北京師範大學
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Jet TMDs

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ICTS Seminar @ USTC

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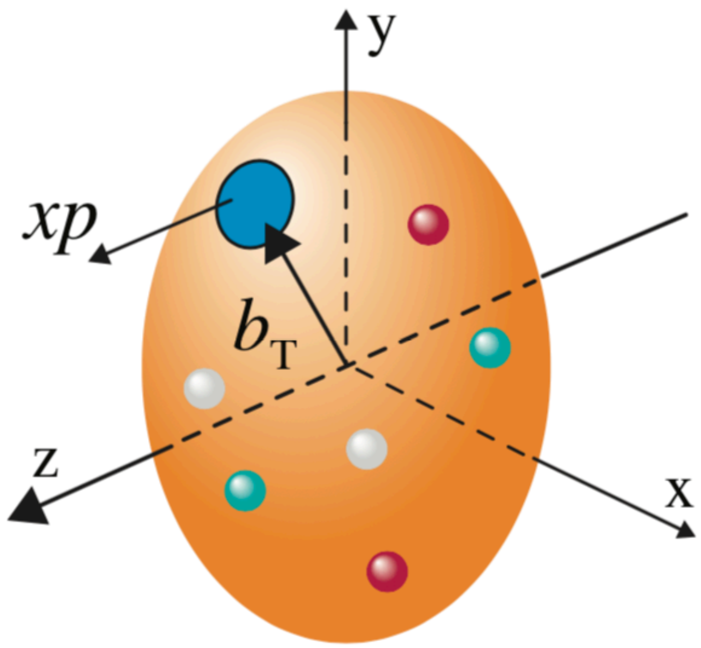
TMD physics

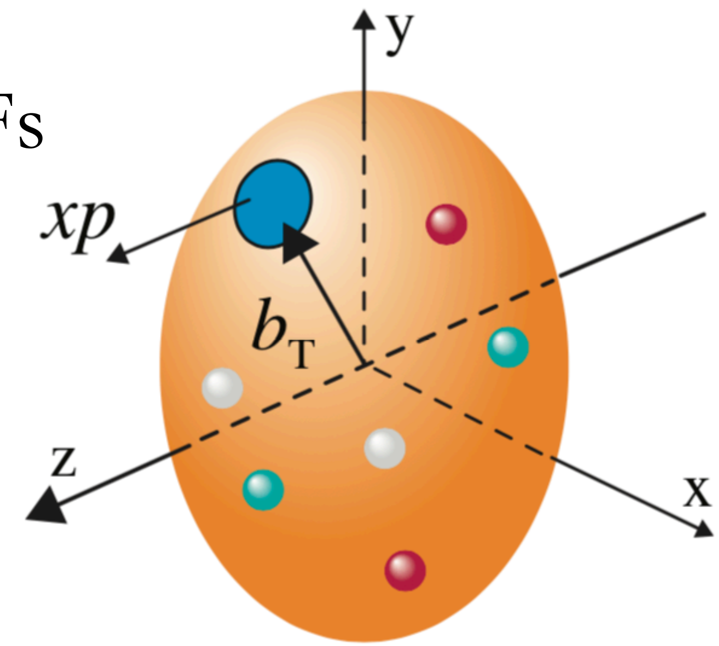
- Efforts in understanding nucleon structures using collisions
  - Collinear PDFs, FFs
    - Important for LHC physics
    - Universal formalism (somehow) well-established
    - But only longitudinal information

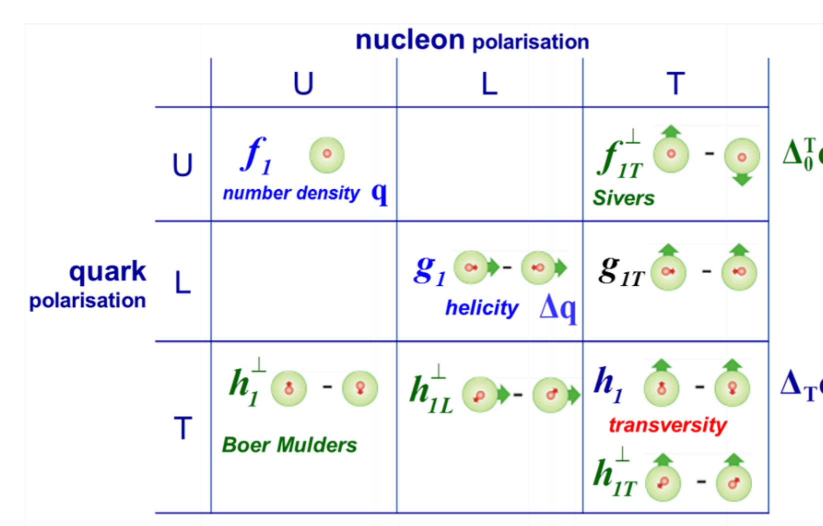


$$\frac{d\sigma}{dQ^2} \simeq \sum_{i,j=q,g} \int_0^1 dx_1 dx_2 \mathcal{H}_{ij}(Q^2, \mu^2) f_{i\leftarrow h}(x_1, \mu^2) f_{j\leftarrow h}(x_2, \mu^2)$$

TMD physics

- Efforts in understanding nucleon structures using collisions
  - Transvers Momentum Dependent PDFs, FFs
    - 3D imaging of Nucleon
    - Information on spin, orbital momentum
    - How to measure ? Force the system TM small enough
    - Non trivial extension of the collinear formalism, (Non-)universalities





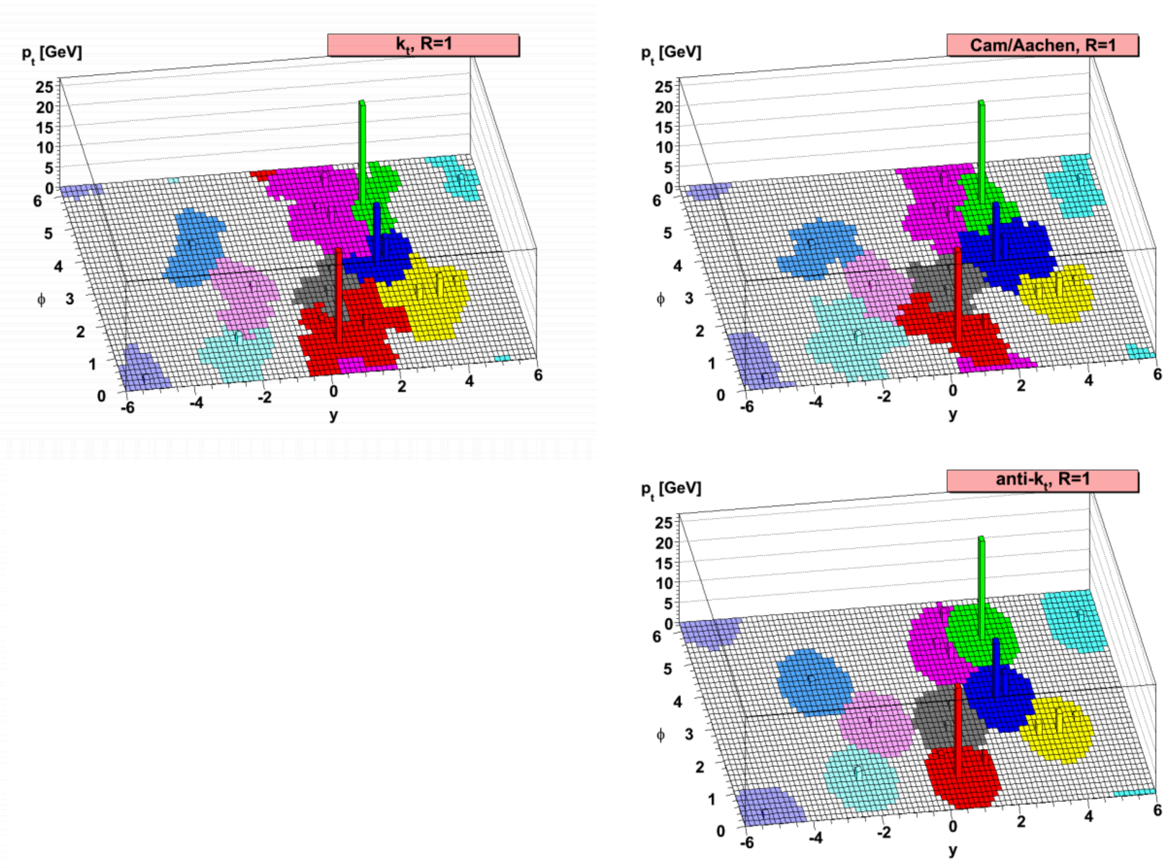
Jets

- A clustering of particles, very natural at the colliders

$$d_{ij} = \min(k_{i,T}^{2p}, k_{j,T}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2}$$

$$d_{iB} = k_{i,T}^{2p}$$

- If d_{iB} is the smallest, then promote i as a jet and remove i from the event sample
- If d_{ij} is the smallest, then cluster i and j to ij
- Iterate



