Λ spin correlation at Belle II

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Belle II Summer Workshop

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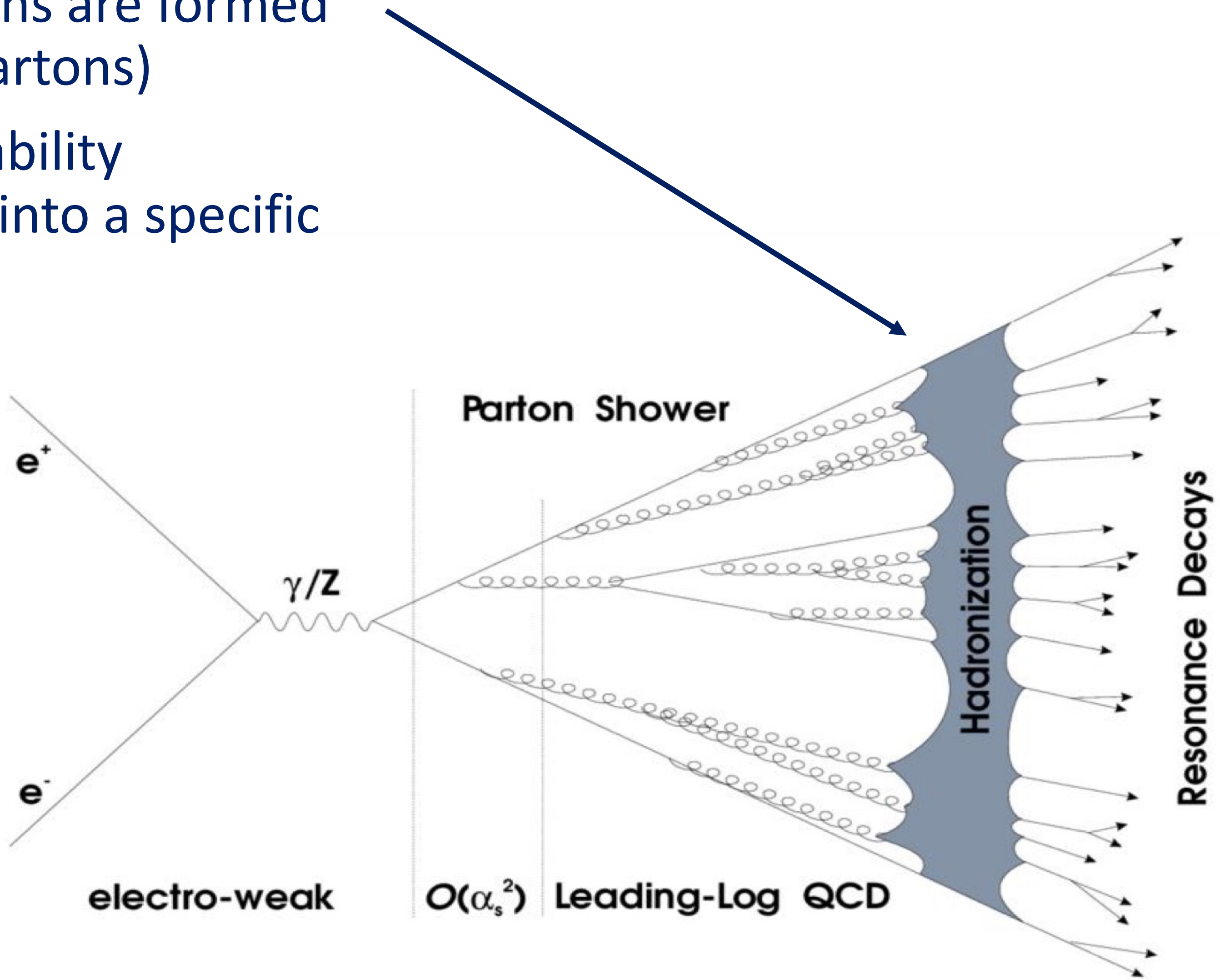
U.S. DEPARTMENT OF ENERGY | Office of Science

Hadronization at Belle II

- **Hadronization:** how particular hadrons are formed from scattered quarks and gluons (partons)
- **Fragmentation Functions (FF):** probability distribution of a parton fragmenting into a specific hadron

$$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes \boldsymbol{FF}$$

Image source: Buskulic et al. (1995)



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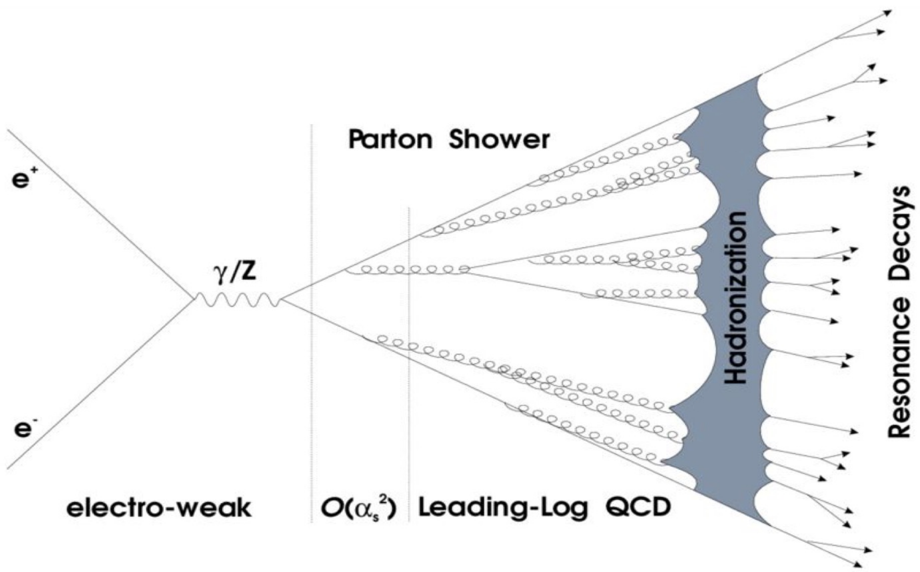
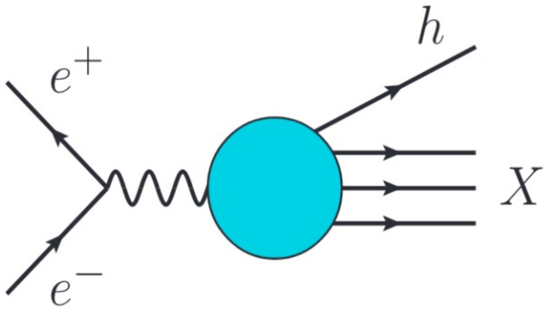
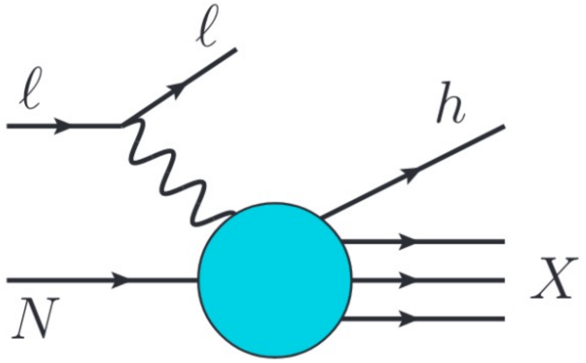


Important processes in studying hadron formation:

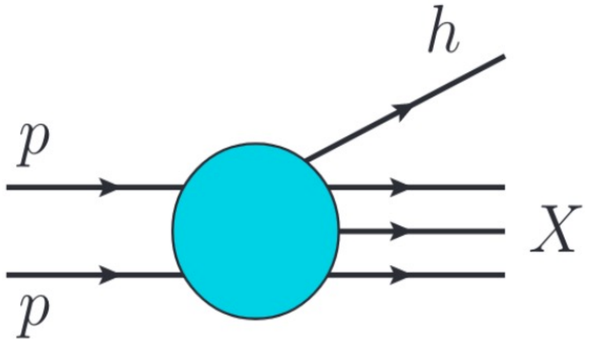
$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes \boldsymbol{FF}$



$\sigma^{lN\to lhX} = PDF \otimes \hat{\sigma} \otimes \boldsymbol{FF}$



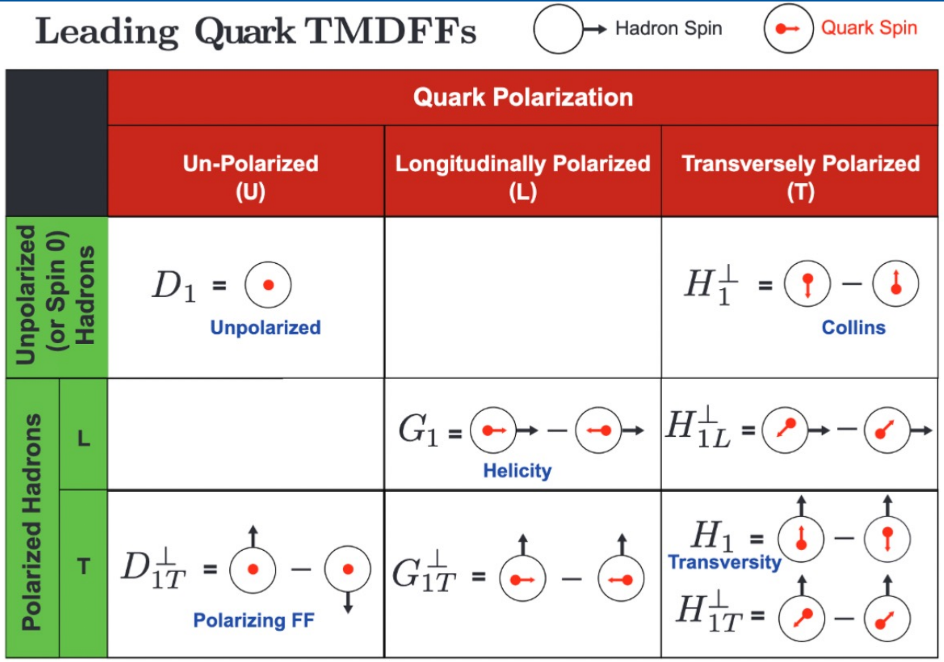
$\sigma^{pp\to hX} = PDF \otimes PDF \otimes \hat{\sigma} \otimes \boldsymbol{FF}$



Hadronization at Belle II

Image from arXiv:2304.03302v1

- **Hadronization:** how particular hadrons are formed from scattered quarks and gluons (partons)
- **Fragmentation Functions (FF):** probability distribution of a parton fragmenting into a specific hadron
- **Transverse momentum dependent (TMD)**: spin-momentum correlations



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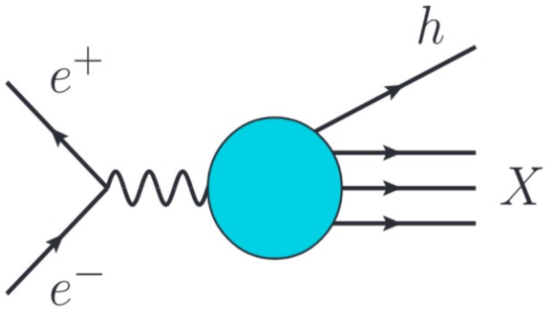

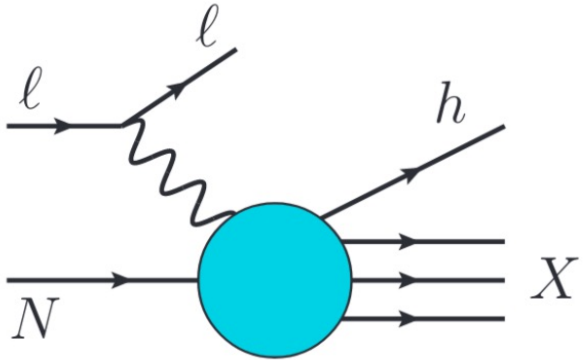

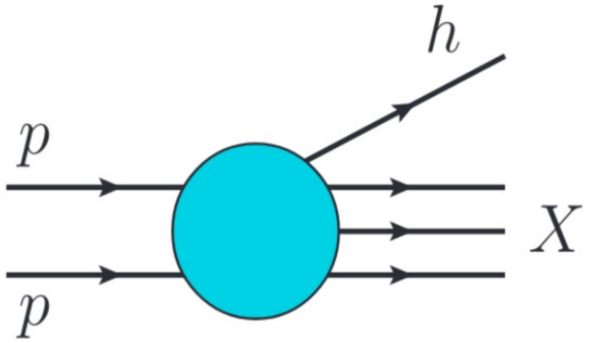

Hadronization at Belle

Belle measurements sensitive to:
- Collins FF
- Di-hadron FF
- Polarizing FF

. . .

Azimuthal asymmetries in inclusive production of hadron

Phys. Rev. Lett. 96, 232002 (2006)Phys. Rev. D 78, 032011 (2008) [*Phys.Rev.D 86, 039905 (2012*]

Transverse polarization asymmetries of charged pion pairs

Phys. Rev. Lett. 107, 072004 (2011)

Inclusive cross sections for pairs of identified light charged hadrons and for single

Phys. Rev. D 92, 092007 (2015)

Invariant-mass and fractional-energy dependence of inclusive production of di-hadrons

Phys. Rev. D 96, 032005 (2017)

Production cross sections of hyperons and charmed baryons

Phys. Rev. D 97, 072005 (2018)

Transverse $\Lambda/\bar{\Lambda}$ Hyperon

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

Transverse momentum dependent production cross sections of charged pions, kaons and protons

Phys. Rev. D 99, 112006 (2019)

Inclusive cross sections of single and pairs of identified light charged hadrons

Phys. Rev. D 101, 092004 (2020)

Recent measurement

Production cross section of light and charmed mesons

Belle preprint 2024-09, KEK Preprint 2024-30, submitted to PRD

Hadronization at Belle II and for the EIC

- **Belle II can offer high precision, comprehensive measurements essential for the Electron-Ion Collider (EIC)**
  - Clean environment for detailed studies of hadronic final states
  - Multi-dimensional analyses of FFs, correlations, heavy flavor, and hadronization effects in jets
  - Essential for understanding transverse momentum of partons in measurements of PDFs and spin-structure of nucleon at the EIC

  + . . .

