Ivan Vitev

Jets at EIC

EIC User Group Meeting , January 6 – 9, 2016

Berkeley, CA

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(mostly focus on expectations for e+A)

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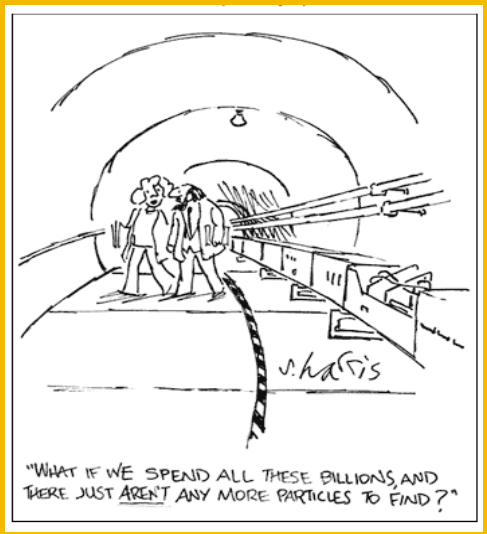
Outline of the Talk

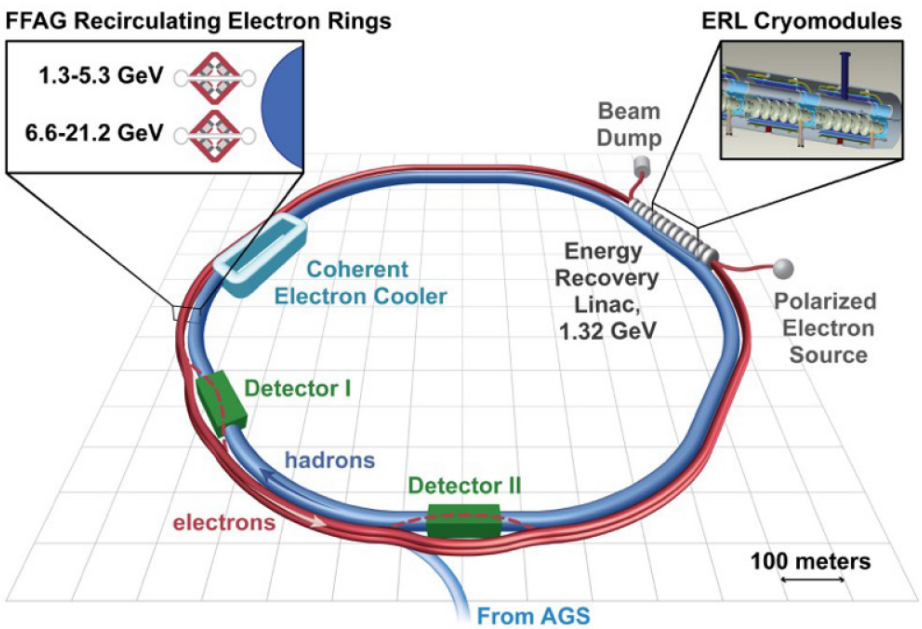
- Background: EIC, design and kinematics suitable for jet physics. Qualitative expectation, comparison between heavy ion collisions and SIDIS/jet production in DIS
- Hadron production and attenuation in semi-inclusive DIS. Energy loss and hadron absorption. QCD evolution techniques to in-medium modification of fragmentation functions
- Reconstructed jets at the EIC, jet cross sections. Jet substructure observables in DIS, jet shapes and jet fragmentation functions
- Event shapes at the EIC. Thrust and N-jettiness, extraction of the strong coupling constant. Polarized reactions
- Summary of EIC physics that can be addressed with jets

I. Background



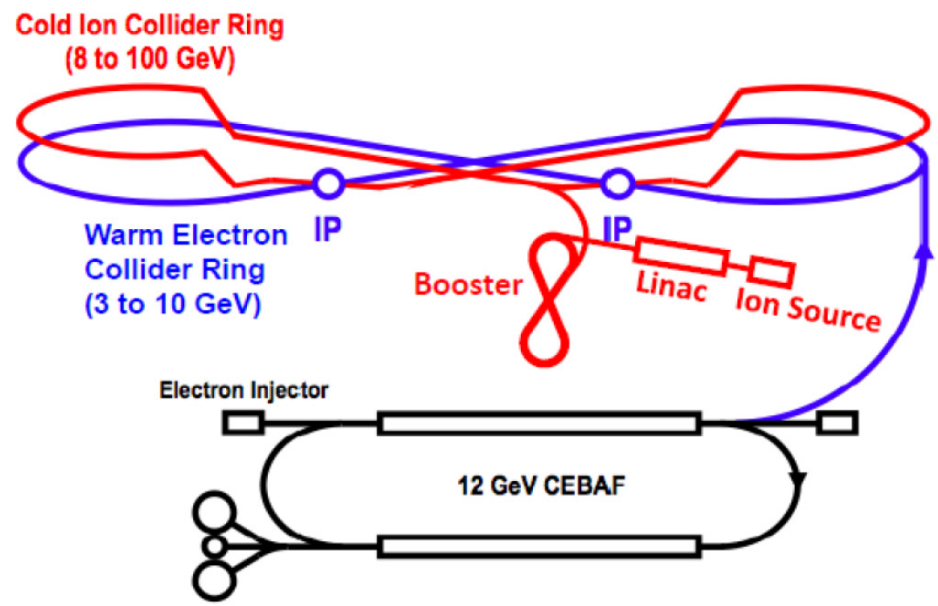
EIC design and capabilities

BNL design



- 5-10 GeV electron ring (upgradable to 20-30 GeV)
- 50-250 GeV proton/ion

JLab design

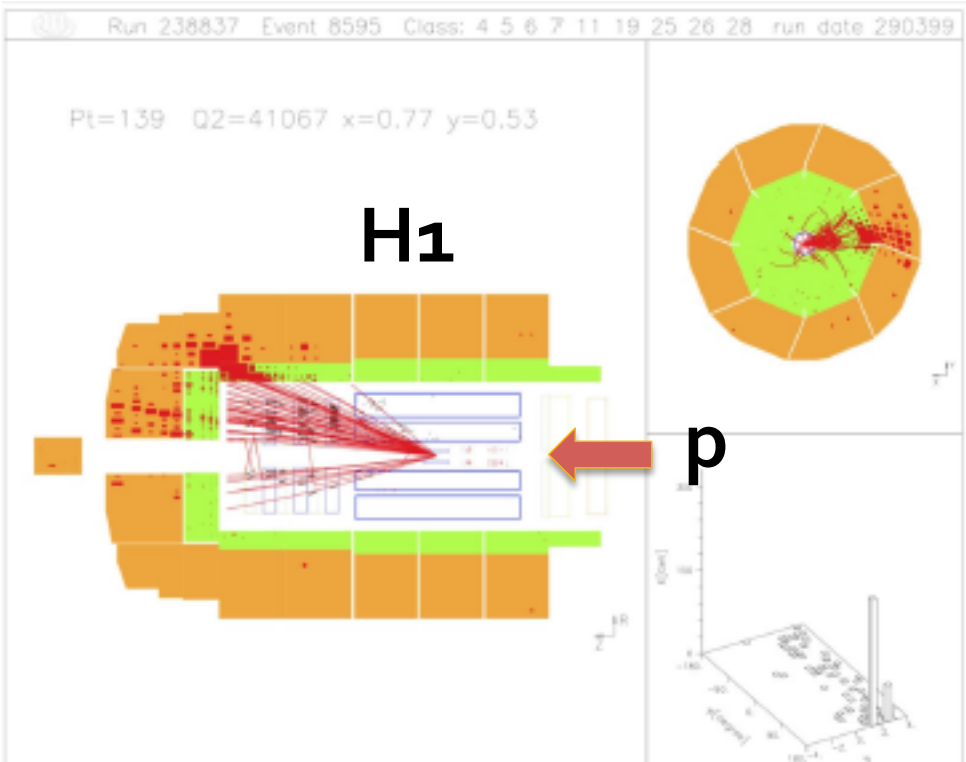


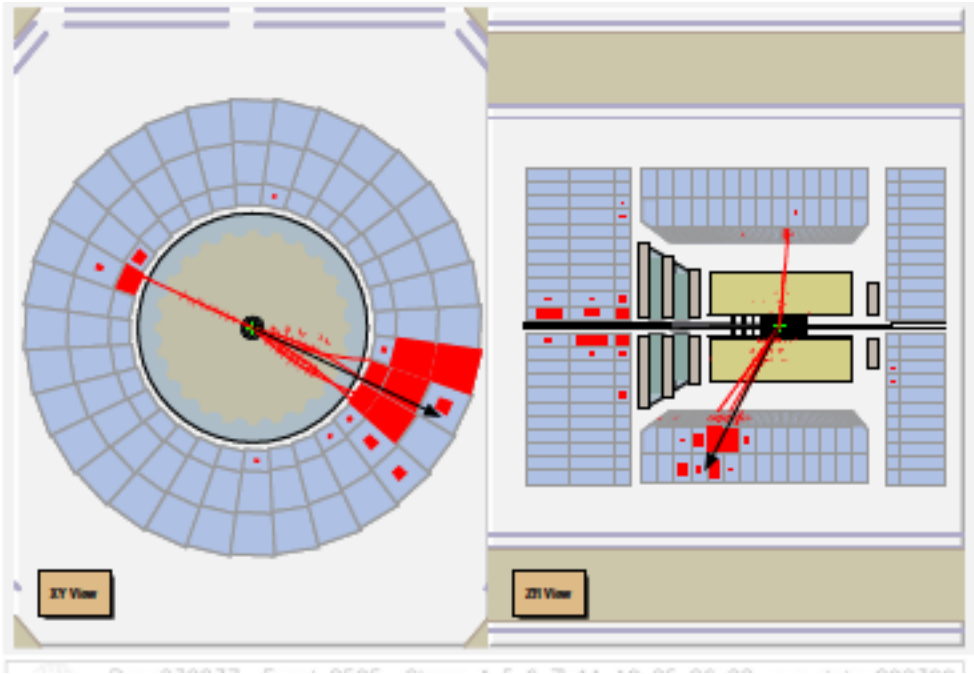
- 3-10 GeV electron ring
  10-100 GeV proton/ion

NSAC long range plan (2015)

Jet and inclusive hadron measurements

- For the purpose of this talk I will assume jet and hadron measurement capabilities, E_T/p_T, rapidity, momentum fraction z, in addition to DIS invariants





