Transverse polarization of Λ hyperons in single-inclusive leptonic annihilations

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The first TH prediction on transverse Λ polarization

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Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

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and

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(Received 5 July 1978)

It is interesting to calculate the deviation from zero for $m_q \neq 0$, to order α_s. The explicit result for $e^+e^- \to q\bar{q}$ is, for arbitrary m_q and large Q^2,

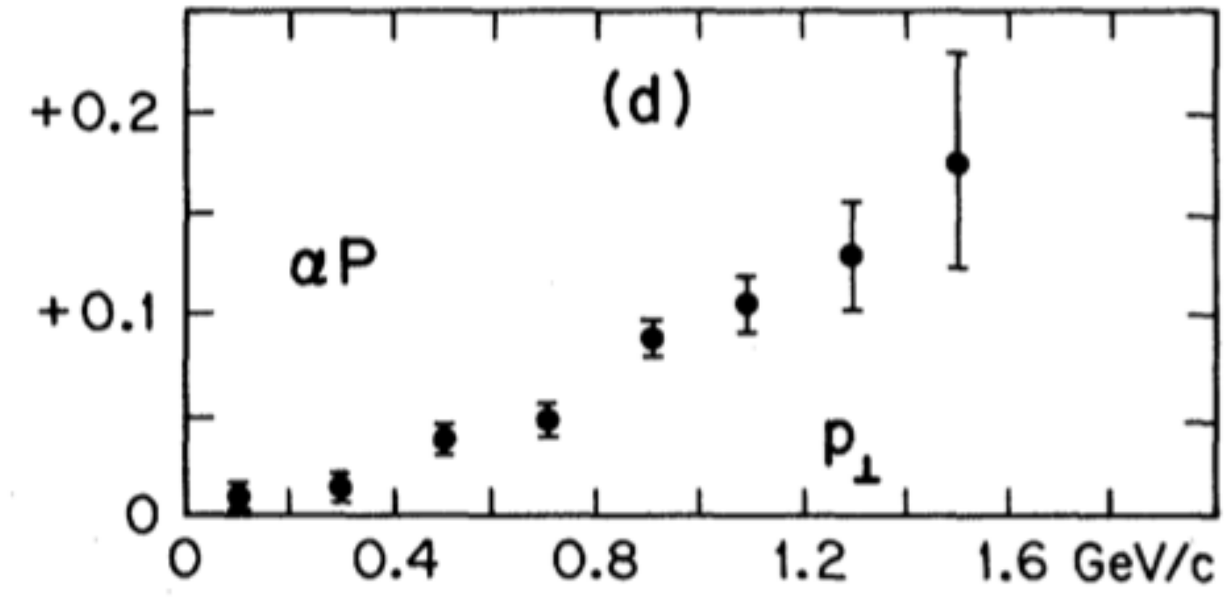
$$P = \left(\frac{4\alpha_s}{3}\right)\frac{m_q}{Q^2}\frac{\sin\theta\cos\theta}{1+\cos^2\theta}.$$

Whatever observable is used, the variation with Q^2 and the c.m. scattering angle θ can be tested. P is the polarization transverse to the scattering plane, calculated through order α_s in QCD.

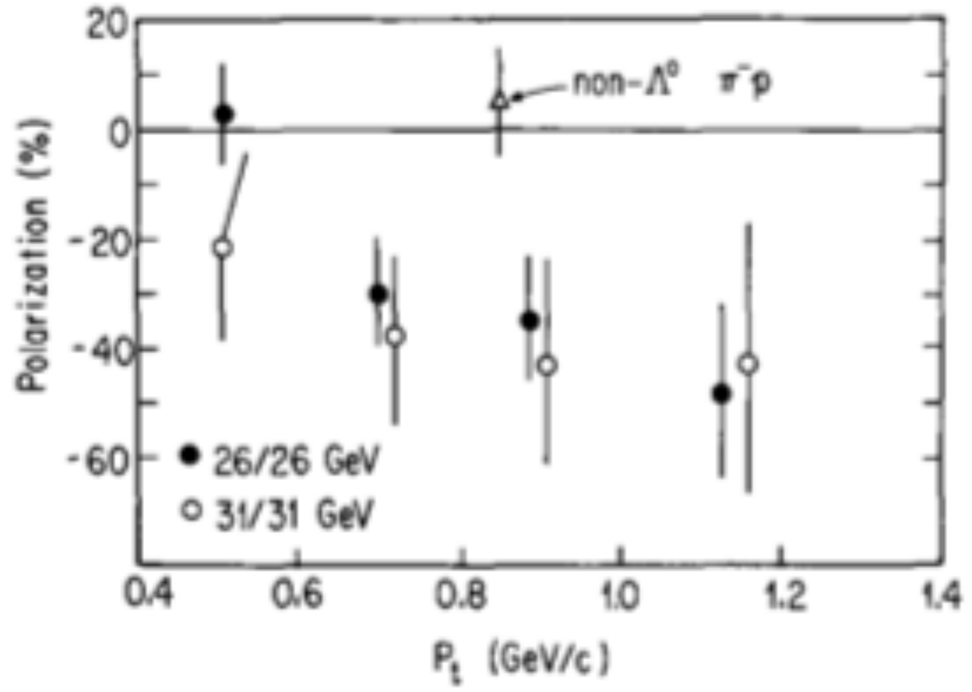
In this note we have pointed out that the asymmetry off a polarized target, and the transverse polarization of a produced quark in $e^+e^- \to q\bar{q}$, or in $qq \to qq$ at large p_T, or in leptoproduction, should all be calculable perturbatively in QCD. The result is zero for $m_q = 0$ and is numerically small if we calculate $m_q/\sqrt{s}$ corrections for light quarks. We discuss how to test the predictions. At least for the cases when P is small, tests should be available soon in large-p_T production [where currently $P(\Lambda) = 25\%$ for $p_T \gtrsim 2$ GeV/c], and e^+e^- reactions. While fragmentation effects could dilute polarizations, they cannot (by parity considerations) induce polarization. Consequently, observation of significant polarizations in the above reactions would contradict either QCD or its applicability.

EXP on transverse Λ polarization

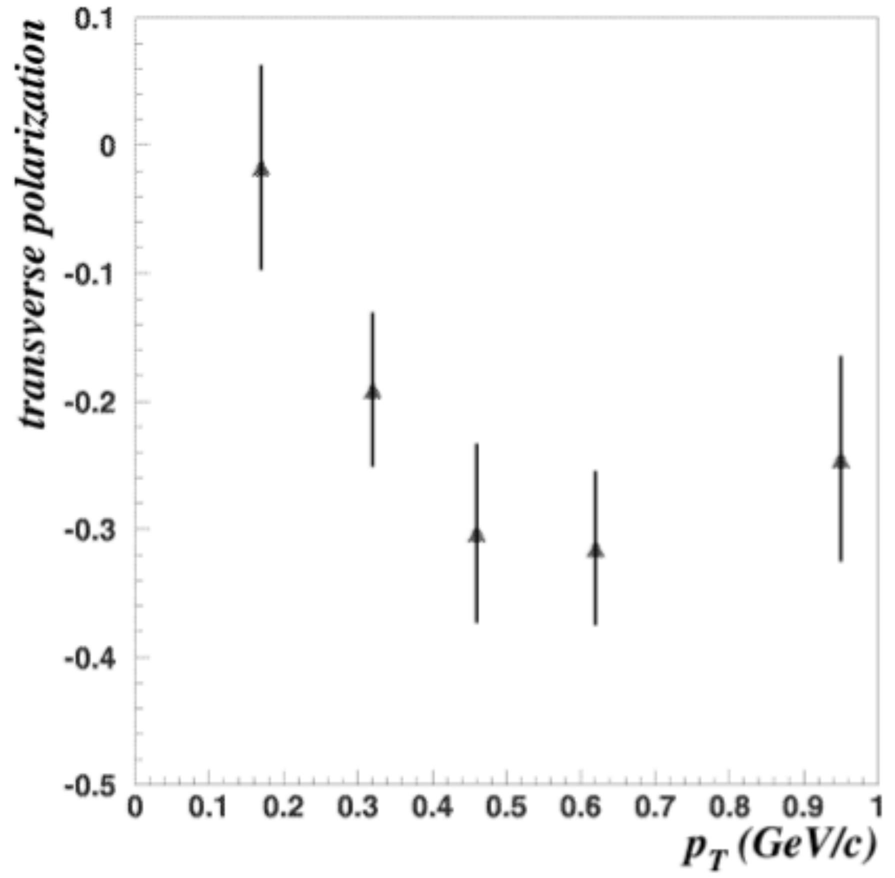
Bunce et.al. '76 $p + Be \to \Lambda^{\uparrow} + X$



