EICUG 2018

Electron Ion Collider User Group Meeting 2018

July 30 - August 2, 2018
Catholic University of America
Washington, DC

Overview on Jets, Energy Loss and Hadronization

Jianwei Qiu

Theory Center, Jefferson Lab

Session: Jets, Energy Loss, Hadronization, and Nuclear Structure

Focus on the connection to EIC environment

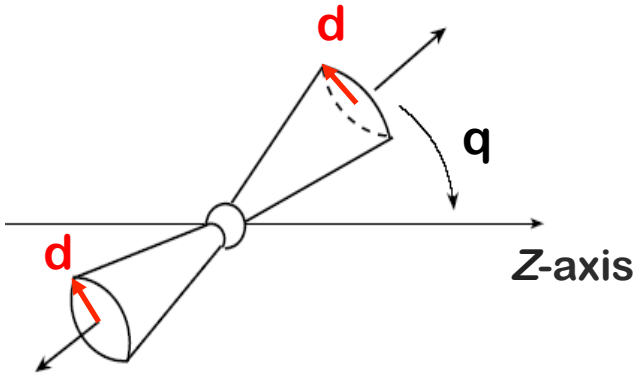
Theory Center

Jefferson Lab
EXPLORING THE NATURE OF MATTER

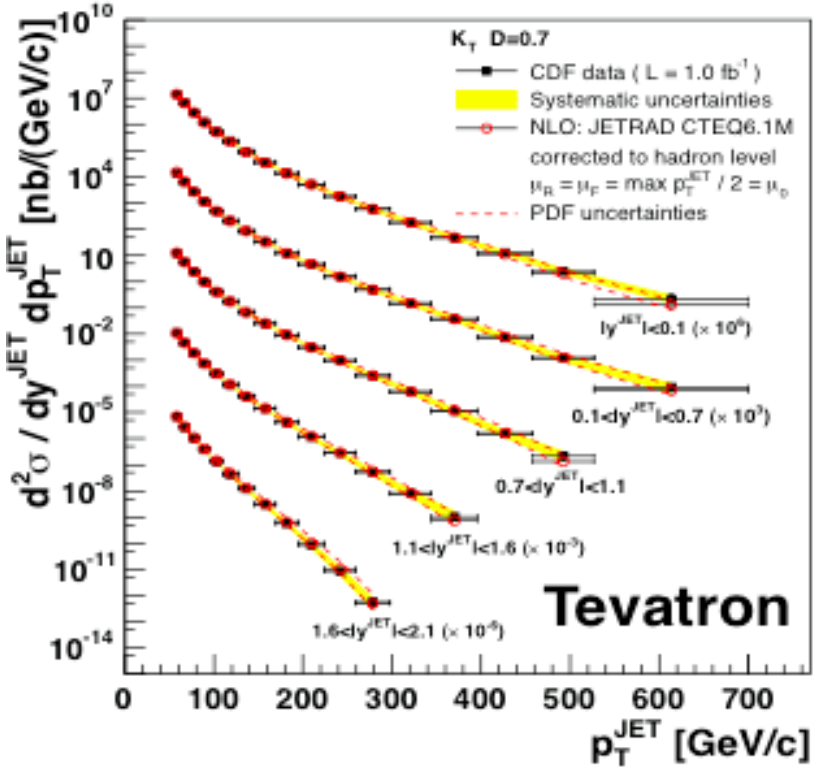
Jets

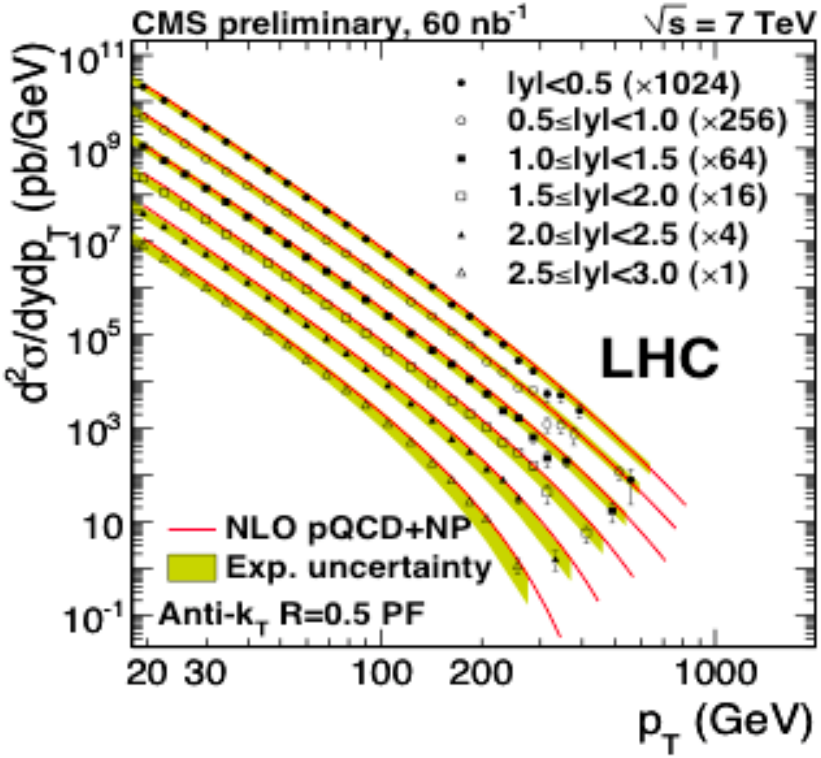
❑ Definition:

- ✧ "footprints" or "trace" of quarks and gluons
- ✧ Inclusive cross section with limited phase space
- ✧ *Well-defined at either hadron or parton level!*

