



2018

Venezia
Quark Matter

Electroweak probes in nuclear collisions

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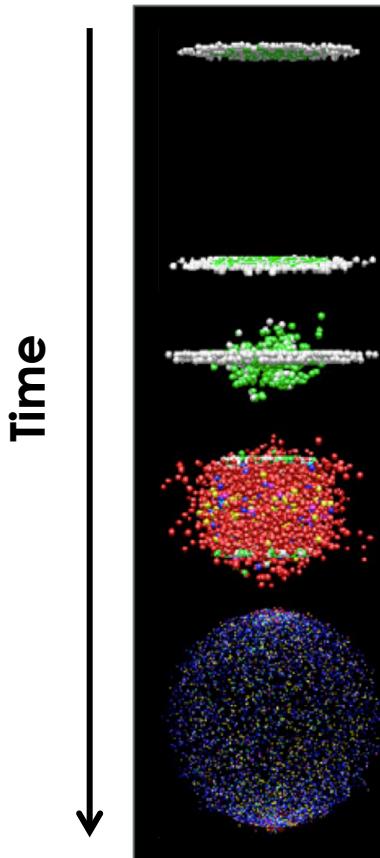
Hard and soft processes

Hard processes:

- prompt photons
- W^\pm/Z production

Soft processes:

- Thermal photons
- di-electrons



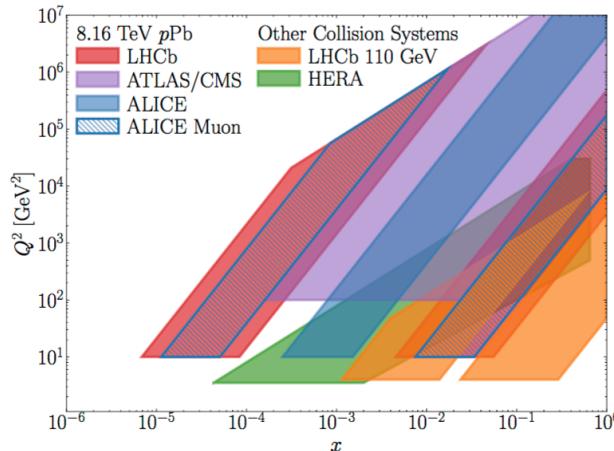
- Probing the cold nuclear effects
- Geometry, N_{coll} scaling
- Calibration of the jet energy
- Evidence of the thermal radiating system
- Temperature and energy density of the system



P+P COLLISIONS

IS IT JUST A BASELINE?

LHCb towards higher rapidities

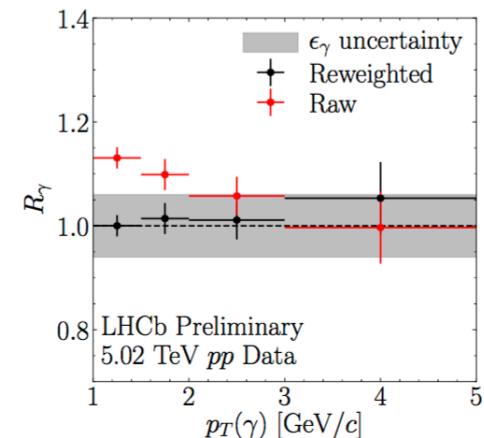
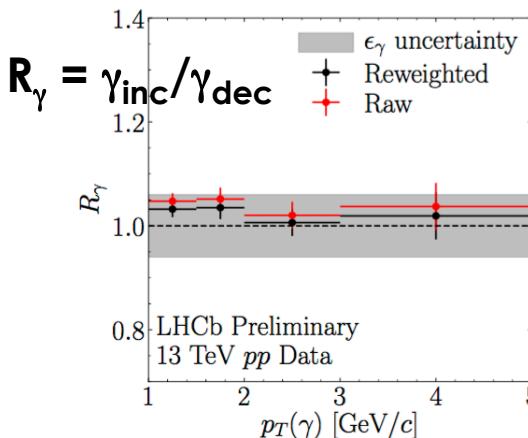


The analysis of the **direct photons** is ongoing in very forward region in the p+p.

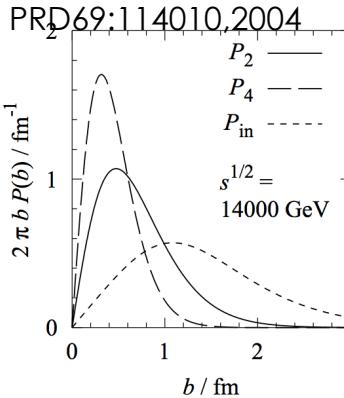
This will be a very interesting measurement also in p+A's.

The **high rapidity** production can help to understand the **initial conditions** of heavy ion collisions.

The LHCb experiment can reach the **saturation region** predicted by the CGC.



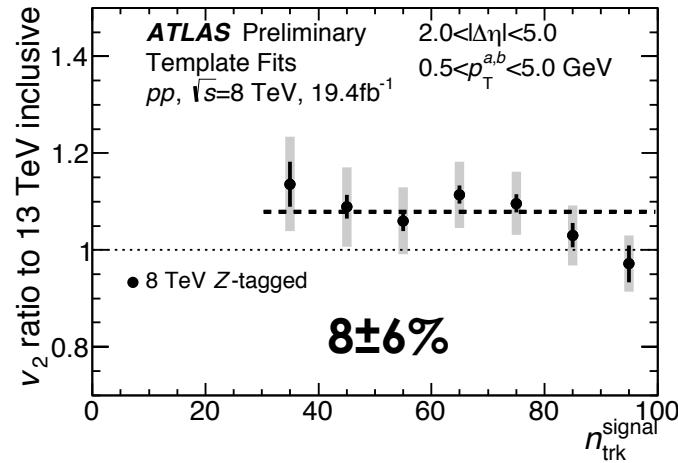
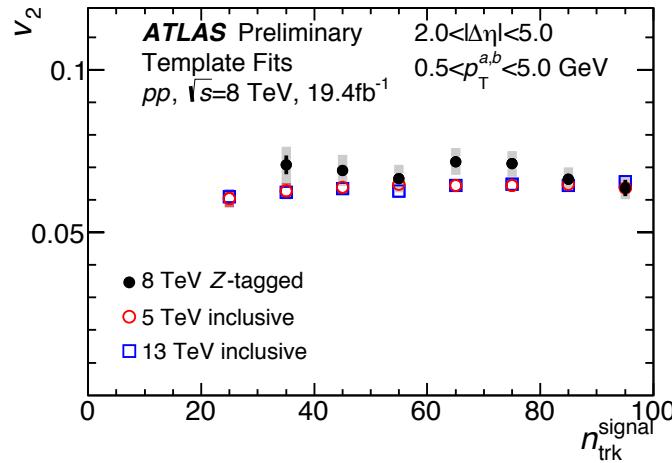
Ridge with higher Q^2 event



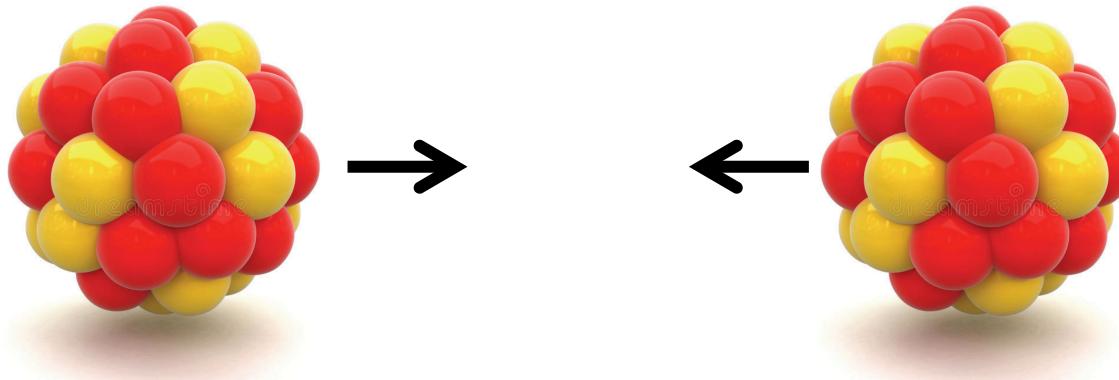
Z-tagged events provide an event with $Q^2 > 90 \text{ GeV}$

Dominated by the low- p_T Z's means very low- p_T jet on the away side.

The ridge (**long-range correlation**) was a surprise in the higher multiplicity p+p collisions. Is there any “coupling” between ridge phenomenon and hard or semi-hard processes (large Q^2)?



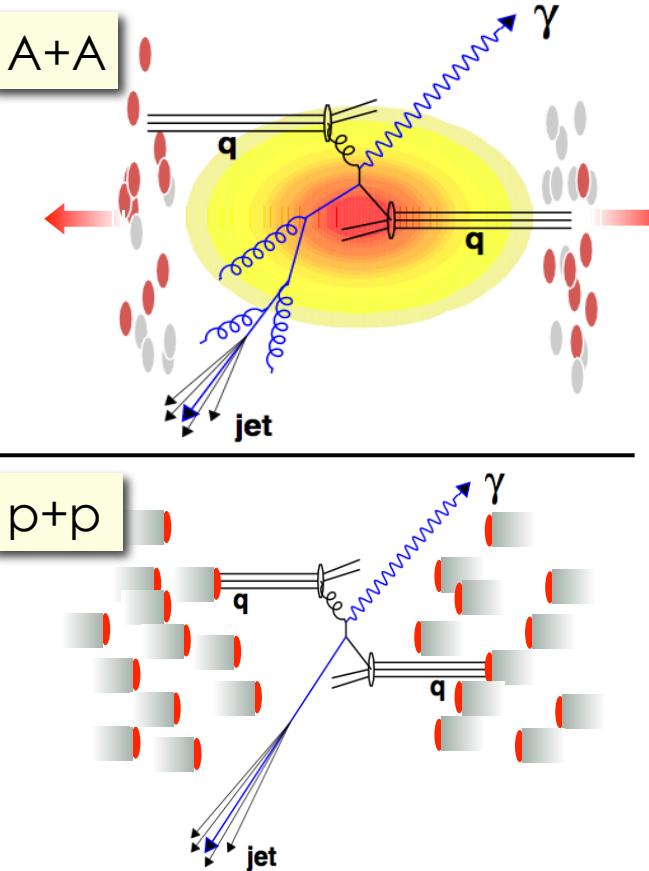
This can be further investigated with di-jet tagging and also in same multiplicity p+Pb collisions



A+A COLLISIONS

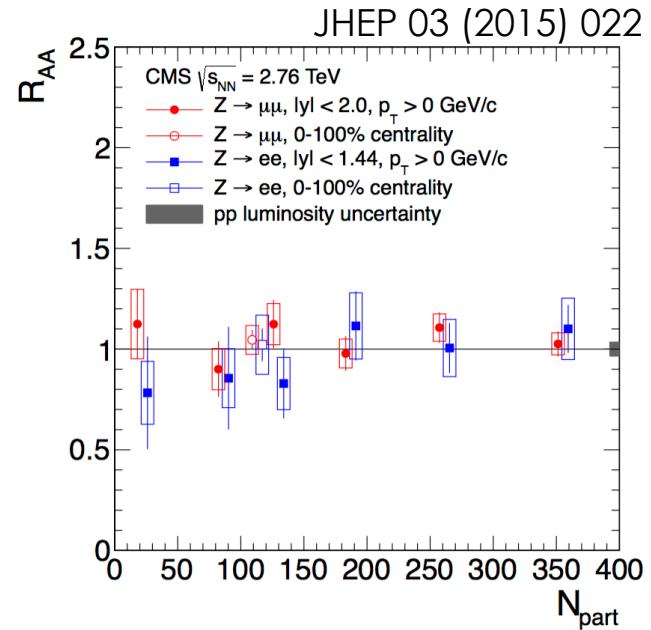
TESTING THE QGP

Geometry in Pb+Pb collisions



Probe to confirm the N_{coll} scaling from Glauber

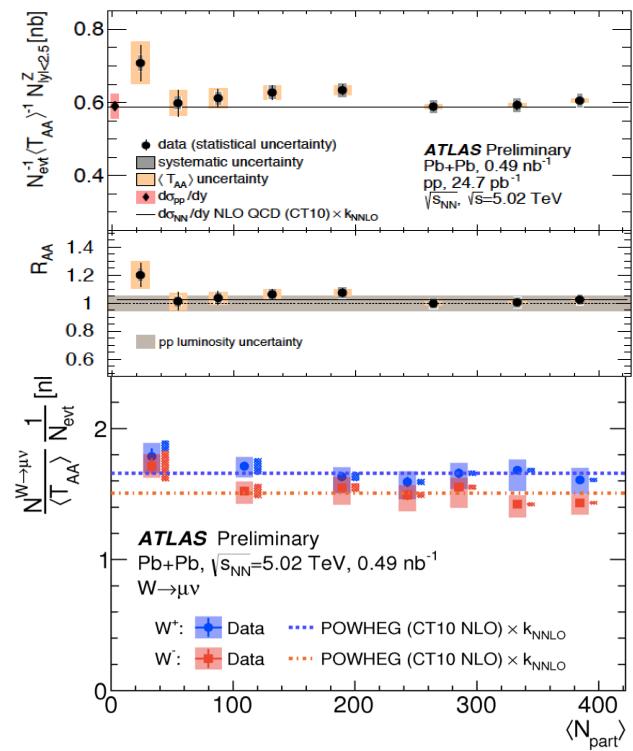
The **electroweak probes** could be used as a calibration (verification) of the **nuclear modification factor**:



$$Z_{AA} = \frac{R_{AA}(X)}{R_{AA}(EW)} = \frac{N_{Pb+Pb}^X}{\sigma_{Pb+Pb}^X} \times \frac{\sigma_{Pb+Pb}^{EW}}{N_{Pb+Pb}^{EW}}$$

