第一届Lambda超子自旋极化跨系统研讨会

质子-质子碰撞中 Lambda超子自旋极化实验进展

张金龙 （山东大学）

2025年3月22日

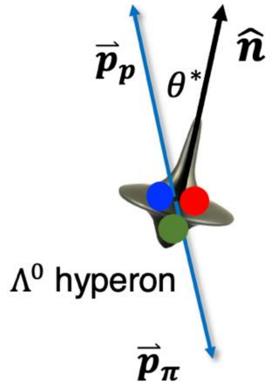
SHANDONG UNIVERSITY

Outline

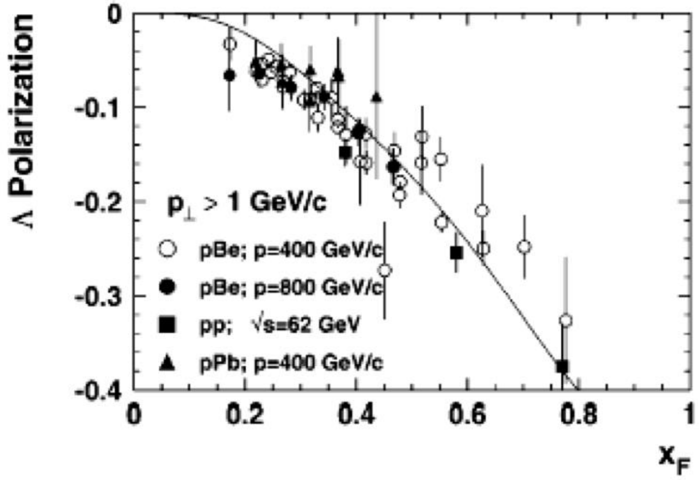
- Lambda “spontaneous” polarization puzzle since 1976
- Beam induced Lambda polarization in pp collisions
- Polarizing Fragmentation Functions in pp/pA collisions

Lambda： final state “polarimetry”

- Self-analyzing weak decay: Lambda polarization can be measured from the angular distribution of its daughter particles: (Br~64%) (Br~36%)



- Λ polarization plays an important role in spin physics
  - Transverse polarization in unpolarized pp, pA (G.Bunce et al 1976)
  - Study pol. fragmentation function and spin content of hyperon
  - Complementary to Kaon SIDIS, study spin structure of nucleon

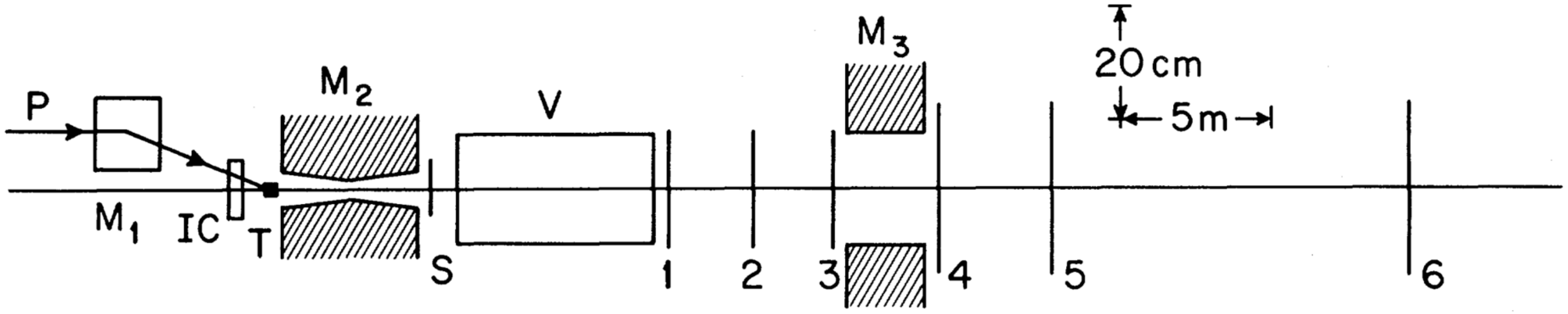


Liang and Boros, PRL79, 3608 (1997)

The result in 1976

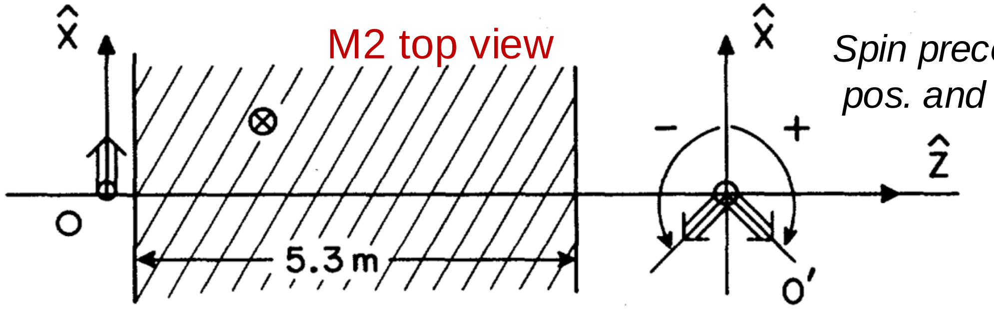
G. Bunce et al. PRL36, 1113 (1976)

300 GeV unpolarized proton on unpolarized Beryllium target

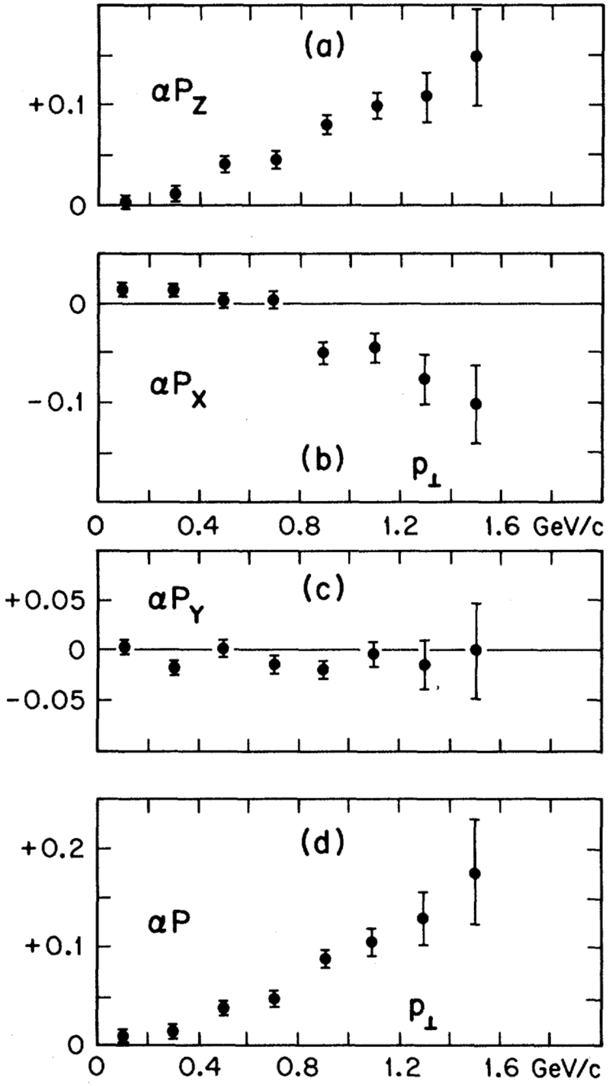


- Scattering angles determined by incoming beam angle
- Recorded Lambda decay after 5.3m collimator inside sweeping magnet M2
- *10%* level polarization observed; increasing vs. p_T

M2 top view



Spin precession for pos. and neg. M2 polarity



10%

Follow-up measurements

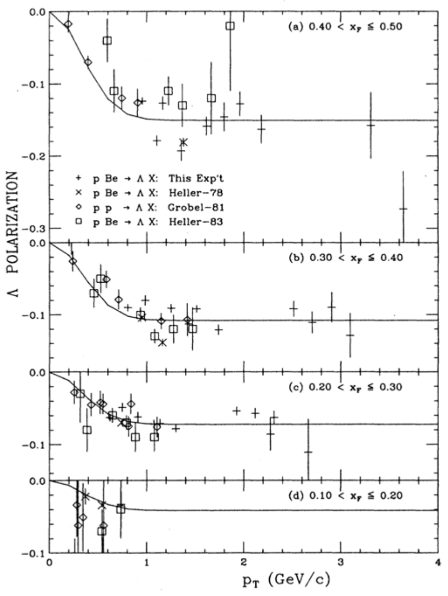
incomplete list

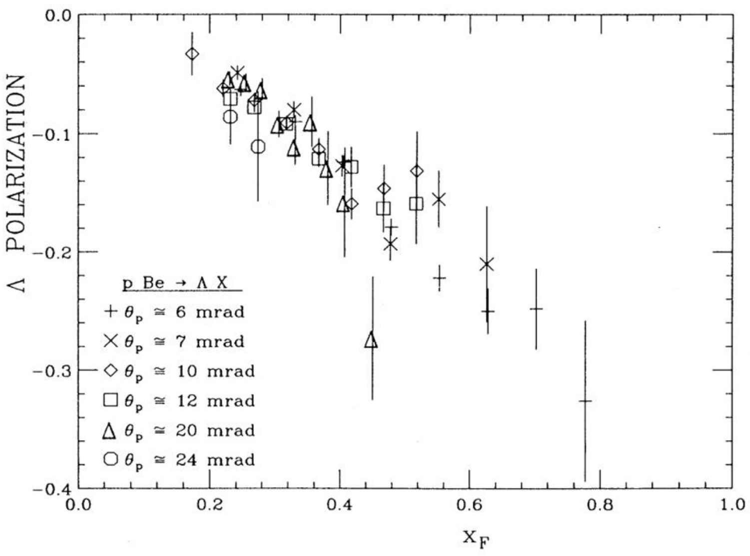
Heller et al., Phys. Lett. B68 480 (1977)	24 GeV proton + Platinum at CERN
Heller et al., Phys. Rev. Lett. 41, 607 (1978)	400 GeV proton + Beryllium at Fermilab (different hyperon)
Erhan et al., Phys. Lett B82, 301 (1979)	$\sqrt{s}$ = 53, 62 GeV proton + proton at CERN (ISR)
Lomanno et al., Phys. Rev. Lett. 43, 1905 (1979)	28.5 GeV proton + Iridium at BNL (AGS)
Heller et al., Phys. Rev. Lett. 51, 2025 (1983)	400 GeV proton + Beryllium/Copper/Lead at Fermilab
Abe et al., Phys. Rev. Lett. 50, 1102 (1983)	12 GeV proton + Tungsten at KEK
Aleev et al., Z. Phys. C 36, 27 (1987)	~40 GeV neutron + Carbon/Aluminum/Copper
Lundberg et al., Phys. Rev. D 40, 3557 (1989)	400 GeV proton + Beryllium at Fermilab (higher pT)
Ramberg et al., Phys. Lett. B 338, 403 (1994)	800 GeV proton + Beryllium at Fermilab
Fanti et al., Eur. Phys. J. C 6 265 (1999)	450 GeV proton + Beryllium at CERN (SPS-NA48)
Abt et al., Phys. Lett. B 638, 415 (2006)	920 GeV proton + Carbon/Tungsten at DESY (HERA-B)
Aad et al., Phys. Rev. D 91, 032004 (2015)	$\sqrt{s}$ = 7 TeV proton + proton at CERN (ATLAS)
Abt et al., JHEP09, 082 (2024)	2.5 TeV proton + Neon at CERN (LHCb-SMOG)

For reviews, see prof. Liang's talk.