p=-1: anti-kT, p=1: kT, p=0 Cambridge/Archen

Cacciari, Salam, Soyez '08

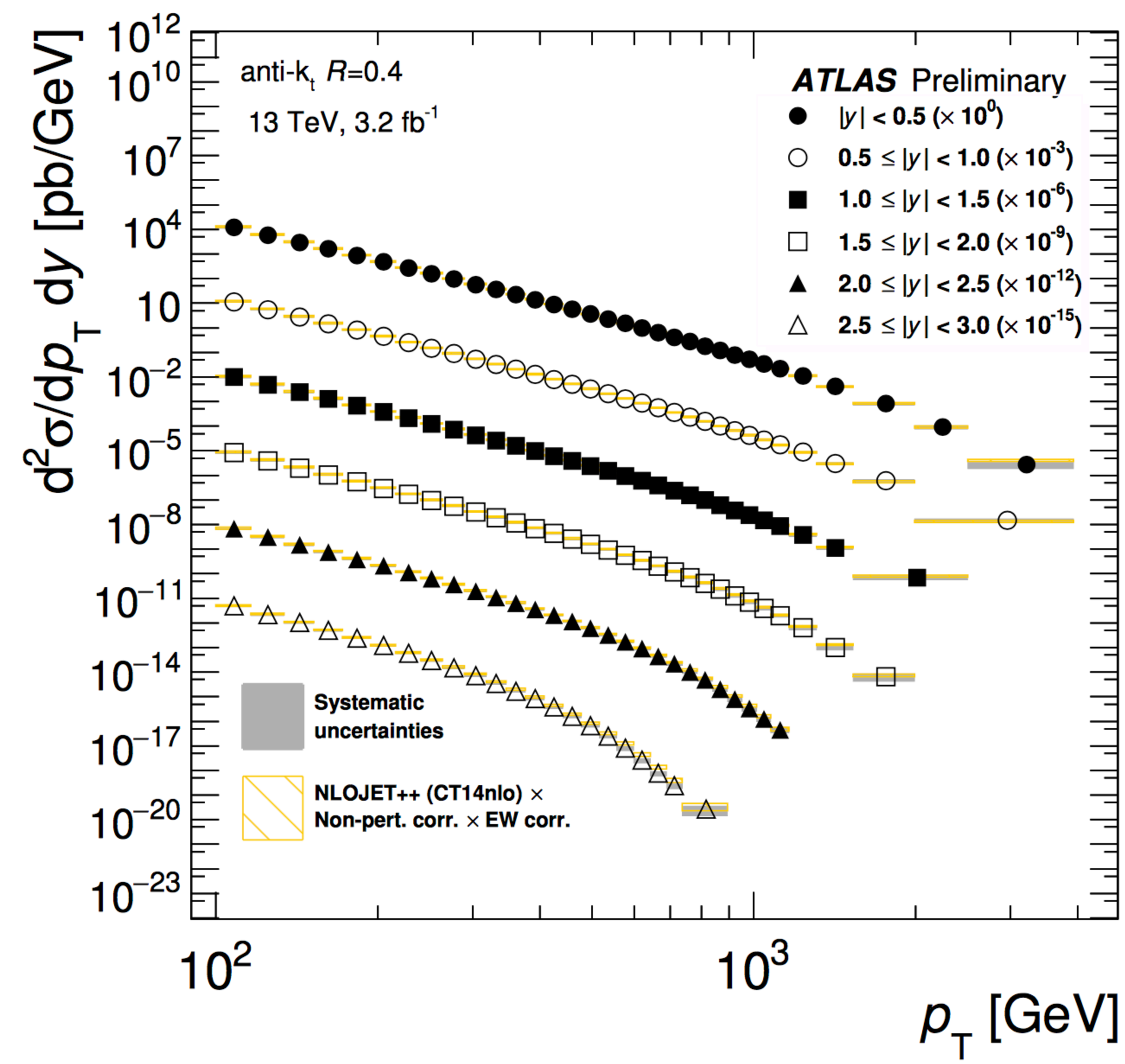
Outline

- Why jet physics?
  - Current status
  - Opportunity for TMDs
- Jet TMDs
  - In-jet TMDs
  - Jet imbalance
- Conclusions

Why jet physics?

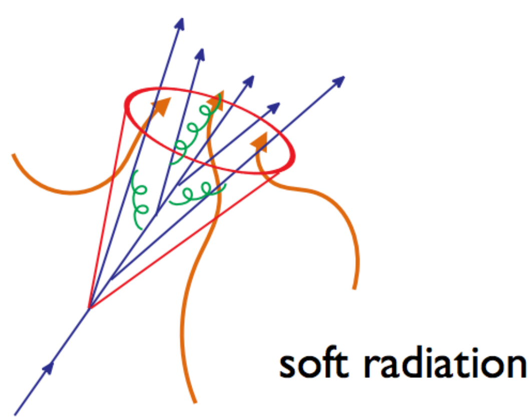
- Most modern colliders are jet machines, LHC, EIC ⋯
  - Benchmark processes with large statistics and small errors
  - Probing QCD ranging over orders of magnitudes in scales

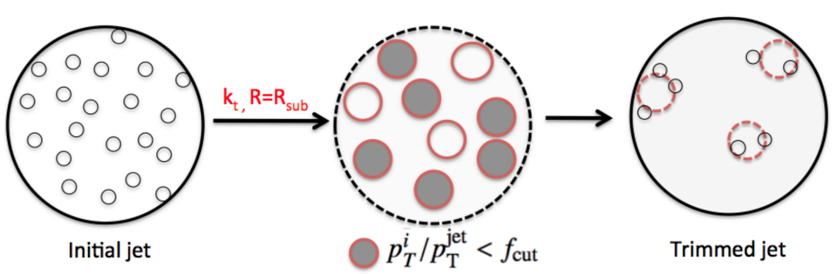
Global quantities probe scales of order 10GeV ~ 1TeV

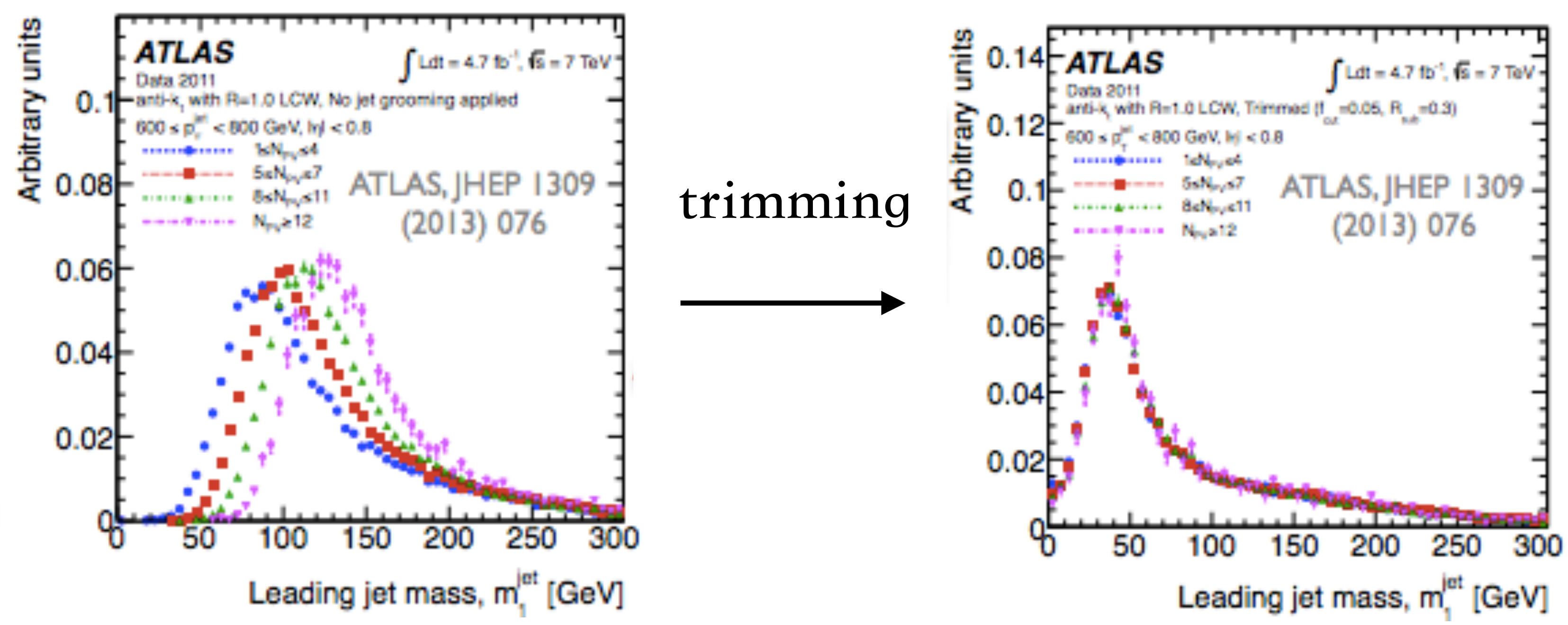


Why jet physics?

- Most modern colliders are jet machines, LHC, EIC ···
  - Benchmark processes with large statistics and small errors
  - Probing QCD ranging over orders of magnitudes in scales
    - Modern jet substructure techniques for extending the scale region, reducing contaminations, distinguish g/q jets ···



