Photon production in high-energy collisions expectations, lessons and questions

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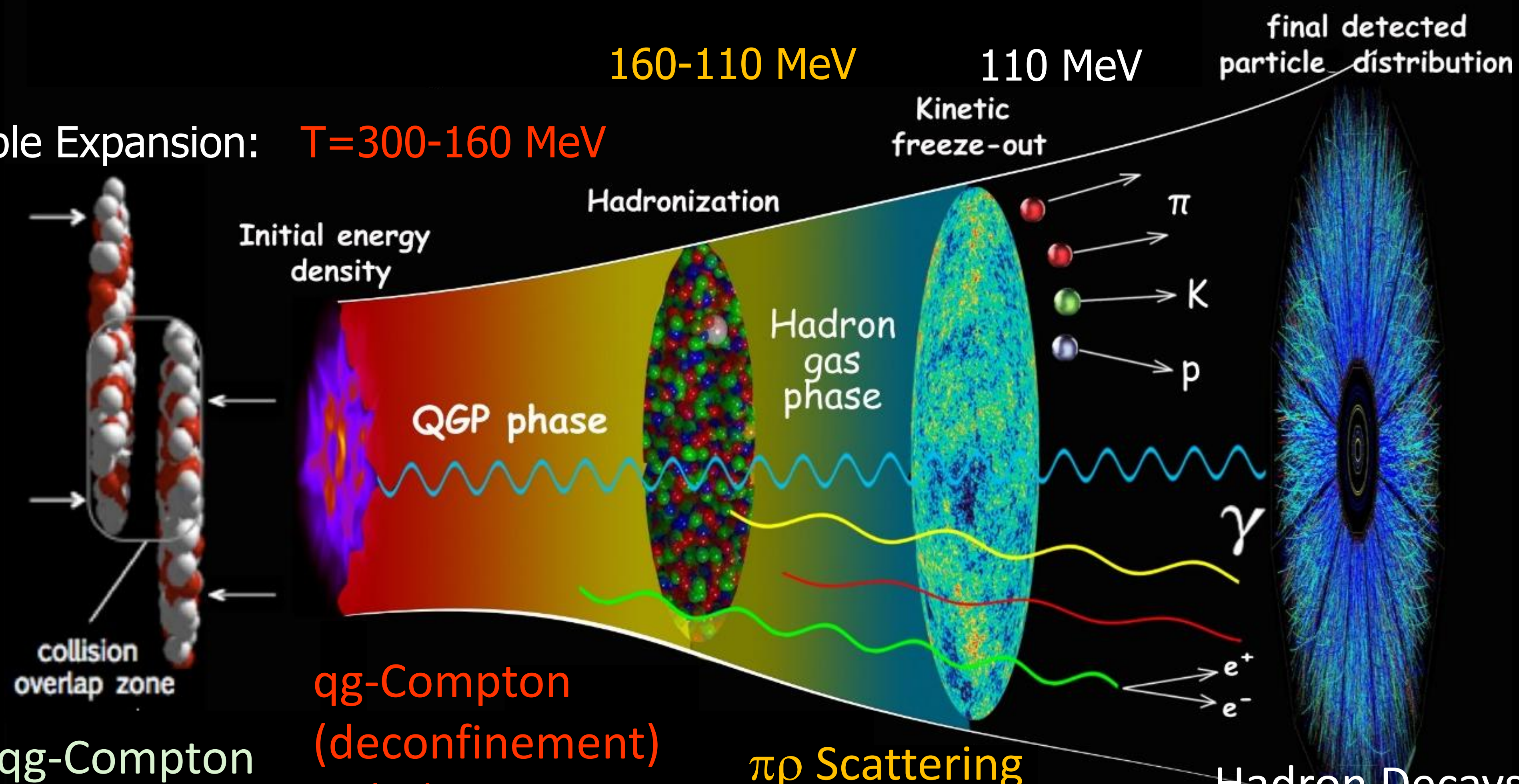
The big picture

Electromagnetic Radiation in A+A Collisions:

160-110 MeV   110 MeV

Hubble Expansion: T=300-160 MeV



Initial qg-Compton
- powerlaw spectrum
- $\propto N_{coll}$
- no collective motion

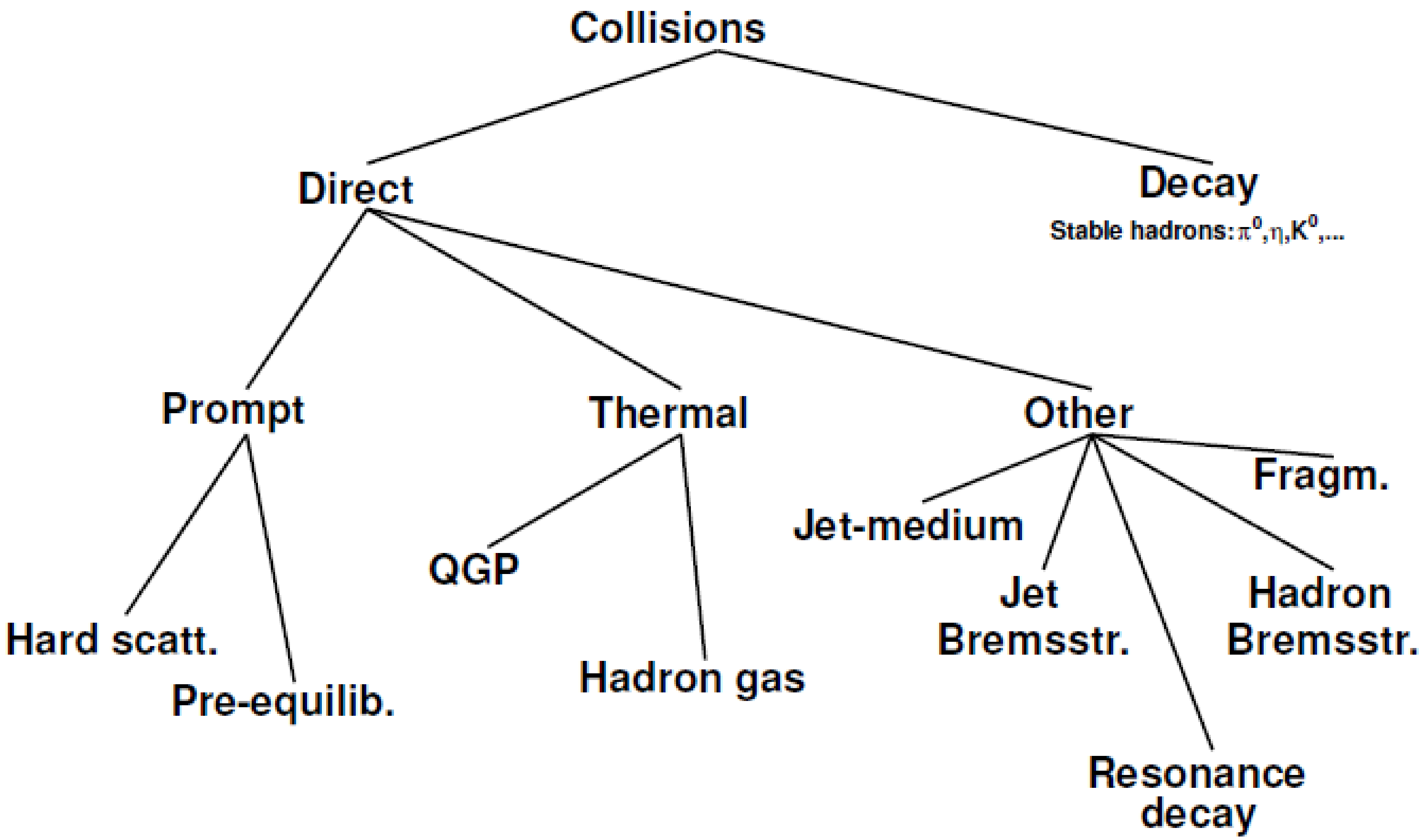
qg-Compton (deconfinement)
- high T spectrum
- little radial flow
- yield $\propto N_{ch}^{\alpha}$ $\alpha \leq 2$

πρ Scattering
- Low T spectrum
- Large flow/ blue shift
- yield $\propto N_{ch}^{\alpha}$ $\alpha > 1$

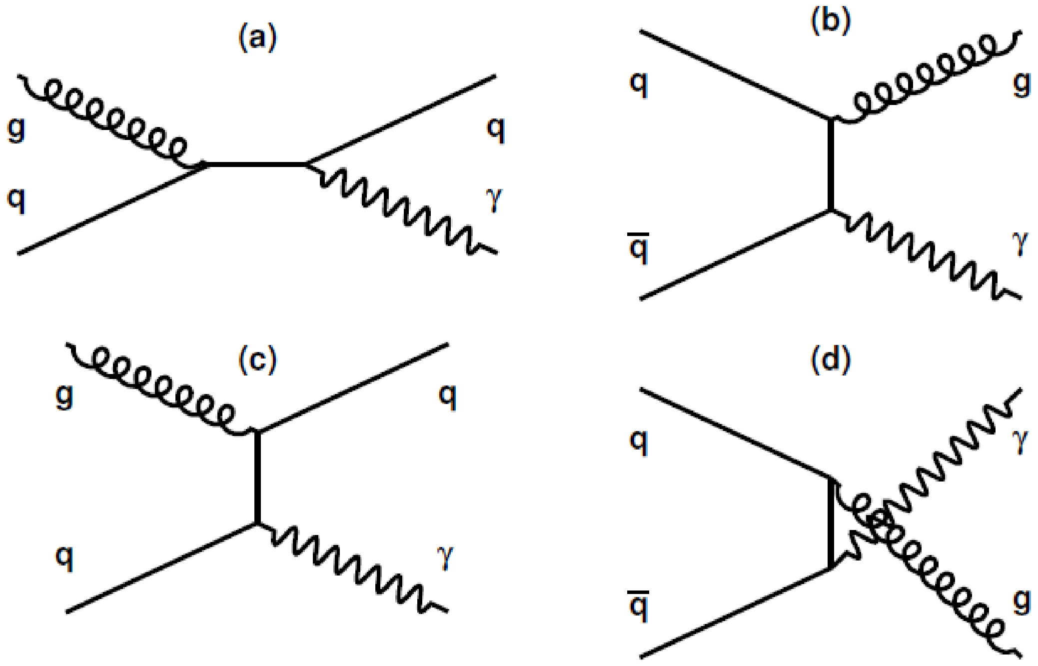
Hadron Decays
- yield $\propto N_{ch}$
- Spectra derived from parent particles

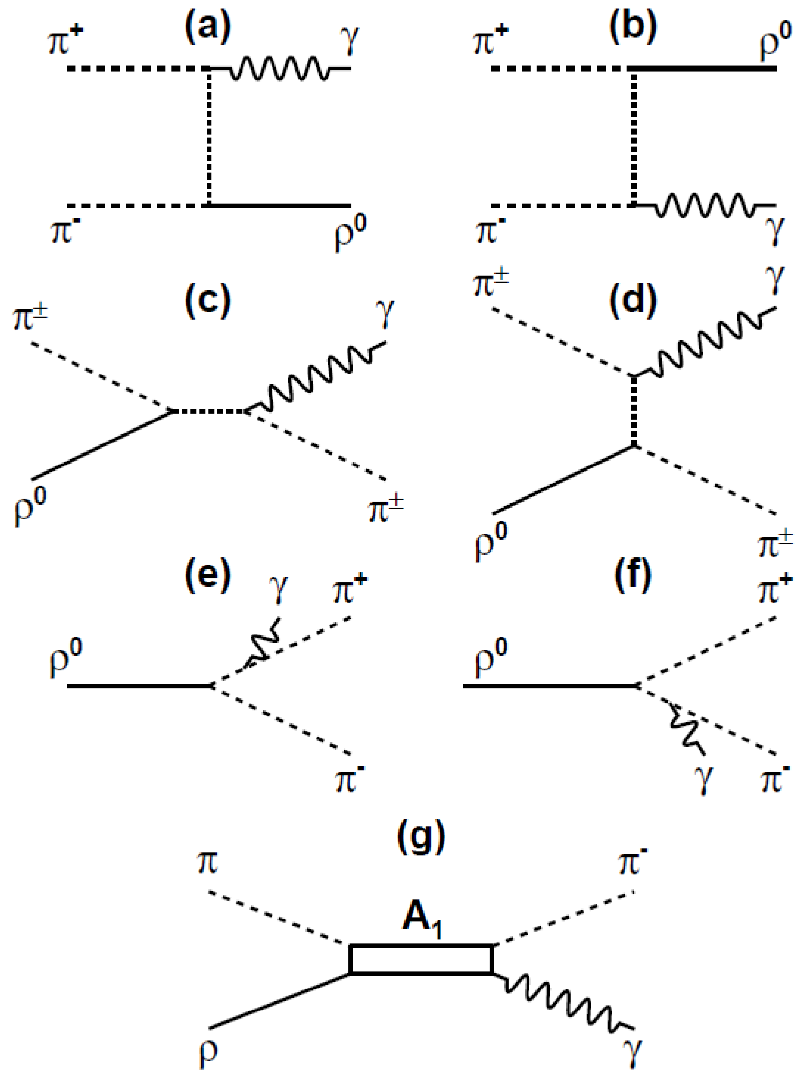
The terminology
Historians of the collision

Terminology – reflecting different sources



The basic partonic and hadronic sources

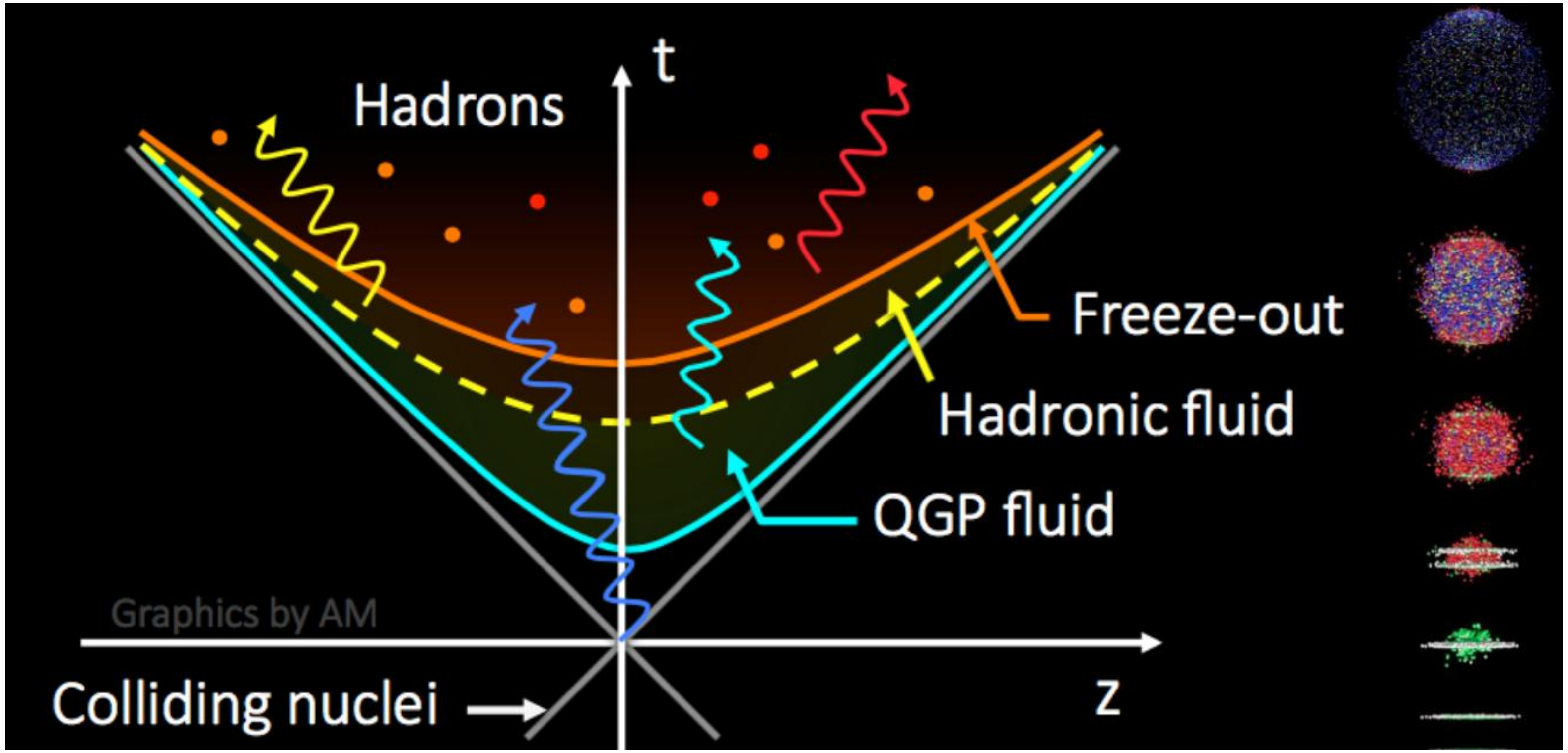


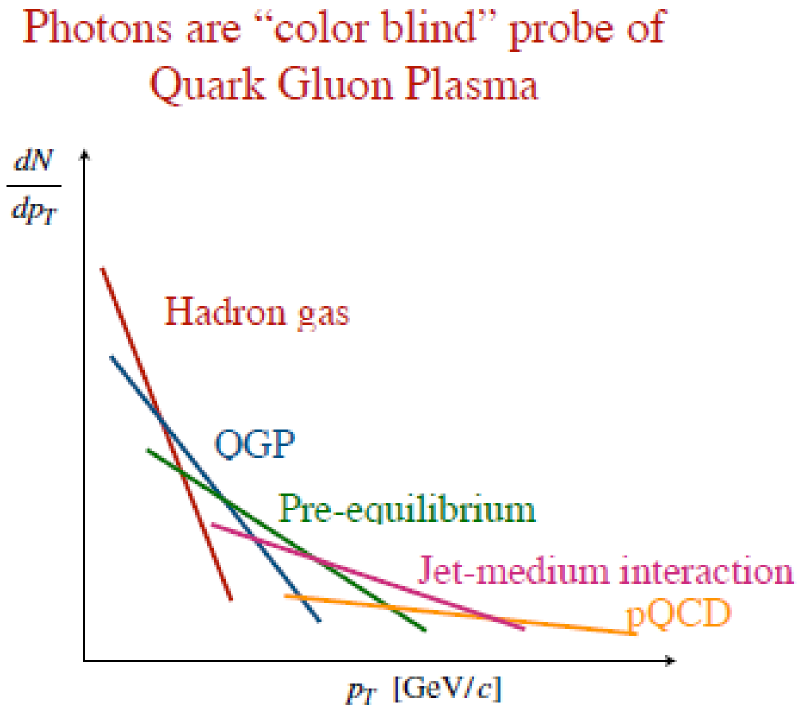


The blessing – and curse – of photons

Penetrating probes, created at all stages

Huge background (FS decays, ~10% S/B)
Hard to differentiate between sources

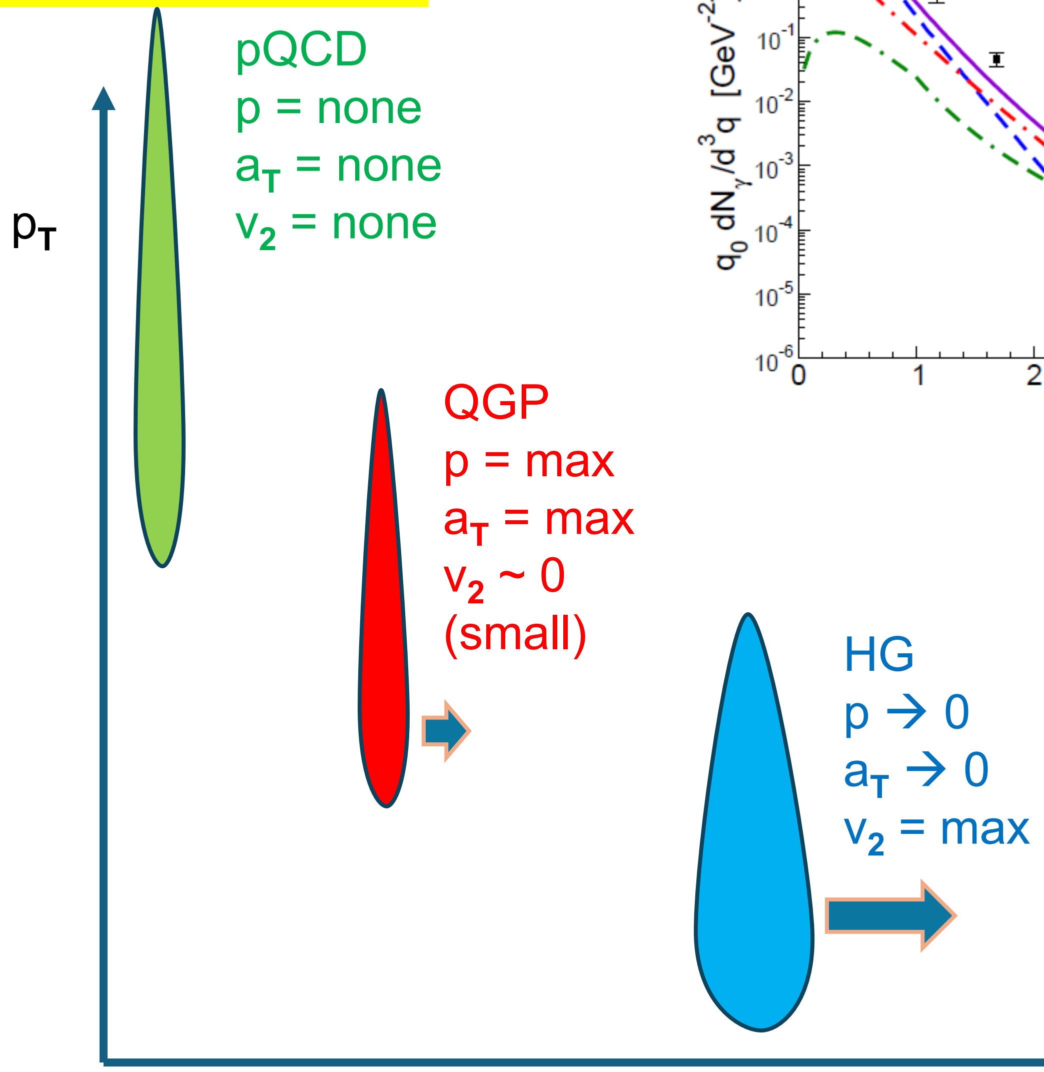


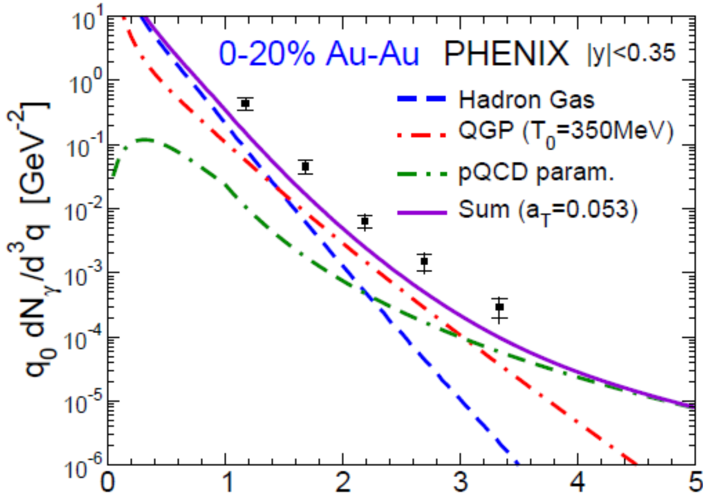


"Historians" of the collision – but convoluted

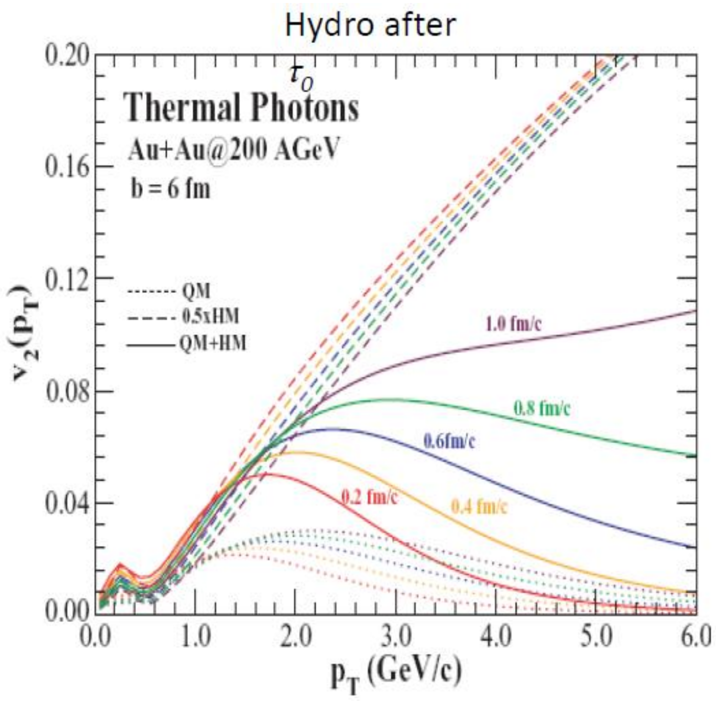
Dominant photon sources (simplified)

Prelude to the "puzzle"





In principle one can try to deconvolute the individual contributions starting from the highest p_T

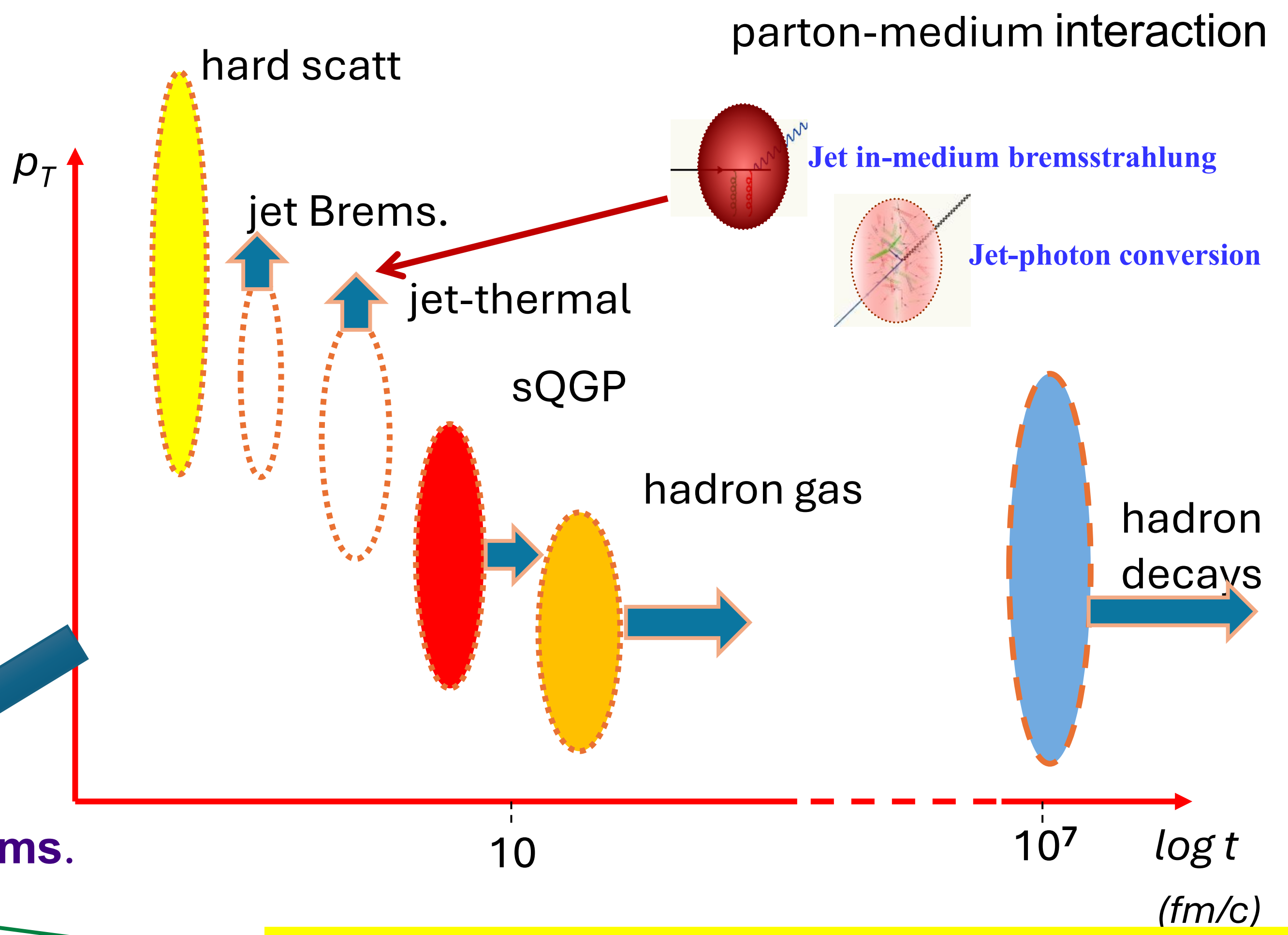


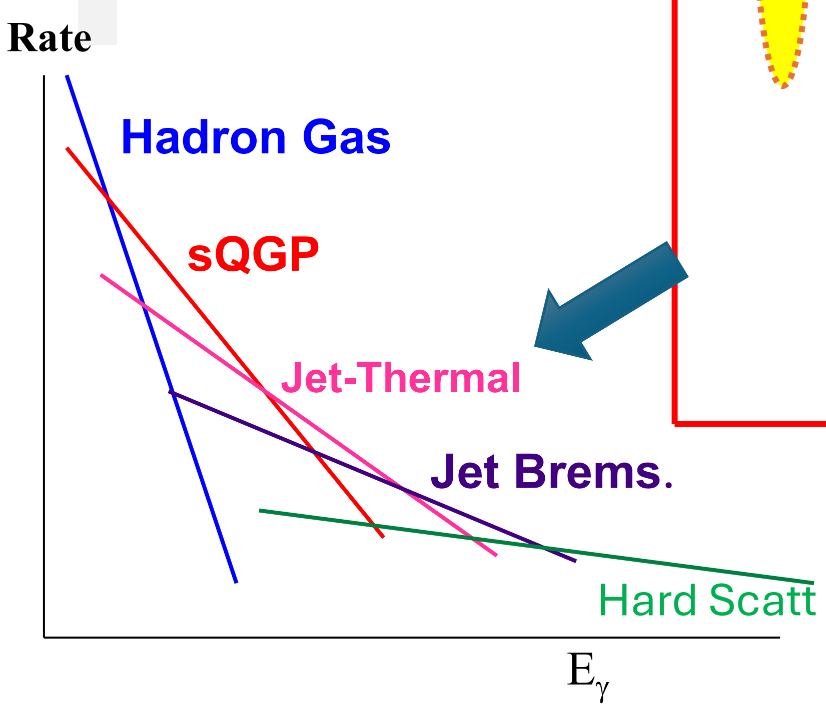
More sources…

Jet fragmentation,
Jet-thermal interaction
(jet-photon conversion)
Initial magnetic field
Bremsstrahlung (hadron gas)
…???

Obviously each new source makes the deconvolution from a single, integrated spectrum more difficult

See e.g., Turbide, Gale, Jeon and Moore, PRC 72, 014906 (2005)





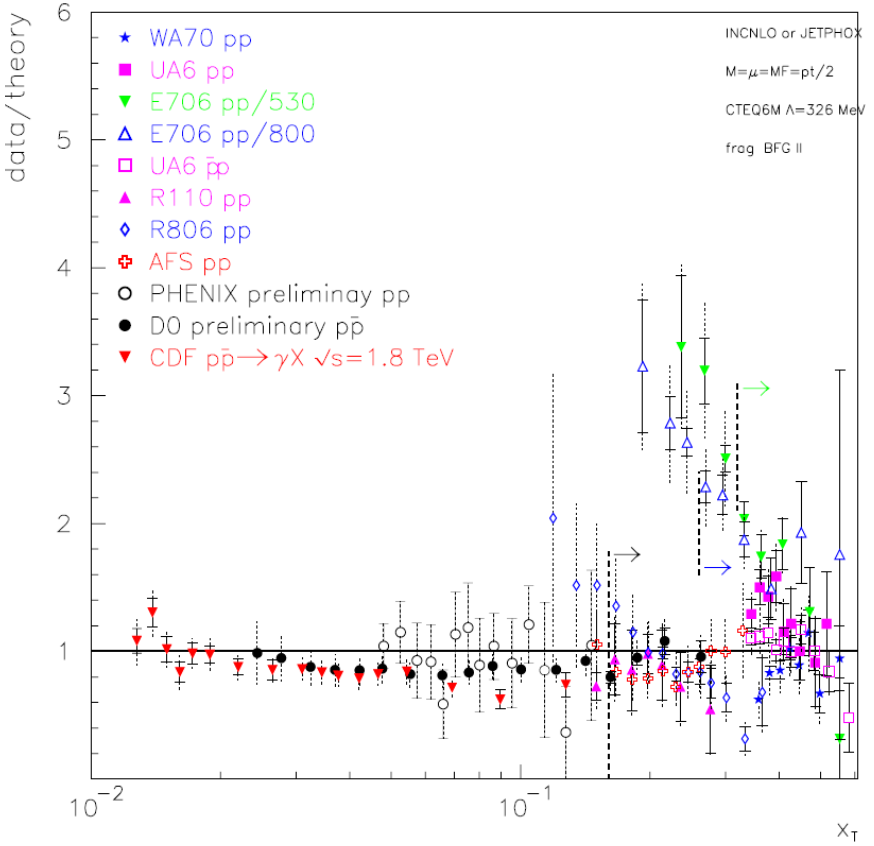
"Historians" of the collision – but convoluted

The reference – or is it? (p+p)

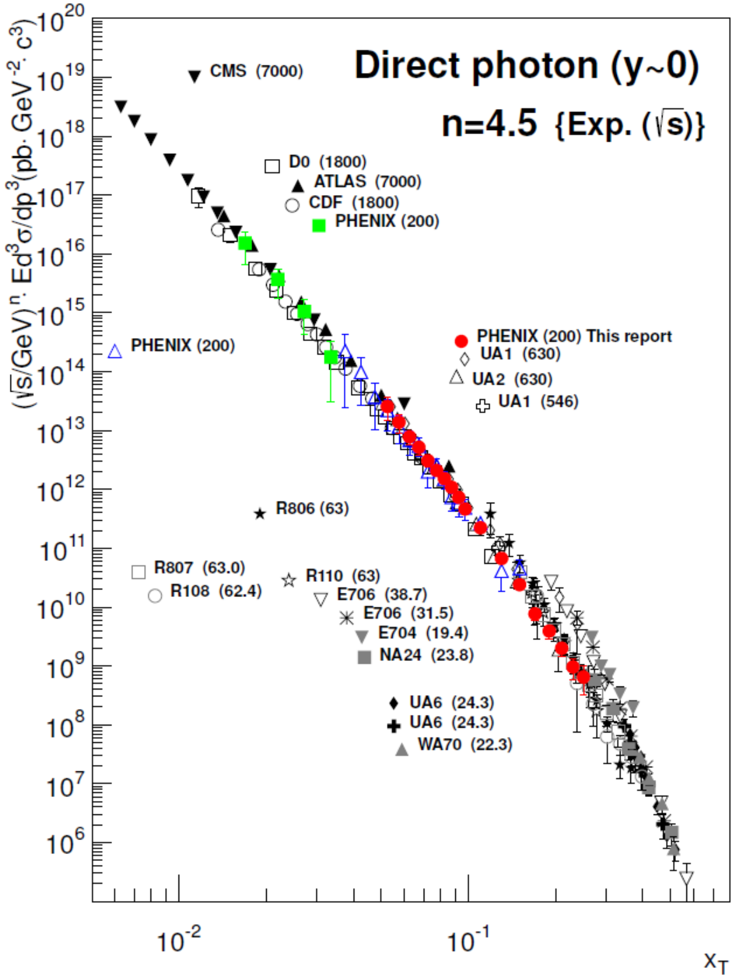
Direct photons in hadron (p+p) collisions, 22 – 7000 GeV

High p_T, scaling with x_T

PRD 73, 094007 (2006)



PRD 86, 072008 (2012)



$$E\frac{d^3\sigma}{dp^3} = \frac{d^3\sigma}{p_T dp_T dy d\phi} = \frac{1}{p_T^{n_{\rm eff}(x_T,\sqrt{s})}} F\left(\frac{p_T}{\sqrt{s}}\right)$$
$$= \frac{1}{(\sqrt{s})^{n_{\rm eff}(x_T,\sqrt{s})}} G(x_T),$$

Over 18 orders of magnitude

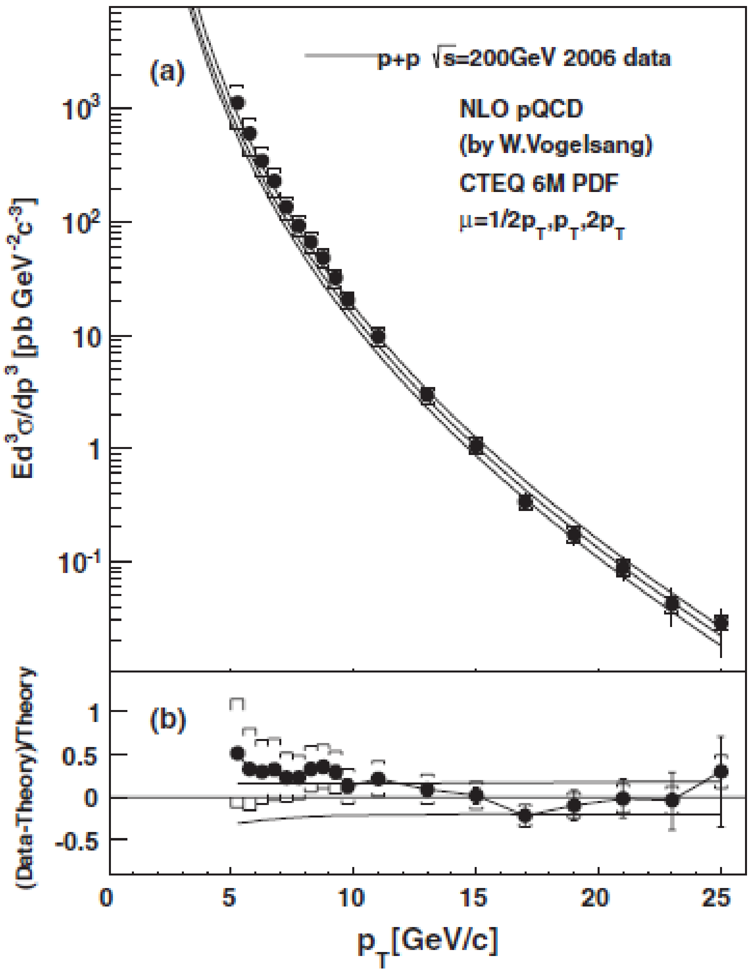
Without evolution of α_s and the structure and fragm. functions n=4

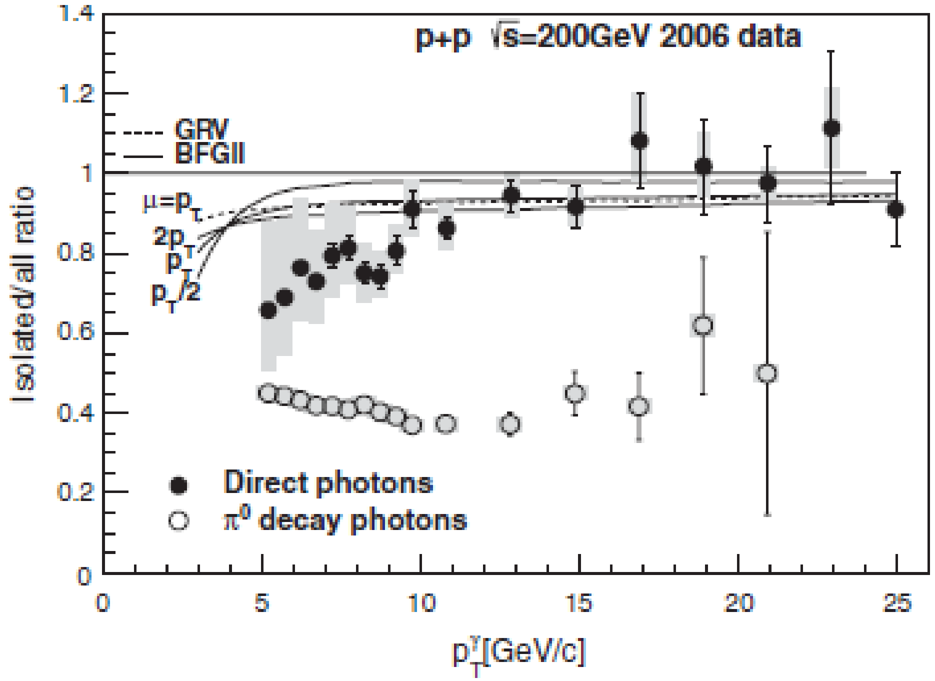
High p_T reasonably well understood

Direct photons in hadron (200 GeV p+p) collisions, 2012

Photons vs NLO pQCD

PRD 86, 072008 (2012)





Fraction of isolated direct photons

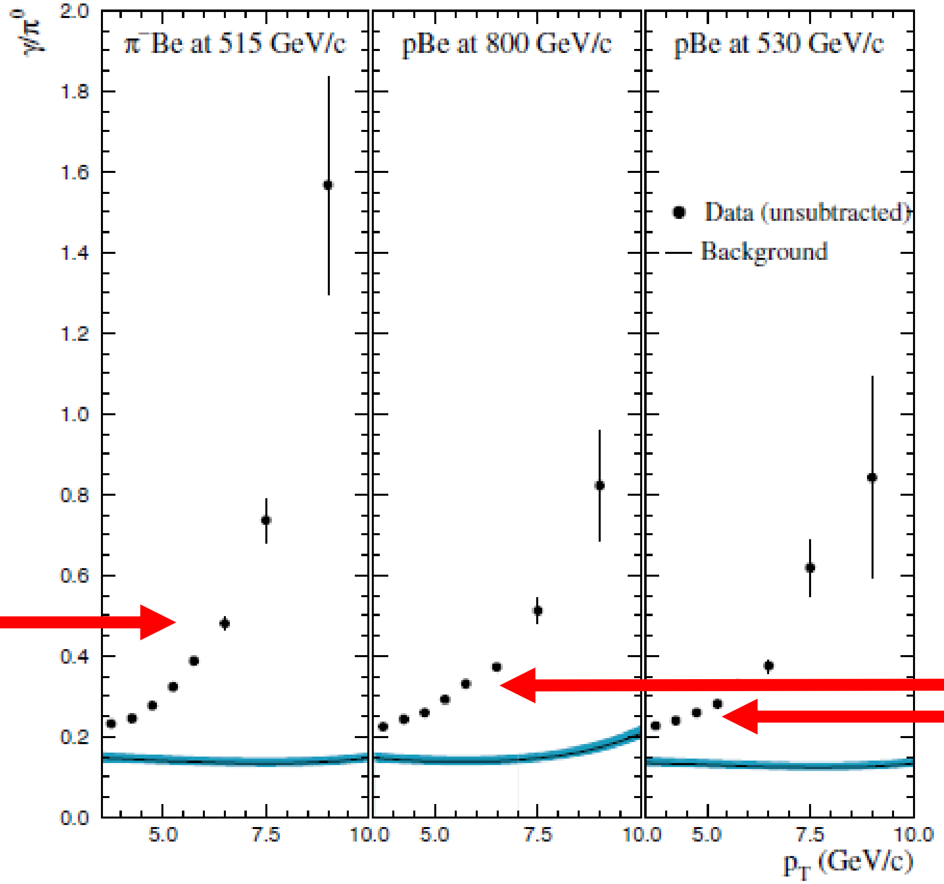
Fragmentation very small above 10 GeV/c

Possible excess below 10 GeV/c?

