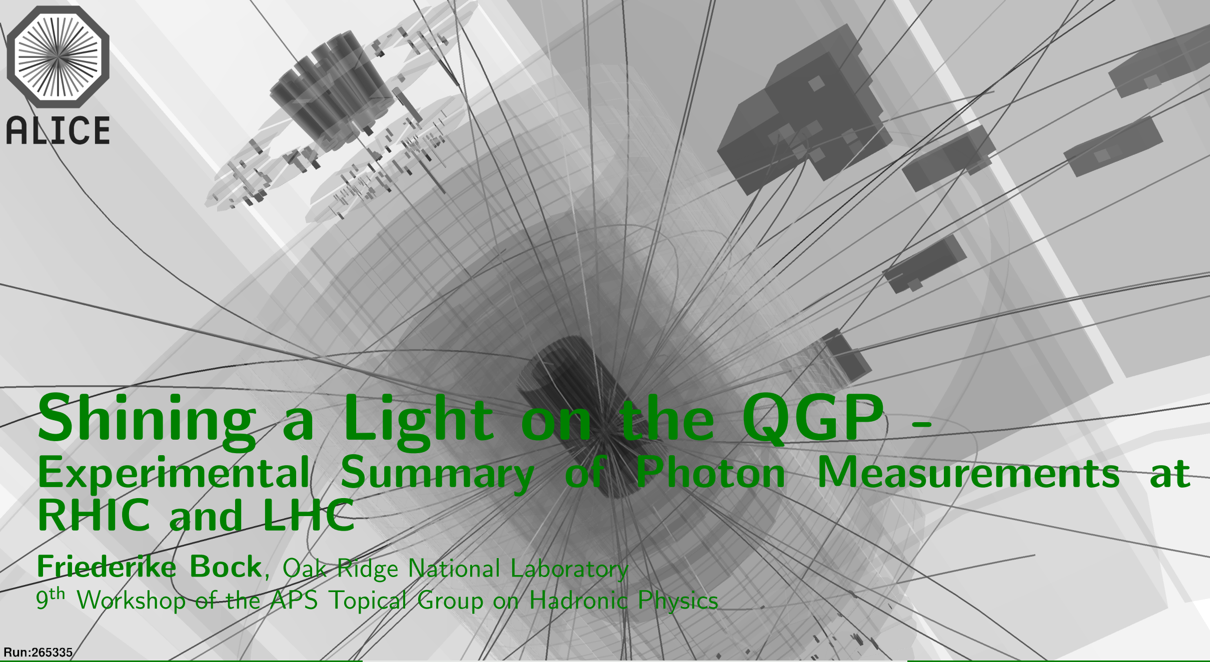
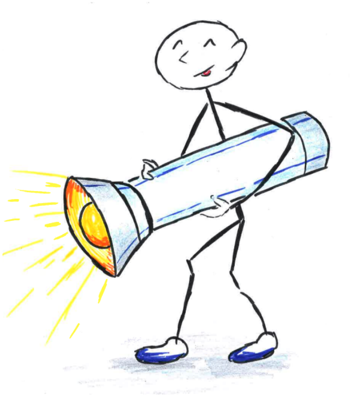


Shining a Light on the QGP – Experimental Summary of Photon Measurements at RHIC and LHC

Friederike Bock, Oak Ridge National Laboratory

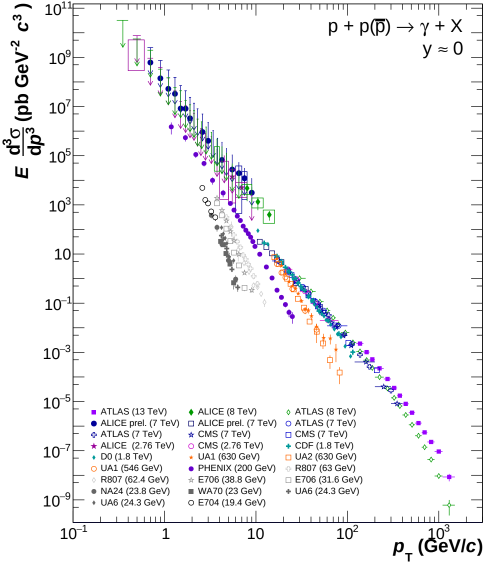
9th Workshop of the APS Topical Group on Hadronic Physics

Probing the QGP with Direct Photons



Can we determine the point where the QGP switches on?

Direct Photon in pp($\bar{\text{p}}$) collisions



Let's start with the base-line!

- Large variety of results available from 19.4 GeV - 13 TeV for (isolated) direct photons
  → **New results at $\sqrt{s} = 13$ TeV**
- Decent agreement at large $\sqrt{s}$ & high p_{T} between pQCD & data
- All pp data seem to align on a common x_T-curve within $\pm(20-50)\%$, if scaled with $(\sqrt{s})^n$ with **n = 4.5**
- Intriguing number:

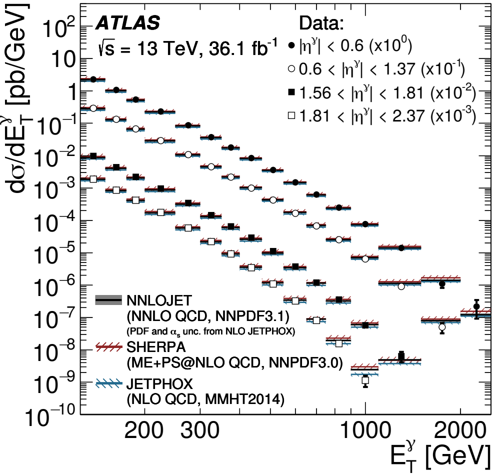
→ Pure vector gluon exchange: $n = 4$

→ Scale breaking effects in QCD could increase this number

→ Closer look needed if data could be described even better by slightly different **n** - could help pin down prompt photon contribution even at low p_{T}

Let's start with the base-line!

CMS: EPJC 79, 20 (2019)
ATLAS: JHEP 10 (2019) 203



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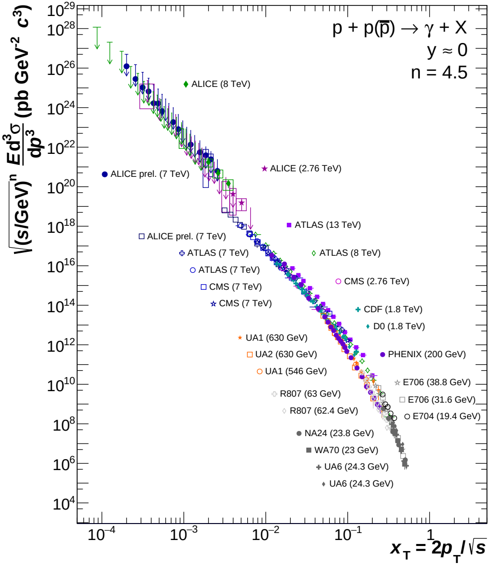

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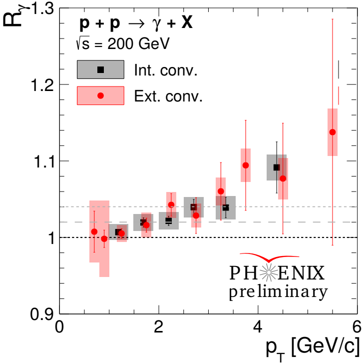
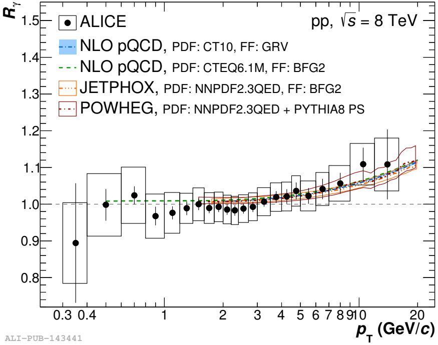
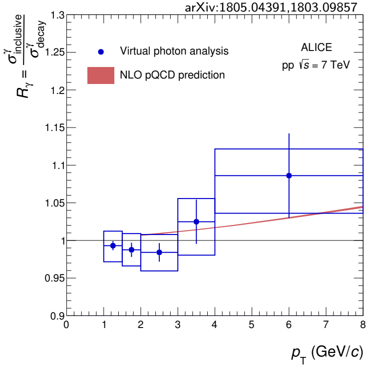
(Virtual) Direct Photons in pp at low p_T







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- No large thermal component expected O(0.1-1%) in pp
- Similar size of uncertainties of real & virtual photon measurements (O(5%)) at LHC at low p_T
- Measuring γ_{dir} for low p_T @ LHC energies very challenging
  @ RHIC energies possible for $p_T > 1.5$ GeV/c

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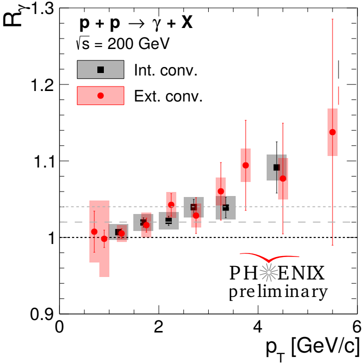
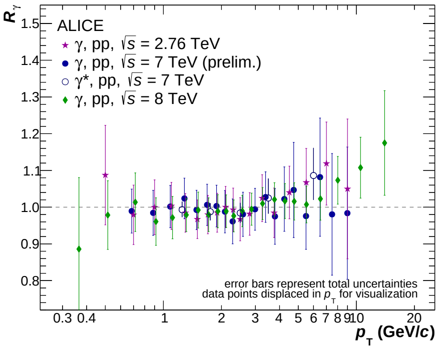
arXiv:1805.04391,1803.09857





