Progress on fragmentation-function studies

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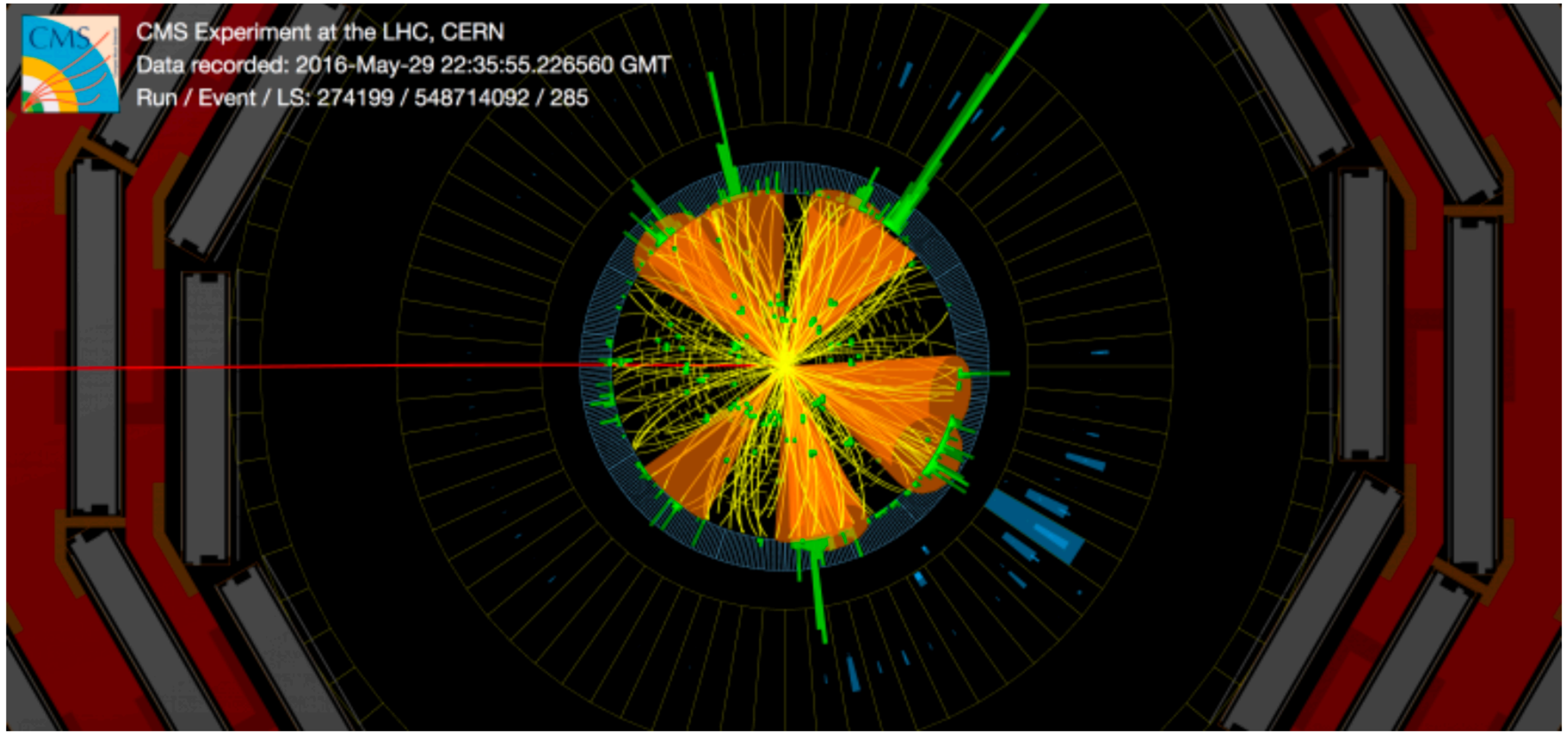
Stony Brook University
SIMONS FOUNDATION

The QCD fragmentation process



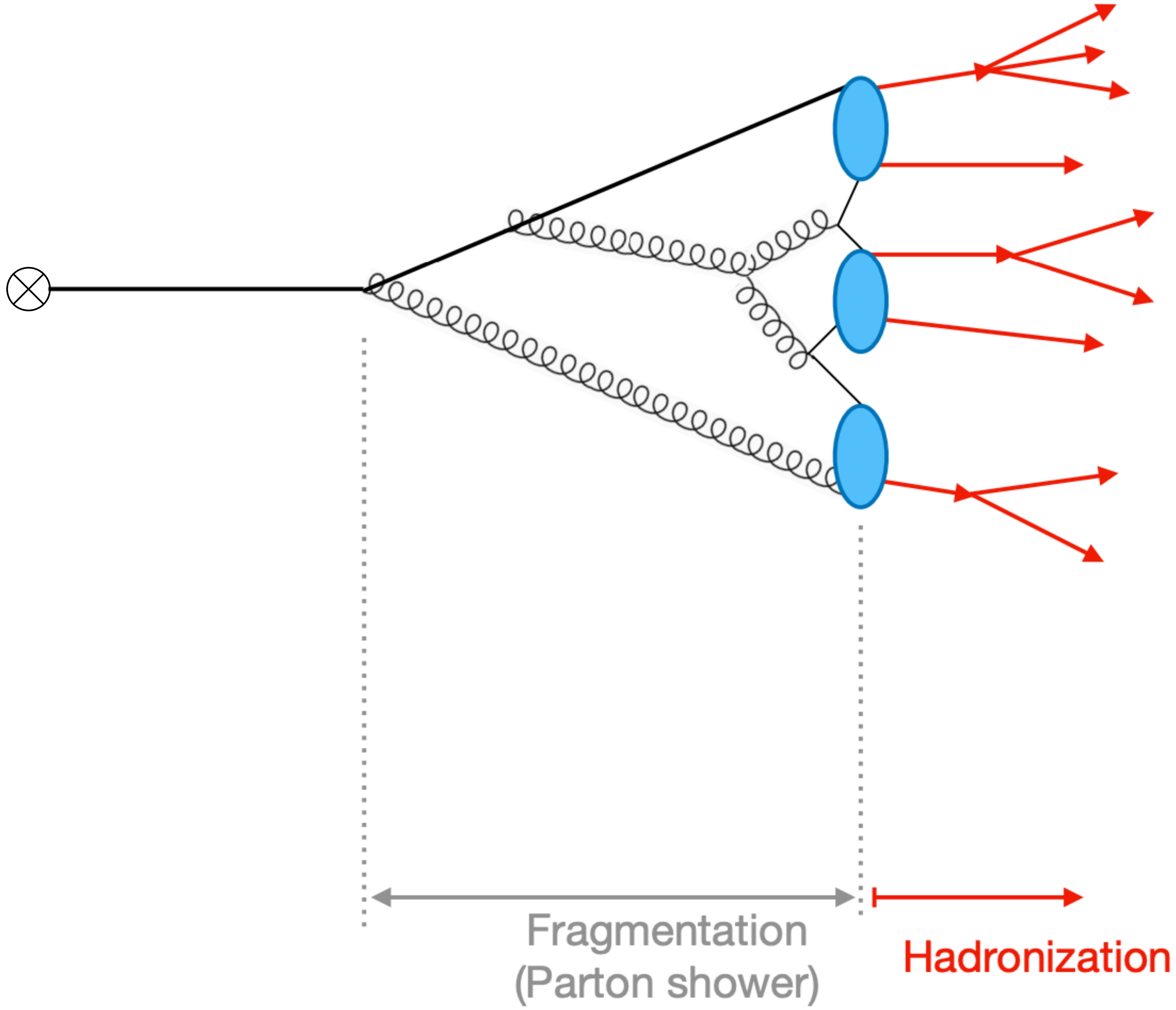
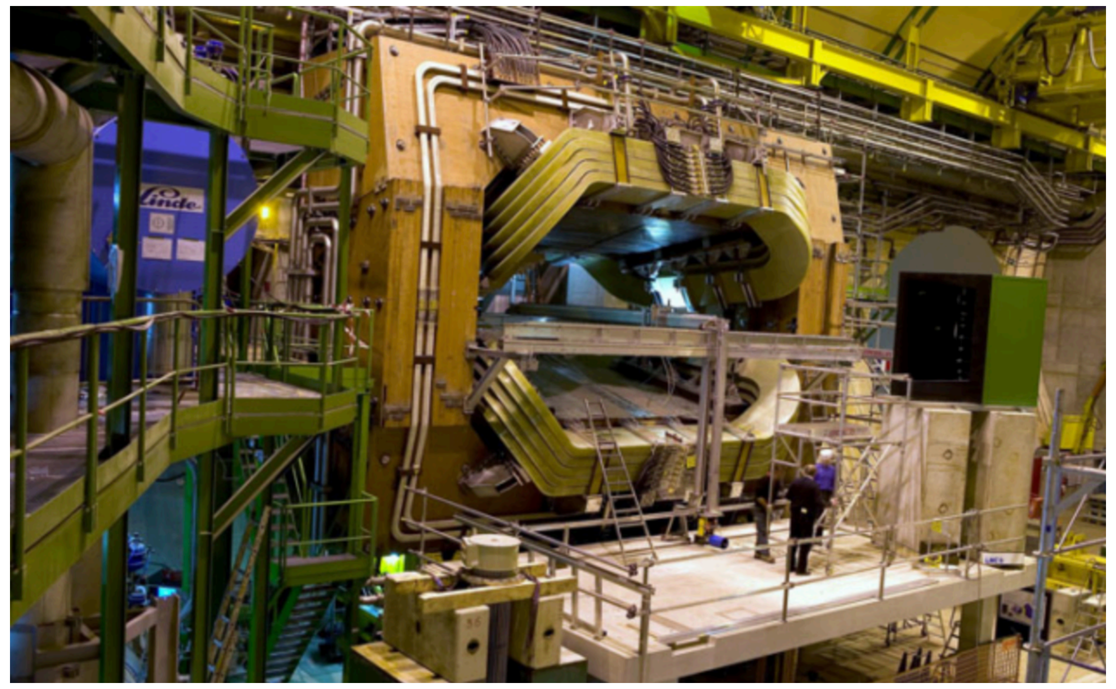