Erhan et.al. '79 $pp \to \Lambda^{\uparrow}X$

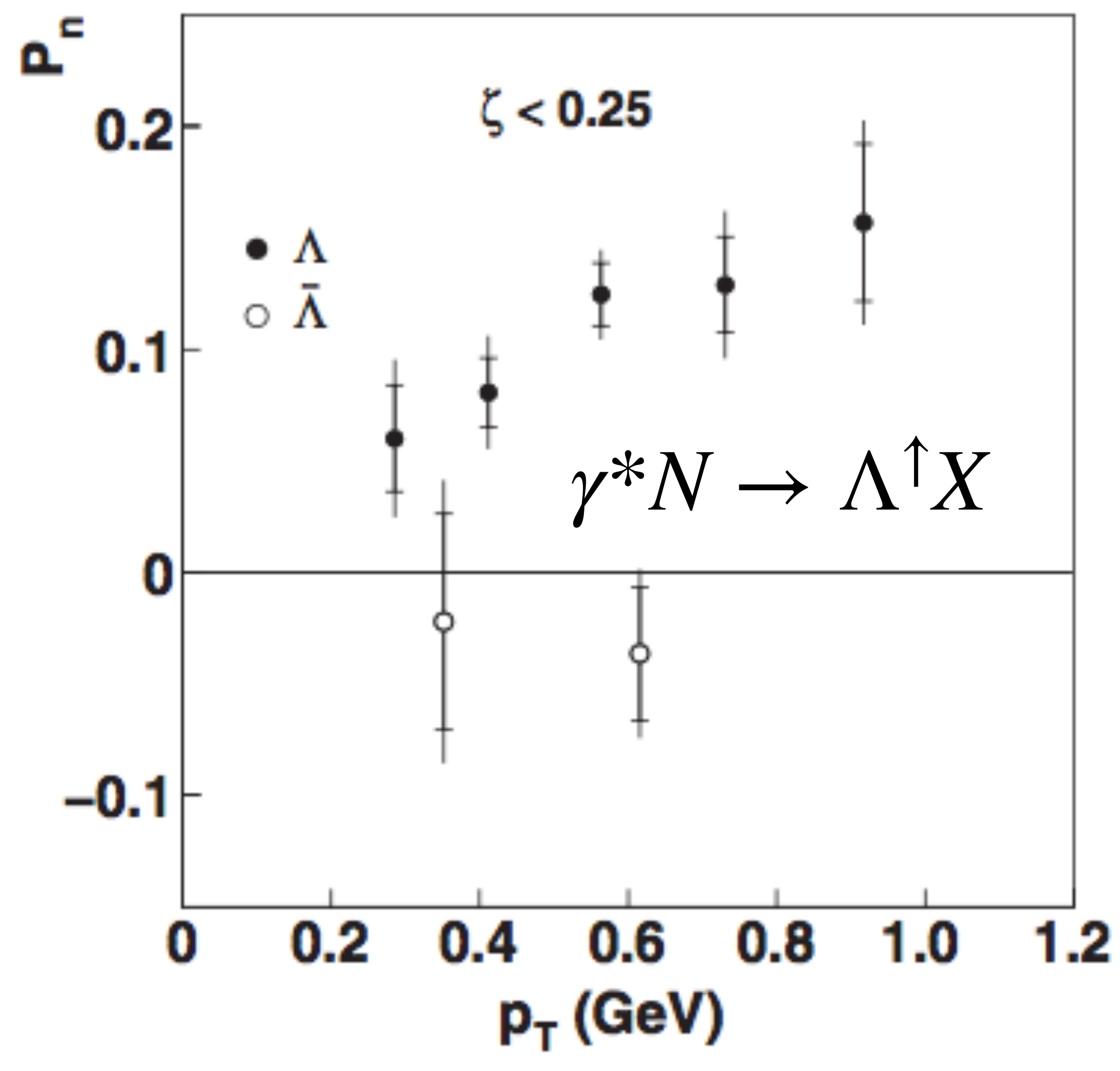


NOMAD '20 $\nu N \to \Lambda^{\uparrow}X$

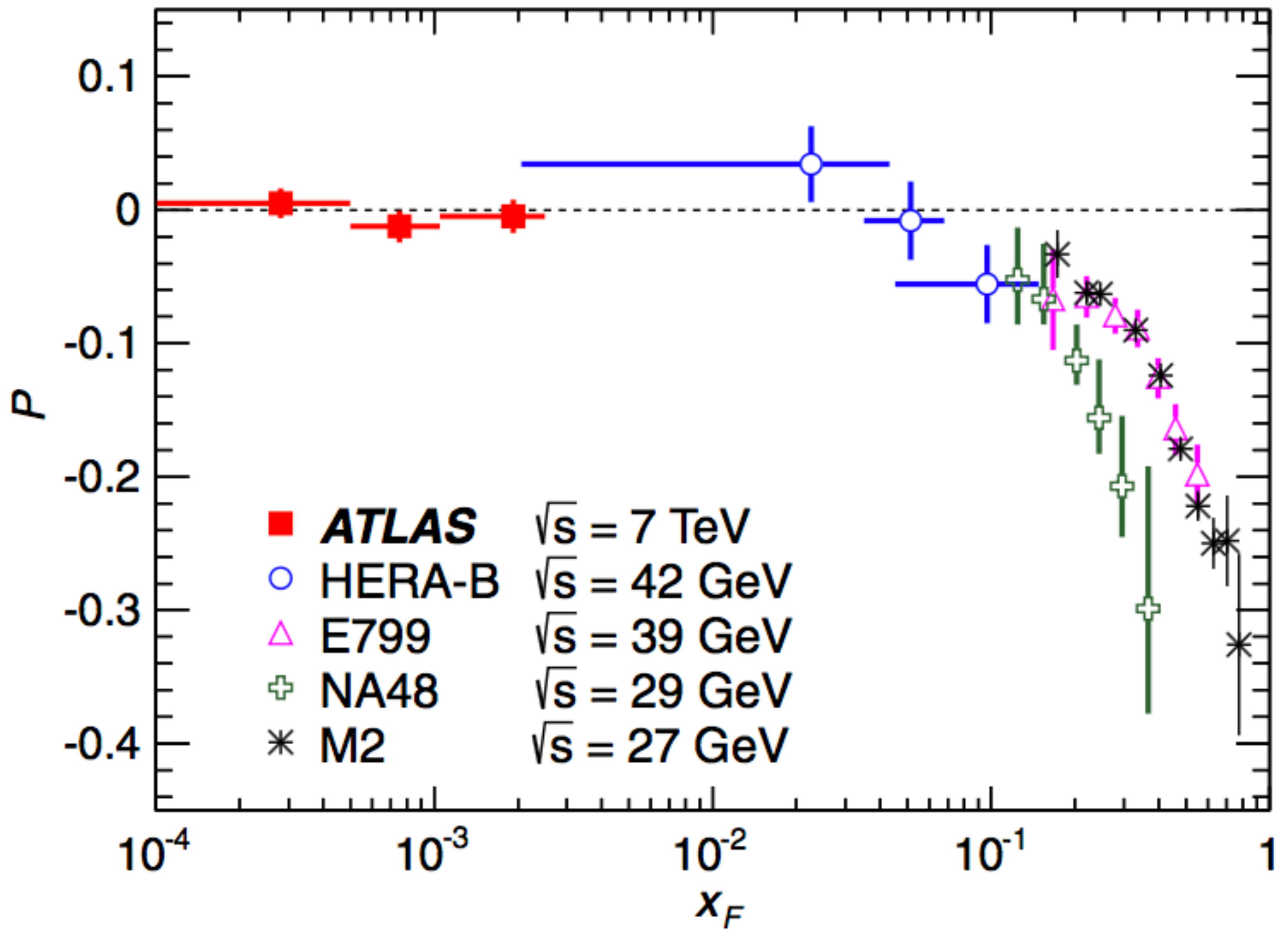


HERMES '76

A. AIRAPETIAN *et al.*



Atlas '15



Ma, Schmidt, Soffer, Yang '01

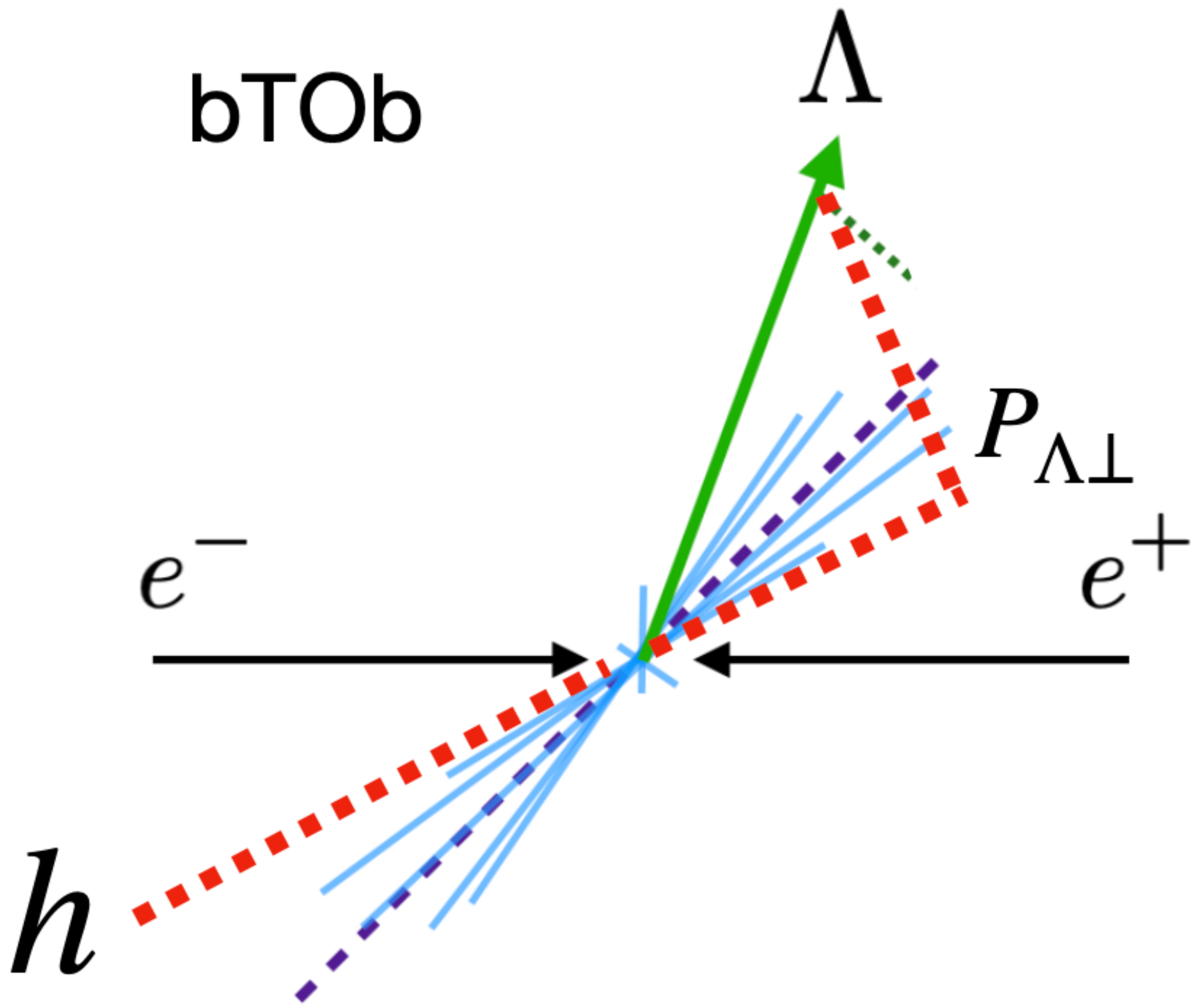
Liang, Wang '06

… …

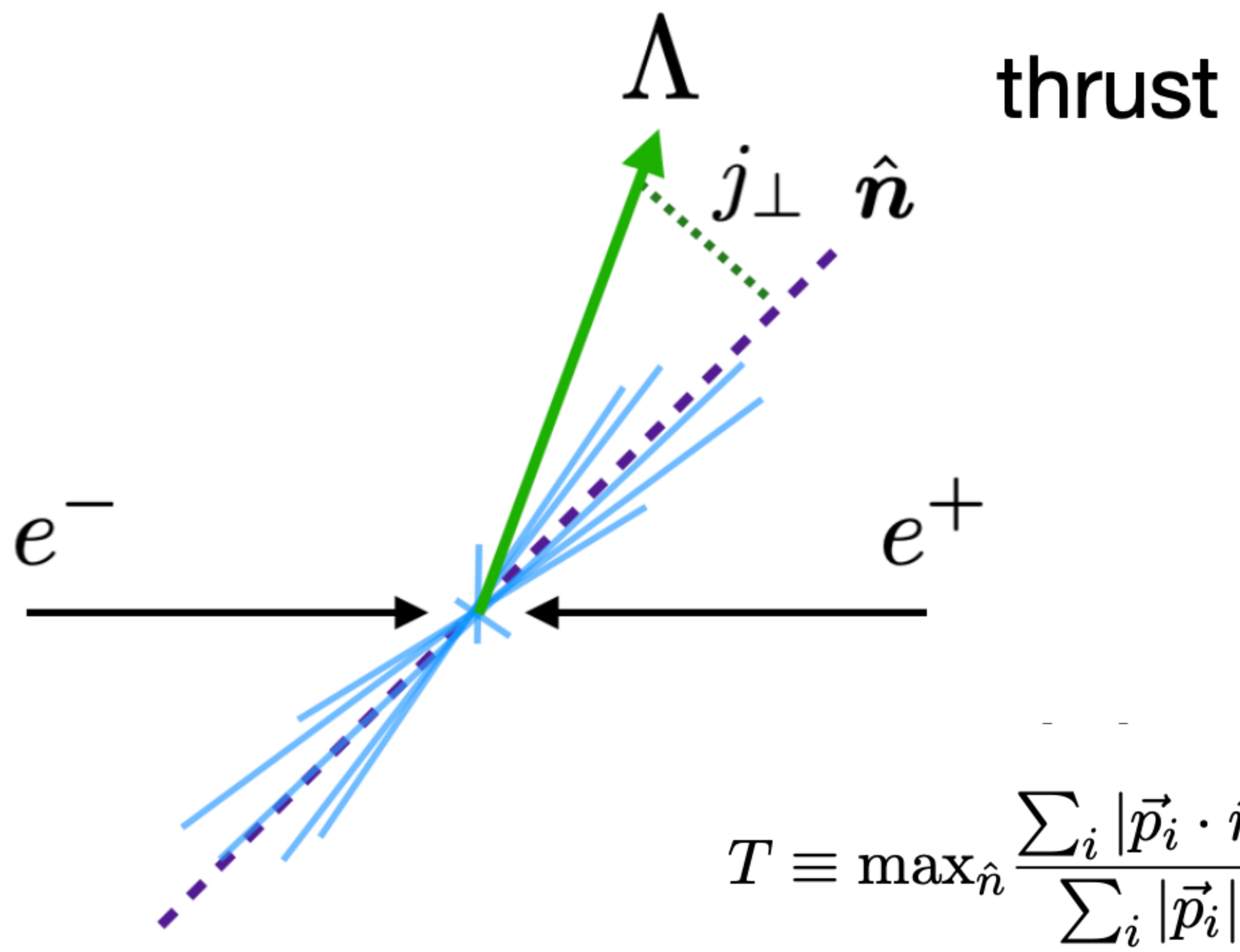
Transverse Λ polarization in electron positron collisions

In N+N or l+N collisions, it is not possible to disentangle initial-state effects, related to dynamics inside the colliding hadrons, and final-state effects, related to the fragmentation of the partons.

$$e^+e^- \to \Lambda^\uparrow h\, X$$



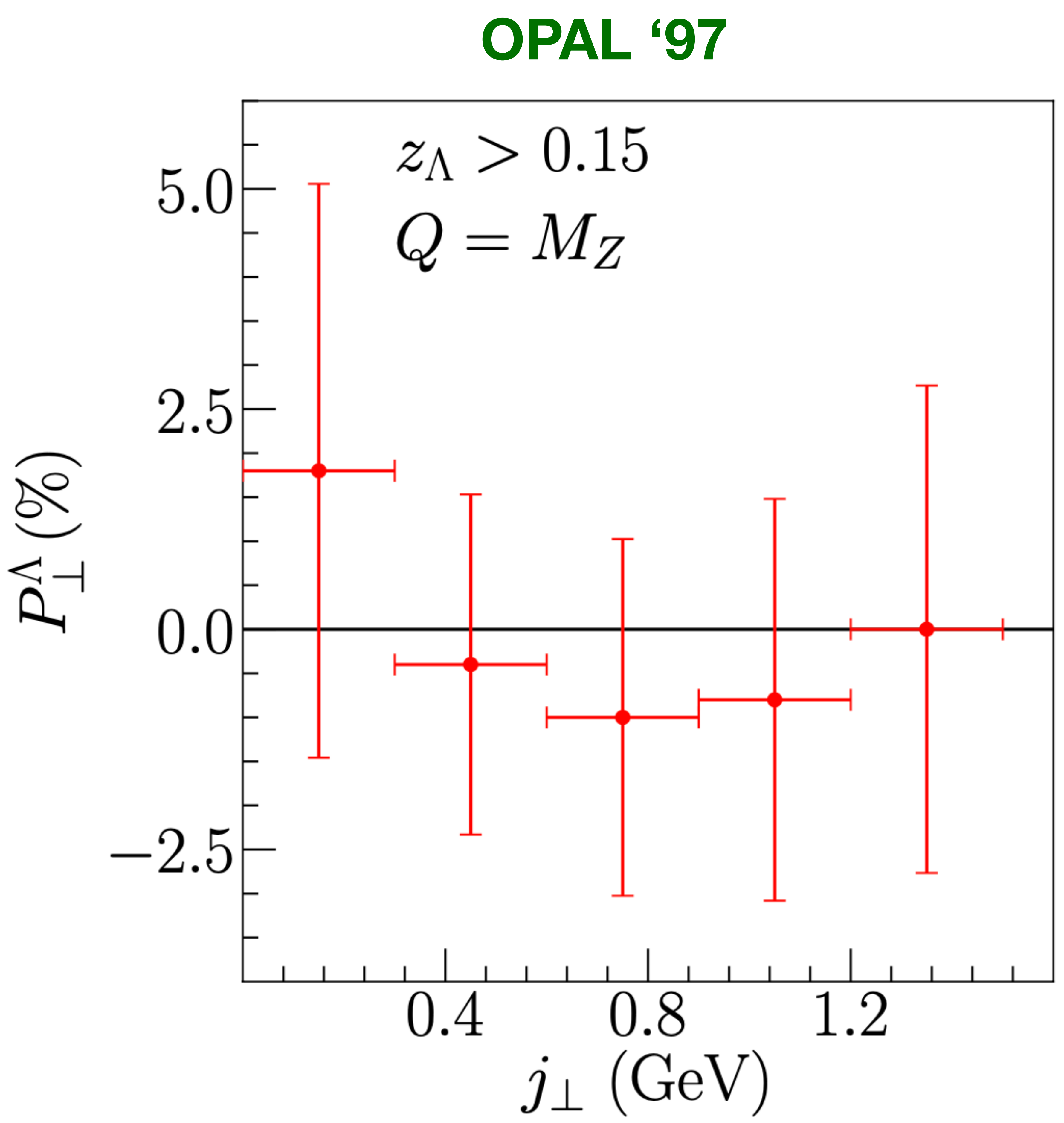
$$e^+e^- \to \Lambda^\uparrow(\text{Thrust})\, X$$

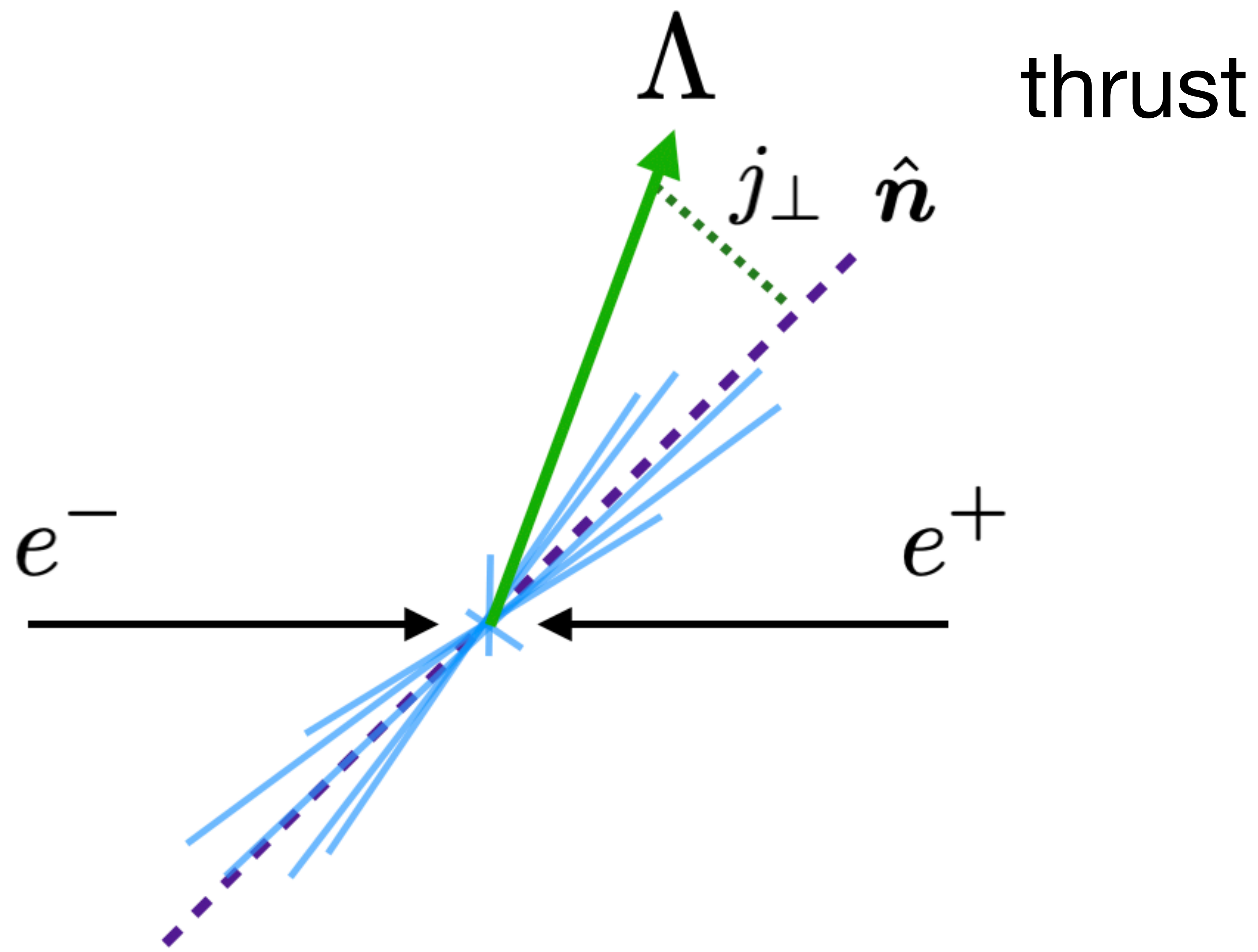


$$T \equiv \max_{\hat{n}} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$$

e^+e^- cleanest way to access fragmentation functions

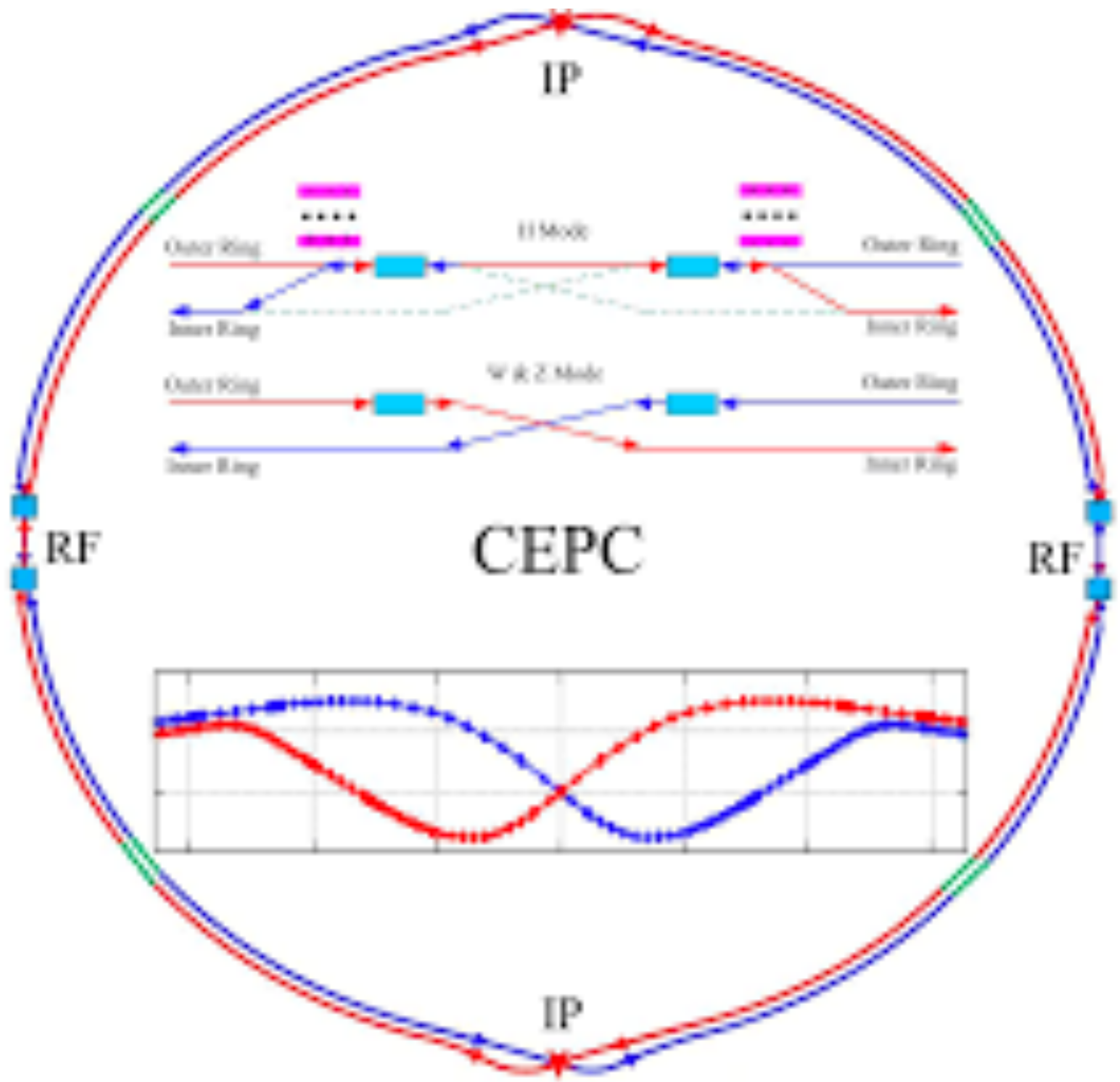
Transverse Λ polarization at the LEP

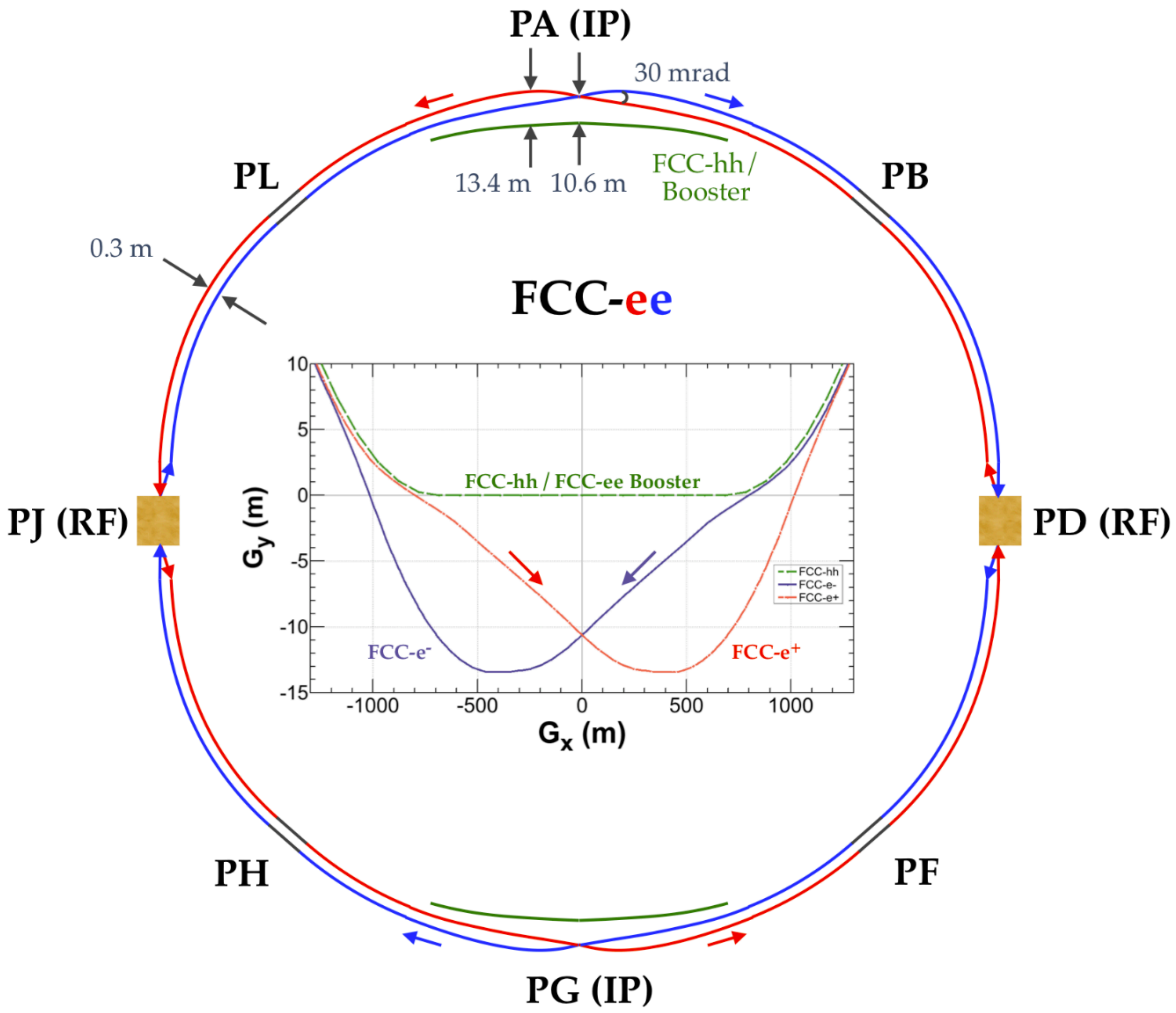




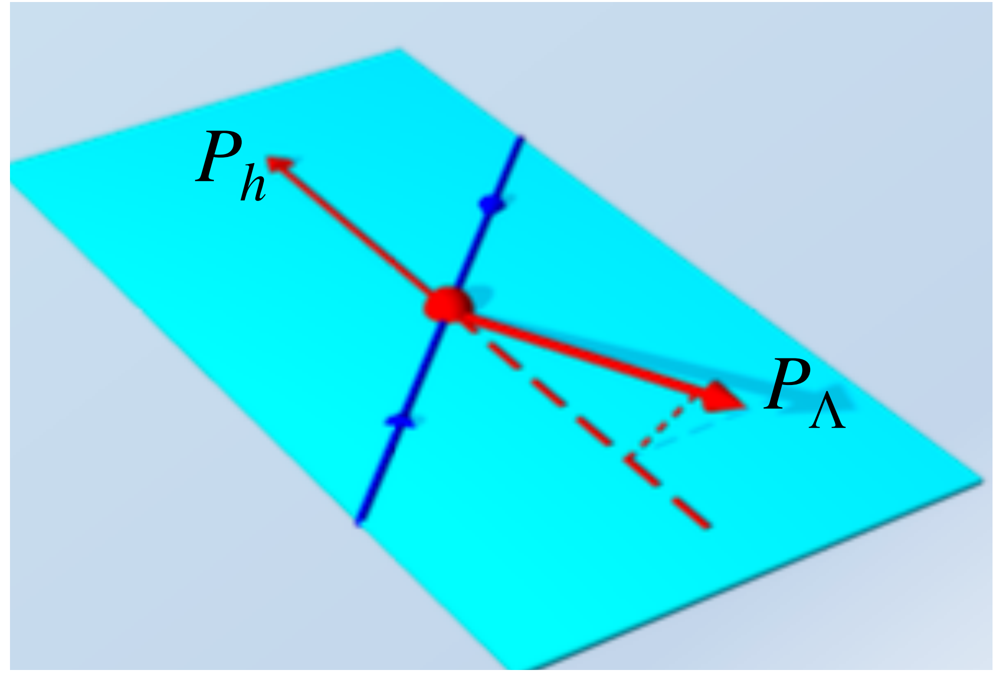
No significant transverse polarization is observed at the LEP