Interlude: Compton scattering dominates over annihilation

E706, fixed target, p and π^- beam

PRD 70, 092009 (2004)



Valence antiquark present

No valence antiquark

Only sea antiquarks in proton
→ small probability for high p_T photon from annihilation

Valence antiquark in p-
→ high p_T photon production increased

Not quite direct proof (γ/π^0), but strong

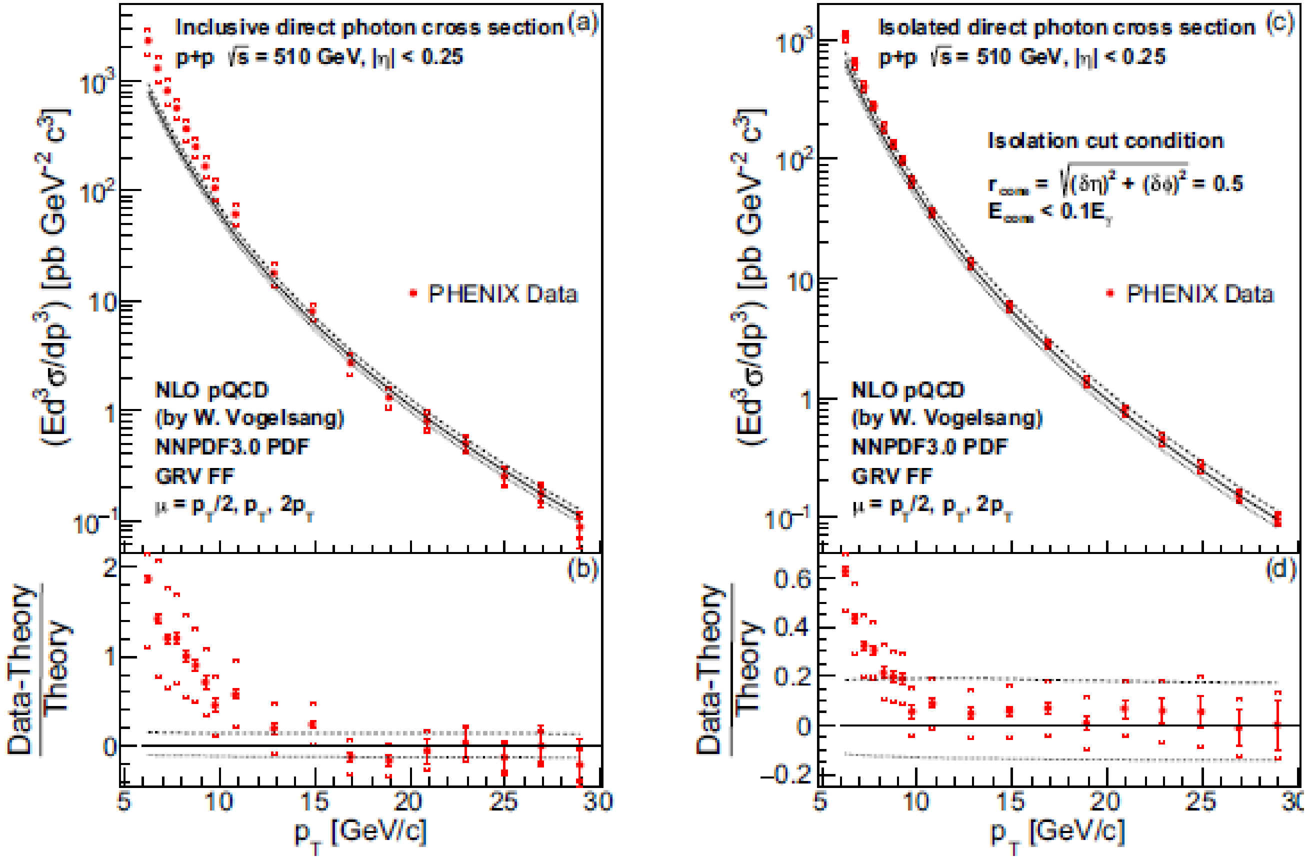
We knew this, but good to see experimentally

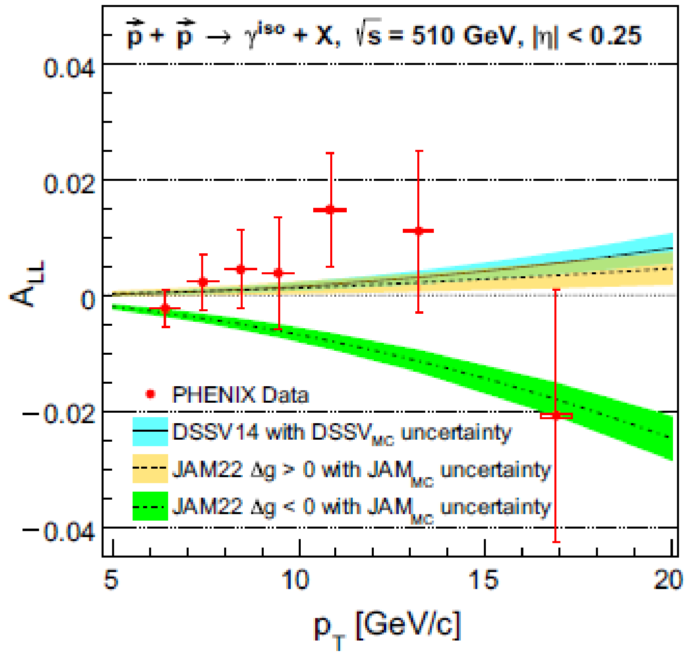
Direct photons in polarized 510 GeV p+p collisions

Polarized gluon contribution to proton spin?

PRL 130, 251901 (2023)

A_{LL} – longitudinal double spin asymmetry





Disfavors netagive Δg

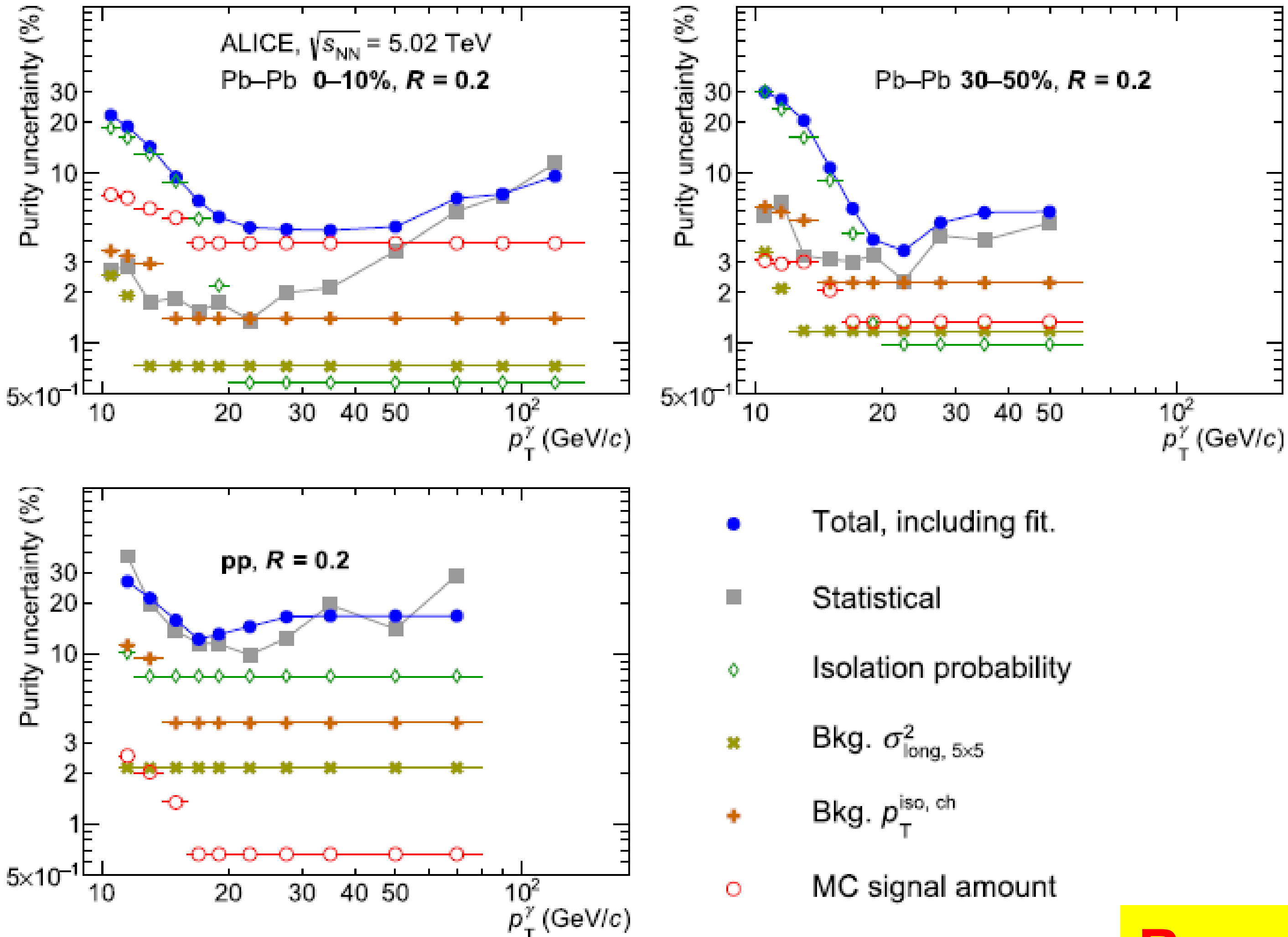
Similar discrepancy below 10 GeV/c, as in 200 GeV collisions – even for isolated photons

Small, positive contribution from gluon

Technical – isolated photon uncertainties (ALICE)

Can you still isolate in PbPb?

Eur. Phys. J. C (2025) 85:553



Isolation cut purity – uncertainties
→ this is the overwhelming term in the total uncertainty on cross-section

Isolation probability
→ ratio of shape distributions of iso and non-iso constant?

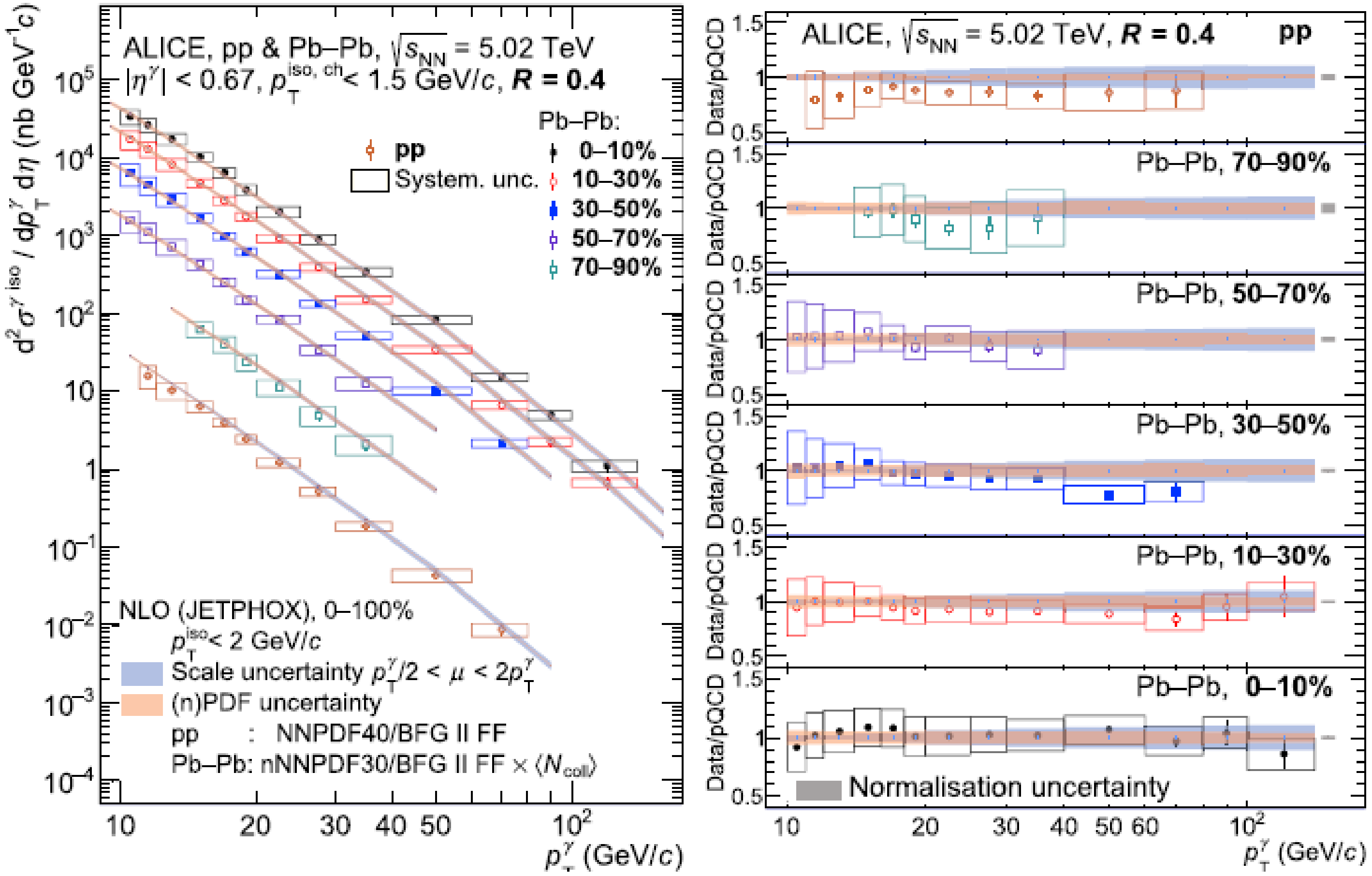
MC signal amount
→ varying signal (γ-jet) by 20% w.r.t. bgd (jet-jet)

Reverse ordering in PbPb vs pp

High p_T isolated photons,, pp and PbPb 5.02 TeV (ALICE)

Is the high p_T region understood?

Eur. Phys. J. C (2025) 85:553

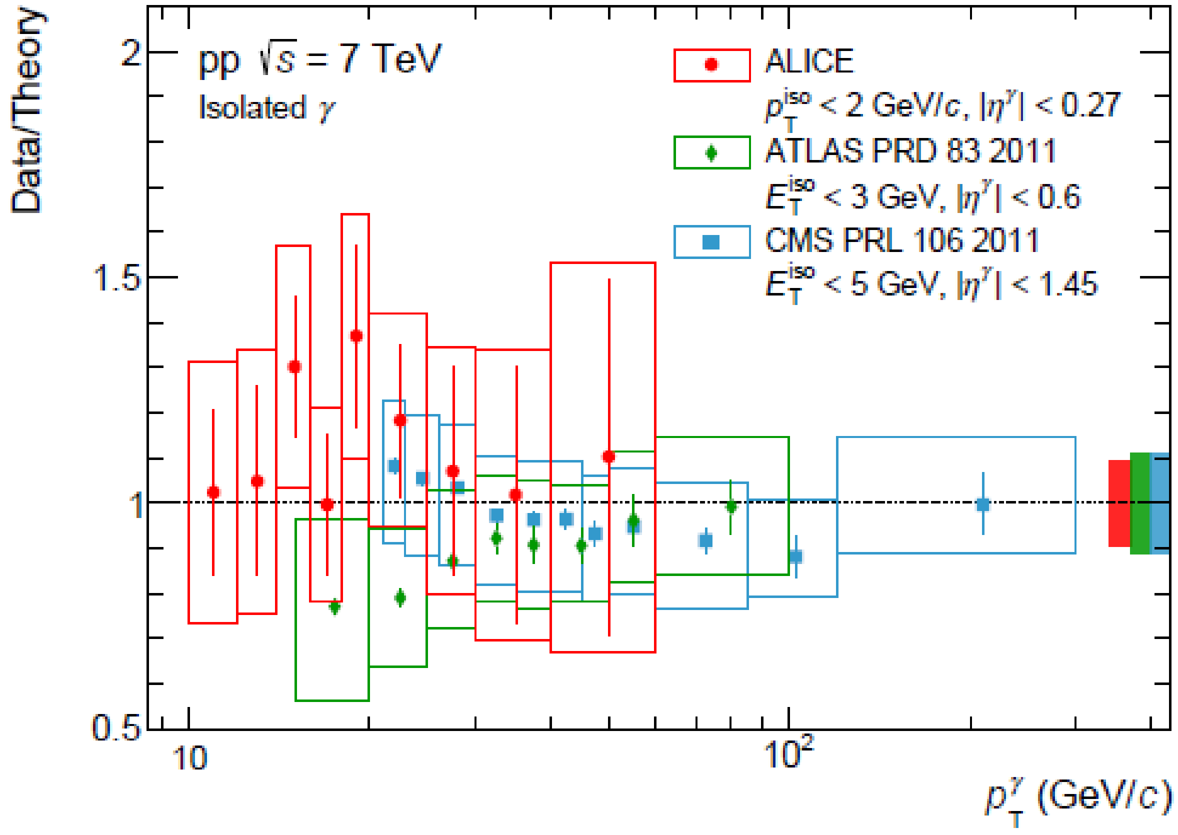


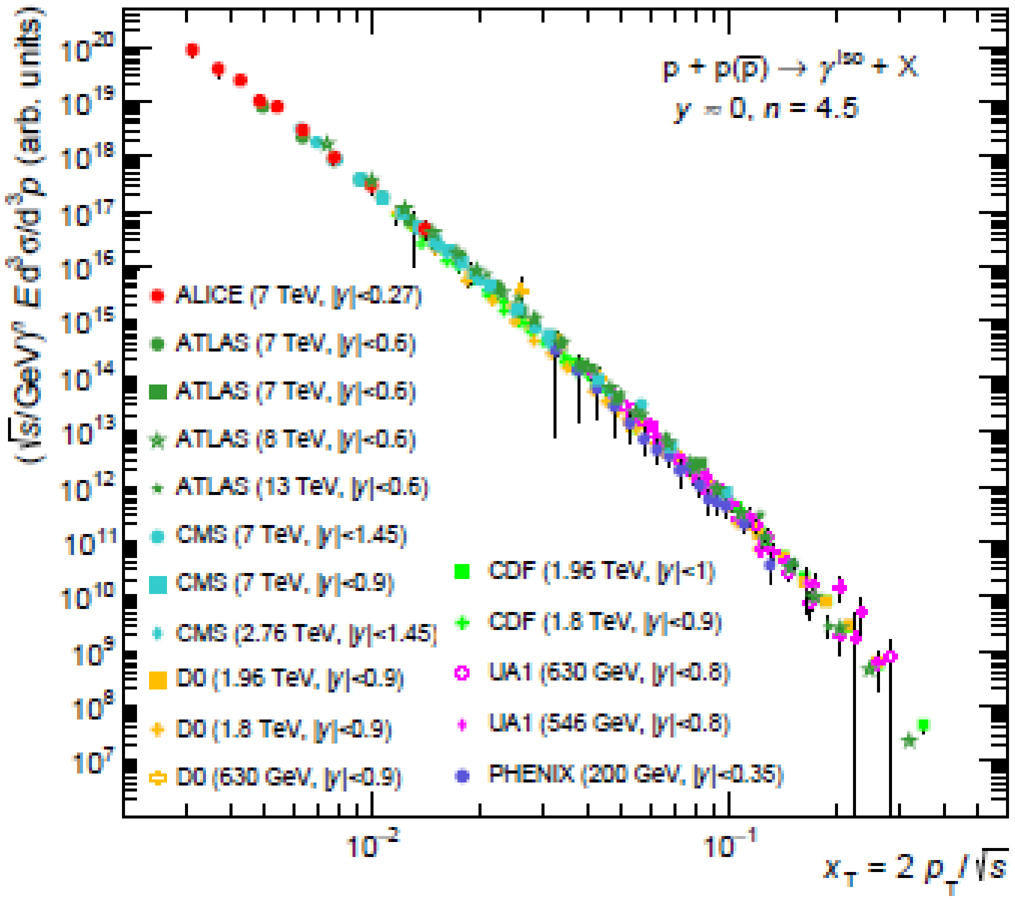
All consistent with JETPHOX pQCD

High p_T isolated photons,, pp 7 TeV (ALICE, ATLAS, CMS)

Is the high p_T region understood?

Eur. Phys. J. C (2019) 79:896



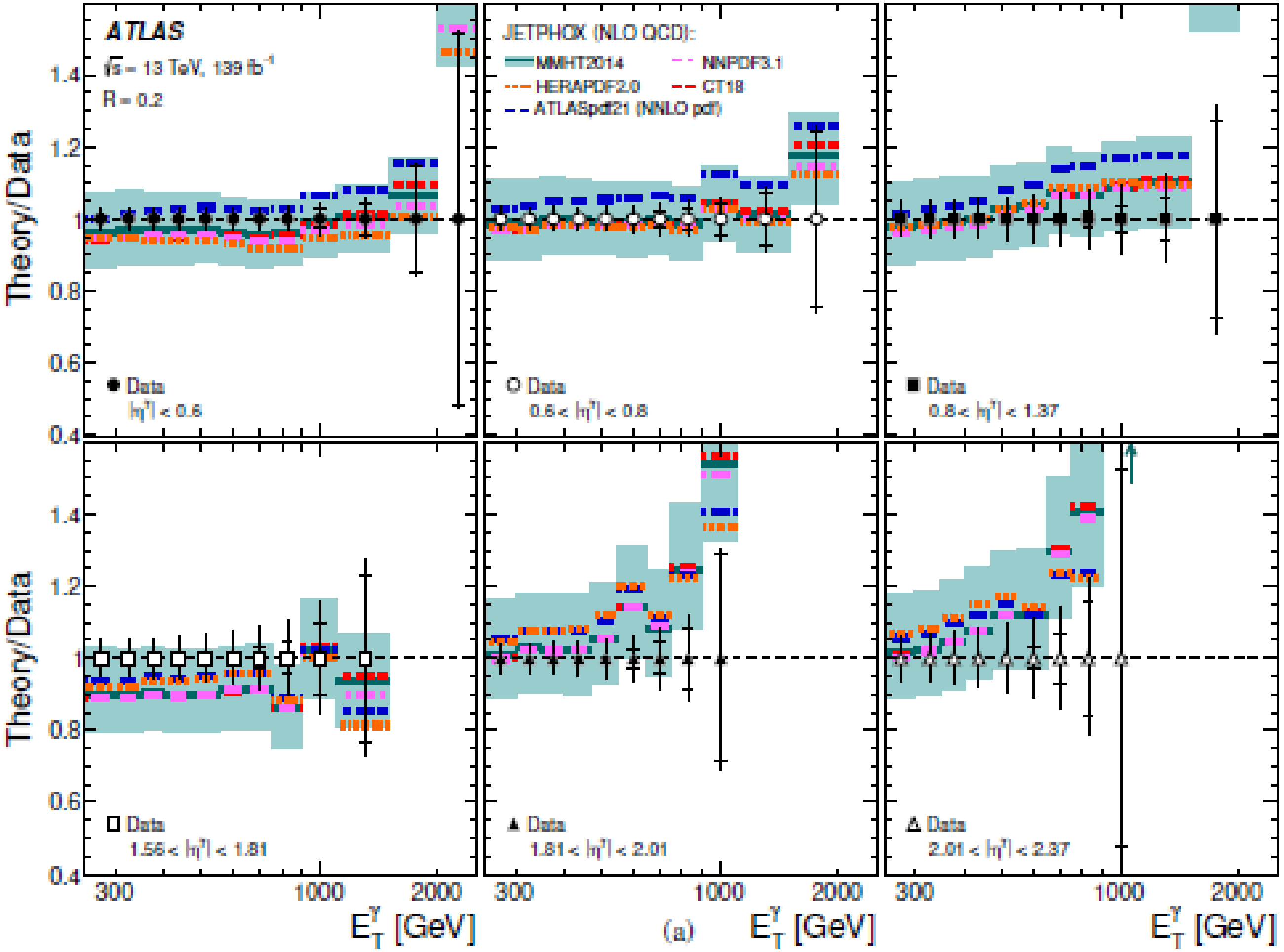


All consistent with JETPHOX pQCD

High p_T isolated photons,, pp 13 TeV (ATLAS)

Rapidity dependence?

JHEP07 (2023) 086



Not well described by JETPHOX pQCD

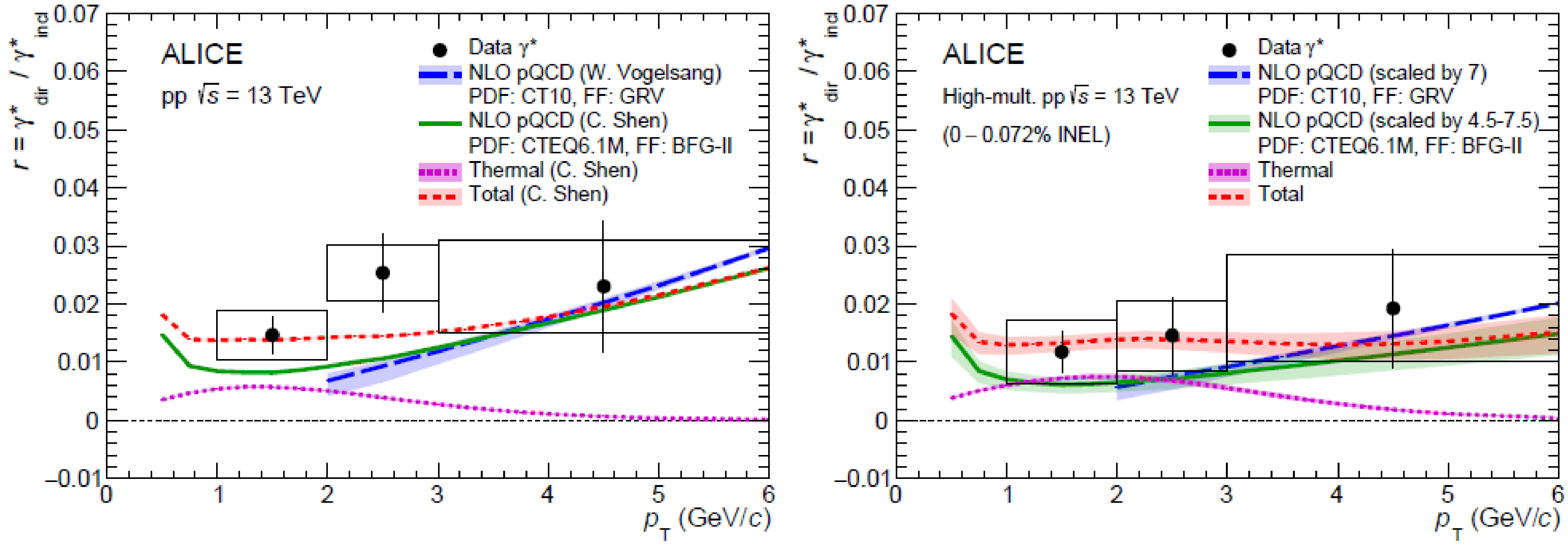
Digression: low p_T photons,, pp, 13 TeV (ALICE)

QGP even in high multiplicity pp?

PLB 868 (2025) 139645

Something like QGP formed already in the highest multiplicity pp events, too?
Internal conversion → γ*

$$r = \gamma^*_{dir} / \gamma^*_{had}$$



No sign of additional "thermal" radiation

Experimental techniques

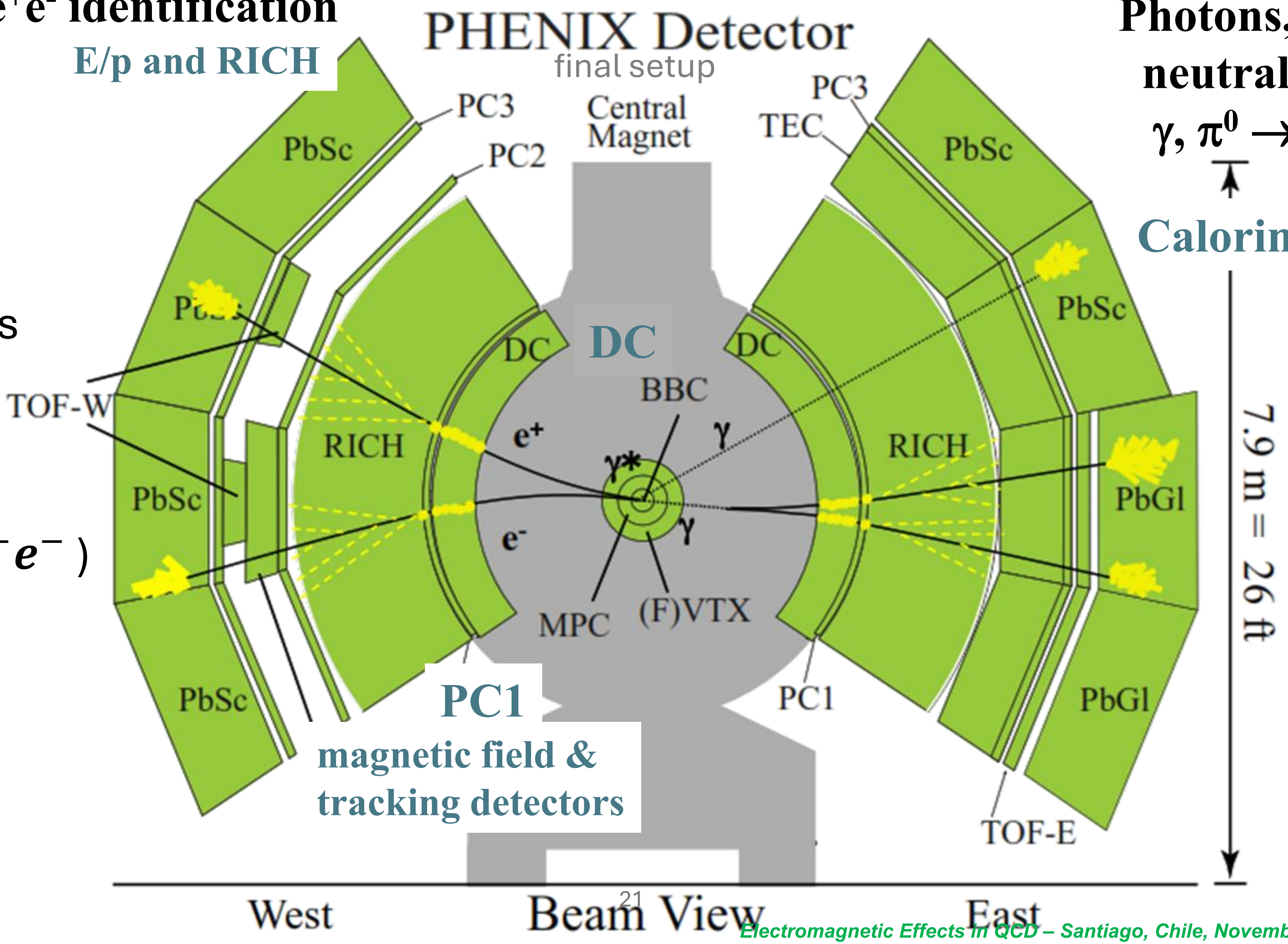
Photon measurements in PHENIX

e^+e^- identification
E/p and RICH

Virtual Photons
$\gamma^* \rightarrow e^+e^-$

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

Photons,
neutral pion
$\gamma, \pi^0 \rightarrow \gamma\,\gamma$
Calorimeter



PC1
magnetic field & tracking detectors

Basic techniques of photon measurements: calorimetry

Real photon captured in an electromagnetic calorimeter

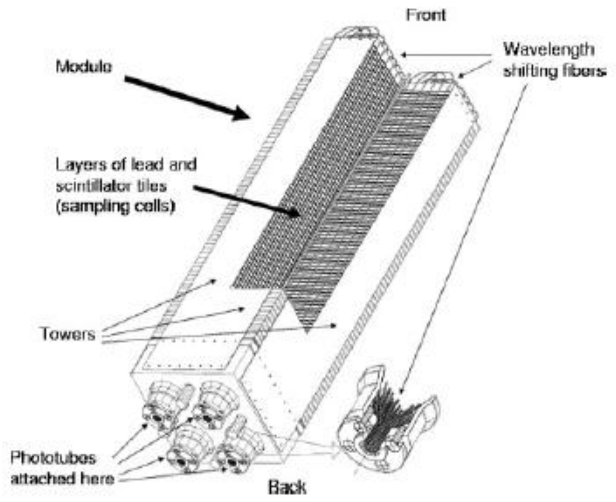
Electromagnetic calorimeter

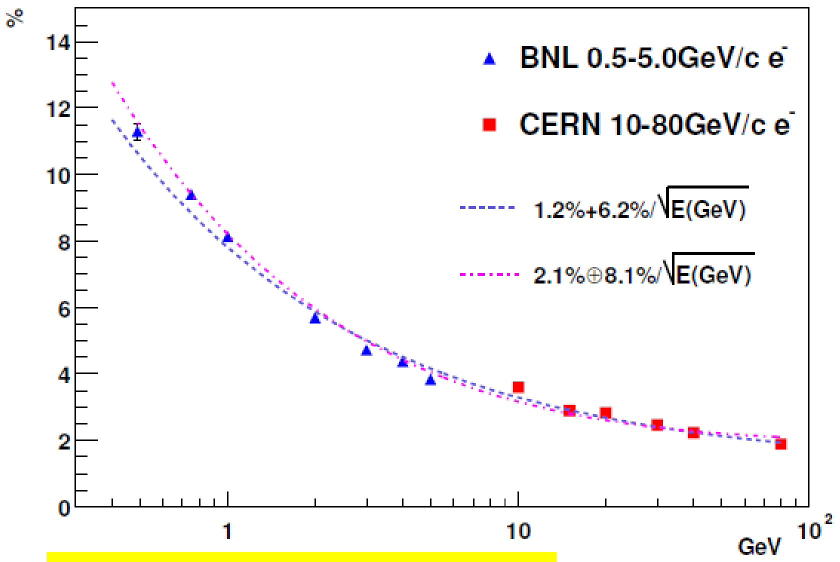
- relatively cheap, large acceptance possible (sampling)
- resolution improves with energy (ideal at high p_T)
- “thin” for hadrons
  → high energy cluster (almost) always electromagnetic
  deposited energy counts, not particle momentum!
- measurement can be almost standalone

But

- issues with resolution and hadron background at low p_T
- issues with merged π^0 decay photons at very high p_T

These can be mitigated: shower maximum detectors (SMD), small Moliere-radius crystal calorimeters, digital calorimeters
→ but at substantial cost increase

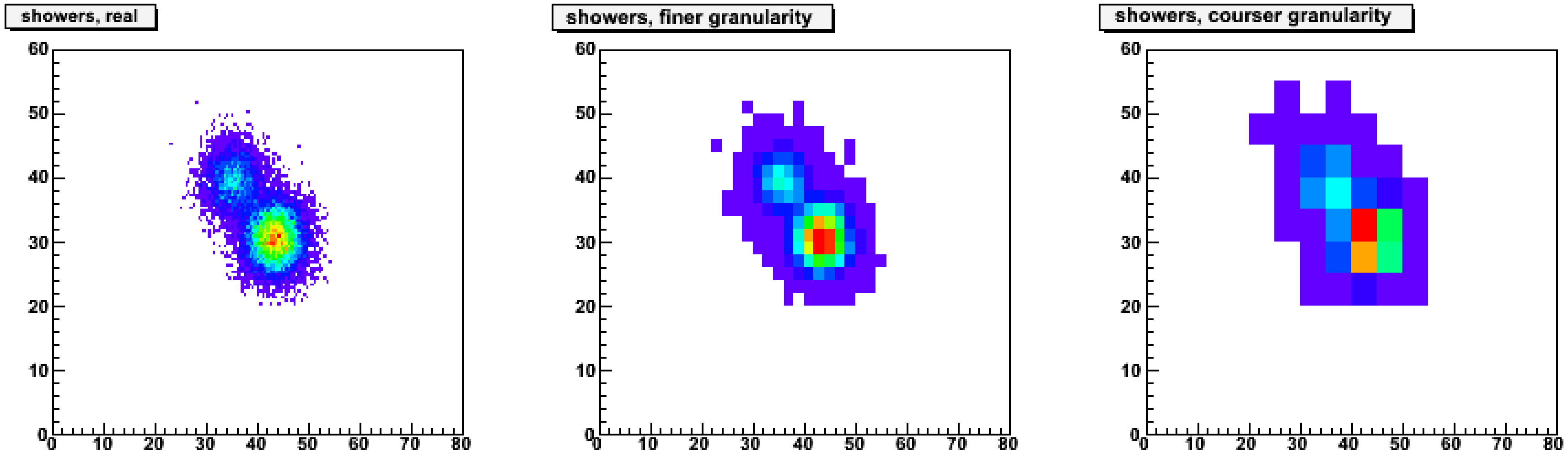




Best at high p_T

Close-by showers – real and as seen

Nature meets detector…



Very high granularity:
- well separated, good measurement for both energy and position

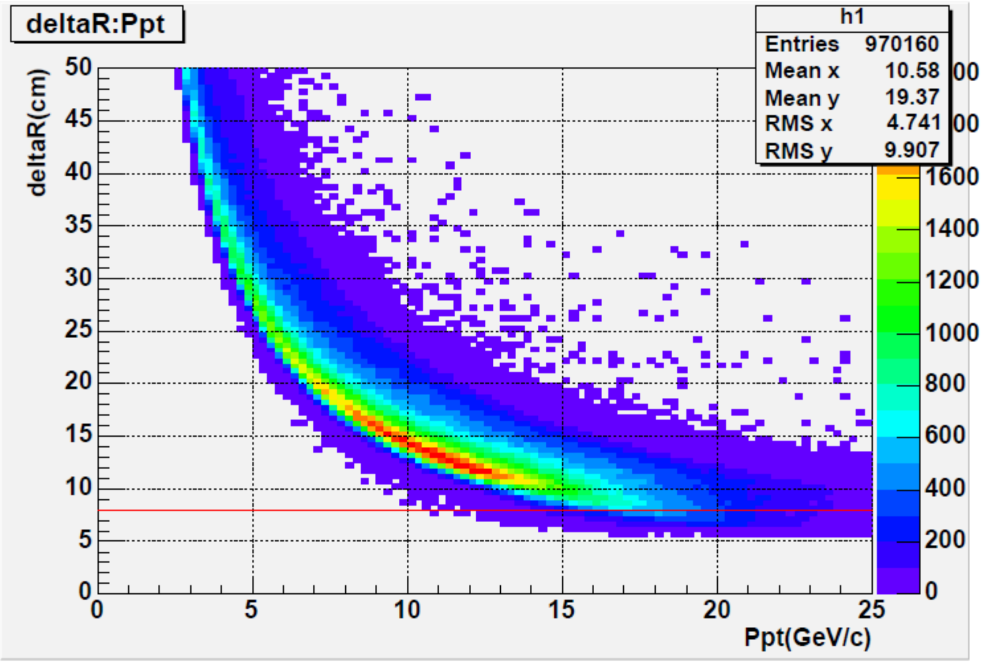
Medium granularity:
- well separated, decent measurement for energy, some shift in position, pair p_T still correct

Low granularity:
- poor separation. questionable energy sharing, position shift, pair p_T still ~correct

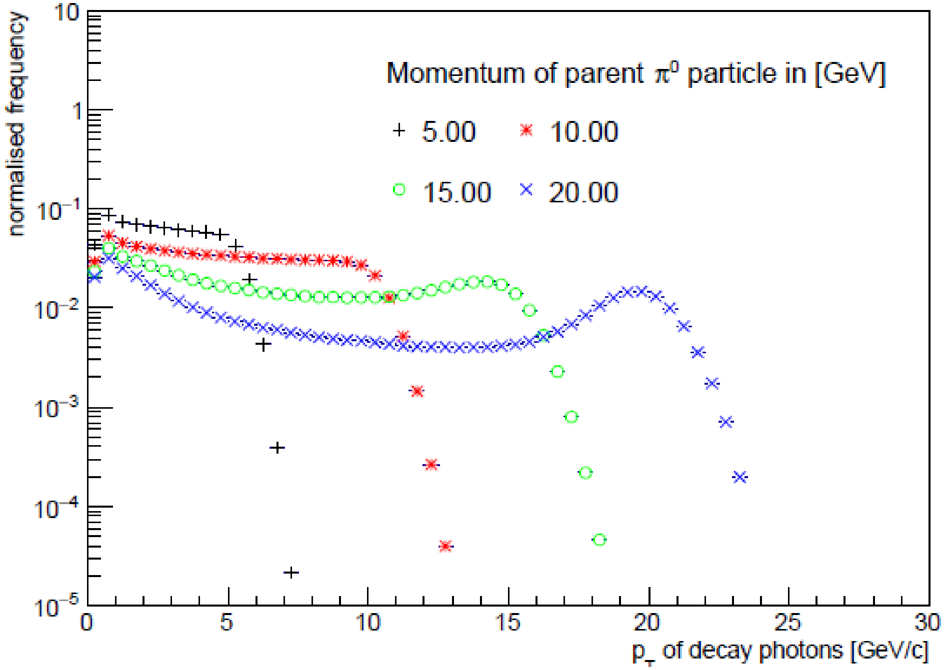
… and loses sometimes

Zooming in on the π^0 problem (at high p_T)

Do you think π^0 decays to two ordinary photons?
WRONG! It decays to two correlated photons



PHENIX – distance between two clusters photons from a π^0 decay



The distribution of measured decay photons should be flat up to the kinematic limit. Instead, you see depletion at medium, enhancement at high p_T. Unless you fully understand this, your direct photons at high p_T will be strongly overestimated!

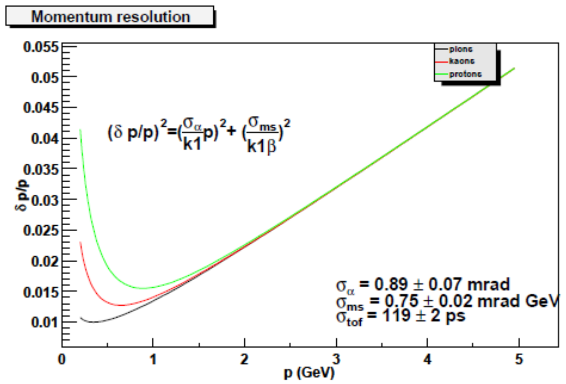
Possible clue to E706?

