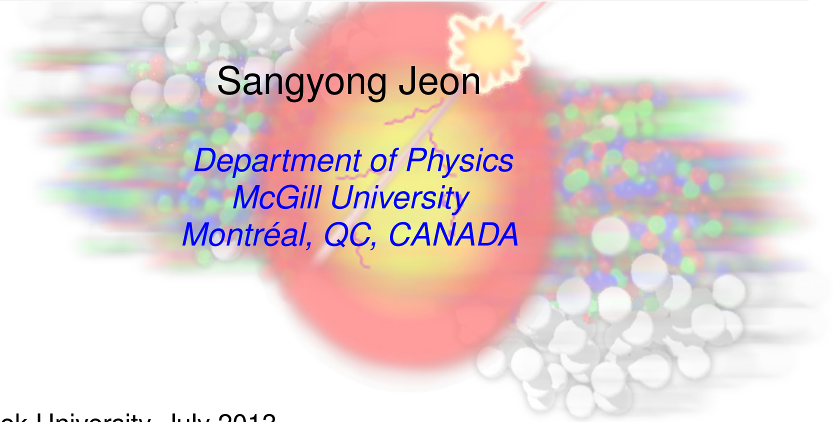
Introduction to Hard Probes in Heavy Ion Collisions



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NNSPP
Stonybrook University, July 2013

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Canada

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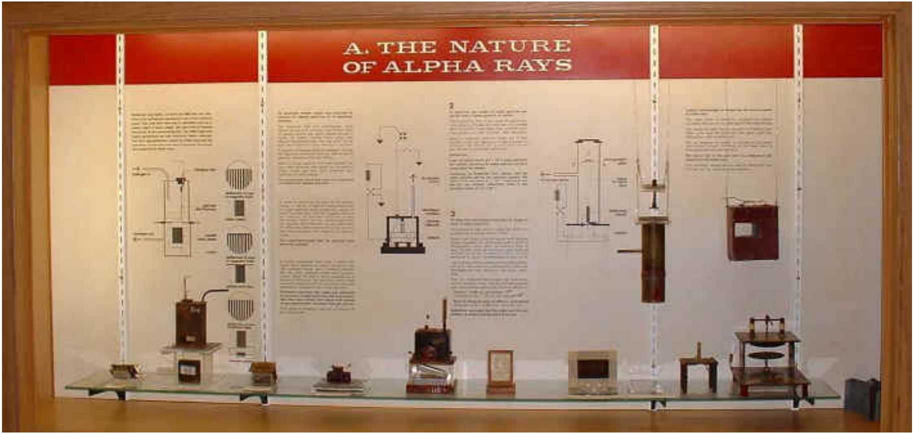
Mr. McGill going home after a hard day's work.

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

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

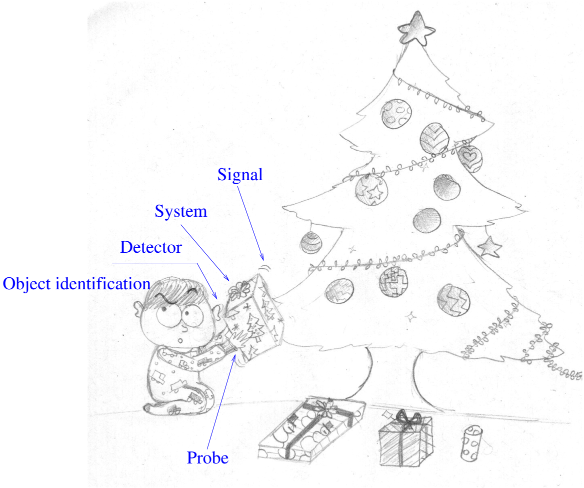
- My goal for these lectures: Qualitative understanding

What is a hard probe?

- Early hard probe experiments

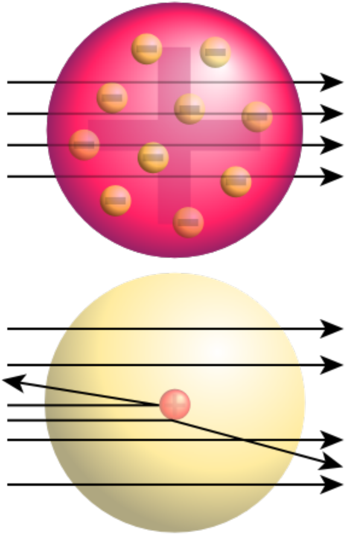
What is a hard probe?

