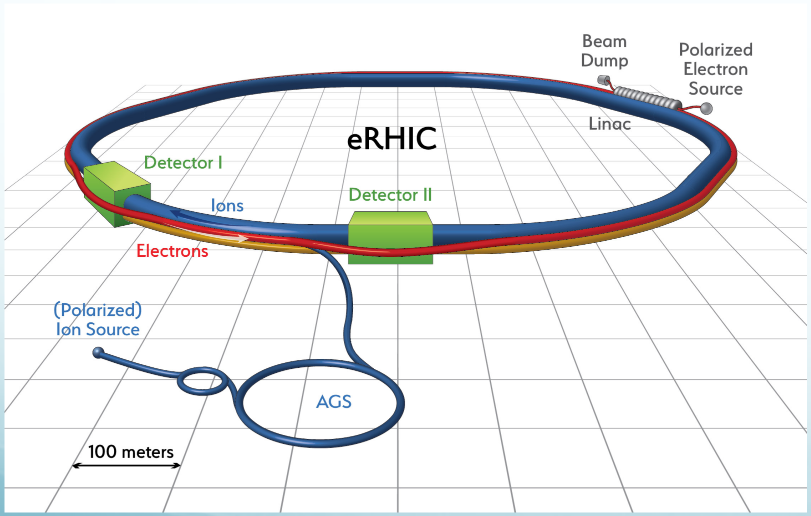
Review: jets in ep/eA DIS

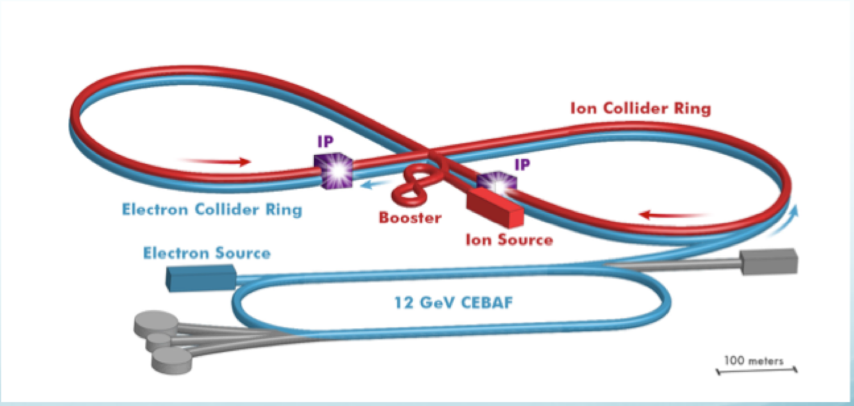
Zhongbo Kang
UCLA

2018 Workshop on Probing Quark-Gluon Matter with Jets
July 23 – 25, 2018

Jets and EIC

- Goal: discuss possible applications of jet physics to both e+p and e+A collisions
  - Consistent with the theme of the workshop, one should discuss the novel tools and observables that are being developed to probe the **cold** quark-gluon matter with jets in electron-ion collisions
- Electron Ion Collider
  - Highest priority for new construction in NSAC 2015 long range plan





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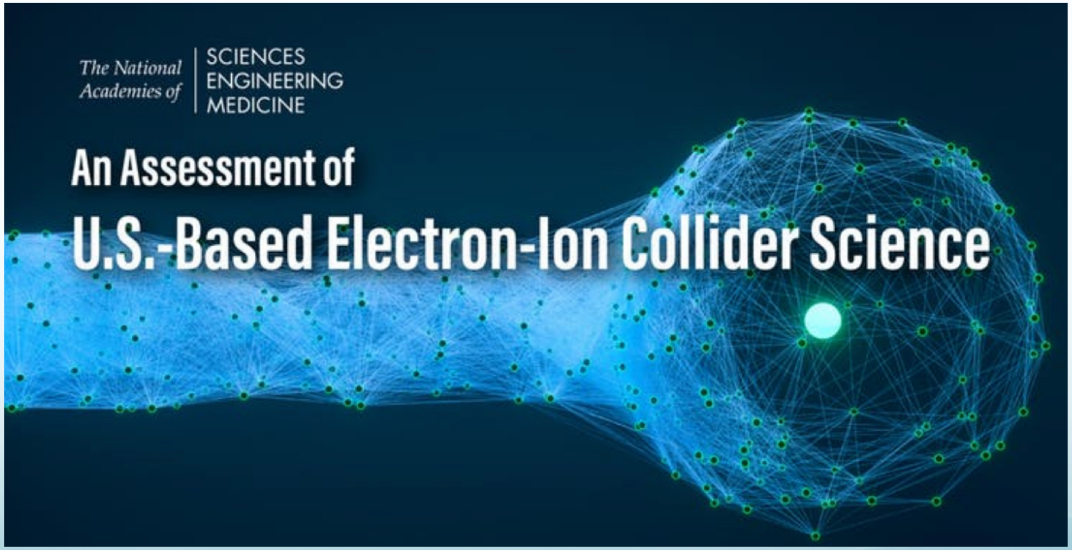
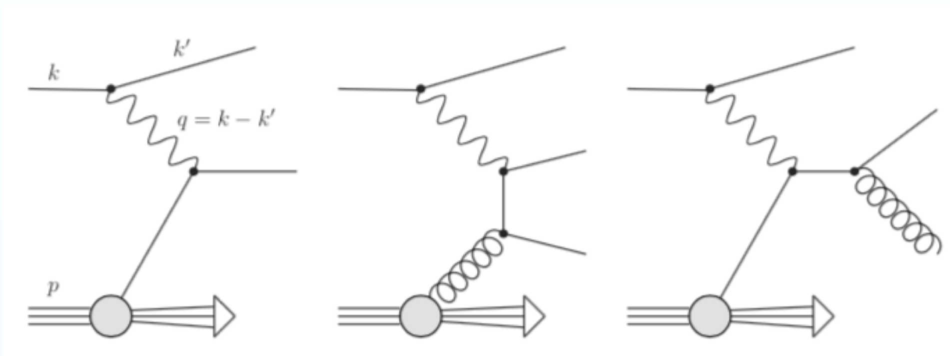
- Electron Ion Collider
  - Highest priority for new construction in NSAC 2015 long range plan
  - National Academy: report on EIC to be released on July 24

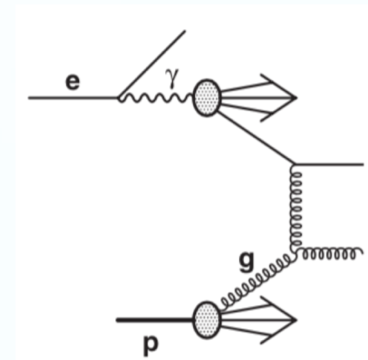


Jets in DIS

- Deep Inelastic Scattering (DIS) and photon-production



direct: Q^2 large



resolved: $Q^2 \sim 0$

- Well established QCD factorization formalism
  - Usual DIS process with virtual photon Q^2 large

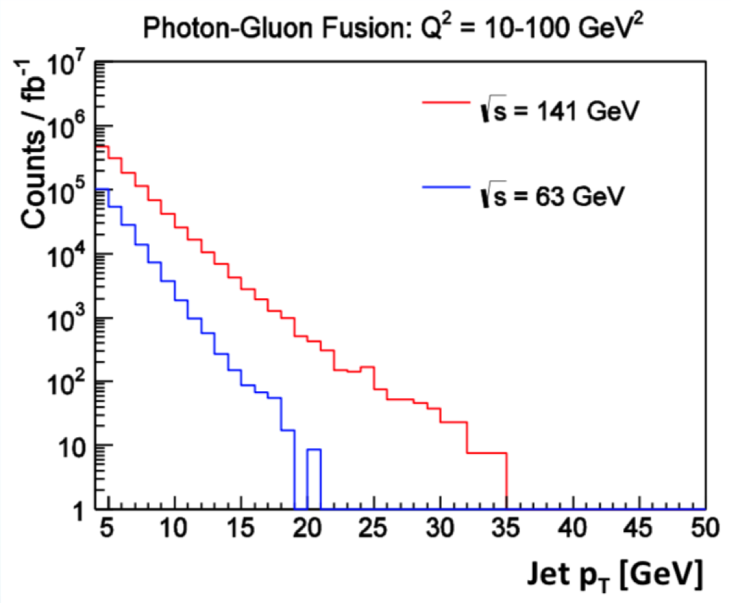
$$d\sigma_{ep\to e+\text{jets}+X} = \sum_a \int_0^1 d\hat{\sigma}_{ea\to cd}(x, \alpha_s(\mu_R), \mu_F, \mu_R) f_{a/P}(x, \mu_F) dx,$$

  - Photon-production

$$d\sigma_{ep\to e+\text{jets}+X} = \sum_{a,b} \int_0^1 dx_\gamma \int_0^1 dx_p f_{\gamma/e} f_{b/\gamma}(x_\gamma, \mu_{F\gamma}) f_{a/p}(x_p, \mu_{Fp}) \, d\hat{\sigma}_{ab\to cd}(x_\gamma, x_p, \alpha_s(\mu_R), \mu_{F\gamma}, \mu_{Fp}, \mu_R),$$

Jets at an EIC

- It was realized only recently that jet measurements are possible at EIC
  - EIC white paper does not contain study on jet physics: arXiv:1212.1701 (recently updated on Nov. 30, 2014)



Brian Page, Santa Fe Jets and Heavy Flavor Workshop 2016

  - Our outstanding experimental colleagues and EIC team made the initial feasibility studies in e+p collisions
  - No (published) jet studies in e+A collisions yet: *EIC would be the very first one*

Purposes of jet/QCD studies in DIS

- I: Studying QCD/jets to probe
  - Fundamental parameters of QCD: strong coupling constant
  - Parton structure of proton
  - Signature for BSM physics

NNLO + resummation

LHC THEORY — TOWARDS 1% PRECISION?

Gavin P. Salam, CERN

Joint CTEQ Meeting and 7th International Conference on Physics Opportunities at an EIC (POETIC 7)

- II: Studying QCD/jets to probe QCD medium
  - Cold nuclear matter in e+A collisions
  - Hot quark-gluon plasma in A+A collisions

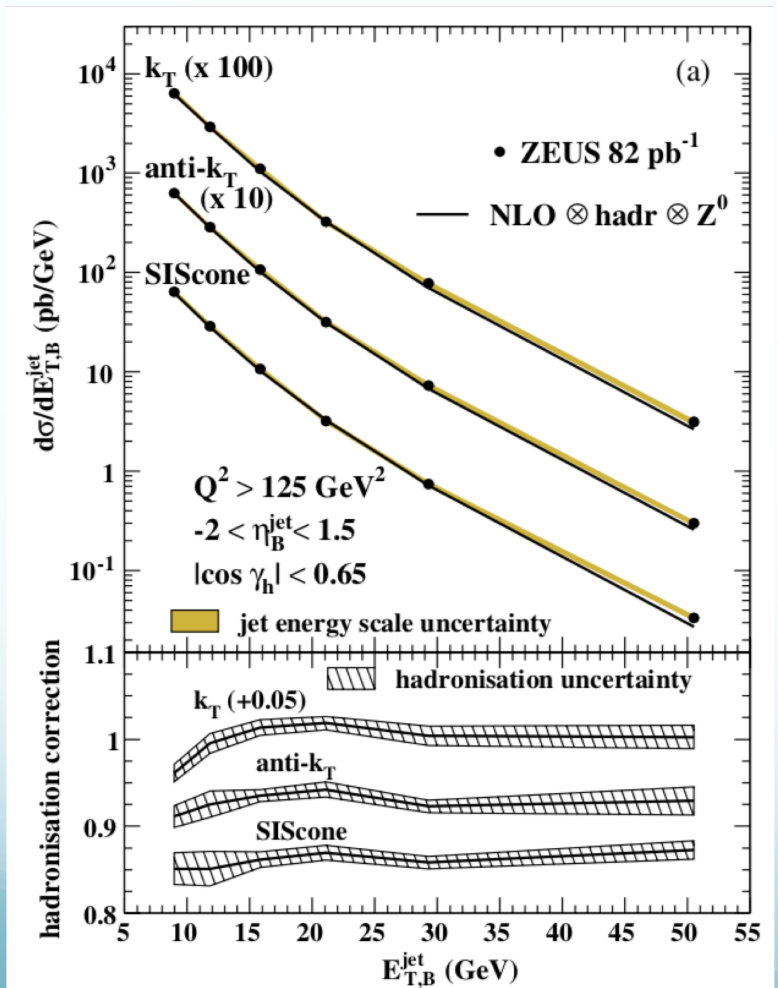
NLO + resummation is probably sufficient at the moment

First e+A jet measurements are still yet to come at EIC

Too many effects need to be taken into account in A+A

Jets in e+p collisions at HERA

- Jet measurements in e+p collisions are only from HERA
  - Theoretical computations could be obtained through NLOJet++ (Zoltan Nagy, based on Catani-Seymour dipole subtraction method)



REVIEWS OF MODERN PHYSICS, VOLUME 86, JULY–SEPTEMBER 2014

The hadronic final state at HERA

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Matthew Wing[†]

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom and DESY, Notkestrasse 85, 22607 Hamburg, Germany