figure R. Cruz Torres

High-energy collider experiments

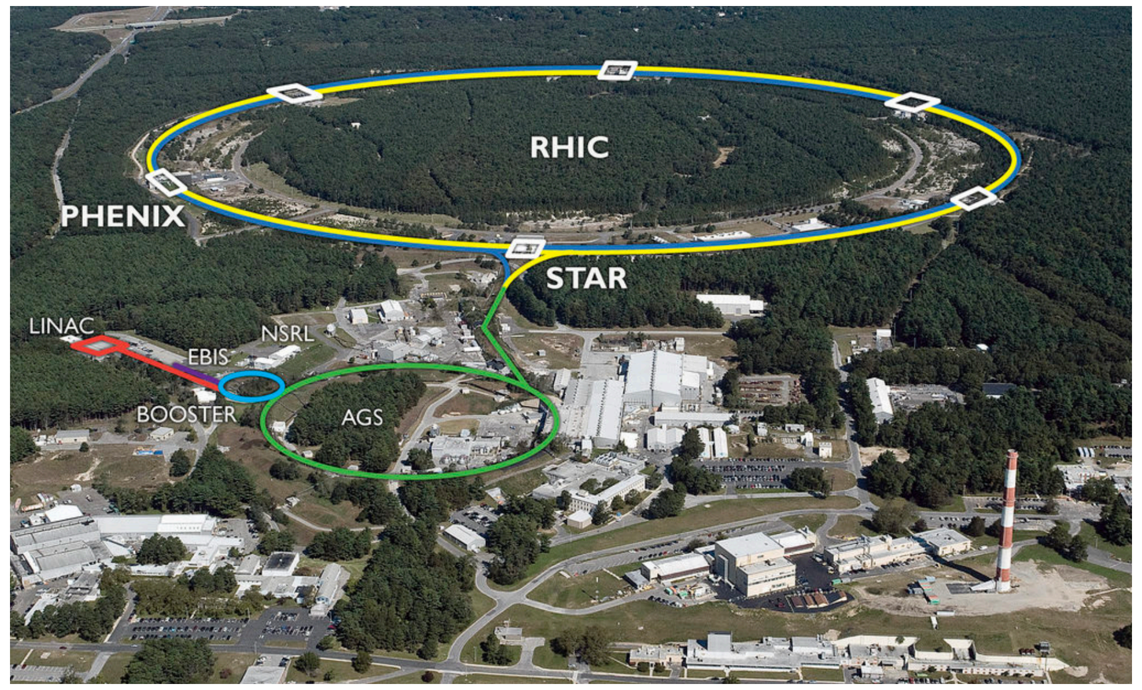
Large Hadron Collider



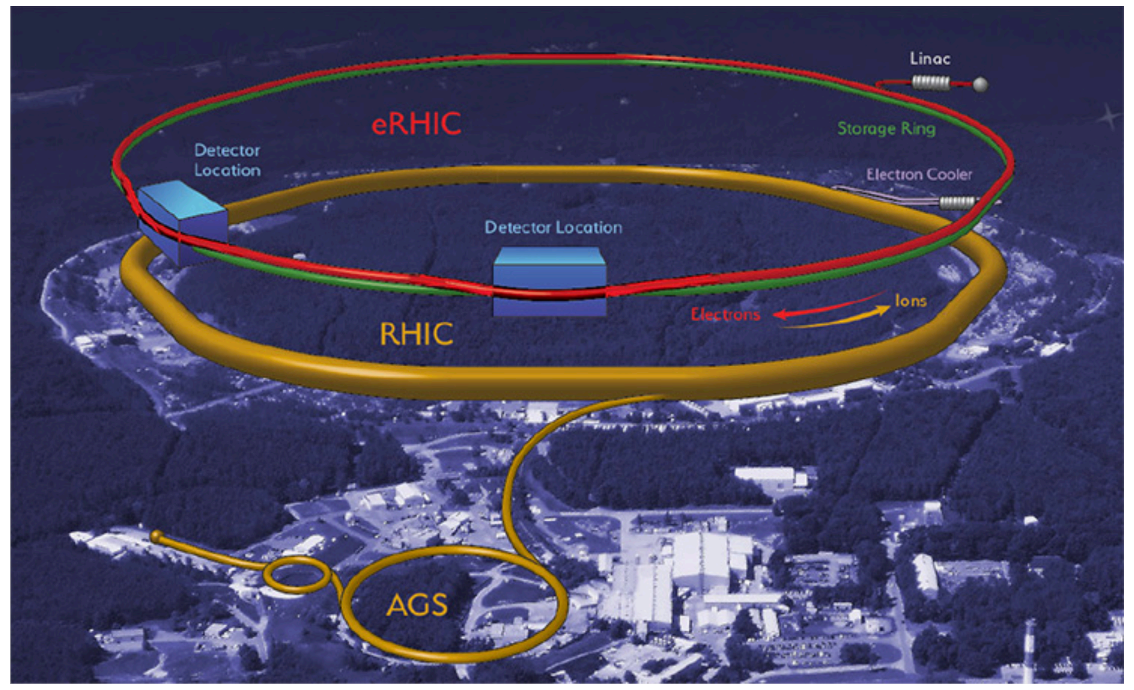
Jefferson Lab

BELLE

Relativistic Heavy Ion Collider



Electron-Ion Collider



Outline

Collinear fragmentation

TMD Fragmentation

Further new developments

Selection of topics

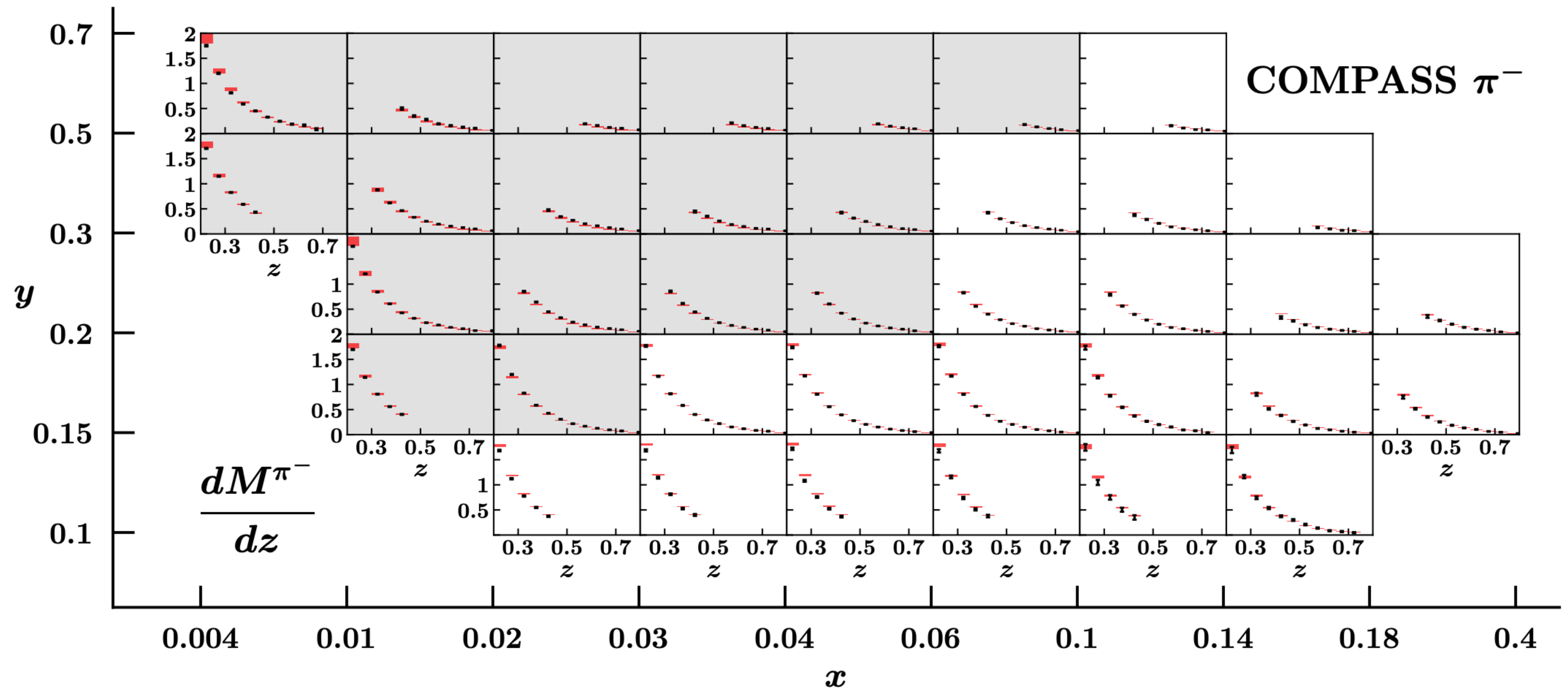
Extraction of collinear fragmentation functions

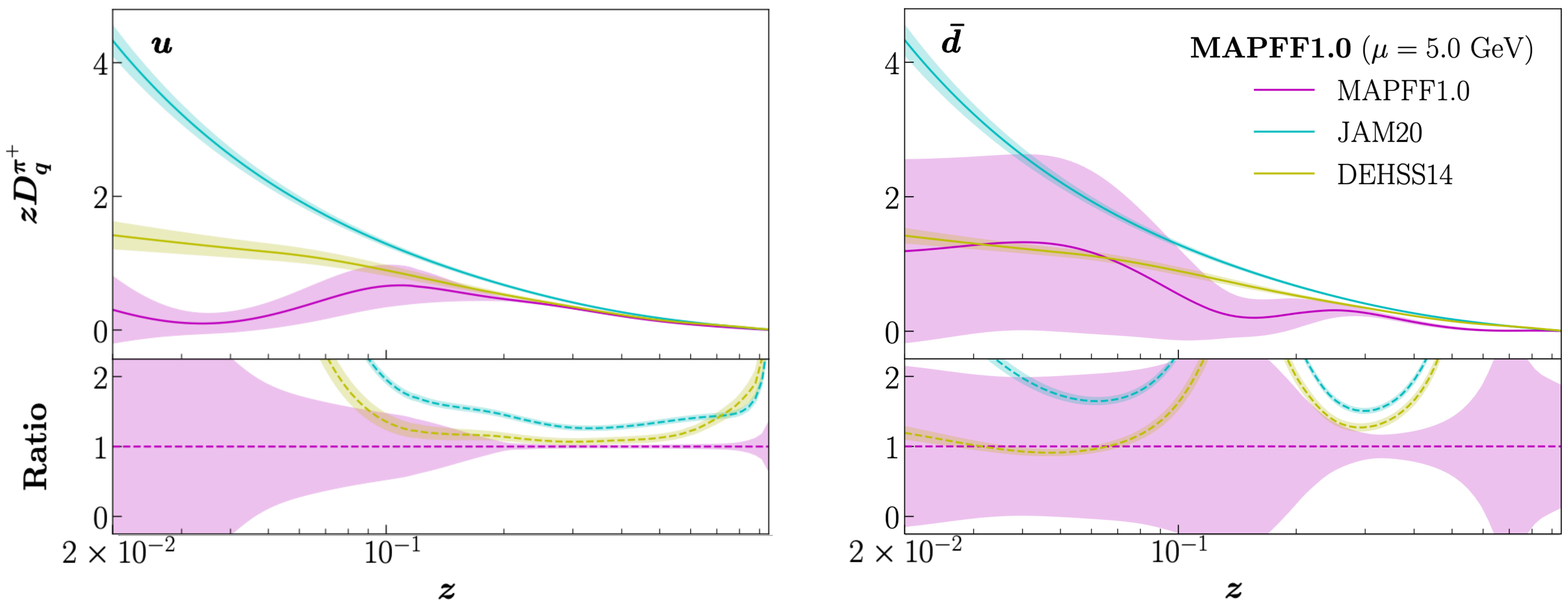
Khalek, Bertone, Nocera `21

- MAPFF1.0
- Neural network parametrization

$$zD_i^{\pi^+}(z,\mu_0 = 5\,\mathrm{GeV}) = \Big(\mathcal{N}_i(z;\boldsymbol{\theta}) - \mathcal{N}_i(1;\boldsymbol{\theta})\Big)^2$$

- Semi-Inclusive DIS & e^+e^- data
- NLO fit + exploration of low-Q^2 data

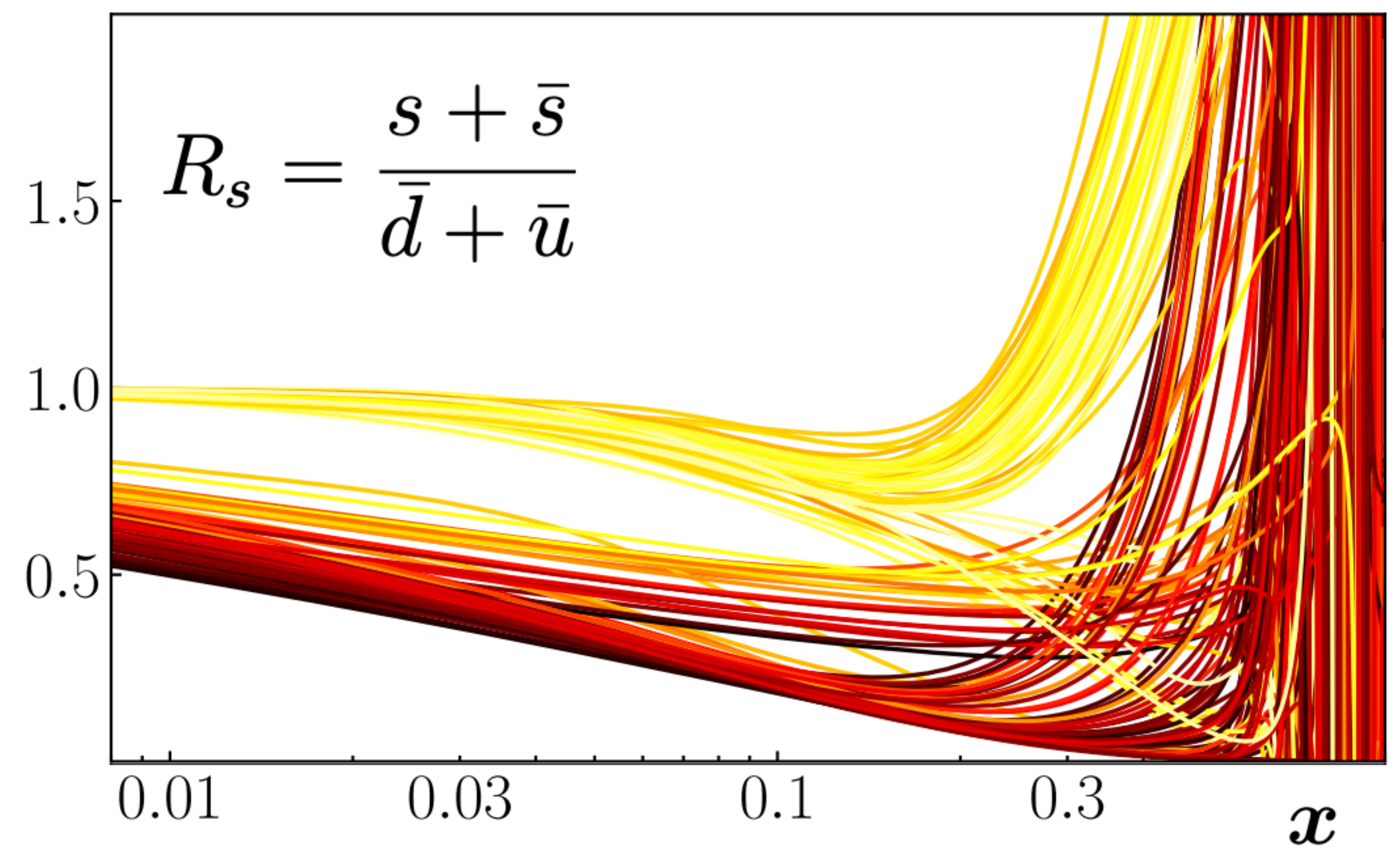




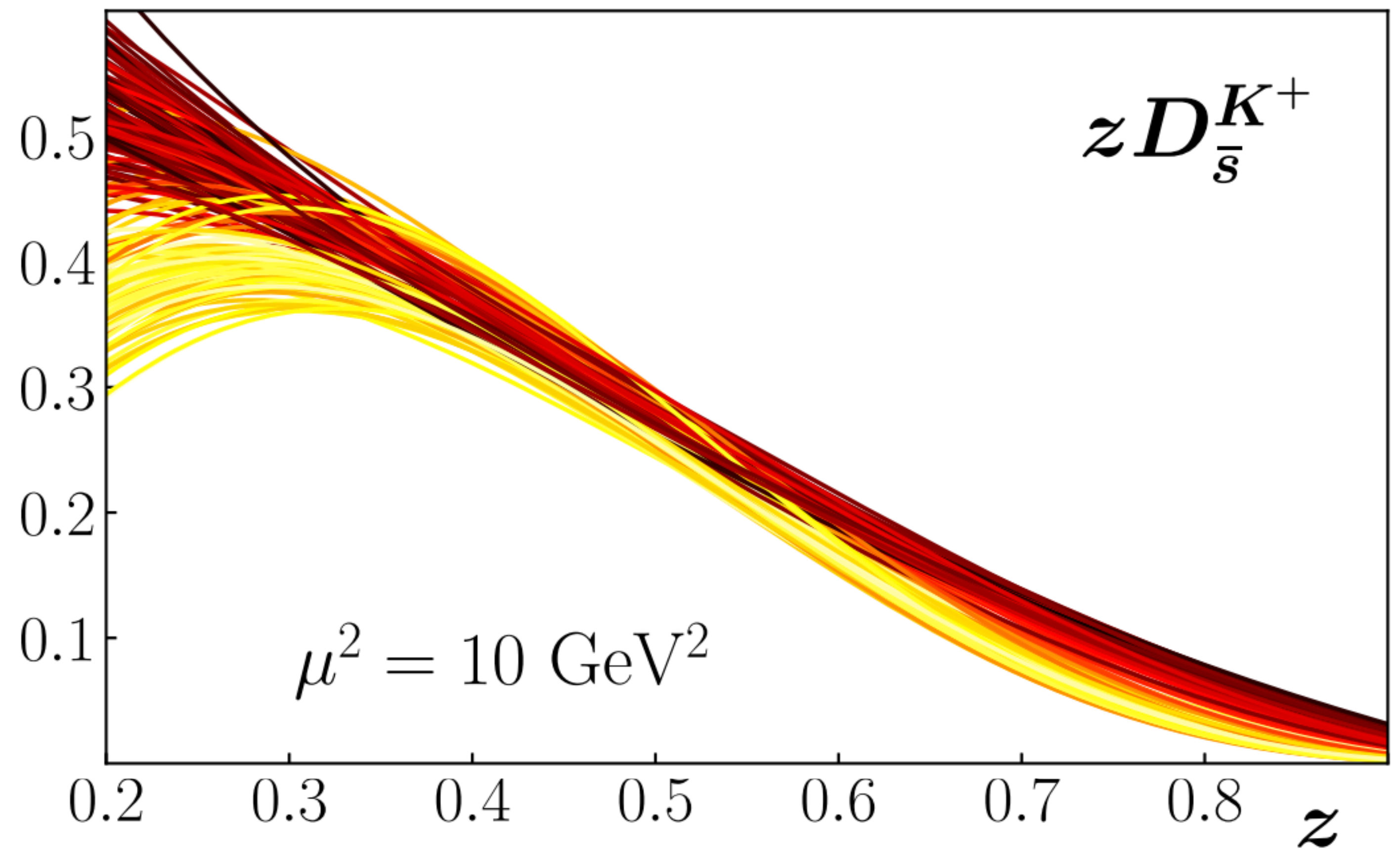
Extraction of collinear fragmentation functions

Moffat, Melnitchouk, Rogers, Sato `21

- Simultaneous extraction of PDFs & FFs, JAM20-SIDIS
- SIDIS, e^+e^- data, Drell-Yan, DIS
- Correlation between PDFs and FFs for kaons
- Larger $\bar{s} \to K^+$ FF compensated for by smaller strange PDF



PDF



FF

Dark - higher likelihood

Semi-Inclusive DIS at NNLO

Abele, de Florian, Vogelsang `21

- One of the missing pieces of global analyses at NNLO
- Approximate results at NNLO using threshold resummation at NNLL'
- Including the dominant contribution at subleading power (qq)

