Probing heavy ion collisions with photons at low and high $\sqrt{s_{NN}}$
Photons as probes of the plasma

- Temperature in GeV

**Central Pb-Pb**

Electromagnetic probes (along with jet energy loss, heavy quarks, ...):

- More direct probes of the hot early plasma

As opposed to **soft hadron** observables:

- Indirect probes of the hot plasma
Sources of photons in heavy ion collisions

Dominant sources of photons (excluding hadronic decays):
- prompt & thermal photons

**Prompt photons**
- Produced in initial hard nucleon collisions

\[
\frac{dN_\gamma}{d^3p} = \frac{N_{binary}}{\sigma_{pp}^{inel}} f_{a/A} \otimes f_{b/B} \otimes d\hat{\sigma}_{ab \to \gamma/c + d} \otimes D_{\gamma/c}
\]

**Thermal photons**
- Radiated by the hot plasma

\[
\frac{dN_\gamma}{d^3p} = \int d^4X \frac{d\Gamma_\gamma}{d^3p} (p, T(X), u^\mu(X), ...)
\]

Temperature [in GeV] and flow velocity profile

Photon emission rate (per volume) for hot QCD plasma

Spacetime profile of plasma from hydrodynamic simulation
Differential spectra & $v_2$ at LHC & top RHIC $\sqrt{s_{NN}}$

**RHIC**
$\sqrt{s_{NN}} = 200$ GeV

**LHC**
$\sqrt{s_{NN}} = 2760$ GeV

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.
Photons in the RHIC beam energy scan

Energy deposited over extended time period at lower $\sqrt{s_{NN}}$

RHIC $\sqrt{s_{NN}}$=19.6 GeV

Photons sensitive to initial energy deposition

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

Ref.: Schenke and Shen, PRC 97 (2018)
Looking at the same data in a different light

Centrality & $\sqrt{S_{NN}}$ dependence?
Use $p_T$-integrated observables
(e.g. photon multiplicity)

Can use different lower $p_T$ cut-offs

Jean-François Paquet (Duke)
Centrality and $\sqrt{s_{NN}}$ dependence of photon production

**Photon multiplicity** (above $p_T$ cutoff) vs proxy for centrality and $\sqrt{s_{NN}}$ (e.g. hadron multiplicity, $N_{part}$)

[fixed & very low cut-off for hadron multiplicity]

**PHENIX PRC 91 (2015)**

$\sqrt{s_{NN}} = 200$ GeV

**PHENIX 2015:**

$$\log \left( N_{pT>cutoff}^\gamma \right) \sim \text{slope}(p_T^{cutoff}) \log(N_{part})$$

**PHENIX 2018 [arXiv:1805.04084]**

**PHENIX 2018:**

$$\log \left( N_{pT>1 \text{ GeV}}^\gamma \right) \sim 1.25 \log(N_{h^\pm})$$

Jean-François Paquet (Duke)
Photons across centralities and $\sqrt{s_{NN}}$

**Prompt photons**

$$\frac{dN_\gamma}{d^3 k} = \frac{N_{\text{binary}}}{\sigma_{pp}^{\text{inel}}} \cdot f_{a/A} \otimes f_{b/B} \otimes d\hat{\sigma}_{ab \rightarrow \gamma/c} + a \otimes D_{\gamma/c}$$

- Scale with the number of binary collisions
- Depends on $\sqrt{s_{NN}}$ through $N_{\text{binary}}$, $\sigma_{pp}^{\text{inel}}$ and $f \otimes f \otimes d\hat{\sigma} \otimes D$

**Thermal photons**

$$\frac{dN_\gamma}{d^3 p} = \int d^4 X \frac{d\Gamma_\gamma}{d^3 p} (k, T(X), u^\mu(X), \ldots)$$

- Different $\sqrt{s_{NN}}$ & centrality $\Rightarrow$ different temperature and flow velocity profiles

**Spacetime profile of plasma from hydrodynamic simulation**

Ref.: QM2017 proceedings [1704.07842]
Varying $\sqrt{s_{NN}}$ at fixed centrality

$\log\left(\frac{N_Y^{p_T > p_T^{\text{min}}}}{p_T^{\text{min}}}\right) \sim \text{slope}(p_T^{\text{min}}) \log(N_\pi)$

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.
\[
\sqrt{s_{NN}} \text{ dependence}
\]