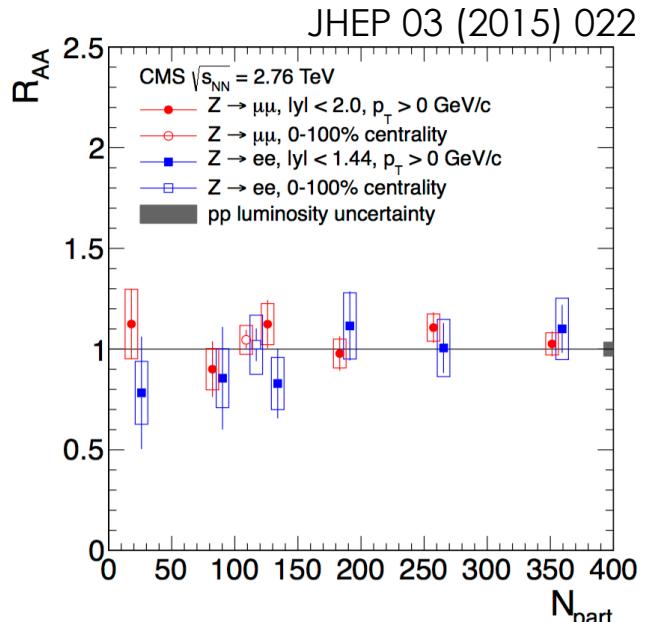
Geometry in Pb+Pb collisions

Zvi Citron, Tue 10:00



Probe to confirm the N_{coll} scaling from Glauber

The electroweak probes could be used as a calibration (verification) of the nuclear modification factor:



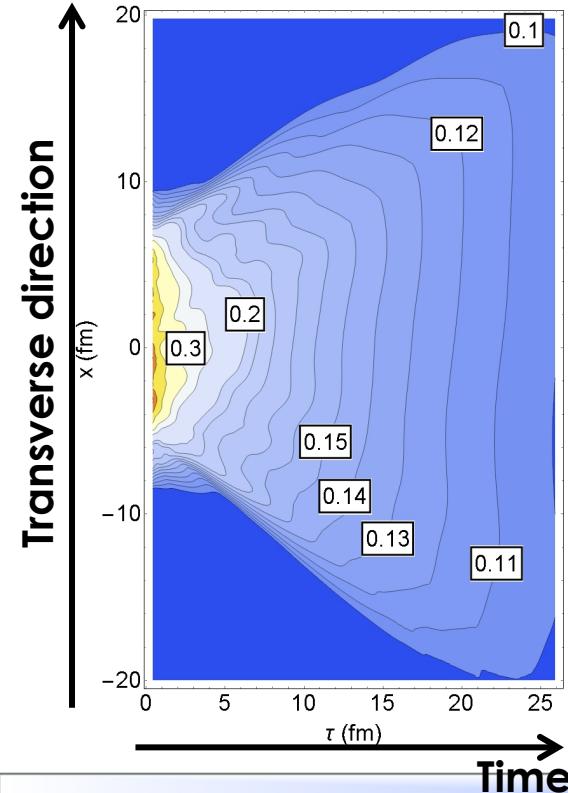
$$Z_{AA} = \frac{R_{AA}(X)}{R_{AA}(EW)} = \frac{N_{Pb+Pb}^X}{\sigma_{Pb+Pb}^X} \times \frac{\sigma_{Pb+Pb}^{EW}}{N_{Pb+Pb}^{EW}}$$

Similar with photons was proposed in [PoS INPC2016 (2017) 345]

Thermal photons

Phys.Rev.Lett. 115 (2015), 132301

Temperature in GeV



Every thermal system should **radiate** in electromagnetic region:

- thermal di-leptons
- thermal photons

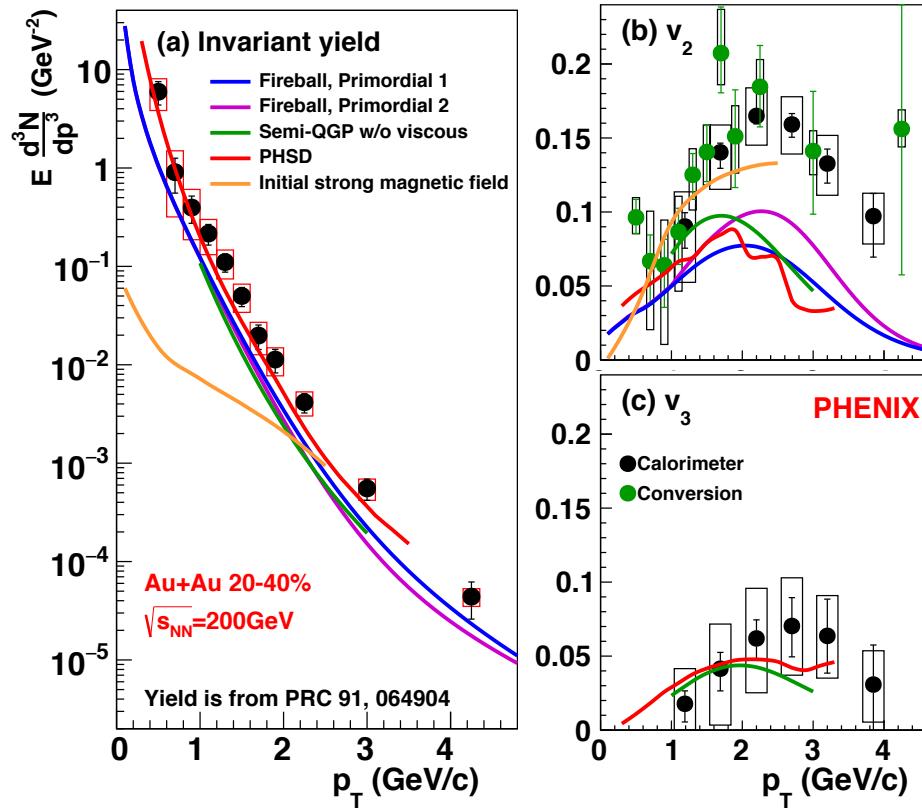
The EM radiation should **escape** the medium without further interaction

In experiments we observe **the time and space integrated** direct photons:

- Prompt and fragmentation
- QGP photons
- HG photons
- other: bremsstrahlung, jet- γ conversion,...

Origin of the direct photon puzzle

Phys.Rev. C94 (2016), 064901



Large yields:

- Suggest large temperatures
- **Early creation** is dominant

Large flow:

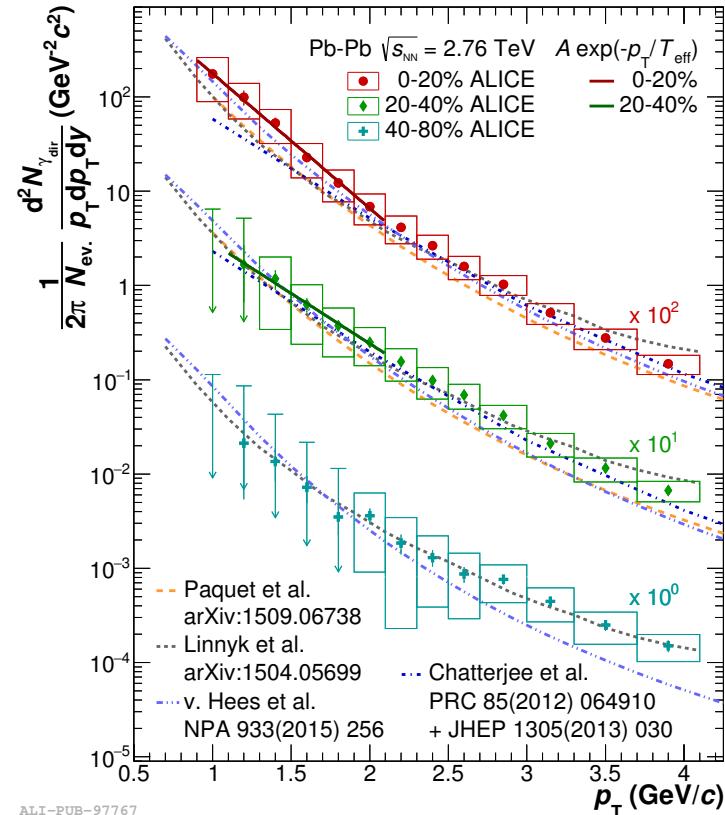
- Suggest moving source
- **Late creation** is dominant

The picture gets better once you include **blue-shift correction**:

- The source is moving towards the detectors
- The low-temperature yields will become shallower

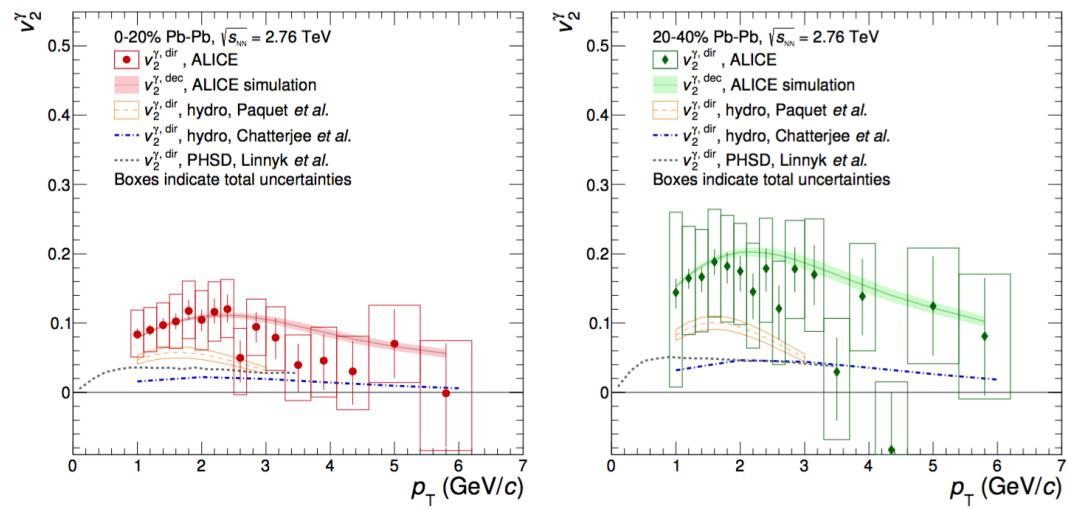
Direct photon puzzle at LHC

Phys.Lett. B754 (2016) 235



Direct photon **puzzle not significant** at LHC:

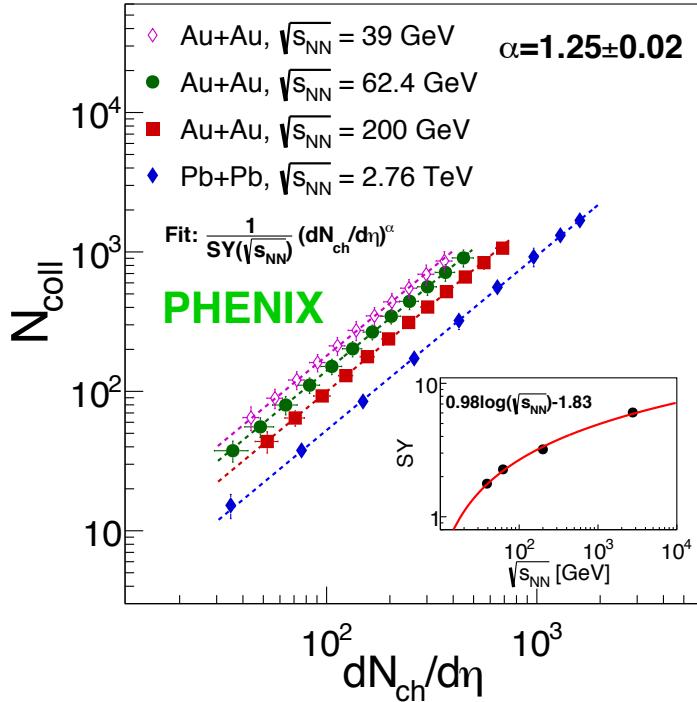
- The yields and v_2 theory calculations are consistent with the data
- Large uncertainties on the data cannot distinguish between the models



ALI-PUB-97767

Scaling of the N_{coll}

arXiv: 1805.04084



R_{AA} of the high- p_T direct photons is ~ 1

- Direct photons at high- p_T would **scale** with the N_{coll}

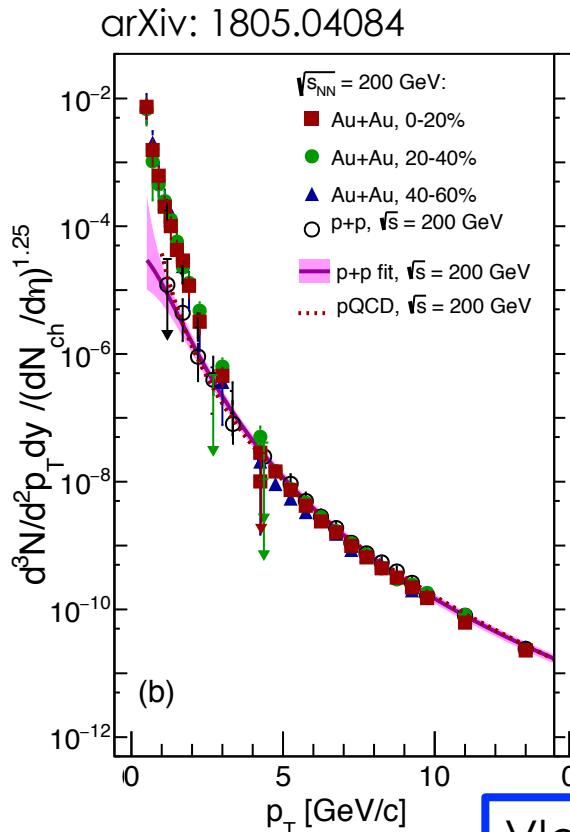
N_{coll} is collision energy dependent

- Instead of the binary collisions, we can use the **multiplicity of charged hadron**
- The N_{coll} can be translated to $(dN_{\text{ch}}/d\eta)^{1.25}$

Direct photons with $dN_{ch}/d\eta$

Direct photon yield in Au+Au/p+p at 200 GeV

Divided by the corresponding $(dN_{ch}/d\eta)^{1.25}$ [$\sim N_{coll}(\sqrt{s_{NN}})$]



Interesting observation is that the direct photons are **scaling** by the multiplicity both in **high- and low- p_T** .

