Studying hadronization at Belle II for the EIC

Cynthia Nuñez
on behalf of the Belle II collaboration

POETIC XI

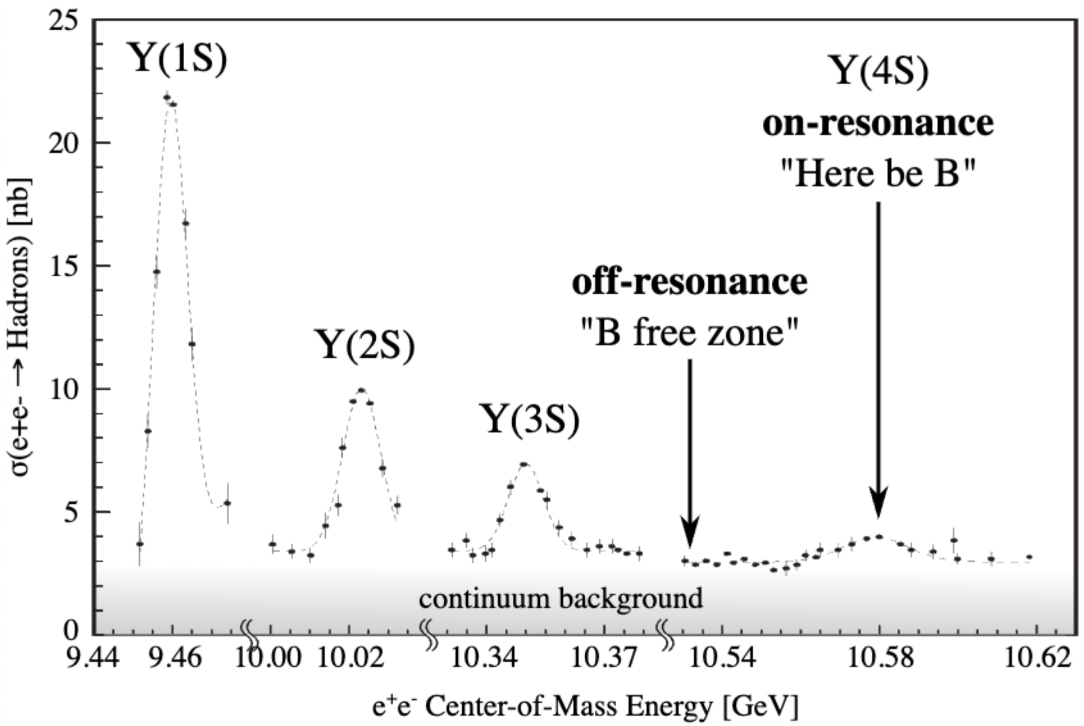
February 24, 2025

Research supported by:

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 $\Upsilon(4S)$



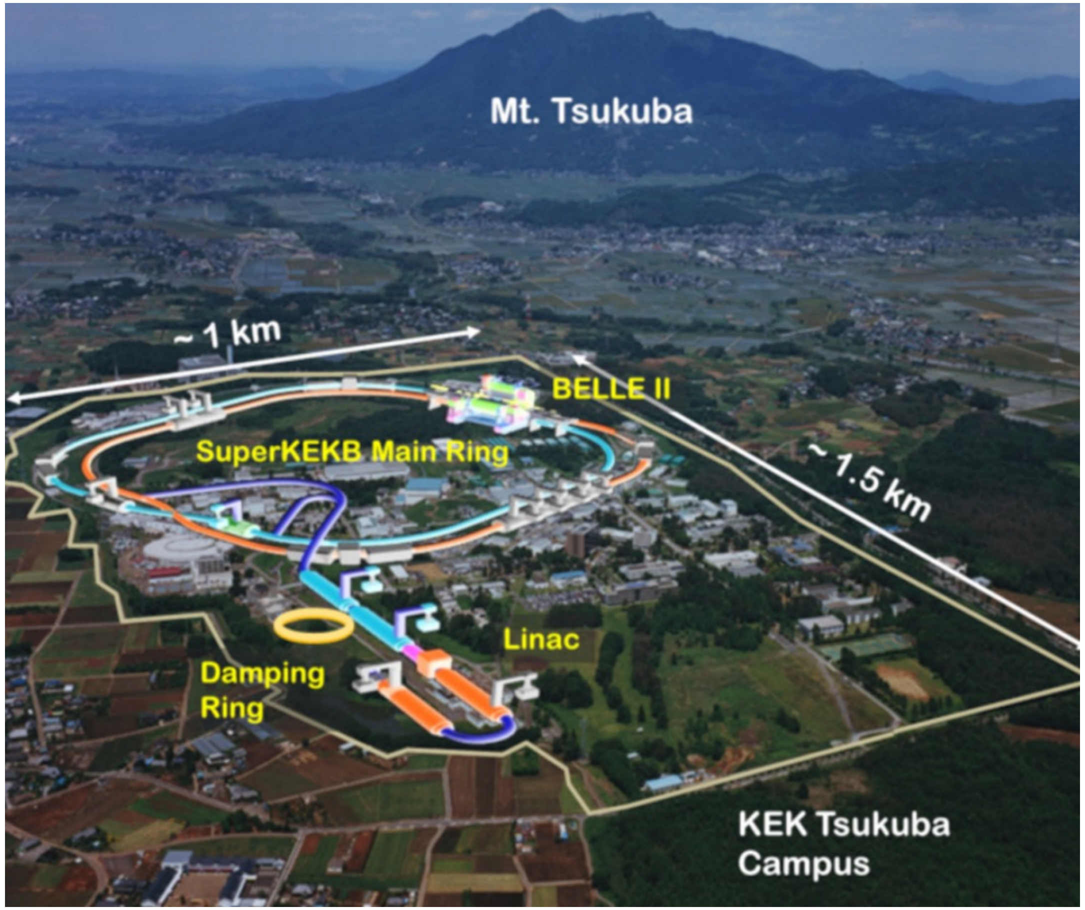


Image from: [Phys. Rev. Accel. Beams 26, 013201 (2023)]

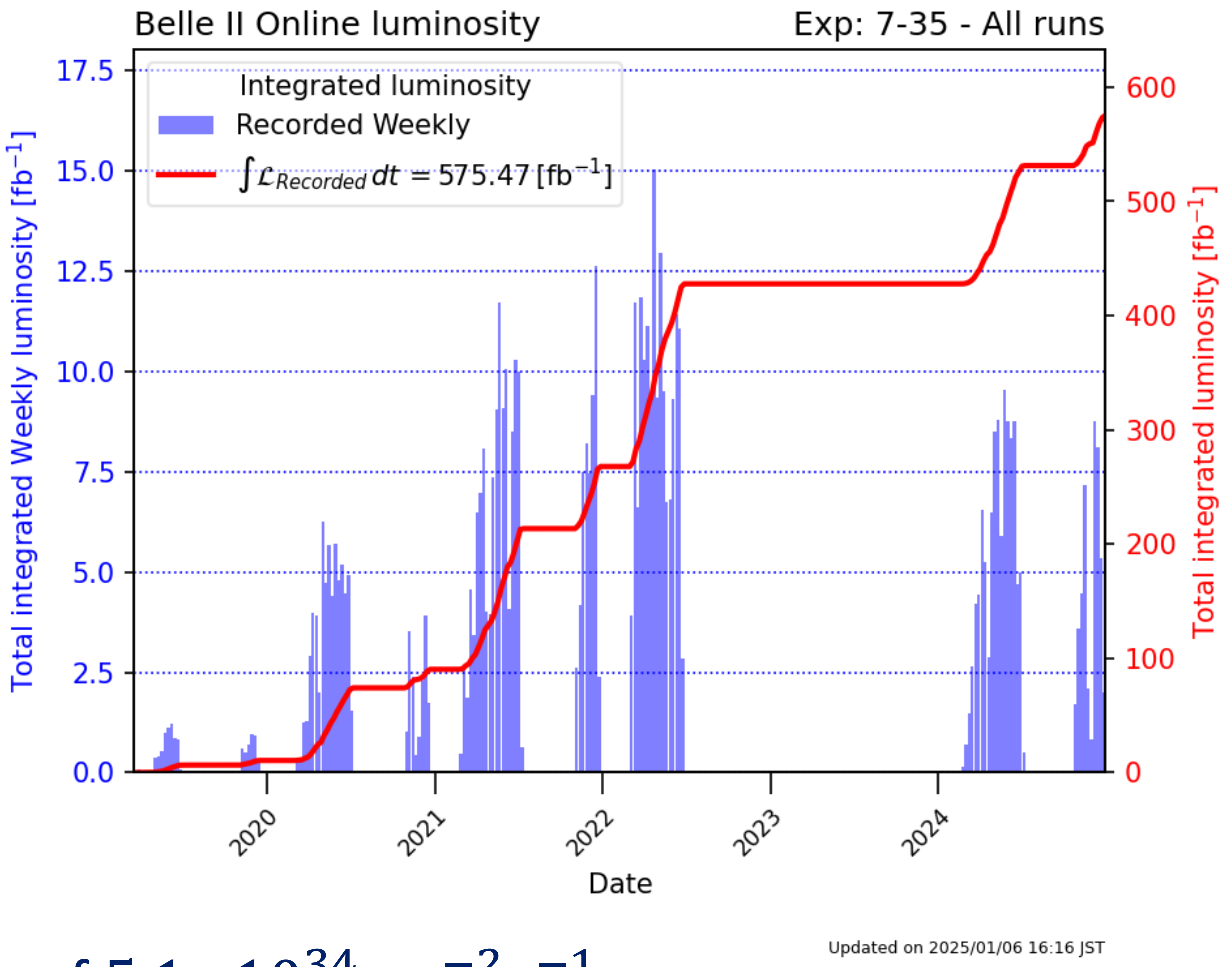
Belle → Belle II

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 $\int \mathcal{L}\mathrm{dt} = 980\ \mathrm{fb}^{-1}$

- **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 $5.1\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



Belle II Detector @ SuperKEKB

- Large acceptance with good vertexing, PID, and tracking

KEK Report 2010-1 [arXiv:1011.0352]

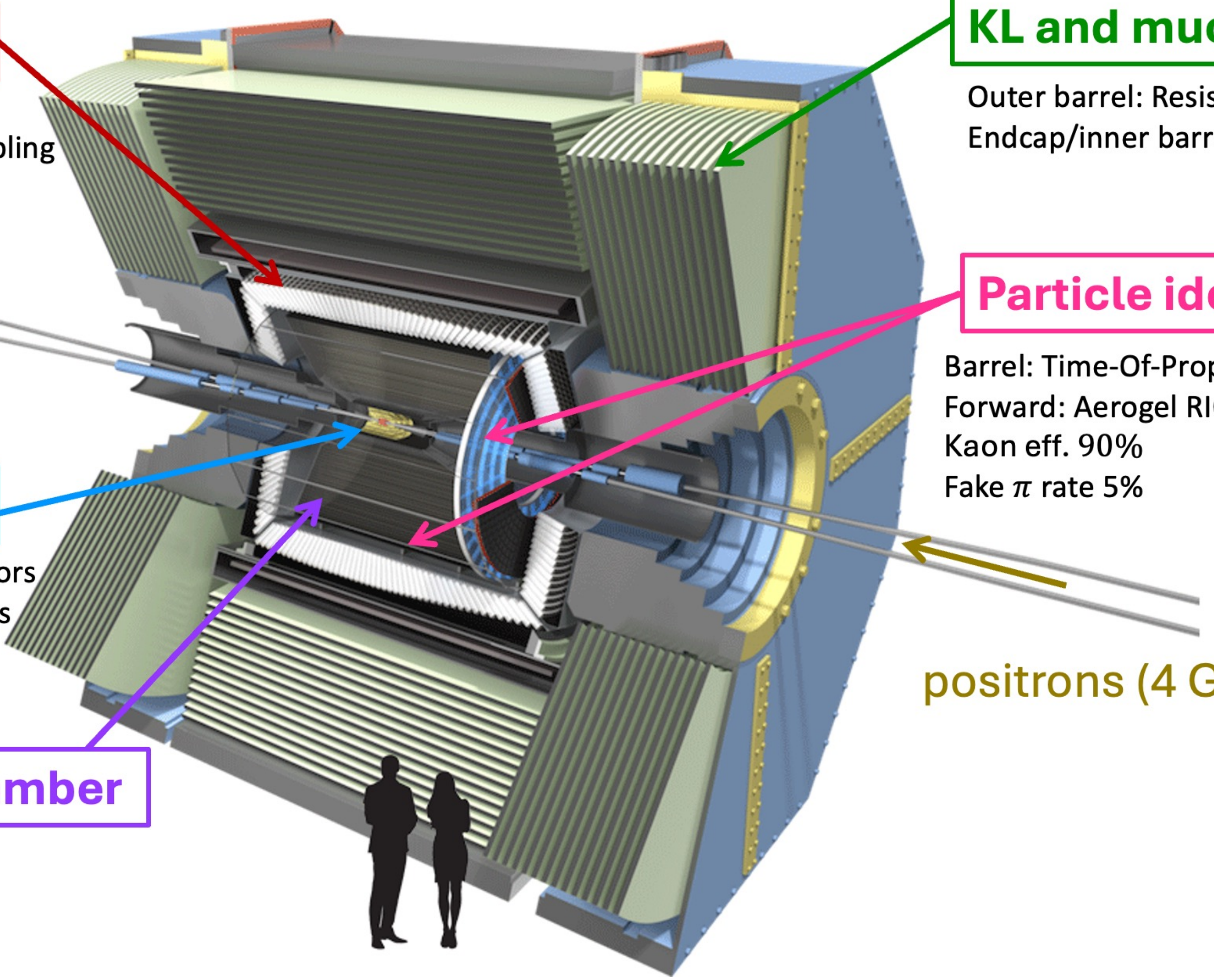
EM calorimeter

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

KL and muon detector

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

electrons (7 GeV)