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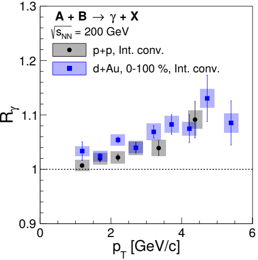
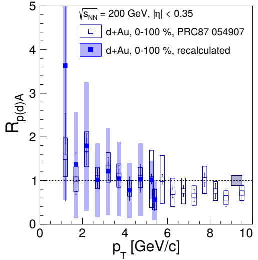
Direct Photons in p–Au at RHIC at low p_T

d-Au MB



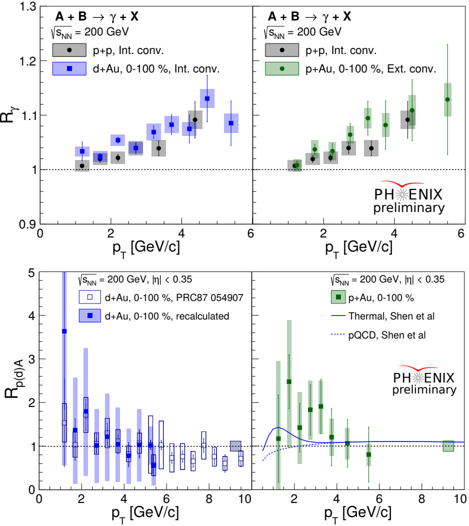


Increasing the system size

- **Measured direct photon excess ratio in MB & 0-5% p–Au collisions at $\sqrt{s_{NN}} = 200$ GeV**
- Reevaluated the pp reference data including external conversions in fit
- No clear excess yield at low p_T seen in d-Au MB & p-Au MB collisions with respect to pp, well described by pQCD calculation
- Excess of low p_T direct photon with respect to pp seen for 0-5% central collisions
- Indication for thermal contribution also in central p–Au collisions

Direct Photons in p–Au at RHIC at low p_T

d-Au MB **p-Au MB**



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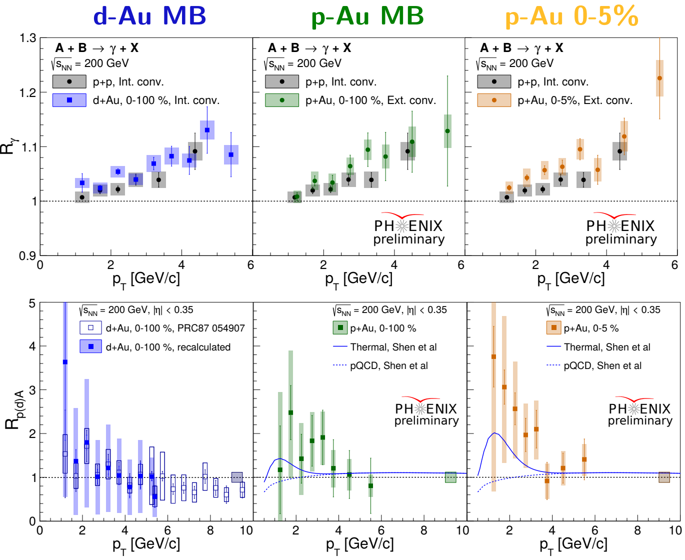

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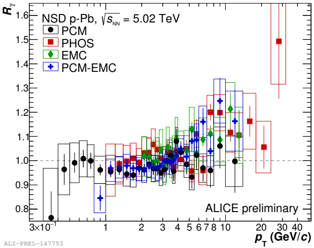
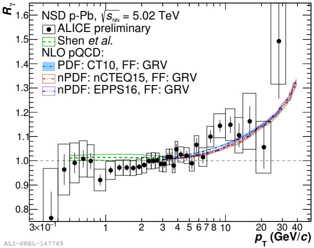
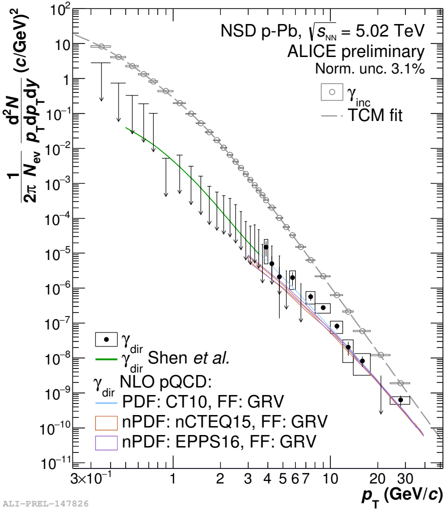
Direct Photons in p–Pb at LHC at low p_T

How about at LHC?

- Combination of 4 reconstruction techniques via BLUE method
- Individual sys uncertainties O(5-10%), combined total O(4-5%)
- Upper limits at 90% C.L. (arrows) determined where R_γ with total uncertainties consistent with unity
- 0-20% central collisions don't show a significant excess
- NLO & thermal (Shen et al.) calculations consistent with measurements







Theory calculations from:
W. Vogelsang (CT10,nCTEQ15,EPPS16/GRV), J.F. Paquet (CTEQ6.1M/BFG), C. Shen

Shen et al. arXiv:1609.02590

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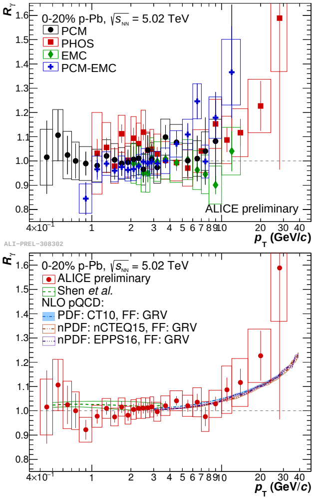

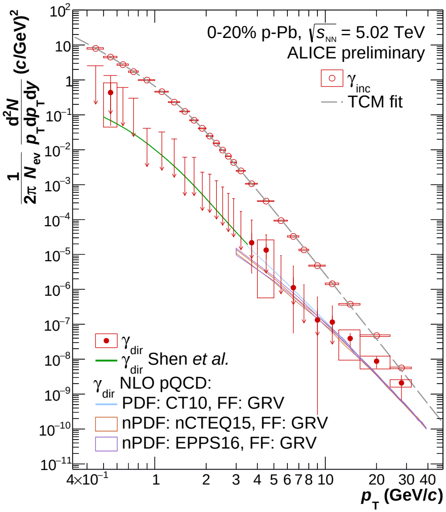

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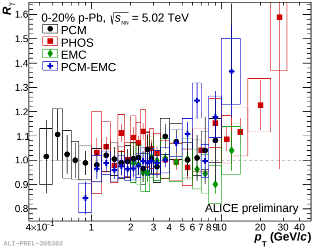

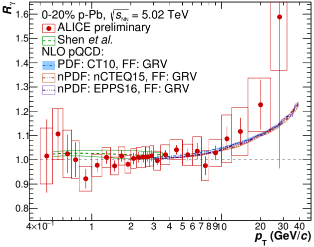

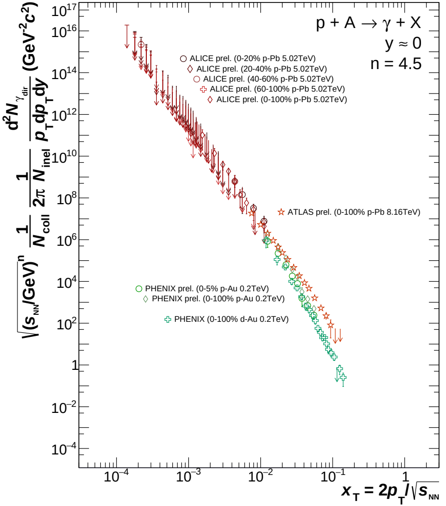

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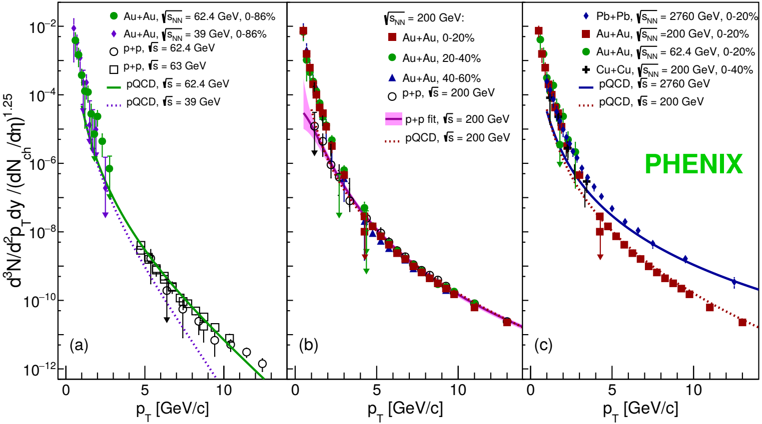
New ATLAS pPb 8.16 TeV publication

PLB 796 (2019) 230
Shen *et al.* arXiv:1609.02590

Direct Photon Spectra at RHIC - BES & Cu-Cu



- **Direct photon yield in Au-Au at $\sqrt{s_{NN}} = 39, 62.4, 200$ GeV & Cu-Cu at $\sqrt{s_{NN}} = 200$ GeV & Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV follow similar behavior at low p_T**
- Spectra normalized by $(dN_{ch}/d\eta)^{\alpha}$, where $\alpha = 1.25 \pm 0.02$ obtained from simultaneous fit to N_{coll} vs $dN_{ch}/d\eta$ for all collision systems

