Discussion session: fragmentation

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INFN Pavia - University of Pavia & Jefferson Lab

REF 2020 workshop

December 9, 2020

Istituto Nazionale di Fisica Nucleare

Outline

Topics

The Belle TMD-thrust data

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- T Factorization of $e^+e^- \to H\,X$ cross section, differential in z_h, P_T and thrust in the 2-jet limit
  M. Boglione, A. Simonelli - 2011.07366

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- E Jets and jet-substructure observables

  J. Osborn

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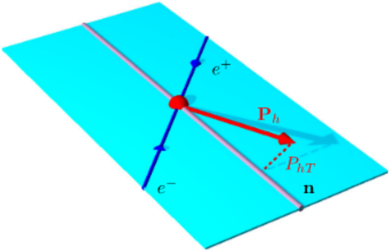
The Belle TMD-thrust data

$e^+e^- \to h\,X$ at Belle

R. Seidl et al. 1902.01552 - PRD
and supplemental material



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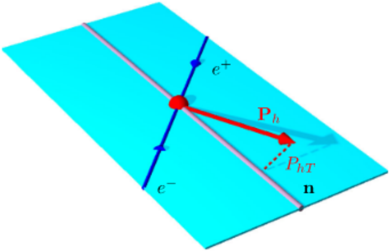

Transverse-momentum-dependent (TMD) single-hadron fragmentation:

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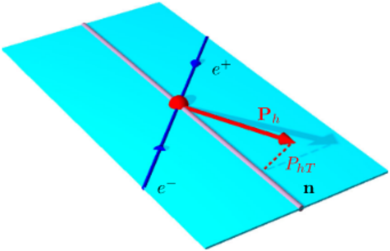

Transverse-momentum-dependent (TMD) single-hadron fragmentation:

- final state hadron: h

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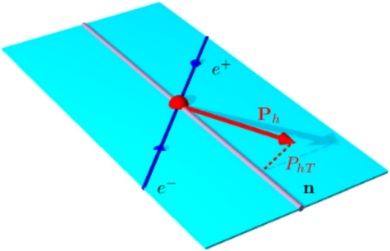

Transverse-momentum-dependent (TMD) single-hadron fragmentation:

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- incoming leptons: e^+e^-

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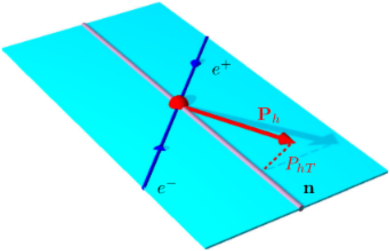

Transverse-momentum-dependent (TMD) single-hadron fragmentation:

- final state hadron: h
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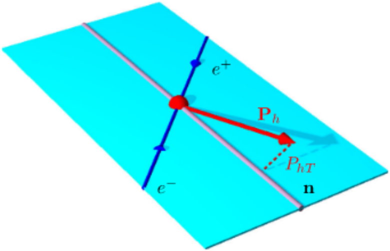
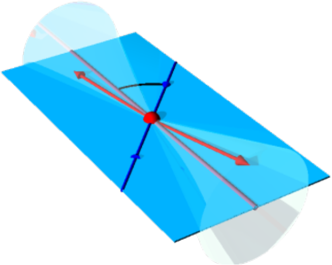


Transverse-momentum-dependent (TMD) single-hadron fragmentation:

- final state hadron: h
- incoming leptons: e^+e^-
- thrust axis: $\vec{n}$
- the hadronic transverse momentum $\vec{P}_{hT}$ is measured relative to the thrust axis $\vec{n}$

Thrust

R. Seidl et al. 1902.01552 - PRD
and supplemental material



The axis $\vec{n}$ such that $T = \max_{\vec{n}} \frac{\sum_i \vec{p}_i \cdot \vec{n}}{\sum_i \vec{p}_i}$

Thrust

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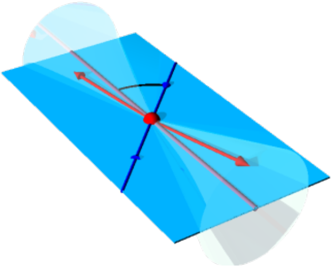

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- the axis that maximizes the sum of the longitudinal momentum components

Thrust

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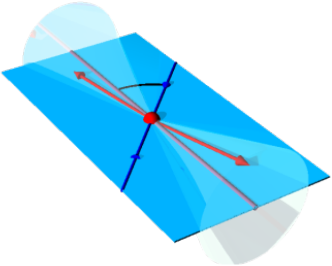

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- $T \to 1/2$ isotropic event

Thrust

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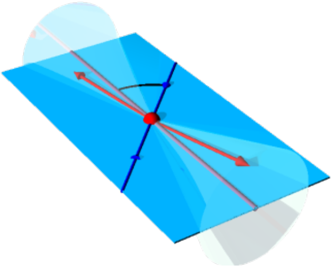

The axis $\vec{n}$ such that $T = \max_{\vec{n}} \frac{\sum_i \vec{p}_i \cdot \vec{n}}{\sum_i \vec{p}_i}$

- the axis that maximizes the sum of the longitudinal momentum components
- $T \to 1/2$ isotropic event
- $T \to 1$ back-to-back event

$e^+e^- \to h\,X$ at Belle

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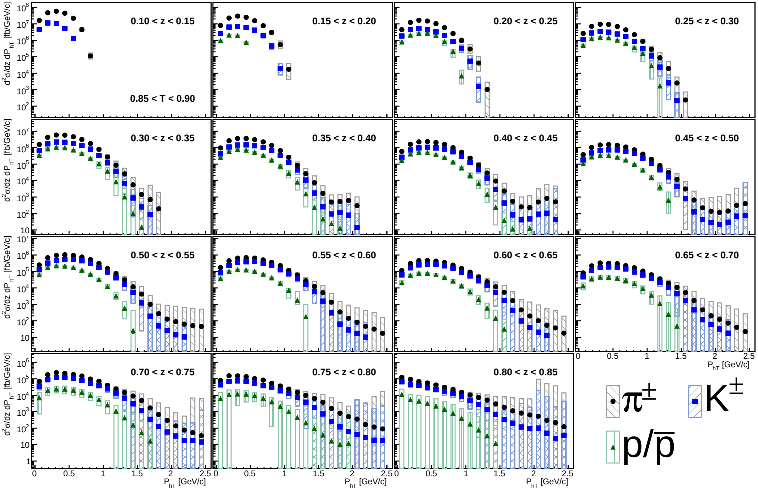

Differential cross section $d^2\sigma/dz\,dP_{hT}$ in bins of z and thrust $0.85 < T < 0.90$

$e^+e^- \to h\,X$ at Belle

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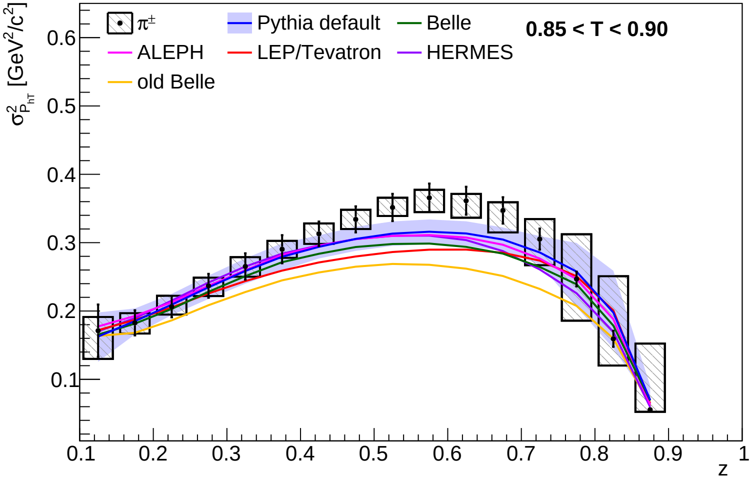


Gaussian widths in P_{hT} for the cross section as a function of z compared to various PYTHIA tunes (pions)

College | Physical Sciences
Mani L. Bhaumik Institute for Theoretical Physics

Center for Frontiers in Nuclear Science

Factorization and resummation on single hadron TMD with the thrust axis

DingYu Shao
UCLA

REF2020, online
Dec 7-11 , 2020

Based on 2007.14425 with Zhong-bo Kang and Fanyi Zhao

Case-I: $e^-e^+ \to h_1 h_2 + X$

$$\frac{d\sigma}{d^2\boldsymbol{q}_T} \sim H \otimes D_{h_1} \otimes D_{h_2} \otimes S$$

Global observable, standard TMD factorization

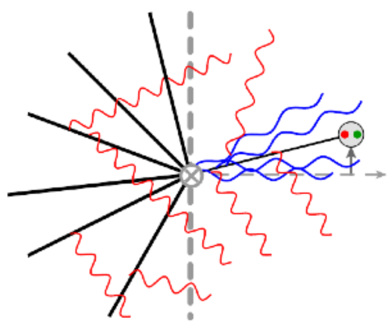
Collins, *"Foundations of perturbative QCD"*

Case-II: $e^-e^+ \to h + X$

$$\frac{d\sigma}{d^2\boldsymbol{q}_T} \sim D_h \otimes \mathcal{H} \otimes \mathcal{S}$$

Non-global observable; new TMD factorization

Kang, DYS, Zhao '20



hard: $p_h \sim Q(1,1,1)$

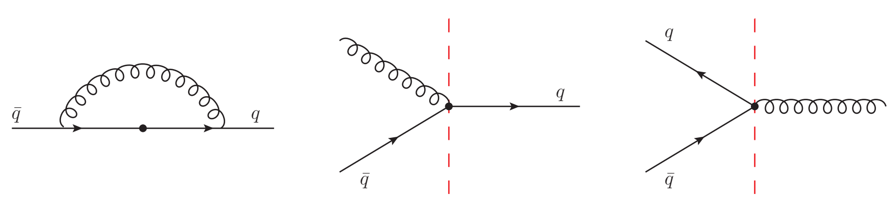
collinear: $p_c \sim Q(\lambda^2,1,\lambda)$ $\qquad \lambda = j_T/Q \ll 1$

soft: $p_s \sim Q(\lambda,\lambda,\lambda)$

Factorization formula: (neglecting NGLs)

$$\frac{d\sigma}{dz_h d^2\vec{j}_T} = \sigma_0 \sum_{i=q,\bar{q},g} e_q^2 \int d^2\vec{k}_T\, d^2\vec{\lambda}_T\, \delta^{(2)}\left(\vec{j}_T - \vec{k}_T - z_h\vec{\lambda}_T\right) \mathcal{H}^i(Q,\mu) D_{h/i}(z_h, k_T, \mu, \zeta^2/\nu) \mathcal{S}_i(\lambda_T, \mu, \nu)$$

NLO hard function:



Divergences are half of the hard function in case-I

NLO soft function:

$$\frac{\alpha_s C_F}{2\pi^2} \frac{e^{\epsilon\gamma_E}}{\Gamma(1-\epsilon)} \int \frac{dk^+ dk^-}{2} \left(\frac{\mu^2}{\vec{\lambda}_T^2}\right)^{\epsilon} \frac{2n\cdot\bar{n}}{k^+k^-} \delta^+(k^+k^- - \vec{\lambda}_T^2) \left|\frac{\nu}{2k_z}\right|^{\eta} \theta\left(1 - \frac{k^+}{k^-}\right)$$

$$= \frac{\alpha_s}{2\pi} C_F \left[\frac{2}{\eta}\left(-\frac{1}{\epsilon} - \ln\left(\frac{\mu^2}{\mu_b^2}\right)\right) + \frac{1}{\epsilon^2} - \frac{1}{\epsilon}\ln\left(\frac{\nu^2}{\mu^2}\right)\right]$$

Divergences are half of the soft function in case-I

Factorization formula (full story)

$$\frac{d\sigma}{dz_h d^2\vec{j}_T} = \sum_{i=q,\bar{q},g} \int \frac{d^2\vec{b}}{(2\pi)^2} e^{i\vec{b}\cdot\vec{j}_T/z_h} \sum_{m=2}^{\infty} \frac{1}{N_c} \mathrm{Tr}_c\left[\boldsymbol{\mathcal{H}}_m^i(\{\underline{n}\}, Q, \mu) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\}, b, \mu, \nu)\right] D_{h/i}(z_h, b, \mu, \zeta/\nu^2)$$

"Multi-Wilson-line structure" Becher, Neubert, Rothen, DYS '15,… (see Becher's talk)

A similar structure is also mentioned in Boglione & Simonelli '20 (see Simonelli's talk)

NLL resummation formula:

$$\frac{d\sigma}{dz_h d^2\vec{j}_T} = \sigma_0 \sum_{i=q,\bar{q}} e_i^2 \int_0^\infty \frac{b\,db}{2\pi} J_0(bj_T/z_h) e^{-S_{\rm pert}(\mu_{b*},\mu_h) - S_{\rm NP}(b,Q_0,Q)} \frac{1}{z_h^2} D_{h/i}(z_h,\mu_{b*}) U_{\rm NG}(\mu_{b*},\mu_h)$$

b*-prescription to avoid Landau pole $b_* = b/\sqrt{1+b^2/b_{\rm max}^2}$ $\mu_{b_*} = 2e^{-\gamma_E}/b_*$

QCD evolution between Q **and** j_T

Linear part: $S_{\rm pert}(\mu_b,\mu_h) = \int_{\mu_b}^{\mu_h} \frac{d\mu}{\mu} \left[\Gamma_{\rm cusp}(\alpha_s)\ln\left(\frac{Q^2}{\mu^2}\right) - 2\gamma^{D_q}(\alpha_s) - \gamma^S(\alpha_s)\right]$