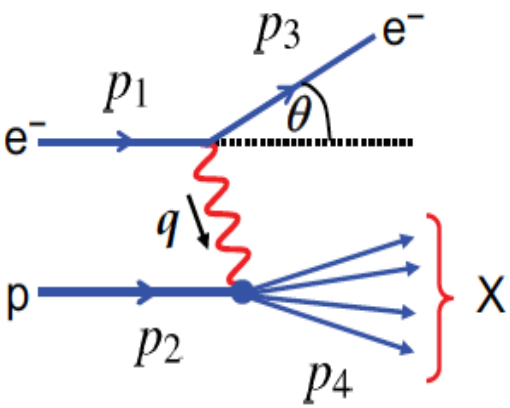
ZEUS

- Tracking, calorimetry, lepton and heavy flavor identification

P. Neuman et al. (2014)

See talk E. Aschenauer

The accessible jet energy



$$x = \frac{Q^2}{2M\nu}$$

$$Q^2 \equiv -q^2 = -(k-k')^2$$

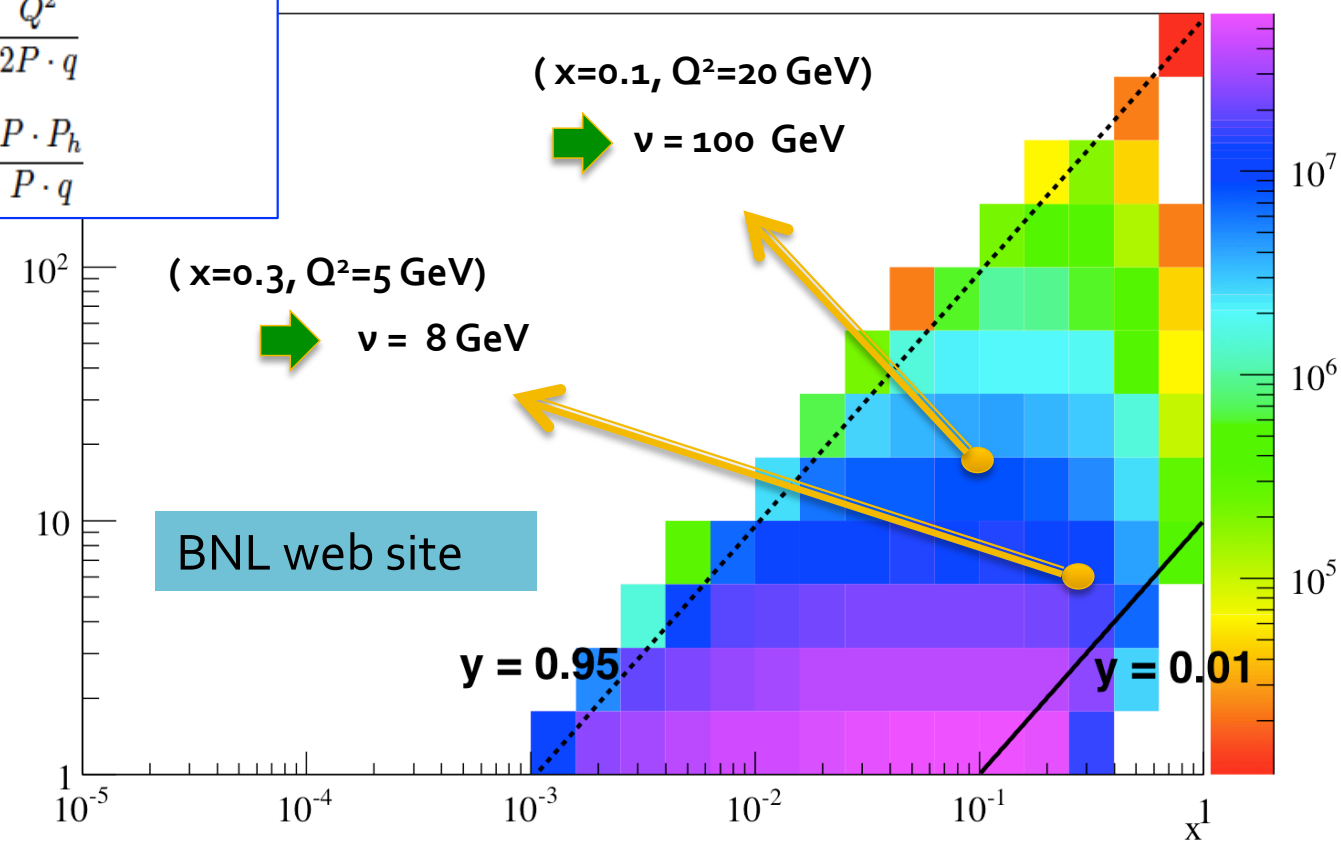
$$y \equiv \frac{P \cdot q}{P \cdot k}$$

$$x \equiv \frac{Q^2}{2P \cdot q}$$

$$z \equiv \frac{P \cdot P_h}{P \cdot q}$$

- Let's take an example that covers both designs

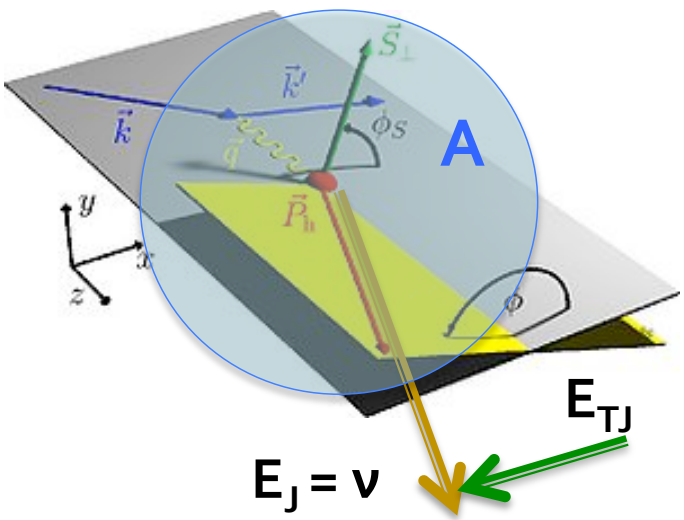
Energies 5 x 50 GeV



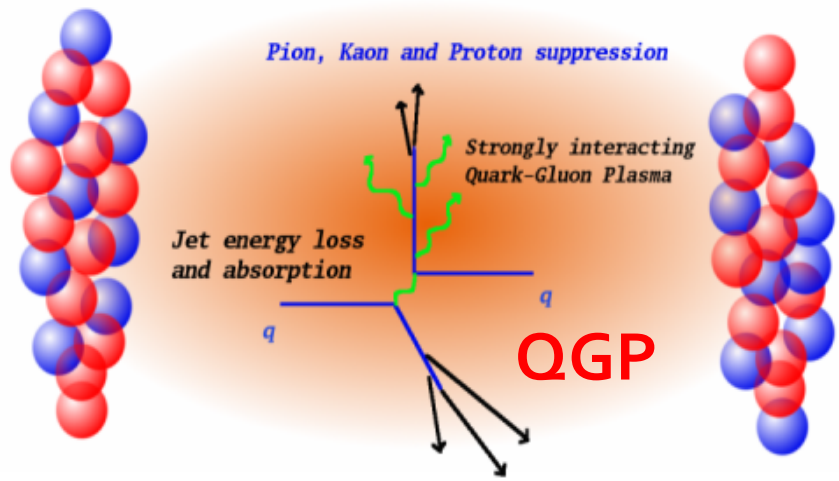
- The important quantity is the energy of the struck quark (patron) in the rest frame of the nucleus, ν

Comparison to RHIC and LHC jet energies

- Medium-induced parton shower modification is evaluated in the rest frame of the medium



ν in the range
(5 GeV – 200 GeV)

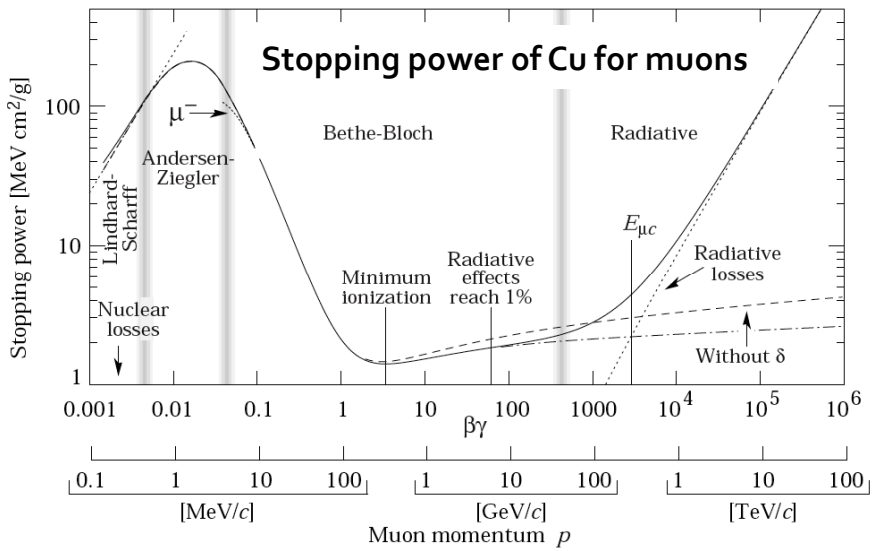


p_T / E_T in the range
(5 GeV – 200 GeV)

- EIC will cover jet energy ranges where the bulk of the jet quenching phenomena are at RHIC and LHC

Parton energy loss at the EIC

- The stopping power of matter is fundamental probe of the matter properties, in QED known to 1-2%



B. Zakharov, (1996)

R. Baier et al., (1997)

M. Gyulassy et al., (2000)

X. Guo et al., (2001)

P. Arnold et al., (2003)

The nature of the QCD theory gives rise to novel phenomena, such as the non-Abelian LPM effect

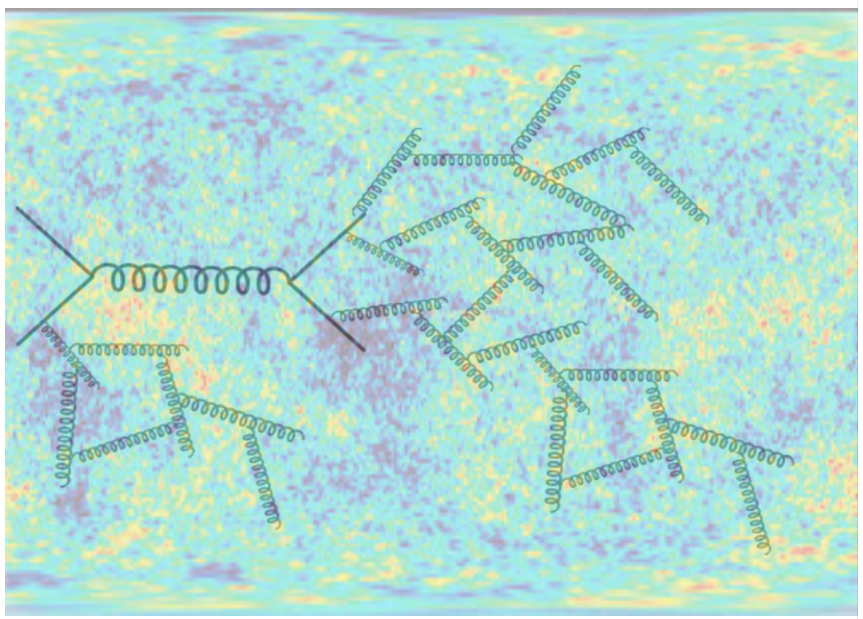
Parametric high energy behavior

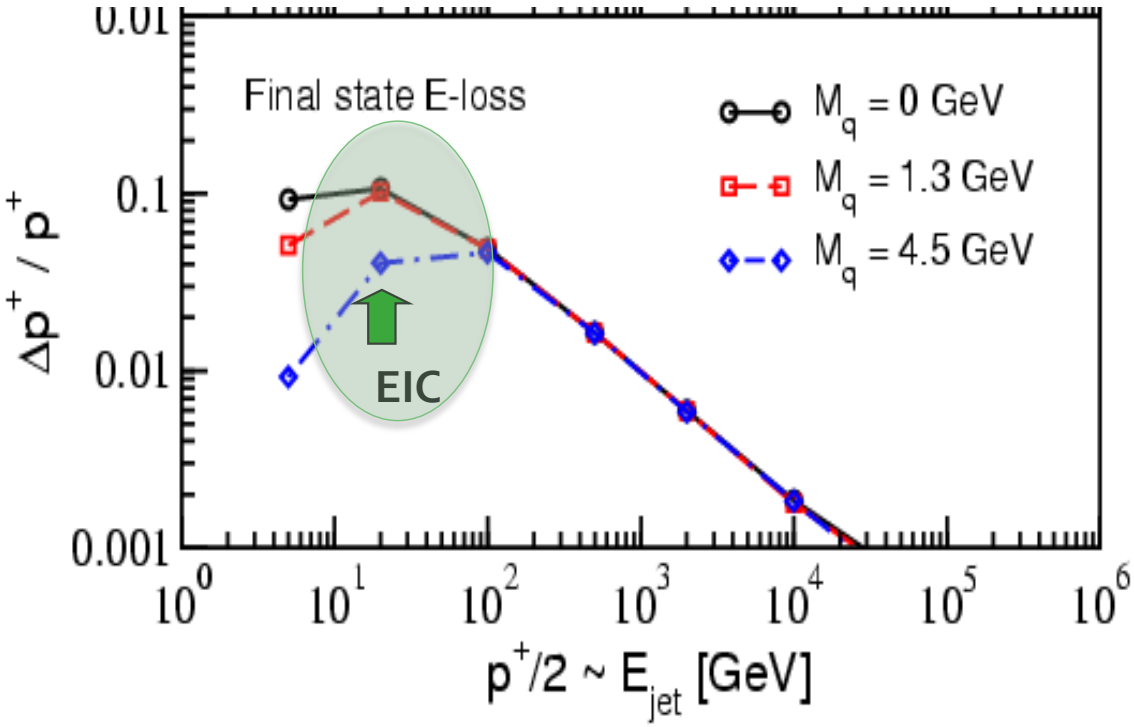
$$k^+ \frac{dN_g}{dk^+ d^2k_\perp} \sim \left[\sum_{m=1}^{n} \left(\cos\left(\sum_{k=2}^{m} \omega_{(k\ldots n)} \Delta z_k \right) - \cos\left(\sum_{k=1}^{m} \omega_{(k\ldots n)} \Delta z_k \right) \right) \right] \Rightarrow \frac{\Delta E}{E} \propto \frac{\mu^2 L^2}{\lambda_g} \frac{\ln E/Q_0}{E}$$

- For processes that involve hard scattering there is cancellation of the medium-induced bremsstrahlung at very high energies

The strength of the jet modification at EIC

- A scenario where the parton shower forms in the strong background gluon field of the nucleus





IV., 2007

- We expect parton energy loss, or more generally, the redistribution of the energy between vacuum and medium induced showers, to be factor of 2 (RHIC)-3 (LHC) smaller than in the QGP but not orders of magnitude smaller.