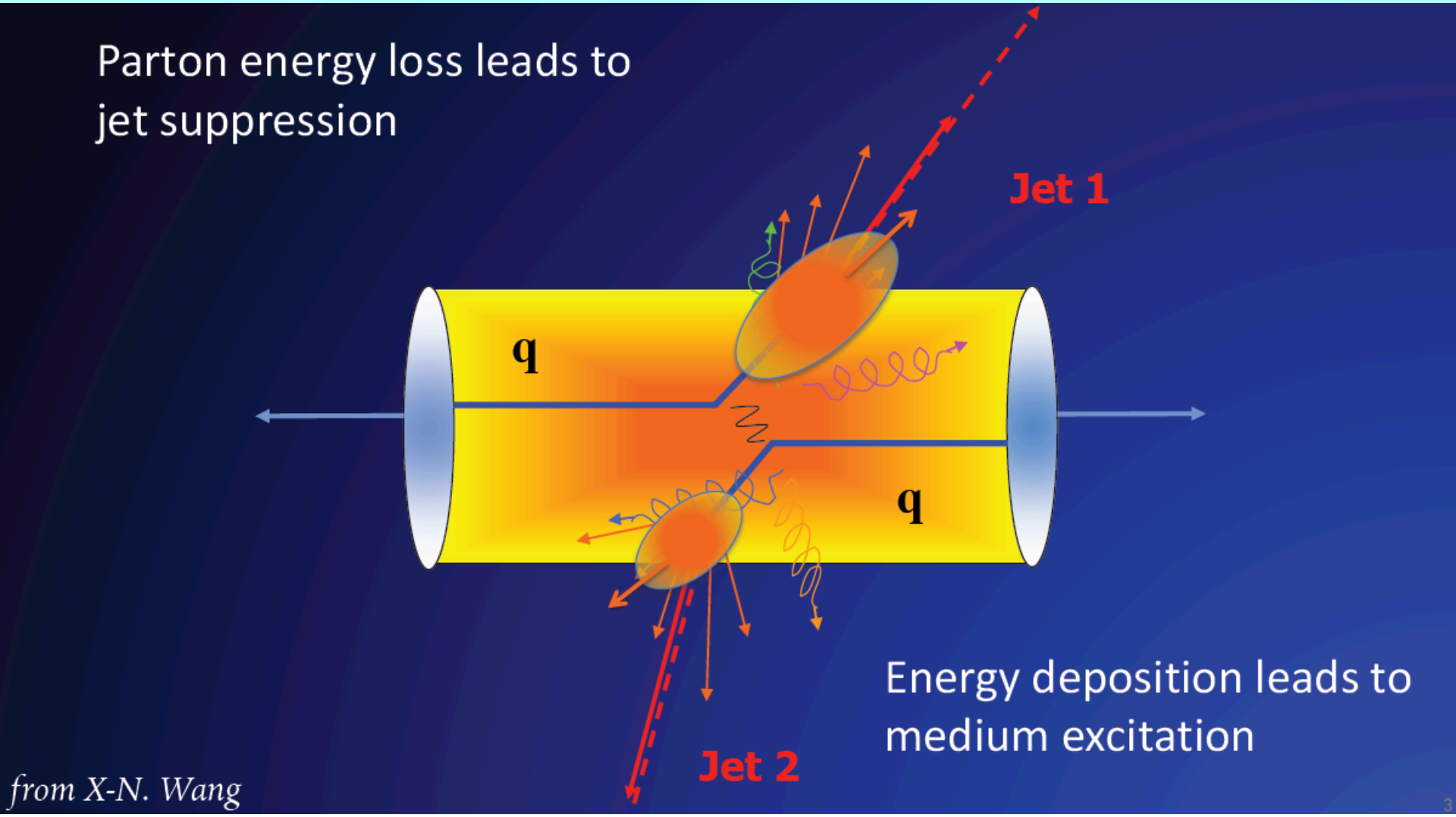


Sterman & Weinberg, PRL 1977





Parton Energy Loss

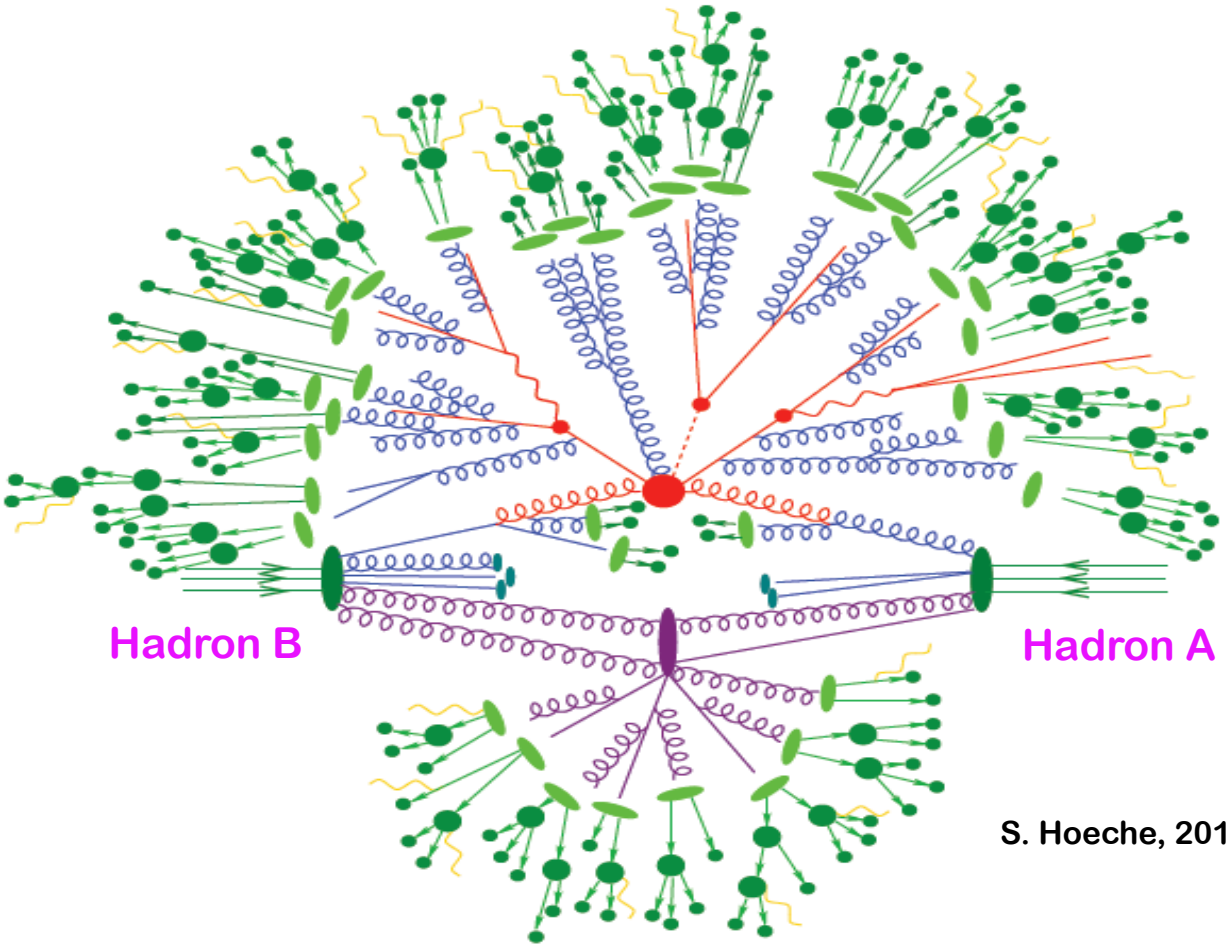


- ✧ ***Not well-defined since we never measure individual parton!***
- ✧ ***Model dependent if we define it at the hadronic level***

Hadronization

- **h+h collision:**

  with a lot of energy

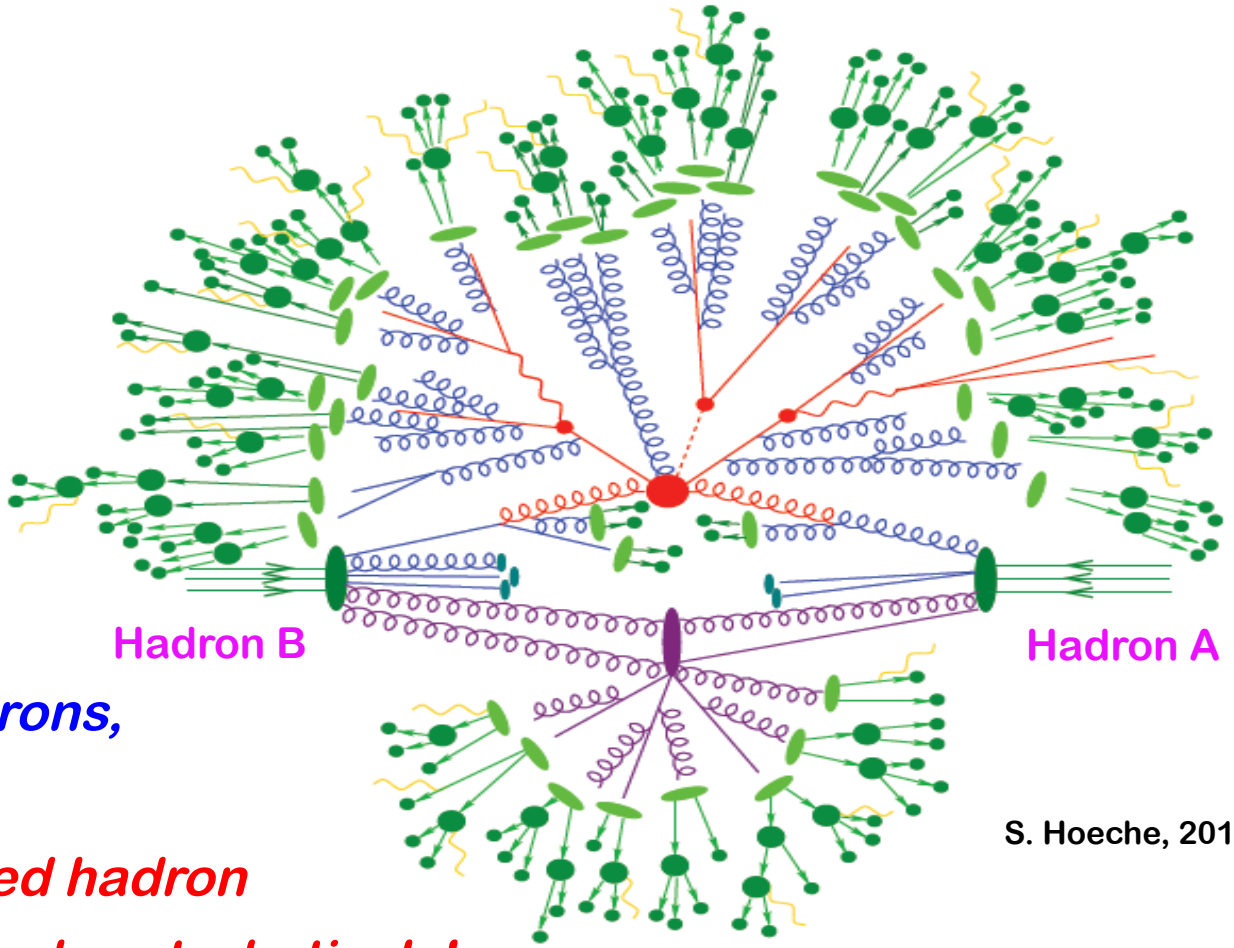


S. Hoeche, 2018

Hadronization

- **h+h collision:**

  with a lot of energy



S. Hoeche, 2018

- ✧ ***Hadronization***

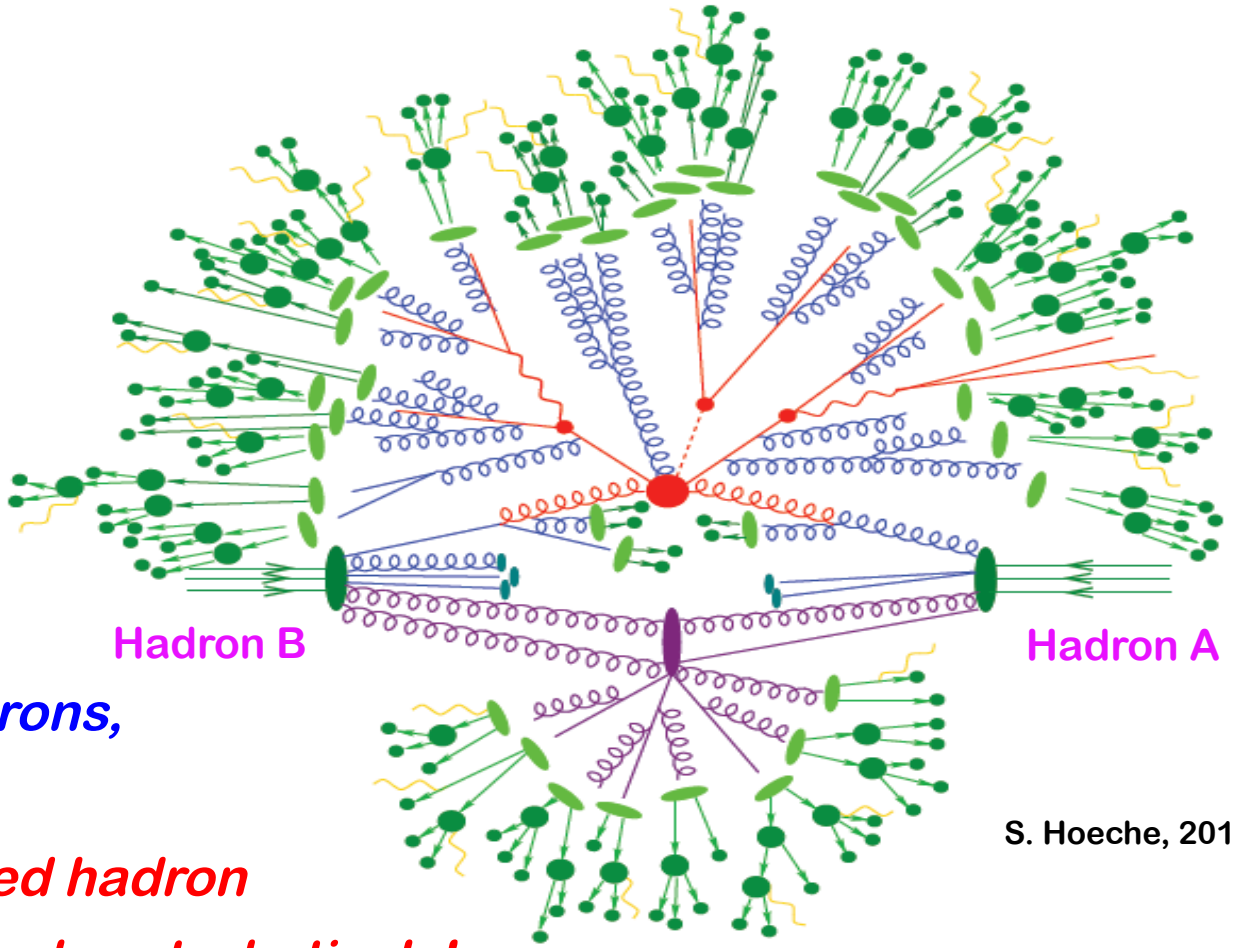
  Emergence of hadrons, leptons, …

- ✧ ***Event with identified hadron cannot be calculated perturbatively!***

Hadronization

- **h+h collision:**

  with a lot of energy



S. Hoeche, 2018

- ***Hadronization***

  Emergence of hadrons, leptons, …

- ***Event with identified hadron cannot be calculated perturbatively!***

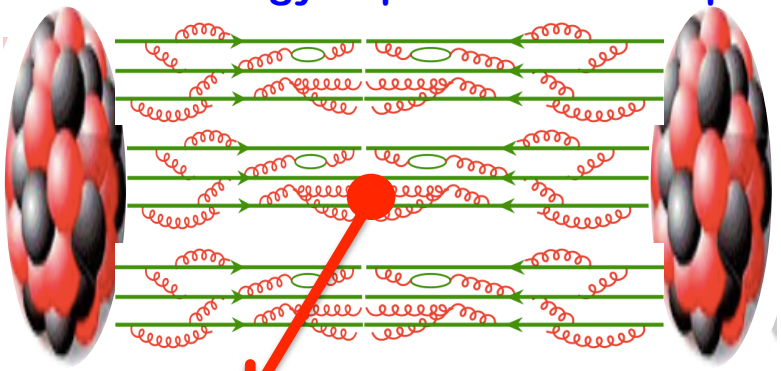
- **No identified hadron – Jet cross sections – inclusive enough**
- **No-perturbative fragmentation function(s)**