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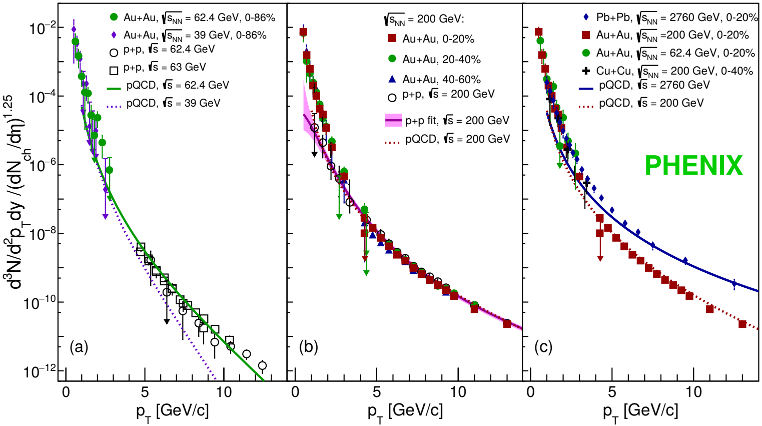
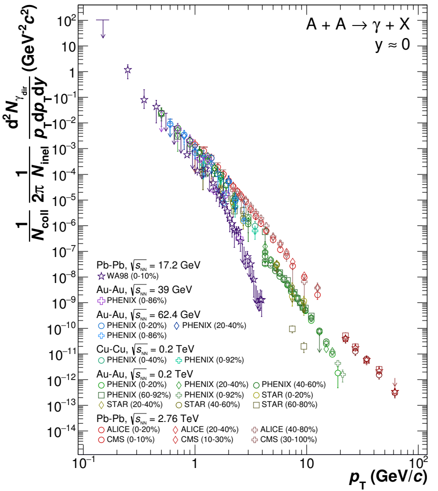


Other scaling relations possible as well!
Needs further thought



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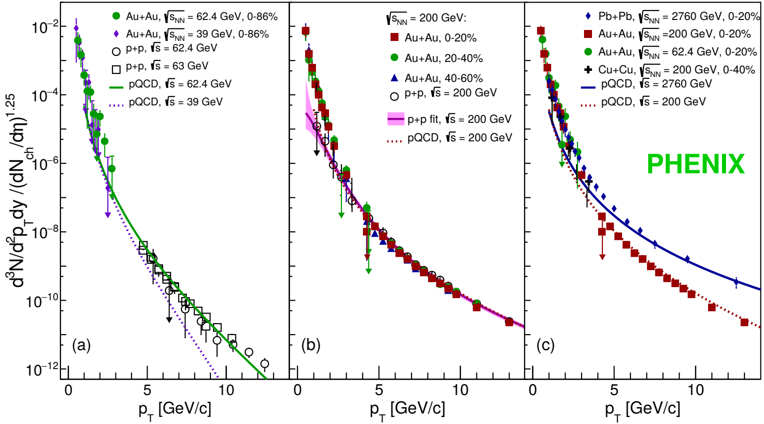

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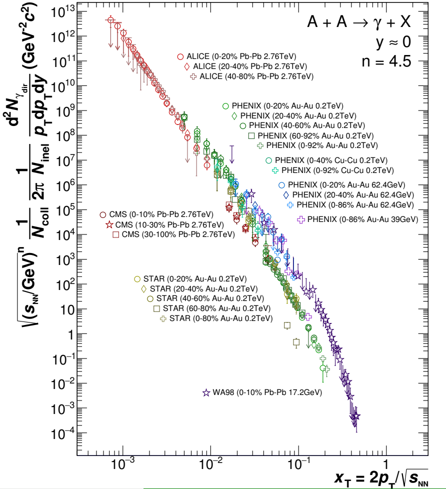

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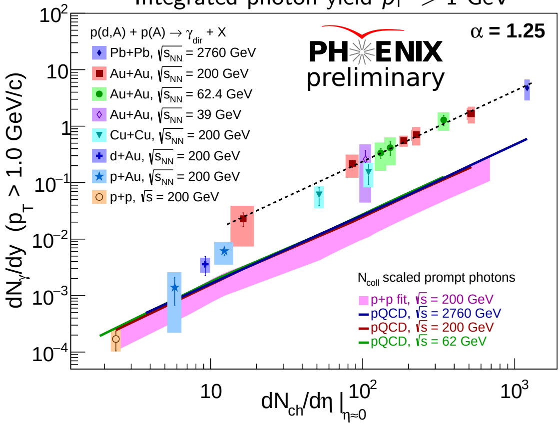
Direct Photon Spectra - N_{ch} scaling?

Integrated photon yield $p_T > 1$ GeV



Why does the low p_T direct photon yield appear to scale with $(dN_{ch}/d\eta)^{\alpha}$?

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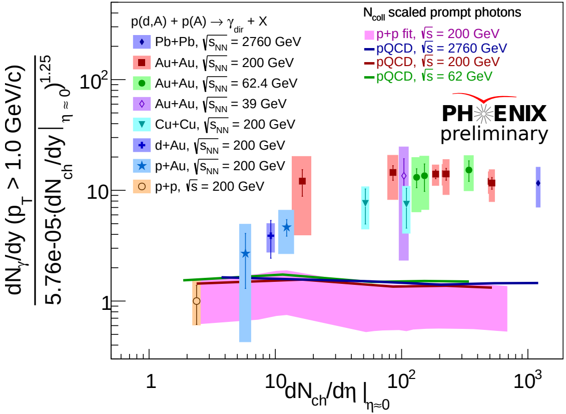

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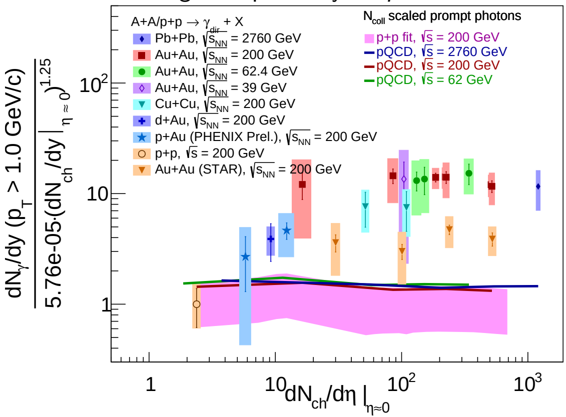
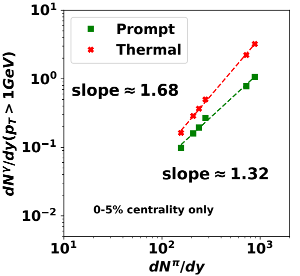
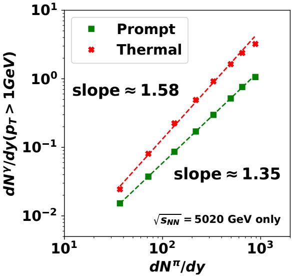


- Story not as clear, when looking at STAR data in addition
- Theoretically not easy to understand scaling across different $\sqrt{s_{NN}}$
- Prompt and thermal photons should scale with different slopes at one $\sqrt{s_{NN}}$
- Can we learn something about admixture from different p_T cuts?

Only very approximate!



Works!



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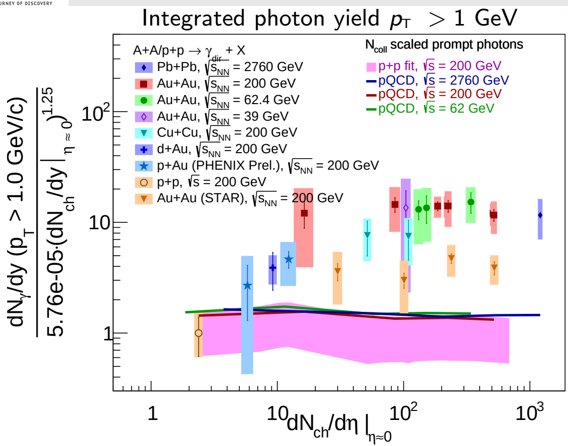

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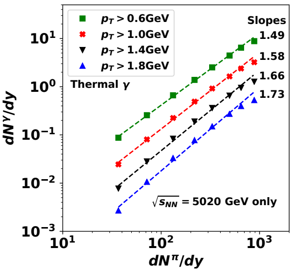
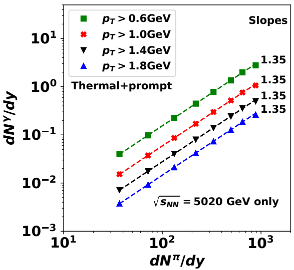
Prompt Photons

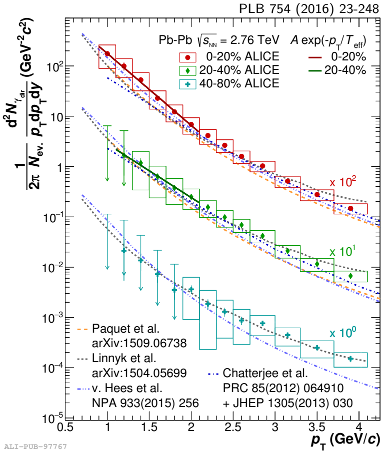


Thermal photons



Direct Photon Yield and Flow - At the LHC

- Central points for direct photon yield and $v_2^{\gamma,\mathrm{dir}}$ underestimated by most theoretical calculations by factors of 2-5



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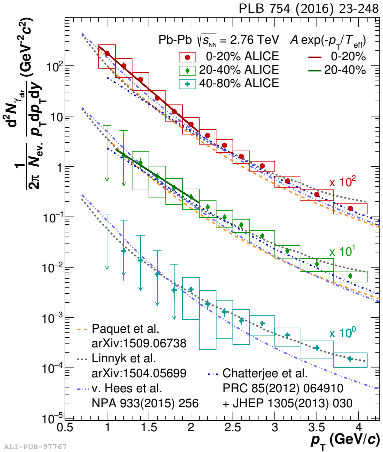
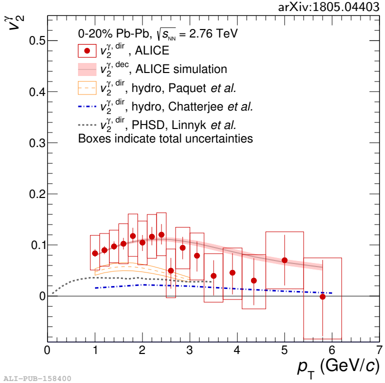
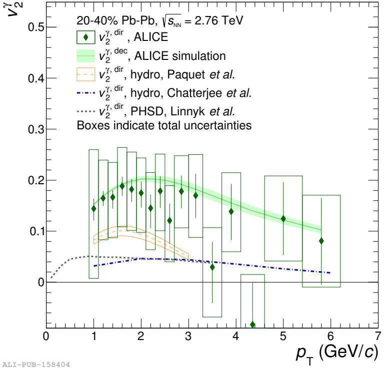