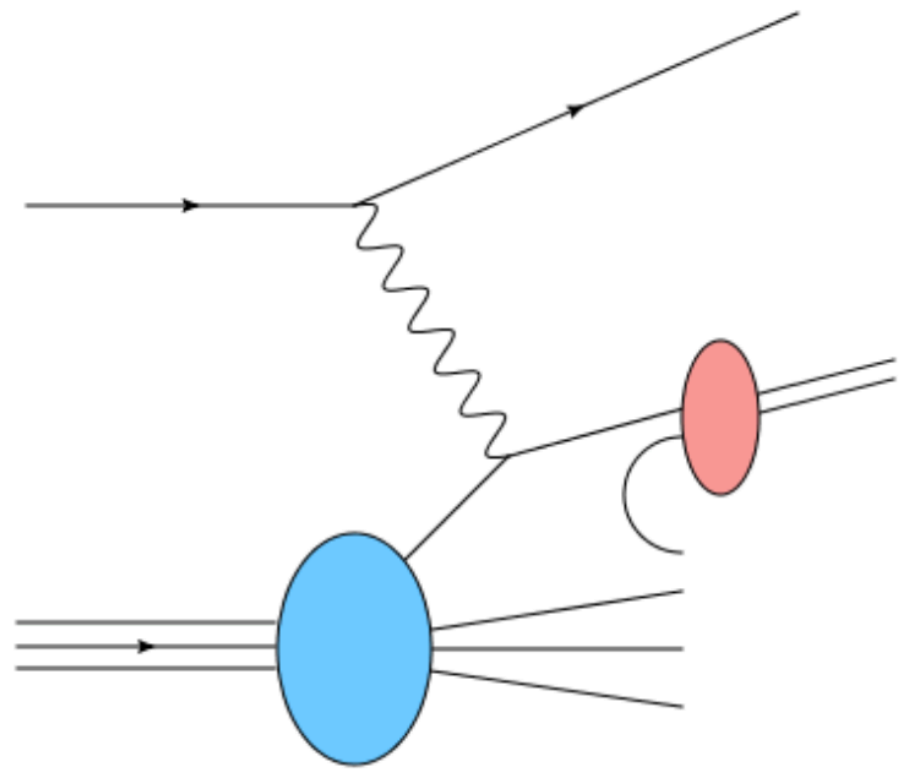
- Mellin space hard function

$$\tilde{\omega}_{qq}^{T}\left(N,M,\alpha_s(\mu_R),\frac{\mu_R}{Q},\frac{\mu_F}{Q}\right) = 1+\frac{\alpha_s(\mu_R)}{\pi}\tilde{\omega}_{qq}^{T,(1)}+\left(\frac{\alpha_s(\mu_R^2)}{\pi}\right)^2\tilde{\omega}_{qq}^{T,(2)}+\mathcal{O}(\alpha_s^3)$$

$$\frac{1}{e_q^2}\tilde{\omega}_{qq}^{T,(2)}\left(N,M,\frac{\mu_R}{Q},\frac{\mu_F}{Q}\right) = 2C_F^2\mathcal{L}^4+4C_F\mathcal{L}^3\left(\frac{\pi}{3}b_0+C_F\ln\frac{\mu_F^2}{Q^2}\right)$$
$$+C_F\mathcal{L}^2\left[C_F\left(-8+\frac{\pi^2}{3}+2\ln^2\frac{\mu_F^2}{Q^2}-3\ln\frac{\mu_F^2}{Q^2}\right)+\left(\frac{67}{18}-\frac{\pi^2}{6}\right)C_A-\frac{5}{9}N_f\right]$$
$$+C_F\mathcal{L}\left[\left(\frac{101}{27}-\frac{7}{2}\zeta(3)\right)C_A-\frac{14}{27}N_f+C_F\ln\frac{\mu_F^2}{Q^2}\left(-8+\frac{\pi^2}{3}-3\ln\frac{\mu_F^2}{Q^2}\right)\right.+\ldots$$

