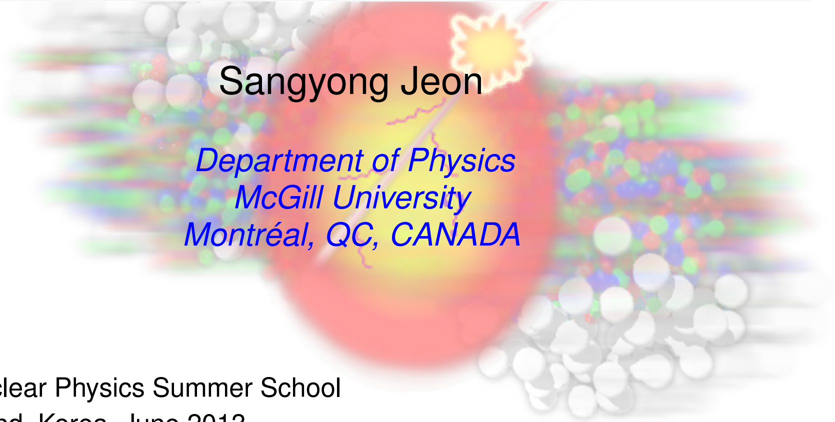
Introduction to Hard Probes in Heavy Ion Collisions



Sangyong Jeon

Department of Physics
McGill University
Montréal, QC, CANADA

11th Nuclear Physics Summer School
Jeju Island, Korea, June 2013

McGill is in Montréal, Québec, Canada

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QC
Canada

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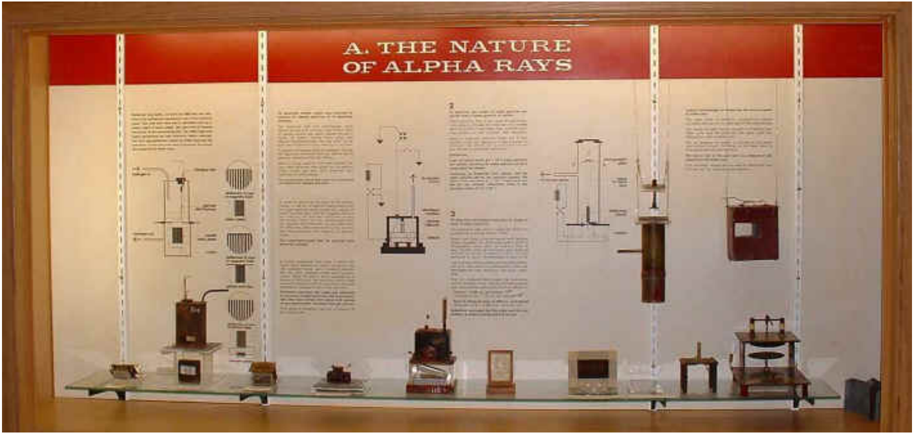
Mr. McGill going home after a hard day's work.

McGill is in Montréal, Québec, Canada



Rutherford carried out his Nobel (1908) winning work at McGill (1898-1907).
His *original* equipments on display

McGill Team

- Charles Gale
- Sangyong Jeon
- *Björn Schenke* (Formerly McGill, now BNL)
- *Clint Young* (Formerly McGill, Now UMinn)
- *Gabriel Denicol*
- *Matt Luzum*
- Sangwook Ryu
- Gojko Vujanovic
- Jean-Francois Paquet
- Michael Richard
- Igor Kozlov
- Khadija El Berhoumi
- Jean-Bernard Rose

Before I begin...
Some thoughts I'd like to share

Success in your Physics career

Disclaimer: These are my own thoughts. Everyone is different. Take these with a grain of salt.

- Passion for Physics!
- Communication skill – Improve your English
  - Writing skill – Writing guide books help
    A good one: *BUGS in Writing: A Guide to Debugging Your Prose*, by Lyn Dupre
  - Presentation skill – Have a look at R. Geroch's *"Suggestions for Giving Talks"*, arXiv:gr-qc/9703019v1.
  - Debate skill – Practice thinking in English
  - Social communication skill – Read novels (paperbacks are better), watch sitcoms, know the culture, slang, ...

Writing/Presentation skill

Approach it as if you're writing a story

Story

- Introduction – Make the reader interested in the rest of the story
- Expanding the story – Main characters, main events, conflicts, puzzles, ...
- Resolution – Story escalates to the ultimate resolution by a big battle, saved by the heroes/heroines.
- Ending – Tie up loose ends. Make the reader want to read the sequel.

Article/Talk

- Introduction – Make the reader interested in the rest of the paper/talk
- Expanding the point – Main physics points, main data, conflicts, puzzles, ...
- Resolution – What big physics the new data/theory illuminates/resolves. Saved by the heroes/heroines.
- Conclusion – Tie up loose ends. Make the reader want to read the sequel.

On to Physics

Relativistic Heavy Ion Collisions

- Why do it?
  - To study QGP
  - Most extreme environment ever created: $T \sim 1$ GeV.
    This existed only at around 1 microsecond after the Big Bang
- How do we understand it?
  - Theory: Many-body QCD
  - Experimental probes:
    - Soft
    - Hard

Hard Probes are useful

- Hard Probes $\sim$ Large momentum/energy phenomena
- pQCD applies – We know how to do this
- Produced *before* QGP is formed in the same way as in hadron-hadron collisions
- Difference between *pp*, *pA* and *AA* tells us about the medium.
- Caveat: How well do we know the *nuclear initial state?*

What do we want to learn?

- Medium properties
  - What is it made of? Quarks? Gluons? Hadrons?
  - Thermodynamic properties – Temperature, Equation of state, etc.
  - Transport properties – Mean-free-path, transport coefficients, etc.
- Tools
  - Jets
  - Hard Photons

Outline

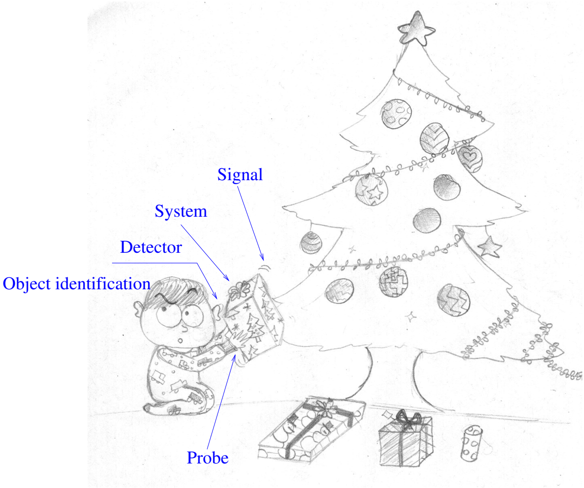
1. pQCD
2. Jet Quenching
3. Hard Photons

What is a hard probe?

- Early hard probe experiments

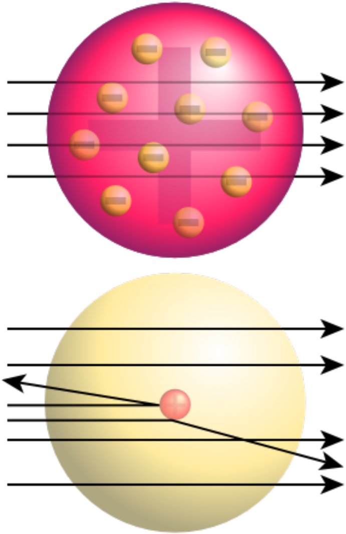
What is a hard probe?

- Early hard probe experiments



What is a hard probe?

- Early hard probe experiments

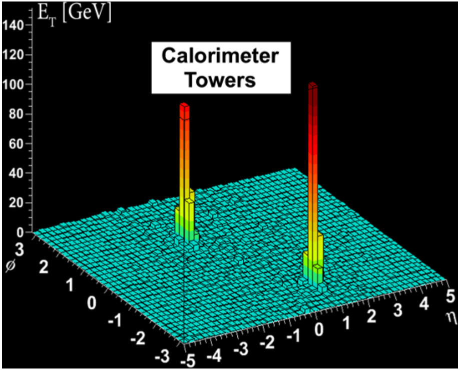


- Rutherford's α scattering experiment

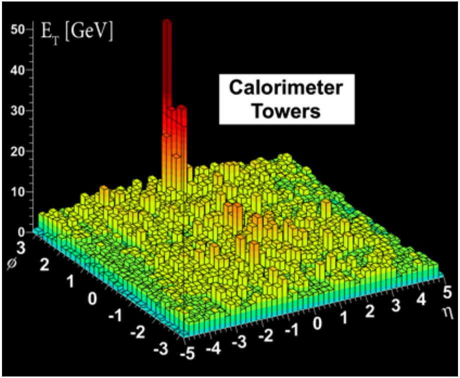
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi}{2} Z^2 \alpha_{\rm EM}^2 \left(\frac{\hbar c}{E_{\rm kin}}\right)^2 \times \frac{1}{(1-\cos\theta)^2}$$

- Small angle scattering dominates $d\sigma/d\cos\theta \propto 1/\theta^4$
- But backscattering prob. is finite, favoring Rutherford's model over Thompson's (which causes no backscattering)

Fast-forward to the present



ATLAS: Intact dijets in Pb+Pb



ATLAS: One jet is fully quenched in Pb+Pb

- Simplest conclusion to draw: The medium is *opaque*.
- We want to know much more than that!

Hard Probe Requirements

- Must be known & calculable using pQCD.
- Must be created *before* QGP forms

Both requirements satisfied if the energy scale is much large compared to $\Lambda_{\mathrm{QCD}} \approx 200\,\mathrm{MeV}$ and the length (time) scale is much shorter than $\sim 1\,\mathrm{fm}$.

Hard Probes

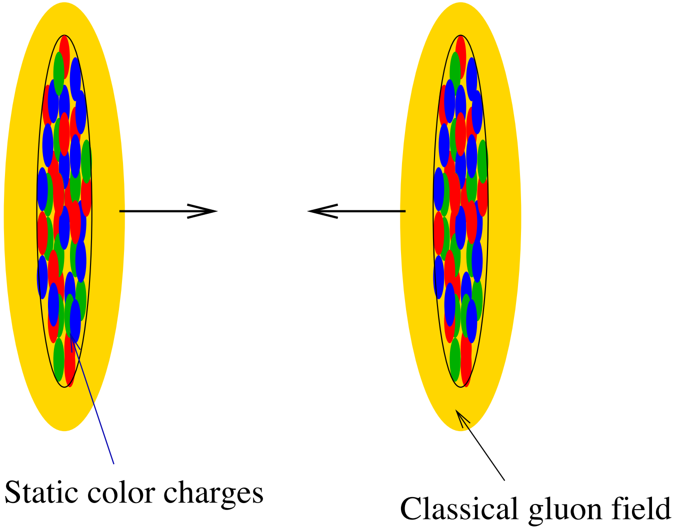
Probes

- Propagation of hard partons or “Jets”
- Quarkonium suppression
- High p_T electromagnetic probes (real and virtual photons)

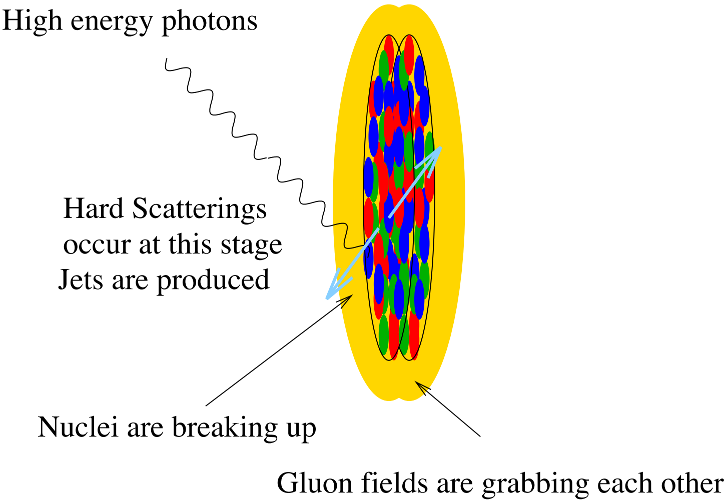
Goal

- To characterize *QGP*
- To characterize initial state (nPDF, CGC?)

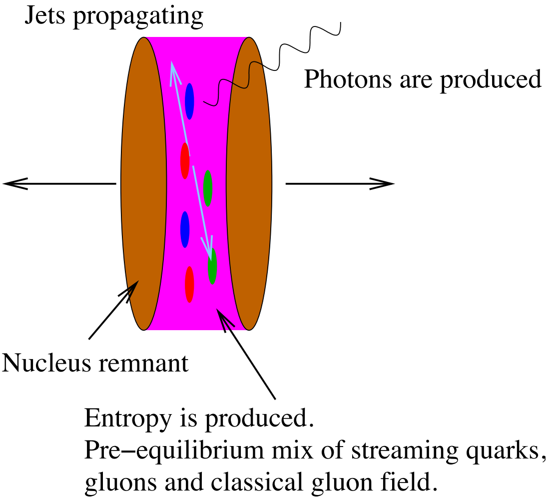
(Very) Schematic view of heavy ion collisions



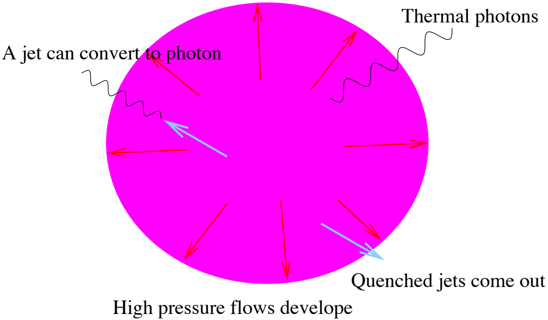
(Very) Schematic view of heavy ion collisions



(Very) Schematic view of heavy ion collisions

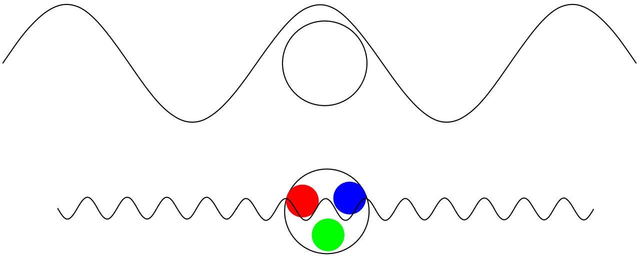


(Very) Schematic view of heavy ion collisions



Review of some basic concepts

- Spatial resolution: $\Delta x \Delta p \geq 1/2$



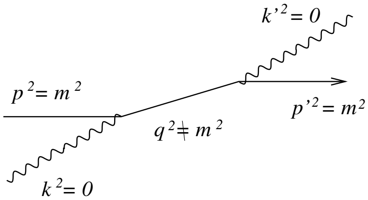
- Shorter the wavelength (larger the momentum) sees spatial details up to $\Delta x \approx \lambda$.

Energy-Time uncertainty: $|\Delta E|\Delta t \geq 1/2$

- $\Delta E = p^0 - \sqrt{\mathbf{p}^2 + m^2}$.
- If $\Delta E = 0$, then $p^\mu p_\mu = m^2$: On-shell
- If $\Delta E \neq 0$, the $p^\mu p_\mu \neq m^2$: Off-shell

Interpretation

- An off-shell state can exist only for $\Delta t \sim 1/|\Delta E|$.

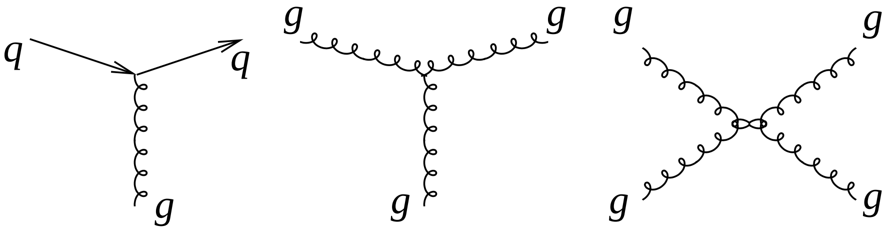


This interaction lasts $\Delta t \sim 1/|(|\mathbf{p}| + |\mathbf{k}| - \sqrt{(\mathbf{p}+\mathbf{k})^2})|$

Perturbative QCD

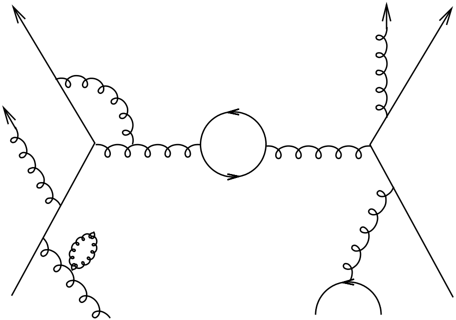
Perturbative QCD (pQCD)

QCD
– *Interaction of quarks and gluons*



- N_f flavors of quarks
- $N_c^2 - 1$ gluons

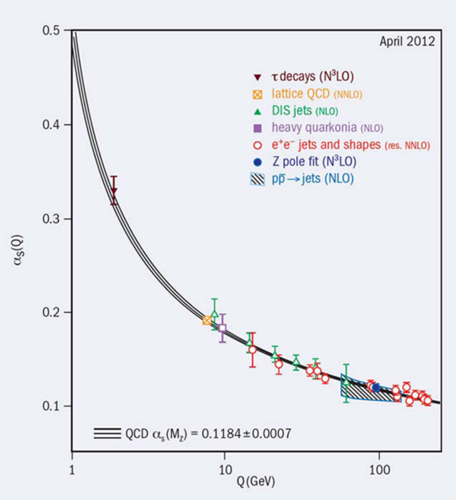
Perturbative QCD (pQCD)



Of course, things can get complicated.

