Inclusive jets and jet substructure for QCD and spin dynamics

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Outline

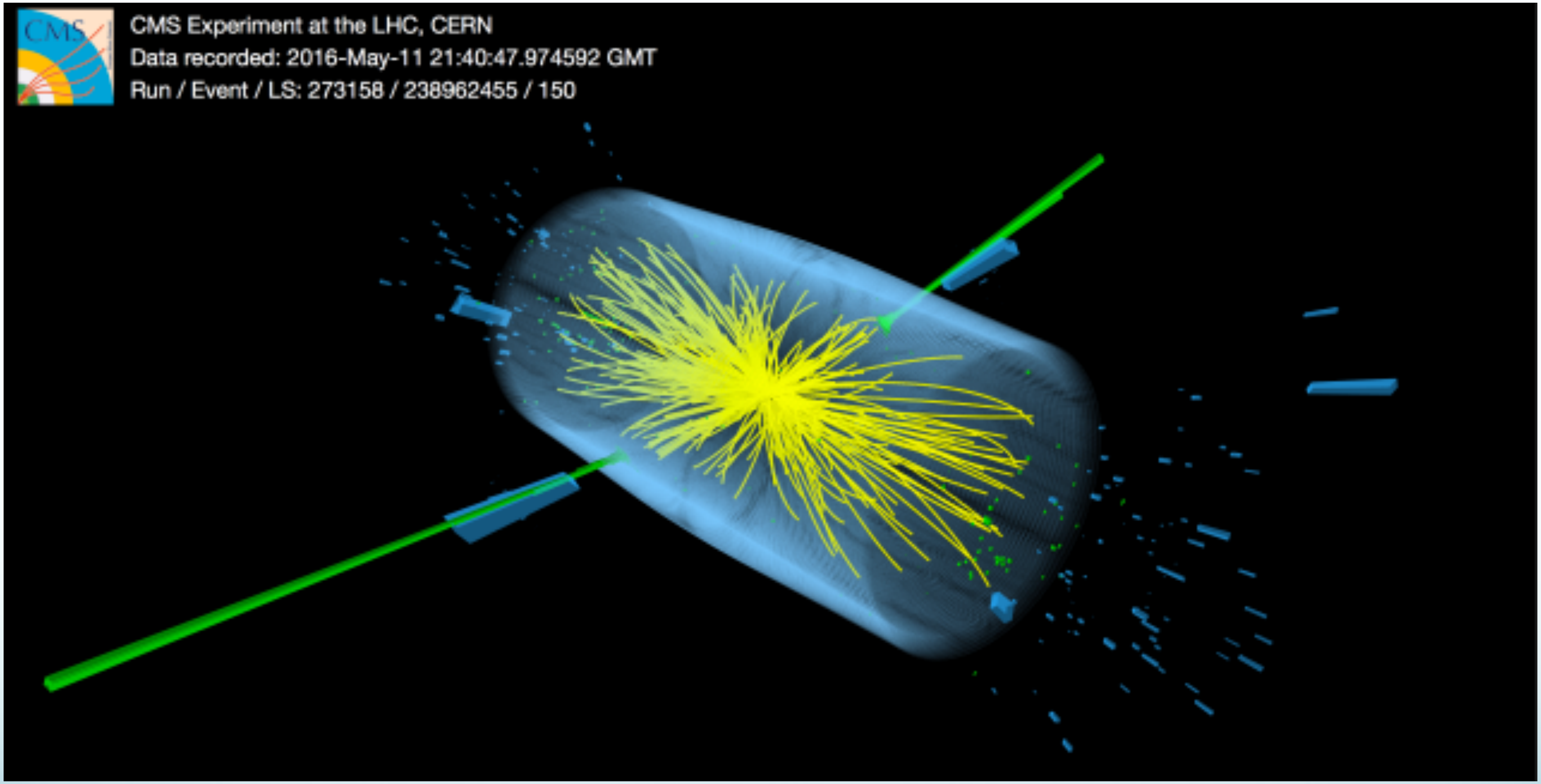
- Introduction and motivation
  - Jets are abundantly produced at the LHC

- Single inclusive jet production
  - A new factorization formalism using semi-inclusive jet function
  - Small jet radius: ln(R) resummation

- Jet substructure
  - Jet fragmentation function: hadron distribution inside the jet

Jets are abundantly produced at the LHC

- They are most common at the LHC



Jets at the LHC

- Test of strong interaction
  - PDFs are constrained by collider jet data, especially gluon distribution functions
  - Extraction of strong coupling constant
  - Precision test for pQCD calculations

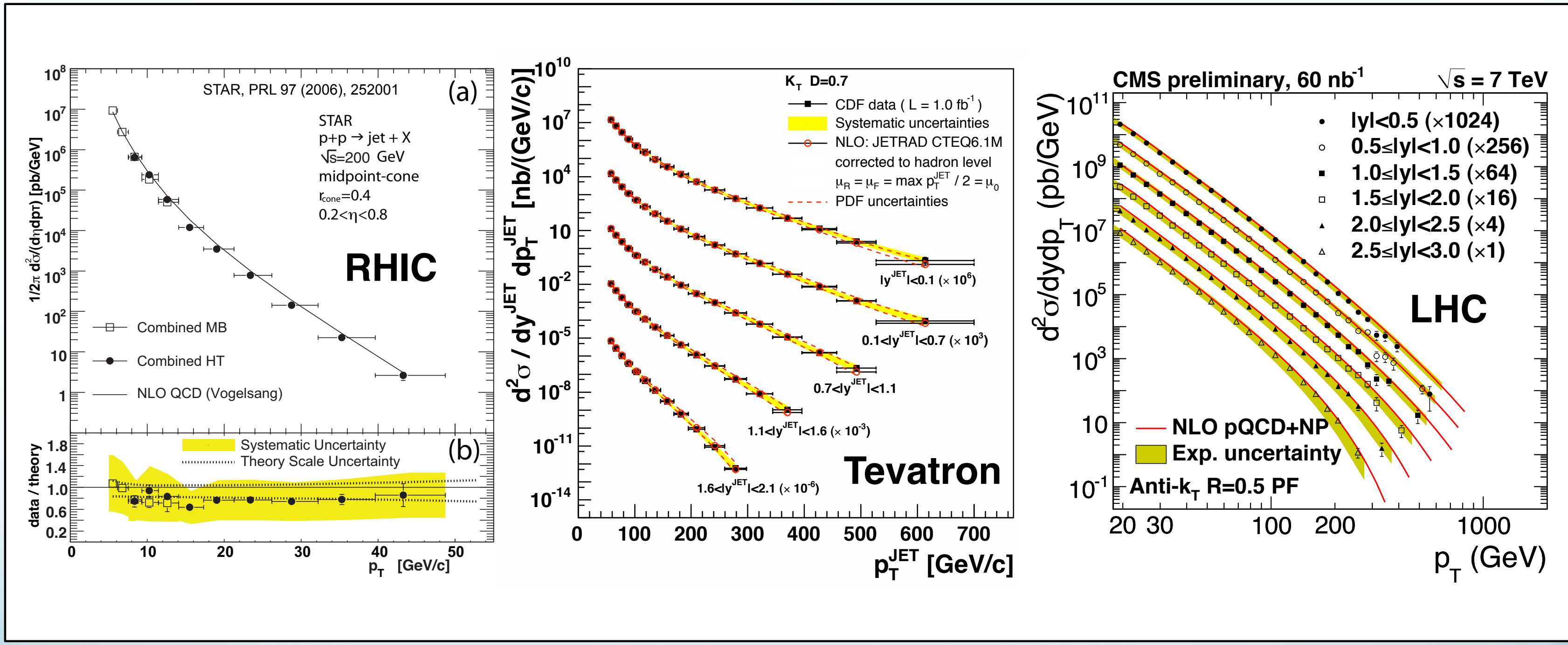
- Beyond Standard Model
  - Most common background in a BSM particle search, e.g., SUSY search in (multiple-) jets + missing ET
  - Jet substructure as a new tool for particle search (new hadronic resonance in boosted regime)

- Heavy ion physics and spin dynamics
  - Used to extract the properties of quark gluon plasma
  - Novel azimuthal observables can reveal important spin dynamics

Lots of data: inclusive jet cross section

- Single inclusive jet cross sections

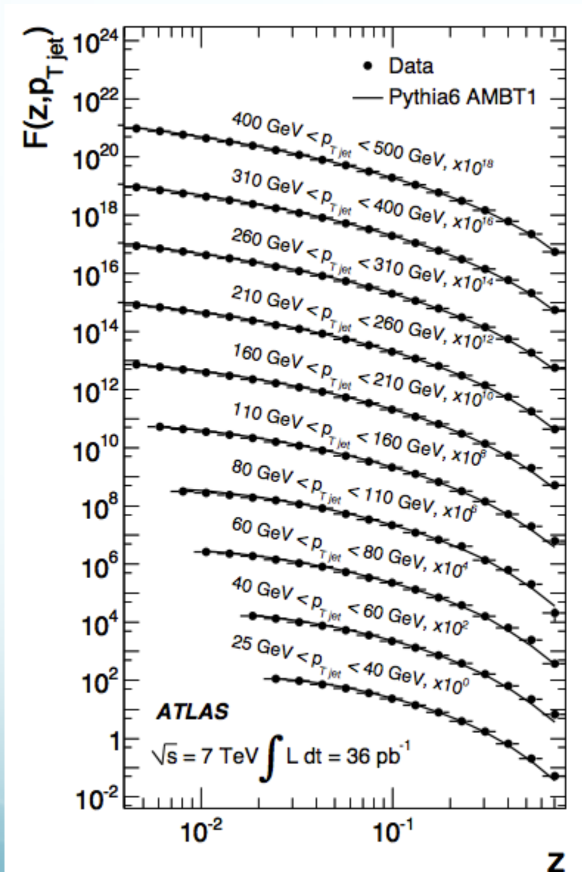
$$p + p \to \text{jet} + X$$



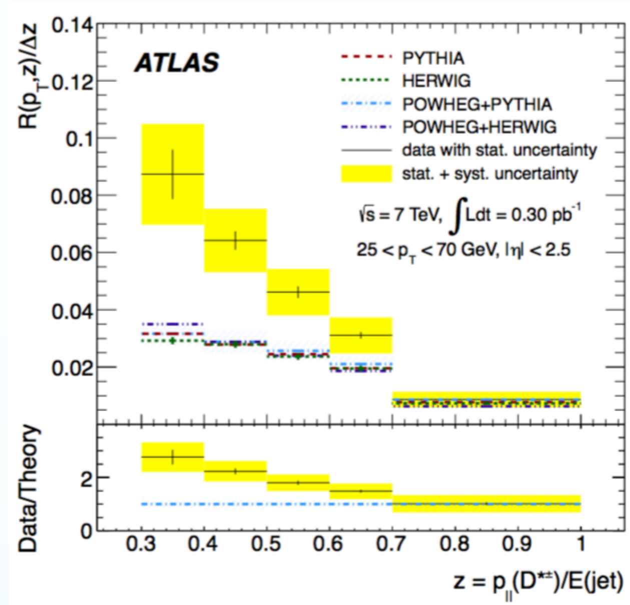
Lots of data: jet fragmentation function