with $\mathcal{L}\equiv\frac{1}{2}\left(\ln(\bar{N})+\ln(\bar{M})\right)$

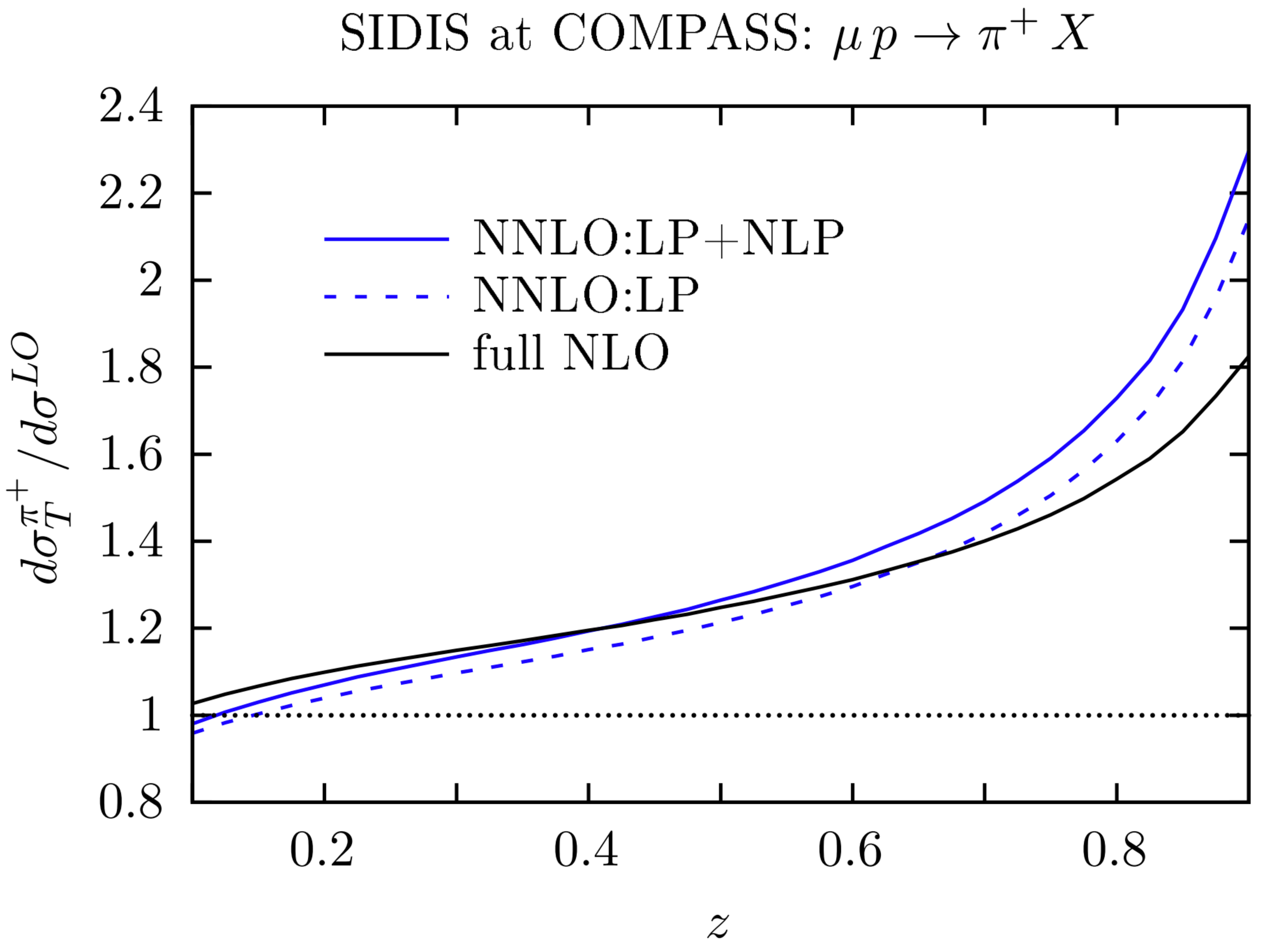
N, M conjugate to x, z



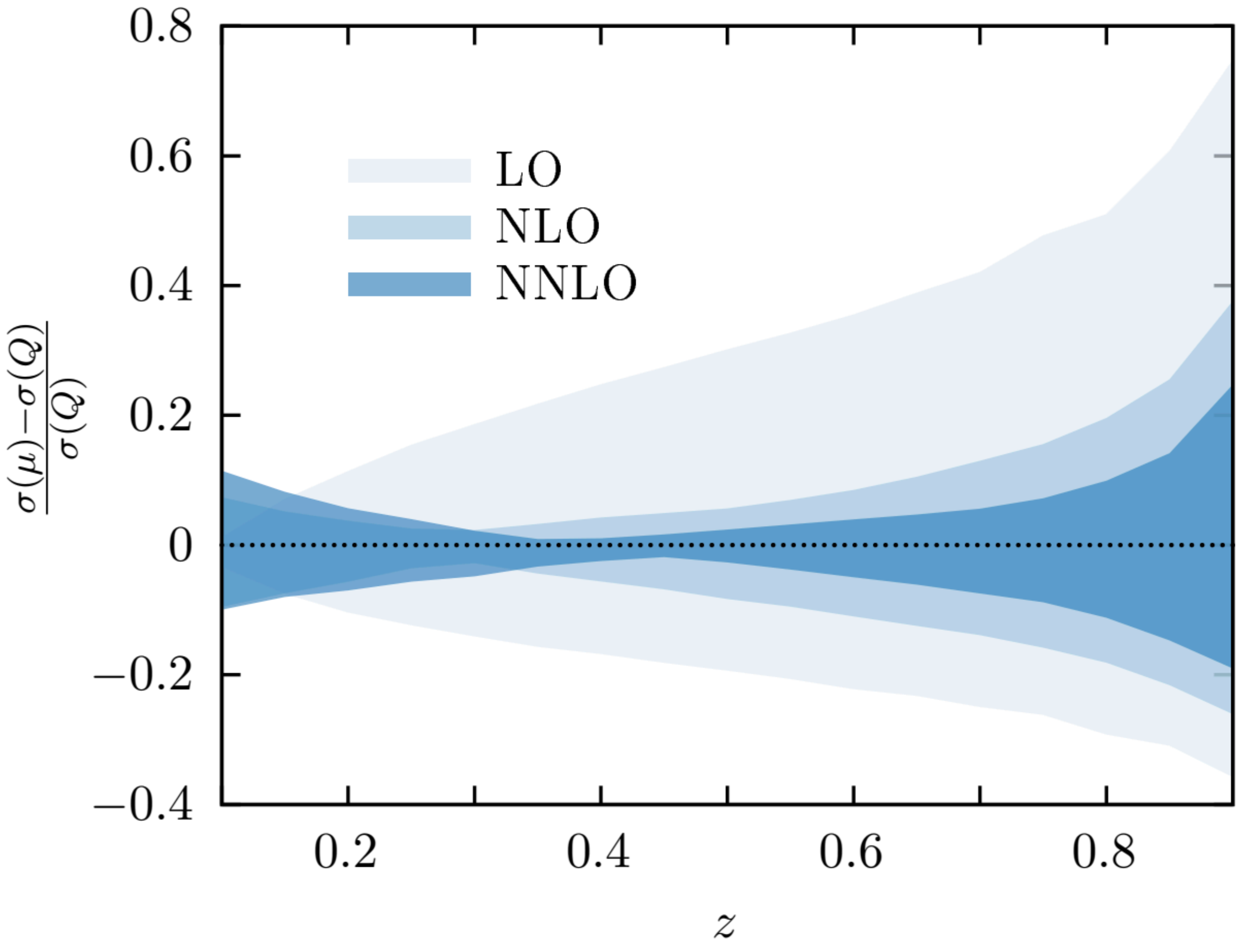
Semi-Inclusive DIS at NNLO

Abele, de Florian, Vogelsang `21

- Size of NNLO corrections



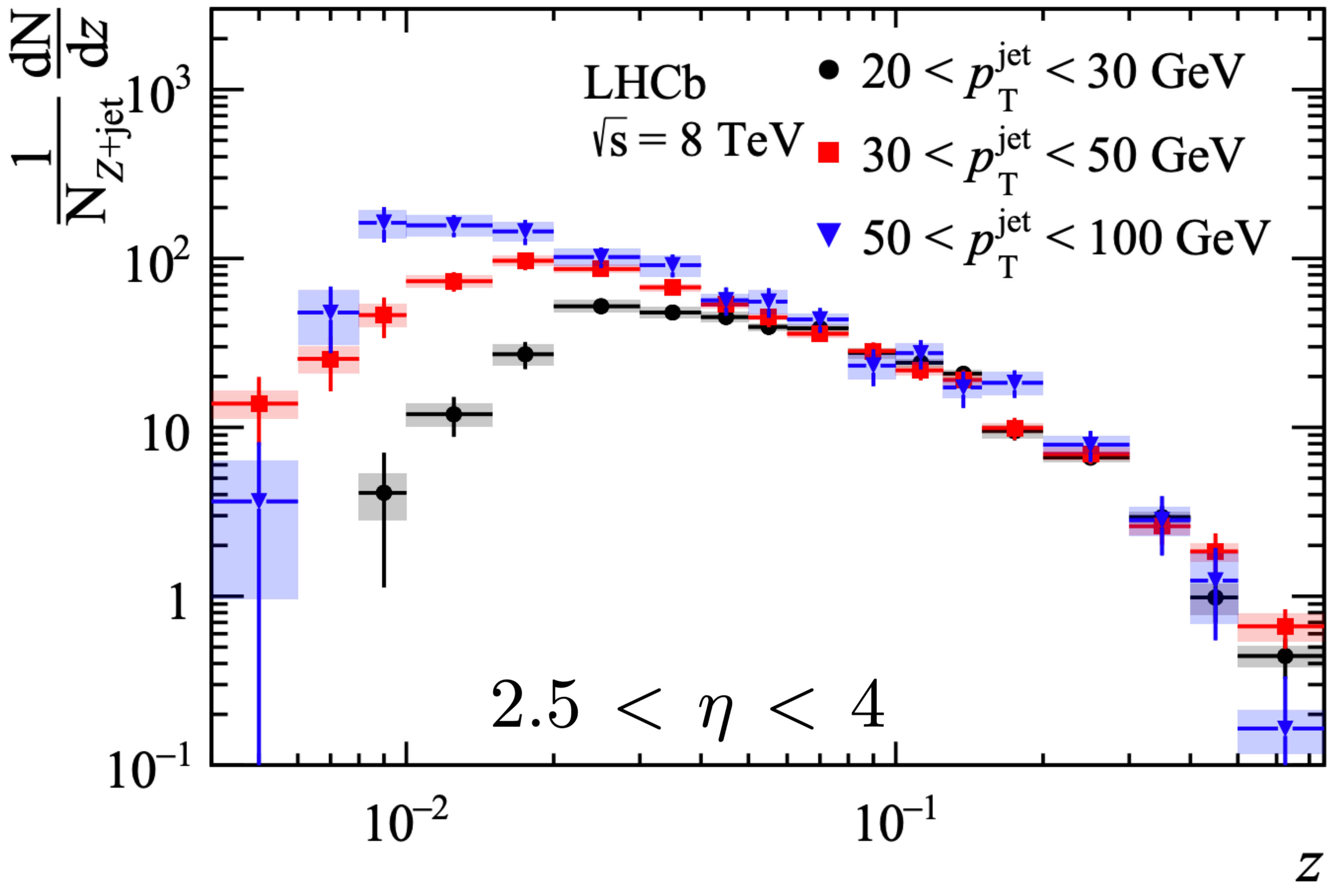
- QCD scale uncertainty

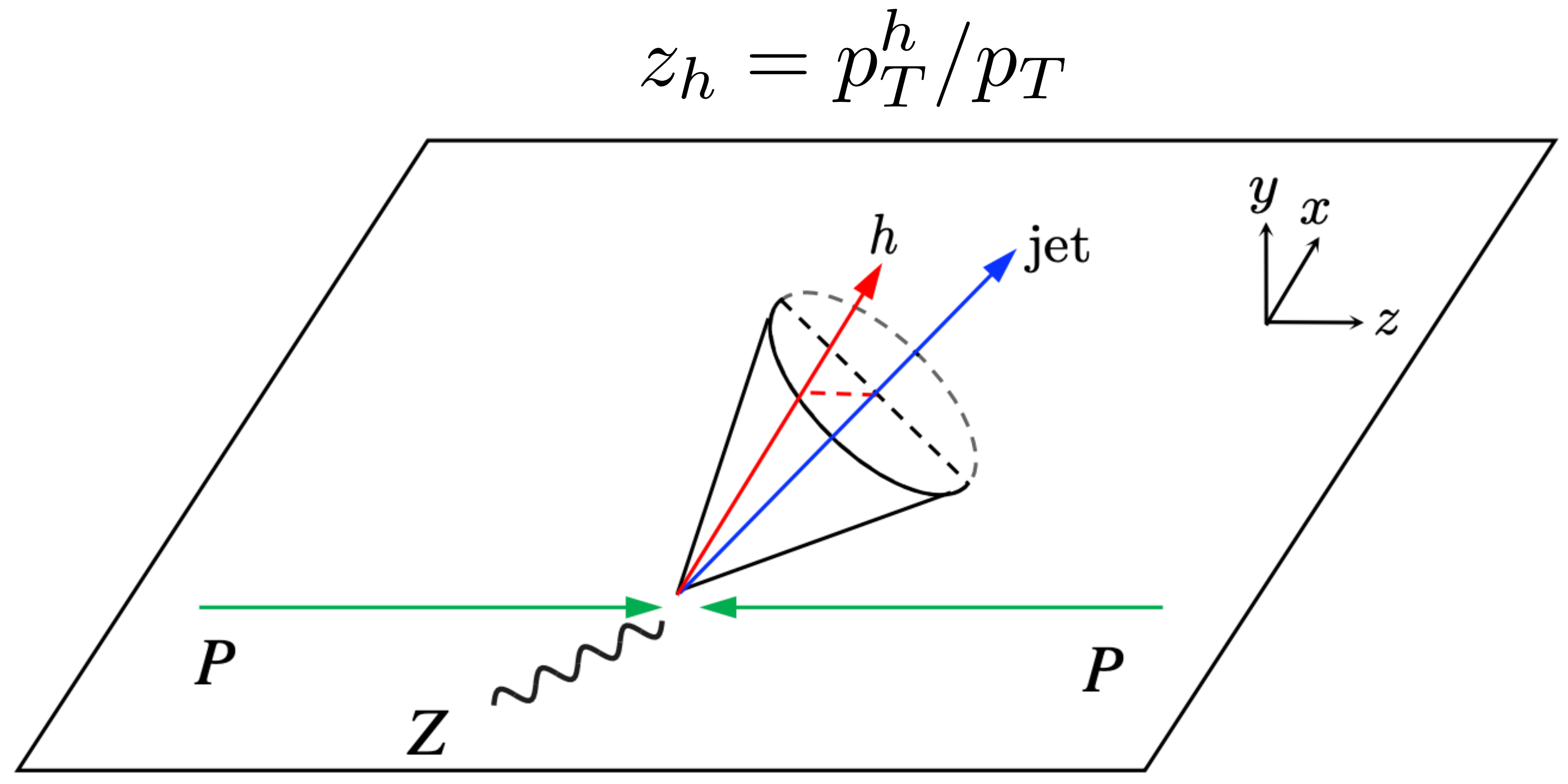


In-jet fragmentation

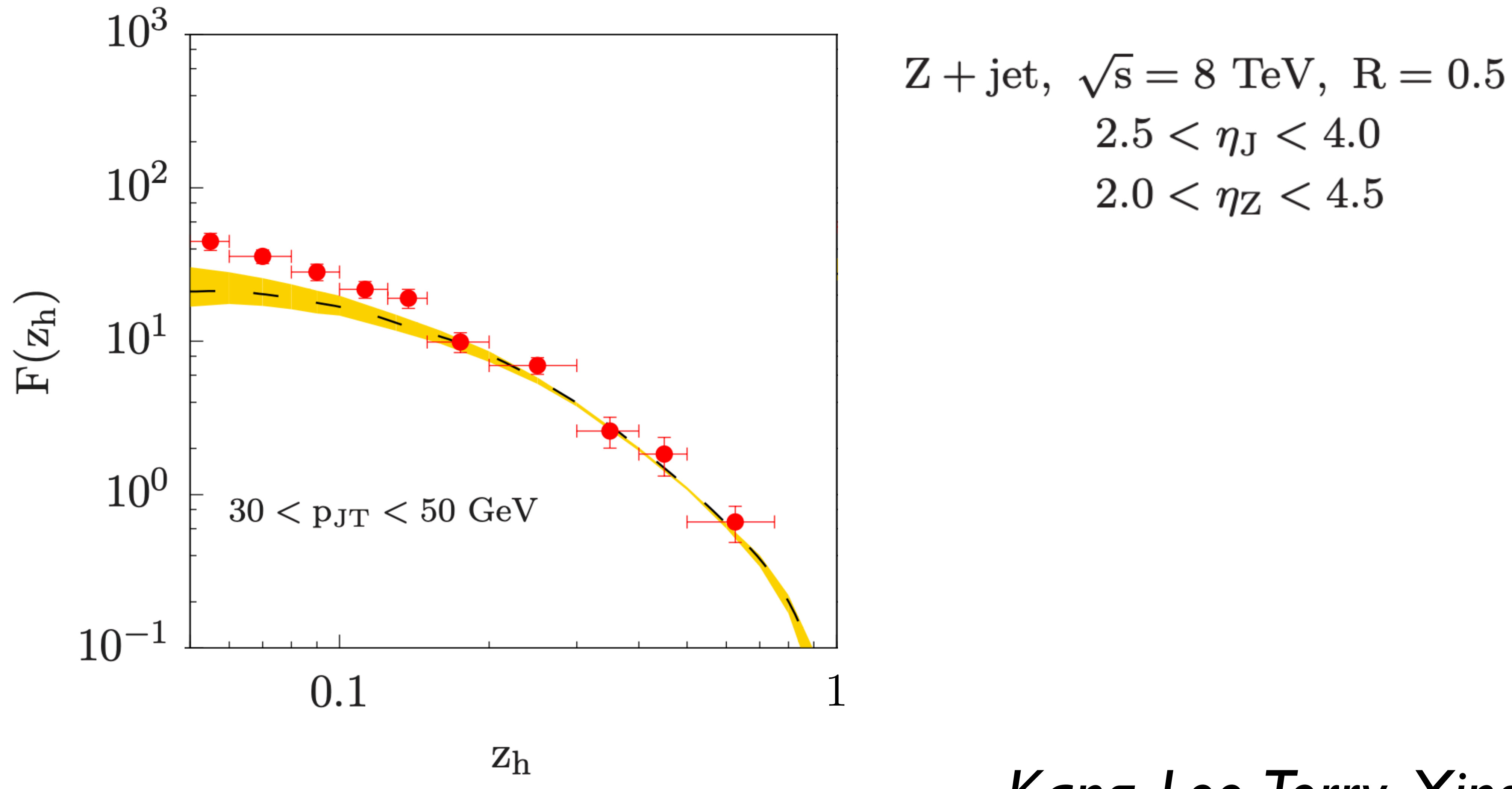
- LHCb data for Z+jet events, charged hadrons

LHCb, PRL 123 (2019) 232001





- Comparison to theory calculations in SCET



Kang, Lee, Terry, Xing `19

- Different quark/gluon fractions compared to inclusive jets

In-jet fragmentation at threshold

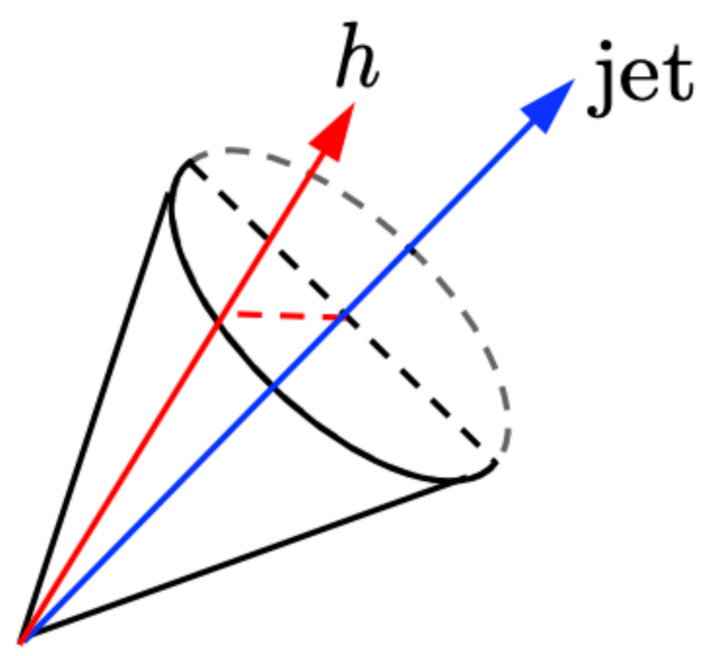
Kaufmann, Liu, Mukherjee, FR, Vogelsang `21

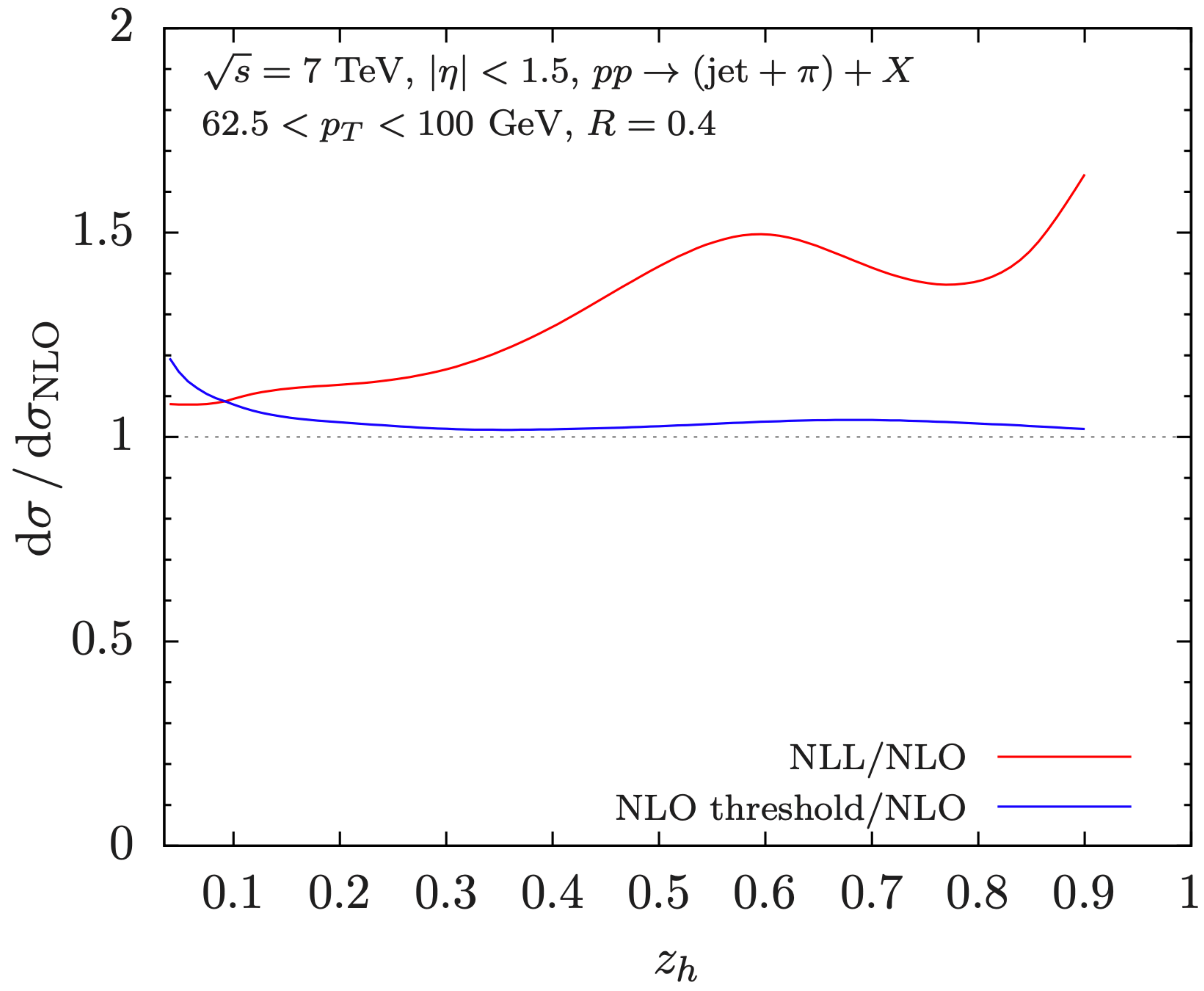
- Double logarithmic threshold corrections for $z_h \to 1$
- Resummation at NLL' within SCET for inclusive jets

$$\mathcal{G}_c^h(z, z_h, p_T R, \mu) \stackrel{\text{NLL}'}{=}$$

$$\sum_d \mathcal{H}_{cd}(z, p_T R, \mu)\, S_d(z_h, p_T R, \mu)$$

$$\otimes S_d^{\text{NG}}(z_h, \mu) \otimes D_d^h(z_h, \mu)$$





see also Procura, Waalewijn `12

Outline

Collinear fragmentation

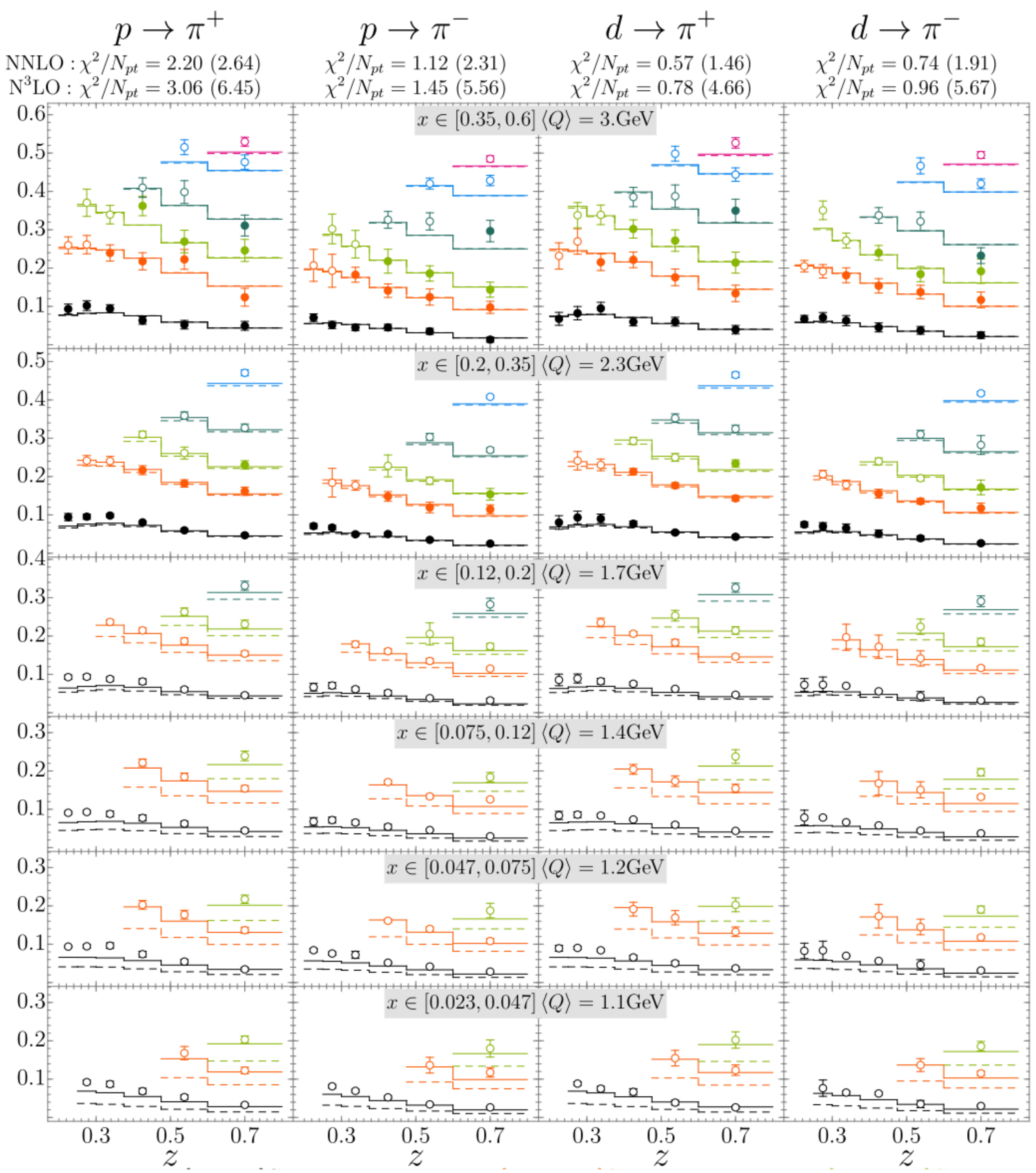
TMD Fragmentation

Further new developments

Extractions of TMD FFs

Scimemi, Vladimirov `19

- SIDIS, Drell-Yan - 1039 data points
- TMD PDF, TMD FF, Rapidity anomalous dimension
- Test of universality $q_T \lesssim 0.25Q$
- N^3LO evolution, NNLO matching



