Jets/event shapes for matter inner structures

Xiaohui Liu

HENPIC online seminar

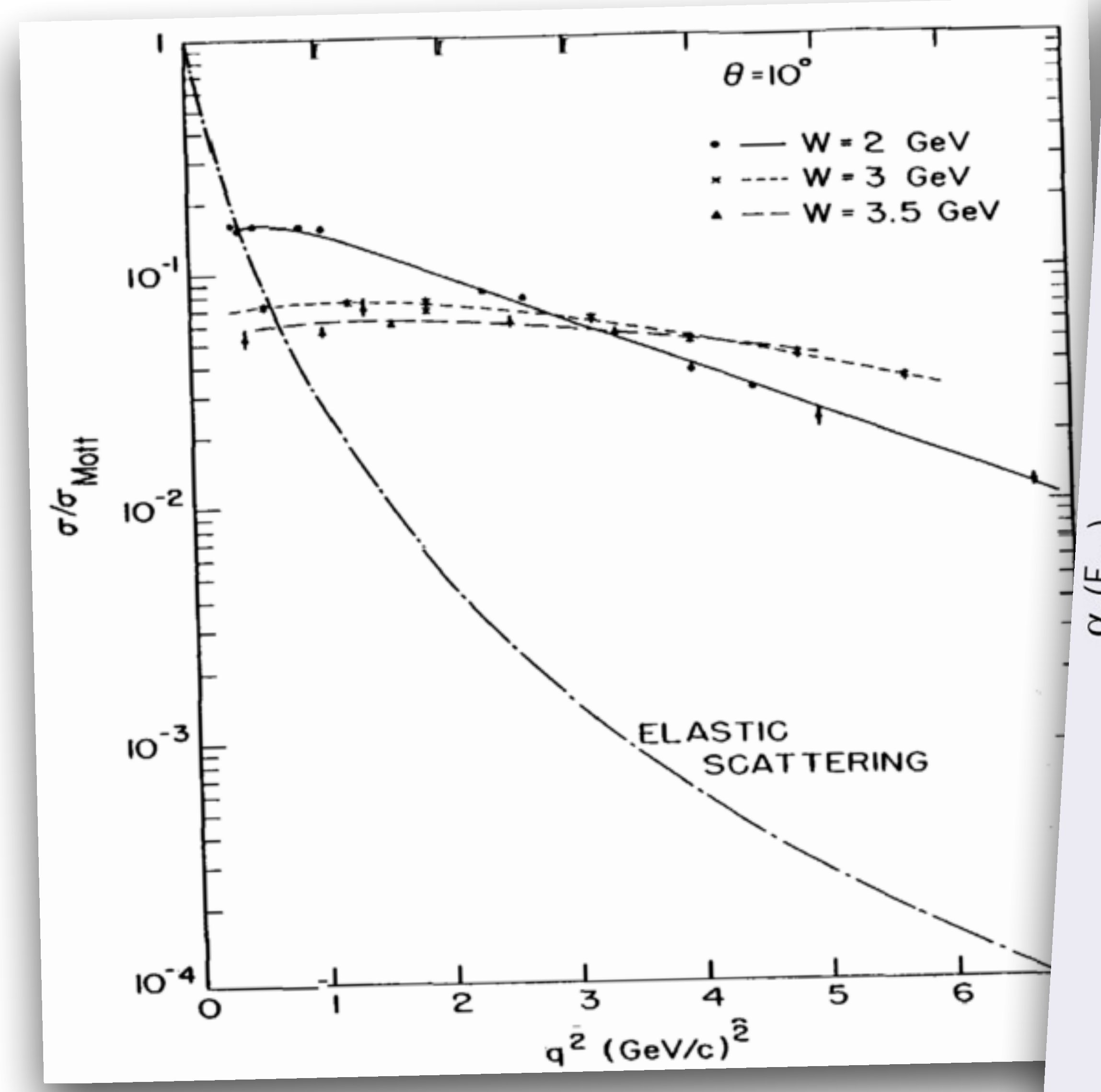
北京師範大學
BEIJING NORMAL UNIVERSITY

Outline

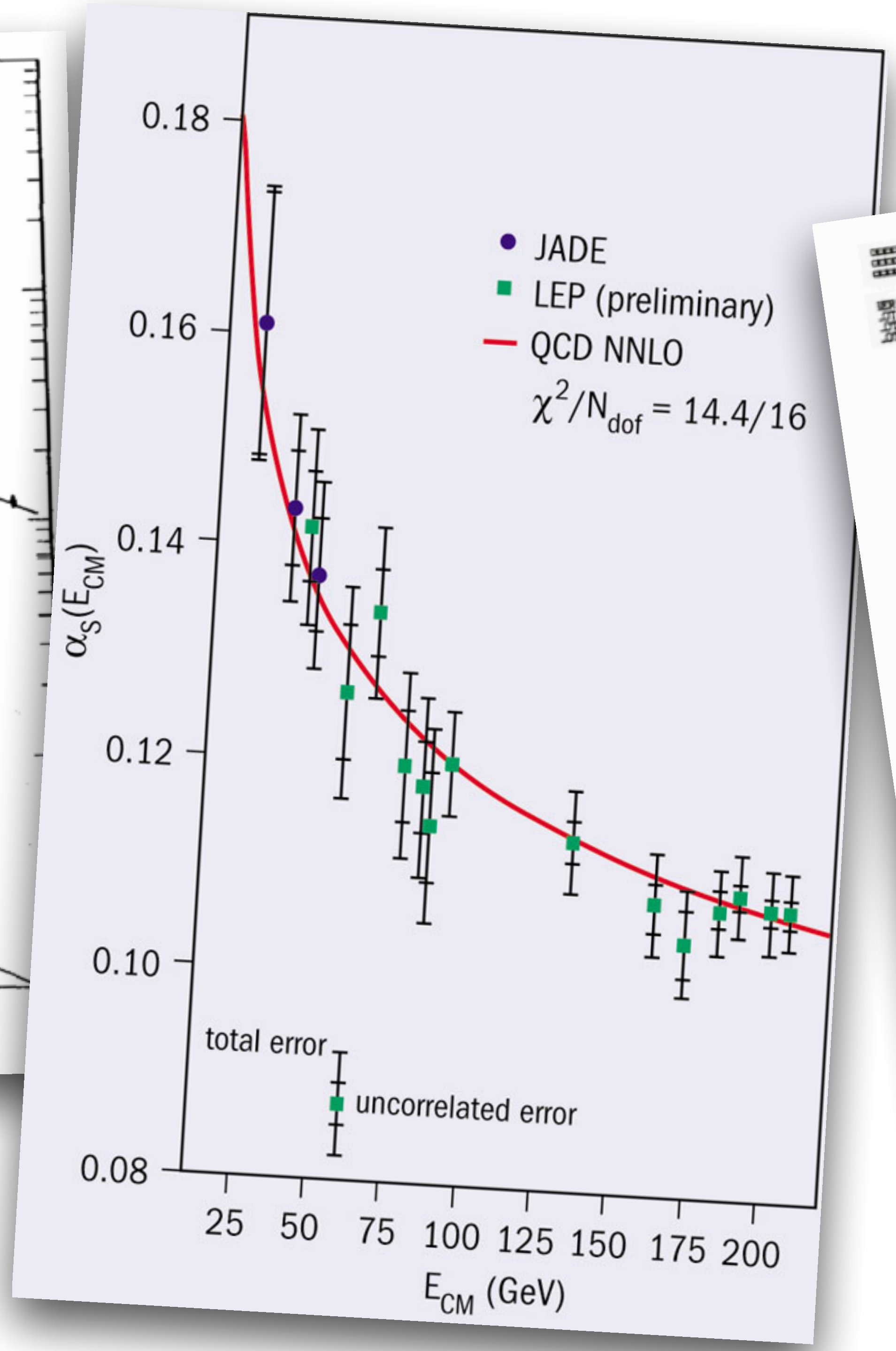
- Factorization, jets and event shapes at colliders
- Examples for inner structures
- Conclusions

Jets and event shapes at colliders

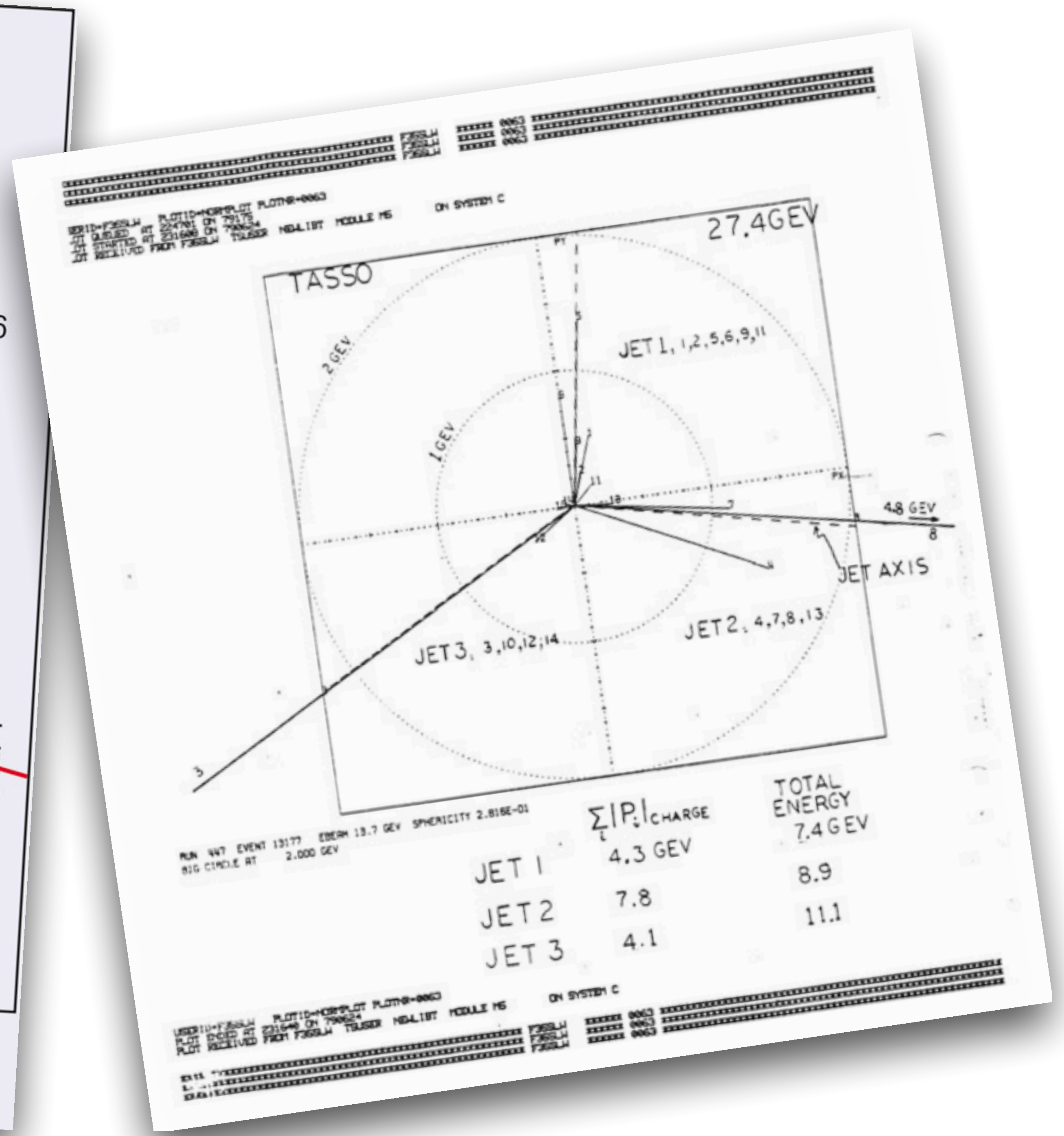
- Long lasting efforts to understand QCD



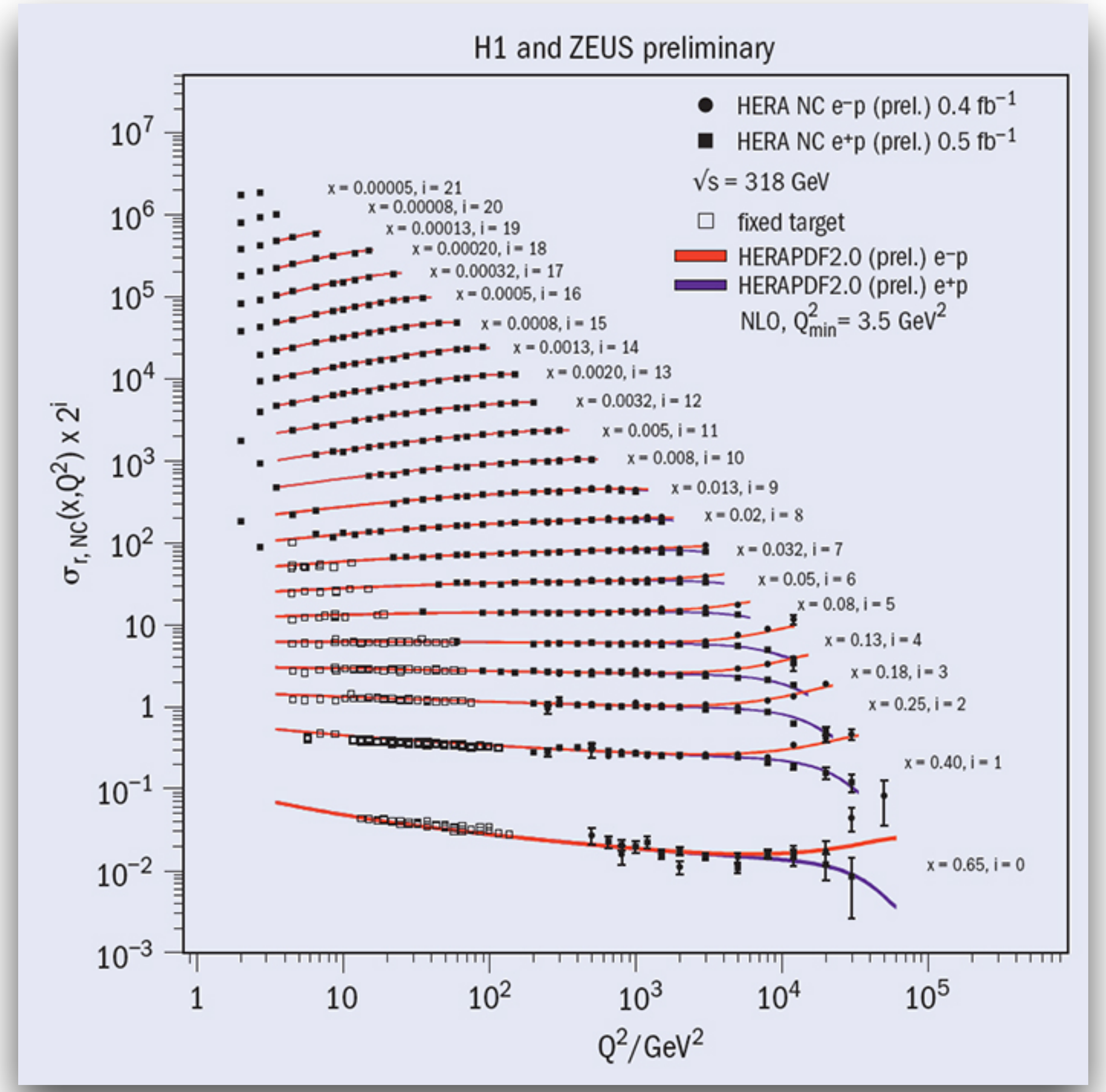
DIS > Partons, 1969



Asymptotic Freedom, 1973



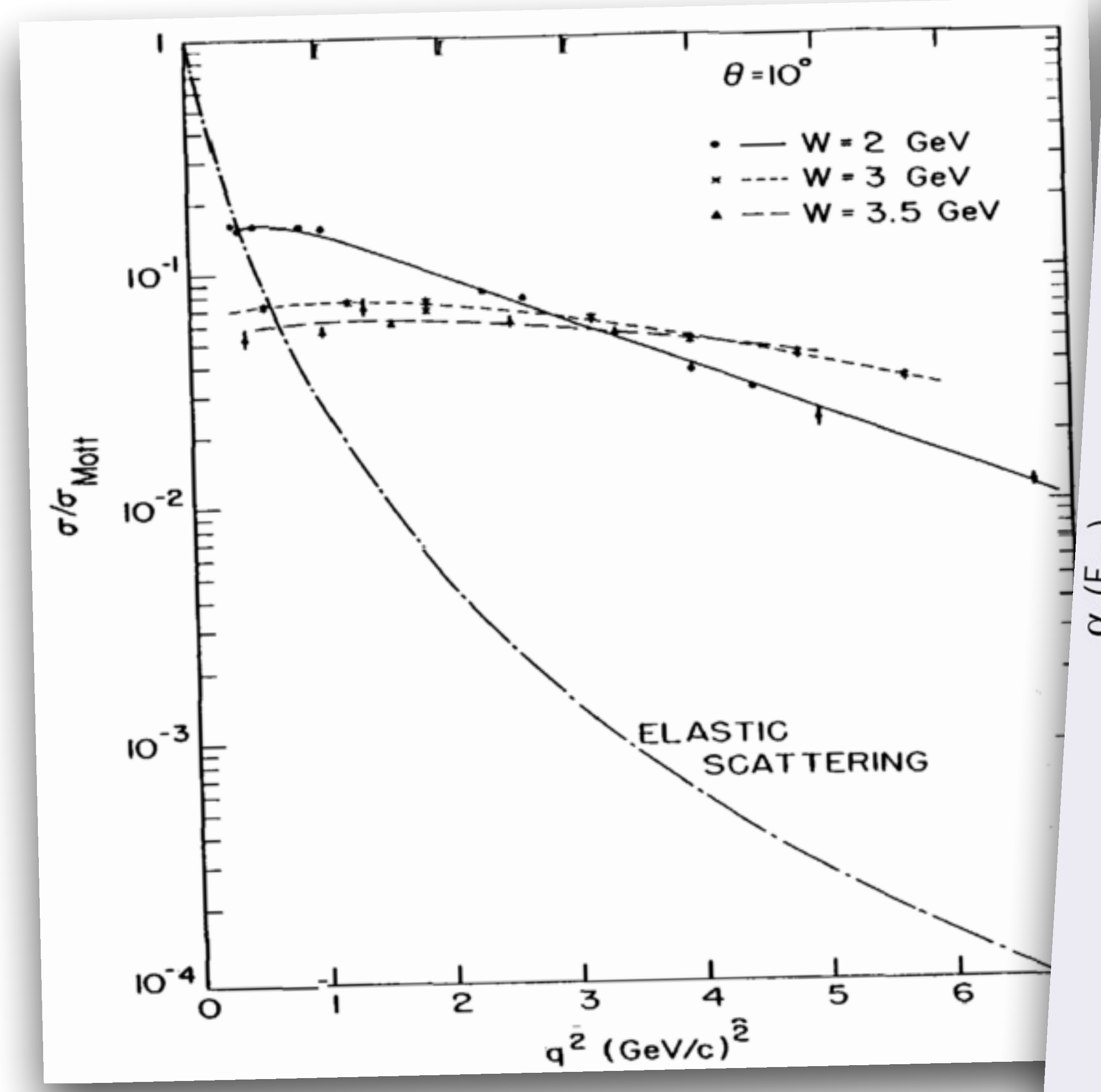
3-`jet`> gluon, 1979



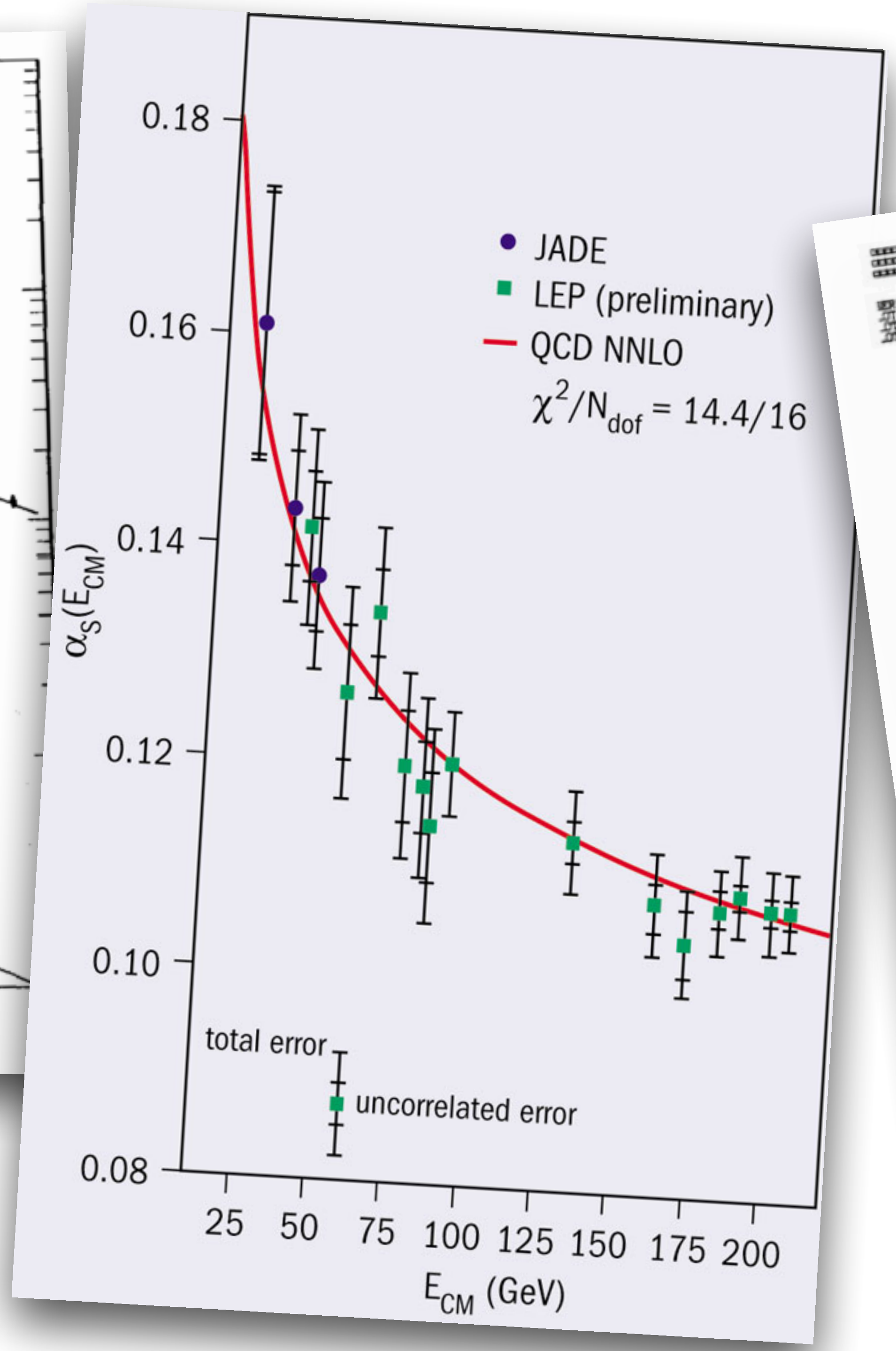
Precision of the PDFs, now

Jets and event shapes at colliders

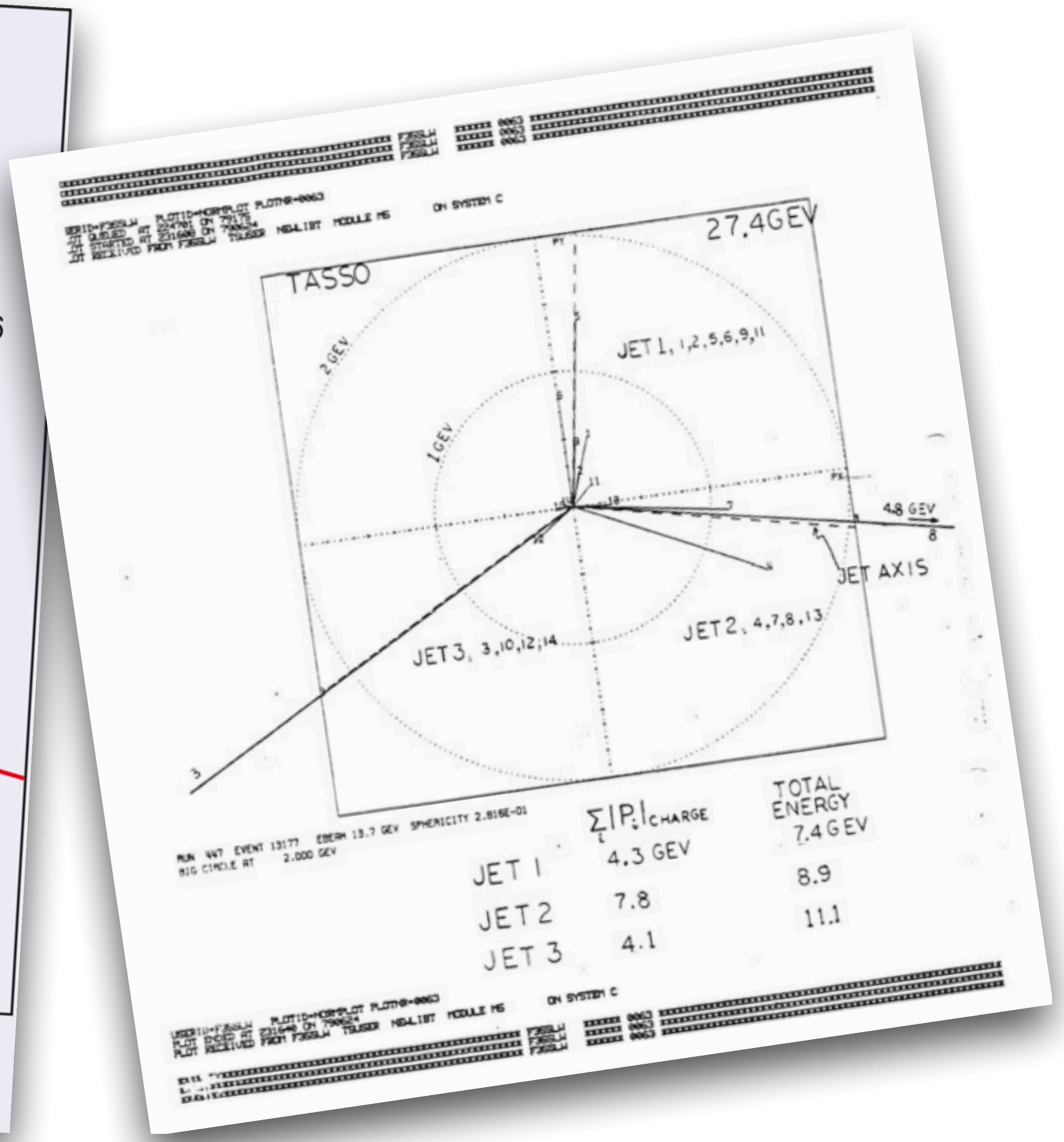
- Long lasting efforts to understand QCD



