Studying hadronization at Belle II

Cynthia Nunez

on behalf of the Belle II collaboration

POETIC XI

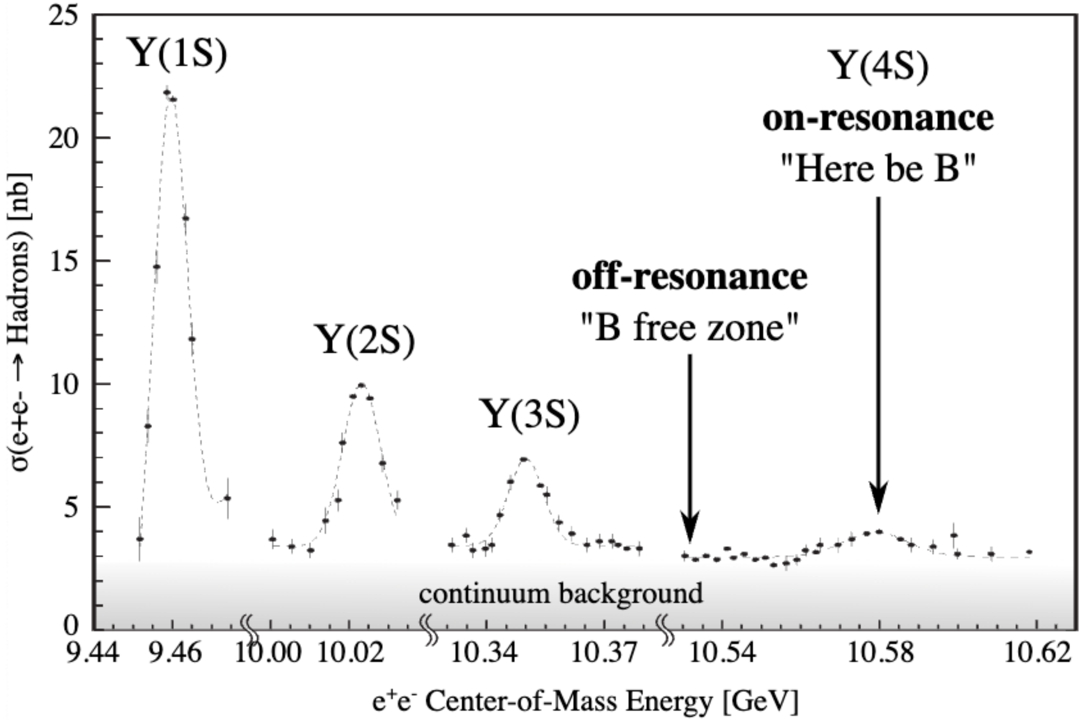
February 24, 2025

Research supported by: U.S. Department of Energy Office of Science

Belle → Belle II

Belle at KEKB (1999 - 2010) → Belle II at SuperKEKB (2019 - present)

- B factory at Tsukuba, Japan
- Asymmetric e^+e^- collider at collision energies at or near $\Upsilon(4S)$



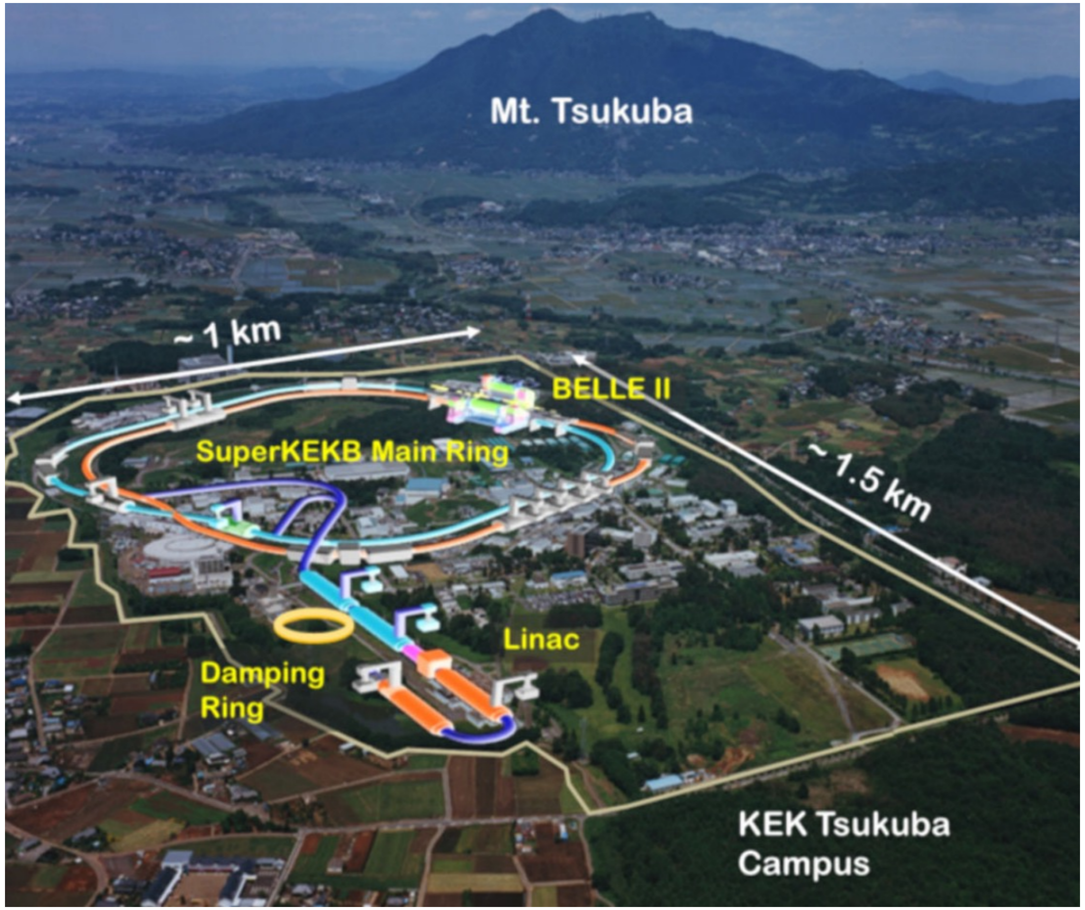


Image from: Phys. Rev. Accel. Beams 26, 013201 (2023)

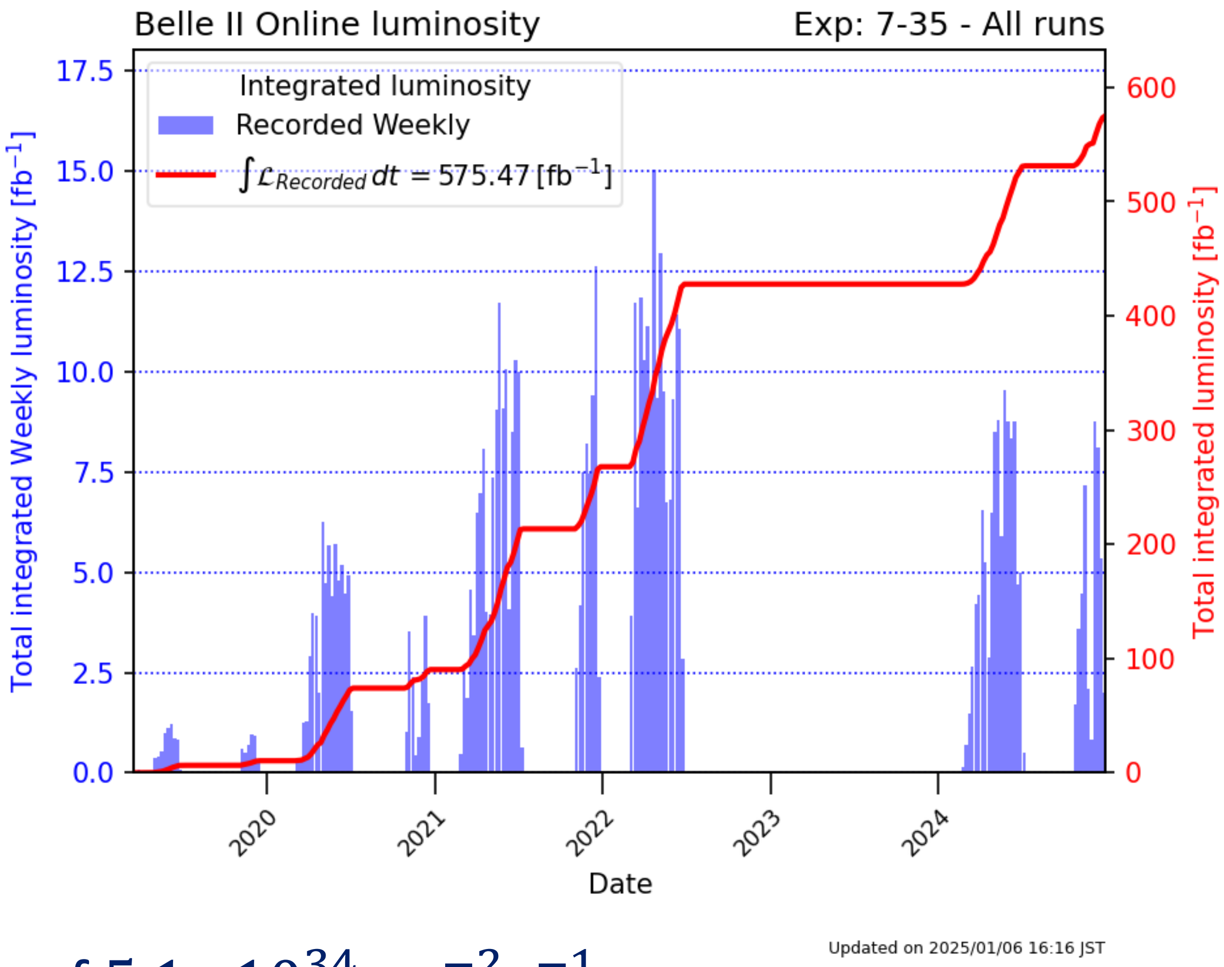
Belle → Belle II

Belle at KEKB (1999 - 2010) → Belle II at SuperKEKB (2019 - present)

- B factory at Tsukuba, Japan
- Asymmetric e^+e^- collider at collision energies at or near $\Upsilon(4S)$

- **Belle**
  - Collected about $\int \mathcal{L}\mathrm{dt} = 1000\ \mathrm{fb}^{-1}$

- **Belle II**
  - Run 1 (2019-2022)
    - $\int \mathcal{L}\mathrm{dt} = 424\ \mathrm{fb}^{-1}$
  - Run 2 (2024-present)
    - In Dec. 2024, achieved luminosity of $5.1{\times}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



Belle II Detector @ SuperKEKB

- Large acceptance with good vertexing, PID, and tracking

KEK Report 2010-1 [arXiv:1011.0352]

EM calorimeter

Energy resolution: 1.6-4%
Barrel: CsI(Tl) + waveform sampling
Endcap: waveform sampling

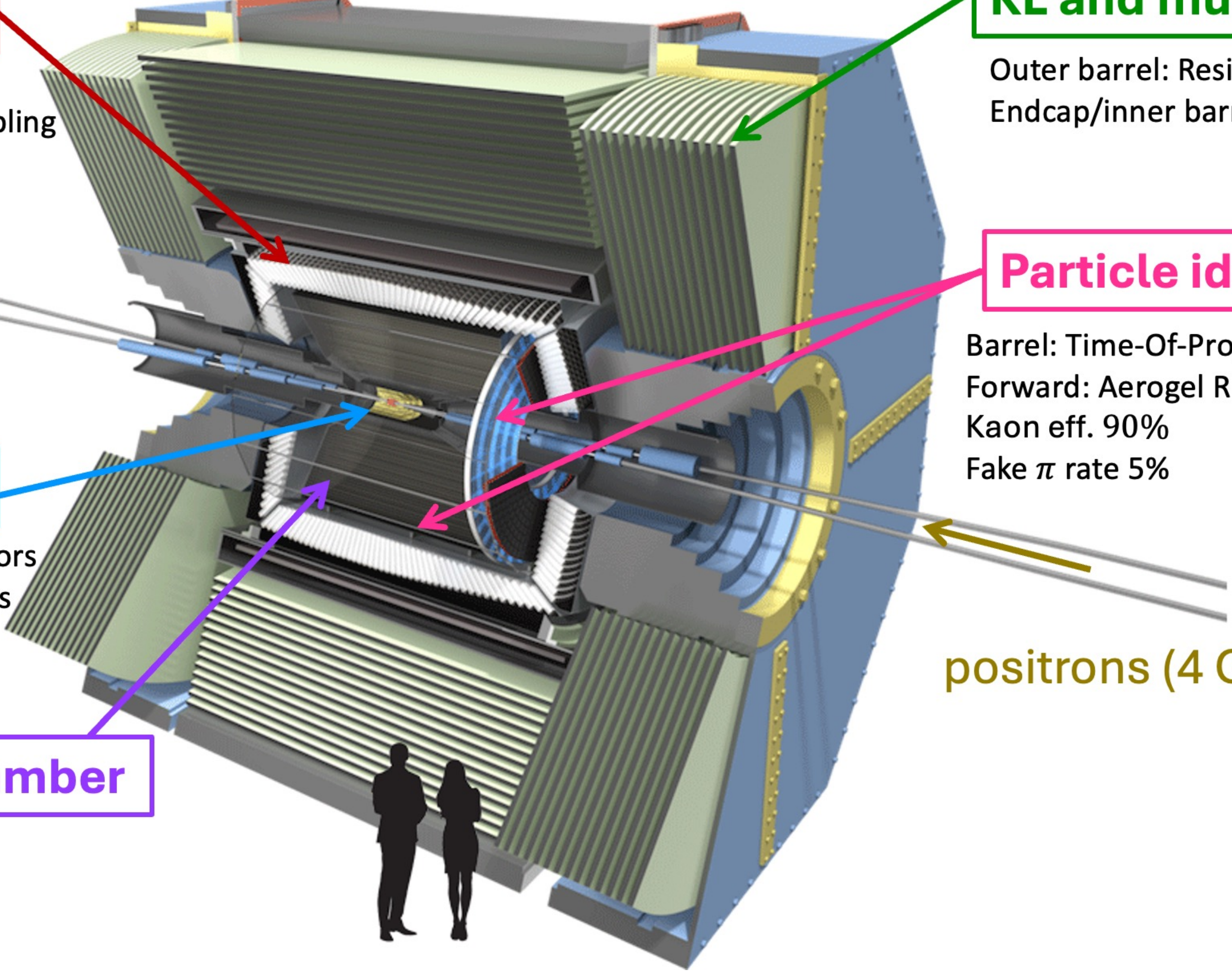
electrons (7 GeV)