Vladimir Khachatryan, Mon 16:50

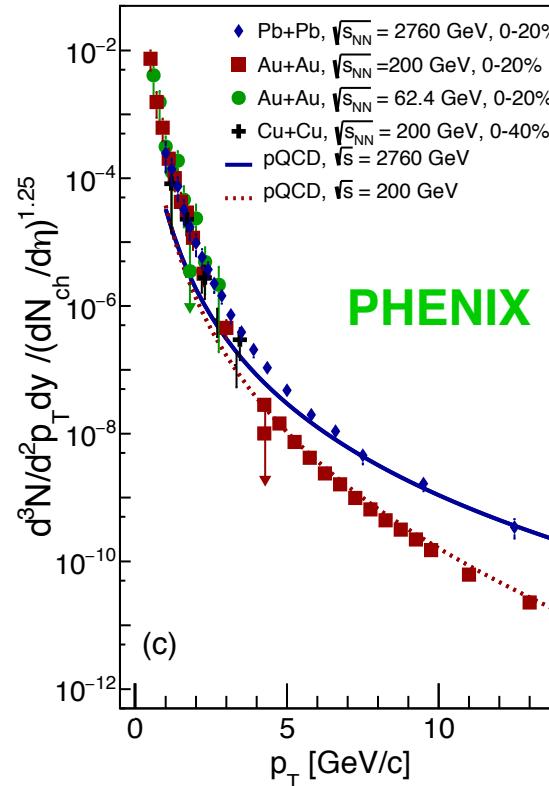
Direct photons with $dN_{ch}/d\eta$

Interesting observation at the low- p_T region.

Across wide range of collision energies from 39-2760 GeV the **normalized direct photon yield in $p_T \sim 1-2$ GeV** is very similar

This was really surprising result.
The low- p_T photon scale as the number of charge multiplicity (or $N_{coll}(\sqrt{s_{NN}})$)

arXiv: 1805.04084



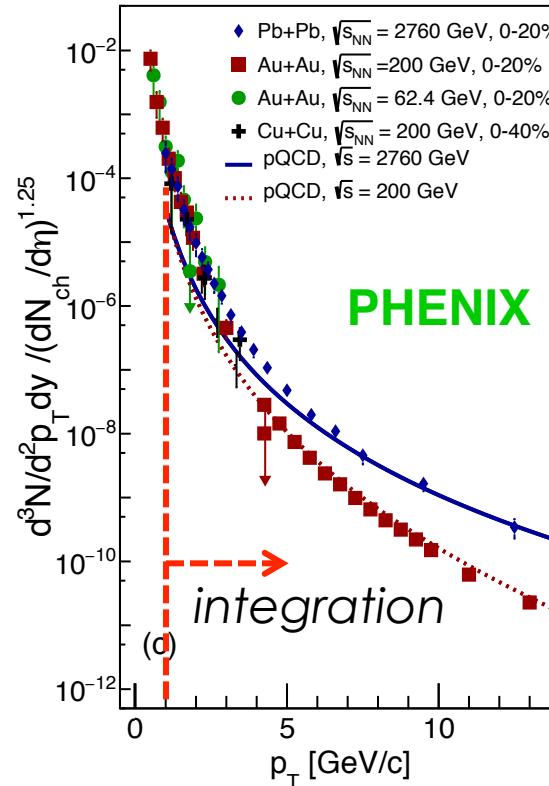
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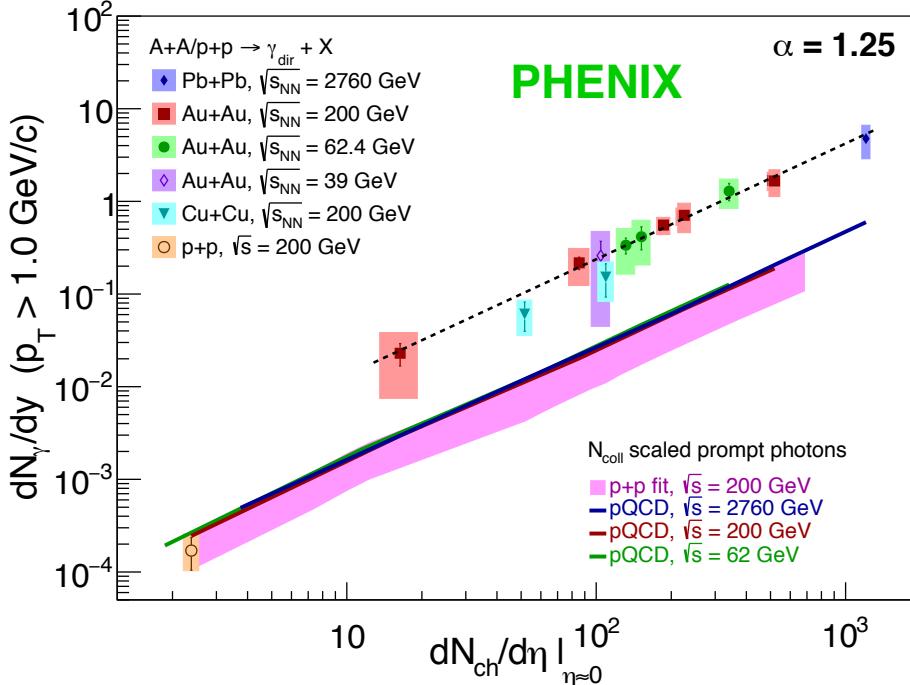
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arXiv: 1805.04084



Scaling behavior of photons

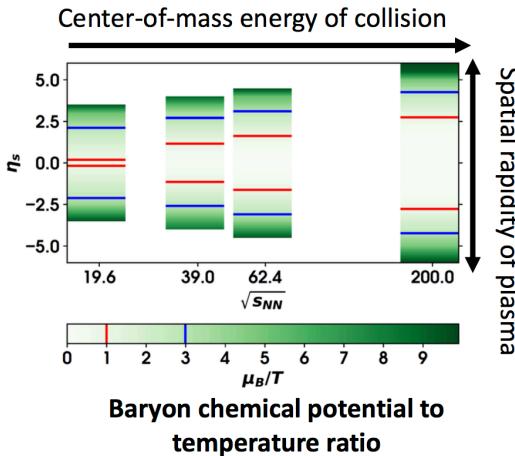
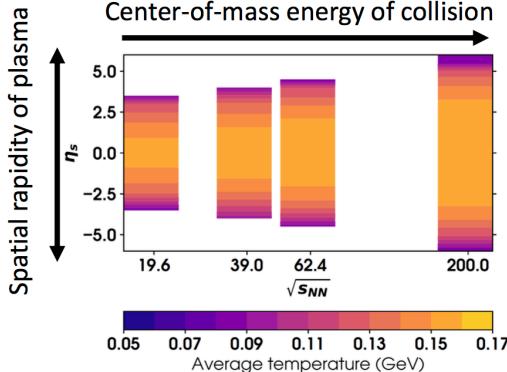
arXiv: 1805.04084



Integrated yield across wide energy range from 39 GeV to 2.76 TeV

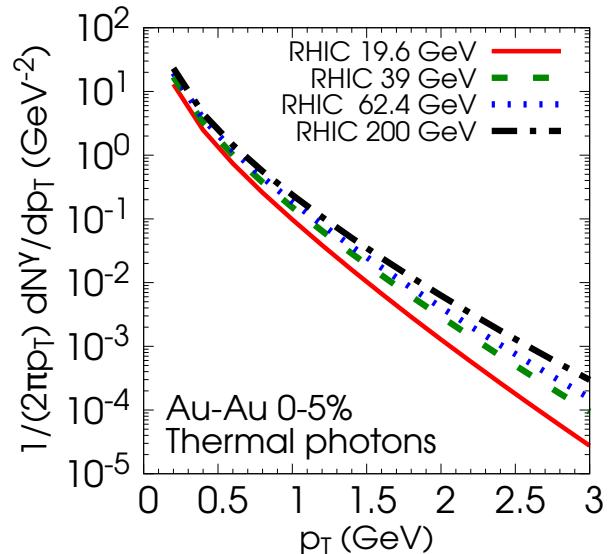
All the available data agree very well with the **scaling** of $(dN/d\eta)^{1.25}$ within the experimental uncertainties

Theory of thermal radiation at lower \sqrt{s}_{NN}



Hydro calculation prediction for the smaller collision energies:

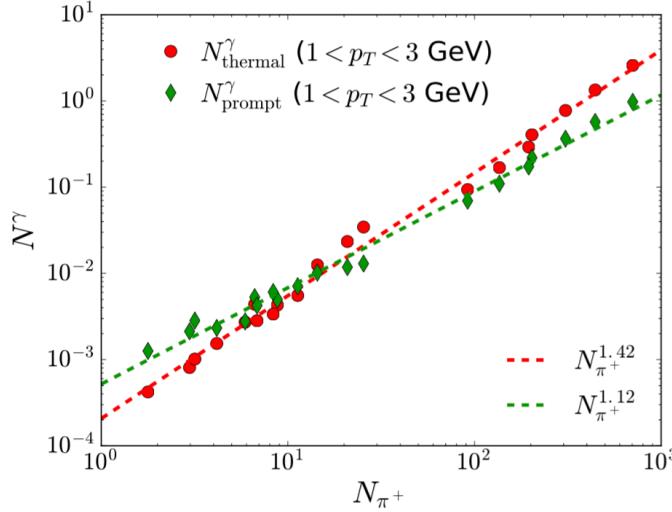
- The average temperature stays very similar in the mid-rapidity, while the baryon chemical potential increases



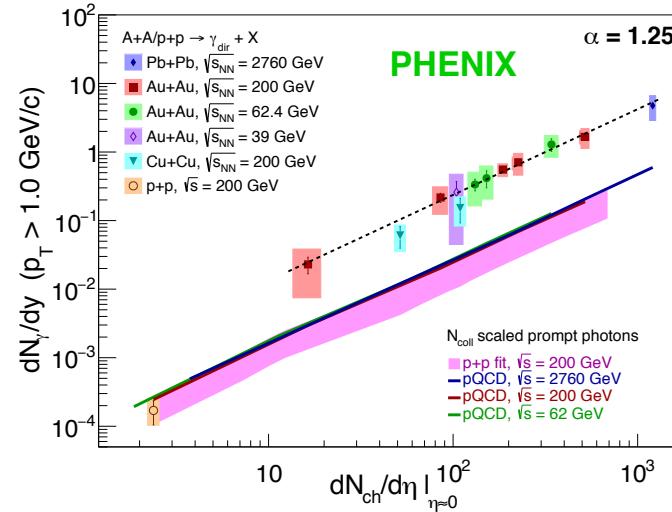
Large thermal yields predicted to low \sqrt{s}_{NN}

What does theory say?

Phys.Rev. C95 (2017), 014906



arXiv: 1805.04084



Theory predicts higher slope as the function of pion multiplicity

Theory slopes:

~1.42 for thermal photons

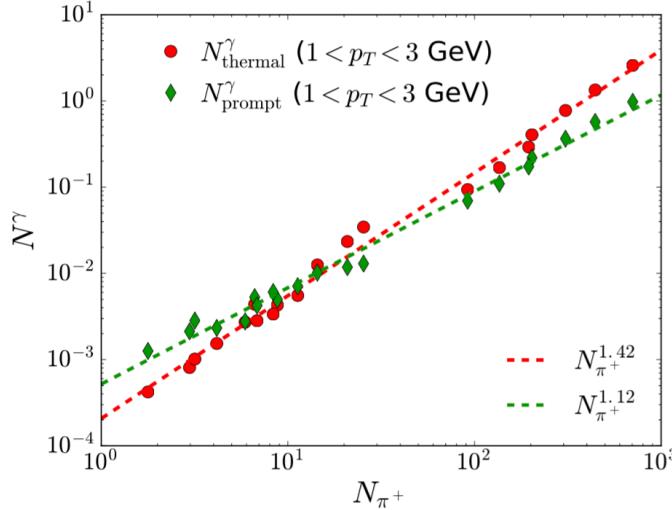
~1.12 for the pQCD photons

prompt < thermal: $N_\pi > 10$

prompt > thermal: $N_\pi < 10$

What does theory say?