- Early hard probe experiments



What is a hard probe?

- Early hard probe experiments

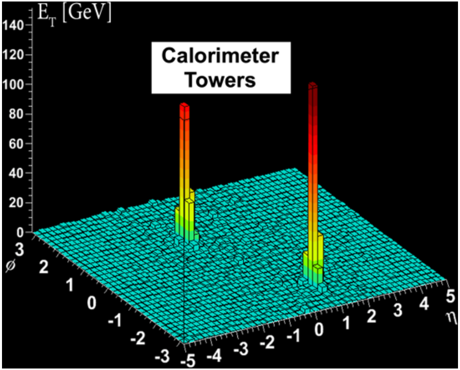


- Rutherford's α scattering experiment (1911)

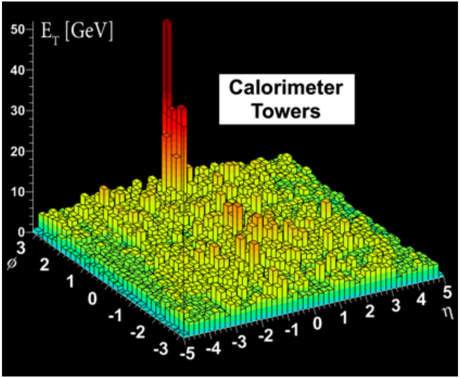
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi}{2} Z^2 \alpha_{\rm EM}^2 \left(\frac{\hbar c}{E_{\rm kin}}\right)^2 \times \frac{1}{(1-\cos\theta)^2}$$

- 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 $\sim 1\,\mathrm{fm}$.
- Example: Jets (high energy partons) with $E \gg 1\,\mathrm{GeV}$ and Heavy quarks (c, b) with $M \gg 1\,\mathrm{GeV}$

Hard Probes

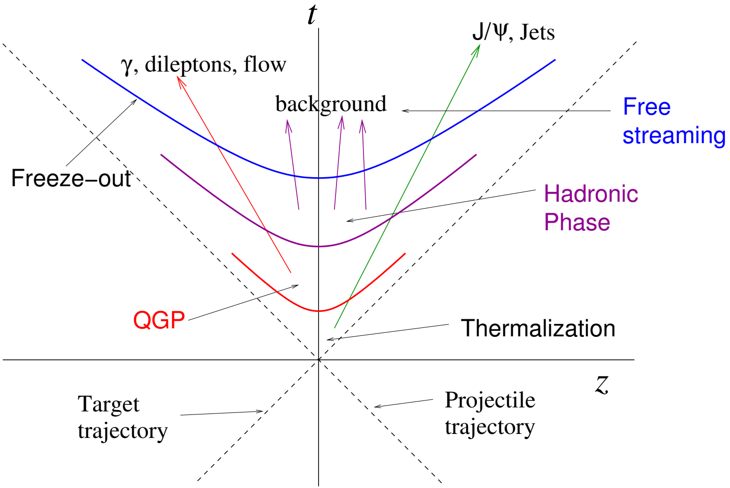
Probes

- 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



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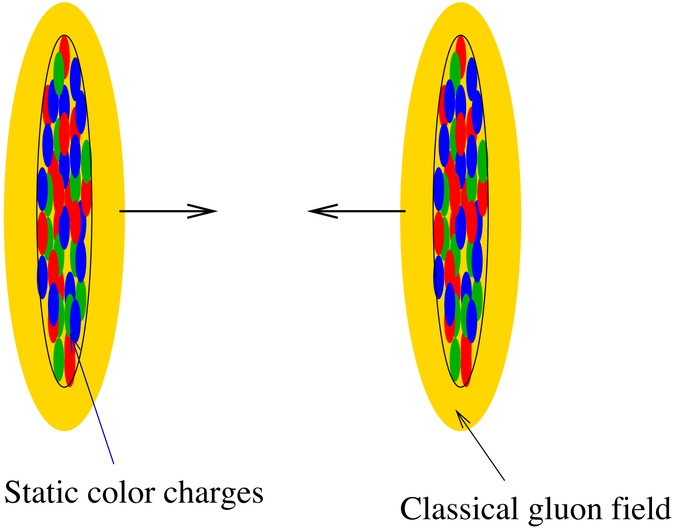

