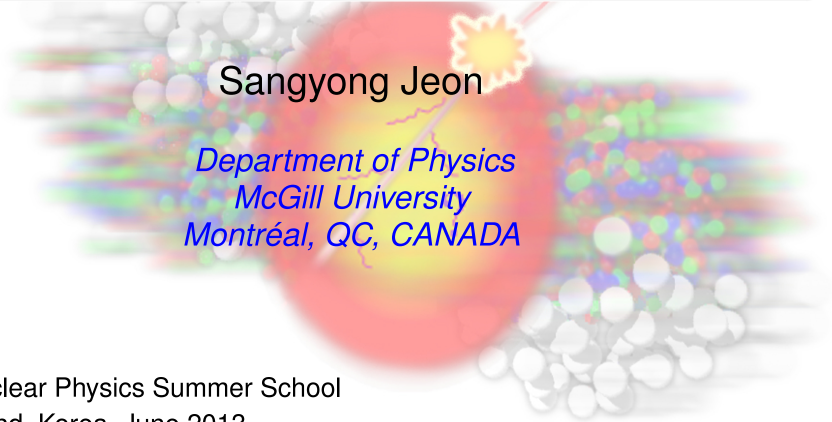
Introduction to Hard Probes in Heavy Ion Collisions



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

McGill is in Montréal, Québec, Canada

Montreal
QC
Canada

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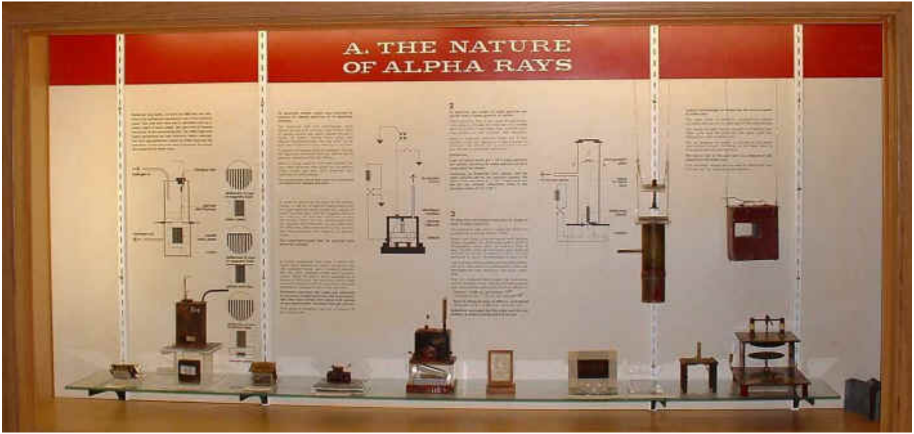
Mr. McGill going home after a hard day's work.

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

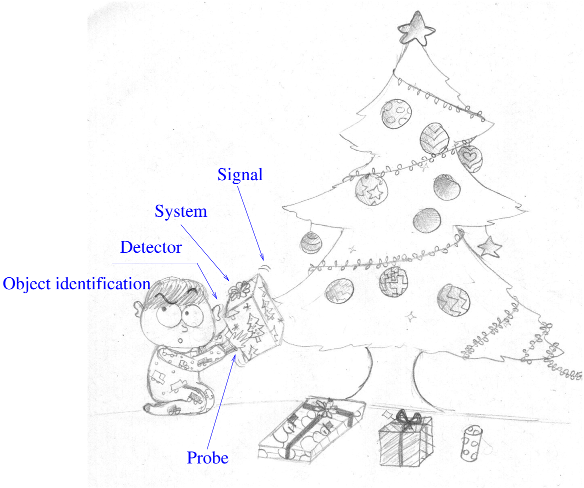
1. pQCD
2. Jet Quenching
3. Hard Photons

What is a hard probe?

- Early hard probe experiments

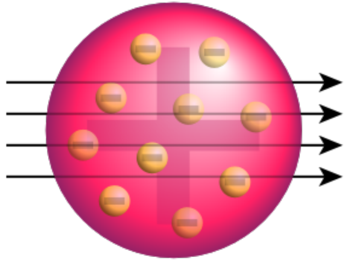
What is a hard probe?

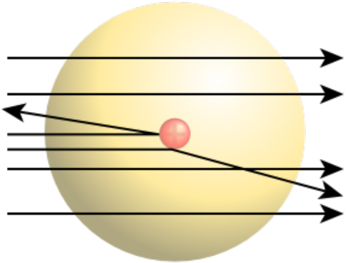
- Early hard probe experiments



What is a hard probe?

- Early hard probe experiments



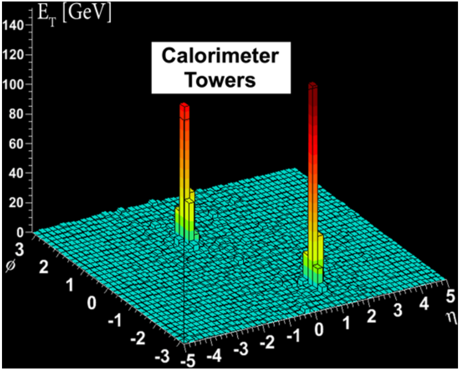


- Rutherford's α scattering experiment

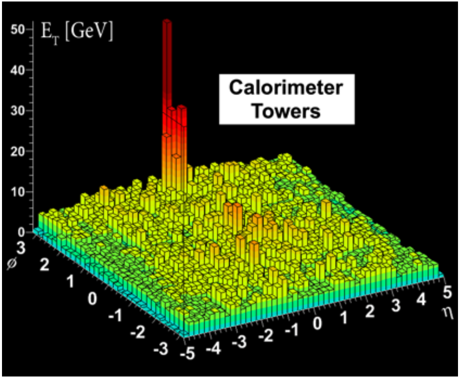
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi}{2} Z^2 \alpha_{\rm EM}^2 \left(\frac{\hbar c}{E_{\rm kin}}\right)^2 \times \frac{1}{(1-\cos\theta)^2}$$