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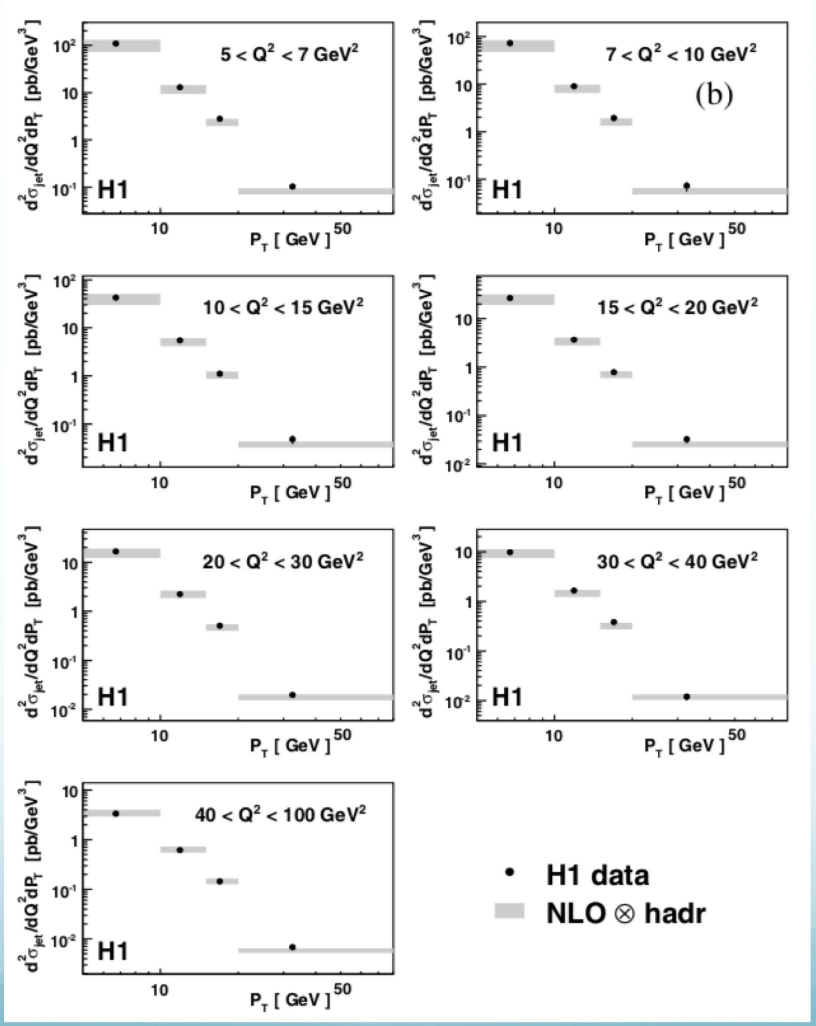


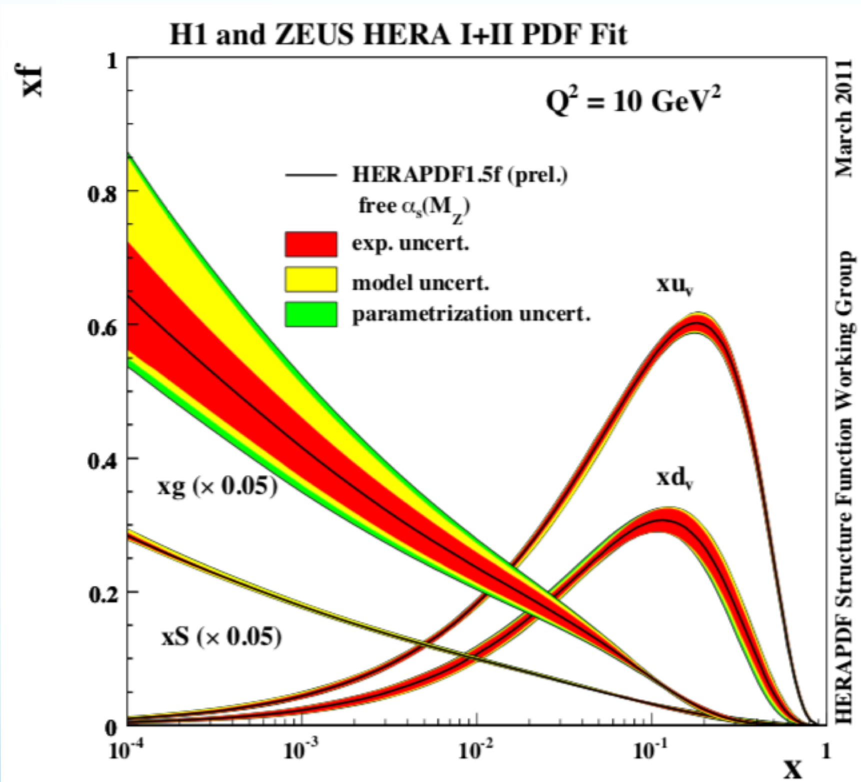
Jets in e+p collisions

- Jets at HERA are extremely important
  - Constraining the gluon PDF

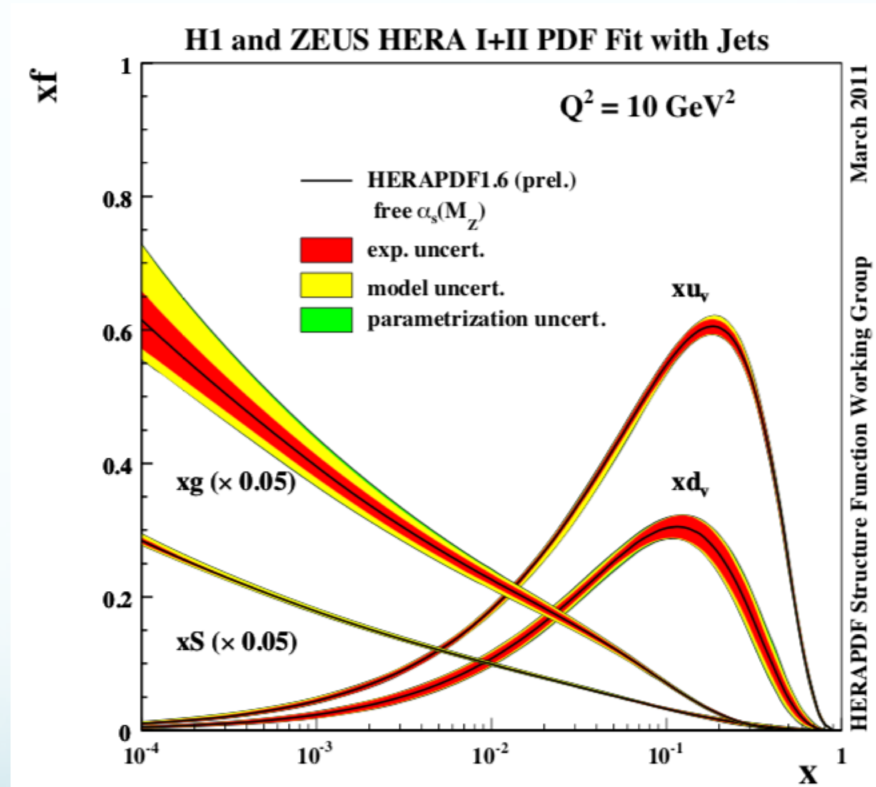
Nuclear Physics B (Proc. Suppl.) 222–224 (2012) January–March 2012

HERA 2011

Proceedings of the Ringberg Workshop
New Trends in HERA Physics 2011



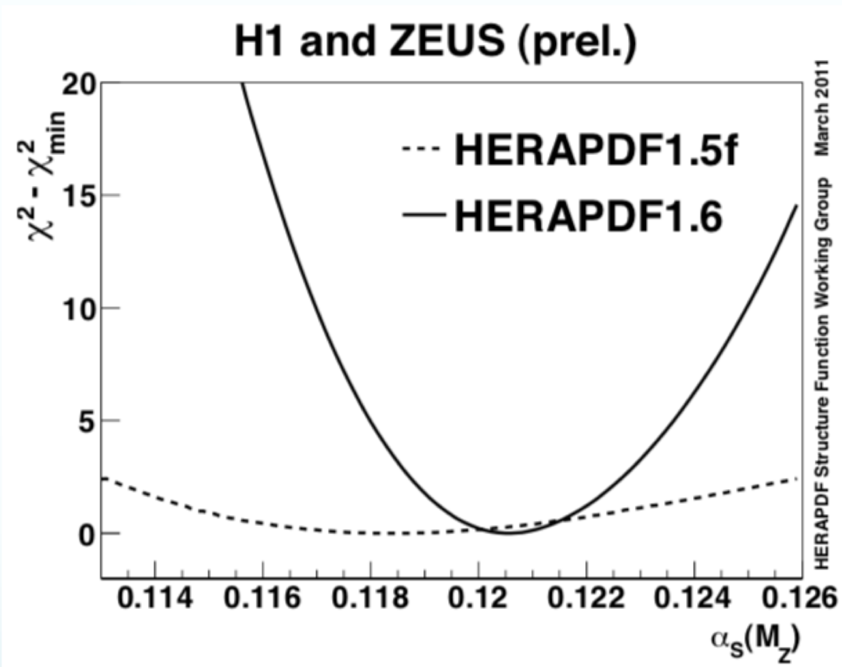
Without jets



With jets

Jets in e+p collisions

- Jets at HERA are extremely important
  - Constraining the gluon PDFs
  - Determine the strong coupling constant



Dashed: without jets
Solid: with jets

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HERA 2011

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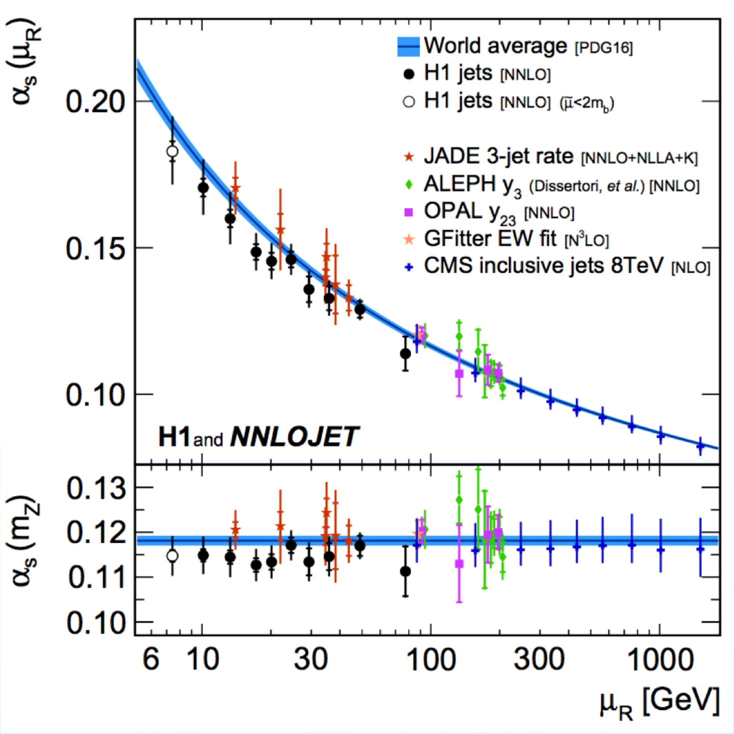
New developments since then

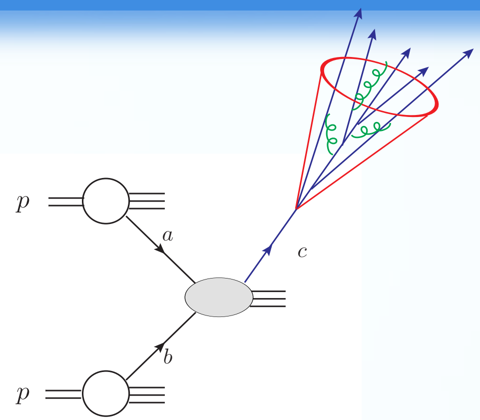
- NNLO have become available
  - arXiv:1607.04921, Abelof, Boughezal, Liu, Petriello
  - arXiv:1703.05977, Currie, Gehrmann, Huss, Niehues



arXiv: 1709.07251, see more at R. Zlebcik's talk

Other development: QCD factorization

- Single inclusive jet production: $p + p \to \text{jet} + X$



$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}$$

partonic hard-scattering cross section

$$H_{ab} = \alpha_s^2 \left(H_{ab}^{(0)} + \alpha_s H_{ab}^{(1)} + \alpha_s^2 H_{ab}^{(2)} + \ldots \right)$$

- The idea is simple: dynamics which happen in very different scales do not interfere with each other: Λ_{QCD} **vs** P_T

NLO 1990

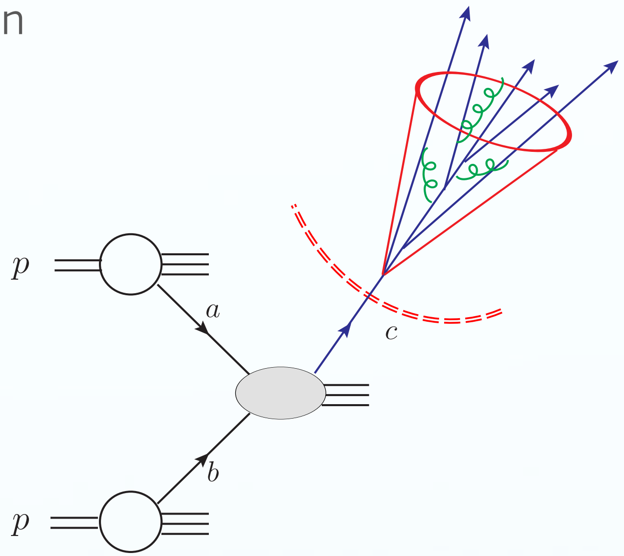
Ellis, Kunszt, Soper `90

NNLO 2016 …

Currie, Glover, Pires `16

Refactorization: semi-inclusive jet function

- When R << 1, the relevant scales for single jet production
  - Two momenta: (1) hard collision: pT (2) jet radius can build one: pT*R
  - A further factorization



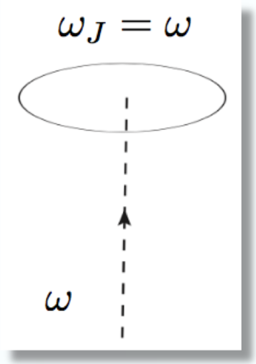
$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(z, \mu \sim p_T R)$$

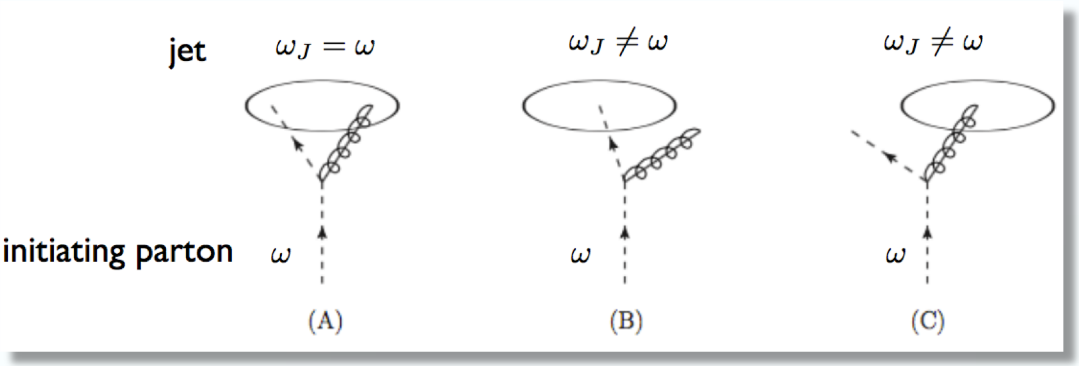
  - Good thing: semi-inclusive jet function $J_{q,g}(z, R)$ are purely perturbative

