Electromagnetic Emission (and energy loss) in the QGP

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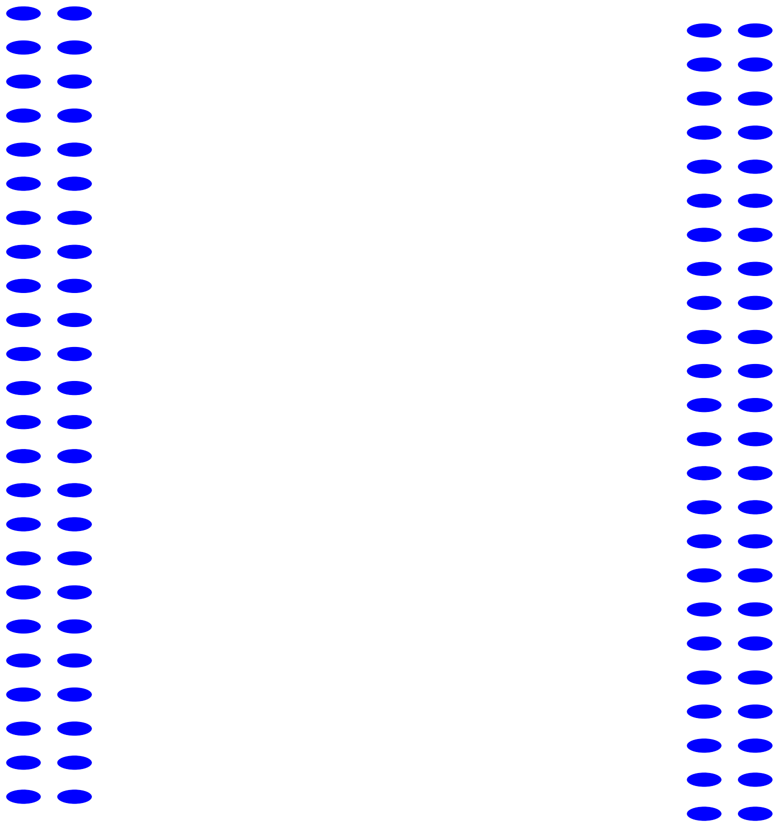
P. Arnold, L. Yaffe, S. Jeon,