Non-linear part: $U_{\rm NG}(\mu_{b*},\mu_h) = \exp\left[-C_A C_F \frac{\pi^2}{3} u^2 \frac{1+(au)^2}{1+(bu)^c}\right]$

Dasgupta, Salam ‘01

Non-perturbative corrections: $j_T \sim \Lambda_{\rm QCD}$

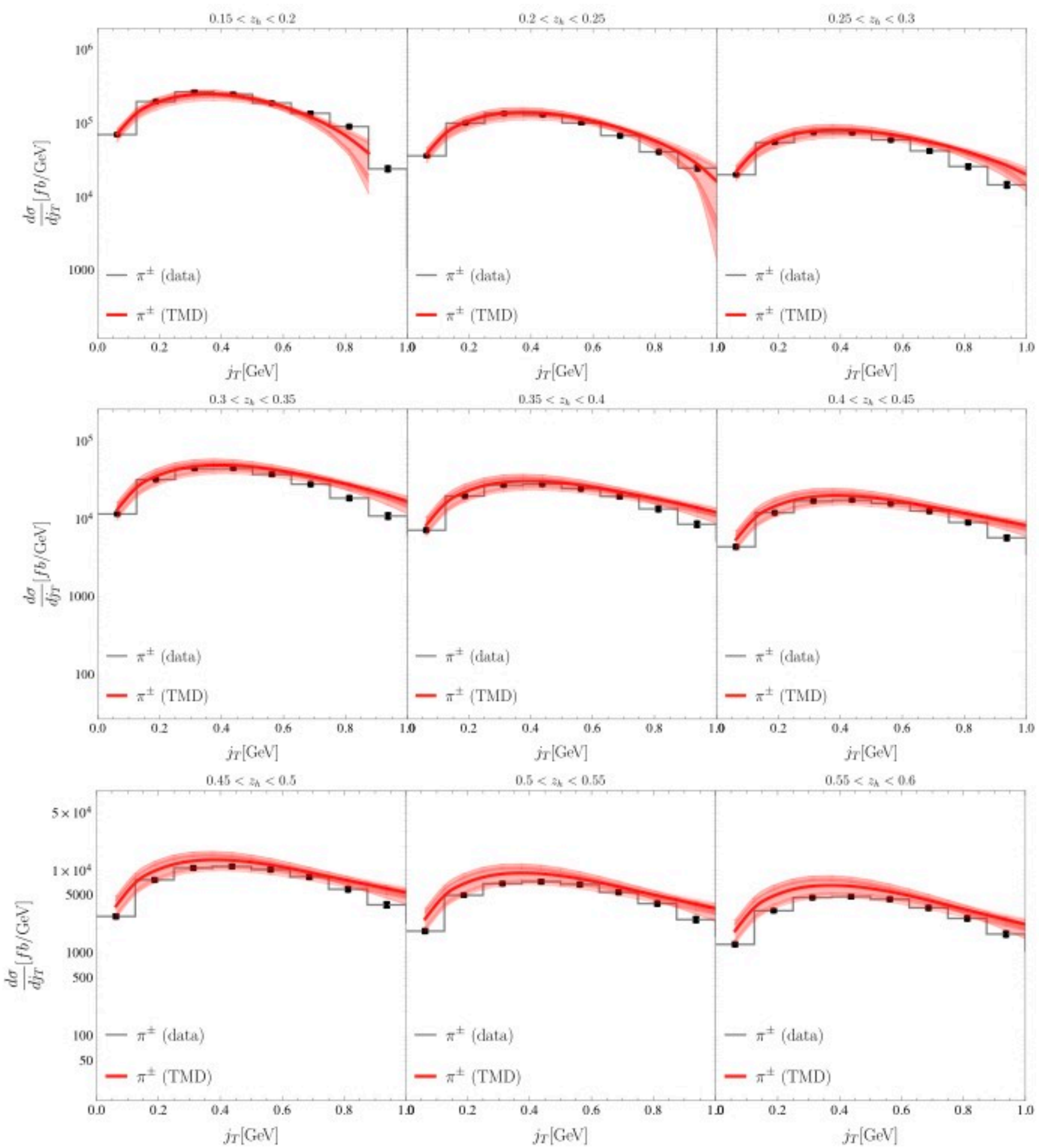
$S_{\rm NP}(b,Q_0,Q) = \frac{g_2}{2}\ln\left(\frac{b}{b_*}\right)\ln\left(\frac{Q}{Q_0}\right) + \frac{g_h}{z_h^2}b^2$ **fitted in standard (global) TMD processes**

Sun,Isaacson,Yuan,Yuan ‘14

Non-perturbative collinear FFs $D_{h/i}(z_h,\mu_{b*})$ **(DSS2014)**

de Florian, *et.al.* '15

Numerical results



- **Belle data (1902.01552) was originally presented in different thrust bins**
- **Since the theoretical formalism we have developed is inclusive in thrust, we thus combine the experimental data to obtain the entire region $0.5 < T < 1.0$**
- **Our TMD resummation formula gives a good description of the shape of j_T distribution as $z_h < 0.65$**
- **As $z_h > 0.65$, one needs to also include threshold resummation effects**

Joint resummation formula: (refactorization of TMD FF)

Li, Neill, Zhu ’16 & Lustermans, Waalewijn, Zeune '16

$$\frac{d\sigma}{dz_h d^2\vec{j}_T} = \sigma_0 \sum_{i=q,\bar{q}} \int_0^\infty \frac{b\,db}{2\pi} J_0(bj_T/z_h) \frac{1}{z_h^2} \int_{z_h}^1 \frac{dz}{z} e^{-\hat{S}_{\rm pert}(\mu_{b*},\mu_h) - \hat{S}_{\rm NP}(b,Q_0,Q)} \frac{e^{-2\gamma_E \eta}}{\Gamma(2\eta)} \frac{1}{1-z} D_{h/i}(z_h/z,\mu_h)\, U_{\rm NG}(\mu_{b*},\mu_h)$$

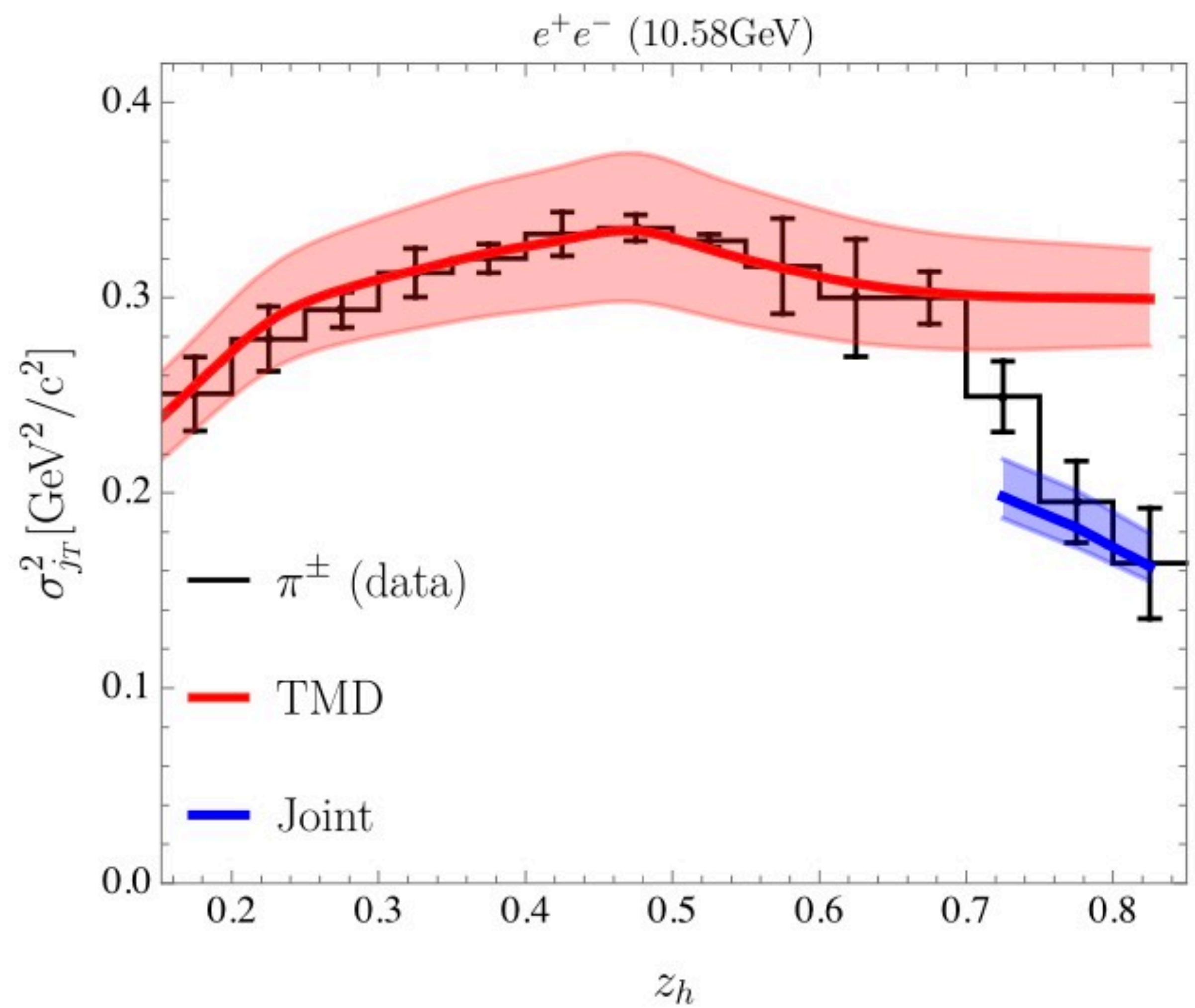
with:

$$\hat{S}_{\rm pert}(\mu_b,\mu_h) = \int_{\mu_b}^{\mu_h} \frac{d\mu}{\mu} \left[\Gamma_{\rm cusp}(\alpha_s) \ln\left(\frac{(1-z)^2 Q^2}{\mu^2}\right)\right]$$

$$\hat{S}_{\rm NP}(b,Q_0,Q) = \frac{g_2}{2} \ln\left(\frac{b}{b_*}\right) \ln\left[\frac{Q(1-z_h)}{Q_0}\right] + \frac{g_h}{z_h^2} b^2$$

$$\frac{d\sigma}{dz_h d^2\vec{j}_T} \propto \frac{1}{\pi\sigma_{j_T}^2} \exp\left(-j_T^2/\sigma_{j_T}^2\right)$$

- **The Gaussian width of the j_T distribution given by the TMD formalism freeze to a certain value.**
- **After including joint threshold and TMD resummation effects, the theoretical predictions are consistent with the data**



Overview

arXiv: 2009.11871 (Y. Makris, F. Ringer, W. J. Waalewijn)

In progress (Y. Makris, J.K.L. Michel, F. Ringer, W. J. Waalewijn)

Joint TMD and Thrust resummation:

- Factorization within SCET
- All elements for up to NNLL provided

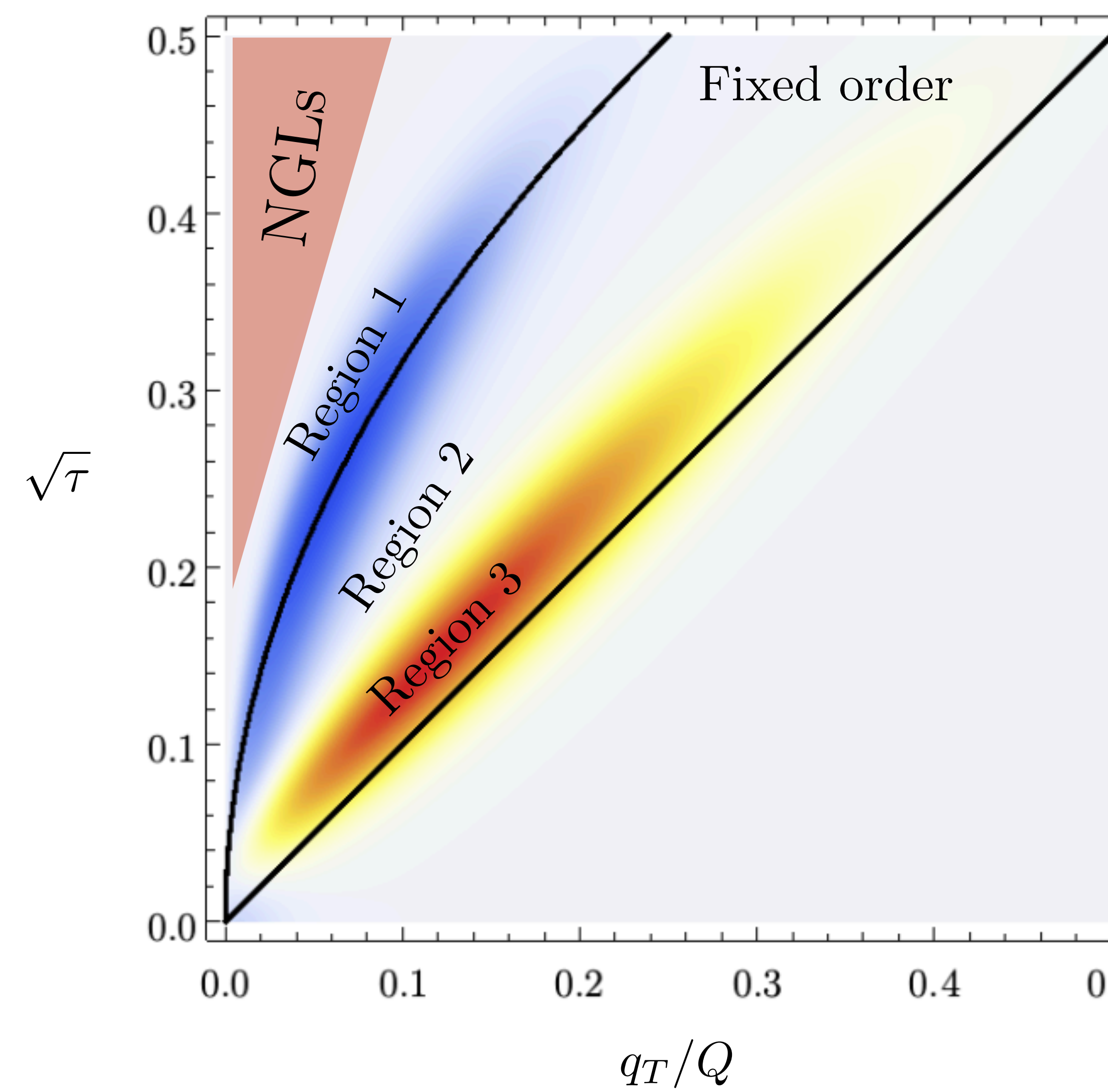
Regions

- Region 1 $1 \gg \sqrt{\tau} \gg q_T/Q \sim \tau$
- Region 2 $1 \gg \sqrt{\tau} \gg q_T/Q \gg \tau$
- Region 3 $1 \gg \sqrt{\tau} \sim q_T/Q \gg \tau$
- Fixed order QCD

