Nuclear collisions as seen through photons

Jean-François Paquet

November 14, 2023

VANDERBILT UNIVERSITY

INSTITUTE for NUCLEAR THEORY

The higher end of the electromagnetic spectrum

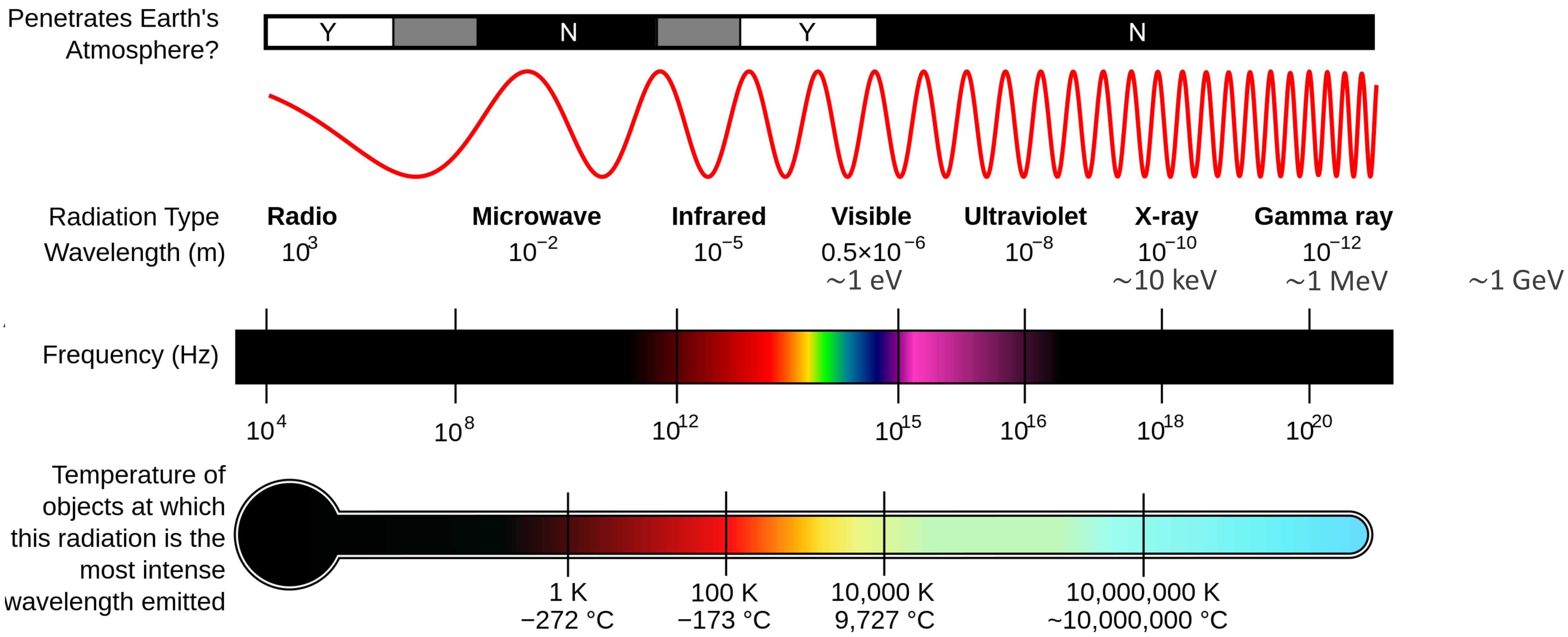


Image modified from Wikimedia

The higher end of the electromagnetic spectrum

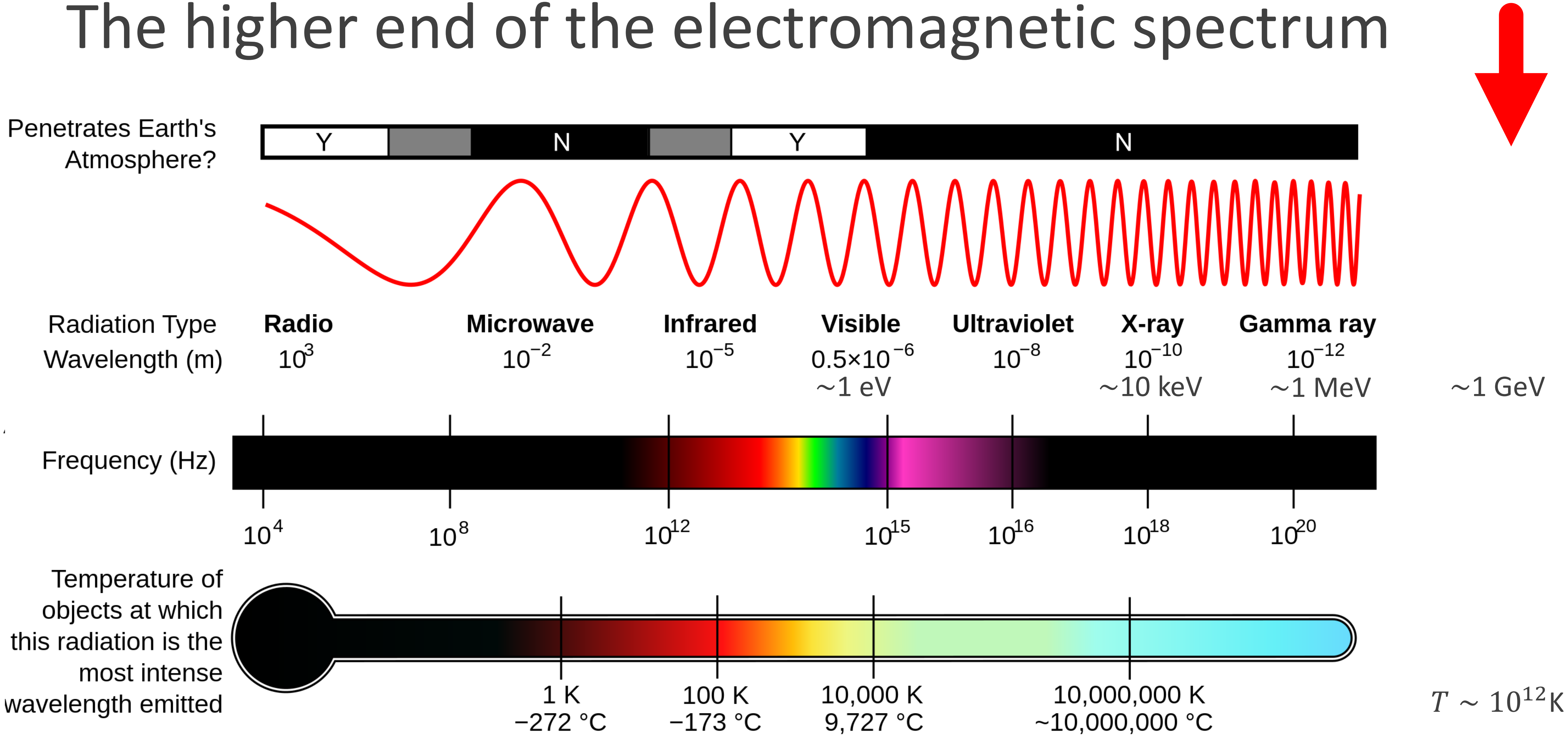
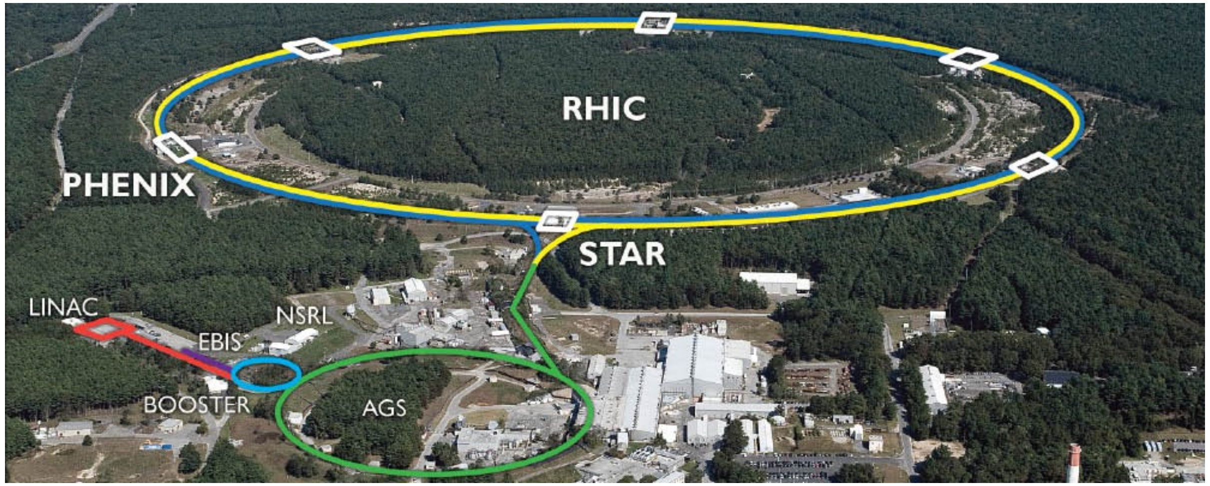


Image modified from Wikimedia

RHIC and LHC

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



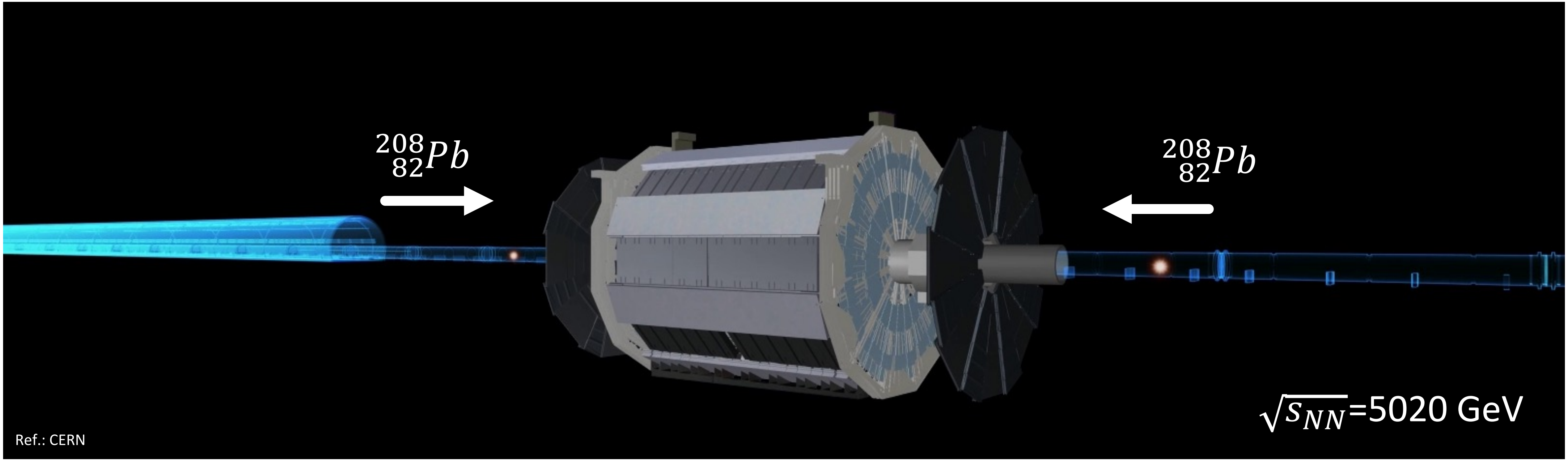
$\sqrt{s_{NN}} \sim 10^2$ GeV

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

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

Nuclear collisions

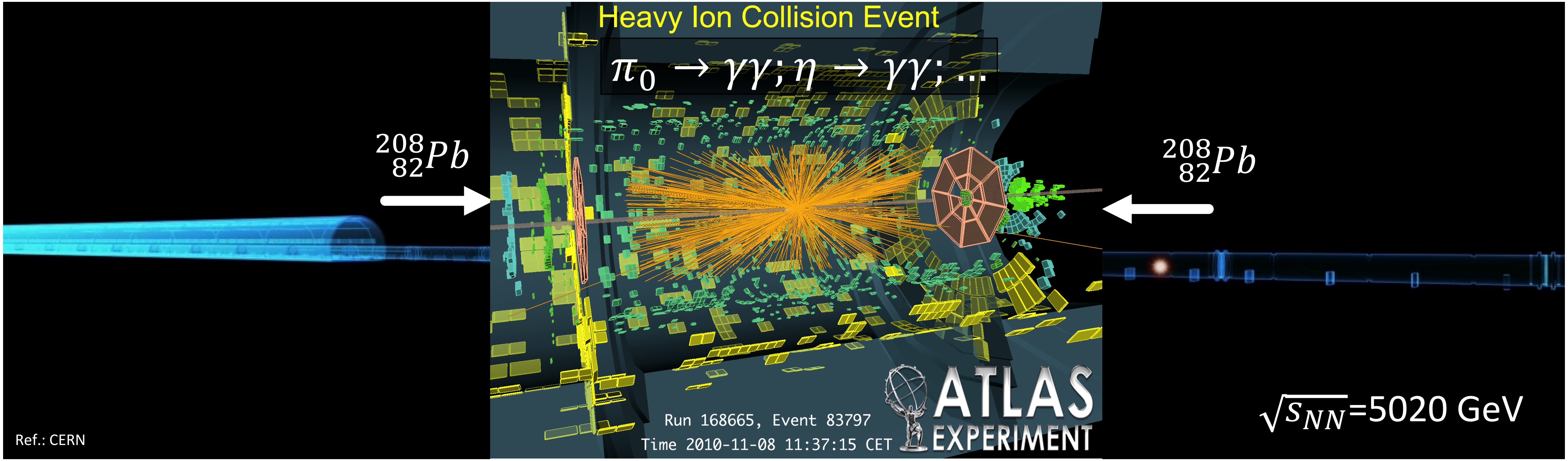
- Kinetic energy of nuclei ~ 100-2500 times mass of nuclei



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

Hadronic decay photons in nuclear collisions

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

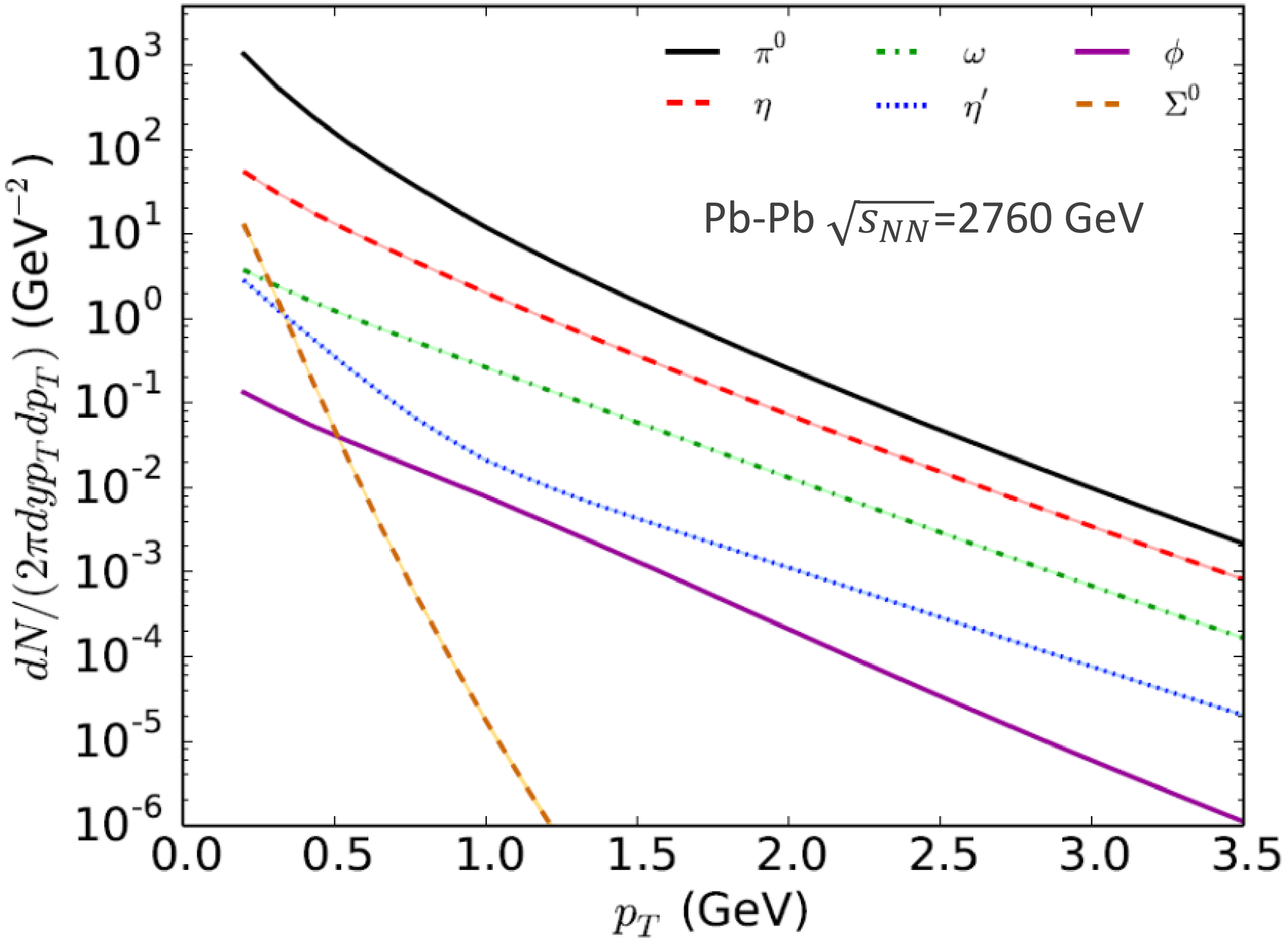


Pb-Pb at rest: $\sqrt{s_{NN}} \approx 2$ GeV

Hadronic decay photons in nuclear collisions

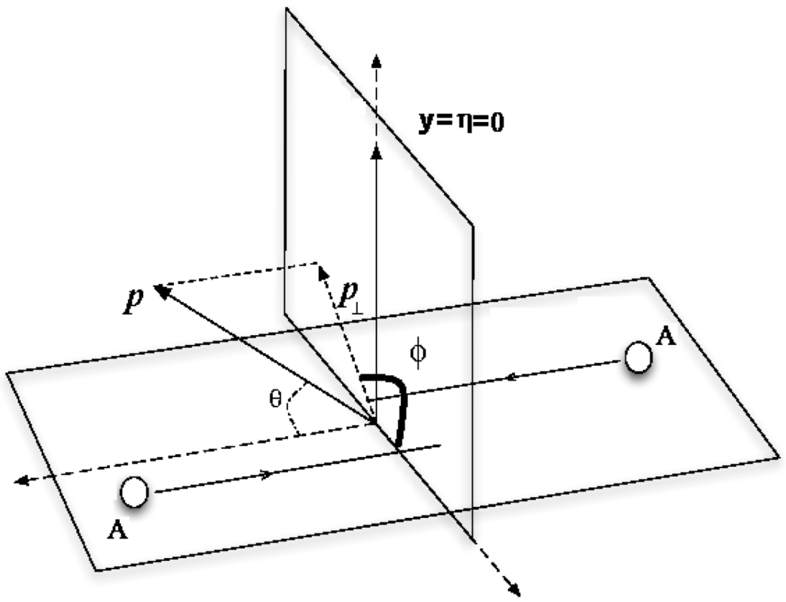
particle	mass (MeV)	decay	BR
π^0	134.98	$\gamma\gamma$	$9.882 \cdot 10^{-1}$
		$e^+e^-\gamma$	$1.174 \cdot 10^{-2}$
η	547.85	$\gamma\gamma$	$3.941 \cdot 10^{-1}$
		$\pi^0\gamma\gamma$	$2.560 \cdot 10^{-4}$
		$\pi^+\pi^-\gamma$	$4.220 \cdot 10^{-2}$
		$e^+e^-\gamma$	$6.899 \cdot 10^{-3}$
		$\mu^+\mu^-\gamma$	$3.090 \cdot 10^{-4}$
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	$\pi^0\gamma$	$8.350 \cdot 10^{-2}$
		$\eta\gamma$	$4.600 \cdot 10^{-4}$
		$\pi^0\pi^0\gamma$	$7.000 \cdot 10^{-5}$
ρ^0	775.49	$\pi^+\pi^-\gamma$	$9.900 \cdot 10^{-3}$
		$\pi^0\gamma$	$6.000 \cdot 10^{-4}$
		$\eta\gamma$	$3.000 \cdot 10^{-4}$
		$\pi^0\pi^0\gamma$	$4.500 \cdot 10^{-5}$

