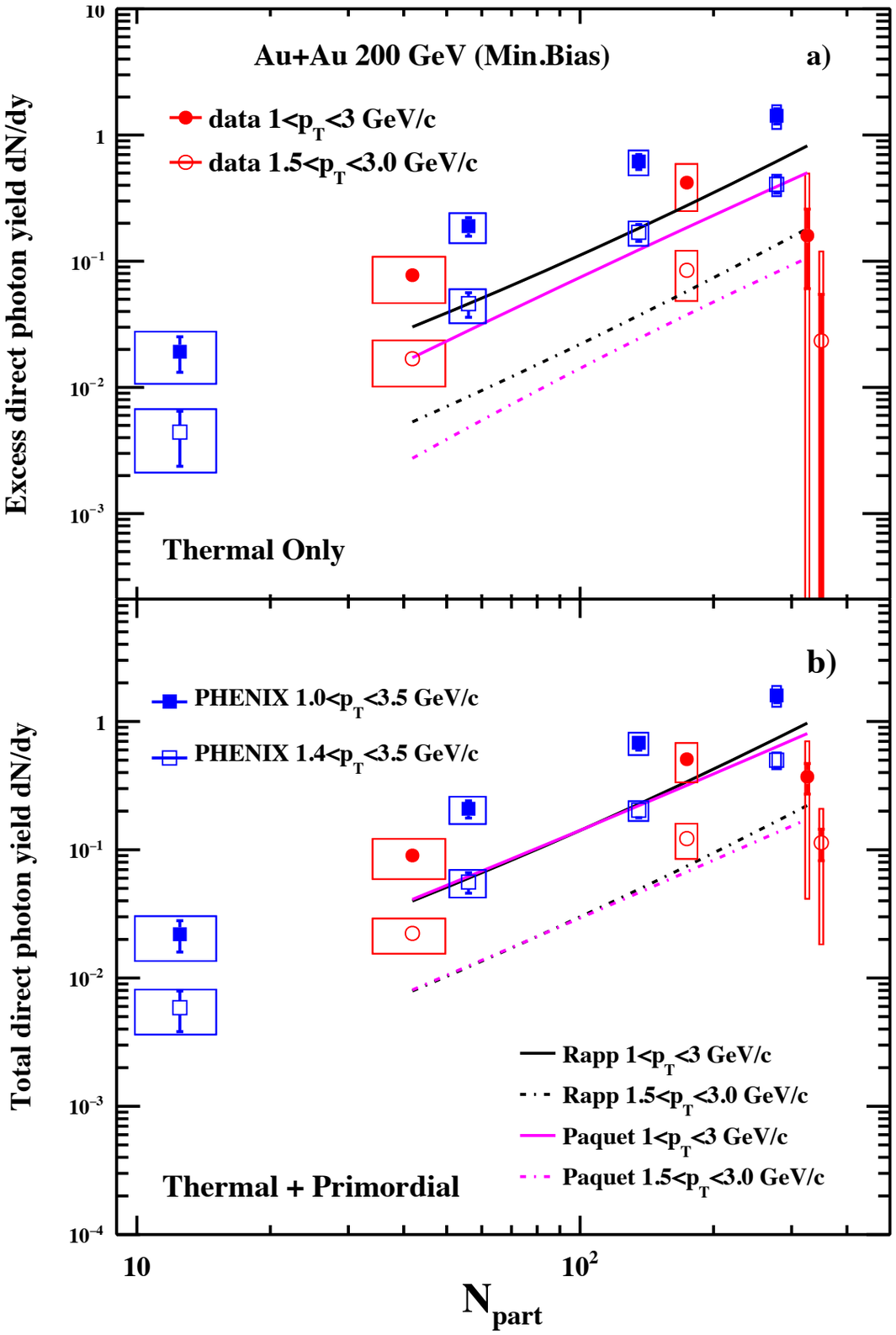
- limited significance for central 0-10%

reasonable description by theoretical models

- Rapp et al. (model 1)
- Paquet et al. (model 2)

Comparison STAR–PHENIX

STAR, arXiv 1607.01447



one-to-one comparison difficult

- different binning in p_T and centrality

indication of significant difference

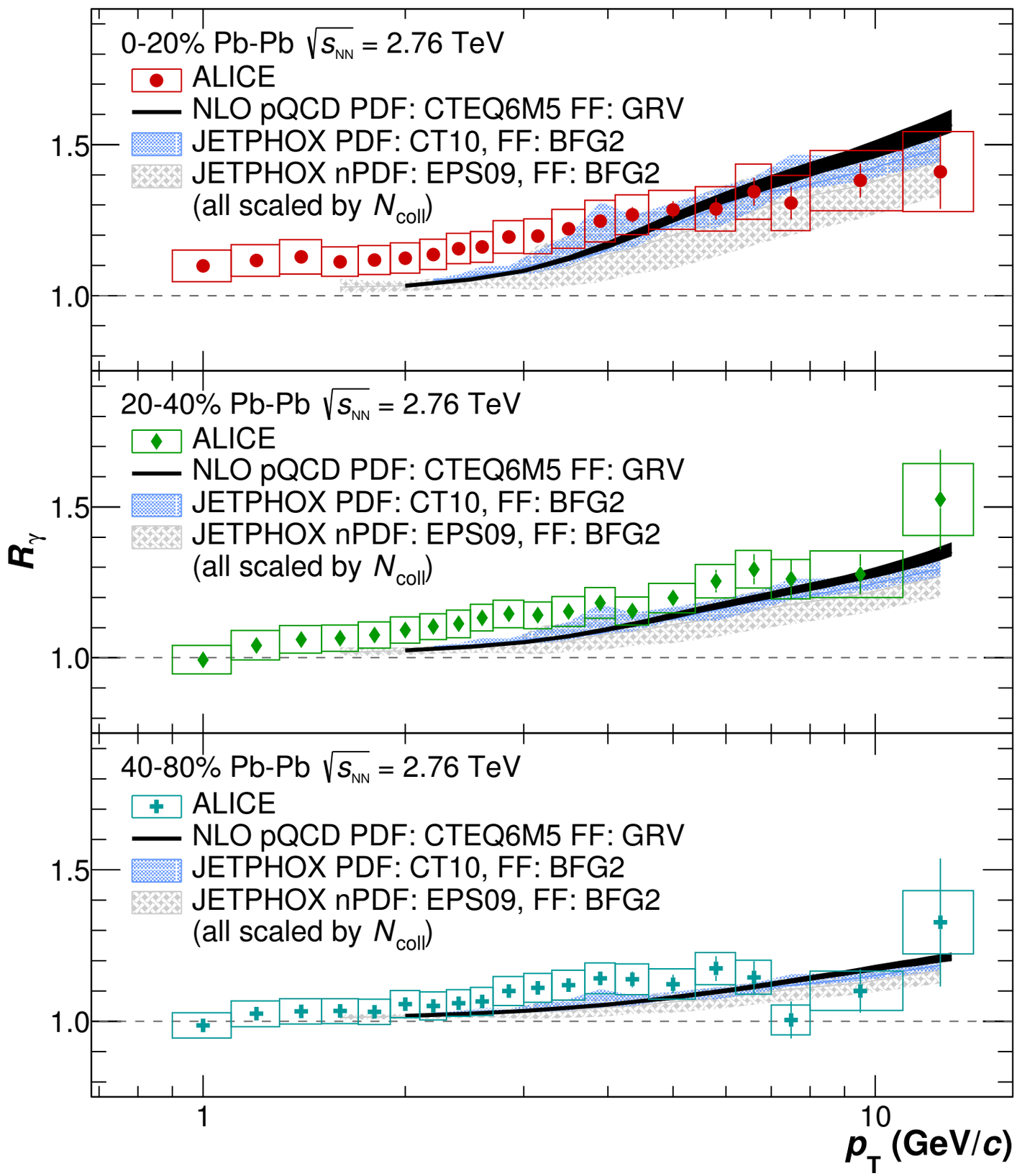
- supported by direct model comparison

no flow results from STAR (yet?)

new light on the direct photon puzzle?

Direct Photons at LHC

ALICE, Phys. Lett. B 754 (2016) 235-248



- direct photons in Pb–Pb at 2.76 TeV in ALICE
  - significance judged via

$$R_\gamma = \frac{N_\gamma^{\mathrm{inc}}}{N_\gamma^{\mathrm{dec}}} = 1 + \frac{N_\gamma^{\mathrm{dir}}}{N_\gamma^{\mathrm{dec}}}$$

- measurement via photon conversion and calorimetry
  - consistent results
- good description with pQCD at high p_T
- excess beyond pQCD at low p_T in central and semi-central collisions