- Hadron distribution inside a jet

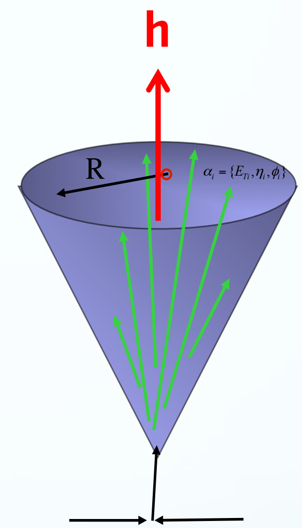
$$p + p \to \text{jet}\,(h) + X$$



Light charged hadrons



D meson

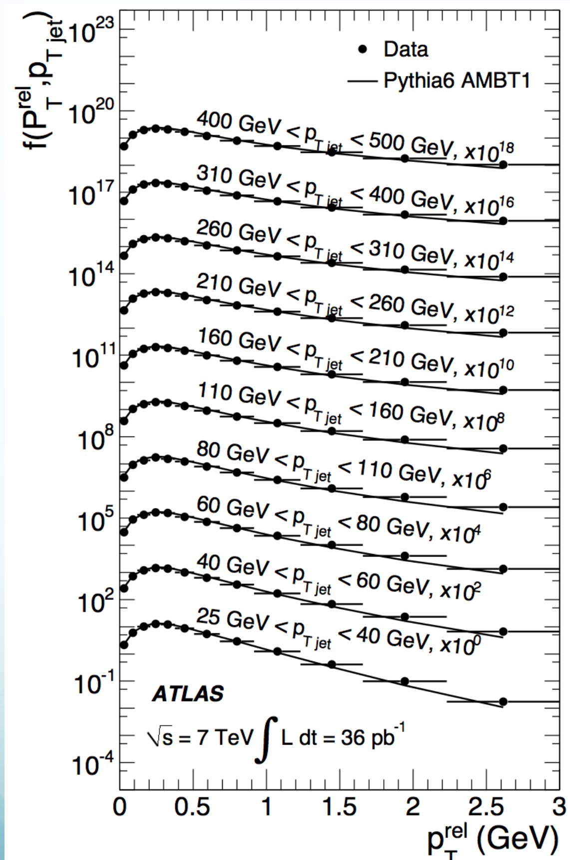


$$z_h = \frac{E_h}{E_{\text{jet}}}$$

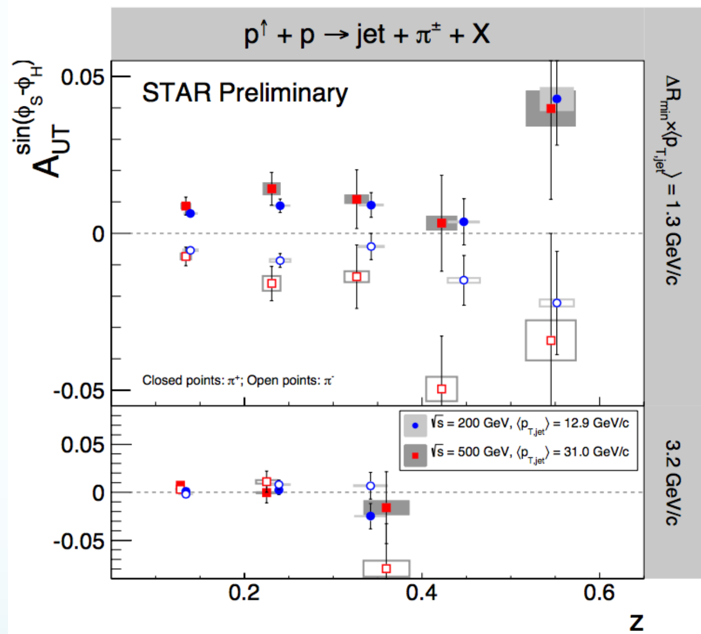
Lots of data: spin correlation inside the jet

- Transverse momentum and azimuthal correlation of hadron inside the jet

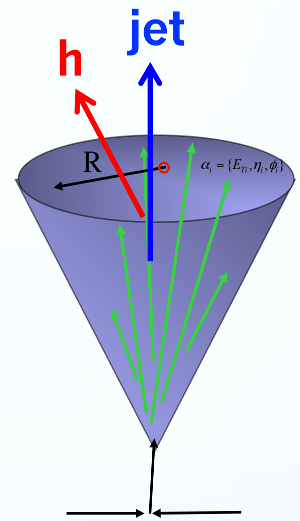
$$p^{\uparrow}\left[\vec{S}_{\perp}(\phi_S)\right] + p \to [\text{jet}\, h(\phi_H)] + X$$



Unpolarized collisions

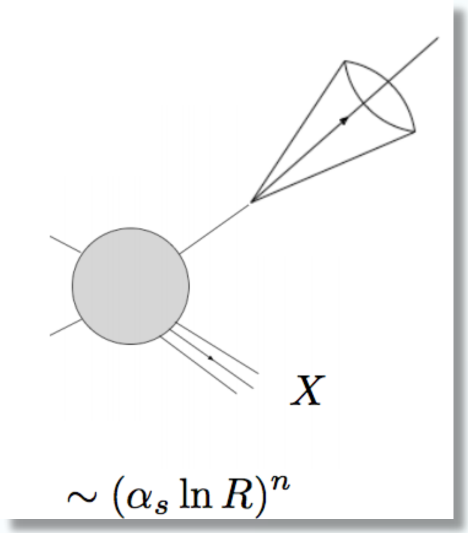


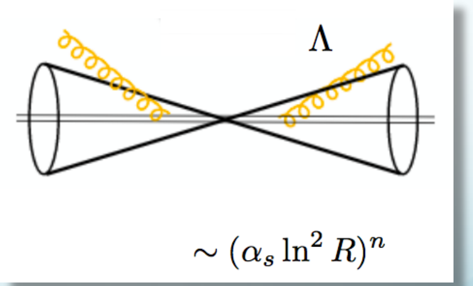
Collins asymmetry



Inclusive jet production

- Earlier work in standard pQCD (MC or NJA)
  - Ellis, Kunszt, Soper, 90, Aversa, Chiappetta, Greco, Guillet, 89
  - Jager, Stratmann, Vogelsange 04, 12
  - Currie, Gehrmann-De Ridder, Glover, Pires 14
  - De Florian, Hinderer, Mukherjee, Ringer, Vogelsang, 14
  - Dasgupta, Dreyer, Salam, Soyez, 15, 16
  - Kang, Ringer, Vitev, 16
  - Dai, Kim, Leibovich, 16
- Earlier work within SCET for exclusive jet production
  - One identifies a certain number of signal jets but vetoes additional jets
  - Ellis, Vermilion, Walsh, Hornig, Lee, 10, Chien, Hornig, Lee 15, Becher, Neubert, Rothern, Shao, 16, Wolodrubetz, Pietrulewicz, Stewart, Tackmann 16

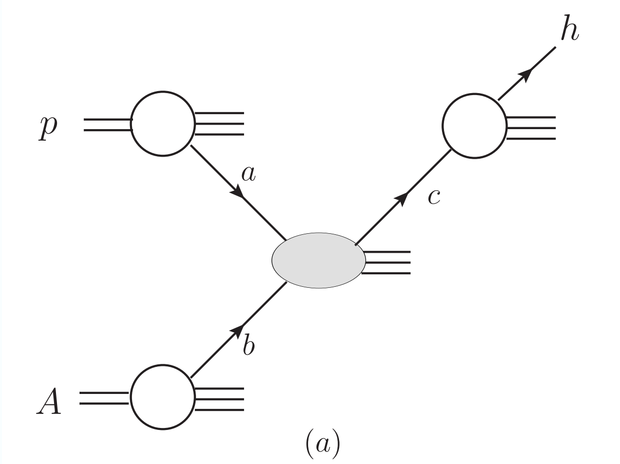




See also talk by C. Lee

Recall single hadron production

- Illustration of single hadron production: $p + p \to h + X$



$$E_h \frac{d\sigma}{d^3 P_h} \propto \sum_{a,b,c} \int \frac{dz}{z^2} D_{c\to h}(z) \int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} f_{b/A}(x) \hat{\sigma}_{ab\to c}$$

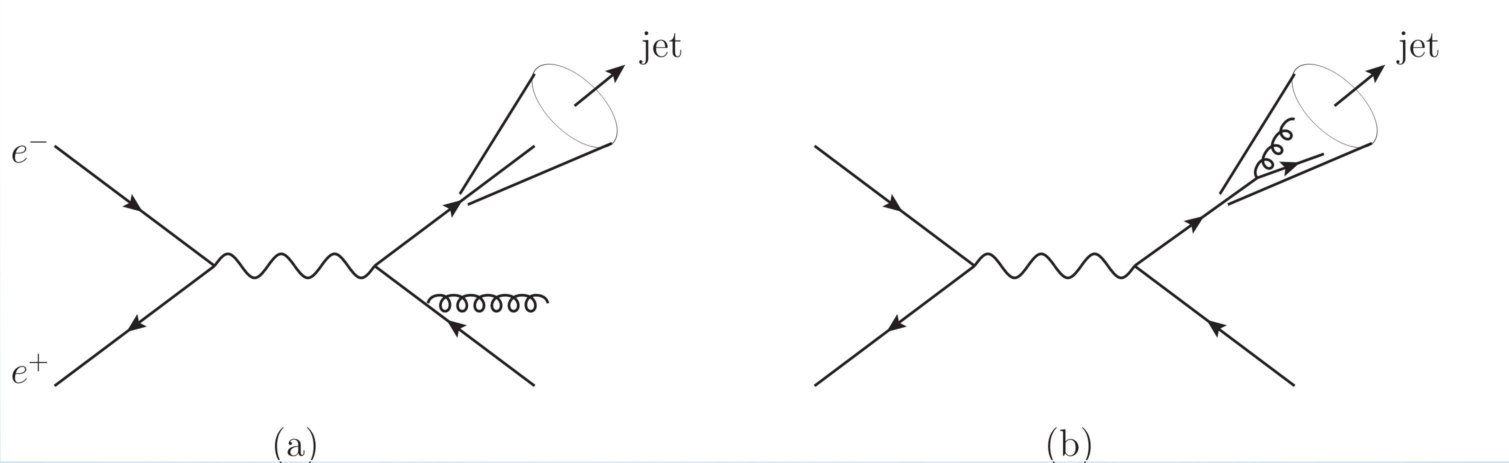
- QCD factorization can be reviewed from the spirit of the effective field theory: physics at very different scales do not affect each other
  - Hard collision happens at scale ~ pT
  - Hadronization/fragmentation happens at a much lower scale ~ mh
  - The interference between these two scales should be suppressed by mh/pT