- 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

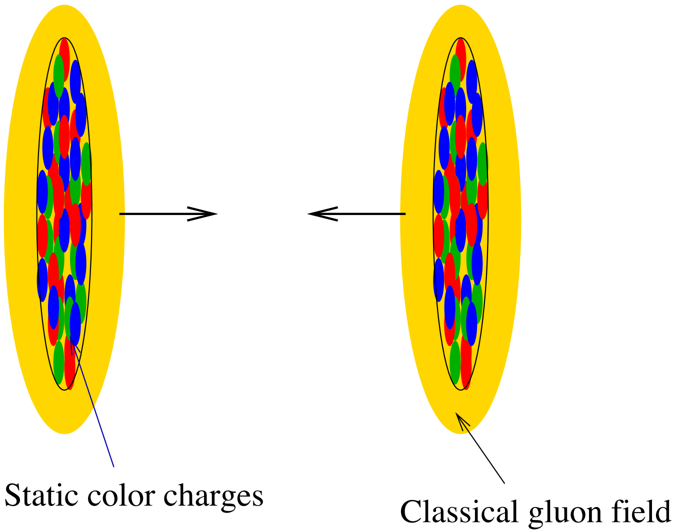
Probes

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

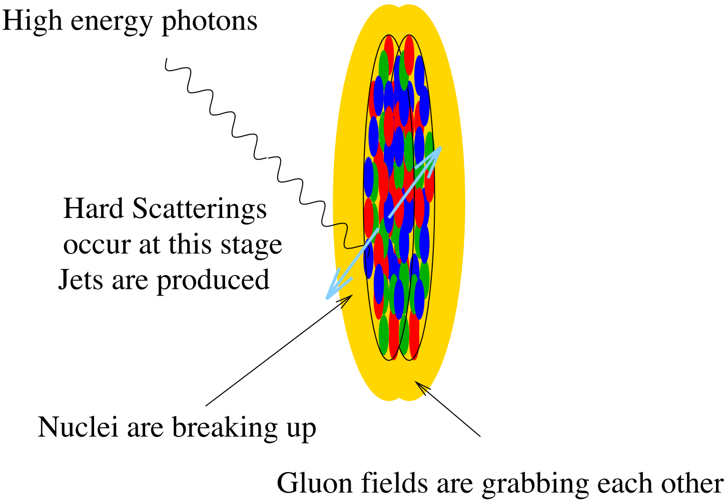
Goal

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

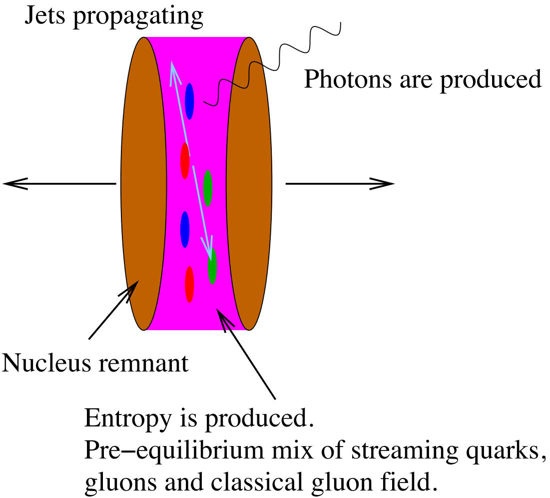
(Very) Schematic view of heavy ion collisions



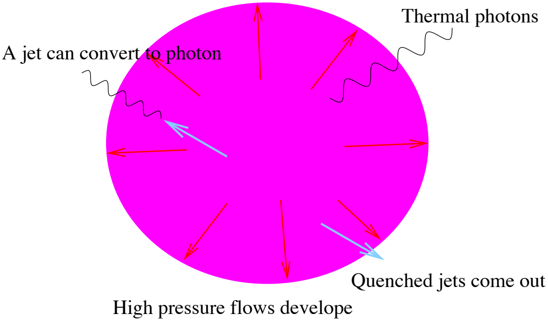
(Very) Schematic view of heavy ion collisions



(Very) Schematic view of heavy ion collisions

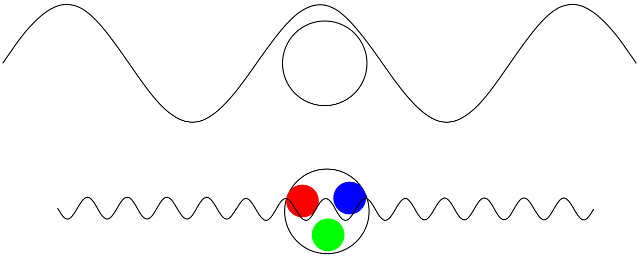


(Very) Schematic view of heavy ion collisions



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 $\Delta x \approx \lambda$.

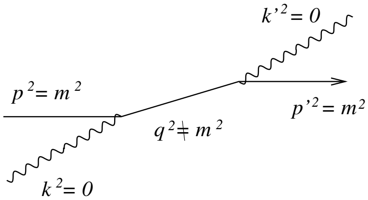
Review of some basic concepts

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

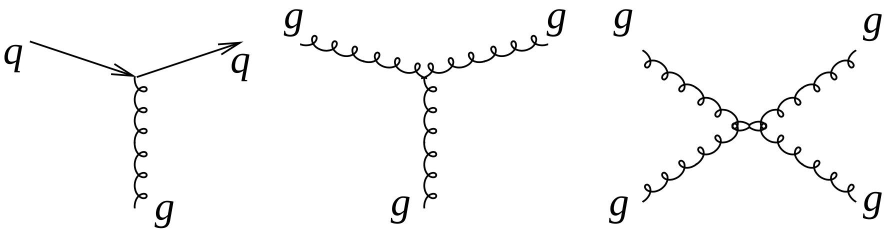
- An off-shell state can exist only for $\Delta t \sim 1/|\Delta E|$.



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

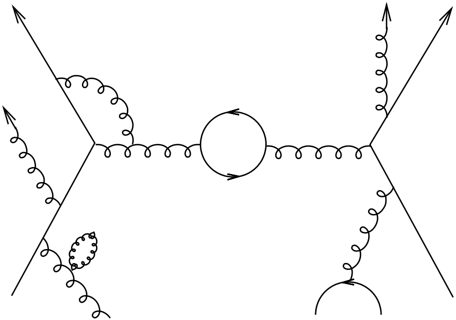
Perturbative QCD

QCD
– Interaction of quarks and gluons



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

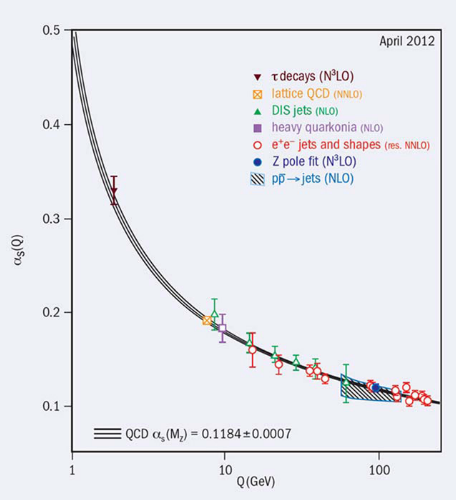
Perturbative QCD (pQCD)



Of course, things can get complicated.