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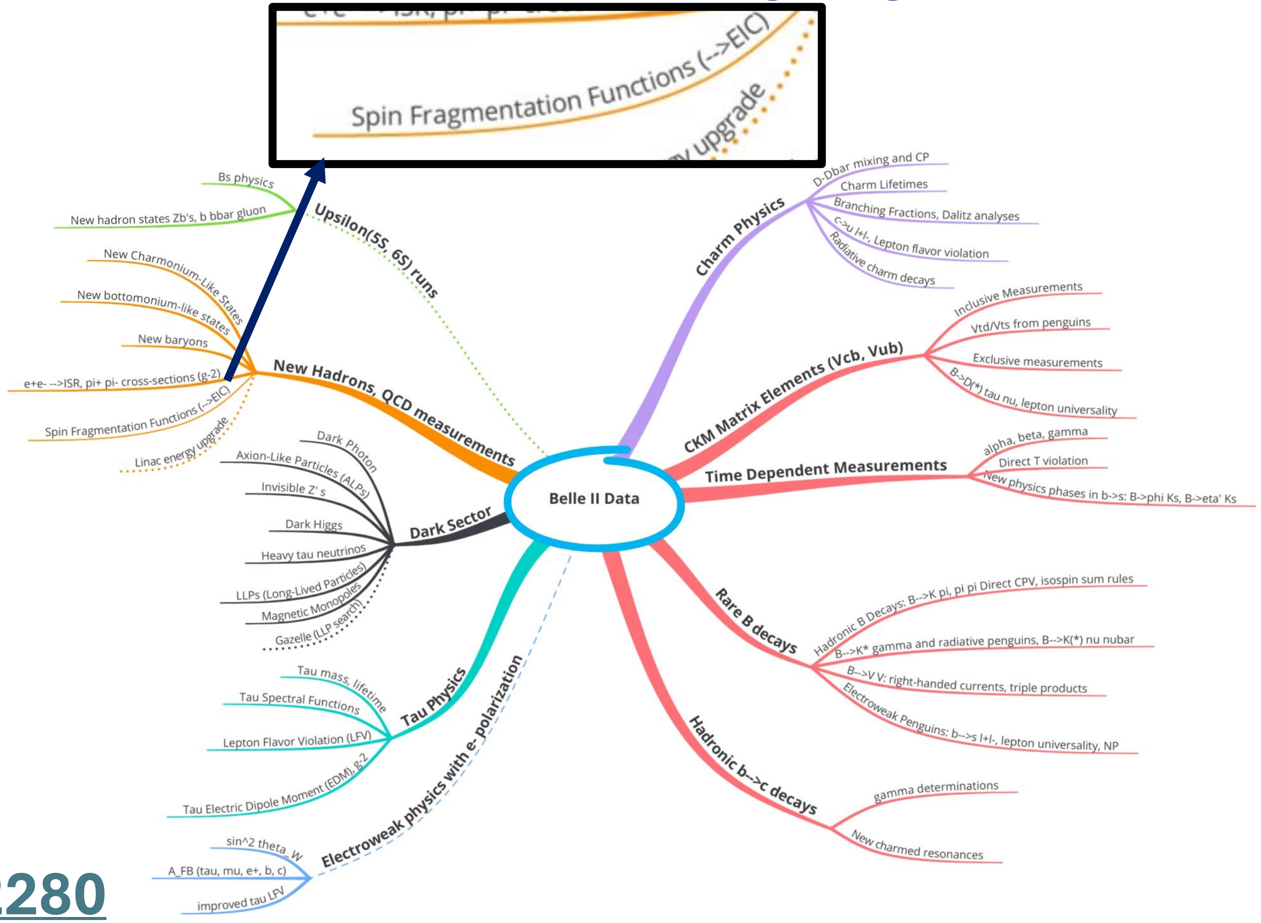


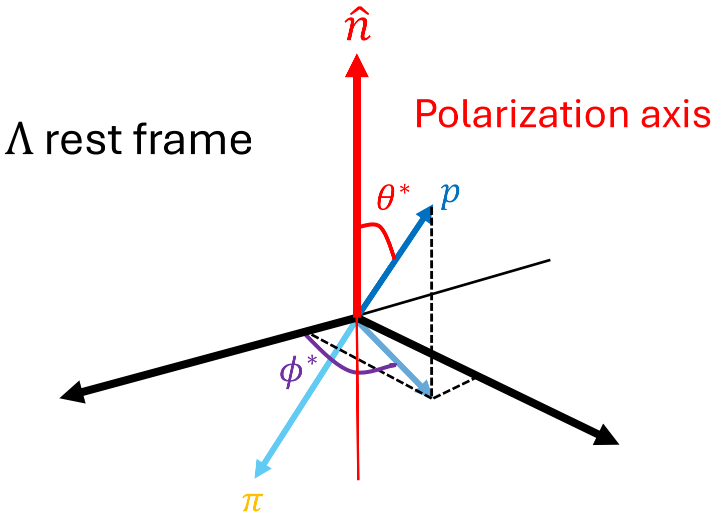
See Snowmass whitepaper [arXiv:2204.02280](https://arxiv.org/abs/2204.02280)

Λ polarization

- $\Lambda \to p\pi^-$ **self analyzing decay**
- The distribution of θ^* for polarized Λ:

$$\frac{1}{N}\frac{dN}{d\cos\theta^*} = (1 + \alpha_\Lambda P\cos\theta^*)$$

α_Λ= 0.748 ± 0.007 (PDG 2023)



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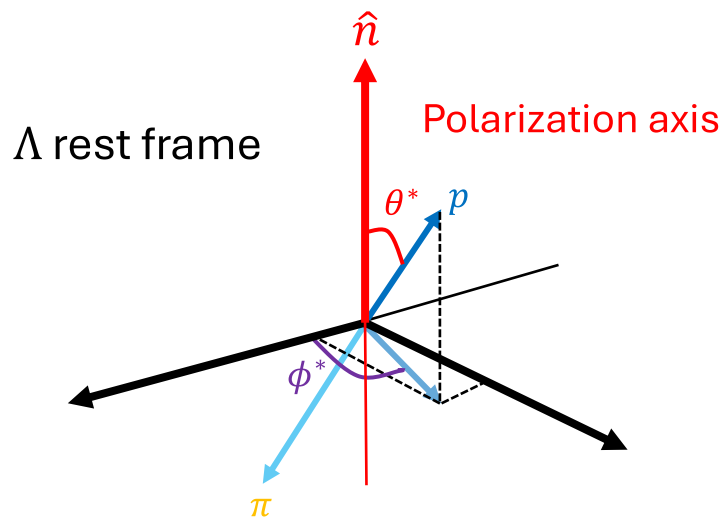
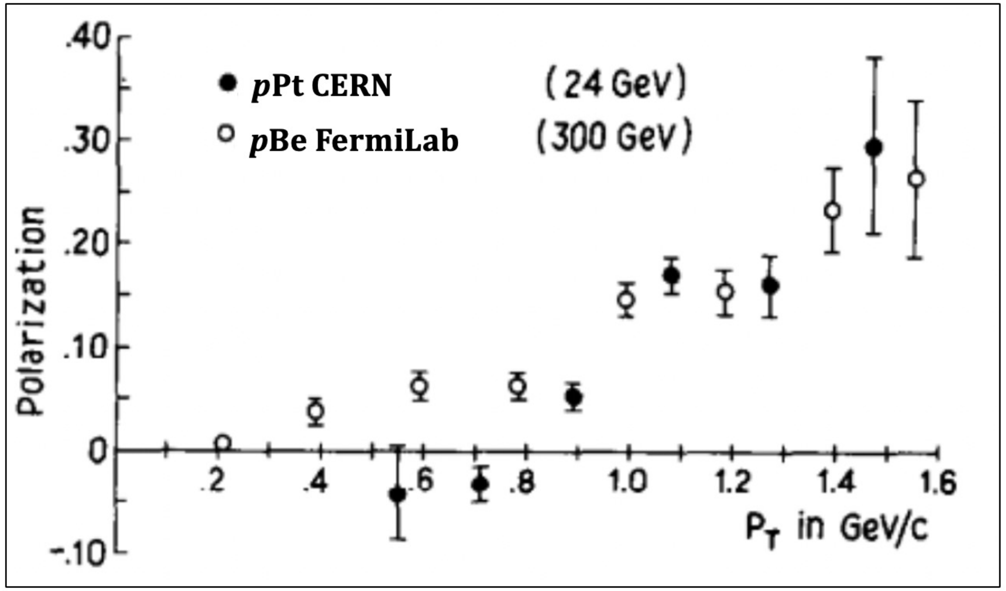
- **Spontaneous transverse Λ Polarization observed in 1976 in unpolarized *p*Be with polarization values up to 30%**



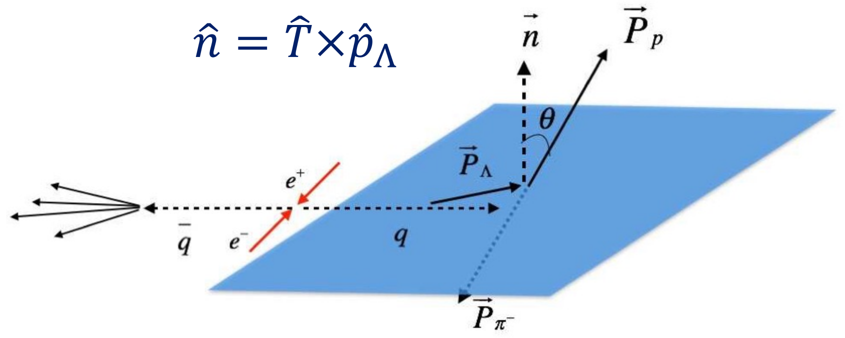


PRL36, 1113 (1976)
PLB68, 480 (1977)
PRL 41, 1689 (1978)
PRL 122, 042001 (2019)

Measurement of Λ polarization [Phys. Rev. Lett. 122, 042001 (2019)]

- **Observed non-zero polarization in**
  $e^+e^- \rightarrow \Lambda X$ at Belle
  $\rightarrow$ hadronization effect

$$\hat{n} = \hat{T} \times \hat{p}_\Lambda$$



Thrust:

$$\mathrm{T} = \max \frac{\Sigma_h \left| P_h^{CMS} \cdot \hat{T} \right|}{\Sigma_h \left| P_h^{CMS} \right|}$$

Measurement of Λ polarization

$z_h = 2E_h/\sqrt{s}$

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

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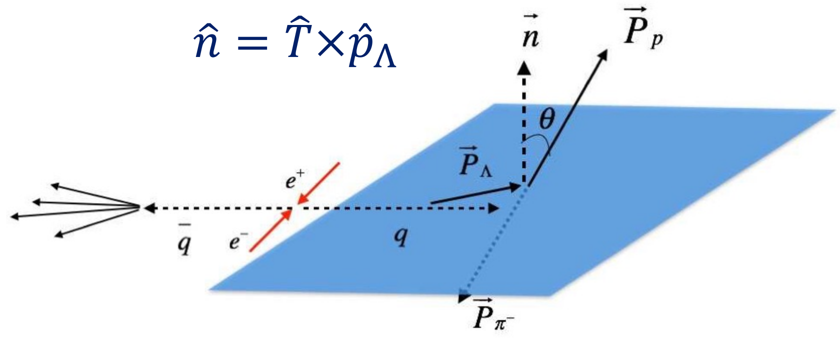
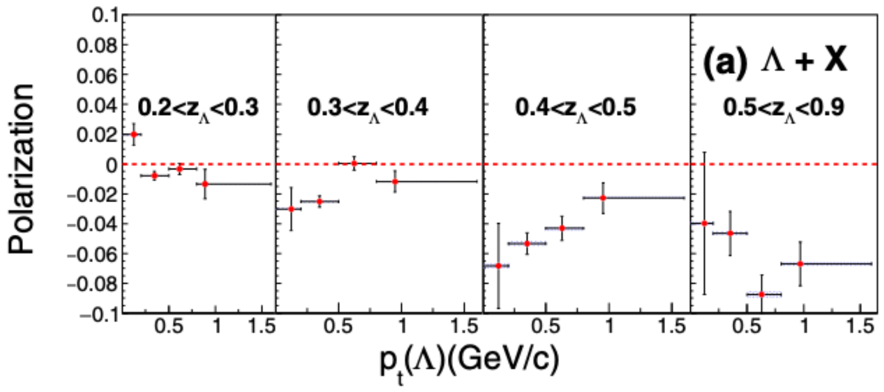
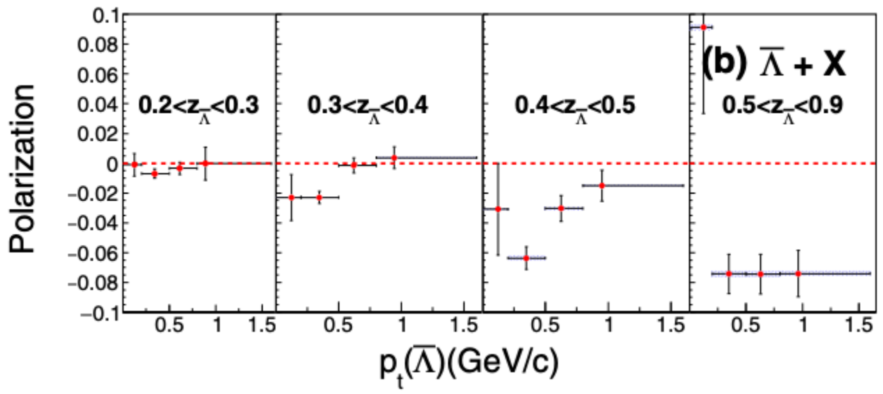


- **Nonzero transverse polarization observed for Λ and $\bar{\Lambda}$ as function of $z_h$and p_T**