Single jet production

- The production of jets should be purely perturbative
  - See recent calculations from Werner Vogelsang, et.al.

$$E\frac{d\sigma}{d^3P} \propto \sum_{a,b}\int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} f_{b/A}(x)\hat{\sigma}_{ab\to \text{jet}}$$

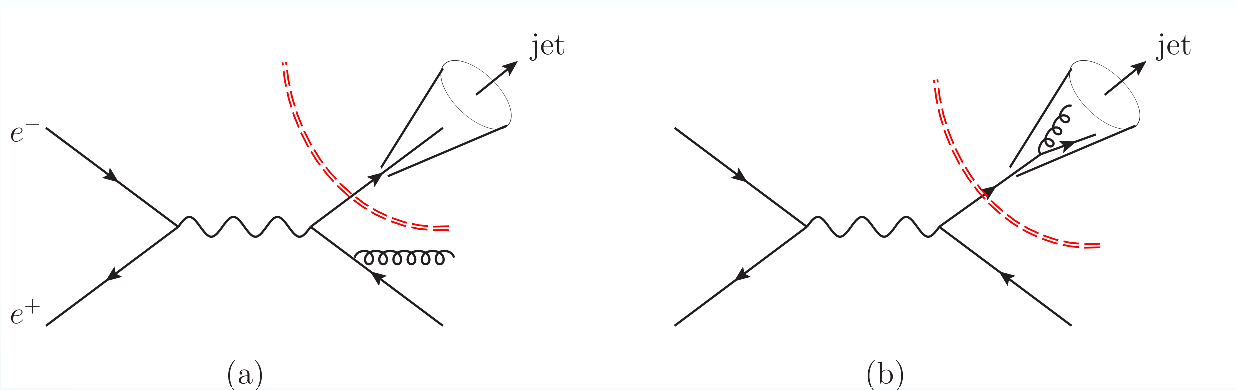
  - Basic idea: produce partons in the final-state, and place kinematic constrains on these finite-number of partons, e.g., LO = 2 partons in the final state, NLO = 3 partons in the final-state

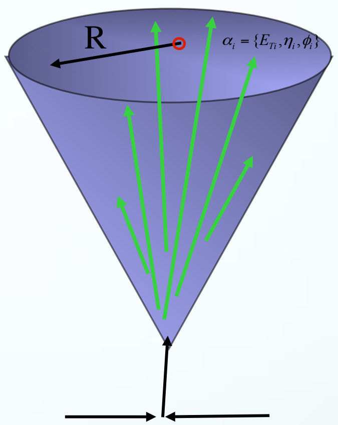


  - Calculations are usually more complicated than the single hadron production

QCD factorization makes things simple

- Think of QCD factorization using the spirit of effective field theory
  - What are the relevant scales for single jet production?
  - Two momenta: (1) hard collision: pT (2) jet radius can build one: pT*R
  - In the small-R limit, one can actually factorizes the jet cross section into two steps, just like single hadron production





$$E\frac{d\sigma}{d^3P} \propto \sum_{a,b,c} \int \frac{dz}{z^2} J_c(z) \int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} f_{b/A}(x) \hat{\sigma}_{ab\to c}$$

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

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

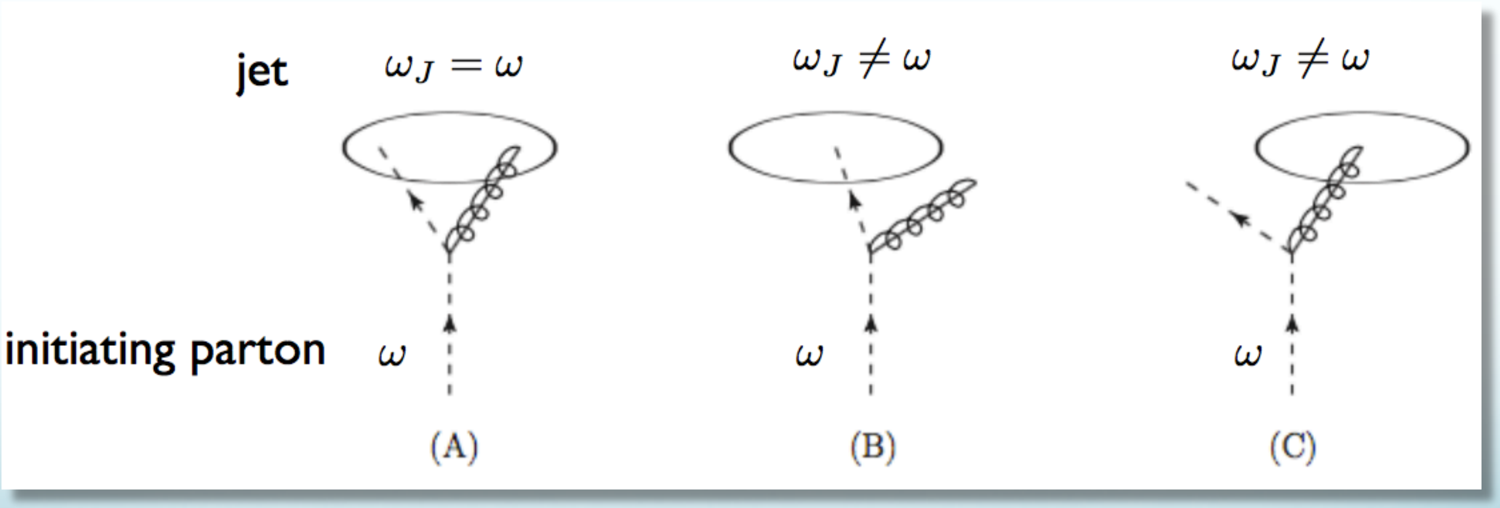
Semi-inclusive jet function

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

$$J_q(z,\omega_J,\mu) = \frac{z}{2N_c}\mathrm{Tr}\left[\frac{\bar{\not{n}}}{2}\langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\chi_n(0)|JX\rangle\langle JX|\bar{\chi}_n(0)|0\rangle\right]$$

$$J_g(z,\omega_J,\mu) = -\frac{z\,\omega}{2(N_c^2-1)}\langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\mathcal{B}_{n\perp\mu}(0)|JX\rangle\langle JX|\mathcal{B}^{\mu}_{n\perp}(0)|0\rangle$$

$$z = \omega_J/\omega$$



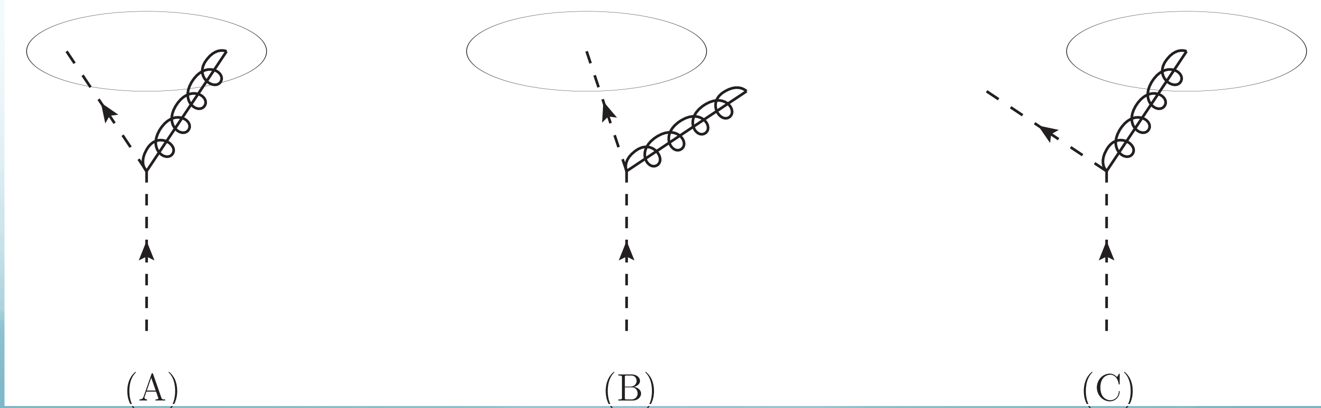
Perturbative computations

- At LO: only one parton becomes the jet

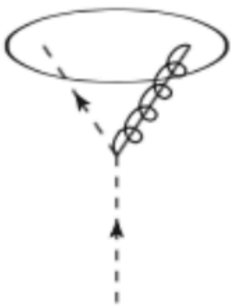
$$J_q^{(0)}(z,\omega_J) = \delta(1-z),$$
$$J_g^{(0)}(z,\omega_J) = \delta(1-z),$$

- At NLO: e.g., for quark-initiated jets
  - Same Feynman diagrams as in seminal work by Ellis, et.al. 10

  - Need to consider three configurations



Both partons are inside the jet



(A)

$$J_q(z,\omega_J) = \delta(1-z)\frac{\alpha_s}{\pi}\left(\frac{\mu^2 e^{\gamma_E}}{4\pi}\right)^{\epsilon}\int_0^1 dx \hat{P}_{qq}(x,\epsilon)\int\frac{dq_\perp}{q_\perp^{1+2\epsilon}}\Theta_{\rm alg}$$

where: anti-k$_T$: $\Theta_{\text{anti-k}_T} = \theta\left(x(1-x)\omega_J\tan\frac{R}{2} - q_\perp\right)$

$$\hat{P}_{qq}(x,\epsilon) = C_F\left[\frac{1+x^2}{1-x} - \epsilon(1-x)\right]$$

$$x = \frac{\ell^- - q^-}{\ell^-}$$

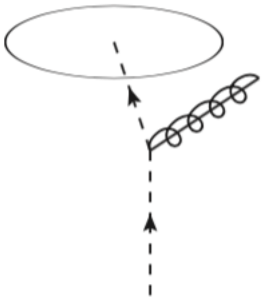
$$J_q(z,\omega_J) = \delta(1-z)\frac{\alpha_s}{2\pi}C_F\left[\frac{1}{\epsilon^2} + \frac{3}{2\epsilon} + \frac{1}{\epsilon}L + \frac{1}{2}L^2 + \frac{3}{2}L + \frac{13}{2} - \frac{3\pi^2}{4}\right]$$