Kang, Ringer, Vitev, arXiv:1606.06732, Dai, Kim, Leibovich, 1606.07411,
see also, Kaufmann, Mukherjee, Vogelsang, 1506.01415

Semi-inclusive jet functions

- Describe how a parton (q or g) is transformed into a jet (with a jet radius R) and energy fraction z





LO

$$J_q^{(0)}(z, \omega_J) = \delta(1-z)$$

NLO

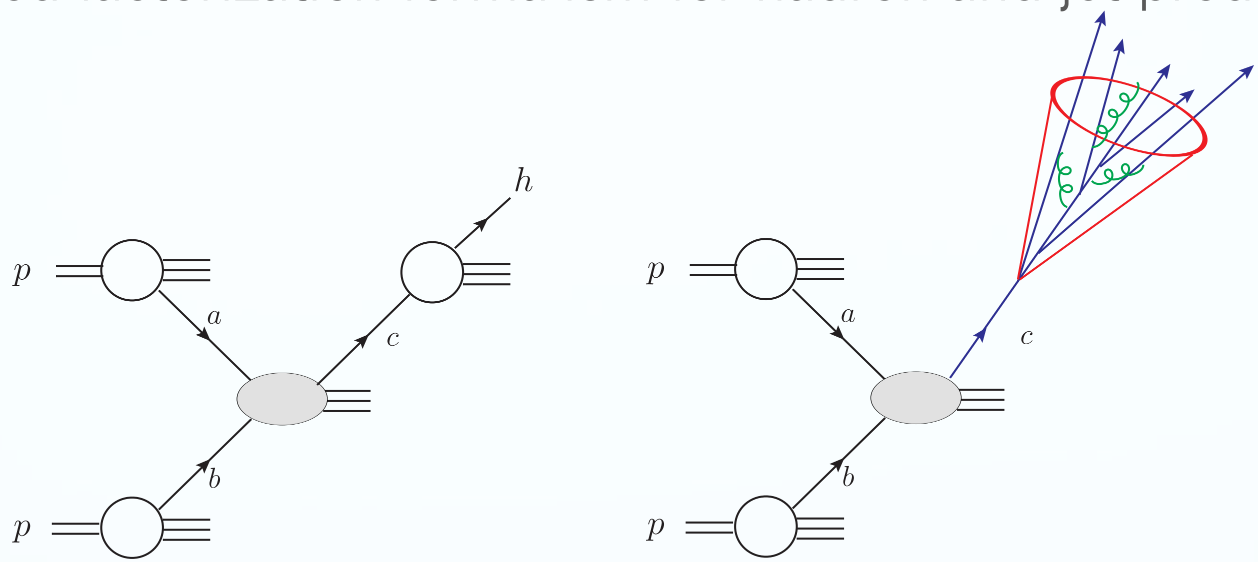
$$z = \omega_J/\omega$$

- Semi-inclusive quark/gluon jet functions follow DGLAP evolution equation, just like hadron fragmentation function

$$\mu \frac{d}{d\mu} J_i(z, \omega_J, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}, \mu\right) J_j(z', \omega_J, \mu)$$

Features: unified formalism

- Unified factorization formalism for hadron and jet production

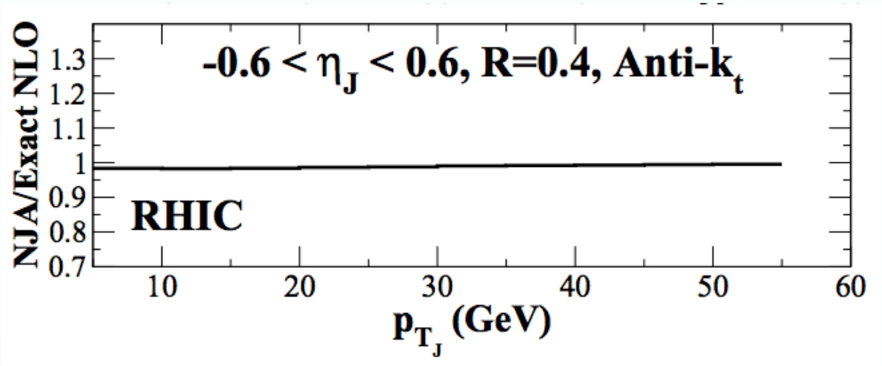


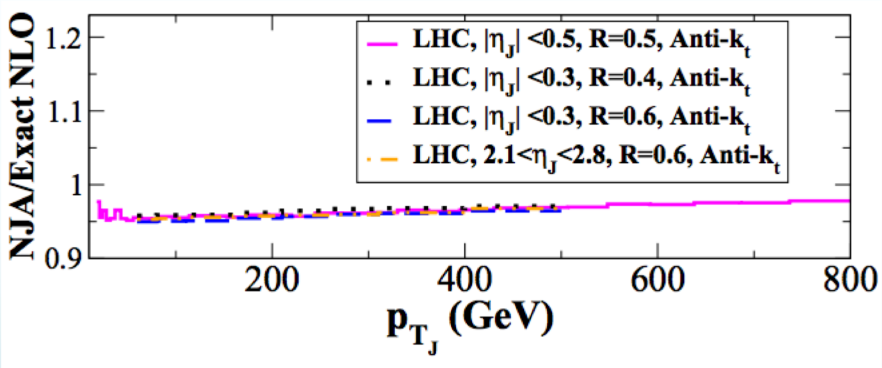
$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h(z,\mu)$$

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(z,\mu \sim p_T R)$$

Small R is a good approximation

- Even though derived for small R, R = 0.7, the difference between small R approximation and full result is less than 5%



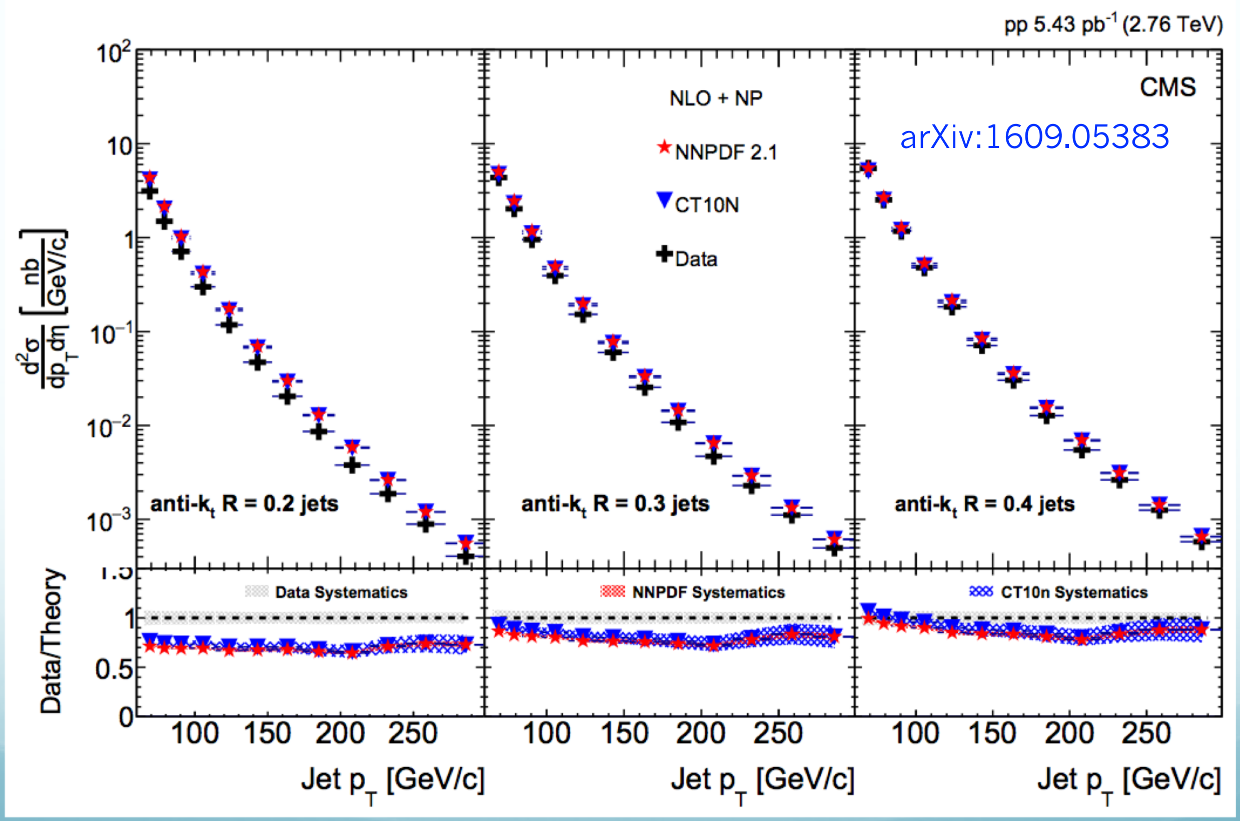


Mukherjee, Vogelsang, arXiv: 1209.1785

Ln(R) resummation

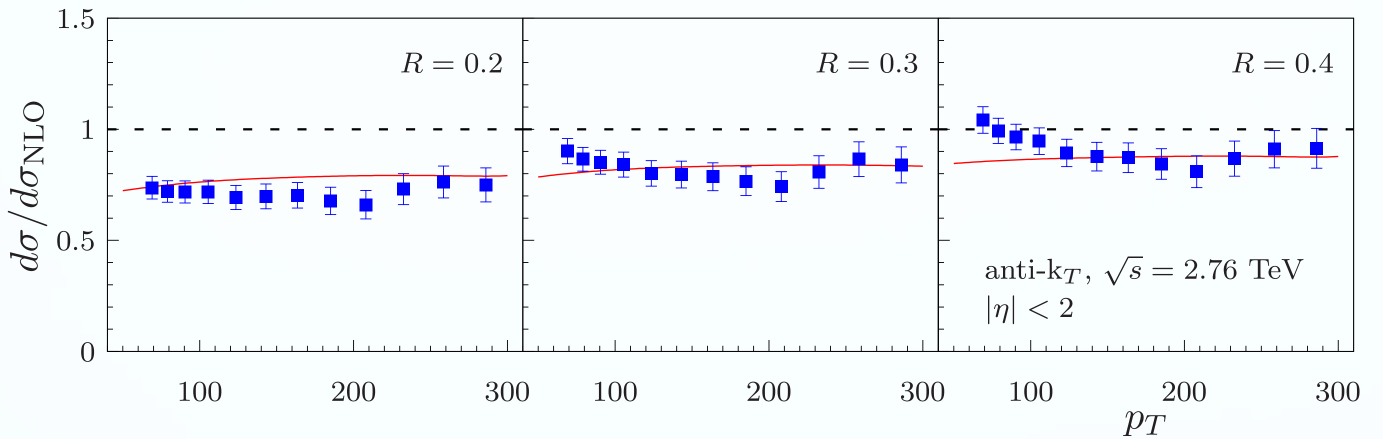
- Natural scale for jet functions: p_T*R
- Jet radius resummation: $(\alpha_s \ln R)^n$
  - Note: ln(R) < 0 when R < 1
- Solve experimental puzzle at LHC

Kang, Ringer, Vitev, arXiv:1606.06732



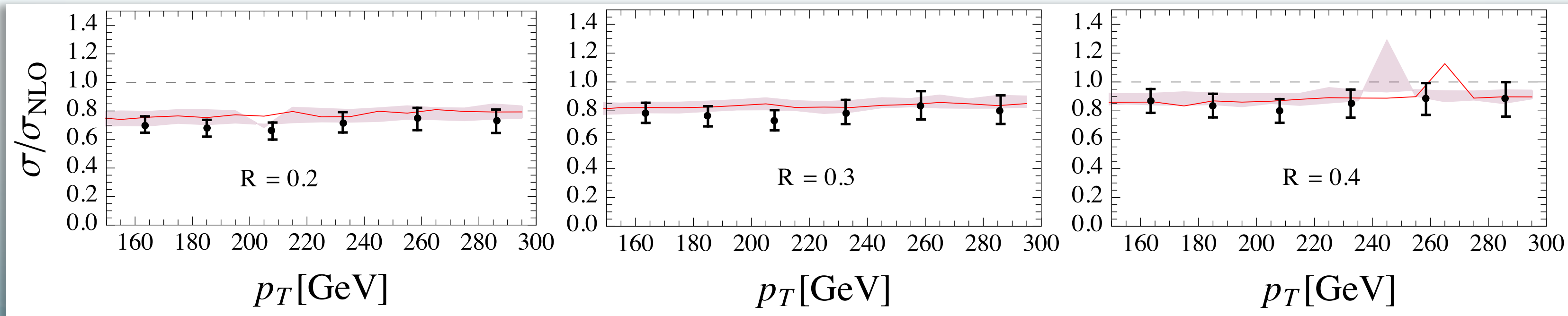
Effect of ln(R) resummation

- The ln(R) is a big source for the discrepancy



Kang, Ringer, Vitev, 1707.00913, PLB 17

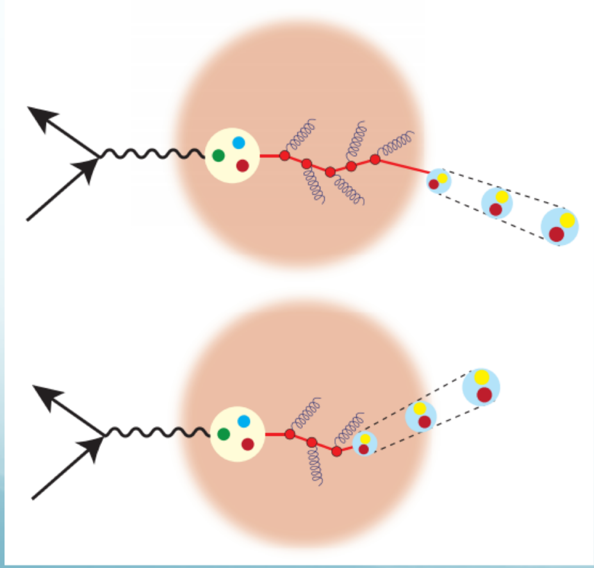
- Threshold resummation further improve the agreement