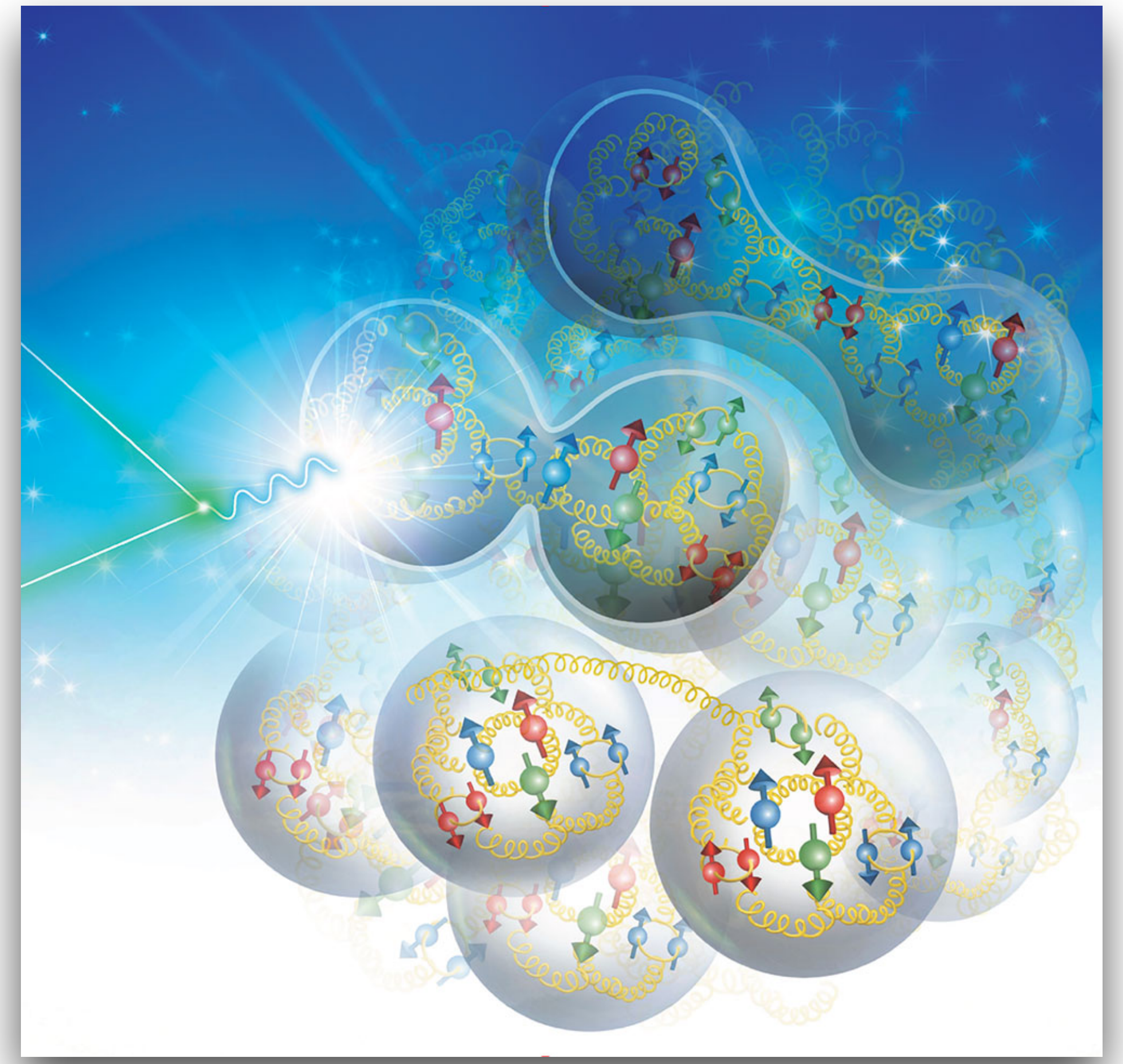
DIS > Partons, 1969



Asymptotic Freedom, 1973



3-`jet`> gluon, 1979



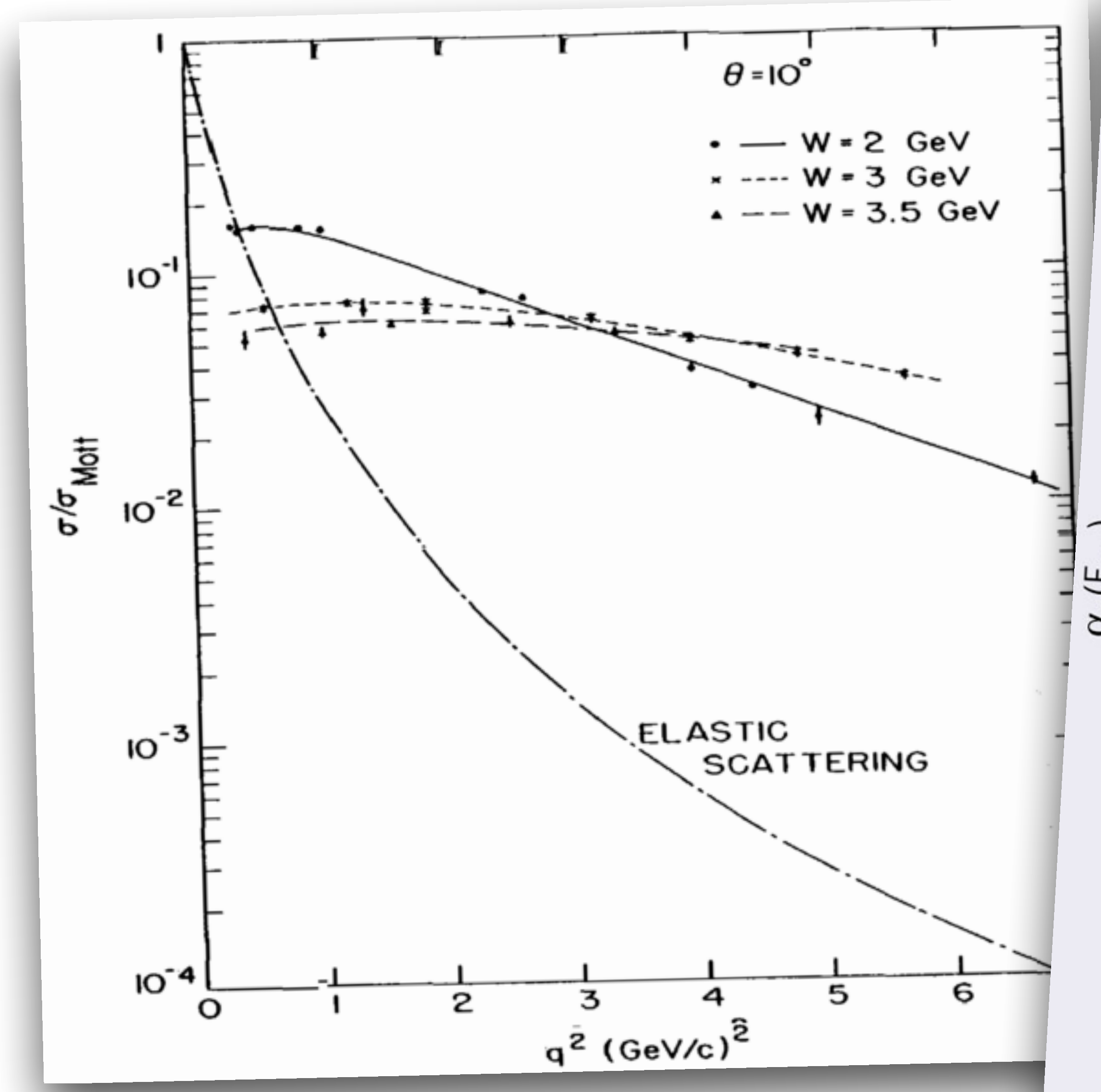
3D Imaging + ⋯ ,

now and the future

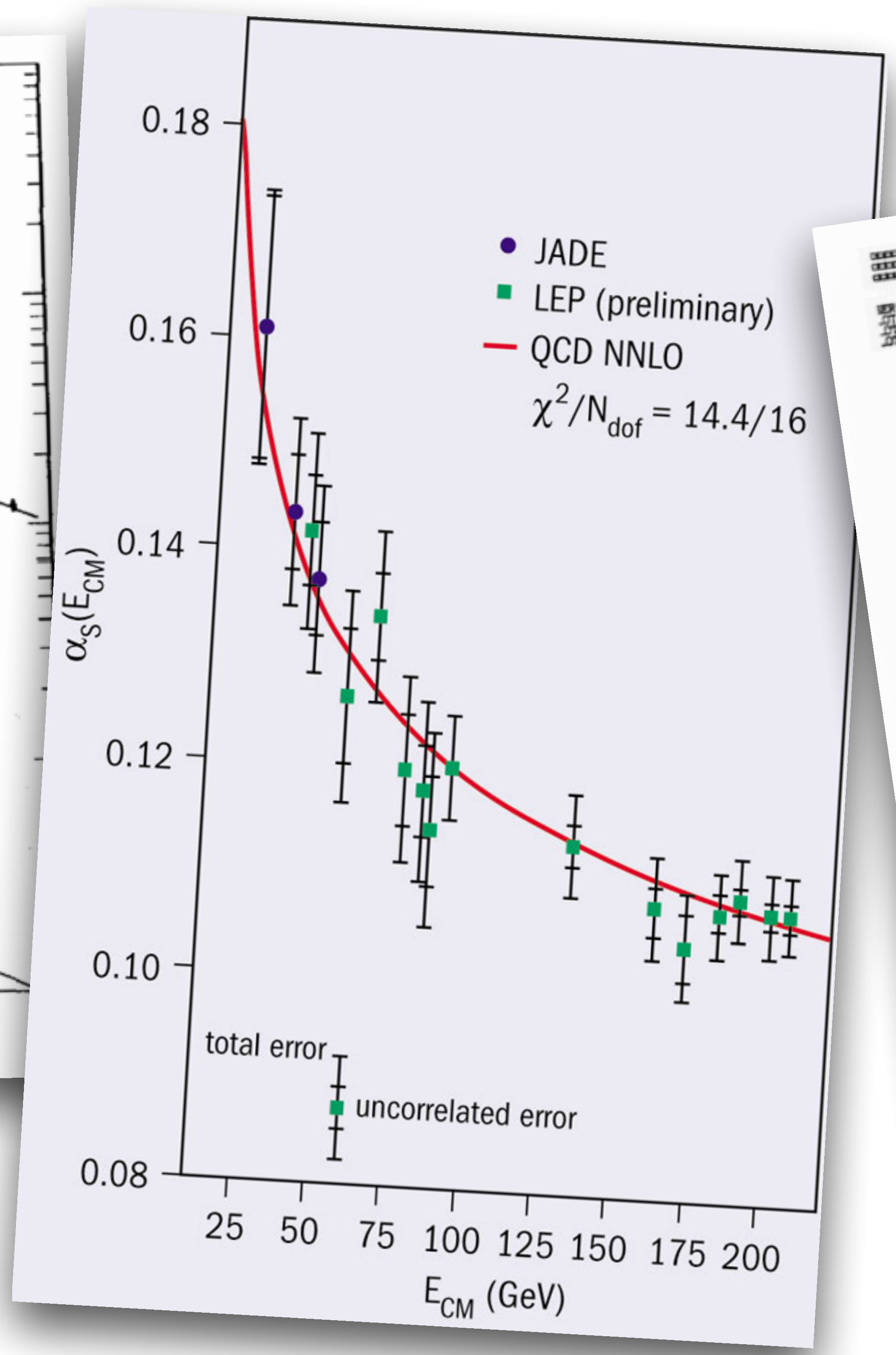
See Kang`s talk in this series

Jets and event shapes at colliders

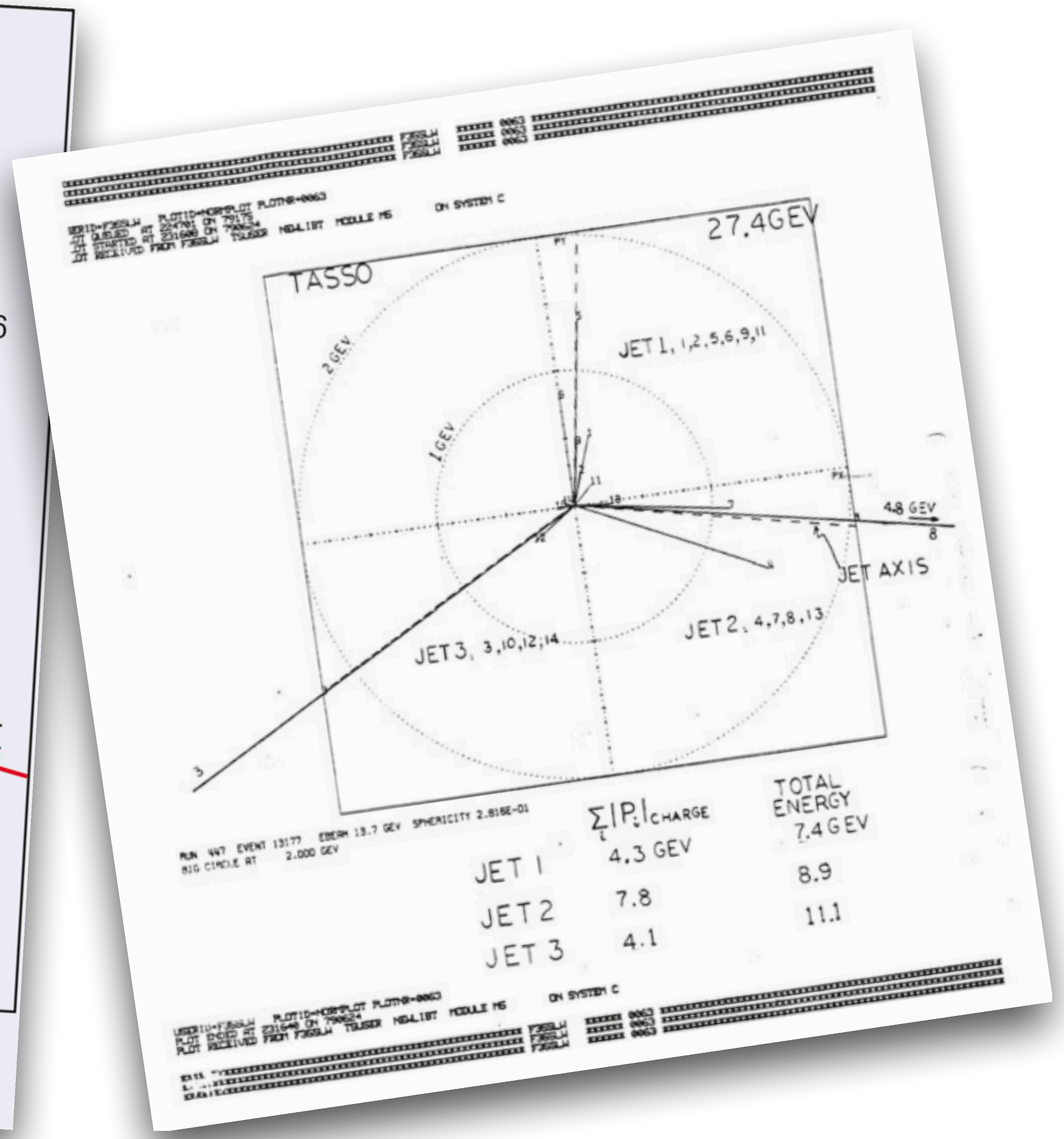
- Long lasting efforts to understand QCD



DIS > Partons, 1969



Asymptotic Freedom, 1973



3-`jet`> gluon, 1979

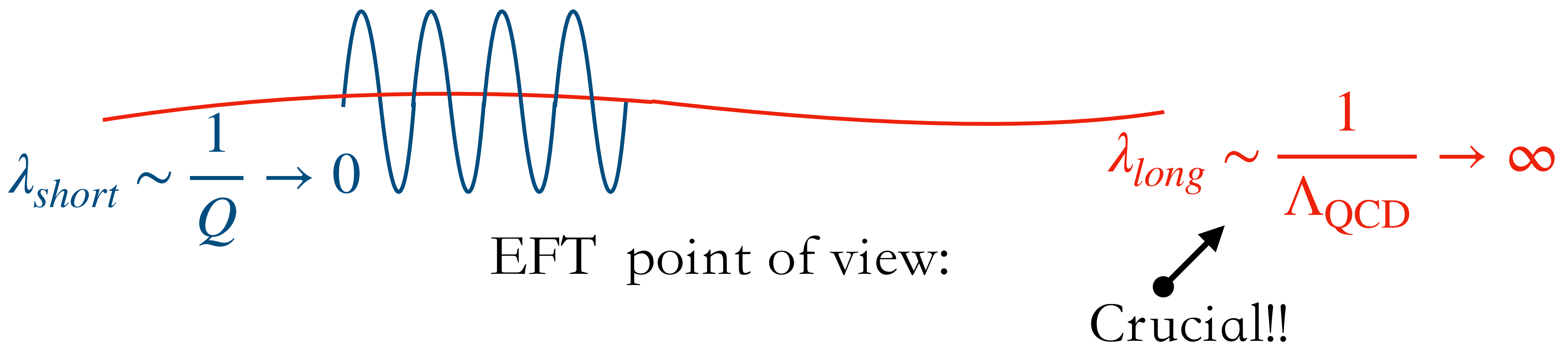
Developed powerful machineries:

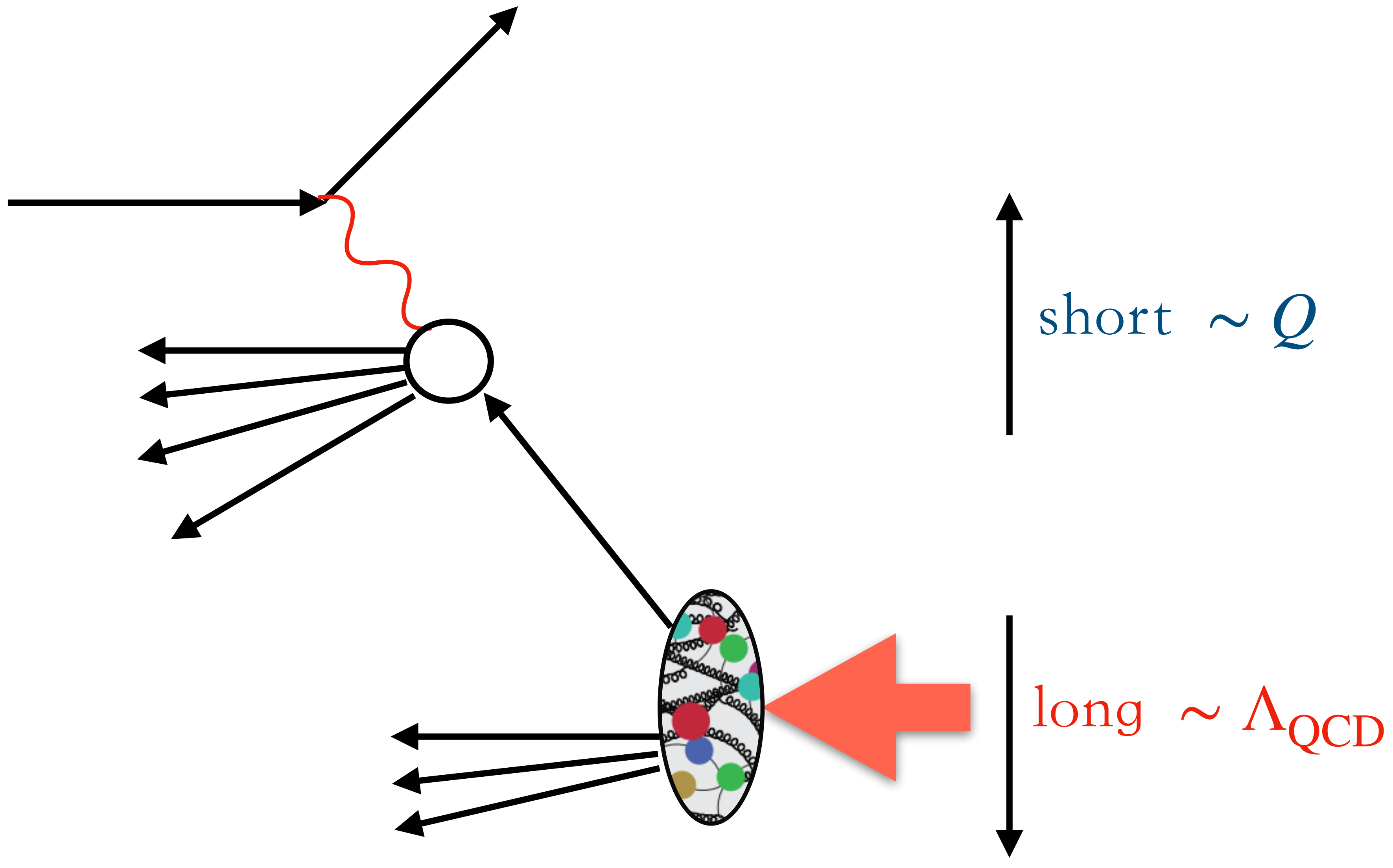
- Factorization
- Jets/event shapes and their outreaches

Jets and event shapes at colliders

- Factorization

$$\sigma = \sum_i \int \mathrm{d}x\, \hat{\sigma}_i(x) f_{i/P}(x) \; + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$

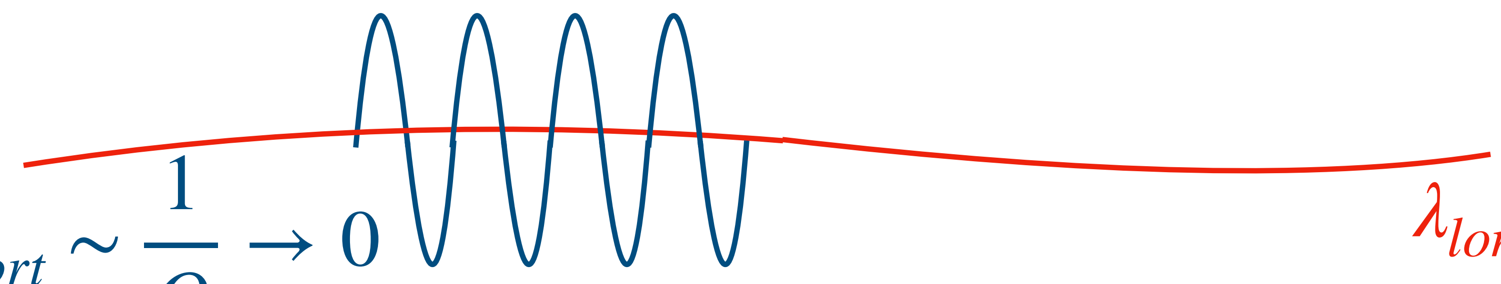




Jets and event shapes at colliders

- Factorization

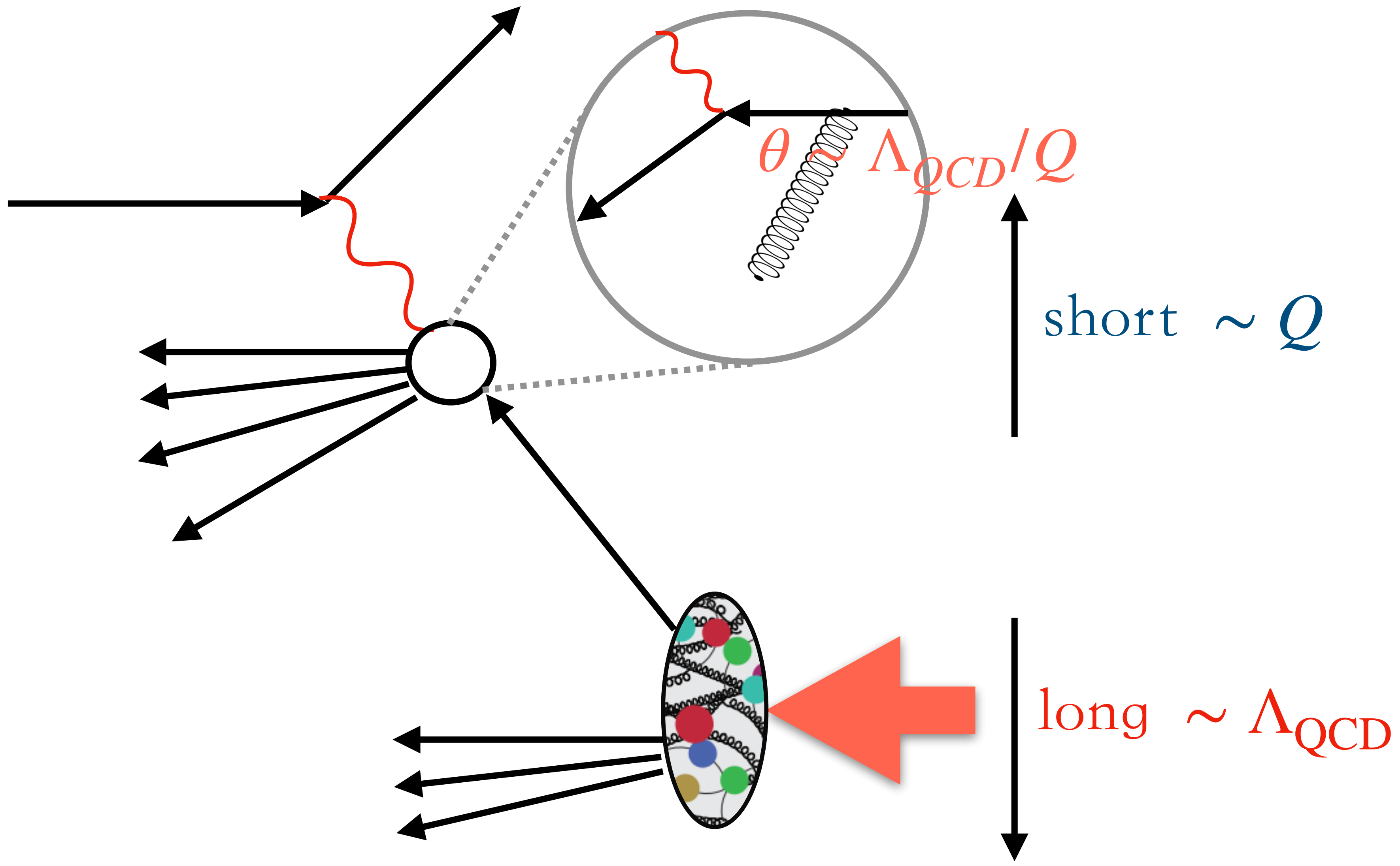
$$\sigma = \sum_i \int \mathrm{d}x\, \hat{\sigma}_i(x) f_{i/P}(x) \; + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$



$\lambda_{short} \sim \dfrac{1}{Q} \to 0$ EFT point of view: $\lambda_{long} \sim \dfrac{1}{\Lambda_{\mathrm{QCD}}} \to \infty$

Crucial!!

$$\sigma \propto \left(\hat{\sigma}_i^{(0)} - \alpha_s \log \frac{m_q}{Q} \ldots\right) f_{i/P}(x, m_q)$$



Lose predictive power

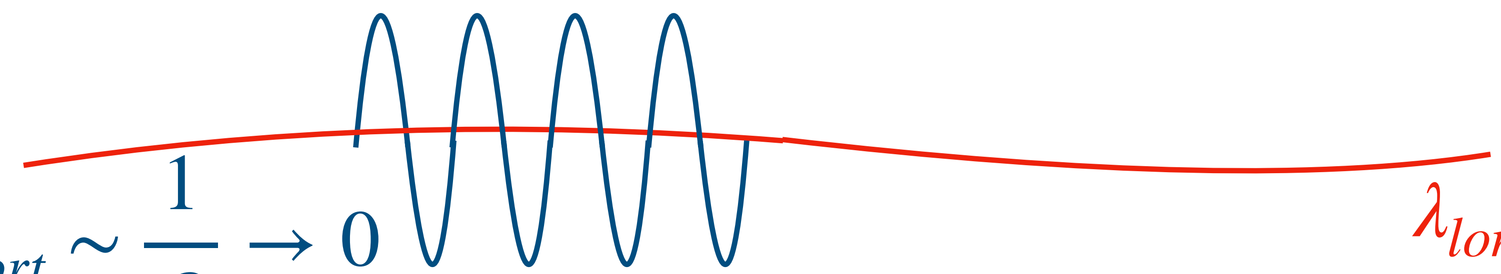
- Mixing pert. and non-pert.
- Huge corrections from logs
- Where to evaluate $f_{i/P}$?