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

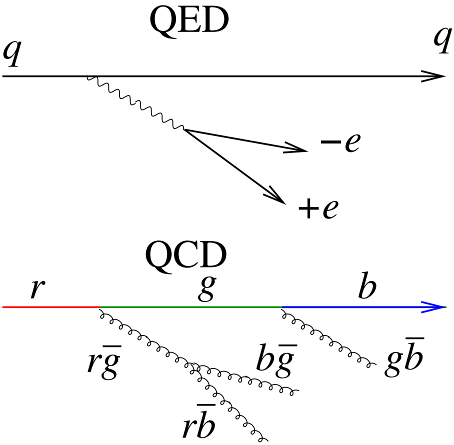
Perturbative QCD (pQCD)



S. Bethke, arXiv:1210.0325.

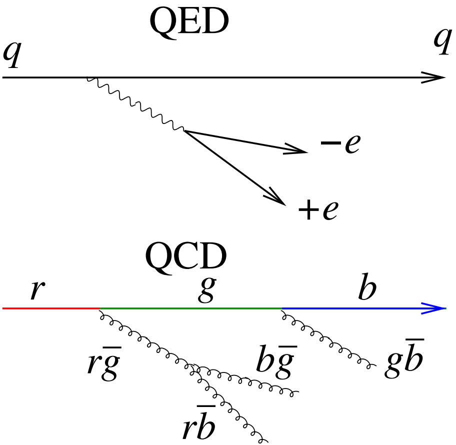
- Perturbative expansion possible because of asymptotic freedom
- $Q^2 \dfrac{\partial \alpha_S}{\partial Q^2} = -\beta_0 \alpha_S^2 - \beta_1 \alpha_S^3 + \cdots$
- $\alpha_S(Q^2) \approx$
$$\frac{1}{((33 - 2n_f)/12\pi) \ln(Q^2/\Lambda^2_{\rm QCD})}$$
- pQCD reliable for $Q \gtrsim 1$ GeV

Intuitive understanding of asymptotic freedom



- QED: Surrounded by virtual $e\bar{e}$ cloud
- Virtual $-e$ cloud drawn closer to $q > 0$ $\Longrightarrow$ Screening
- Larger Q $\Longrightarrow$ smaller distance $\Longrightarrow$ Sees less of the cloud $\Longrightarrow$ 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

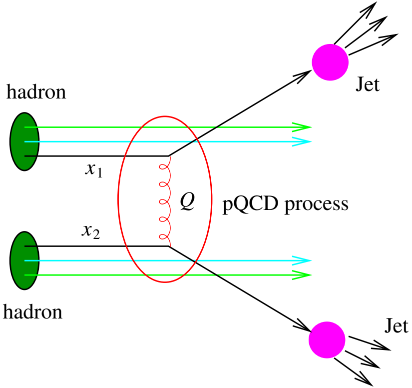
Difficulties with QCD

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

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

- 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.

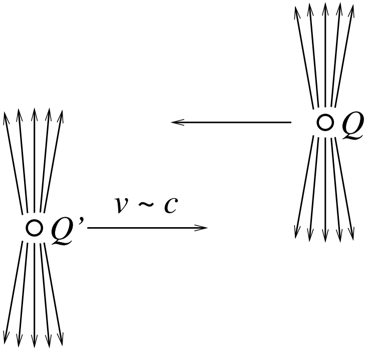
Factorization Theorem

- 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

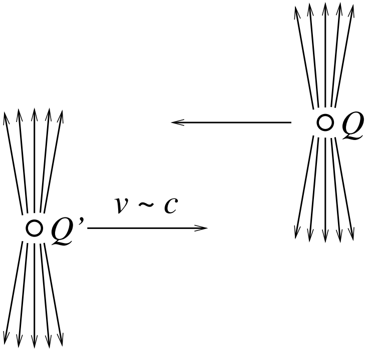
$$\varphi = Q/|\mathbf{r}|$$

- 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

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

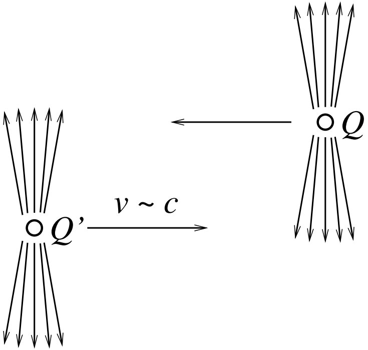
- In the moving frame

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

- 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

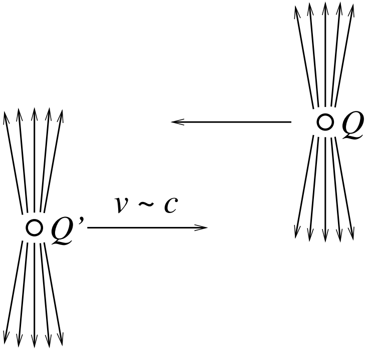
  $F^{\mu\nu} \approx 0$ unless $z \approx vt$

- 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.

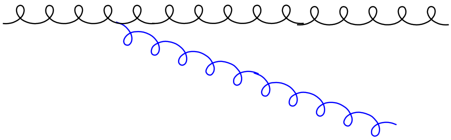
DGLAP Equation

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

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

DGLAP Equation

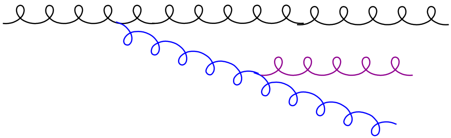
- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.



$Q_0 < Q_1$: Start to resolve another parton

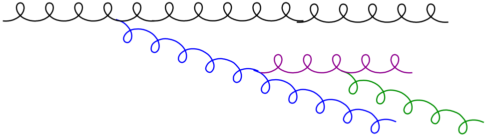
DGLAP Equation

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



$Q_0 < Q_1 < Q_2$: And another

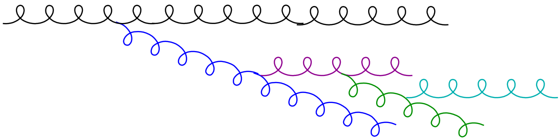
- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.