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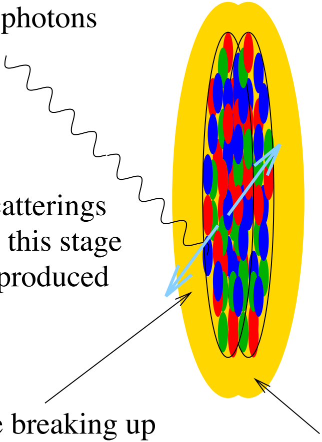
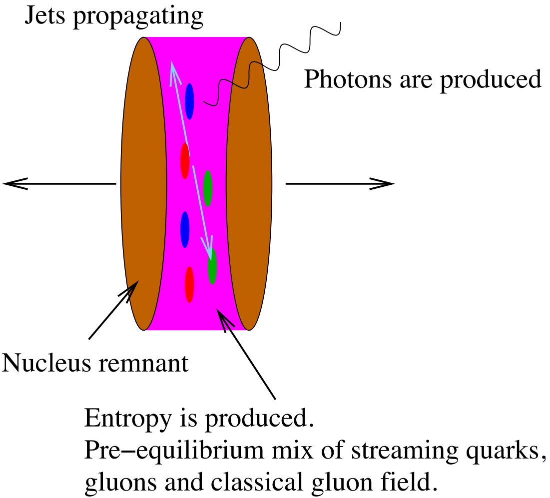


(Very) Schematic view of heavy ion collisions



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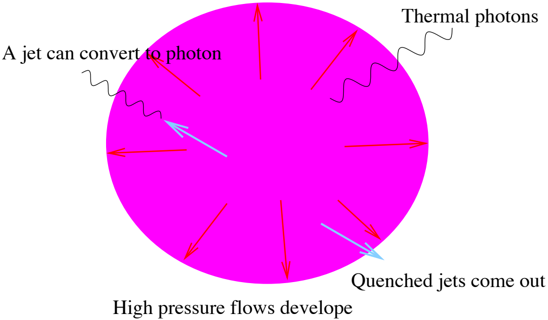
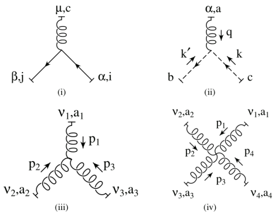


Review of some basic concepts - Feynman Rules



(a) Propagators: Gluon, quark, and ghost lines of momentum k

ν, a — μ, b: $i\frac{\delta_{ba}}{k^2+i\epsilon}[-g^{\mu\nu} + \left(1 - \frac{1}{\lambda}\right)\frac{k^\mu k^\nu}{k^2+i\epsilon}]$ covariant gauge

$i\frac{\delta_{ba}}{k^2+i\epsilon}[-g^{\mu\nu} + \frac{k^\mu n^\nu + n^\mu k^\nu}{n\cdot k} - n^2\frac{k^\mu k^\nu}{(n\cdot k)^2}]$ physical gauge

α, i —($k \rightarrow$)— β, j: $i\frac{\delta_{ij}}{k^2-m^2+i\epsilon}[\not k + m]_{\beta\alpha}$

a - - - b: $i\frac{\delta_{ba}}{k^2+i\epsilon}$

(b) Vertices (all momenta defined to flow in)

(i) $-ig[T_c^{(F)}]_{ji}[\gamma_\mu]_{\beta\alpha}$

(ii) $gC_{abc}k'_\alpha$

(iii) $-gC_{a_1a_2a_3}[g^{\nu_1\nu_2}(p_1-p_2)^{\nu_3} + g^{\nu_2\nu_3}(p_2-p_3)^{\nu_1} + g^{\nu_3\nu_1}(p_3-p_1)^{\nu_2}]$

(iv)
$$\begin{aligned} -ig^2[\ & C_{ea_1a_2}C_{ea_3a_4}(g^{\nu_1\nu_3}g^{\nu_2\nu_4} - g^{\nu_1\nu_4}g^{\nu_2\nu_3}) \\ + \ & C_{ea_1a_3}C_{ea_4a_2}(g^{\nu_1\nu_4}g^{\nu_3\nu_2} - g^{\nu_1\nu_2}g^{\nu_3\nu_4}) \\ + \ & C_{ea_1a_4}C_{ea_2a_3}(g^{\nu_1\nu_2}g^{\nu_4\nu_3} - g^{\nu_1\nu_3}g^{\nu_4\nu_2})] \end{aligned}$$