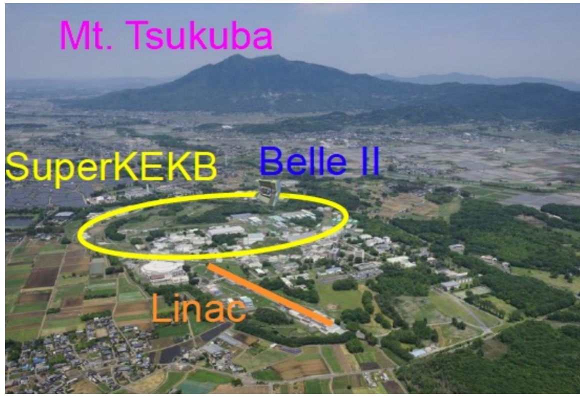
Particle identification

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

Vertex detector

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

positrons (4 GeV)



Central drift chamber

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

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

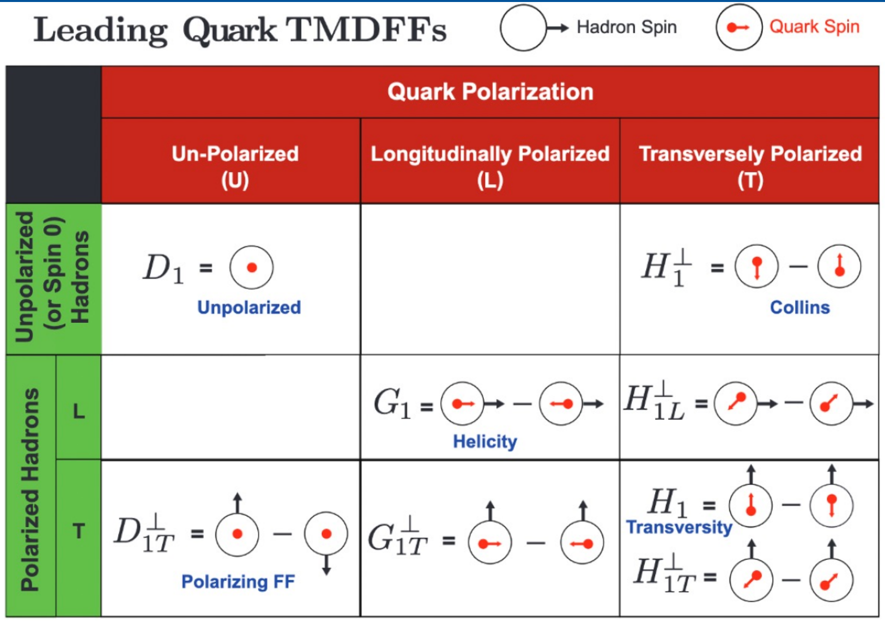


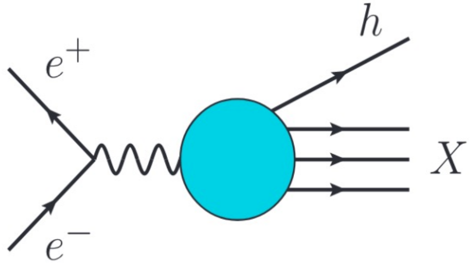
Image from arXiv:2304.03302v1

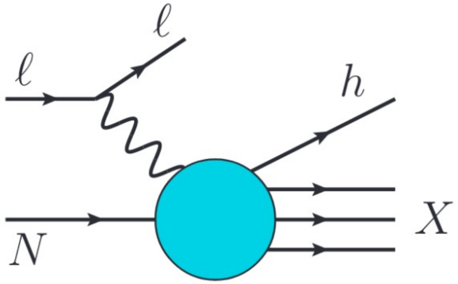
Important processes in studying hadron formation

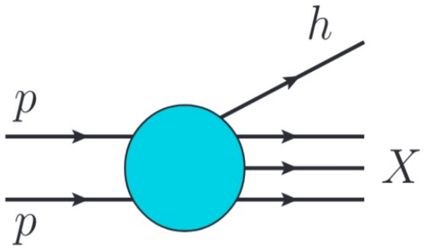
$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes FF$

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

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







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

Hadronization at Belle

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

. . .

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

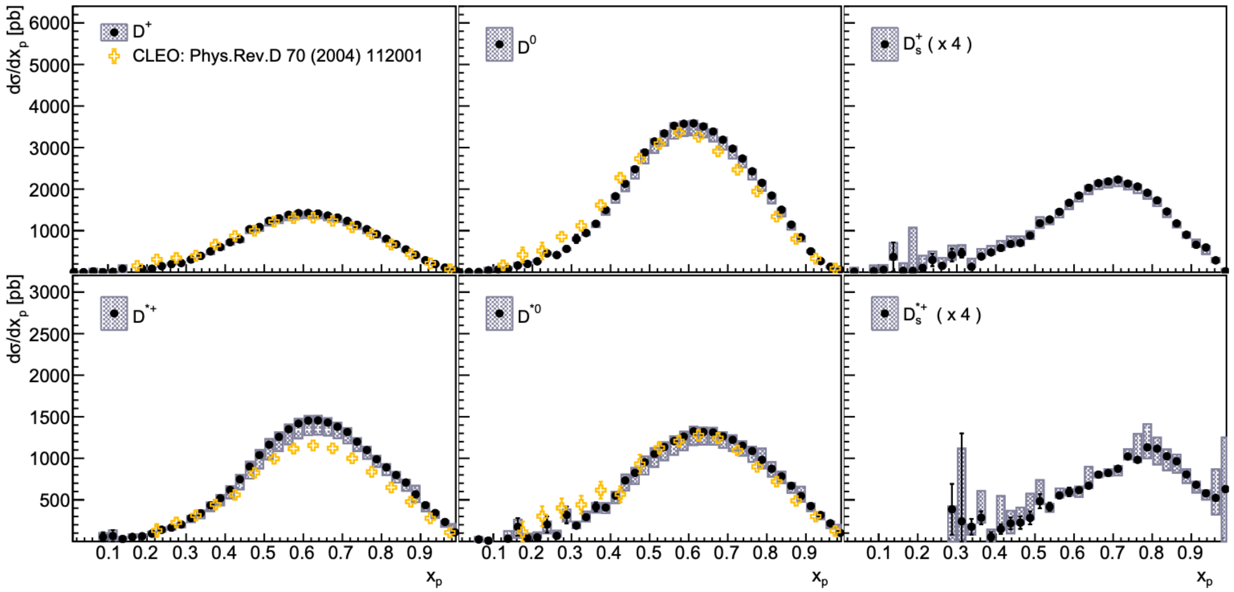
$x_p = p_h / p_{max}$

R. Seidl, "Production cross sections of light and charmed mesons in e^+e^- annihilation near 10.58 GeV"

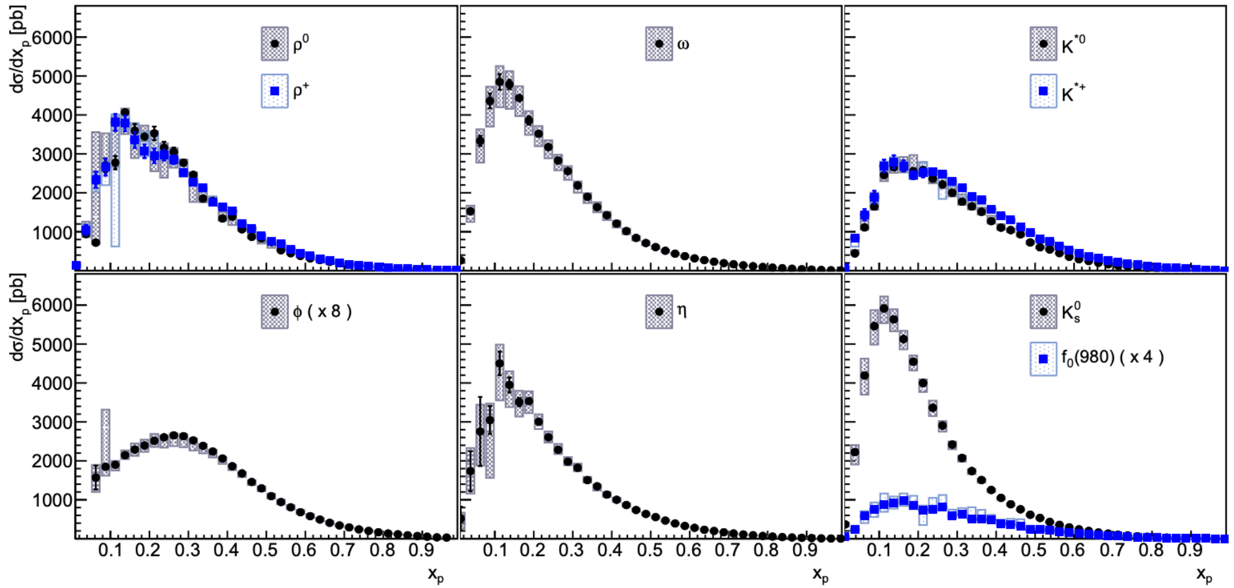
Belle preprint 2024-09, KEK Preprint 2024-30, submitted to PRD

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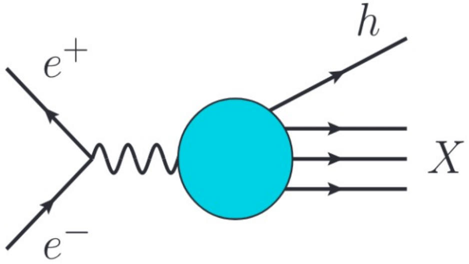
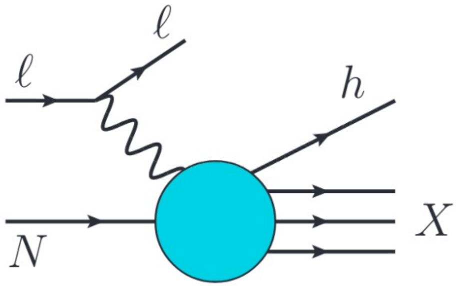
$$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes FF$$





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

See Snowmass whitepaper [arXiv:2204.02280]

Current ongoing analyses at Belle II

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

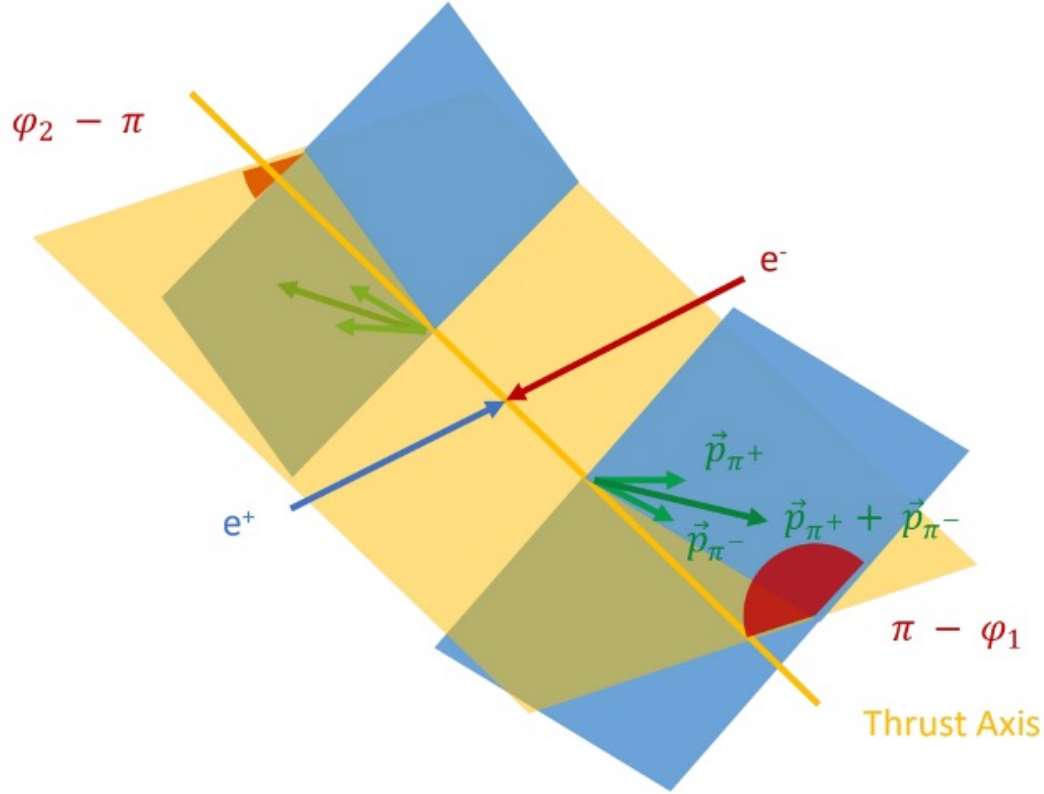
Di-hadron Fragmentation Functions (DiFF)

- $H_1^{\sphericalangle}(z, M, P_h, \theta)$ 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:

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

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

Ongoing analysis: Katherine Parham, Duke University

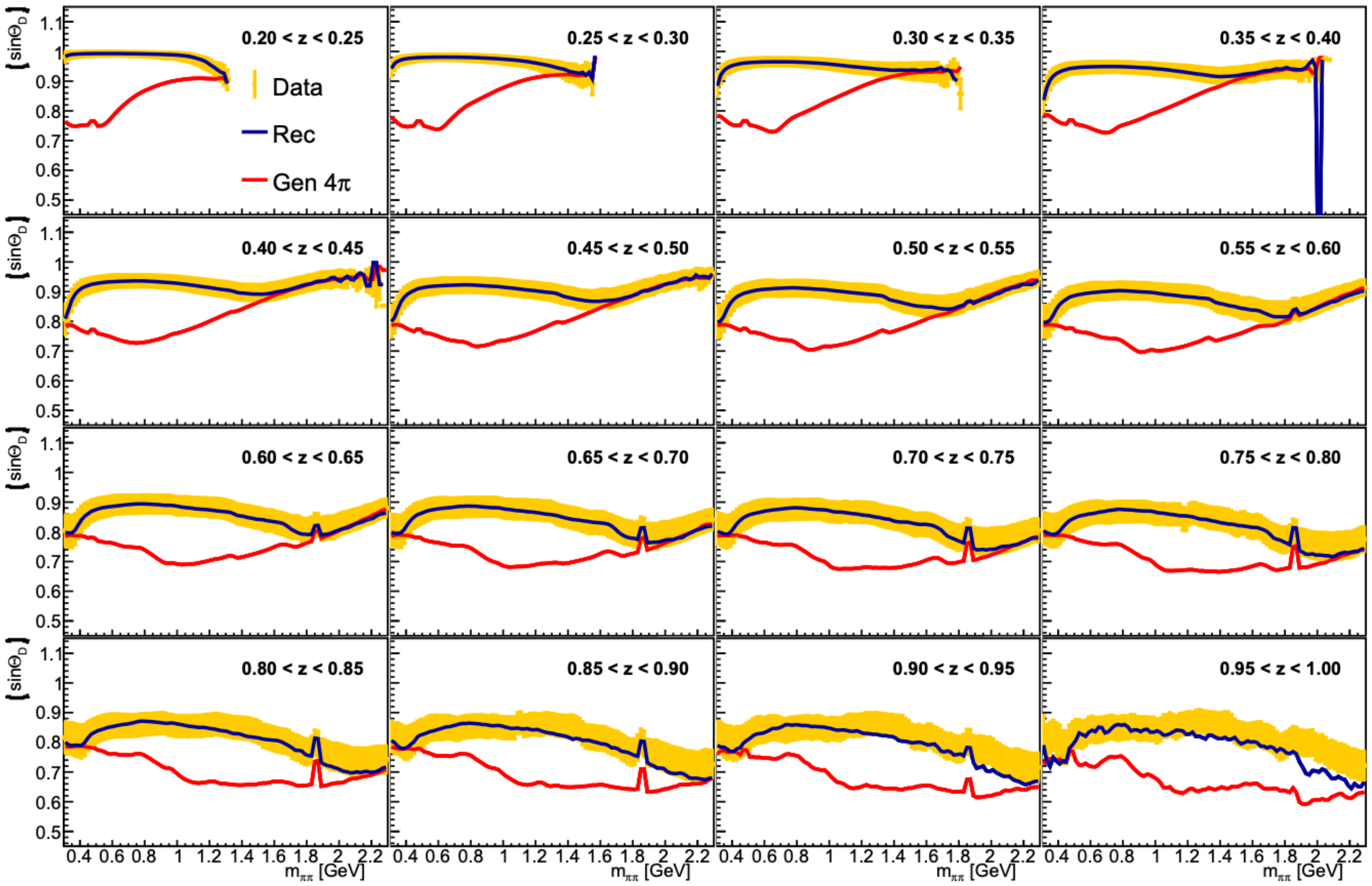
Di-hadron Fragmentation Functions (DiFF)

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



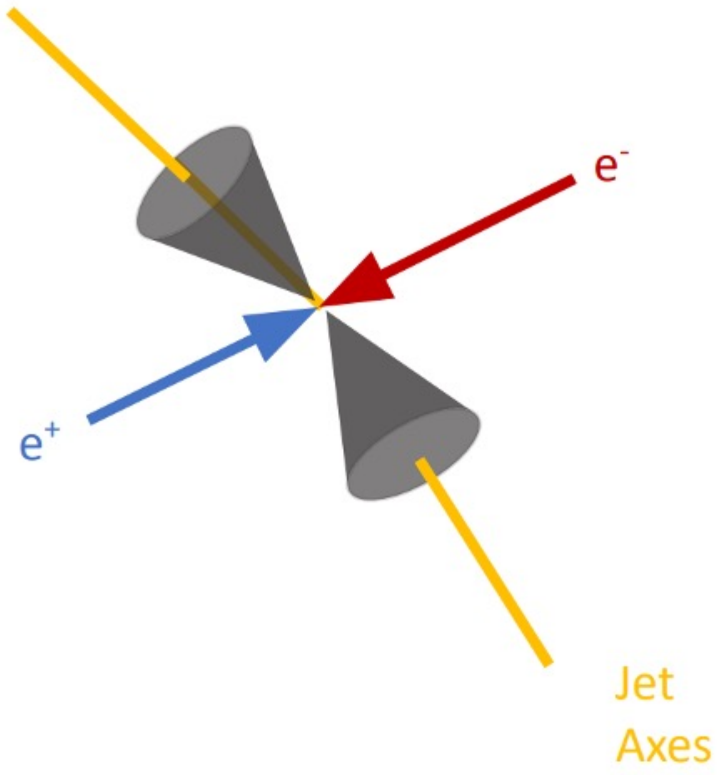
$\sin\theta_D$ decay moment for $\pi^+\pi^-$ pairs; Belle results (655 fb^{-1})

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

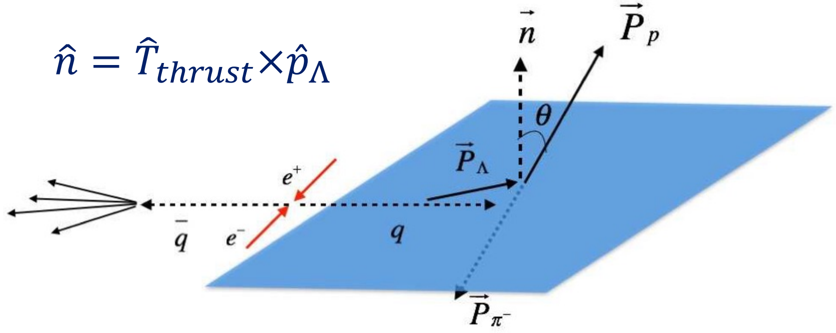
$z_{\mathrm{h}} = 2E_{\mathrm{h}}/\sqrt{s}$

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

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

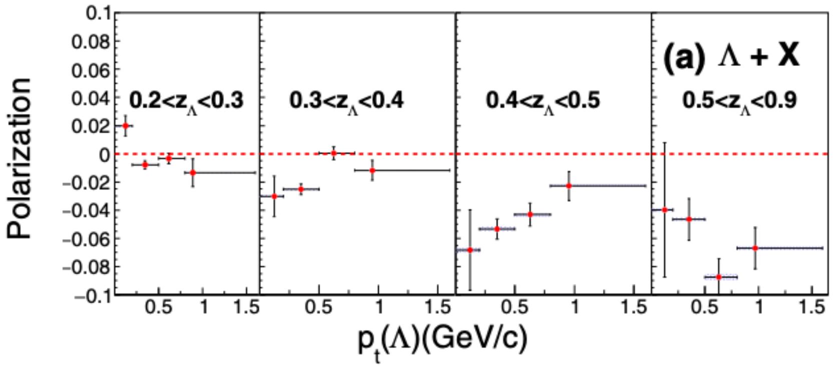
α_Λ= 0.748 ± 0.007 (PDG 2023)

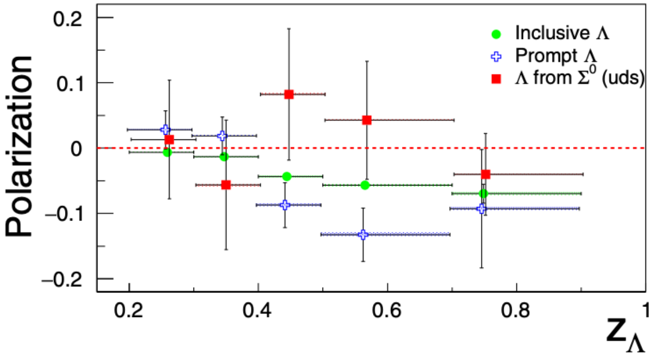
$\hat{n} = \hat{T}_{thrust} \times \hat{p}_\Lambda$

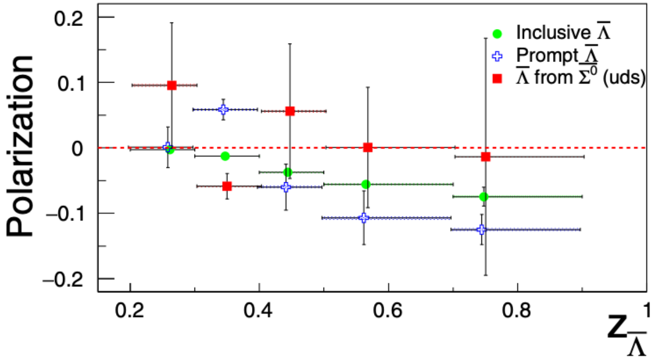


- Nonzero transverse polarization observed for Λ and $\overline{\Lambda}$ as function of z and p_T
- Investigate feed-down contributions from Σ^0 and charm decays

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







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

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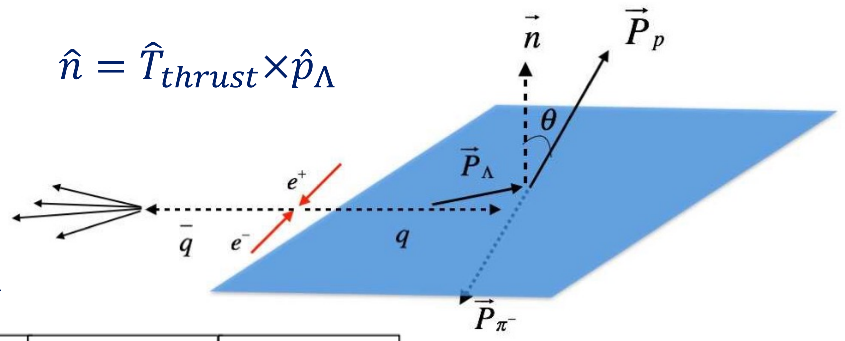
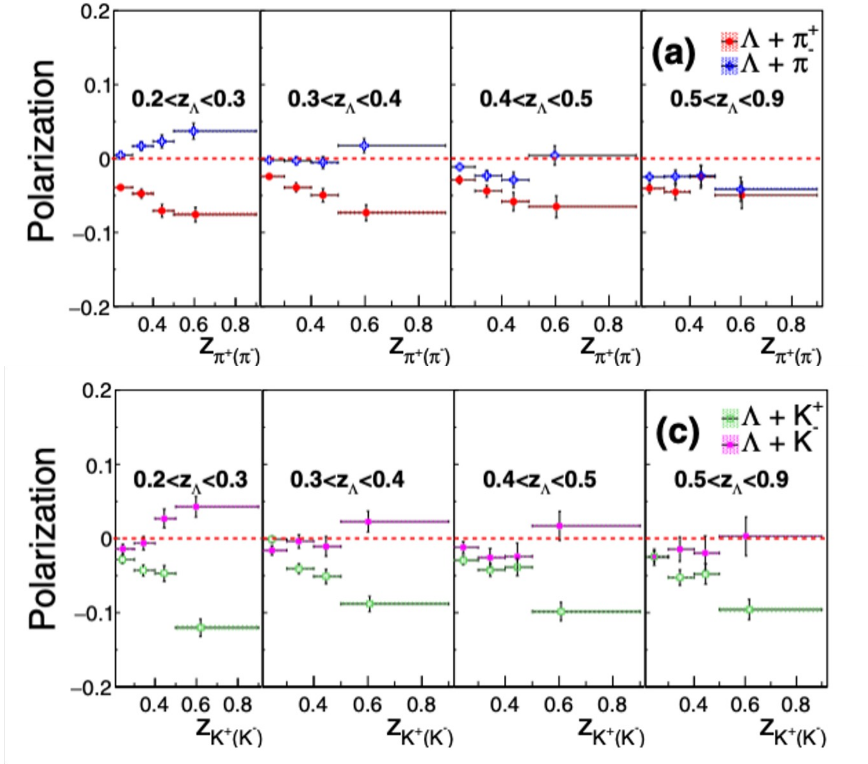