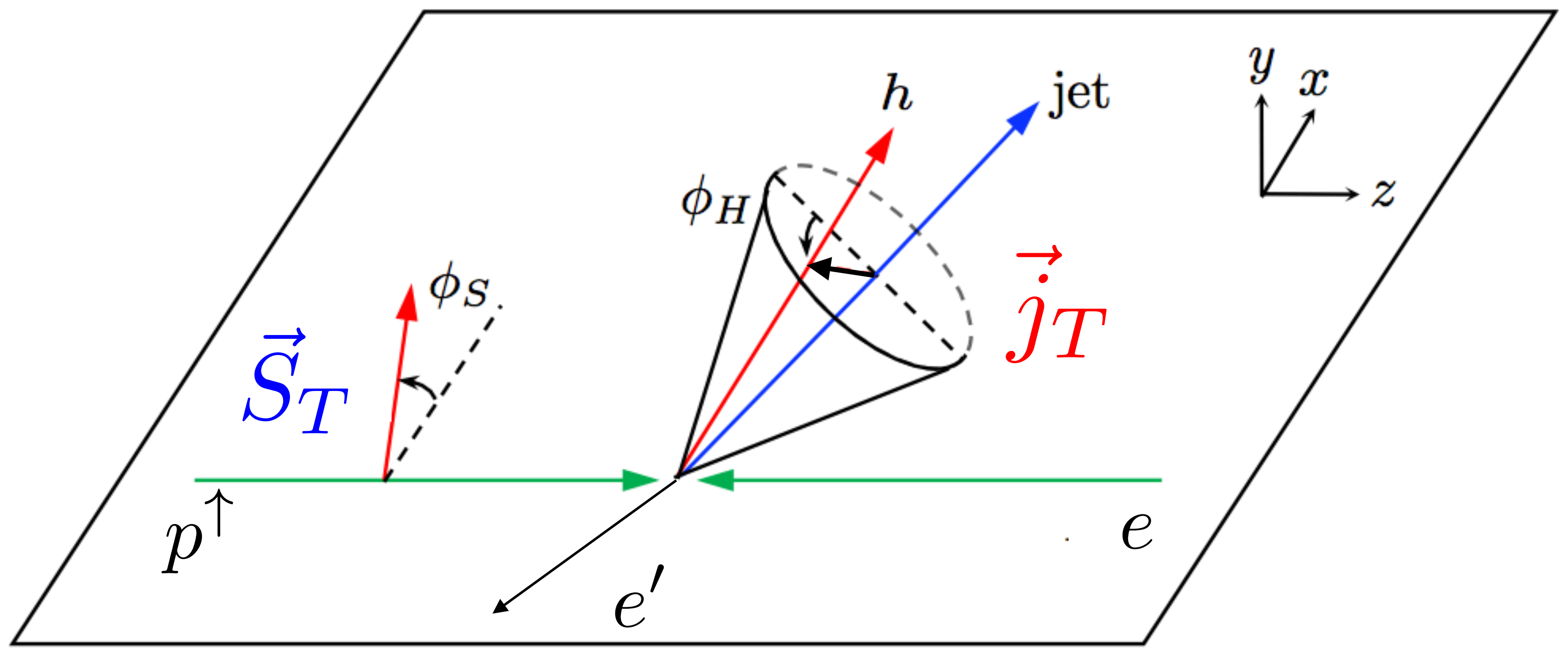
SIDIS multiplicities, HERMES

see also Bacchetta, Delcarro, Pisano, Radici, Signori `18
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato `20

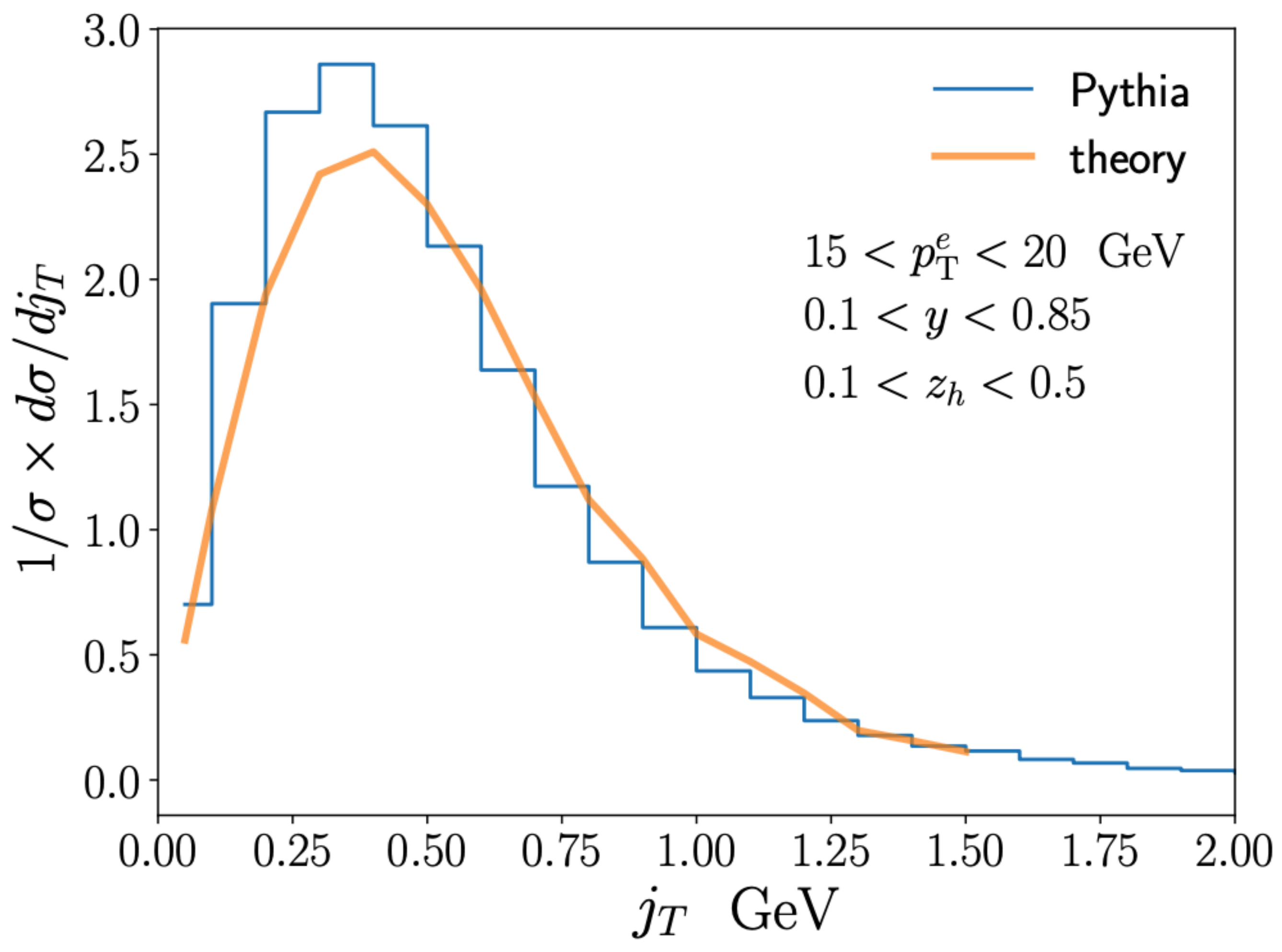
In-jet TMD fragmentation

Liu, Ringer, Vogelsang, Yuan `18
Kang, Prokudin, Ringer, Yuan `17
Arratia, Kang, Prokudin, Ringer `20

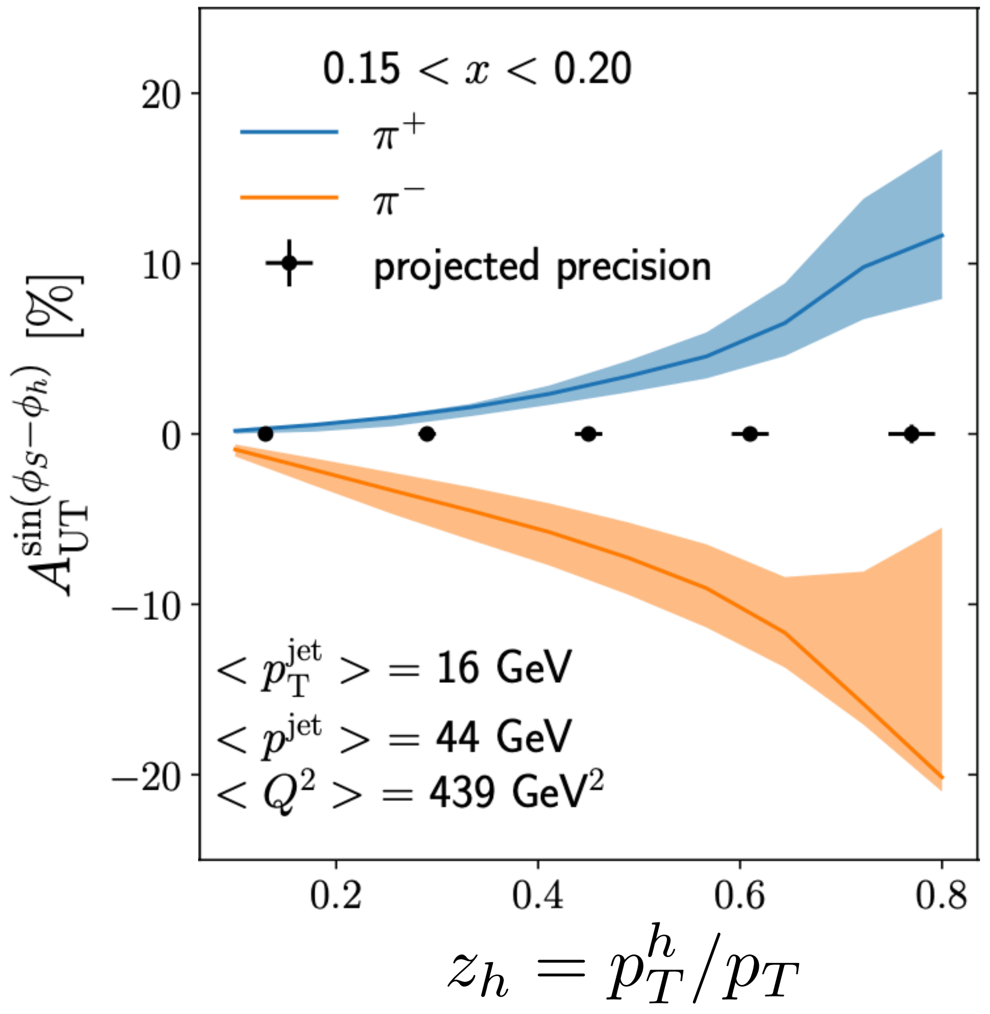
- Measure hadrons inside a jet relative the jet axis
- Azimuthal transverse spin asymmetries
- Independent handle on transversity and the Collins TMD FF $H_1^{\perp\, q}(z_h, \vec{j}_T)$
- Leading power in the jet radius avoids sensitivity to TMD PDF