Thermal Photons at LHC

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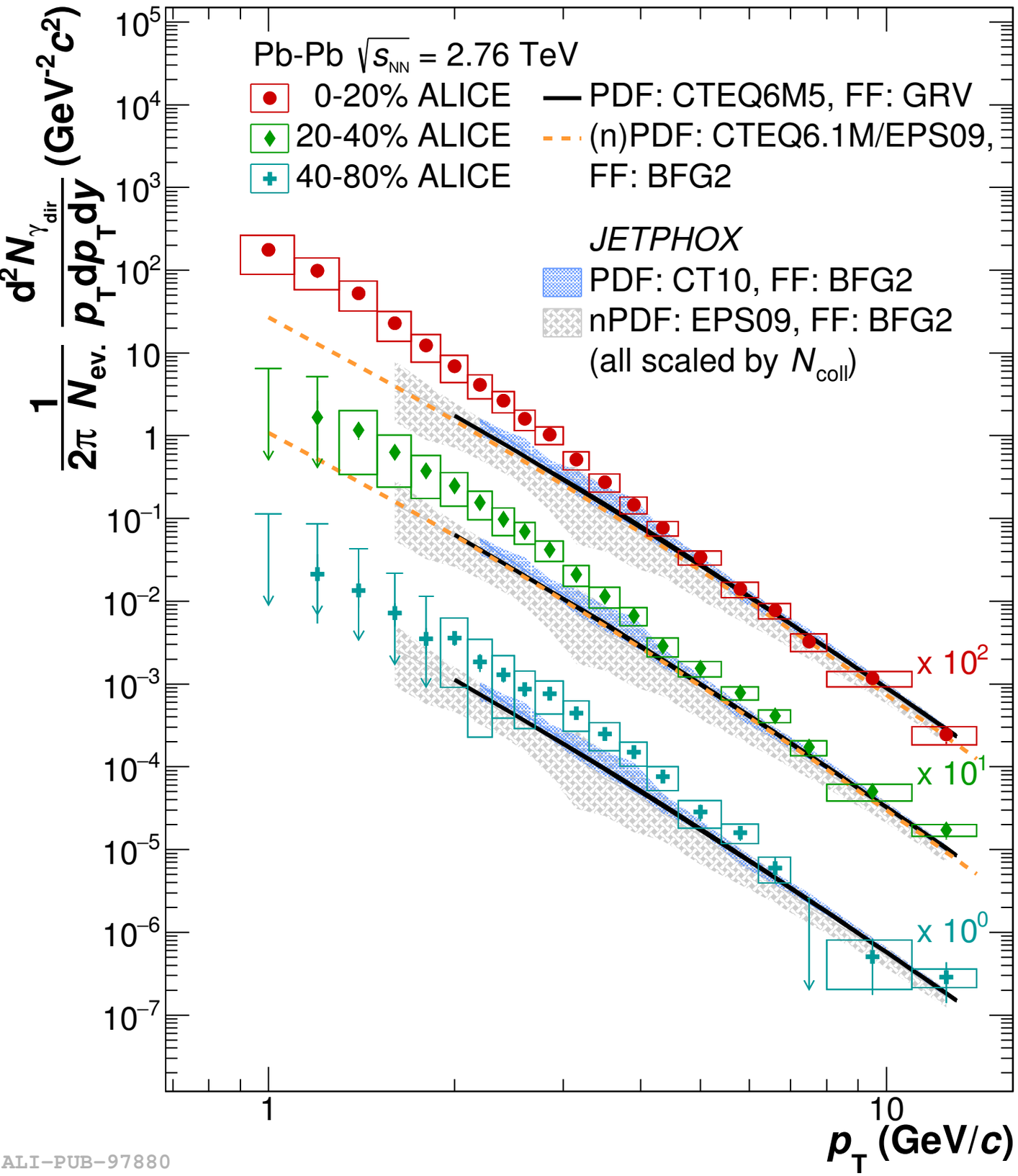
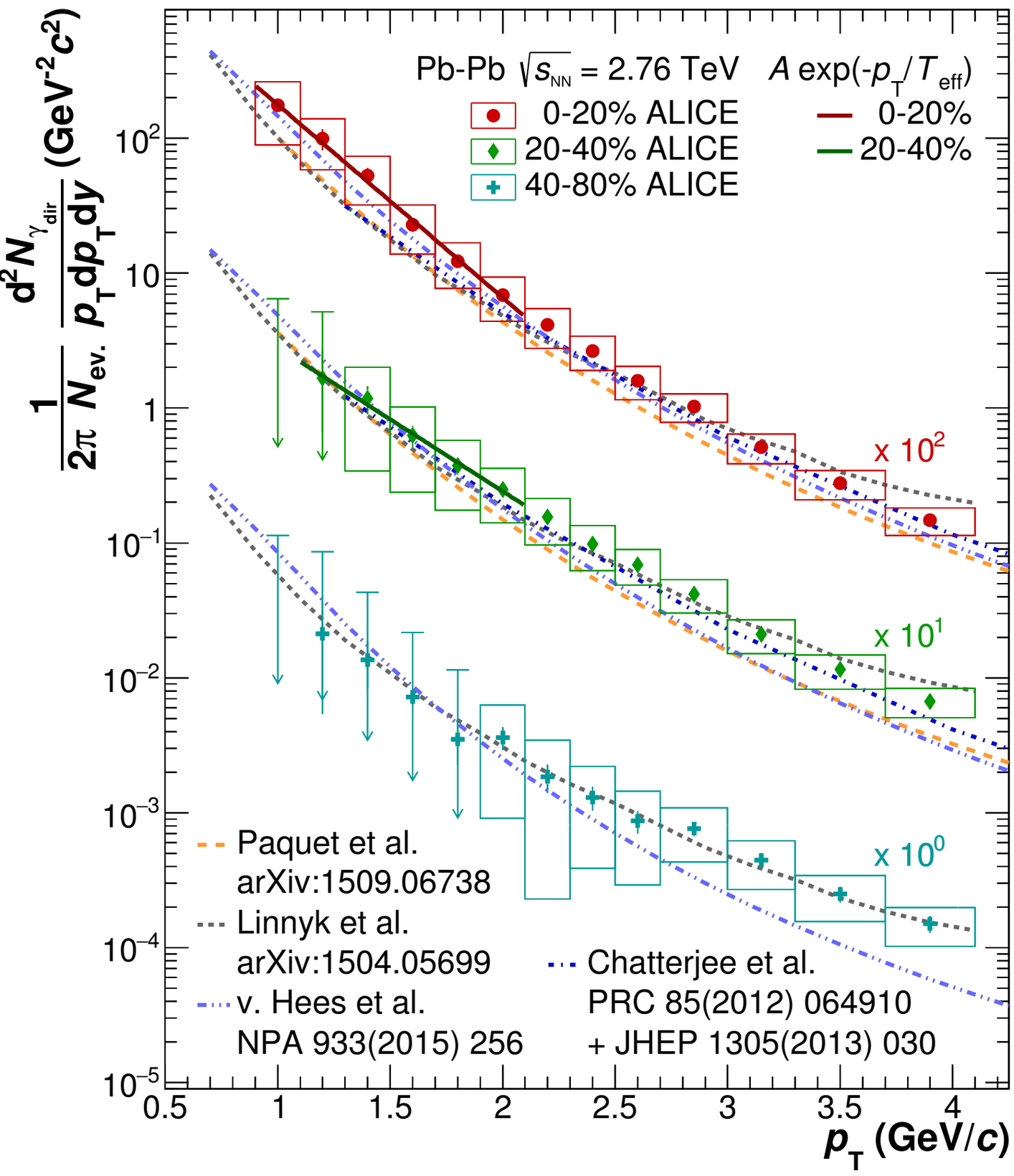


- final spectra of direct photons in Pb–Pb at 2.76 TeV
- good description with pQCD at high p_T
- can use extrapolation of pQCD towards low p_T to obtain thermal photon spectra

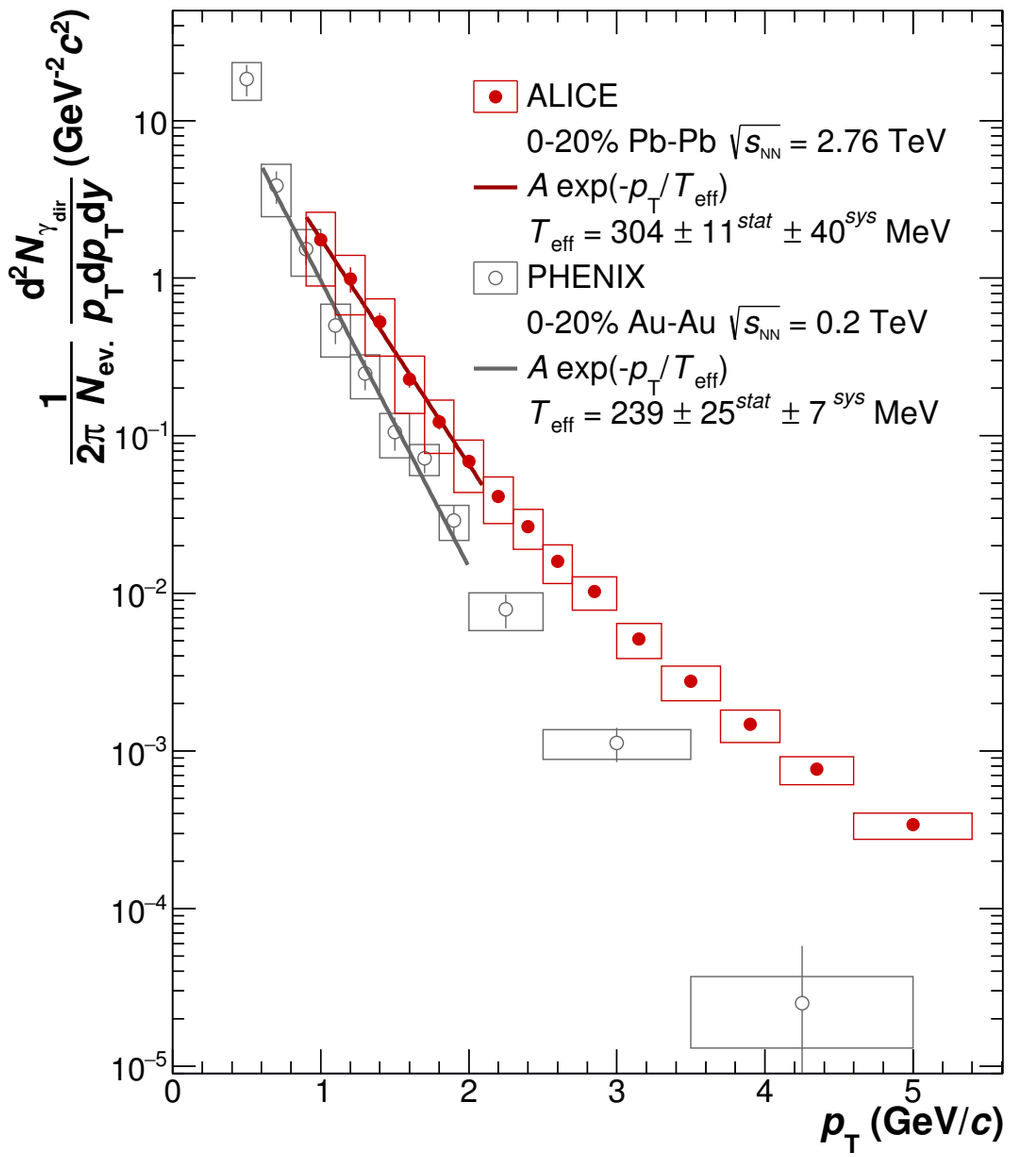
Thermal Photons at LHC

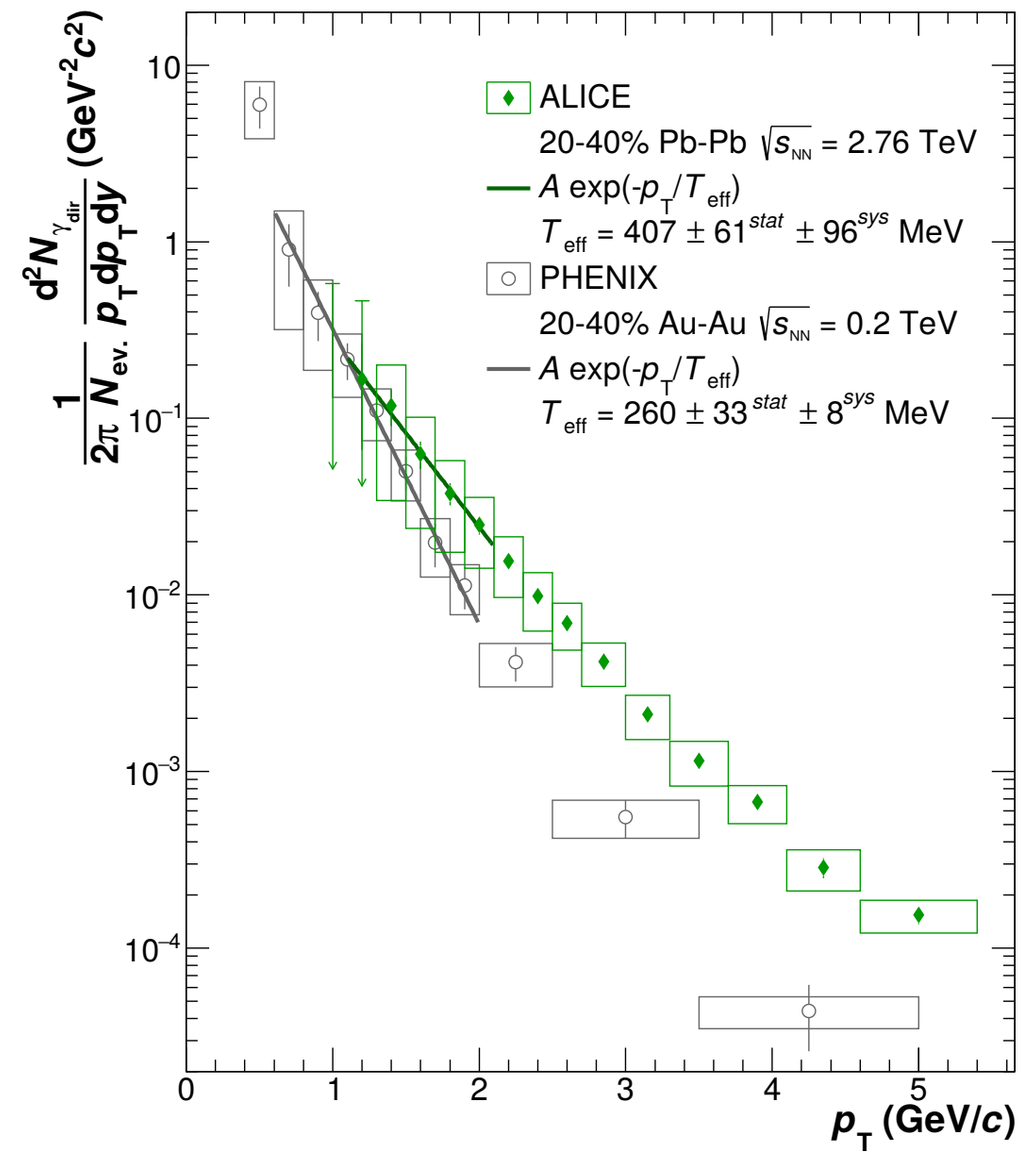
ALICE, Phys. Lett. B 754 (2016) 235-248



- here: compare to models including thermal and prompt sources
- similar theories as above
  - enhanced yields from e.g. pseudo critical enhancement or hadronic Bremsstrahlung
- photon spectra not fully described
  - smaller (?) discrepancy as compared to PHENIX

