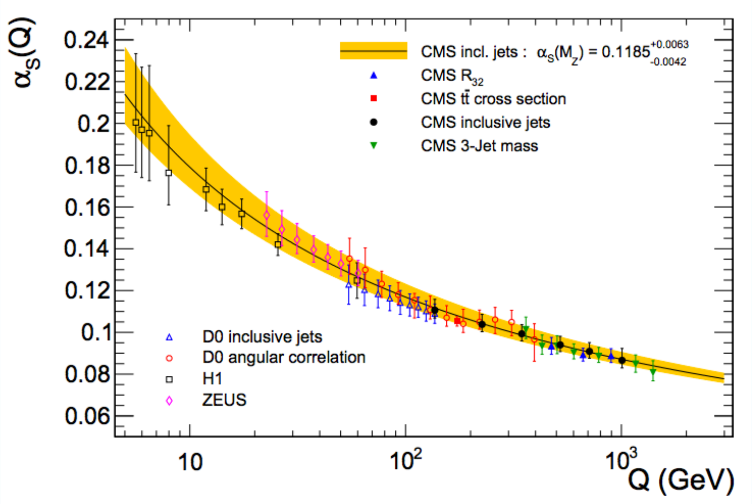
Hadron distribution insides jets for hadronization and spin dynamics

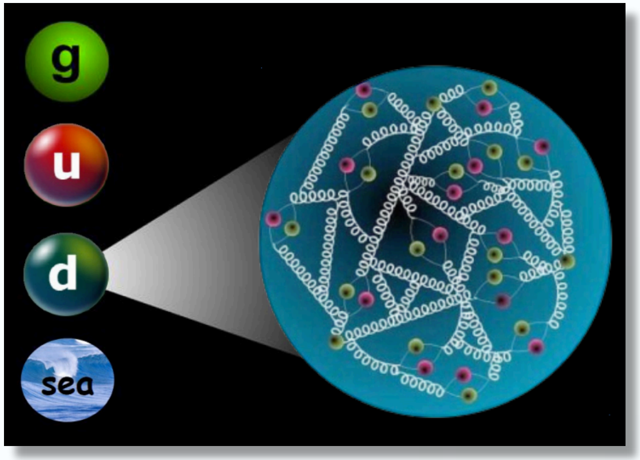
Zhongbo Kang
UCLA

RBRC Workshop: Synergies of pp and pA Collisions with an EIC
June 26 - 28, 2017

Jets as a precision probe of QCD

- Extraction of strong coupling constant

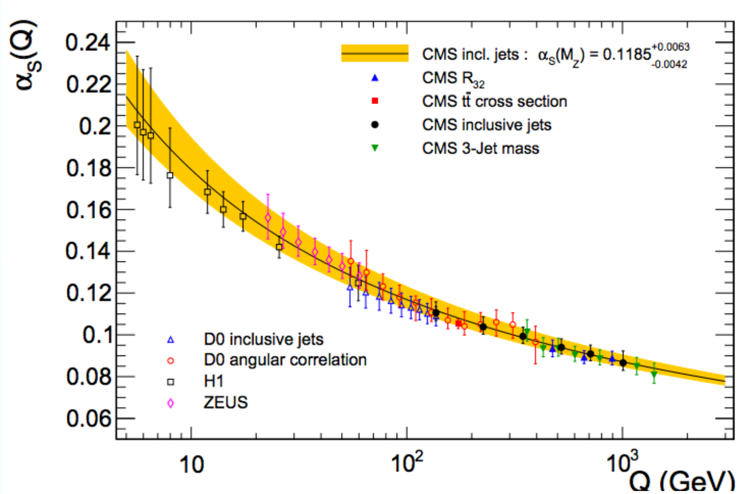


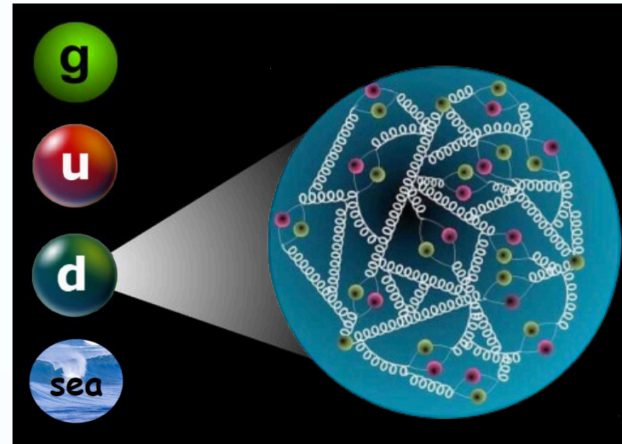


- PDFs are constrained by collider jet data, especially gluon distribution functions

Jets as a precision probe of QCD

- Extraction of strong coupling constant





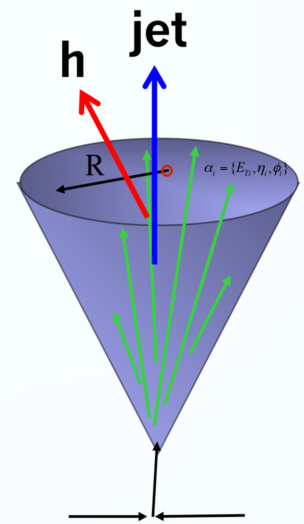
- PDFs are c
distributio

process	sensitivity to PDFs
W asymmetry	→ quark flavour separation
W and Z production (differential)	→ valence quarks
W+c production	→ strange quark
Drell-Yan (DY): high invariant mass	→ sea quarks, high-x
Drell-Yan (DY): low invariant mass	→ low-x
W,Z +jets	→ gluon medium-x
Inclusive jet and di-jet production	→ gluon and $\alpha_s(M_Z)$
Direct photon	→ gluon medium, high-x
ttbar, single top	→ gluon and $\alpha_s(M_Z)$

Hadron distribution inside the jet

- Study a hadron distribution inside a fully reconstructed jet

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



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

$$F(z_h, j_\perp; p_T) = \frac{d\sigma^h}{dp_T d\eta dz_h d^2 j_\perp} \Big/ \frac{d\sigma}{dp_T d\eta}$$

$$z_h = p_T^{\rm h} / p_T^{\rm jet}$$

$j_\perp$: hadron transverse momentum with respect to the jet direction

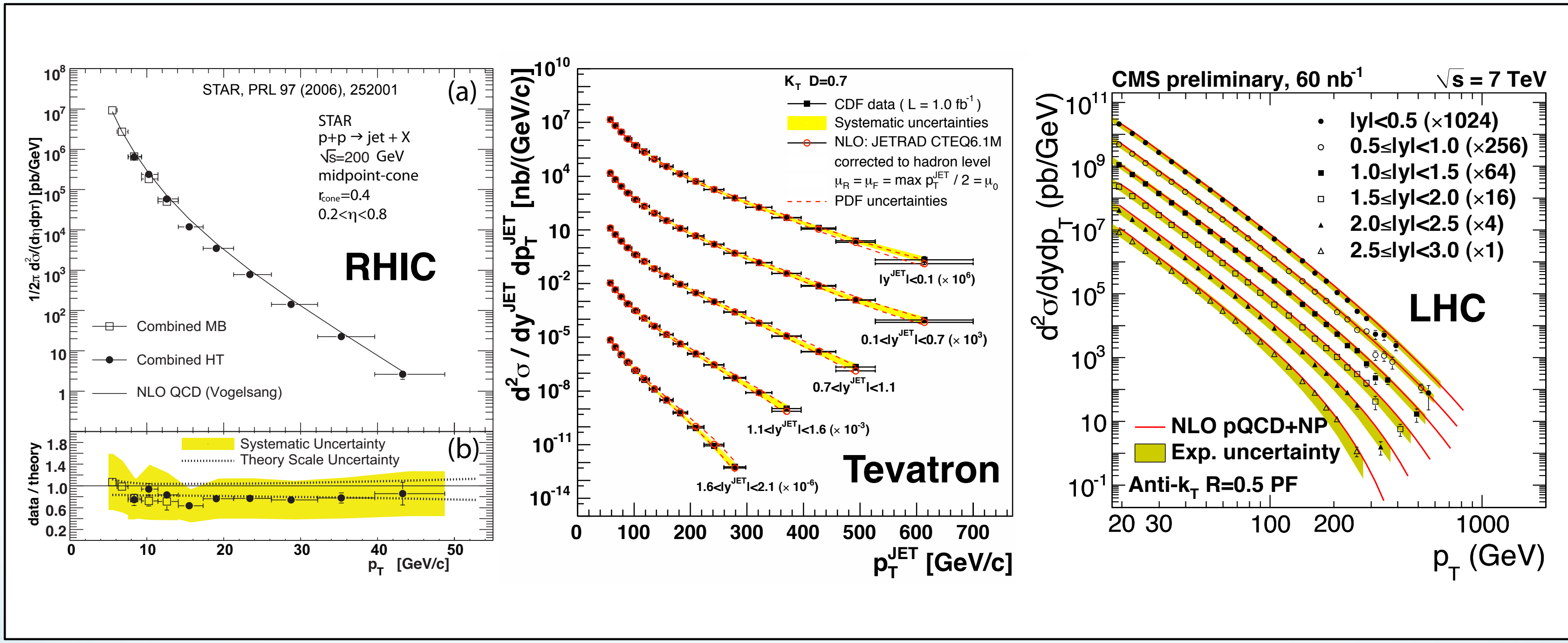
- The 1st observable is like collinear fragmentation function, while the 2nd observable is more like a TMD fragmentation function

- Both RHIC and LHC performed measurements for this observable

Lots of data: inclusive jet cross section

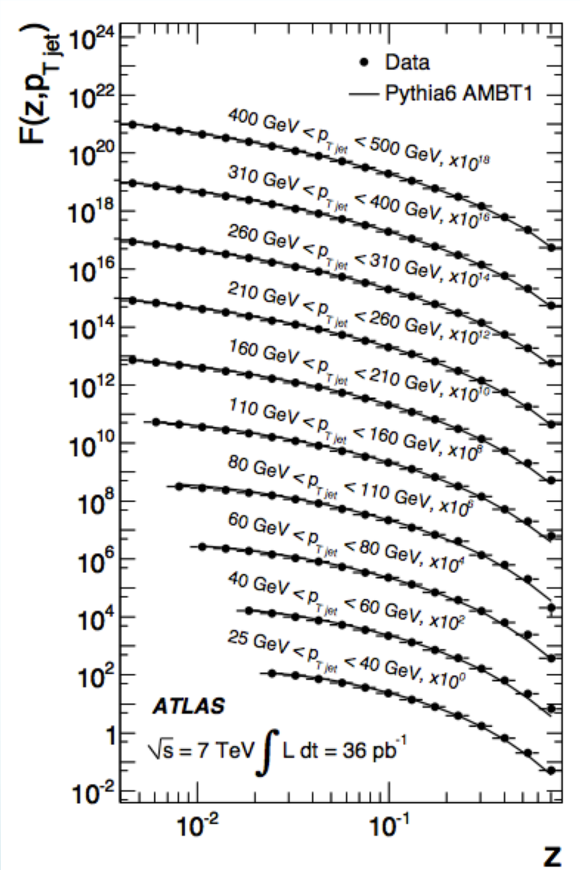
- Single inclusive jet cross sections

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

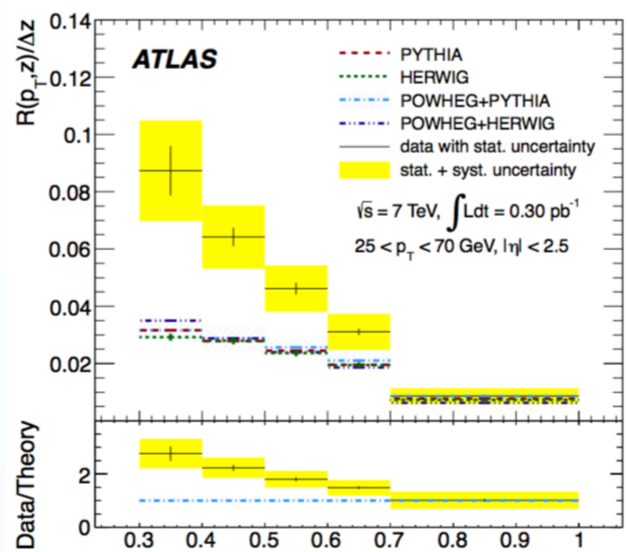


Lots of data: jet fragmentation function

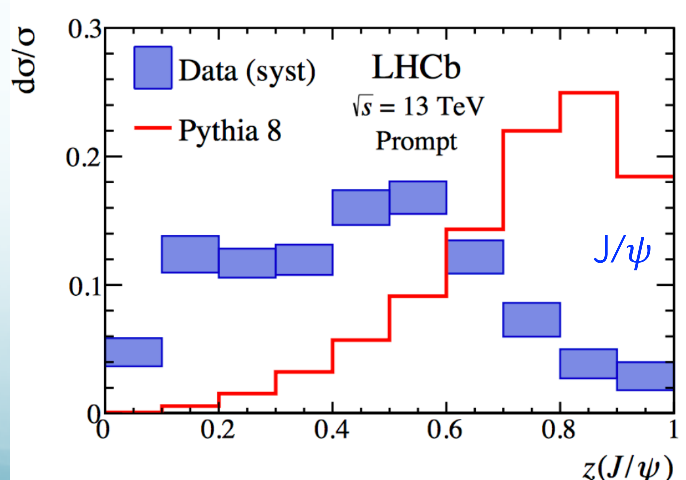
- Hadron distribution inside a jet $p + p \to \text{jet}\,(h) + X$

