Direct Photon Production and Flow at Low Transverse Momenta in pp, p-Pb and Pb-Pb Collisions

Friederike Bock for the ALICE Collaboration
CERN

Main Publications
arXiv:1803.09857
Poster ELW-23, Mike Sas - arXiv:1805.04403
Direct Photons in pp, p–Pb and Pb–Pb Collisions

\[ \gamma \text{ created during entire space time evolution after collision, leave medium unaffected} \]
\[ \Rightarrow \text{ideal probe} \]

**pp, p–Pb & Pb–Pb collisions**

**Prompt Photons**
- Calculable within NLO pQCD
- Test of binary scaling in p–Pb & Pb–Pb at high \( p_T \)
- Not affected by collective expansion

**Additional sources Pb–Pb (p–Pb, pp?) collisions**

**Thermal Photons**
- Scattering of thermalized particles
- Exponentially decreasing, dominant at low \( p_T \)
- Susceptible to flow evolution

**Jet-Medium Interactions**
- Scattering of hard partons with thermalized partons
- In-medium (photon) bremsstrahlung emitted by quarks
- Possibly affected by flow evolution

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Direct Photons at the LHC

May 14, 2018
Direct Photon Extraction

Subtraction Method:

\[ \gamma_{\text{direct}} = \gamma_{\text{inc}} - \gamma_{\text{decay}} = \left(1 - \frac{\gamma_{\text{decay}}}{\gamma_{\text{inc}}} \right) \cdot \gamma_{\text{inc}} \]

\[ = \left(1 - \frac{1}{R_{\gamma}} \right) \cdot \gamma_{\text{inc}} \]

- Inclusive photons: measure all photons that are produced
- Decay photons: calculated by decay simulation from measured or \( m_T \) scaled particle spectra

Double Ratio:

\[ R_{\gamma} = \frac{\gamma_{\text{inc}}}{\frac{\pi^0}{\pi^0_{\text{param}}} / \frac{\gamma_{\text{decay}}}{\pi^0}} \quad \text{if} \quad > 1 \text{ direct photon signal} \]

Numerator: Measured inclusive \( \gamma \) spectrum per \( \pi^0 \)
Denominator: Estimated sum of all decay photons per \( \pi^0 \)

→ advantage of ratio method: cancellation of some large uncertainties

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Double Ratio:

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\]

if > 1 direct photon signal

Numerator: Measured inclusive \(\gamma\) spectrum per \(\pi^0\)  Denominator: Estimated sum of all decay photons per \(\pi^0\)

→ advantage of ratio method: cancellation of some large uncertainties
Measuring Photons, $\pi^0$ and $\eta$ Mesons with ALICE

**Photon Conversion Method (PCM)**
- ITS and TPC
- $|\eta| < 0.9$, $0^\circ < \varphi < 360^\circ$
- conversion in detector material
  - $X/X_0 = (11.4 \pm 0.5\%)$
  - conv. probability $\sim 8\%$

**EMCal calorimeter**
- Pb/scintillator sampling calorimeter
- $|\eta| < 0.7$, $80^\circ < \varphi < 180^\circ$

**PHOS calorimeter**
- PbWO$_4$ crystals
- $|\eta| < 0.12$, $260^\circ < \varphi < 320^\circ$ (2009-2013)
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**EMCal**

**PCM**

**PHOS**

**arXiv:1801.07051**

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Systematic uncertainties of individual measurements dominated by $p_T$-independent material uncertainty of 4.5% PCM, 2.8% EMC & global E-scale uncertainty of 3% PHOS.

- $p_T$ reach:
  - $0.4 < p_T < 10$ GeV/$c$ in pp, $\sqrt{s} = 2.76$ TeV
  - $0.3 < p_T < 14$ GeV/$c$ in pp, $\sqrt{s} = 8$ TeV
  - $0.3 < p_T < 32$ GeV/$c$ in p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
Direct Photons in pp & p–Pb (1)