Thermal Photons – RHIC vs LHC





central collisions:

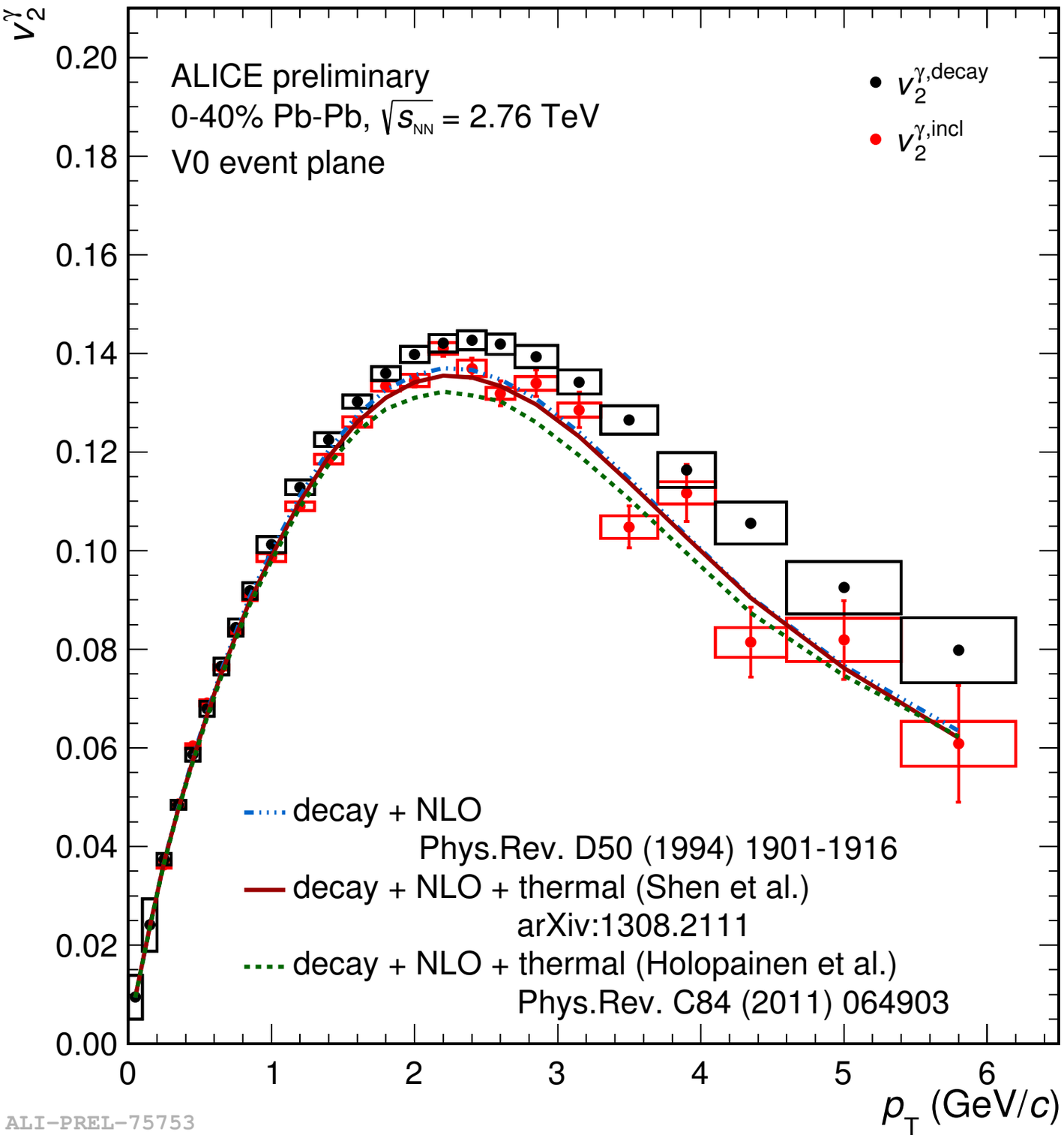
- higher yield and
- larger effective slope

of photon spectra in ALICE vs PHENIX

less clear picture
in semi-central collisions

Direct Photon Flow at LHC: Status

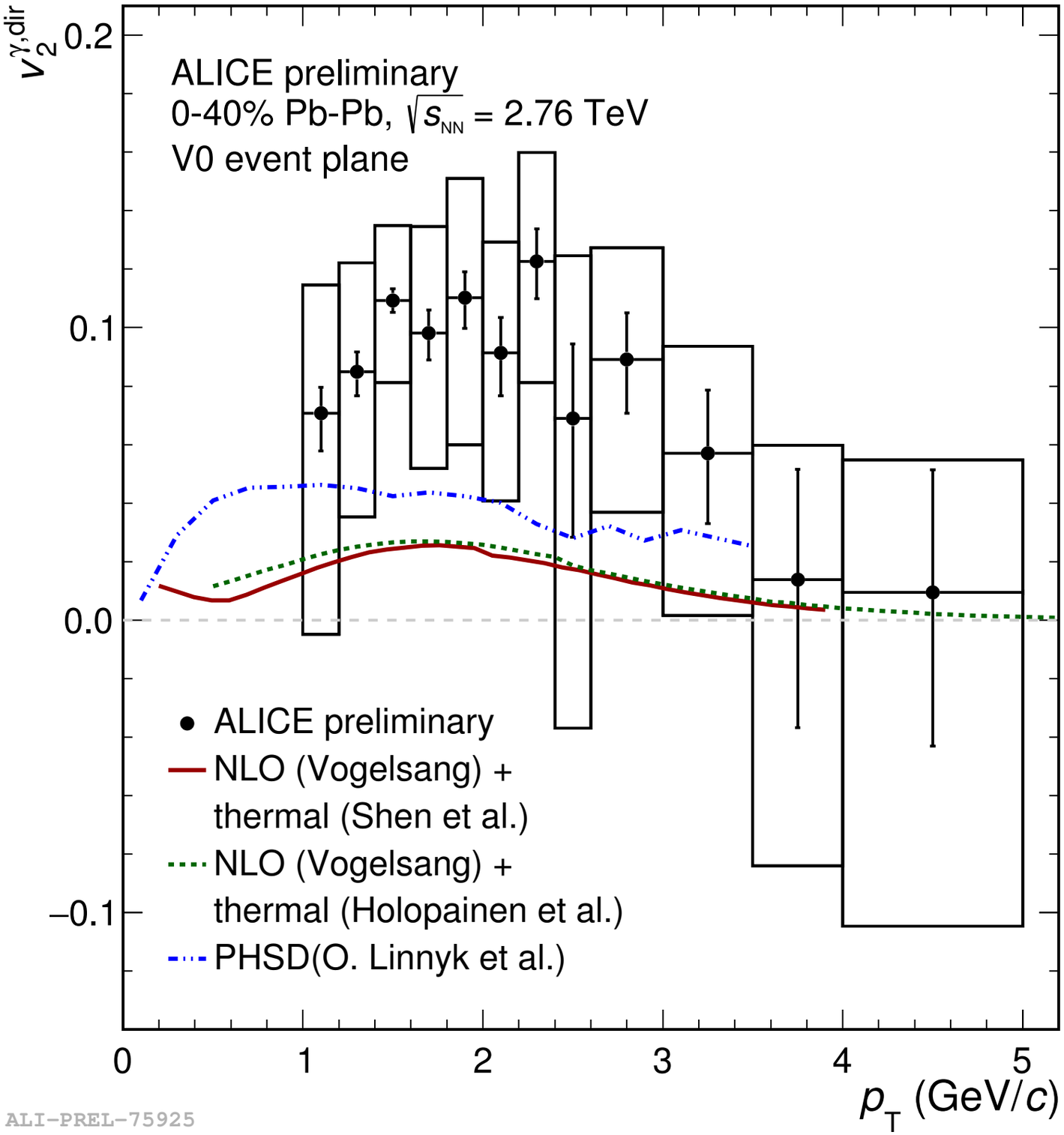
D. Lohner (ALICE), Journal of Physics: Conference Series 446 (2013) 012028



- preliminary results for central collisions (0-40%)
  - measured by conversions only
  - different centrality bins than final yields
- comparison of inclusive photon flow and decay photon flow

Direct Photon Flow at LHC: Status

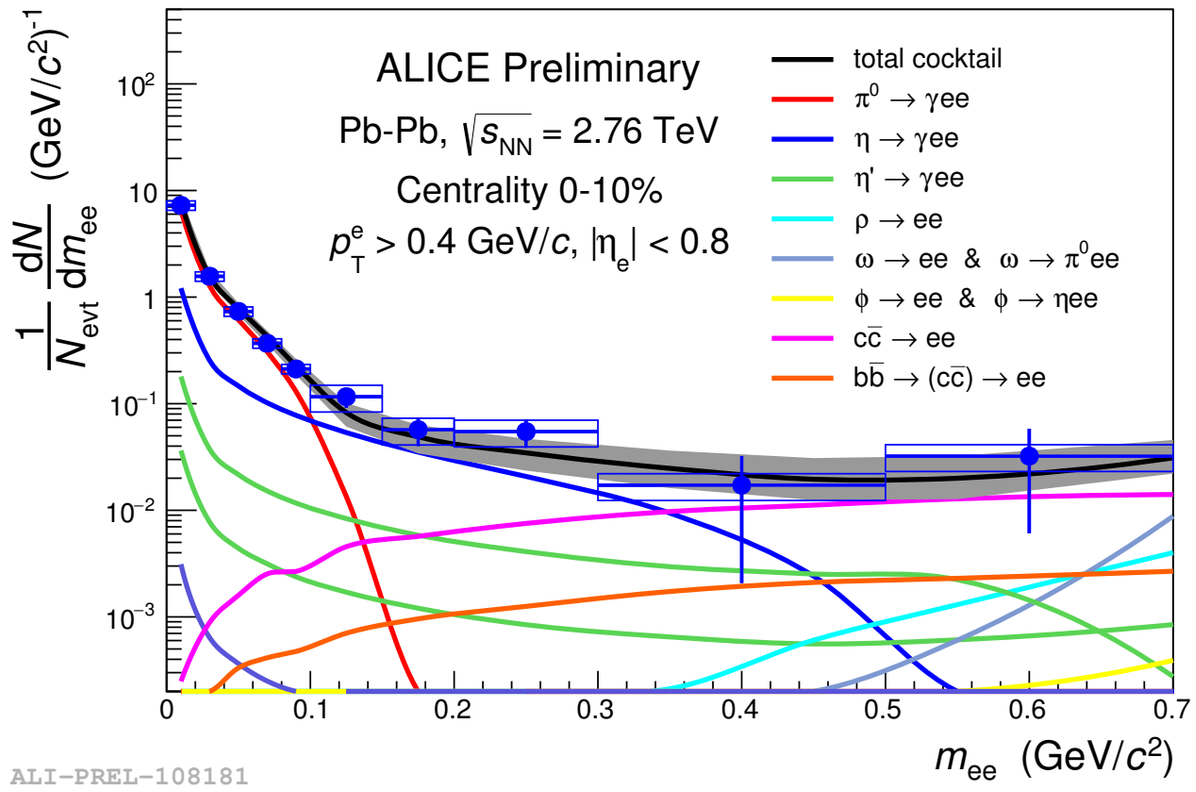
D. Lohner (ALICE), Journal of Physics: Conference Series 446 (2013) 012028

