Nuclear collisions as seen through photons

Jean-François Paquet

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VANDERBILT UNIVERSITY

Theoretical Physics Colloquium

Arizona State University

The higher end of the electromagnetic spectrum

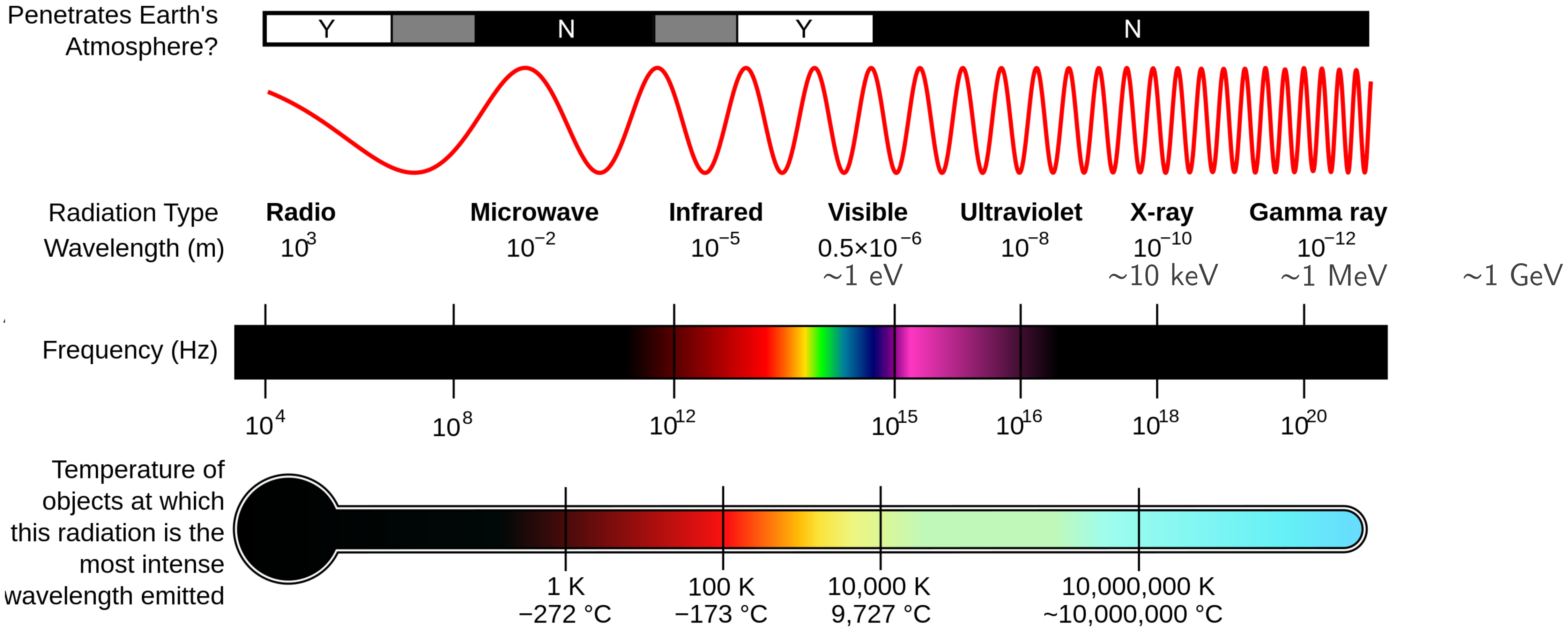
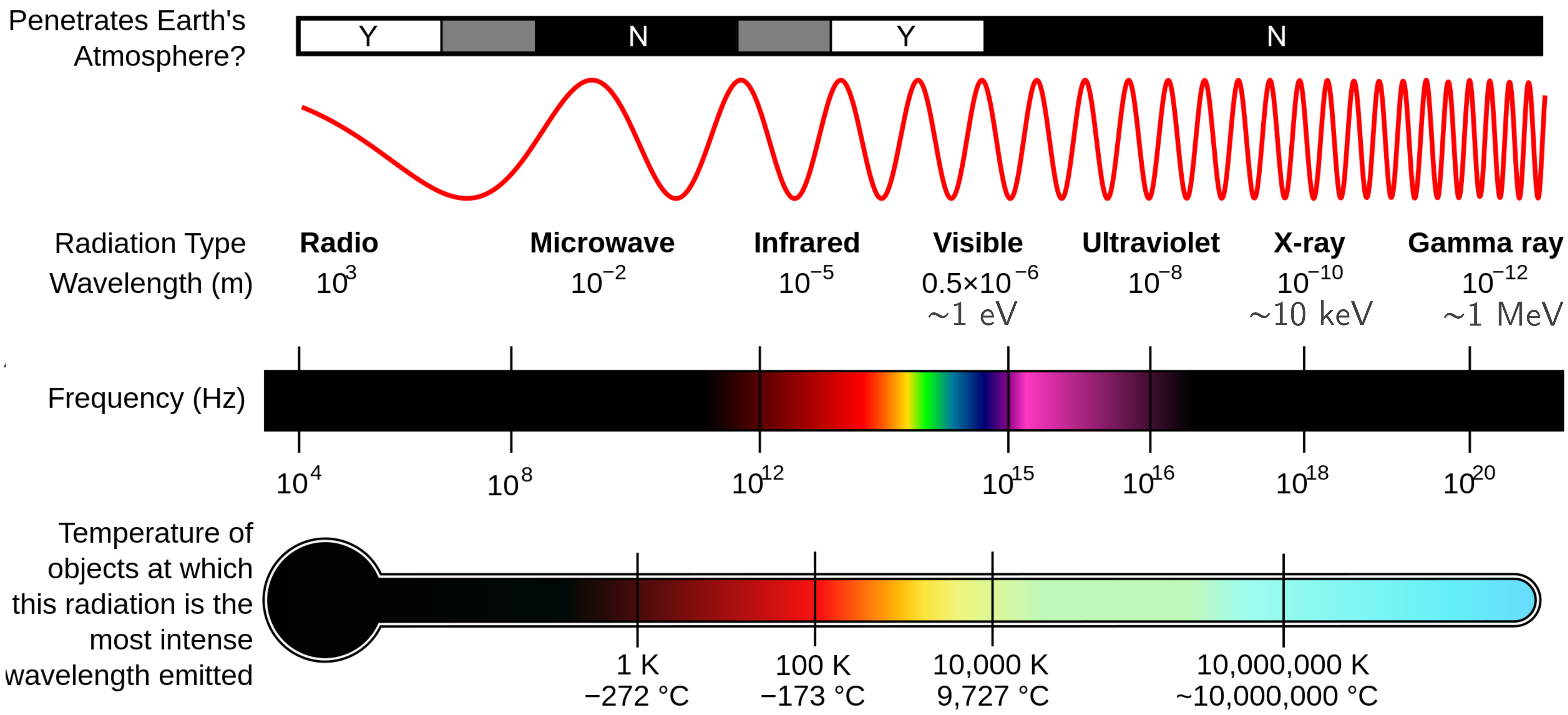


Image modified from Wikimedia

The higher end of the electromagnetic spectrum



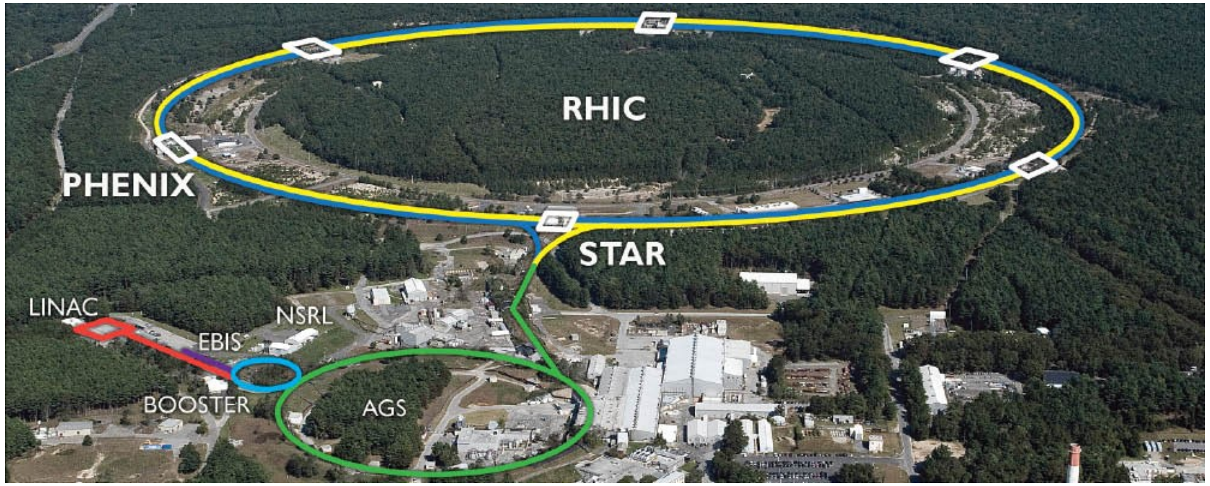
~ 1 GeV

$T \sim 10^{12}$K

Image modified from Wikimedia

RHIC and LHC

Relativistic Heavy Ion Collider (RHIC)
[Brookhaven National Lab, Long Island, NY]



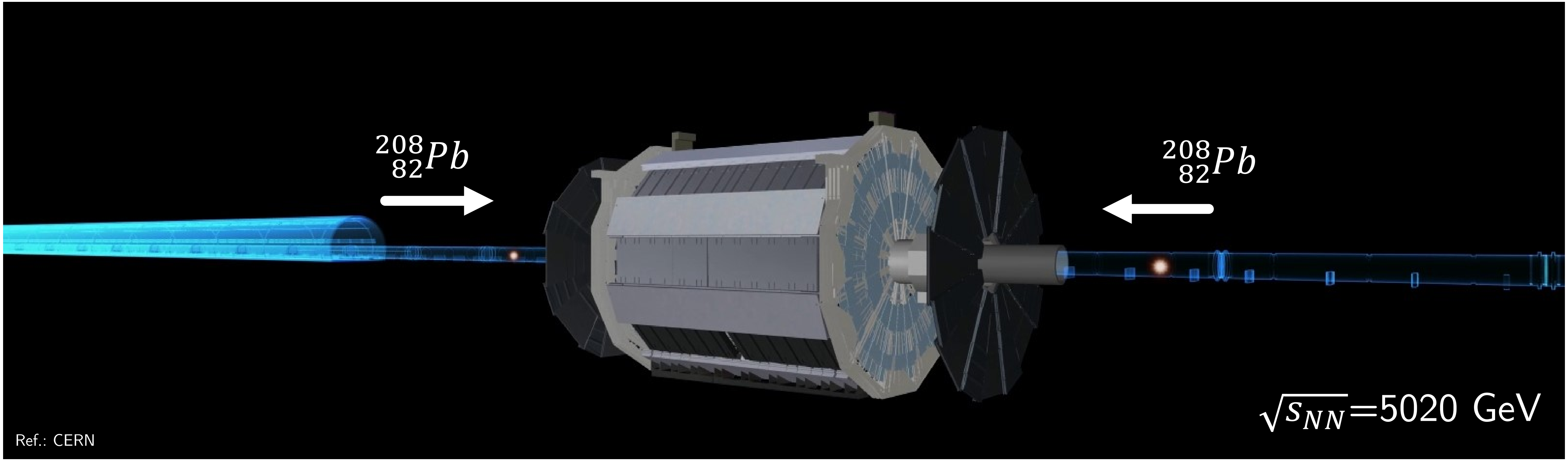
$\sqrt{s_{NN}} \sim 10^2$ GeV

Large Hadron Collider (LHC)
[CERN, Geneva, Switzerland/France]

$\sqrt{s_{NN}} \sim 10^3 - 10^4$ GeV

Nuclear collisions

- Kinetic energy of nuclei ~ 100-2500 times mass of nuclei



Pb-Pb at rest: $\sqrt{s_{NN}} \approx 2$ GeV

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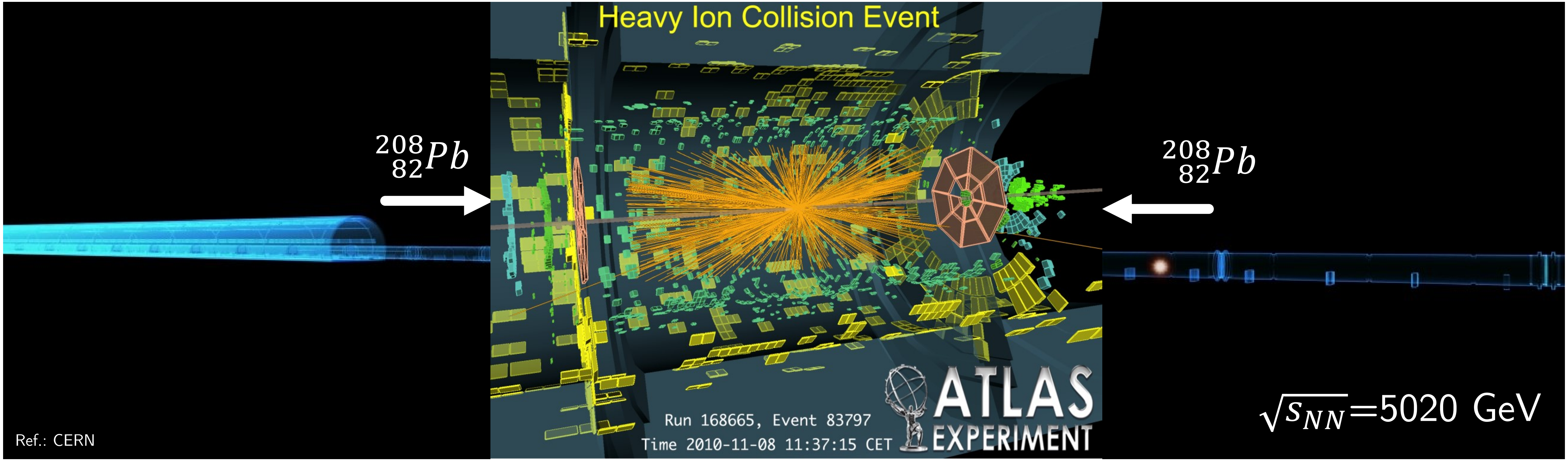

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Hadronic decay photons in nuclear collisions

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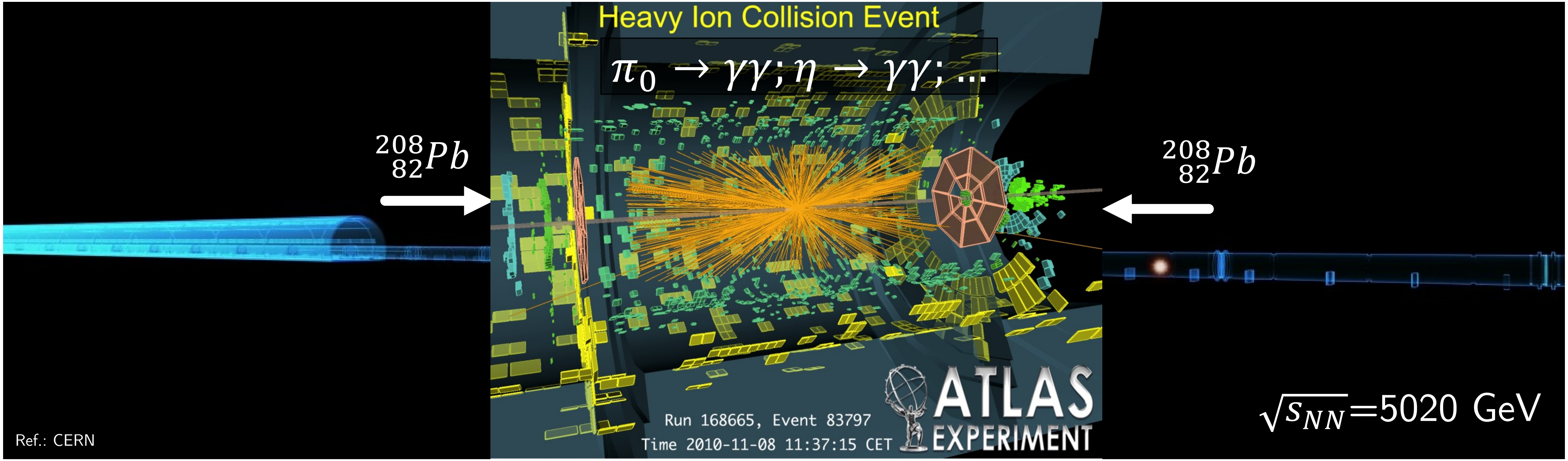

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Hadronic decay photons in nuclear collisions

particle	mass (MeV)	decay	BR
π^0	134.98	$\gamma\gamma$	$9.882 \cdot 10^{-1}$
		$e^+e^-\gamma$	$1.174 \cdot 10^{-2}$
η	547.85	$\gamma\gamma$	$3.941 \cdot 10^{-1}$
		$\pi^0\gamma\gamma$	$2.560 \cdot 10^{-4}$
		$\pi^+\pi^-\gamma$	$4.220 \cdot 10^{-2}$
		$e^+e^-\gamma$	$6.899 \cdot 10^{-3}$
		$\mu^+\mu^-\gamma$	$3.090 \cdot 10^{-4}$
η'	957.66	$\rho^0\gamma$	$2.908 \cdot 10^{-1}$
		$\omega\gamma$	$2.746 \cdot 10^{-2}$
		$\gamma\gamma$	$2.198 \cdot 10^{-2}$
		$\mu^+\mu^-\gamma$	$1.080 \cdot 10^{-4}$
ω	782.65	$\pi^0\gamma$	$8.350 \cdot 10^{-2}$
		$\eta\gamma$	$4.600 \cdot 10^{-4}$
		$\pi^0\pi^0\gamma$	$7.000 \cdot 10^{-5}$
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		$\eta\gamma$	$3.000 \cdot 10^{-4}$
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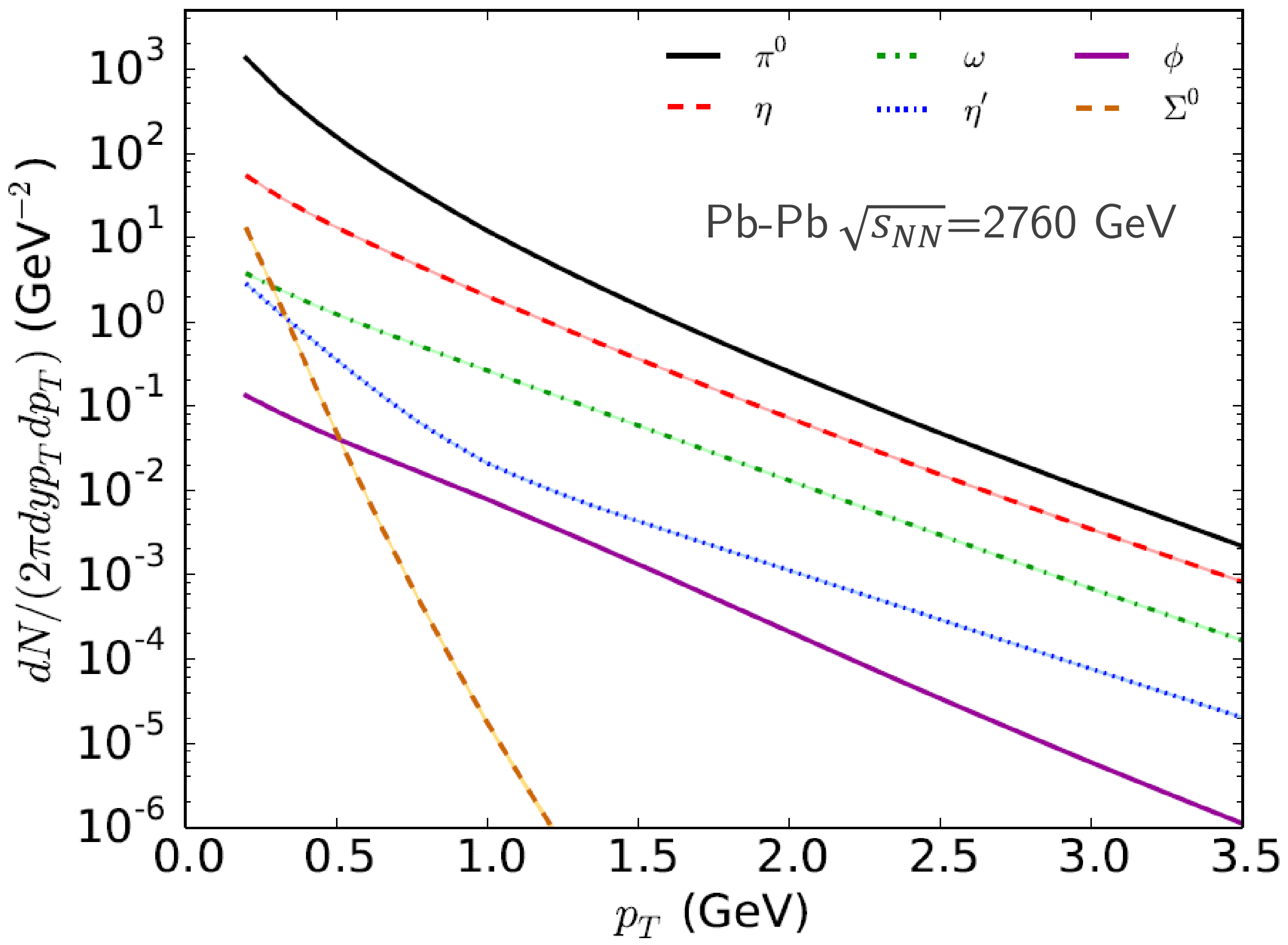
Ref: F. Bock, PhD thesis



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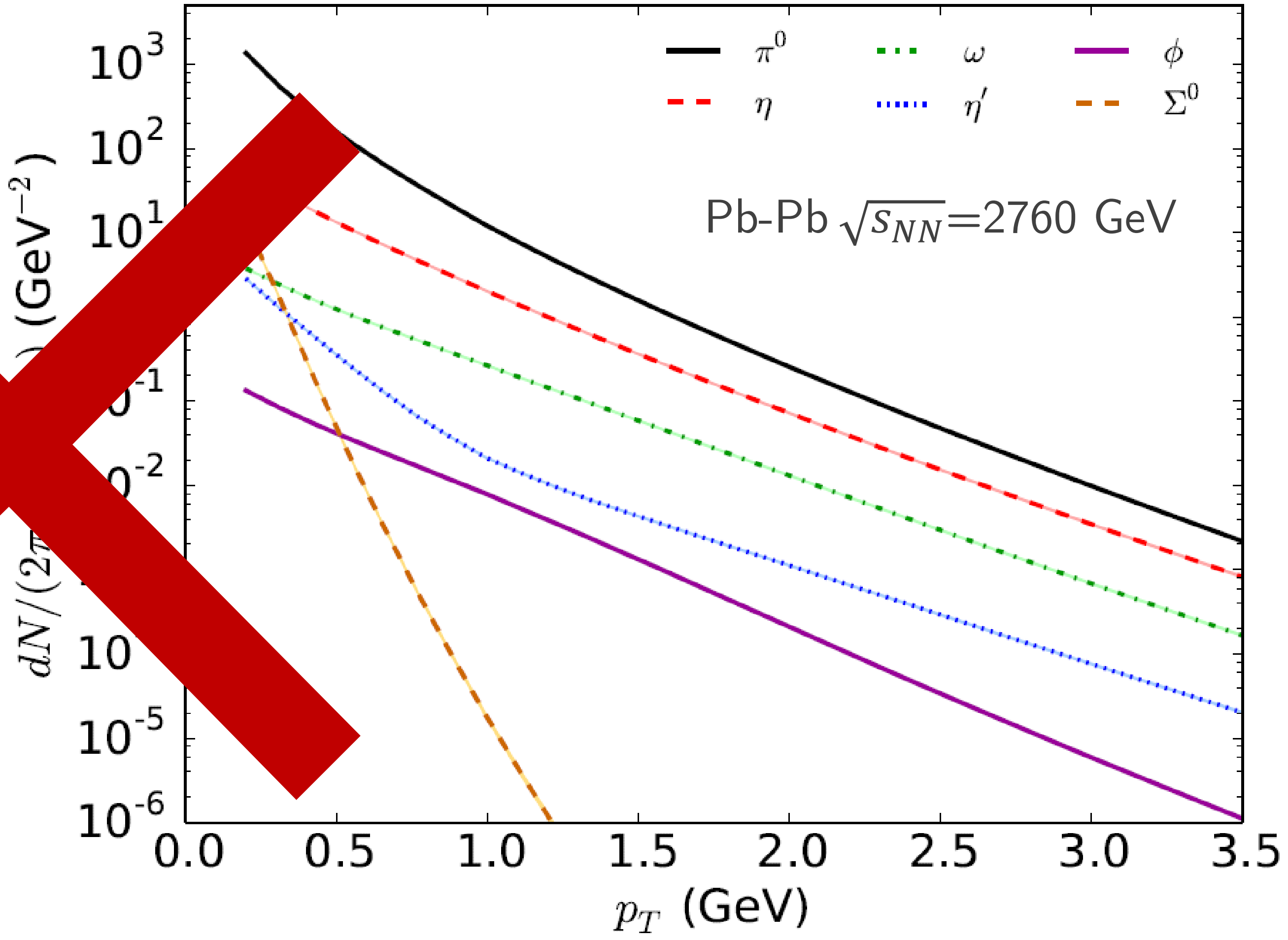

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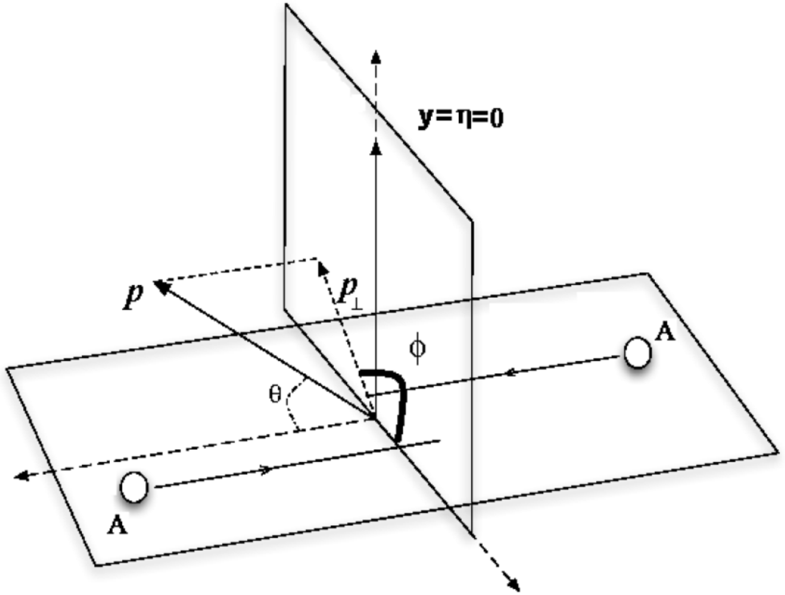
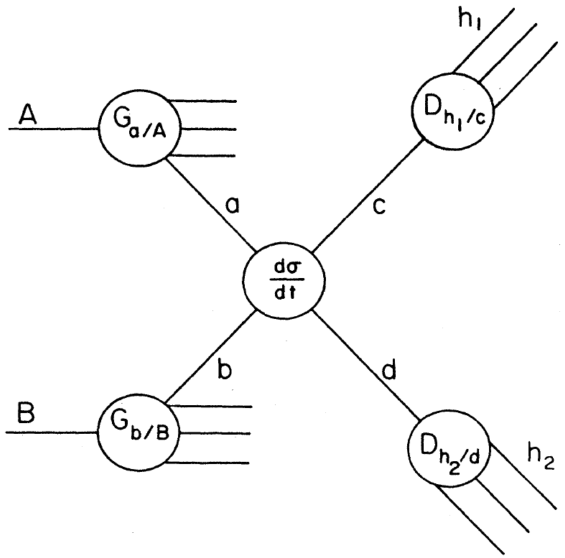
Figure adapted from K. Tuchin (2013) AHEP