- Systematic uncertainties of individual meas. → dominated by $p_T$-independent material unc. of 4.5% PCM, 2.8% EMC & global E-scale unc. 3% PHOS
- $p_T$ reach
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  - $0.3 < p_T < 14$ GeV/$c$ in pp, $\sqrt{s} = 8$ TeV
  - $0.3 < p_T < 32$ GeV/$c$ in p–Pb $\sqrt{s_{NN}} = 5.02$ TeV
- Combination of 3 (4) reconstruction techniques via BLUE method
- NLO prediction plotted as $R_{NLO} = 1 + (\gamma_{NLO}^{dir} \cdot N_{Coll})/\gamma_{dec}$
- Within uncertainties no significant excess at low $p_T$ observed → supports interpretation in Pb–Pb as medium effects
- About $1 - 2\sigma$ deviation from unity for $p_T > 7$ GeV/$c$
Upper limits at 90% C.L. (arrows) determined where $R_γ$ with total uncertainties consistent with unity

NLO & thermal (Shen et al.) calculations consistent with measurements at all pp energies and for NSD p–Pb collisions

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

Shen et al. arXiv:1609.02590
Direct Photons in Pb-Pb

- Direct photon excess measured with combined PCM + PHOS in 3 centrality classes with 2010 Pb–Pb data
- \( R_{\gamma} \) excess at high \( p_T \) for all centralities
- \( \gamma^{\text{dec}} \) suppressed by \( \approx R_{\gamma}^{\pi^0} \)
  \( \rightarrow \) 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
Direct Photons in Pb-Pb

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Cocktail Simulation of Decay Photon $v_2$

Decay photon $v_2$:

- $KE_T$ scaling: $v_2$ of mesons scales with $KE_T$
  $KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$
  $\Rightarrow v_2^{\pi^0} \approx v_2^{\pi^\pm}$ ($m_{\pi^0} \approx m_{\pi^\pm}$)

- $v_2$ of various mesons ($X$) calculated via $KE_T$ (quark number) scaling from $v_2^{K^\pm}$
  $v_2^X(p_T^X) = v_2^{K^\pm}(\sqrt{(KE_T^X + m_{K^\pm})^2} - (m_{K^\pm})^2)$

- Decay photon $v_2$ from different mesons obtained from cocktail calculation
$\gamma^2$ Inclusive and Decay

- $\gamma^2,_{inc}$ 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%)
$v_2^{\gamma,\text{inc}}$ measured with PCM & PHOS

→ Corrected for BG flow from impurities

[arXiv:1805.04403]

→ Assumed to be independent

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

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

⇒ Either no contribution of $\gamma_{\text{dir}}$

or $v_2^{\gamma,\text{inc}} \approx v_2^{\gamma,\text{dec}}$

⇒ Theory $\sim 30 - 40\%$ too high

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

⇒ Direct photon $v_2$ contribution with $v_2^{\text{direct}} < v_2^{\text{decay}}$

⇒ Mainly prompt photons

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Direct Photons at the LHC

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Direct Photon $v_2$ 0-20 & 20-40

Direct photon $v_2$:

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

- Measured $R_\gamma$ often less than $2\sigma_{\text{sys}}$ deviation from 1
  - Central value & unc. calculated using MC simulation following Bayesian approach with probability distributions of true values of $R_\gamma^t(p_T)$, $v_2^{\gamma, \text{dec}, t}(p_T)$, $v_2^{\gamma, \text{inc}, t}(p_T)$ assuming $R_\gamma$ can’t be smaller unity & partially $p_T$ correlated unc.
- Large direct photon $v_2$ for $p_T < 3$ GeV/c measured
- Magnitude of $v_2^{\gamma, \text{dir}}$ comparable to hadrons
  - Result points to late production times of direct photons after flow is established

ALICE Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

0-20% $v_2^{\gamma, \text{inc}}$, $v_2^{\gamma, \text{dec}}$

20-40% $v_2^{\gamma, \text{inc}}$, $v_2^{\gamma, \text{dec}}$

Boxes indicate total uncertainties

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Direct Photon $v_2$ 0-20 & 20-40

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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- Large direct photon $v_2$ for $p_T < 3$ GeV/c measured
- Magnitude of $v_2^{\gamma,\text{dir}}$ comparable to hadrons
- Result points to late production times of direct photons after flow is established
Central points for direct photon yield and $n_{2, \gamma, dir}$ underestimated by most theoretical calculations by factors of 2-5
Central points for direct photon yield and $v_2^{\gamma,\text{dir}}$ underestimated by most theoretical calculations by factors of 2-5.