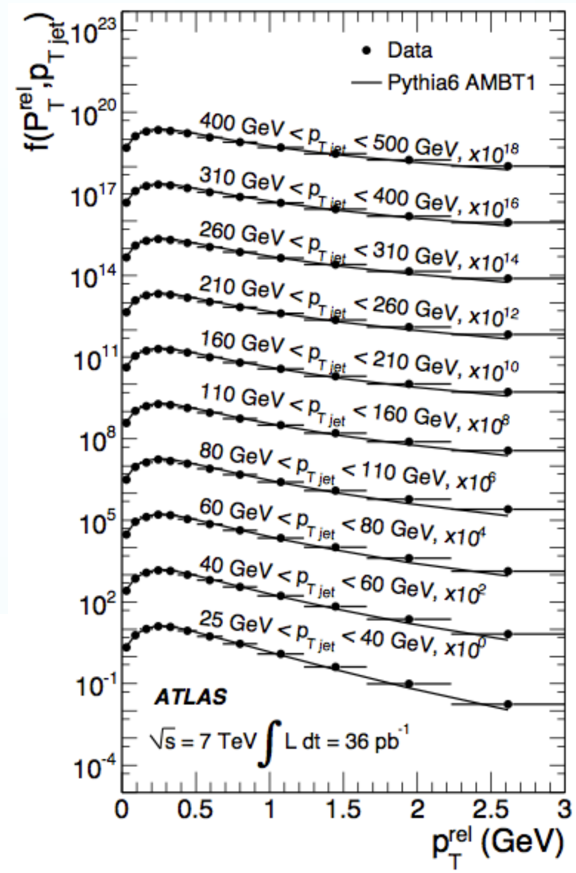


Light charged hadrons



D meson





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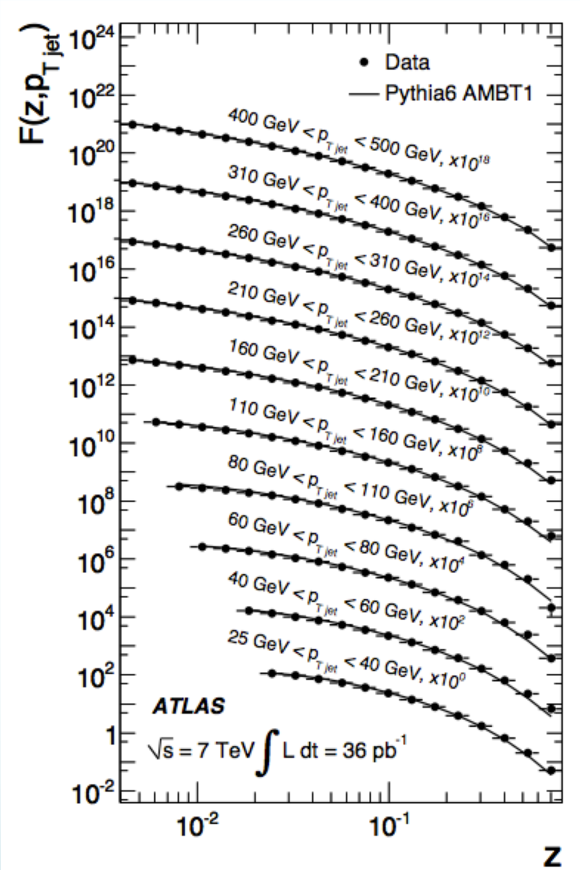
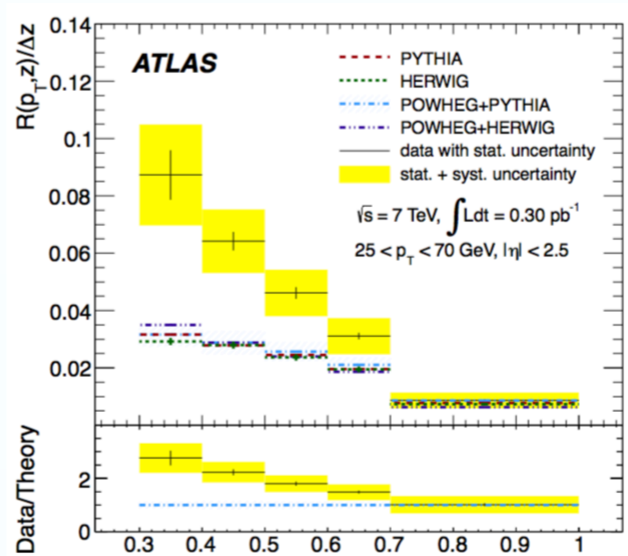
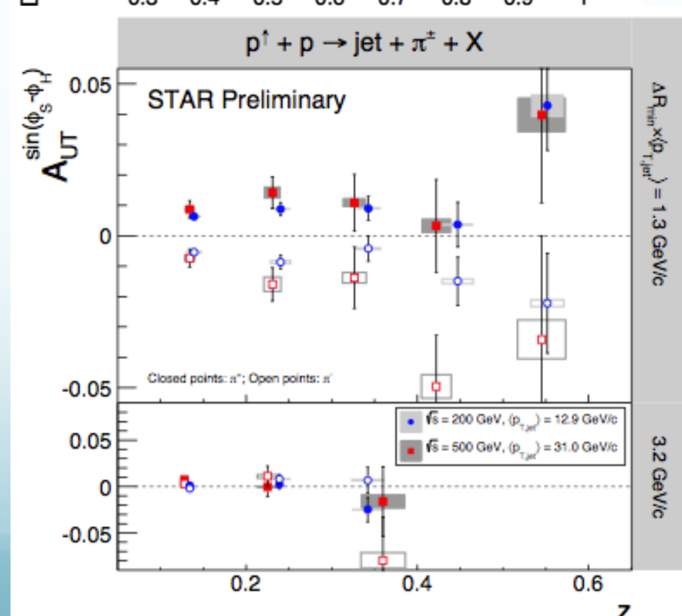
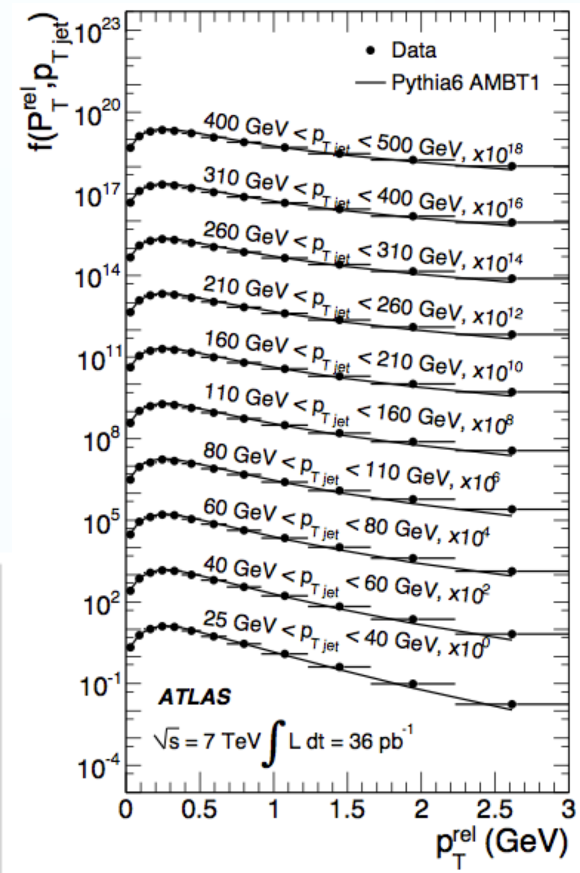




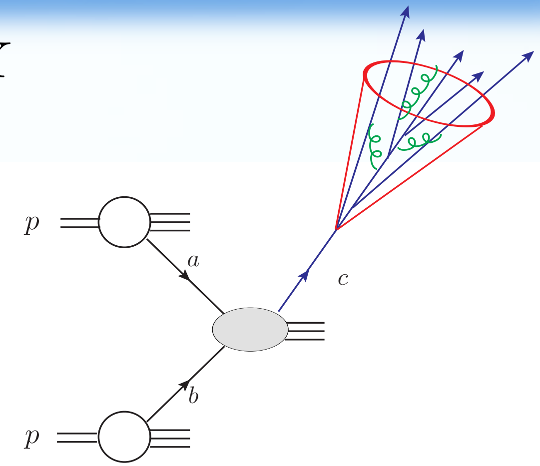




Light charged hadrons

Theoretical tools: QCD factorization

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



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

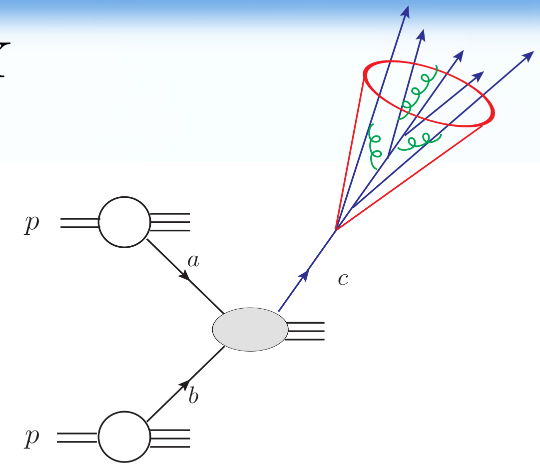
partonic hard-scattering cross section

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

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

Theoretical tools: QCD factorization

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



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

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$$\ldots^{(2)}_{ab} + \ldots\Big)$$

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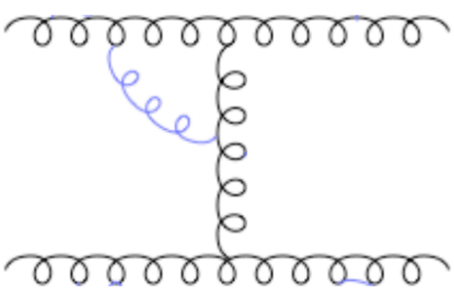
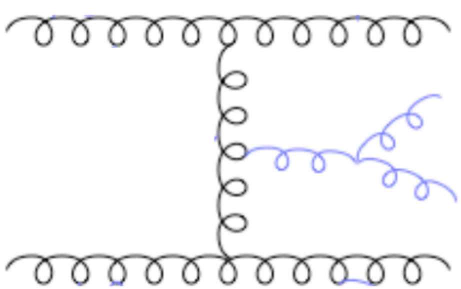