Vertex detector

PXD: inner 2 layers pixel detectors
SVD: outer 4 layers strip sensors
IP resolution: 15 μm

Central drift chamber

Spatial resolution 100 μm
dE/dx resolution 5%
p_T resolution 0.4%



KL and muon detector

Outer barrel: Resistive Plate Counter
Endcap/inner barrel: scintillator

Particle identification

Barrel: Time-Of-Propagation counters (TOP)
Forward: Aerogel RICH (ARICH)
Kaon eff. 90%
Fake π rate 5%

positrons (4 GeV)

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
- **Transverse-momentum-dependent (TMD)**: spin-momentum correlations

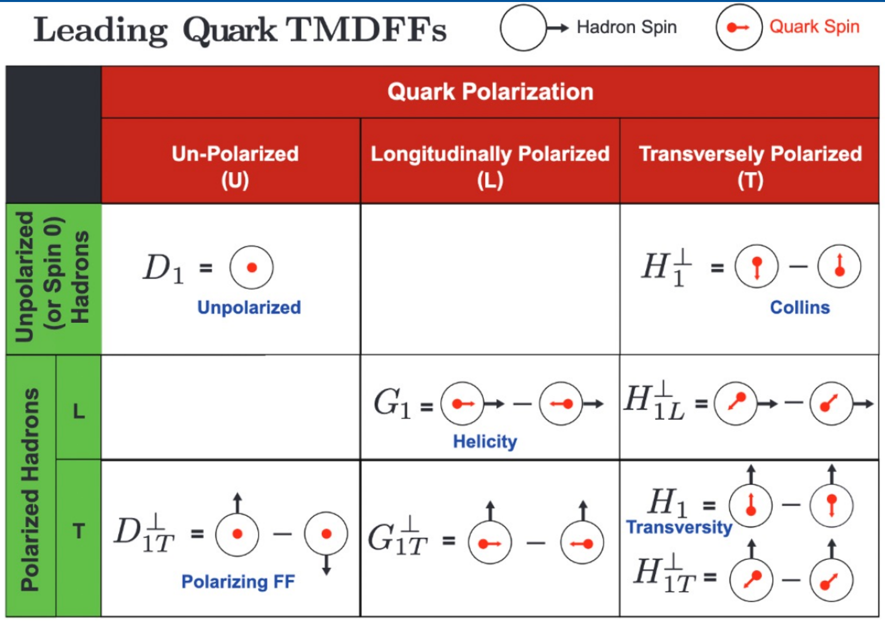
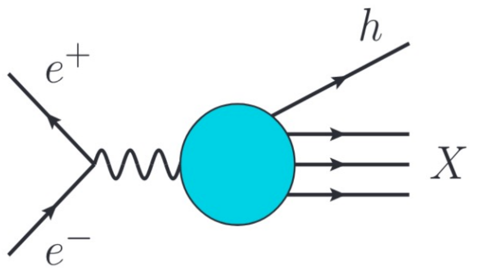


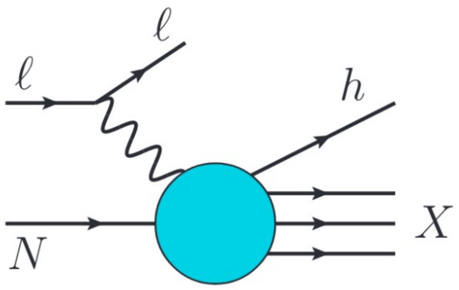
Image from arXiv:2304.03302v1

<u>Important processes in studying hadron formation</u>

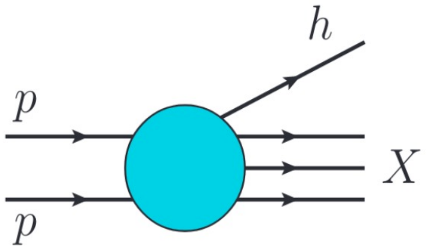
$$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes FF$$



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



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



Progress in Particle and Nuclear Physics (2016) pp. 136-202

Hadronization at Belle

Belle measurements sensitive to:

- Collins FF
- Di-hadron FF
- Polarizing FF

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Recent measurement

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)

Production cross section of light and charmed mesons

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

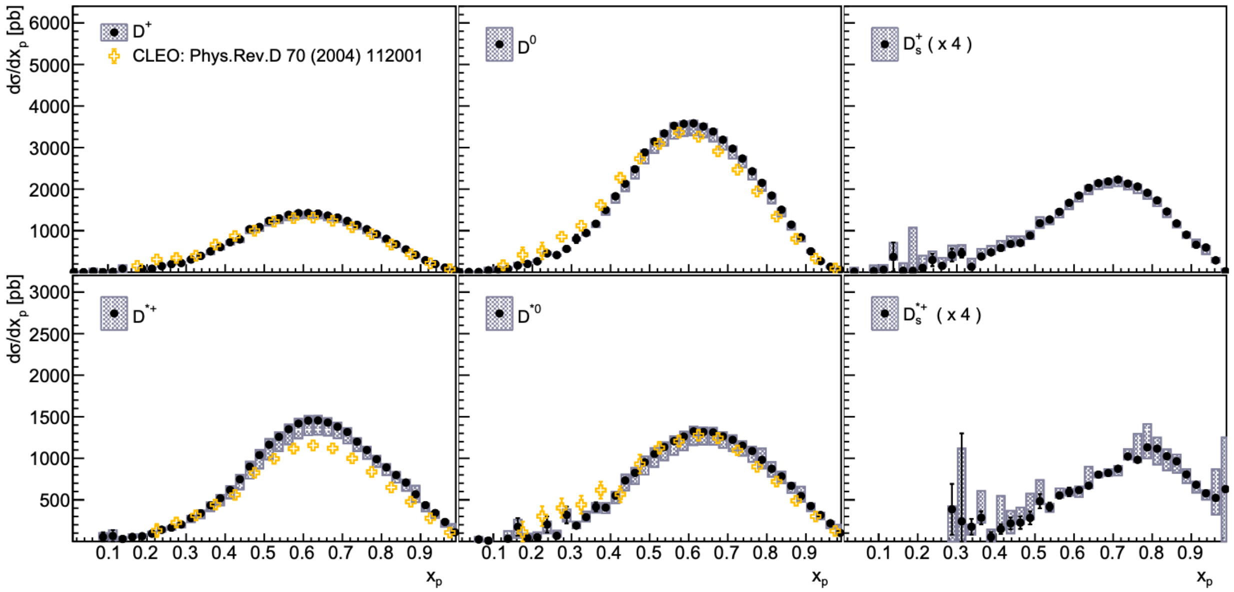
Hadronization at Belle

$x_p = p_h/p_{max}$

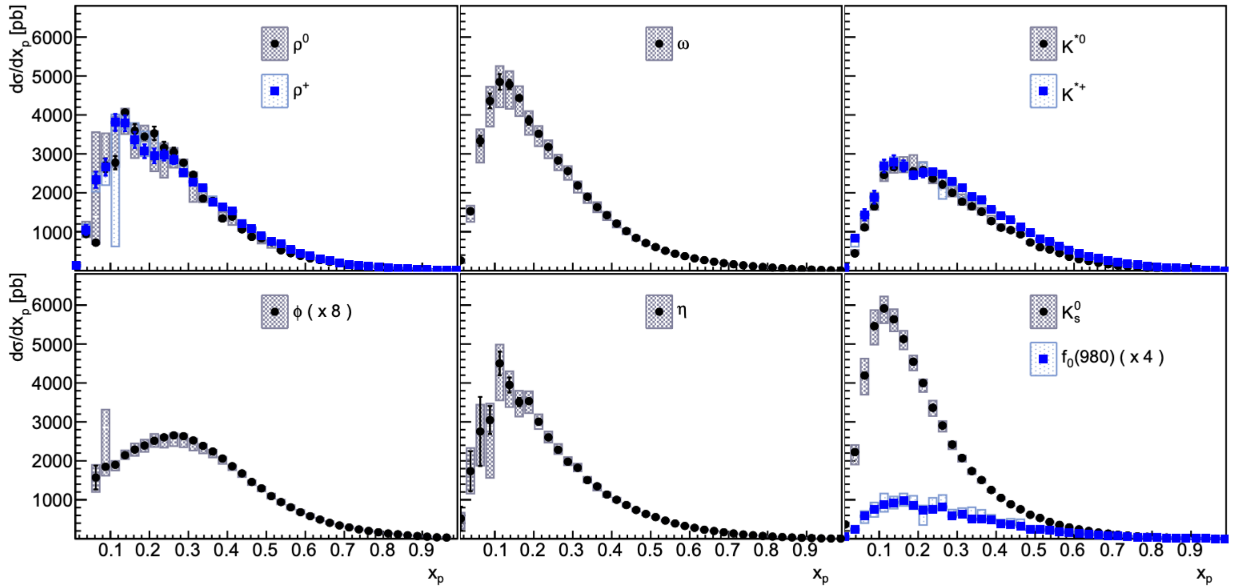
R. Seidl, "Production cross sections of light and charmed mesons in e^+e^- annihilation near 10.58 GeV"
Belle preprint 2024-09, KEK Preprint 2024-30, submitted to PRD

- Comprehensive study of production cross section of light and charmed mesons
- Improved ISR corrections for D-mesons, and detailed comparison with various MC tunes
- Important for future SIDIS measurements at the EIC

Charmed mesons



Light mesons



Hadronization at Belle II and for the EIC

- **Belle II can offer high precision, comprehensive measurements essential for the 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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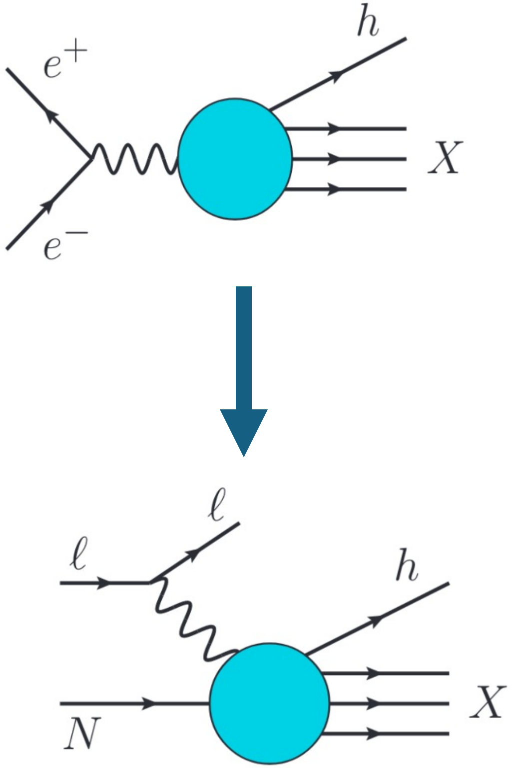
$$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes FF$$



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

See Snowmass whitepaper arXiv:2204.02280

Current ongoing analyses at Belle II

1. Di-hadron Fragmentation Functions
2. Λ Polarization
3. TMD Jet Functions

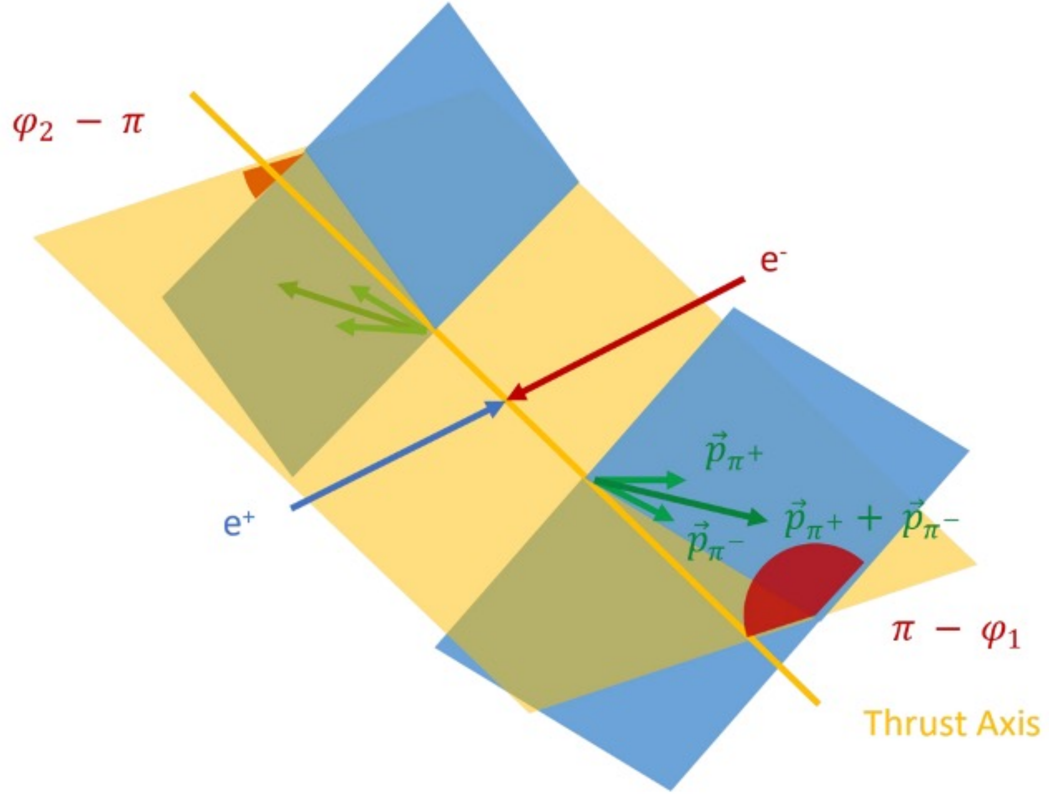
Di-hadron Fragmentation Functions (DiFF)

