$\Lambda^{\uparrow}$ Polarization in e^+e^- collisions

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arXiv:2102.05553

U.S. DEPARTMENT OF ENERGY | Office of Science

TMD Collaboration

Outline

- Motivation to study on $\Lambda^{\uparrow}$ physics long standing challenge describe via QCD factz.
- Review "outsized" role of Lambda in studying TSSAs look @ data
- Twist -2 TMD fact. description in terms of PFF. $D_{1T}^{\perp}(z, p_{\perp}, Q^2)$
  - ⋆ Thrust observable $\Lambda\,(\mathrm{Thrust}) + X$ $\quad e^+e^- \to \Lambda^{\uparrow}(\mathrm{Thrust})\,X$
  - ⋆ Back to back hadrons $h + \Lambda$ $\quad e^+e^- \to \Lambda^{\uparrow}\,h\,X$
- Inclusive process $e^+e^- \to \Lambda^{\uparrow}X$ possible & interesting to process to study
- Twist -3 fact. description in terms of $D_T(z, Q^2)$

✱ Change of ref frame COM of e^+e^- pair $\quad e^+e^- \to \Lambda^{\uparrow}X$

Test of naive time reversal in QCD

Dilemma

VOLUME 41, NUMBER 25 — PHYSICAL REVIEW LETTERS — 18 DECEMBER 1978

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)

We point out that the polarization P of a scattered or produced quark is calculable perturbatively in quantum chromodynamics for $e^+e^- \to q\bar{q}$, large-p_T hadron reactions, and large-Q^2 leptoproduction, and is infrared finite. The quantum-chromodynamics prediction is that $P=0$ in the scaling limit. Experimental tests are or will soon be possible in $pp \to \Lambda X$ [where presently $P(\Lambda) \simeq 25\%$ for $p_T > 2$ GeV/c] and in $e^+e^- \to$ quark jets.

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.

TMD factorization says otherwise:

Mulders Tangerman, NPB1996
Boer, Jakob, Mulders NPB1997, 2000
Anselmino Boer, D'Alesio, Murgia. PRD 2001, 2002
Boer, Kang, Vogelsang, Yuan, PRL 2010

Measurement of Lambda-polarization through weak decay $\Lambda^0 \to p\,\pi^-$

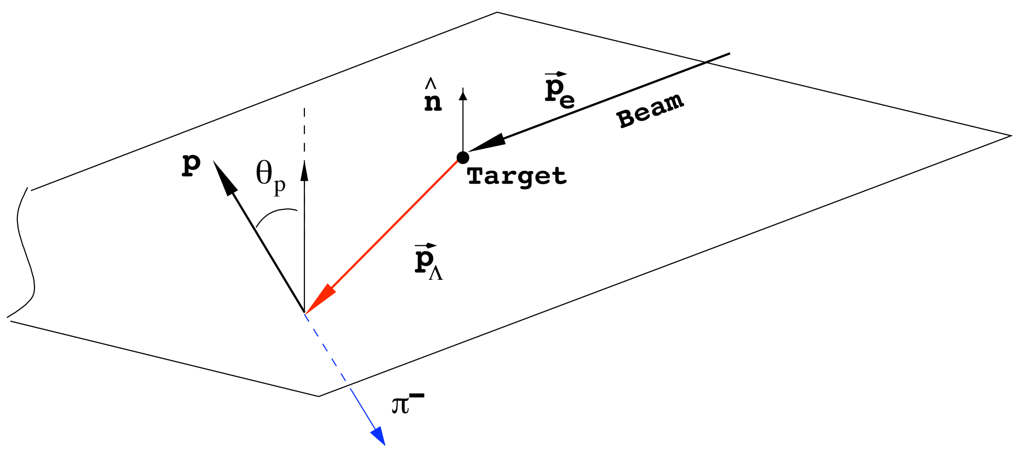


FIG. 1: Schematic diagram of inclusive Λ production and decay. The angle θ_p of the decay proton with respect to the normal $\hat{n}$ to the production plane is defined in the Λ rest frame.

- Proton preferentially emitted along Λ-spin
- In Λ rest frame: pol. decay distribution

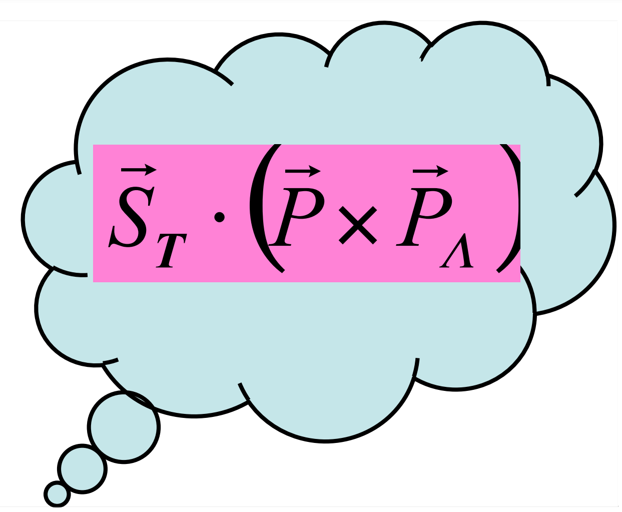
$$\left(\frac{dN}{d\Omega_p}\right)_{\text{pol}} = \left(\frac{dN}{d\Omega_p}\right)_{\text{unpol}} (1 + \alpha\, P_n^\Lambda \cos(\theta_p))$$

P^Λ: Transverse Lambda Polarization

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

QCD is Parity conserving so any final state hadron must be polarised perpendicular to the production plane

The Status of Transverse Spin Physics . . .



What does Exp Say …

$$pA \to \Lambda^{\uparrow} X$$

$$pp \to \Lambda^{\uparrow} X$$

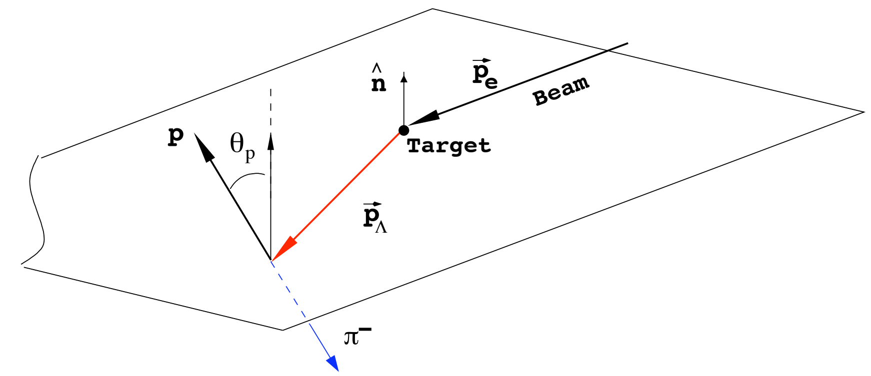


FIG. 1: Schematic diagram of inclusive Λ production and decay. The angle θ_p of the decay proton with respect to the normal $\hat{n}$ to the production plane is defined in the Λ rest frame.

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

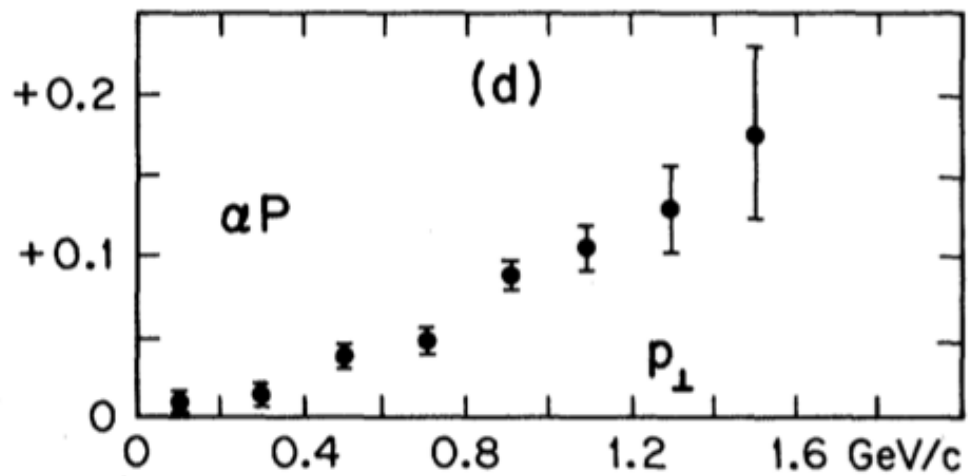
$$\gamma^* N \to \Lambda^{\uparrow} X$$ **HERMES**

$$e^+e^- \to \Lambda^{\uparrow} X$$

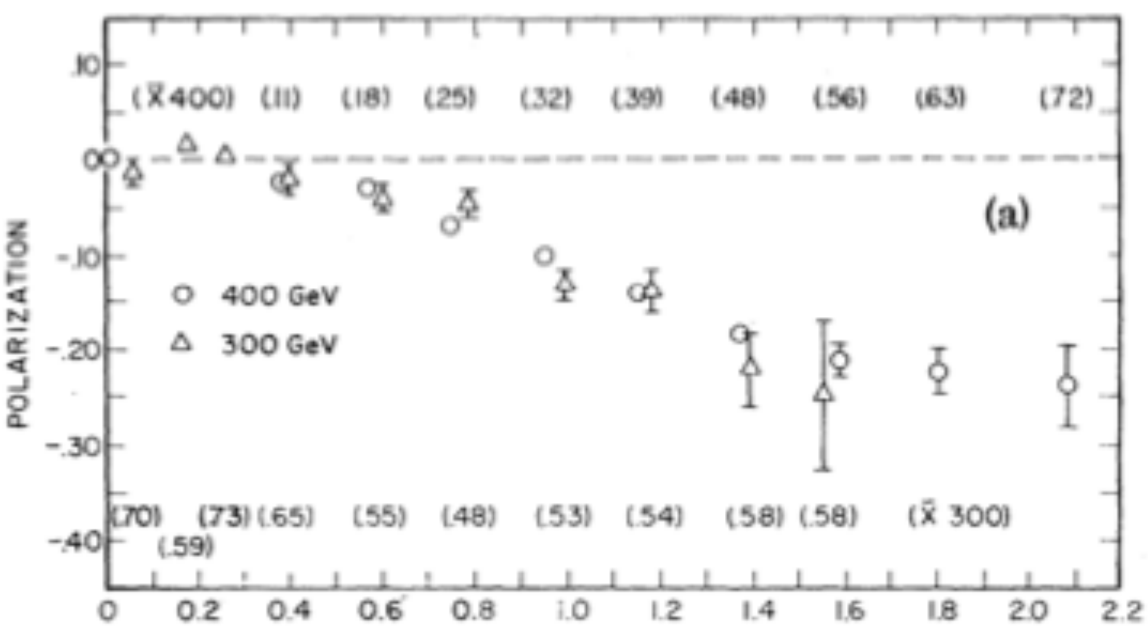
Transverse Λ polarisation a long history

$$p + Be \rightarrow \Lambda^{\uparrow} + X$$

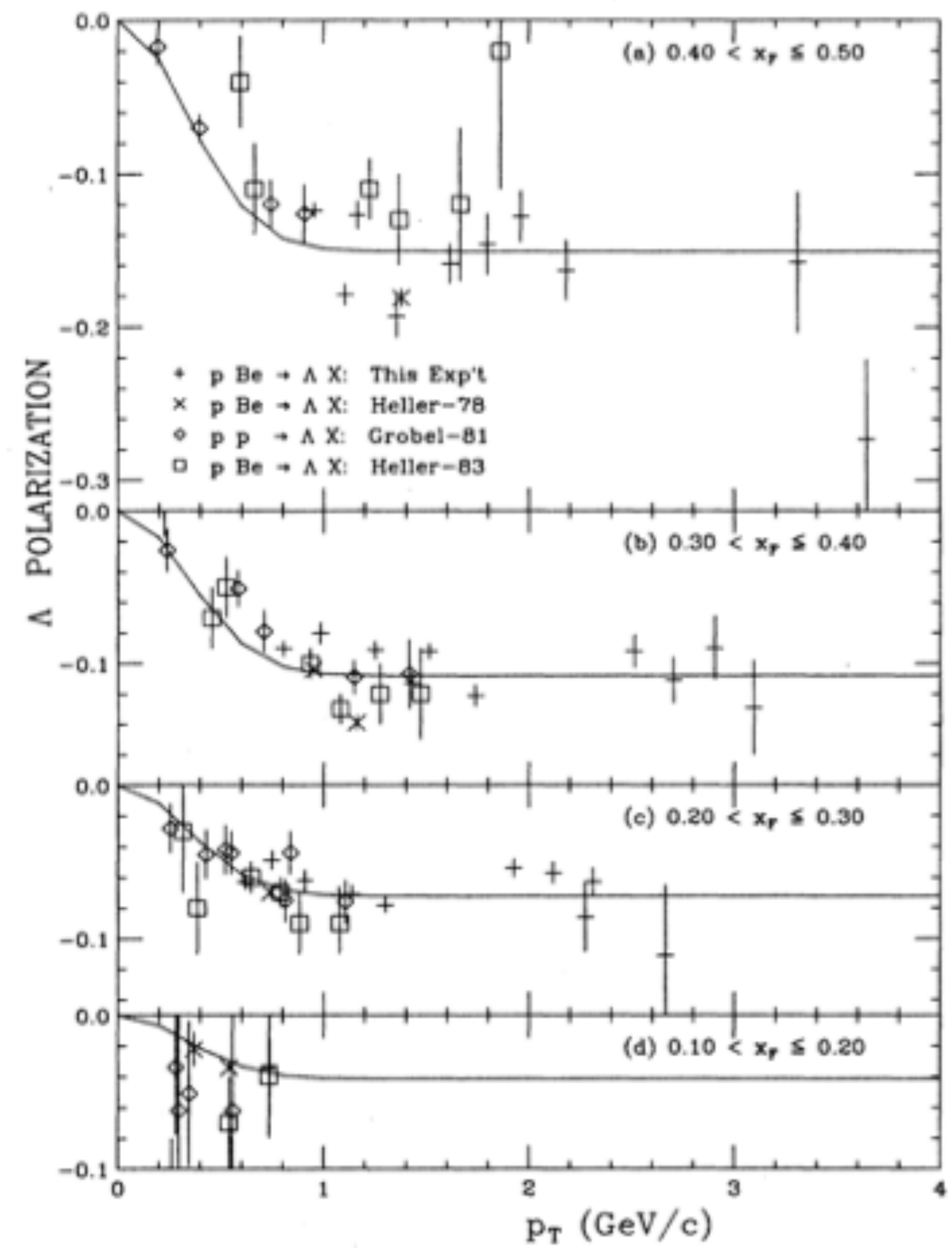
One of the first transverse spin effects at Fermilab (1976):



Bunce PRL 76
Heller PRL 78



PRD 89 Lundberg



Proton-Nuclei cont ...