A common approach to jet-medium interactions

- Jet physics presents a multi-scale problem, EFT treatment

SCET (Soft Collinear Effective Theory)

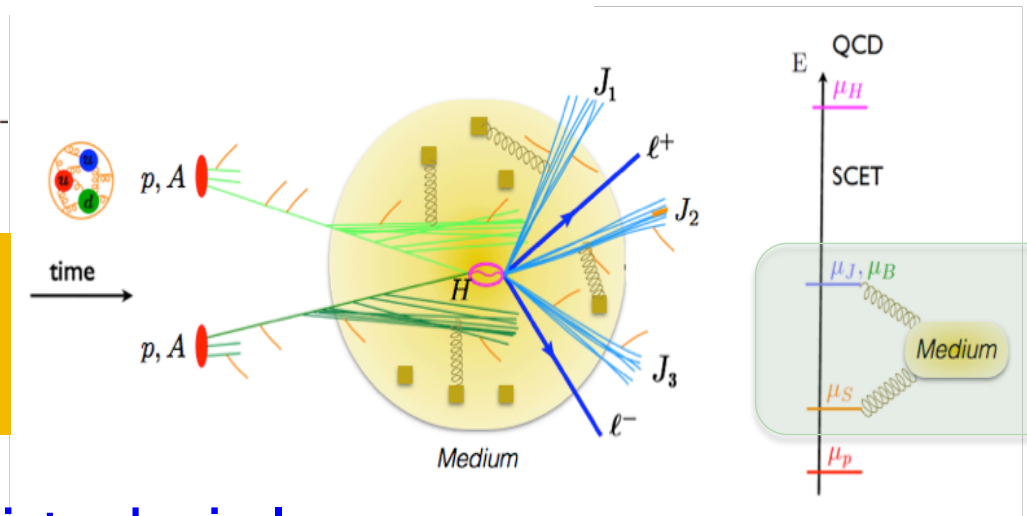
C. Bauer et al. (2001)

D. Pirol et al. (2004)

modes	$p^\mu = (+,-,\perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda, \lambda, \lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$

QGP CNM

$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j$$



$\sim E_J$

$\sim k_\perp, q_\perp$

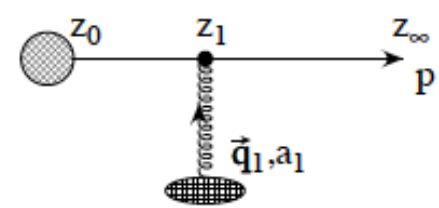
$\sim T, gT, \ldots \quad \sim \hat{q},\ Q_s, \ldots$

$\sim \Lambda_{QCD}$

- Factorization, with modified J, B, S

Glauber gluons to mediate physical interactions with the QCD medium

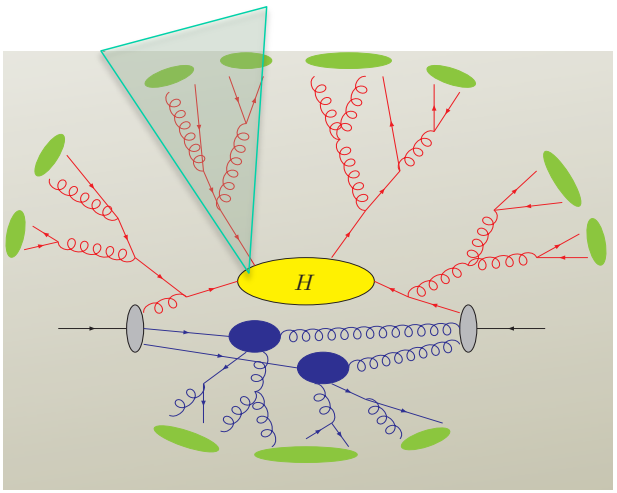
$$q = (\lambda^2, \lambda^2, \lambda)Q$$



A. Idilbi et al. (2008)

Ovanesyan et al. (2011)

Effective Field Theory Advances



G. Altarelli et al. (1977)

In-medium splitting functions beyond the soft gluon approximation

$$\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp} \left[-\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)^2 + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\right) \right.$$
$$\times\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right)$$
$$+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\left(1-\cos[(\Omega_2-\Omega_3)\Delta z]\right) + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\right)\cos[\Omega_4\Delta z]$$
$$\left. +\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\cos[\Omega_5\Delta z] + \frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)\right].$$

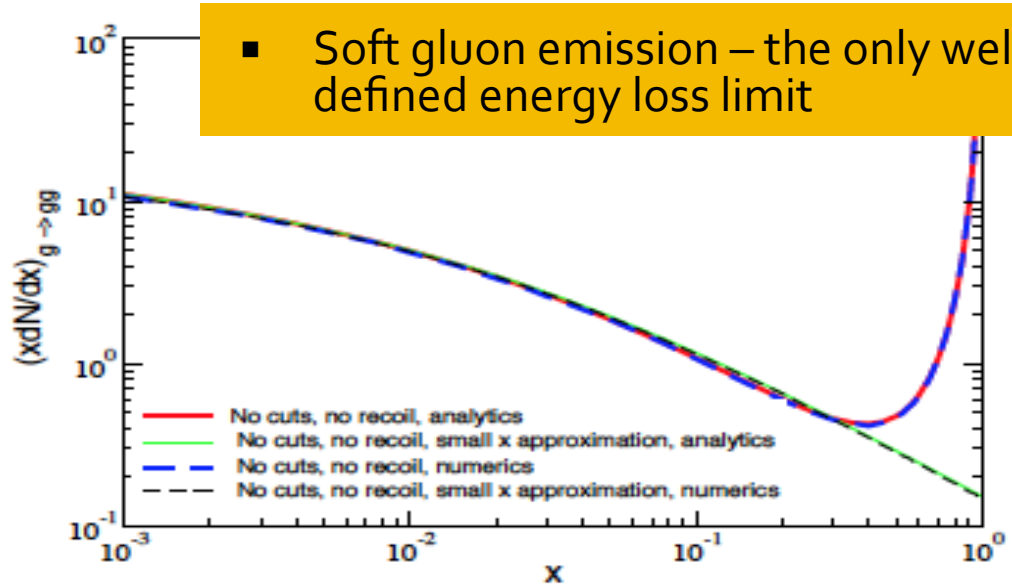
As in vacuum, a total of 4 splitting functions

- Implemented in DGLAP evolution equations

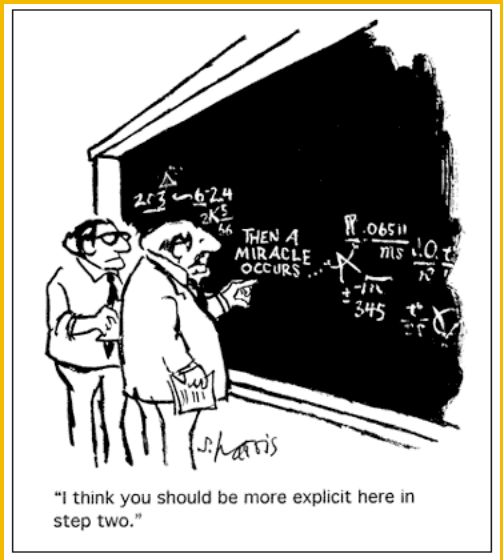
$$\frac{dN(tot.)}{dx d^2k_\perp} = \frac{dN(vac.)}{dx d^2k_\perp} + \frac{dN(med.)}{dx d^2k_\perp}$$

G. Ovanesyan et al. (2012)

- Soft gluon emission – the only well defined energy loss limit



II. Semi-inclusive DIS, e-loss and hadronization

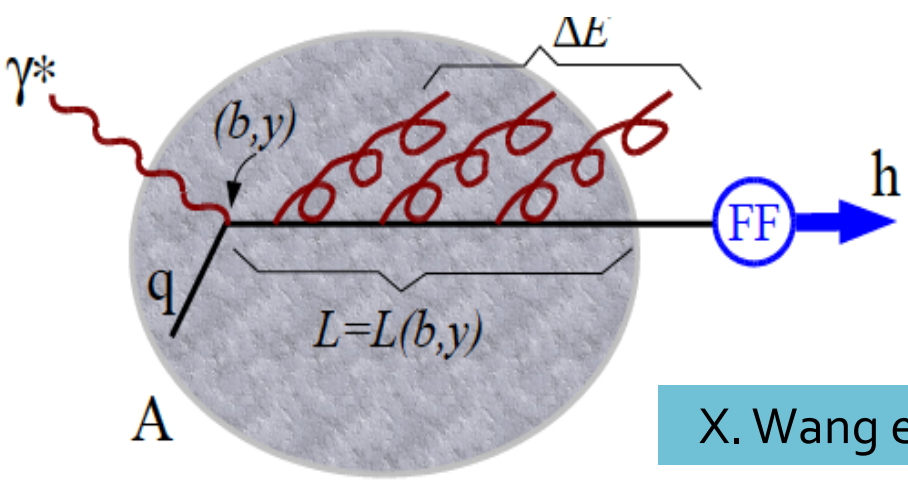


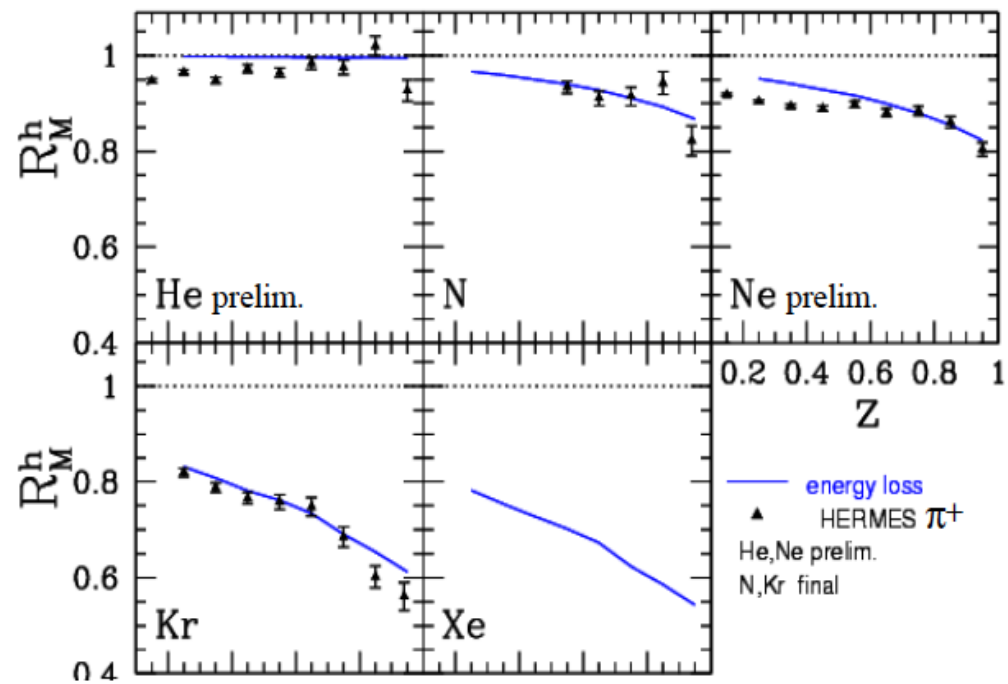
"I think you should be more explicit here in step two."