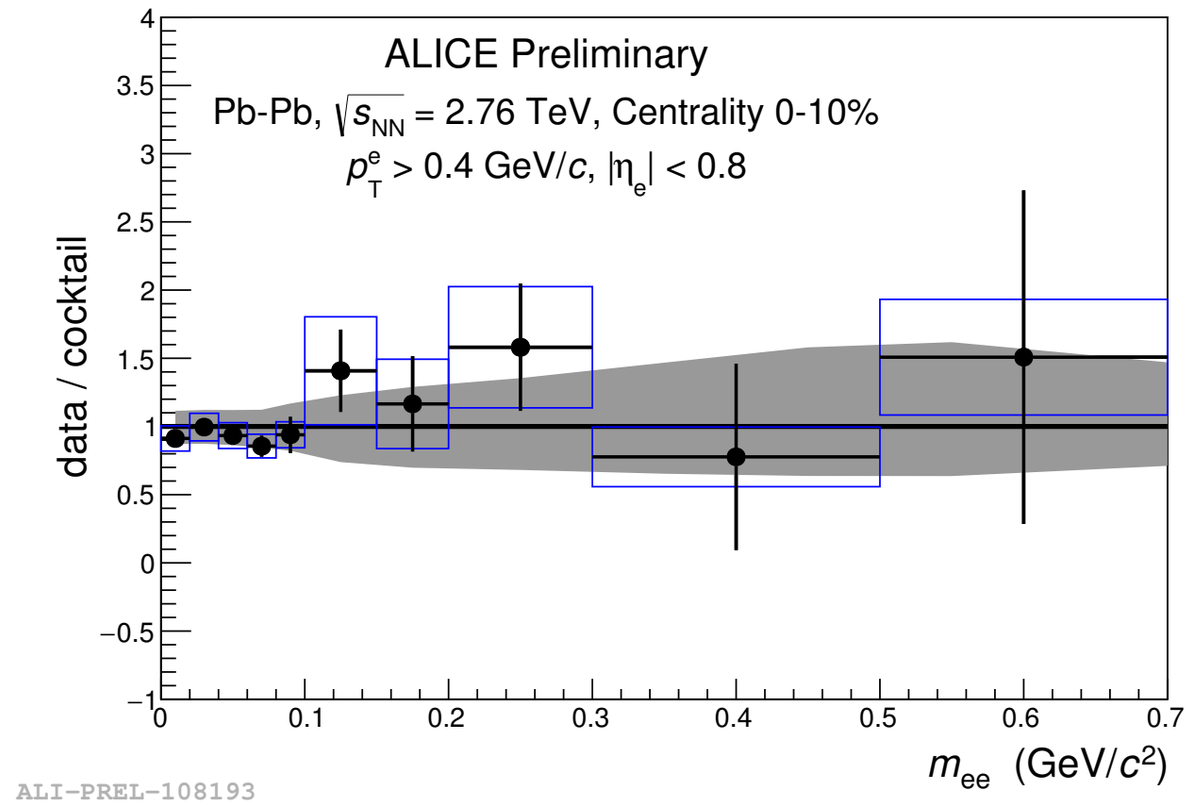


- preliminary results for central collisions (0-40%)
  - use preliminary extracted photon yields to extract direct photon flow
- comparison of direct photon flow to theoretical models
  - large uncertainties
  - under-prediction by models
- final results in preparation
  - using final direct photon yields
  - revisit error estimates

Outlook: Zero-Mass Virtual Photons

A. Caliva (ALICE), talk at SQM 2016



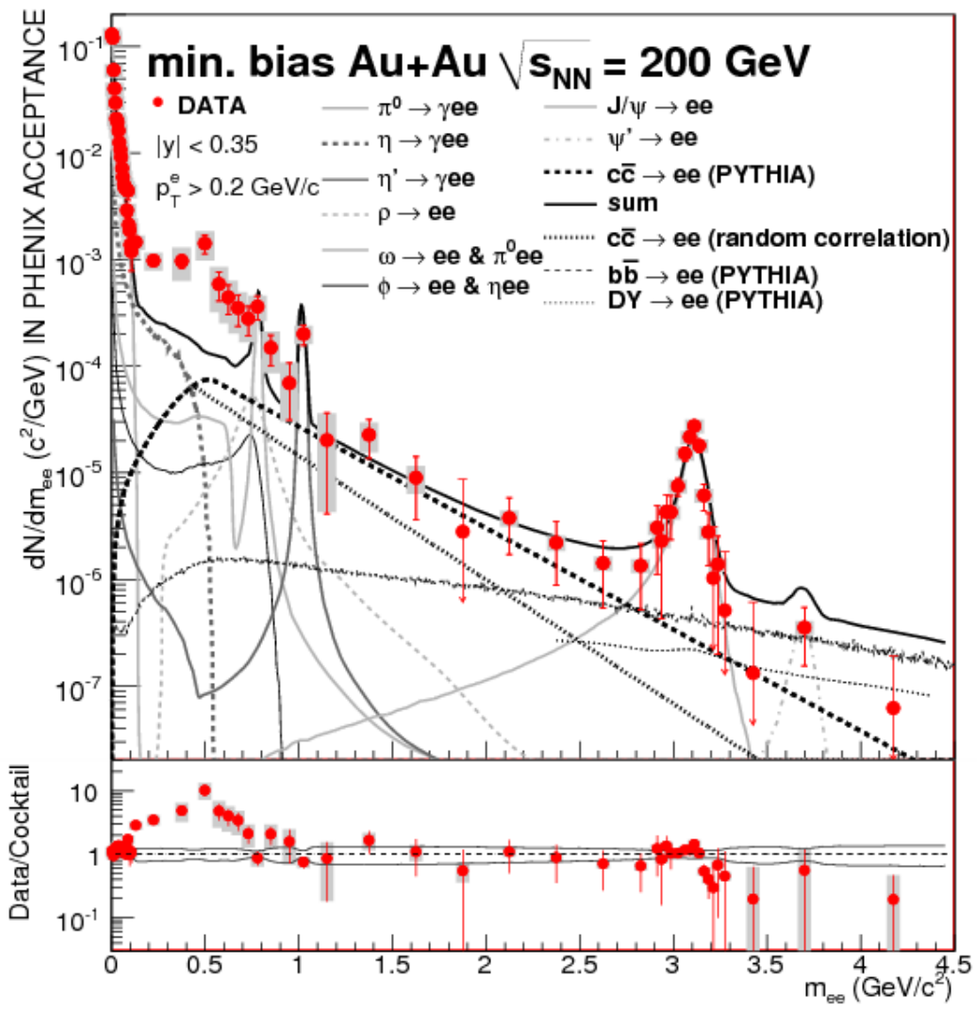


- extract real photons from low-mass dielectron mass spectrum
- measurement statistics limited from LHC Run 1
- so far only upper limit for photon yield: looking forward to Run 2!