P. Aurenche, F. Gelis, H. Zaraket,

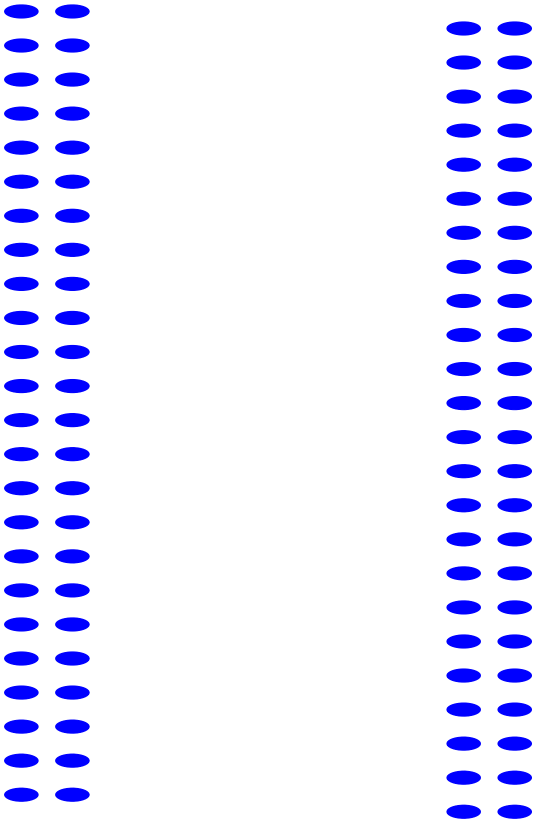
and of course many others

Why Photons are Interesting

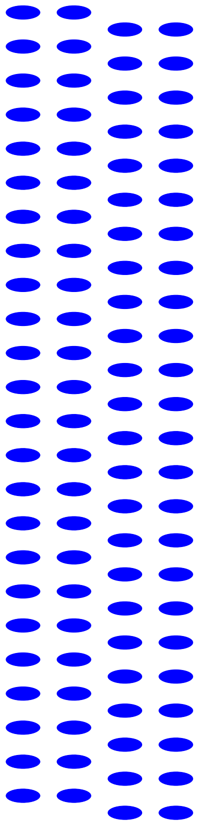


Initial heavy ions, made up of primary partons

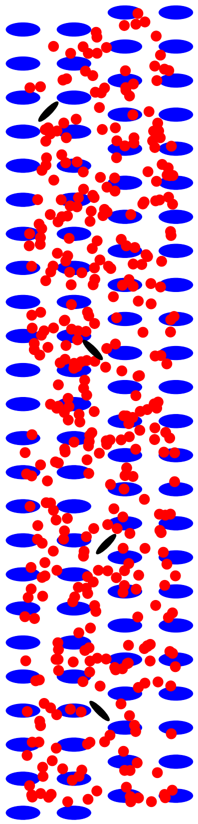
Why Photons are Interesting



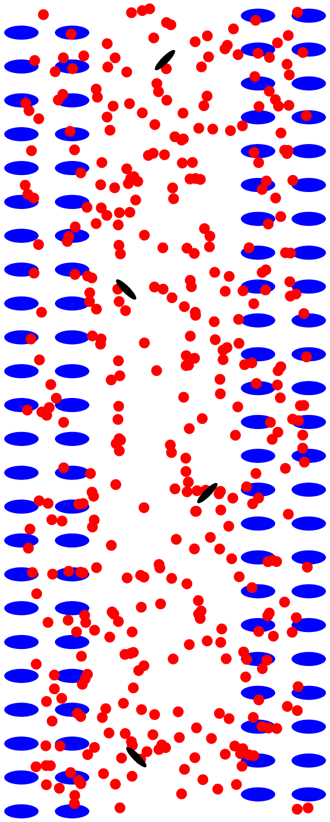
Fly at each other



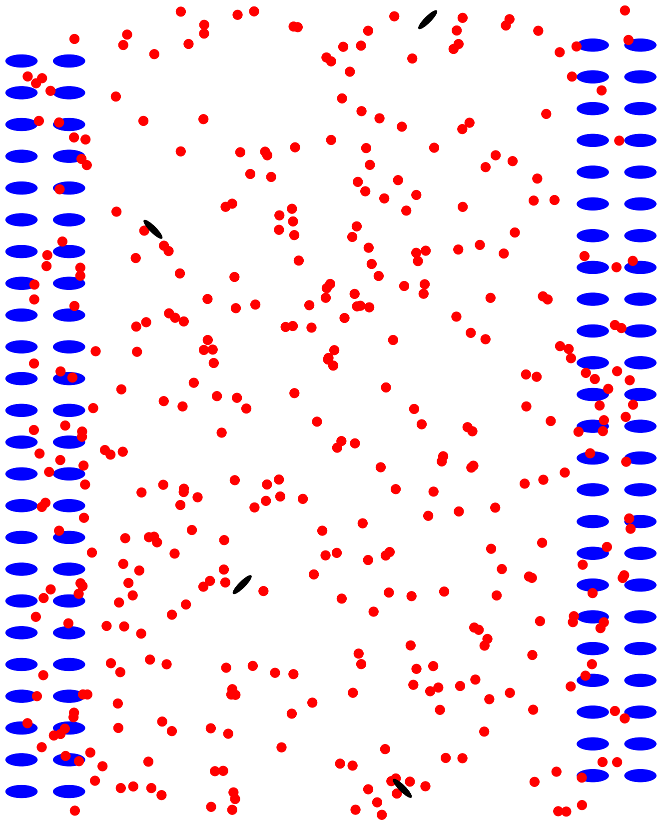
Fly at each other



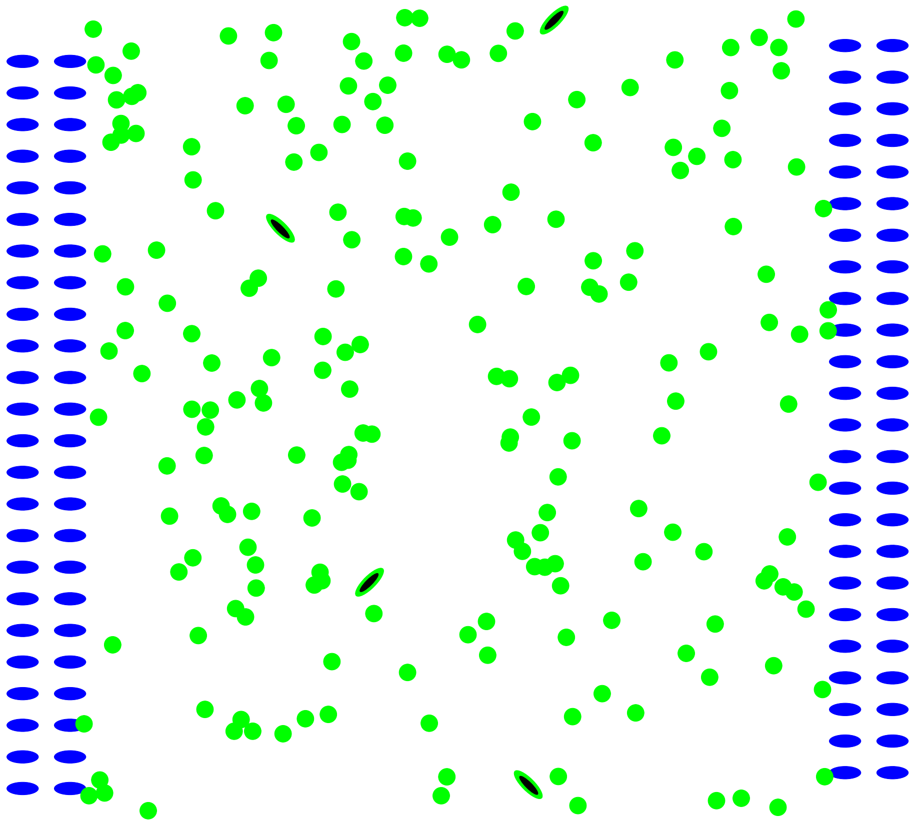
And collide, producing a QGP of secondaries



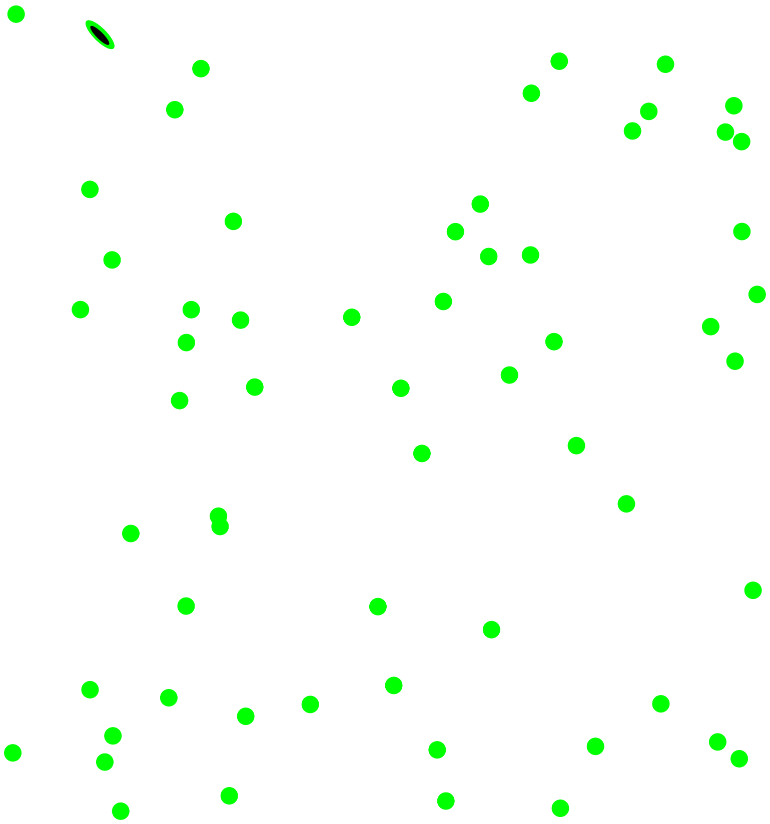
Secondaries rescatter, mostly thermalizing



Secondaries rescatter, mostly thermalizing



and eventually hadronize, continue to re-scatter,



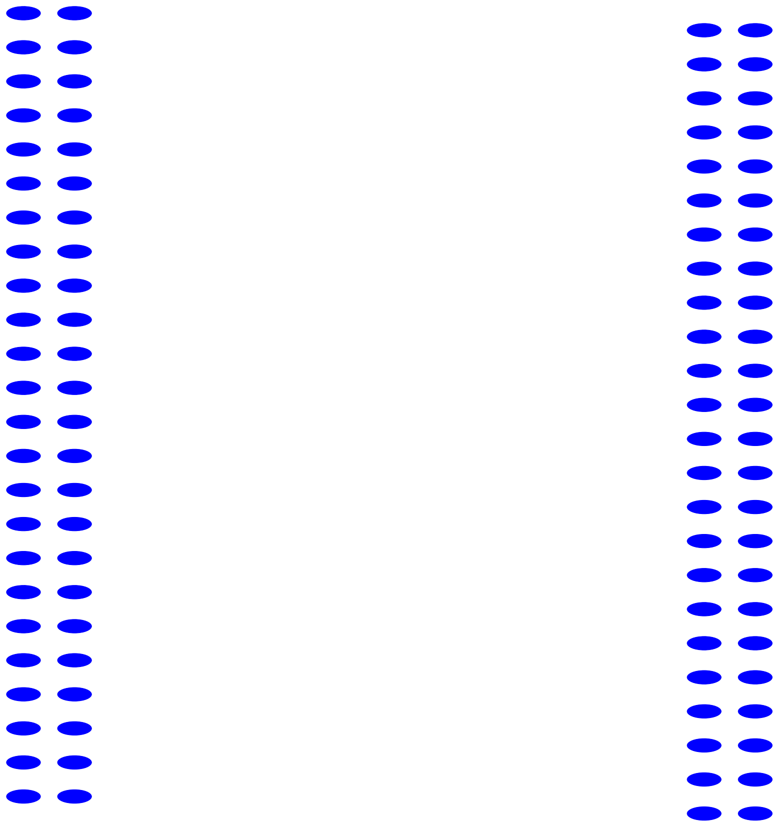
and the hadrons escape

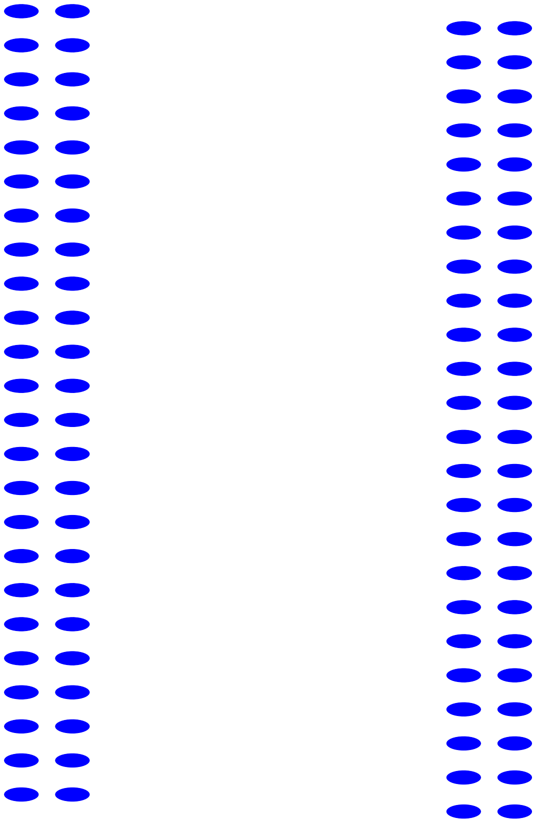
Interesting part: the behavior of secondaries making up the QGP

