Probing heavy ion collisions with photons at low and high $\sqrt{s_{NN}}$

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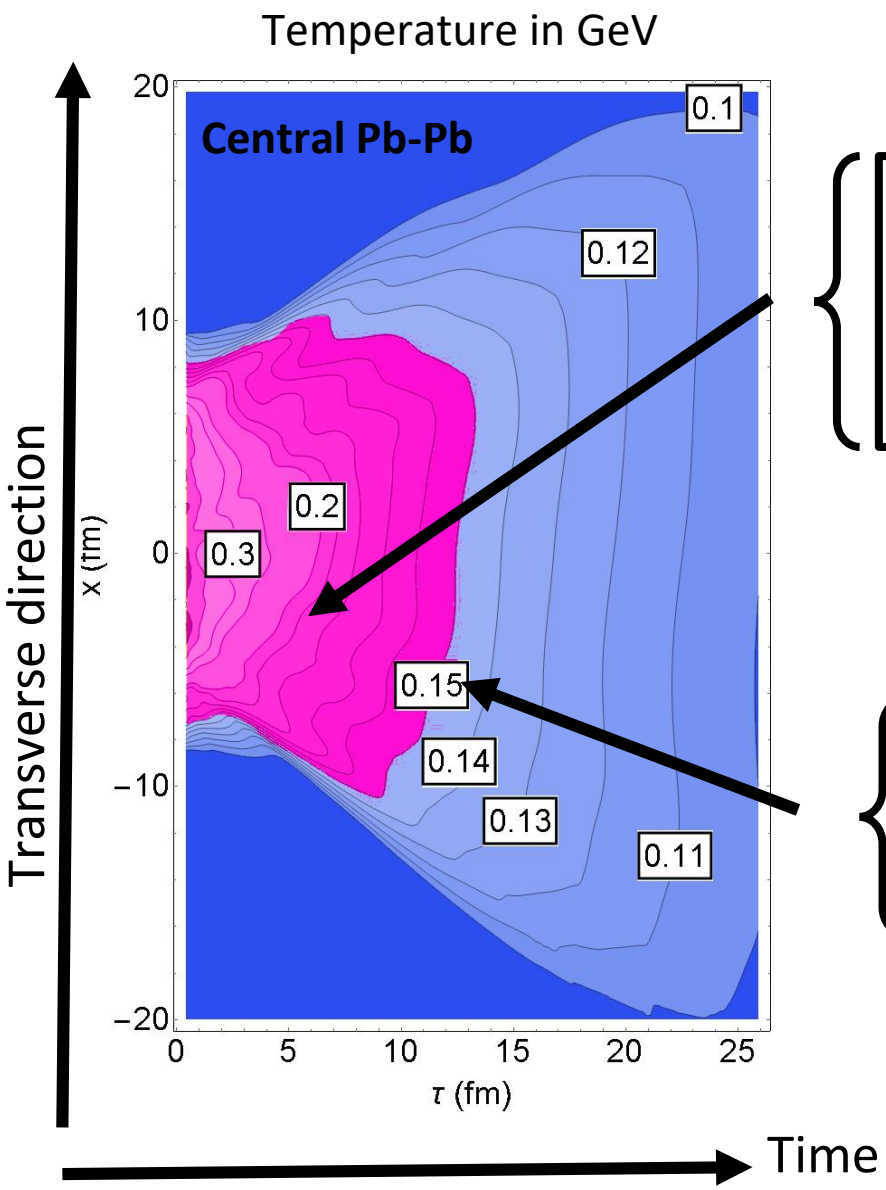
Duke UNIVERSITY

in collaboration with
Charles Gale, Sangyong Jeon,
Scott McDonald & Chun Shen

Photons as probes of the plasma



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

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \frac{N_{binary}}{\sigma_{pp}^{inel}} \underbrace{f_{a/A} \otimes f_{b/B} \otimes \mathrm{d}\hat{\sigma}_{ab\to\gamma/c+d} [\otimes D_{\gamma/c}]}_{\text{NLO pQCD [INCNLO] } (p_T \text{ dependence})}$$

[Could also use fit to p+p data]

Thermal photons

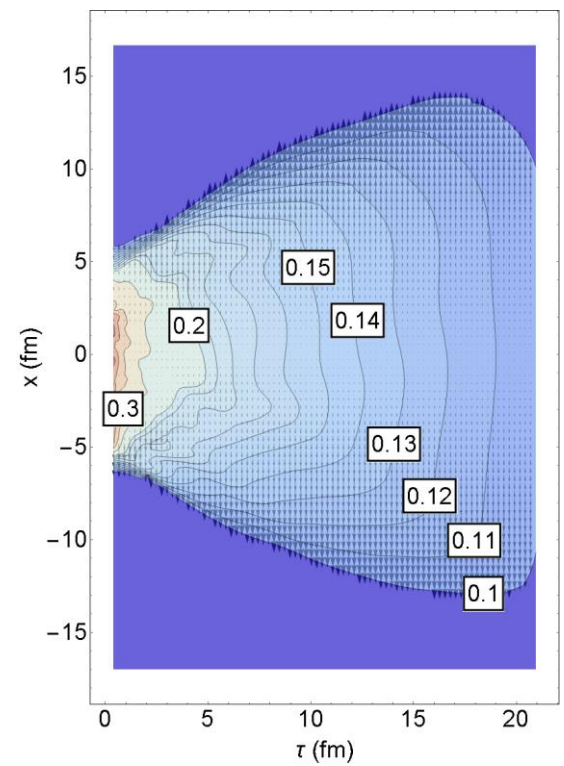
- Radiated by the hot plasma

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \int \mathrm{d}^4X \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}(\mathrm{p}, \underbrace{T(X), u^\mu(X), \ldots}_{})$$

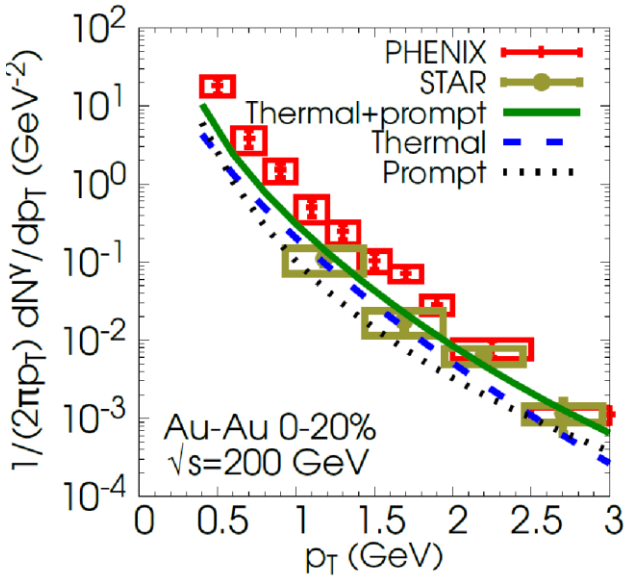
Photon emission rate
(per volume)
for hot QCD plasma

Spacetime profile of
plasma from
hydrodynamic simulation

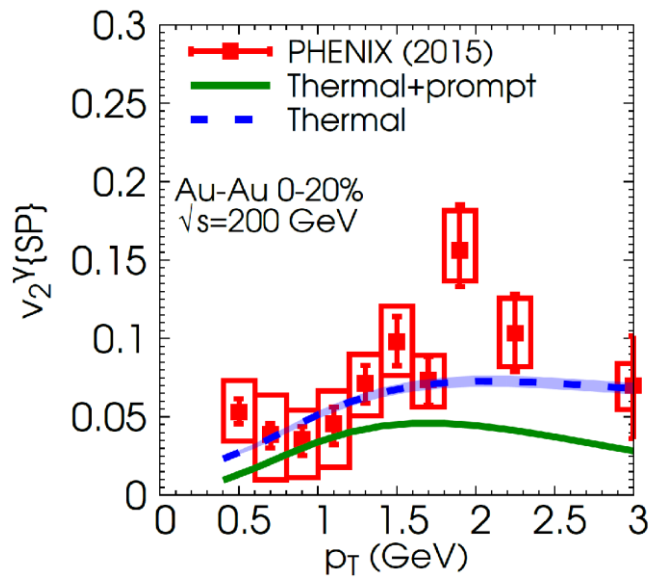
Temperature [in GeV] and
flow velocity profile

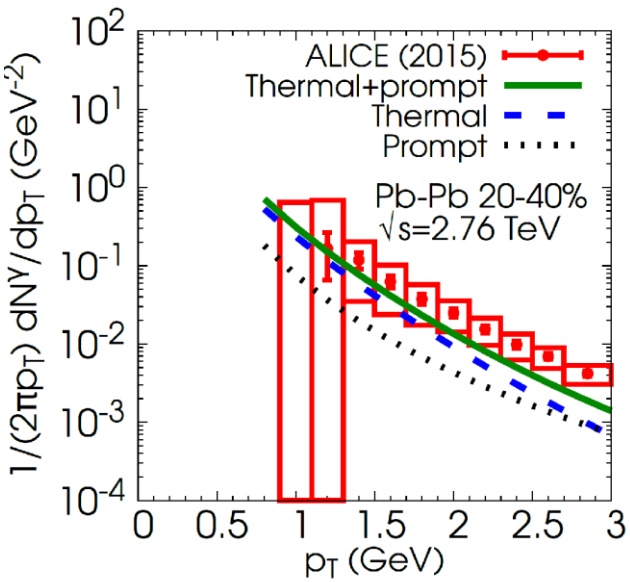


Differential spectra & v_2 at LHC & top RHIC $\sqrt{s_{NN}}$



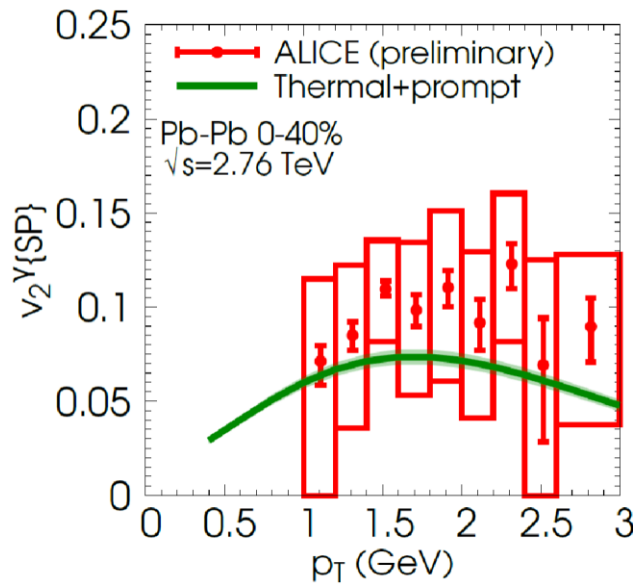
RHIC
$\sqrt{s_{NN}}$=
200 GeV



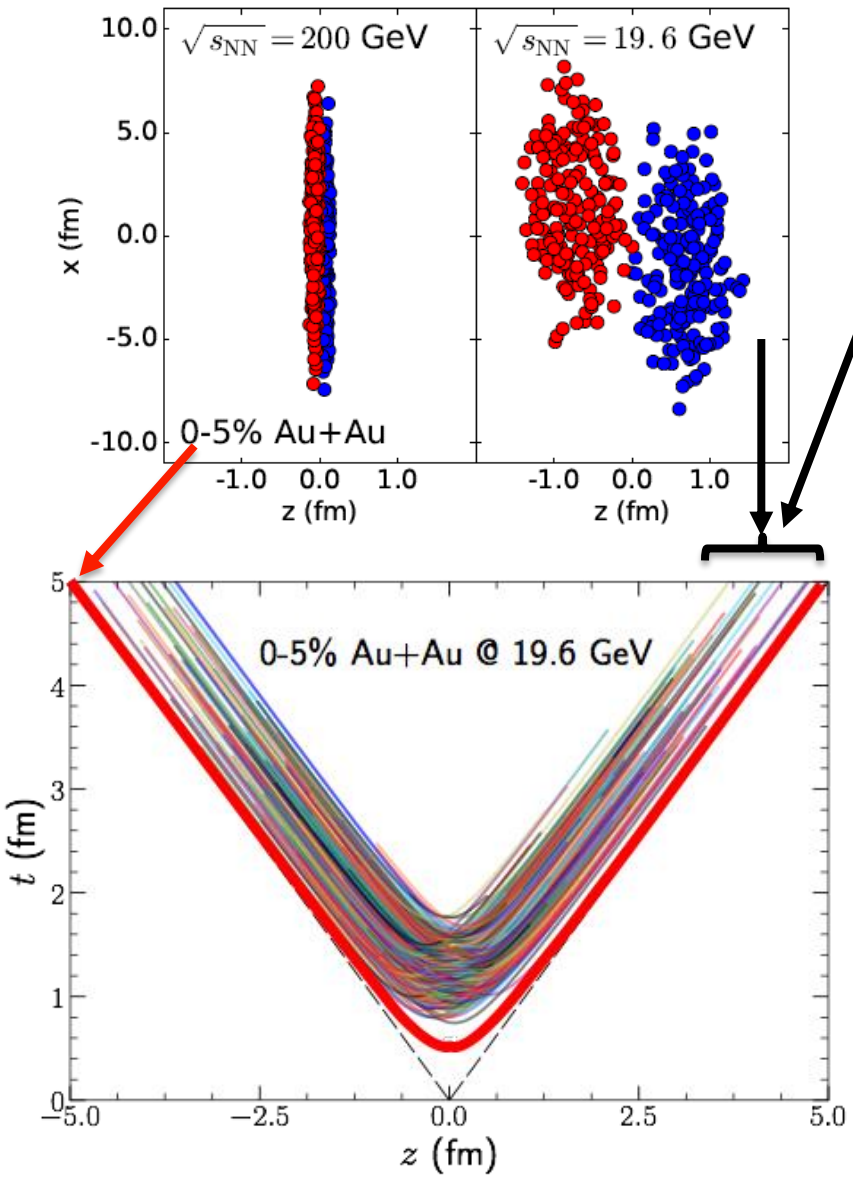


LHC
$\sqrt{s_{NN}}$=
2760 GeV

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



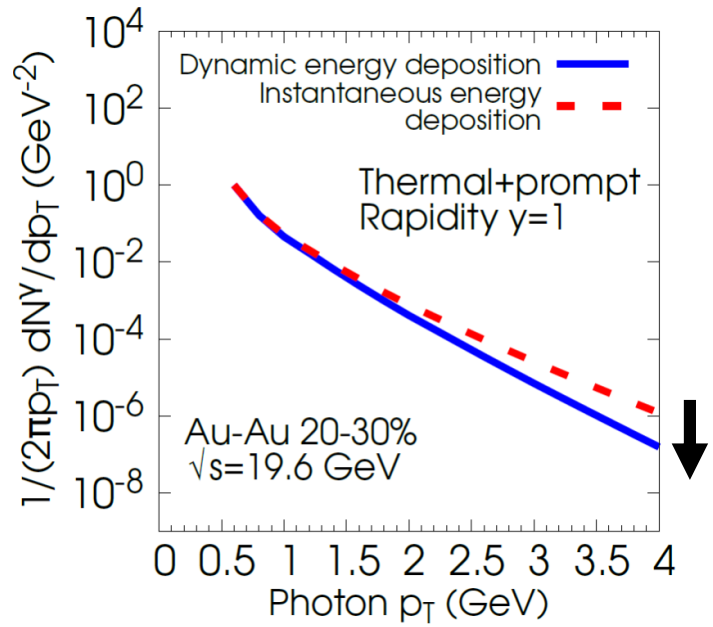
Photons in the RHIC beam energy scan



Ref.: Schenke and Shen, PRC 97 (2018)

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

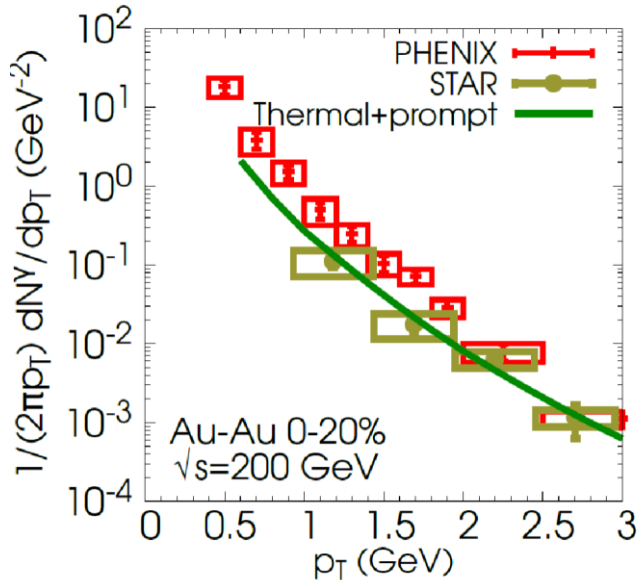
RHIC $\sqrt{s_{NN}}$=19.6 GeV



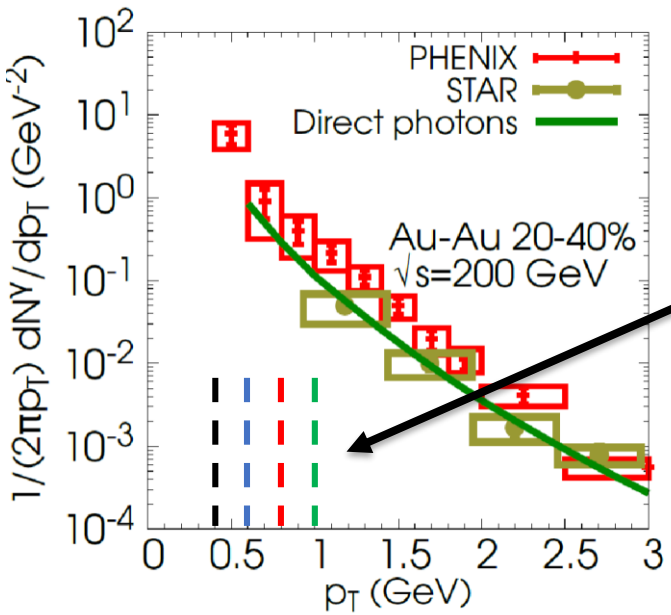
Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

Photons sensitive to initial energy deposition

Looking at the same data in a different light



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

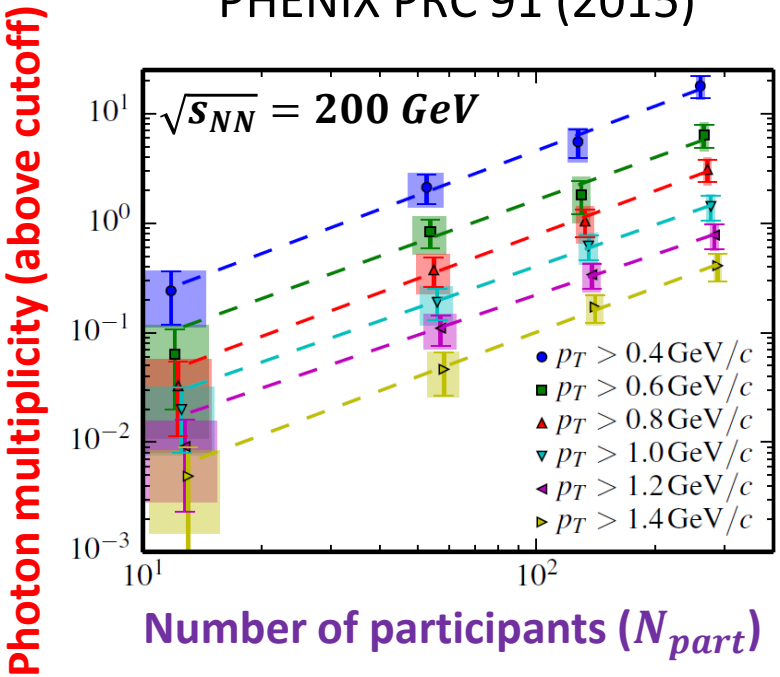


Can use different lower p_T cut-offs

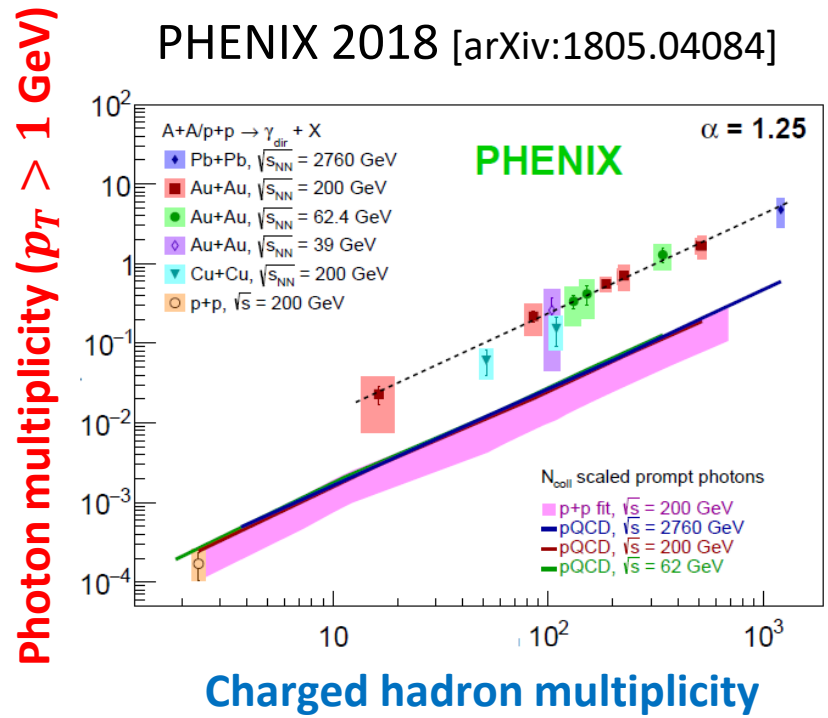
Centrality&$\sqrt{s_{NN}}$ dependence of photon production

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

PHENIX PRC 91 (2015)



PHENIX 2018 [arXiv:1805.04084]



PHENIX 2015:

$$\log\left(N^{\gamma}_{p_T>p_T^{cut}}\right) \sim slope(p_T^{cut})\,\log(N_{part})$$

PHENIX 2018:

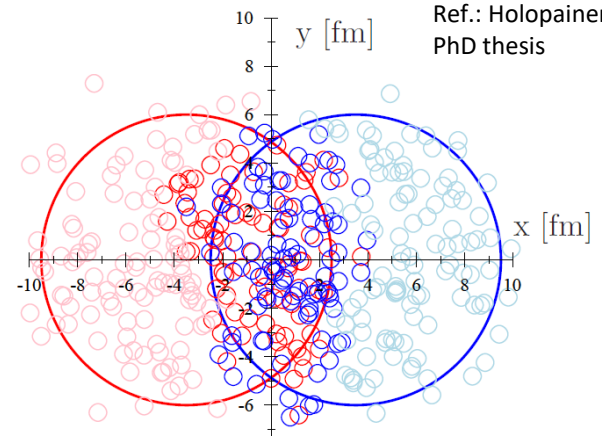
$$\log\left(N^{\gamma}_{p_T>1\ GeV}\right) \sim 1.25\,\log(N^{h^{\pm}})$$

Photons across centralities and $\sqrt{s_{NN}}$

Prompt photons

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

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



Ref.: Holopainen, PhD thesis

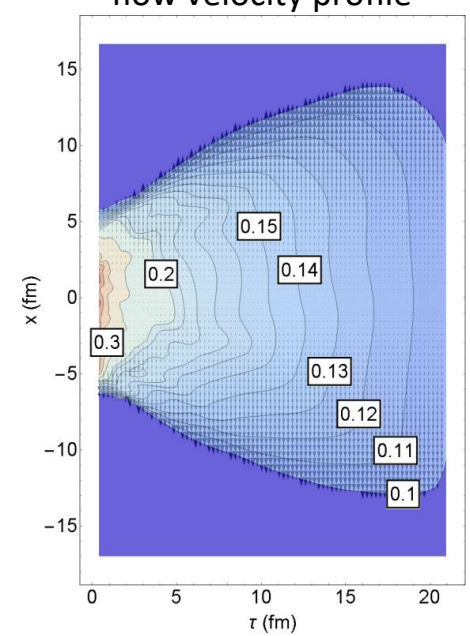
Thermal photons

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

Photon emission rate (per volume) for hot QCD plasma

Spacetime profile of plasma from hydrodynamic simulation

Temperature [in GeV] and flow velocity profile



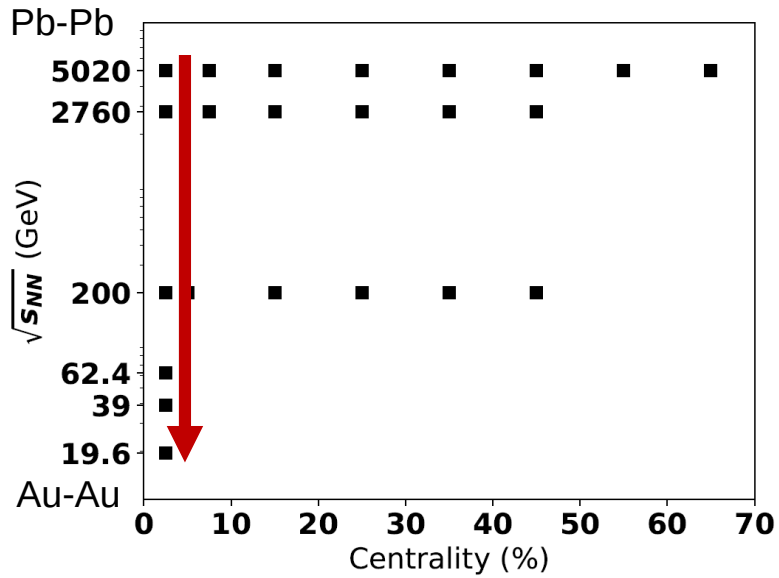
Ref.: QM2017 proceedings [1704.07842]