NGLs: $q_T \ll Q\tau$

- NGLs not relevant for the three regions
- We give the LO contributions: $\mathcal{O}(\alpha_s^2)$

$$S^{\rm NG}\left(\frac{q_T}{\tau Q}\right) = 1 - \frac{\alpha_s^2 C_F C_A}{12} \ln^2\left(\frac{q_T}{\tau Q}\right) + \mathcal{O}(\alpha_s^3)$$



Factorization-Evolution-Resummation

Region 1 $\sqrt{\tau} \gg q_T/Q \sim \tau$

$$d\sigma \sim H(Q,\mu) J(\tau,\mu) \otimes_\tau \boxed{S(\tau,b,\mu,\nu)} \times \boxed{D_{i\to h}(b,z_h,\mu,\nu)}$$

Double differential soft function   Universal (unsubtracted) TMDFF

Region 2 $\sqrt{\tau} \gg q_T/Q \gg \tau$

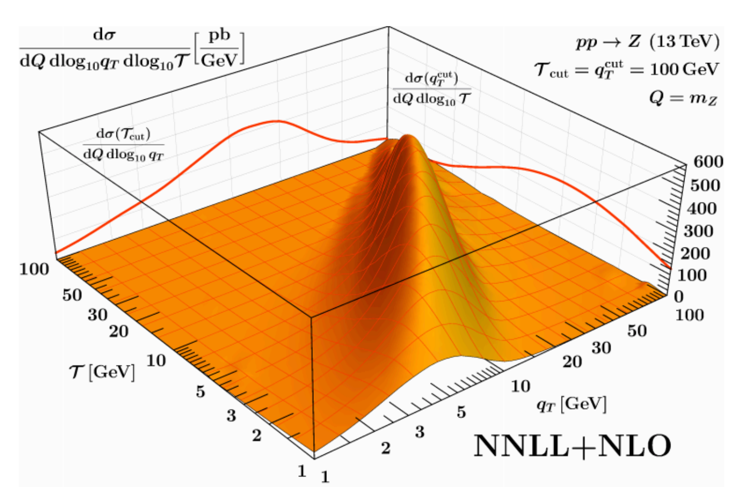
$$d\sigma \sim H(Q,\mu) J(\tau,\mu) \otimes_\tau S(\tau,\mu) \otimes_\tau \boxed{\mathcal{C}(\tau,b,\mu,\nu)} \times \boxed{D_{i\to h}(b,z_h,\mu,\nu)}$$

Region 3 $\sqrt{\tau} \sim q_T/Q \gg \tau$

$$d\sigma \sim H(Q,\mu) J(\tau,\mu) \otimes_\tau S(\tau,\mu) \otimes_\tau \boxed{\mathcal{G}_{i\to h}(\tau,b,z_h,\mu)}$$

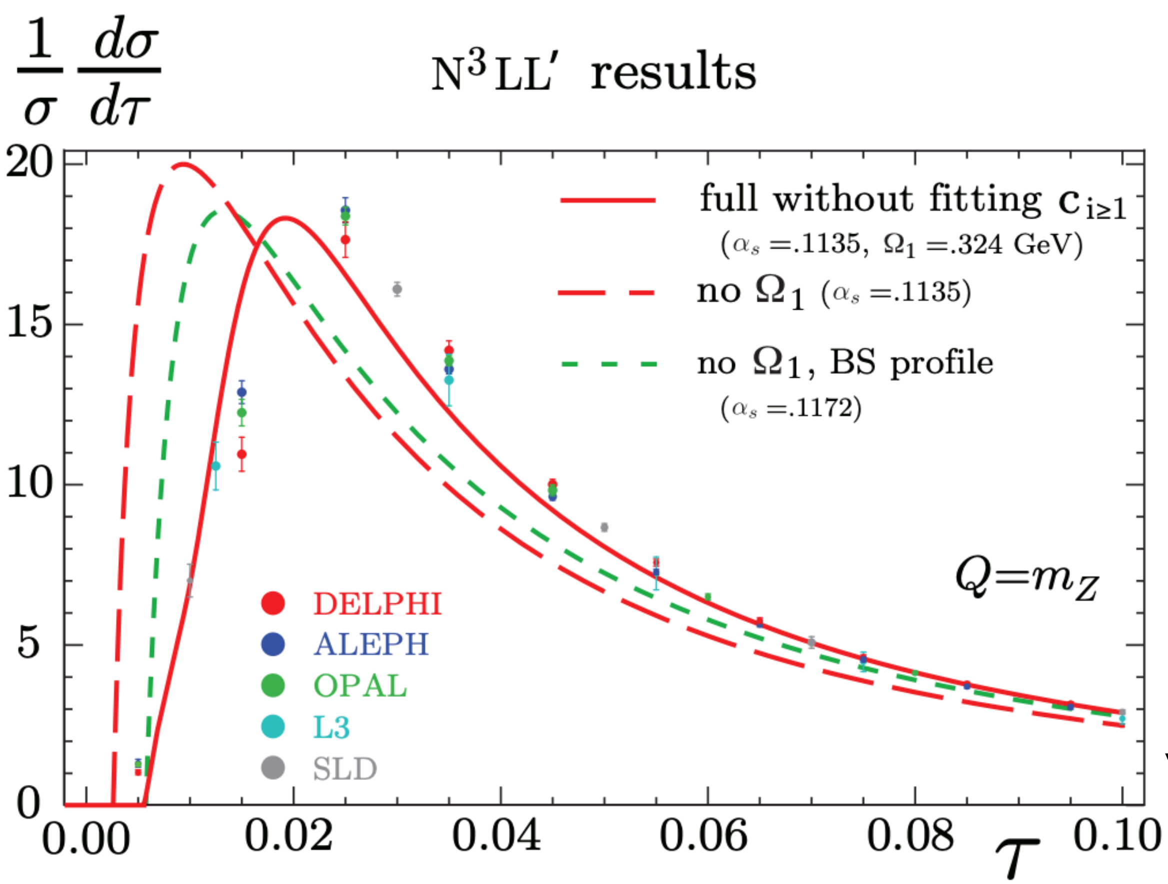
Double differential
Fragmenting jet function
No rapidity divergences

Drell-Yan:



arXiv: 1901.03331 (G. Lustermans, J. K. L. Michel, F. J. Tackmann, and W. J. Waalewijn)

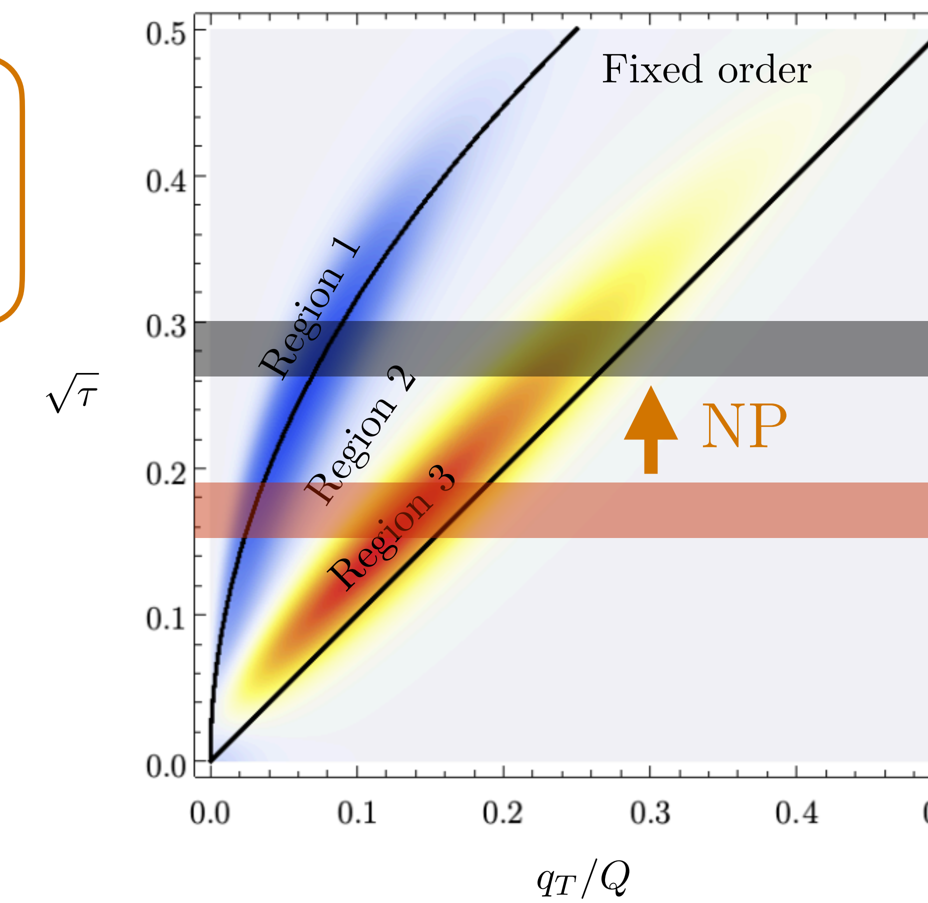
Non-perturbative effects (naive first expectations)

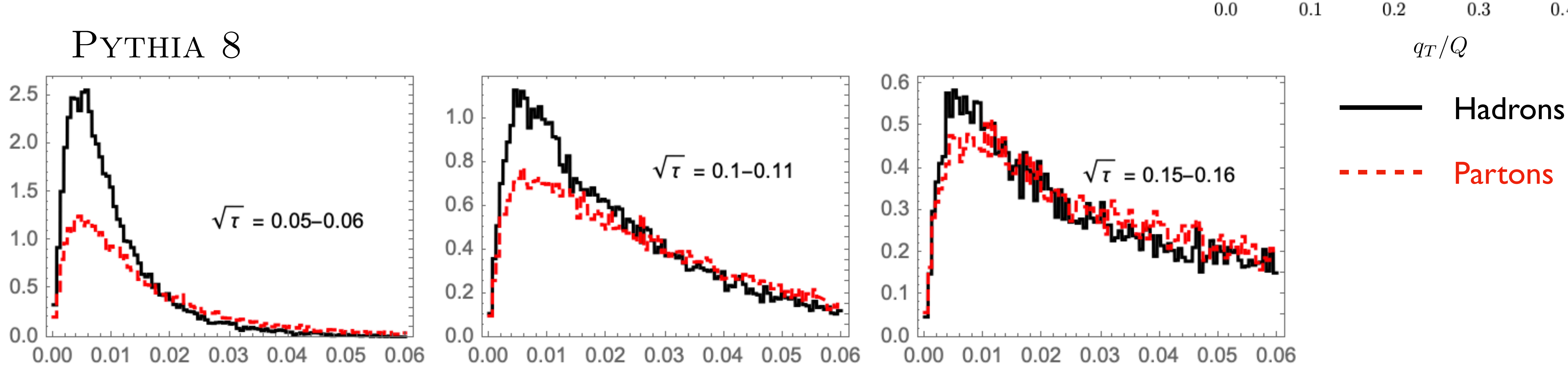


arXiv: 0611061 (C. Lee, G. Sterman)

$$\frac{d\sigma}{d\tau}(\tau) \xrightarrow[\text{NP}]{} \frac{d\sigma}{d\tau}\left(\tau - \frac{\Lambda}{Q}\right)$$

Figure from: arXiv:1006.3080 (R. Abbate, M. Fickinger, A.H. Hoang, V. Mateu, and I.W. Stewart)