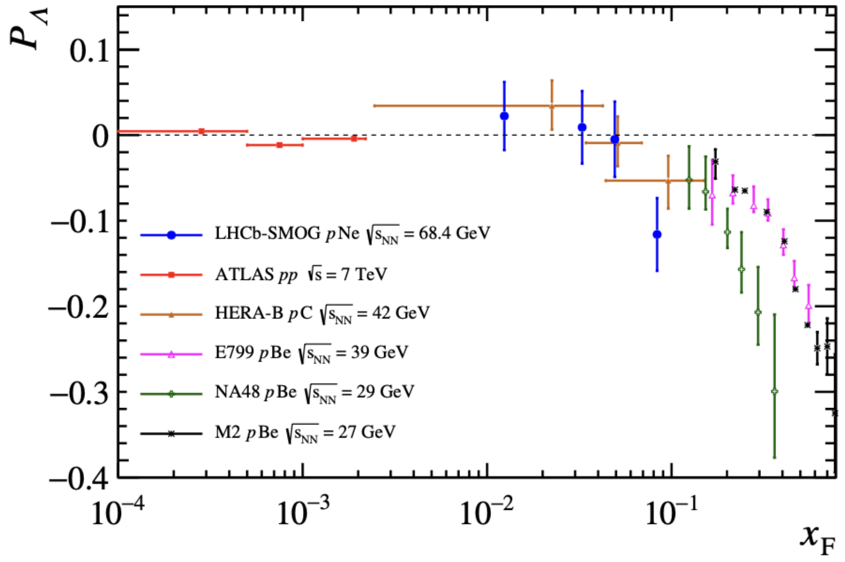
Dependence on p_T and x_F

Lundberg et al. Phys. Rev. D 40, 3557 (1989)





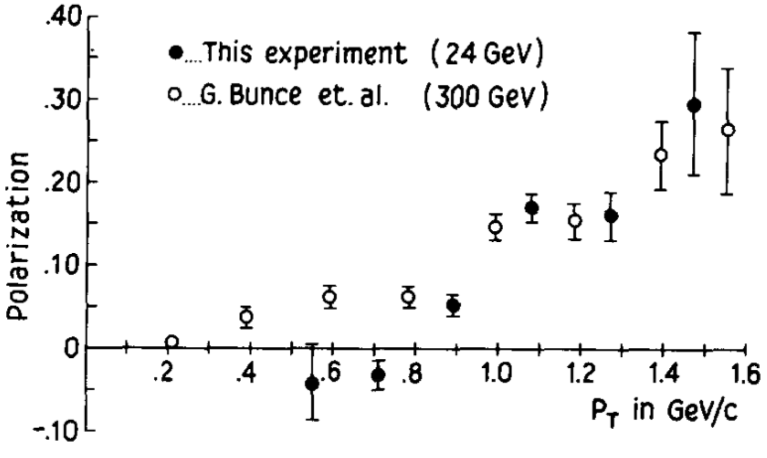
Abt et al, JHEP09, 082 (2024)



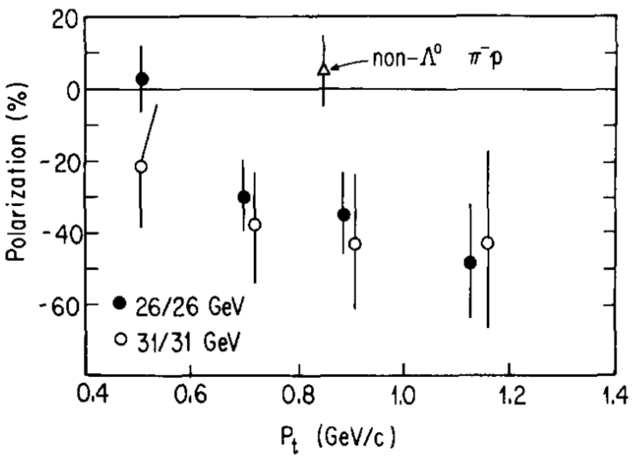
- Increase vs. p_T and saturate at ~1 GeV
- Increase vs. x_F

Dependence on energy

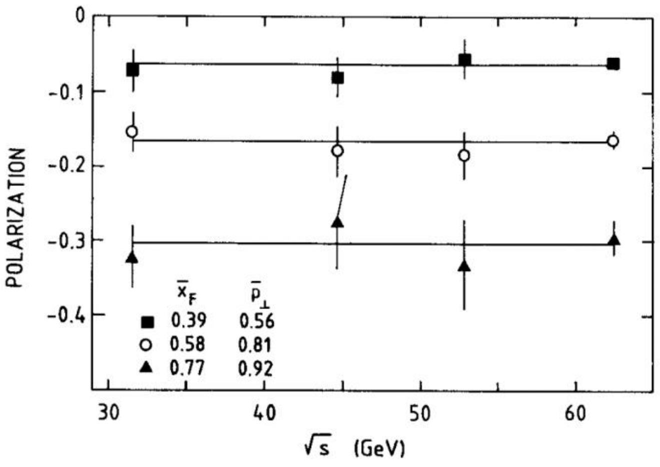
Heller et al.,
Phys. Lett. B68 480 (1977)



Erhan et al.
Phys. Lett B82, 301 (1979)



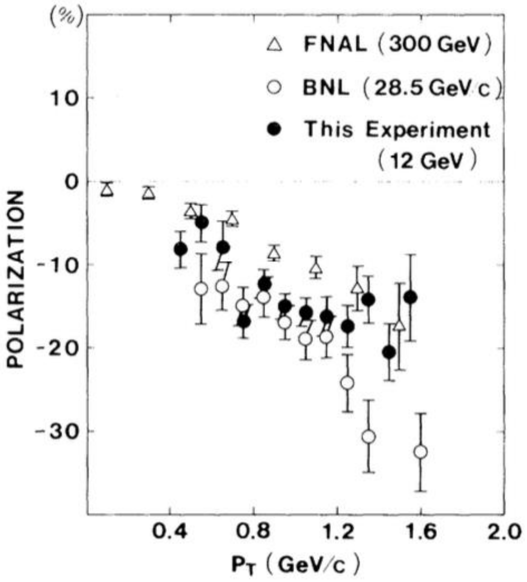
A.D. Panagiotou,
Int.J.Mod.Phys.A 5, 1197,(1990)



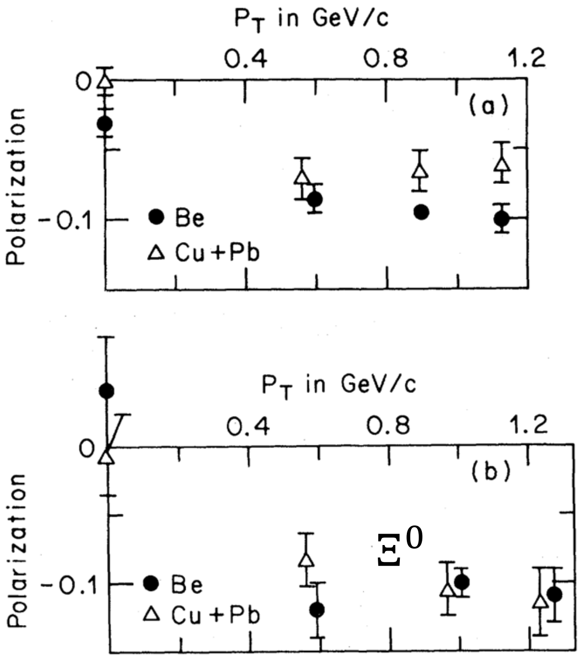
- Almost NOT dependent on energy

Dependence on target-mass

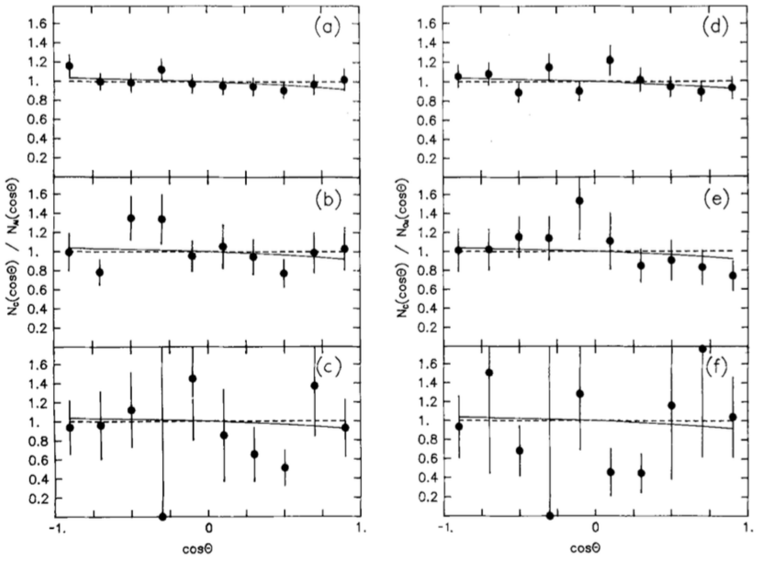
Abe et al.,
Phys. Rev. Lett. 50, 1102 (1983)



Heller et al.,
Phys. Rev. Lett. 51, 2025 (1983)



Aleev et al.,
Z. Phys. C 36, 27 (1987)

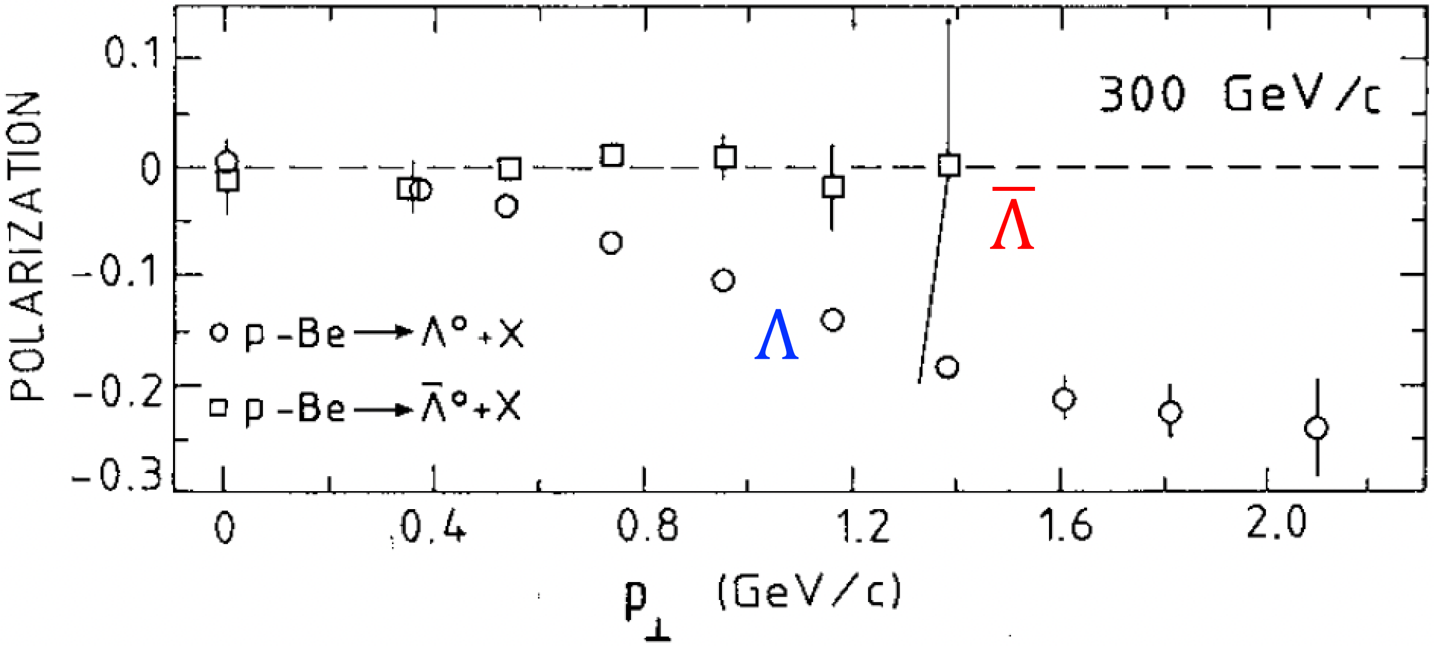


- Weakly dependent on target-mass

  --> Nucleon level or even parton level reaction

Anti-Lambda polarization ~ 0

A.D. Panagiotou, Int.J.Mod.Phys.A 5, 1197,(1990)



Lambda-bar polarization is consistent with zero up to 1.4 GeV, as expected from the combination of the three sea antiquarks.

Features of lambda spontaneous polarization

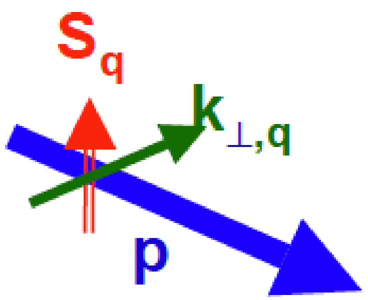
- Lambda transverse polarization is significantly.
- Anti-lambda is not polarized.
- Polarization is (almost) independent of beam energy.
- x_f and p_T dependence scales with energy.
- Weak target-mass dependence: $pA \approx pp$, parton level reaction.

Non-perturbative effects at Initial and Final States

Partonic scattering (pQCD) cannot explain the large polarization.

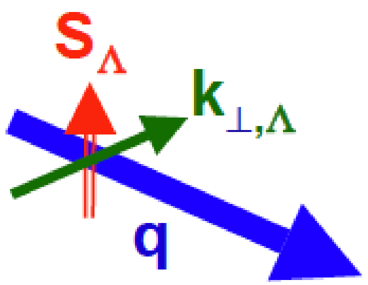
Then, must be non-pQCD effects from *initial state and/or final state.*

Parton distributions



$\longleftarrow \vec{S}\cdot(\vec{p}\times\vec{k}_{\perp}) \longrightarrow$

Parton fragmentations



Can not distinguish in pp;

ep and e^+e^- can separate.