- Tree diagrams of $n \leftrightarrow m$ processes
- Corrections to vertices
- Corrections to propagators

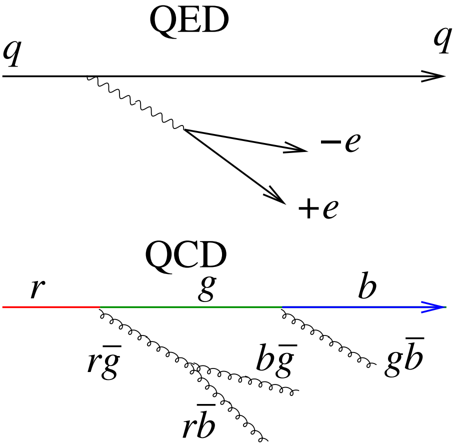
Perturbative QCD (pQCD)



S. Bethke, arXiv:1210.0325.

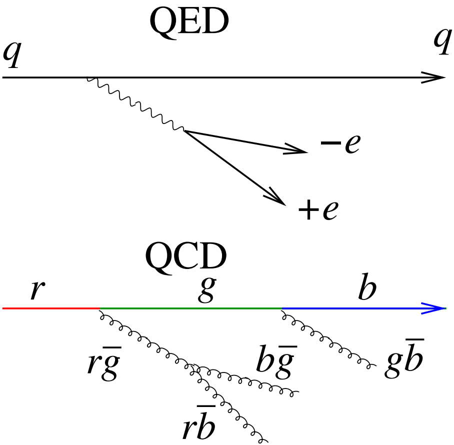
- Perturbative expansion possible because of asymptotic freedom
- $Q^2 \dfrac{\partial \alpha_S}{\partial Q^2} = -\beta_0 \alpha_S^2 - \beta_1 \alpha_S^3 + \cdots$
- $\alpha_S(Q^2) \approx$
$$\frac{1}{((33-2n_f)/12\pi)\ln(Q^2/\Lambda^2_{\rm QCD})}$$
- pQCD reliable for $Q \gtrsim 1$ GeV

Intuitive understanding of asymptotic freedom



- QED: Surrounded by virtual $e\bar{e}$ cloud
- Virtual $-e$ cloud drawn closer to $q > 0 \implies$ Screening
- Larger $Q \implies$ smaller distance $\implies$ Sees less of the cloud $\implies$ Closer to bare charge
- Possible because the original q never changes and photons do not carry charges

Intuitive understanding of asymptotic freedom



- QCD: Can resolve more soft virtual gluons at larger Q
- The color of the real particle can change whenever a gluon is emitted.
- Larger $Q \Longrightarrow$ More frequent changes $\Longrightarrow$ Less average color charge $\Longrightarrow$ Asymptotic freedom

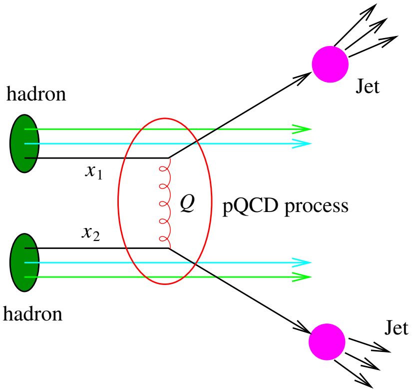
Difficulties with QCD

- As $Q \to \Lambda_{\rm QCD}$,

$$\alpha_S(Q^2) \approx \frac{1}{((33 - 2n_f)/12\pi)\ln(Q^2/\Lambda_{\rm QCD}^2)} \to \infty$$

- Hadrons are $O(\Lambda_{\rm QCD})$ objects.
- Anything that has to do with hadron properties such as color confinement and hadronization is *non-perturbative.*
- In the IR limit, perturbation theory does not work $\Longrightarrow$ Factorize what can be calculated with pQCD (UV) and what cannot be calculated (IR)

Factorization Theorem



Hadron-Hadron Jet production scheme:

$$\sigma = \int_{abcd} f_{a/A}(x_a, Q_f) f_{b/B}(x_b, Q_f) \times \sigma_{ab\to cd} D_{C/c}(z_C, Q)$$

Factorization Theorem

- How realistic pQCD calculations are done

$$\sigma_{hh'\to C+X} = \int_{abcd} dx_1 dx_2 f_{a/h}(x_1, Q_f) f_{b/h'}(x_2, Q_f) \sigma_{ab\to cd}(Q_R) D_{C/c}(z_C, Q_f')$$

- $f_{a/h}(x_1, Q_f)$: Parton distribution function. Probability to have a parton type a with the momentum fraction x_1 in a hadron h. Depends on the factorization scale Q_f.
- $D_{C/c}(z_C, Q_f')$: Fragmentation function. Probability to create a hadron type C our of parton type c carrying the momentum fraction z_c.
- $\sigma_{ab\to cd}(Q_R)$: Parton-parton scattering cross-section.

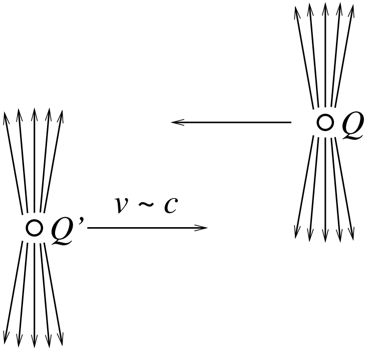
Factorization Theorem

- How realistic pQCD calculations are done

$$\sigma_{hh'\to C+X} = \int_{abcd} dx_1 dx_2 f_{a/h}(x_1, Q_f) f_{b/h'}(x_2, Q_f) \sigma_{ab\to cd}(Q_R) D_{C/c}(z_C, Q'_f)$$

- pQCD controls the *evolutions* of $f_{a/h}(x_1, Q_f)$ and $D_{C/c}(z_C, Q'_f)$. But pQCD cannot determine the initial data because this is dominated by IR processes.
- pQCD *can* calculate $\sigma_{ab\to cd}(Q_R)$ when the renormalization scale Q_R can be set high (that is, when $\sqrt{s}$ is large)

How to think about the initial state factorization – QED analogy



- Weizsäcker-Williams field – Highly contracted in the z direction
- Coulomb potential in the rest frame of the charge

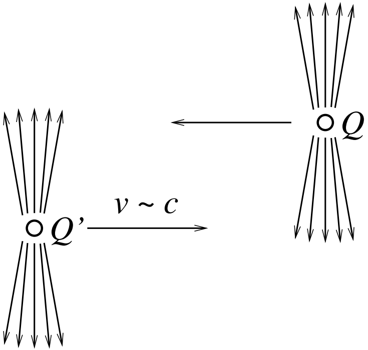
$$\varphi = Q/|\mathbf{r}|$$

- In the moving frame

$$A^\mu(x') = \Lambda^\mu_\nu A^\nu(x(x'))$$

- The coordinate in the moving frame $x' = (t, x, y, z)$. This corresponds to the rest frame position $x = (t\gamma - z\gamma v, x, y, z\gamma - t\gamma v)$.

How to think about the initial state factorization – QED analogy



- Weizsäcker-Williams field – Highly contracted in the z direction
- Coulomb potential in the rest frame of the charge

$$\varphi = Q/|\mathbf{r}|$$

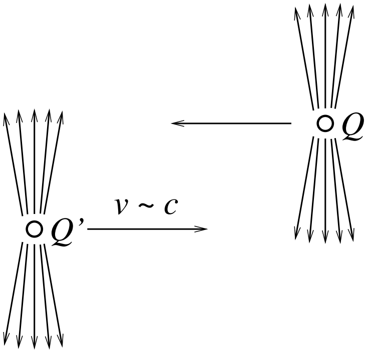
- In the moving frame

$$A^\mu = \frac{Q(\gamma, 0, 0, \gamma v)}{\sqrt{(z - vt)^2\gamma^2 + \Delta\mathbf{x}_\perp^2}}$$

- Pure gauge in the $v \to 1$ limit

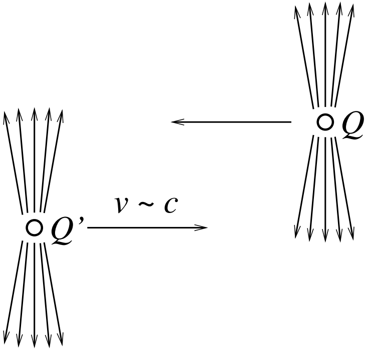
$$A^\mu \approx \frac{Q(1, 0, 0, 1)}{|z - vt|} = Q\partial_\mu \ln|z - vt|$$

How to think about the initial state factorization – QED analogy



- Weizsäcker-Williams field – Highly contracted in the z direction
  $F^{\mu\nu} \approx 0$ unless $z \approx vt$
- In the rest frame: Coulomb field is made up of space-like virtual photons $q^\mu q_\mu = -\mathbf{q}^2$ with $q_0 = 0$.
- In the Lab frame:
  $q'^\mu = (q^z \sinh\eta, \mathbf{q}_\perp, q^z \cosh\eta)$
- For large η,
  $|\Delta E| = |q^- - |\mathbf{q}|| \sim e^{-\eta}\mathbf{q}^2/q_z$
  $\Longrightarrow \Delta t \sim 1/|\Delta E| \sim e^{\eta} q_z/\mathbf{q}^2 \Longrightarrow$ virtual photons look almost like real photons.

How to think about the initial state factorization – QED analogy



- Weizsäcker-Williams field – Highly contracted in the z direction

  $F^{\mu\nu} \approx 0$ unless $z \approx vt$

- To a first approximation, the approaching particles *do not* know about each other until they are on top of each other.

- Initial photon momentum distribution *factorizes*: $F(x_1, x_2) = f(x_1)f(x_2)$ but this is not exact.

- In QCD, color neutrality of hadrons help.

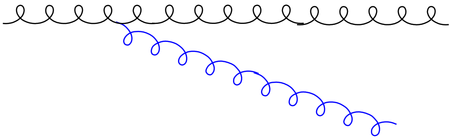
DGLAP Equation

- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.

Q_0: Coarse grained. You see one almost on-shell parton.

DGLAP Equation

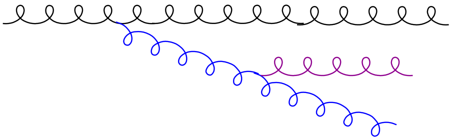
- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.



$Q_0 < Q_1$: Start to resolve another parton

DGLAP Equation

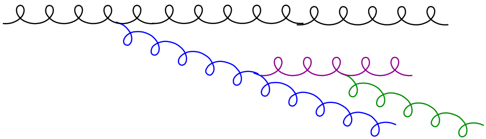
- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.



$Q_0 < Q_1 < Q_2$: And another

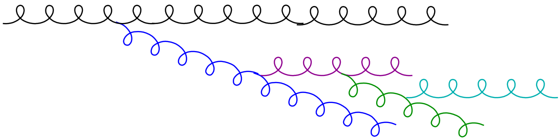
DGLAP Equation

- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.



$Q_0 < Q_1 < Q_2 < Q_3$: And another

- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.



You get the idea

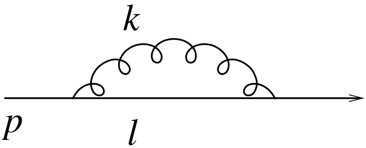
DGLAP Equation

- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.

$$Q^2 \frac{\partial}{\partial Q^2} \begin{pmatrix} q^S \\ g \end{pmatrix} = \frac{\alpha_S(Q^2)}{2\pi} \begin{pmatrix} P_{qq} & 2n_f P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q^S \\ g \end{pmatrix}$$

where P_{ij}: Splitting function $\sim$ Probability to end up with ij in the final state.

Splitting can cause IR divergence



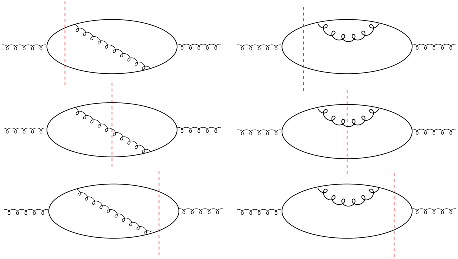
- p is on-shell: $p^2 = 0$
- Diverges when either k or l is on-shell
- This happens either k is very soft so that

$$l^2 = (p - k)^2 \approx p^2$$

- or p and k are almost collinear

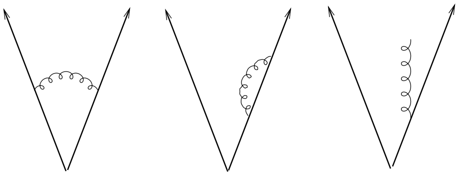
$$l^2 = (p - k)^2 = p^2 + k^2 - 2pk$$
$$\approx 0$$

Splitting can cause IR divergence



- $g \to q\bar{q}$ and $g \to q\bar{q}g$
- Only the *sum* is IR finite because soft and collinear divergences
- Splitting functions know about this

Splitting can cause IR divergence



- Observables must be IR safe.
- 3rd diagram must be treated as 2-jet when the radiation is soft or collinear $\Longrightarrow$ IR-safe Jet definitions

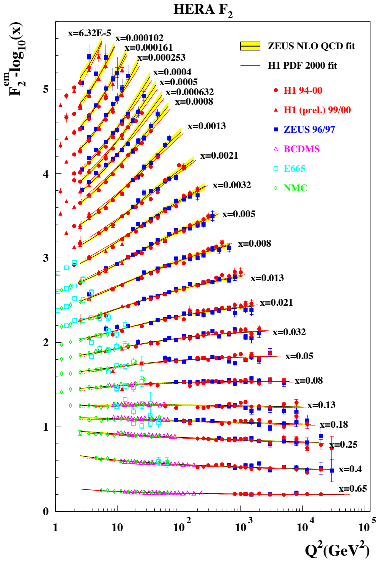
Factorization Theorem

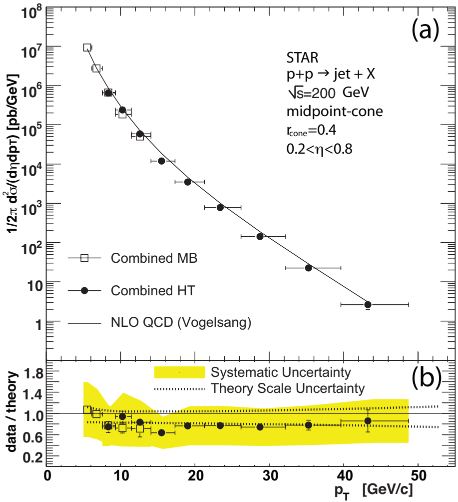
- Splitting function similarly runs
- 3 different scales: Q_f for the pdf, Q_R for $\sigma(Q_R)$ and Q'_f for the fragmentation function
- In principle, physical observables should not depend on these scales. However, factorization theorem is only *approximate*.
- Lots of freedom to choose the scales. Usually something like

$$Q_f = Q_R = Q'_f = \# p_T$$

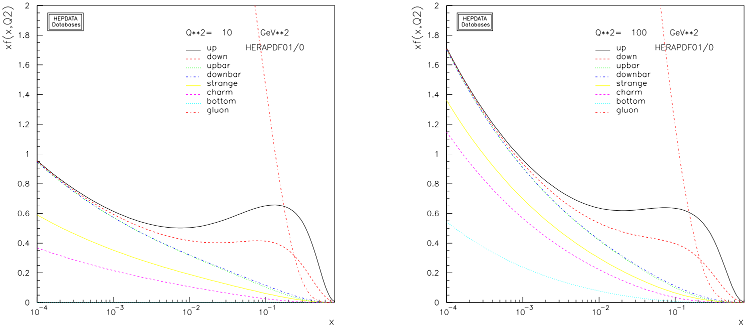
works OK where p_T is the momentum of the *final* state particle.

pQCD & Factorization at work



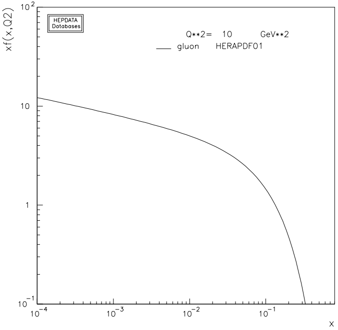


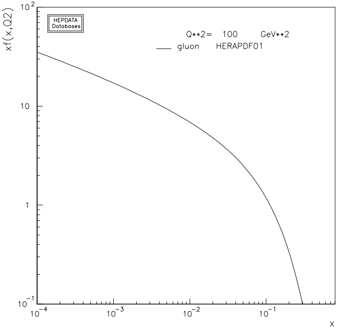
pQCD & Factorization at work



- CTEQ 06 Proton PDF's
- Larger $Q \Longrightarrow$ More soft partons

pQCD & Factorization at work





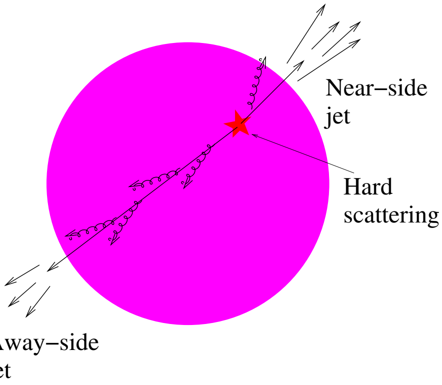
- Gluon distributions for $Q^2 = 10\,\text{GeV}^2$ and $Q^2 = 100\,\text{GeV}^2$.