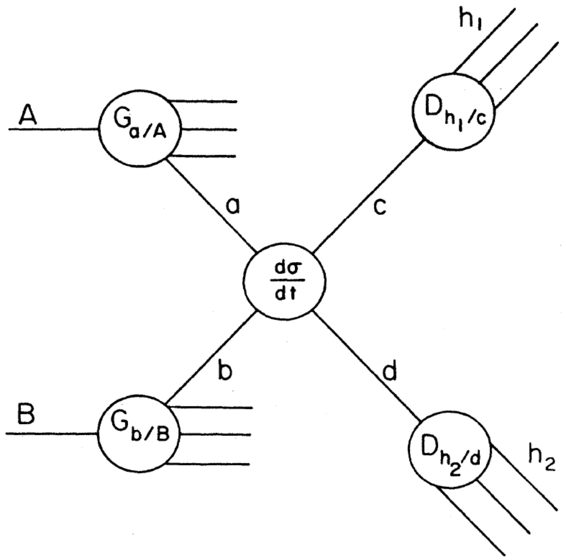
Ref: F. Bock, PhD thesis



Ref: Chun Shen, PhD thesis

Figure adapted from K. Tuchin (2013) AHEP

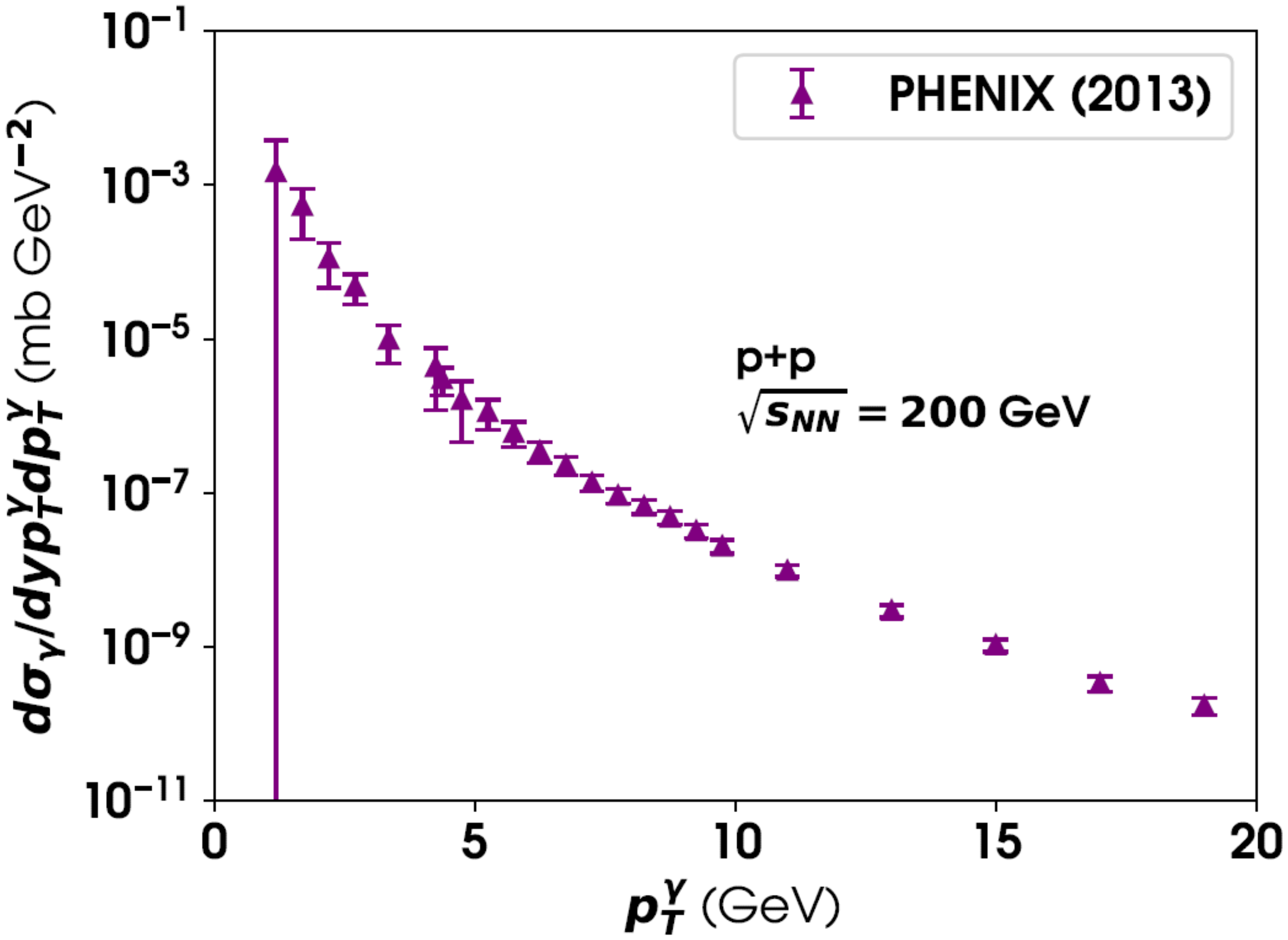




Ref: Owens (1987) RMP

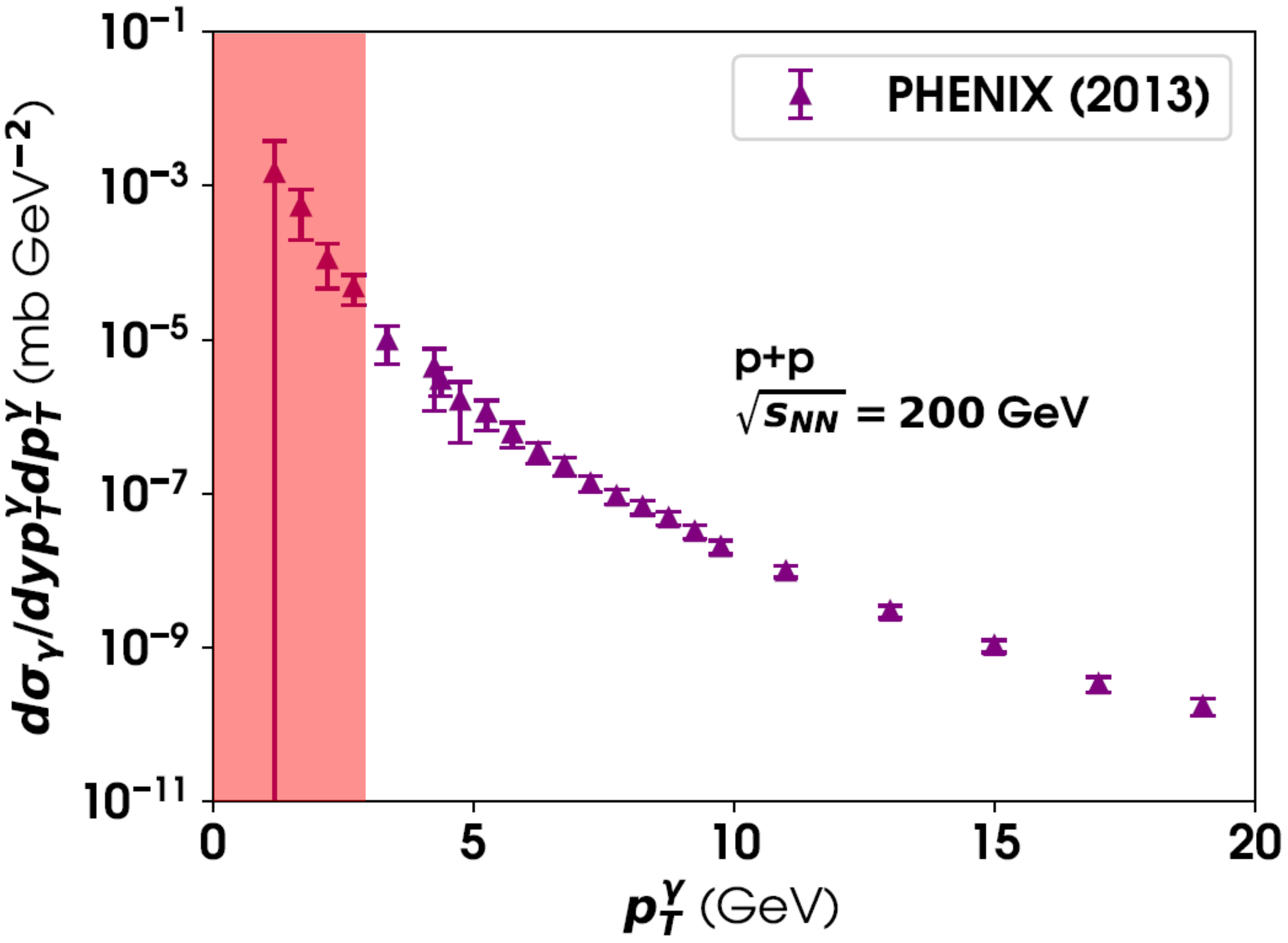
PROTON-PROTON COLLISIONS

Direct (non-decay) photons in proton-proton collisions

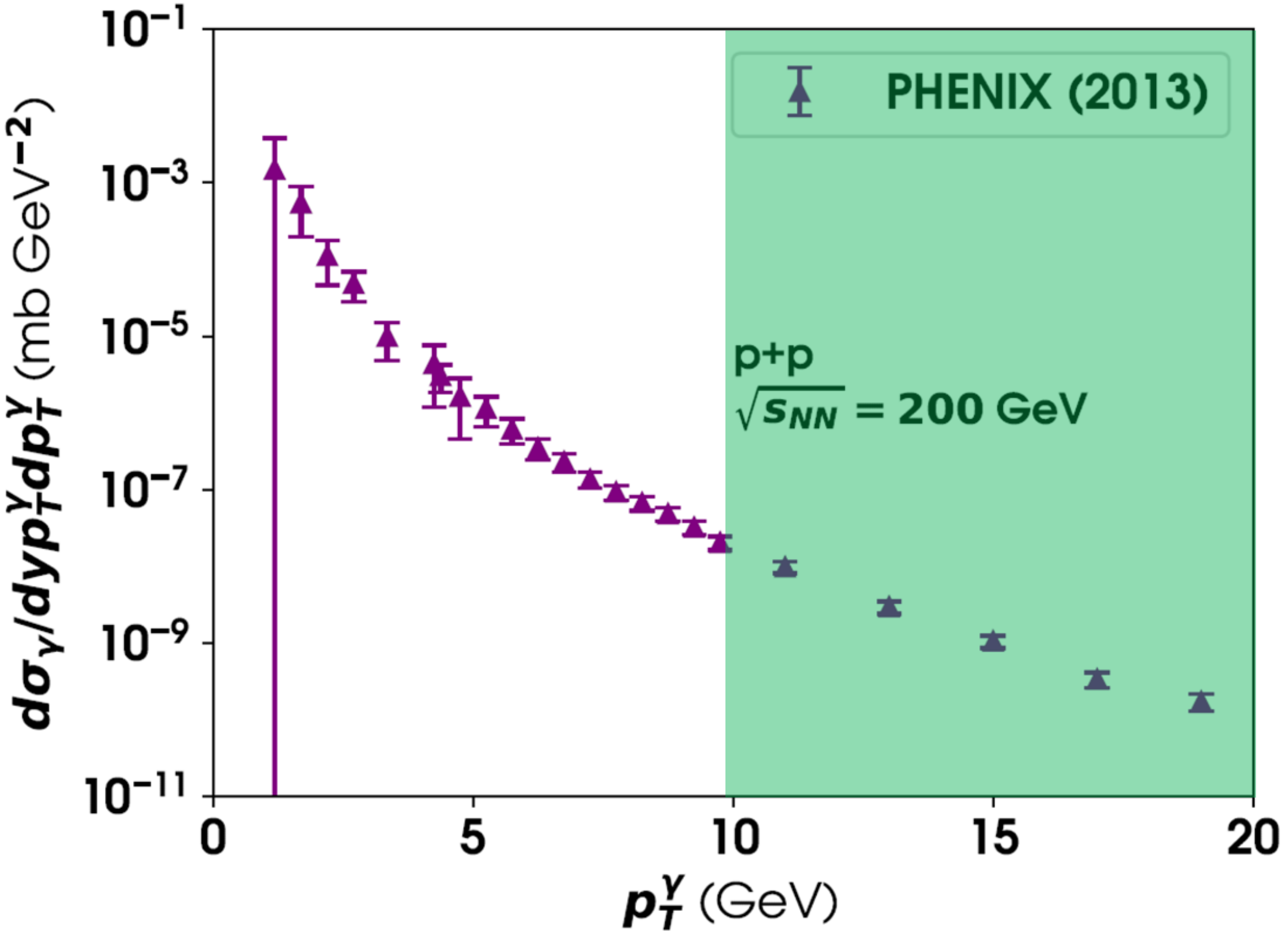


Direct photons in proton-proton collisions: “low” energy

- 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



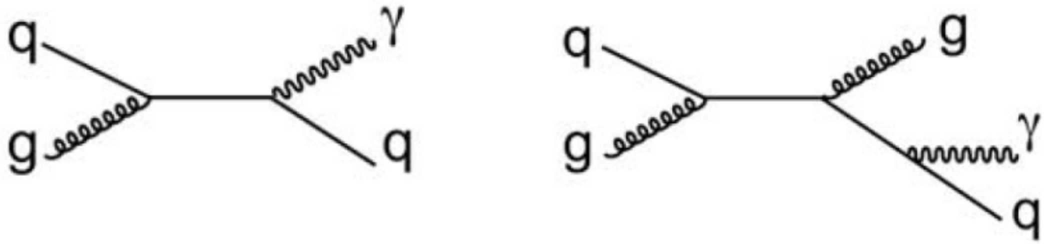
Nuclear Physics B327 (1989) 105–143
North-Holland, Amsterdam

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

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



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

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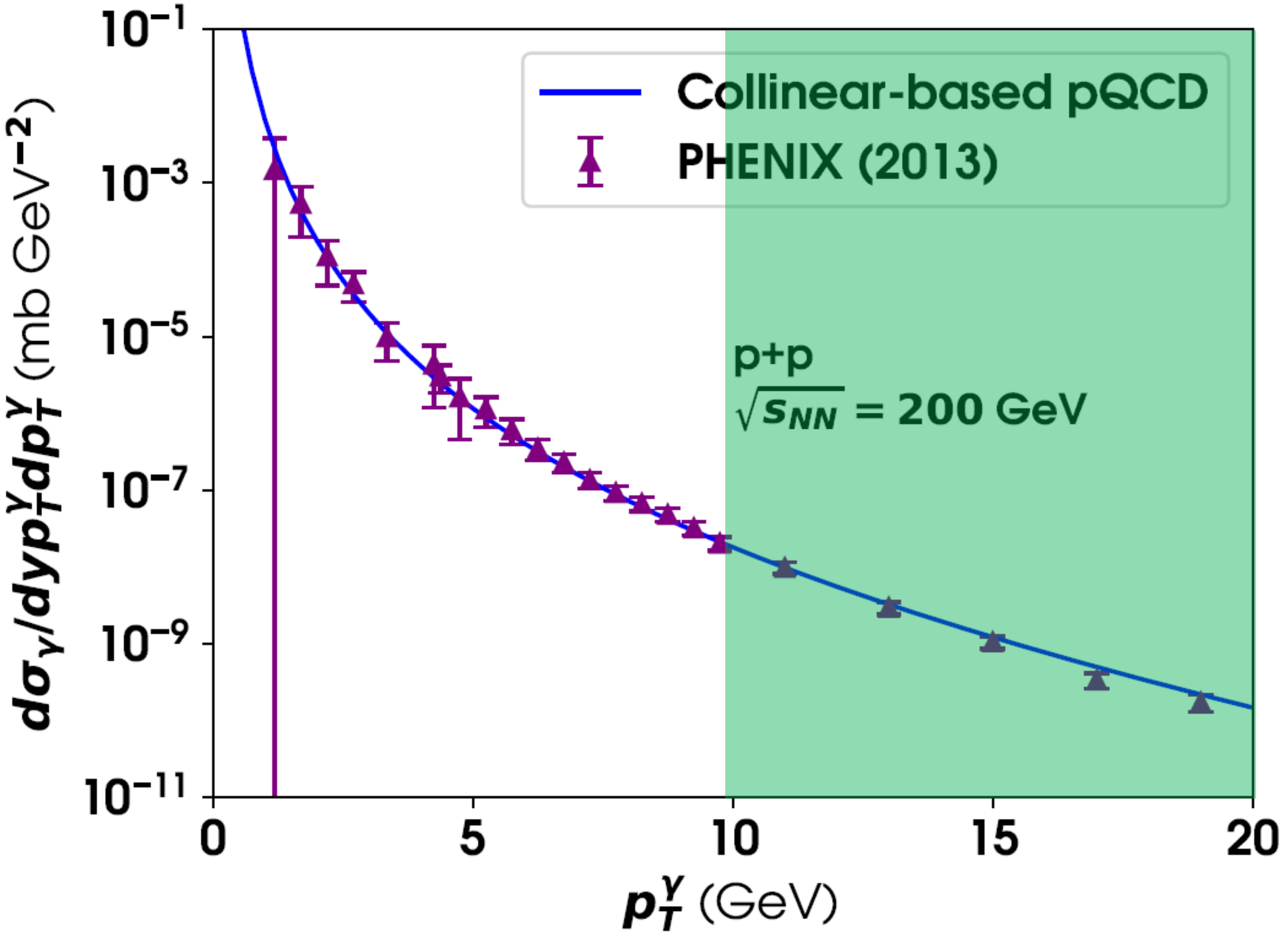

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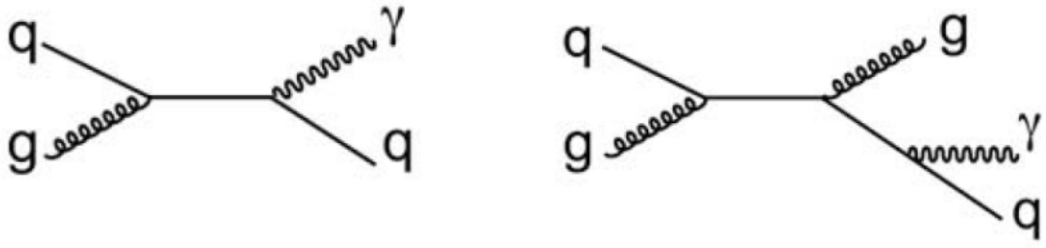

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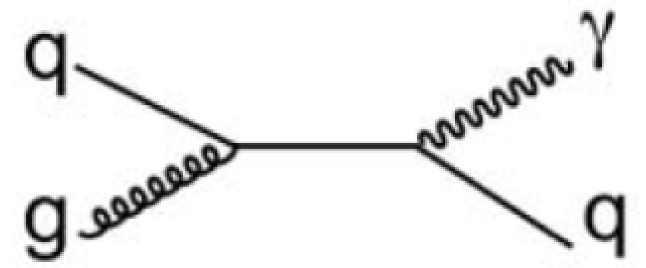
Direct photons in proton-proton collisions: channels

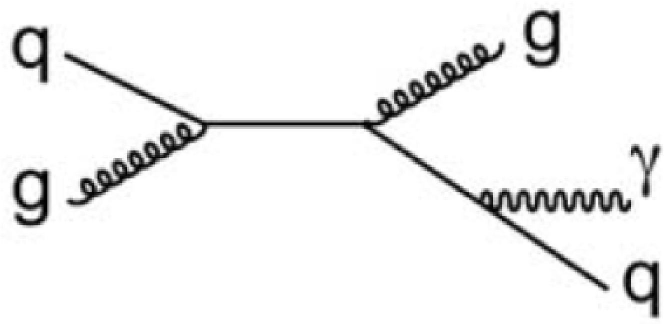
- Hard partonic collisions
  - "Isolated"



(Can be calculated at NNLO)

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

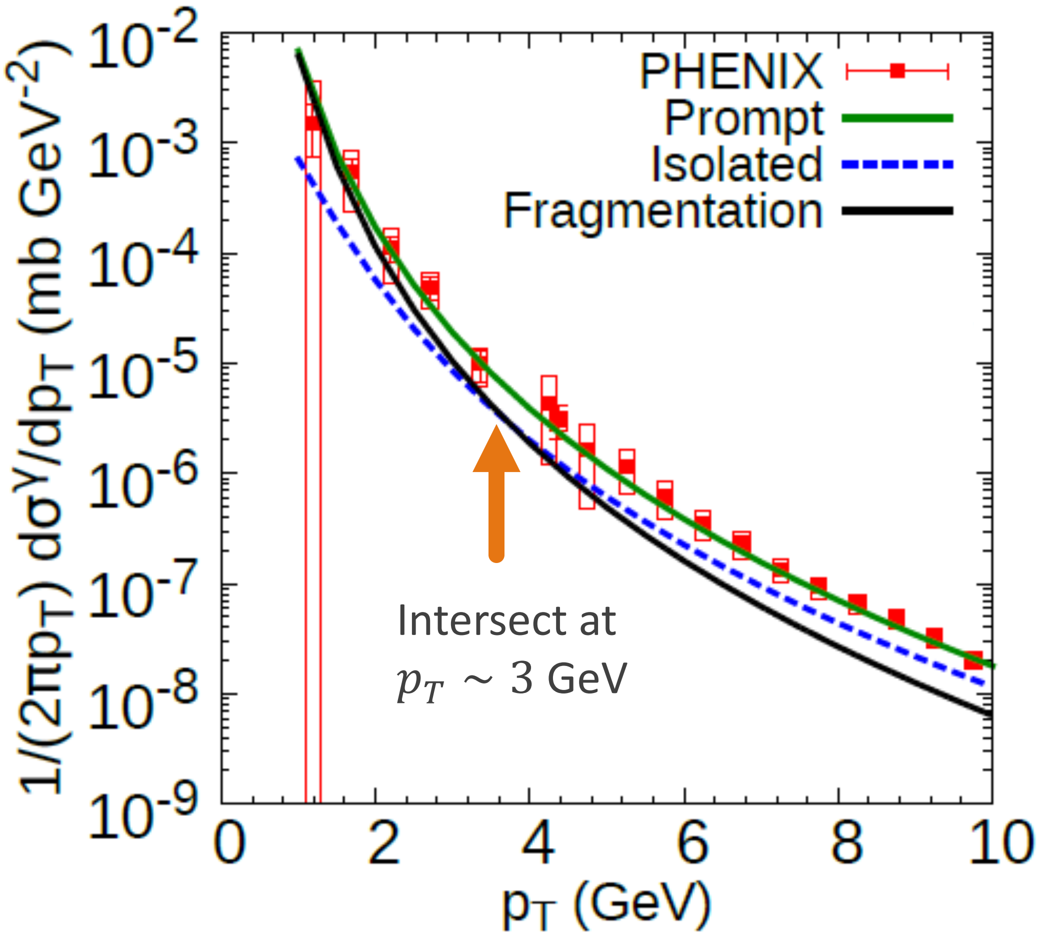
  - Fragmentation



(Fragmentation function unmeasured at NNLO and poorly constrained at NLO)

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

p+p $\sqrt{s}$=0.2 TeV



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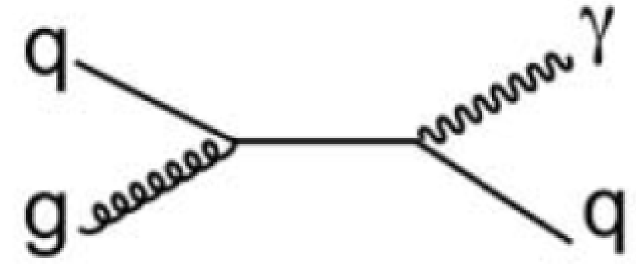

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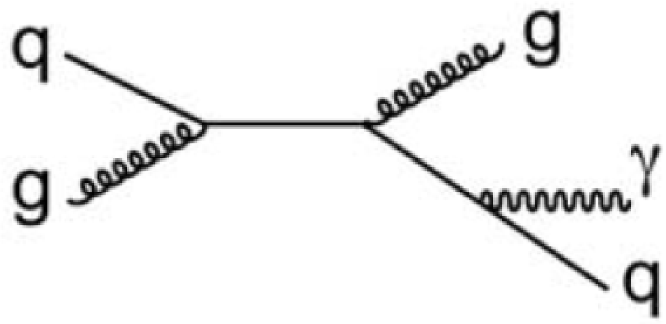
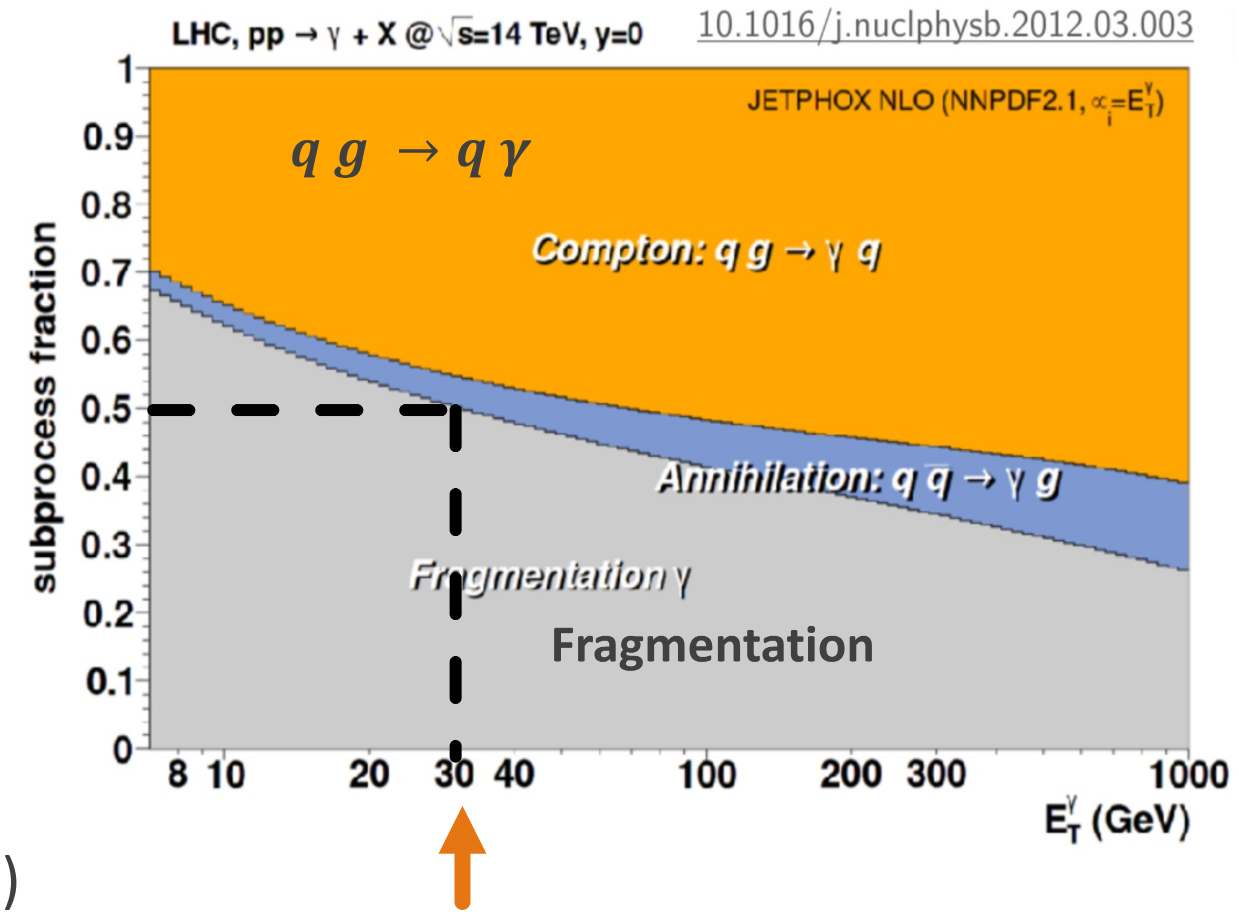


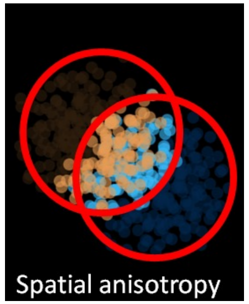
(Fragmentation function unmeasured at NNLO and poorly constrained at NLO)

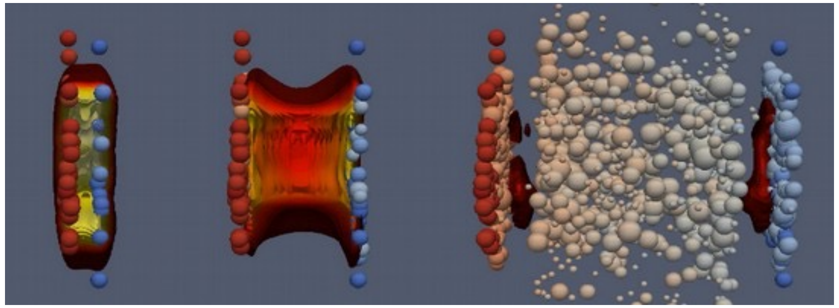
$$d\sigma_{\gamma}^{pp}/dp_T = f_a \otimes f_b \otimes d\hat{\sigma}_{ab\to\gamma/c+d} \otimes D_{\gamma/c}$$

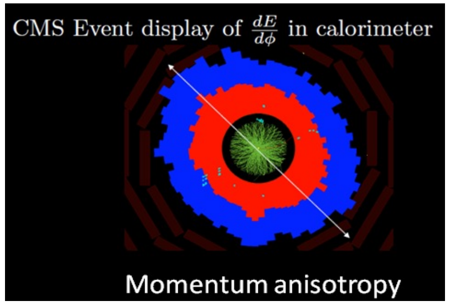
p+p $\sqrt{s}$=14 TeV



Intersect at $p_T \sim$ 30 GeV

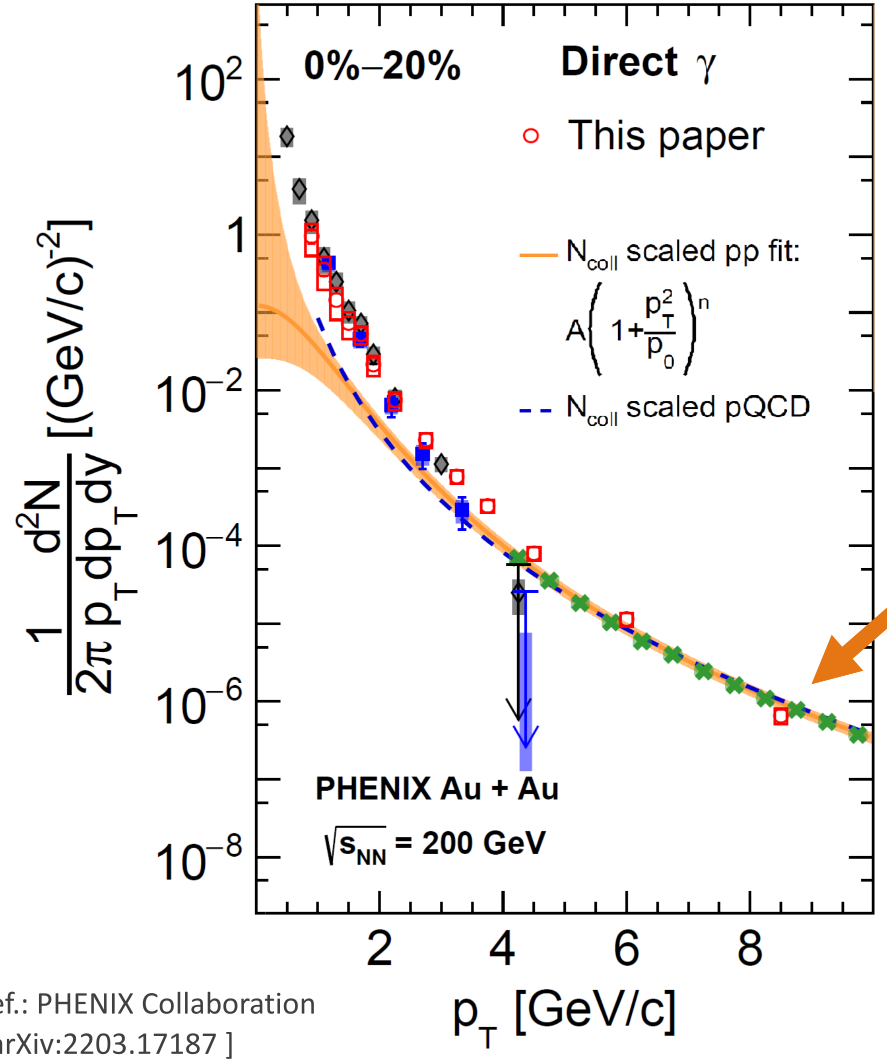






HEAVY-ION COLLISIONS:
PHOTONS FROM "PROTON+PROTON-LIKE" MECHANISMS

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 [RHIC] and ALICE [LHC] Collaborations)