- Spin transfer from initial state: parton is polarized in <u>polarized proton</u> — Helicity/Transiversity

  parton is polarized in <u>unpolarized proton</u> — Boer-Mulders

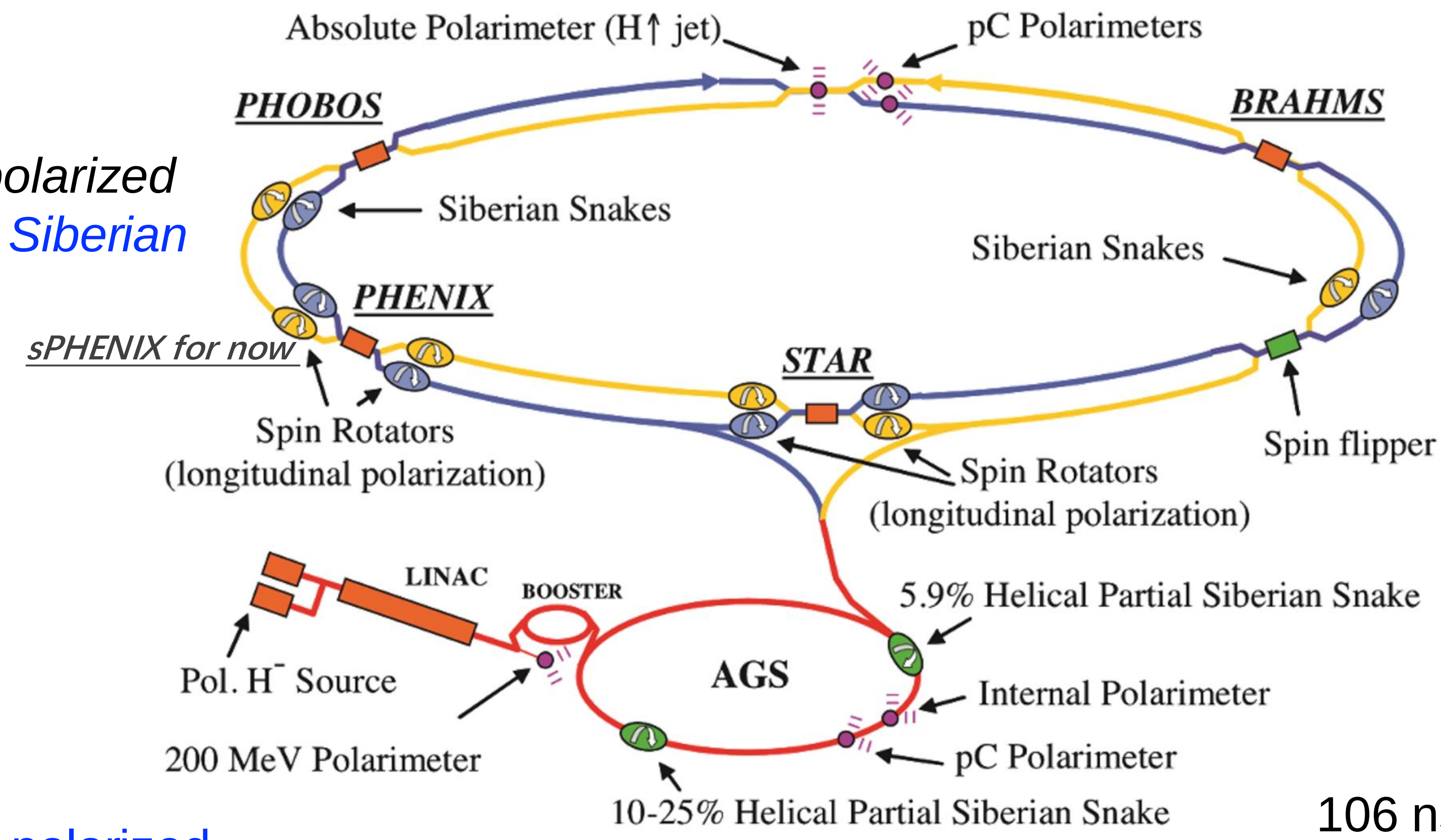
- Polarization arising at final state: parton is <u>unpolarized</u> but fragmenting into <u>polarized</u> hadron. — Polarizing FFs

Polarized RHIC: a very big deal

- High current polarized proton source (OPPIS)
- Ability to accelerate polarized protons with Siberian Snakes demonstrated, and became a routine, at the highest energy!
- Ability to manipulate spin direction(spin rotator) and monitor that, demonstrated and became a routine.
- 106 ns bunch crossing with pre-determined spin directions a major boon for controlling systematics

Polarized RHIC

Accelerate polarized protons with Siberian Snakes



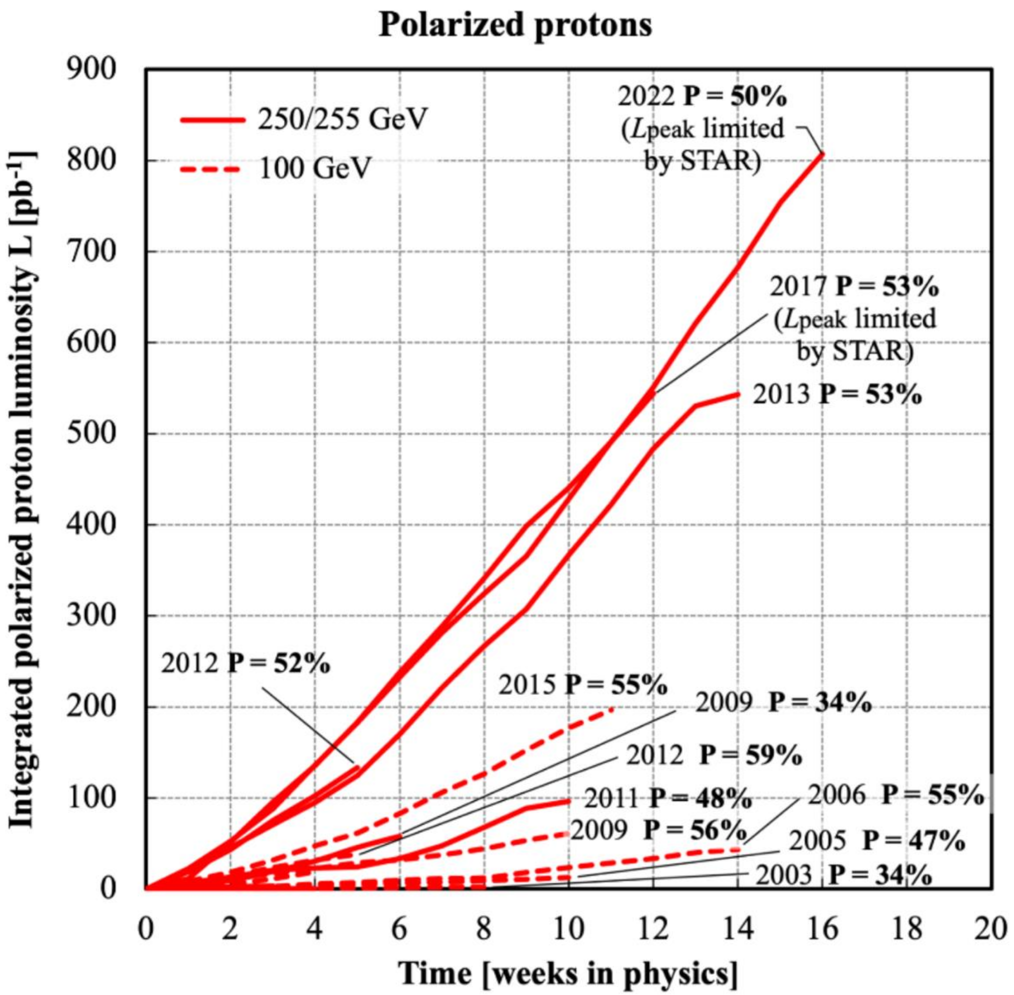
Manipulate spin direction with spin rotator

High current polarized proton source

106 ns bunch crossing with pre-determined spin directions

Shutting down in 2025, next stage: Electron-ion Collider

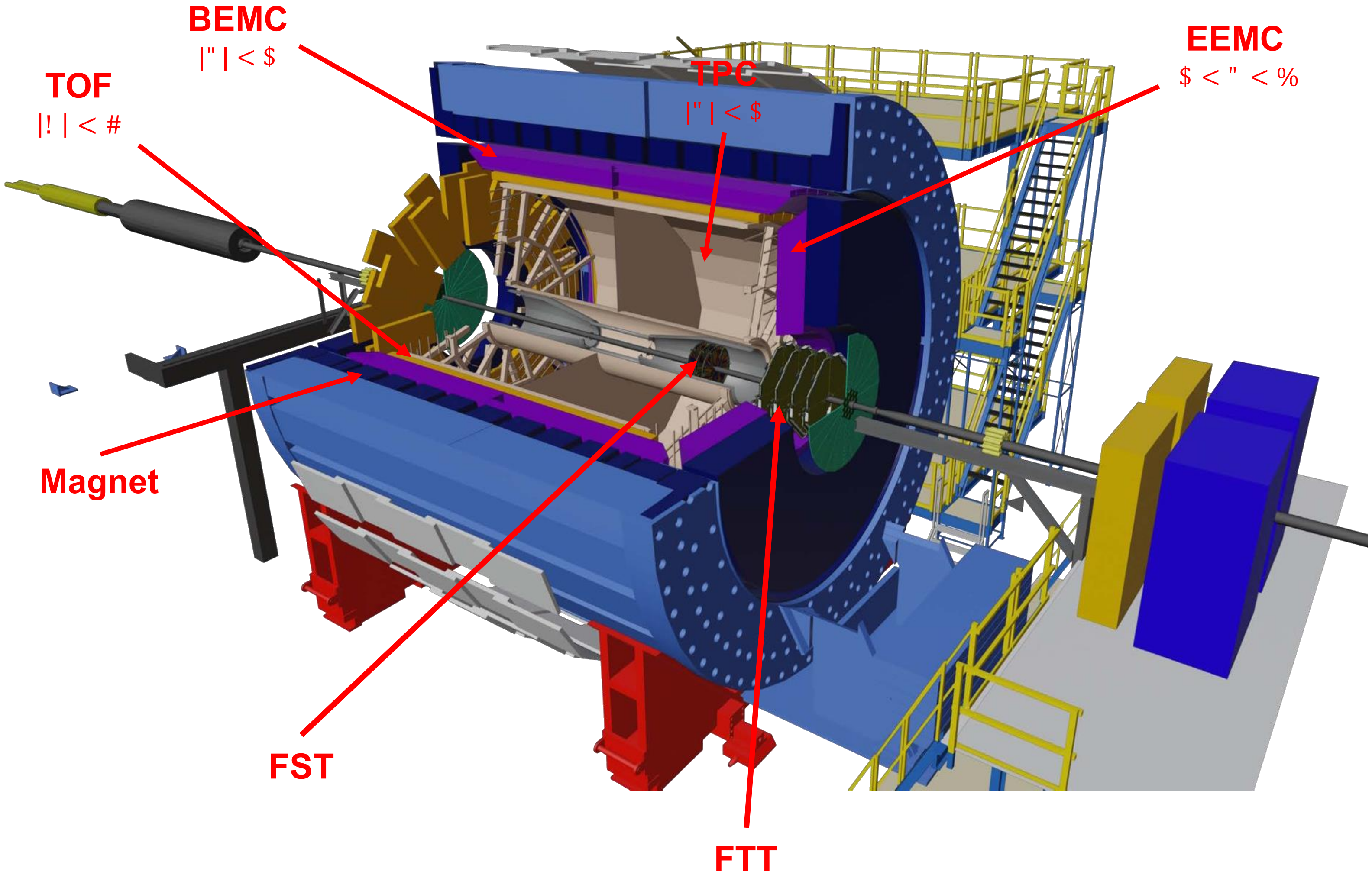
RHIC spin data accumulation



	Year	√s (GeV)	L (pb^{-1})	<P> (%)
Long	2006	62.4	--	48
		200	6.8	57
	2009	200	25	38
		500	10	55
	2011	500	12	48
	2012	510	82	56
	2013	510	256	56
	2015	200	52	53
Trans	2006	62.4	0.2	48
		200	8.5	57
	2008	200	7.8	45
	2011	500	25	55
	2012	200	22	60
	2015	200	52	53
	2017	510	350	55
	2022	508	400	52
	2024	200	164	55

by STAR

STAR detector overview



Tracking + PID

Time Projection Chamber
- charged track momentum msmt
- particle identification dE/dx,
- vertex reconstruction
- coverage $|\eta| < 1$

Time of Flight detector
- particle identification
- coverage $|\eta| < 1$

Barrel and Endcap E.M. Cal.
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $|\eta| < 1$ and 1< $\eta < 2$