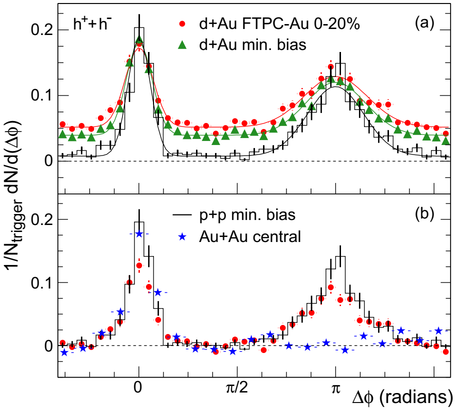
Jet Quenching

What do we want to learn?

- Medium properties
  - What is it made of? QGP or HG?
  - Thermodynamic properties – Temperature, Equation of state, etc.
  - Transport properties – Mean-free-path, transport coefficients, etc.
- Tools – Change in jet properties
  - Jet Quenching
  - Jet Broadening

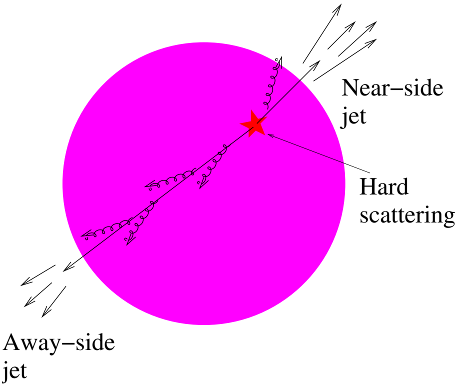
Away side jet disappears! – Proof of principle

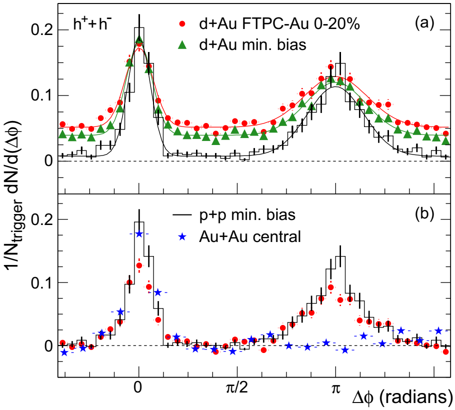




STAR PRL91, 072304 (2003)

Away side jet disappears! – Proof of principle

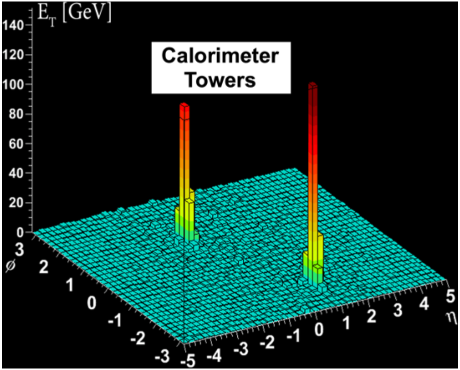




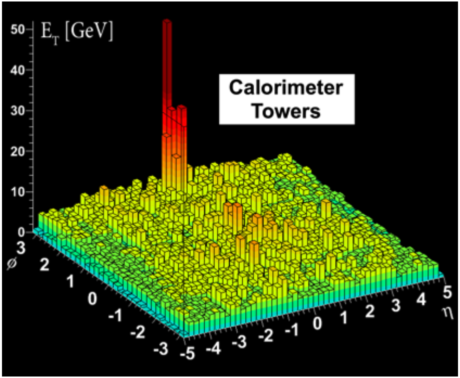
STAR PRL91, 072304 (2003)

Now we need more informative observables to study detailed properties of the medium.

Away side jet disappears! – Proof of principle

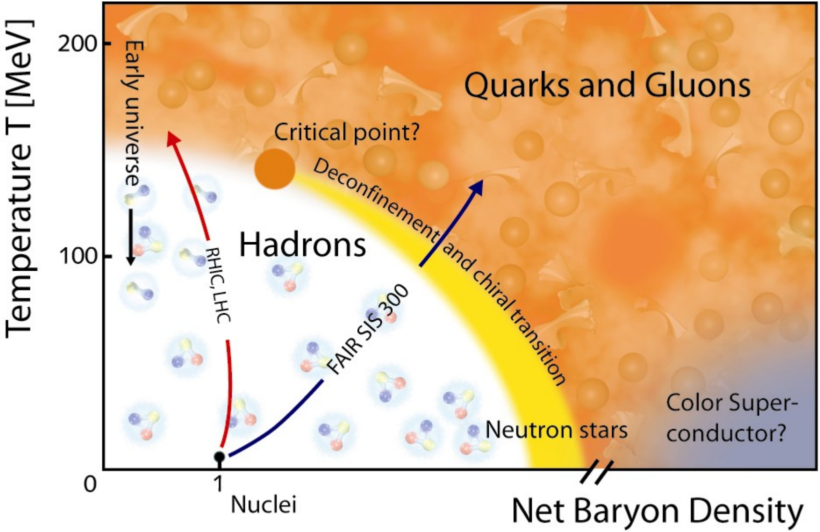


ATLAS: Intact dijets in Pb+Pb



ATLAS: One jet is fully quenched in Pb+Pb

QCD Phase Diagram



Picture credit: GSI (www.gsi.de)

Nobelprize.org

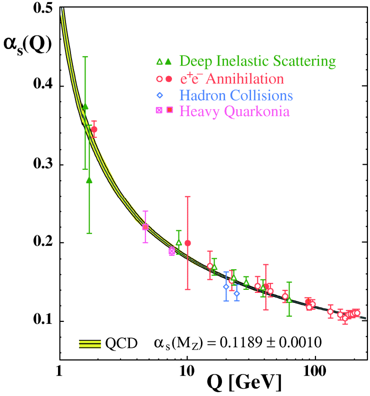
The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

David J. Gross	H. David Politzer	Frank Wilczek
1/3 of the prize	1/3 of the prize	1/3 of the prize
USA	USA	USA
University of California, Kavli Institute for Theoretical Physics Santa Barbara, CA, USA	California Institute of Technology (Caltech) Pasadena, CA, USA	Massachusetts Institute of Technology (MIT) Cambridge, MA, USA
b. 1941	b. 1949	b. 1951

Titles, data and places given above refer to the time of the award.

QCD is asymptotically free.



Bethke, hep-ex/0606035

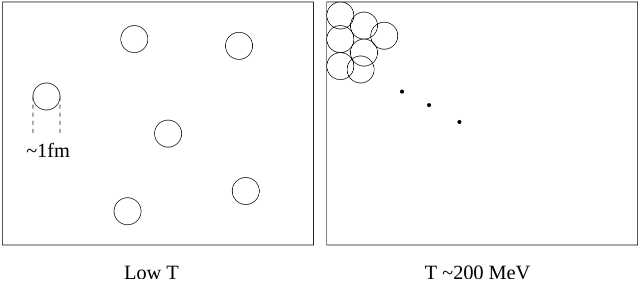
At high T

- Running coupling

$$\alpha_s(\mu^2) = \frac{12\pi}{(33 - 2N_f)\ln(\mu^2/\Lambda^2_{\rm QCD})}$$

  - When $\mu \sim \Lambda_{\rm QCD} \sim 200\,\text{MeV}$, the above expression blows up: Not physical. Indicates breakdown of perturbation theory.
  - Perturbative QCD is a theory of quarks and gluons *not* hadrons.
  - At high T, $\mu \sim T$.
  - Possible phase transition around $T \sim \Lambda_{\rm QCD}$?
  - If $\mu \sim T \to \infty$, $\alpha_s \to 0$: Weakly coupled
  - At $\mu \sim$ few GeV, $\alpha_s \sim 0.2 - 0.4$

Another estimate of $T_{\rm transition}$



- Density: Consider a pion gas.

$$n = 3\int \frac{d^3p}{(2\pi)^3}\frac{1}{e^{E_p/T}-1} \propto T^3$$

As T becomes larger, more and more pair creation results.

- Inter particle distance:

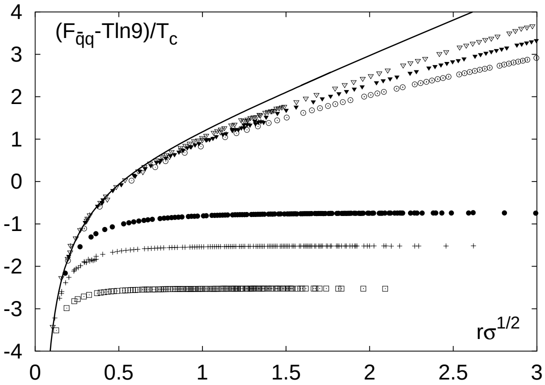
$$l_{\rm inter} = n^{1/3} \approx 1/T$$

At $T = 200\,\text{MeV}$, $l_{\rm inter} \approx 1\text{ fm} \approx r_\pi$

Story so far

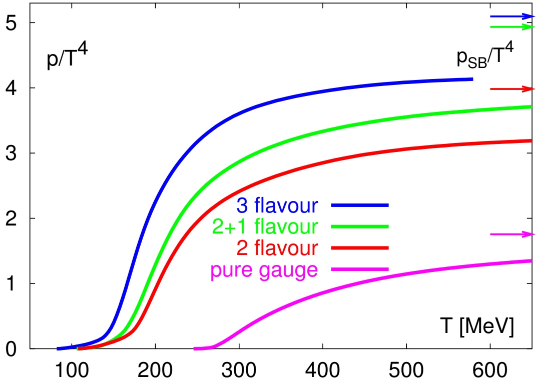
- Perturbative calculation possible much above $\mu = \Lambda_{\rm QCD}$
- $\mu \sim T$ at high T
- If T is much above the binding energy of hadrons
  $\Longrightarrow$ Deconfinement
- At high enough T, the system is a plasma of weakly interacting quarks and gluons
- All the above arguments are plausible but not a proof

Lattice QCD Evidence



- F. Karsch, hep-lat/0403016. The color averaged heavy quark free energy at temperatures $T/T_c = 0.9,\ 0.94,\ 0.98,\ 1.05,\ 1.2,\ 1.5$ (from top to bottom) obtained in quenched QCD.

Lattice QCD – QGP



- QCD is an asymptotically free theory - High $T \implies$ Free quarks and gluons
- Phase transition happens – Hadrons should 'melt' at around $T = 170\,\mathrm{MeV} = 2 \times 10^{12}\,\mathrm{K}$ [F.Karsch et al.] "Cross-over"

Expected properties

- High number density

$$n \approx (24+16)\int \frac{d^3p}{(2\pi)^3}\, e^{-p/T} \approx 4\,T^3$$
$$= 4\left(\frac{T}{200\,\mathrm{MeV}}\right)^3 \mathrm{fm}^{-3}$$

- High energy density

$$\varepsilon \approx (24+16)\int \frac{d^3p}{(2\pi)^3}\, p\, e^{-p/T} \approx 12\,T^4$$
$$= 2.4\left(\frac{T}{200\,\mathrm{MeV}}\right)^4 \mathrm{GeV}/\mathrm{fm}^3$$

Simple Estimate

- 1 mole of hydrogen atom: 6.2×10^{23} atoms $= 1$ g (Avogadro's number)
- 1 hydrogen atom $m_p \approx (1/6) \times 10^{-23}$ g
- $m_p = 940\,\text{MeV} \approx 1\,\text{GeV}$
- $E = mc^2$: $1\,\text{GeV} \approx (1/6) \times 10^{-23}$ g

$$
\begin{aligned}
2.4\,\text{GeV}/\text{fm}^3 &= 0.4 \times 10^{-23}\,\text{g}/(10^{-13}\,\text{cm})^3 \\
&= 0.4 \times 10^{-23+39}\,\text{g/cm}^3 \\
&= 0.4 \times 10^{16}\,\text{g/cm}^3 \\
&= 4 \times 10^{12}\,\text{kg/cm}^3
\end{aligned}
$$

- Typical human: ~ 100 kg

$$2.4\,\text{GeV}/\text{fm}^3 \sim 4 \times 10^{10}\,\text{human/cm}^3$$

How do you achieve high temperature?

- Temperature = energy (1 eV $\approx 12,000$K)
- More usefully, the energy density:

$$\varepsilon = g \int \frac{d^3p}{(2\pi)^3} E_p \, e^{-E_p/T} \approx \frac{3g}{\pi^2} T^4$$

- To get high temperature: Get high energy density $\Longrightarrow$ Cram maximum possible energy into the smallest possible volume while randomizing the momenta $\Longrightarrow$ Relativistic heavy ion collisions.
- What to expect: $dN/d\eta$ and $dE/d\eta$ grow something like $(\ln s)^n$ with $n \sim 1$ $\Longrightarrow$ T should behave something like $(\ln s)^n$ with $n \sim 1$

Observable Consequence

- High temperature $\Longrightarrow$ Thermal photons
- High density $\Longrightarrow$ *Jet quenching*
- High pressure $\Longrightarrow$ Hydrodynamic flow
  - The size of the eliptic flow depends on the shear viscosity η.
  - If weakly coupled, $\eta/s \gg 1$: $\approx$ Ideal gas
  - If stronlgy coupled, $\eta/s \ll 1$: $\approx$ Perfect (Ideal) fluid.
- Neutrality $\Longrightarrow$ Tight unlike-sign correlation
- Critical point $\Longrightarrow$ Large momentum fluctuations

Back in 1990...

In fig. 4 EMC- and SLAC-data on the ratio of integrated particle yields

$$\bar{\mathscr{R}}_A \equiv \int_{x_{\min}}^{1} dx \frac{1}{\sigma_{eA}} \frac{d\sigma_{eA}}{dx} \Big/ \int_{x_{\min}}^{1} dx \frac{1}{\sigma_{eN}} \frac{d\sigma_{eN}}{dx} \qquad (7)$$

$e^- + Cu \longrightarrow h^\pm + X$

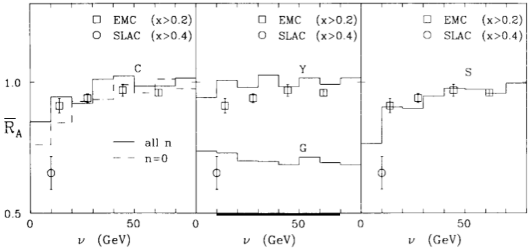


Fig. 4. The ν-dependence of the ratio $\mathscr{R}_A$ of hadrons produced in the forward region. The histograms labeled Y, C, G and S correspond to the yoyo formation model, the constituent formation model, the Glauber limit ($l \equiv 0$) and to the string-flip model, respectively. For the constituent formation model, the zero scattering component has been included (dashed histogram). The data are from refs. [1, 2].

Miklos Gyulassy and Michael Plümer *Jet quenching in lepton nucleus scattering* in Nuclear Physics B Volume 346, 1 (1990).

Key Idea: Compare high p_T spectrum in sth-N and sth-A by plotting the ratio.

How jets are disappearing in hot/dense medium can tell us about the medium

Back in 1990...

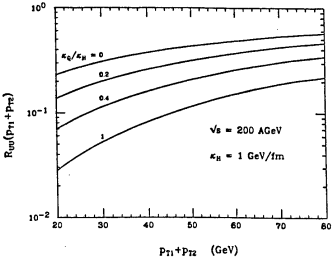


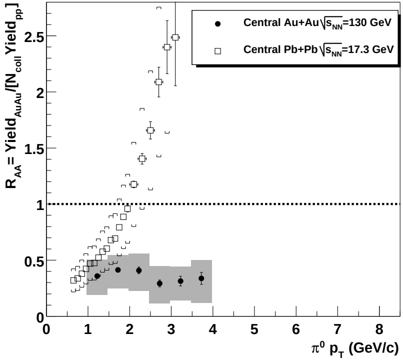
Fig. 7 Dijet reduction factor for central $U+U$ collisions at $\sqrt{s}$ =200 GeV/n as a function of the dijet energy $E = P_{T1} + P_{T2}$, for different values of κ_Q/κ_H assuming κ_H =1 GeV/fm.

transverse coordinate, ϕ the azimuthal angle of the jet and $\tau_f(r,\phi)$ the escape time. Assuming only Bjorken[31] scaling longitudinal expansion and a Bag model equation of state[31], one can find the time dependence of $dE(\tau)/dx$ and get the reduction rate of jet production at fixed P_T by averaging over the initial coordinates (r,ϕ)[22],

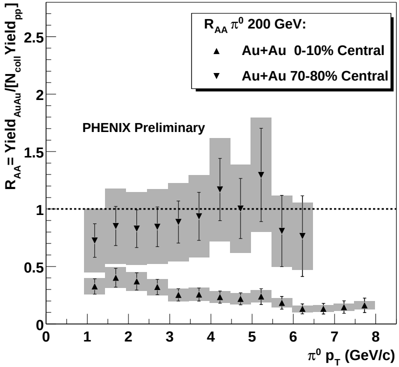
$$R_{AA}(E) = \frac{\sigma^{jet}(E)_{quenching}}{\sigma^{jet}(E)_{no-quenching}}. \qquad (11)$$

In the plasma phase, the temperature decreases as $T(\tau)/T_c = (\tau_Q/\tau)^{1/3}$. According to Eq. 9, $dE/dx \approx \kappa_Q(\tau_Q/\tau)^{2/3}$, denoting the energy loss in the plasma phase by

Xin-Nian Wang and Miklos Gyulassy,
Jets in relativistic heavy ion collisions
in BNL RHIC Workshop 1990:0079-102 (QCD199:R2:1990)

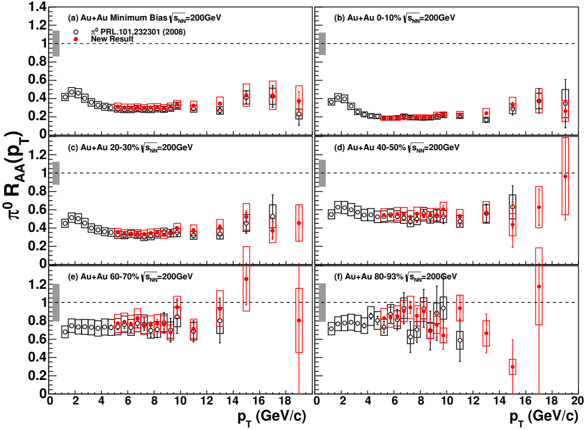


R_{AA} (π^0) for central Pb+Pb collisions at $\sqrt{s_{NN}} = 17$ GeV and central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV.