see also LHCb, PRL 123 (2019) 232001



Unpolarized



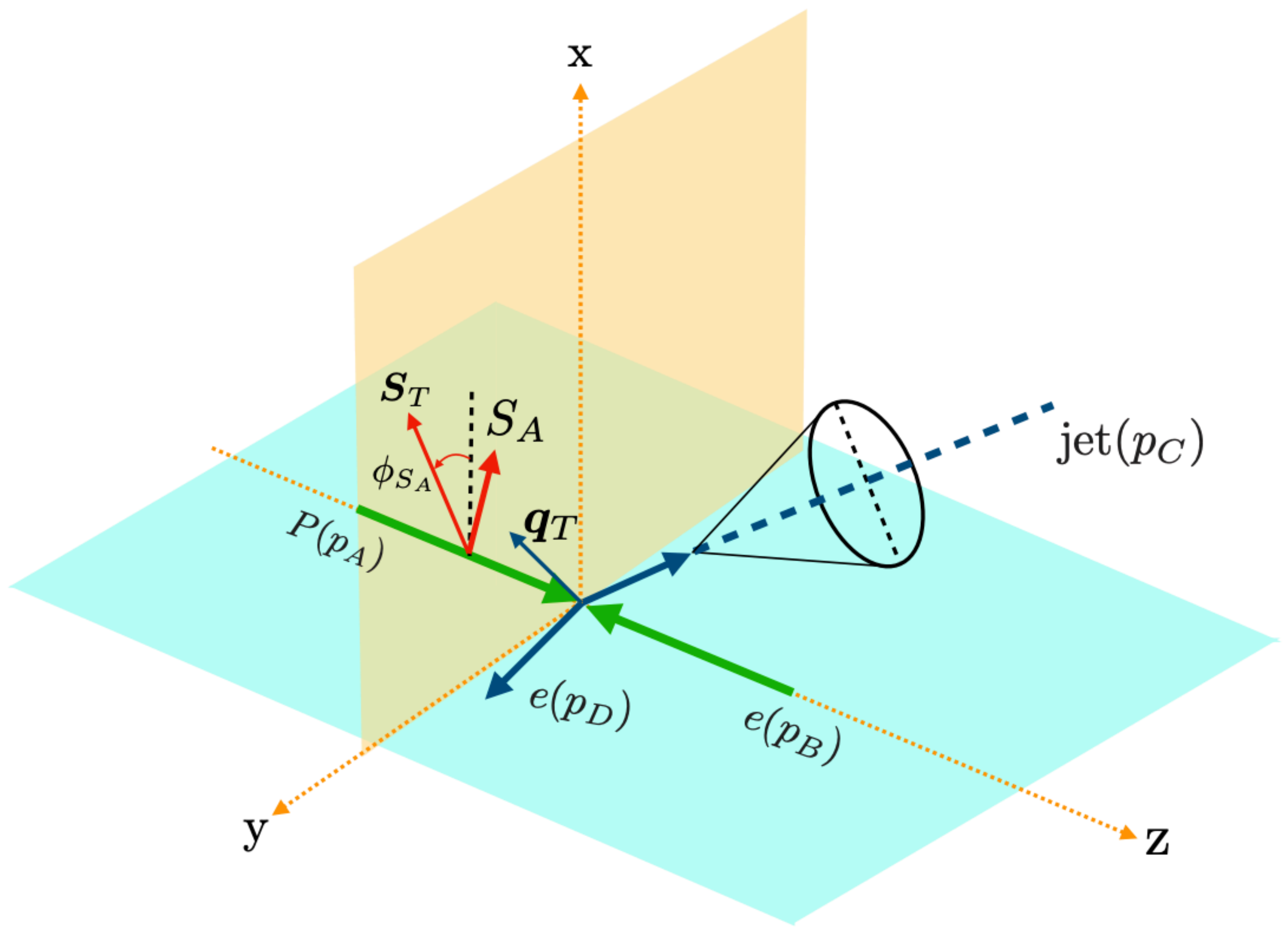
Polarized

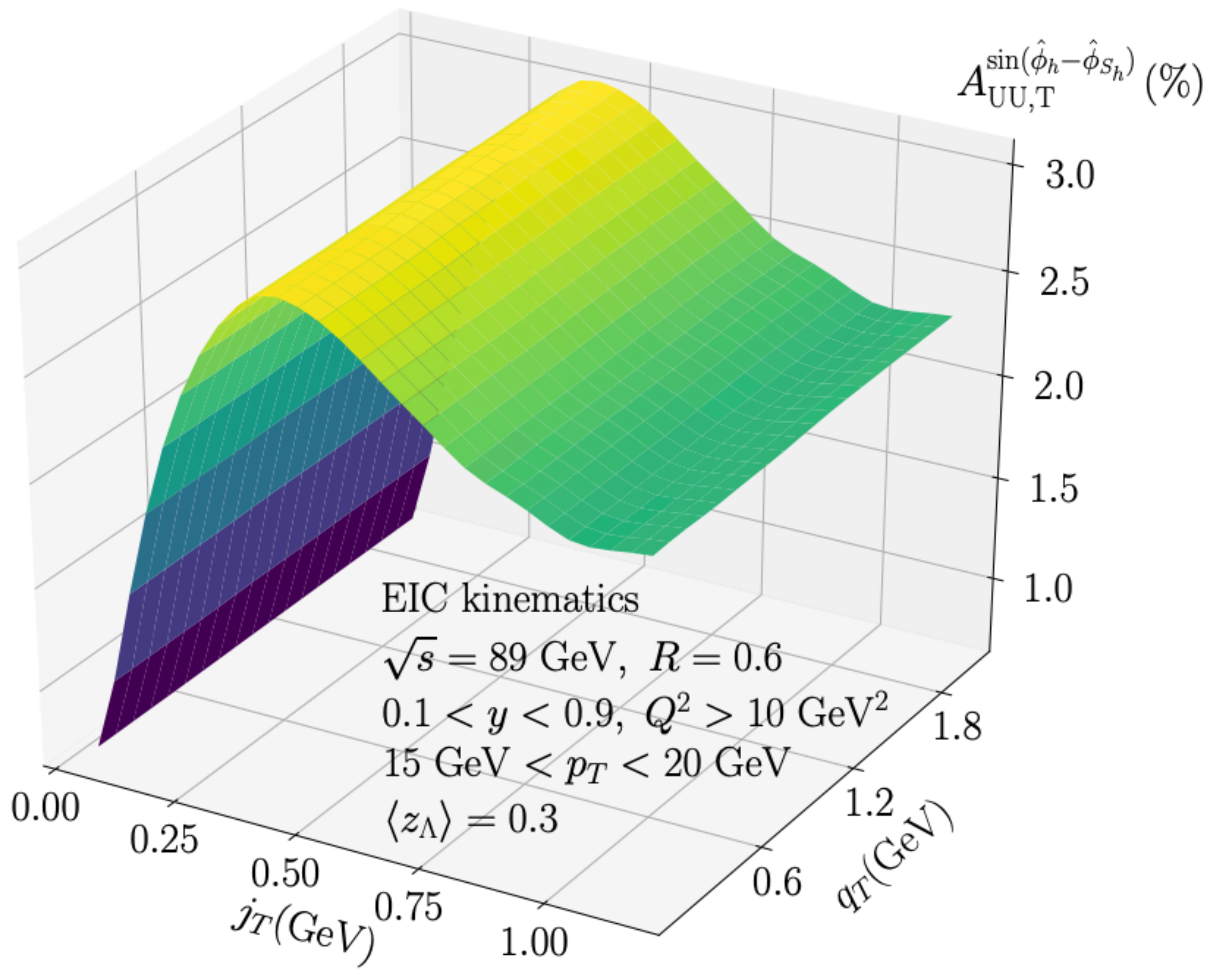
In-jet TMD fragmentation

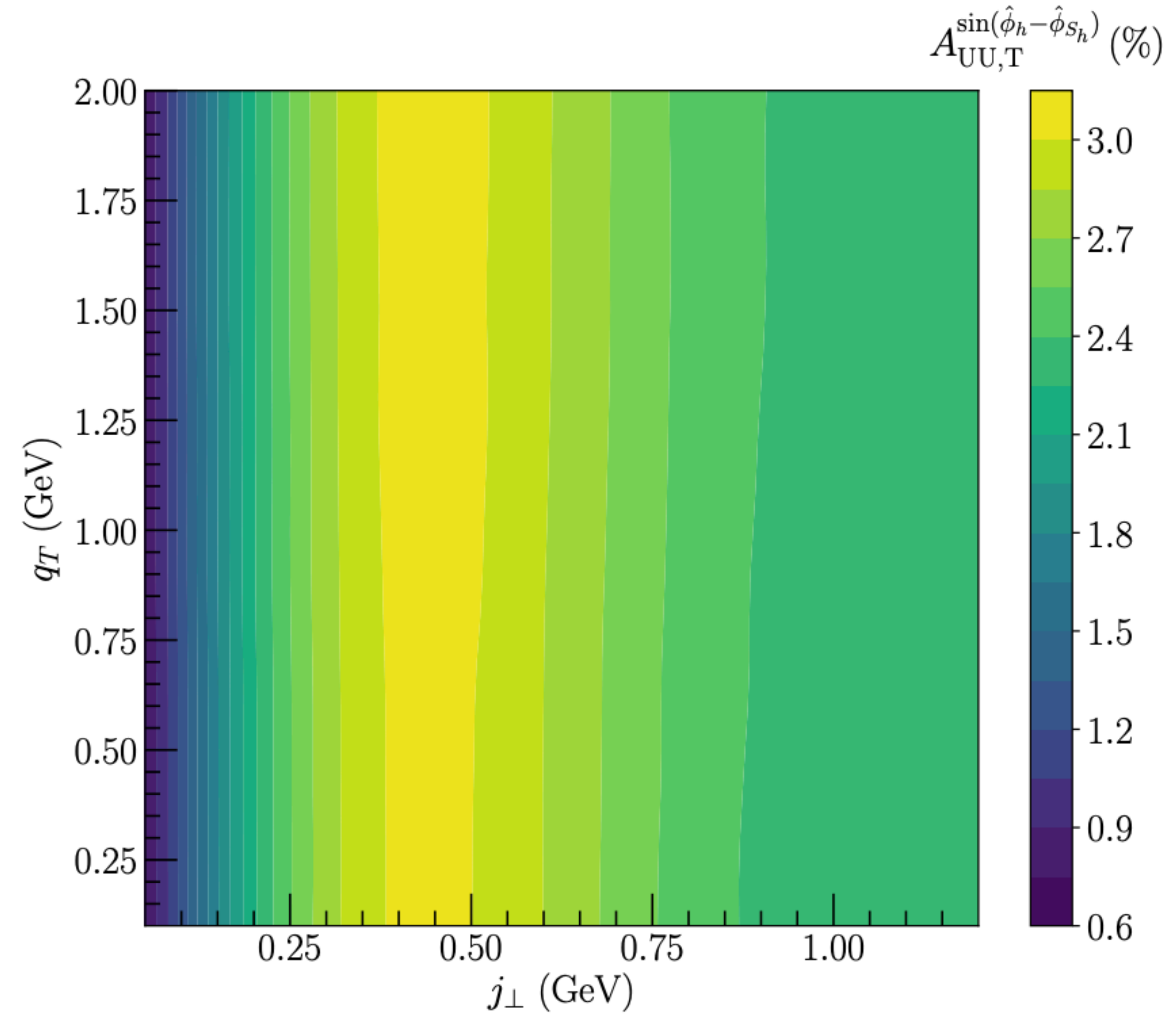
Kang, Lee, Shao, Fanyi `21

- Generalize to full initial & final state spin dependence
- E.g. Lambda production in the jet
- Correlation of $\boldsymbol{S}_{\Lambda\perp}$ and $\boldsymbol{j}_\perp$
- Asymmetry

$$A_{UU,T}^{\sin(\hat\phi_\Lambda - \hat\phi_{S_\Lambda})} = \frac{F_{UU,T}^{\sin(\hat\phi_\Lambda - \hat\phi_{S_\Lambda})}}{F_{UU,U}}$$





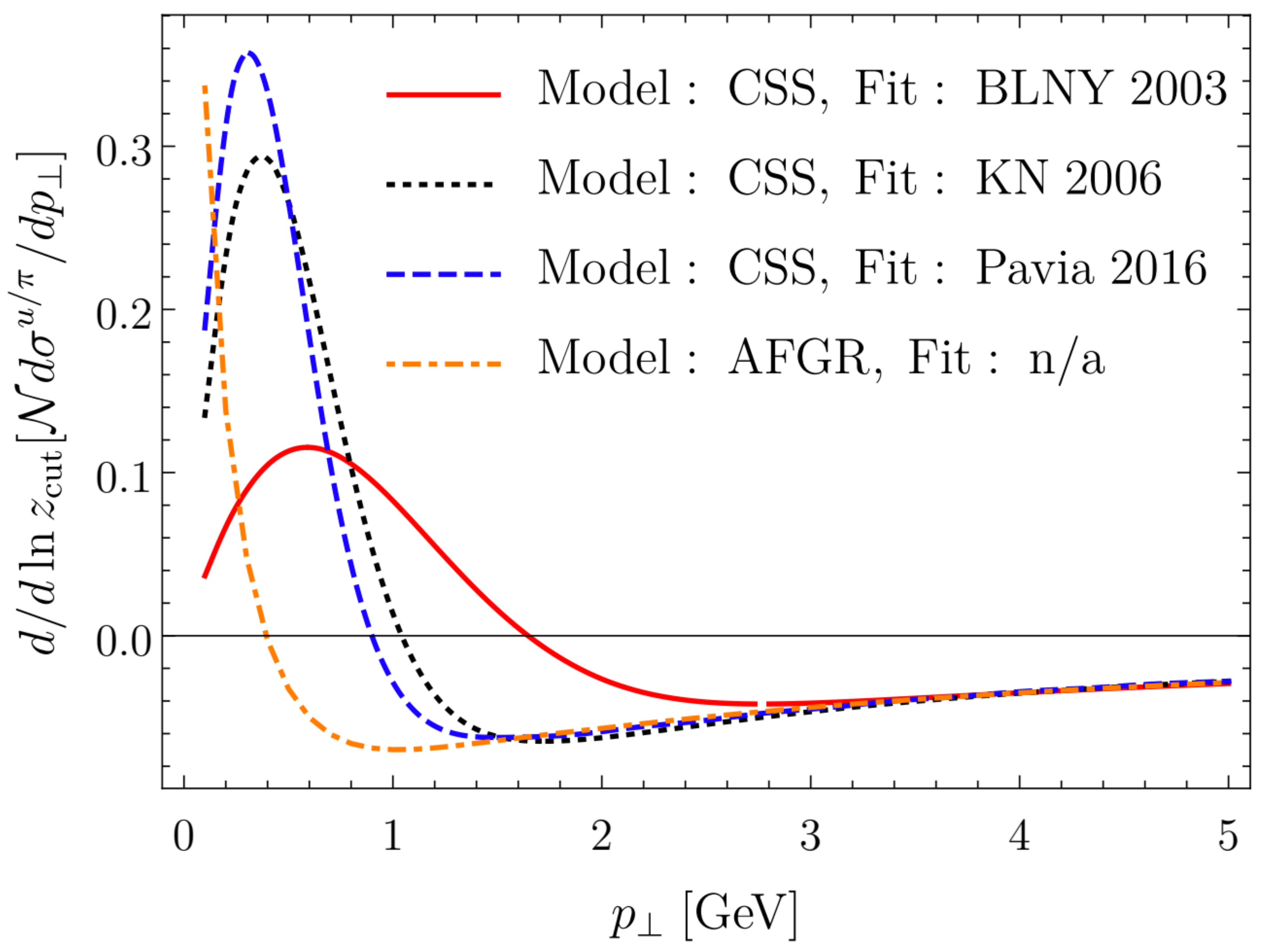


see also Gamberg, Kang, Shao, Terry, Zhao `21

Jet grooming & TMD fragmentation

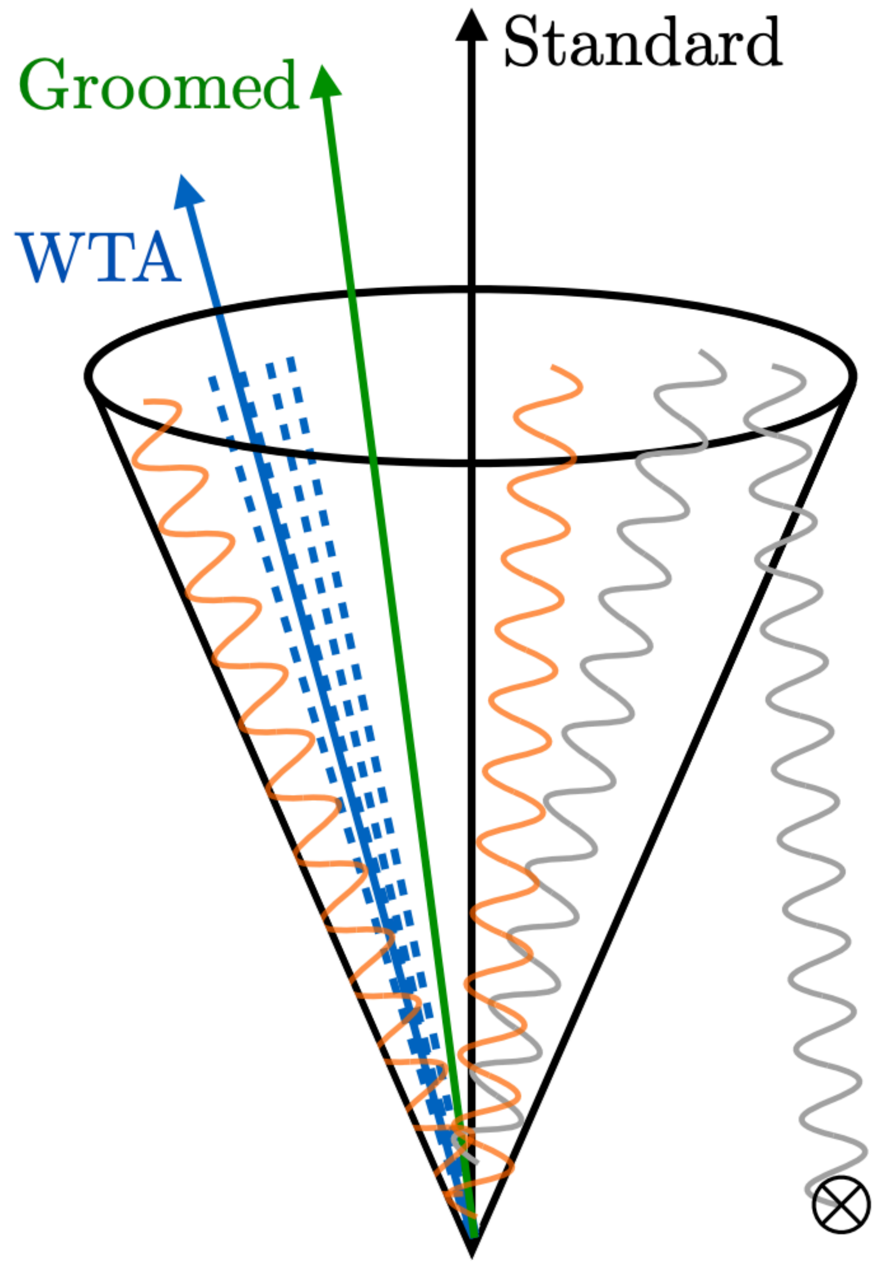
Makris, Neill, Vaidya `18

- Measure hadrons with respect to the groomed jet axis
- Grooming parameter gives additional handle on TMD evolution



- Soft drop grooming

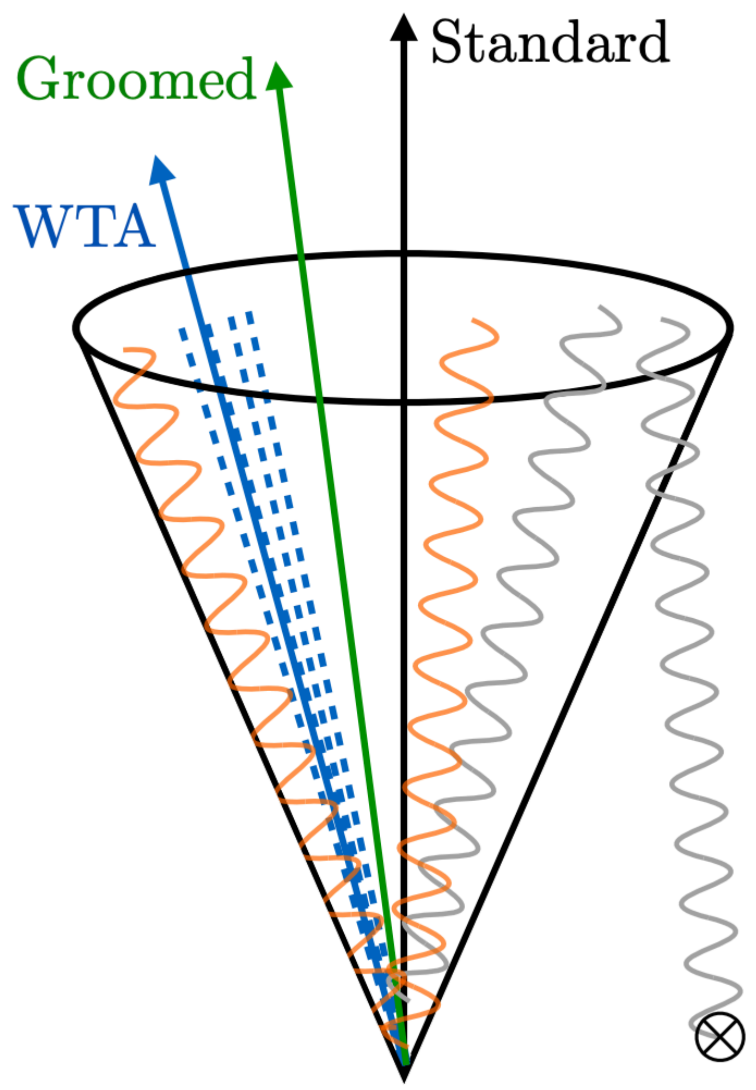
  Remove branches in the jet with $z < z_{\rm cut}$