High energy nuclear collisions

- A-A:

Nucleus

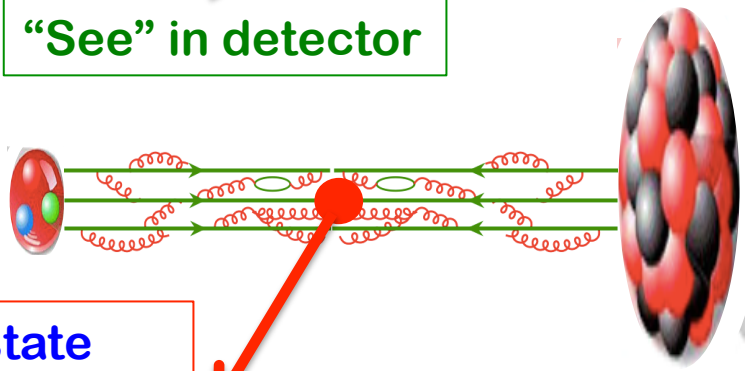
Sufficient energy to produce lots of pions



"See" in detector

- p-A:

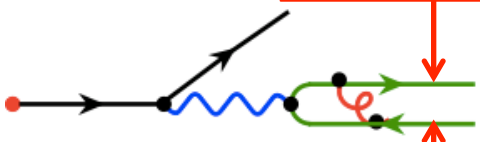
Proton



Final-state controlled probe!

- e-A:

Lepton



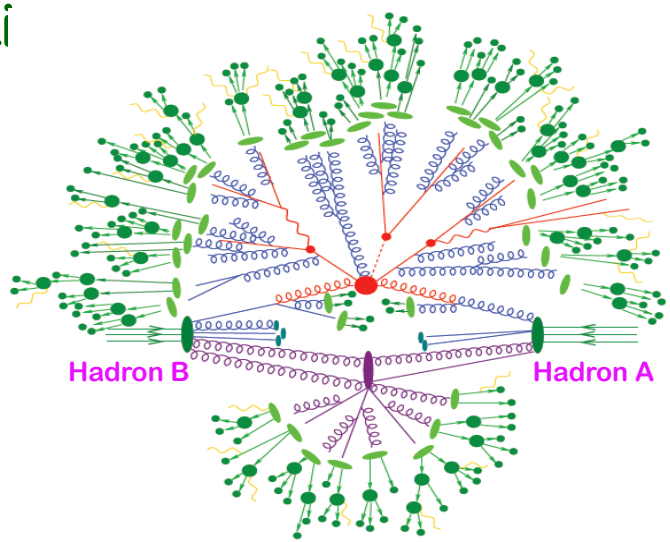
Color probe

1/Q

Initial-state controlled probe!

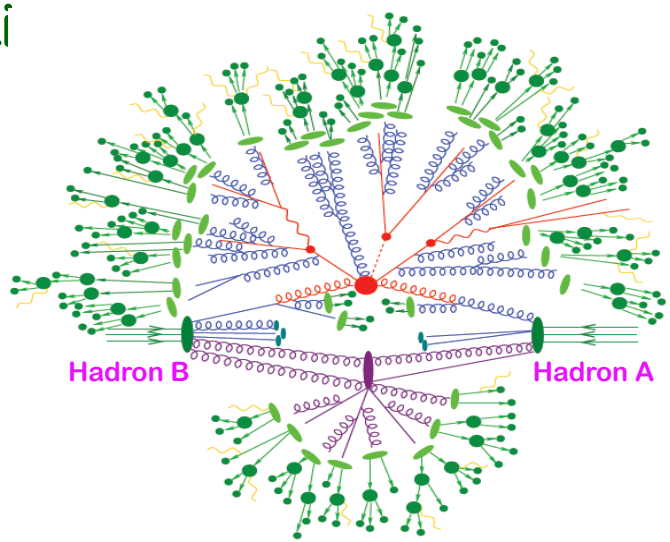
Two theoretical approaches

- Analytic – with controllable approximati
  - Rely on our understanding of physics
    - Make the right approximations, …
    - Give insight to what really happened, …
  - Motivate experimental measurement, …
  - Cannot capture the full story, …



Two theoretical approaches

- Analytic – with controllable approximati
  - Rely on our understanding of physics
    - Make the right approximations, …
    - Give insight to what really happened, …
  - Motivate experimental measurement, …
  - Cannot capture the full story, …



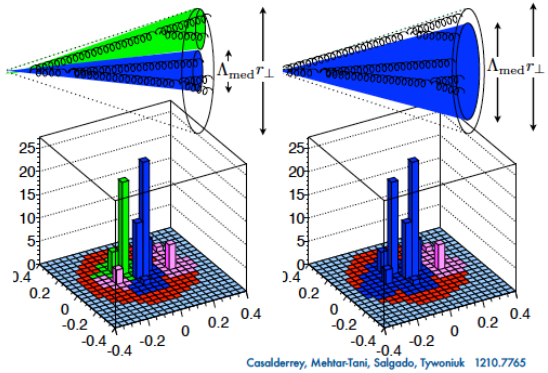
- Numerical – Monte Carlo Event Generator:
  - Looking like a black box, …
  - Output depends on what we put in (thinking of lattice QCD?) , …
    - Can in principle include all the right physics, including nuclei, medium effects, energy loss, …
    - But, it is often working in progress, …
  - Could give the real "event", with experimental constraints, …

I will focus on the more "analytic" approach, … ➡ Miss a lot of work for RHIC, LHC, …

Jet definition – not unique!

❑ Jet definition – how to combine particles into a jet

✧ **Recombination algorithms (almost all e+e- cases):**



- **Recombination metric:** $y_{ij} = \dfrac{M_{ij}^2}{E_{c.m.}^2}$

  $M_{ij}^2 = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$

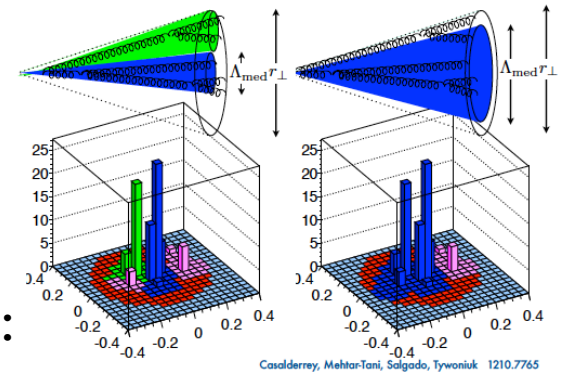
- **Combine particle pair** (i,j) **with the smallest** y_{ij}**:**

  $(i,j) \to k \qquad e.g.\ \mathrm{E\ scheme}: \ p_k = p_i + p_j$

Jet definition – not unique!

❑ Jet definition – how to combine particles into a jet

✧ Recombination algorithms (almost all e+e- cases):



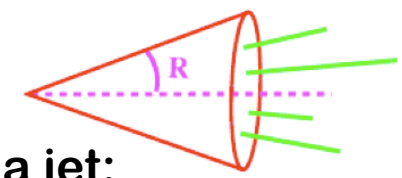
- **Recombination metric:** $y_{ij} = \dfrac{M_{ij}^2}{E_{c.m.}^2}$

  $M_{ij}^2 = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$

- **Combine particle pair** (i,j) **with the smallest** y_{ij}**:**

  $(i,j) \to k \qquad e.g.\ \mathrm{E\ scheme}: \quad p_k = p_i + p_j$

✧ Cone jet algorithms (CDF, …, colliders):



- **Cluster all particles into a cone of half angle** R **to form a jet:**
- **Recombination metric:** $d_{ij} = \min\left(k_{T_i}^{2p}, k_{T_j}^{2p}\right)\dfrac{\Delta_{ij}^2}{R^2}$

  $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$

- **Classical choices:**

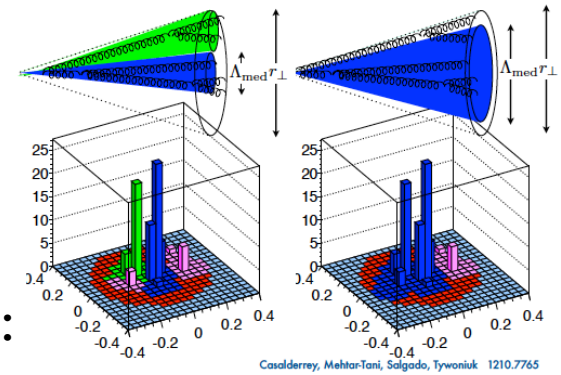
  "k_T algorithm" ($p=1$ **), "anti-k_T" (** $p=-1$ **), …**

- **Require a minimum visible jet energy:** $E_{jet} > \epsilon$

Jet definition – not unique!