R_{AA} (π^0) for central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

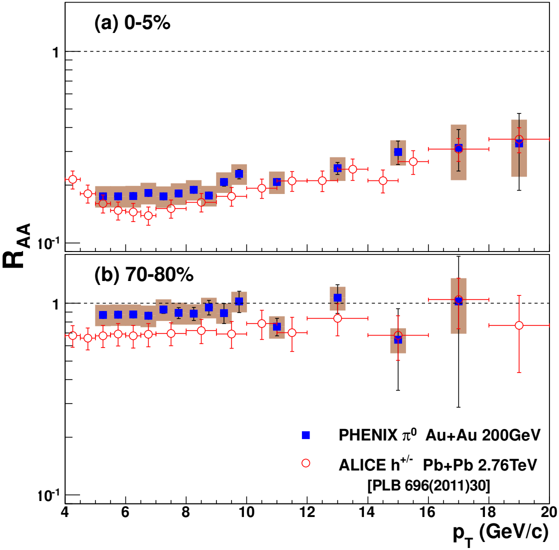
Presented by S. Mioduszewski at QM 2002



PHENIX, arXiv:1208.2254

$$\frac{dN_{AA}/dp_T}{N_{\rm coll}\, dN_{pp}/dp_T} \approx \mathrm{Const.}$$

Slight rising is becoming evident at high p_T.

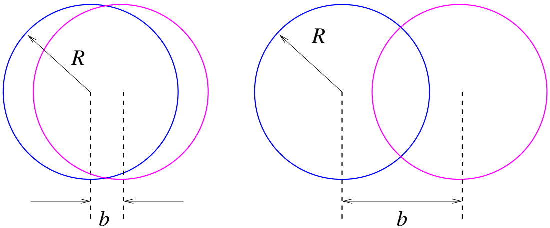


PHENIX, arXiv:1208.2254

$$\frac{dN_{AA}/dp_T}{N_{\rm coll}\, dN_{pp}/dp_T} \approx \text{Const.}$$

Slight rising is becoming evident at high p_T.

Centrality



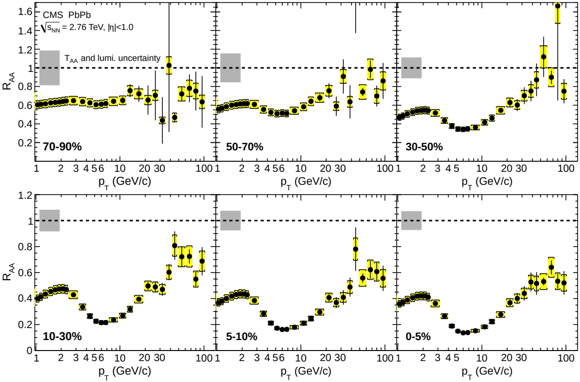
Central collisions
0 % means b = 0

Peripheral collisions
100 % means b = 2R
That is, they missed.

For instance:

- 0 – 5 % means top 5 % of all collisions in terms of the number of particles produced (multiplicity).
- 70 – 80 % means the collection of events whose multiplicity ranks between bottom 30 % and bottom 20 %.
- Centrality and impact parameter *b* not strictly 1 to 1, but very close.

In 2012

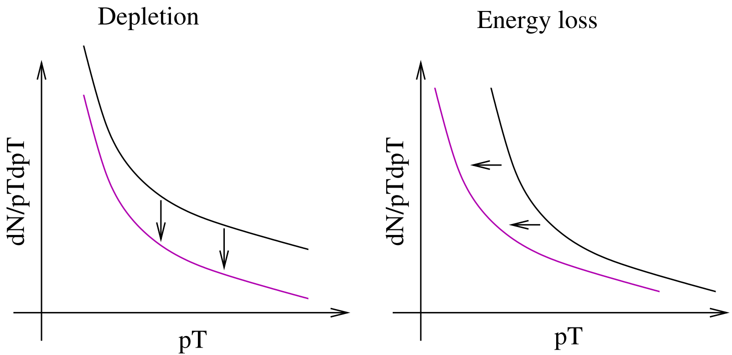


$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{\rm coll}\, dN_{pp}/dp_T}$$

No longer flat.
Logarithmic rise for $p_T \gtrsim 10\,\mathrm{GeV}$.

CMS, 1208.6218v1

Two ways to understand $R_{AA} < 1$



- The spectrum can shift down when particles actually disappear (depletion)
- The spectrum can shift to the left by energy loss – *This is the more realistic scenario.*

Very Rough Understanding

- For high p_T, $dN_{\rm pp}/dp_T \approx 1/p_T^n$.
- Suppose, on average, a particle with p_T loses Δp_T while traversing QGP.
- Then the number of particles with p_T in AA is the same as the number of particles with $p_T + \Delta p_T$ in pp.

$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{\rm col} dN_{pp}/dp_T} \approx \frac{dN_{pp}/dp_T|_{p_T+\Delta p_T}}{dN_{pp}/dp_T|_{p_T}}$$

- What we want to learn: Behavior of Δp_T in the medium
- Shape of R_{AA} depends very much on the shape of dN_{pp}/dp_T

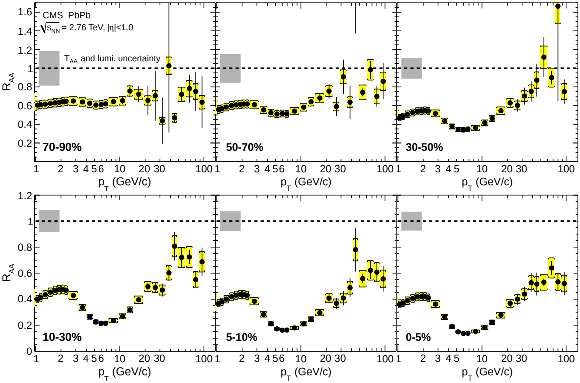
Very Rough Understanding

- Suppose $dN_{pp}/dp_T = 1/p_T^n$ (realistic for high p_T)

$$R_{AA} \approx \left(\frac{p_T}{p_T + \Delta p_T}\right)^n = \left(\frac{1}{1 + \Delta p_T/p_T}\right)^n$$

- Let $\Delta p_T \propto p_T^s$.
- R_{AA} constant if $s = 1$
- R_{AA} approaches 1 as $p_T \to \infty$ if $s < 1$.
- R_{AA} approaches 0 as $p_T \to \infty$ if $s > 1$.

In 2012



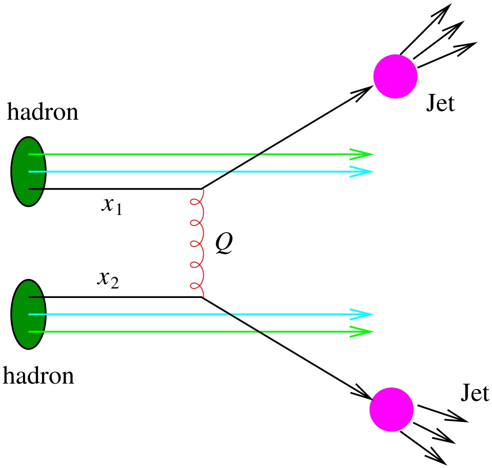
CMS, 1208.6218v1

- Let $\Delta p_T \propto p_T^s$.
- R_{AA} constant if $s = 1$
- R_{AA} approaches 1 as $p_T \to \infty$ if $s < 1$.
- R_{AA} approaches 0 as $p_T \to \infty$ if $s > 1$.

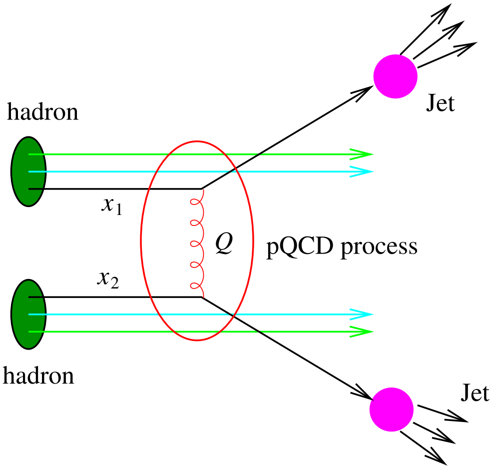
Data suggests that for up to about 5 GeV, $\Delta p_T \propto p_T^{1+a}$ and after that $\Delta p_T \propto p_T^{1-b}$

Jet Quenching
– Schematic Ideas

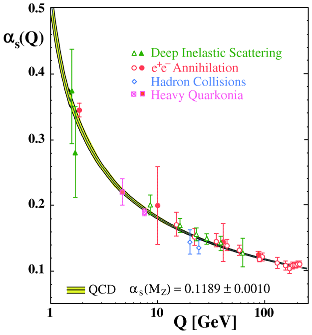
Hadronic Jet production



Hadronic Jet production

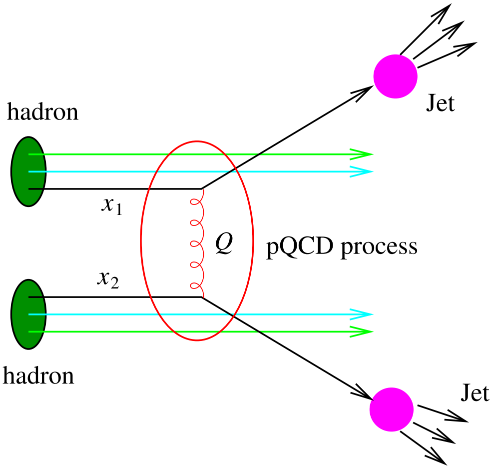


If $Q \gg \Lambda_{\rm QCD}$, $\alpha_s(Q) \ll 1$:
Jet production is perturbative.



Bethke, hep-ex/0606035

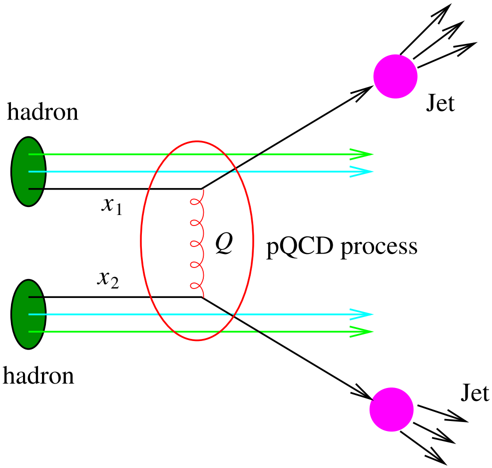
Hadronic Jet production



If $Q \gg \Lambda_{\rm QCD}$, $\alpha_s(Q) \ll 1$:
Jet production is perturbative.

➥ Calculation is possible.

Hadronic Jet production

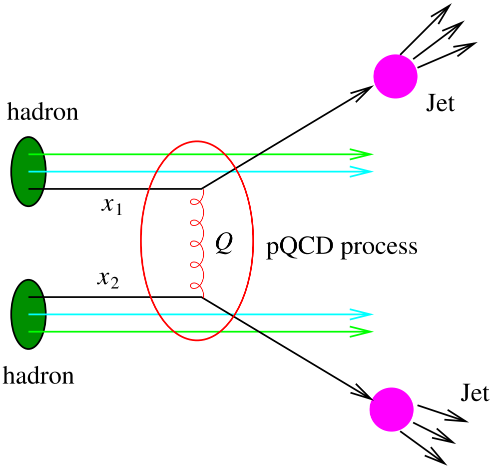


If $Q \gg \Lambda_{\text{QCD}}$, $\alpha_s(Q) \ll 1$:
Jet production is perturbative.

➥ Calculation is possible.

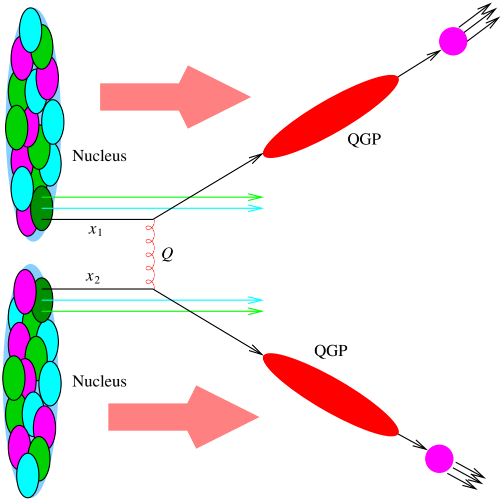
➥ We understand this process in hadron-hadron collisions.

Hadronic Jet production



Hadron-Hadron Jet production scheme:

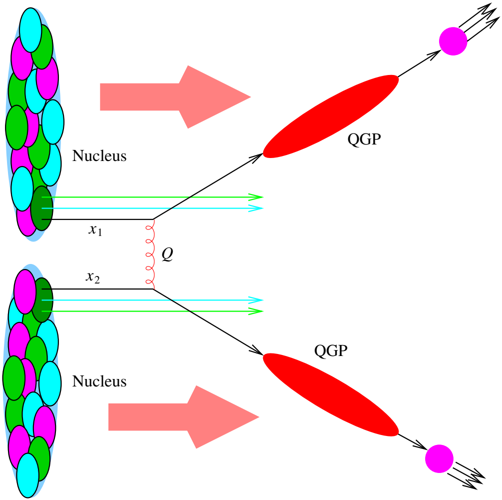
$$\frac{d\sigma}{dt} = \int_{abcd} f_{a/A}(x_a, Q_f) f_{b/B}(x_b, Q_f) \times \frac{d\sigma_{ab\to cd}}{dt} D(z_c, Q)$$



What we want to study:

- How does QGP modify jet property?

Heavy Ion Collisions



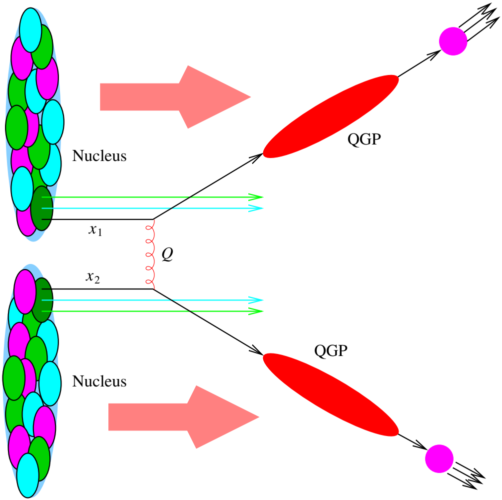
What we want to study:

- How does QGP modify jet property?

Complications:
How well do we know the *initial condition?*

- Nuclear initial condition?
- What happens to a jet between the production and the formation of (hydrodynamic) QGP?