Semi-inclusive hadron suppression

- Energy loss-based approach compared to Hermes data

$$R_A^h(z,\nu) = \left(\frac{N^h(z,\nu)}{N^e(\nu)}|_A\right) / \left(\frac{N^h(z,\nu)}{N^e(\nu)}|_D\right)$$
$$= \left(\frac{\Sigma e_q^2 q(x)\widetilde{D}_q^h(z)}{\Sigma e_q^2 q(x)}|_A\right) / \left(\frac{\Sigma e_q^2 q(x) D_q^h(z)}{\Sigma e_q^2 q(x)}|_D\right)$$





X. Wang et al. (2002)

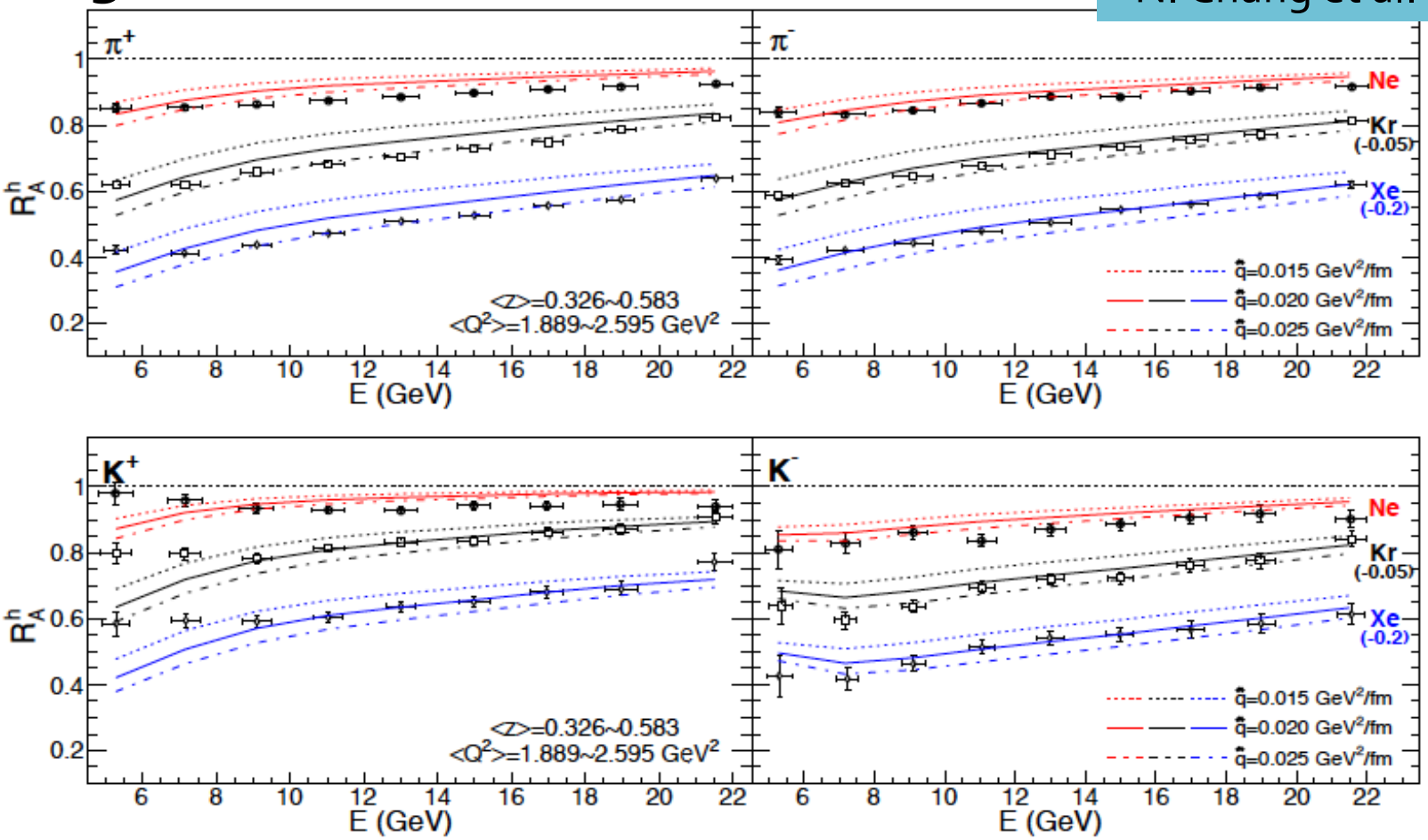
F. Arleo et al. (2003)

- A wide range of $\hat{q}$ obtained from < 0.1 GeV²/fm to 0.7 GeV²/fm

Hybrid approach to hadron attenuation at the EIC

Using E-loss initial conditions

N. Chang et al. (2014)



- A quite small $\hat{q} = 0.02\ GeV^2 / fm$. Again factor of 10 discrepancy in the transport properties of cold nuclear matter

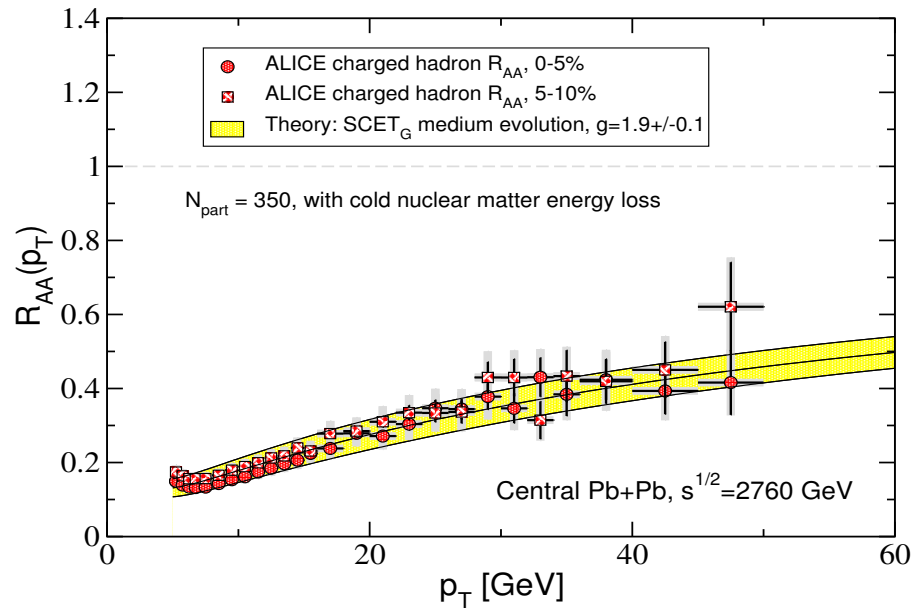
Full QCD evolution approach

- Based on DGLAP evolution with with $SCET_G$ medium-induced splitting kernels (LHC example)

$$\frac{\mathrm{d}D_{h/q}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left[P^{\mathrm{med}}_{q\to qg}(z',Q;\beta)D_{h/q}\left(\frac{z}{z'},Q\right) + P^{\mathrm{med}}_{q\to gq}(z',Q;\beta)D_{h/g}\left(\frac{z}{z'},Q\right)\right],$$

$$\frac{\mathrm{d}D_{h/g}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left[P^{\mathrm{med}}_{g\to gg}(z',Q;\beta)D_{h/g}\left(\frac{z}{z'},Q\right) + P^{\mathrm{med}}_{g\to q\bar{q}}(z',Q;\beta)\sum_q D_{h/q}\left(\frac{z}{z'},Q\right)\right].$$

Z. Kang et al. (2014)



- With larger Q^2 and jet energy, this will be implemented for the EIC

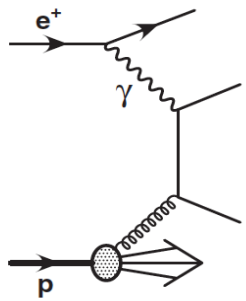
Dijet momentum imbalance and transverse momentum broadening

- One way to further constrain is the transverse momentum broadening or two particle momentum imbalance

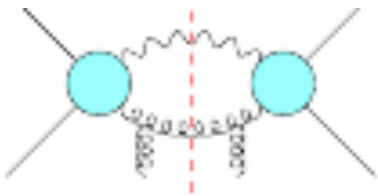
EIC reaction

Dijet imbalance

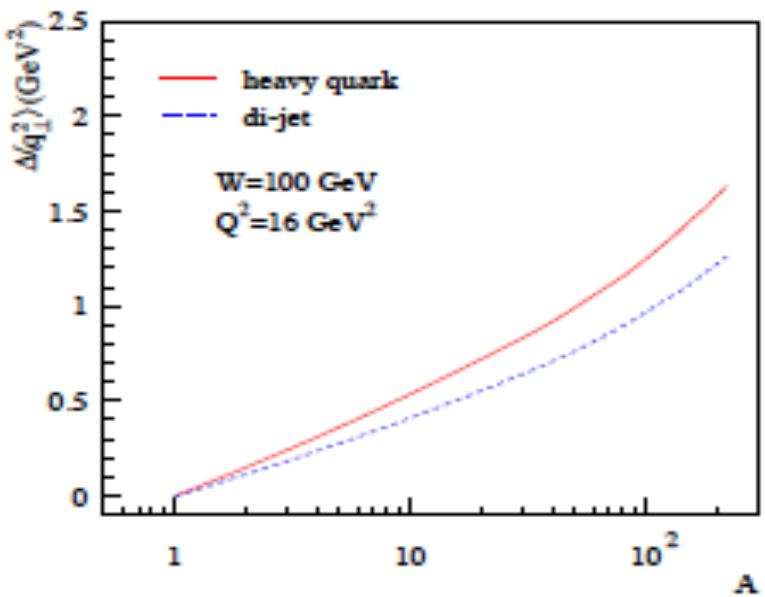
Dihadron imbalance



$$\gamma^*(P_{\gamma^*}) + A(P) \to J_1(p_1) + J_2(p_2) + X$$



H. Xing et al . (2012)



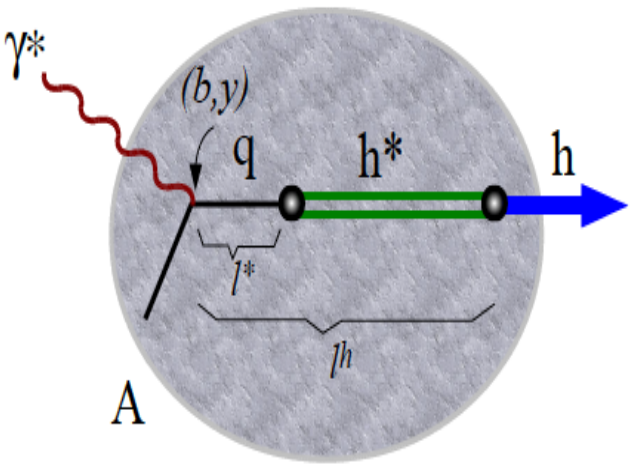
See talk by H. Xing

- Can directly constrain the transport properties of large nuclei

A. Schafer et al . (2012)

- Transverse momentum broadening, Cronin effect and scale dependence of the broadening. At present some discrepancy in SIDIS and DY broadening. EIC et higher Q^2 and energy will provide definitive answers