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

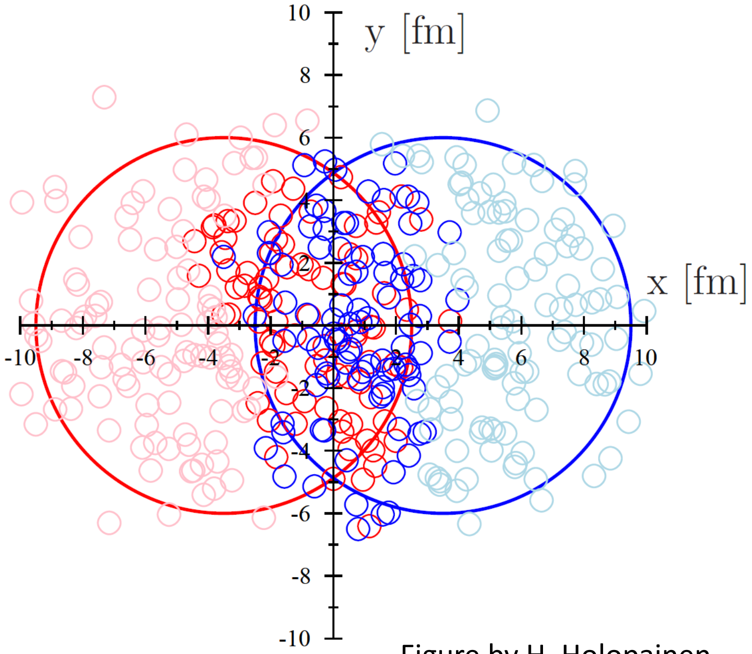
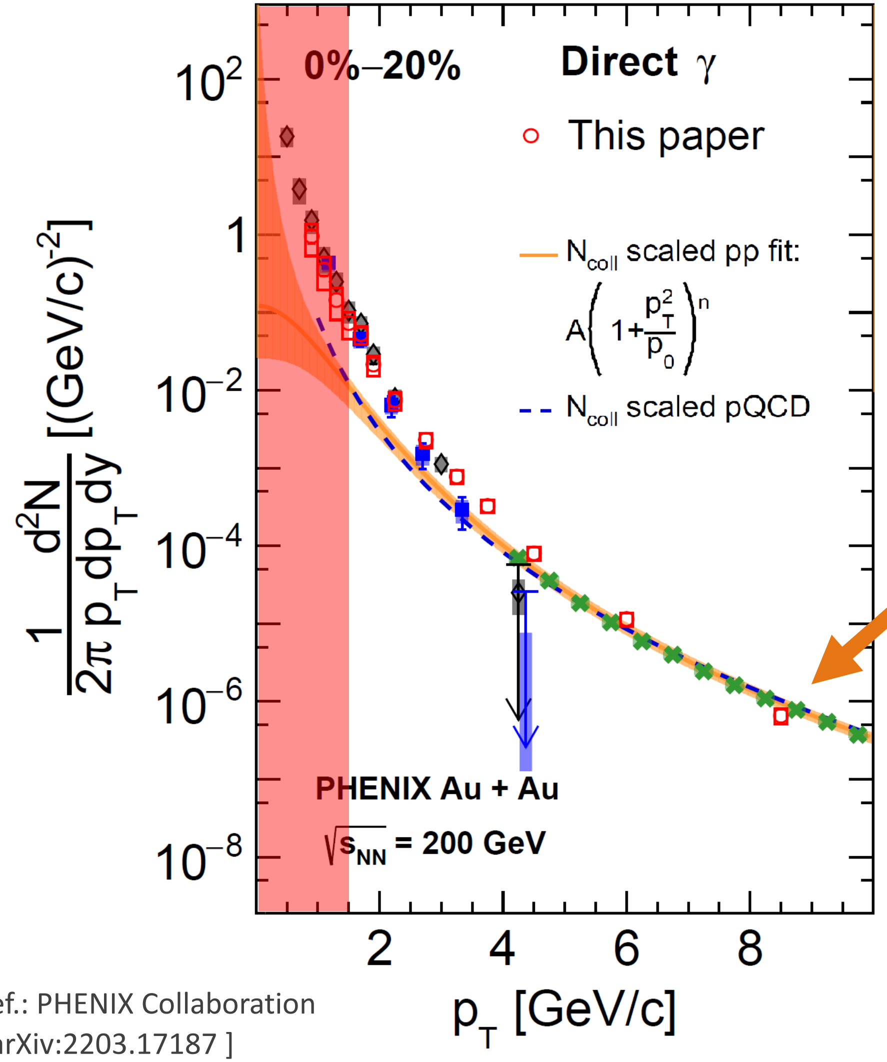


Figure by H. Holopainen

Photon energy spectrum in heavy-ion collisions



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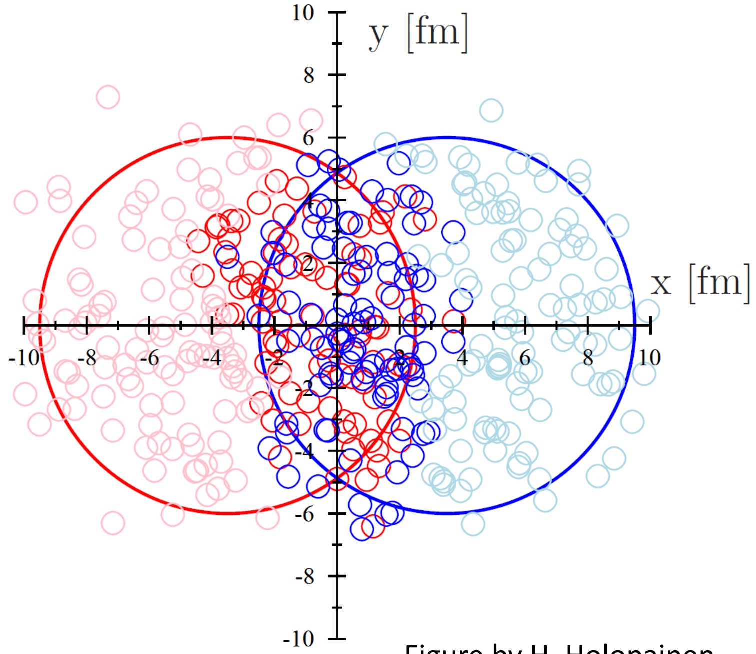
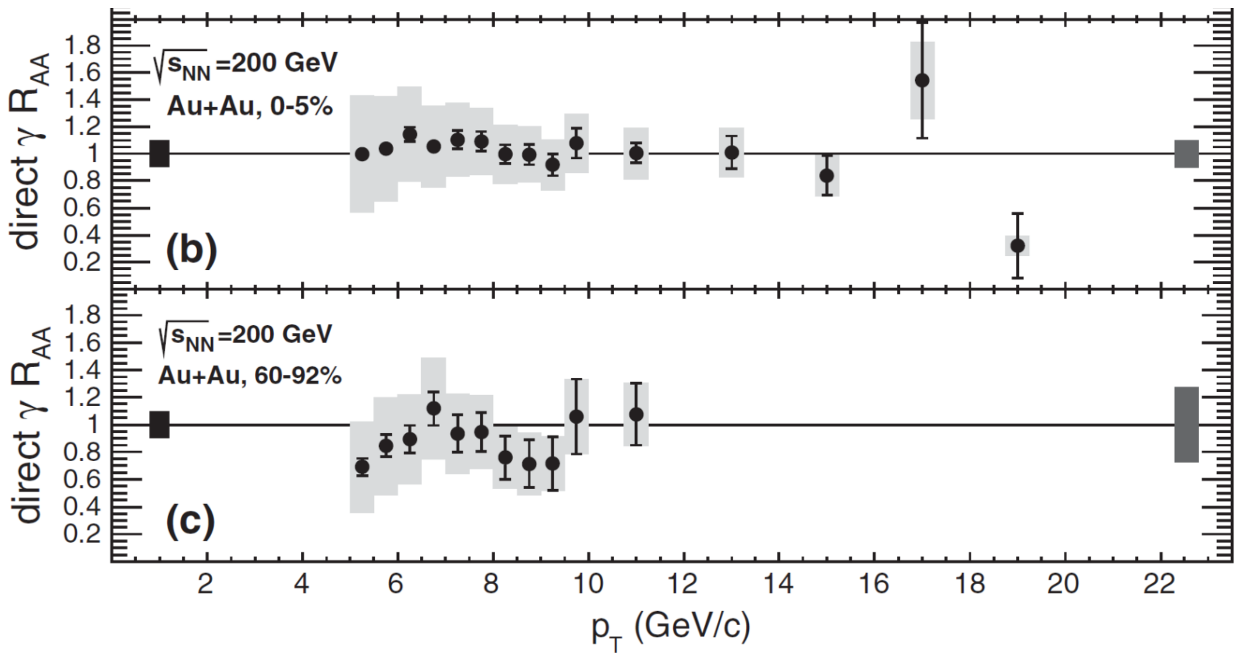


Figure by H. Holopainen

Photons in heavy-ion collisions: high p_T

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



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

Ref.: PHENIX Collaboration (2012) PRL

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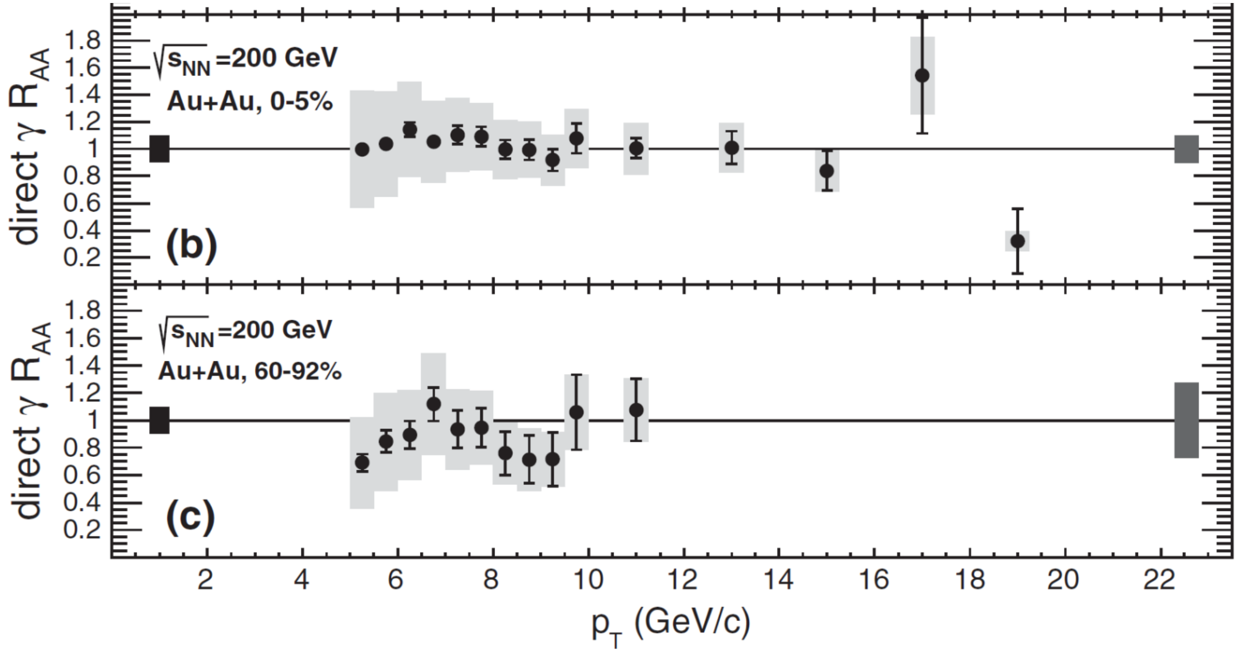

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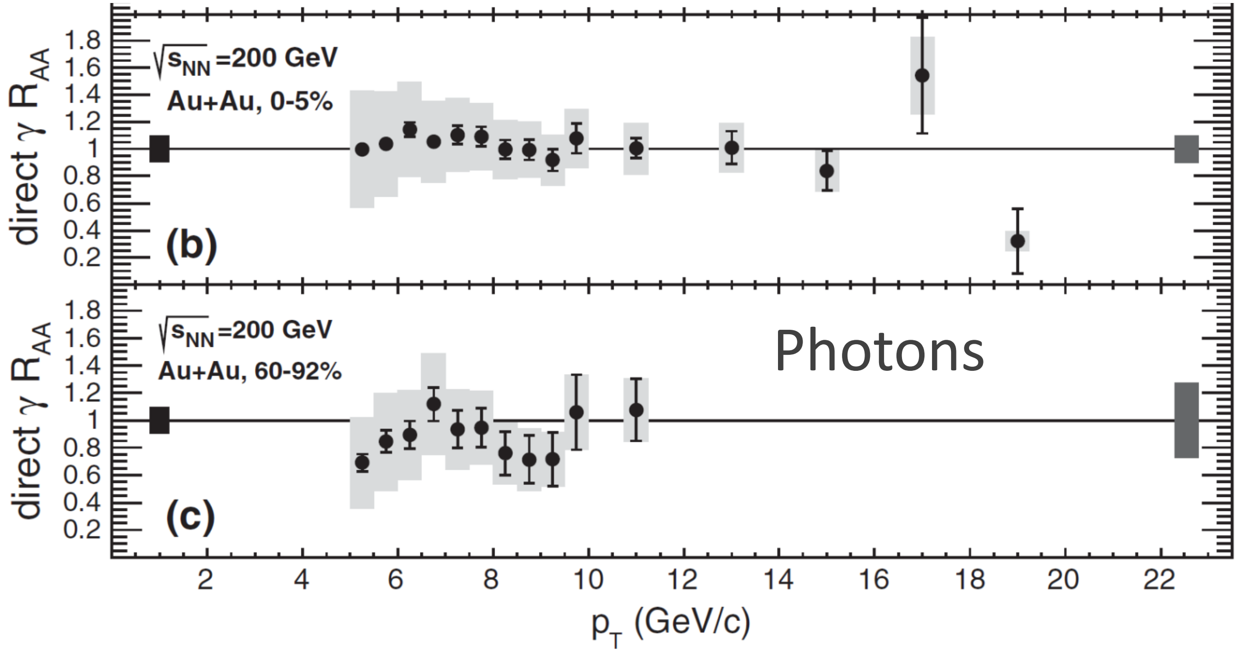
Deviations from $R_{AA}^{\gamma} = 1$ originate from:

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

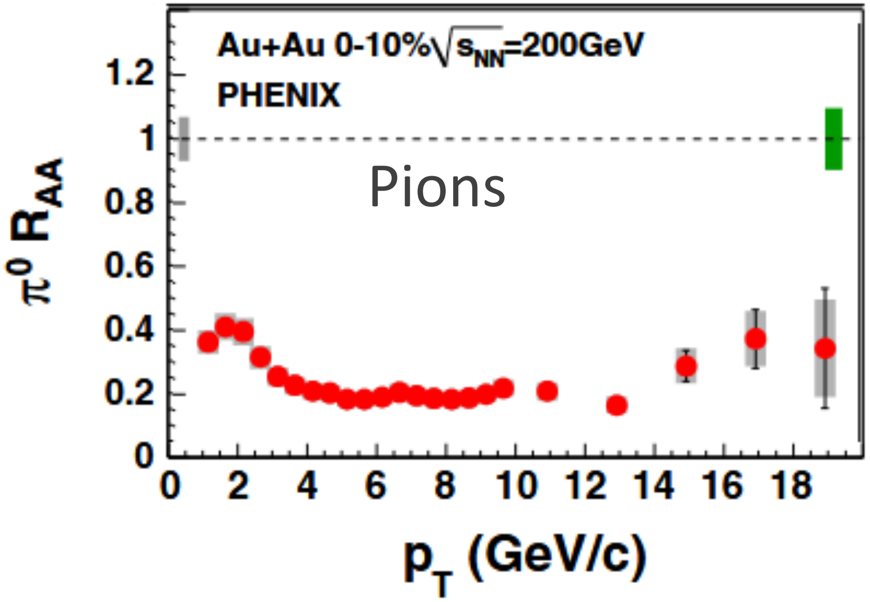
Photons vs π^0 in heavy-ion collisions

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



Ref.: PHENIX Collaboration (2012) PRL

Ref.: PHENIX Collaboration (2008) PRL

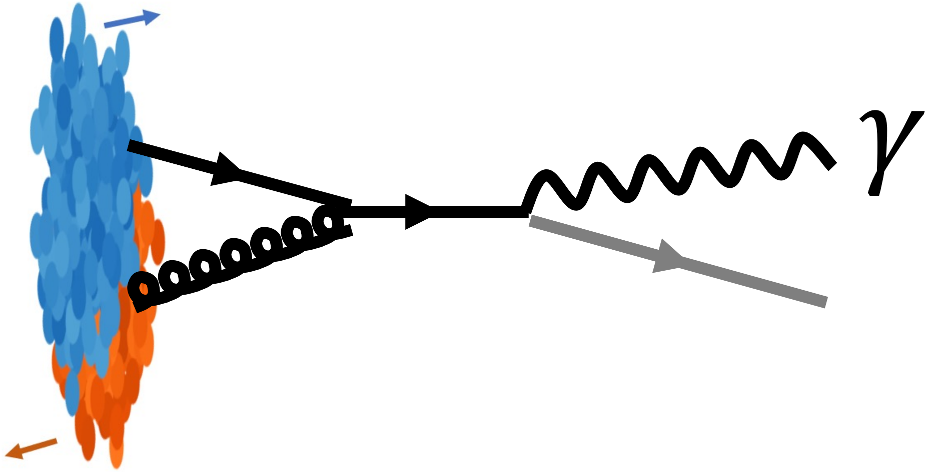


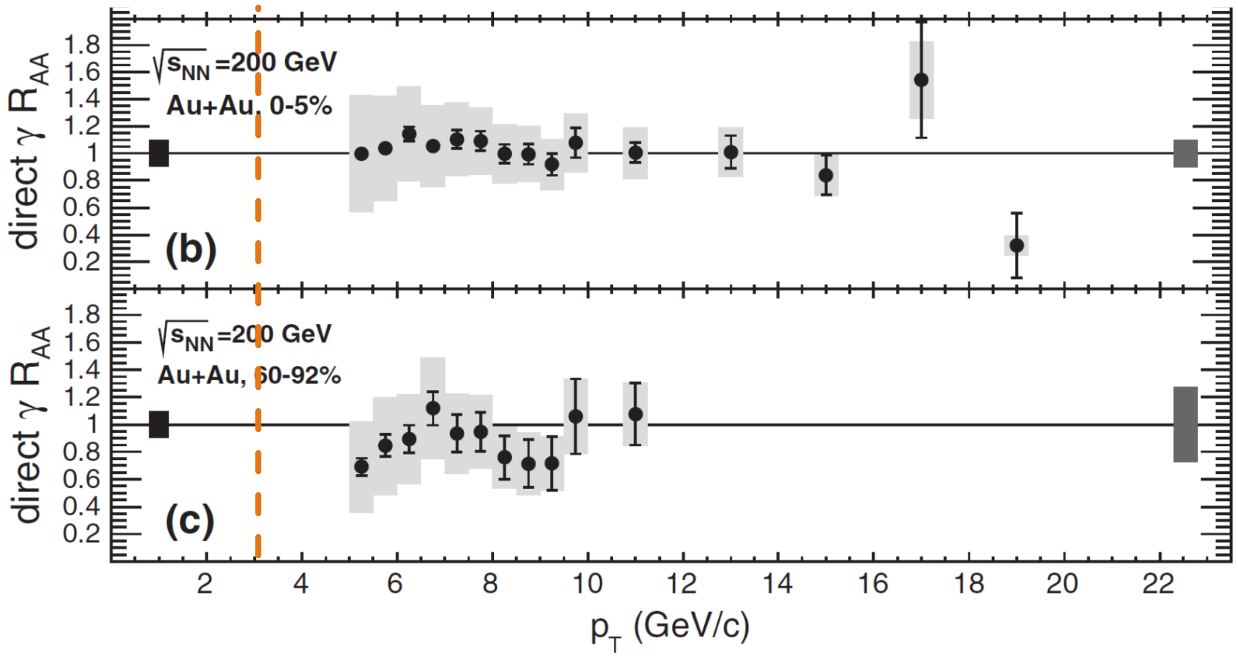
$$R_{AA}^{\gamma} = \frac{\frac{dN_{\gamma}^{A}}{dp_T}}{\left(\frac{N_{binary}}{\sigma_{pp}^{inel}}\right)\frac{d\sigma_{\gamma}^{pp}}{dp_T}} \approx 1$$

Isolated photons in heavy-ion collisions

$$q + \bar{q} \rightarrow g + \gamma$$
$$q + g \rightarrow q + \gamma$$

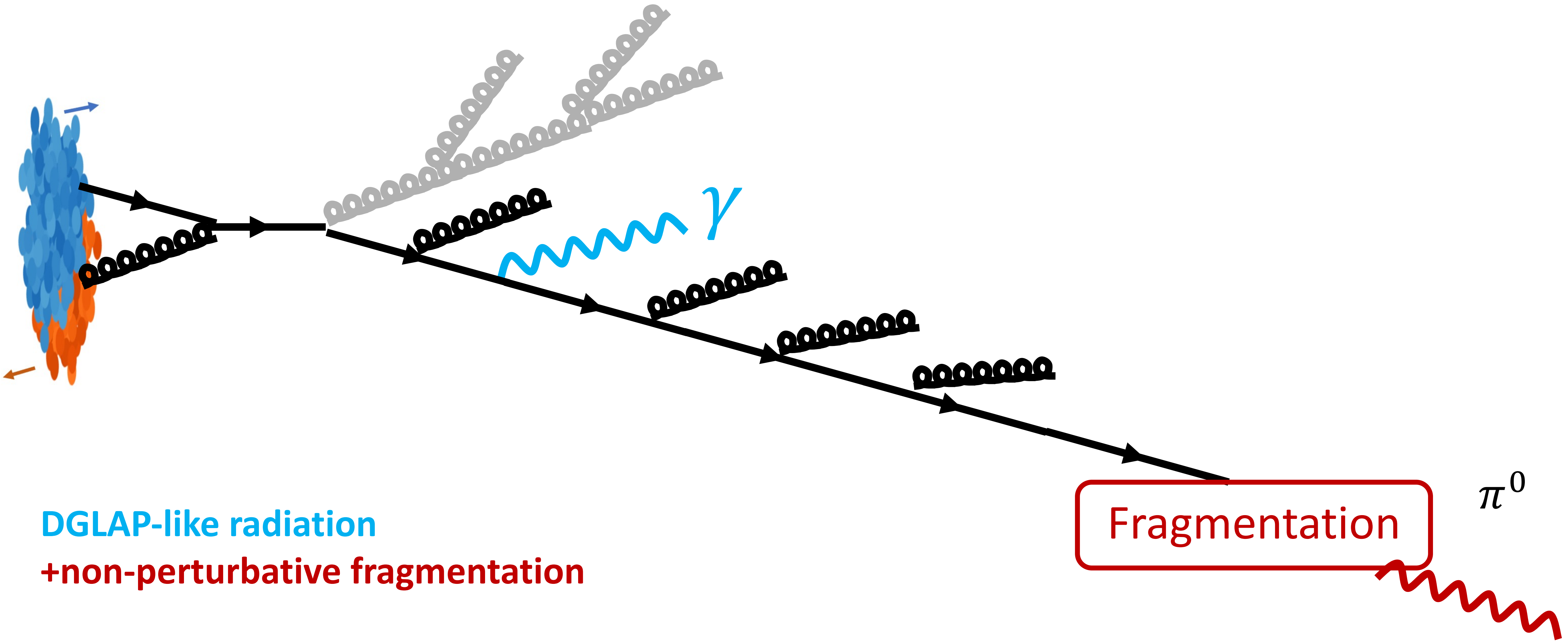
$$q + g \rightarrow q + g + \gamma\ ?$$





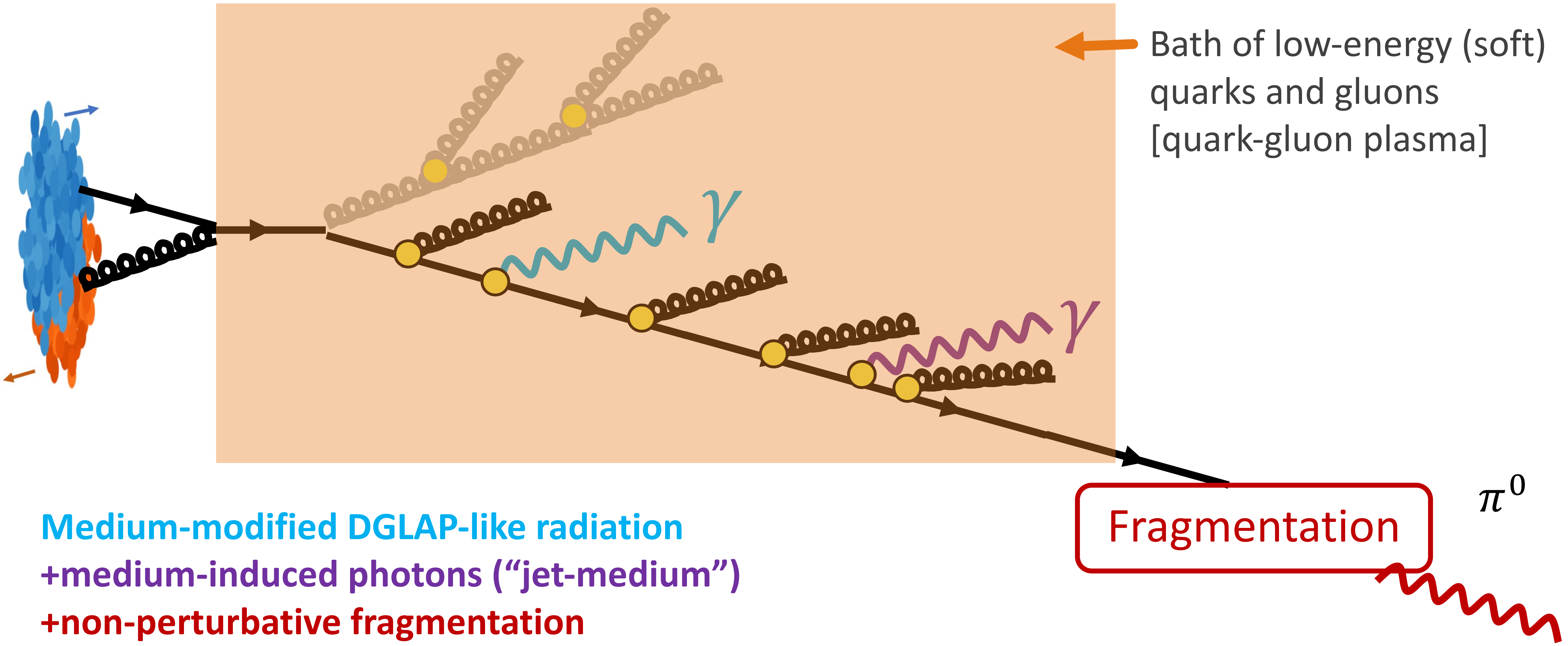
Ref.: PHENIX Collaboration (2012) PRL

Fragmentation photons and pions in p+p collisions



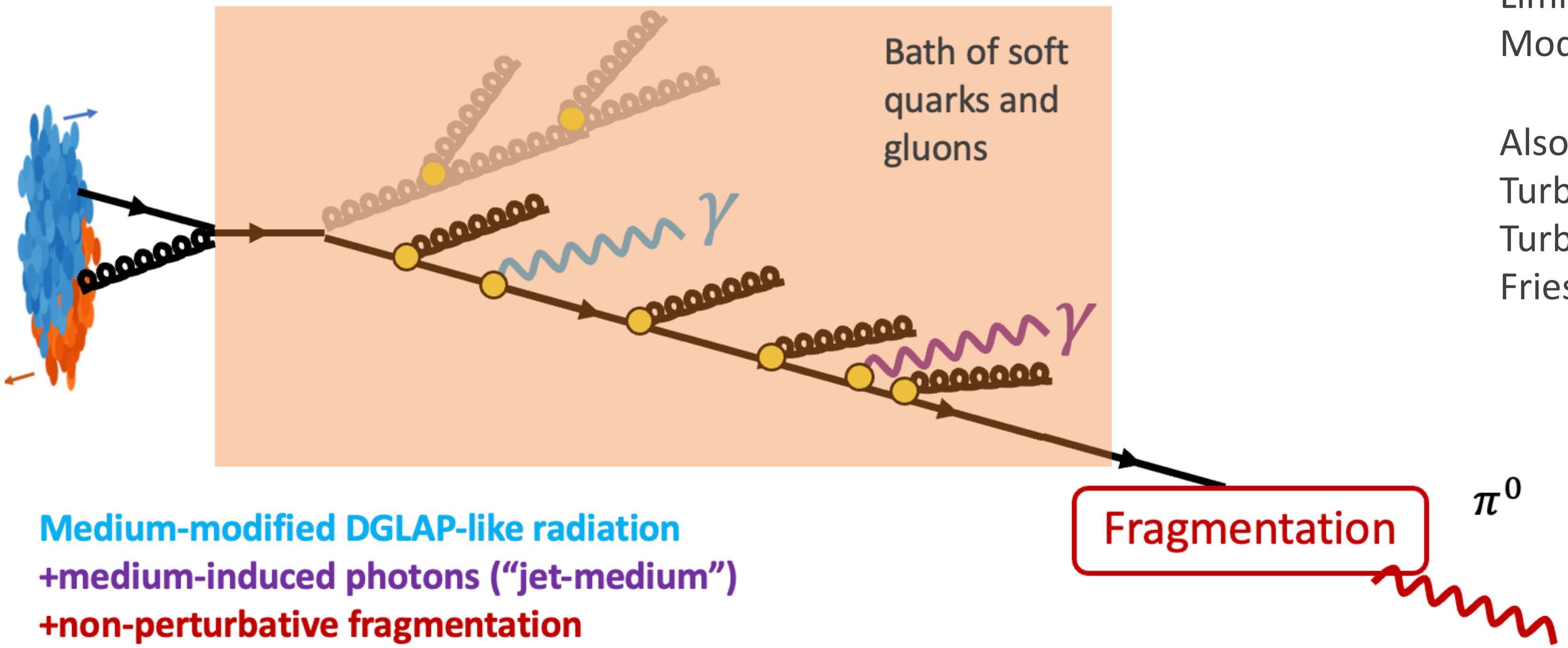
DGLAP-like radiation
+non-perturbative fragmentation