Heavy Ion Collisions

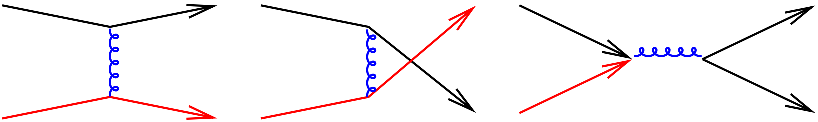


Schematically,

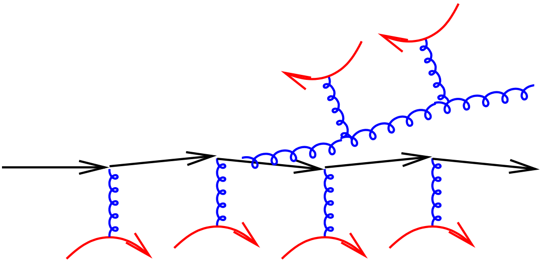
$$\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} \times f_{a/A}(x_a, Q_f) f_{b/B}(x_b, Q_f) \times \frac{d\sigma_{ab\to cd}}{dt} \times \mathcal{P}(x_c \to x'_c | T, u^\mu) \times D(z'_c, Q)$$

$\mathcal{P}(x_c \to x'_c | T, u^\mu)$: Medium modification of high energy parton property $\Longrightarrow$ Jet quenching

Relevant processes for E-loss



Elastic scatterings with thermal particles



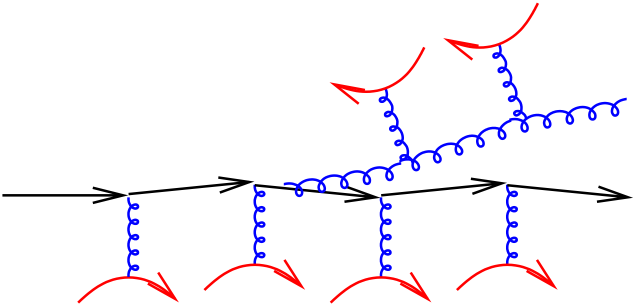
Collinear radiation

Why it is not-trivial

- Hot and dense system – Requires resummation: HTL & LPM
- Finite size system
- System is evolving

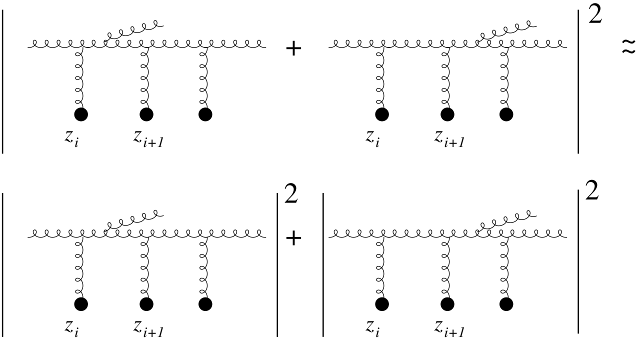
Radiational Energy Loss
– Why coherence matters

Process to study



- Radiative (Inelastic) energy loss via collinear gluon emission

Incoherent emission



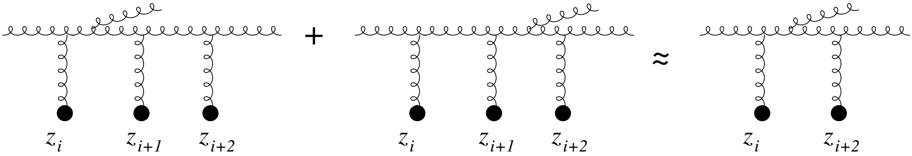
- $|\sum_n T_n|^2 \approx \sum |T_n|^2$
- Interference terms $T_n^* T_m$ with $n \neq m$ negligible.
- Single emission probabilist scales like the number of scatterers:

$$\mathcal{P}_{\mathrm{N_{sc}}} \approx N_{\mathrm{sc}} \mathcal{P}_1$$

- In a unit length, there are $N_{\mathrm{sc}} = \frac{1}{l_{\mathrm{mfp}}}$ number of scatterers. MFP = mean free path.

Coherent emission

- If there is a destructive interference,



- Single emission probability scales like

$$\mathcal{P}_{N_{\rm sc}} \approx \frac{N_{\rm sc}}{N_{\rm coh}} \mathcal{P}_1$$

where $N_{\rm coh}$ is the number of scattering centers that destructively interfere.

- The medium's power to induce radiation is *reduced*.
- In the unit length, there are effectively,

$$N_{\rm eff.\ sc} = \frac{1}{l_{\rm coh}} = \frac{1}{l_{\rm mfp}} \frac{1}{N_{\rm coh}} = \frac{1}{l_{\rm coh}}$$

Effective Emission rate

- Coherent Emission rate:

$$\frac{d\mathcal{P}}{dt} \approx \frac{c}{l_{\rm coh}} \mathcal{P}_1$$

- Incoherent Emission rate:

$$\frac{d\mathcal{P}}{dt} \approx \frac{c}{l_{\rm mfp}} \mathcal{P}_1$$

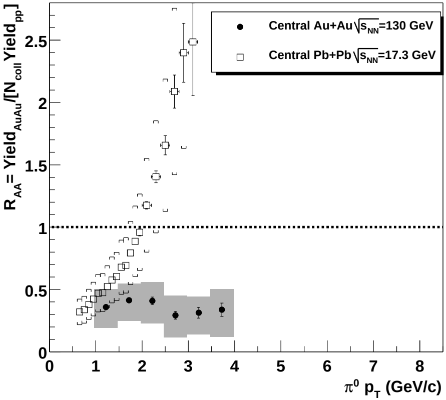
- Here, $\mathcal{P}_1$: Bethe-Heitler

$$\mathcal{P}_1 \approx \frac{\alpha_S N_c}{\pi\omega}$$

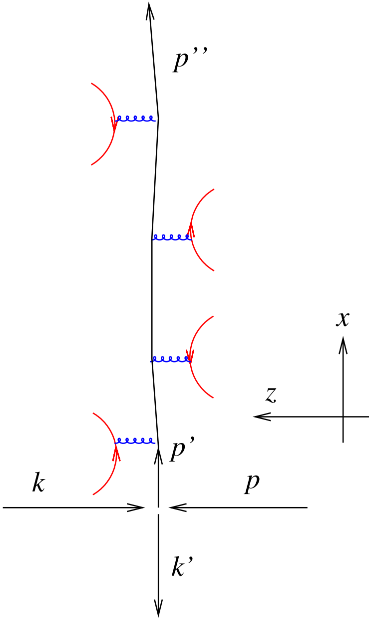
for small ω

Understanding the radiative energy loss

$R_{AA} > 1$

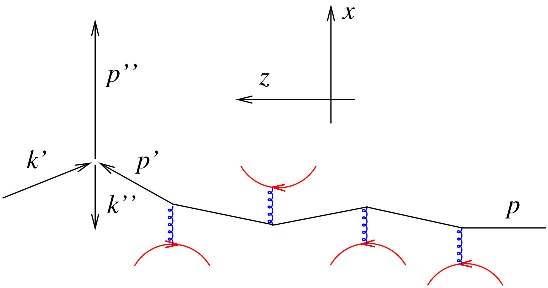


- $R_{AA} < 1$: Energy loss
- $R_{AA} > 1$: Energy gain



- High energy particle
- Initial energy $E_p = p_z$
- Just after collision: $p'_x = p_z$
- *Final state interactions* with the QGP medium add little bits to p'_z but *subtract little bits* from p'_x.
- Resulting in:
  $E_{\rm jet} = \sqrt{p''^2_x + p''^2_z} \approx p''_x < E_p$
  $\Longrightarrow$ Energy loss

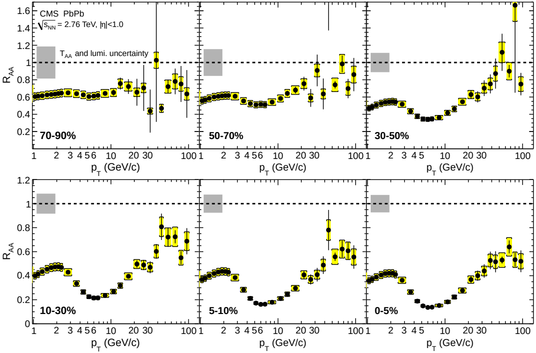
$R_{AA} > 1$



- Low energy particle
- *Initial state interactions* with other nucleons add not-so-small momentum (compared to the original energy) in both directions.
- $|p'| > |p|$
- After the hard collision:
  $p''_x \approx |p'| > p_z \implies$ Energy gain

First goal for today

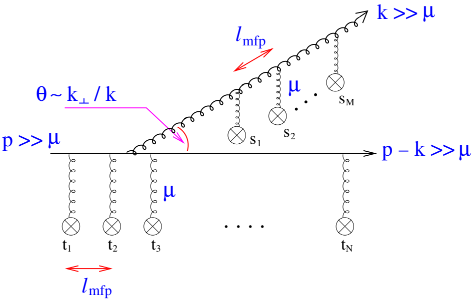
CMS: Up to $p_T = 100\,\text{GeV}$



Can we understand these features in terms of microscopic processes in QGP?

Radiational (Inelastic) Energy Loss – Qualitative understanding

Following BDMPS

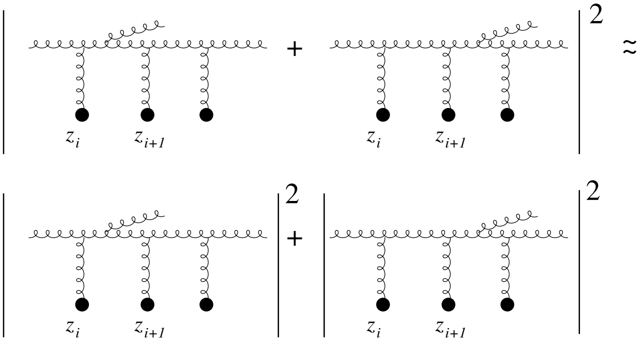


- What we need to calculate R_{AA}: Differential gluon radiation rate $\omega \frac{dN_g}{d\omega dz}$
  Medium dependence comes through a scattering length scale $l \approx t$

$$\omega \frac{dN_g}{d\omega dz} \approx \frac{1}{l} \omega \left. \frac{dN_g}{d\omega} \right|_{\rm BH}$$

Length Scales

Following BDMPS

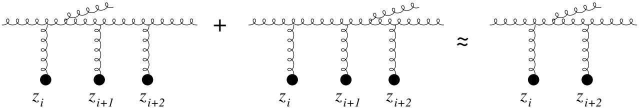


- If all scatterings are incoherent ($l_{\rm mfp} > l_{\rm coh}$),

$$l = l_{\rm mfp} = 1/\rho\sigma$$

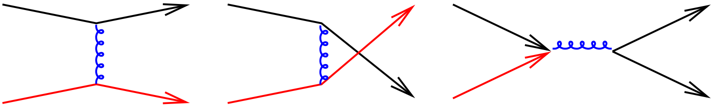
Length Scales

Following BDMPS



- If $l_{\rm coh} \geq l_{\rm mfp} \implies$ LPM effect:
  All scatterings within $l_{\rm coh}$ effectively count as a single scattering.
- $l = l_{\rm coh}$

Estimation of $l_{\rm mfp}$



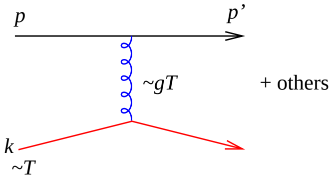
- Mean free path (textbook definition)

$$\frac{1}{l_{\rm mfp}} \equiv \int d^3k\, \rho(k) \int dq^2\, (1 - \cos\theta_{pk}) \frac{d\sigma^{\rm el}}{dq^2}$$

where

  - $\rho(k)$: density, $(1 - \cos\theta_{pk})\Delta E \approx q^2/2k$: flux factor
  - Elastic cross-section (Coulombic) $\dfrac{d\sigma}{dq^2} \approx C_R \dfrac{2\pi\alpha_s^2}{(q^2)^2}$

Estimation of $l_{\rm mfp}$



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where

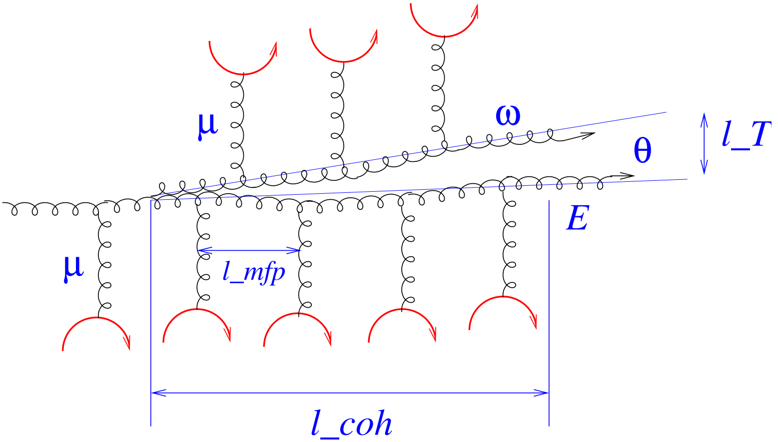
- $\rho(k)$: density, $(1 - \cos\theta_{pk})\Delta E \approx q^2/2k$: flux factor
- Elastic cross-section (Coulombic) $\dfrac{d\sigma}{dq^2} \approx C_R \dfrac{2\pi\alpha_s^2}{(q^2)^2}$

Estimation of l_{mfp}

- With thermal $\rho(k)$, this yields

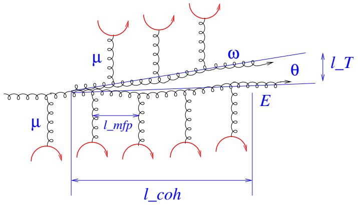
$$\frac{1}{l_{\mathrm{mfp}}} \sim \int d^3k\rho(k) \int_{m_D^2}^{\infty} dq^2 \frac{\alpha_S^2}{q^4} \sim T^3\alpha_S^2/m_D^2 \sim \alpha_S T$$

Estimation of l_{coh}



- $E \gg \omega_g \gg \mu$

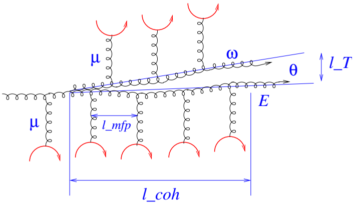
Estimation of $l_{\rm coh}$



- $\omega \ll E \implies$ The radiated gluon random walks away from the original parton. Original parton's trajectory is less affected.
- From the geometry $\dfrac{\omega_g}{k_T^g} \approx \dfrac{l_{\rm coh}}{l_T}$
- Separation condition: l_T is longer than the transverse size of the radiated gluon. $l_T \approx 1/k_T^g$
- Putting together,

$$l_{\rm coh} \approx \frac{\omega_g}{(k_T^g)^2}$$

Estimation of $l_{\rm coh}$



- Putting together,

$$l_{\rm coh} \approx \frac{\omega_g}{(k_T^g)^2}$$

- After suffering $N_{\rm coh}$ collisions (random walk),

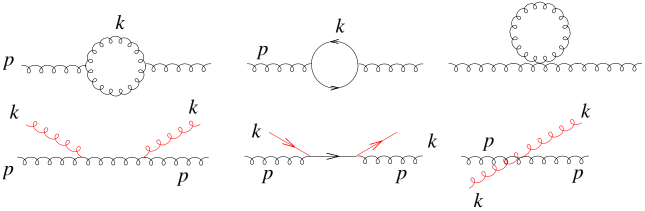
$$\left\langle (k_T^g)^2 \right\rangle = N_{\rm coh}\mu^2 = \frac{l_{\rm coh}}{l_{\rm mfp}}\mu^2$$

- Becomes, with $\hat{q} = \mu^2/l_{\rm mfp}$ and $E_{\rm LPM} = \mu^2 l_{\rm mfp}$,

$$l_{\rm coh} \approx l_{\rm mfp}\sqrt{\frac{\omega_g}{E_{\rm LPM}}} = \sqrt{\frac{\omega_g}{\hat{q}}}$$

Estimation of μ^2

- Debye mass

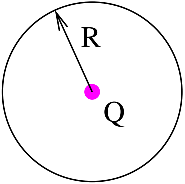


- Second row: Physical forward scattering with particles in the medium
- The last term is easiest to calculate:

$$m_D^2 \propto g^2 \int \frac{d^3k}{E_k} f(k) \propto g^2 T^2$$

- Effectively add $m_D^2 A_0^2 \implies$ NOT gauge invariant $\implies$ Gauge invariant formulation: Hard Thermal Loops

Physical origin of Debye mass



- E & M
- Let $Q > 0$. Within the range R
  - Positive charges are pushed away: $Q_+ = Q_0 = \delta Q$
  - Negative charges are pulled in: $Q_- = Q_0 + \delta Q$
- At position R, apparent net charge is *reduced*

$$Q_{\text{net}} = Q + (Q_0 - \delta Q) - (Q_0 + \delta Q) = Q - 2\delta Q$$

  This is screening.
- When it's moving, there is a net potential energy associated with Q even in charge neutral medium $\Longrightarrow$ Acts like a "mass"

Physical origin of Debye mass

- E & M
- Potential in a thermal system

$$\nabla^2 \Phi(\mathbf{r}) = -\rho(\mathbf{r})$$

- Medium composed of many charged particles

$$\rho(\mathbf{r}) = q n_+(\mathbf{r}) - q n_-(\mathbf{r})$$

- Boltzmann Density:

$$\begin{aligned} n_\pm(\mathbf{r}) &= \int \frac{d^3k}{(2\pi)^3}\, e^{-E/T} \\ &= \int \frac{d^3k}{(2\pi)^3}\, e^{-\sqrt{k^2+m^2}}\, e^{\mp q\Phi(\mathbf{r})/T} \\ &= n_0(T) e^{\mp q\Phi(\mathbf{r})/T} \\ &\approx n_0(T)(1 \mp q\Phi(\mathbf{r})/T) \end{aligned}$$