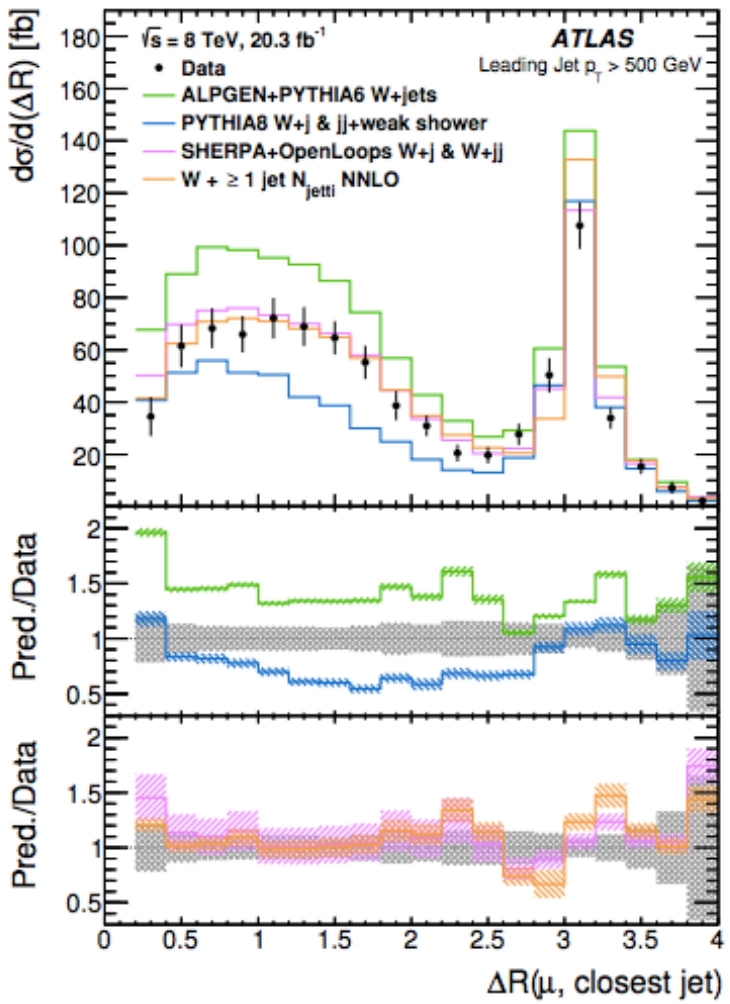


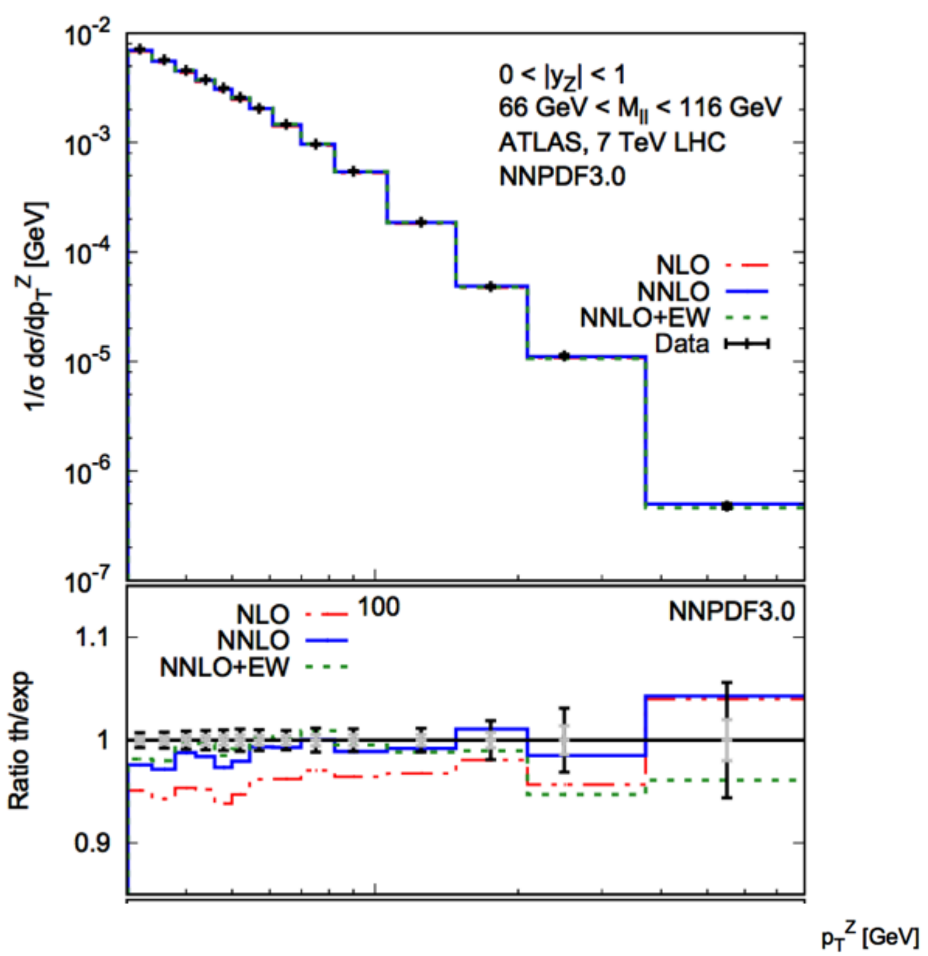


Why jet physics?

- Precision first principle theoretical understanding
    - Exciting fixed order precision achievements
        - N^2LO or N^3LO predictions, V+J, J+J, DIS jet···

Boughezal, XL, Petriello +; Gehrmann, Glover, +; ···





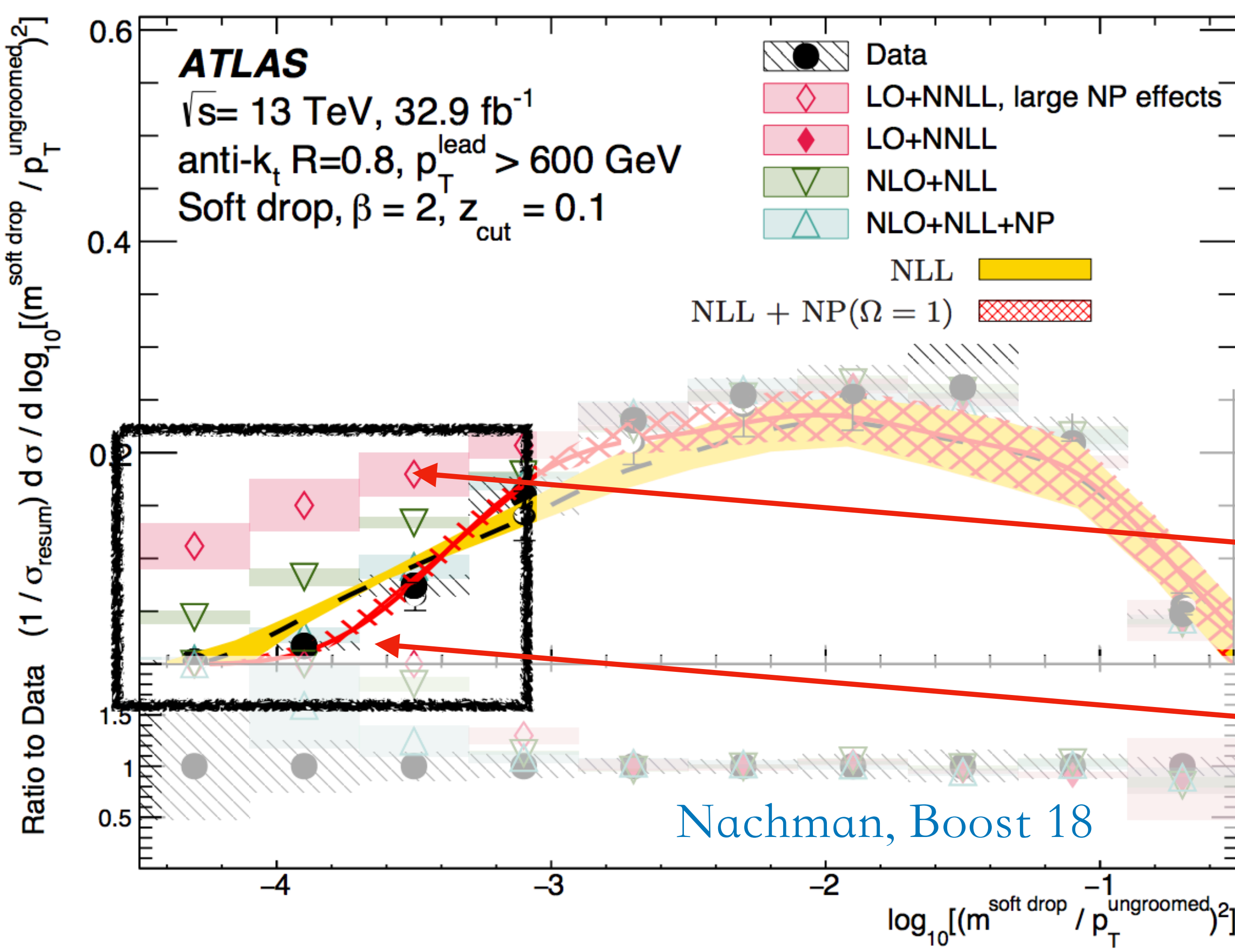
Why jet physics?

- Precision first principle theoretical understanding
  - Resummation frameworks for jet observables
    - Jet R
    - (un-)groomed jet shapes
    - …

Precision for jet physics, though challenging but feasible now

Why jet physics?

- Precision data + precision theory
  - Jet physics can be tested with high accuracy
  - Sensitive to minor differences in the theories



Predictions with different q/g fractions

Only LO q/g fraction

Full NLO q/g fraction

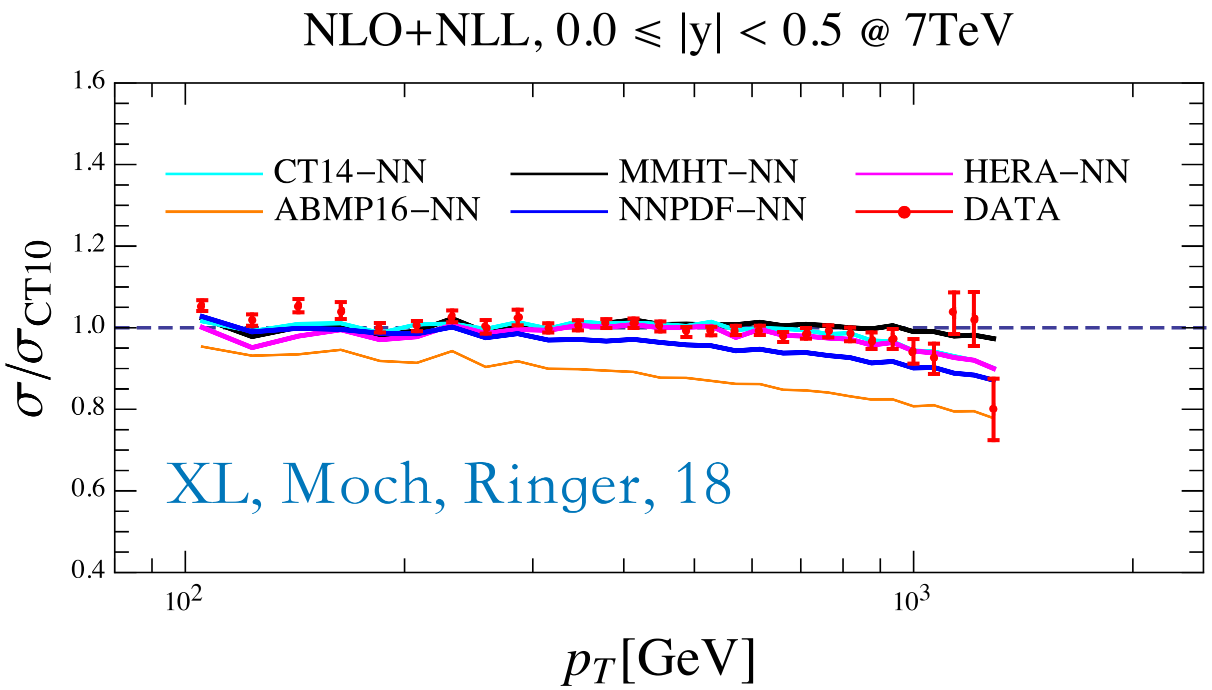
Kang, Lee, XL, Ringer, 17

Why jet physics?