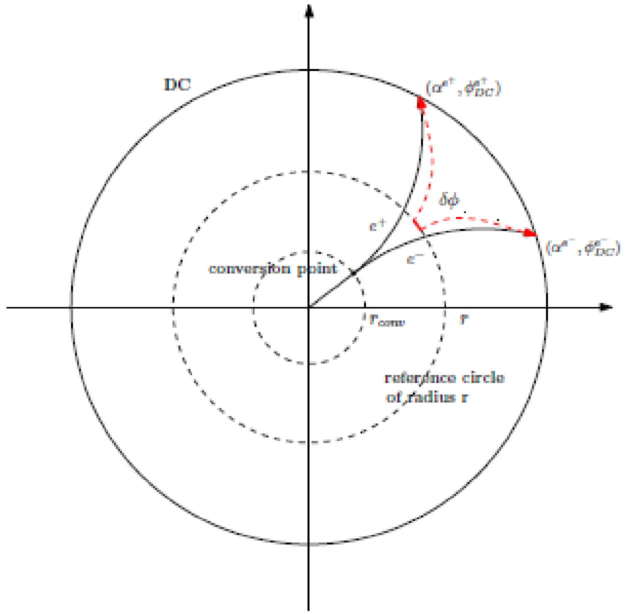
Basic techniques of photon measurements: external conversion

Wenqing Fan, SBU, PhD thesis

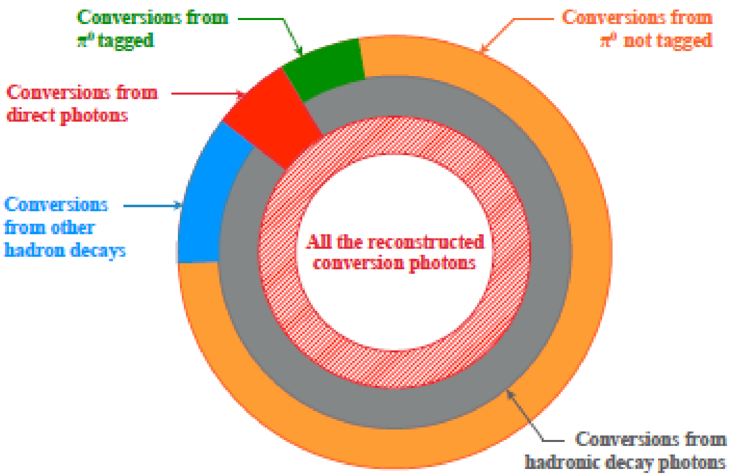
Real photon converts to e^+e^- on detector material

Pro:
- tracking: higher resolution
- viable at low p_T
- not sensitive to Dalitz (origin!)
- feasible in "crowded" detectors





Con
- electron ID difficult
- small acceptance*efficiency
- sensitive to material location
- cocktail (discuss later)

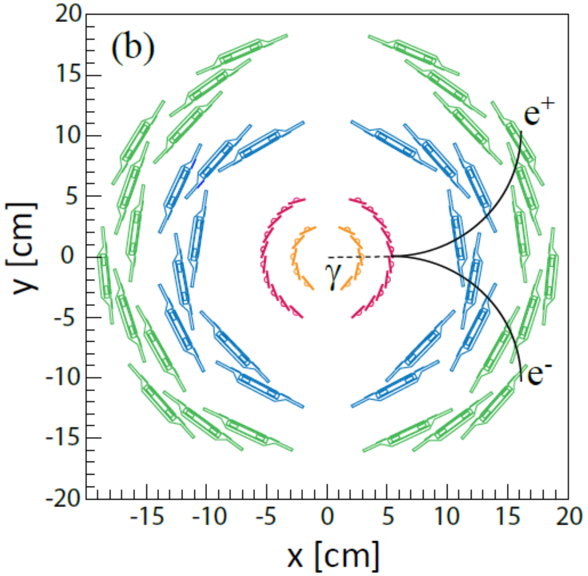


Method of choice at low p_T

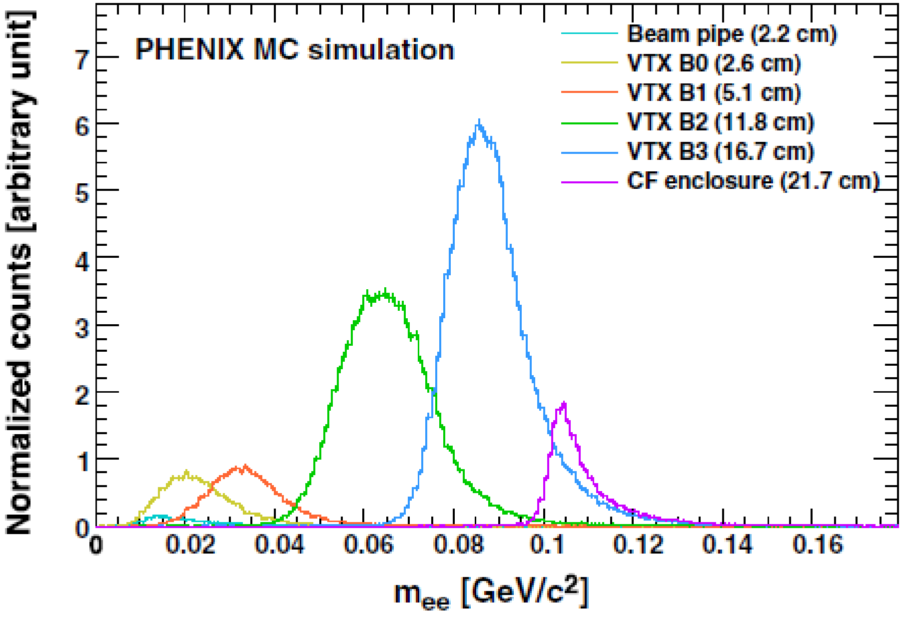
External conversion, PHENIX

PRC 109, 044912 (2024)

Real photon converts to e^+e^- on detector material

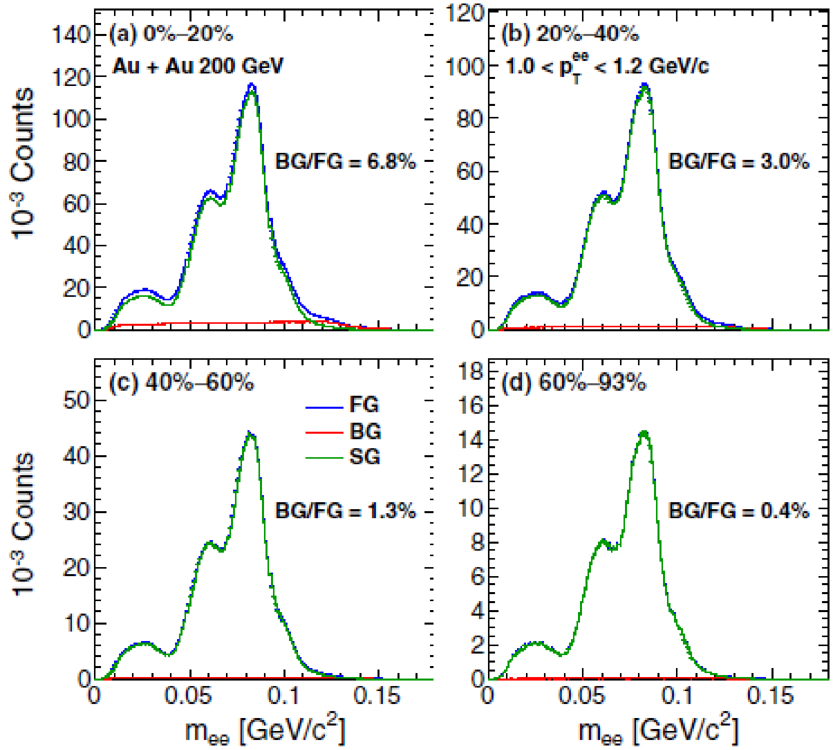


VTX detector



Simulation
Reconstructed conv. photon "mass"
(DC tracking assumes collision vtx!)

$1.0 < p_T < 1.2$ GeV/c



Data
Reconstructed conv. photon "mass"

Photon purity: ~99%

But is it a direct photon?

Viable at low p_T – complements calorimetry

Tagging photons from hadron decay

Majority of photon are from hadron decays

On the face of it simple:
- pair up conversion photons with real photons in the calorimeter
- tag those that reconstruct a π^0

But:
- tremendous combinatorial at low p_T
- limited acceptance, efficiency
- ignores double conversions

Delicate balance:
- increasing material increases conversion (i.e. our signal)
- too much material promotes double conversions

$M_{ee\gamma}$

Conv + real photon invariant mass

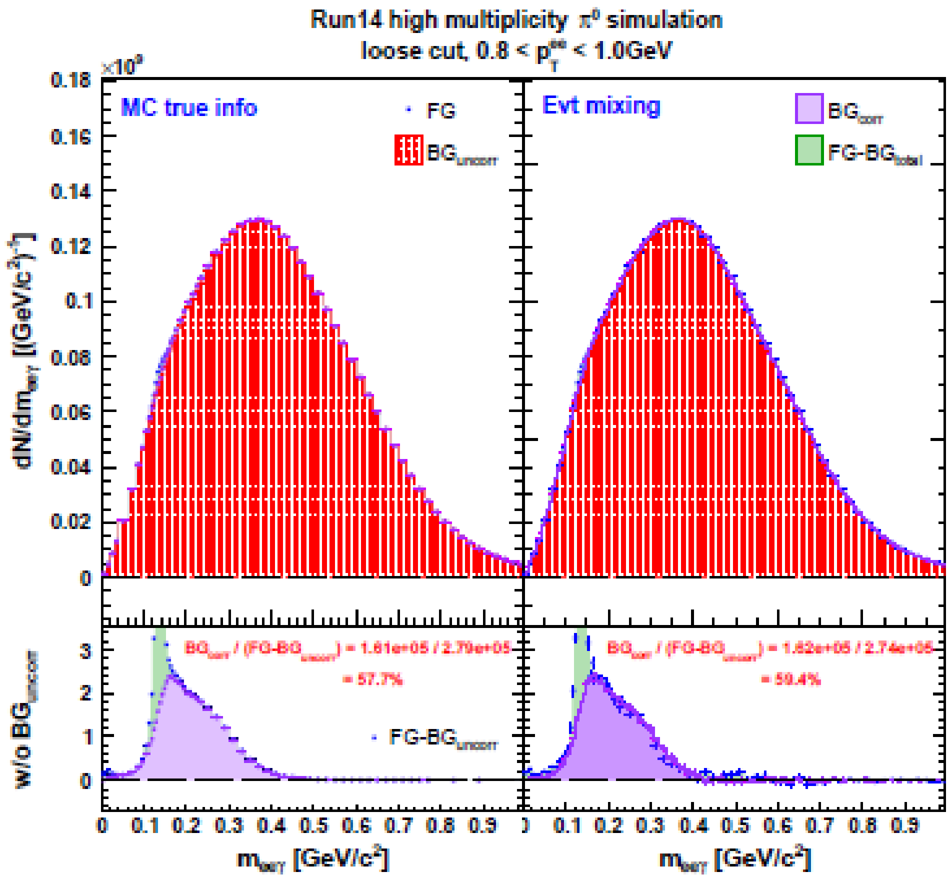


Figure 3.26: Invariant mass distributions of $e^+e^-\gamma$ pairs.

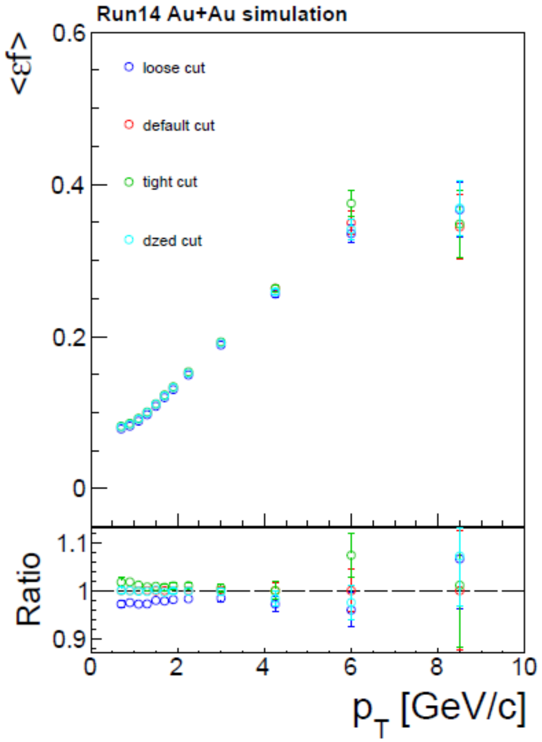
Large combinatorial

Conditional probability of tagging, Rγ

How often is the partner π^0 photon found in the calorimeter?

$$\left(\frac{N_\gamma^{\mathrm{incl}}}{N_\gamma^{\pi^0,\mathrm{tag}}}\right)_{\mathrm{Data}} = \frac{\gamma^{\mathrm{incl}} \cdot \cancel{p_{\mathrm{conv}}} \cdot \cancel{a_{e^+e^-}} \cdot \cancel{\epsilon_{e^+e^-}}}{\gamma^{\pi^0} \cdot \cancel{p_{\mathrm{conv}}} \cdot \cancel{a_{e^+e^-}} \cdot \cancel{\epsilon_{e^+e^-}} \cdot \langle \epsilon_\gamma f \rangle} = \frac{\gamma^{\mathrm{incl}}}{\gamma^{\pi^0} \cdot \langle \epsilon_\gamma f \rangle}$$

Many systematics cancel



After accounting for other hadrons (cocktail, to be discussed later)

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left(\frac{N_\gamma}{N_\gamma^{\pi^0 tag}}\right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}}\right)^{MC}}$$

Powerful for R_γ in terms of uncertainties

Virtual photon ("internal conversion") method

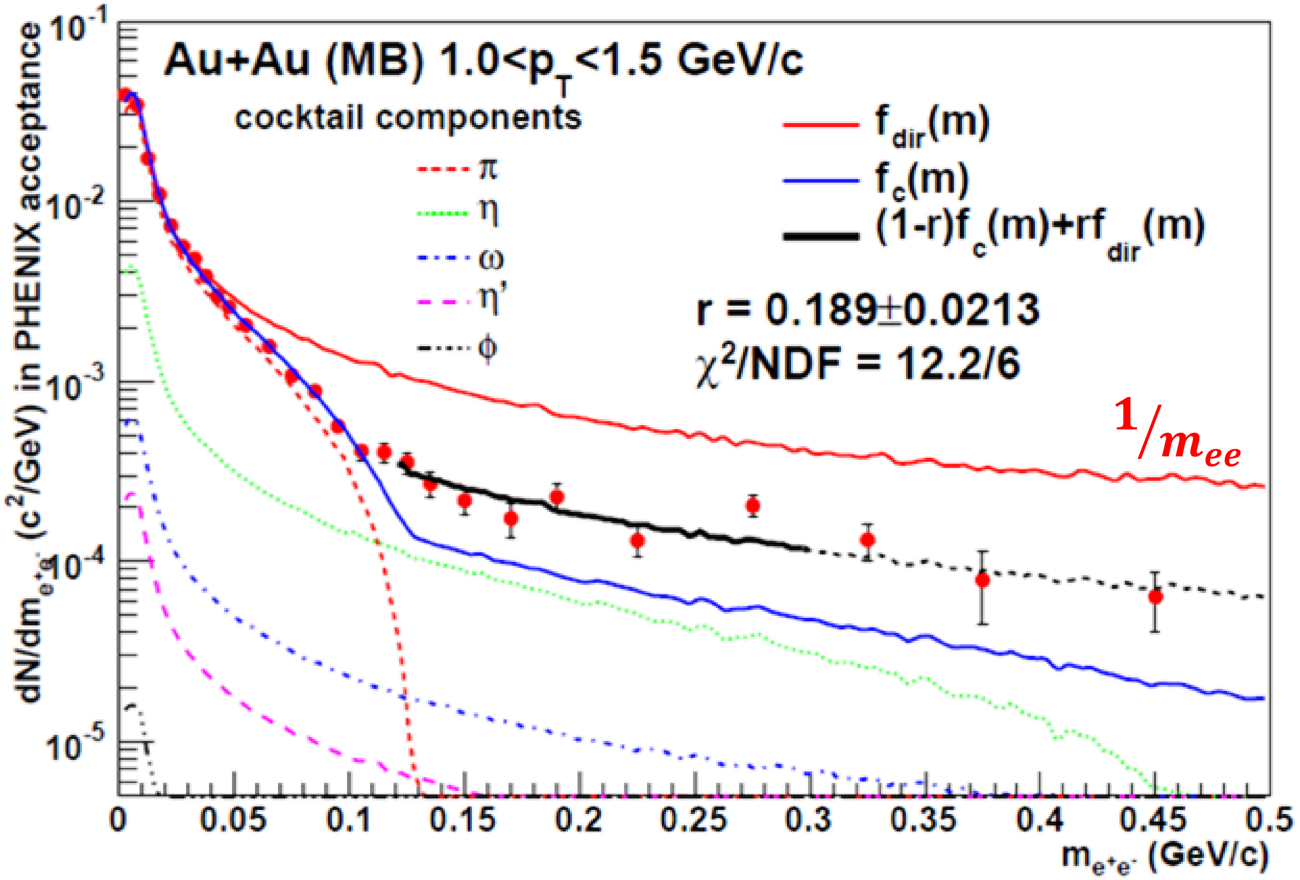
Kroll-Wada

$$\frac{d^2 n_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S\,dn_\gamma$$

γ_{dir}: $S \sim 1$ for $m_{ee} \ll p_T$

γ_{had}: $S = \left(1-\frac{m_{ee}^2}{M_{had}^2}\right)^3 |F(m_{ee}^2)|^2$

PHENIX: Phys. Rev. Lett. 104 (2010) 132301



- Using virtual photons $\gamma^* \to e^+e^-$:
  - any process that radiates γ will also radiate $\gamma^* \to e^+e^-$
  - for $m_{ee} \ll p_T$ extrapolate γ^* to $m_{ee} = 0$
  - $m_{ee} > m_\pi$ cut improves S/B by factor 10
  - sys. uncertainty cancelation in ratio $\gamma^*_{dir}/\gamma^*_{incl}$

Works above 1 GeV/c
Hadronic "cocktail" important

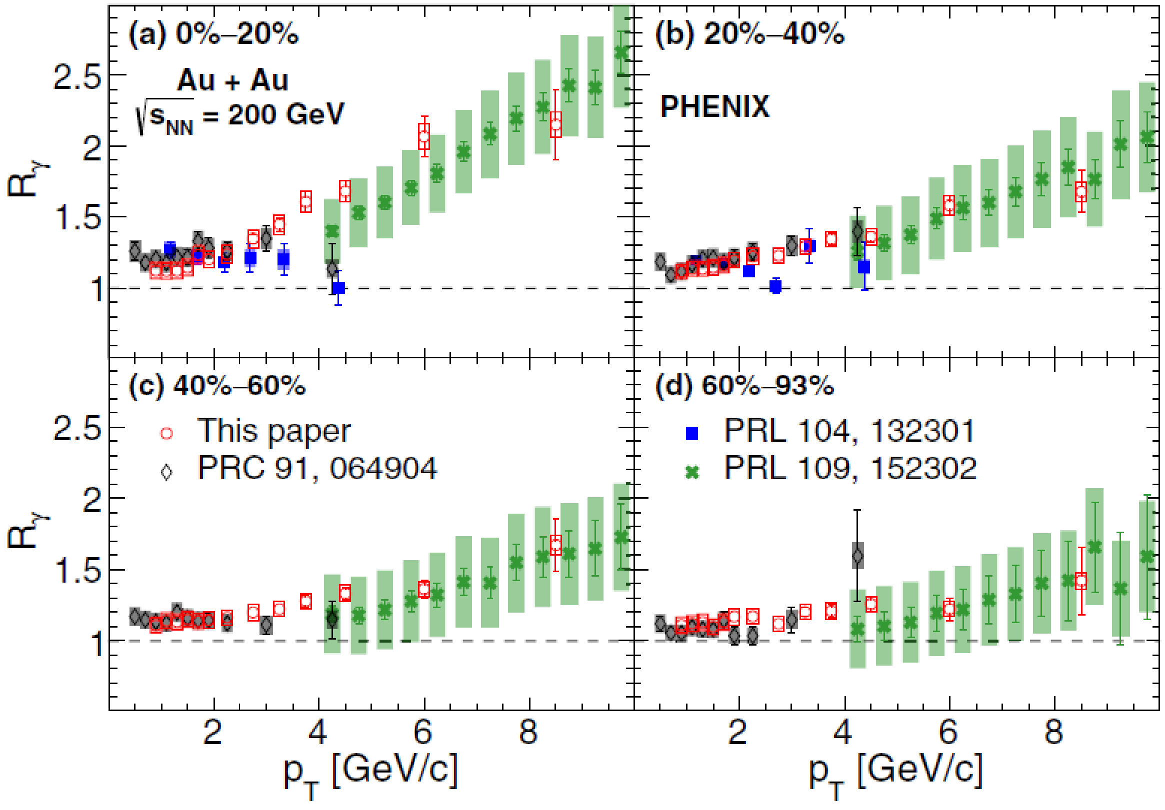
Direct γ^* yield fitted in range 120 to 300 MeV
Insensitive to π^0 yield

Direct photons in heavy ion collisions

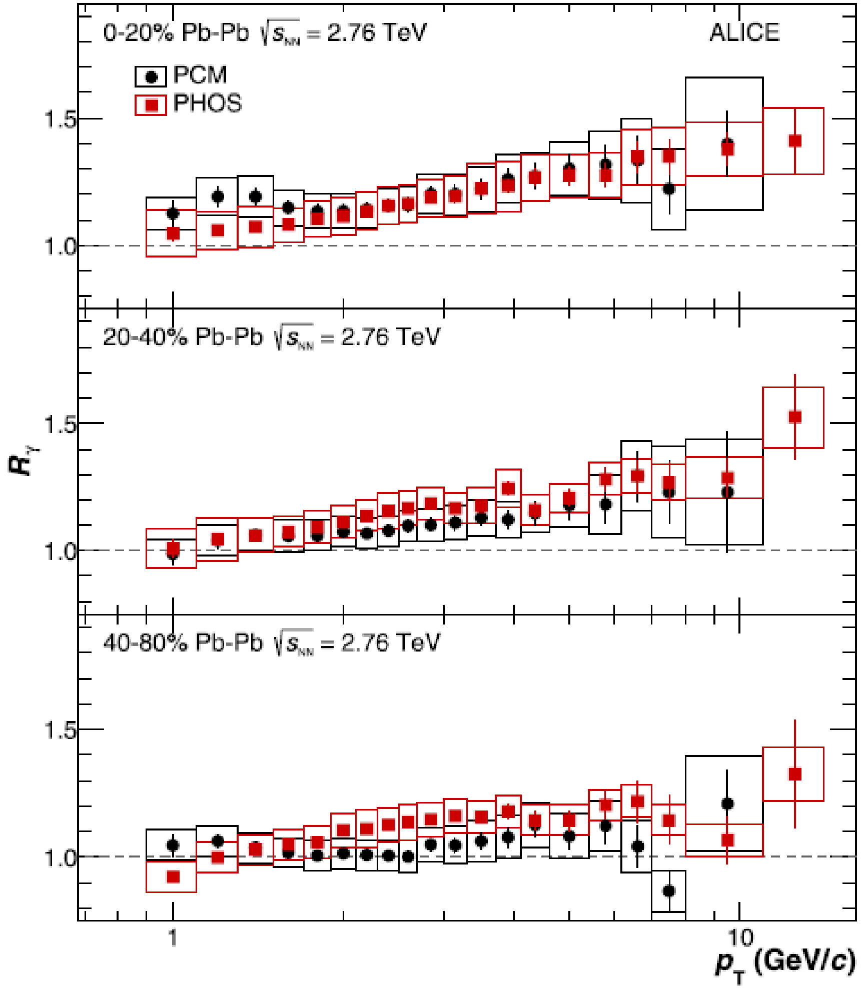
Direct photons with multiple methods (PHENIX, ALICE)

R_γ with different methods

PRC 109, 044912 (2024) (PHENIX)



PLB 754 (2016) 235-248 (ALICE)



$$\gamma^{\text{direct}} = (R_\gamma - 1)\gamma^{\text{hadron}}$$

Remember this, when interpreting spectra

Invariant yields – 200 GeV AuAu – PHENIX

Direct photons and non-prompt photons

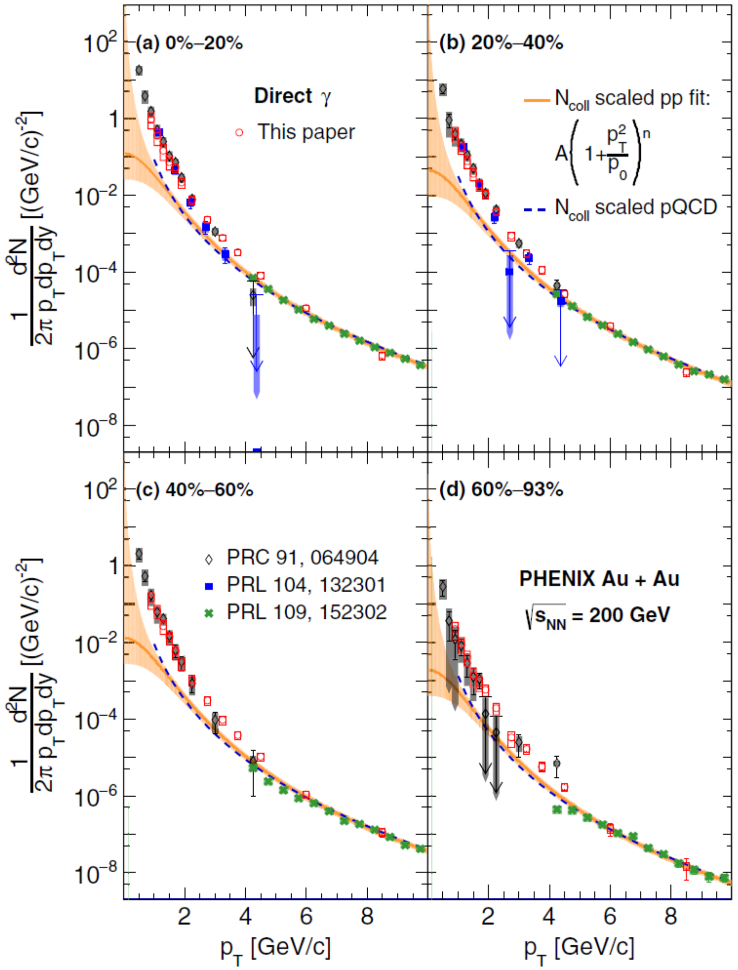
PRC 109, 044912 (2024)

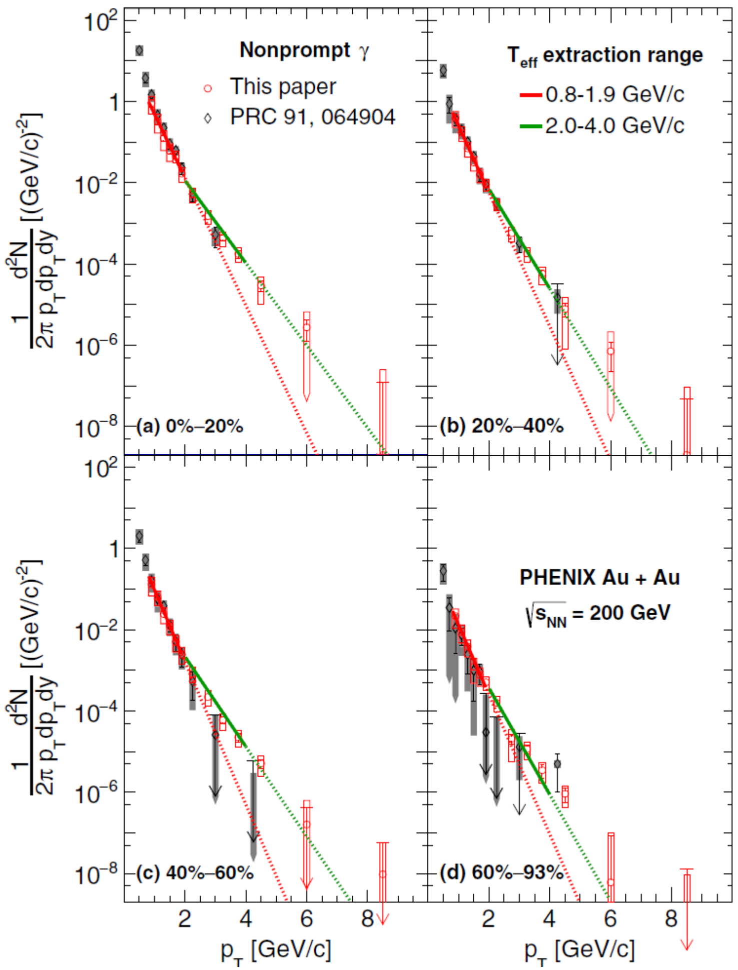
Non-prompt: properly scaled p+p yields subtracted

N_{coll} → number of binary nucleon-nucleon collisions (estimated with Glauber MC)

At lower p_T varying exponential slopes (T_{eff})

Above 4 GeV/c hard scattering dominates



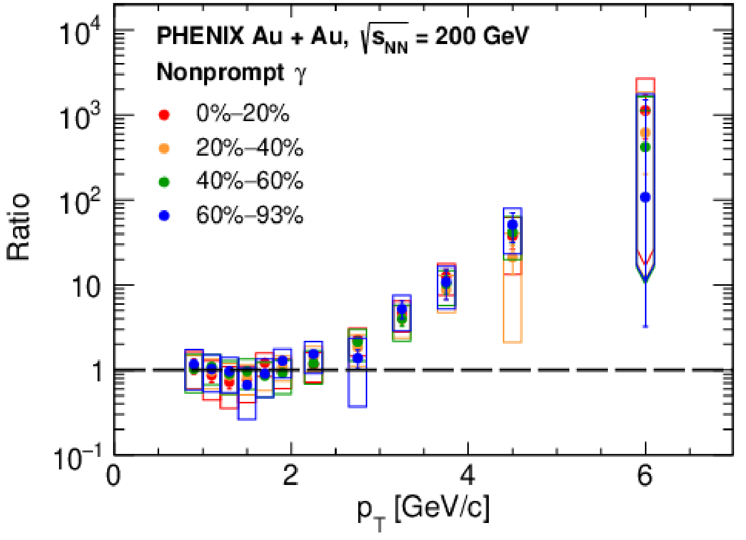


Three methods, consistent results

T_{eff} vs the p_T range and centrality

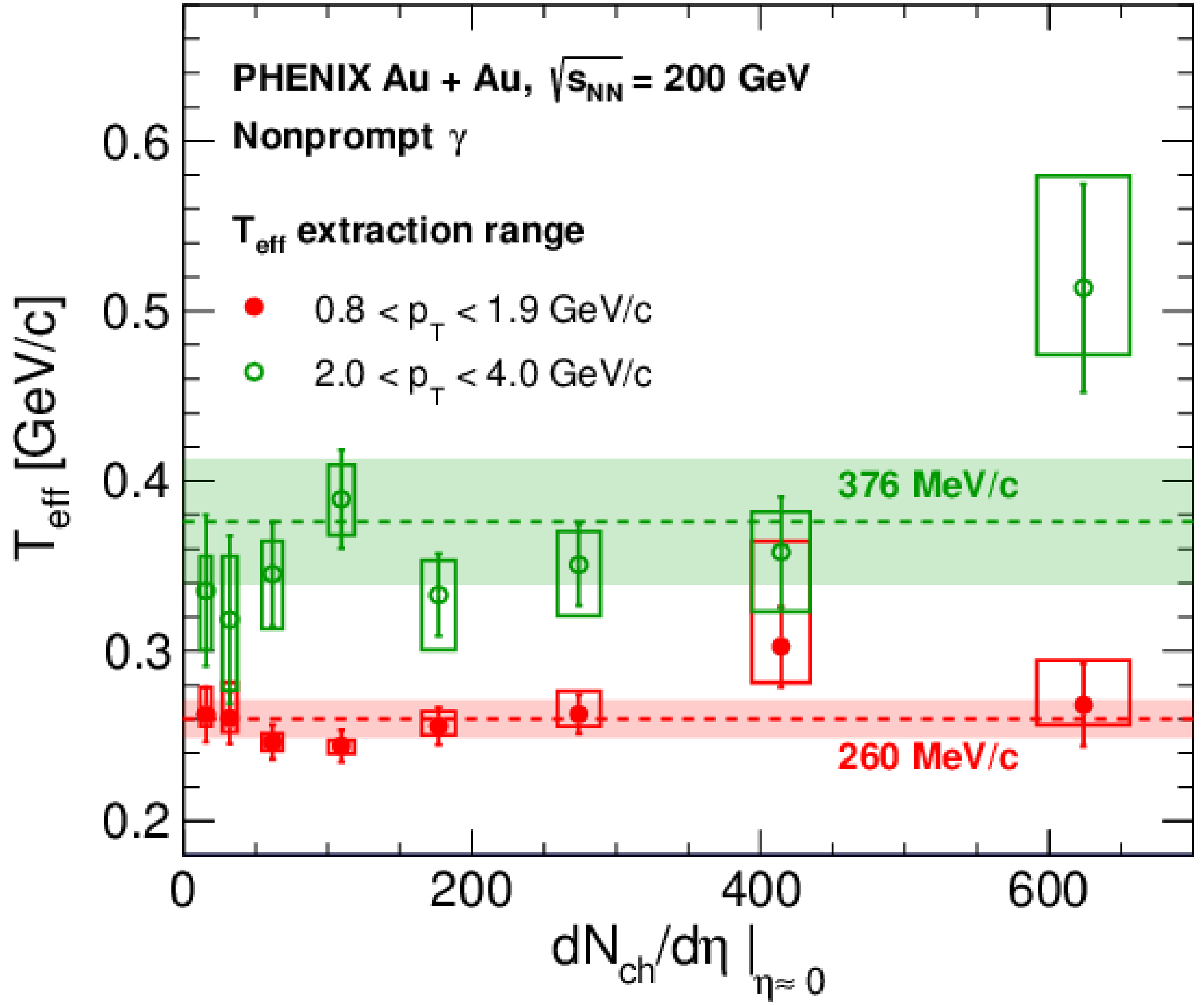
No dependence on centrality

Strong dependence on p_T
Composition and relative weight of different sources always the same?



Ratio of the yield to a fixed exponential (T_{eff} = 0.26 GeV)

PRC 109, 044912 (2024)

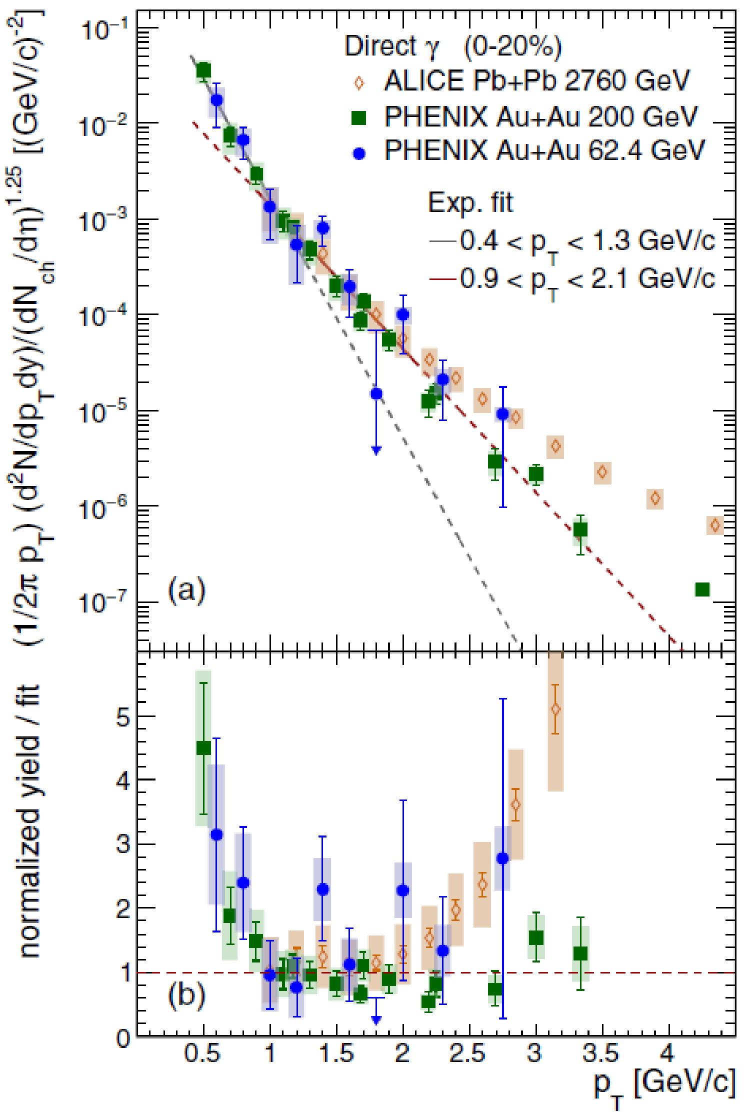


Yields: universal scenario?

Slope vs p_T

Dependence on collision energy

PRC 107, 024914 (2023)



Data vary from 62 to 2760 GeV!

Slopes vary with pT
→ imprint of T_{eff} evolution?
(different times, different sources, different p_T)

Normalized yields very similar at low p_T

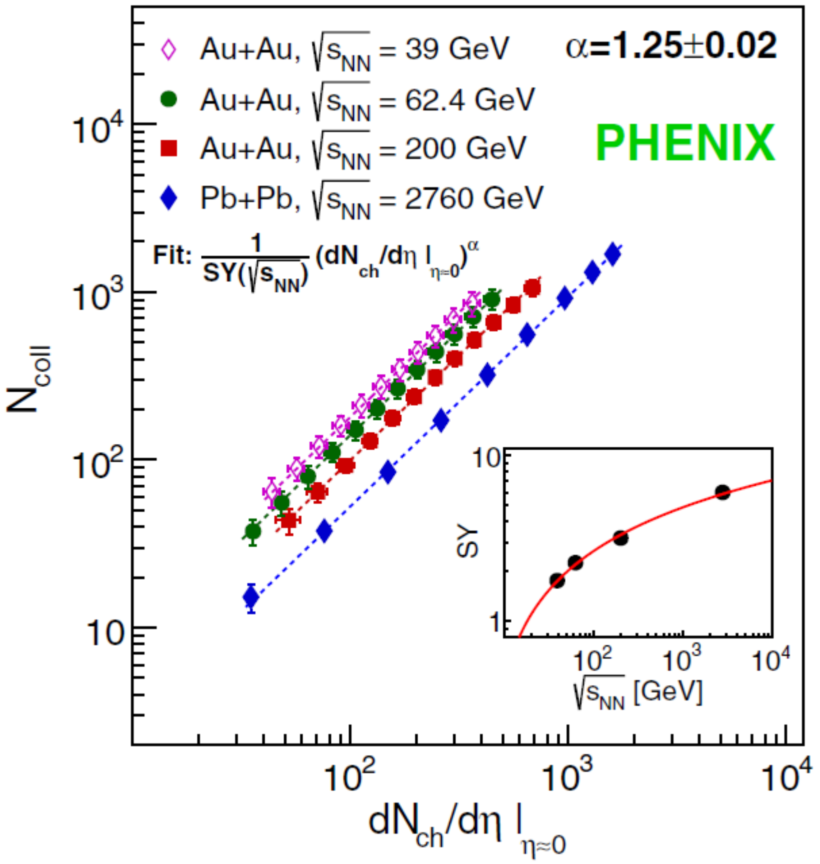
Possible interpretation:
no matter where the QGP started, the endgame will always be the same
(no surprise, but good to see)

By freeze-out everything is similar

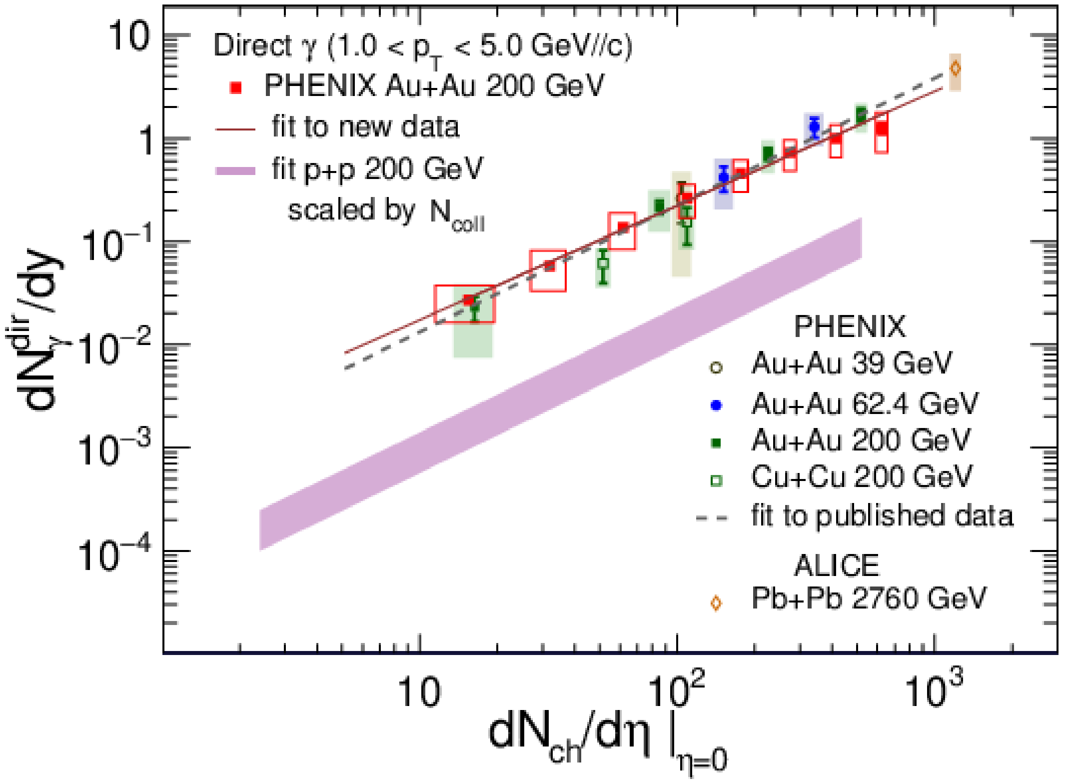
Scaling with N_{ch} (N_{coll})?

In larger systems yields scale with N_{ch}?