Figure 1: Perturbation theory rules for QCD.
19

- $G^{\mu\nu}_{ba} = \frac{i\delta_{ba}}{k^2+i\epsilon}\left(-g^{\mu\nu} + (1-1/\lambda)\frac{k^\mu k^\nu}{k^2+i\epsilon}\right)$
- $S^{\beta\alpha}_{ij} = i\frac{\delta_{ij}}{k^2-m^2+i\epsilon}\left(k_\mu\gamma^\mu + m\right)_{\beta\alpha}$
- $-ig[T_c^{(F)}]_\beta[\gamma_\mu]_{\beta\alpha}$
- $-gf_{a_1a_2a_3}\left(g^{\nu_1\nu_2}(p_1-p_2)^{\nu_3} + \text{perm.}\right)$
- $-ig^2(f_{ea_1a_2}f_{ea_3a_4}(g^{\nu_1\nu_3}g^{\nu_2\nu_4} - g^{\nu_1\nu_4}g^{\nu_2\nu_3})$ $+\text{perm. on 234})$

Review of some basic concepts

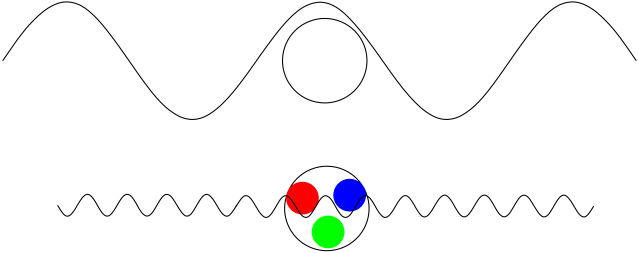
- Basic unit:

$$\hbar c = 197.3\,\text{MeV} \cdot \text{fm} \approx 0.2\,\text{GeV} \cdot \text{fm}$$

- With $\hbar = c = 1$
- Units
  Mass: GeV/c^2
  Momentum: GeV/c
  Energy: GeV
  Length: $\hbar c/\text{GeV}$
- $200\,\text{MeV} \leftrightarrow 1/\text{fm}$
- $1\,\text{fm} \leftrightarrow 1/(200\,\text{MeV})$
- Thermal energy $k_B = 8.617 \times 10^{-5}\text{eVK}^{-1}$
  With $k_B = 1$,
  $1\,\text{eV} = 11,605\,\text{K}$ or $290\,\text{K} \approx \frac{1}{40}\,\text{eV}$

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 $\Delta x \approx \lambda$.

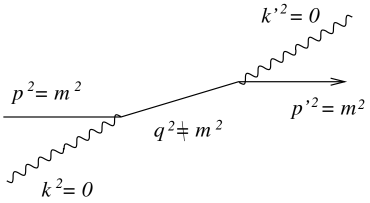
Review of some basic concepts

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

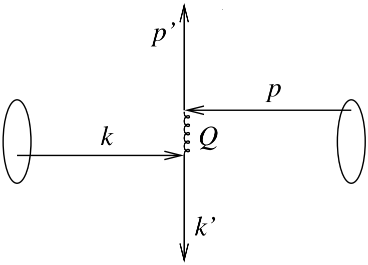
Interpretation

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



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

Hard Probe time scale



Off-shell scale with $k' = k + Q$

$$Q^2 = (k - k')_\mu (k - k')^\mu = (|\mathbf{k}| - |\mathbf{k}|)^2 - (|\mathbf{k}| - 0)^2 - (0 - |\mathbf{k}|)^2 \propto \sqrt{s}$$

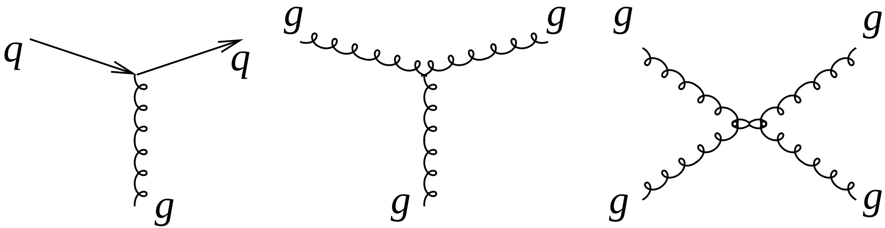
Time scale:

$$\Delta\tau \sim 1/\sqrt{|(k - k')^2|} \sim 1/\sqrt{s}$$

Perturbative QCD

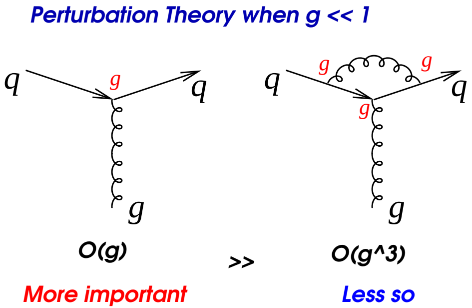
QCD

– Interaction of quarks and gluons



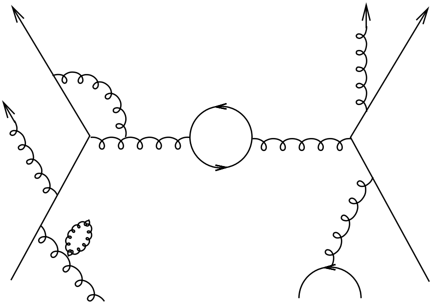
- N_f flavors of quarks
- $N_c^2 - 1$ gluons

Perturbative QCD (pQCD)



- Calculate physical quantities as an expansion in the small coupling constant g
- Corrections to vertices
- Corrections to propagators

Perturbative QCD (pQCD)



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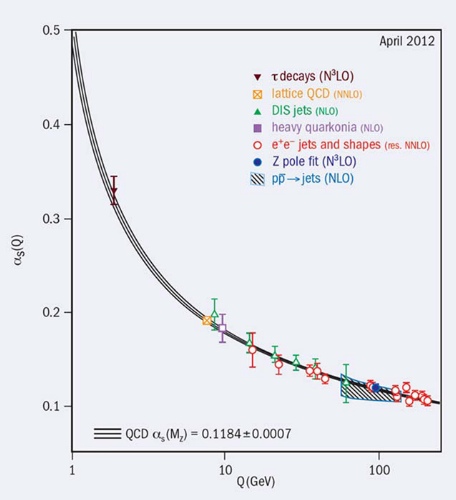
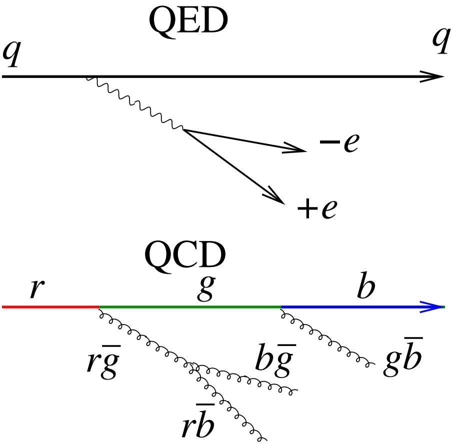
Perturbative QCD (pQCD)



S. Bethke, arXiv:1210.0325.

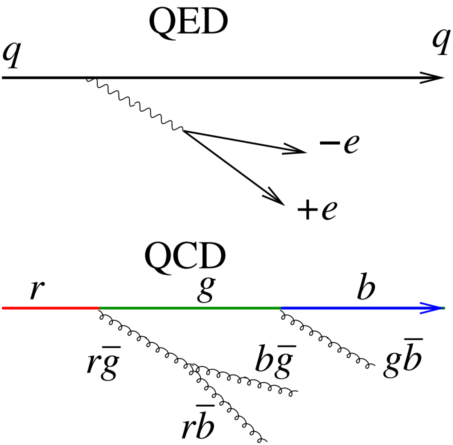
- Perturbative expansion possible because of asymptotic freedom
- $Q^2 \dfrac{\partial \alpha_S}{\partial Q^2} = -\beta_0 \alpha_S^2 - \beta_1 \alpha_S^3 + \cdots$
- $\alpha_S(Q^2) \approx \dfrac{1}{((33 - 2n_f)/12\pi) \ln(Q^2/\Lambda^2_{\rm QCD})}$
- pQCD reliable for $Q \gtrsim 1$ GeV

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

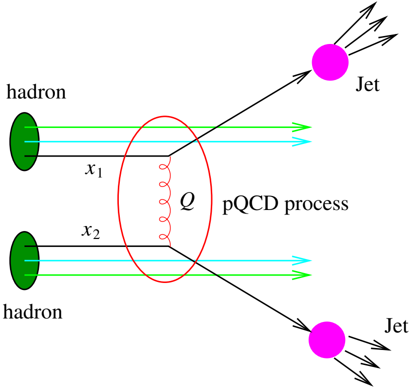
Difficulties with QCD

- 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.