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

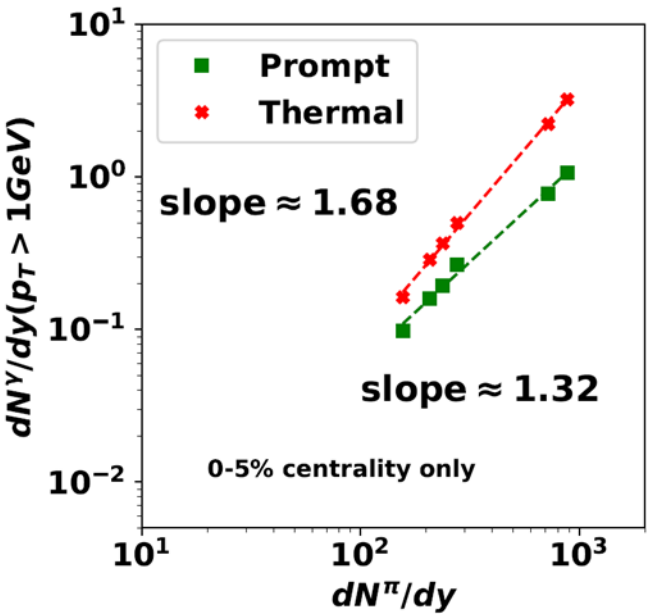
$\sqrt{s_{NN}}$ dependence

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

Preliminary results



$$\log\left(N^{\gamma}_{p_T>p_T^{min}}\right) \sim slope(p_T^{min}) \log(N^{\pi})$$

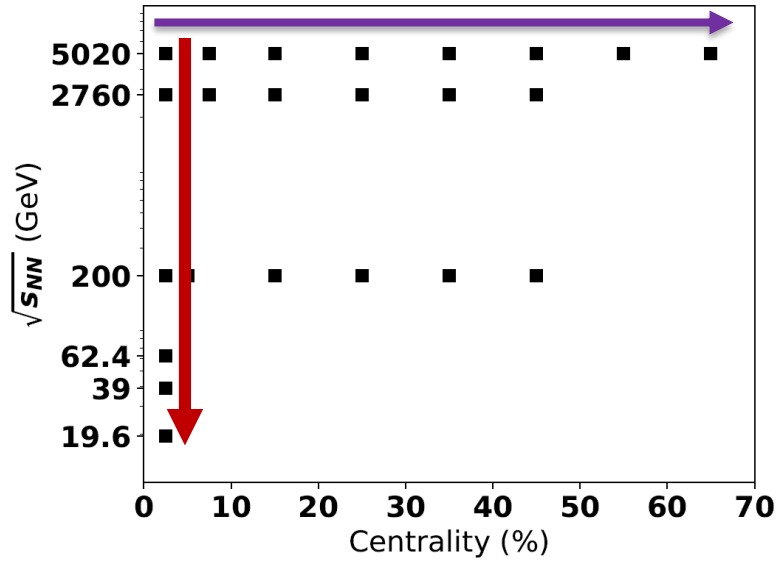


Varying $\sqrt{s_{NN}}$ at fixed centrality

$\sqrt{s_{NN}}$ dependence

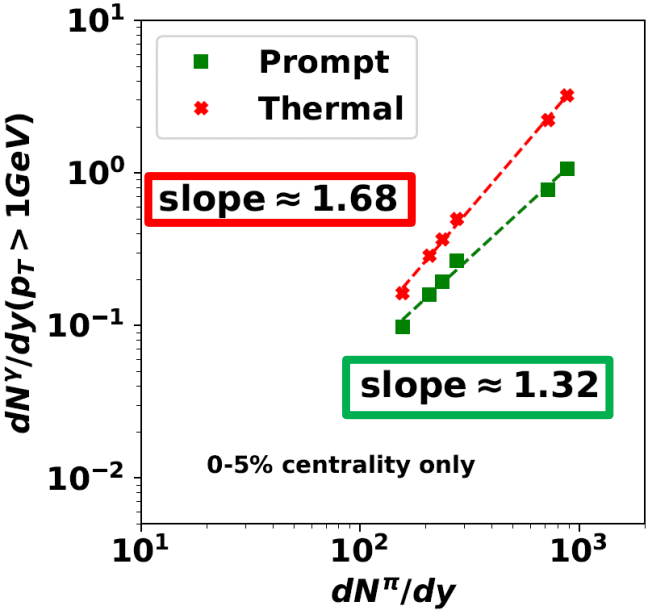
Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

Preliminary results



$$\log\left(N^{\gamma}_{p_T>p_T^{min}}\right) \sim slope(p_T^{min}) \log(N^{\pi})$$

Varying centrality at fixed $\sqrt{s_{NN}}$



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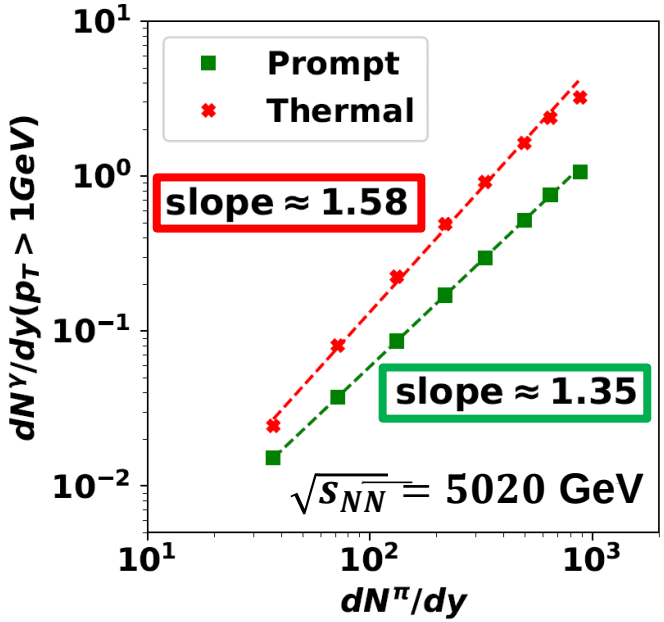


$\sqrt{s_{NN}}$ dependence

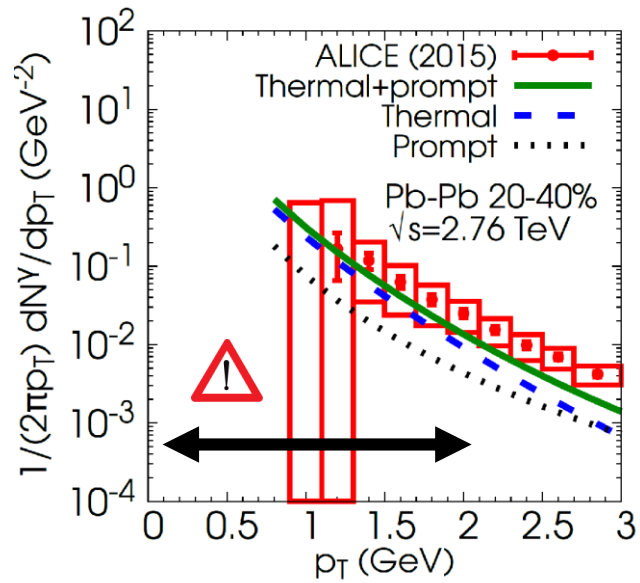
Ref.: Gale, Jeon, McDonald, Paquet, Shen, in preparation.

Preliminary results

Prompt photons

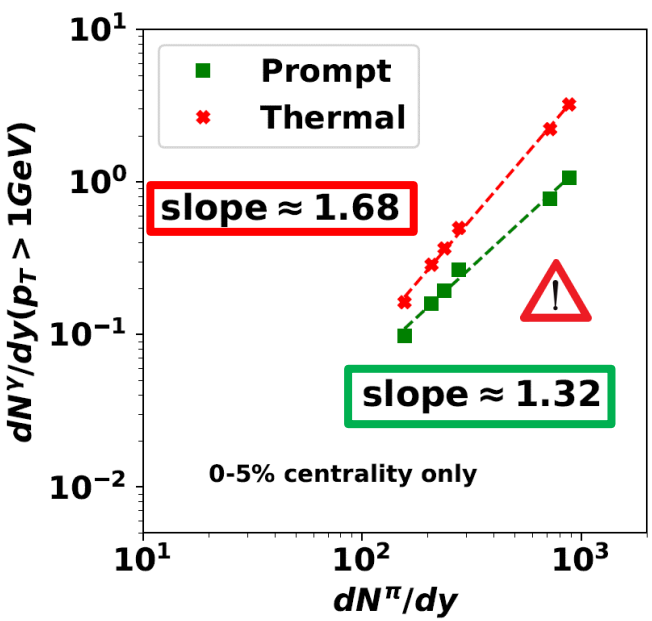
pQCD: not accurate at low p_T

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



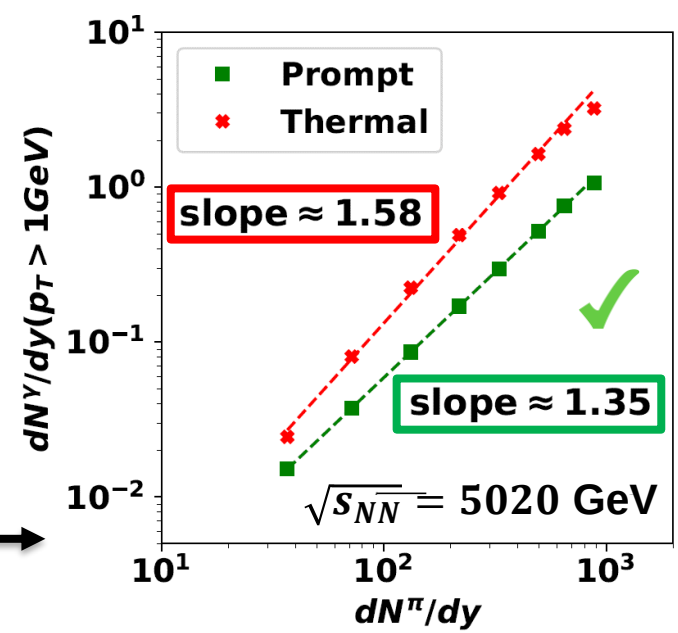
Fixed centrality:

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



Careful with low p_T prompt photon calculations (large uncertainty)

Centrality dependence under better control

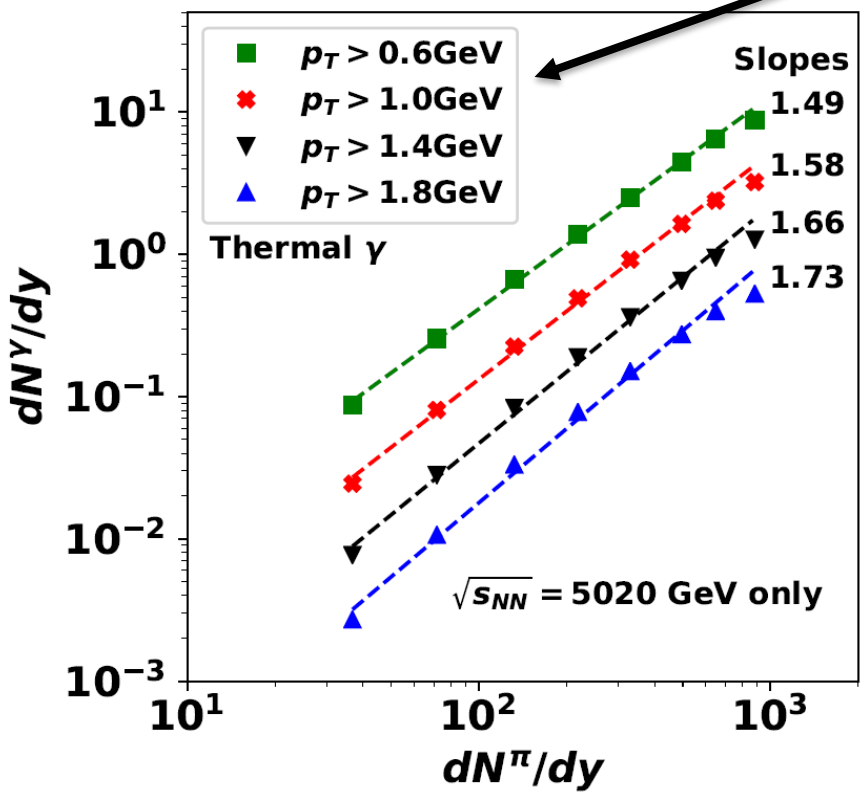


Photon vs pion multiplicity using centrality

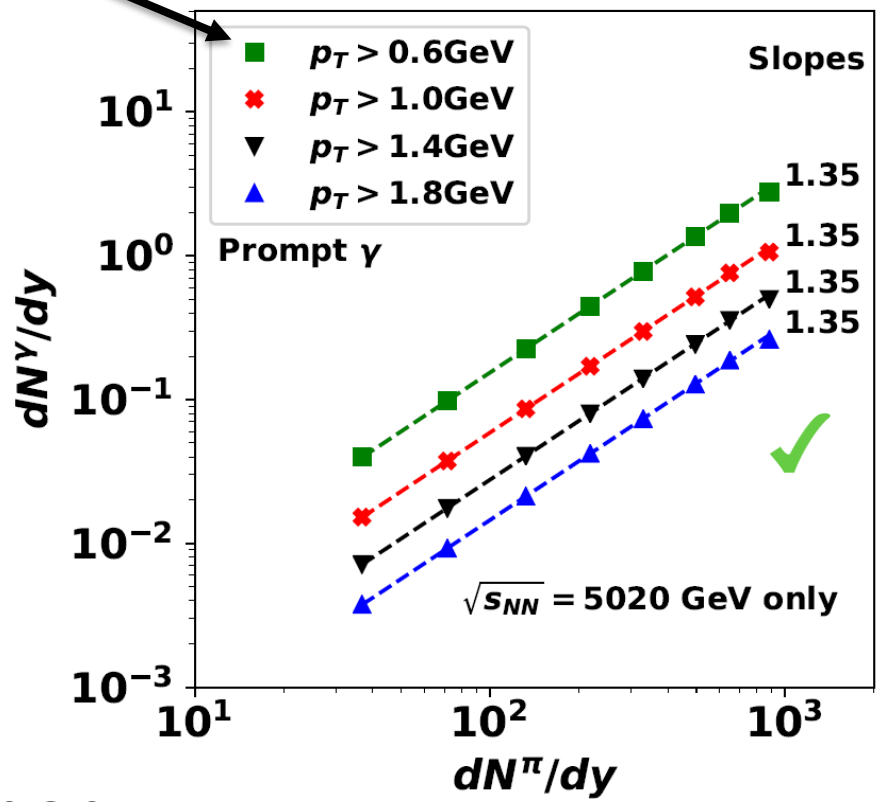
Preliminary results

$p_T > p_T^{min}$

Thermal photons



Prompt photons



$\sqrt{s_{NN}} = 5020$ GeV

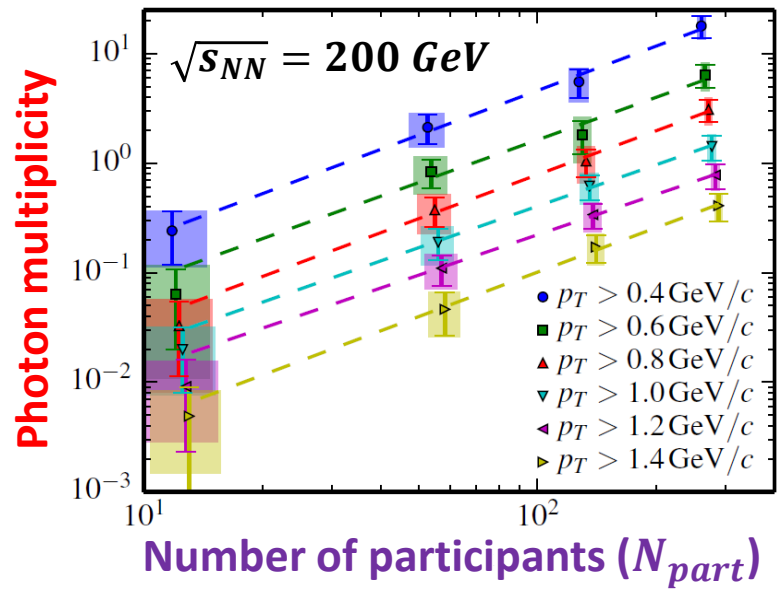
Simple test: p_T **cut-off dependence** for **thermal photons**, **NOT** for prompt

Photon vs N_{part} using centrality

Preliminary results

What does the data say?

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



Ref.: PHENIX PRC 91 (2015)

p_T^{min} (GeV/c)	Slopes vs N_{part}
0.4	$1.36 \pm 0.08 \pm 0.08$
0.6	$1.41 \pm 0.14 \pm 0.12$
0.8	$1.42 \pm 0.07 \pm 0.11$
1.0	$1.35 \pm 0.06 \pm 0.07$
1.2	$1.36 \pm 0.09 \pm 0.07$
1.4	$1.40 \pm 0.06 \pm 0.10$

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

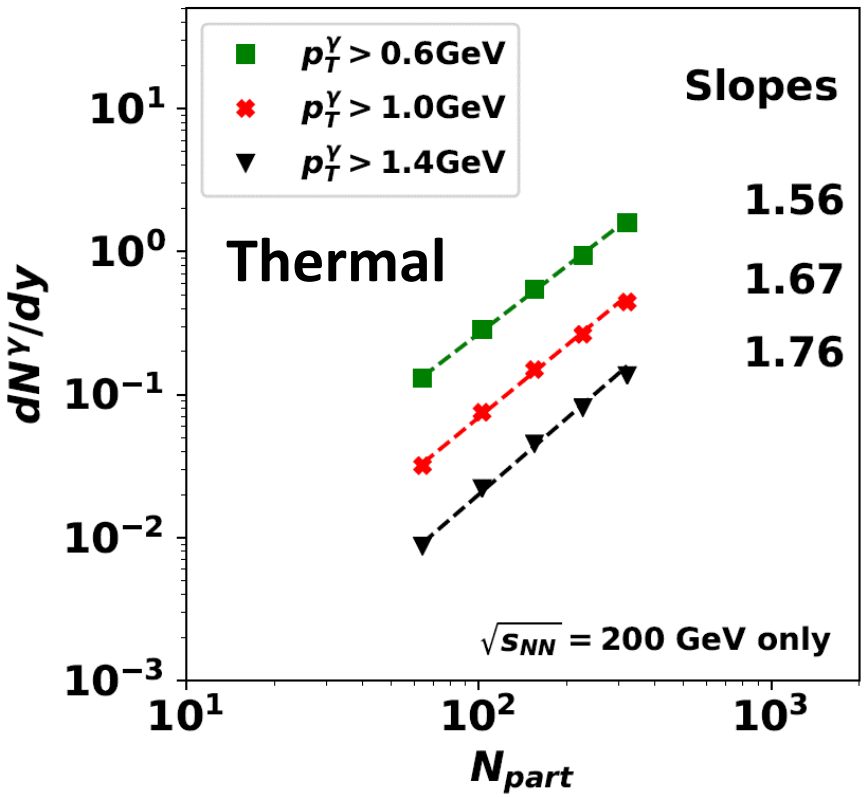
Photon vs pion multiplicity using centrality

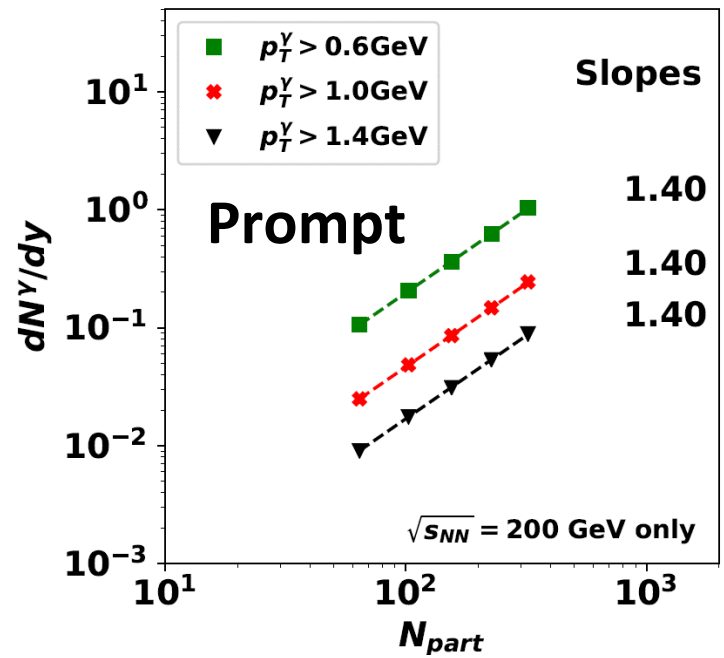
Preliminary results

What does the data say?

Few centralities and large uncertainties but little sign of p_T dependence

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





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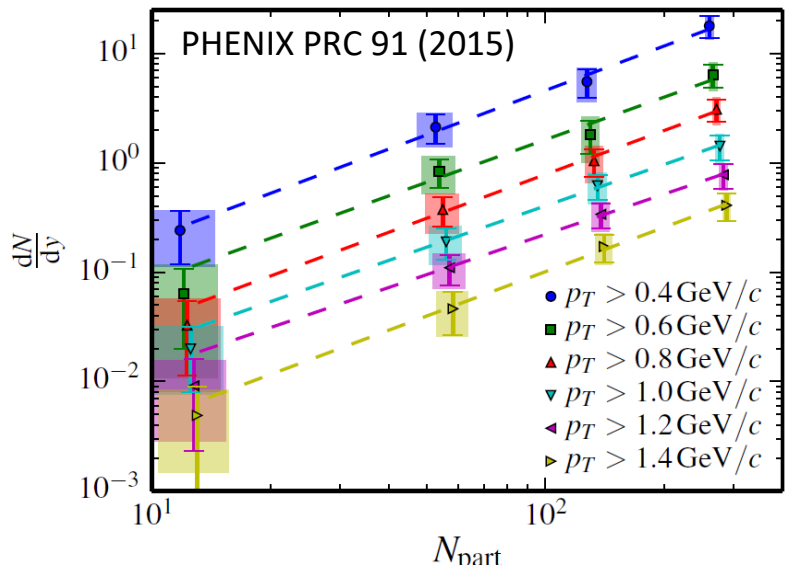
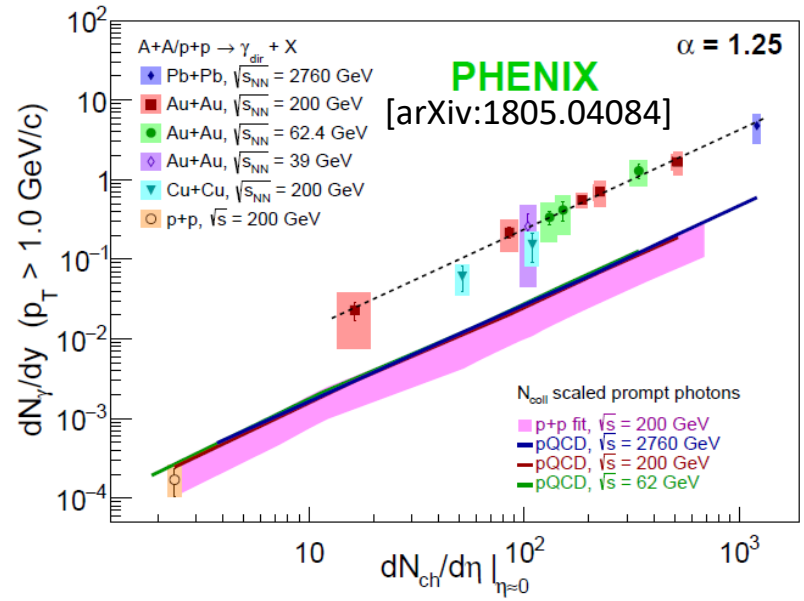
Note: STAR also has data [PRB 770 (2017) 451] but uncertainties too large

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

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

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, ...