❑ Jet definition – how to combine particles into a jet

✧ Recombination algorithms (almost all e+e- cases):



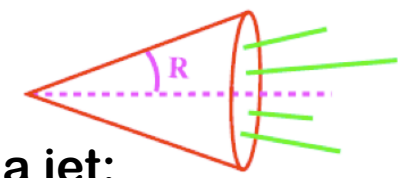
- **Recombination metric:** $y_{ij} = \dfrac{M_{ij}^2}{E_{c.m.}^2}$

  $M_{ij}^2 = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$

- **Combine particle pair** (i,j) **with the smallest** y_{ij}**:**

  $(i,j) \to k \qquad e.g.\ \mathrm{E\ scheme}: \quad p_k = p_i + p_j$

✧ Cone jet algorithms (CDF, …, colliders):



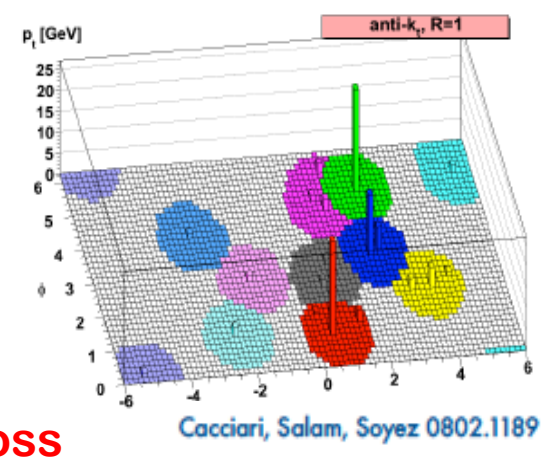
- **Cluster all particles into a cone of half angle** R **to form a jet:**
- **Recombination metric:** $d_{ij} = \min\left(k_{T_i}^{2p}, k_{T_j}^{2p}\right)\dfrac{\Delta_{ij}^2}{R^2}$

  $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$

- **Classical choices:**

  "k_T algorithm" ($p = 1$), **"anti-k_T"** ($p = -1$), …

- **Require a minimum visible jet energy:** $E_{jet} > \epsilon$
- **Particle could be outside the "cone" → energy loss**



Infrared safety for jet-definition

- For any observable with a phase space constraint, Γ,

$$d\sigma(\Gamma) \equiv \frac{1}{2!}\int d\Omega_2 \frac{d\sigma^{(2)}}{d\Omega_2}\Gamma_2(k_1,k_2) + \frac{1}{3!}\int d\Omega_3 \frac{d\sigma^{(3)}}{d\Omega_3}\Gamma_3(k_1,k_2,k_3) + \ldots + \frac{1}{n!}\int d\Omega_n \frac{d\sigma^{(n)}}{d\Omega_n}\Gamma_n(k_1,k_2,\ldots,k_n) + \ldots$$

Where $\Gamma_n(k_1,k_2,\ldots,k_n)$ are constraint functions and invariant under Interchange of n-particles

- Conditions for IRS of $d\sigma(\Gamma)$:

$$\Gamma_{n+1}\left(k_1,k_2,\ldots,(1-\lambda)k_n^\mu,\lambda k_n^\mu\right) = \Gamma_n\left(k_1,k_2,\ldots,k_n^\mu\right) \quad \text{with} \quad 0 \le \lambda \le 1$$

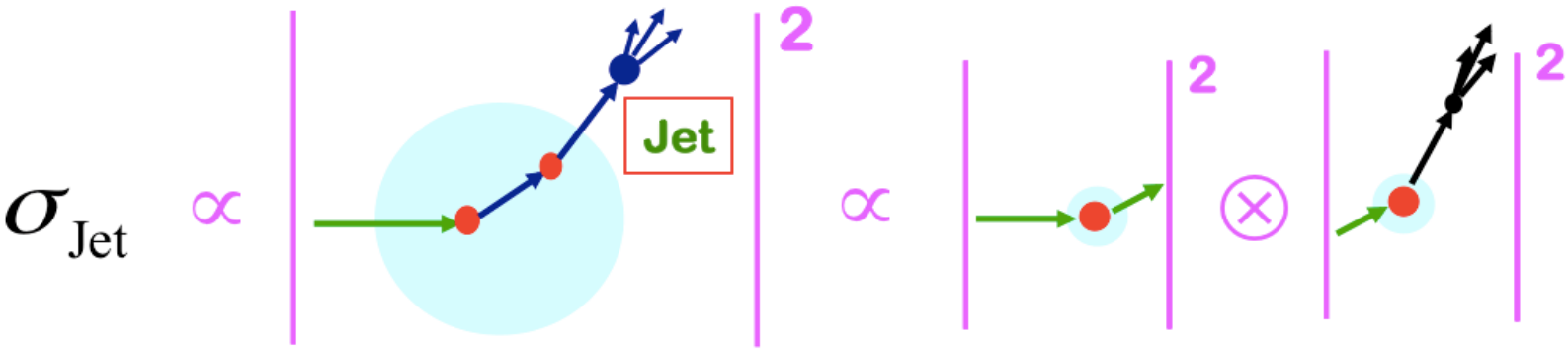
Physical meaning:

Measurement cannot distinguish a state with a zero/collinear momentum parton from a state without the parton

Special case: $\Gamma_n\left(k_1,k_2,\ldots,k_n\right) = 1$ for all n $\Rightarrow$ $\sigma^{(\mathrm{tot})}$

Incoherent/independent multiple scattering

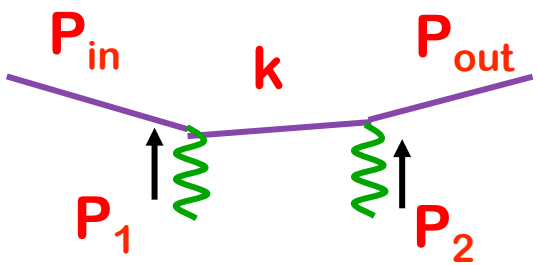
- **Weak quantum interference between scattering centers:**



- **Modify jet spectrum without changing the total rate**
- **Nuclear dependence from the scattering centers**
  - number density of scattering centers
  - nature of the scattering centers – partonic or hadronic
  - momentum distribution and cut-off (new scale)
  - etc

Partonic multiple scattering

❑ Classical multiple scattering – cross section level:



Kinematics fix only $P_1 + P_2$

→ either P_1 or P_2 can be ~ zero

$$d\sigma^{\text{Double}} : \sigma^{\text{single}}(p_{in}, p_1) \cdot \sigma^{\text{single}}(p_2, p_{out}) dp_1 dp_2 \delta(p_1 + p_2 + p_{in} - p_{out})$$

❑ Parton level multiple scattering (incoherent/independent)

In massless pQCD, above $\sigma^{\text{single}} \to \infty$ as p_1 or $p_2 \to 0$

- ✧ Parton distribution at x=0 is ill-defined
- ✧ Pinch poles of k in above definition

→ $d\sigma^{\text{double}} \to \infty$ as p_1 or $p_2 \to 0$

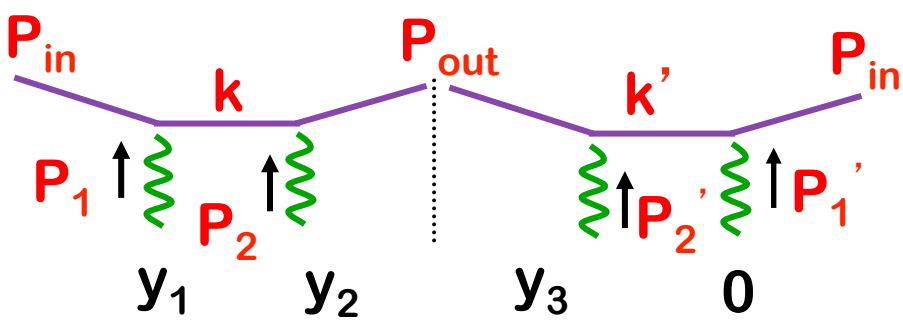
→ Introduce a cutoff

coherent multiple scattering – quantum interference

Coherent multiple scattering in QCD

❑ Quantum mechanical multiple scattering

- Amplitude level



- ✧ 3-independent parton momenta
- ✧ no pinched poles
- ✧ depends on 4-parton correlation functions

$$\langle A | \phi^+(0)\phi^+(y_3)\phi(y_2)\phi(y_1) | A \rangle$$

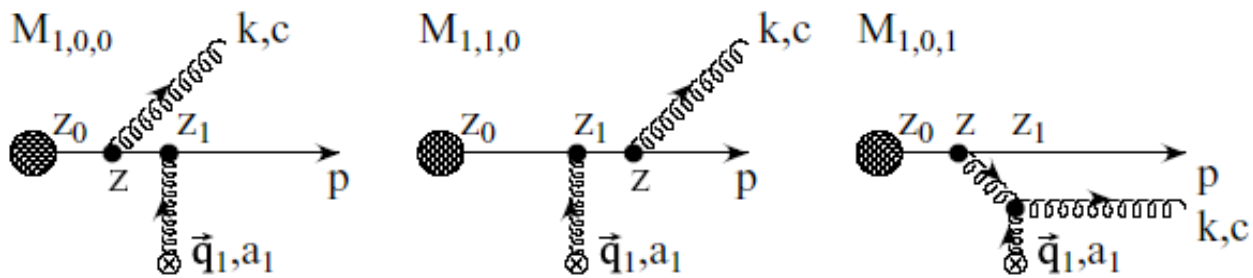
$$\rightarrow \quad d\sigma^{\text{double}} \propto C^{\text{double}}(p_{in}, p_1, p_2, p_1', p_2', p_{out}) T^{\text{double}}(p_1, p_2, p_1', p_2')$$
$$\times \; dp_1 dp_2 dp_1' dp_2' \delta(p_1 + p_2 + p_1' + p_2' + p_{in} - p_{out})$$

$$T^{\text{double}}(p_1, p_2, p_1', p_2') \propto \langle A | \phi^+(0)\phi^+(y_3)\phi(y_2)\phi(y_1) | A \rangle dy_1 dy_2 dy_3$$

Multiparton correlation, no probability interpretation!

