Workshop "3D Parton Distributions: path to the LHC", Nov. 30, 2016, Frascati, Italy

Spin physics at LHC

Marc Schlegel
Institute for Theoretical Physics
University of Tübingen

Possibilities for spin physics at the LHC?

Possibilities for spin physics at the LHC?

LHC proton beams are unpolarized
→ no spin in the *initial* states (Exception: AFTER@LHC)

Possibilities for spin physics at the LHC?

LHC proton beams are unpolarized
→ no spin in the *initial* states (Exception: AFTER@LHC)

"Internal" spin of quarks, gluons, resonances, …
→ angular / azimuthal modulations
→ e.g., linear gluon polarization (talks by Boer, Pisano, …)

Possibilities for spin physics at the LHC?

LHC proton beams are unpolarized
→ no spin in the *initial* states (Exception: AFTER@LHC)

"Internal" spin of quarks, gluons, resonances, …
→ angular / azimuthal modulations
→ e.g., linear gluon polarization (talks by Boer, Pisano, …)

"External" spin of particles in the *final* state
→ decay products of the particle, e.g., J/ψ, Λ_s-hyperon …

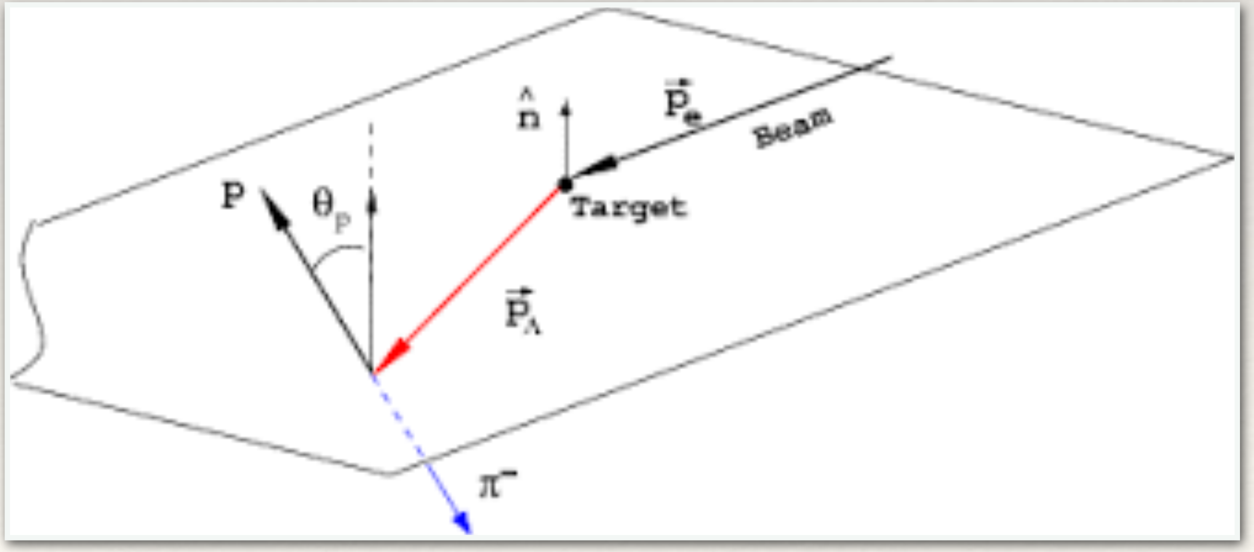
Possibilities for spin physics at the LHC?

LHC proton beams are unpolarized
→ no spin in the *initial* states (Exception: AFTER@LHC)

"Internal" spin of quarks, gluons, resonances, …
→ angular / azimuthal modulations
→ e.g., linear gluon polarization (talks by Boer, Pisano, …)

"External" spin of particles in the *final* state
→ decay products of the particle, e.g., J/ψ, Λ_S-hyperon …

Measurement of Λ-spin through decay $\Lambda \longrightarrow p\pi^-$



- 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

Transverse Λ polarization in pA: long history…

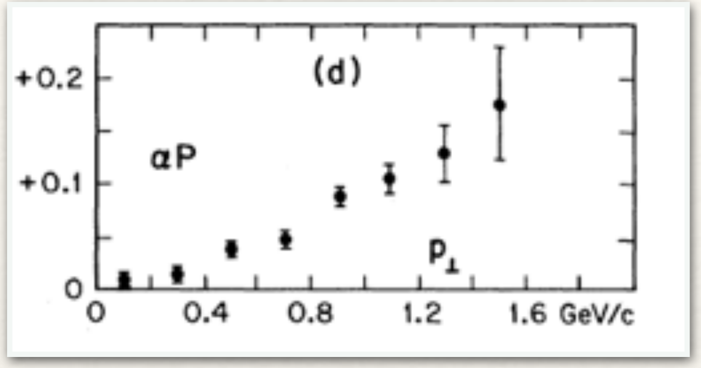
One of the first transverse spin effects at Fermilab (1976): $p+Be \longrightarrow \Lambda^0+X$

and many more follow-up measurements with 300 - 800 GeV proton beams (E799)

Transverse Λ polarization in pA: long history…

One of the first transverse spin effects at Fermilab (1976): p+Be⟶Λ^0+X

and many more follow-up measurements with 300 - 800 GeV proton beams (E799)

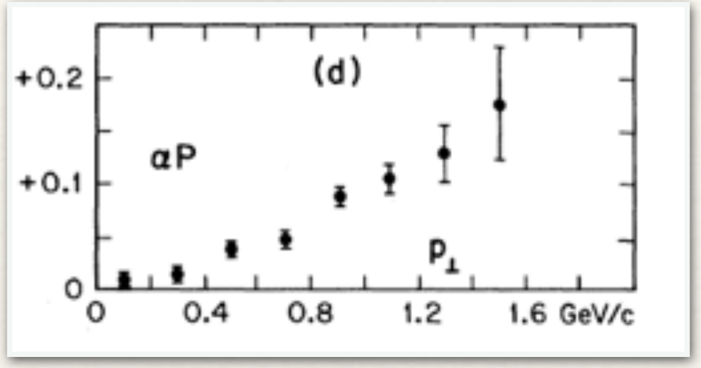


Λ polarization was found to be sizeable!

Transverse Λ polarization in pA: long history…

One of the first transverse spin effects at Fermilab (1976): p+Be⟶Λ^0+X

and many more follow-up measurements with 300 - 800 GeV proton beams (E799)



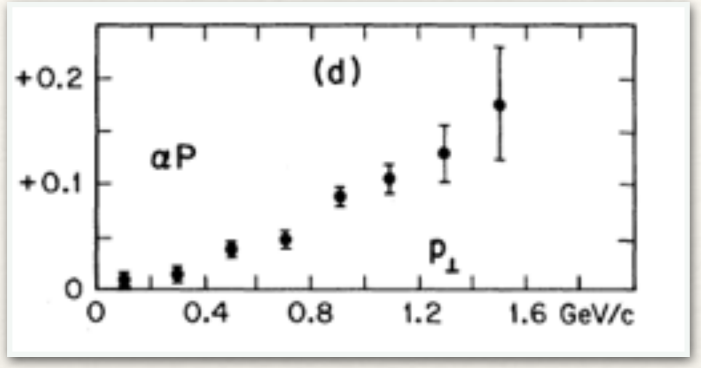
Λ polarization was found to be sizeable!

… and at CERN SPS (NA48 1998): p+N⟶Λ^0+X (450 GeV)

Transverse Λ polarization in pA: long history…

One of the first transverse spin effects at Fermilab (1976): p+Be⟶Λ^0+X

and many more follow-up measurements with 300 - 800 GeV proton beams (E799)



Λ polarization was found to be sizeable!

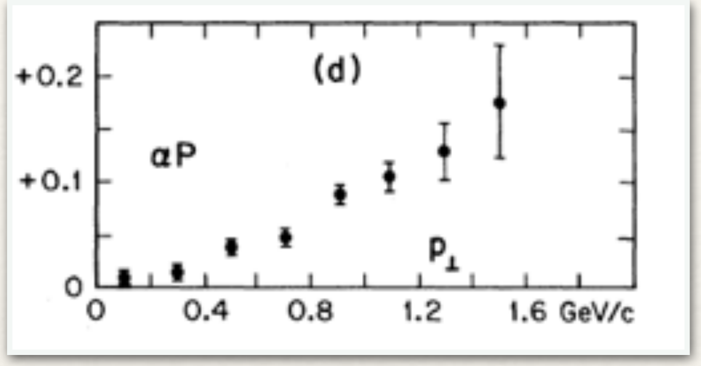
… and at CERN SPS (NA48 1998): p+N⟶Λ^0+X (450 GeV)

… and at HERA-B (2006): p+(C,W)⟶Λ^0+X (950 GeV)

Transverse Λ polarization in pA: long history…

One of the first transverse spin effects at Fermilab (1976): p+Be⟶Λ^0+X

and many more follow-up measurements with 300 - 800 GeV proton beams (E799)



Λ polarization was found to be sizeable!

… and at CERN SPS (NA48 1998): p+N⟶Λ^0+X (450 GeV)

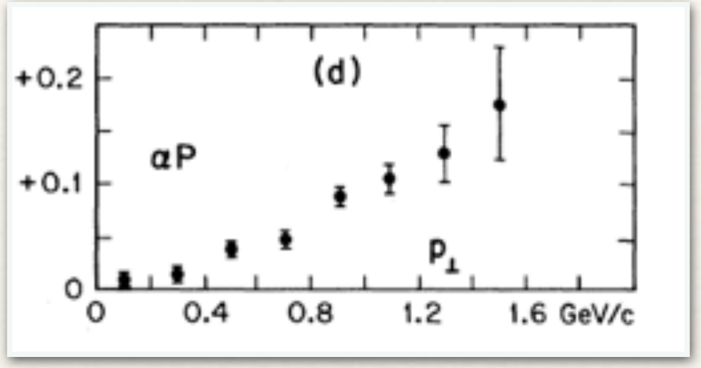
… and at HERA-B (2006): p+(C,W)⟶Λ^0+X (950 GeV)

What about LHC? Is it feasible at a high energy collider?