Jets and event shapes at colliders

- Factorization

$$\sigma = \sum_i \int \mathrm{d}x\, \hat{\sigma}_i(x) f_{i/P}(x) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{Q}\right)$$

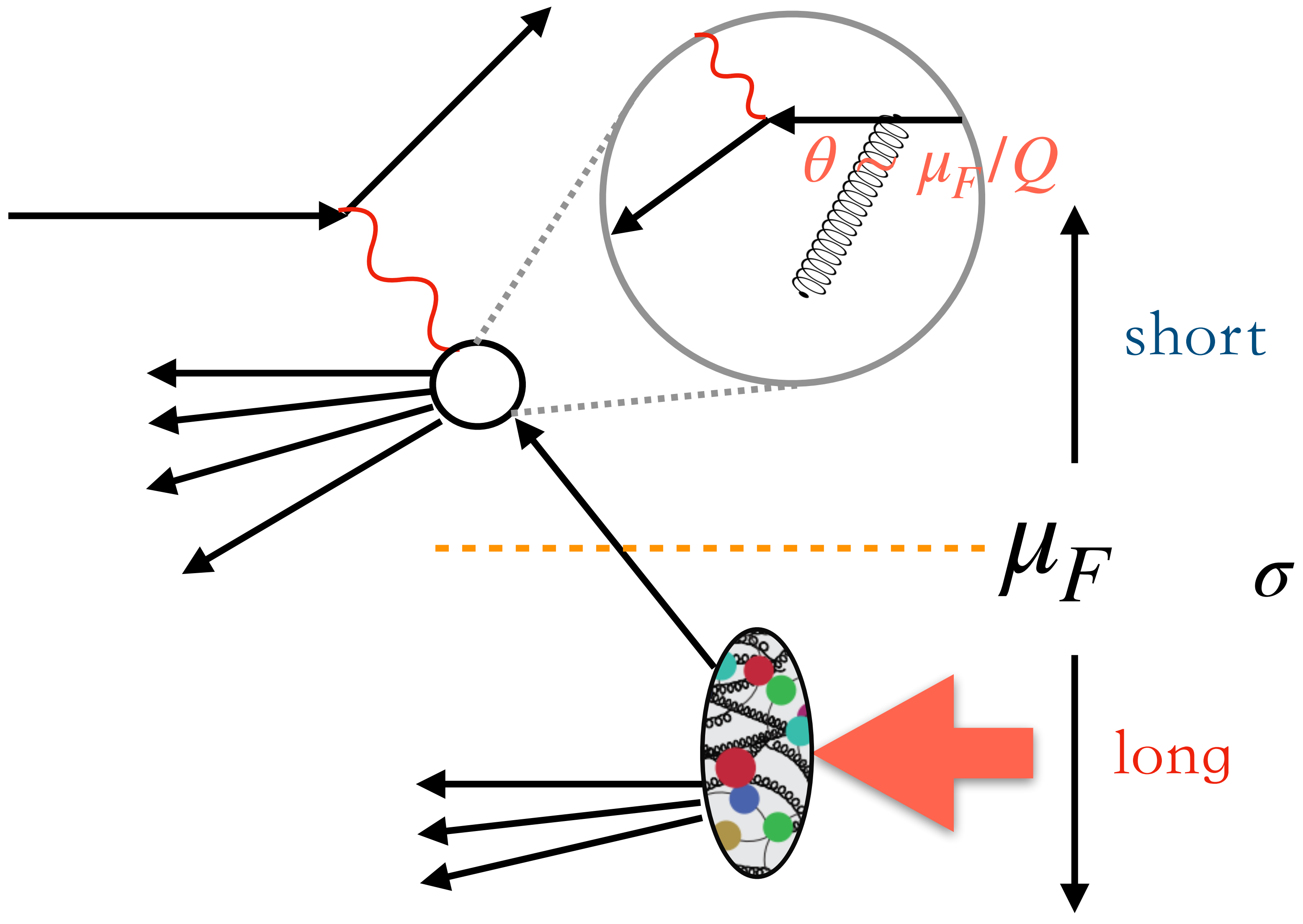
$\lambda_{short} \sim \frac{1}{Q} \to 0$



$\lambda_{long} \sim \frac{1}{\Lambda_{\rm QCD}} \to \infty$

EFT point of view:

Crucial!!



$$\sigma \propto \left(\hat{\sigma}_i^{(0)} - \alpha_s \log\frac{m_q}{Q} \dots\right) f_{i/P}(x, m_q)$$

$m_q \sim \Lambda_{\rm QCD} = 0$ in $\hat{\sigma}_i$

Lose predictive power

- Mixing pert. and non-pert.
- Huge corrections from logs
- Where to evaluate $f_{i/P}$?

$$\sigma \propto \left[\hat{\sigma}_i^{(0)} + \alpha_s\left(-\frac{1}{\epsilon}P(x) - P(x)\log\frac{\mu_F}{Q} + \dots\right)\right] f(x, \mu_F)$$

$$\mu_F\, \mathrm{d}\sigma/\mathrm{d}\mu_F = 0 \longrightarrow \begin{array}{l} \mu_F\, \mathrm{d}\hat{\sigma}_i/\mathrm{d}\mu_F = -P(x) \otimes \hat{\sigma}_i \\ \mu_F\, \mathrm{d}f_i/\mathrm{d}\mu_F = P(x) \otimes f_i \end{array}$$

With predictive power

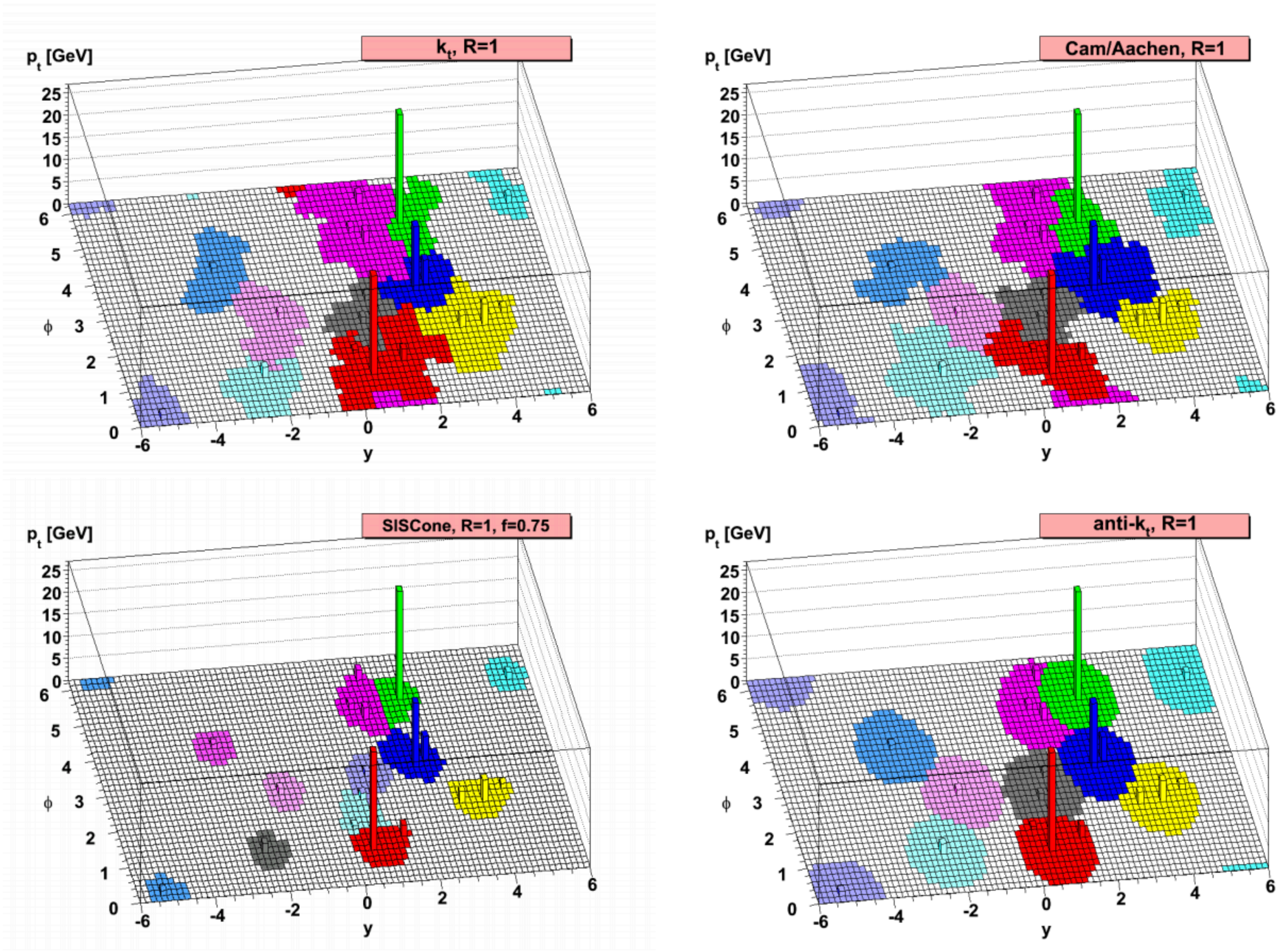
- Pay a price of an artificial cutoff or even divergence, but cancels against the long distance physics
- No large logs if μ_F is set to Q. Behind that is the resummation of large logs
- Applicable to other multiple scale problems, pert. or non-pert.

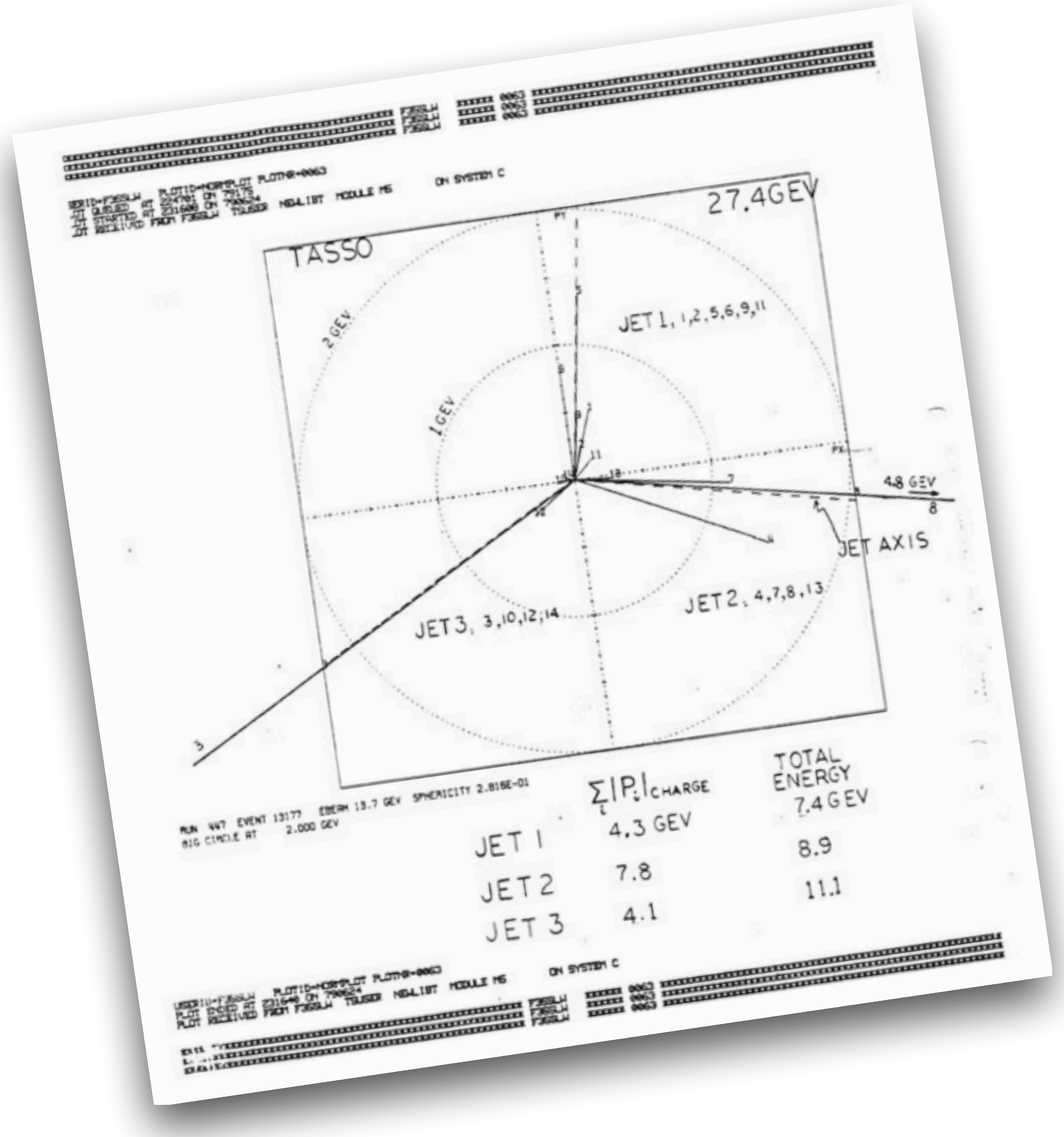
Jets and event shapes at colliders

- Jets and event shapes

Jets (anti-k_T , $\cdots$)

- Local objects, contain part of the (QCD) final states





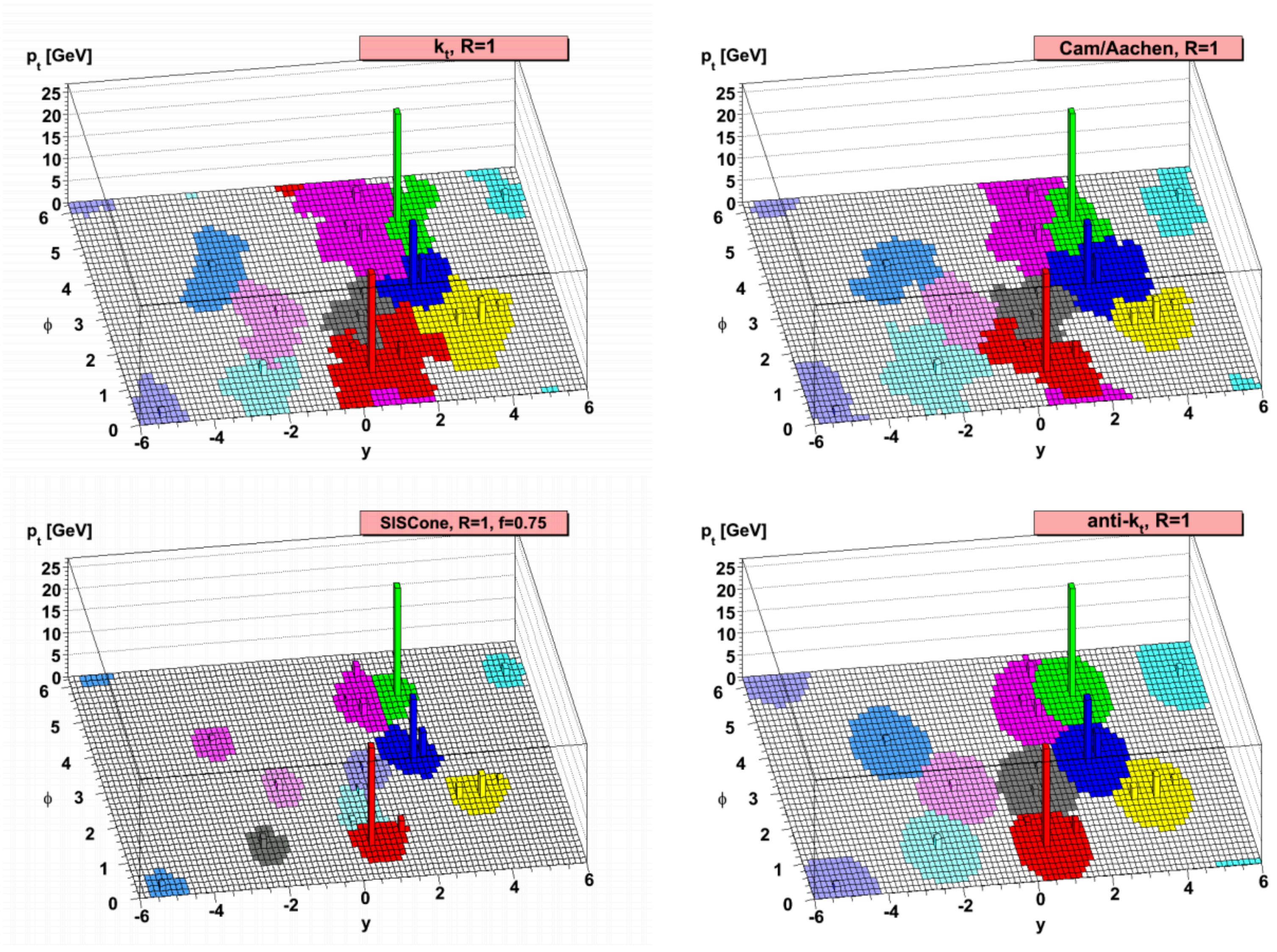
Jet-like or `jettiness`

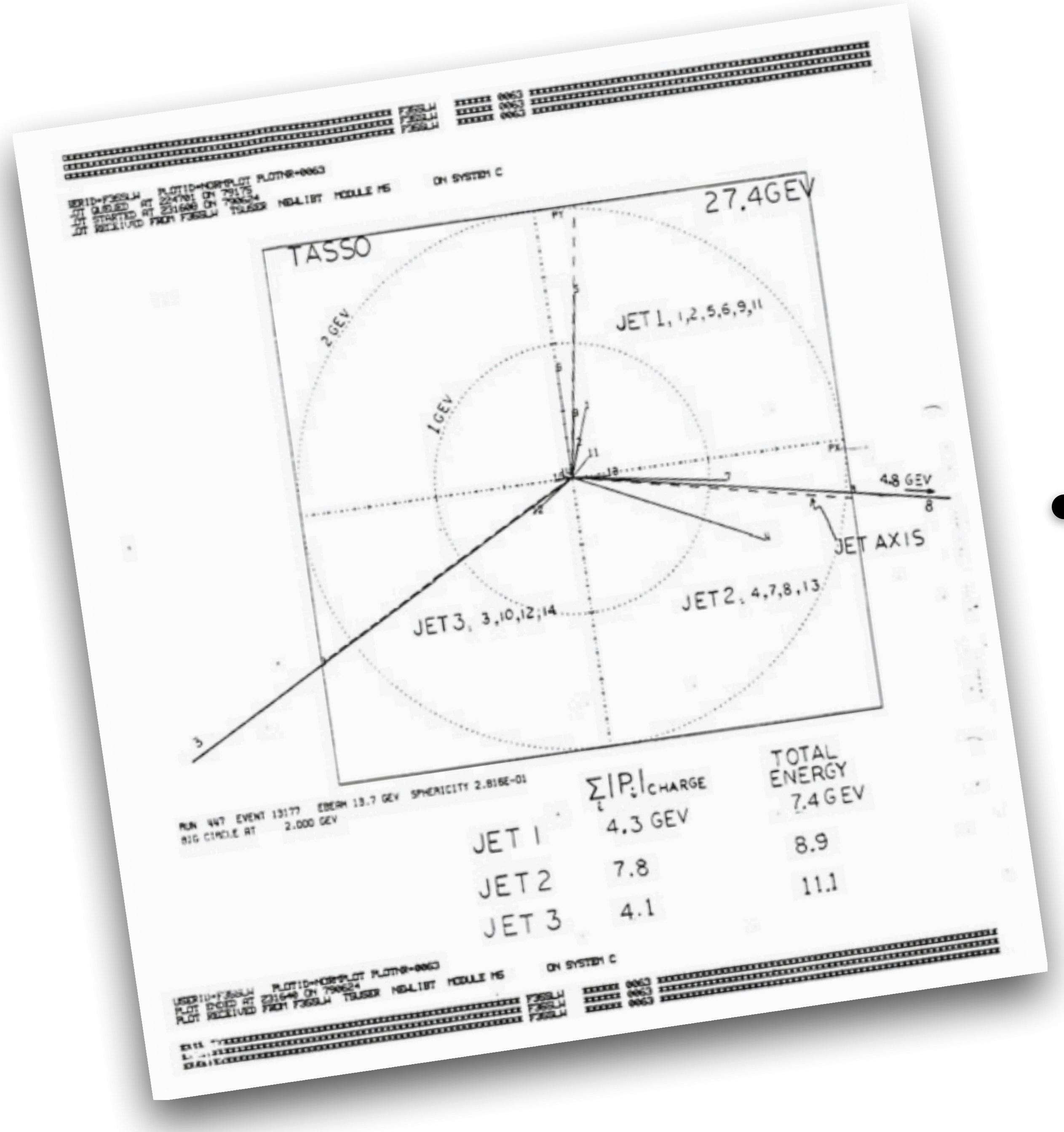
Jets and event shapes at colliders

- Jets and event shapes

Jets (anti-k_T, $\cdots$)

- Local objects, contain part of the (QCD) final states

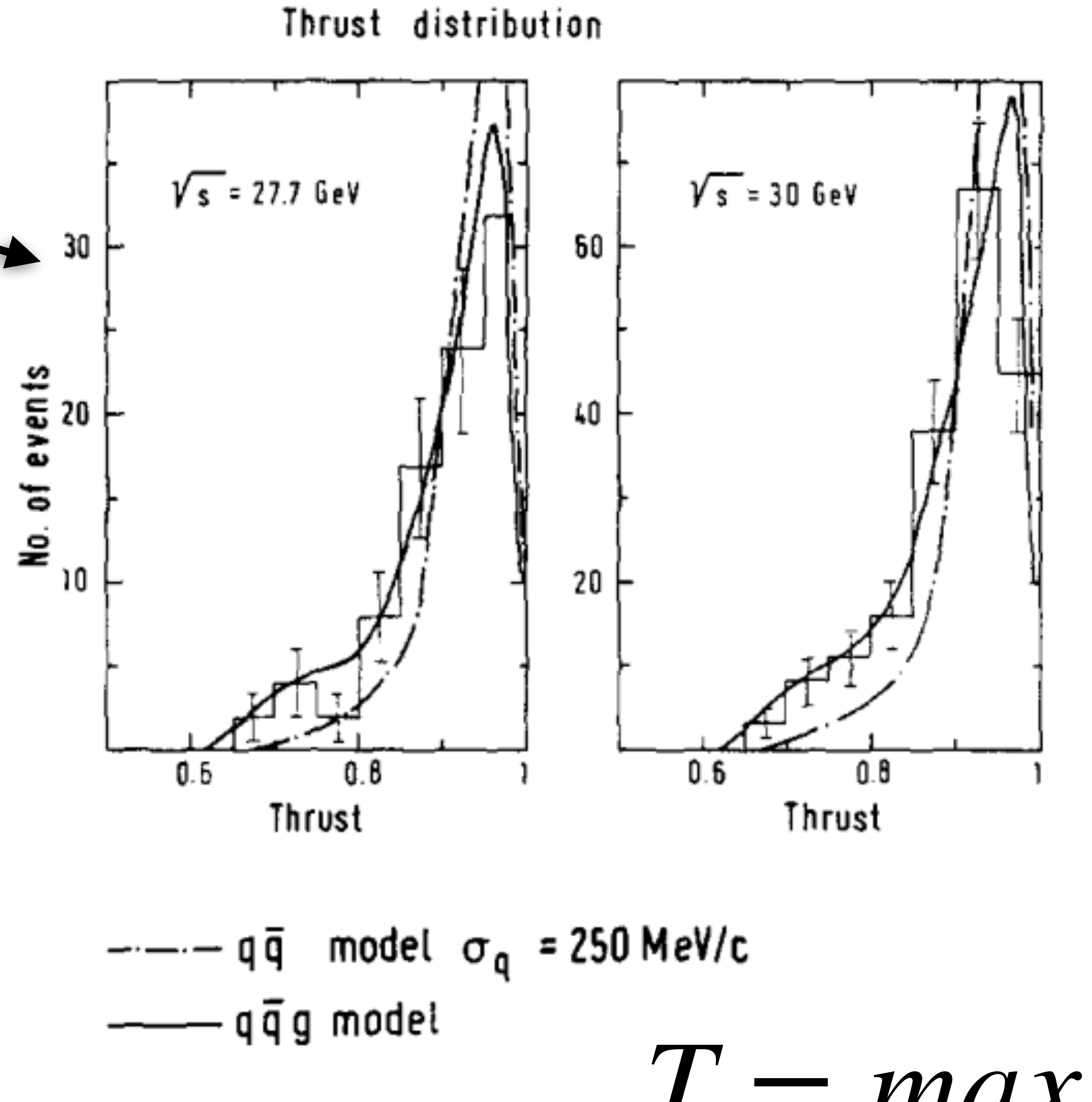




Jet-like or `jettiness`

Event shapes (T, q_T, $\cdots$)

- Global objects, count all the (QCD) final states



$$T = max_n \frac{\sum k_i \cdot n}{\sum k_i}$$

Jets and event shapes at colliders

- Jets and event shapes

Jets (anti-k_T, $\cdots$)

- Local: demand less for the detectors: coverage $\cdots$
- Suppress the contaminations
- More differential, more flexible

Event shapes (T, q_T, $\cdots$)

- Global: demand more for the detectors: coverage $\cdots$
- More sensitive to the contaminations
- Inclusive

LEP: event shapes, jets

LHC: jets

EIC: jets? event shapes?

- Experimental feasibility
- Theoretical Precision

Jets and event shapes at colliders

- Jets and event shapes

Jets (anti-k

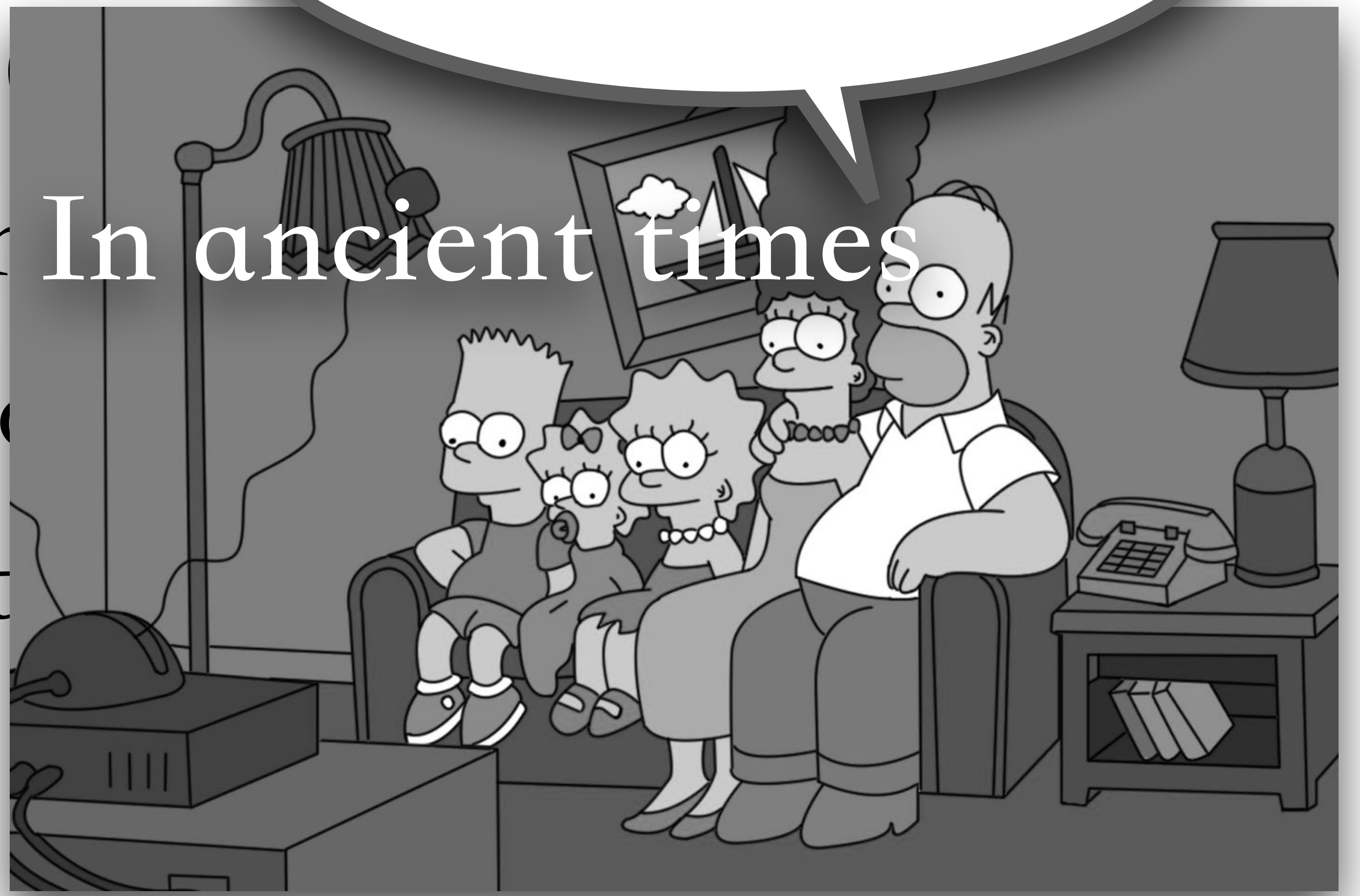
etectors:

minations

more flexible

Event shapes

- Global: dem
  detectors: c
- More sensit
- Inclusive



LEP: event shapes, jets

LHC: jets

EIC: jets? event shapes?