NLO 1990

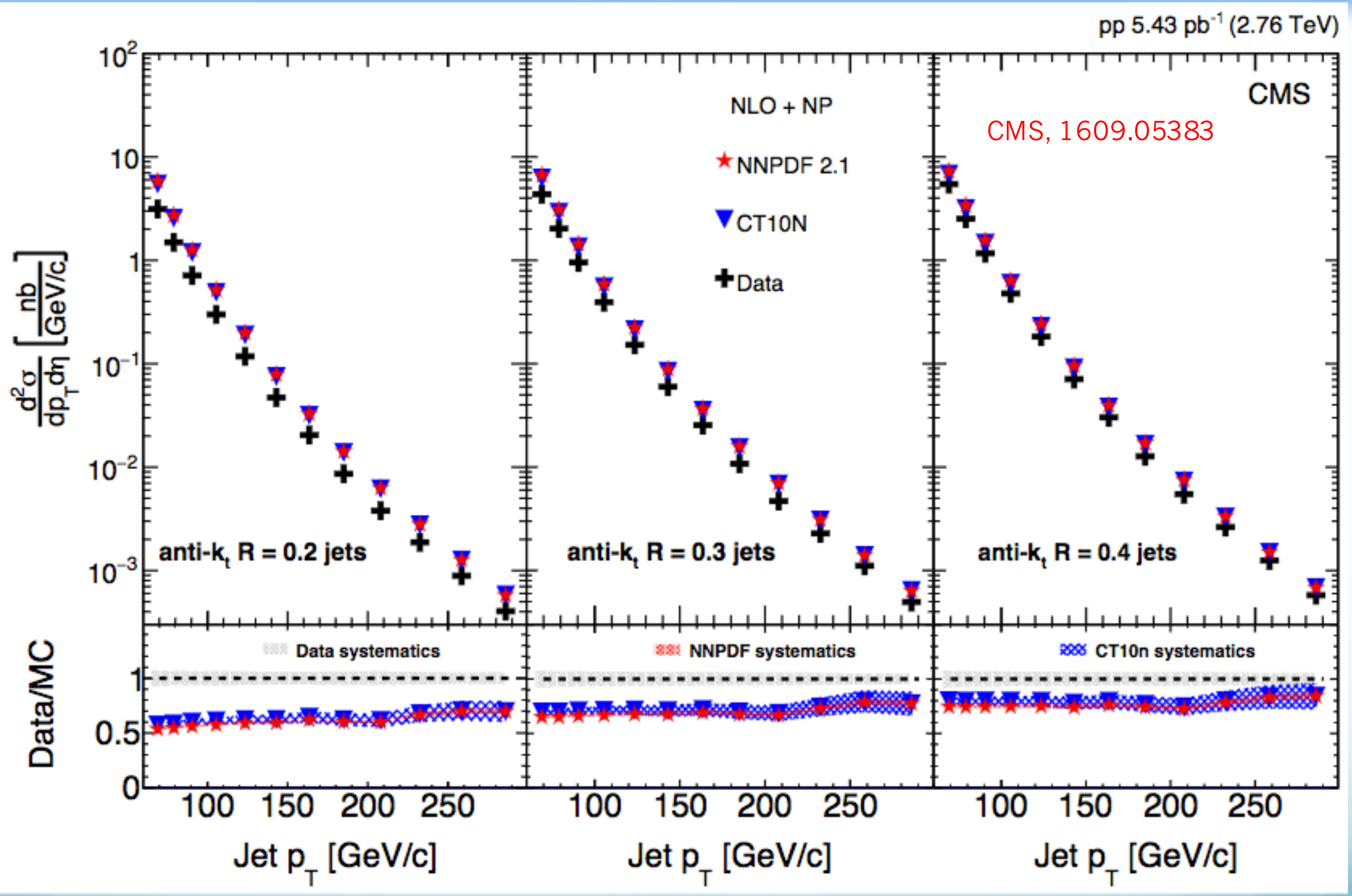
Ellis, Kunszt, Soper `90



NNLO 2016 …

Currie, Glover, Pires `16

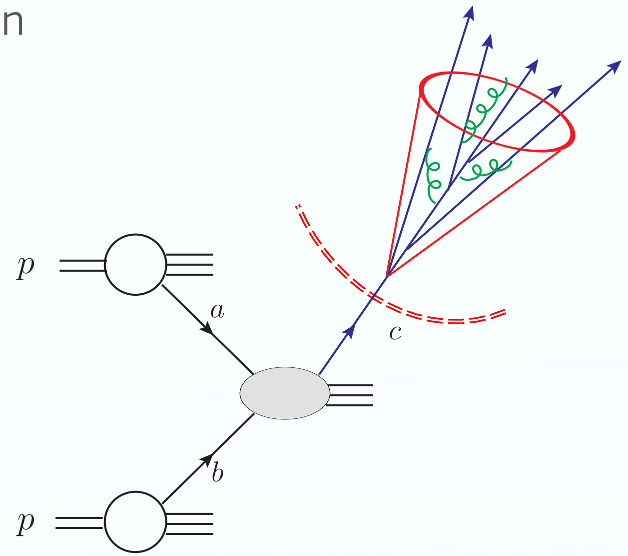
Most recent jet measurements



Jet radius R is small: 0.2 – 0.4, $[\alpha_s \ln(R)]^n$ resummation?

QCD factorization makes things simple

- 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



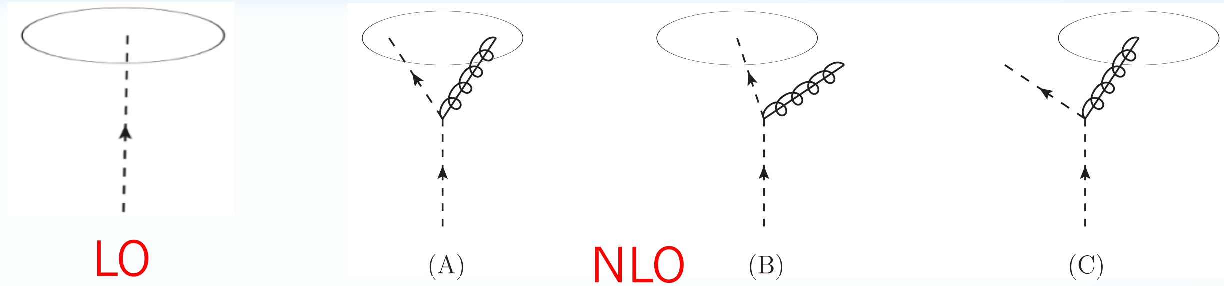
$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(z, \mu \sim p_T R)$$

  - 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

- NLO quark jet



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

- Evolution equation of semi-inclusive jet functions

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

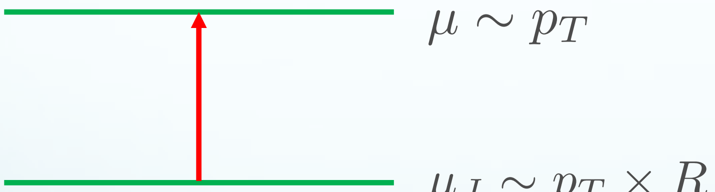
$$
\mu\frac{d}{d\mu}J_i(z,\omega_J,\mu) = \frac{\alpha_s(\mu)}{\pi}\sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'},\mu\right) J_j(z',\omega_J,\mu)
$$

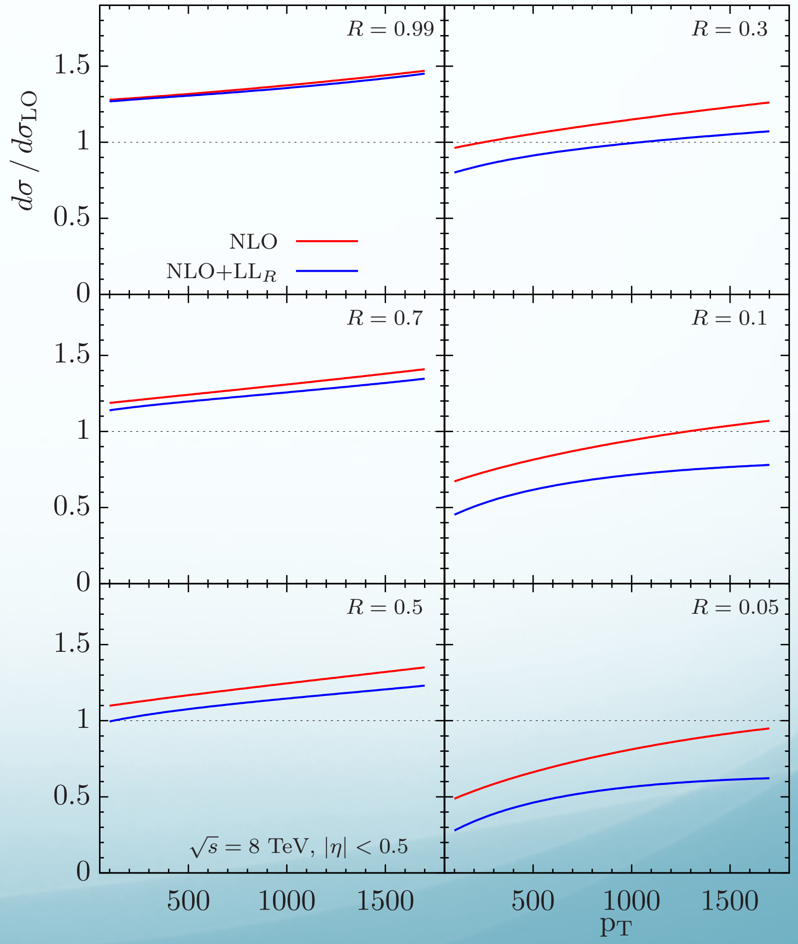
Ln(R) resummation

- Natural scale for jet dynamics

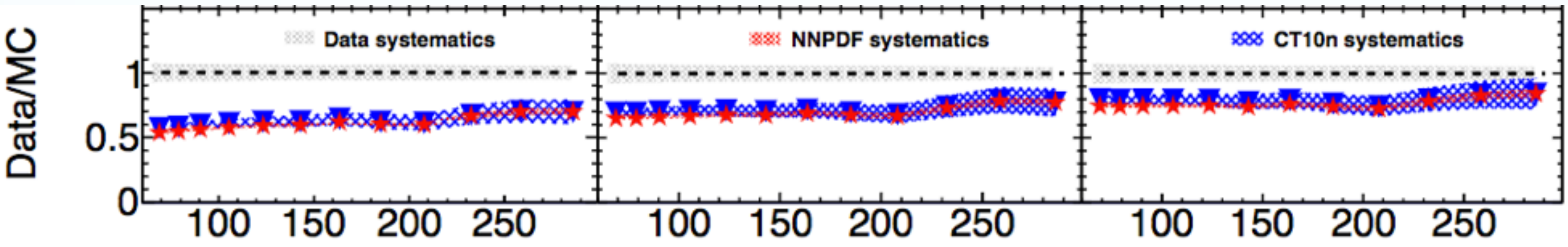
$$L = \ln \frac{\mu^2}{\omega_J^2 \tan^2 \frac{\mathcal{R}}{2}} \to \mu = \omega_J \tan \frac{\mathcal{R}}{2} = p_T \cdot R$$

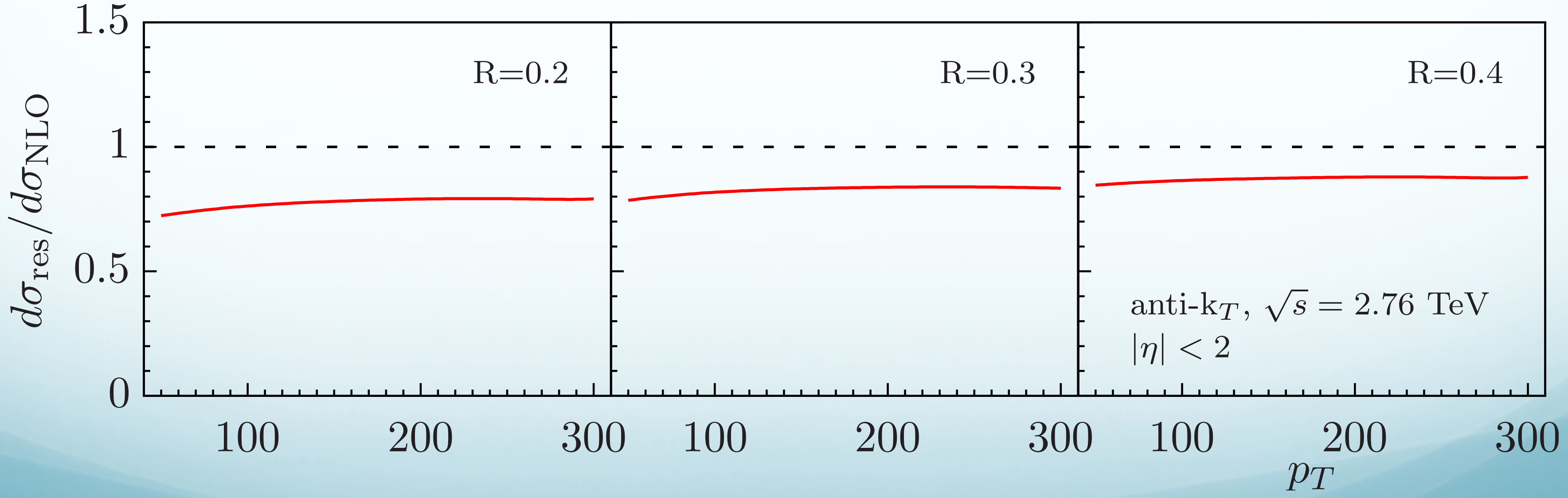
- Jet radius resummation: $(\alpha_s \ln R)^n$





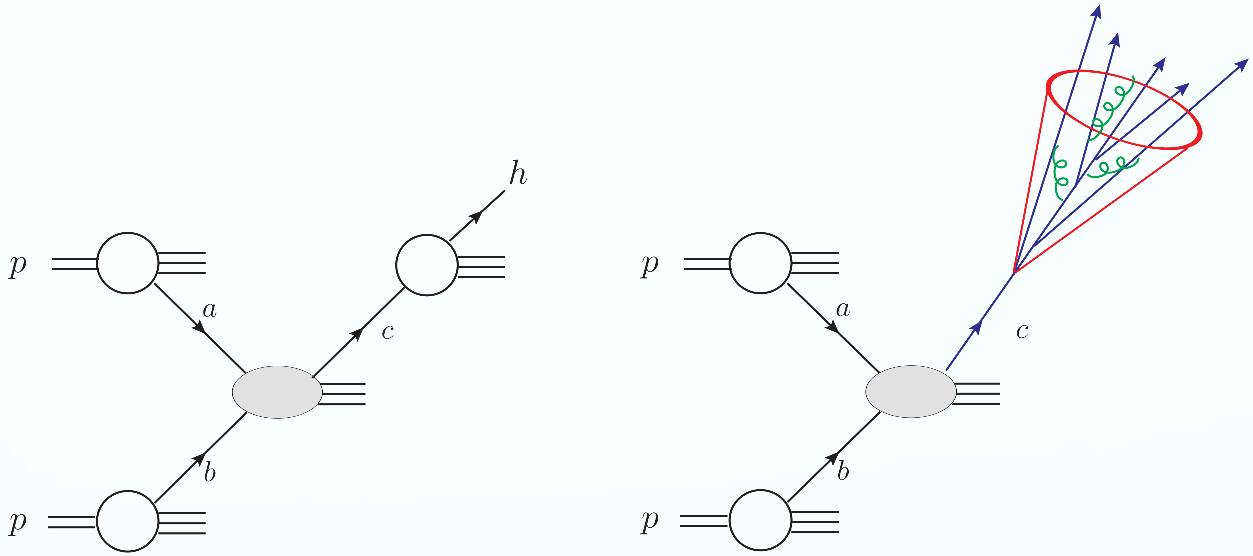
Effect of ln(R) resummation





Other properties of the new formalism

- Unified factorization formalism for hadron and jet production



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

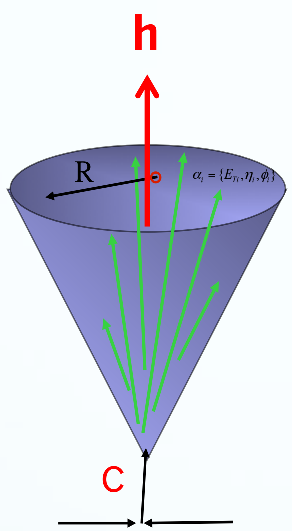
$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(\mu \sim p_T R)$$