Fragmentation photons and pions in heavy-ion collisions



Medium-modified DGLAP-like radiation
+medium-induced photons ("jet-medium")
+non-perturbative fragmentation

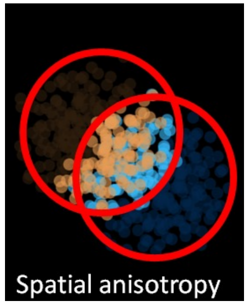
Fragmentation photons and pions in heavy-ion collisions

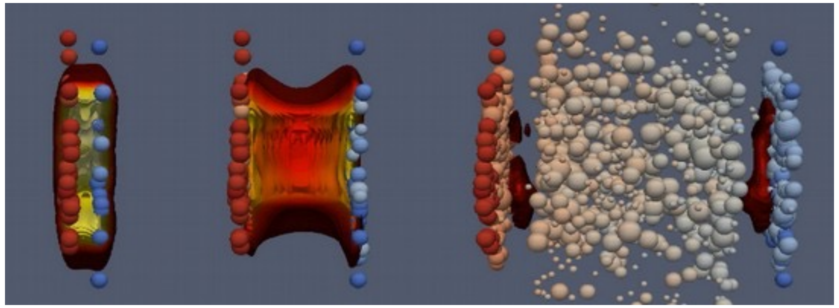


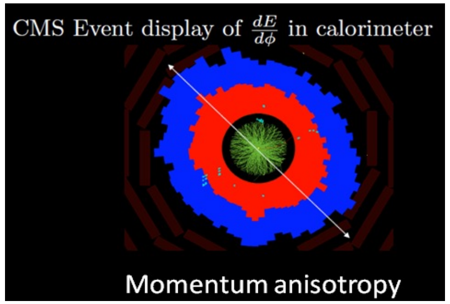
Limited number of recent studies;
Modarresi Yazdi, Shi, Gale, Jeon [arXiv:2207.12513]

Also:
Turbide, Gale, Frodermann & Heinz (2008) PRC;
Turbide, Gale, Srivastava, Fries (2008) PRC;
Fries, Müller, Srivastava (PRL) 2003

- Challenging because mixes:
  - Spacetime macroscopic description of the soft bath (plasma)
  - Momentum-space description of showers and fragmentation

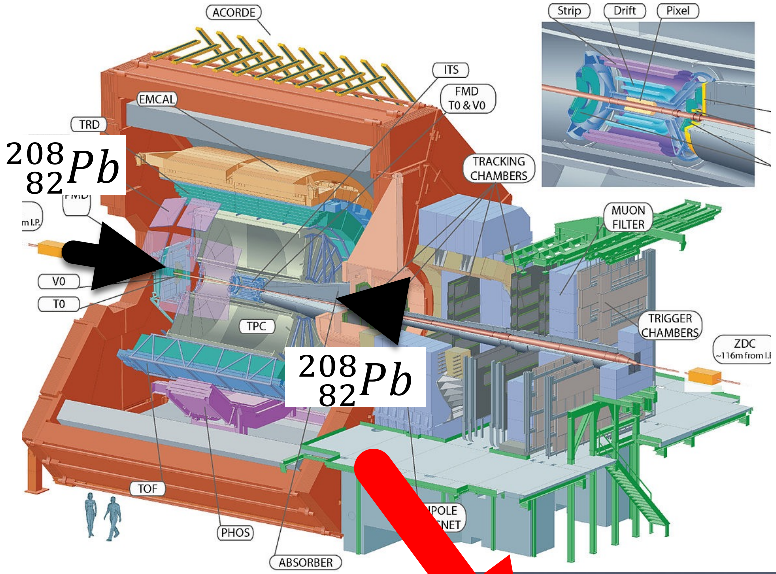




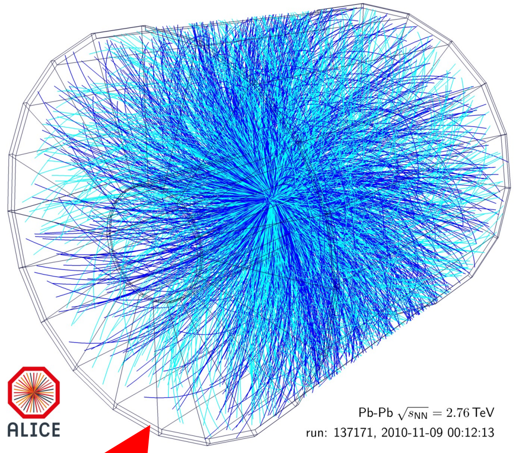


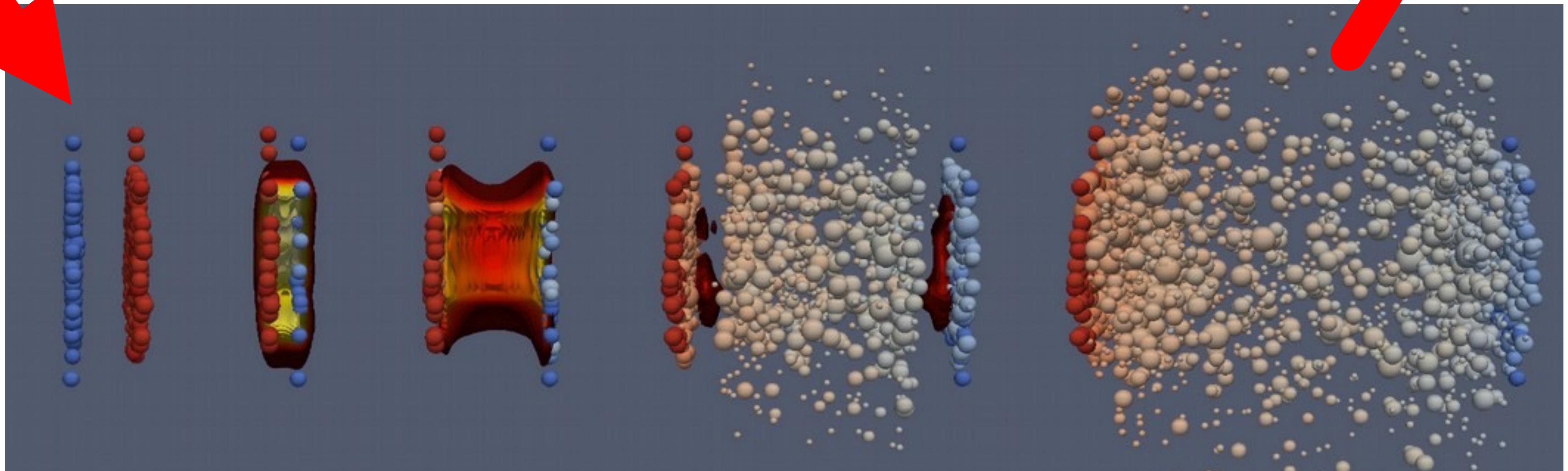
HEAVY-ION COLLISIONS:
PHOTONS FROM THE SOFT BATH [QUARK-GLUON PLASMA]

Heavy-ion collisions



Ref.: ALICE, CERN

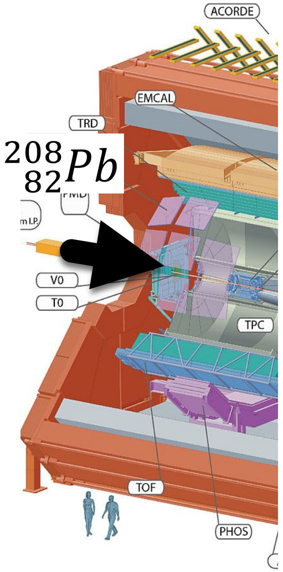




Ref: MADAI collaboration, Hannah Elfner and Jonah Bernhard

Heav

$^{208}_{82}Pb$



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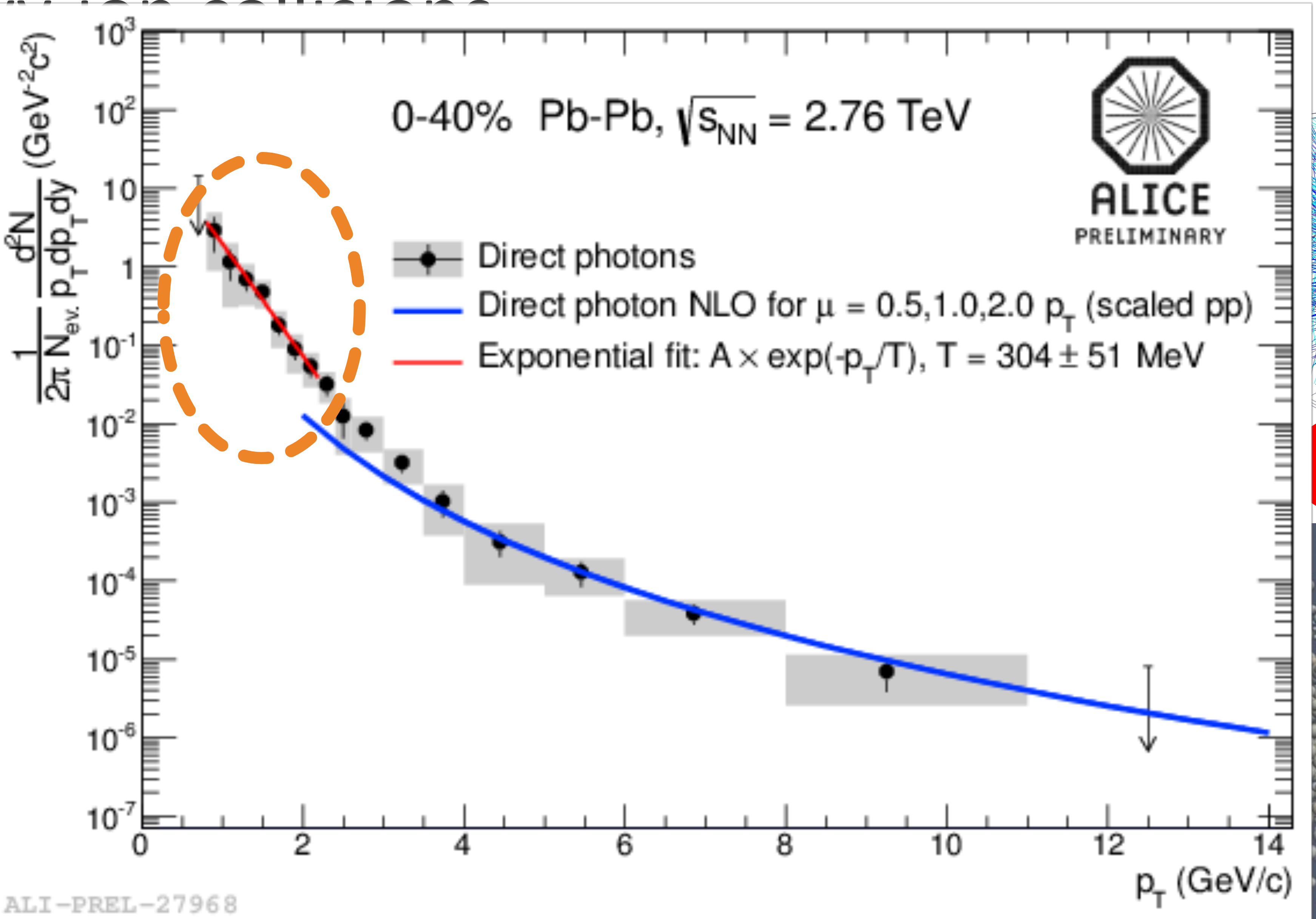

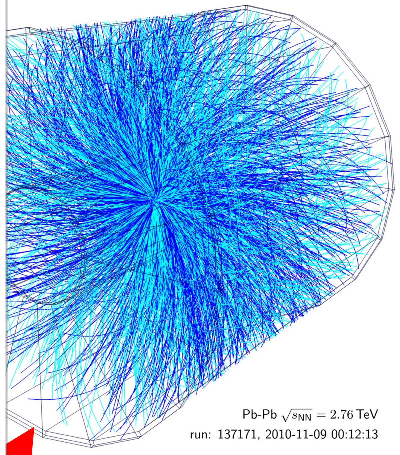

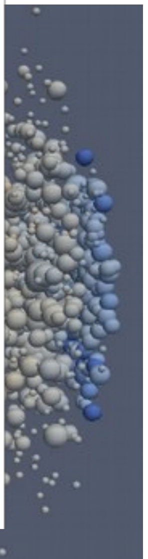

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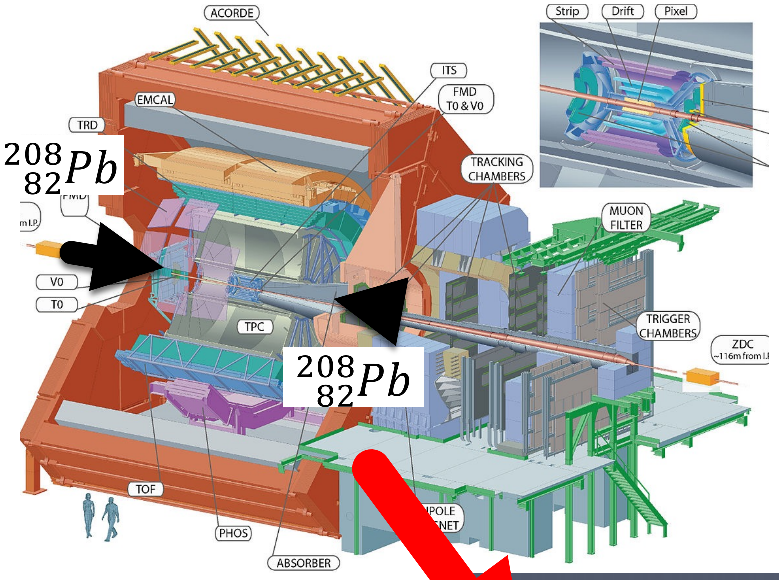
Heavy-ion collisions



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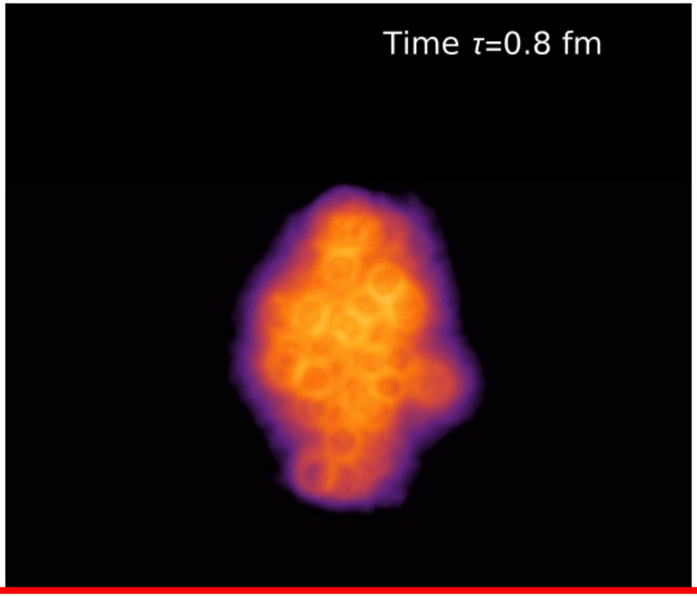
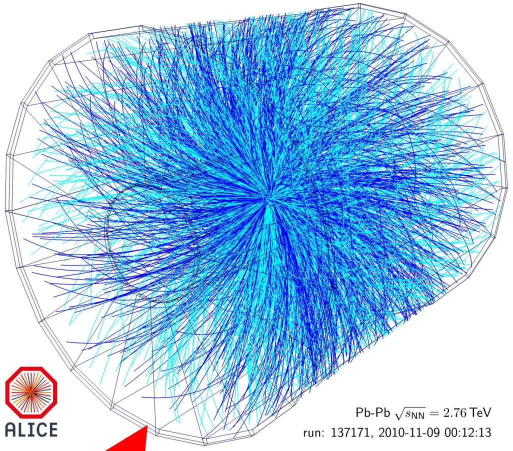
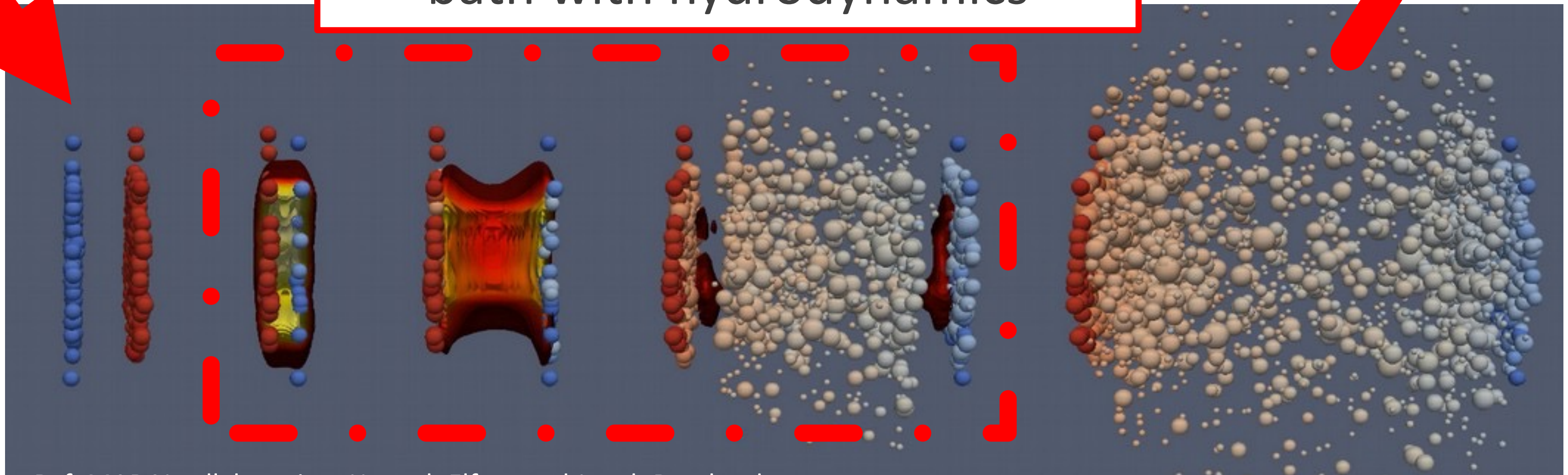




Macroscopic description of soft bath with hydrodynamics



Ref: MADAI collaboration, Hannah Elfner and Jonah Bernhard

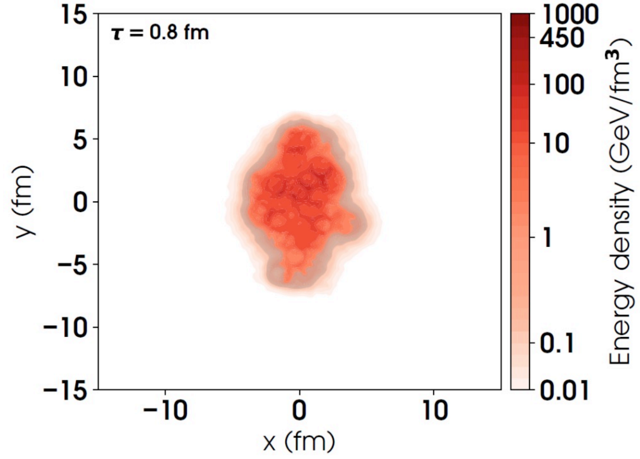
Relativistic hydrodynamics

- Evolution of the energy-momentum tensor in space&time

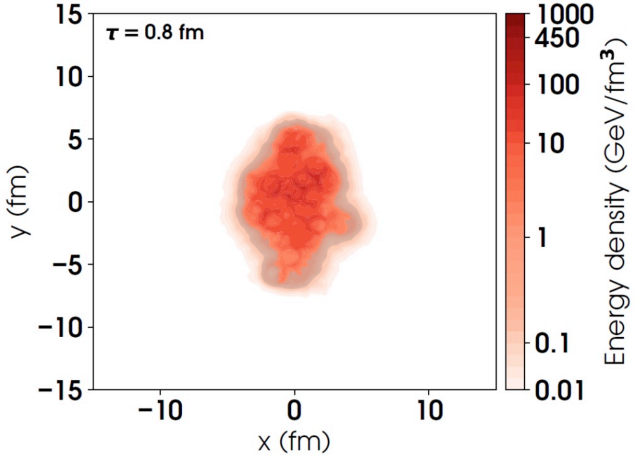
$$T^{\mu\nu} = \epsilon u^{\mu} u^{\nu} - (P + \Pi)(g^{\mu\nu} - u^{\mu} u^{\nu}) + \pi^{\mu\nu}$$

  - ϵ is the energy density
  - u^{μ} is the flow velocity (Landau frame: $T^{\mu\nu} u_{\nu} = \epsilon u^{\mu}$)
  - Π and are $\pi^{\mu\nu}$ viscous components

Initial conditions



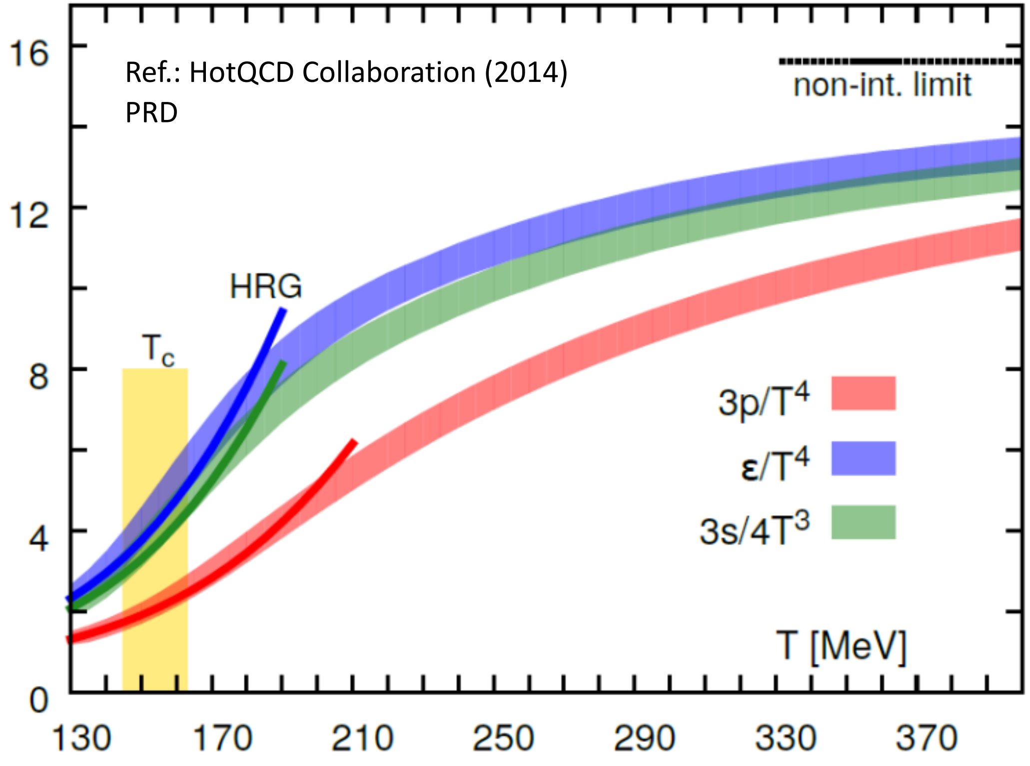
Initial conditions

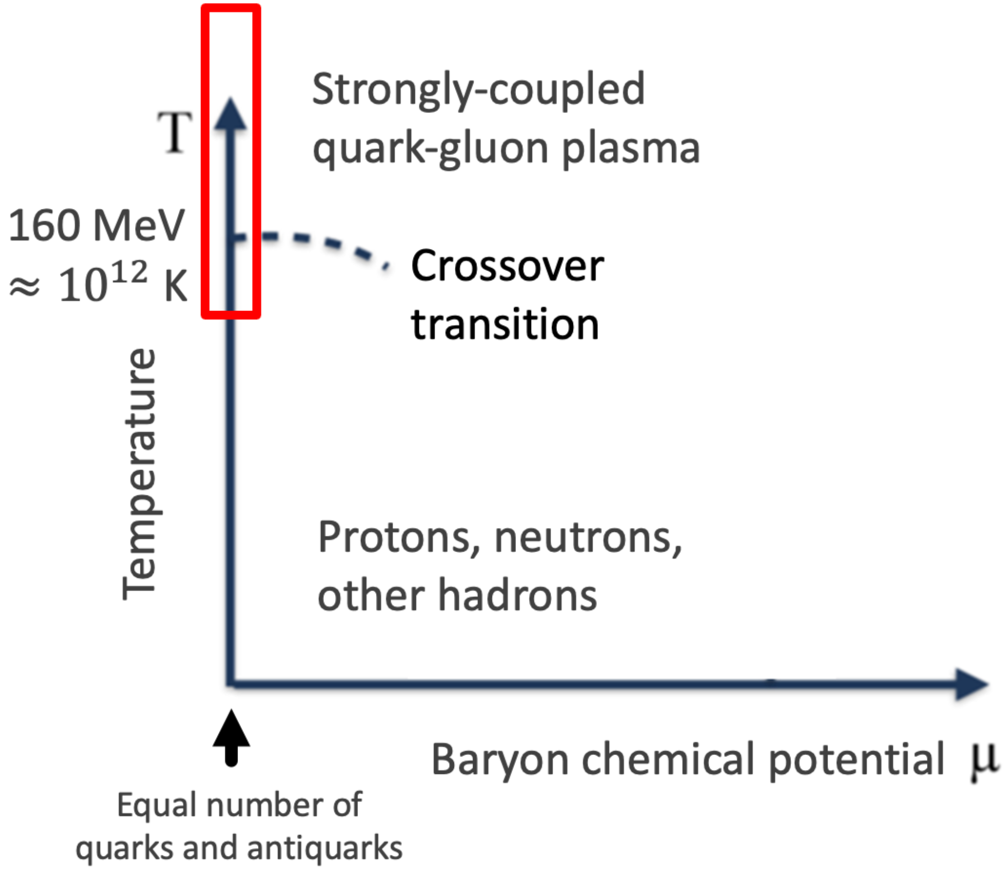


- Evolution of the energy-momentum tensor in space&time

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

- First-principle equation of state





Viscous relativistic hydrodynamics

- Evolution of the energy-momentum tensor in space&time

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

- Conservation of energy and momentum:

$$\partial_\nu T^{\mu\nu} = 0$$

Mueller (1967) Zeit. fur Phys;
Israel&Stewart (1979) Ann. Phys.