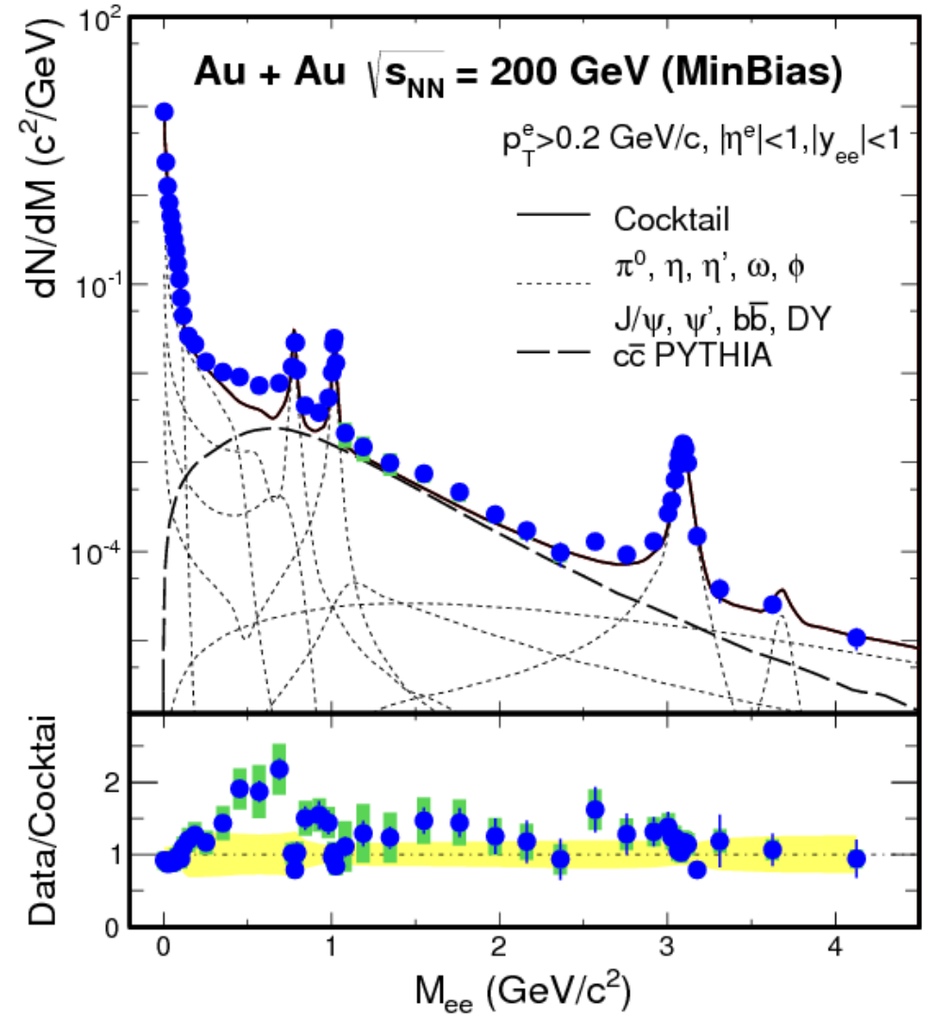
Low-Mass Dileptons

Low-Mass Dileptons – Status pre-QM2015

PHENIX, PRC 81 (2010) 034911



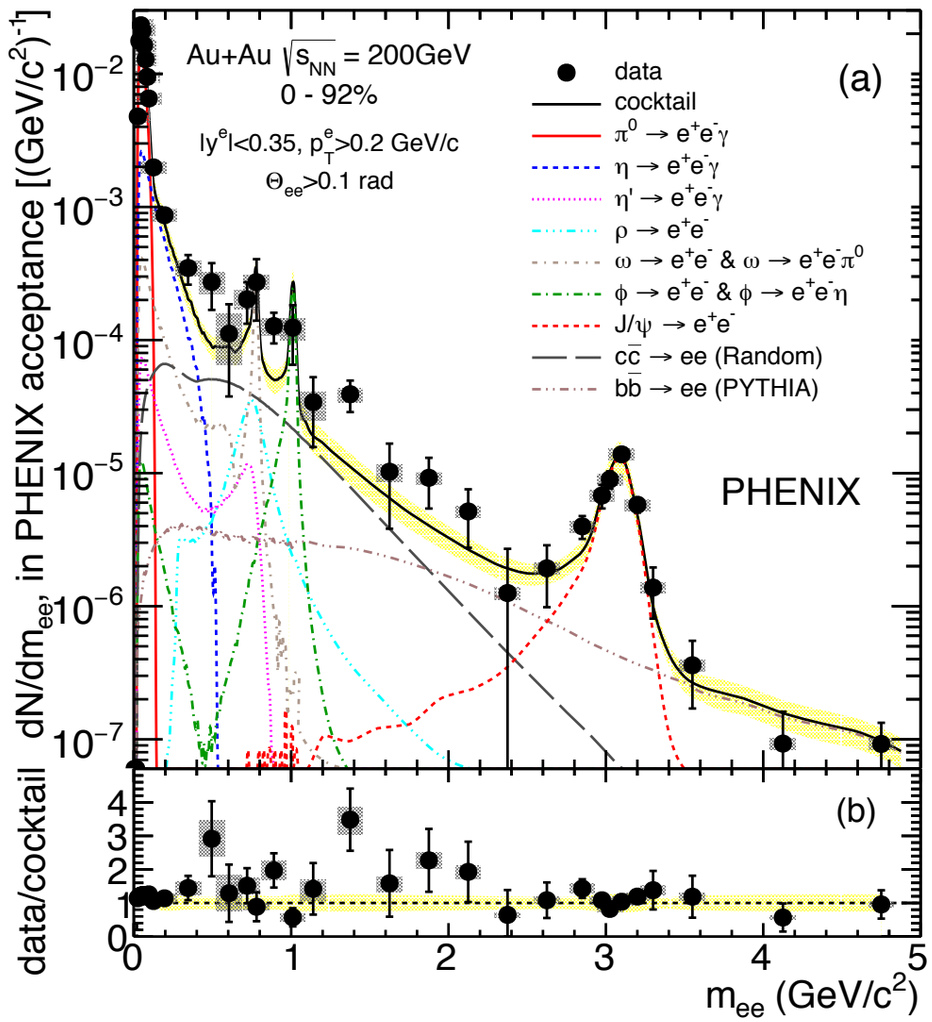
STAR, PRC 92 (2015) 024912



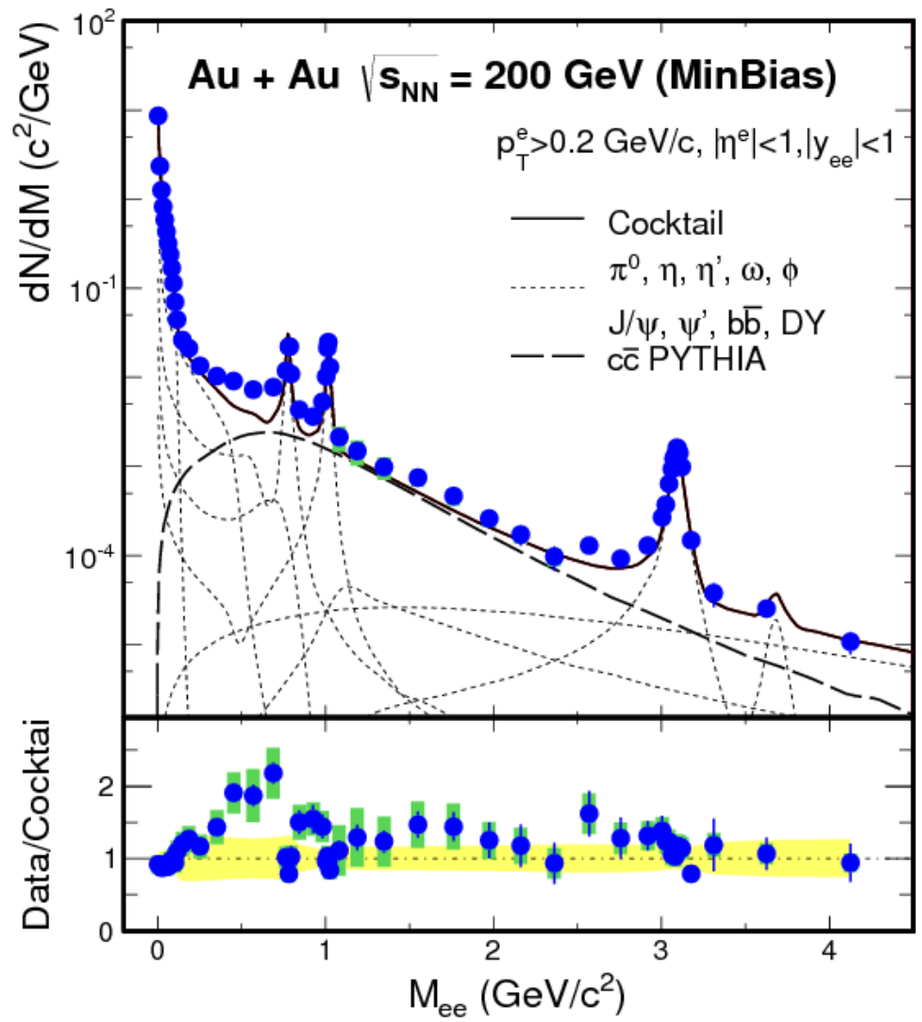
- significant difference of enhancement in low-mass region

Low-Mass Dileptons

PHENIX, PRC 93 (2016) 014904



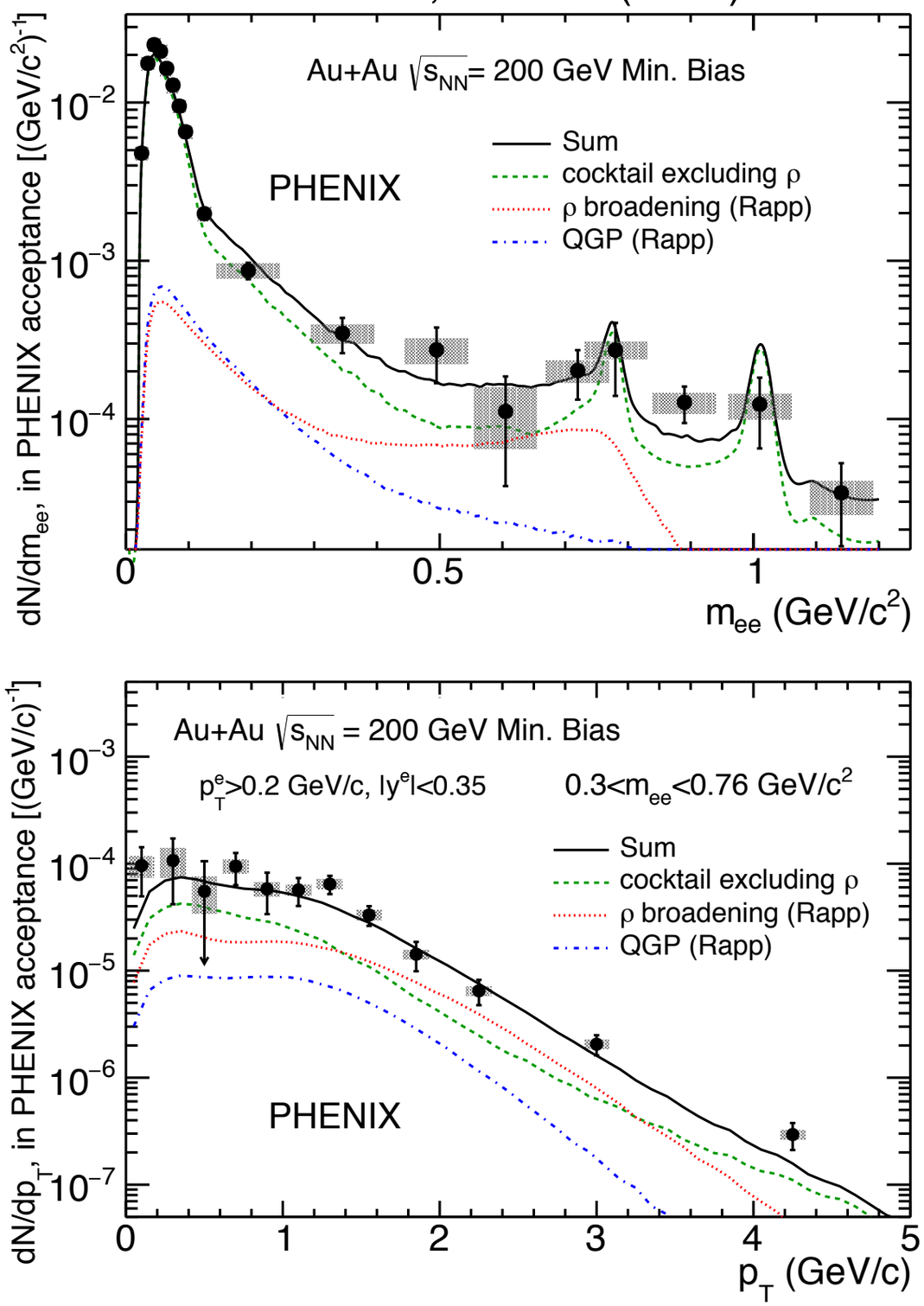
STAR, PRC 92 (2015) 024912



- new analysis of PHENIX data:
  - good agreement with STAR, similar LM excess

Low-Mass Dileptons at RHIC

PHENIX, PRC 93 (2016) 014904

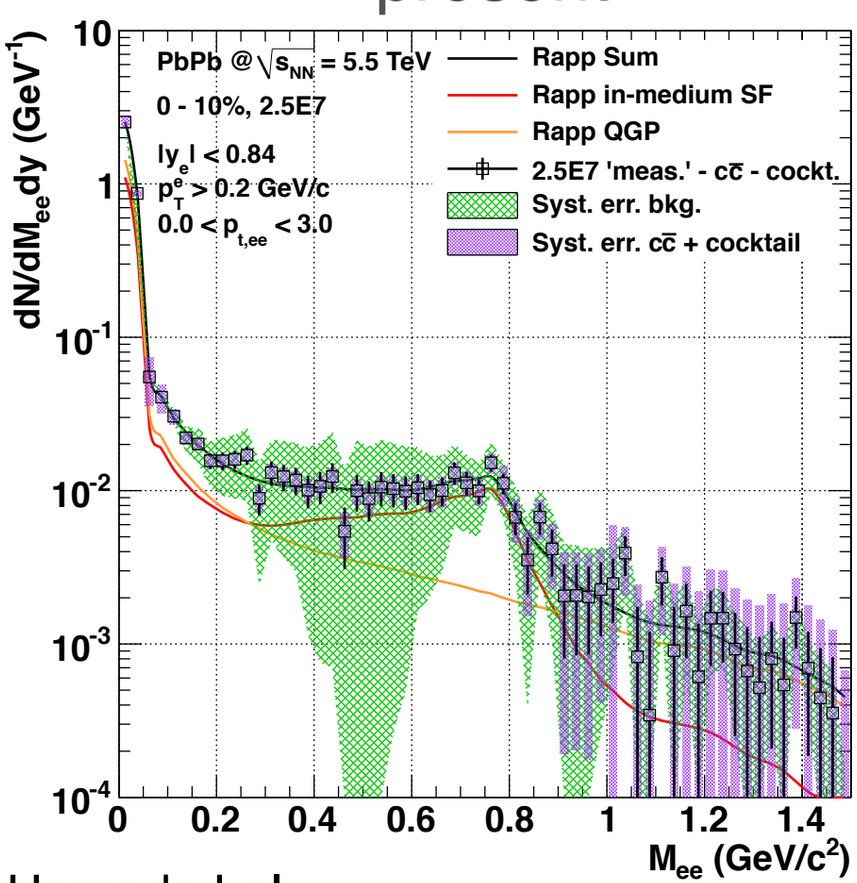


- good description of dileptons in LMR by theory
- main contribution to excess beyond known decays:
  - thermal radiation of hadronic origin with broadened ρ meson spectral function