Hadron formation and absorption

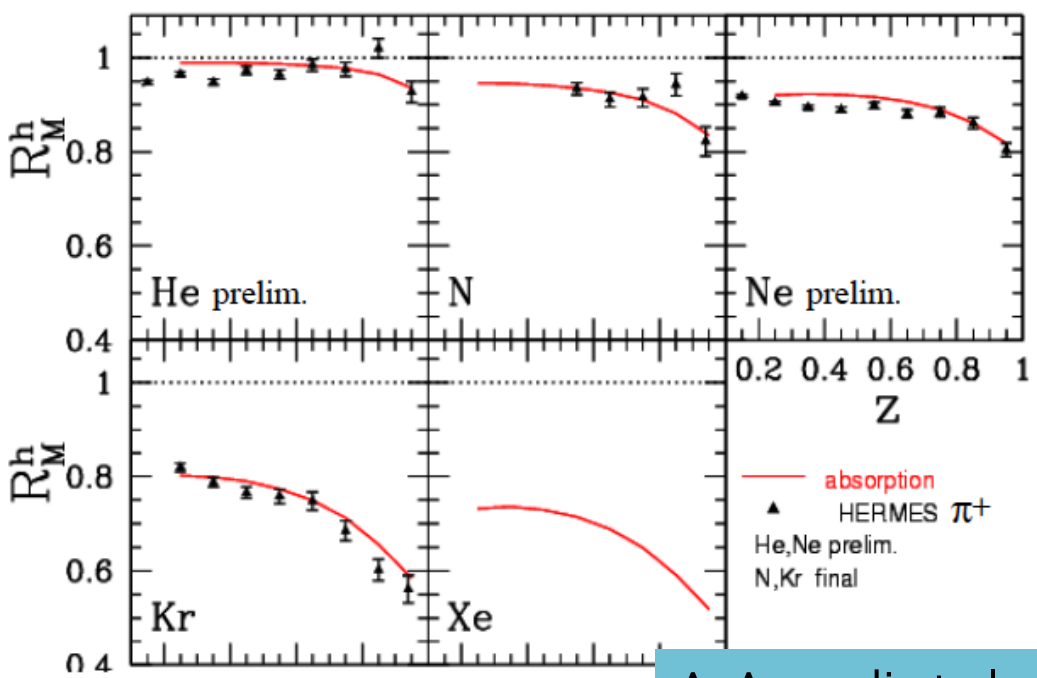


- Includes hadron but also pre-hadron formation and absorption

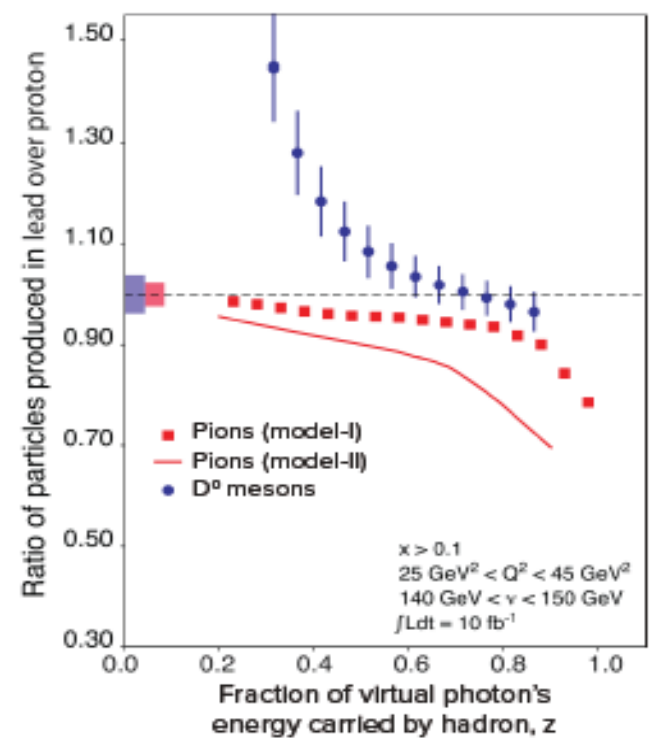
A. Accardi et al., 2003

B. Kopeliovich et al., 2003

$$\Delta y^{+} = \frac{1}{\Delta p^{-}} = \frac{(0.2\ GeV.fm)\ 2z(1-z)p^{+}}{k_{\perp}^{2} + (1-z)m_{h}^{2} - z(1-z)M_{q}^{2}}$$



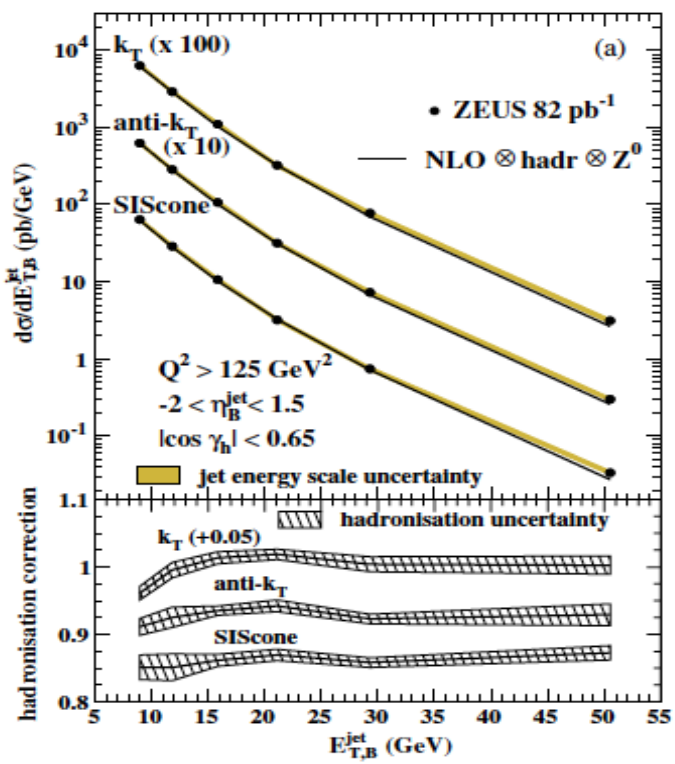
A. Accardi et al., 2005



III. Jet production at the EIC and jet substructure

Jet production at the EIC, e+p

- For e+p results for 2 and 3 jets are known to NLO



Inclusive jet production

Abramovitz et al, 2010

Direct production

Mirkes et al. (1996)

Catani et al. (1997)

Nagy et al. (2001)

Photo production

Gordon et al. (1992)

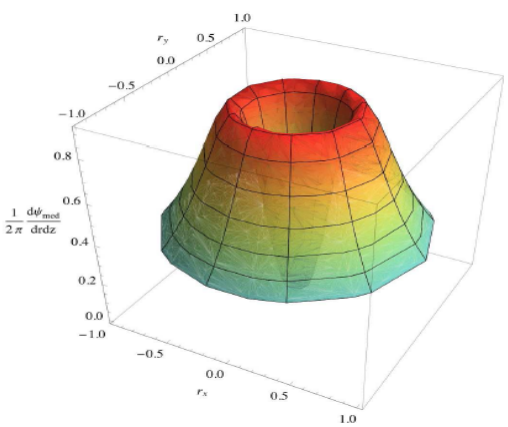
Harris et al. (1997)

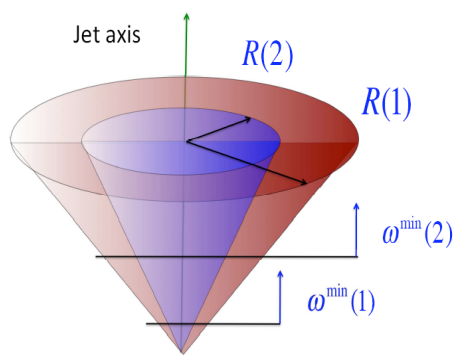
- Provides excellent test for QCD formalisms. Compare and connect the collinear and k_T factorization formalisms

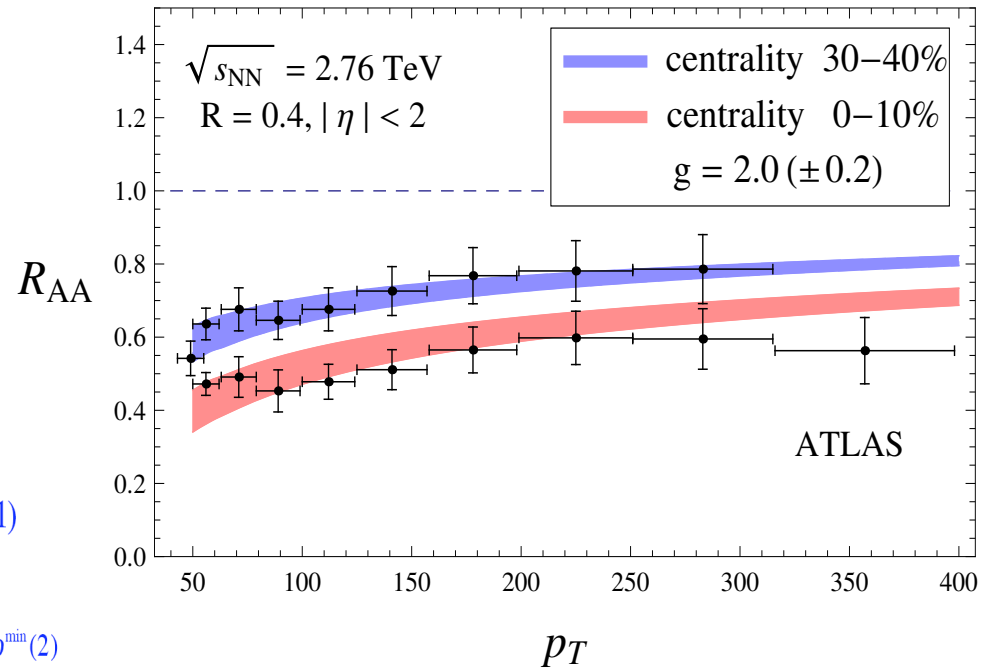
Generally smaller hadronization corrections

Jet cross section attenuation at the LHC and EIC, e+A

- The key physics that jets in QCD matter probe is the modification of the partion shower (broader and softer)







Y.-T. Chien et al. (2015)

- The in-medium parton splitting allow to generalize the concept of jet energy loss beyond the soft gluon approximation

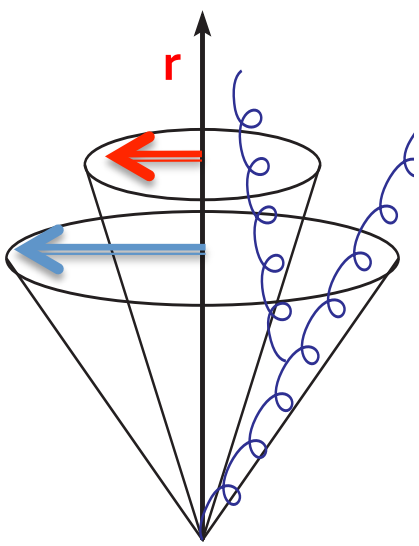
$$\epsilon_q = \frac{2}{\omega}\Big[\int_0^{\frac{1}{2}} dx k^0 + \int_{\frac{1}{2}}^1 dx (p^0 - k^0)\Big] \int_{\omega x(1-x)\tan\frac{R}{2}}^{\omega x(1-x)\tan\frac{R_0}{2}} dk_\perp \frac{1}{2}\Big[\mathcal{P}^{med}_{q\to qg}(x,k_\perp) + \mathcal{P}^{med}_{q\to gq}(x,k_\perp)\Big]$$