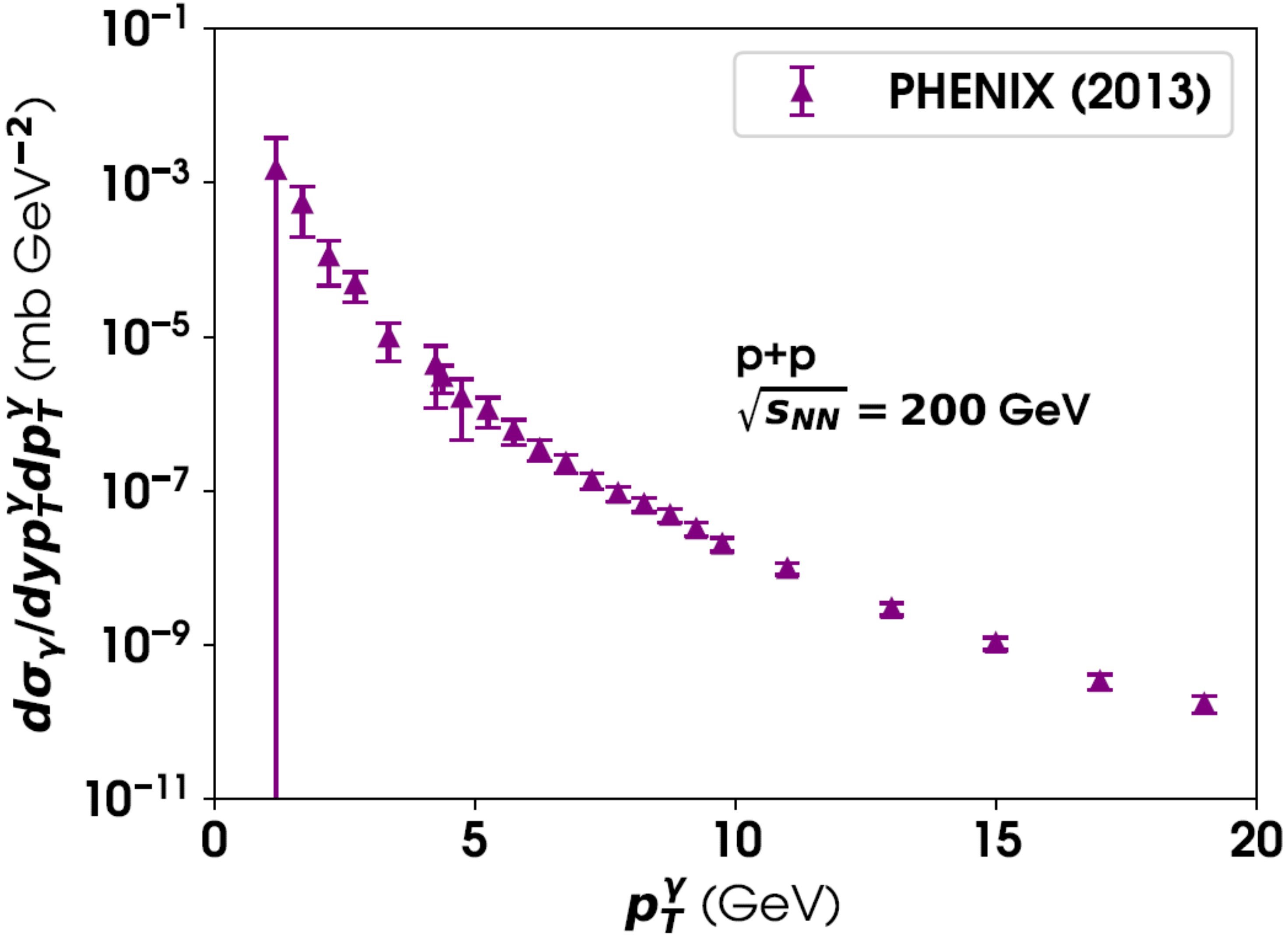




Ref: Owens (1987) RMP

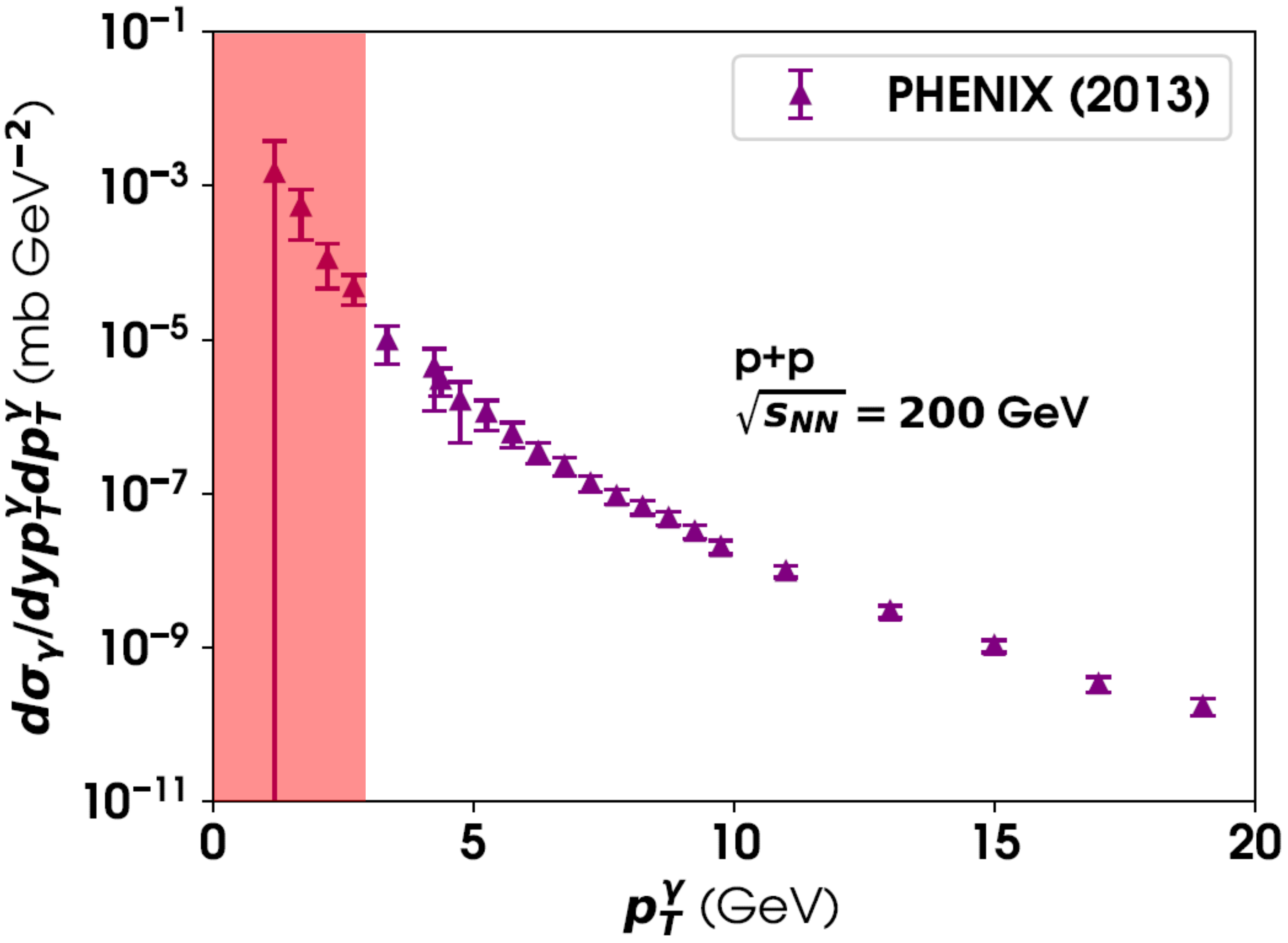
PHOTONS IN PROTON-PROTON COLLISIONS

Direct photons in proton-proton collisions



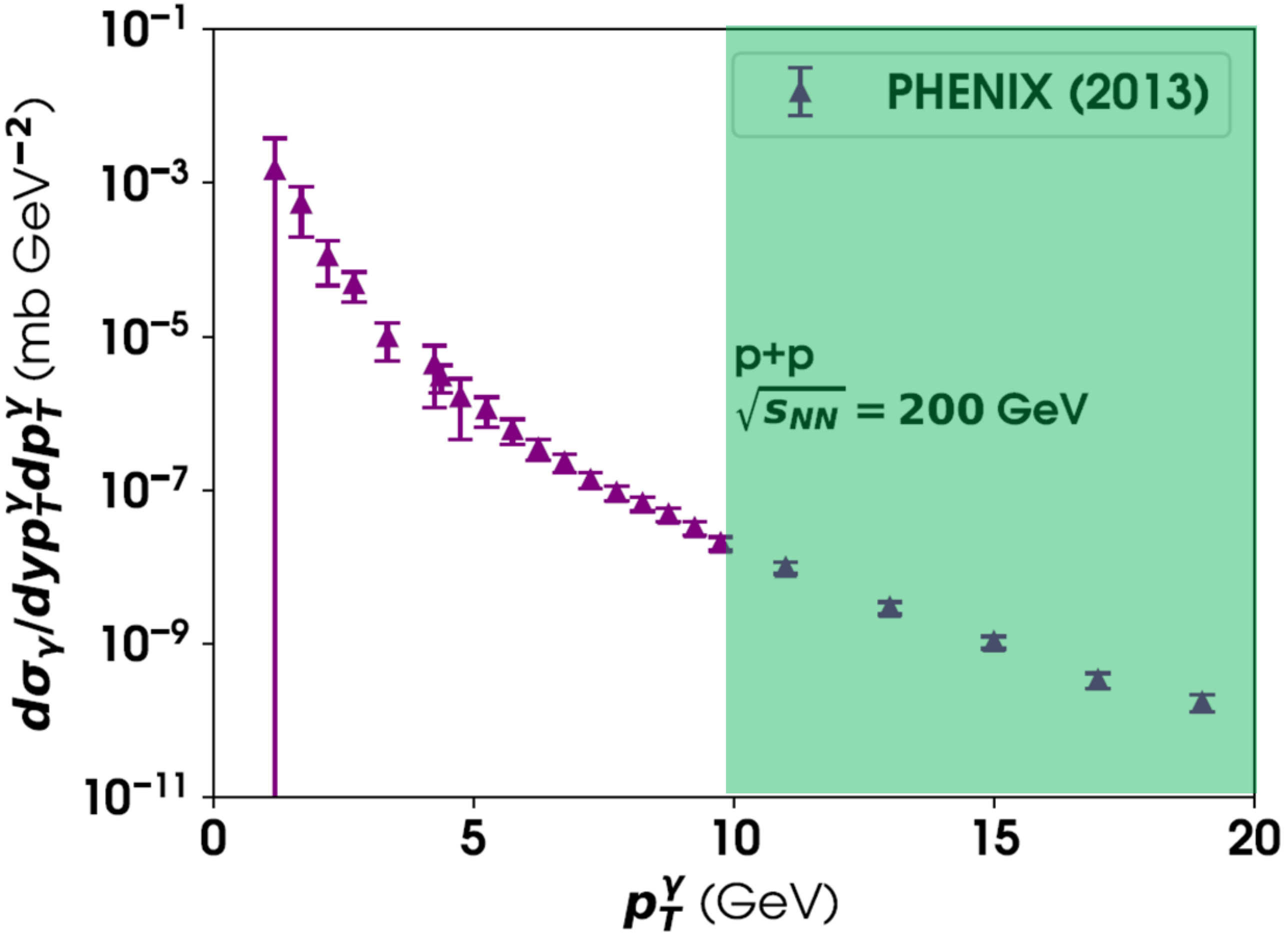
Direct photons in proton-proton collisions: “low” energy

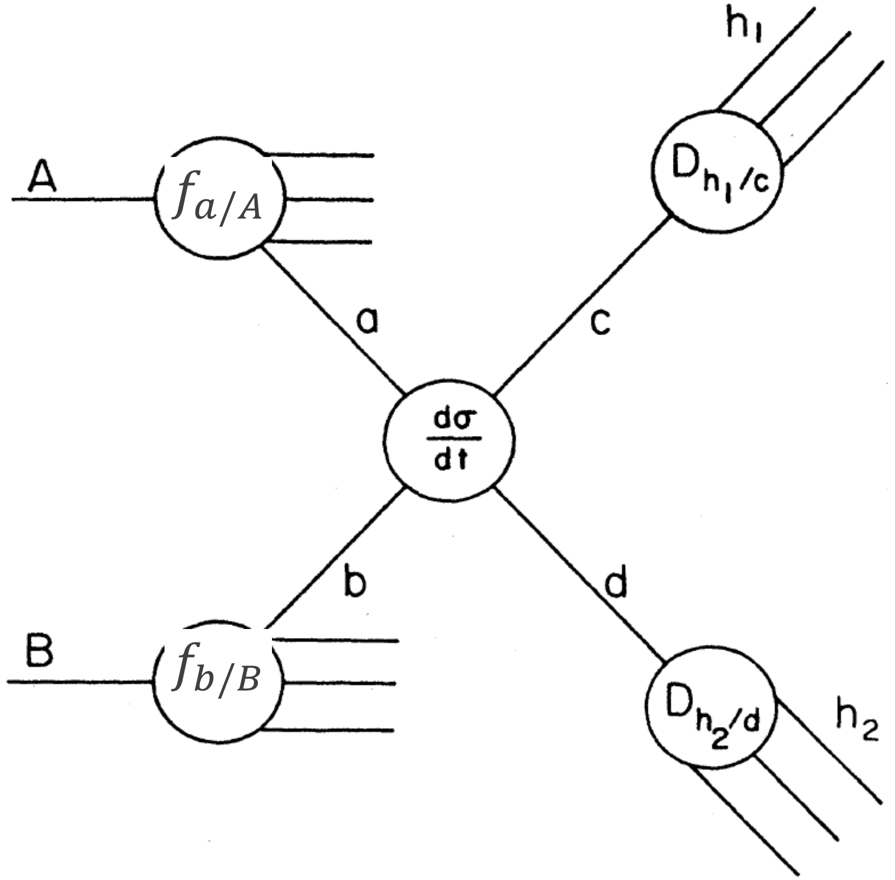
- Low p_T photons:
  - Few measurements (in proton-proton collisions)
  - Difficult to compute from first principles
  - Non-perturbative effects likely significant



Direct photons in p-p collisions: high energy

Figure ref:
Owens (1987) RMP





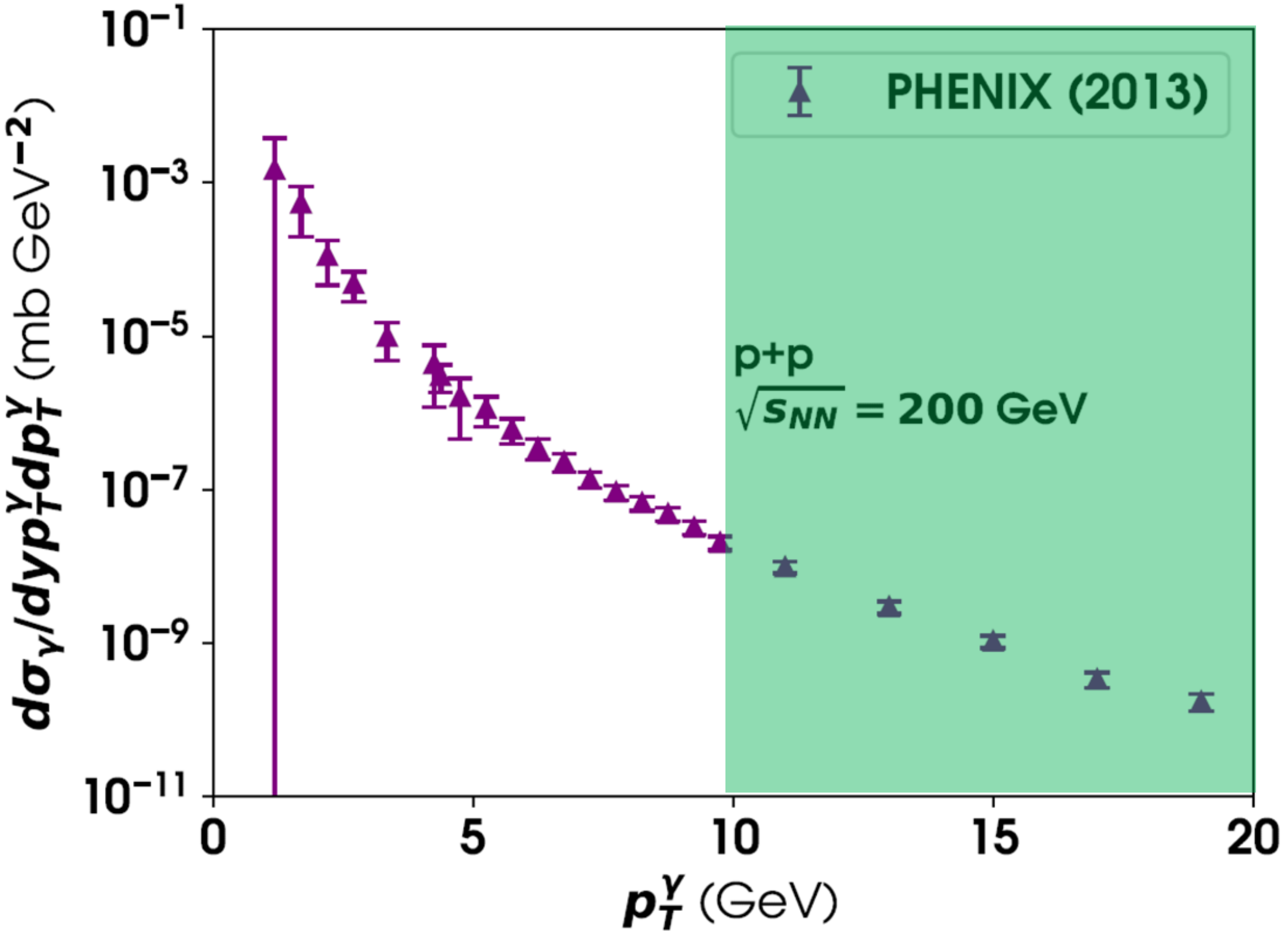
$$\frac{\mathrm{d}\sigma_\gamma^{pp}}{dp_T} = f_a \otimes f_b \otimes \mathrm{d}\hat{\sigma}_{ab\to\gamma/c+d}[\otimes D_{\gamma/c}]$$

Direct photons in p-p collisions: high energy

Nuclear Physics B327 (1989) 105–143
North-Holland, Amsterdam

QCD CORRECTIONS TO PARTON–PARTON SCATTERING PROCESSES

F. AVERSA*, P. CHIAPPETTA, M. GRECO*, J.Ph. GUILLET**



- Can be calculated in collinear-factorization based perturbative QCD, up to next-to-leading order

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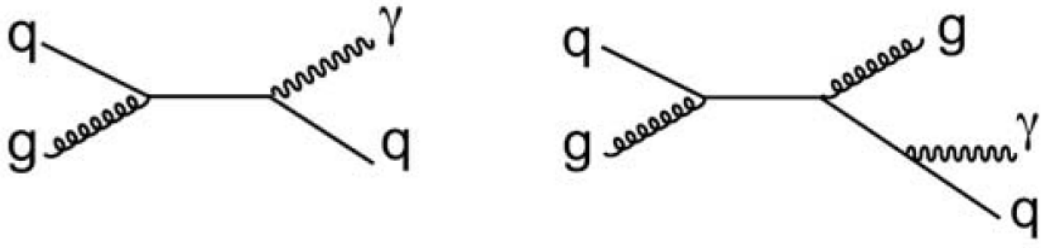

Frag fct: Bourhis, Fontannaz, Guillet (1998) EPJ

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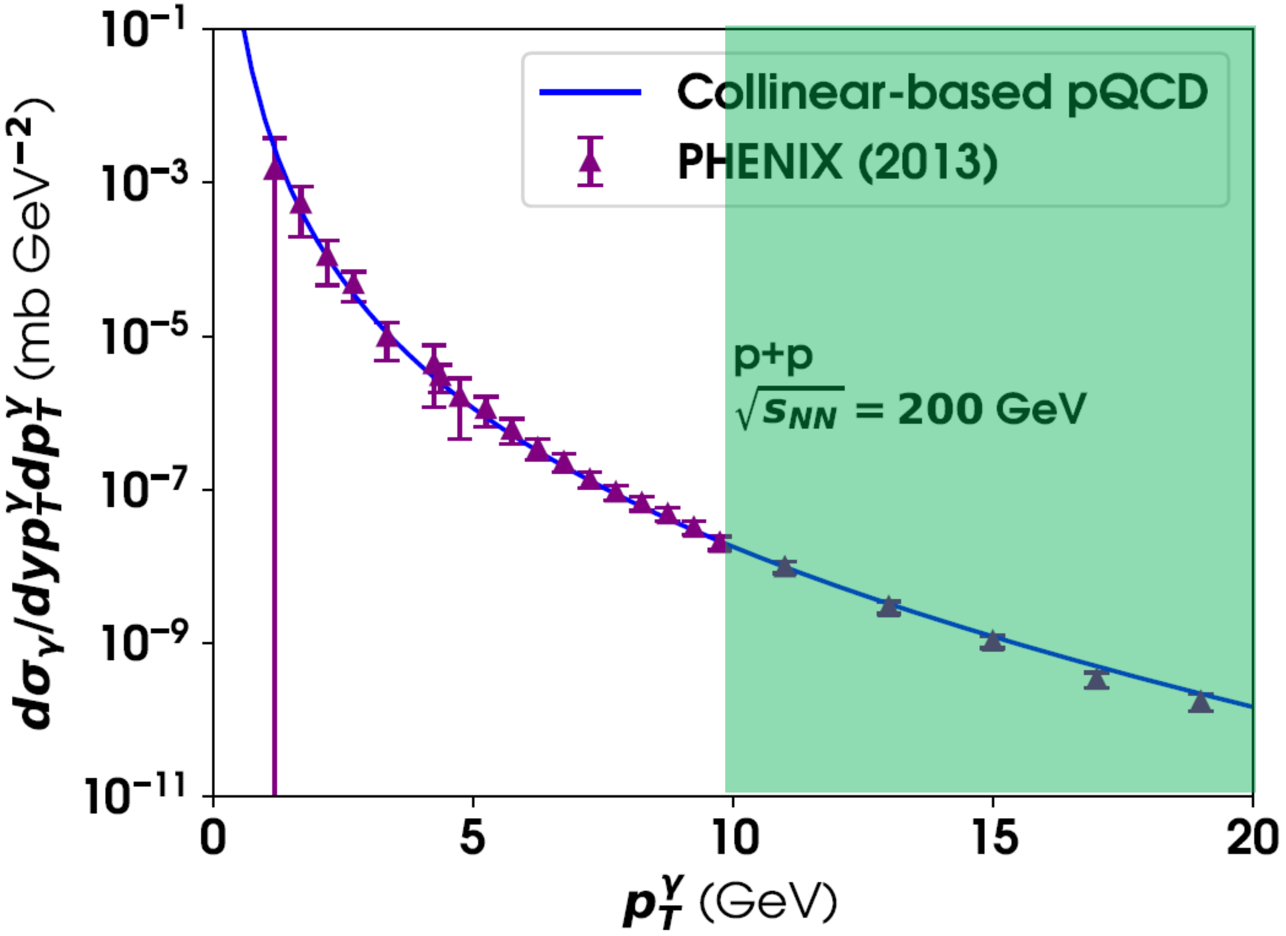

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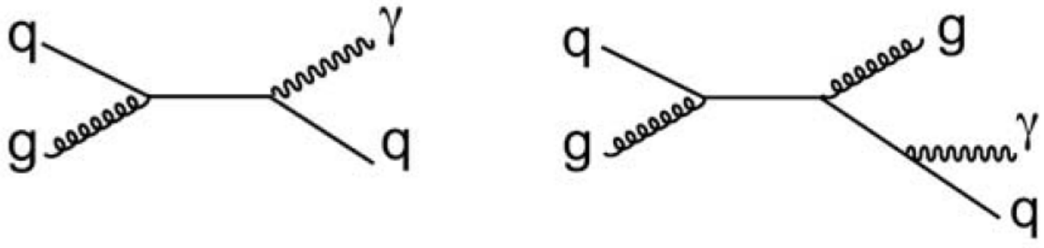

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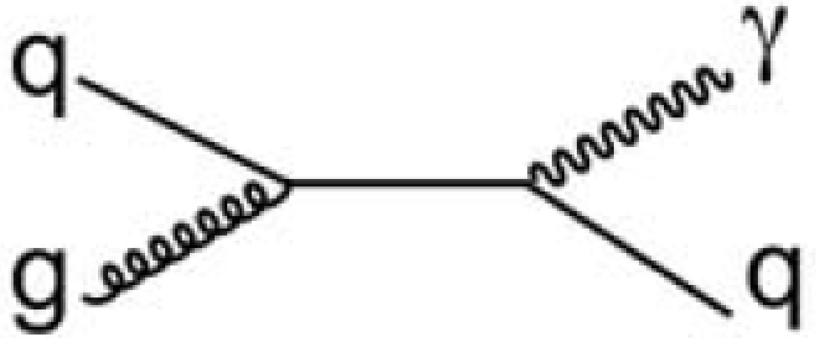
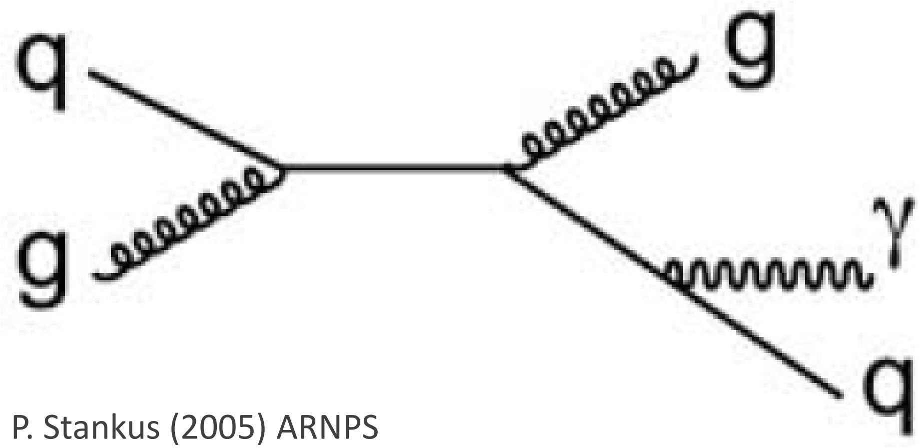
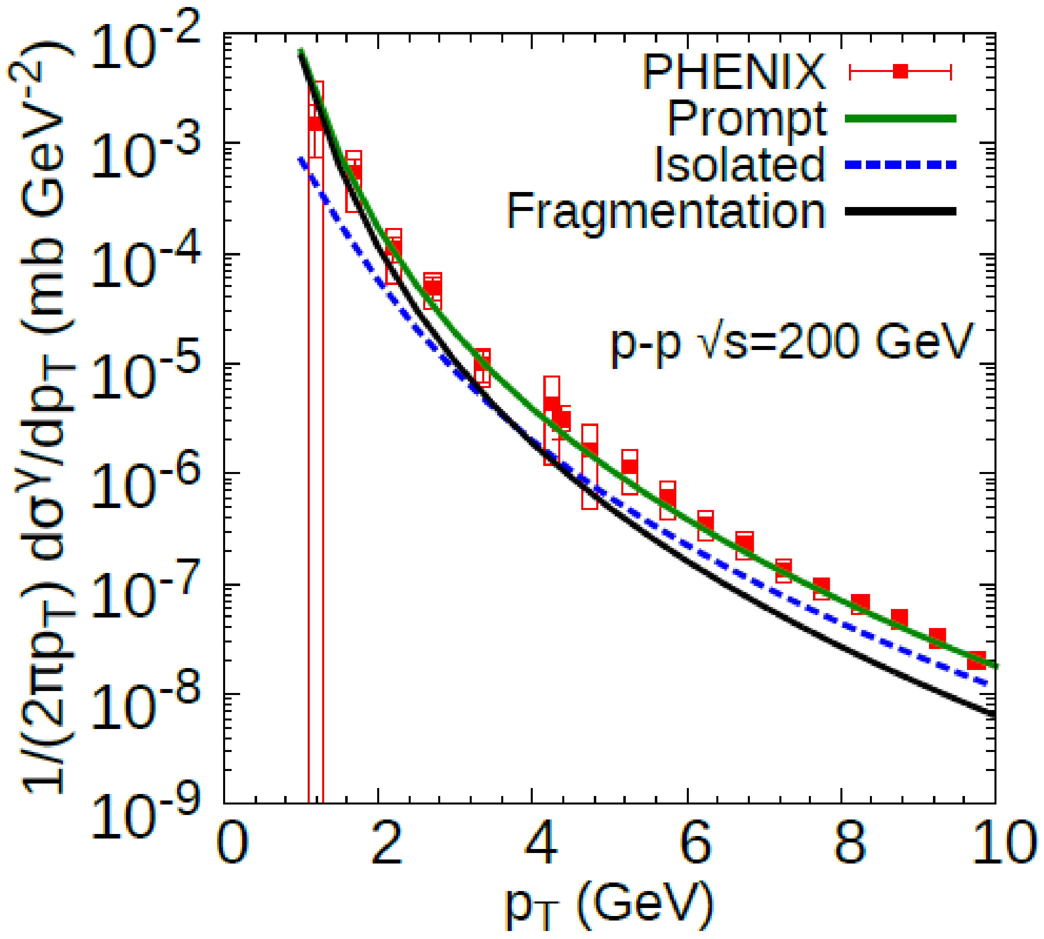
Direct photons in proton-proton collisions: channels

- Hard partonic collisions
  - "Isolated"

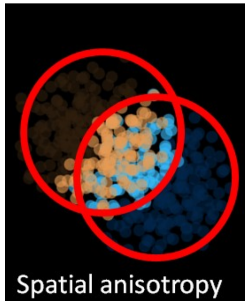


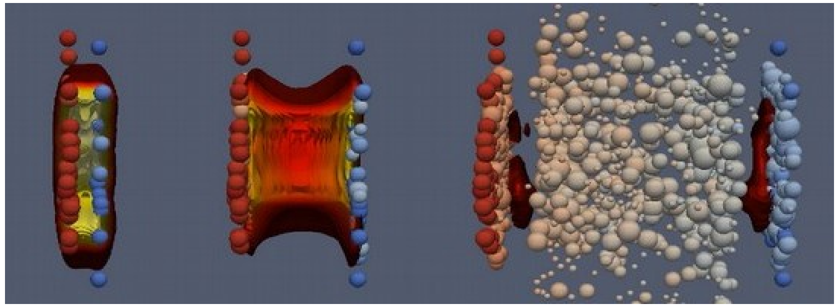
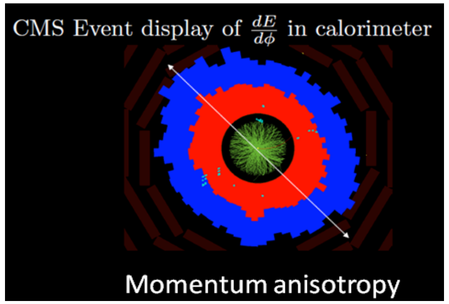
  - Fragmentation





Ref: P. Stankus (2005) ARNPS

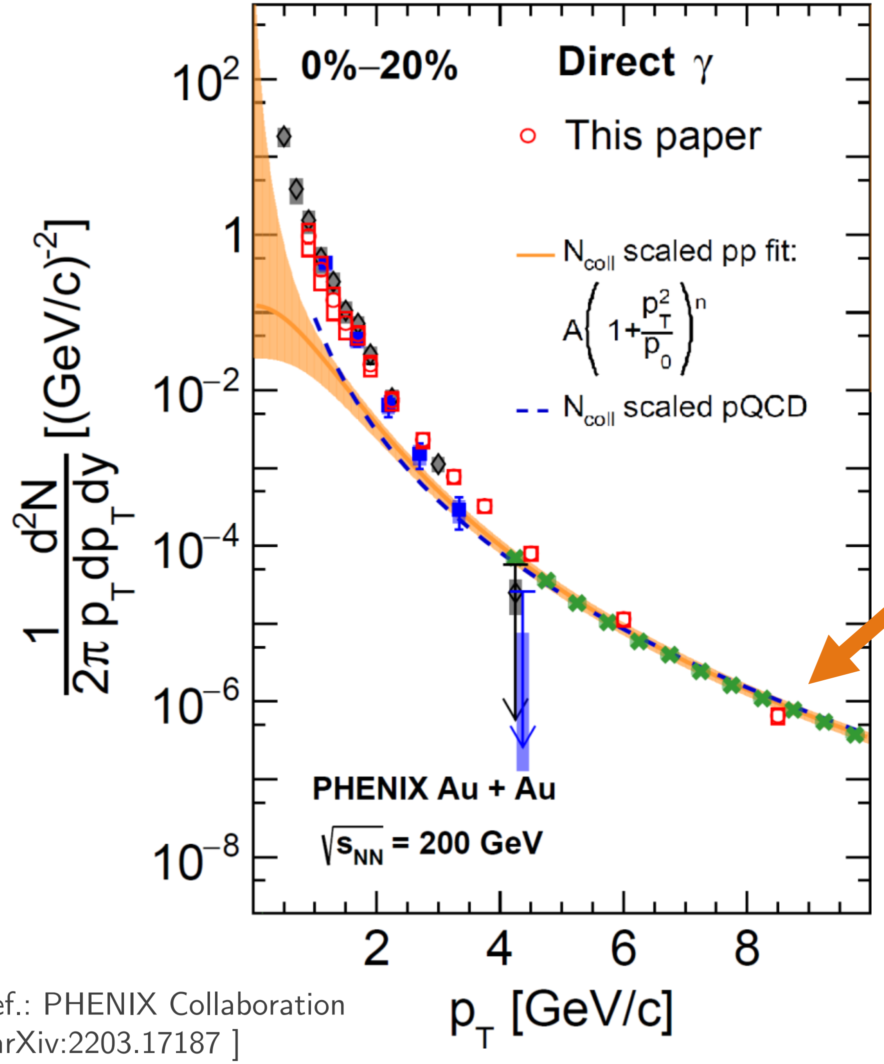


PHOTONS IN HEAVY-ION COLLISIONS

THE PHOTON ENERGY SPECTRUM

Photon energy spectrum in heavy-ion collisions



Ref.: PHENIX Collaboration
[arXiv:2203.17187]