Boglione, Simonelli, 2007.13674, 2011.07366

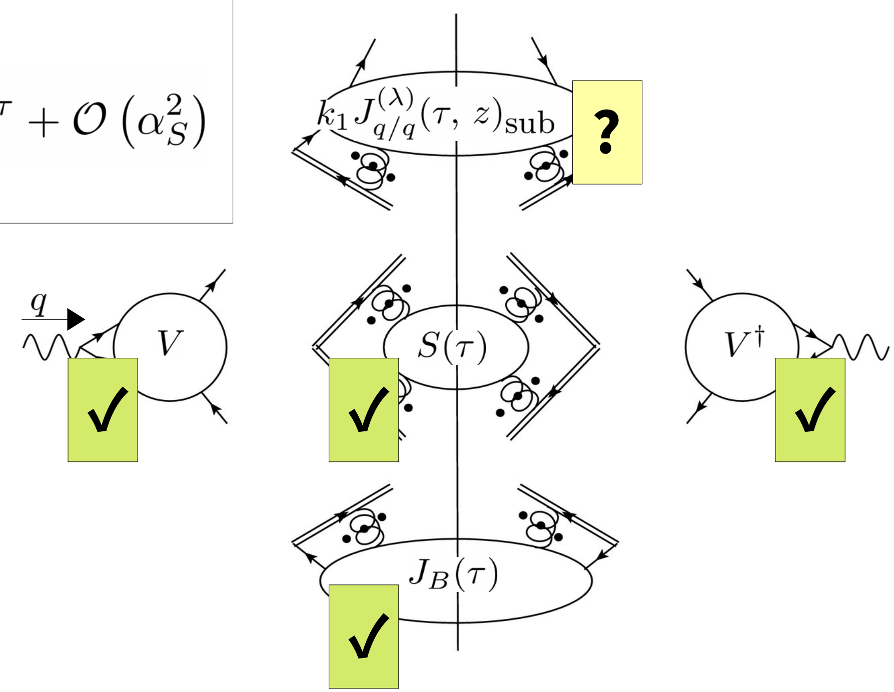
- $e^+e^- \to HX$ cross section, differential in z_h, P_T and T, factorized (CSS) as a convolution of a partonic cross section (computable in pQCD) and a TMD FF.
- Result valid to all orders and computed at NLO, NLL.
- Predictions in exceptional agreement with BELLE experimental measurements.

$$\frac{d\sigma}{dz_h\, dT\, dP_T^2} = \pi \sum_f \int_{z_h}^{1} \frac{dz}{z} \frac{d\widehat{\sigma}_f}{dz_h/z\, dT} D_{1,\pi^\pm/f}(z,\, P_T,\, Q,\, (1-T)\, Q^2)$$

Partonic Cross Section (pQCD)

$$\frac{d\widehat{\sigma}_f}{dz\, dT} \overset{\text{NLO}}{=} -\sigma_B e_f^2 N_C \frac{\alpha_S}{4\pi} C_F \delta(1-z) \frac{3 + 8 \log \tau}{\tau} e^{-\frac{\alpha_S}{4\pi} 3 C_F \log^2 \tau} + \mathcal{O}\left(\alpha_S^2\right)$$

NO THRUST RESUMMED



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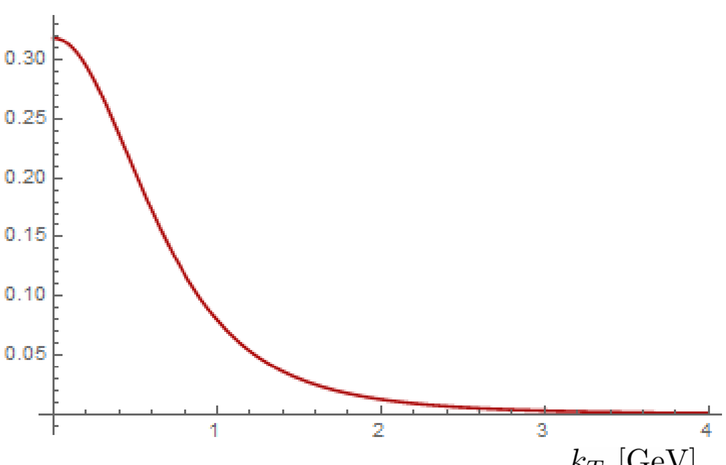
Power-law

$$\mathcal{FT}\{M_D\} = \frac{\Gamma(p)}{\pi\,\Gamma(p-1)}\,\frac{m^{2(p-1)}}{(k_T^2+m^2)^p}$$

$$m = 1\ \mathrm{GeV},\ \ p = 2$$



Unpolarized TMD FF

NNFF10NLO

$$\widetilde{D}_{1,\,\pi^\pm/f}(z,\,b_T;\,Q,\,\tau Q^2) = \frac{1}{z^2}\sum_k \left[d_{\pi^\pm/k}\otimes\mathcal{C}_{k/f}\right](\mu_b)\,\times$$

$$\exp\left\{\frac{1}{4}\,\widetilde{K}\,\log\frac{\tau Q^2}{\mu_b^2} + \int_{\mu_b}^{Q}\frac{d\mu'}{\mu'}\left[\gamma_D - \frac{1}{4}\,\gamma_K\,\log\frac{\tau Q^2}{\mu'^2}\right]\right\}\times$$

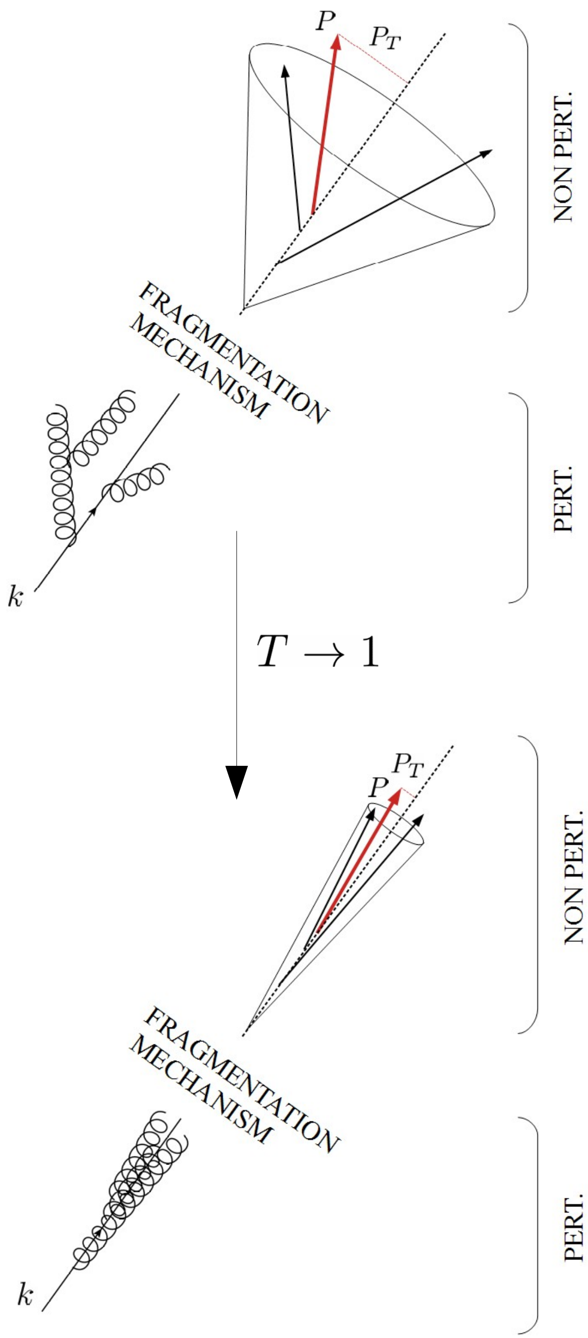
NLL

$$(M_D)_{f,\,\pi^\pm}(z,\,b_T)\,\exp\left\{-\frac{1}{4}\,g_K(b_T)\,\log\left(\tau\,\frac{z_h^2\,Q^2}{M_H^2}\right)\right\}$$

NP

Quadratic behavior $g_K(b_T) = a\,b_T^2,\ a = 0.05\ \mathrm{GeV}^2$

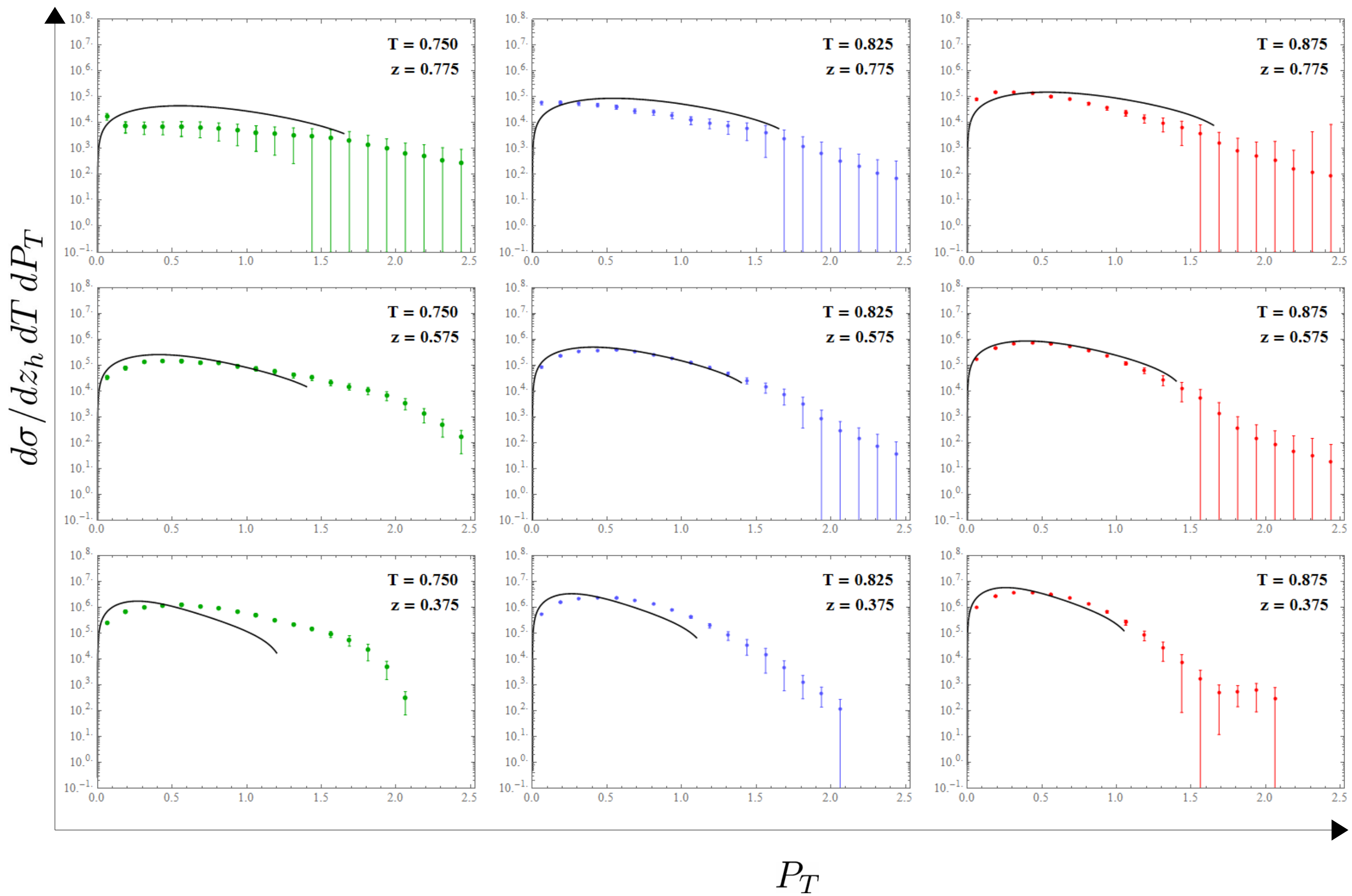
Boglione, Simonelli, 2007.13674, 2011.07366



$$\frac{d\sigma}{dz_h\, dT\, dP_T^2} = \pi \sum_f \int_{z_h}^{1} \frac{dz}{z} \frac{d\widehat{\sigma}_f}{dz_h/z\, dT} D_{1,\pi^\pm/f}(z,\, P_T,\, Q,\, (1-T)\, Q^2)$$

Rapidity cut-off

Thrust dependence
(First Phenomenological analysis – prototype)