- Consistent definition of what are called quark/gluon jets: relative ratio

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

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, JHEP

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

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

Two DGLAPs

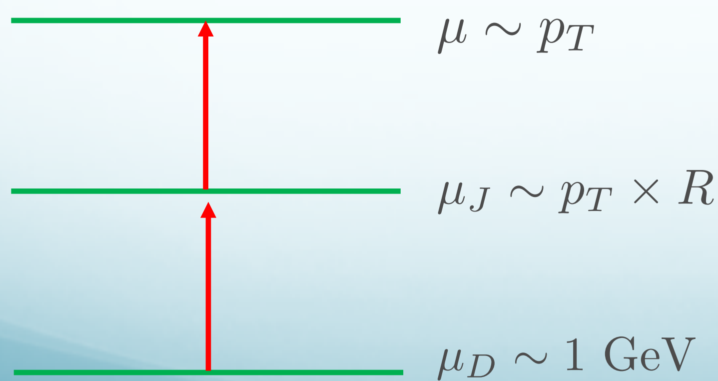
- Again DGLAP evolution: evolution is for variable z

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

- Relation to standard FFs: relevant to variable z_h

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

Kang, Ringer, Vitev, arXiv:1606.07063

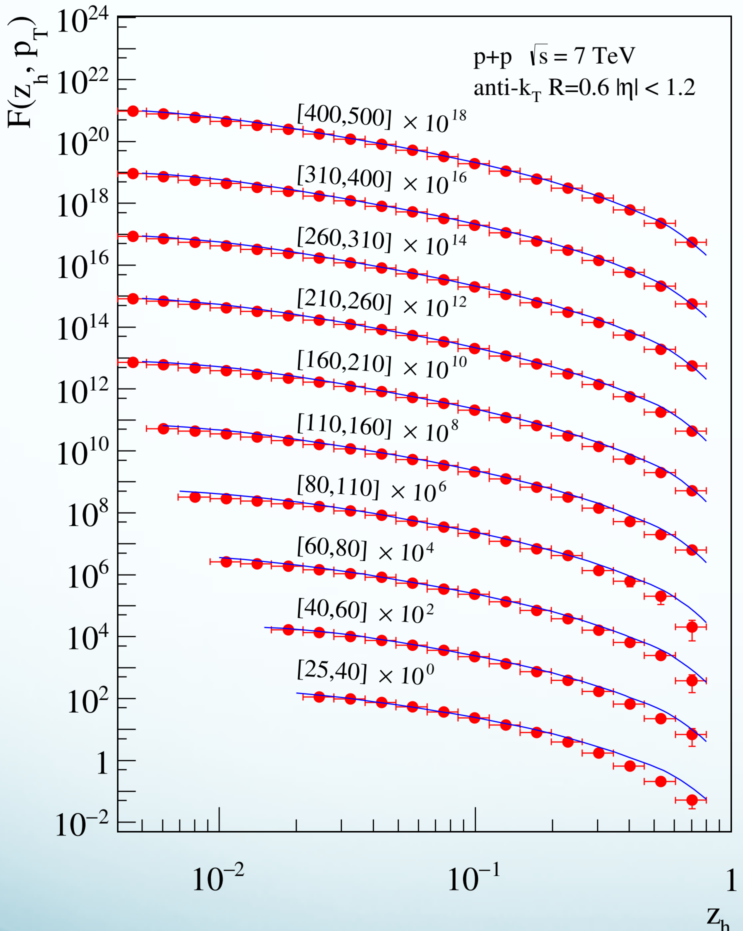


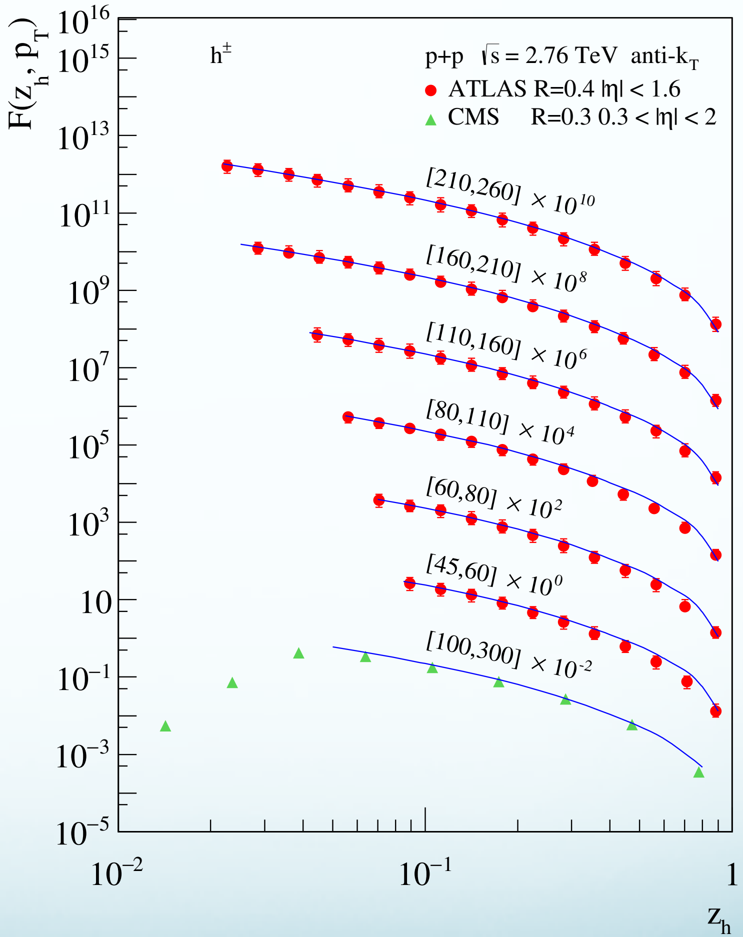
Resum ln(R)

Evolve standard FFs from 1 GeV to pT*R

Some interesting phenomenology

- Works pretty well in comparison with experimental data

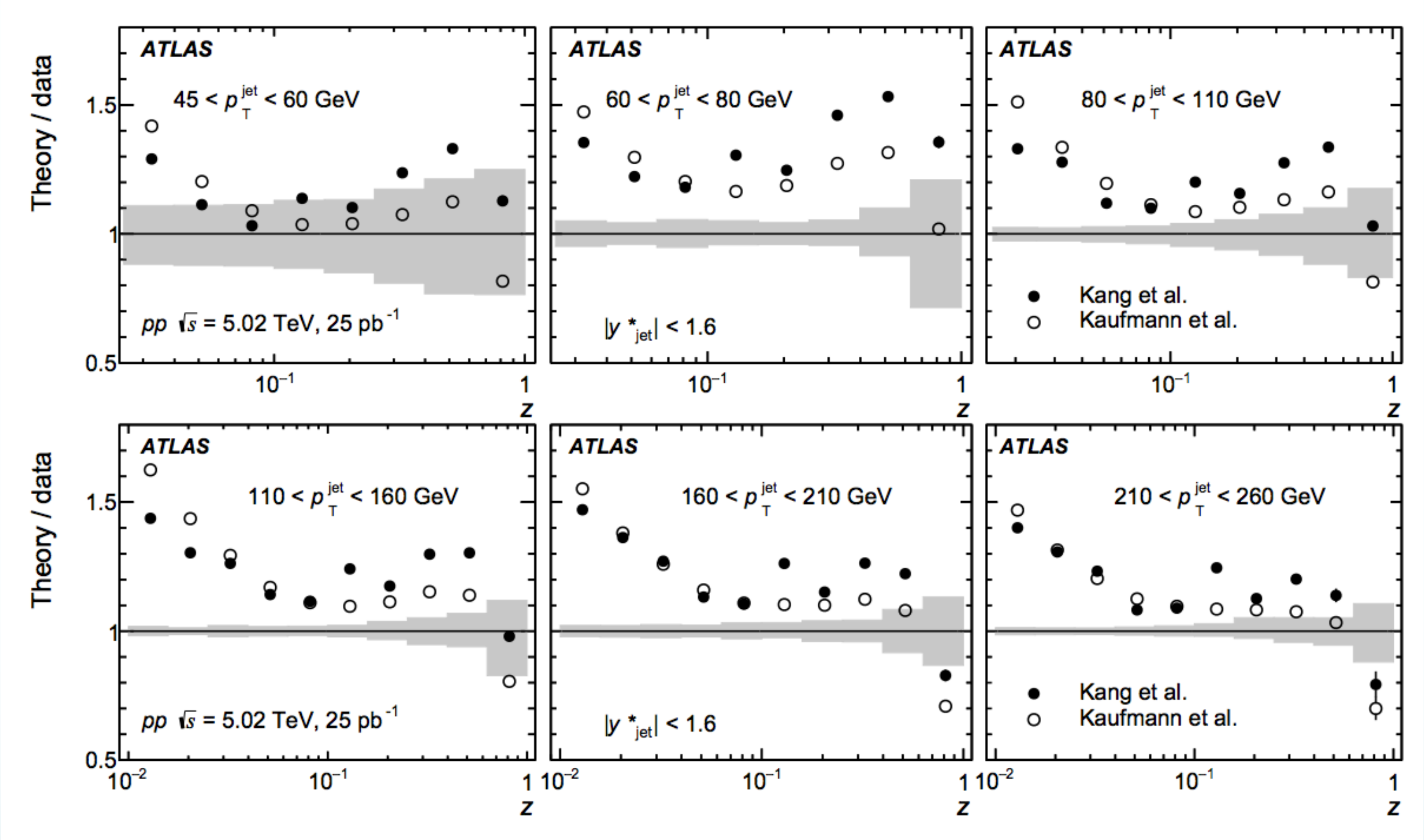




Kang, Ringer, Vitev, arXiv:1606.07063, JHEP

Further improve light-hadron FFs

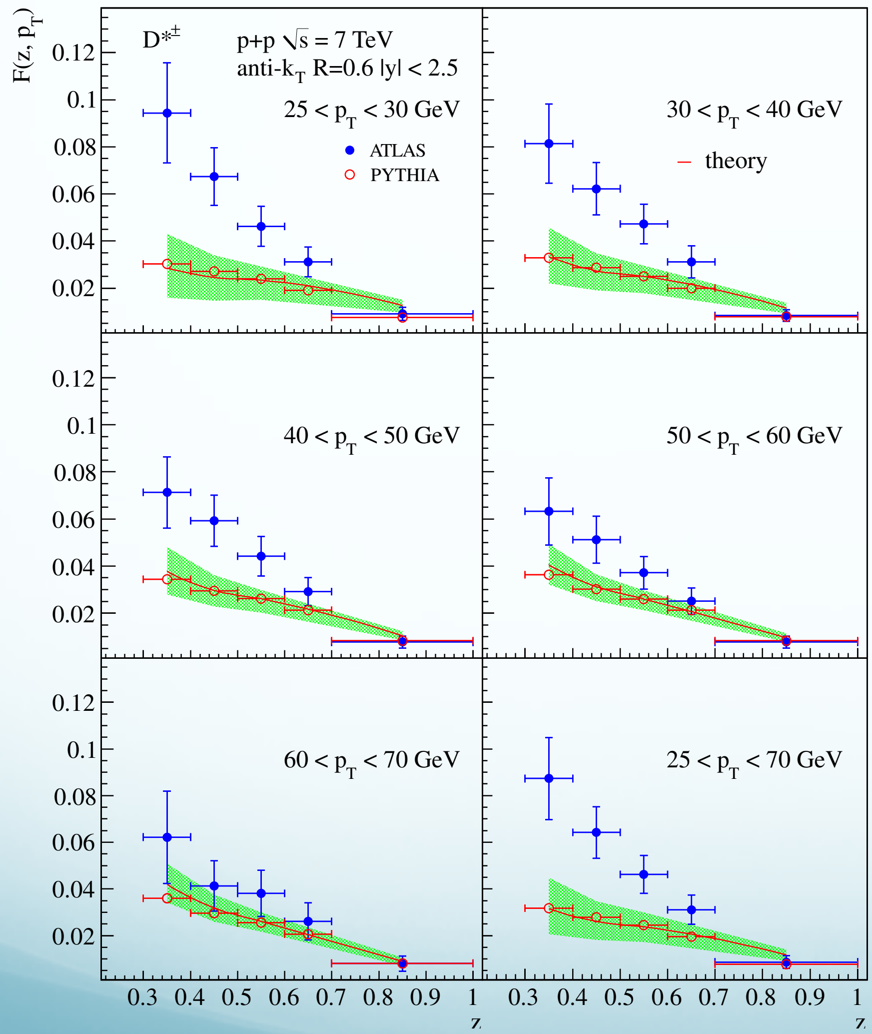
- arXiv:1706.02859



- An ideal observable to constrain collinear FFs, at both small and large z region, *especially for gluon FFs*