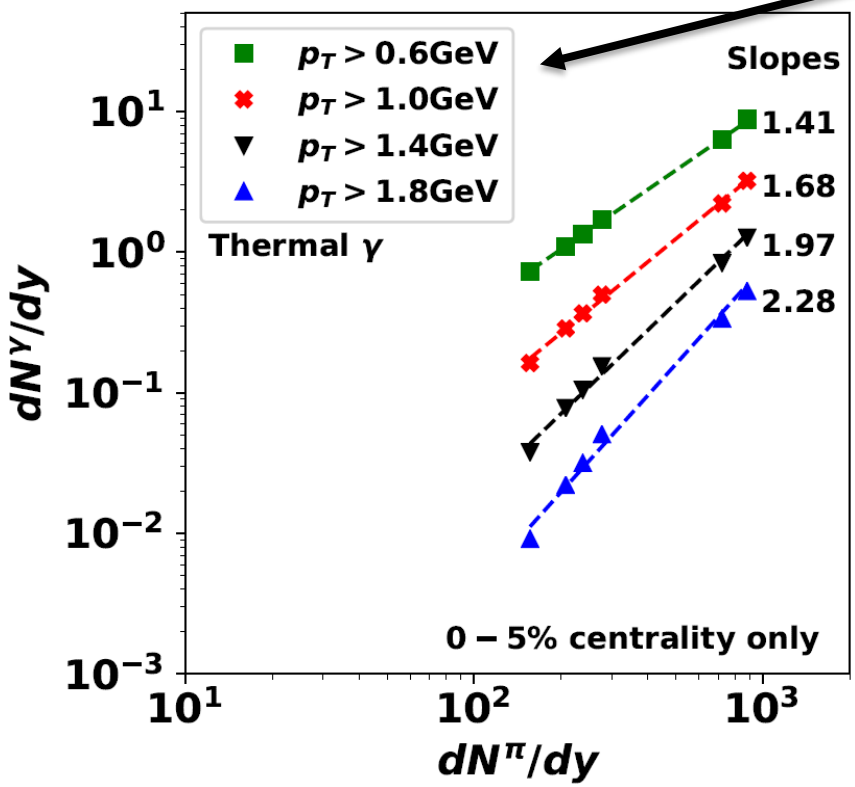
Jean-François Paquet (Stony Brook) 17

QM2017

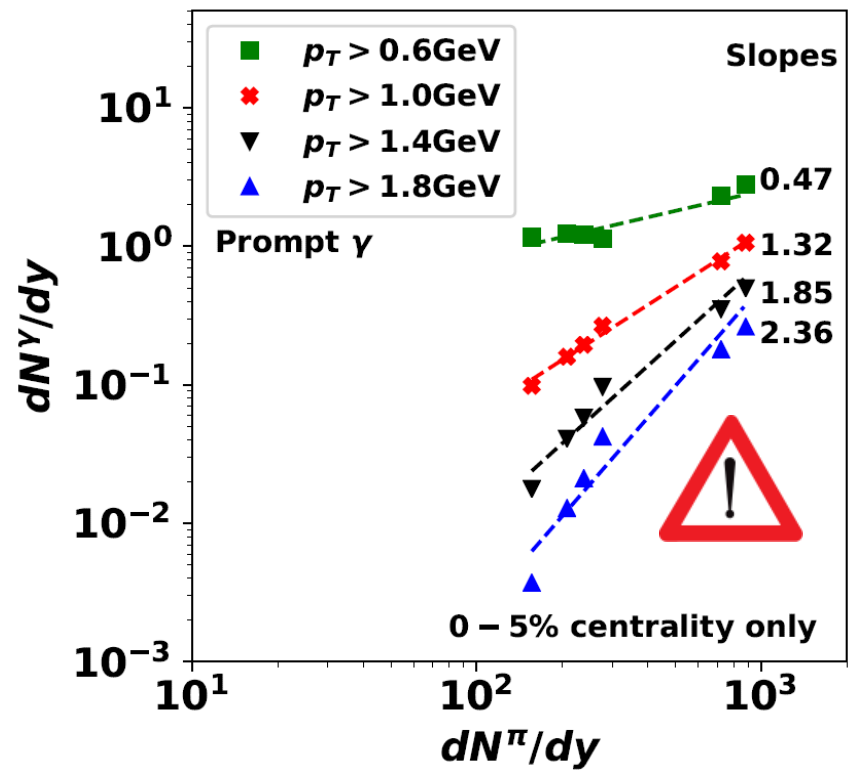
Photon vs pion multiplicity using $\sqrt{s_{NN}}$

Preliminary results

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



Thermal photons

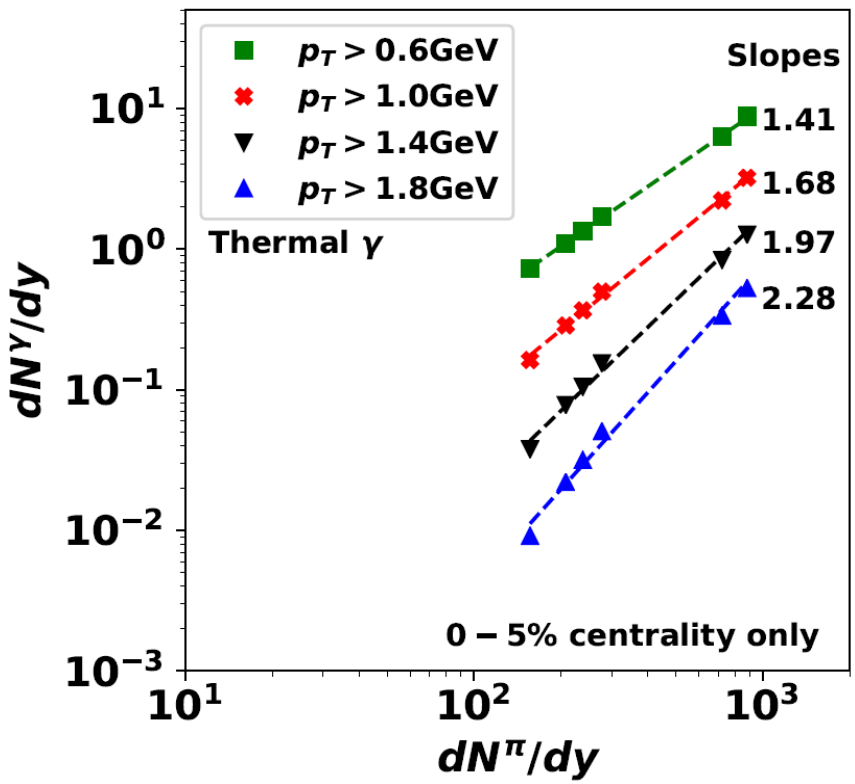


Prompt photons

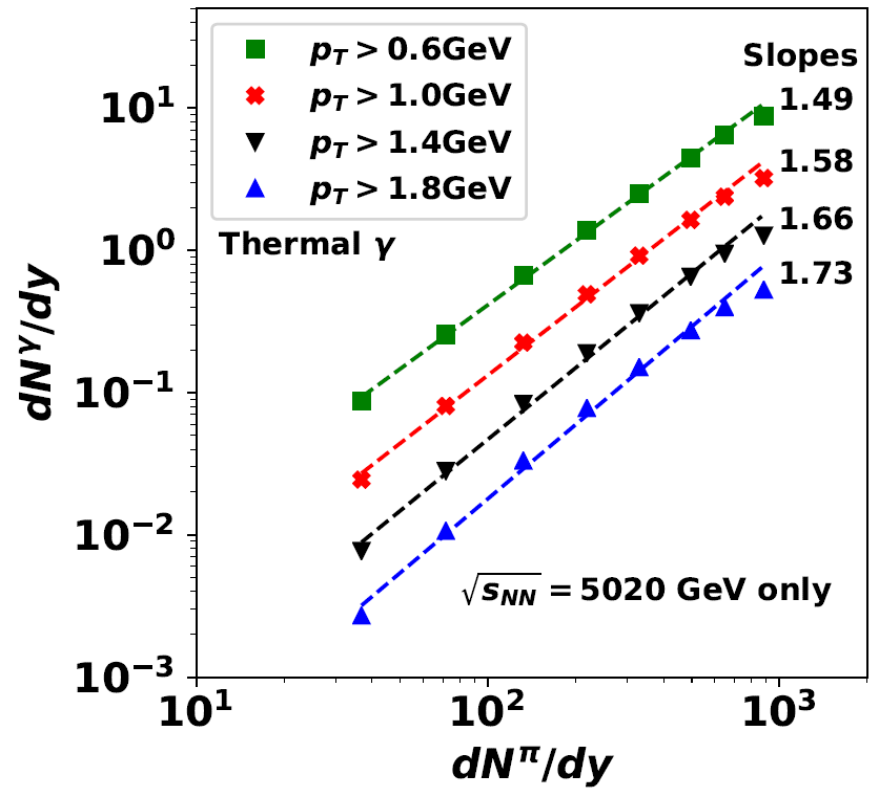
Difficult to draw conclusion from slope

Thermal photons

Preliminary results



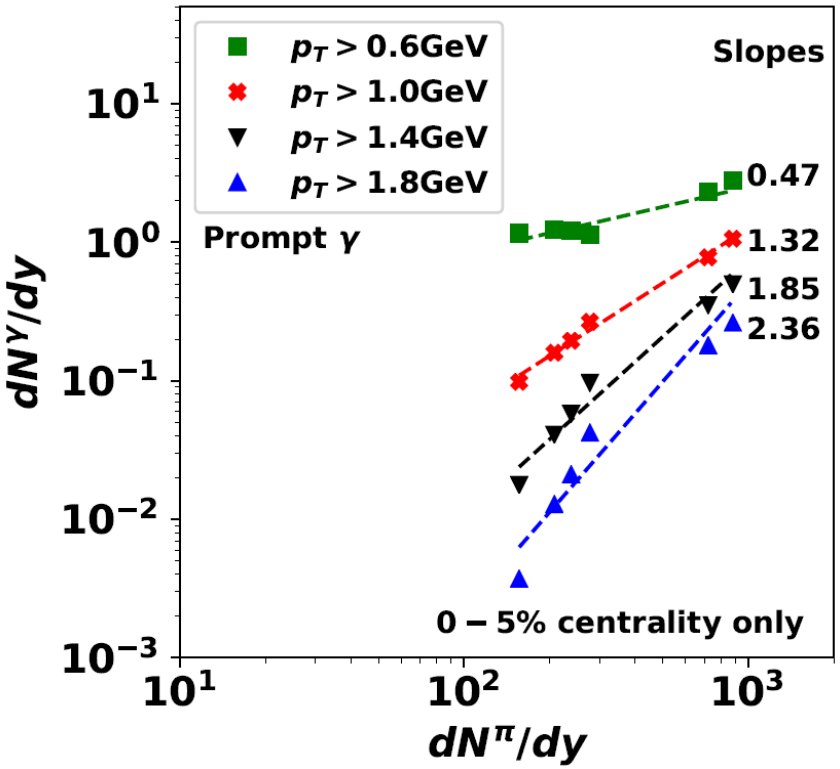
Sqrt(s)



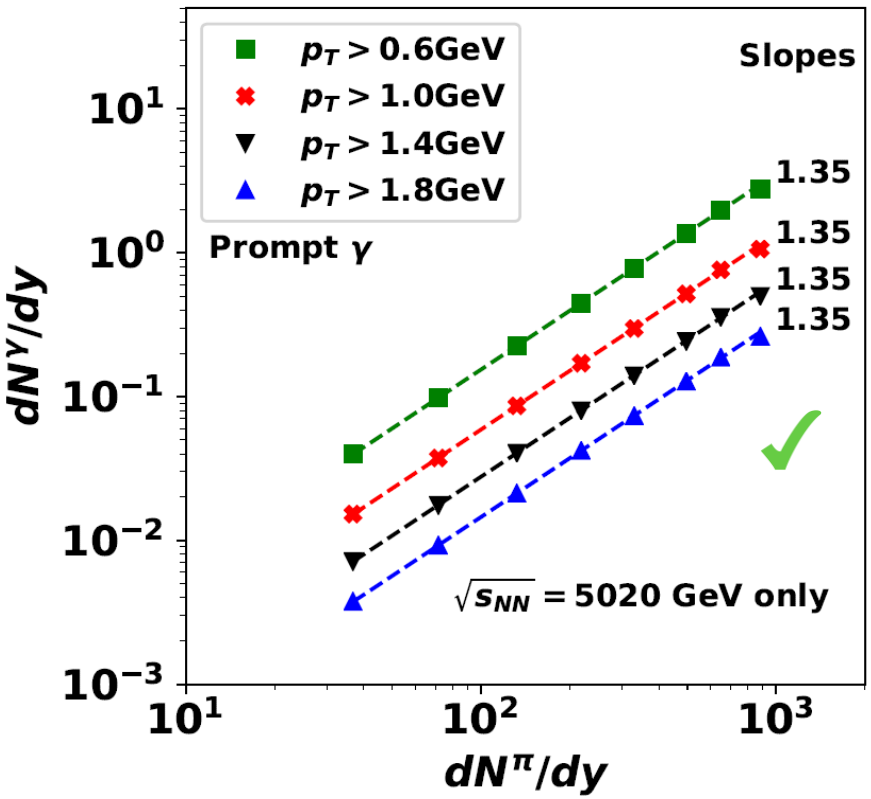
Centrality

Prompt photons

Preliminary results



Sqrt(s)

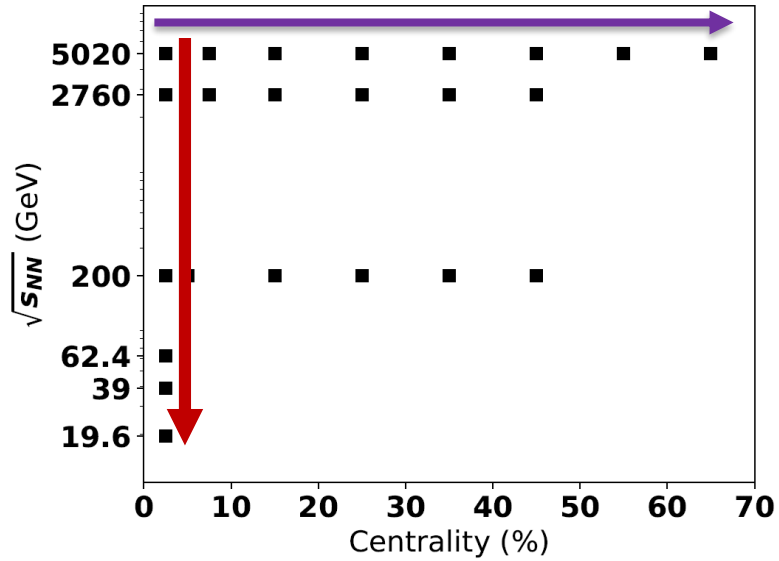


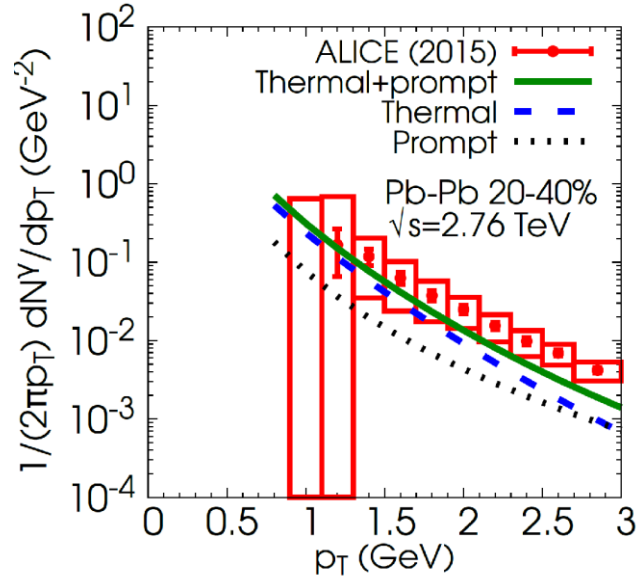
Centrality

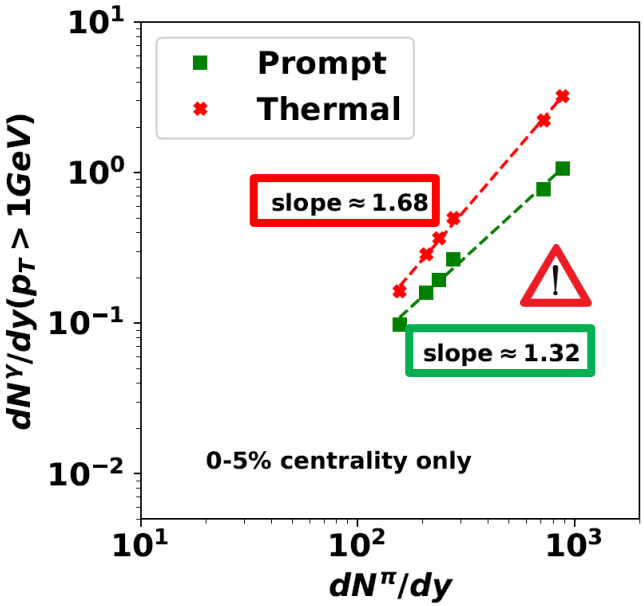
$\sqrt{s_{NN}}$ dependence

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

Preliminary results

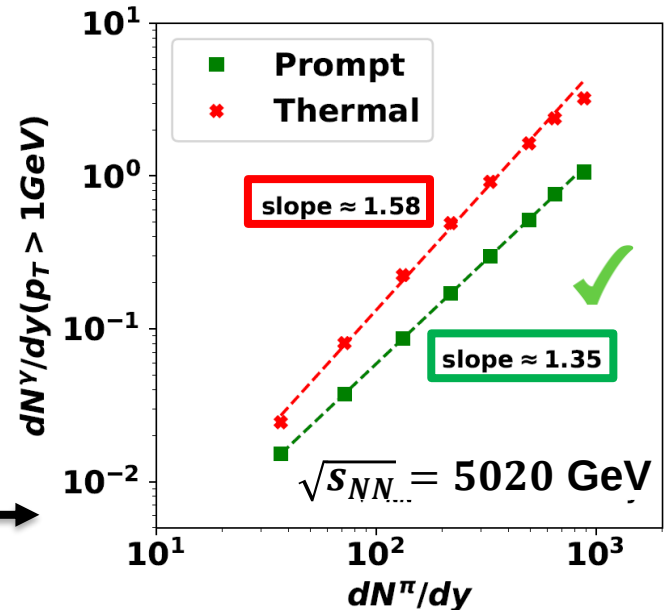






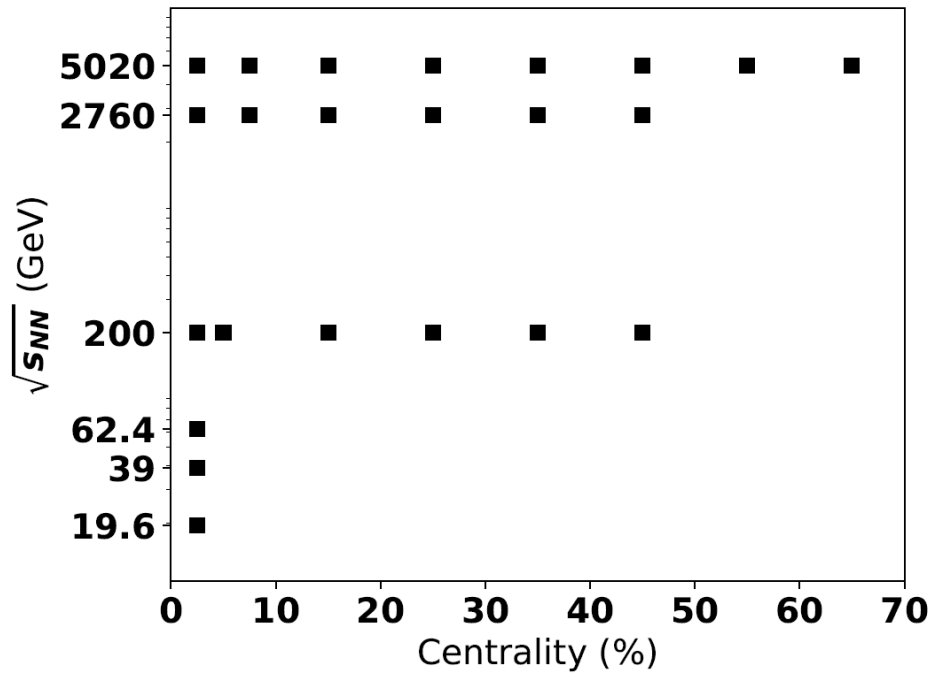
Careful with low p_T prompt photon calculations (large uncertainty)

Centrality dependence under better control



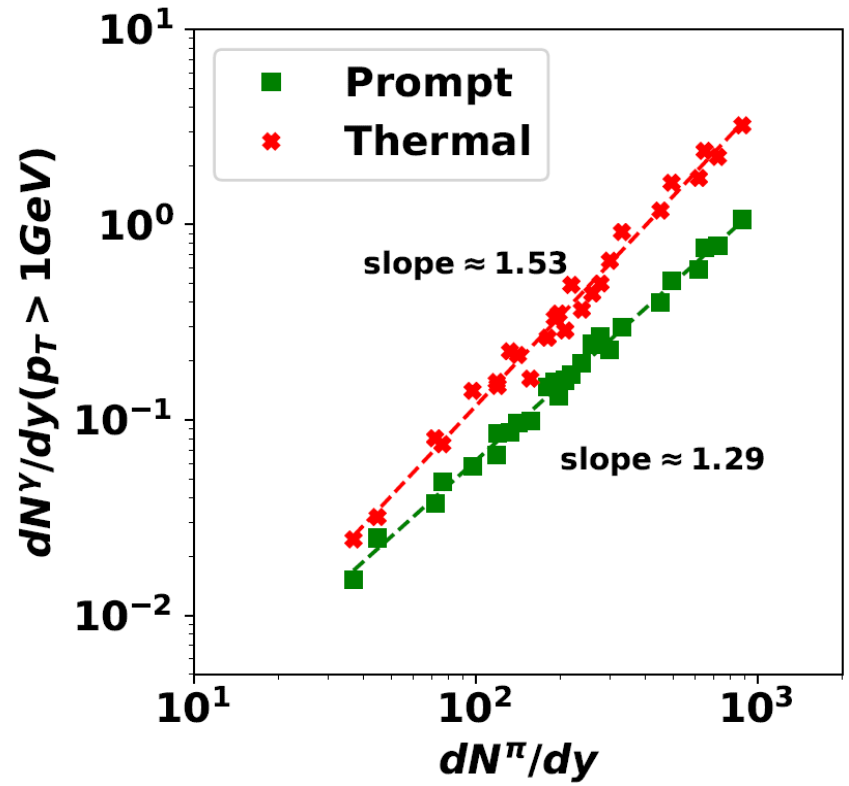
Centrality&$\sqrt{s_{NN}}$ dependence of photon production

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



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

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

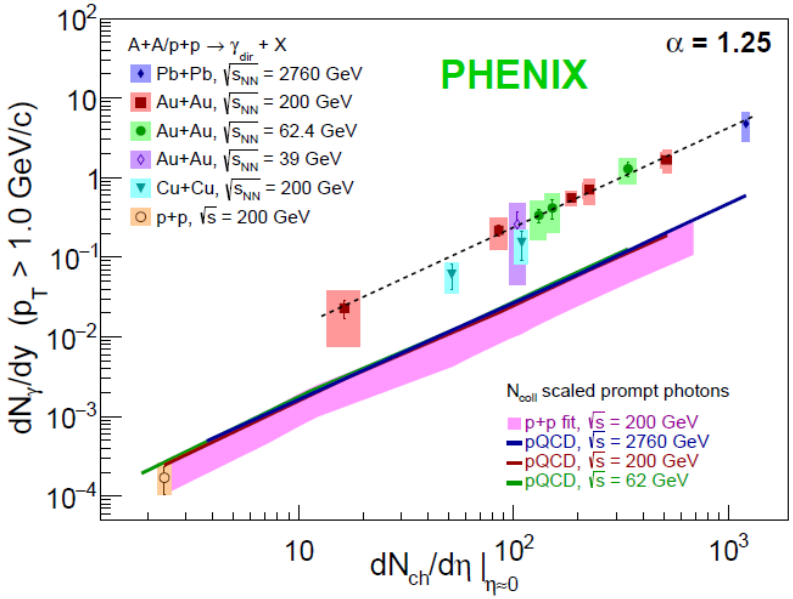


$$\log\left(N^{\gamma}_{p_T>1\ GeV}\right) \sim \boldsymbol{slope}\ \log(N^{\pi})$$