Medium induced rescattering

❑ Basic leading order calculation:



$$M_{1,1,0} = J(p)e^{ipx_0}(-i)\int \frac{d^2\mathbf{q}_1}{(2\pi)^2} v(0,\mathbf{q}_1)\, e^{-i\mathbf{q}_1\cdot\mathbf{b}_1} \times$$

$$\times\,(-2ig_s)\,\frac{\epsilon\cdot\mathbf{k}}{\mathbf{k}^2}\, e^{i\omega_0 z_1}\, c a_1 T_{a_1} \;.$$

$$M_{1,0,1} = J(p)e^{ipx_0}\,(-i)\int \frac{d^2\mathbf{q}_1}{(2\pi)^2} v(0,\mathbf{q}_1)\, e^{-i\mathbf{q}_1\cdot\mathbf{b}_1} \times$$

$$\times\, 2ig_s\,\frac{\epsilon\cdot(\mathbf{k}-\mathbf{q}_1)}{(\mathbf{k}-\mathbf{q}_1)^2}\, e^{i(\omega_0-\omega_1)z_1}\left(e^{i\omega_1 z_1} - e^{i\omega_1 z_0}\right)[c,a_1]T_{a_1}$$

Answer depends on:

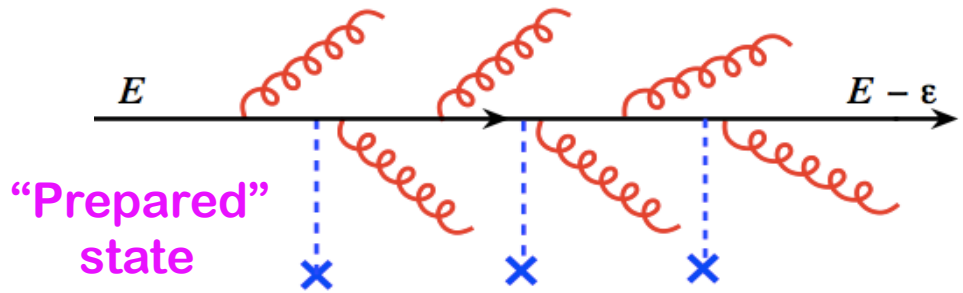
- ✧ choice of source potential $v(0,\vec{q}_1)$
- ✧ scattering phases

Introduce approximation to make sense of the calculation

➡ **Physics insight!**

Color propagation and rescattering

❑ With gluon radiation:



✧ **BDMPS mechanism (2D S-eq)**

Baier, et al. 1996, 1997, …

✧ **Path integral formulation**

Zakharov, 1996, …,
Wiedemann, 2000, …

✧ **Reaction operator approach**

Gyulassy et al., 2000, …

❑ Without gluon radiation:

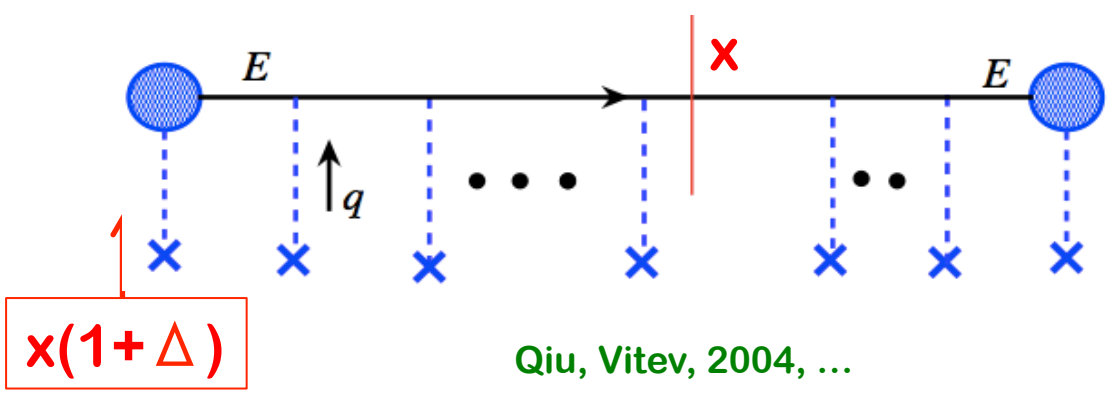
Coherent multiple scattering:

$$f(x,Q^2) \to \sum_{n=0}^{N} \frac{1}{n!}\left[\frac{\xi^2}{Q^2}L\right]^n x^n \frac{d^n}{dx^n} f(x,Q^2)$$

$$\approx \exp\left[\Delta\, x \frac{d}{dx}\right] f(x,Q^2)$$

$$= f(x(1+\Delta),Q^2)$$

$$\Delta = \frac{\xi^2}{Q^2} L \qquad \xi^2 \propto \langle F^{+\alpha} F_\alpha{}^{+} \rangle$$



Qiu, Vitev, 2004, …

Energy loss in QCD

- **BDMPS:**
  - **Transport coefficient:** $\hat{q} = \frac{\mu^2}{\lambda}$

    μ : Typical momentum transfer in single rescattering (~ Debye mass M_D ~ gT)

    λ : Mean free path of the radiated gluon

    – characterizes the scattering property of the medium
  - **Energy loss is proportional to the** $\hat{q}$
  - **In static cold nuclear matter:**

$$-\Delta E_{\rm cold} = \frac{\alpha_s C_R}{4}\,\hat{q}\,L^2$$

Plus some logarithmic corrections

  - **Relationship between energy loss and momentum broadening:**

$$-\frac{dE_{\rm cold}}{dx} = \frac{\alpha_s N_c}{4}\,\langle p_\perp^2\rangle$$

Independent of parton flavors

  - **Leading order pQCD calculation for cold nuclear matter:**

$$\hat{q} = \frac{4\pi^2\alpha_s N_c}{N_c^2-1}\,\rho\, xG(x,Q^2)|_{x=x_s} \approx 0.02\ {\rm GeV}^2/{\rm fm}$$

JET Collaboration
Updated #

How energy loss is implemented?

❑ Inclusive single hadron production (analytic, …):

✧ **Assumption:**

Poisson approximation for independent multiple gluon emission

✧ **Probability for fractional energy loss:** $\varepsilon = \Delta E / E_{jet}$

$$P(\varepsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dN(\omega_i)}{d\omega} \right] e^{-\int d\omega \frac{dN}{d\omega}} \delta \left(\varepsilon - \sum_{i=1}^{n} \frac{\omega_i}{E_{jet}} \right)$$

✧ **Medium modified fragmentation functions:**

$$D_{h/f}^{\mathrm{med}}(z, \mu^2) \equiv \int_0^1 d\varepsilon \, P(\varepsilon) \, \frac{1}{1-\varepsilon} \, D_{h/f}^{\mathrm{vac}} \left(\frac{z}{1-\varepsilon}, \mu^2 \right)$$

Salgado, Wiedemann, PRL 89 (2002)

$$\rightarrow D_{h/f}^{\mathrm{vac}} \left(z, \mu^2 \right) \qquad \text{If } P(\varepsilon) = \delta(\varepsilon)$$

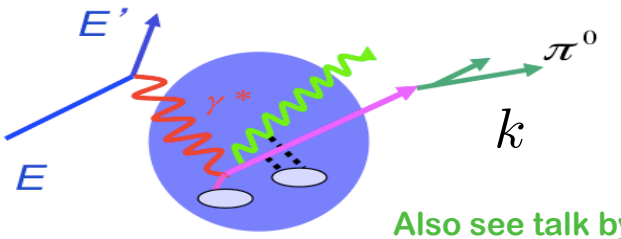
❑ Final-state medium effect – energy loss:

$$D_{h/f}^{\mathrm{vac}} \left(z, \mu^2 \right) \rightarrow D_{h/f}^{\mathrm{med}} \left(z, \mu^2 \right)$$

Semi-inclusive DIS

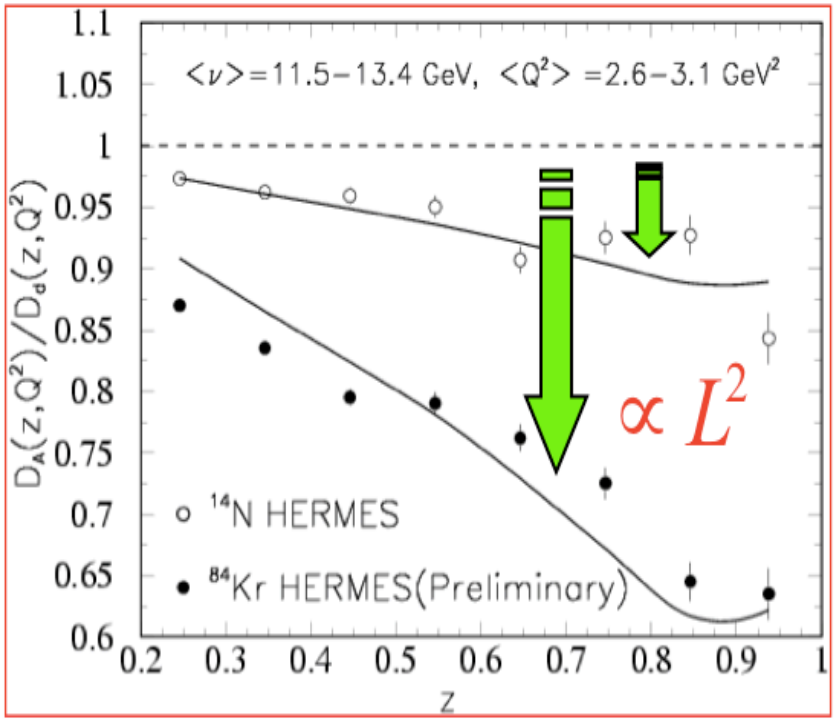
- **Better controlled kinematics:**

$$\nu = E - E' \qquad z = \frac{p \cdot k}{p \cdot q}$$



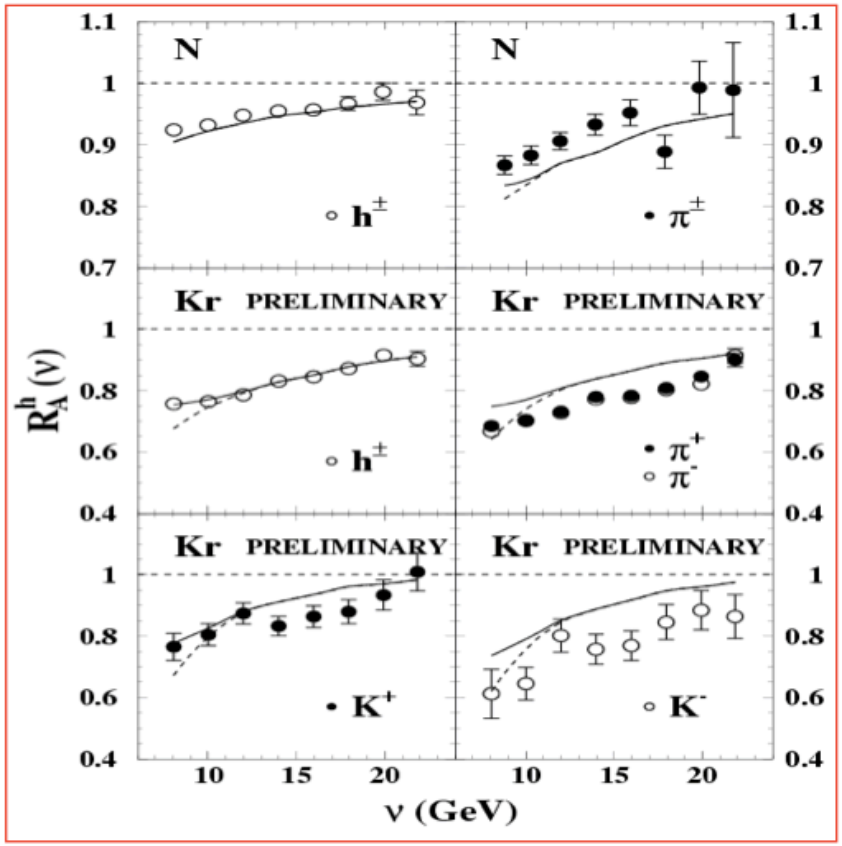
Also see talk by W. Brooks

- **Compare with HERMES data:**



$$\langle -dE/dL \rangle_{cold} \approx 0.5 - 0.6 \ GeV/fm$$

E.Wang, X.-N.Wang, PRL 89 (2002)