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

DGLAP Equation

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



You get the idea

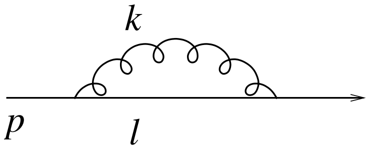
DGLAP Equation

- $f(x, Q_f)$: 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



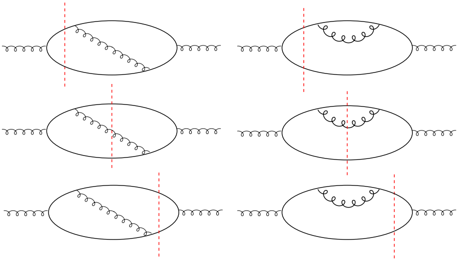
- p is on-shell: $p^2 = 0$
- Diverges when either k or l is on-shell
- This happens either k is very soft so that

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

- or p and k are almost collinear

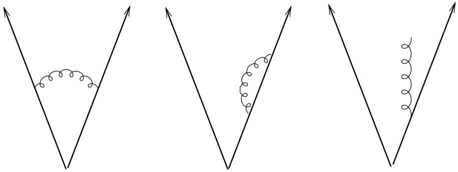
$$l^2 = (p - k)^2 = p^2 + k^2 - 2pk$$
$$\approx 0$$

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

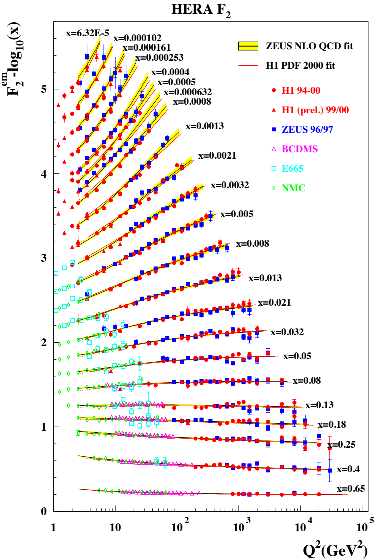
Factorization Theorem

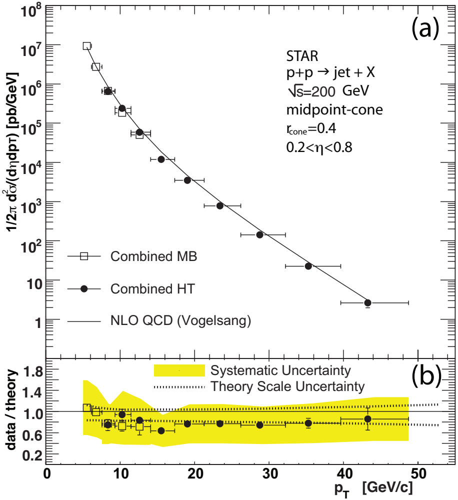
- Splitting function similarly runs
- 3 different scales: Q_f for the pdf, Q_R for $\sigma(Q_R)$ and Q_f' for the fragmentation function
- In principle, physical observables should not depend on these scales. However, factorization theorem is only *approximate*.
- Lots of freedom to choose the scales.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

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

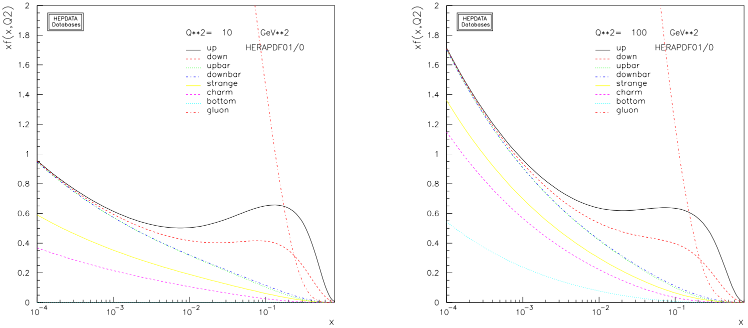
works OK where p_T is the momentum of the *final* state particle.

pQCD & Factorization at work

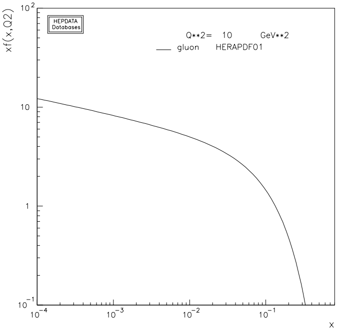


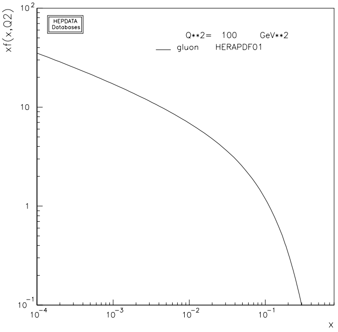


pQCD & Factorization at work



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





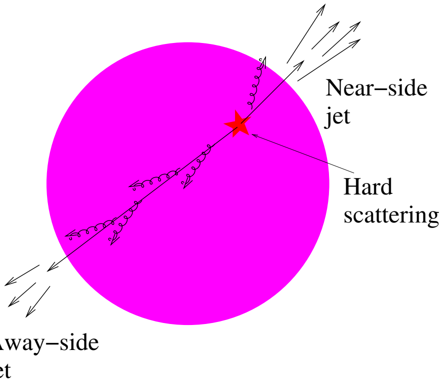
- Gluon distributions for $Q^2 = 10\,\mathrm{GeV}^2$ and $Q^2 = 100\,\mathrm{GeV}^2$.

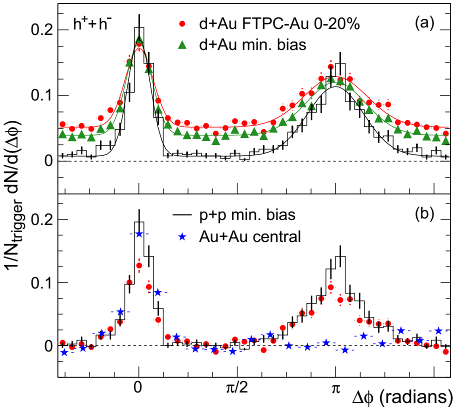
Jet Quenching

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

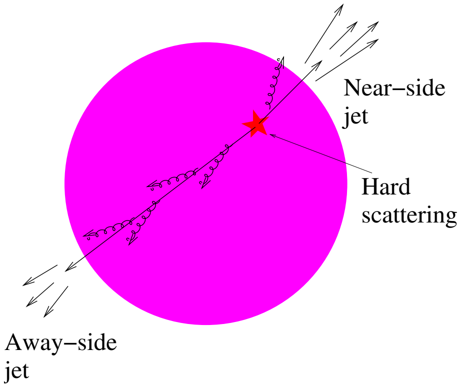
Away side jet disappears! – Proof of principle