Transverse Λ polarization in pA: long history…

One of the first transverse spin effects at Fermilab (1976): p+Be⟶Λ^0+X

and many more follow-up measurements with 300 - 800 GeV proton beams (E799)

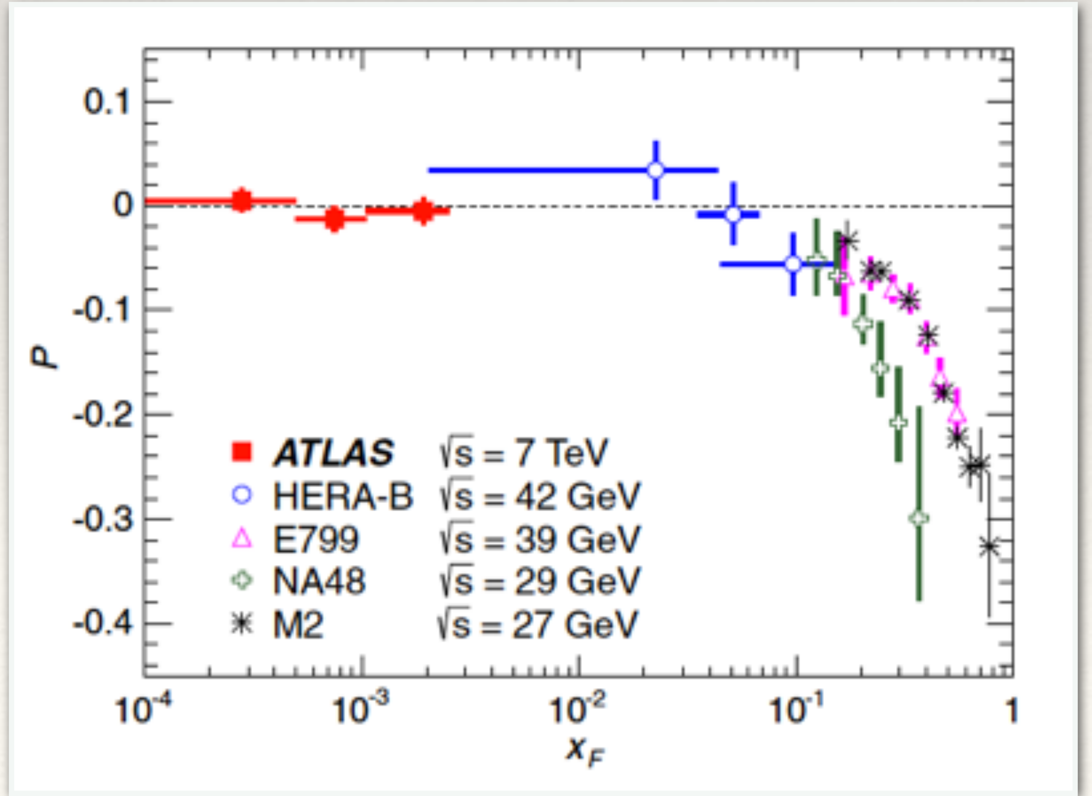


Λ polarization was found to be sizeable!

… and at CERN SPS (NA48 1998): p+N⟶Λ^0+X (450 GeV)

… and at HERA-B (2006): p+(C,W)⟶Λ^0+X (950 GeV)

What about LHC? Is it feasible at a high energy collider?



Recent ATLAS measurement at √S = 7 TeV

[ATLAS, PRD 91, 032004 (2015)]

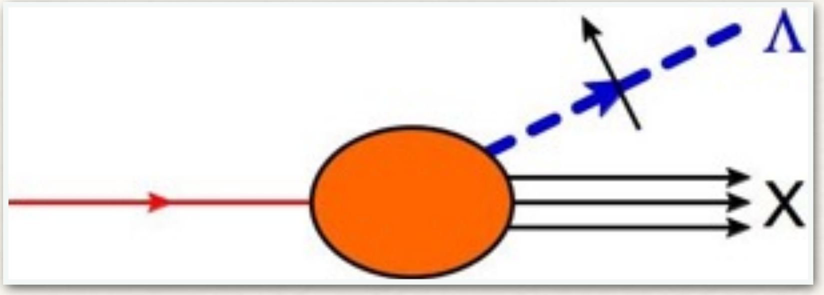
Polarization small $P^\Lambda \sim 1\%$

Λ polarization at LHC possible

Can Λ polarization be useful for LHC physics?

Tool in particle physics?

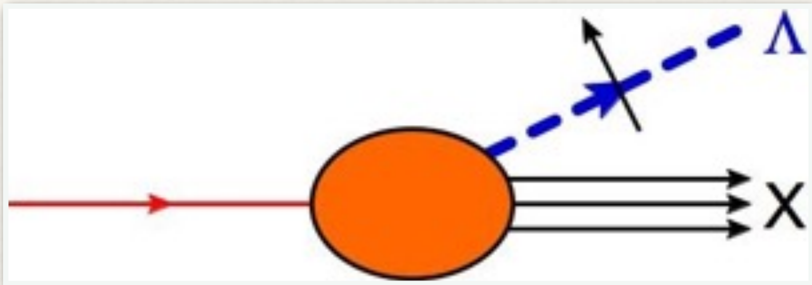
Perturbative QCD: Λ fragmentation



parton $\longrightarrow$ Λ + X transition:

$$\langle P_\Lambda, S_\Lambda; X |\, \bar{q}(0)\, |0\rangle$$

Perturbative QCD: Λ fragmentation



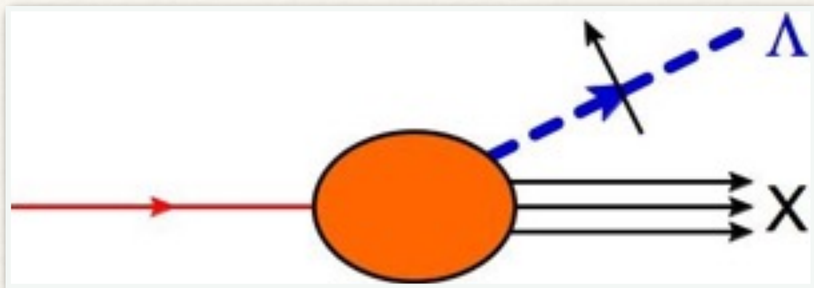
parton $\longrightarrow$ Λ + X transition:

$$\langle P_\Lambda , S_\Lambda ; X | \, \bar{q}(0) \, |0\rangle$$

'square of the amplitude'

$$\Delta_{ij}(z) = \frac{1}{N_c} \sum_X \int \frac{d\lambda}{2\pi} \, \mathrm{e}^{-i\frac{\lambda}{z}} \, \langle 0| \, [\infty m, 0] \, q_i(0) | P_\Lambda , S_\Lambda ; X \rangle \langle P_\Lambda , S_\Lambda ; X | \, \bar{q}_j(\lambda m) [\lambda m, \infty m] \, |0\rangle$$

Perturbative QCD: Λ fragmentation



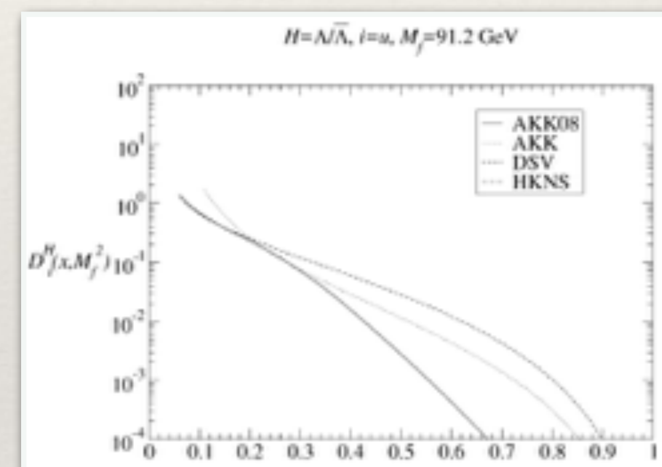
parton $\longrightarrow$ Λ + X transition:

$$\langle P_\Lambda, S_\Lambda; X | \, \bar{q}(0) \, |0\rangle$$

'square of the amplitude'

$$\Delta_{ij}(z) = \frac{1}{N_c} \sum_X \int \frac{d\lambda}{2\pi} \, \mathrm{e}^{-i\frac{\lambda}{z}} \, \langle 0| \, [\infty m, 0] \, q_i(0) | P_\Lambda, S_\Lambda; X\rangle \langle P_\Lambda, S_\Lambda; X | \, \bar{q}_j(\lambda m) [\lambda m, \infty m] \, |0\rangle$$

Λ fragmentation functions

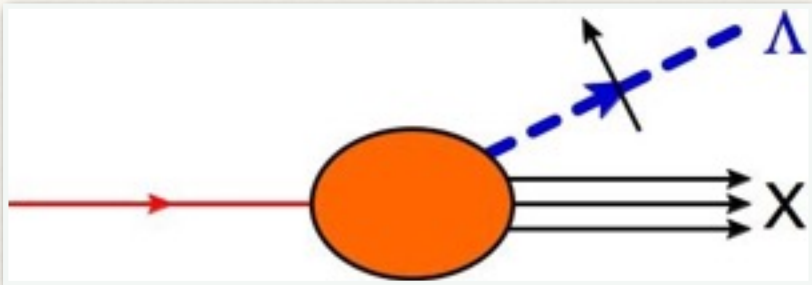


$$D_1^{\Lambda/q}(z)$$

FF of unpolarized q $\longrightarrow$ Λ:

fairly known [fits by AKK08, DSV, …]

Perturbative QCD: Λ fragmentation



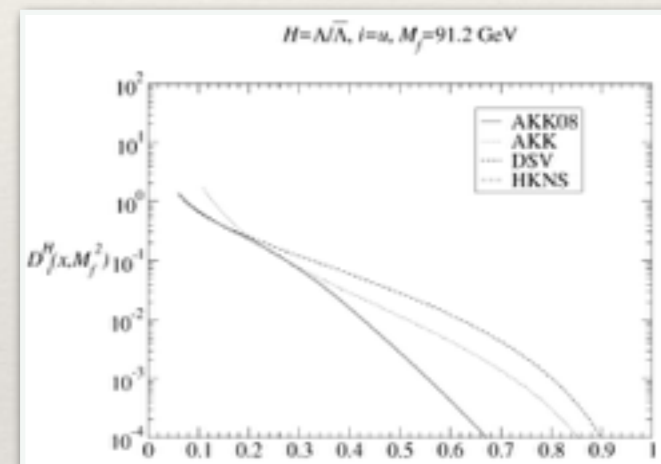
parton $\longrightarrow$ Λ + X transition:

$$\langle P_\Lambda, S_\Lambda; X | \, \bar{q}(0) \, |0\rangle$$

'square of the amplitude'

$$\Delta_{ij}(z) = \frac{1}{N_c} \sum_X \int \frac{d\lambda}{2\pi} \, \mathrm{e}^{-i\frac{\lambda}{z}} \, \langle 0| \, [\infty m, 0] \, q_i(0) | P_\Lambda, S_\Lambda; X \rangle \langle P_\Lambda, S_\Lambda; X | \, \bar{q}_j(\lambda m) [\lambda m, \infty m] \, |0\rangle$$

Λ fragmentation functions



$$D_1^{\Lambda/q}(z)$$

FF of unpolarized q $\longrightarrow$ Λ:

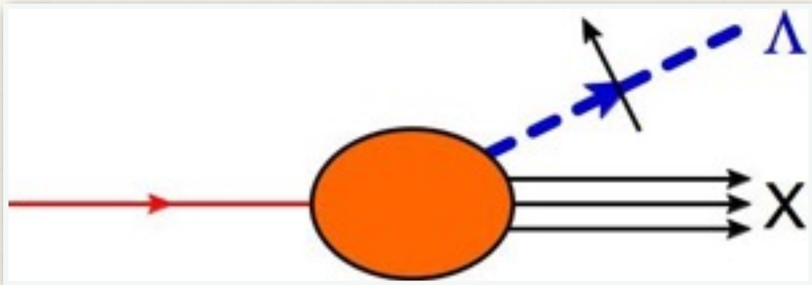
fairly known [fits by AKK08, DSV, ...]

$$G_1^{\Lambda/q}(z)$$

FF of longitudinally pol. q $\longrightarrow$ Λ:

poorly known [attempts by DSV to fit LEP data]