Liu, Moch, Ringer, PRL 2017

Open questions in e+A DIS

- What is the fundamental quark-gluon structure of light and heavy nuclei?
  - Distribution of quarks and gluons in a nucleus: shadowing, gluon saturation, ...
- Can the nucleus, serving as a color filter, provide novel insights into the propagation, attenuation and hadronization of colored quarks and gluons?
  - Parton propagation, parton energy loss, shower development, ... in the nucleus

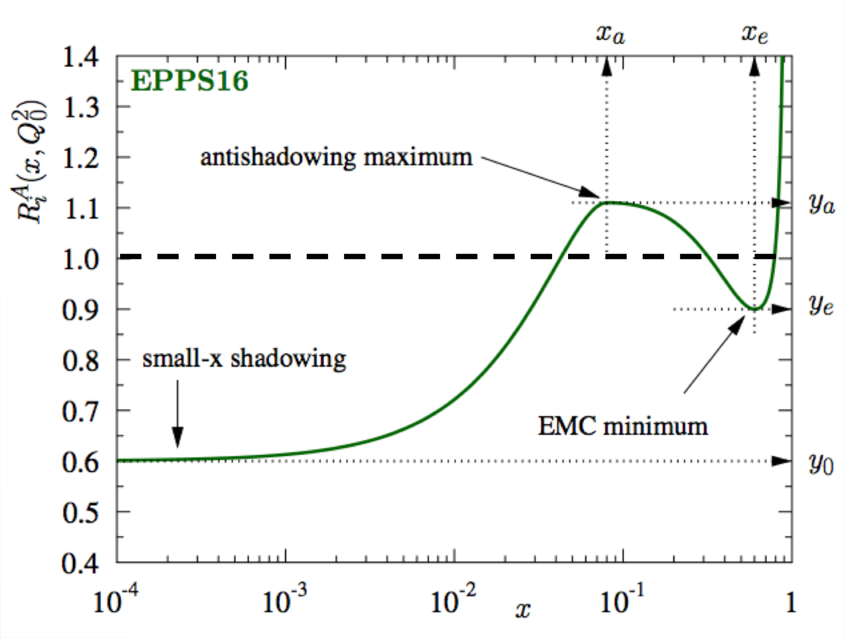


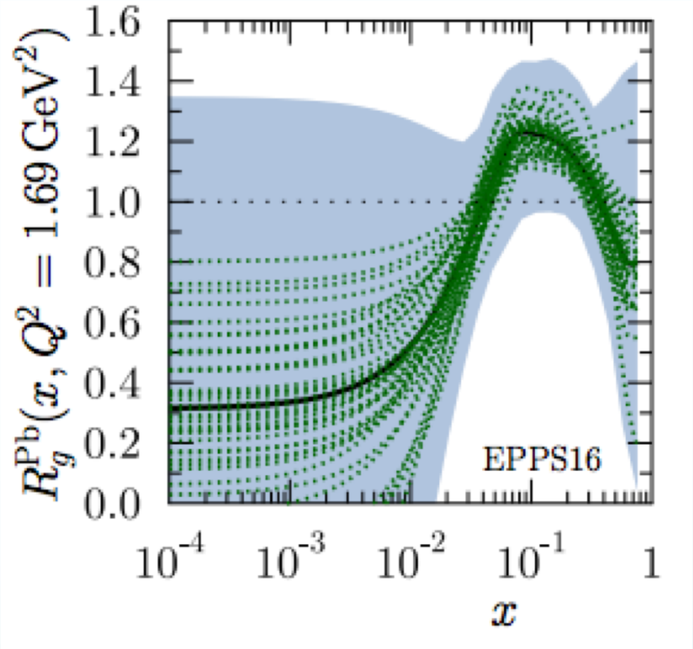
Initial-state effect
(from modification of PDFs)
+
Final-state effect
(propagation through the nucleus)

Lesson learned: initial-state effect

- Modification of PDFs in nuclei
  - Very important in describing inclusive DIS data

Eskola, et.al., arXiv: 1612.05471



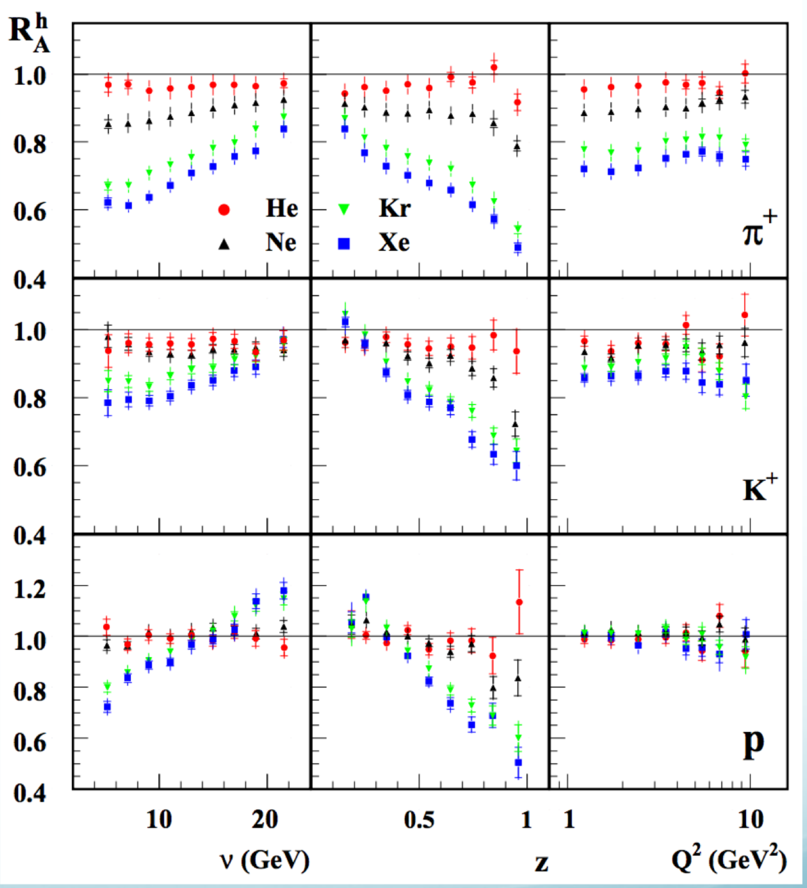


- Of course, small-x effects (color glass condensate) can be studied similarly

Lesson learned: final-state interaction

- Normalized through inclusive DIS measurements
  - Effects of PDFs in nuclei cancel out in the ratio
  - Modification if there are, must come from final-state interaction in the nucleus

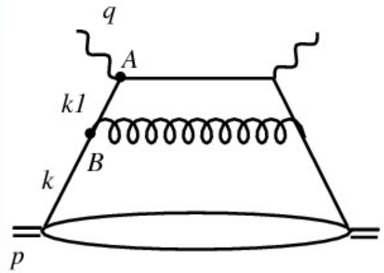
$$R_A^h(\nu, Q^2, z, p_t^2) = \frac{\left(\frac{N^h(\nu,Q^2,z,p_t^2)}{N^e(\nu,Q^2)}\right)_A}{\left(\frac{N^h(\nu,Q^2,z,p_t^2)}{N^e(\nu,Q^2)}\right)_D},$$

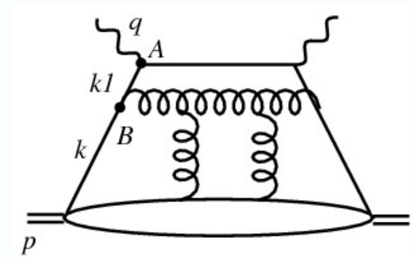


HERMES, arXiv:0704.3270

What happens in a large nucleus?

- One method follows from pioneer work of Mueller and Qiu





Nuclear Physics B268 (1986) 427–452

GLUON RECOMBINATION AND SHADOWING AT SMALL VALUES OF x*

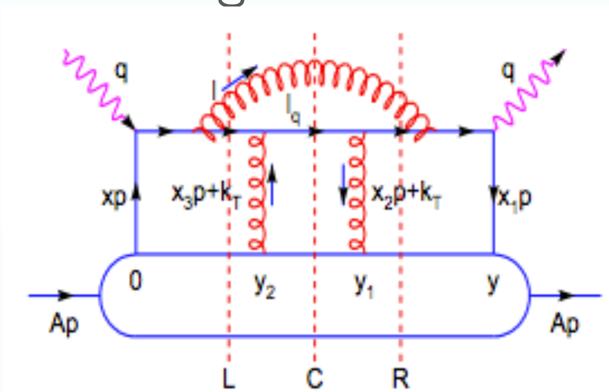
A.H. MUELLER and Jianwei QIU

$$Q^2 \frac{\partial}{\partial Q^2} xG(x,Q^2) = \frac{\alpha C_A}{\pi}\int_x^1 \frac{\mathrm{d}x'}{x'}\frac{x}{x'}\gamma^{GG}\left(\frac{x}{x'}\right)x'G(x',Q^2) - \frac{4\pi^3}{N^2-1}\left(\frac{\alpha C_A}{\pi}\right)^2 \frac{1}{Q^2}\int_x^1 \frac{\mathrm{d}x'}{x'}(x')^2 G^{(2)}(x',Q^2)$$

A power correction term to the usual DGLAP-type evolution

High-twist approach to jet quenching

- SIDIS as an example: multiple scattering in the medium leads to induced gluon radiation

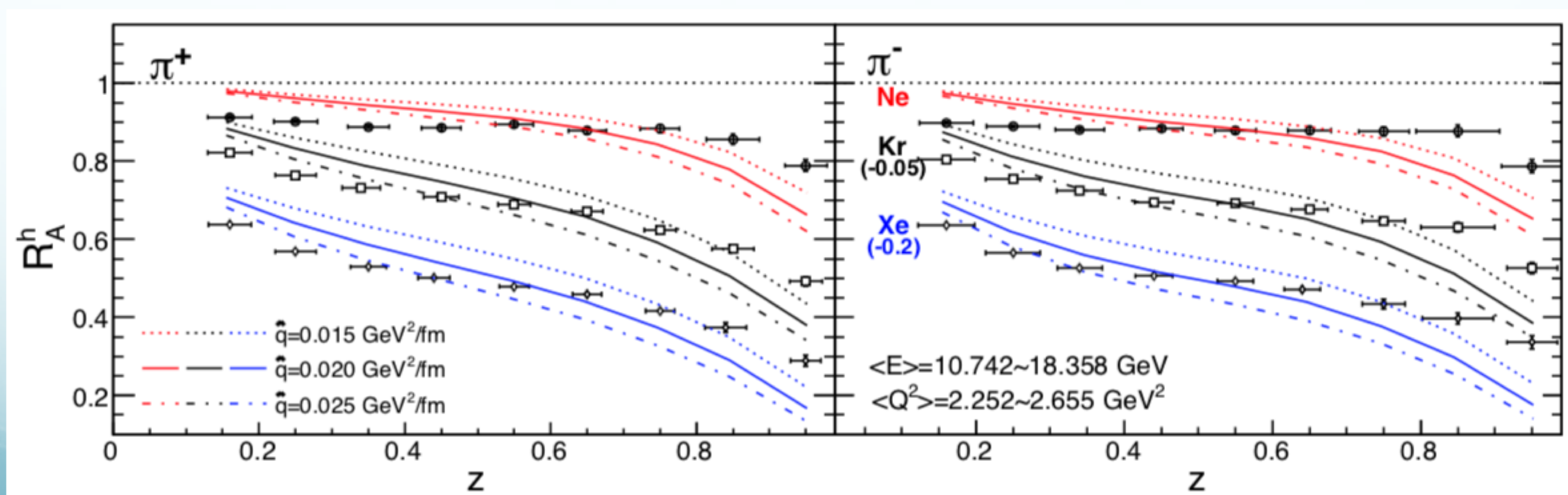


Framework: Qiu, Sterman, 90s
Applications: Wang, Guo, Qin, Majumder, et.al.

$$\frac{\partial D_i^h(z,\mu)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi}\left[P_{ji}^{\rm vac} + P_{ji}^{\rm med}\right] \otimes D_j^h(z,\mu)$$

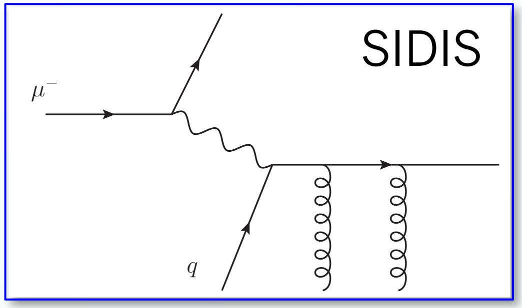
- Evolution of fragmentation function is modified

Xin-Nian Wang, et.al., 1401.5109



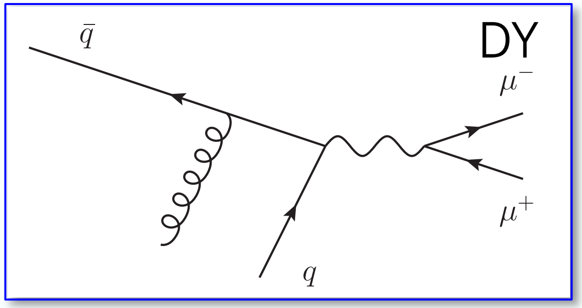
Parton multiple scattering in the medium