Preliminary results

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

\[
\log \left( N_{p_T>p_T^{\text{min}}}^{\gamma} \right) \sim \text{slope} \left( p_T^{\text{min}} \right) \log(N^{\pi})
\]

Varying centrality at fixed \( \sqrt{s_{NN}} \)

Varying \( \sqrt{s_{NN}} \) at fixed centrality

Jean-François Paquet (Duke)
\( \sqrt{s_{NN}} \) dependence

**Prompt photons**

\[
\frac{dN_{\gamma}}{d^3p} = \frac{N_{binary}}{\sigma_{pp}^{inel}} f_{a/A} \otimes f_{b/B} \otimes d\hat{\sigma}_{ab \rightarrow \gamma/c} + d[\otimes D_{\gamma/c}]
\]

**Fixed centrality:**

\[
\log \left( \frac{N_{\gamma}^{p_T>p_T^{min}}}{N_{binary}} \right) = \log(N_{binary}) + \log(pQCD) \\
\approx 1.35 \log(N^{\pi}) + \log(pQCD)
\]

Careful with low \( p_T \) prompt photon calculations (large uncertainty)

Centrality dependence under better control

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

Preliminary results
Photon vs pion multiplicity using **centrality**

**Thermal photons**

\[ p_T > p_T^{\text{min}} \]

**Prompt photons**

**Preliminary results**

Simple test: \( p_T \) cut-off dependence for thermal photons, **NOT** for prompt
Photon vs \( N_{part} \) using centrality

What does the data say?

\[ \sqrt{s_{NN}} = 200 \text{ GeV}; \ p_T > p_T^{\text{min}} \]

Ref.: PHENIX PRC 91 (2015)

<table>
<thead>
<tr>
<th>( p_T^{\text{min}} ) (GeV/c)</th>
<th>Slopes vs ( N_{part} )</th>
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<tr>
<td>0.4</td>
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Note: STAR also has data [PRB 770 (2017) 451] but uncertainties too large
Photon vs pion multiplicity using centrality

What does the data say?
Few centralities and large uncertainties but little sign of $p_T$ dependence

$\sqrt{S_{NN}} = 200$ GeV; $p_T > p_T^{\text{min}}$

$\sqrt{S_{NN}} = 200$ GeV only

Thermal

Slopes

$\frac{dN}{dy}$

10

100

1

0.1

10

$N_{\text{part}}$

10

100

1000

$\sqrt{S_{NN}} = 200$ GeV only

Note: STAR also has data [PRB 770 (2017) 451] but uncertainties too large

Ref.: PHENIX PRC 91 (2015)

Preliminary results
Summary & outlook

- Realistic calculation of photon production across wide range of centrality/\(\sqrt{S_{NN}}\)
- Photon multiplicity vs centrality/\(\sqrt{S_{NN}}\) can provide additional insights
  - Prediction for centrality dependence cleaner and more robust
  - Prediction for \(\sqrt{S_{NN}}\) difficult because of prompt photons

Jet-medium photons: include medium effects to improve prompt photons

Calculate centrality dependence of other production mechanisms
Ref.: Charles Gale, Sangyong Jeon, Scott McDonald (McGill), Jean-François Paquet (Duke) & Chun Shen (Wayne State/RIKEN BNL), in preparation

Questions?
Backup slides
**Thermal EM probes: thermal rate**

\[
\frac{d^4 N_{\gamma^+/\gamma^-}}{d^4 k} = \int d^4 X \frac{d^4 \Gamma_{\gamma^+/\gamma^-}}{d^4 k} (K^\mu, u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X))
\]

**Gas of hadrons:** ~100 MeV

**Deconfinement:** ~160 MeV

**Max T at RHIC:** ~400 MeV

**Max T at LHC:** ~600 MeV

**Effective hadronic models**
- Texas A&M/McGill rates; Stony Brook rates; ...

**AdS/CFT and other holography**

**Effective QCD models**
- Caron-Huot et al (AdS/CFT); Finazzo and Rougemont (bottom-up holography); BNL et al (semi-QGP), ...