$$pA \to \Lambda^{\uparrow} X$$

Lundberg et al PRD40 (1989) 400 GeV

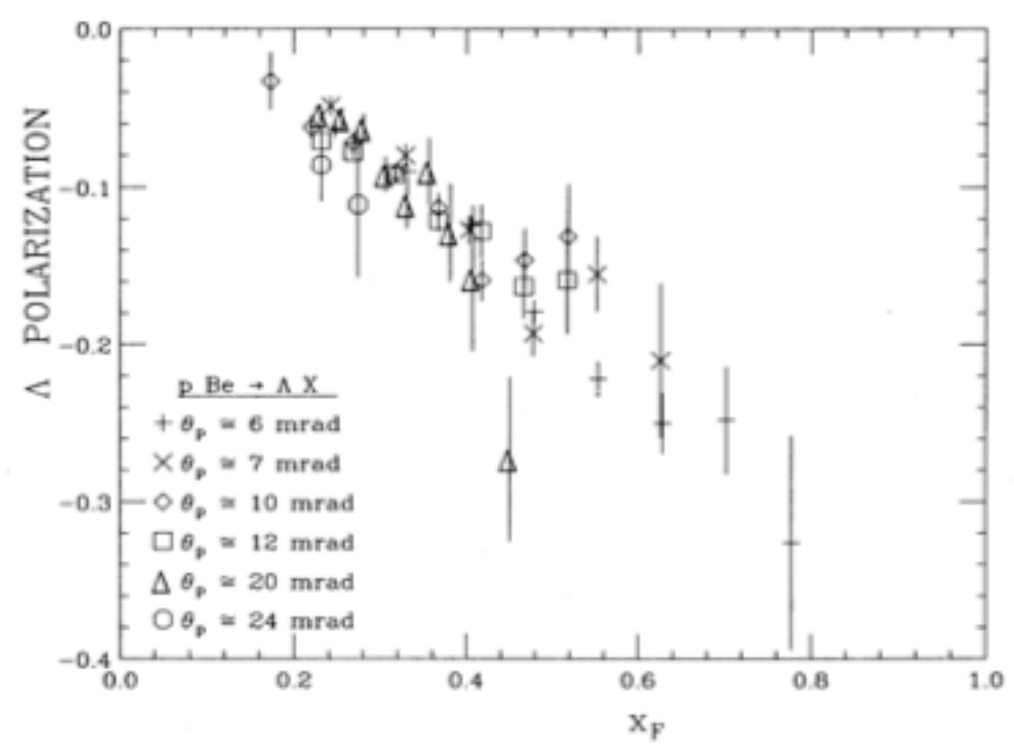
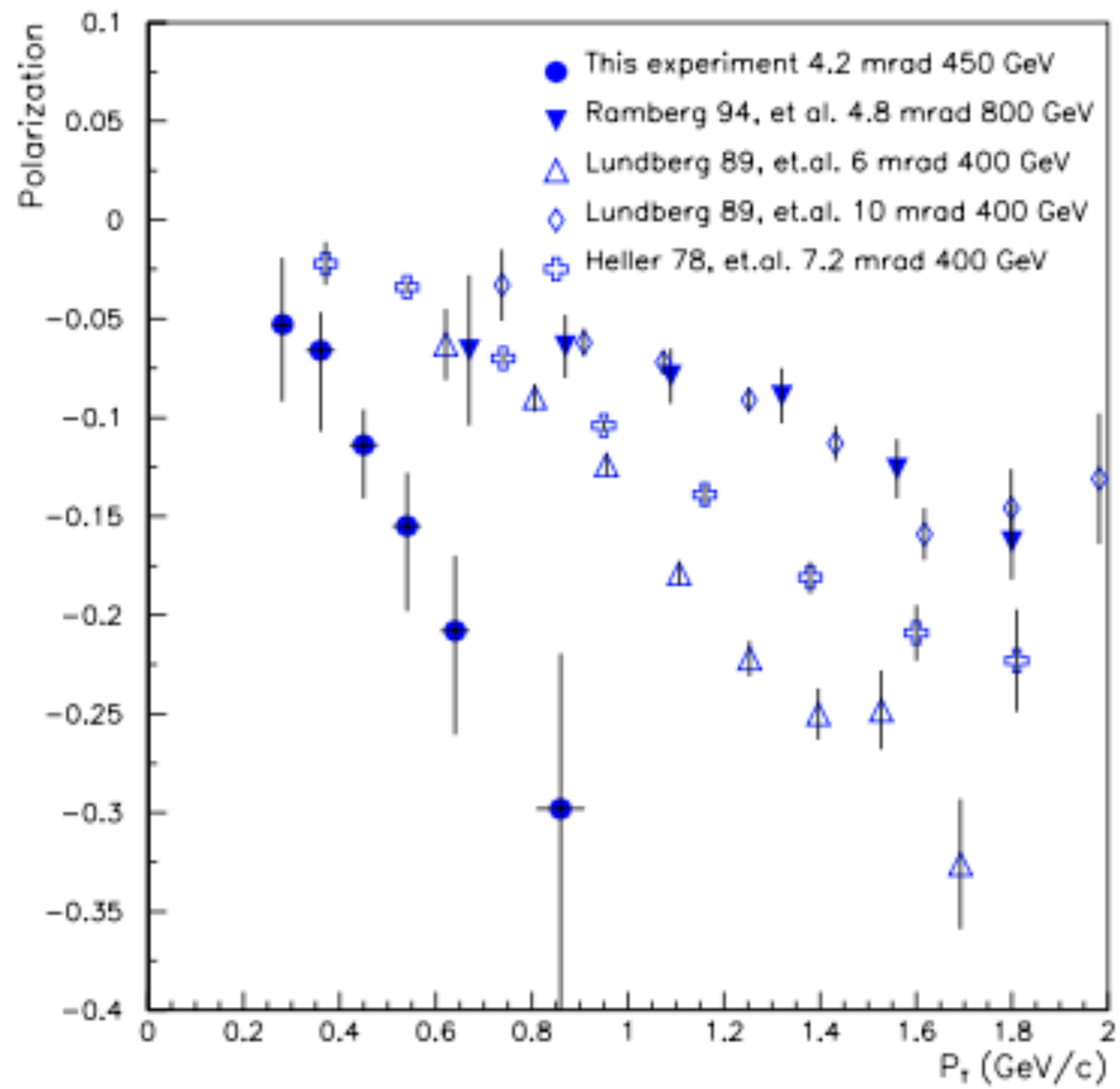


FIG. 4. The Λ polarization is shown as a function of x_F for all production angles. Over this range of production angles and within experimental uncertainties, the polarization is angle (or p_T) independent.

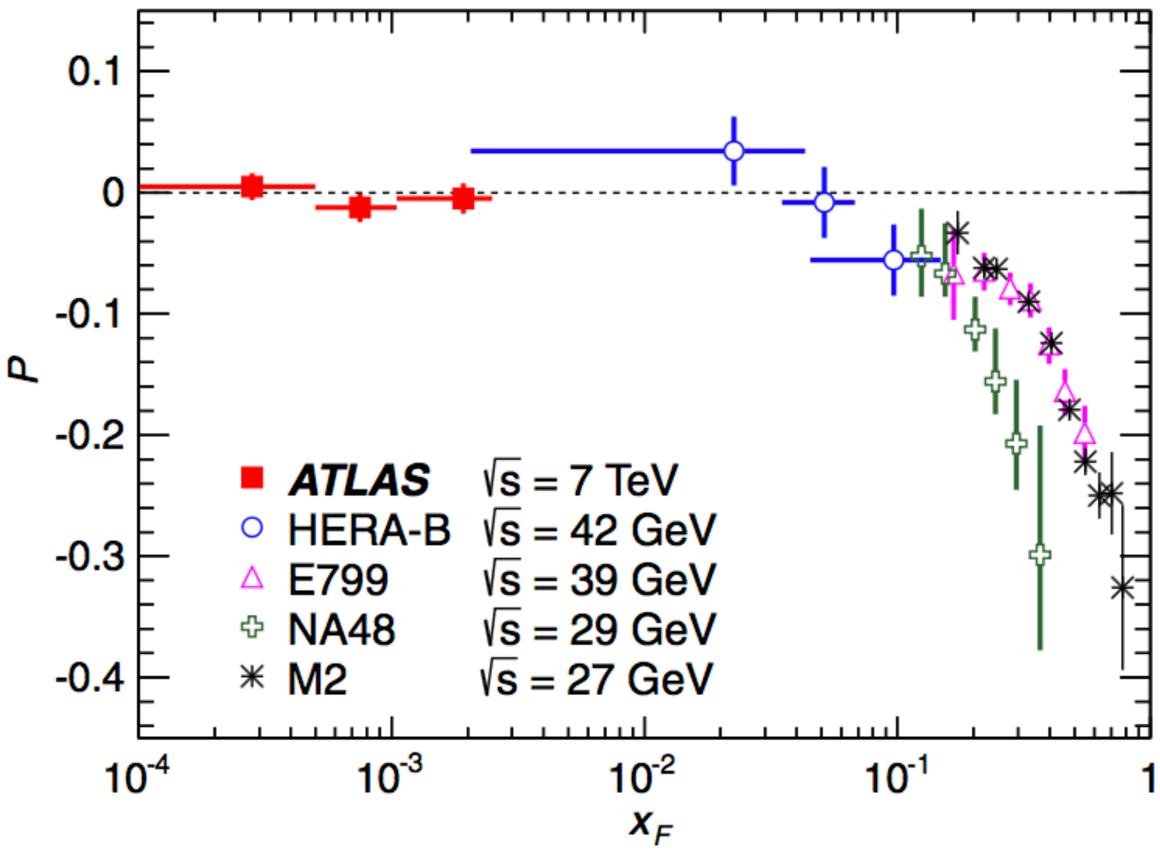
V. Fanti et al.: NA 48 450 GeV proton energy

Eur. Phys. J. C 6, 265–269 (1999) **CERN SPS**



What about LHC?

Is it feasible at a high energy collider?



Recent ATLAS measurement

at $\sqrt{S}$ = 7 TeV

PRD 91, 032004 (2015)

Small Polarisation at mid rapidity but

Such exps. demonstrate
feasibility to study $\Lambda^{\uparrow}$ **@ hi energy**

What does Exp Say ...

$$pA \to \Lambda^{\uparrow} X$$

$$pp \to \Lambda^{\uparrow} X$$

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

$$\gamma^* N \to \Lambda^{\uparrow} X$$ **HERMES**

$$e^+ e^- \to \Lambda^{\uparrow} X$$

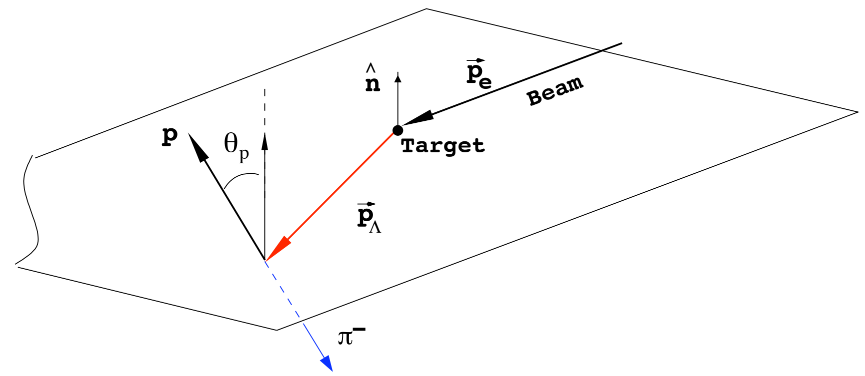
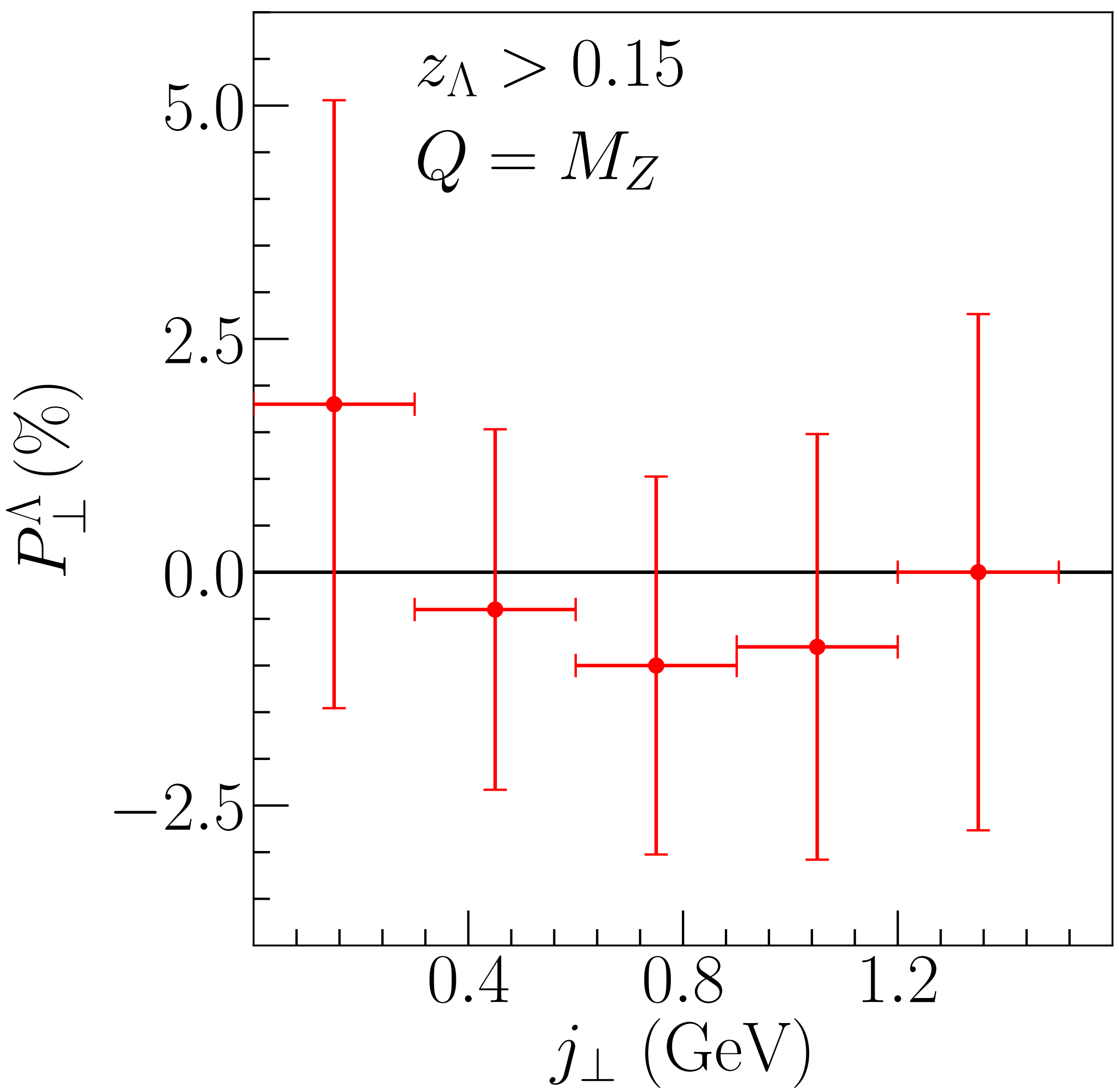


FIG. 1: Schematic diagram of inclusive Λ production and decay. The angle θ_p of the decay proton with respect to the normal $\hat{n}$ to the production plane is defined in the Λ rest frame.