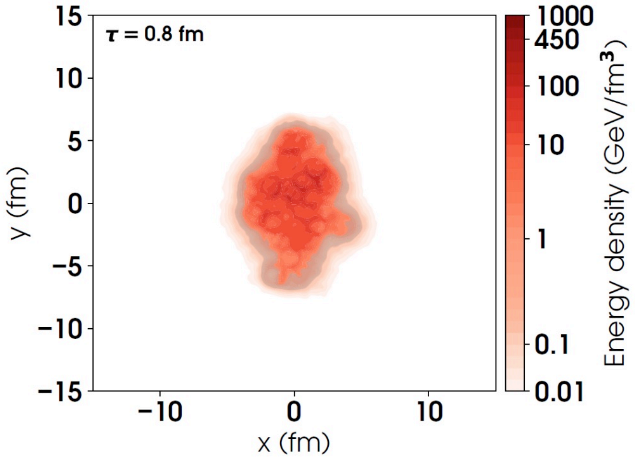
- Mueller-Israel-Stewart relativistic viscous hydrodynamics

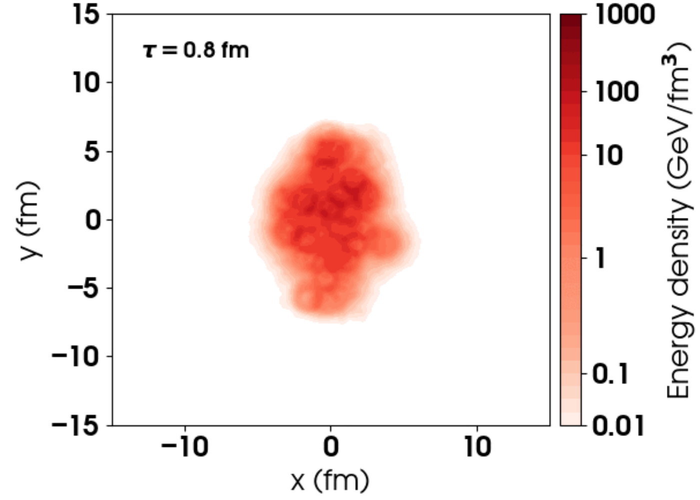
$$\tau_\Pi \dot{\Pi} + \boxed{\Pi = -\zeta\, \partial_\mu u^\mu} + (2^{nd} \text{ order terms})$$

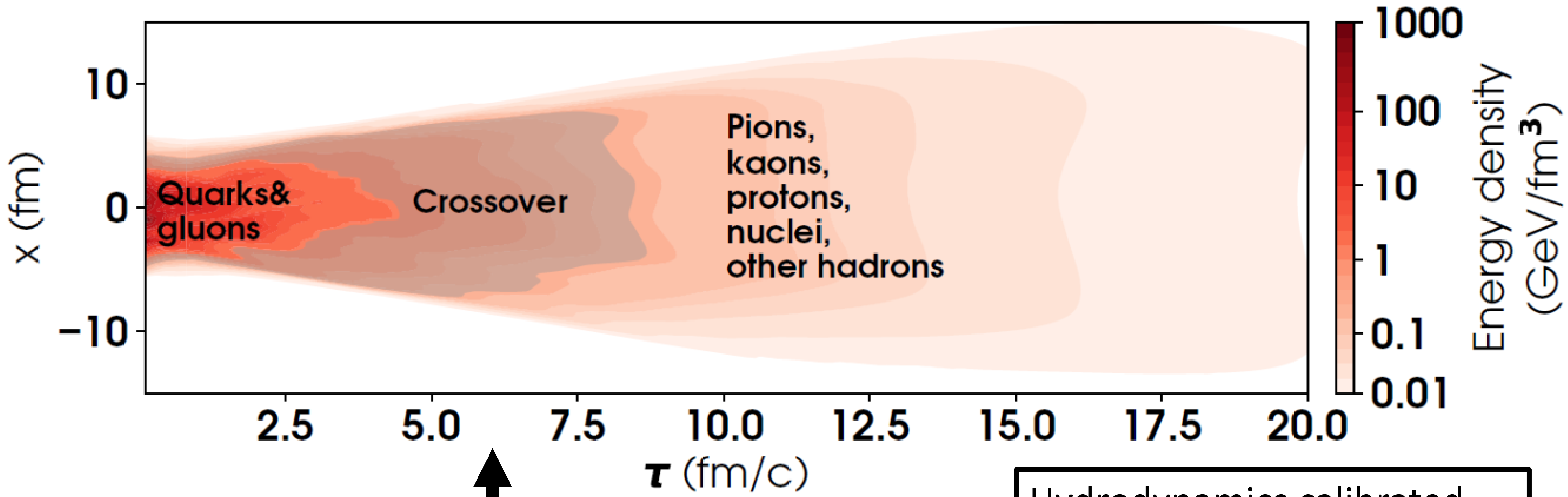
$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} \dot{\pi}^{\alpha\beta} + \boxed{\pi^{\mu\nu} = 2\,\eta(\partial_\mu u^\nu + \cdots)} + (2^{nd} \text{ order terms})$$

Solve hydrodynamics equations numerically (finite volume)

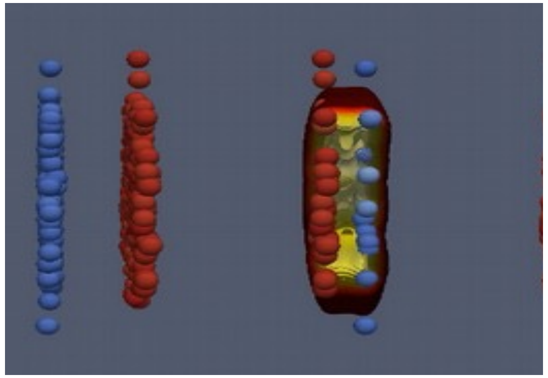
Initial conditions

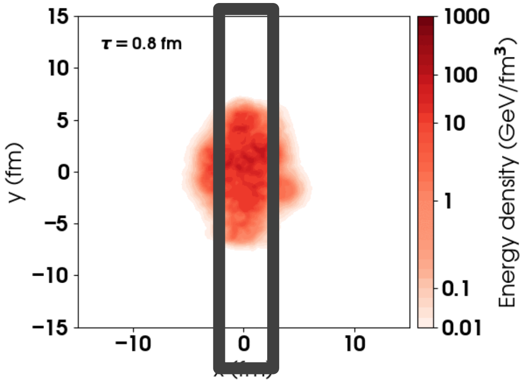


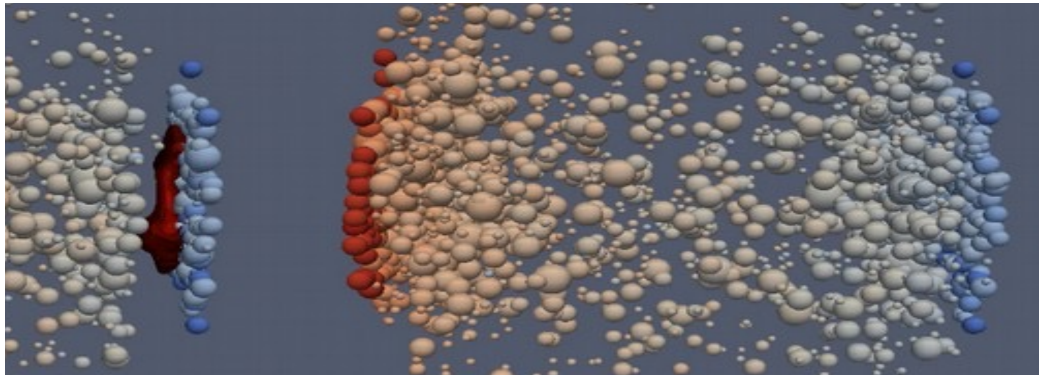




Hydrodynamics calibrated on hadronic measurements

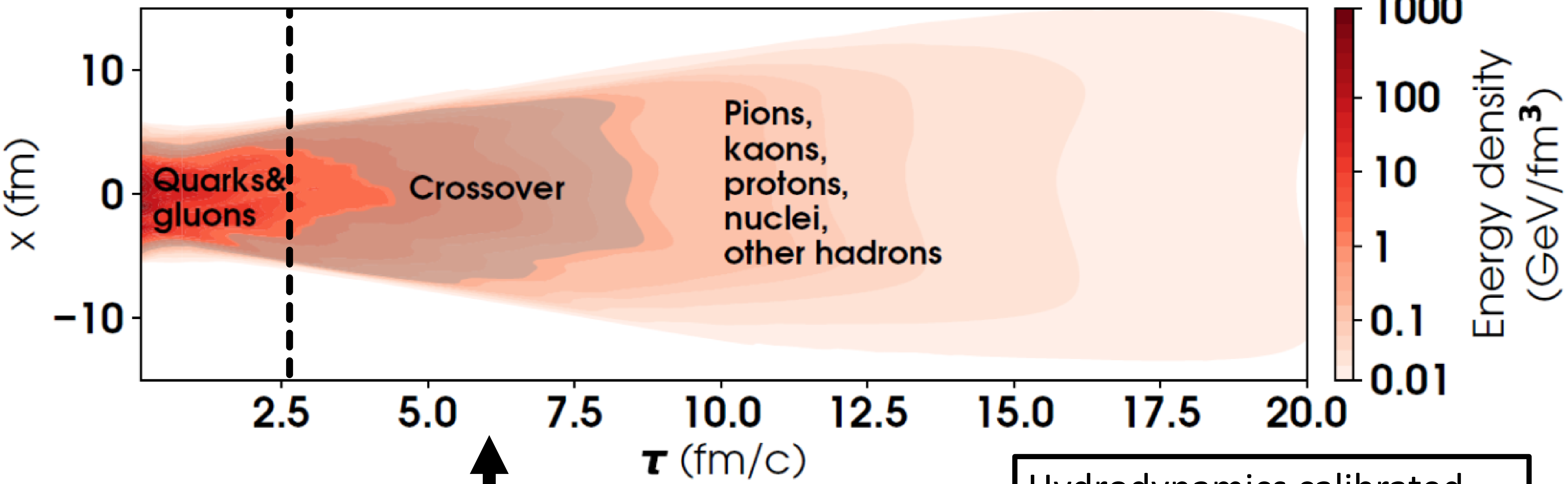




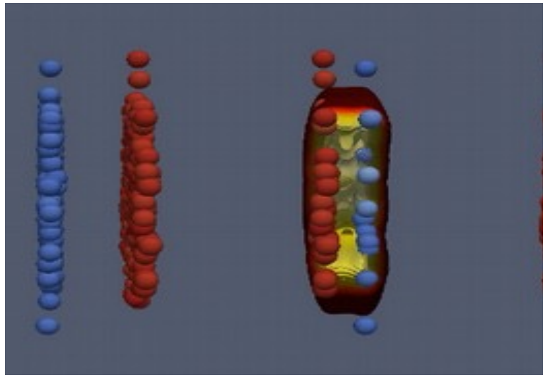


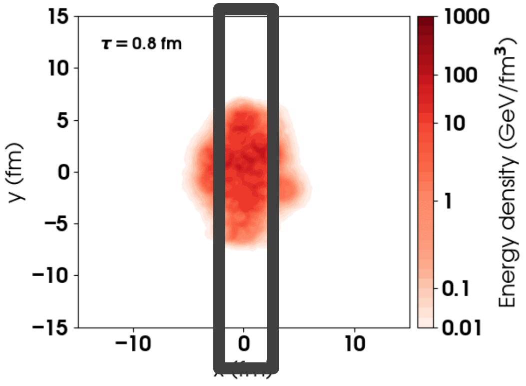
Longitudinal expansion

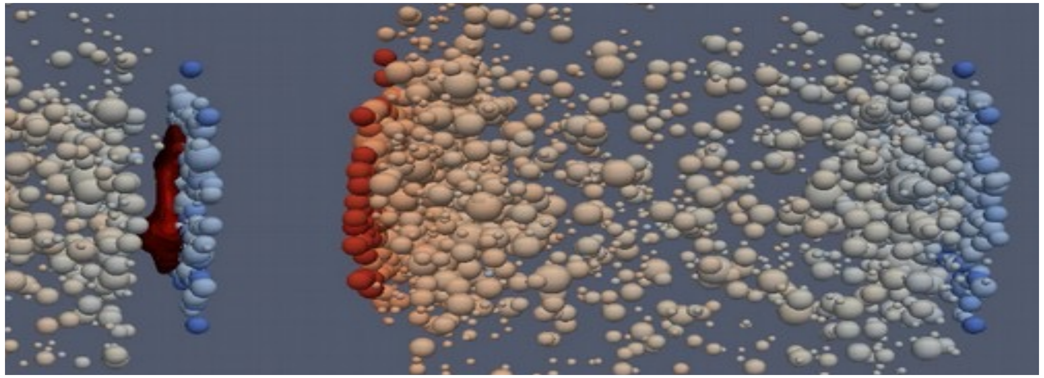
Transverse expansion



Hydrodynamics calibrated on hadronic measurements

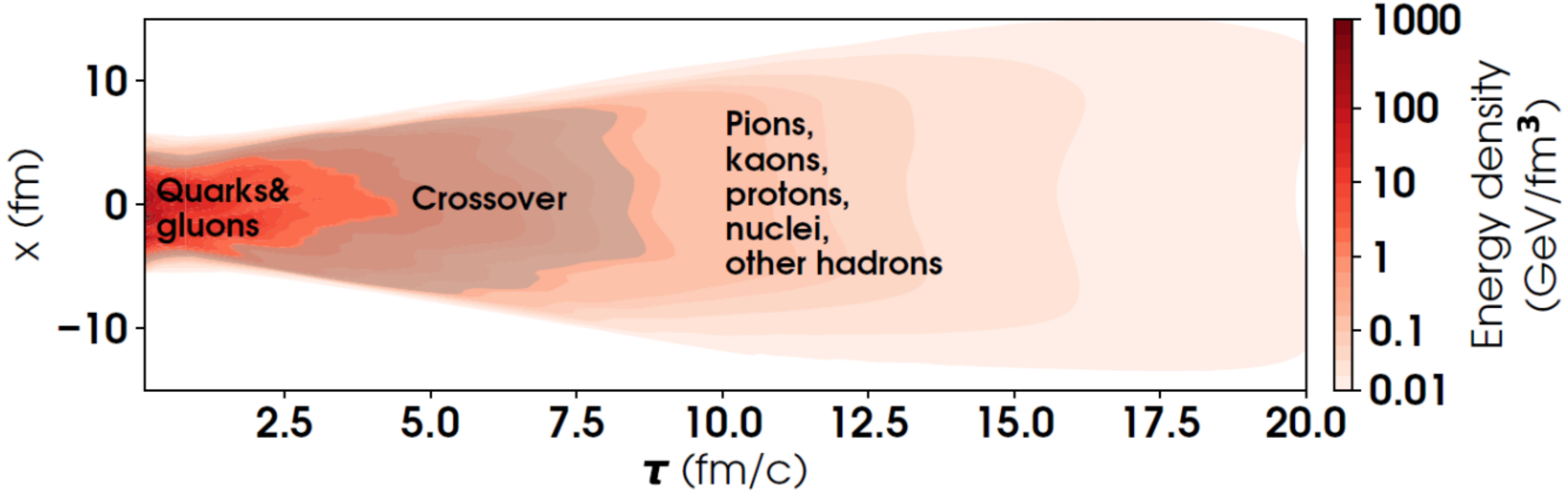






“Macroscopic” calc. of photons from deconfined plasma

- 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

“Macroscopic” calc. of photons from deconfined plasma

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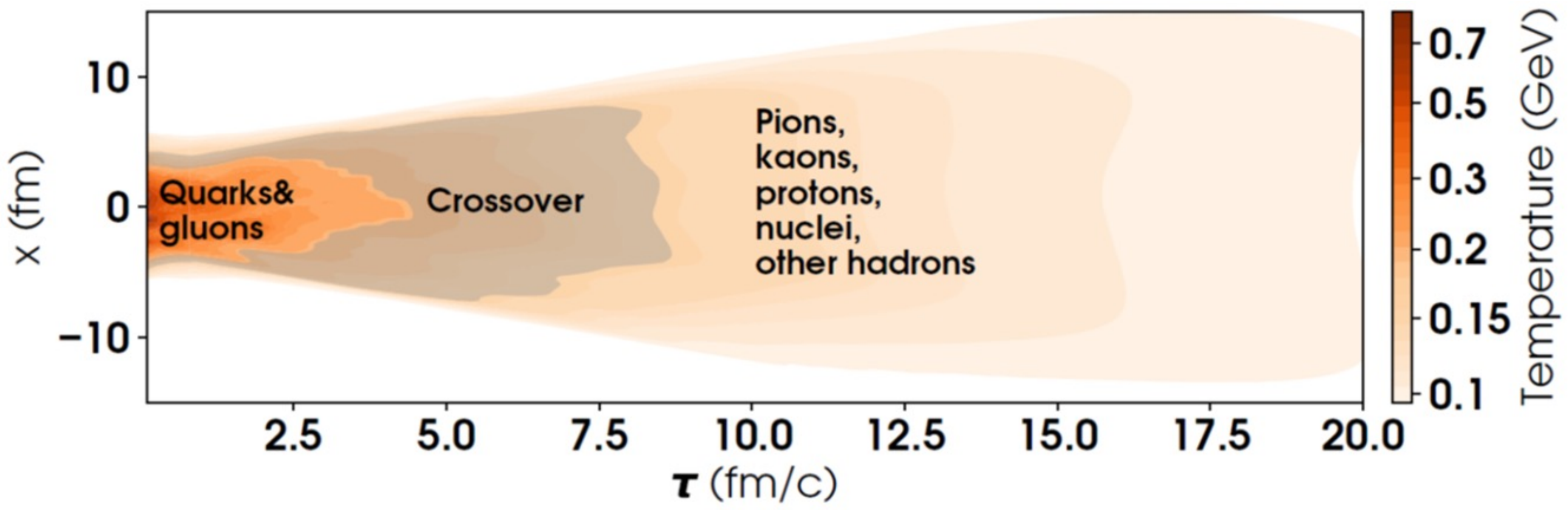

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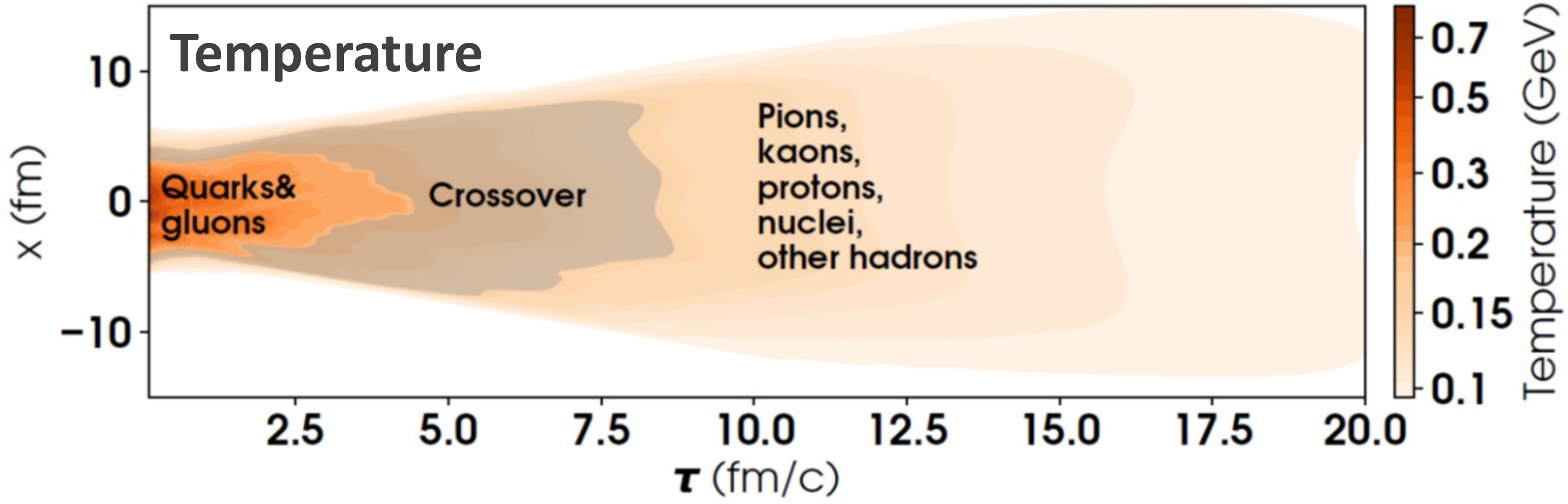
Photons from deconfined plasma

- 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

Spacetime profile of plasma

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

Photon emission rate

State of matter/Temperatures	Photon emission rate
Gas of hadr	Effective hadronic models
Deconfinemen	
Strongly- for T	apolated rates from low/high temperatures; ce QCD, holography, effective models
Weakly-coupled QGP at $T \gg 1$ GeV	Perturbative QCD

Photon emission from quark gluon plasma: Complete leading order results

Peter Brockway Arnold (Virginia U.), Guy D. Moore (Washington U., Seattle), Laurence G. Yaffe (Washington U., Seattle)

Nov, 2001

Photon emission rate

Spacetime profile of plasma

- Photon production: $\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \int \mathrm{d}^4X \, \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}\left(p, \overbrace{T(X), u^\mu(X), \ldots}\right)$

Photon emission rate

State of matter/Temperatures

Hadronic production of thermal photons

Simon Turbide (McGill U.), Ralf Rapp (Nordita), Charles Gale (McGill U.)
Aug, 2003

Thermal photons from heavy ion collisions: A spectral function approach

Kevin Dusling (Brookhaven), Ismail Zahed (SUNY, Stony Brook)
Nov, 2009

Photon emission rate

Effective hadronic models

Extrapolated rates from low/high temperatures

Lattice QCD, holography, effective models

Perturbative QCD

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 emissivity of the quark-gluon plasma: A lattice QCD analysis of the transverse channel

Marco Cè (U. Bern, AEC and Bern U. and CERN), Tim Harris (Edinburgh U.), Ardit Krasniqi (U. Mainz, PRISMA), Harvey B. Meyer (U. Mainz, PRISMA and Helmholtz Inst., Mainz and Darmstadt, GSI), Csaba Török (U. Mainz, PRISMA)

May 5, 2022

26 pages

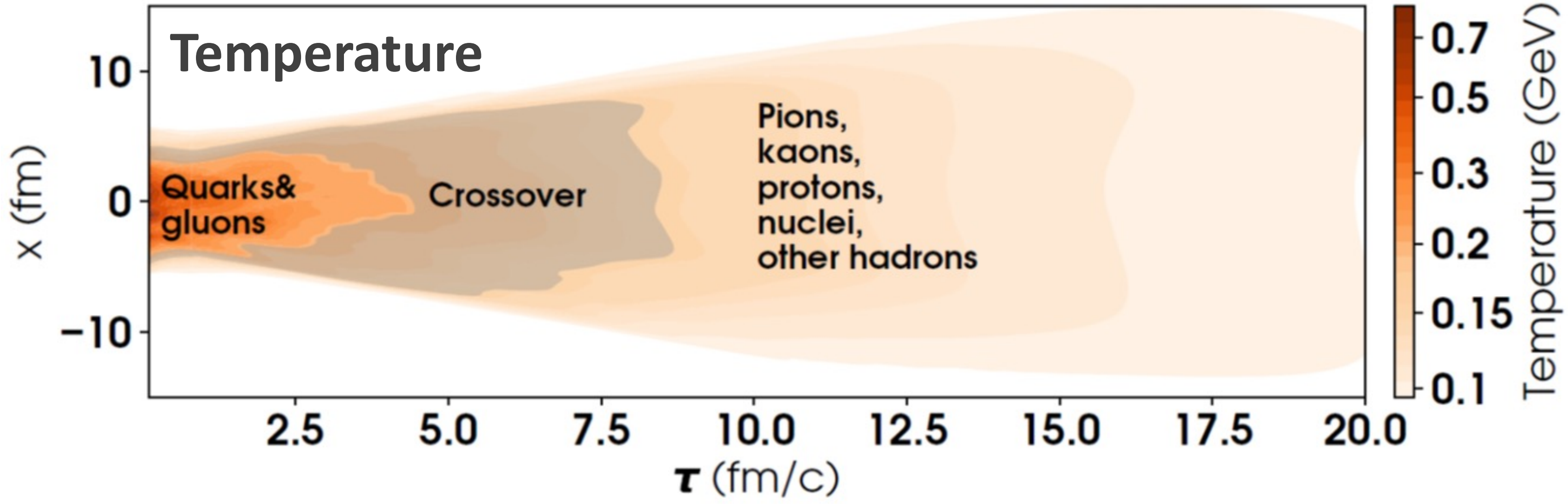
Weakly coupled QGP at $T \gg 1$ GeV

Photon emission rate

Effective hadronic models
Extrapolated rates from low/high temperatures Lattice QCD, holography, effective models
Perturbative QCD

Photons from deconfined plasma

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

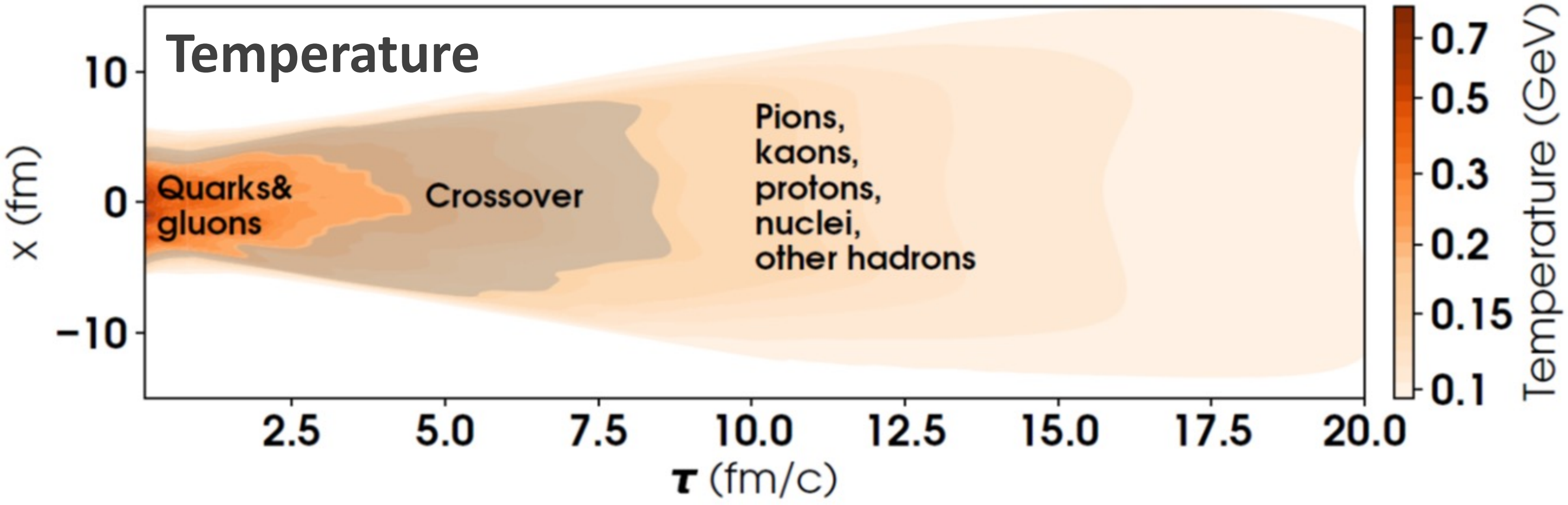


- Photon production:

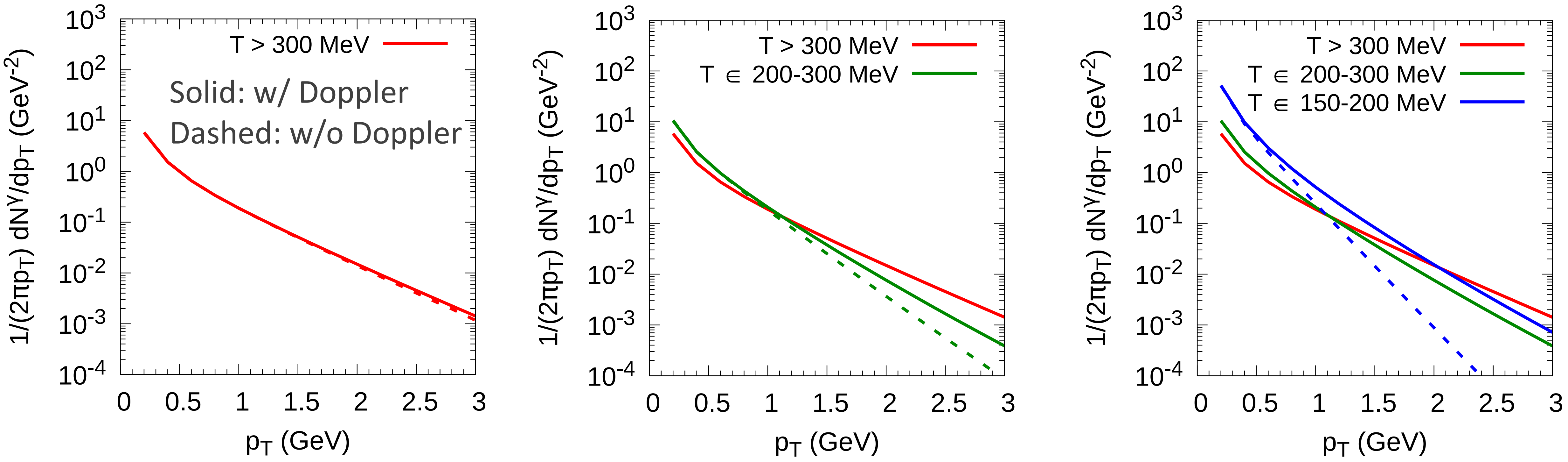
Spacetime profile of plasma

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

Photon emission rate

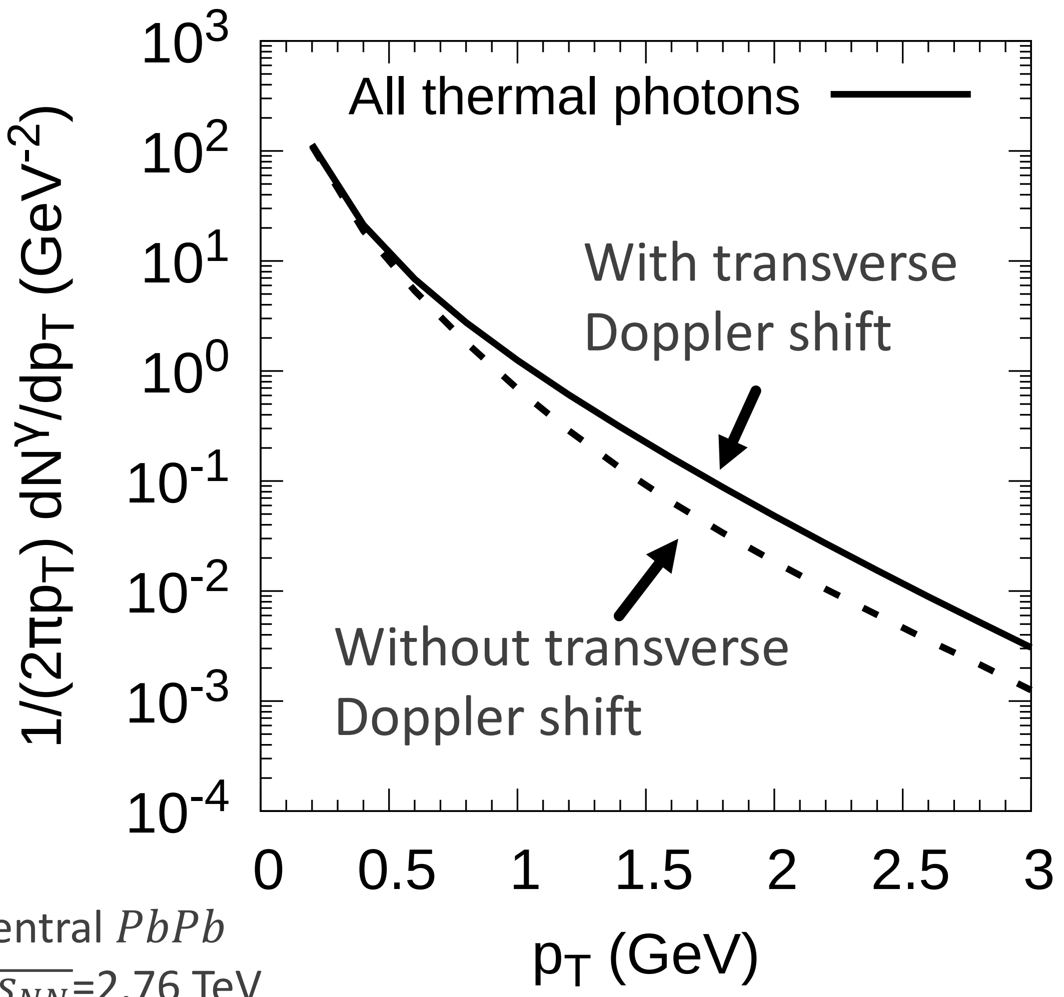


The later (or lower temperature) photons are produced, the more Doppler-shifted

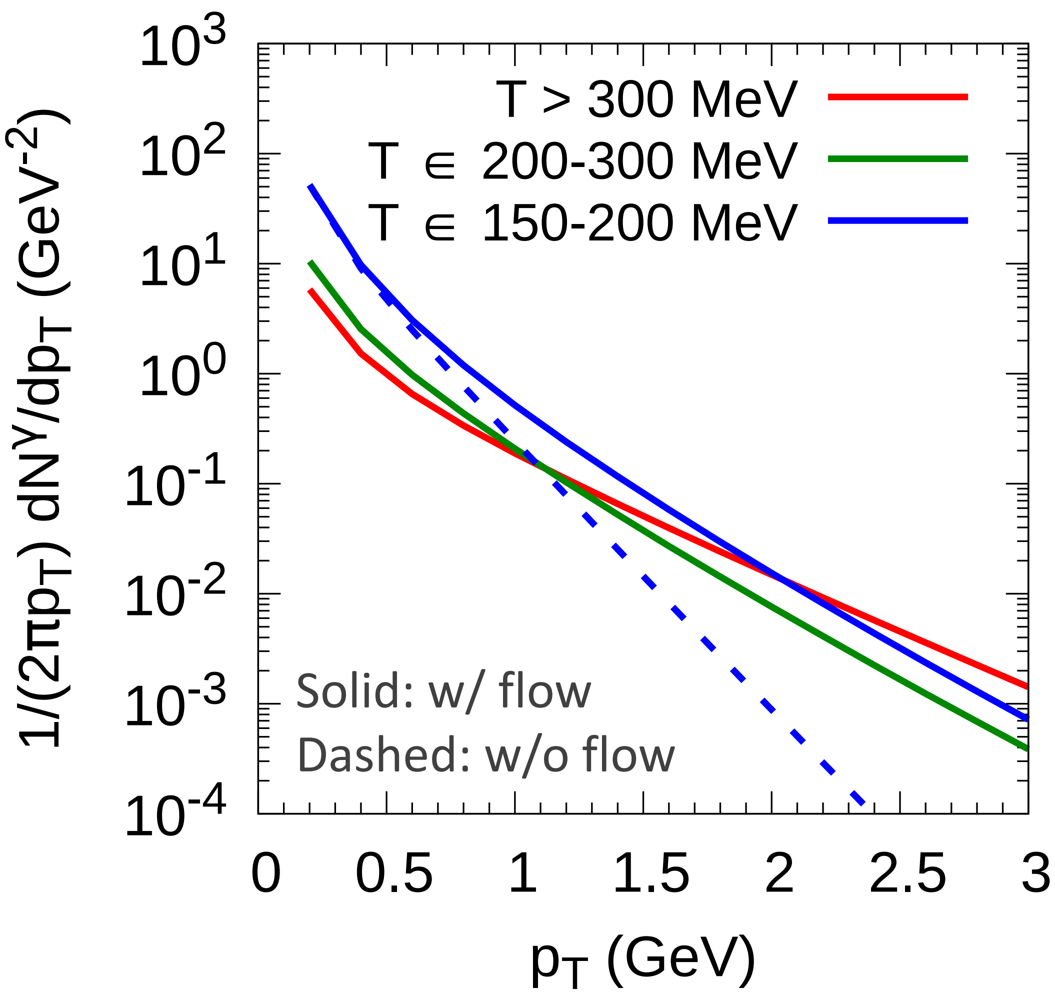


Effect of transverse Doppler shift in realistic calculation

Global effect of Doppler shift

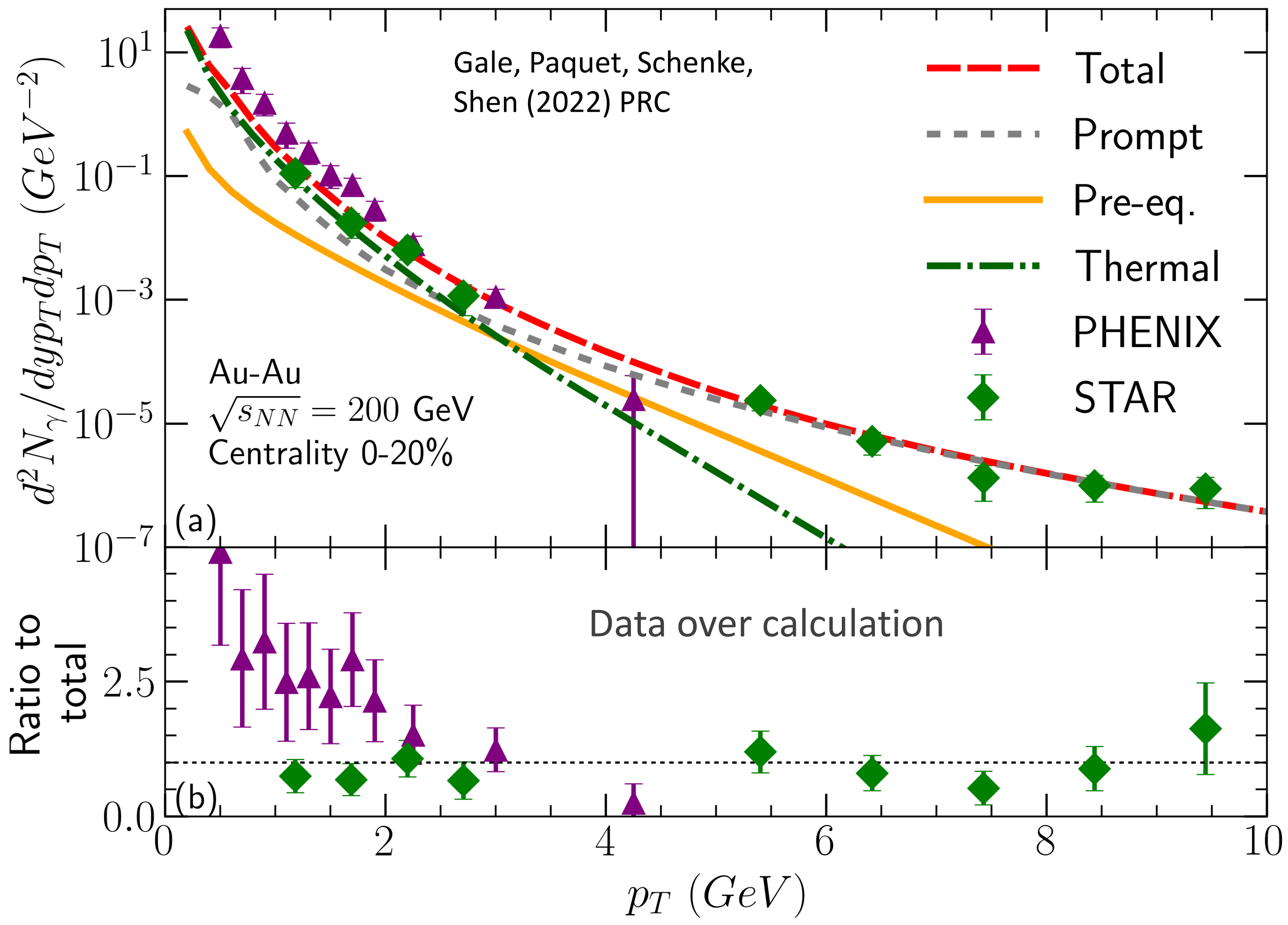


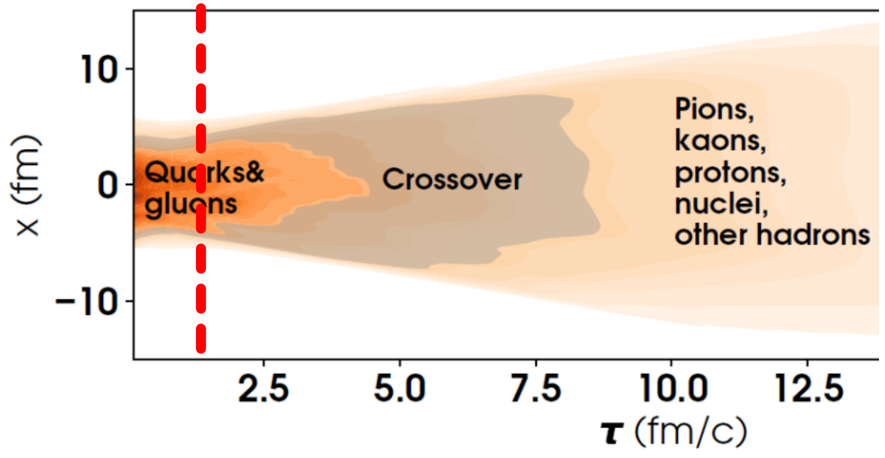
Local effect of Doppler shift



Central $PbPb$
$\sqrt{s_{NN}}$=2.76 TeV

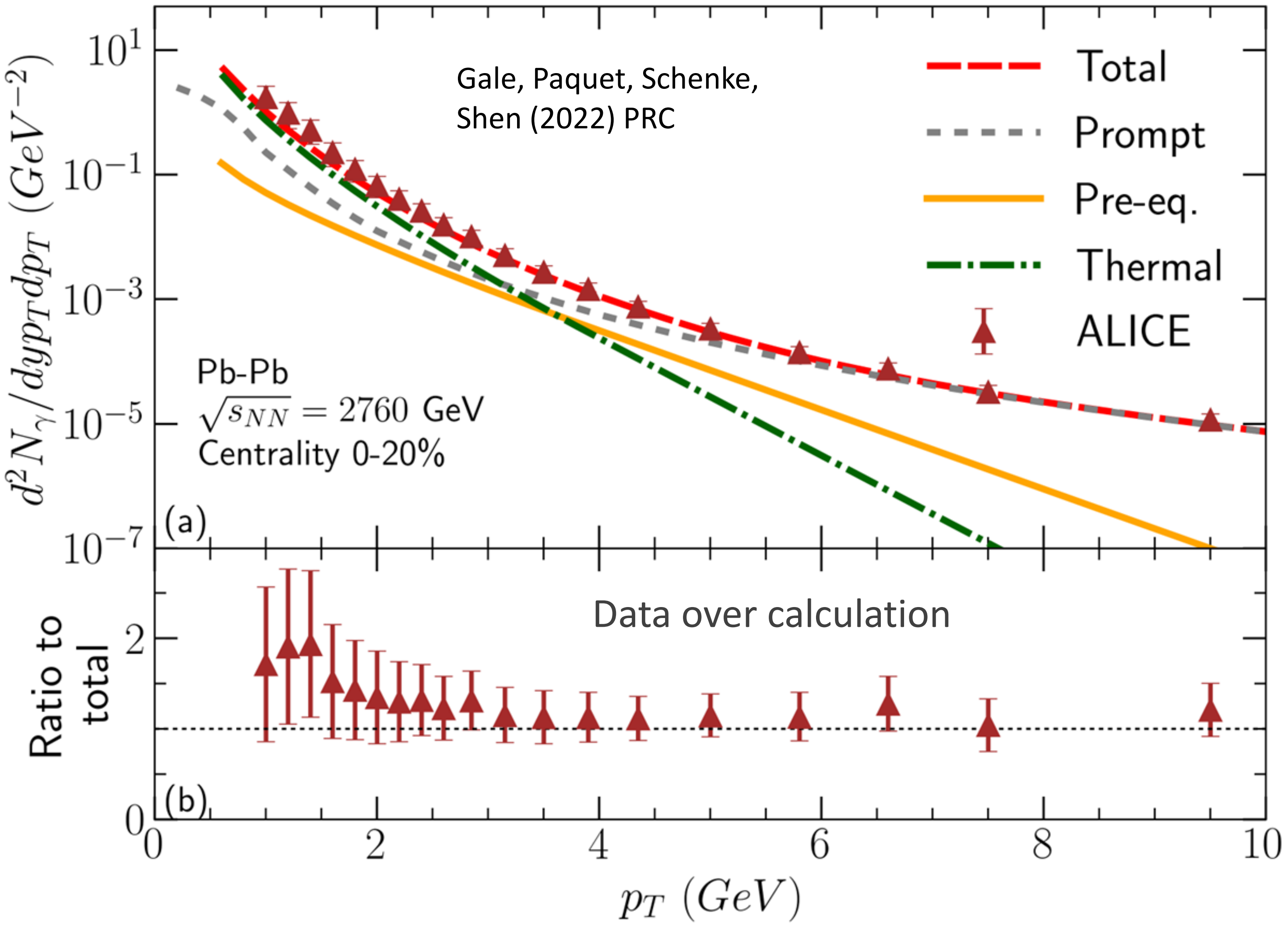
Results: Au-Au $\sqrt{s_{NN}}$ =200 GeV, 0-20%





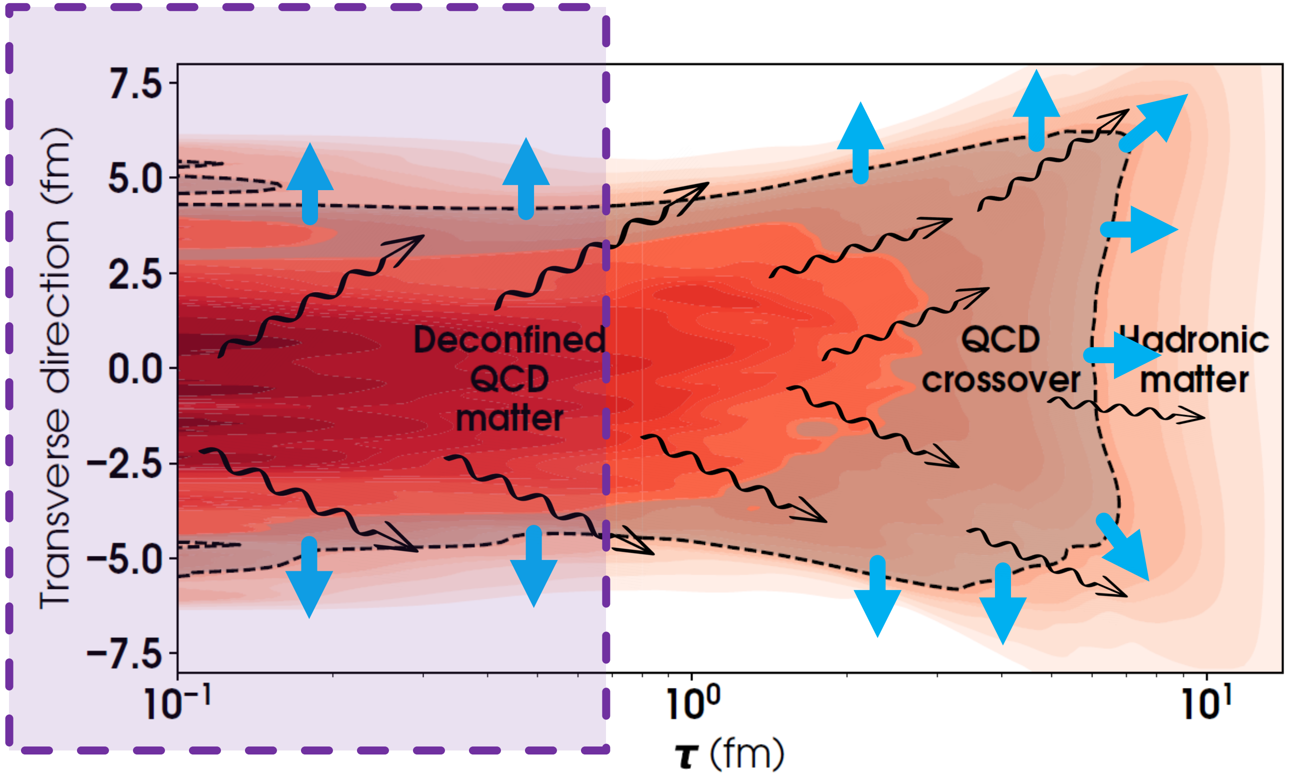
- Soft-bath ("thermal") photons dominate at low energy/p_T
- Experimental uncertainties large
- ± Some tension between measurements

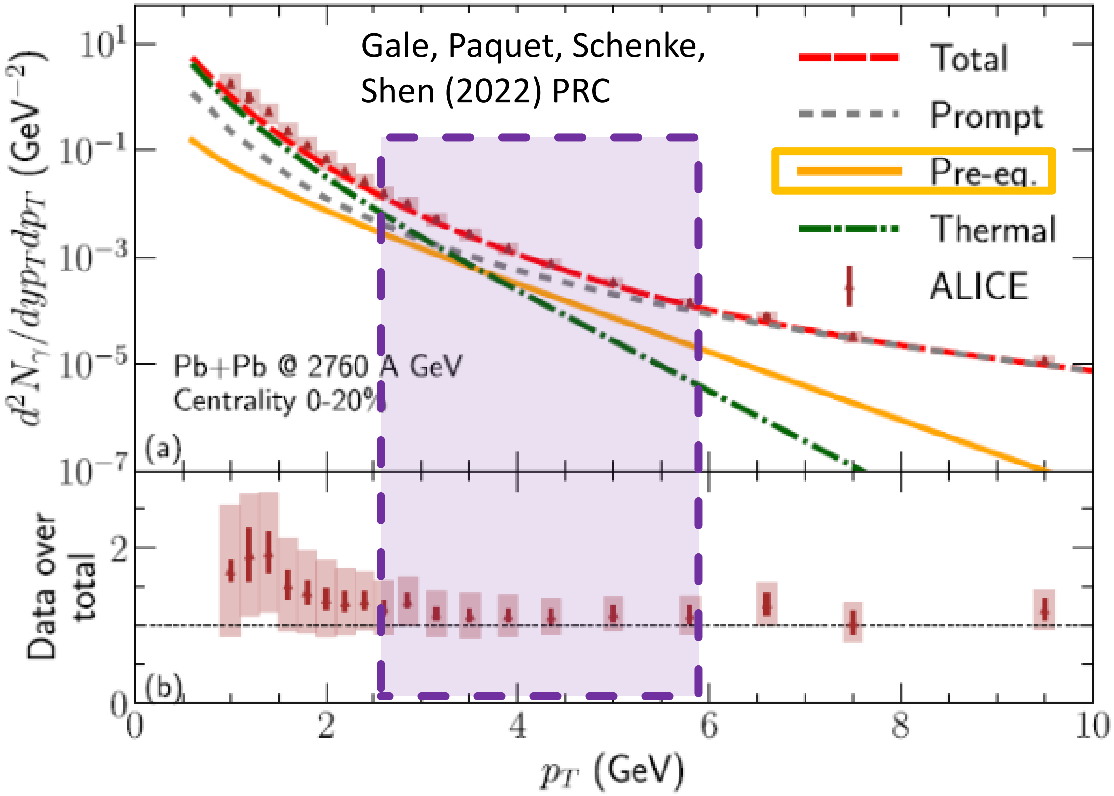
Results: Pb-Pb $\sqrt{s_{NN}}$ =2760 GeV, 0-20%



- Soft-bath ("thermal") photons dominate at low energy/p_T
- Experimental uncertainties large
- $\pm$ Some tension between measurements

Photons from the early stage of the collision





- Use photons to study the earliest stage of the collisions:
  - Approach to chemical equilibrium (from gluon dominated to quark&gluon equilibrium)
  - Understand formation of the soft bath and "emergence of hydrodynamics"

Results: momentum anisotropy

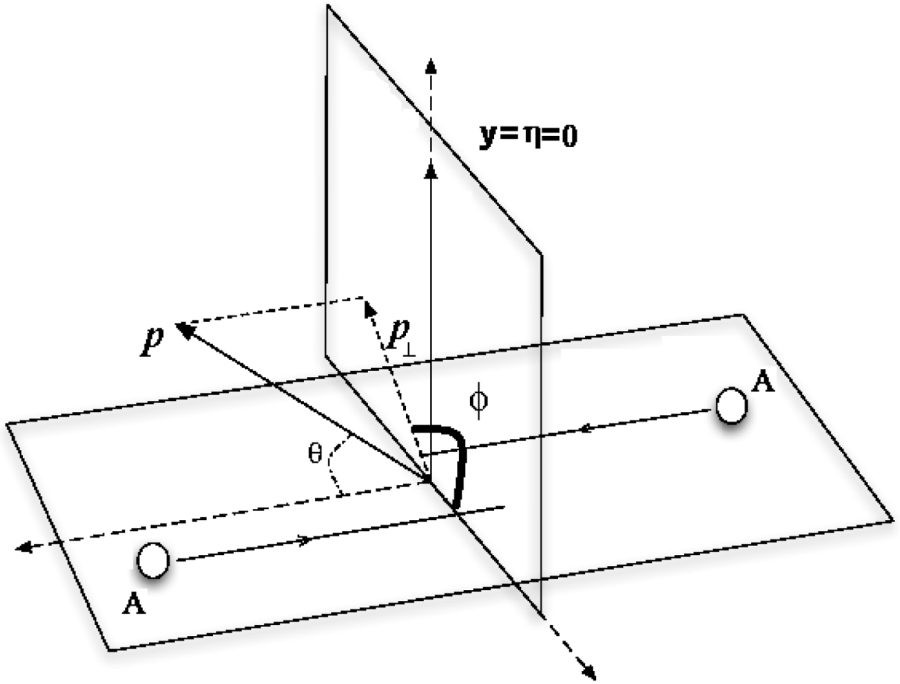


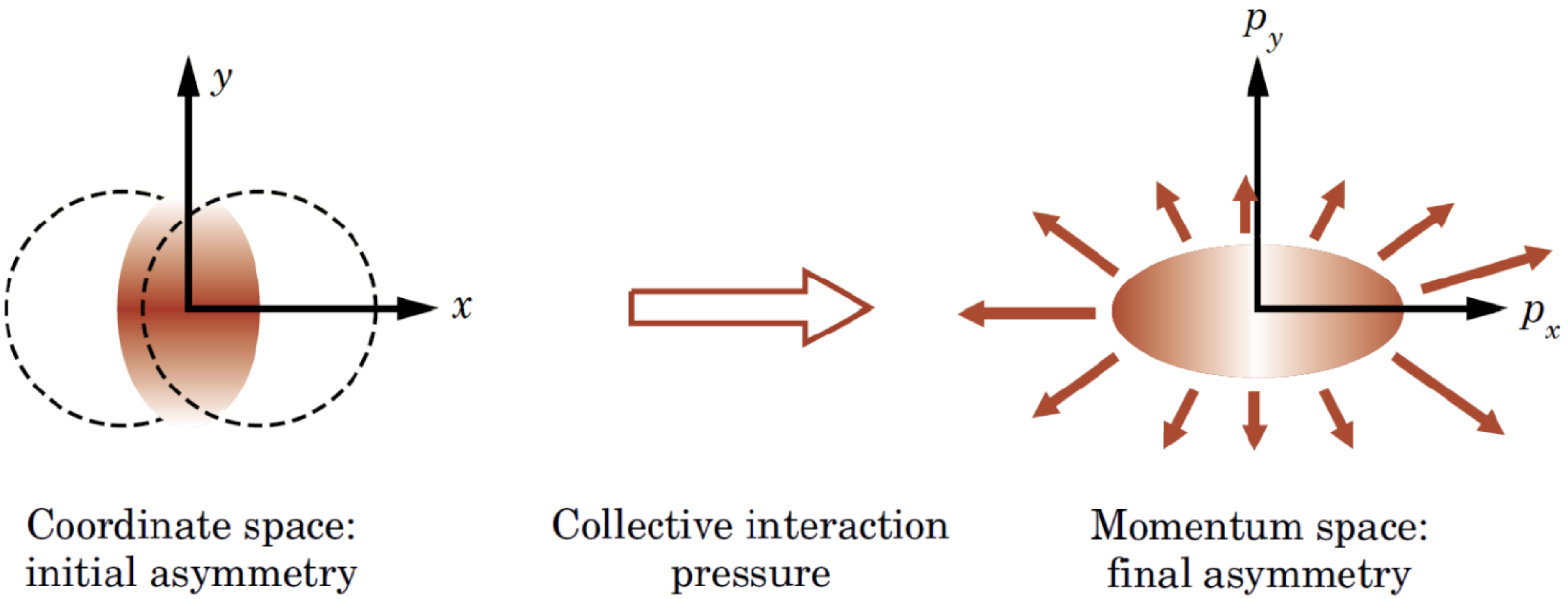
Figure adapted from K. Tuchin (2013) AHEP