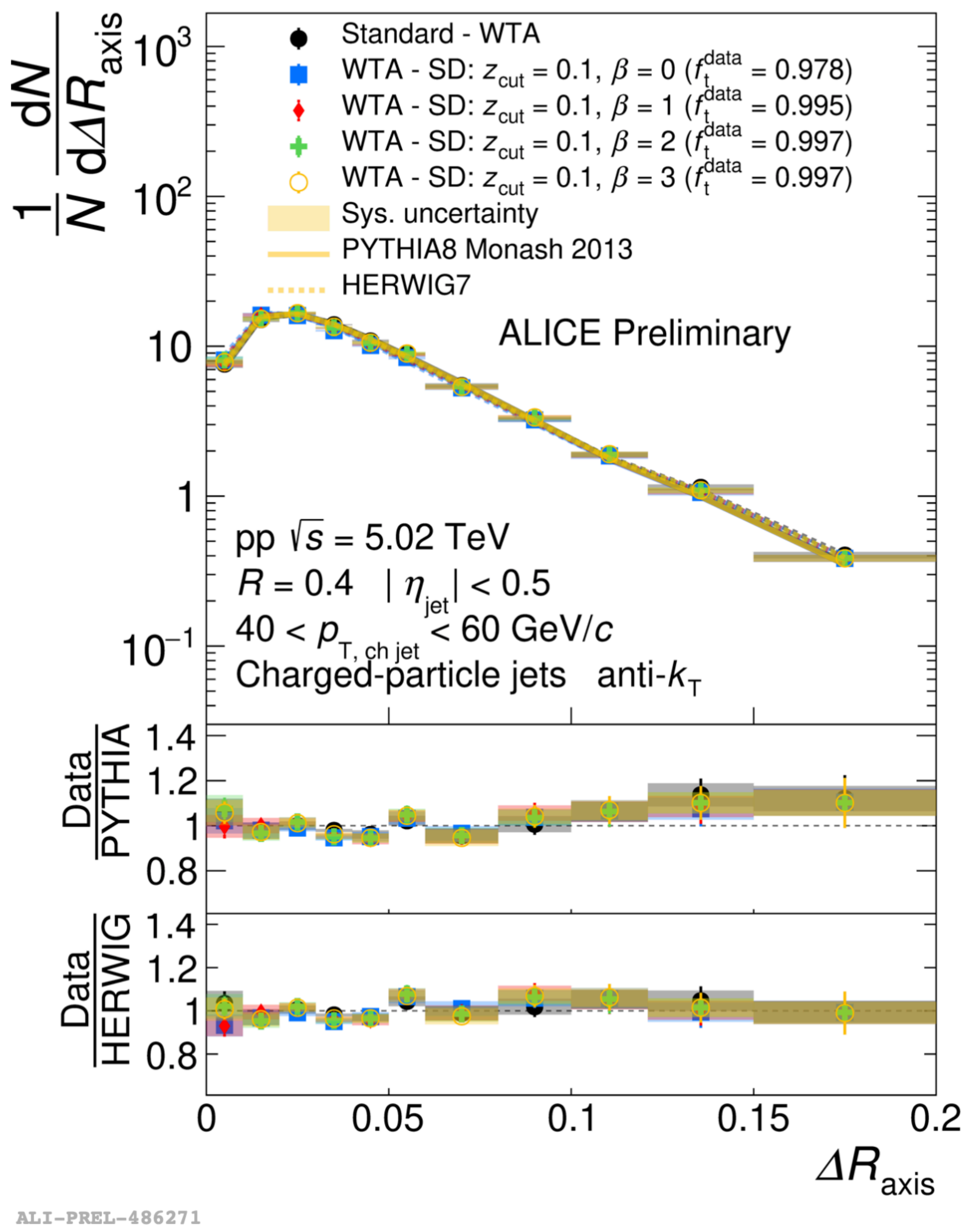


Dasgupta, Fregoso, Salam `13
Larkoski, Marzani, Soyez, Thaler `14

Jet grooming & TMD fragmentation

- Measure opening angle between different jet axes (IRC safe)
- Recent results from the ALICE Collaboration





Cal, Neill, FR, Waalewijn `19

ALICE, preliminary, see Rey Cruz Torres PANIC2021

Outline

Collinear fragmentation

TMD Fragmentation

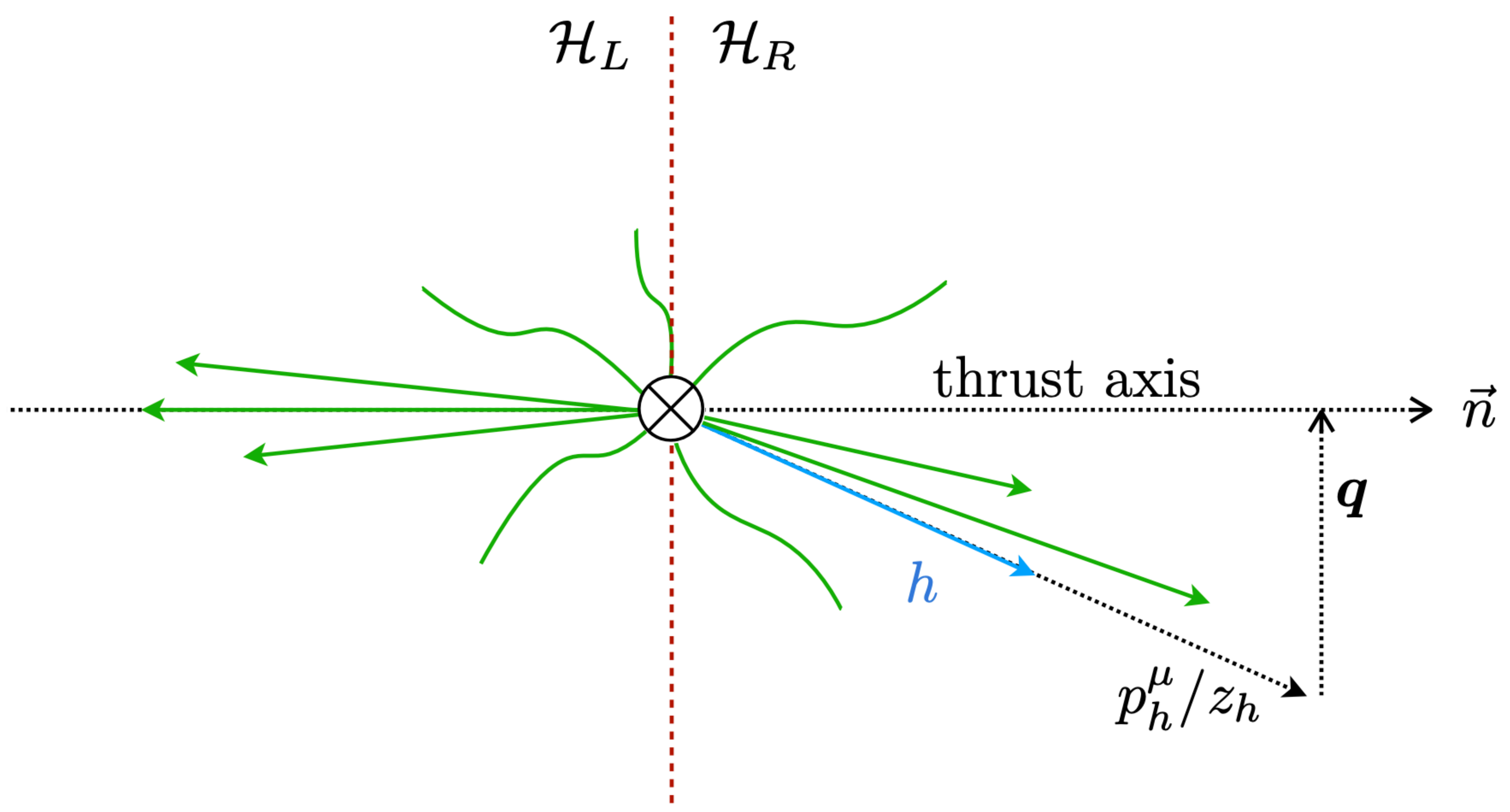
Further new developments

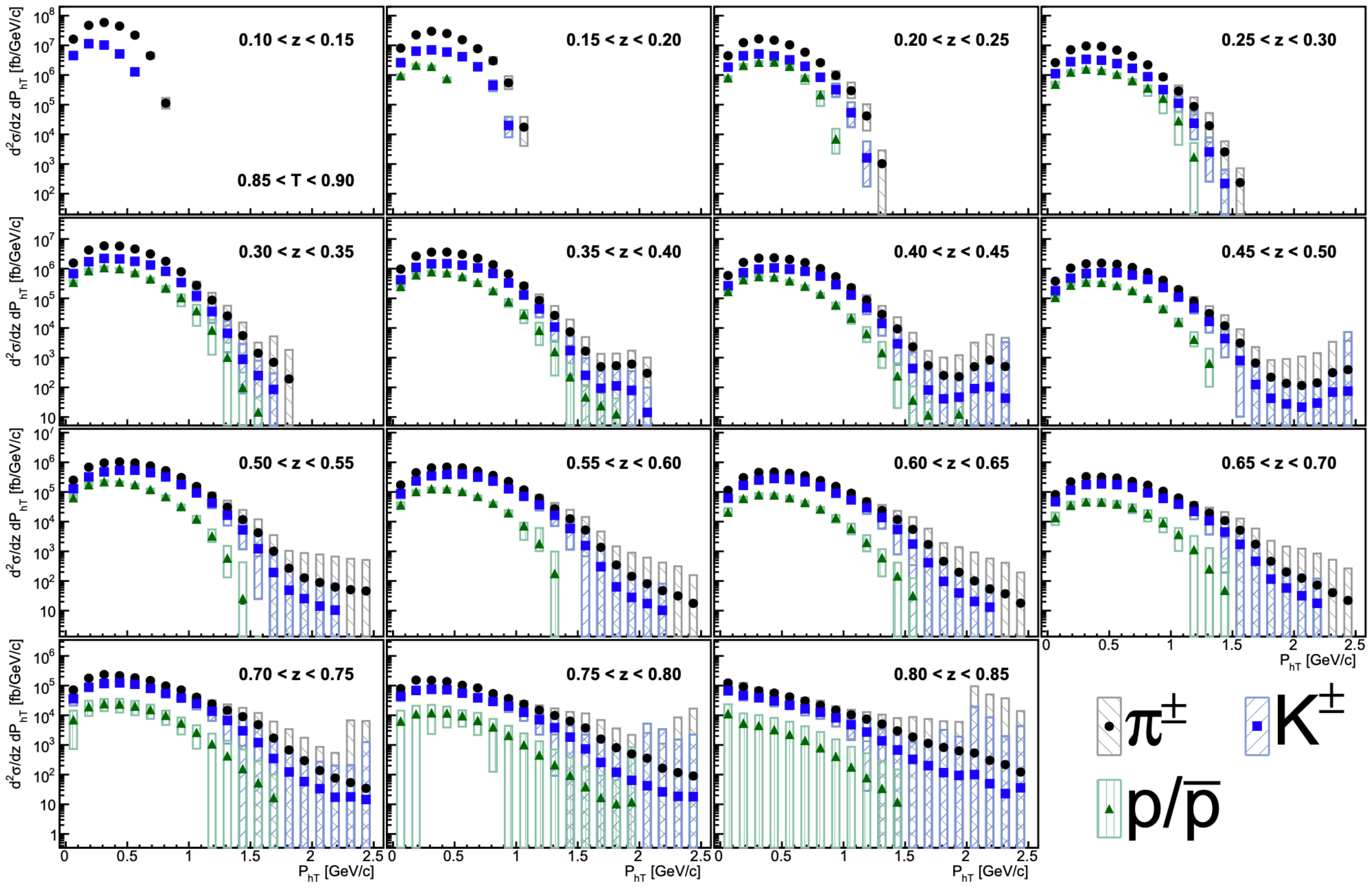
Thrust-TMD measurements at BELLE

BELLE Collaboration, PRD 99 (2019) 112006

- Thrust

$$T \equiv \max_{\hat{n}} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$$





- Triple differential measurement

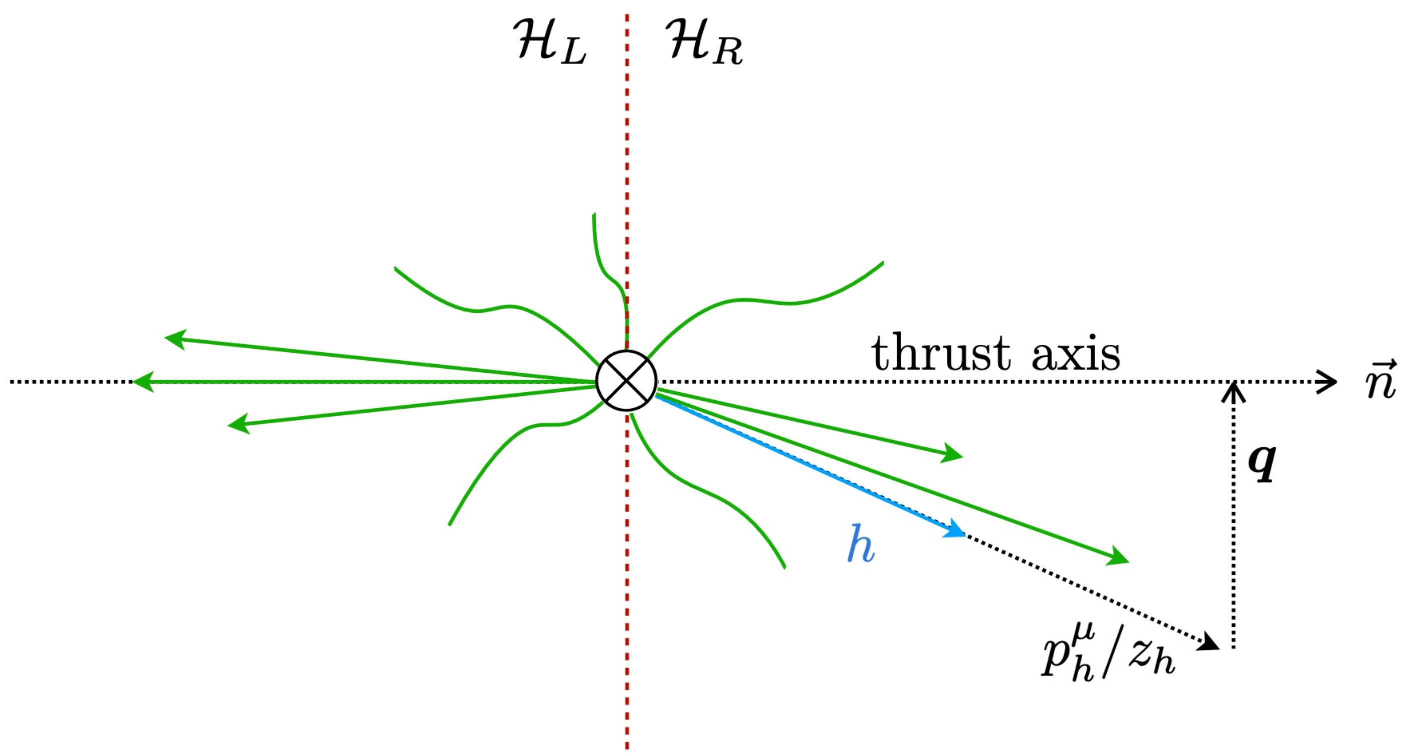
$$z_h = 2E_h/Q\,, \quad p_{hT} \equiv |\boldsymbol{p}_h|\,, \quad T$$

Thrust-TMD measurements at BELLE

Makris, FR, Waalewijn `20

- Triple differential measurement

$$z_h = 2E_h/Q\,, \quad p_{hT} \equiv |\boldsymbol{p}_h|\,, \quad T = 1-\tau$$



- Requires joint resummation of multiple large logarithms

- Identification of 3 kinematic regions with different factorizations $q_T = p_{hT}/z_h$

$$\begin{aligned} &\text{Region 1:} \quad \sqrt{\tau} \gg q_T/Q \sim \tau \\ &\text{Region 2:} \quad \sqrt{\tau} \gg q_T/Q \gg \tau \\ &\text{Region 3:} \quad \sqrt{\tau} \sim q_T/Q \gg \tau \end{aligned}$$