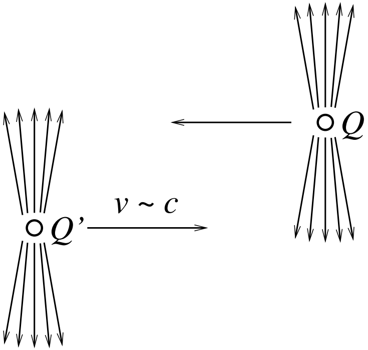
Factorization Theorem

- 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

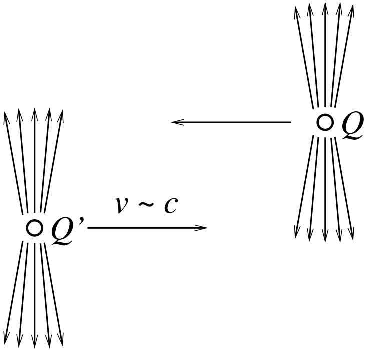
$$\varphi = Q/|\mathbf{r}|$$

- 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

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

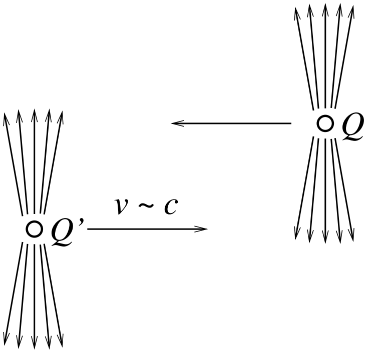
- In the moving frame

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

- 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

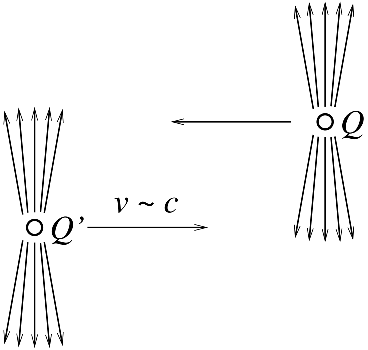
  $F^{\mu\nu} \approx 0$ unless $z \approx vt$

- 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.

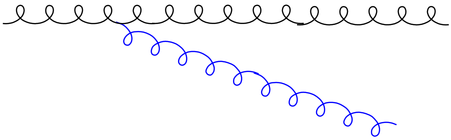
DGLAP Equation

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

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

DGLAP Equation

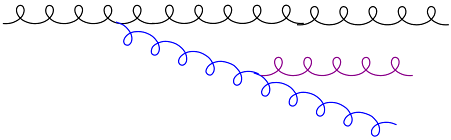
- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.



$Q_0 < Q_1$: Start to resolve another parton

DGLAP Equation

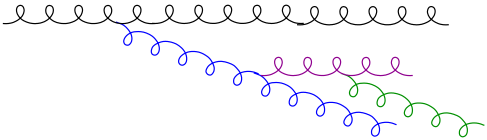
- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.



$Q_0 < Q_1 < Q_2$: And another

DGLAP Equation

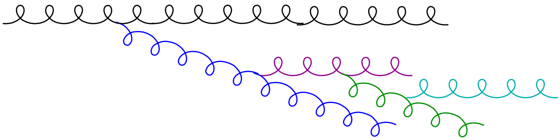
- $f(x, Q_f)$: Probability density of partons with the virtuality *less than* Q_f.