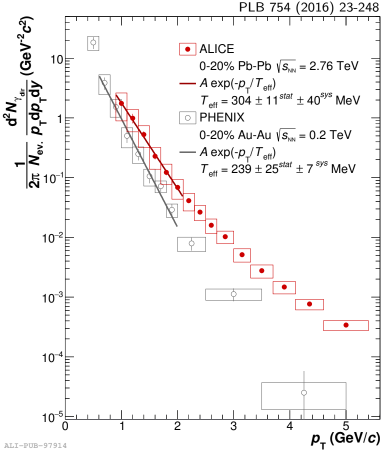


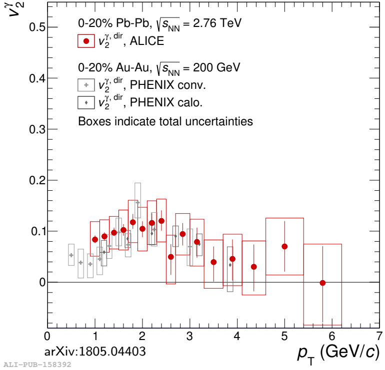


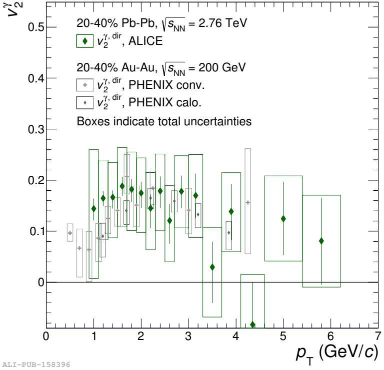
- **New:** $v_2^{\gamma,\mathrm{dir}}$ **compatible with** $v_2^{\gamma,\mathrm{dir}} = 0$ **within** $1.4(1.0)\sigma$ **in** p_T **range** $(0.9 < p_T < 2.1$ **GeV**$/c)$
- No deviation beyond 2σ from theory observed for spectra or v_2
- Similar observations for all theoretical calculations despite very different setups

Direct Photon Yield and Flow - Comparison to PHENIX

- Photon yield increased by $\approx$ factor 2 for $p_T < 3$ GeV/c
- T_{eff} appears to change







- v_2 at LHC compatible with v_2 measured at $\sqrt{s_{NN}} = 0.2$ TeV
- Similar scaling behavior of direct photon v_2 as for charged hadrons

$\Rightarrow$ Many photons produced in late stages of collision - HG-phase

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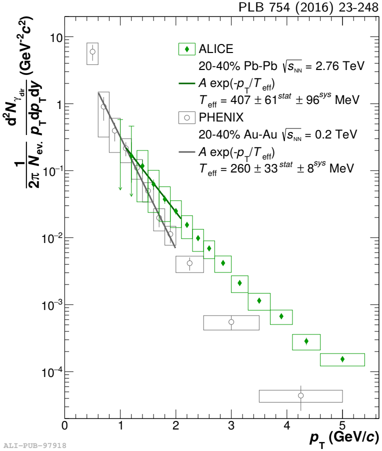

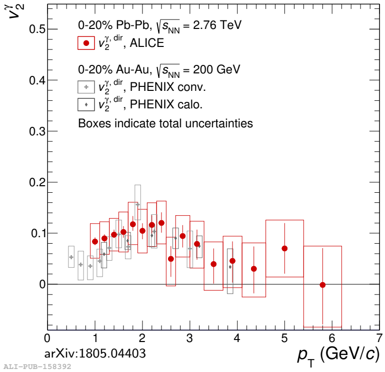

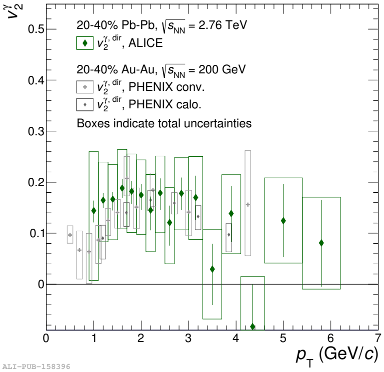

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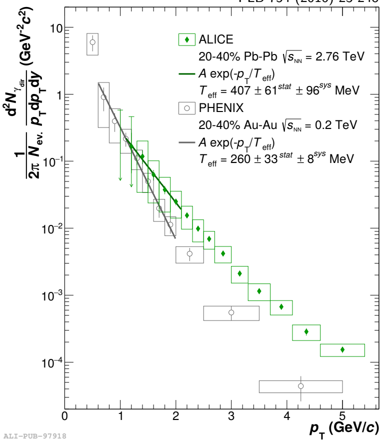
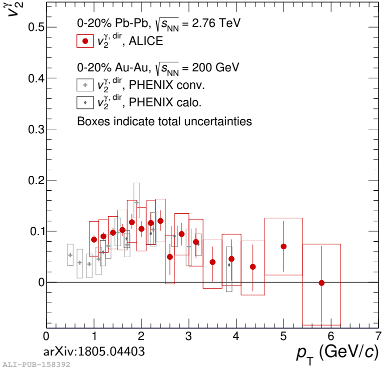
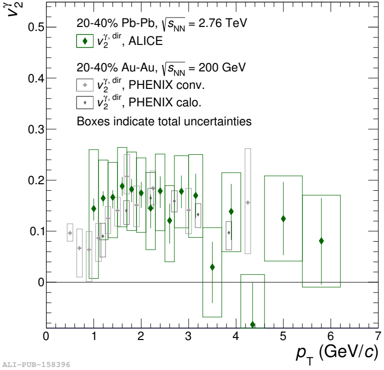
PLB 754 (2016) 23-248







- v_2 at LHC compatible with v_2 measured at $\sqrt{s_{NN}} = 0.2$ TeV
- Similar scaling behavior of direct photon v_2 as for charged hadrons

$\Rightarrow$ Many photons produced in late stages of collision - HG-phase

Is there a way to disentangle the contributions of the two phases at RHIC & LHC?

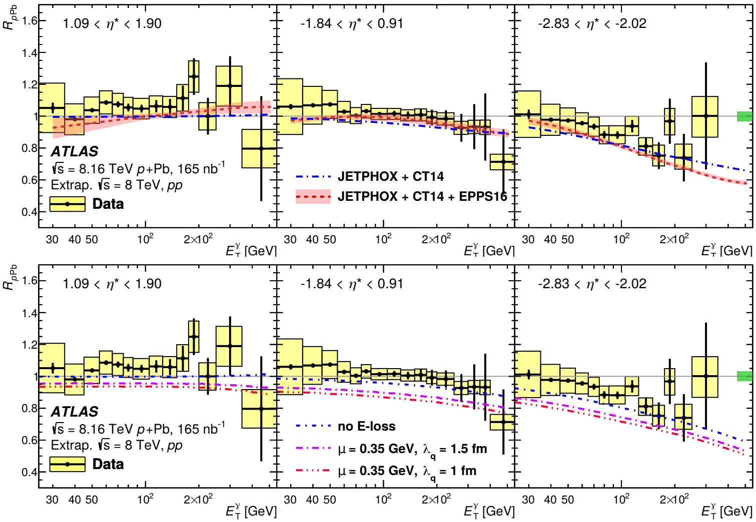
Photons as probes for the initial state & scaling properties

What can we learn about the scaling properties when going from pp $\rightarrow$ p-A $\rightarrow$ A-A from γ spectra?

Direct Photons in p–Pb at LHC at high p_T

Isolated direct photon measurement in p–Pb collisions at $\sqrt{s_{NN}} = 8$ TeV by ATLAS

- N_{coll} scaling works at mid rapidity
- Prompt photon production at large p_T in forward and backward region could constrain nPDFs & energy loss scenarios significantly
- Current precision not yet sufficient to do so
- Slight preference for no energy loss in p–Pb collisions

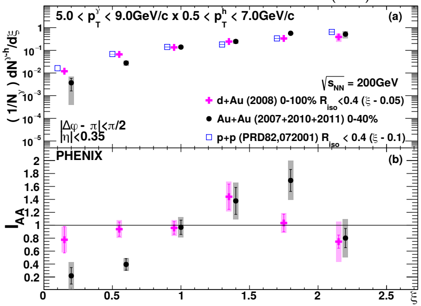


JHEP 10 (2019) 203

Isolated Photons as calibration & tagging objects for jet modification studies in p-A and A-A collisions

γ-h and γ-jet correlations in p(d)-A & A-A collisions

PRC 102 (2020) 054910



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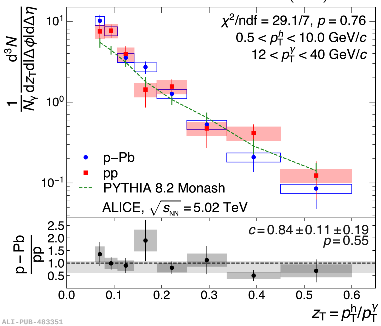
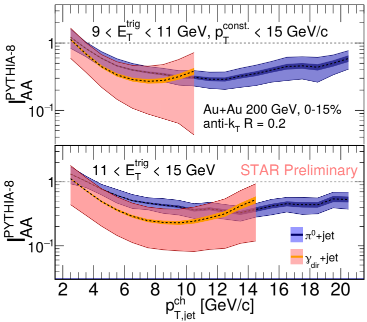
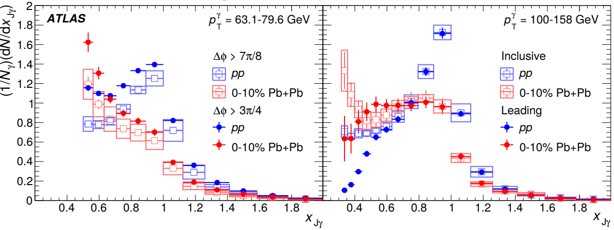