- Precision data + precision theory
  - Jet physics can be tested with high accuracy
  - Sensitive to minor differences in the theories
  - Interesting Non.Pert. quantities can be extracted with confidence, PDFs, (TMD-)FFs, Sivers Function⋯

A sophisticated industry at the LHC

Goal of the TMD physics



Why jet physics?

- Jets for TMD physics
  - Conventional TMDs: DY, SIDIS and e^+e^- thus far
    - Simple and well-established
    - Lots of data so far

Why jet physics?

- Jets for TMD physics
  - Conventional TMDs: DY, SIDIS and e^+e^- thus far
    - Simple and well-established. Exciting opportunities for jet.
    - Lots of data so far. So are the jet processes, with more options

Modern jets will offer more

- Global TMDs
- In-jet TMDs
- TMD w.r.t different axis: beam/jet axis, photon $\cdots$
- Probing the factorization breaking effects: Rogers-Mulders 10, Qiu-Collins 07.

We will develop formalism for these, for both polarized and unpolarized TMDs

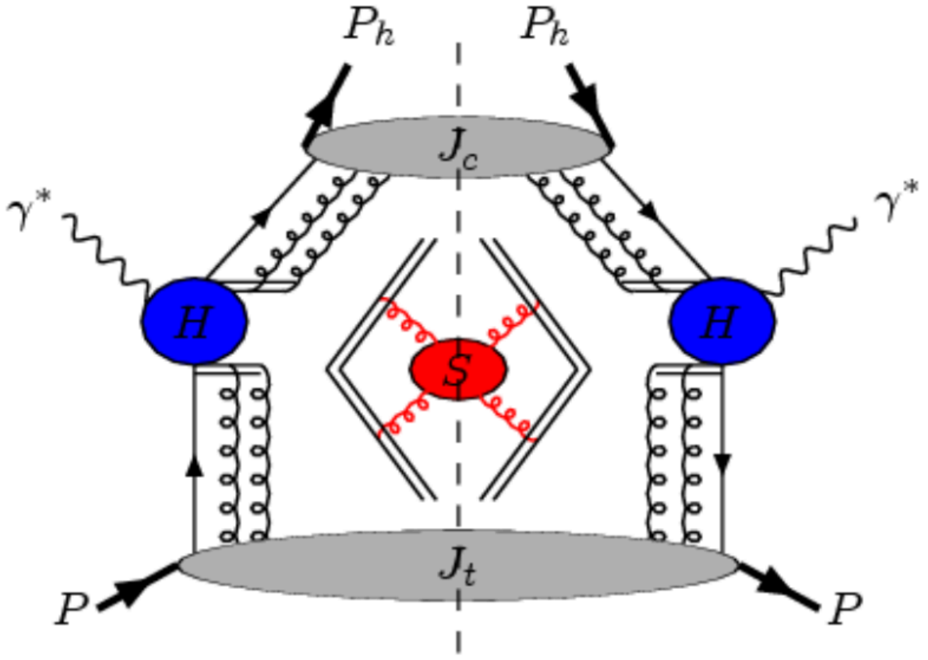
In-jet TMDs

Jet TMDs: In-jet TMDs

- Conventional approach to TMD FFs
    - SIDSI, e^+e^-

For SIDIS

$$F_{UU}(x_B, z_h, Q^2, P_{h\perp}) = \sum_{q=u,d,s,\dots} e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp d^2\vec{\lambda}_\perp \times q\left(x_B, k_\perp\right) \hat{q}\left(z_h, p_\perp\right) \left(S(\vec{\lambda}_\perp)\right)^{-1} \times H_{UU}\left(Q^2\right) \delta^{(2)}\left(z_h \vec{k}_\perp + \vec{p}_\perp + \vec{\lambda}_\perp - \vec{P}_{h\perp}\right)$$



Entanglement between TMD FFs and TMD PDFs

Hard to probe gluon FFs

Jet TMDs: In-jet TMDs

- Hadron in jet as an alternative
  - Possibility for gluon TMD FFs
  - With more experimental controls
  - Dis-entangle final TMDs from ISR

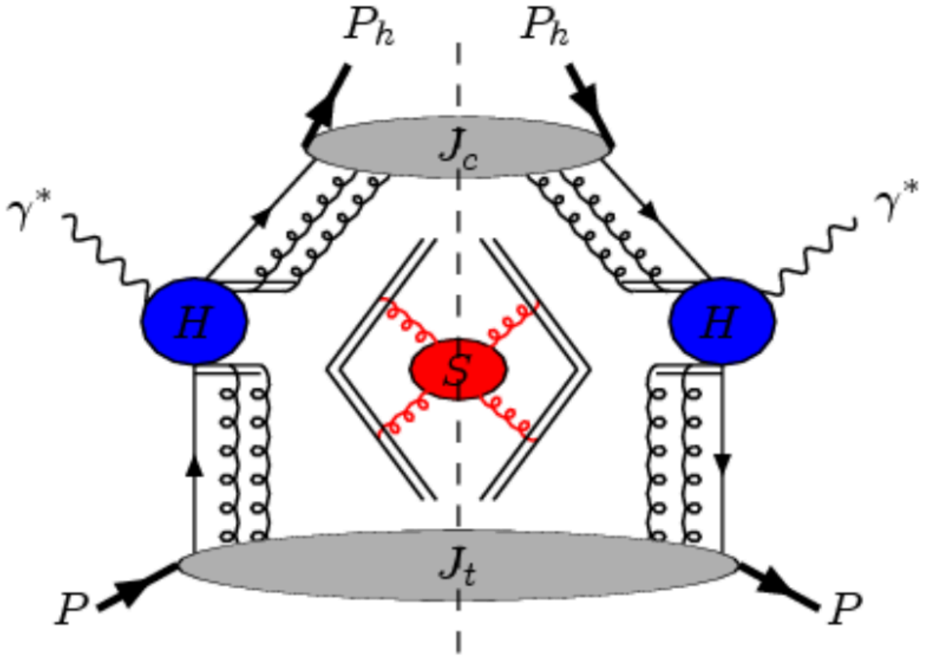
For SIDIS

$$F_{UU}(x_B, z_h, Q^2, P_{h\perp}) = \sum_{q=u,d,s,\ldots} e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp d^2\vec{\lambda}_\perp \times q\left(x_B, k_\perp\right) \hat{q}\left(z_h, p_\perp\right) \left(S(\vec{\lambda}_\perp)\right) \times H_{UU}\left(Q^2\right) \delta^{(2)}\left(z_h\vec{k}_\perp + \vec{p}_\perp + \vec{\lambda}_\perp - \vec{P}_{h\perp}\right)$$

For in-jet TMDs

The TMD PDFs will be absent!

Cleaner probe of the TMD FFs



Jet TMDs: In-jet TMDs

- Hadron TMDs in the inclusive jet production
  - A multi-scale problem

$$p_T >> p_T R >> j_T > \Lambda_{QCD}$$

$p_T \sim 20 - 1000\text{GeV}$, $R \sim 0.2 - 0.5$

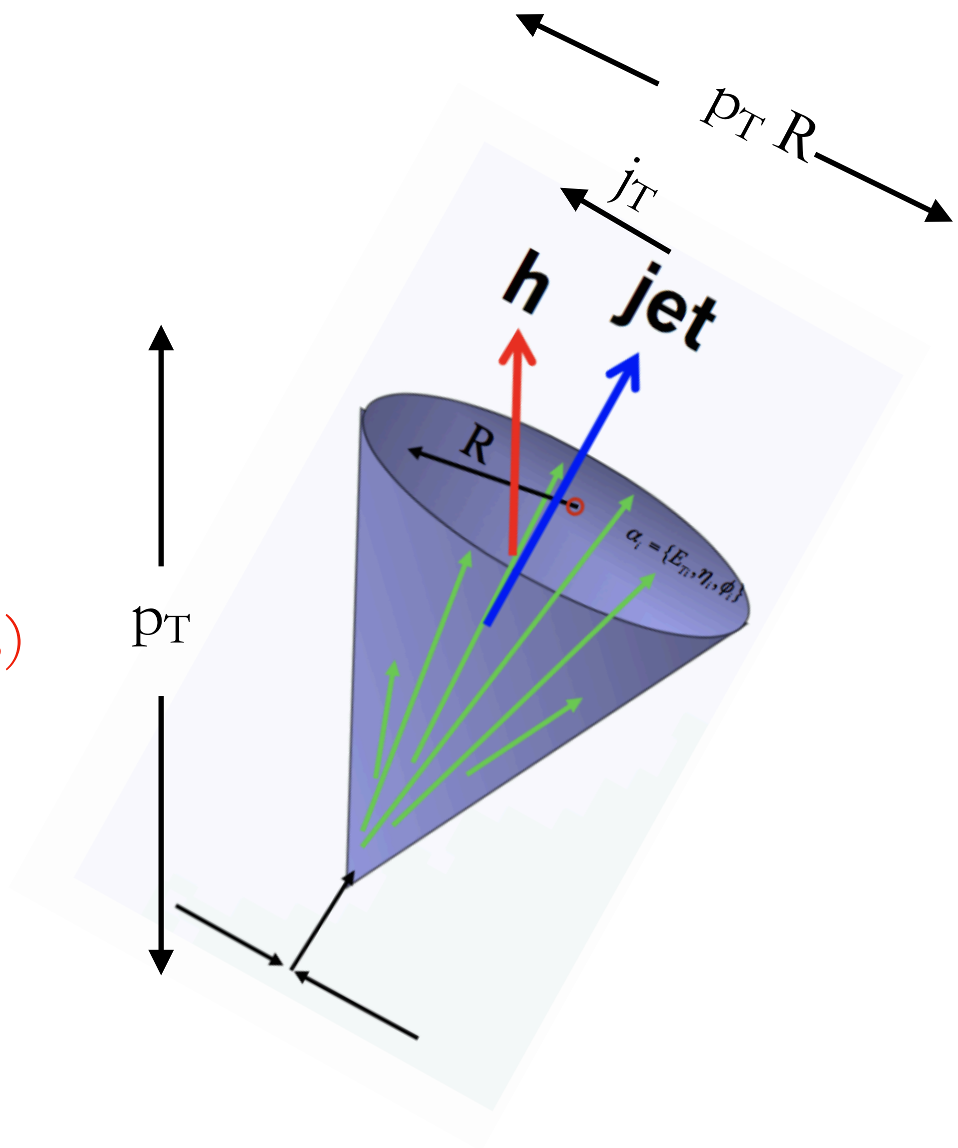
$j_T \sim 100\text{MeV} - 5\text{ GeV}$

Con:

- Fixed order breaks down due to log(hierarchies)

Pro:

- Factorization and resummation
- Universality



Kang, XL, Ringer, Xing, 2017

Jet TMDs: In-jet TMDs

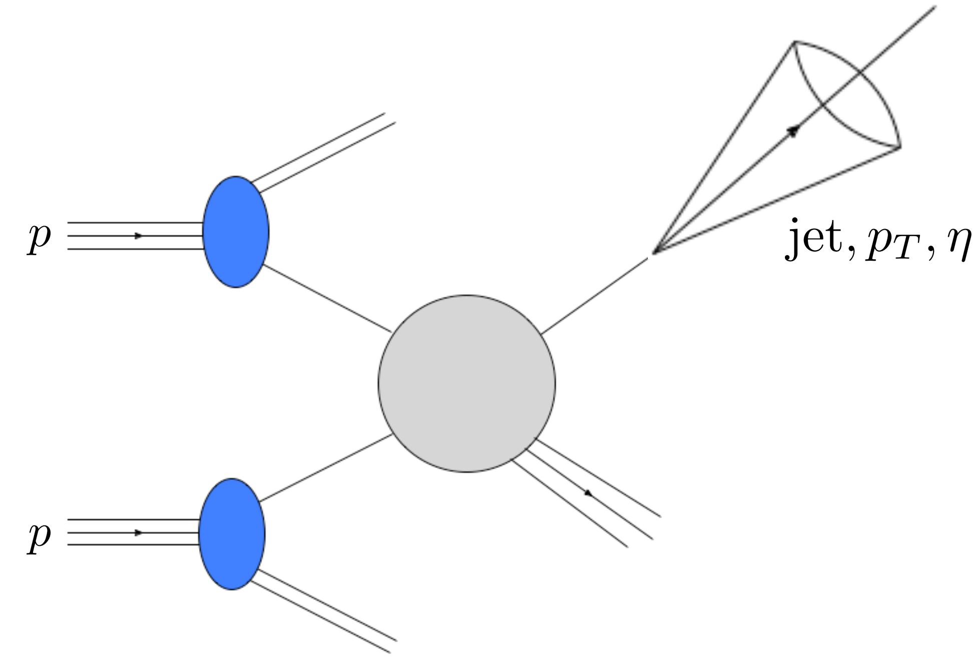
- Hadron TMDs in the inclusive jet production
  - Factorization

$$\frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} = \sum_{a,b,c} f_a(x_a,\mu)\otimes f_b(x_b,\mu)\otimes H_{ab}^c(x_a,x_b,\eta,p_T/z,\mu)\otimes \mathcal{G}_c^h(z,z_h,\omega_J R,\boldsymbol{j}_\perp,\mu)$$

H: partonic cross section for producing a parton(hadron), known to NLO (Vogelsang)

f: collinear PDFs

G: Universal semi inclusive jet function (analog of hadron FFs), all the j dependence encoded here. Same function for EIC.



Fully differential in the jet kinematics

Kang, XL, Ringer, Xing, 2017

Jet TMDs: In-jet TMDs

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  - Factorization

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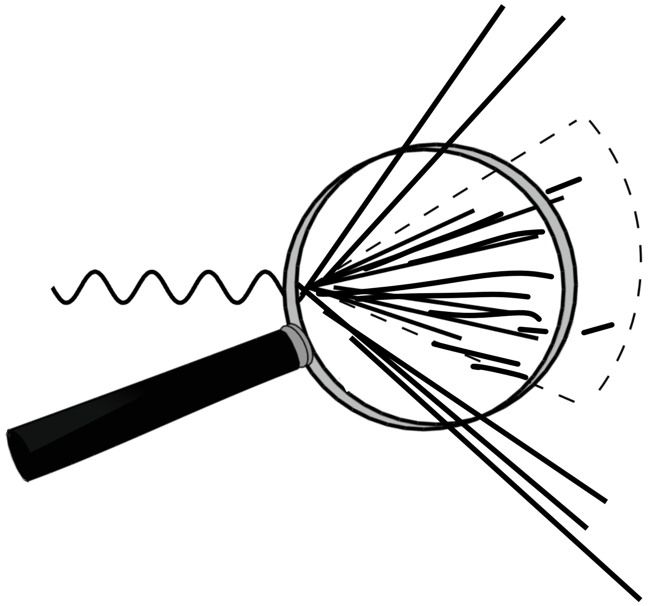


Valid for p_T R ~ j

Kang, XL, Ringer, Xing, 2017

Jet TMDs: In-jet TMDs

- Hadron TMDs in the inclusive jet production
  - Factorization

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

H: radiations out-side the jet cone, not allowed into the jet

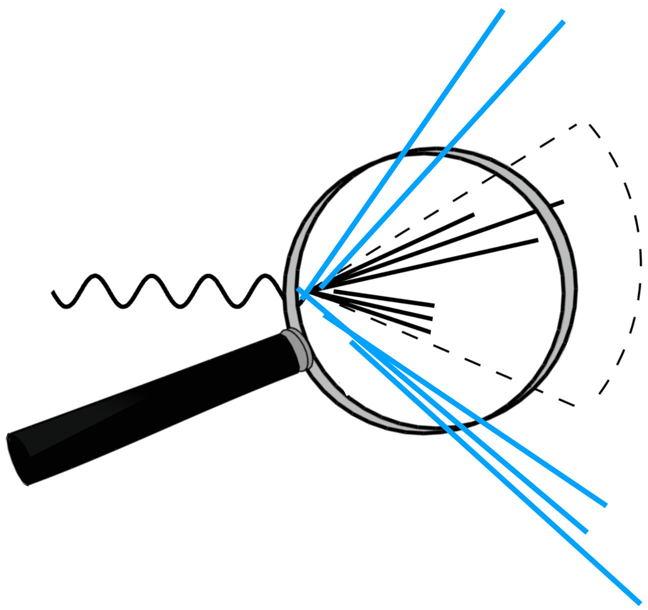
S: soft radiations

D: unsubtracted TMD FFs. Which is Non.Pert., if $j \sim \Lambda_{QCD}$

S.D : standard TMD FFs as in SIDIS

Universal

Valid for $j << p_T R$



Kang, XL, Ringer, Xing, 2017

Jet TMDs: In-jet TMDs

- Hadron TMDs in the inclusive jet production
  - Resummation

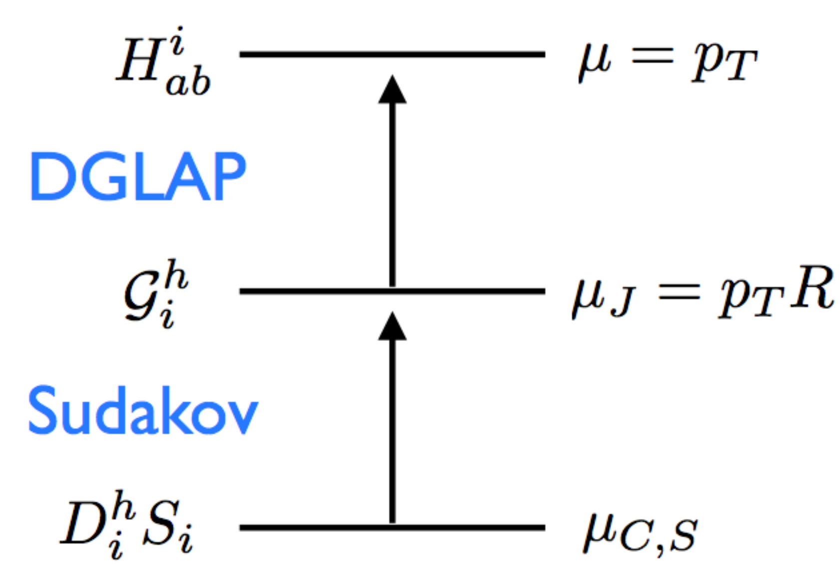
perturbative Sudakov factor

$$\hat{\mathcal{D}}_{h/i}(z_h, \boldsymbol{j}_\perp; \mu_J) = \frac{1}{z_h^2}\int \frac{b\,db}{2\pi} J_0(j_\perp b/z) C_{j\leftarrow i} \otimes D_{h/j}(z_h, \mu_{b_*}) e^{-S_{\rm pert}^i(b_*,\mu_J) - S_{\rm NP}^i(b,\mu_J)}$$

Perturbative matching   Non-perturbative input

RG evolution

$$S_{\rm pert}^i(b_*, \mu_J) = \int_{\mu_{b*}}^{\mu_J} \frac{d\mu'}{\mu'}\left(\Gamma_{\rm cusp}^i \ln\left(\frac{\mu_J^2}{\mu'^2}\right) + \gamma^i\right)$$