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

Plots and data from various sources, including ALICE simulation, Chatterjee et al., Paquet et al., Linnyk et al., and others, showing the observed direct photon yield and flow at different $p_T$ and centrality bins. Boxes indicate total uncertainties.
Direct Photon Yield and Flow - Comparison to PHENIX

- Photon yield increased by \( \approx \) factor 2 for \( p_T < 3 \text{ GeV}/c \)
- Larger \( T_{\text{eff}} \) for direct photons at LHC energies

\[ \gamma^2 v \]

Boxes indicate total uncertainties

0-20\% Pb-Pb, \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)

\[ v_2^{\gamma^2 v}, \text{ALICE} \]

0-20\% Au-Au, \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)

\[ v_2^{\gamma^2 v}, \text{PHENIX conv.} \]

\[ v_2^{\gamma^2 v}, \text{PHENIX calo.} \]

1. \( v_2 \) compatible with \( v_2 \) measured at \( \sqrt{s_{\text{NN}}} = 0.2 \text{ TeV} \)
2. Similar scaling behavior of direct photon \( v_2 \) as for charged hadrons
3. Larger significance for PHENIX result due to larger \( R_\gamma \) and larger significance of \( R_\gamma \) at \( \sqrt{s_{\text{NN}}} = 0.2 \text{ TeV} \)
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Summary

\[ \gamma_{\text{dir}} \text{ production in } pp \& p\text{Pb collisions:} \]
- First direct photon measurements at the LHC for pp and p–Pb collisions at low transverse momenta
- No significant direct photon excess observed in thermal photon region \((p_T < 3 \text{ GeV}/c)\)
- Consistent with NLO pQCD calculations at higher \(p_T\)

\[ \gamma_{\text{dir}} \text{ production and flow in Pb-Pb Collisions:} \]
- Direct photon excess for \(p_T < 3 \text{ GeV}/c\) observed with \(2.6\sigma\) for 0-20% and \(1.5\sigma\) in 20-40% consistent with theory expectations
- Spectrum consistent with NLO pQCD calculations at high \(p_T\)
- First direct photon flow measurement at the LHC with 2 independent reconstruction techniques in 0-20% and 20-40% Pb–Pb collisions
- Direct photon \(v_2\) in 0-20% & 20-40% of similar size as the charged hadron flow and inclusive photon flow, but compatible with 0 within \(1.4(1.0)\sigma\) in \(p_T\) range \((0.9 < p_T < 2.1 \text{ GeV}/c)\)
Backup Slides
Direct Photons in pp, p–Pb, Pb–Pb Collisions

\[ R_{pT} = \frac{N_{\gamma}}{N_{\pi^0}} \]

\( \gamma \) created during entire space time evolution after collision, leave medium unaffected
⇒ ideal probe

\[ pp, p–Pb & Pb–Pb \text{ collisions} \]

**Prompt Photons**
- Calculable within NLO pQCD
- Dominant at high \( p_T \)
- Test of binary scaling in Pb–Pb

**Additional sources Pb–Pb (p–Pb, pp?) collisions**

**Thermal Photons**
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Direct Photons at the LHC

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Initial azimuthal asymmetry in coordinate space in non-central A+A
\[ \Rightarrow \text{asymmetry in momentum space} \]

\[ \frac{dN}{d\phi} = \frac{1}{2\pi} \left( 1 + 2 \sum_{n \geq 1} v_n \cos(n(\varphi - \Psi_{n}^{RP})) \right) \]

- \( v_2 \): elliptic flow, collective expansion at low \( p_T \)
- \( v_3 \): triangular flow

**Thermal Photon \( v_2 \)**
- Constrains onset of direct photon production
  - Early production \( \rightarrow \) small \( v_2 \)
  - Late production \( \rightarrow \) hadron-like \( v_2 \)
Measuring photons, $\pi^0$ and $\eta$ Mesons in ALICE

THE ALICE DETECTOR

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Dipole Magnet
15. PMD
16. AD
17. ZDC
18. ACORDE
19. ITS SPD (Pixel)
20. ITS SDD (Drift)
21. ITS SSD (Strip)
22. V0 and T0
23. FMD