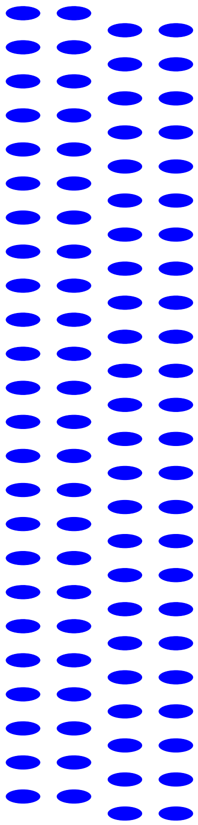
Problem: rescattering destroys much of primary information

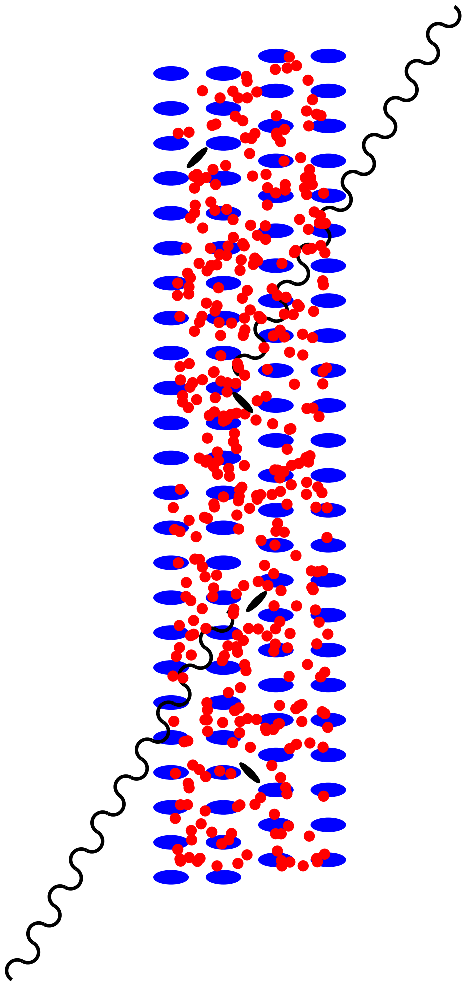
But photons are produced at each stage

And almost all photons escape unscathed.

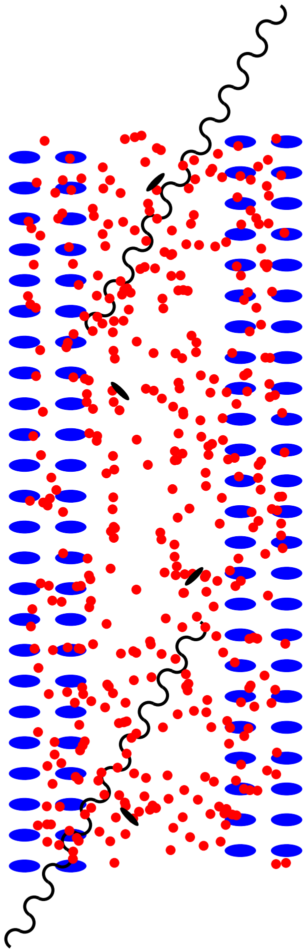




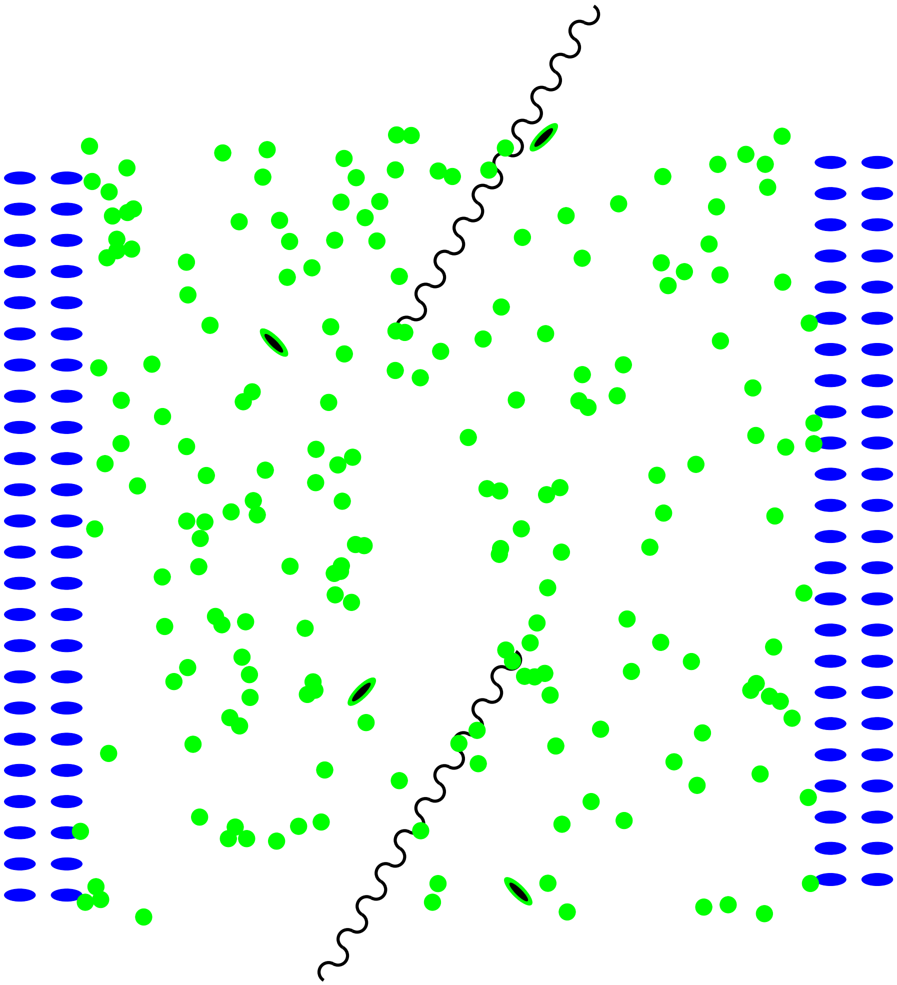




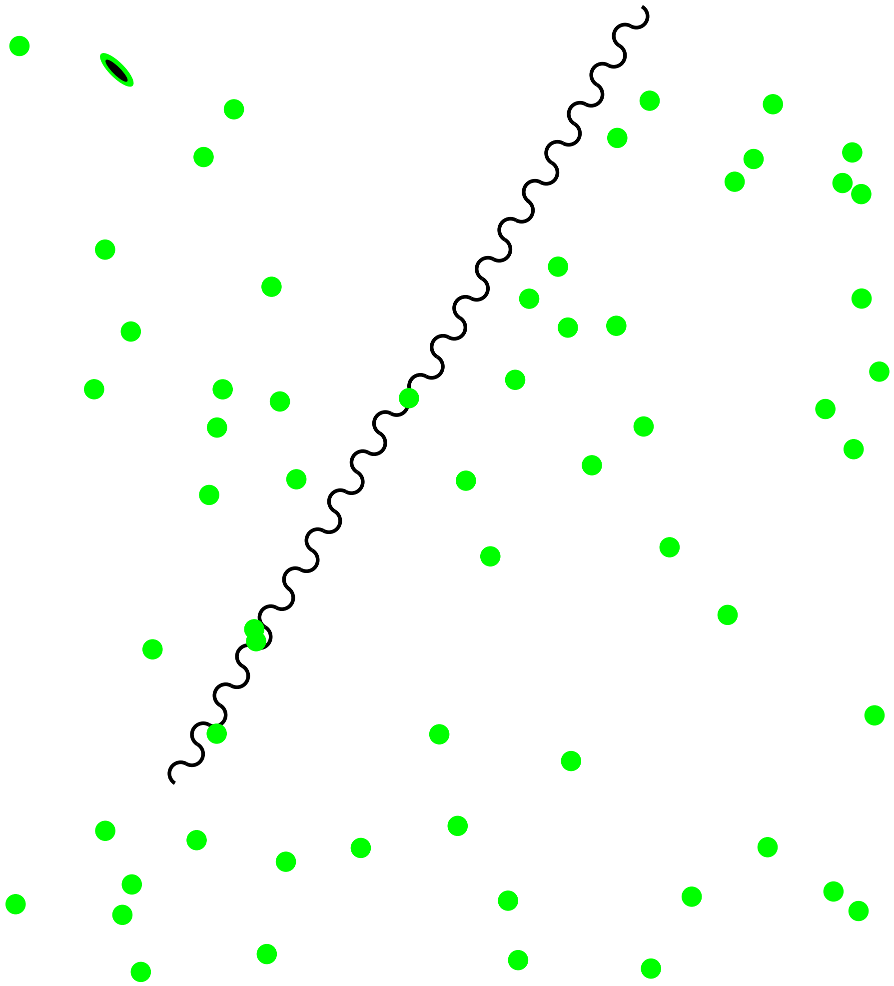
Prompt photons from collisions of primary partons