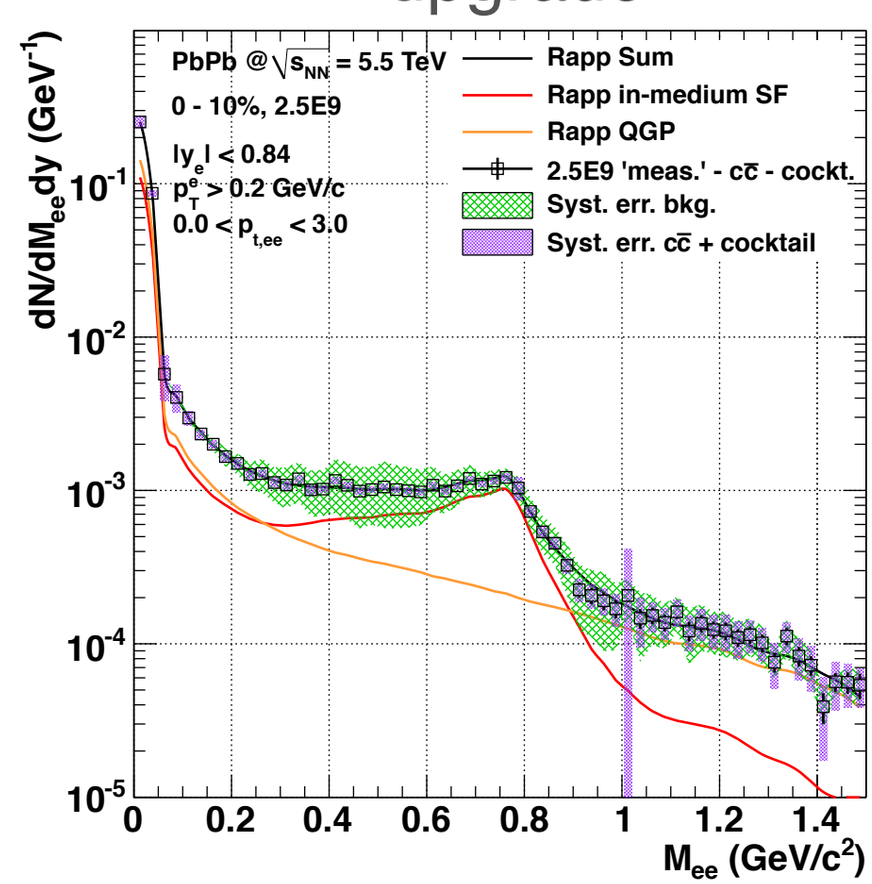
LMR Dileptons at LHC: ALICE Upgrades

- uncertainties with current ITS
  - limited by background subtraction and statistics
- high rate measurement with new ITS (B = 0.2T instead of 0.5T)
  - more efficient cuts to reduce background, high statistics: allows for detailed measurement of low-mass dielectrons

present



upgrade



ALICE Upgrade LoI

Conclusions

- High p_T prompt photons well described by pQCD
  - test initial state modifications: non observed
  - proposed forward measurement: promising signal for CGC
- Thermal photons observed at RHIC and LHC
  - very prominent at RHIC with high yield and strong v_2.
    - challenge for theory
    - new STAR results: what do they tell us?
  - also high yield at LHC, possibly less tension with theory
    - coming: final v_n results, future: higher statistics from Run 2
- Consistent picture for low-mass dileptons at RHIC
  - agreement between experiments and good description by theory

Backup

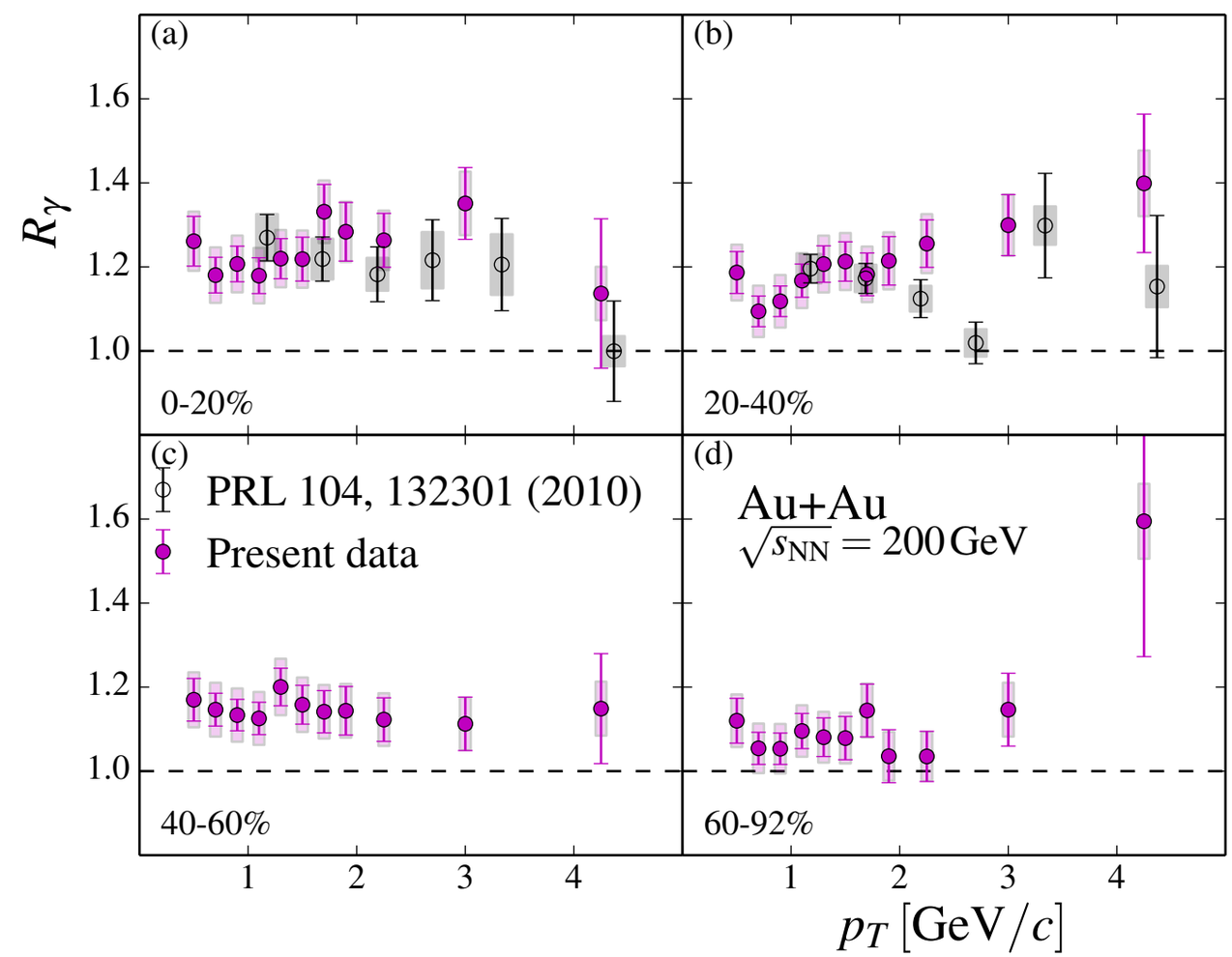
Direct Photons in Au-Au 200 GeV (PHENIX)

- for thermal photons: lower p_T
- more difficult:
  - smaller S/B expected

$$R_\gamma = \frac{N_\gamma^{\mathrm{inc}}}{N_\gamma^{\mathrm{dec}}} = 1 + \frac{N_\gamma^{\mathrm{dir}}}{N_\gamma^{\mathrm{dec}}}$$

- S/B improves for central Au–Au
  - main contribution to decay photons (neutral mesons) suppressed in Au–Au

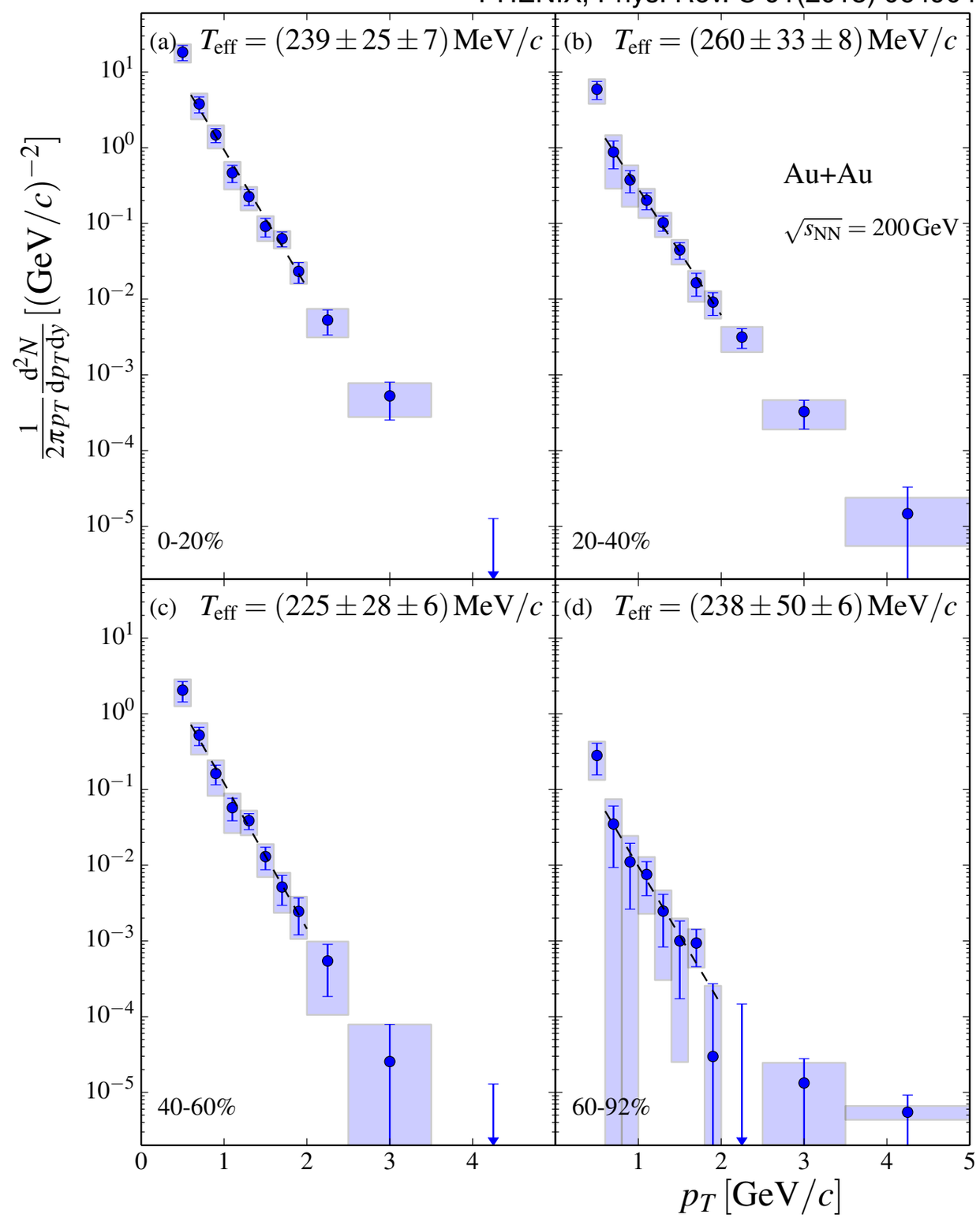
PHENIX, Phys. Rev. C 91(2015) 064904



Thermal Photons in Au-Au 200 GeV (PHENIX)