Essentially the same result as in the exclusive case

Ellis, Vermilion, Walsh, Hornig, Lee `10

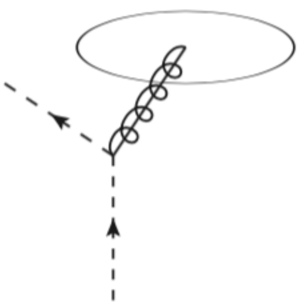
where $L = \ln\left(\frac{\mu^2}{\omega_J^2\tan^2(R/2)}\right)$

Only one parton forms the jet



(B)

$$J_{q\to q(g)}(z,\omega_J) = \frac{\alpha_s}{2\pi}\delta(1-z)\left[-\frac{1}{\epsilon^2}-\frac{1}{\epsilon}L-\frac{1}{2}L^2+\frac{\pi^2}{12}\right] + \frac{\alpha_s}{2\pi}\left[\left(\frac{1}{\epsilon}+L\right)\frac{1+z^2}{(1-z)_+}-2(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+-(1-z)\right]$$



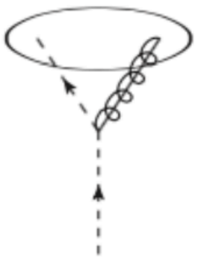
(C)

$$J_{q\to(q)g}(z,\omega_J) = \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon}+L\right)P_{gq}(z)-\frac{\alpha_s}{2\pi}\left[P_{gq}(z)2\ln(1-z)+C_F z\right]$$

Double poles cancel

- Only a single logarithmic ln(R) remains

$\overline{\text{MS}}$ **scheme,** anti-k$_T$



(A)

$$J_q(z,\omega_J) = \delta(1-z)\frac{\alpha_s}{2\pi}C_F\left[\frac{1}{\epsilon^2} + \frac{3}{2\epsilon} + \frac{1}{\epsilon}L + \frac{1}{2}L^2 + \frac{3}{2}L + \frac{13}{2} - \frac{3\pi^2}{4}\right]$$

Essentially the same result as in the exclusive case

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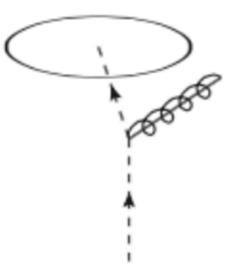
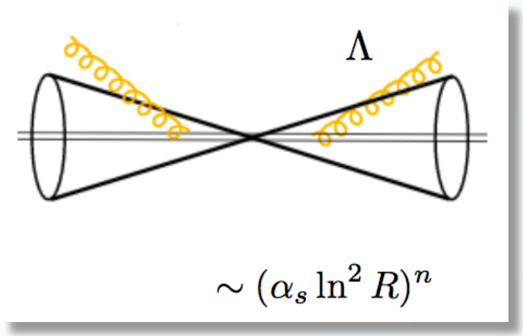


(B)

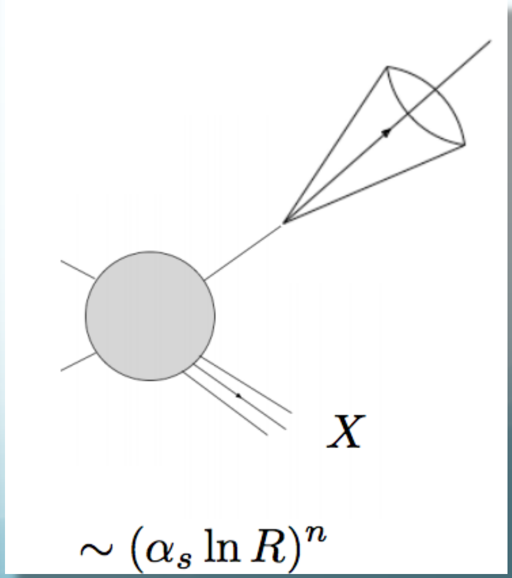
$$J_q(z,\omega_J) = \frac{\alpha_s}{2\pi}\delta(1-z)\left[-\frac{1}{\epsilon^2} - \frac{1}{\epsilon}L - \frac{1}{2}L^2 + \frac{\pi^2}{12}\right] + \frac{\alpha_s}{2\pi}\left[\left(\frac{1}{\epsilon} + L\right)\frac{1+z^2}{(1-z)_+} - 2(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ - (1-z)\right]$$

Difference from exclusive jet production

- For exclusive jet production case
  - If one places an energy cut on the total energy outside of the observed jets to veto additional jets, then configuration in which only one parton is inside the jet is power suppressed by Λ/ω_J
  - See details in Ellis et.al. 10



- For inclusive jet production case
  - As long as the jet energy passes the kinematic cut (energetic enough to be observed), it will be identified as a jet
  - No suppression for one-parton-in-jet configurations

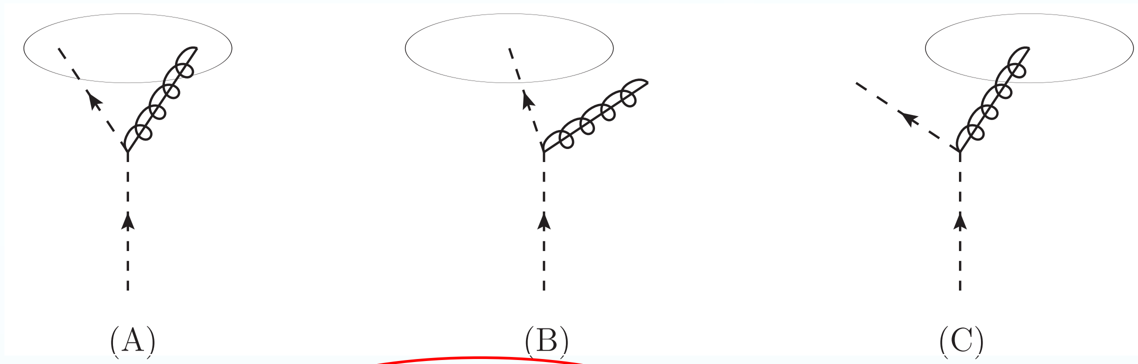


Semi-inclusive jet functions

- At LO: only one parton becomes the jet

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

- At NLO: e.g., for quark-initiated jets



$$J_q^{(1)}(z,\omega_J) = \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon}+L\right)\left[P_{qq}(z)+P_{gq}(z)\right] - \frac{\alpha_s}{2\pi}\left\{C_F\left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right] - \delta(1-z)d_J^{q,\text{alg}} + P_{gq}(z)2\ln(1-z) + C_F z\right\},$$

- Divergent: needs renormalization

Gluon-initiated jets

- For gluon jets

$$J_g^{(1)}(z,\omega_J) = \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon}+L\right)\left[P_{gg}(z)+2n_f P_{qg}(z)\right]$$
$$-\frac{\alpha_s}{2\pi}\left[\frac{4C_A(1-z+z^2)^2}{z}\left(\frac{\ln(1-z)}{1-z}\right)_+ - \delta(1-z)d_J^{g,\mathrm{alg}}\right.$$
$$\left.+4n_f\left(P_{qg}(z)\ln(1-z)+T_F z(1-z)\right)\right],$$

- Natural scale for quark/gluon jet functions

$$L = \ln\frac{\mu^2}{\omega_J^2\tan^2\frac{\mathcal{R}}{2}} \to \mu = \omega_J \tan\frac{\mathcal{R}}{2} = p_T\cdot R$$

Kang, Ringer, Vitev, arXiv:1606.06732, JHEP

Renormalization and RG evolution

- Bare – renormalized semi-inclusive jet function

$$J_{i,\mathrm{bare}}(z,\omega_J) = \sum_j \int_z^1 \frac{dz'}{z'} Z_{ij}\left(\frac{z}{z'},\mu\right) J_j(z',\omega_J,\mu)$$

- RG evolution

$$\mu\frac{d}{d\mu}J_i(z,\omega_J,\mu) = \sum_j \int_z^1 \frac{dz'}{z'} \gamma_{ij}^J\left(\frac{z}{z'},\mu\right) J_j(z',\omega_J,\mu)$$

- Anomalous dimension, can be determined from perturbative calculations

$$\gamma_{ij}^J(z,\mu) = -\sum_k \int_z^1 \frac{dz'}{z'} (Z)^{-1}_{ik}\left(\frac{z}{z'},\mu\right) \mu\frac{d}{d\mu} Z_{kj}(z',\mu) \qquad \gamma_{ij}^J(z,\mu) = \frac{\alpha_s(\mu)}{\pi} P_{ji}(z)$$

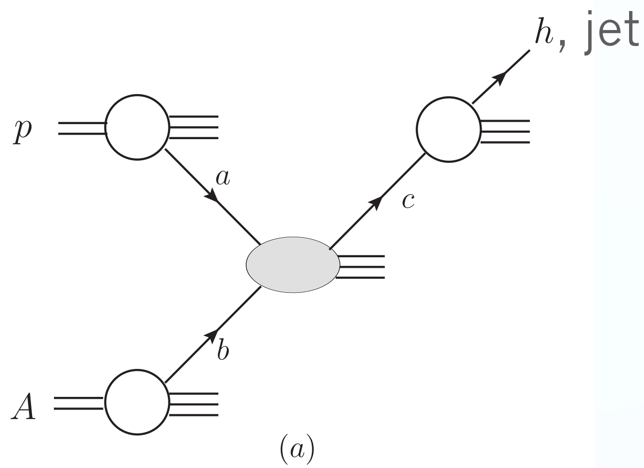
After renormalization, one will find: semi-inclusive quark/gluon jets follow DGLAP evolution equation, just like hadron fragmentation functions

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

Kang, Ringer, Vitev, arXiv:1606.06732, JHEP

Same factorization formalisms

- Now single hadron and single jet share the same factorization formalisms



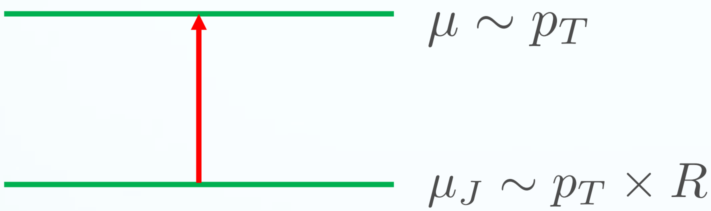
$$E_h \frac{d\sigma}{d^3P_h} \propto \sum_{a,b,c} \int \frac{dz}{z^2} D_{c\to h}(z) \int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} f_{b/A}(x) \hat{\sigma}_{ab\to c}$$

$$E \frac{d\sigma}{d^3P} \propto \sum_{a,b,c} \int \frac{dz}{z^2} J_c(z) \int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} f_{b/A}(x) \hat{\sigma}_{ab\to c}$$