**Perturbative QCD**
- Arnold, Moore, Yaffe (AMY); Ghiglieri, Teaney; Laine, ...

**Toward asymptotic QGP**

QM2017
Photon vs pion multiplicity using $\sqrt{s_{NN}}$

0 – 5% centrality; $p_T > p_T^{\text{min}}$

Thermal photons

- $p_T > 0.6\text{GeV}$
- $p_T > 1.0\text{GeV}$
- $p_T > 1.4\text{GeV}$
- $p_T > 1.8\text{GeV}$

Slopes:
- Thermal $\gamma$: 1.41, 1.68, 1.97, 2.28

Prompt photons

- $p_T > 0.6\text{GeV}$
- $p_T > 1.0\text{GeV}$
- $p_T > 1.4\text{GeV}$
- $p_T > 1.8\text{GeV}$

Slopes:
- Prompt $\gamma$: 0.47, 1.32, 1.85, 2.36

Difficult to draw conclusion from slope
Thermal photons

Preliminary results

Sqrt(s)

Centrality

\sqrt{s_{NN}} = 5020\text{ GeV only}
Prompt photons

Preliminary results

\[ \text{Sqrt}(s) \]

Centrality

\[ \frac{dN}{dy} \]

\[ \frac{dN^{\pi}}{dy} \]

Prompt \( \gamma \)

\[ p_T > 0.6\text{GeV} \]
\[ p_T > 1.0\text{GeV} \]
\[ p_T > 1.4\text{GeV} \]
\[ p_T > 1.8\text{GeV} \]

Slopes

0 – 5% centrality only

\[ \sqrt{s_{NN}} = 5020 \text{ GeV only} \]
\[ \sqrt{s_{NN}} \text{ dependence} \]

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

Preliminary results

\[ \sqrt{s_{NN}} = 5020 \text{ GeV} \]

Careful with low \( p_T \) prompt photon calculations (large uncertainty)

Centrality dependence under better control

Jean-François Paquet (Duke)
Centrality and $\sqrt{s_{NN}}$ dependence of photon production

**Photon multiplicity** (above $p_T$ cutoff) 
**vs hadron multiplicity** (proxy for centrality and $\sqrt{s_{NN}}$)

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

RHIC $\sqrt{s_{NN}}$=19.6, 39, 62.4 & 200 GeV; 
LHC $\sqrt{s_{NN}}$=2760 & 5020 GeV

$$\log \left( \frac{N^\gamma}{p_T > 1 \text{ GeV}} \right) \sim \text{slope} \log (N^\pi)$$
Centrality & $\sqrt{s_{NN}}$ dependence of photon production

Photon multiplicity (above $p_T$ cutoff) vs hadron multiplicity (proxy for centrality & $\sqrt{s_{NN}}$)
[fixed & very low cut-off for hadron multiplicity]

PHENIX 2018 [arXiv:1805.04084]

PHENIX:
Measured photon multiplicity in Pb+Pb, Au+Au and Cu+Cu has slope 
$\sim 1.25$ vs charged hadron multiplicity

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.
Photon vs pion multiplicity using centrality

What does the data say?
(few centralities and large uncertainties)

$\sqrt{s_{NN}} = 200 \text{ GeV}; \ p_T > p_T^{\text{min}}$

Note: STAR also has data [PRB 770 (2017) 451] but uncertainties too large

Ref.: PHENIX PRC 91 (2015)
Photon vs pion multiplicity using centrality

What does the data say?
Few centralities and large uncertainties

\( \sqrt{s_{NN}} = 200 \text{ GeV}; \quad p_T > p_T^{\text{min}} \)

Note: STAR also has data [PRB 770 (2017) 451] but uncertainties too large

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Differential spectra & $v_2$ in RHIC beam energy scan

Energy & baryon number deposited over extended time period at lower $\sqrt{s_{NN}}$

"Instantaneous" energy deposition (high collision energy limit)

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

Figure ref.: Modified from Schenke and Shen
Centrality & $\sqrt{s_{NN}}$ dependence of photon production

Another approach: integrate photon spectra $dN/dp_T$ above $p_T$ cutoff & plot with respect to hadron multiplicity (proxy for centrality & $\sqrt{s_{NN}}$)

Ref.: QM2015 proceedings [1704.07842]

Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

RHIC $\sqrt{s_{NN}}$=200 GeV
LHC $\sqrt{s_{NN}}$=2760 GeV

RHIC $\sqrt{s_{NN}}$=19.6, 39, 62.4 & 200 GeV
LHC $\sqrt{s_{NN}}$=2760 & 5020 GeV
Photon vs pion multiplicity using centrality

\[ \sqrt{s_{NN}} = 5020 \text{ GeV}; \ p_T > p_T^{\text{min}} \]