Jet substructure observables

- The jet shape

S. Ellis et al. (1993)

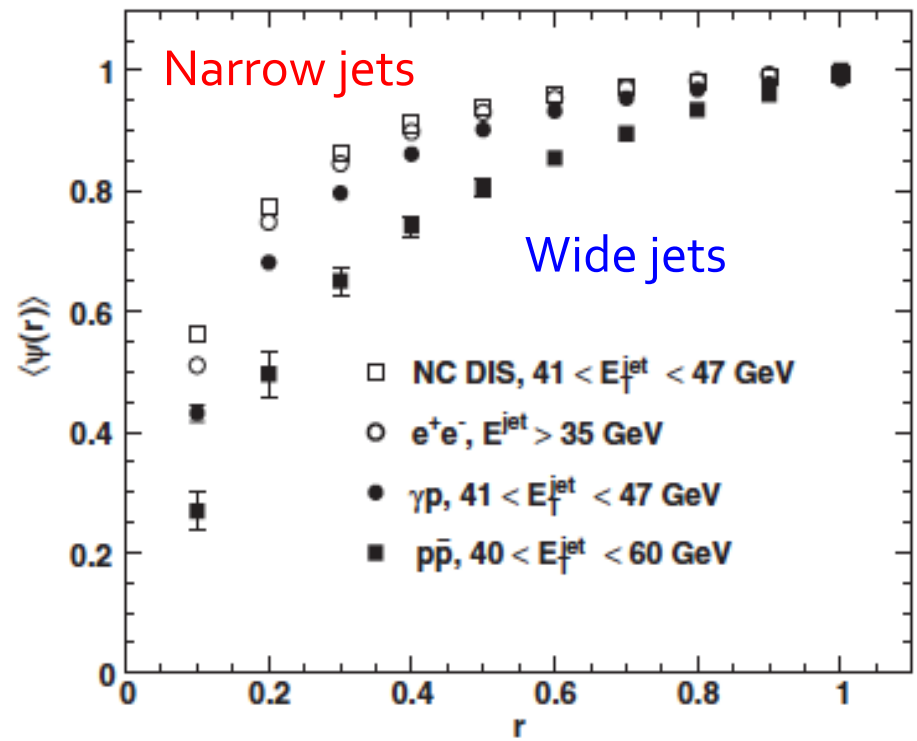
S. Ellis et al. (1993)



$$\Psi_{\rm int}(r;R) = \frac{\sum_i (E_T)_i \Theta(r-(R_{\rm jet})_i)}{\sum_i (E_T)_i \Theta(R-(R_{\rm jet})_i)}$$

$$\psi(r;R) = \frac{d\Psi_{\rm int}(r;R)}{dr}\,.$$

The transverse energy density inside a jet



Akers et al. (1994)

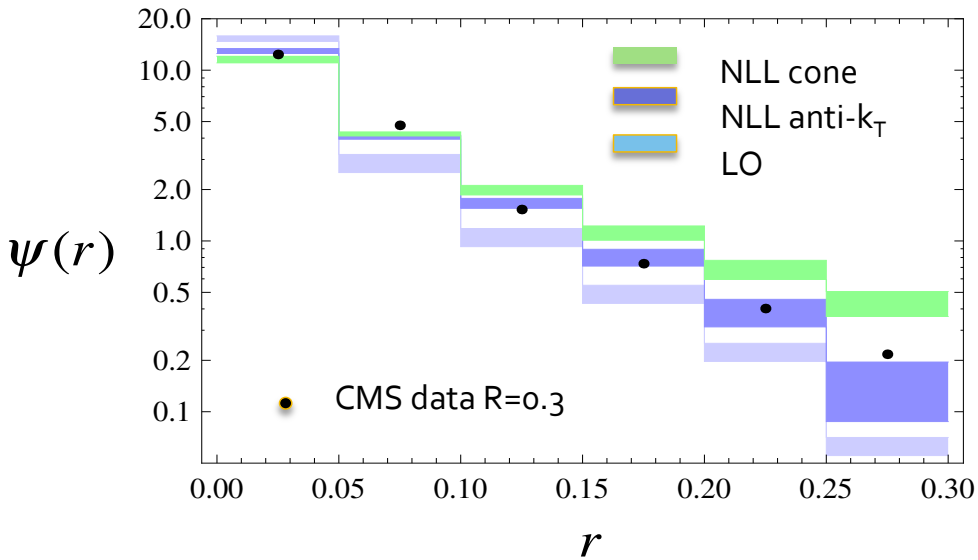
Breitweig et al. (1999)

Abe et al. (1993)

- A lot of advances in understanding jet substructure come from SCET, motivated by boosted heavy particle decay

NLL calculation of jet shapes

- The jet shape is defined by the ratio of two jet energy functions



- The algorithm dependence of the jet shapes (anti)k_T vs cone is included
- Significant improvement over fixed order calculation
- Examples for Tevatron, LHC

H-n. Li et al. (2011)

$$\Psi_\omega(r) = \frac{\langle E_r \rangle_\omega}{\langle E_R \rangle_\omega} = \frac{J_\omega^{E_r}(\mu)/J_\omega(\mu)}{J_\omega^{E_R}(\mu)/J_\omega(\mu)} = \frac{J_\omega^{E_r}(\mu)}{J_\omega^{E_R}(\mu)}$$

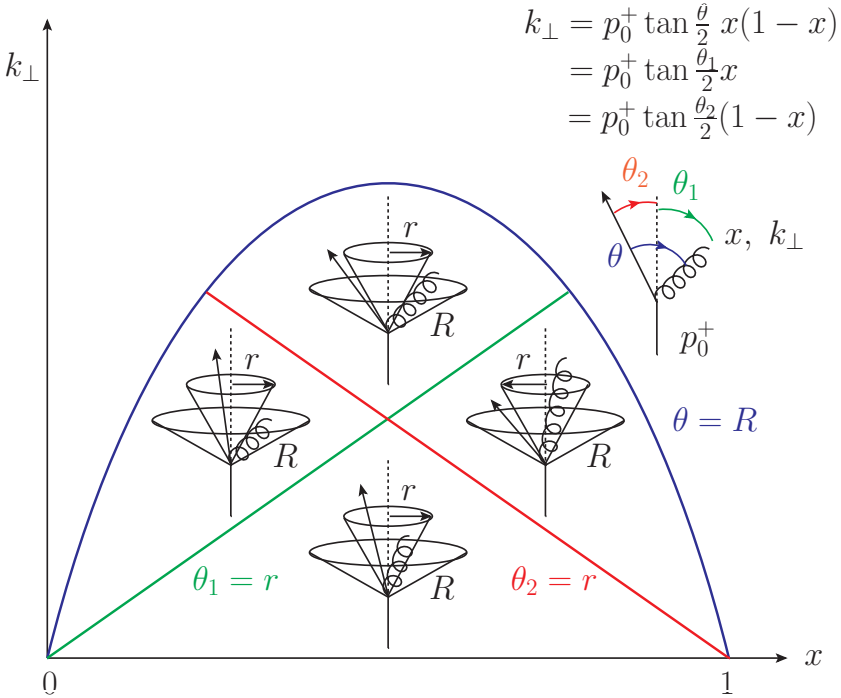
- To resum the jet shape to NLL accuracy we use SCET RG evolution techniques

$$\frac{dJ_\omega^{qE_r}(\mu)}{d\ln\mu} = \left[-C_F\Gamma_{\rm cusp}(\alpha_s)\ln\frac{\omega^2\tan^2\frac{R}{2}}{\mu^2} - 2\gamma^q(\alpha_s)\right] J_\omega^{qE_r}(\mu)$$

$$\frac{dJ_\omega^{gE_r}(\mu)}{d\ln\mu} = \left[-C_A\Gamma_{\rm cusp}(\alpha_s)\ln\frac{\omega^2\tan^2\frac{R}{2}}{\mu^2} - 2\gamma^g(\alpha_s)\right] J_\omega^{gE_r}(\mu)$$

Y.-T. Chien et al. (2014)

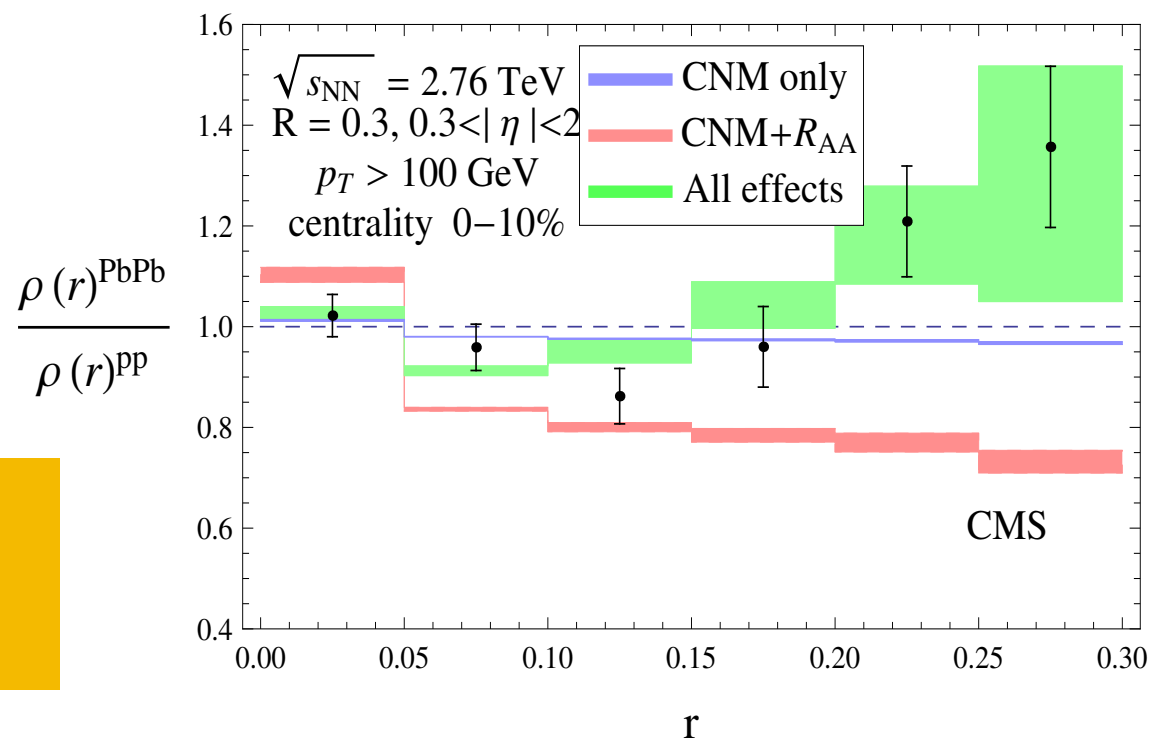
Medium-modified jet shapes



- One can evaluate the jet energy functions from the splitting functions

$$J^i_{\omega,E_r}(\mu) = \sum_{j,k} \int_{PS} dx dk_\perp \mathcal{P}_{i\to jk}(x,k_\perp) E_r(x,k_\perp)$$

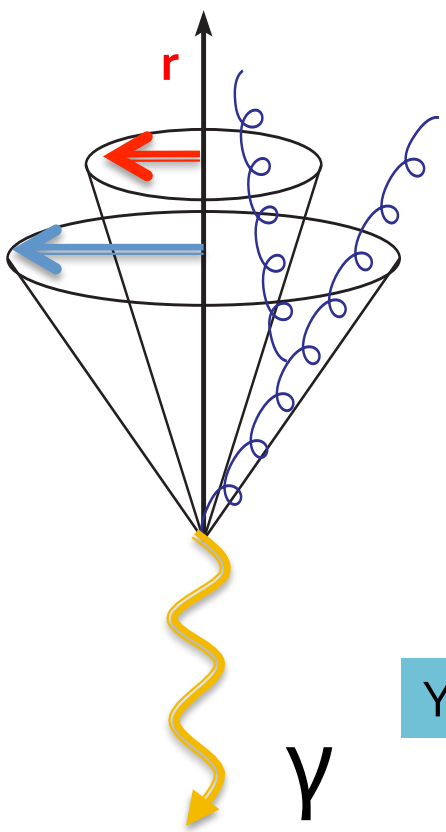
$$J_{\omega,E_r}(\mu) = J^{vac}_{\omega,E_r}(\mu) + J^{med}_{\omega,E_r}(\mu).$$