- $H_1^{\sphericalangle}(z, M, P_h, \theta)$ FF describe fragmentation of polarized quark into pair of spin-0 hadrons

- Spin correlation between the $q\bar{q}$ pair results in correlating between the azimuthal angles of dihadron pairs produced

- Belle measured the azimuthal asymmetries for dihadrons measured as a function of z_h and m_h

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



Thrust:

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

Cuts on thrust provide clean $q\bar{q}$ $(q \in u, d, s, c)$ event sample

Ongoing analysis: Katherine Parham, Duke University

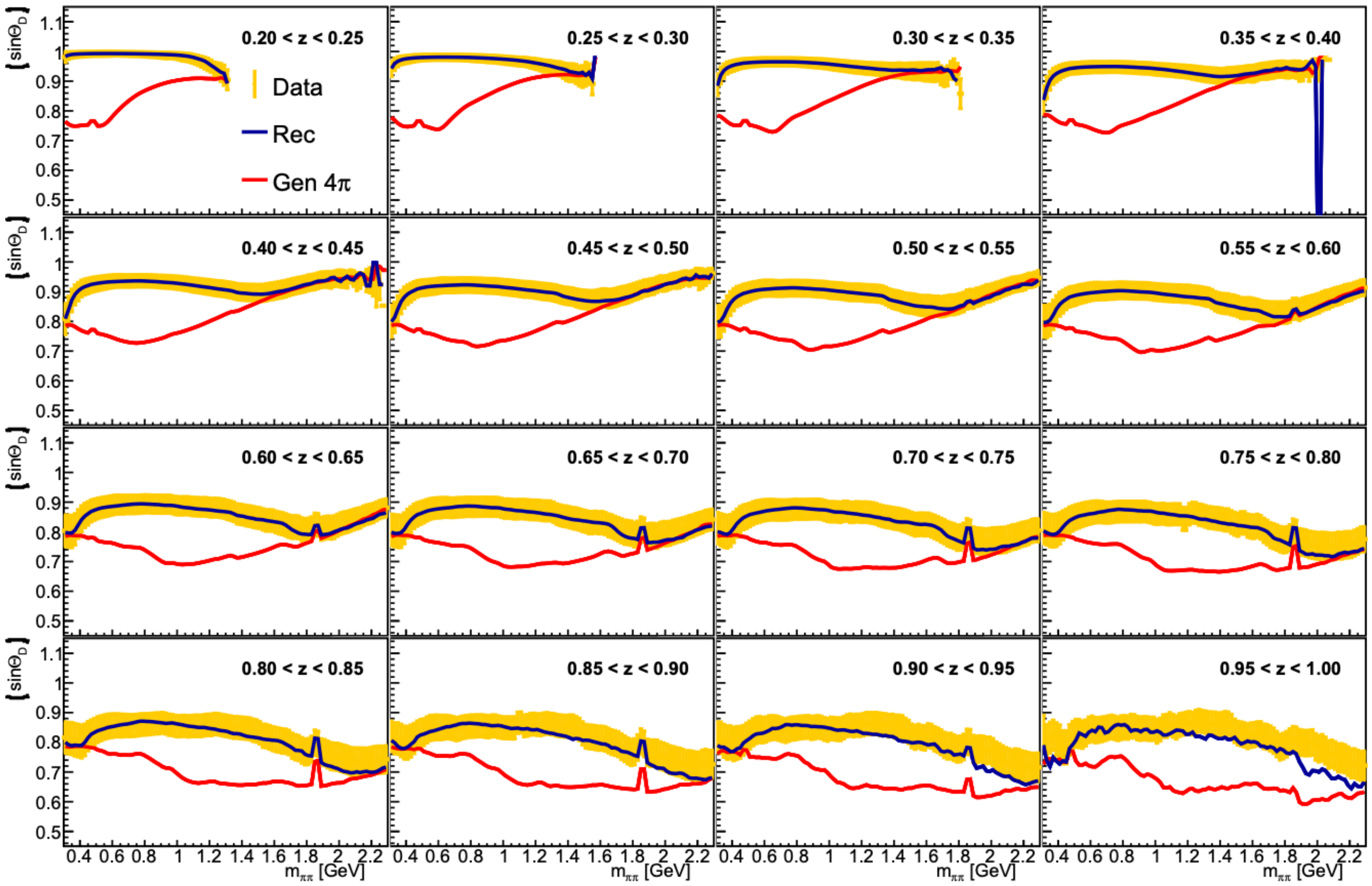
Di-hadron Fragmentation Functions (DiFF)

Phys. Rev. D 96, 032005 (2017)

Partial wave expansion

- More complex partial wave contribution to transverse polarization dependent DiFF
- Dependence on m, z, p_t, θ, ϕ
- Important to understanding production at the EIC
- Belle II statistics enable multidimensional analysis

JPS Conf.Proc. 37 (2022) 020109



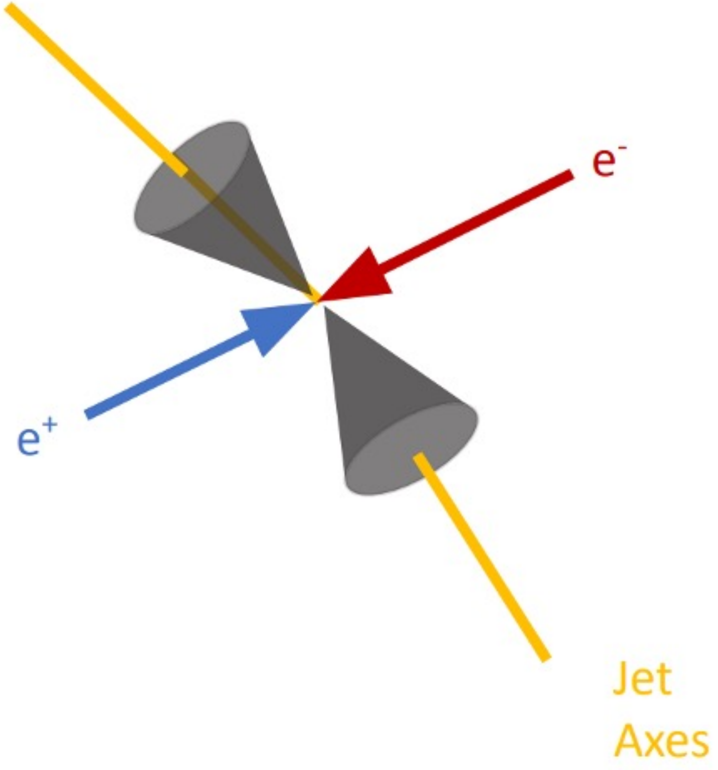
$\sin\theta_D$ decay moment for $\pi^+\pi^-$ pairs; Belle results (655 fb^{-1})

Di-hadron Fragmentation Functions (DiFF)

- **Kaon inclusive**
  - Measurement with K^+K^-, $K^+\pi^-$, or π^+K^- pairs
  - Results of $H_1^{\sphericalangle}$ can be used to describe strange quark distribution in the nucleon
- **Jet axis**
  - Using jets axis instead of $q\bar{q}$ thrust axis
  - Results link FFs in e^+e^- to SIDIS

New measurement important for upcoming experiments at JLab and the EIC

Jets: collimated spray of particles originating from partons in collision



Ongoing analysis: Katherine Parham, Duke University

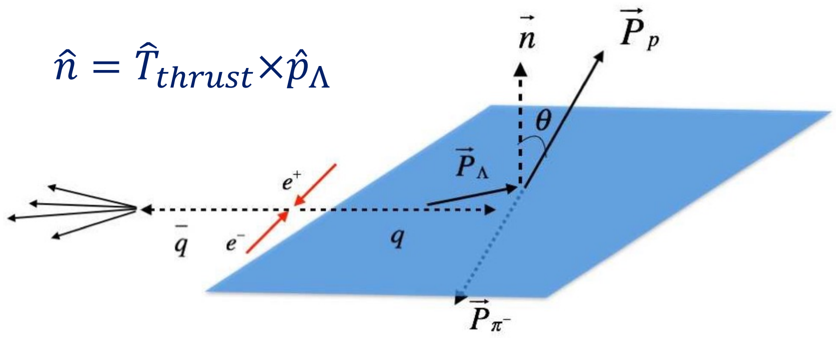
Transverse Λ Polarization at Belle

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

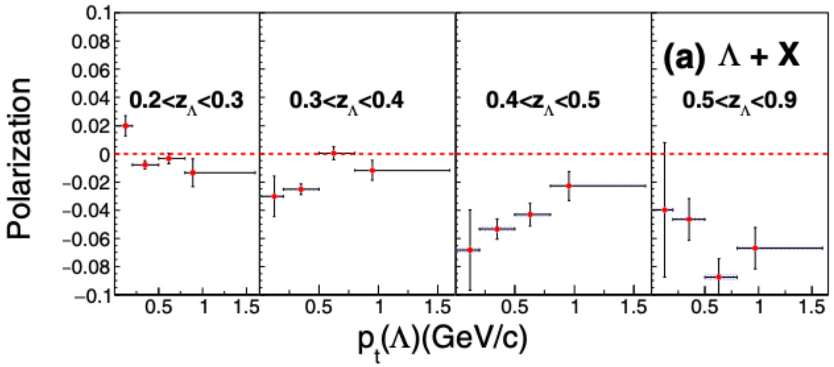
- $\Lambda \rightarrow p\pi^-$ **self analyzing decay**

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

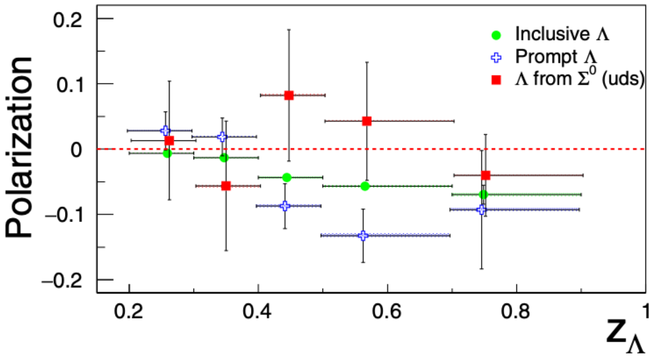
α_Λ= 0.748 ± 0.007 (PDG 2023)

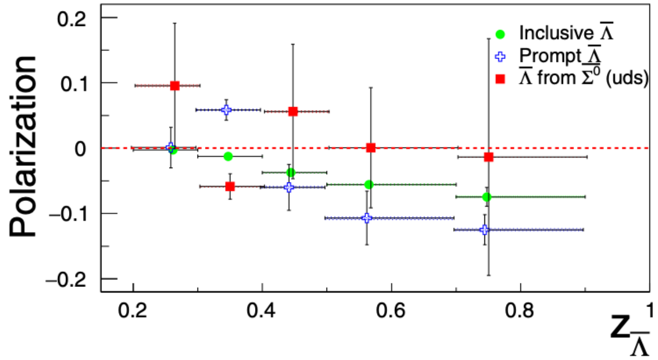


$e^+e^- \rightarrow \Lambda X$



- Nonzero polarization observed for Λ and $\bar{\Lambda}$ as function of z and p_T
- Investigate feed-down contributions from Σ^0 and charm decays





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

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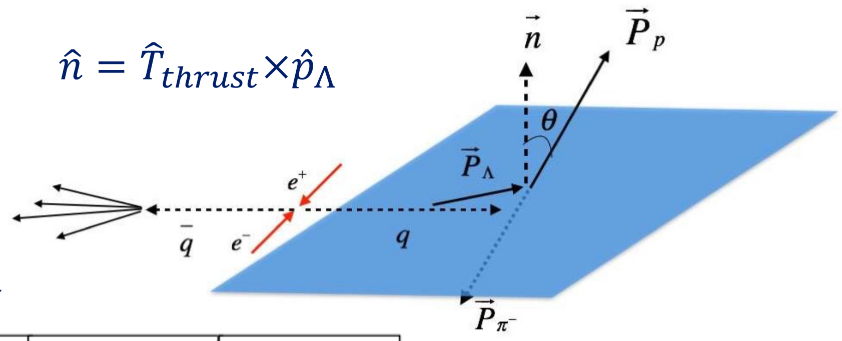
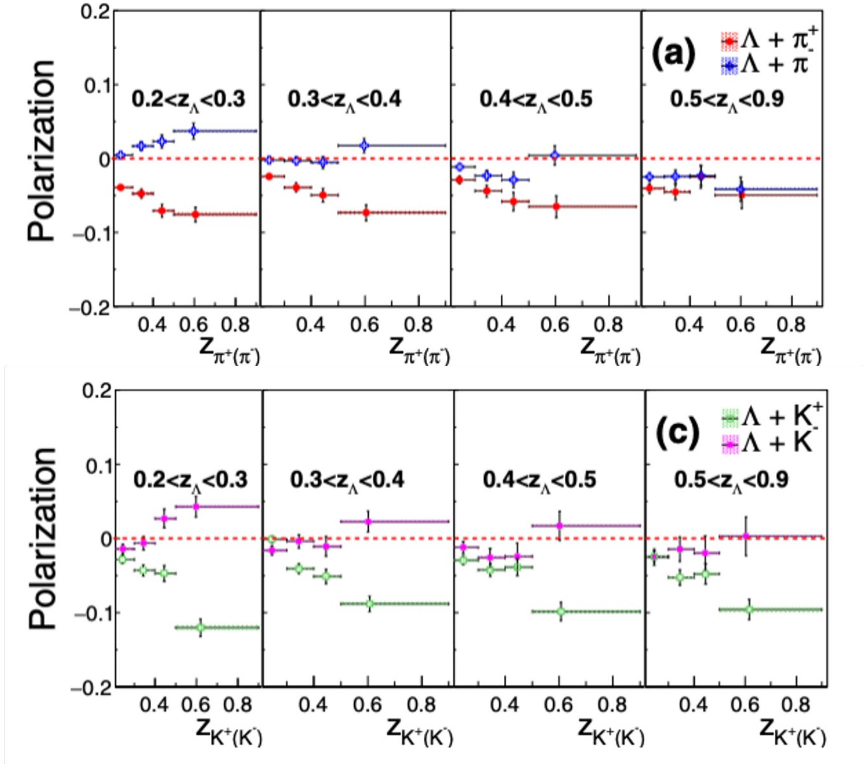
$\hat{n} = \hat{T}_{thrust} \times \hat{p}_\Lambda$