- Experimental feasibility
- Theoretical Precision

Big ideas, well-designed observables to turn impossible to possible

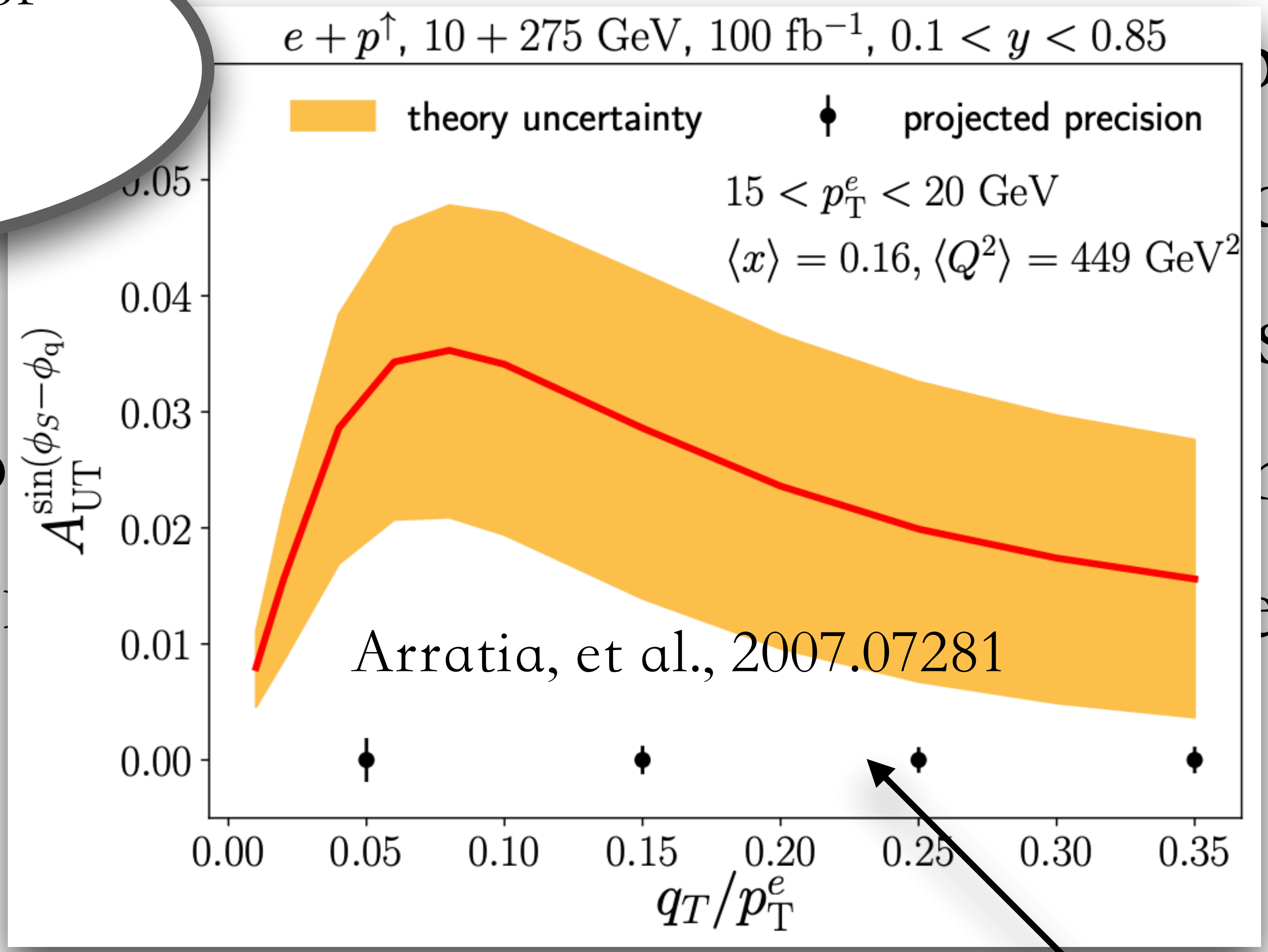
Jets and event shapes at colliders

- Jets and event shapes

Jets (anti-*k*

inatio

ore fle



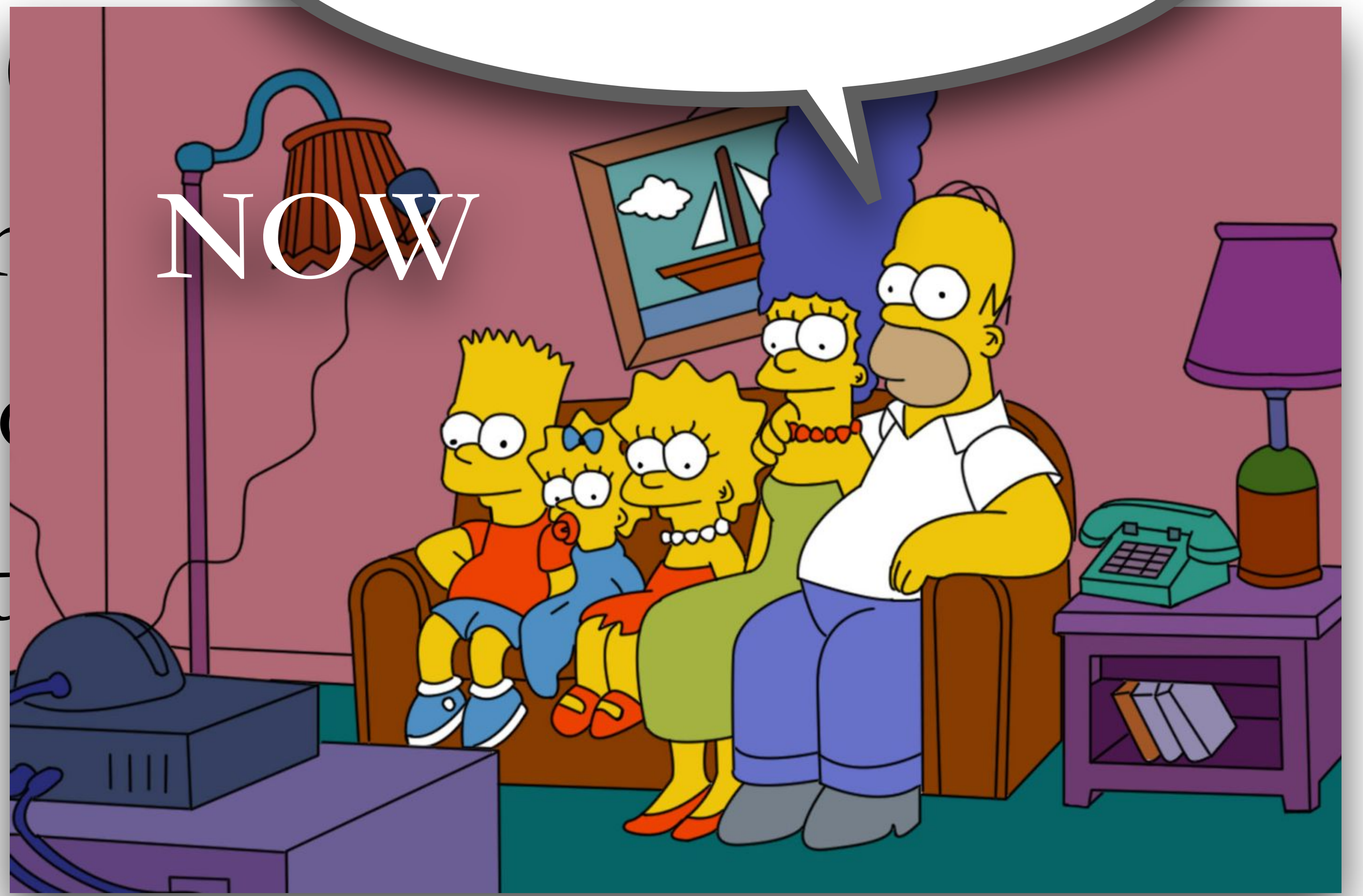
pes

dem

s: c

nsit

e



LEP: event shapes, jets

LHC: jets

EIC: jets? event shapes?

- Experimental feasibility
- Theoretical Precision

$$\sigma = \sum_i \int dx\, \hat{\sigma}_i(x) f_{i/P}(x)$$

$$\downarrow$$

$$\text{data} = \sum_i \int dx\, \hat{\sigma}_i(x) f_{i/P}(x)$$

Any errors will propagate into f

Jets and event shapes at colliders

- Jets and event shapes

Jets (anti-k_T, $\cdots$)

- Better parton proxies, $R \gg \Lambda_{\rm QCD}/Q$
- Complicated phase space manipulations, computation hard, recent efforts for NNLO or beyond
- Local: resummation accuracy unclear: non-global logs, $\cdots$

Event shapes (T, q_T, $\cdots$)

- Better parton proxies, $1 - T \gg \Lambda_{\rm QCD}/Q$
- Computation friendly, analytic FO calculations
- Global: clean resummation

EIC: jets and event shapes

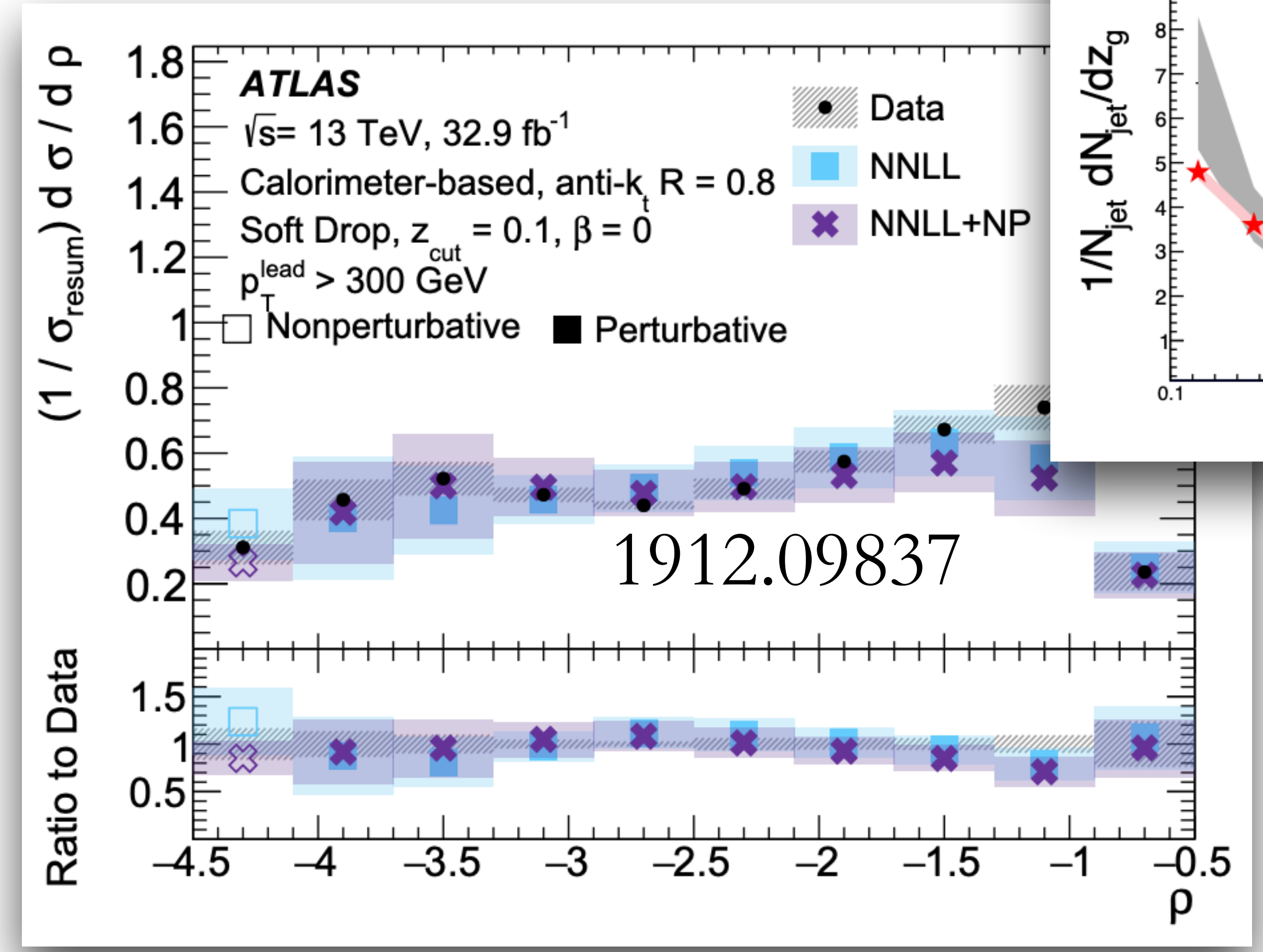
- Experimental feasibility
- Theoretical Precision

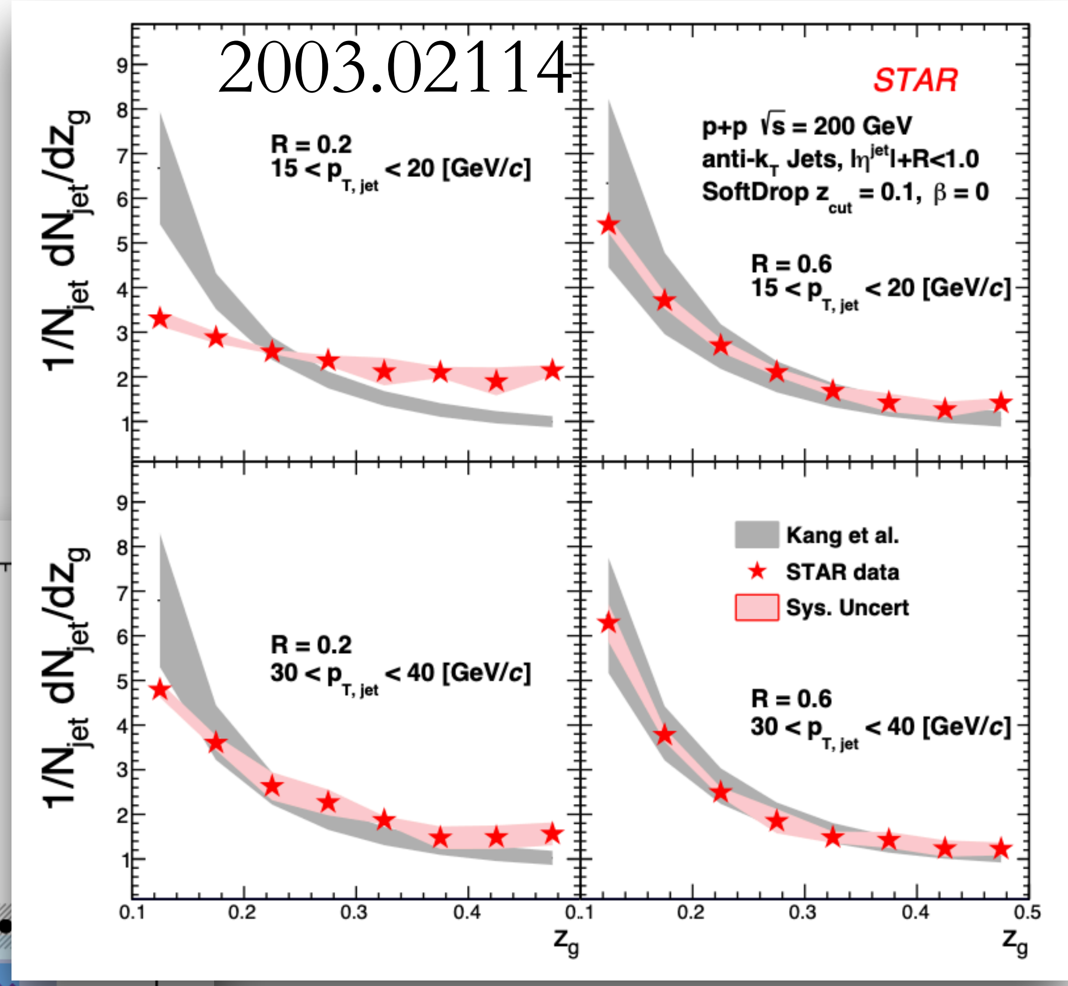
$$\text{data} = \sum_i \int \mathrm{d}x\, \hat{\sigma}_i(x) f_{i/P}(x)$$

Je

Event shapes within jets: jets substructures

- Active for both HEP and HNP
- BSM searching
- Precision measurement
- Tagging
- Probe NP/medium effects
- Machine learning





...lytic FO

• ...ion

global logs, ⋯

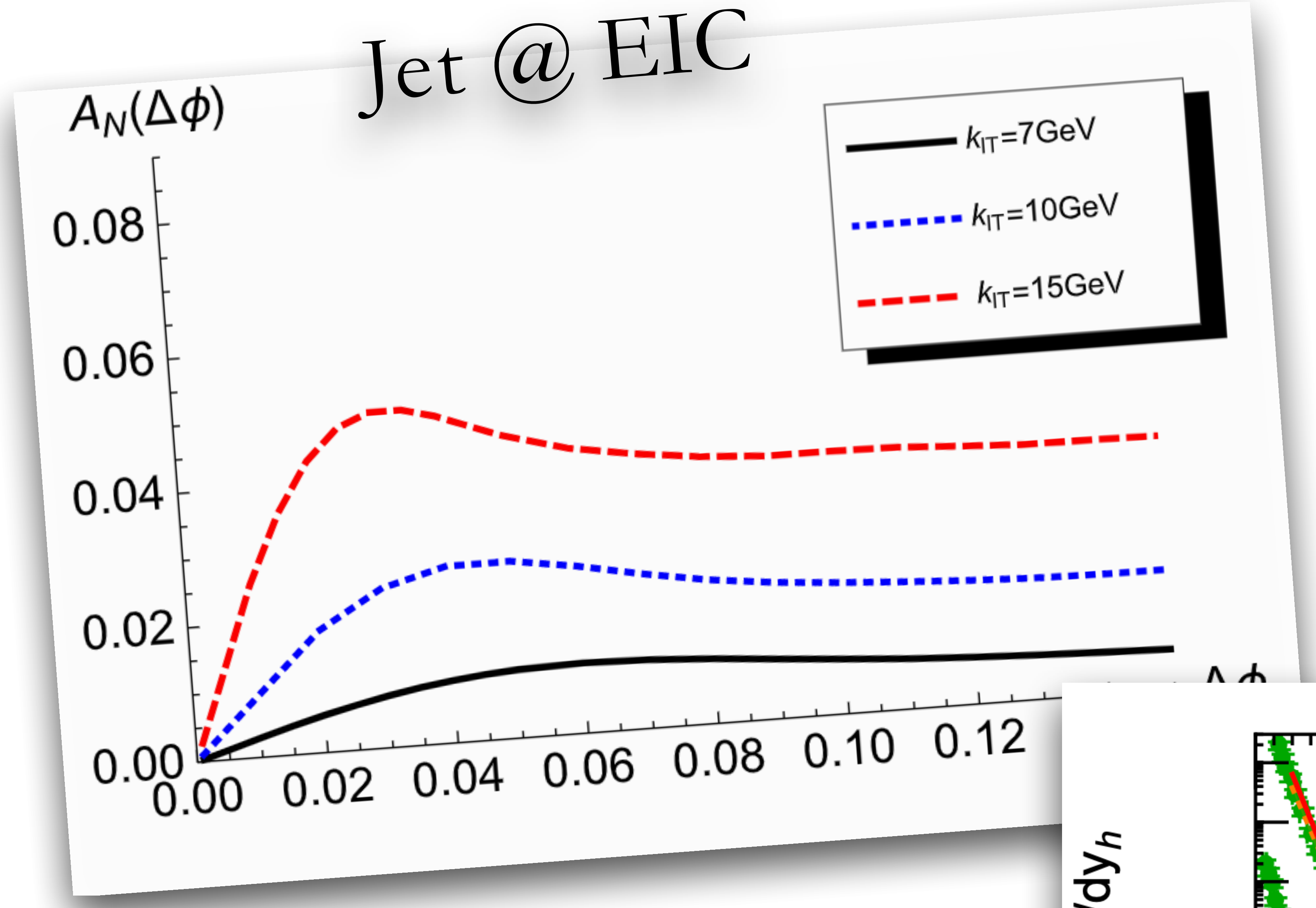
EIC: jets and event shapes

- Experimental feasibility
- Theoretical Precision

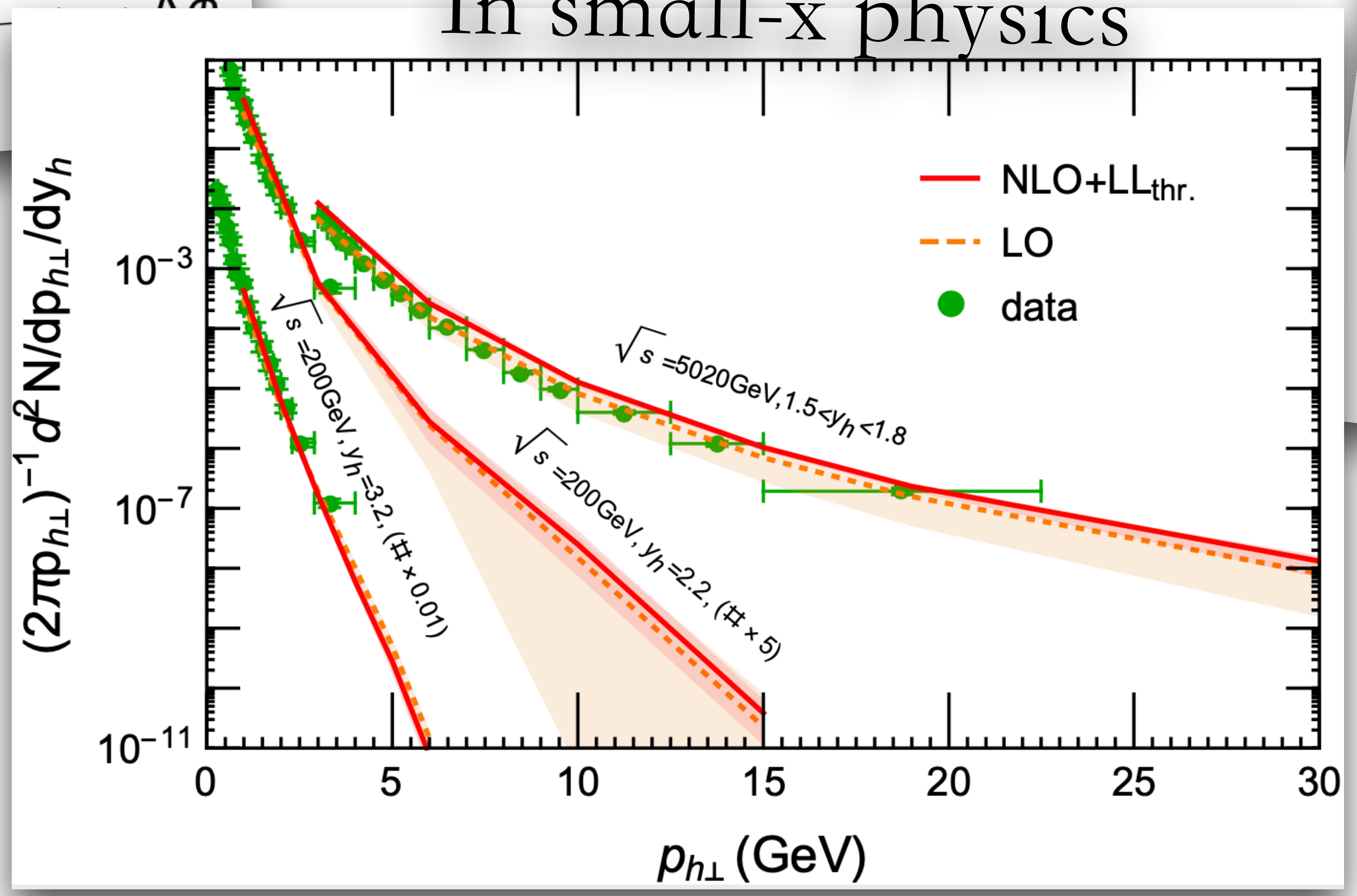
$$\text{data} = \sum_i \int \mathrm{d}x\, \hat{\sigma}_i(x) f_{i/P}(x)$$

Examples for inner structures

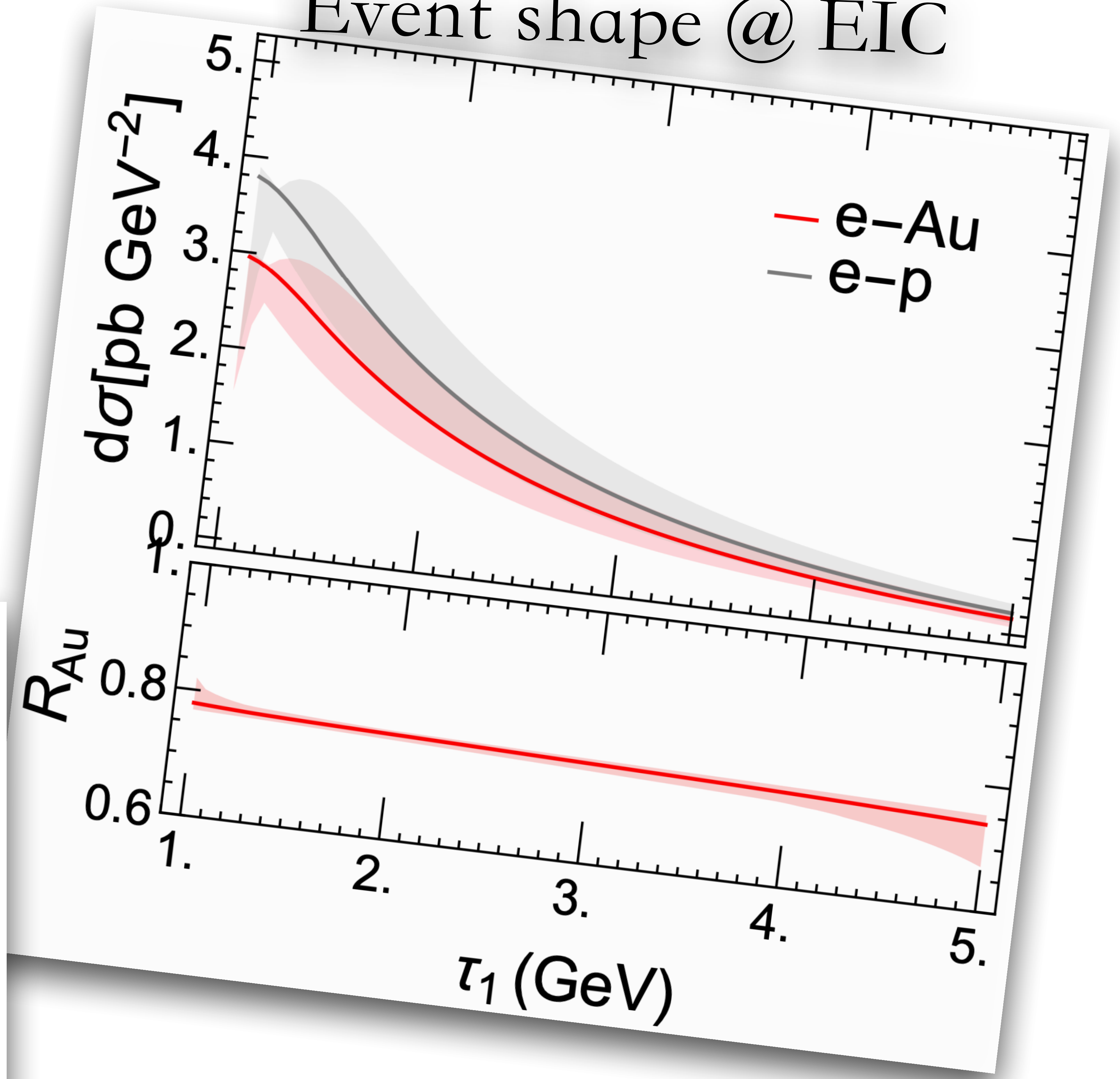
Jet @ EIC



In small-x physics



Event shape @ EIC

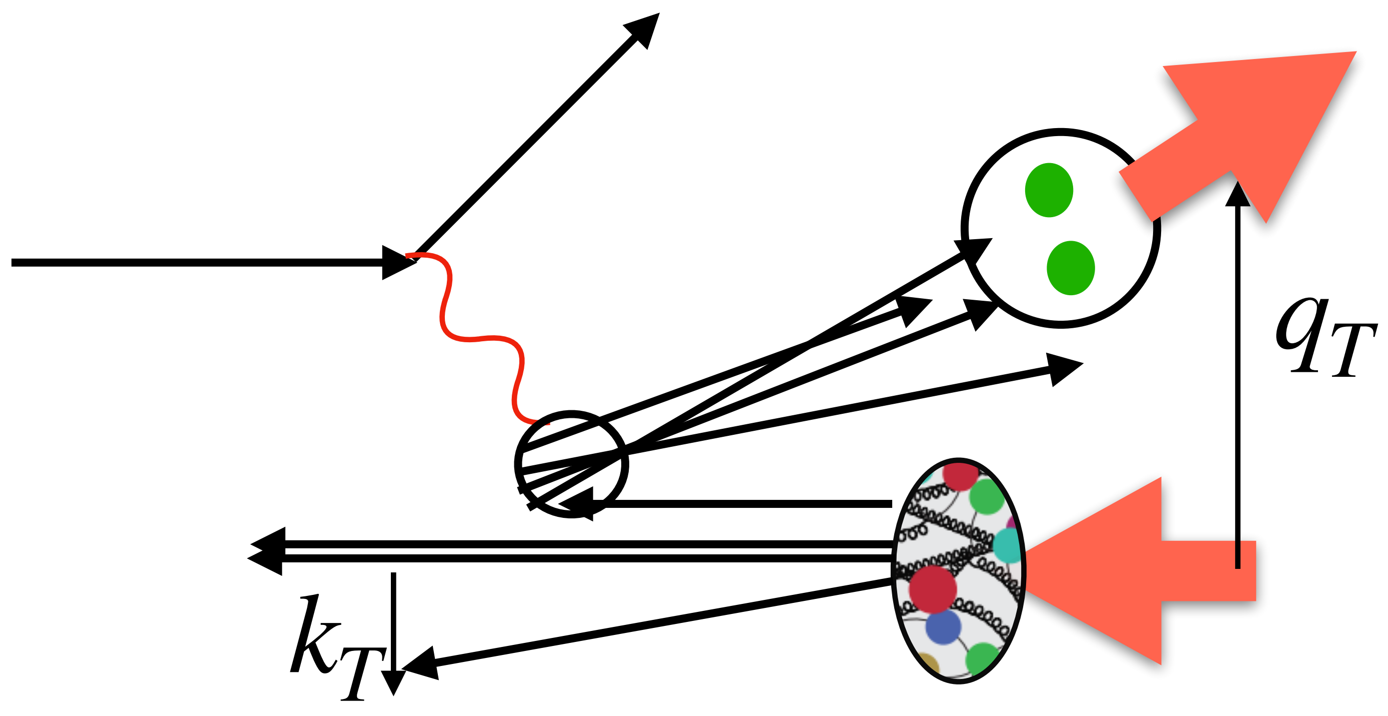


Examples for inner structures

- Jet @ EIC

Standard TMDs: DY, SIDIS and e^+e^-

- Simple, clean, well-established TMD factorization ✓
- Relatively high precision, e.g. DY NNLO or beyond ✓