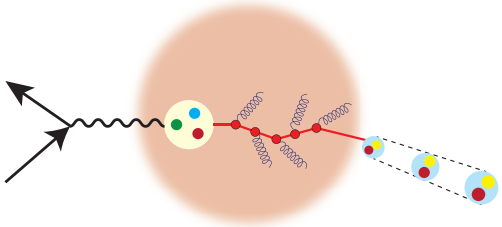


F.Arleo, Eur.Phys.J. C30 (2003)

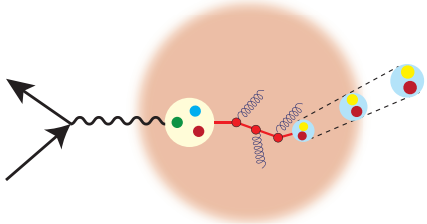
Semi-inclusive DIS @ EIC

Also see talk by W. Brooks

❑ Femtometer sized detector:



$$\nu = \frac{Q^2}{2mx}$$

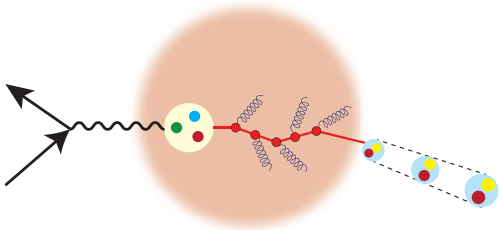


Control of ν and medium length!

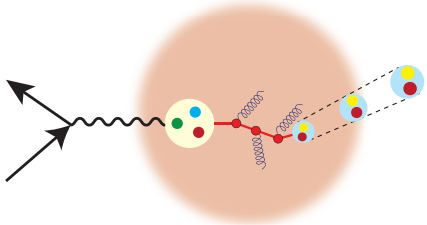
Semi-inclusive DIS @ EIC

Also see talk by W. Brooks

❑ Femtometer sized detector:



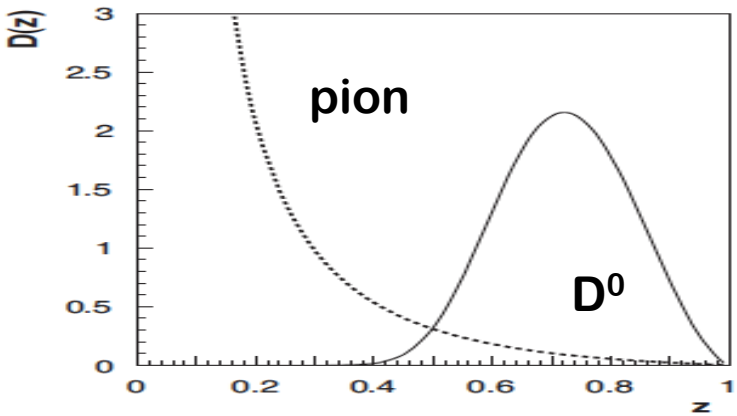
$$\nu = \frac{Q^2}{2mx}$$



Control of ν and medium length!

❑ Heavy quark energy loss:

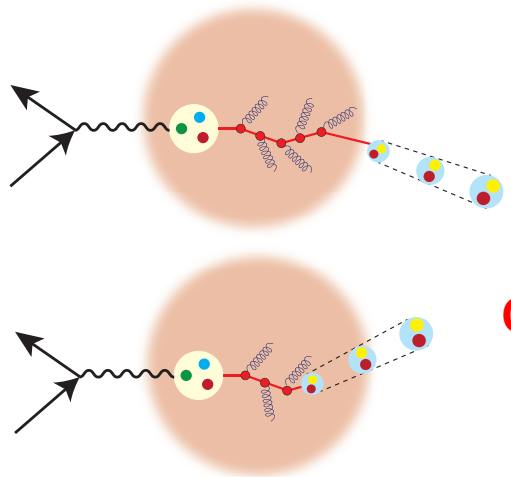
- Mass dependence of fragmentation



Semi-inclusive DIS @ EIC

Also see talk by W. Brooks

❑ Femtometer sized detector:

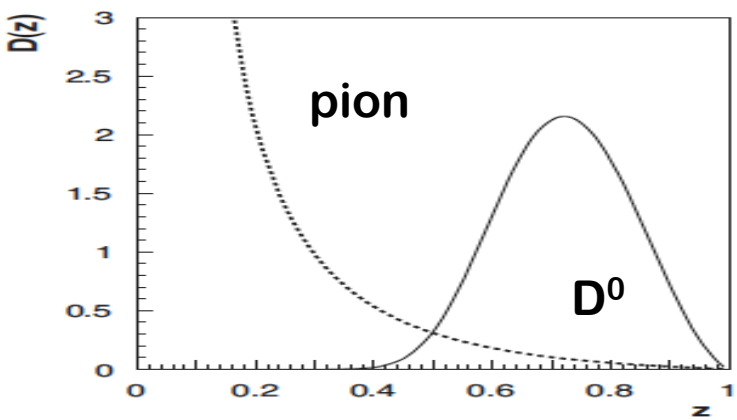


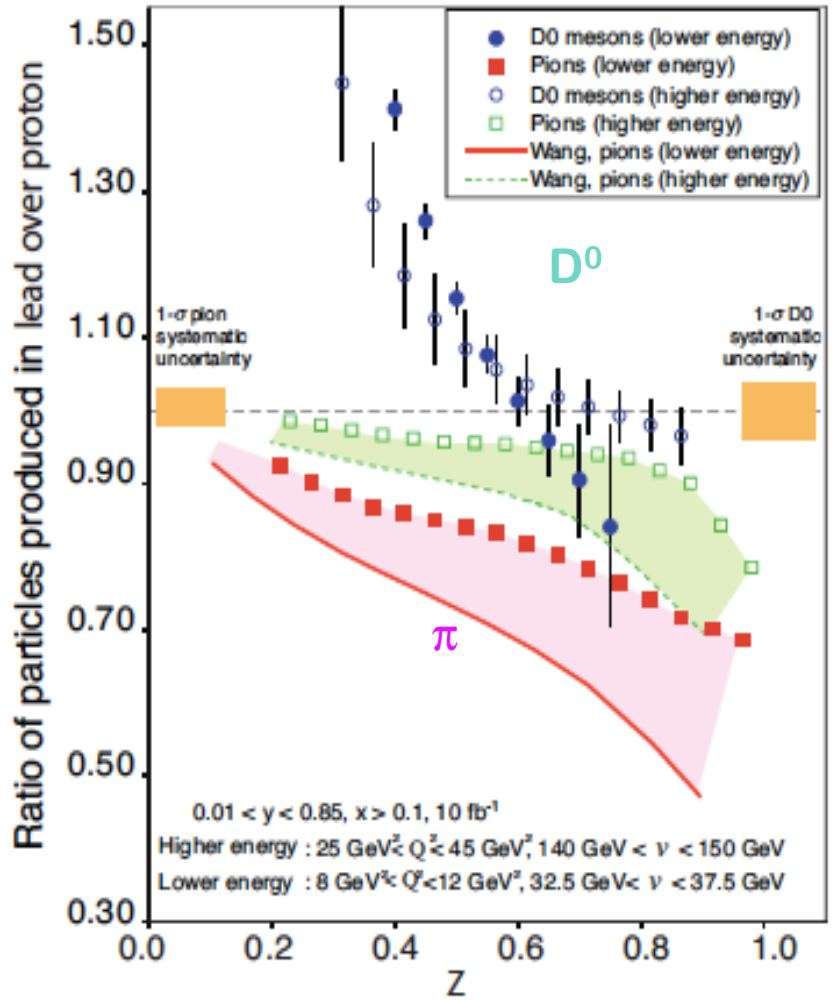
$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

❑ Heavy quark energy loss:

- **Mass dependence of fragmentation**



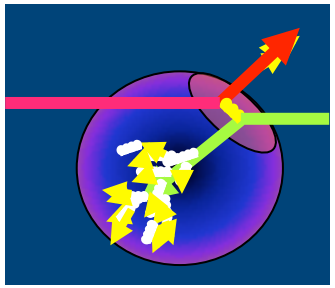


Need the collider energy of EIC and its control on parton kinematics

Jets – where does the lost energy go?

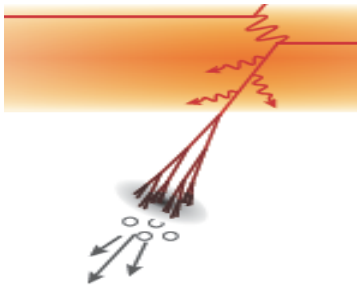
- Medium induced radiation:
  - Small angle in/near cone

No suppression if the cone is bigger enough!



  - Thermalize with the medium:

Radiation is gone!



  - Broaden the jet

Jet "cone" dependence!
Jet transverse shape
Hadronization pattern, …

- Where does the lost energy go?

We do not know, since we did not keep track of every particles

- What if we do keep track of every particles?