PRL 123, 022301 (2019)



PRC109, 044912 (2024)



Yes, but α (slope) controversial

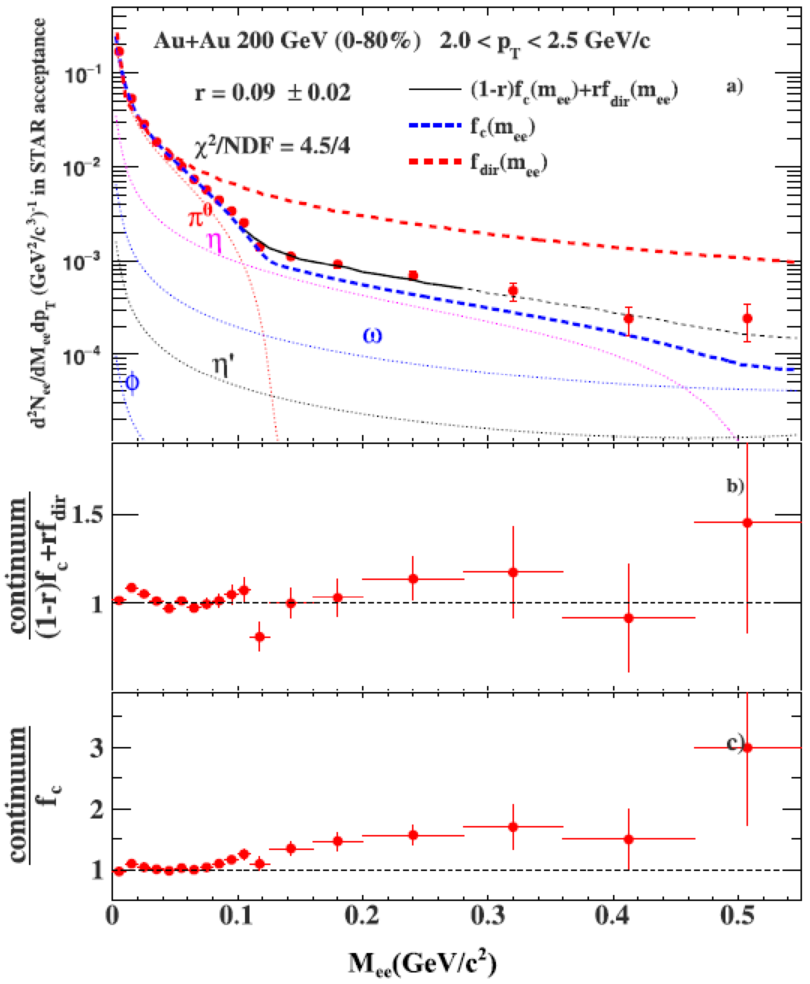
STAR 200 GeV Au+Au

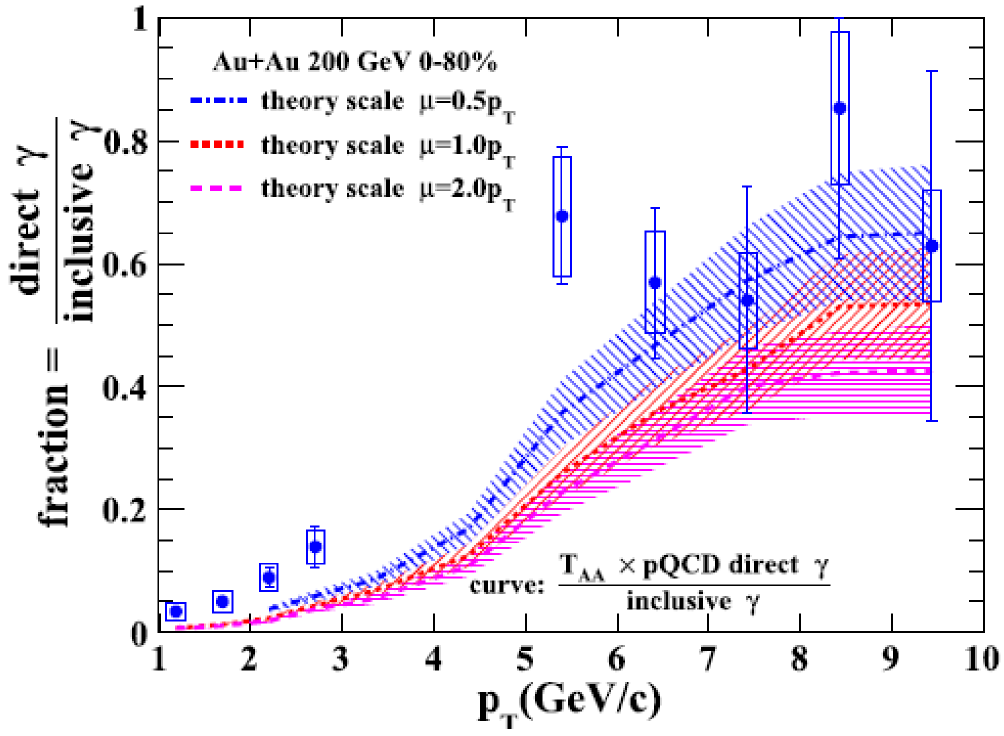
Two methods: internal conversion / calorimeter

PLB 770 (2017) 451-458

(same as the first PHENIX measurement)

fraction → r = (Rγ – 1) / Rγ

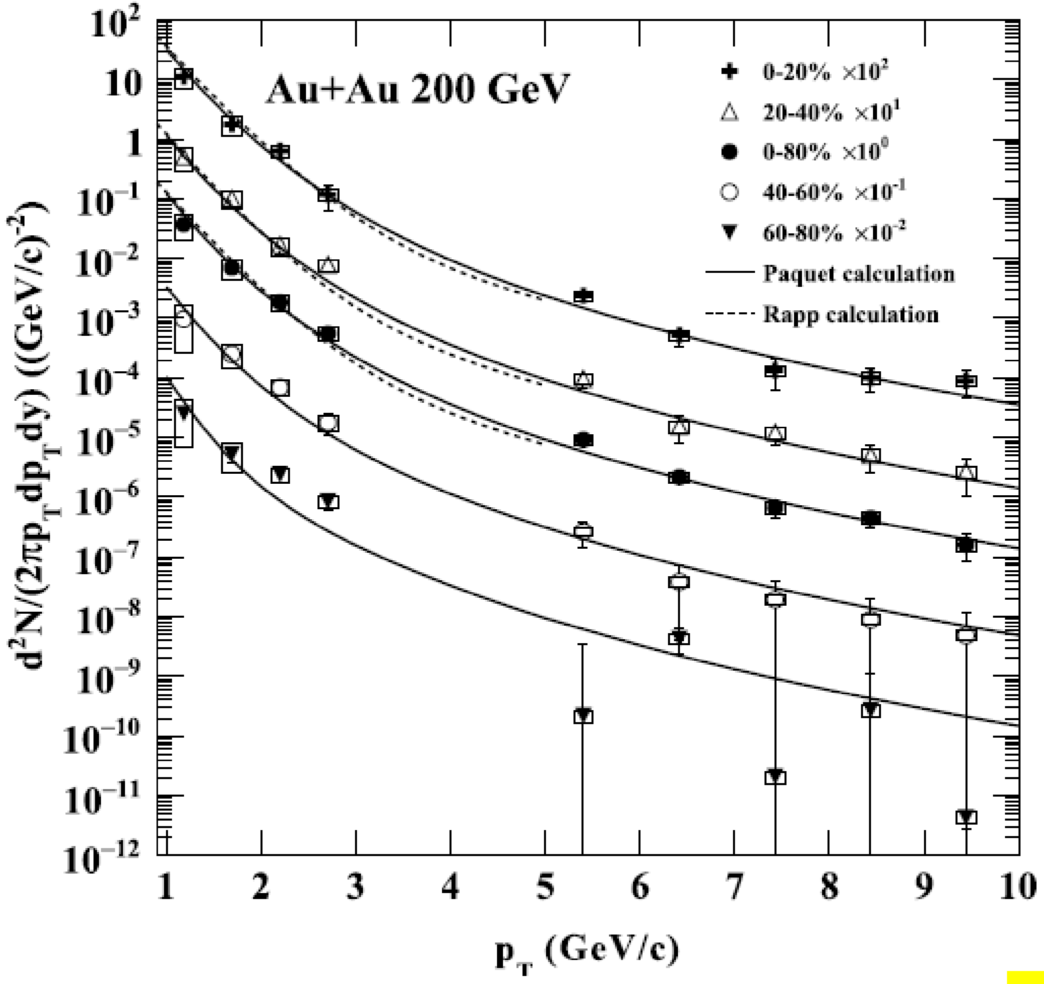




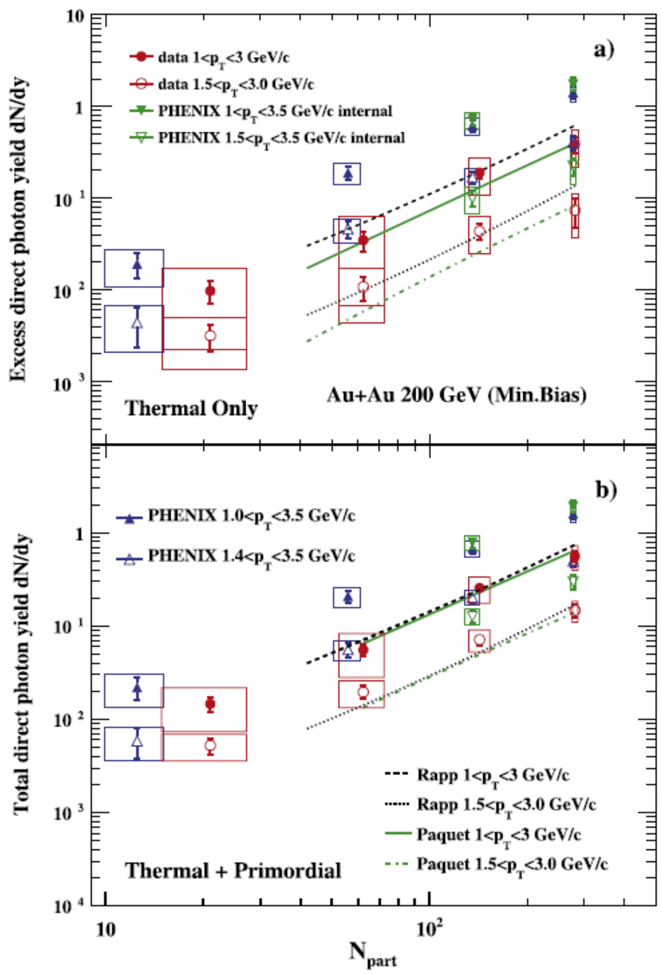
“Tension” with PHENIX, will discuss later

STAR 200 GeV Au+Au

Two methods: internal conversion / calorimeter



PLB 770 (2017) 451-458



Integrated yields disagree with PHENIX

ALICE 2.76 TeV PbPb -- updated

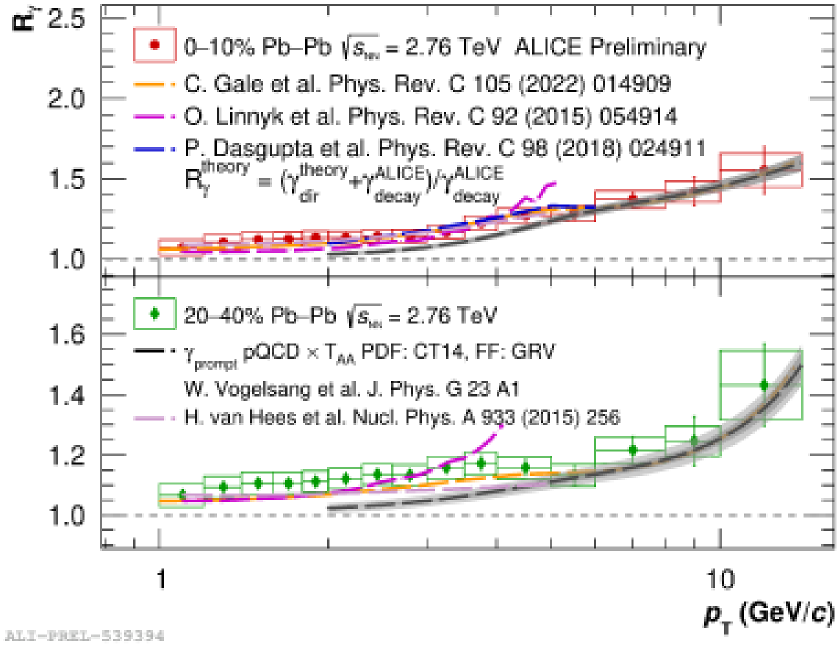
Improved significance

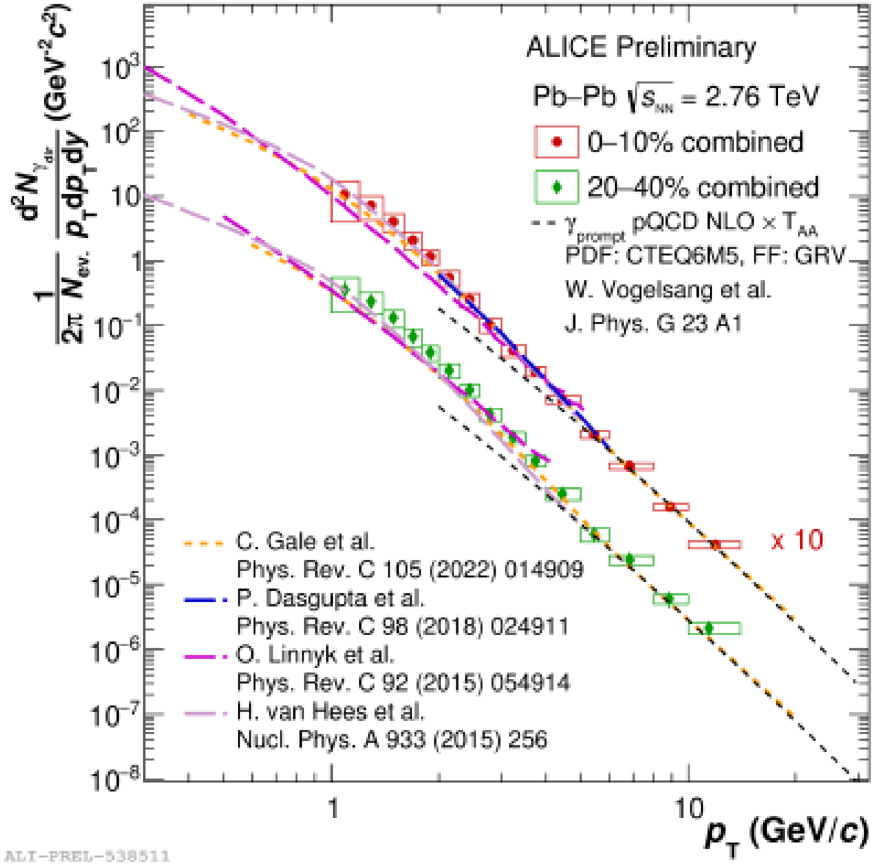
PoS (HardProbes2023) 061

First publication: PLB 754 (2016) 235-248

Direct photon signal
down to 1 GeV/c
but quite weak

T_{eff} ~ 340 MeV for
both centralities
(1.1-2.1 GeV/c region)





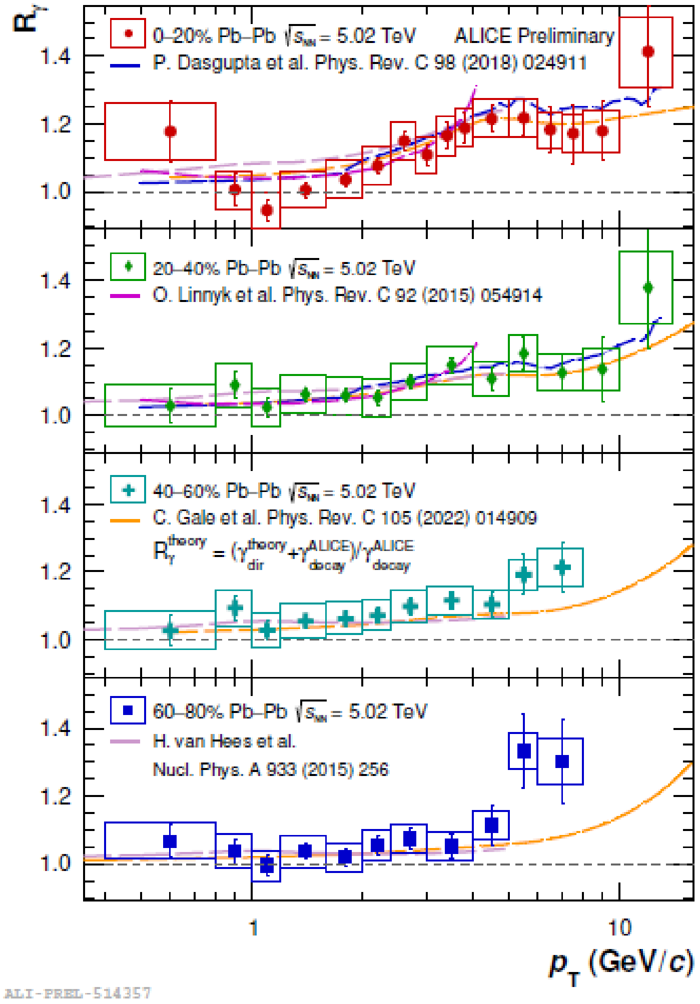
“Thermal” radiation not exceeding PHENIX

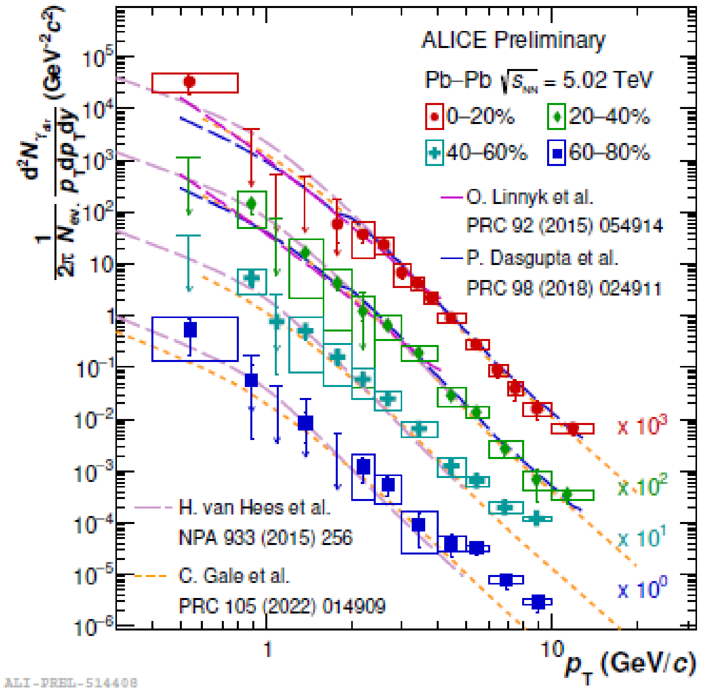
ALICE 5.02 TeV PbPb

PoS (HardProbes2023) 061

Increase energy

No significant direct photon signal at low p_T



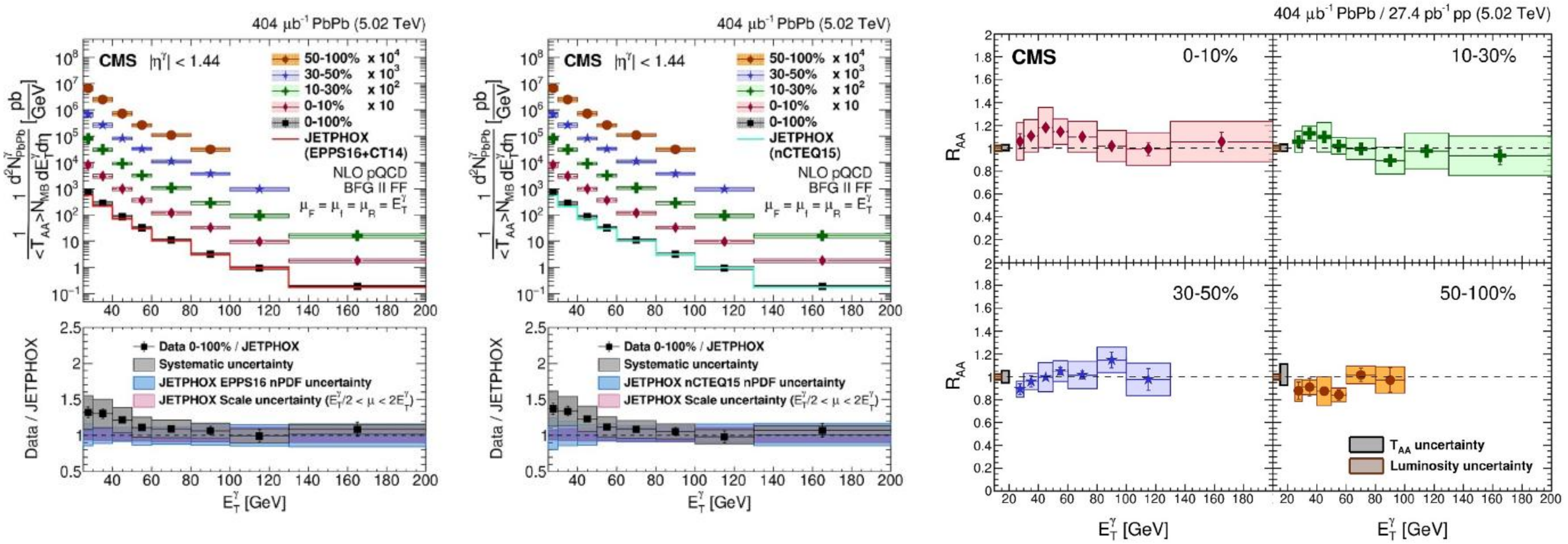


Thermal signal fading out???

CMS 5.02 TeV PbPb

JHEP07 (2020) 116

Does high p_T still look as expected?

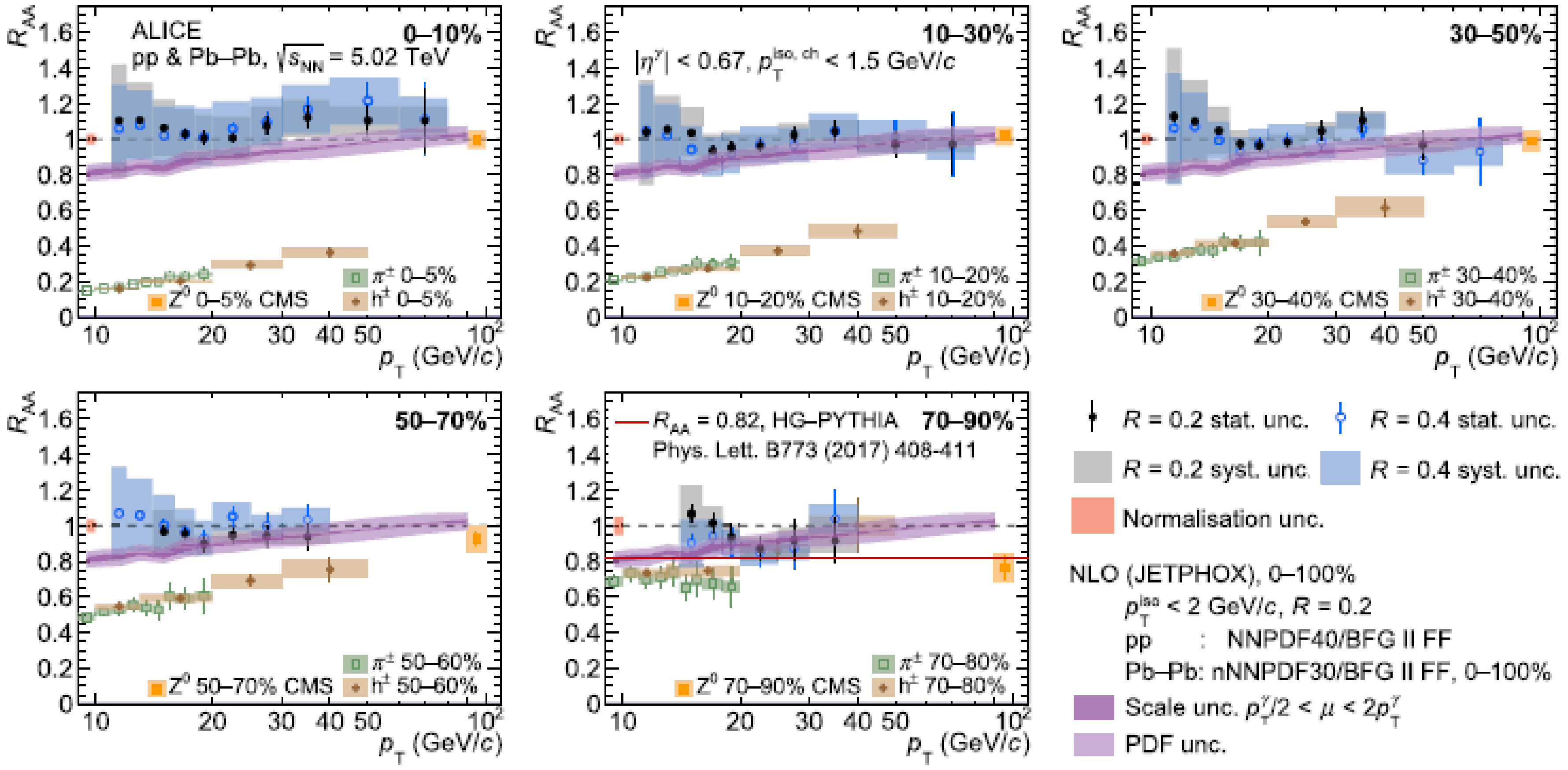


Good news: no nuclear modification at high p_T

R_{AA} of isolated photons, ALICE PbPb 5.02 TeV

Any nuclear modification?

Eur. Phys. J. C (2025) 85:553



$R_{AA} = 1 \rightarrow$ isolated photons scale with N_{coll}

The centrality, R_{AA} and photon saga

What's the big deal about R_{AA} = 1?

Connecting impact parameter to observables

PRC 90, 034902 (2014)

Ann.Rev.Nucl.Part.Sci.57:205-243,2007

3.1 Methodology

N_{ch}
charged mult
(large η gap)

N_{part}
participating
(wounded) nucleons

N_{coll}
binary (NN)
collisions

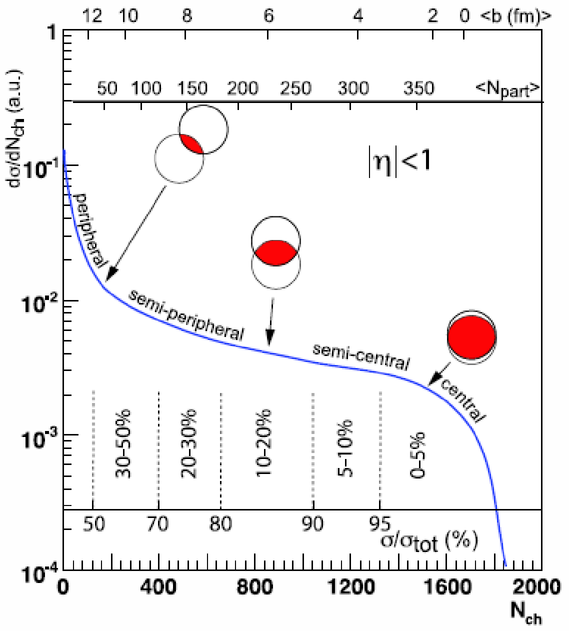
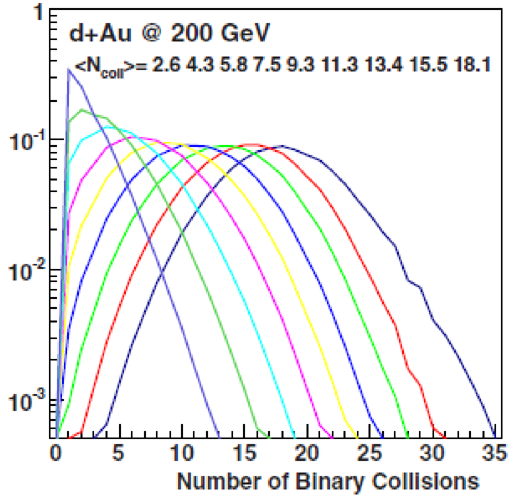
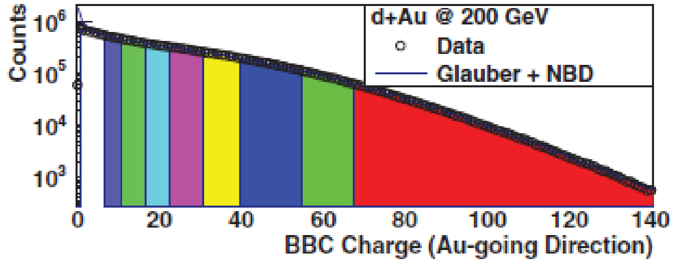
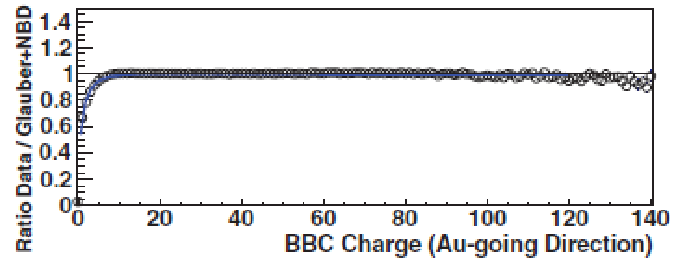


Figure 8: A cartoon example of the correlation of the final state observable N_{ch} with Glauber calculated quantities (b, N_{part}). The plotted distribution and various values are illustrative and not actual measurements (T. Ullrich, private communication).





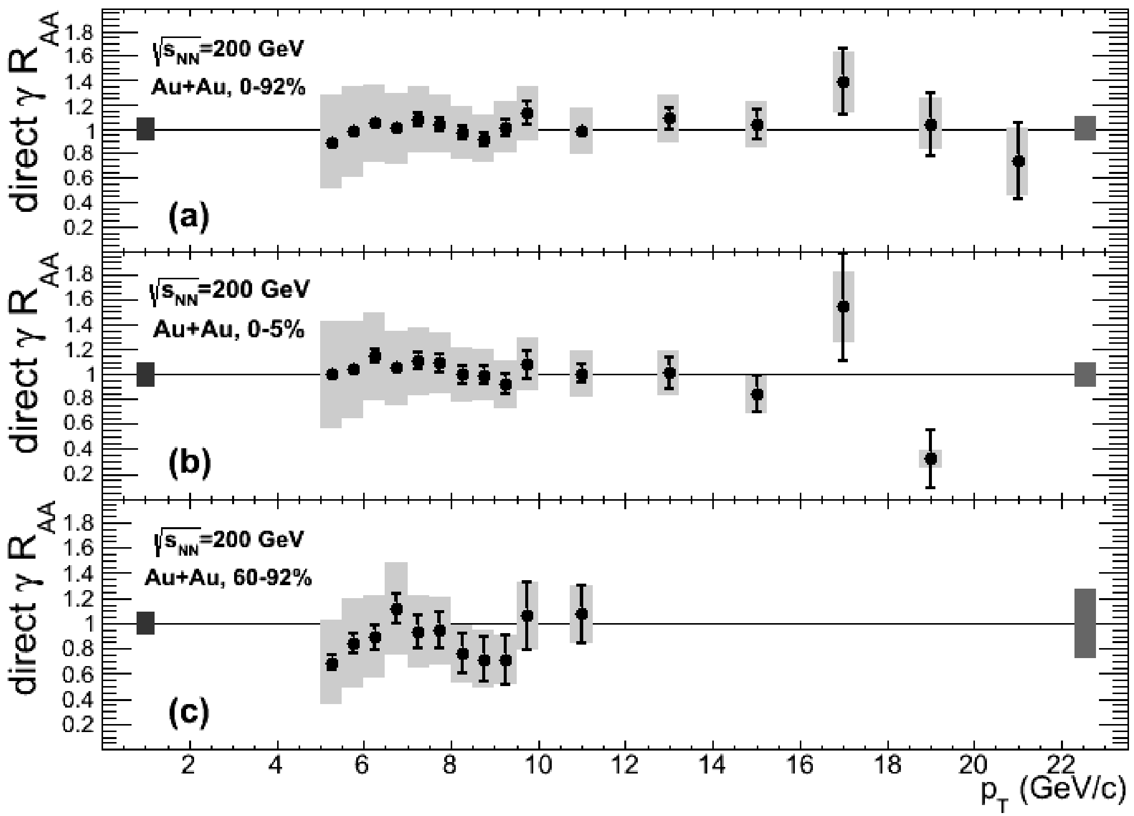


"In heavy ion collisions, we manipulate the fact that the majority of the initial state nucleon-nucleon collisions will be analogous to minimum bias p+p collisions…"

Glauber MC works in A+A – experimental proof

Hard e.m. probes (mostly) immune to FS effects

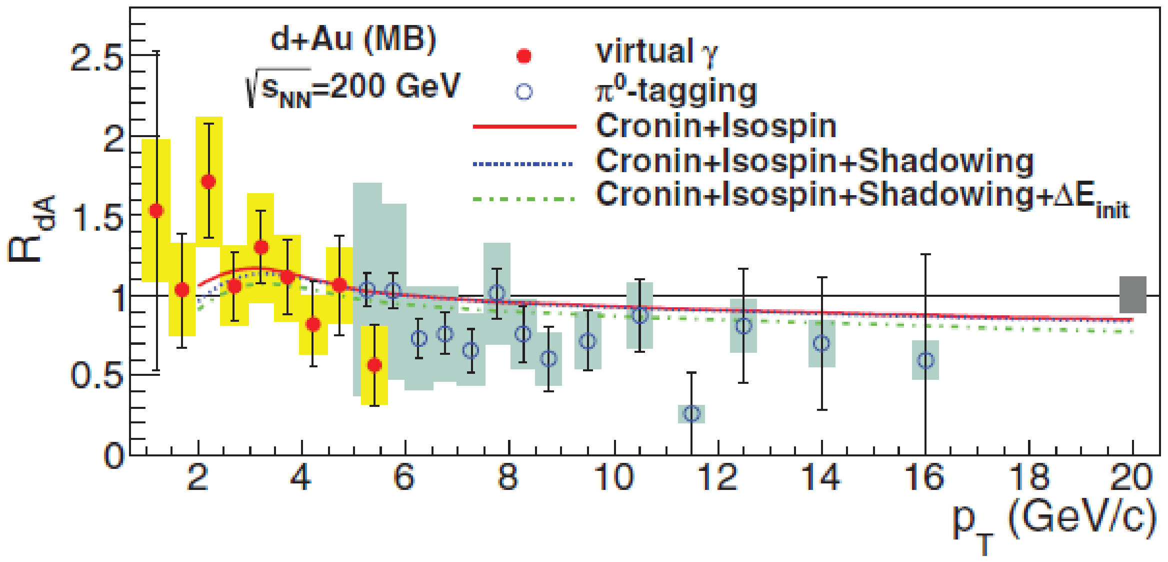
Au+Au



PHENIX, PRL 109, 152302 (2012)

d+Au

PHYSICAL REVIEW C 87, 054907 (2013)

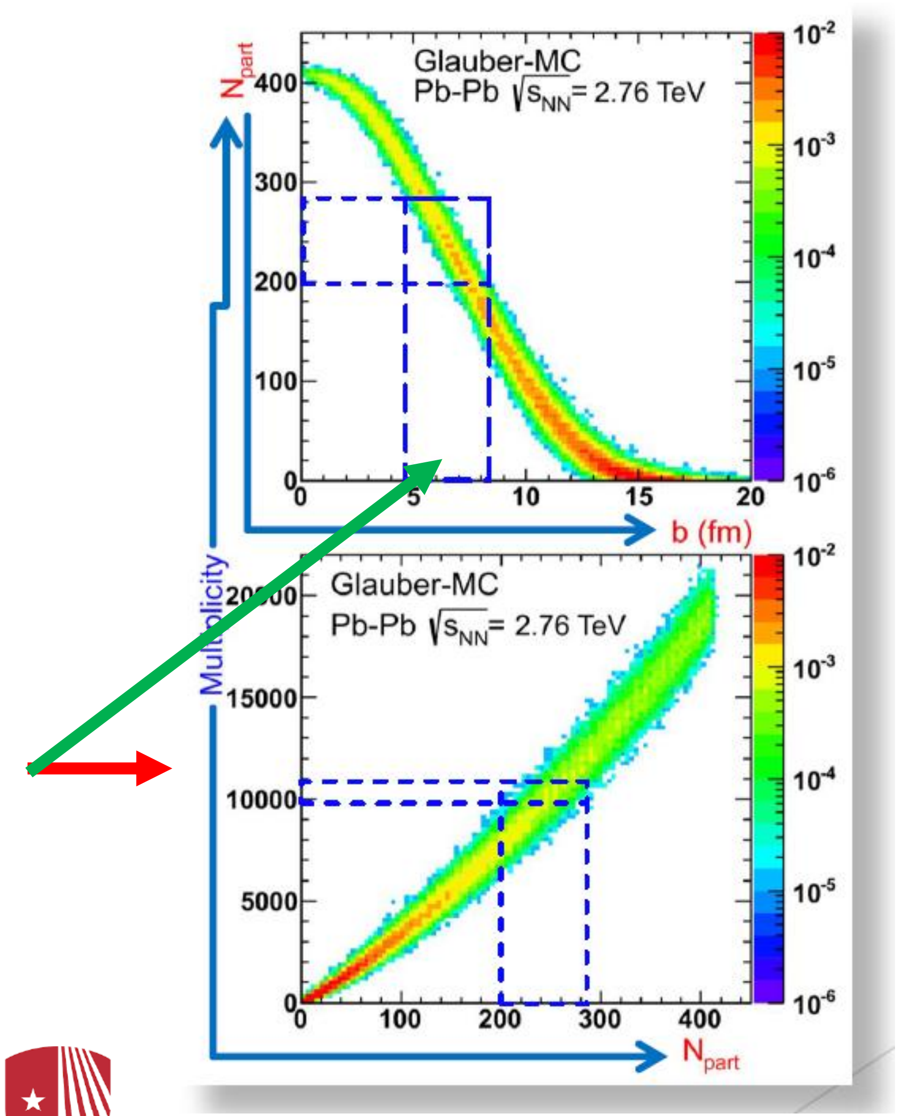


Large uncertainties, but hints of isospin effect

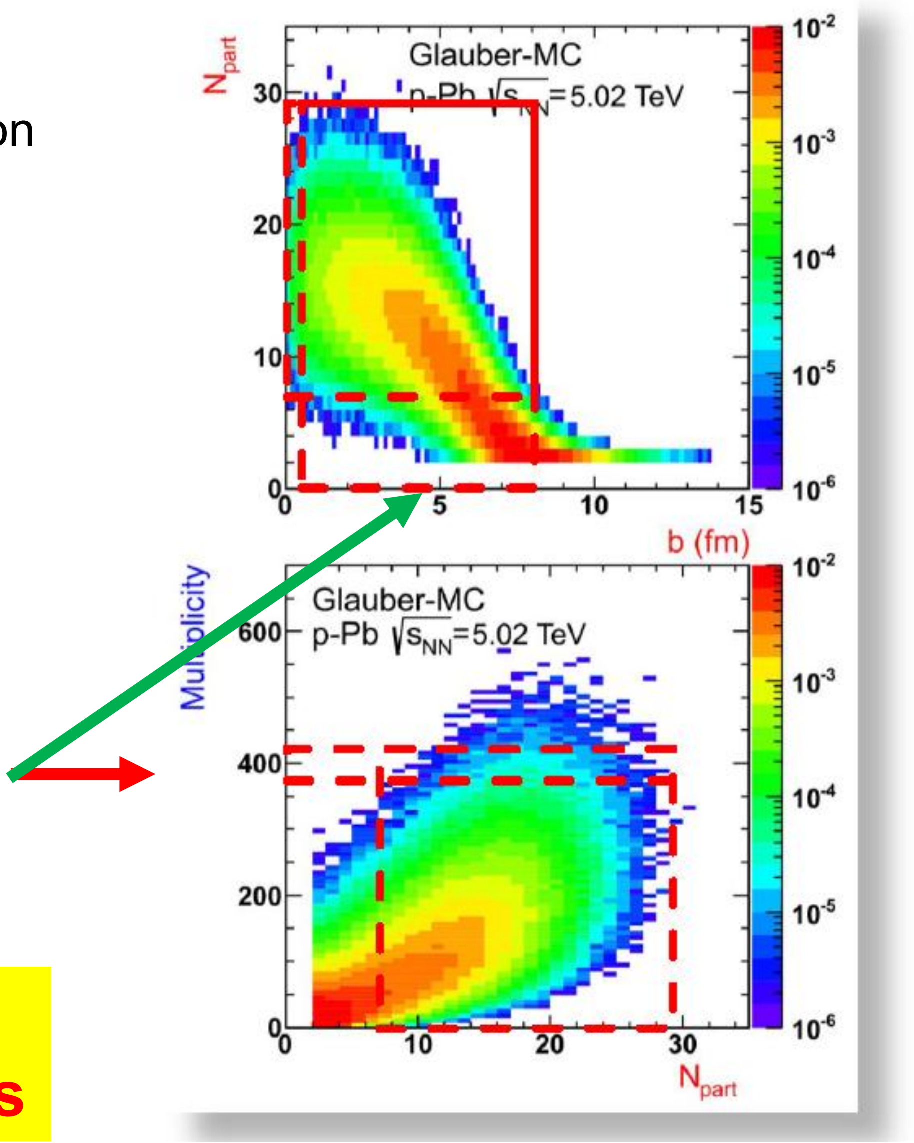
Some caveats (like isospin effect)

(Un)ambiguity of centrality determination – PbPb, pPb

Connecting b (th) → N_{part} (th) → N_{ch} (exp)



N_{ch}, N_{part}, ***b*** correlation
tight in PbPb,
very loose in pPb



Ambiguity in small systems

Also: centrality from bulk observables – but where?

Signal: η~0, "bulk": |η|>>0

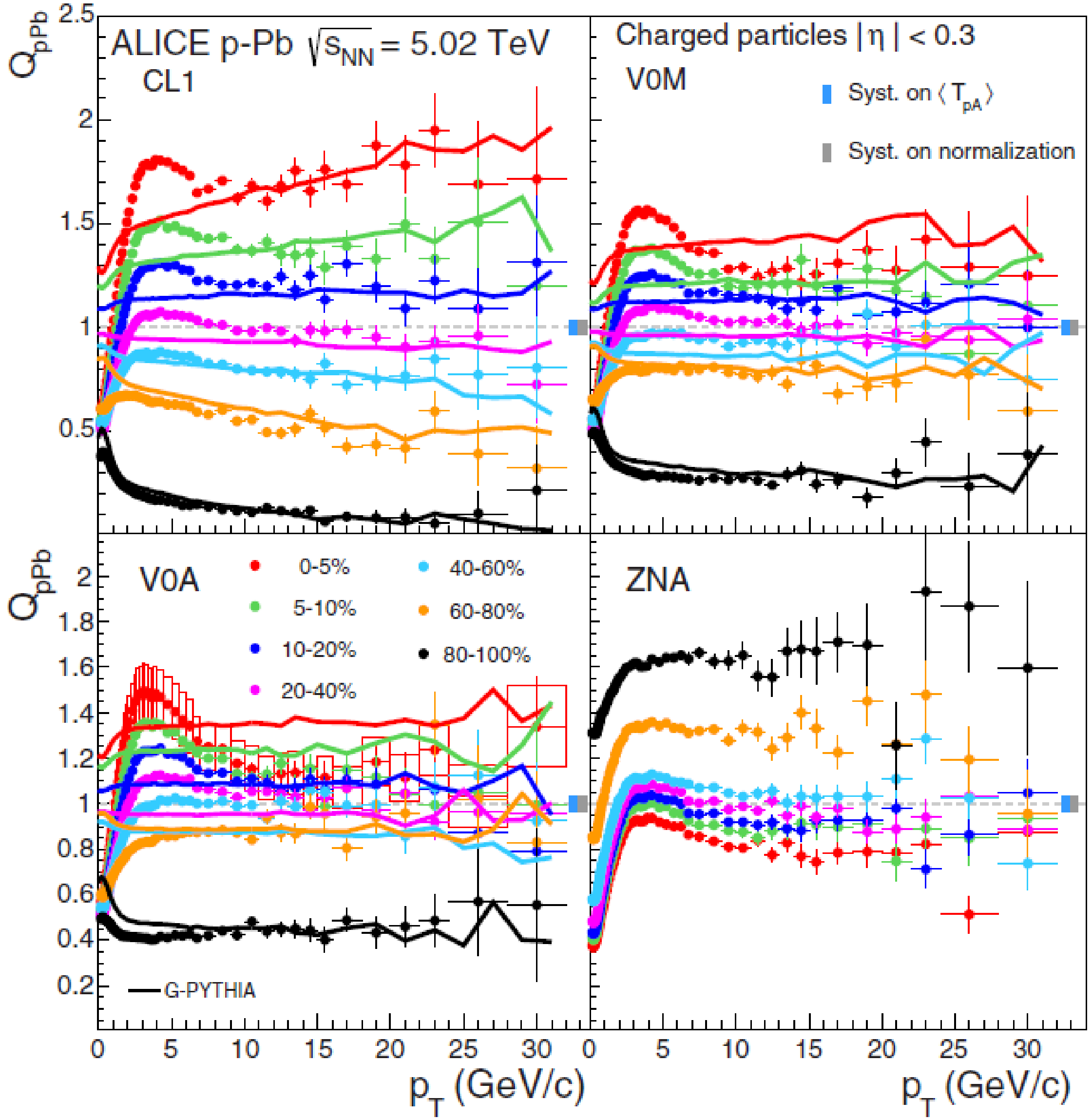
ALICE PRC 91 (2015) 064905

CL1 → |η| < 0.9
V0A → 2.8 < η < 5.1 (Pb-going side)
V0C → -3.7 < η < -1.7 (p-going side)
V0M → V0A + V0C
ZNA → ZDC on Pb-going side

Watch strong auto-correlation in CL1 central, jet veto bias in peripherals

Smaller fluctuations in V0A, mostly around unity, except vastly displaced peripheral due to multiplicity bias (?)

Reverse ordering for ZNA, as expected (as expected???)