$e^+e^- \to \Lambda h^\pm X$

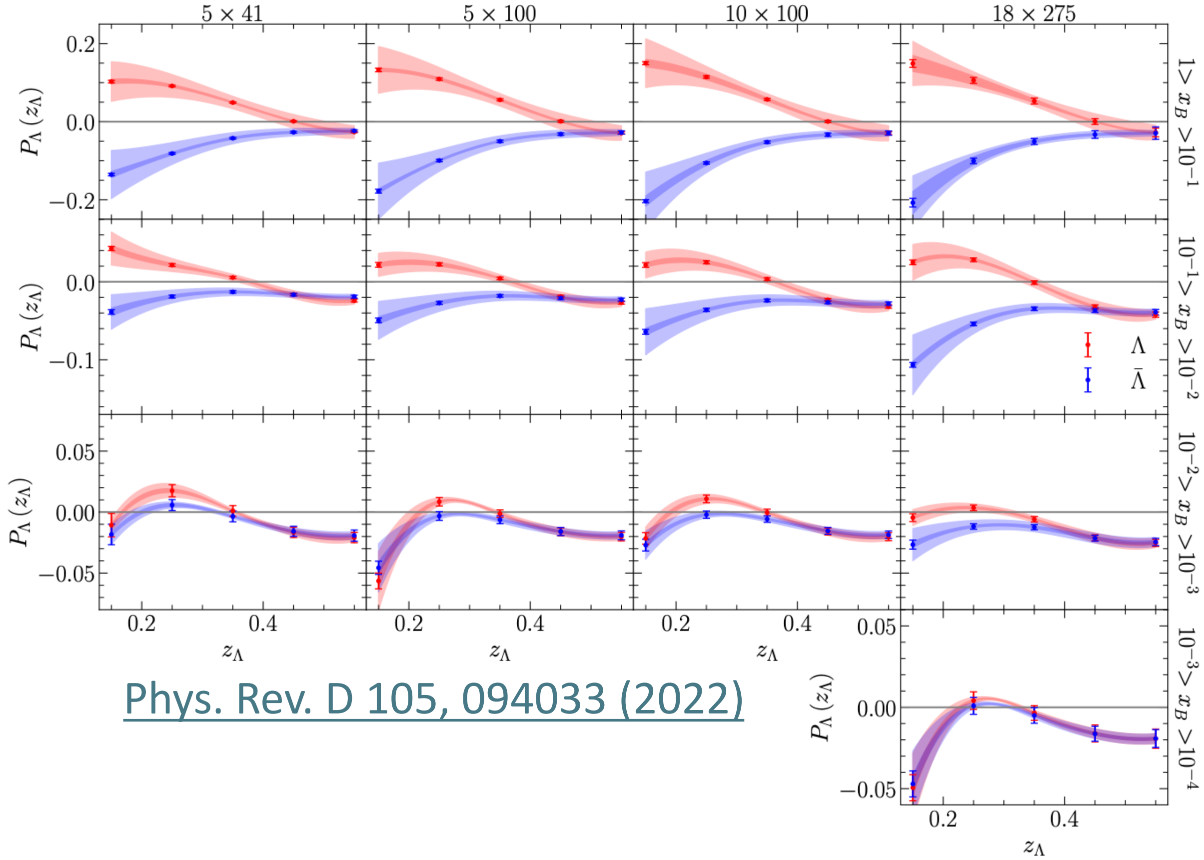


- Nonzero transverse polarization observed for Λ and $\overline{\Lambda}$ as function of z and p_T
- Investigate feed-down contributions from Σ^0 and charm decays
- Polarization measurement also with respect to hadron in opposite hemisphere

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)

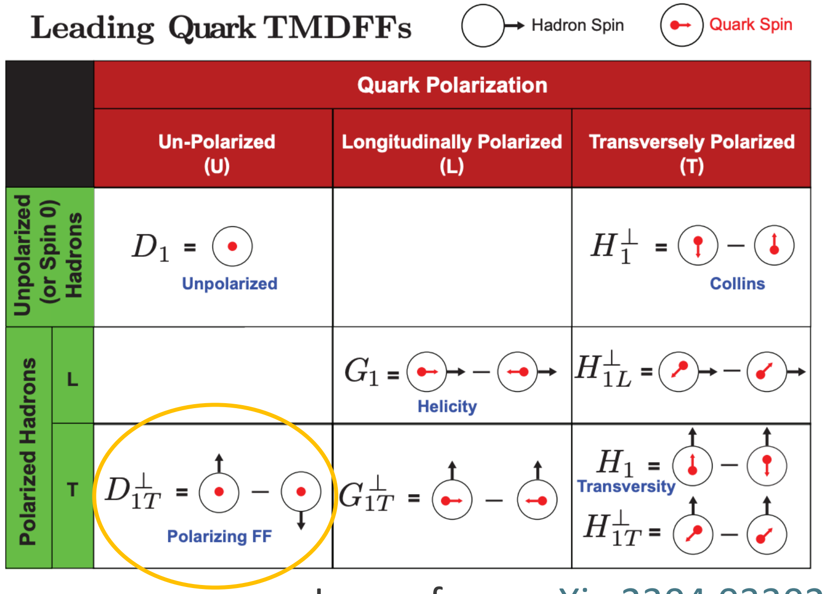


Image from arXiv:2304.03302v1

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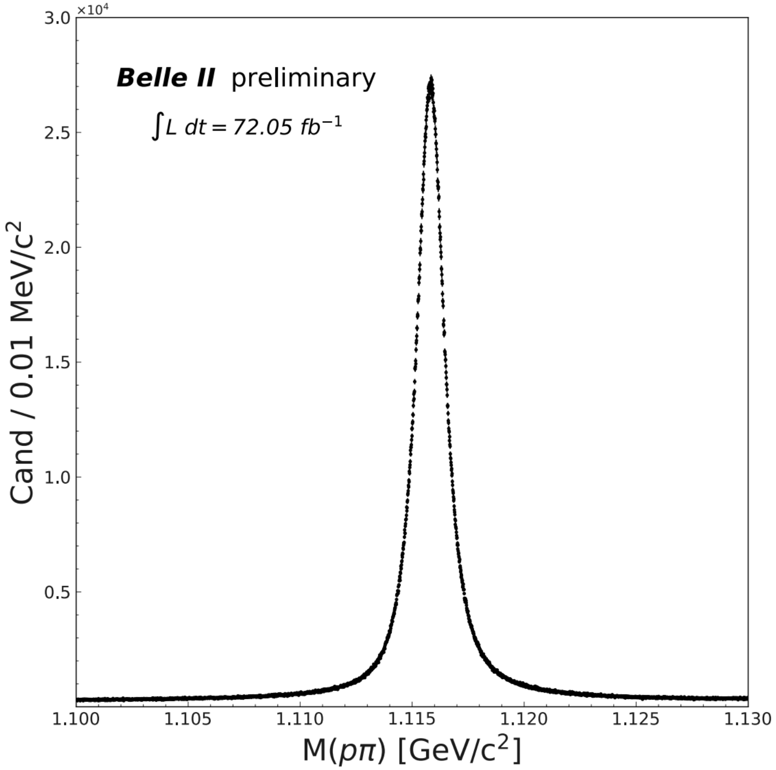


BELLE2-NOTE-PL-2020-031

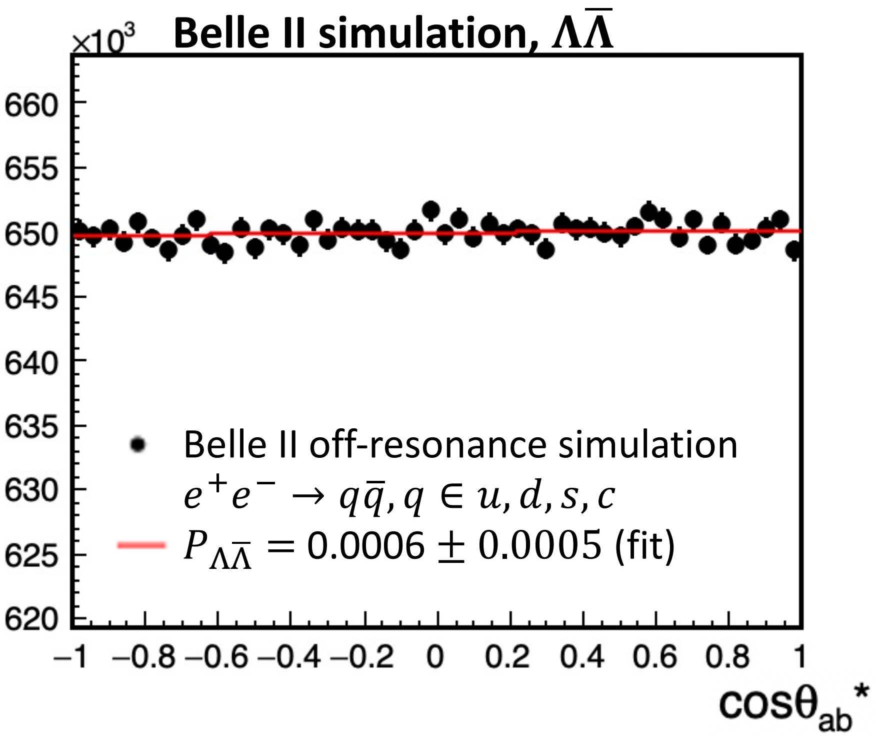
Measurements at Belle II:

- 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



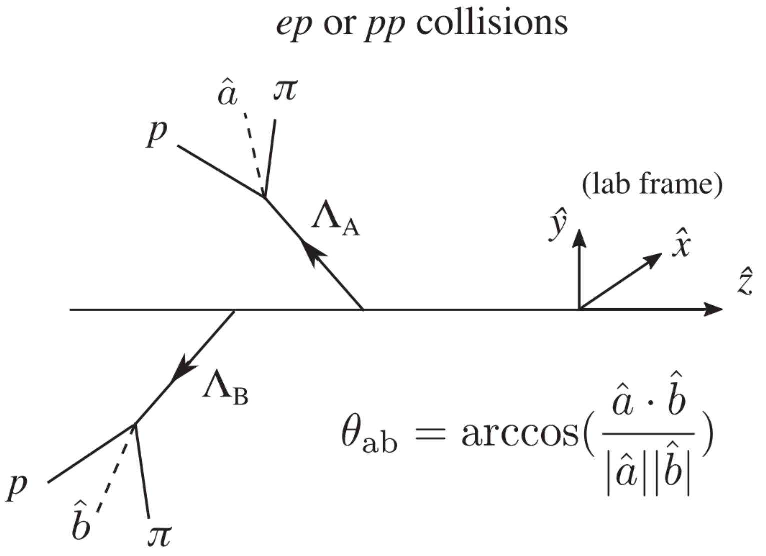


FIG. 3. Illustration of double Λ polarization; here $\hat{a}$ ($\hat{b}$) denotes the momentum direction of Λ_A (Λ_B) daughter particle in the Λ_A (Λ_B) rest frame.

Longitudinal spin transfer via dihadron polarization

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

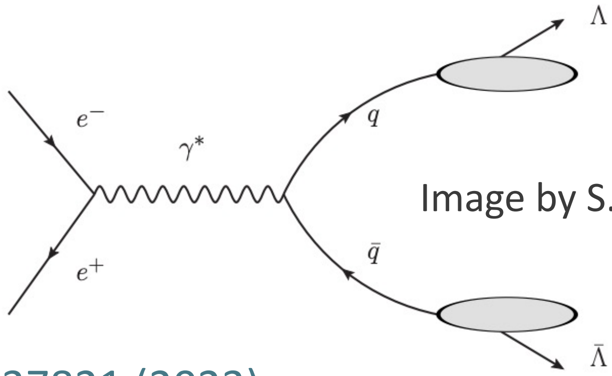


Image by S.Y. Wei, DIS24

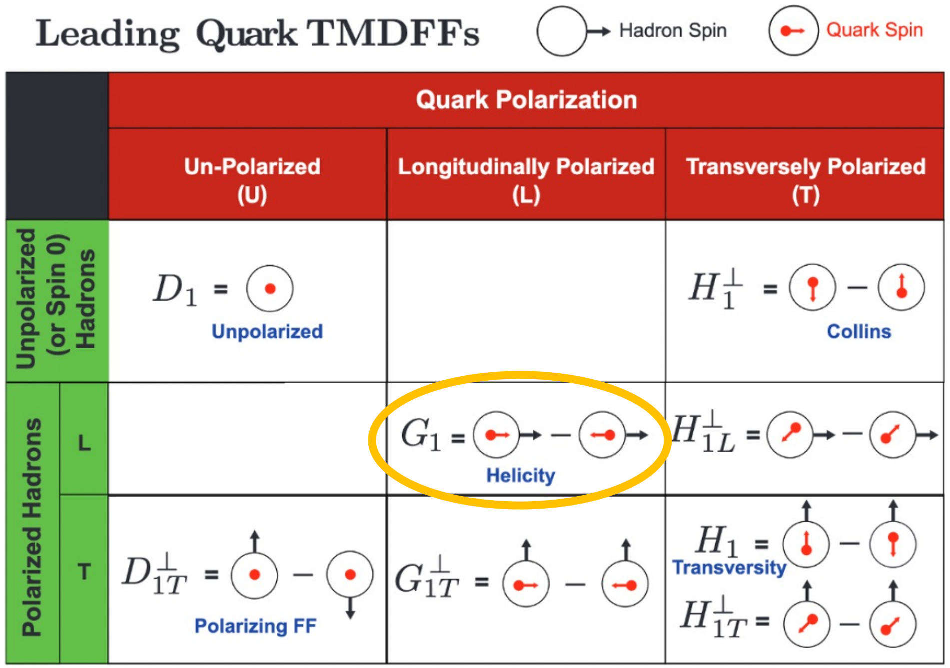
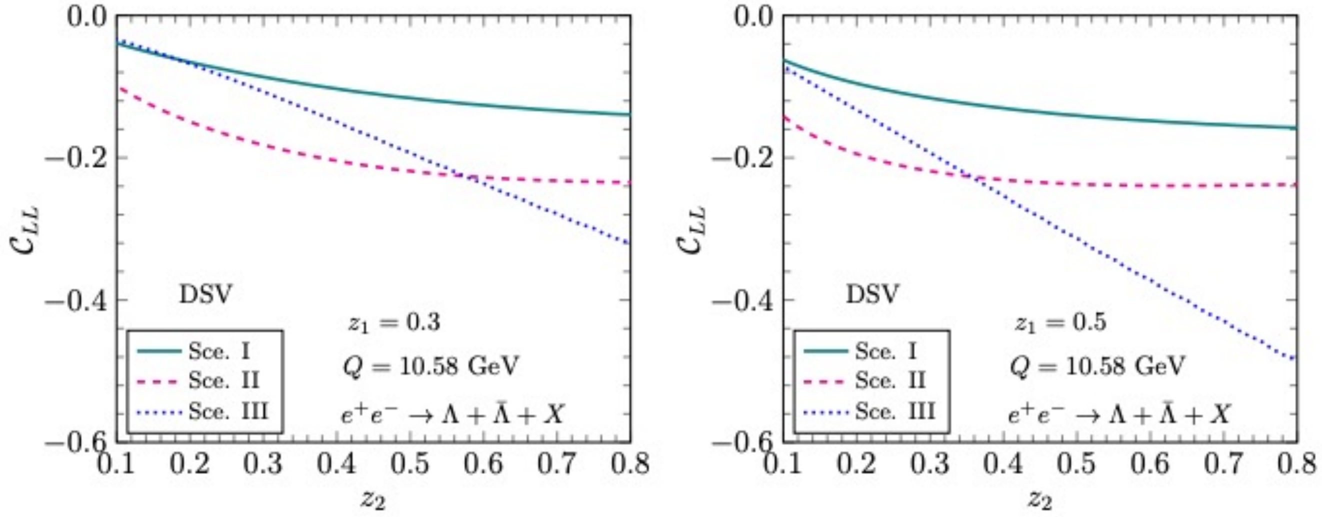