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Direct Photons at the LHC

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Closer Look at the Central Barrel - ITS and TPC

**Inner Tracking System - ITS**

- Full azimuth coverage, six cylindrical layers
- Three different detector types: silicon pixel / drift / stripes
- Designed for primary / secondary vertex finding (inner radius $R_{BP} = 2.94$ cm)
- Tracks charged particles down to $p_T = 100$ MeV/c

**Time Projection Chamber - TPC**

- Main tracking and PID detector
- Full azimuth coverage, $R = 84.8$ cm up to 246.6 cm
- Tracking: 100 MeV/c (primary) or 50 MeV/c (secondary) up to 100 GeV/c
**γ - Ray Tomography of ALICE**

- Cuts on the decay topology of photons and electron track properties
- Background is mainly combinatorial - Strange particle contribution negligible

Very useful tool to check the material budget:
- Effective radiation length: $X/X_0 = 0.114 \pm 0.005$ (\(|\eta| < 0.9, R < 180\ \text{cm}\))
- Final systematic error is $\sim 4.5\%$

Performance of the ALICE Experiment at the CERN LHC

arXiv:1402.4476 [nucl-ex]
Definition of Excess in Central Pb–Pb collisions

Experimental definition of Direct Photons:

- Every photon which is not directly produced by: $\pi^0$, $\eta$, $\omega$, $\eta'$, $\varphi$, $\rho^0$ and $\Sigma^0$
- Decay photons simulated via a cocktail calculation based on measured yield of $\pi^0$ (Pb–Pb, p-Pb, pp) and $\eta$ (p-Pb, pp), remaining spectra are obtained from $m_T$ scaling of measured $\pi^0$, K, p etc. (if not measured)

Experimental measurement of $\pi^0$:

- Published $\pi^0$ measurements contain feed-down from higher mass particles going to $\pi^0$, except $\pi^0$ from $K_s^0$
- Measured spectra are taken as input for cocktail calculation

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

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Direct Photons at the LHC

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Cocktail Generation

Decay photon spectra are obtained via calculation

- Based on a fit to measured $\pi^0$ (Pb–Pb, pp) and $\eta$ (pp)
- Other particle spectra obtained via $m_T$-scaling of measured $\pi^0$, K, p
- Incorporated mesons: $\pi^0$, $\eta$, $\eta'$, $\omega$, $\varphi$, $\rho^0$, $\rho^\pm$, $K_S^0$, $K_L^0$
- and baryons: $\Sigma^0$, $\Delta^0,+,\ldots$

$m_T$-Scaling:

Same shape of cross sections, $f(m_T)$, of various mesons

$E \frac{d^3\sigma}{dp_T^3} = C_m \cdot f(m_T)$

<table>
<thead>
<tr>
<th>Meson ($C_m$)</th>
<th>meas.</th>
<th>Mass</th>
<th>Decay Branch</th>
<th>B. Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>pp, p–Pb</td>
<td>134.98</td>
<td>$\gamma\gamma$</td>
<td>98.82%</td>
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<tr>
<td></td>
<td>Pb–Pb</td>
<td></td>
<td>$e^+ e^- \gamma$</td>
<td>1.174%</td>
</tr>
<tr>
<td>$\eta$</td>
<td>pp, p–Pb</td>
<td>547.3</td>
<td>$\gamma\gamma$</td>
<td>39.21%</td>
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<tr>
<td></td>
<td>Pb–Pb</td>
<td></td>
<td>$\pi^+ \pi^- \gamma$</td>
<td>4.22%</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$e^+ e^- \gamma$</td>
<td>0.69%</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>pp</td>
<td>770.0</td>
<td>$\pi^+ \pi^- \gamma$</td>
<td>0.99%</td>
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<td>$\pi^0 \gamma$</td>
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<td></td>
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<td>$\eta\gamma$</td>
<td>0.03%</td>
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<tr>
<td>$\rho^\pm$</td>
<td>(1.0)</td>
<td>775.49</td>
<td>$\pi^\pm \gamma$</td>
<td>0.045%</td>
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<tr>
<td>$\omega$</td>
<td>(0.9)</td>
<td>781.9</td>
<td>$\pi^0 \gamma$</td>
<td>8.5%</td>
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<td></td>
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<td></td>
<td>$\eta\gamma$</td>
<td>0.46%</td>
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<td>$\eta'$</td>
<td>957.8</td>
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<td>$\rho^0 \gamma$</td>
<td>29.08%</td>
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<td>$\omega \gamma$</td>
<td>2.75%</td>
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<td></td>
<td>$\gamma\gamma$</td>
<td>2.20%</td>
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<tr>
<td>$\varphi$</td>
<td>pp, p–Pb</td>
<td>1019.5</td>
<td>$\eta\gamma$</td>
<td>1.31%</td>
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<td></td>
<td>Pb–Pb</td>
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<td>$\pi^0 \gamma$</td>
<td>0.125%</td>
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<td></td>
<td></td>
<td></td>
<td>$\pi^\pm \gamma$</td>
<td>0.013%</td>
</tr>
<tr>
<td>$\Lambda$ (1.0)</td>
<td>1115.68</td>
<td>$\eta\gamma$</td>
<td>0.084%</td>
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<td>$\Sigma^0$ (1.0)</td>
<td>1192.6</td>
<td>$\Lambda\gamma$</td>
<td>100%</td>
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<td>$\Delta^0$ (1.0)</td>
<td>1232.0</td>
<td>$\eta\gamma$</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>$\Delta^+$ (1.0)</td>
<td>1232.0</td>
<td>$\eta\gamma$</td>
<td>0.6%</td>
<td></td>
</tr>
</tbody>
</table>