- Transverse momentum broadening (TMB) is sensitive to multiple scattering



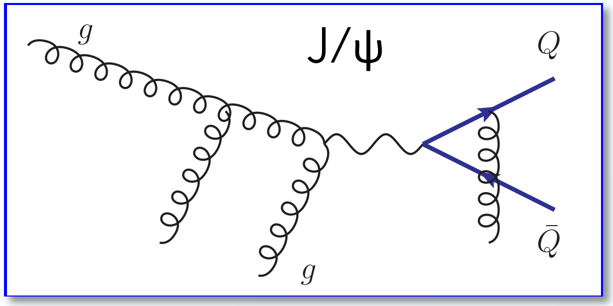
$e + A \to e + h + X$

Final-state



$p + A \to \mu^+\mu^- + X$

Initial-state



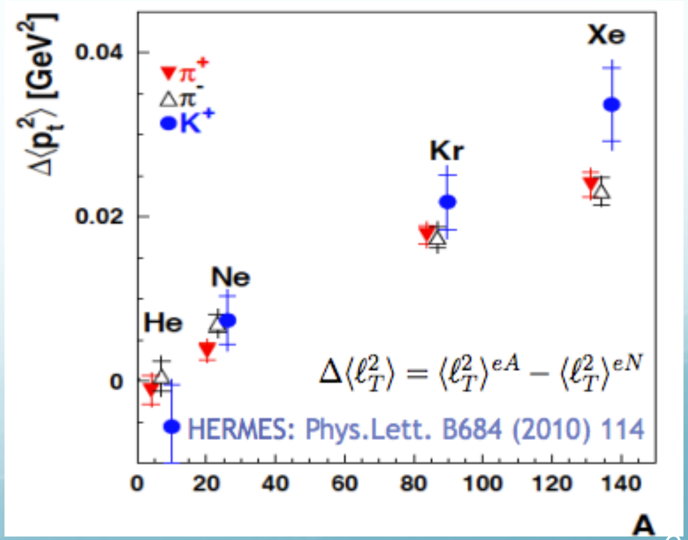
$p + A \to J/\psi + X$

Both

- First non-trivial: double scattering

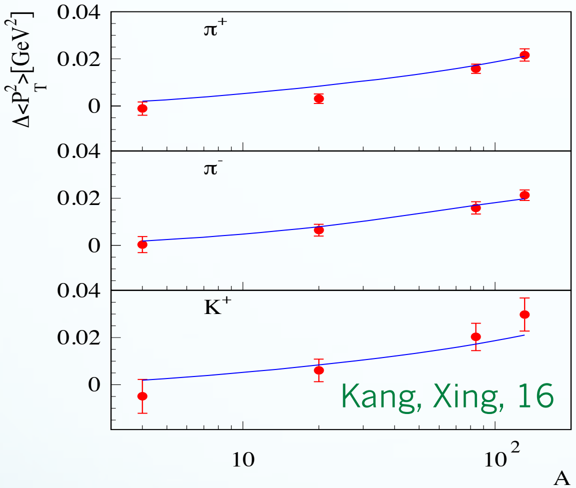
$$\Delta\langle \ell_{hT}^2 \rangle = \langle \ell_{hT}^2 \rangle_{eA} - \langle \ell_{hT}^2 \rangle_{ep}$$

$$\approx \frac{\int d^2\ell_{hT}\,\ell_{hT}^2 \frac{d\sigma^D}{dQ^2 d^2\ell_{hT}}}{\frac{d\sigma}{dQ^2}}$$

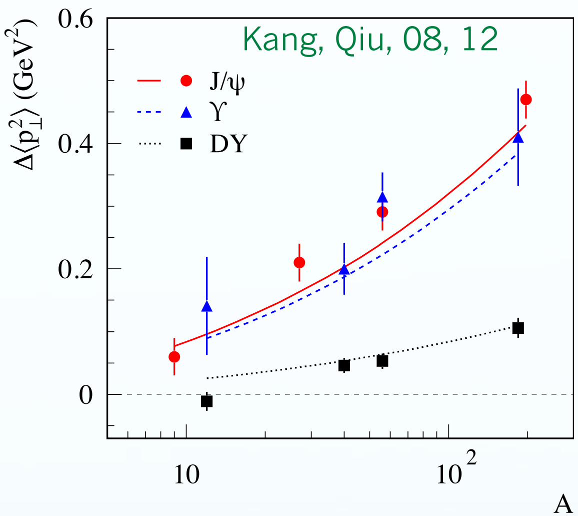


Works pretty well

- Description of the data using single set of correlation functions

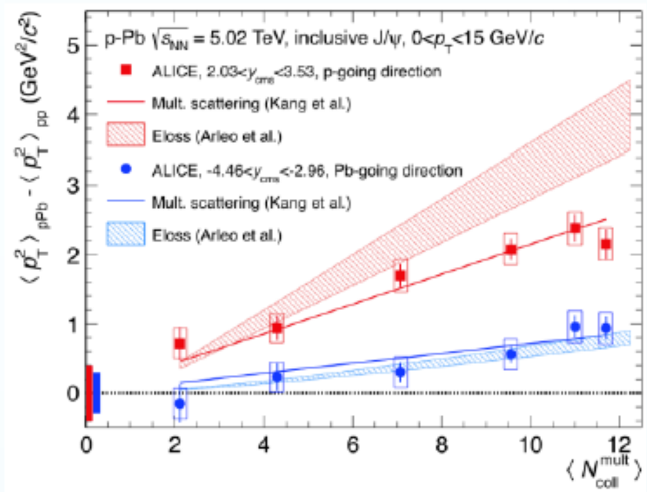


HERMES



Fermilab, SPS

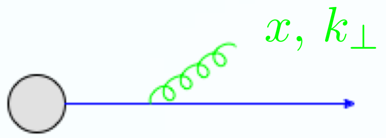
ALICE, 1506.08808



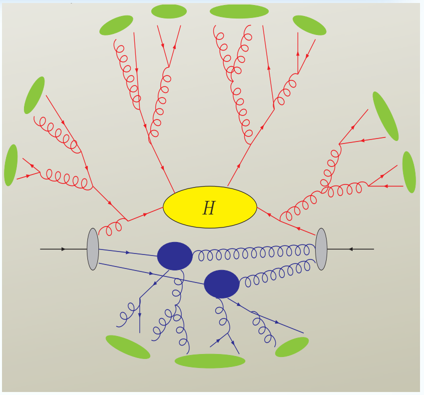
ALICE

Generalized to hot QCD medium

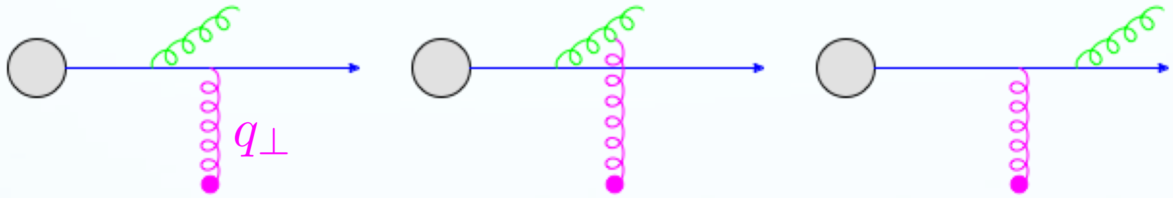
- Vacuum splitting



$$\frac{dN^{\rm vac}}{dxd^2k_\perp} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \frac{1}{k_\perp^2}$$



- Medium splitting (SCET$_G$)
  - transverse momentum kick through Glauber gluons $q \sim (\lambda^2, \lambda^2, \lambda)$



$$\frac{dN^{\rm med}}{dxd^2k_\perp} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2q_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2q_\perp} \left[\frac{B_\perp}{B_\perp^2} \cdot \left(\frac{B_\perp}{B_\perp^2} - \frac{C_\perp}{C_\perp^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) + \cdots \right]$$

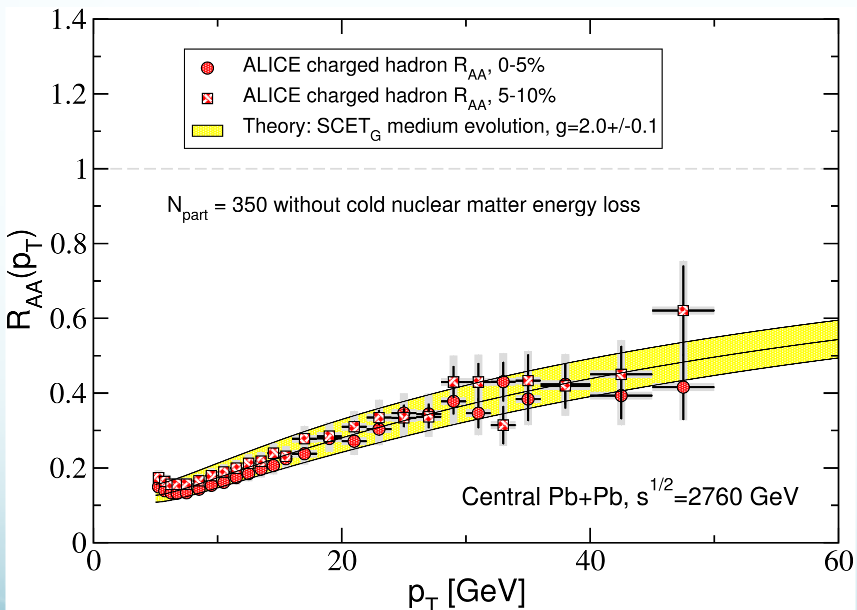
GLV formalism

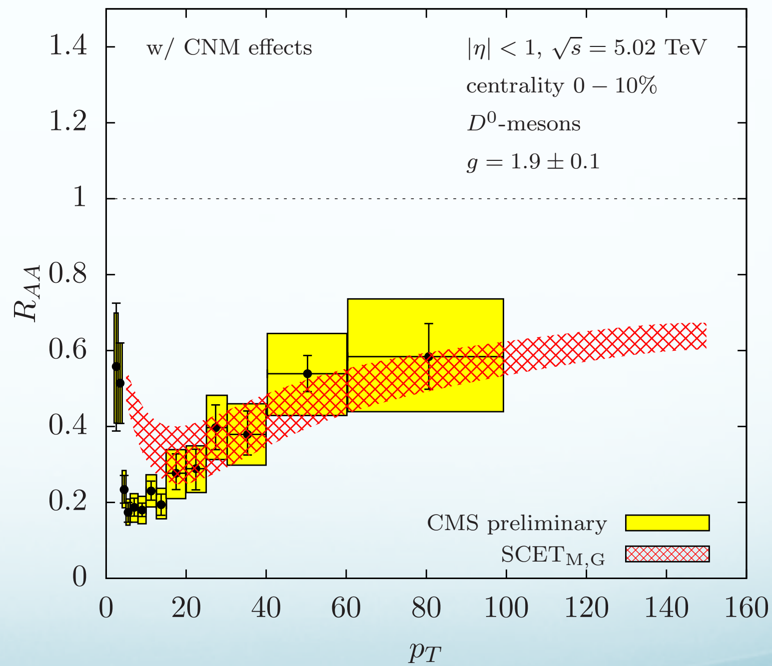
Gyulassy, Levai, Vitev, 02, Idilbi, Majumder 08,
D'Eramo, Liu, Rajagopal, 10, Ovanesyan, Vitev, 11, ...

Light and heavy meson modification

- The fragmentation function modified this way does lead to good description of light and heavy meson in A+A collisions

$$\frac{\partial D_i^h(z,\mu)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi}\left[P_{ji}^{\rm vac} + P_{ji}^{\rm med}\right] \otimes D_j^h(z,\mu)$$



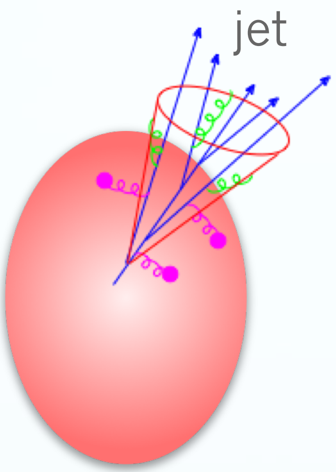


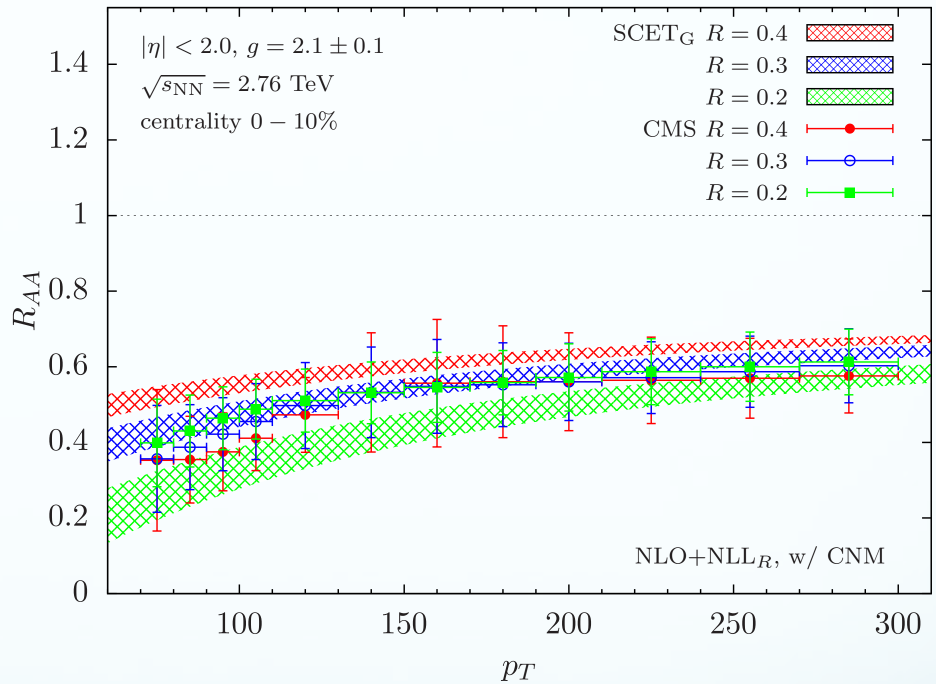
Kang, Ovanesyang, Vitev, et.al., PRL (2015)
Chien, Kang, Ovanesyang, Vitev, et.al., PRD (2016)

Kang, Ringer, Vitev, 1610.02043

Works also for jets

- Inclusive jet cross section also gets modified





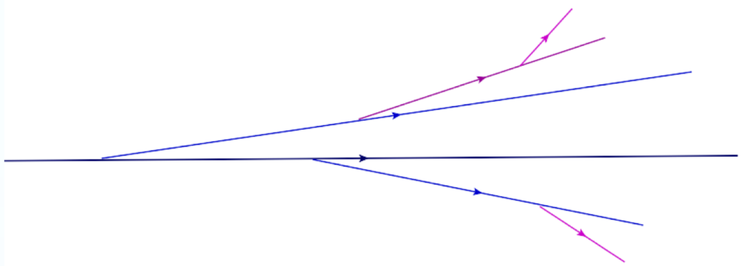
Kang, Ringer, Vitev, 1701.05839

- Expect this framework to be working for
  - Nuclear modification of jet cross section in e+A collisions