Phys.Rev. C95 (2017), 014906



Theory slopes:

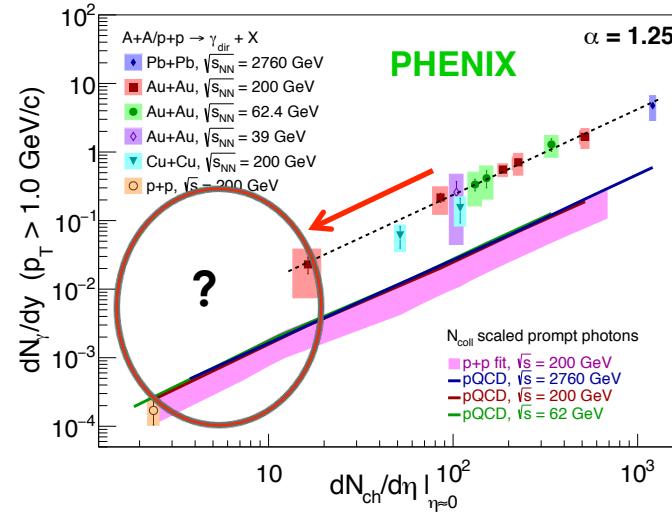
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arXiv: 1805.04084



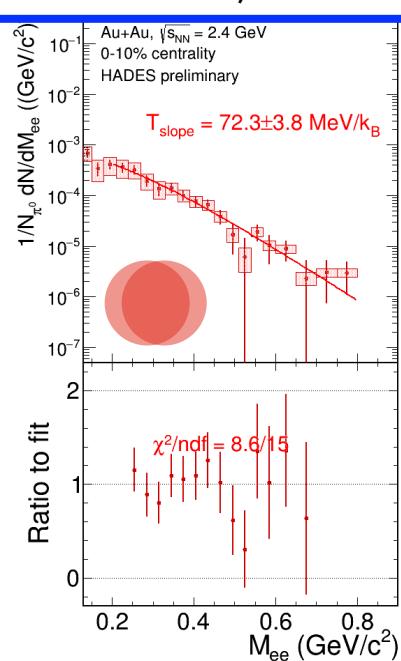
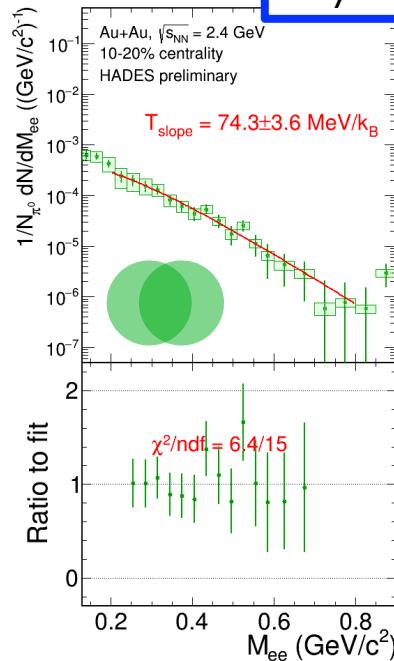
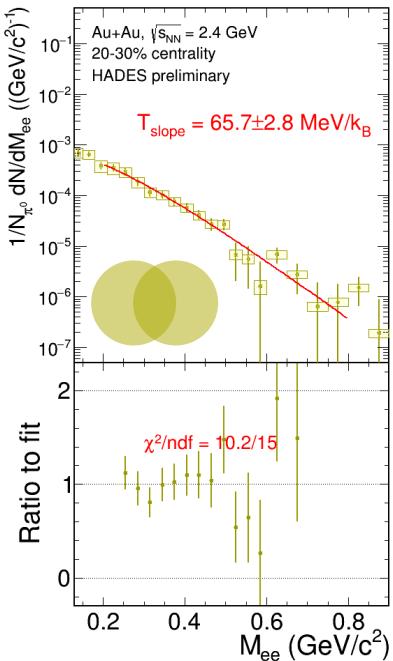
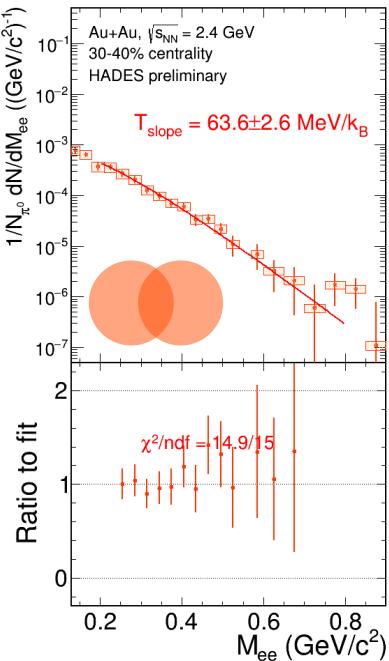
How about the transition region?

Data show a transition region between 2-20 multiplicities:

- More peripheral A+A
- Lower \sqrt{s}_{NN} A+A

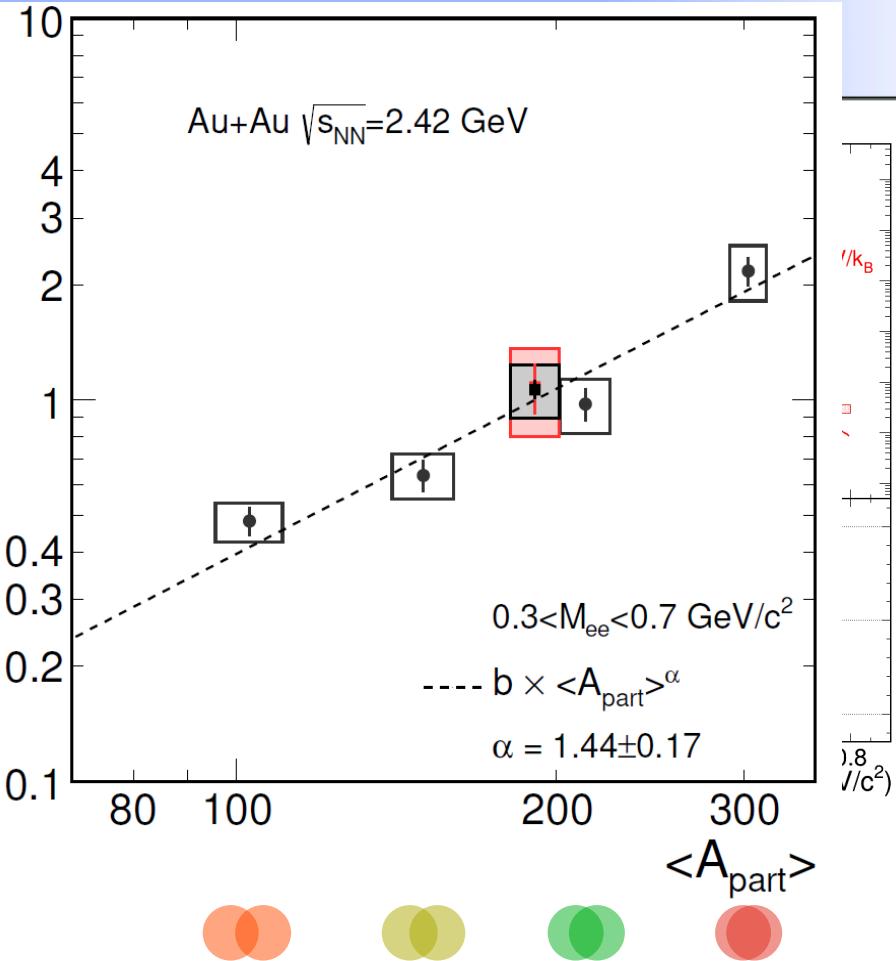
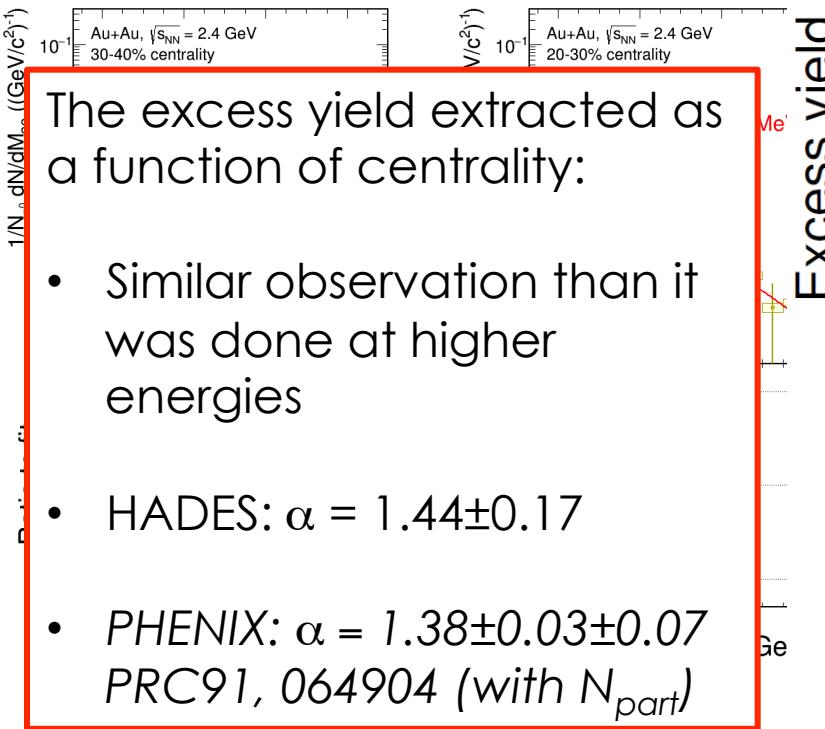
Hades in Au+Au at 2.42 GeV

Szymon Harabasz, Tue 17:30

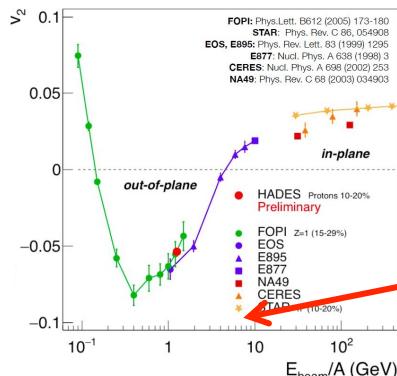


Di-electron results in the thermal photon region.
Advantage of using di-leptons as they do not suffer from the blue shift

Hades in Au⁺

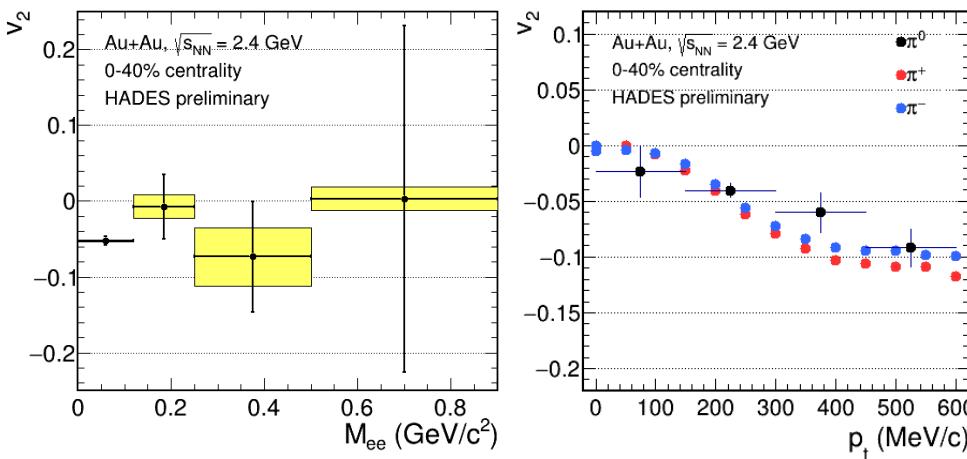


Hades on the flow of thermal radiation



Just a reminder about the energy regime:

at 2.42 GeV A+A collisions the azimuthal asymmetry is **negative** (not positive as at high energy)

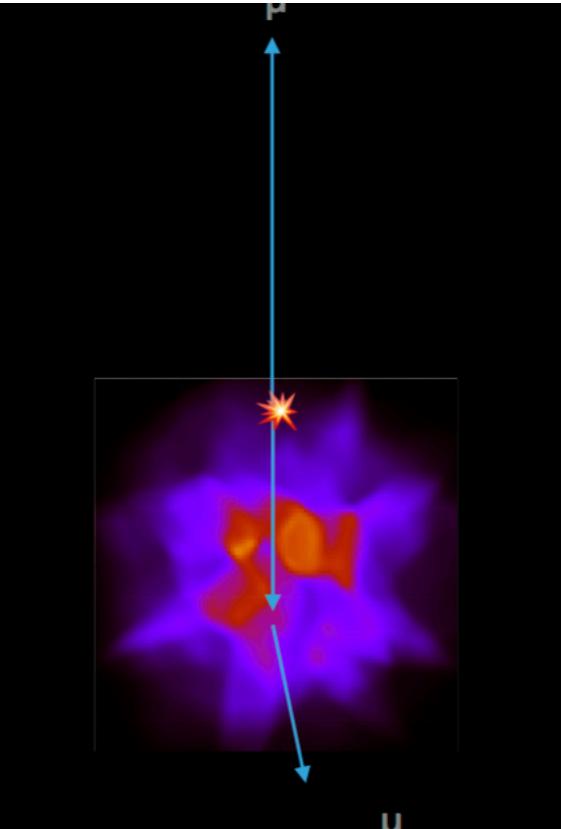


First di-lepton v_2 measurement:

at the π^0 mass region the v_2 agrees with the measured v_2 of π^\pm

In thermal region the $v_2 \sim 0$ within the uncertainties

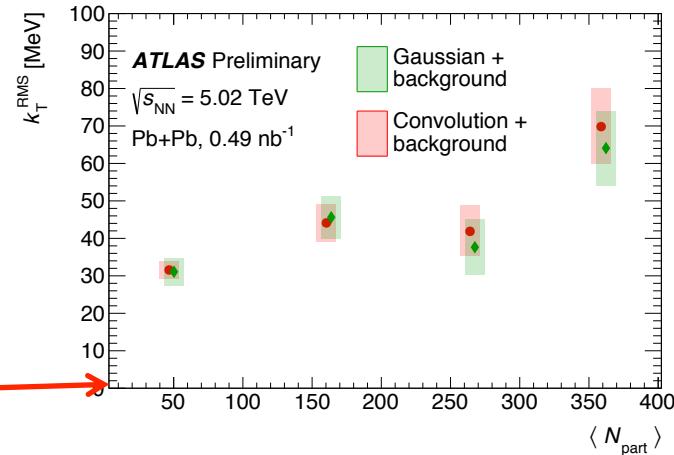
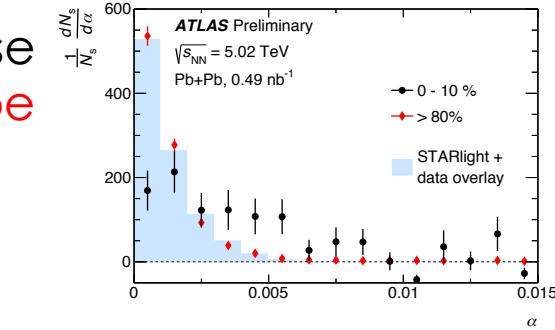
Muon probing the QGP?