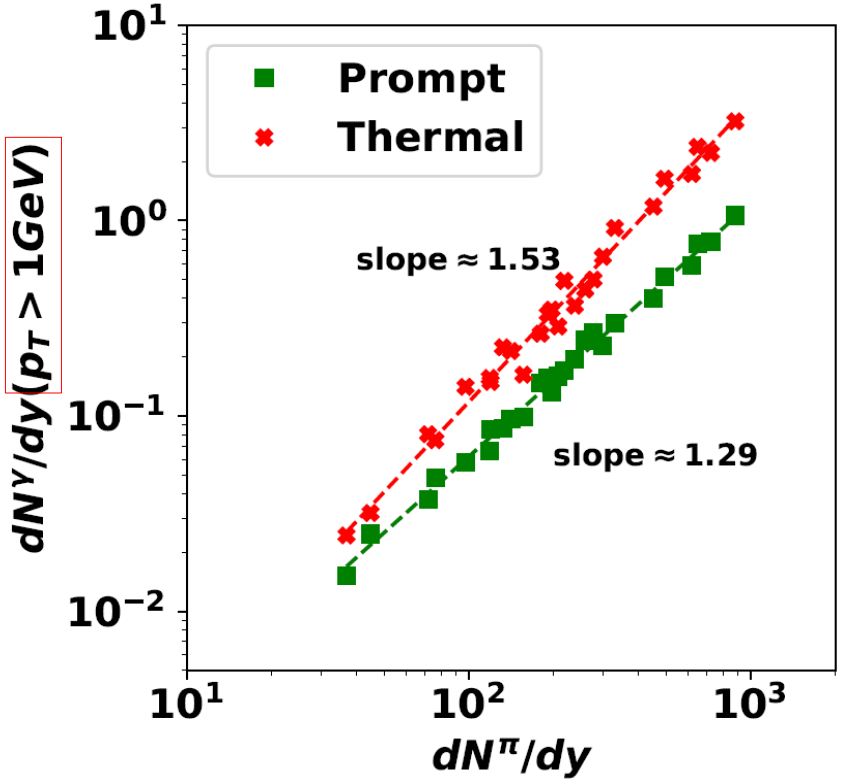
Centrality&$\sqrt{s_{NN}}$ dependence of photon production

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]



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



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

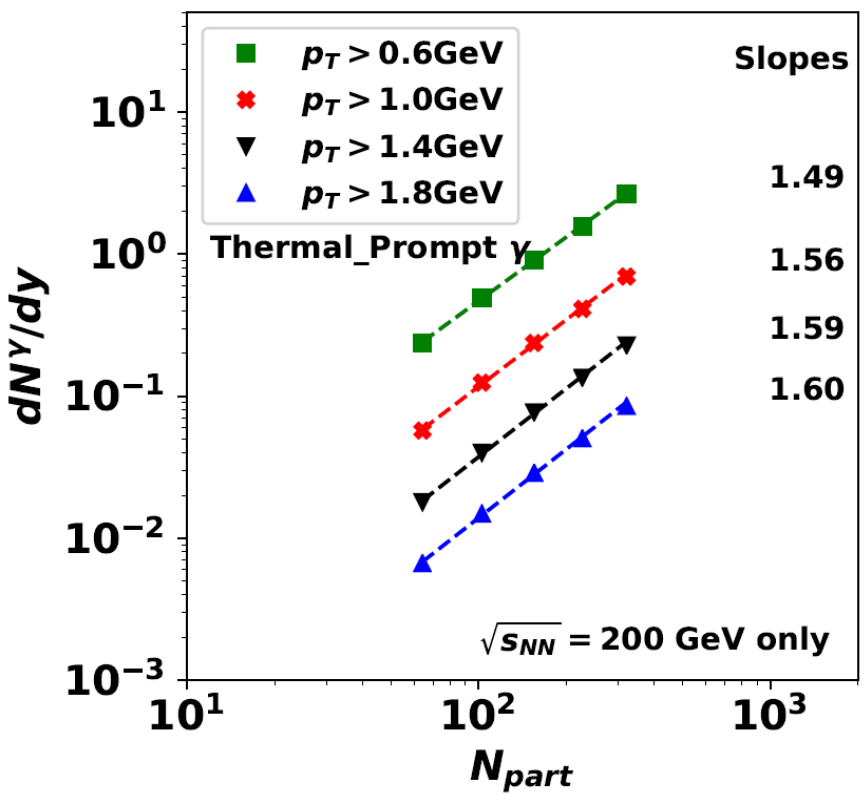
Photon vs pion multiplicity using centrality

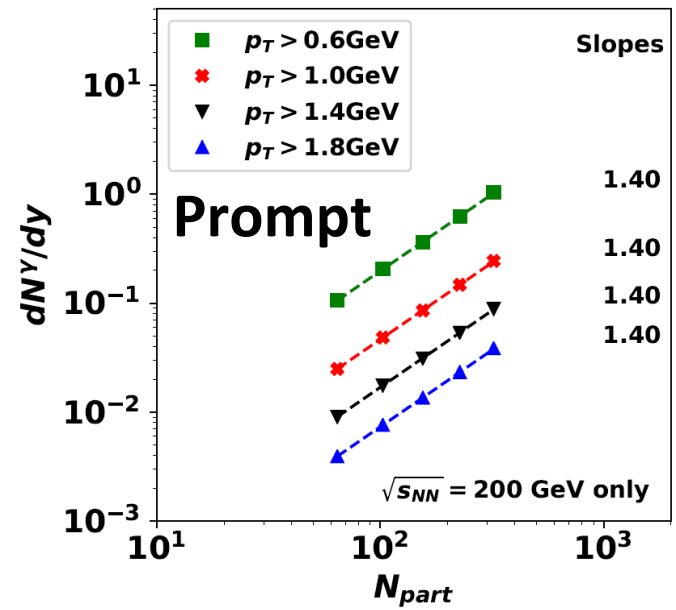
Preliminary results

What does the data say?

(few centralities and large uncertainties)

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





Ref.: PHENIX PRC 91 (2015)

p_T^{min} (GeV/c)	Slopes vs N_{part}
0.4	$1.36 \pm 0.08 \pm 0.08$
0.6	$1.41 \pm 0.14 \pm 0.12$
0.8	$1.42 \pm 0.07 \pm 0.11$
1.0	$1.35 \pm 0.06 \pm 0.07$
1.2	$1.36 \pm 0.09 \pm 0.07$
1.4	$1.40 \pm 0.06 \pm 0.10$

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

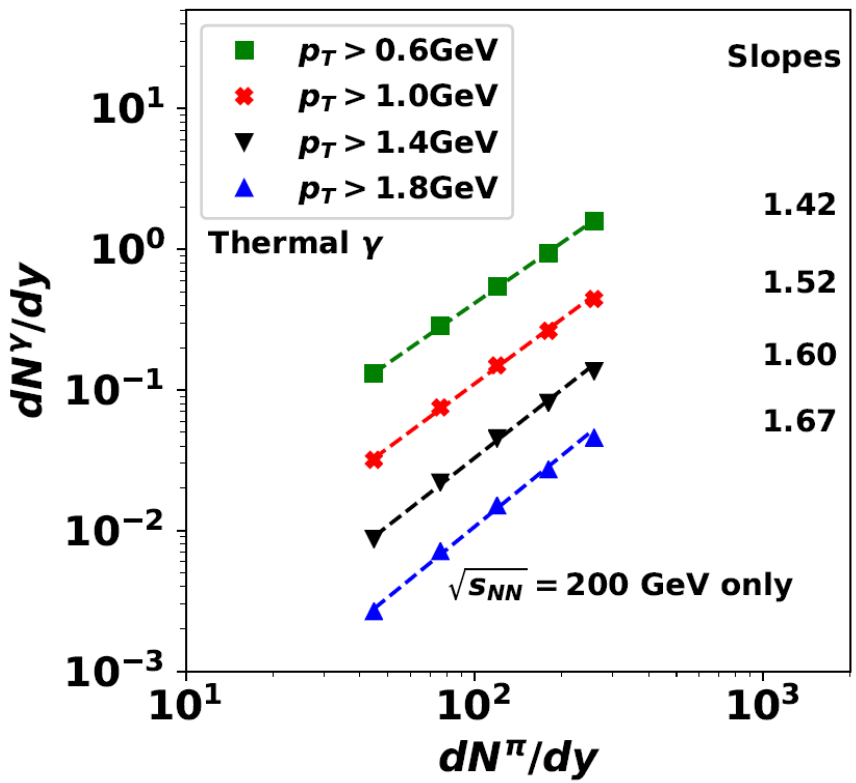
Photon vs pion multiplicity using centrality

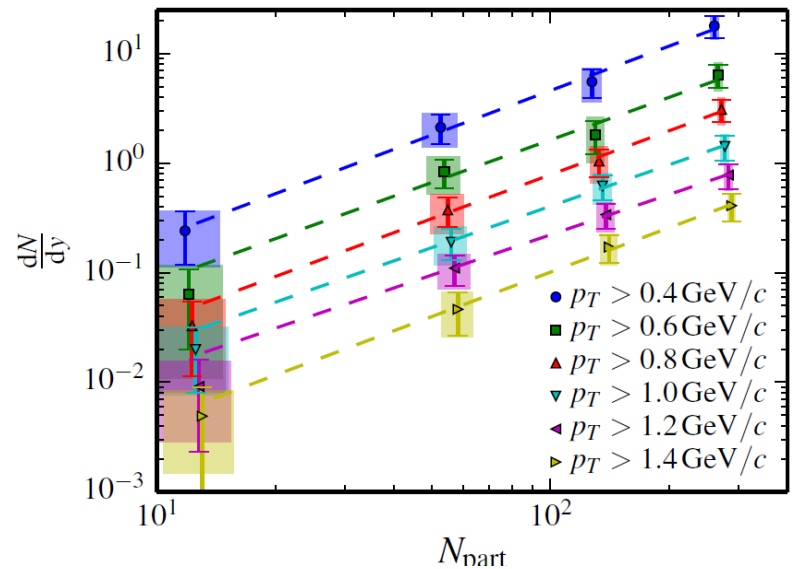
Preliminary results

What does the data say?

Few centralities and large uncertainties

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





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

Differential spectra & v_2 in RHIC beam energy scan

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

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

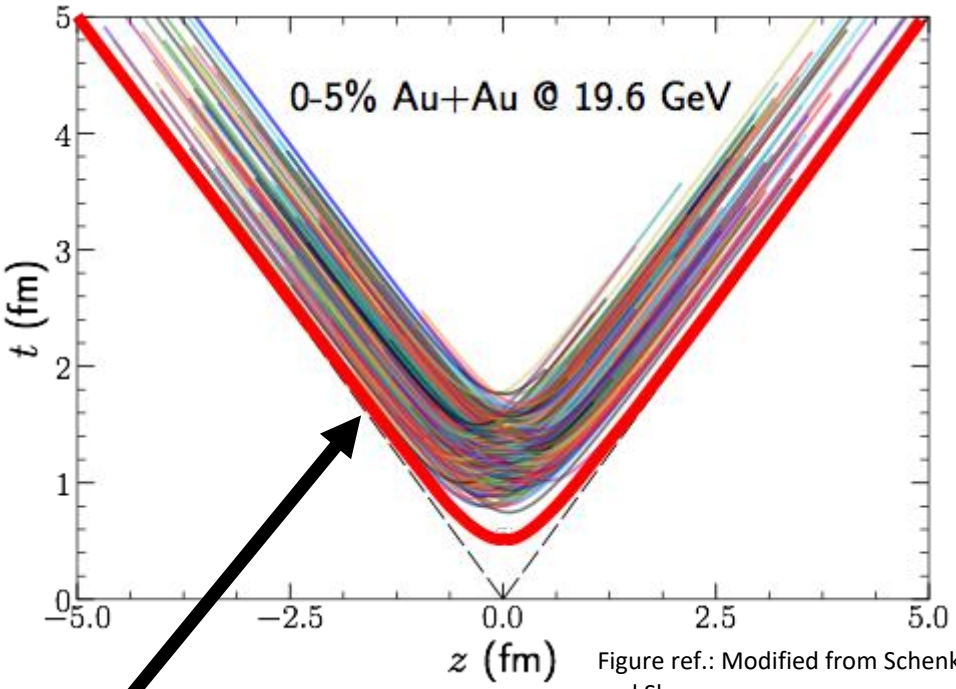
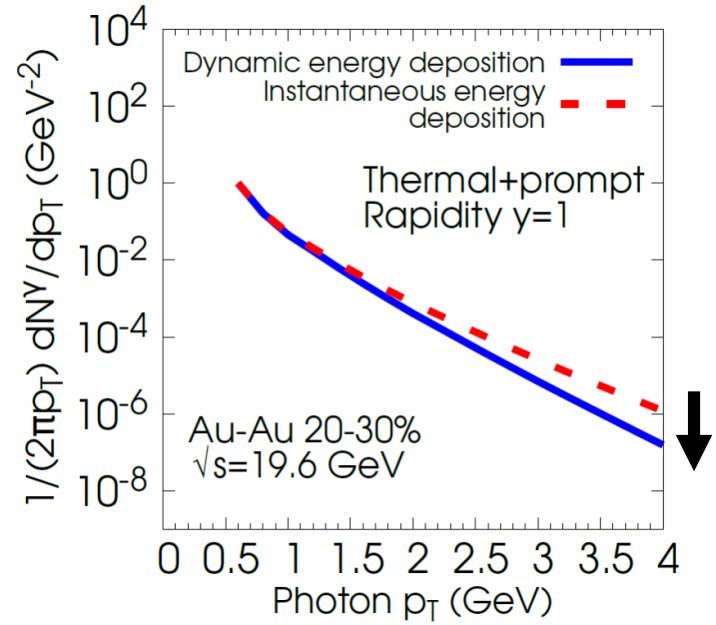
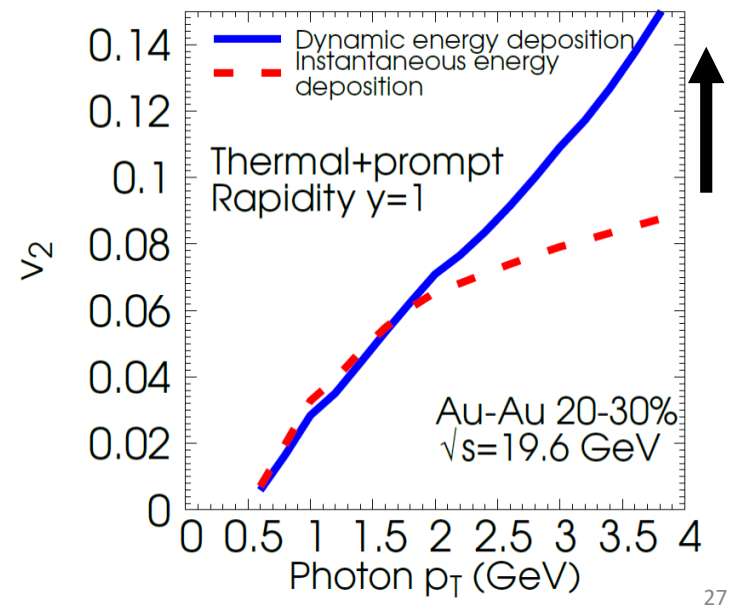


Figure ref.: Modified from Schenke and Shen



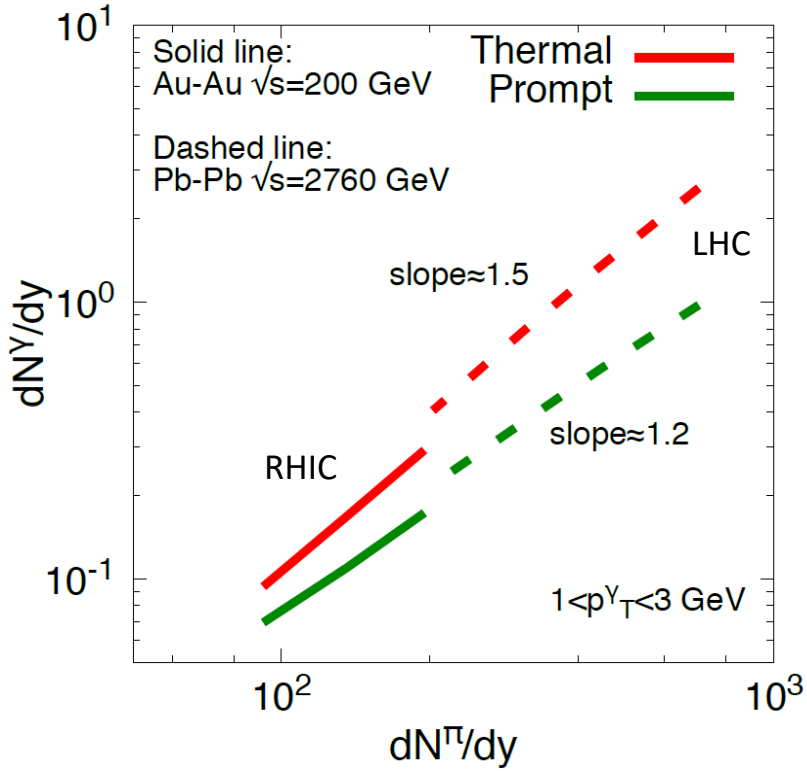


"Instantaneous" energy deposition (high collision energy limit)

Centrality&$\sqrt{s_{NN}}$ dependence of photon production

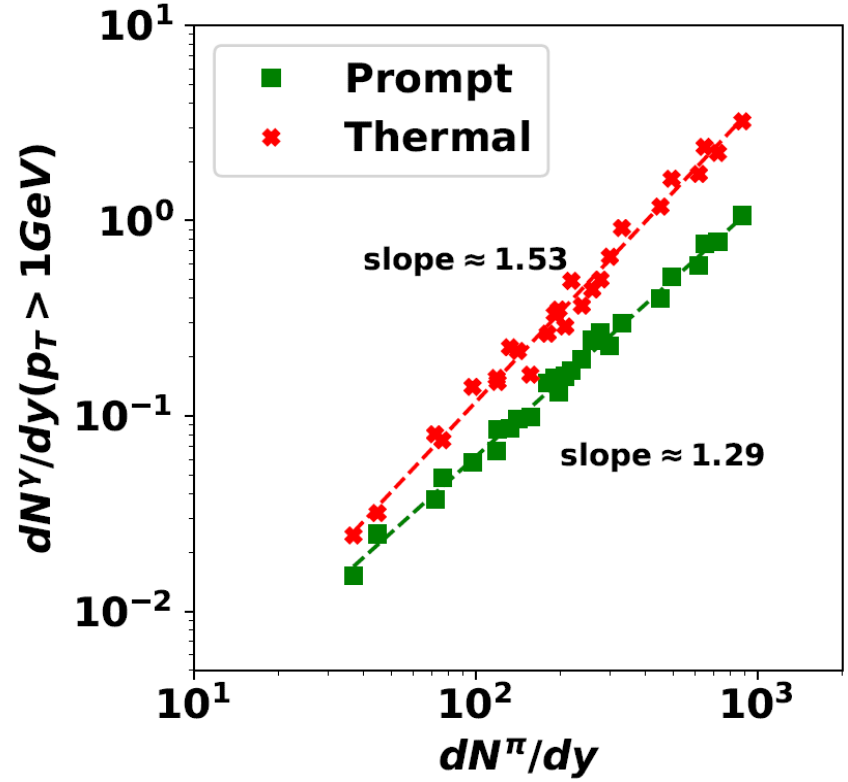
Another approach: integrate photon spectra dN/dp_T above p_T cutoff **& plot with respect to hadron multiplicity** (proxy for centrality&$\sqrt{s_{NN}}$)

Ref.: QM2015 proceedings [1704.07842]



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

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

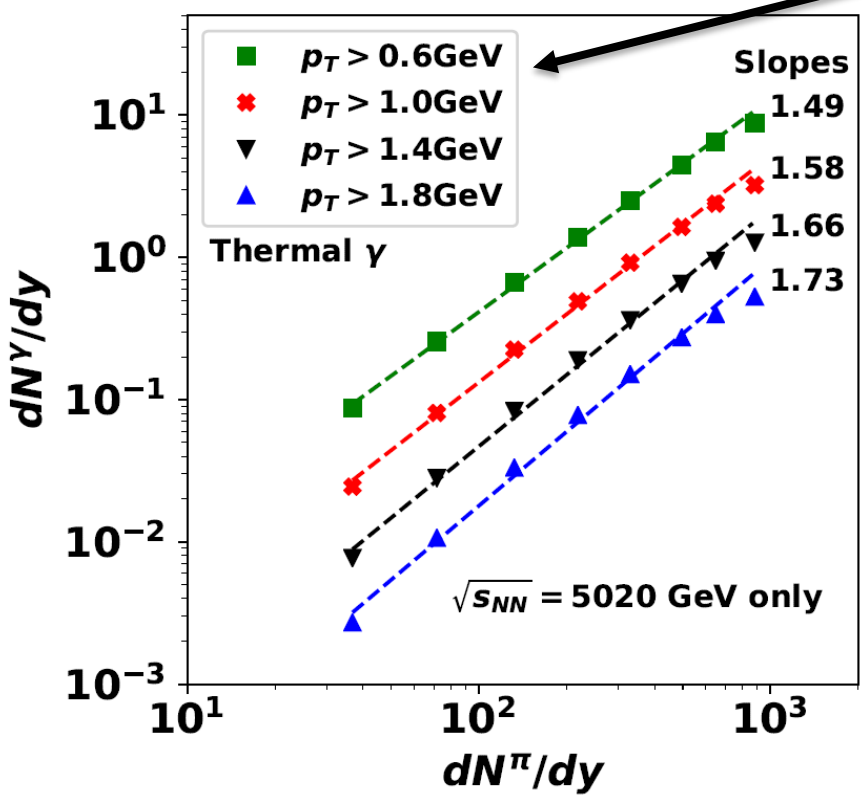


RHIC $\sqrt{s_{NN}}$=19.6, 39, 62.4 & 200 GeV
LHC $\sqrt{s_{NN}}$=2760 & 5020 GeV

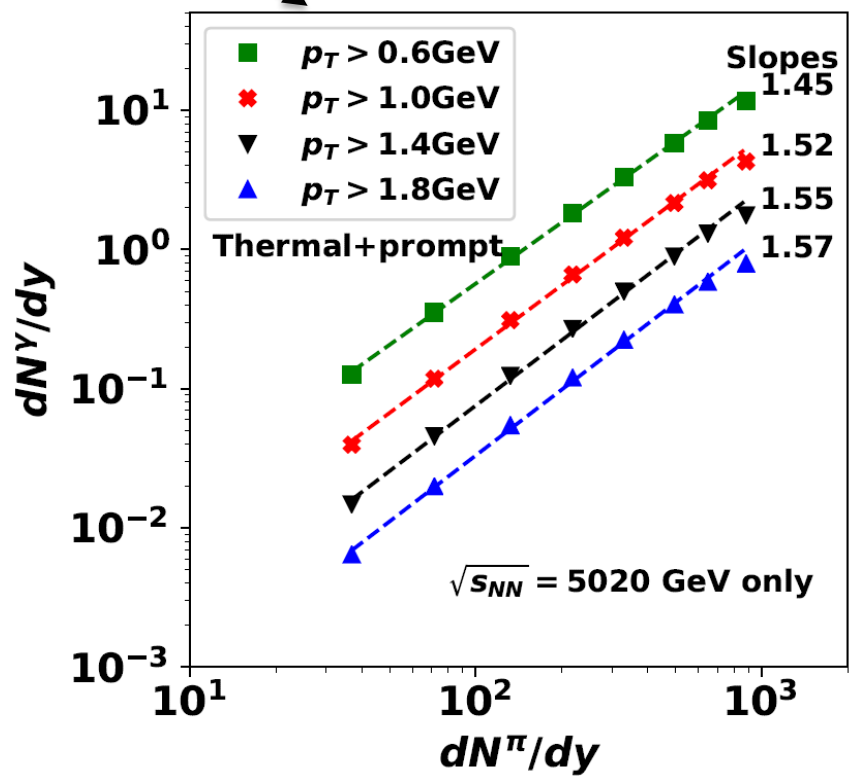
Photon vs pion multiplicity using centrality