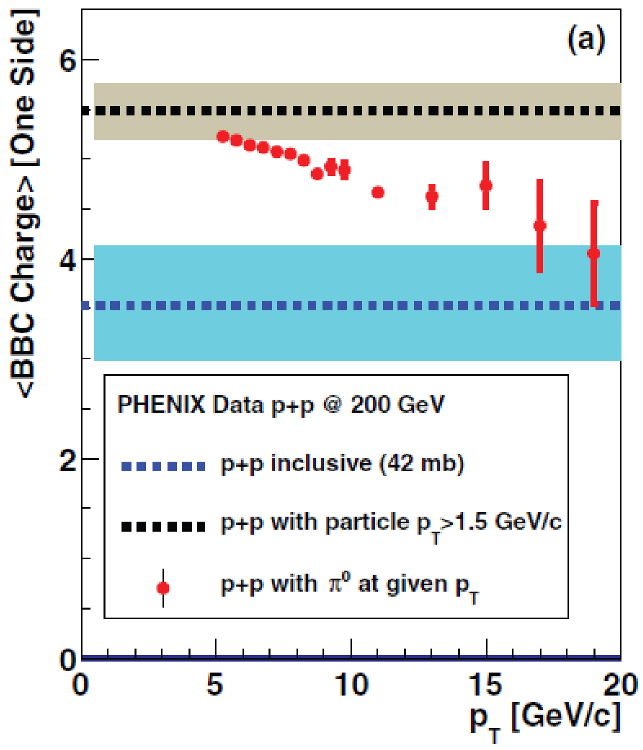
How about energy conservation?

Color transparency or energy conservation in R_{xA}?

Max p_T at η~0, N_{ch} at $|\eta|$>>0 in p+p

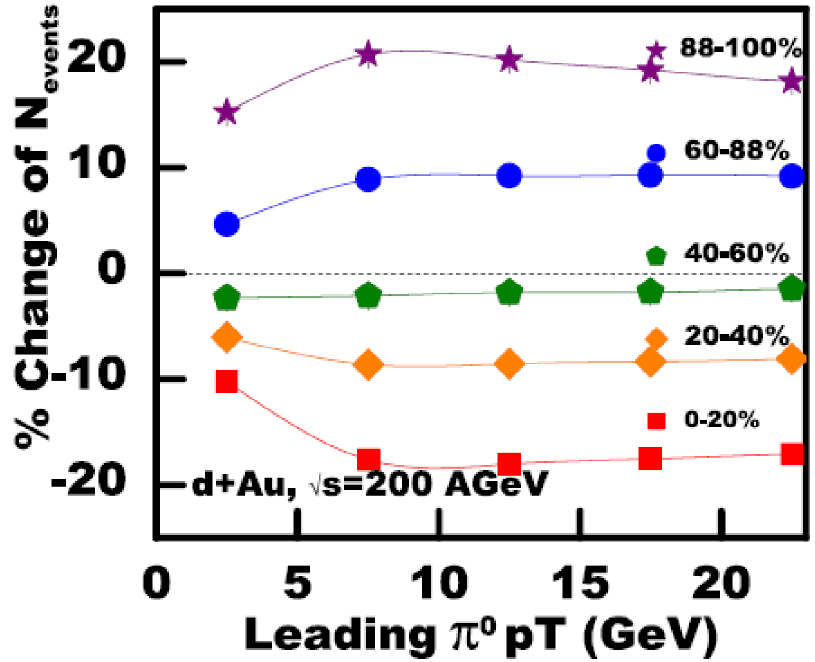
Kordell, Majumder PRC 97, 054907 (2018)

"…the puzzling enhancement in peripheral events … as well as the suppression seen in central events… are possibly due to ***mis***-binning of central and semicentral events, containing a jet, as peripheral events… due to suppression of soft particle production away from the jet, caused by the depletion of energy available in a nucleon of the deuteron in d-Au or proton in p-Pb after the production of a hard jet… "



PRC 90, 034902 (2014)

Initial enhancement of N_{ch} forward with mid-rapidity p_T, then depletion (p+p data)

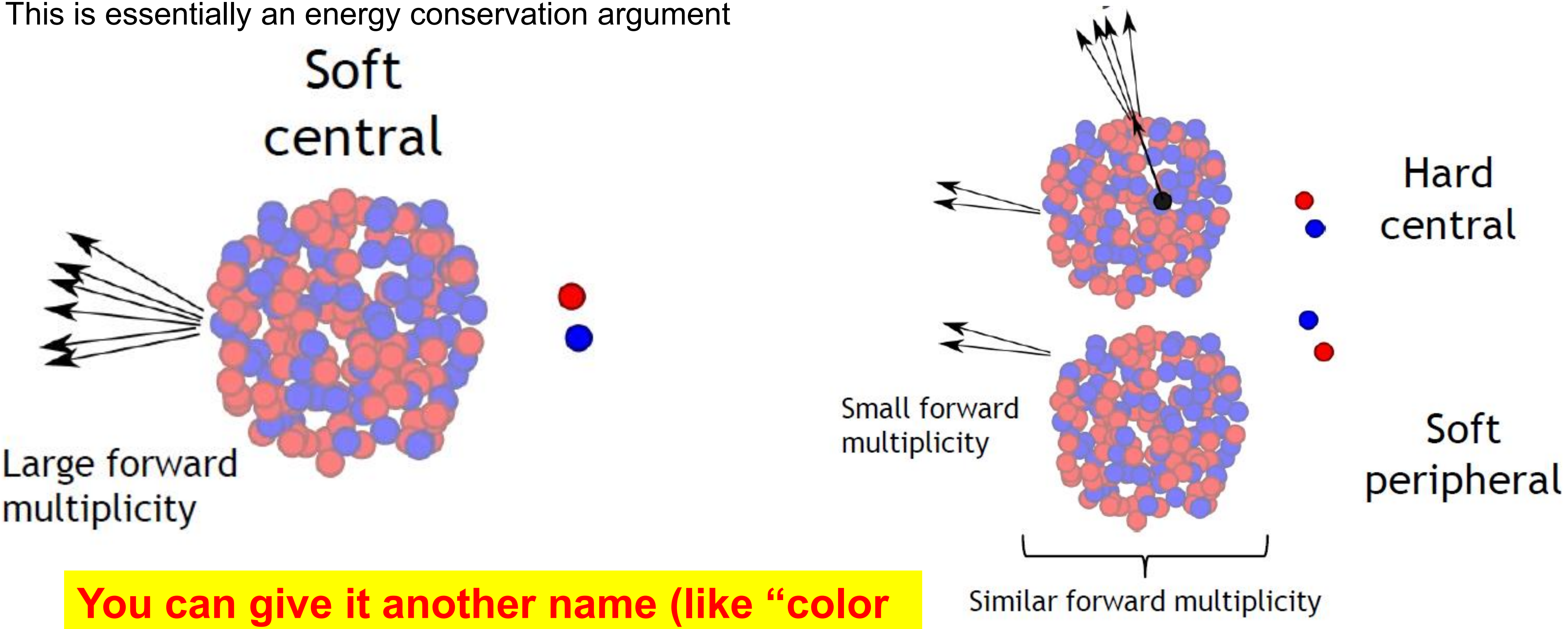


Anticorrelation at sufficiently high p_T

Very large p_T at η = 0 – mis-binning of centrality?

The same (few) projectile nucleons have to produce both hard scattering and "bulk" forward

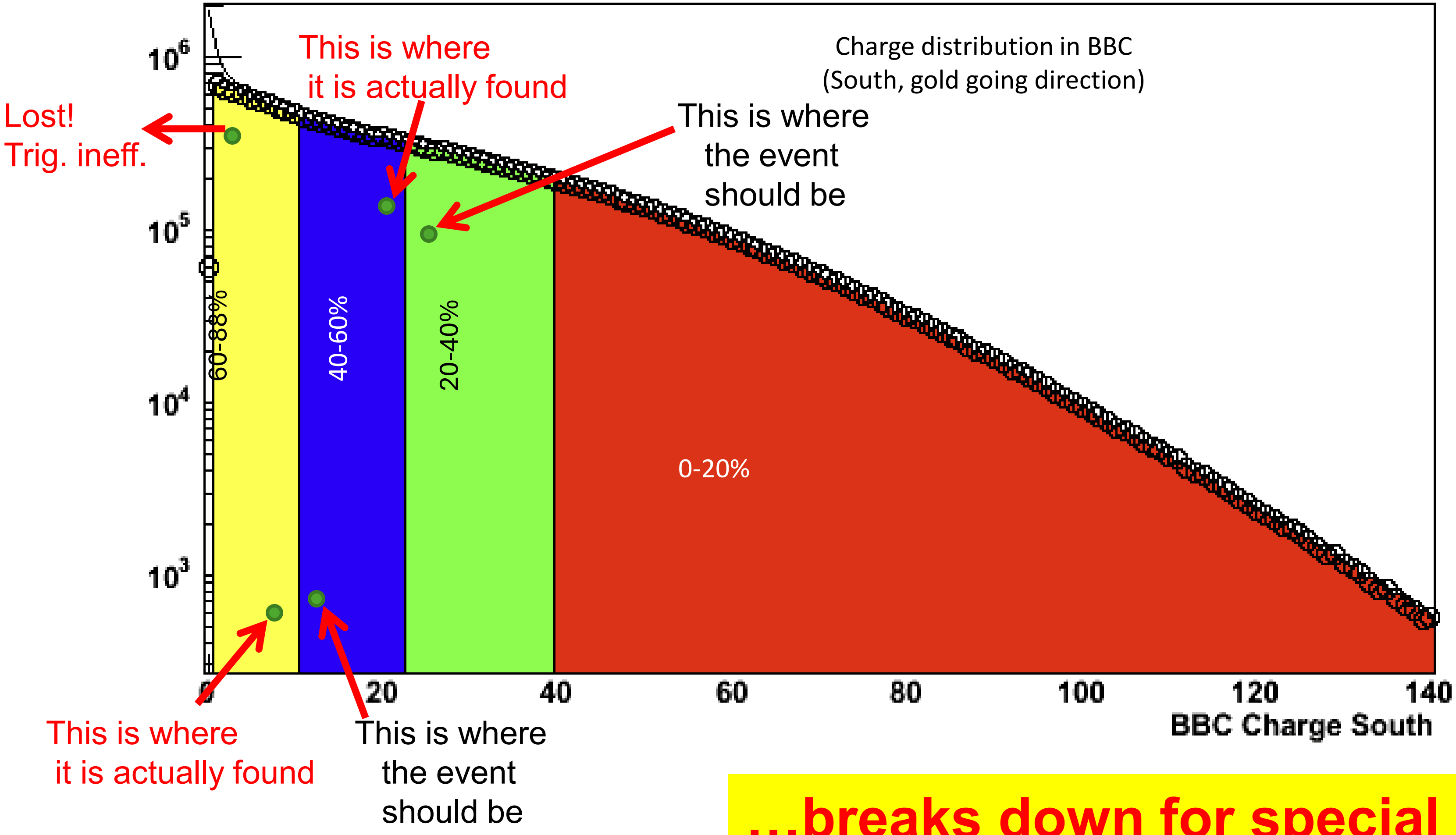
This is essentially an energy conservation argument



You can give it another name (like "color fluctuation") but it is still the same thing

Illustration: shift between multiplicity classes

Mapping N_{ch} to b using average events…



…breaks down for special (high p_T) events

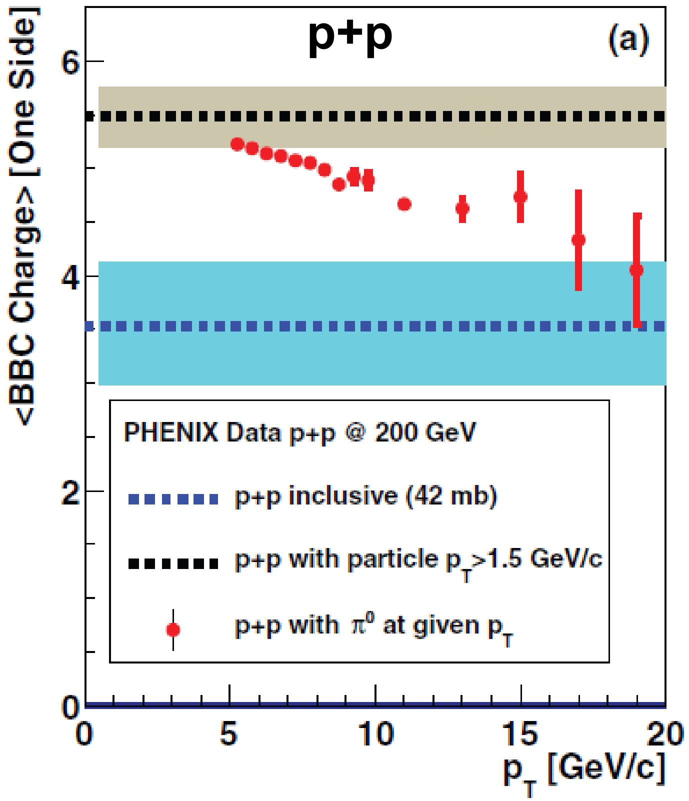
If (experimental) centrality is determined with fixed (forward) multiplicity thresholds, irrespective of what happened at η~0, events may end up in the wrong centrality class – and attributed an incorrect $\langle N_{coll} \rangle$

Does bulk observable-based centrality fix N_{coll} once and for all?

One more time…

"In heavy ion collisions, we manipulate the fact that the majority of the initial state nucleon-nucleon collisions will be analogous to minimum bias p+p collisions…"

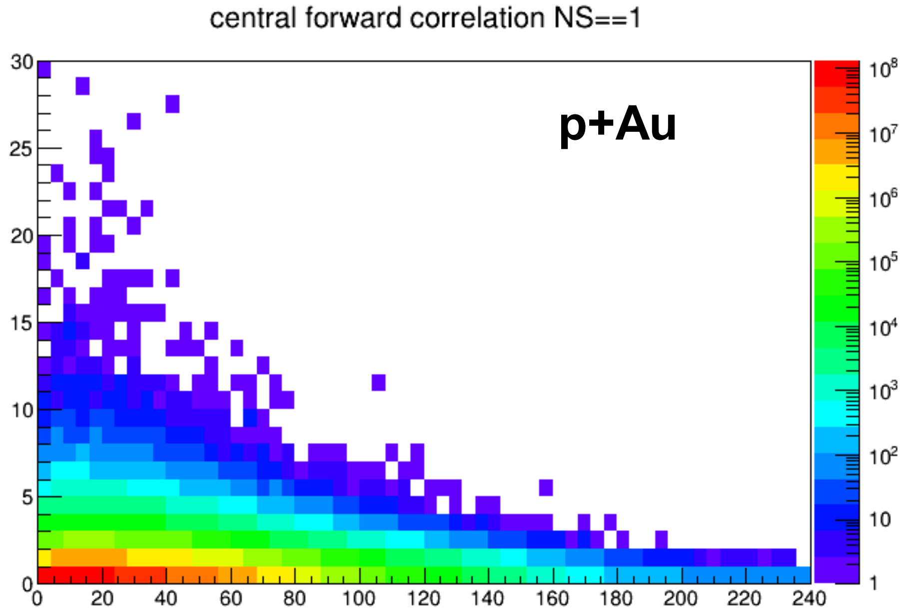
No, it is biased, and the bias changes as a function of the hardest scattering seen at mid-rapidity!



PRC 90, 034902 (2014)

Highest p_T seen at η = 0

Anticorrelation!



Charge seen at -3.9 < η < -3.0

In A+A the story is very different!

A way out: actually measure N_{coll}

You still categorize events with N_{ch}, but override Glauber MC

Is it possible? Yes, at least you can get close, and at the very least get rid of fake final state effects in R_{xA}.

Remember, photons don't care about FS → mostly true, at high p_T most of them are from initial hard scattering and have 200+ *fm* mean free path in QGP (e.g. *Rept.Prog.Phys.* 83 (2020) 4, 046301)

For an arbitrary "centrality" classification just take the ratio of the direct photon and hadron spectra
→ pure centrality bias (even if p_T-dependent) will affect both similarly
→ if the ratios change with centrality, there's a genuine final state effect on hadrons

Same idea, different realization: you can get N_{coll} experimentally from the $Y^{g}(AB,p_T)/Y^{g}(pp,p_T)$ direct photon yield ratios

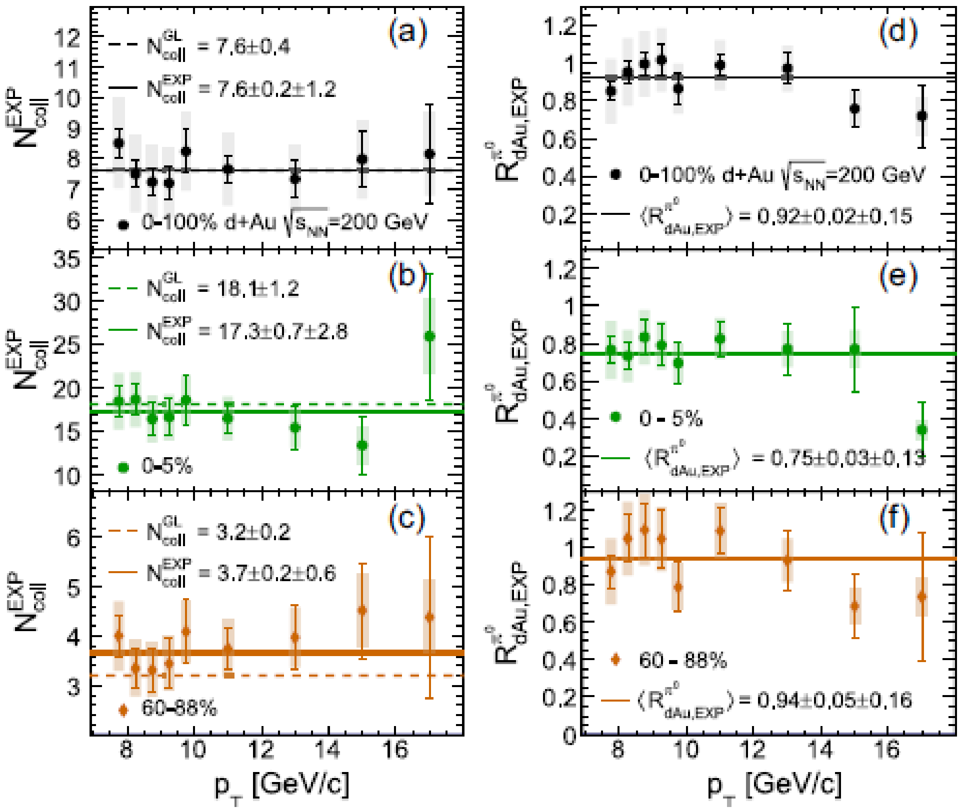
$$N_{coll}^{EXP} = \frac{\left(\frac{d^2N_\gamma}{dp_T d\eta}\right)_{AB}}{\left(\frac{d^2N_\gamma}{dp_T d\eta}\right)_{pp}} = \frac{Y_{AB}^{\gamma}}{Y_{pp}^{\gamma}}$$

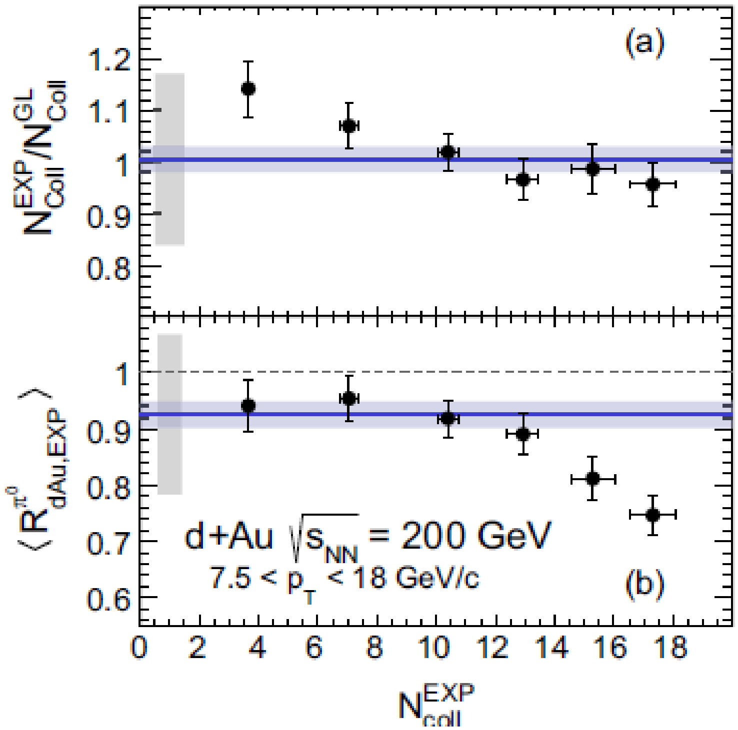
Some caveats…

Nuclear modification of π^0 in dAu

Earlier unphysical enhancement in peripherals gone

PRL 134, 022302 (2025)





Ultimate test: pAu, dAu, ^{3}HeAu "excitation" function (in the works)

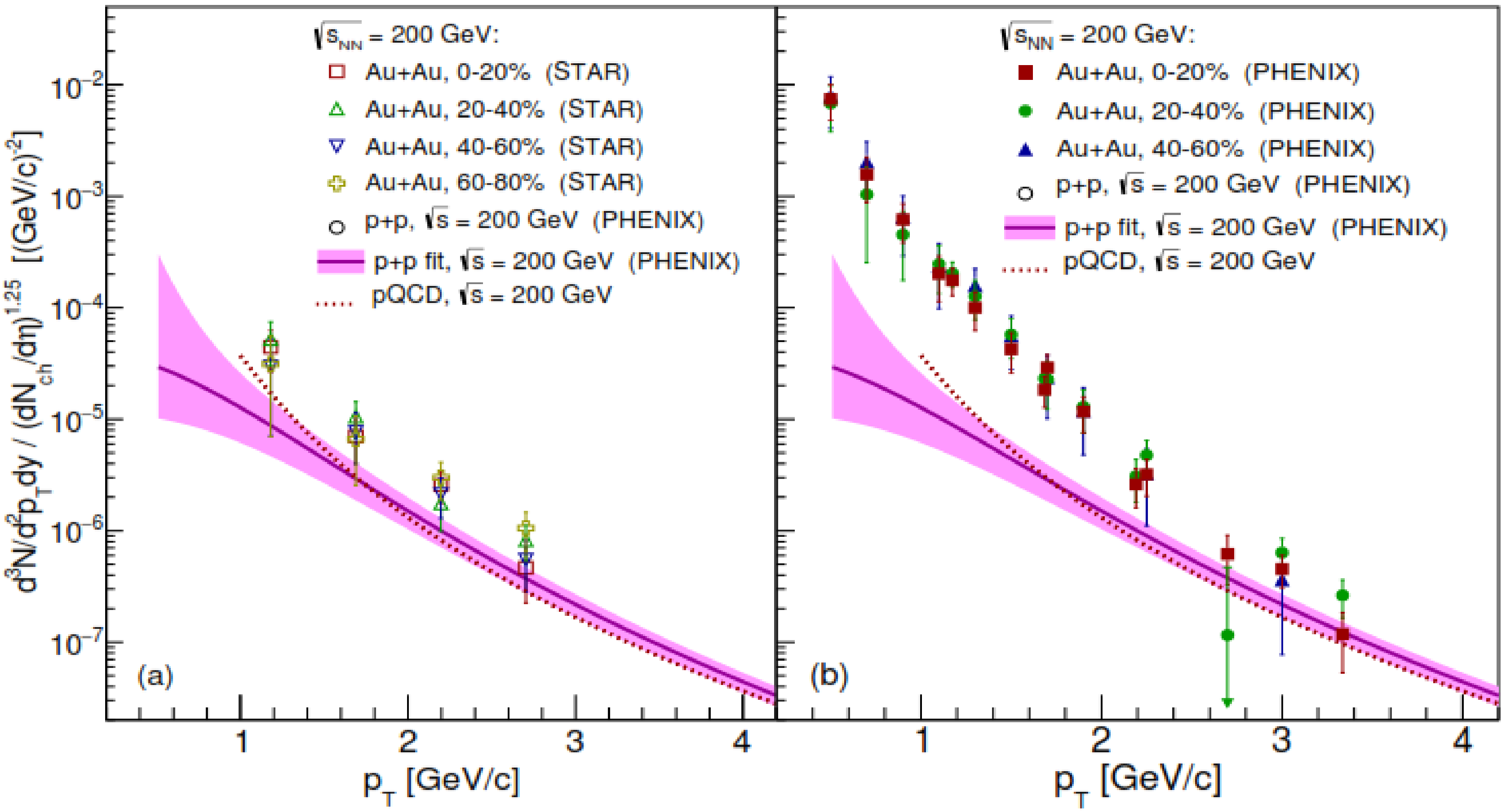
PHENIX / STAR discrepancy
Main culprit: cocktail?

PHENIX / STAR discrepancy (at low p_T)

A sore point since 2016

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

STAR: Phys. Lett. B770 (2017) 451

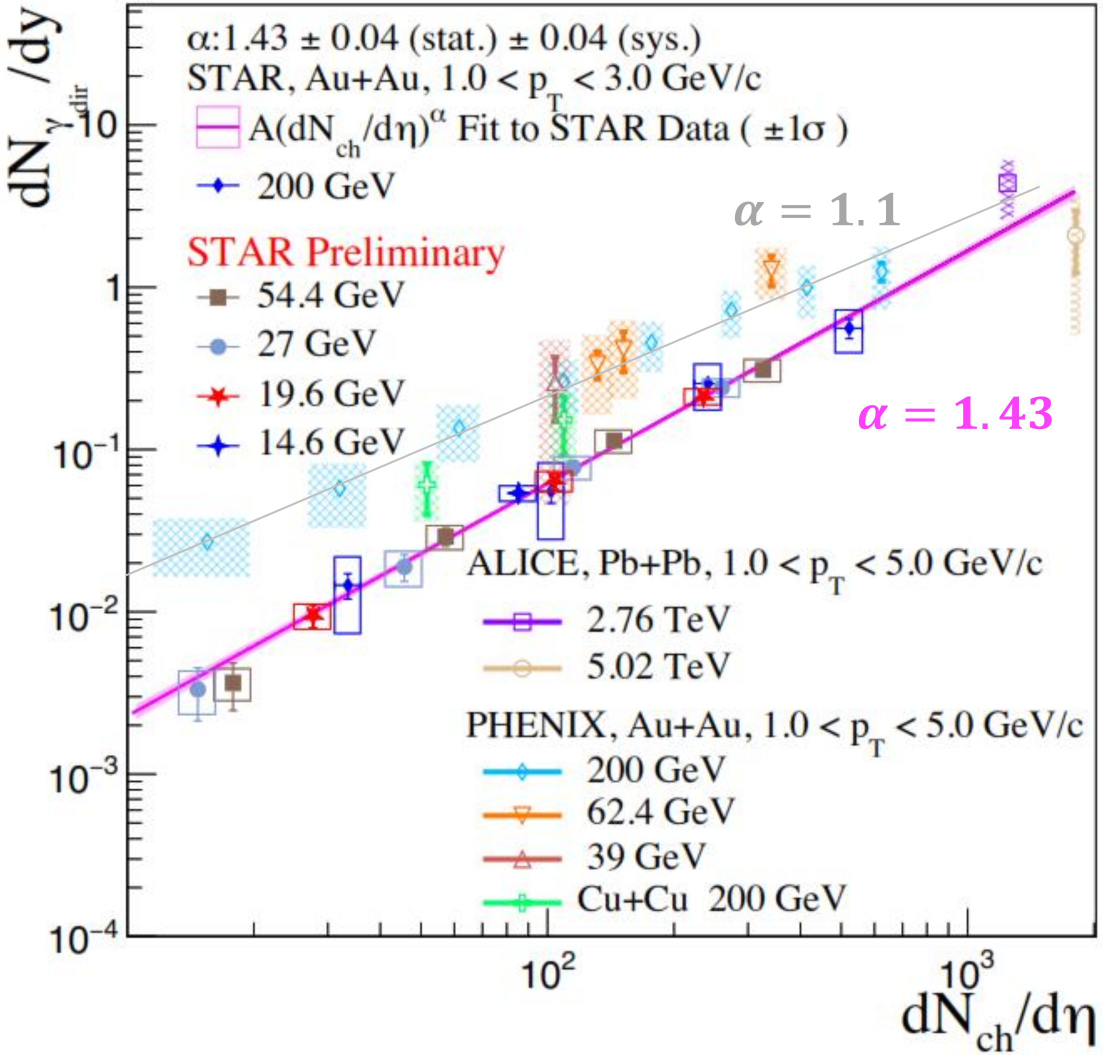


Renewed efforts since QM2025

Credit: Axel Drees, SBU

Integrated yields vs N_{ch} (and slopes)

Different evolution with centrality



STAR at QM2025

- STAR results:
  - Virtual photon analysis $\gamma^* \rightarrow e^+e^-$ for Au+Au at 14.6, 19.6, 27, 54.4, 200 GeV
  - Self consistent analyses & results across energies
  - Direct photon yield scales with $N_\gamma^{dir} \sim \left(\frac{dN_{ch}}{d\eta}\right)^\alpha$ with $\alpha \sim 1.43$
- Compared to PHENIX results:
  - STAR yield a factor of 3-5 below PHENIX
  - $\alpha \sim 1.43$ versus $\alpha \sim 1.1$ for PHENIX

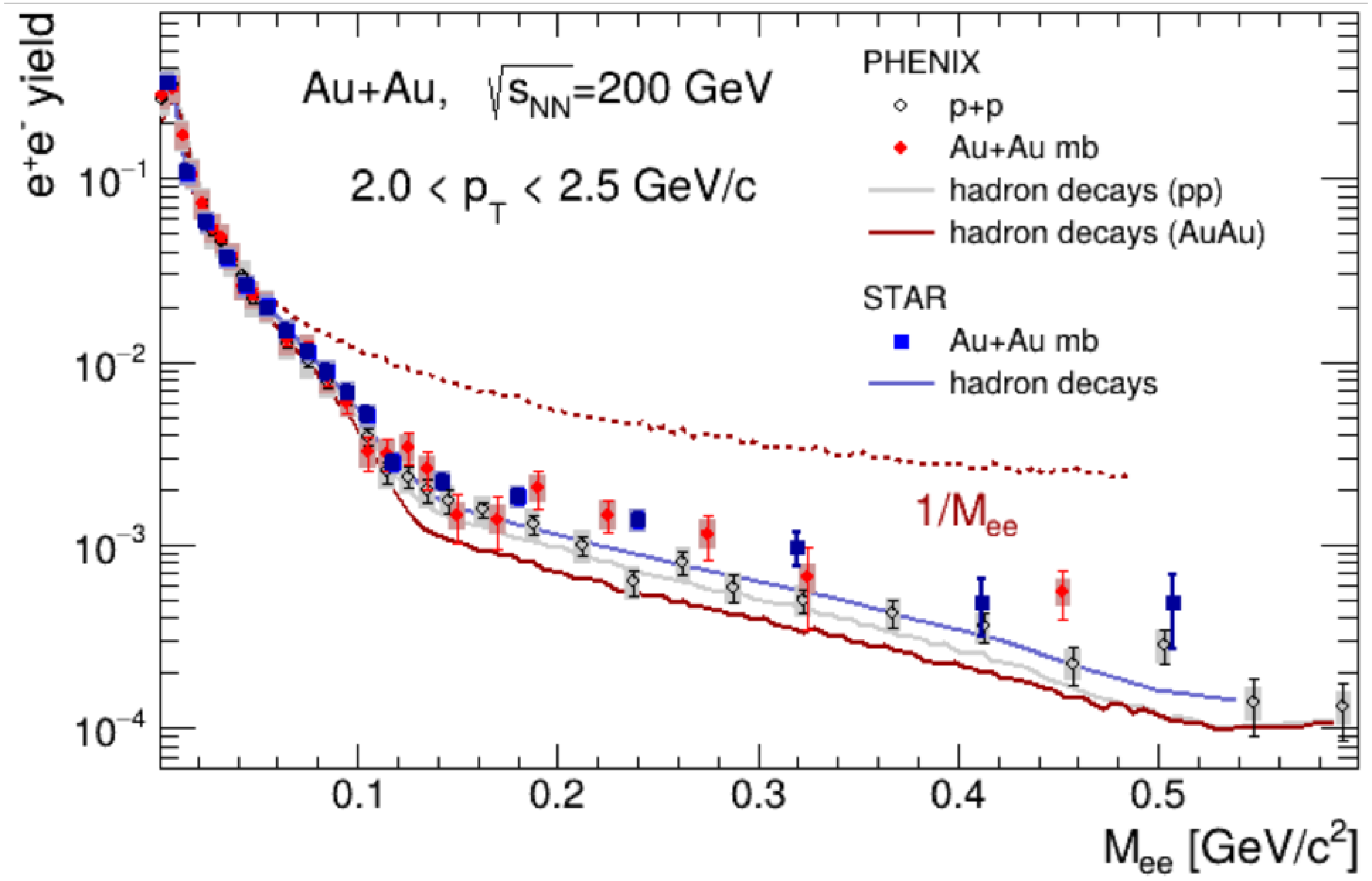
Credit: Axel Drees, SBU

Very different physics message!

Compare in a particular p_T range

Au+Au minimum bias data

Credit: Axel Drees, SBU



Same pt selection

All data is normalized for m<30 MeV

STAR and PHENIX data agree well in π^0 and η Dalitz region

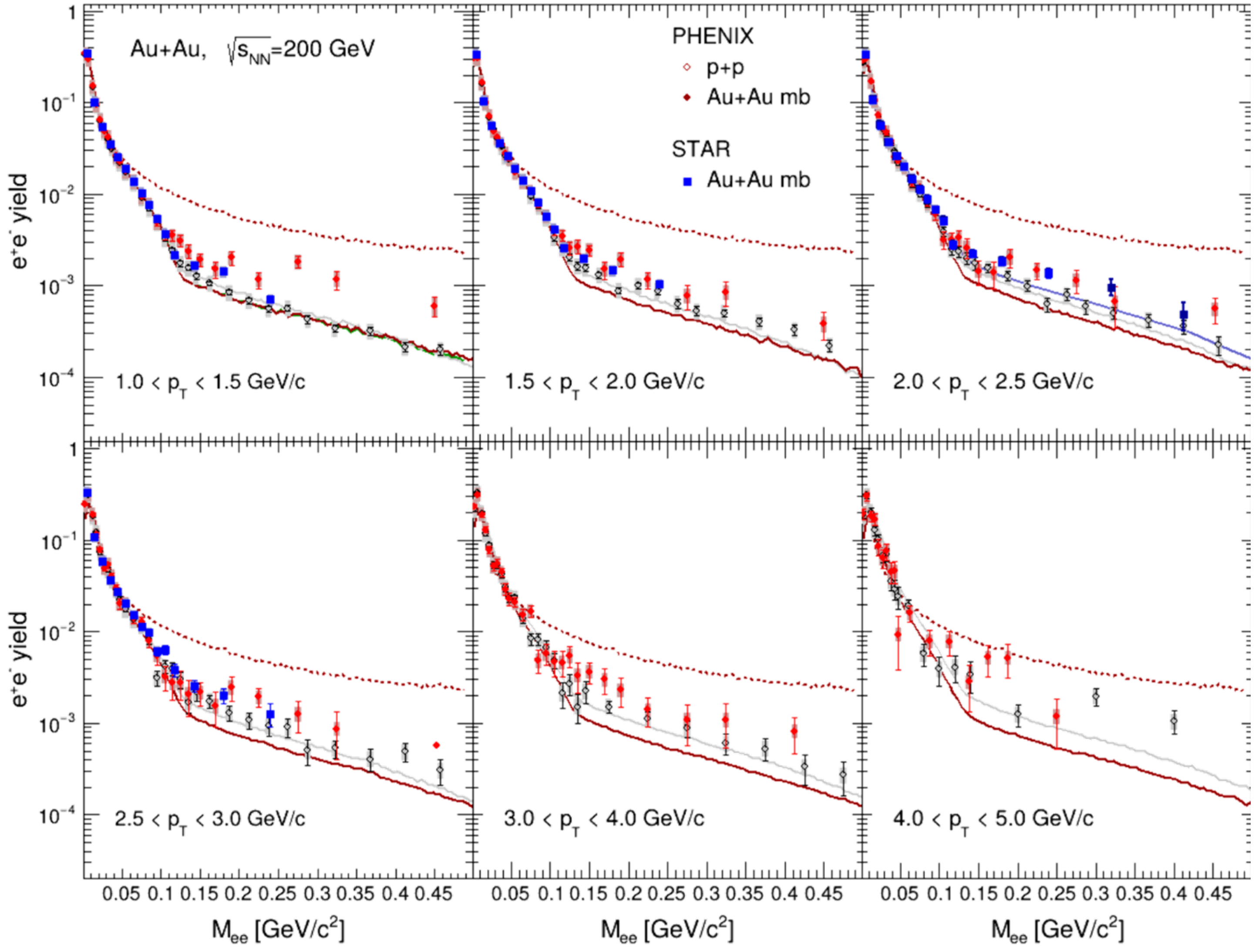
η/π^0 at low p_T higher in STAR

Cocktails do not agree!

Evolution with p_T

How does it evolve with p_T?

Credit: Axel Drees, SBU



Data seem to be consistent for p_T > 2 GeV/c

Difference at lower p_T

Converges

What next?

Collaborate with STAR

Exchange AuAu virtual gamma data (not all in public domain or HEP data)

Provide standalone software that reproduces experimental data

Independently analyse data from both experiments with same cocktail

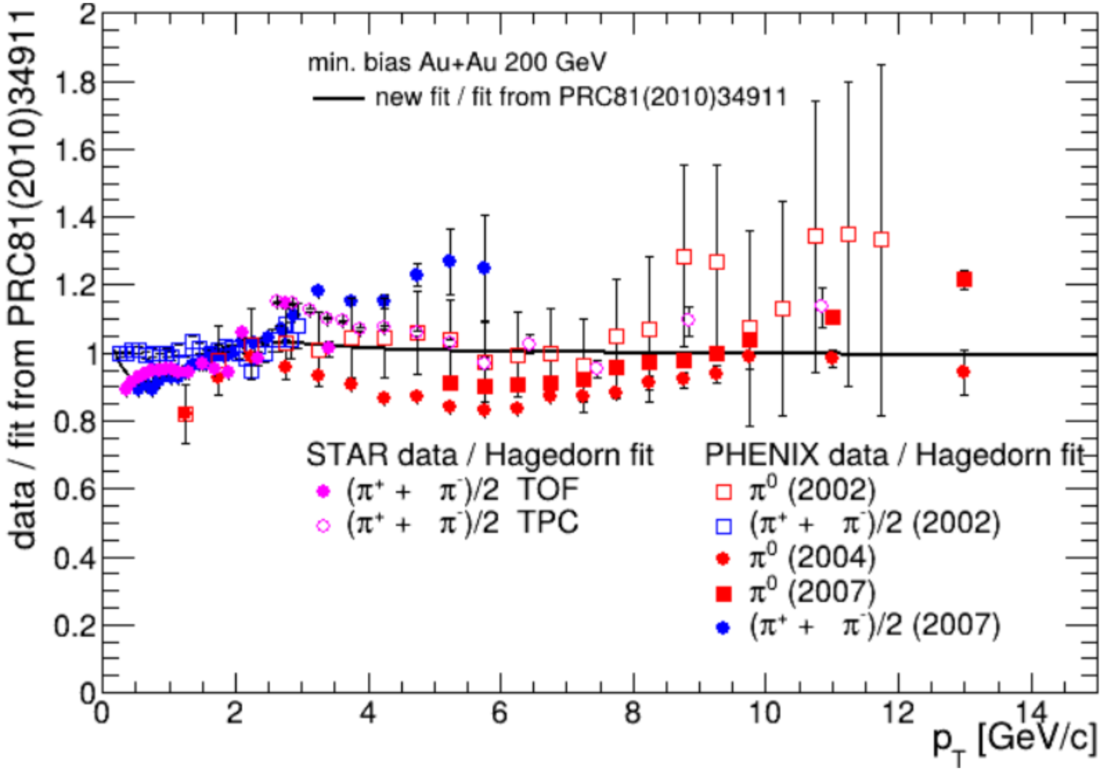
Compare & discuss

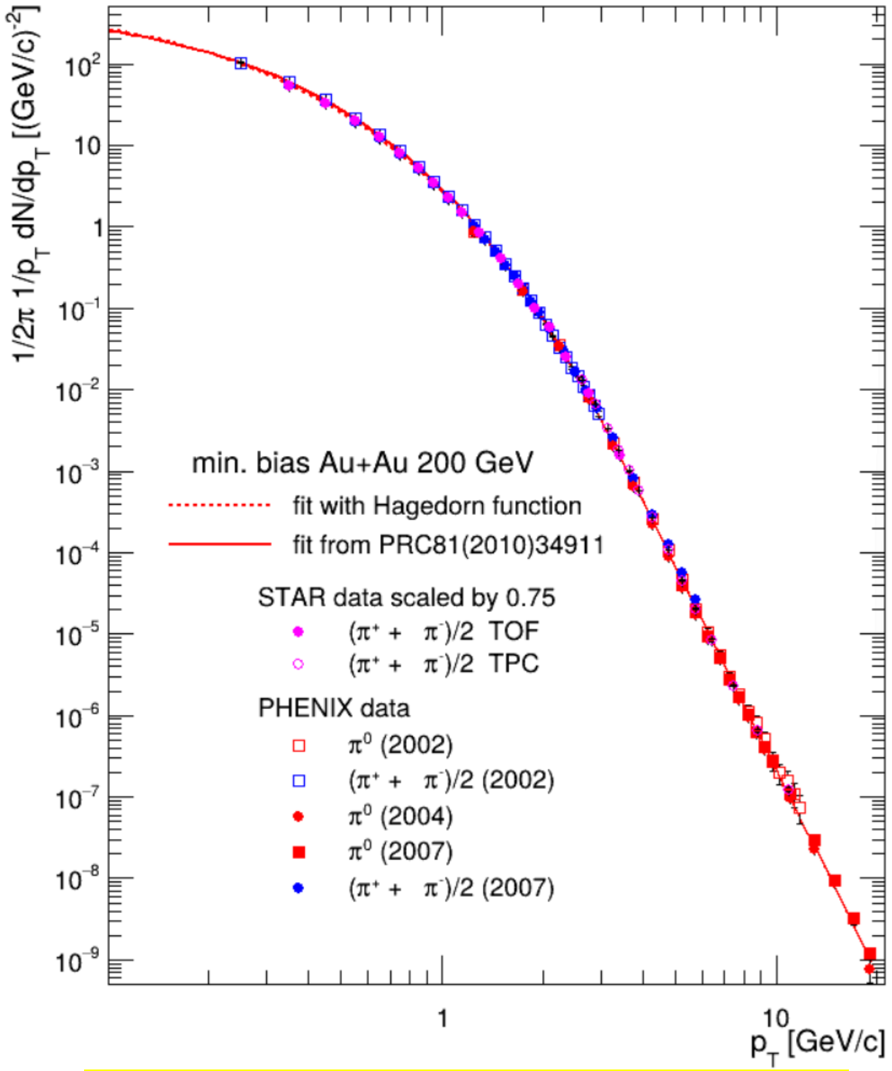
- On the PHENIX side
  - Collect data in sharable form
  - Develop standalone PHENIX simulator
  - Create new cocktail based on today's knowledge

Ongoing work with STAR

Consistency of π^0

Compare to charged pions, STAR

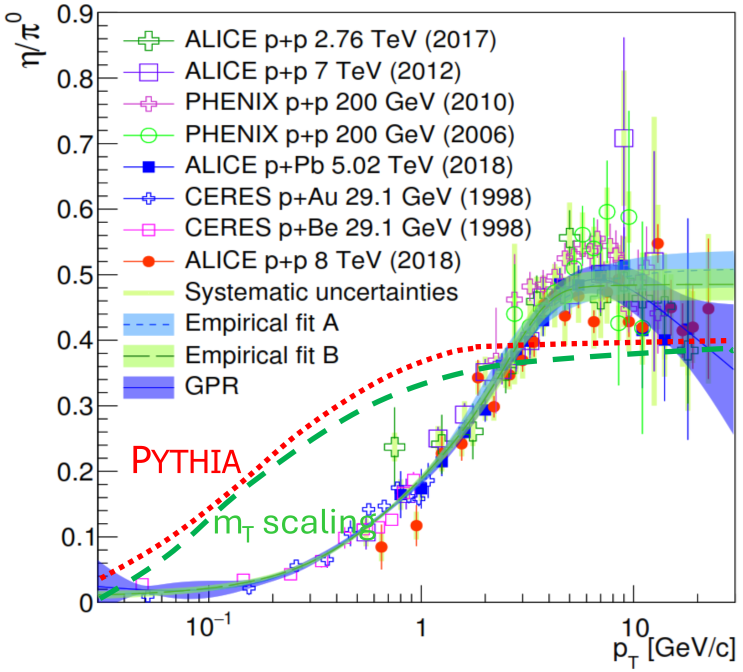




Reasonable agreement

The second highest contributor: η

Recent study of world data



η/π^0 PRC 104, 054902 (2021)

η/π^0 vs collision energy

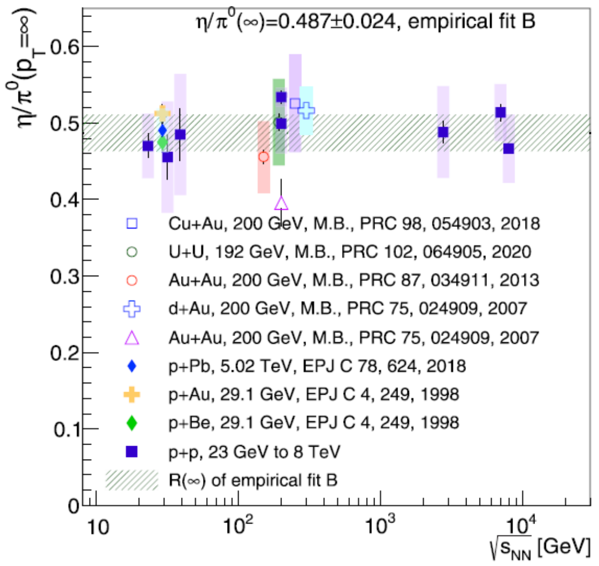


FIG. 4. Values of $R^{\infty} = \eta/\pi^0(p_T \to \infty)$ as a function of $\sqrt{s_{NN}}$ for the minimum bias $p+p$, $p+A$, and A+B data sets. Statistical errors are shown as bars, and systematic uncertainties are shown as bands. Also shown is a band representing 0.487 ± 0.024, the result of the empirical fit B to the combined $p+p$ and $p+A$ data. Note that the A+B data at 200 GeV are offset in $\sqrt{s_{NN}}$ to avoid overlap of data sets.