- Systematic excess of low energy photons in nucleus collisions

  (also observed by STAR and ALICE Collaborations)

Orange band:
Result for incoherent superposition of proton-proton collisions

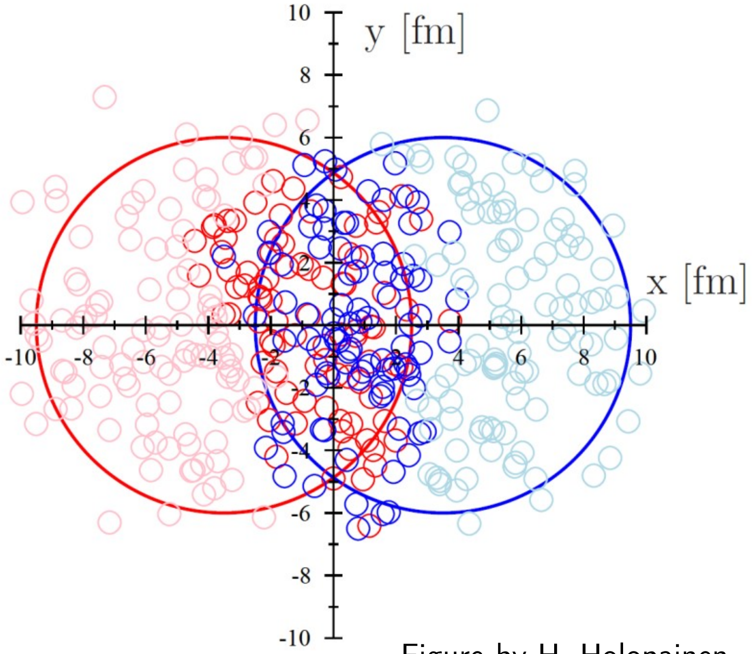
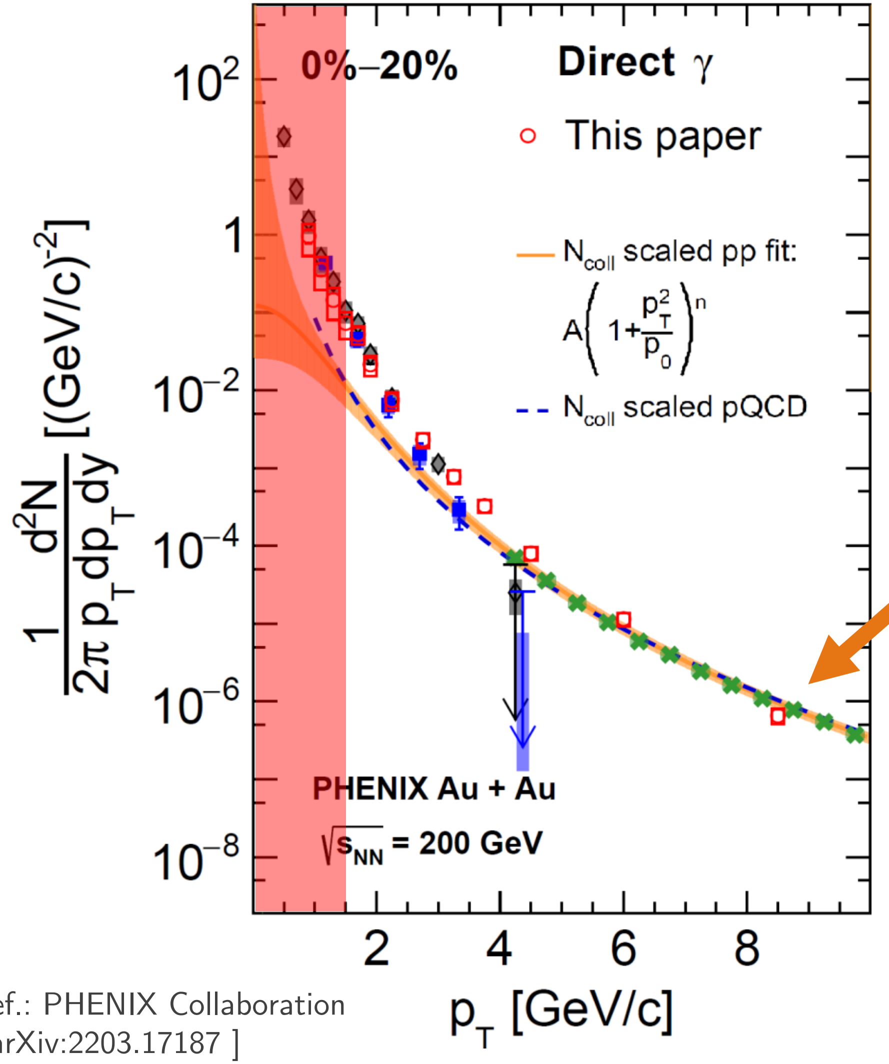


Figure by H. Holopainen

Photon energy spectrum in heavy-ion collisions



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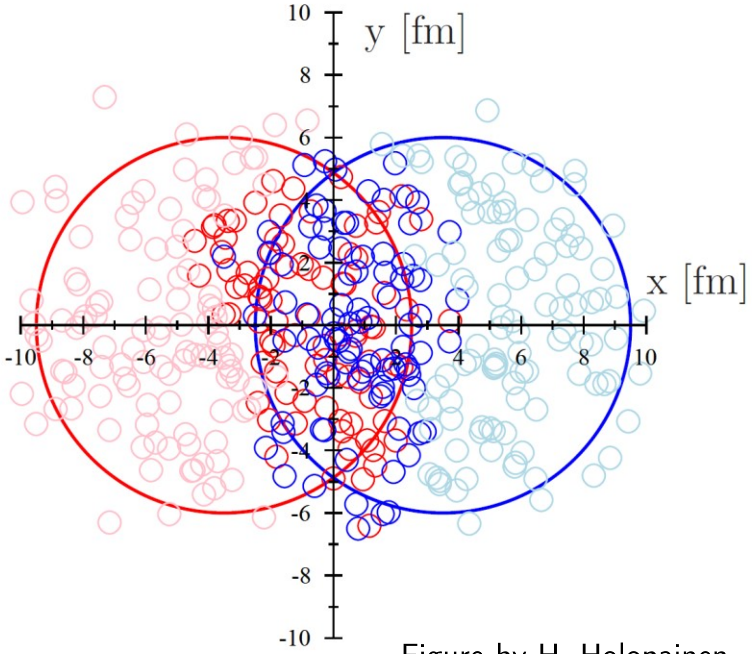
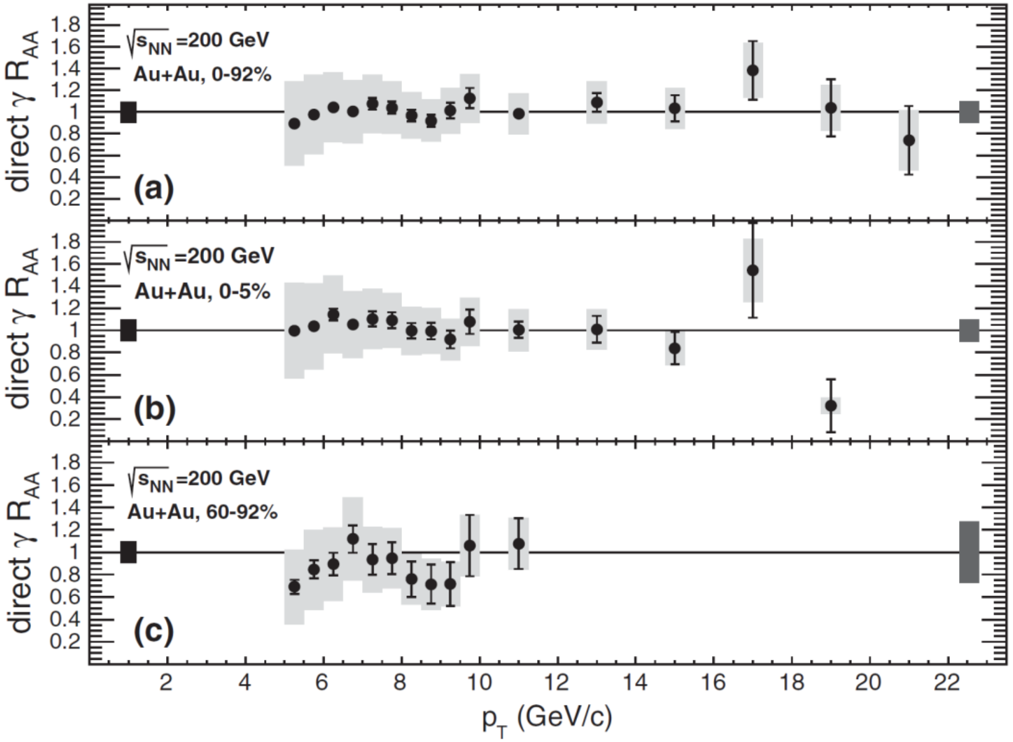


Figure by H. Holopainen

Photons in heavy-ion collisions: high p_T

- **Prompt photons** produced as superposition of nucleon-nucleon collisions ("binary scaling")



Ref.: PHENIX Collaboration (2012) PRL

$$R_{AA}^{\gamma} = \frac{\frac{\mathrm{d}N_{\gamma}^{AA}}{dp_T}}{\left(\frac{N_{binary}}{\sigma_{pp}^{inel}}\right)\frac{\mathrm{d}\sigma_{\gamma}^{pp}}{dp_T}} \approx 1 \qquad (\text{at high } p_T)$$

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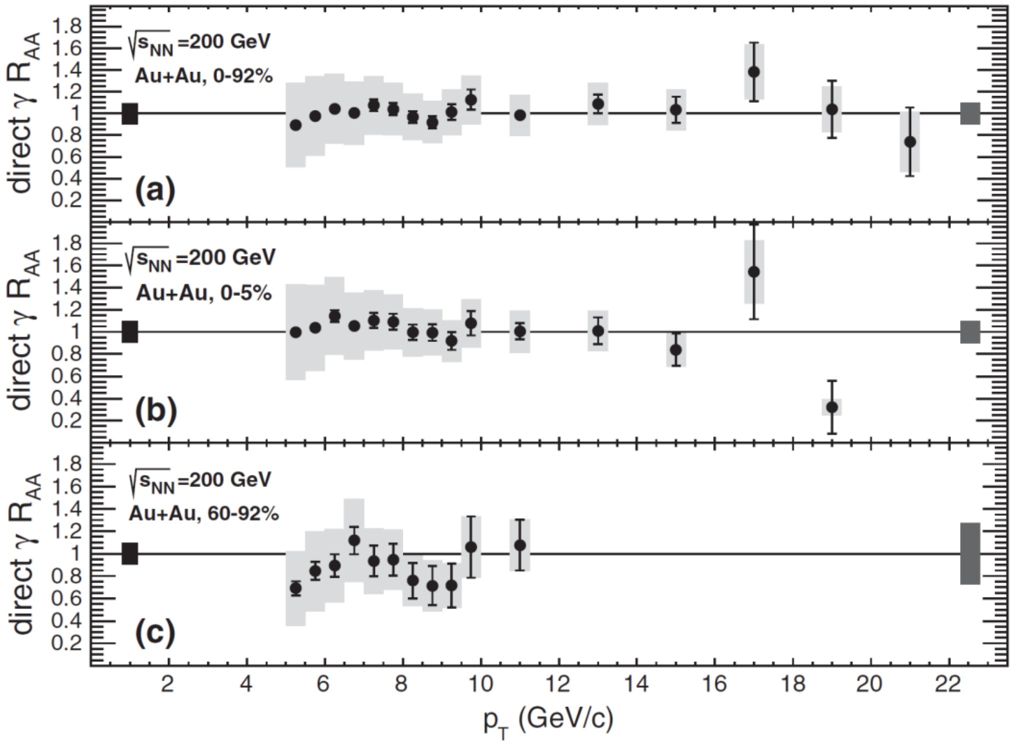

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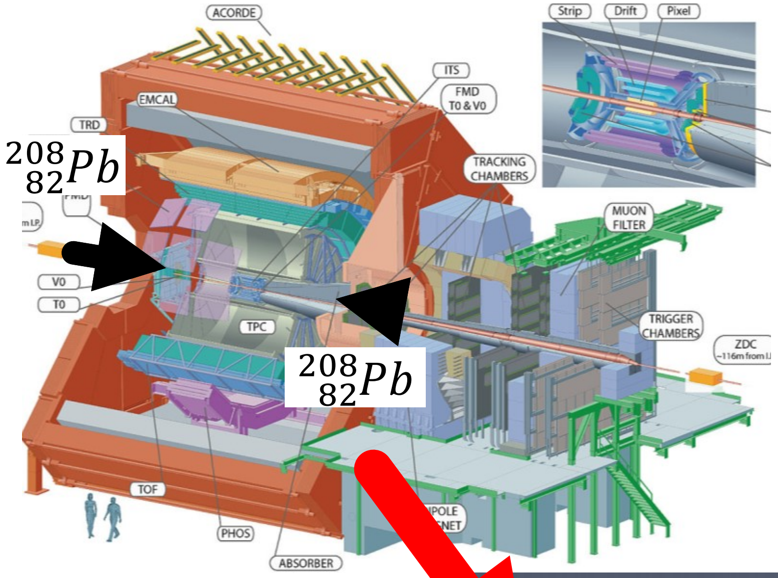
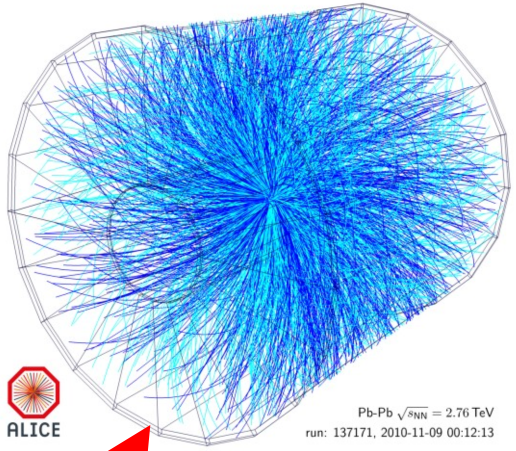
Deviations from $R_{AA}^{\gamma} = 1$ originate from:

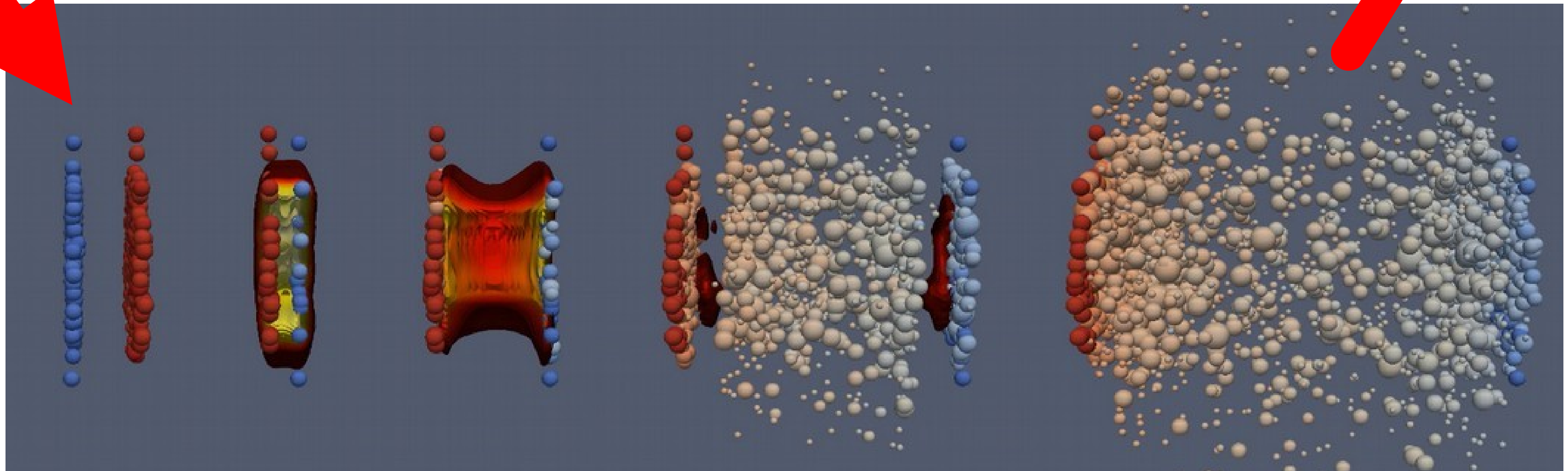
- Isospin effect (parton content of n vs p)
- Nuclear effects on parton distribution functions
- Parton energy loss [more about this later]

Heavy-ion collisions



Ref.: ALICE, CERN





Ref: MADAI collaboration, Hannah Elfner and Jonah Bernhard

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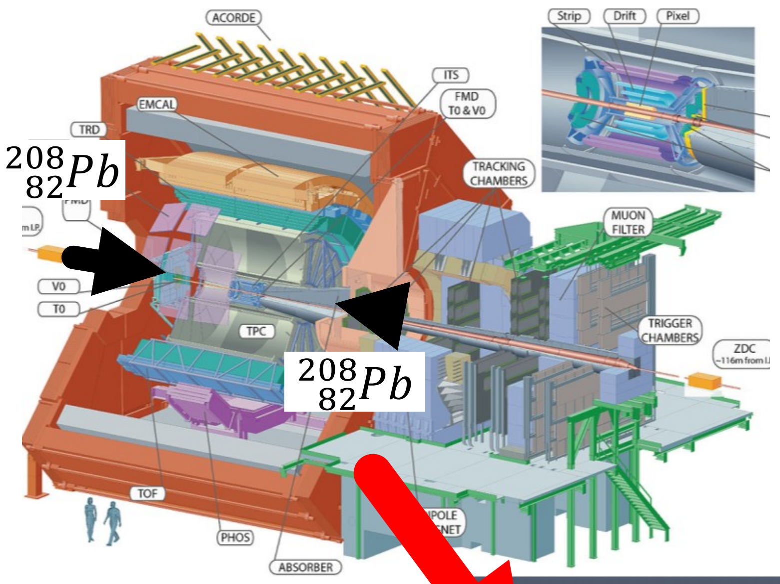

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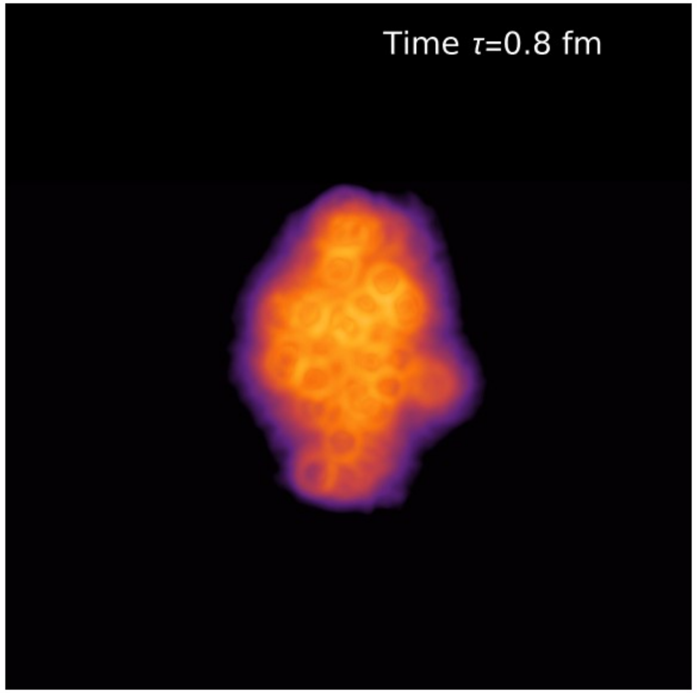

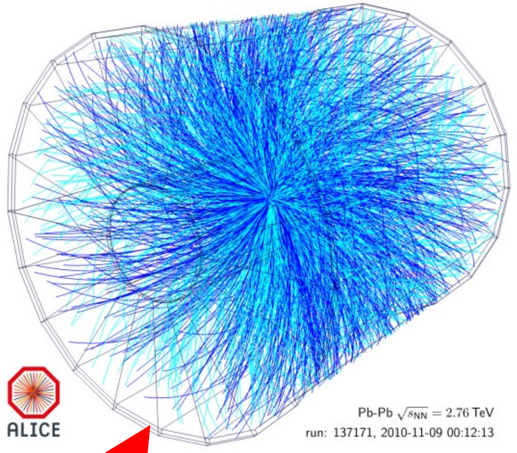

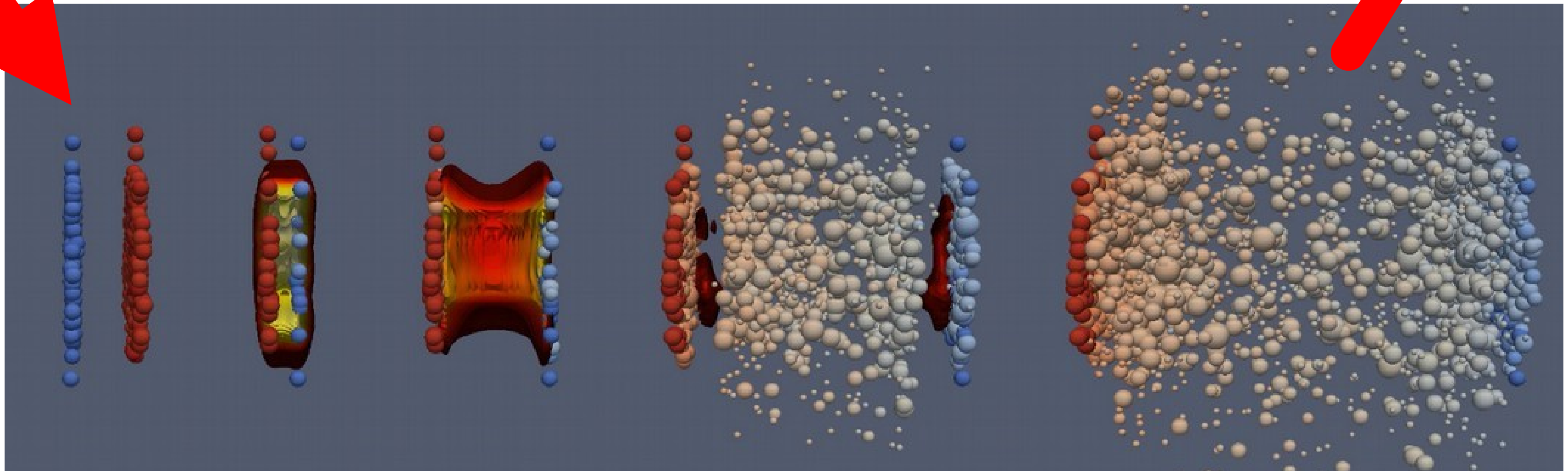

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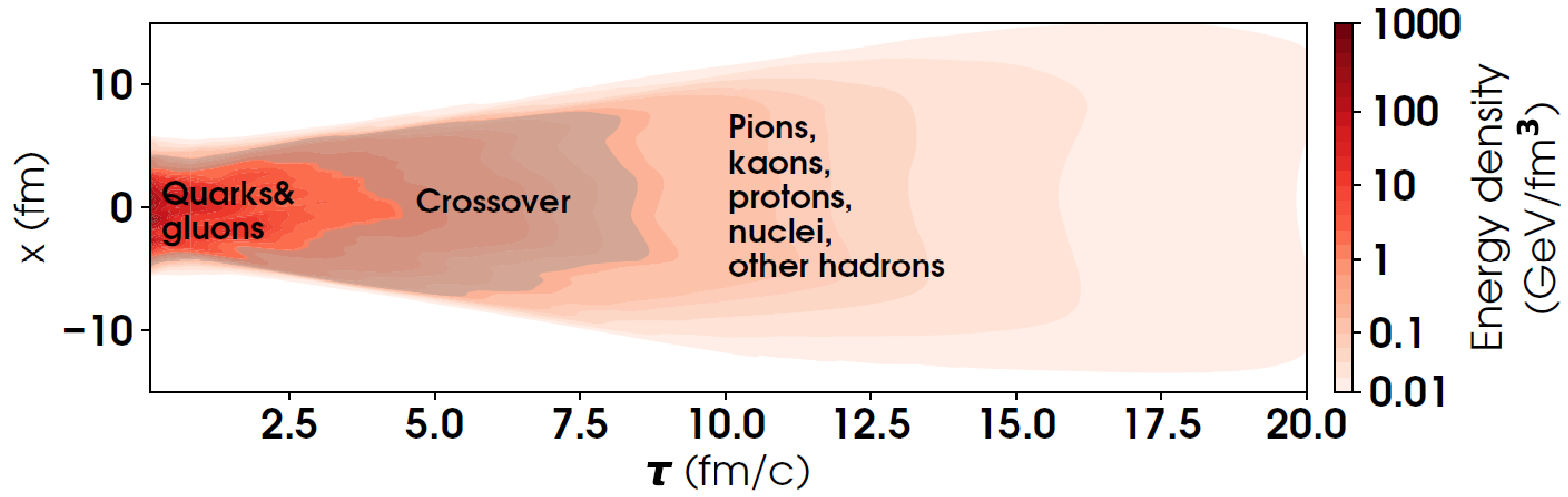
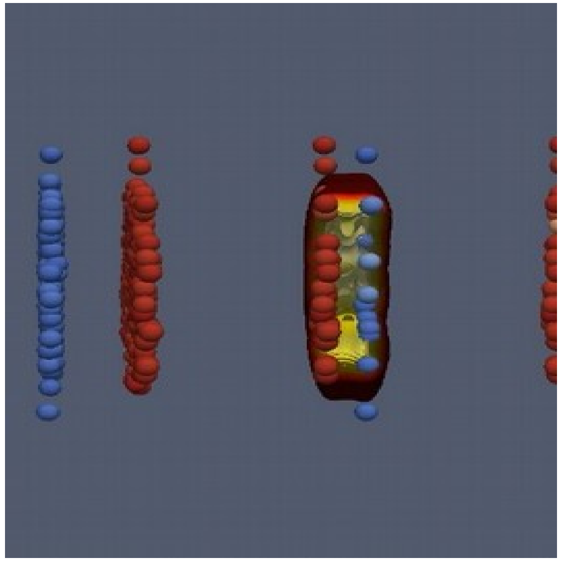
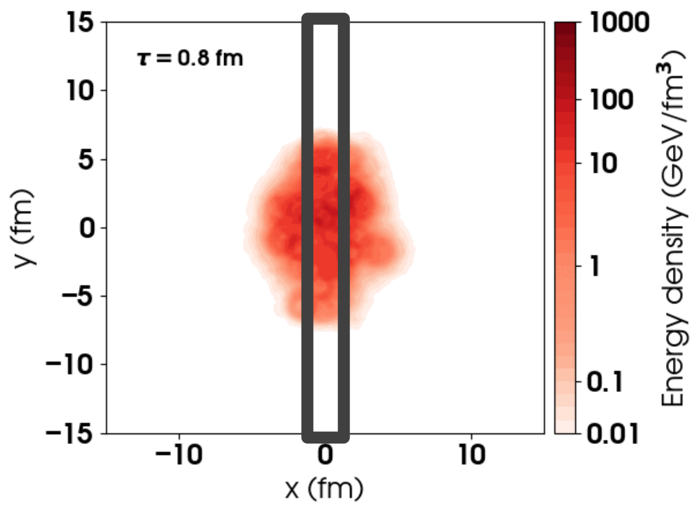
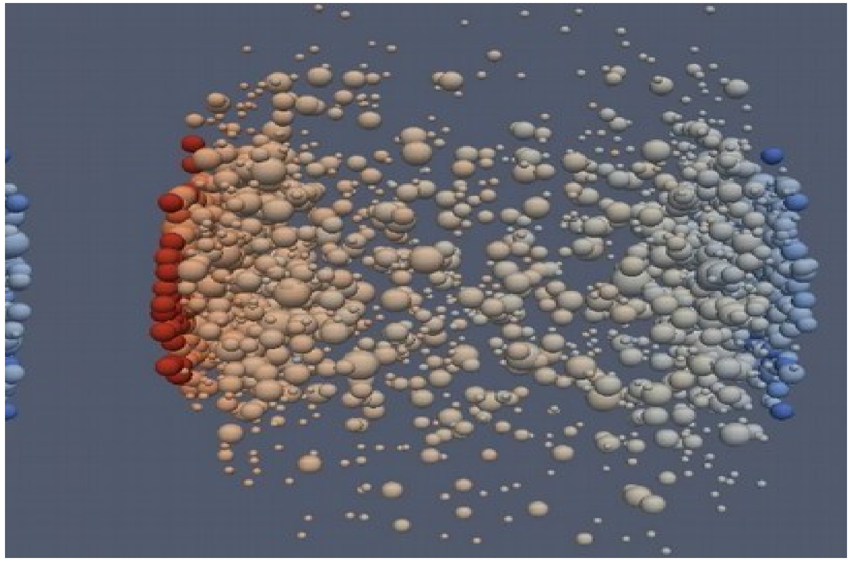

Quarks&
gluons
Crossover
Pions,
kaons,
protons,
nuclei,
other hadrons
x (fm)
10
0
−10
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
τ (fm/c)
1000
100
10
1
0.1
0.01
Energy density
(GeV/fm³)

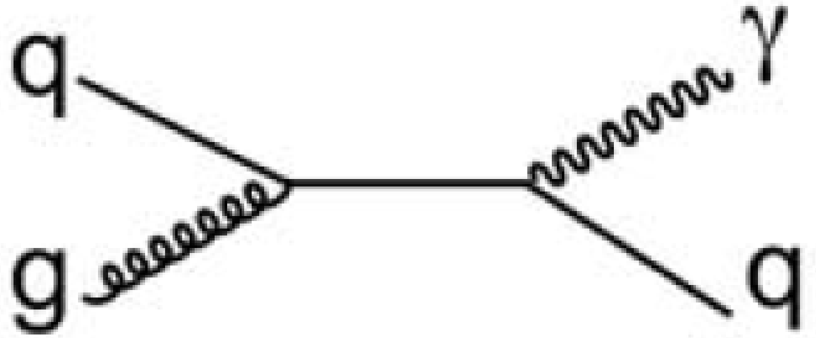



τ = 0.8 fm
15
10
5
0
−5
−10
−15
y (fm)
−10
0
10
x (fm)
1000
100
10
1
0.1
0.01
Energy density (GeV/fm³)