Preliminary results

$\sqrt{s_{NN}} = 5020$ GeV; $p_T > p_T^{min}$



Thermal photons

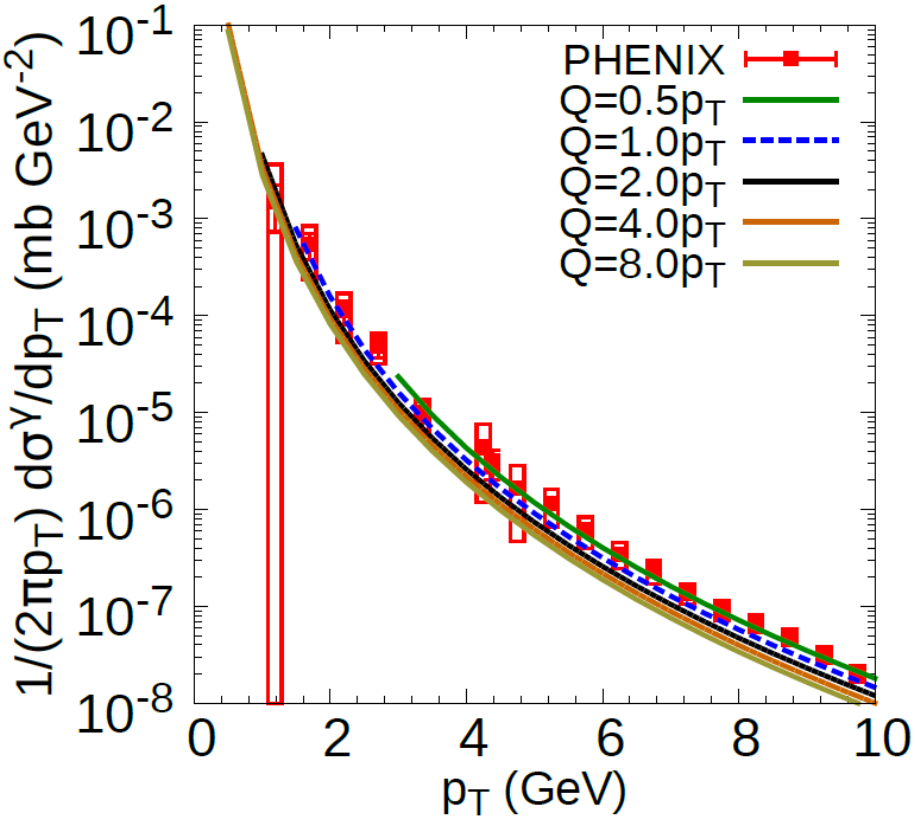


Thermal+prompt photons

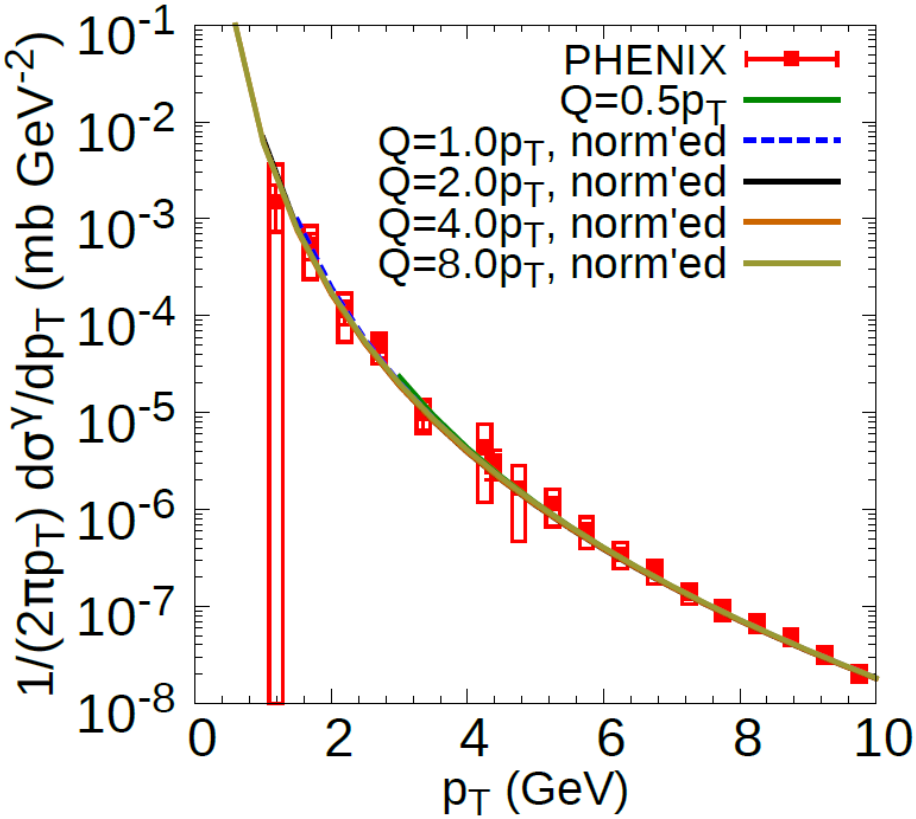
Prompt photon slope: 1.35

Simple test: p_T **cut-off dependence** for **thermal photons**, **NOT** for prompt

Prompt photons

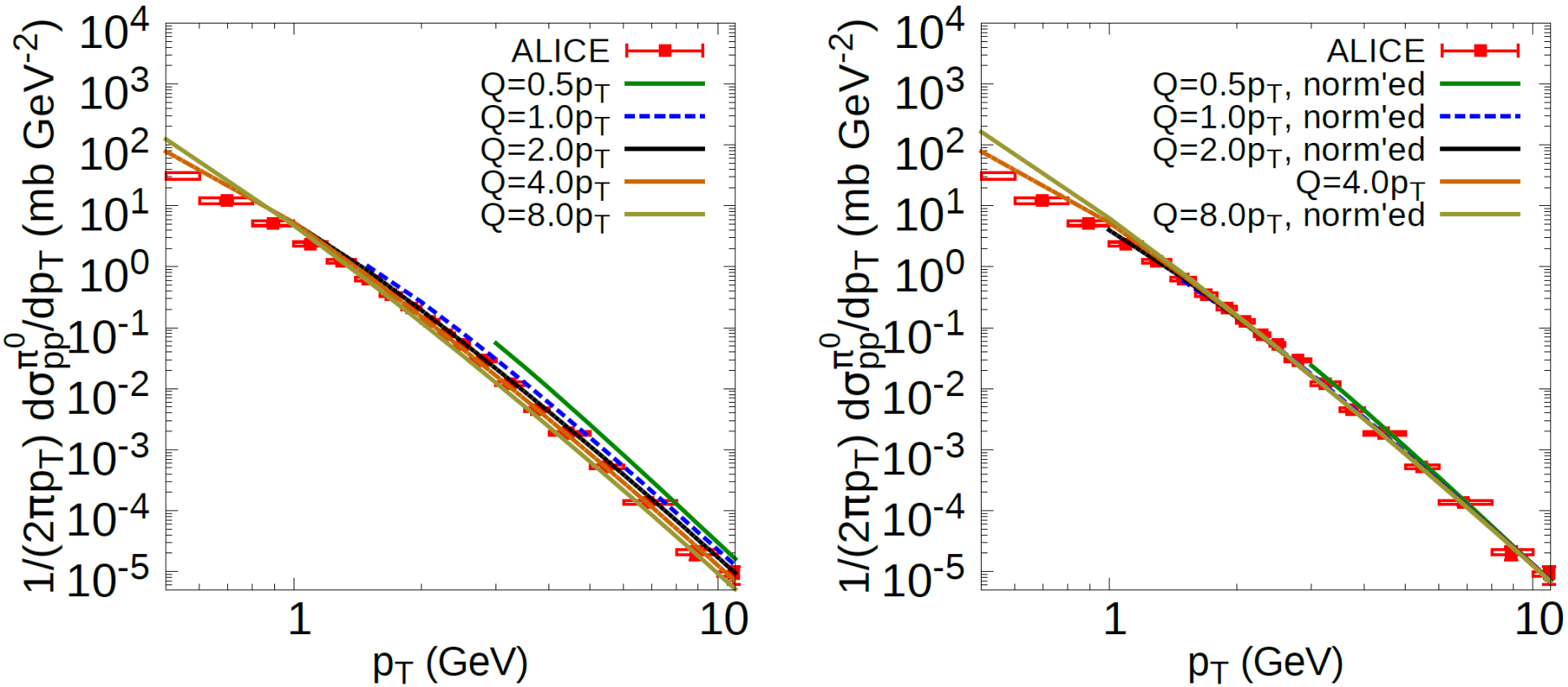


(a)



(b)

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)



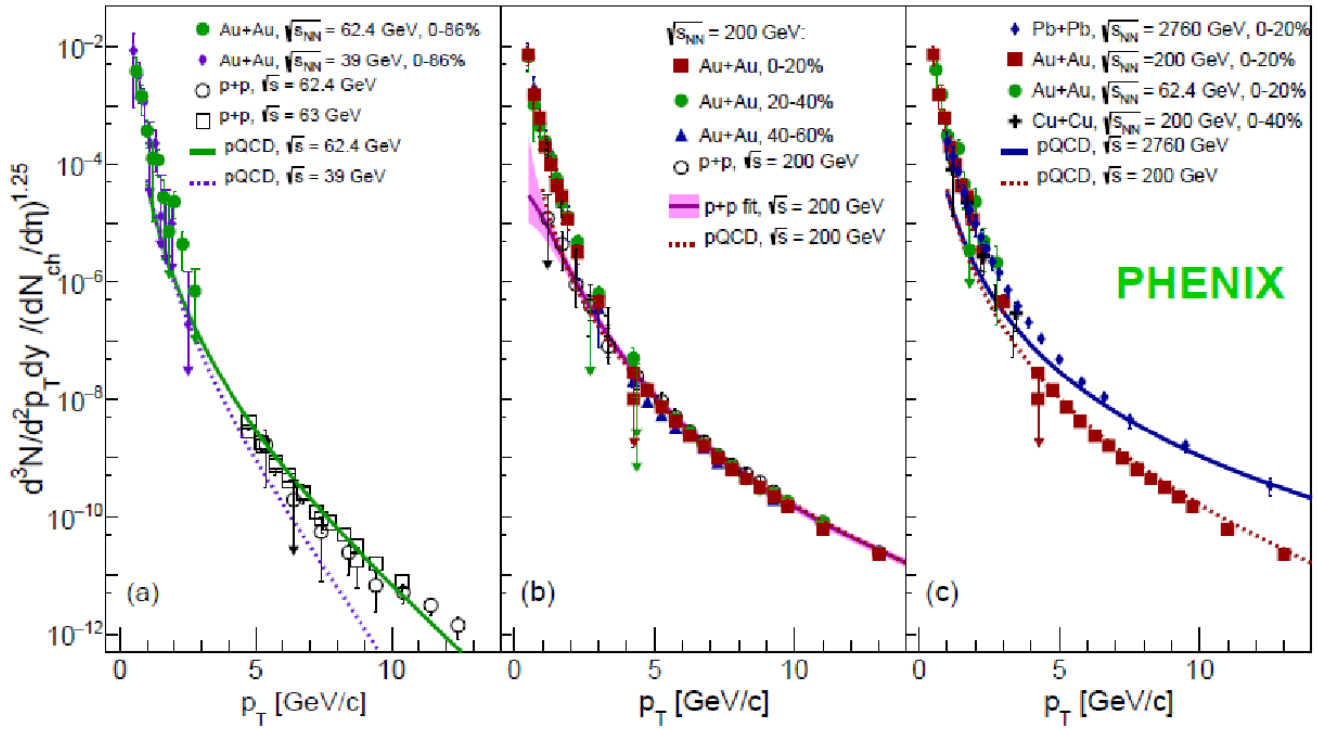
(a) (b)

Figure A.2: Same as Figure A.1 for pions measured in $\sqrt{s_{NN}} = 2.76$ TeV proton-proton collisions at the LHC

PHENIX collaboration

Beam-energy and centrality dependence of direct-photon emission from ultra-relativistic heavy-ion collisions

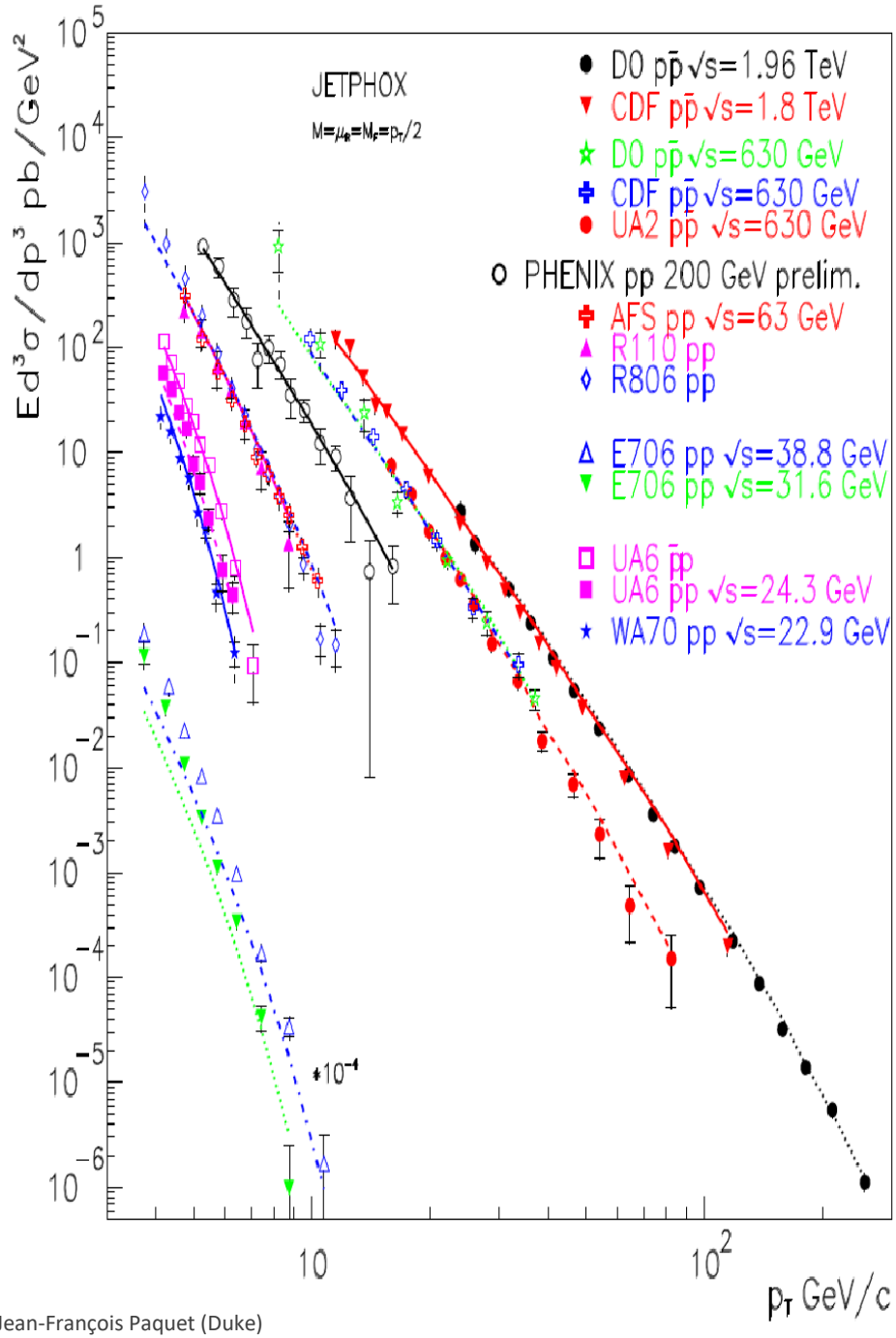
arXiv:1805.04084v1 [hep-ex] 10 May 2018



Aurenche et al: prompt photons in p+p

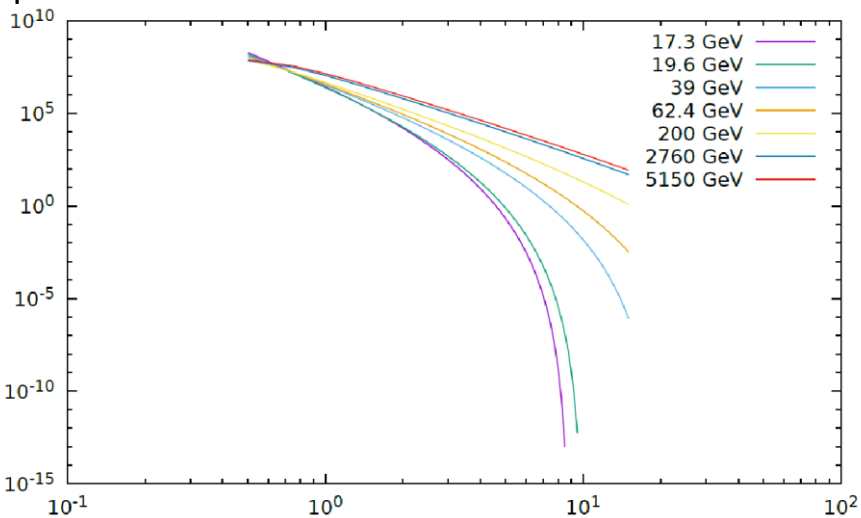
A NEW CRITICAL STUDY OF PHOTON PRODUCTION IN HADRONIC COLLISIONS

P. Aurenche[1], M. Fontannaz[2], J.Ph. Guillet[1], E. Pilon[1], M. Werlen[1]



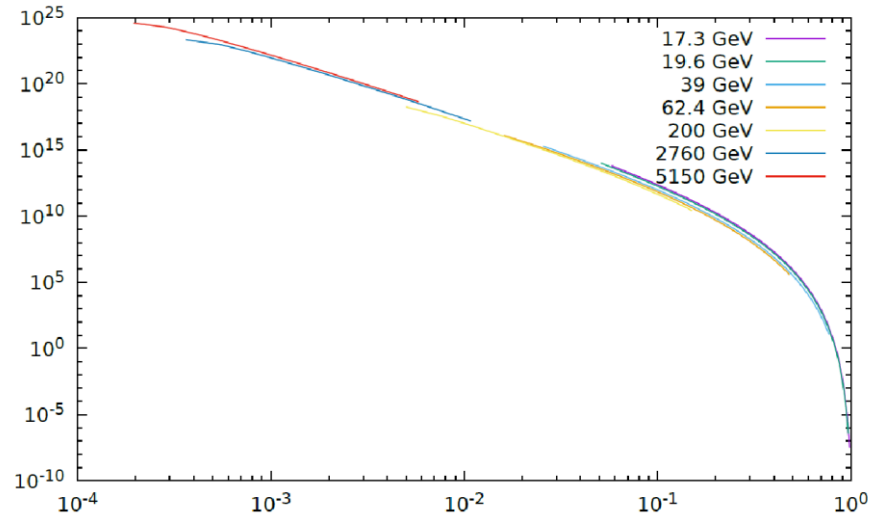
Prompts

dN/dp
T



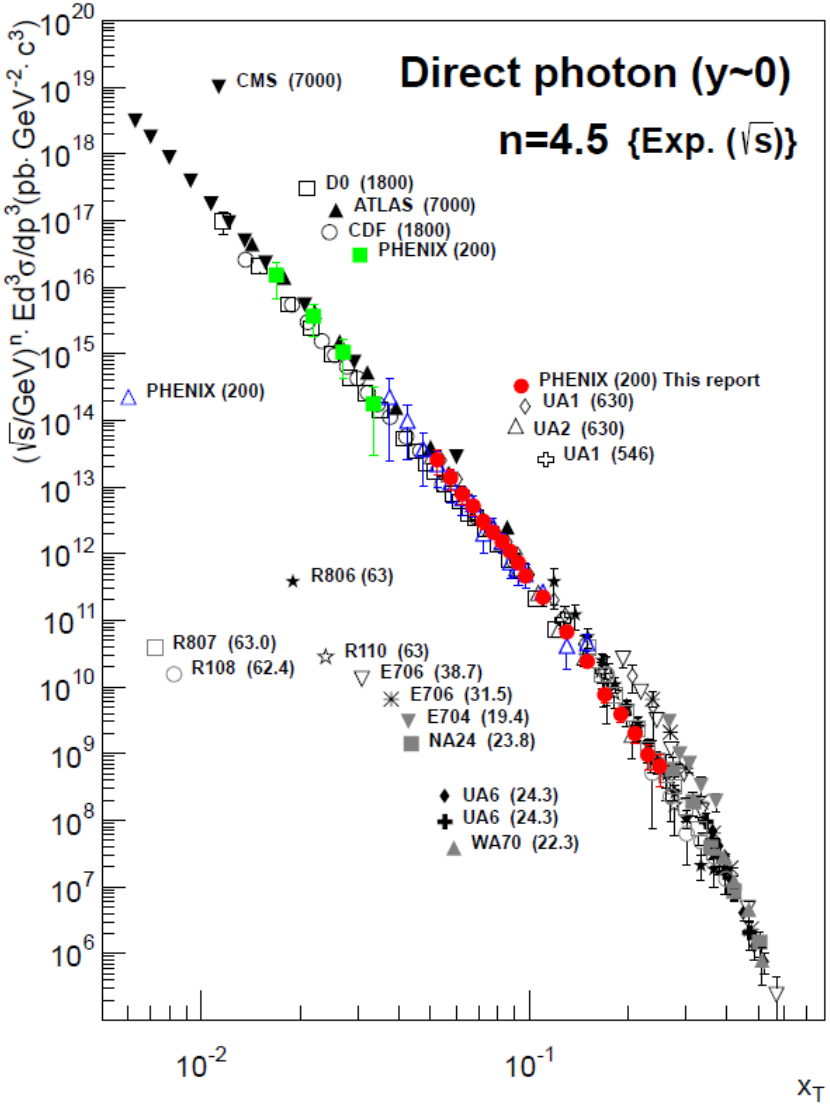
pT

Sqrt(s)^4.5*dN/dpT

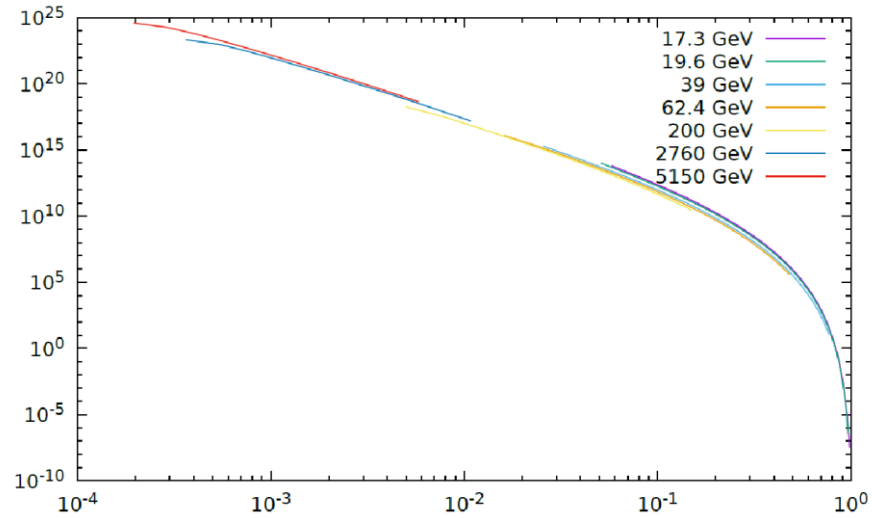


xT

Prompts



Sqrt(s)^4.5*dN/dpT



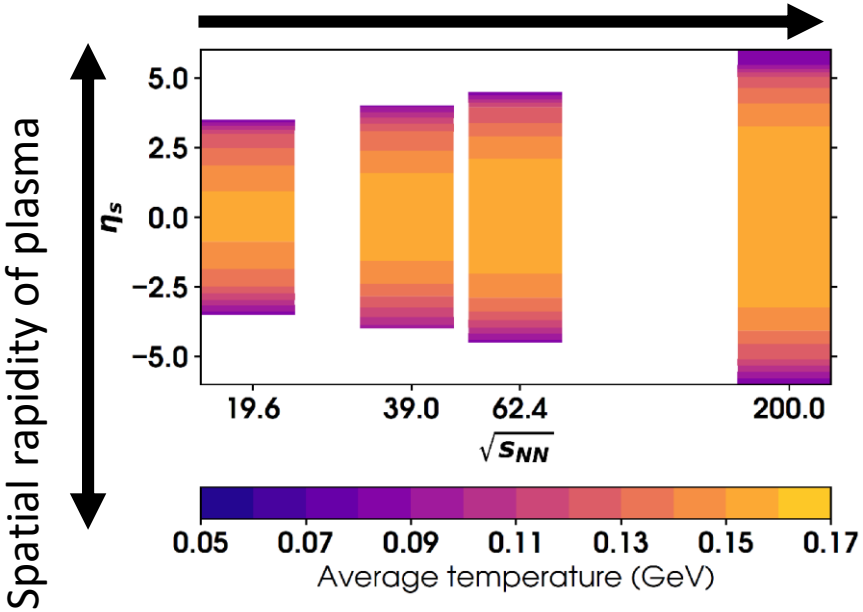
xT

PHENIX, PRD86 (2012) 072008

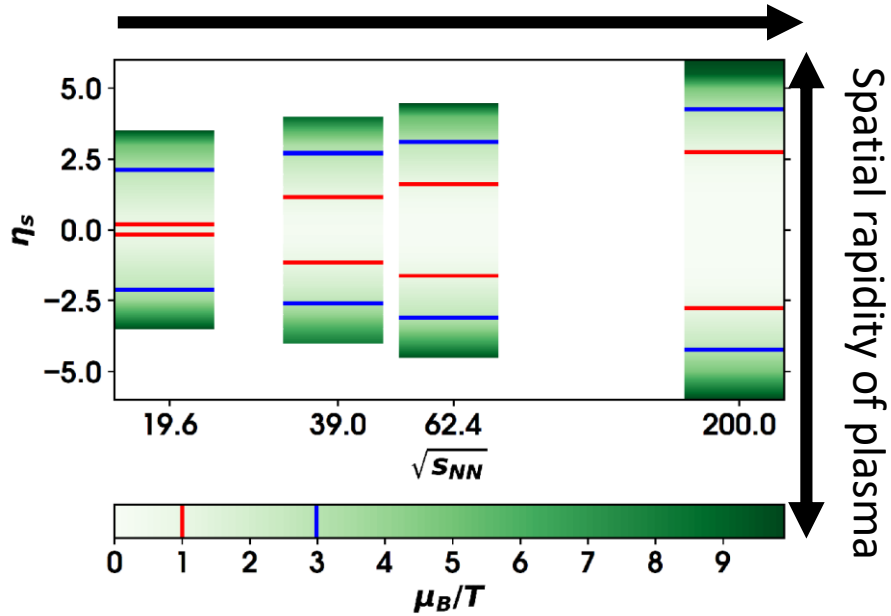
More about photons in BES

Medium properties for Au+Au at low $\sqrt{s_{NN}}$

Center-of-mass energy of collision



Center-of-mass energy of collision



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

Baryon chemical potential to temperature ratio

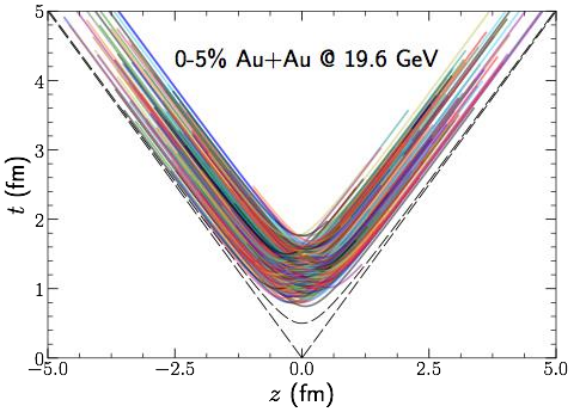
(markers at μ_B/T=1 and μ_B/T= 3 to guide the eye)