- First quantitative pQCD/ SCET description of jet shapes in QCD matter

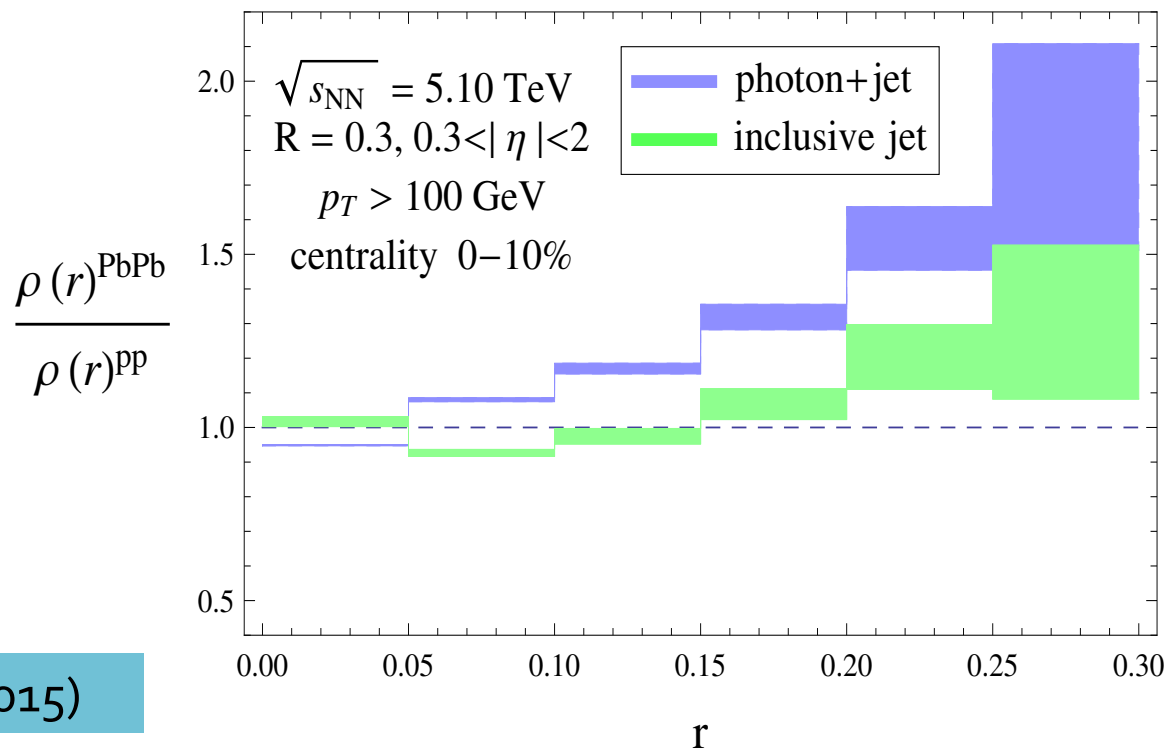
What can we expect at the EIC?

- At EIC, in the kinematic region of interest there is a dominance of quark initiated jets. Excellent for jet substructure studies



We can mimic this in hadronic collisions by photon tagging

Y.-T. Chien et al. (2015)

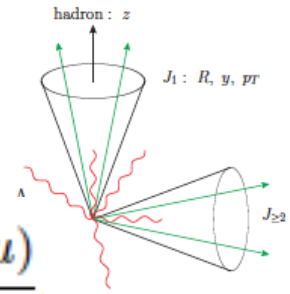


- Larger broadening of narrower quark jets

Jet fragmentation functions

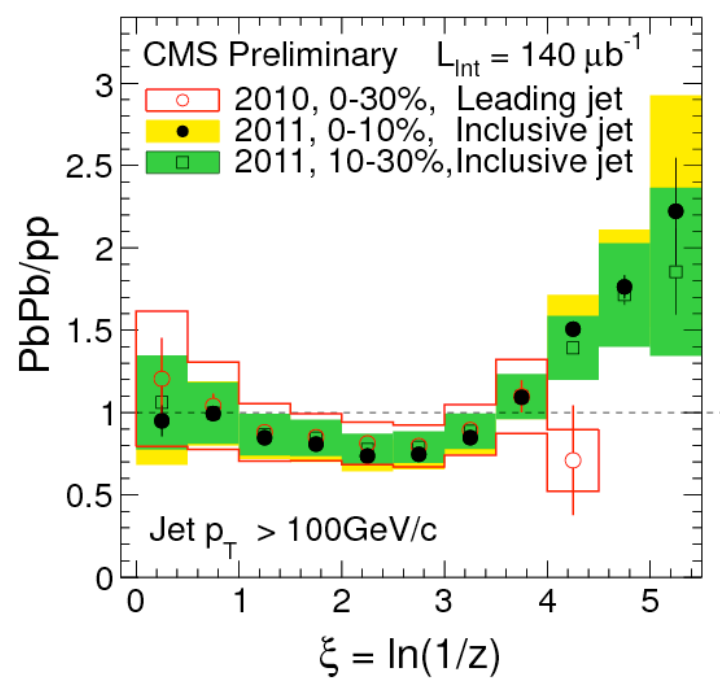
- Jet fragmentation functions probe the longitudinal jet substructure

Definition



$$F_{\omega_1}(z, p_{T_i}) = \frac{d\sigma^h}{dy_i dp_{T_i} dz} \Big/ \frac{d\sigma}{dy_i dp_{T_i}} = \frac{\mathcal{G}^h_{\omega_1}(z,\mu)}{J_{\omega_1}(\mu)}$$

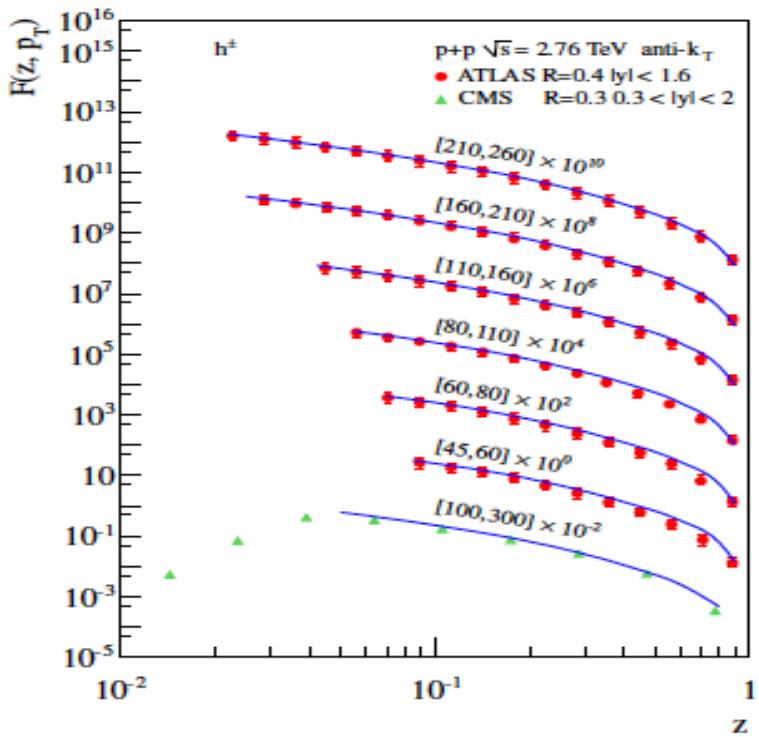
$$\mathcal{G}^h_i(\omega, R, z, \mu) = \sum_j \int_z^1 \frac{dx}{x} \mathcal{J}_{ij}(\omega, R, x, \mu)\, D^h_j(\frac{z}{x}, \mu) + \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{\omega^2 \tan^2(R/2)}\right)$$



Y. T. Chien et al. (2015)

- A ratio of a fragmenting jet function and unmeasured jet function, resummed to NLL accuracy

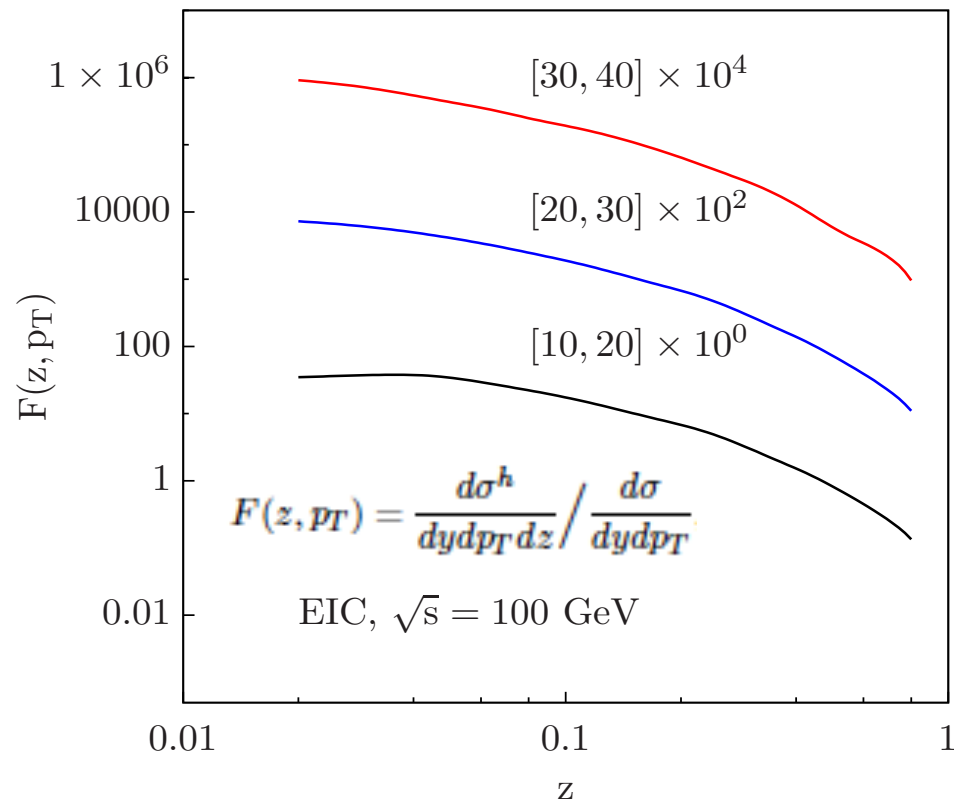
Results for jet fragmentation functions at LHC and EIC



- Very good comparison to data for z not too small and light hadrons. Both MC and pQCD / SCET fail for heavy flavor

T. Kauffman et al. (2015)

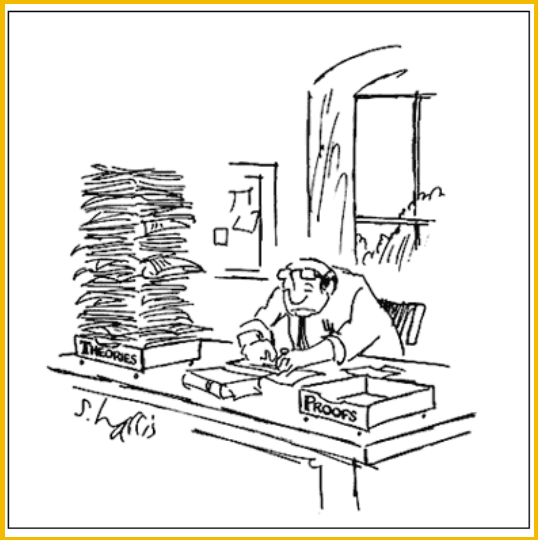
Y.-T. Chien et al. (2015)



- EIC, fairly high CM energy chosen, integrated over rapidities. Can constrain non-perturbative physics, such as the FFs