D meson distribution inside jets

- Jet FFs for D meson: use FFs fitted from e+e- data



Kneesch, Kniehl, Kramer, Schienbein, 08

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

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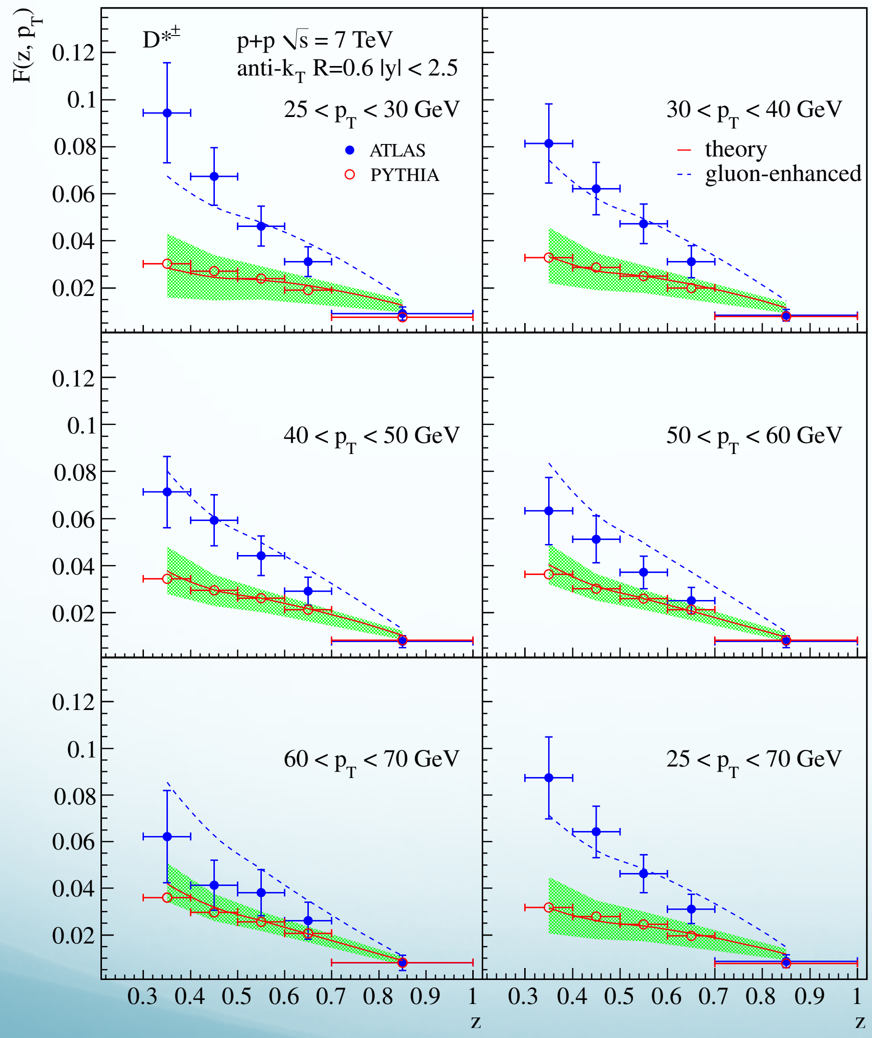

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Using ZM-VFNS scheme:
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1512.06851, JHEP 16

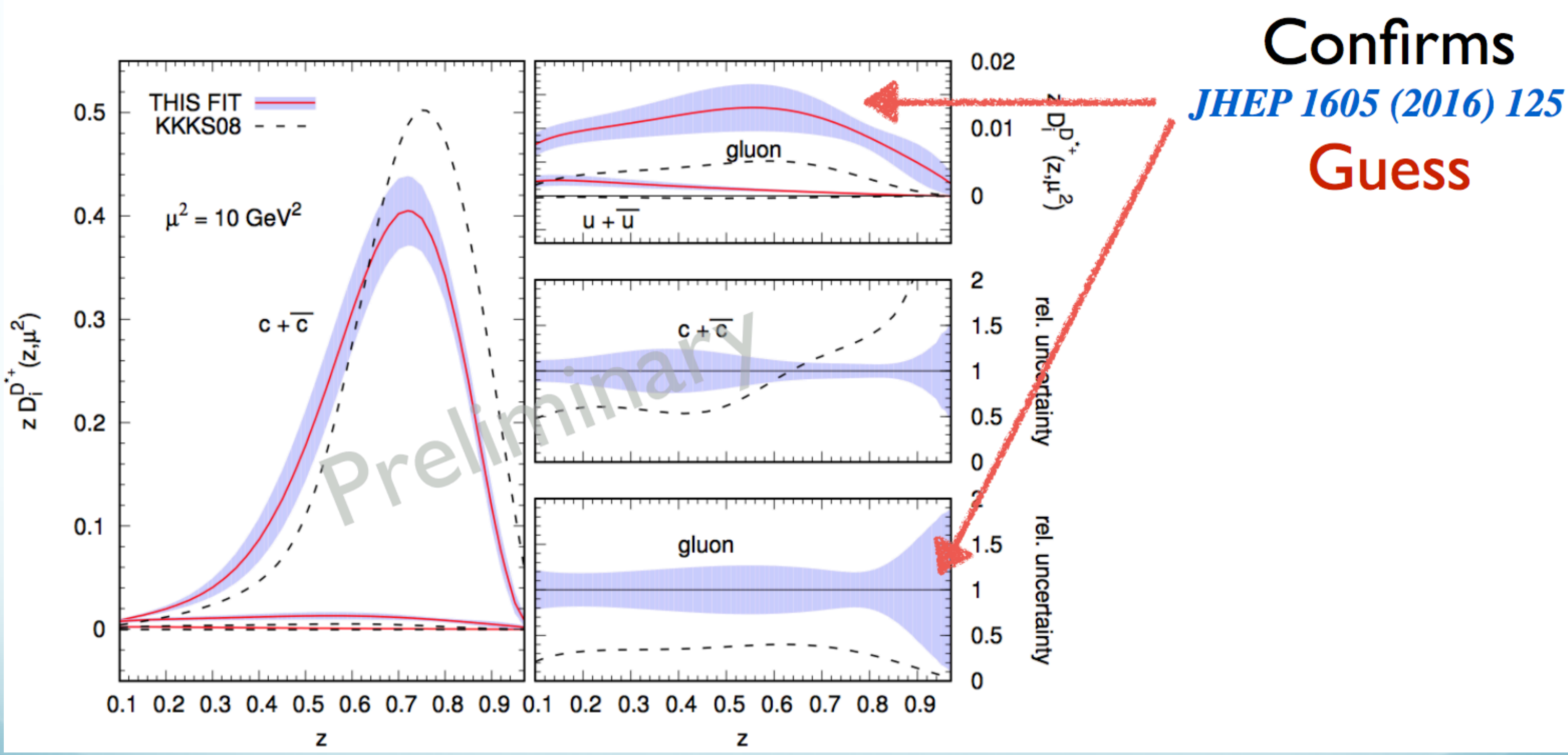
$$D_g^D(z,\mu) \to 2D_g^D(z,\mu)$$

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

A new global analysis of FFs

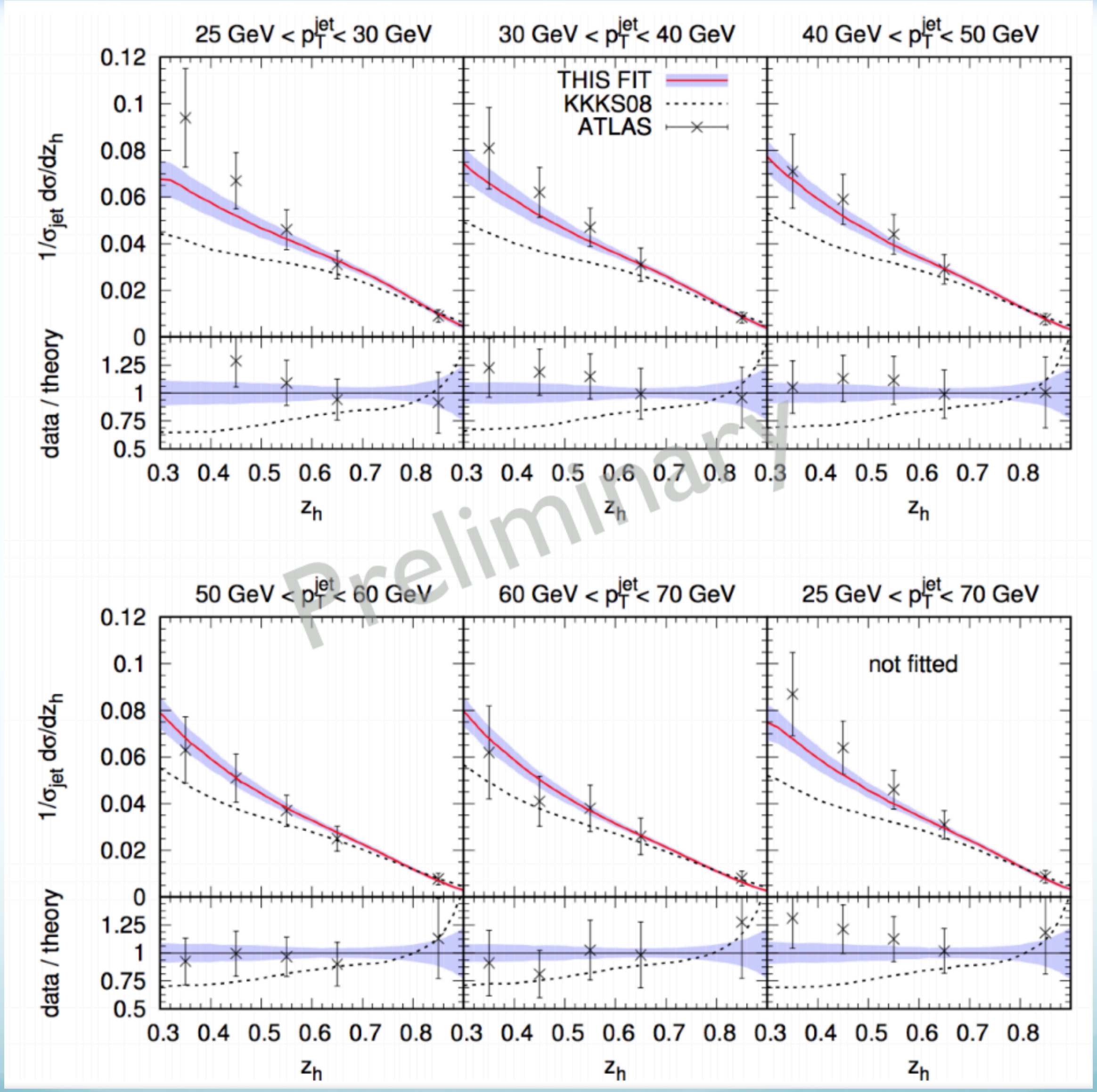
- New fit of D-meson FFs

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



Anderle, talk at QCD Evolution Workshop 2017

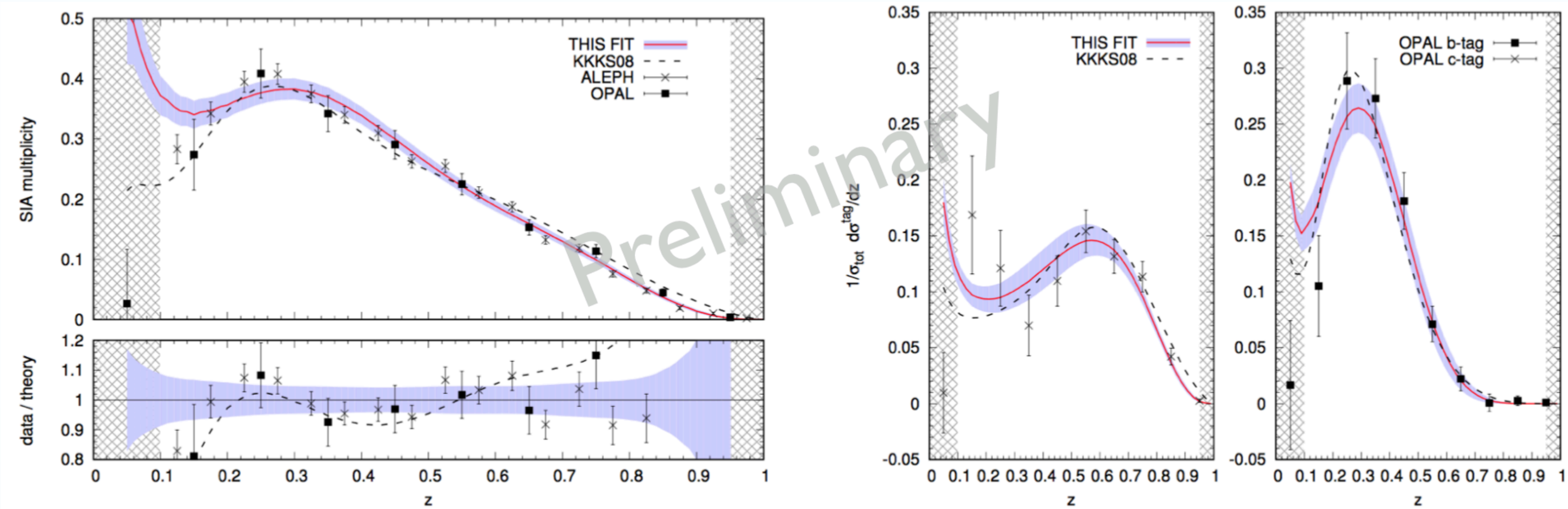
The new fit



25 GeV < p_T^{jet} < 30 GeV
30 GeV < p_T^{jet} < 40 GeV
40 GeV < p_T^{jet} < 50 GeV
50 GeV < p_T^{jet} < 60 GeV
60 GeV < p_T^{jet} < 70 GeV
25 GeV < p_T^{jet} < 70 GeV
THIS FIT
KKKS08
ATLAS
not fitted
Preliminary
$1/\sigma_{jet}\ d\sigma/dz_h$
data / theory
z_h