- **Base-line measurements in pp & p-Pb 5 TeV (ALICE)**
- Access to intermediate photon p_T triggered correlation (10-40 GeV/c) functions even @ LHC energies
- No significant modification of jet fragmentation observed in p-A collisions
- γ_{dir}+jet and π^0 +jet show similar level of suppression of recoil jet, stronger for $R = 0.2$ than for $R = 0.5$

Modification of jet properties in Pb-Pb collisions

Constraining quark-jet modification



γ+jet p_T-balance & γ-tagged jet FF

- pp-like peaked $x_{J\gamma}$ in peripheral Pb-Pb, smeared in central Pb-Pb

→ Variation in jet-by-jet E-loss

- γ-tagged jet frag. functions different modification in central evts. than inclusive jets

ξ_T^γ & gamma-tagged Jet shape

- Central PbPb collisions → enhancement of low-p_T part. and a depletion of high-p_T part. ξ_T^γ modified stronger compared to ξ_{jet}
- Larger enhancement at large r & Smaller depletion at intermediate r compared to di-jets

→ Increased quark fraction (70-80%)?

→ Lower jet p threshold (higher fraction of quenched jets)?

ATLAS: PLB 789 (2019) 167
CMS: PLB 785 (2018) 14, PRL 121, 242301 (2018)

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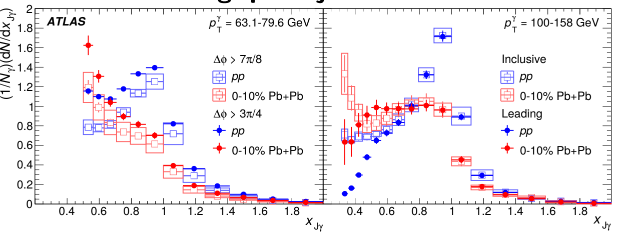

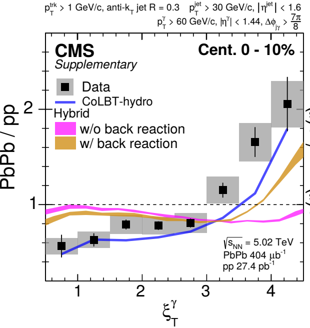

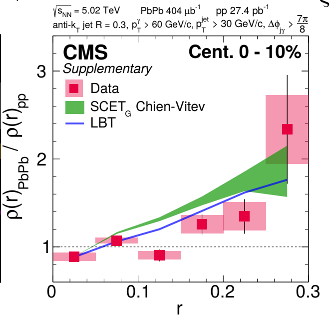

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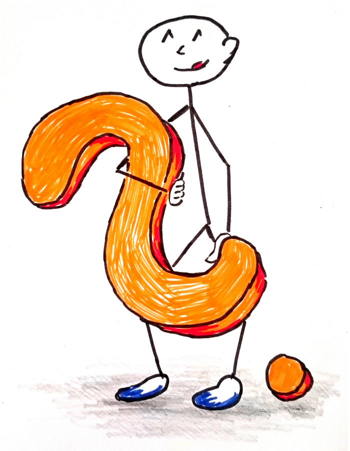
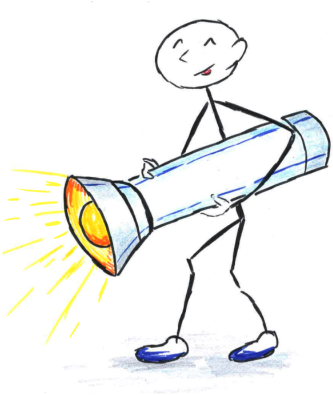
Thanks to all speakers & the organizers for making this conference possible!

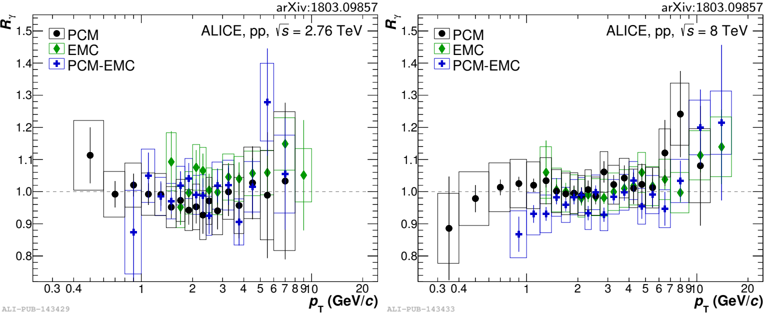
Questions?



BACKUP



Direct Photons in pp at LHC at low p_T



- Systematic uncertainties of individual meas.
  $\rightarrow$ dominated by p_T-independent material unc. of 4.5% PCM, 2.8% EMC & global E-scale unc. 3% PHOS
- Combination of 3 reconstruction techniques via BLUE method
- NLO prediction plotted as

$$R_{\mathrm{NLO}} = 1 + (\gamma_{\mathrm{dir}}^{\mathrm{NLO}} \cdot N_{\mathrm{Coll}})/\gamma_{\mathrm{dec}}$$

- Upper limits at 90% C.L. (arrows) determined where R_γ with total uncertainties consistent with unity

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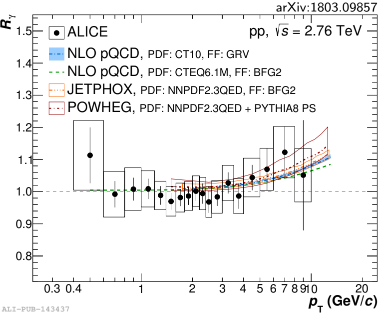

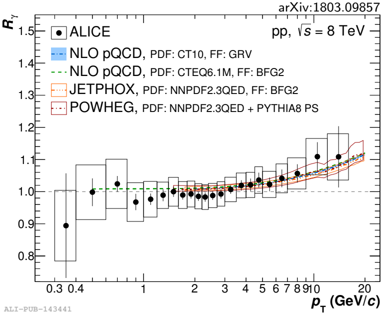

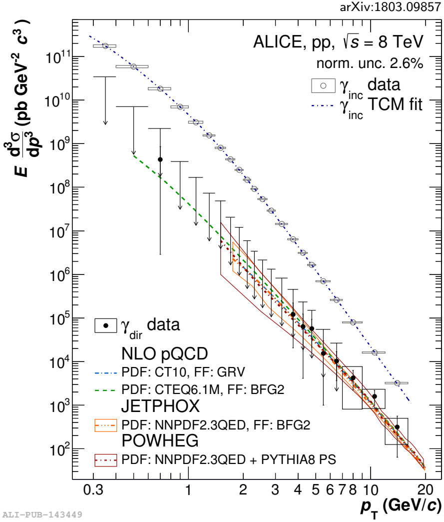

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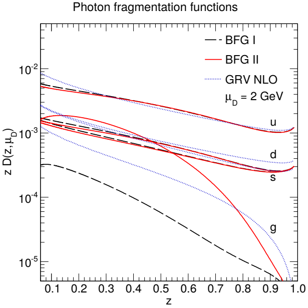
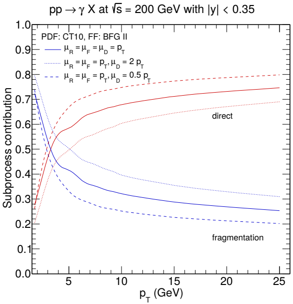
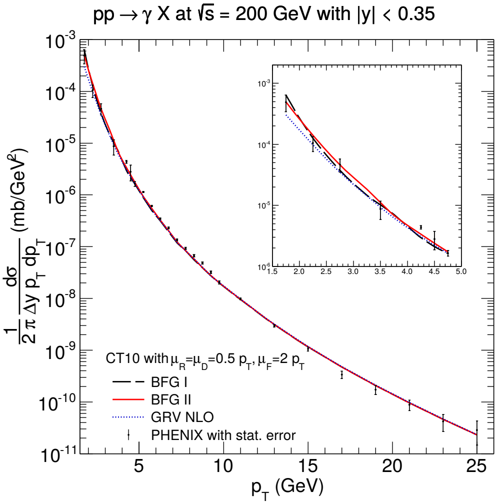
Constraints to FF from RHIC





arXiv:1403:2290

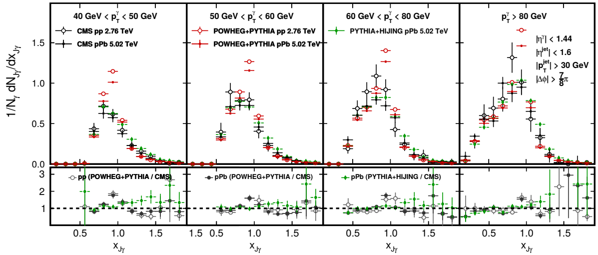


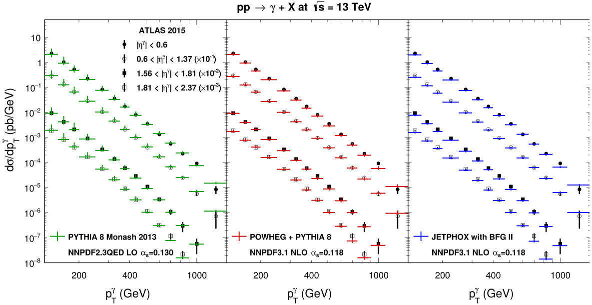
- pQCD calculation depend on fragmentation component
- High precision data from PHENIX further constrains FF
- Data favor BFG II FF over BFG I and GLV