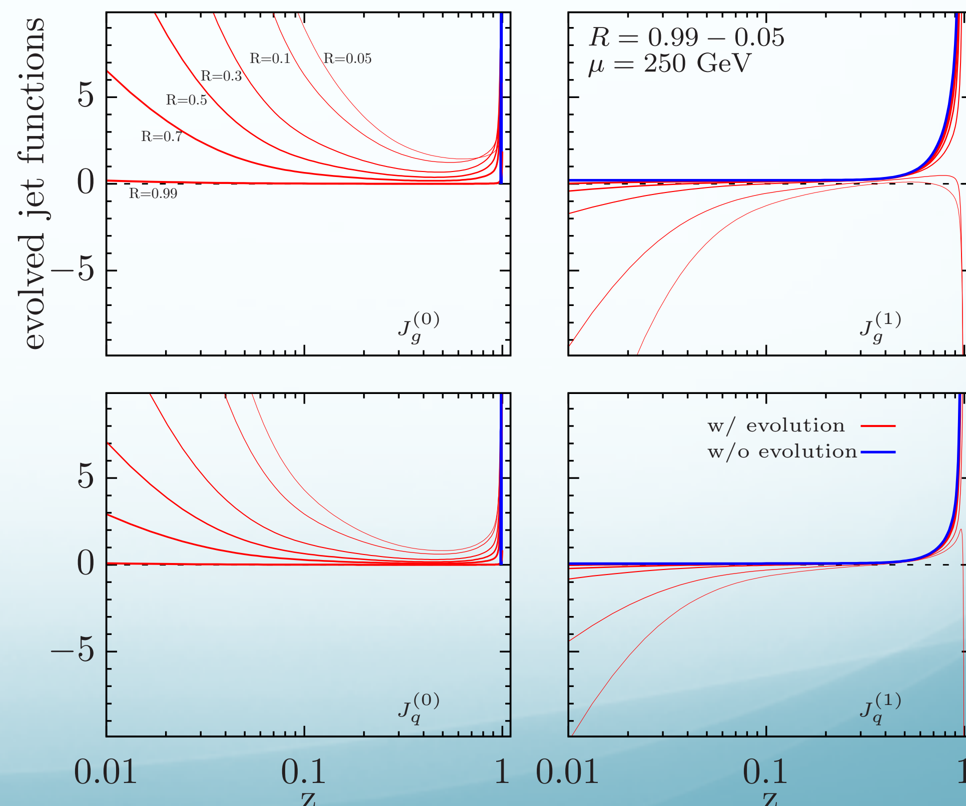
- Same partonic cross sections, only replace FFs by semi-incusive jet functions
  - FFs are non-perturbative, has to be fitted from experimental data
  - Semi-inclusive jet functions are purely perturbative

Ln(R) resummation through DGLAP evolution

- DGLAP evolution of semi-inclusive jet function leads to ln(R) resummation
  - Semi-inclusive jet functions are calculable, and have a natural scale pT*R
  - Run DGLAP from pT*R to pT, one naturally resums $(\alpha_s \ln R)^n$



$$J_i = J_i^{(0)} + J_i^{(1)}$$



NLO+LL$_R$ (or NLL$_R$) resummation

- Match onto NLO fixed-order calculations, one performs an expansion

$$d\sigma^{pp\to \mathrm{jet}X} \sim \left(d\hat\sigma_{ab}^{c,(0)} + d\hat\sigma_{ab}^{c,(1)}\right) \otimes \left(J_c^{(0)} + J_c^{(1)}\right)$$
$$= \left(d\hat\sigma_{ab}^{c,(0)} + d\hat\sigma_{ab}^{c,(1)}\right) \otimes J_c^{(0)} + d\hat\sigma_{ab}^{c,(0)} \otimes J_c^{(1)} + \mathcal{O}(\alpha_s^2)$$

- With evolved $J^{(0)}$ and $J^{(1)}$ using LL (or NLL) DGLAP evolution equation, we then achieve NLO+LL$_R$ or NLO+NLL$_R$ accuracy

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

LO/NLO expressions for $P_{ji}(z, \mu)$ corresponds to LL/NLL resummation

Dealing with z→1 limit

- Evolved jet functions are still singular for $z \to 1$
  - Adopted a prescription proposed for quarkonium fragmentation functions

Bodwin, Chao, Chung, Kim, Lee, Ma, 16

$$\int_{z_c^{\min}}^{1} \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^c(z_c)}{dvdz} J_c(z_c) = \int_{z_c^{\min}}^{1-\varepsilon} \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^c(z_c)}{dvdz} J_c(z_c) + \int_{1-\varepsilon}^{1} \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^c(z_c)}{dvdz} J_c(z_c)$$

  - Rewrite the 2nd term

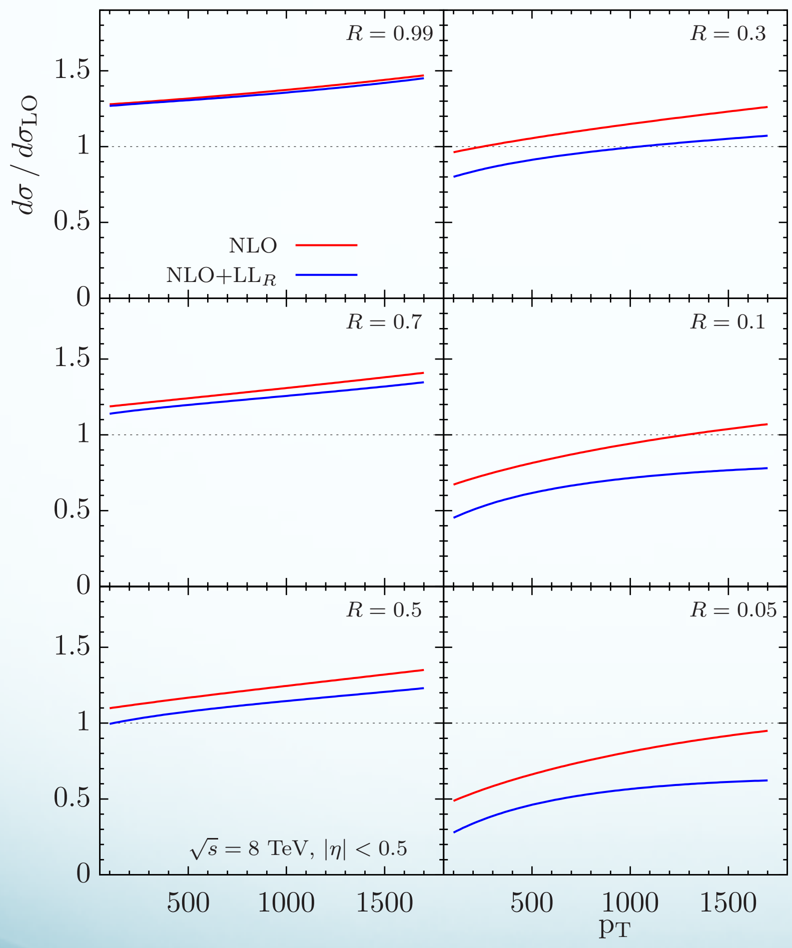
$$\int_{1-\varepsilon}^{1} \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^c(z_c)}{dvdz} J_c(z_c) = \int_{1-\varepsilon}^{1} \frac{dz_c}{z_c^2} \left[\frac{d\hat{\sigma}_{ab}^c(z_c)}{dvdz} z_c^{-N}\right] \left[z_c^N J_c(z_c)\right]$$

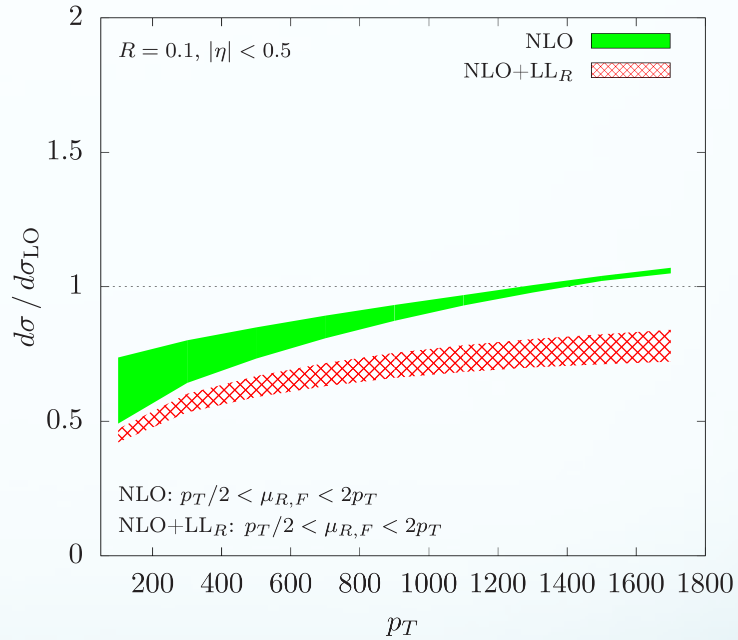
$$\approx \left[\frac{d\hat{\sigma}_{ab}^c(z_c)}{dvdz}\right]_{z_c=1} \times \int_{1-\varepsilon}^{1} dz_c\, z_c^{N-2} J_c(z_c)$$

$$= \left[\frac{d\hat{\sigma}_{ab}^c(z_c)}{dvdz}\right]_{z_c=1} \times \left[\int_0^1 dz_c\, z_c^{N-2} J_c(z_c) - \int_0^{1-\varepsilon} dz_c\, z_c^{N-2} J_c(z_c)\right]$$