With the e+e- and pp inclusive cross section

- The new fit does not spoil the comparison with inclusive data



With the e+e- and pp inclusive cross section

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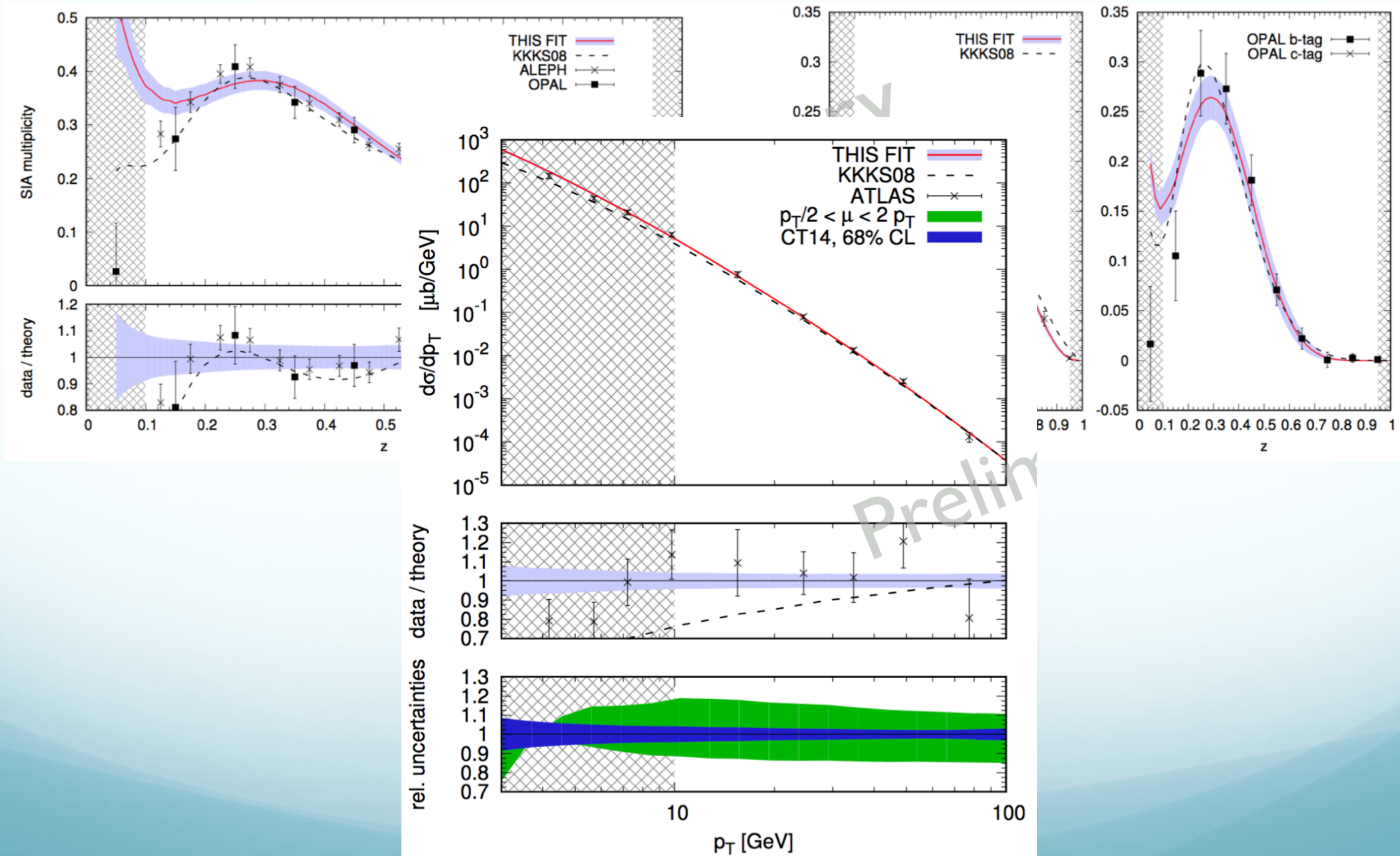
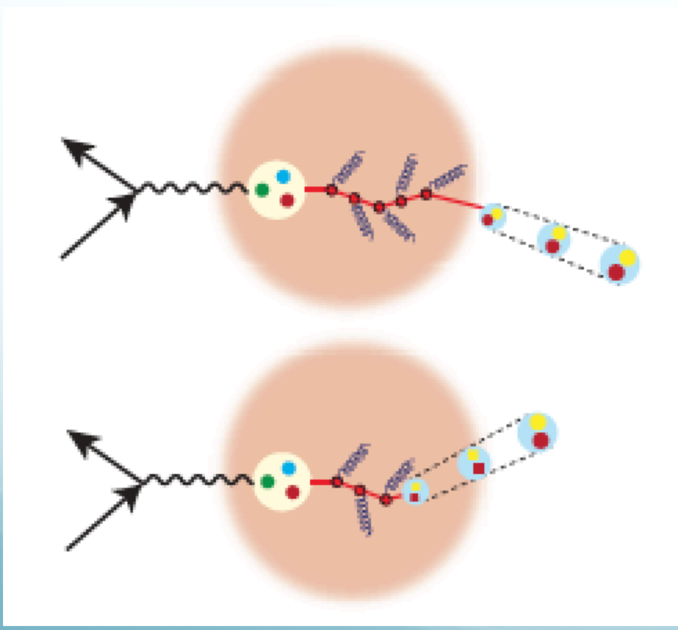
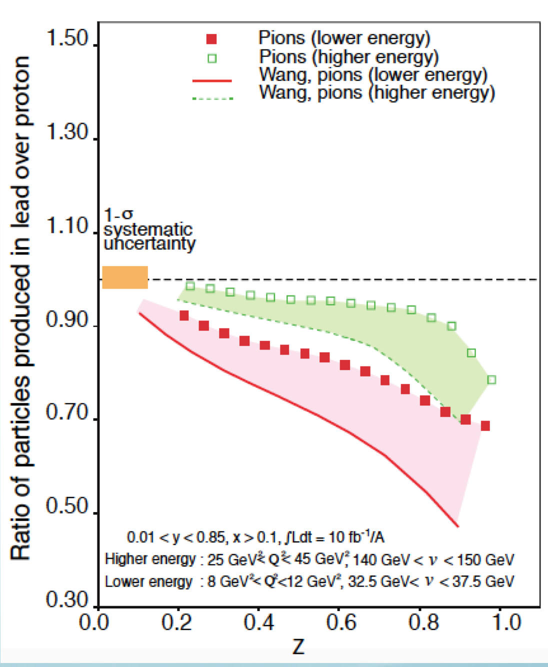
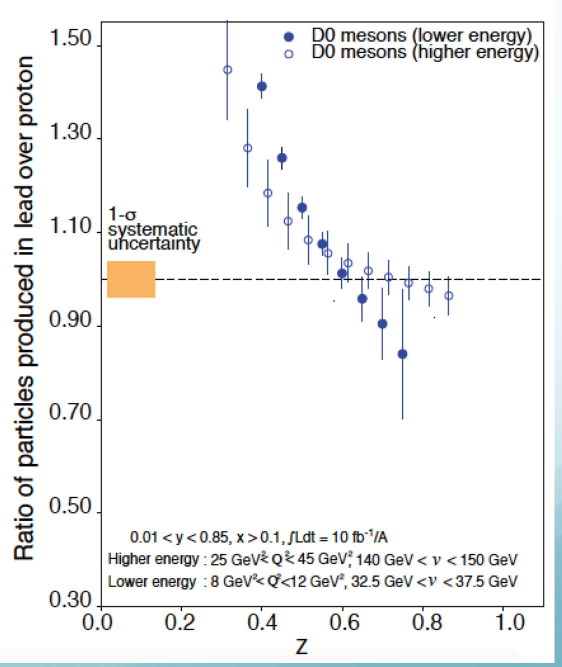


Hadronization modification in p+A/e+A?

- For jet fragmentation functions, by construction/definition, the effects from the modification of PDFs in the target nucleus do NOT matter
  - Mostly cancel out in the ratio
- Thus any modification should be coming from the modification of hadronization process, *one of key observables at EIC white paper*



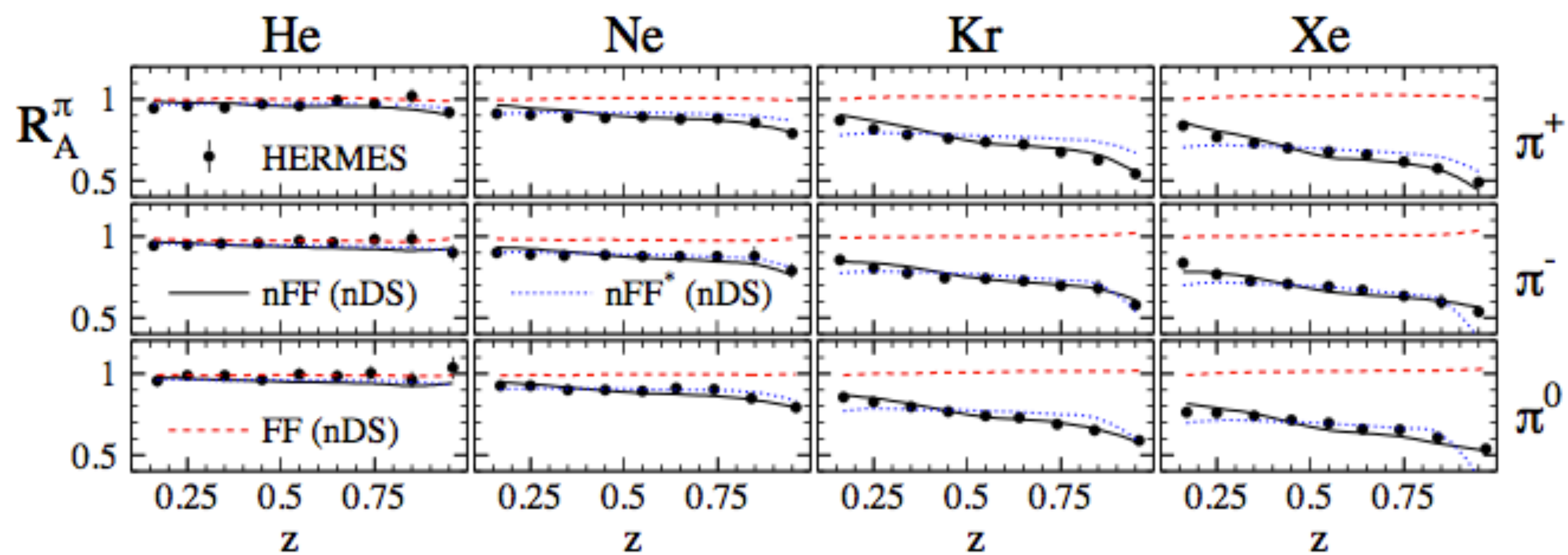




Nuclear modification of fragmentation function

- Earlier evidence for nuclear modification of hadronization process

HERMES, 0704.3270



$$R_A^H(\nu, Q^2, z, p_T^2) = \frac{\left(\frac{N^H(\nu,Q^2,z,p_T^2)}{N^e(\nu,Q^2)}\right)_A}{\left(\frac{N^H(\nu,Q^2,z,p_T^2)}{N^e(\nu,Q^2)}\right)_d}$$

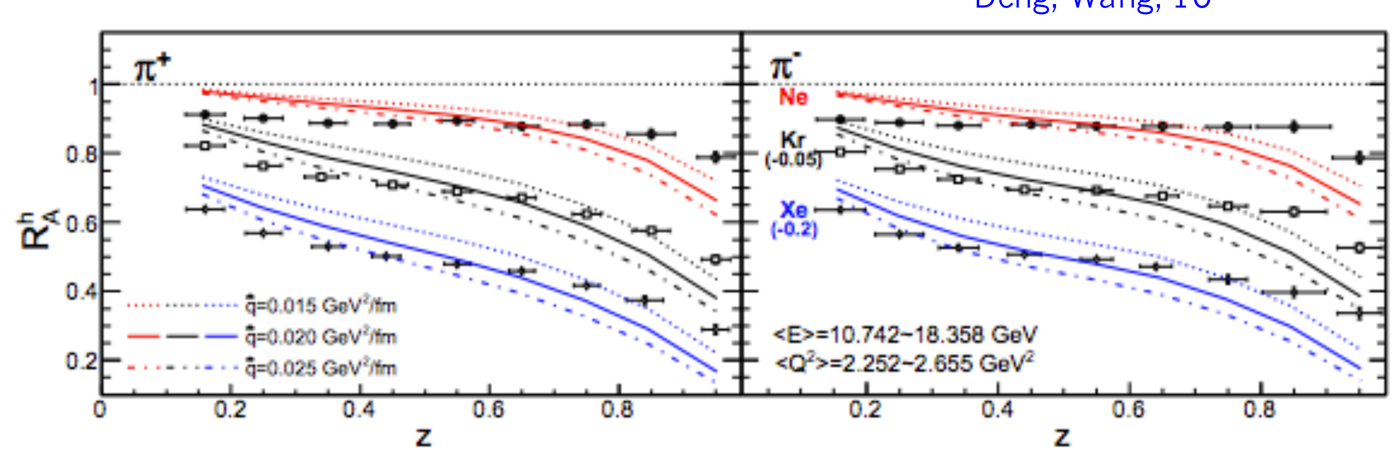
- By construction, *the observable is insensitive to nuclear PDFs*