Perturbative QCD: Λ fragmentation



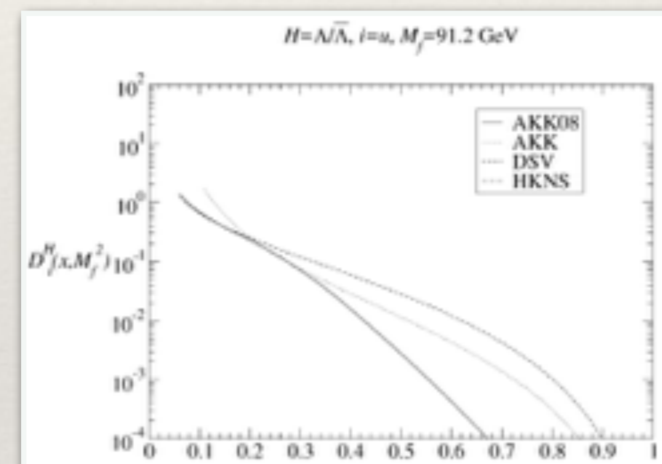
parton $\longrightarrow$ Λ + X transition:

$$\langle P_\Lambda, S_\Lambda; X|\, \bar{q}(0)\, |0\rangle$$

'square of the amplitude'

$$\Delta_{ij}(z) = \frac{1}{N_c} \sum_X \int \frac{d\lambda}{2\pi}\, \mathrm{e}^{-i\frac{\lambda}{z}}\, \langle 0|\, [\infty m, 0]\, q_i(0) |P_\Lambda, S_\Lambda; X\rangle \langle P_\Lambda, S_\Lambda; X|\, \bar{q}_j(\lambda m) [\lambda m, \infty m]\, |0\rangle$$

Λ fragmentation functions



$D_1^{\Lambda/q}(z)$

FF of unpolarized q $\longrightarrow$ Λ:

fairly known [fits by AKK08, DSV, …]

$G_1^{\Lambda/q}(z)$

FF of longitudinally pol. q $\longrightarrow$ Λ:

poorly known [attempts by DSV to fit LEP data]

$H_1^{\Lambda/q}(z)$

FF of transversely pol. q $\longrightarrow$ Λ:

unknown, chiral-odd, hard to extract from single-inclusive processes

Candidate to explain large transverse Λ polarization?

Collinear Twist-3 formalism

'intrinsic' twist-3 FF with transverse spin: $G_T^{\Lambda/q}(z)$ $D_T^{\Lambda/q}(z)$

Collinear Twist-3 formalism

'intrinsic' twist-3 FF with transverse spin: $G_T^{\Lambda/q}(z)$ $D_T^{\Lambda/q}(z)$

'kinematic' twist-3 FF with transverse spin:

$$\Delta_\partial^\alpha(z) = \int d^2p_T\, p_T^\alpha\, \Delta(z, zp_T) \longrightarrow G_{1T}^{\perp(1),\Lambda/q}(z) \quad D_{1T}^{\perp(1),\Lambda/q}(z)$$

Collinear Twist-3 formalism

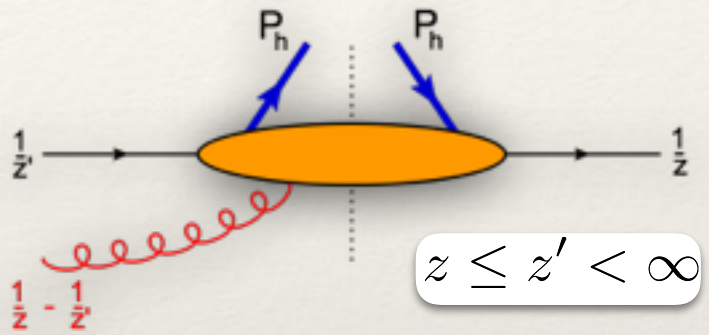
'intrinsic' twist-3 FF with transverse spin: $G_T^{\Lambda/q}(z)$ $D_T^{\Lambda/q}(z)$

'kinematic' twist-3 FF with transverse spin:

$$\Delta_\partial^\alpha(z) = \int d^2p_T\, p_T^\alpha\, \Delta(z, zp_T) \longrightarrow G_{1T}^{\perp(1),\Lambda/q}(z) \quad D_{1T}^{\perp(1),\Lambda/q}(z)$$

'dynamical' twist-3 FF with transverse spin:

$$\Delta_F^\alpha(z,z') \sim \langle 0|\, q(\lambda m)\, gF^{m\alpha}(\mu m)|P_\Lambda, S_\Lambda; X\rangle\langle P_\Lambda, S_\Lambda; X|\, \bar{q}(0)\,|0\rangle$$
$$\Longrightarrow \hat{D}_{FT}^{\Lambda/q}(z,z')\,,\ \hat{G}_{FT}^{\Lambda/q}(z,z')$$



$z \leq z' < \infty$

complex functions: $FF(z,z)=0$ $FF(z,0)=0$ $\frac{\partial}{\partial z'}FF(z,z')\Big|_{z'=z}=0$

Collinear Twist-3 formalism

'intrinsic' twist-3 FF with transverse spin: $G_T^{\Lambda/q}(z)$ $D_T^{\Lambda/q}(z)$

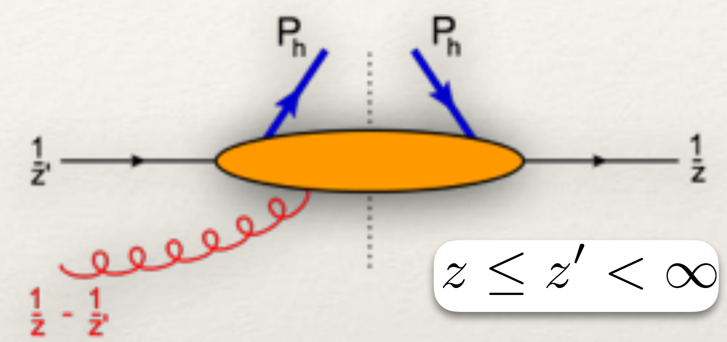
'kinematic' twist-3 FF with transverse spin:

$$\Delta_\partial^\alpha(z) = \int d^2p_T\, p_T^\alpha\, \Delta(z, zp_T) \longrightarrow G_{1T}^{\perp(1),\Lambda/q}(z) \quad D_{1T}^{\perp(1),\Lambda/q}(z)$$

'dynamical' twist-3 FF with transverse spin:

$$\Delta_F^\alpha(z,z') \sim \langle 0|\, q(\lambda m)\, gF^{m\alpha}(\mu m) |P_\Lambda, S_\Lambda; X\rangle\langle P_\Lambda, S_\Lambda; X|\, \bar{q}(0)\, |0\rangle$$

$$\Longrightarrow \hat{D}_{FT}^{\Lambda/q}(z,z'),\ \hat{G}_{FT}^{\Lambda/q}(z,z')$$



$$z \le z' < \infty$$

complex functions: $FF(z,z) = 0$ $\quad FF(z,0) = 0$ $\quad \frac{\partial}{\partial z'} FF(z,z')\Big|_{z'=z} = 0$

Relations: Equation of Motion & Lorentz-Invariance

[Kanazawa, Koike, Metz, Pitonyak, MS, PRD 93, 054024 (2016)]

$$D_{1T}^{\perp(1)}(z) + \frac{D_T(z)}{z} = \int_0^1 d\beta \frac{\Im[\hat{D}_{FT}(z,z/\beta)] - \Im[\hat{G}_{FT}(z,z/\beta)]}{1-\beta}$$

$$G_{1T}^{\perp(1)}(z) - \frac{G_T(z)}{z} = \int_0^1 d\beta \frac{\Re[\hat{D}_{FT}(z,z/\beta)] - \Re[\hat{G}_{FT}(z,z/\beta)]}{1-\beta}$$

$$\frac{D_T(z)}{z} = -\left(1 - z\frac{d}{dz}\right) D_{1T}^{\perp(1)}(z) - 2\int_0^1 d\beta \frac{\Im[\hat{D}_{FT}(z,z/\beta)]}{(1-\beta)^2}$$

$$\frac{G_T(z)}{z} = \frac{G_1(z)}{z} + \left(1 - z\frac{d}{dz}\right) G_{1T}^{\perp(1)}(z) - 2\int_0^1 d\beta \frac{\Re[\hat{G}_{FT}(z,z/\beta)]}{(1-\beta)^2}$$

Two equations, three functions → eliminate 'intrinsic & kinematical twist-3'

Single inclusive Λ production in e^+e^- - annihilation

$(e^+e^- \longrightarrow \Lambda X)$

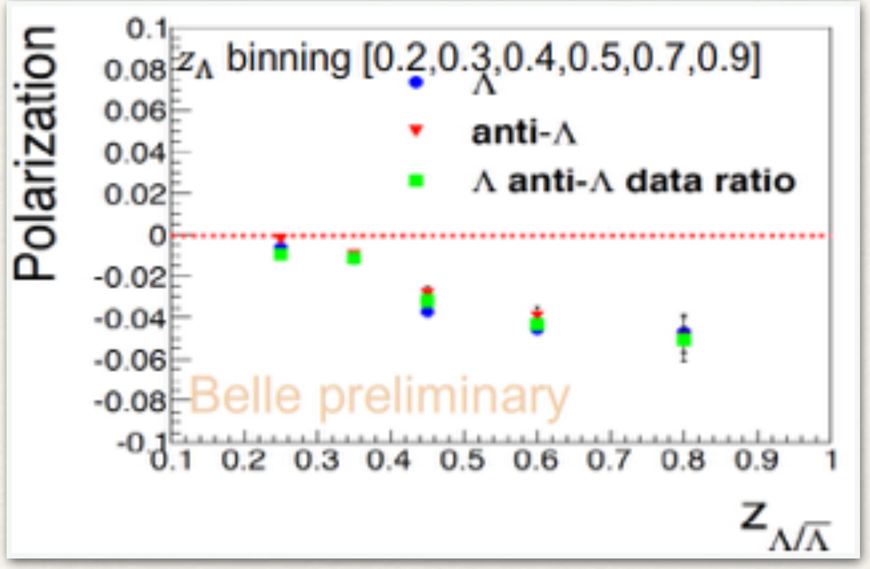
$\sqrt{S} \gg \Lambda_{QCD}$

Simplest and cleanest process to study fragmentation…

Experimental status:

- OPAL at LEP on Z-pole [Eur.Phys.J C2, 49 (1998)]:
  Longitudinal Polarization,
  no significant Transverse Polarization