Preliminary results

Thermal photons

Simple test: \( p_T \) cut-off dependence for thermal photons, NOT for prompt photons

Prompt photon slope: 1.35
Prompt photons
Figure A.1: Direct photon spectrum measured in $\sqrt{s_{NN}} = 200$ GeV proton-proton collisions at RHIC compared with (a) perturbative QCD calculations made with different scales $Q$ (b) normalised perturbative QCD calculations (Equation A.1)
Figure A.2: Same as Figure A.1 for pions measured in $\sqrt{s_{NN}} = 2.76$ TeV proton-proton collisions at the LHC
Beam-energy and centrality dependence of direct-photon emission from ultra-relativistic heavy-ion collisions

Jean-François Paquet (Duke)
Aurenche et al: prompt photons in p+p

A NEW CRITICAL STUDY OF PHOTON PRODUCTION IN HADRONIC COLLISIONS

P. Aurenche\textsuperscript{1}, M. Fontannaz\textsuperscript{2}, J.Ph. Guillet\textsuperscript{1}, E. Pilon\textsuperscript{1}, M. Werlen\textsuperscript{1}
Prompts

dN/dp

$p_T$

$\sqrt{s}^{4.5}dN/dpT$

$x_T$
Prompts

\[
\sqrt{s}^{4.5} dN/dp_T
\]

Direct photon (y~0)

\[ n = 4.5 \ \text{Exp.}\ (\sqrt{s}) \]

**PHENIX, PRD86 (2012) 072008**
Jean-François Paquet (Duke)
More about photons in BES
Medium properties for Au+Au at low $\sqrt{s_{NN}}$

Center-of-mass energy of collision

Spatial rapidity of plasma

$\eta_s$

Average temperature (GeV)

Temperature averaged over the plasma’s lifetime (depends on freeze-out energy density)

Baryon chemical potential to temperature ratio (markers at $\mu_B/T=1$ and $\mu_B/T=3$ to guide the eye)
Spacetime description at low $\sqrt{S_{NN}}$

Thermal photons: radiated by the hot plasma

$$\frac{dN_\gamma}{d^3k} = \int d^4X \frac{d\Gamma_\gamma}{d^3k}(k, T(X), u^\mu(X), ...)$$

Spacetime profile of plasma from hydrodynamic simulation

Thermal photons: radiated by the hot plasma

Spacetime evolution of plasma described with hydrodynamic model

See Chun Shen’s talk on Wednesday at 11h30
(Collective dynamics III Session)

- Viscous 3+1D hydrodynamics with conserved baryon current
- Finite $\mu_B$ equation of state
- Dynamical initialization of hydrodynamics over extended period of time (at small $\sqrt{s_{NN}}$) using
  sources:
  $$\partial_\mu T^{\mu\nu} = S^\nu$$
  $$\partial_\mu J_B^\mu = \rho_B$$
- Freeze-out at constant energy density 0.16 GeV/fm$^3$
- Tuned to soft hadron data

Ref.: Denicol, Gale, Jeon, Monnai, Schenke, Shen (2018)

Ref.: Shen & Schenke (2018)

Jean-François Paquet (Duke)
**Photon thermal rates**

Temperature

- 100 MeV
- 180 MeV
- 300+ MeV

Photon rate from hadronic degrees of freedom

Photon rate from quark and gluon (QGP) degrees of freedom

Baryon chemical potential

**QGP rate**: Compton scattering, $q\bar{q}$ annihilation & bremsstrahlung (with LPM) at finite $\mu_B$
Refs.: Traxler, Vija, Thoma (1995); Gervais, Jeon (2012); This work

**Hadronic rates**: meson interaction, baryon interaction (at finite $\mu_B$)
Refs.: Turbide, Rapp, Gale (2004); Heffernan, Hohler, Rapp (2014); Holt, Hohler, Rapp (2016)
Effect of finite $\mu_B$ on thermal photon rate

QGP photon rate

Hadronic photon rate

Baryon chemical potential $\mu_B$ increases the photon rate at low momenta

$e^{-(E-\mu_B)/T}$
Photon production in low $\sqrt{s_{NN}}$ collisions

High $p_T$ thermal photon visible against prompt photons estimate as $\sqrt{s_{NN}}$ is decreased