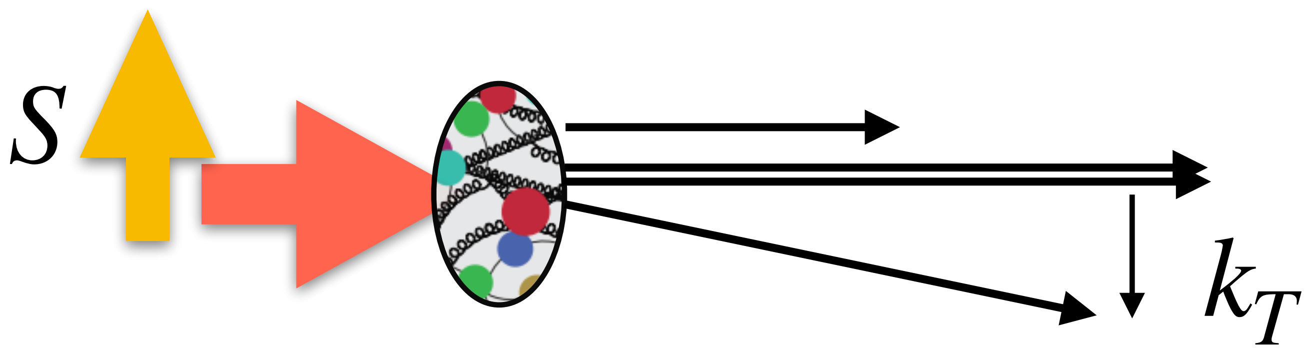


For Unpolarized SIDIS in Breit Frame $Q = (0,0,0,-Q)$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T} \sim \hat{\sigma}_{ji}(Q) D_{h/j}(z, k_{T_j}) \otimes f_{i/P}(x, k_{T,i}) \otimes S(k_{T,k}) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$

$Q \gg q_T$

For transversely polarized proton



$$f_{i/P\uparrow} = f_{i/P} - \frac{1}{M} f_{1T}^{\perp,q}(x, k_\perp) S \cdot (P \times k_\perp)$$

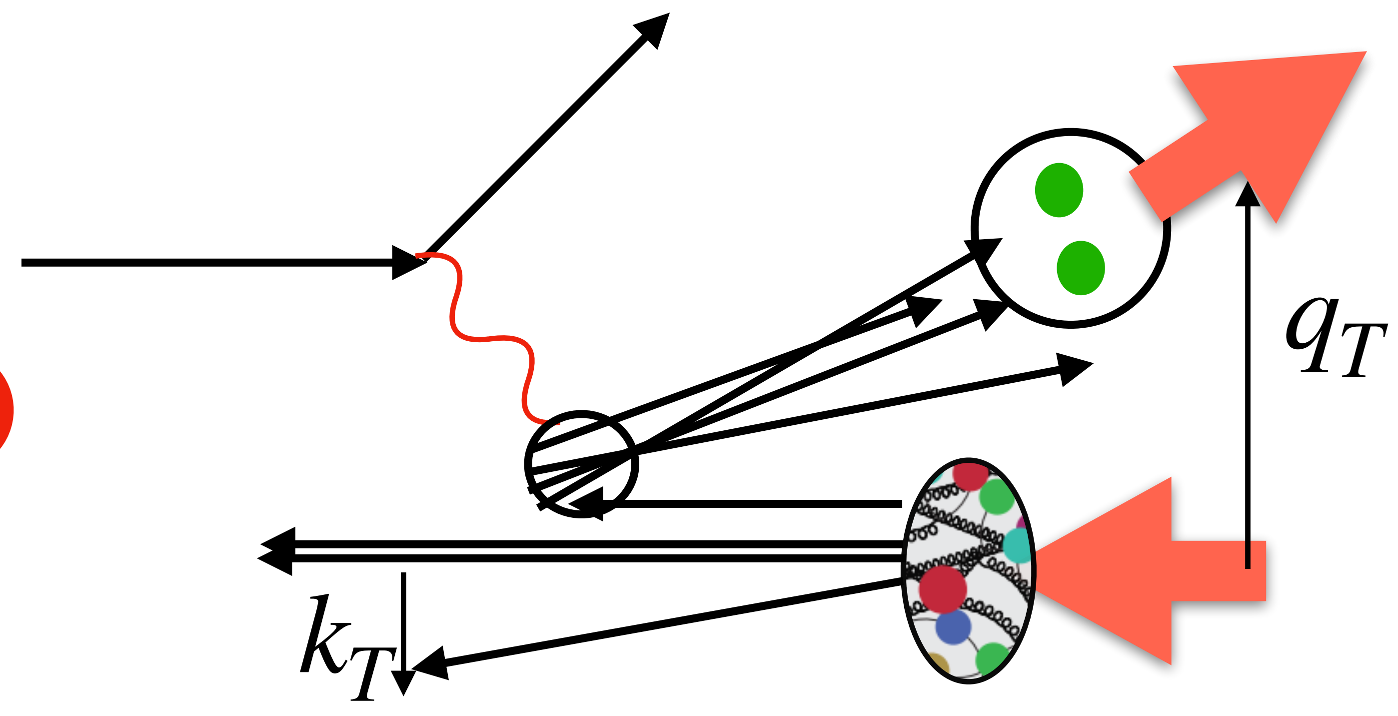
$$f_{1T}^{\perp,DIS}(x, k_\perp) = -f_{1T}^{\perp,Drell}(x, k_\perp)$$

Examples for inner structures

- Jet @ EIC

Standard TMDs: DY, SIDIS and e^+e^-

- Too simple, isn't that boring? Miss opportunities ✖
- Possible entanglement between different un-known objects ✖



For Unpolarized SIDIS in Breit Frame $Q = (0,0,0,-Q)$

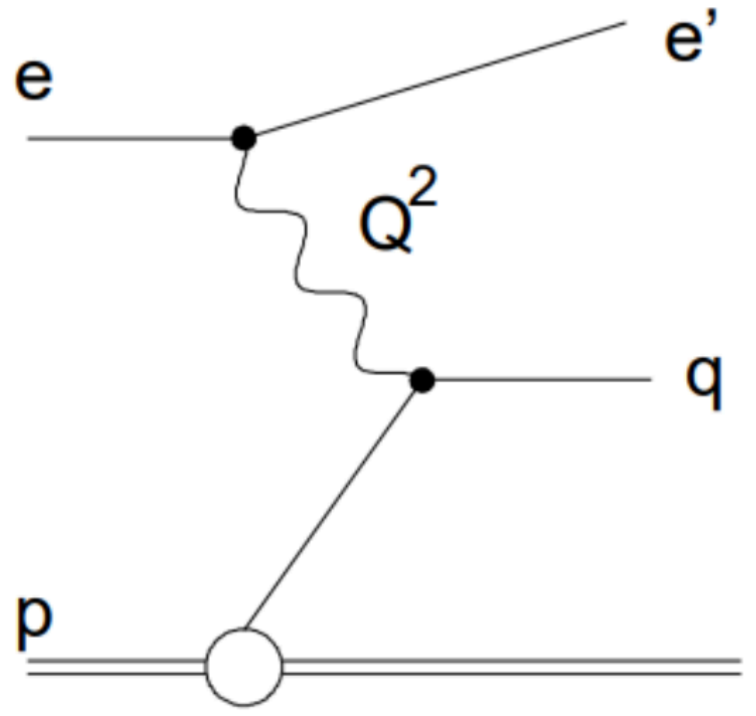
$$\frac{d\sigma}{dq_T} \sim \hat{\sigma}_{ji}(Q) D_{h/j}(z, k_{T_j}) \otimes f_{i/P}(x, k_{T,i}) \otimes S(k_{T,k}) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$

$Q \gg q_T$

Examples for inner structures

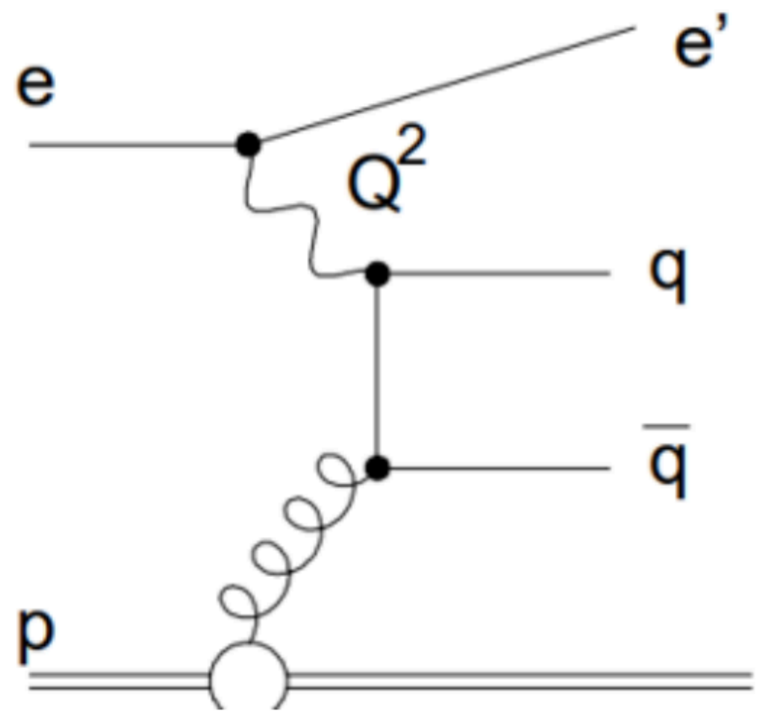
- Jet @ EIC

General status



LO in *e-p* COM frame

- More LHC like
- More stats
- Option w/o tagging e
- $\mathcal{O}(\alpha_s^3)$ unpolarized w/ tagging *e* and $\mathcal{O}(\alpha_s^2\alpha^2)$
- $\mathcal{O}(\alpha_s^2)$ longitudinal polarized w tagging *e*, $\mathcal{O}(\alpha_s\alpha)$



LO in Breit frame

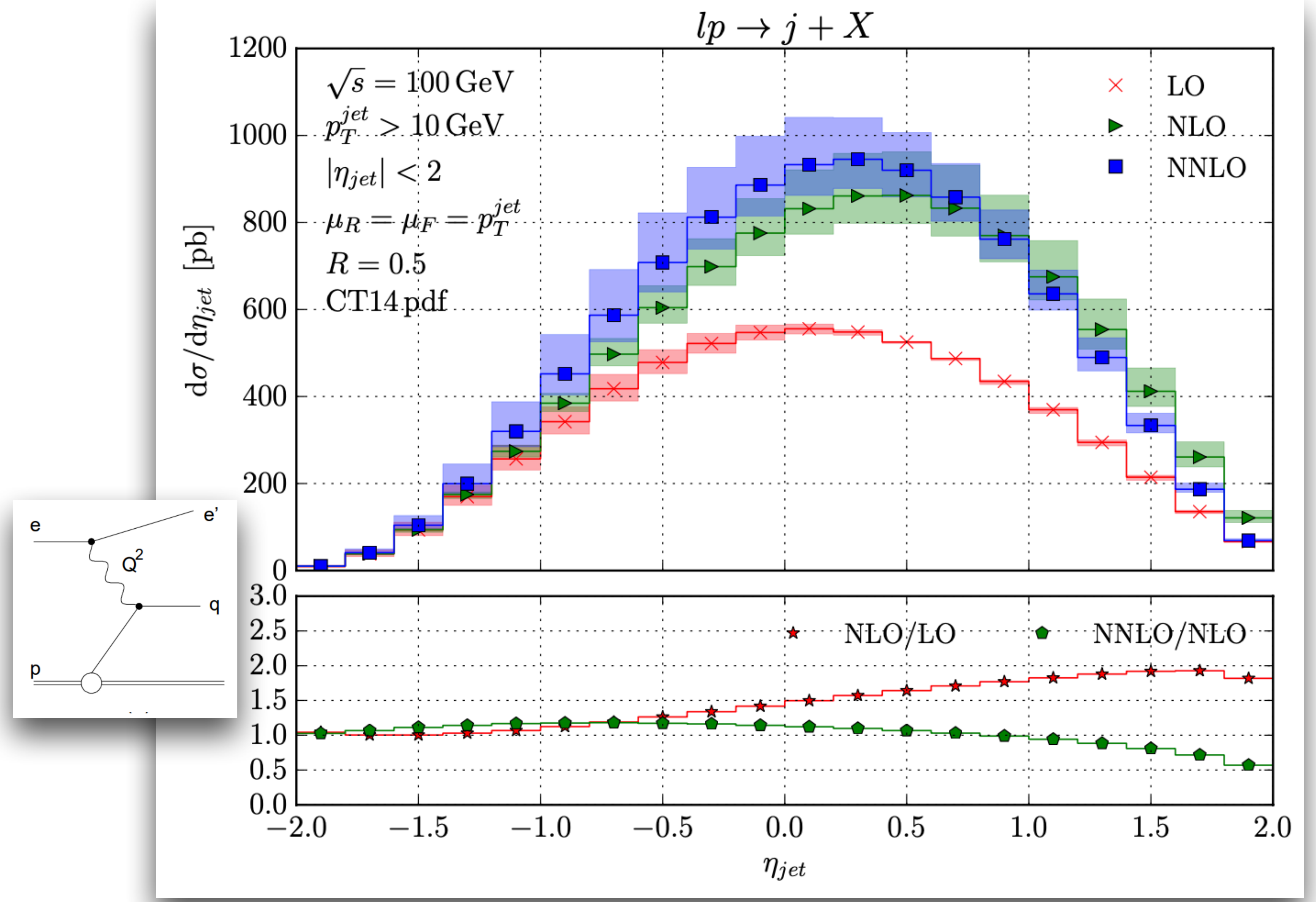
- Probe initial gluons
- $\mathcal{O}(\alpha_s^2)$ Unpolarized

BOTTOM LINE:
Jet @ EIC shares the same FO accuracy as the other standard processes

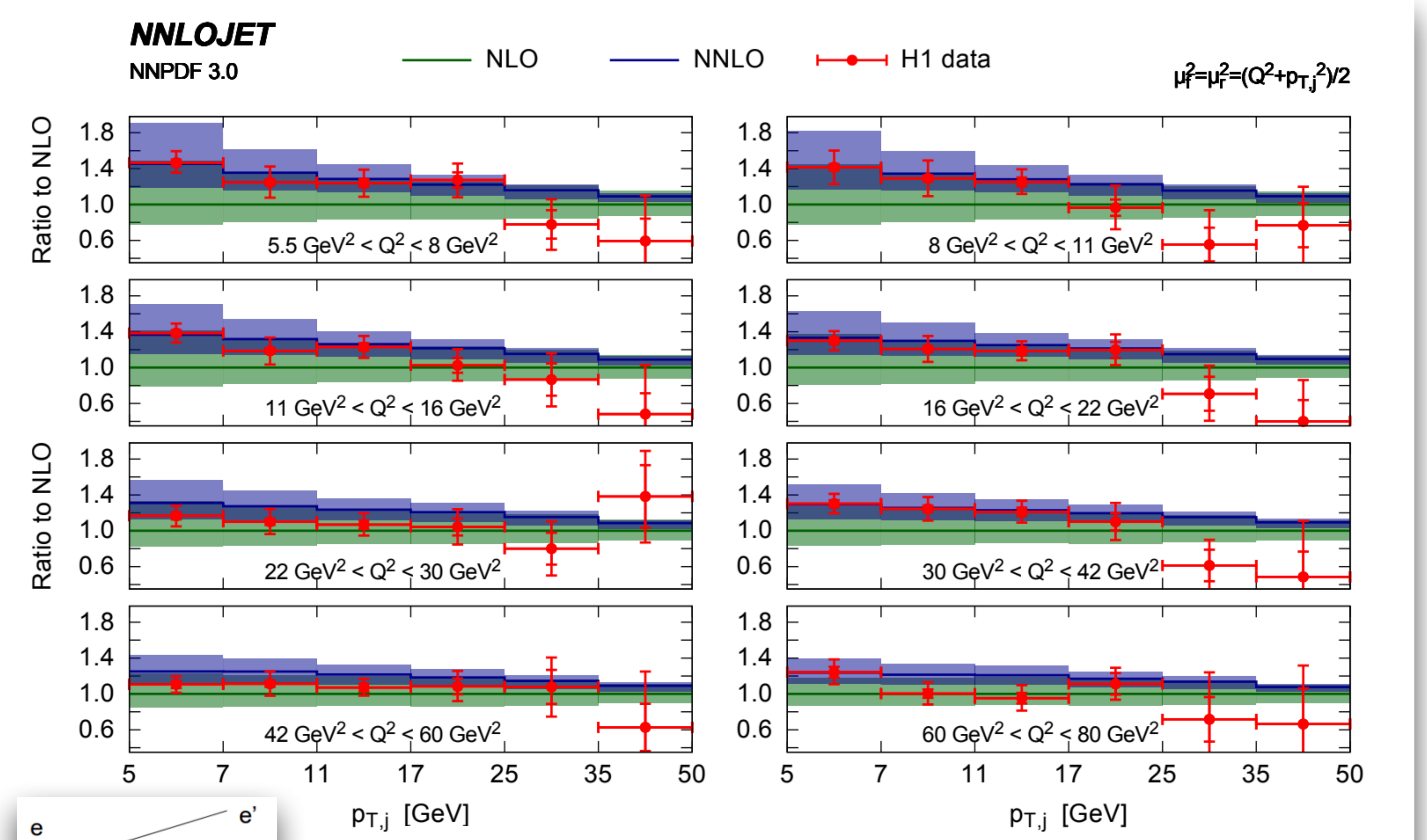
Examples for inner structures

- Jet @ EIC

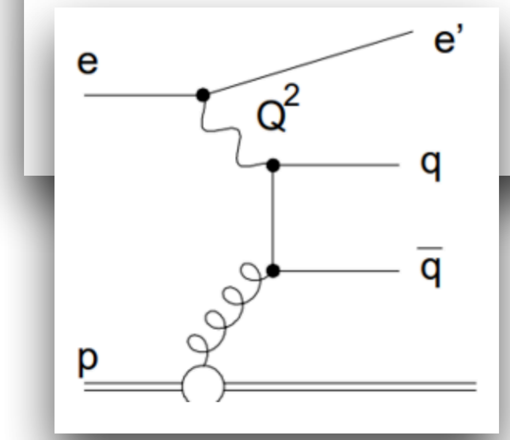
General status



Abelof, Boughezal, XL, Petriello, 2018



Currie, Gehrmann, Huss, Niehues, 2017

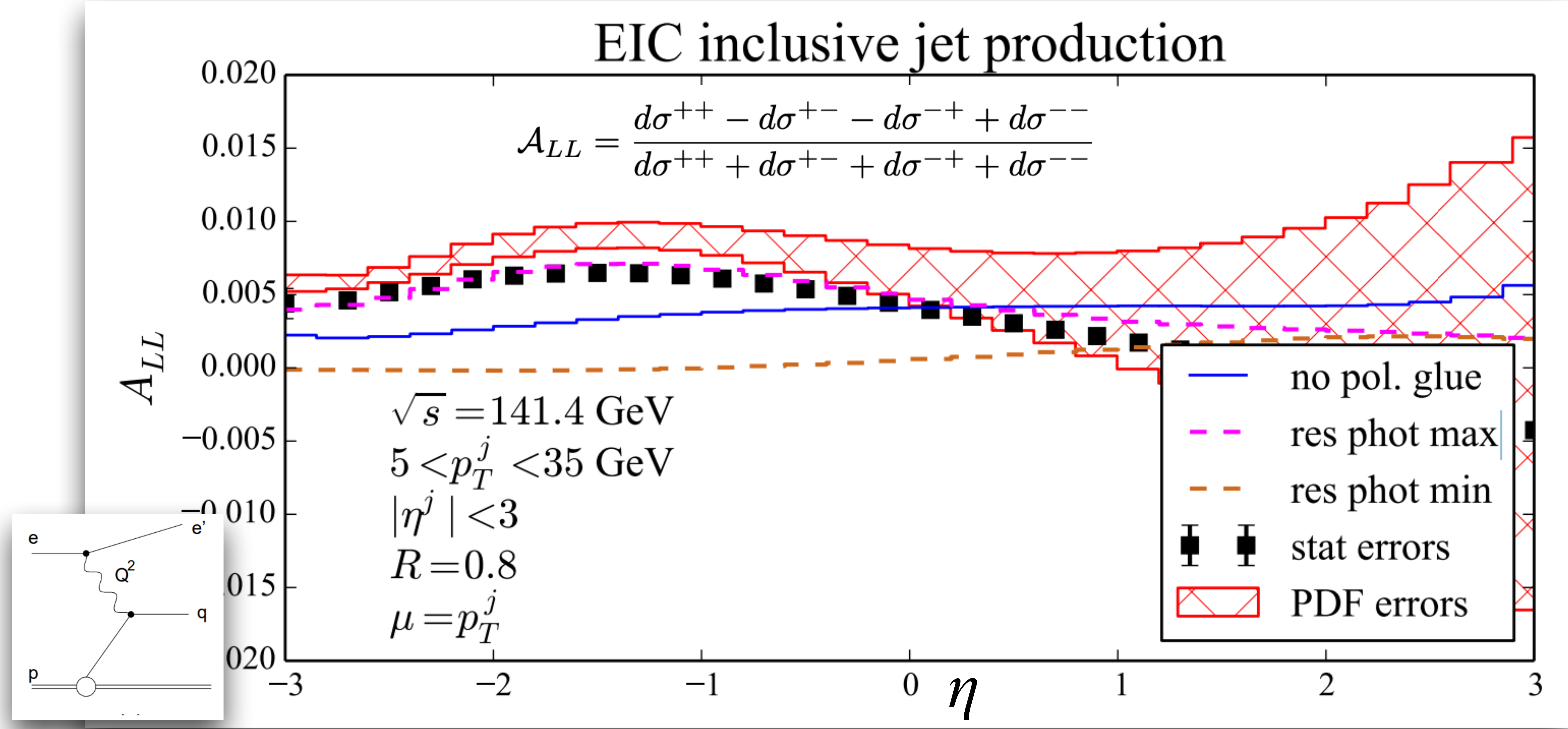


- In both cases, higher order corrections are visible and become substantial for small $p_{T,j}$ and low Q^2, and affect the shapes
- New partonic channels open up, e.g., qq, gq

Examples for inner structures

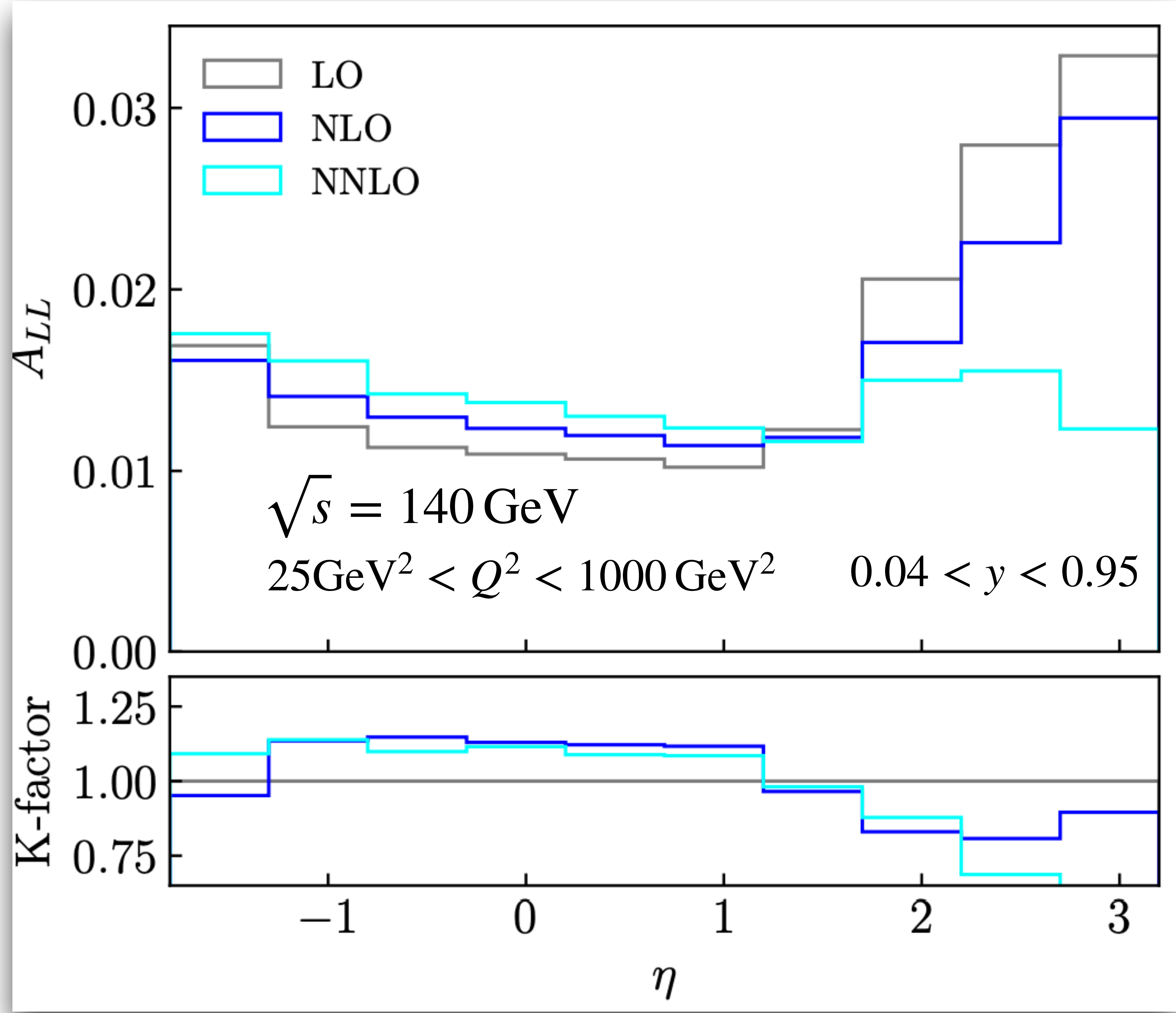
- Jet @ EIC

General status



Boughezal, Petriello, Xing, 2018

See also Hinderer, Schlegel, Vogelsang



Borsa, de Florian, Pedron, 2020

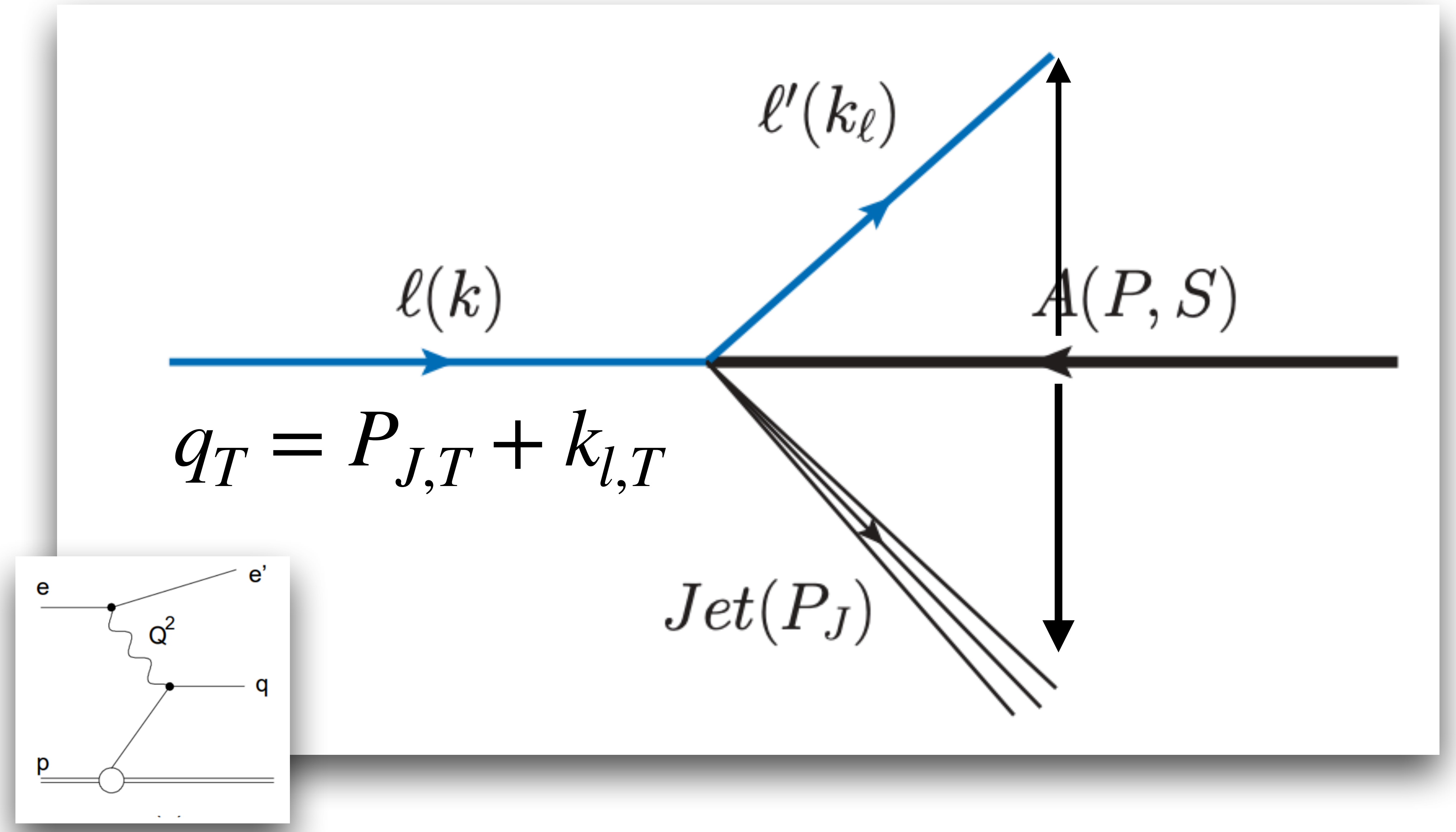
- Again, higher order corrections are substantial
- EIC will be sensitive to the proton helicity information by selecting η ranges