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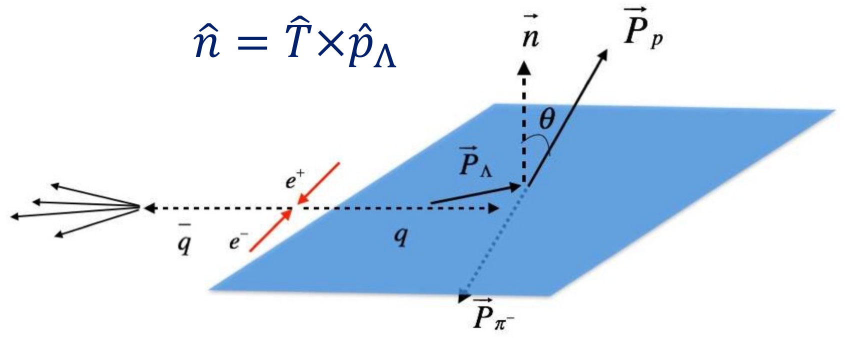
Phys. Rev. Lett. 122, 042001 (2019)



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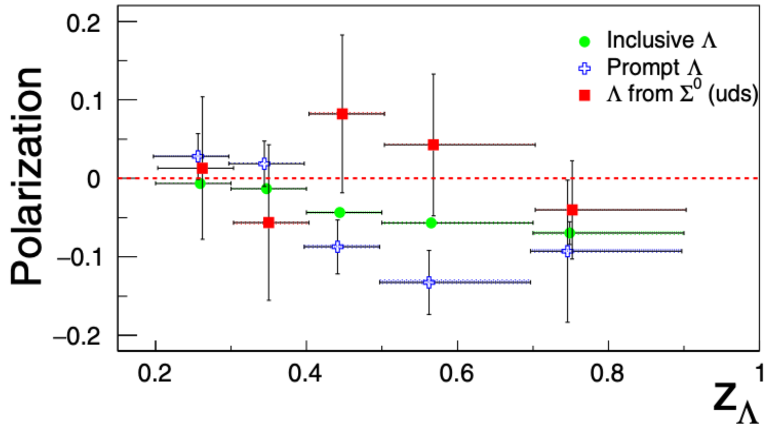
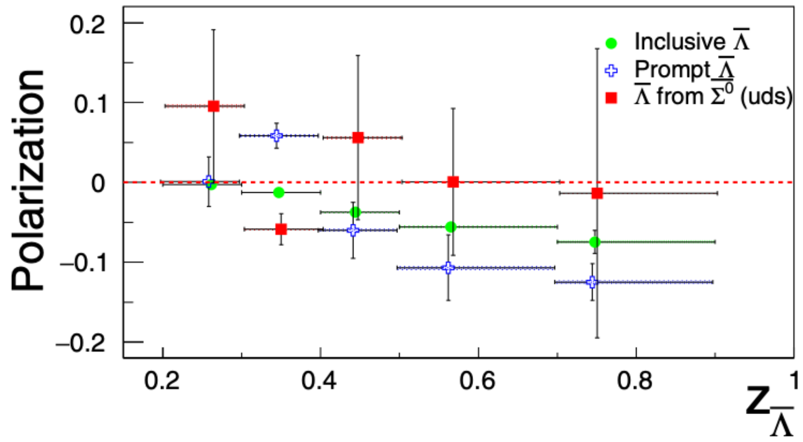
  $\to$ **hadronization effect**
- **Nonzero transverse polarization observed for Λ and $\bar{\Lambda}$ as function of z_h and p_T**
- **Investigate feed-down contributions from Σ^0 and charm decays**





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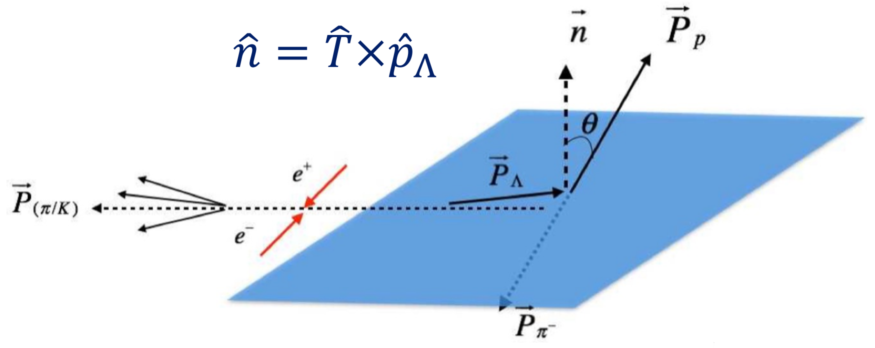
  $\rightarrow$ **hadronization effect**

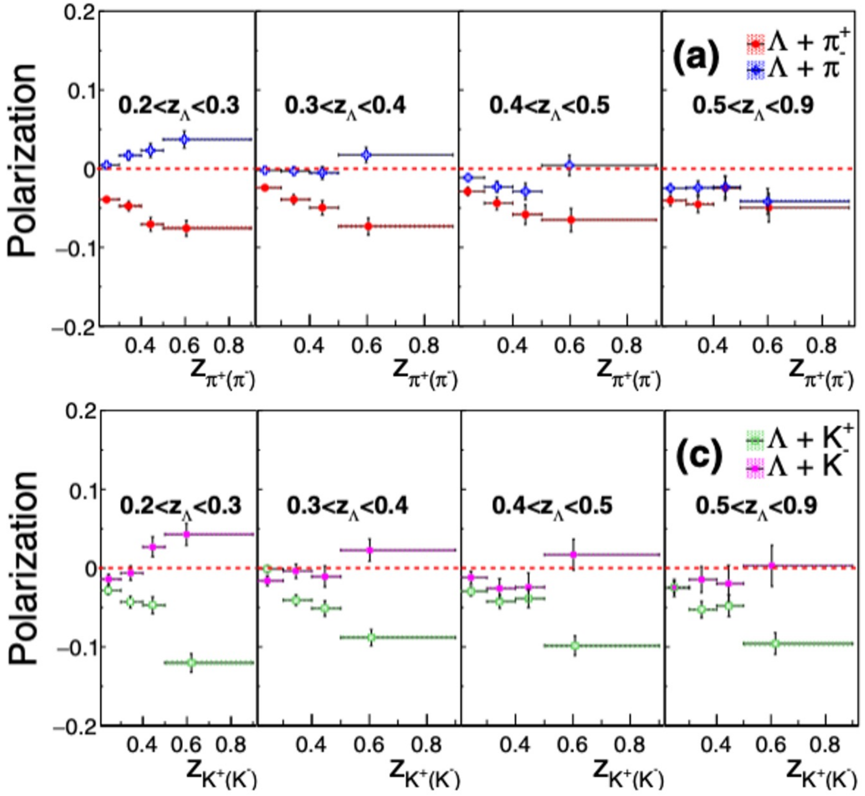
- Nonzero transverse polarization observed for Λ and $\overline{\Lambda}$ as function of z_h and p_T

- Investigate feed-down contributions from Σ^0 and charm decays

- **Polarization measurement also with respect to hadron in opposite hemisphere**

$\hat{n} = \hat{T} \times \hat{p}_\Lambda$





Transverse Λ polarization

- Measurement sensitive to **polarizing transverse-momentum dependent (TMD) fragmentation functions (FF)** $D_{1T}^{\perp\Lambda/q}\left(z,k_{\perp}^{2}\right)$

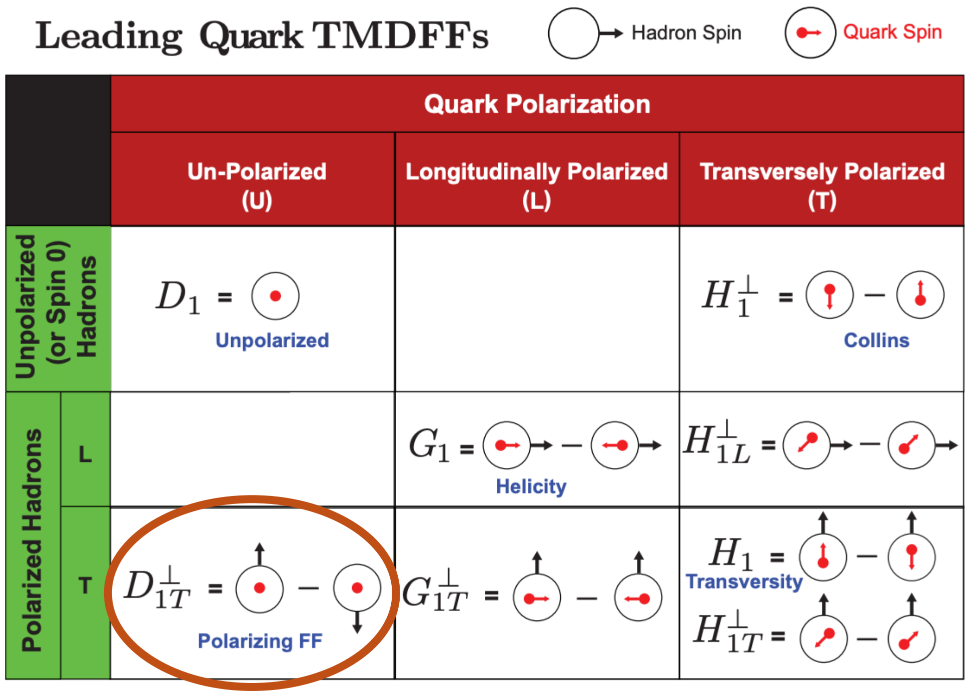


Image from arXiv:2304.03302v1

Transverse Λ polarization

- Measurement sensitive to **polarizing transverse-momentum dependent (TMD) fragmentation functions (FF)** $D_{1T}^{\perp\Lambda/q}\left(z, k_{\perp}^{2}\right)$
- Belle measurement data accurate enough for **phenomenological studies to extract FF**
  - Phys. Rev. D 102, 054001 (2020)
  - Phys. Rev. D 102, 096007 (2020)
  - Phys. Lett. B 809, 135756 (2020) + . . .

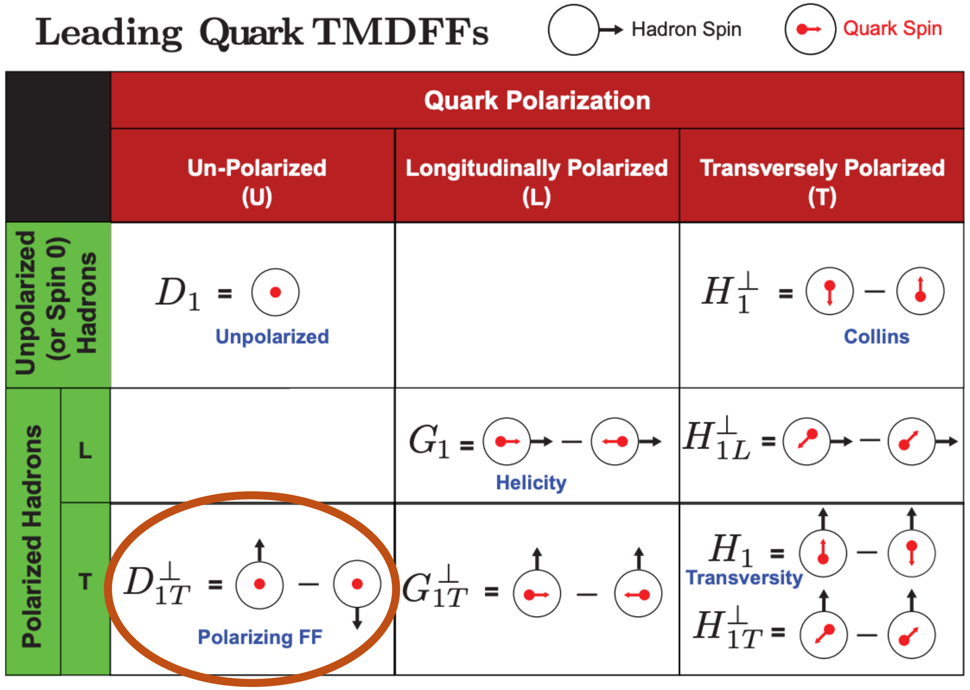
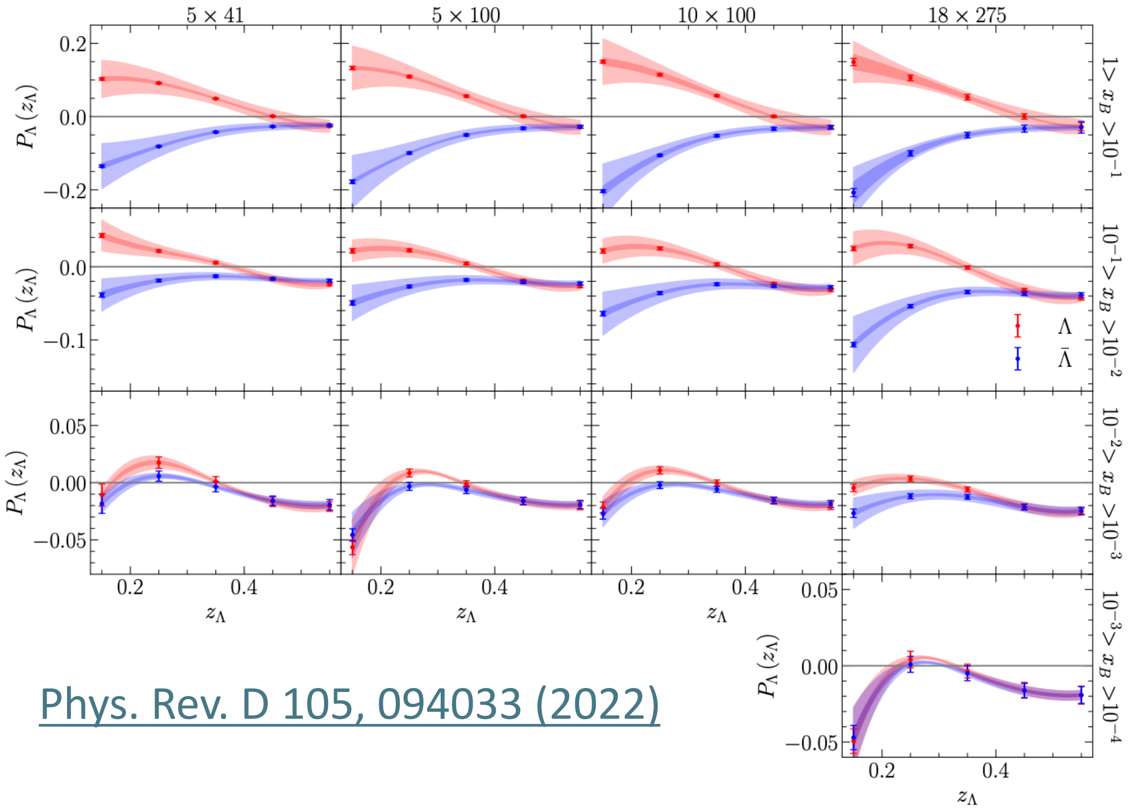