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

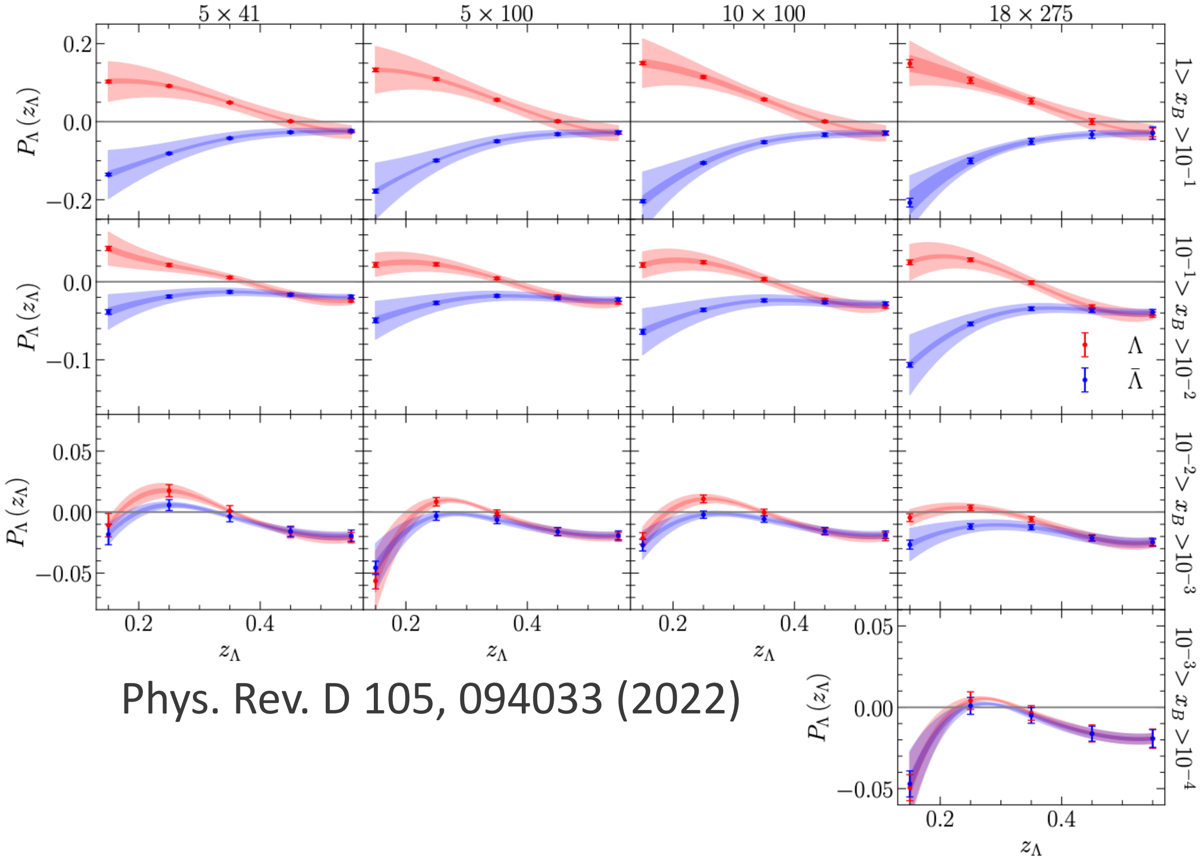


- Nonzero polarization observed for Λ and $\overline{\Lambda}$ as function of z and p_T
- Investigate feed-down contributions from Σ^0 and charm decays
- Polarization measurement also with respect to hadron in opposite hemisphere

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

Transverse Λ Polarization

- Belle measurement data accurate enough for phenomenological studies.
- Used for extractions of polarizing FF and Λ polarization predictions in $ep \to \Lambda X$; for example:



Phys. Rev. D 105, 094033 (2022)

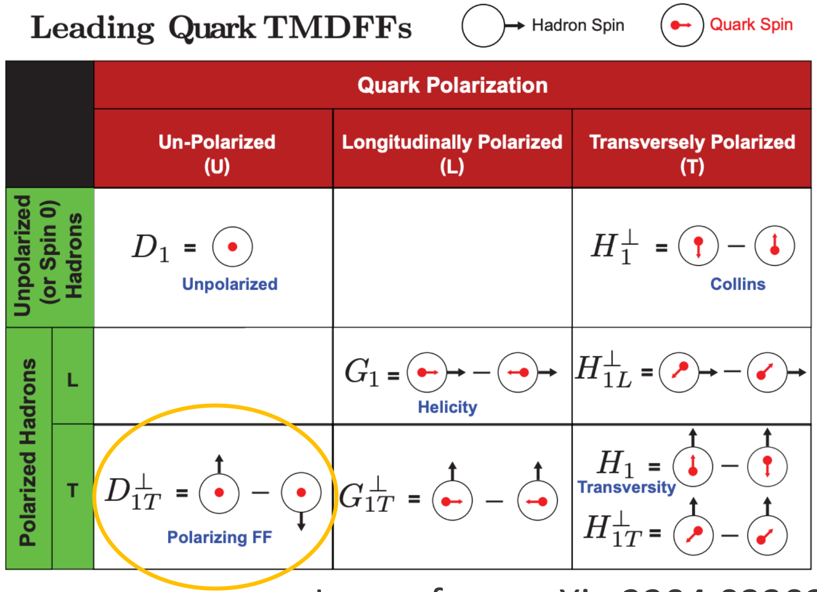


Image from arXiv:2304.03302v1

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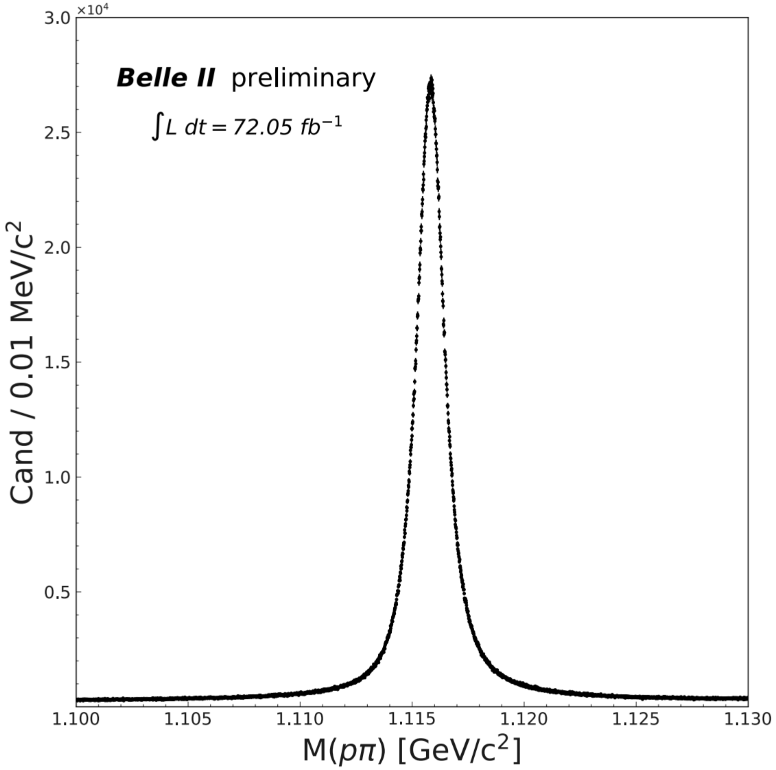


BELLE2-NOTE-PL-2020-031

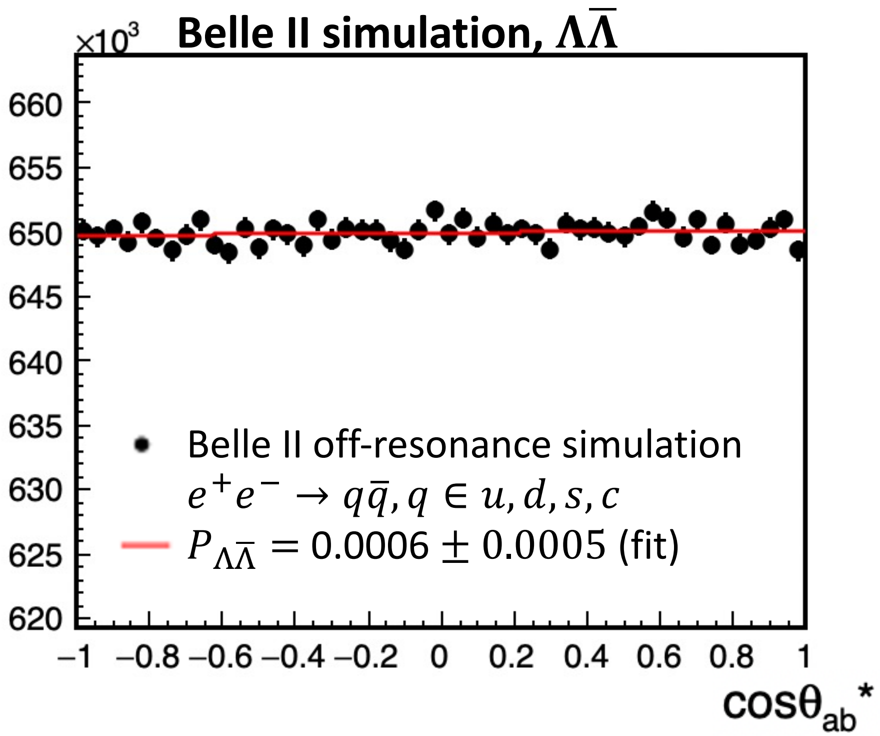
Measurements at Belle II:

- Reduce uncertainties from feed-down and the prompt Λ
- Λ polarization with respect to the plane spanned by beam axis and Λ momentum

Λ Spin Correlation

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

- Entanglement as a probe to hadronization
  - Spin correlation extracted from the correlation of relative spin projections
  - $N \propto 1 + \alpha^2 P_{\Lambda,\Lambda} \cos(n\theta_{ab})$
  - Get expected zero result in simulation



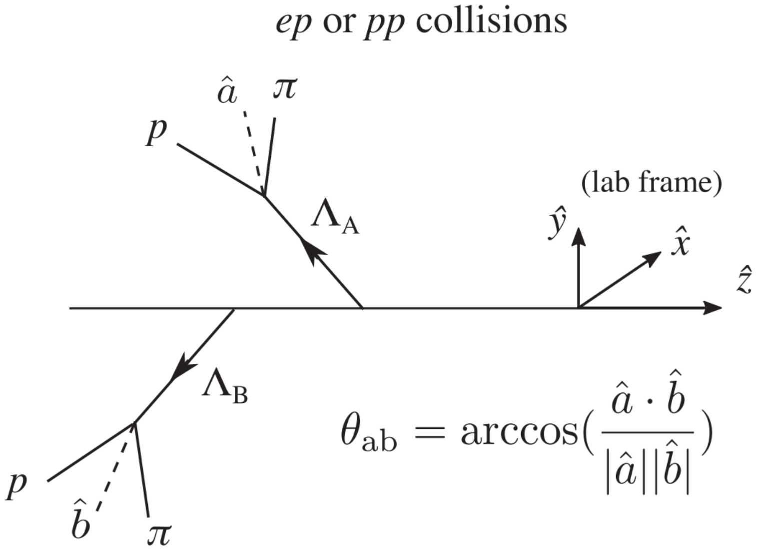


FIG. 3. Illustration of double Λ polarization; here $\hat{a}$ ($\hat{b}$) denotes the momentum direction of Λ_A (Λ_B) daughter particle in the Λ_A (Λ_B) rest frame.