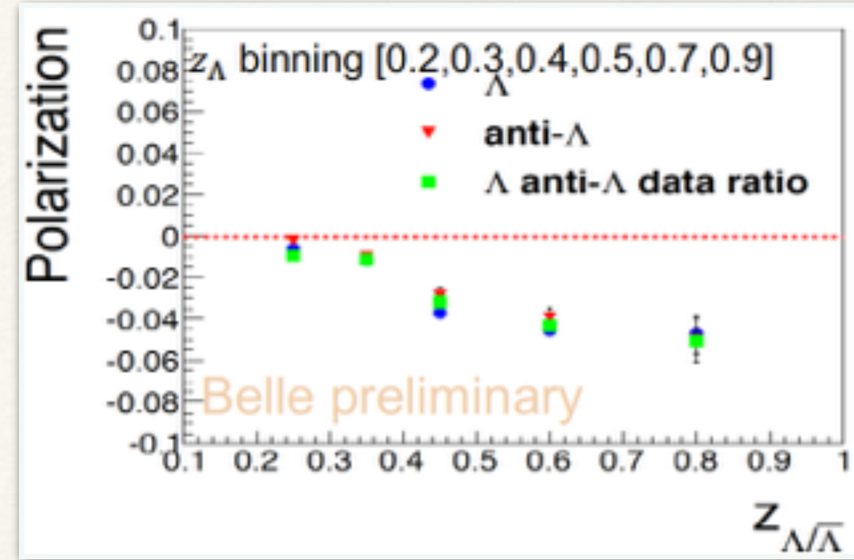
- Preliminary Belle data: Transverse Polarization
  [Yinghui Guan, SPIN 2016]



Experimental status:

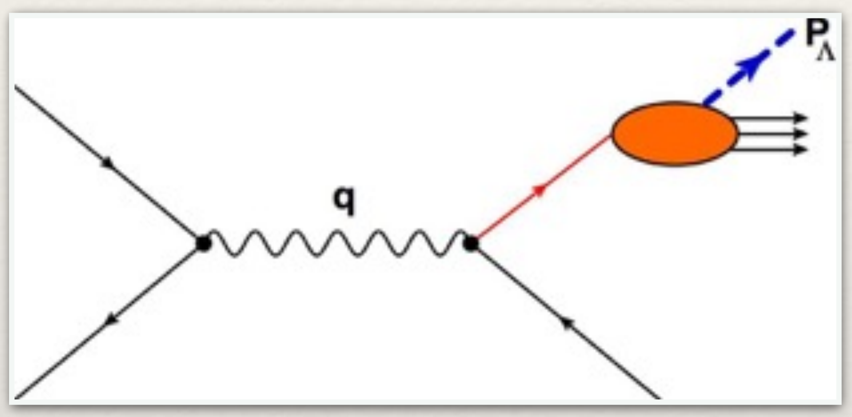
- OPAL at LEP on Z-pole [Eur.Phys.J C2, 49 (1998)]:
  Longitudinal Polarization,
  no significant Transverse Polarization

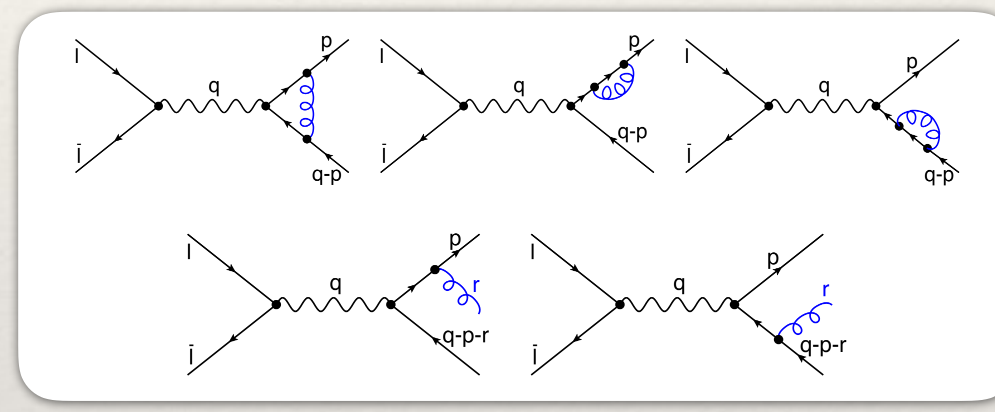
- Preliminary Belle data: Transverse Polarization
  [Yinghui Guan, SPIN 2016]



Theory at LO & NLO

$$z_h = \frac{2P_\Lambda \cdot q}{q^2}$$





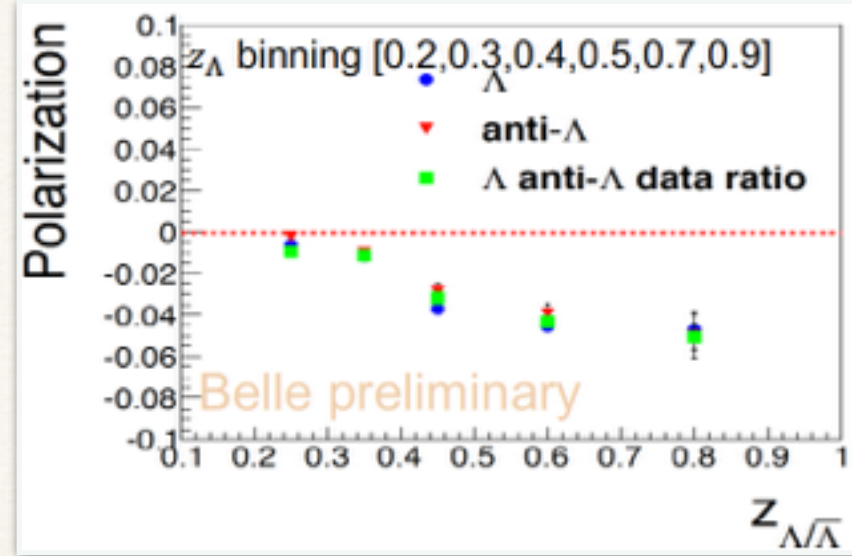
"Parton Model like" observables at LO

$$\frac{d\sigma}{\sigma\, dz_h} \propto \sum_q e_q^2\, z_h\, D_1^{\Lambda/q}(z_h)$$

$$\Delta\sigma \propto \lambda_\Lambda \sum_q e_q^2\, z_h\, G_1^{\Lambda/q}(z_h)$$

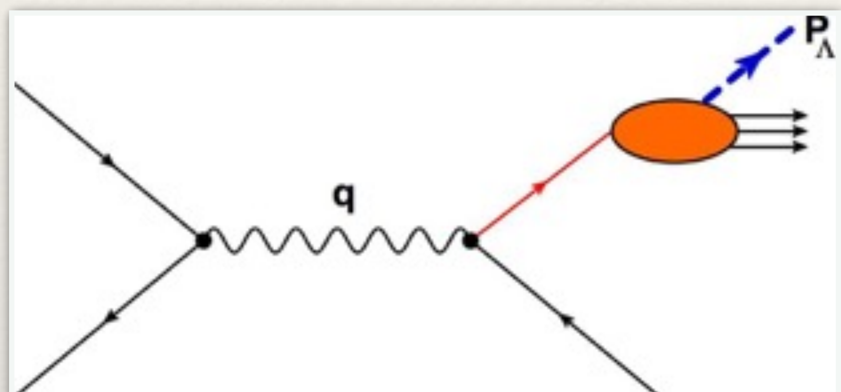
Experimental status:

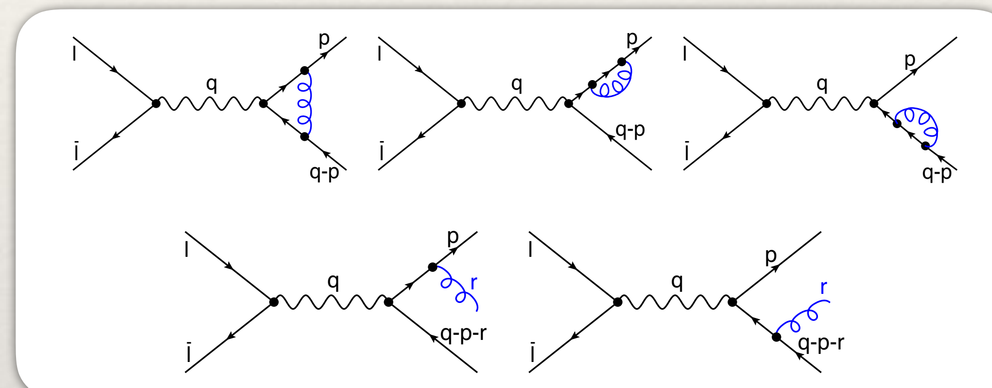
- OPAL at LEP on Z-pole [Eur.Phys.J C2, 49 (1998)]: Longitudinal Polarization, no significant Transverse Polarization
- Preliminary Belle data: Transverse Polarization [Yinghui Guan, SPIN 2016]



Theory at LO & NLO

$$z_h = \frac{2P_\Lambda \cdot q}{q^2}$$





"Parton Model like" observables at LO

$$\frac{d\sigma}{\sigma\, dz_h} \propto \sum_q e_q^2\, z_h\, D_1^{\Lambda/q}(z_h)$$

$$\Delta\sigma \propto \lambda_\Lambda \sum_q e_q^2\, z_h\, G_1^{\Lambda/q}(z_h)$$

NLO:

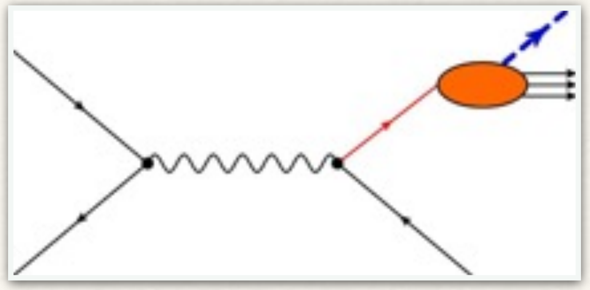
$$\left(\frac{d\sigma}{\sigma\, dz_h}\right)_{\rm NLO} \propto \sum_q e_q^2 \int_{z_h}^1 \frac{dw}{w}\, \hat{\sigma}^{\overline{\rm MS}}(w, s/\mu^2) D_1^{\Lambda/q}(z_h/w, \mu)$$

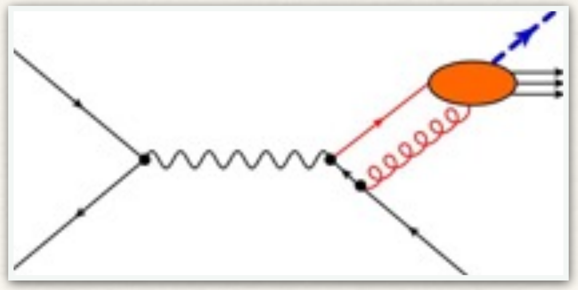
$$(\Delta\sigma)_{\rm NLO} \propto \lambda_\Lambda \sum_q e_q^2 \int_{z_h}^1 \frac{dw}{w}\, \Delta\hat{\sigma}^{\overline{\rm MS}}(w, s/\mu^2)\, G_1^{\Lambda/q}(z_h/w, \mu)$$

Typical NLO features:

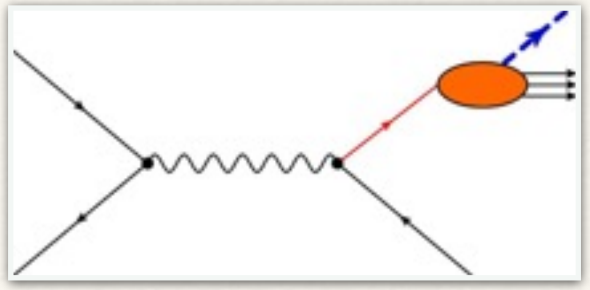
- infrared safe (cancellation of $1/\varepsilon^2$ - poles in dim. reg.)
- MSbar renormalization of fragmentation functions → DGLAP evolution