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

DGLAP Equation

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



You get the idea

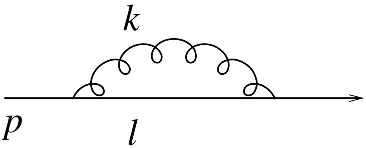
DGLAP Equation

- $f(x, Q_f)$: 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



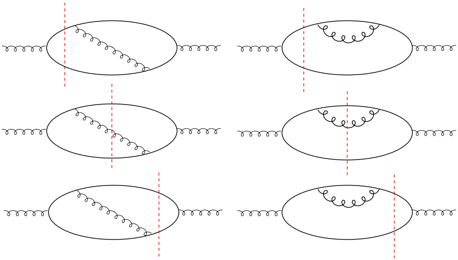
- p is on-shell: $p^2 = 0$
- Diverges when either k or l is on-shell
- This happens either k is very soft so that

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

- or p and k are almost collinear

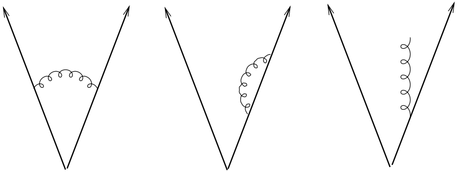
$$l^2 = (p - k)^2 = p^2 + k^2 - 2pk$$
$$\approx 0$$

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

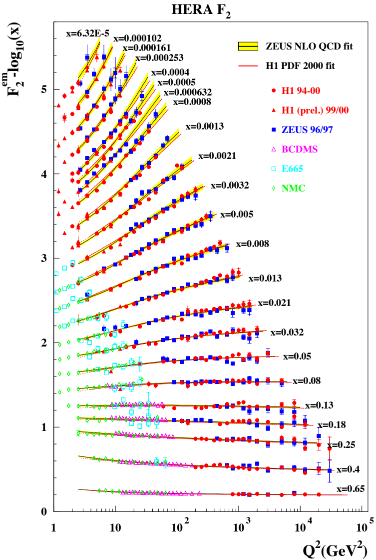
Factorization Theorem

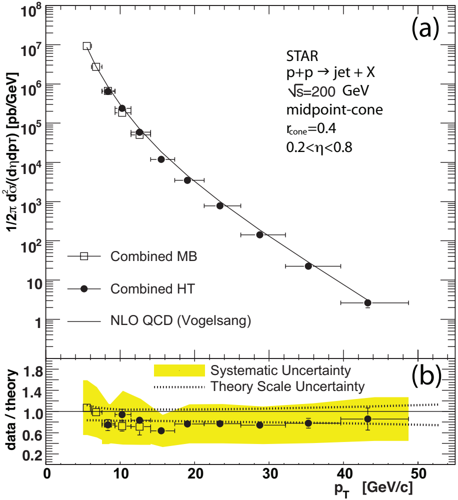
- Fragmentation function similarly runs
- 3 different scales: Q_f for the pdf, Q_R for $\sigma(Q_R)$ and Q'_f for the fragmentation function
- In principle, physical observables should not depend on these scales. However, factorization theorem is only *approximate*.
- Lots of freedom to choose the scales.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

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

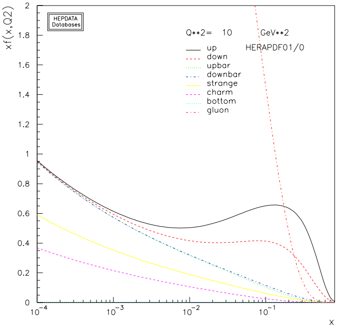
works OK where p_T is the momentum of the *final* state particle.

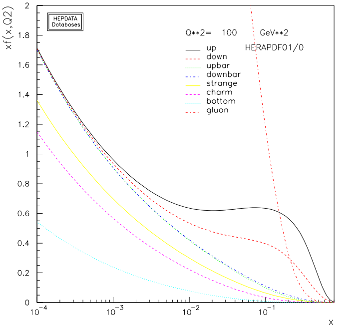
pQCD & Factorization at work





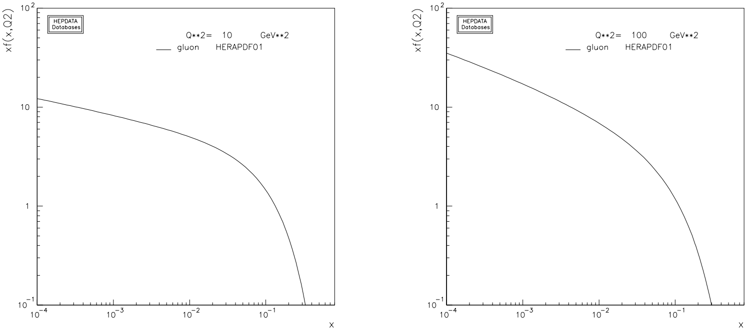
pQCD & Factorization at work





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

pQCD & Factorization at work



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