η/π^0 vs N_{ch} (centrality)

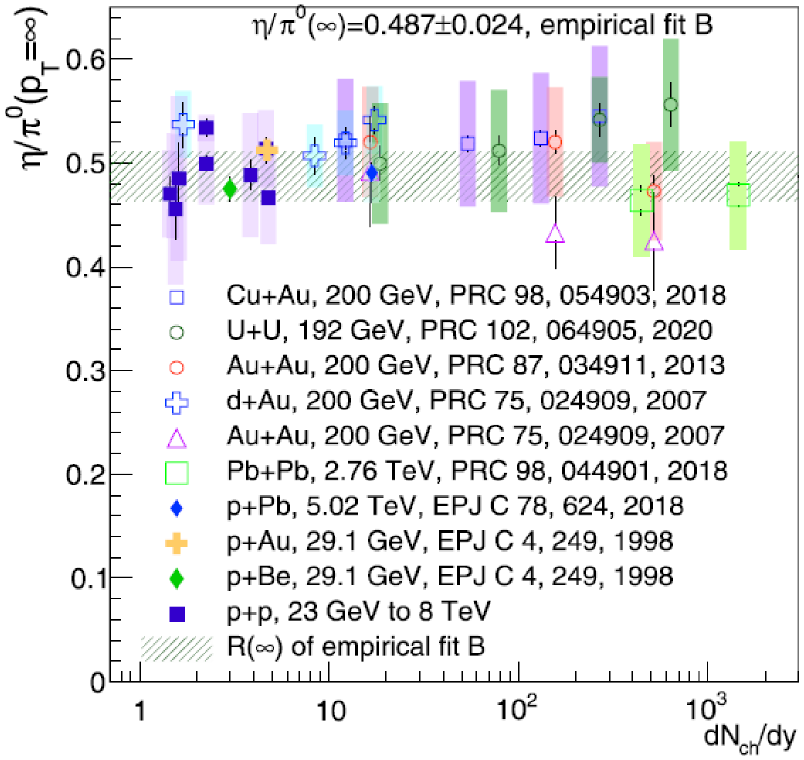
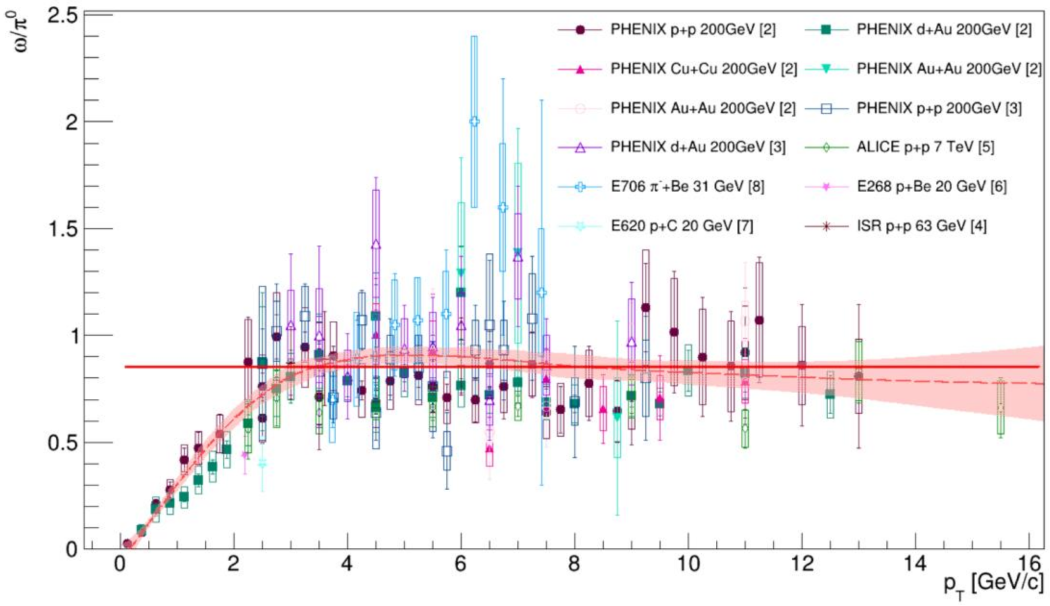


FIG. 5. Values of $R^{\infty} = \eta/\pi^0(p_T \to \infty)$ as a function of $dN_{ch}/d\eta$. The presentation is identical to Fig. 4; however, for A+B collisions results from different centrality classes are shown rather than results for the minimum bias sample.

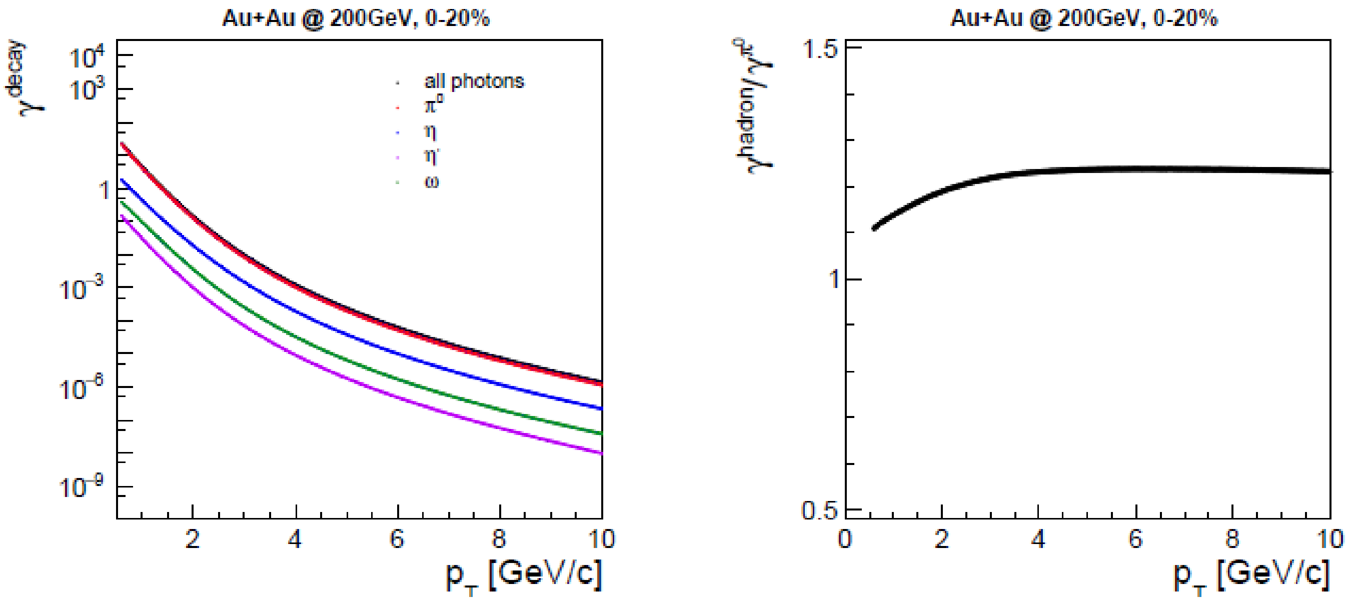
Is it truly constant at high p_T?

Other contributors – ω, η' …

Small contribution, but we need a precision measurement



Axel Drees, Konstantin Bauer, SBU 2023 (unpublished)



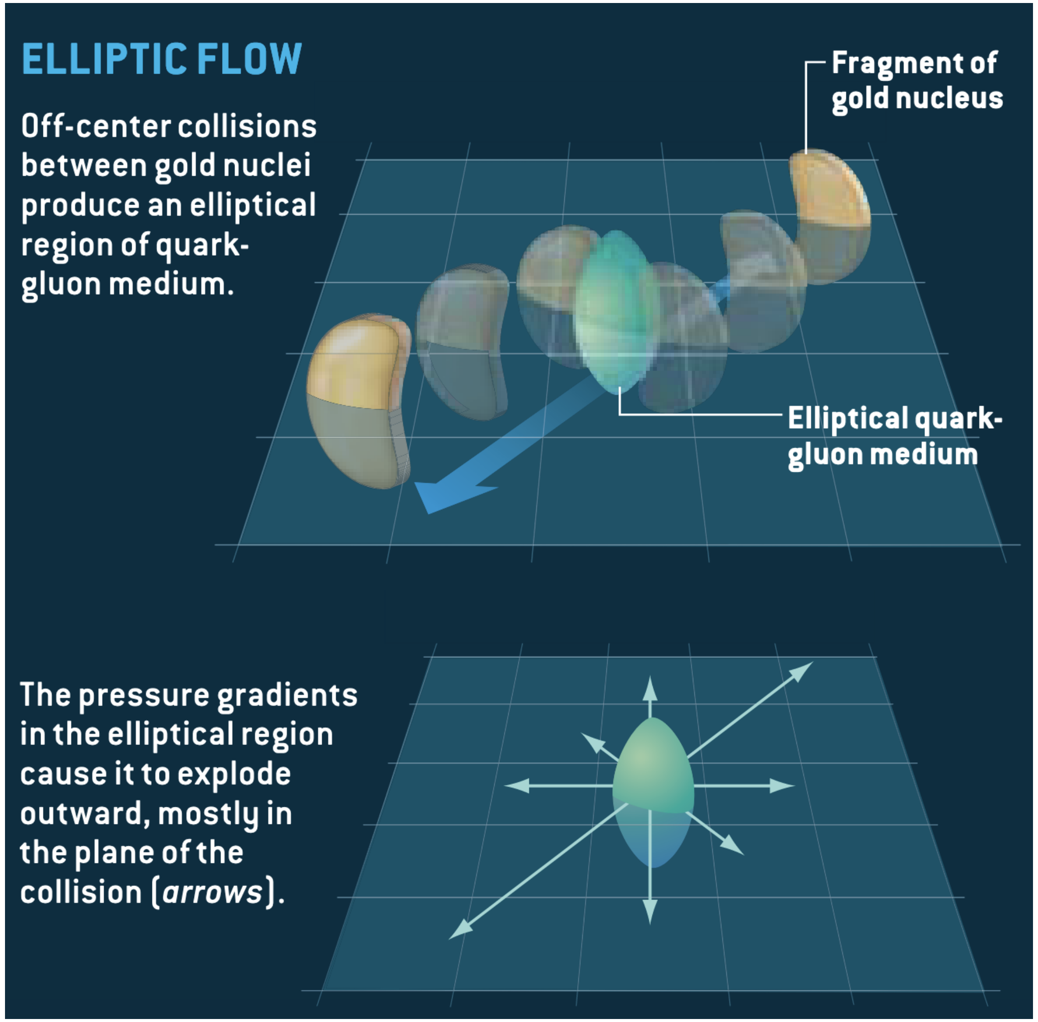
Wenqing Fan, SBU, PhD thesis

Few measurements available
Changes with collision energy

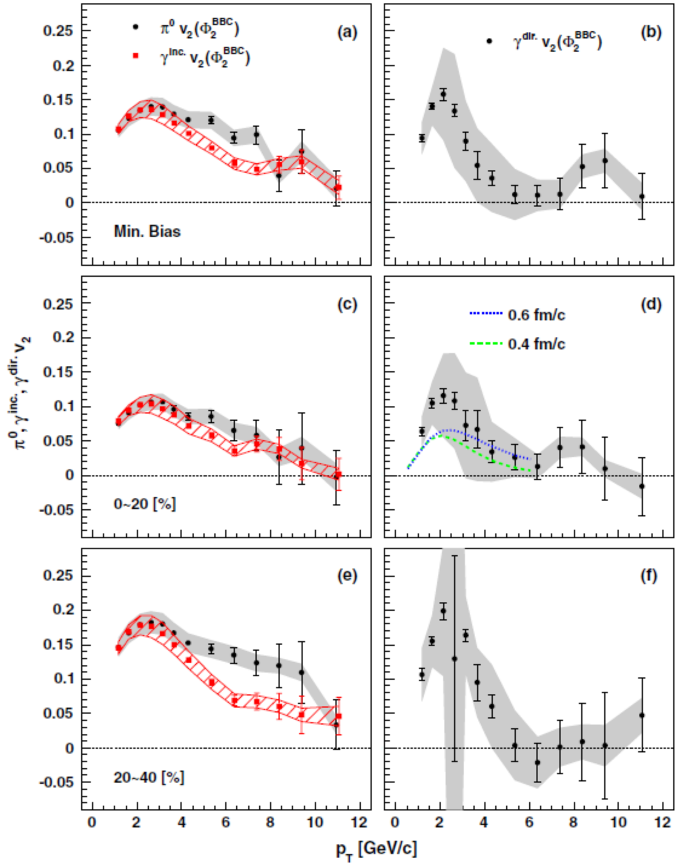
“Direct photon puzzle”

Azimuthal anisotropy in photon emission

I hate the word "flow"… it implies a particular dynamics



PRL 109, 122302 (2012)



At low p_T π^0 and hadron v_2 similar!

The direct photon puzzle – Au+Au, 200 GeV

What is it?

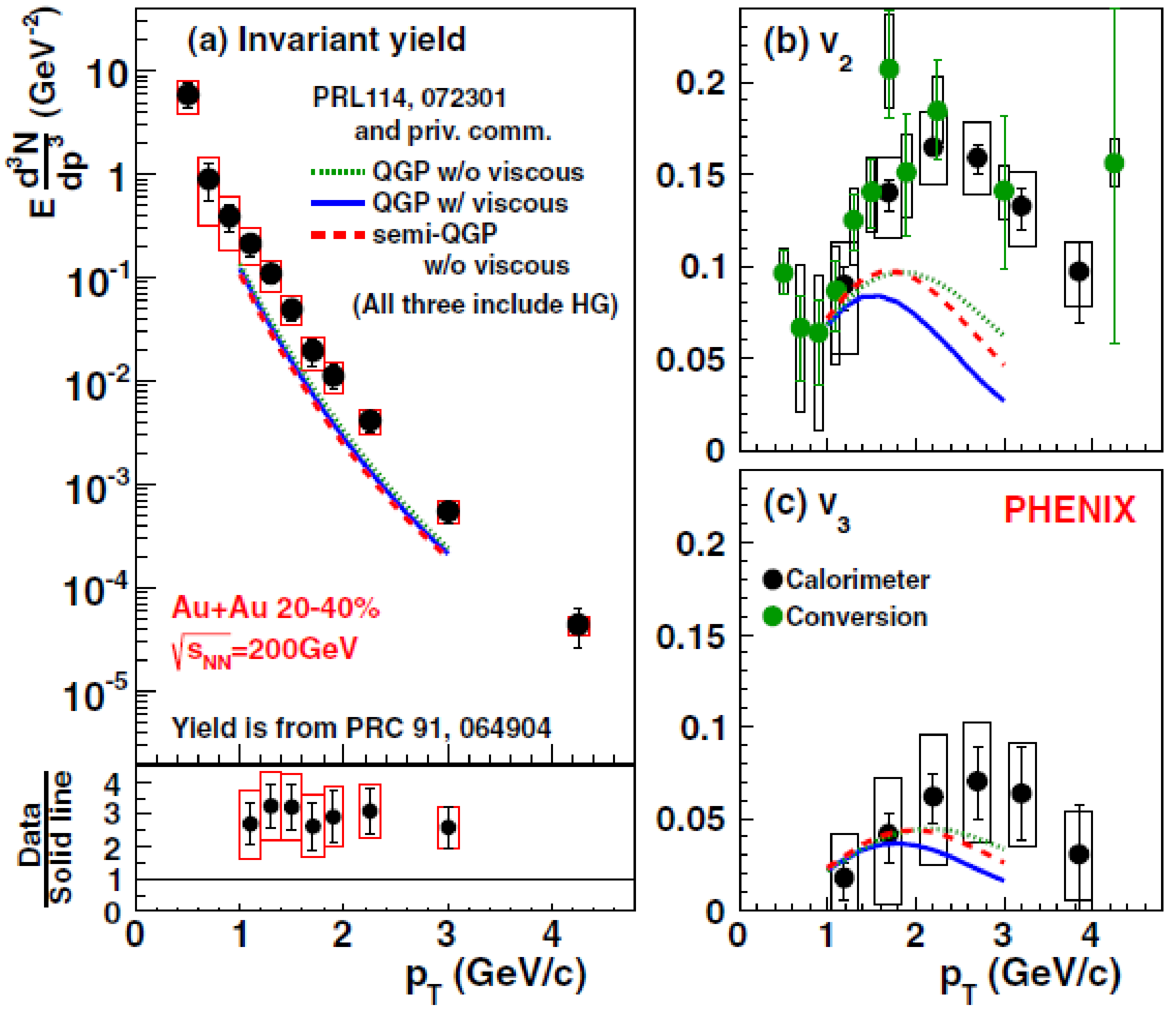
PHENIX PRC 94, 064901 (2016)

Long-time paradigm:
mostly thermal radiation
from QGP and HG

Large yield: early emission, high T

Large azimuthal anisotropies:
late emission, low T

Models could not explain
large yield and v_2 simultaneously

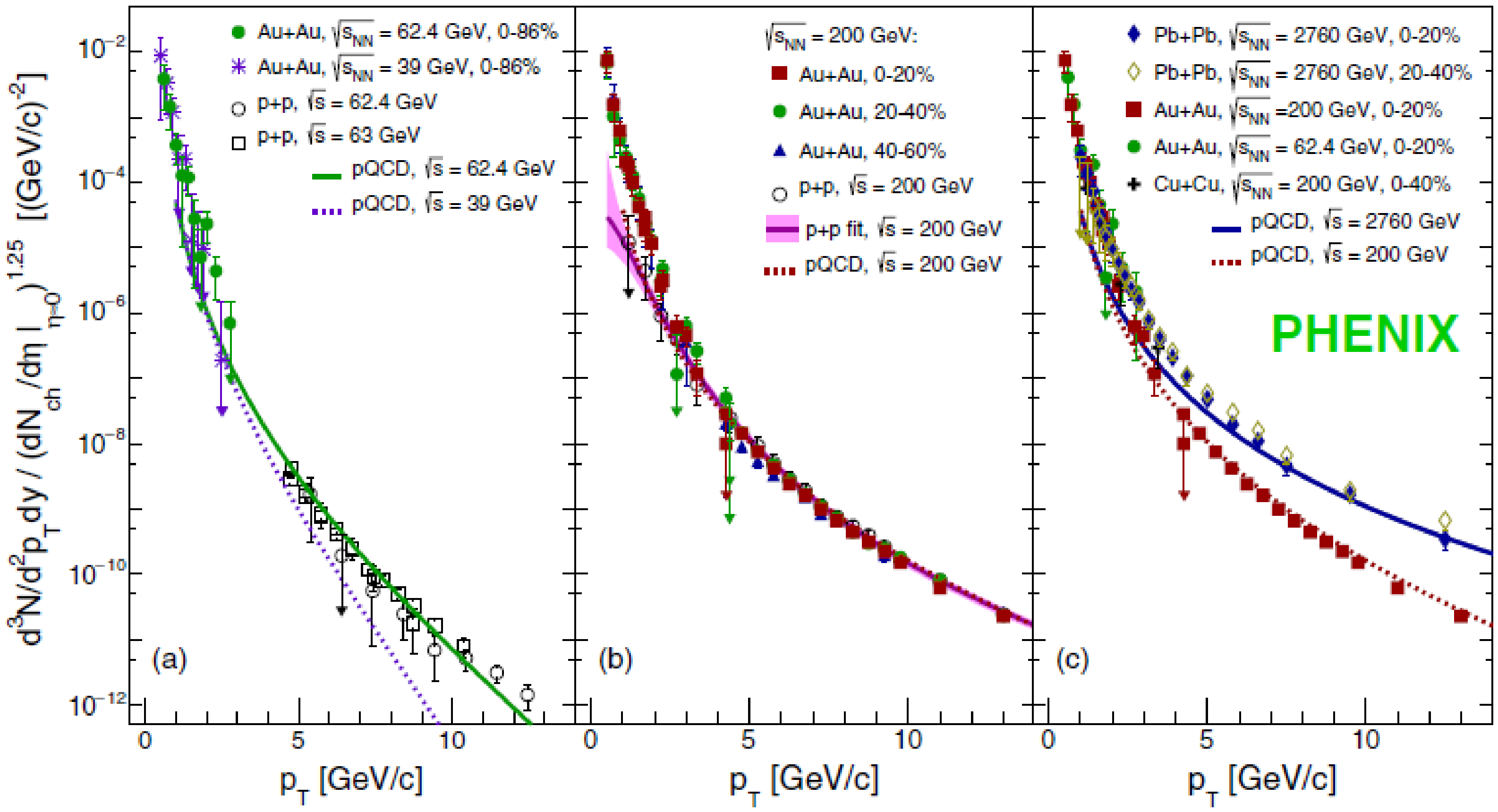


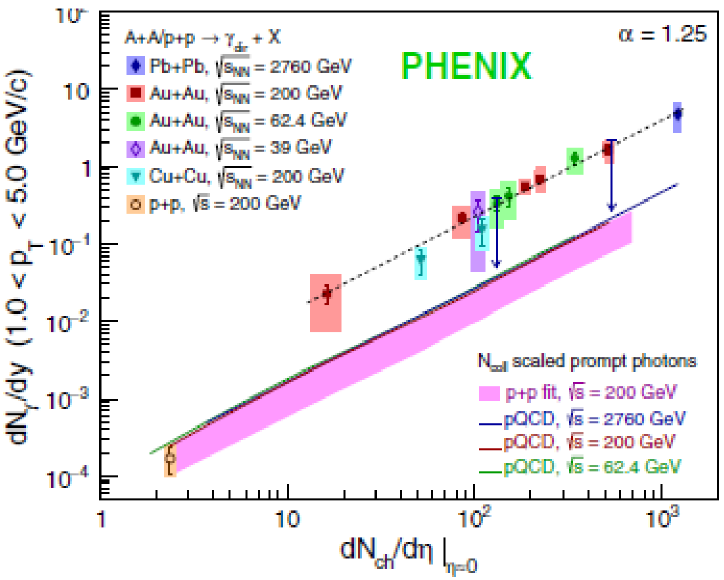
Paradigm shift needed?

Scaling: part of the puzzle?

Universality over system size, collision energy?

$$\frac{dN_\gamma}{dy} = \int_{p_{T,\min}}^{p_{T,\max}} \frac{dN_\gamma^{\rm dir}}{dp_T dy} dp_T = A \times \left(\frac{dN_{\rm ch}}{d\eta}\right)^\alpha$$



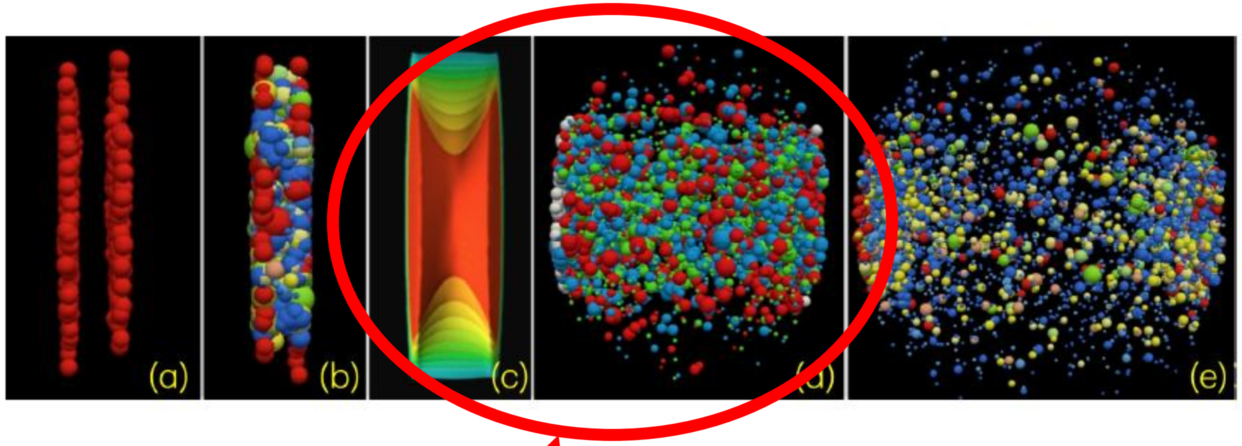


Surprisingly small power (α=1.25)

PRL 123, 022301 (2019)

Is there a "puzzle" at all?

Thermal/hydro paradigm: yield → "early", flow → "late"



Concentrating on this region and as a (locally) thermalized hydro system is too narrow-minded?

Logical – and tractable! – assumption
but why would thermal source be super-dominant?
No a priori reason
"Unconventional" sources?

Gale arXiv:2502.13938

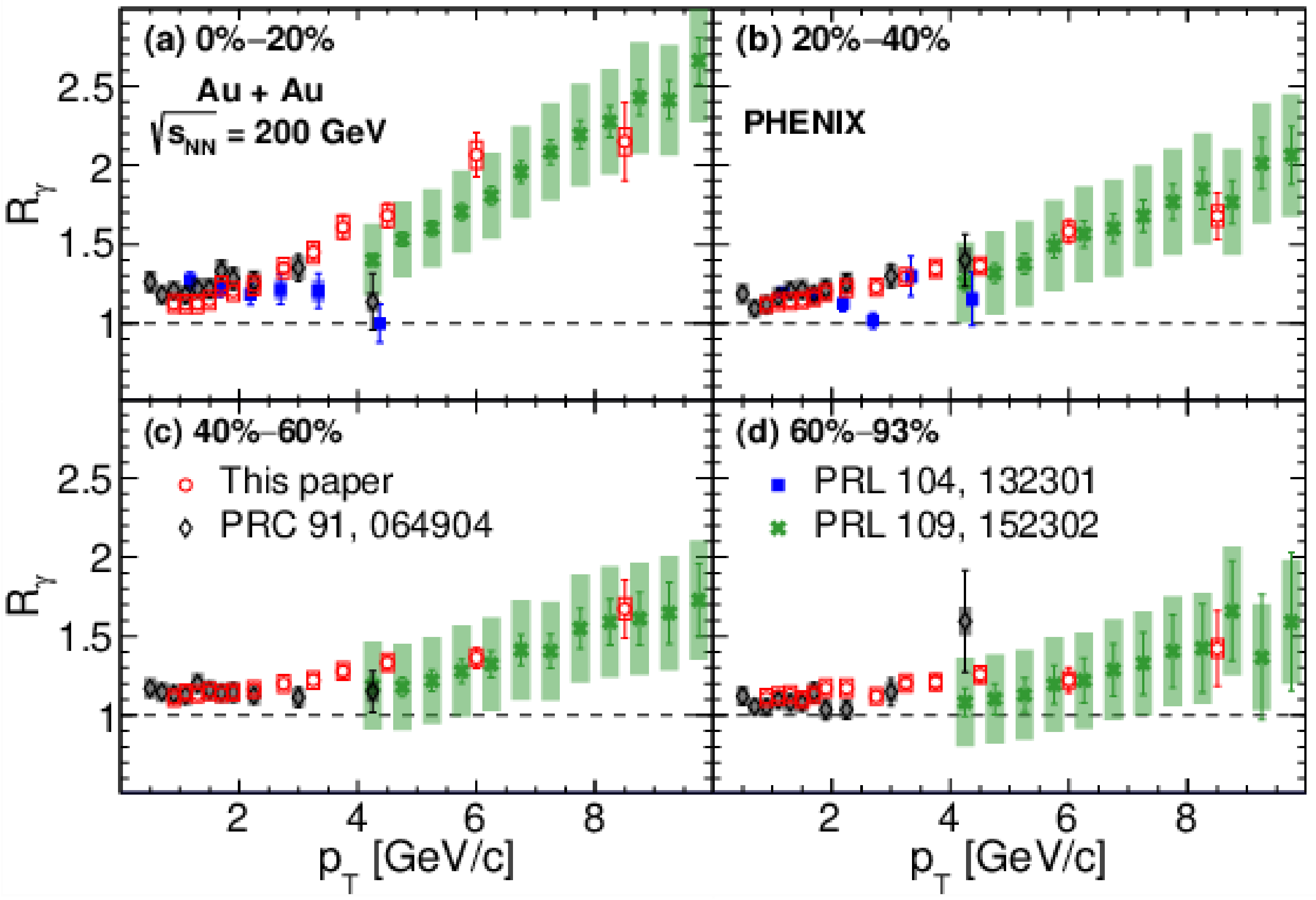
Is the puzzle just due to some tunnel-vision?

Consistency

Four different analysis techniques…

$$R_\gamma = \frac{\gamma^{inclusive}}{\gamma^{decay}}$$

Clear excess in the "thermal" region, depending on centrality

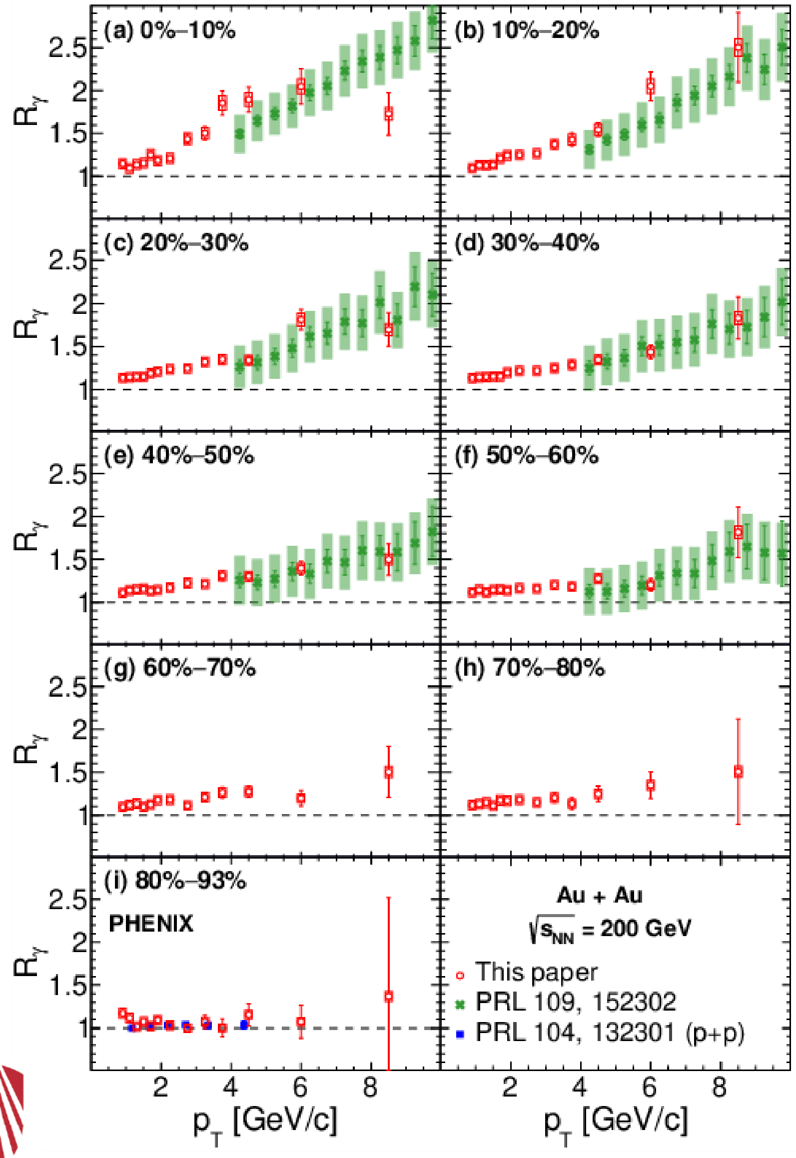


PRC 109, 044912 (2024)

…giving consistent results

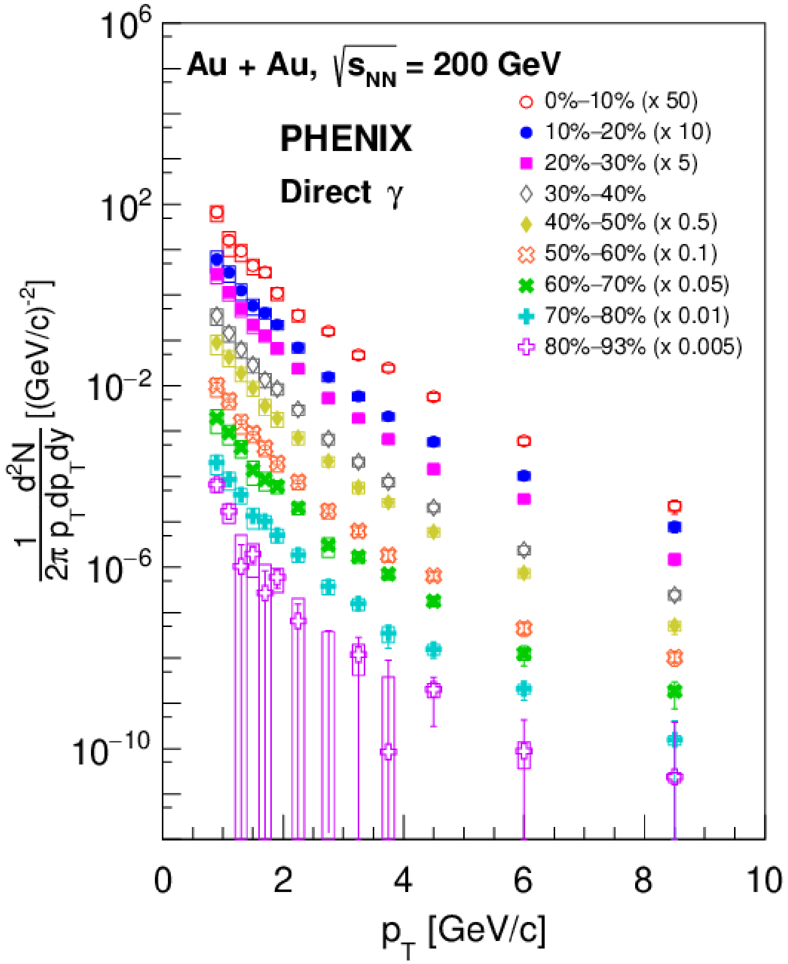
A closer look at Rγ and direct γ

External conversion in VTX



Rγ – and its uncertainty – is crucial in the analysis of azimuthal asymmetries

PRC 109, 044912 (2024)



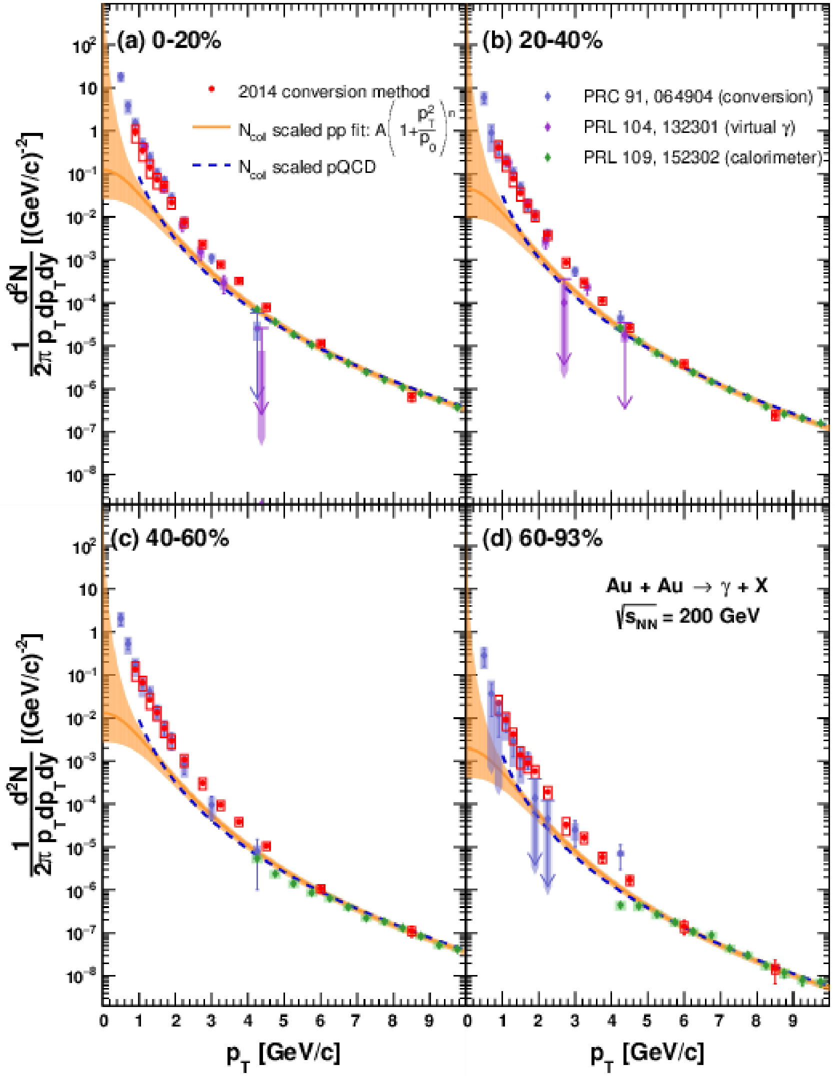
Limited range
→ high precision
(Conversion)

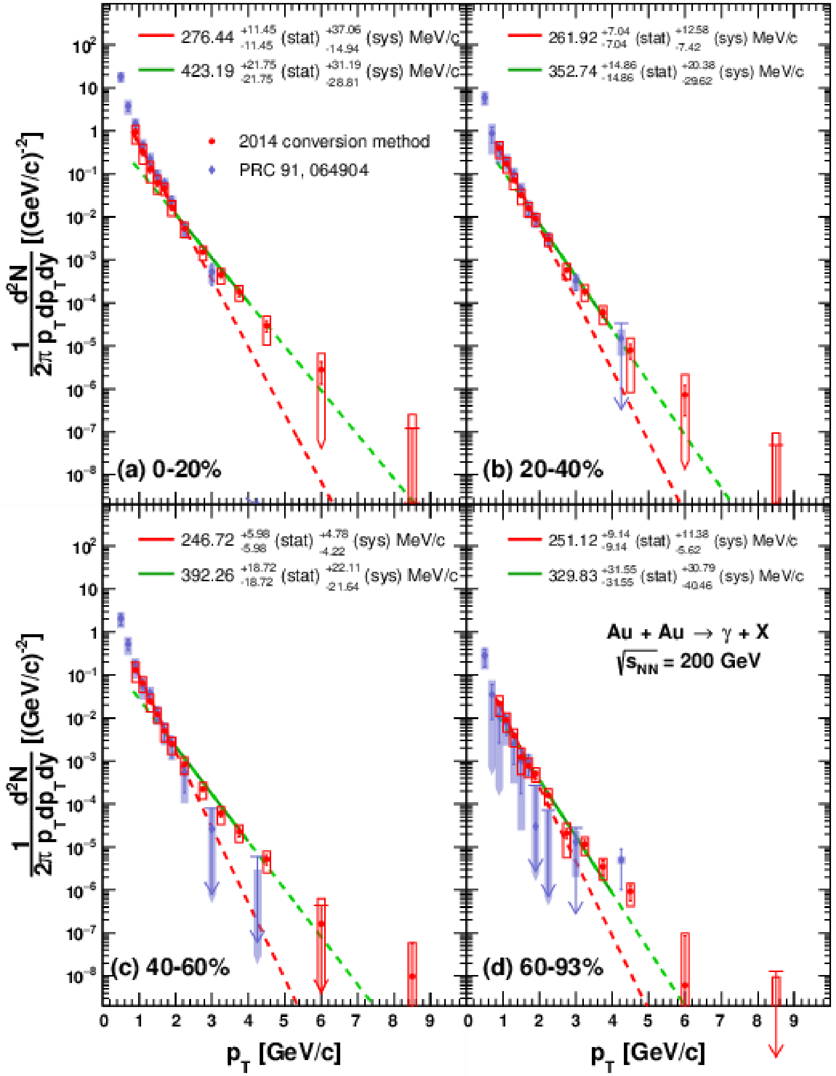
Consistent, solid overlap with calorimeter data

Direct and non-prompt photons

Non-prompt: subtract p+p (extrapolated)

PRC 109, 044912 (2024)





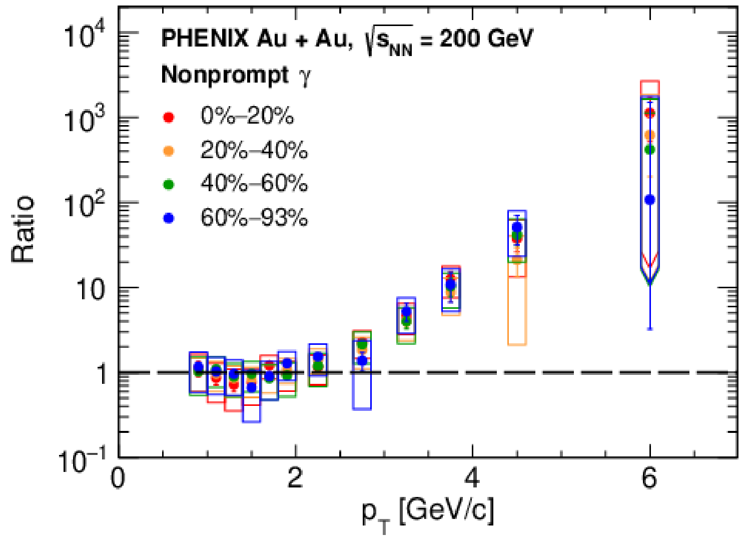
Non-prompt: not a single exponential ("Thermal" is frowned upon ☺)

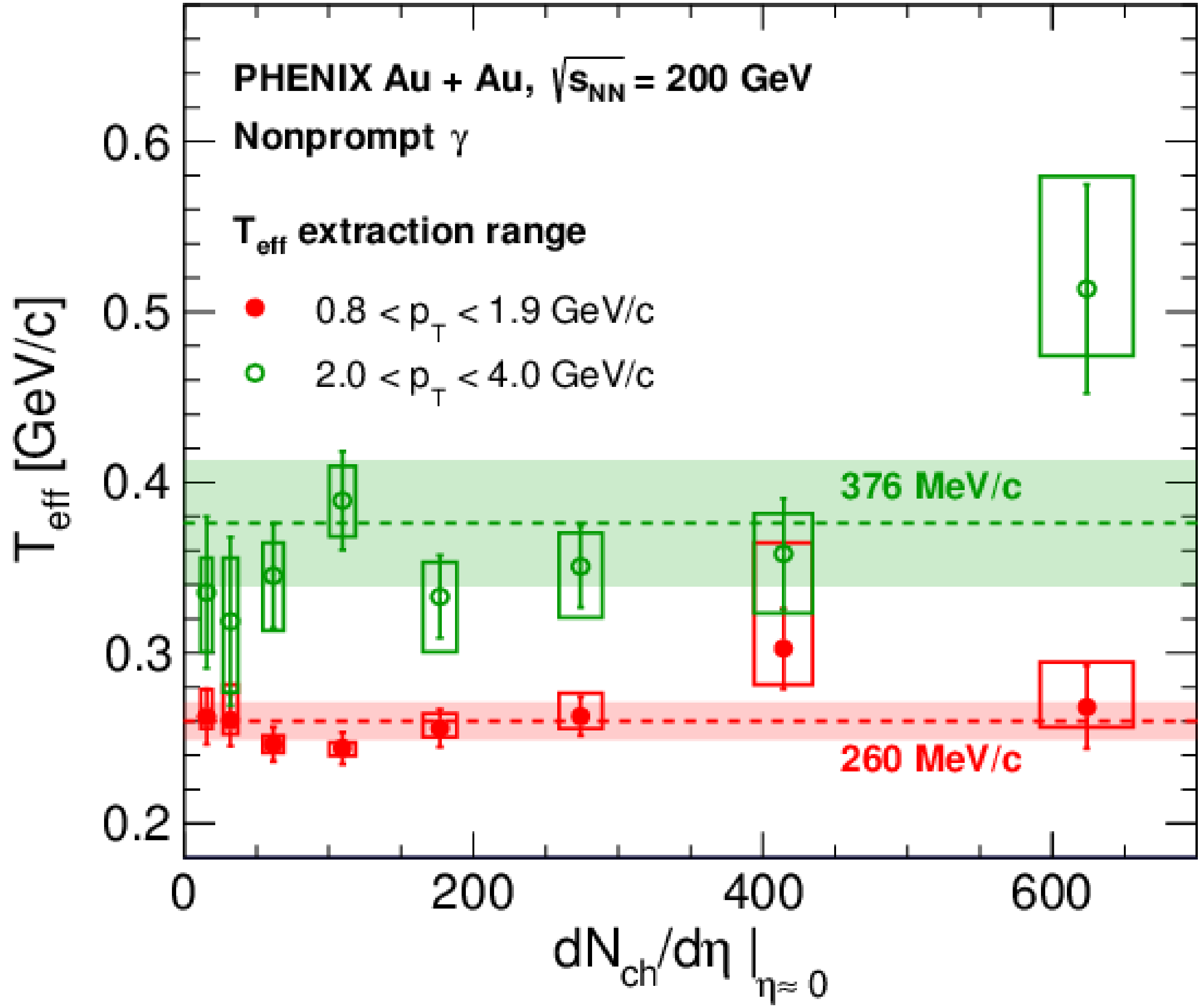
T_{eff} increases with p_T

T_{eff} vs the p_T range and centrality

No dependence on centrality

Strong dependence on p_T
Composition and relative weight of different sources always the same?