Examples for inner structures

- Jet @ EIC

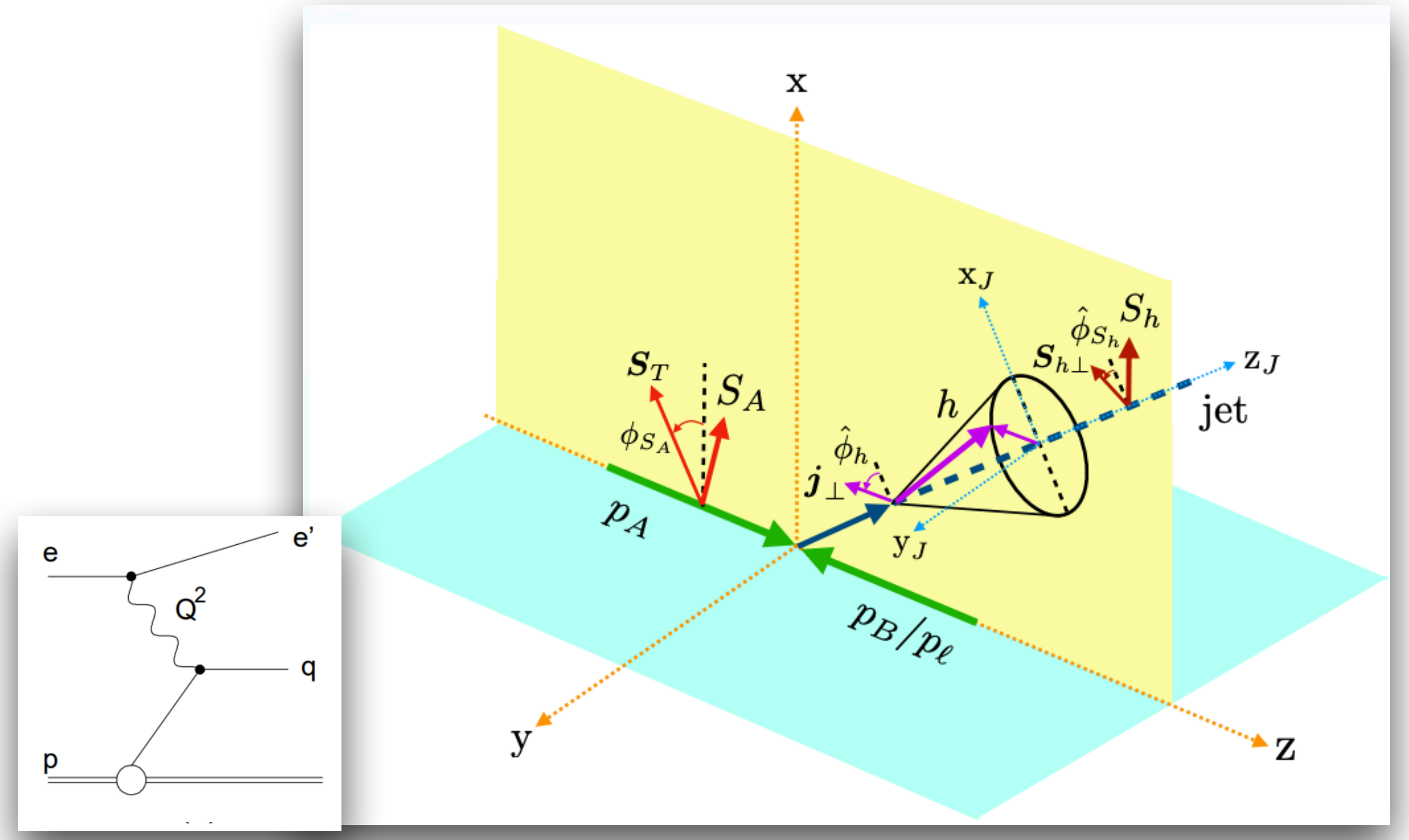
Jet TMDs

- Various approaches
- Well-established factorization theorem
- Disentangle inital-final unconstrained objects
- Guaranteed FO precision



$$\frac{d\sigma}{dq_T} \sim \sigma_0(x) H(Q)\, J_i(p_{J,T}R) S_J(k_{T,j}R) \otimes x f_i(x, k_{T,i})$$

Free of final state TMDs



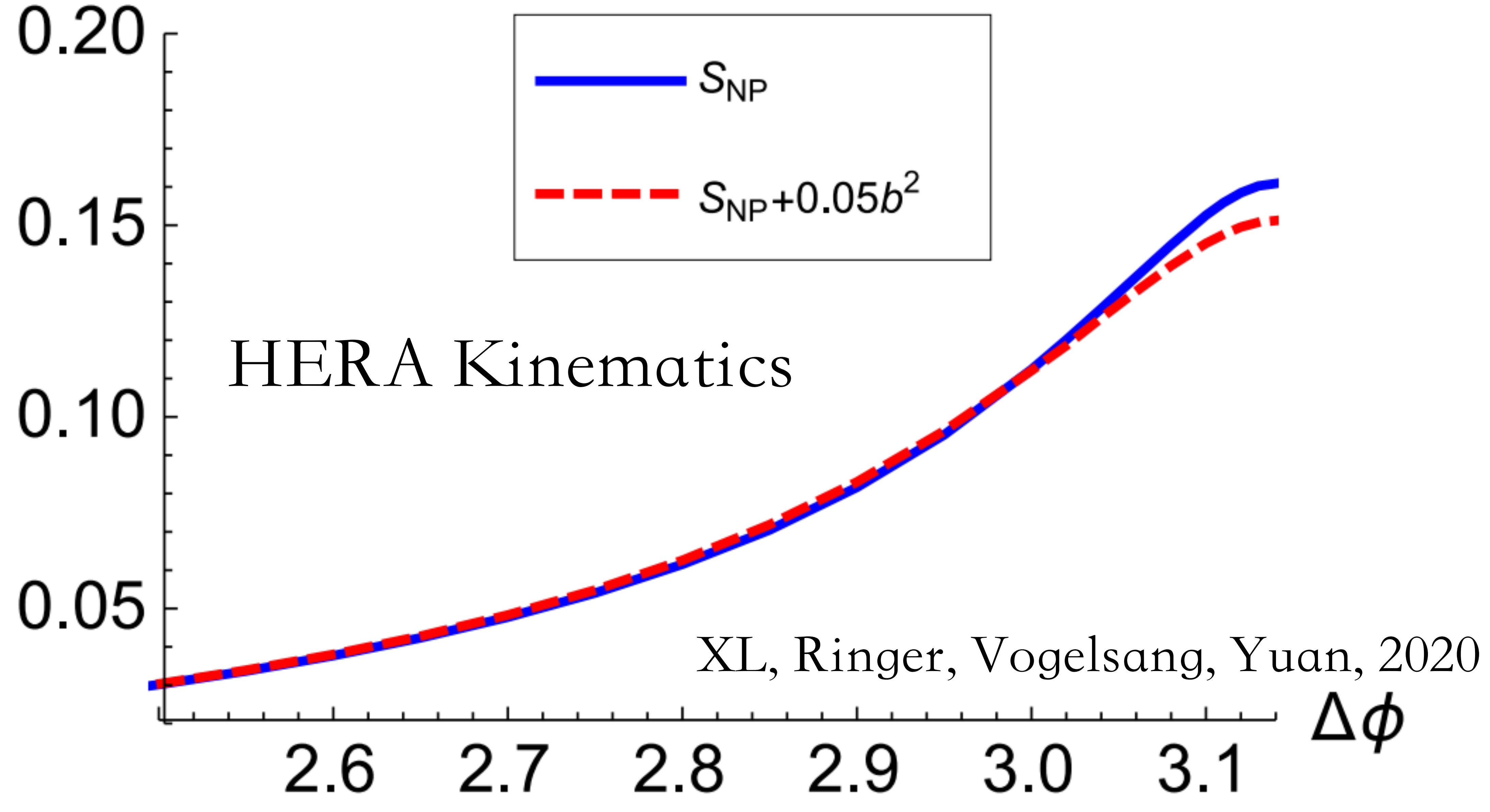
$$\frac{d\sigma}{dq_T} \sim \sigma_{li\to j}(x) f_i(x) \mathcal{J}_j(p_T R) \mathcal{S}_J(k_{T,j}R) \otimes D(z, k_{T,i})$$

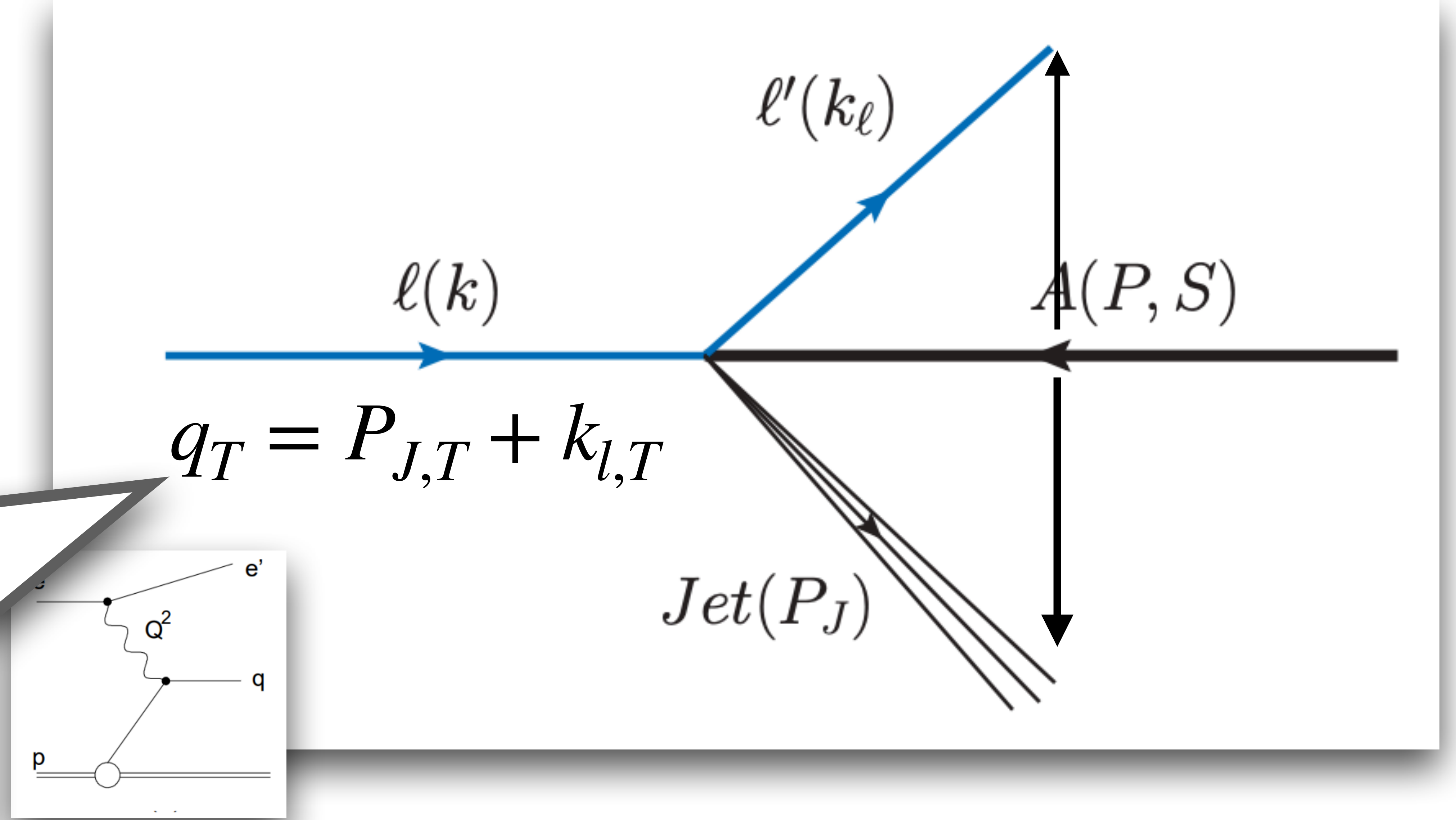
Free of initial state TMDs

Examples for inner structures

- Jet @ EIC

Jet TMDs





$$\frac{d\sigma}{dq_T} \sim \sigma_0(x)H(Q)\,J_i(p_{J,T}R)S_J(k_{T,j}R) \otimes xf_i(x,k_{T,i})$$

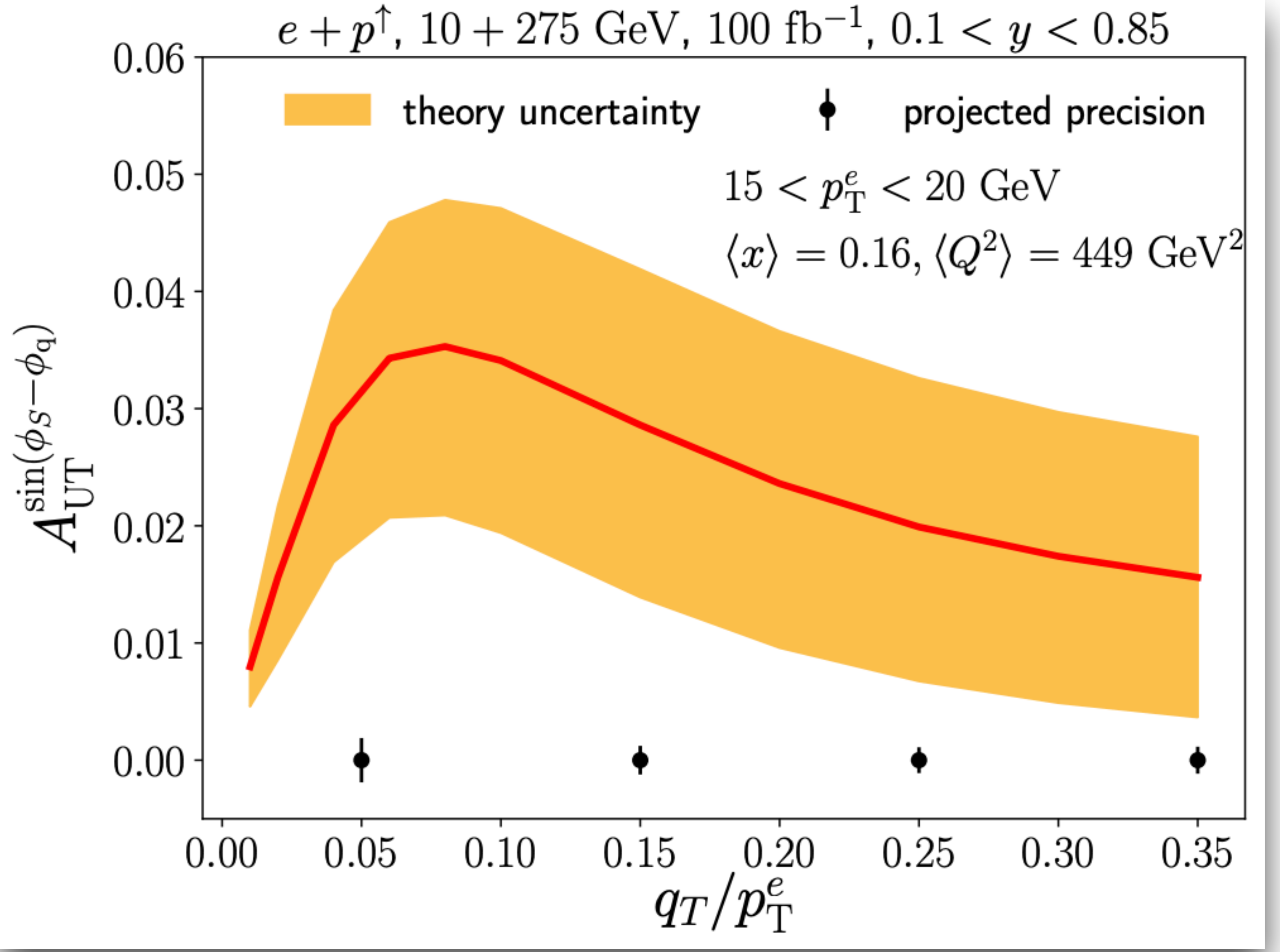
Free of final state TMDs

Possible probe of gluon saturation effect in the future See also, Marguet, Xiao, Feng, 2009

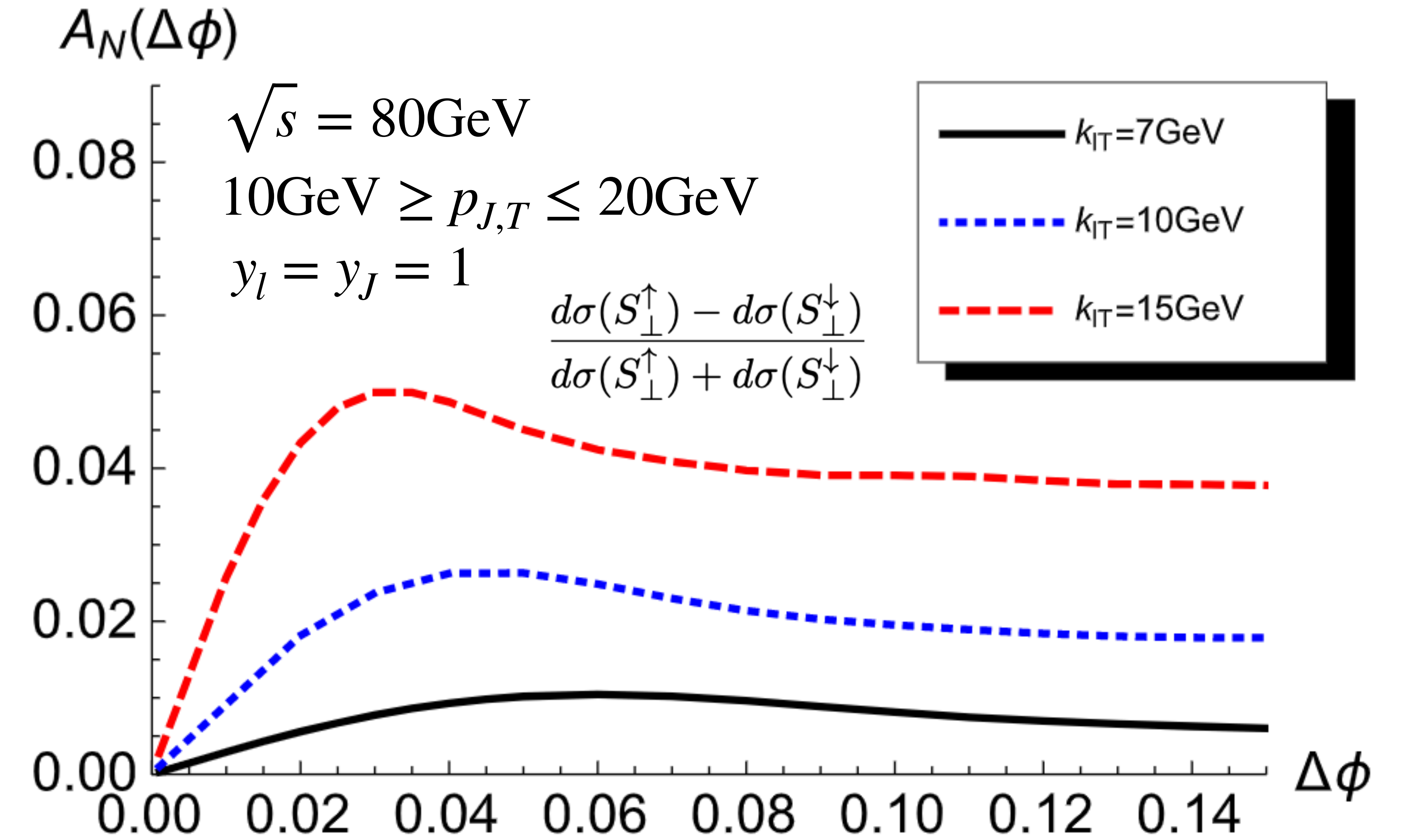
Examples for inner structures

- Jet @ EIC

Jet TMDs



Arratia, Kang, Prokudin, Ringer, 2020



XL, Ringer, Vogelsang, Yuan, 2019

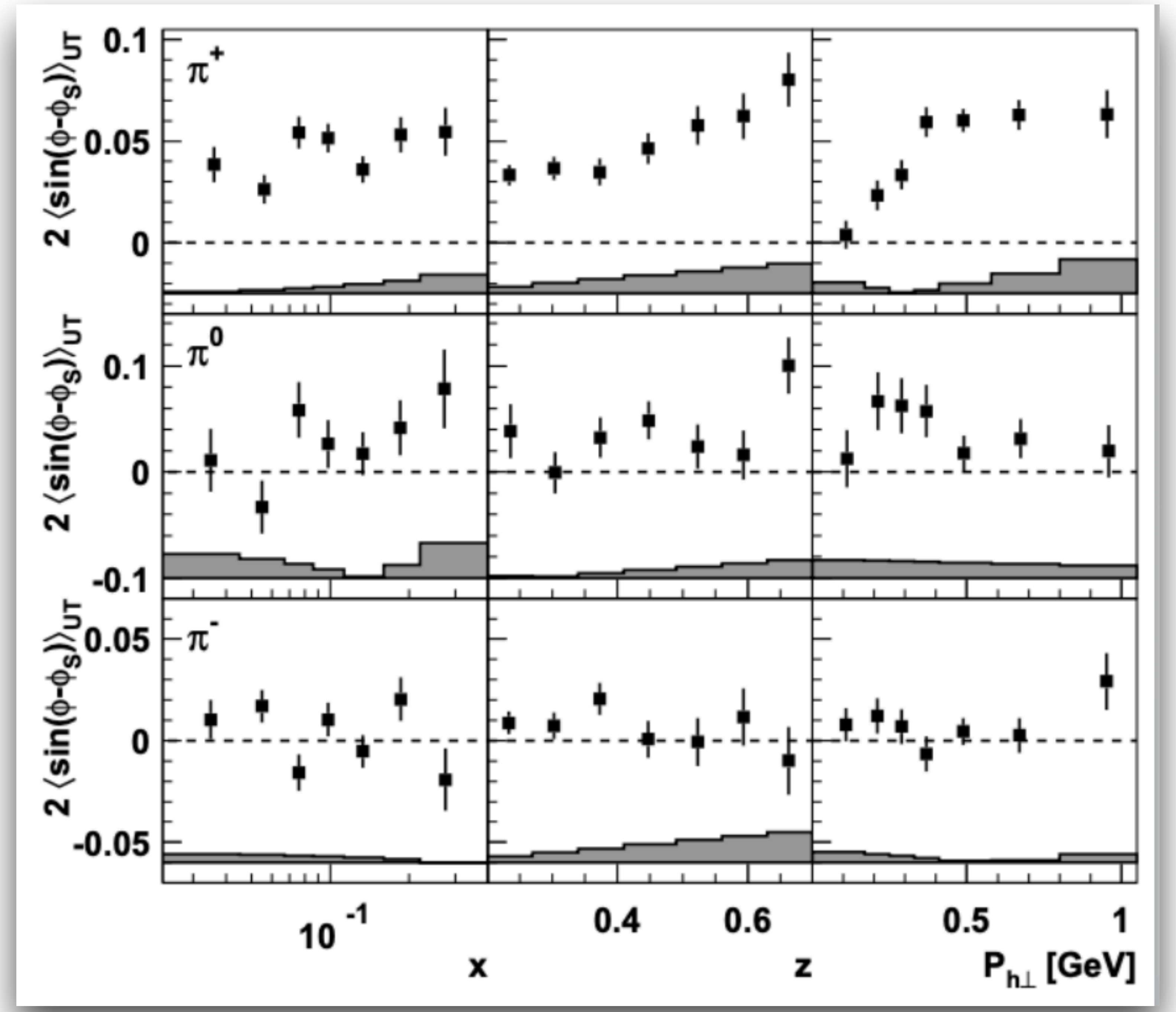
$$\frac{d\Delta\sigma}{dq_T} \sim \sigma_0(x)\epsilon_\perp^{\alpha\beta} S_\alpha H(Q)\, J_i(p_{J,T}R) S_J(k_{T,j}R) \otimes x\tilde{f}_{1T,i}^{\perp\beta}(x, k_{T,i})$$

- Extendable to transversed polarized case
- Future EIC data could constrain the Sivers function

Examples for inner structures

- Jet @ EIC

Jet TMDs



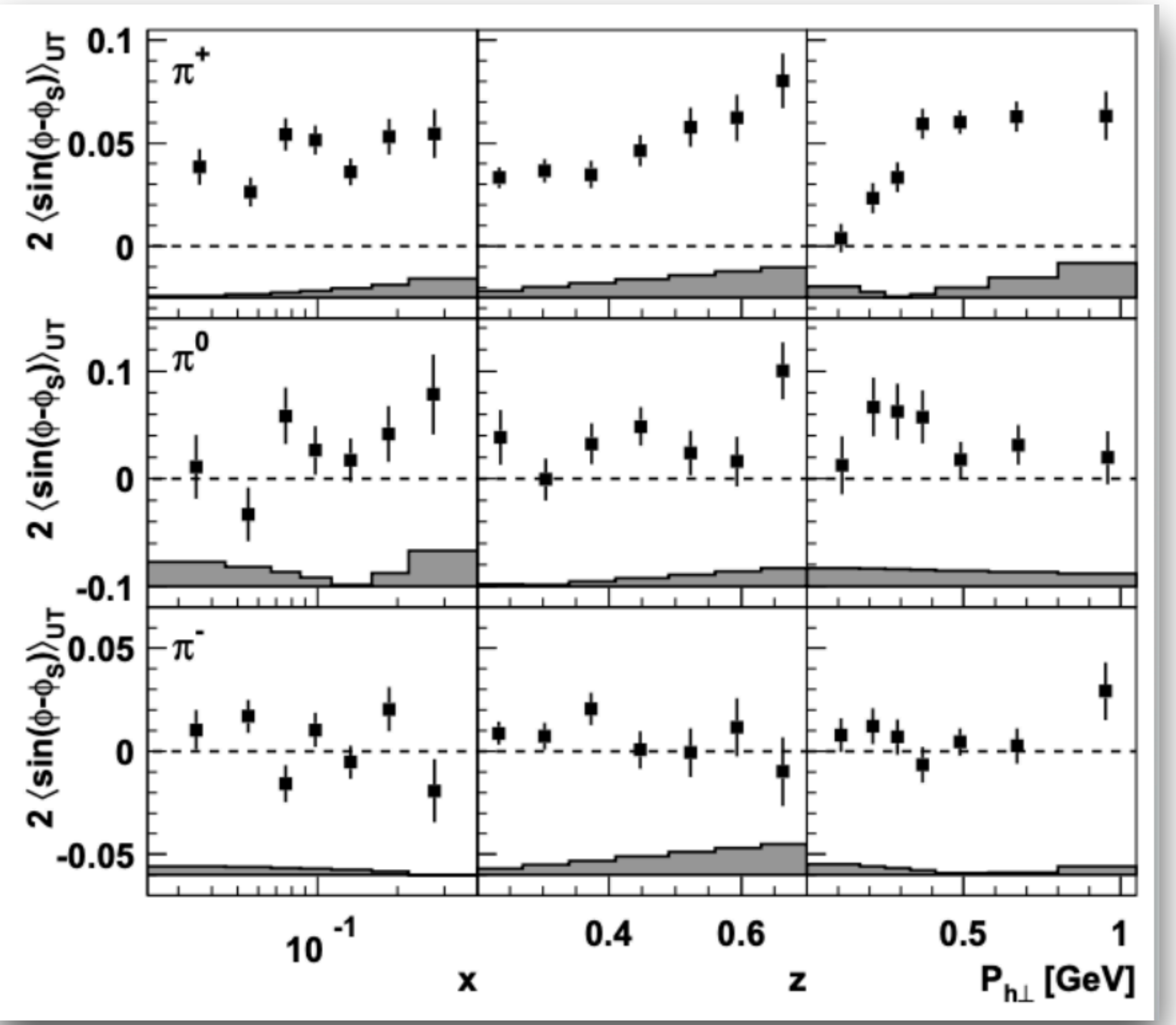
HERMES collaboration, 2009

- Mapping out the flavor and spin structure, possible in SIDIS
- Flavor separation in jet?