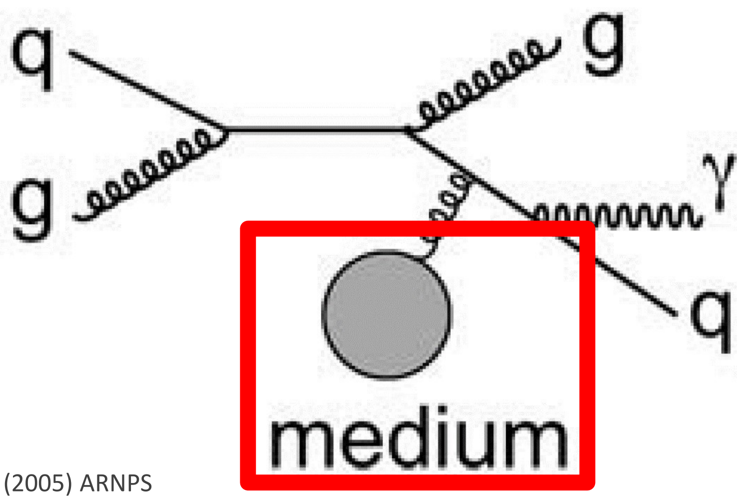


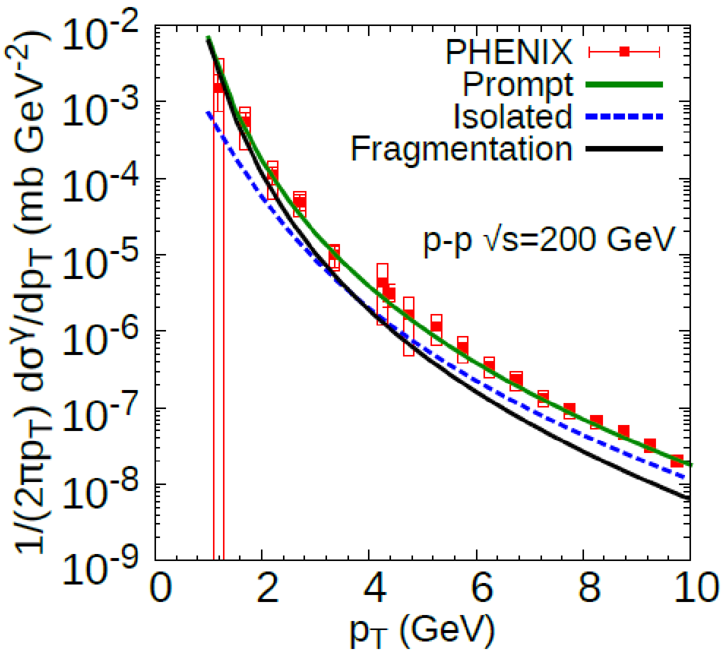
Prompt photons in heavy-ion collisions

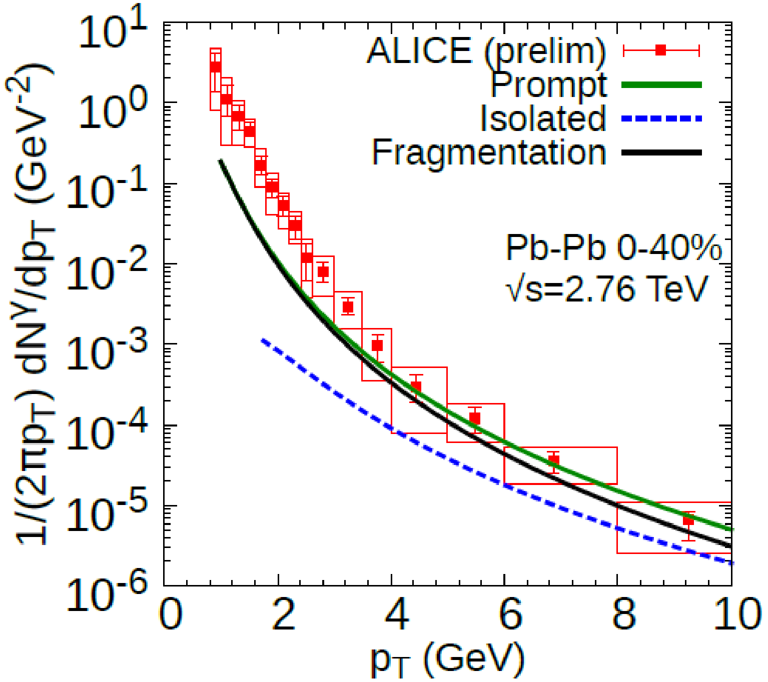
- Hard partonic collisions
  - "Isolated"

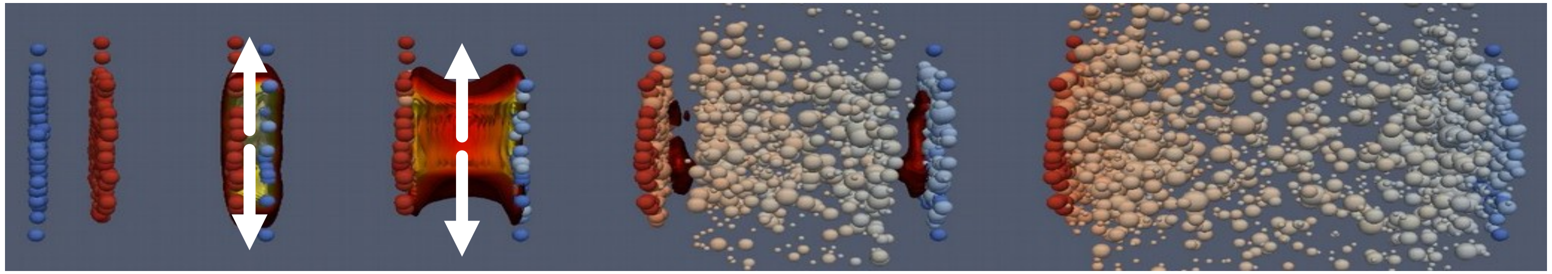


  - Fragmentation



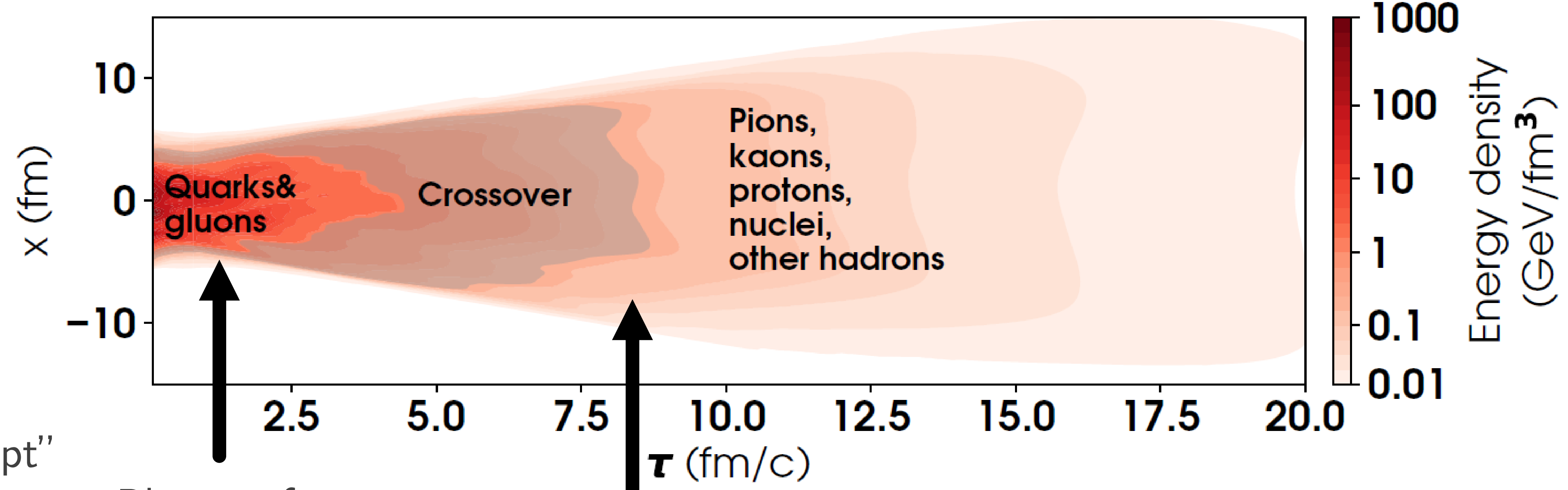






Ref: P. Stankus (2005) ARNPS

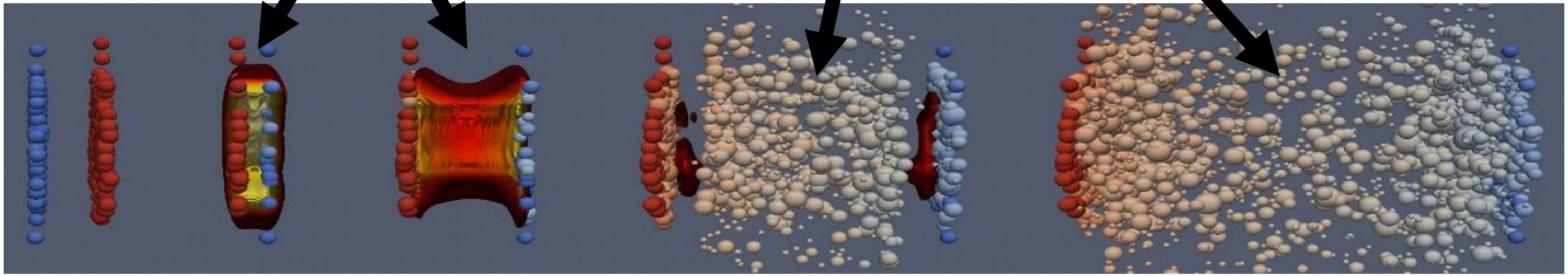
Limited number of recent studies; see e.g. Modarresi Yazdi, Shi, Gale, Jeon [arXiv:2207.12513]



"Prompt" photons

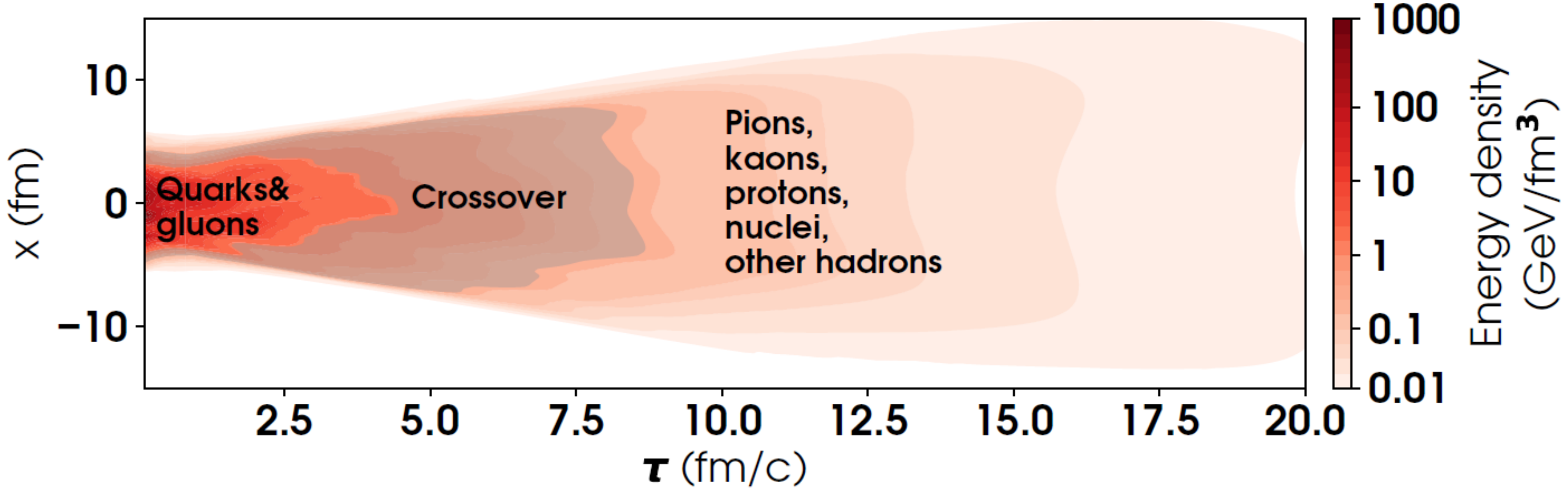
Photons from quark&gluon interactions

- Photons from hadronic interactions
- Photons from hadronic decays



Photons from deconfined plasma

- What is the spacetime and momentum profile of quarks/gluons/hadrons?



- How much radiation is emitted in each region?

- Note: No clear separation between **quark/gluon** phase and **hadronic** phase

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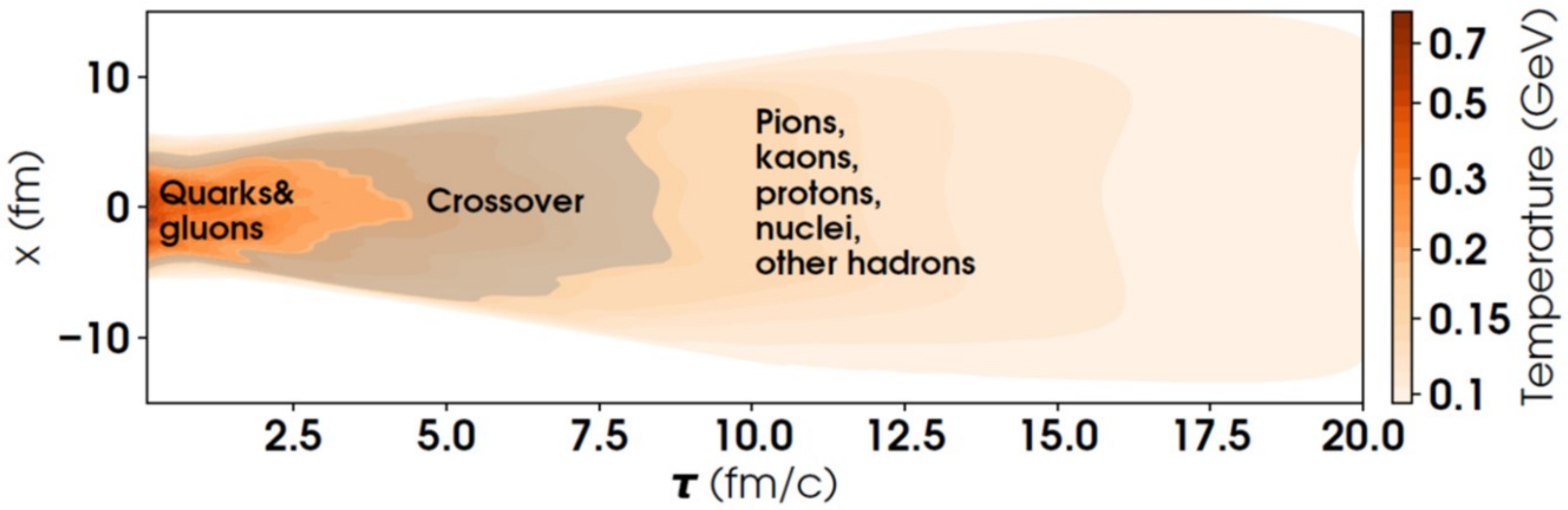

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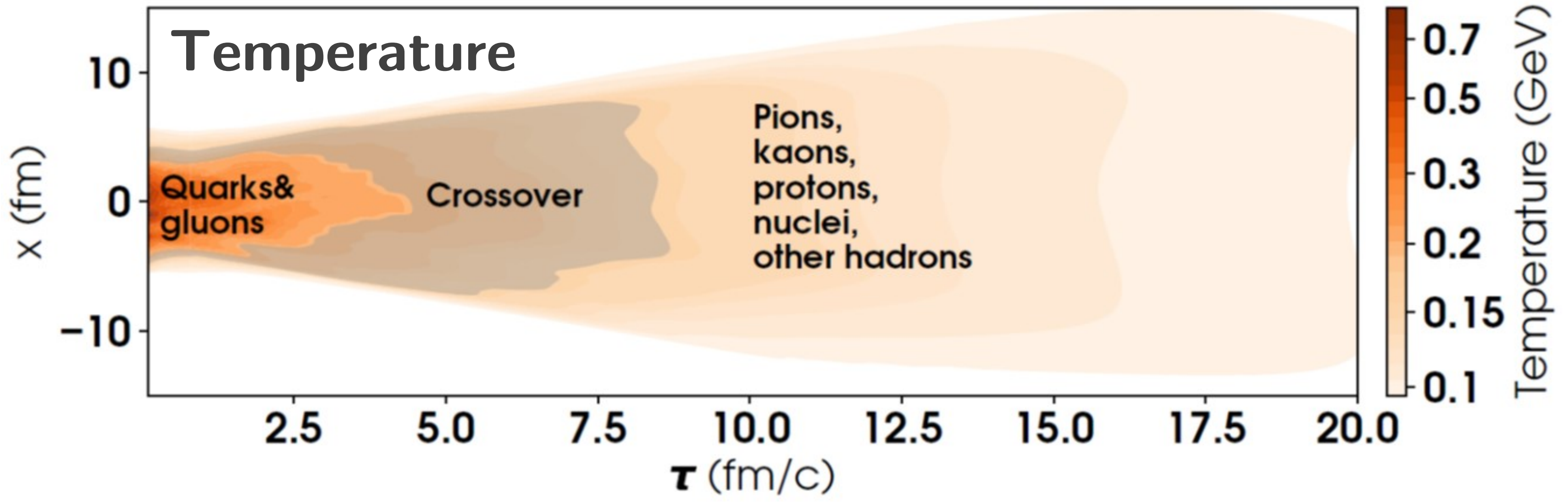
Photons from deconfined plasma

- What is the spacetime profile of quarks/gluons/hadrons?



- Photon production: $$\frac{dN_\gamma}{d^3p} = \int d^4X \, \frac{d\Gamma_\gamma}{d^3p}(p, \overbrace{T(X), u^\mu(X), \ldots}^{\text{Spacetime profile of plasma}})$$

Photon emission rate

Photon emission rate

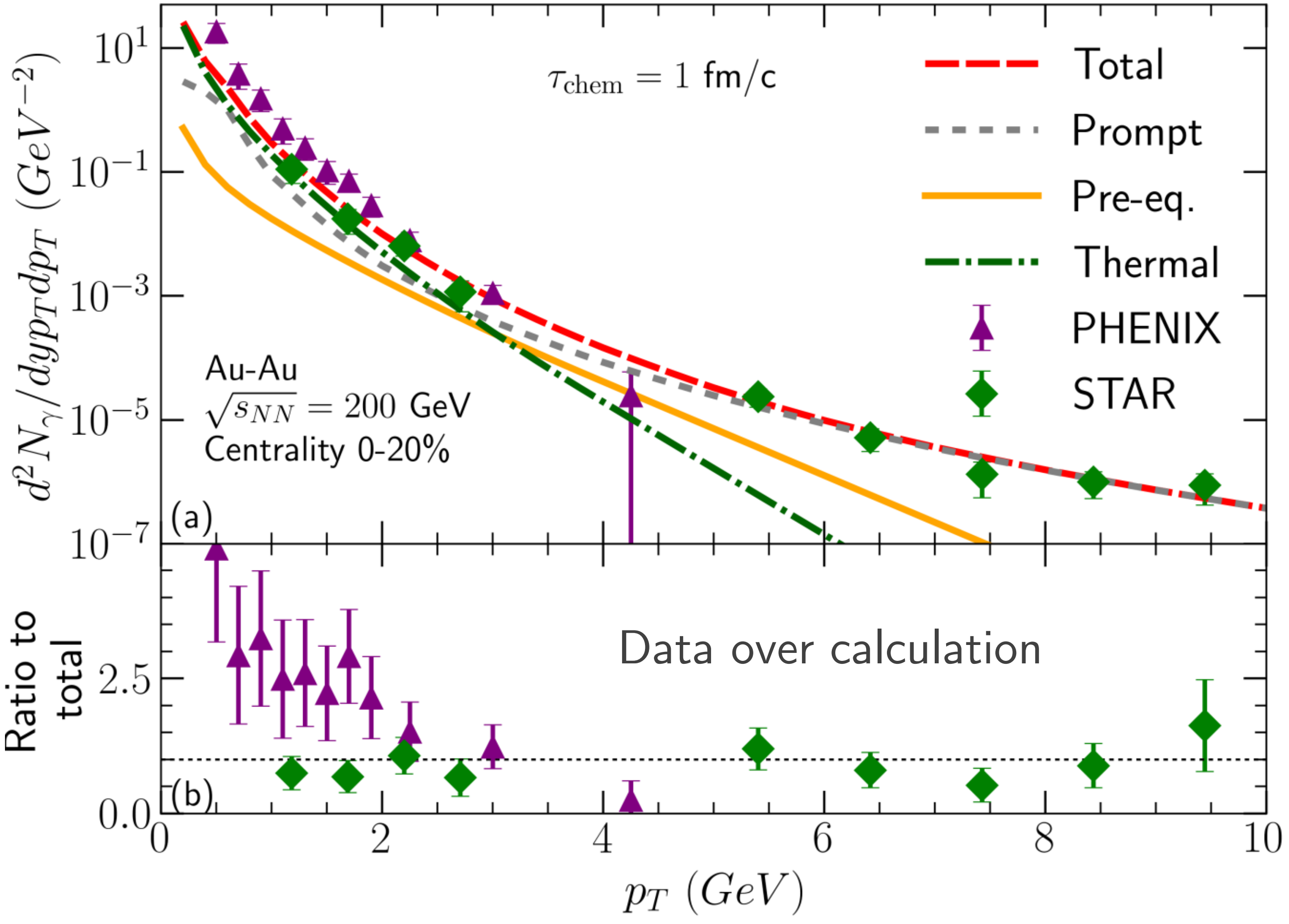
- Photon production: $\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \int \mathrm{d}^4X \, \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}(p, \overbrace{T(X), u^\mu(X), \dots}^{\text{Spacetime profile of plasma}})$

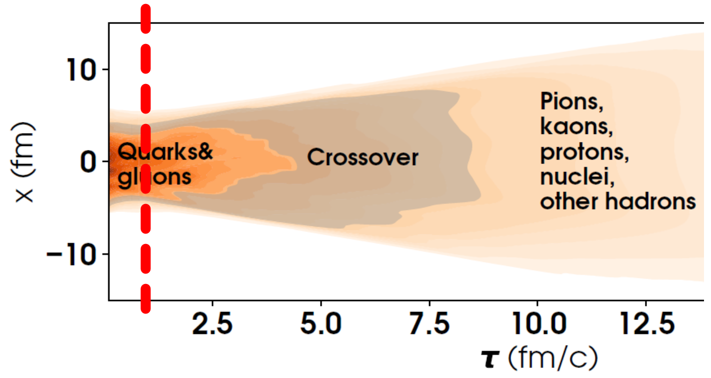
Photon emission rate

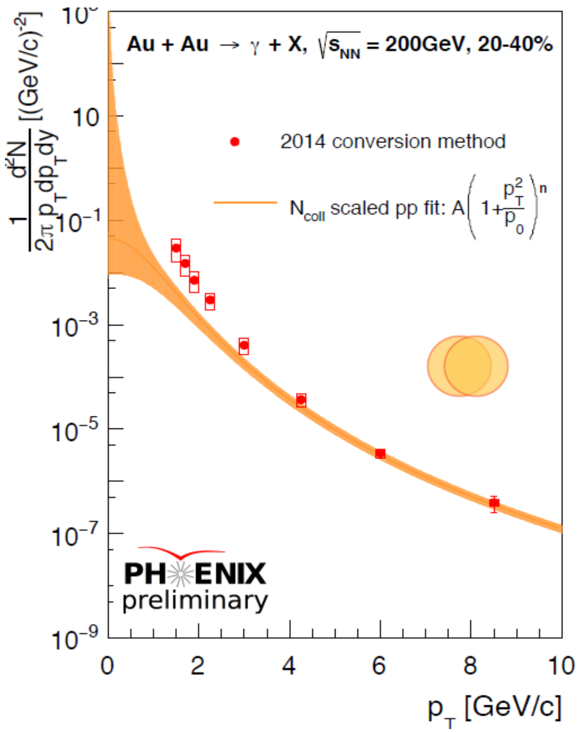
State of matter/Temperatures	Photon emission rate
Gas of hadrons below $T \approx 160$ MeV	Effective hadronic models
Deconfinement for $T \approx 160 - 200$ MeV	Extrapolated rates from low/high temperatures
Strongly-coupled quark/gluons for $T \sim 200 - 500$ MeV	Lattice QCD, holography, effective models
Weakly-coupled QGP at $T \gg 1$ GeV	Perturbative QCD

Results: Au-Au $\sqrt{s_{NN}}$ =200 GeV, 0-20%

Gale, Paquet, Schenke, Shen (2022) PRC

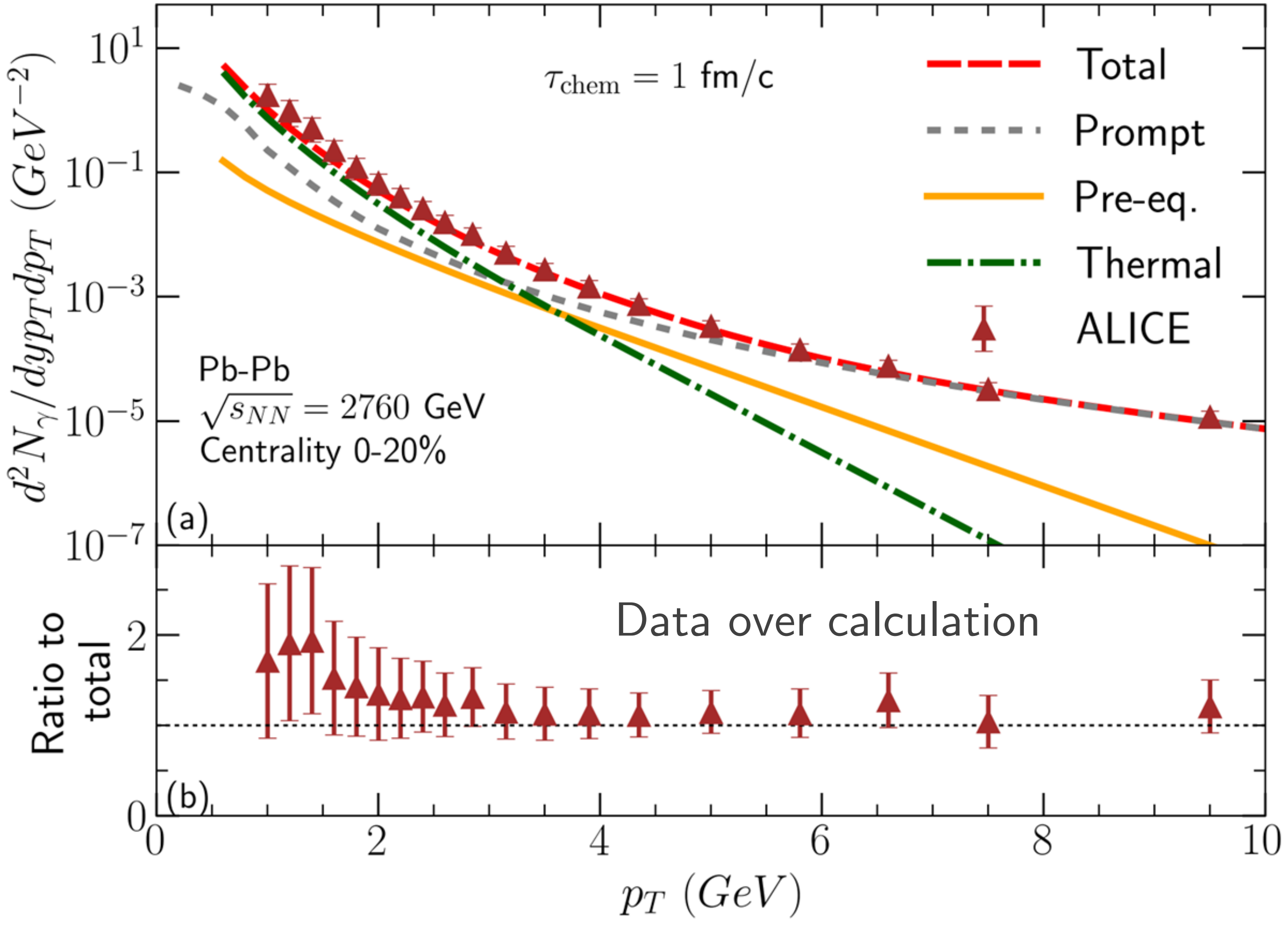






Results: Pb-Pb $\sqrt{s_{NN}}$ =2760 GeV, 0-20%

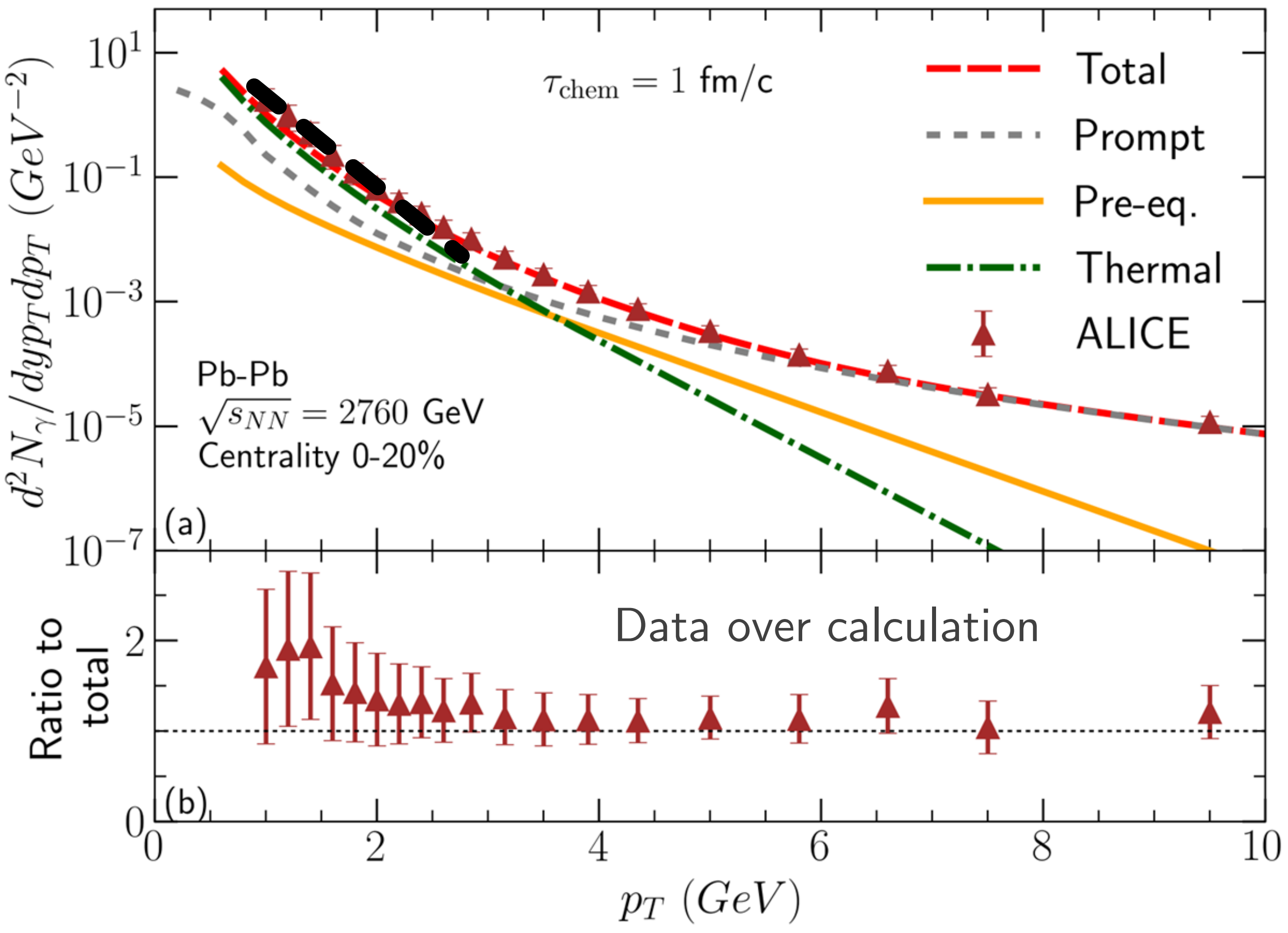
Gale, Paquet, Schenke, Shen (2022) PRC



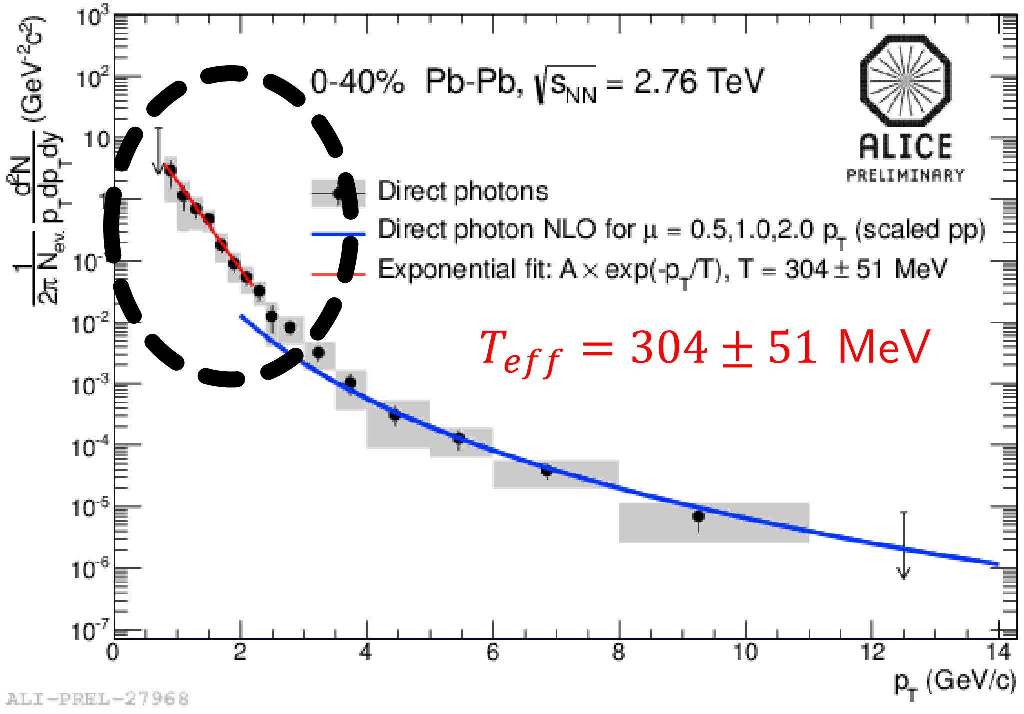
Thermal photons dominate at low energy (p_T)