Simplest and cleanest process : $e^+e^- \to \Lambda^\uparrow(\mathrm{Thrust})\,X$

OPAL at LEP at Z-pole [Eur.Phys.J C2, 49 (1998)]

Longitudinal Polarization, small/zero Transverse Polarization w/ errors



QCD is Parity Conserving TSSAs Scattering plane transverse to spin

Naively "T-odd"

$$\Delta\sigma \sim iS_T\cdot(\mathbf{P}\times P_\perp)\otimes(\text{"}T-odd\text{" QCD} - \text{phases})$$

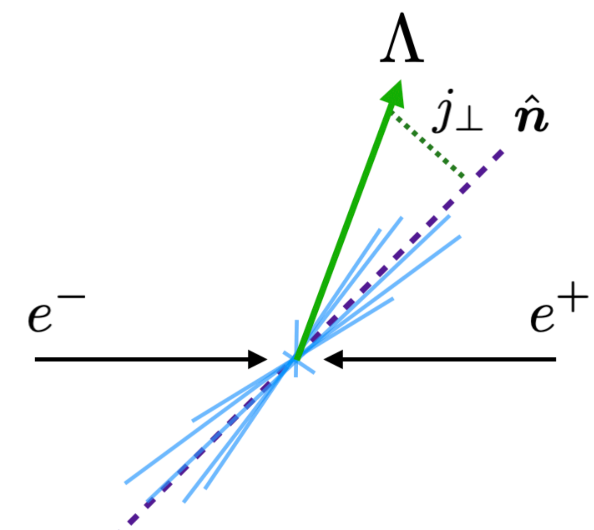
Spin orbit

Simplest and cleanest process $\Lambda^{\uparrow}$ in e^+e^-

Belle data: Transverse Polarization

Y. Guan, et al. PRL 122 (2019) → talk by Anselm here @ Jets Workshop

⇒ significant transverse polarization

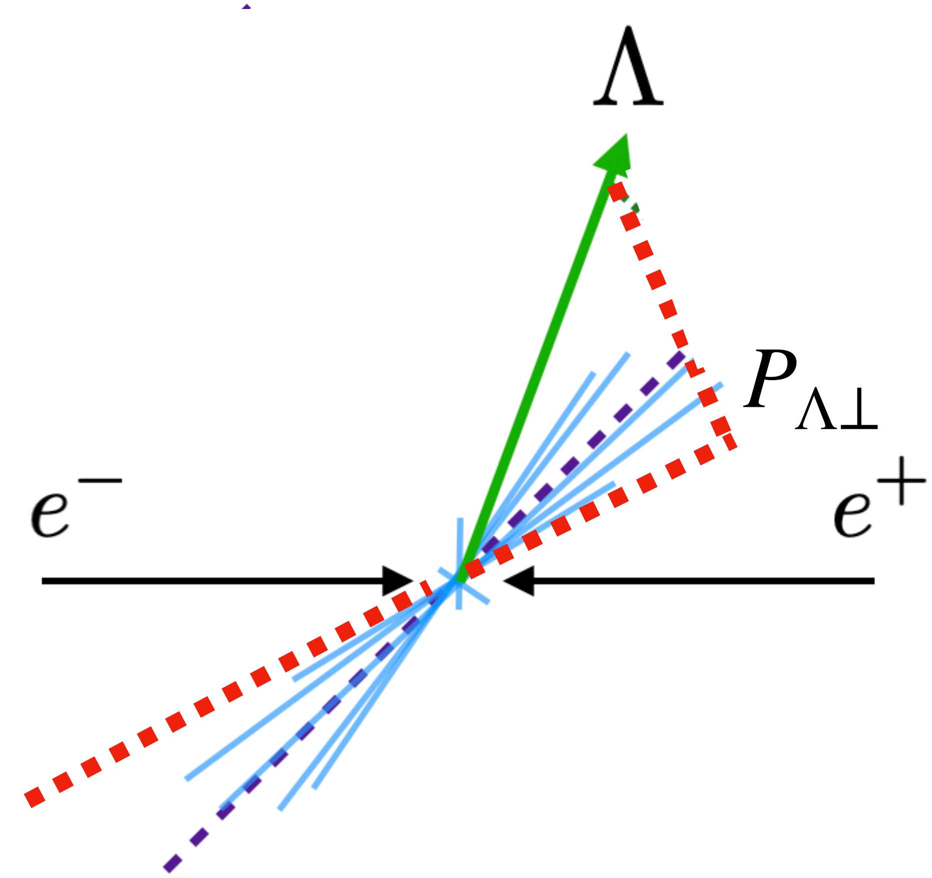


$$e^+e^- \to \Lambda^{\uparrow}(\mathrm{Thrust})\, X$$

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

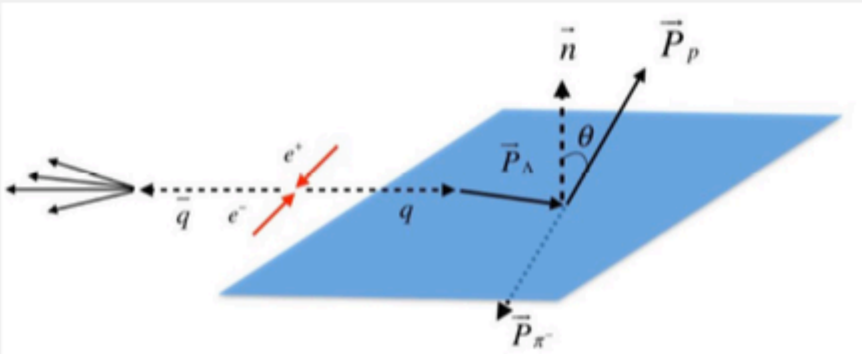
Measured w.r.t. thrust axis &

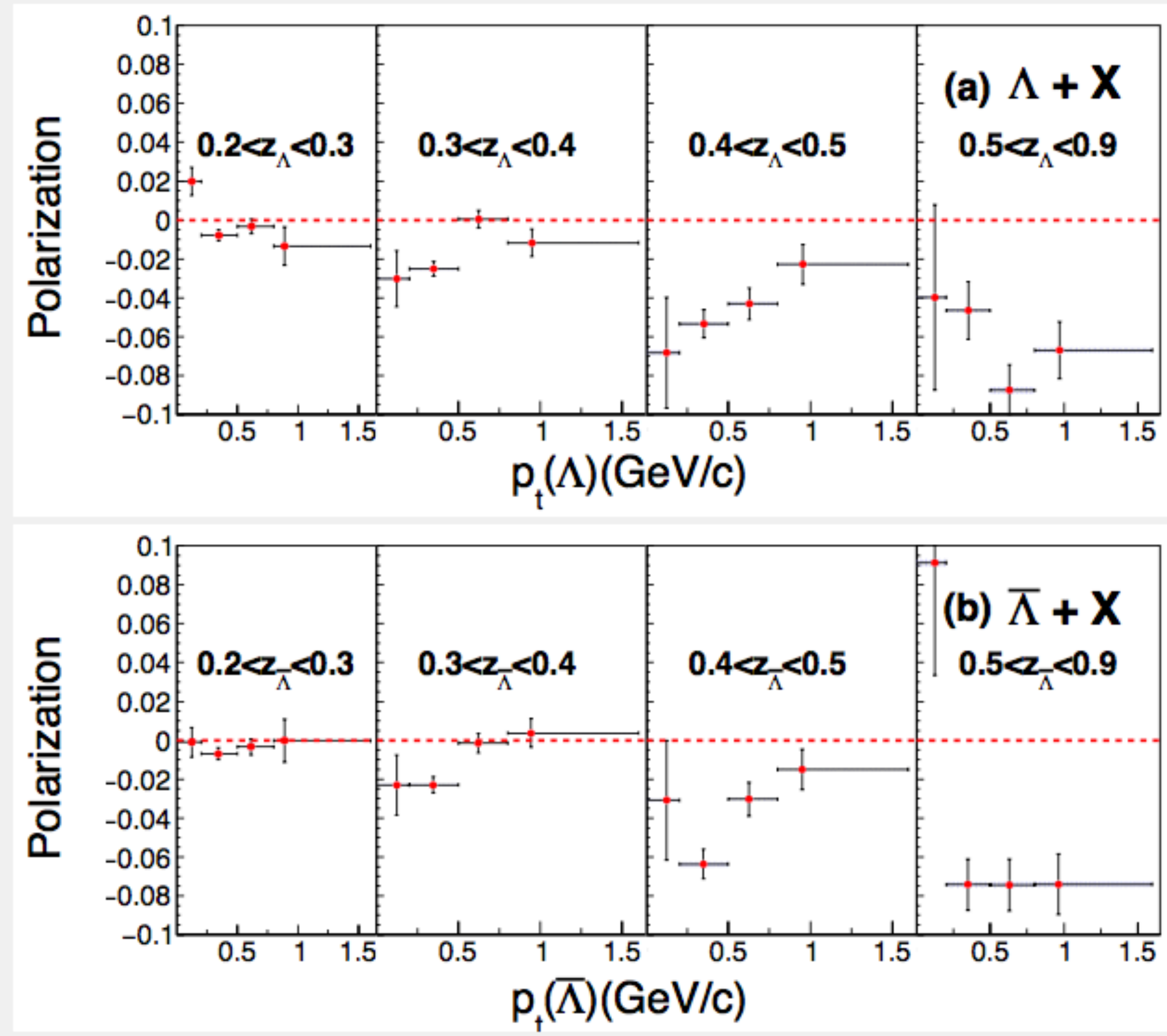
back to back hadrons="bTOb"



FIRST OBSERVATION BY BELLE

Thrust





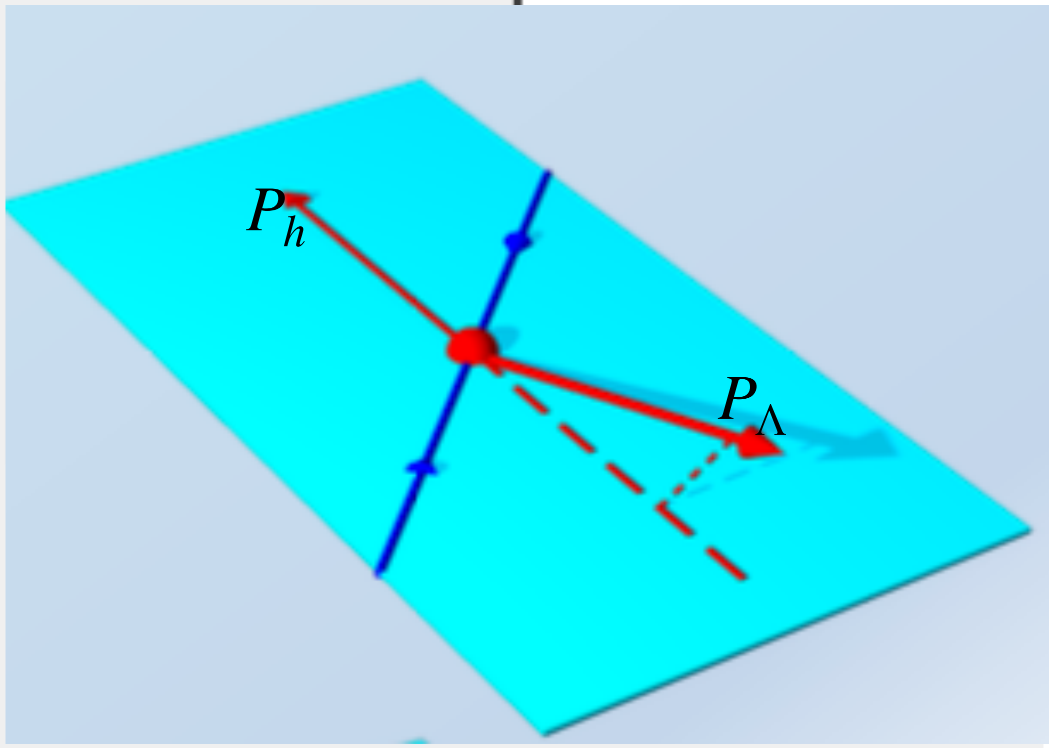
PHYSICAL REVIEW LETTERS 122, 042001 (2019)

From Anselm's INT talk

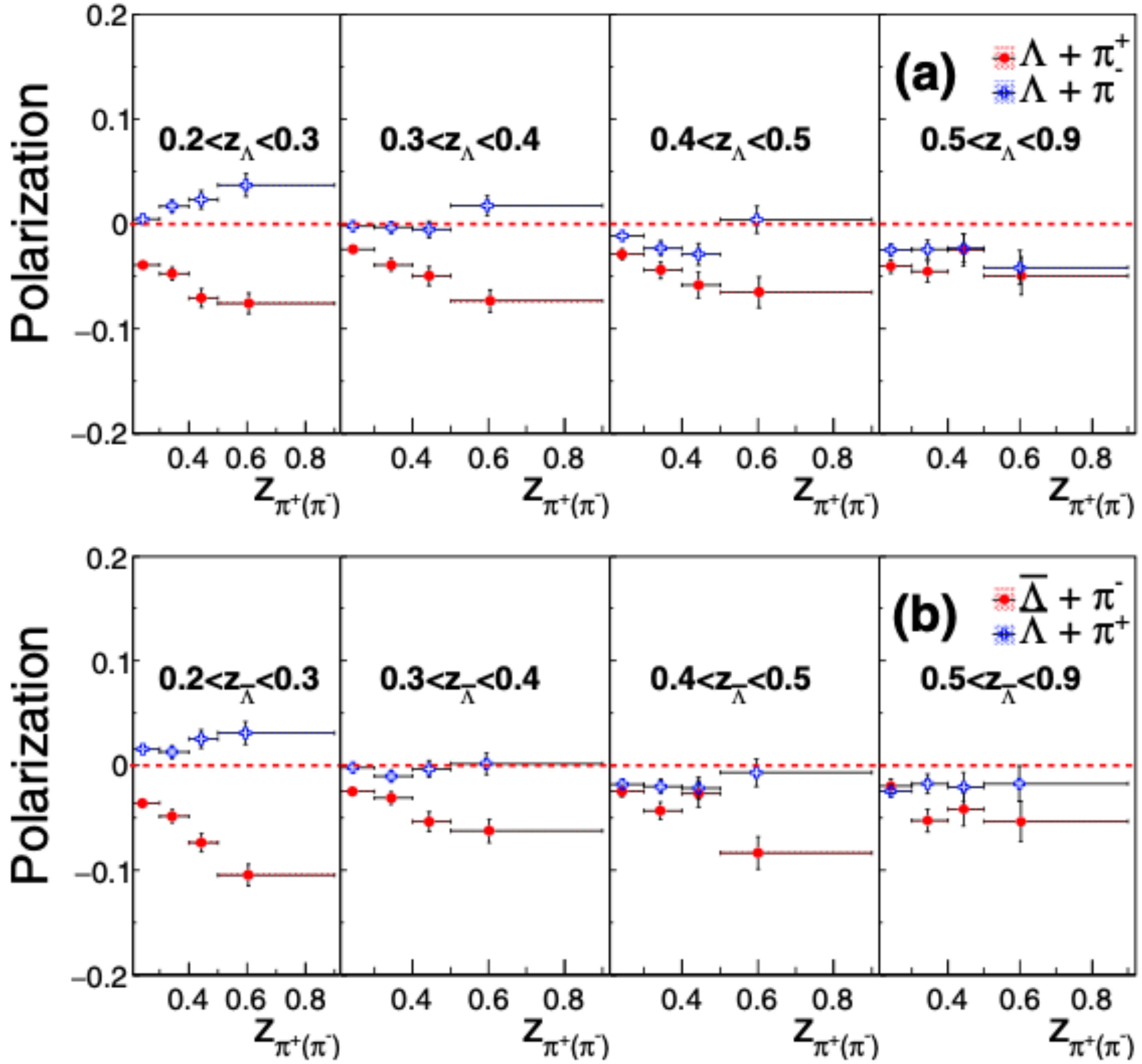
The P_t is measured as the transverse momentum of Λ relative to the **thrust axis**

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

FIRST OBSERVATION BY BELLE bTOb



From Anselm's INT talk



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

Back to back hadrons
integrated over $p_\perp$ NOT SMALL

Question for gobal analysis
& to test Universality Belle BeS BaBar + EIC

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

Questions/issues: is "mechanism" the same ??