Spacetime description at low $\sqrt{s_{NN}}$

Thermal photons:
radiated by the hot plasma

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

Spacetime profile of plasma from hydrodynamic simulation



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 μ_B equation of state

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

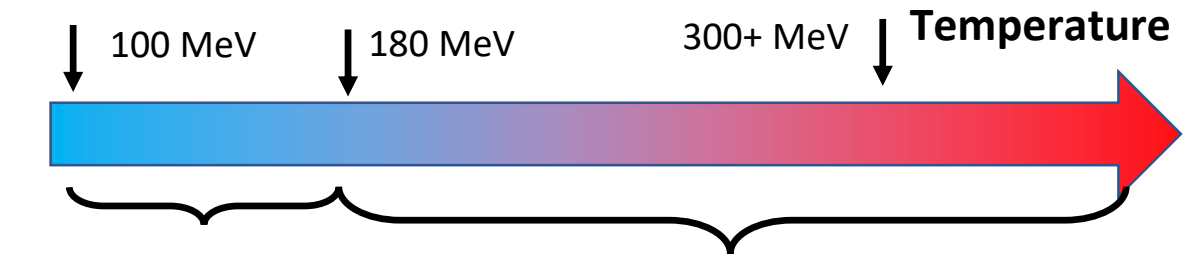
- **Dynamical initialization** of hydrodynamics over extended period of time (at small $\sqrt{s_{NN}}$) using sources:

$$\partial_\mu T^{\mu\nu} = S^\nu$$
$$\partial_\mu J^\mu_{\mathrm{B}} = \rho_B$$

Ref.: Shen & Schenke(2018)

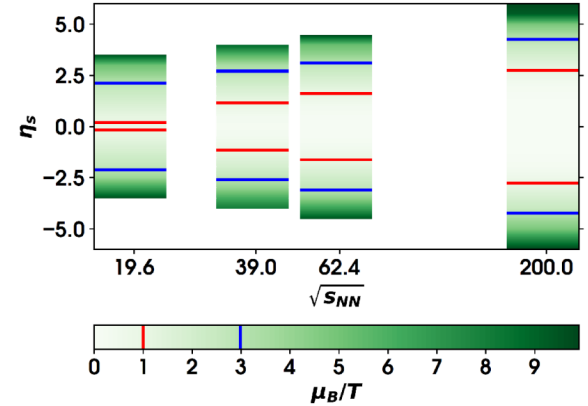
- Freeze-out at **constant energy density** 0.16 GeV/fm^3
- Tuned to soft hadron data

Photon thermal rates



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 μ_B

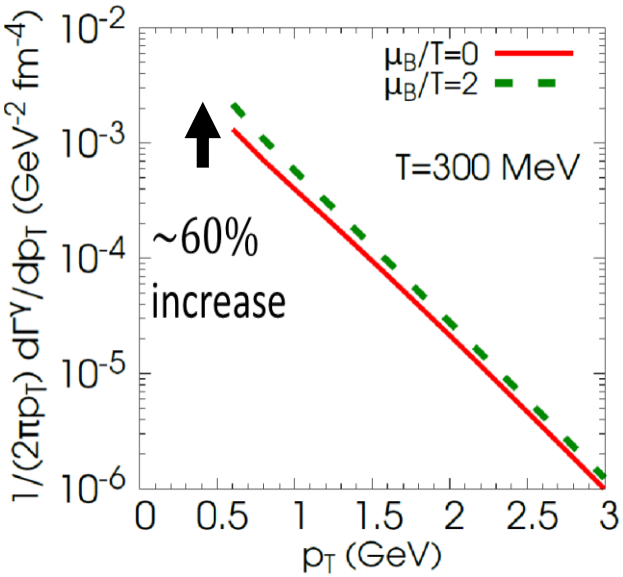
Refs.: Traxler, Vija, Thoma (1995); Gervais, Jeon (2012); This work

Hadronic rates: meson interaction, baryon interaction (at finite μ_B)

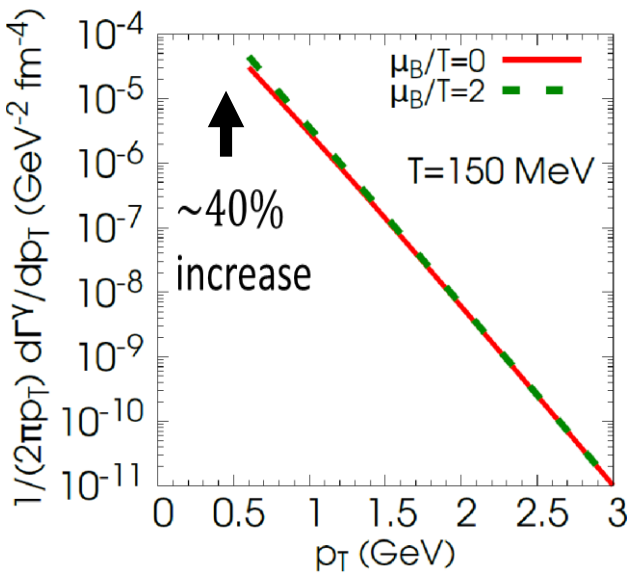
Refs.: Turbide, Rapp, Gale (2004); Heffernan, Hohler, Rapp (2014); Holt, Hohler, Rapp (2016)

Effect of finite μ_B on thermal photon rate

QGP photon rate



Hadronic photon rate

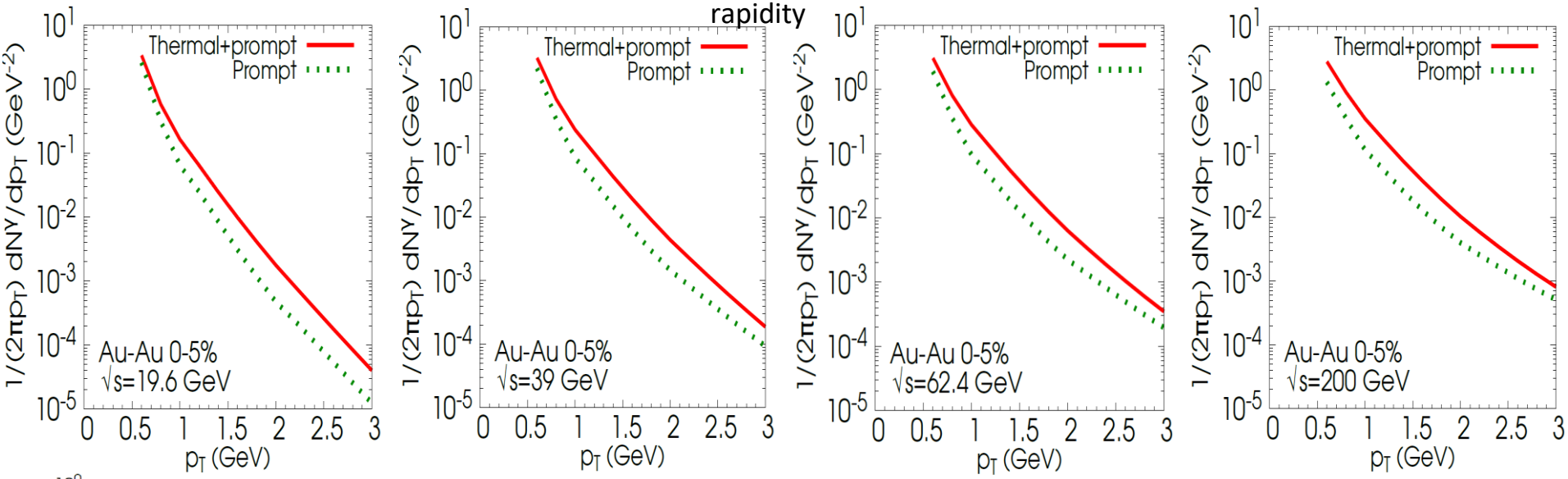


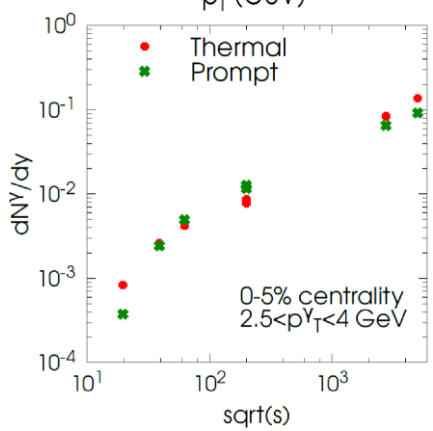
↑ Baryon chemical potential μ_B **increases the photon rate at** $\underbrace{\text{low momenta}}_{e^{-\left(\frac{E-\mu_B}{T}\right)}}$

Photon production in low $\sqrt{s_{NN}}$ collisions

$\sqrt{s_{NN}}$

19.6 GeV | 39 GeV | Mid-rapidity | 62.4 GeV | 200 GeV





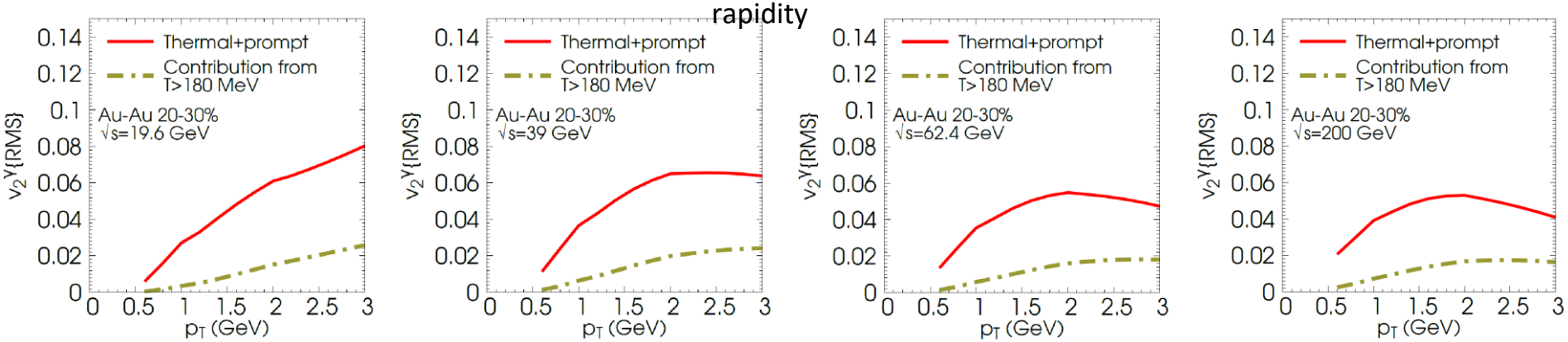
High p_T thermal photon visible against prompt photons estimate as $\sqrt{s_{NN}}$ is decreased

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

$\sqrt{s_{NN}}$

19.6 GeV | 39 GeV | Mid-rapidity | 62.4 GeV | 200 GeV



Larger photon v_2

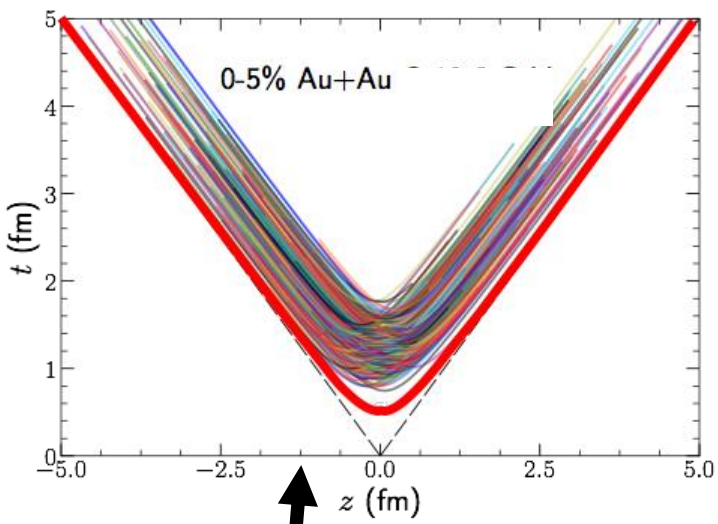
Significant v_2 across $\sqrt{s_{NN}}$

Higher fraction of v_2 from high T photons

$$v_n^{\phi} = \frac{\left\langle \frac{dN^{th,T>180\ MeV}}{d\phi} \right\rangle_{\phi} v_n^{th,T>180\ MeV} + \left\langle \frac{dN^{th,T<180\ MeV}}{d\phi} \right\rangle_{\phi} v_n^{th,T<180\ MeV}}{\left\langle \frac{dN^{th,T>180\ MeV}}{d\phi} \right\rangle_{\phi} + \left\langle \frac{dN^{th,T<180\ MeV}}{d\phi} \right\rangle_{\phi} + \left\langle \frac{dN^{prompt}}{d\phi} \right\rangle_{\phi}}$$

Probing the dynamical plasma

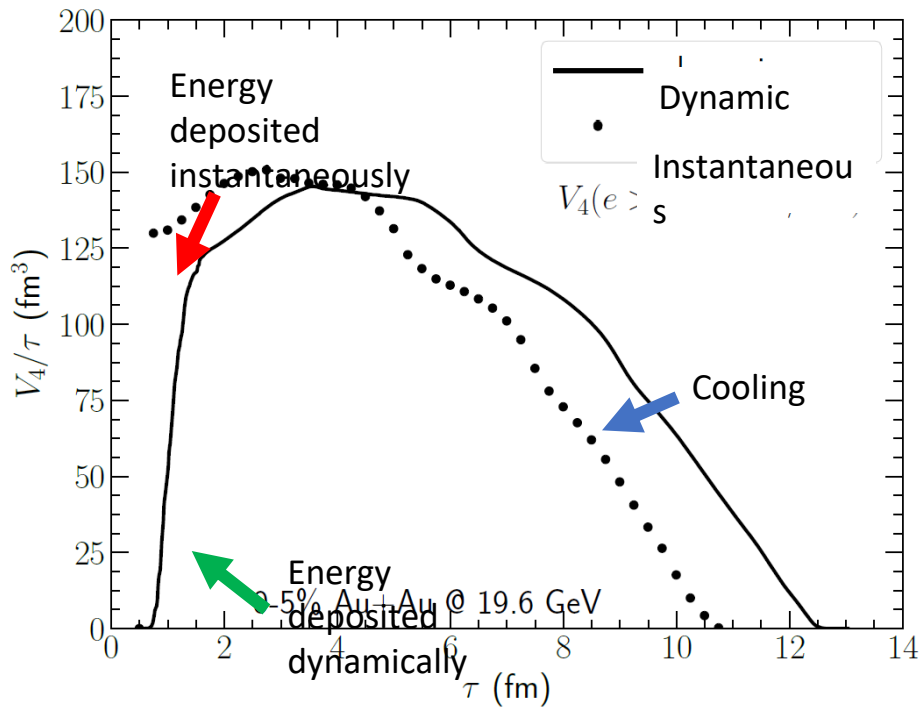
Energy & baryon number **deposited over extended time** period **at lower** $\sqrt{s_{NN}}$



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

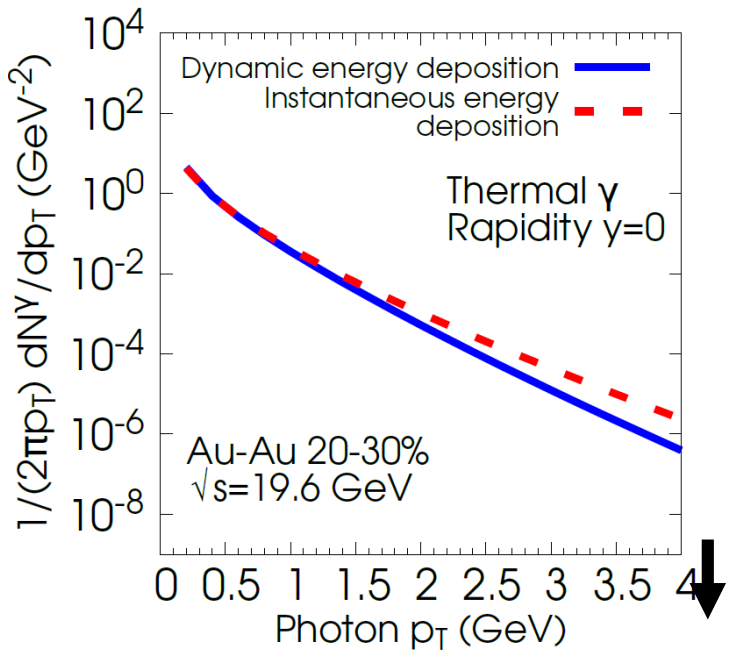
"Instantaneous" energy deposition (high collision energy limit)

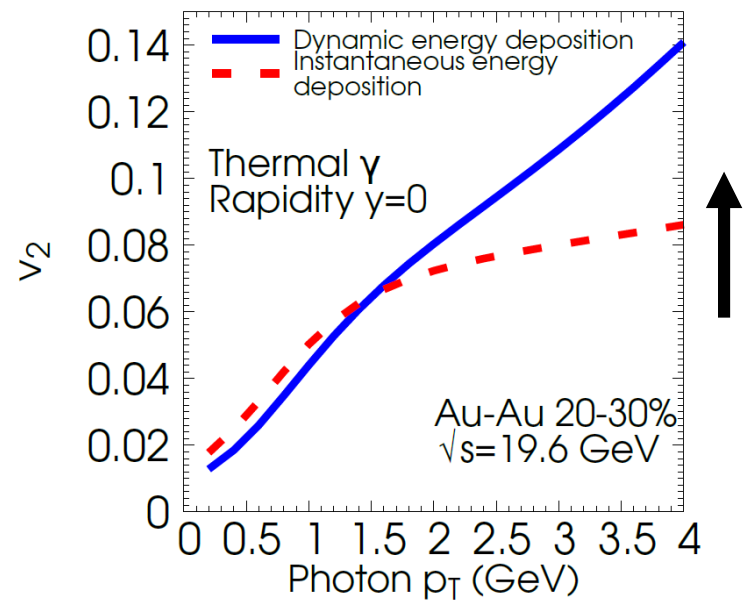
Space-time 4-volume (above freeze-out) versus time



Early plasma dynamics at low $\sqrt{s_{NN}}$ (19.6 GeV)