Image from arXiv:2304.03302v1

- Used for **Λ polarization predictions in $ep \to \Lambda X$**:

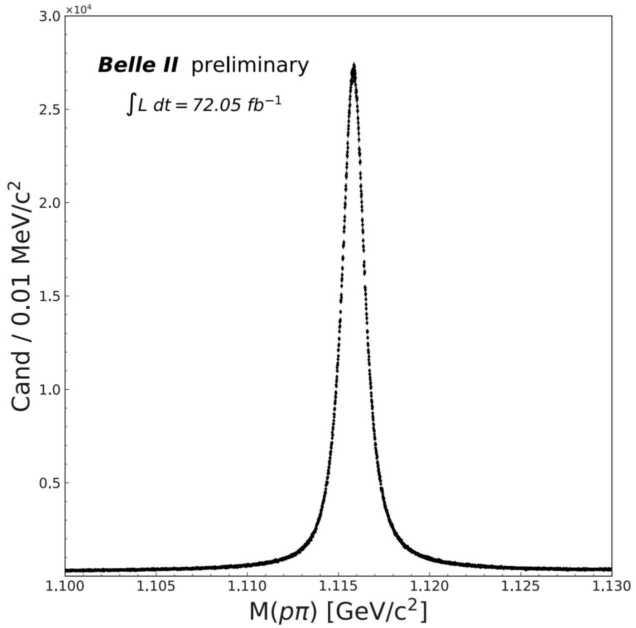


Phys. Rev. D 105, 094033 (2022)

Λ polarization at Belle II

- FFs give insight into spin structure of the Λ
- Λ as polarimeter to explore baryon/hyperon structure
- **Transverse Λ polarization at Belle II**
    - Reduce uncertainties from feed-down and the prompt Λ
    - Λ polarization with respect to the plane spanned by beam axis and Λ momentum

BELLE2-NOTE-PL-2020-031



Λ polarization at Belle II

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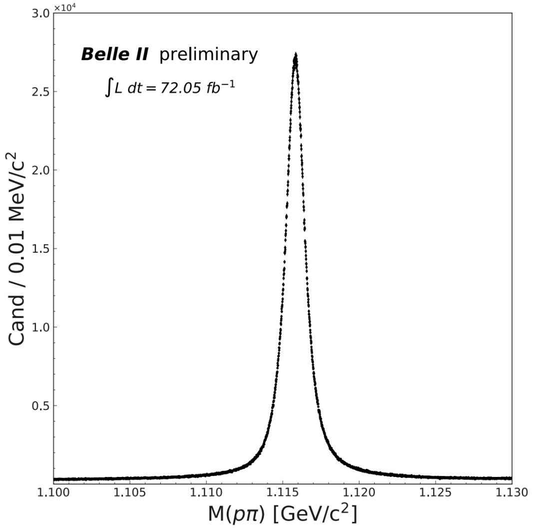
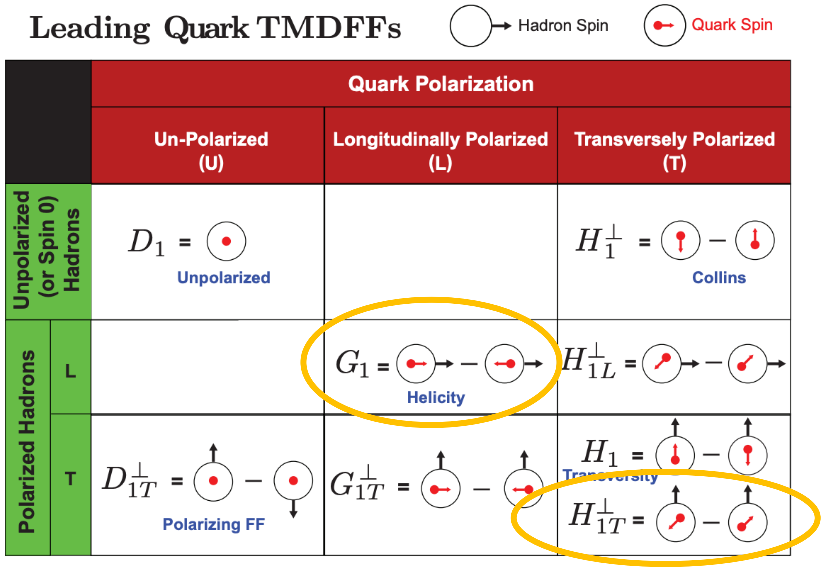
- Transverse Λ polarization at Belle II
  - Reduce uncertainties from feed-down and the prompt Λ
  - Λ polarization with respect to the plane spanned by beam axis and Λ momentum
- **$\Lambda\Lambda$ spin correlations**
  - Entanglement as a probe to hadronization

    Parton spin correlations and **entanglement** give rise to the Λ polarization ?
  - Entangled $s\bar{s} \rightarrow \Lambda\bar{\Lambda}$
  - Sensitivity to spin transfer FFs $G_{1T}^{\perp}$ and $H_{1T}^{\perp}$

BELLE2-NOTE-PL-2020-031



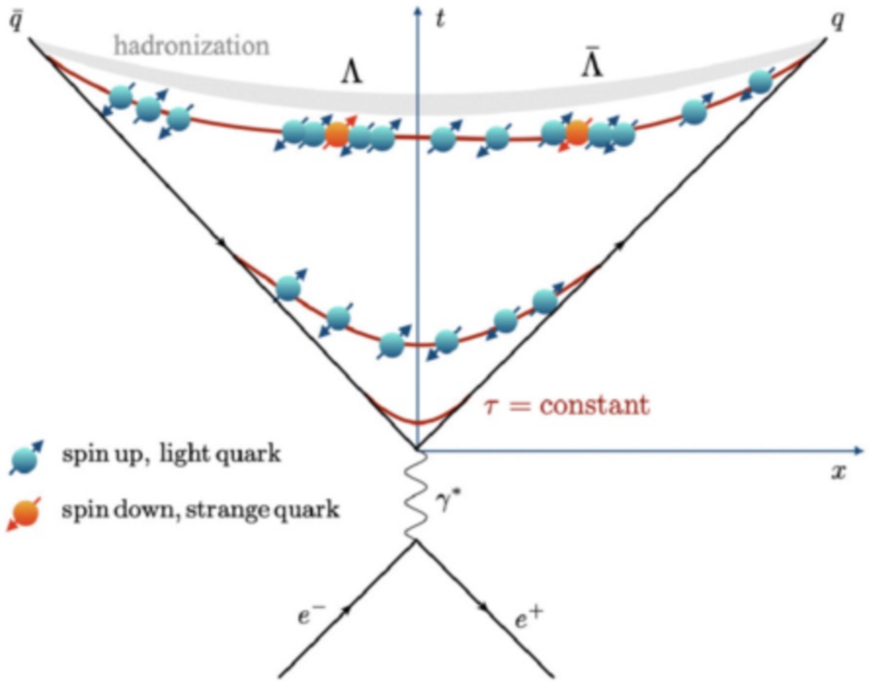


$\Lambda\Lambda$ spin correlation measurement

Entanglement via $\Lambda\Lambda$ spin correlations

Phys. Rev. D 106, L031501 (2022)
Phys. Rev. D 109, 116003 (2024)

- **Entanglement as a probe to hadronization**
  - Experimentally track entangled $s\bar{s}$ quark into hadrons
  - **Theoretical framework:**
    - Quantum simulations to validate entanglement observable
    - Real time dynamics modeled via 1+1D four-flavor Schwinger model with string-breaking dynamics



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  - Experimentally track entangled $s\bar{s}$ quark into hadrons
  - Theoretical framework:
    - Quantum simulations to validate entanglement observable
    - Real time dynamics modeled via 1+1D four-flavor Schwinger model with string-breaking dynamics
  - **Experimental:**
    - Spin correlation extracted from the correlation of relative spin projections $N \propto 1 + \alpha^2 P_{\Lambda,\Lambda} \cos(n\theta_{ab})$

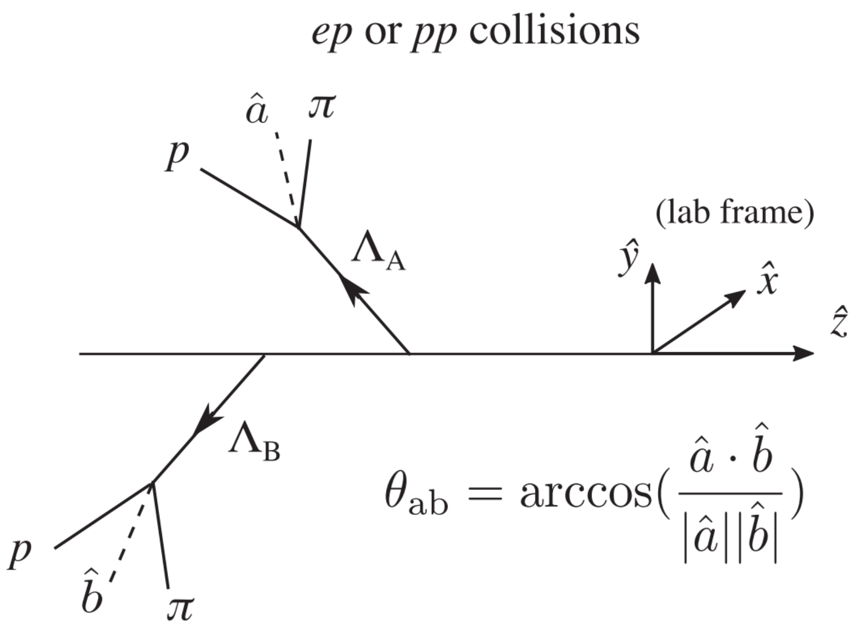


FIG. 3. Illustration of double Λ polarization; here $\hat{a}$ ($\hat{b}$) denotes the momentum direction of Λ_A (Λ_B) daughter particle in the Λ_A (Λ_B) rest frame.

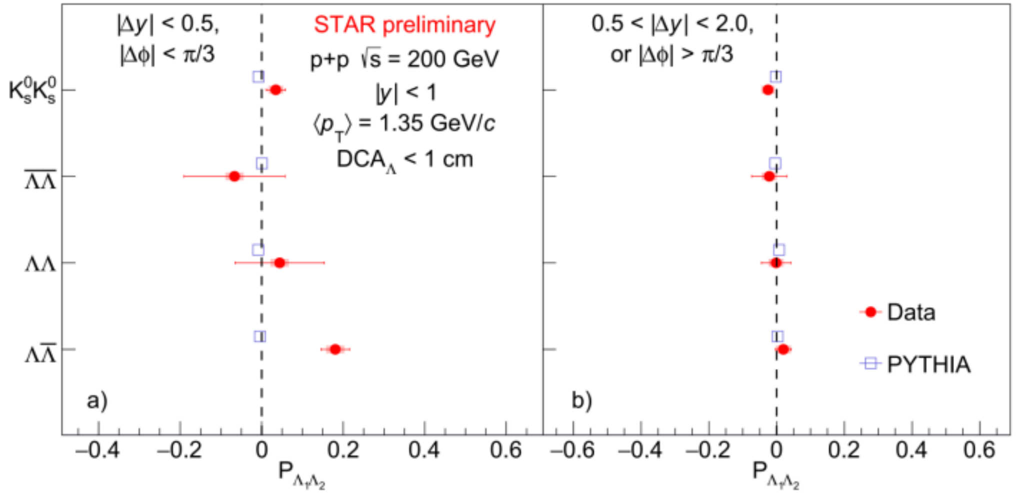
Entanglement via ΛΛ spin correlations

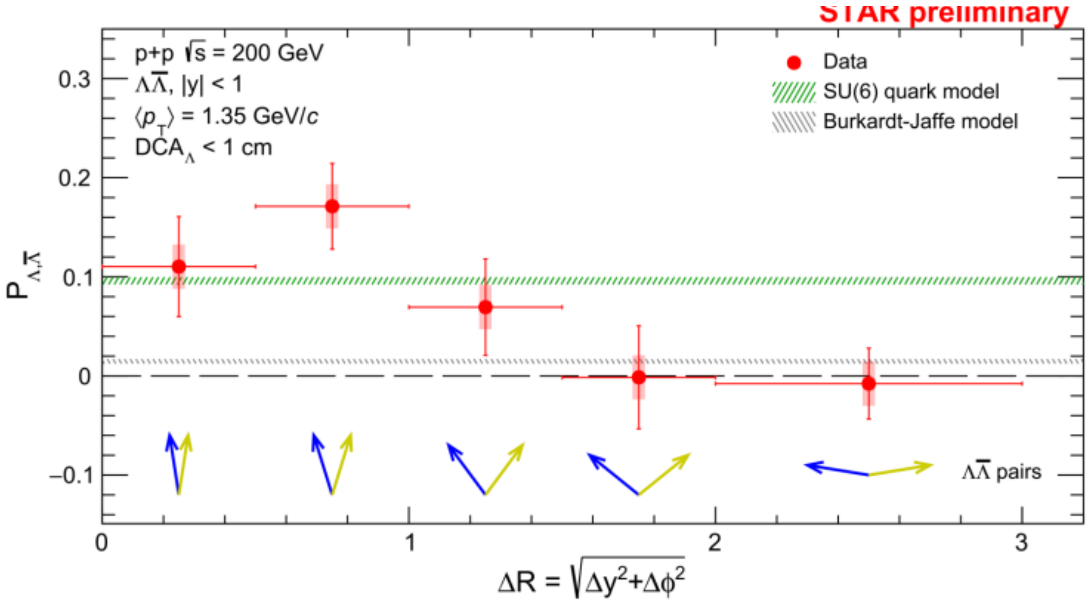
- Past particle correlation measurements have been carried out at a wide variety of collisions
- Limited by low statistics for spin analyses
- Recently, Λ hyperon pair spin-spin correlation in *pp* collisions measurement at STAR

Λ particle correlation measurement examples:

DELPHI Collaboration, Phys. Lett. B 318 249-262 (1993)
OPAL Collaboration, Phys. Lett. B 384 377-387 (1996)
ALEPH Collaboration, Phys. Lett. B. 475 395-406 (1999)
NA49 Collaboration, Nucl. Phys. A 715 55-64 (2002)
SELEX Experiment, J. Phys.: Conf. Ser. 295 012089 (2011)
STAR Collaboration, Phys. Rev. Lett. 114 022301 (2015)
. . .