Discussion

Discussion contribution
REF2020 – Fragmentation/Hadronization

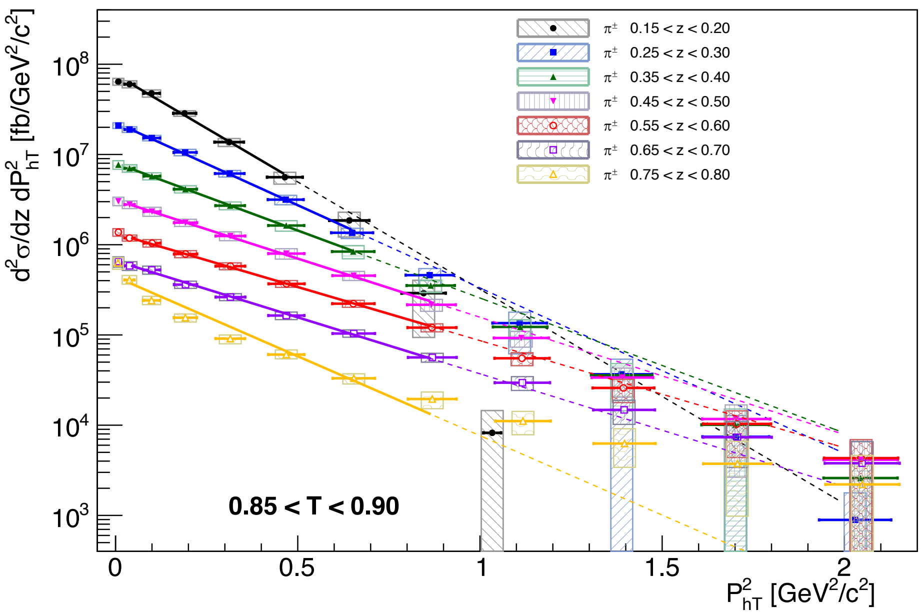
Anselm Vossen

Research supported by the
U.S. DEPARTMENT OF ENERGY | Office of Science

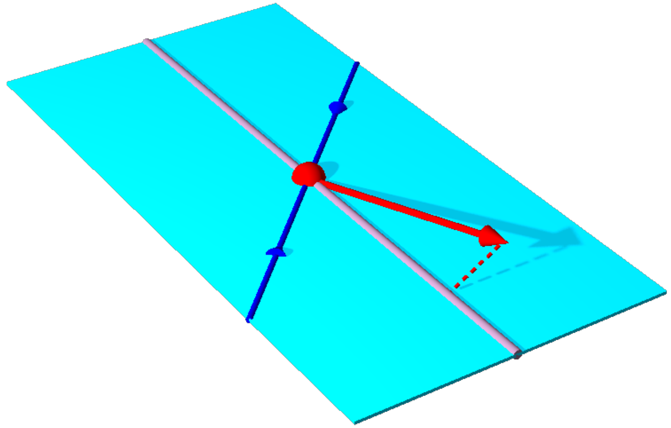
Duke UNIVERSITY

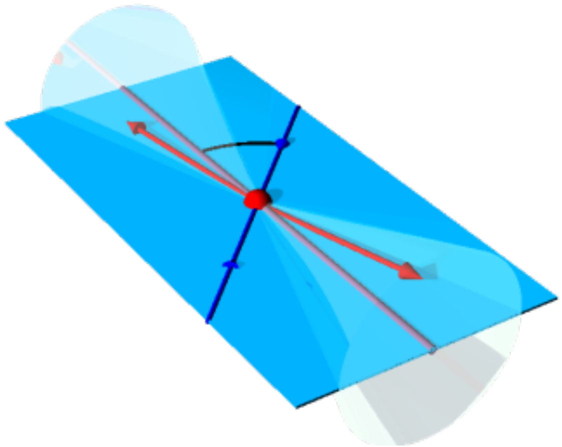
Jefferson Lab

Current and near-term future at Belle



Thrust axis

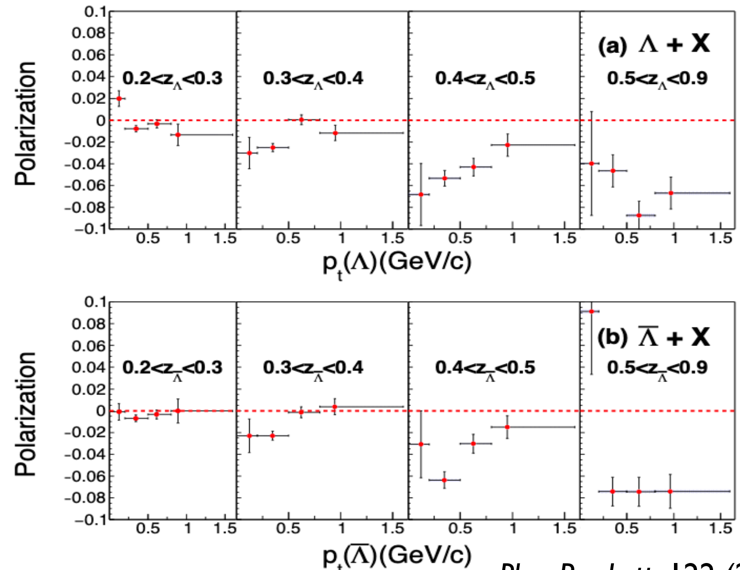




- Observation of k_t dependence wrt thrust axis
- Next: k_T dependence in back-to-back measurements
- In Jets?

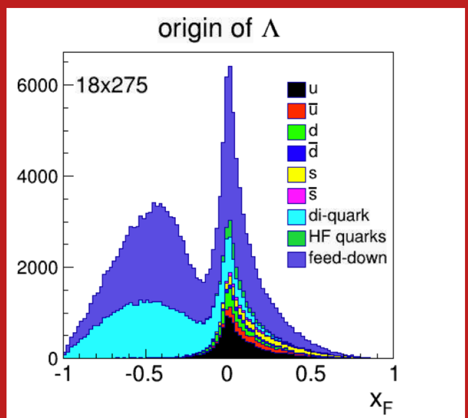
Polarized Fragmentation at Belle/Belle II and JLab/EIC

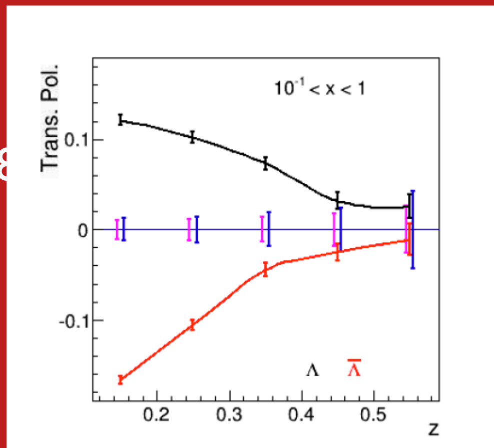
- Observation of polarized FFs at Belle
- What do we learn from fragmentation in jets?
- Next: Measure twist3 D_T
- Program at Jlab and EIC
- Issues in interpretation
  - Feed-down
  - Gluons (EIC)



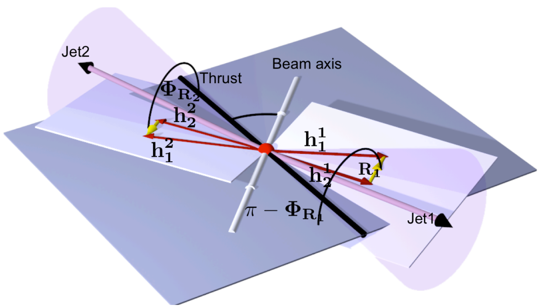
Phys.Rev.Lett. 122 (2019) 4, 042001

EIC 18x275

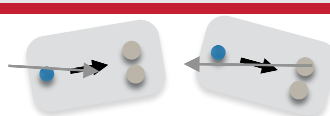




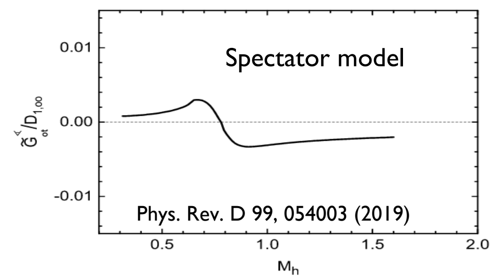
Di-hadrons in SIDIS, e^+e^-

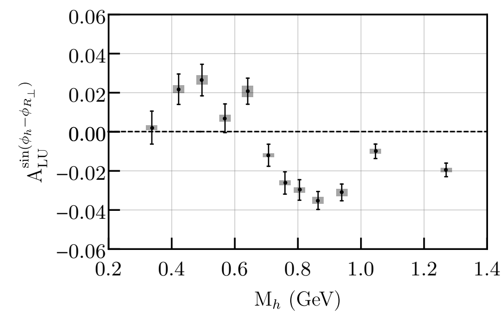


- Additional degrees of freedom
- Carry rel OAM
- Interplay with single hadrons, e.g. transverse momentum
- Started comprehensive program at Jlab, Belle, Belle II, EIC
- Idea to measure BM w/o Cahn, less higher order corrections
- More applications?
- (also single hadron program e.g. Collins ongoing)
- Belle pioneering, Belle II precision



First di-hadron TMD measurement at CLAS12!



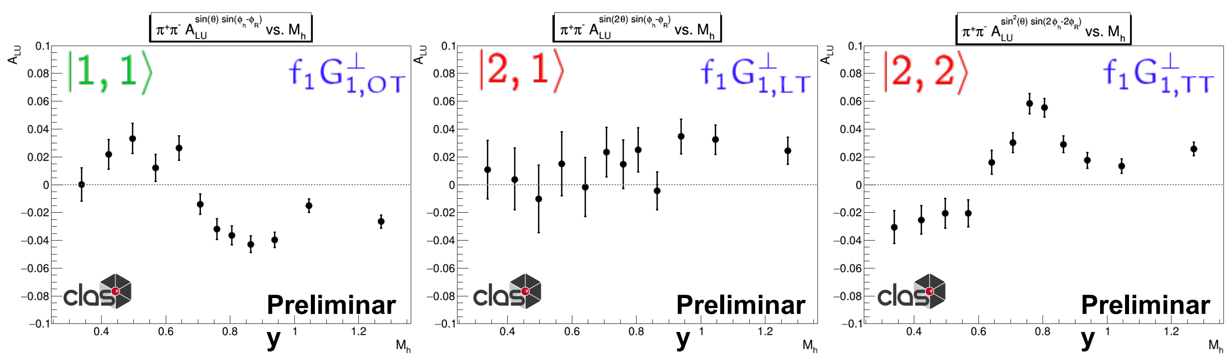


$|0,0\rangle$ — **ℓ=0 – ss interference:** UU

$|1,-1\rangle$ $|1,0\rangle$ $|1,1\rangle$ — **ℓ=1 – sp interference:** UL or UT

$|2,-2\rangle$ $|2,-1\rangle$ $|2,0\rangle$ $|2,1\rangle$ $|2,2\rangle$ — **ℓ=2 – pp interference:** LL, LT, or TT

-2 -1 m=0 1 2

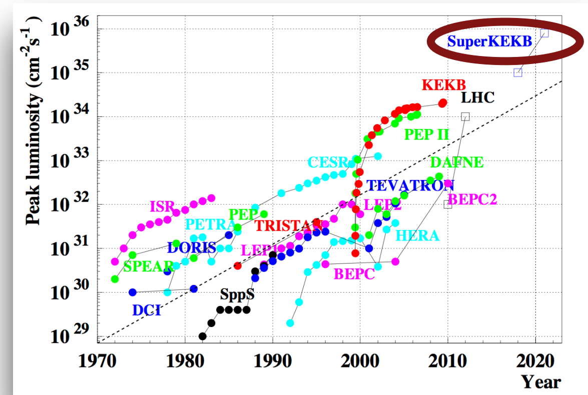


Jets and more at Belle II

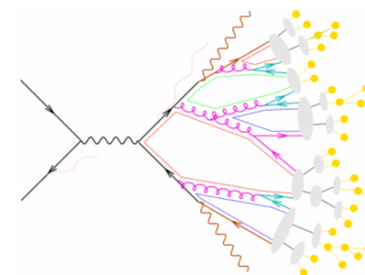
Snowmass 2021 Letter of Interest:
QCD and Hadronization Studies at Belle II

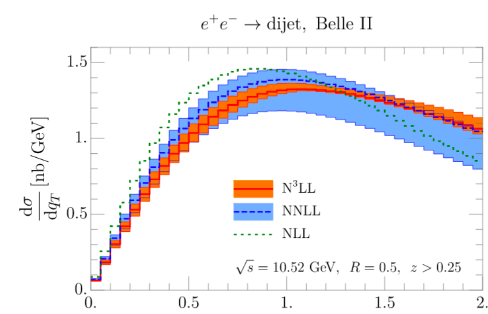
on behalf of the U.S. Belle II Collaboration

Corresponding Author:
Anselm Vossen (Duke University), anselm.vossen@duke.edu



- Comprehensive Hadronization Program at Belle II
- Precision FFs for EIC
- Study of jets (e.g. q_T spectrum, jet-hadron,)
- Energy correlation
- MC comparison
  - Implementation in Rivet →Is this interesting for phenomenology too?
  - Correlation of strangeness and baryon numbers
  - ..?
- Plan to have polarized beams at Belle II





JHEP 10 (2019) 031

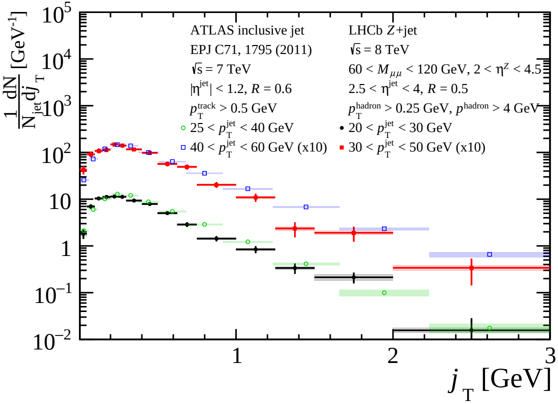
Experimental perspectives on hadronization

Resummation, Evolution, Factorization Workshop

Joe Osborn, ORNL

December 10, 2020

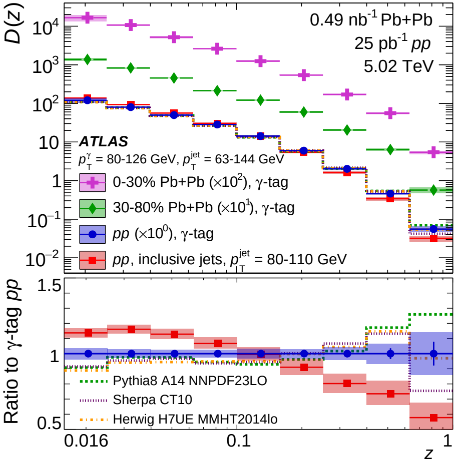
Recent experimental advances

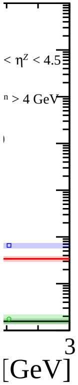


Phys. Rev. Lett. 123, 232001 (2019)