Longitudinal spin transfer via dihadron polarization

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

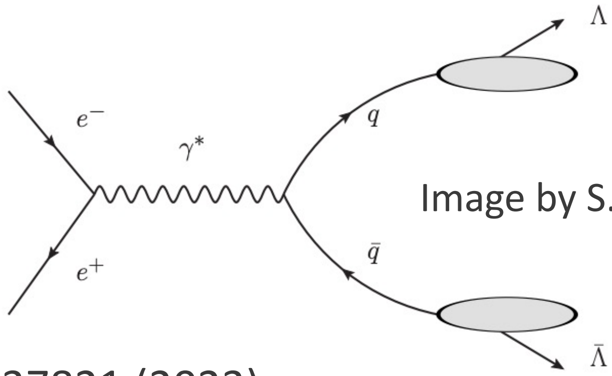


Image by S.Y. Wei, DIS24

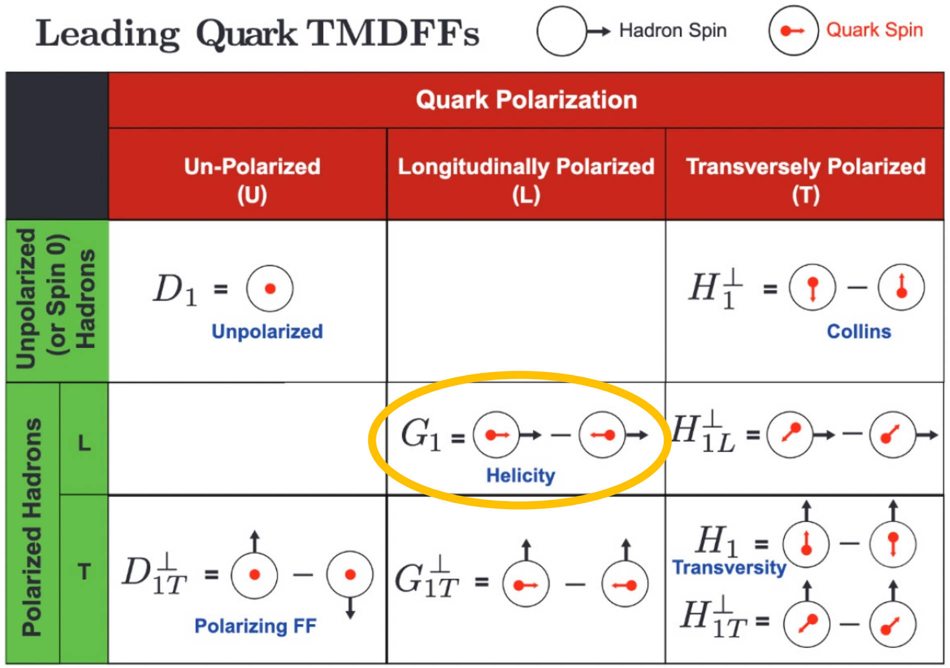
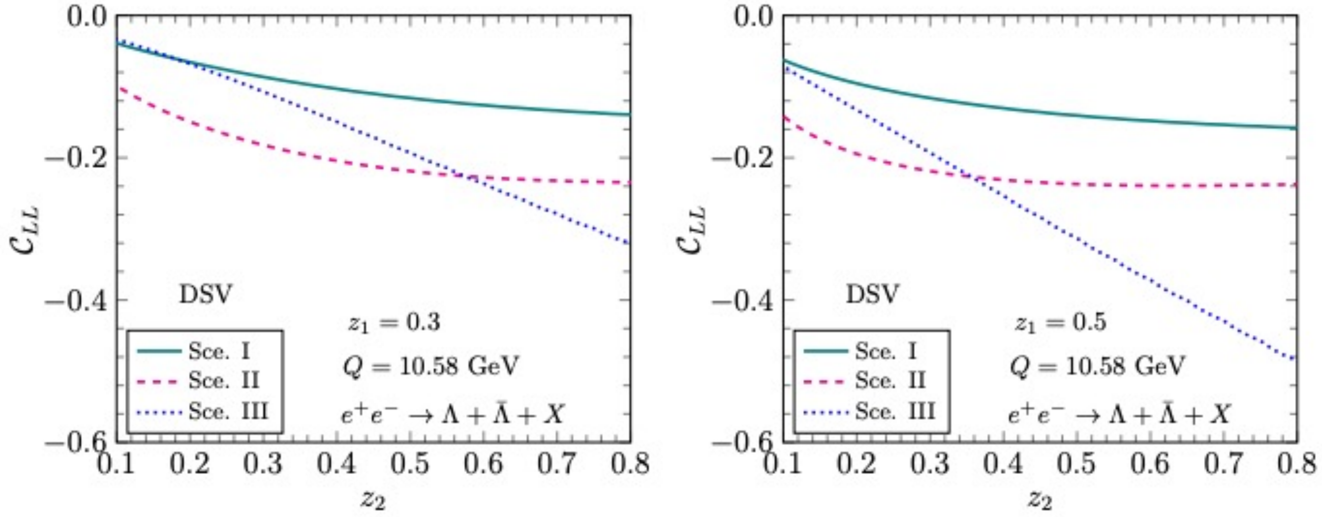


Image from arXiv:2304.03302v1

Phys.Lett.B 839, 137821 (2023)



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

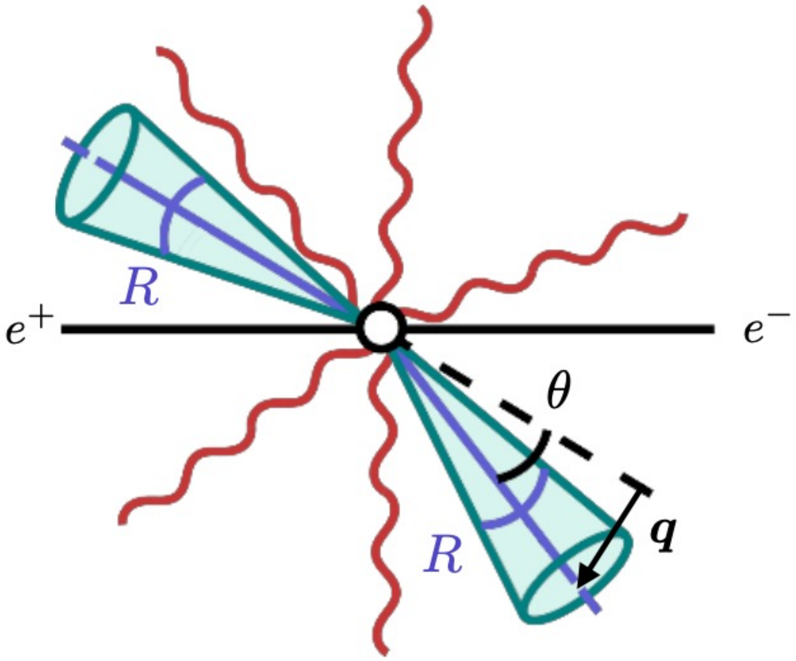
TMD Jet Functions

Phys. Rev. Lett. 121, 162001 (2018)
J. High Energ. Phys. 2019, 31 (2019)

- **TMD FF → TMD Jet Functions**
  - Use jets (instead of hadrons) in final state
    - Jet momentum is perturbatively calculable
    - Reduce uncertainty and improve sensitivity to PDFs in SIDIDS
  - Measuring the jet q_T spectrum:

$$\boldsymbol{q} = \frac{\boldsymbol{p_1}}{z_1} + \frac{\boldsymbol{p_2}}{z_2}$$

Require decorrelation to be small: $q_T \equiv |\boldsymbol{q}| \ll \frac{\sqrt{s}}{2}$

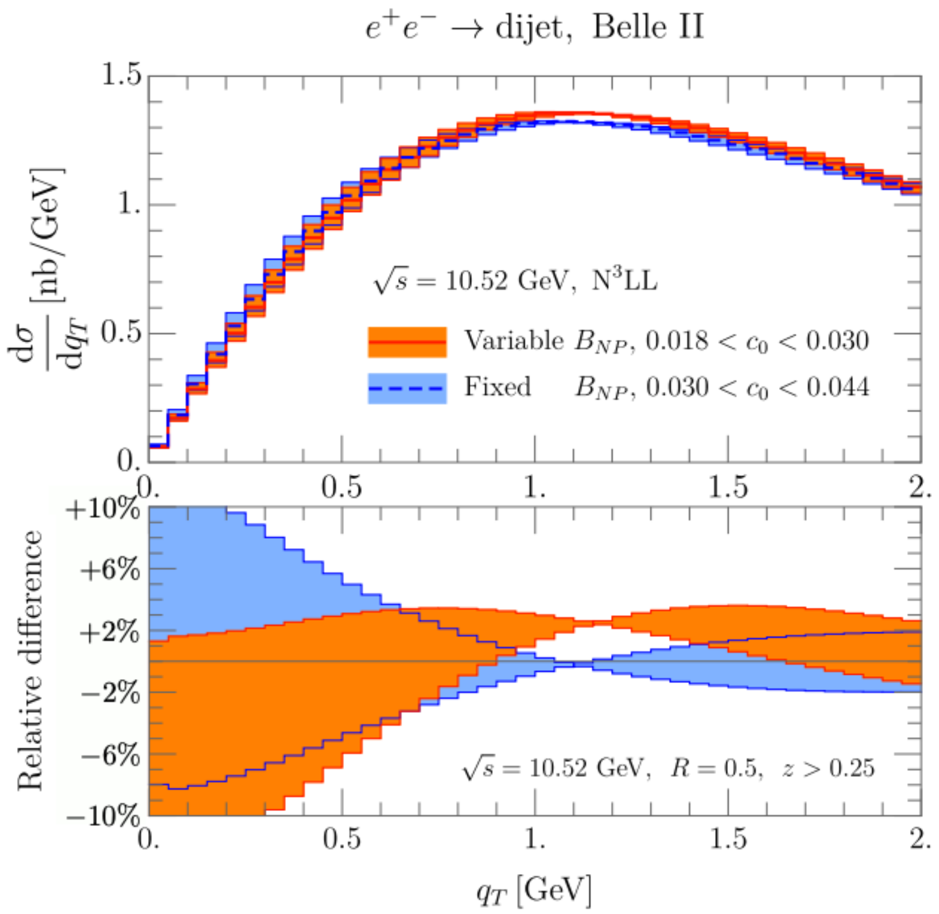


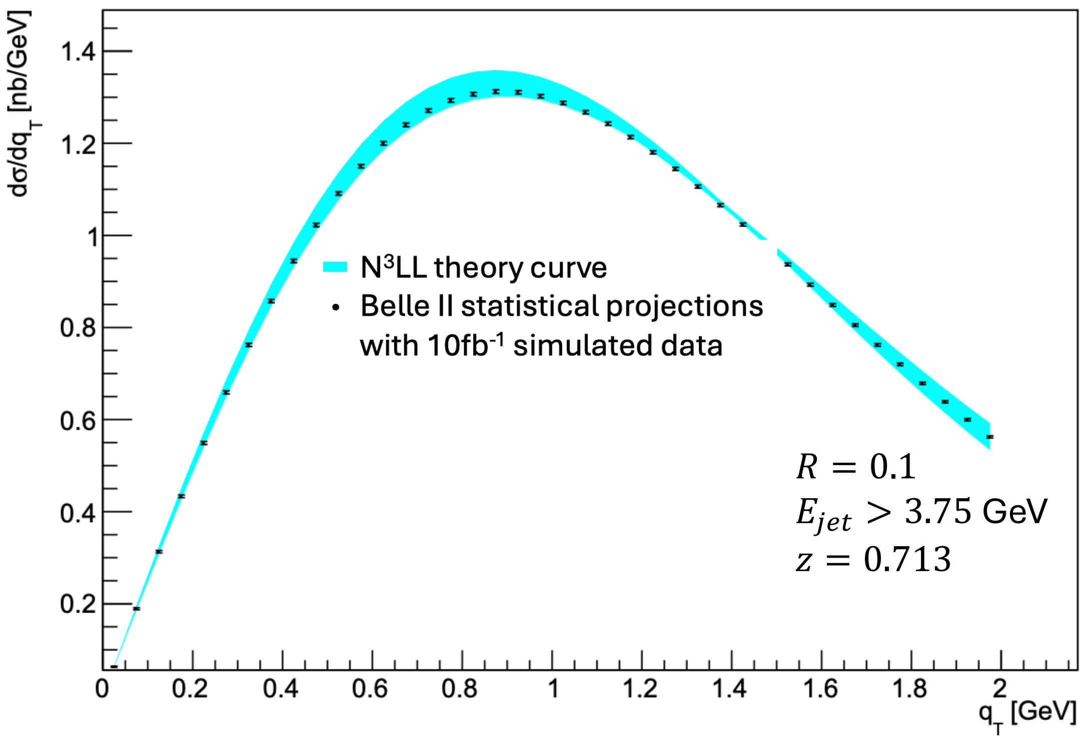
Ongoing analysis: Simon Schneider, Duke University

TMD Jet Functions – q_T Spectrum

Theoretical predictions for q_T predictions

JHEP10(2019)031
arXiv:2204.02280v2





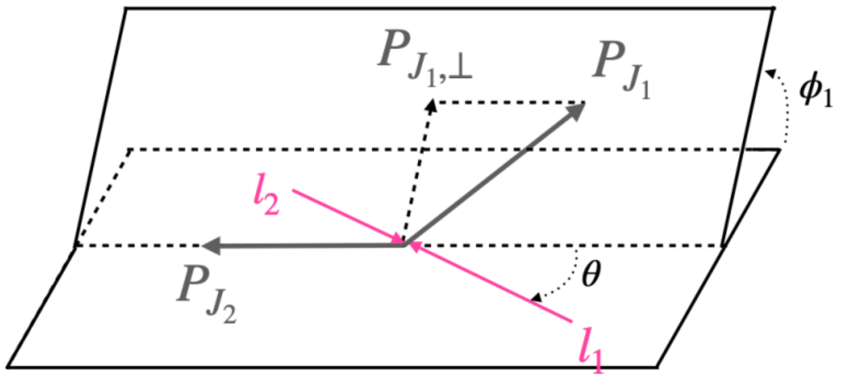
- Sensitivity of the TMD to nonperturbative effects
- Statistical projections with Belle II simulation