Preliminary results from Quark Matter 2025, Jan Vanek





Belle II analysis

$\Lambda + \bar{\Lambda}$ reconstruction

- **The following selection requirements made in inclusive Λ skim**
  - Opposite charged proton and pion candidates combined to common vertex fit
  - Mass range [1.10, 1.13] GeV
  - Proton identification probability using information from all available detectors

$$\mathcal{L}_{\mathrm{p}}/(\mathcal{L}_{\mathrm{e}}+\mathcal{L}_{\mathrm{\mu}}+\mathcal{L}_{\mathrm{\pi}}+\mathcal{L}_{\mathrm{K}}+\mathcal{L}_{\mathrm{p}}+\mathcal{L}_{\mathrm{d}})$$

    - ProtonID(p) > 0.1
  - Additional selections including on:
    - the cosine angle between momentum and vertex vector (connecting IP and fitted vertex) of the Λ
    - flight distance of Λ
    - and proton and Λ momentum ratio
- **Events with at least one Λ is saved**

$\Lambda + \bar{\Lambda}$ reconstruction

- Only consider pairs in opposite hemispheres.

- Pair sample → Events with at least one pair of Λ's are saved ($\Lambda\bar{\Lambda}$, $\Lambda\Lambda$, or $\bar{\Lambda}\bar{\Lambda}$). All valid pair combinations are considered when multiple candidates present in the same event.

Off-resonance simulation (udsc)

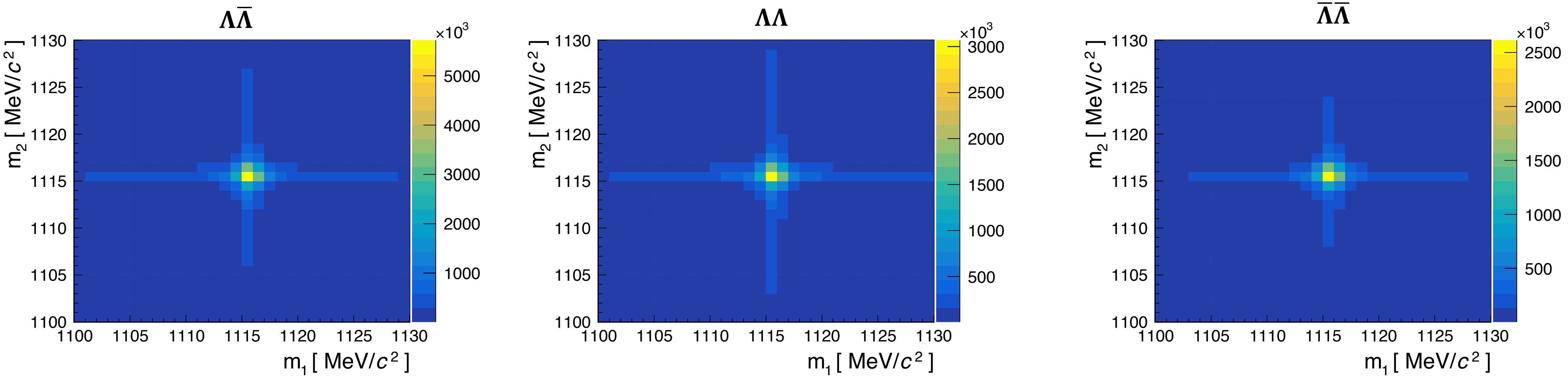
Type of pairs	$\boldsymbol{\Lambda\bar{\Lambda}}$	$\boldsymbol{\Lambda\Lambda}$	$\boldsymbol{\bar{\Lambda}\bar{\Lambda}}$
MC (udsc)	88,523,131	53,483,445	36,281,866
Signal pairs			
MC (udsc)	31,804,757	16,446,138	15,063,164

Signal and background modeling

- Signal will be extracted from 2D invariant mass distributions of pairs
- 2D invariant mass distribution features:
  - Peak: two signal pairs
  - Ridges: signal paired with combinatorial background
  - Continuum: combinatorial background

Belle II off-resonance simulation

$e^+e^- \rightarrow q\bar{q}, q \in u, d, s, c$

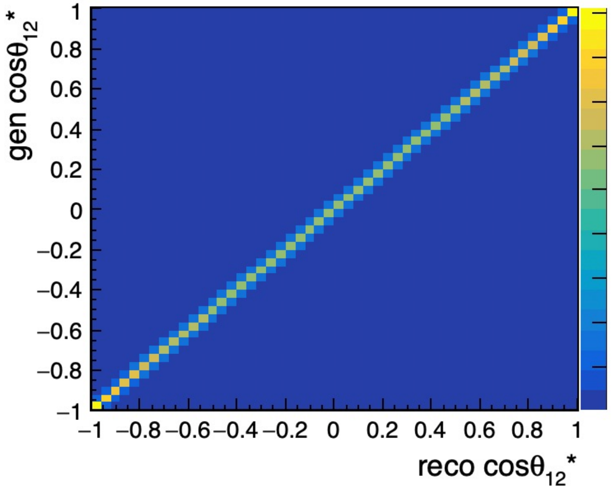


Decay angle resolution and correlation fit

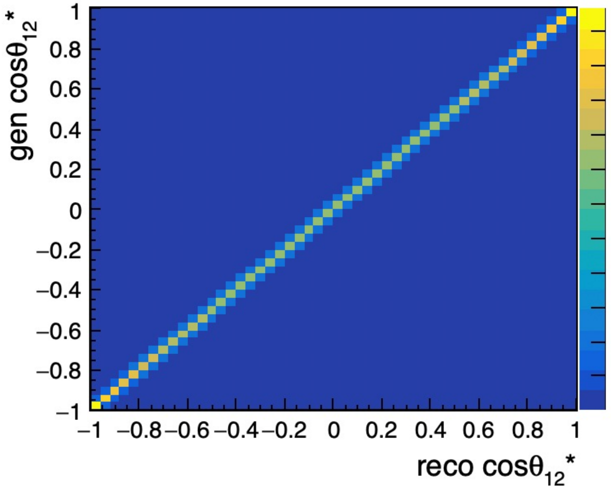
- Angular distribution and correlation in simulation (null result)

Belle II off-resonance simulation
$\boldsymbol{e^+e^- \to q\bar{q}, q \in u, d, s, c}$

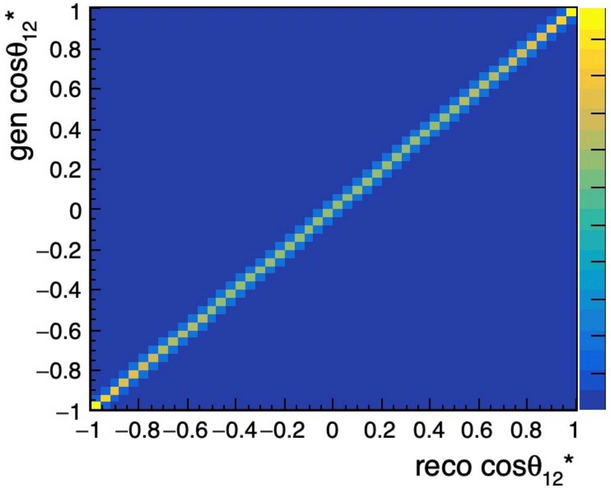
$\Lambda\bar{\Lambda}$

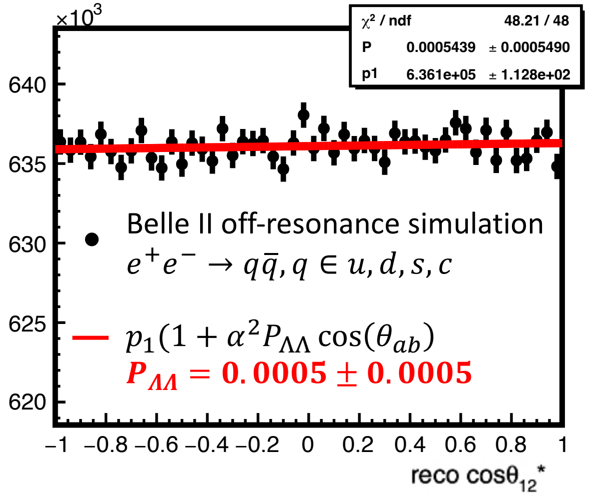


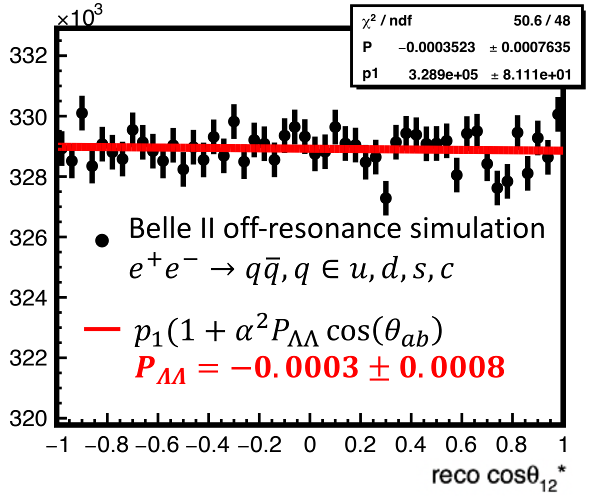
$\Lambda\Lambda$

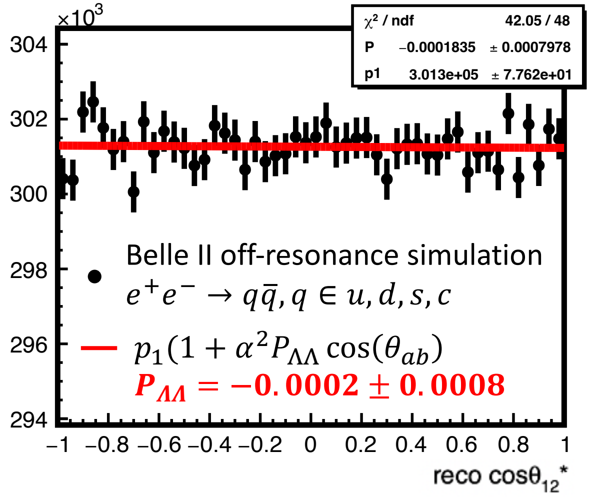


$\overline{\Lambda\Lambda}$









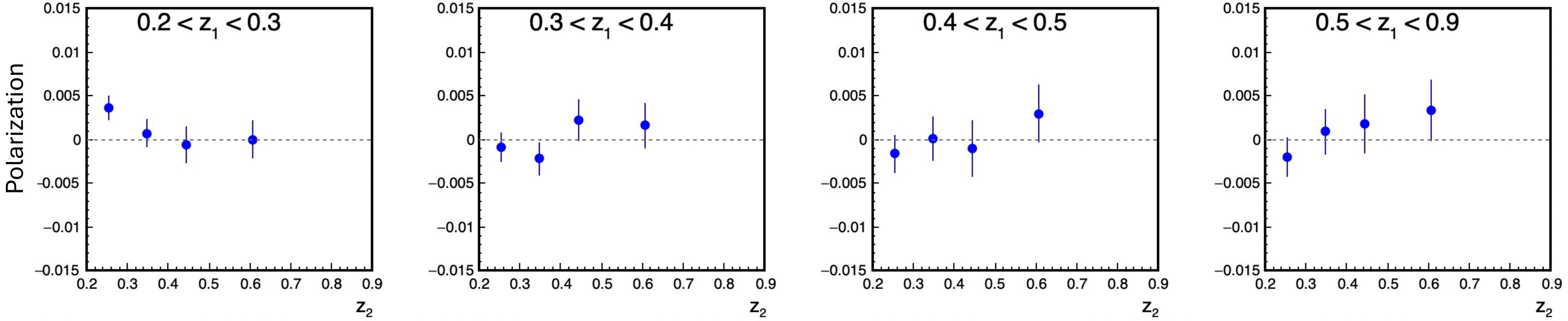
Polarization in simulation

$z_{\mathrm{h}} = 2E_{\mathrm{h}}/\sqrt{s}$

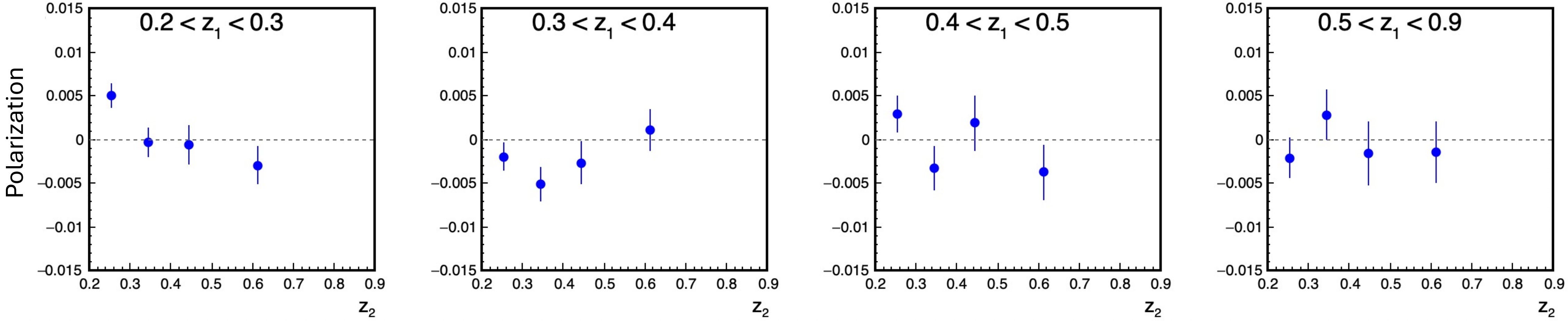
- Plan to measure polarization as a function of z_h for each Λ