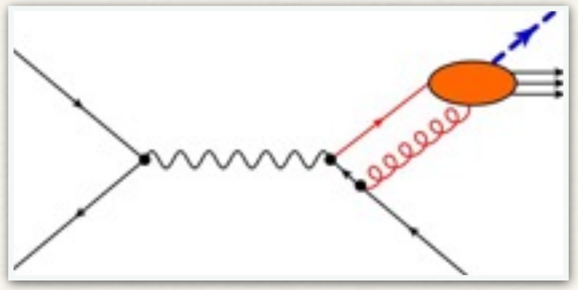
Transverse Λ polarization at LO





Transverse Λ polarization at LO





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

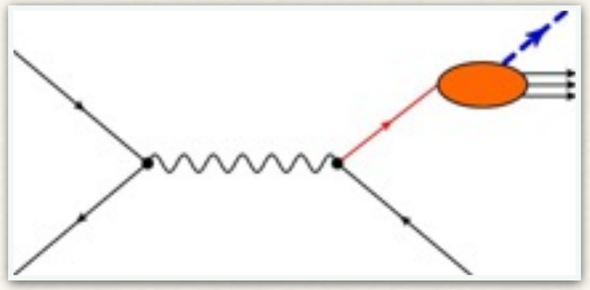
→ Equation of Motion:

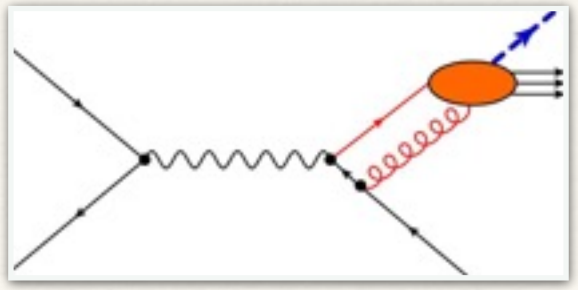
$$\frac{d\sigma(S_{\Lambda T})}{dz_h\, d\phi} = C\, |S_{\Lambda T}| \sin(\phi_S) \sum_q e_q^2 \left[2\, \frac{D_T^{\Lambda/q}(z_h)}{z_h} \right]$$

Single-Transverse Λ Spin observable

- Unique effect driven by a single fragmentation function D_T → absent in DIS (1γ)
- to do: fit to Belle data → first information on D_T

Transverse Λ polarization at LO





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

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

Single-Transverse Λ Spin observable

- Unique effect driven by a single fragmentation function D_T → absent in DIS (1γ)
- to do: fit to Belle data → first information on D_T

$$\Delta\sigma(S_{\Lambda T}) = C\ |S_{\Lambda T}| \cos(\phi_S) \sum_q e_q^2 \left[\frac{G_T^{\Lambda/q}(z_h)}{z_h} + G_{1T}^{\perp(1)\Lambda/q}(z_h) - \int_0^1 d\beta\, \frac{\Re[\hat{D}_{FT} - \hat{G}_{FT}]^{\Lambda/q}(z_h, z_h/\beta)}{1-\beta} \right]$$

→ Equation of Motion: $$\Delta\sigma(S_{\Lambda T}) = C\ |S_{\Lambda T}| \cos(\phi_S) \sum_q e_q^2 \left[2\, \frac{G_T^{\Lambda/q}(z_h)}{z_h} \right]$$

→ LIR: $$\Delta\sigma(S_{\Lambda T}) = 2\, C\ |S_{\Lambda T}| \cos(\phi_S) \sum_q e_q^2 \left[\int_{z_h}^1 \frac{dw}{w}\, \frac{G_1^{\Lambda/q}(z_h/w)}{z_h/w} + \int (\ldots\Re[\hat{D}_{FT}] + \ldots\Re[\hat{G}_{FT}]) \right]$$

Double Longitudinal Lepton - Transverse Λ Spin observable

- Effect driven by a single fragmentation function G_T → present in DIS (g_2)
- Wandzura-Wilczek approximation: valid for fragmentation as well?

Transverse Λ polarization at NLO

[Gamberg, Kang, M.S., Xing, Yoshida, work in progress]

- Study the NLO dynamics for twist-3 fragmentation in the simplest process
- Different compared to twist-3 distributions (no pole contributions)

Transverse Λ polarization at NLO

[Gamberg, Kang, M.S., Xing, Yoshida, work in progress]

- Study the NLO dynamics for twist-3 fragmentation in the simplest process
- Different compared to twist-3 distributions (no pole contributions)

Virtual & Real diagrams (qg/q - channel only)

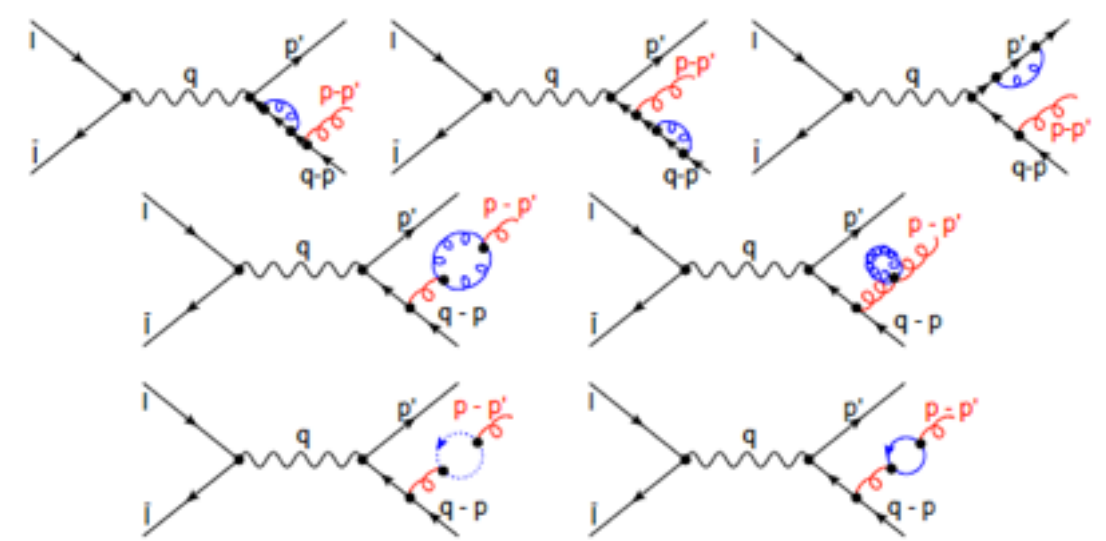


Figure 6: Self-energy corrections

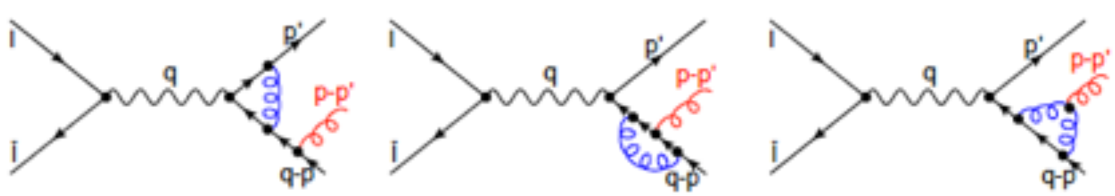


Figure 7: Vertex corrections

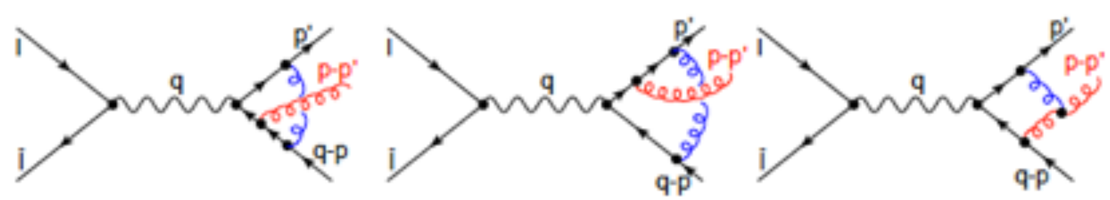


Figure 8: Box corrections

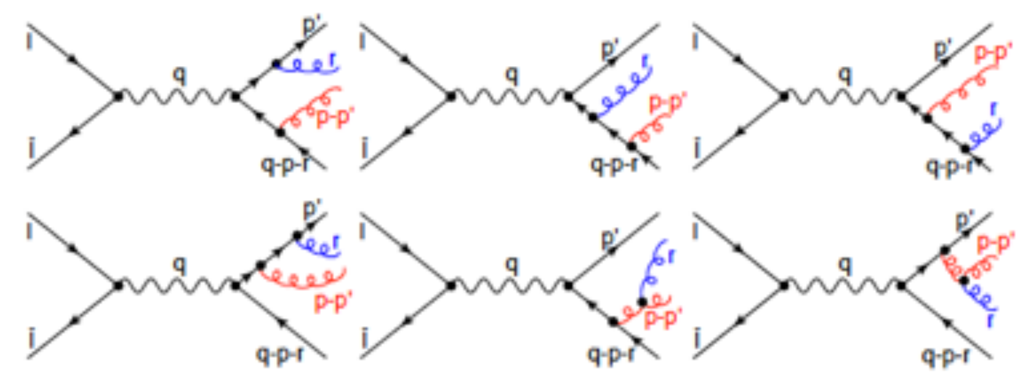


Figure 9: Real corrections

- E.o.M. - and L.I.R. relations are crucial: Combine 'intrinsic', 'kinematical' & 'dynamical' twist-3 contributions
- Imaginary parts: In the dynamical fragmentation process & loop diagrams
- Infrared $1/\varepsilon^2$ - poles cancel ✔
- $1/\varepsilon$ - poles of imaginary parts of loops cancel through E.o.M. ✔
- $1/\varepsilon$ - collinear poles of real parts of loops through MSbar - renormalization

Transverse Λ polarization at NLO

[Gamberg, Kang, M.S., Xing, Yoshida, work in progress]

- Study the NLO dynamics for twist-3 fragmentation in the simplest process
- Different compared to twist-3 distributions (no pole contributions)

Virtual & Real diagrams (qg/q - channel only)