Thermal (and Athermal) photons from collisions between secondaries of the QGP

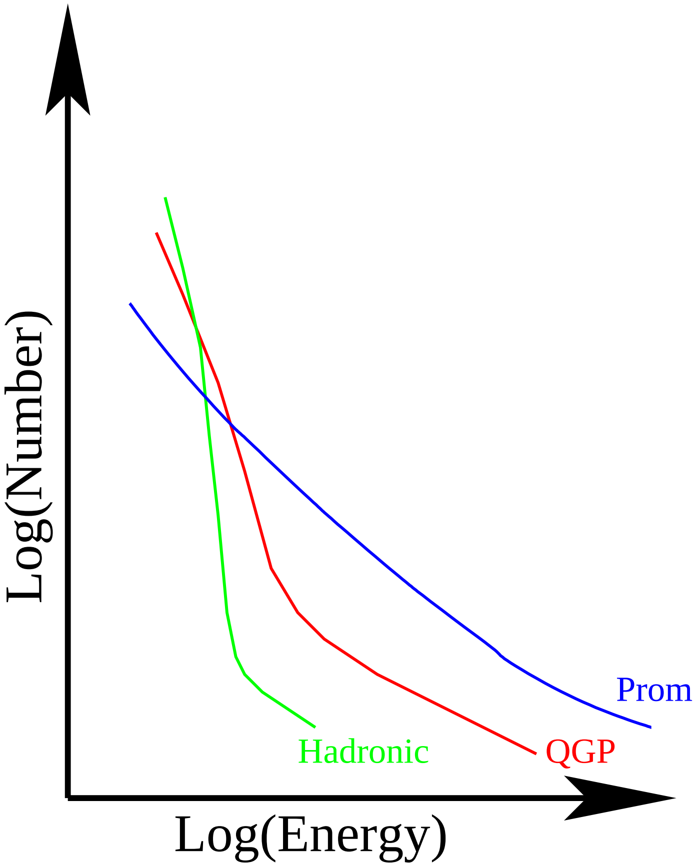


More thermal photons from hadronic collisions, and



Decay photons: decays in flight of π^0 and η

Cartoon of yields of each process

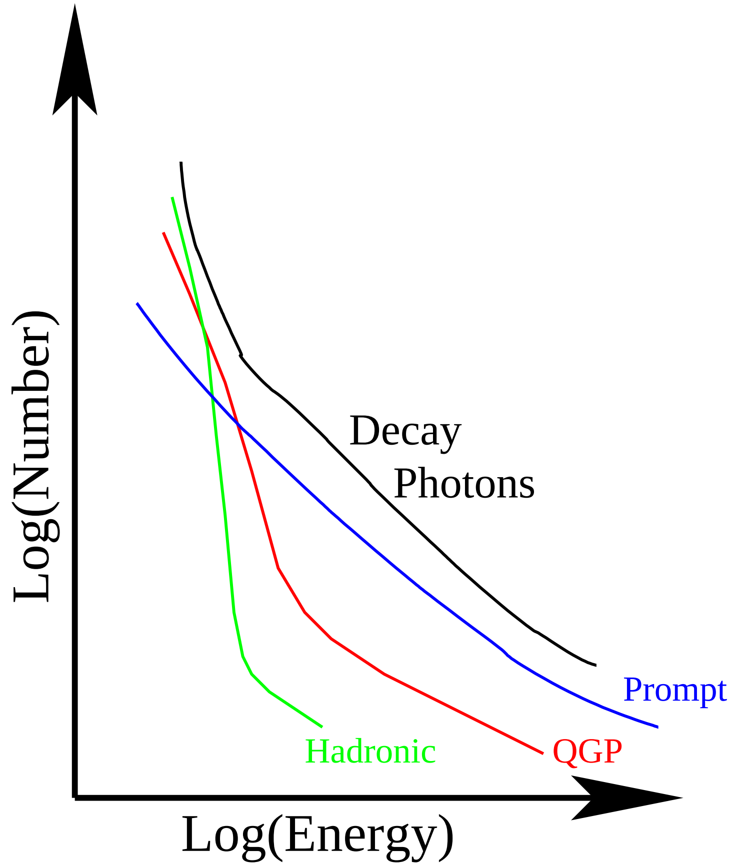


Prompt: power law hard tail

QGP: thermal (exp. tail) plus small powerlaw tail

Hadronic: like QGP but softer

The bad news is



Probably more Decay photons than Direct photons at every energy!

Why? direct photons have no α_{EM} suppression

Seeing the prompt photons

Prompt photon yield should be calculable

- Perturbative calculation

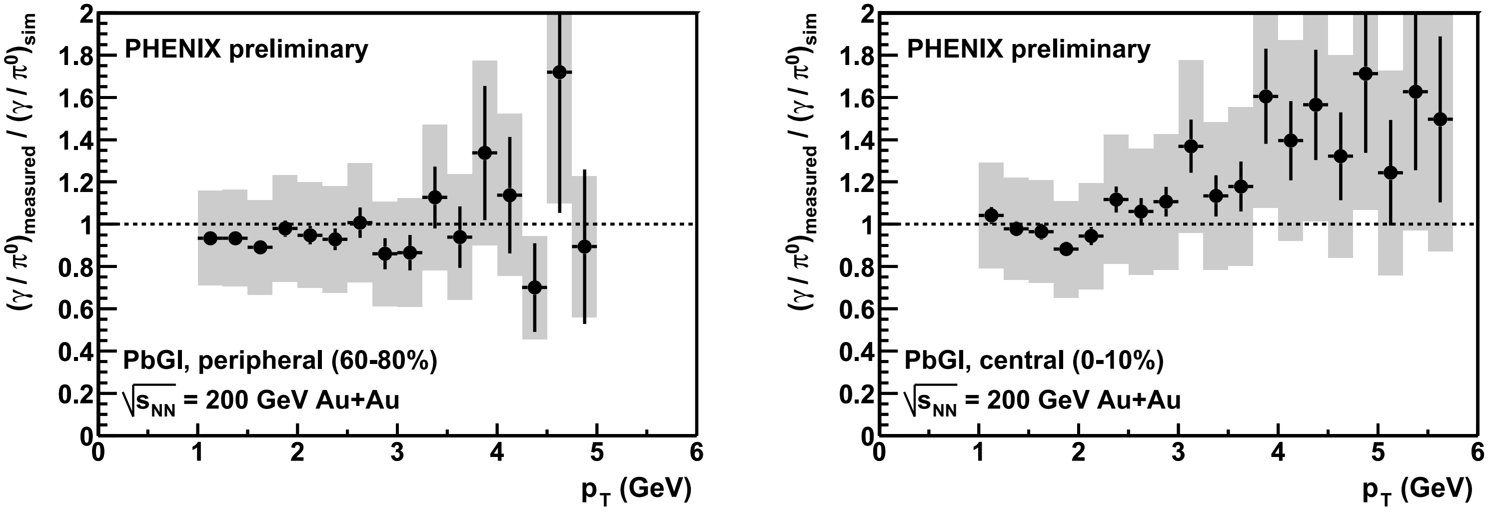
  Not easy: relatively small x, scale dependence

- Measurement in pp collisions

May be visible above the backgrounds!