Belle II off-resonance simulation
$e^+e^- \rightarrow q\bar{q}, q \in u, d, s, c$

$\boldsymbol{\Lambda\bar{\Lambda}}$



$\boldsymbol{\Lambda\Lambda + \bar{\Lambda}\bar{\Lambda}}$



Longitudinal spin transfer via dihadron polarization

- Helicity correlation of two produced partons
- Alternative approach to traditional methods using polarized beams and targets

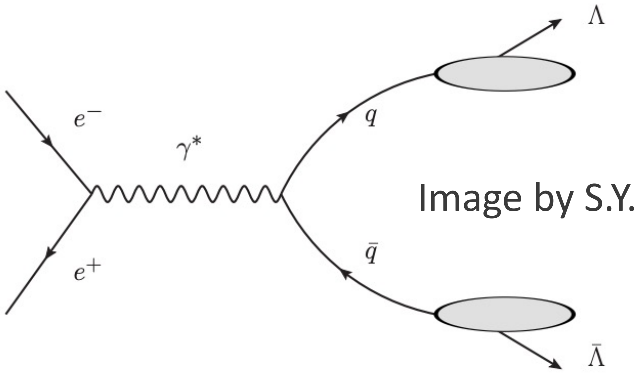


Image by S.Y. Wei, DIS24

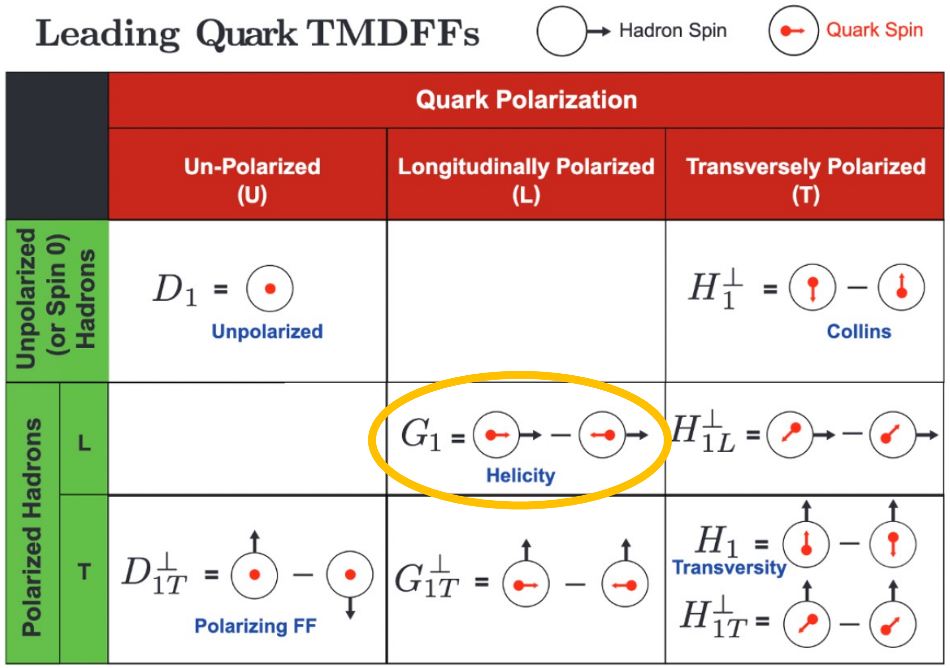


Image from arXiv:2304.03302v1

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- Helicity correlation of two produced partons
- Alternative approach to traditional methods using polarized beams and targets

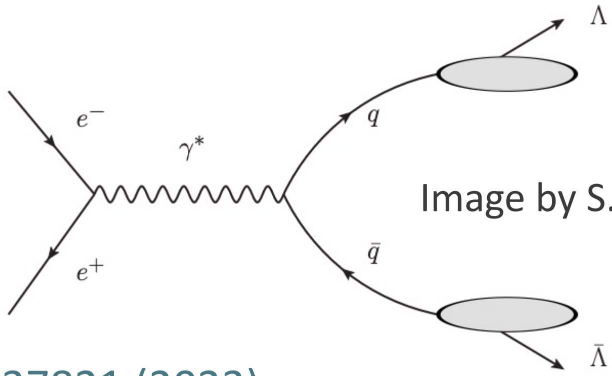


Image by S.Y. Wei, DIS24

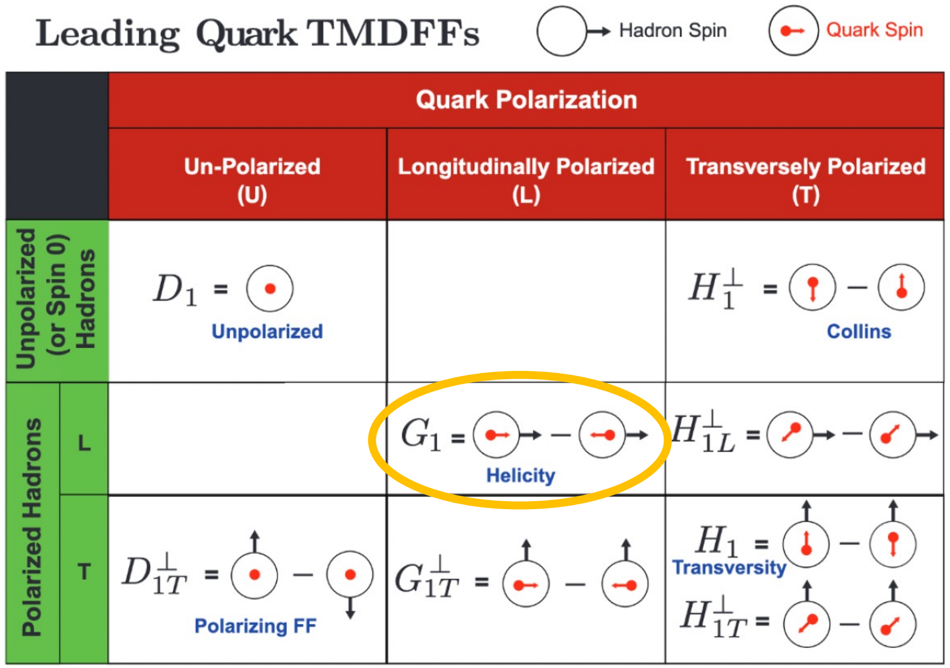
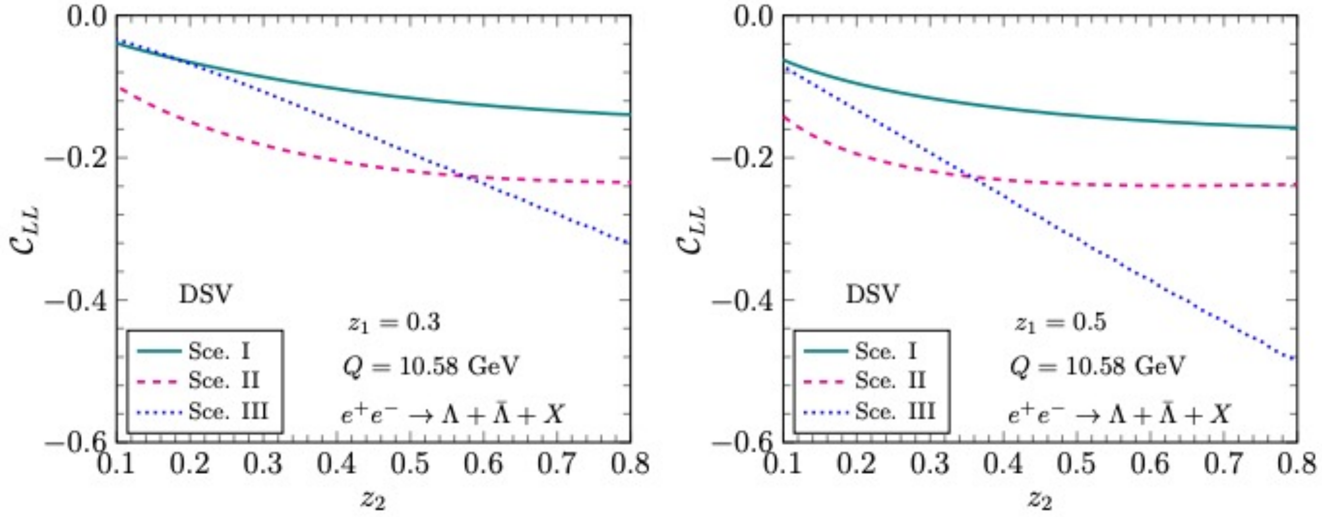


Image from arXiv:2304.03302v1

Phys.Lett.B 839, 137821 (2023)



$$\frac{1}{N}\frac{dN}{d\cos\theta_1^* d\cos\theta_2^*} = \frac{1}{4} + P_L^{\Lambda}\frac{1}{4}\alpha\cos\theta_1^* + P_L^{\bar{\Lambda}}\frac{1}{4}\alpha\cos\theta_2^* + \mathcal{C}_{LL}\frac{1}{4}\alpha^2\cos\theta_1^*\cos\theta_2^*,$$

Longitudinal spin transfer via dihadron polarization

- **Experimental considerations:**
  - Contributions from longitudinal polarization not exactly zero (but expected to be small)
- **Other possible future measurement** 2410.20917
  - Transverse spin correlation of two Λ hyperons sensitive to H_{1T}
  - Measurement of transverse spin correlation of two Λ hyperons normal to the hadron production plane (defined by thrust axis)

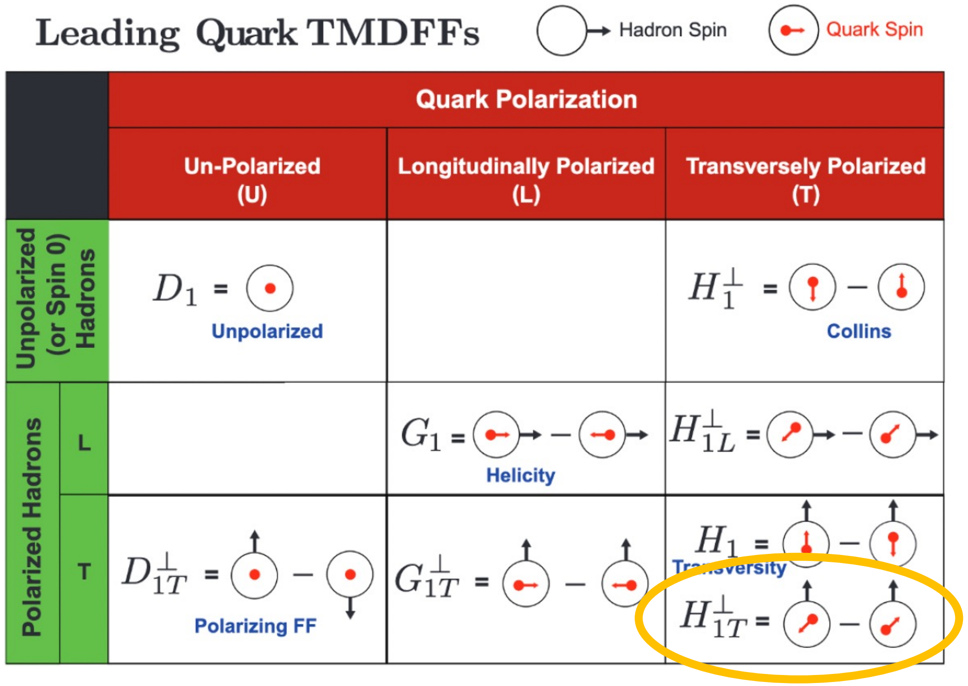


Image from arXiv:2304.03302v1

Summary

Summary

- **Belle II plays an important role in understanding hadronization dynamics** (arXiv:2204.02280)
- **Λ spin-correlation provides insight on the hadronization process**
  - Entanglement as a probe for hadronization process
  - Probe the longitudinal and transverse spin transfer in unpolarized e^+e^-
- **Several current ongoing hydronization analyses underway**
  - Ongoing analysis studying Λ spin-correlations
  - Ongoing analysis sensitive to the di-hadron fragmentation functions (Katherine Parham)
  - Ongoing analysis sensitive to transverse momentum dependent jet functions (Simon Schneider)
- **Future QCD studies with polarized electron beams at SuperKEKB**