Only running detector at RHIC in 2017-2022

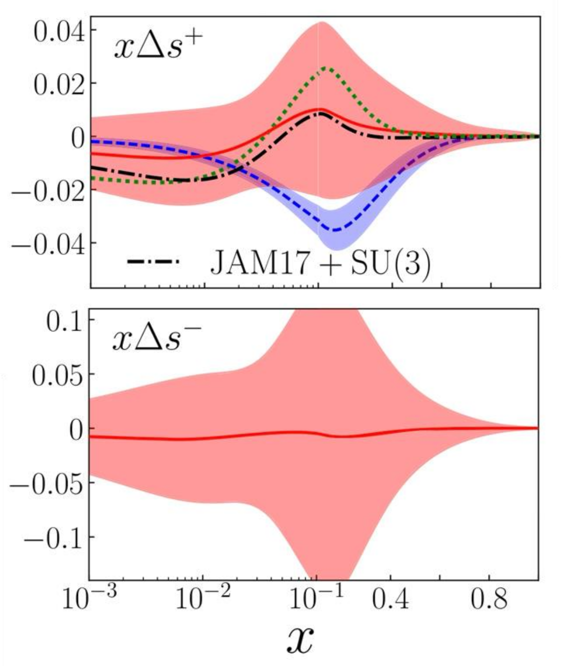
Longitudinal spin transfer in polarized pp collision

The factorized framework enables perturbative description

$$D_{LL}^{\Lambda} \equiv \frac{d\sigma^{p^+p\to\Lambda^+X} - d\sigma^{p^+p\to\Lambda^-X}}{d\sigma^{p^+p\to\Lambda^+X} + d\sigma^{p^+p\to\Lambda^-X}} = \frac{d\Delta\sigma}{d\sigma}$$

$$d\Delta\sigma \propto \Delta f_a(x_a) f_b(x_b) \Delta\sigma^{ab\to cd} \Delta D^{\Lambda}(z)$$

helicity distribution | pQCD calculable | longitudinally polarized FFs

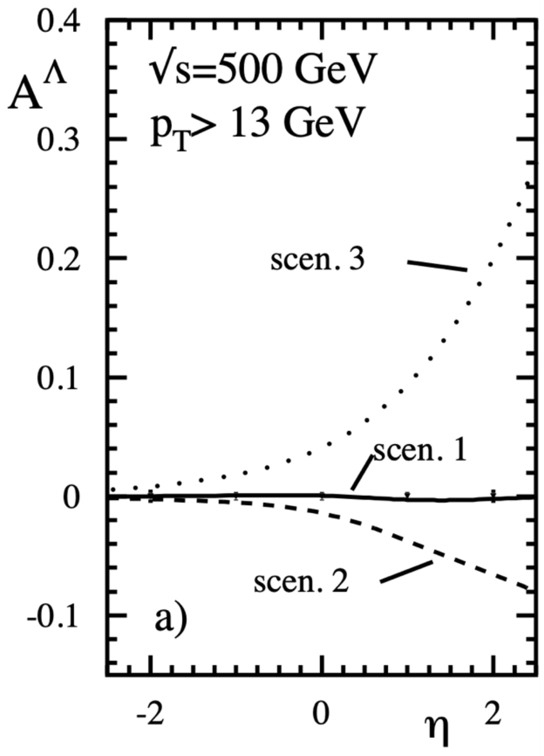


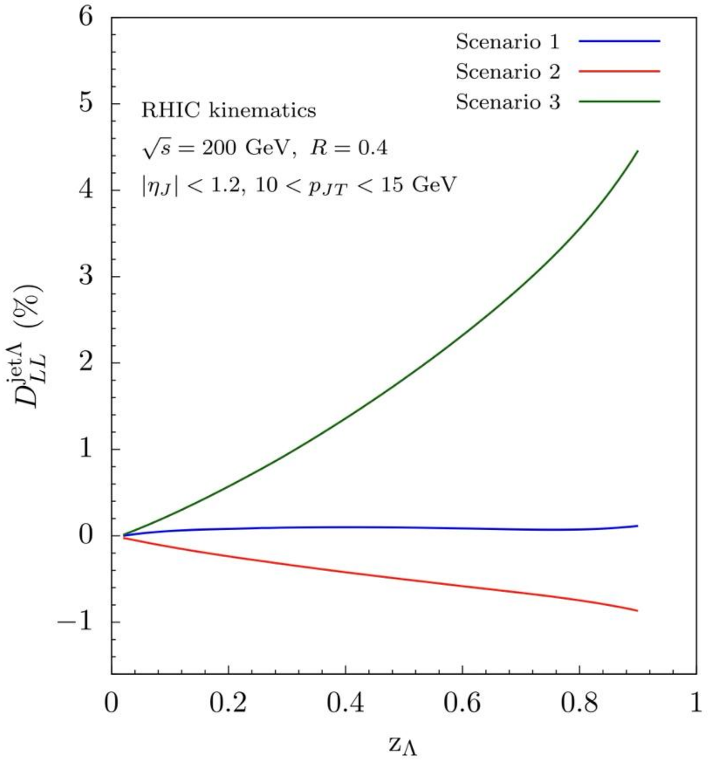
JAM, Phys. Rev. Lett. **119**, 132001 (2017).

D_{LL} can provide constraints on both polarized FFs and polarized PDFs of s and s-bar

D_{LL} vs *z* can provide direct probe to the polarized FFs

D_{LL} predictions for pp at RHIC





D. de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. 81, 4 (1998).

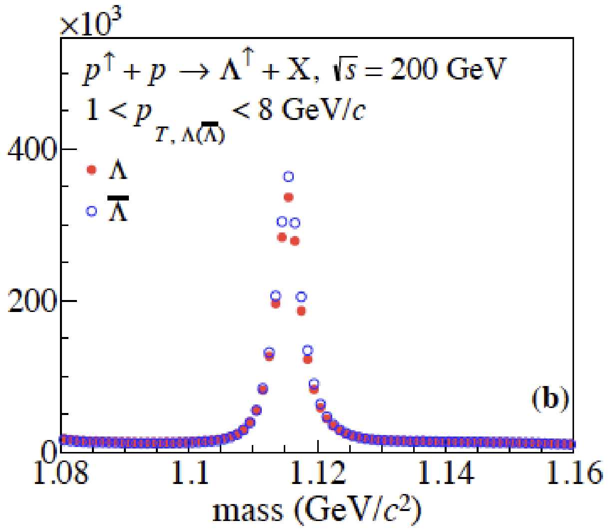
Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B 809, 135756 (2020).

scenario 1: only s quark can contribute to polarization.
scenario 2: u and d quarks have the same contribution to polarized but u and d have an opposite sign from s quark.
scenario 3: u, d and s quarks have the same contribution to the polarized

Dramatic different predictions between different extreme scenarios

D_{LL} measurements at STAR

1. Select hard scattering events using a jet trigger based on the energy deposits in the EMC
2. Topological cuts to reduce background
3. Side-band method to estimate residual background
4. Require hyperons to be part of a jet



D_{LL} has been extracted from Lambda counts with opposite beam polarization within a small interval of $\cos\theta^*$. *STAR, PRD80, 111102 (2009)*

$$D_{LL} = \frac{1}{\alpha \cdot P_{beam} < \cos\theta^* >} \cdot \frac{N^+ - N^-}{N^+ + N^-}$$

$$N^+ = N^{++}\frac{L_{--}}{L_{++}} + N^{+-}\frac{L_{--}}{L_{+-}}$$

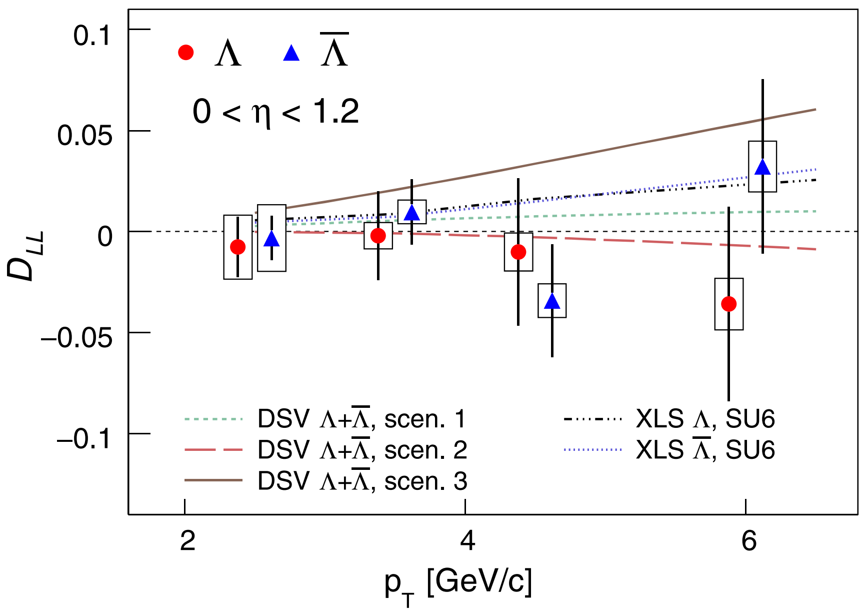
$$N^- = N^{-+}\frac{L_{--}}{L_{-+}} + N^{--}$$

where the acceptance canceled out.

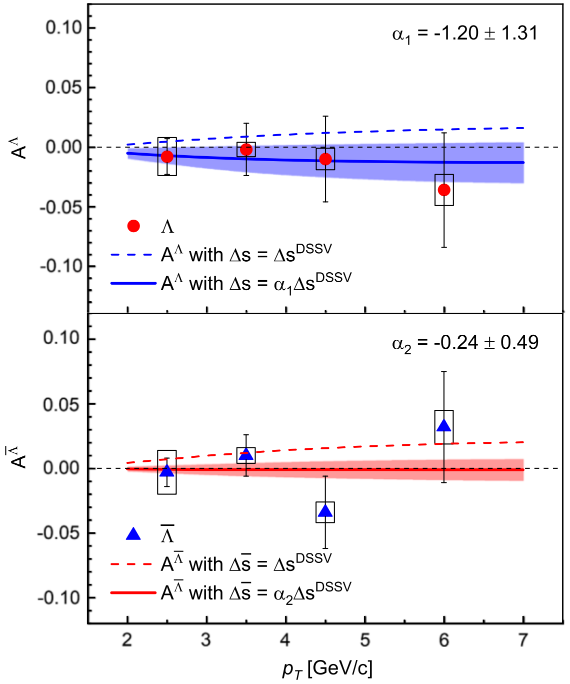
Relative luminosity ratio measured with VPD, ZDC

D_{LL} results in pp 200 GeV

STAR, Phys. Rev. D 98, 112009 (2018)



X.N. Liu, B.Q. Ma. Eur. Phys. J. C 10 (2019).

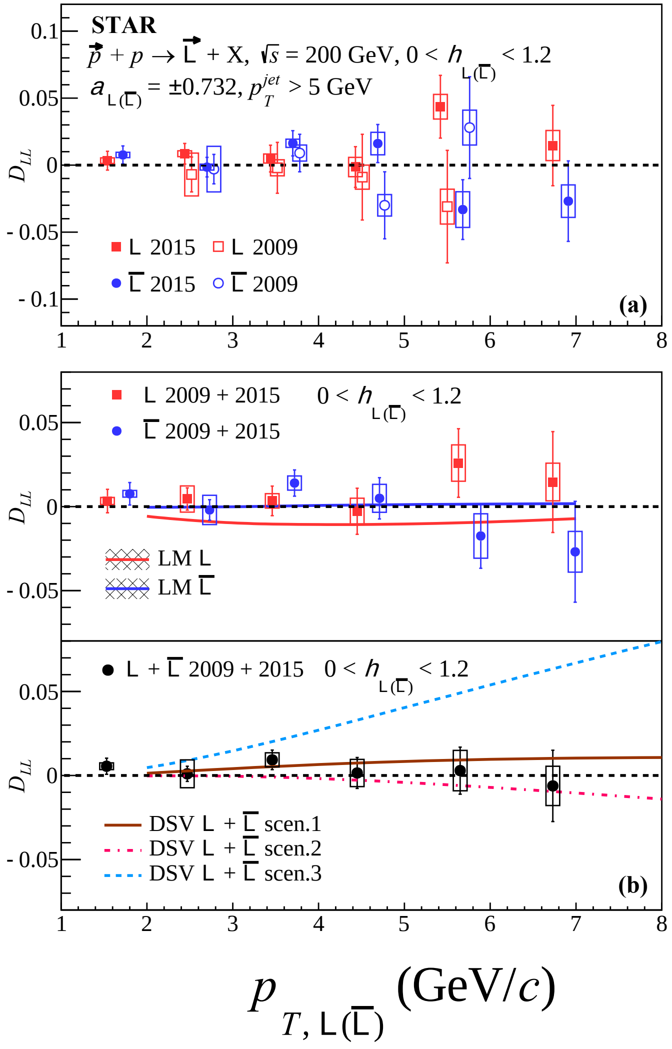


See prof. Ma's talk

- Second D_{LL} measurement from STAR, improved but still tatistically limited.
- Theoretical: when fit to data, provide constraints to (anti)strange quark polarization