- Main background: π^0 decays
- π^0 rate is measurable (with errors)
- π^0 production is suppressed (Jet Quenching)

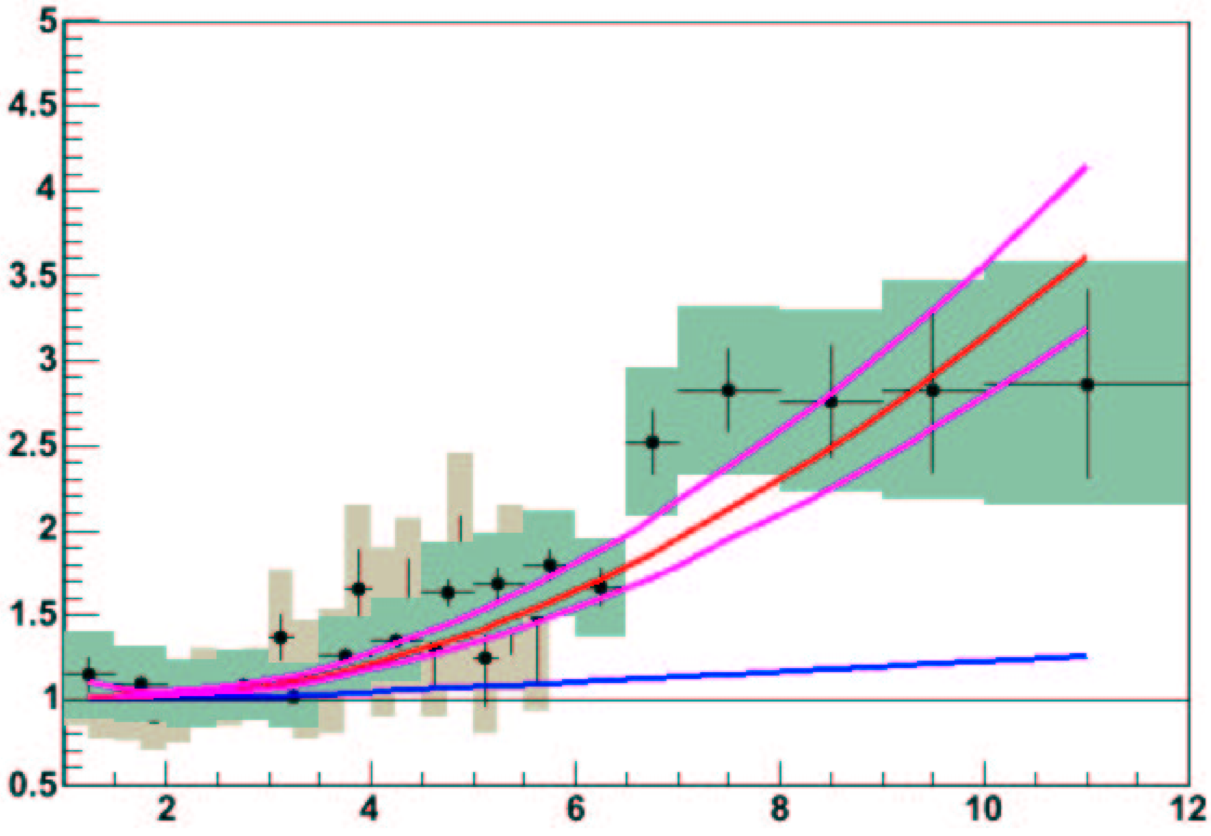
Direct photons: Already observed?



Phenix observation can be interpreted as seeing photon excess in central collisions at high p_T.

At $p_T \sim 5$ GeV, probably “direct” photons.

Direct photons: Already observed!

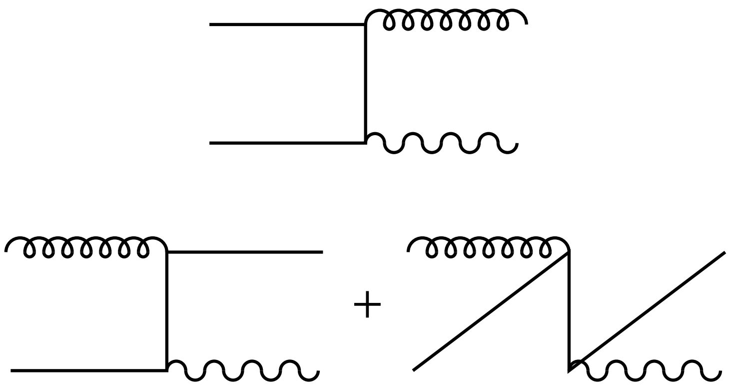


E_γ(GeV)

QM2004 data, most central bin

Thermal Photons: an Interesting Theoretical Problem

- Approximate/Assume QGP to be in equilibrium
- Compute $dN_\gamma(k,T)/d^3k d^4x$ by Thermal Field Theory
- Insert into hydrodynamic evolution of the QGP



Leading order diagrams.

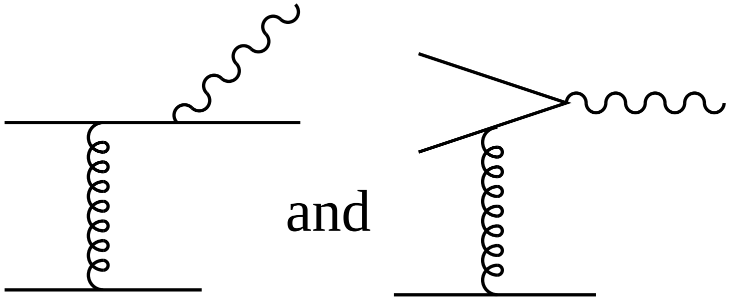
Parametrically $O(\alpha_{\rm s}\alpha_{\rm EM})$.

Logarithmically enhanced.

Problem believed solved in 1989

That treatment is incomplete!

Aurenche, Gelis, Kobes, Zaraket

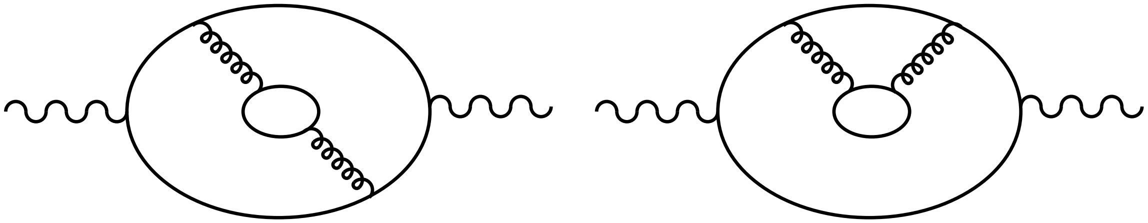


naively $O(\alpha_\mathrm{s}^2\alpha_\mathrm{EM})$

actually $O(\alpha_\mathrm{s}\alpha_\mathrm{EM})$

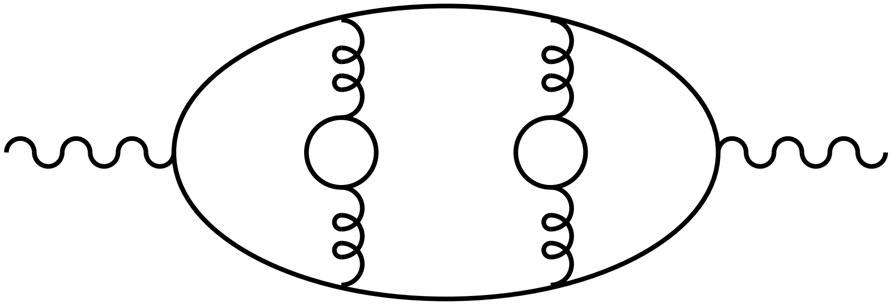
Bremsstrahlung, inelastic annihilation: collinear enhancements

Thermal QFT diagrams, summing all lines but γ:

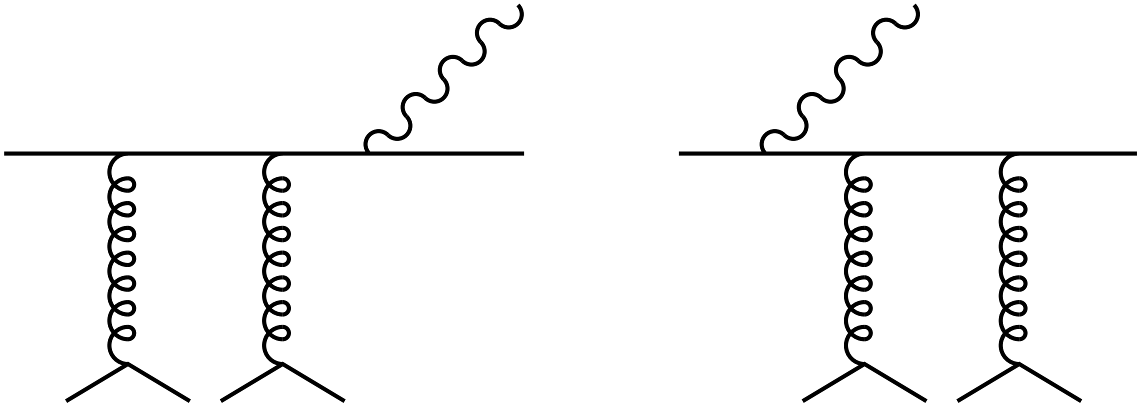


Treatment STILL incomplete!