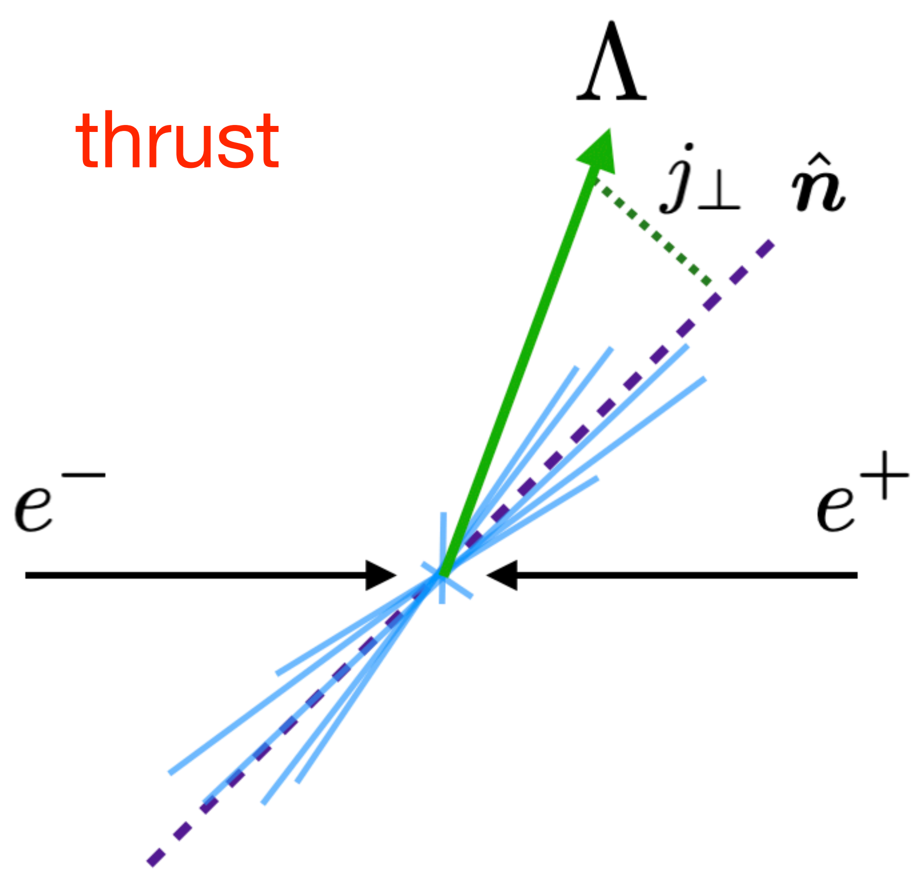
- TMD factorization "2" two scale fact. Theorems ?
  - ✳TMD factorization formalism ?? for thrust axis measurement
- ….

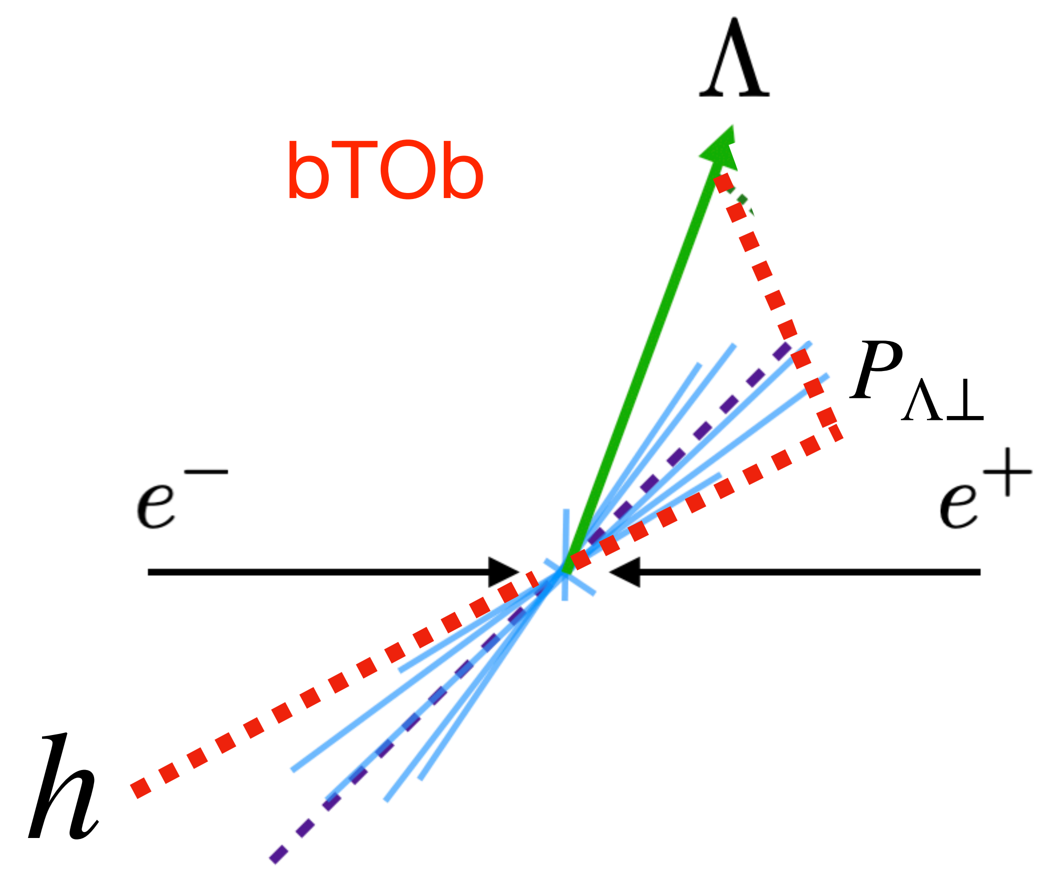
$$\Lambda_{QCD} \lesssim p_\perp \ll Q$$

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

Global analysis test Universality Belle BeS BaBar + EIC

Is it same PFF function in bTOb hadron & hadron + thrust measurements ?





$$T = \frac{\sum_i |\boldsymbol{p}_i \cdot \hat{n}|}{\sum_i |\boldsymbol{p}_i|}$$

The thrust axis defined by vector, $\hat{n}$ which maximizes the thrust variable T

- What about "T"-odd universality can we test it with all data?

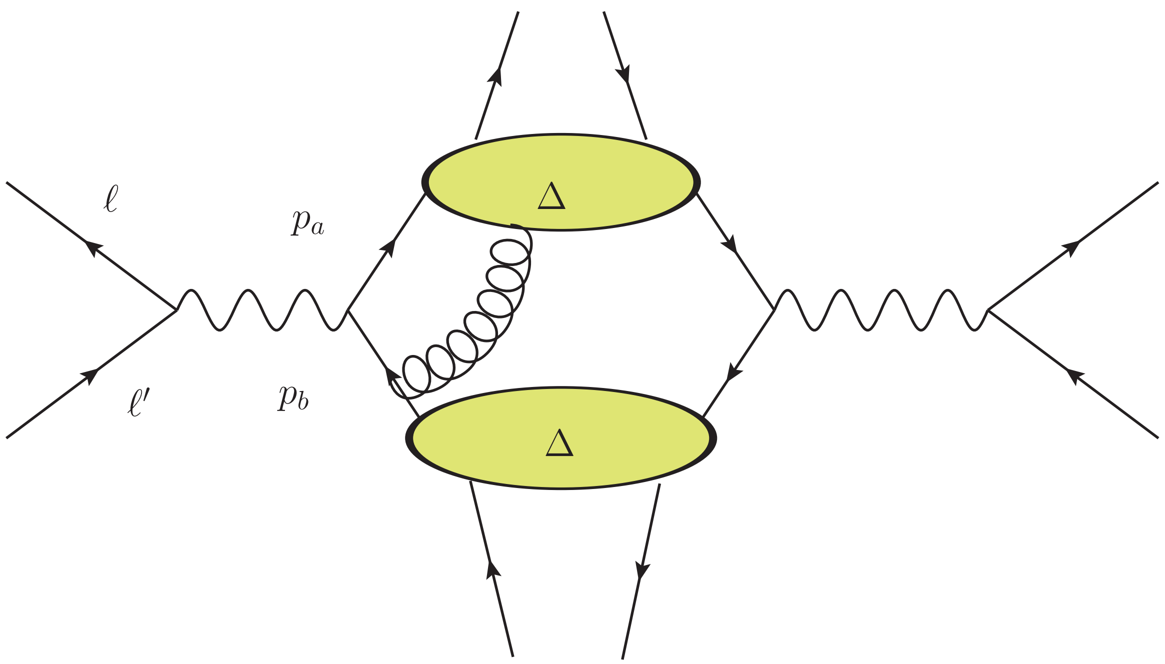
Explain non trivial $P_{\Lambda^\uparrow}$ via TMD FFs
polarization fragmentation function PFF unsurpressed

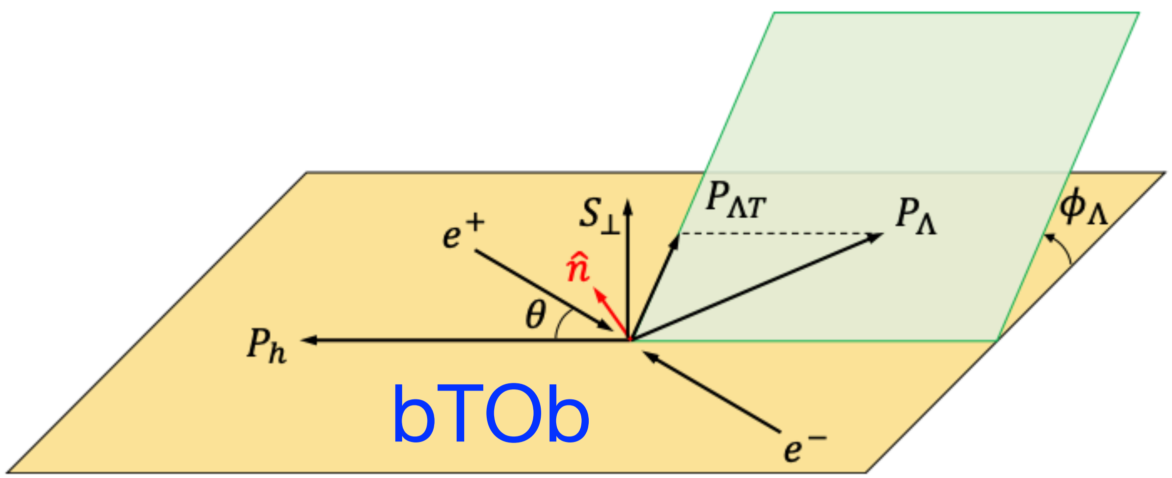
TMD framework for bTOb production of

$\Lambda + h$ chiral even, naively T-odd fragmentation function, universal

Parton Model factorization Mulders & Tangerman 1996, Boer Jakob Mulders 1996

Boer & Mulders 1997





$$\hat{D}_{\Lambda/q}(z_\Lambda, \mathbf{p}_\perp, \mathbf{S}_\perp, Q) = \frac{1}{2}\left[D_{\Lambda/q}(z_\Lambda, p_{\Lambda\perp}, Q) + \frac{1}{z_\Lambda M_\Lambda} D^\perp_{1T,\Lambda/q}\left(z_\Lambda, p_\perp, Q\right) \epsilon_{\perp\rho\sigma} p_\perp^\rho S_\perp^\sigma\right]$$

Explain via TMD fact.

TMD PDFs (x, k_T)

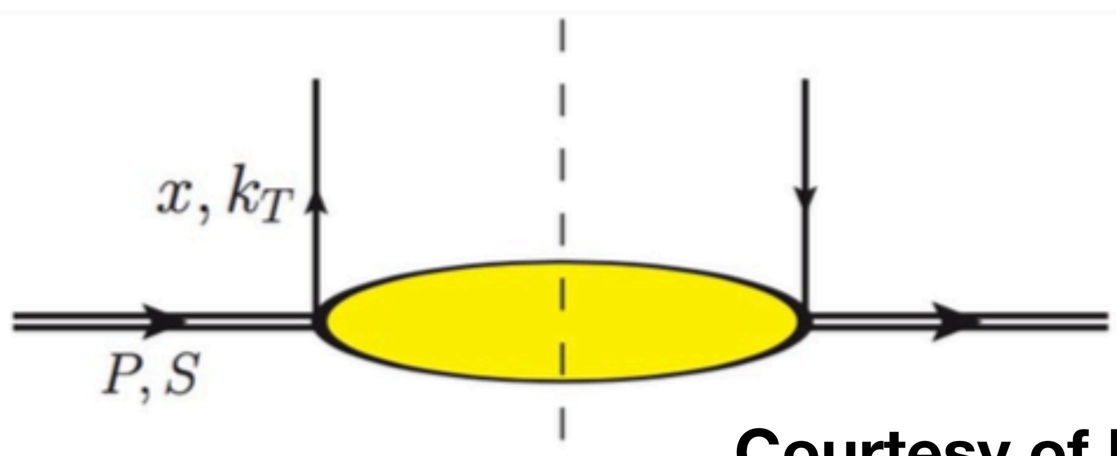
q pol. / H pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_{1T} $h_{1T}^\perp$

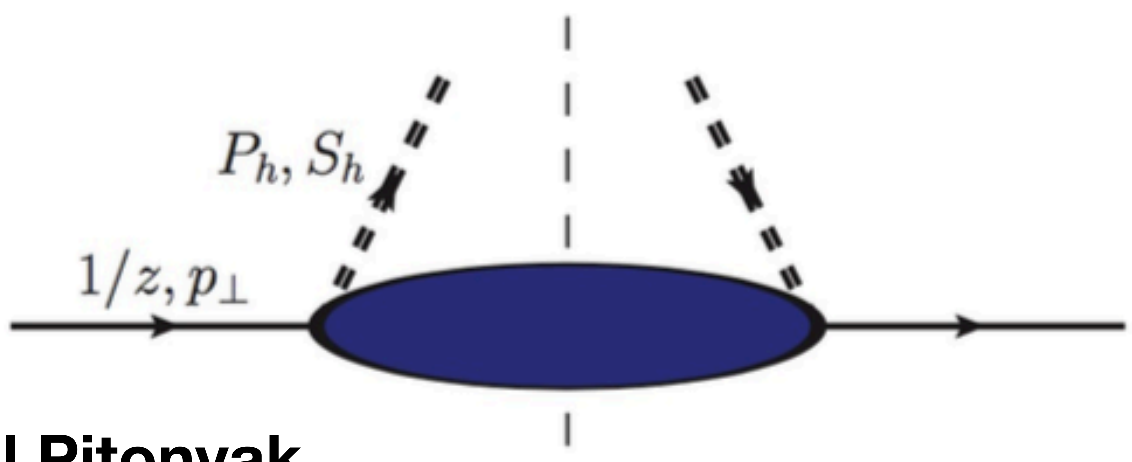
(Mulders, Tangerman (1996); Goeke, Metz, Schlegel (2005))

TMD FFs $(z, p_\perp)$

q pol. / H pol.	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_{1T} $H_{1T}^\perp$

(Boer, Jakob, Mulders (1997))