Latest D_{LL} results in pp

STAR, Phys. Rev. D **109**, 012004 (2024)



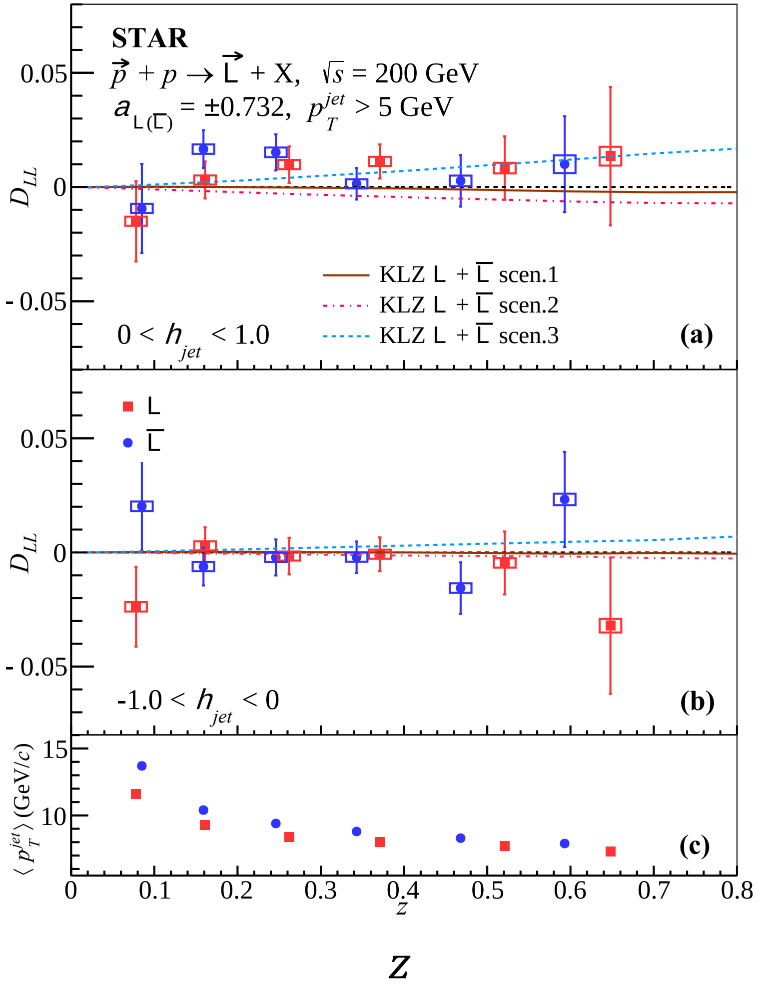
- Twice statistics larger as STAR 2009 data
- Most precise measurements up to date.
- Consistent results between and
- Two year’s results are consistent
- Results are consistent with LM calculation
- Strong disfavor of the scenario 3 for the polarized FFs

Model predictions:

- X.N. Liu, B.Q. Ma. Eur. Phys. J. C 10 (2019).
- D. de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. 81, 530 (1998).

D_{LL} vs z

STAR, Phys. Rev. D **109**, 012004 (2024)



- The results directly probe the polarized fragmentation functions
- Results are comparable to model predictions within uncertainties
- Indication of small helicity distributions of (anti-) strange quark and/or small polarized fragmentation functions

Model predictions:

- Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B 809, 135756 (2020).

Transverse spin transfer in polarized pp collision

Transverse spin transfer of hyperons provide access to transversity and transversely pol. frag. function:

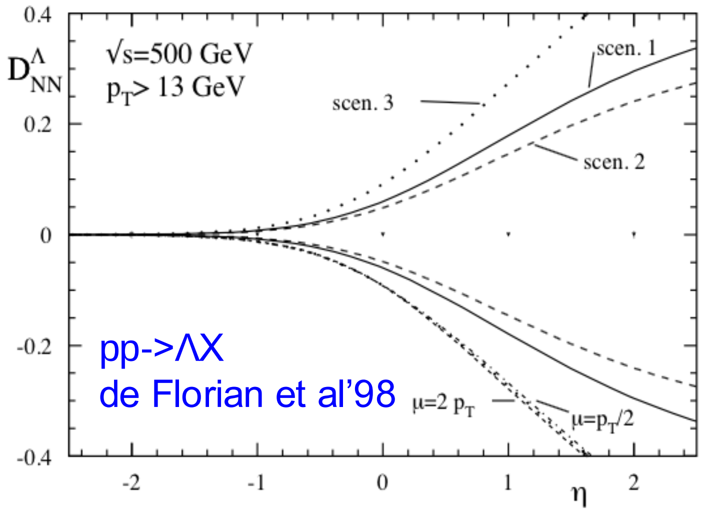
$$D_{TT} \equiv \frac{d\sigma^{(p^{\uparrow} p \to H^{\uparrow} X)} - d\sigma^{(p^{\uparrow} p \to H^{\downarrow} X)}}{d\sigma^{(p^{\uparrow} p \to H^{\uparrow} X)} + d\sigma^{(p^{\uparrow} p \to H^{\downarrow} X)}} = \frac{d\Delta_T \sigma}{d\sigma}$$

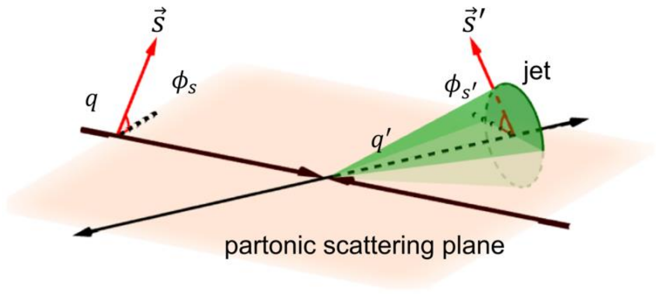
$$d\Delta_T\sigma^{(pp\to HX)} \propto \sum_{abcd} \int dx_a\, dx_b\, dz\, \delta f_a(x_a) f_b(x_b) \Delta_T D_c^H(z) d\Delta_T \hat{\sigma}^{(ab\to cd)}$$

transversity distribution

Transversely polarized fragmentation function

pQCD





- D. de Florian, J. Soffer, M. Stratmann, W. Vogelsang, PLB439, 176 (1998).
- Q. Xu , Z. T. Liang, PRD70, 034015 (2004).
- Q. Xu, Z. T. Liang, E. Sichtermann, PRD73, 077503 (2006).

Earlier transverse spin transfer measurements in pp

Bonner et al, Phys. Rev. Lett. 58, 447 (1987) Transversely polarized proton 13.3/18.5 GeV

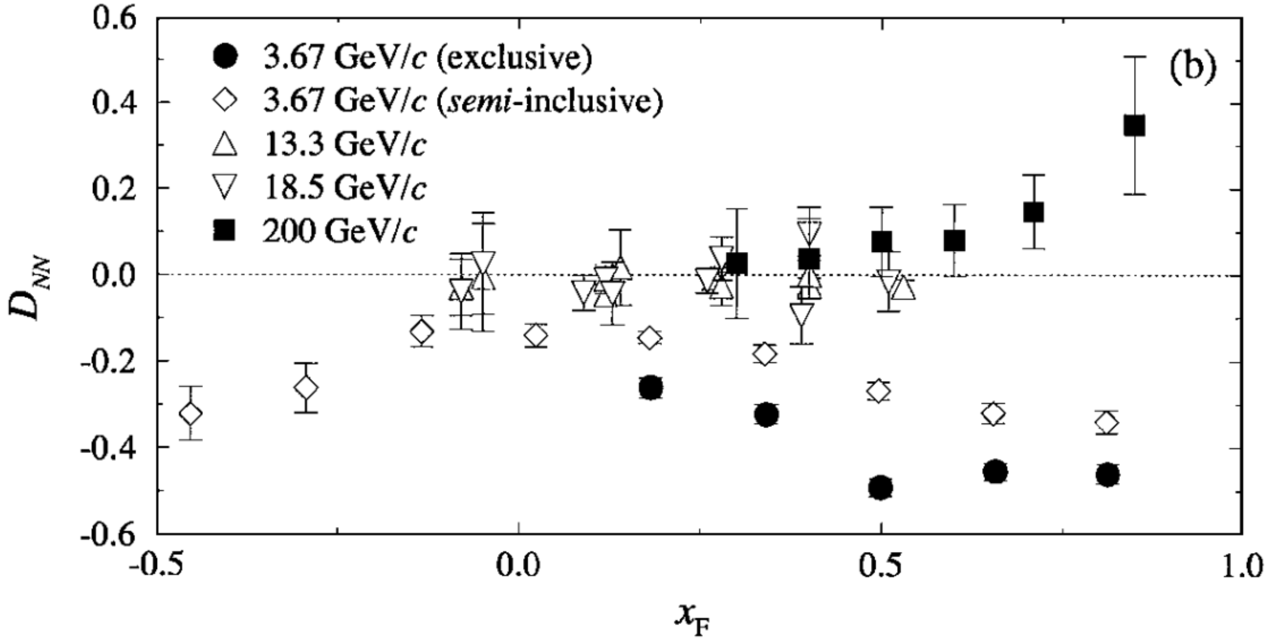
E704, Phys. Rev. Lett. 78, 4003 (1997) Transversely polarized proton 200 GeV

Low pT

DISTO, *Phys. Rev. Lett. 83, 1534 (1999)* Transversely polarized proton 3.67 GeV Exclusive/Simi-inclusive

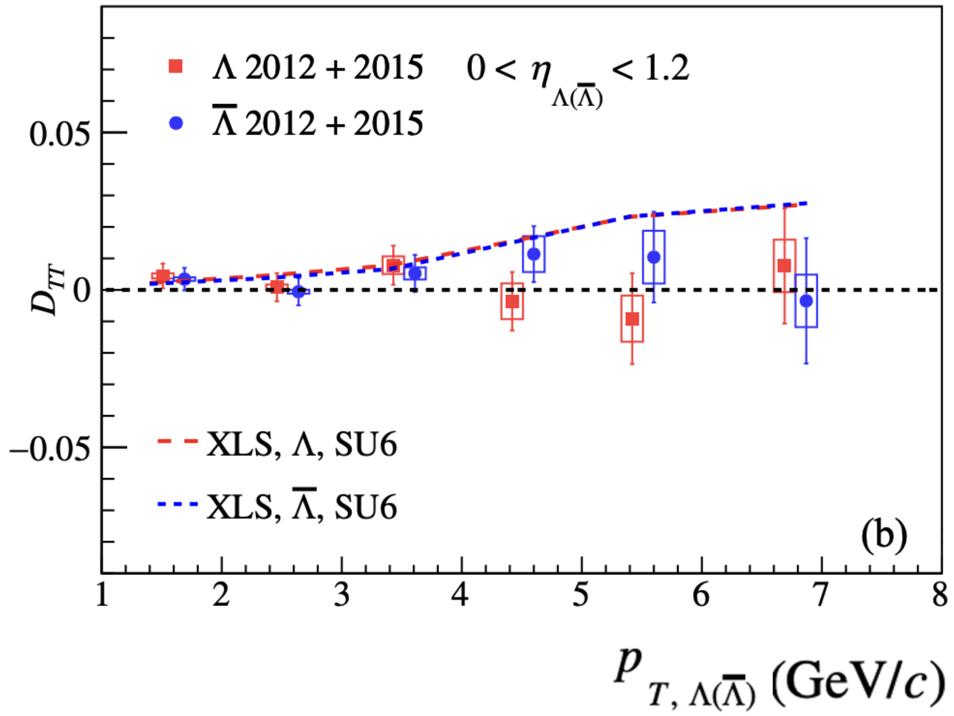
$$D_{NN} = \frac{E\frac{d^3\sigma}{dp^3}^{\uparrow\uparrow} - E\frac{d^3\sigma}{dp^3}^{\uparrow\downarrow}}{E\frac{d^3\sigma}{dp^3}^{\uparrow\uparrow} + E\frac{d^3\sigma}{dp^3}^{\uparrow\downarrow}}$$

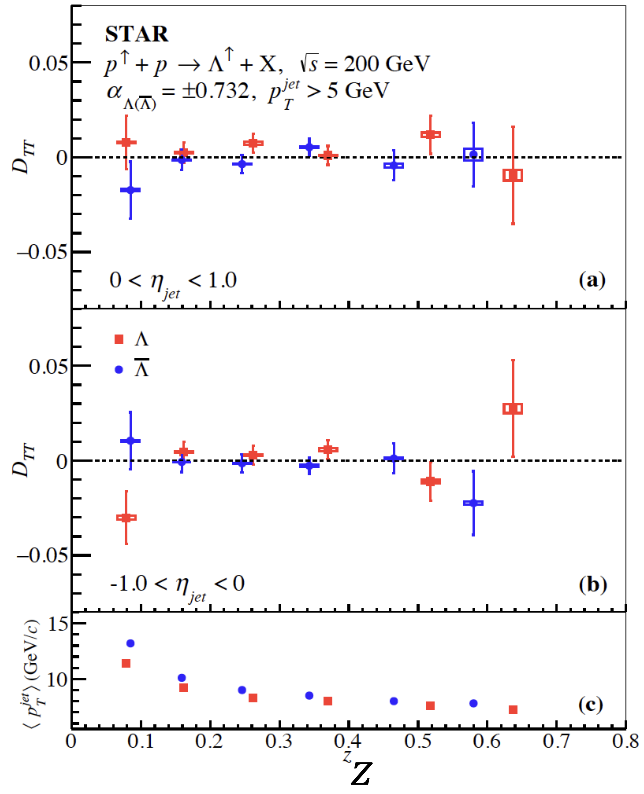
Both polarization transverse to production plane



Latest D_{TT} measurements at RHIC

STAR, PRD109, 012004 (2024)

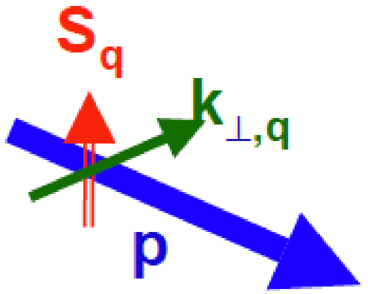




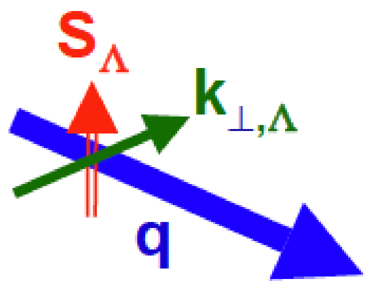
- The D_{TT} results are consistent with model calculations within uncertainties, also consistent with 0.
- First measurement of D_{TT} vs. z in p+p collisions, providing constraints on transversely polarized fragmentation functions.