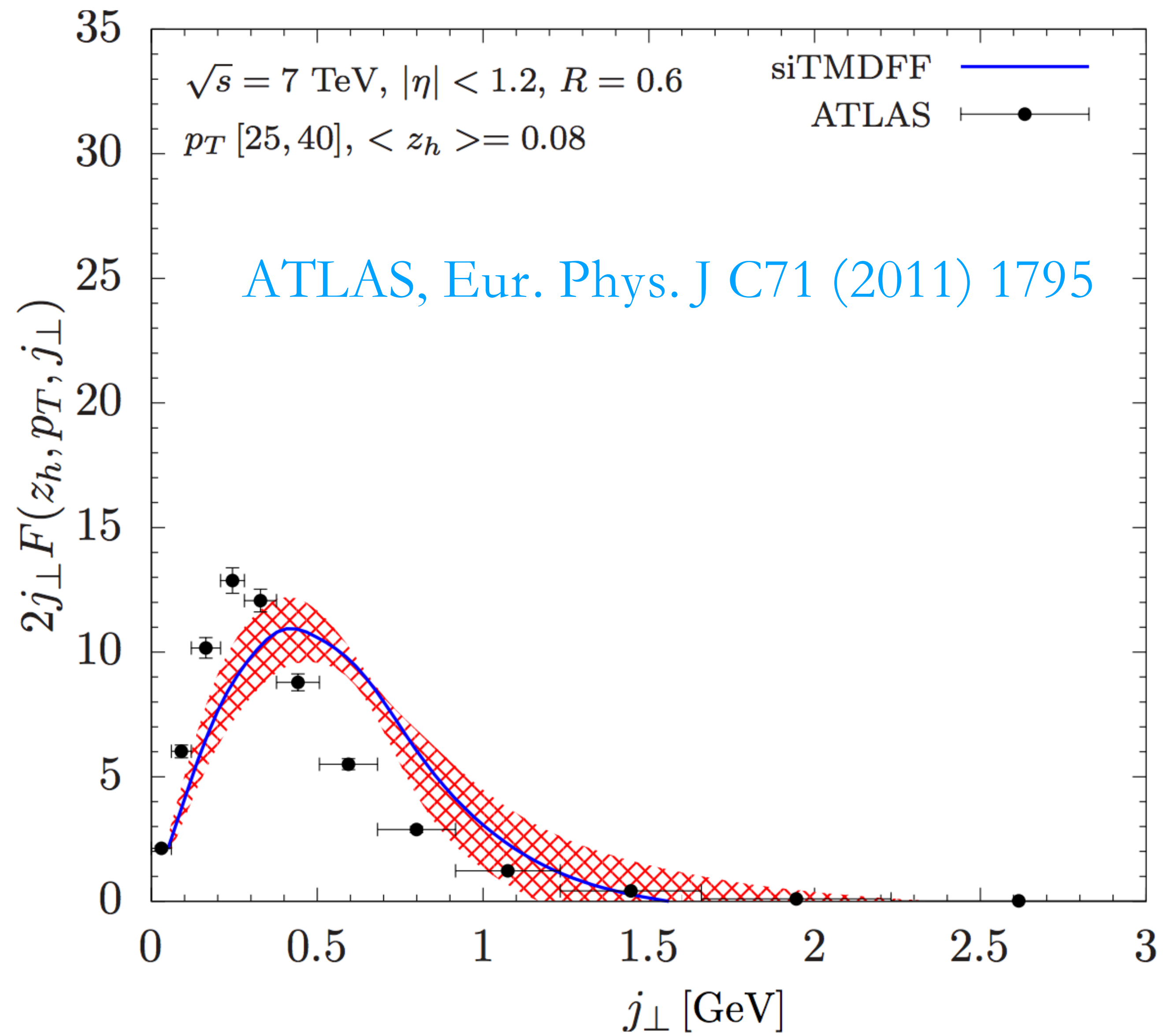


NP input from standard SIDIS/e+e-
Sun, Kang, Prokudin, Yuan'16

Kang, XL, Ringer, Xing, 2017

Jet TMDs: In-jet TMDs

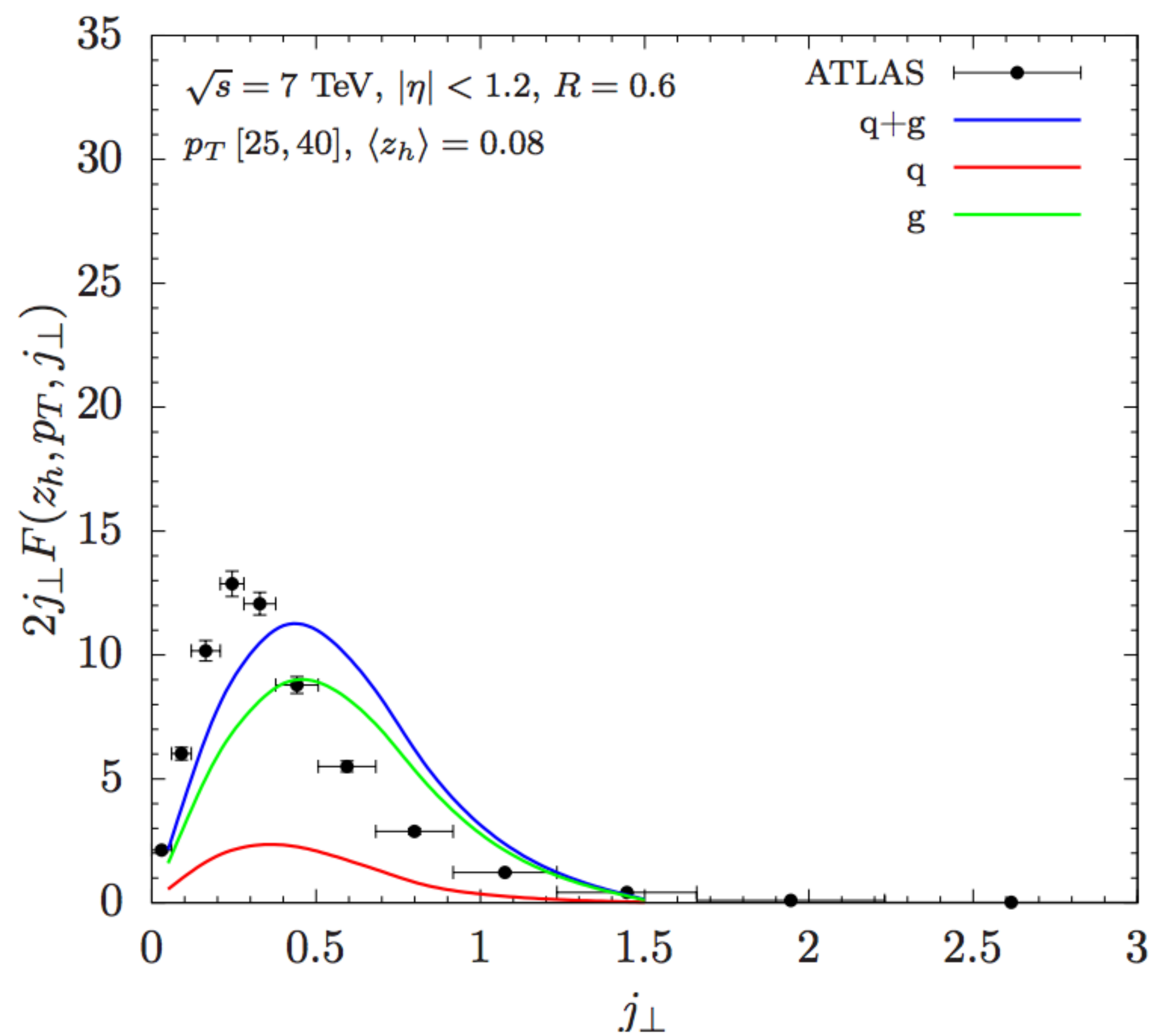
- Hadron TMDs in the inclusive jet production
  - Phenomenology
  - No z_h bin measures but integrated over [0,1]
  - Would be great if RHIC has such a measurement



Kang, XL, Ringer, Xing, 2017

Jet TMDs: In-jet TMDs

- Hadron TMDs in the inclusive jet production
  - Phenomenology
  - Control pT to pick the g/q TMDFFs
  - Better opportunity for gluon TMDFFs

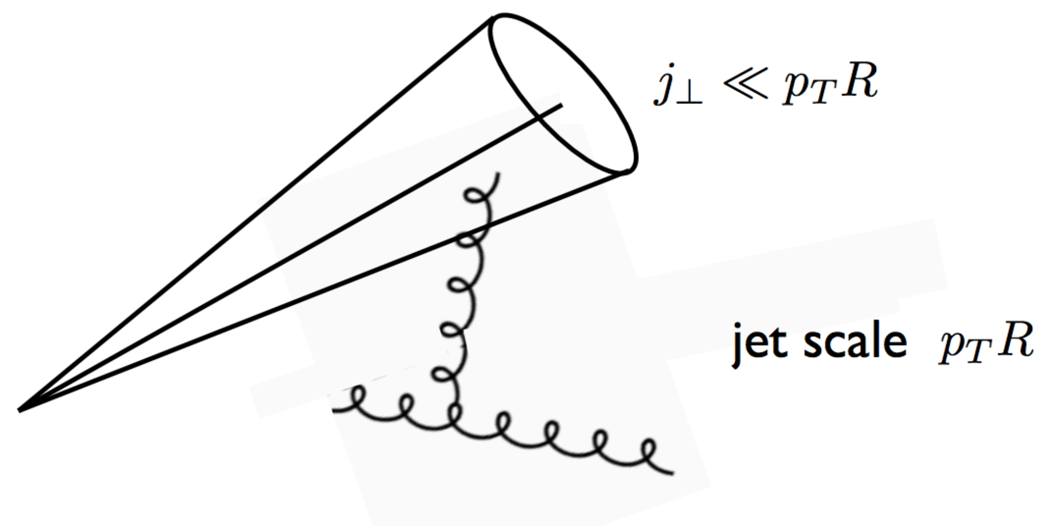


Kang, XL, Ringer, Xing, 2017

Jet TMDs: In-jet TMDs

- Hadron TMDs in the inclusive jet production
  - Interesting to the HEP QCD
    - Non-global logarithms

$$d\sigma = \sum_{abcd} f_a\, f_b\, H^c_{ab}\, \mathcal{H}_{cd}\, \hat{\mathcal{D}}_d \times S_{d,\mathrm{NGL}}$$



- Discovered by G. Salam et. al. (hep-ph/0104277), start at NNLO
- Can not be resummed using conventional CSS formalism
- Reduced for ratios (asymmetry $\cdots$)