Results: Pb-Pb $\sqrt{s_{NN}}$ =2760 GeV, 0-20%

Gale, Paquet, Schenke, Shen (2022) PRC

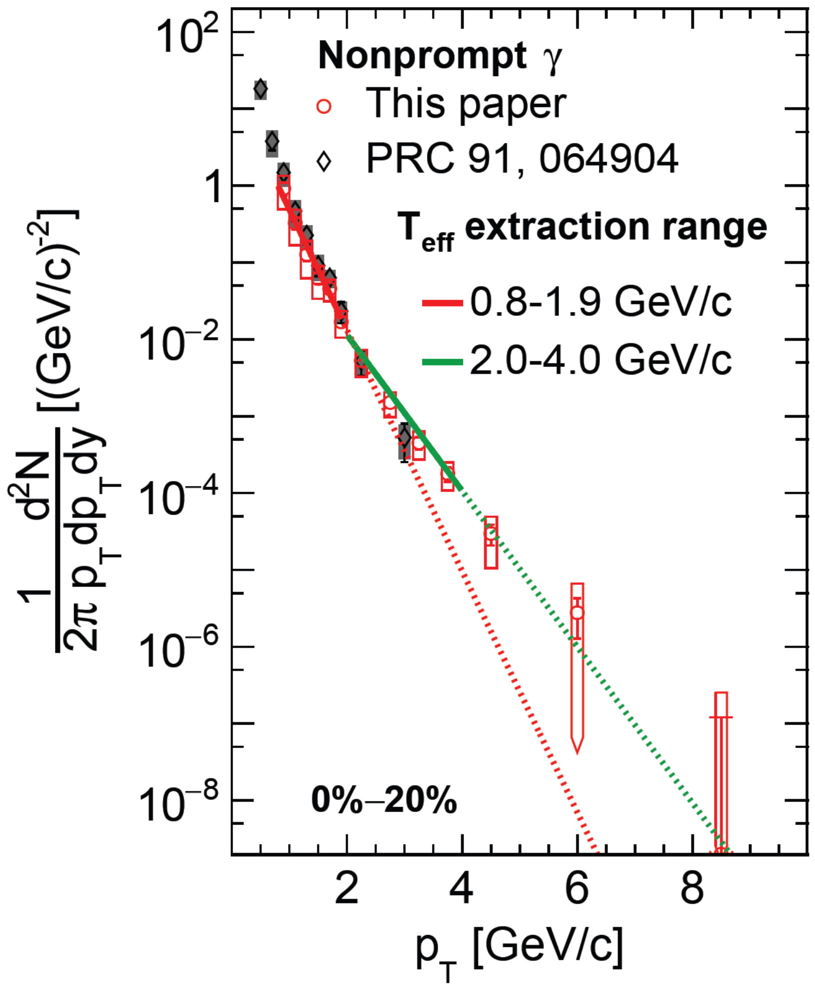


$$\ln\left(\frac{1}{2\pi E}\frac{dN}{dE\,dy}\right) = cte - \frac{E}{T_{eff}}$$



Results: Au-Au $\sqrt{s_{NN}}$ =200 GeV, 0-20%

Ref.: PHENIX Collaboration (2012) PRL

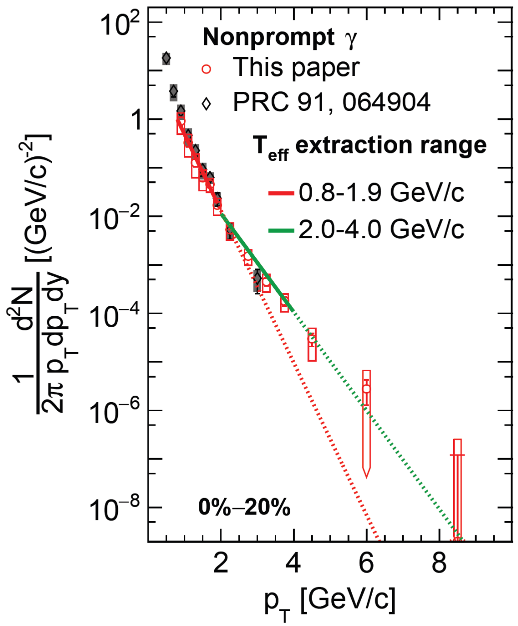


$$\ln\left(\frac{1}{2\pi E}\frac{dN}{dE\,dy}\right) = cte - \frac{E}{T_{eff}}$$

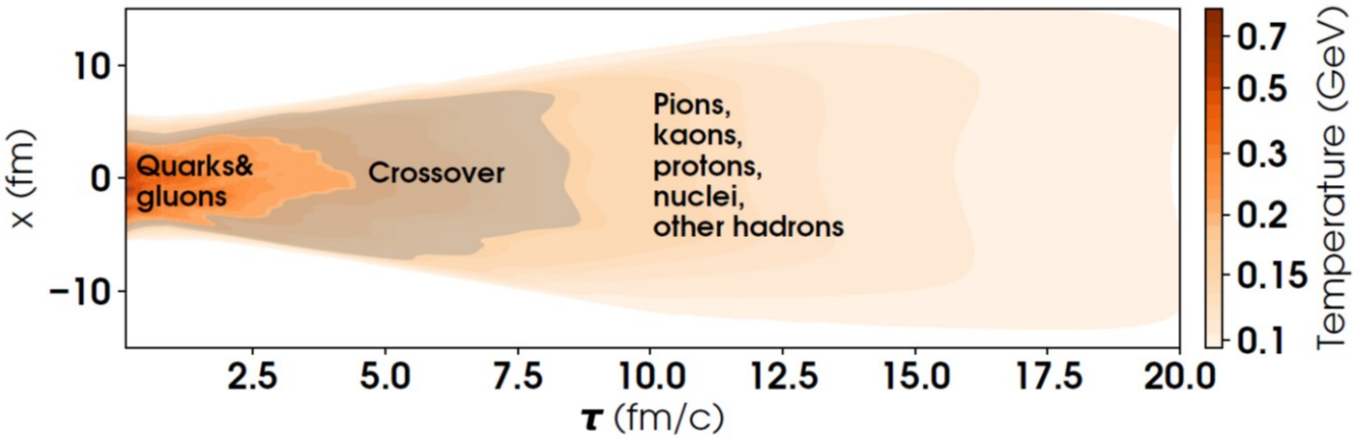
centrality	$T_{\rm eff}$ (GeV/c) $0.8 < p_T < 1.9$ GeV/c	$T_{\rm eff}$ (GeV/c) $2 < p_T < 4$
0%–20%	$0.277 \pm 0.017\ ^{+0.036}_{-0.014}$	$0.428 \pm 0.031\ ^{+0.031}_{-0.030}$
20%–40%	$0.264 \pm 0.010\ ^{+0.014}_{-0.007}$	$0.354 \pm 0.019\ ^{+0.020}_{-0.030}$
40%–60%	$0.247 \pm 0.007\ ^{+0.005}_{-0.004}$	$0.392 \pm 0.023\ ^{+0.022}_{-0.022}$
60%–93%	$0.253 \pm 0.011\ ^{+0.012}_{-0.006}$	$0.331 \pm 0.036\ ^{+0.031}_{-0.041}$

(Prompt photons subtracted before fit)

Ref.: PHENIX Collaboration (2012) PRL



centrality	T_{eff} (GeV/c) $0.8 < p_T < 1.9$ GeV/c	T_{eff} (GeV/c) $2 < p_T < 4$
0%–20%	$0.277 \pm 0.017\ ^{+0.036}_{-0.014}$	$0.428 \pm 0.031\ ^{+0.031}_{-0.030}$

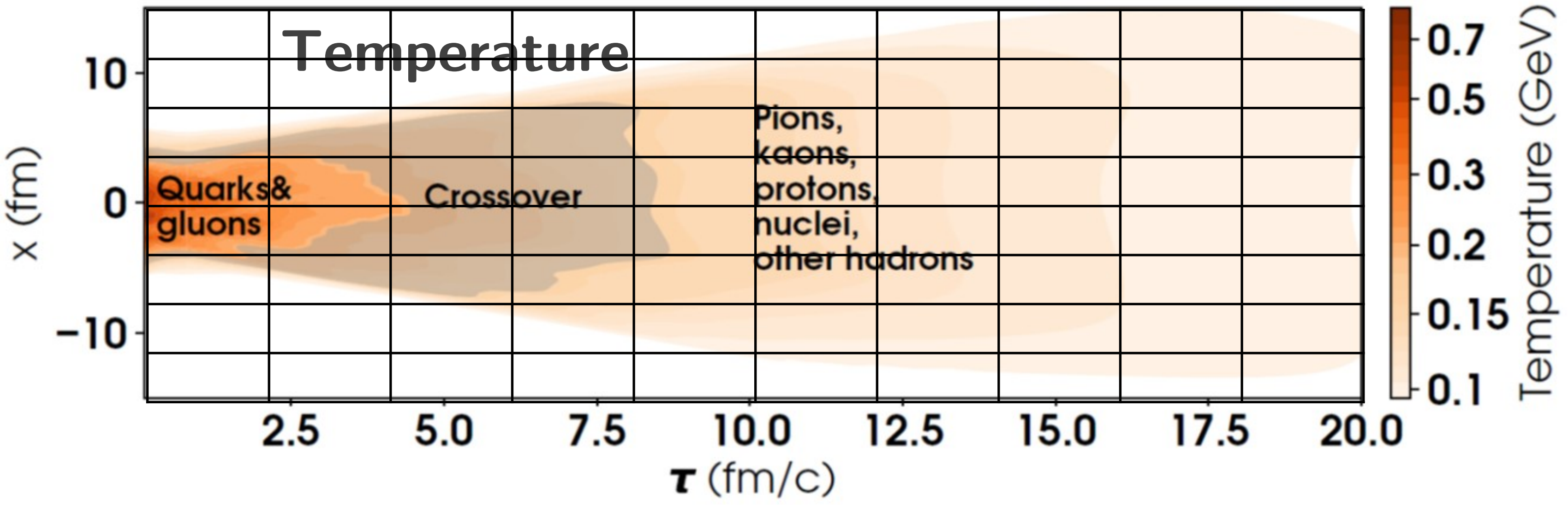


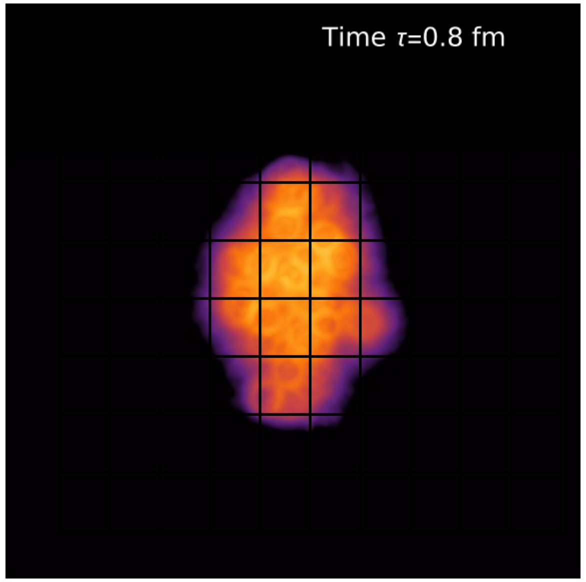
PHOTONS IN HEAVY-ION COLLISIONS

PLASMA TEMPERATURE VS PHOTON ENERGY SPECTRUM

Photons from deconfined plasma

- Photons produced at different temperature, and with different Doppler shifts





- Photon production: $$\frac{dN_\gamma}{d^3p} = \int d^4X \, \frac{d\Gamma_\gamma}{d^3p}\big(p, \overbrace{T(X), u^\mu(X), \ldots}^{\text{Spacetime profile of plasma}}\big)$$

Photon emission rate

Thermal photon spectrum: Doppler shift

$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) = \ln\left(\int \mathrm{d}^4X \frac{1}{E}\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}(p, T(X), u^\mu(X), \dots)\right) \sim cte - \frac{E}{T_{eff}}?$$

Photon emission rate: $\frac{1}{\mathrm{E}}\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p} \sim e^{-\frac{E}{T}}$

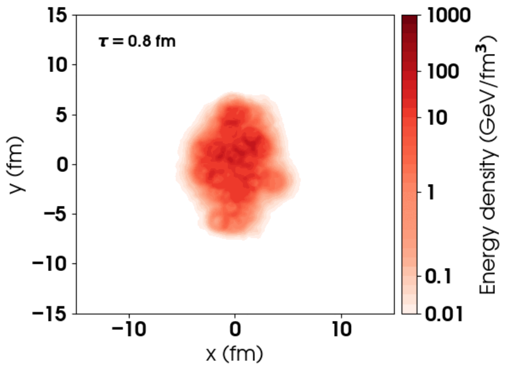
Doppler shift

$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx \ln\left(\int \mathrm{d}^4X\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte = \ln\left(\int d\phi\, d\eta_s\, dx_\perp\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$

At midrapidity, $P \cdot u = p_T\left(\cosh(\eta_s)\sqrt{1+u_\perp^2} - u_\perp \cos(\phi)\right)$

Thermal photon spectrum: Doppler shift

$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) = \ln\left(\int \mathrm{d}^4X \frac{1}{E}\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}(p, T(X), u^\mu(X), \dots)\right) \sim cte - \frac{E}{T_{eff}}?$$



Photon emission rate: $\frac{1}{\mathrm{E}}\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p} \sim e^{-\frac{E}{T}}$

Doppler shift

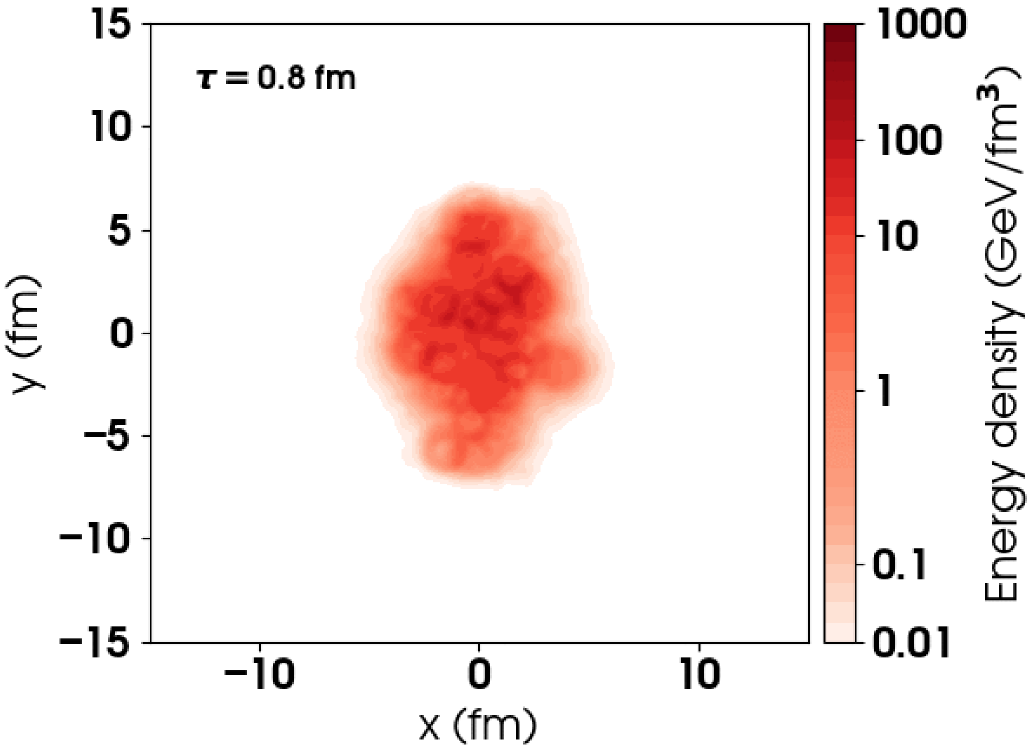
$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx \ln\left(\int \mathrm{d}^4X\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte = \ln\left(\int d\phi d\eta_s dx_\perp\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$

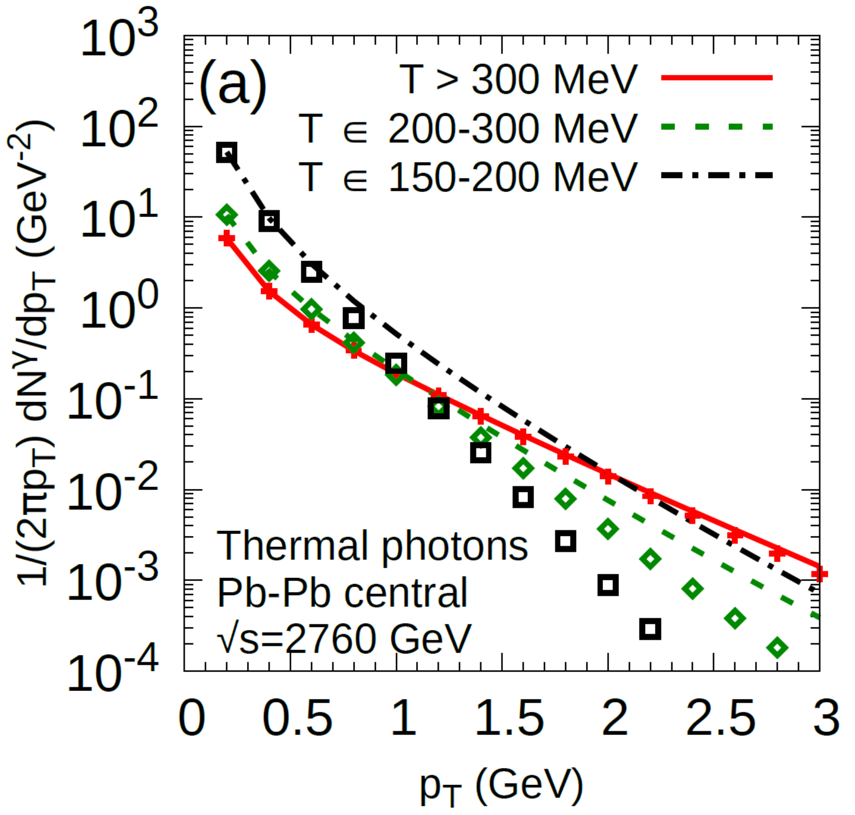
$$\approx \ln\left(\int dx_\perp \exp\left(-\frac{E}{T\left(1+\frac{u_\perp^2}{4E/T}(1+(E/T-2)(E/T))\right)}\right)\right) + cte$$

Thermal photon spectrum: Doppler shift

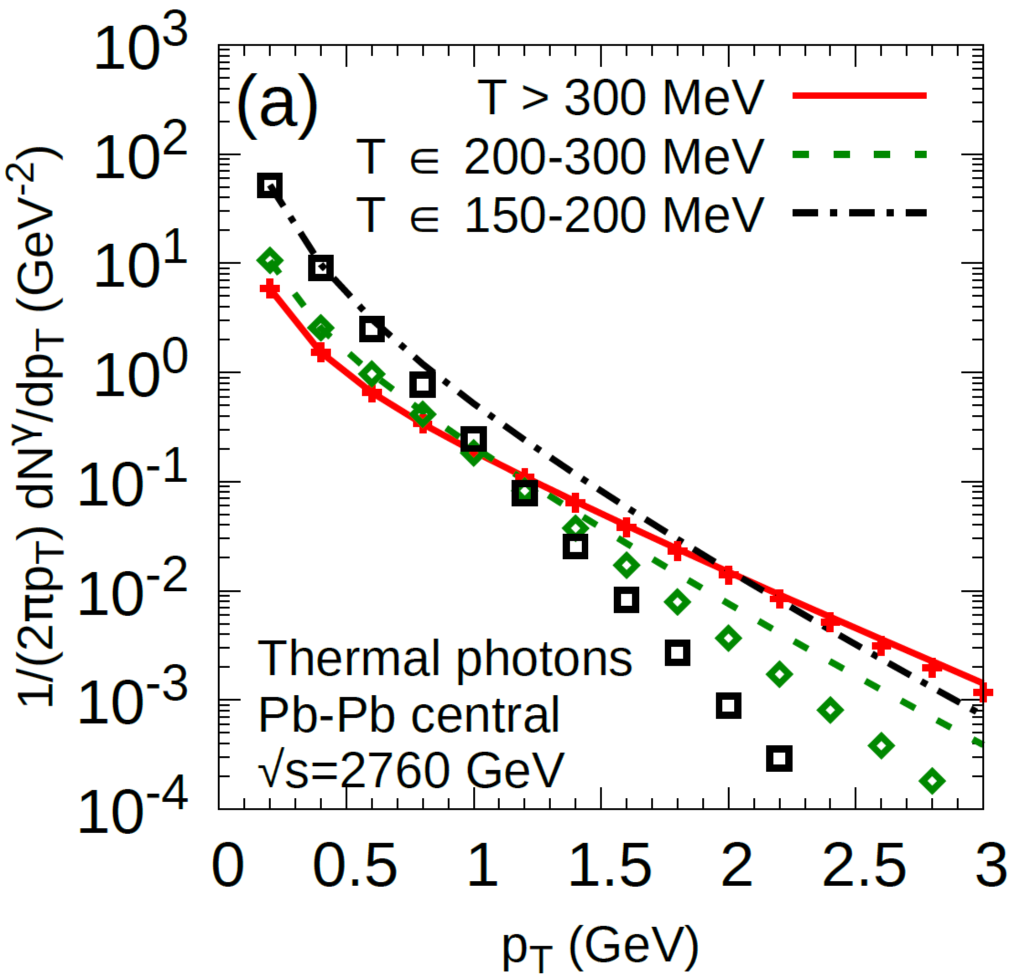
$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx \ln\left(\int dx_\perp \exp\left(-\frac{E}{T\left(1+\frac{u_\perp^2}{4E/T}(1+(E/T-2)(E/T))\right)}\right)\right) + cte$$

Transverse Doppler shift

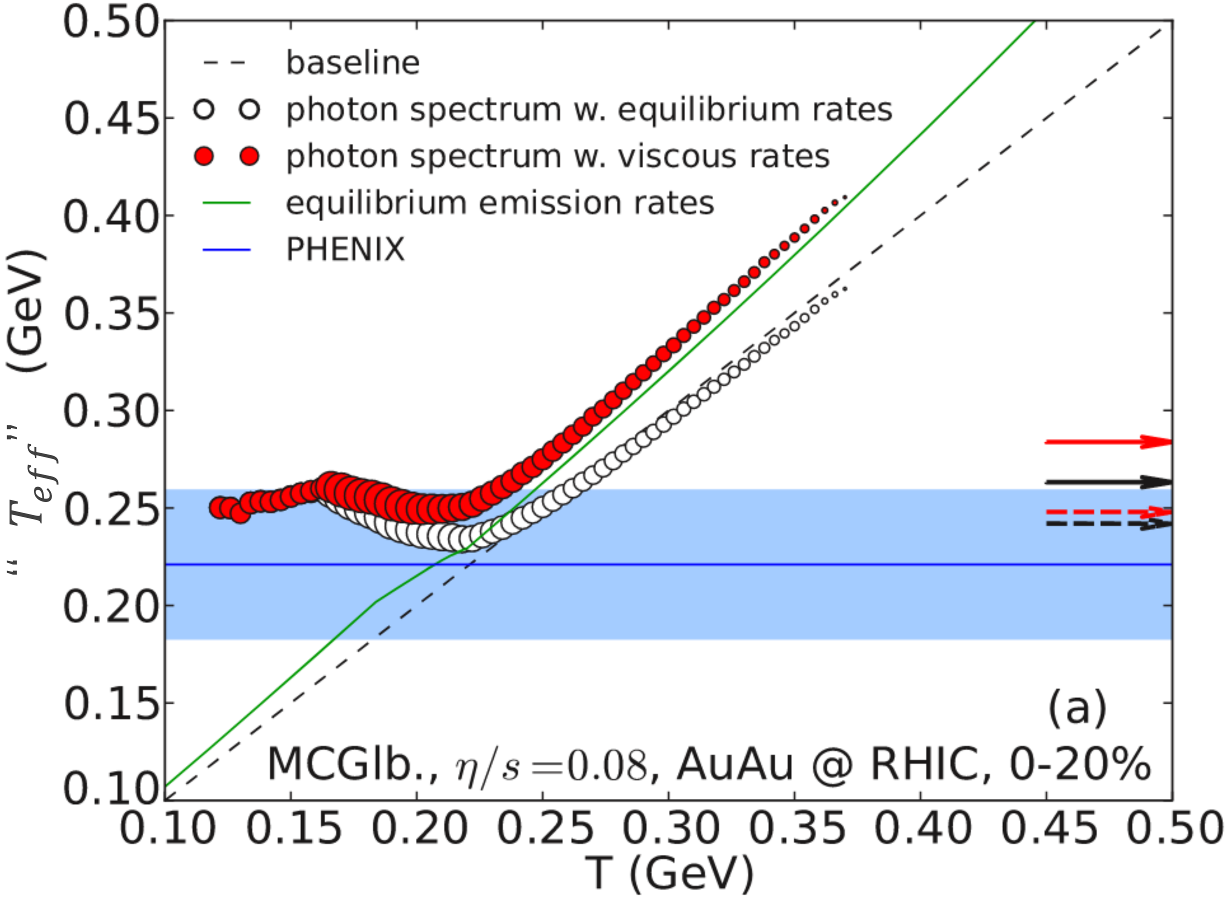




Effect of transverse Doppler shift

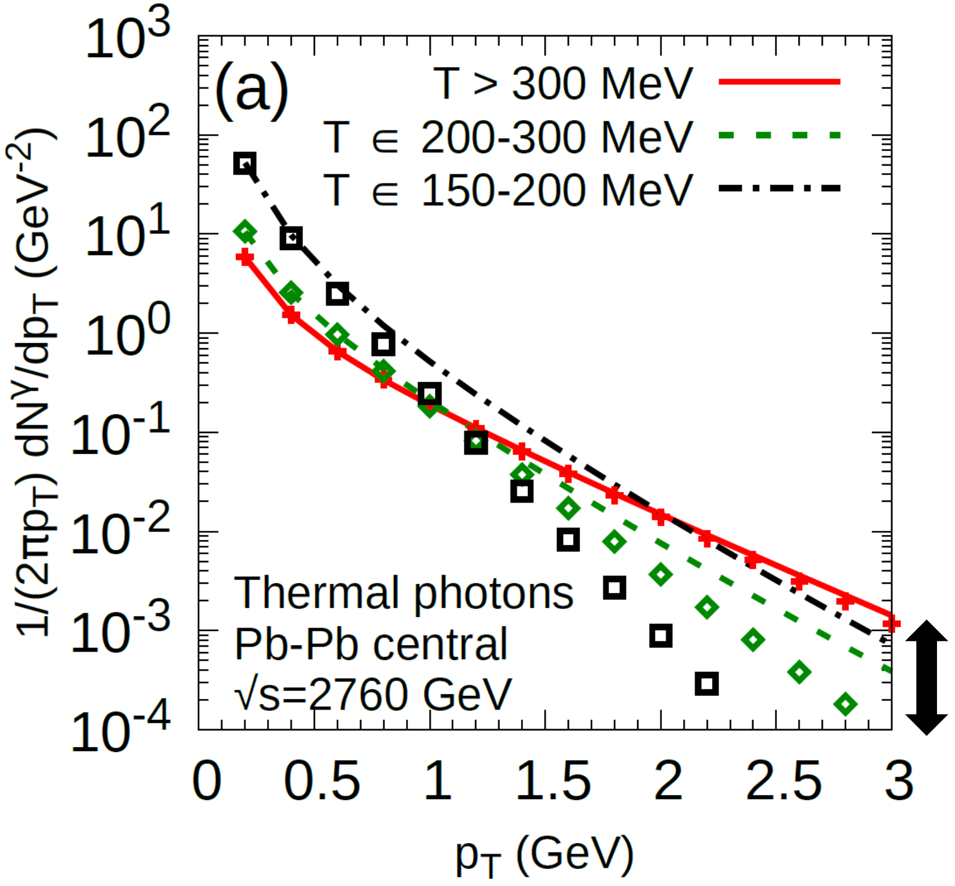


Local effect of Doppler shift

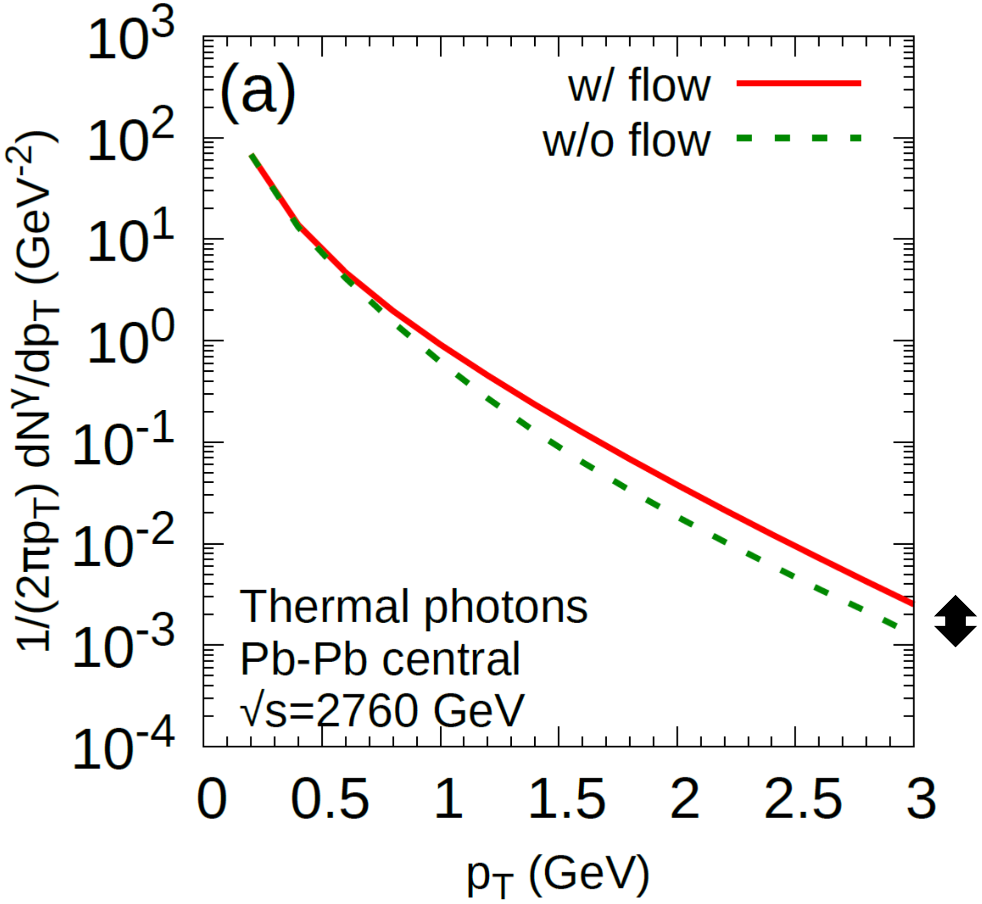


Ref.: Shen, Heinz, Paquet, Gale (2014) PRC;
See also van Hees, Gale, Rapp (2011) PRC