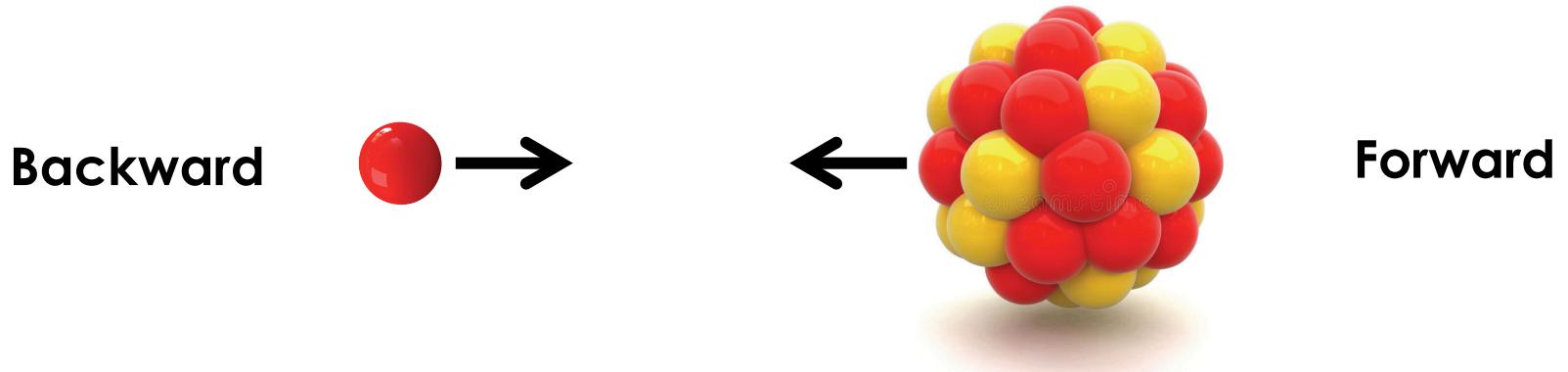


Very interesting proposal to use the created **di-muons to probe the QGP charge density profile.**

Observation of the widening of the muon pair:

- Small centrality dependence is observed
- The **UPC contributions are subtracted**

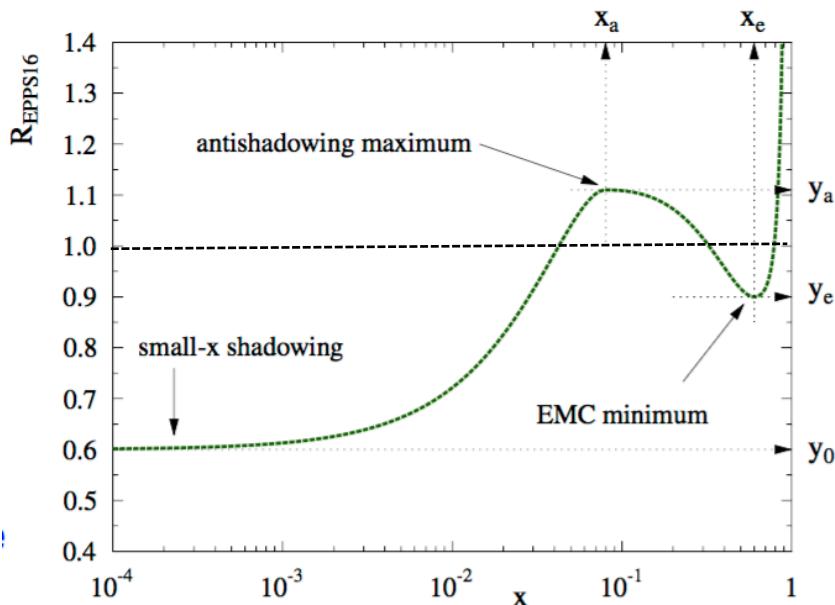




P+A COLLISIONS

nPDF? Mini-QGP?

Nuclear PDF (nPDF)



The standard way to look at the nPDF:

$$f_i^{p/A}(x, Q^2) \equiv R_i^A(x, Q^2)$$

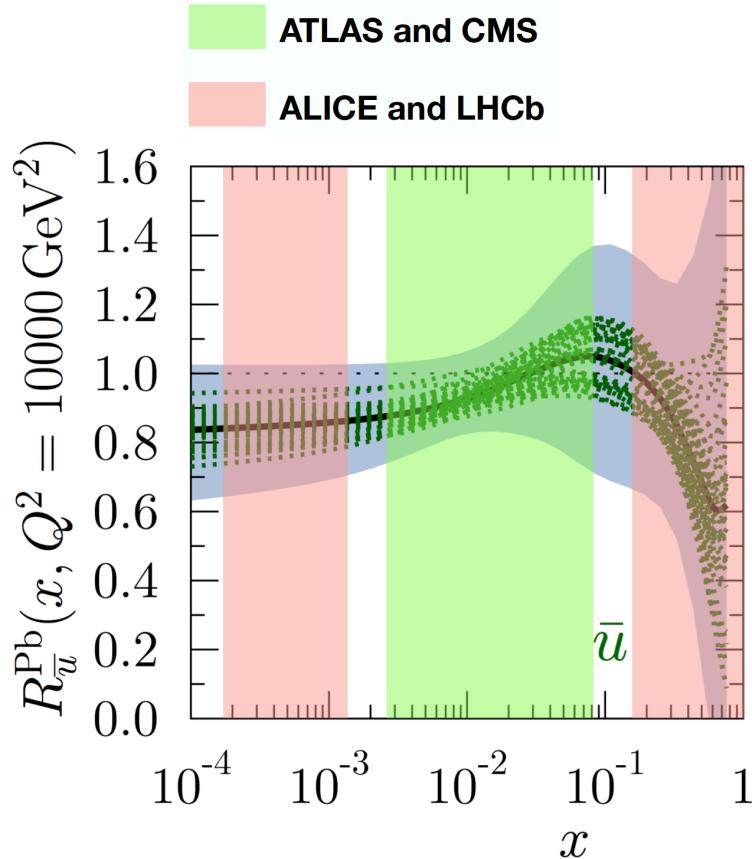
Nuclear modifications

$$f_i^p(x, Q^2)$$

Free proton baseline

At different x we expect different nuclear effects: EMC, anti-shadowing, shadowing.

Nuclear PDF (nPDF)



The standard way to look at the nPDF:

$$f_i^{\text{p}/A}(x, Q^2) \equiv \frac{R_i^A(x, Q^2)}{f_i^{\text{p}}(x, Q^2)}$$

Nuclear modifications

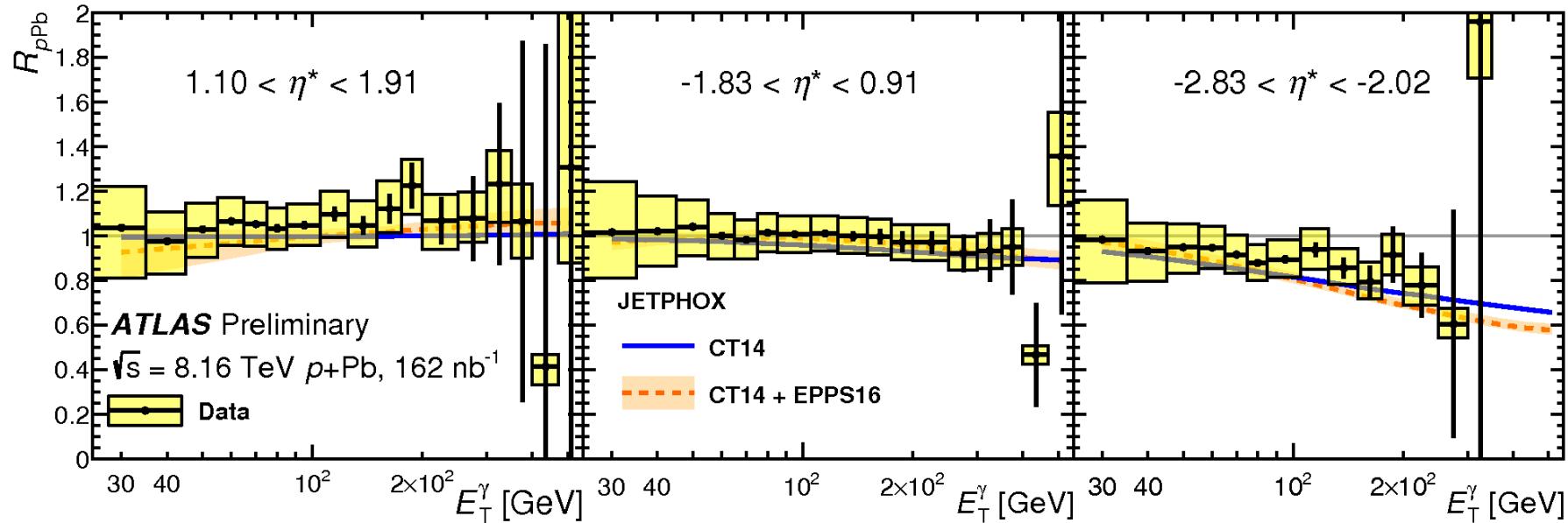
Free proton baseline

At different x we expect different nuclear effects: EMC, anti-shadowing, shadowing.

Need more experimental datasets to constrain nPDFs

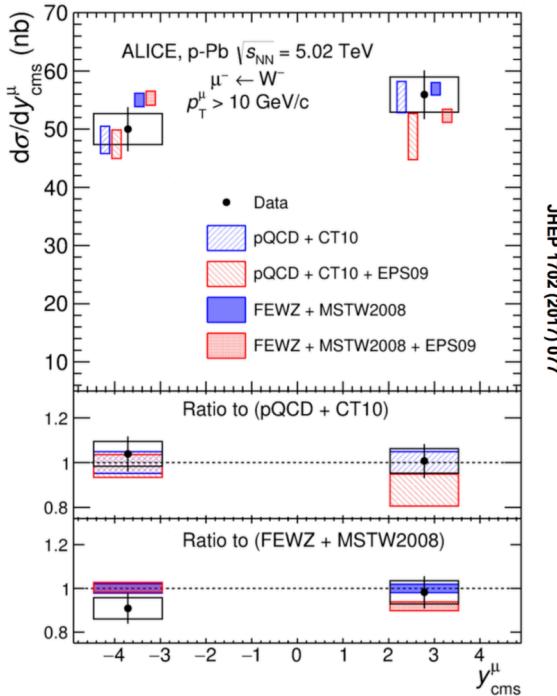
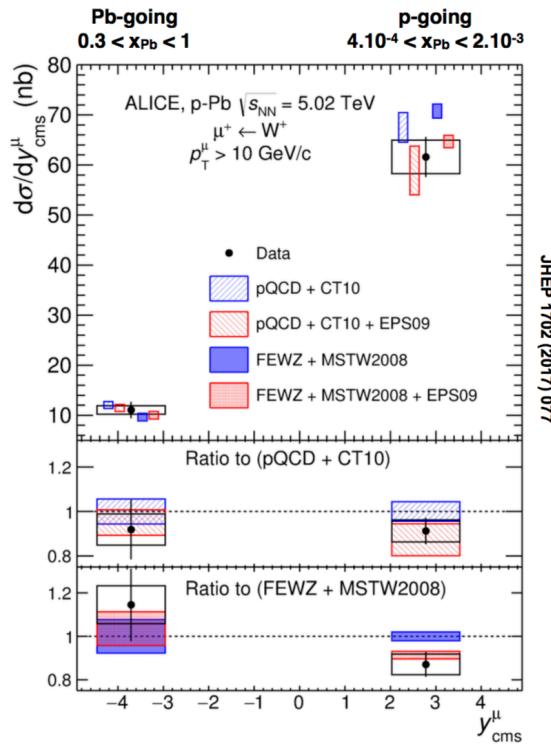
Prompt Photon in p+Pb

Zvi Citron, Tue 10:00



Prompt photon production in the forward and backward region.
The data is not yet precise to distinguish about the nPDF effects