Image from arXiv:2304.03302v1

Phys.Lett.B 839, 137821 (2023)



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

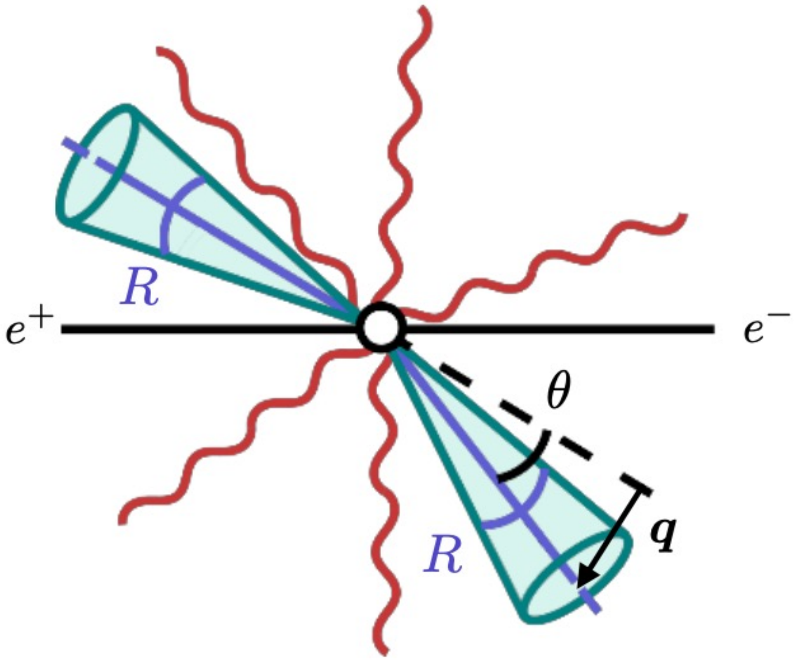
TMD Jet Functions

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

- **TMD FF $\rightarrow$ 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:

$$\boldsymbol{q} = \frac{\boldsymbol{p}_1}{z_1} + \frac{\boldsymbol{p}_2}{z_2}$$

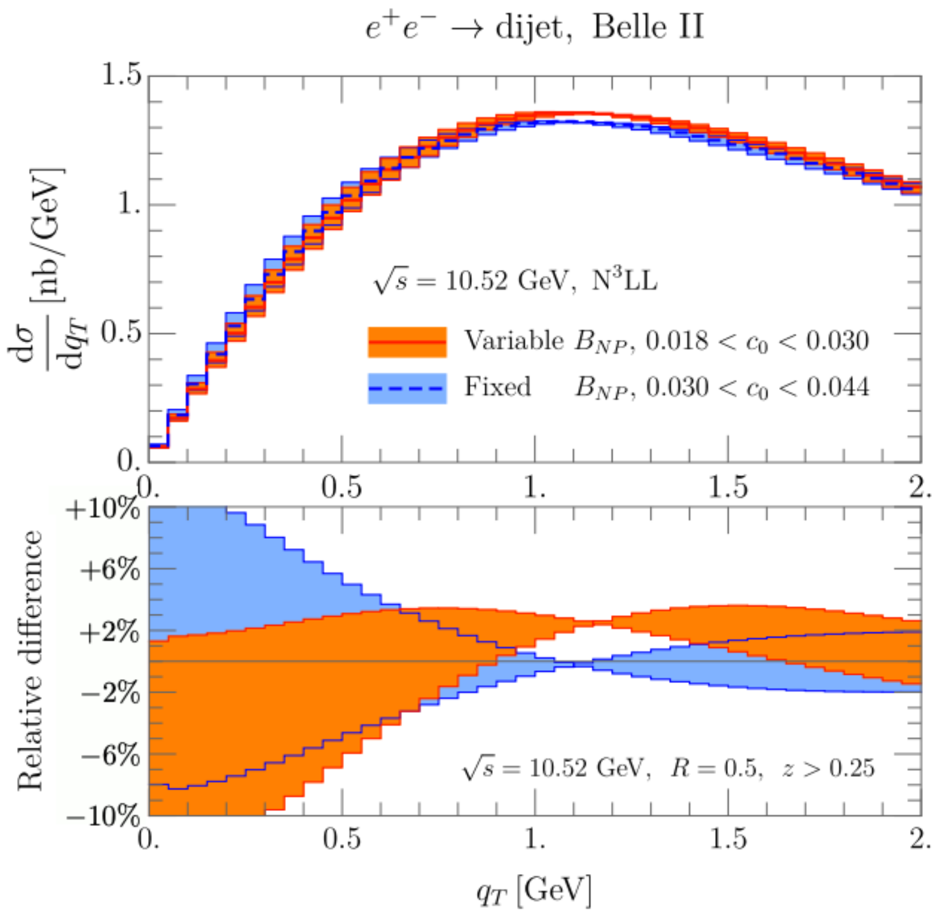
Require decorrelation to be small: $q_T \equiv |\boldsymbol{q}| \ll \frac{\sqrt{s}}{2}$

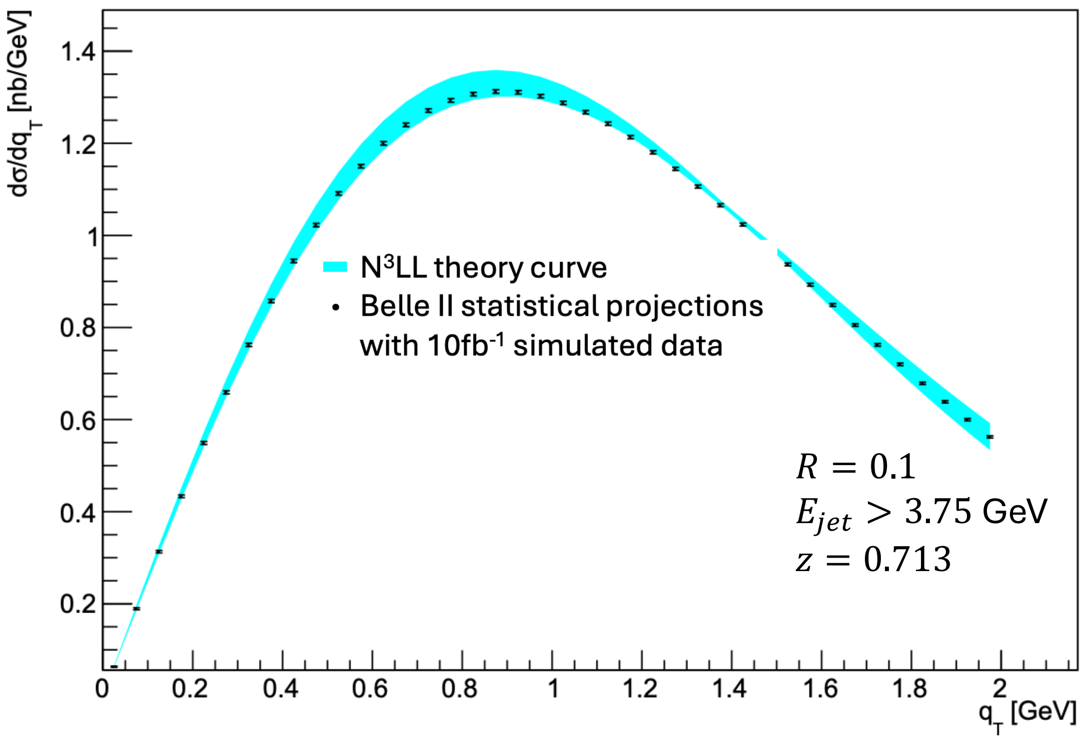


TMD Jet Functions – q_T Spectrum

Theoretical predictions for q_T predictions

JHEP10(2019)031
arXiv:2204.02280v2





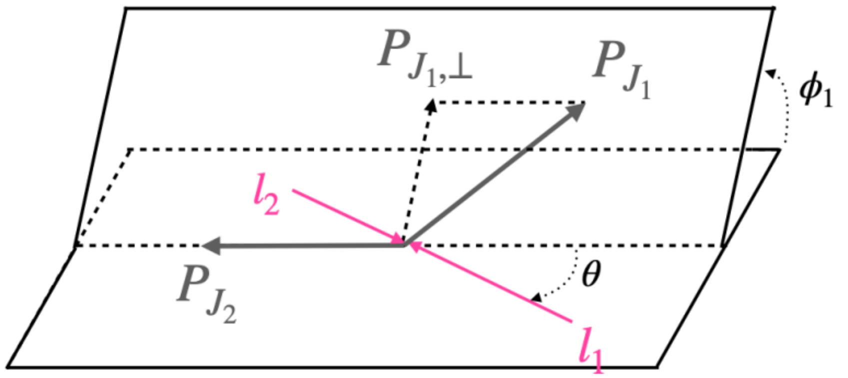
- Sensitivity of the TMD to nonperturbative effects
- Statistical projections with Belle II simulation

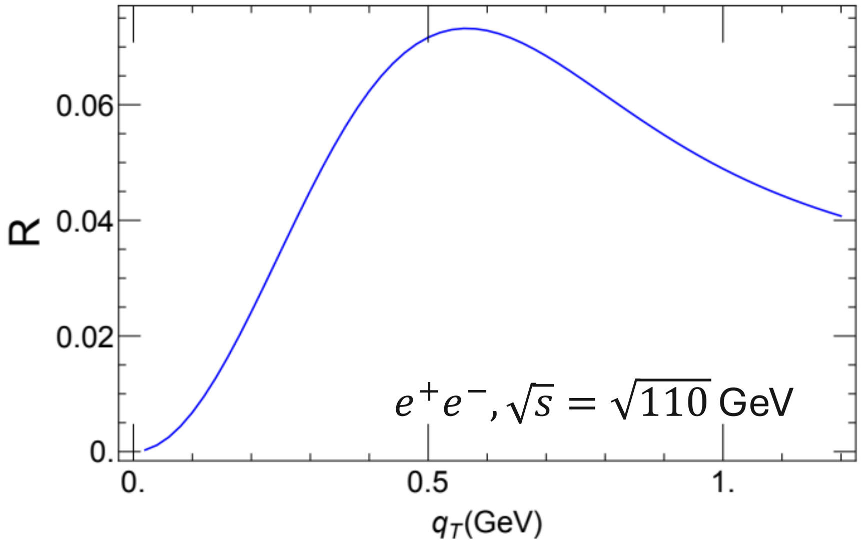
Ongoing analysis: Simon Schneider, Duke University

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]





Azimuthal asymmetry

$$R^{J_1 J_2} = 1 + \cos(2\phi_1) \frac{\sin^2\theta}{1+\cos^2\theta} \frac{F_T(q_T)}{F_U(q_T)}$$

$$R = 2\int d\cos\theta \frac{d\phi_1}{\pi} \cos(2\phi_1) R^{J_1 J_2}$$

Ongoing analysis: Simon Schneider, Duke University

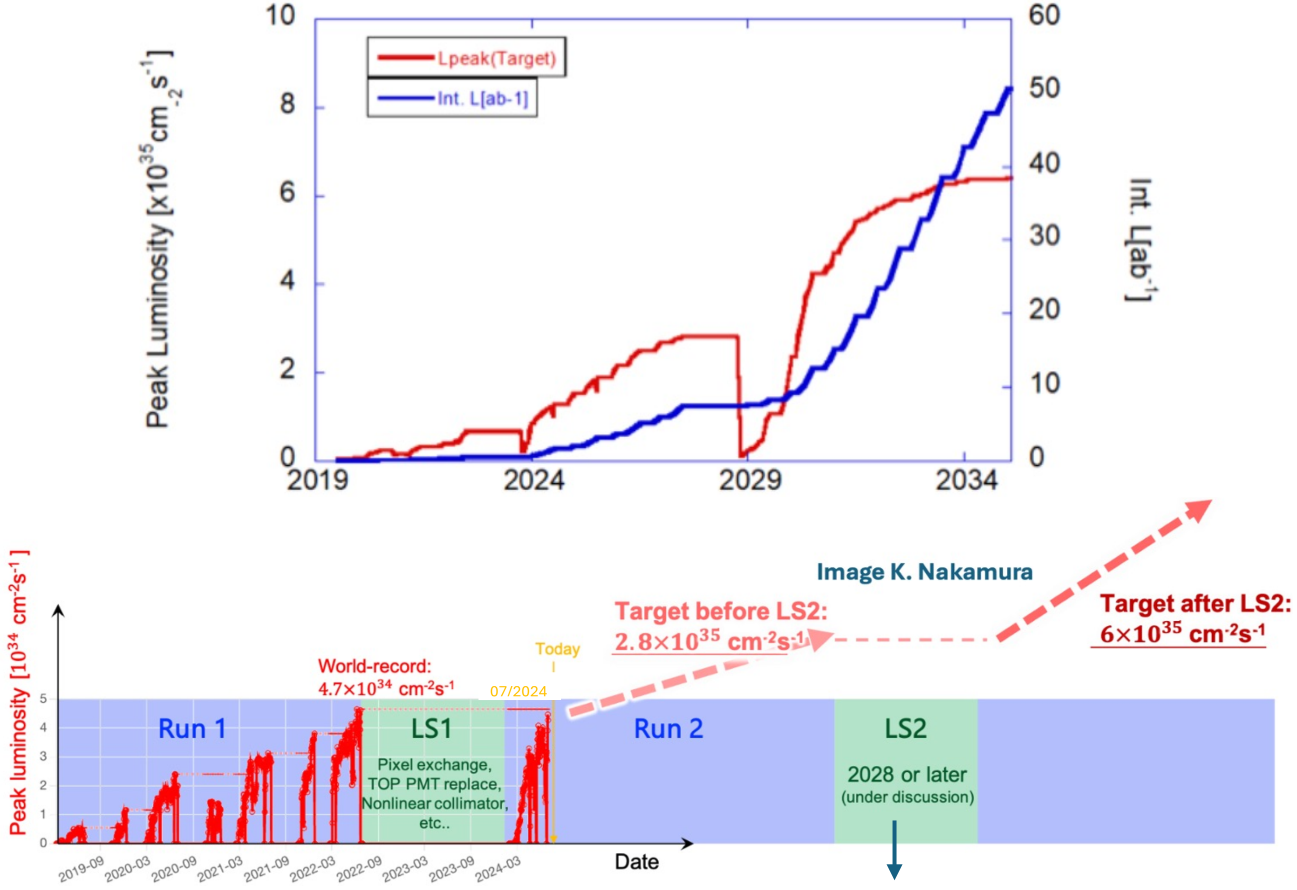
Summary

- Belle II is currently collecting data during Run 2
- Belle and Belle II play an important role in understanding hadronization dynamics

  arXiv:2204.02280

- Provide key information on hadronization for future EIC measurements
- Lots of measurement opportunities at Belle II, with several current ongoing analyses underway
- Future QCD studies with polarized electron beams at SuperKEKB