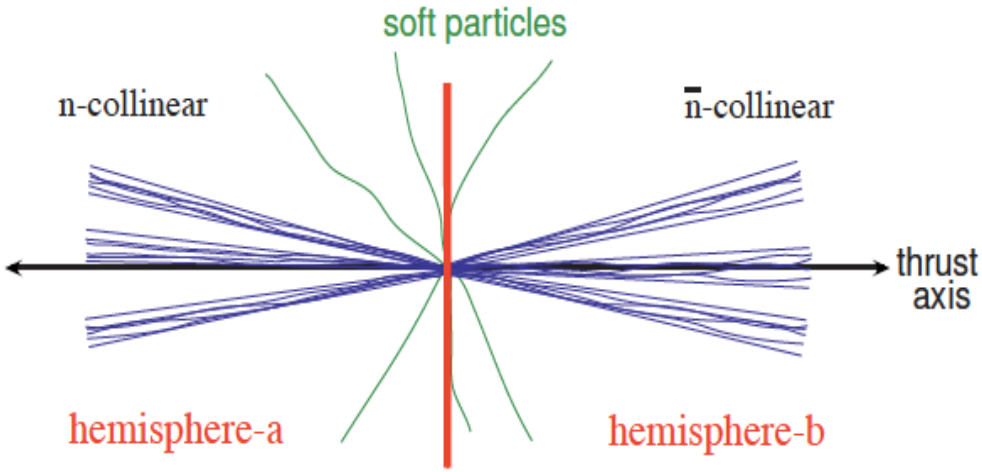
We should know the full event shape!

Event shapes

- Event shapes are theoretically cleaner (more inclusive!):

- Thrust, as an example:

$$T = \max_{\hat{\mathbf{t}}} \frac{\sum_i |\hat{\mathbf{t}} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$$



- Two jet configurations obtained in the limit:

$$T \to 1$$

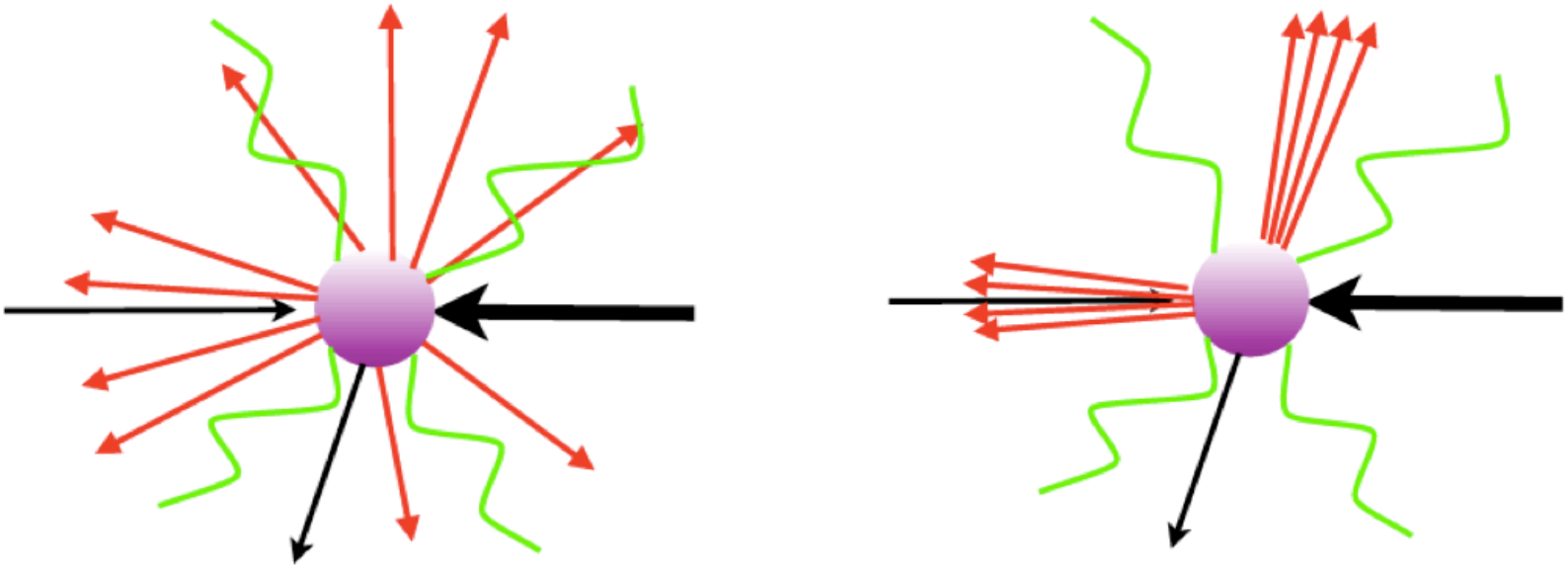
- Resummation of logarithms of (1-T), corresponds to a resummation of the jet veto logs

- Structure of resummation is simpler, *no jet algorithm dependence* (jet algorithm dependence begins at NNLO with two emissions)

1-Jettiness event shape

Z. Kang, Mantry, Qiu, PRD, 2012
D. Kang, Lee, Stewart, PRD, 2013
…

- DIS event shape with 1-jettness:



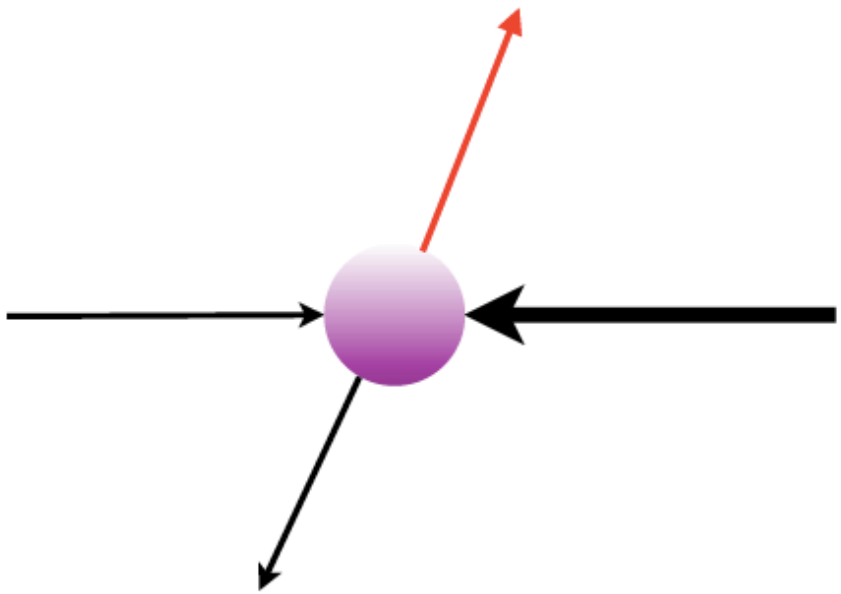
$\tau_1 \sim P_{J_T}$ $\tau_1 \ll P_{J_T}$

The 1-jettiness could be a probe of nuclear multiple scattering, quantifying the medium induced radiation, without "cone", …

Tree-level 1-jettiness distribution

Z. Kang, Mantry, Qiu, PRD, 2012
D. Kang, Lee, Stewart, PRD, 2013

$$d\sigma_A \equiv \frac{d^3\sigma(e^- + N_A \to J + X)}{dy\, dP_{J_T}\, d\tau_1}$$



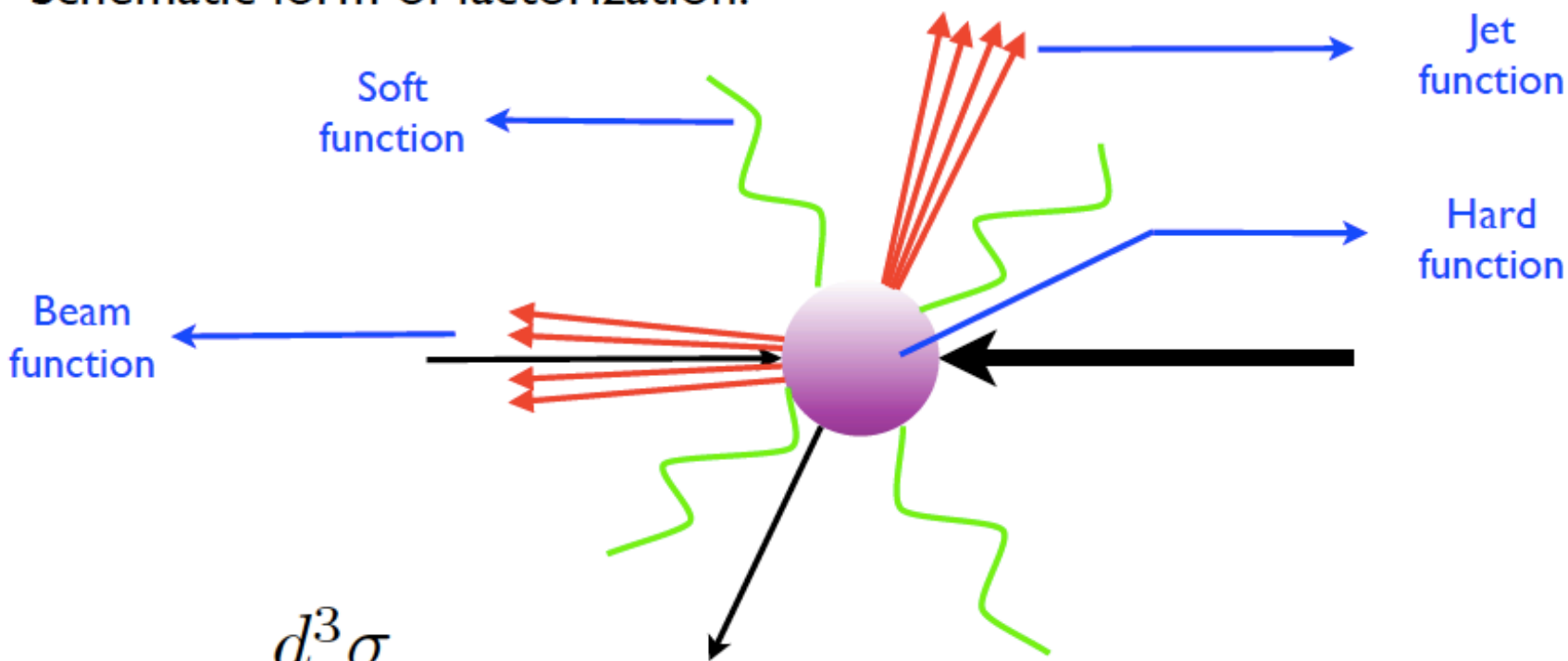
- Tree-level distribution in 1-jettiness:

$$\frac{d^3\sigma^{(0)}}{dy dP_{JT} d\tau_1} = \sigma_0 \delta(\tau_1) \sum_q e_q^2 \frac{1}{A} f_{q/A}(x_A, \mu)$$

Factorization

Z. Kang, Mantry, Qiu, PRD, 2012
D. Kang, Lee, Stewart, PRD, 2013

- Schematic form of factorization:



$$\frac{d^3\sigma}{dy\,dP_{JT}\,d\tau_1} \sim H \otimes B_A \otimes J \otimes \mathcal{S},$$