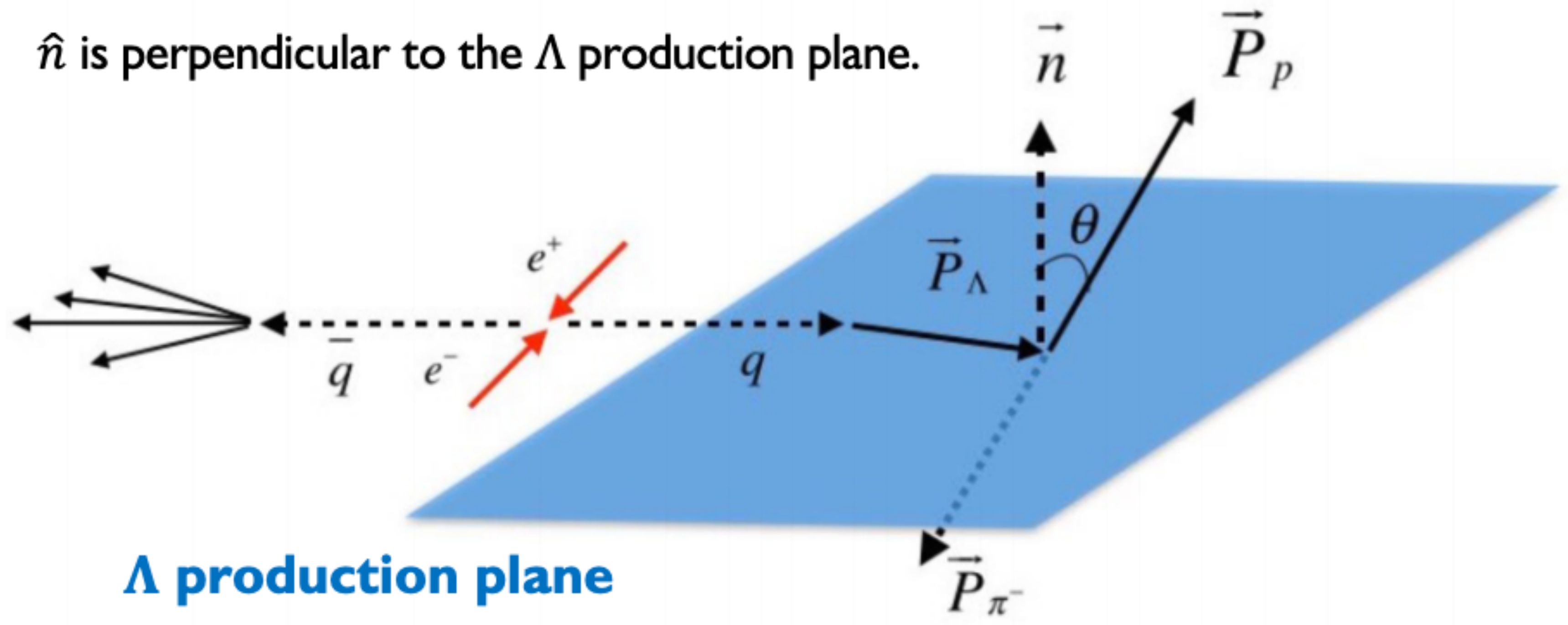
Transverse Λ polarization at the future e^+e^- collider ??



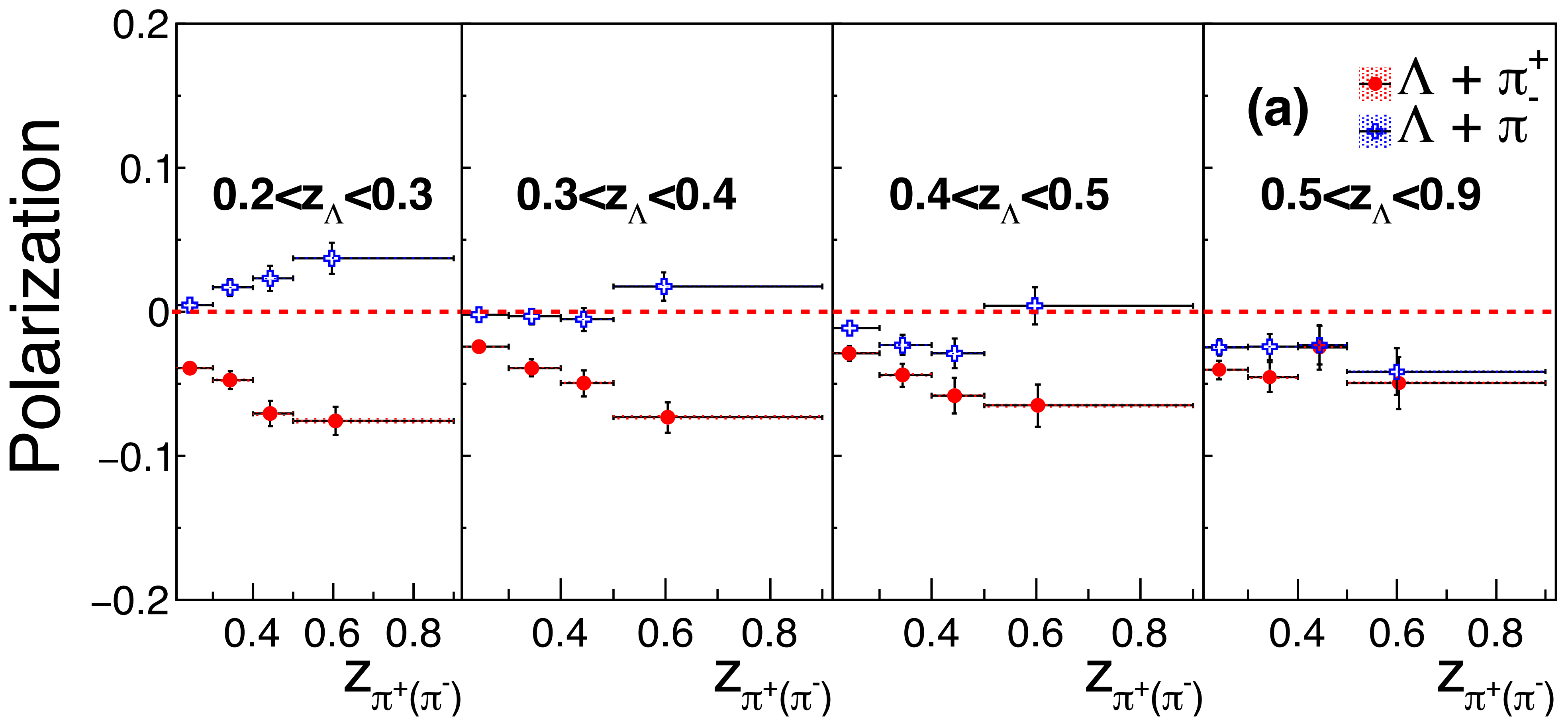


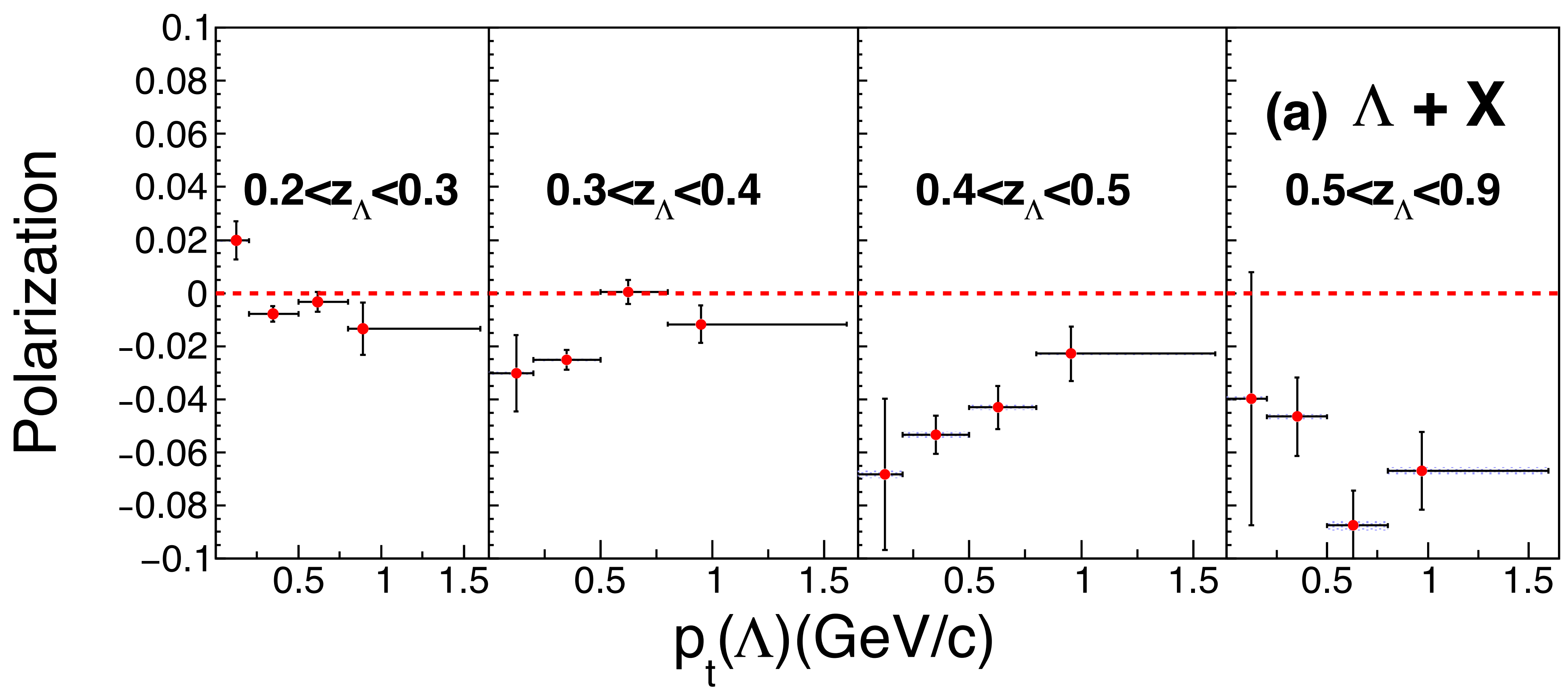
Transverse Λ polarization at the Belle





Belle '18 PRL





$$e^+e^- \to \Lambda^\uparrow h\, X$$

$$e^+e^- \to \Lambda^\uparrow(\mathrm{Thrust})\, X$$

Theory framework on transverse Λ polarization

$$e^+e^- \to \Lambda^\uparrow h\, X$$

Collins-Soper-Sterman, Ji-Ma-Yuan, Soft-Collinear Effective Theory… …

$$e^+e^- \to \Lambda^\uparrow(\mathrm{Thrust})\, X$$

???

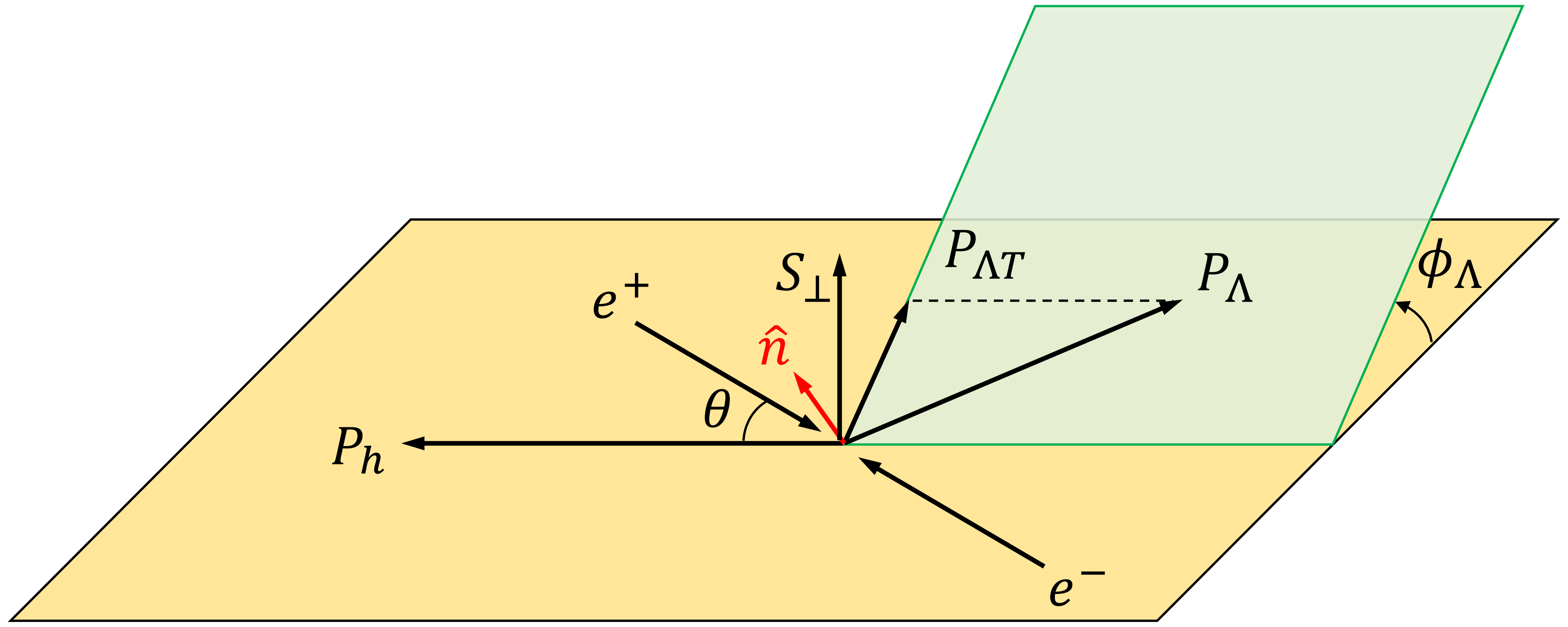
TMD factorization two scale problem

$$\Lambda_{QCD} \lesssim j_\perp \ll Q$$

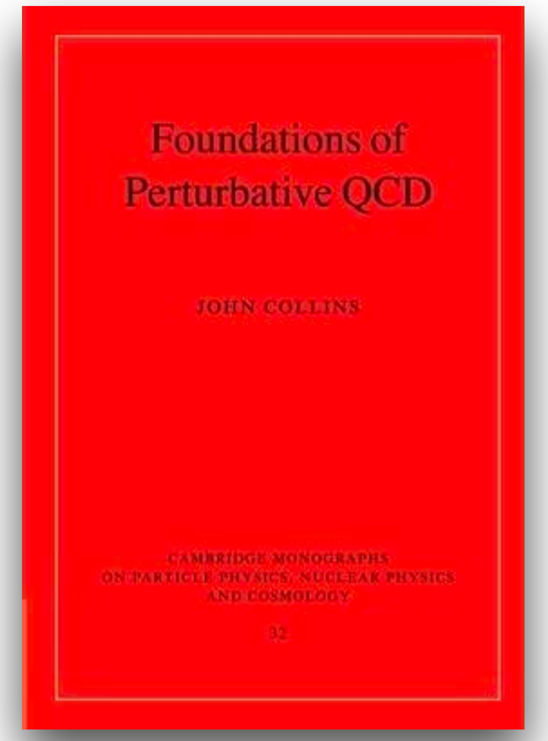
Is it the same (polarizing) fragmentation function in these two measurements ???

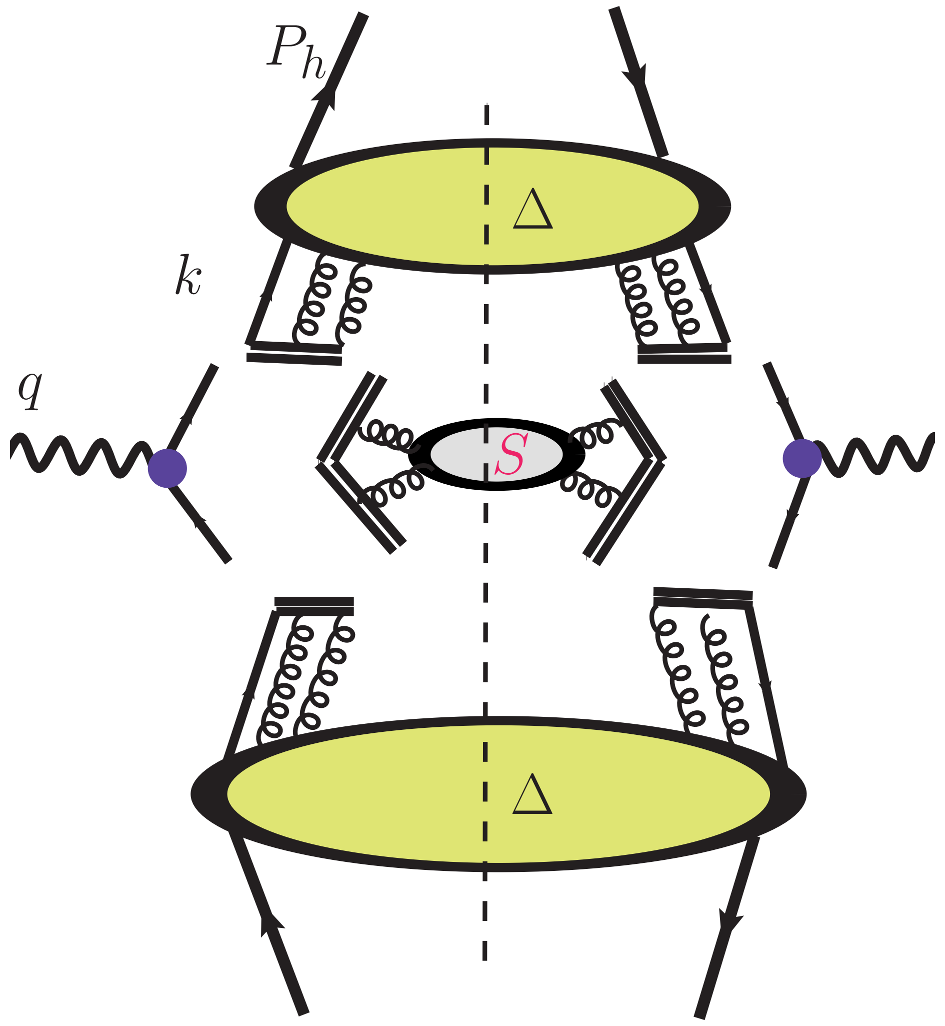
Back-to-back Λ+h

$$e^-(\ell) + e^+(\ell') \to \gamma^*(q) \to h(P_h) + \Lambda(P_\Lambda, \boldsymbol{S}_\perp) + X$$