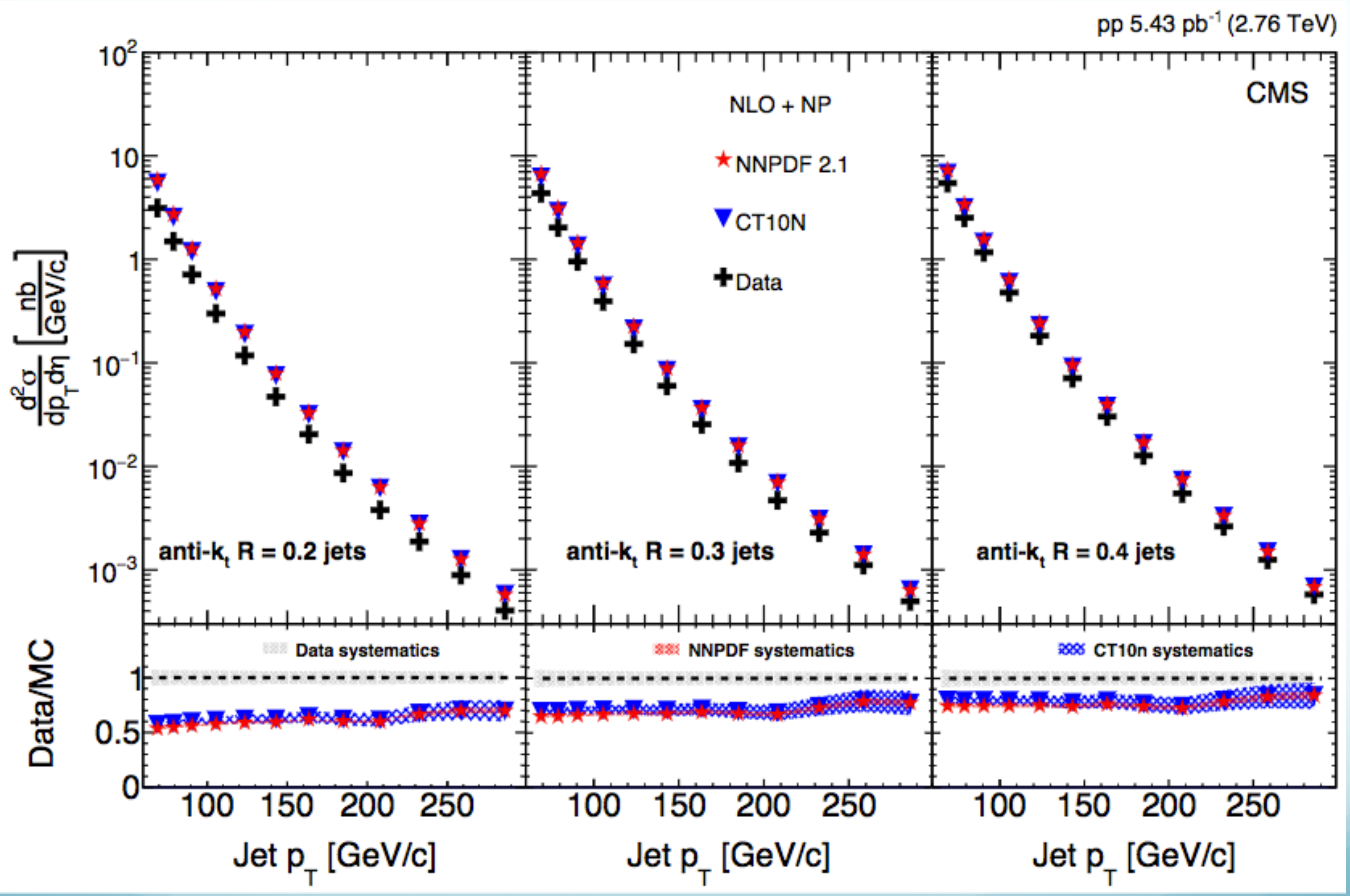
    - Check the calculation is independent of ε and N
    - Check the calculation agrees with NLO when $R \to 1$

Jet radius resummation: ln(R)

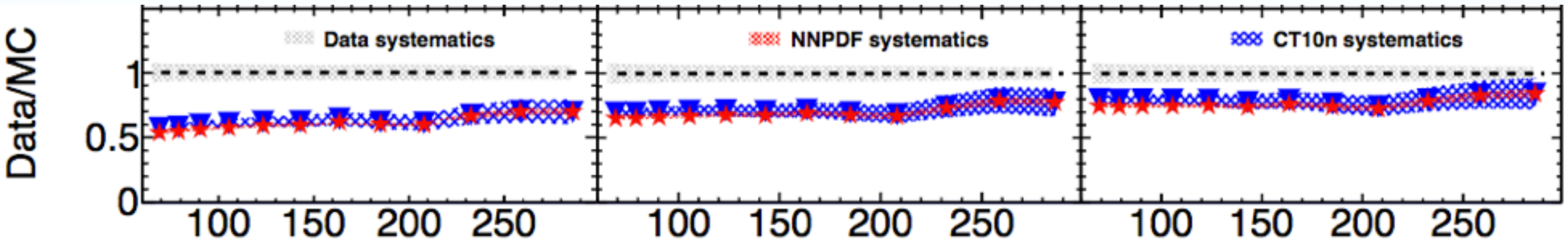


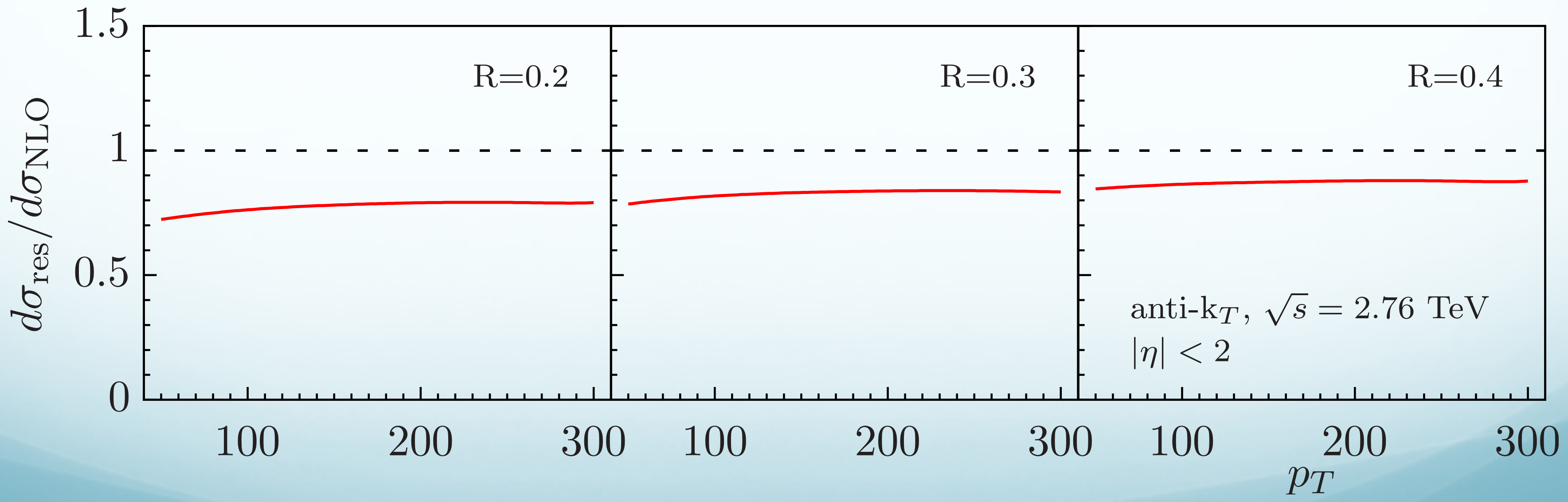


Most recent jet measurements



Effect of ln(R) resummation





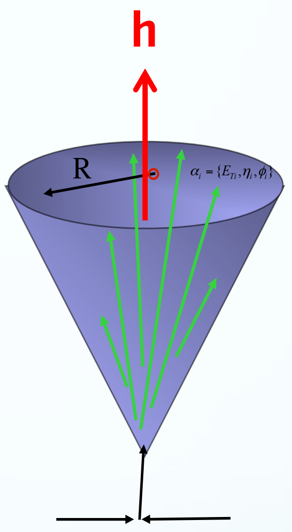
Jet fragmentation function

- Definition

$$F(z_h, p_T) = \frac{d\sigma^h}{dy dp_T dz_h} \Big/ \frac{d\sigma}{dy dp_T}$$

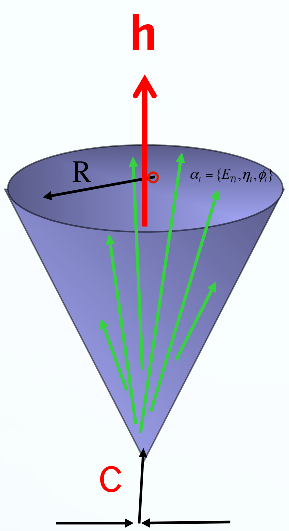
- Lots of studies in the past, e.g., from SCET
  - Procura, Stewart, 10, Procura, Waalewijn 11, 12, Bauer, Mereghetti 14
  - Baumgart, Leibovich, Mehen, Rothstein 14
  - Chien, Kang, Ringer, Vitev, Xing, 15
  - Kang, Ringer, Vitev, 16

- Fixed NLO calculations
  - Arleo, Fontannaz, Guillet, Nguyen 14
  - Kaufmann, Mukherjee, Vogelsang, 15



Jet fragmentation function

- First produce a jet, and then further look for a hadron inside the jet



$$F(z_h, p_T) = \frac{d\sigma^h}{dy\,dp_T\,dz_h} \Big/ \frac{d\sigma}{dy\,dp_T}$$

$$z_h = p_T^h / p_T$$

$$z = p_T / p_T^{c}$$

Kang, Ringer, Vitev, arXiv:1606.07063

- Just like the single inclusive jet production, we have
  - Semi-inclusive fragmenting jet function

$$\frac{d\sigma}{dy\,dp_T\,dz_h} \propto \sum_{a,b,c} \int \frac{dz}{z^2} \mathcal{G}_c^h(z, z_h, \mu) \int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} f_{b/A}(x) \hat{\sigma}_{ab\to c}$$

Semi-inclusive fragmenting jet functions

- Certainly, they cannot be purely perturbative any more, because we now observe a hadron inside the jet
  - Good thing: they can be expanded in terms of the standard fragmentation functions, with calculable coefficients
  - The perturbative calculations are still rather useful, since they will reveal how they evolve

- At LO: simple

$$\mathcal{G}_i^{j,(0)}(z, z_h, \mu) = \delta_{ij}\delta(1-z)\delta(1-z_h)$$

- At NLO: perturbative calculations determine the running of these new jet functions, as well as how they are related to the standard FFs

Semi-inclusive fragmenting jet function

- Perturbative results up to NLO

quark-quark:

IR

UV

$$\mathcal{G}_{q,\mathrm{bare}}^{q}(z, z_h, \omega_J, \mu) = \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\left(-\frac{1}{\epsilon} - L\right) P_{qq}(z_h)\delta(1-z)$$
$$+ \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon} + L\right) P_{qq}(z)\delta(1-z_h)$$
$$+ \delta(1-z)\frac{\alpha_s}{2\pi}\left[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + 2P_{qq}(z_h)\ln z_h\right]$$
$$- \delta(1-z_h)\frac{\alpha_s}{2\pi}\left[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\right],$$

Renormalization and matching

- UV divergence relates to the RG running: involves variable z
  - Again DGLAP evolution equation