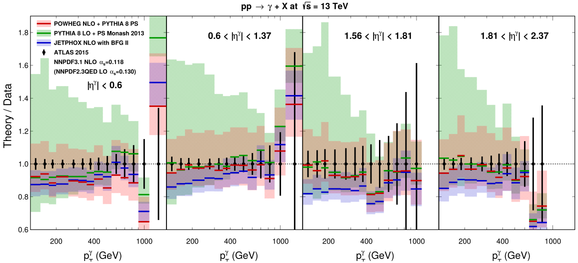
→ BFG II FF has largest gluon contribution

Direct Photons in pp at LHC at high p_T

arXiv:1709.04154







- More differential data available from ATLAS & CMS for inclusive direct photon production at 7,8 & 13 TeV (isolated)
- Reasonable agreement with different pQCD calculations & event generators
- New results on isolated γ + N jet production test pQCD up to $O(\alpha_{em}\alpha s^4)$

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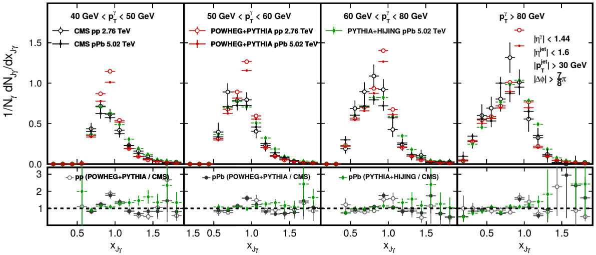
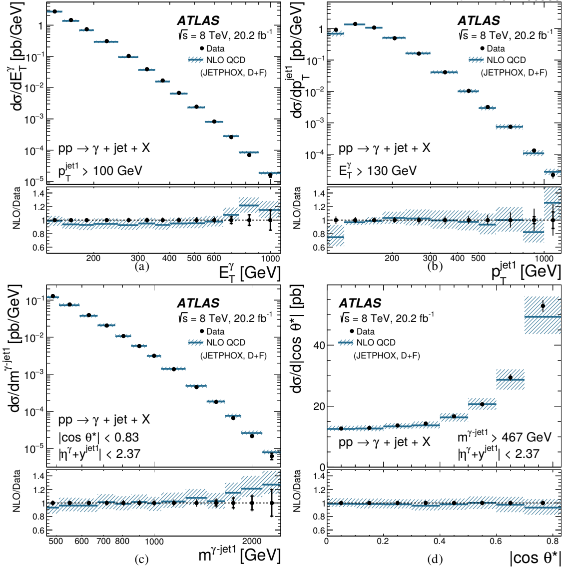
arXiv:1709.04154



arXiv:1611.06586



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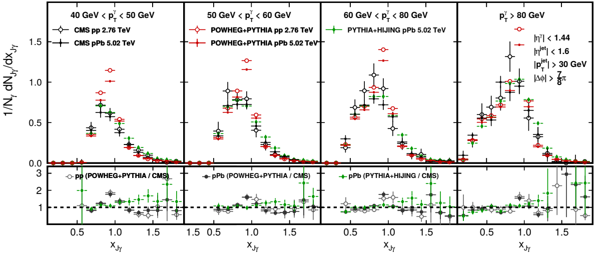

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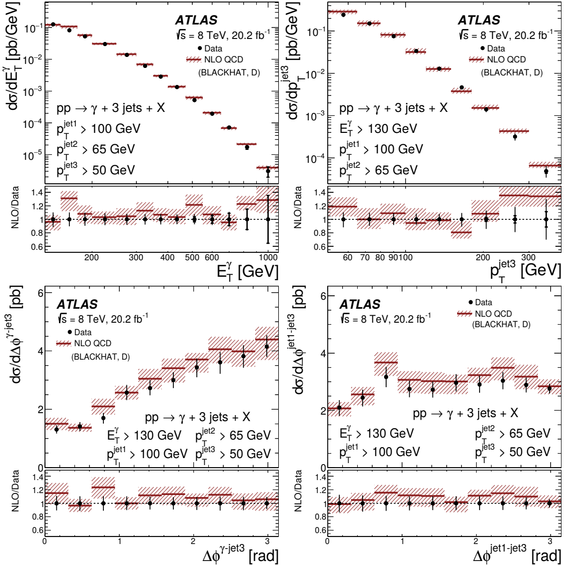

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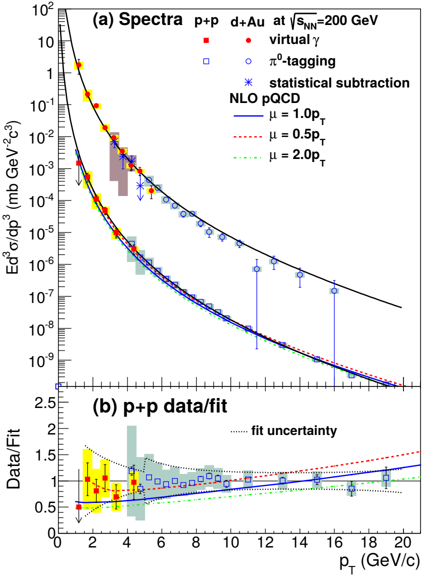
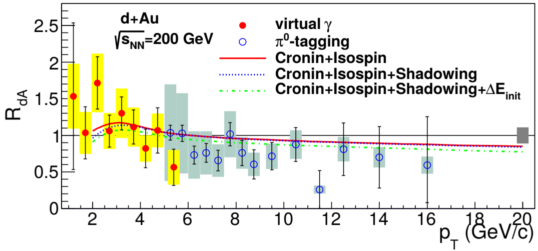
Direct Photons in d–Au at RHIC





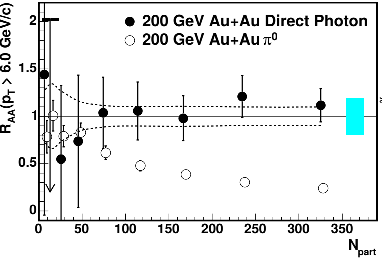
arXiv:1208.1234

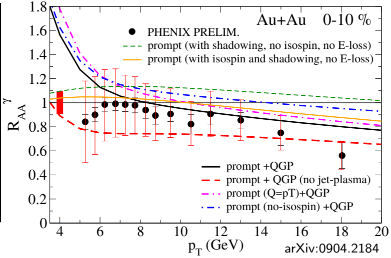
- Measured direct photon excess ratio in d–Au collisions at $\sqrt{s_{NN}} = 200$ GeV over wide p_T range
- Small hint at suppression at high p_T, statistical precision not sufficient

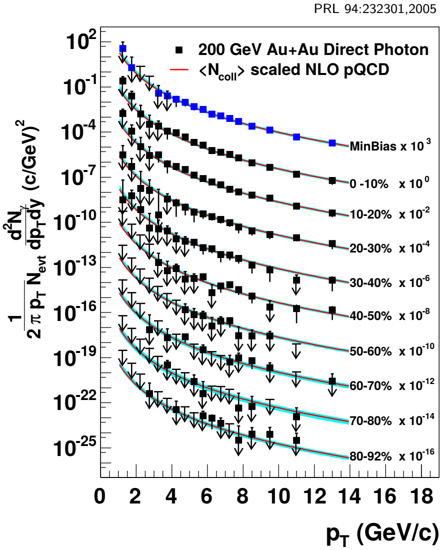
$\rightarrow$ R_{dA} slightly better described if Cronin, isospin and shadowing effect are included

- No significant low p_T R_{dA}

Direct Photon Spectra in Au–Au at RHIC - 200 GeV (I)



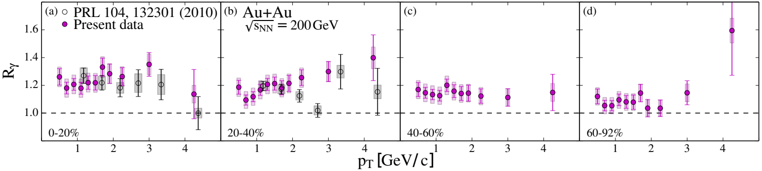


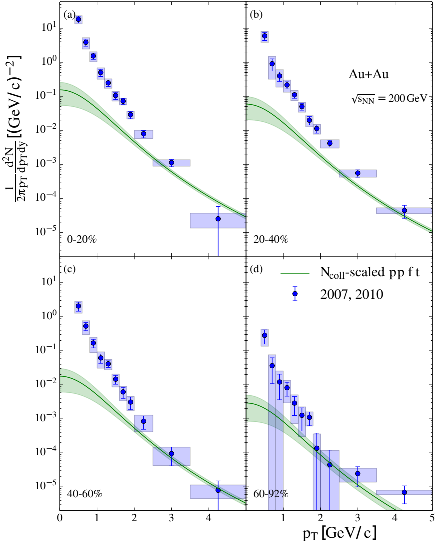


- High p_T γ_{dir} scale with N_{Coll}
- No indication of nuclear effects

$\Rightarrow$ **hadronic suppression = Final State Effect**

- Indication for relevance of photons from jet-plasma interactions for $p_T < 6$ GeV/c
- 20-30% reduction of direct photon R_{AA} expected due to energy loss