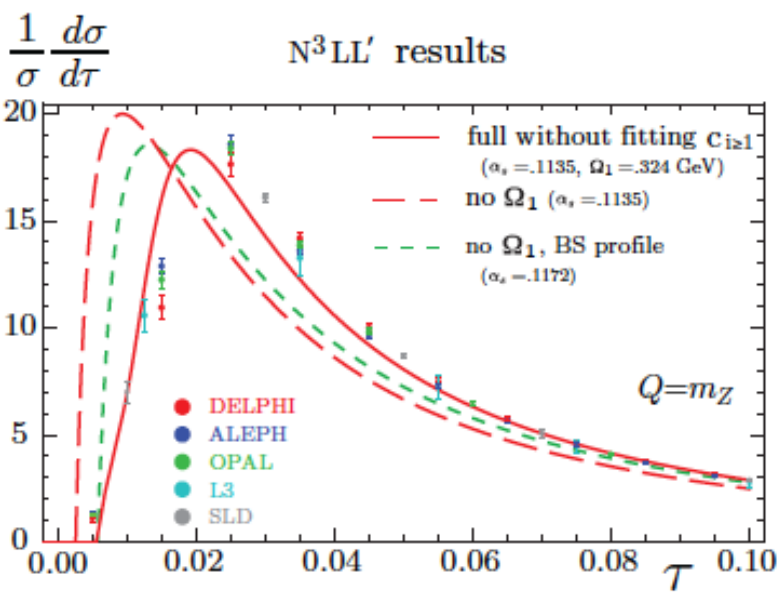
See talk by F. Ringer

IV. Event shapes at the EIC and α_s



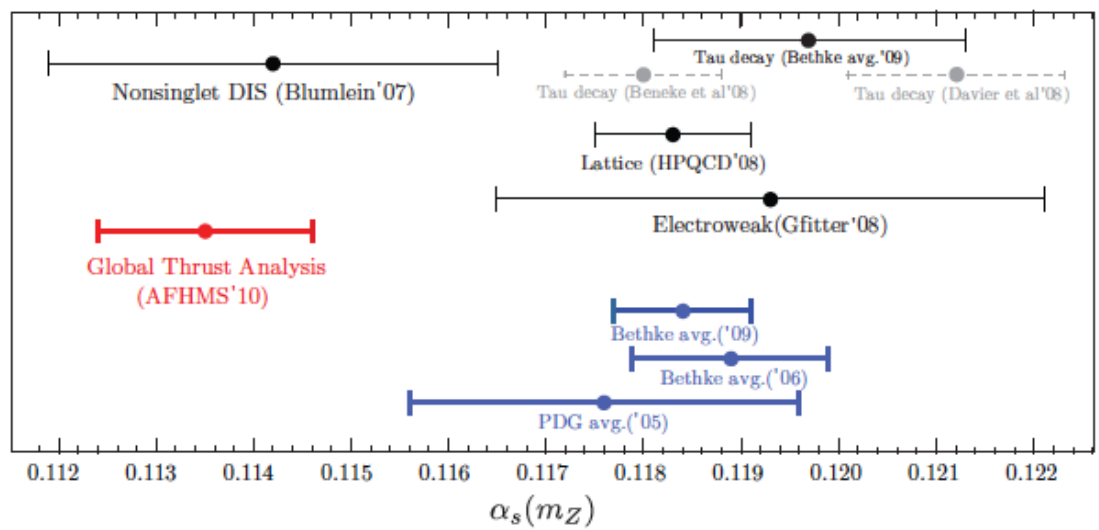
Global event shape observables

- Thrust, jet broadening, angularities, N-jettiness



R. Abatte et al. (2010)

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



Extraction of α_s

- Although the treatment of thrust is the most complete, there is discrepancy with the PDG average. Large (but universal) non-perturbative effects Ω

N-jettiness, α_s extraction

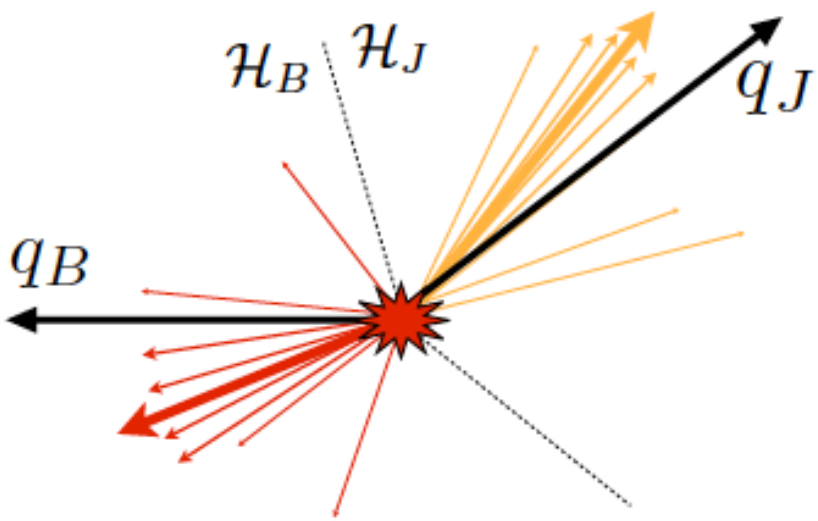
- Generalization of thrust with N+1 collinear directions

$$\tau_N = \frac{2}{Q^2} \sum_i \min\{q_B \cdot p_i, q_1 \cdot p_i, \ldots, q_N \cdot p_i\}$$

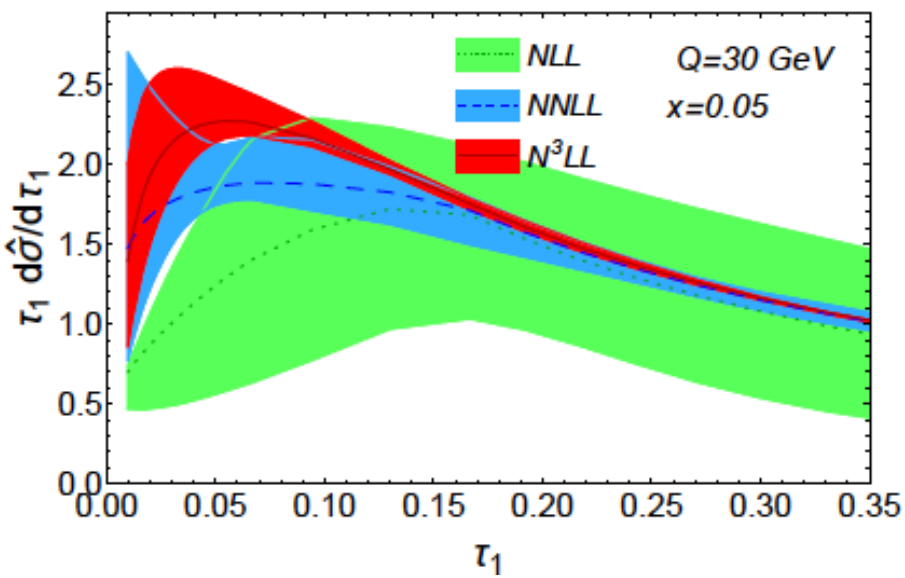
I. Stewart et al. (2010)

Z. Kang et al. (2012)

D. Kang et al. (2013)



- 1-jettines considered to avoid certain complications (NGL)

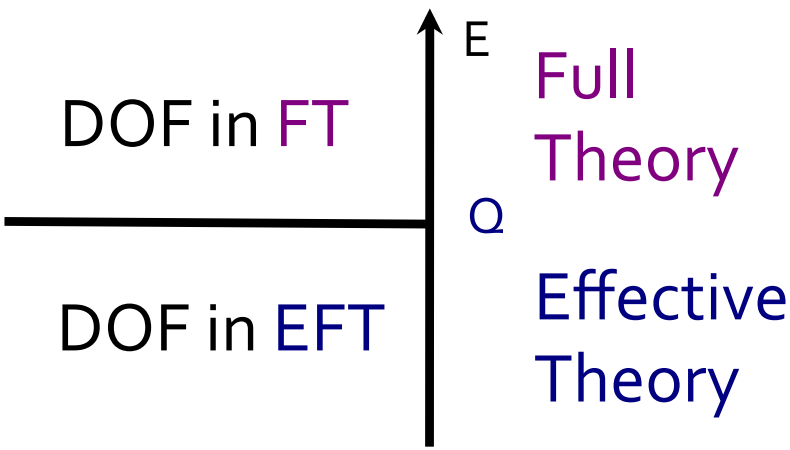


C. Lee et al. in preparation

Conclusions

- EIC opens unique possibilities to study jet/hadron production in cold dense QCD matter and provides ideal kinematics
- Jet and hadron production at the EIC will pinpoint the transport properties of large nuclei, the stopping power nuclear matter, and test the strong gluon field paradigm
- Hadron production and attenuation in semi-inclusive DIS will shed light on the process of hadronization and the nature of color neutralization and confinement
- Jet substructue observables will provide a detailed picture of in-medium parton shower (longitudinal and transverse structure) in the background of strong color fields
- Event shape observables can be used for precise extraction of the strong coupling constant

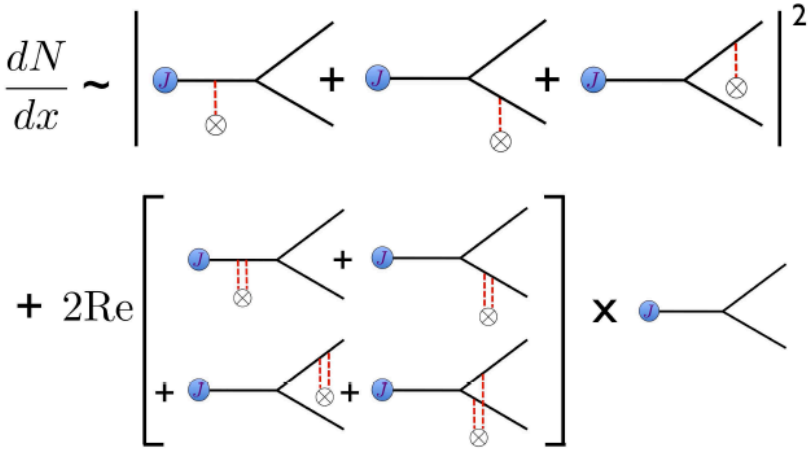
Examples of effective field theories [EFTs]



- Simple but powerful idea to concentrate on the significant degrees of freedom [DOF]. Manifest power counting

	Q	power counting	DOF in FT	DOF in EFT
Chiral Perturbation Theory (ChPT)	Λ_{QCD}	p/Λ_{QCD}	q, g	K,π
Heavy Quark Effective Theory (HQET)	m_b	Λ_{QCD}/m_b	ψ,A	h_v,A_s
Soft Collinear Effective Theory (SCET)	Q	$p_\perp/Q$	ψ,A	ξ_n, A_n, A_s

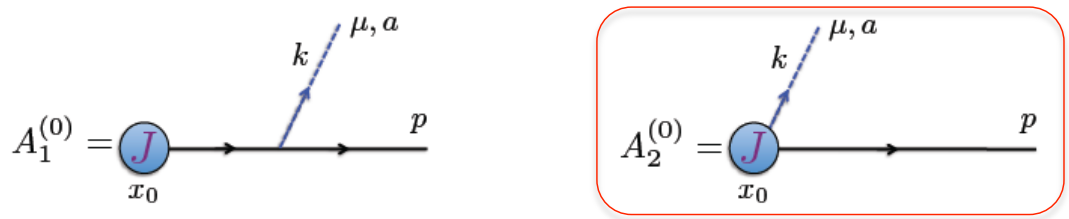
III. Main results: in-medium splitting / parton energy loss



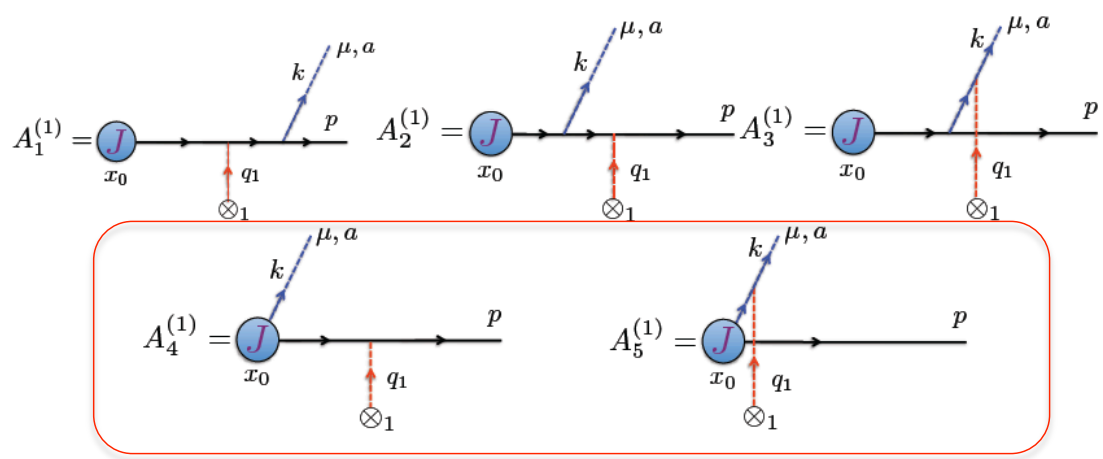
Gluon splitting functions factorize form the hard scattering cross section only for spin averaged processes

Altarelli-Parisi splitting

G. Altarelli et al. (1978)



$$\Gamma_W^{\alpha,a}(k) = gT_r^a \frac{\bar{n}^\alpha}{k^+ + i\epsilon}$$

- Note that a collinear Wilson line appears in the R_ξ gauge

Single Born diagrams