ALICE W^\pm in p+Pb forward/backward



ALICE is extracting the W^\pm boson from very forward region:

p+Pb: $2.03 < y_{\text{cms}} < 3.53$

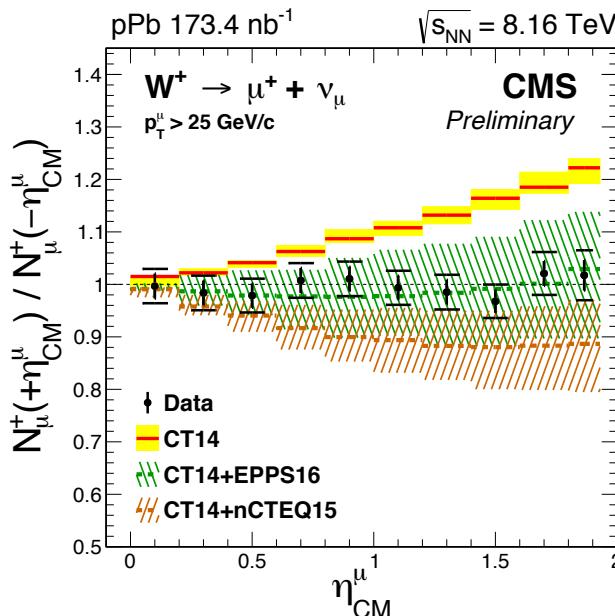
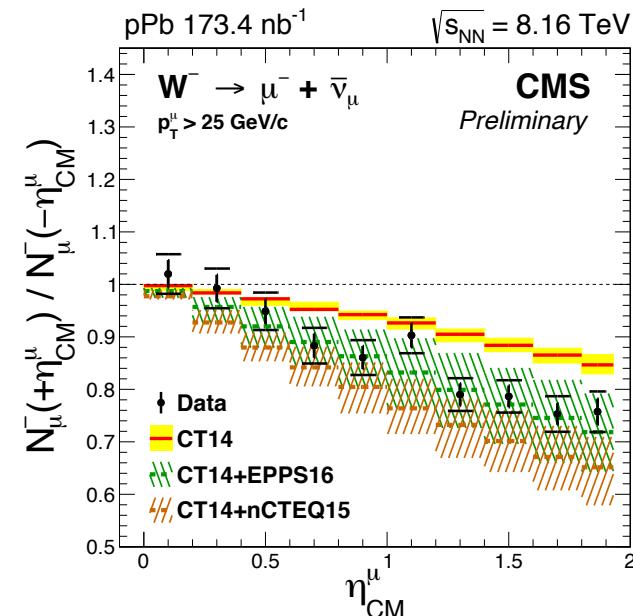
Pb+p: $-4.46 < y_{\text{cms}} < -2.96$

Pb+Pb: $2.5 < y_{\text{cms}} < 4$

Data precision cannot conclude on the nPDF

Mohamad Tarhini, Wed 11:15

$$P(\chi^2) = <0.01\% \text{ CT14}, 83\% \text{ nCTEQ15}, 95\% \text{ EPPS16}$$



Andre Ståhl, Wed 11:30

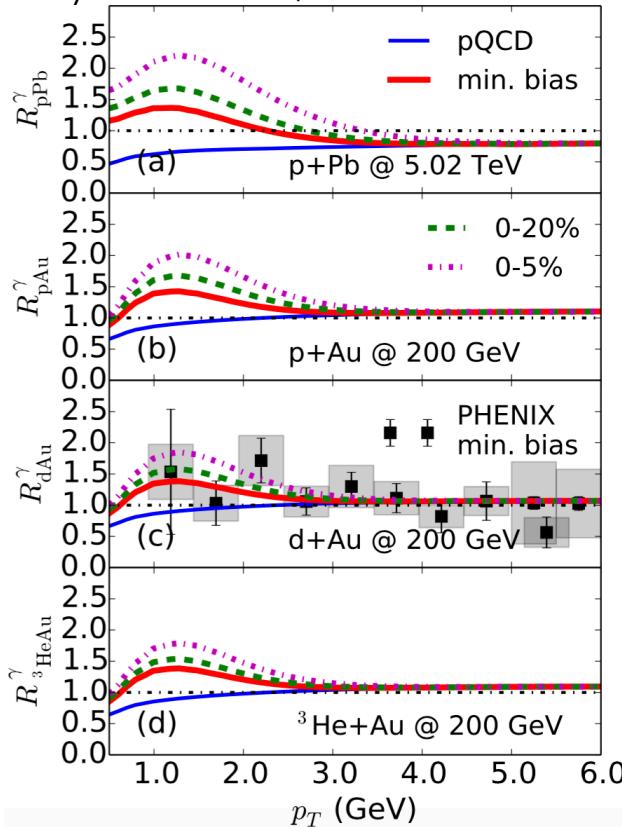
New results of the W measurement from CMS in p+Pb at 8.16 TeV.

Exclude the free nucleon PDF to 7σ significance

Experimental uncertainties are smaller and the nPDF uncertainties

Thermal radiation at small systems?

Phys. Rev. C **95**, 014906



Collectivity is observed in all ‘small systems’ from high multiplicity $p+p$ to $p+A$ collisions.

Question: Is there a **QGP** formed in these collisions?

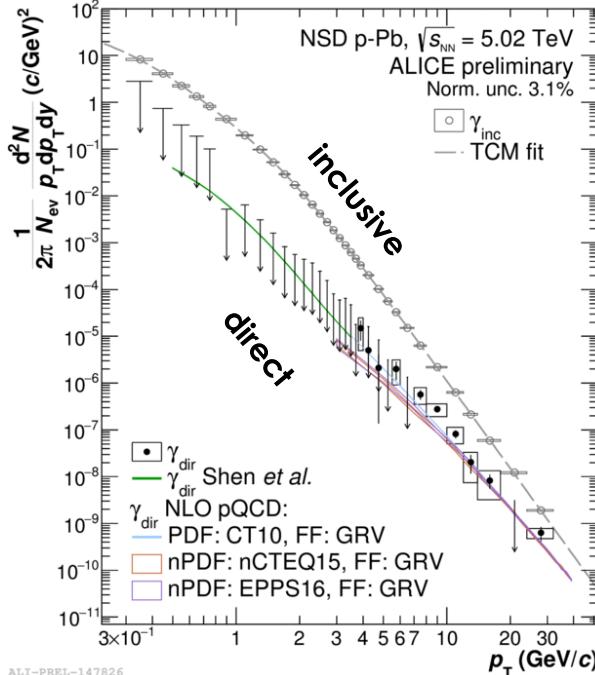
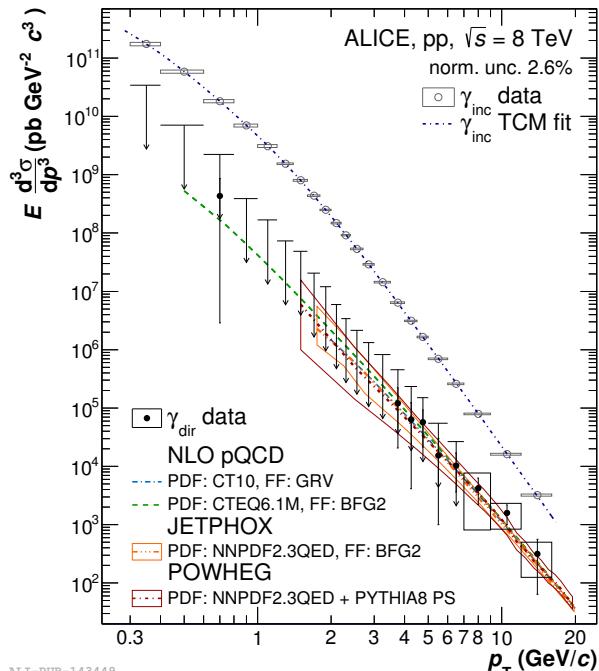
Theory model predicts also a thermal enhancement in the low- p_T direct photons:

- Largest at LHC, less visible in the larger ‘small systems’ $R_{p\text{Pb}} > R_{p\text{Au}} > R_{d\text{Au}} > R_{{}^3\text{He}\text{Au}}$

Currently had only the $d+Au$ minimum bias data and it was not conclusive. Data is consistent with the enhancement and with unity.

ALICE measurement in p+p and p+Pb

arXiv:1803.09857

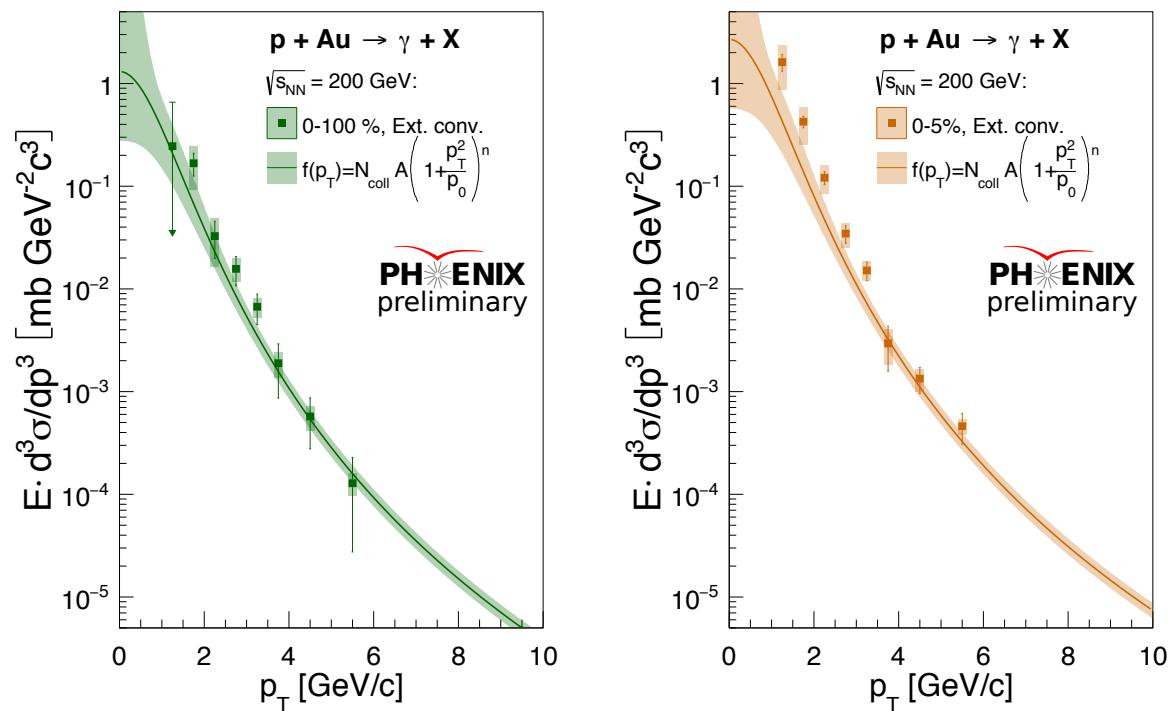


- Consistent with no direct photons at $p_T < 3 \text{ GeV}$ in both p+p and p+Pb.
- Also consistent with the enhanced thermal production of photons (green line)

Combine all available techniques and available data to further **decrease** the **uncertainties**.

PHENIX measurement in small systems

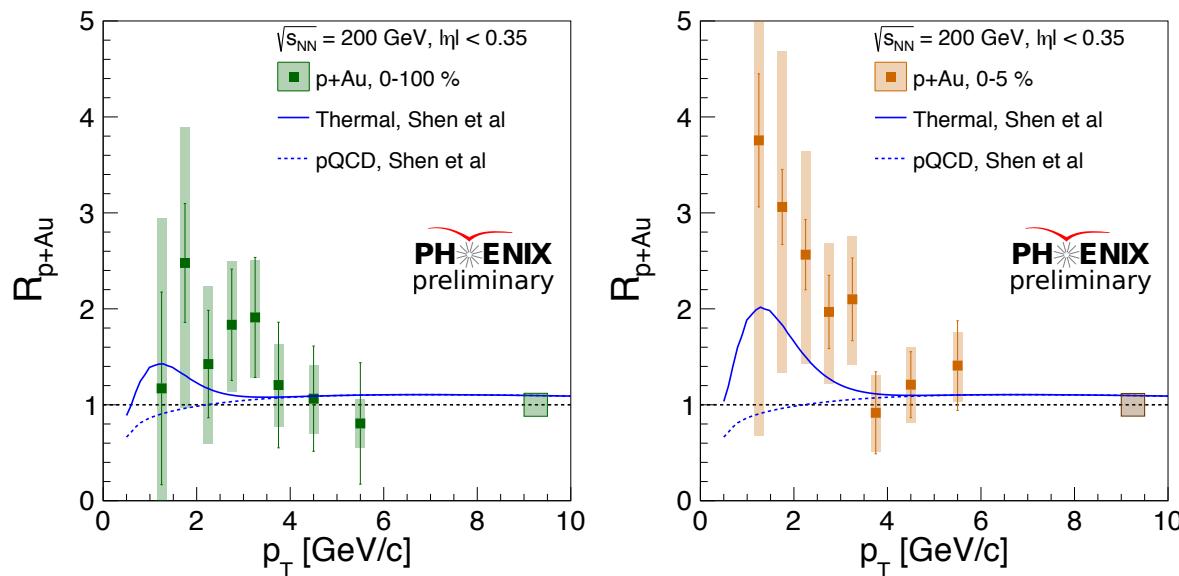
Vladimir Khachatryan, Mon 16:50



PHENIX measured the direct photon yield in p+Au collision.

PHENIX measurement in small systems

Vladimir Khachatryan, Mon 16:50



Are there really thermal photons in $p+Au$?