Physical origin of Debye mass

- E & M
- Boltzmann Density:

$$n_\pm(\mathbf{r}) \approx n_0(T)(1 \mp q\Phi(\mathbf{r})/T)$$

- Linearized equation for the potential:

$$\nabla^2\Phi - m_D^2\Phi \approx 0$$

where

$$m_D^2 = 2q^2(n_0(T)/T)$$

What we learned so far

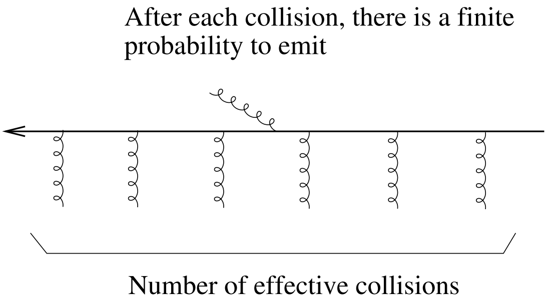
Coherence length

$$l_{\rm coh} \approx l_{\rm mfp}\sqrt{\frac{\omega_g}{E_{\rm LPM}}} = \sqrt{\frac{\omega_g}{\hat{q}}}$$

where $\hat{q} = \mu^2/l_{\rm mfp}$ (average momentum transfer squared per collision)
If your chosen process is

- Soft gluon emission, $\omega_g < \mu^2 l_{\rm mfp}$,
  $\Longrightarrow$ Coherence matters not. BH should suffice. No need to resum.
- Hard gluon emission, $E \gg \omega_g > \mu^2 l_{\rm mfp}$,
  $\Longrightarrow$ Coherence matters. Resummation needed.
- Both
  $\Longrightarrow$ Need the cross-section that is correct in both limits.
- Key quantity: $E_{\rm LPM} = \mu^2 l_{\rm mfp} \sim T$ in pert. thermal QCD
- Key quantity: $\hat{q} \sim \alpha_S^2 T^3$ in pert. thermal QCD

Rough Idea – Multiple Emission (Poisson ansatz)



- Let the emission probability be p
- Total number of *effective* collisions $N_{\rm trial}$ taking into account of $l_{\rm mfp}$ and $l_{\rm coh}$.
- Average number of emissions $\langle n \rangle = N_{\rm trial} p$
- Probability to emit n gluons

$$P(n) = \frac{N_{\rm trial}!}{n!(N_{\rm trial} - n)!} p^n (1-p)^{N_{\rm trial} - n}$$

Rough Idea – Multiple Emission (Poisson ansatz)

- Poisson probability: Limit of binary process as $\lim_{N_{\rm trial}\to\infty} N_{\rm trial}\, p \to \langle n\rangle$

$$P(n) = e^{-\langle n\rangle}\frac{\langle n\rangle^n}{n!}$$

- Average number of gluons emitted up to $t_i < t$

$$\langle n\rangle = \int_{-\infty}^{E} d\omega \int_{t_i}^{t} dz \frac{dN}{dz\,d\omega} = \int_{-\infty}^{E} d\omega\, \frac{dN}{d\omega}(t)$$

- Probability to lose ϵ amount of energy by emitting n gluons:

$$\begin{aligned}\langle n\rangle^n &\to D(\epsilon, t)\\ &= \int_{-\infty}^{E} d\omega_1 \frac{dN}{d\omega_1}\int_{-\infty}^{E} d\omega_2 \frac{dN}{d\omega_2}\cdots\int_{-\infty}^{E} d\omega_n \frac{dN}{d\omega_n}\delta(\epsilon - \sum_{k=1}^{n}\omega_k)\end{aligned}$$

Rough Idea – Multiple Emission (Poisson ansatz)

Parton spectrum at t

$$P(p,t) = \int d\epsilon\, D(\epsilon,t)\, P_0(p+\epsilon)$$

where

$$D(\epsilon,t) = e^{-\int d\omega \frac{dN}{d\omega}(\omega,t)} \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dN}{d\omega_i}(\omega_i,t)\right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i\right)$$

Can easily show that this Poisson ansatz solves:

$$\frac{dP(p,t)}{dt} = \int d\omega \frac{dN_{\text{Poiss.}}}{d\omega dt}(\omega) P(p+\omega,t) - P(p,t) \int d\omega \frac{dN_{\text{Poiss.}}}{d\omega dt}(\omega)$$

with the p (jet energy) independent rate

$$\frac{dN}{d\omega}(\omega,t) = \int_{t_0}^{t} dt' \frac{dN_{\text{Poiss.}}}{d\omega dt}(\omega,t')$$

Rough Idea - The behavior of R_{AA}

Use $R_{AA} \approx 1/(1+\epsilon/p)^n \approx e^{-n\epsilon/p}$ when $n \gg 1$. Include gain by absoprtion or $\omega < 0$:

$$R_{AA}(p) = \frac{P(p)}{P_0(p)} \approx \exp\left(-\int_{-\infty}^{\infty} d\omega \int_0^t dt'\,(dN_{\mathrm{inel+el}}/d\omega dt)(1-e^{-\omega n/p})\right)$$

For the radiation rate, use simple estimates

$$\frac{dN}{d\omega dt} \approx \frac{\alpha}{\pi\omega}\frac{N_c}{l_{\mathrm{mfp}}} \quad \text{for} \quad 0 < \omega < l_{\mathrm{mfp}}\mu^2$$

$$\frac{dN}{d\omega dt} \approx \frac{\alpha}{\pi\omega}N_c\sqrt{\frac{\mu^2}{l_{\mathrm{mfp}}\omega}} \quad \text{for} \quad l_{\mathrm{mfp}}\mu^2 < \omega < l_{\mathrm{mfp}}\mu^2(L/l_{\mathrm{mfp}})^2$$

$$\frac{dN}{d\omega dt} \approx \frac{\alpha}{\pi\omega}\frac{N_c}{L} \quad \text{for} \quad l_{\mathrm{mfp}}\mu^2(L/l_{\mathrm{mfp}})^2 < \omega < E$$

$$\frac{dN}{d\omega dt} \approx \frac{\alpha}{\pi|\omega|}\frac{N_c}{l_{\mathrm{mfp}}}e^{-|\omega|/T} \quad \text{for} \quad \omega < 0$$

Rough Idea - The behavior of R_{AA}

For elastic energy loss,

$$
\begin{aligned}
R_{AA}^{\mathrm{el}} &\approx \exp\left(-\int_{-\infty}^{\infty} d\omega \int_0^t dt'\,(d\Gamma_{\mathrm{el}}/d\omega dt)(1-e^{-\omega n/p})\right)\\
&\approx \exp\left(-t\left(\frac{dE}{dt}\frac{K(\omega_0)}{|\omega_0|}\right)\right)\\
&\approx \exp\left(-t\left(\frac{dE}{dt}\right)\left(\frac{n}{p}\right)\left(1-\frac{nT}{p}\right)\right)
\end{aligned}
$$

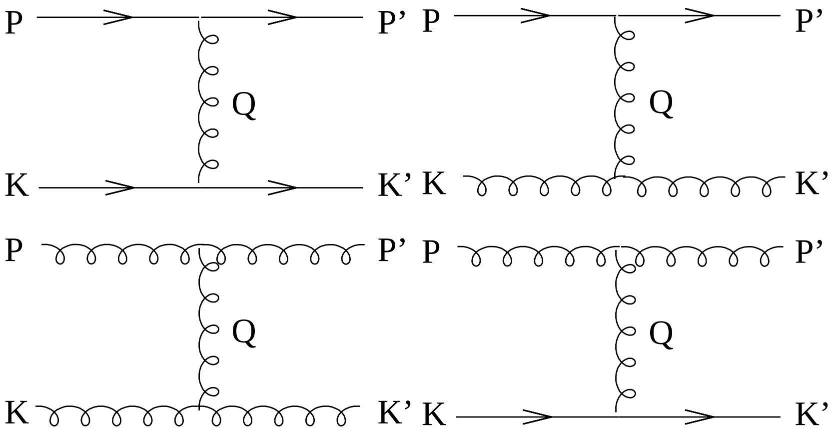
valid for $p > nT$ and we used

$$
\begin{aligned}
K(\omega_0) &= (1+n_B(|\omega_0|))(1-e^{-|\omega_0|n/p}) + n_B(|\omega_0|)(1-e^{|\omega_0|n/p})\\
&\approx |\omega_0|\left(\frac{n}{p}\right)\left(1-\frac{nT}{p}\right) \quad \text{for small } \omega_0
\end{aligned}
$$

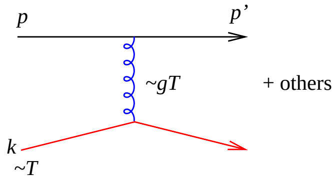
where ω_0 is the typical gluon energy

Elastic scattering rate

Coulombic *t*-channel dominates



Rough Idea - Elastic energy loss(Following Bjorken)



- Mean free path (textbook definition)

$$\frac{1}{l_{\rm mfp}} \equiv \int d^3k\,\rho(k) \int dq^2\,(1 - \cos\theta_{pk})\frac{d\sigma^{\rm el}}{dq^2}$$

- Energy loss per unit length

$$\frac{dE}{dz} = \int d^3k\,\rho(k) \int dq^2\,(1 - \cos\theta_{pk})\Delta E\frac{d\sigma^{\rm el}}{dq^2}$$

where

  - $\rho(k)$: density, $(1 - \cos\theta_{pk})\Delta E \approx q^2/2k$: flux factor
  - Elastic cross-section (Coulombic) $\dfrac{d\sigma}{dq^2} \approx C_R\dfrac{2\pi\alpha_s^2}{(q^2)^2}$

Rough Idea - Elastic energy loss(Following Bjorken)

- With thermal ρ, this yields

$$\left(\frac{dE}{dz}\right)_{\rm coll} \sim \int d^3k\rho(k)/k \int dq^2\alpha_S^2/q^2 \sim \alpha_S^2 T^2 \ln(ET/m_D^2)$$

Upper limit determined by

$$q^2 = (p-k)^2 = p^2 + k^2 - 2pk \approx -2pk \sim ET$$

when $|\mathbf{p}| = E$ (emitter) and $|\mathbf{k}| = O(T)$ (thermal scatterer)
Lower limit determined by the Debye mass $m_D = O(gT)$.

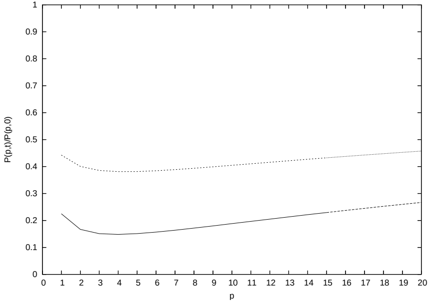
Elastic scattering rate

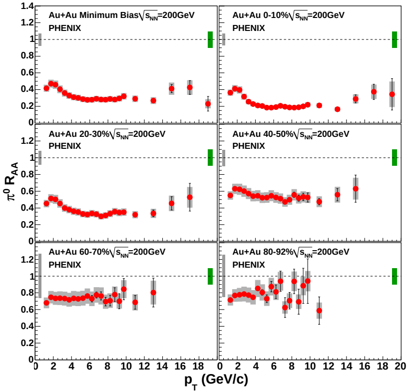
More precisely,

$$\frac{dE}{dt} = \frac{1}{2E}\int_{k,k',p'} \delta^4(p+k-p'-k')\,(E-E')|M|^2\, f(E_k)[1\pm f(E'_k)]$$
$$= C_r\pi\,\alpha_s^2 T^2\left[\ln(ET/m_g^2) + D_r\right]$$

where C_r and D_r are channel dependent $O(1)$ constants.

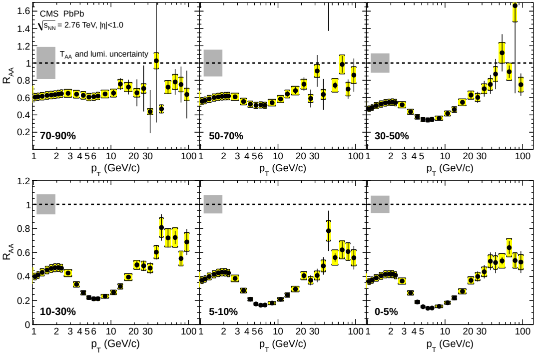
Rough Idea - The behavior of R_{AA}





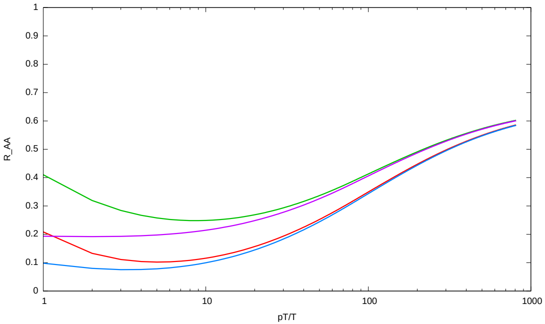
- Upper line: Without elastic
- Lower line: With elastic
- Flat R is produced in both cases up to $O(10\,T)$.
- R just not that sensitive to p in the RHIC-relevant range.

CMS: Up to $p_T = 100\,\text{GeV}$



No longer flat. Logarithmic rise for $p_T \gtrsim 10\,\text{GeV}$.
Can we understand these features?

Rough Idea - The behavior of R_{AA}



- Red: Elastic on, thermal absorption on
- Blue: Elastic on, thermal absorption off
- Green: Elastic off, thermal absorption on
- Magenta: Elastic off, thermal absorption off
- Dip, rise, leveling-off roughly reproduced
- *No dip if thermal absorption is turned off*

For other features, first recall

Use $R_{AA} \approx 1/(1+\epsilon/p)^n \approx e^{-n\epsilon/p}$ when $n \gg 1$. Include gain by absoprtion or $\omega < 0$:

$$R_{AA}(p) = \frac{P(p)}{P_0(p)} \approx \exp\left(-\int_{-\infty}^{\infty} d\omega \int_0^t dt'\,(dN_{\rm inel+el}/d\omega dt)(1-e^{-\omega n/p})\right)$$

For the radiation rate, use simple estimates

$$\frac{dN}{d\omega dt} \approx \frac{\alpha}{\pi\omega}\frac{N_c}{l_{\rm mfp}} \quad \text{for} \quad 0 < \omega < l_{\rm mfp}\mu^2$$

$$\frac{dN}{d\omega dt} \approx \frac{\alpha}{\pi\omega} N_c \sqrt{\frac{\mu^2}{l_{\rm mfp}\omega}} \quad \text{for} \quad l_{\rm mfp}\mu^2 < \omega < l_{\rm mfp}\mu^2 (L/l_{\rm mfp})^2$$

$$\frac{dN}{d\omega dt} \approx \frac{\alpha}{\pi\omega}\frac{N_c}{L} \quad \text{for} \quad l_{\rm mfp}\mu^2 (L/l_{\rm mfp})^2 < \omega < E$$

$$\frac{dN}{d\omega dt} \approx \frac{\alpha}{\pi|\omega|}\frac{N_c}{l_{\rm mfp}} e^{-|\omega|/T} \quad \text{for} \quad \omega < 0$$

Interpretation

With $E = p$ (original parton energy) and the system size L and $(1 - e^{-n\omega/E}) \approx n\omega/E$:

- If $E < E_{\rm LPM} = \mu^2 l_{\rm mfp}$,

$$\ln R_{AA} \approx -L \int_0^E d\omega \, \frac{dN}{d\omega dt} \left(\frac{n\omega}{E}\right) \approx \frac{nL}{E} \int_0^E d\omega\omega \, \left(\frac{\alpha_S}{\pi\omega} \frac{N_c}{l_{\rm mfp}}\right) \sim \text{Const.}$$

  Flat R_{AA}

- If $E_{\rm LPM} < E < E_L = L^2\mu^2/l_{\rm mfp}$,

$$\begin{aligned}
\ln R_{AA} &\approx -\frac{nL}{E} \int_0^{E_{\rm LPM}} d\omega\omega \, \left(\frac{\alpha_S}{\pi\omega} \frac{N_c}{l_{\rm mfp}}\right) \\
&\quad - \frac{nL}{E} \int_{E_{\rm LPM}}^{E} d\omega\omega \, \left(\frac{\alpha_S}{\pi\omega} N_c \sqrt{\frac{\mu^2}{l_{\rm mfp}\omega}}\right) \\
&= -\frac{nL\alpha_S N_c}{\pi l_{\rm mfp}} \left(2\sqrt{\frac{E_{\rm LPM}}{E}} - \frac{E_{\rm LPM}}{E}\right)
\end{aligned}$$

  Slowly rising R_{AA}

Plateau at high p_T

- If $l_{\rm coh} > L$, effectively only a single scattering happens. $\Longrightarrow$ Goes back to BH

If $E > E_L = L^2\mu^2/\lambda$,

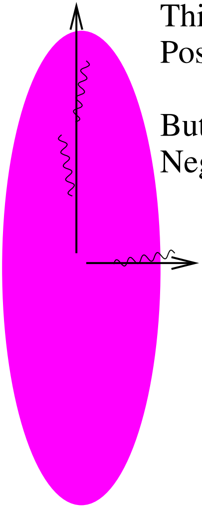
$$\begin{aligned}
\ln R_{AA} &\approx -\frac{nL}{E}\int_0^{E_{\rm LPM}} d\omega\omega\left(\frac{\alpha_S}{\pi\omega}\frac{N_c}{l_{\rm mfp}}\right) \\
&\quad - \frac{nL}{E}\int_{E_{\rm LPM}}^{E_L} d\omega\omega\left(\frac{\alpha_S}{\pi\omega}N_c\sqrt{\frac{\mu^2}{l_{\rm mfp}\omega}}\right) \\
&\quad - \frac{nL}{E}\int_{E_L}^{E} d\omega\omega\left(\frac{\alpha_S}{\pi\omega}\frac{N_c}{L}\right) \\
&\approx -n\frac{\alpha_S N_c}{\pi}\left(1 + \frac{E_L}{E}(1 - l_{\rm mfp}/L)\right)
\end{aligned}$$

This is approximately constant for large E.