Polarizing Fragmentation Function

See Dingyu's talk



$$\longleftarrow \vec{S}\cdot(\vec{p}\times\vec{k}_\perp) \longrightarrow$$



Quark pol. (columns) / Hadron pol. (rows)

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

TMD PDFs

Quark pol. (columns) / Hadron pol. (rows)

	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	$H_1, H_{1T}^\perp$

TMD FFs

Unpolarized quark fragmenting into transversely polarized hadron

Measurements in e^+e^- annihilation

- LEP ($\sqrt{s} = 90$ GeV): no significant polarization
  - ALEPH $P_T^{\Lambda,\bar{\Lambda}} = 0.016 \pm 0.007$

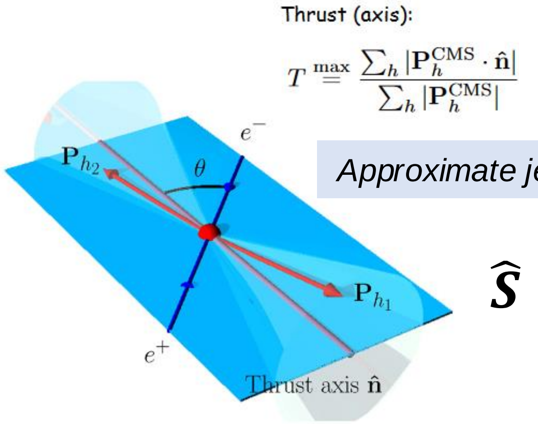
  ALEPH, PLB 374, 319 (1996)
  - OPAL $P_T^{\Lambda} = 0.019 \pm 0.014$ ($p_T > 0.3$ GeV/c)

  OPAL, EPJC 2, 49 (1998)
- At Belle ($\sqrt{s} = 10.6$ GeV) *Belle, PRL 122, 042001 (2019)*
  - Significant polarization with fractional energy z dependence
- Extraction of polarizing Fragmentation Function(pFFs)

  Callos, Kang, Terry, PRD 102, 096007 (2020)

  D'Alesio, Murgia, Zaccheddu, PRD 102, 054001 (2020)

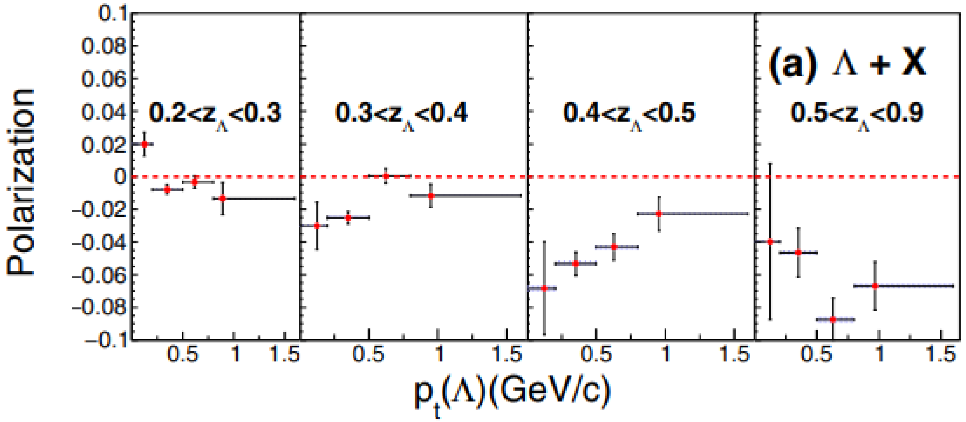
  Chen, Liang, Pan, Song, Wei, PLB 816, 136217 (2021)
- The difference between LEP and Belle is energy scale dependence?



Approximate jet axis

$$\hat{\boldsymbol{S}} = \hat{\boldsymbol{n}}_{\text{thrust}} \times \hat{\boldsymbol{p}}_{\Lambda}$$

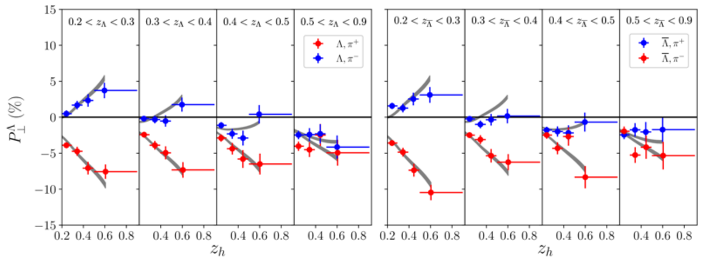
$$z_\Lambda = \frac{2E_\Lambda}{\sqrt{s}}$$

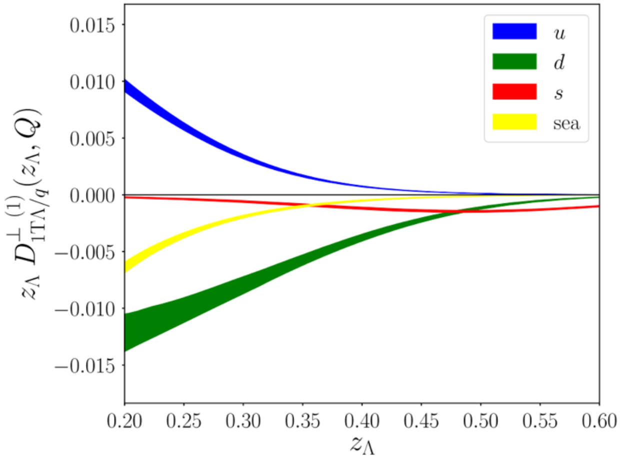


Global analyses of Belle results

Callos, Kang, Terry,

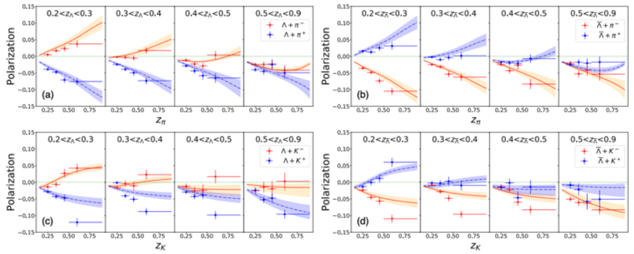
PRD 102, 096007 (2020)

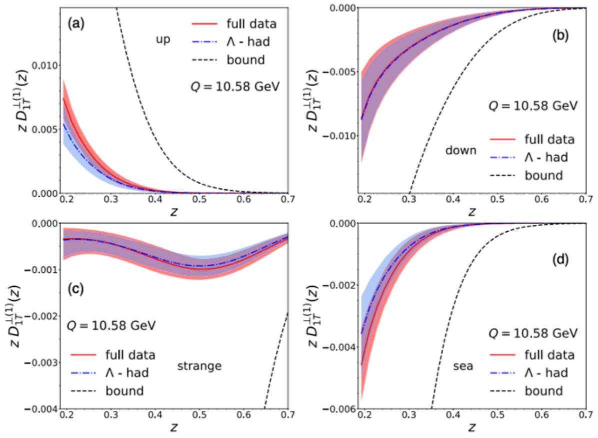




D'Alesio, Murgia, Zaccheddu,

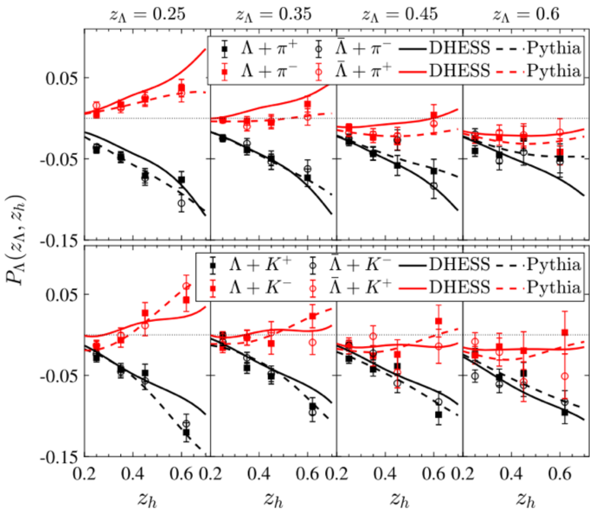
PRD 102, 054001 (2020)





Chen, Liang, Pan, Song, Wei,

PLB 816, 136217 (2021)



Isospin symmetry constrained

$$D_{1Tu}^{\perp\Lambda} = D_{1Td}^{\perp\Lambda}$$

Also Twist-3 FF: Gamberg, Kang, Shao, Terry, Zhao, PLB818, 136371 (2021)

What can we do in pp/pA collision at RHIC and LHC?

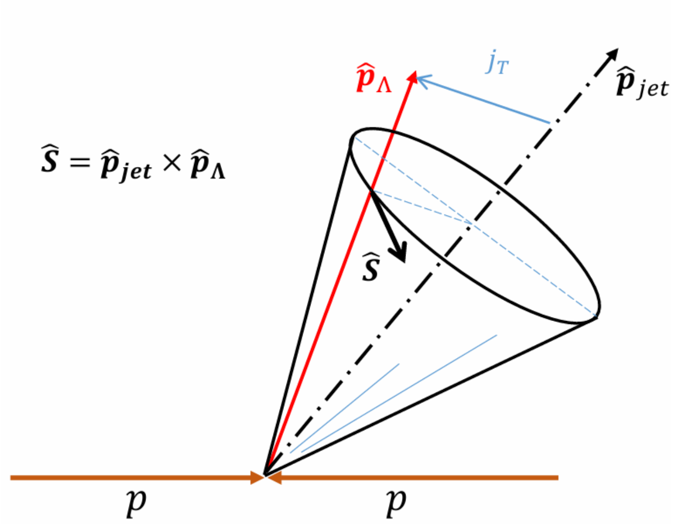
- Polarizing Fragmentation Functions(pFFs) can be accessed by transverse polarization of Λ-in-jet in pp collision

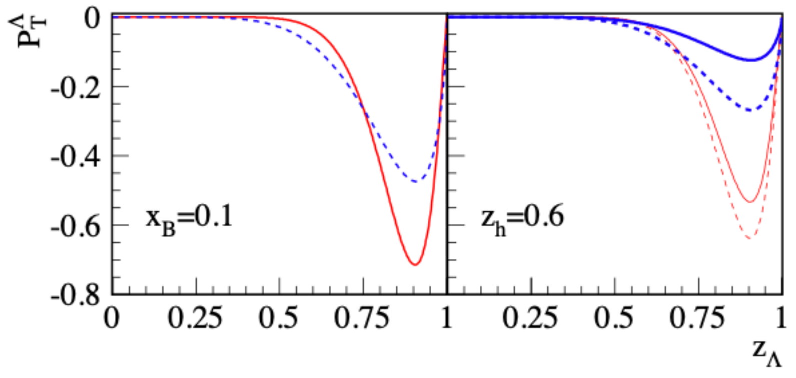
  Boer et al, PLB 671, 91-98 (2008)

  Kang, Lee, Zhao, PLB 809, 135756 (2020)

- Polarization direction normal to the production plane constructed by jet and Λ momentum

