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

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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?
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 $p_T$

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New: First results on virtual photon measurement in pp collisions at 7 TeV & 13 TeV

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 $\gamma_{\text{dir}}$ for low $p_T$ @ LHC energies very challenging

@ RHIC energies possible for $p_T > 1.5 \text{ GeV/c}$
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Direct Photons in p–Au at RHIC at low $p_T$

**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

F. Bock (ORNL)
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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 $R_\gamma$ 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
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New ATLAS pPb 8.16 TeV publication
PLB 796 (2019) 230
Shen et al. arXiv:1609.02590
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: $A + A \rightarrow \gamma + X$ for $y = 0$
Direct Photon Spectra at RHIC - BES & Cu-Cu

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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?

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Central points for direct photon yield and $v_2^{\gamma, \text{dir}}$ underestimated by most theoretical calculations by factors of 2-5.
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New: $v_2^{\gamma,\text{dir}}$ compatible with $v_2^{\gamma,\text{dir}} = 0$ within 1.4(1.0)$\sigma$ in $p_T$ range ($0.9 < p_T < 2.1$ 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.
Photon yield increased by $\approx$ factor 2 for $p_T < 3$ GeV/$c$

$T_{\text{eff}}$ 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

⇒ Many photons produced in late stages of collision - HG-phase
Direct Photon Yield and Flow - Comparison to PHENIX

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\[ dN/dy \propto \frac{1}{2\pi N_{\text{ch}} p_T} \]

\[ \hat{v}_2 \text{ at LHC compatible with } \hat{v}_2 \text{ measured at } \sqrt{s_{NN}} = 0.2 \text{ TeV} \]
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**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 $\text{pp} \rightarrow \text{p-A} \rightarrow \text{A-A}$ from $\gamma$ spectra?
Isolated direct photon measurement in p–Pb collisions at $\sqrt{s_{NN}} = 8$ TeV by ATLAS

- $N_{\text{coll}}$ 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
Isolated Photons as calibration & tagging objects for jet modification studies in p-A and A-A collisions
- $\gamma$-h and $\gamma$-jet correlations in p(d)-A & A-A collisions

- **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
- $\gamma_{dir} + \text{jet}$ and $\pi^0 + \text{jet}$ 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

**$\gamma$+jet $p_T$-balance & $\gamma$-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
- $\gamma$-tagged jet frag. functions different modification in central evts. than inclusive jets

**$\xi_T$ & gamma-tagged Jet shape**
- Central PbPb collisions $\rightarrow$ enhancement of low-$p_T$ part. and a depletion of high-$p_T$ part. $\xi_T^\gamma$ modified stronger compared to $\xi_{jet}$
- 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)?
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& gamma-tagged Jet shape from CMS

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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.
  - 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
  $$ R_{\text{NLO}} = 1 + \left( \gamma_{\text{dir}}^{\text{NLO}} \cdot N_{\text{Coll}} \right) / \gamma_{\text{dec}} $$
- Upper limits at 90% C.L. (arrows) determined where $R_\gamma$ with total uncertainties consistent with unity
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Constraints to FF from RHIC

- 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

\[
\frac{1}{2\pi\Delta y} \frac{d\sigma}{dp_T}
\]
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 $\gamma + N$ jet production test pQCD up to $O(\alpha_{em}^4)$
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Measured direct photon excess ratio in d–Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) over wide \( p_T \) range

- Small hint at suppression at high \( p_T \), statistical precision not sufficient

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

- No significant low \( p_T \) \( R_{dA} \)

\[ \text{Data/Fit} \]

\[ \gamma_{\text{virtual}} \text{-tagging} \]

\[ \pi^0 \text{-tagging} \]

\[ \text{statistical subtraction} \]

\[ \text{NLO pQCD} \]

\[ \mu = 1.0p_T \]

\[ \mu = 0.5p_T \]

\[ \mu = 2.0p_T \]

\[ \text{initE} \Delta \text{Cronin+Isospin+Shadowing} \]

\[ \text{d+Au} = 200 \text{ GeVNNs} \]

\[ \text{dAR} \]

\[ \text{γ}_{\text{virtual}} \text{-tagging} \]

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\[ \text{Cronin+Isospin} \]

\[ \text{Cronin+Isospin+Shadowing} \]

\[ \text{Cronin+Isospin+Shadowing+ΔE} \text{init} \]

\[ \text{(GeV/c)} \]

\[ T_p \]

\[ 0 2 4 6 8 10 12 14 16 18 20 \]

\[ 0 0.5 1 1.5 2 \]

\[ \text{fit uncertainty} \]

\[ \text{(b) p+p data/fit} \]
High $p_T \gamma_{dir}$ 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 $p_T < 6 \text{ GeV/c}$

- 20-30% reduction of direct photon $R_{AA}$ expected due to energy loss
Nearly no centrality dependence in $R_\gamma$, 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 ($T_{\text{eff}} \approx 235 \pm 40$ MeV/c)
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 Photon Excess in Pb-Pb at LHC

- 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 $\approx R_{\text{AA}}^\pi^0$ → 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
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- 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 $\nu_3$
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?

⇒ Direct Photon Puzzle
Cocktail Simulation of Decay Photon $v_2$

Decay photon $v_2$:

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

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

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

- Decay photon $v_2$ from different mesons obtained from cocktail calculation
\( \nu_2^{\gamma,\text{inc}} \) measured with PCM & PHOS

→ Corrected for BG flow from impurities

[\text{JPFG 44 (2917) no. 2, 025106}]

→ Assumed to be independent

→ Consistent, \( p \)-values of 0.93 (0-20%) & 0.43 (20-40%)
$\nu_2^\gamma$ Inclusive and Decay

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  - Corrected for BG flow from impurities
  - Assumed to be independent
  - Consistent, $p$-values of 0.93 (0-20%) & 0.43 (20-40%)

- $p_T < 3 \text{ GeV}/c$: $\nu_2^\gamma,\text{inc} = \nu_2^\gamma,\text{dec}$
  - Either no contribution of $\gamma_{\text{dir}}$
  - or $\nu_2^\gamma,\text{inc} \approx \nu_2^\gamma,\text{dec}$
  - Theory $\sim 30 - 40\%$ too high

- $p_T > 3 \text{ GeV}/c$: $\nu_2^\gamma,\text{inc} < \nu_2^\gamma,\text{dec}$
  - Direct photon $\nu_2$ contribution with $\nu_2^{\text{direct}} < \nu_2^{\text{decay}}$
  - Mainly prompt photons
Direct Photon $v_2$ 0-20 & 20-40 % Pb-Pb at LHC

**Direct photon $v_2$:**

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

- 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
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Jet observables: a quick reminder

\[ \xi^{\text{jet}} = \ln \frac{|p^{\text{jet}}|^2}{p^{\text{track}} \cdot p^{\text{jet}}} \] (1)

\[ \xi^{\gamma}_{T} = \ln \frac{-|p^{\gamma}_{T}|^2}{p^{\text{track}}_{T} \cdot p^{\gamma}_{T}} \] (2)