Effect of transverse Doppler shift

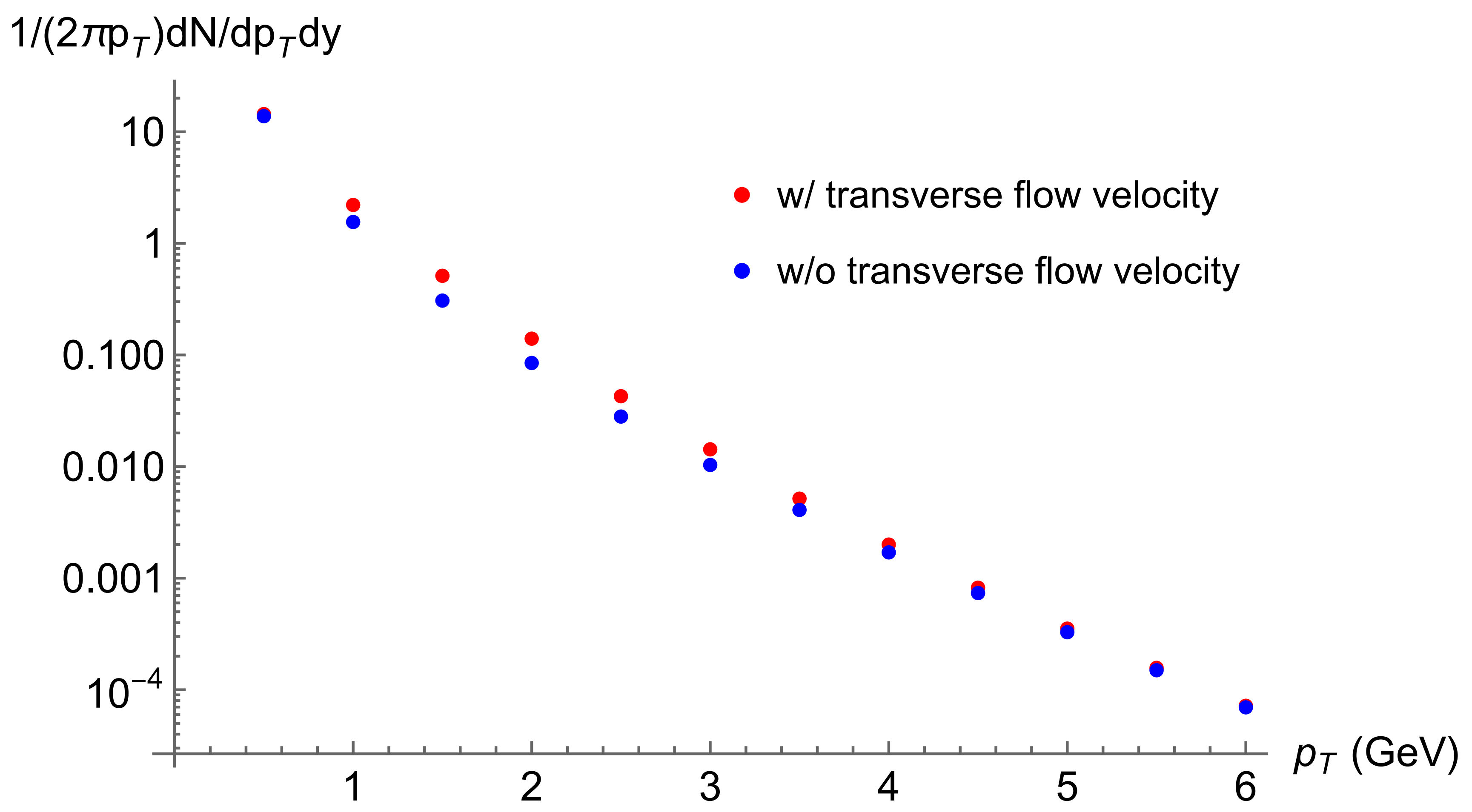


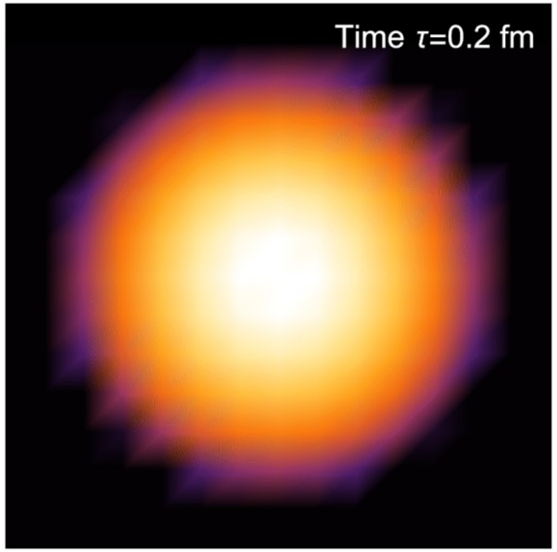
Local effect of Doppler shift



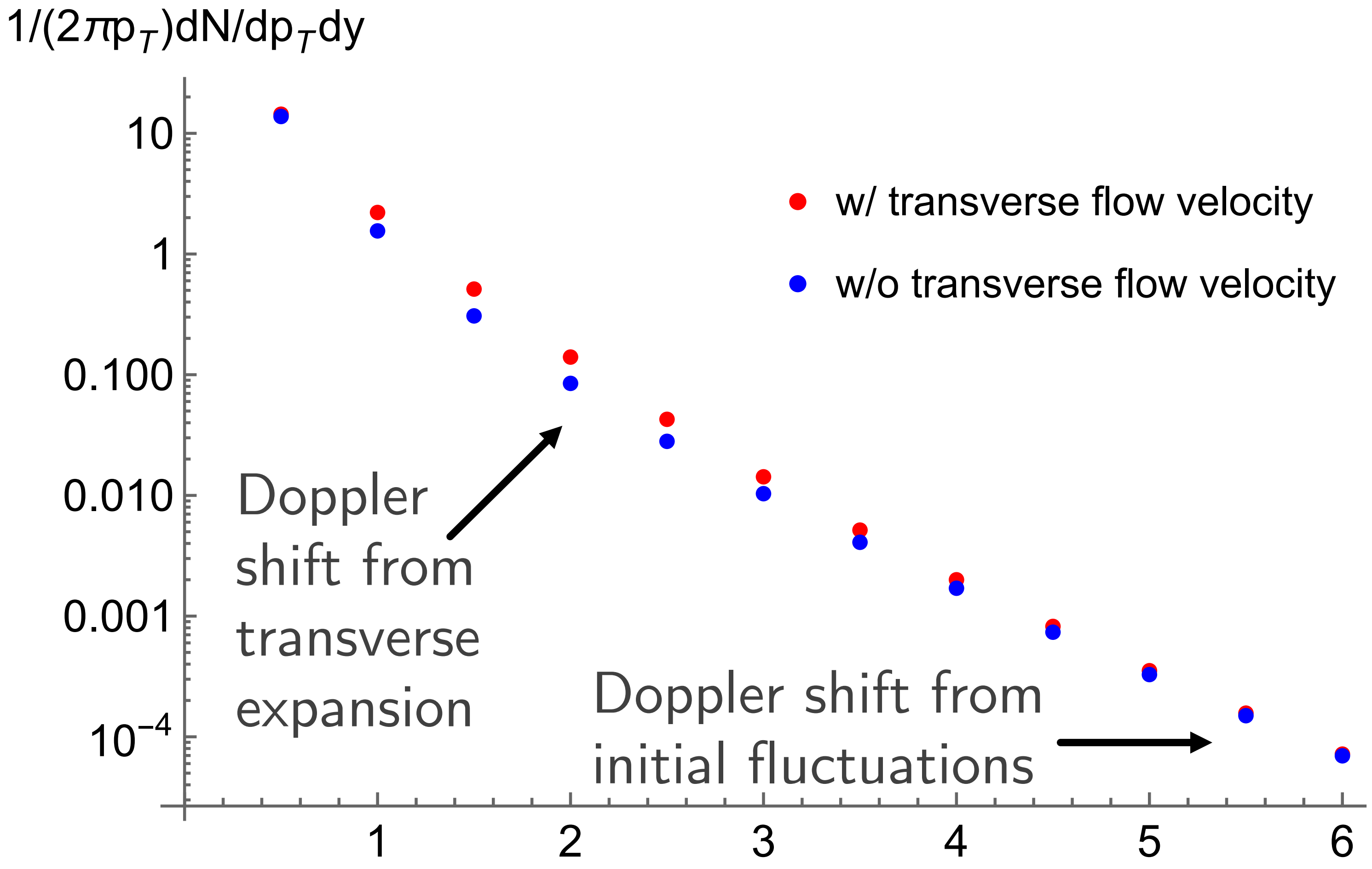
Global effect of Doppler shift

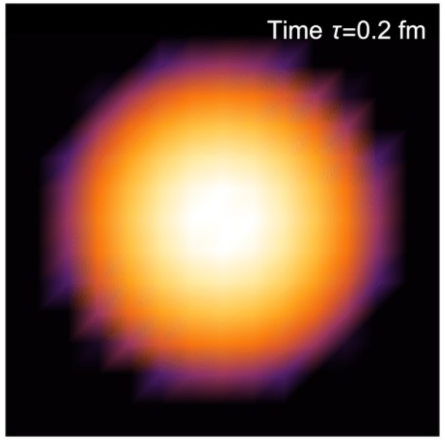
Not all Doppler shifts are equal

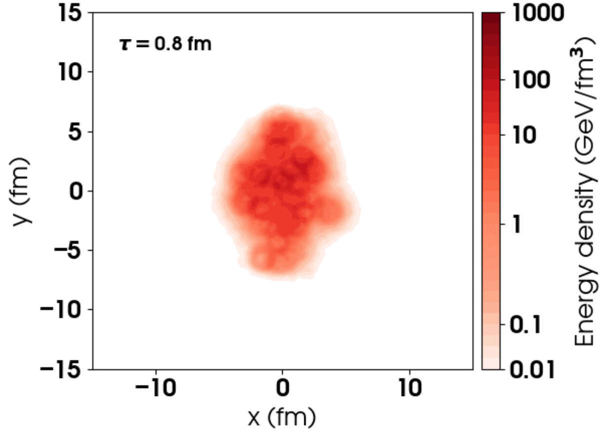




Not all Doppler shifts are equal

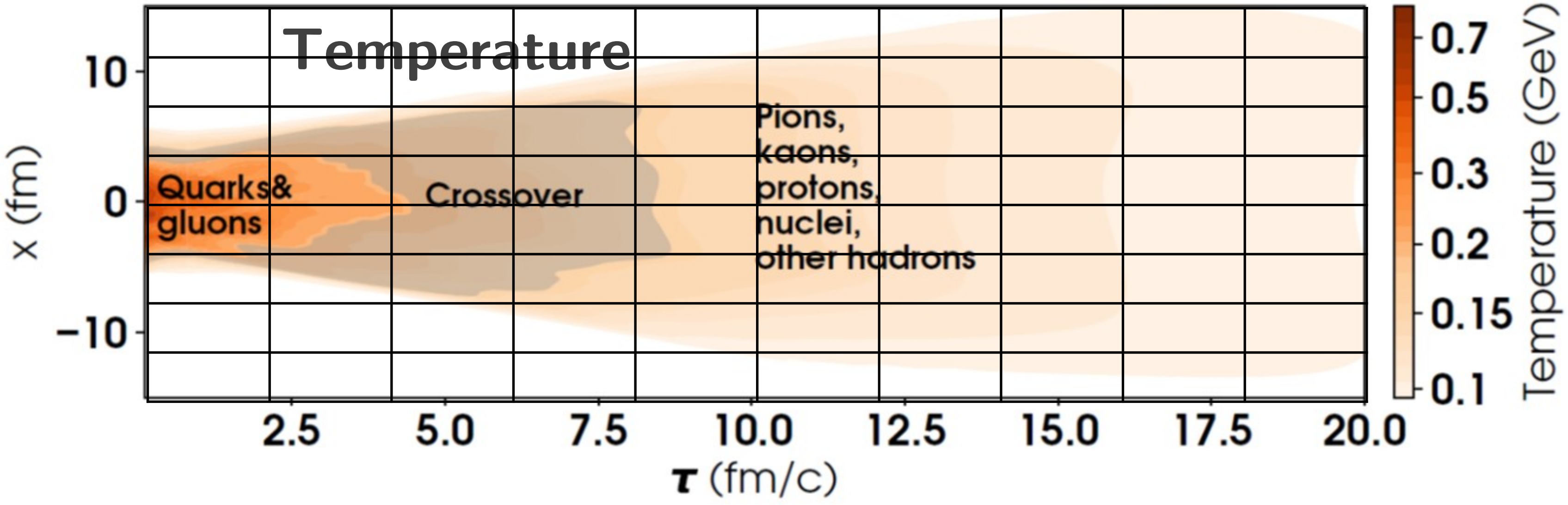


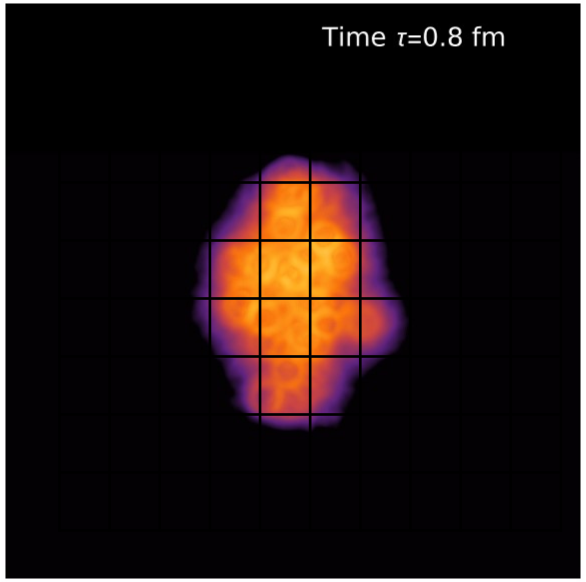




Photons from deconfined plasma

- Photons produced at different temperature, and with different Doppler shifts



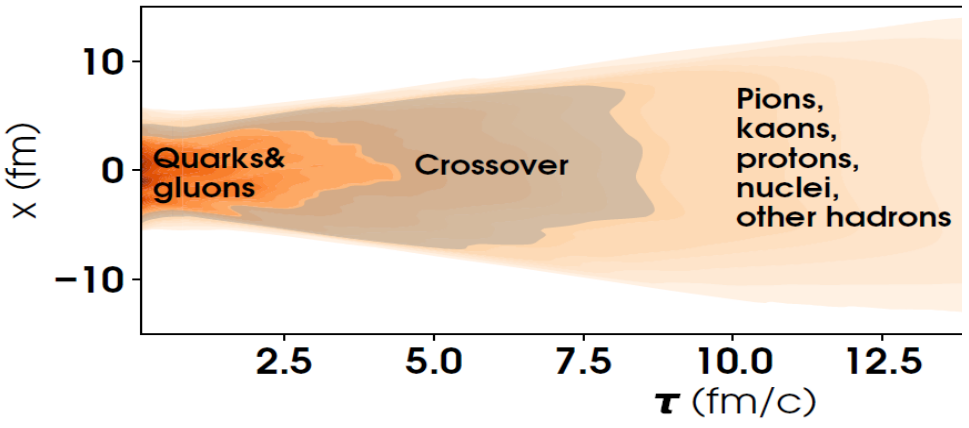


- Photon production: $$\frac{dN_\gamma}{d^3p} = \int d^4X \, \frac{d\Gamma_\gamma}{d^3p}\overbrace{(p, T(X), u^\mu(X), \ldots)}^{\text{Spacetime profile of plasma}}$$

Photon emission rate

Thermal photon spectrum

$$\ln\left(\frac{1}{E}\frac{dN_\gamma}{d^3p}\right) \approx \ln\left(\int d\phi d\eta_s dx_\perp\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$

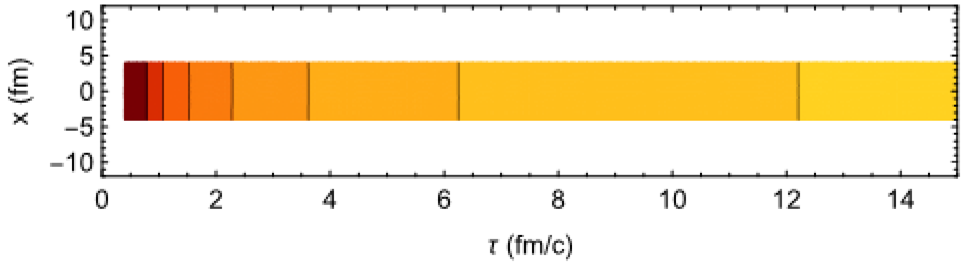


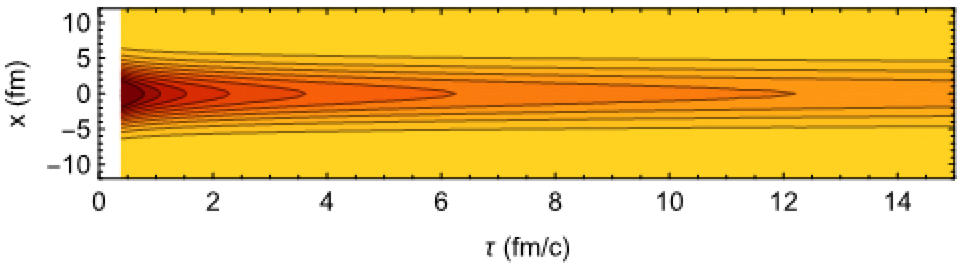
Spacetime profile of plasma: complicated, but can look at simple models

Bjorken hydrodynamics for longitudinal-dominated expansion: $T(\tau) = \mathrm{T}_0\left(\frac{\tau_0}{\tau}\right)^{c_s^2}$

➡ Black disk approx: $T(\tau, r<\sigma) = \mathrm{T}_0\left(\frac{\tau_0}{\tau}\right)^{c_s^2}$

➡ Gaussian approx: $T(\tau, r) = \mathrm{T}_0 e^{-\frac{r^2}{2\sigma^2}}\left(\frac{\tau_0}{\tau}\right)^{c_s^2}$





Paquet and Bass [arXiv:2205.12299]

Thermal photon spectrum

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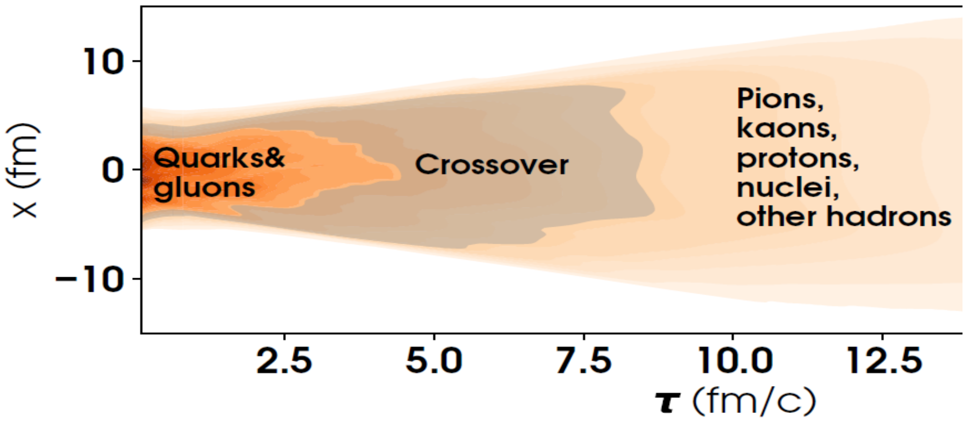
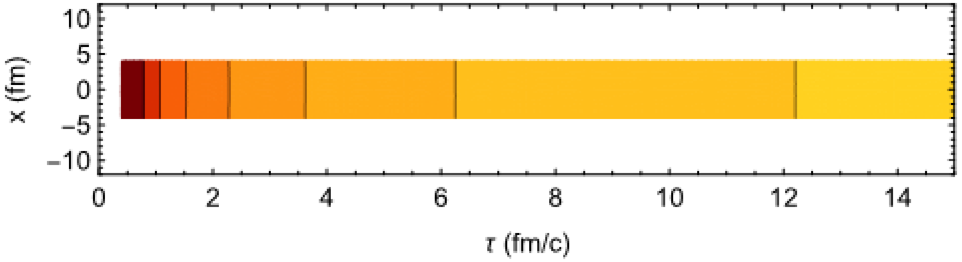
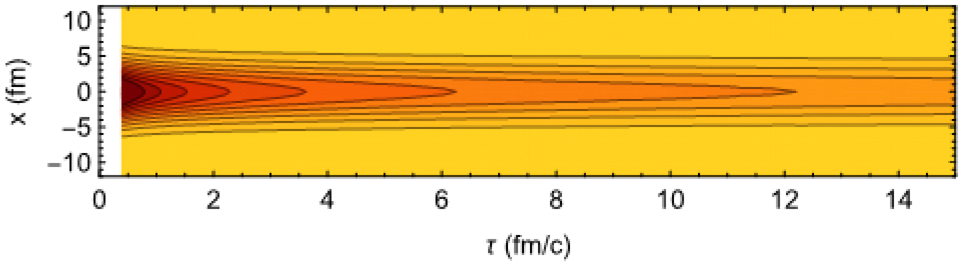


$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx -\frac{E}{T_0} + \frac{3}{2}\log\left(\frac{T_0}{E}\right) + cte + O\left(\frac{T_0}{E}\right)$$



Paquet and Bass [arXiv:2205.12299]

$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx -\frac{E}{T_0} + \frac{5}{2}\log\left(\frac{T_0}{E}\right) + cte + O\left(\frac{T_0}{E}\right)$$

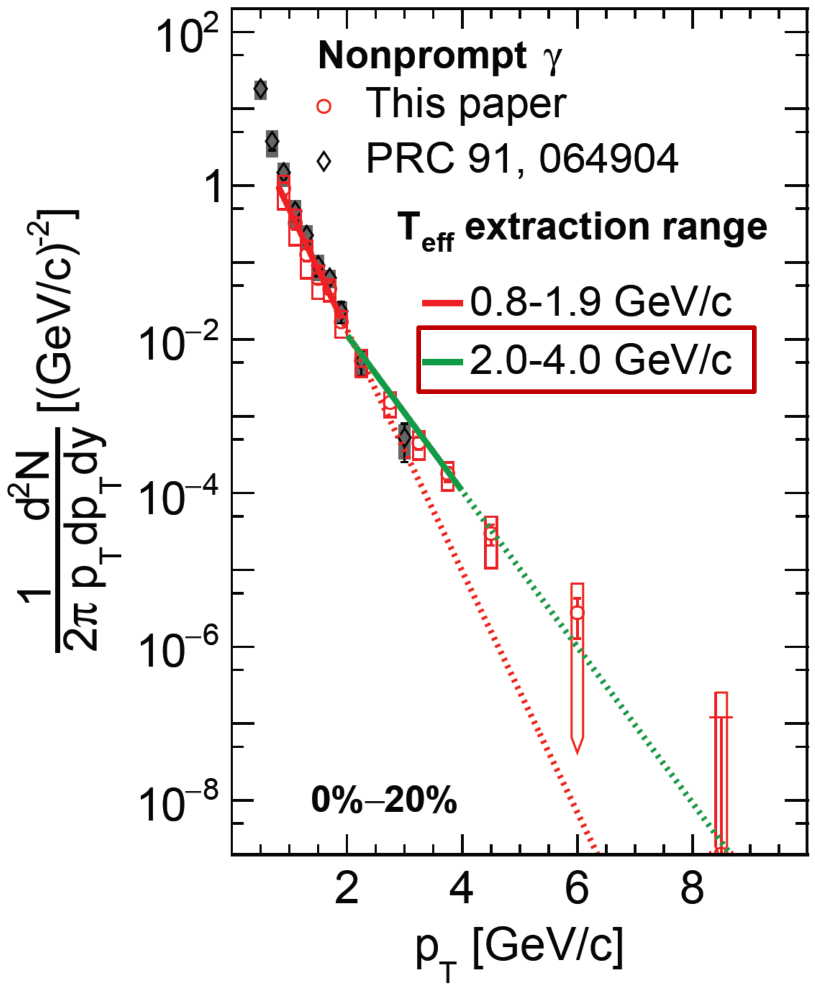


$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx -\frac{E}{T_0} + \mu\log\left(\frac{T_0}{E}\right) + cte \approx -\frac{E}{T_{eff}} + cte$$

$$T_0 \approx \frac{T_{eff}}{1-\frac{T_{eff}}{E}\mu\ln\mu}$$

Results: Au-Au $\sqrt{s_{NN}}$ =200 GeV, 0-20%

Paquet and Bass [arXiv:2205.12299]



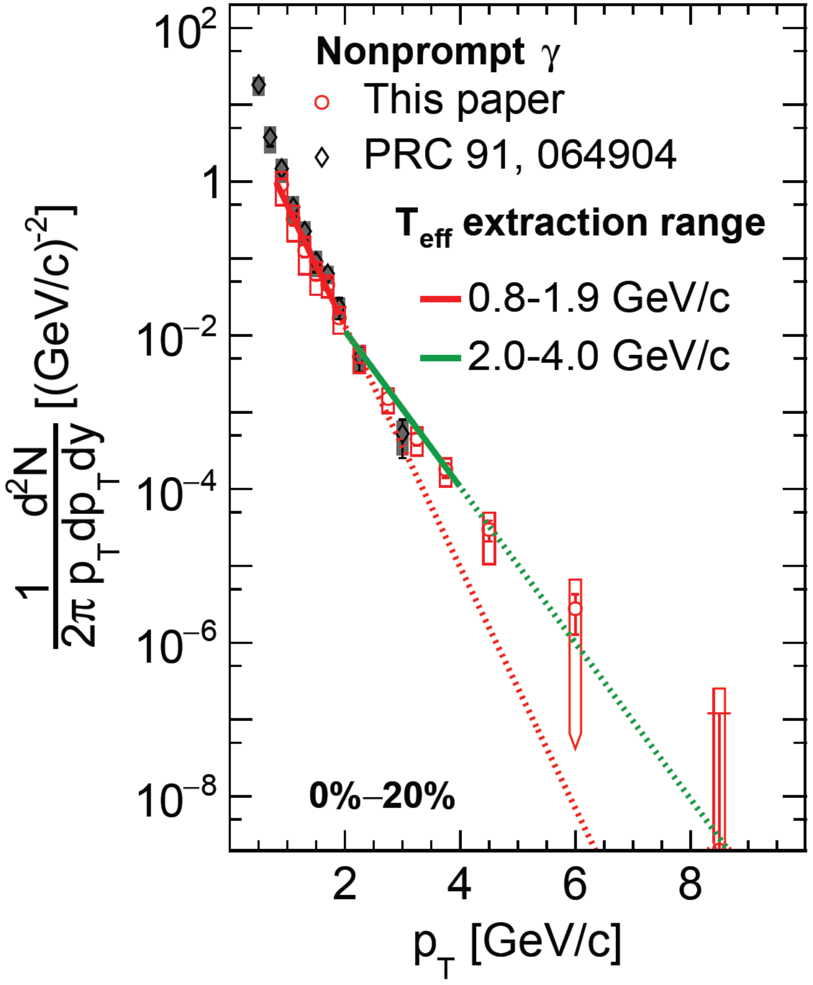
$$\ln\left(\frac{1}{2\pi E}\frac{dN}{dE\,dy}\right) = cte - \frac{E}{T_{eff}}\,; \quad T_0 \approx \frac{T_{eff}}{1 - \frac{T_{eff}}{E}\mu \ln \mu}$$

centrality	$T_0(GeV)$	$T_{\rm eff}$ (GeV/c) $0.8 < p_T < 1.9$ GeV/c	$T_0(GeV)$	$T_{\rm eff}$ (GeV/c) $2 < p_T < 4$
0%–20%	0.48	$0.277 \pm 0.017\ ^{+0.036}_{-0.014}$	0.64	$0.428 \pm 0.031\ ^{+0.031}_{-0.030}$