TMD factorization theorems have been established for back-to-back Λ+h





$$W^{\mu\nu} \overset{\text{prelim}}{=} \frac{8\pi^3 z_A z_B}{Q^2} \sum_f \mathrm{Tr}\, k^+_{A,\gamma}\gamma^- H^\nu_f(Q)\, k^-_{B,\gamma}\gamma^+ \overline{H}^\mu_f(Q)$$
$$\times \int \frac{d^{2-2\epsilon}\boldsymbol{b}_T}{(2\pi)^{2-2\epsilon}} e^{-i\boldsymbol{q}_{hT}\cdot\boldsymbol{b}_T}\, \tilde{S}(b_T)\tilde{D}_{1,\,H_A/f}(z_A, b_T)\, \tilde{D}_{1,\,H_B/\bar{f}}(z_B, b_T)$$
$$+ \text{polarized terms.}$$

also see Hui Li's talk

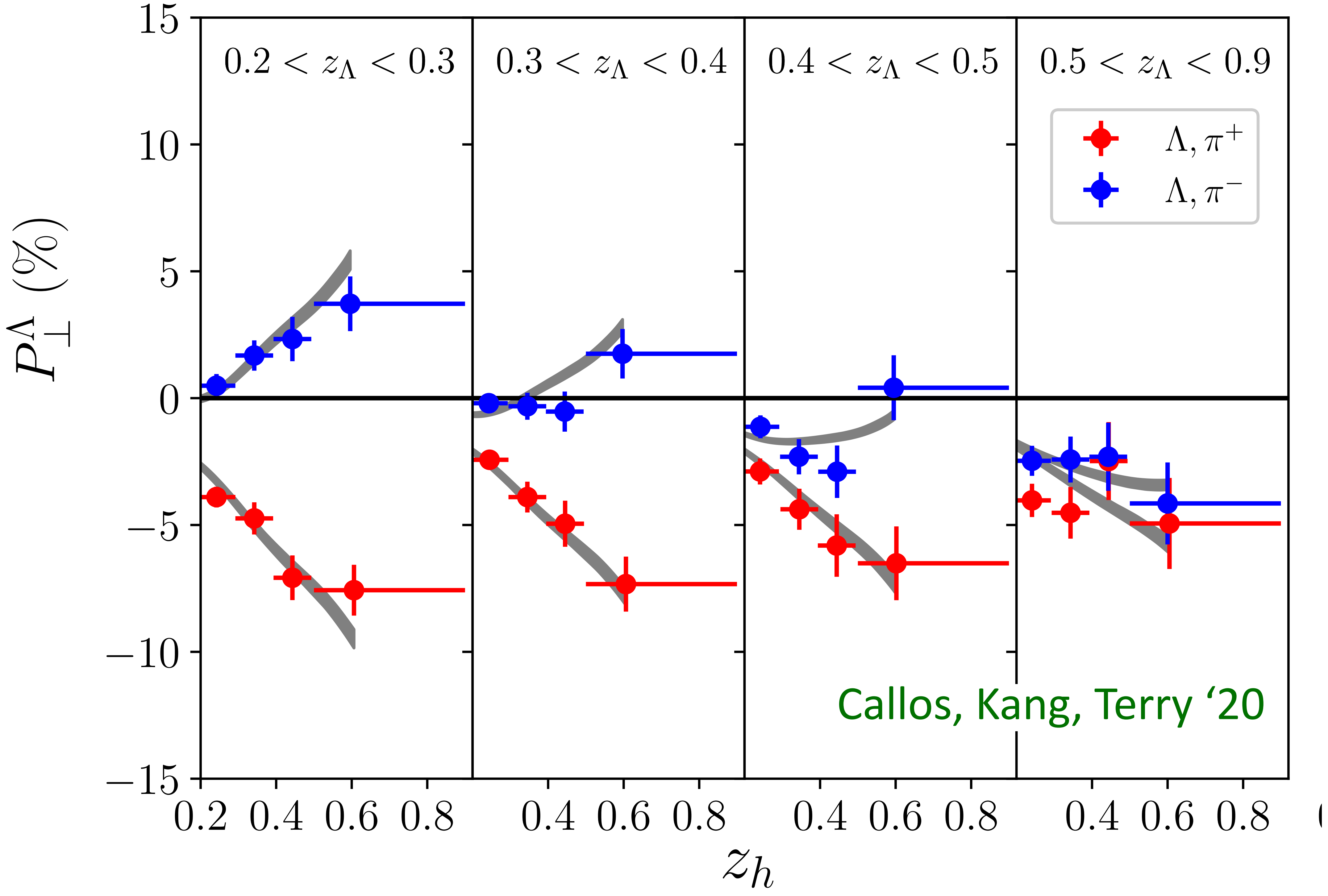
Spin-dependent cross section is factorized as:

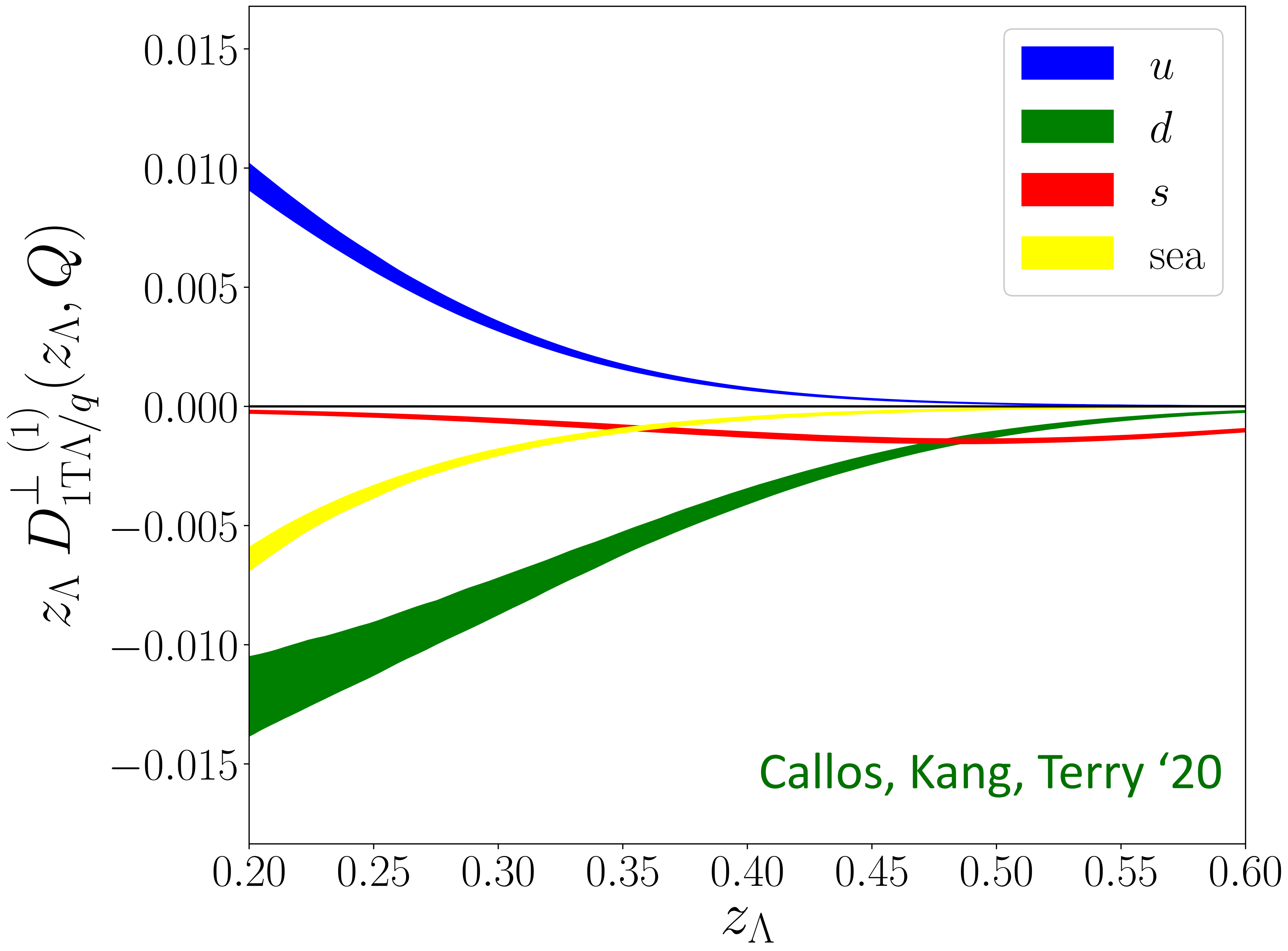
$$\frac{d\sigma(\boldsymbol{S}_\perp)}{d\mathcal{PS}d^2\boldsymbol{q}_\perp} = \sigma_0\left\{\mathcal{F}\left[D_{\Lambda/q}D_{h/\bar{q}}\right] + |\boldsymbol{S}_\perp|\sin(\phi_S - \phi_\Lambda)\frac{1}{z_\Lambda M_\Lambda}\mathcal{F}\left[\hat{\boldsymbol{P}}_{\Lambda T}\cdot\boldsymbol{p}_{\Lambda\perp}D^\perp_{1T,\Lambda/q}D_{h/\bar{q}}\right] + \cdots\right\}$$

Polarizing fragmentation function

see Xue's talk on Collins functions

Fitting of PFFs from Λ+h data

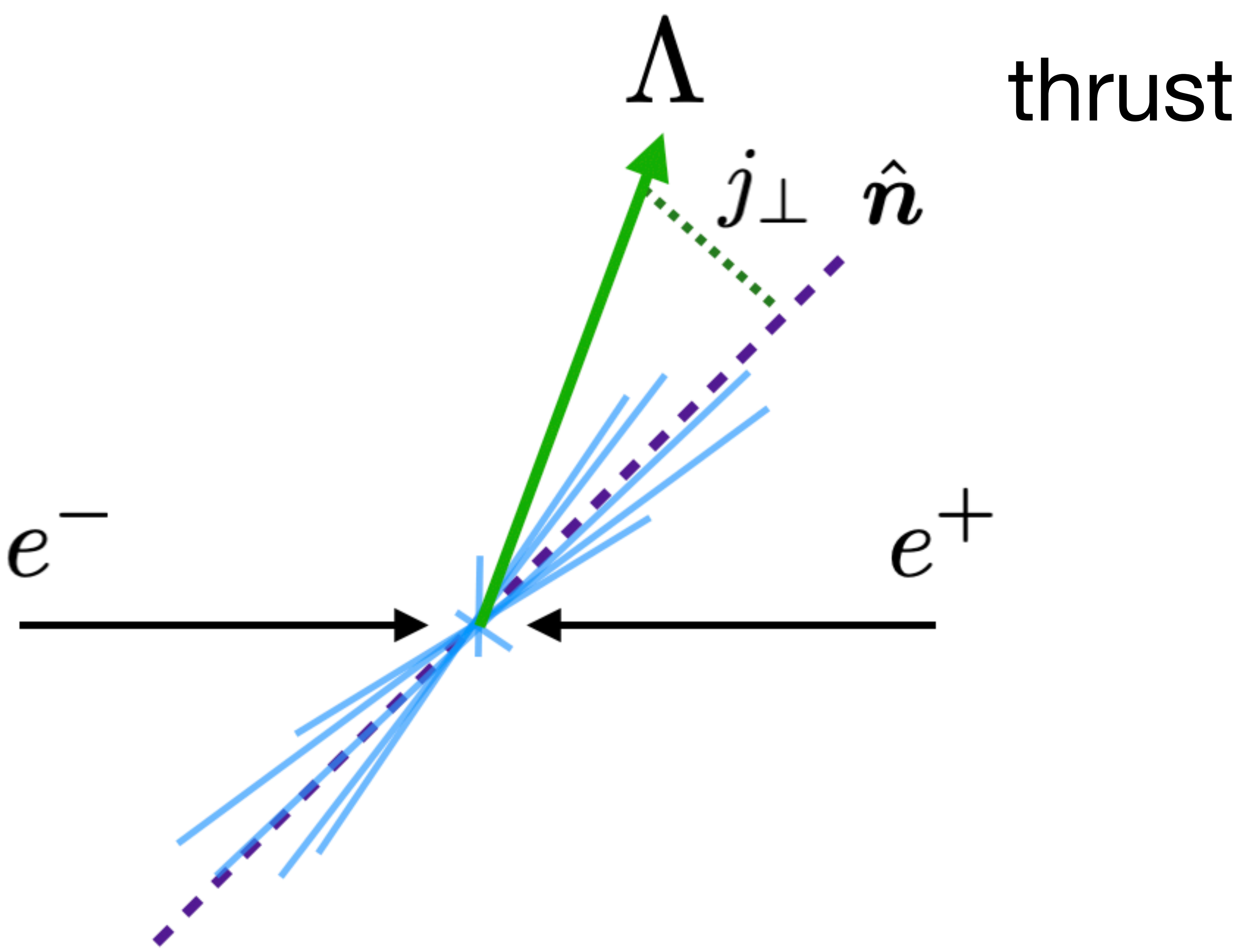




Yang, Lu, Schmidt '17
D'Alesio, Murgia, Zaccheddu '20
Callos, Kang, Terry '20
Li, Wang, Yang, Lu '20
… …

Spectator model: see Mao's talk
Light-front quantization: See Chandan, Lan, Xu, Zhao's talk
……

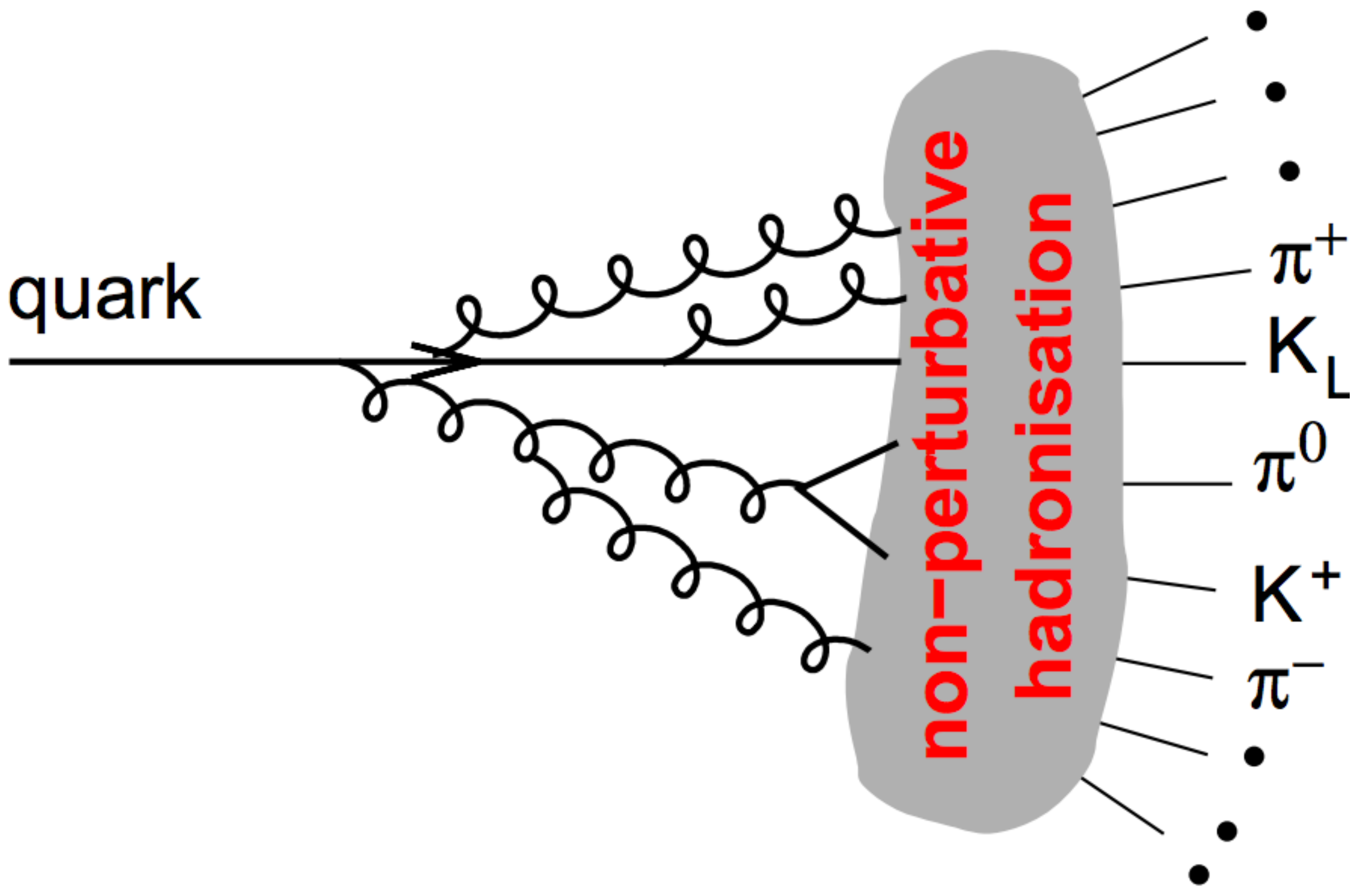
TMD factorization for Λ(thrust)



Wei, Chen, Song, Liang '14; Yang, Chen, Liang '17,……(Twist-4 FF, Parton model on the jet)

Parton (quark or gluon) fragmentation and hadronization

High-energy partons lead to collimated bunches of hadrons



Jets are not the same as partons

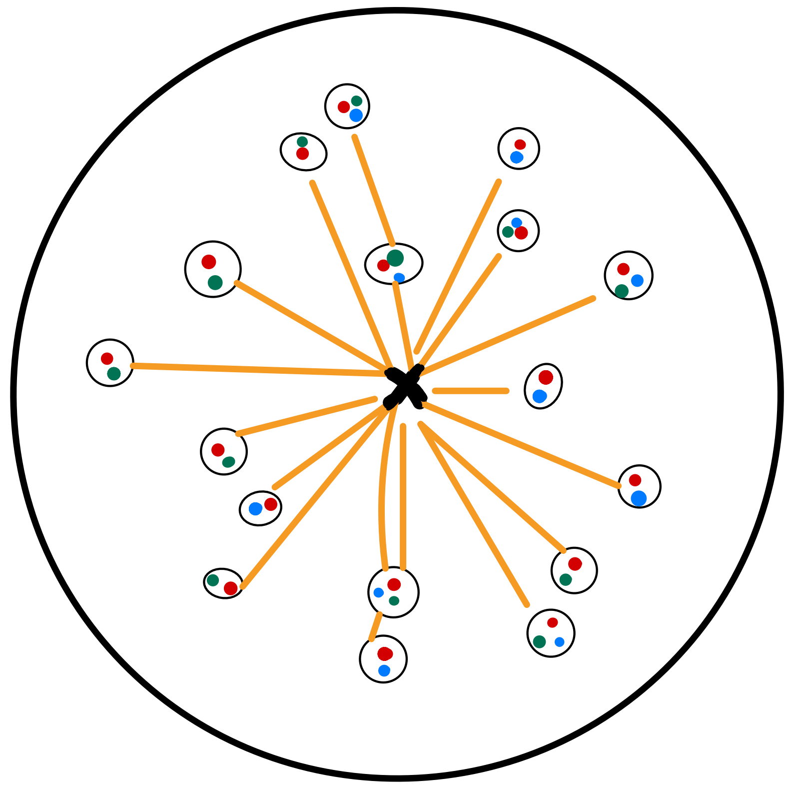
Jets inherit quantum property of partons

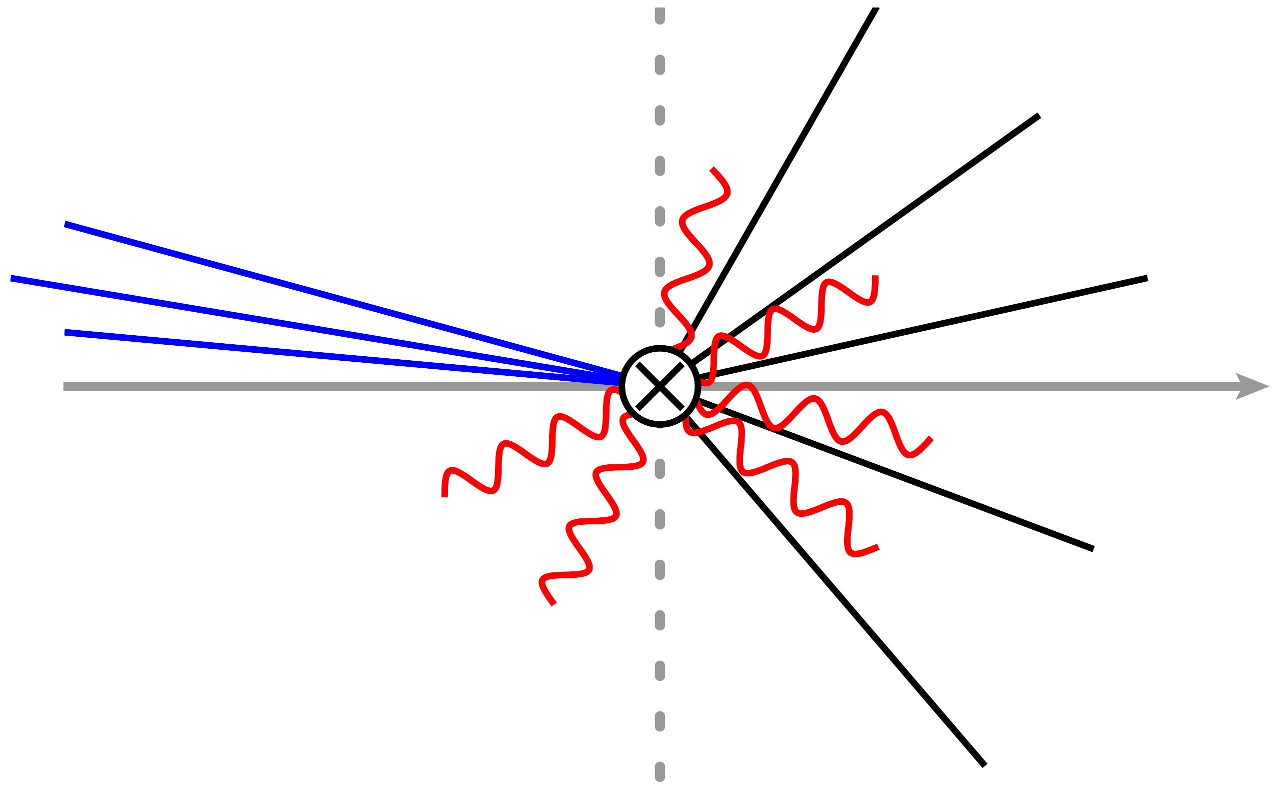
TMD factorization formula on the jet broadening