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

- IR is related to standard fragmentation functions: relevant to z_h

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

- Matching coefficients can be determined from perturbative results, e.g.
  - Standard partonic FFs: $D_i^j(z_h,\mu)=\delta_{ij}\delta(1-z_h)+\frac{\alpha_s}{2\pi}P_{ji}(z_h)\left(-\frac{1}{\epsilon}\right)$
  - Partonic semi-inclusive fragmenting jet function calculated above

Matching coefficients

- Some matching coefficients for quark jets

$$
\begin{aligned}
\mathcal{J}_{qq}(z, z_h, \mu) =& \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\Bigg\{ L\left[P_{qq}(z)\delta(1-z_h) - P_{qq}(z_h)\delta(1-z)\right] \\
&+ \delta(1-z)\left[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + \mathcal{I}_{qq}^{\rm alg}(z_h)\right] \\
&- \delta(1-z_h)\left[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\right]\Bigg\}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{J}_{qg}(z, z_h, \mu) =& \frac{\alpha_s}{2\pi}\Bigg\{ L\left[P_{gq}(z)\delta(1-z_h) - P_{gq}(z_h)\delta(1-z)\right] \\
&+ \delta(1-z)\left[2P_{gq}(z_h)\ln(1-z_h) + C_F z_h + \mathcal{I}_{qg}^{\rm alg}(z_h)\right] \\
&- \delta(1-z_h)\left[2P_{gq}(z)\ln(1-z) + C_F z\right]\Bigg\}
\end{aligned}
$$

Two DGLAPs

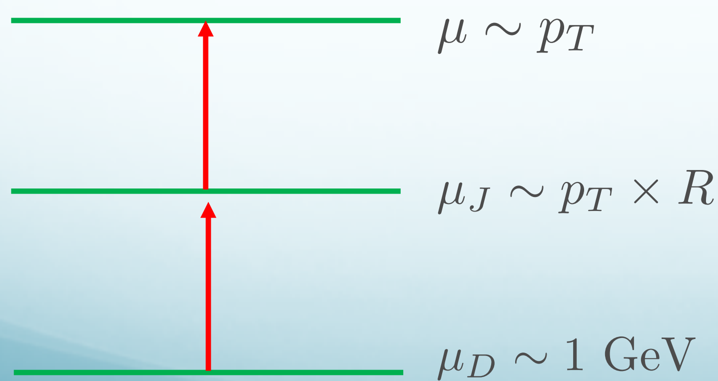
- Again DGLAP evolution: evolution is for variable z

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

- Relation to standard FFs: relevant to variable z_h

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

Kang, Ringer, Vitev, arXiv:1606.07063

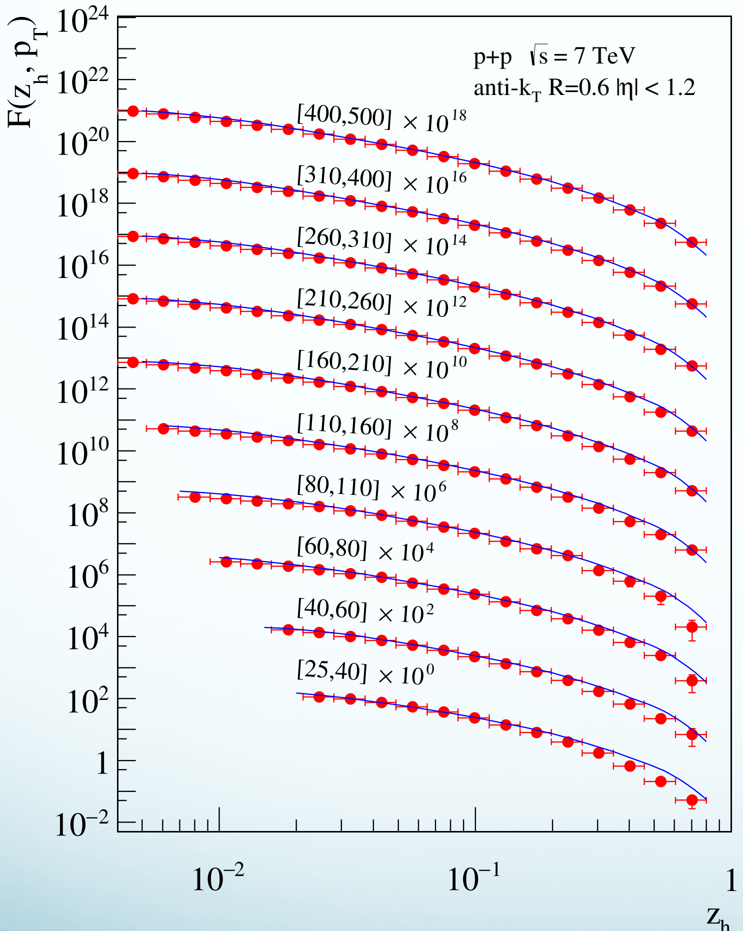


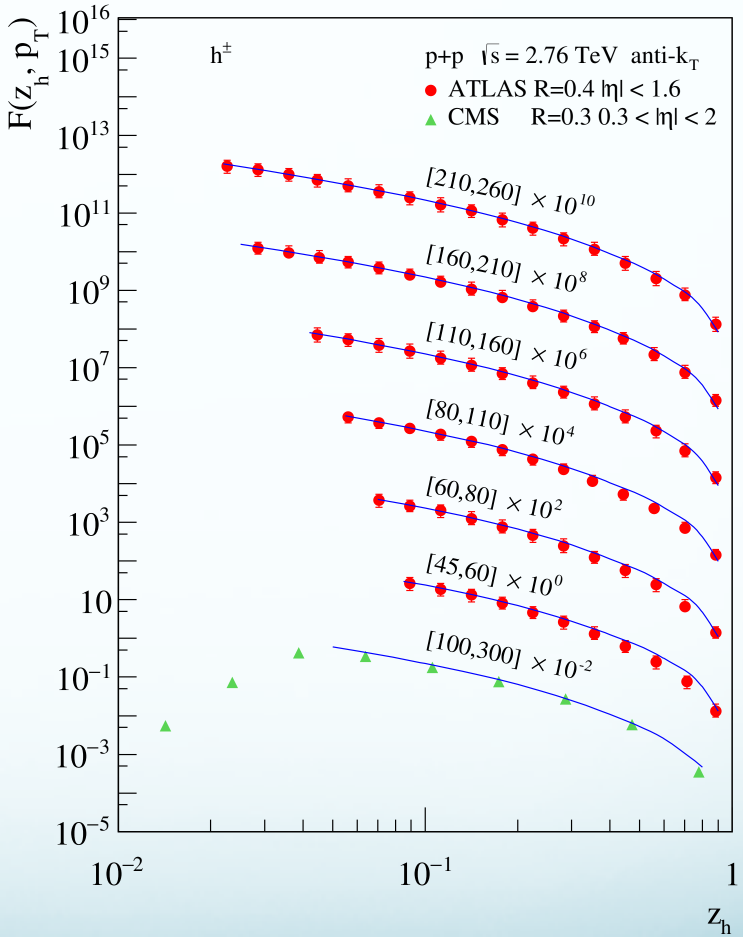
Resum ln(R)