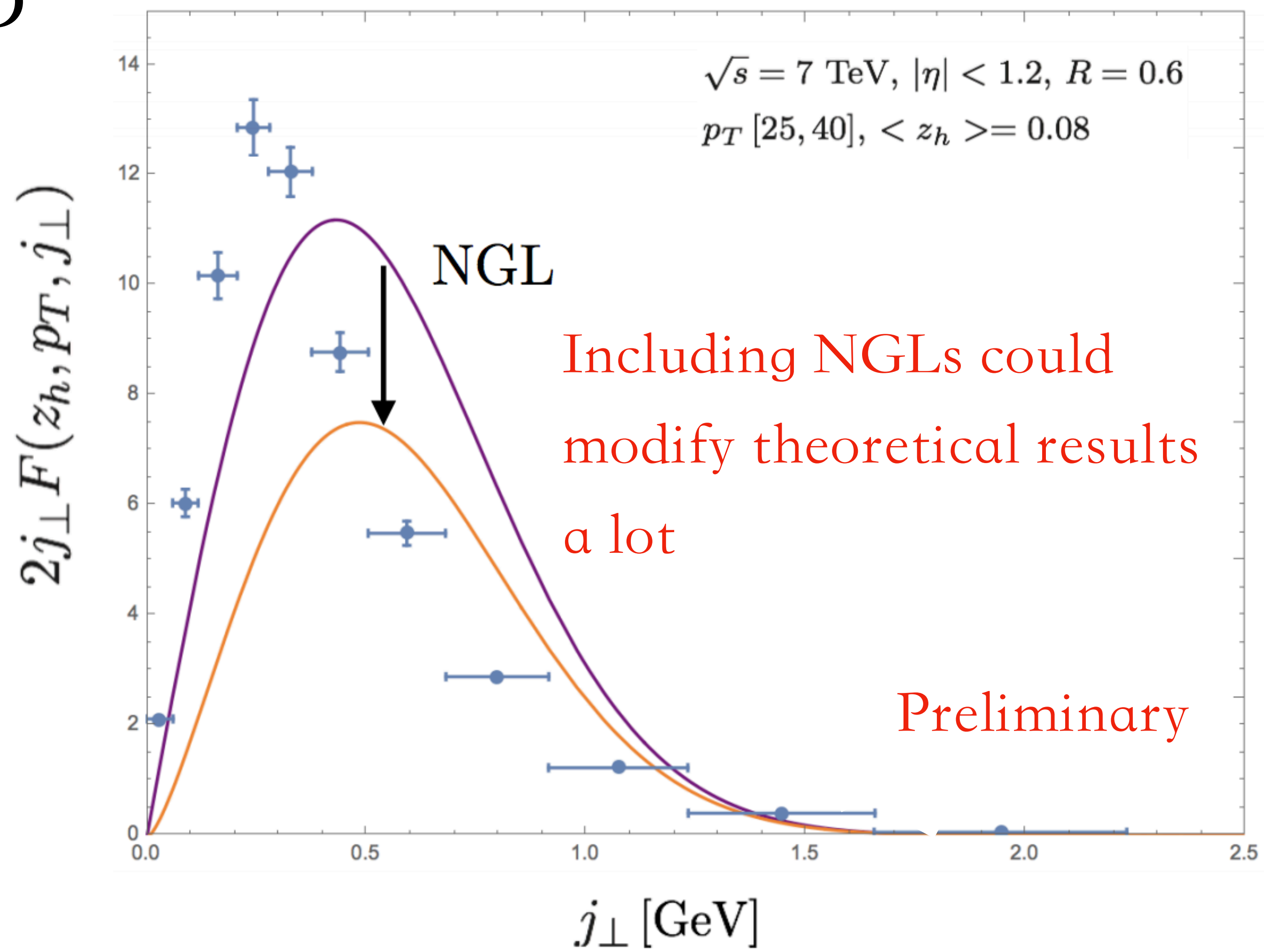
NGLs are there, but NO direct phenomenology studies now.. too small

However, things may be different here since j is too small!

Jet TMDs: In-jet TMDs

- Hadron TMDs in the inclusive jet production
    - Interesting to the HEP QCD
        - Non-global logarithms

$$d\sigma = \sum_{abcd} f_a \, f_b \, H^c_{ab} \, \mathcal{H}_{cd} \, \hat{\mathcal{D}}_d \times S_{d,\mathrm{NGL}}$$



In-jet TMD may provide the very first experimental demonstration of the NGLs

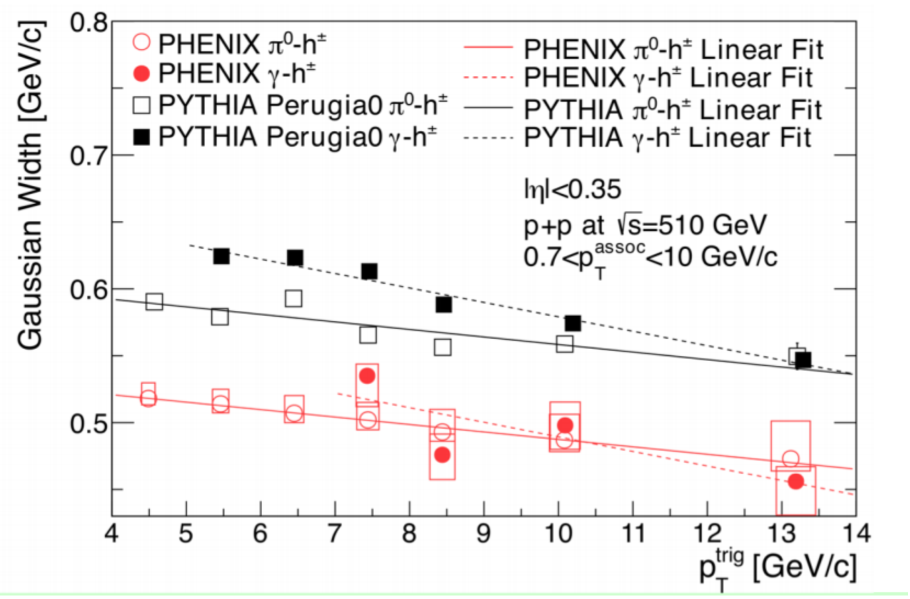
Alternatively, groomed away NGLs, see Makris, Neill, Vaidya, 2017, but hard to relate to the normal TMD.

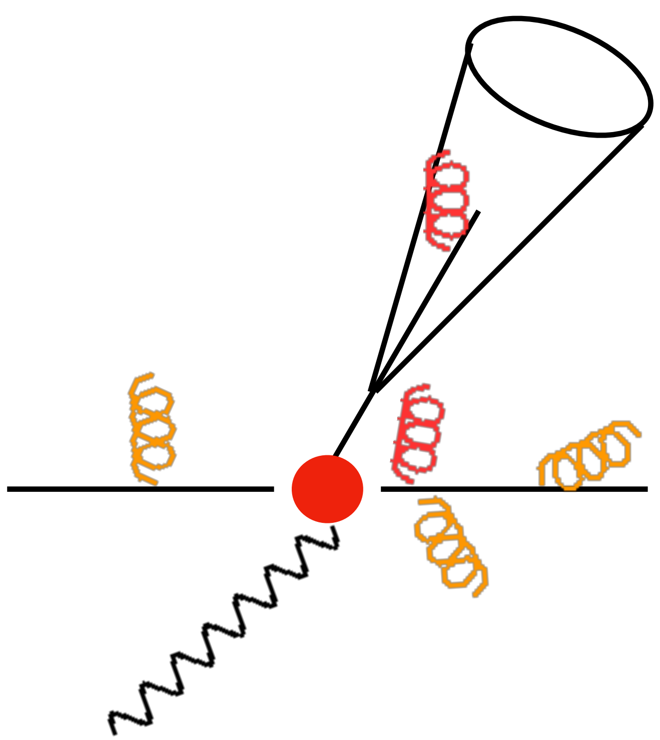
Jet Imbalance

Jet TMDs: Jet Imbalance

- For probing the factorization breaking effects
  - Theo. says the factorization breaks down, but how large is the effect?
  - exp. does measure the process or sth. similar, and no theory to compare with

Example:
Gaussian widths in
pp -> photon + h





qT measured w.r.t. the beam

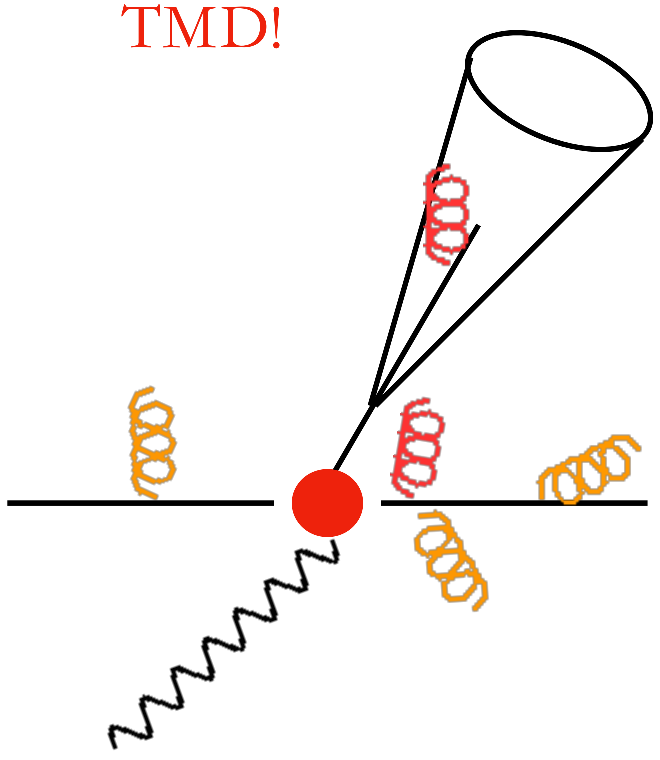
Buffing, Kang, Lee, XL

Jet TMDs: Jet Imbalance

- For probing the factorization breaking effects

$$\frac{d\sigma}{d\mathcal{PS}} = \sum_{a,b,c} \int d\phi_J \int \prod_i^4 d^2\vec{k}_{i\perp} \delta^{(2)}(\vec{q}_\perp - \sum_i^4 \vec{k}_{i\perp})$$
$$\times f_a^{\rm unsub}(x_a, k_{1\perp}^2) f_b^{\rm unsub}(x_b, k_{2\perp}^2) S_{n\bar{n}n_J}^{\rm global}(\vec{k}_{3\perp})$$
$$\times S_{n_J}^{cs}(\vec{k}_{4\perp}, R) H_{ab\to c\gamma}(p_\perp) J_c(p_\perp R)\,,$$

Exactly Standard TMD!