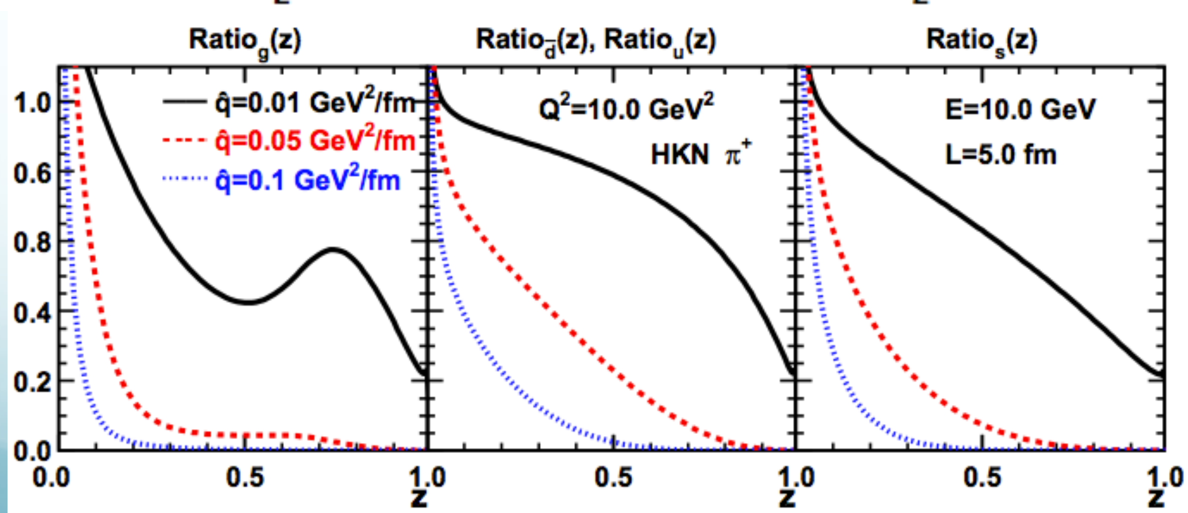
Two models describe the data

- Parton energy loss in cold nuclear matter leads to an effective change of the fragmentation function

$$\tilde{D}_{a\to h}(z) \approx \frac{1}{1-\Delta z} D_{a\to h}\left(\frac{z}{1-\Delta z}\right)$$

Chang, Deng, Wang, PRC 14
Deng, Wang, 10

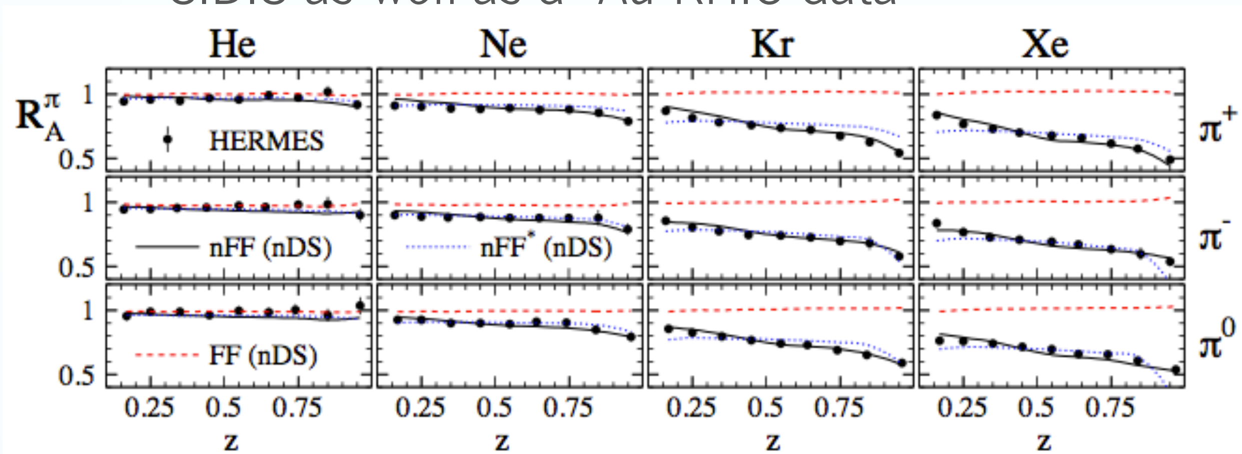


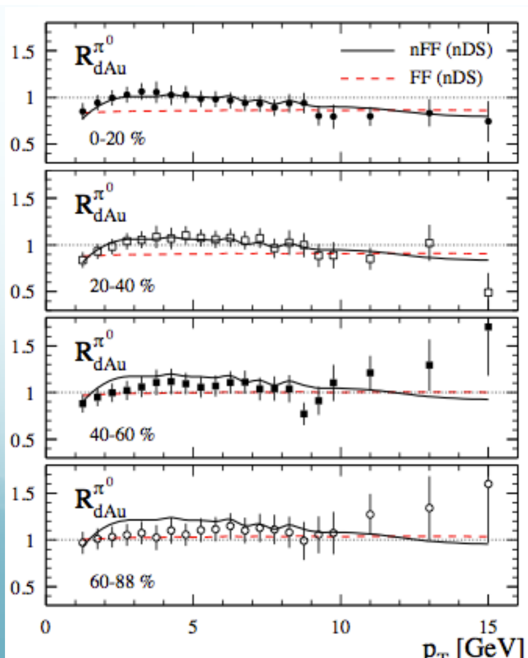


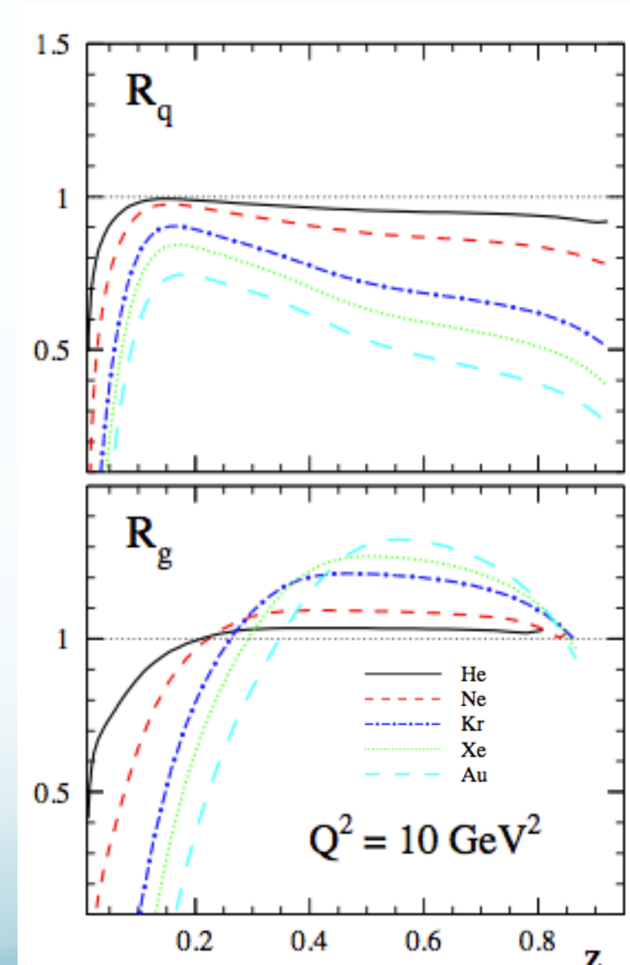
Fragmentation function in nuclei

- Phenomenological model of Sassot, Stratmann, Zurita: global fitting of SIDIS as well as d+Au RHIC data

Sassot, Stratmann, Zurita, 0912.1311

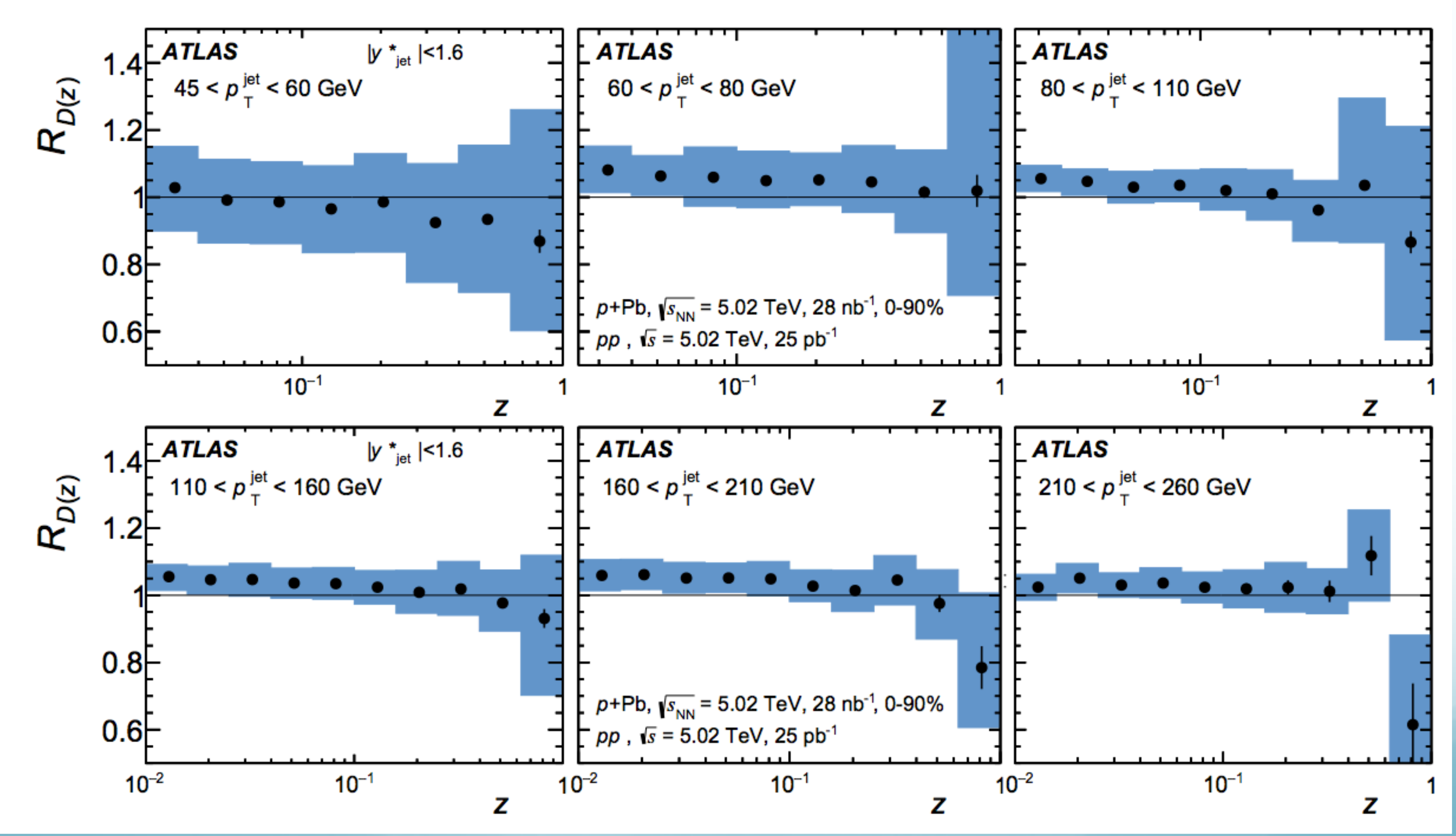






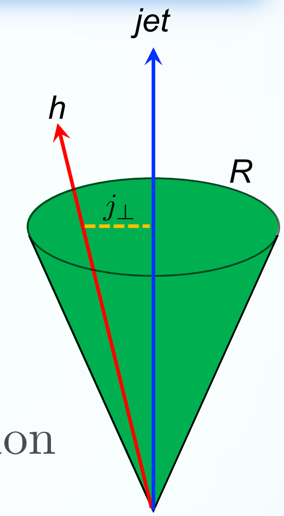
P+Pb collisions at the LHC

- arXiv:1706.02859 – usually at smaller jet pT, these effects should be more dramatic, *RHIC as an ideal place* – both light and heavy meson



What about TMD FFs?