Thermal photons

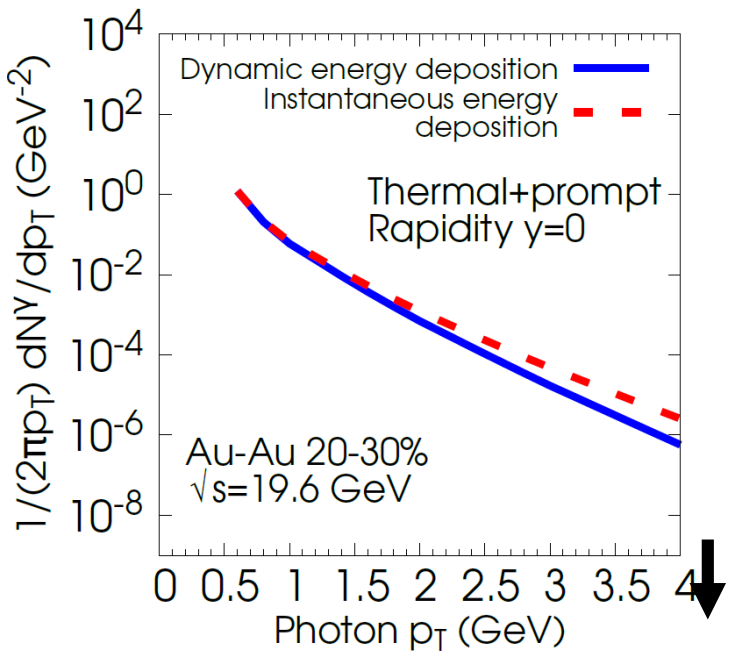


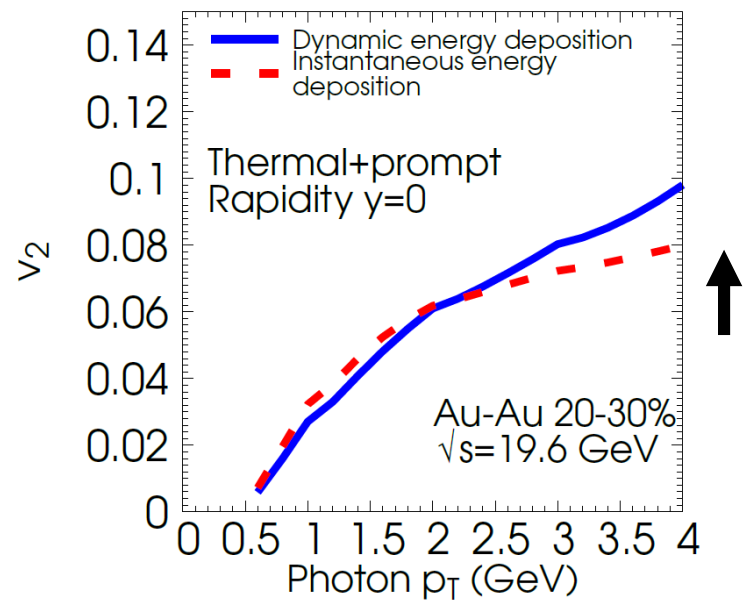


Effect of energy deposition (instantaneous vs dynamic) visible in photons

At low $\sqrt{s_{NN}}$ (19.6 GeV): thermal+prompt

Thermal+prompt photons

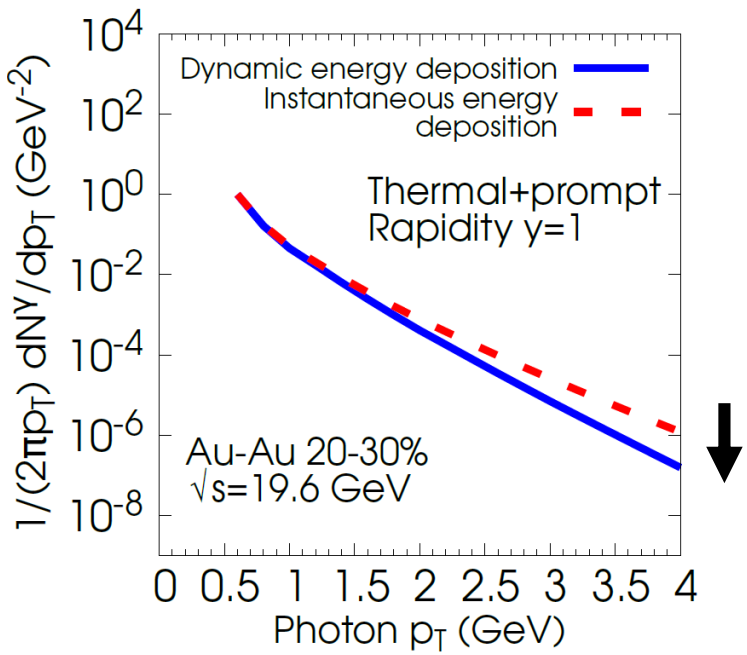


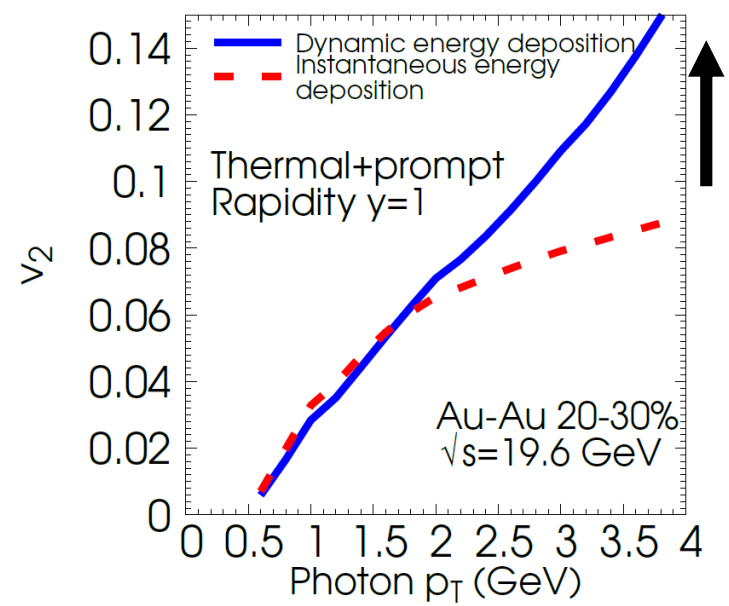


Effect of energy deposition (instantaneous vs dynamic) visible in photons

At low $\sqrt{s_{NN}}$ (19.6 GeV): away from mid-rapidity

Thermal+prompt photons

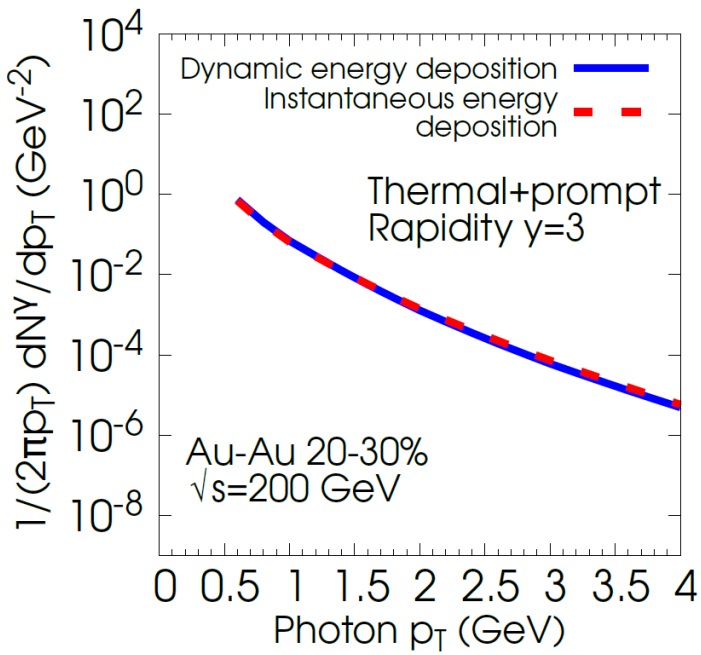


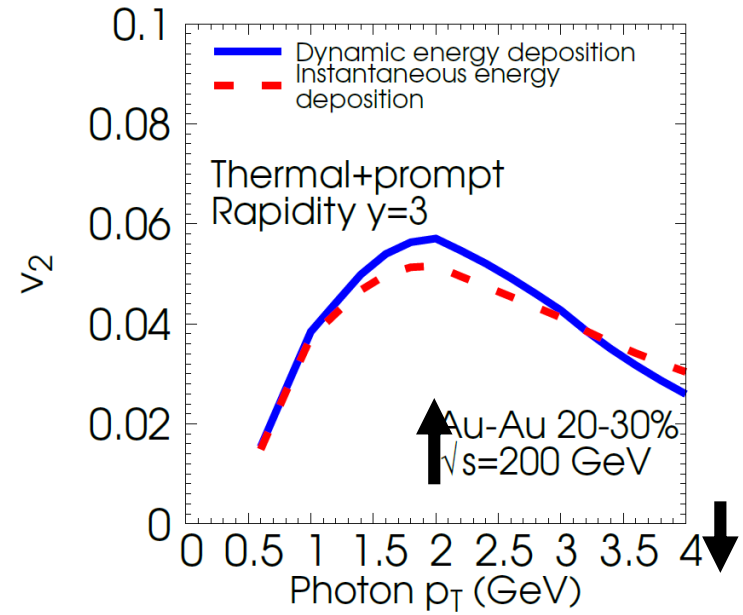


Effect of energy deposition (instantaneous vs dynamic) visible in photons

At high $\sqrt{s_{NN}}$ (200 GeV) & high rapidity

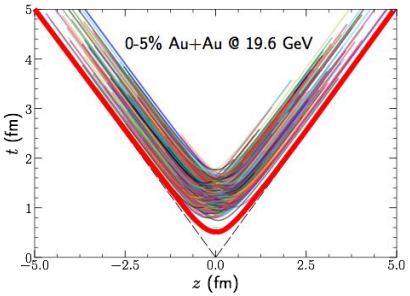
Thermal+prompt photons



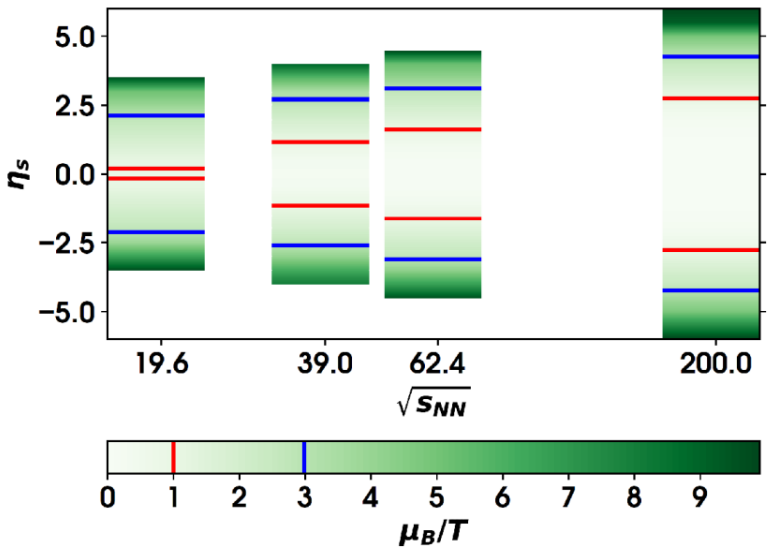


At high $\sqrt{s_{NN}}$, effect of dynamic energy deposition visible at **higher rapidity**

Summary



- **Significant** thermal **photon signal** at low $\sqrt{s_{NN}}$
- Small effect of μ_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 $\gtrsim$ 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

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

$$\frac{dN}{d\phi} = \frac{dN^{th,T>180\,MeV}}{d\phi} + \frac{dN^{th,T<180\,MeV}}{d\phi} + \frac{dN^{prompt}}{d\phi}$$

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

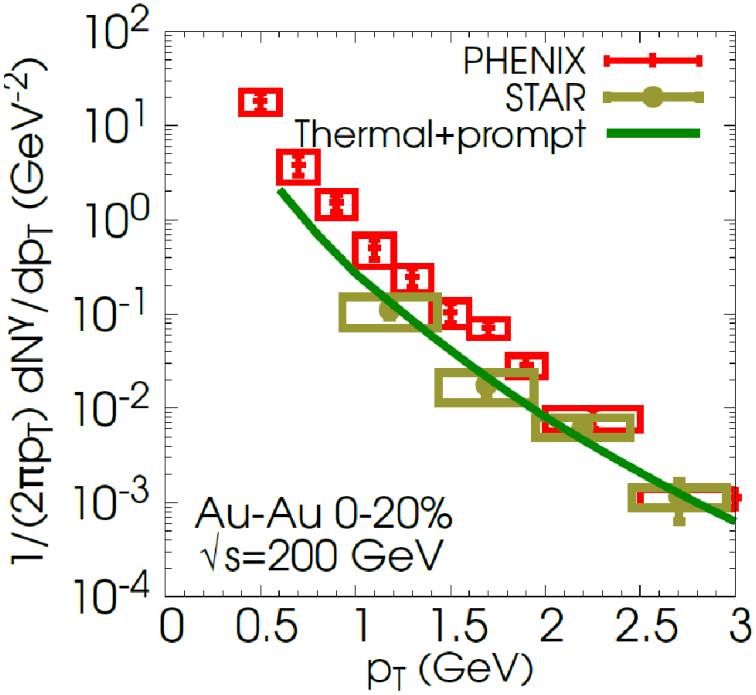
$$v_n = \frac{\int d\phi \frac{dN^{th,T>180\,MeV}}{d\phi} e^{in(\phi-\Psi_n)} + \int d\phi \frac{dN^{th,T<180\,MeV}}{d\phi} e^{in(\phi-\Psi_n)}}{\int d\phi \left(\frac{dN^{th,T>180\,MeV}}{d\phi} + \frac{dN^{th,T<180\,MeV}}{d\phi} + \frac{dN^{prompt}}{d\phi} \right)}$$

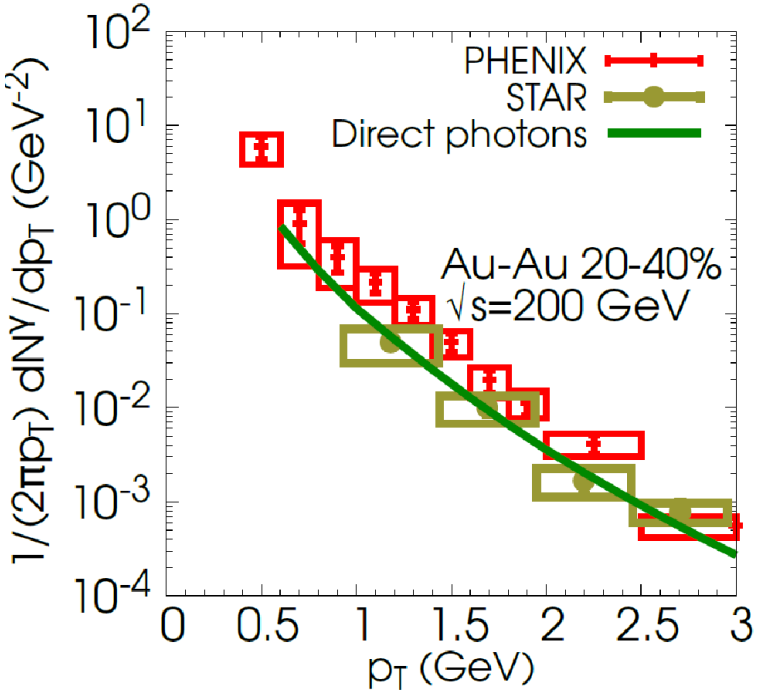
$$v_n = \frac{\left\langle \frac{dN^{th,T>180\,MeV}}{d\phi} \right\rangle_\phi v_n^{th,T>180\,MeV} + \left\langle \frac{dN^{th,T<180\,MeV}}{d\phi} \right\rangle_\phi v_n^{th,T<180\,MeV}}{\left\langle \frac{dN^{th,T>180\,MeV}}{d\phi} \right\rangle_\phi + \left\langle \frac{dN^{th,T<180\,MeV}}{d\phi} \right\rangle_\phi + \left\langle \frac{dN^{prompt}}{d\phi} \right\rangle_\phi}$$

$$\langle \ldots \rangle_\phi = \frac{1}{2\pi} \int d\phi \ \ldots$$

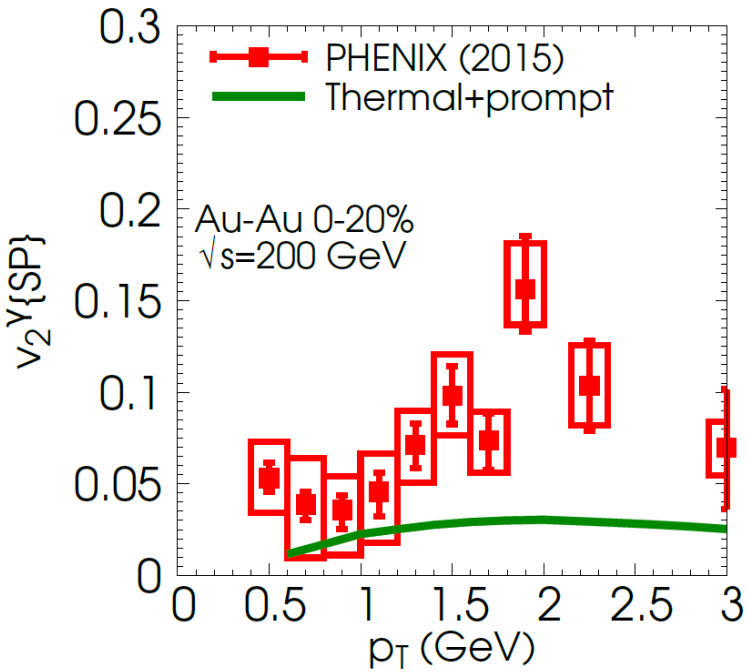
Comparison with available data

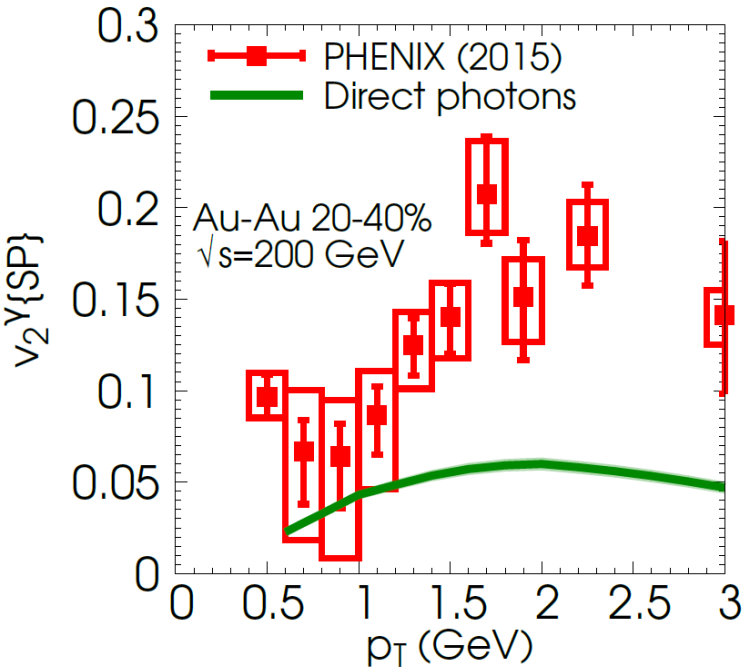
Spectra at 200 GeV



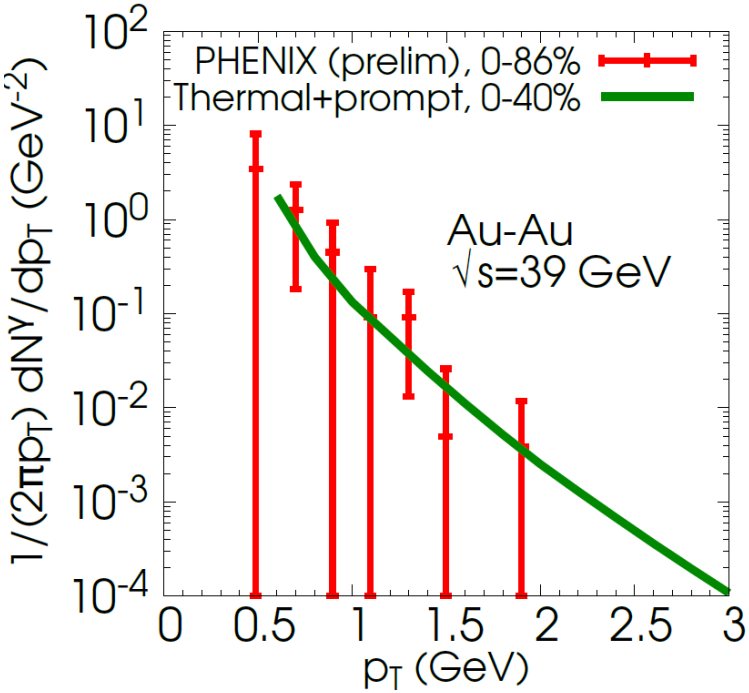


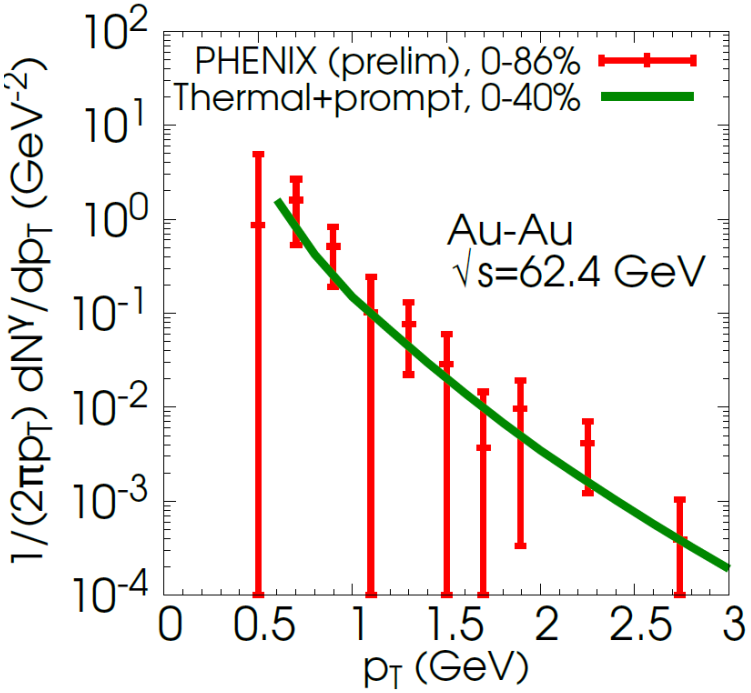
v_2 at 200 GeV


PHENIX (2015)
Thermal+prompt
Au-Au 0-20%
√s=200 GeV
v2γ{SP}
pT (GeV)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.5
1
1.5
2
2.5
3


PHENIX (2015)
Direct photons
Au-Au 20-40%
√s=200 GeV
v2γ{SP}
pT (GeV)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.5
1
1.5
2
2.5
3

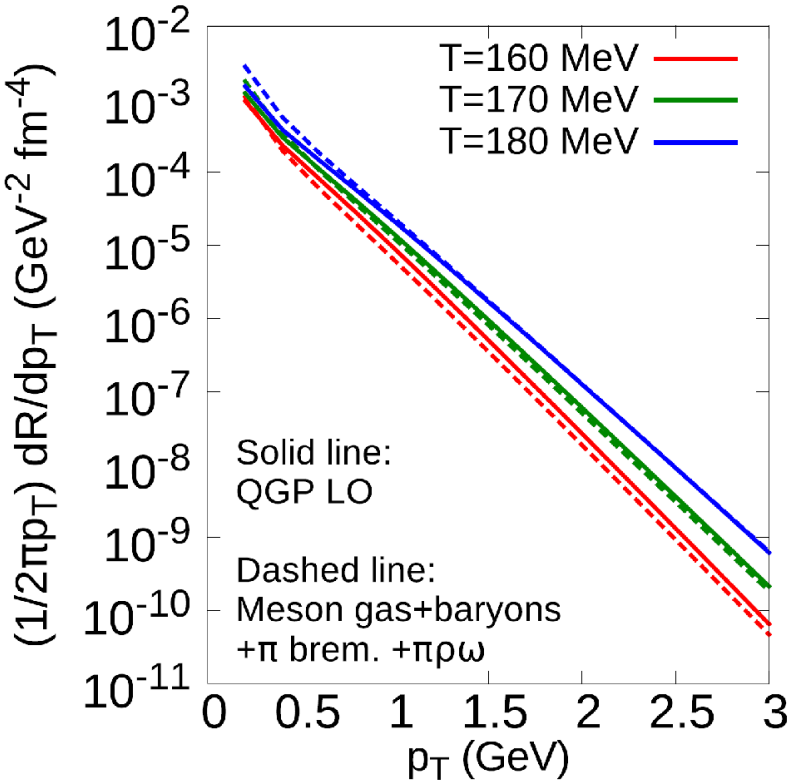
Spectra at 39 & 62.4 GeV:
0-40% centrality calculation vs 0-86% data