Non-trivial relation between inverse slope and plasma temperature

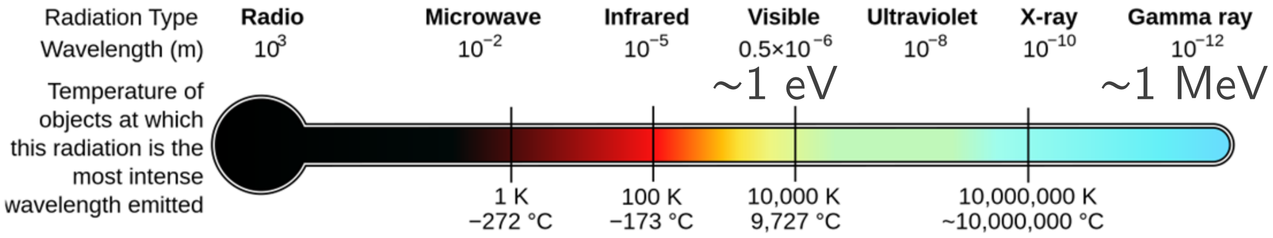
Remember: Doppler shift introduces more complications

Results: Au-Au $\sqrt{s_{NN}}$ =200 GeV, 0-20%



centrality	$T_0(GeV)$	T_{eff} (GeV/c) $0.8 < p_T < 1.9$ GeV/c	$T_0(GeV)$	T_{eff} (GeV/c) $2 < p_T < 4$
0%–20%	0.48	$0.277 \pm 0.017 \,^{+0.036}_{-0.014}$	0.64	$0.428 \pm 0.031 \,^{+0.031}_{-0.030}$

$$T = 500\ MeV = 6 \times 10^{12} K$$

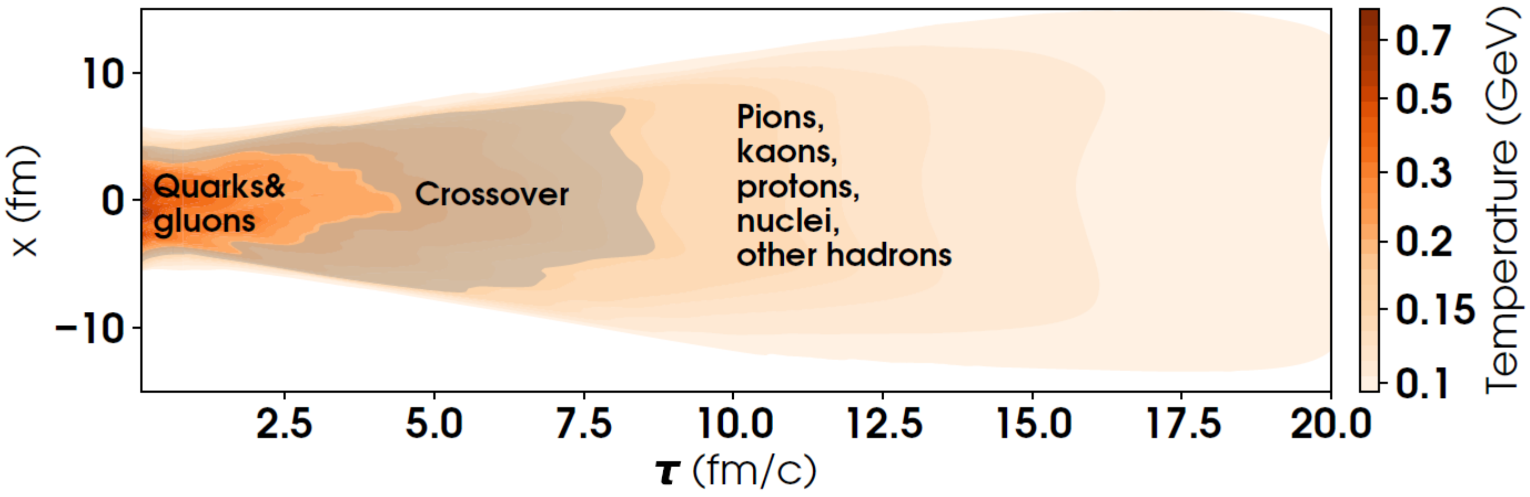


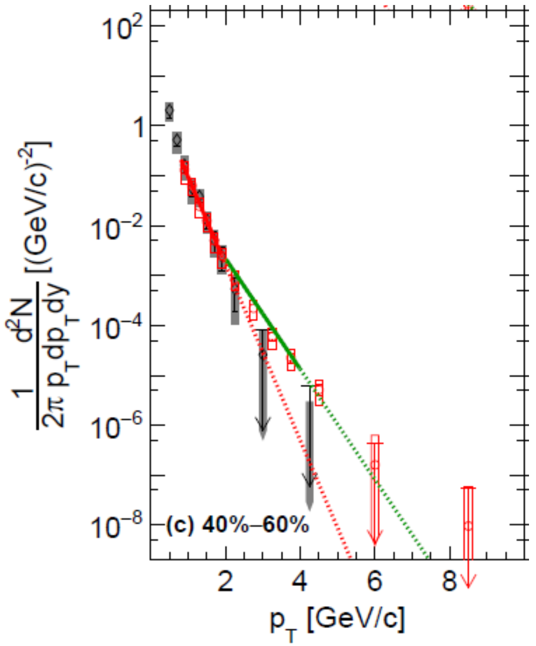
~1 eV

~1 MeV

E_γ ~1 GeV

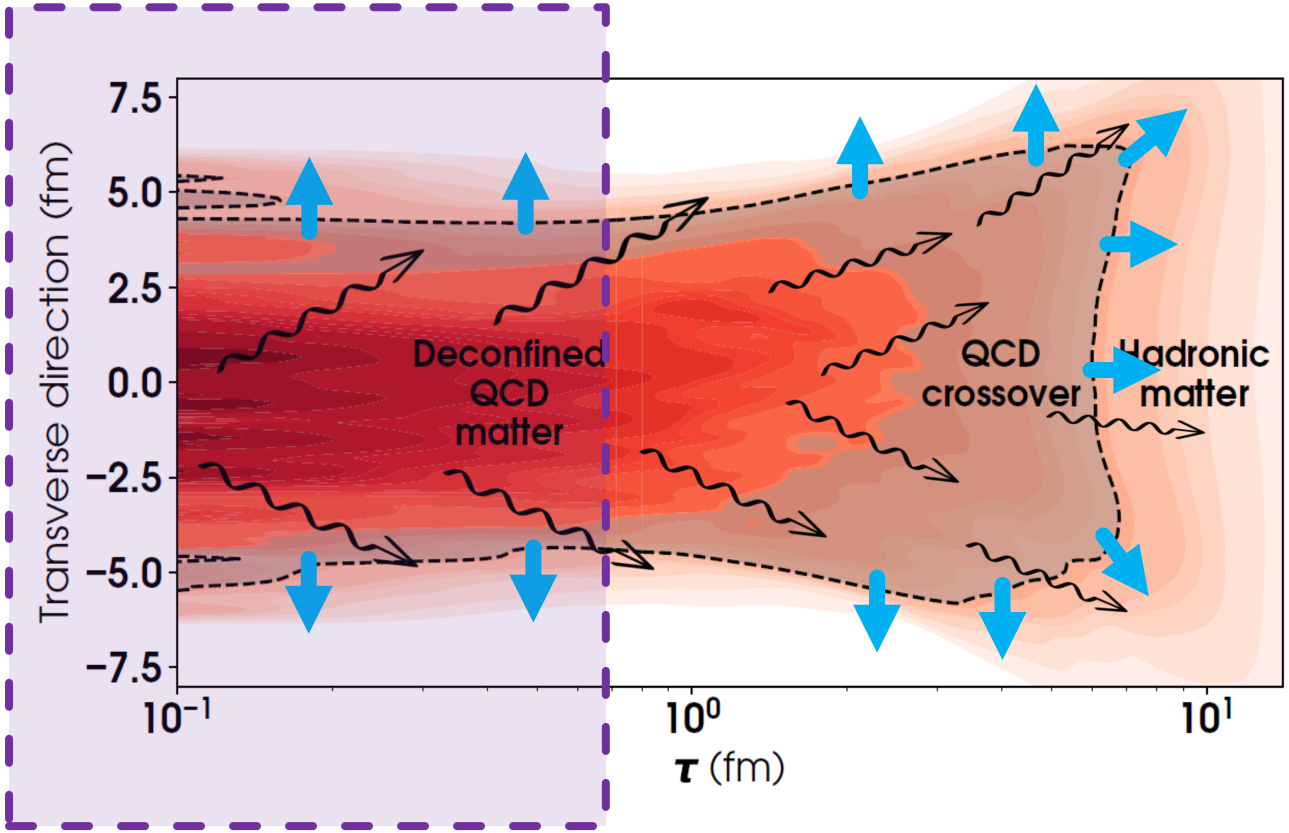
$T \sim 10^{12}$K



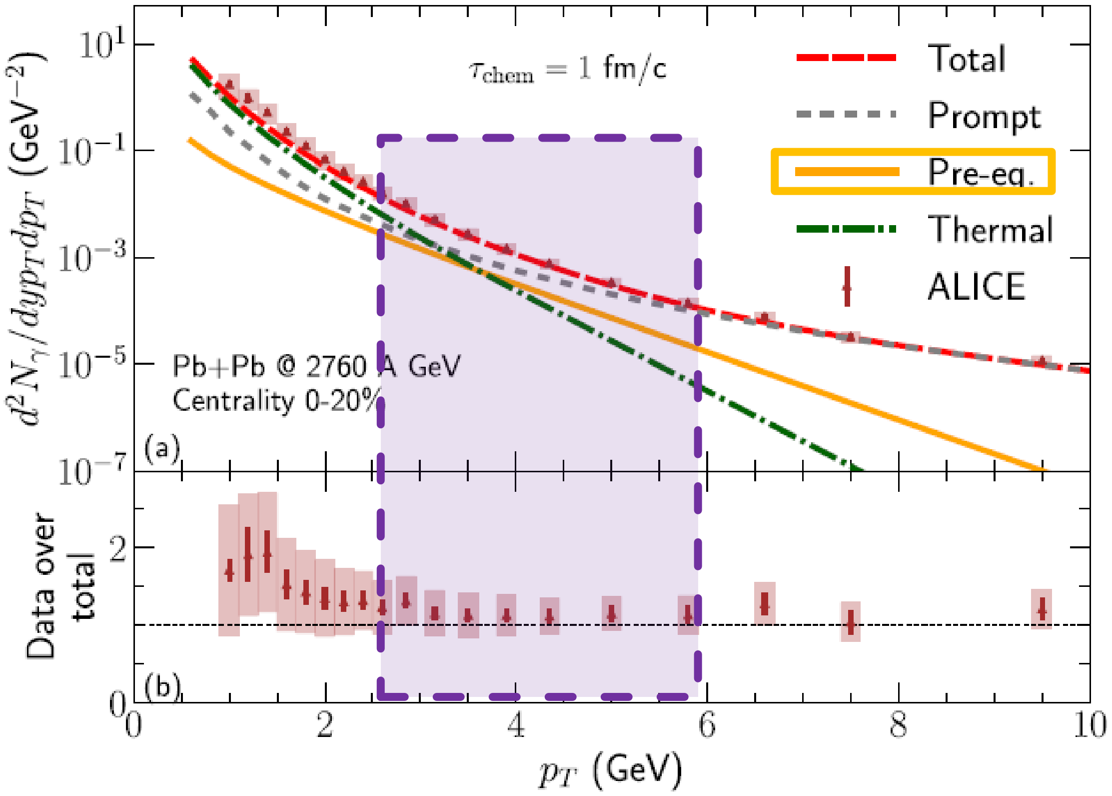


PRE-EQUILIBRIUM PHOTONS

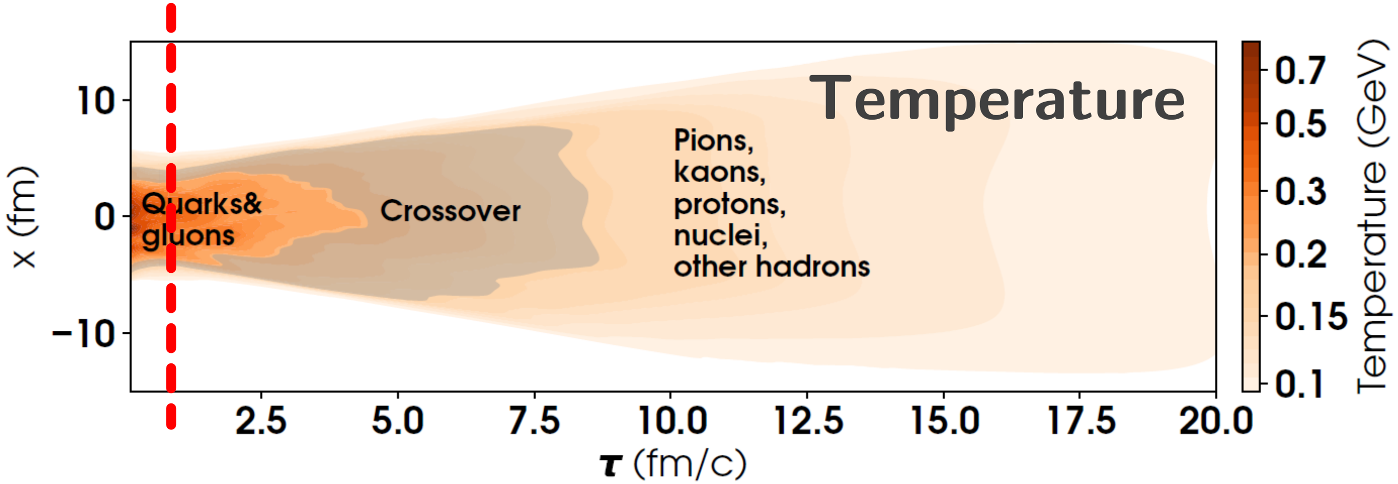
Photons from the early stage of the collision



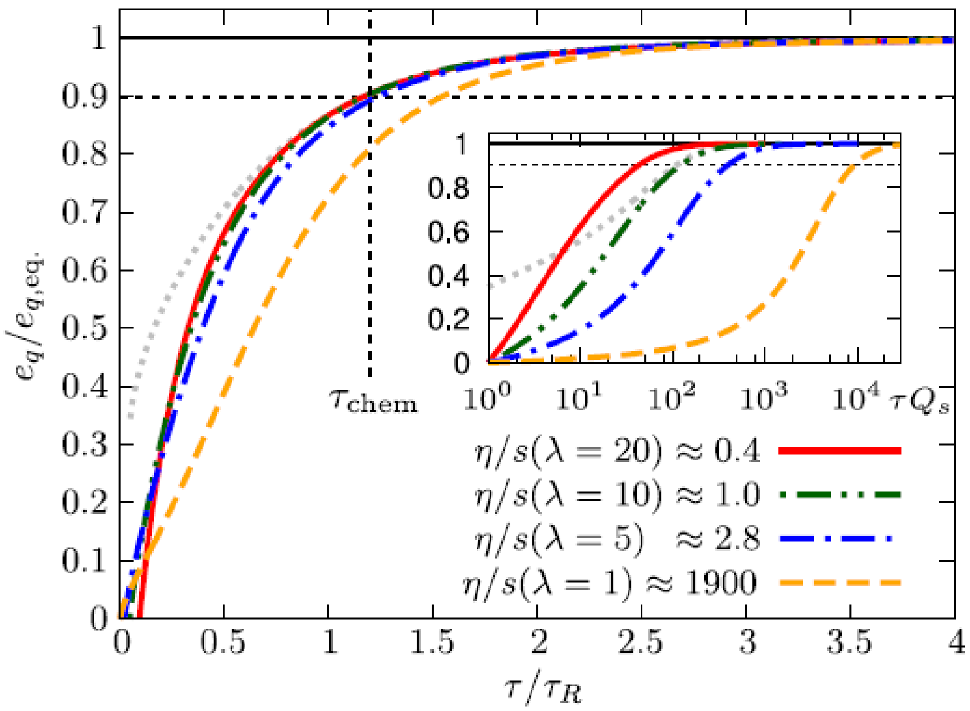
Gale, Paquet, Schenke, Shen (2022) PRC



Quark-gluon chemical equilibration time



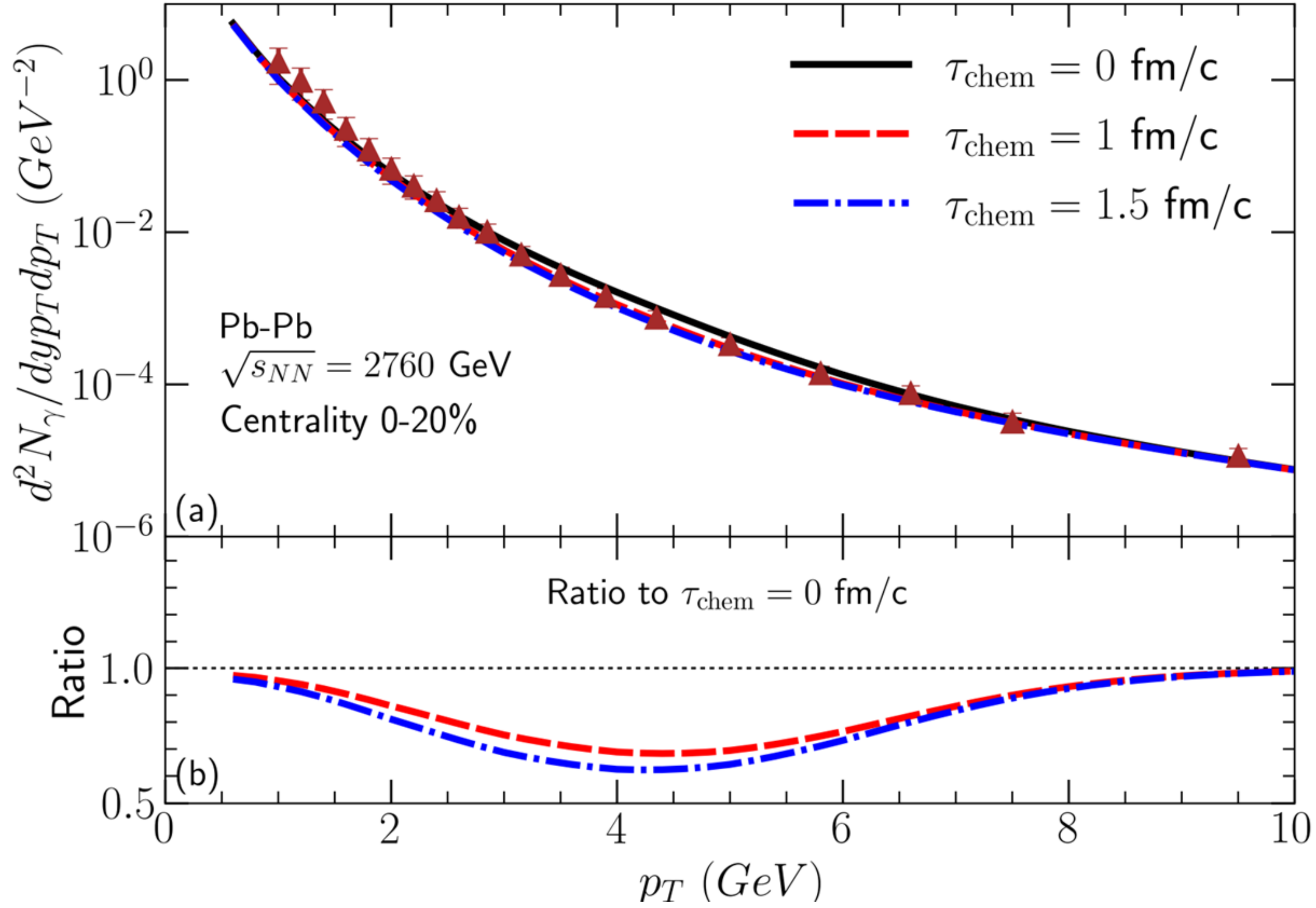
Kurkela and Mazeliauskas (2019) PRL

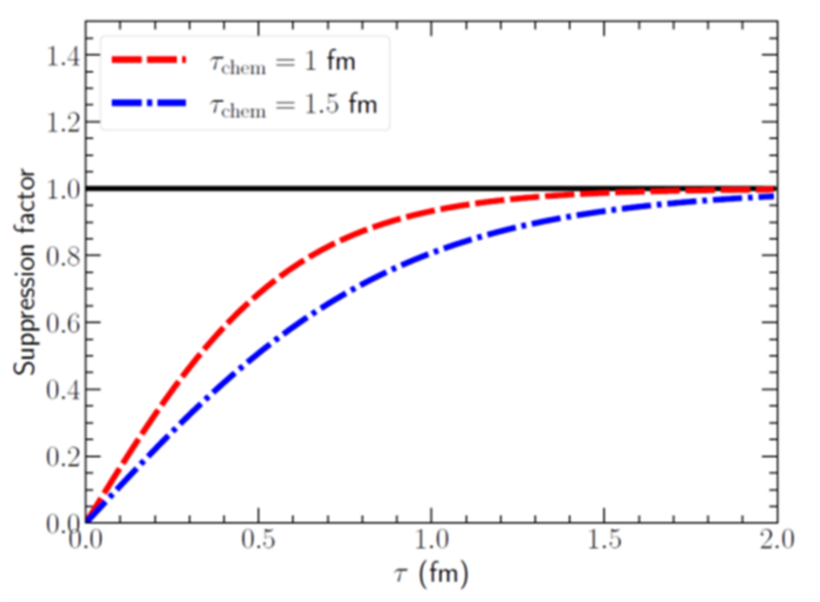


Energy density carried by quarks, compared to that in chemical equilibrium

Estimating the effect of chemical equilibration time

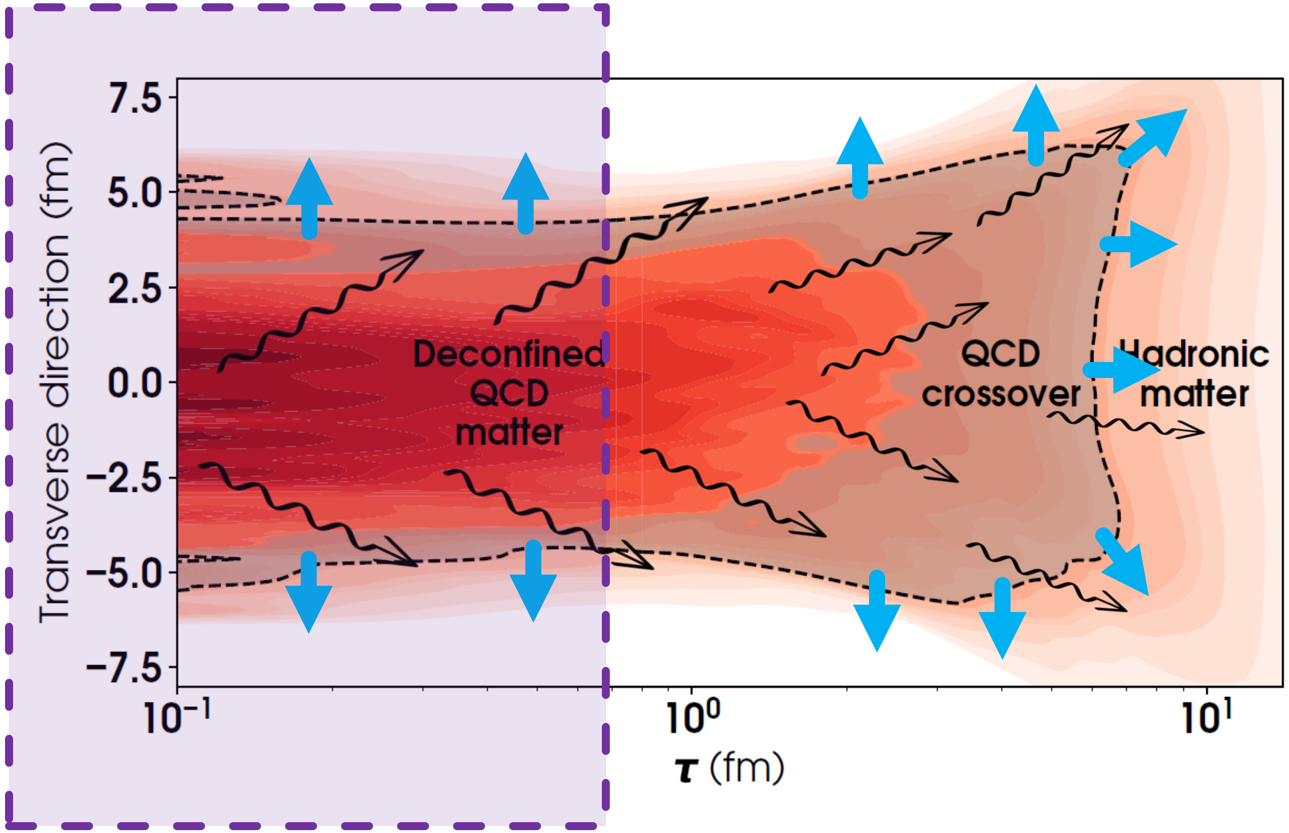
Kurkela and Mazeliauskas (2019) PRL



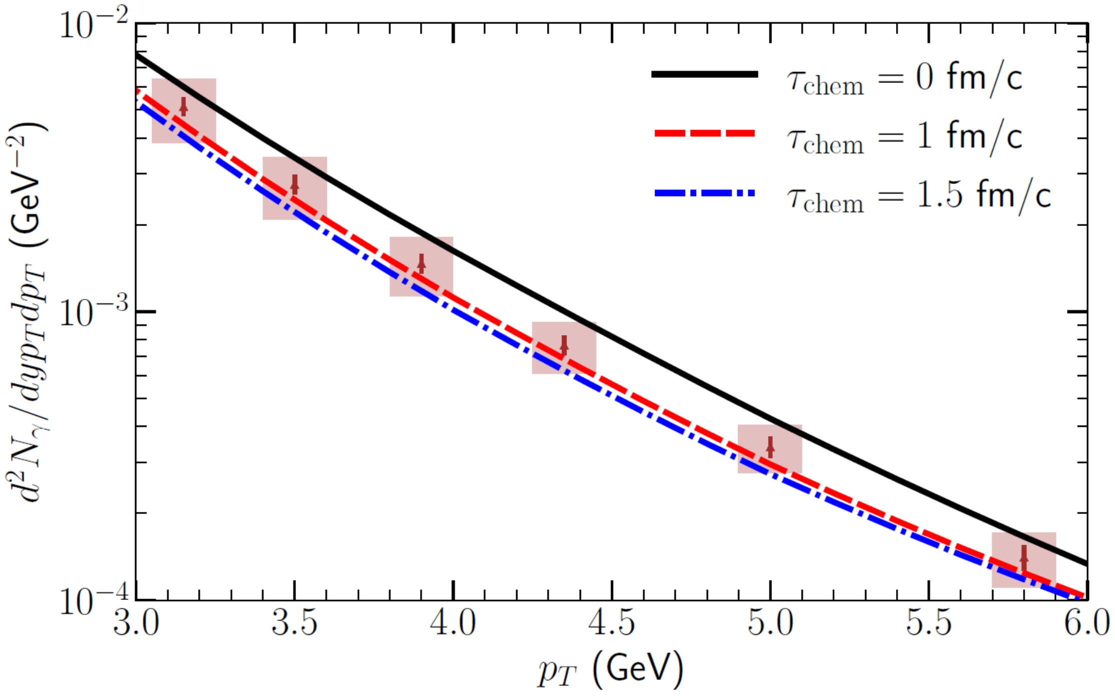


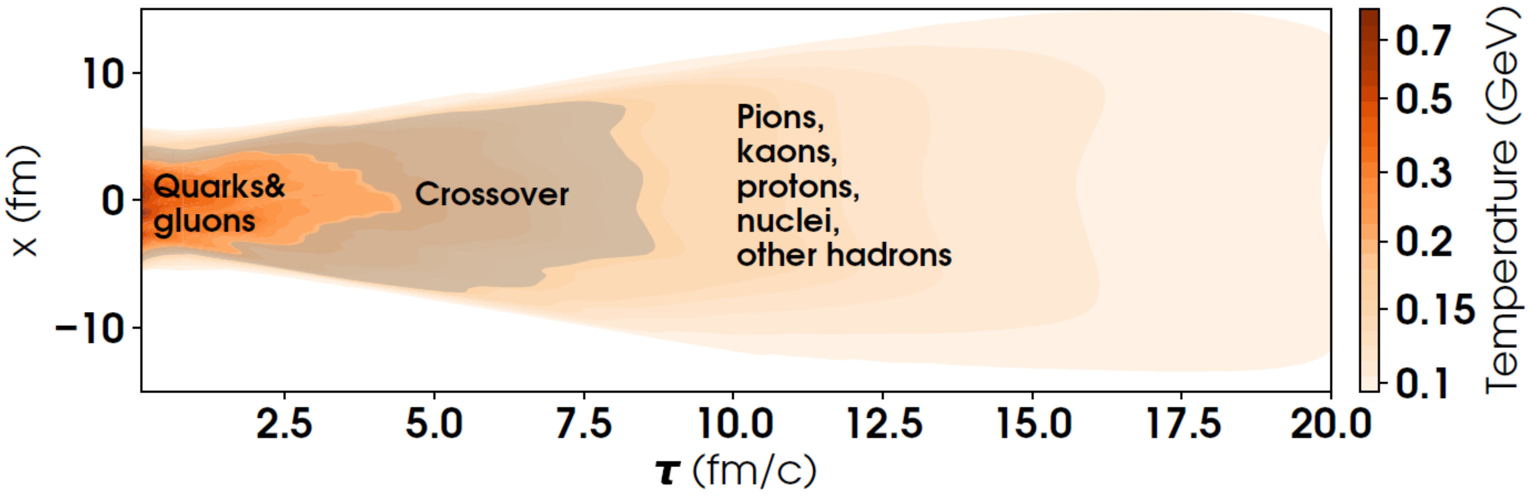
Delayed chemical equilibration: significant effect on the photon spectra

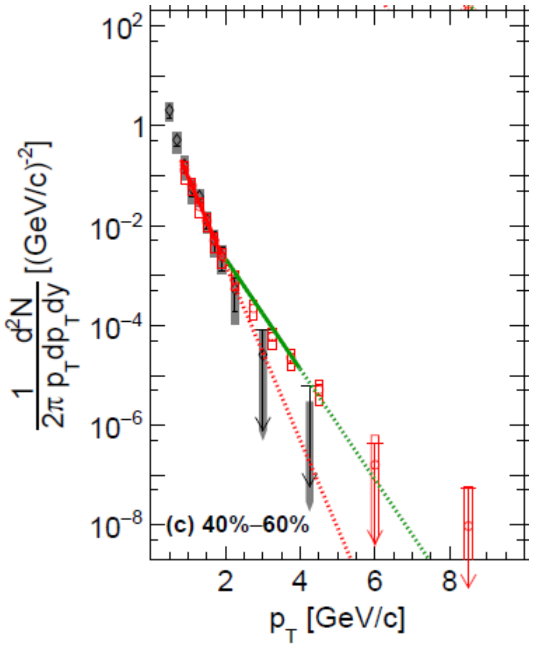
Photons from the early stage of the collision