Courtesy of Daniel Pitonyak

bTOb beyond leading order
TMD Factorization

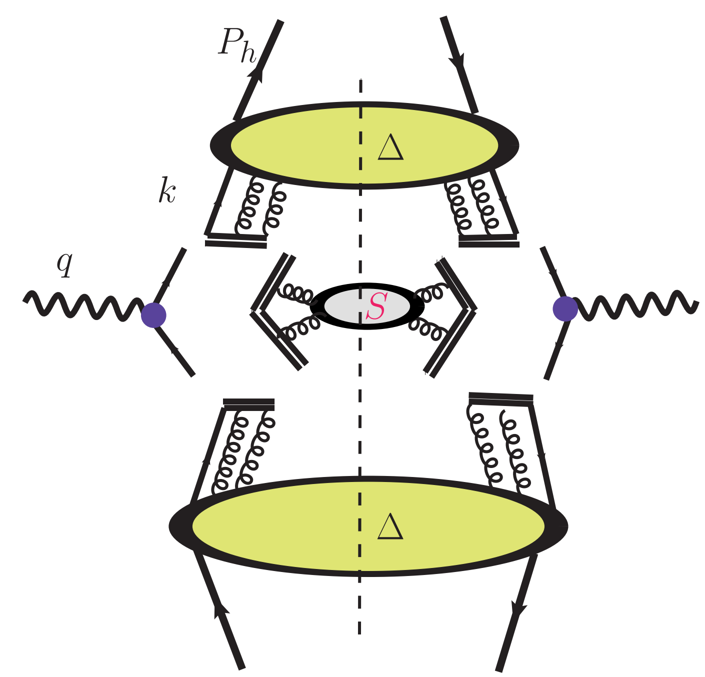
QCD factorization Collins Soper 1982 NPB,

Collins Foundations of PQCD Cambridge Press 2011

Collins Soper (81,82), Collins, Soper, Sterman (85), Boer (01) (09) (13), Ji, Ma, Yuan (04,05,06), Collins-Cambridge University Press (11), Aybat Rogers PRD (11), Abyat, Collins, Qiu, Rogers (11), Aybat, Prokudin, Rogers (11), Bacchetta, Prokudin (13), Sun, Yuan (13), Echevarria, Idilbi, Scimemi JHEP 2012, Collins Rogers 2015 ….
SCET: Bauer, Flemming Pirjol Rothstein, Stewart PRD 2002, Chiu, Jain, Neill, Rothstein JHEP 2013, Rothstein & Stewart JHEP 2016, …

JCC Soft factor further "repartitioned"
This is done to

1) cancel LC divergences in "unsubtracted" TMDs
2) separate "right & left" movers i.e. full factorization
3) remove double counting of momentum regions



$$\tilde{D}^{\rm sub}_{H/j}(z_A, b_T;\mu,\zeta) = \lim_{\substack{y_A\to+\infty \\ y_B\to-\infty}} \underbrace{\tilde{D}^{\rm unsub}_{H/j}(z_A, b_T;\mu, y_A - y_B)} \sqrt{\frac{\tilde{S}(b_T;y_A,y_n)}{\tilde{S}(b_T;y_A,y_B)\tilde{S}(b_T;y_n,y_B)}} \times UV_{renorm}$$

$$\Updownarrow$$

$$\tilde{D}^{\rm unsub}_{H/j}(z_A, b_T;\mu, y_P - y_B) = \frac{1}{z_A}\int \frac{db^+}{2\pi} e^{-ik_A^- b^+} \langle 0|\gamma^- \mathcal{U}_{[0,b]}\psi(b)|X P_A\rangle\langle P_A X|\bar{\psi}(0)|0\rangle\big|_{b^-=0}$$

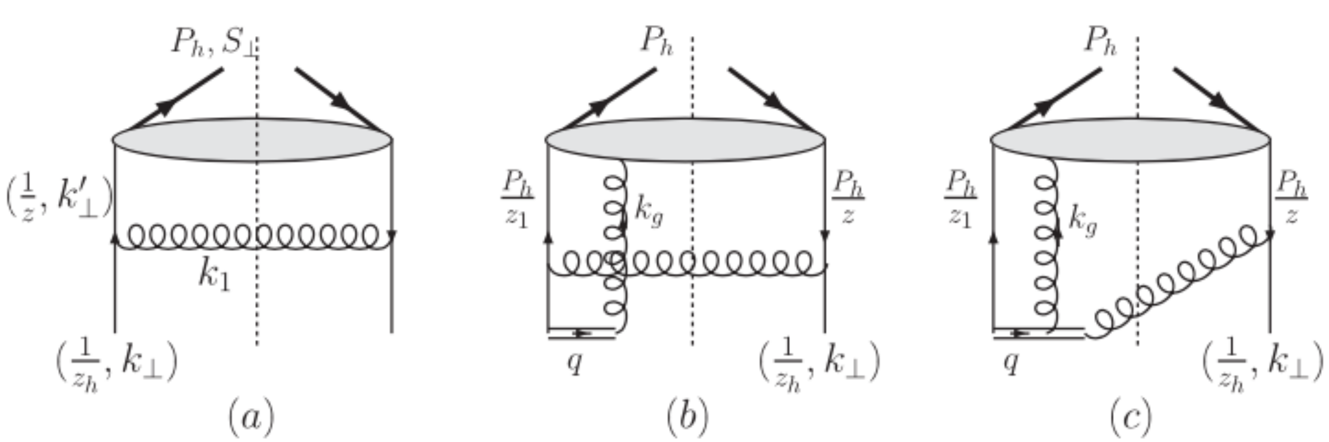
Use both data sets to study universality of T-odd fragmentation?
What is prediction of TMD Factorization

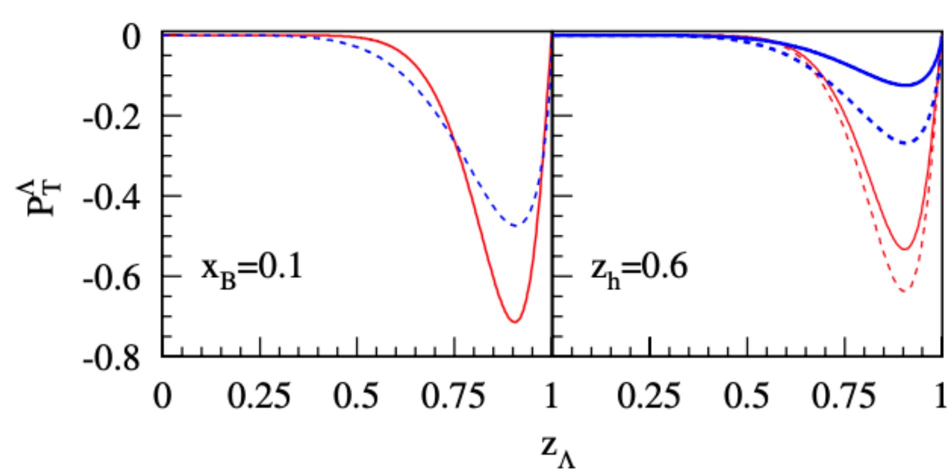
Universality of T-odd Collins function: $H_{1,\pi/q}^{\perp(1)}(z,b,Q)$

Metz PLB2002,
Boer Mulders Pijlman NPB2003
Collins Metz PRL 2004,
Gamberg, Mukerjee, Mulders PRD2007,
Meissner Metz PRL 2009,
Gamberg Mukherjee, Mulders PRD 2008

Universality of T-odd PFF prediction from pQCD - $D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda,b,Q)$ phase from FSI but not gluonic/fermionic pole

Boer, Kang, Vogelsang, Yuan PRL 2010





Λ Belle data fall into 2 classes

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

$$D^{\perp}_{1T,\Lambda/q}\left(z_\Lambda, p_\perp, Q\right)$$

? Is it true that the PFF is the same TMD in both process?

Recent extractions address this

1) D'Alesio & Murgia ZacchedduPRD2020 bTOb + Thrust assumed same factz.here
2) Callos, Kang, Terry PRD2020 bTOb only

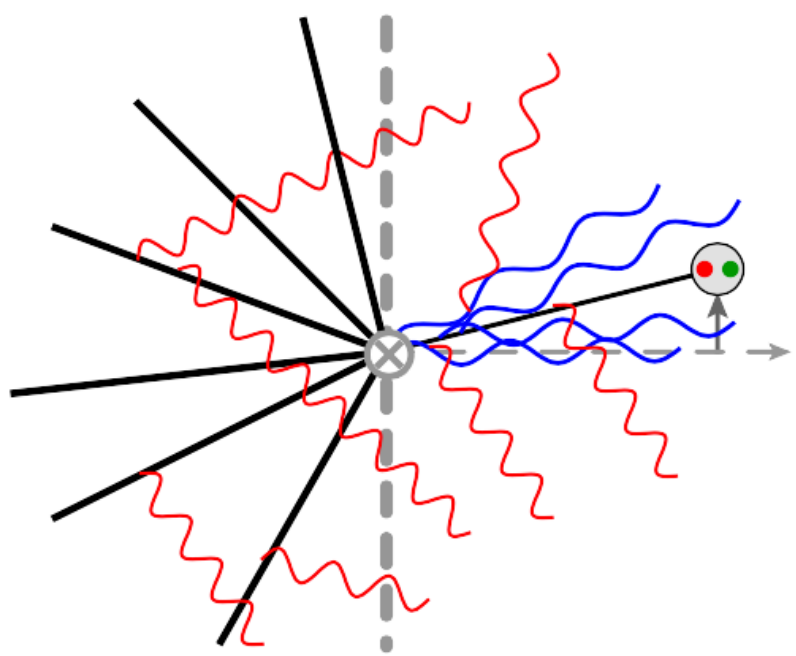
Other pheno studies

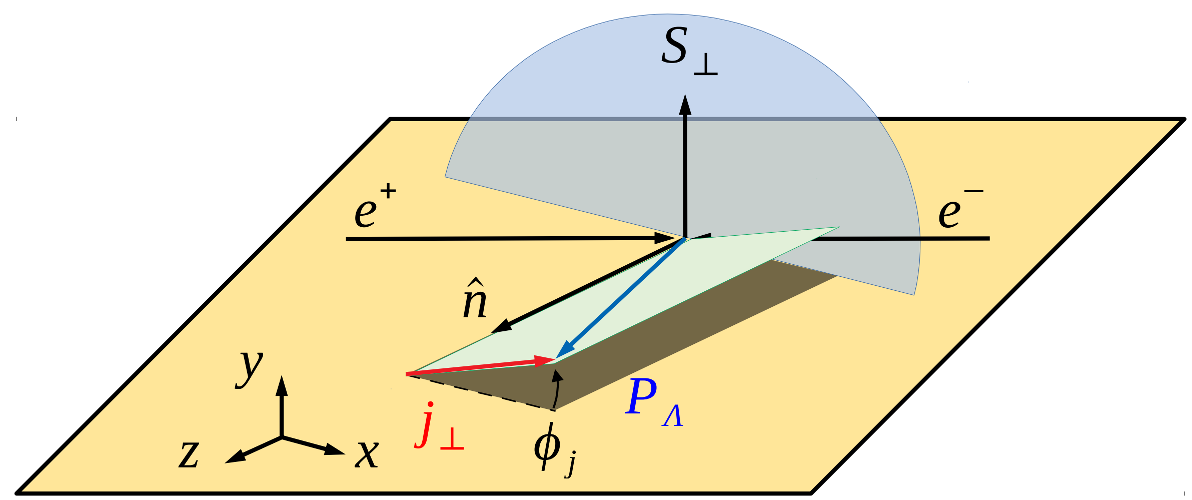
* Anselmino, Kishore, Mukherjee PRD 2019
  single inclusive case and the role of the PFFs
  twist-2 in place of twist-3 ?
* Earlier Anselmino Boer, D'Alesio, Murgia. PRD 2001, 2002
  TMD factorization applied to inclusive process ?

? Same PFF ? in $e^+e^- \to \Lambda^\uparrow(\mathrm{Thrust})$

In TMD factorization framework for production of Λ (Thrust) we have non-global observable "right hemisphere" only

? chiral even, naively T-odd fragmentation function, universal ?





- Z.B Kang, D.Y. Shao, F. Zhao 2007.14425

?

$$\hat{D}_{\Lambda/q}(z_\Lambda, \mathbf{p}_\perp, \mathbf{S}_\perp, Q) = \frac{1}{2}\Big[D_{\Lambda/q}(z_\Lambda, p_{\Lambda\perp}, Q) + \frac{1}{z_\Lambda M_\Lambda} D^\perp_{1T,\Lambda/q}(z_\Lambda, p_\perp, Q)\, \epsilon_{\perp\rho\sigma} p_\perp^\rho S_\perp^\sigma\Big]$$

TMD factorization & Thrust observable

Recent work

- M. Boglione & A. Simonelli, 2007.13674
- Z.B Kang, D.Y. Shao, F. Zhao 2007.14425
- M. Boglione & A. Simonelli, 2007.13674

Z.B Kang, D.Y. Shao, F. Zhao 2007.14425—see talk of Dingyu

Derive TMD factorization for unpolarized transverse momentum distribution for the single hadron production with the thrust axis in electron-positron collision

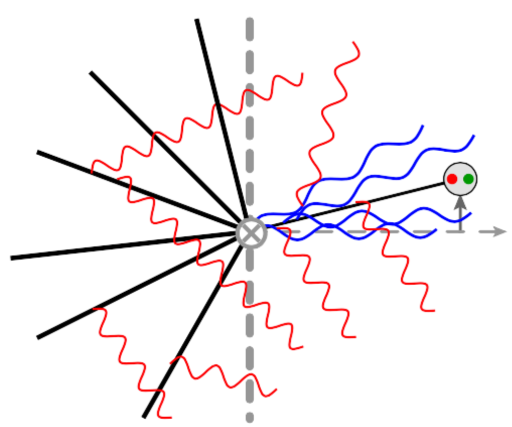
Lets Drill Down TMD factorization

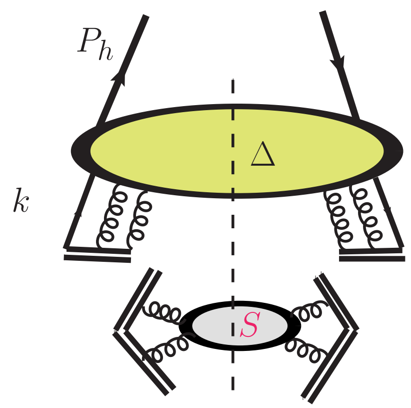
Recent work

- Z.-B Kang, D.Y. Shao, F. Zhao 2007.14425

Derive TMD factorization for unpolarized TMD FF for single hadron production with the thrust axis in electron-positron collision $e^+e^- \to \Lambda^\uparrow(\text{Thrust})$ non-global observable

$$\frac{d\sigma}{dz_\Lambda d^2\boldsymbol{j}_\perp} = \sigma_0 H(Q,\mu)\sum_q e_q^2 \int d^2p_\perp d^2\lambda_\perp \delta^{(2)}(\boldsymbol{j}_\perp - \boldsymbol{p}_\perp - z_\Lambda \boldsymbol{\lambda}_\perp) D_{\Lambda/q}(z_\Lambda, p_\perp, \mu, \zeta/\nu^2) S_{\text{hemi}}(\lambda_\perp, \mu, \nu)$$