- Complement to $e^{-}e^{+}$:
  - Cover a wide range of jet p_T: 5~50 GeV at RHIC and higher at LHC
  - Test universality of pFFs

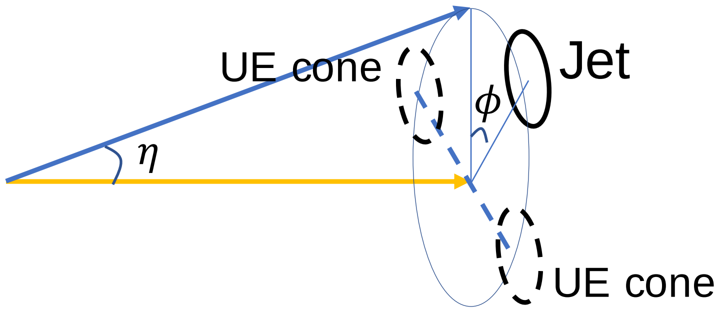


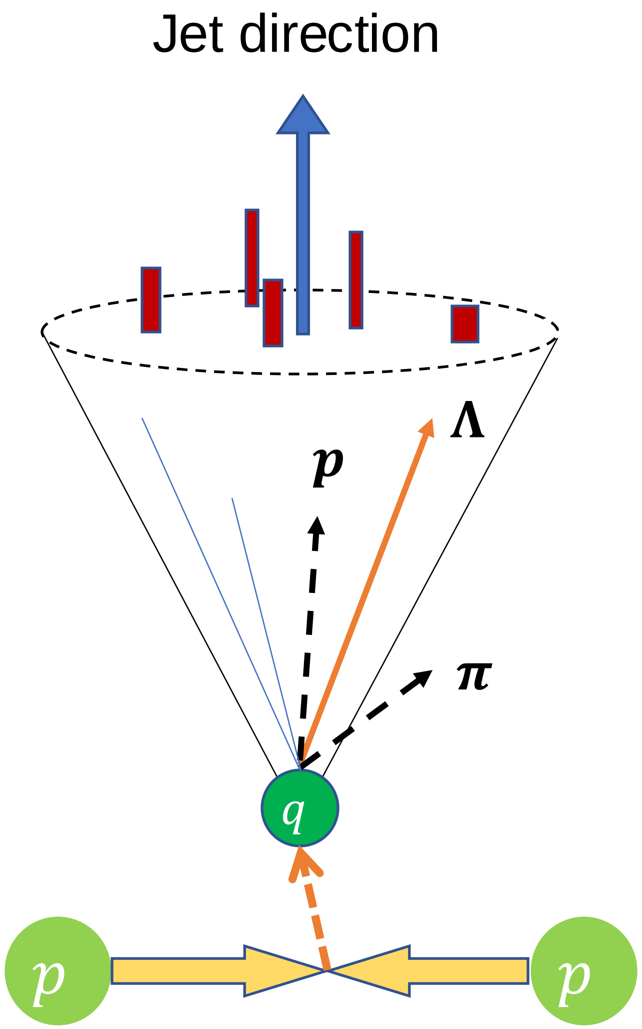


Boer et al, Phys.Rev. Lett. 105.202001 (2010)

V0-jet reconstruction

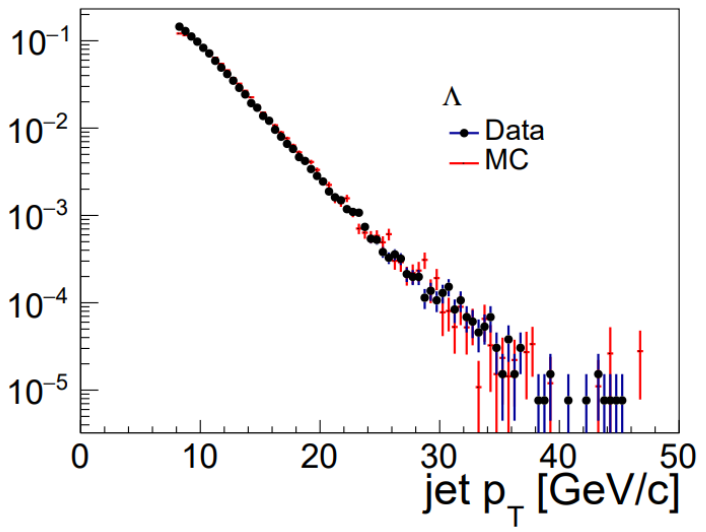
- Jet reconstruction
  - Anti-k_T with $\mathrm{R} = 0.6$
  - Particle list: TPC tracks and EMC energy deposit
  - $\Lambda, \bar{\Lambda}$ as input particles
  - Removing daughter particles to avoid double counting
- Underlying event correction by off-axis method

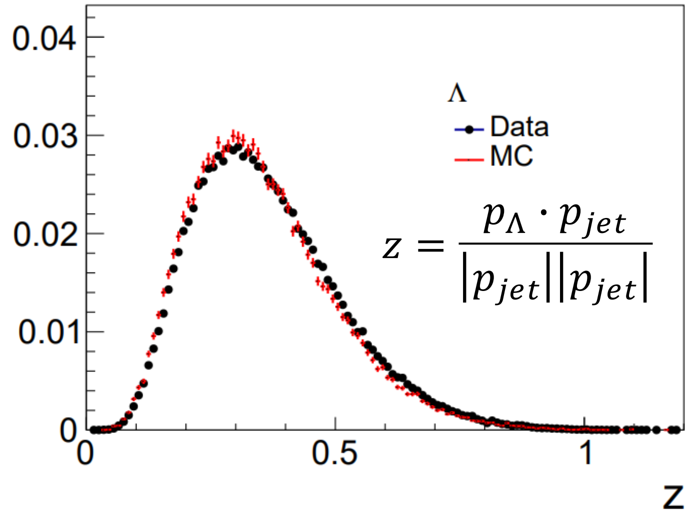




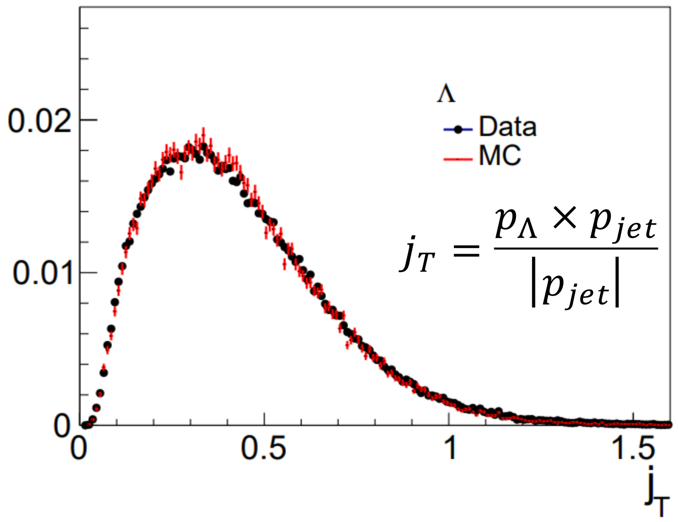
MC simulation

- Generator: PYTHIA 6.4.28
- Full GEANT3 simulation of detector response
- Λ filter and trigger filter
- Same analysis algorithm applied for MC sample as for data





Jet momentum fraction carried by $\Lambda(\bar{\Lambda})$

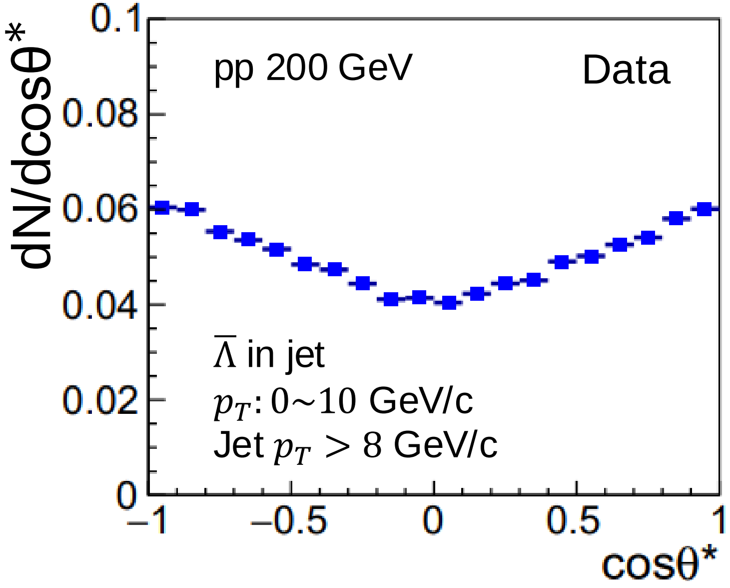


Transverse momentum of $\Lambda(\bar{\Lambda})$ w.r.t. jet axis

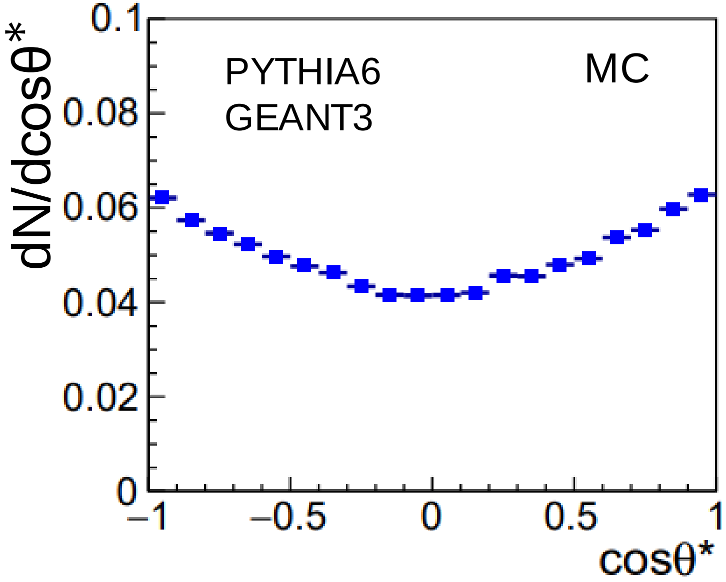
Acceptance correction and polarization extraction

Extracting polarization through fitting: $\frac{dN}{d\cos\theta^*} \propto A(\cos\theta^*)(1 + \alpha P \cos\theta^*)$

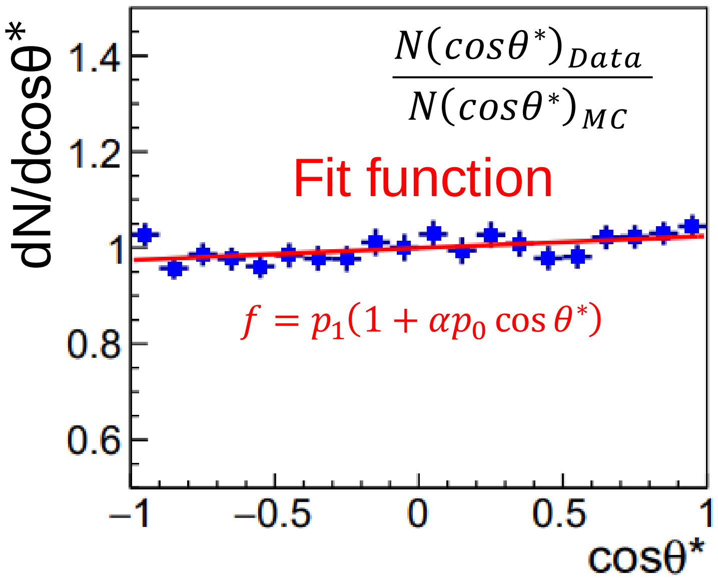
Note: normalized to 1



The shape of $cos\theta^*$ caused by detector acceptance



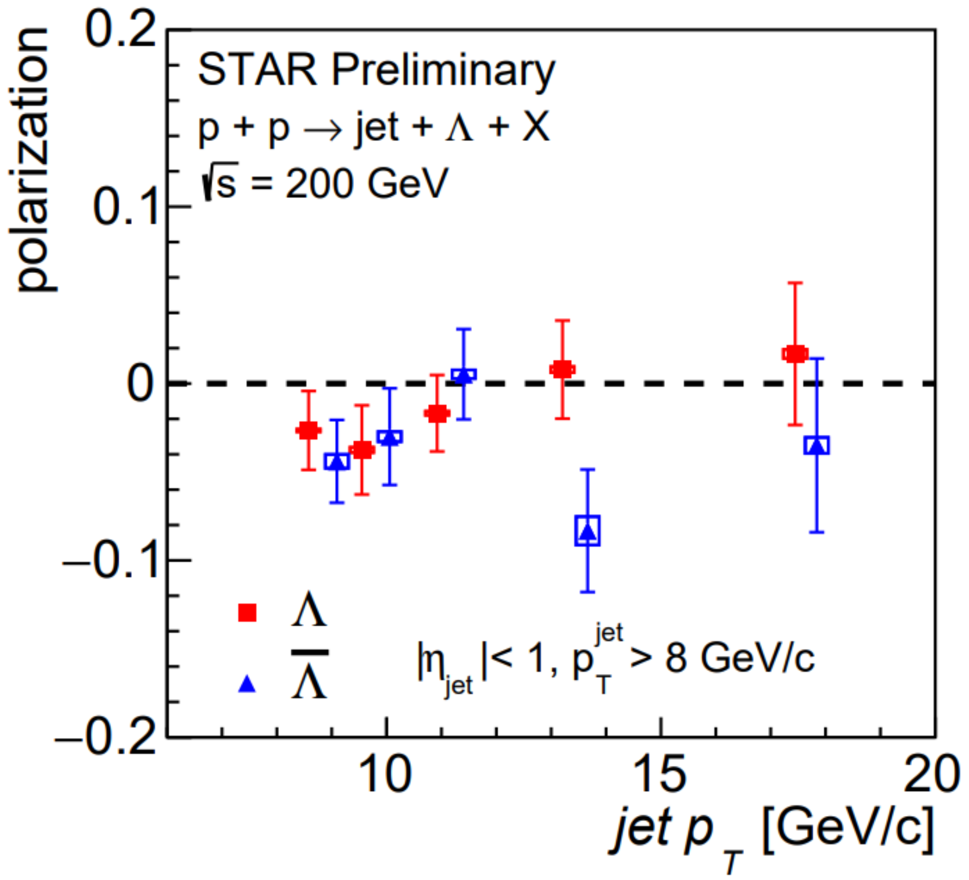
$A(\cos\theta^*)$: Acceptance correction function obtained from MC simulation