- Experimentalists starting to use processes to better identify parton→hadron relations
  - γ/Z^0+jet (predominantly u/d →hadrons)

Recent experimental advances



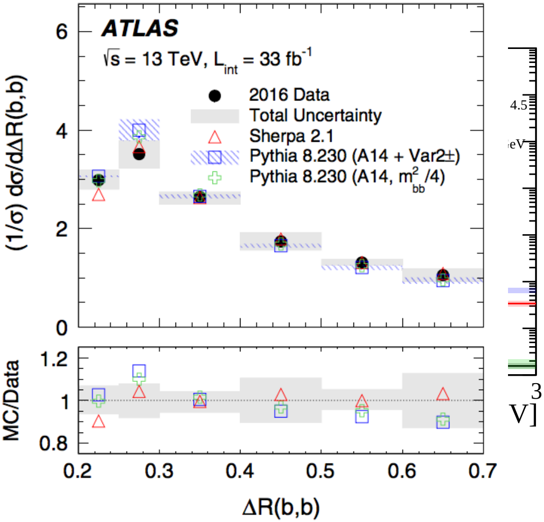


Phys. Rev. Lett. 123, 042001 (2019)

- Experimentalists starting to use processes to better identify parton→hadron relations
  - γ/Z^0+jet (predominantly u/d →hadrons)

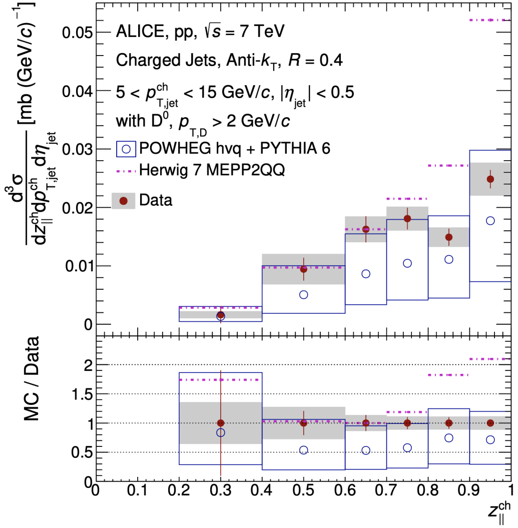
Recent experimental advances

Phys. Rev. D 99, 052004 (2019)



- Experimentalists starting to use processes to better identify parton→hadron relations
  - γ/Z^0+jet (predominantly u/d →hadrons)
  - $g \rightarrow b\bar{b}$

Recent experimental advances

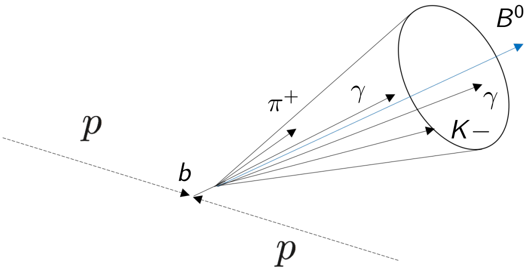


JHEP 133, 396 (2019)

- Experimentalists starting to use processes to better identify parton→hadron relations
  - γ/Z^0+jet (predominantly u/d →hadrons)
  - $g \to b\bar{b}$
  - $c \to D^0$
  - ...

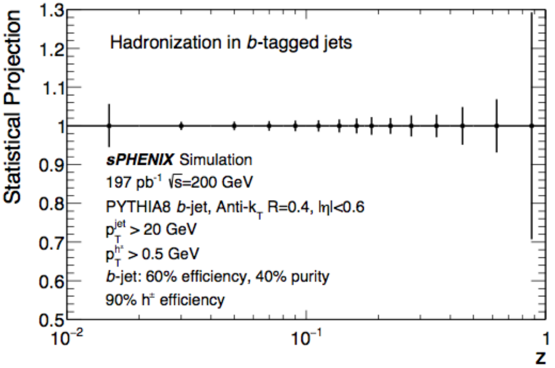
Plans for the future

- Continue along the direction of connecting parton-to-hadron $\rightarrow$ what can be done with PID?
  - PID at STAR, ALICE, and LHCb give possibility of PIDed hadron-in-jet
    - More at EIC...



Plans for the future

- Continue along the direction of connecting parton-to-hadron $\rightarrow$ what can be done with PID?
  - PID at STAR, ALICE, and LHCb give possibility of PIDed hadron-in-jet
    - More at EIC...
- sPHENIX and STAR at RHIC in the 2020's - Collins asymmetries and heavy flavor jets



Discussion points

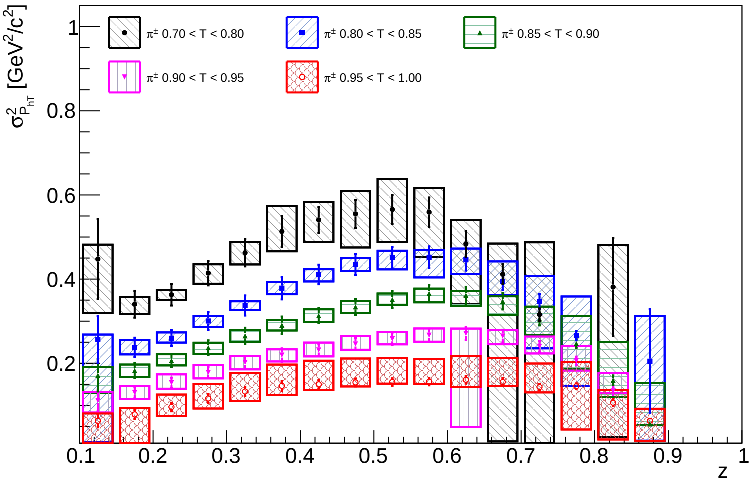
- What should experimentalists be thinking about in their measurements?
  - Are multidifferential measurements of (z, j_T) possible in hadronic collisions? See e.g. PRD 99, 112006 (2019), PRC 100, 064901 (2019)
  - Currently low z is difficult to handle theoretically - what can we learn from soft contributions to jets?
- Can we push towards measuring correlations rather than single hadrons?
  - e.g. K^+K^- correlations to test string breaking type picture?
- What about baryons?
  - Typically (at hadron colliders) measure "charged hadrons." What can we learn about the physical process of hadronization from e.g. baryon vs. meson comparisons? Or more exotic baryons like Λs etc.? See e.g. PRL 124, 172301 (2020) etc.

Discussion

Backup

$e^+e^- \to h\,X$ at Belle

R. Seidl et al. 1902.01552 - PRD
and supplemental material



Gaussian widths in P_{hT} for the cross section as a function of z and thrust (pions)

Relation to other formalisms in 2009.11871 & 2011.07366

The authors consider joint thrust and TMD resummation

$$1-\tau = T = \max_{\hat{t}} \frac{\sum_i |\hat{t}\cdot\vec{p}_i|}{\sum_i |\vec{p}_i|}$$

Regime:	1: $\sqrt{\tau} \gg q_T/Q \sim \tau$	2: $\sqrt{\tau} \gg q_T/Q \gg \tau$
n-collinear	$(q_T^2/Q, Q, q_T)$	$(q_T^2/Q, Q, q_T)$
$\bar{n}$-collinear	$Q(1, \tau, \sqrt{\tau})$	$Q(1, \tau, \sqrt{\tau})$
n-collinear-soft		$(\tau Q, q_T^2/(\tau Q), q_T)$
soft	$q_T(1,1,1)$	$\tau Q(1,1,1)$

Our EFT

$\tau \sim \mathcal{O}(1)$

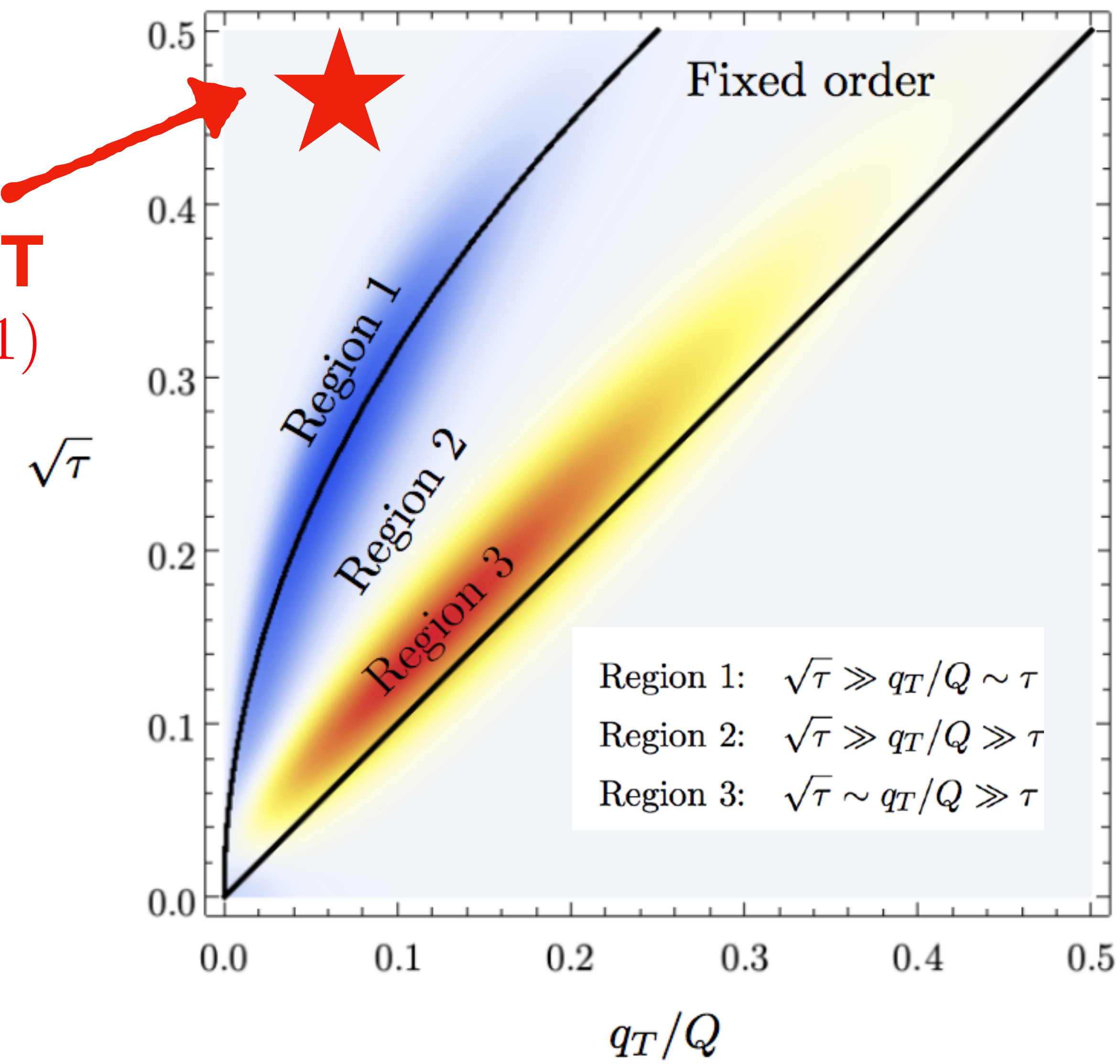
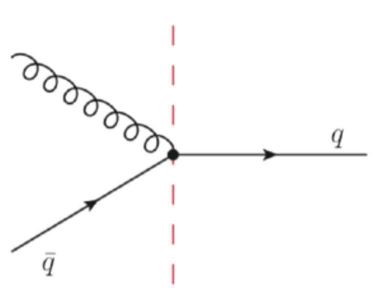