- TMD hadron distribution inside the jet



$$F(z_h, j_\perp; p_T) = \frac{d\sigma^h}{dp_T d\eta dz_h d^2 j_\perp} \Big/ \frac{d\sigma}{dp_T d\eta}$$

$$z_h = p_T^{\mathrm{h}}/p_T^{\mathrm{jet}}$$

$j_\perp$: hadron transverse momentum with respect to the jet direction

- Factorization formalism

Kang, Liu, Ringer, Xing, 1705.08443

$$\frac{d\sigma}{dp_T d\eta dz_h d^2 j_\perp} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, \omega_J R, j_\perp, \mu)$$

- Re-factorization of semi-inclusive fragmenting jet function

$$\mathcal{G}_c^h(z, z_h, \omega_J R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, \omega_J R, \mu) \int d^2\boldsymbol{k}_\perp d^2\boldsymbol{\lambda}_\perp \delta^2\left(z_h \boldsymbol{\lambda}_\perp + \boldsymbol{k}_\perp - \boldsymbol{j}_\perp\right)$$
$$\times D_{h/i}(z_h, \boldsymbol{k}_\perp, \mu, \nu) S_i(\boldsymbol{\lambda}_\perp, \mu, \nu R)$$

TMD factorization for DY: $p+p \to [\gamma^* \to \ell^+\ell^-] + X$

- Factorized form and mimic "parton model"

$$\frac{d\sigma}{dQ^2 dy d^2q_\perp} \propto \int d^2k_{1\perp}\, d^2k_{2\perp}\, d^2\lambda_\perp H(Q) f(x_1, k_{1\perp}) f(x_2, k_{2\perp}) S(\lambda_\perp) \delta^2(k_{1\perp} + k_{2\perp} + \lambda_\perp - q_\perp)$$

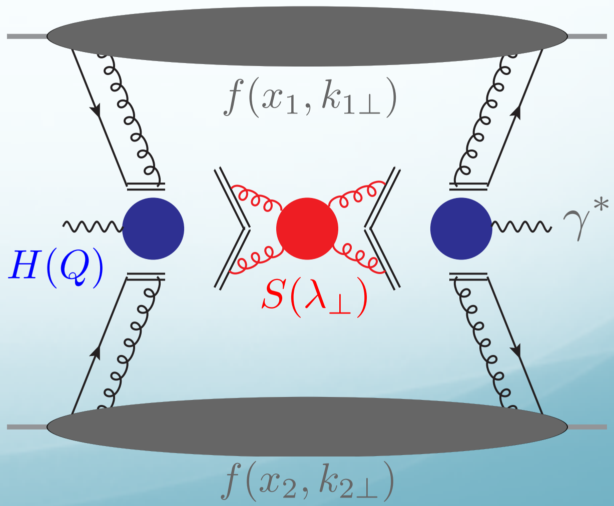
$$= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) f(x_1, b) f(x_2, b) S(b)$$

$$F(x,b) = f(x,b)\sqrt{S(b)}$$

$$\boxed{= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)}$$

- Rapidity divergences cancel between

$$F(x,b) = f(x,b)\sqrt{S(b)}$$

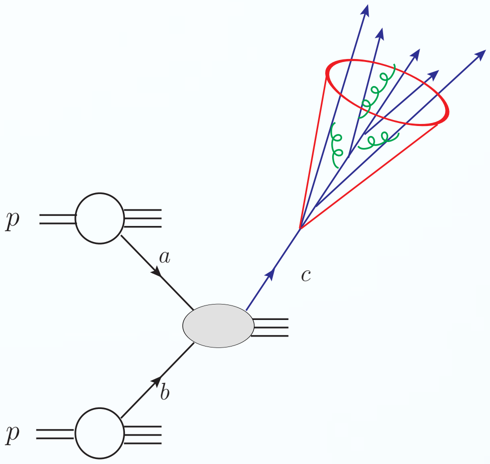


What's different for hadron in the jet?

- Soft radiation has to happen inside the jet
  - For single inclusive jet production, first we produce a high-pt jet
  - This process only involves hard-collinear factorization, and such a process is not sensitive to any soft radiation
  - This is the usual standard "collinear factorization"

$$\int_0^\infty \frac{dy}{y} \Rightarrow \int_0^{\tan^2\frac{R}{2}} \frac{dy}{y}$$

$$y \sim \frac{\ell^+}{\ell^-}$$



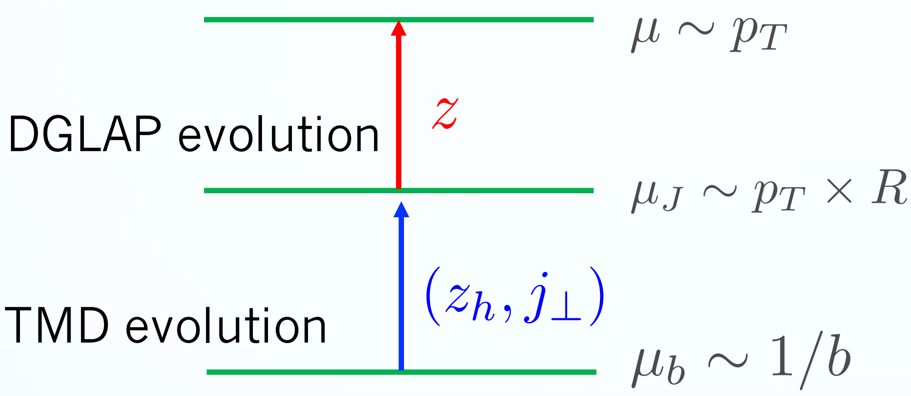
  - Once such a high-pt jet is produced, we further observe a hadron inside the jet
  - At this step, we measure the relative transverse momentum of hadron w.r.t the jet. For such a step, soft radiation matters
  - However, only those soft radiation that happens inside the jet matters
  - Restricts soft radiation to be within the jet: cuts half of the rapidity divergence

- Rapidity divergence cancel between restricted "soft factor" and TMD FFs
  - At least up to this order, the combined evolution is the same as the usual TMD evolution in SIDIS, DY, e+e-; justify the use of same TMD evolution here

$$\sqrt{S(b)}\,D_c^h(z_h, b)_{\mathrm{e^+e^-}} \Rightarrow S(b,R)\,D_c^h(z_h, b)_{\mathrm{pp}}$$

TMD + DGLAP evolution

- Evolution structure



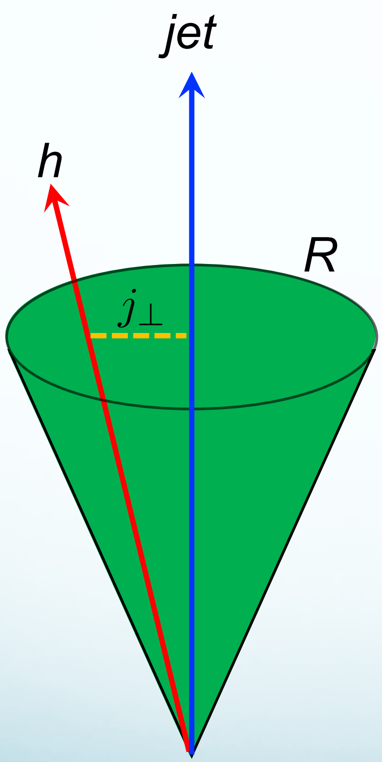
Resum ln(R)

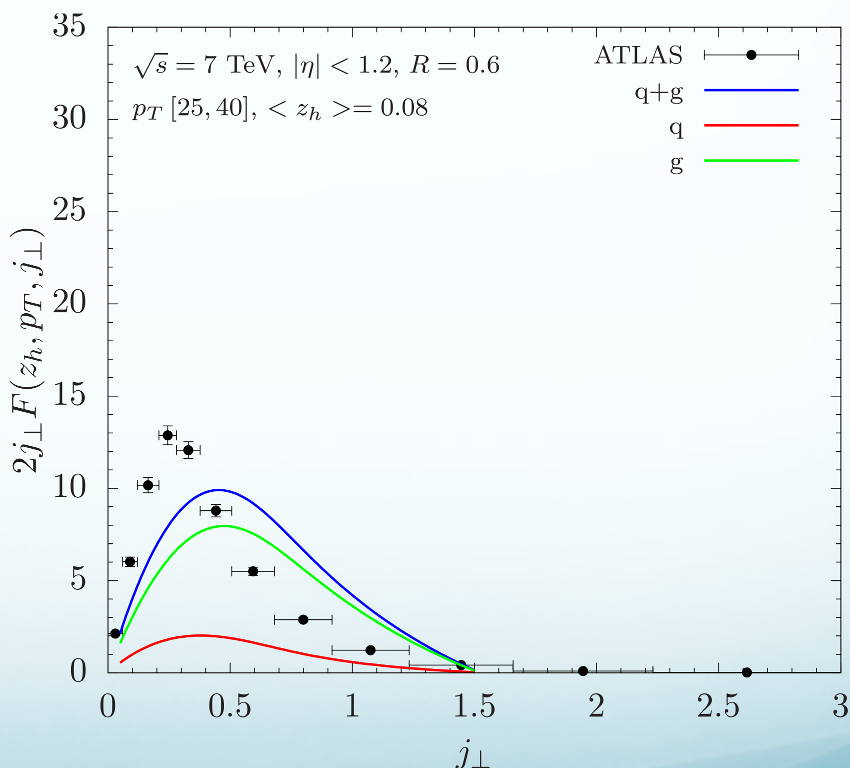
Evolve TMD FFs from $\boldsymbol{\mu}_b$ to pT*R

- TMD FFs thus are related to the usual TMD FFs in SIDIS at scale pT*R
- Thus hadron TMD distribution inside the jet could be used to test the universality of TMD FFs from SIDIS, e+e- processes

Hadron TMD distribution inside jets

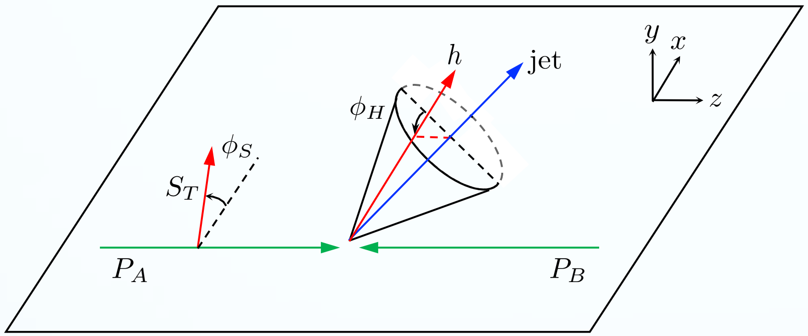
- Unpolarized p+p collisions: very sensitive to gluon TMDs
- If we want to be able to compare gluon TMDs in p+p and e+p, then p+p measurements are essentially necessary



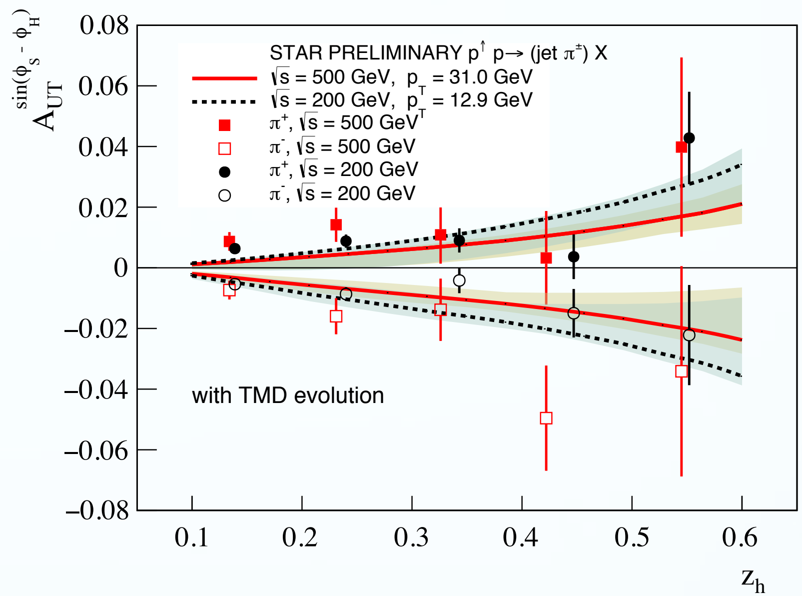


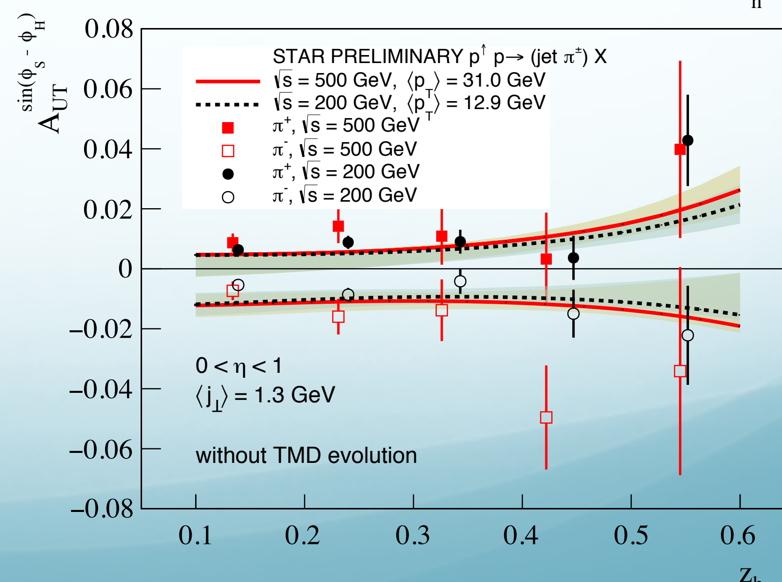
Collins azimuthal asymmetry

- Transversely polarized p+p collisions



Kang, Prokudin, Ringer, Yuan, 1706.xxxx, to appear





- *Test universality of Collins function between e+p, e+e, and p+p*
- *Test TMD evolution*

Summary

- jet cross section and jet substructure for inclusive jet production follow a two-step factorization
  - First step: parton-to-jet production
  - Second step: jet internal substructure
- The hard function associated with the 1st step is the same as that for single inclusive hadron production: DGLAP evolution
- For jet substructure, one could then concentrate on the 2nd step
- Collinear and TMD distribution of hadron in a jet are great processes to probe collinear and/or TMD FFs
  - Great opportunities to study spin-independent and spin-dependent hadorization/fragmentation effects in both vacuum and cold nuclear medium
  - New places to test TMD evolution effects

Thank you!