(Becher, Rahn, DYS '17 JHEP)

Definition of the broadening:

$$b_N = \sum_{i \in \text{jets}} |\vec{p}_i^{\,\perp}|$$





Construction of the theory formalism $b_N \ll Q$

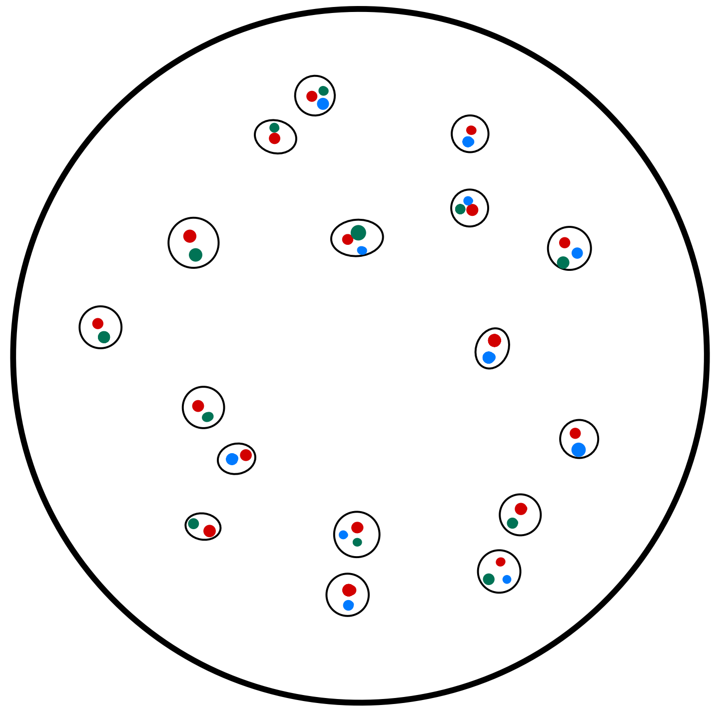
- **Two scales in the problem**
- **Rely on effective field theory: SCET + Jet Effective Theory** (Becher, Neubert, Rothen, DYS '16 PRL)

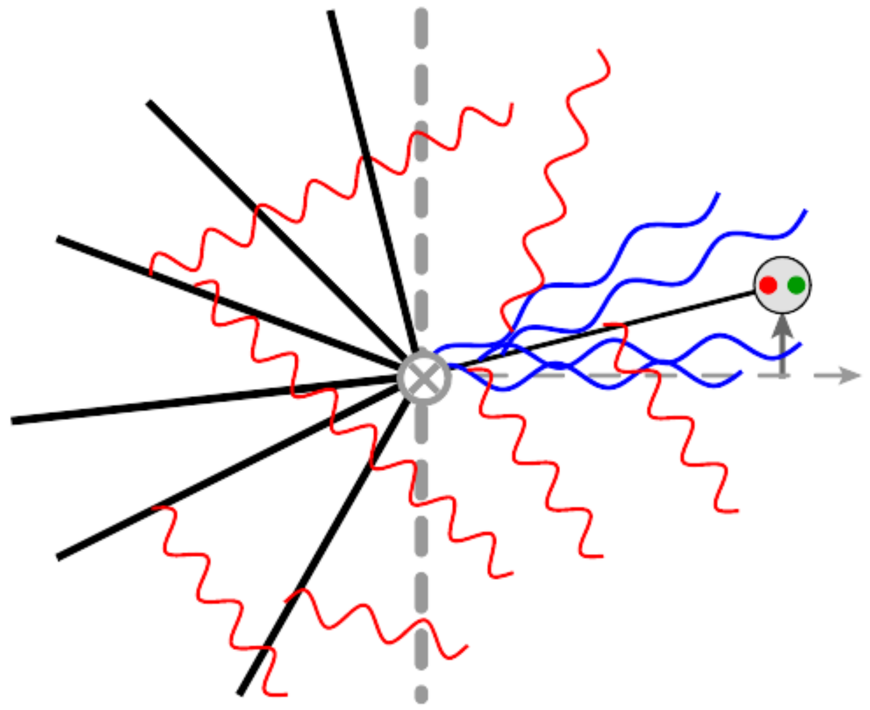
$$\frac{d\sigma}{db_N} = \sum_{f=q,\bar{q},g} \int db_N^s \int d^{d-2}p_N^\perp \mathcal{J}_f\left(b_N - b_N^s, p_N^\perp\right) \sum_{m=1}^{\infty} \langle \mathcal{H}_m^f(\{\underline{n}\}, Q) \otimes \mathcal{S}_m\left(\{\underline{n}\}, b_N^s, -p_N^\perp\right)\rangle$$

Rapidity divergence cancellation is verified at two-loop order !!!

Factorization on single hadron unpolarized TMDs

(Kang, DYS, Zhao '20 JHEP)





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

collinear: $p_c \sim Q(\lambda^2,1,\lambda)$

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

$$\lambda = j_T/Q \ll 1$$

TMD factorization formula:

TMDFFs

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

"Multi-Wilson-line structure" Becher, Neubert, Rothen, DYS '16 PRL,…

A similar structure is also mentioned in Boglione & Simonelli '20 within the CSS framework

All-order resummation formula:

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

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: $j_T \sim \Lambda_{\rm QCD}$

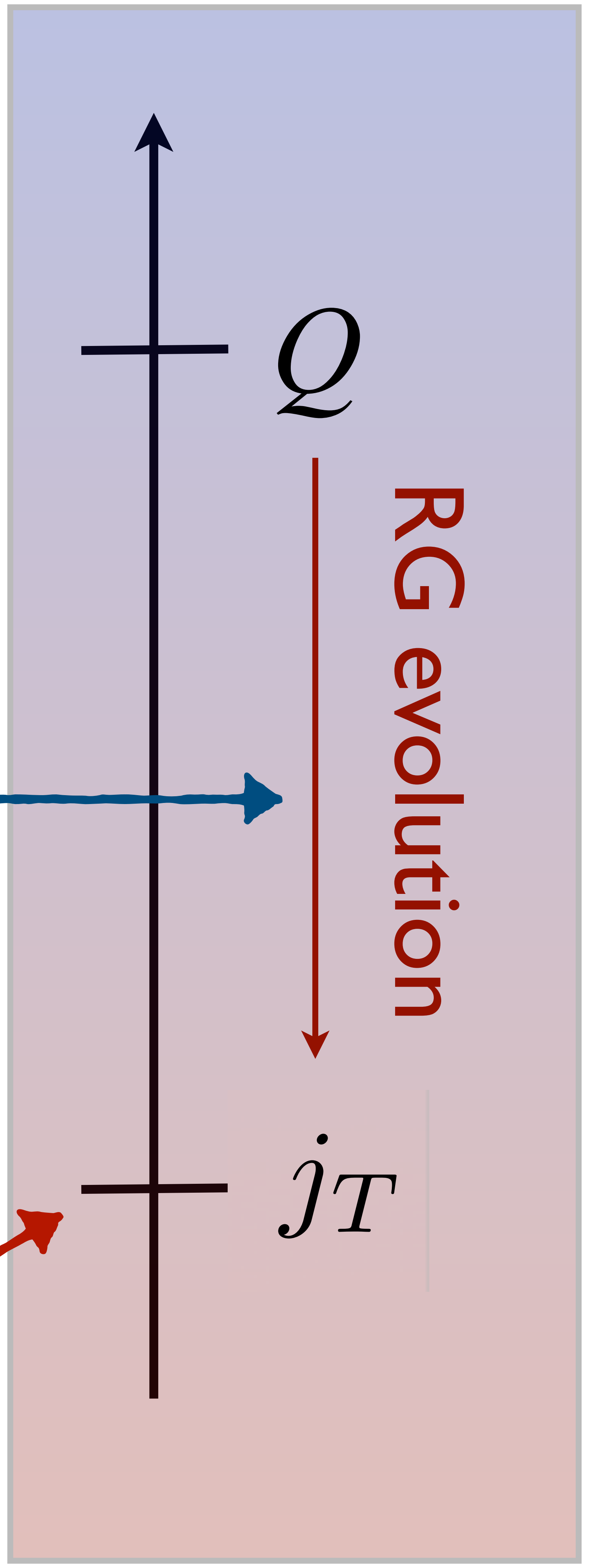
$S_{\rm NP}(b,Q_0,Q) = \frac{g_2}{2}\ln\left(\frac{b}{b_*}\right)\ln\left(\frac{Q}{Q_0}\right) + \frac{g_h}{z_h^2}b^2$ **fitted in standard TMD processes**

Sun,Isaacson,Yuan,Yuan '14

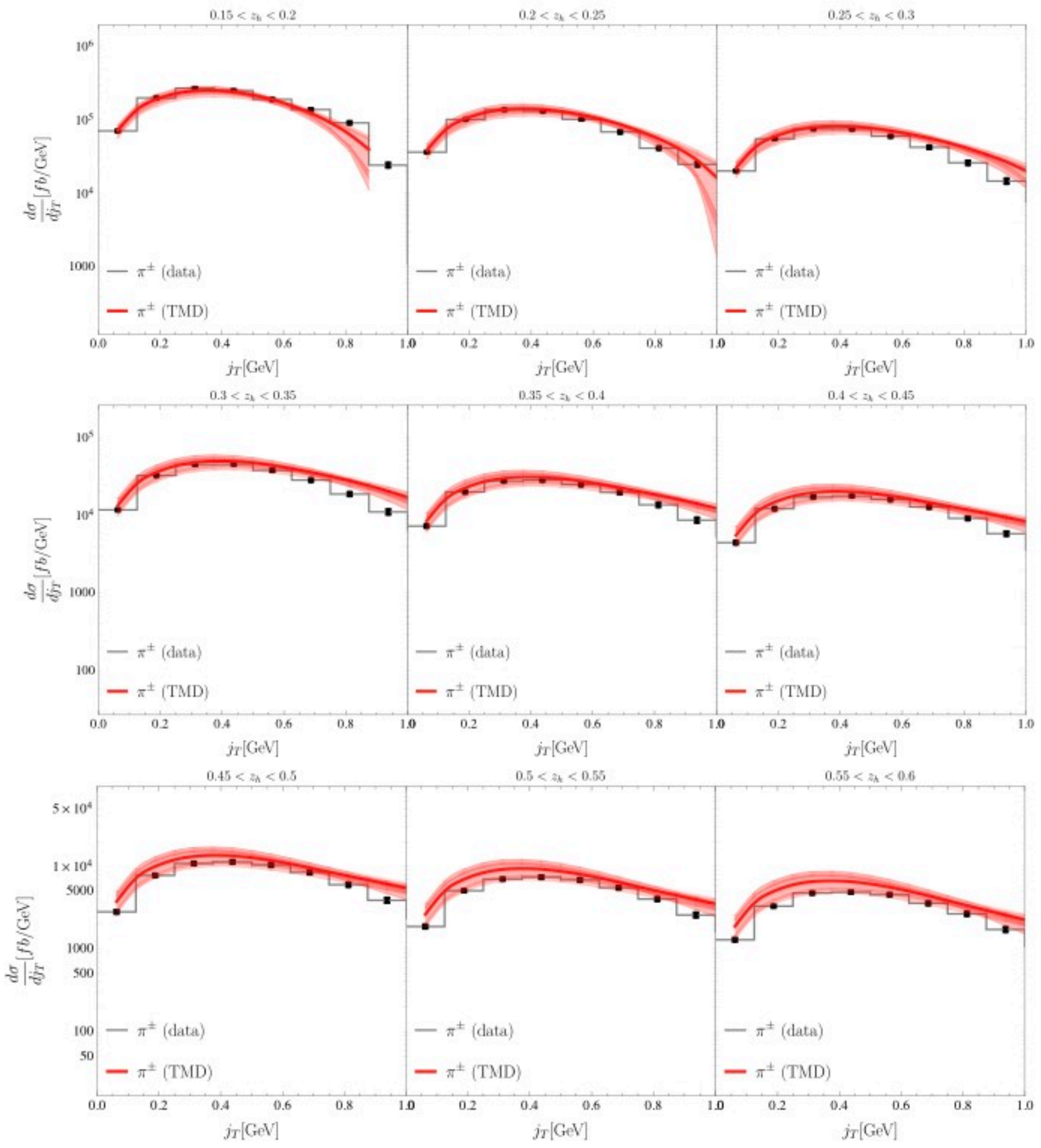
also see Yibo Yang's talk on LQCD predictions

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

de Florian, *et.al.* '15

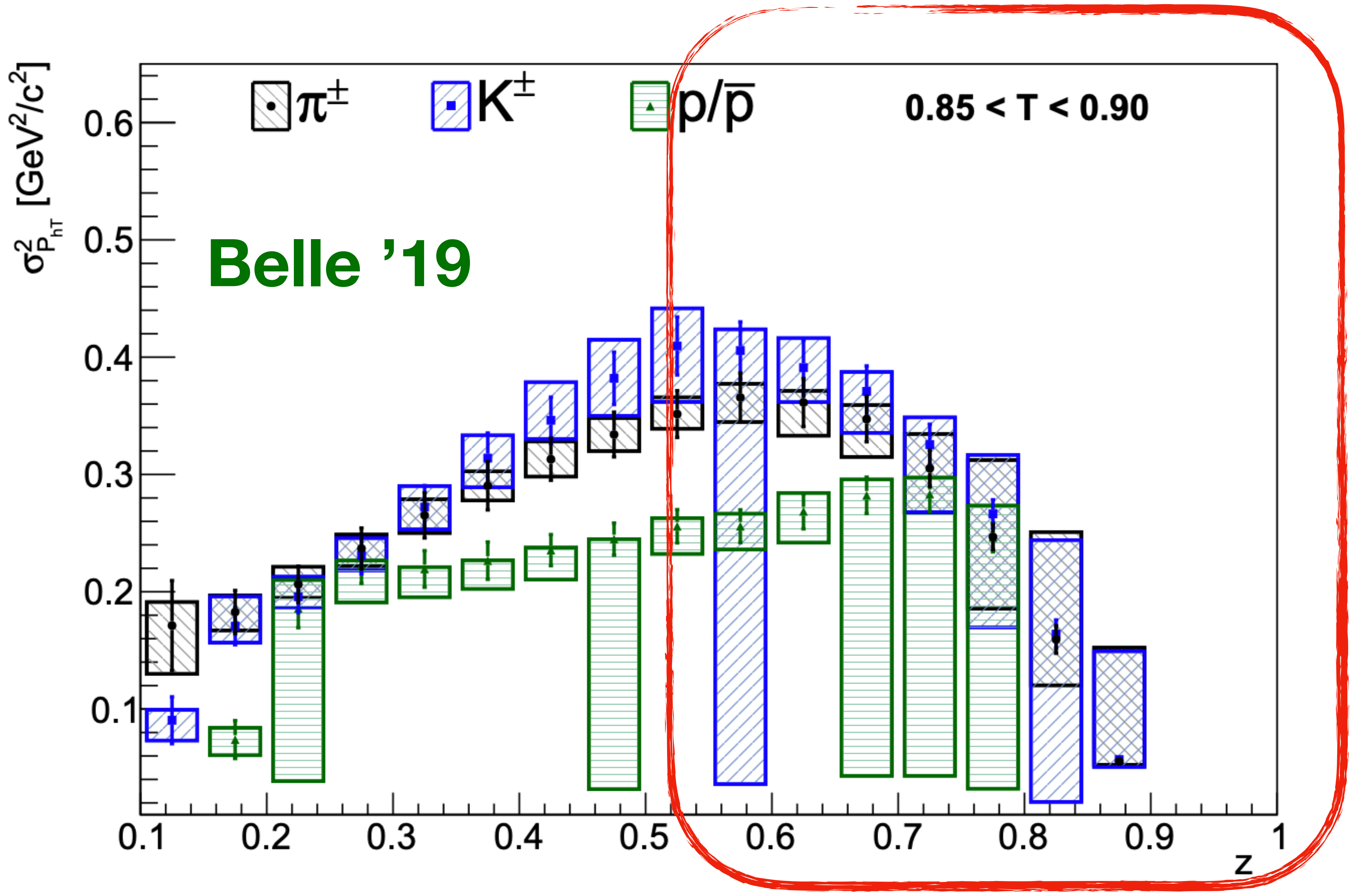


Numerical results

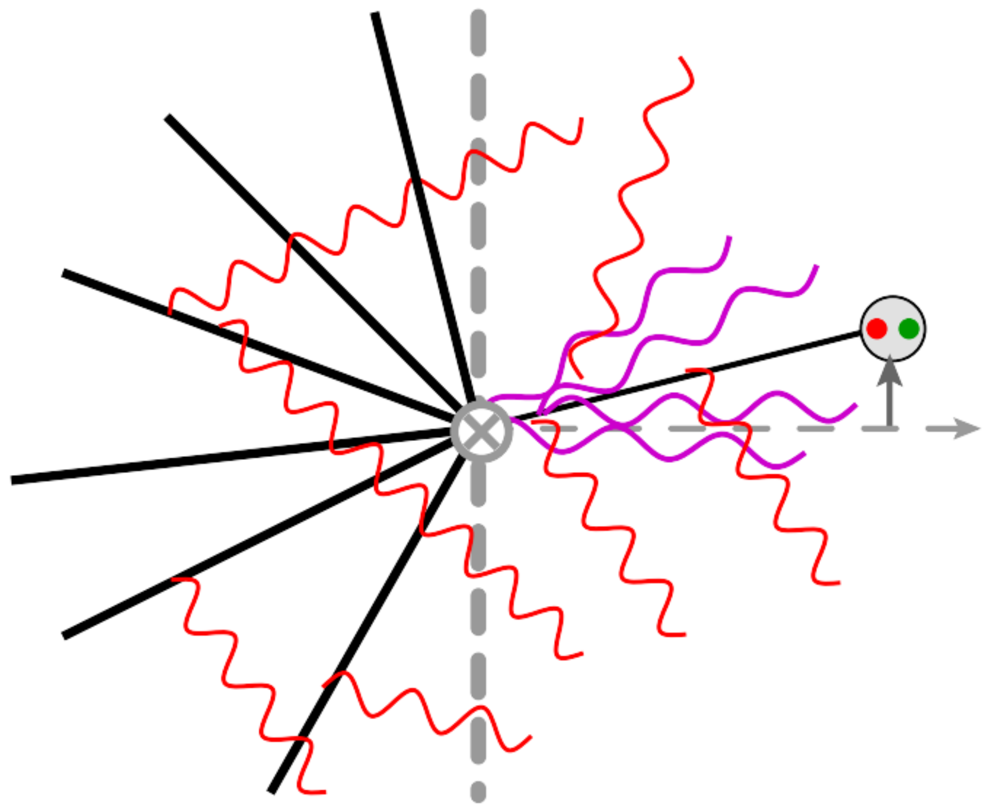


- **Our TMD resummation formula gives a good description of the shape of j_T distribution as $z_h < 0.65$**
- **As $z_h > 0.65$, one needs to also include threshold resummation effects**