Fig from 2009.11871

$\tau \sim \mathcal{O}(1)$

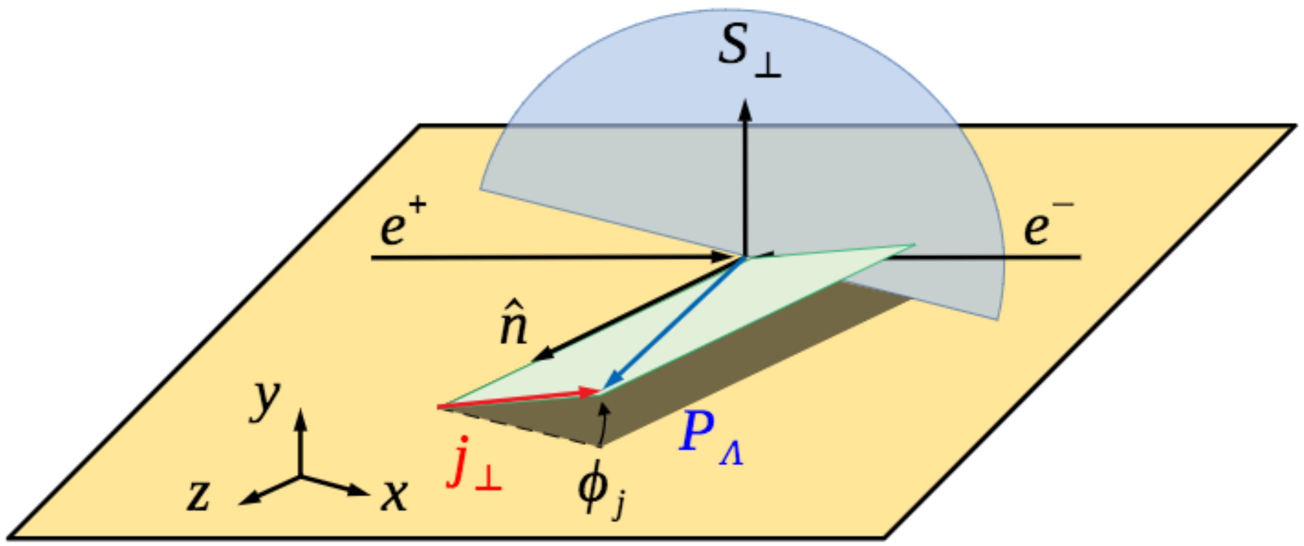
NLO hard function

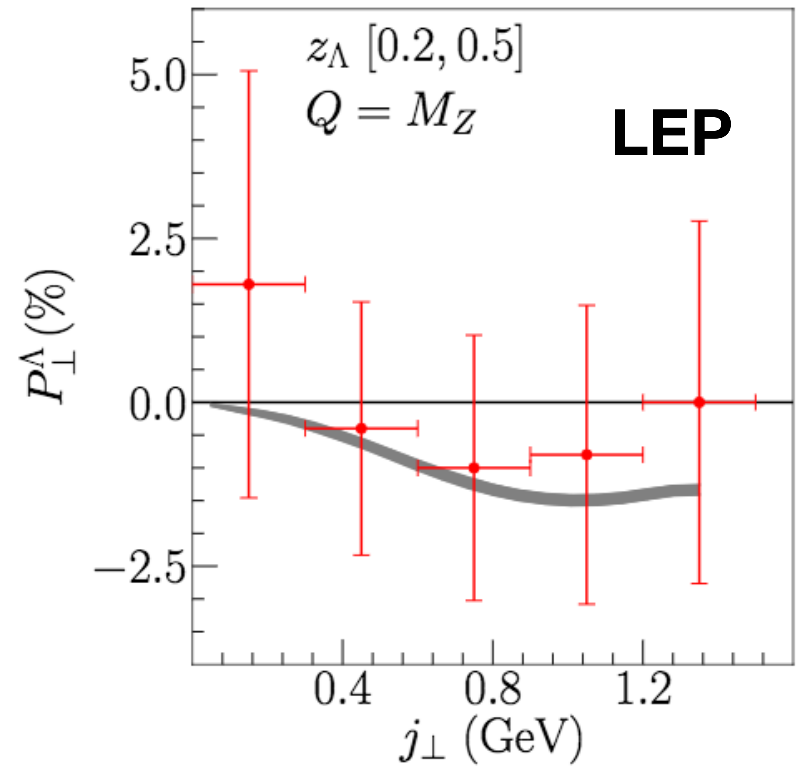


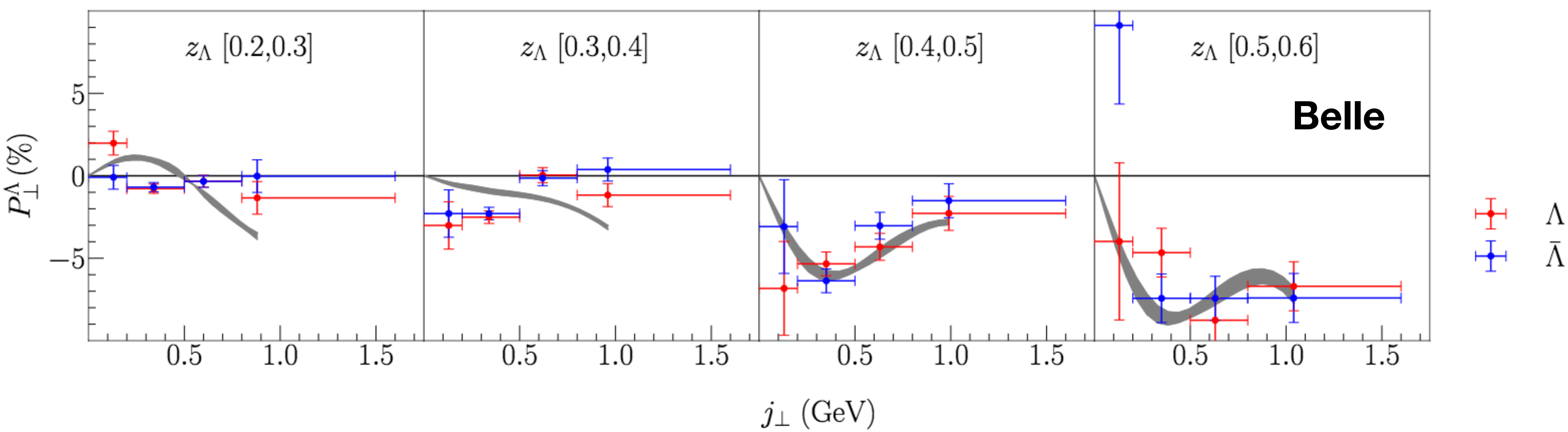
NLO soft function is same in the hemisphere containing the identified hadron while scaleless in the other hemisphere

Transverse polarized Λ hyperon production

Gamberg, Kang, DYS, Terry, Zhao 2012.XXXXX

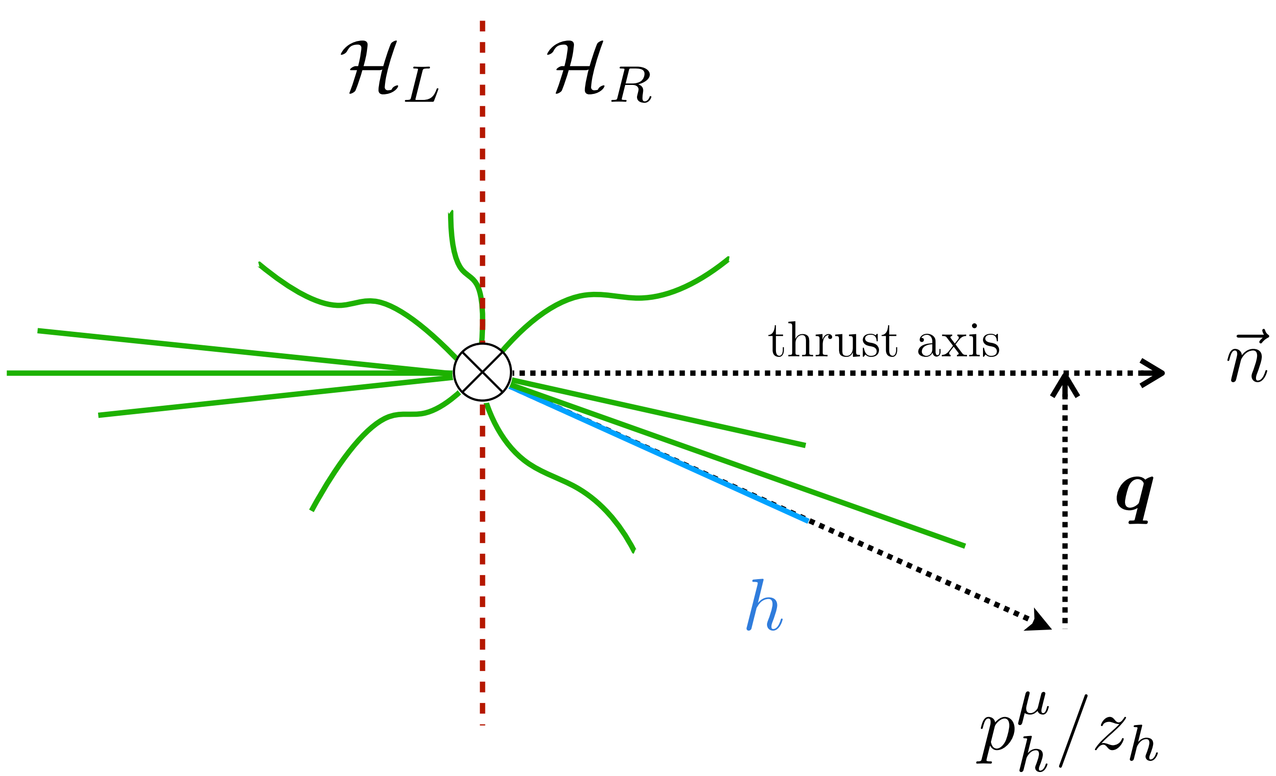




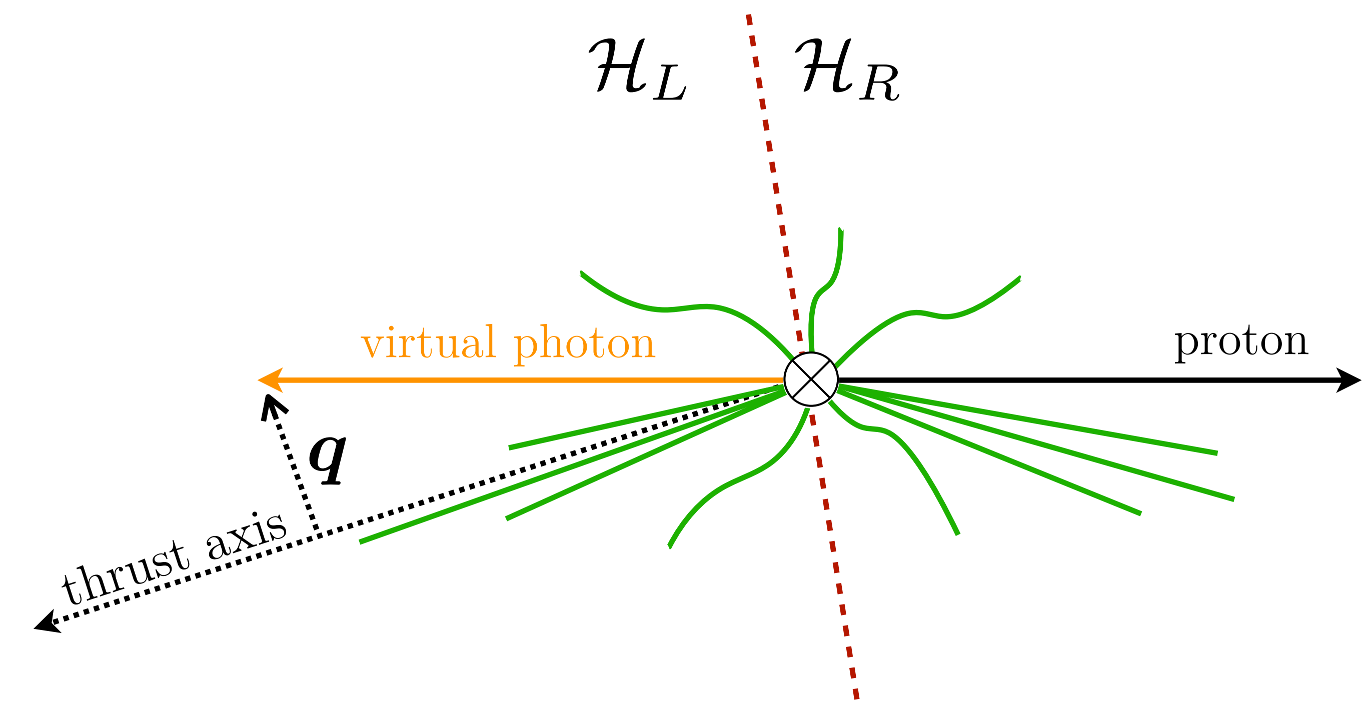


Thrust - TMDs

electron-positron annihilation



DIS

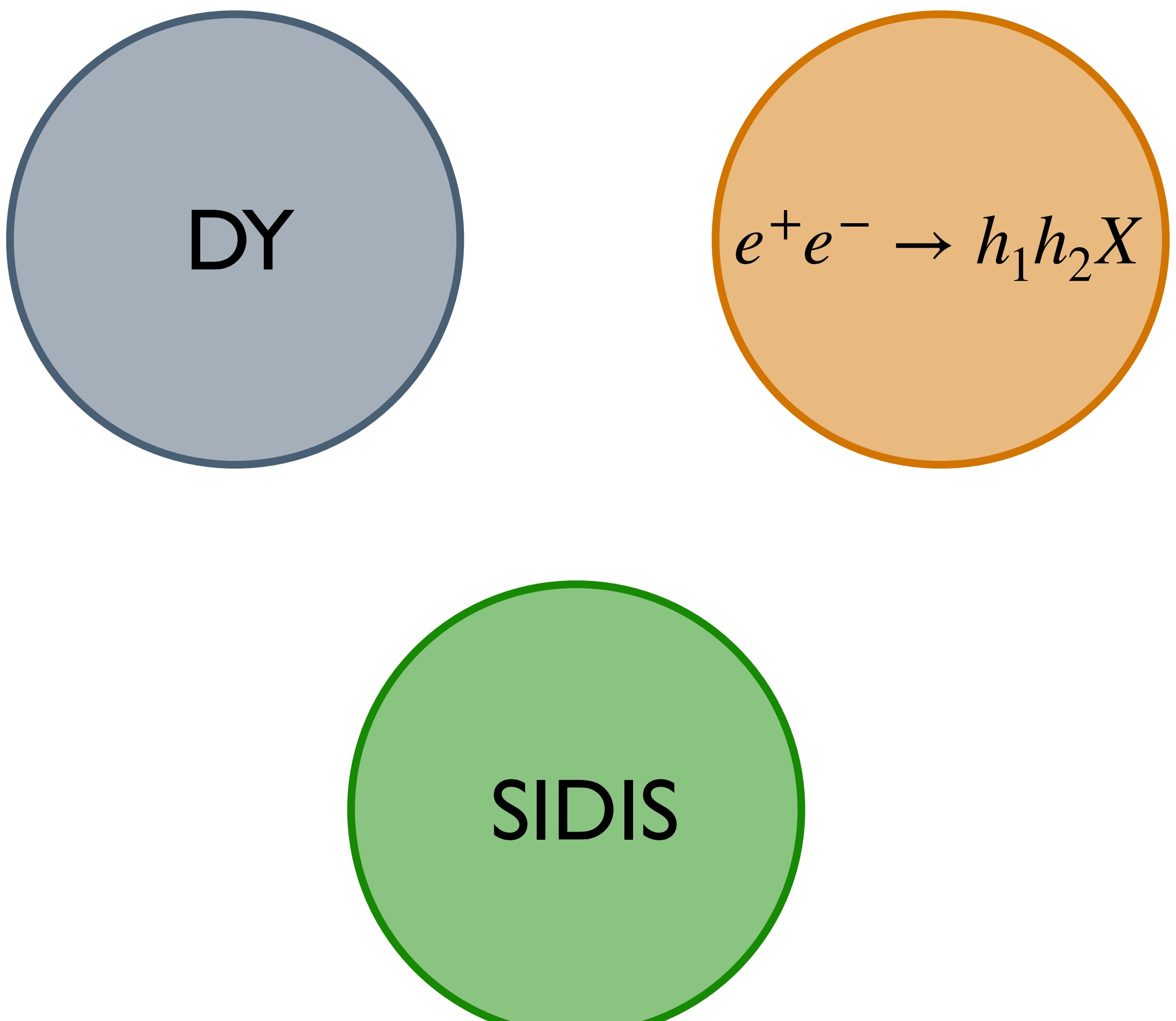


Transverse momentum sensitive about R-hemisphere (contrast with SIDIS)