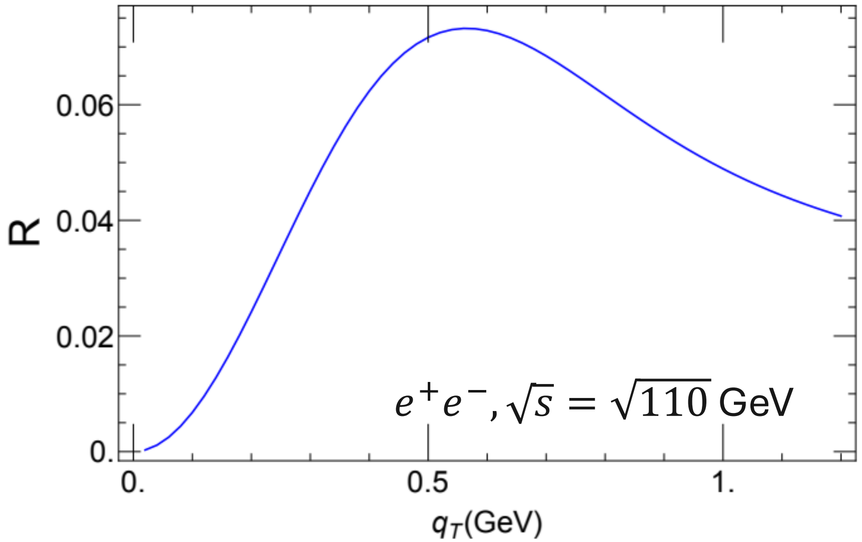
Ongoing analysis: Simon Schneider, Duke University

TMD Jet Functions – T-odd side of jets

- T-odd jet components:
  - Recently found to survive due to non-perturbative effects
  - Important to access nucleon spin structure
- T-odd component can couple to the proton transversity at the EIC

arXiv:2104.03328 [hep-ph]





<u>Azimuthal asymmetry</u>

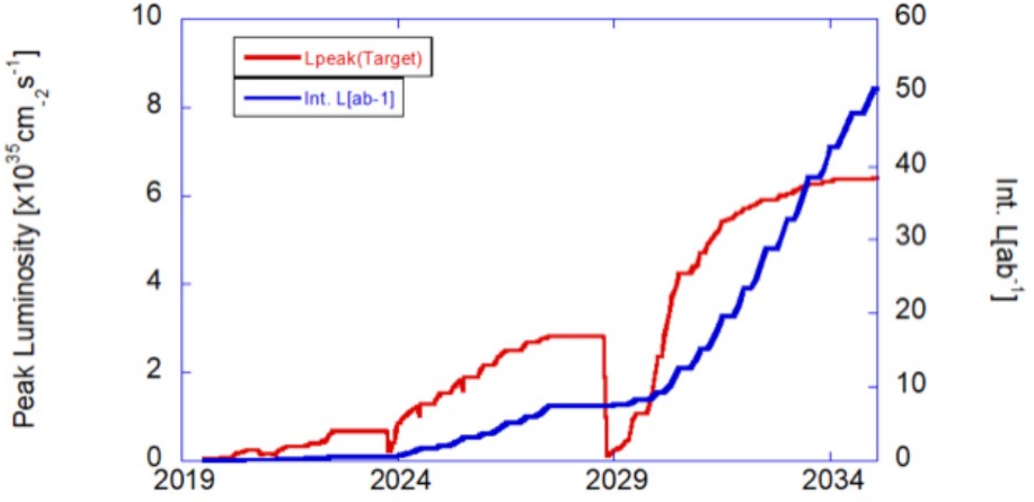
$$R^{J_1J_2} = 1 + \cos(2\phi_1)\frac{\sin^2\theta}{1+\cos^2\theta}\frac{F_T(q_T)}{F_U(q_T)}$$

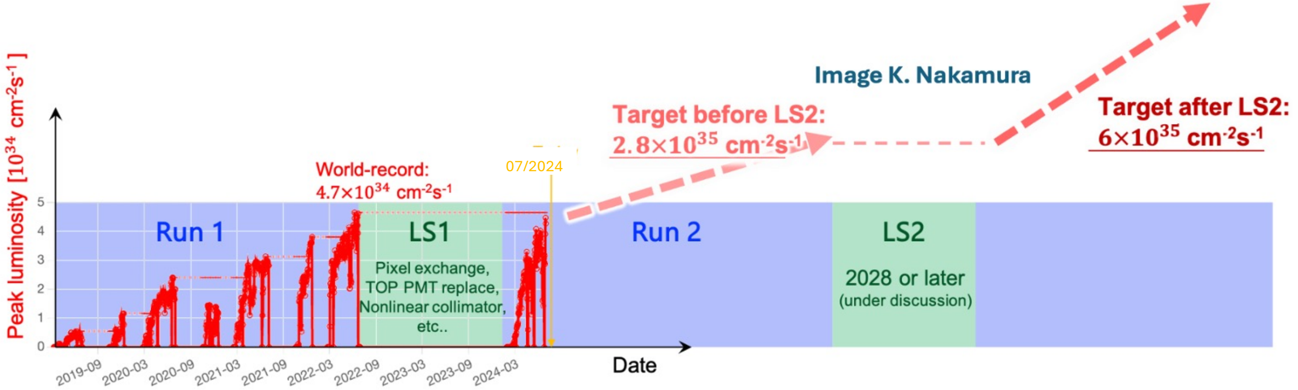
$$R = 2\int d\cos\theta\,\frac{d\phi_1}{\pi}\cos(2\phi_1)R^{J_1J_2}$$

Ongoing analysis: Simon Schneider, Duke University

Summary

- Belle II is currently collecting data during Run 2
- Belle and Belle II play an important role in understanding hadronization dynamics
- Provide key information on hadronization for future EIC measurements
- Lots of measurement opportunities at Belle II, with several current ongoing analyses underway





Thank You!

Thanks for help in preparing this presentation to S. Schneider, K. Parham, A. Vossen, and the Belle II collaboration!

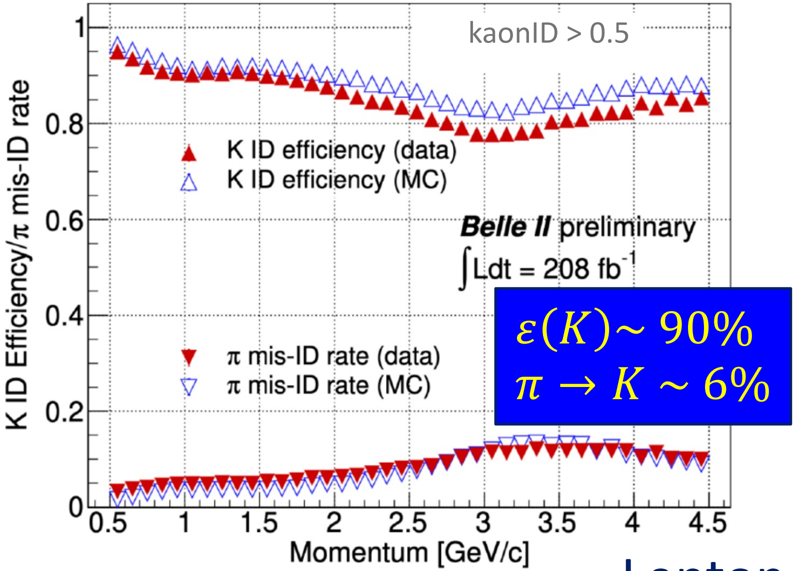
Back up

Belle II Detector @ SuperKEKB

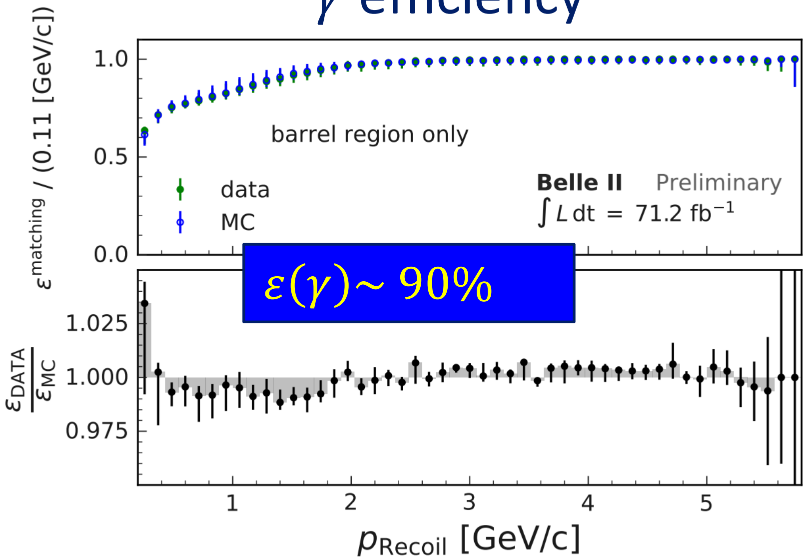
BELLE2-NOTE-PL-2020-024
BELLE2-CONF-PH-2022-003

BELLE2-NOTE-PL-2021-008
BELLE2-NOTE-PL-2020-031
BELLE2-CONF-PH-2021-002

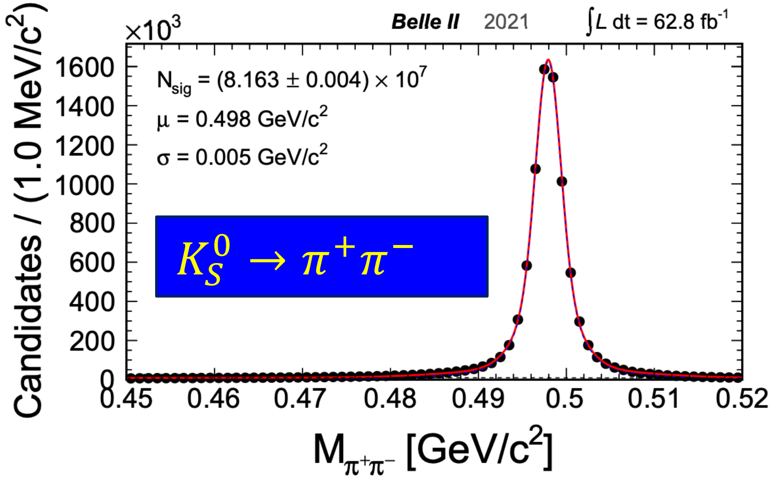
Kaon identification



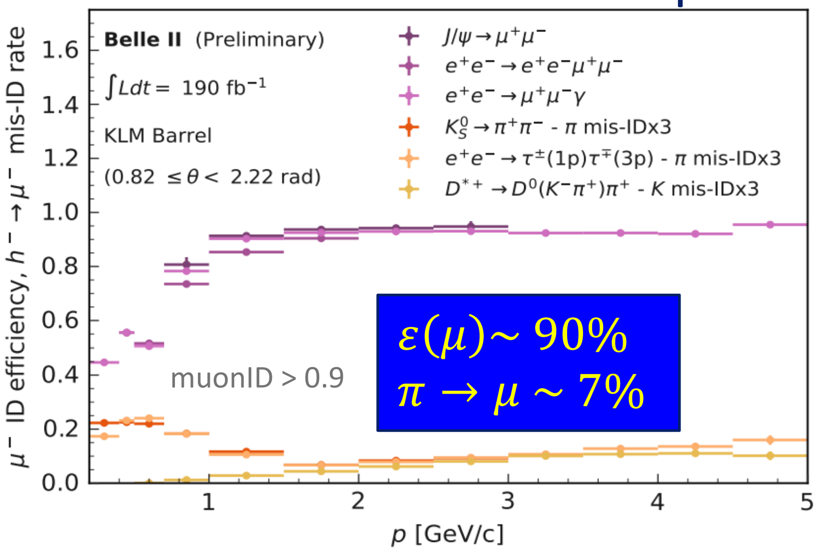
γ efficiency

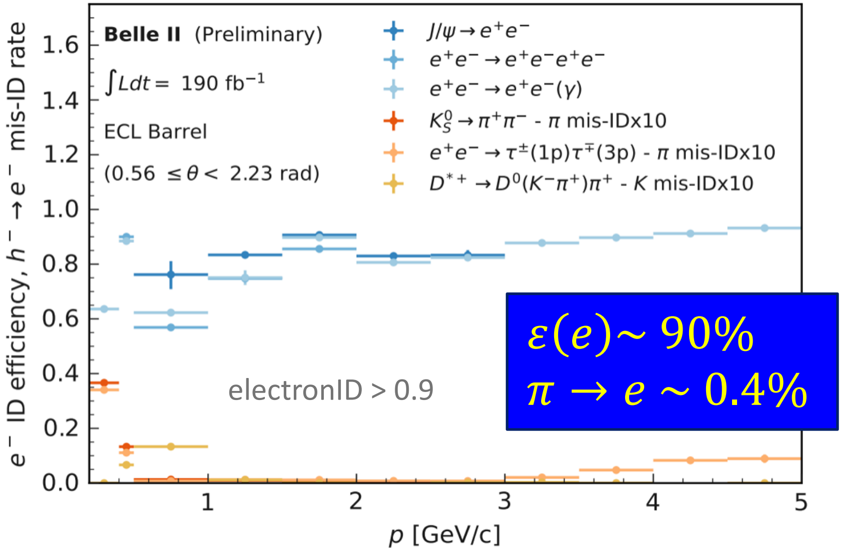


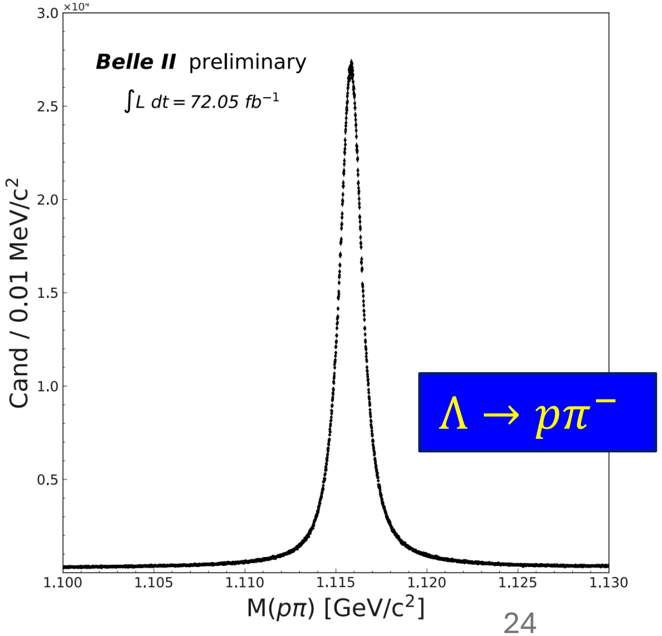
V^0 Reconstruction



Lepton identification



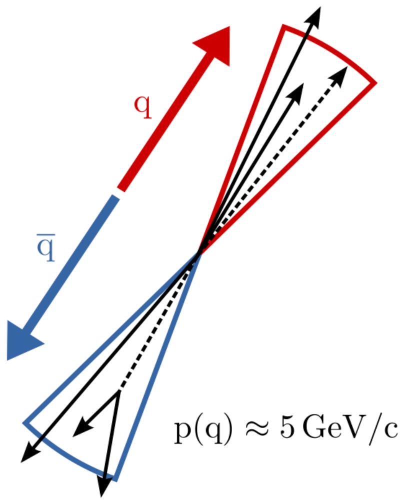




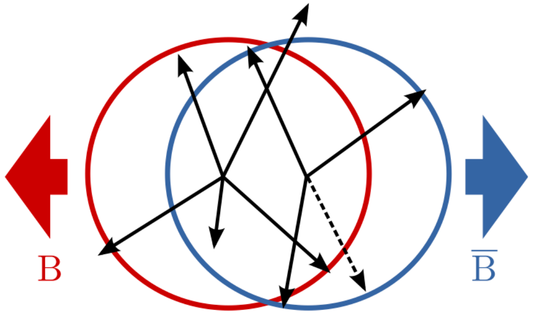
Belle II event shape: thrust axis

- Using B-factory for hadronization studies
  - Events produced at or near $\Upsilon(4S)$ have different shapes
  - Cuts on thrust provide clean $q\bar{q}$ event sample