Loop diagrams like



corresponding to the interference between diagrams,

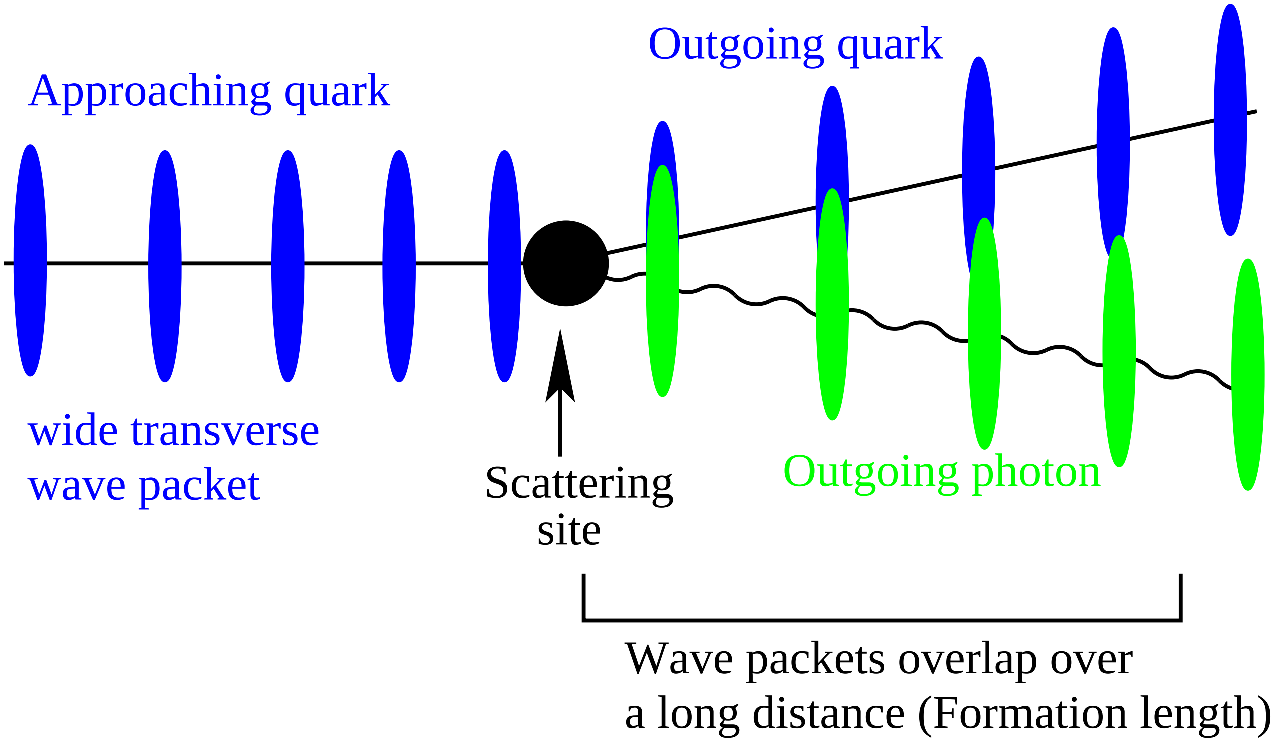


are also $\alpha_\mathrm{s}\alpha_\mathrm{EM}$! (Double collinear enhancement)

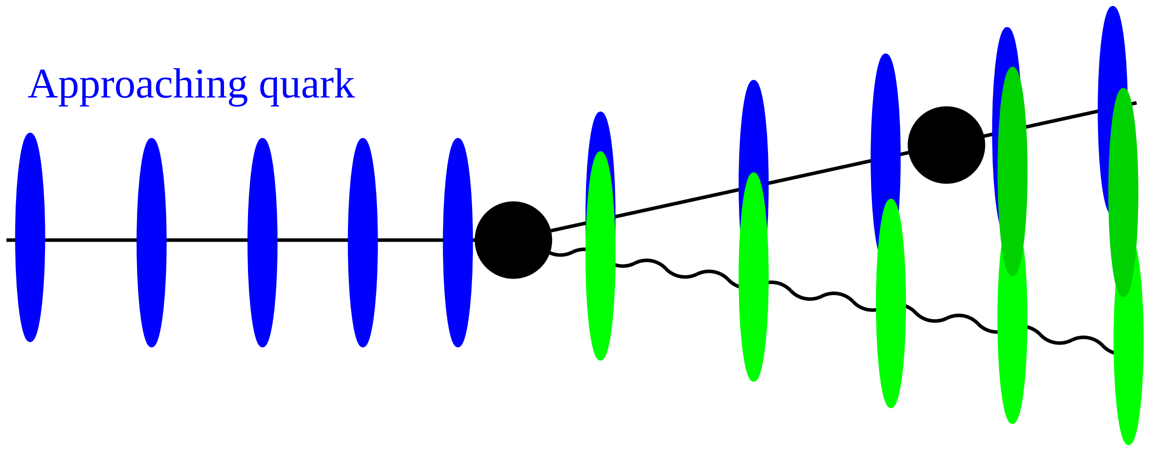
Physical reason

Opening angle $\sim g_{\mathrm{s}}T/E \ll 1$, and $v_{\mathrm{quark}} \simeq c$.

Wave packet transverse size $\sim 1/g_{\mathrm{s}}T$.



Second scattering while wave packets still overlap:



Emissions from scatterings overlap and interfere in amplitude.

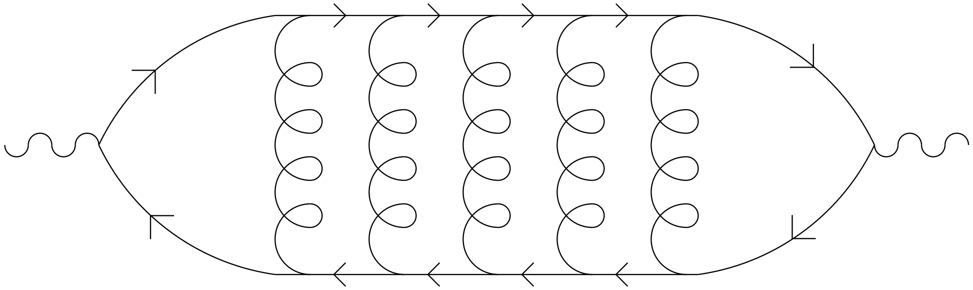
For $E \sim T$, $\tau_{\rm form}^{-1} \sim g_{\rm s}^2 T$, and scattering width $\Gamma \sim g_{\rm s}^2 T$.

Some–incomplete–interference expected. LPM effect!