  Chiral Belle Project: arXiv:2205.12847v3

Belle II @ Duke


Anselm Vossen


Frank Meier


Katherine Parham


Simon Schneider


Cynthia Nuñez


Leonel Lin

Back up

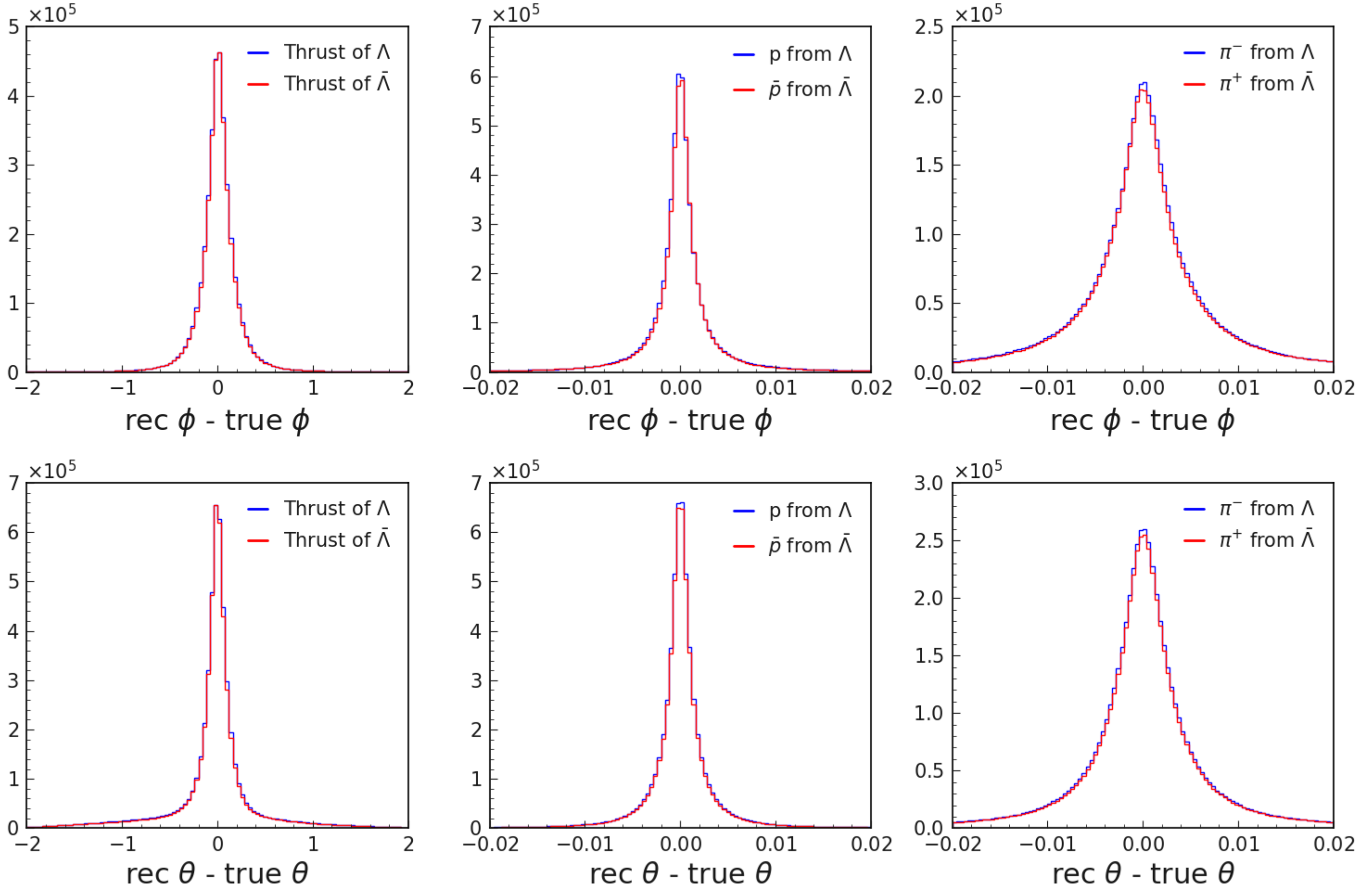
$\Lambda + \bar{\Lambda}$ reconstruction

- InclusiveLambda skim:
- Events with at least one Λ is saved

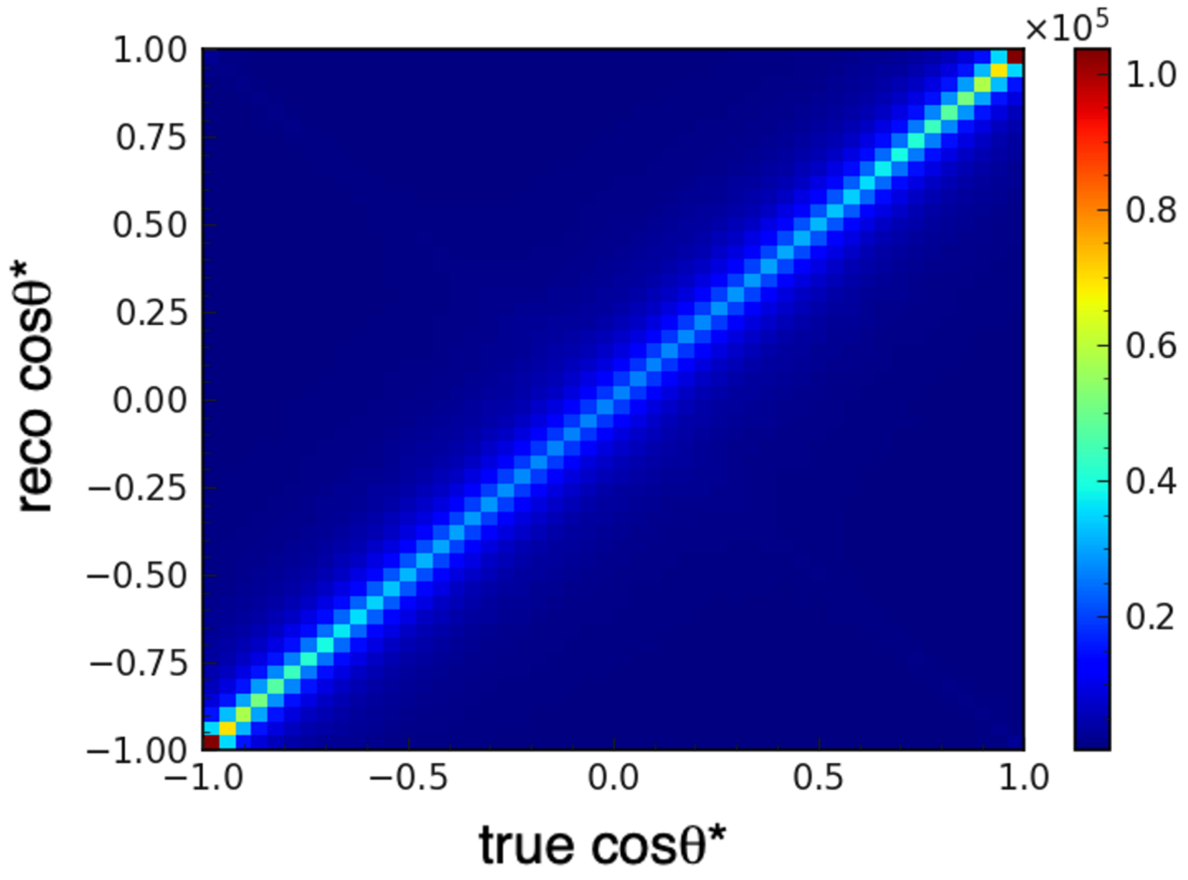
Merged Λ with vertex fit performed	stdLambda Lambda0:merged -> p+:all pi+:all Mass range [1.10, 1.13] GeV Vertex fit with TreeFit
Proton identification probability $\mathcal{L}_p/(\mathcal{L}_e+\mathcal{L}_\mu+\mathcal{L}_\pi+\mathcal{L}_K+\mathcal{L}_p+\mathcal{L}_d)$ Using information from all available detectors	ProtonID $(p) > 0.1$
Angle between momentum and vertex vector (connecting IP and fitted vertex) of the Λ	cosAngleBetweenMomentumAndVertexVector > 0.75
Flight distance cut on the Λ	flightDistance/flightDistanceErr > 0.
Momentum ratio cut	0.5 < p_proton/p_Lambda < 1.25 GeV/c

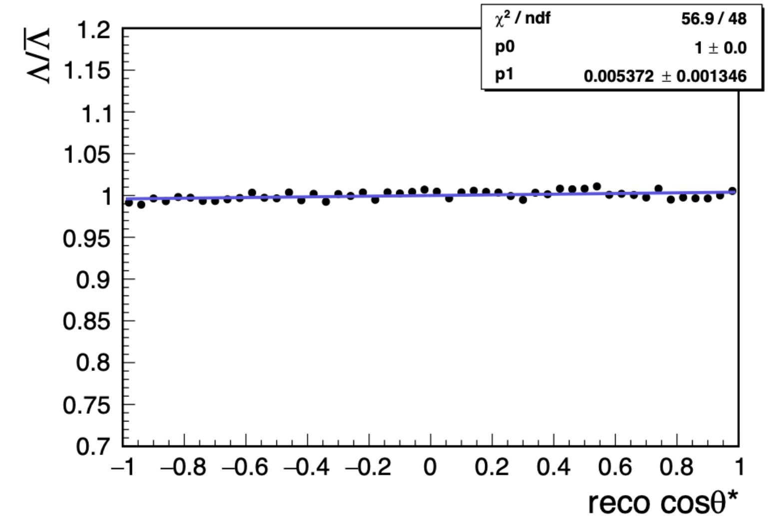
Polarization in simulation

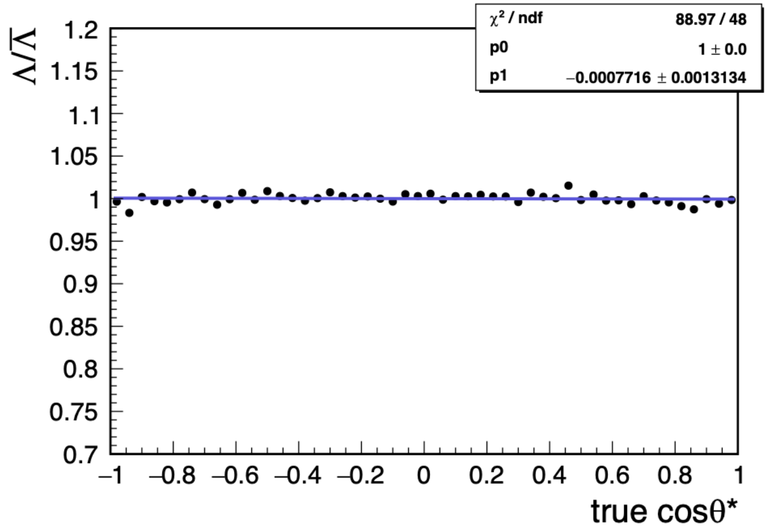
- Simulation has $P_{\Lambda} = P_{\overline{\Lambda}} = 0$ therefore extracting the polarization from the ratio $\Lambda/\overline{\Lambda}$ should be zero
- No shift observed for Λ and $\overline{\Lambda}$ distributions using updated momentums for proton and pion after vertex fit