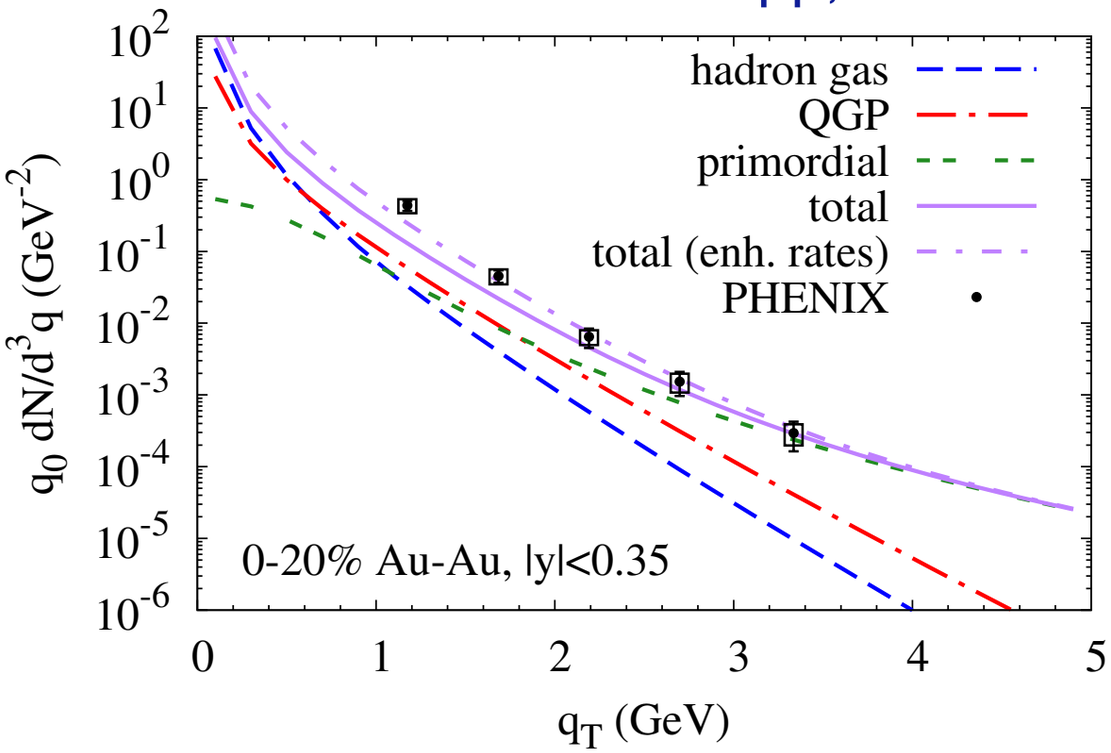
- centrality dependence of photon excess
  - increases more strongly than number of participants
- fit with exponential yield similar slope parameter for all with T ≈ 240 MeV
  - expectation from theory?

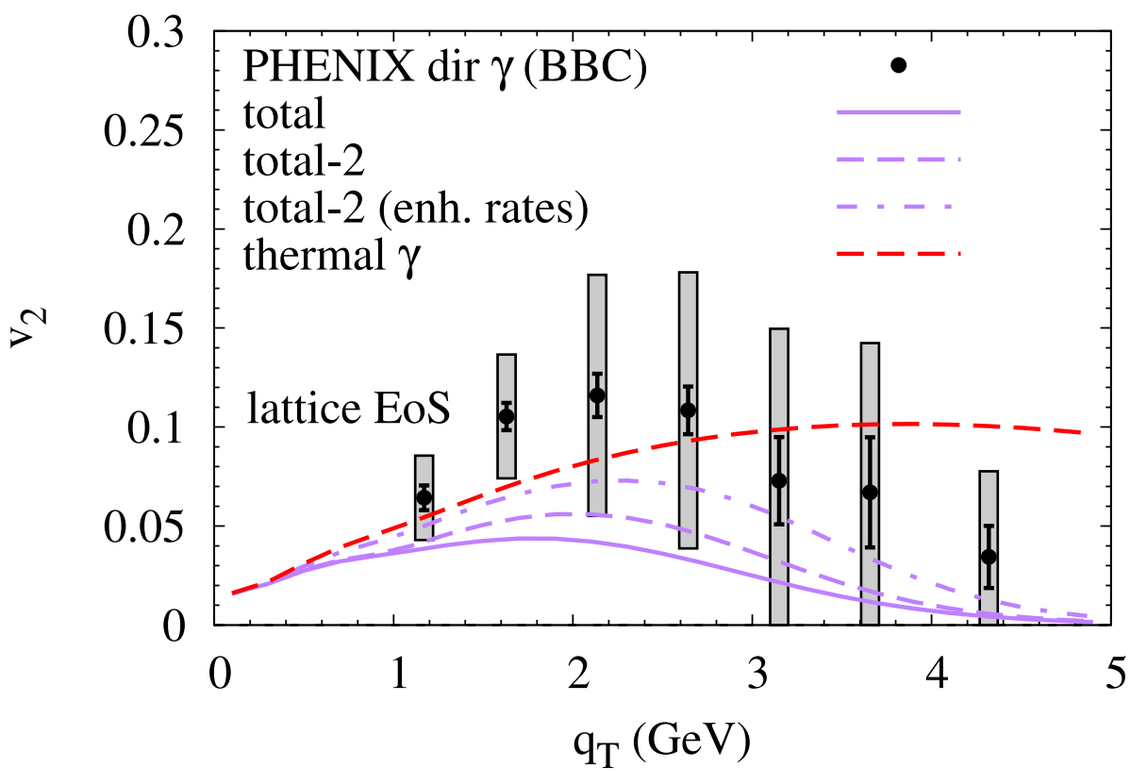
PHENIX, Phys. Rev. C 91(2015) 064904



Thermal Photon Puzzle?

R. Rapp, H.van Hees, M. He, arXiv 1408.0612

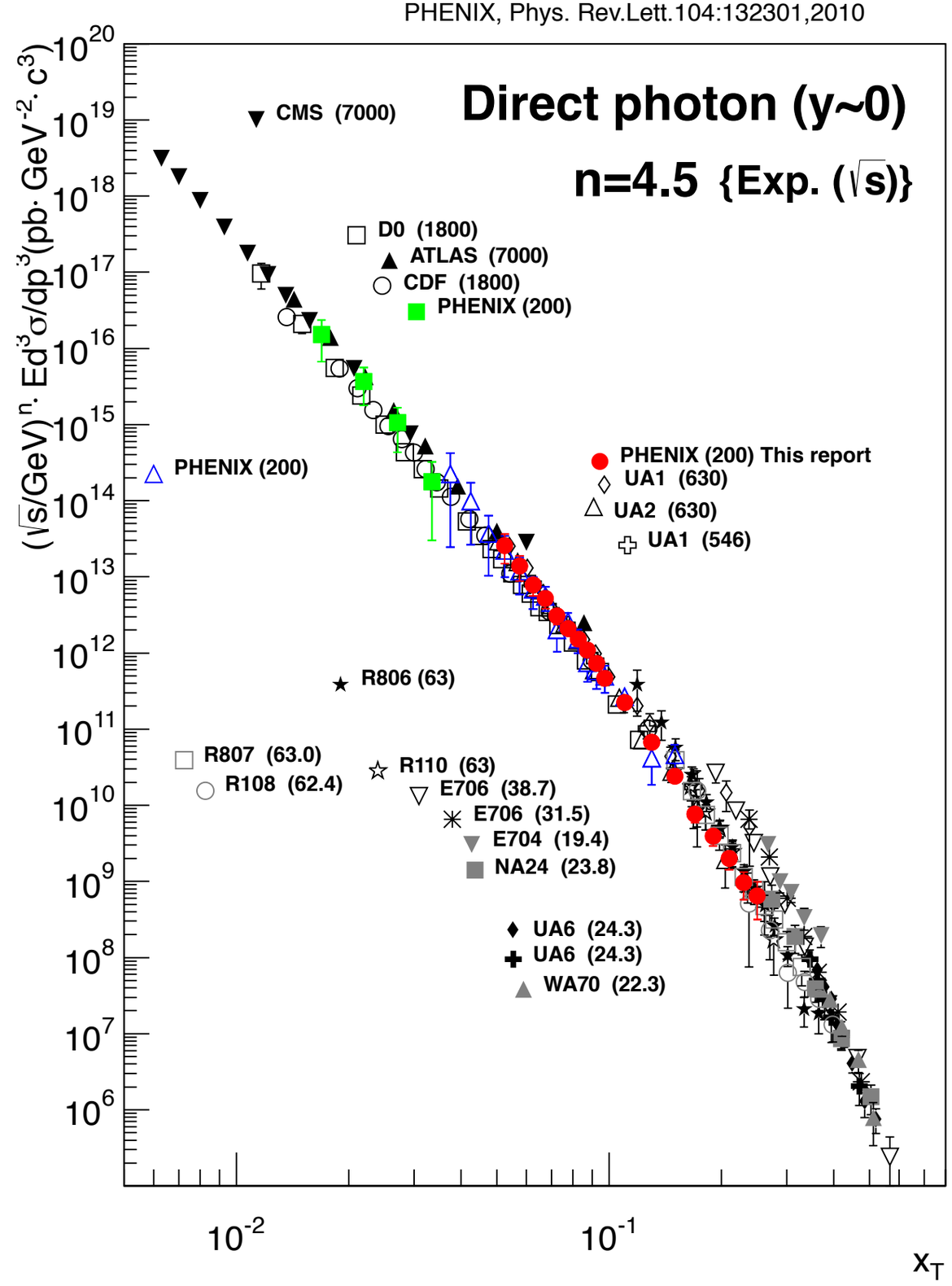




- theoretical challenges:
- high photon rates with relatively small (constant?) slope
- large anisotropy
  - favours late photon emission
- proposed:
  - “pseudocritical enhancement”?
    - maximum photon emission near transition
  - enhanced hadronic rates
    - baryonic contribution