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

- More precisely: momentum anisotropy through photon-hadron correlation

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

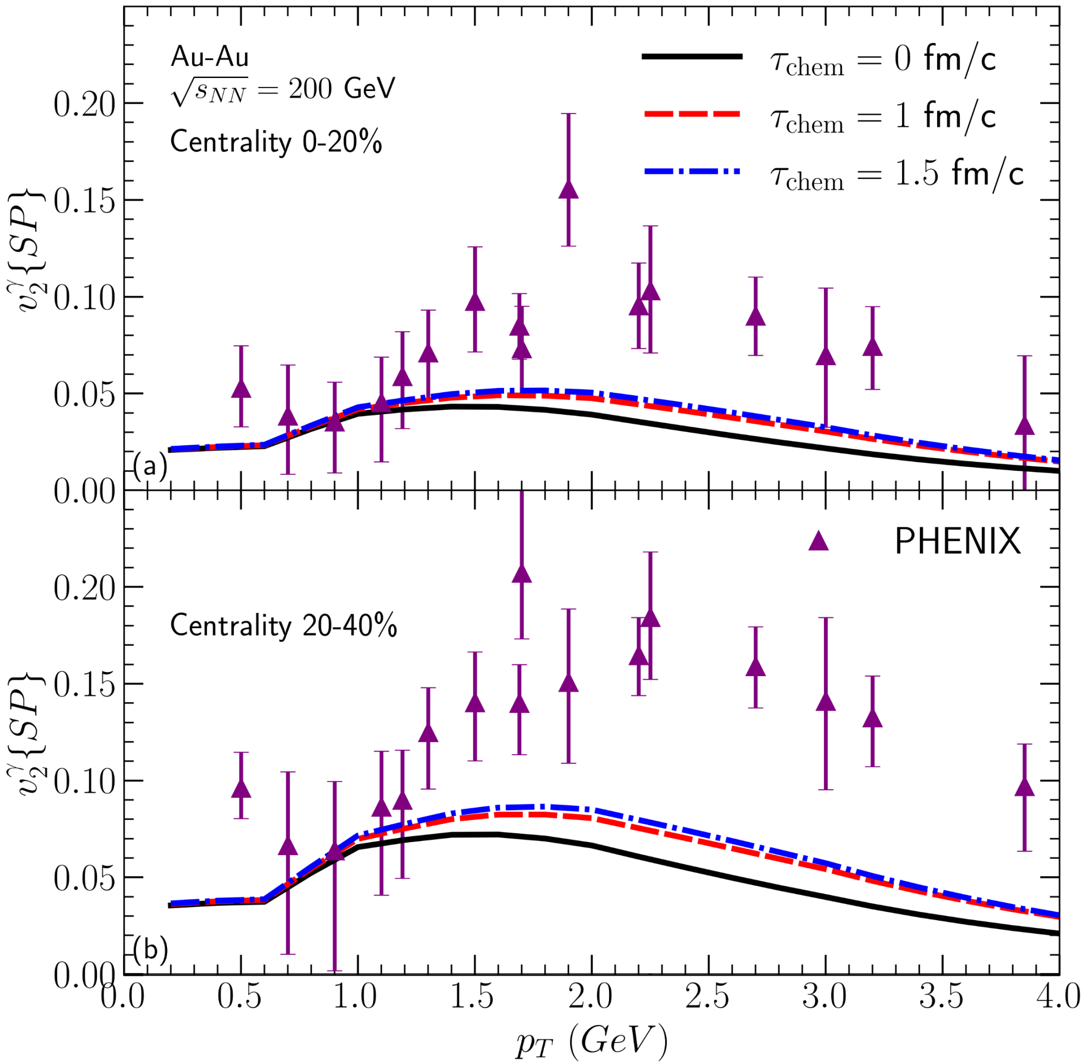
Momentum anisotropy from geometrical anisotropy

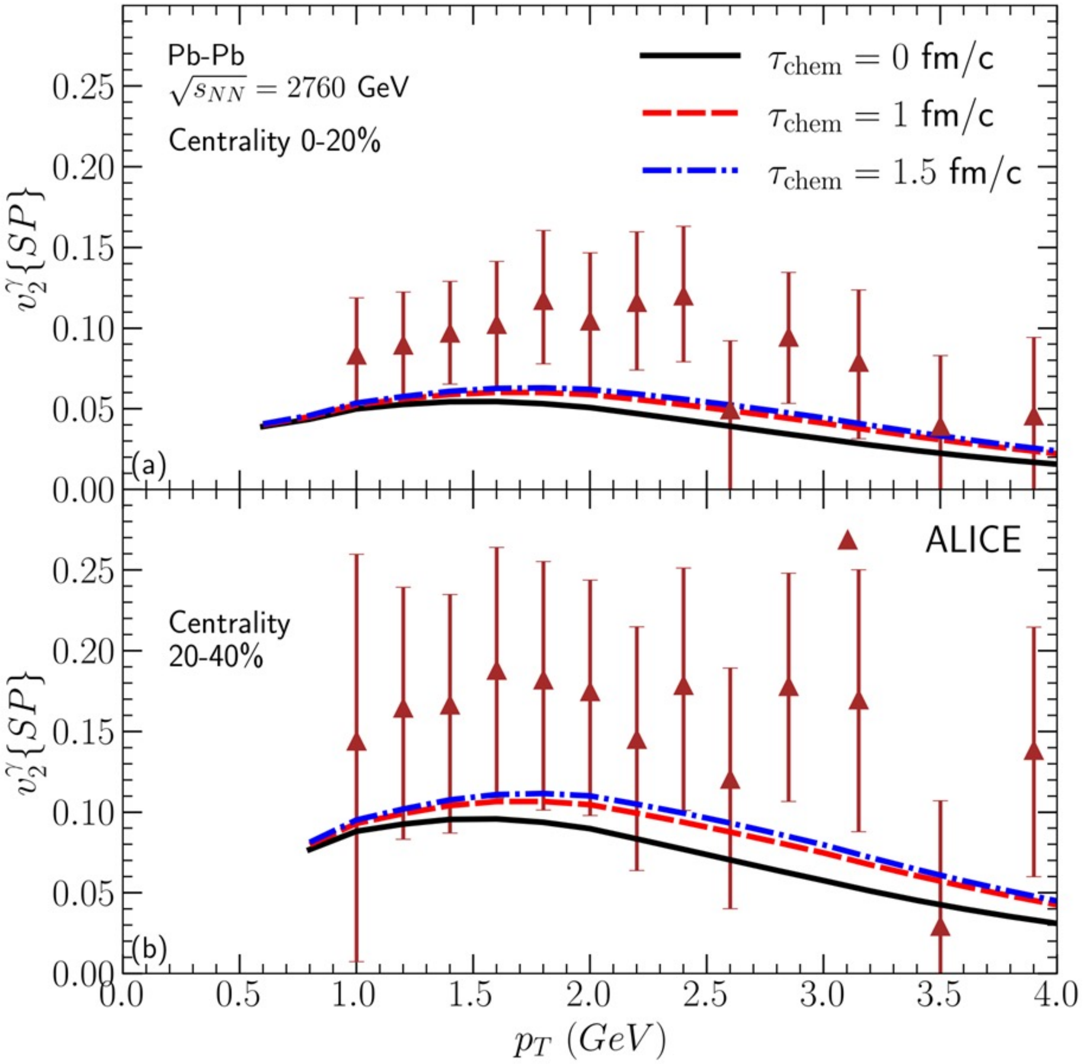


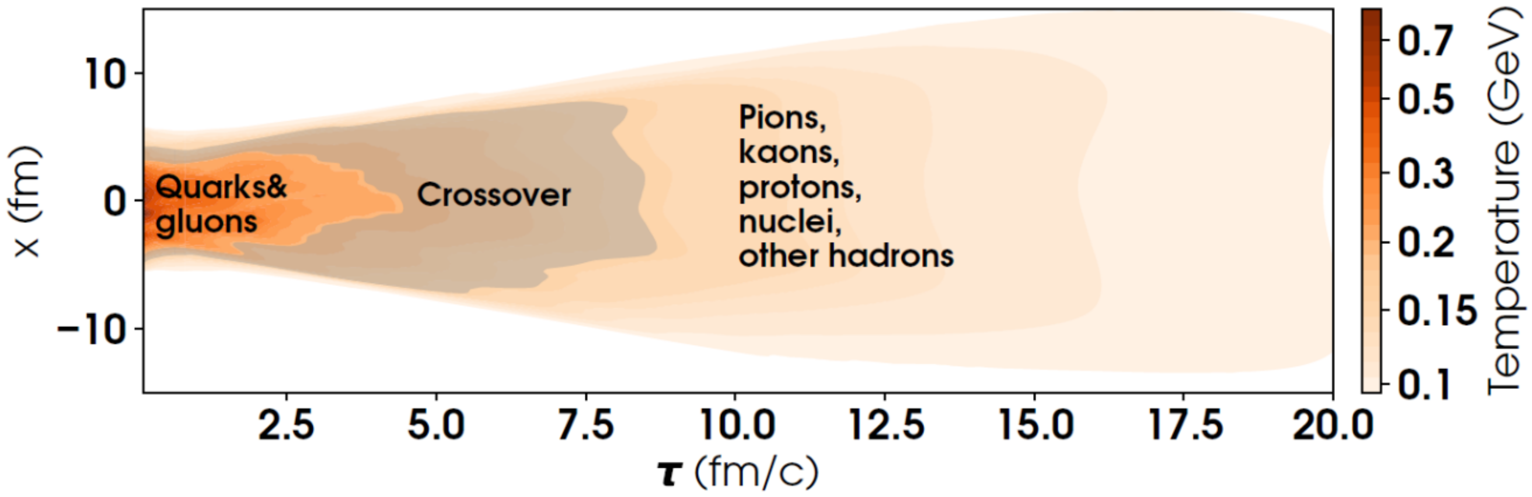
$$\frac{1}{2\pi p_T}\frac{dN}{dp_T d\phi} = \left(\frac{1}{2\pi p_T}\frac{dN}{dp_T}\right)\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))\right]$$

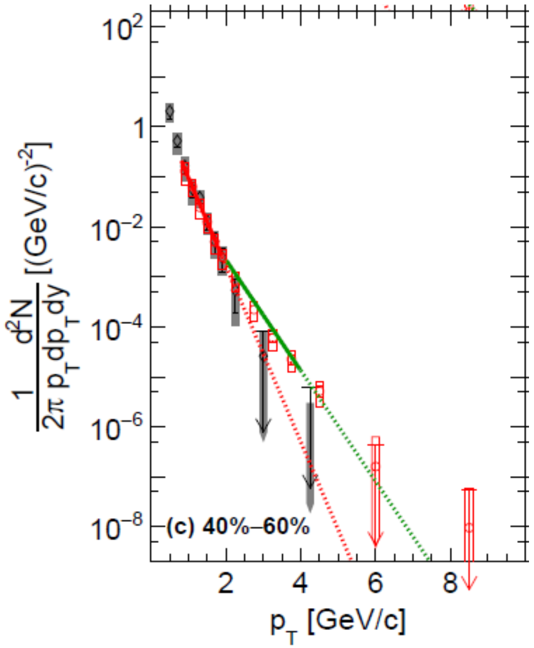
Photon momentum anisotropy

(Compare different chemical equilibration scenarios)





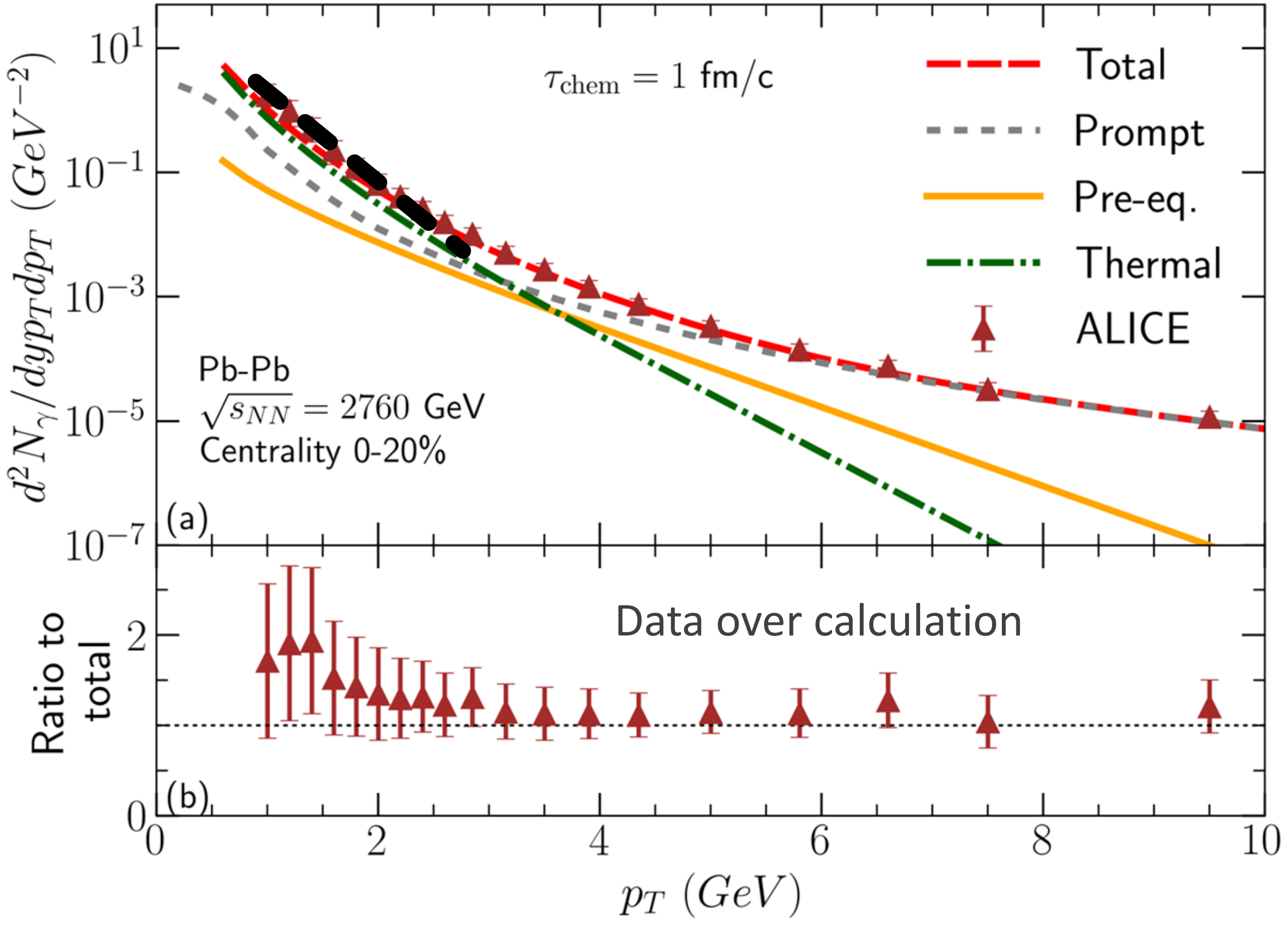




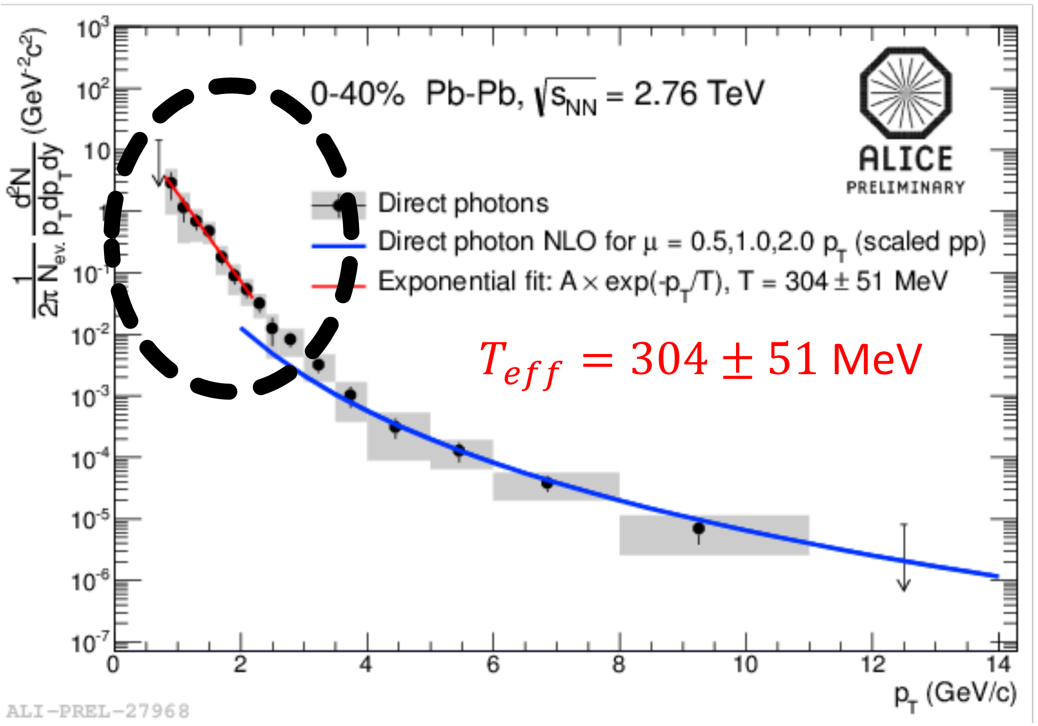
PLASMA TEMPERATURE FROM PHOTON ENERGY SPECTRUM

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

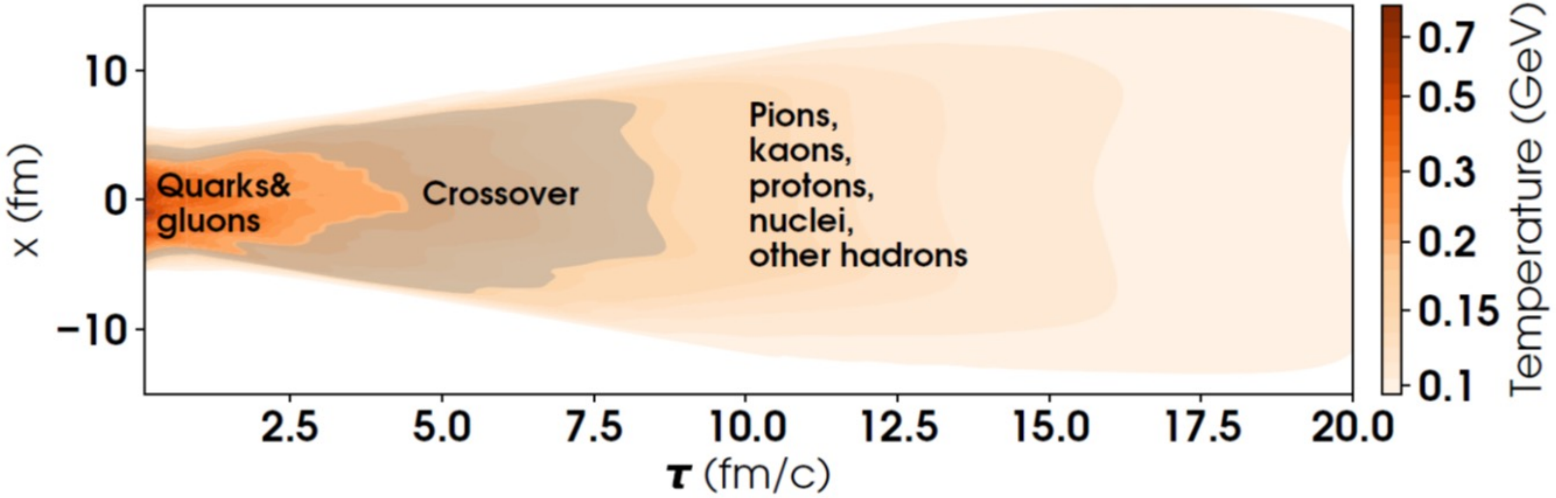
Gale, Paquet, Schenke, Shen (2022) PRC



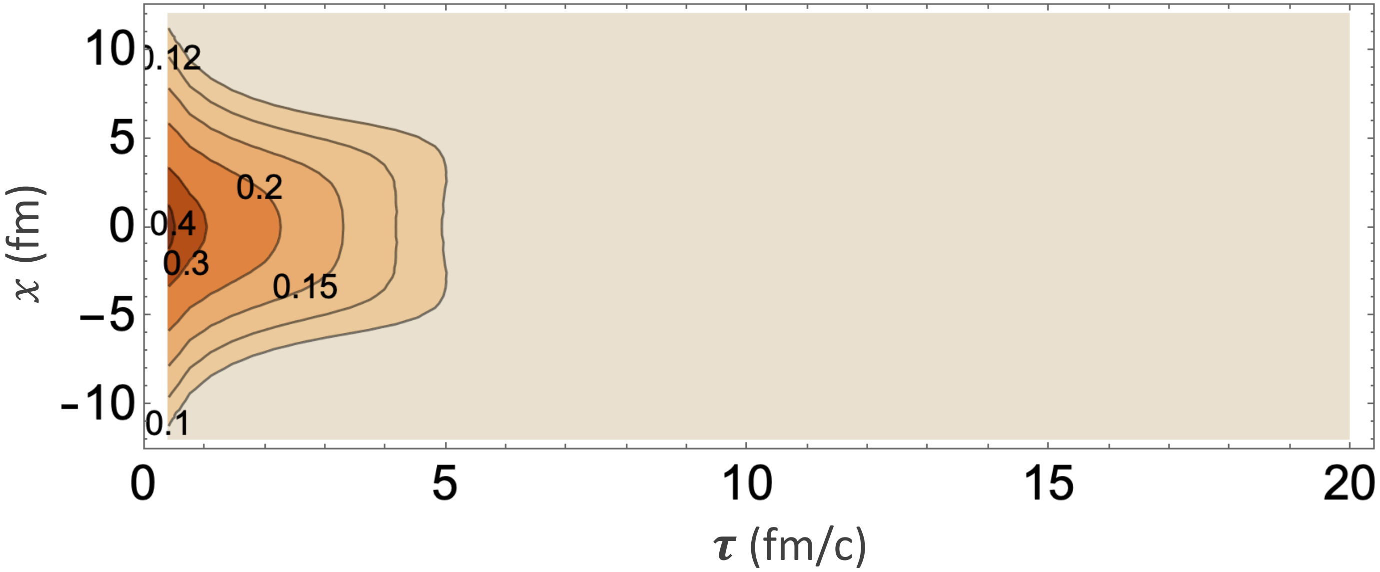
$$\ln\left(\frac{1}{2\pi E}\frac{dN}{dE\,dy}\right) = cte - \frac{E}{T_{eff}}$$



- Can we estimate the maximum temperature of the plasma with the photon spectrum?



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

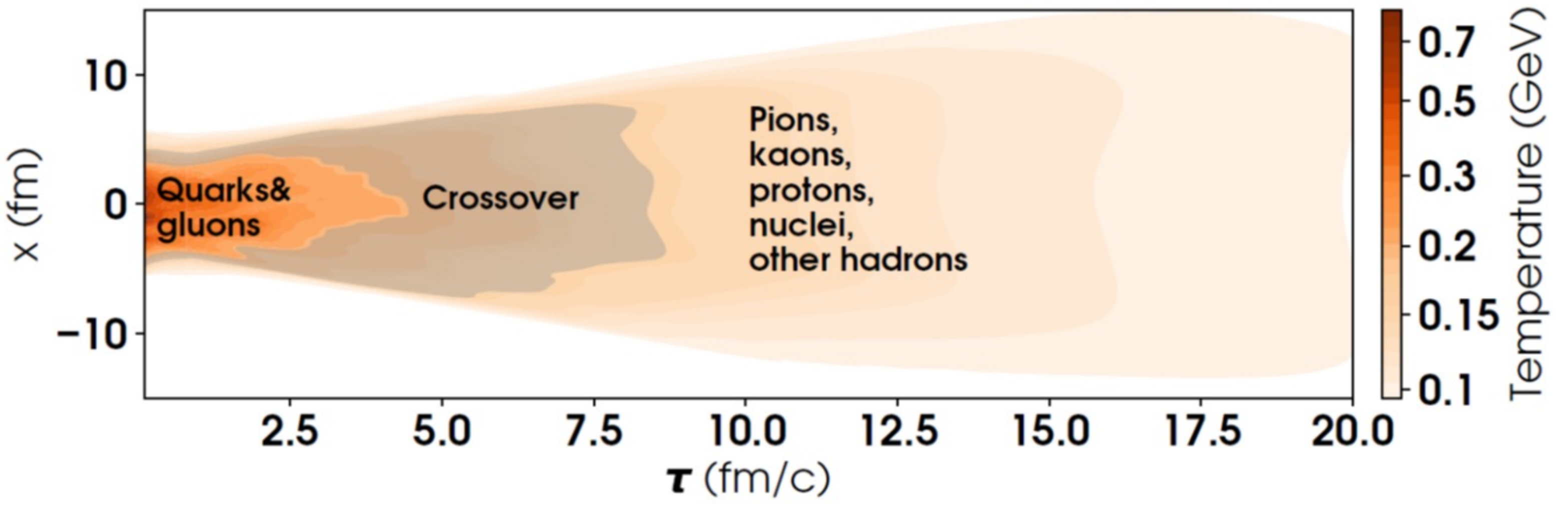


Symmetry constraints on generalizations of Bjorken flow

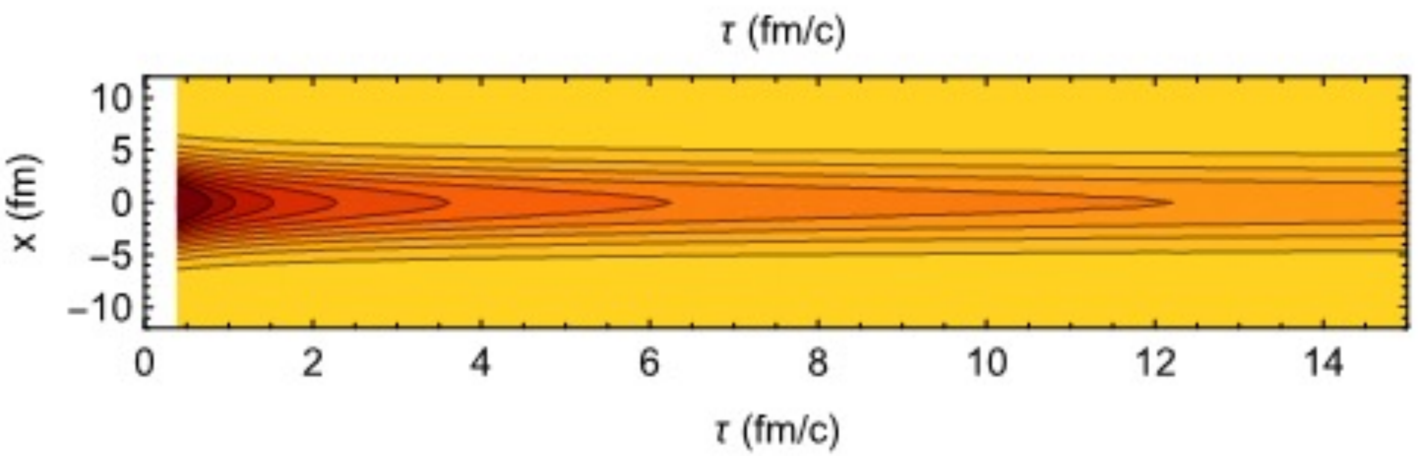
Steven S. Gubser
Phys. Rev. D **82**, 085027 – Published 26 October 2010

$$T(\tau, r) \propto \frac{(2q\tau)^{\frac{2}{3}}}{\tau\left(1 + 2q^2(\tau^2 + r^2) + q^4(\tau^2 - r^2)^2\right)^{1/3}}$$

- Can we estimate the maximum temperature of the plasma with the photon spectrum?