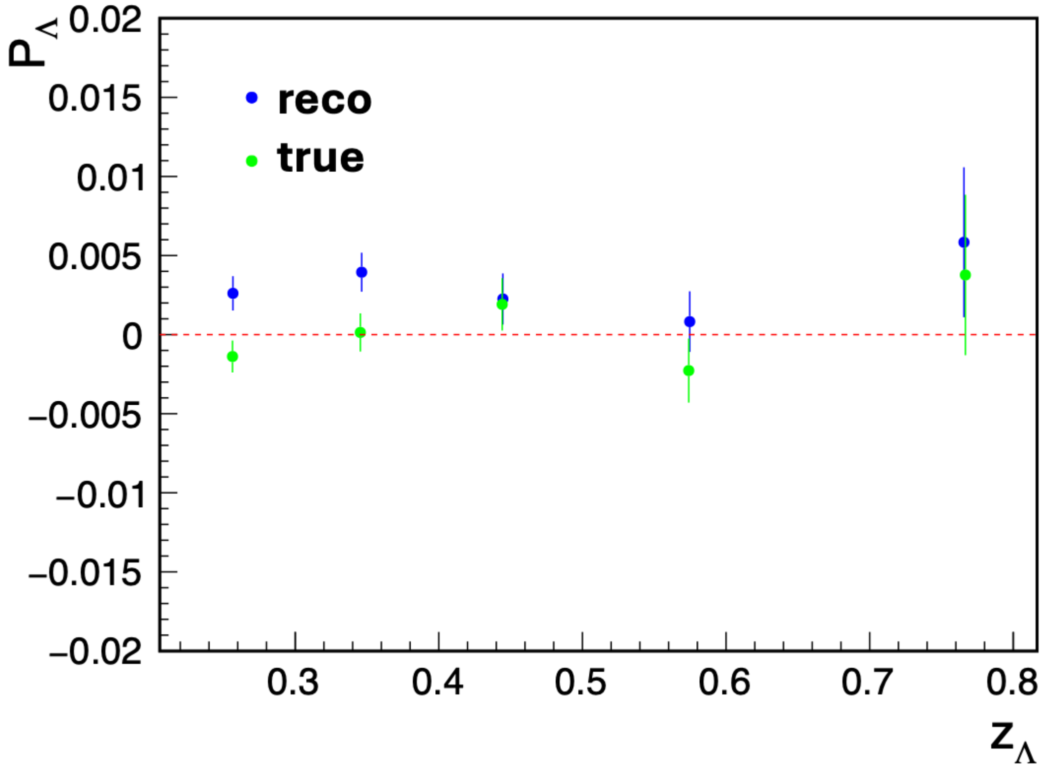
Transverse angular distribution

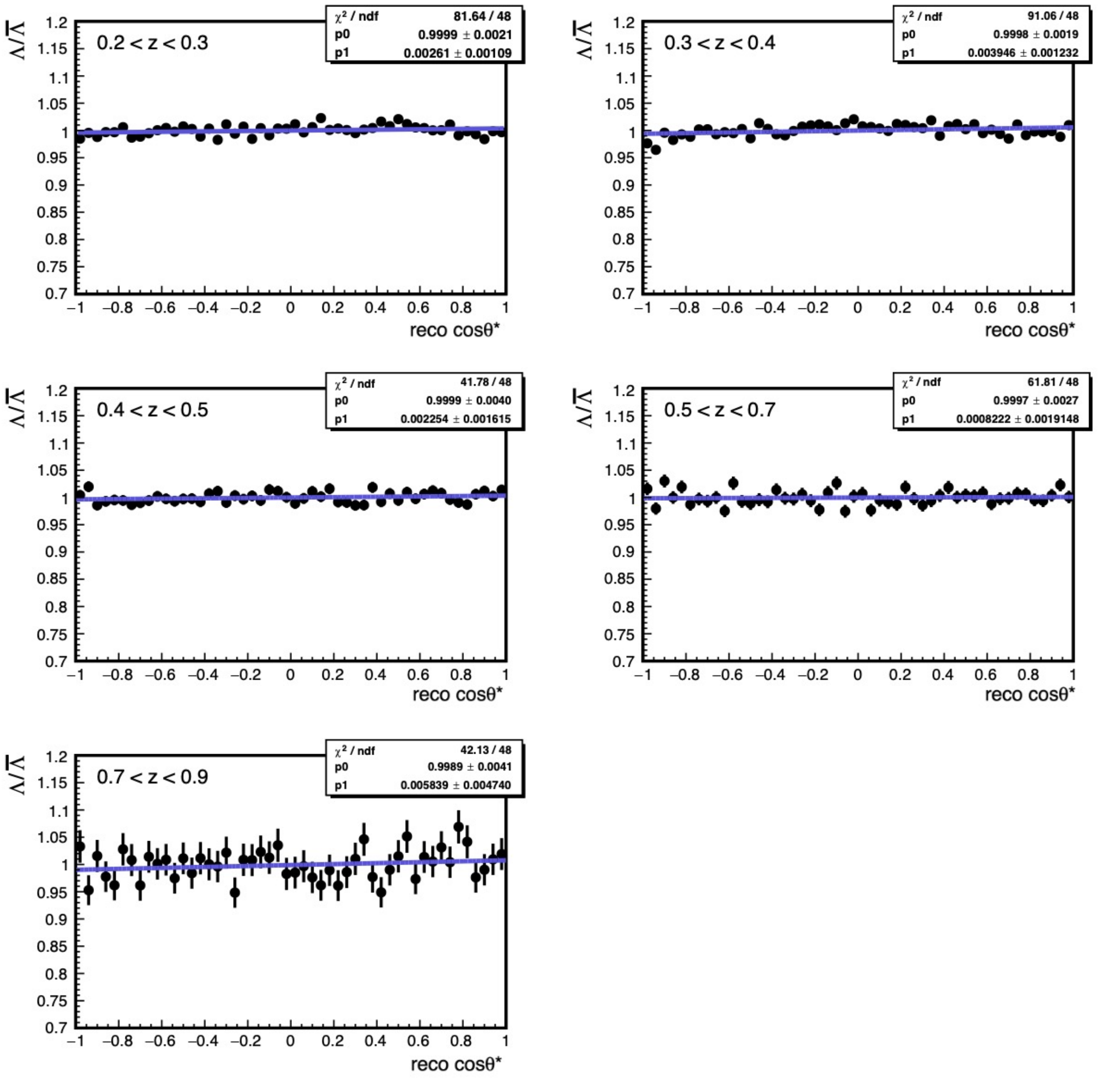






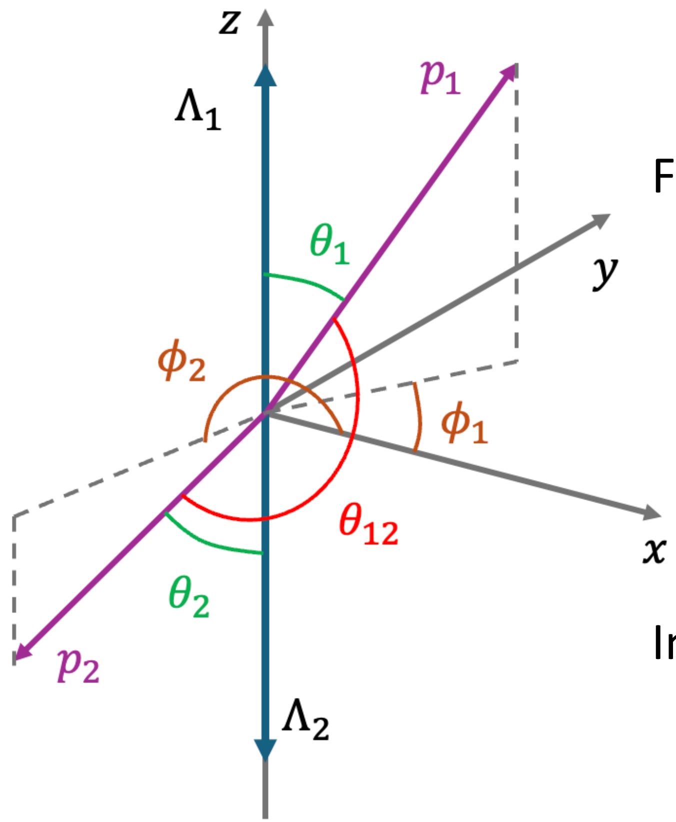
Transverse polarization





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

Decay angle



For a single Λ

$$\frac{dw(n)}{d\Omega_n} = \frac{1}{4\pi}(1 + \alpha_\Lambda \boldsymbol{P}_{\boldsymbol{\Lambda}} \cdot \boldsymbol{n})$$

For double angular distribution

$$\frac{d^2 w(\boldsymbol{n_1}, \boldsymbol{n_2})}{d\Omega_{\boldsymbol{n_1}} d\Omega_{\boldsymbol{n_2}}}$$

$$= \frac{1}{16\pi^2}\left(1 + \alpha_{\Lambda_1} \boldsymbol{P}_{\boldsymbol{\Lambda_1}} \cdot \boldsymbol{n_1} + \alpha_{\Lambda_2} \boldsymbol{P_2} \cdot \boldsymbol{n_2} + \alpha_{\Lambda_1}\alpha_{\Lambda_2} \sum_{i=1}^{3}\sum_{j=1}^{3} T_{ij} n_{1i} n_{2j}\right)$$

Integrate over all angles except angle between $\mathbf{n_1}$ and $\mathbf{n_2}$

$$\frac{dw(\cos\theta_{12})}{d\cos\theta_{12}} = \frac{1}{2}(1 + \alpha_{\Lambda_1}\alpha_{\Lambda_2} P_{\Lambda_1\Lambda_2}\cos\theta_{12})$$

Two angle relation:

$$\cos\theta_{12} = \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2) - \cos\theta_1 \cos\theta_2$$

$$< \phi_1 - \phi_2 > = 0$$

$$< \cos\theta_{12} > = < \cos\theta_1 \cos\theta_2 >$$

Eur. Phys. J. C. (2012) 72:1877
Nucl. Phys. A820 (2009) 311c–314c

Signal and background modeling

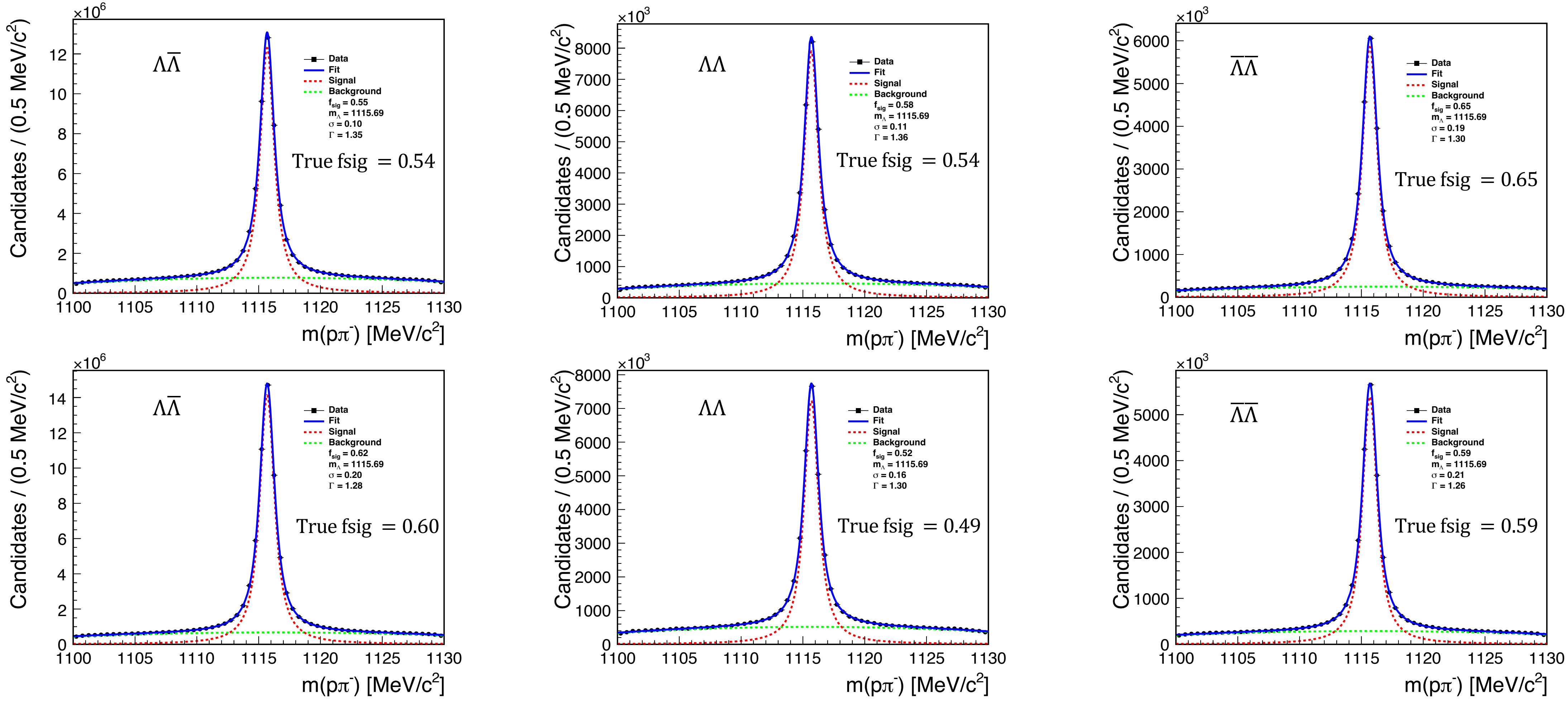
- Fitted with Voigtian and 2nd order Bernstein background

Belle II off-resonance simulation

$e^+e^- \to q\bar{q}, q \in u, d, s, c$

Λ_1

Λ_2

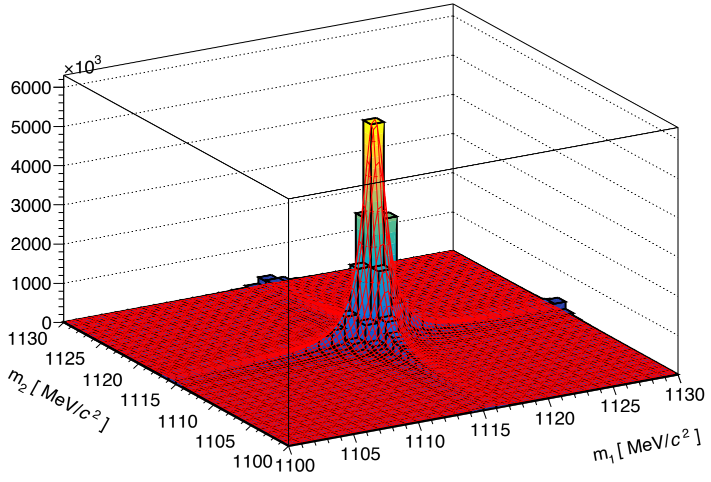


Signal and background modeling

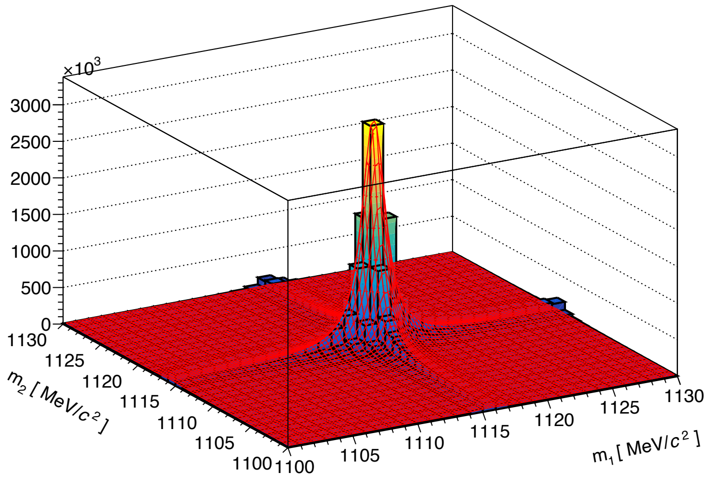
- Signal extracted from 2D invariant mass distributions of pairs
- 2D PDFs is built by multiplying the two 1D PDFs for extended maximum likelihood fit:

$$M(m_1, m_2) = N_{sig}M_{sig}(m_1)M_{sig}(m_2) + N_{bkg}M_{bkg}(m_1)M_{bkg}(m_2)$$

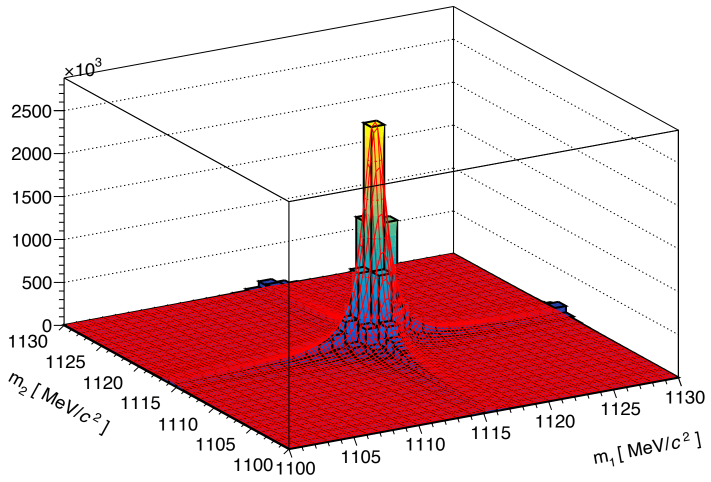
$\boldsymbol{\Lambda\bar{\Lambda}}$



$\boldsymbol{\Lambda\Lambda}$



$\boldsymbol{\bar{\Lambda}\bar{\Lambda}}$



Belle II off-resonance simulation

$\boldsymbol{e^+e^- \to q\bar{q}, q \in u, d, s, c}$

In simulation, testing mass fit with 2D Gaussian signal and 2D polynomial background