PRC 109, 044912 (2024)

Yields: universal scenario?

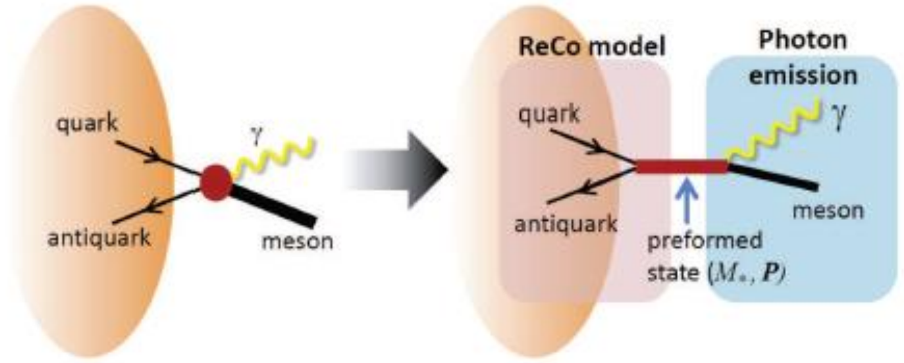
Easing a tension on α being too small?

Issue: photon yield vs N_{ch}

$dN\gamma/dy \sim (dN_{ch}/d\eta)^{\alpha}$

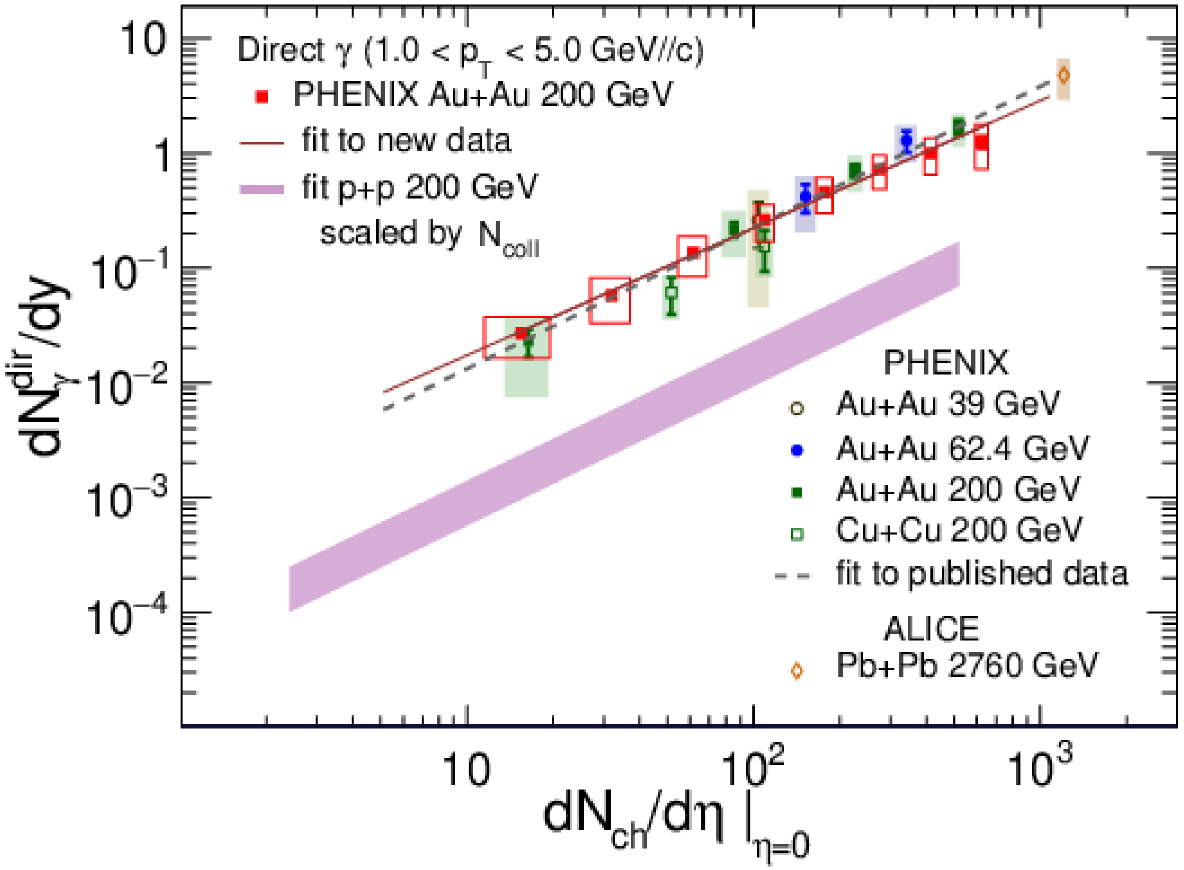
α from QGP ~ 1.85
α from HG ~ 1.25
α measured ~ 1.11

But radiative hadronization: $N\gamma \sim N_{ch}$



PRC 106, 034906 (2022)

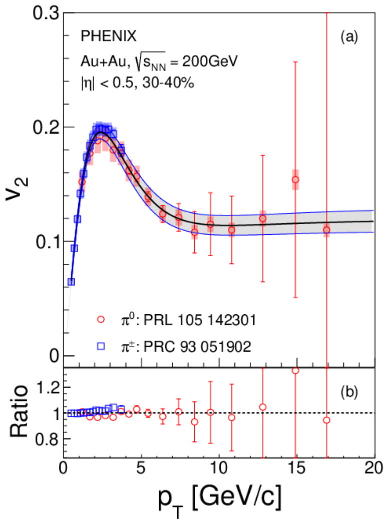
PRC109, 044912 (2024)



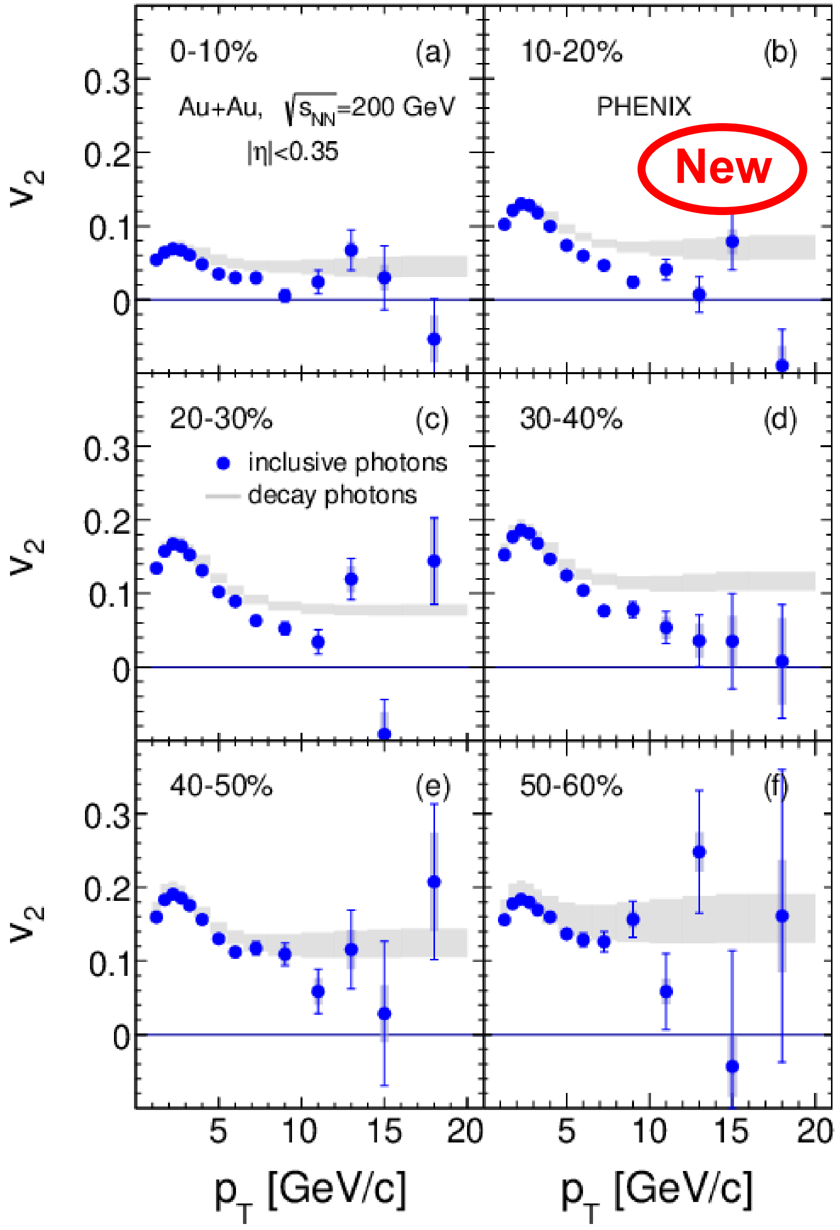
May help to explain small α observed

Direct photon v_2 – starts with inclusive and decay v_2

Inclusive γ
Decay γ
(cocktail)



Pion v_2 and fit
(used for decay v_2)



arXiv:2504.02955

At low p_T inclusive (blue)
and decay (gray band)
v_2 almost identical

At high p_T strong separation
(prompt photon v_2 ~ 0)

$$v_2^{dir} = \frac{R_\gamma v_2^{inc} - v_2^{dec}}{R_\gamma - 1}$$

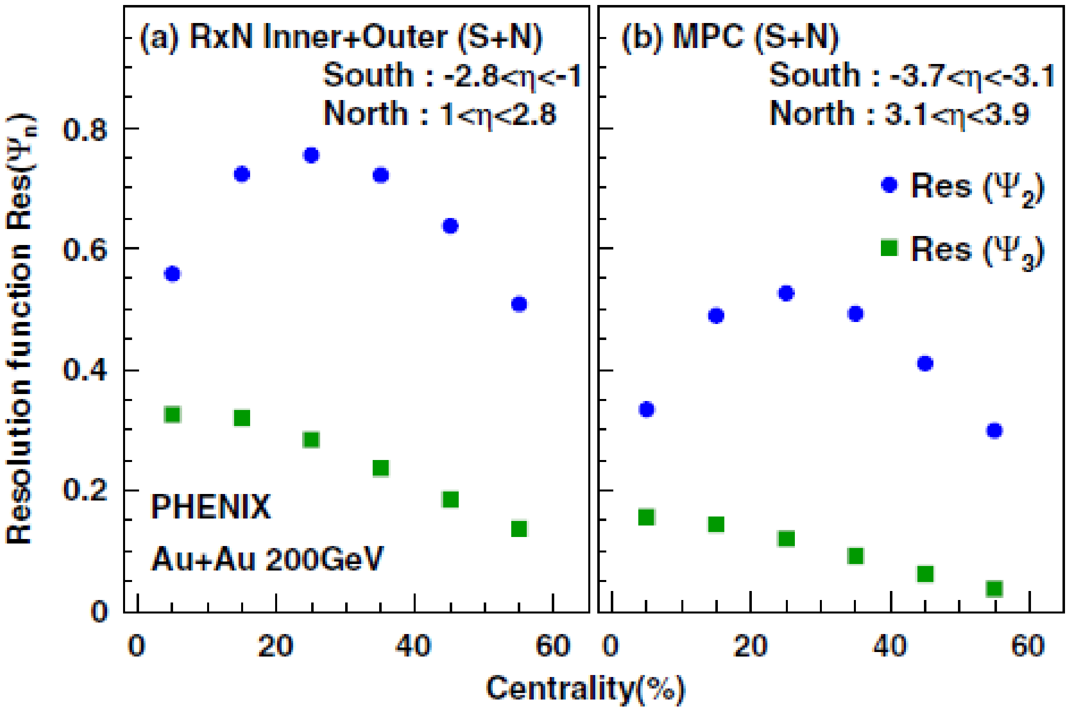
v_2 hyper-sensitive to Rγ

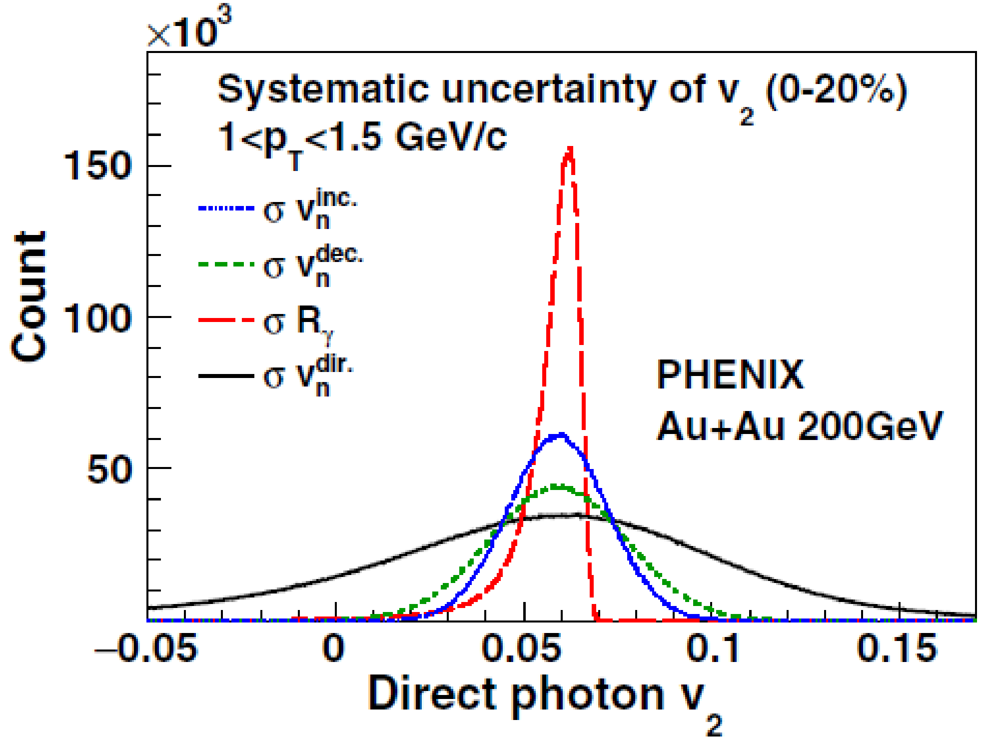
Reaction plane resolution, uncertainties on v_2

PRC 94, 064901 (2016)

Main sources of uncertainties

$$v_n = v'_n / \mathrm{Res}(\Psi_n).$$





$$v_2^{dir} = \frac{R_\gamma v_2^{inc} - v_2^{dec}}{R_\gamma - 1}$$

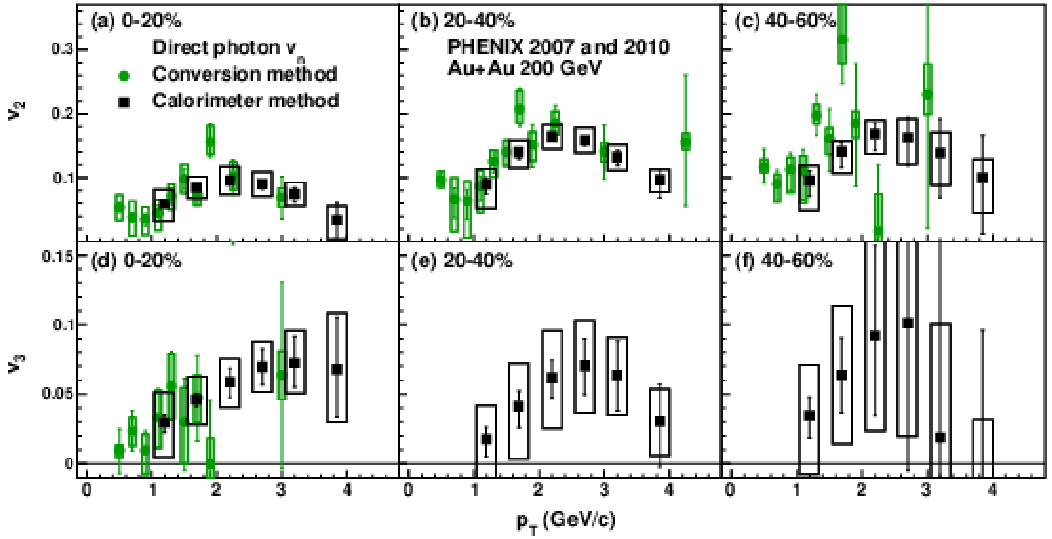
v_2 hyper-sensitive to Rγ

Direct photon v_2 – the new result

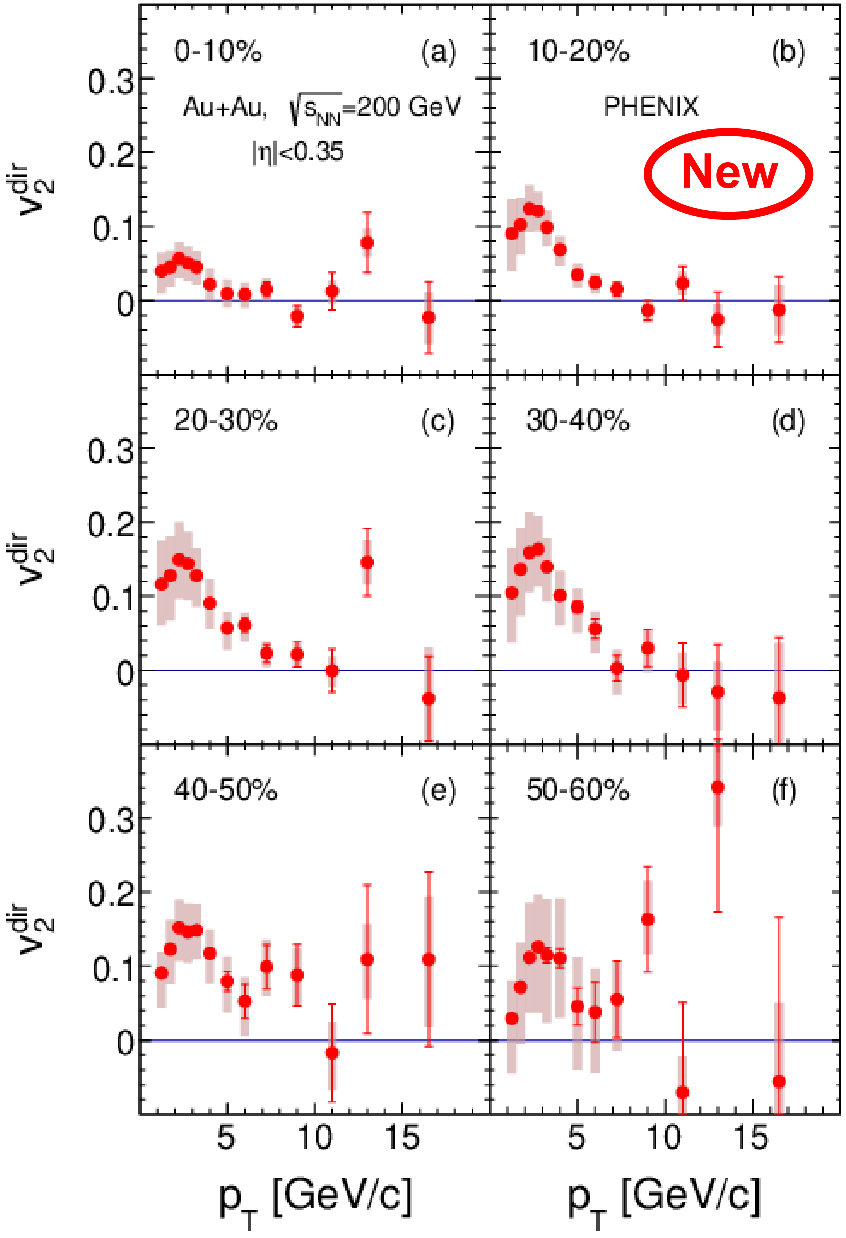
arXiv:2504.02955

Issue: magnitude, p_T dependence

Previous: PRC 94, 064901 (2016)



Conversion, calorimeter
Limited p_T range
Significant v_2



10% centrality

Wide p_T range

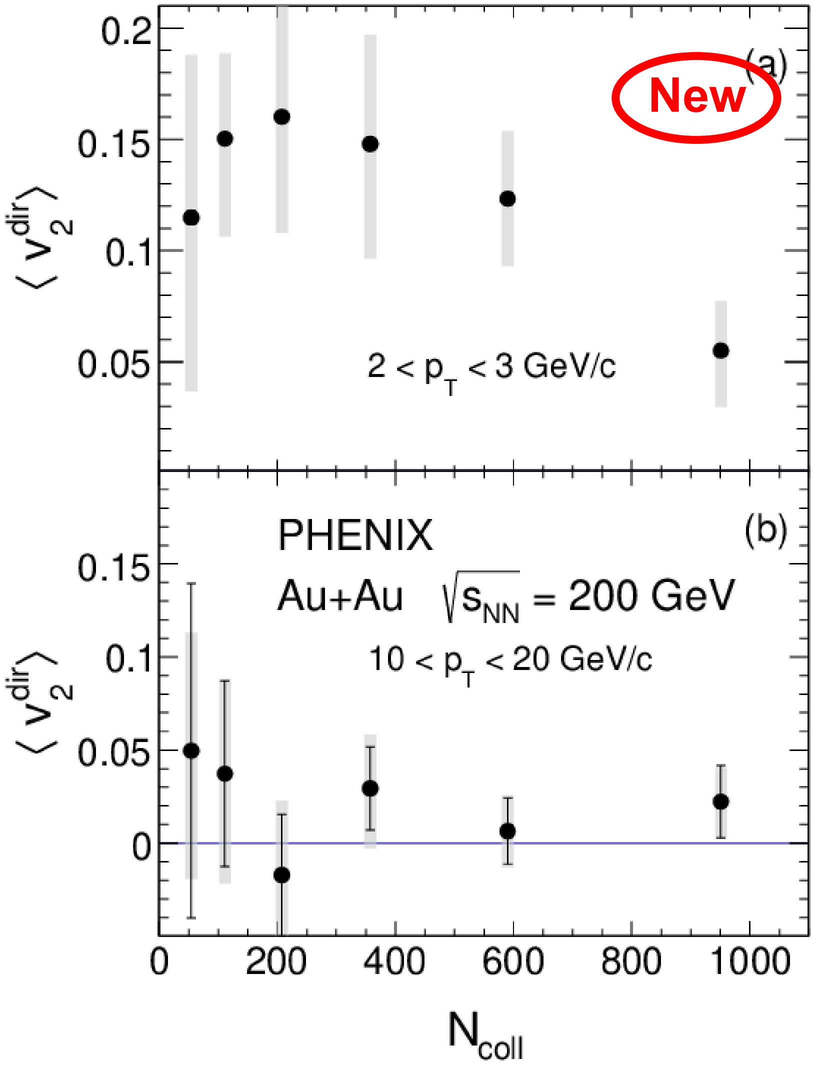
Calorimeter

Large at low p_T vanishes at high p_T

Average v_2 vs p_T and centrality

arXiv:2504.02955

Low and high p_T regions



Low p_T (non-prompt)
→ large v_2, centrality dependence

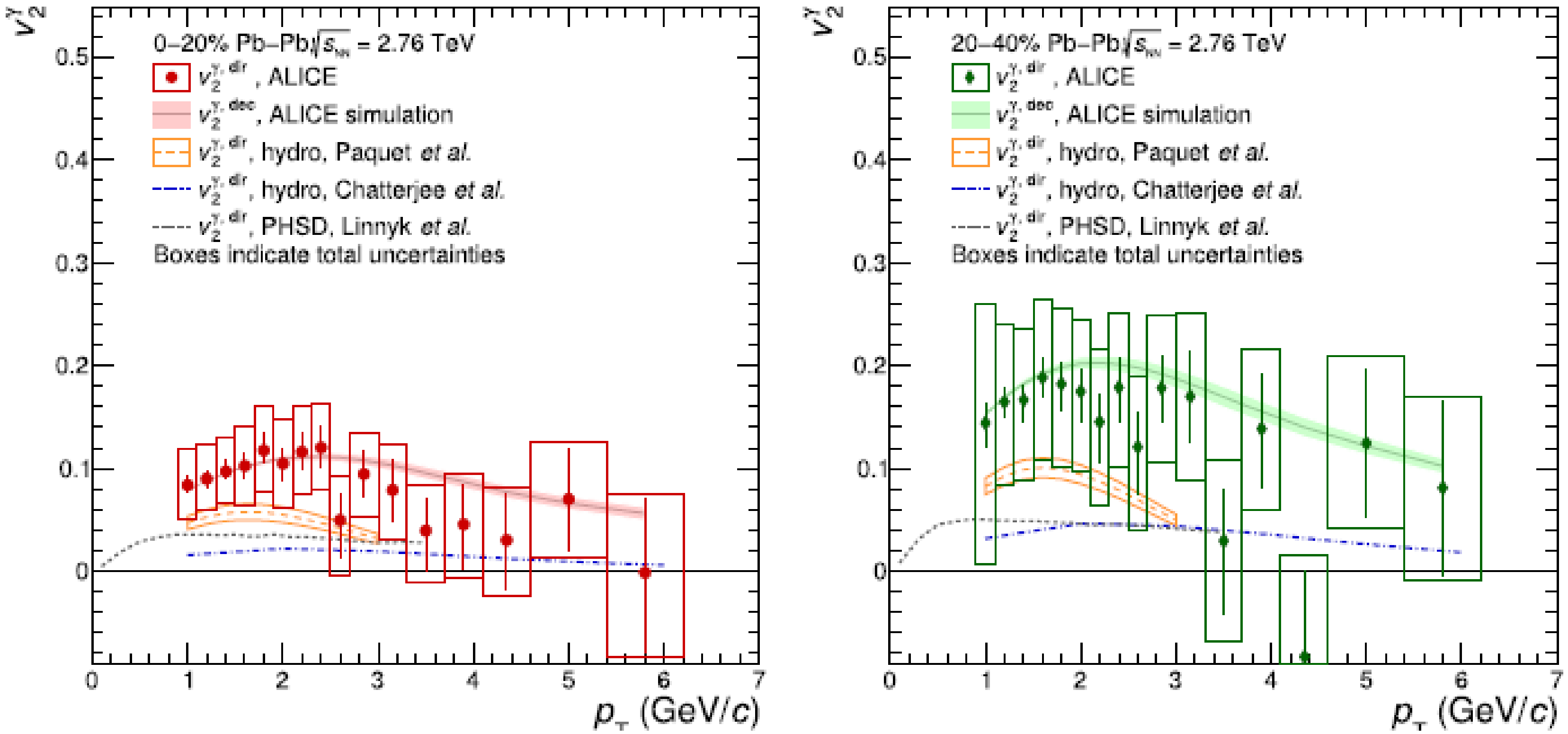
High p_T (prompt)
→ $v_2 \sim 0$, no centrality dependence

Hard scattering – $v_2 \sim 0$

Direct photon v_2 in 2.76 PbPb (ALICE)

PLB 789 (2019) 308-322

Low and high p_T regions



Similar as at PHENIX

Direct photon v_2 uncertainties in 2.76 PbPb (ALICE)

Precision on R_γ crucial

PLB 789 (2019) 308-322

$$v_2^{dir} = \frac{R_\gamma v_2^{inc} - v_2^{dec}}{R_\gamma - 1}$$

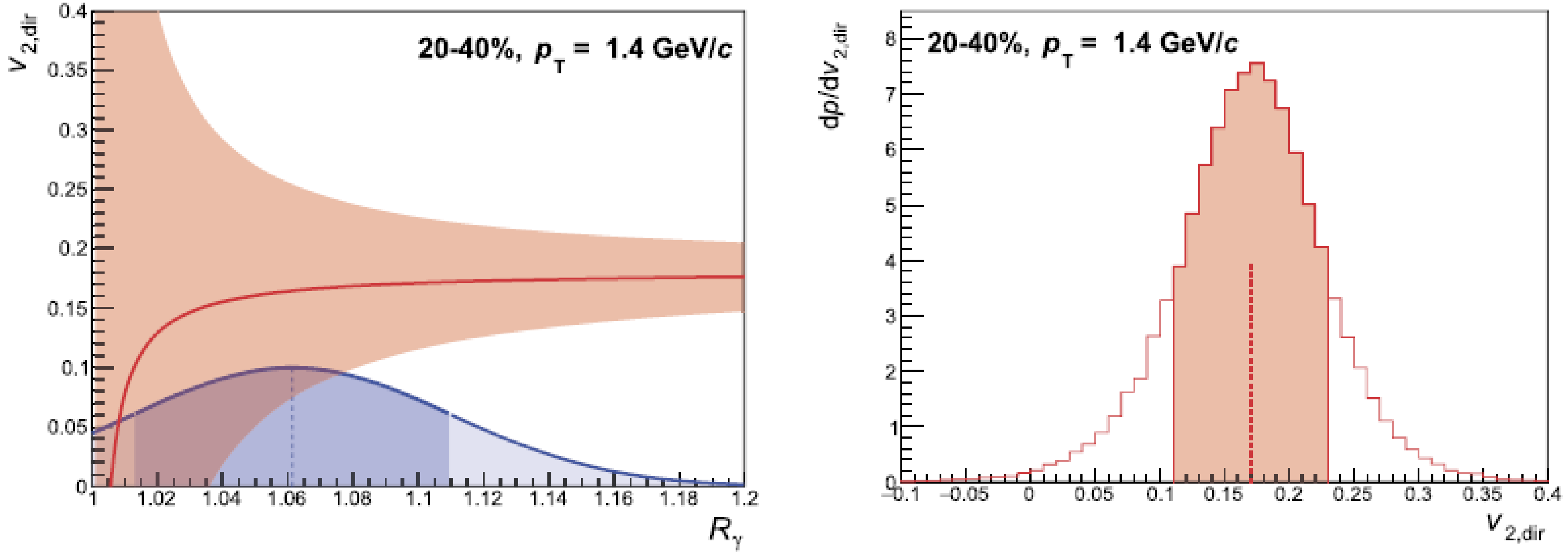


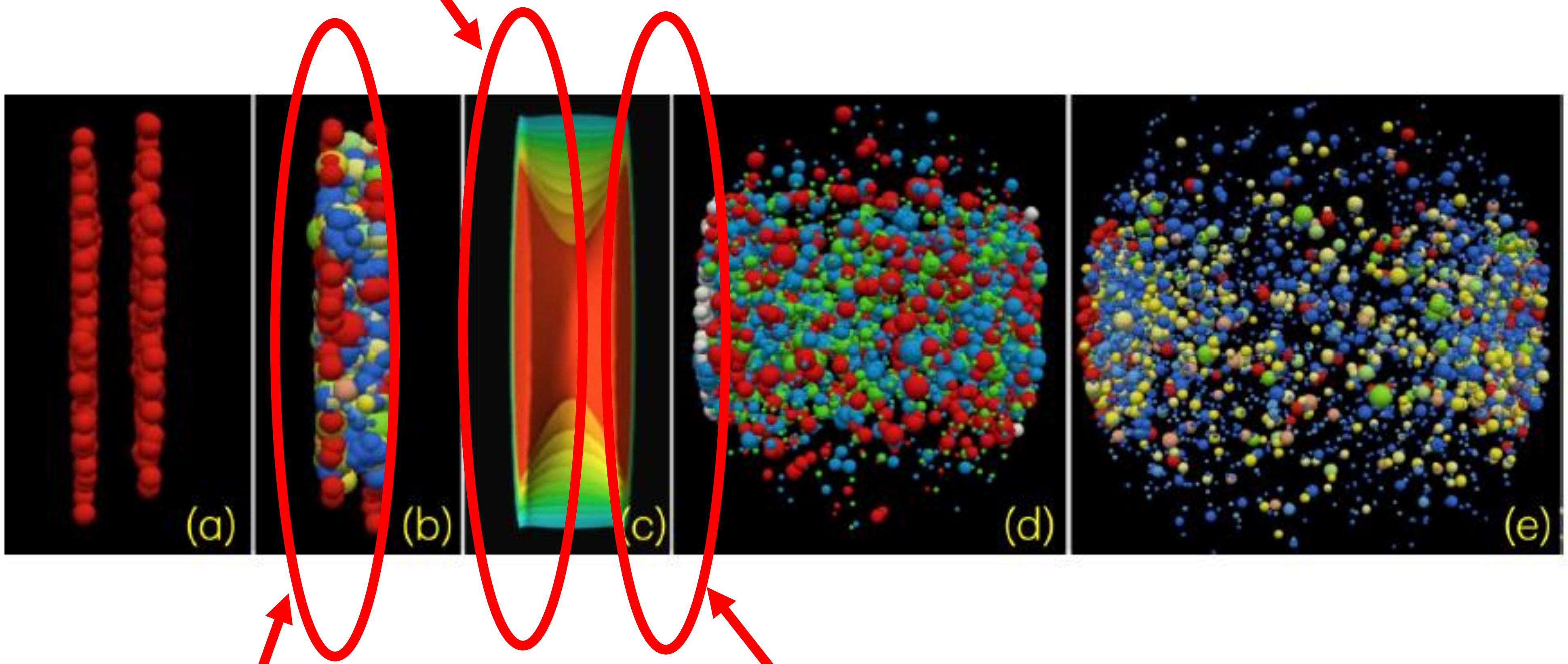
Fig. 4. Left: Central value (solid red line) and uncertainty of the direct-photon v_2 for a selected p_T interval. The upper and lower edges of the red shaded area correspond to the total uncertainty of $v_2^{\gamma,dir}$ as obtained from linear Gaussian propagation of the uncertainties $\sigma(v_2^{\gamma,inc})$ and $\sigma(v_2^{\gamma,dec})$. The Gaussian (with arbitrary normalization) reflects the measured value of R_γ in this p_T interval (blue dashed line) and its $\pm 1\sigma$ uncertainty (dark-blue shaded interval). Right: Posterior distribution of the true value of $v_2^{\gamma,dir}$ for the same interval in the Bayesian approach. Note that the distribution has a non-Gaussian shape, implying that the $\pm 2\sigma$ interval typically corresponds to a probability of less than 95.45% as would be the case for a Gaussian.

Asymmetric, and v_2 can even go negative

New photon sources considered

Add “unconventional” sources

Weak magnetic γ from QGP



Pre-equilibrium

Radiative hadronization

Stepping past the thermal paradigm

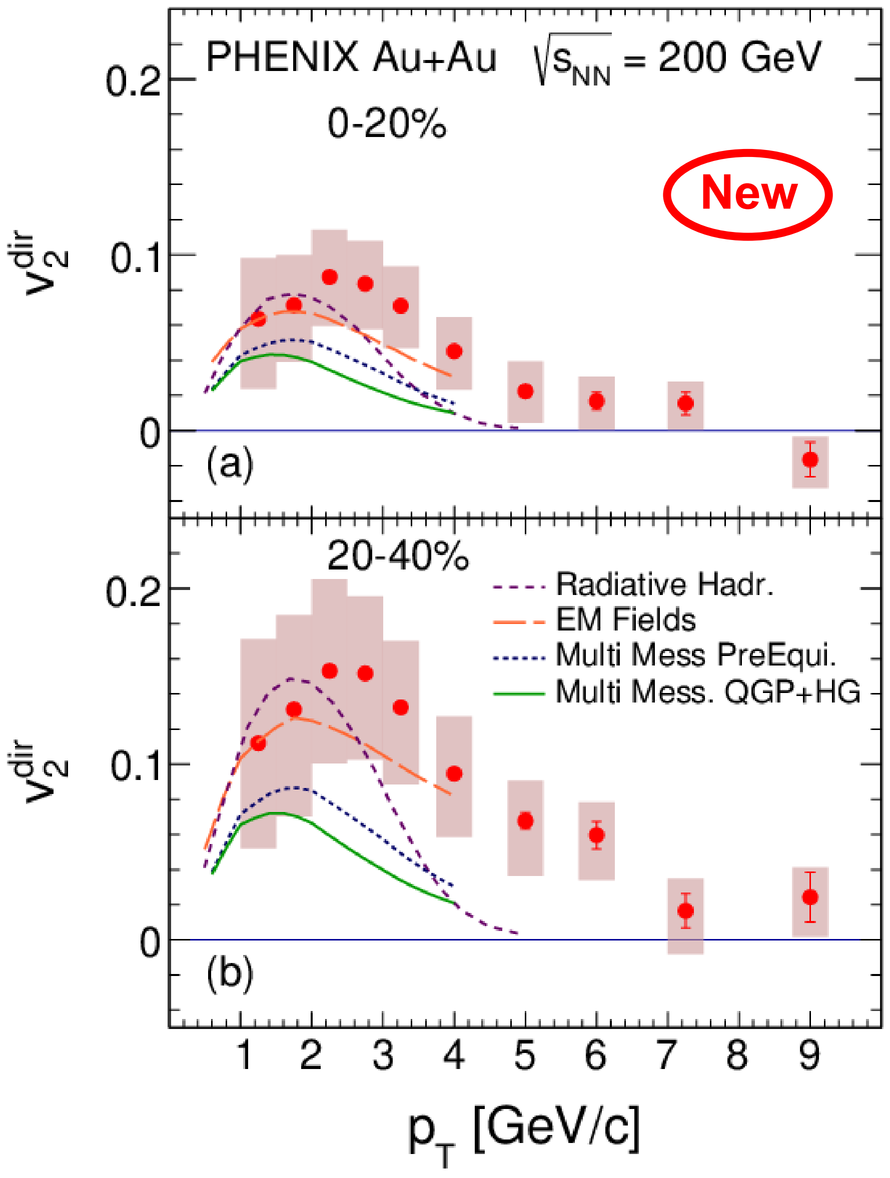
Comparisons of photon v_2 to recent models

Data from arXiv:2504.02955

Different approaches

Multi-messenger PRC 105, 014909 (2022)
Radiative hadronization PRC 106, 034906 (2022)
Magnetic emission Nucl. Phys. Rev 41, 1 (2024)

source	multim.	rad. hadr.	magnetic
prompt	X	X	X
magnetic			X
pre-eq	X		X
QGP th	X	X	X
HG th	X	X	X
rad. hadr.		X	



Could (should???) all those sources be combined?