What is R_{AA} telling us?

- Dip-rise-flat feature qualitatively understandable
- Opaque medium
- Density of the medium
- Dip in R_{AA}: Could be an indirect indication of the initial temperature.
- Plateau at high p_T: Could be an indication that $l_{\rm coh} > L$ is reached.
  $\Longrightarrow$ Extract $\hat{q}$ from $l_{\rm coh} \approx \sqrt{\omega/\hat{q}}$?

Understanding high p_T part of v_2



This jet loses more energy:
Positive v2

But it radiates more photons:
Negative photon v2

Understanding high p_T part of v_2

- For $E \lesssim E_{\rm LPM}$, $\Delta E \propto E \ln R_{AA} \propto LE$
  Roughly speaking,

$$v_2 = \frac{p_x - p_y}{p_x + p_y} \propto (L_y - L_x)$$

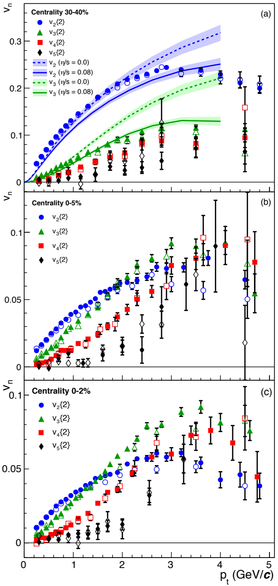
- For $E_{\rm LPM} \lesssim E \lesssim E_L$, $\Delta E \propto E \ln R_{AA} \propto \sqrt{\hat{q}E}L$
  then

$$v_2 = \frac{p_x - p_y}{p_x + p_y} \propto (L_y - L_x)\frac{\sqrt{\hat{q}}}{\sqrt{E}}$$

- For $E \gtrsim E_{\rm L}$ $\Delta E \propto (E + E_L)$
  then

$$v_2 \sim \frac{(L_y^2 - L_x^2)}{E}$$

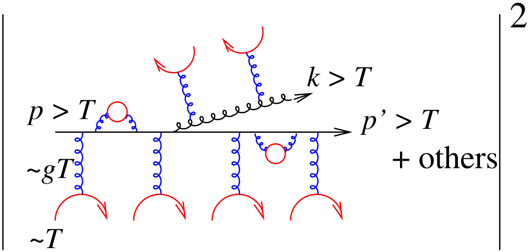
LHC Data



- Data: ALICE, 1105.3865v2
- High p_T v_2: Flat, then falls like $1/\sqrt{p_T}$ and then $1/p_T$.
- Can understand high p_T data qualitatively although $1/p_T$ behavior may not be visible since this is for $E > E_L$.
- The slope $dv_2/dp_T \propto -\sqrt{\hat{q}}$
- Of course, this is very rough: Viscosity also curves it down and $p_T \gtrsim 3\,\text{GeV}$ may not be high enough.

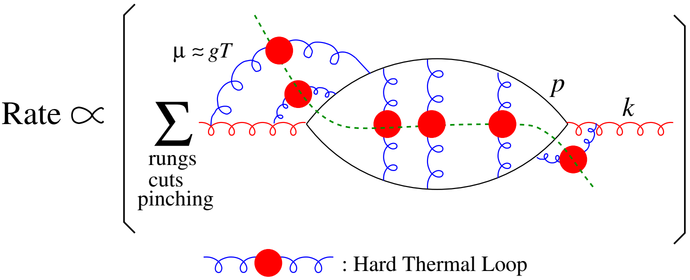
Thermal QCD calculation of the radiation rate

McGill-AMY



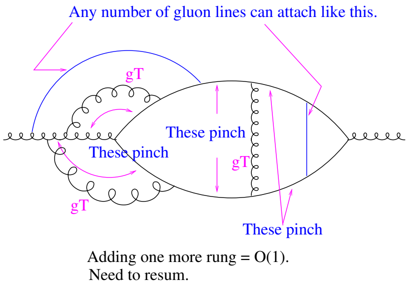
- Medium is weakly coupled QGP with thermal quarks and gluons
- Requires $g \ll 1$, $p > T$, $k > T$

McGill-AMY



- Medium is weakly coupled QGP with thermal quarks and gluons
- Requires $g \ll 1$, $p > T$, $k > T$
- Sum all interactions with the medium including the self-energy

McGill-AMY



- Medium is weakly coupled QGP with thermal quarks and gluons
- Requires $g \ll 1$, $p > T$, $k > T$
- Sum all interactions with the medium including the self-energy
- Leading order: 3 different kinds of collinear pinching poles

- What pinching does: Let

$$P = \left(\frac{i}{p_1^2 + m_2^2 + 2iE_1\Gamma_1}\right)^* \frac{i}{p_2^2 + m_1^2 + 2iE_2\Gamma_2}$$

- Poles for positive energies at $p_1^0 = E_1 - i\Gamma_1$ and $p_2^0 = E_2 + i\Gamma_2$
- If $p_1^0 = E_1 - i\Gamma_1$ puts p_2 also almost on-shell,

$$P \propto \frac{1}{E_1 E_2}\delta(p_1^0 - E_1)\frac{1}{\delta E + i\Gamma_2 + i\Gamma_1}$$

  where δE: difference in the real part of the energy
- Physically, this means that an almost on-shell particle lives a long time $\Delta t \sim 1/\delta E \sim 1/\Gamma \implies$ Introduces a secular divergence

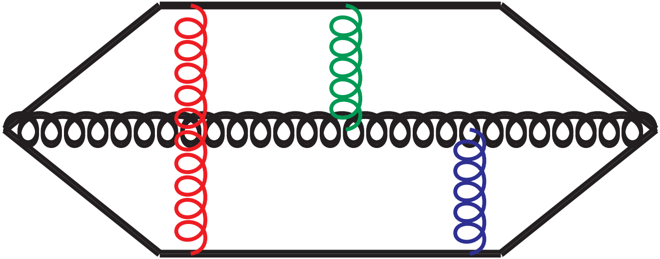
McGill-AMY

- Pinching poles occur when
  - $p_1 \approx p_2$: Soft momentum exchange or radiation.
    If $p_1^2 + m^2 = O(g^2T^2)$, so is $p_2^2 + m^2 = O(g^2T^2)$.
  - $p_2 = xp_1$: Collinear radiation.
    When $p_1^2 + m^2 = O(g^2T^2)$,

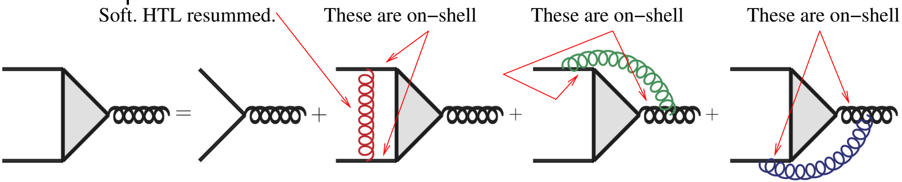
$$p_2^2 + m^2 = x^2p_1^2 + m^2 + O(g^2T^2) = (1 - x^2)m^2 + O(g^2T^2)$$

    When $m \approx gT$, the whole expression is $O(g^2T^2)$.

McGill-AMY



- SD-Eq:



Figures from G. Qin

McGill-AMY

- SD Equation for the vertex **F**

$$2\mathbf{h} = i\delta E(\mathbf{h},p,k)\mathbf{F}_s(\mathbf{h}) + g^2 \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} C(\mathbf{q}_\perp) \times$$
$$\times \Big\{ (C_s - C_{\rm A}/2)[\mathbf{F}_s(\mathbf{h}) - \mathbf{F}_s(\mathbf{h}{-}k\,\mathbf{q}_\perp)]$$
$$+(C_{\rm A}/2)[\mathbf{F}_s(\mathbf{h}) - \mathbf{F}_s(\mathbf{h}{+}p\,\mathbf{q}_\perp)]$$
$$+(C_{\rm A}/2)[\mathbf{F}_s(\mathbf{h}) - \mathbf{F}_s(\mathbf{h}{-}(p{-}k)\,\mathbf{q}_\perp)] \Big\},$$
$$\delta E(\mathbf{h},p,k) = \frac{\mathbf{h}^2}{2pk(p{-}k)} + \frac{m_k^{g2}}{2k} + \frac{m_{p-k}^{s2}}{2(p{-}k)} - \frac{m_p^{s2}}{2p}.$$

- $\mathbf{h} = (\mathbf{p}\times\mathbf{k})\times\mathbf{e}_{||}$ — Must keep track of both $\mathbf{p}_\perp$ and $\mathbf{k}_\perp$ now. For photons, we could just set $\mathbf{k}_\perp = 0$.

- SD Equation for the vertex **F**

$$
\begin{aligned}
2\mathbf{h} &= i\delta E(\mathbf{h},p,k)\mathbf{F}_s(\mathbf{h}) + g^2 \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} C(\mathbf{q}_\perp) \times \\
&\times \Big\{ (C_s - C_{\rm A}/2)[\mathbf{F}_s(\mathbf{h}) - \mathbf{F}_s(\mathbf{h}-k\,\mathbf{q}_\perp)] \\
&\quad +(C_{\rm A}/2)[\mathbf{F}_s(\mathbf{h}) - \mathbf{F}_s(\mathbf{h}+p\,\mathbf{q}_\perp)] \\
&\quad +(C_{\rm A}/2)[\mathbf{F}_s(\mathbf{h}) - \mathbf{F}_s(\mathbf{h}-(p-k)\,\mathbf{q}_\perp)] \Big\}, \\
\delta E(\mathbf{h},p,k) &= \frac{\mathbf{h}^2}{2pk(p-k)} + \frac{m_k^{g2}}{2k} + \frac{m_{p-k}^{s2}}{2(p-k)} - \frac{m_p^{s2}}{2p} .
\end{aligned}
$$

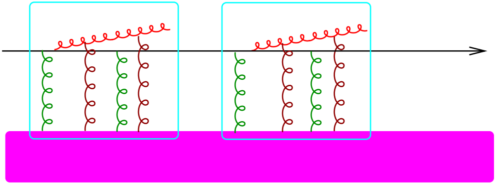
- s: Process dependence. $q \to qg$, $g \to gg$, $g \to q\bar{q}$.
- $g \to q\bar{q}$: Exchange coeff. of the first and second line
- m_s^2: Medium induced thermal masses of the emitter.

McGill-AMY

- Rate for $p > T, k > T$ (valid for $p \gg T$ and $k \gg T$ as well)

$$
\begin{aligned}
\frac{dN_g(p,k)}{dkdt} &= \frac{C_s g_s^2}{16\pi p^7} \frac{1}{1 \pm e^{-k/T}} \frac{1}{1 \pm e^{-(p-k)/T}} \times \\
&\times \left\{ \begin{array}{cc} \frac{1+(1-x)^2}{x^3(1-x)^2} & q \to qg \\ N_f \frac{x^2+(1-x)^2}{x^2(1-x)^2} & g \to q\bar{q} \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g \to gg \end{array} \right\} \\
&\times \int \frac{d^2\mathbf{h}}{(2\pi)^2} 2\mathbf{h} \cdot \mathrm{Re}\, \mathbf{F}_s(\mathbf{h}, p, k),
\end{aligned}
$$

- s: Process dependence.

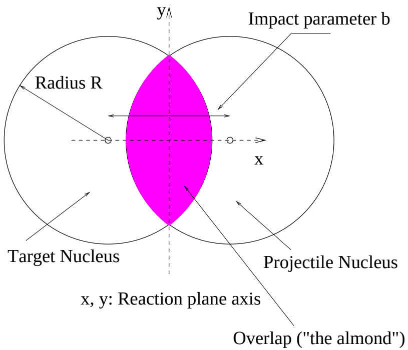


- Evolution - Medium enters through $T(t,\mathbf{x})$ and $u^\mu(t,\mathbf{x})$

$$\frac{d\mathcal{P}_q(p)}{dt} = \int_k \mathcal{P}_q(p+k)\frac{dN^q_{qg}(p+k,k)}{dkdt} - \mathcal{P}_q(p)\int_k \frac{dN^q_{qg}(p,k)}{dkdt} + \int_k 2\mathcal{P}_g(p+k)\frac{dN^g_{q\bar{q}}(p+k,k)}{dkdt},$$

$$\frac{d\mathcal{P}_g(p)}{dt} = \int_k \mathcal{P}_q(p+k)\frac{dN^q_{qg}(p+k,p)}{dkdt} + \int_k \mathcal{P}_g(p+k)\frac{dN^g_{gg}(p+k,k)}{dkdt} - \mathcal{P}_g(p)\int_k\left(\frac{dN^g_{q\bar{q}}(p,k)}{dkdt} + \frac{dN^g_{gg}(p,k)}{dkdt}\Theta(k-p/2)\right)$$

McGill-AMY

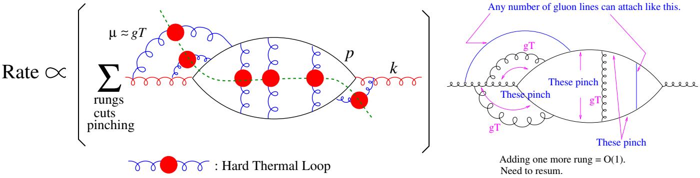


- Modified fragmentation function with jet initial condition $\mathbf{s}, \mathbf{n}, p_i$

$$\bar{D}_{\pi^0,c}(z,Q;\mathbf{s},\mathbf{n}) = \int dp_f \frac{z'}{z} \left(\mathcal{P}_{qq/c}(p_f;p_i) D_{\pi^0/q}(z',Q) + \mathcal{P}_{g/c}(p_f;p_i) D_{\pi^0/g}(z',Q) \right) ,$$

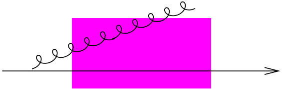
$$\tilde{D}(z,Q) = \int d^2s \, \frac{T_A(\mathbf{s})T_B(\mathbf{s}+\mathbf{b})}{T_{AB}(\mathbf{b})} \, \bar{D}_{\pi^0,c}(z,Q;\mathbf{s},\mathbf{n})$$

McGill-AMY

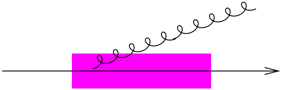


- Collision geometry including path length fluctuations are all included.
- Both BH and LPM limits included
- Includes all leading order splittings
- Includes thermal absorption
- All produced quarks and gluons fragment
- Medium evolution ($T(t, \mathbf{x})$, $u_\mu(t, \mathbf{x})$) fully taken into account including the effect of flow vector
- Easy to add other process such as elastic coll. γ production within leading order QCD/QED.

What is not included yet (vacuum-medium interference)



Included in the PDF scale dependence



Correctly dealt with in the AMY−McGill approach

These two can interfere.

Part of this in the fragmentation function

What is not included yet (vacuum-medium interference)

- The L^2 dependence in the heuristic BDMPS expression we got before

$$\ln R_{AA} \approx -n\frac{\alpha_S N_c}{\pi}\left(1 - \frac{L\mu^2}{E} + \frac{E_L}{E}\right)$$

  cannot be reproduced since original AMY always assumes $L > l_{\rm coh}$.

- Finite size effect is being worked on (Caron-Huot and Gale).

The Evolving Medium

Hydrodynamic evolution

- As the jets propagate, medium undergoes an evolution of its own.
- Best modeling tool we have: Ideal Hydrodynamics. It solves

$$\partial_\mu T^{\mu\nu} = 0 \text{ and } \partial_\mu j_B^\mu = 0$$

with the Ideal hydro ansatz

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu + P g^{\mu\nu} \;\text{ and }\; j_B^\mu = \rho_B u^\mu$$

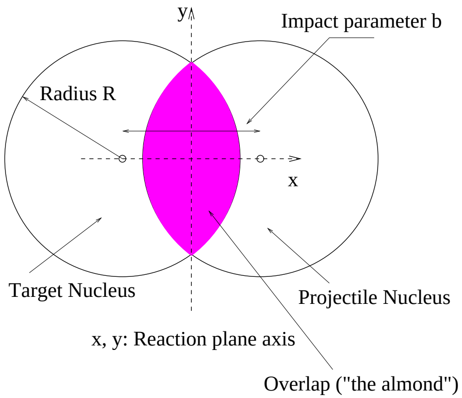
and an EoS

$$P = f(\varepsilon, \rho_B)$$

with *suitable* initial conditions.