Prompt photon calculations difficult at low $p_T$ and $\sqrt{s_{NN}}$: p+p measurements valuable
Photon $v_2$ in low $\sqrt{s_{NN}}$ collisions

Larger photon $v_2$

Significant $v_2$ across $\sqrt{s_{NN}}$

$\phi$

$\phi$

$\phi$

$\phi$

Jean-François Paquet (Duke)
Probing the dynamical plasma

Energy & baryon number deposited over extended time period at lower $\sqrt{s_{NN}}$

$\sqrt{s_{NN}} = 19.6$ GeV

"Instantaneous" energy deposition (high collision energy limit)

Space-time 4-volume (above freeze-out) versus time

Energy deposited dynamically

Energy deposited instantaneously

Cooling

Jean-François Paquet (Duke)
Early plasma dynamics at low $\sqrt{s_{NN}}$ (19.6 GeV)

Thermal photons

Effect of energy deposition (instantaneous vs dynamic) visible in photons
At low $\sqrt{s_{NN}}$ (19.6 GeV): thermal+prompt

Thermal+prompt photons

Effect of energy deposition (instantaneous vs dynamic) visible in photons
At low $\sqrt{s_{NN}}$ (19.6 GeV): away from mid-rapidity

Thermal+prompt photons

Effect of energy deposition (instantaneous vs dynamic) visible in photons
At high $\sqrt{s_{NN}}$ (200 GeV) & high rapidity

Thermal+prompt photons

At high $\sqrt{s_{NN}}$, effect of dynamic energy deposition visible at higher rapidity
Summary

• **Significant** thermal photon signal at low $\sqrt{s_{NN}}$

• Small effect of $\mu_B$ on photon rate;
  dominant effect is distinct spacetime profile of medium

• Early initial conditions can be studied with photons using
  - Low $\sqrt{s_{NN}}$ collisions
  - Rapidity $y \geq 2$ for higher $\sqrt{s_{NN}}$ collisions

Photons are unique **direct** probes of complex dynamics of low $\sqrt{s_{NN}}$ collisions
Contributions to $v_n$
Simple derivation

\[ v_n = \frac{\int d\phi \frac{dN}{d\phi} e^{in(\phi-\Psi_n)}}{\int d\phi \frac{dN}{d\phi}} \]

\[ v_n = \frac{\int d\phi \left( \frac{dN_{th,T>180 \text{ MeV}}}{d\phi} + \frac{dN_{th,T<180 \text{ MeV}}}{d\phi} + \frac{dN_{\text{prompt}}}{d\phi} \right) e^{in(\phi-\Psi_n)}}{\int d\phi \left( \frac{dN_{th,T>180 \text{ MeV}}}{d\phi} + \frac{dN_{th,T<180 \text{ MeV}}}{d\phi} + \frac{dN_{\text{prompt}}}{d\phi} \right)} \]

\[ v_n = \frac{\int d\phi \frac{dN_{th,T>180 \text{ MeV}}}{d\phi} e^{in(\phi-\Psi_n)}}{\int d\phi \left( \frac{dN_{th,T>180 \text{ MeV}}}{d\phi} + \frac{dN_{th,T<180 \text{ MeV}}}{d\phi} + \frac{dN_{\text{prompt}}}{d\phi} \right)} + \int d\phi \frac{dN_{th,T<180 \text{ MeV}}}{d\phi} e^{in(\phi-\Psi_n)} \]

\[ v_n = \left( \frac{dN_{th,T>180 \text{ MeV}}}{d\phi} \right)_\phi v_{n_{th,T>180 \text{ MeV}}} + \left( \frac{dN_{th,T<180 \text{ MeV}}}{d\phi} \right)_\phi v_{n_{th,T<180 \text{ MeV}}} \]

\[ \langle ... \rangle_\phi = \frac{1}{2\pi} \int d\phi \ldots \]
Comparison with available data
Spectra at 200 GeV

1/\langle 2m_T \rangle dN/dp_T (GeV^{-2})

- Thermal + prompt
- Direct photons

Au-Au 0-20%
√s = 200 GeV

Jean-François Paquet (Duke)
$v_2$ at 200 GeV

[Graphs showing $v_2(y, p_T)$ for different centrality classes Au-Au collisions at $\sqrt{s}=200$ GeV.]
Spectra at 39 & 62.4 GeV: 0-40% centrality calculation vs 0-86% data
Transition temperature for photon rates
QGP vs hadronic photon rates around $T_c$
Photon production for different transition $T_T$