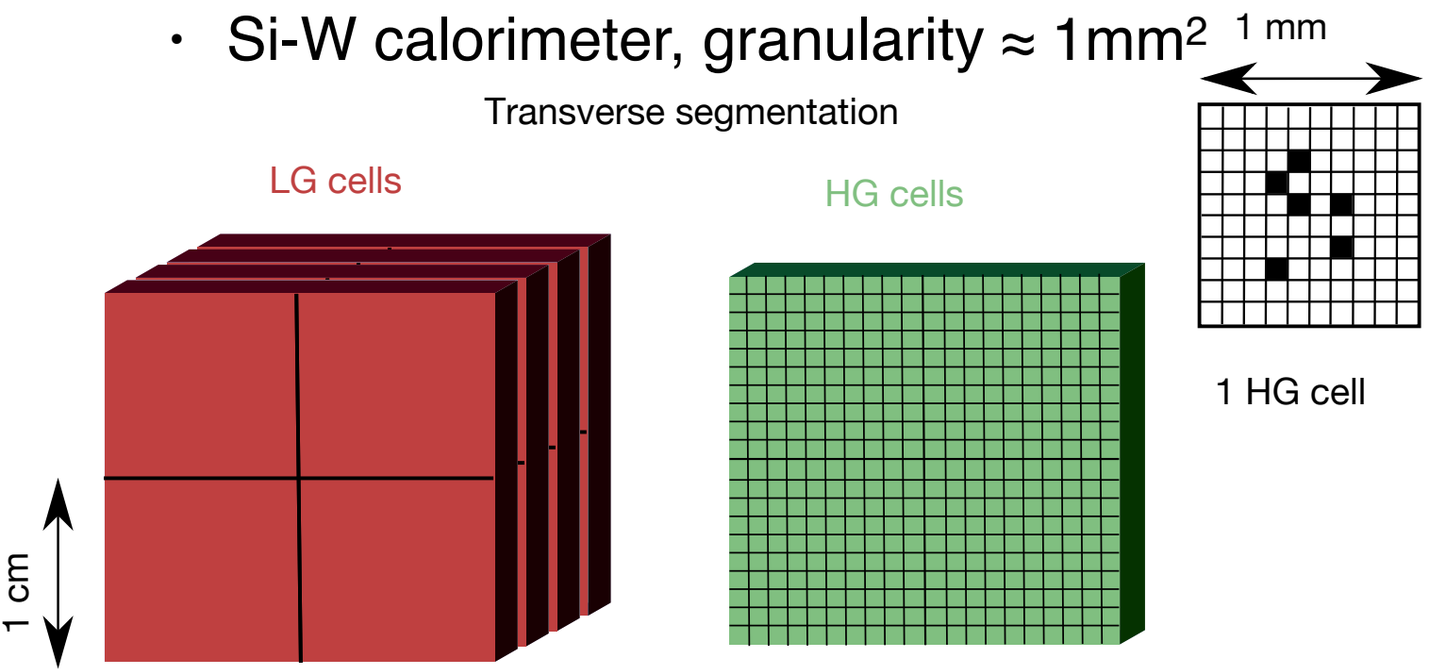
Prompt Photons Overview

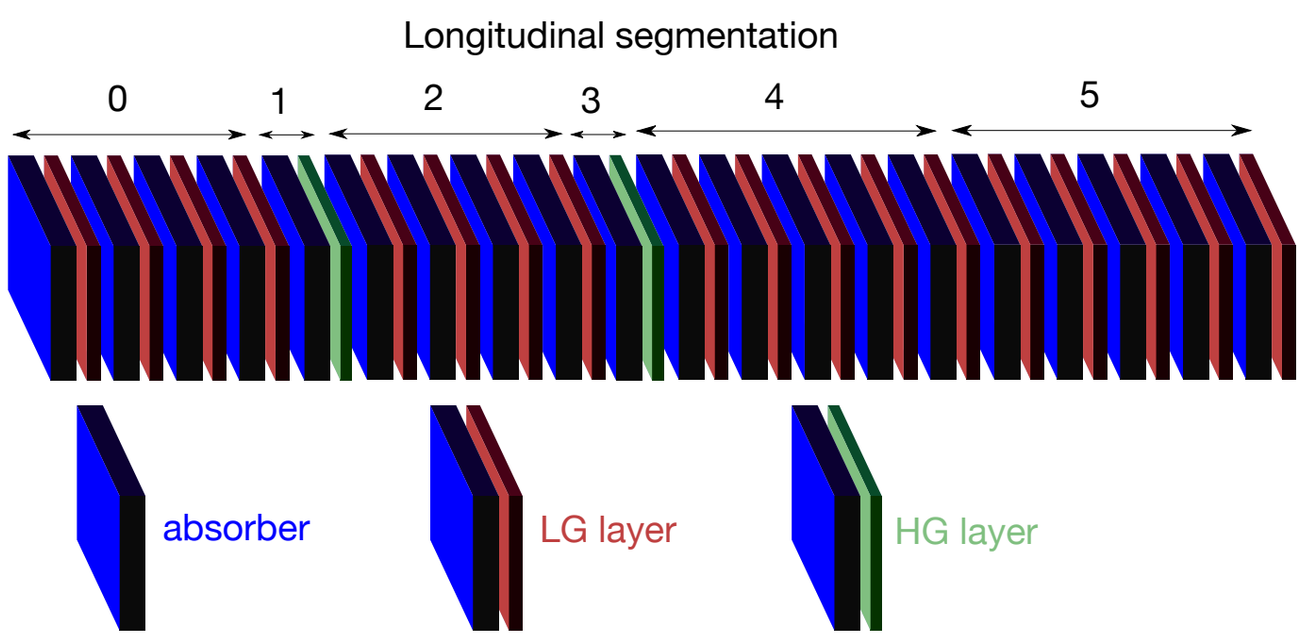
PHENIX, Phys. Rev.Lett.104:132301,2010



FoCal Strawman Design

- main challenge: separate γ/π^0 at high energy
- need small Molière radius, high-granularity read-out
  - Si-W calorimeter, granularity ≈ 1mm²



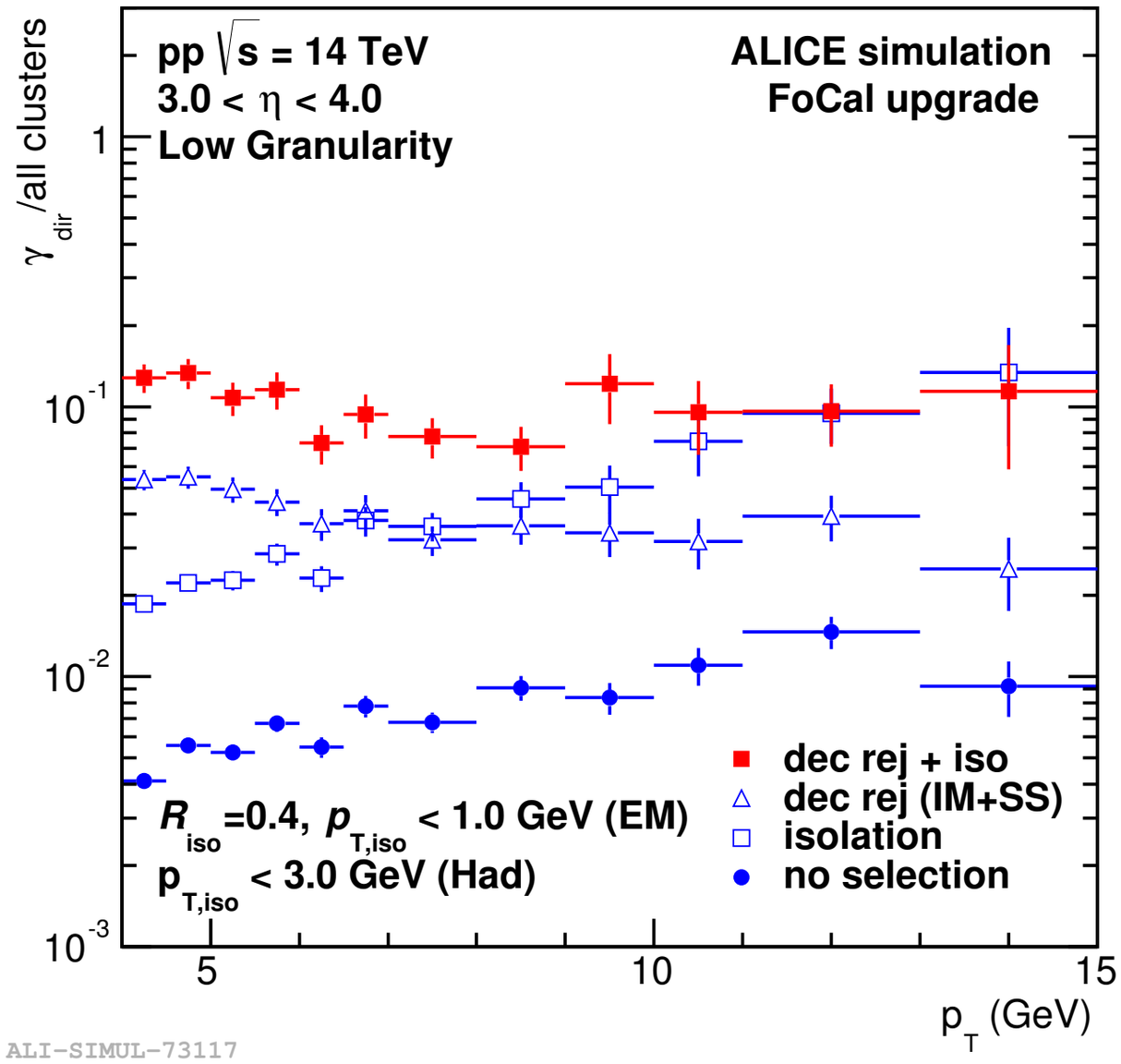


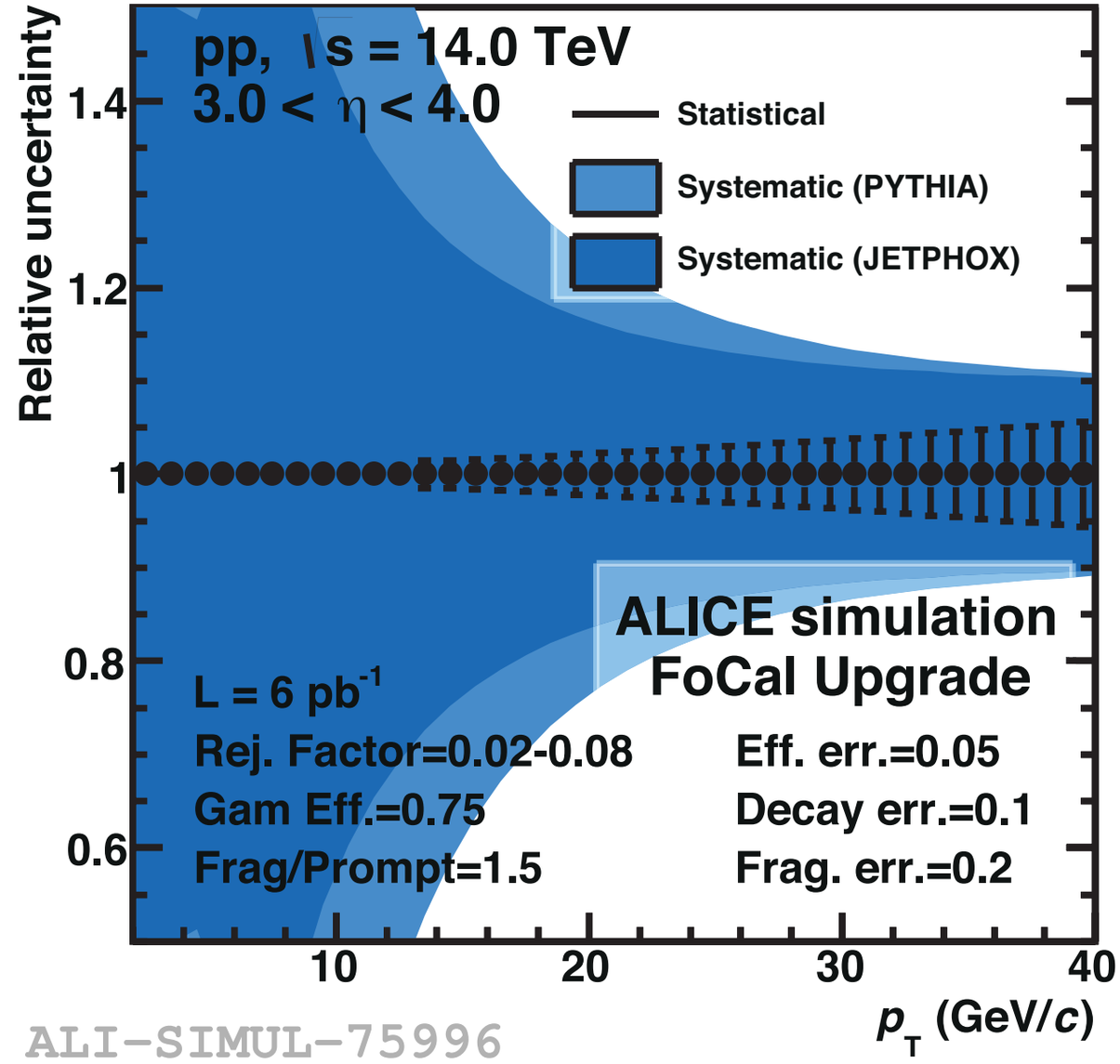
studied in performance simulations:

24 layers:
W (3.5mm ≈ 1 X_0) +
Si-sensors (2 types)

- low granularity (≈ 1 cm²), Si-pads
- high granularity (≈ 1 mm²), obtained with pixels (e.g. CMOS-MAPS)

Low Granularity Measurement





- low granularity (1cm²) does not allow efficient decay rejection
- direct photon/all ≈ 0.1 for all p_T

significant measurement not possible at low p_T

NB: conditions similar to LHCb