Gale, Paquet, Schenke, Shen (2022) PRC







PHOTON MOMENTUM ANISOTROPY

Results: momentum anisotropy

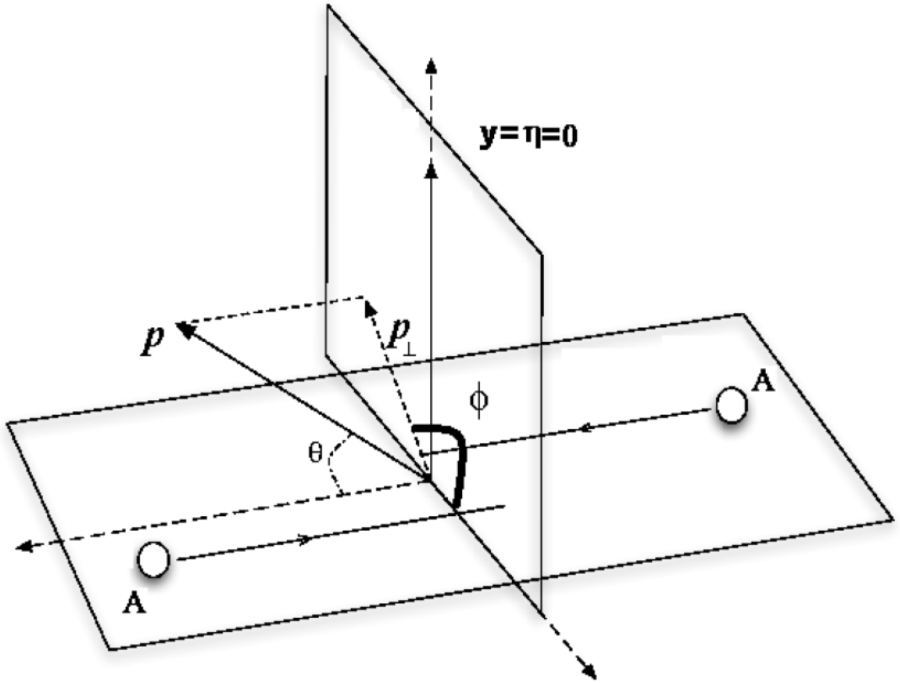


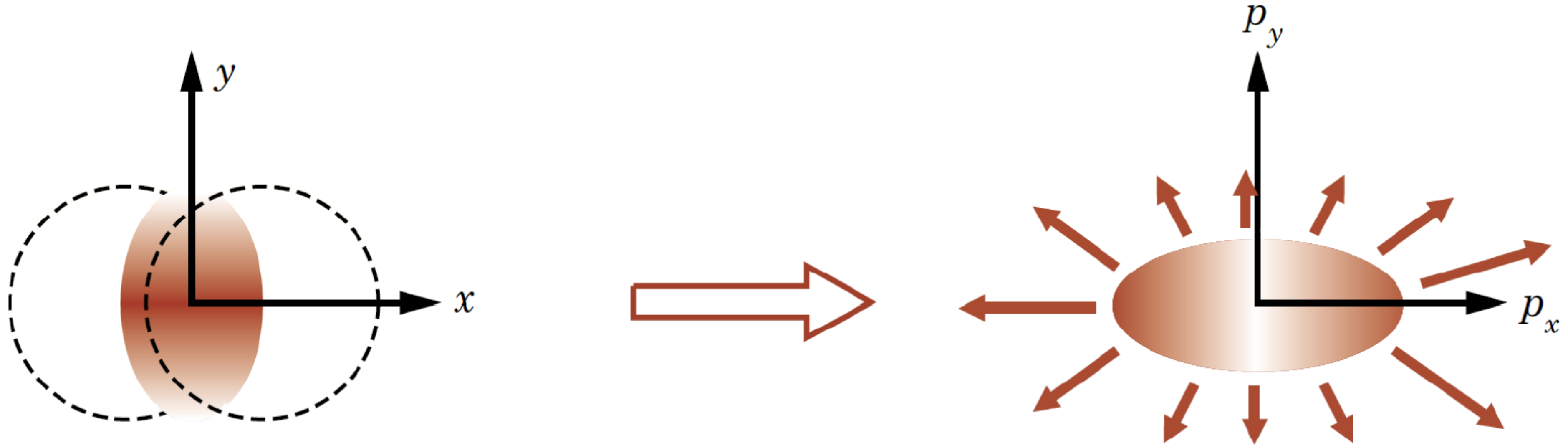
Figure adapted from K. Tuchin (2013) AHEP

$$\frac{1}{2\pi p_T}\frac{dN}{dp_T d\phi} = \left(\frac{1}{2\pi p_T}\frac{dN}{dp_T}\right)\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))\right]$$

- More precisely:
  momentum anisotropy through photon-hadron correlation

$$v_n\{SP\}(p_T) = \frac{\left\langle v_n^{\gamma}(p_T) v_n^{h} \cos\left(n\left(\Psi_n^{\gamma}(p_T) - \Psi_n^{h}\right)\right)\right\rangle}{\sqrt{\left\langle \left(v_n^{h}\right)^2 \right\rangle}}$$

Momentum anisotropy from geometrical anisotropy



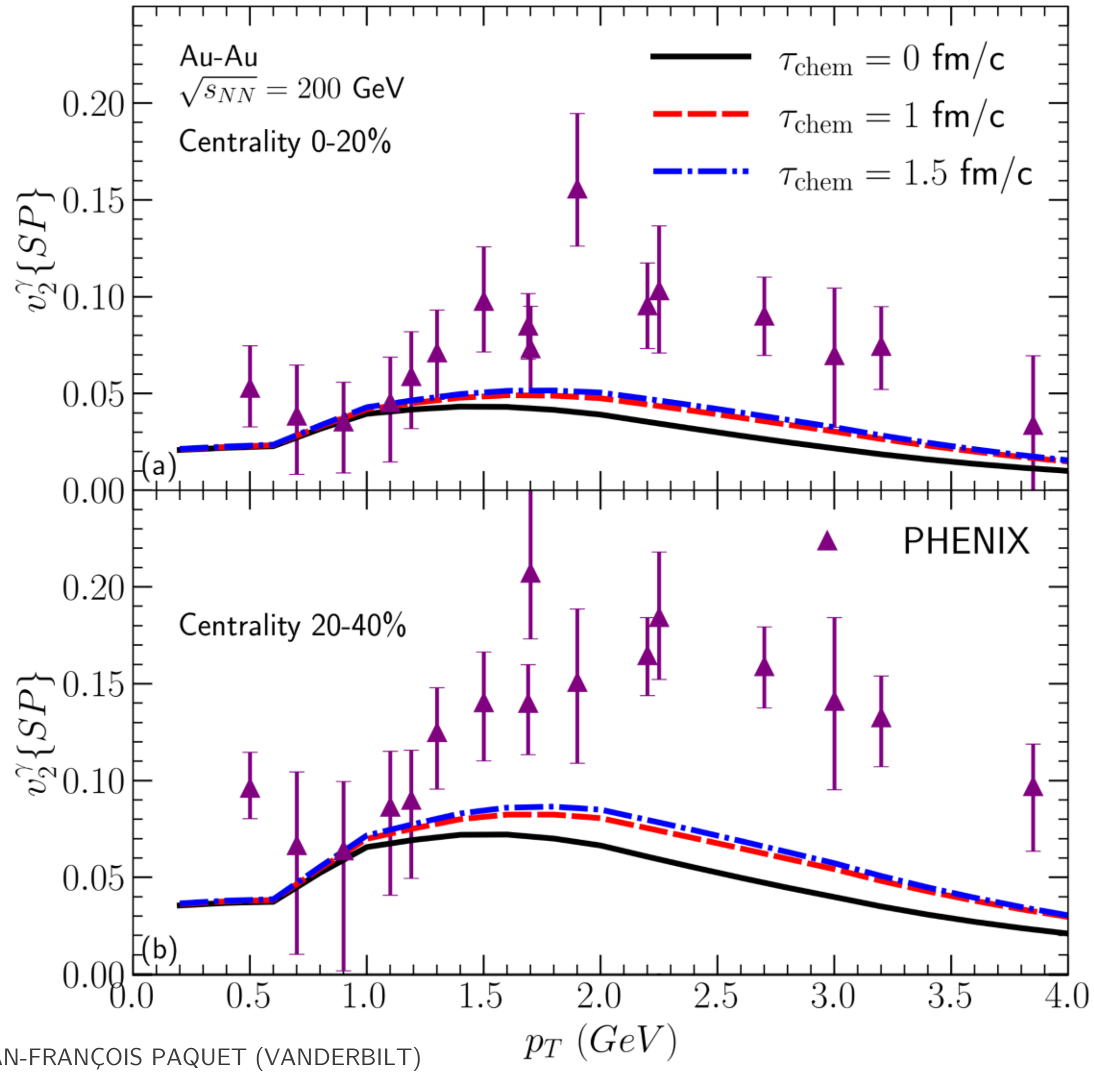
Coordinate space: initial asymmetry

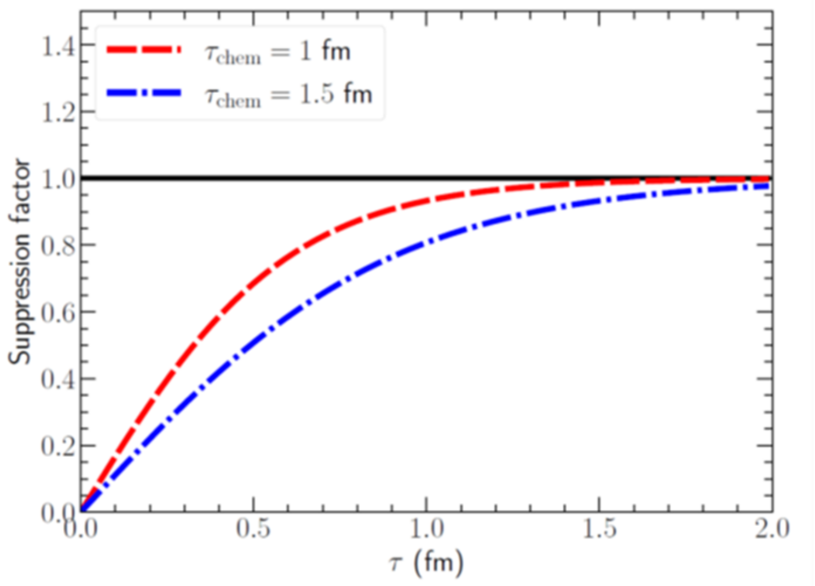
Collective interaction pressure

Momentum space: final asymmetry

$$\frac{1}{2\pi p_T}\frac{dN}{dp_T d\phi} = \left(\frac{1}{2\pi p_T}\frac{dN}{dp_T}\right)\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))\right]$$

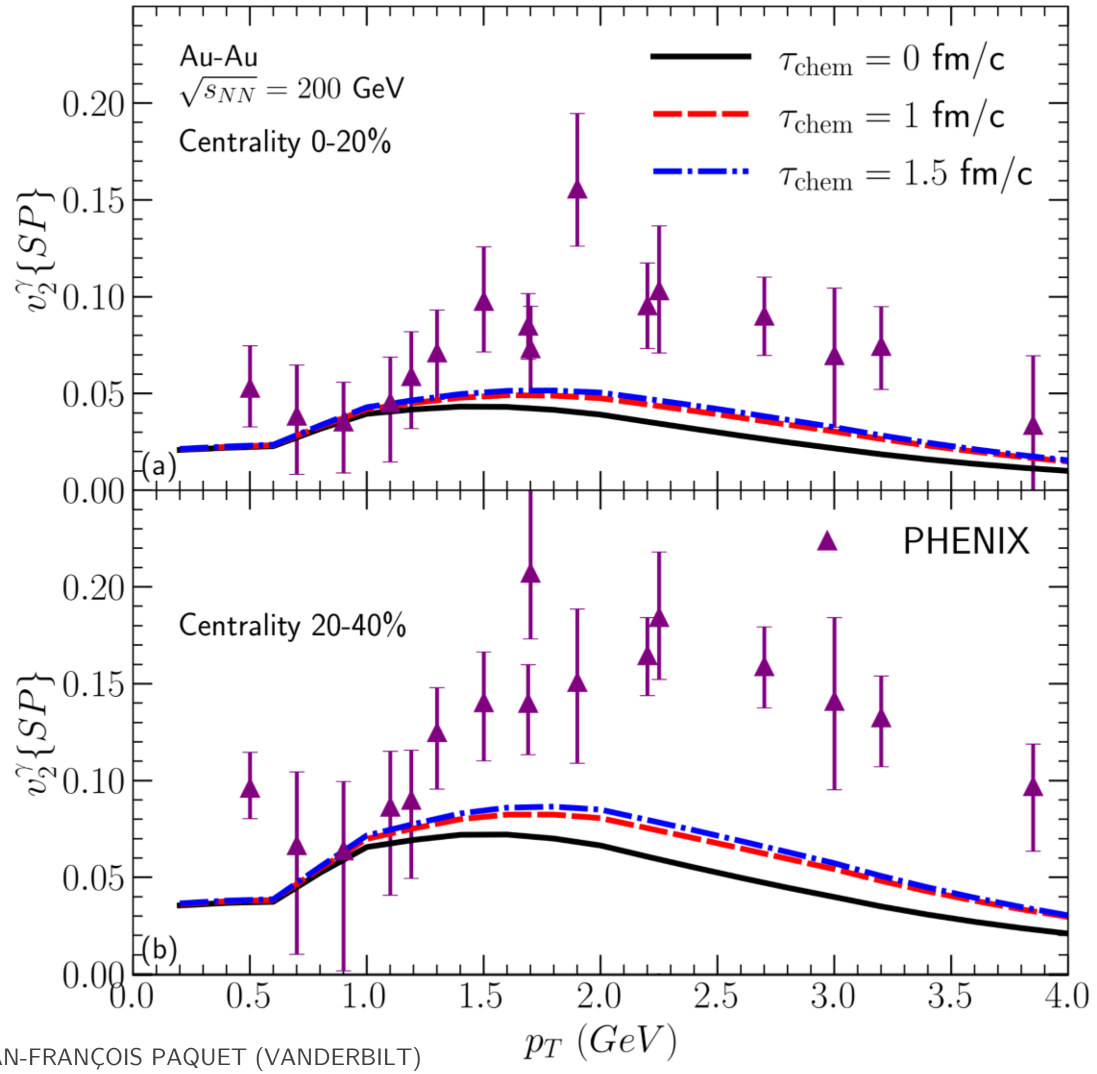
Results: Au-Au $\sqrt{s_{NN}}$ =200 GeV

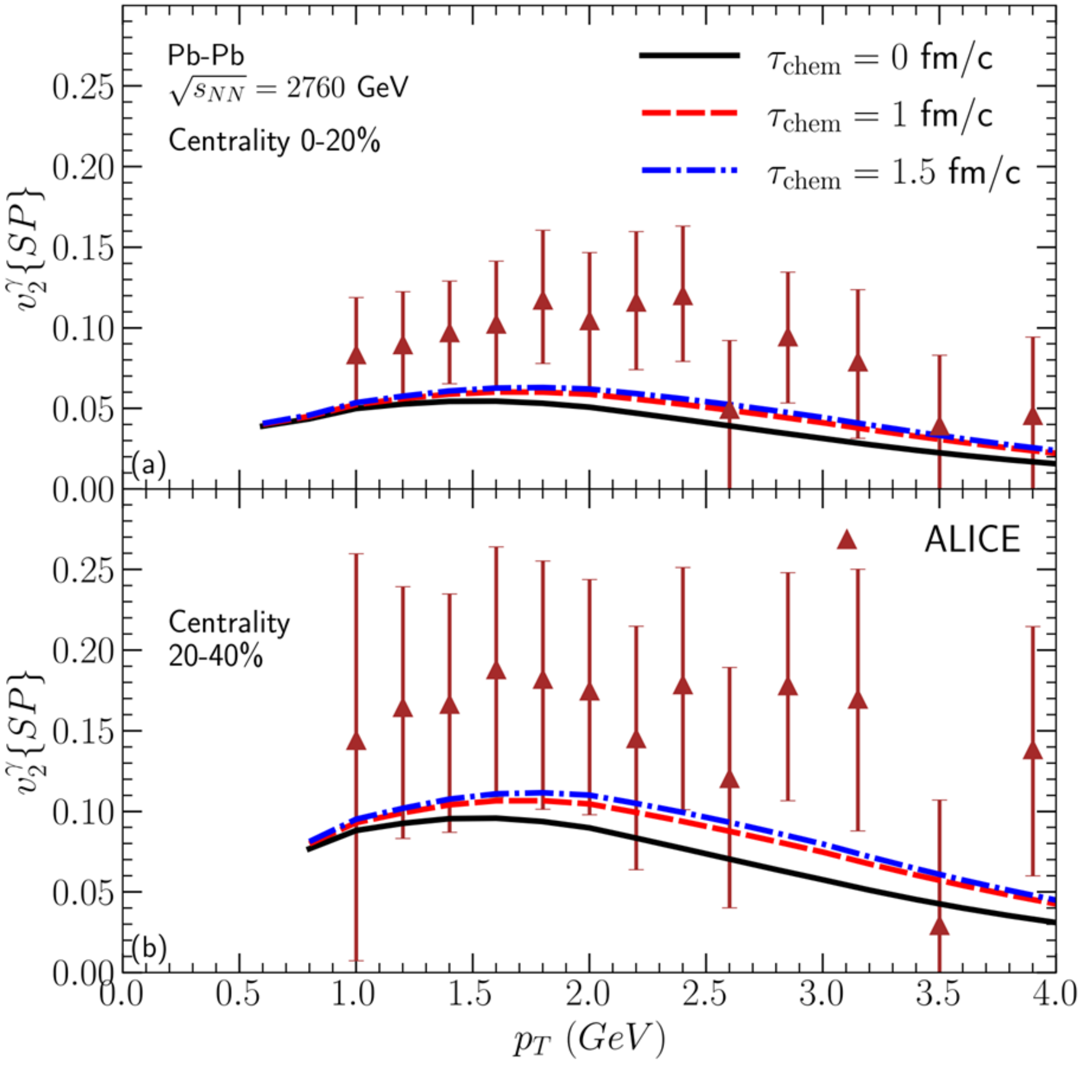


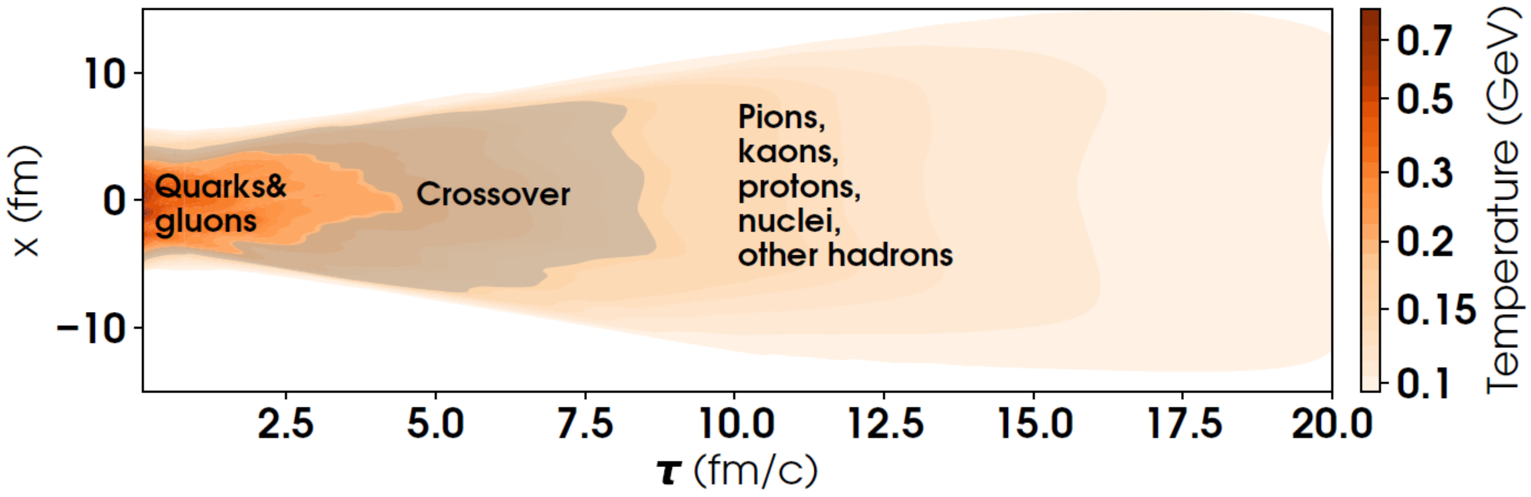


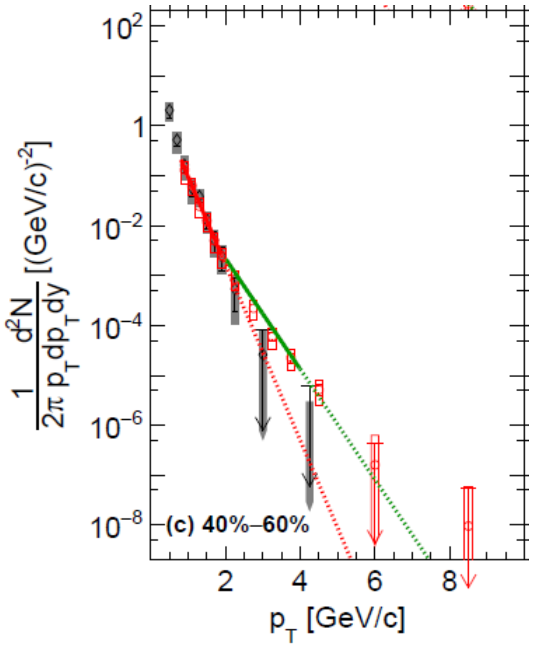
High p_T v_2^γ increased by delayed chemical equilibration

The direct photon puzzle





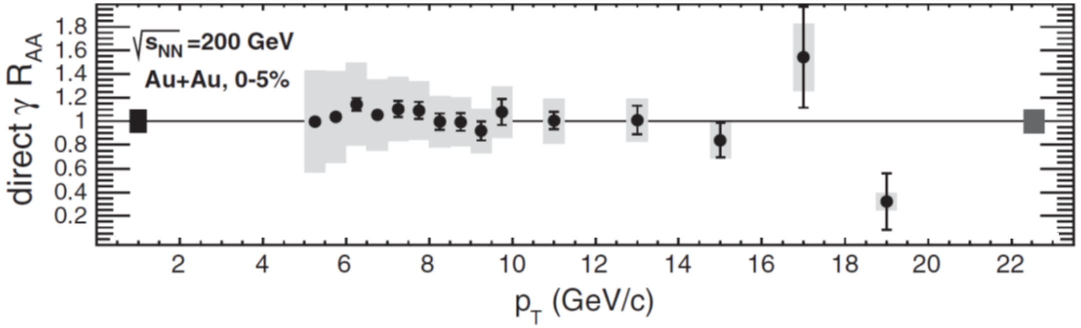




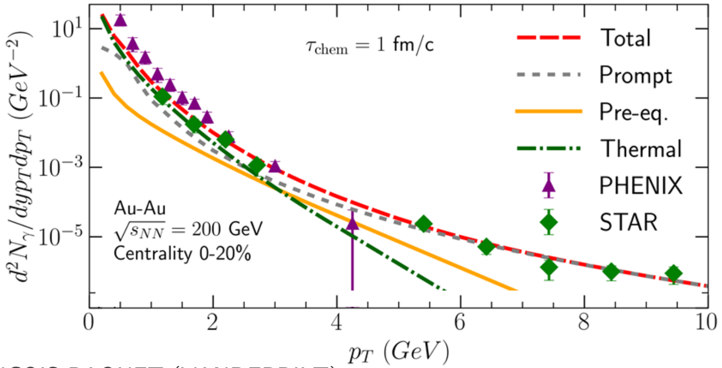
SUMMARY AND OUTLOOK

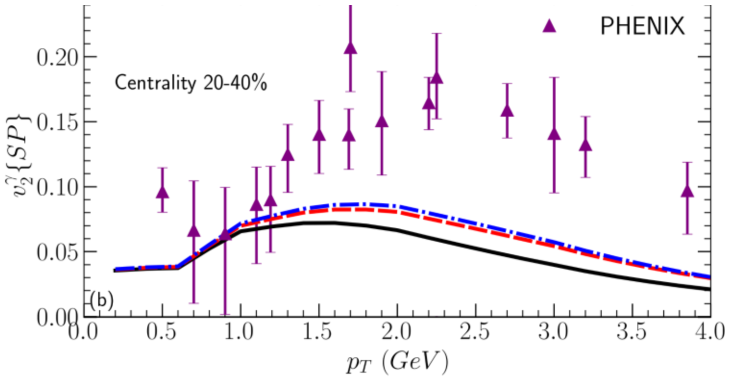
Summary

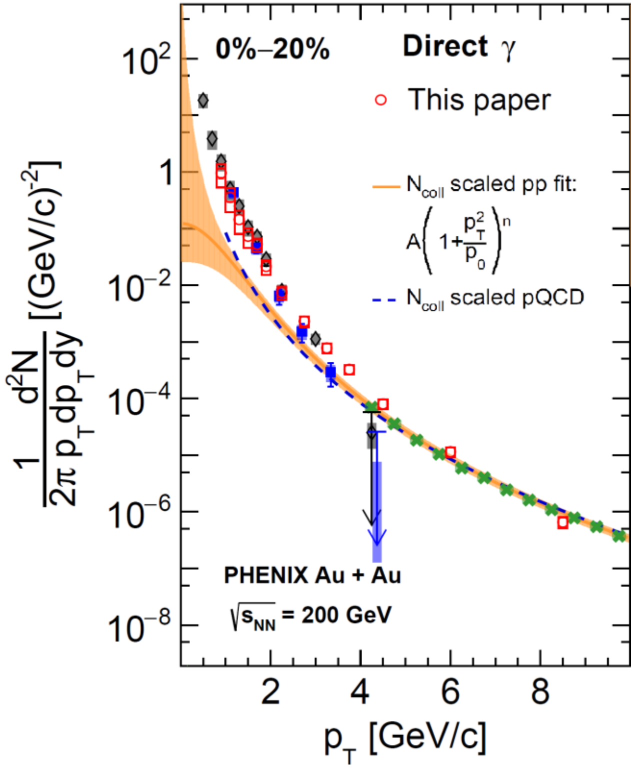
- High-energy photons:
  heavy-ion collisions similar to proton-proton case



- Low-energy photons:
  - Enhancement with respect to proton-proton collisions
  - Exponential spectrum ± consistent with thermal radiation from $T_{max} \sim 500\ MeV$ deconfined plasma
  - Azimuthal anisotropy: important complementary information

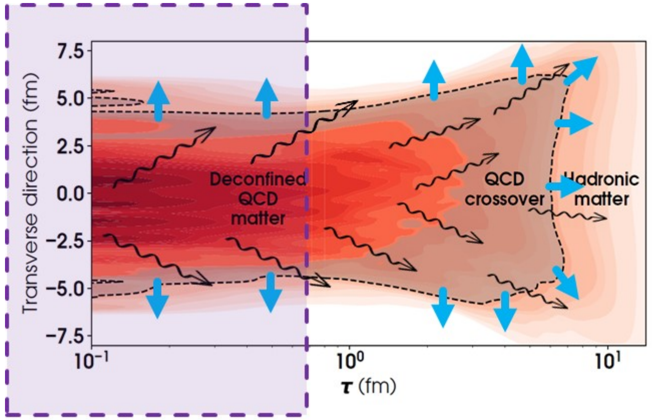




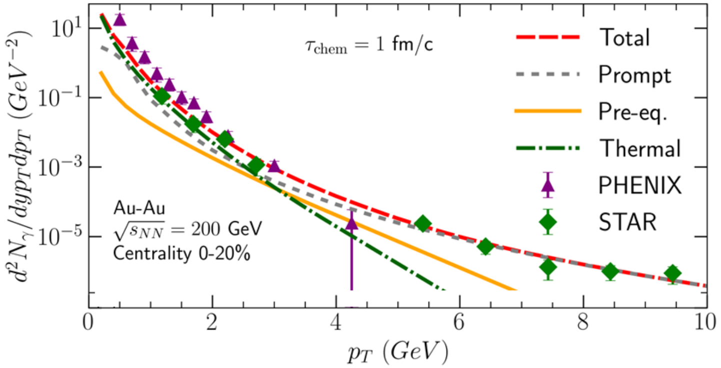


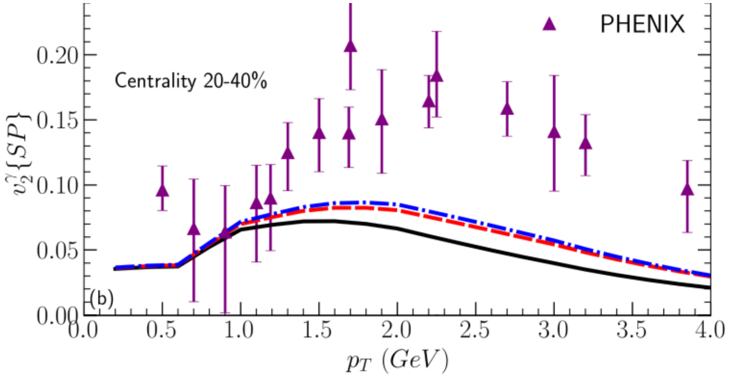
Outlook

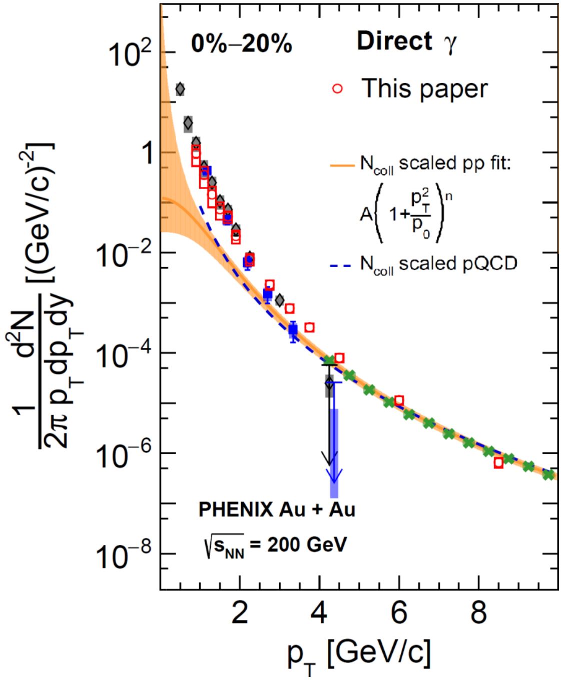
Gale, Paquet, Schenke, Shen (2022) PRC



- Studying the early stage of heavy-ion collisions with photons
- "Multi-messenger" study of heavy-ion collisions
- Understanding low p_T photons in proton-proton collisions?







- Many opportunities with dileptons as well