  Chiral Belle Project: arXiv:2205.12847v3



Chiral Belle (polarized e^- beams)

Thank You!

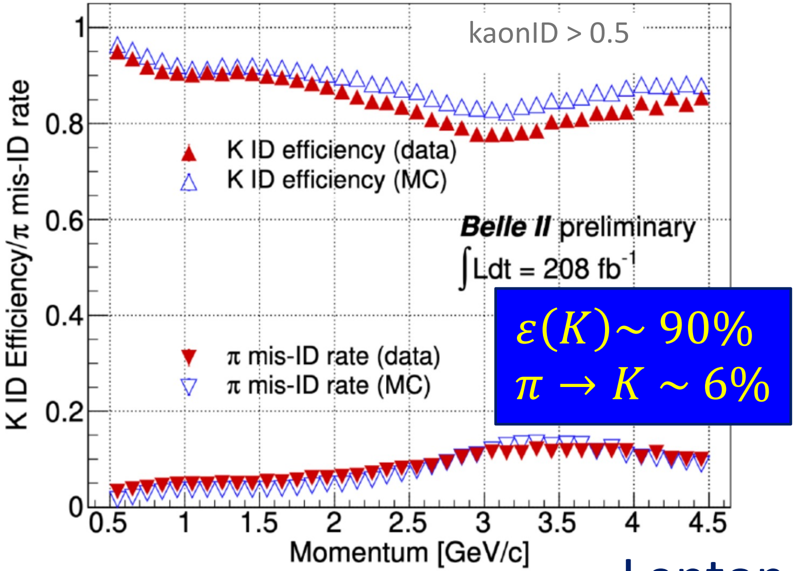
Thank you for the help in preparing this presentation to S. Schneider, K. Parham, A. Vossen, and the Belle II collaboration!

Back up

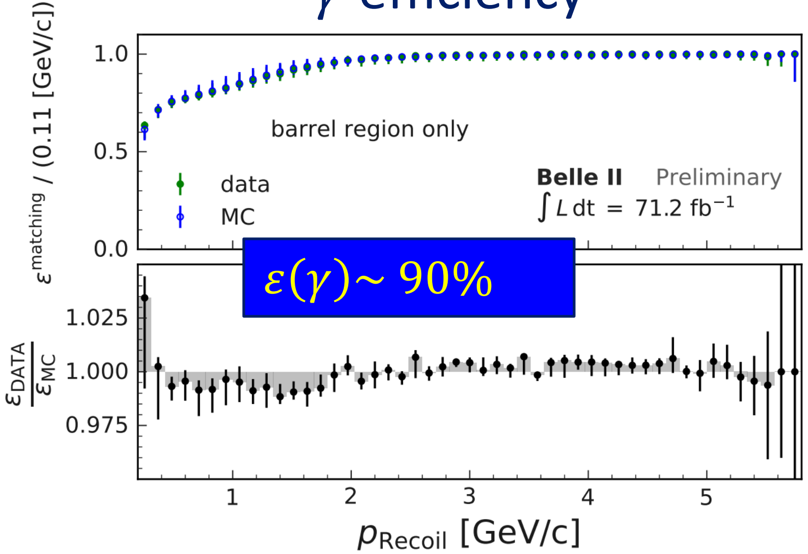
Belle II Detector @ SuperKEKB

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

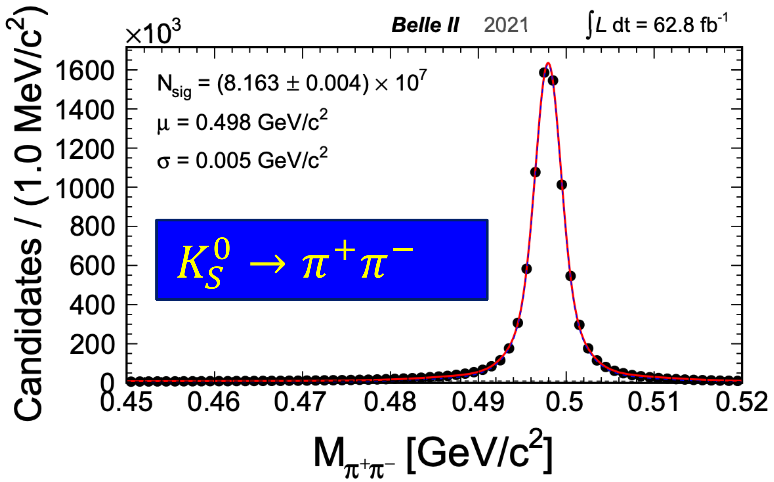
Kaon identification

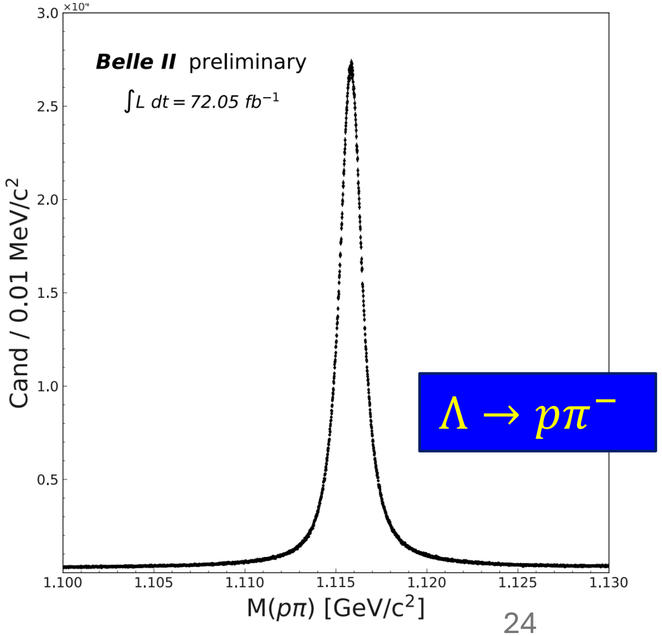


γ efficiency

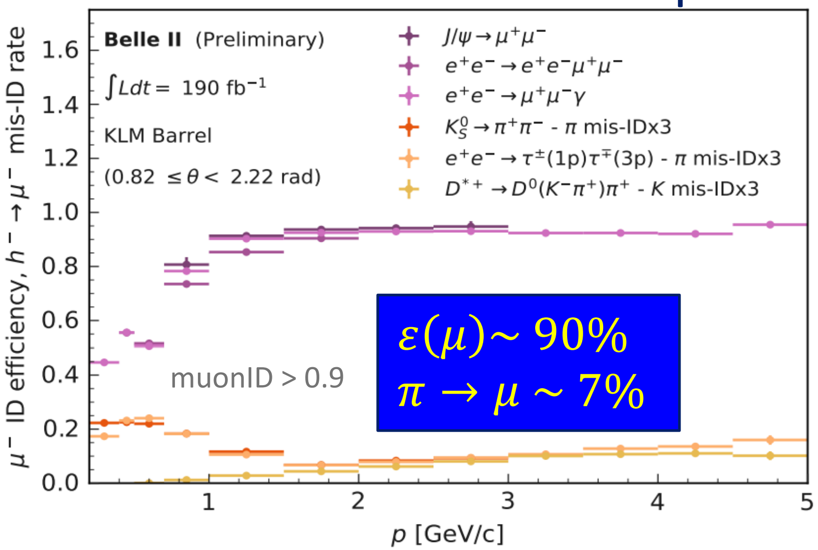


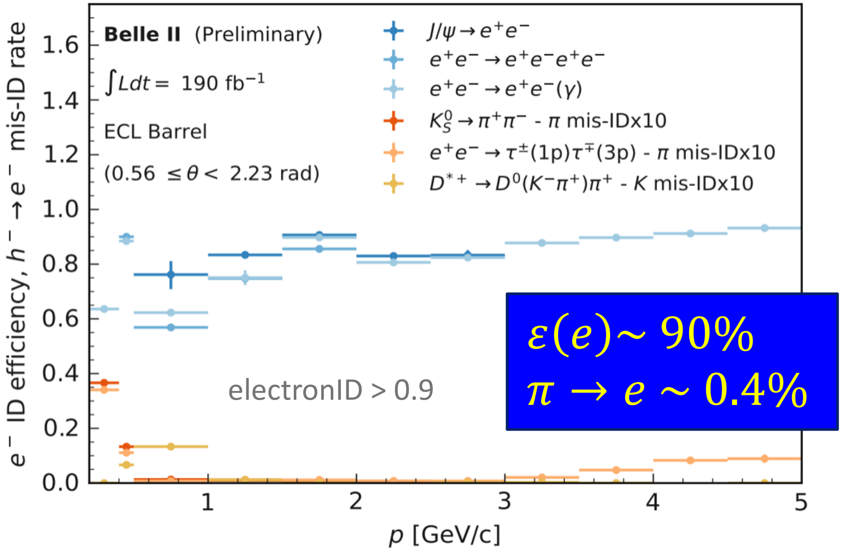
V^0 Reconstruction





Lepton identification

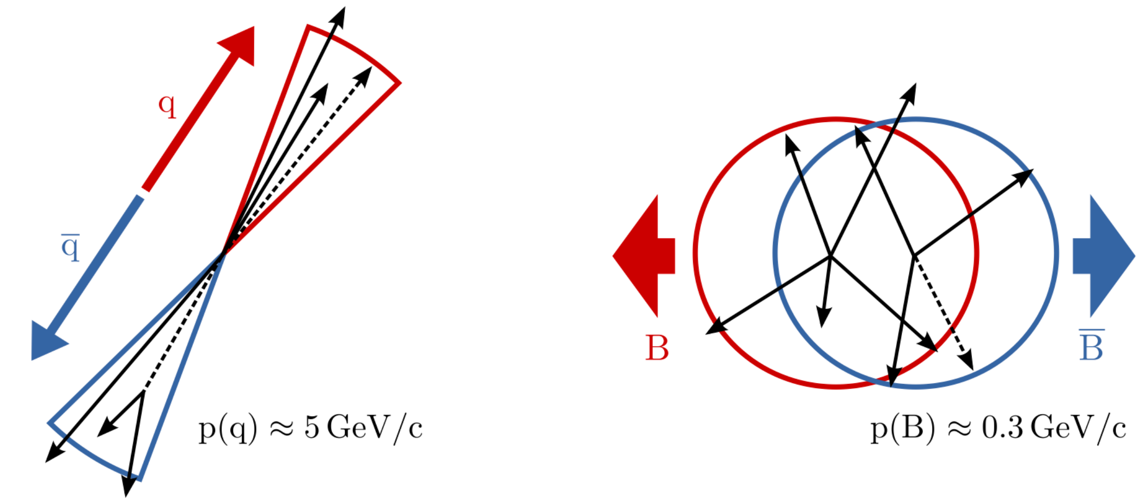




Belle II event shape: thrust axis

- 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

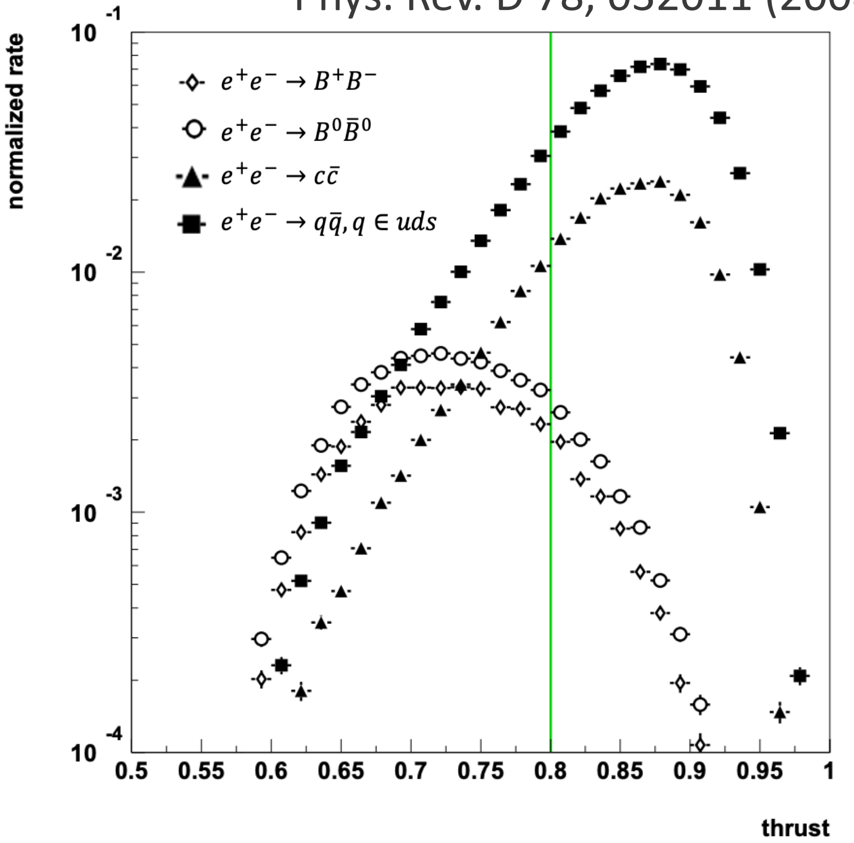
$$T = \max \frac{\Sigma_h \left| P_h^{CMS} \cdot \hat{T} \right|}{\Sigma_h \left| P_h^{CMS} \right|}$$