Hard function | Beam function | Jet function | Soft function

Factorized cross section

Z. Kang, Mantry, Qiu, PRD, 2012
D. Kang, Lee, Stewart, PRD, 2013

- Detailed form of factorization:

$$\frac{d^3\sigma}{dy dP_{JT} d\tau_1} = \frac{\sigma_0}{A}\sum_{q,i} e_q^2 \int_0^1 dx \int ds_J \int dt_a$$

Hard function →
$$\times H(xAQ_e P_{J_T} e^{-y}, \mu; \mu_H)\delta\left[x - \frac{e^y P_{J_T}}{A(Q_e - e^{-y}P_{J_T})}\right]$$

Jet function →
$$\times J^q(s_J, \mu; \mu_J) B^q(x, t_a, \mu; \mu_B)$$
← Beam function

$$\times \mathcal{S}\left(\tau_1 - \frac{t_a}{Q_a} - \frac{s_J}{Q_J}, \mu; \mu_S\right),$$
← Soft Function

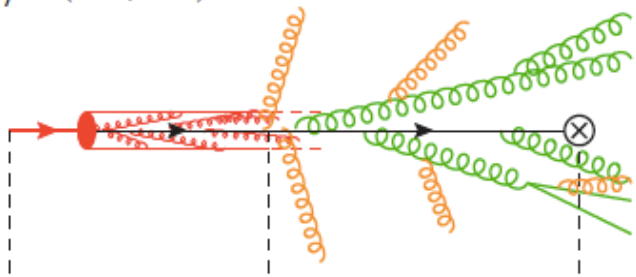
- Beam function matching onto the PDF:

(Fleming, Leibovich, Mehen; Jouttenus, Stewart, Tackmann, Waalewijin)

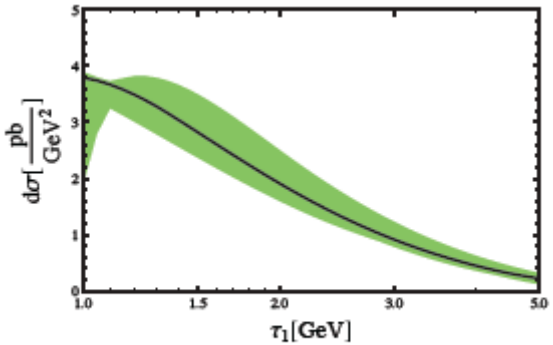
$$B^q(x, t_a, \mu; \mu_B) = \int_x^1 \frac{dz}{z} \mathcal{I}^{qi}\left(\frac{x}{z}, t_a, \mu; \mu_B\right) f_{i/A}(z, \mu_B)$$

- Tree-level matching:

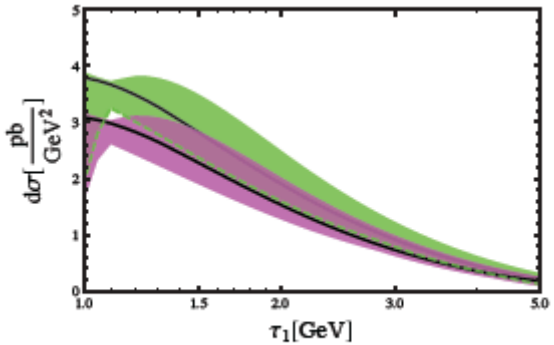
$$B^q(x, t_a, \mu_B) = \delta(t_a) f_{q/A}(x, \mu_B)$$



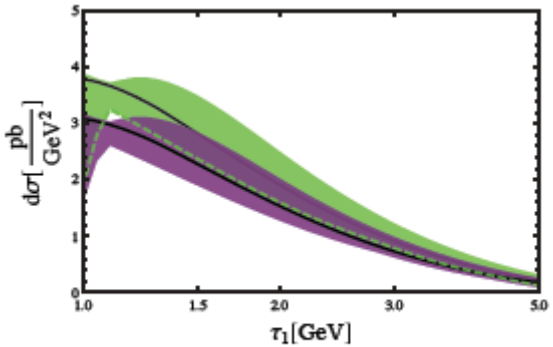
1-jettiness distribution for various nuclei



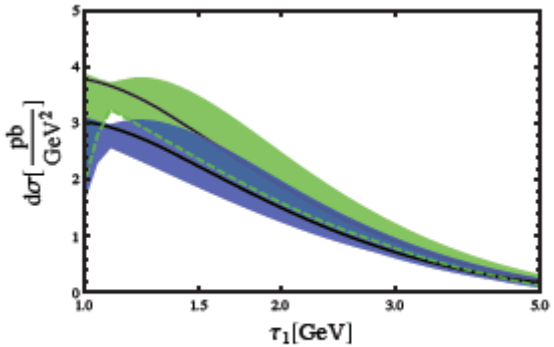
(a)Proton



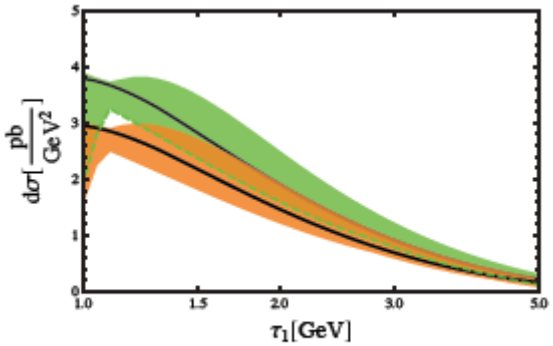
(b)C and Proton



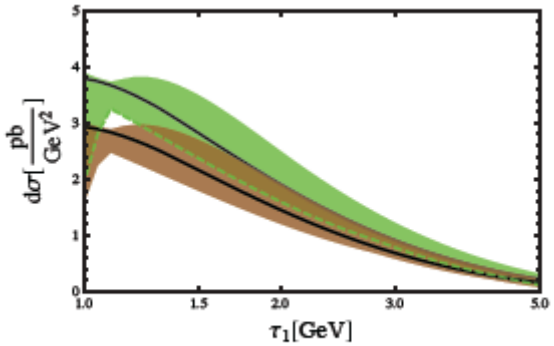
(c)Ca and Proton



(d)Fe and Proton



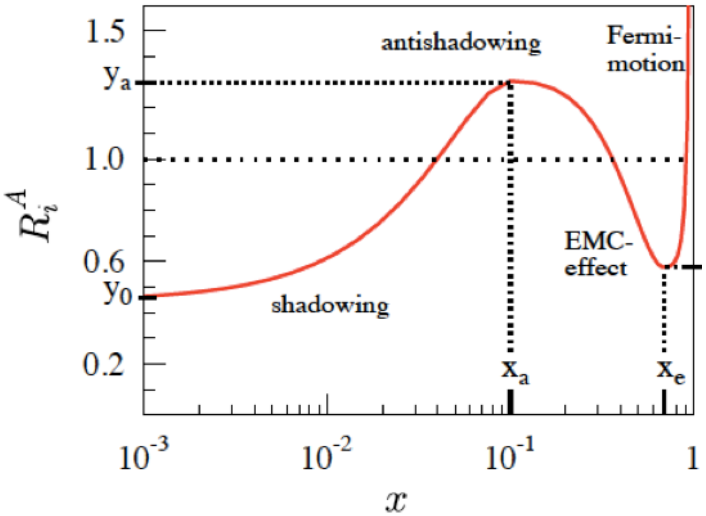
(e)Au and Proton



(f)Ur and Proton

Effect of nPDFs and smearing

$$R_L(x,\mu) = \frac{\sum_q e_q^2 f_{q/A}^{EPS09}(x,\mu)}{\sum_q e_q^2 f_{q/p}(x,\mu)}$$



NNLL resummation

$Q_e = 90$ GeV

$P_{J_T} = 20$ GeV

$y = 0$

arXiv:1303.3063

Summary

- Jet is a well-defined observable – not unique!
  - a "footprint", or "living story" of an energetic quark/gluon
- QCD parton energy loss is a very interesting and rich topic
  - Color confinement and gluon self-interaction distinguish it from QED energy loss
  - Parton dE/dx is not a direct physical observable!
  - But, it does influence the observed hadronic cross section
- Jet's transverse structure – measurable/calculable!
  - A time-dilated hadronization or color neutralization process
- Event shape based analysis can be a useful tool
  - Quantify gluon shower, medium induced radiation, …
- QCD dynamics is rich – EIC will help explore it!

Thanks!

Backup slides

Medium induced gluon production

G.Bertsch and F.Gunion, PRD25 (1982)

❑ Approximation:

$$\mathcal{M}_1 = -2ig_s e^{it_0\omega_0}\vec{\epsilon}_\perp \cdot \left\{ \cancel{\vec{H}a_1 c} + \vec{B}_1 e^{it_{10}\omega_0}\,[c, a_1] + \cancel{\vec{C}_1 e^{-it_{10}(\omega_1-\omega_0))}}\,[c, a_1] \right\} .$$

$$\mathbf{H} = \frac{\mathbf{k}}{\mathbf{k}^2}\,, \qquad \mathbf{C}_{(i_1 i_2 \cdots i_m)} = \frac{(\mathbf{k} - \mathbf{q}_{i_1} - \mathbf{q}_{i_2} - \cdots - \mathbf{q}_{i_m})}{(\mathbf{k} - \mathbf{q}_{i_1} - \mathbf{q}_{i_2} - \cdots - \mathbf{q}_{i_m})^2}\,,$$

$$\mathbf{B}_i = \mathbf{H} - \mathbf{C}_i\,, \qquad \mathbf{B}_{(i_1 i_2 \cdots i_m)(j_1 j_2 \cdots i_n)} = \mathbf{C}_{(i_1 i_2 \cdots j_m)} - \mathbf{C}_{(j_1 j_2 \cdots j_n)}\,.$$

❑ Induced gluon production:

$$\frac{dN_g^{(GB)}}{dy d^2\vec{k}_\perp} = C_A \frac{\alpha_s}{\pi^2} \frac{q_1^2}{k_\perp^2 (k - q_1)_\perp^2}$$

Where $y = \ln 1/x$ is interpreted as rapidity

❑ Gluon production in a medium:

$$\left\langle \frac{dN_g^{BG}}{dy d^2 k_T} \right\rangle_{q-transfer} = \int d^2 q_T \left[\frac{\mu^2}{\pi (q_T^2 + \mu^2)^2} \right] \frac{C_A \alpha_s(k_T)}{\pi^2} \frac{q_T^2}{k_T^2 (k_T - q_T)^2}$$

$$\sim \frac{C_A \alpha_s(k_T)}{\pi^2} \frac{\mu^2}{k_T^2 (k_T^2 + \mu^2)}$$

Introduce screen mass μ