Evolve standard FFs from 1 GeV to pT*R

Some interesting phenomenology

- Works pretty well in comparison with experimental data

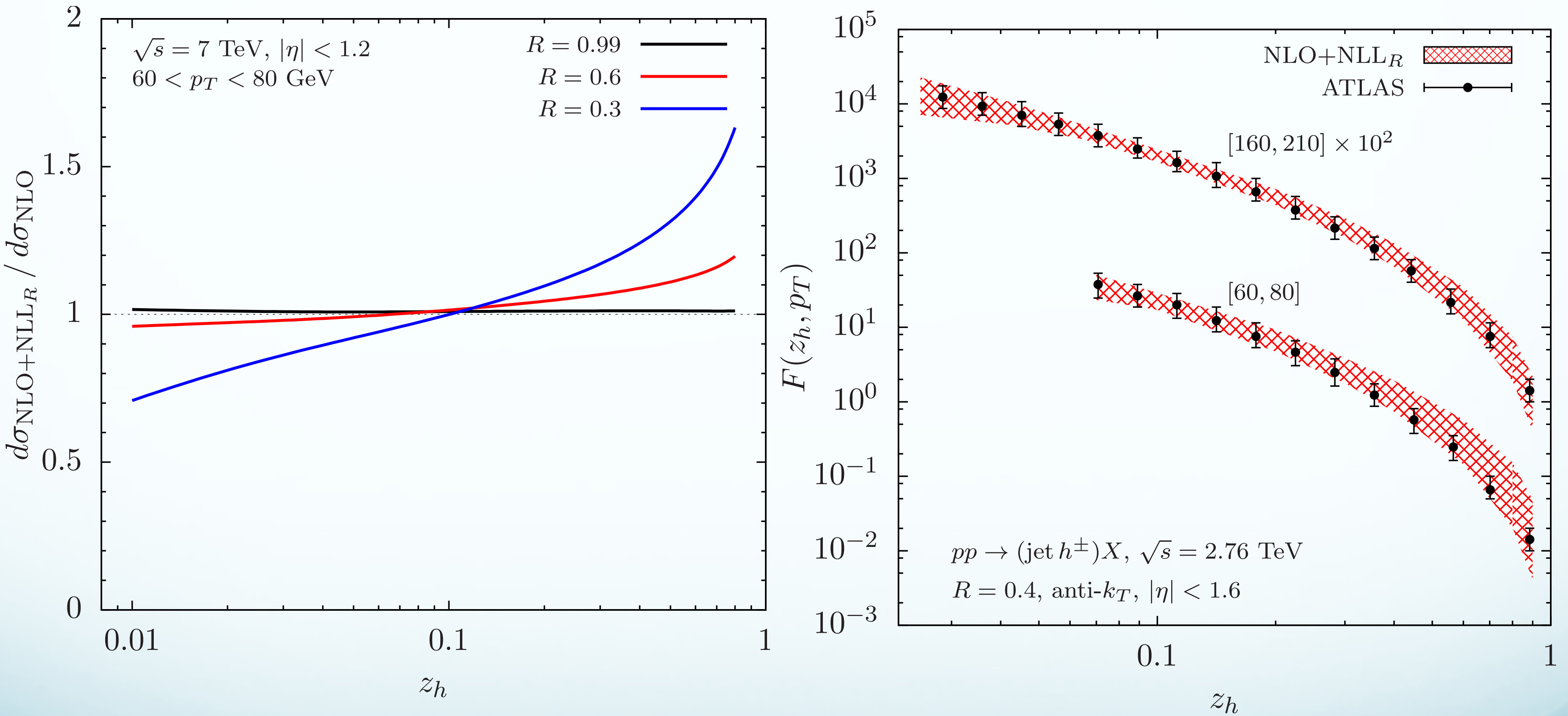




Kang, Ringer, Vitev, arXiv:1606.07063

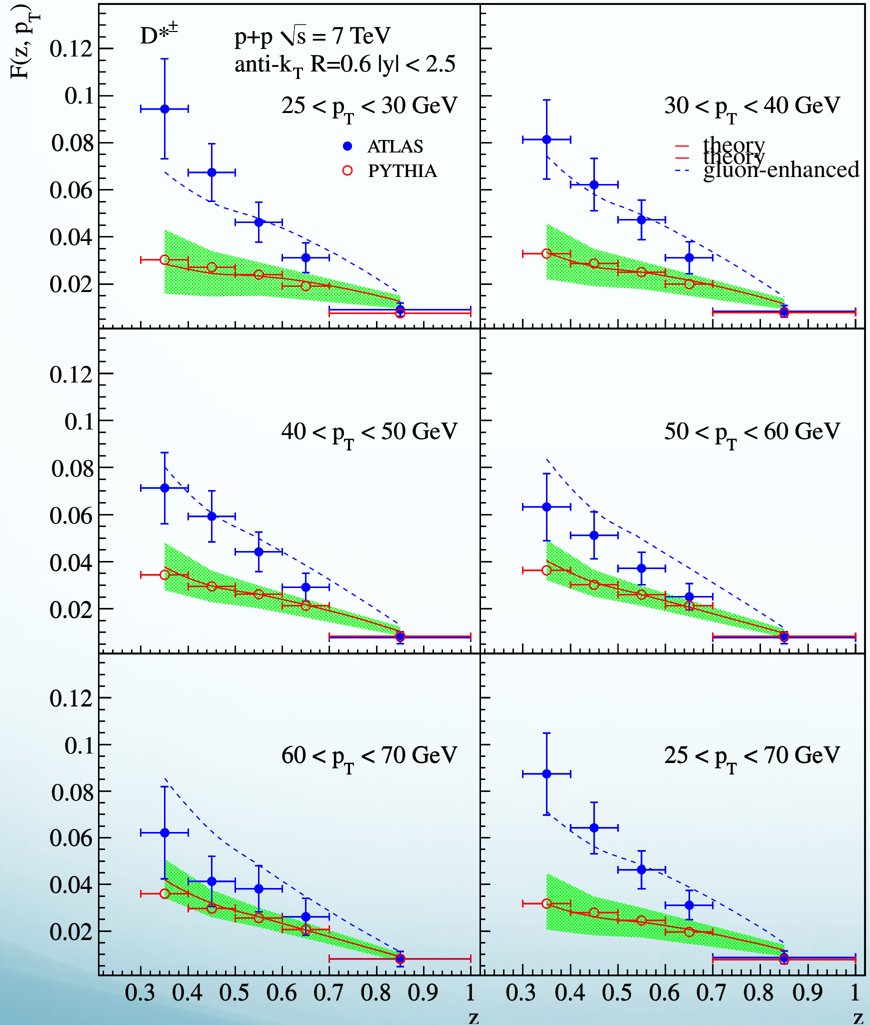
Comparison with fixed NLO results

- The effect of radius R resummation is quite significant



Jet fragmentation function for heavy meson

- Using D meson FFs fitted from e+e- data Kneesch, Kniehl, Kramer, Schienbein, 08



Using ZM-VFNS scheme:
Chien, Kang, Ringer, Vitev, Xing, 1512.06851, JHEP 16

$$D_g^D(z,\mu) \to 2D_g^D(z,\mu)$$

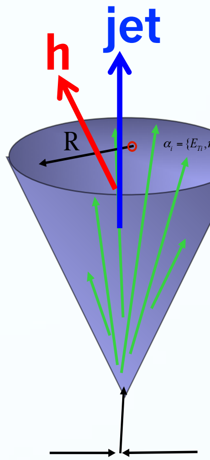
New fit of D-meson FFs:
Anderle, Kang, Ringer, Stratmann, Vitev, in progress

Transverse momentum dependence and spin correlation

- Now study transverse momentum dependence of the hadron distribution inside the jet

$$p^{\uparrow}\left[\vec{S}_{\perp}(\phi_S)\right] + p \to [\mathrm{jet}\, h(\phi_H)] + X$$

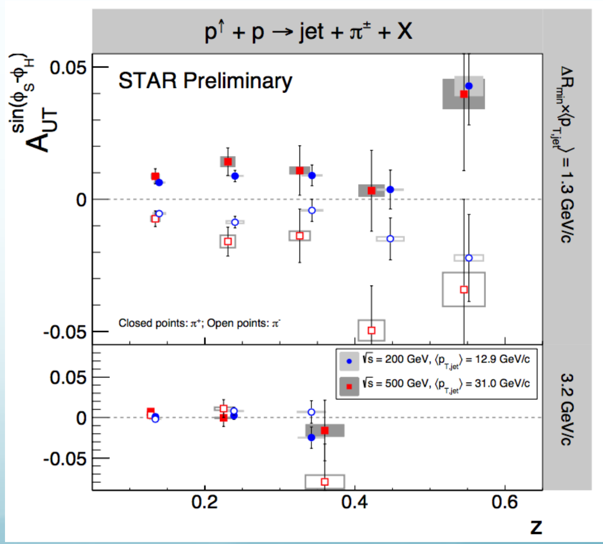
$$\frac{d\sigma}{dy d^2 p_{\perp}^{\mathrm{jet}} dz d^2 j_T} = F_{UU} + \sin(\phi_S - \phi_H) F_{UT}^{\sin(\phi_S - \phi_H)}$$



j_T : hadron transverse momentum with respect to the jet direction

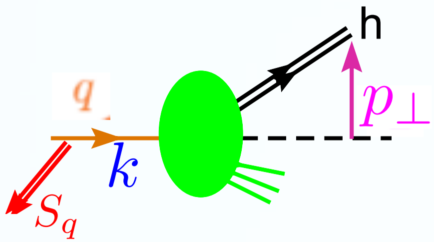
- Collins asymmetry

$$A_{UT}^{\sin(\phi_S - \phi_H)} = F_{UT}^{\sin(\phi_S - \phi_H)} \Big/ F_{UU}$$



Collins function: universal

- Collins function: unpolarized hadron from a transversely polarized quark



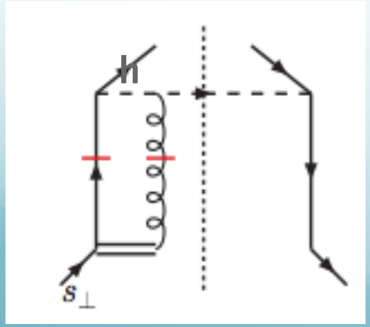
$$D_{h/q}(z,p_\perp) = D_1^q(z,p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z,p_\perp^2)\vec{S}_q \cdot \left(\hat{k} \times p_\perp\right)$$

Spin-independent Spin-dependent

- ✓ 2002: A. Metz studied the universality property of Collins function in a model-dependent way – very subtle – finally found it is universal between SIDIS and e+e-
- ✓ 2004: Collins and Metz have general argume
- ✓ 2008: Yuan generalizes to pp
- ✓ 2010: Boer, Kang, Vogelsang, and Yuan perf demonstrate the gauge link does not contribute


Submission history
From: Andreas Metz [view email]
[v1] Thu, 5 Sep 2002 10:11:18 GMT (16kb)
[v2] Wed, 18 Sep 2002 17:02:44 GMT (16kb)
[v3] Wed, 2 Oct 2002 17:42:40 GMT (16kb)
[v4] Wed, 30 Oct 2002 01:36:34 GMT (17kb)

subtle issue dealt by great physicist



$$H_1^{\perp \mathrm{SIDIS}}(z,p_\perp^2) = H_1^{\perp e^+e^-}(z,p_\perp^2) = H_1^{\perp \mathrm{pp}}(z,p_\perp^2)$$

Metz 02, Collins, Metz 04, Yuan 08,
Boer, Kang, Vogelsang, Yuan, PRL 10, ...

Work in progress

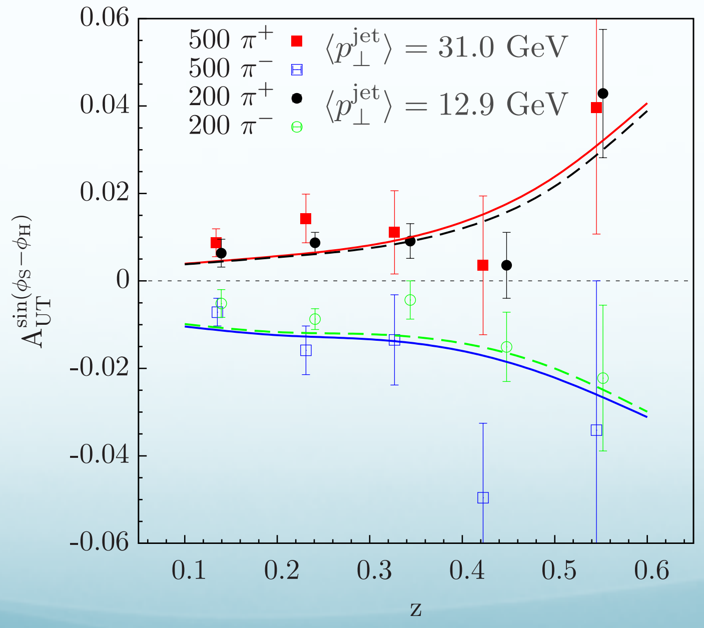
- Factorization formalism
  - Not dealing with non-global logs

Kang, Liu Ringer, Xing, in preparation

$$\frac{d\sigma}{dy dp_\perp^{\rm jet} dz_h d^2 j_T} \propto \sum_{a,b,c} \int \frac{dz}{z^2} \int d^2k_T d^2\lambda_T \mathcal{G}_c^h(z, z_h, k_T) S(\lambda_T, R) \delta^2(\vec{k}_T + \vec{\lambda}_T - \vec{j}_T)$$
$$\times \int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} f_{b/A}(x) \hat{\sigma}_{ab\to c}$$

  - LO formula

Kang, Prokudin, Ringer, Sun, Yuan, in preparation



Summary

- Inclusive jet production follows the same factorization formalism as the single inclusive hadron production, with the FFs replaced by semi-inclusive jet functions
- These novel semi-inclusive jet functions are purely perturbative, and follow the usual DGLAP evolution equations, which can be used to perform ln(R) resummation
- Jet substructure for inclusive jets can be computed similarly

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Thank you!