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



Joint threshold and TMD factorization

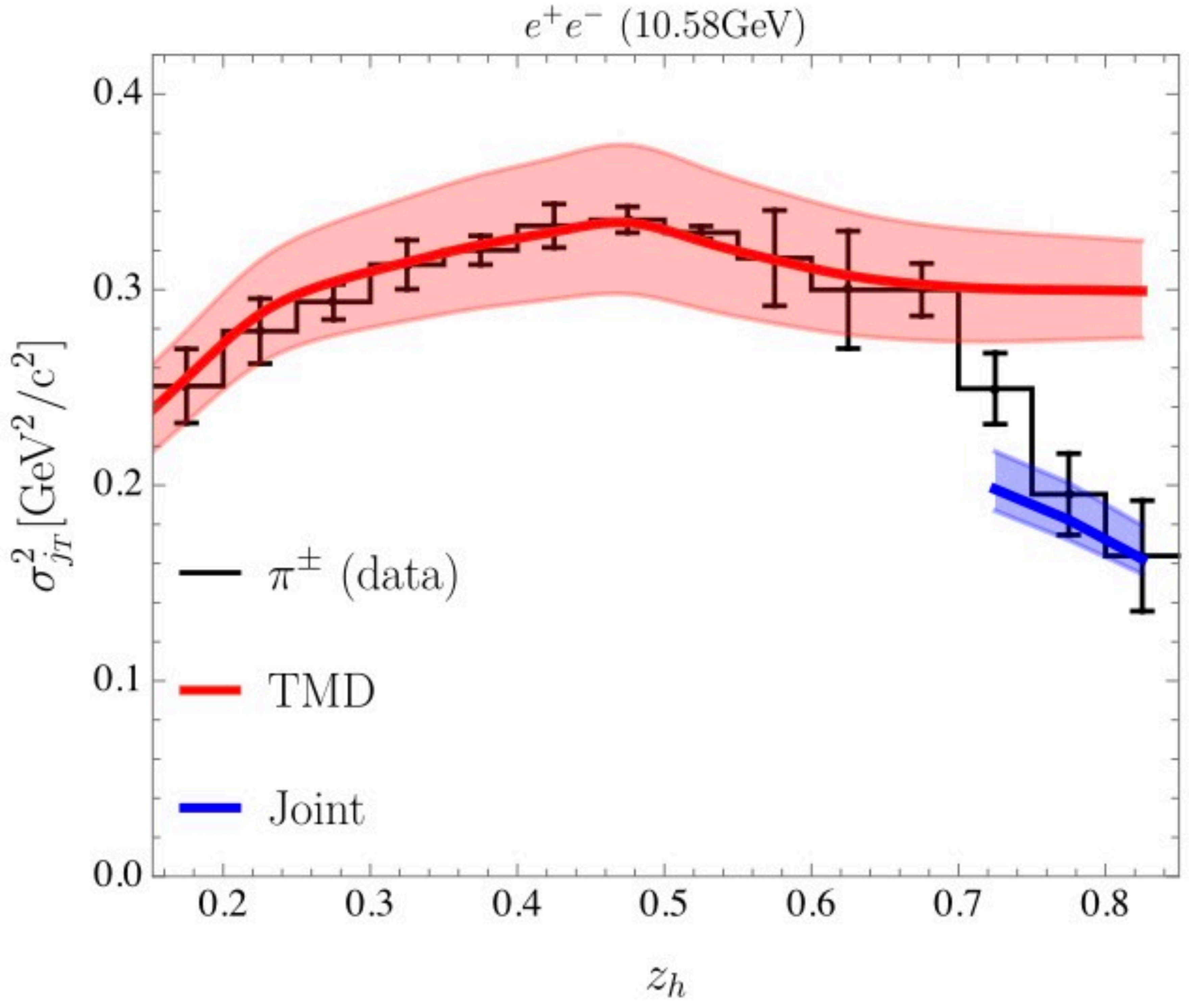


Joint factorization: $z_h \to 1$ & $j_T \ll Q$

Resummation formula:

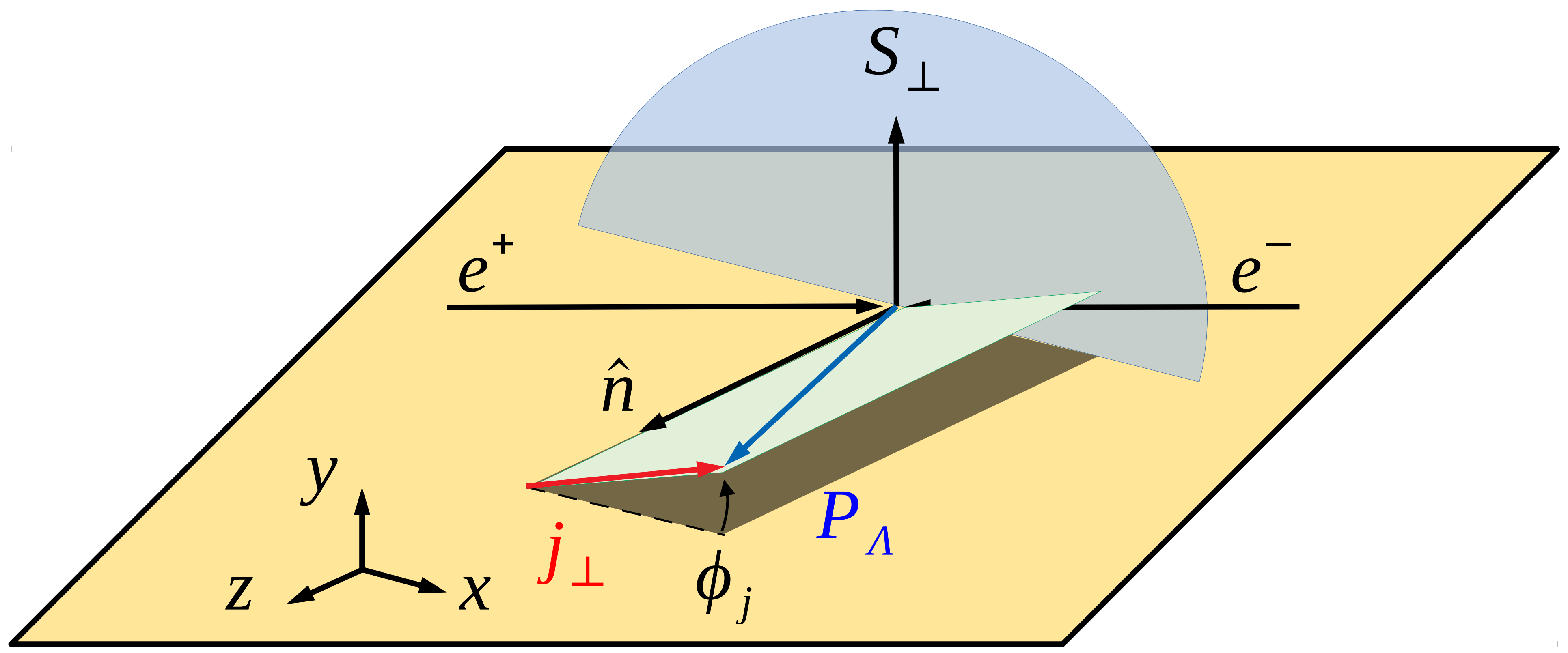
$$\frac{d\sigma}{dz_h d^2\vec{j}_T} = \sigma_0 \sum_{i=q,\bar{q}} \int_0^\infty \frac{b\,db}{2\pi} J_0(bj_T/z_h) \frac{1}{z_h^2} \int_{z_h}^1 \frac{dz}{z} e^{-\hat{S}_{\rm pert}(\mu_{b*},\mu_h) - \hat{S}_{\rm NP}(b,Q_0,Q)} \frac{e^{-2\gamma_E \eta}}{\Gamma(2\eta)} \frac{1}{1-z} D_{h/i}(z_h/z,\mu_h)\,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

- **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**



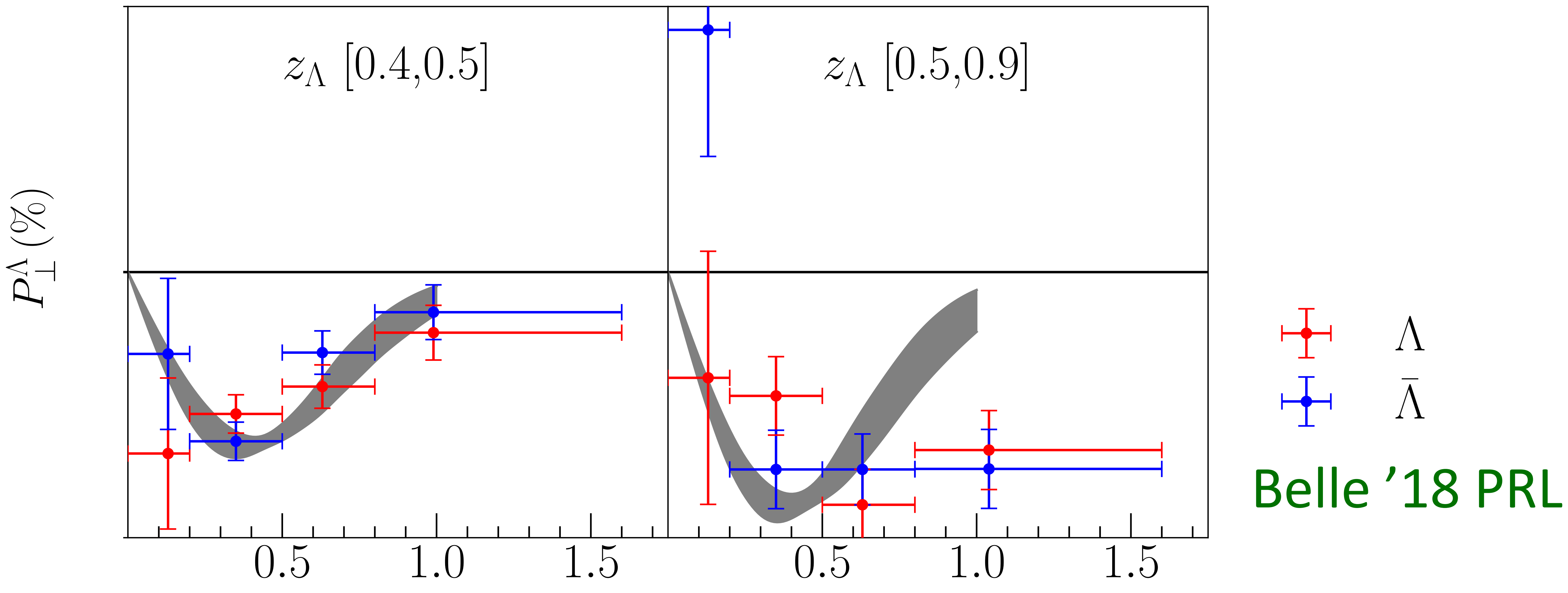
Factorization on transverse polarized Λ hyperon production with the thrust axis

Gamberg, Kang, DYS, Terry, Zhao 2101.XXXXX



$$P_\perp^\Lambda(z_\Lambda, j_\perp) = \frac{d\Delta\sigma}{dz_\Lambda d^2\boldsymbol{j}_\perp} \Big/ \frac{d\sigma}{dz_\Lambda d^2\boldsymbol{j}_\perp}$$

Theory predictions are consistent with Belle data

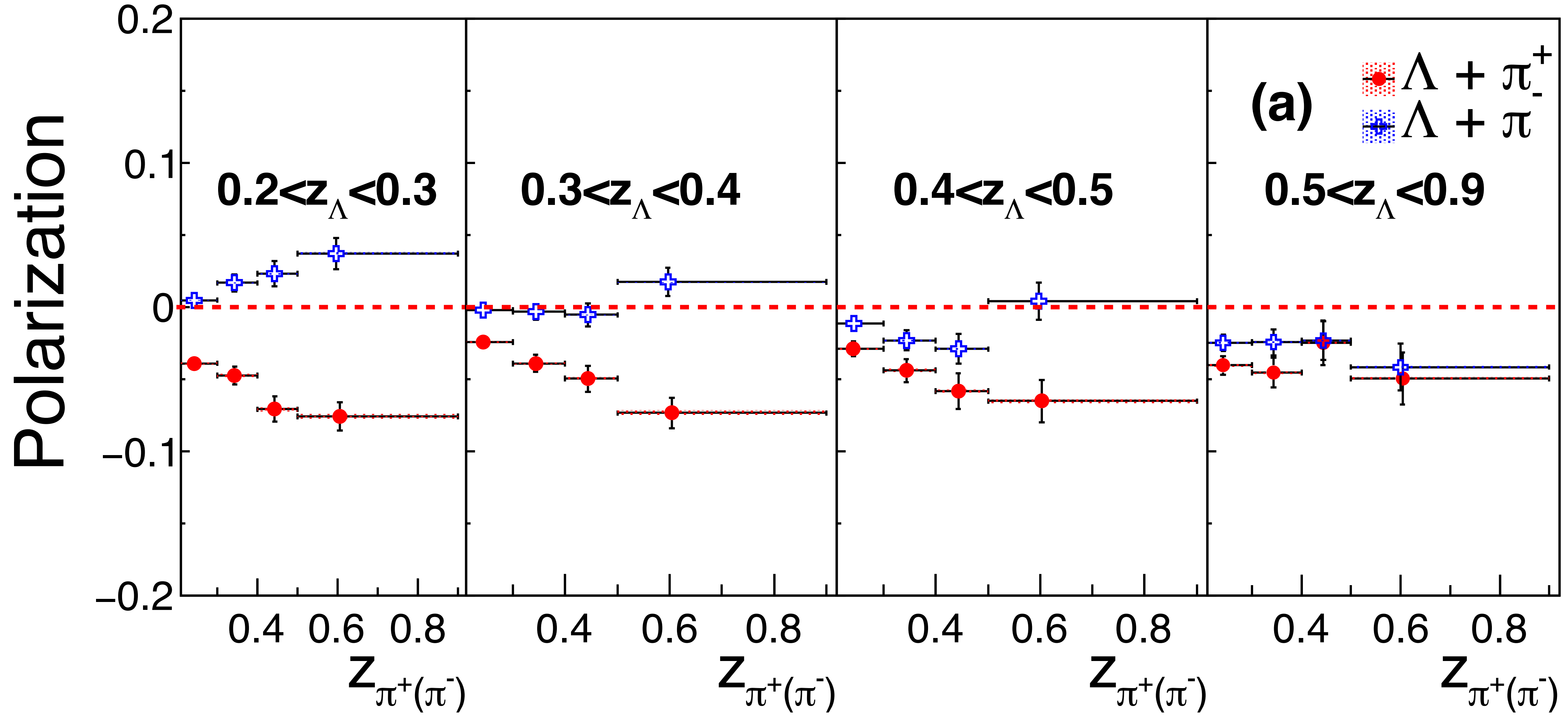


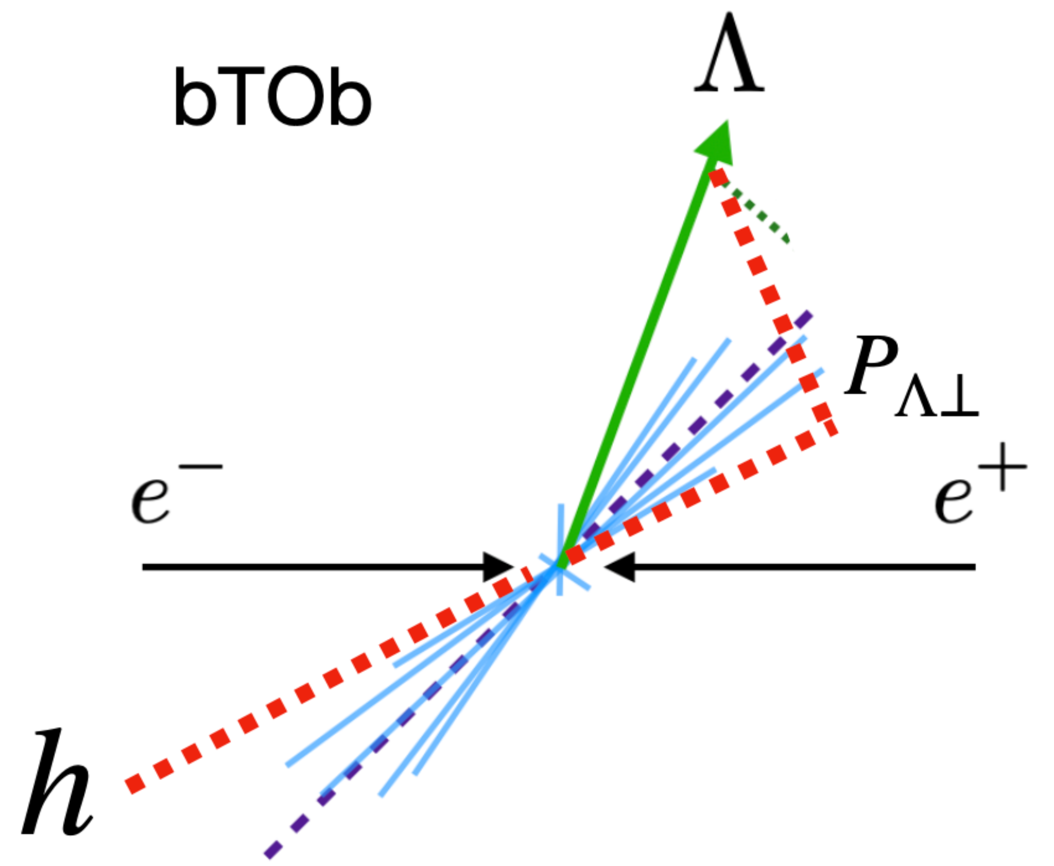
Theory formula including QCD evolution

$$\frac{d\Delta\sigma}{dz_\Lambda d^2 j_\perp} = \frac{d\sigma\left(\boldsymbol{S}_\perp\right)}{dz_\Lambda d^2\boldsymbol{j}_\perp} - \frac{d\sigma\left(-\boldsymbol{S}_\perp\right)}{dz_\Lambda d^2\boldsymbol{j}_\perp}$$
$$= \sigma_0 \sin\left(\phi_s - \phi_j\right) \sum_q e_q^2 \int_0^\infty \frac{b^2 db}{2\pi} J_1\left(\frac{b j_\perp}{z_\Lambda}\right)$$
$$\times \frac{M_\Lambda}{z_\Lambda^2} D_{1T,\Lambda/q}^{\perp(1)}\left(z_\Lambda, \mu_{b_*}\right) e^{-S_{\rm NP}^\perp\left(b, z_\Lambda, Q_0', Q\right) - S_{\rm pert}\left(\mu_{b_*}, Q\right)}$$
$$\times U_{\rm NG}\left(\mu_{b_*}, Q\right)$$

Flavor separation of PFFs

Belle '18 PRL

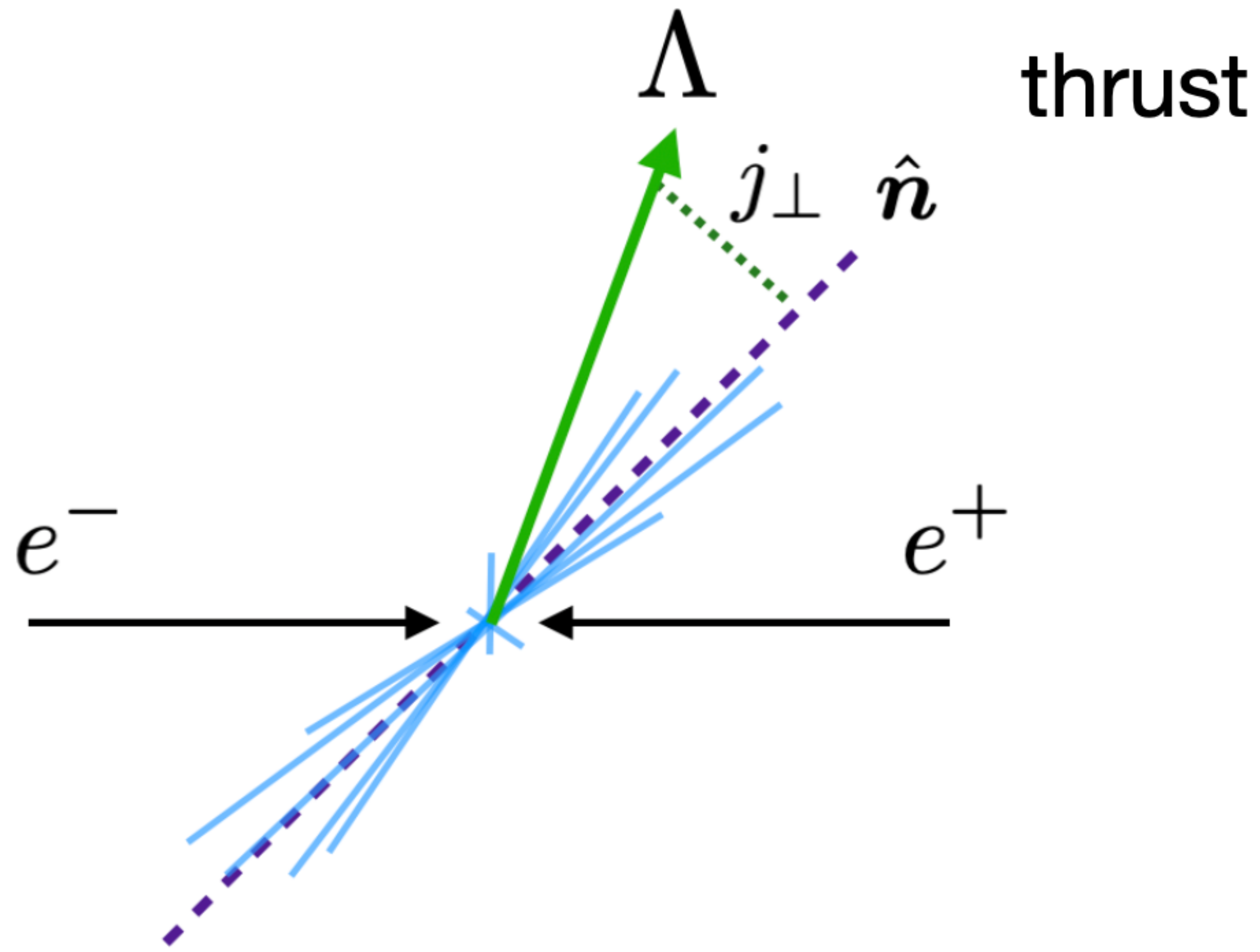




Jets inherit quantum property of partons !!!