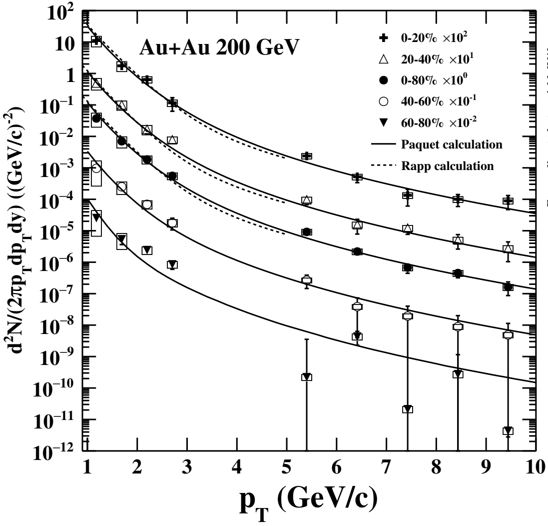
arXiv:1405.3940

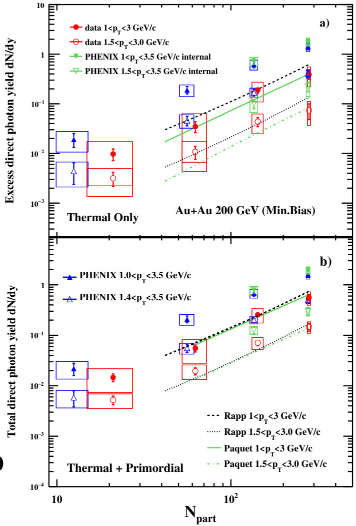
- Nearly no centrality dependence in R_γ, peripheral still $\sim 5\%$ excess, although not statistically significant anymore
- Excess $\approx 20\%$ in 0-20% Au–Au, systematic uncertainties O(5%)
- Strong excess above extrapolated pp measurement (green curve) seen in all centrality classes
- Slope of excess depends very little on centrality ($T_{eff} \approx 235 \pm 40$ MeV$/c$)

Direct Photon Spectra in Au-Au at RHIC - 200 GeV (III)

arXiv:1607.01447

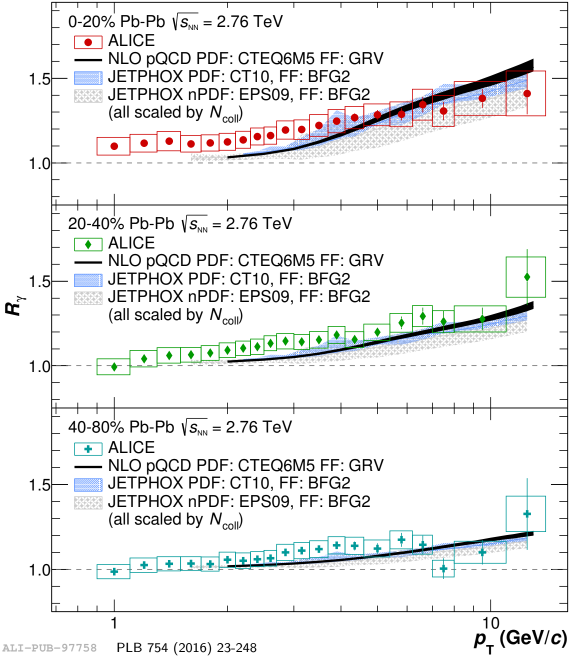
- Virtual direct photon spectrum measured by STAR at low p_T disagrees between 1-3 GeV/c by a factor 2
- BUT: Large syst. errors due to unmeasured eta contribution at low p_T





Direct Photons in Pb-Pb at LHC

- Direct photon excess measured with combined PCM + PHOS in 3 centrality classes with 2010 Pb–Pb data
- R_γ excess at high p_T for all centralities
- γ^{dec} suppressed by $\approx R_{AA}^{\pi^0}$
  $\rightarrow$ larger excess in central collisions
- Low p_T $\sim 15\%$ excess in $0-20\%$ and $\sim 9\%$ in $20-40\%$
- In agreement with NLO pQCD, JETPHOX above 5 GeV/c
- No low p_T excess seen in pp collisions at same center-of-mass energy
- Scaled pp spectrum & upper limits fully consistent with Pb–Pb results



PLB 754 (2016) 23-248

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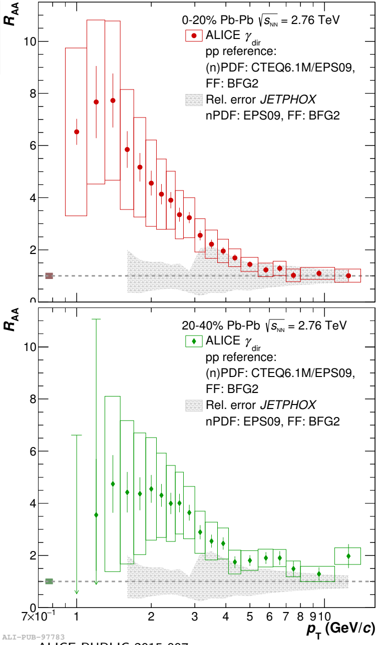

ALICE-PUBLIC-2015-007

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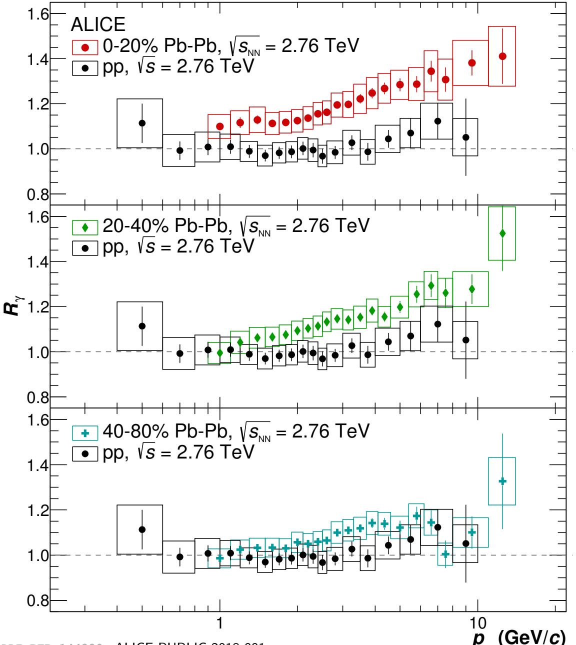

ALICE-PUBLIC-2018-001

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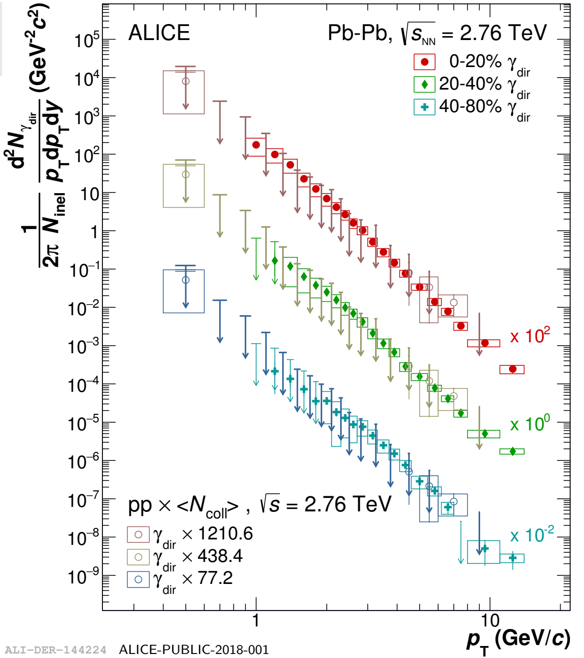
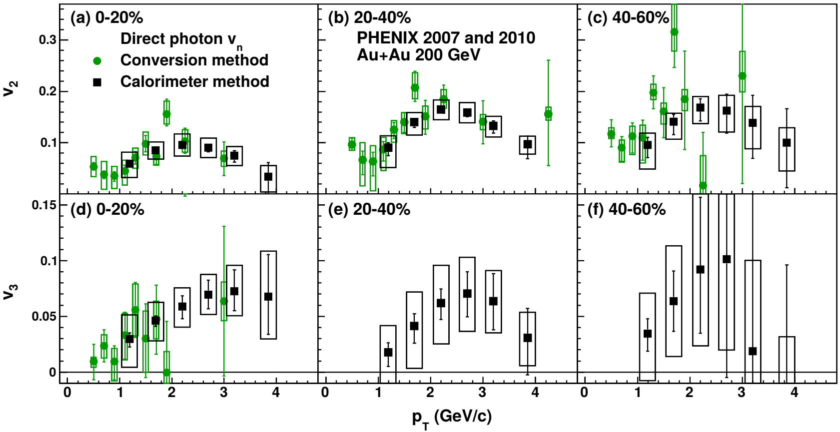


PHENIX Direct Photon ν_2/ν_3 Results - Au-Au

arXiv:1509.07758

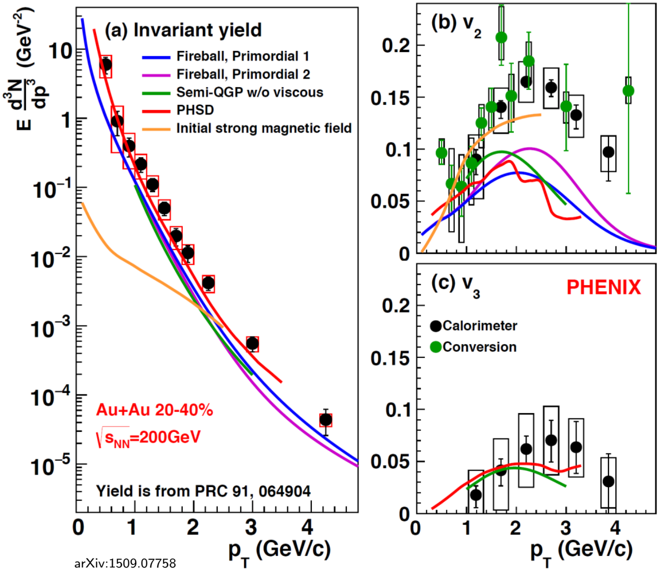


- Direct photon ν_2 & ν_3 comparable to that of other hadrons
- Two independent methods give comparable result
- Theory not able to reproduce large ν_2 and even less ν_3

Direct Photon Yield and Flow - At RHIC

- Large yield and large anisotropy have been observed in Au–Au at 200 GeV by PHENIX
- Challenge for theory to describe both measurements simultaneously
- Large yield from early emission?
- Large v_2 from late emission?