arXiv:1710.01933
Propagation and Correlation of Errors on the $R_\gamma$

- Measured $R_\gamma$ often less than $2\sigma_{\text{sys}}$ deviation from 1
- Gaussian error propagation only applicable if:
  a) Relation between observable and input observables is linear or
  b) Uncertainties sufficiently small

both conditions not fulfilled

Gaussian error propagation:

$$\frac{\partial v_n^{\gamma, \text{dir}}}{\partial R_\gamma} = \frac{v_n^{\gamma, \text{dec}} - v_n^{\gamma, \text{inc}}}{(R_\gamma - 1)^2}$$

- Central values and errors for $v_n^{\gamma, \text{dir}}(p_T)$ calculated using MC simulation following Bayesian approach with probability distributions of true values of $R_\gamma(p_T)$, $v_n^{\gamma, \text{dec},t}(p_T)$, $v_n^{\gamma, \text{inc},t}(p_T)$ assuming $R_\gamma$ can’t be smaller unity
- $p_T$ correlated uncertainty, like material budget (4.5%), complicates error propagation
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- Measured $R_γ$ often less than $2σ_{sys}$ deviation from 1
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- Both conditions not fulfilled

Gaussian error propagation:

$$\frac{\partial v_n^γ, \, \text{dir}}{\partial R_γ} = \frac{v_n^γ, \, \text{decay} - v_n^γ, \, \text{inc}}{(R_γ - 1)^2}$$

- Central values and errors for $v_n^γ, \, \text{dir}(p_T)$ calculated using MC simulation following Bayesian approach with probability distributions of true values of $R_γ^{t,\gamma}(p_T)$, $v_n^{γ,\text{dec,}t}(p_T)$, $v_n^{γ,\text{inc,}t}(p_T)$ assuming $R_γ$ can’t be smaller unity
- $p_T$ correlated uncertainty, like material budget (4.5%), complicates error propagation
Strong excess above extrapolated pp measurement (green curve) seen in all centrality classes

- Slope of excess depends very little on centrality ($T_{\text{eff}} \approx 235 \pm 40 \text{ MeV/c}$)

F. Bock (CERN)

Direct Photons at the LHC
Interlude: Situation at RHIC
Direct Photon Spectra

- Direct photon spectrum measured by STAR in MB (via virtual photons) disagrees between 1-3 GeV/c by a factor 2
- BUT: Large syst. errors due to unmeasured eta contribution at low $p_T$
Interlude: Situation at RHIC

PHENIX Direct Photon $\nu_2/\nu_3$ Results

- Direct photon $\nu_2$ & $\nu_3$ comparable to that of other hadrons
- Two independent methods give comparable result
- Theory not able to reproduce large $\nu_2$ and even less $\nu_3$