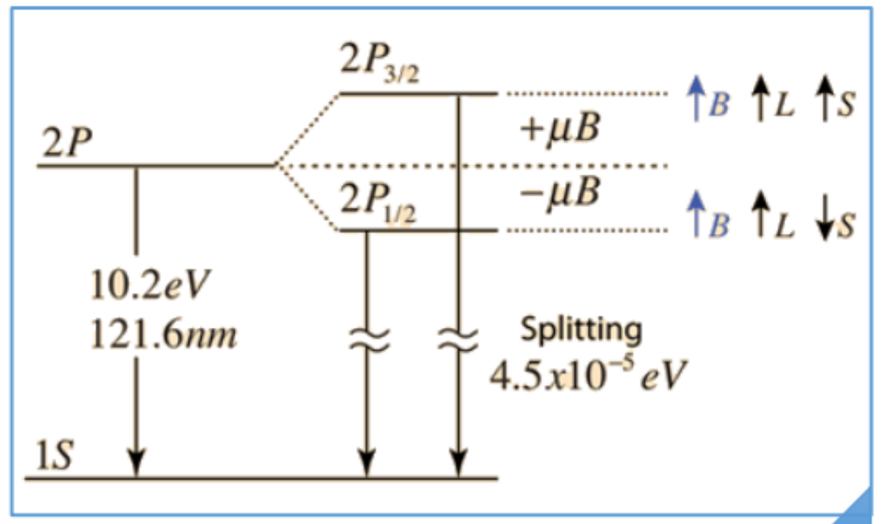
↓

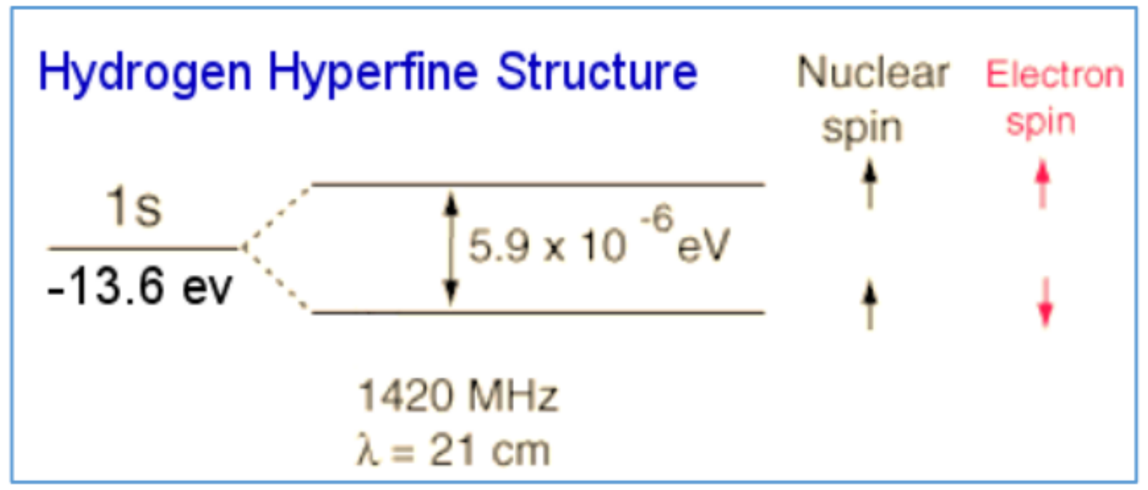
Jet substructure



Why spectroscopy—Atomic

We need high precision





$$\frac{1}{\lambda_{\text{vac}}} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

Rydberg formula

Fine structure

Hyperfine structure

Johannes Rydberg

Niels Henrik David Bohr

Edward W. Morley

Arnold Sommerfeld

Albert Abraham Michelson

Wolfgang Pauli

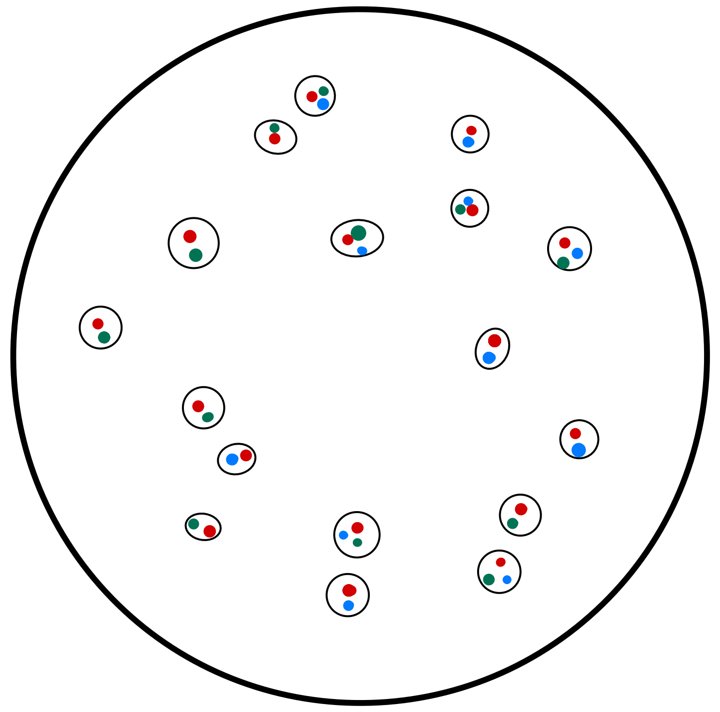
Lisheng Geng’s talk

Flavor separation and the jet electric charge

A PARAMETRIZATION OF THE PROPERTIES OF QUARK JETS *

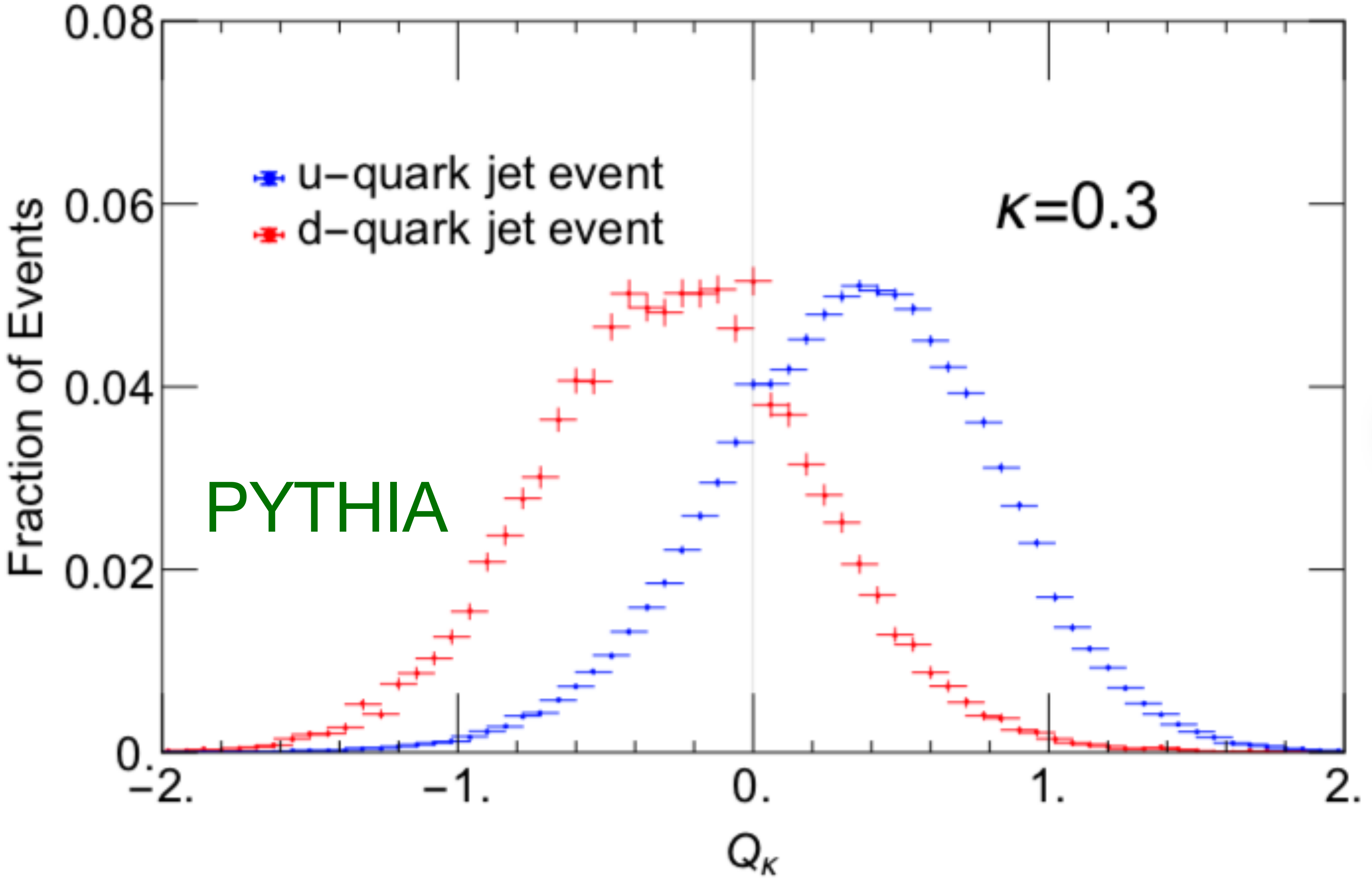
R.D. FIELD and R.P. FEYNMAN
California Institute of Technology, Pasadena, California 91125, USA

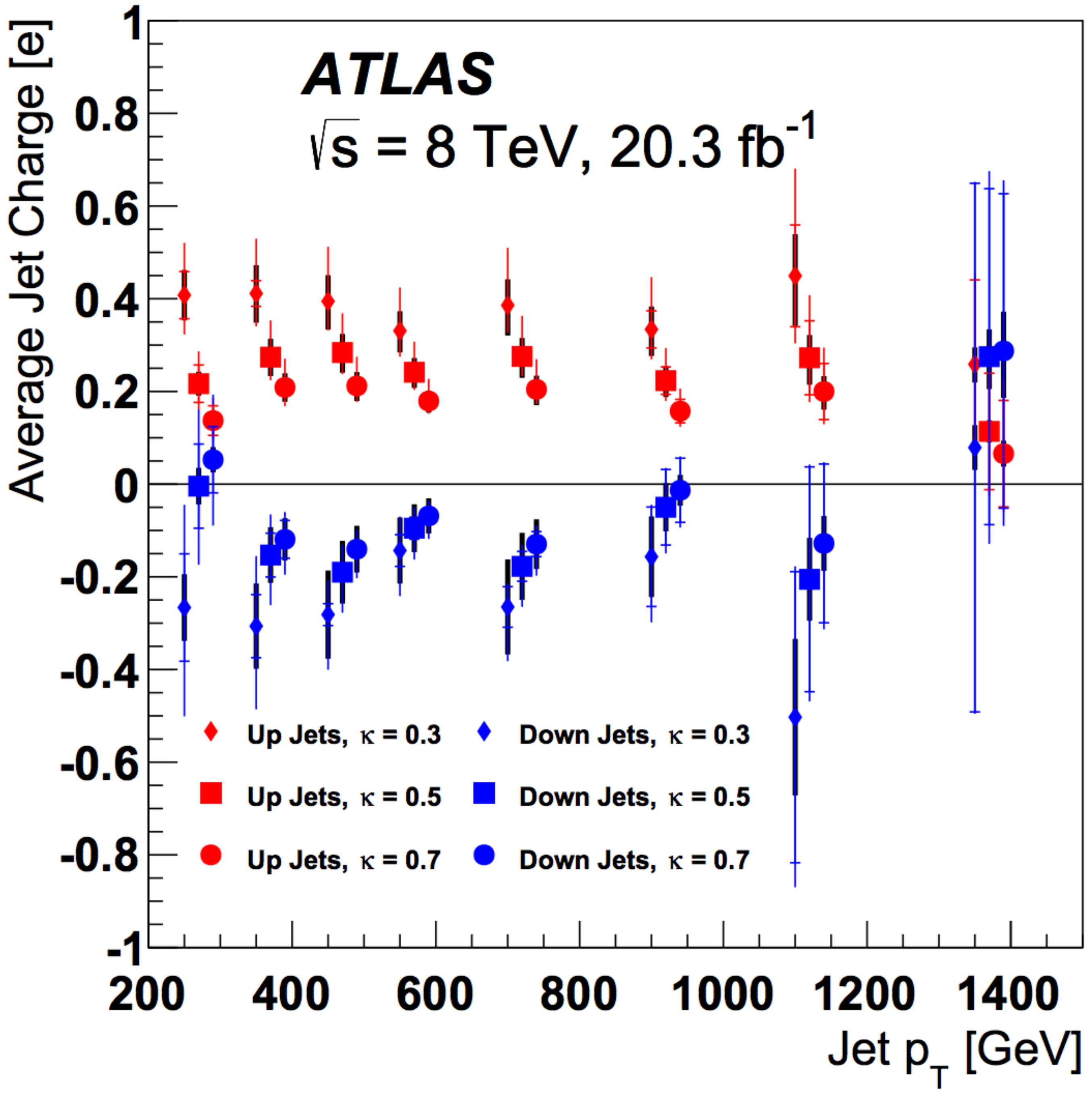
Received 11 October 1977



Definition:

$$Q_\kappa = \sum_i \left(\frac{p_{i,T}}{p_J}\right)^\kappa Q_i$$





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Jet Charge: A Flavor Prism for Spin Asymmetries at the Electron-Ion Collider

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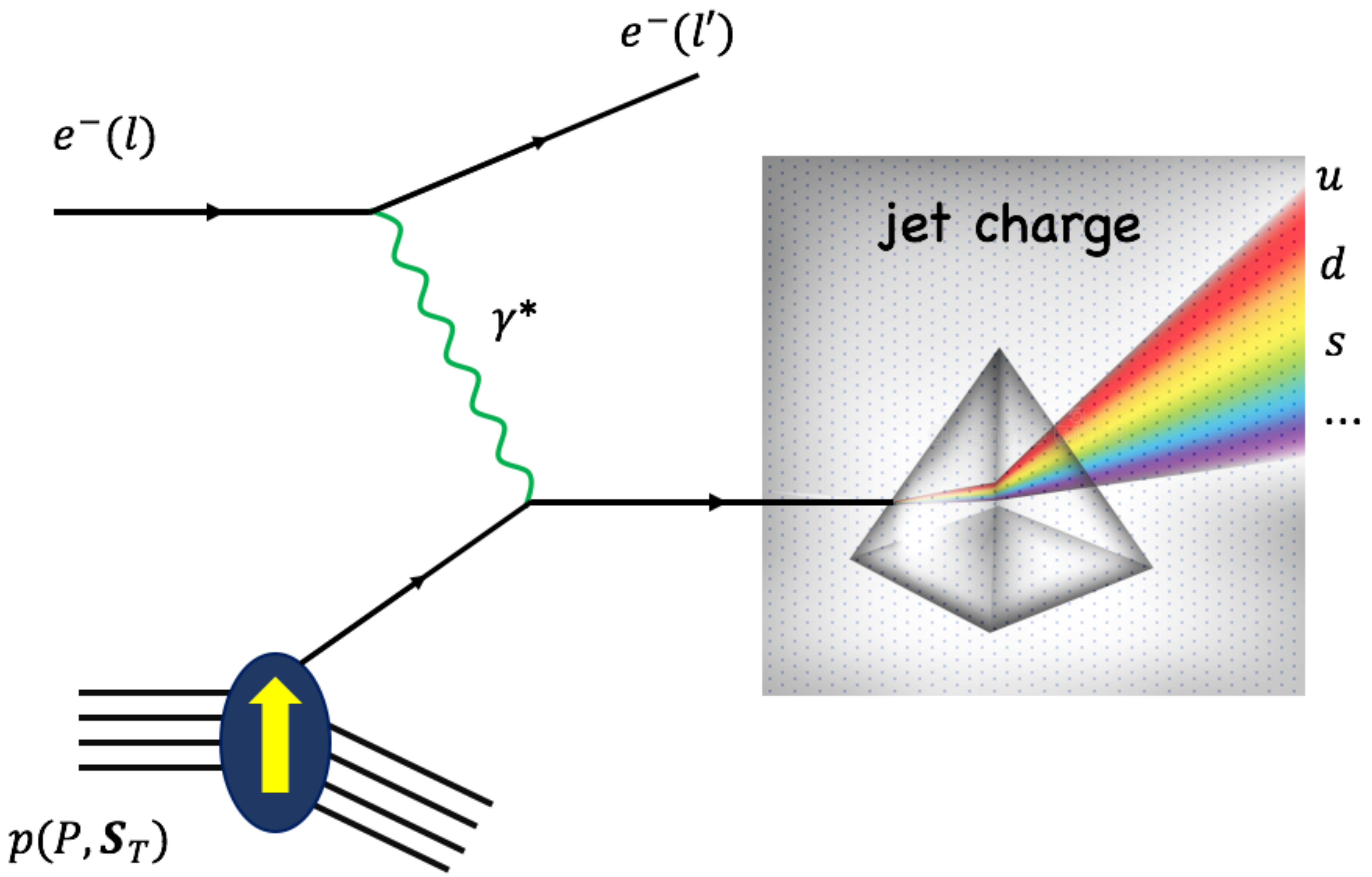

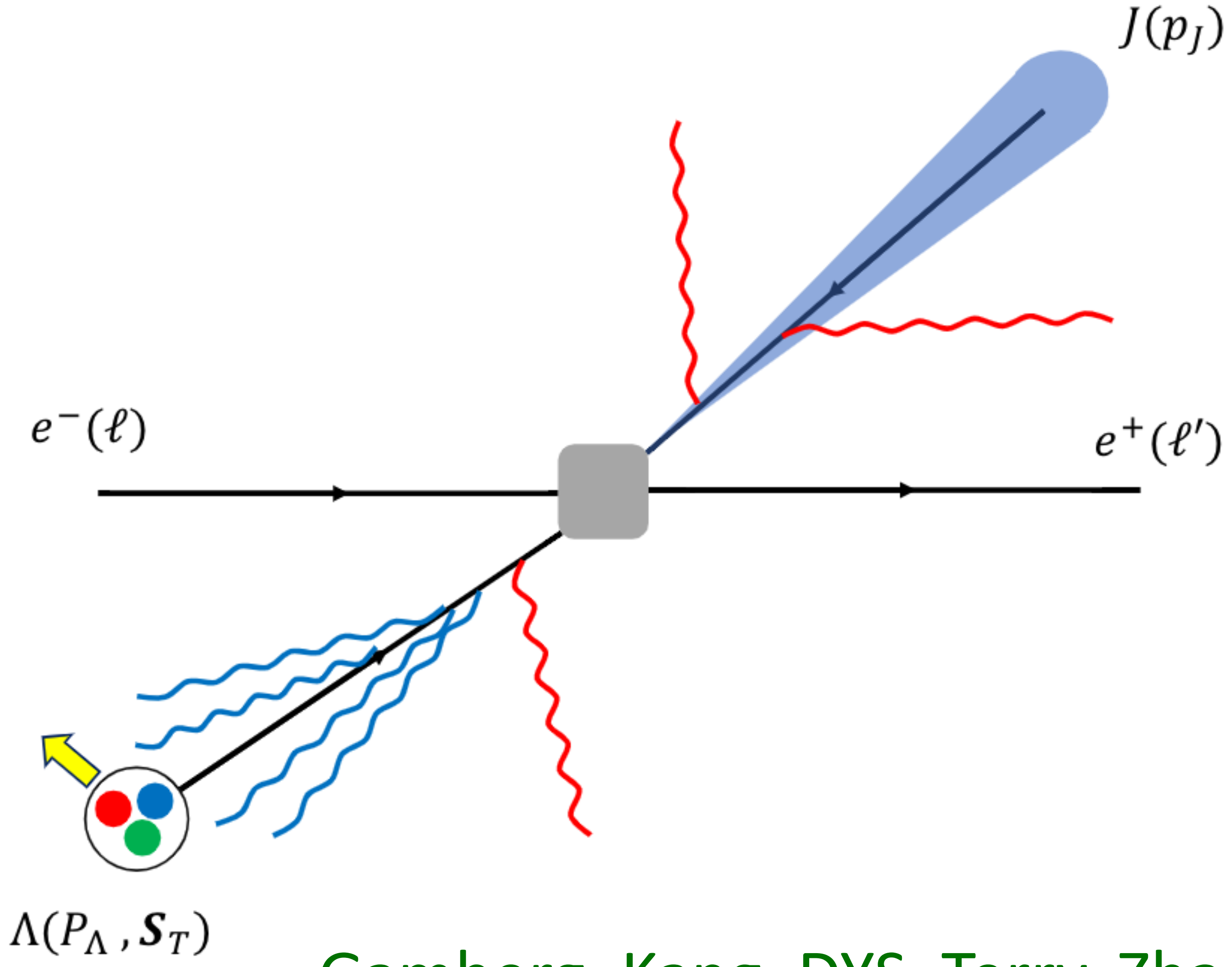

Gamberg, Kang, DYS, Terry, Zhao in progress

Summary and Outlook

- We develop the theory framework to study transverse polarization effects for Λ(thrust) production in e^+e^- collisions
  - EFT approach, model independent
  - TMD factorization formula, rapidity divergence is cancelled at two loop
  - Include QCD evolution (both linear and non-linear) from Q to $j_T \gtrsim \Lambda_{QCD}$
  - Our predictions are consistent with Belle data
  - Verify the universality of polarizing fragmentation function
  - We propose to use jet charge to separate different flavors of PFFs at the Belle
- Jets and jet substructures can be calculated in pQCD, which offer new opportunity to understand hadron structures

Thank you

Welcome to Fudan!!!