$\Rightarrow$ **Direct Photon Puzzle**



arXiv:1509.07758

Cocktail Simulation of Decay Photon v_2

Decay photon v_2:

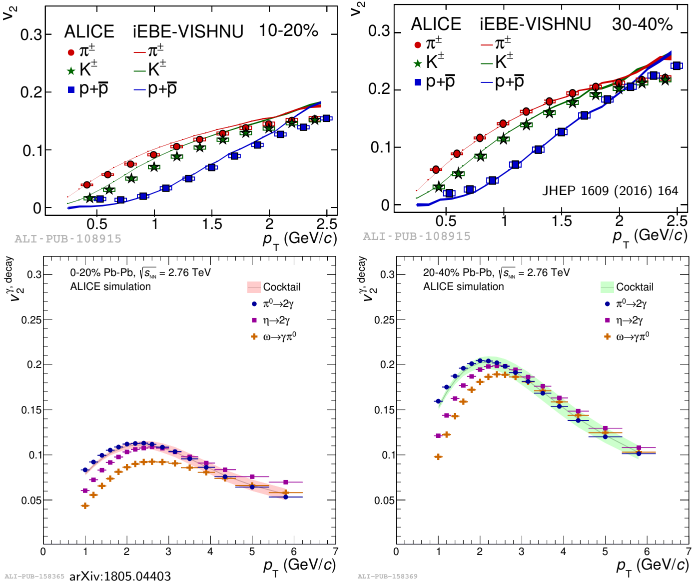
- KE_T scaling: v_2 of mesons scales with KE_T
  $KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$

$\Rightarrow$ $v_2^{\pi^0} \approx v_2^{\pi^\pm}$ $(m^{\pi^0} \approx m^{\pi^\pm})$

$\rightarrow$ v_2 of various mesons (X) calculated via KE_T (quark number) scaling from $v_2^{K^\pm}$

$$v_2^X(p_T^X) = v_2^{K^\pm}\left(\sqrt{(KE_T^X + m^{K^\pm})^2 - (m^{K^\pm})^2}\right)$$

- Decay photon v_2 from different mesons obtained from cocktail calculation



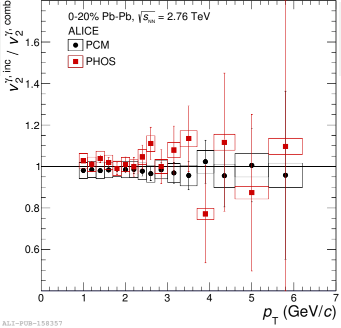
v_2^{γ} Inclusive and Decay

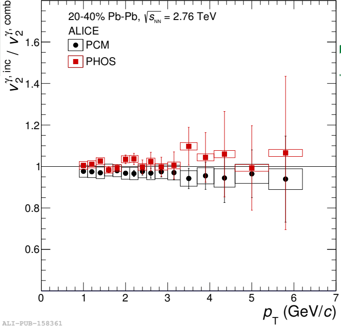
- $v_2^{\gamma,\mathrm{inc}}$ measured with PCM & PHOS

→ Corrected for BG flow from impurities
[JPG 44 (2917) no. 2, 025106]

→ Assumed to be independent

→ Consistent, p-values of
0.93 (0-20%) & 0.43 (20-40%)





arXiv:1805.04403

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[JPG 44 (2917) no. 2, 025106]

$\rightarrow$ Assumed to be independent

$\rightarrow$ Consistent, p-values of 0.93 (0-20%) & 0.43 (20-40%)

- **$\mathbf{p_T} < 3$ GeV/c: $v_2^{\gamma,\mathrm{inc}} = v_2^{\gamma,\mathrm{dec}}$**

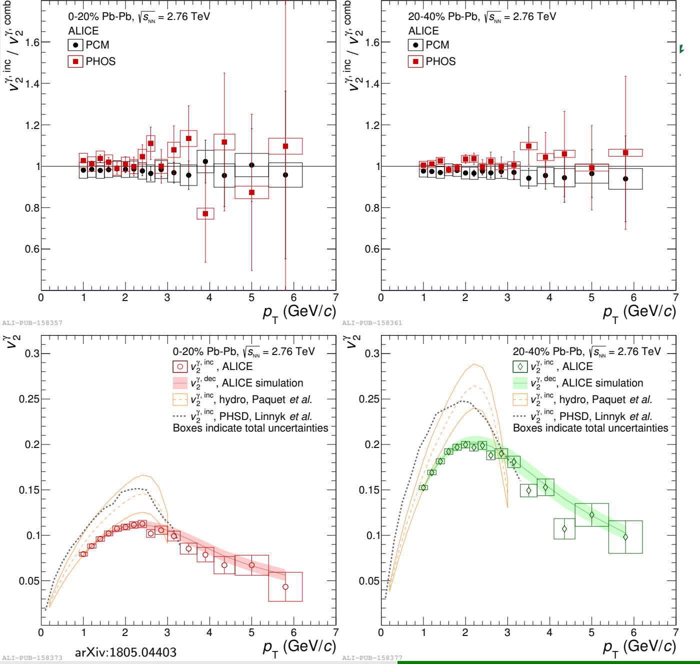
$\Rightarrow$ Either no contribution of γ_{dir} or $v_2^{\gamma,\mathrm{inc}} \approx v_2^{\gamma,\mathrm{dec}}$

$\rightarrow$ Theory $\sim 30 - 40\%$ too high

- **$\mathbf{p_T} > 3$ GeV/c: $v_2^{\gamma,\mathrm{inc}} < v_2^{\gamma,\mathrm{dec}}$**

$\rightarrow$ Direct photon v_2 contribution with $v_2^{\mathrm{direct}} < v_2^{\mathrm{decay}}$

$\rightarrow$ Mainly prompt photons



Direct Photon v_2 0-20 & 20-40 % Pb-Pb at LHC

Direct photon v_2:

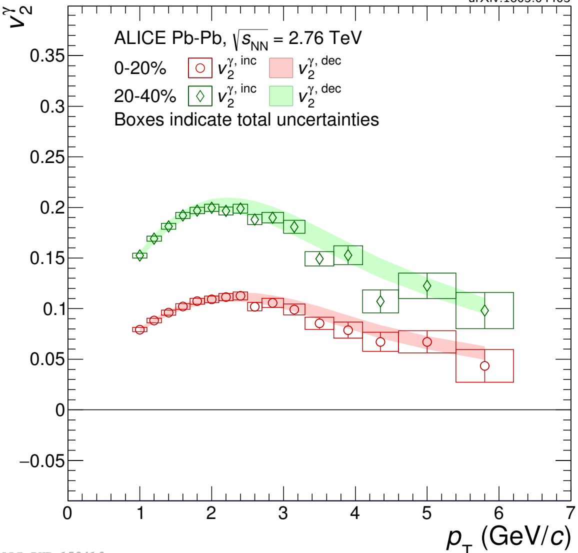
$$v_2^{\gamma,\mathrm{dir}} = \frac{R_\gamma \cdot v_2^{\gamma,\mathrm{inc}} - v_2^{\gamma,\mathrm{dec}}}{R_\gamma - 1}$$

- Measured R_γ often less than $2\sigma_{\mathrm{sys}}$ deviation from 1

⇒ Central value & unc. calculated using MC simulation following Bayesian approach with probability distributions of true values of $R^{\mathrm{t}}_\gamma(p_\mathrm{T})$, $v_2^{\gamma,\mathrm{dec,t}}(p_\mathrm{T})$, $v_2^{\gamma,\mathrm{inc,t}}(p_\mathrm{T})$ assuming R_γ can't be smaller unity & partially p_T correlated unc.

- Large direct photon v_2 for $p_\mathrm{T} < 3$ GeV/c measured
- Magnitude of $v_2^{\gamma,\mathrm{dir}}$ comparable to hadrons
- Result points to late production times of direct photons after flow is established

arXiv:1805.04403



ALI-PUB-158416

Direct Photon v_2 0-20 & 20-40 % Pb-Pb at LHC

Direct photon v_2:

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

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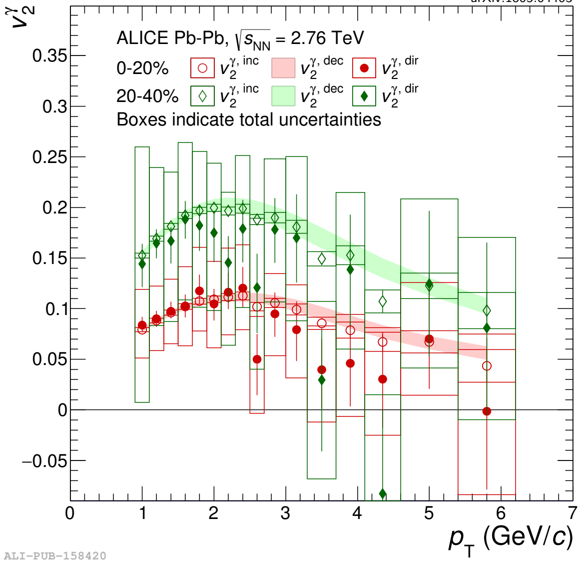

ALI-PUB-158420

Jet observables: a quick reminder

$$\xi^{jet} = \ln \frac{|\mathbf{p}^{jet}|^2}{\mathbf{p}^{track} \cdot \mathbf{p}^{jet}} \quad (1)$$

$$\xi_T^{\gamma} = \ln \frac{-|\mathbf{p}_T^{\gamma}|^2}{\mathbf{p}_T^{track} \cdot \mathbf{p}_T^{\gamma}} \quad (2)$$