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

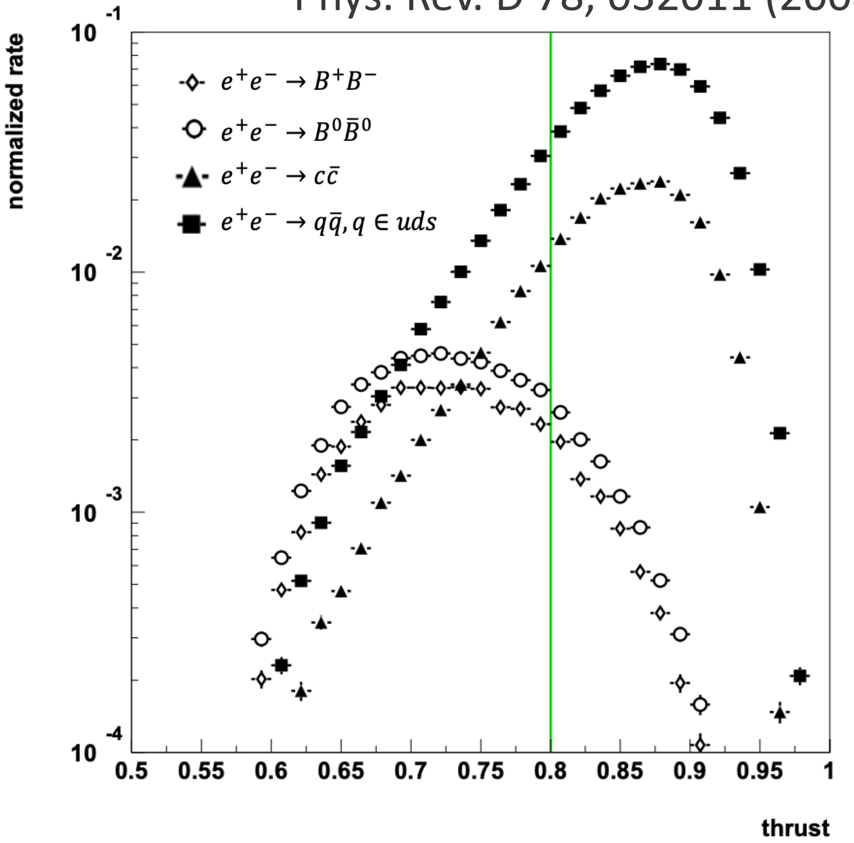


$e^+e^- \to q\bar{q} \quad (q \in \{u, d, s, c\})$



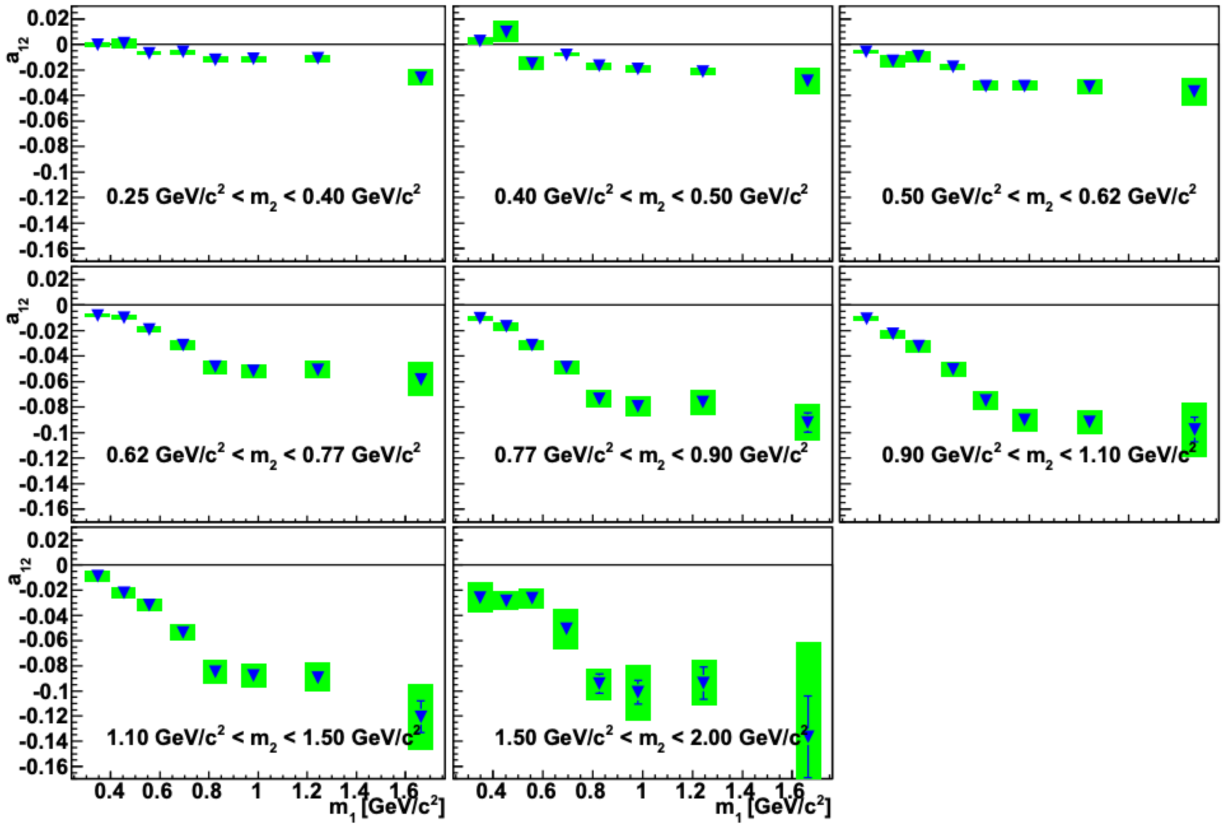
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

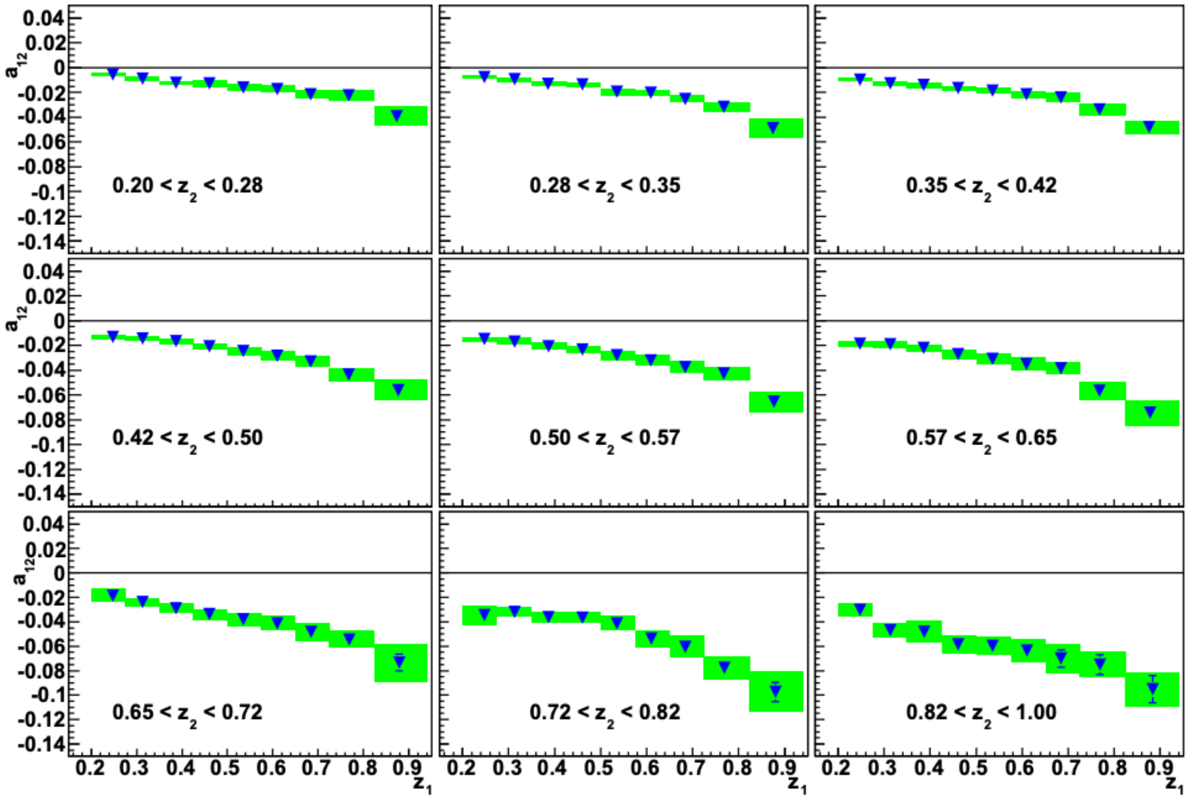
Phys. Rev. D 78, 032011 (2008)



Di-hadron Fragmentation Functions (DiFF)

Azimuthal asymmetries for $e^+e^- \rightarrow (\pi^+\pi^-)(\pi^+\pi^-)$ Belle results (670 fb^{-1})





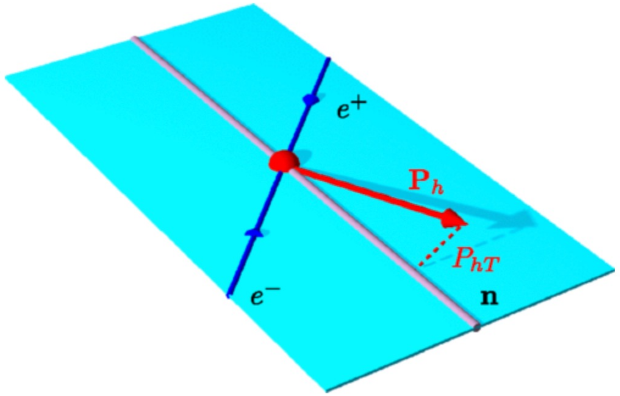
Phys. Rev. Lett. 107, 072004 (2011)

Belle results – a recent review

Belle data provided essential measurements, including recent results:

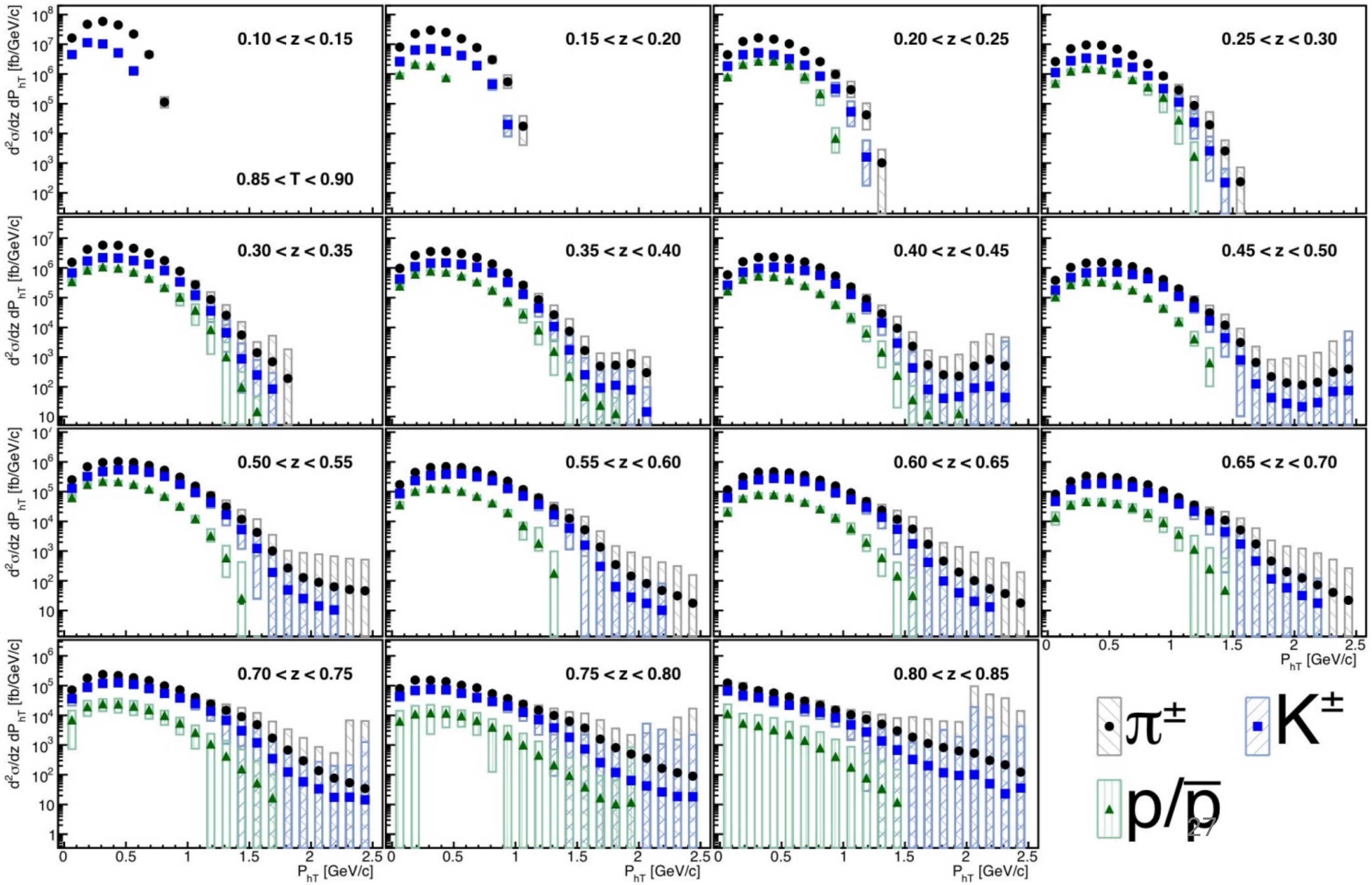
R. Seidl et al., "Transverse momentum dependent production cross sections of charged pions, kaons and protons produced in inclusive $e^{+}e^{-}$ annihilation" at $\sqrt{s}$=10.58 GeV

Phys. Rev. D 99, 112006 (2019)



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

$$T \overset{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}$$

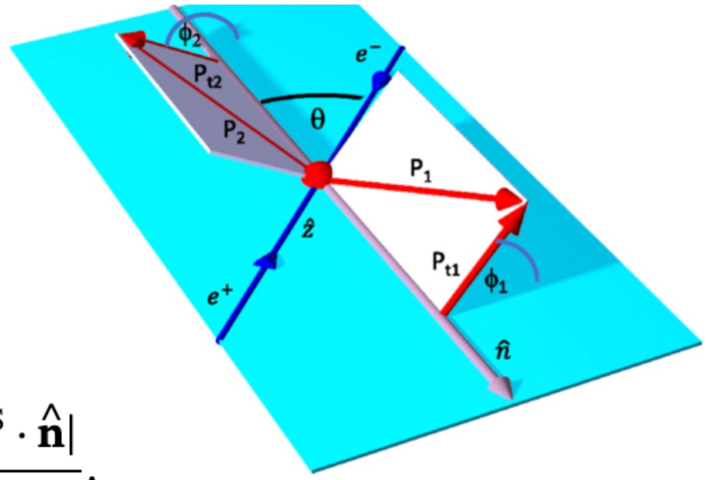


Belle results – a recent review

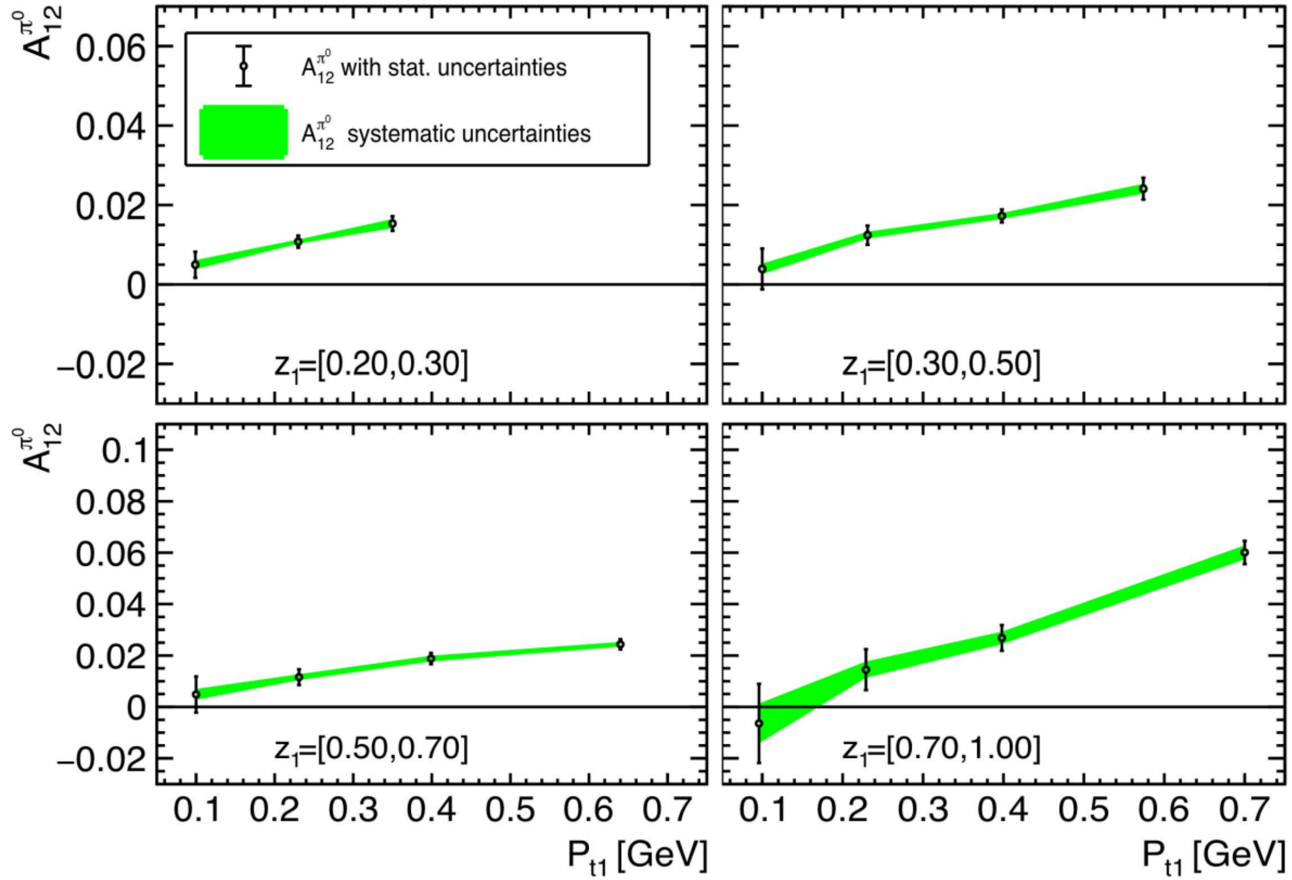
Belle data provided essential measurements, including recent results:

H. Li, A. Vossen, et al., “Azimuthal asymmetries of back-to-back $\pi^{\pm} - (\pi^0, \eta, \pi^{\pm})$ pairs in $e^{+}e^{-}$ annihilation” **Phys.Rev.D 100 9, 092008 (2019)**

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



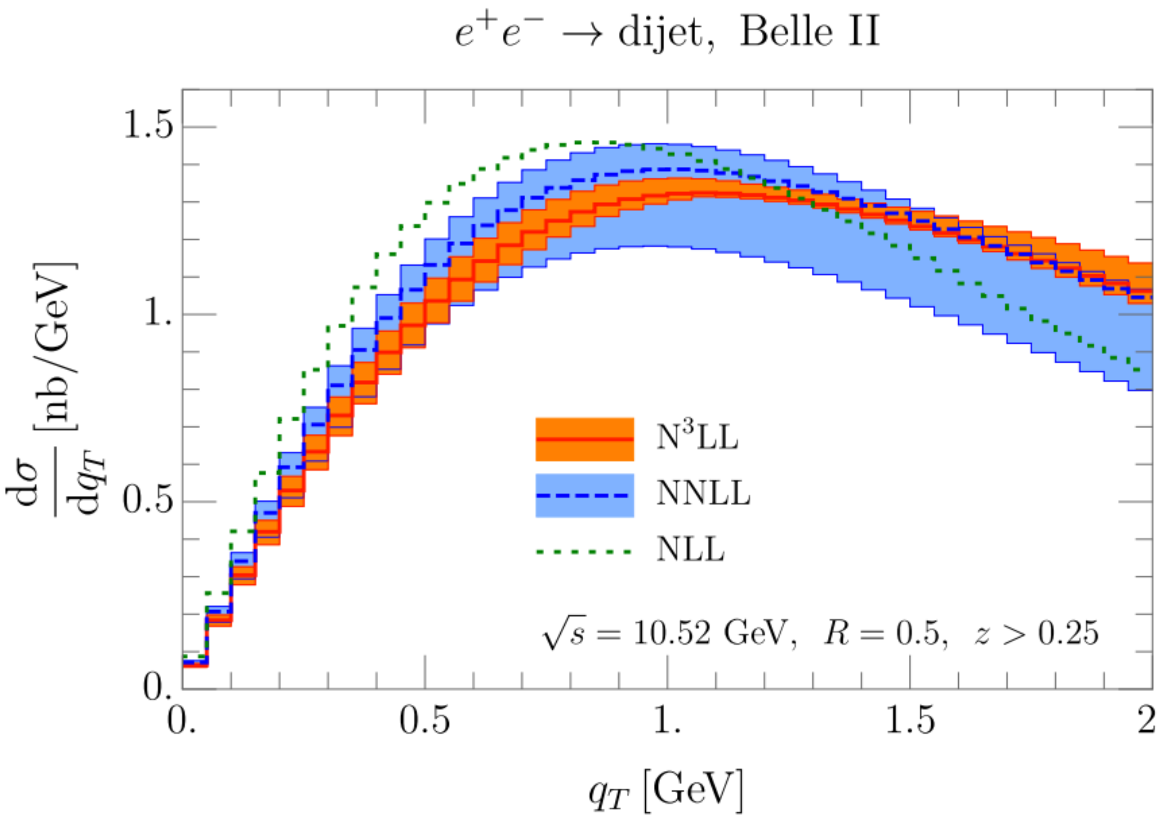
$$T \underset{=}{\max} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}.$$

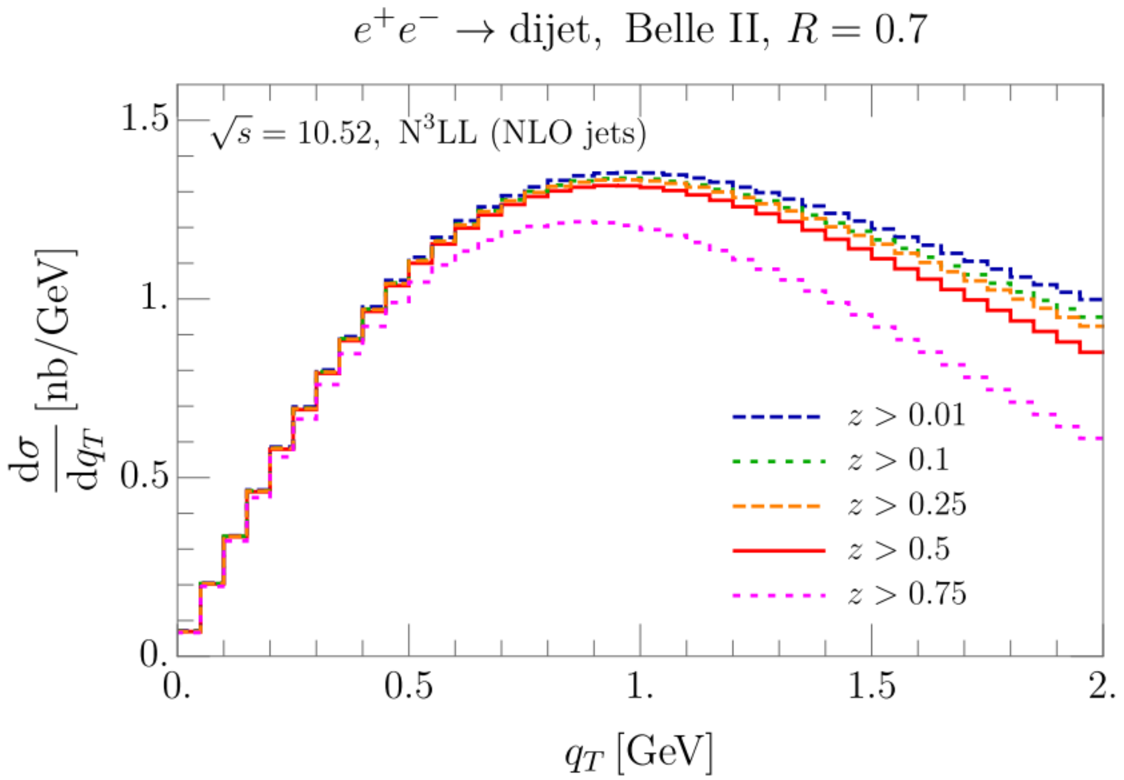


TMD Jet Functions – q_T Spectrum

Theoretical predictions for q_T predictions

J. High Energ. Phys. 2019, 31 (2019)





- Perturbative convergence of cross-section
- Dependence on z

Ongoing analysis: Simon Schneider, Duke University

Belle II upgrades