Calculated to NLO and NLL

$$S_{\text{hemi}}(b,\mu,\nu) = \sqrt{S(b,\mu,\nu)}$$

$$D^{\text{TMD}}_{\Lambda/q}(z_\Lambda, b, \mu, \zeta) = D_{\Lambda/q}(z_\Lambda, b, \mu, \zeta/\nu^2)\sqrt{S(b,\mu,\nu)}$$

$$\frac{d\sigma}{dz_{la} d^2\boldsymbol{j}_\perp} = \sigma_0^{\text{TMD}} \sum_q e_q^2 \int_0^\infty \frac{bdb}{(2\pi)} J_0\left(\frac{b\, j_\perp}{z_\Lambda}\right) \frac{1}{z_\Lambda^2} D_{\Lambda/q}(z_\Lambda, \mu_{b_*})\, e^{-S_{\text{NP}}(b, z_\Lambda, Q_0, Q) - S_{\text{pert}}(\mu_{b_*}, Q)} U_{\text{NG}}(\mu_{b_*}, Q)$$

Non-global logs resummed

Factorization theorem ∃

Becher Rahn Shao JHEP 2017

M.Dasgupta & G.Salam PLB2001

We extend TMD factorization PFF

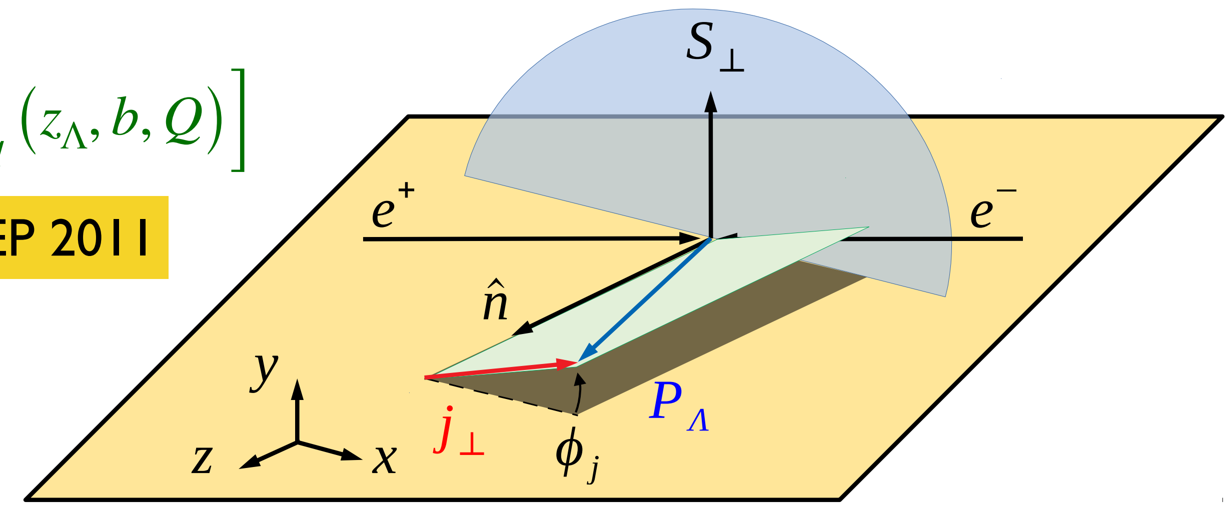
$$e^+e^- \to \Lambda^\uparrow(\mathrm{Thrust})$$

Gamberg, Kang, Shao, Terry, Zhao arXiv:2102.05553

$$\hat{D}_{\Lambda/q}(z_\Lambda, \mathbf{b}, \mathbf{S}_\perp, Q) = \frac{1}{2}\Big[D_{\Lambda/q}(z_\Lambda, p_{\Lambda\perp}, Q) - i\epsilon_{\perp\rho\sigma} b^\rho S_\perp^\sigma \, M_\Lambda D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda, b, Q)\Big]$$

Boer, Gamberg, Musch, Prokudin JHEP 2011

Spin dependent
FF Obeys CSS equation



$$\frac{d\Delta\sigma}{dz_\Lambda d^2\boldsymbol{j}_\perp} = \frac{d\sigma(\boldsymbol{S}_\perp)}{dz_\Lambda d^2\boldsymbol{j}_\perp} - \frac{d\sigma(-\boldsymbol{S}_\perp)}{dz_\Lambda d^2\boldsymbol{j}_\perp}$$

$$= \sigma_0^{\mathrm{TMD}} \sin(\phi_s - \phi_j) \sum_q e_q^2 \int_0^\infty \frac{b^2 db}{4\pi} J_1\left(\frac{bj_\perp}{z_\Lambda}\right)$$

$$\times \frac{M_\Lambda}{z_\Lambda^4} D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda, \mu_{b_*}) e^{-S_{\mathrm{NP}}^{\perp}(b, z_\Lambda, Q_0', Q) - S_{\mathrm{pert}}(\mu_{b_*}, Q)} U_{\mathrm{NG}}(\mu_{b_*}, Q)$$

UV & Rapidity subtracted TMD Universal PFF

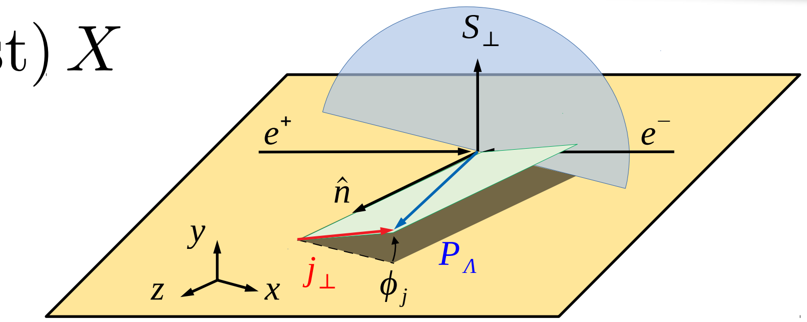
Also, see paper of JW Qiu, T. Rogers, B. Wang *Phys.Rev.D* 101 (2020) regarding proper definitions of weighted TMDs and talk in this workshop

Establish factorization for thrust axis factorization
carry out pheno to describe
Belle P_T and OPAL

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

Postage stamp of input for Pheno

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



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

$$S_{\rm NP}(b, z_\Lambda, Q_0, Q) = g_h \frac{b^2}{z_\Lambda^2} + \frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b}{b_*}$$

Aidala Field Gamberg Rogers PRD 2014

$$g_h = 0.042\,\text{GeV}^2 \qquad g_2 = 0.84\,\text{GeV}^2$$

Implementation Issacson Sun Yuan 2014 MPA

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

Dasgupta Salam, PLB 2001

$$\text{with } a = 0.85 C_A,\ b = 0.86 C_A,\ c = 1.33$$

$$u \equiv \int_{\mu_{b_*}}^{Q} \frac{d\mu}{\mu}\frac{\alpha_s(\mu)}{2\pi} = \frac{1}{\beta_0}\ln\left[\frac{\alpha_s(\mu_{b_*})}{\alpha_s(Q)}\right]$$

$$D_{1T,h/q}^\perp(z, p_\perp, Q_0') = \frac{M_\Lambda}{\langle M_D^2\rangle} D_{1T,h/q}^\perp(z, Q_0') \frac{e^{-p_\perp^2/\langle M_D^2\rangle}}{\pi\langle M_D^2\rangle}$$

$$D_{1T,h/q}^\perp(z, Q_0') = \mathcal{N}_q(z) D_{h/q}(z, Q_0') \qquad Q_0' = 10.58\ \text{GeV}$$

$$\mathcal{N}_q(z) = N_q z^{\alpha_q}(1-z)^{\beta_q}\frac{(\alpha_q+\beta_q-1)^{\alpha_q+\beta_q-1}}{(\alpha_q-1)^{\alpha_q-1}\beta_q^{\beta_q}}$$

$$S_{NP}^\perp(b, z, Q_0', Q) = \frac{\langle M_D^2\rangle}{4}\frac{b^2}{z^2} + \frac{g_2}{2}\ln\frac{Q}{Q_0'}\ln\frac{b}{b_*}$$

Parameters fit from bTOb Belle data
Callos, Kang, Terry PRD2020

Belle data fit $e^+e^- \to \Lambda^\uparrow h X$

$D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda, Q)$

Recent extractions address this
Callos, Kang, Terry PRD2020 bTOb only

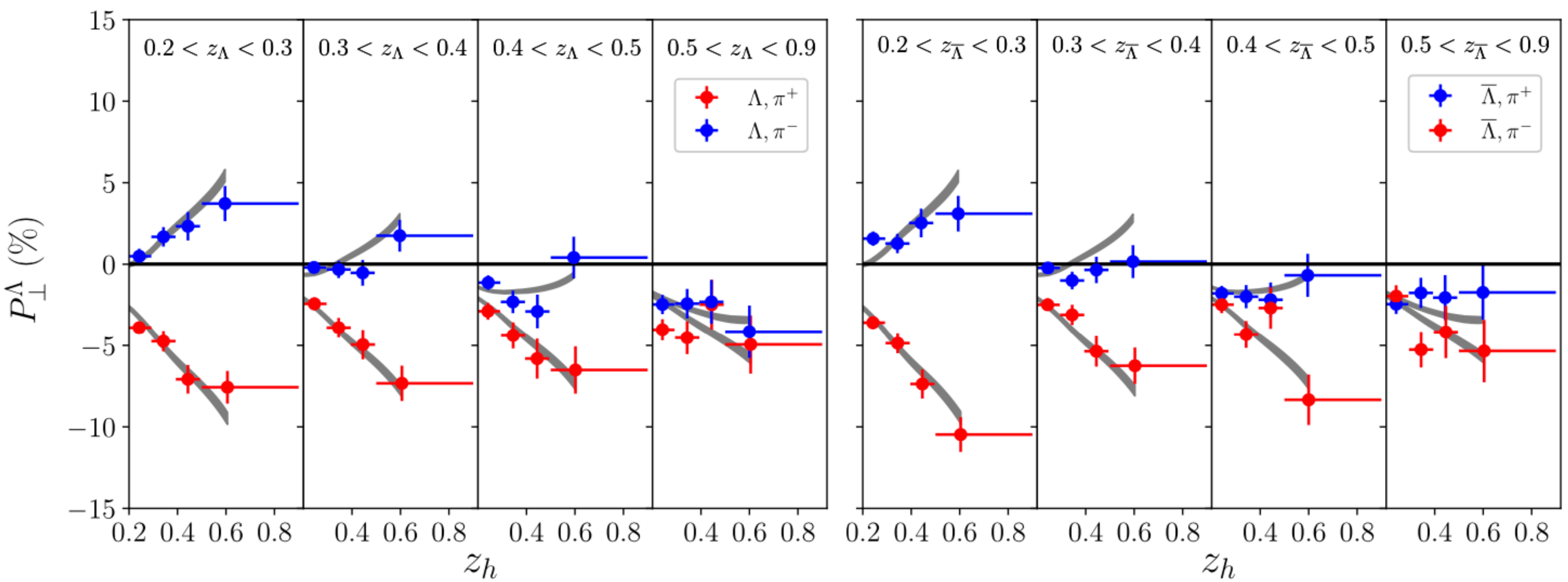


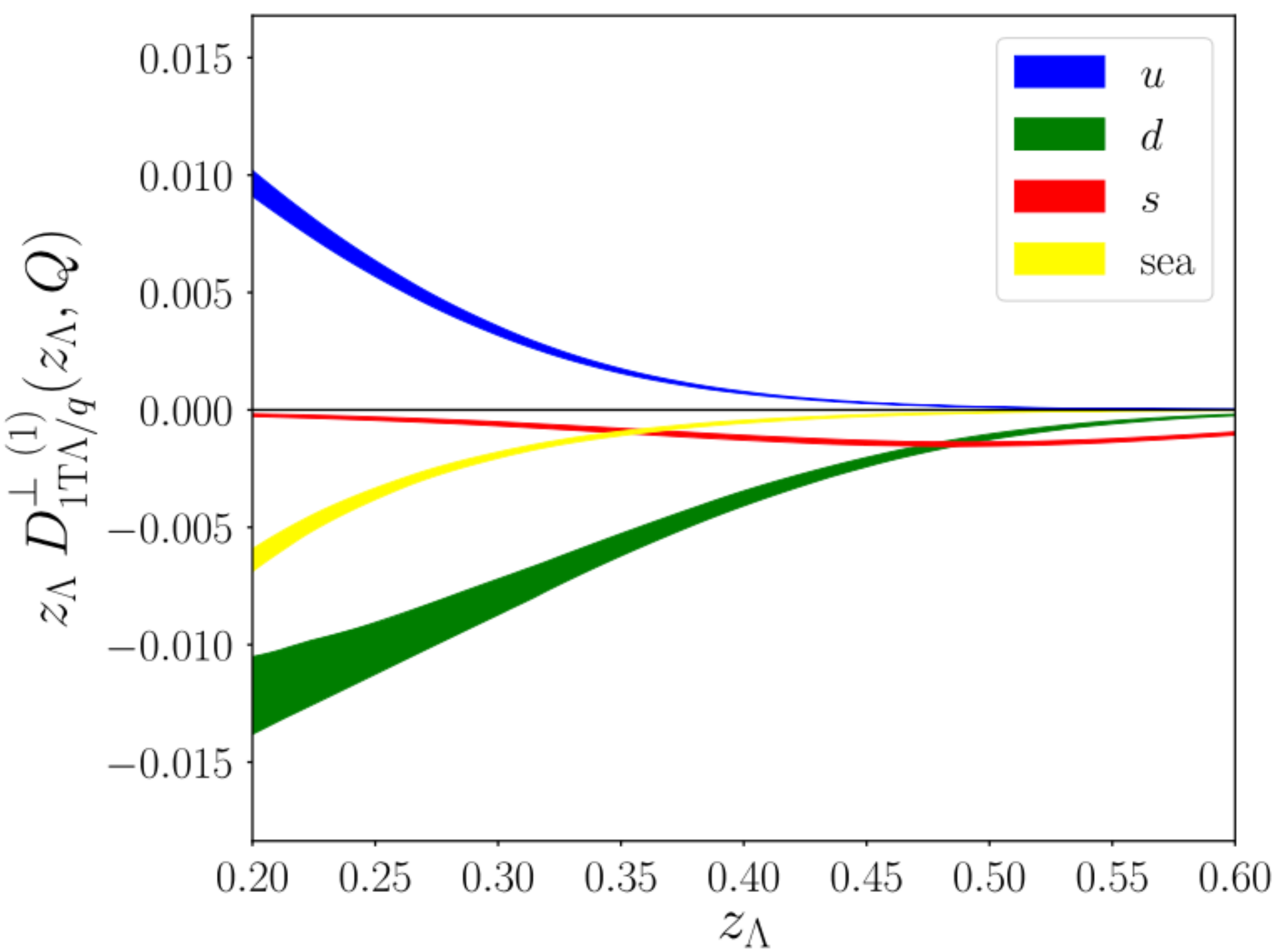
FIG. 3. The fit to the experimental data for π mesons is shown, with the gray uncertainty band displayed is generated by the replicas at 68% confidence. The left plots are for the production of $\Lambda + \pi^{\pm}$, while the right plots are for the production of $\bar\Lambda + \pi^{\pm}$.