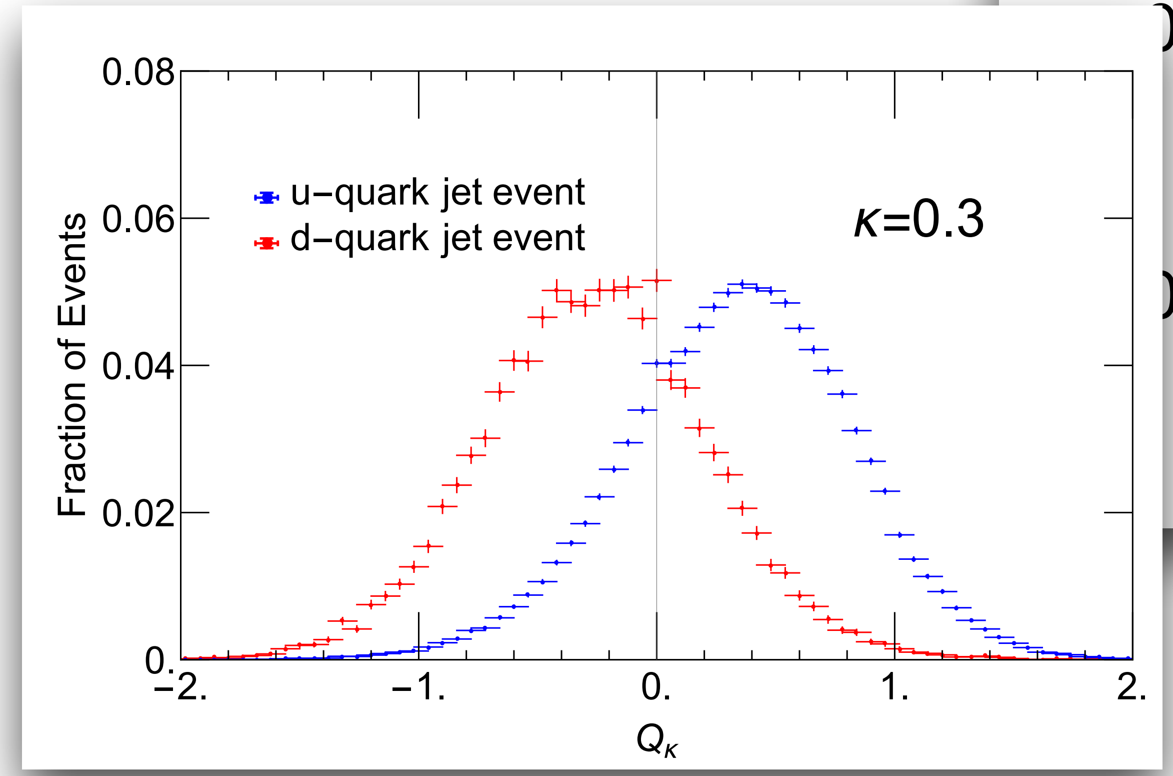
Examples for inner structures

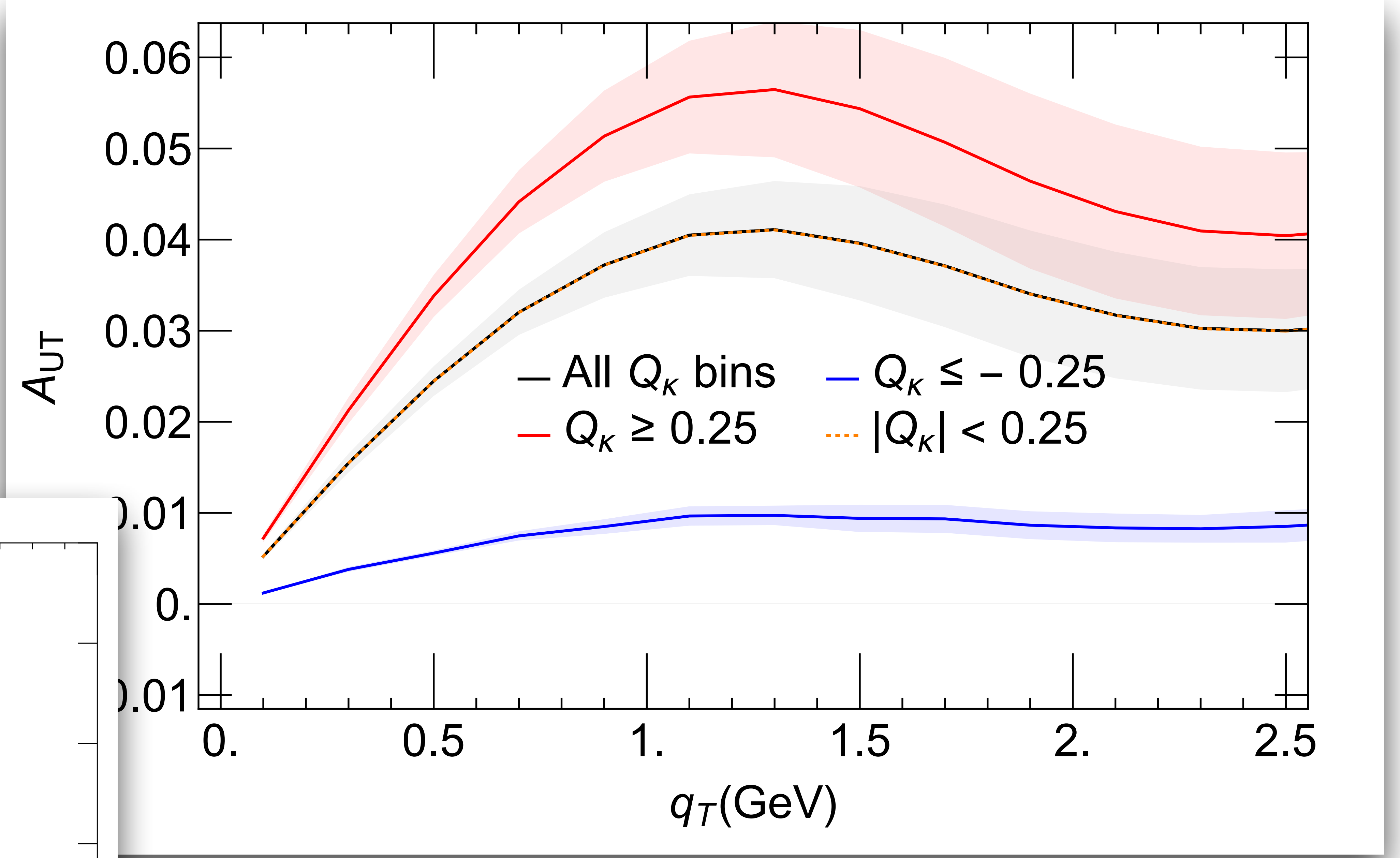
- Jet @ EIC

Jet TMDs



HERMES collaboration, 2009





Kang, Liu, Mantry, Shao, 2020

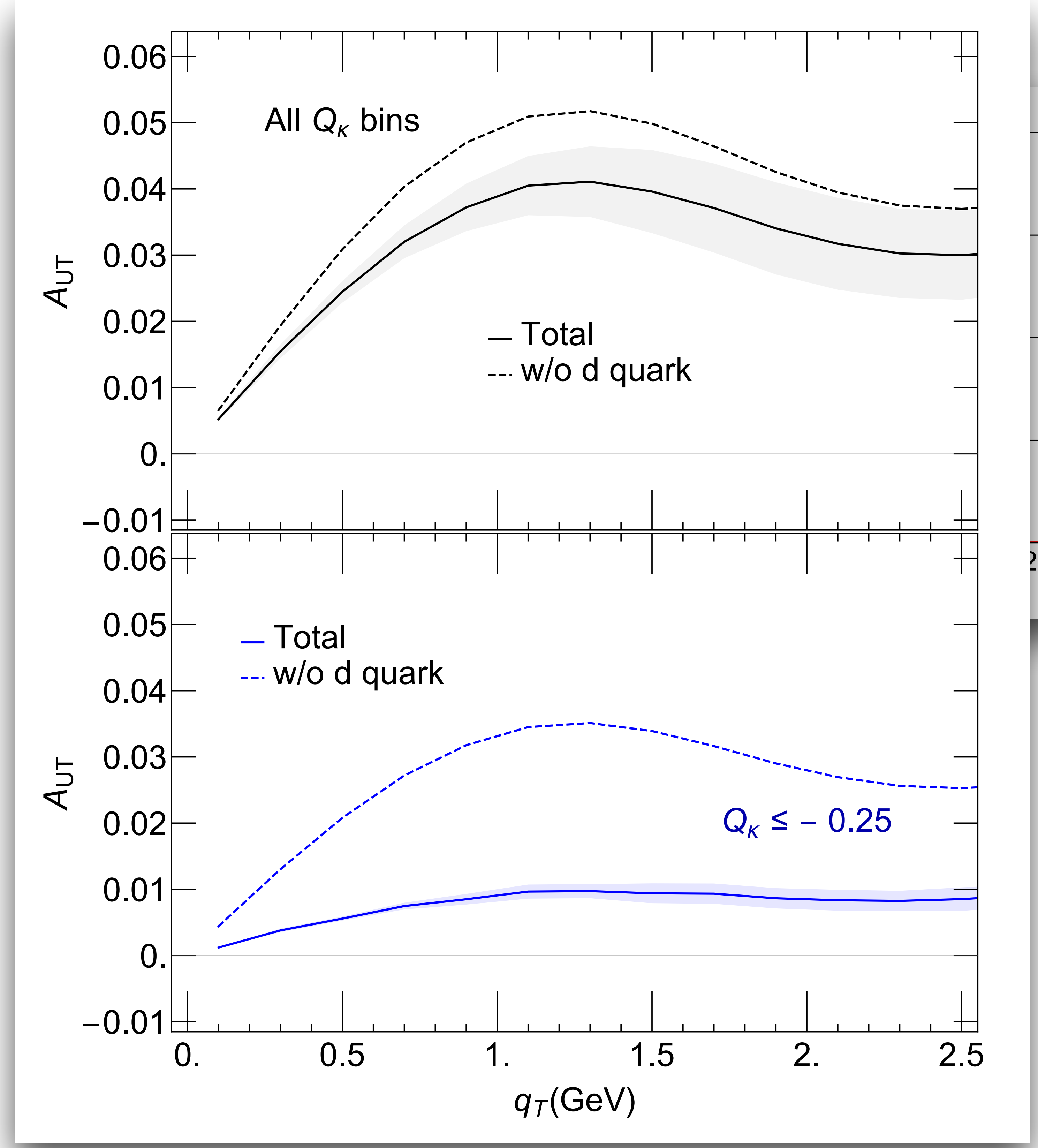
- Mapping out the flavor and spin structure, possible in SIDIS
- Flavor separation in jet? Yes! By jet charge

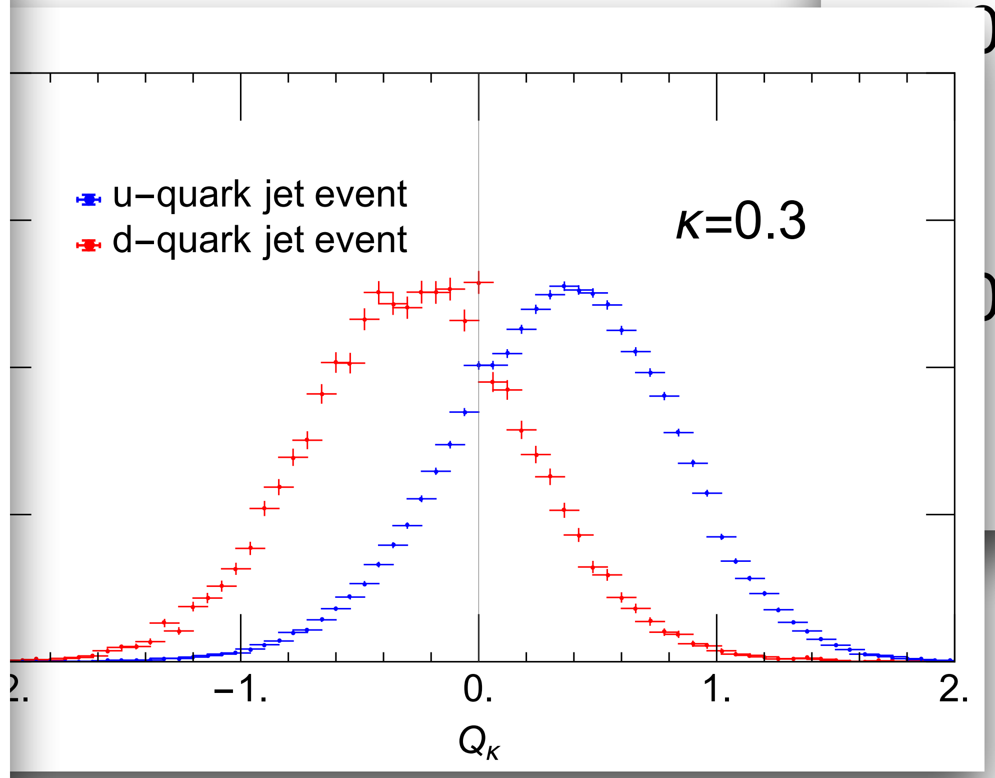
$$Q_\kappa = \sum_i \left(\frac{p_{i,T}}{p_J}\right)^\kappa Q_i \qquad \frac{d\sigma_i}{dq_T} \to \frac{d\sigma_i}{dq_T} \times \text{fraction of evets}$$

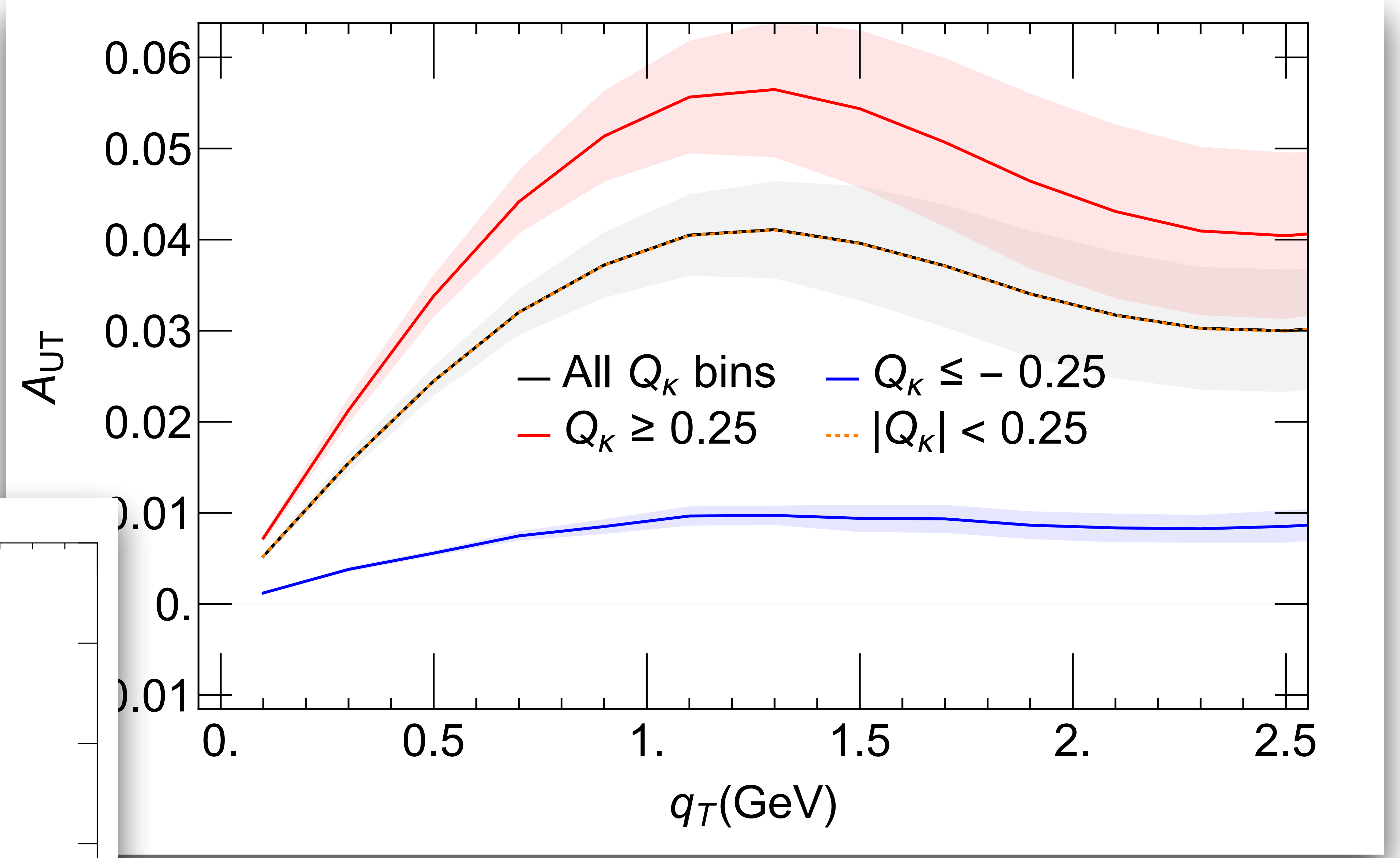
Examples for inner structures

- Jet @ EIC

Jet TMDs







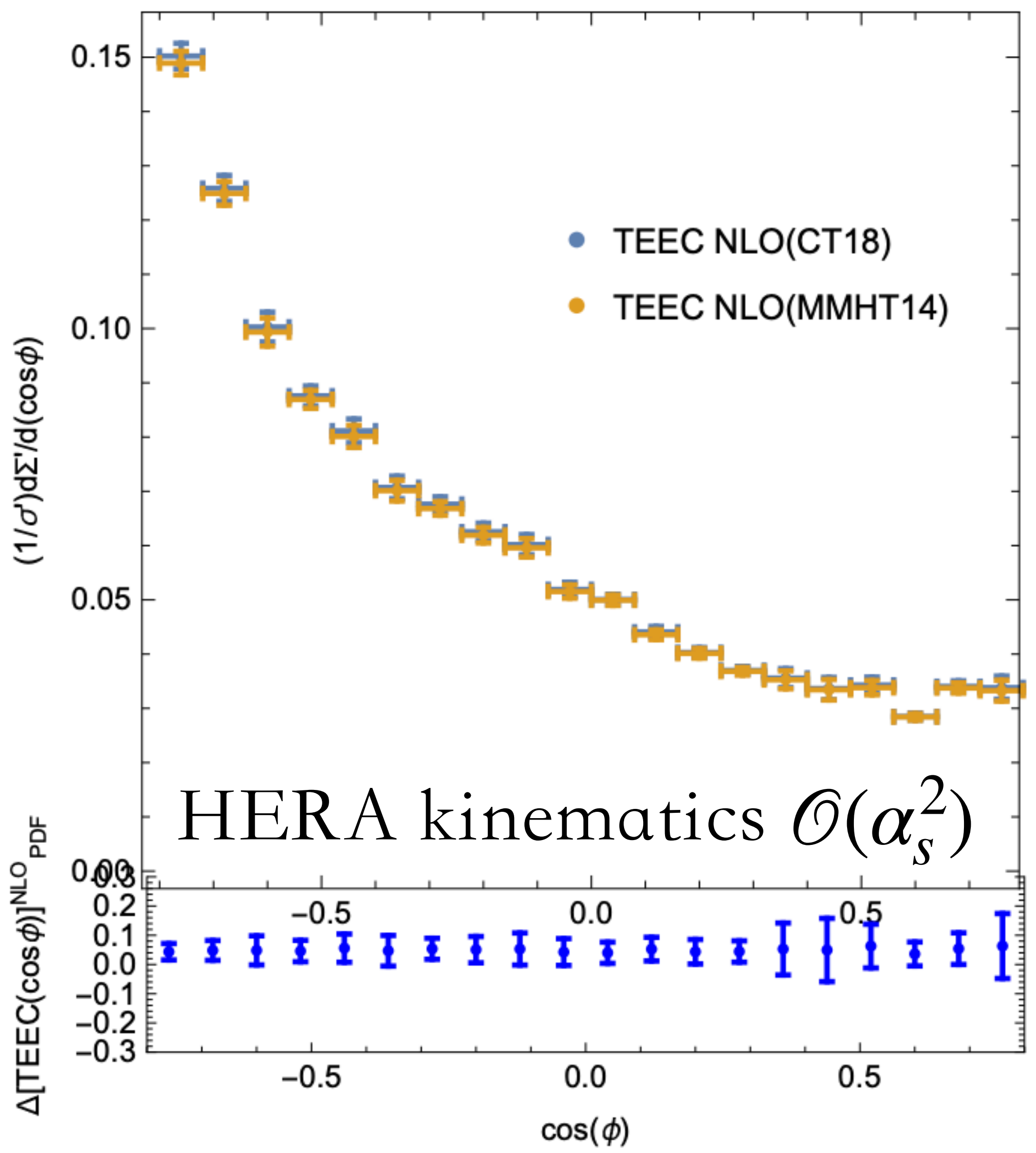
Kang, Liu, Mantry, Shao, 2020

- Mapping out the flavor and spin structure, possible in SIDIS
- Flavor separation in jet? Yes! By jet charge
- Improved sensitivity to d quark Sivers

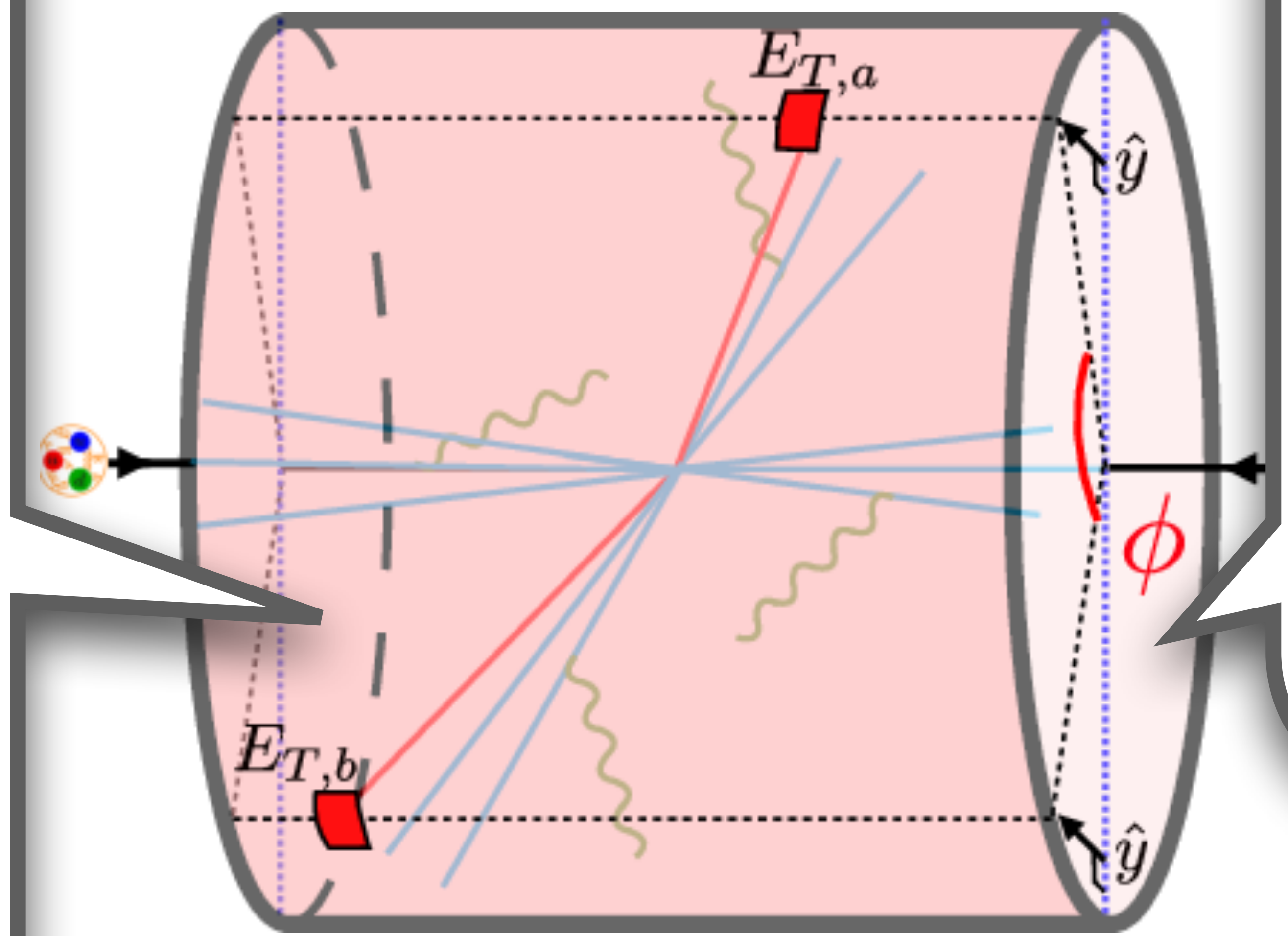
For other applications, see Chen, Zhang, Wang, 2019, HT Li, Vitev, 2020

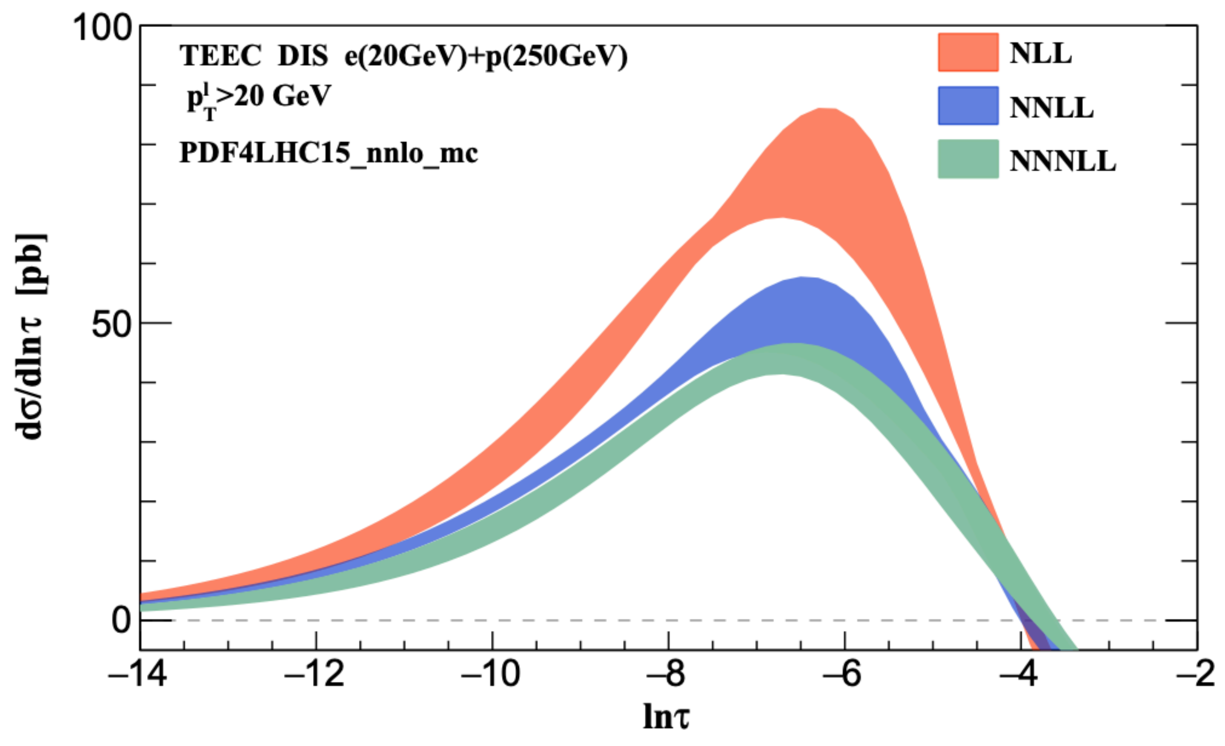
Examples for inner structures

- Event shape @ EIC
  - Some pioneer works
  - But far away from reaching its full potential