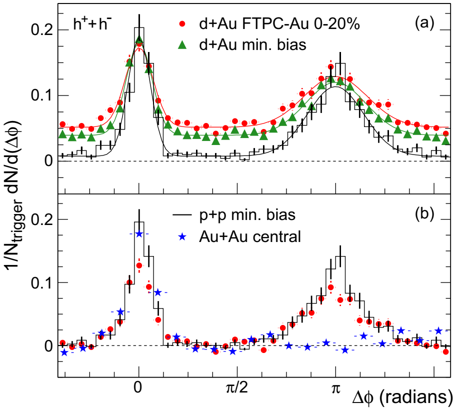




STAR PRL91, 072304 (2003)

Away side jet disappears! – Proof of principle

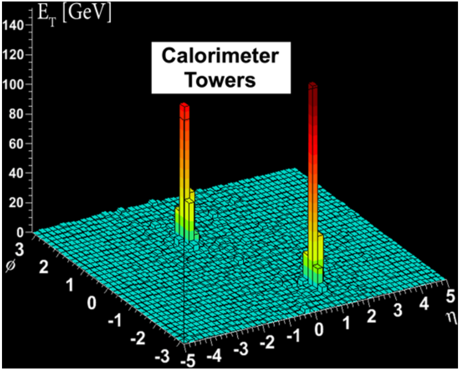




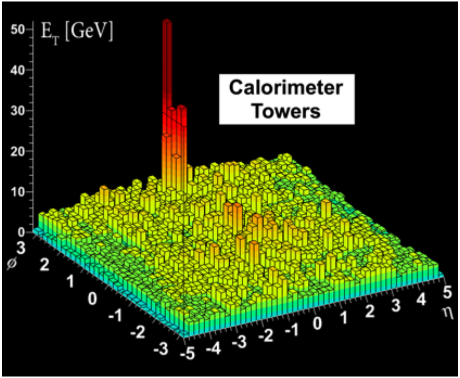
STAR PRL91, 072304 (2003)

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

Away side jet disappears! – Proof of principle

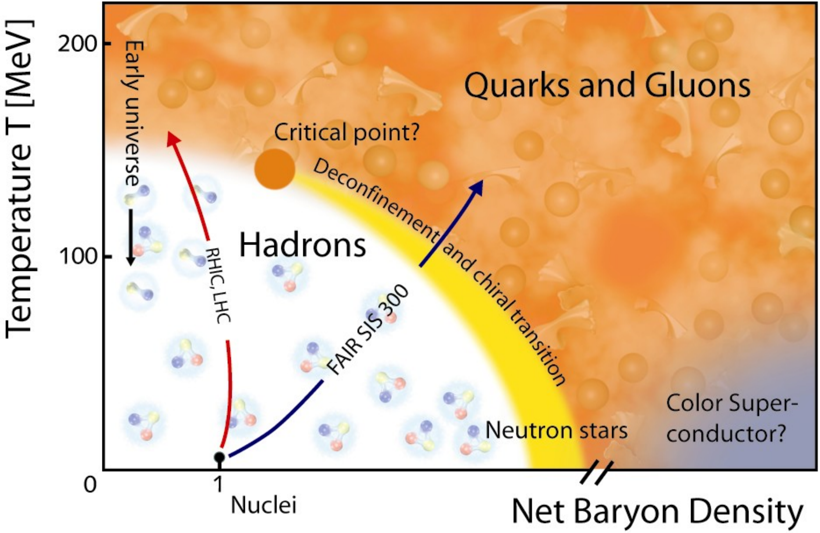


ATLAS: Intact dijets in Pb+Pb



ATLAS: One jet is fully quenched in Pb+Pb

QCD Phase Diagram



Picture credit: GSI (www.gsi.de)

Nobelprize.org

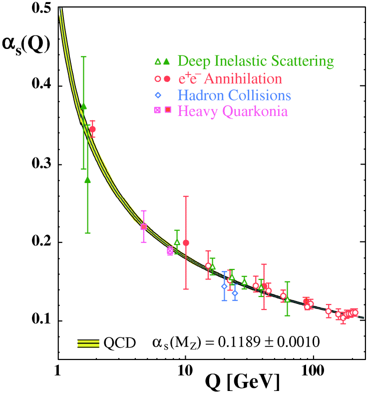
The Nobel Prize in Physics 2004

"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

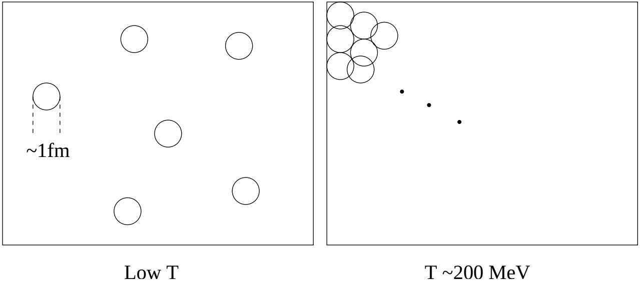
At high T

- 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 $T_{\text{transition}}$



- 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:

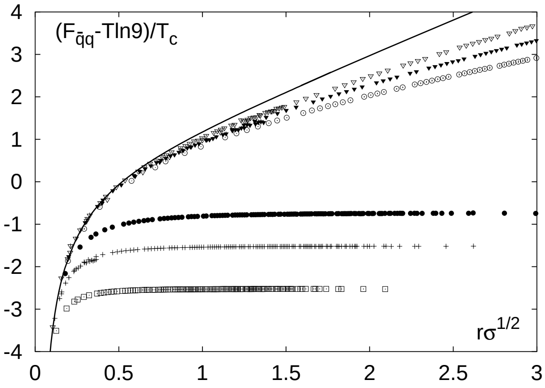
$$l_{\text{inter}} = n^{1/3} \approx 1/T$$

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

Story so far

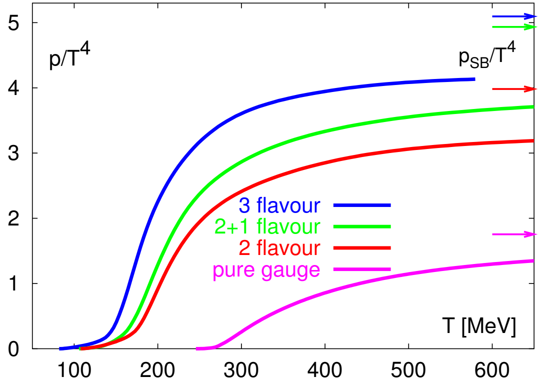
- Perturbative calculation possible much above $\mu = \Lambda_{\rm QCD}$
- $\mu \sim T$ at high T
- If T is much above the binding energy of hadrons
  $\Longrightarrow$ Deconfinement
- At high enough T, the system is a plasma of weakly interacting quarks and gluons
- All the above arguments are plausible 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 $T = 170\,\text{MeV} = 2 \times 10^{12}\,\text{K}$ [F.Karsch et al.] "Cross-over"