- Medium evolution: $\epsilon(t, \mathbf{x})$, $u^\mu(t, \mathbf{x})$
- Equivalently, $T(t, \mathbf{x})$, $u^\mu(t, \mathbf{x})$

Geometry



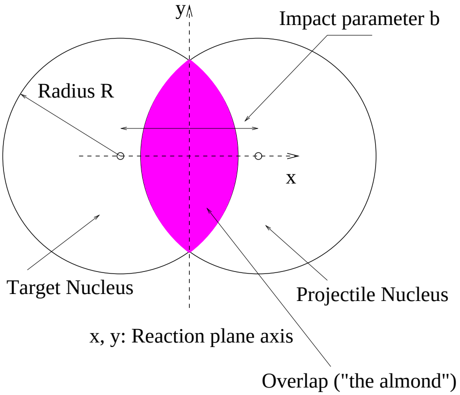
- Density function

$$T_A(\mathbf{s}) = \int dz\, \rho_A(\mathbf{s}, z)$$

- Overlap function:

$$T_{AB}(\mathbf{s}, \mathbf{b}) = T_A(\mathbf{s})\, T_B(\mathbf{b} + \mathbf{s})$$

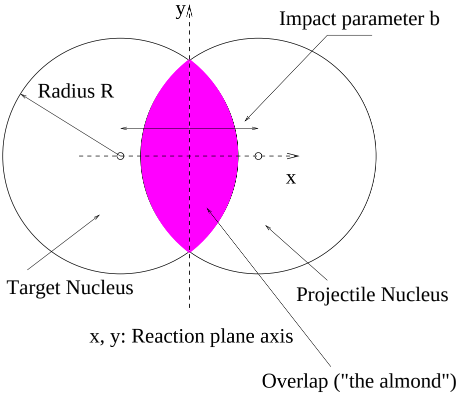
Geometry



- Participants: $N_{\rm part}(\mathbf{s},\mathbf{b}) \propto T_A(\mathbf{s}) + T_B(\mathbf{b}+\mathbf{s})$
- Binary scatterings: $N_{\rm bin}(\mathbf{s},\mathbf{b}) \propto T_{AB}(\mathbf{s},\mathbf{b})$
- Initial energy density

$$\varepsilon(\mathbf{s},\mathbf{b}) = c_1\,[T_A(\mathbf{s}) + T_B(\mathbf{b}+\mathbf{s})] + c_2\,T_{AB}(\mathbf{s},\mathbf{b})$$

Geometry



- Ultimately, initial geometry determines the initial conditions and the final flow pattern.
- Initial geometry also determines number of jets at **s** and the path conditions for those jets.

Static vs Dynamic medium

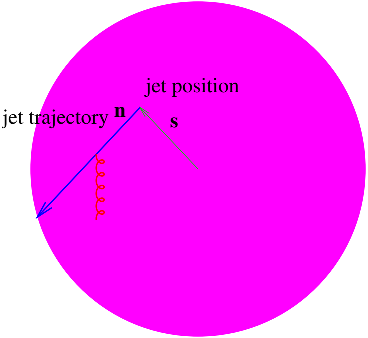
- Three places where "Dynamic" medium enters.
  - Cross-section

$$\frac{d\sigma_{GW}}{dq^2} = \frac{C}{(q^2+\mu^2)^2} \quad \text{vs} \quad \frac{d\sigma_{QCD-HTL}}{dq^2} = \frac{C}{q^2(q^2+m_D^2)}$$

  - Space-time dependence of T or $\mu, \hat{q}$.
  - The effect of flow

Two possible approaches to evolution

- $\frac{dN}{d\omega dt}$ is independent of the jet energy
  - Determine the position of the jet **s**.
  - Fix the direction **n** to get the straight line trajectory.



Two possible approaches to evolution

- $\dfrac{dN}{d\omega dt}$ is independent of the jet energy
  - Determine the position of the jet **s**.
  - Fix the direction **n** to get the straight line trajectory.
  - Calculate the average number of emitted gluons

$$\langle N_g \rangle = \int d\omega \int_{t_0}^{t_f} dt \, \frac{dN_g}{d\omega dt}$$

along the trajectory. $dN_g/d\omega dt$ depends on $(t, \mathbf{x})$ through T or $(\mu, \hat{q})$.

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$$P_n = e^{-\langle N_g \rangle} \frac{\langle N_g \rangle^n}{n!}$$

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  - Can express it as $P_n(\epsilon)$ using an energy conserving δ-function

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  - Works as long as one can easily calculate $\dfrac{dN_g}{d\omega}$ along the trajectory

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  - Use the Poisson ansatz to get probability to emit n gluons

$$P_n = e^{-\langle N_g \rangle} \frac{\langle N_g \rangle^n}{n!}$$

  - Relatively simple to implement

Two possible approaches to evolution

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  - BDMS, (D)GLV, AWS, ...

Two possible approaches

- $\frac{dN_g}{d\omega dt}$ depends on the jet energy
  - Determine the position **s**
  - Determine the direction **n**
  - Solve (numerically)

$$\frac{dP(p,t)}{dt} = \int_k \frac{dN}{d\omega dt}(p+k,k)P(p+k,t) - P(p,t)\int_k \frac{dN}{d\omega dt}(p,k)$$

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  - Can deal with changing environment and changing trajectory

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  - Can keep track of both quarks and gluons at the same time

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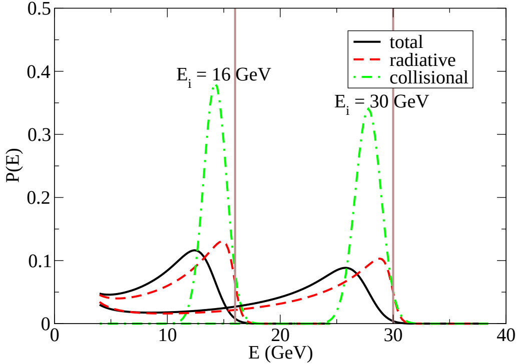
  - Can deal with changing environment and changing trajectory
  - Can keep track of both quarks and gluons at the same time
  - Easy to add other processes including γ production
  - McGill-AMY

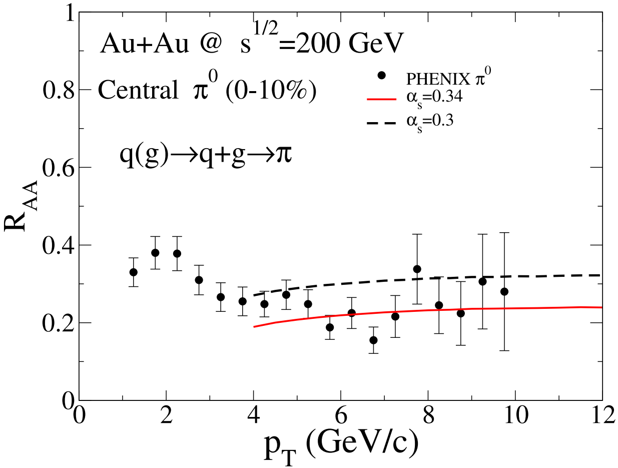
Example evolution of a single jet (Qin)

- The final momentum distribution $P(E, t_f)$ of a single quark jet after passing through RHIC medium ($b = 2.4$ fm)



- Medium described by (3+1)D ideal hydrodynamics.
- The jet starts at the center and propagates in plane.
- Jet energy loss turned off in hadronic phase.

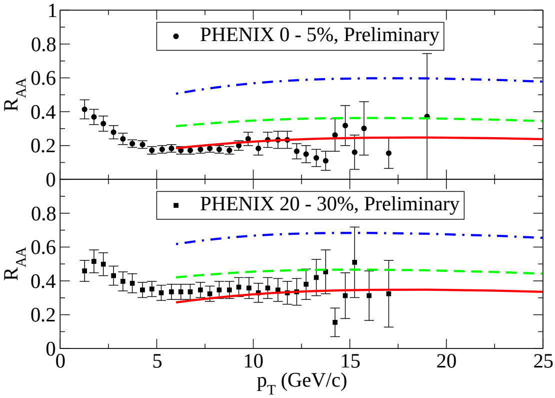
R_{AA} at RHIC - π^0 - Radiation only (Turbide)



$T_i = 370\,\text{MeV}$, $dN/dy = 1260$. 1-D Bjorken expansion.

Best $\alpha_s = 0.33$ S.Turbide, C.Gale, S.J. and G.Moore, PRC72:014906,2005

R_{AA} at RHIC – π^0 - Full (Qin)

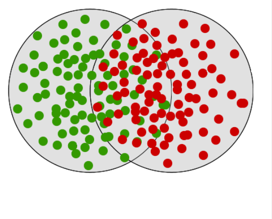


- 3+1D hydro
- Includes radiational *and* collisional energy loss: rad+coll, rad, coll
- Strong coupling α_s: 0.33 (rad) and 0.27 (rad+coll)

Guangyou Qin, J. Ruppert, C. Gale, S. Jeon, G.D. Moore, M.G. Mustafa

Phys.Rev.Lett.100: 072301, 2008

Monte Carlo Approach - MARTINI

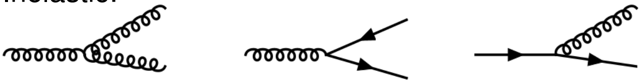


- Sample overlapping region for binary collisions
- Produce high p_T partons by PYTHIA 8.1
- Put them in the hydro background. Sample the total collision rate at each time step according to the local environment and decide whether to interact with the medium.
- If yes, decide which process to enact according to the branching ratio.
- Sample the chosen process to simulate change 4-momentum of the jet parton
- Hadronize by PYTHIA 8.1 when the parton is outside QGP

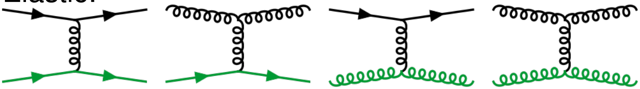
Monte Carlo Approach - MARTINI

Process include in MARTINI (all of them can be switched on & off):

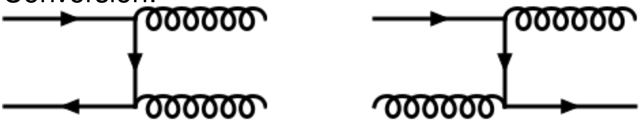
- Inelastic:



- Elastic:

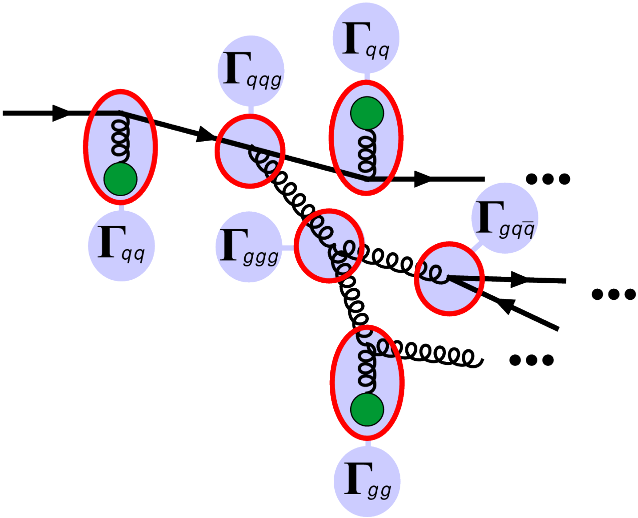


- Conversion:



- Photon: emission & conversion

Monte Carlo Approach - MARTINI



An example path in MARTINI

Ideal MUSIC

- While this is happening in the background ...

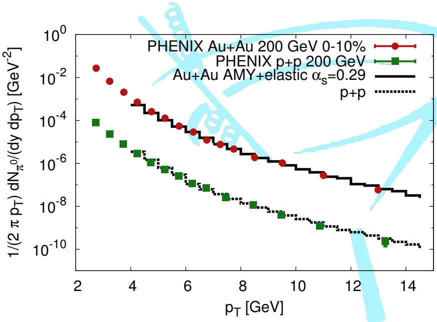
Projection on to the longitudinal plane

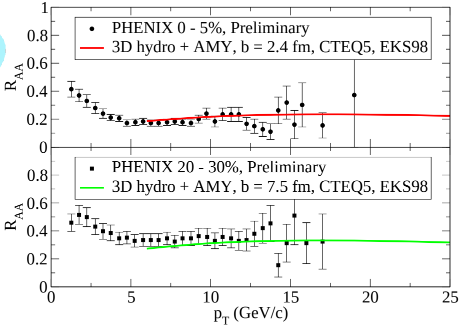
Projection onto the transverse plane

Pion production

[Schenke, Jeon and Gale, Phys. Rev. C 80, 054913 (2009)]

- π^0 spectra and R_{AA}

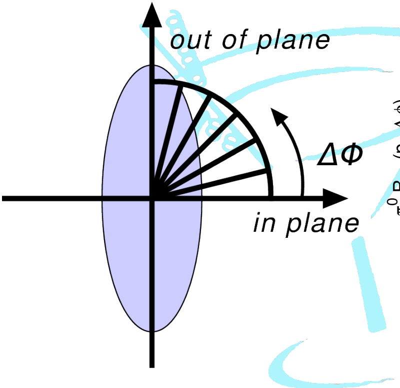


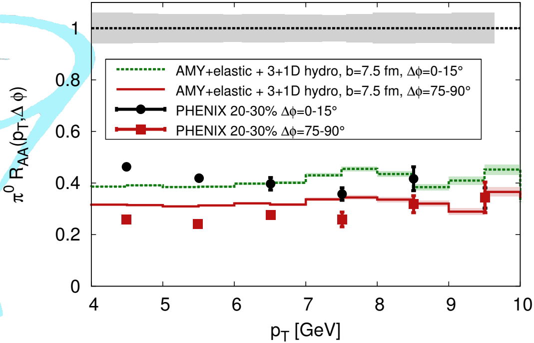


- For RHIC, $\alpha_S = 0.29$

Azimuthal dependence of R_{AA}

- $R_{AA}(p_T, \Delta\phi)$

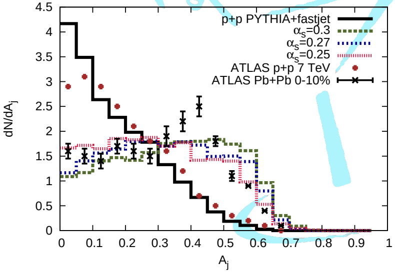


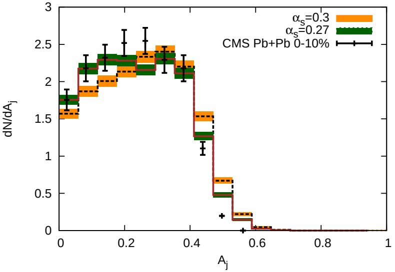


- $\alpha_S = 0.29$

[Young, Schenke, Jeon, Gale, Phys. Rev. C 84, 024907 (2011)].

- $A = (E_t - E_a)/(E_t + E_a)$
- This is with ideal hydro with a smooth initial condition
- Full jet reconstruction with FASTJET
- $\alpha_S = 0.27$ seems to work.





ATLAS, PRL 105 (2010) 252303

CMS, arXiv: 1102.1957 (2011)

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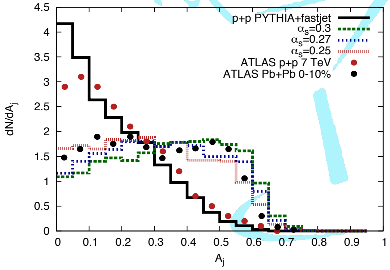
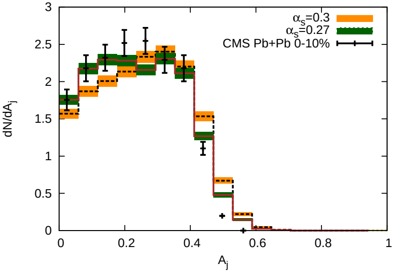


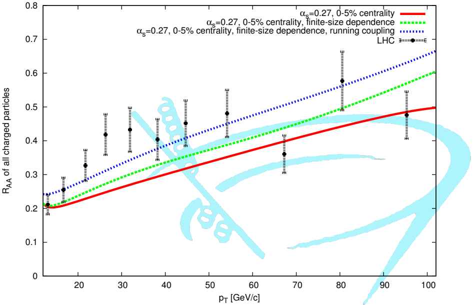
ATLAS, QM 2011

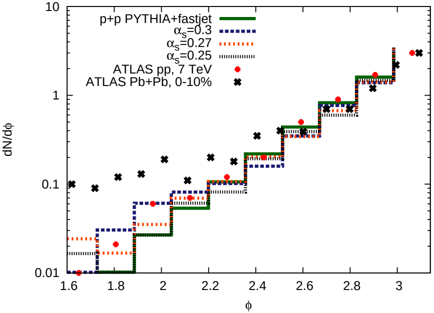


CMS, arXiv: 1102.1957 (2011)

Not the full story

[Clint's HP2012 Proceedings]





- R_{AA} – For LHC, constant α_S suppresses jets too much.
- Need to incorporate finite length effect (Caron-Huot-Gale) and running α_s. This is with maximum $\alpha_S = 0.27$.
- Don't quite get azimuthal dependence yet. $\Delta\phi$ broadening may be due to the background fluctuations $\Longrightarrow$ Need to combine UrQMD background?

Few last words

- So many nuclear experiments are being done/planned. – RHIC, LHC, Raon, FRIB, FAIR, JPARC, Dubina,...
- There never have been a time in history so much information is so readily available.
- This is a great time to be/become a nuclear physicist.
- Work hard. Think hard. Dream big.
- Never say/think, that that should be good enough. Make sure that it is *always excellent*!
- Attention to details, but don't lose sight of the big picture.
- Look around you.