Other thinking of jet evolution in medium

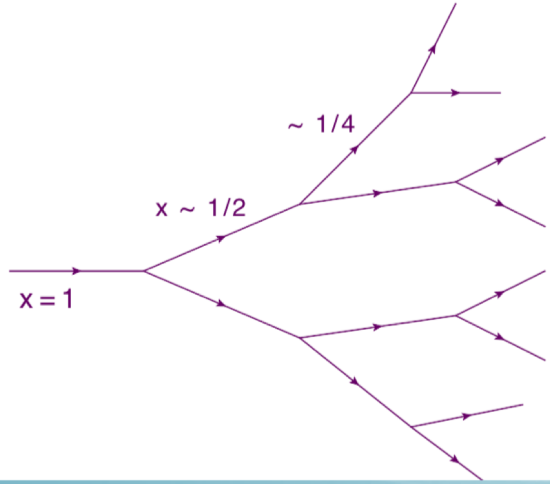
- Vacuum

E. Iancu, hard probe 2015



- quasi-collinear splittings
- pQCD: DGLAP equation
- energy carried by a few partons with large x
- energy remains within a narrow jet

- Medium



- LPM effect $\Longrightarrow$ BDMPSZ emission rate
- multiple, quasi-democratic, branchings
- wave turbulence : highly efficient energy transmission from large x to small x

Blaizot, Dominguez, E.I., Mehtar-Tani (2012...)
Apolinário, Armesto, Milhano, Salgado (2014)
Kurkela, Wiedemann (2014)

Jet physics is promising at EIC

- Plots from EIC team

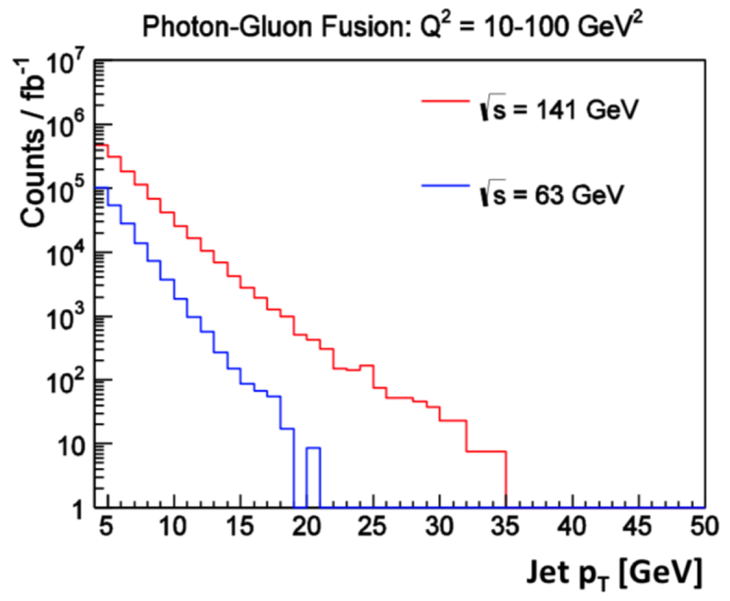
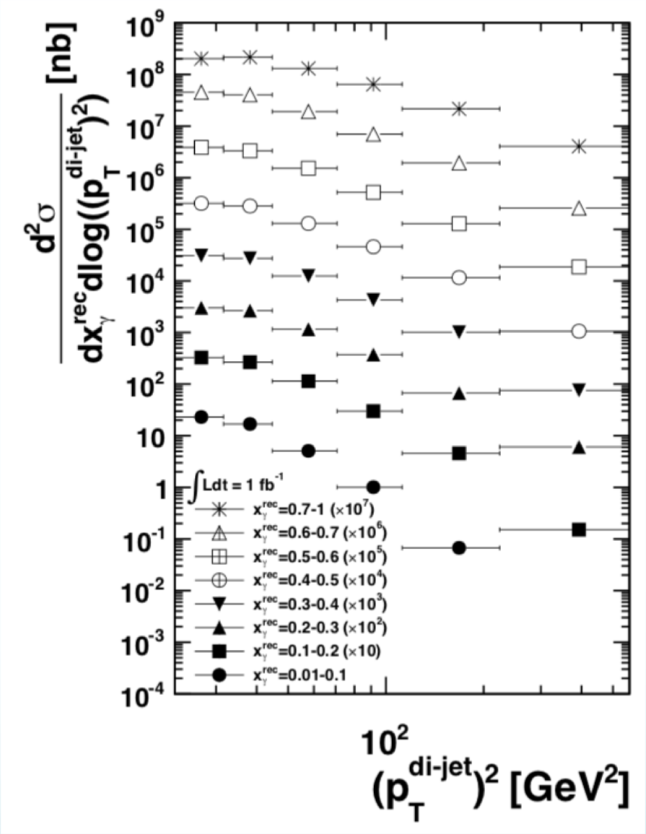


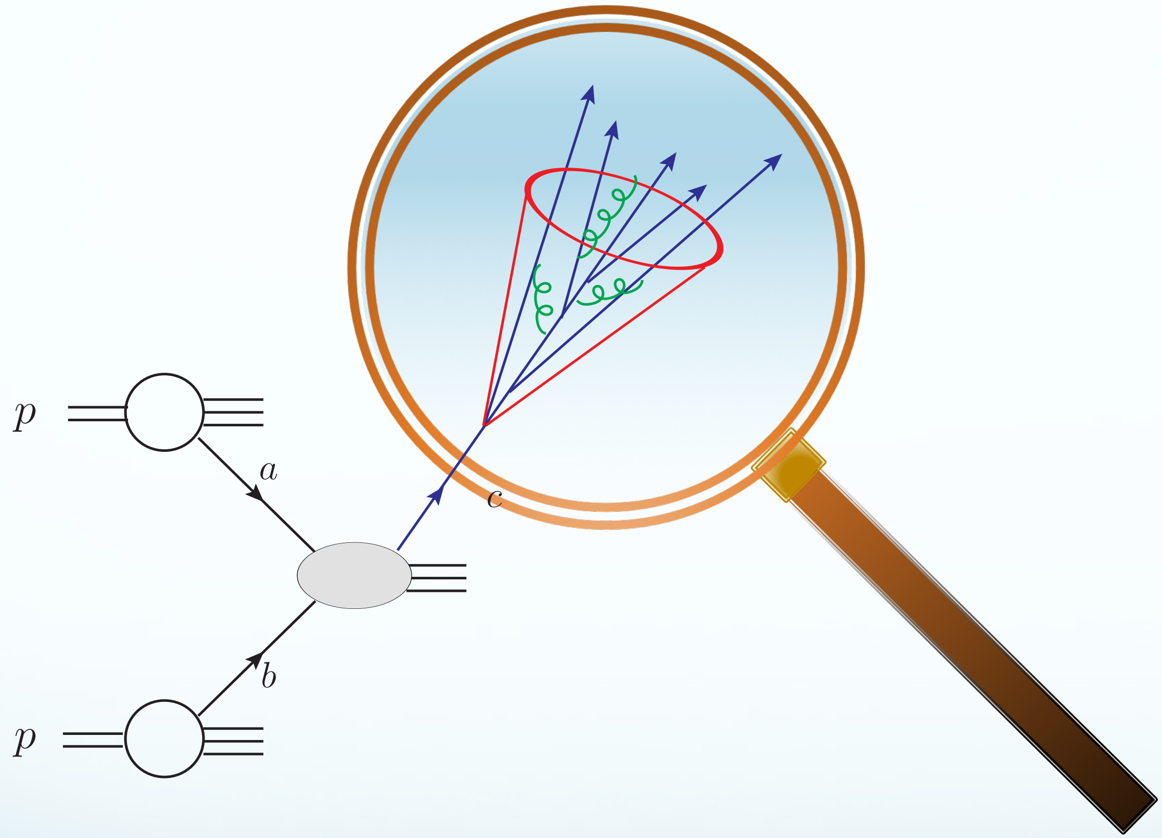
Photo-production of dijet



See more from B. Page's talk

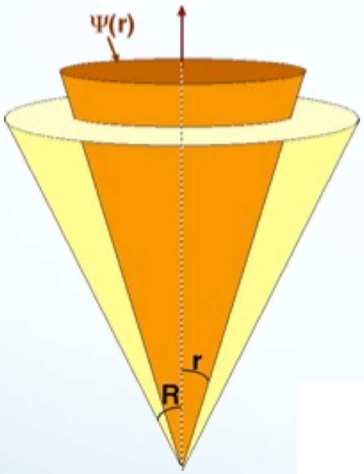
Jet substructure

- Look inside the jet

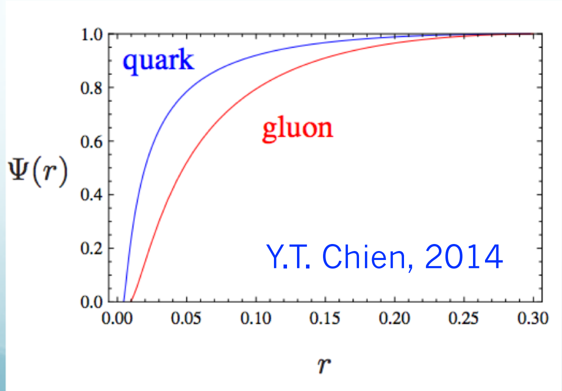


Jet energy profile

- Jet shape: internal energy profile of the jet
- Make sense of the data
  - Quark jet is narrower than gluon jet due to the smaller color charge (C_F vs C_A)
  - DIS is dominated by quark jets
  - ppbar is dominated by gluon jets



$$\langle \psi(r) \rangle = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{E_T(r)}{E_T^{\text{jet}}}$$



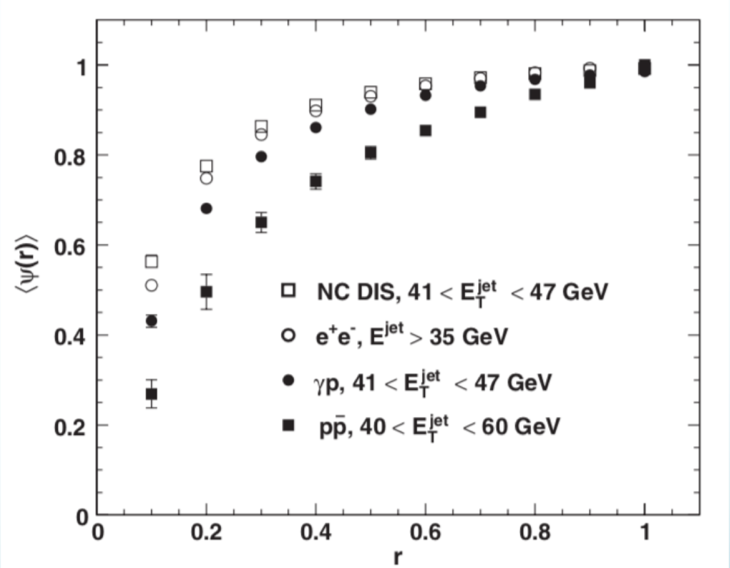


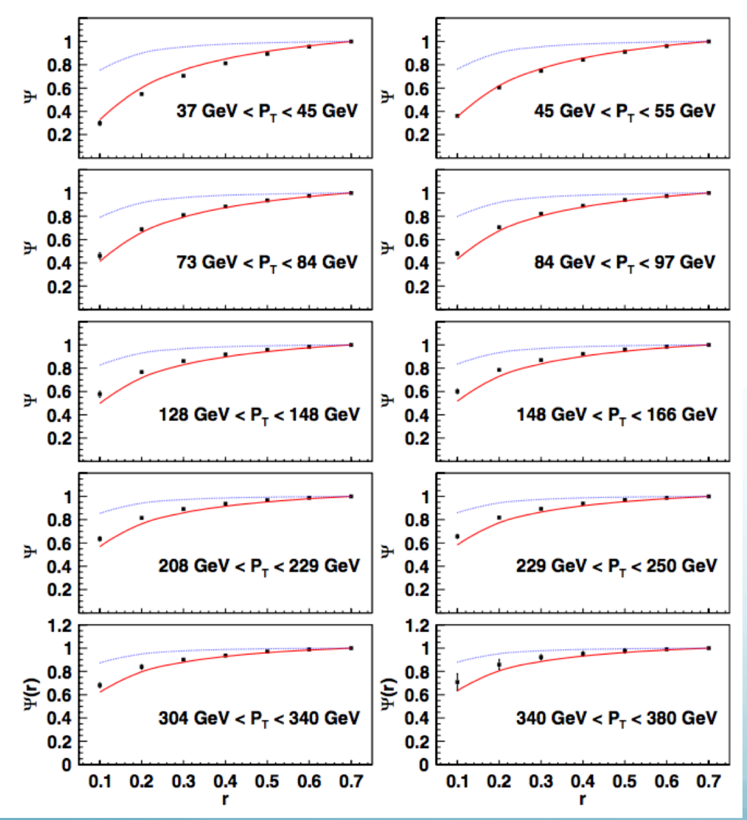
FIG. 13. Measured jet shapes in e^+e^- scattering (Akers *et al.*, 1994), from ZEUS in DIS (Breitweg *et al.*, 1999c) and photo-production (Breitweg *et al.*, 1998e), and in $p\bar{p}$ collisions (Abe *et al.*, 1993a; Abachi *et al.*, 1995b). From Butterworth and Wing, 2005.