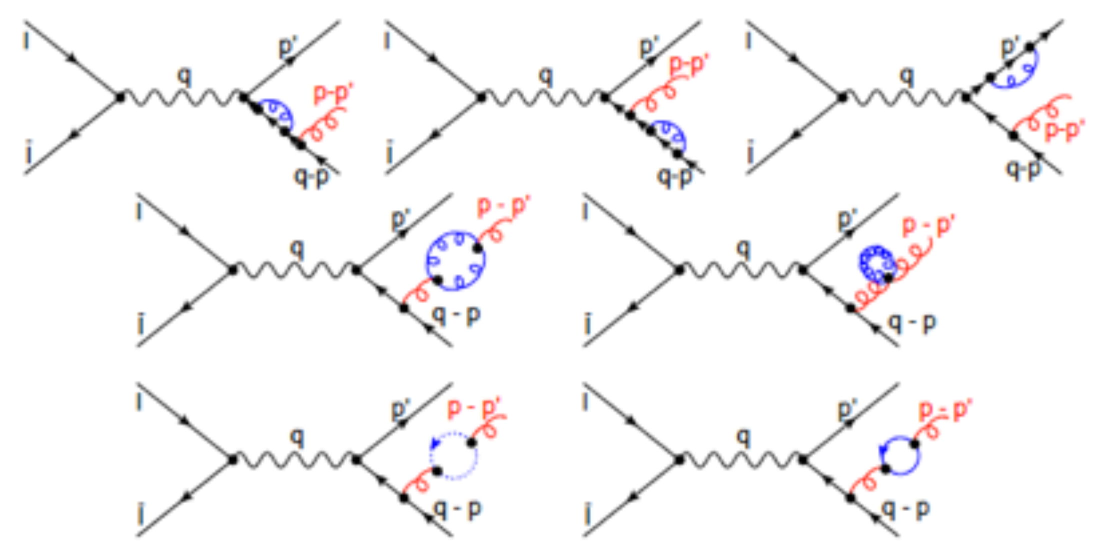


Figure 6: Self-energy corrections

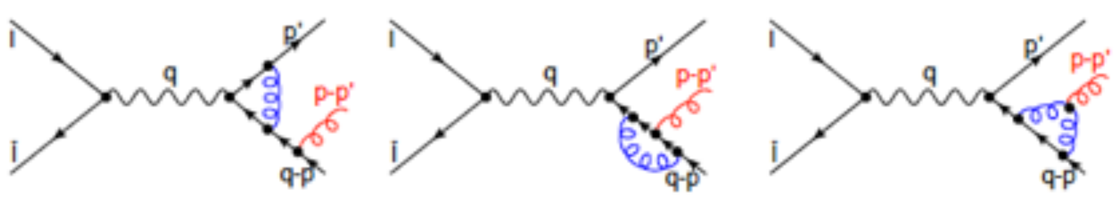


Figure 7: Vertex corrections

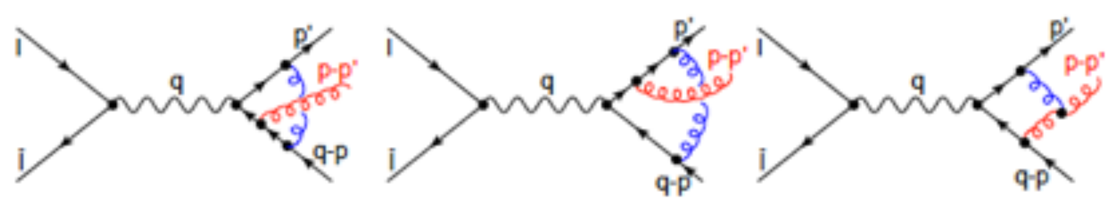


Figure 8: Box corrections

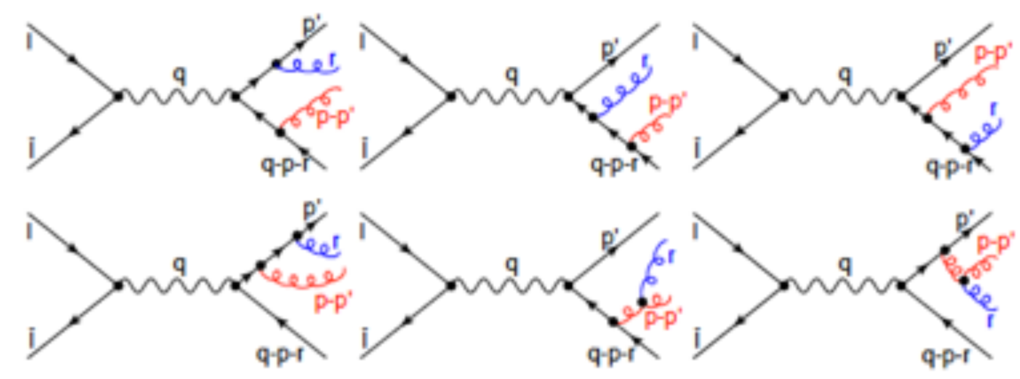


Figure 9: Real corrections

- E.o.M. - and L.I.R. relations are crucial: Combine ‘intrinsic’, ‘kinematical’ & ‘dynamical’ twist-3 contributions
- Imaginary parts: In the dynamical fragmentation process & loop diagrams
- Infrared $1/\varepsilon^2$ - poles cancel ✔
- $1/\varepsilon$ - poles of imaginary parts of loops cancel through E.o.M. ✔
- $1/\varepsilon$ - collinear poles of real parts of loops through MSbar - renormalization

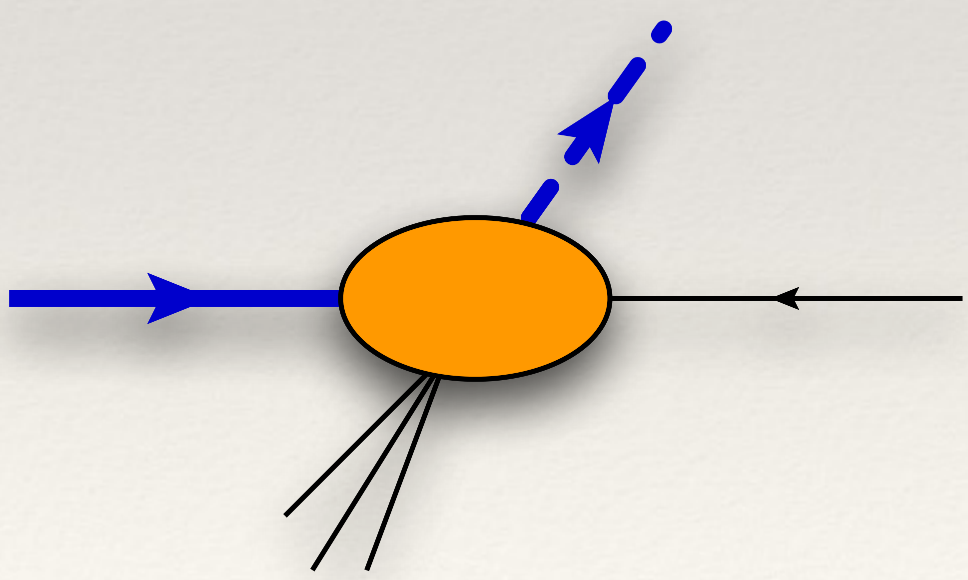
$$\left(\frac{d\sigma(S_{\Lambda T})}{dz_h\, d\phi}\right)_{\rm NLO} \propto \int_{z_h}^{1} \frac{dw}{w} \int_0^1 d\beta \Big[\hat{\sigma}_1^{\overline{\rm MS}}(w,\beta,s/\mu^2)\, \Im[\hat{D}_{FT}^{\Lambda/q}(\tfrac{z_h}{w},\tfrac{z_h}{w\beta},\mu)] + \hat{\sigma}_2^{\overline{\rm MS}}(w,\beta,s/\mu^2)\, \Im[\hat{G}_{FT}^{\Lambda/q}(\tfrac{z_h}{w},\tfrac{z_h}{w\beta},\mu)]$$
$$+\hat{\sigma}_3(w,\beta)\, \Re[\hat{D}_{FT}^{\Lambda/q}(\tfrac{z_h}{w},\tfrac{z_h}{w\beta},\mu)] + \hat{\sigma}_4(w,\beta)\, \Re[\hat{G}_{FT}^{\Lambda/q}(\tfrac{z_h}{w},\tfrac{z_h}{w\beta},\mu)]\Big]$$

Single inclusive Λ production in e - N collisions

$(e + N \longrightarrow \Lambda + X)$

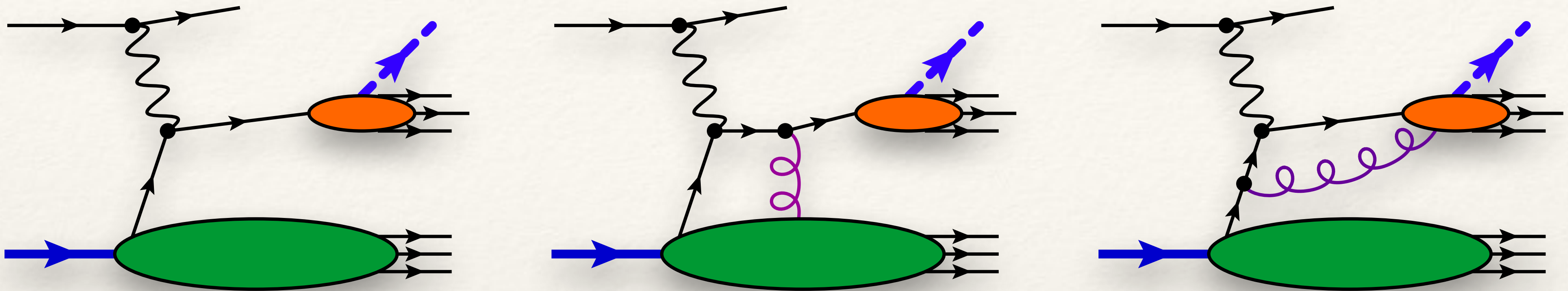
at EIC

$P_T \gg \Lambda_{QCD}$



LO calculation of transverse Λ spin observables:

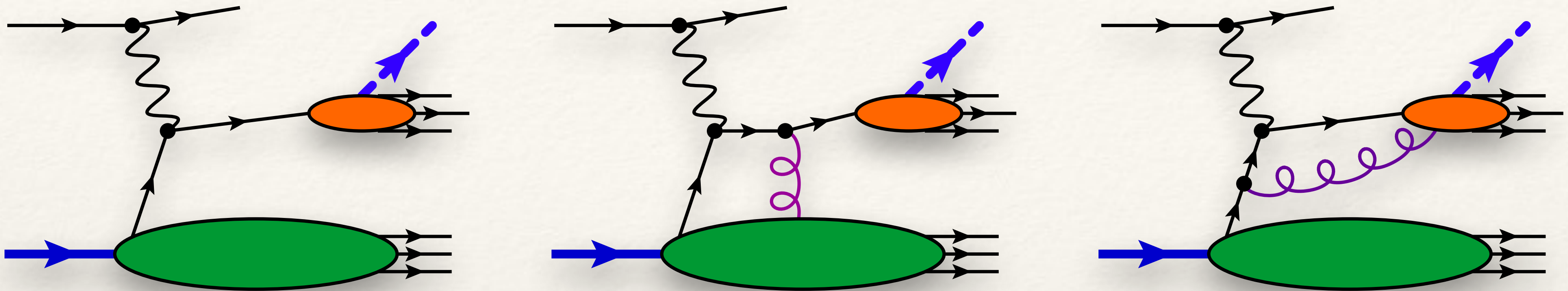
[Kanazawa, Metz, Pitonyak, M.S., PLB (2014) ; Kanazawa, Koike, Metz, Pitonyak, M.S., PRD (2016)]



like SIDIS, but final state lepton not observed

LO calculation of transverse Λ spin observables:

[Kanazawa, Metz, Pitonyak, M.S., PLB (2014) ; Kanazawa, Koike, Metz, Pitonyak, M.S., PRD (2016)]



like SIDIS, but final state lepton not observed

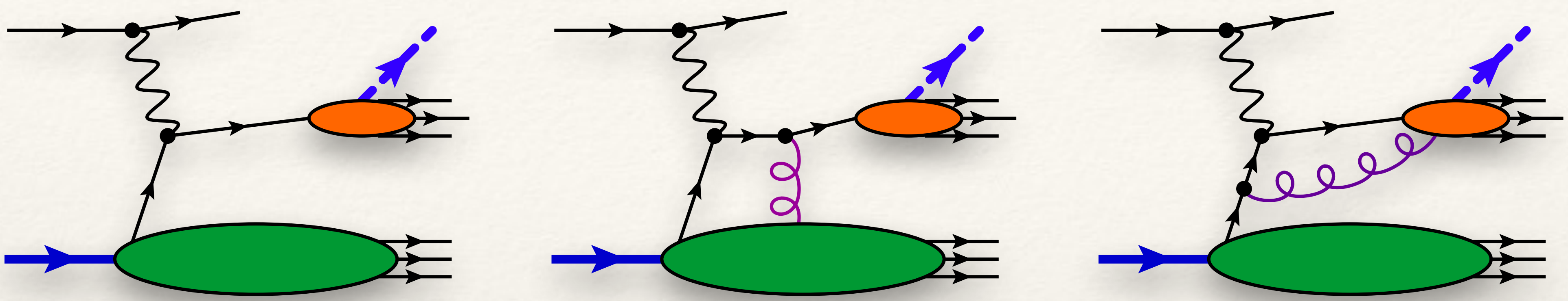
$$E_\Lambda \frac{d\sigma(S_\Lambda)}{d^3\vec{P}_\Lambda} \propto \int dx \int dz\, \delta(s+t+u) \left[\frac{dh_1^{\perp(1)}}{dx}(x)\, H_1(z) + f_1^q(x) \left(\hat{\sigma}_1 \frac{D_T(z)}{z} + \hat{\sigma}_2\, z \frac{dD_{1T}^{\perp(1)}}{dz}(z) \right) \right]$$

Single-Transverse Λ Spin Asymmetry

- E.o.M. & L.I.R.: eliminate for dynamical twist-3 fragmentation functions
- if Boer-Mulders function $h_1^{\perp(1)}$ not too large: study D_T and $D_{1T}^{\perp(1)}$ with flavour separation

LO calculation of transverse Λ spin observables:

[Kanazawa, Metz, Pitonyak, M.S., PLB (2014) ; Kanazawa, Koike, Metz, Pitonyak, M.S., PRD (2016)]



like SIDIS, but final state lepton not observed

$$E_\Lambda \frac{d\sigma(S_\Lambda)}{d^3\vec{P}_\Lambda} \propto \int dx \int dz\, \delta(s+t+u) \left[\frac{dh_1^{\perp(1)}}{dx}(x)\, H_1(z) + f_1^q(x) \left(\hat{\sigma}_1 \frac{D_T(z)}{z} + \hat{\sigma}_2\, z \frac{dD_{1T}^{\perp(1)}}{dz}(z) \right) \right]$$

Single-Transverse Λ Spin Asymmetry

- E.o.M. & L.I.R.: eliminate for dynamical twist-3 fragmentation functions
- if Boer-Mulders function $h_1^{\perp(1)}$ not too large: study D_T and $D_{1T}^{\perp(1)}$ with flavour separation

$$\Delta\sigma(S_\Lambda) \propto \int dx \int dz\, \delta(s+t+u) \left[e(x)\, H_1(z) + f_1^q(x) \left(\Delta\hat{\sigma}_1 \frac{G_1(z)}{z} + \Delta\hat{\sigma}_2 \frac{G_T(z)}{z} + \hat{\sigma}_3\, z \frac{dG_{1T}^{\perp(1)}}{dz}(z) \right) \right]$$

Double Longitudinal Lepton-Transverse Λ Spin Asymmetry

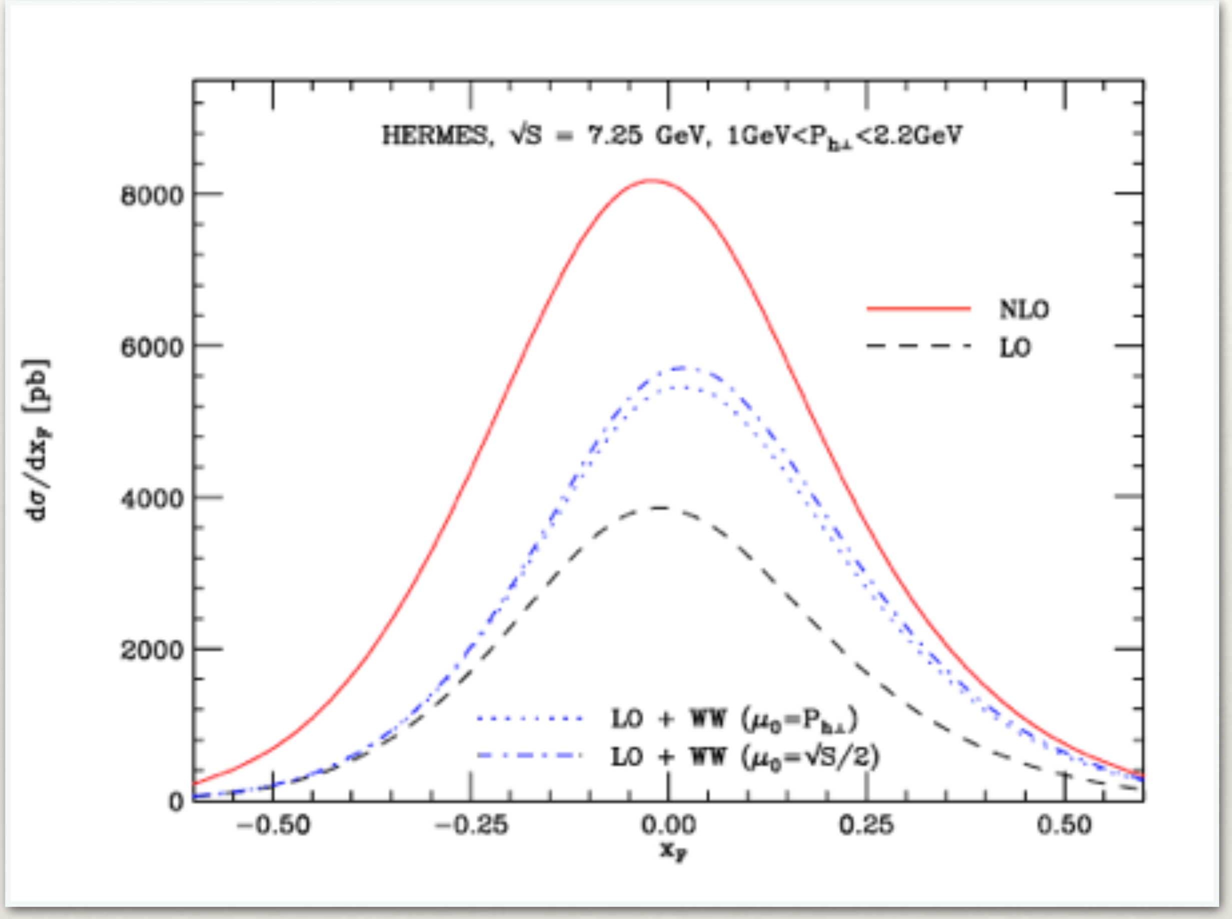
- E.o.M. & L.I.R.: Wandzura-Wilczek twist-2 part + dynamical twist-3
- if twist-3 distribution $e(x)$ not too large & G_1 better known: study validity of WW-approx.

How well do we understand this process?

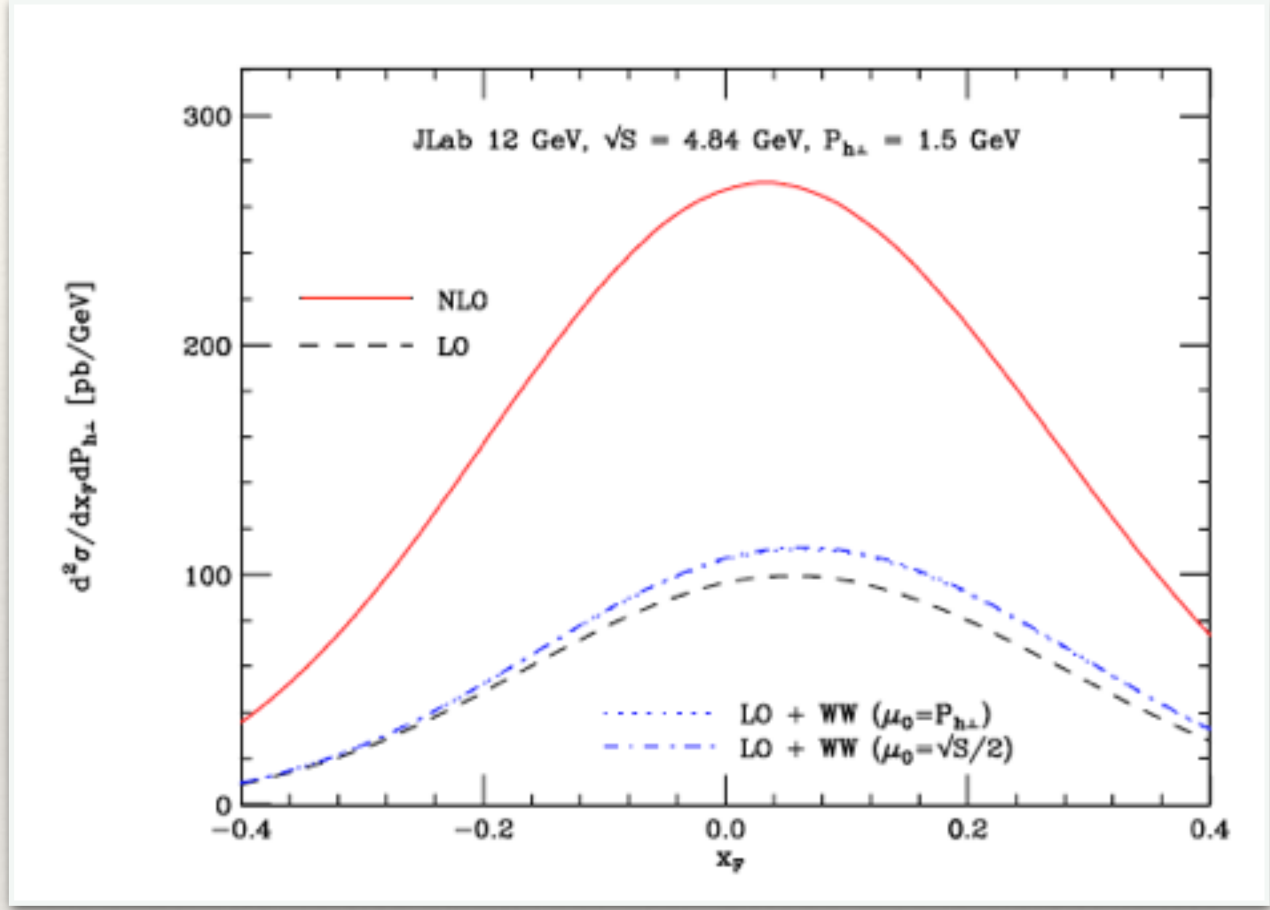
Unpolarized Cross Section for π-production at NLO