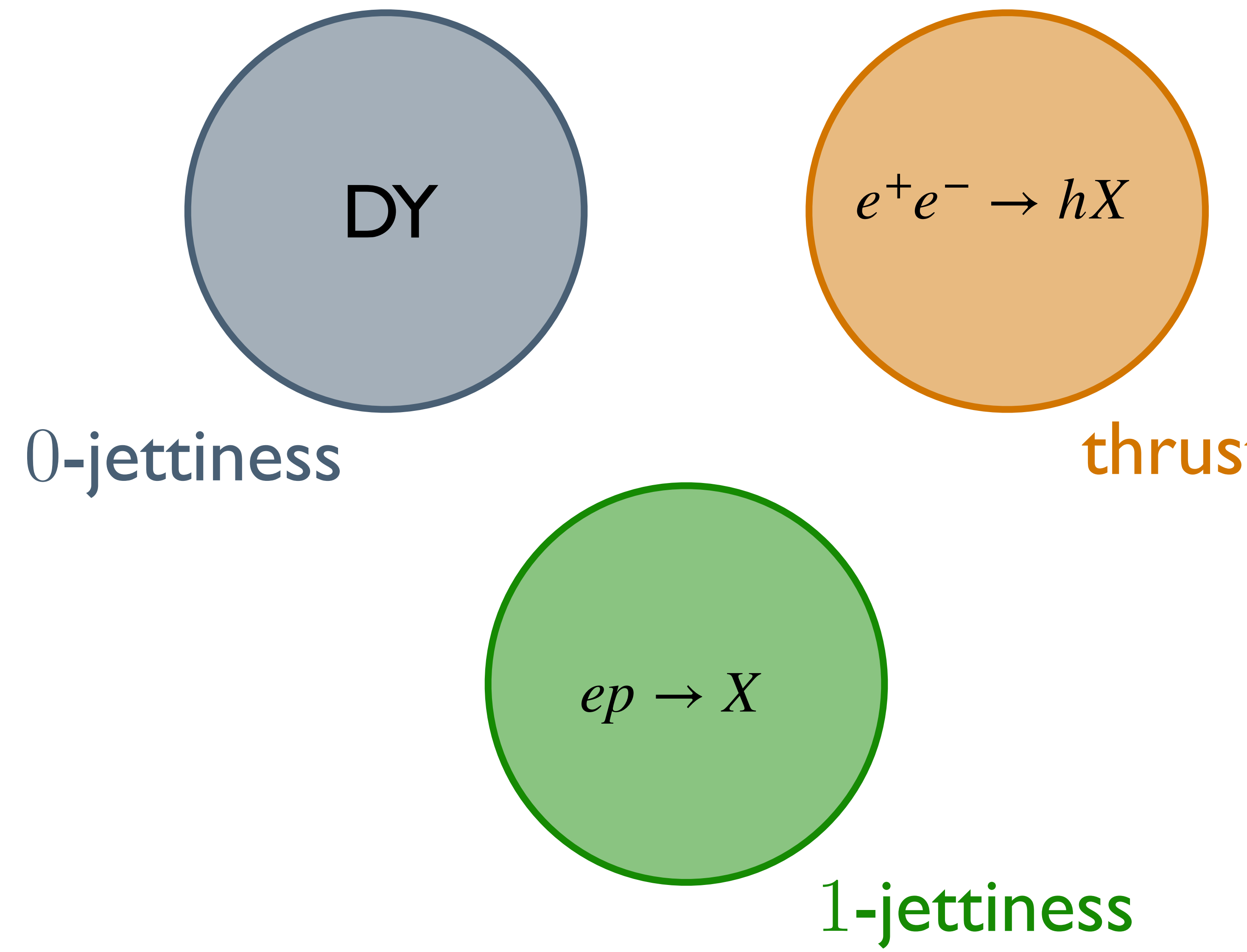
Trust is a global observable

Thrust - TMDs

Conventional TMDs



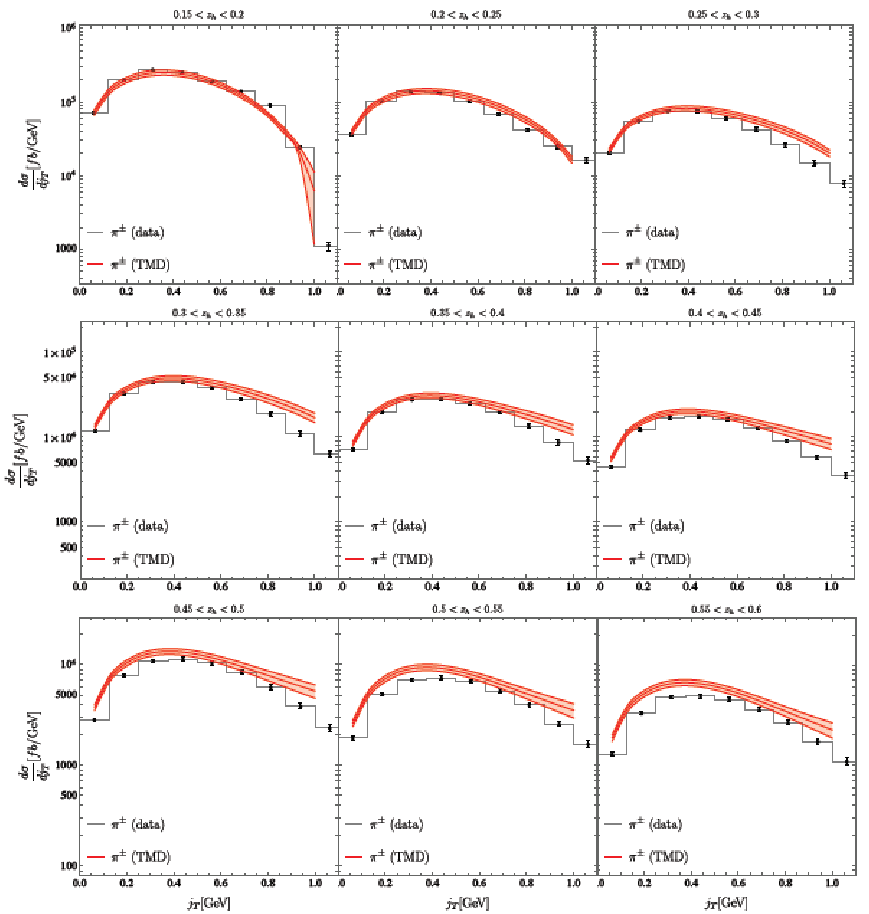
"Thrust" TMDs



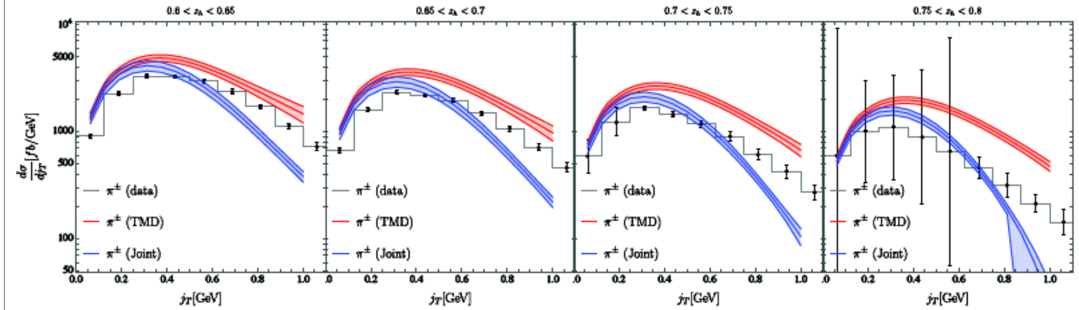
Kang, Shao, Zhao, 2007.14425

- Two different kinematic regions are considered, $j_T << Q$ and $j_T << Q(1-z_h) << Q$.
- Using effective theory methods, $\log Q/j_T$ and $\log(1-z_h)$ are resummed to all orders.
- Thrust dependence integrated out.

Differential Cross Section ($\pi^{\pm}$) as function of j_T TMD resummation applied.

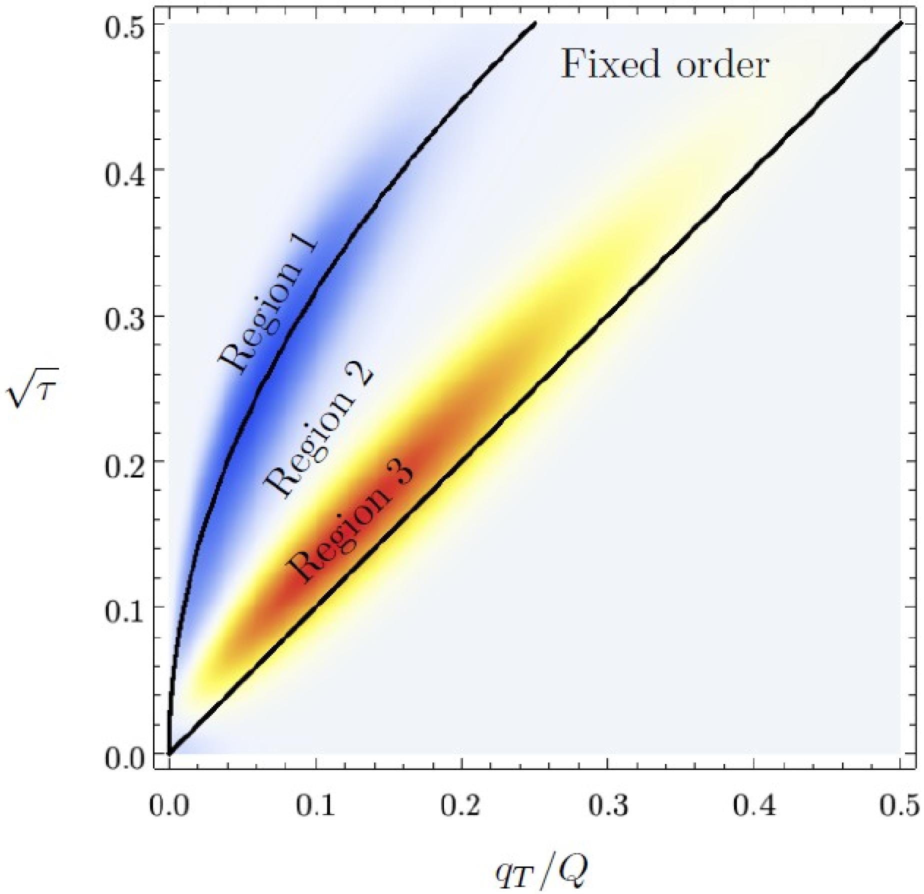


j_T-distribution ($\pi^{\pm}$) given by TMD resummation (red band) and joint TMD and threshold resummation (blue band)



Makris, Ringer, Walewijin, 2009.11871

- Three different kinematic regions are identified.
- Factorization theorems within SCET for each individual region provide the cross section of $e^+e^- \to HX$, differential in z_h, P_T and T .
- Joint resummation of the transverse momentum and thrust spectrum at NNLL accuracy.
- Final result obtained by matching the cross sections in the three kinematic regions.



Region 1: $\sqrt{\tau} \gg q_T/Q \sim \tau$

Region 2: $\sqrt{\tau} \gg q_T/Q \gg \tau$

Region 3: $\sqrt{\tau} \sim q_T/Q \gg \tau$

Matching:

$$d\sigma = d\sigma_2|_{\mu_2} + [d\sigma_1 - d\sigma_2]_{\mu_1} + [d\sigma_3 - d\sigma_2]_{\mu_3} + \\ + [d\sigma_{\rm FO} - d\sigma_1 - d\sigma_3 - d\sigma_2]_{\mu_{\rm FO}}$$