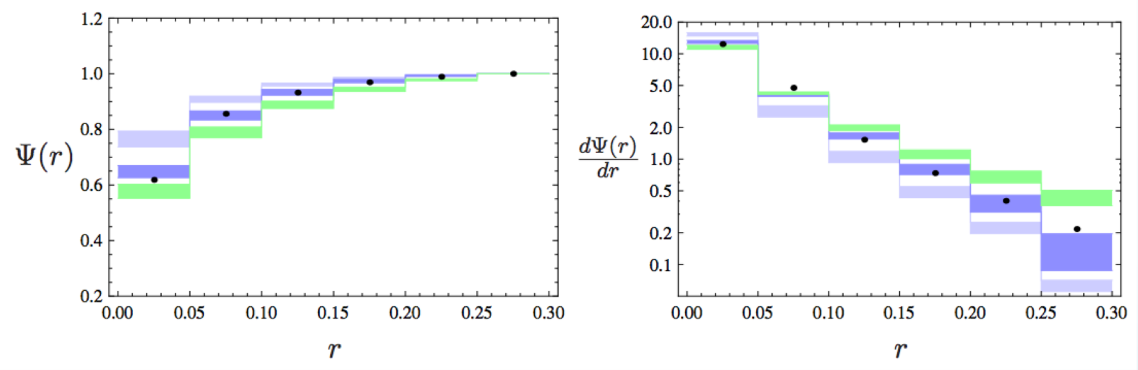
Progress since HERA time

- At the time of HERA (pre-LHC), jet substructure is mostly compared with event generators
  - Jet shape: either fixed-order computations or Seymour's MLL results
  - R >> r: need resummation ln(R/r)

Compare with jet shape at CDF
H.n. Li, Z. Li, C.P. Yuan, 2011, 2012

Improved results from Y.T. Chien, I. Vitev, 2014





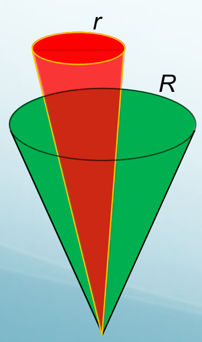
Further Progress since HERA time

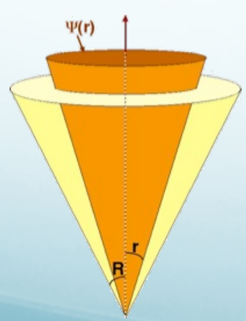
- So far all the theoretical formalism is concentrated only on
  - jet function: only collinear degrees of freedom

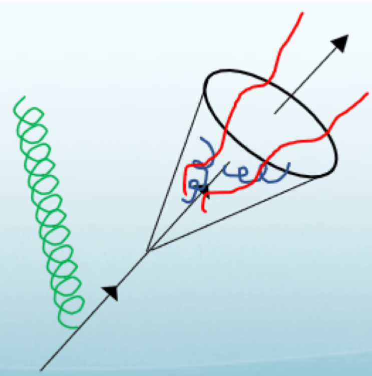
$$\Psi(r) = \sum_f \int \frac{dP_T}{P_T} \frac{d\sigma_f}{dP_T} \bar{J}_f^E(1, P_T, \nu_{\rm fi}^2, R, r) \times \left[\sum_f \int \frac{dP_T}{P_T} \frac{d\sigma_f}{dP_T} \bar{J}_f^E(1, P_T, \nu_{\rm fi}^2, R, R) \right]^{-1}$$

- Recently, we find the soft radiation is also important, in order to write down the consistent factorization formalism

$$\hat{\mathcal{G}}_i^{\rm jet}(z, z_r, \omega_R, r, R, \mu) = H_{ij}(z, \omega_R R, \mu) \int \mathrm{d}^2 k_\perp \, C_j(z_r, \omega_r r, k_\perp, \mu, \nu) \, S_j(k_\perp, R, \mu, \nu)$$







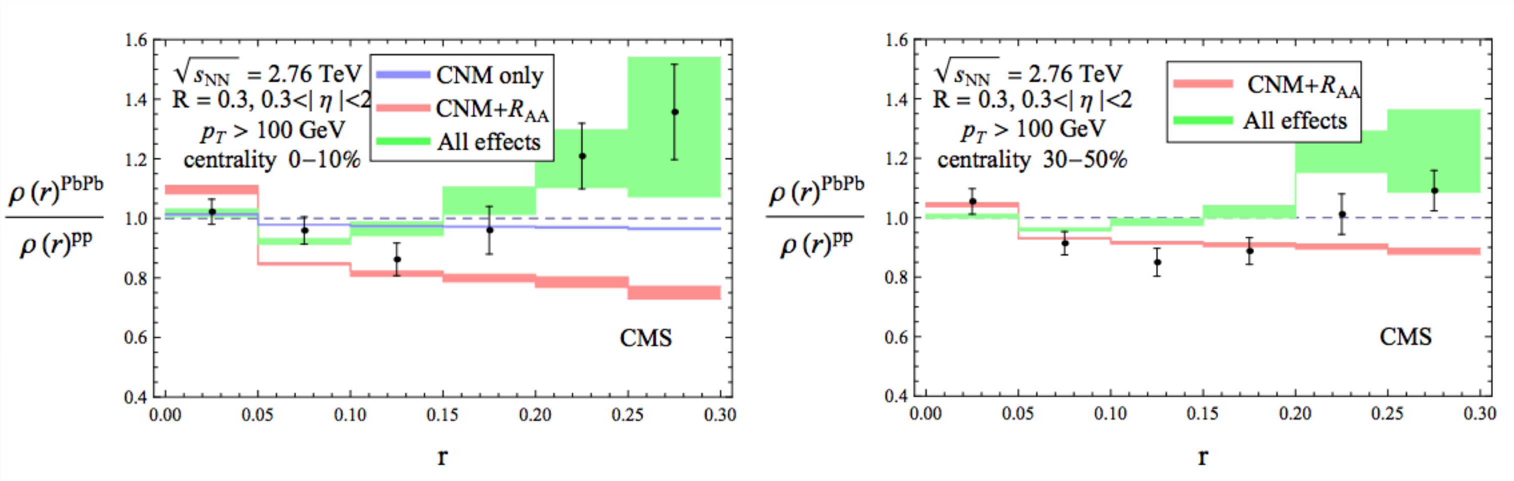
Kang, Ringer, Waalewijn, 1705.05375

It would be nice to see the phenomenological consequences

Further Progress in A+A collisions

- Used the same medium-induced splitting functions

Improved results from Y.T. Chien, I. Vitev, 2015

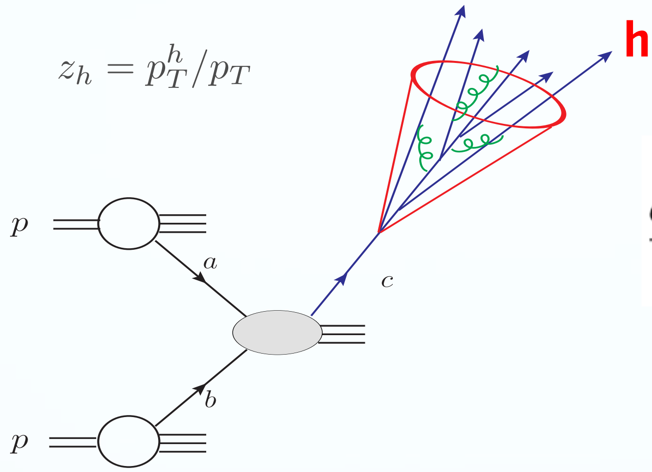


- It would be interesting to make computations for jet shape for both e+p and e+A collisions using new formalism

Fragmentation inside a jet

- Semi-inclusive fragmenting jet function

Kang, Ringer, Vitev, 1606.07063, JHEP 16

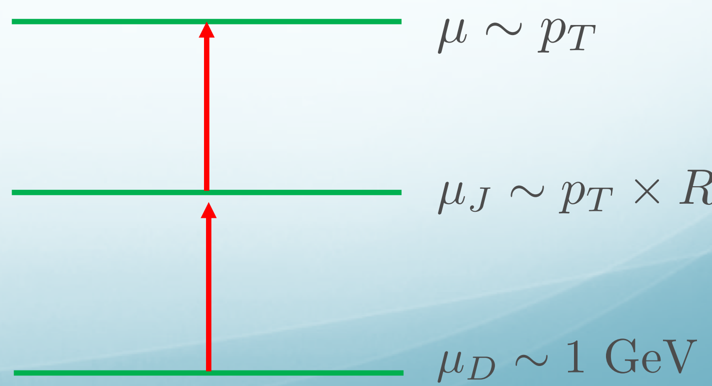


$$\frac{d\sigma^{pp\to(\text{jet }h)+X}}{d\eta\, dp_T\, dz_h} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{\mathcal{G}_c^h}$$

- Two DGLAPs:

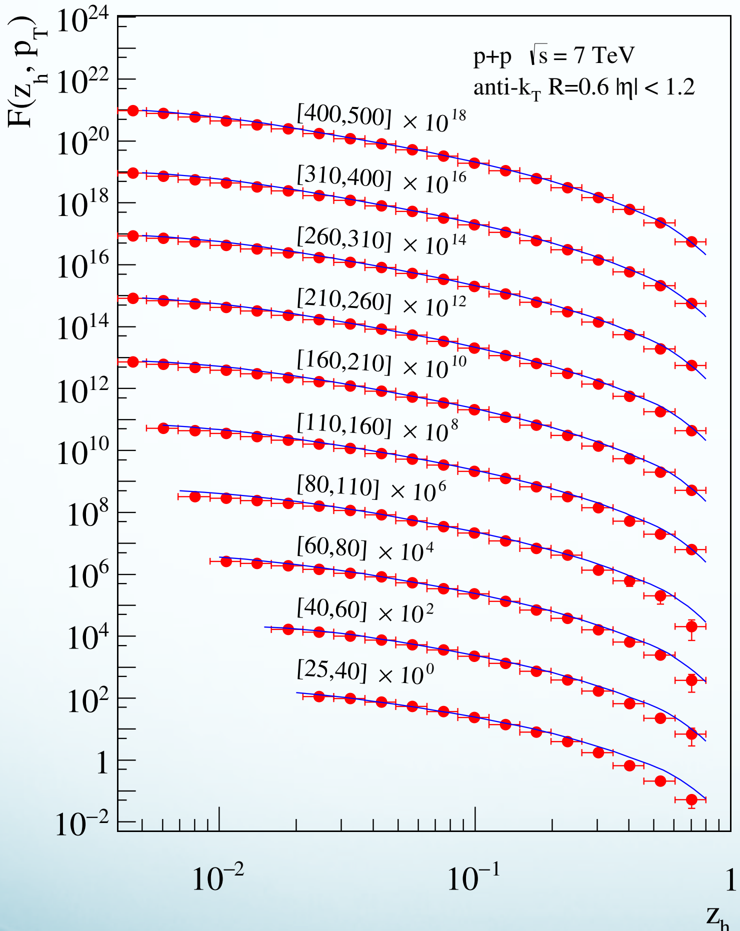
$$\mu\frac{d}{d\mu}\mathcal{G}_i^h(z, z_h, \mu) = \frac{\alpha_s(\mu)}{\pi}\sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}\right)\mathcal{G}_j^h(z', z_h, \mu)$$

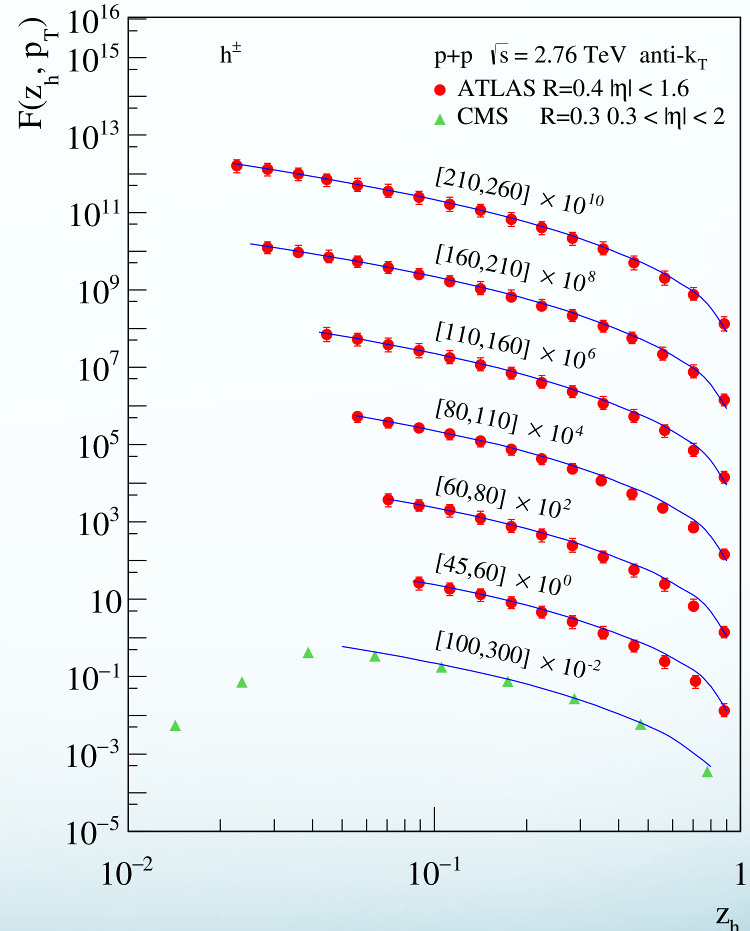
$$\mathcal{G}_i^h(z, z_h, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h', \mu)\, D_j^h\left(\frac{z_h}{z_h'}, \mu\right)$$