And for kaons …

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

$D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda, Q)$

Recent extractions
Callos, Kang, Terry PRD2020 bTOb only

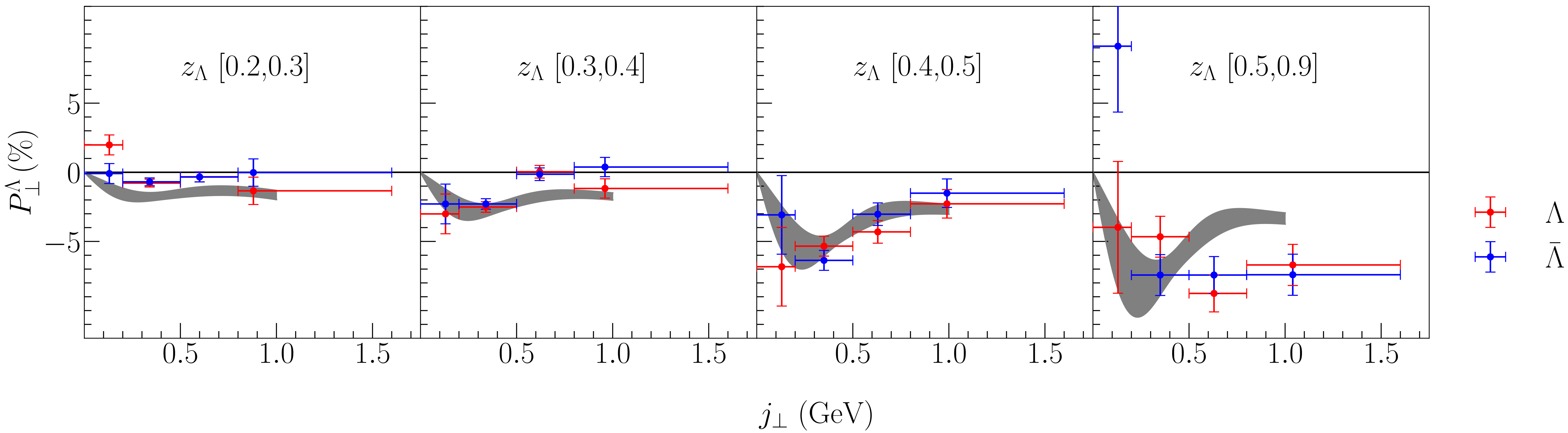


Exploit Universality to describe $e^+e^- \to \Lambda^\uparrow(\text{Thrust})$

Compare theory predictions to OPAL & Belle

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

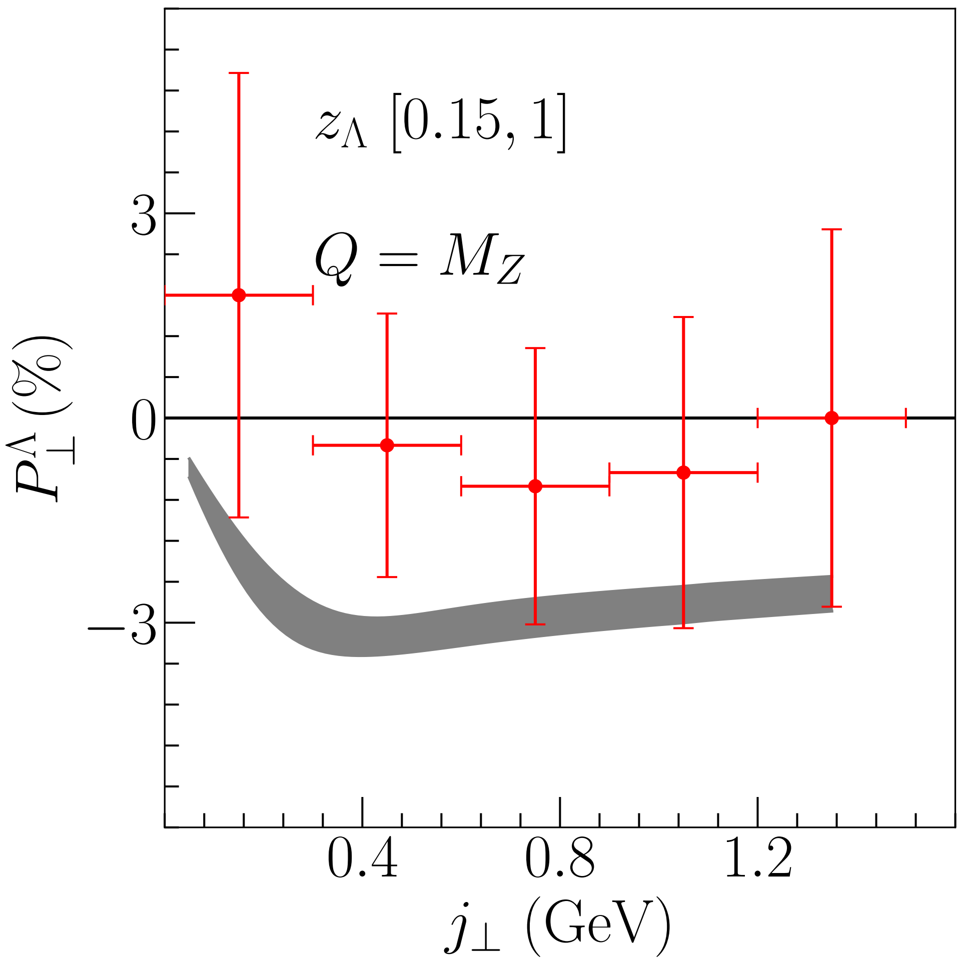
Gamberg, Kang, Shao,Terry, Zhao arXiv:2102.05553



- $P_\perp^\Lambda(z_\Lambda, j_\perp)$ for the Belle data [20]; left to right theory integrated from $0.2 < z_\Lambda < 0.3$, $0.3 < z_\Lambda < 0.4$, $0.4 < z_\Lambda < 0.5$, $0.5 < z_\Lambda < 0.6$
- The data in red is for Λ production while the data in blue is for $\bar{\Lambda}$ production
- Data plotted with total exp. uncertainty as vertical error bar & uncertainty on $j_\perp$ horizontal error bar
- Gray band is the theoretical uncertainty which was generated from the replicas for the TMD PFF, Callos, Kang, Terry PRD2020

Compare theory predictions to OPAL & Belle data

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



Gamberg, Kang, Shao,Terry, Zhao arXiv:2102.05553

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

QCD is Parity Conserving TSSAs Scattering plane transverse to spin

Naively "T-odd"

$$\Delta\sigma \sim iS_T \cdot (\mathbf{P} \times P_\perp) \otimes (\text{"}T - odd\text{" QCD} - \text{phases})$$

Spin orbit

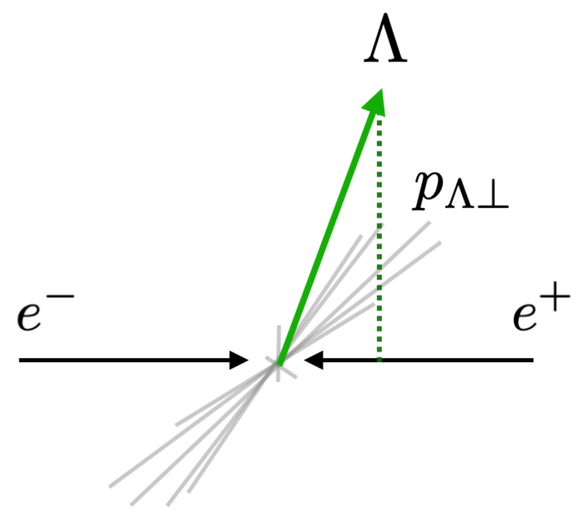
$P_\perp^\Lambda(z_\Lambda, j_\perp)$ for OPAL data [19]: Theory curve is integrated over the region 0.2 $< z_\Lambda <$ 0.5.

total experimental uncertainty vertical error bar $j_\perp$ horizontal error bar.

Error band, standard deviation of the replicas for TMD PFF in Callos, Kang, Terry PRD2020.

Fully inclusive process $e^+e^- \to \Lambda^\uparrow X$

$\Rightarrow$ significant transverse polarization ?



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

Measure w.r.t. COM in principle can measure at Belle ?

Questions/issues:

QCD prediction of Physics twist-3

- Twist-3 factorization one hard scale

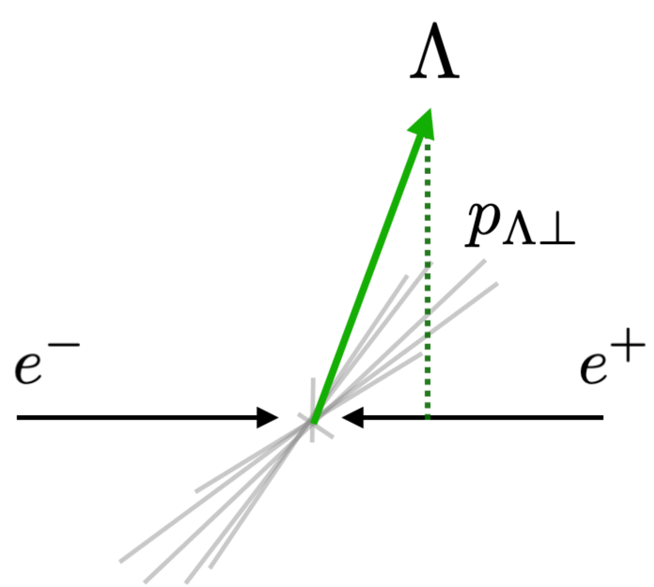
Simplest and cleanest process $e^+e^- \to \Lambda^\uparrow X$

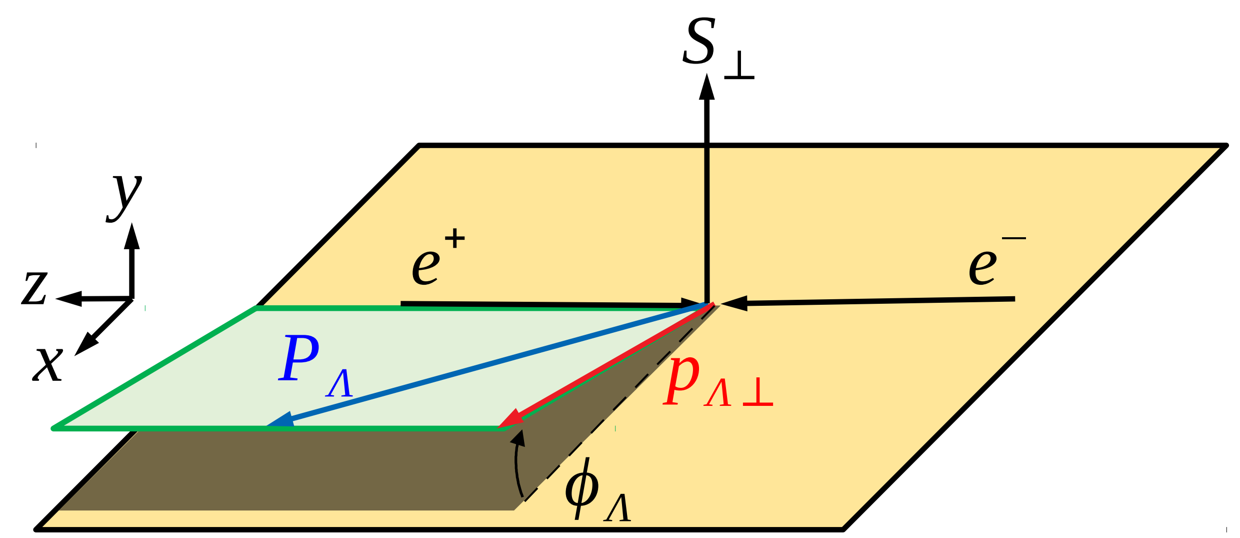
$\Rightarrow$ significant transverse polarization ?

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

$P_{\Lambda\perp} \sim Q$ twist-3 factorization

And can be measured w.r.t. COM of e^+e^- on large scale $P_T \sim Q$



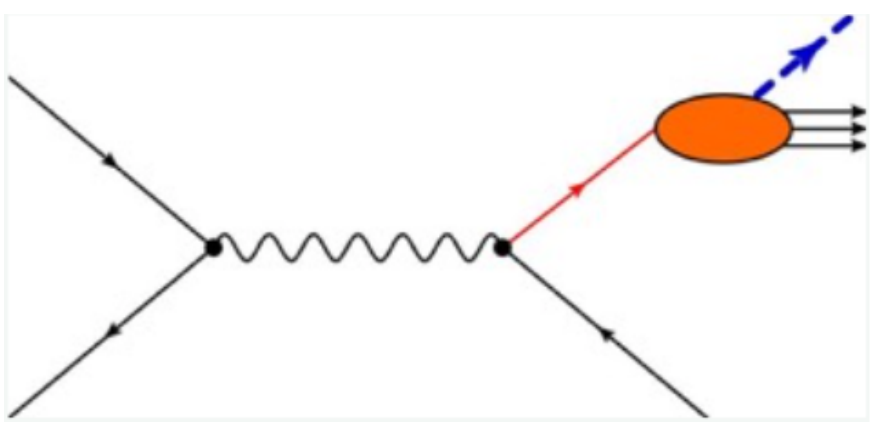


Consider Transverse $e^+e^- \to \Lambda^\uparrow X$ polarization

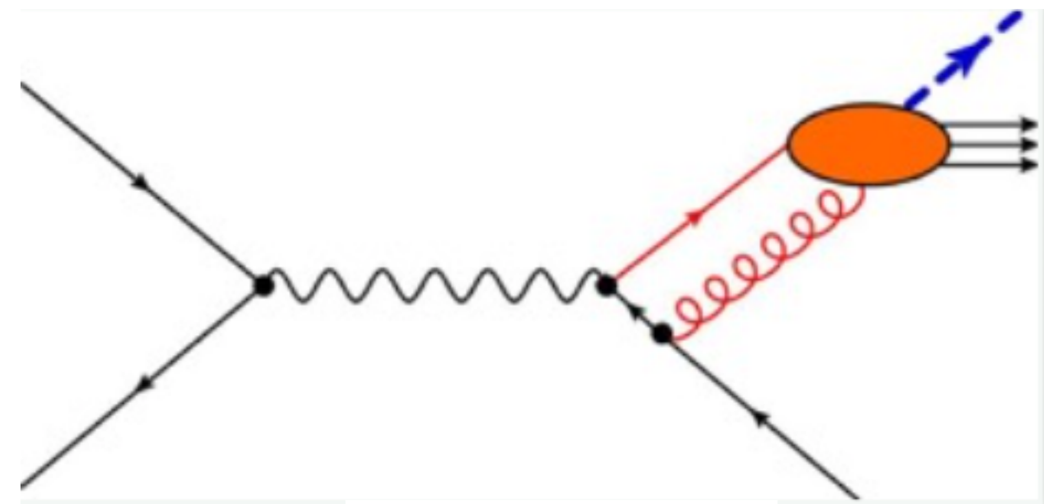
Gamberg, Kang, Pitonyak, Schlegel, Yoshida JHEP 2019, LO & NLO

There are contributions from

'Intrinsic' & 'kinematical' twist-3 FF



Dynamical' twist-3 FF:



Intrinsic Kinematical Dynamical

$$\frac{d\sigma(S_{\Lambda T})}{dz_h\, d\phi} = C\,|S_{\Lambda T}|\sin(\phi_S)\sum_q e_q^2\left[\frac{D_T^{\Lambda/q}(z_h)}{z_h} - D_{1T}^{\perp(1)\Lambda/q}(z_h) + \int_0^1 d\beta\, \frac{\Im[\hat{D}_{FT} - \hat{G}_{FT}]^{\Lambda/q}(z_h, z_h/\beta)}{1-\beta}\right]$$

Using the EOMs and LIRs CS can be expressed soley in terms of $D_T^{\Lambda/q}(z)$

$$\frac{d\sigma(S_{\Lambda T})}{dz_h\, d\phi} = C\,|S_{\Lambda T}|\sin(\phi_S)\sum_q e_q^2\left[2\,\frac{D_T^{\Lambda/q}(z_h)}{z_h}\right]$$