- Regions 1,2 are sensitive to TMD physics

- Resummation at NNLL in SCET, e.g. region 1

$$\frac{\mathrm{d}\sigma_1}{\mathrm{d}z_h\,\mathrm{d}\boldsymbol{q}\,\mathrm{d}\tau} = \sum_j \sigma_{0,j}(Q) \int_{-\infty}^{\infty} \frac{\mathrm{d}\boldsymbol{b}}{(2\pi)^2} \int_{\gamma-\mathrm{i}\infty}^{\gamma+\mathrm{i}\infty} \frac{\mathrm{d}u}{2\pi\mathrm{i}}\, e^{\mathrm{i}\boldsymbol{b}\cdot\boldsymbol{q}+u\tau} H(Q,\mu)$$

$$J\Big(\frac{u}{Q^2},\mu\Big)\, S\Big(\boldsymbol{b},\frac{u}{Q},\mu,\nu\Big)\, D_{1,j\to h}\Big(z_h,\boldsymbol{b},\mu,\frac{\nu}{Q}\Big)$$

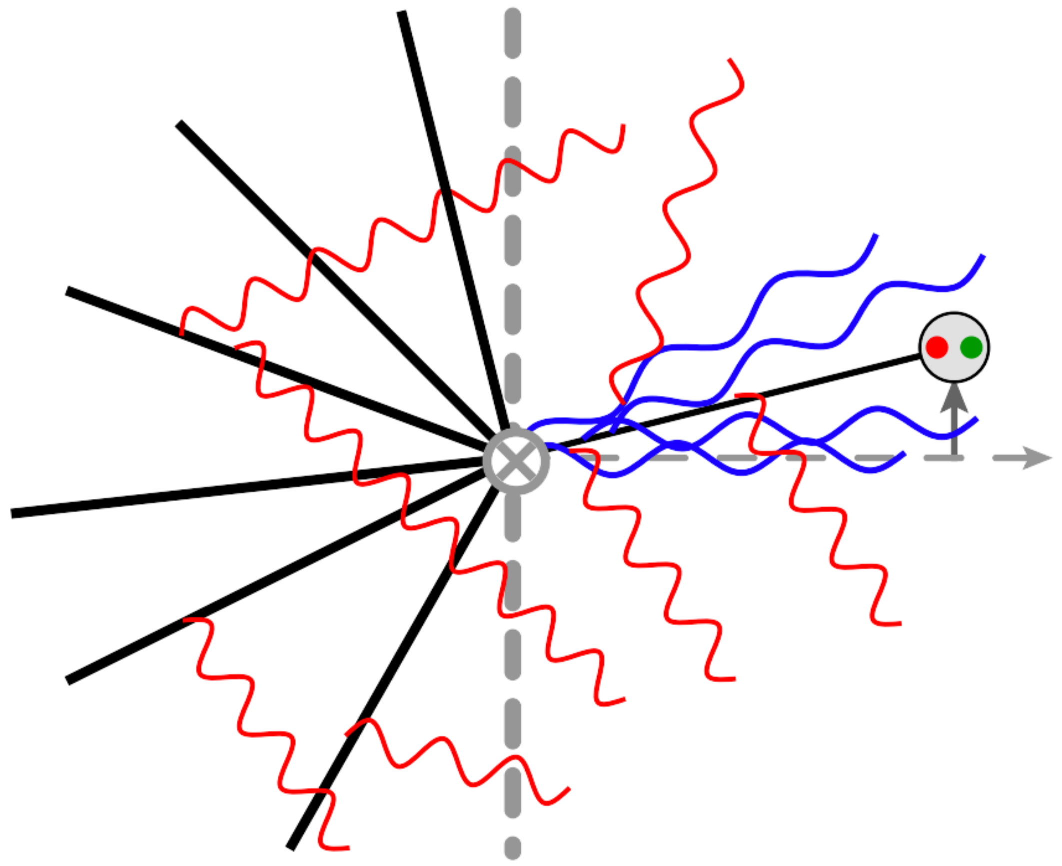
see also Boglione, Simonelli `20-`21
Lustermans, Michel, Tackmann, Waalewijn `19

Thrust-TMD measurements at BELLE

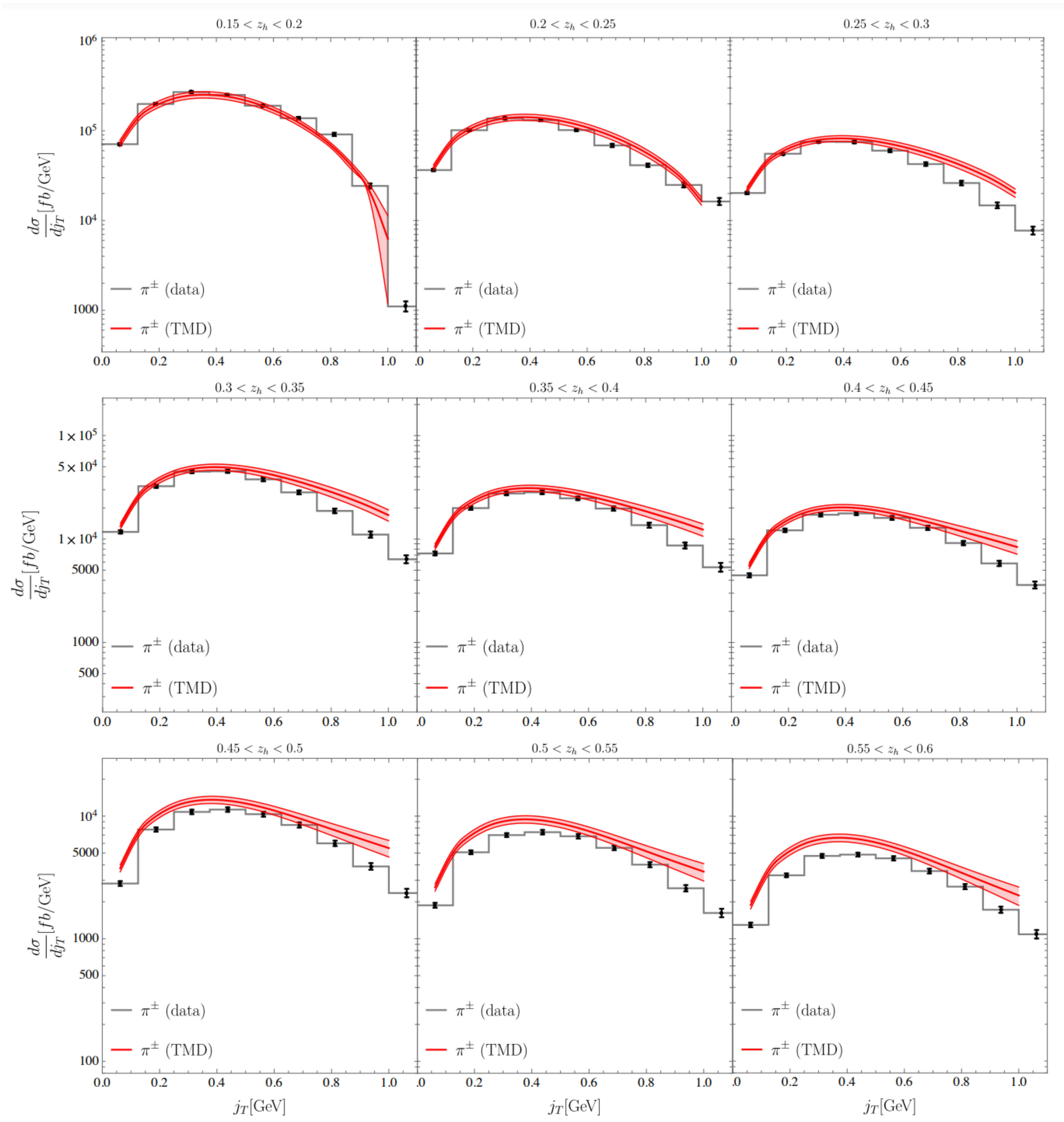
- Integrate out the thrust dependence
- Double differential measurement

$$z_h = 2E_h/Q\,, \quad p_{hT} \equiv |\boldsymbol{p}_h|$$

- Joint TMD & threshold resummation
- Introduces non-global logarithms



Kang, Shao, Zhao `20



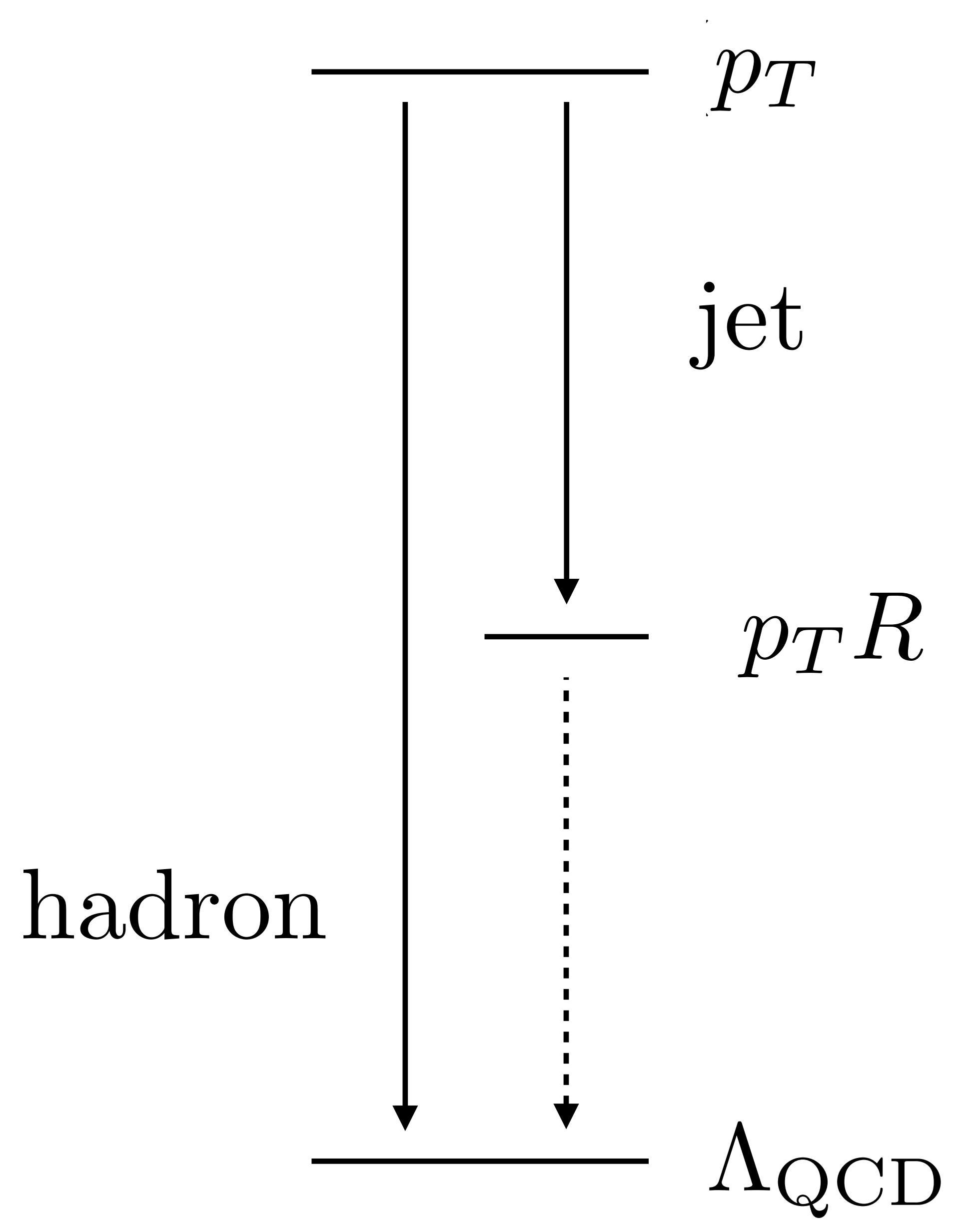
Hadrons from jet physics

Neill `20

- Can we calculate hadrons as jets with zero radius?

$$d\sigma \sim H_i \otimes J_i \sim H_i \otimes e^{-P_{ji}} \otimes J_j$$

DGLAP evolution factor



- Requires resummation of small-z logarithms

- Angular ordered DGLAP

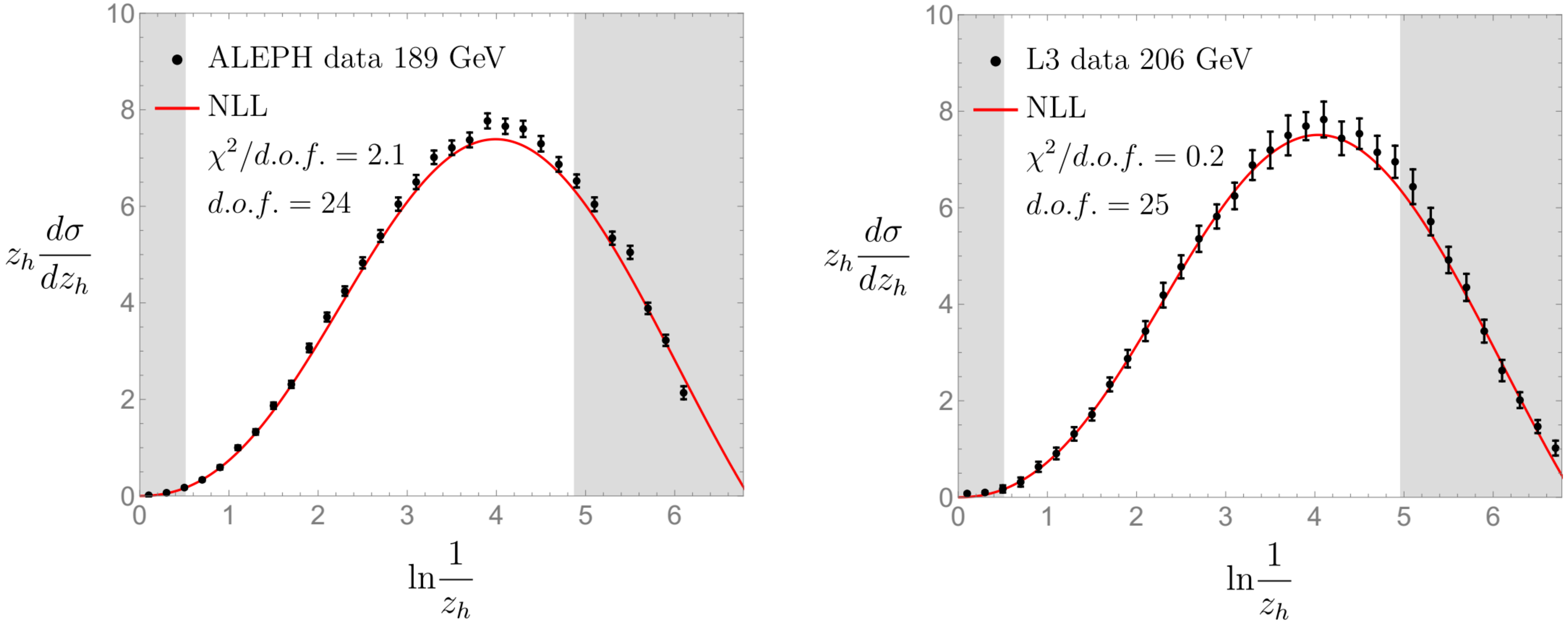
Neill, Ringer `20

$$R^2 \frac{\partial}{\partial R^2} x^{1+2\epsilon} d_a\left(x, R, \frac{\mu^2}{Q^2}\right) = \sum_b \rho_{ab}\left(\frac{\mu^2}{R^2 Q^2}\right) x^{1+2\epsilon} d_b\left(x, R, \frac{\mu^2}{Q^2}\right)$$
$$+ \sum_b \int_x^1 \frac{dz}{z} P_{ab}\left(\frac{x}{z}; \frac{\mu^2}{z^2 R^2 Q^2}\right) z^{1+2\epsilon} d_b\left(z, R, \frac{\mu^2}{Q^2}\right)$$

Hadrons from jet physics

Neill `20

- Can we calculate hadrons as jets with zero radius?



$e^+e^- \to h + X$

Charged hadrons

- Does not require the fit of a collinear fragmentation function - only the cutoff scale & the normalization are fitted!

Outline

Collinear fragmentation

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Conclusions

- New multi-differential data sets
- Higher order QCD corrections
- New observables probing fragmentation
- Energy-energy correlators, leading hadrons, …
- New approach to hadron fragmentation from jet physics