Expected properties

- High number density

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

- High energy density

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

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
- $m_p = 940$ MeV ≈ 1 GeV
- $E = mc^2$: 1 GeV $\approx (1/6) \times 10^{-23}$ g

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

- Typical human: ~ 100 kg

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

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

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

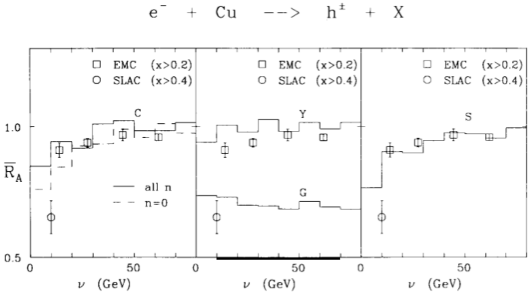


Fig. 4. The ν-dependence of the ratio $\bar{\mathscr{R}}_A$ of hadrons produced in the forward region. The histograms labeled Y, C, G and S correspond to the yoyo formation model, the constituent formation model, the Glauber limit ($l \equiv 0$) and to the string-flip model, respectively. For the constituent 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...

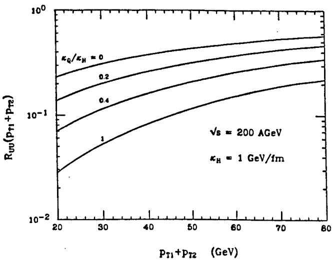


Fig. 7 Dijet reduction factor for central $U+U$ collisions at $\sqrt{s}$ =200 GeV/n as a function of the dijet energy $E = P_{T1} + P_{T2}$, for different values of κ_Q/κ_H assuming κ_H =1 GeV/fm.

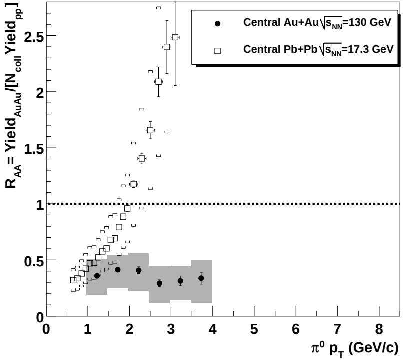
transverse coordinate, ϕ the azimuthal angle of the jet and $\tau_f(r,\phi)$ the escape time. Assuming only Bjorken[31] scaling longitudinal expansion and a Bag model equation of state[31], one can find the time dependence of $dE(\tau)/dx$ and get the reduction rate of jet production at fixed P_T by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

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

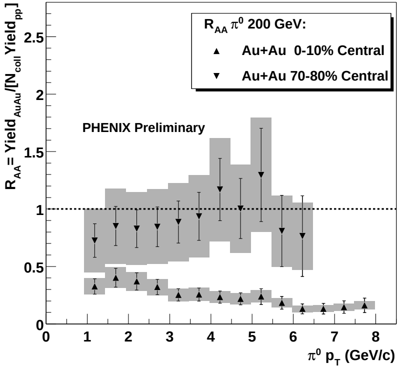
In the plasma phase, the temperature decreases as $T(\tau)/T_c = (\tau_Q/\tau)^{1/3}$. According to Eq. 9, $dE/dx \approx \kappa_Q(\tau_Q/\tau)^{2/3}$, denoting the energy loss in the plasma phase by

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

QM 2002 (PHENIX)



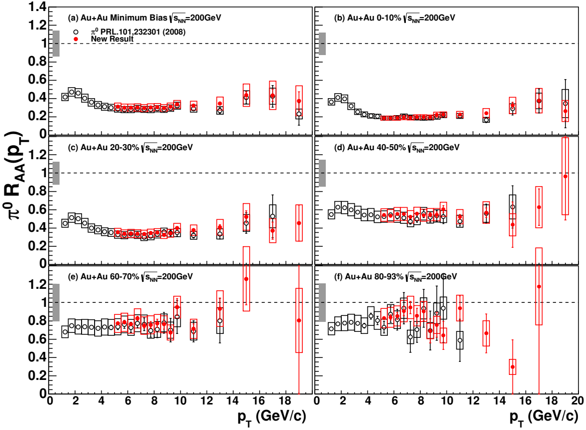
R_{AA} (π^0) for central Pb+Pb collisions at $\sqrt{s_{NN}} = 17$ GeV and central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV.



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

Presented by S. Mioduszewski at QM 2002

In 2012

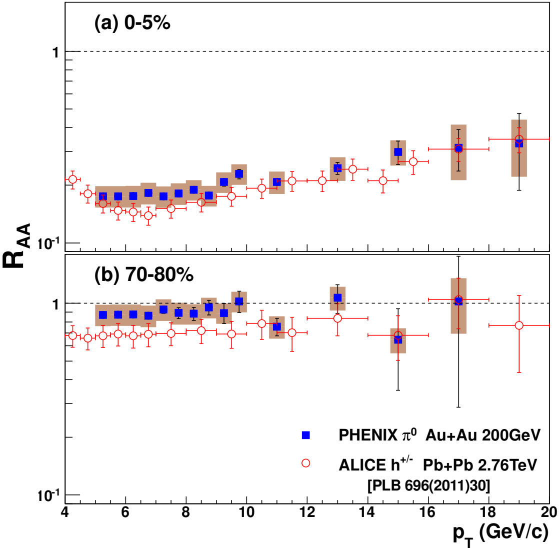


PHENIX, arXiv:1208.2254

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

Slight rising is becoming evident at high p_T.

In 2012

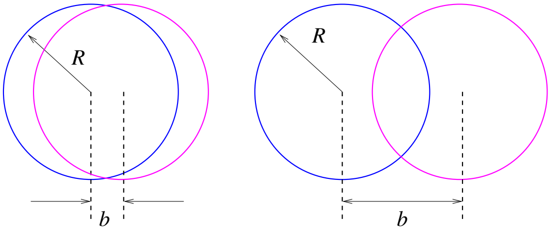


PHENIX, arXiv:1208.2254

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

Slight rising is becoming evident at high p_T.