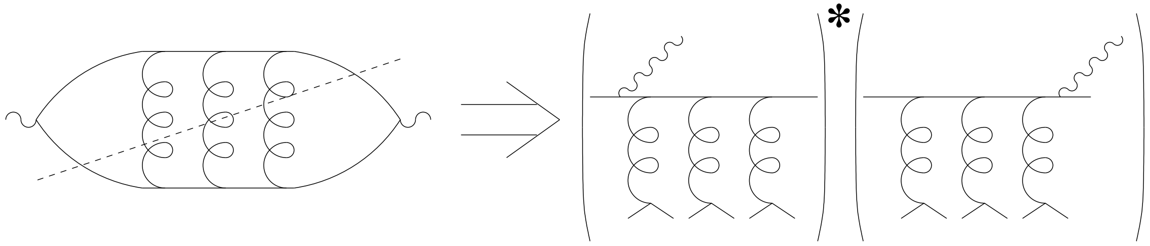
Diagrammatic Analysis

Lengthy power counting analysis (Arnold, GM, Yaffe)

One must include diagrams of form



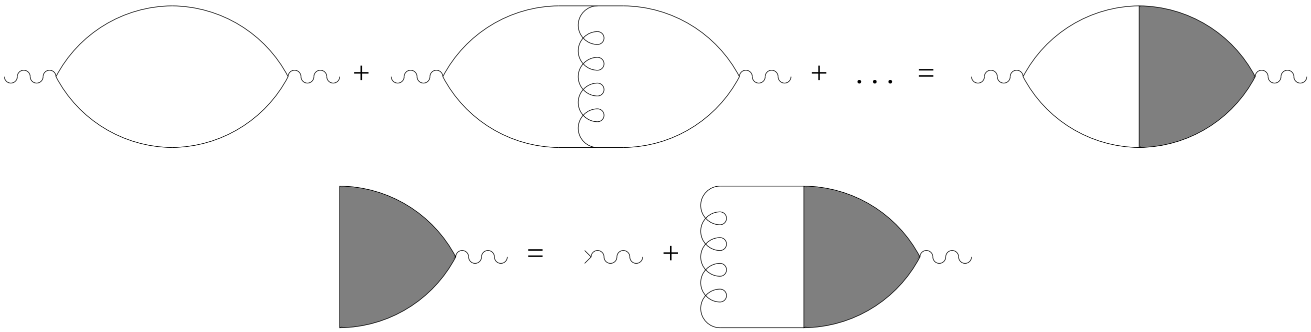
corresponding roughly to



But no other diagrams needed

Resummation of Diagrams

Diagrams may be resummed by defining a dressed vertex,



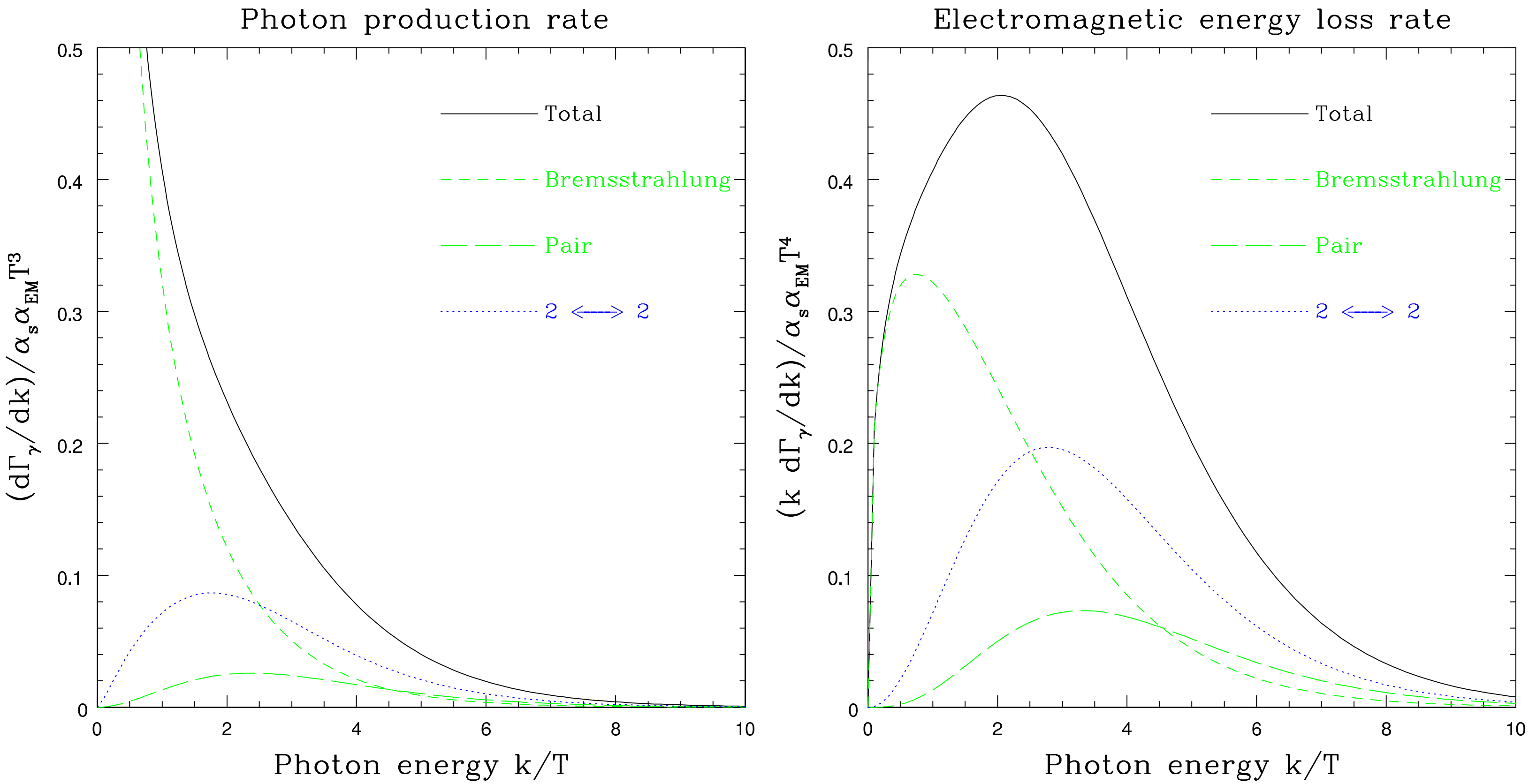
determined by an integral equation (second line).

Emission rate from thermal QGP (3 light flavors) is AMY

$$
\begin{aligned}
\frac{dN_\gamma}{d^3\mathbf{k}d^4x} &= \frac{2\alpha_{\rm EM}}{4\pi^2 k}\int_{-\infty}^{\infty}\frac{dp}{2\pi}\int\frac{d^2\mathbf{p}_\perp}{(2\pi)^2}\,\frac{n_f(k{+}p)\,[1{-}n_f(p)]}{2[p\,(p{+}k)]^2}\times \\
&\quad\times\left[p^2+(p{+}k)^2\right]\mathrm{Re}\left\{2\mathbf{p}_\perp\cdot\mathbf{f}(\mathbf{p}_\perp;p,k)\right\} && (1)\\
2\mathbf{p}_\perp &= i\delta E\,\mathbf{f}(\mathbf{p}_\perp;p,k)+\frac{2\pi}{3}g_{\rm s}^2\int\frac{d^2q_\perp}{(2\pi)^2}\,\frac{m_{\rm D}^2\,T}{q_\perp^2\,(m_{\rm D}^2{+}q_\perp^2)}\times \\
&\quad\times\left[\,\mathbf{f}(\mathbf{p}_\perp;p,k)-\mathbf{f}(\mathbf{q}{+}\mathbf{p}_\perp;p,k)\right], && (2)\\
\delta E &= \frac{\mathbf{p}_\perp^2+m_\infty^2}{2}\;\frac{k}{p(k{+}p)} && (3)
\end{aligned}
$$

Note, (2) is implicit and must be solved numerically.

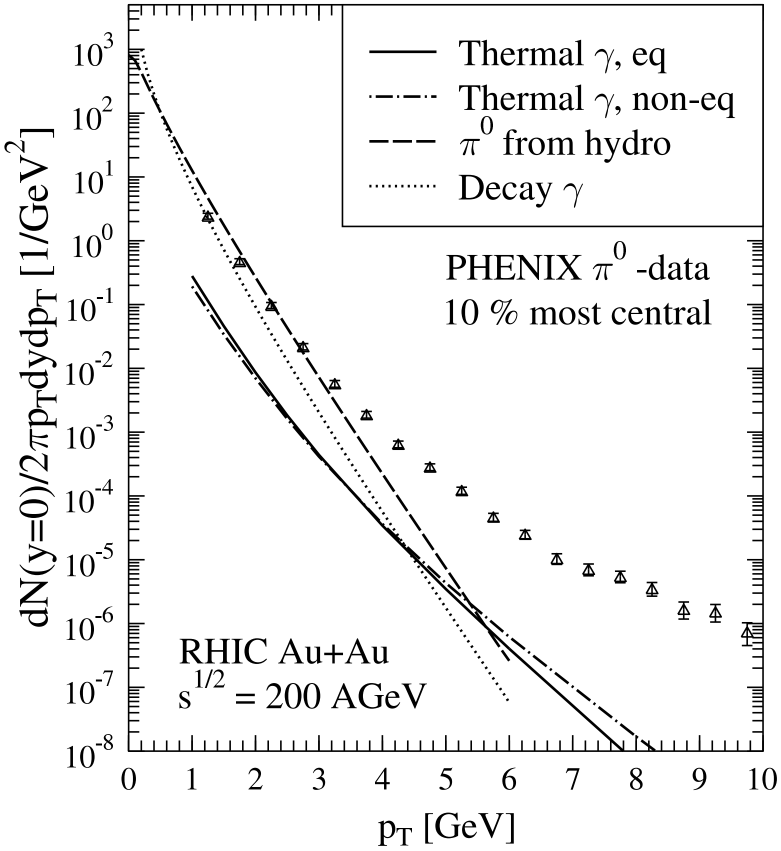
Result



Brem/pair type and $2 \leftrightarrow 2$ production rates are comparable.