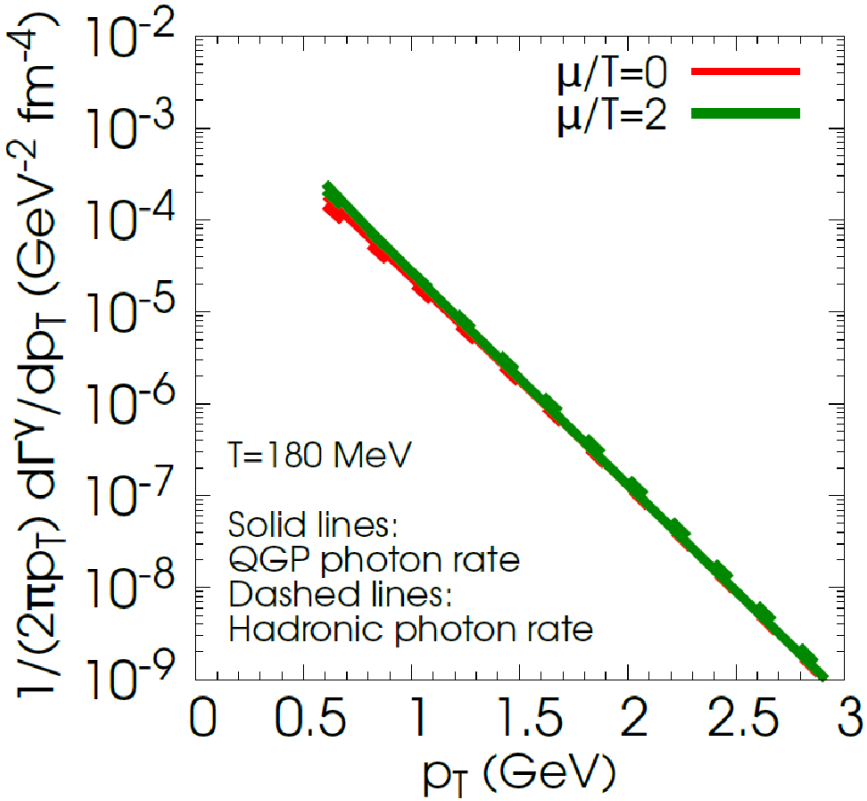




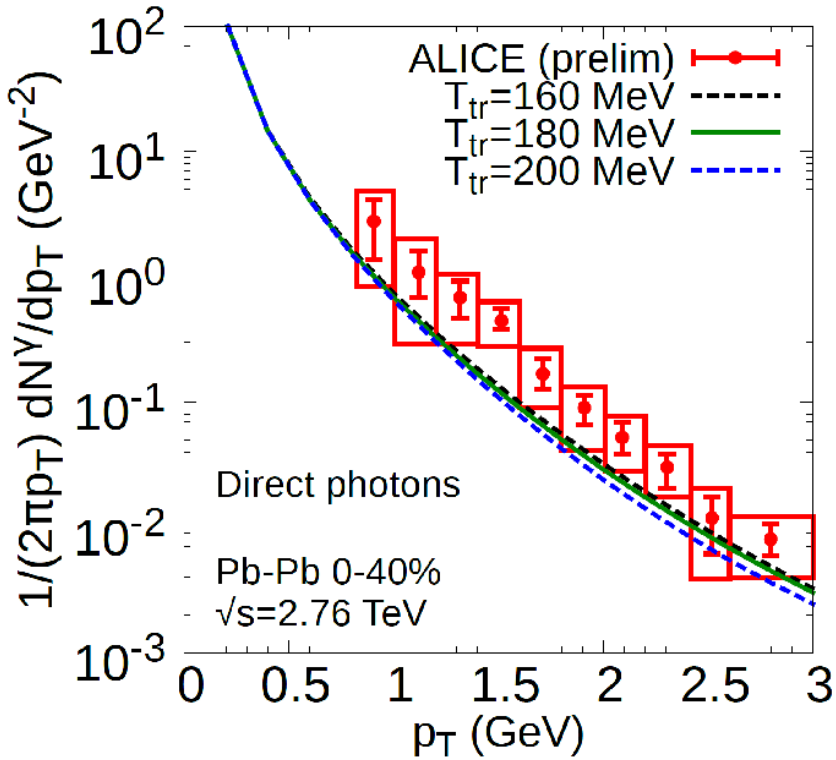
Transition temperature for photon rates

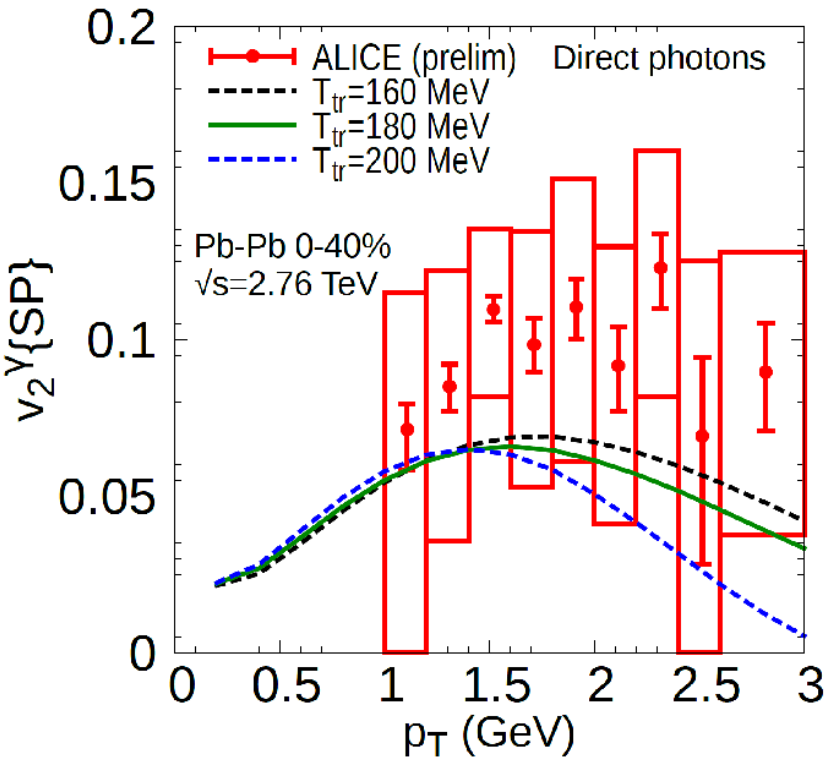
QGP vs hadronic photon rates around T_c





Photon production for different transition T





Thermal EM probes: thermal rate

QM2017

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

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

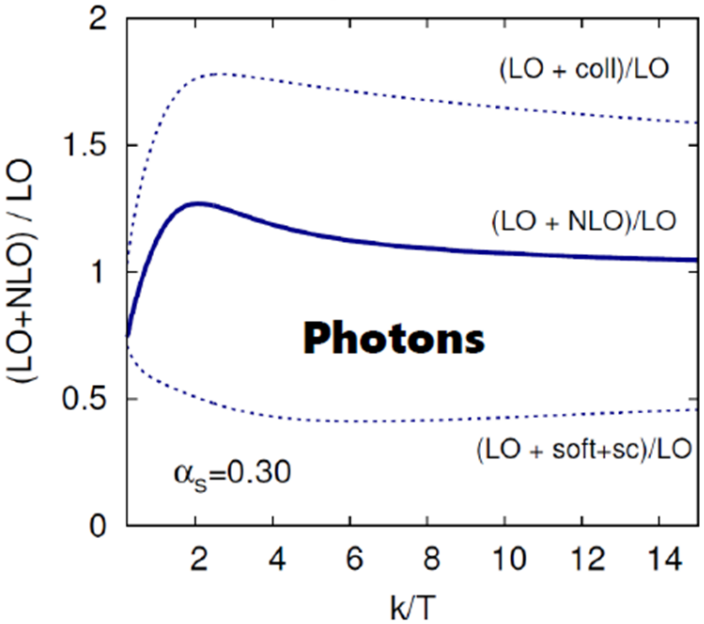
Arnold, Moore, Yaffe (AMY); Ghiglieri, Teaney; Laine, ...

Jean-François Paquet (Stony Brook) 17

Perturbative rate at LO and NLO in g_s

QM2017

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



NLO (g_s^3) correction to photon rate is <u>small</u>

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

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

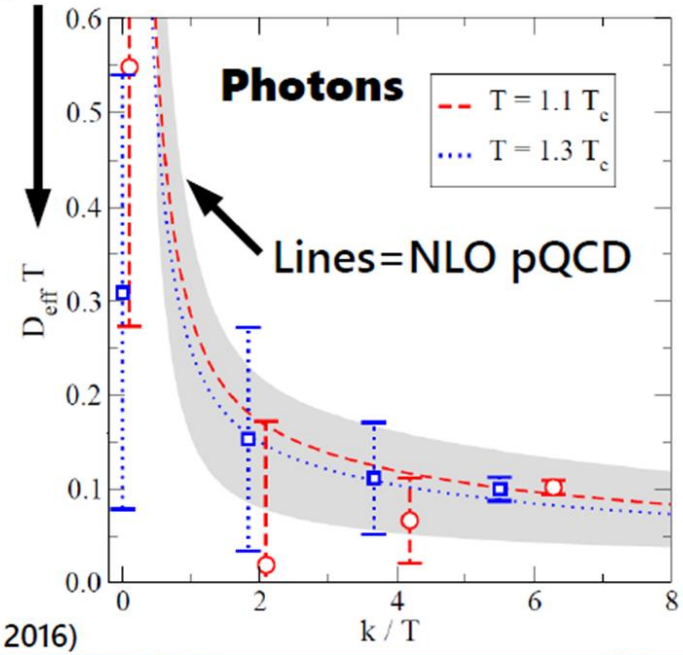
Perturbative photon rate vs lattice

QM2017

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

$$\frac{d\Gamma_\gamma(\mathbf{k})}{d^3\mathbf{k}} = \frac{2\alpha_{em}\chi_q}{3\pi^2} n_B(k) D_{eff}(k)$$

Proportional to photon rate



(note: quarks are quenched in both the lattice and pQCD calculations)

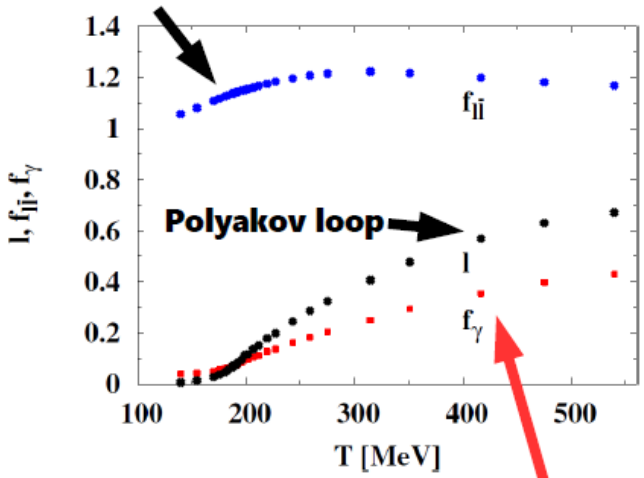
(Ref.: Ghiglieri, Kaczmarek, Laine & Meyer, PRD, 2016)

Effective QGP model

QM2017

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)

$$k\frac{d^3\Gamma_\gamma^{LO}}{d\boldsymbol{k}} = k\frac{d^3\Gamma_\gamma^{2\to 2}}{d\boldsymbol{k}} + k\frac{d^3\Gamma_\gamma^{collinear}}{d\boldsymbol{k}}$$

Suppression factor for "2→ 2" part of photon rate

(possibly **less suppression** for **collinear** rate)

(Refs.: Gale et al, PRL, 2015; Hidaka, Lin, Pisarski & Satow, JHEP, 2015)

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

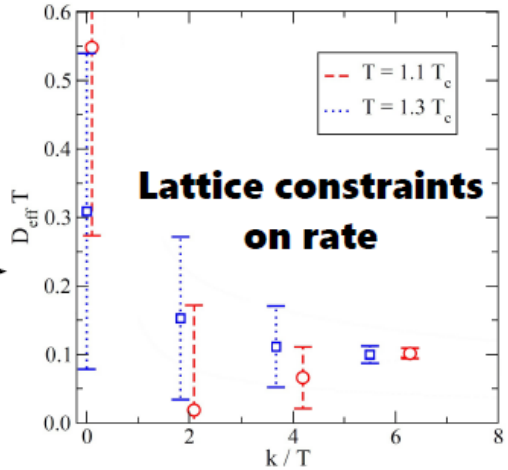
QM2017

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

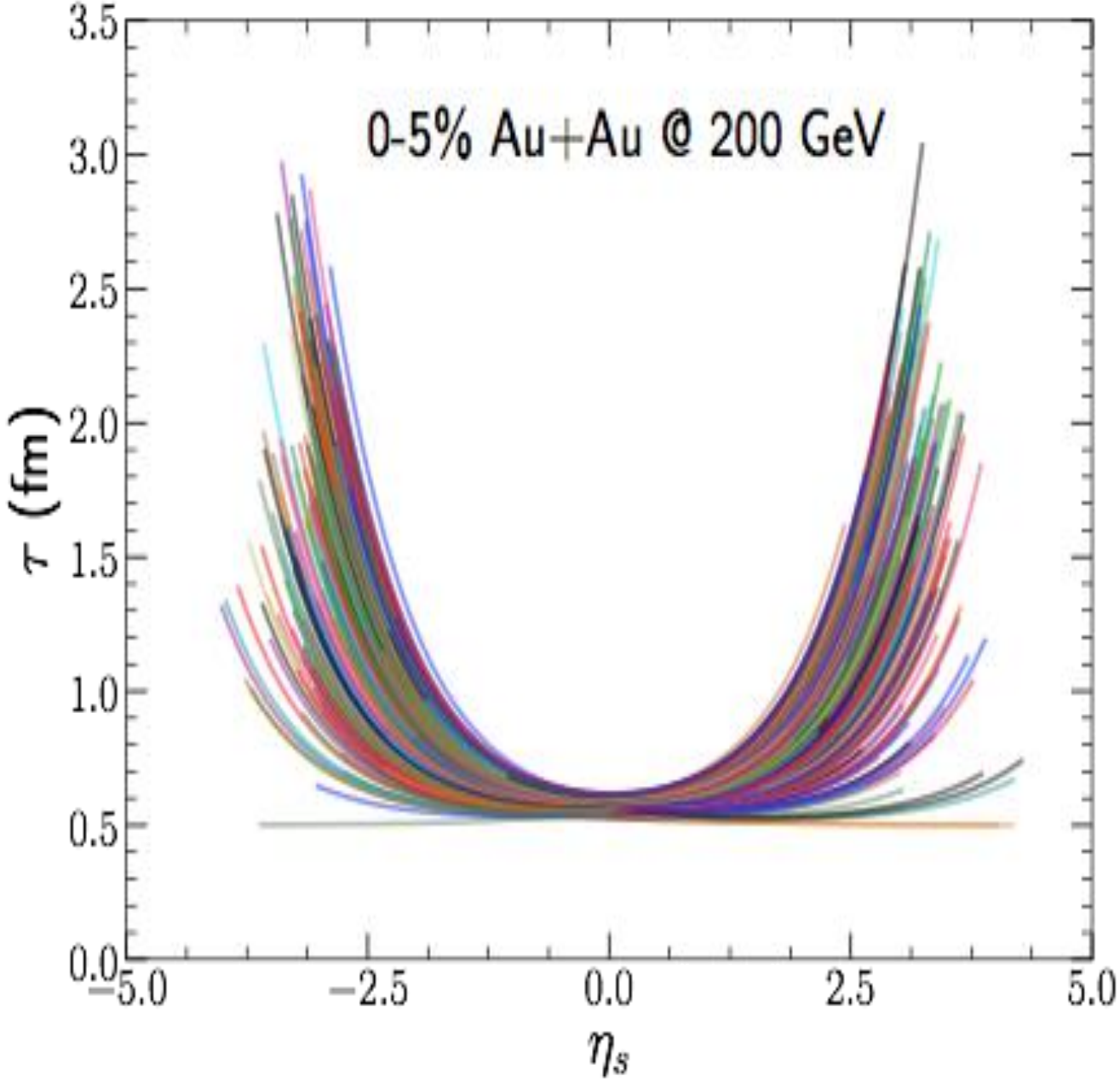
>> Mixed signal from different approaches <<

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?

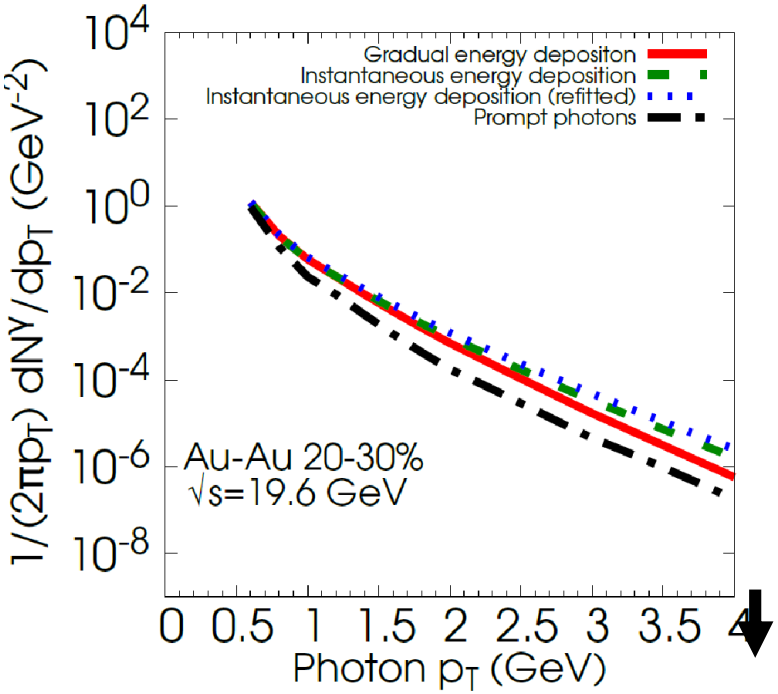


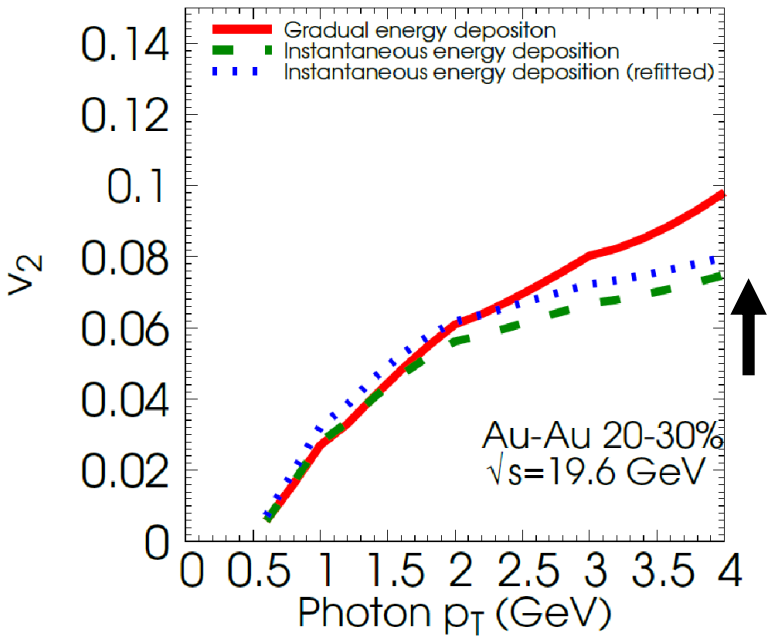
Energy deposition at high rapidity – sqrt(s)=200 GeV


0-5% Au+Au @ 200 GeV
τ (fm)
η_s
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−5.0
−2.5
0.0
2.5
5.0

Instantaneous energy deposition - refitting

Probing the early plasma: low $\sqrt{s_{NN}}$



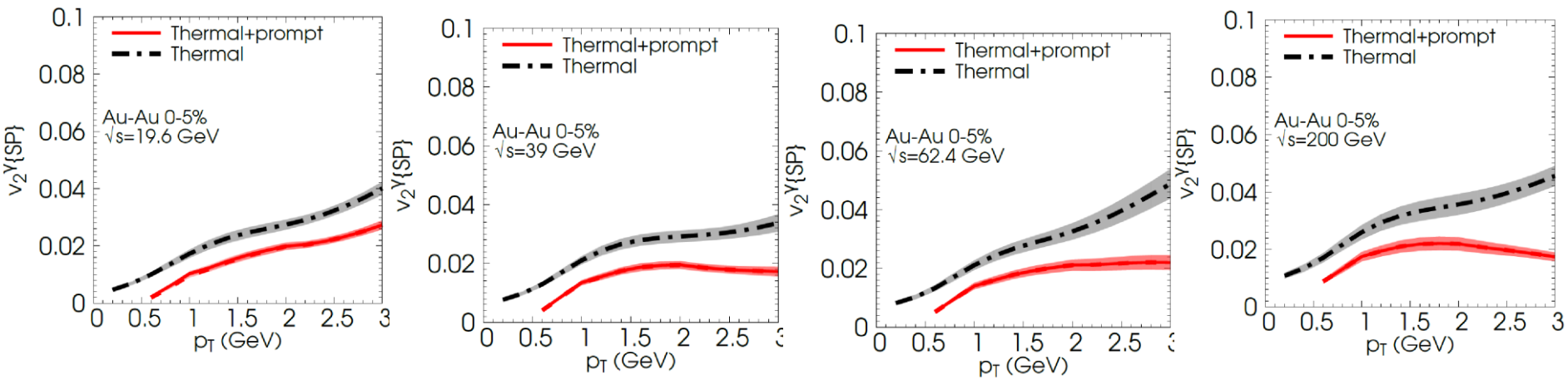


Photon v_2: before prompt dilution

Photon v_2 in low $\sqrt{s_{NN}}$ collisions

Center-of-mass energy of collision

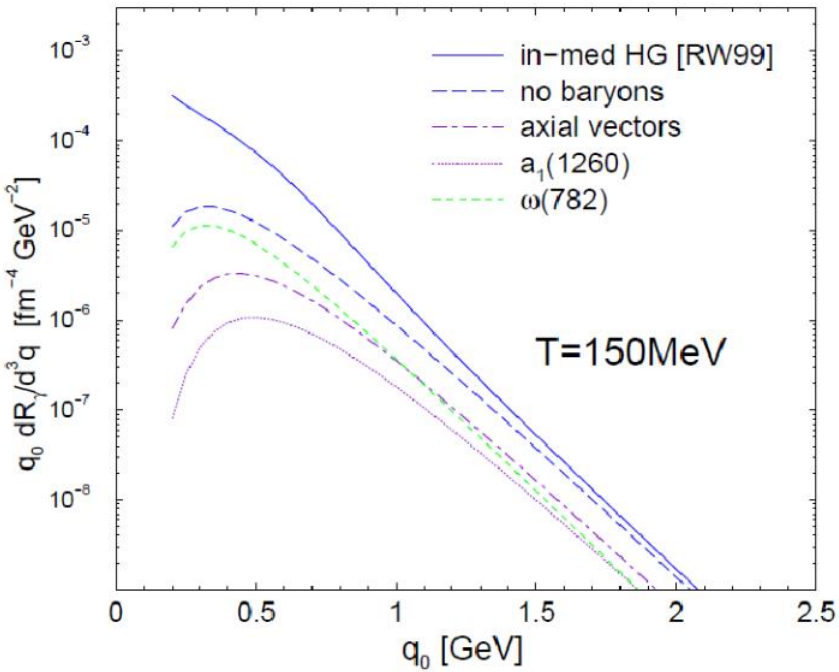
19.6 GeV | 39 GeV | 62.4 GeV | 200 GeV

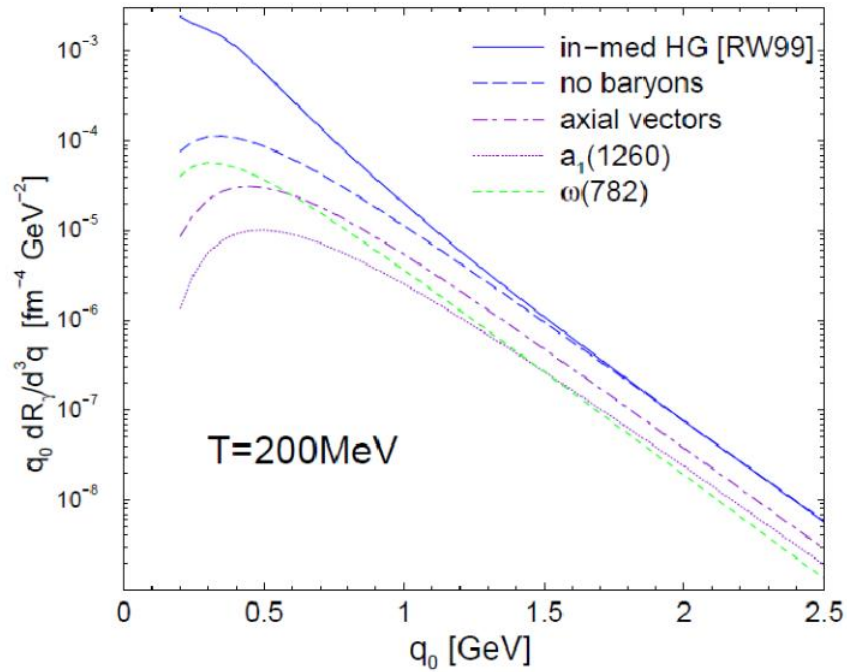


Significant v_2 across $\sqrt{s_{NN}}$

Photon rates: extra details

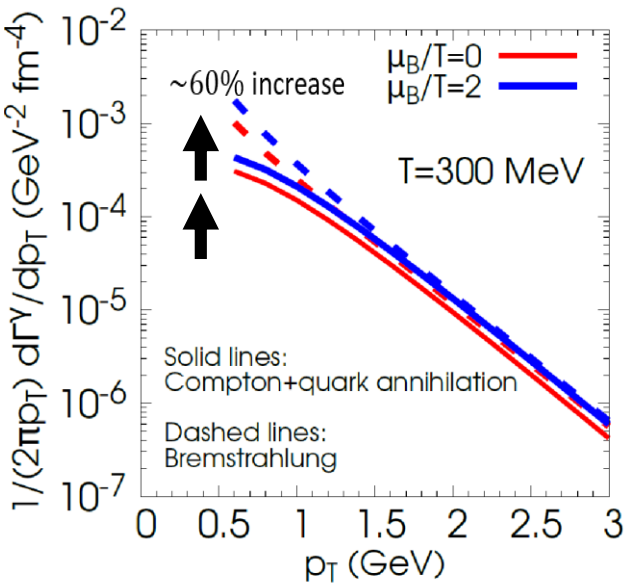
Hadronic photon rate at zero μ_B : from Turbide, Rapp and Gale (2004)



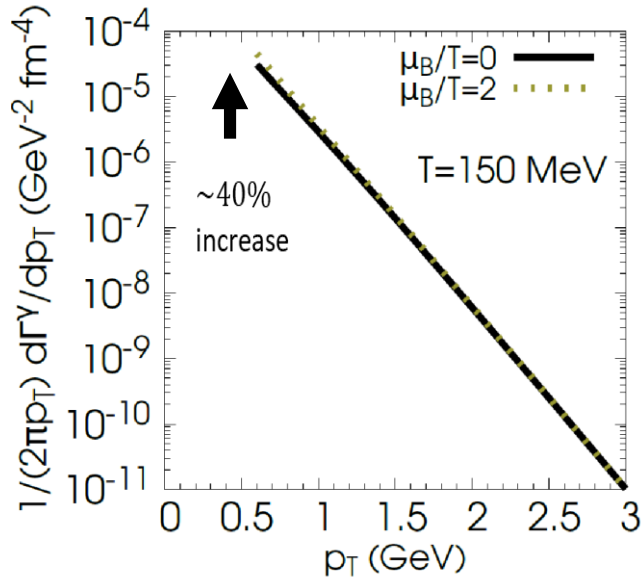


Effect of finite μ_B on thermal photon rate

QGP photon rate



Hadronic photon rate



↑ Baryon chemical potential μ_B **increases the photon rate at** $\underbrace{\text{low momenta}}_{e^{-\left(\frac{k-\mu_B}{T}\right)}}$