- **Not yet conclusive**, but very suggestive

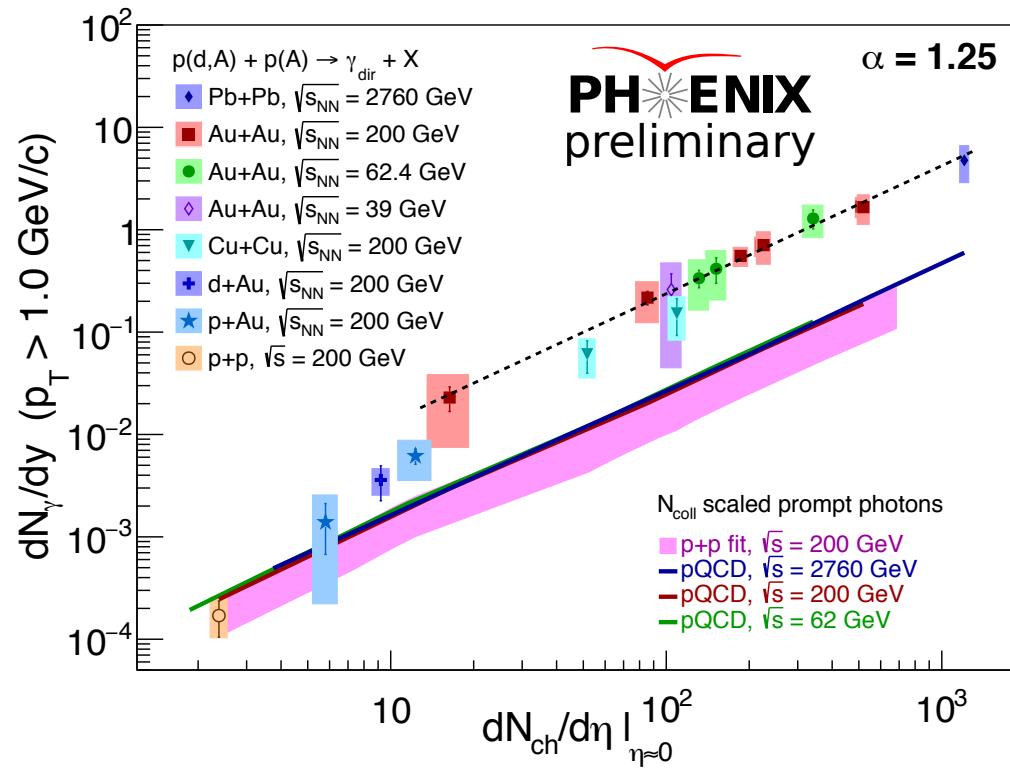
PHENIX measured the direct photon yield in $p+Au$ collision.

- Min. bias is consistent with enhancement or unity – similar as in $d+Au$ collisions
- The 0-5% centrality is **indicating beyond 1σ enhancement** from scaled $p+p$ collisions.

Direct photon scaling in transition region

Adding the direct photons from small systems in the scaling plot.

The small systems seem to fill the **transition region between 5-20 multiplicities**



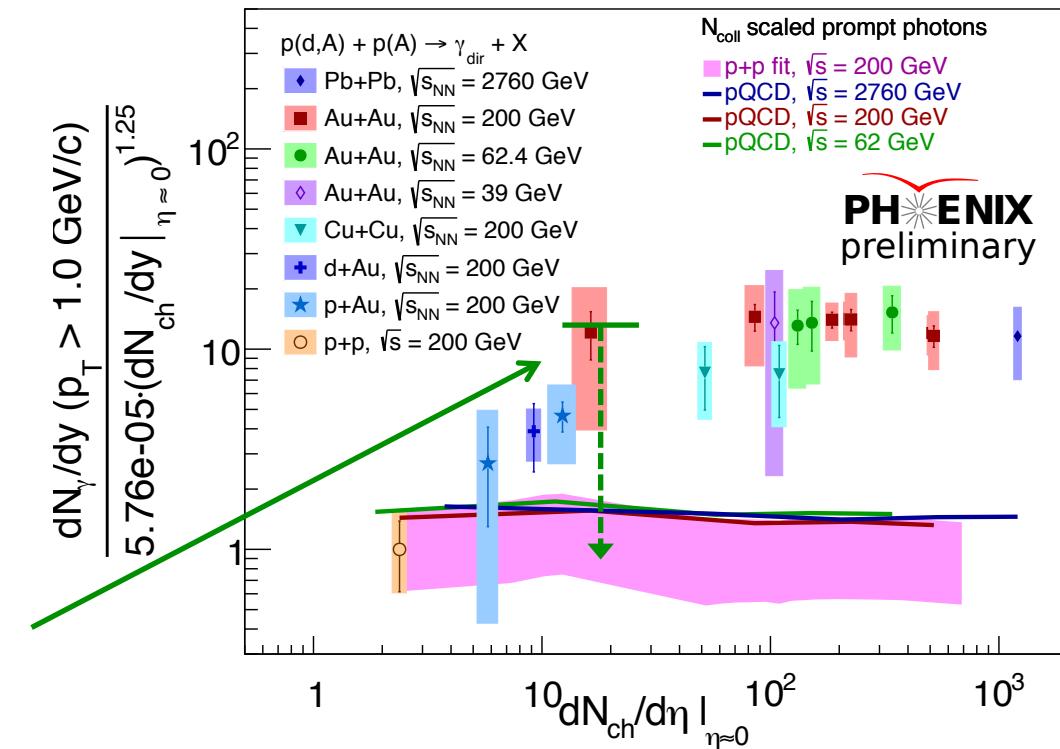
Direct photon scaling in transition region

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The small systems seem to fill the **transition region between 5-20 multiplicities**

Divided by the slope

Eye-balling the ALICE upper limits in p+Pb min. bias at 5 TeV



Summary

- Interesting proposal to study the p+p geometry with hard scale:
 - No large effect is seen in p+p collisions
- Large system scaling properties:
 - photon, W^\pm , Z boson as a geometry baseline
 - muon to probe the QGP?
 - Thermal photons across different systems and collision energies can be described by two parameter function.
- Small systems:
 - W^\pm data already can constrain the uncertainties on the nPDF
 - Hint of an additional direct photon (thermal?) production in the p+Au collisions

THANK YOU!

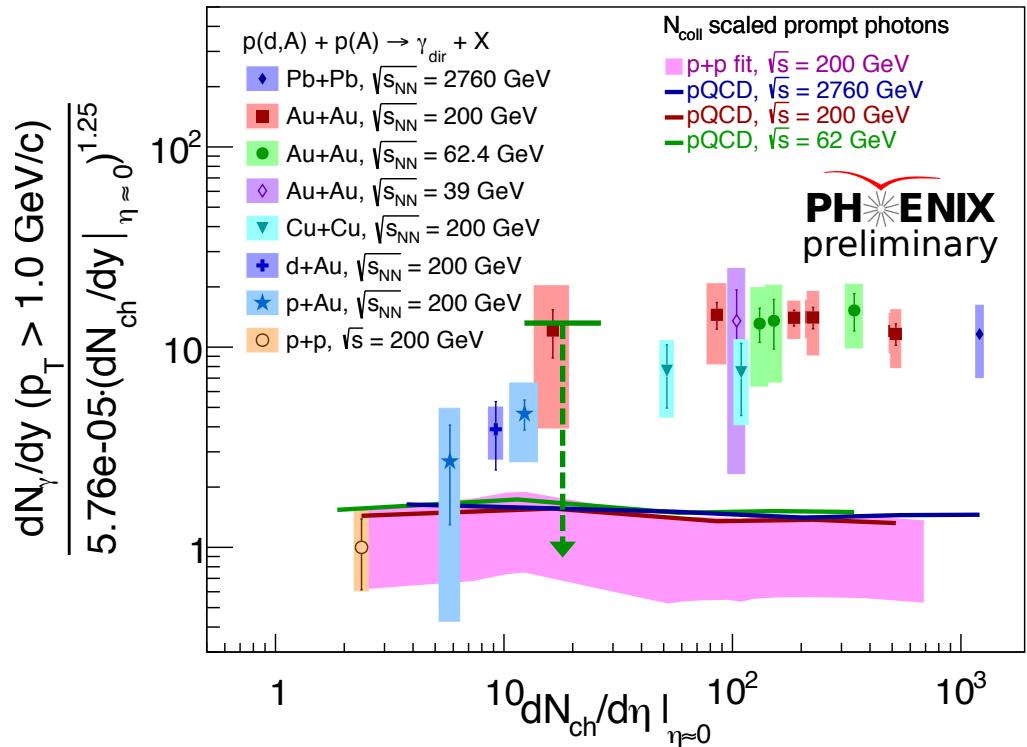
AND THE VALUABLE INPUT FROM MANY COLLEAGUES

BACKUP

Divided by the slope

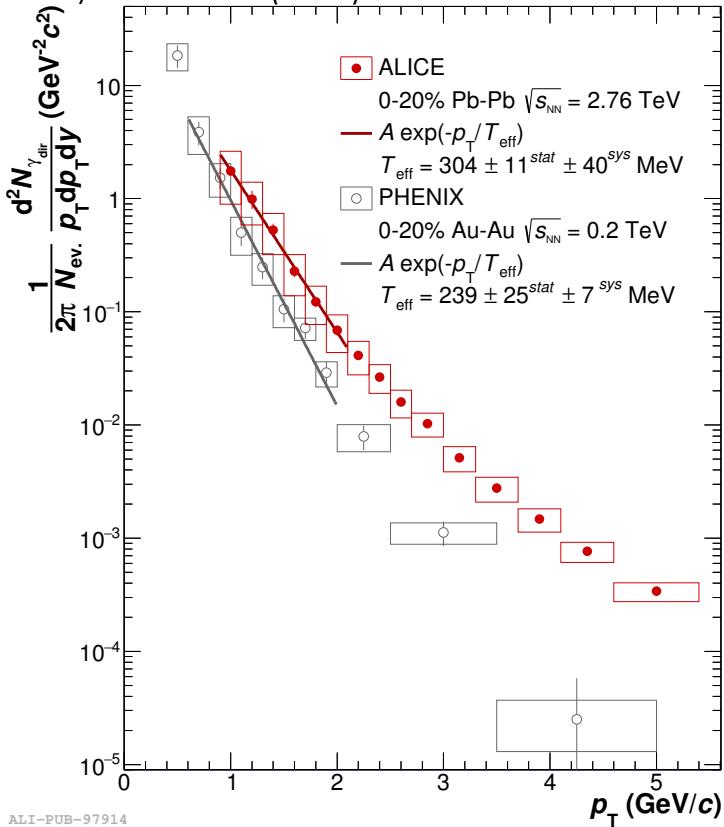
The transition region is more obvious in this plotting.

The transition happens in very narrow multiplicity bin, 2-30



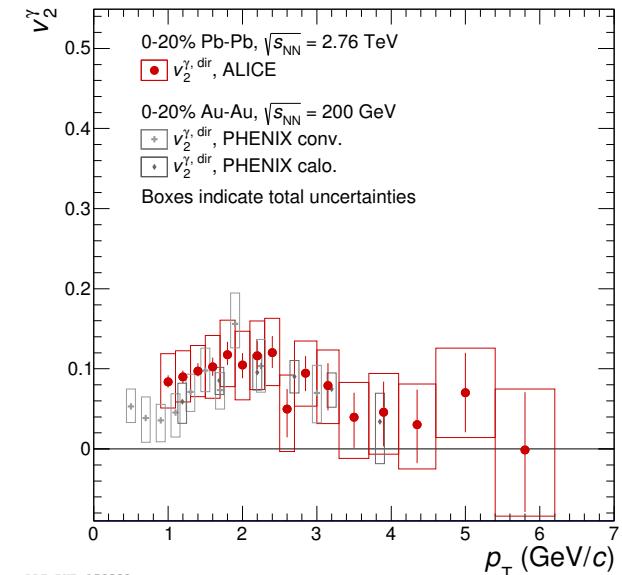
PHENIX and ALICE

Phys.Lett. B754 (2016) 235



The direct photon yield is larger at LHC energies than at RHIC

The direct photon flow is comparable between the two energies

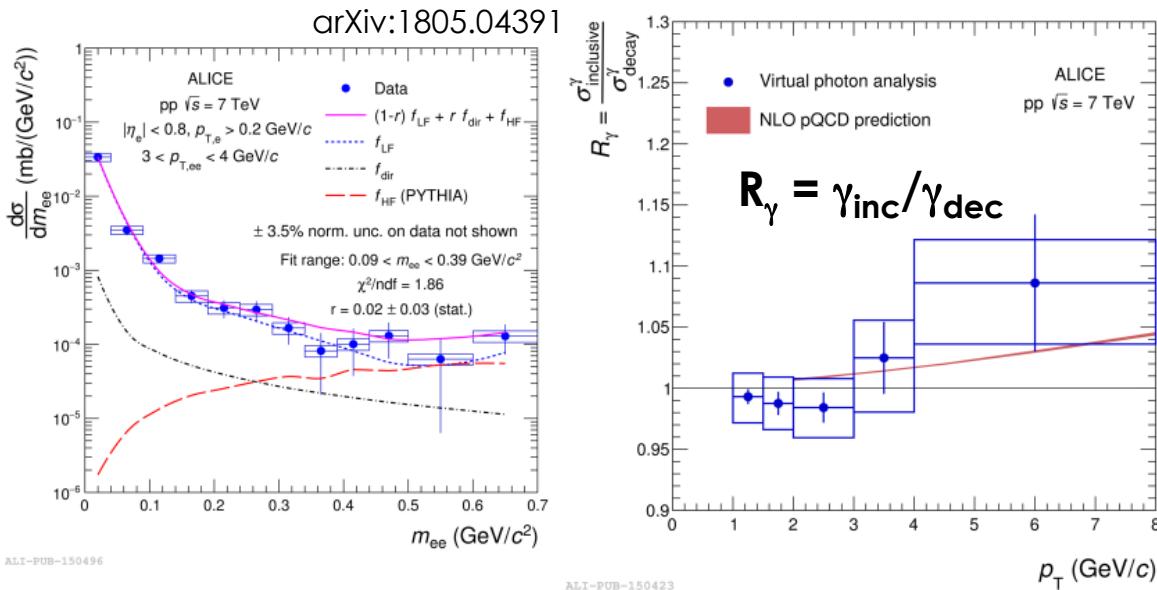


Virtual Photon measurement in ALICE

New virtual measurement in ALICE p+p at 7 TeV

The uncertainties are still very large, consistent with the pQCD calculation.