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

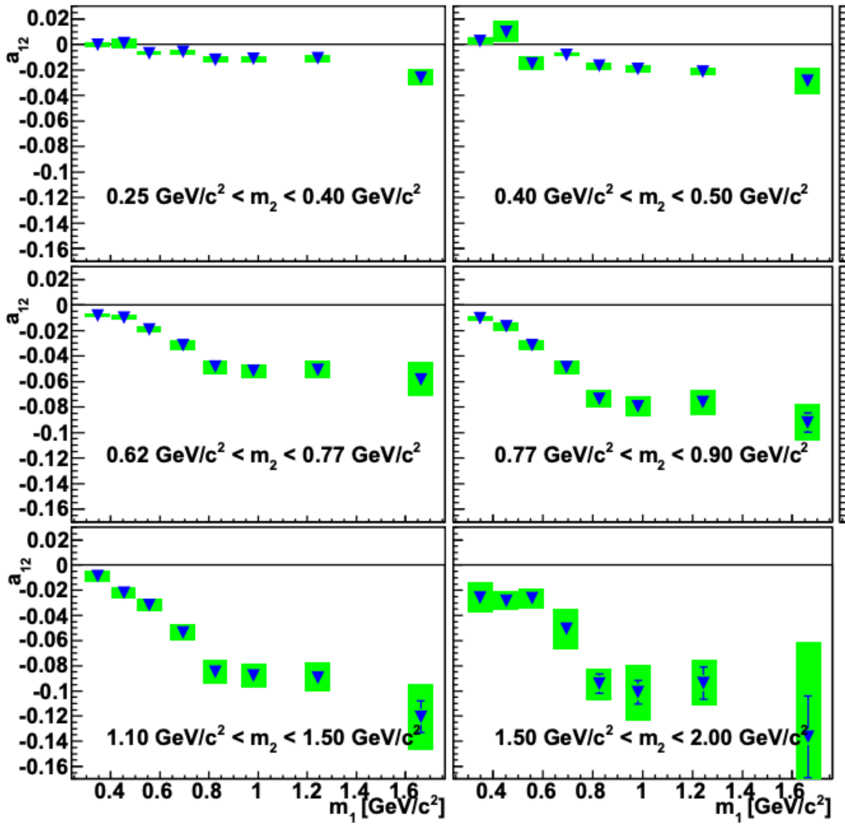
$e^+e^- \to \Upsilon(4S) \to B\overline{B}$

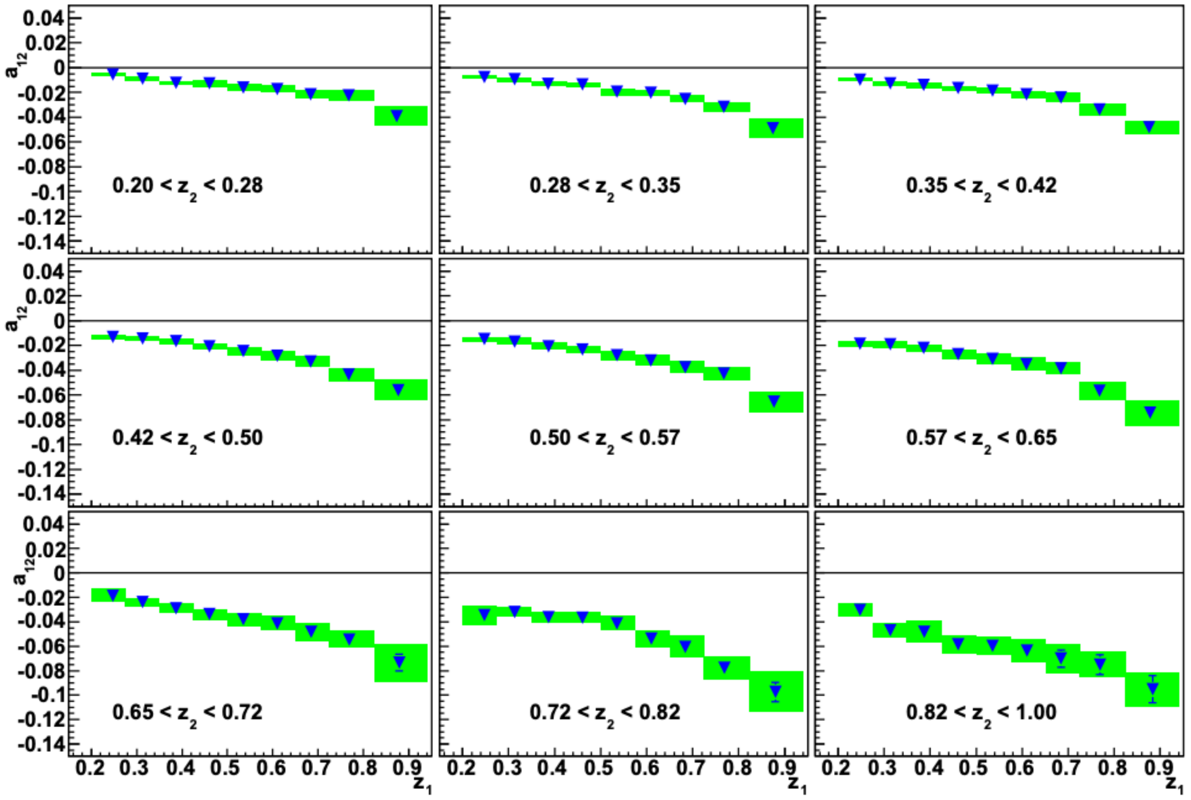
Phys. Rev. D 78, 032011 (2008)



Di-hadron Fragmentation Functions (DiFF)

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





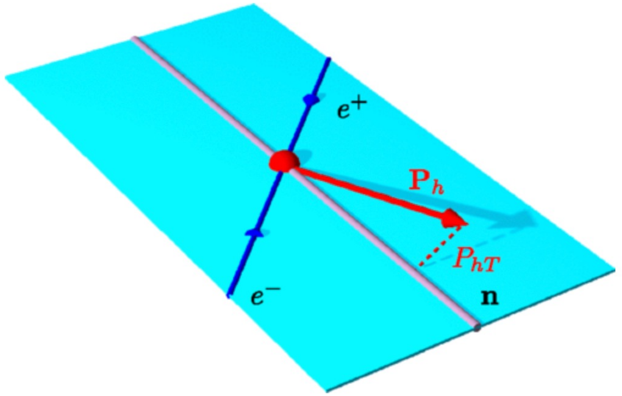
Phys. Rev. Lett. 107, 072004 (2011)

Belle results – a recent review

Belle data provided essential measurements, including recent results:

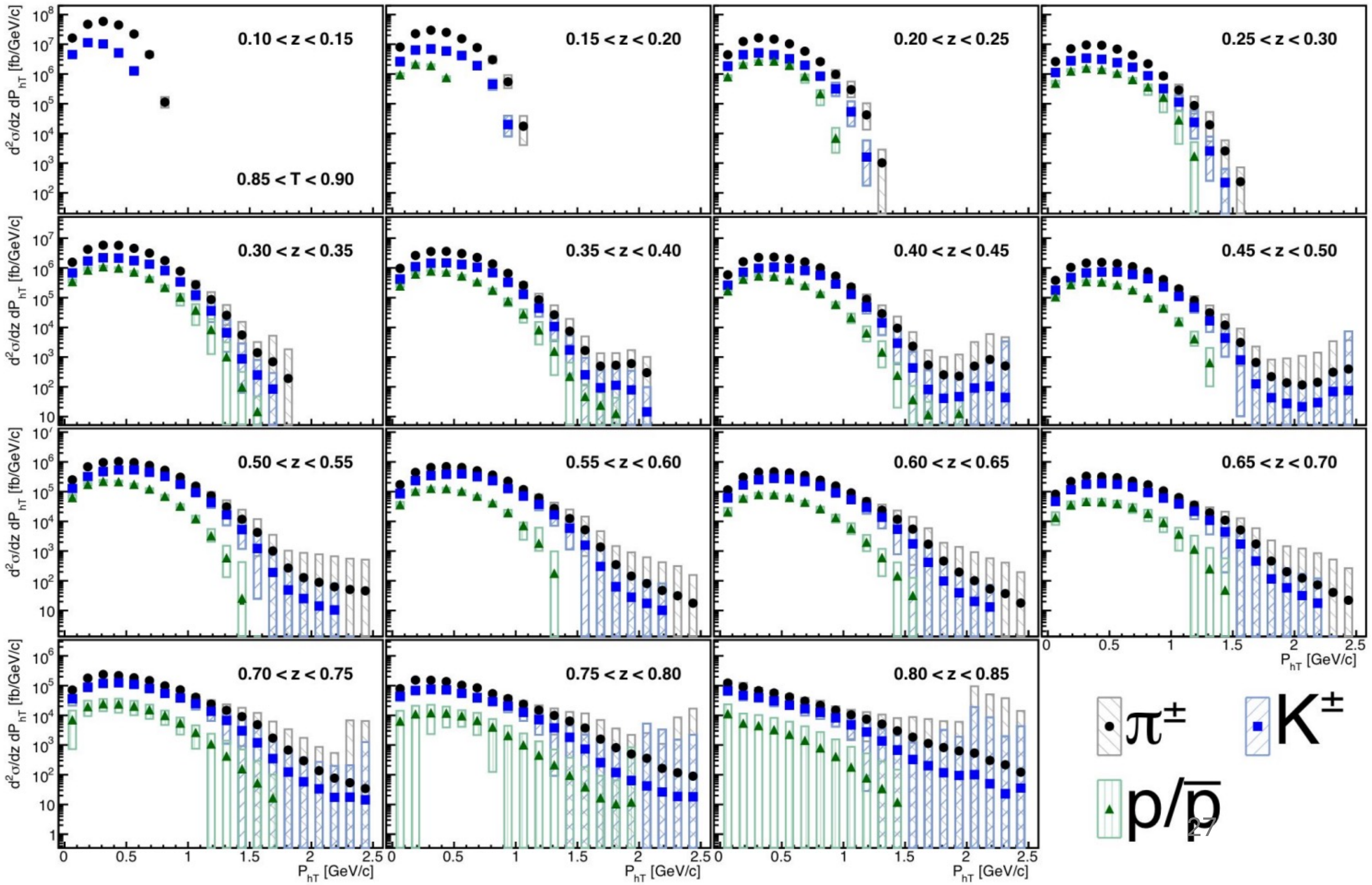
R. Seidl et al., “Transverse momentum dependent production cross sections of charged pions, kaons and protons produced in inclusive e^+e^- annihilation” at $\sqrt{s}$=10.58 GeV

Phys. Rev. D 99, 112006 (2019)