Light hadrons: work well

- Light charged hadrons

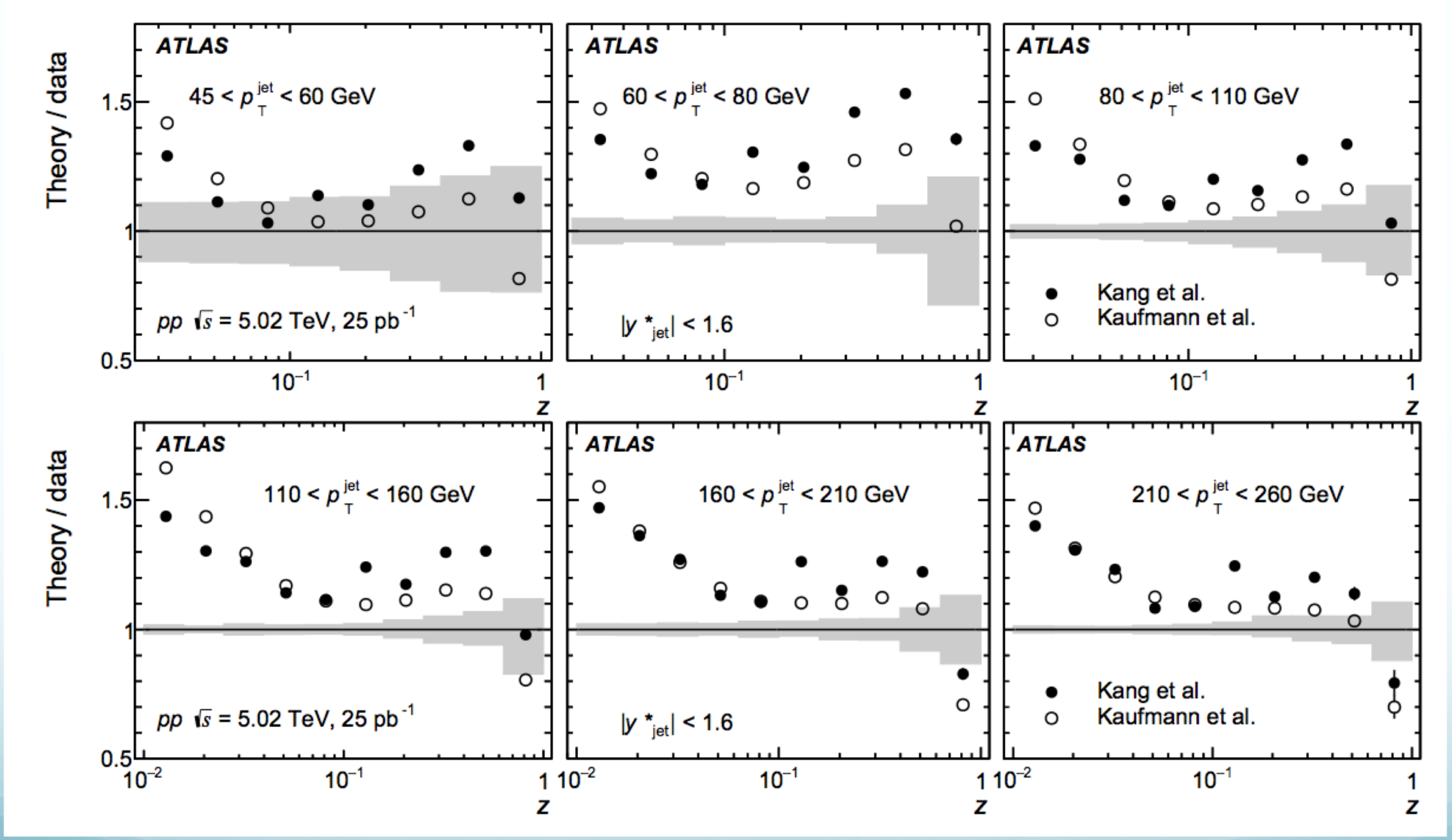




Kang, Ringer, Vitev, 1606.07063, JHEP, 16

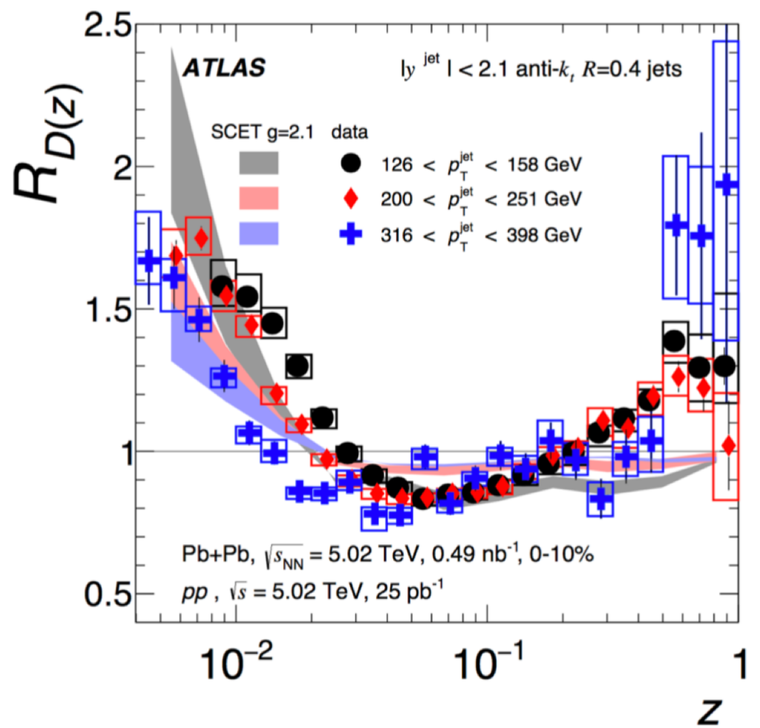
Further improvement

- So far standard FFs are only constrained for z > 0.05
  - These data can constrain small-z
  - One might need threshold resummation for large z region



Jet fragmentation function in A+A collisions

- Medium modification can be computed similarly once the medium induced splitting functions are given (actual phenomenology is more subtle)



ATLAS, arXiv:1805.05424

Similarly CMS, Phys. Rev. C 90 (2014) 024908

Ringer, CIPANP 2018

- With additional R in control, should have more power than the usual SIDIS fragmentation functions in e+A collisions

Jet angularity

- Trust was defined as an event shape parameter to understand radiation pattern

$$T = \frac{1}{Q}\mathrm{max}_{\mathbf{t}} \sum_{i \in X} |\mathbf{t}\cdot\mathbf{p}_i| = 1 - \tau_0$$

  - $\tau_0 \to 0$ is equivalent to dijet limit
  - A generalized class of IR safe observables, angularity (applied to jet)

$$\tau_a^{e^+e^-} = \frac{1}{E_J}\sum_{i \in J} E_i\,\theta_{iJ}^{2-a}$$

$$\tau_a^{pp} = \frac{1}{p_T}\sum_{i \in J} p_{Ti}\,(\Delta R_{iJ})^{2-a}$$

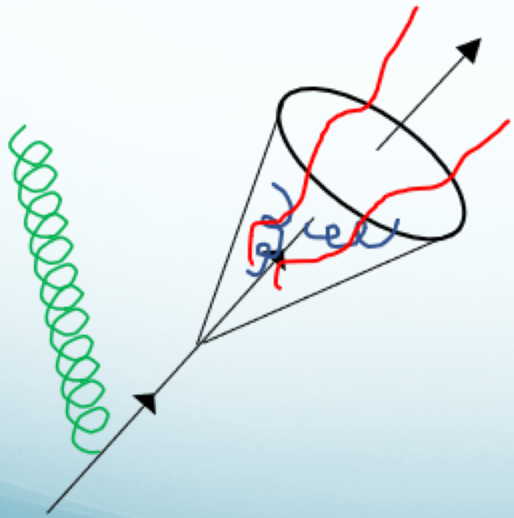
Sterman, et.al. 03, 08, C. Lee, et.al. 10
Hornig, Makris, Mehen, 16

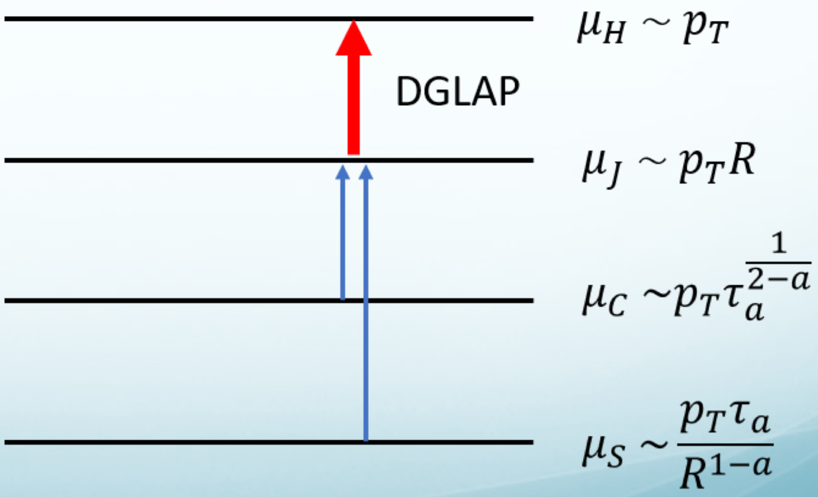
  - a=0 related to thrust (jet mass)
  - a=1 related to jet broadening

Jet angularity

- Similar replacement: $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau_a, \mu)$
- Refactorization

$$\mathcal{G}_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu)$$
$$\times \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{\frac{1}{2-a}}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu)$$

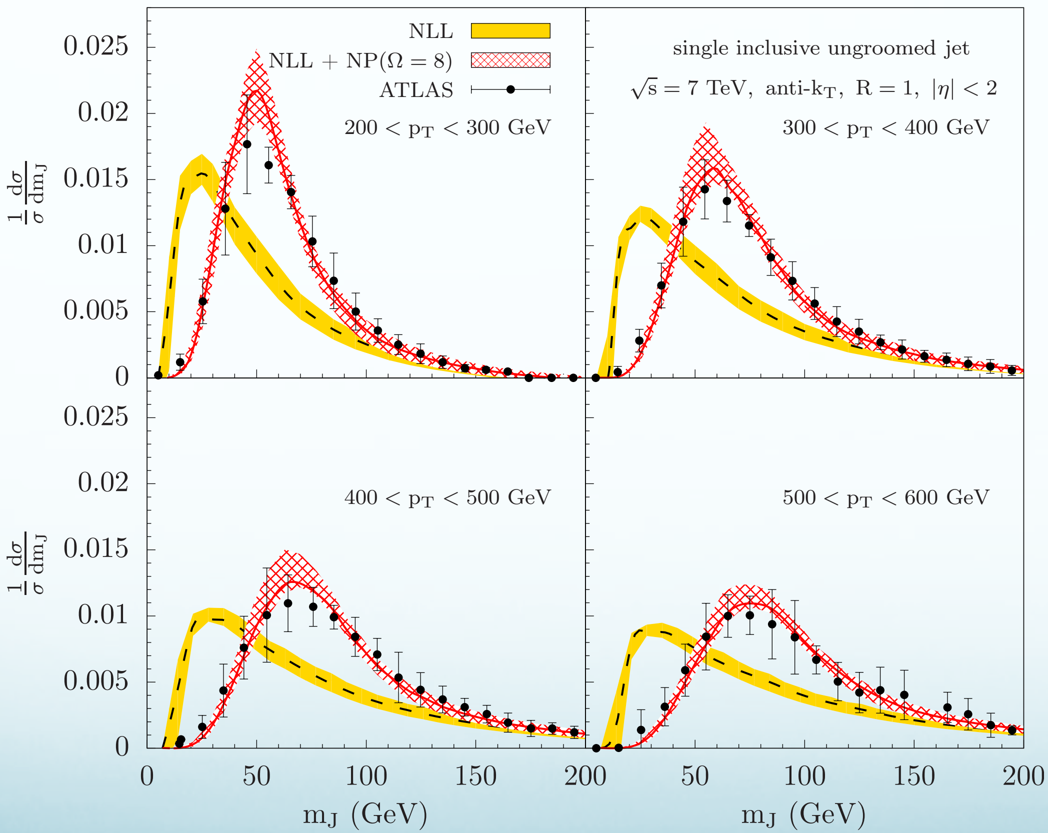




Kang, Lee, Ringer, 1801.00790, 1803.03645, see more from Kyle Lee's talk

Jet mass: a = 0

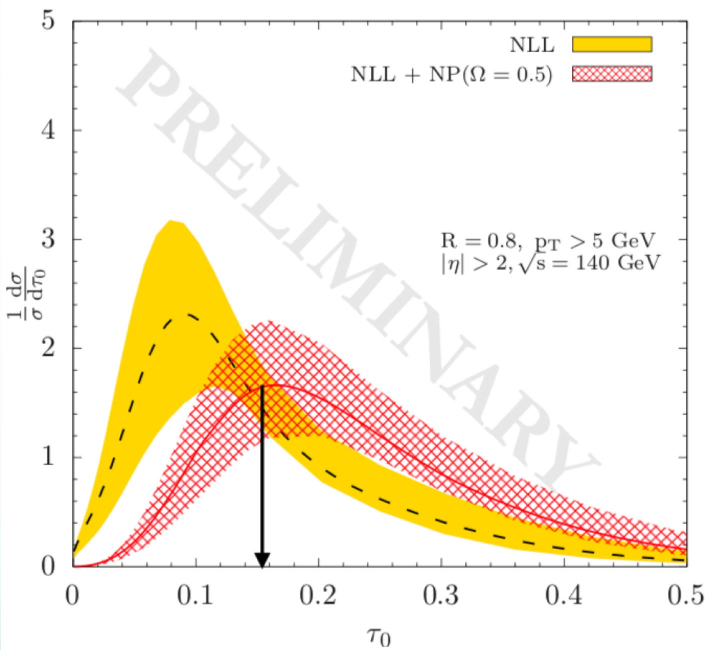
- Comparison with jet mass measurements at the LHC
  - Need a large non-perturbative parameter
  - Strong non-perturbative sensitivity: multi-parton interactions (MPI), pileups, and hadronization (generally need to apply “grooming”, e.g. soft drop grooming

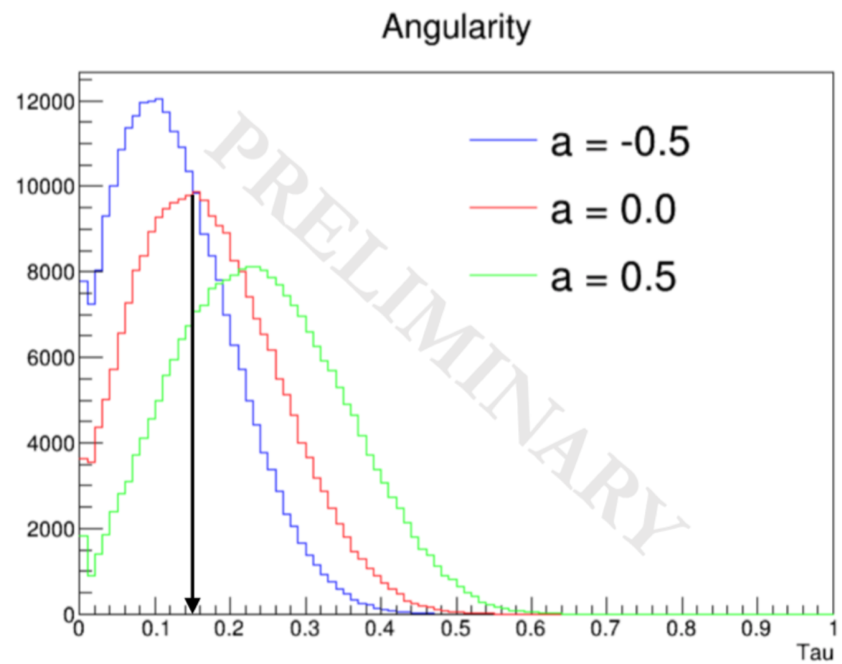


See details from Kyle Lee’s talk

Jet mass at an EIC

- Computation and comparison with event generator
  - e+A collision is much cleaner environment, likely the main non-perturbative contribution is hadronization effects





- **Monte Carlo**

Help from B. Page, E. Aschenauer

Summary

- Even though jet capability at the future EIC is realized only recently, we found that jet physics could be very powerful
  - To understand parton propagation and energy loss in cold QCD matter
  - Especially with the advancement in jet and jet substructure from LHC, the clean environment of e+A collisions should be ideal to constrain the properties of cold QCD matter, probe the underlying mechanism
  - In turn it should lead to better understanding of hot QCD matter
- Exciting jet physics program at EIC

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Thank you!