A few recent models to resolve the puzzle

Strongly coupled plasma with constant magnetic field

An early attempt

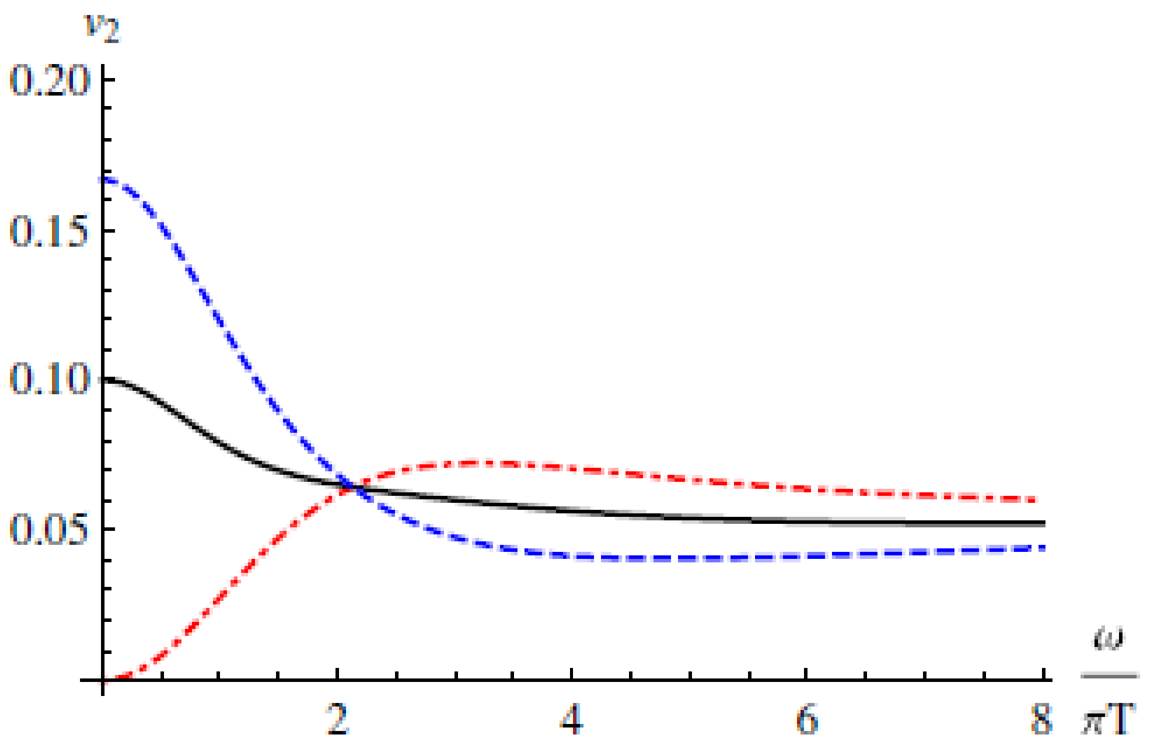
Mueller PRD 89, 026013 (2014)

Generated solely by magnetic field in the strong coupling scenario

Photon v_2 does not vanish at low p_T

Two polarizations: in-plane (blue) and out-of-plane (red)

Only a fraction of all v_2



Upper bound only

Magnetic field – synchrotron radiation

Non-prompt photon yields

Tuchin PRC 91, 014902 (2015)

PHENIX AuAu data

Authors conclusions:
- a significant fraction of photon excess in the region $k\perp$ = 1–3 GeV can be attributed to the synchrotron radiation
- this source alone would predict v_2 = 4/7 and v_4 = 1/10 independent of photon momentum and centrality
- odd terms (v_3, ...) should vanish
- can contribute a significant fraction of non-prompt photons at 2-3 GeV/c
- temperatures should be below T = 400 MeV (since then synchrotron photons would account for all observed photons)

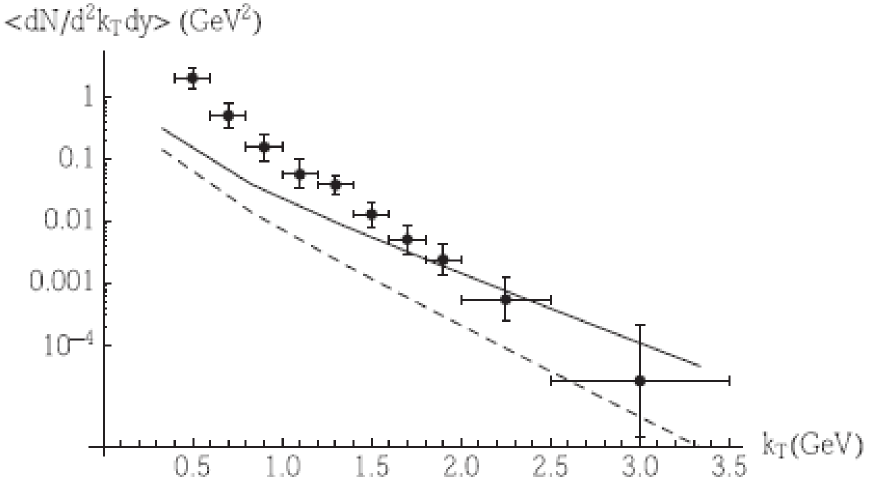


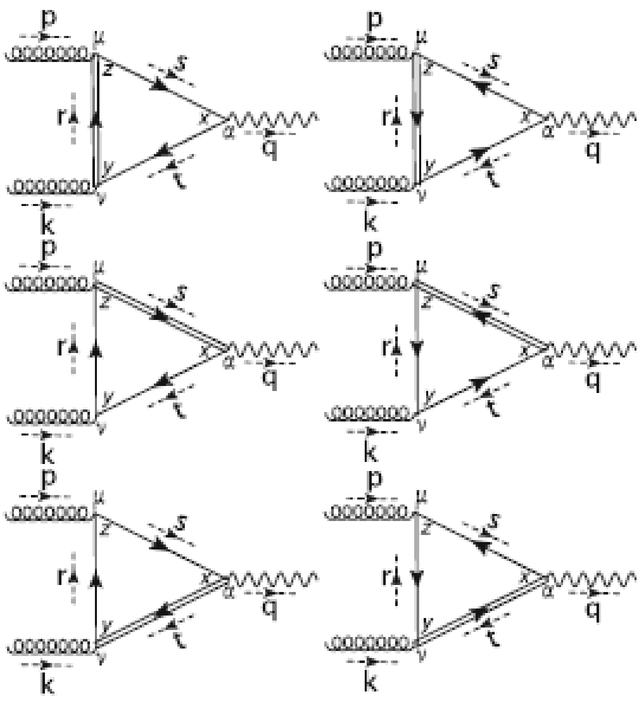
FIG. 2. Spectrum of synchrotron photons averaged over the azimuthal angle versus photon transverse momentum $k_\perp$ at rapidity $y = 0$ and centrality 40%–60% ($b = 10.2$ fm [27]). Solid line: $T = 400$ MeV; dashed line: $T = 200$ MeV. Data are from [1]; they represent the direct photon k_T spectra after subtraction of the Ncoll scaled $p + p$ contribution (Fig. 8 there).

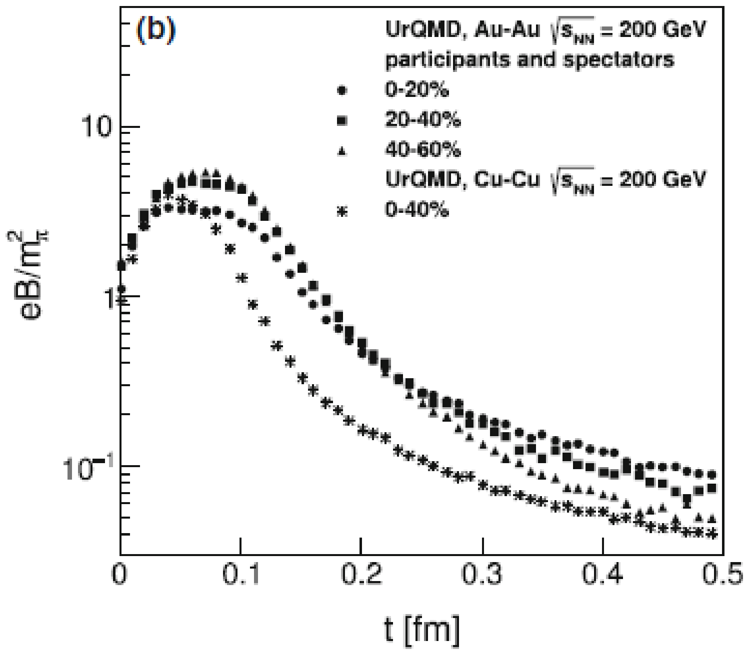
Early attempt, very incomplete

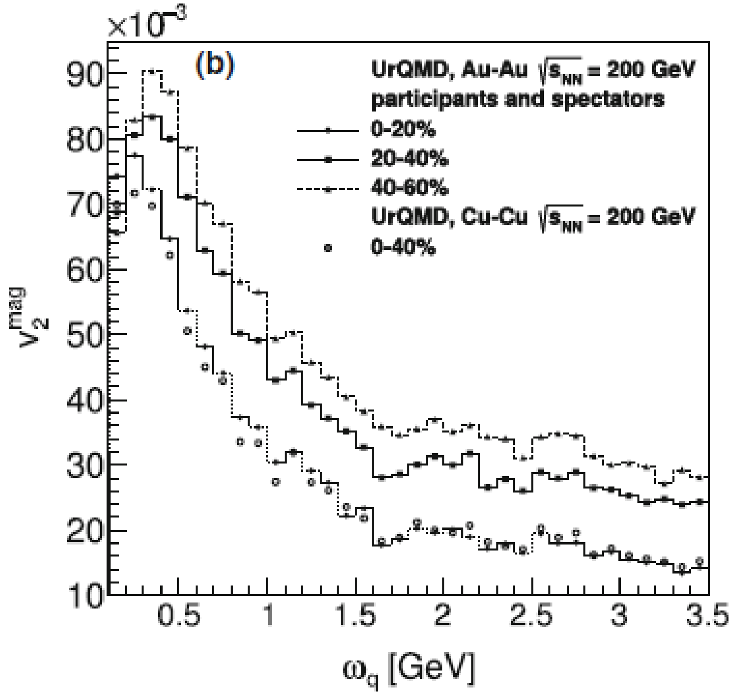
Magnetic field induced gluon fusion and splitting

Pre-hydro source

Ayala+ Eur. Phys. J. A (2020) 56:53







Gluon fusion / splitting
Issue: short lifetime of B
Thermal effects (hydro) start
after magnetic pulse
Similar magnitude as Mueller
Non-zero flow at low p_T!

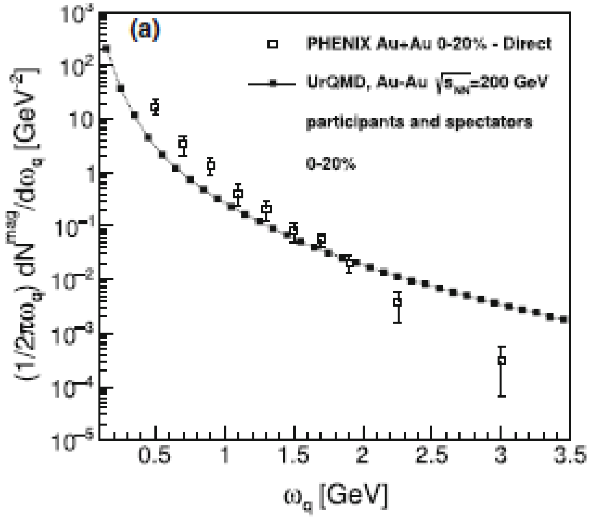
“Magnetic flow” only –
needs to be weighted

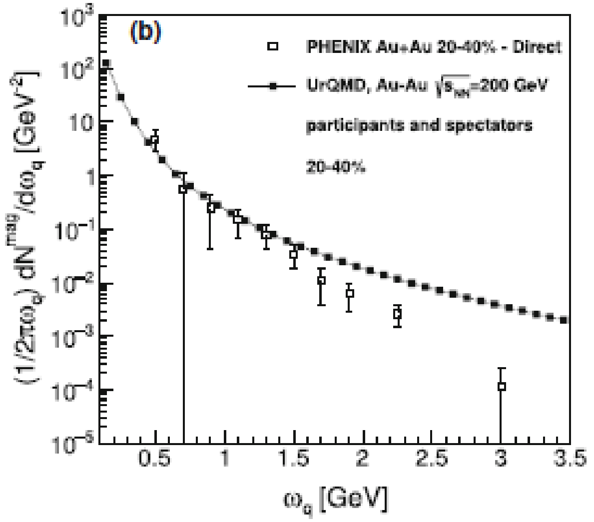
Short lifetime, $v_2(p_T=0)>0$

Participants, spectators

Ayala+ Eur. Phys. J. A (2020) 56:53

Yields and v_2 have to be explained simultaneously

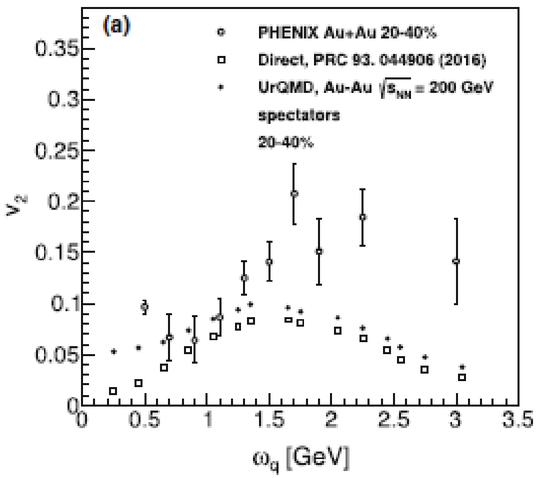


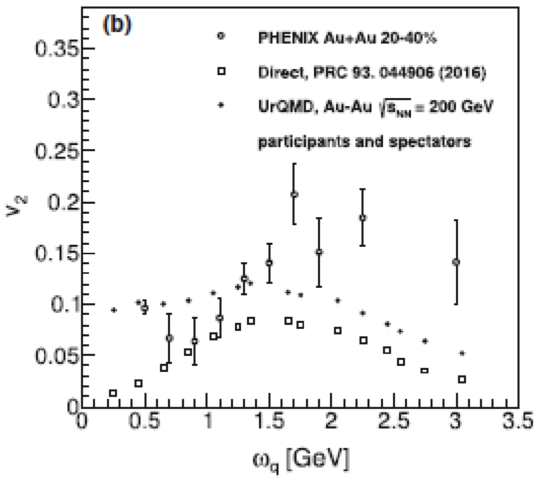


Moving in the right direction
but significant shape difference

Overpredict yield, underpredict
v_2 above 1.5 GeV/c

Enhancement at $p_T = 0$
(what is hard to measure)



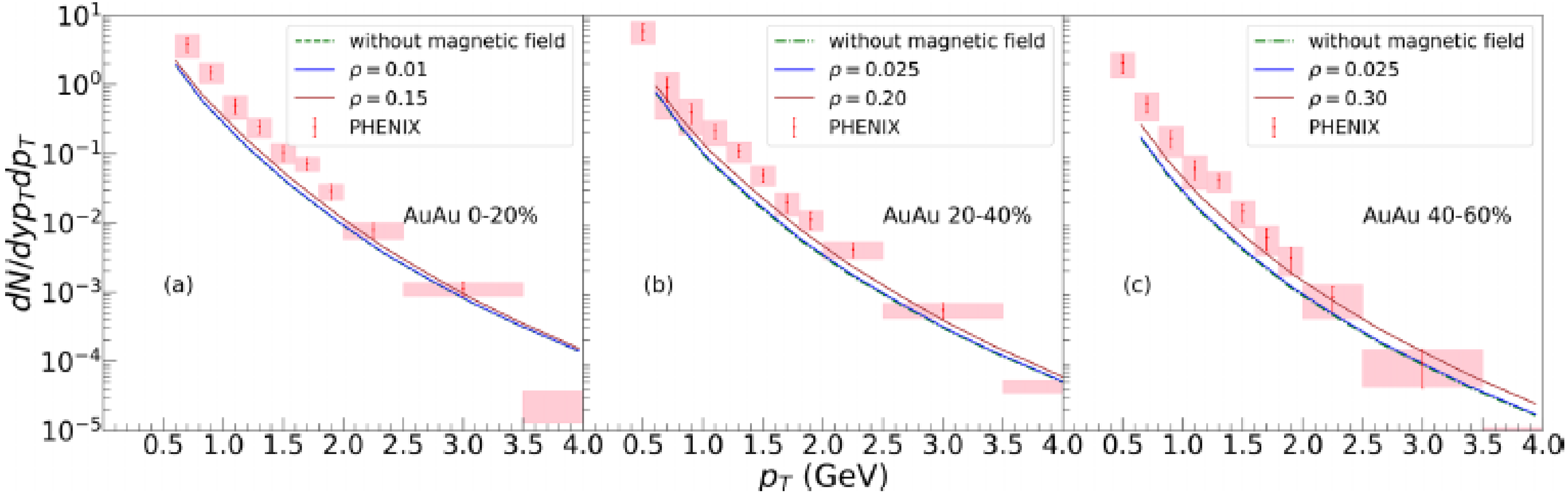


Challenge to experimentalists: get $v_2(p_T=0)$

“Weak” field in QGP, hydro, RHIC

Induced radiation, e-b-e viscous hydro

Sun, Yan PRC 109, 034917 (2024)



PHENIX data, PRC 91, 064904 (2015)

Effects of the weak magnetic field during QGP evolution
Interplay of magnetic field and longitudinal dynamics of medium

$$\rho \equiv \frac{\sigma_{\rm el}}{T}\frac{\overline{eB_y}}{m_\pi^2},$$

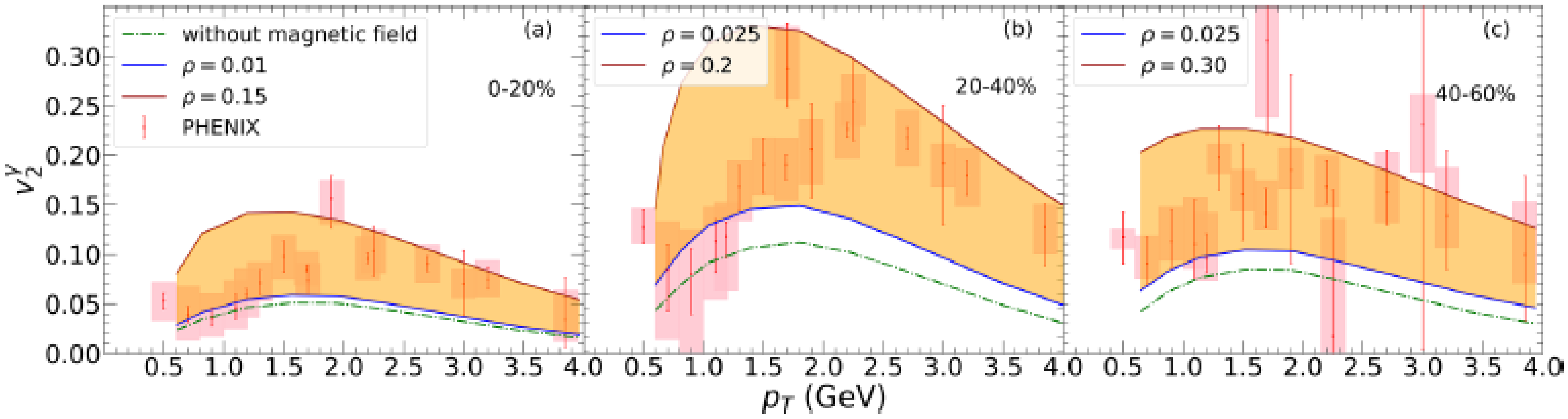
Small correction to yield

“Weak” field in QGP, hydro, RHIC

Induced radiation, e-b-e viscous hydro

Sun, Yan PRC 109, 034917 (2024)

$$\rho \equiv \frac{\sigma_{\rm el}}{T}\frac{\overline{eB_y}}{m_\pi^2},$$



PHENIX data PRC 94, 064901 (2016)

v_3 emerges (novel)
Yield increase marginal
flow increase large

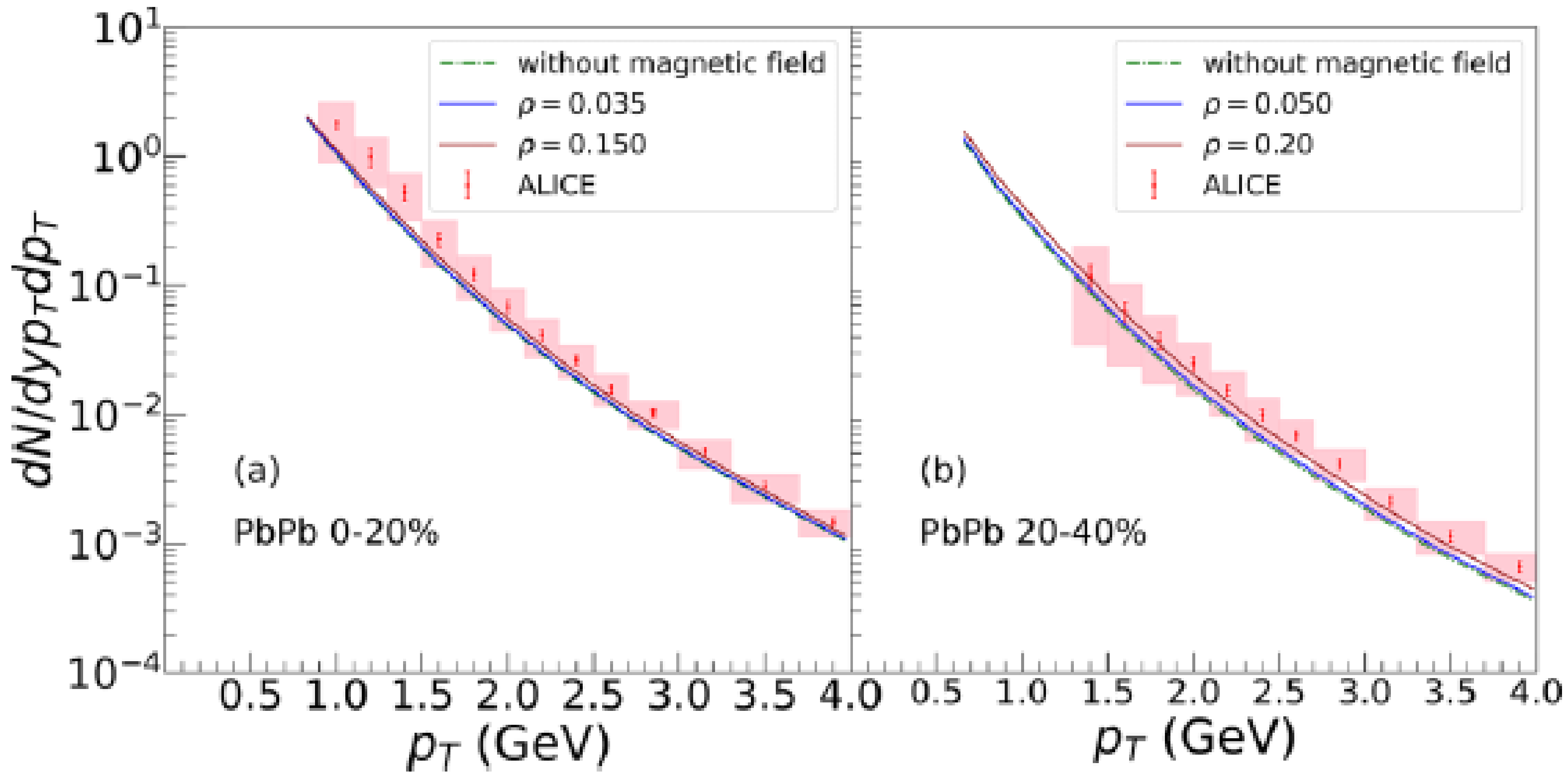
Field 0.1m^2_π ~10^{16} G

Get ρ (field strength) from flow

“Weak” field in QGP, hydro, LHC

Induced radiation, e-b-e viscous hydro

Sun, Yan PRC 109, 034917 (2024)



ALICE, PbPb, 2.76 TeV (data PLB 789, 308 (2019))

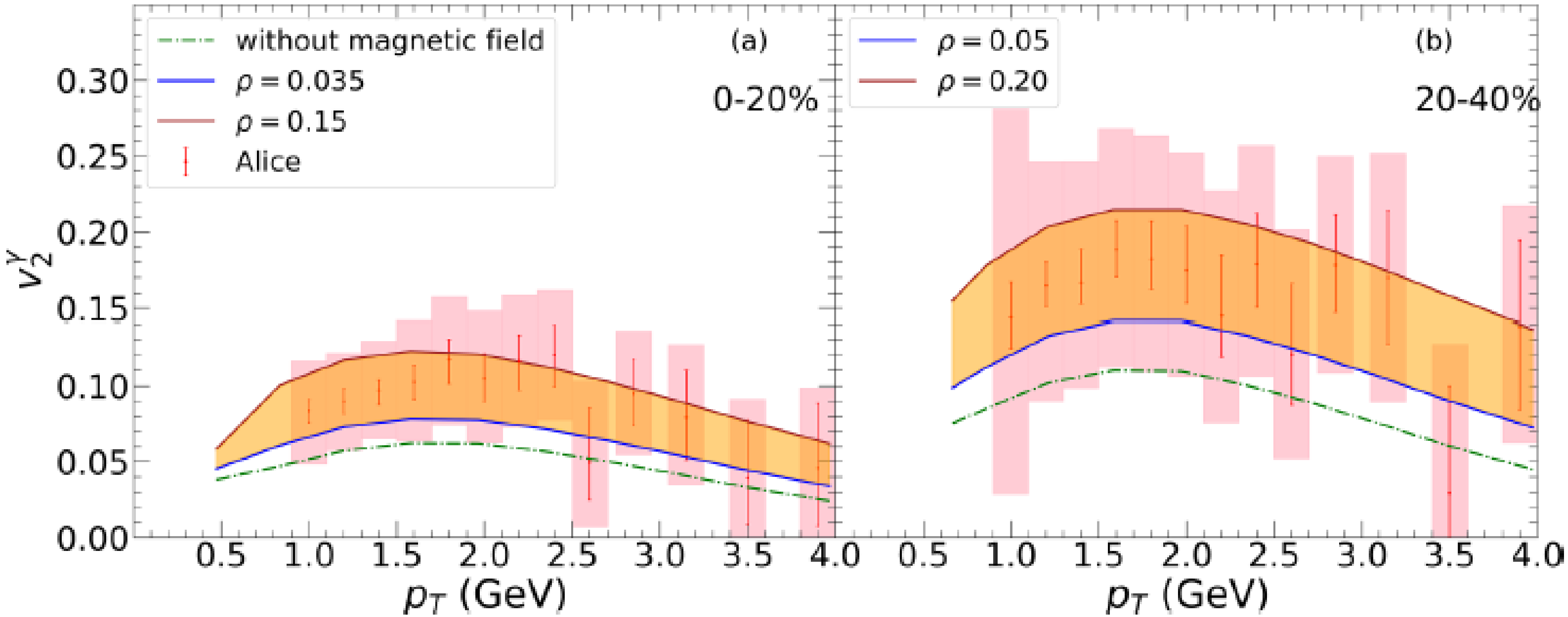
Small correction to yield

"Weak" field in QGP, hydro, LHC

Induced radiation, e-b-e viscous hydro

Sun, Yan PRC 109, 034917 (2024)

$$\rho \equiv \frac{\sigma_{\rm el}}{T}\frac{\overline{eB_y}}{m_\pi^2},$$



ALICE, PbPb, 2.76 TeV (data PLB 789, 308 (2019))

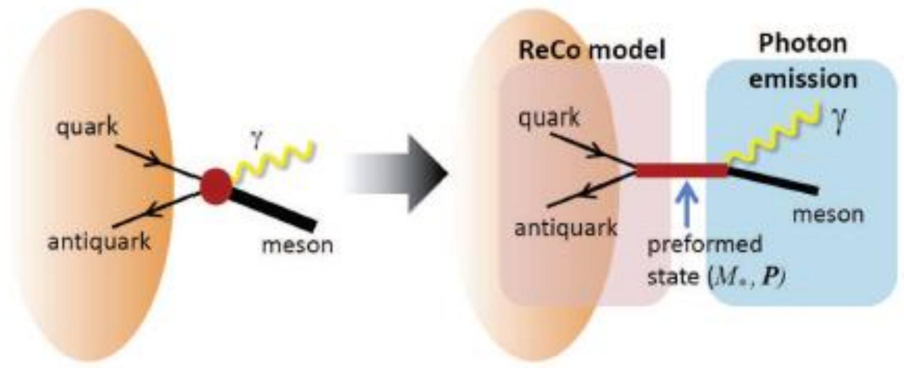
ρ (field strength) somewhat higher than at RHIC

Radiative hadronization – RHIC

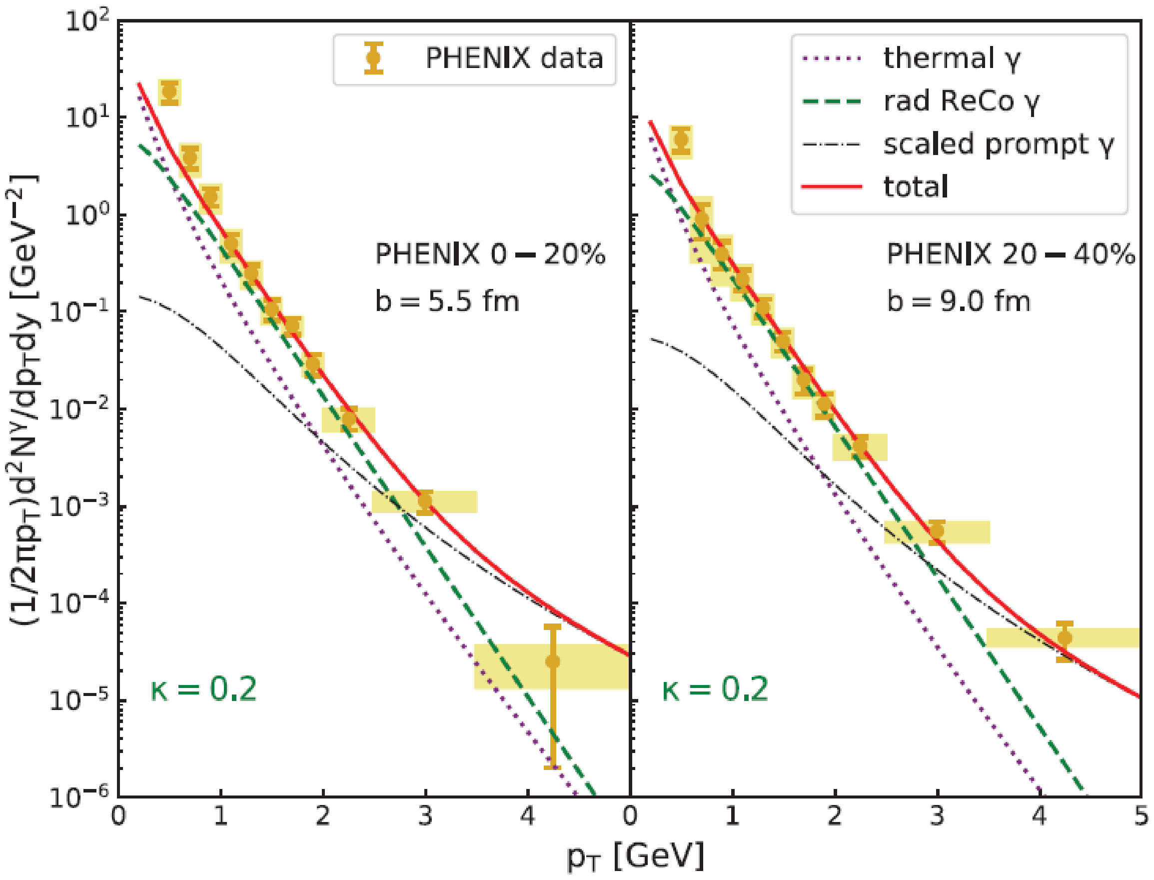
Circumvents the "old paradigm"

Old paradigm: yield early, high T, flow late
Here: new source at the time of hadronization
Recombination off-shell, then come on-shell by radiating a photon
Will inherit v_2 at the time of phase transition

κ chosen so that thermal, prompt and radiative photons describe the data



Fujii et al, PRC 106, 034906 (2022)



PHENIX, PRC 91, 064904 (2015)

κ is adjusted to describe data

Radiative hadronization – RHIC

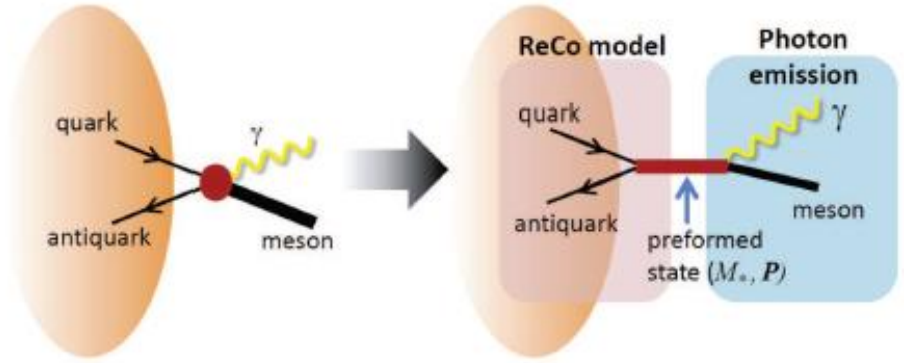
What about v_2?

Old paradigm: yield early, high T, flow late

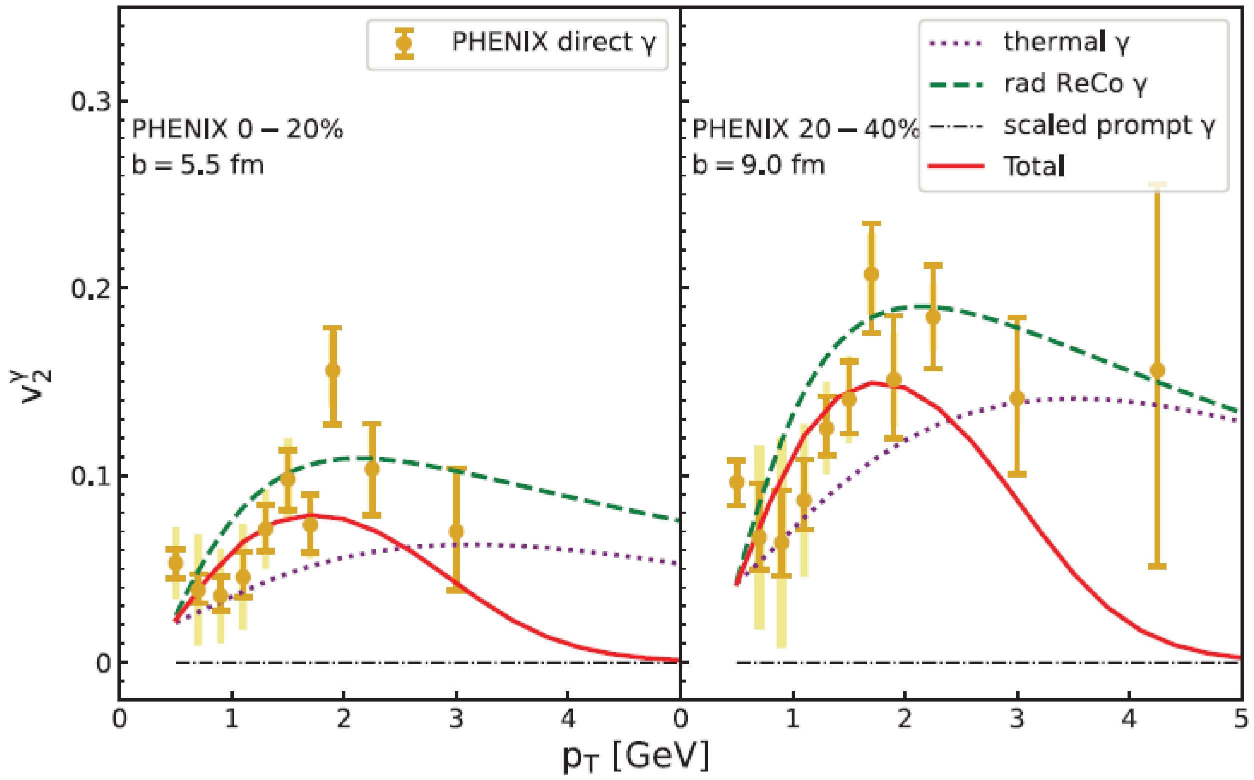
Here: new source at the time of hadronization

Recombination off-shell, then come on-shell by radiating a photon

Will inherit v_2 at the time of phase transition



Fujii et al, PRC 106, 034906 (2022)



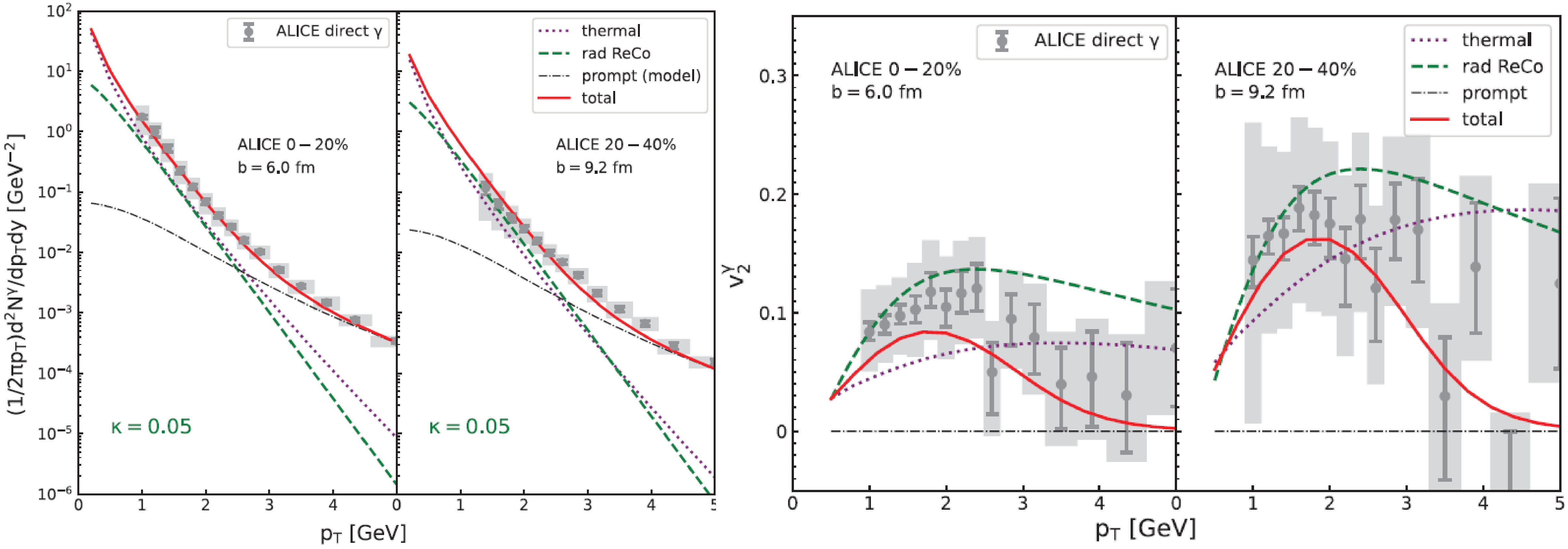
PHENIX, PRC 94, 064901 (2016)

Starts to fail above 2 GeV/c

Radiative hadronization – LHC

Does it work at LHC? (should!)

Fujii et al, PRC 106, 034906 (2022)



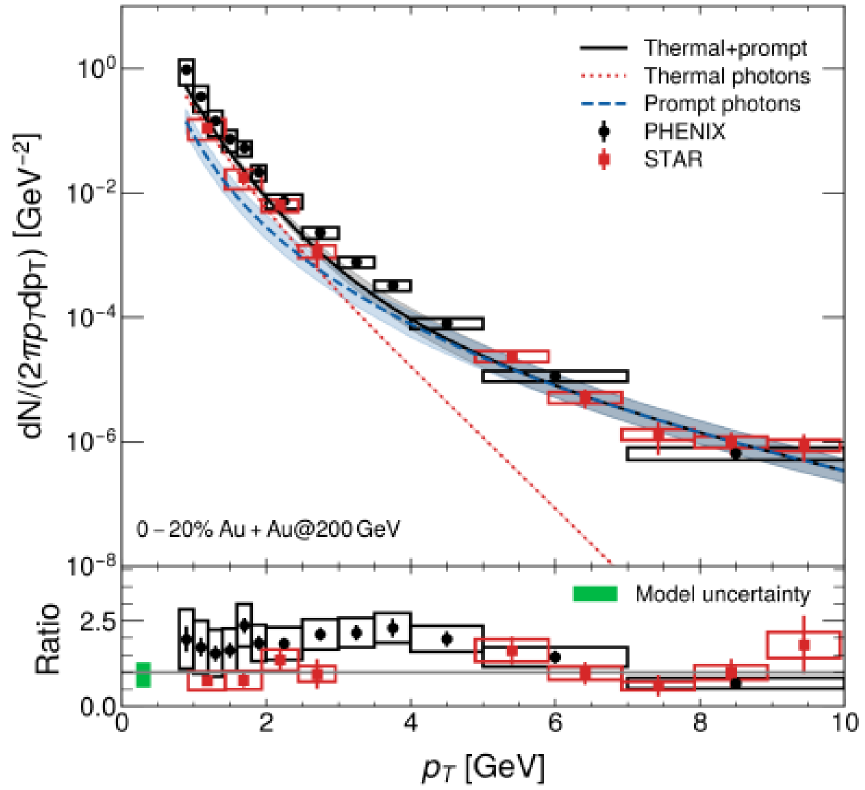
Remember: the transition itself at RHIC and LHC appeared to be similar (low p_T slopes, scaling)

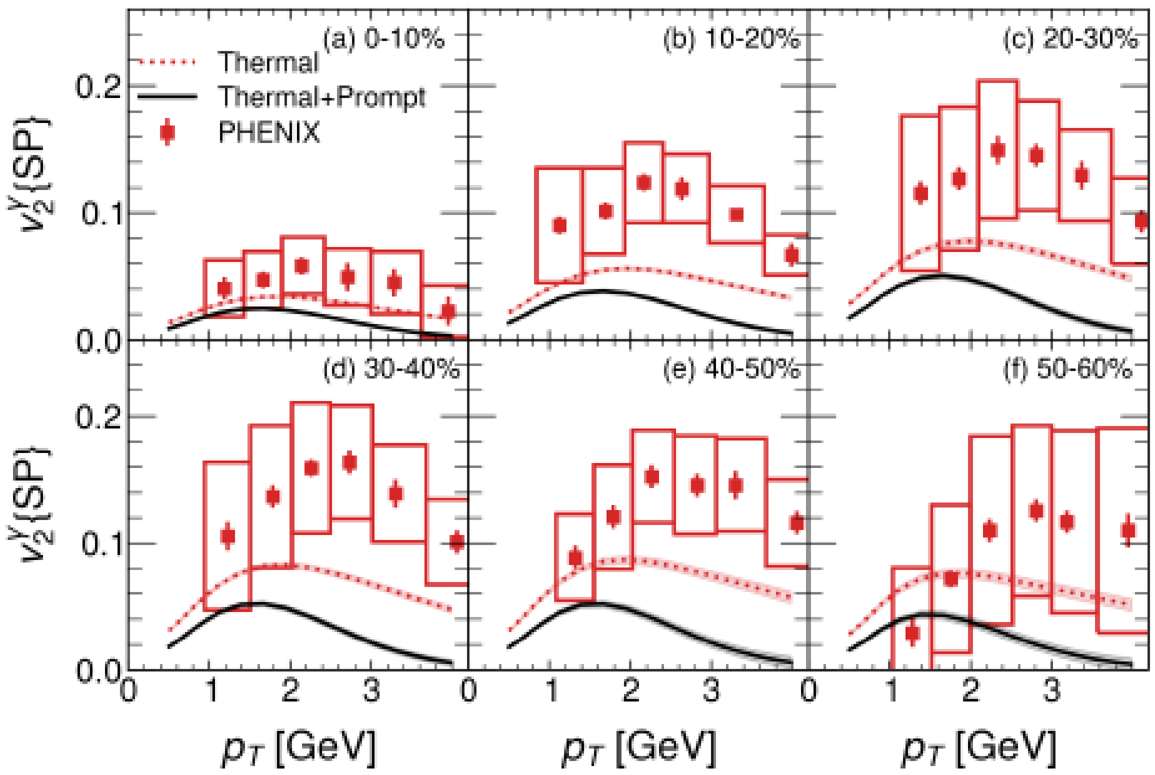
κ very different at RHIC and LHC

Multistage (multi-messenger) model

Pre-equilibrium, MUSIC, UrQMD afterburner

Gale et al. arXiv 2511.08773





Add rad. hadr., magnetic?

Where does this leave us?

Summary

Photon at high p_T well understood

At low p_T the direct photon puzzle still not resolved

Interesting and plausible new sources suggested

Experimental uncertainties still too large

We never had an honest-to-God direct photon experiment,
built without compromises to other physics (and we are paying the price)

We should have one!

Further argument in GD *Rept.Prog.Phys.* 83 (2020) 4, 046301

Backup