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

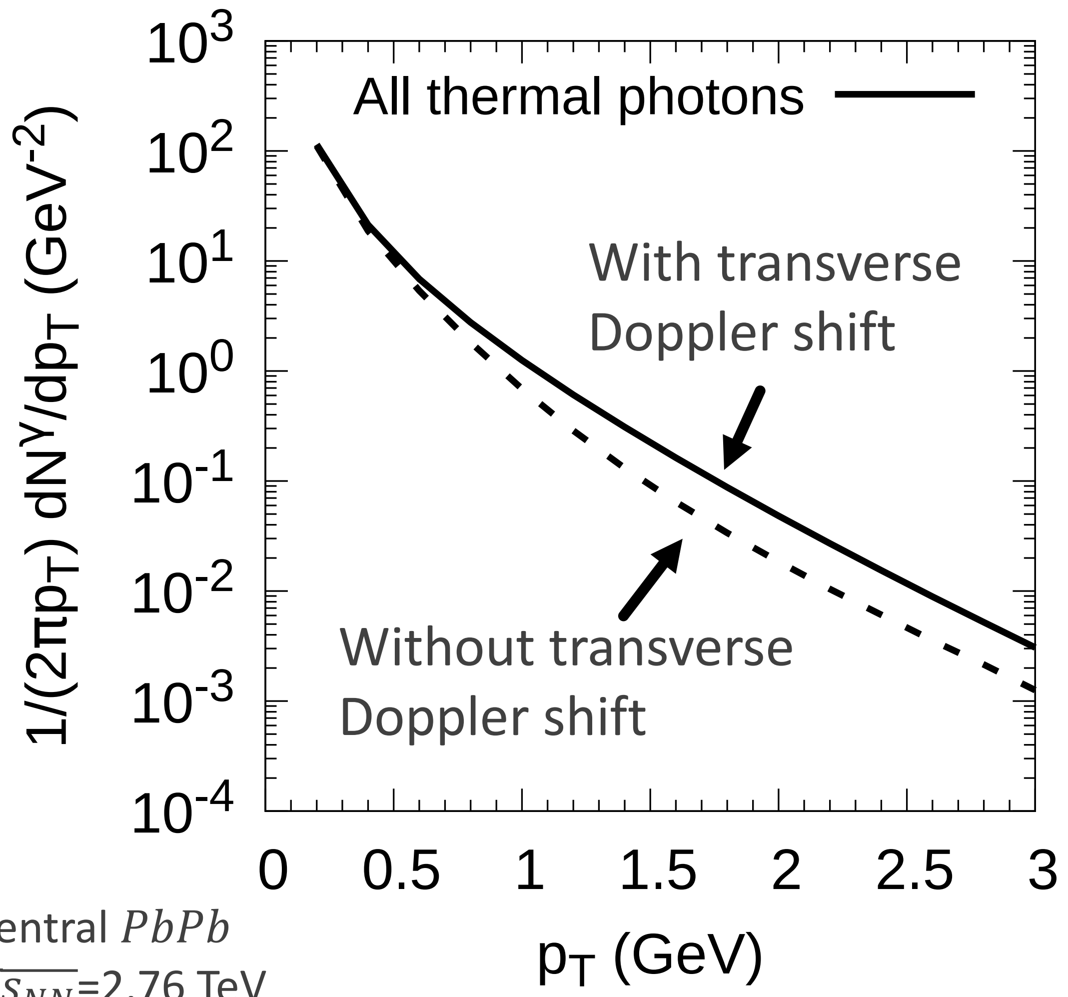


Gaussian transverse profile, but only longitudinal hydrodynamic expansion

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

Effect of transverse Doppler shift

Global effect of Doppler shift



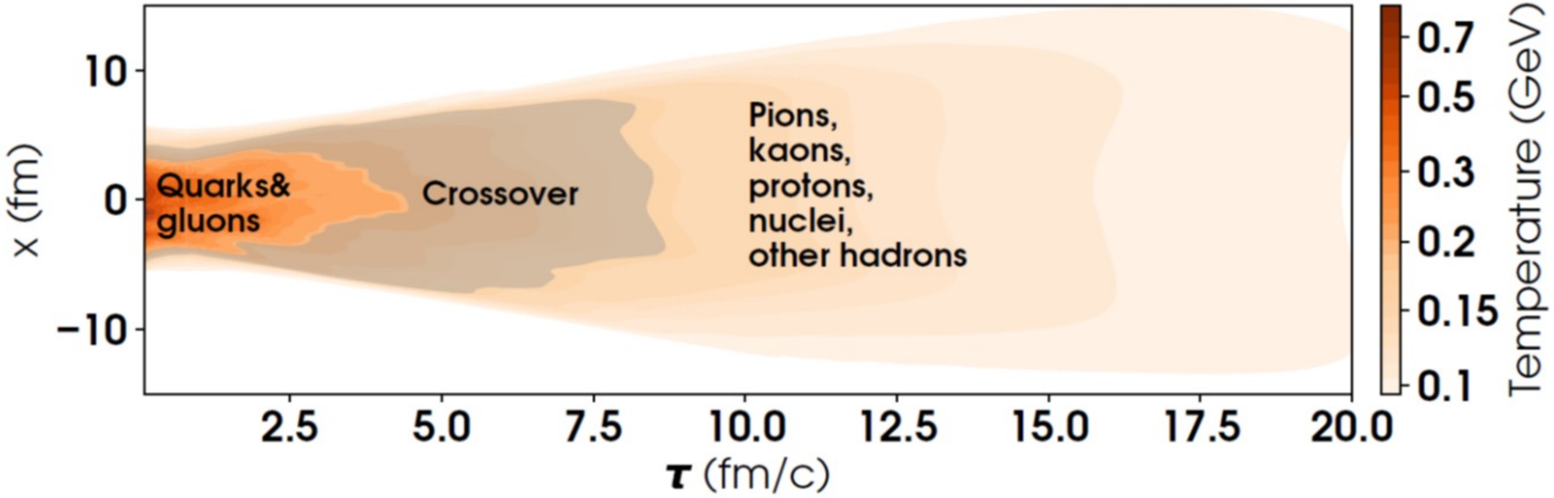
Central $PbPb$
$\sqrt{s_{NN}}$=2.76 TeV

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} \approx \int \mathrm{d}^4X \, \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}(p, T, u^\mu = (1,0,0,0))$$

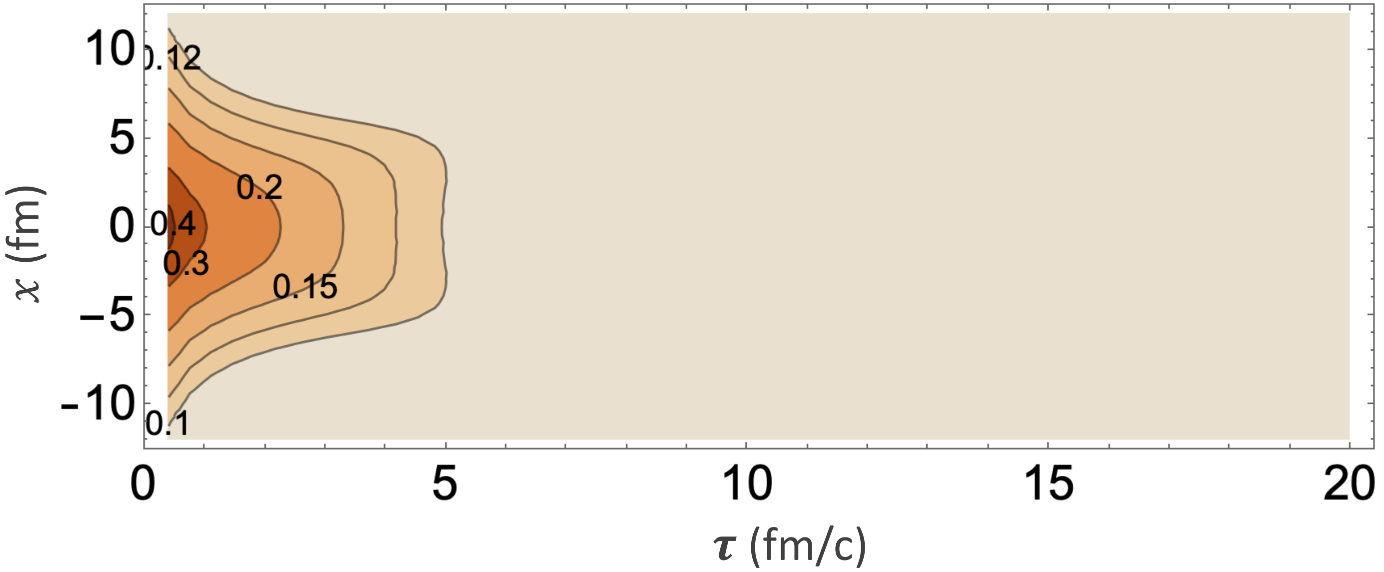
$$\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p} \sim e^{-p/T}$$

Paquet and Bass [arXiv:2205.12299]
Paquet [arXiv:2305.10669]

- Can we estimate the maximum temperature of the plasma with the photon spectrum?



$$\frac{dN_\gamma}{d^3p} \approx \int d^4X \, \frac{d\Gamma_\gamma}{d^3p}(p,T)$$



$$\frac{dN_\gamma}{d^3p} \propto \left(\frac{T_0}{p_T}\right)^{5/2} E\,\frac{d\Gamma_\gamma}{d^3p}(p_T, T_0)$$

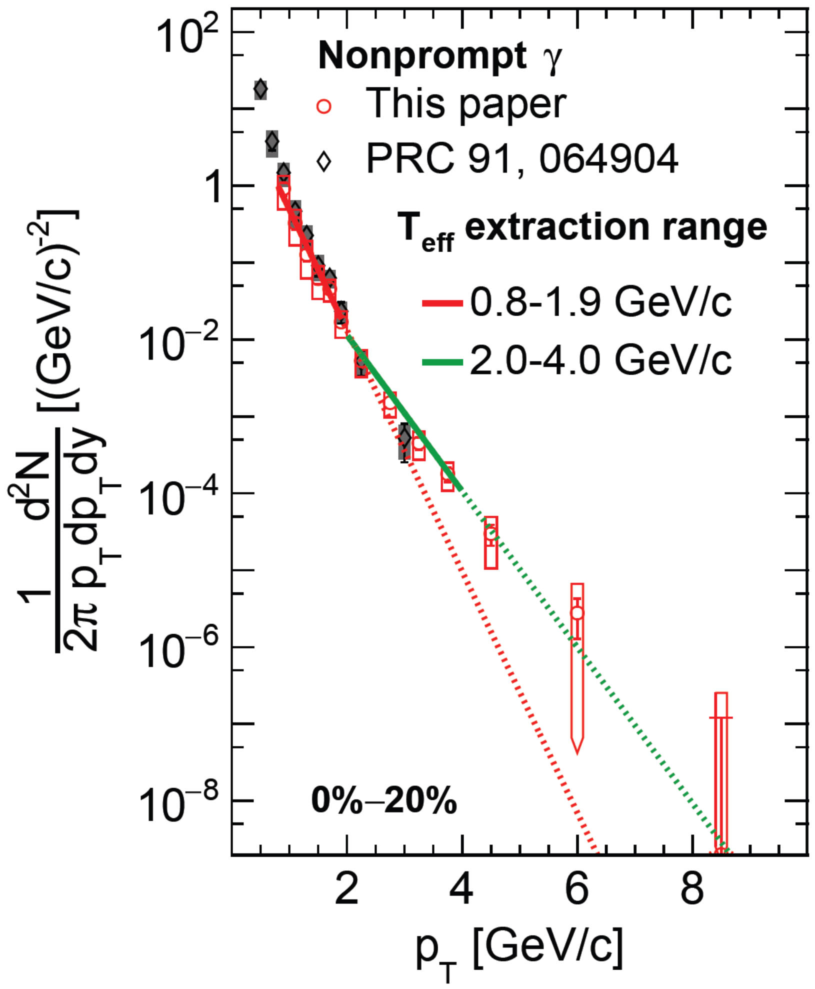
Inverse slope:

$$-\frac{1}{T_{eff}} \approx -\frac{1}{T_0} - \frac{5}{2}\frac{1}{p_T} + O\left(\frac{T_0}{p_T^2}\right)$$

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

Caveats: other sources of photons (e.g. pre-equilibrium), viscosity, ...

Ref.: PHENIX Collaboration [arXiv:2203.17187]



p_T cut	T_{eff}	$T_0 = \frac{T_{eff}}{1-\frac{5}{2}\frac{T_{eff}}{p_T}}$
$0.8 < p_T < 1.9$ GeV	277 MeV	570 MeV
$2 < p_T < 4$ GeV	428 MeV	670 MeV

From hydro fit to hadronic data: $T_0 \approx 530$ MeV

[from Gale, Paquet, Schenke, Shen (2022) PRC]

Partly explains large p_T-cut dependence of T_{eff}

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

Caveats: other sources of photons (e.g. pre-equilibrium), viscosity, ...

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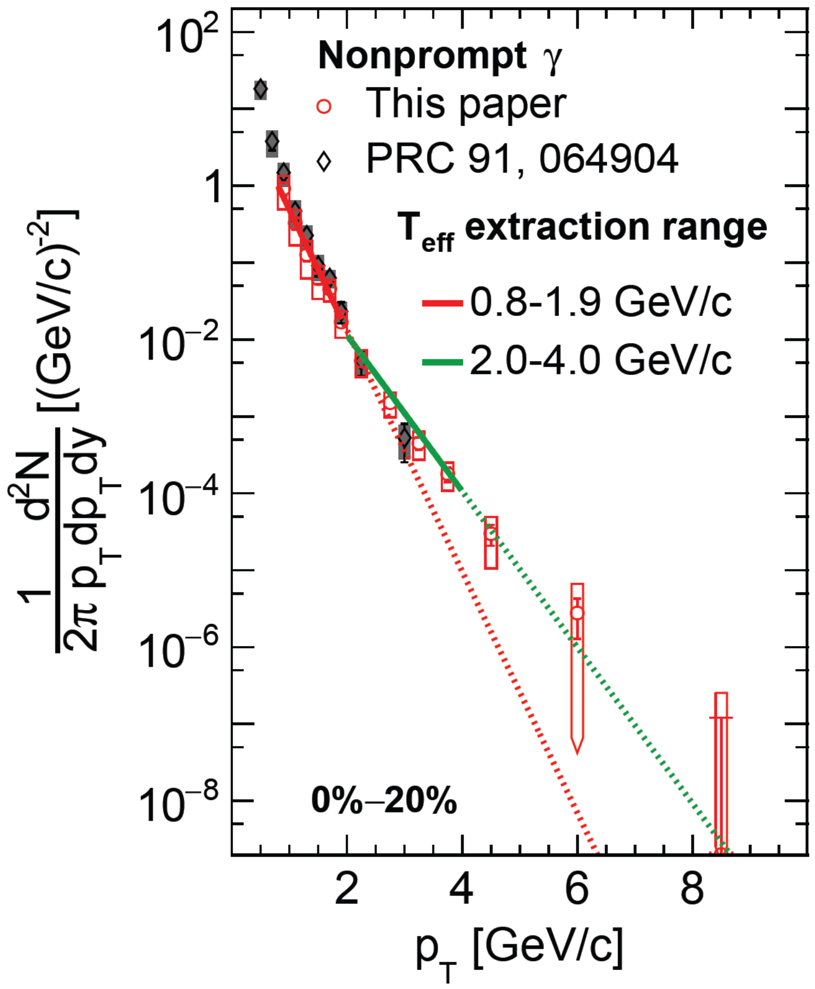

p_T *cut*	T_{eff}	$T_0 = \frac{T_{eff}}{1-\frac{5}{2}\frac{T_{eff}}{p_T}}$
$0.8 < p_T < 1.9$ GeV	277 MeV	570 MeV
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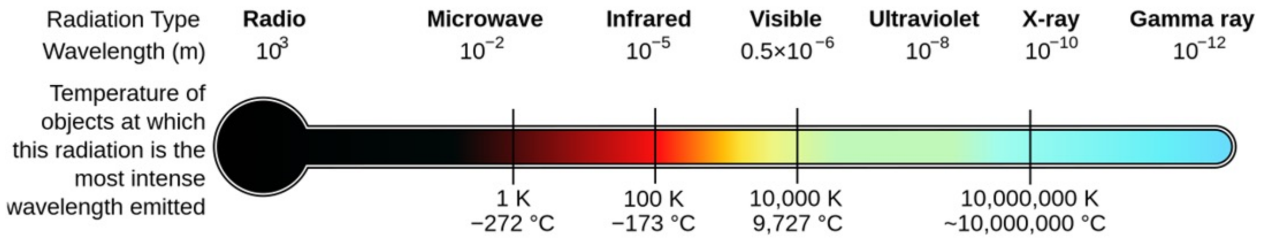
$$T = 500\text{ MeV} = 6\times10^{12}K$$

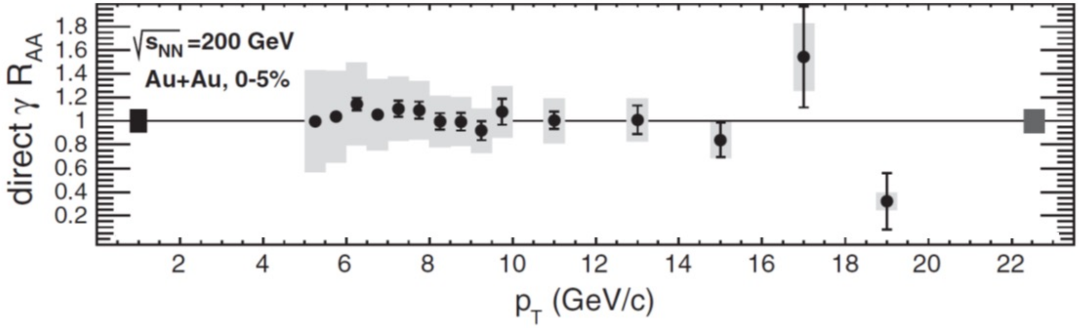


E_γ ~1 GeV

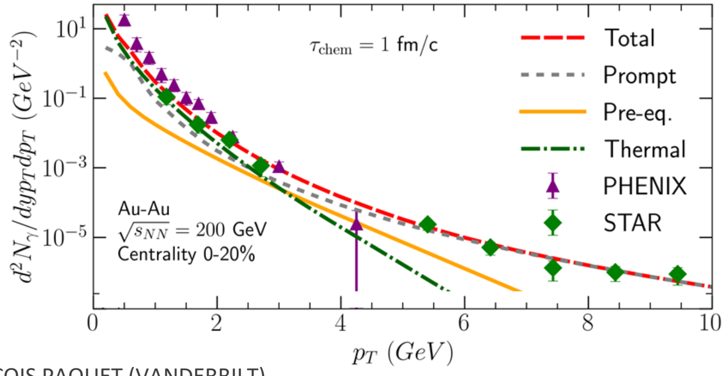
$T \sim 10^{12}$K

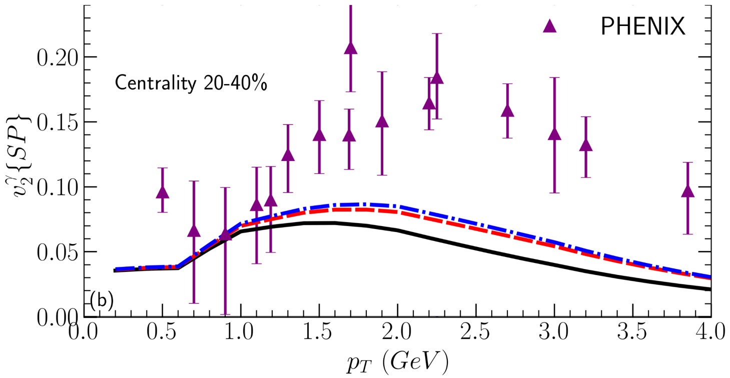
Summary and outlook

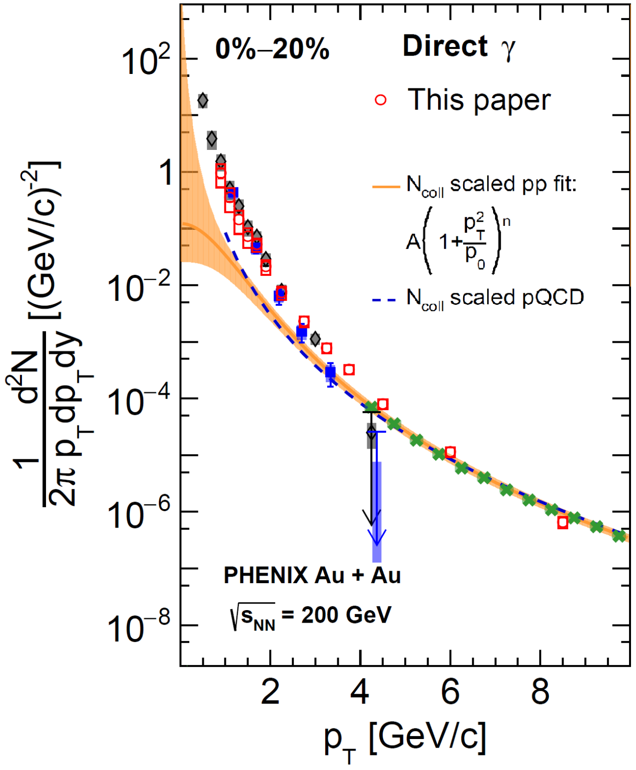
Summary



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

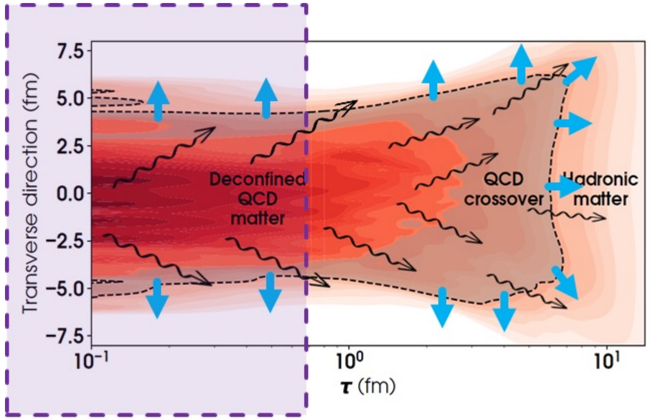




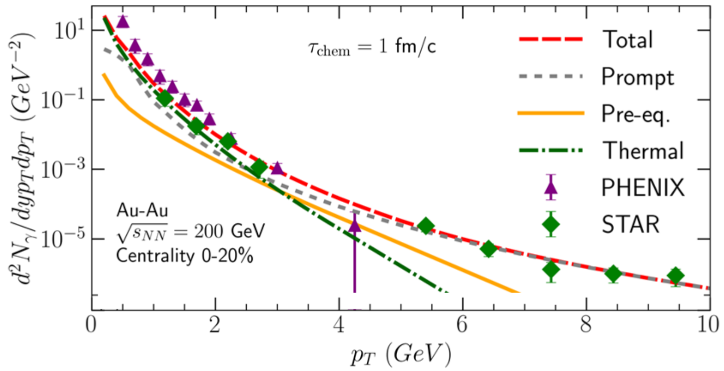


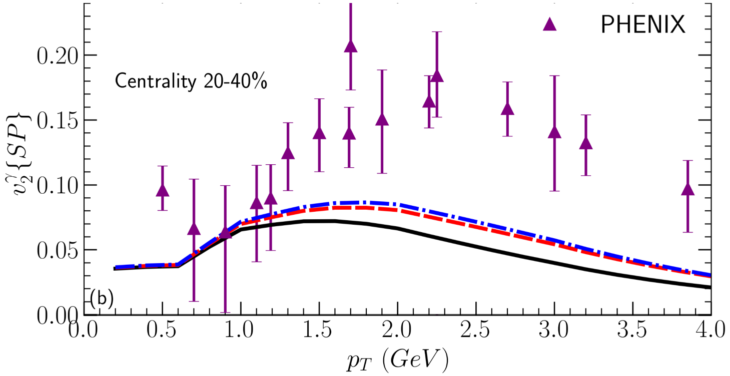
Outlook

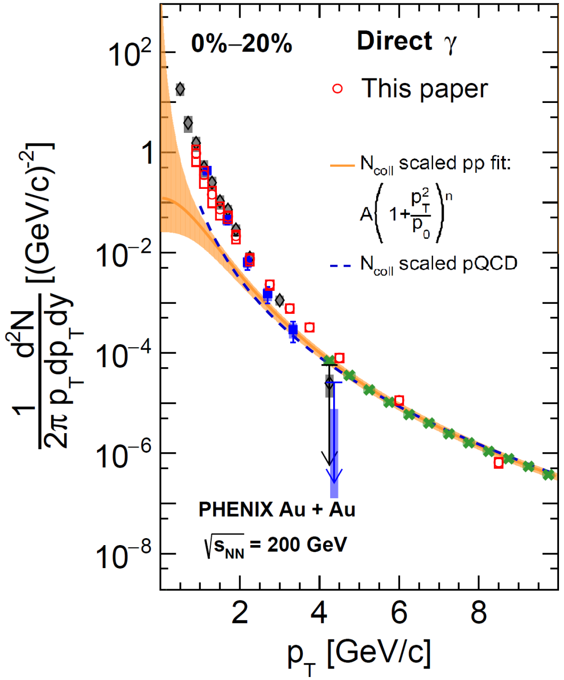
Gale, Paquet, Schenke, Shen (2022) PRC



- 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

Questions