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

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

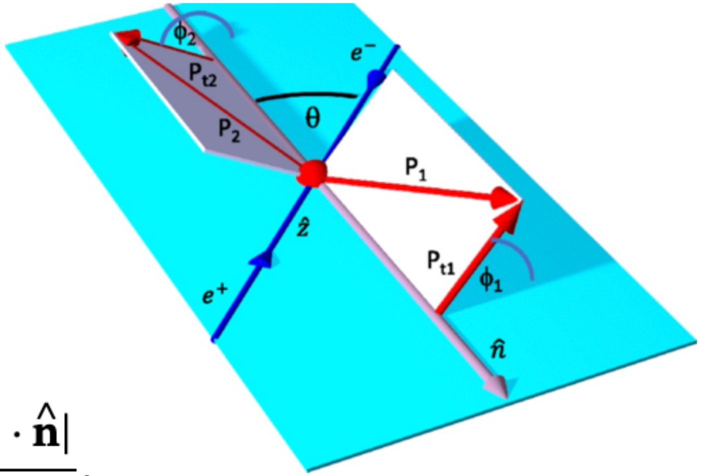


Belle results – a recent review

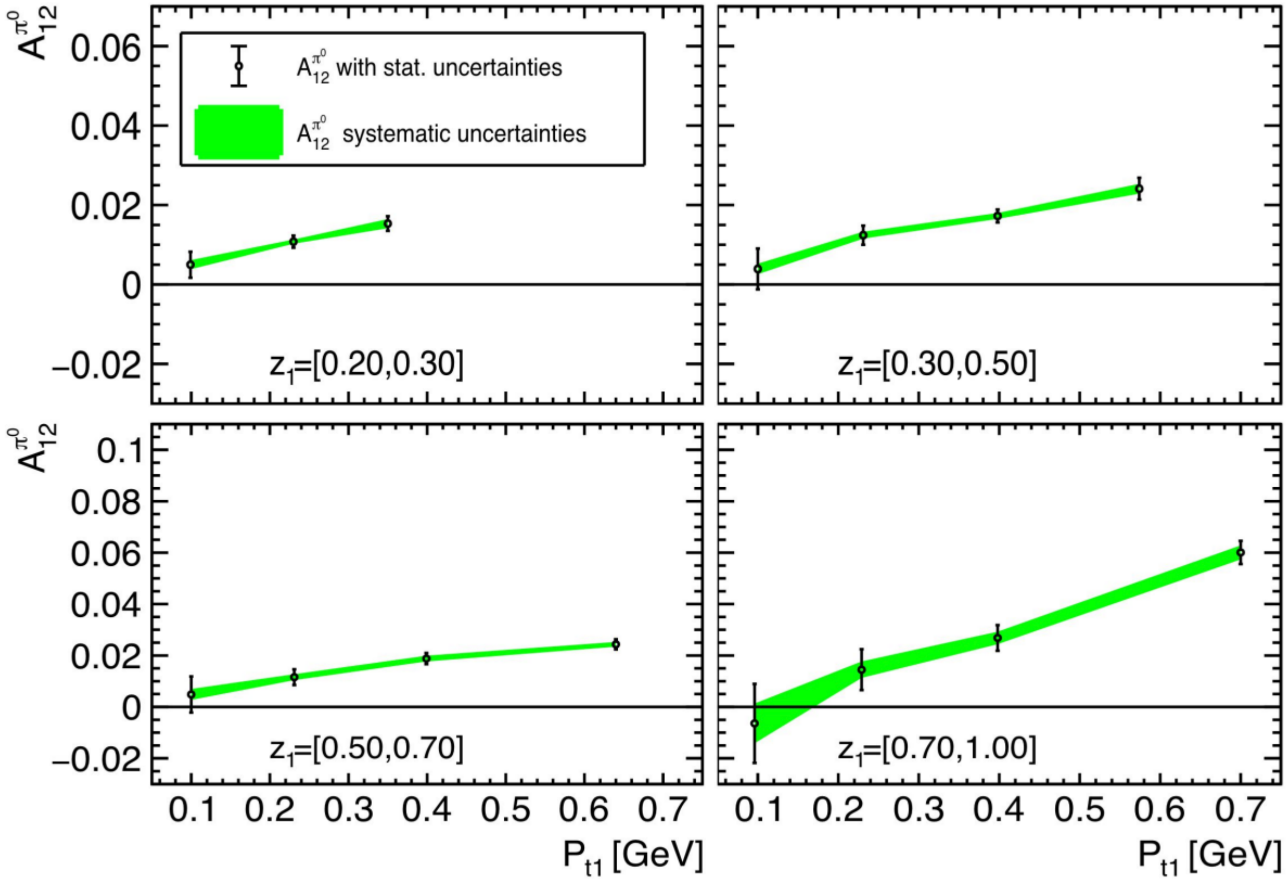
Belle data provided essential measurements, including recent results:

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)

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



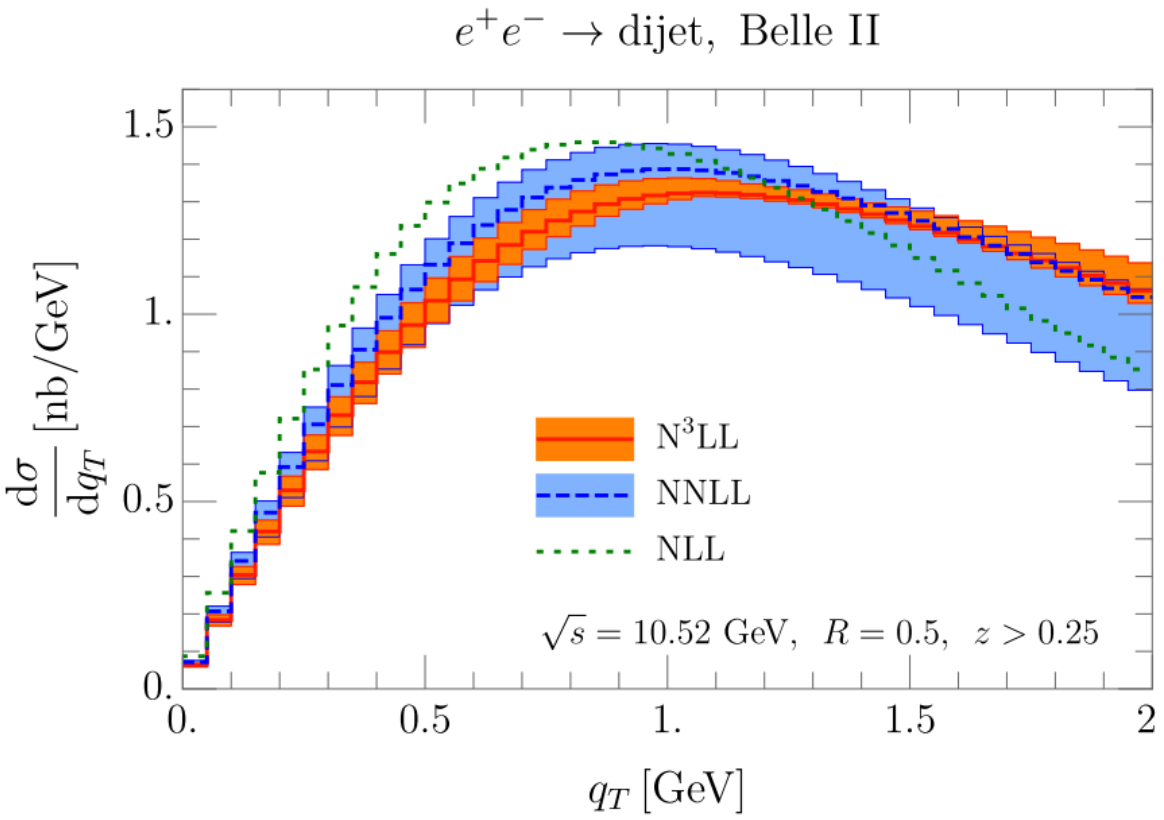
$$T \underset{=}{\max} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}.$$

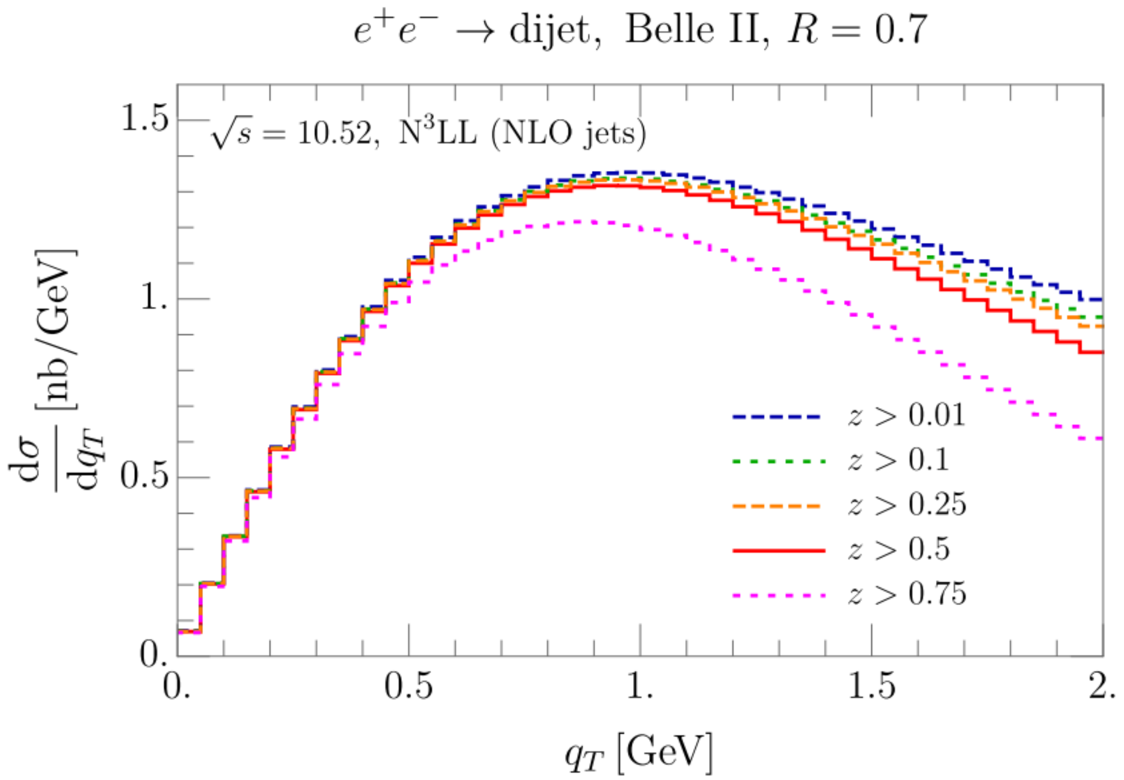


TMD Jet Functions – q_T Spectrum

Theoretical predictions for q_T predictions

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

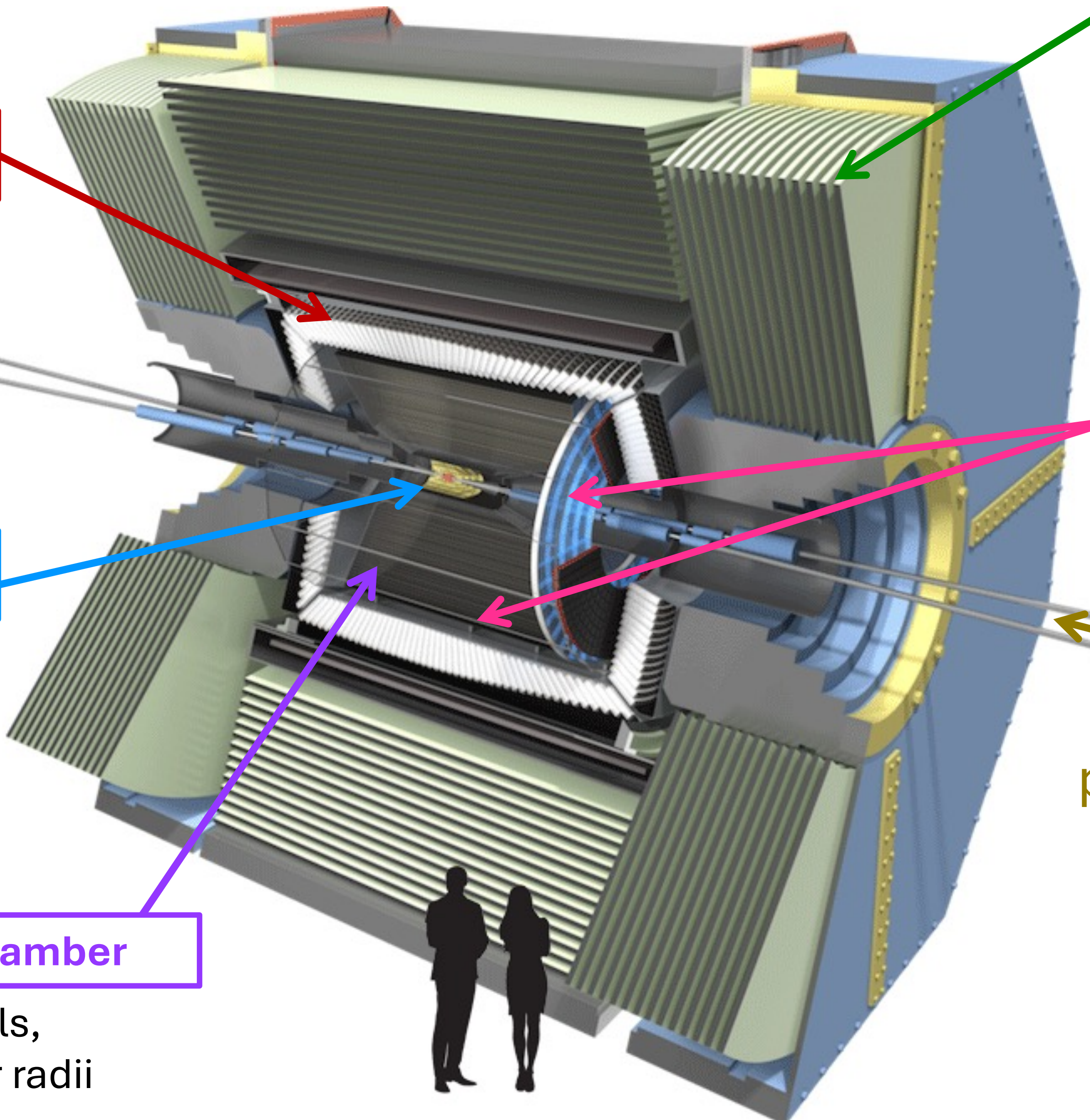




- Perturbative convergence of cross-section
- Dependence on z

Ongoing analysis: Simon Schneider, Duke University

Belle II upgrades



EM calorimeter

upgrade electronics

electrons (7 GeV)

Vertex detector

2 innermost silicon strips (SVD) replaced with pixel detectors (PXD)

Central drift chamber

Smaller drift cells, reaches smaller radii

KL and muon detector

2 innermost barrel RPCs and endcaps replaced with scintillators

Particle identification

- TOP (barrel)

- ARICH (forward)

TOP replaced TOF

ARICH replaced endcap ACC

positrons (4 GeV)