[Hinderer, M.S., Vogelsang, PRD (2015), arXiv:1505.06415]

HERMES: $K = \sigma_{NLO}/\sigma_{LO} = 2 - 2.5$



JLab12: $K = \sigma_{NLO}/\sigma_{LO} = 2.5 - 3.5$



large NLO - corrections for HERMES & JLab12

mild NLO - corrections for COMPASS & EIC (K ~ 1.2 - 1.5)

jet production at EIC (K ~ 2)

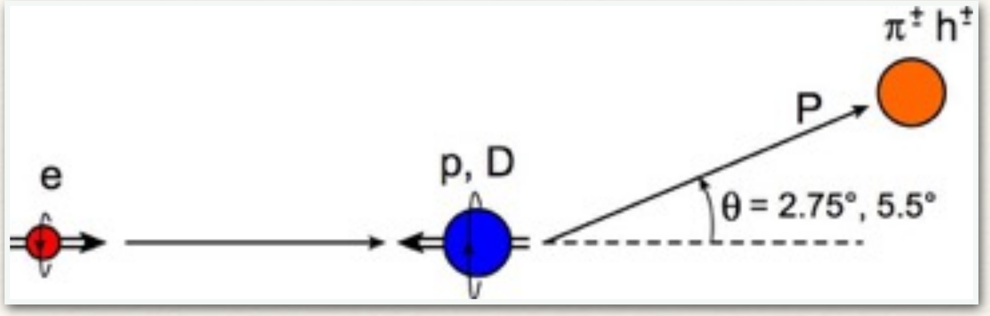
→ NNLO[Abelof, Boughezal, Liu, Petriello, arXiv:1607.04921]: perturbative series converges

Longitudinal Spin Asymmetry at NLO

[Hinderer, M.S., Vogelsang, in preparation]

SLAC E155 (1999):

$$e^{\rightarrow} + (p^{\rightarrow}, D^{\rightarrow}) \longrightarrow (\pi^{\pm}, h^{\pm}) + X$$

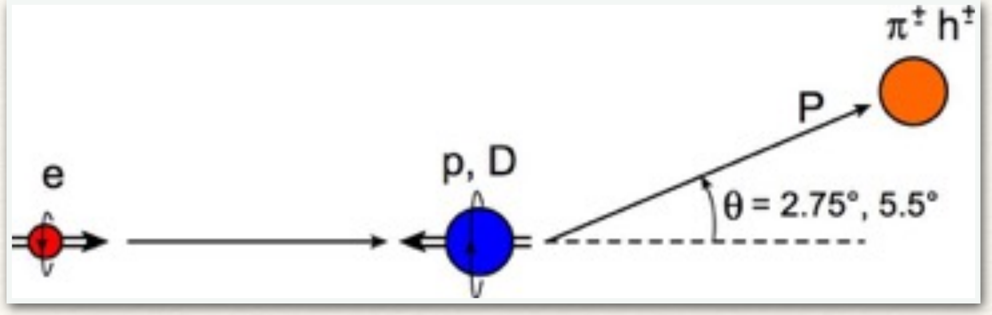


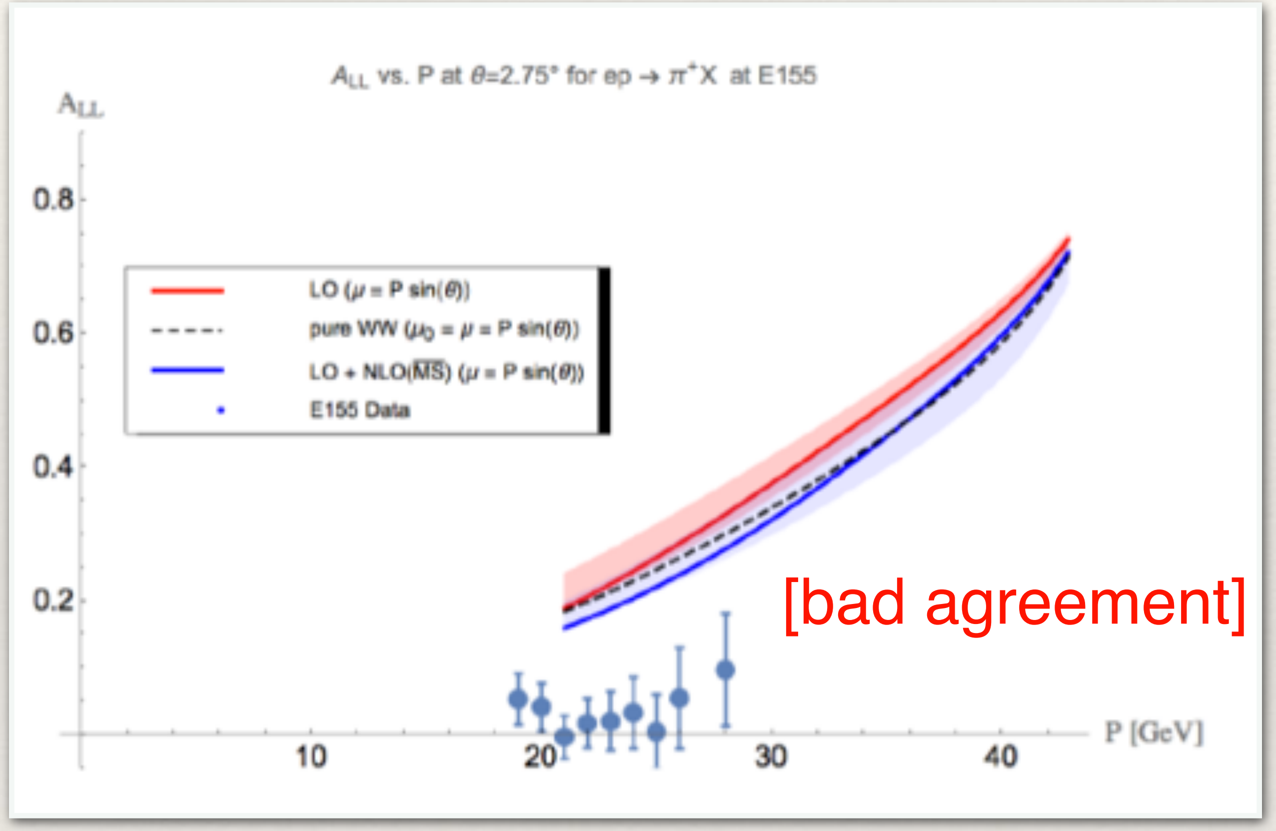
Longitudinal Spin Asymmetry at NLO

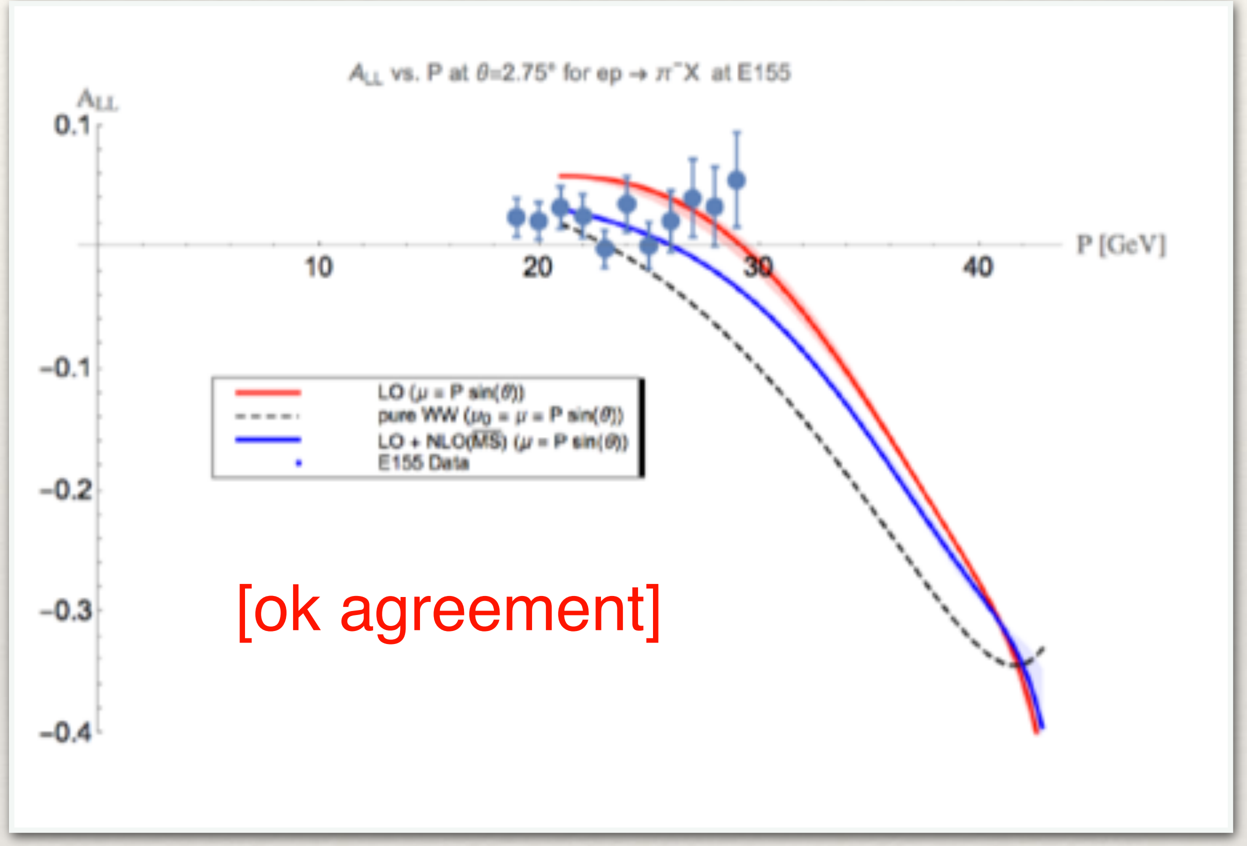
[Hinderer, M.S., Vogelsang, in preparation]

SLAC E155 (1999):

$e^{\rightarrow} + (p^{\rightarrow}, D^{\rightarrow}) \longrightarrow (\pi^{\pm}, h^{\pm}) + X$







Agreement with data not satisfactory, no systematics: Why?

- Theory: NNLO? Higher twists (P_T ~ 1-2 GeV)? Refit of helicity distributions/FFs?
- Experiment: Errors underestimated?

Measurements (unpol. and pol.) should be repeated at COMPASS, JLab, (EIC), …

Summary

- Λ Polarization: Long history, measured in pp-collisions, recently at ATLAS → feasible at a high-energy collider
- Recent measurement at Belle in e^+e^-: clean processes to determine polarized Λ fragmentation functions
- Theory for e^+e^-: Transverse Λ single-spin asymmetry through D_T, consequence of missing T-reversal → unique feature
- NLO underway, more processes in e^+e^- to be studied (Λ+π - final state)
- Single-inclusive Λ production at EIC, COMPASS: additional information on Λ polarization
- Need to understand better single-inclusive hadron production