Centrality



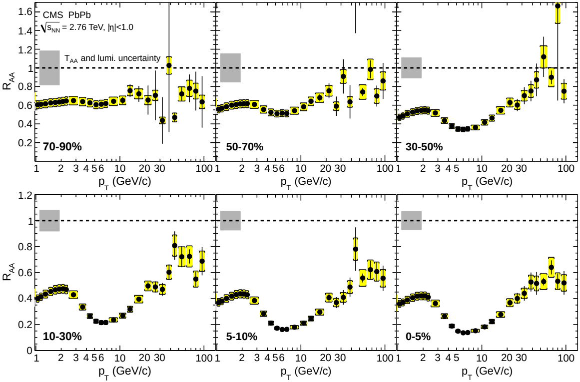
Central collisions
0 % means b = 0

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

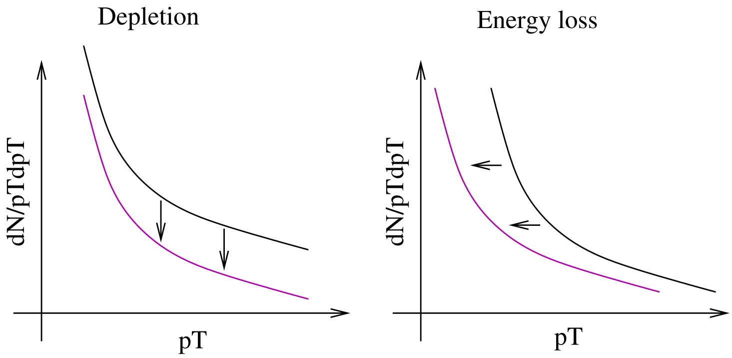


$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{\rm coll}\, dN_{pp}/dp_T}$$

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

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

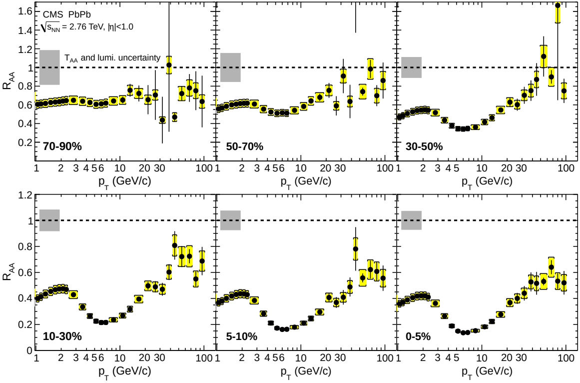
Very Rough Understanding

- 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



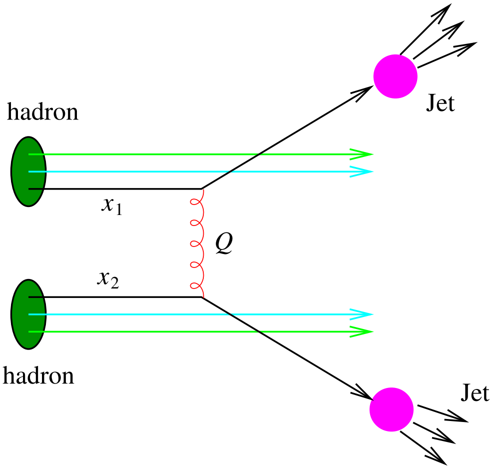
CMS, 1208.6218v1

- 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 $s > 1$.

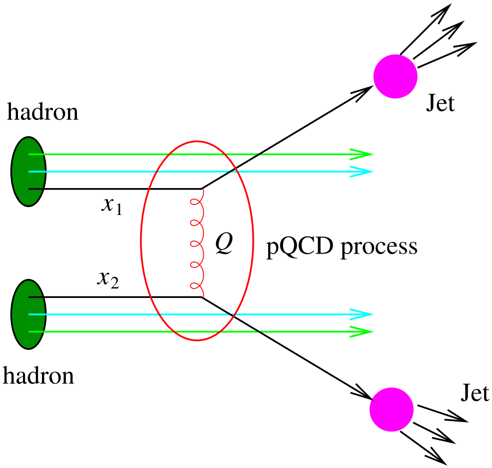
Data suggests that for up to about 5 GeV, $\Delta p_T \propto p_T^{1+a}$ and after that $\Delta p_T \propto p_T^{1-b}$

Jet Quenching
– Schematic Ideas

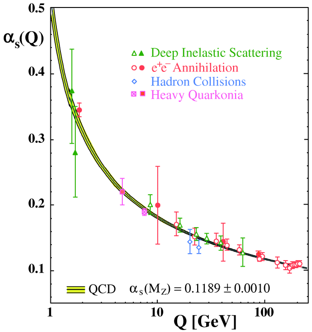
Hadronic Jet production



Hadronic Jet production

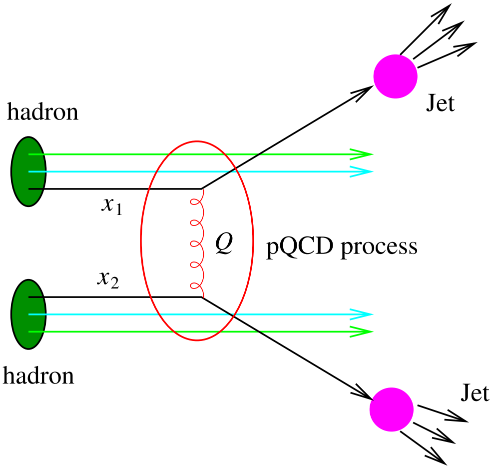


If $Q \gg \Lambda_{\mathrm{QCD}}$, $\alpha_s(Q) \ll 1$:
Jet production is perturbative.



Bethke, hep-ex/0606035

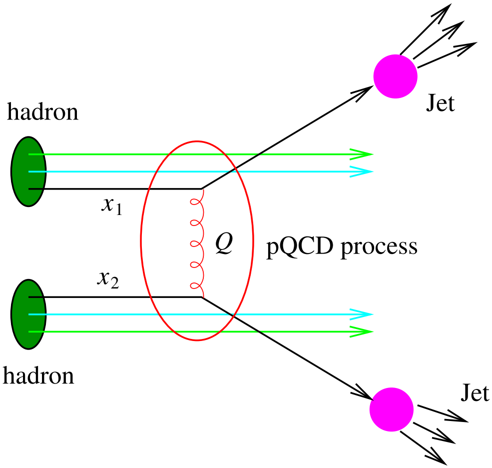
Hadronic Jet production



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

➥ Calculation is possible.

Hadronic Jet production

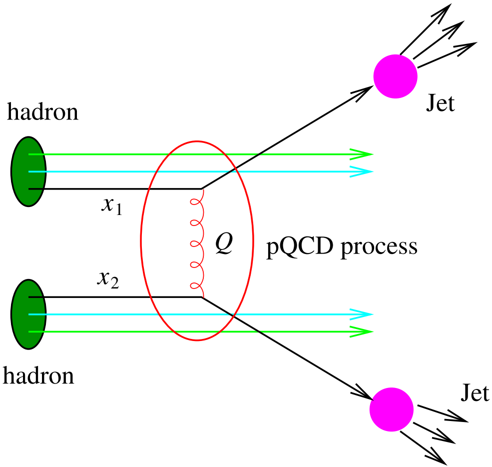


If $Q \gg \Lambda_{\mathrm{QCD}}$, $\alpha_s(Q) \ll 1$:
Jet production is perturbative.