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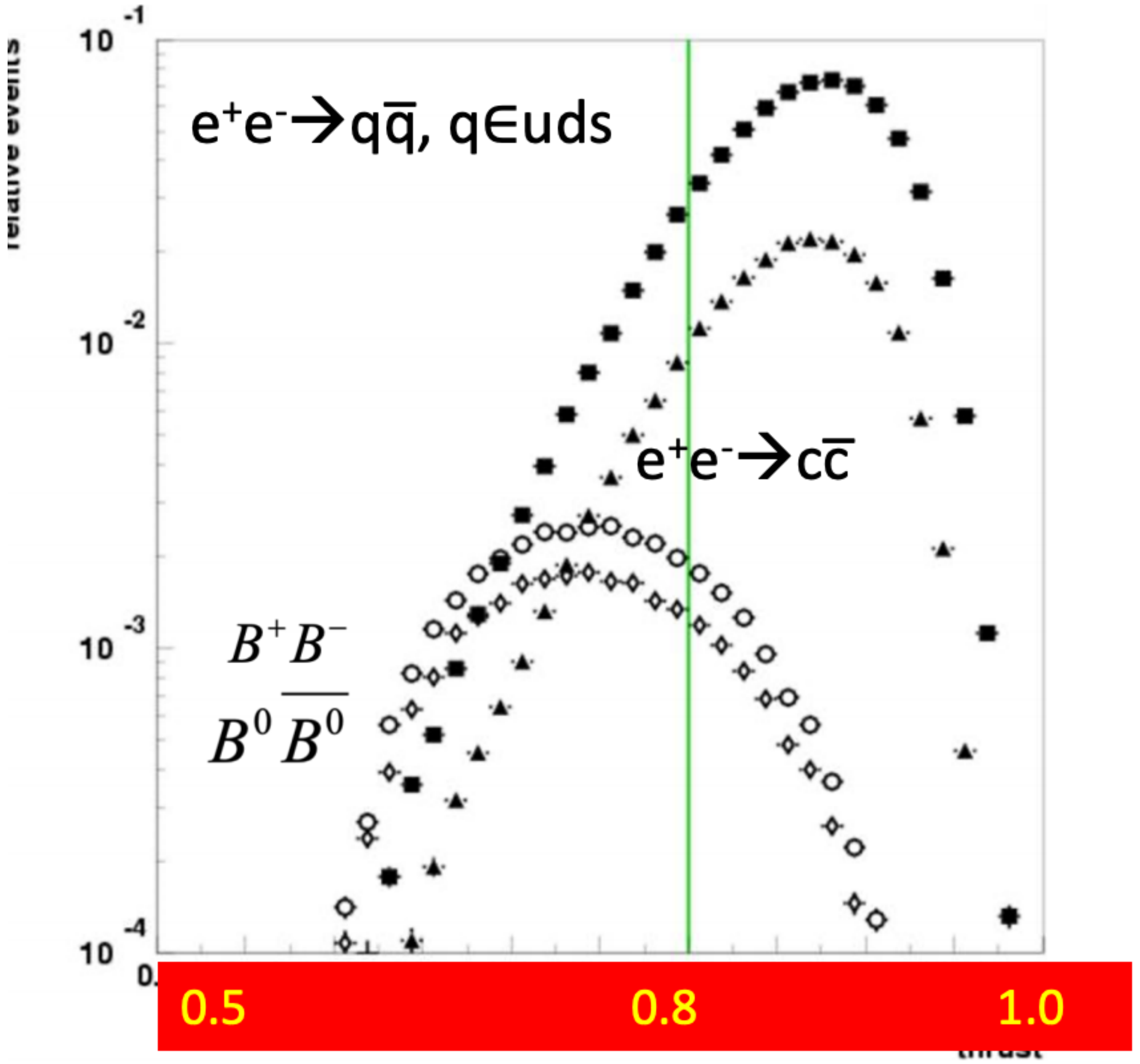
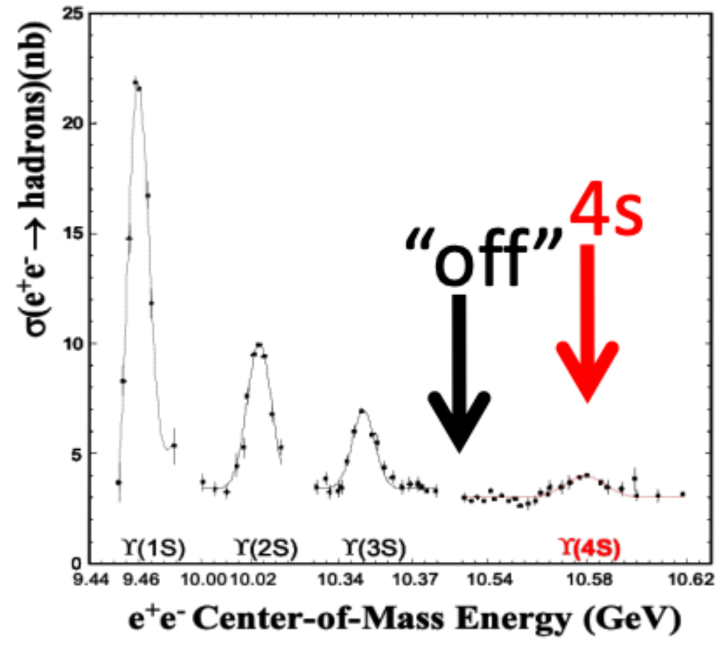
Backup

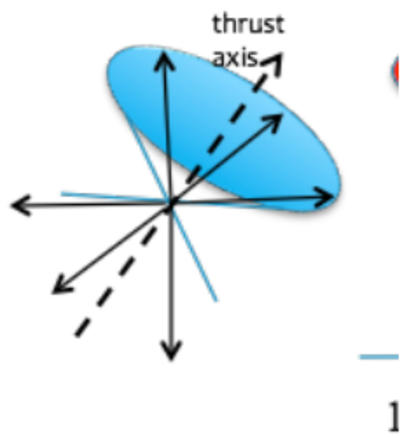
Lots of data off resonance, easy to remove resonance background



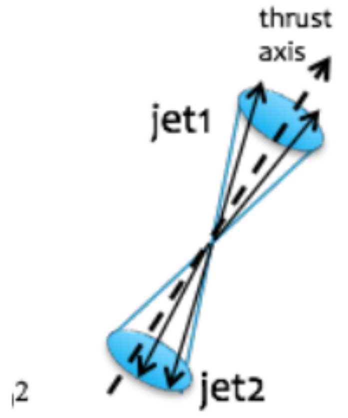
$$Thrust: T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$



- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under Υ (4S) resonance
- ~100 fb^{-1} ➔ ~1000 fb^{-1}

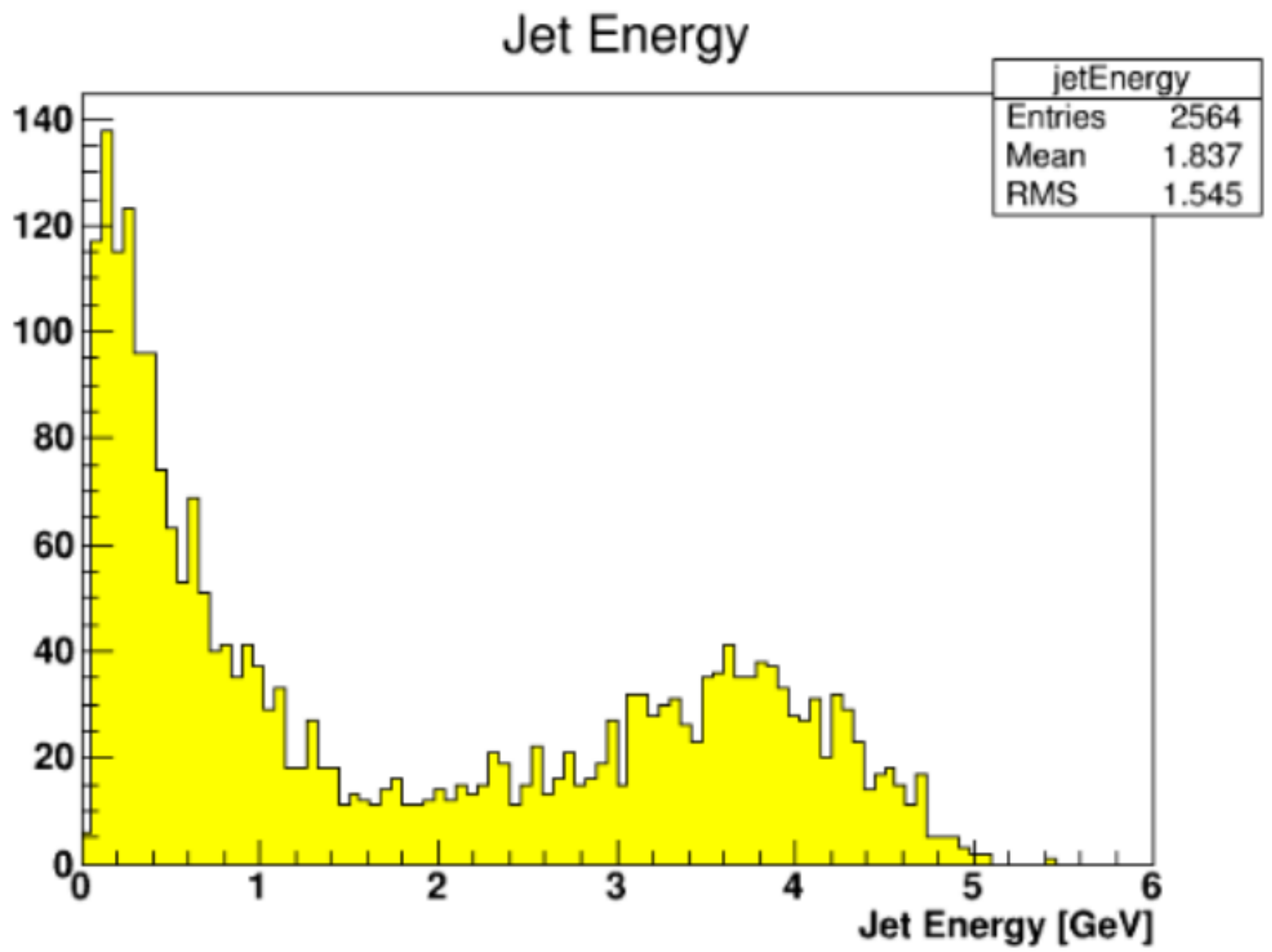


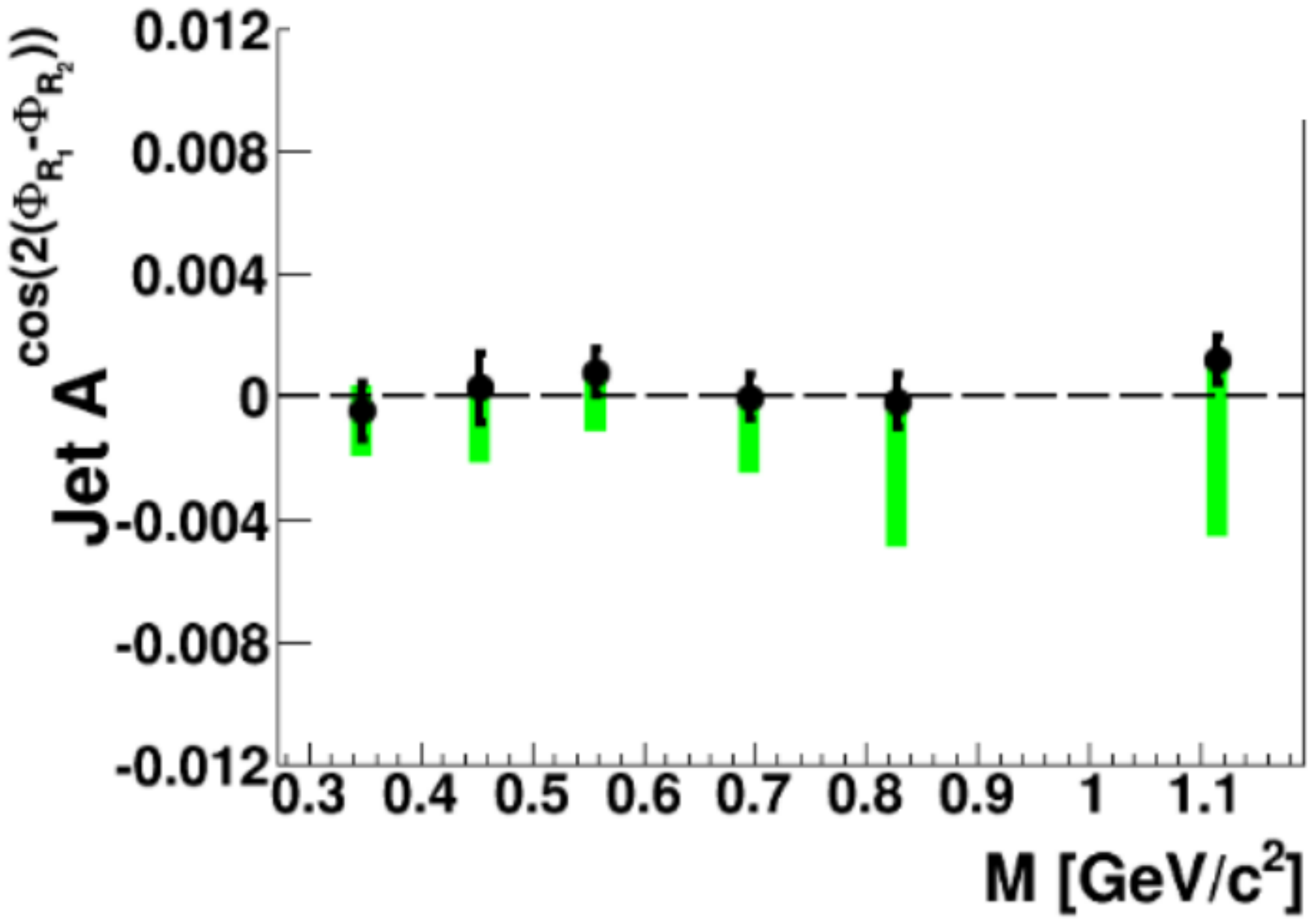
T~0.5

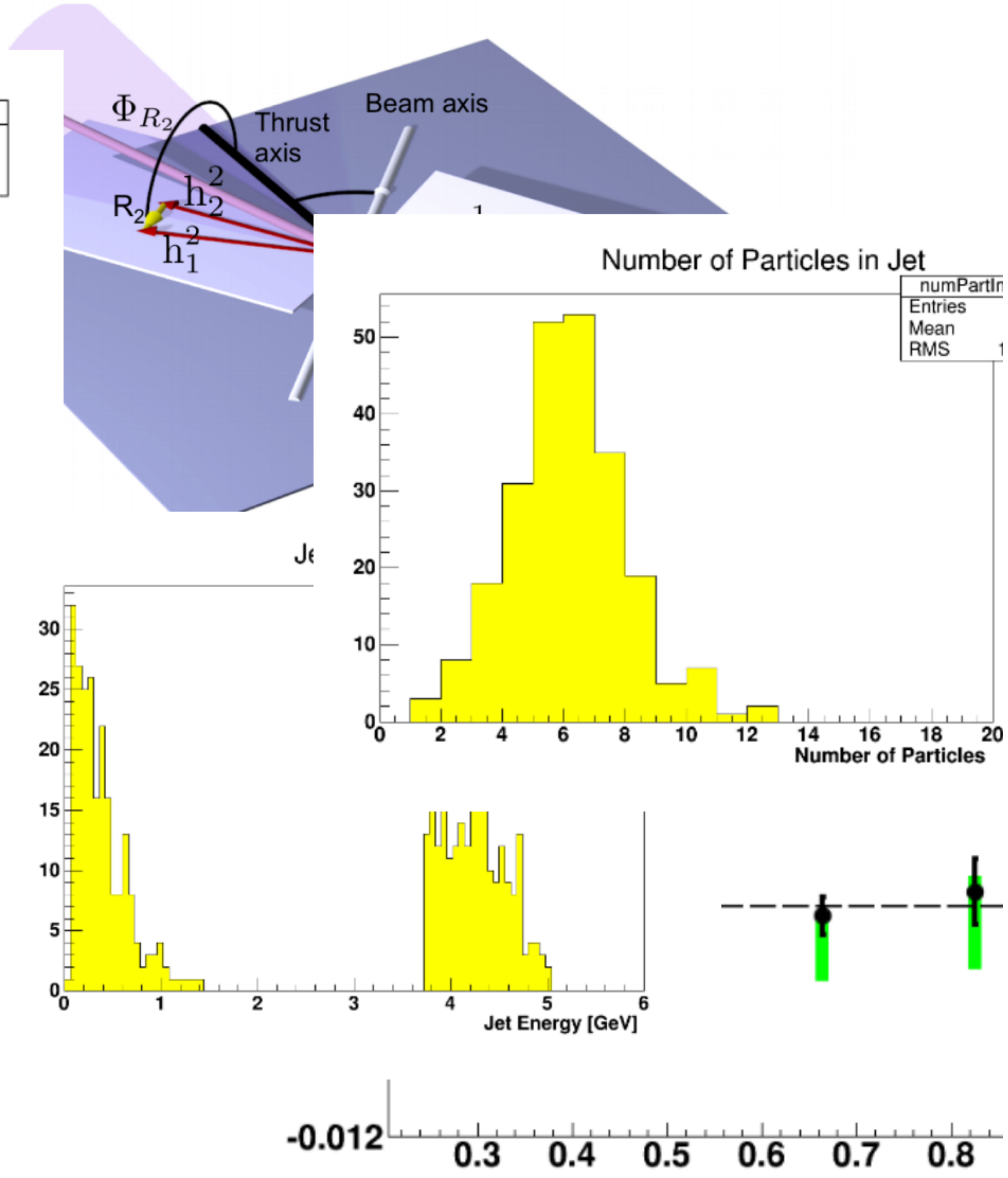


T~1

5


Jet Energy
jetEnergy
Entries 2564
Mean 1.837
RMS 1.545
Jet Energy [GeV]


Jet A$^{\cos(2(\Phi_{R_1}-\Phi_{R_2}))}$
M [GeV/c^2]


Φ_{R_2}
Thrust axis
Beam axis
R_2
h_2^2
h_1^2
Number of Particles in Jet
Entries
Mean
RMS
Number of Particles
Jet Energy [GeV]