Boer, Jakob, Mulders NPB (1997)
in TMD framework at twist-3

See talk of F. Aslan on the subtleties of applying LIRs and EOMs

Twist - 3 Pheno

$$\frac{d\Delta\sigma}{dz_\Lambda\, d^2p_{\Lambda\perp}} = -\sin(\phi_s - \phi_\Lambda)\sigma_0^{\text{Col}}\left(\frac{8M_\Lambda}{Q}\right)\frac{p_{\Lambda\perp}}{Q}\frac{1}{z_\Lambda^3}\sum_q e_q^2 \frac{D_{T,\Lambda/q}(z_\Lambda, Q)}{z_\Lambda}$$

To describe this process, only need a parameterization for $D_{T,\Lambda/q}(z_\Lambda, Q)$

Given our lack of knowledge of this fundamental twist-3 T-odd fragmentation function we will employ the approach outlined in
Gamberg, Metz, Pitonyak, Prokudin PLB 2017

Re-express the $D_{T,\Lambda/q}(z_\Lambda)$ in terms of our knowledge of $D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda)$

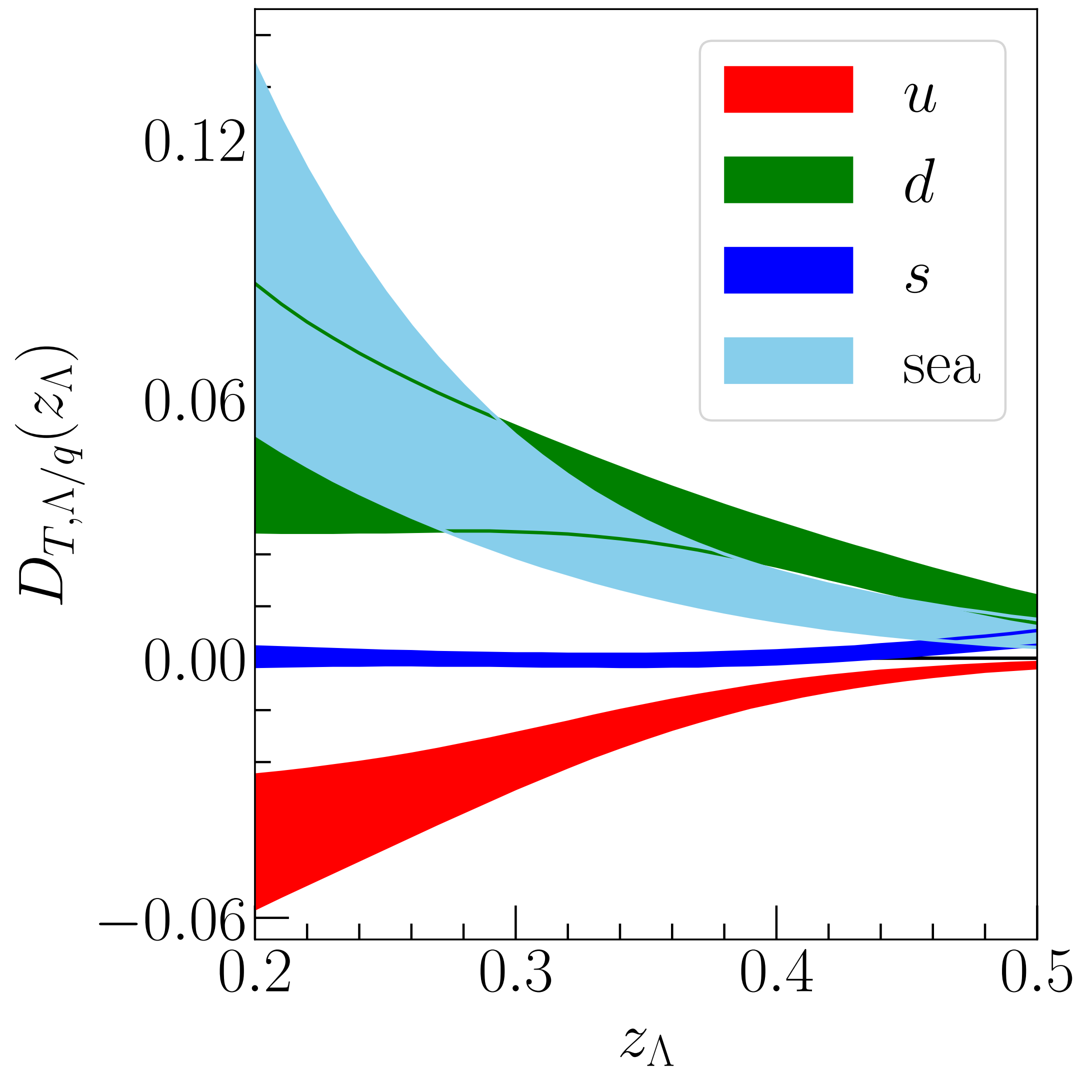
Twist - 3 Pheno

$$\frac{d\Delta\sigma}{dz_\Lambda\, d^2p_{\Lambda\perp}} = -\sin(\phi_s - \phi_\Lambda)\sigma_0^{\mathrm{Col}} \left(\frac{8M_\Lambda}{Q}\right) \frac{p_{\Lambda\perp}}{Q} \frac{1}{z_\Lambda^3} \sum_q e_q^2 \frac{D_{T,\Lambda/q}(z_\Lambda, Q)}{z_\Lambda}$$

Re-express the $D_{T,\Lambda/q}(z_\Lambda)$ in terms of our knowledge of $D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda)$

$$\frac{1}{z_\Lambda} D_{T,\Lambda/q}(z_\Lambda) = -\left(1 - z_\Lambda \frac{d}{dz_\Lambda}\right) D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda) - 2\int_0^1 d\beta \frac{\Im\left[\hat{D}_{FT}^{qg}(z_\Lambda, \beta)\right]}{(1-\beta)^2}$$

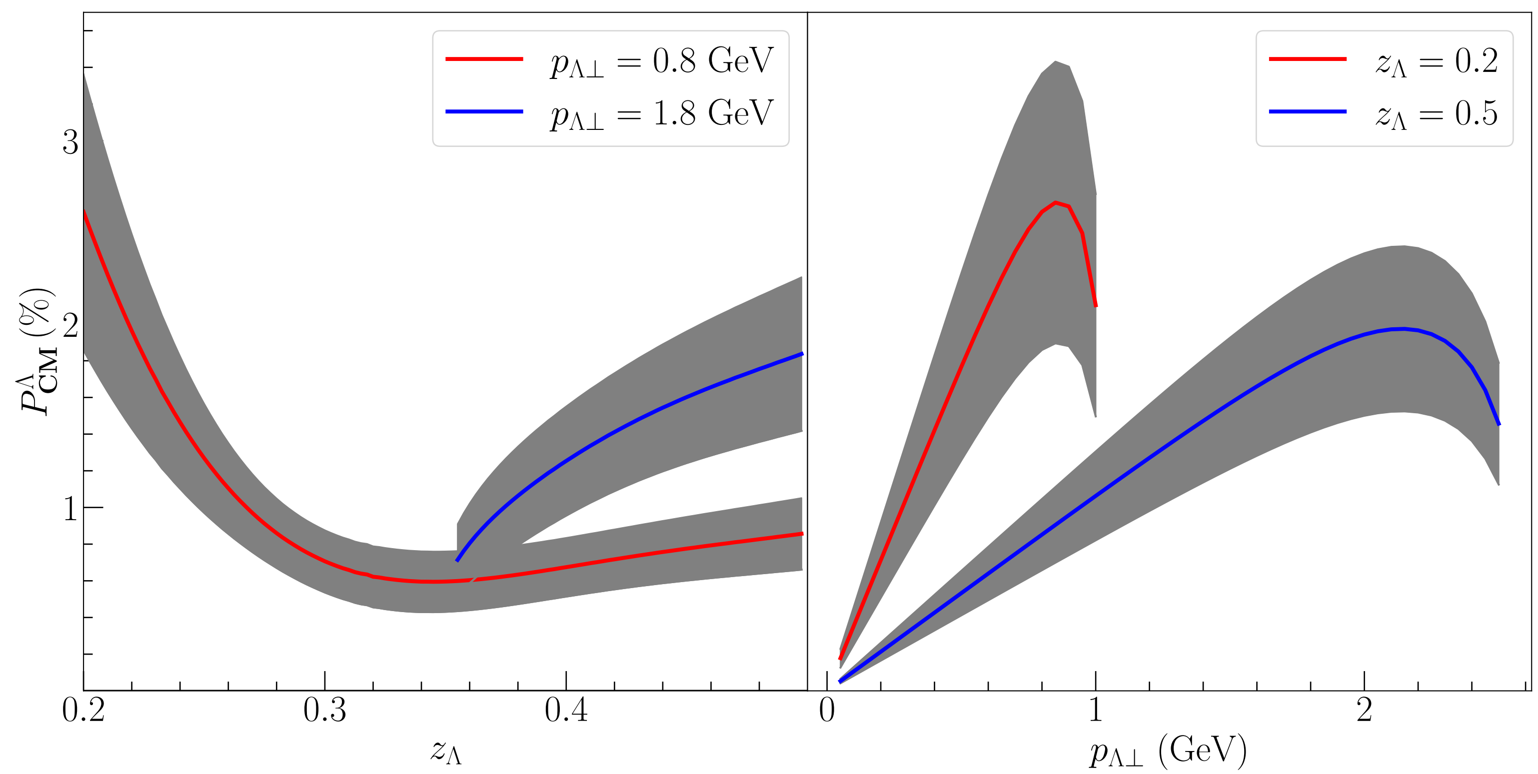
$$\frac{1}{z_\Lambda} D_{T,\Lambda/q}(z_\Lambda) \approx -\left(1 - z_\Lambda \frac{d}{dz_\Lambda}\right) D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda)$$



Prediction for Belle

Gamberg, Kang, Shao,Terry, Zhao arXiv:2102.05553

$$P_{\mathbf{CM}}^{\Lambda}(z_\Lambda, p_{\Lambda\perp}) = \frac{d\Delta\sigma}{dz_\Lambda\, d^2p_{\Lambda\perp}} \Bigg/ \frac{d\sigma}{dz_\Lambda\, d^2p_{\Lambda\perp}}\,.$$



$P_{\mathrm{CM}}^{\Lambda}$ — 3-D plot of the polarization in z_Λ and $p_{\Lambda\perp}$

Center:Plot of the polarization as a function of only z_Λ ,

Right: Plot of the polarization as a function of $p_{\Lambda\perp}$: polarization in our scheme is ~ 1-2%

Plots are generated only using the central fit

The red and blue curves are generated using the central fit, gray band is the theoretical uncertainty

Take aways I

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

- Interesting that while these two measurements probe different distribution functions, they differ only by the definition of the measurement axis.

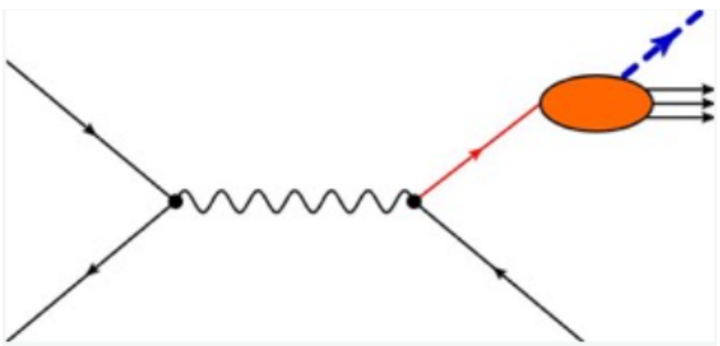
- That is, a measurement the polarization as a function of $j_\perp$ is a useful process for probing the properties of the PFF $D_{1T}^{\perp}$ with respect to the thrust axis

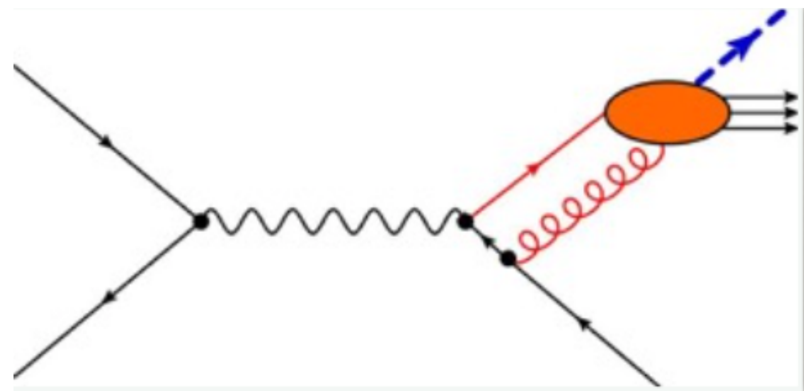
- While a measurement if polarization as a function of $p_{\Lambda\perp}$, the transverse momentum of the Λ in the lepton center-of-mass (COM) frame, is a useful process for probing the D_T function.

- Therefore the polarization in the COM frame can in principle be studied from the existing Belle data by reanalyzing the data for the inclusive $e^+e^- \to \Lambda(\text{Thrust})\,X$ measurement in COM $e^+e^- \to \Lambda\,X$

Single-Transverse $\Lambda^{\uparrow}$ spin asymmetry

Unique effect driven by a single fragmentation function $D_T^{\Lambda/q}(z)$ → absent in DIS (1 γ)





Intrinsic

$$\frac{d\sigma(S_{\Lambda T})}{dz_h\, d\phi} = C\,|S_{\Lambda T}|\sin(\phi_S)\sum_q e_q^2\left[2\,\frac{D_T^{\Lambda/q}(z_h)}{z_h}\right]$$

See also Boer, Jakob, Mulders NPB (1997)

n.b. **some intuition …**

Consider crossing this process to inclusive DIS for transverse polarised target

Would have the function $f_T^{q/\Lambda}(x)$, $\frac{d\sigma(S_{\Lambda\,T})}{dx d\phi} \sim \sin(\phi_S)\sum_q e_q^2 f_T^{q/\Lambda}(x) = 0 \quad !!!$

Constraints from time reversal on quark correlation function

Goeke, Metz, Schlegel PLB 2006, Bacchetta et al JHEP 2007, Christ & Lee 1960

A unique test of time reversal in QCD: Non-zero intrinsic

Unique effect driven by a single fragmentation function $D_T^{\Lambda/q}(z)$ $\rightarrow$ absent in DIS (1 γ)

Single-Transverse $\Lambda^{\uparrow}$ spin asymmetry

$$\frac{d\sigma(S_{\Lambda T})}{dz_h\, d\phi} = C\,|S_{\Lambda T}|\sin(\phi_S)\sum_q e_q^2\left[2\,\frac{D_T^{\Lambda/q}(z_h)}{z_h}\right]$$

$$\frac{d\sigma(S_{\Lambda\, T})}{dxd\phi} \sim \sin(\phi_S)\sum_q e_q^2 f_T^{q/\Lambda}(x) = 0 \quad !!! \qquad f_T^{q/\Lambda}(x)$$

Constraints from time reversal on quark correlation function
Goeke, Metz, Schlegel PLB 2006, Bacchetta et al JHEP 2007, Christ & Lee 1960

Take aways II

- Non-zero $e^+e^- \to \Lambda^\uparrow X$ inclusive result is an indication that there are no gluonic poles in ffs, ie time reversal is not a constraint on FFs: the simplest process is an interesting a test of time reversal in QCD, $D_T^{\Lambda/q} \neq 0$

- We are performing a test of twist-3 factorisation at NLO in
$e^+e^- \to \Lambda^\uparrow X$

- Would be great if Belle carried out a fully inclusive measurement to directly test $D_T^{\Lambda/q} \neq 0$