Ali, Li, Wang, Xing, 2020





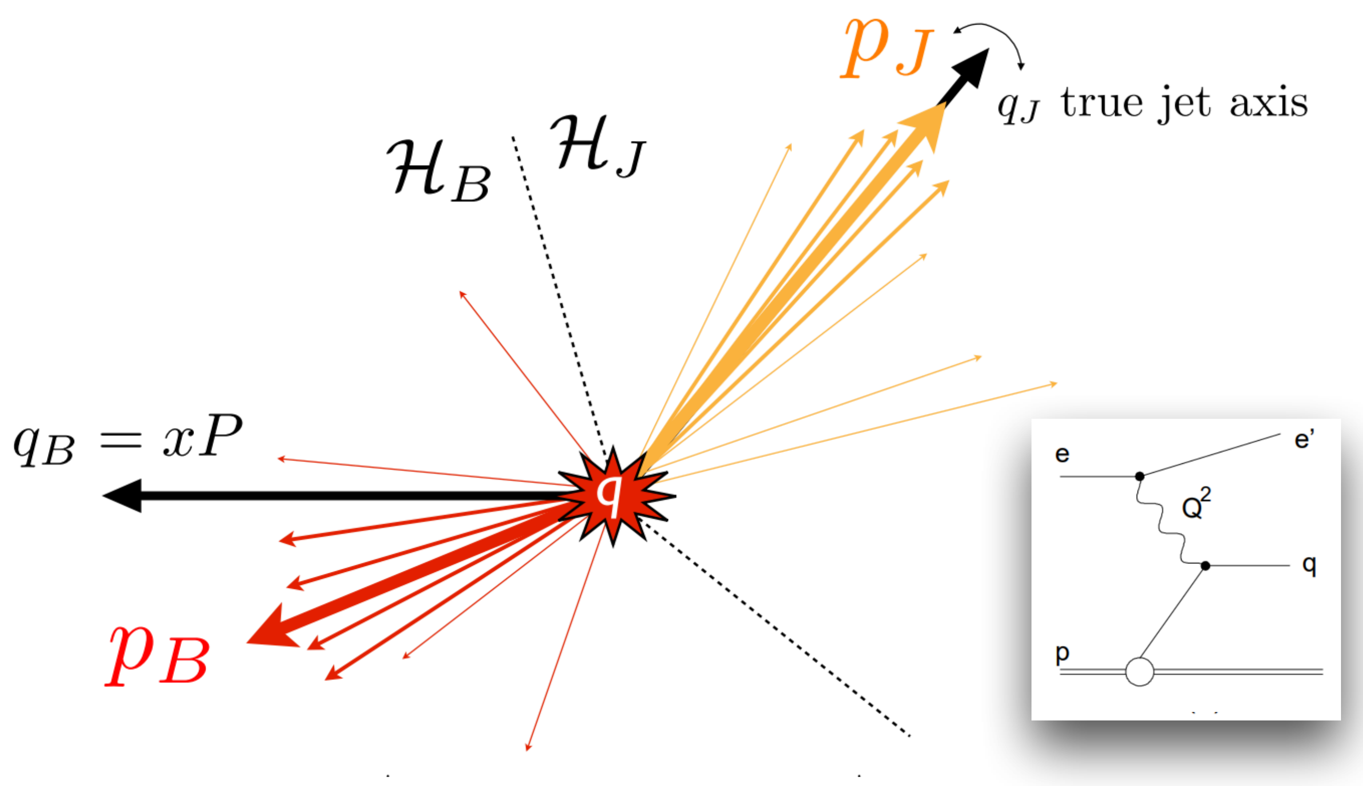
HT Li, Vitev, YJ Zhu, 2020

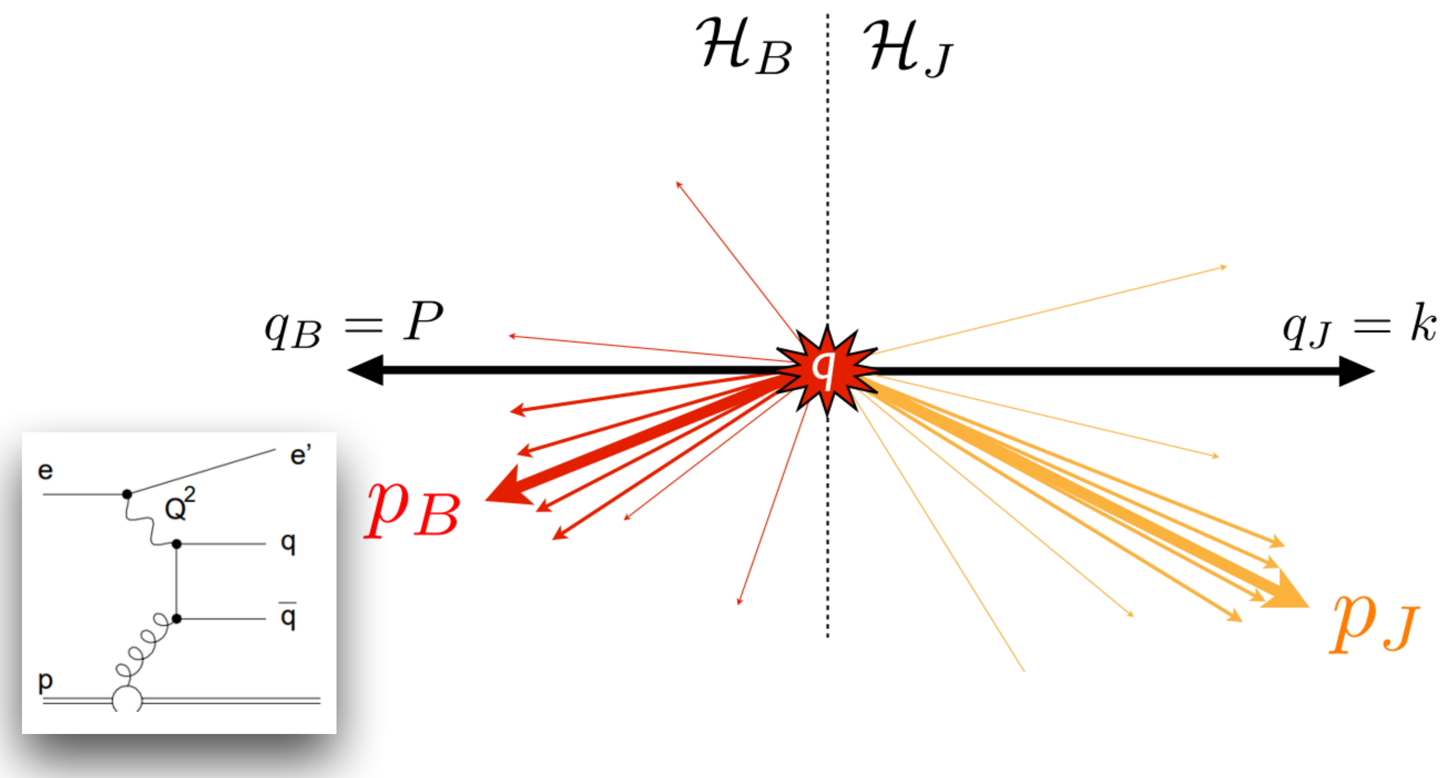
Examples for inner structures

- Event shape @ EIC
  - Jettiness for Nuclear dynamics

$$\tau_1 = \sum_k \min\left(\frac{2q_B \cdot p_k}{Q_B}, \frac{2p_J \cdot p_k}{Q_J}\right)$$

Stewart, Tackmann, Waalewijn, 2010





- A generalization of the thrust
- Global event shape, more sensitive to all radiation patterns
- Flexibility in frame choices
- Factorization known to high precision, N^{3}LL

Kang, Mantry, Qiu 2012

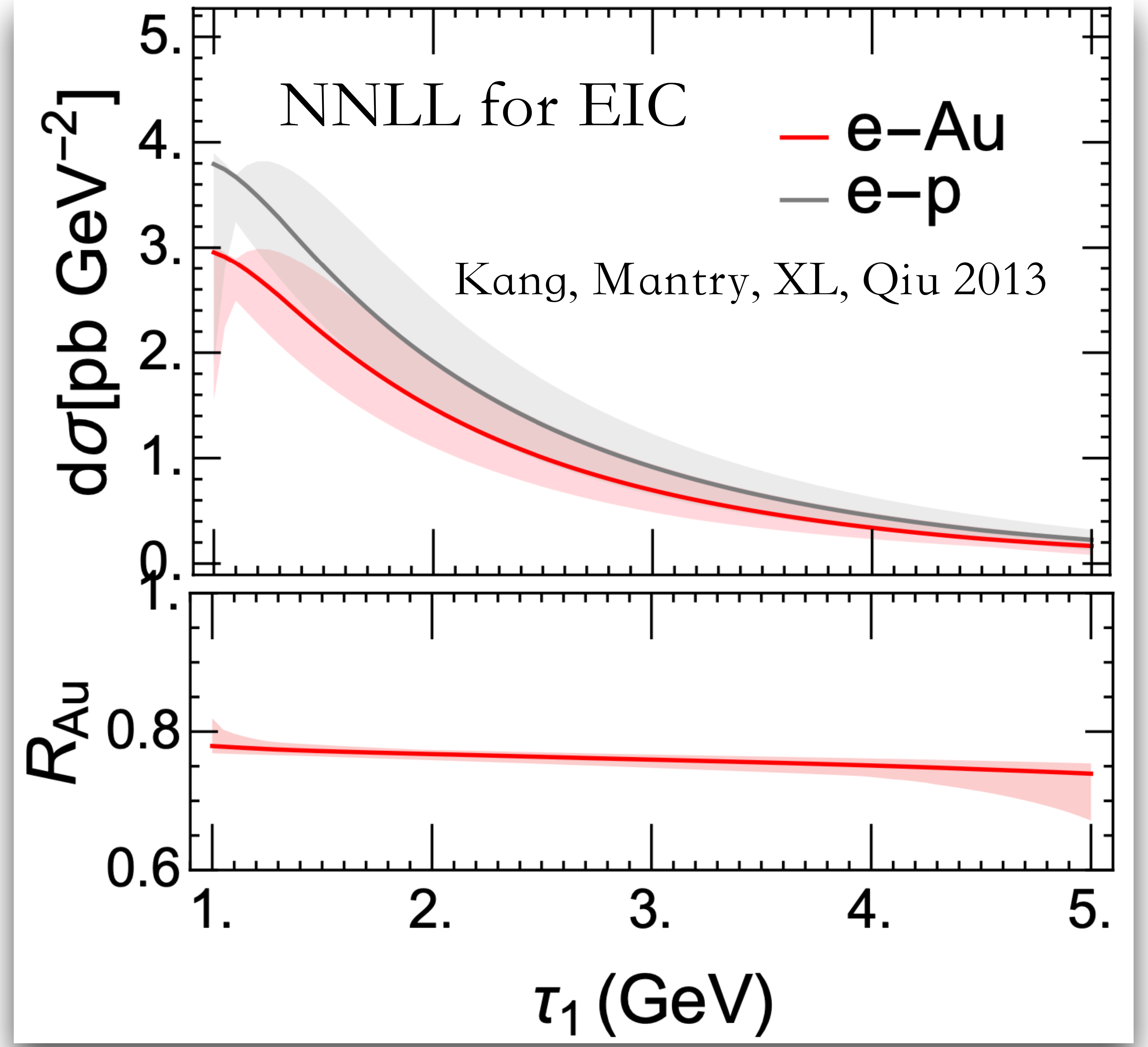
Kang, Mantry, XL, Qiu 2013, D. Kang, Lee, Stewart, 2013

$$\sigma \sim H\, J \otimes I \otimes S\, f_{i/A} + \mathcal{O}\left(\frac{Q_s^2(A)}{\tau_1}\right) \qquad Q_s^2 \sim A^\alpha \Lambda_{\rm QCD}^2$$

Small higher twist correction for proton and large for nucleus

Examples for inner structures

- Event shape @ EIC
  - Jettiness for Nuclear dynamics $\tau_1 = \sum_k \min\left(\frac{2q_B \cdot p_k}{Q_B}, \frac{2p_J \cdot p_k}{Q_J}\right)$



- A quantitative measure of the hadronic activity or the pattern of radiation
- Sensitive to differences in the nuclear PDFs, which allows one to study the nuclear shadowing, anti-shadowing, and the EMC effect
- Deviation will shed light on nuclear effect: jet quenching and energy loss mechanisms

$$\sigma \sim H\, J \otimes I \otimes S\, f_{i/A} + \mathcal{O}\left(\frac{Q_s^2(A)}{\tau_1}\right) \quad Q_s^2 \sim A^{\alpha}\Lambda^2_{\rm QCD}$$

Small higher twist correction for proton and large for nucleus

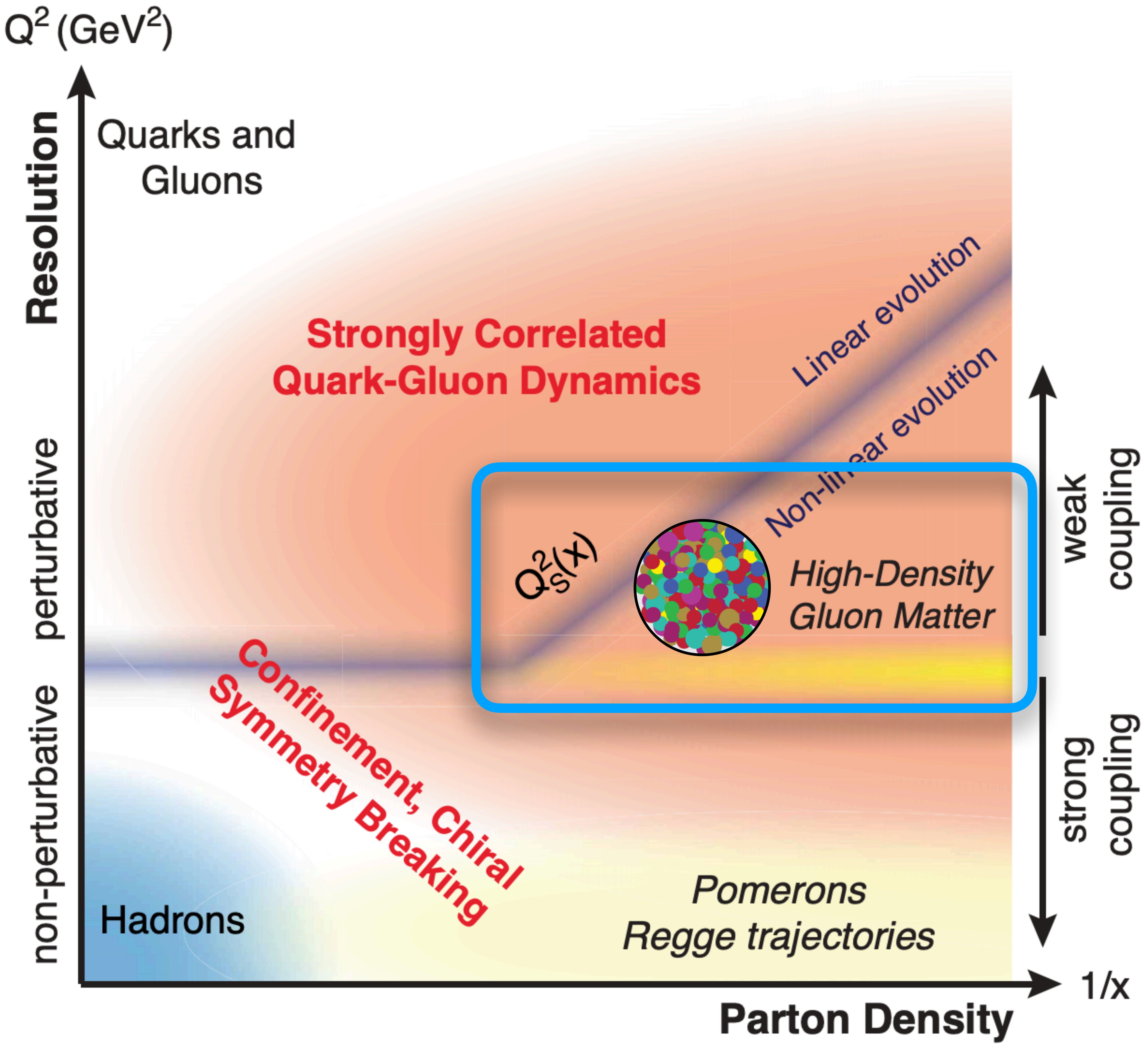
Examples for inner structures

- Forward jet production

One of the major pillar at EIC: gluon saturation and the color glass condensate (CGC)

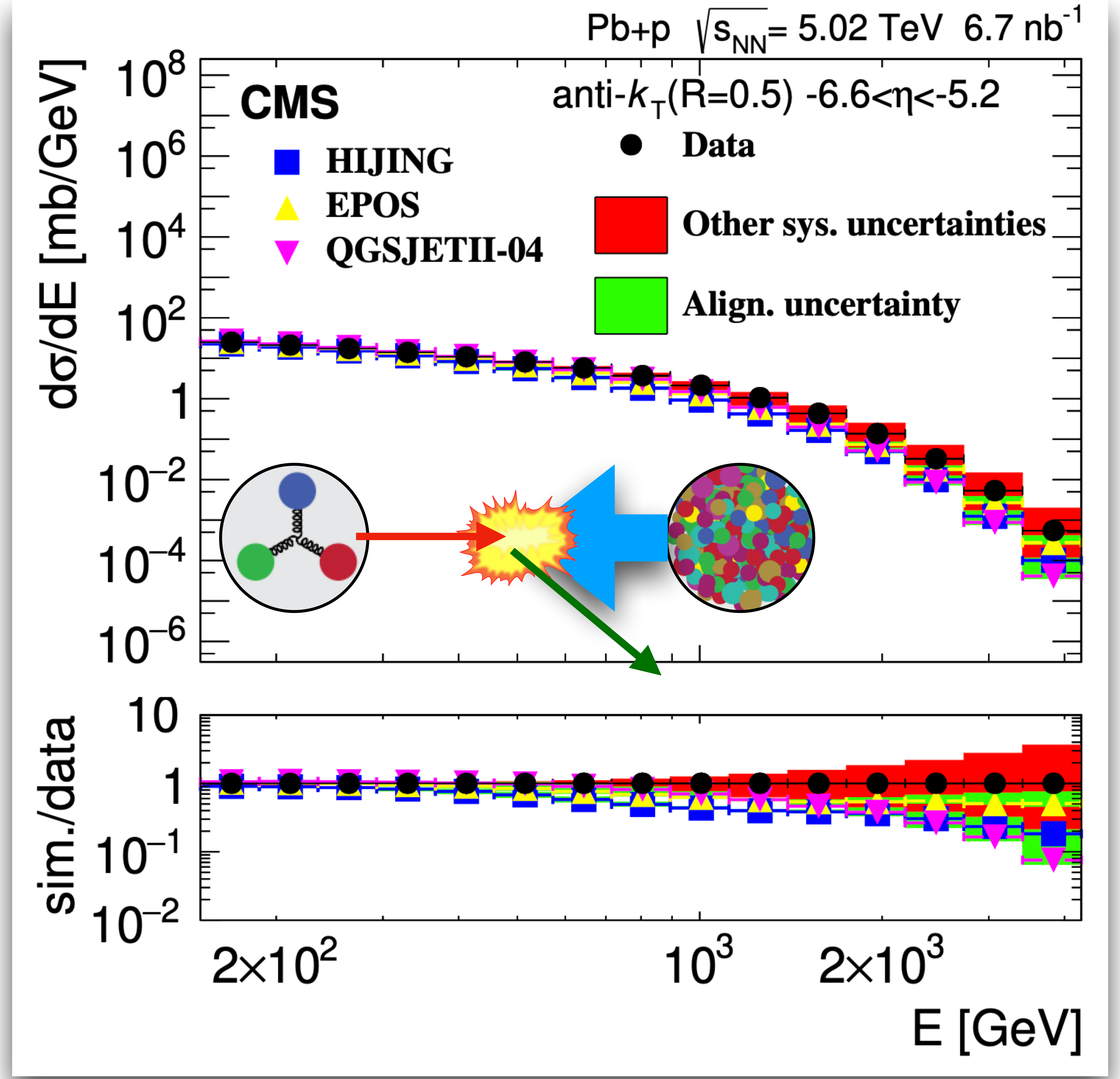
Forward jet production was proposed for small-x   Hatta, Xiao, Feng, 2016

Also measured by CMS



Examples for inner structures

- Forward jet production
  - Monte Carlo simulations describe the data well, except for large E region
  - In principle it can be understood perturbatively due to large saturation scale
  - So far no such perturbative calculation beyond LO exists
    - Honest jet algorithm in the calculation, no model needed for the jet (reason for jet is to avoid modeling)
    - Satisfy all the criteria of the factorization (no cut off breaks factorization)



$$\frac{d\sigma^{(0)}}{dE_J dy_J} \sim \sigma(\mu) x f_{i/P}(x,\mu)\, \mathscr{F}_A^{(2)}(k_\perp,\nu)$$

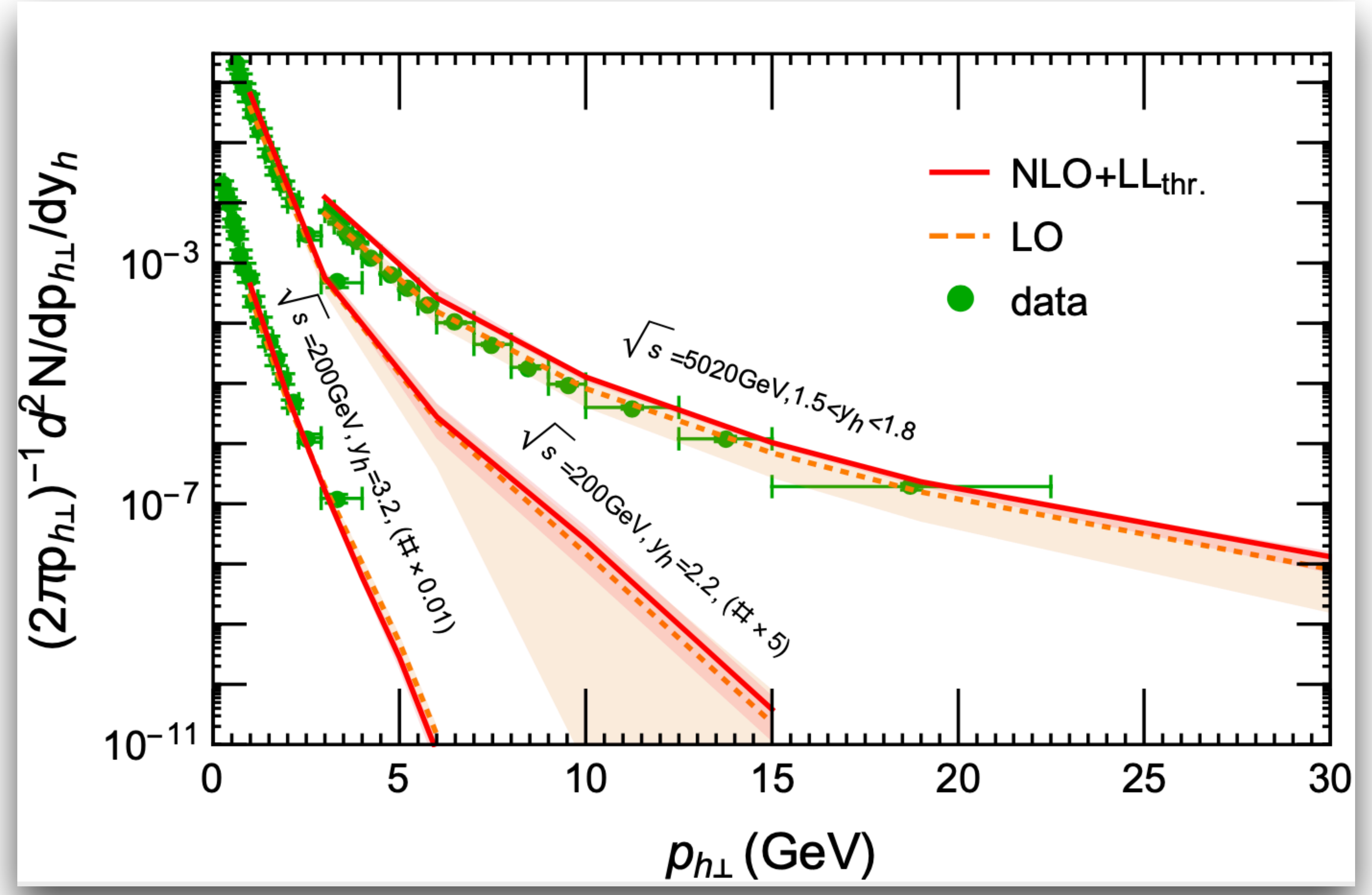
For hadron production see, Chirilli, Xiao, Yuan, 2012 + ⋯

Examples for inner structures

- Forward jet production
  - Monte Carlo simulations describe the data well, except for large E region
  - In principle it can be understood perturbatively due to large saturation scale
  - So far no such perturbative calculation beyond LO exists
    - Honest jet algorithm in the calculation, no model needed for the jet (reason for jet is to avoid modeling)
    - Satisfy all the criteria of the factorization (no cut off breaks factorization)

- Developed a factorized framework for small-x physics within CGC
  Kang, XL, 2019,
  see also Chao, HY Liu, Ma, 2019
- Allows systematic FO and resummation
- Good for forward hadron production

POSITIVE!! Ready for pheno applications



Kang, HY liu, XL, 2020

Examples for inner structures

- Forward jet production
  - Monte Carlo simulations describe the data well, except for large E region
  - In principle it can be understood perturbatively due to large saturation scale
  - So far no such p
    beyond LO exist
    - Honest jet algo
      model needed f
      avoid modeling)
    - Satisfy all the criteria of the factorization (no cut off breaks factorization)

- Developed a factorized framework for small-x physics within CGC
- Allows systematic FO and resummation
- Good for forward hadron production
- Generalized to jet with full jet algorithm

$$\frac{\alpha_s}{2\pi}\int_0^1 d\xi \int d^2 p_{k\perp} \frac{1+\xi^2}{(1-\xi)}\frac{N_c}{2}\Big\{\theta_1(\xi, p_{k\perp}) x f(x) \mathcal{F}_F(p'_{k\perp}; X)\frac{1}{(\xi p'_{k\perp} - p_{J\perp})^2}$$

$$+\theta_2(\xi, p_{k\perp}) \tau f(\tau)\mathcal{F}_F(p_{J\perp}; X)\frac{1}{[p_{k\perp}-(1-\xi)p_{J\perp}]^2} - \tau f(\tau)\mathcal{F}_F(p_{k\perp}+\xi p_{J\perp}; X)\frac{1}{[p_{k\perp}-(1-\xi)p_{J\perp}]^2}\Big\}$$

$$+\frac{\alpha_s}{2\pi}\int_0^1 d\xi \int \frac{d^{D-2}p_{k\perp}}{(2\pi)^{D-4}}\frac{1+\xi^2+\frac{(D-4)}{2}(1-\xi)^2}{(1-\xi)^\eta}\left(\frac{\lambda}{p_i^+}\right)^\eta \frac{N_c}{2}\tau f(\tau)\mathcal{F}_F(p_{k\perp}+\xi p_{J\perp}; X)\frac{1}{[p_{k\perp}-(1-\xi)p_{J\perp}]^2}$$

Full jet algorithm dependence, free of divergence, numerical friendly

WORK IN PROGRESS

IR counter term, calculated analytically, poles cancel agains virtual

Conclusions

- Jets and event shapes are both idea probes of internal structures
  - Open up abundant opportunities
  - Reliable theoretical fundaments
- Jets have been substantially studied while event shapes yet to be explored in 3D imaging, small-x and even heavy ions

Thanks