➥ Calculation is possible.

➥ We understand this process in hadron-hadron collisions.

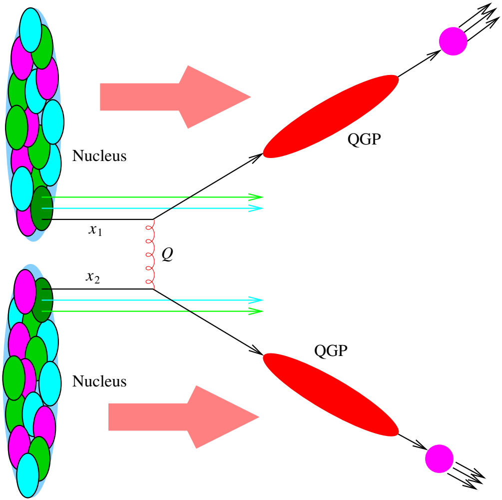
Hadronic Jet production



Hadron-Hadron Jet production scheme:

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

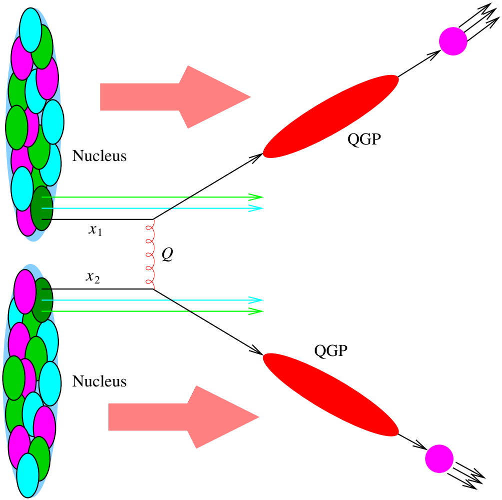
Heavy Ion Collisions



What we want to study:

- How does QGP modify jet property?

Heavy Ion Collisions



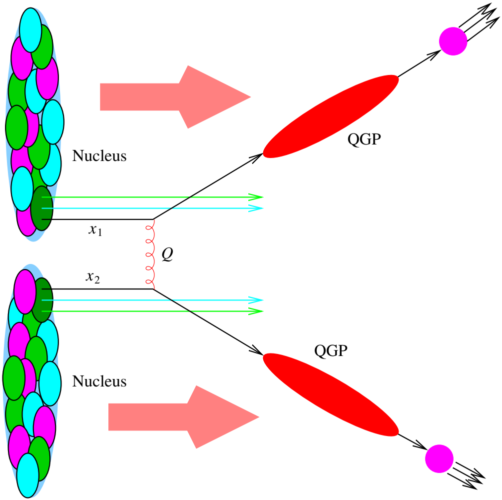
What we want to study:

- 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

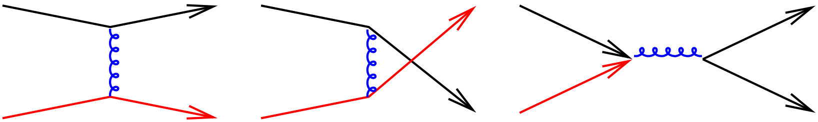


Schematically,

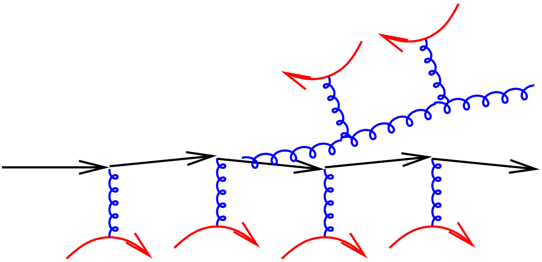
$$\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} \times f_{a/A}(x_a, Q_f) f_{b/B}(x_b, Q_f) \times \frac{d\sigma_{ab\to cd}}{dt} \times \mathcal{P}(x_c \to x'_c | T, u^\mu) \times D(z'_c, Q)$$

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

Relevant processes for E-loss



Elastic scatterings with thermal particles



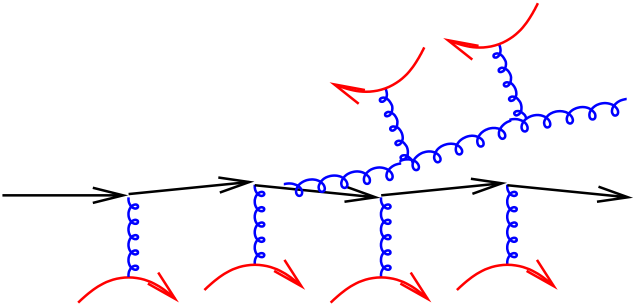
Collinear radiation

Why it is not-trivial

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

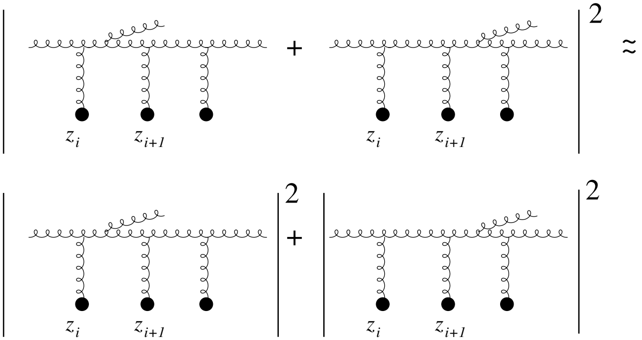
Radiational Energy Loss
– Why coherence matters

Process to study



- Radiative (Inelastic) energy loss via collinear gluon emission

Incoherent emission



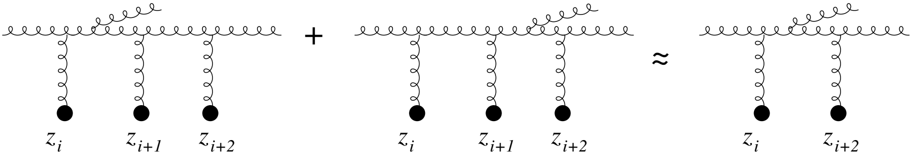
- $|\sum_n T_n|^2 \approx \sum |T_n|^2$
- Interference terms $T_n^* T_m$ with $n \neq m$ negligible.
- Single emission probabilist scales like the number of scatterers:

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

- 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