Folding into a hydro code:

Hydro model dependence $\gg$ rate uncertainty!



Ruuskanen et. al.

Thermal $\gamma \sim \gamma(\pi^0)/10$.

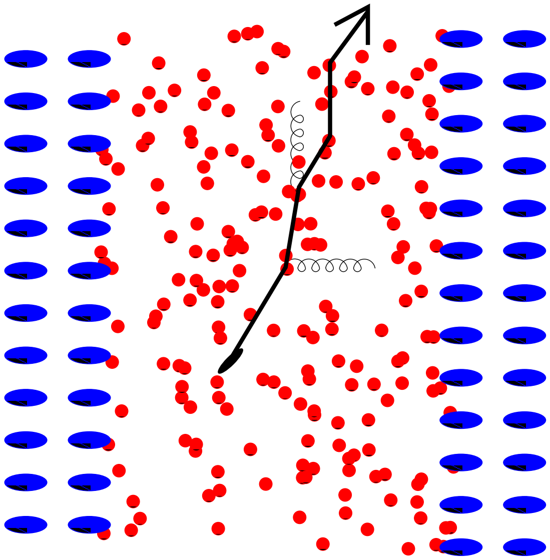
Challenging but not impossible experimentally

Jet quenching

A few hard partons are produced when the primaries collide.

They must escape through the QGP.

Lose energy on the way, mostly to gluon brem.



Jet quenching, γ production similar: brem, LPM...

Emission rate, per dk of gluon energy and dt of time:

$$\begin{aligned}\frac{d\Gamma(p,k)}{dkdt} \quad = \quad & \frac{C_s g_{\rm s}^2}{16\pi p^7}\frac{1}{1\pm e^{-k/T}}\frac{1}{1\pm e^{-(p-k)/T}} \times \\ & \times \left\{ \begin{array}{cc} \frac{1+(1-x)^2}{x^3(1-x)^2} & q\to qg \\ N_{\rm f}\,\frac{x^2+(1-x)^2}{x^2(1-x)^2} & g\to qq \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g\to gg \end{array} \right\} \times \\ & \times \int \frac{d^2\mathbf{h}}{(2\pi)^2} 2\mathbf{h}\cdot {\rm Re}\,\mathbf{F}(\mathbf{h},p,k)\,,\end{aligned}$$

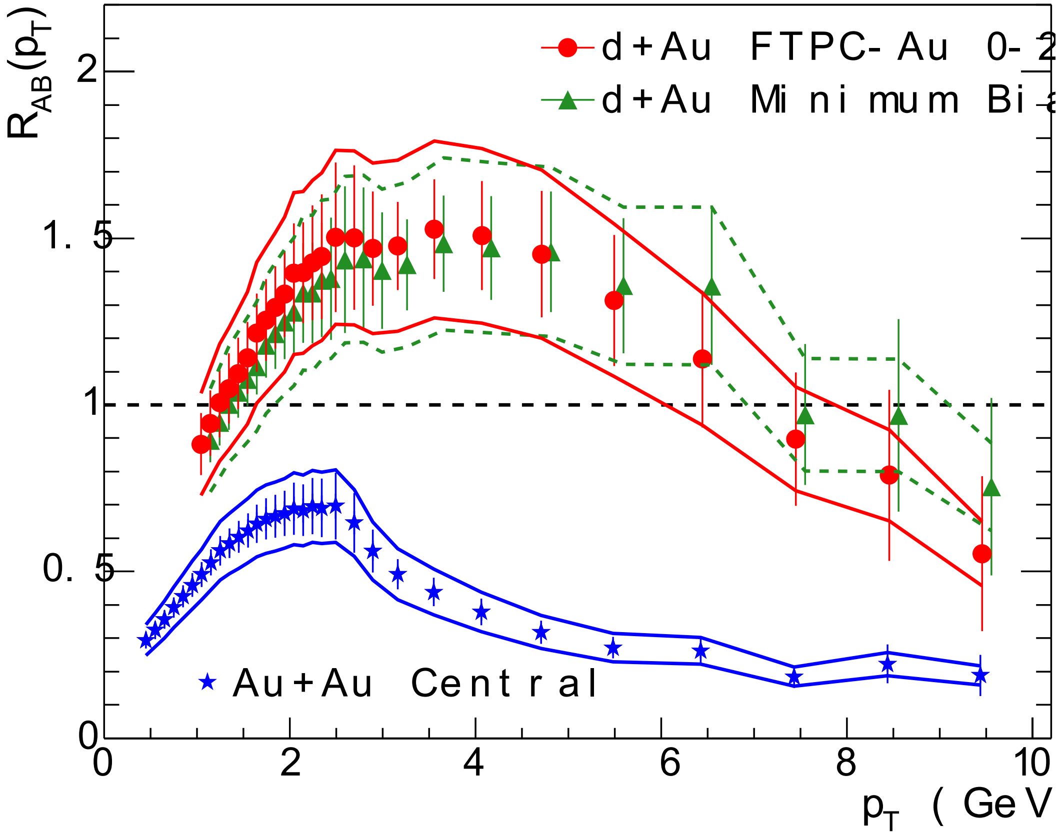
(p: parton energy; $x\equiv k/p$; $\mathbf{h}$: measure of non-collinearity)

Here $\mathbf{F}$ is given by

$$\begin{aligned}
2\mathbf{h} = \quad & i\delta E(\mathbf{h},p,k)\mathbf{F}(\mathbf{h}) + g^2 \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} C(\mathbf{q}_\perp) \times \\
& \times \Big\{ (C_s - C_{\rm A}/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h}{-}k\,\mathbf{q}_\perp)] \\
& \quad +(C_{\rm A}/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h}{+}p\,\mathbf{q}_\perp)] \\
& \quad +(C_{\rm A}/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h}{-}(p{-}k)\,\mathbf{q}_\perp)] \Big\}, \\
\delta E(\mathbf{h},p,k) \quad & = \frac{\mathbf{h}^2}{2pk(p{-}k)} + \frac{m_k^2}{2k} + \frac{m_{p-k}^2}{2(p{-}k)} - \frac{m_p^2}{2p} \,.
\end{aligned}$$

with $C(\mathbf{q}_\perp) = \frac{m_{\rm D}^2}{\mathbf{q}_\perp^2\,(\mathbf{q}_\perp^2 + m_{\rm D}^2)}\,, \quad m_{\rm D}^2 = \frac{g_{\rm s}^2 T^2}{6}(2N_{\rm c}{+}N_{\rm f})\,.$

Jet quenching has been observed!



STAR data: charged yield (scaled to pp), AA vs. DA.

A calculation of γ production and jet quenching using the same formalism and hydro model should inter-relate them.

There are also γ produced as secondaries off the jets as they quench (the bremsstrahlung is sometimes a γ not a gluon).

Work in progress S. Jeon, GM

preliminary results of γ production from hard jets not promising: γ yield 10^{-3} of energetic partons–but see Gale's talk.

Conclusions

- Direct γ's are intrinsically interesting
- Decay γ's should outnumber direct γ's, making observation of direct γ's challenging
- Computing γ production from QGP is Challenging due to LPM, but is nevertheless broadly under control
- uncertainties in QGP γ dominated by Hydro, not QFT
- Connection between γ production and jet quenching deserves more attention, and may help constrain hydro (and other) uncertainties.