At $p_T < 4 \text{ GeV}/c$ no significant direct photon yield was observed

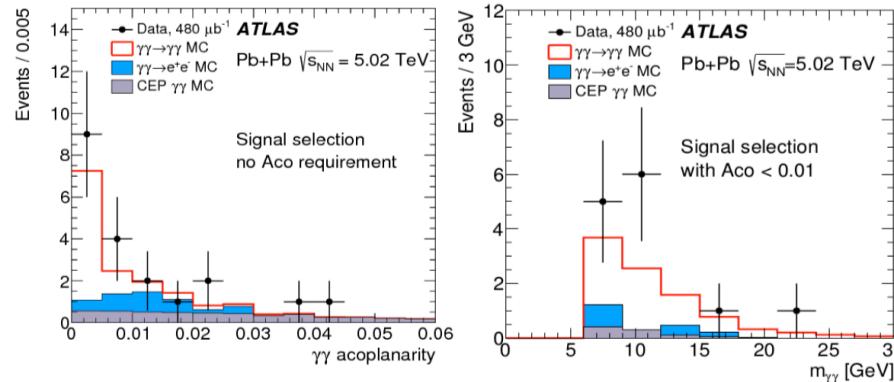


The predicted yield of the direct photons at these energies are around $\sim 1\%$

Raphaelle Bailhache, Mon 18:10

Light-by-Light scattering

Nature Phys. 13 (2017) 852



ATLAS found the evidence of light-by-light scattering in Pb+Pb collisions:
13 counts measured (2.6 bkg)
 $\sigma(\text{fid}) = 70 \pm 20 (\text{stat}) \pm 17 (\text{syst}) \text{ nb}$
 $\sigma(\text{SM}) = 45 \pm 9 \text{ nb}$
Significance obs. (exp.): $4.4(3.8)\sigma$

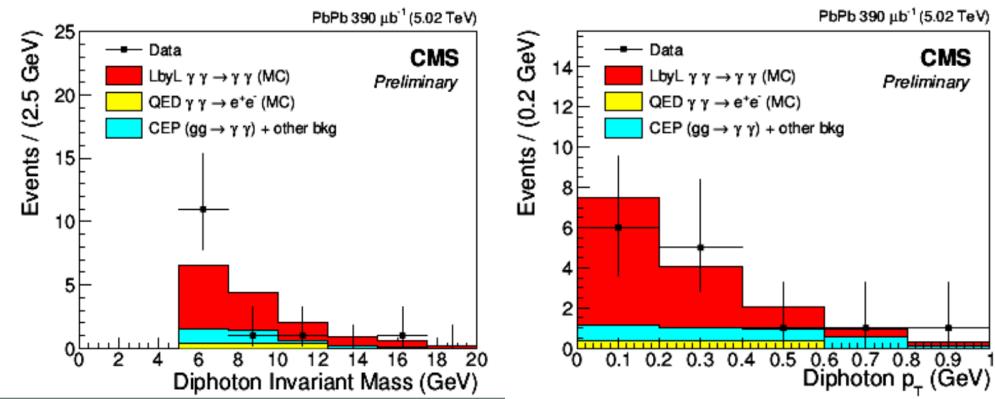
CMS measured the light-by-light scattering:

14 counts measured (3.8 bkg)

$\sigma(\text{fid}) = 122 \pm 46 (\text{stat}) \pm 29 (\text{syst}) \pm 4 (\text{th}) \text{ nb}$

$\sigma(\text{SM}) = 138 \pm 14 \text{ nb}$

Significance obs. (exp.): $4.1(4.4)\sigma$

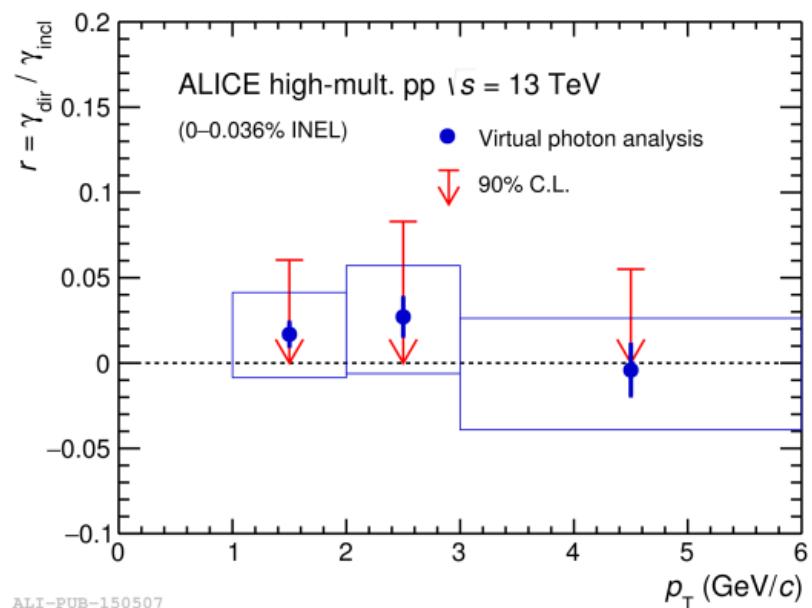
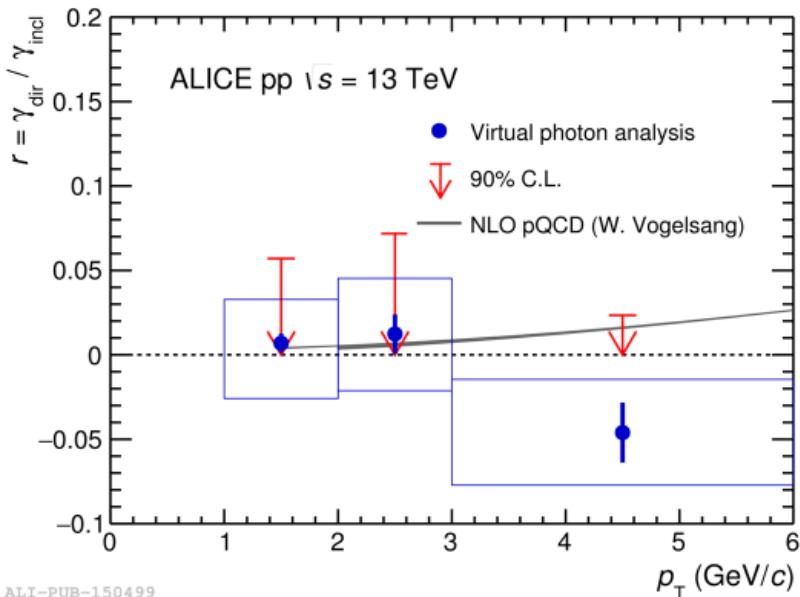


David D'Enterria, Mon 12:30

May 18, 2018

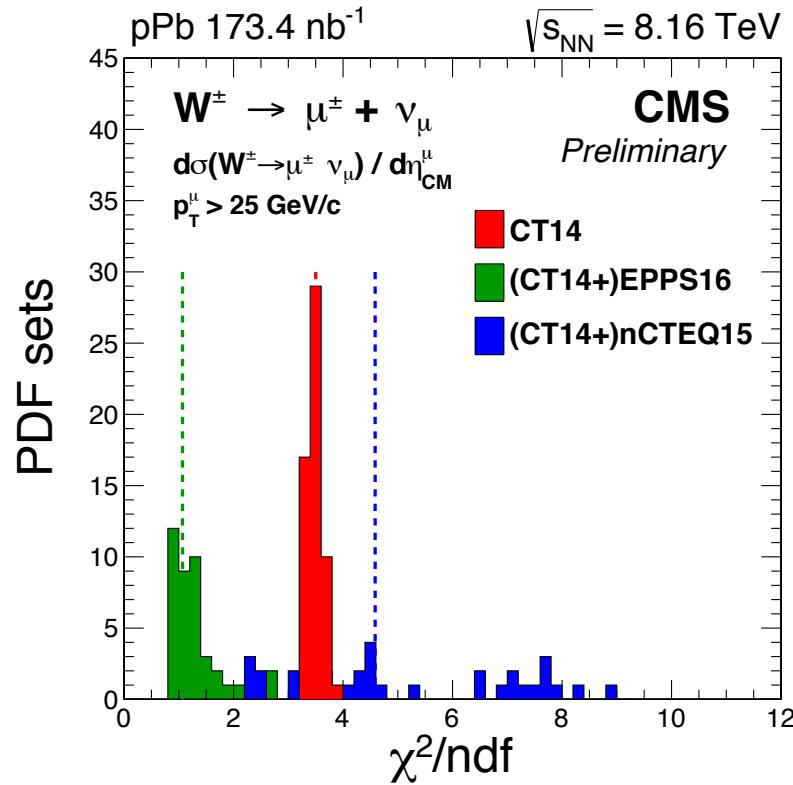
Norbert Novitzky

42

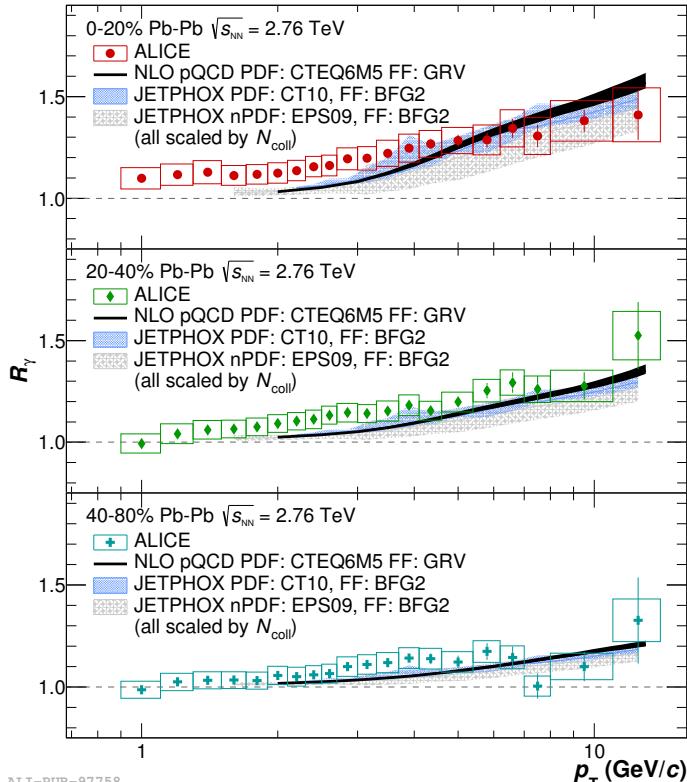


χ^2 analysis of the W boson

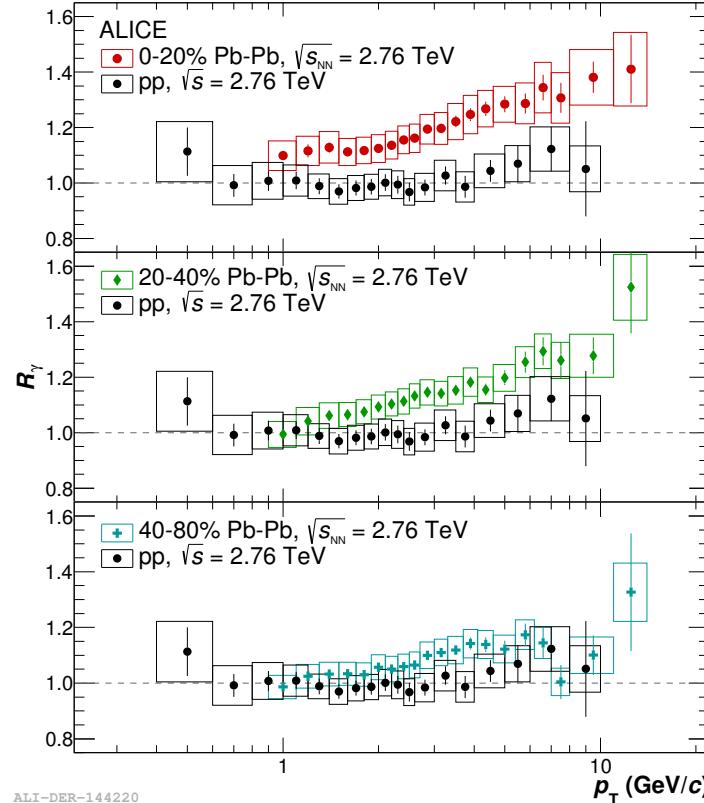
CMS-PAS-HIN-17-007



ALICE R_{γ}

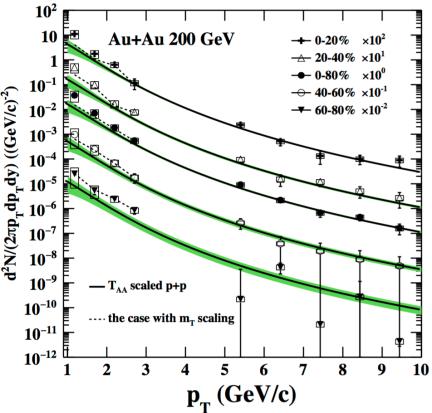


ALI-PUB-97758



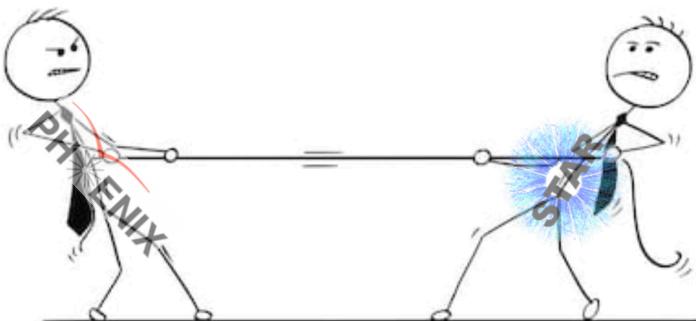
ALI-DER-144220

PHENIX vs STAR



STAR measured the direct photon spectra:

- $p_T < 3$ virtual photon method
- $p_T > 5$ real photons in EMCal



Tension between the two experiments is not resolved yet

We need to push for more work on the resolution of this issue