- Everything are known to at least NLO
- Resummation both qT and R at NLL
- the prediction is precise
- Deviation from future data will shed light on the factorization breaking effects

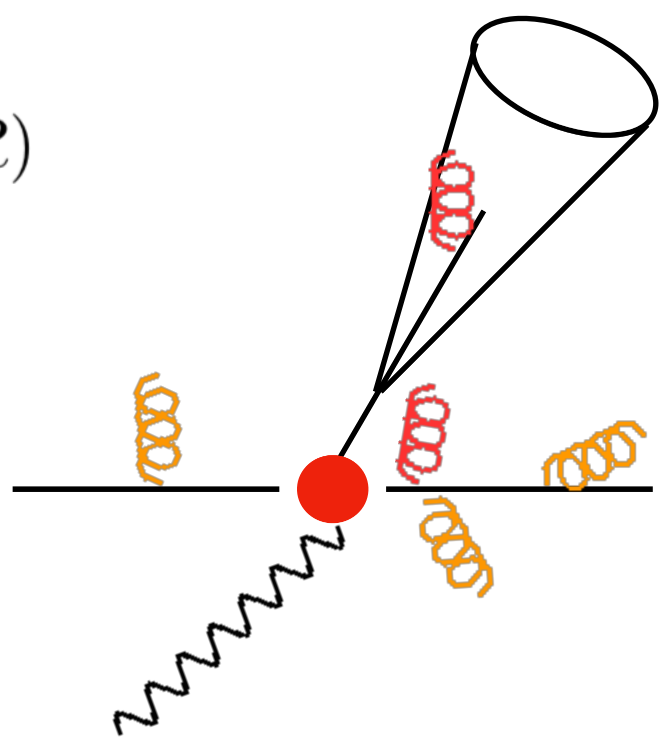
Buffing, Kang, Lee, XL

Jet TMDs: Jet Imbalance

- For probing the factorization breaking effects

$$\frac{d\Delta\sigma}{d\mathcal{PS}} = \epsilon^{\alpha\beta} s_\perp^\alpha \sum_{a,b,c} \int d\phi_J \int \prod_i^4 d^2\vec{k}_{i\perp} \delta^{(2)}(\vec{q}_\perp - \sum_i^4 \vec{k}_{i\perp})$$
$$\times \frac{k_{1\perp}^\beta}{M} f_{1T,a}^{\perp\,\mathrm{SIDIS}}(x_a, k_{1\perp}^2) f_b^{\mathrm{unsub}}(x_b, k_{2\perp}^2)$$
$$\times S_{n\bar{n}n_J}(\vec{k}_{3\perp}) S_{n_J}^{cs}(\vec{k}_{4\perp}, R) H_{ab\to c\gamma}^{\mathrm{Sivers}}(p_\perp) J_c(p_\perp R)$$

- Can be done for the polarized case
- Sensitive to the Sivers function in SIDIS



NB, can be readily extended to the hadron imbalance for the PHENIX results

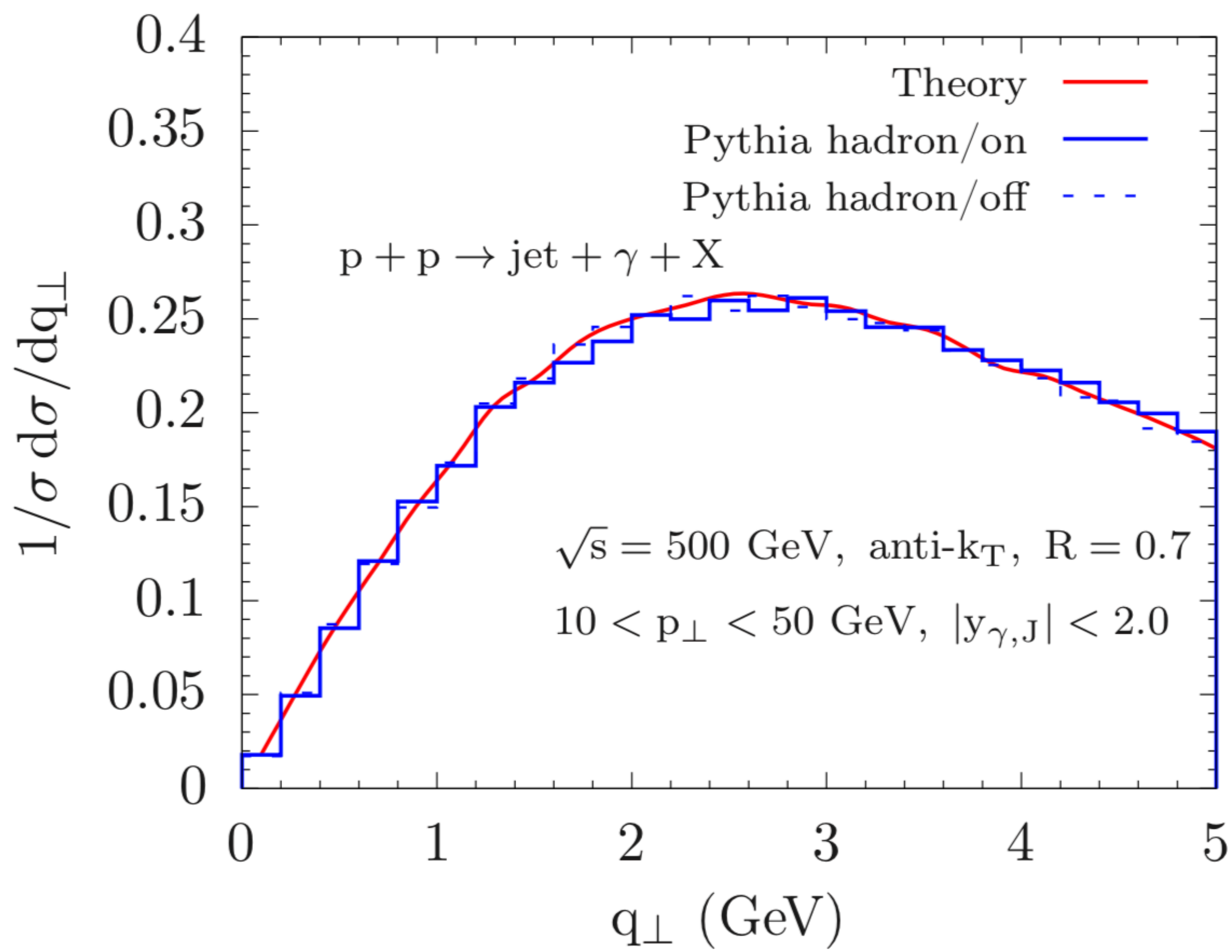
Buffing, Kang, Lee, XL

Jet TMDs: Jet Imbalance

- For probing the factorization breaking effects

No data yet, so we test against Pythia

- No obvious sign of factorization breaking
- A unique opportunity for gluon TMD pdfs, especially the gluon Sivers functions



Buffing, Kang, Lee, XL

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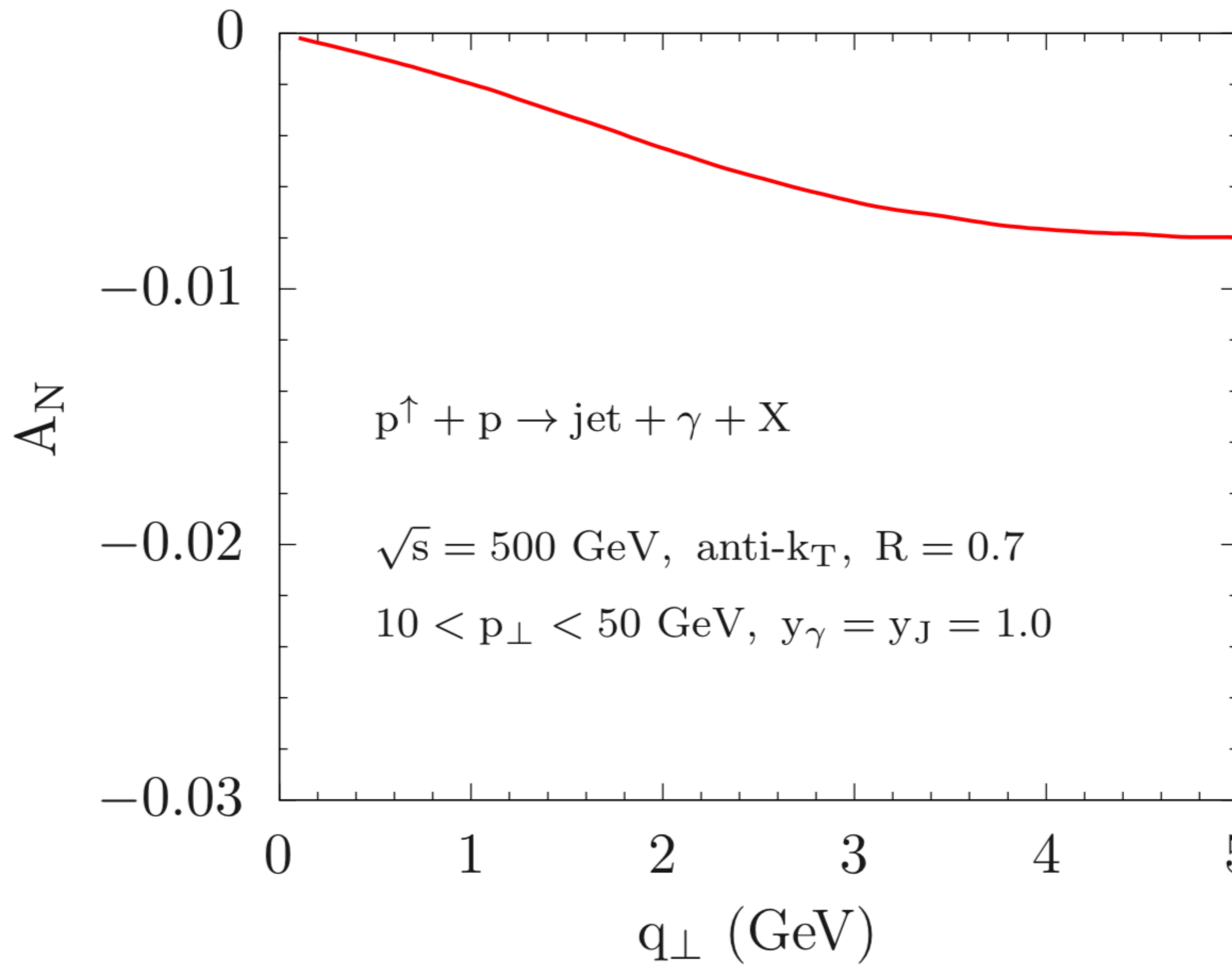

Buffing, Kang, Lee, XL

Conclusions

- We can control jets as good as DY, SIDIS, e^+e^-, both theoretically and experimentally.
- Jets provide different and thorough approaches to the TMD physics
  - In jet TMDs
  - Global TMDs
  - Precise phenomenological test

Thanks