![Graph showing photon production for different $T_T$ values.](image)
Thermal EM probes: thermal rate

\[
\frac{d^4 N_{\gamma/l+l-}}{d^4 k} = \int d^4 X \frac{d^4 \Gamma_{\gamma/l+l-}}{d^4 k} (K^\mu, u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X))
\]

Gas of hadrons: \(~100\) MeV
Deconfinement: \(~160\) MeV
Max T at RHIC: \(~400\) MeV
Max T at LHC: \(~600\) MeV

Toward asymptotic QGP

Effective hadronic models
- Texas A&M/McGill rates
- Stony Brook rates

AdS/CFT and other holography

Effective QCD models
- Caron-Huot et al (AdS/CFT)
- Finazzo and Rougemont (bottom-up holography)
- BNL et al (semi-QGP)

Perturbative QCD
- Arnold, Moore, Yaffe (AMY)
- Ghiglieri, Teaney, Laine
- ...
**Perturbative rate at LO and NLO in $g_s$**

(Ref.: Ghiglieri, Hong, Kurkela, Lu, Moore & Teaney, JHEP, 2013)

**NLO ($g_s^3$) correction to photon rate is small**

(Unlike e.g. heavy quark energy loss and shear viscosity)

NLO = "LO" + "collinear (coll)" + "soft" + "semi-collinear (sc)"

Jean-François Paquet (Stony Brook)
Perturbative photon rate vs lattice

For $T \sim T_c^+$, perturbative QGP photon rate 
~ consistent with lattice 
(via vector correlation functions)

(Ref.: Ghiglieri, Kaczmarek, Laine & Meyer, PRD, 2016)
Effective QGP model

Semi-QGP: Mean field with suppressed Polyakov loop

Enhancement factor for dilepton rate [compared to pQCD]

Dilepton enhancement also seen in other calculations
(Lee and Zahed, PRC, 2014; Islam et al, JHEP 2015)

Suppression factor for “2 → 2” part of photon rate
(possibly less suppression for collinear rate)

Thermal $\gamma/\ell^+\ell^-$ rate around $T_c$?

Is the perturbative photon rate reliable at $T$ as low as 200-300 MeV?

>> Mixed signal from different approaches <<

Outlook

- Rate from **bottom-up holography**?
e.g. Yang et al, arXiv:1609.07208 [poster Monday]
Finazzo & Rougemont, PRD, 2016;

- **Comparing** holography/semi-QGP with lattice calculations?

- Holography vs perturbative rate at high temperature?

Lattice constraints on rate
Energy deposition at high rapidity – $\sqrt{s}=200$ GeV
0-5% Au+Au @ 200 GeV

\( \tau \) (fm) vs. \( \eta_s \)
Instantaneous energy deposition - refitting
Probing the early plasma: low $\sqrt{s_{NN}}$

![Graph showing photon $p_T$ distribution](image)

- Gradual energy deposition
- Instantaneous energy deposition
- Instantaneous energy deposition (refitted)
- Prompt photons

**Au-Au 20-30%**

$\sqrt{s}=19.6$ GeV
Photon $v_2$: before prompt dilution
Photon $v_2$ in low $\sqrt{s_{NN}}$ collisions

Center-of-mass energy of collision

- 19.6 GeV
- 39 GeV
- 62.4 GeV
- 200 GeV

Significant $v_2$ across $\sqrt{s_{NN}}$
Photon rates: extra details
Hadronic photon rate at zero $\mu_B$ : from Turbide, Rapo and Gale (2004)
Effect of finite $\mu_B$ on thermal photon rate

**QGP photon rate**

- $1/(2\pi p_T) \, dR/dp_T \, (GeV^2 \, fm^{-4})$
- $\mu_B/T = 0$ (red)
- $\mu_B/T = 2$ (blue)
- $T = 300 \, MeV$
- ~60% increase

**Hadronic photon rate**

- $1/(2\pi p_T) \, dR/dp_T \, (GeV^2 \, fm^{-4})$
- $\mu_B/T = 0$ (black)
- $\mu_B/T = 2$ (gray)
- $T = 150 \, MeV$
- ~40% increase

↑ Baryon chemical potential $\mu_B$ increases the photon rate at low momenta

$e^{-\left(\frac{k-\mu_B}{T}\right)}$