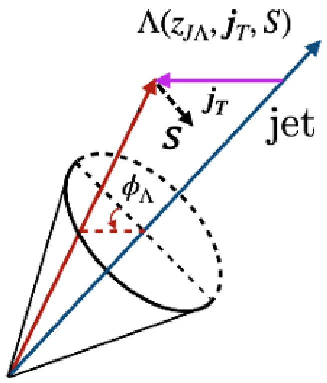


Polarization extraction by corrected $cos\theta^*$ distribution

Preliminary results from 200 GeV pp collision

Polarization as a function of jet p_T





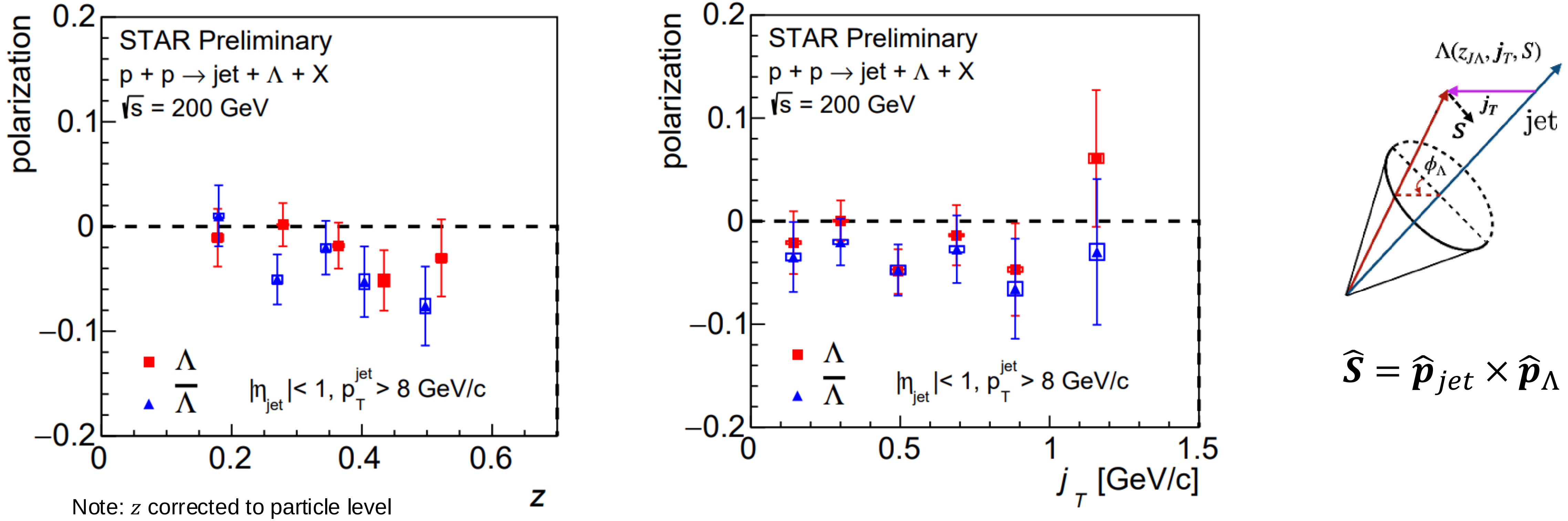
$\hat{\boldsymbol{S}} = \hat{\boldsymbol{p}}_{jet} \times \hat{\boldsymbol{p}}_\Lambda$

- Cover jet p_T range: 8~25 GeV/c
- No significant jet p_T dependence
- Indication of non-zero $\bar{\Lambda}$ polarization ($\sim 2\sigma$) from average value

Note: $\Lambda(\bar{\Lambda})$ jet p_T corrected to particle level

Preliminary results from 200 GeV pp collision

Polarization as a function of z and j_T

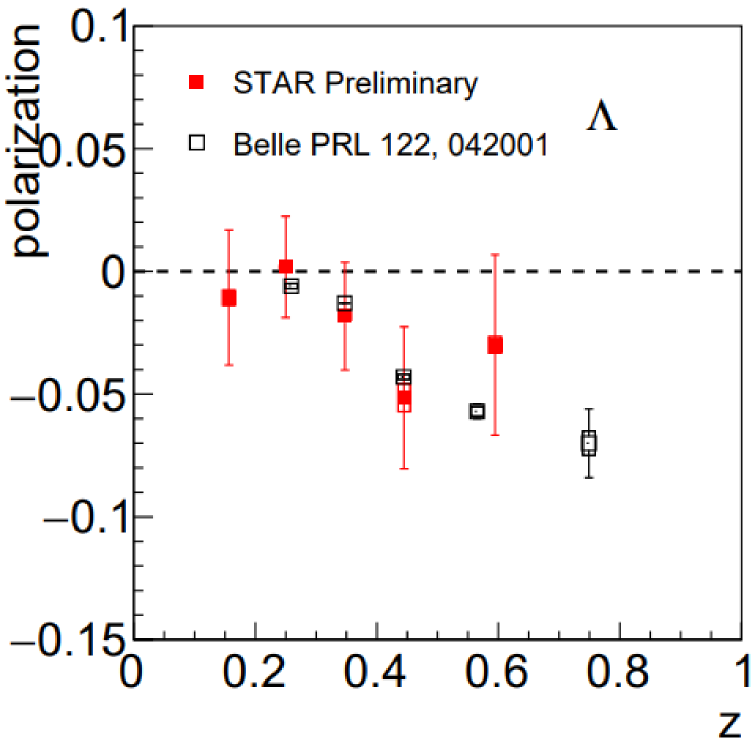


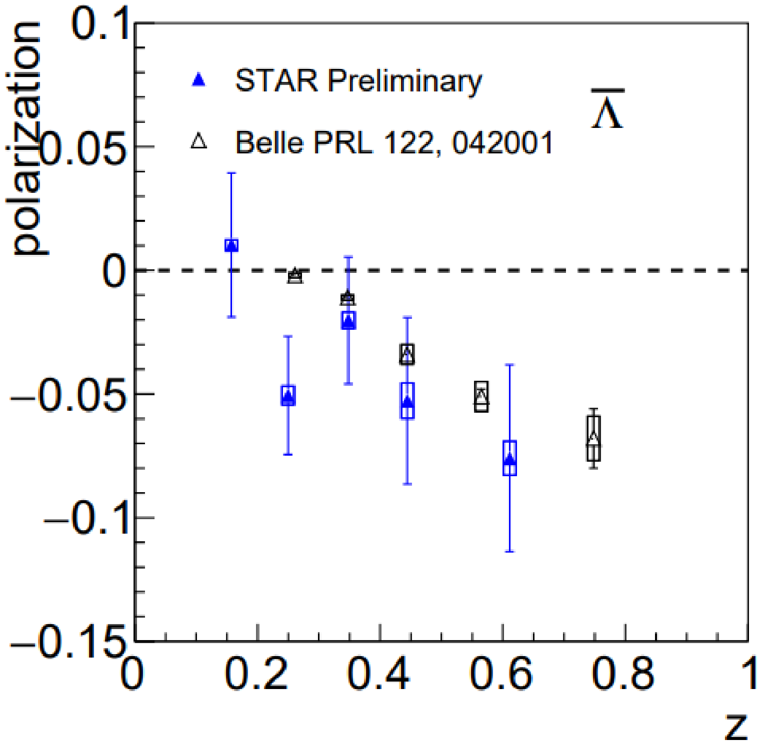
Note: z corrected to particle level

$$\hat{S} = \hat{p}_{jet} \times \hat{p}_\Lambda$$

- Weak z dependence of polarization; no significant j_T dependence
- Providing new data for pFFs, with significant gluon contribution.
- First universality test vs e+e- results

Comparison with e^+e^- results

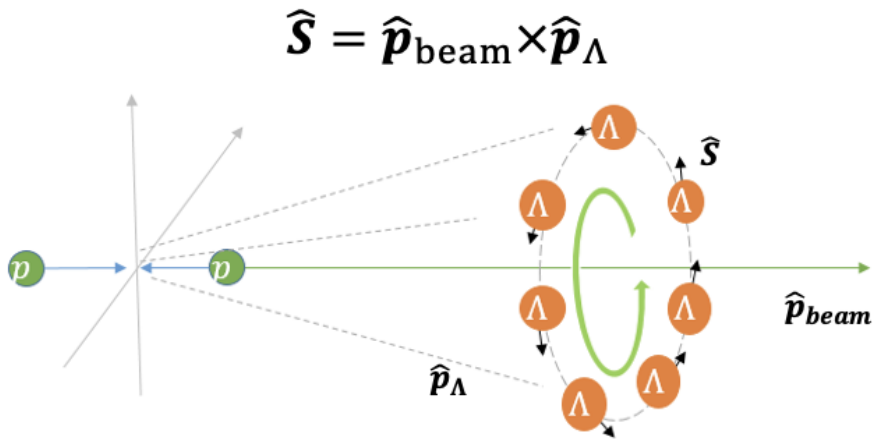




- STAR energy scale: jet $\langle p_T \rangle \sim 11$ GeV/c
- Λ production at pp is different from Belle
- Similar polarization trend as Belle

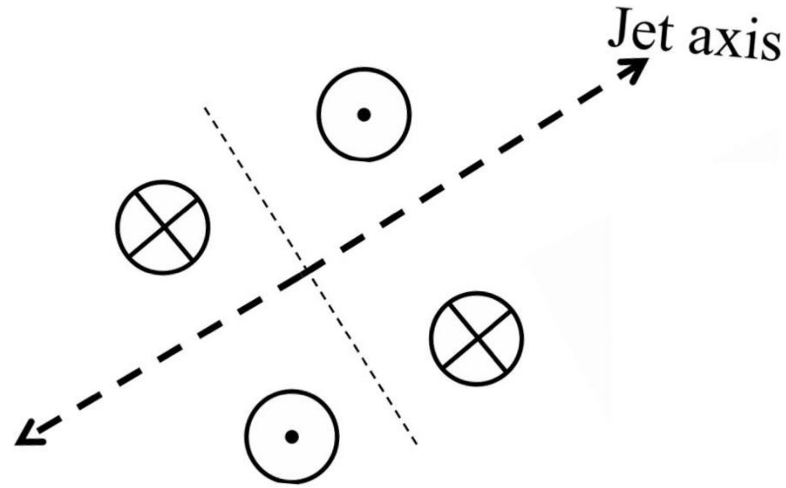
Possible connection to other observables?

To production plane polarization



When Lambda-in-Jet is selected with bias, production planes spanned by beam and lambda consistent with by jet axis and lambda

To local polarization with low multiplicity



See Zhenyu's talk

When (leading) di-jet or mutli-jet impact event plan reconstruction, polarization surrounding jet axis can be observed as "local polarization"

Summary for lambda in pp (or effective pp)

- Lambda “spontaneous” polarization: longstanding puzzle is still standing after ~50 years
- Lambda spin transfer results could constrain pPDFs and pFFs, in global analysis.
  - 200 GeV data analyzed;
  - 500 GeV on disk to be analyzed.
- Polarization of Lambda in jet could access polarizing FFs and hopefully answer some puzzling questions.
  - Completing analysis of pp 200 GeV;
  - Ongoing analysis for pp500 GeV, pAu 200 GeV and pPb 8.26 TeV

Thanks for your attention!