QCD Program at Belle II

Anselm Vossen
representing the Belle II collaboration

Based on
"Opportunities for precision QCD physics in hadronization at Belle II -- a snowmass whitepaper"
e-Print: 2204.02280 [hep-ex]

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U.S. DEPARTMENT OF ENERGY Office of Science

Duke UNIVERSITY Jefferson Lab

Overview

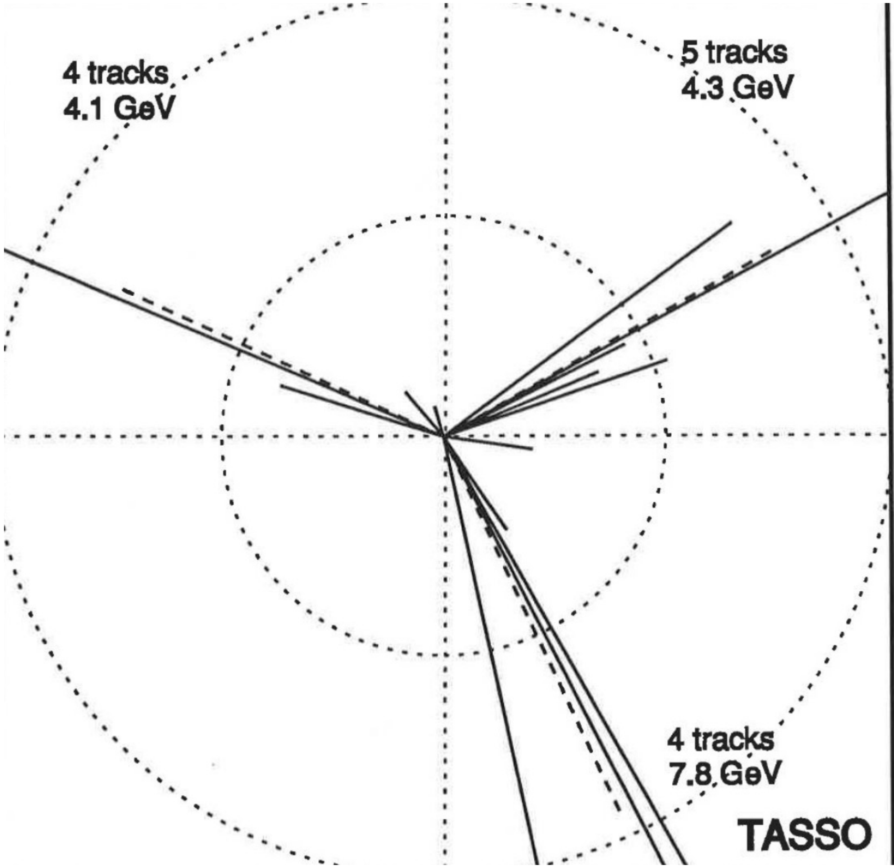
- Belle and Belle II experiments at KEK
- Highlights of Fragmentation studies at Belle
- Opportunities for Fragmentation studies with the Belle II dataset

- Hadronization Studies ←→MC Model Tuning
- Jet studies

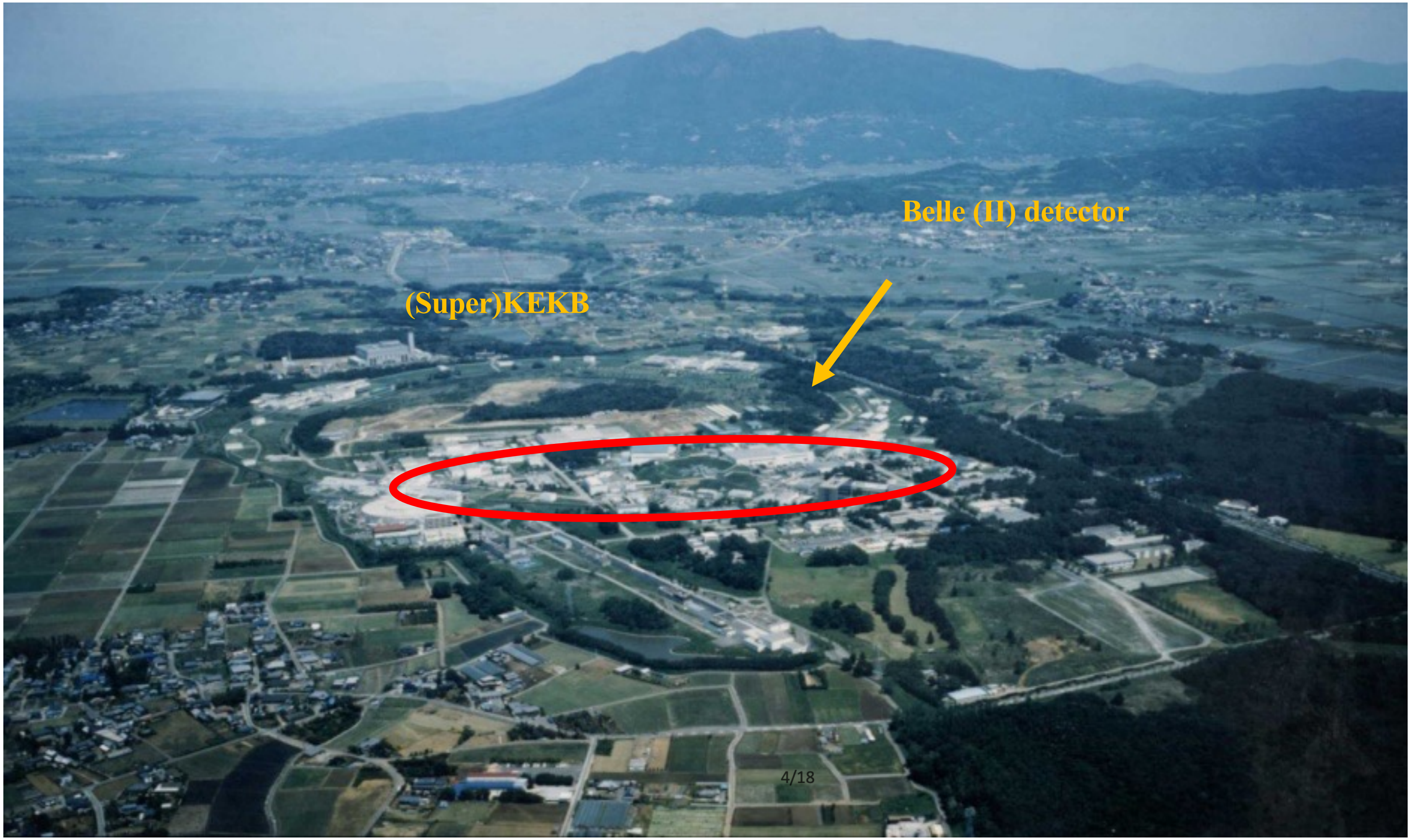
- More QCD topics
  - Input to $g-2$
  - α_S
  - Jet mass
  - …

e^+e^- has a long history in studying QCD

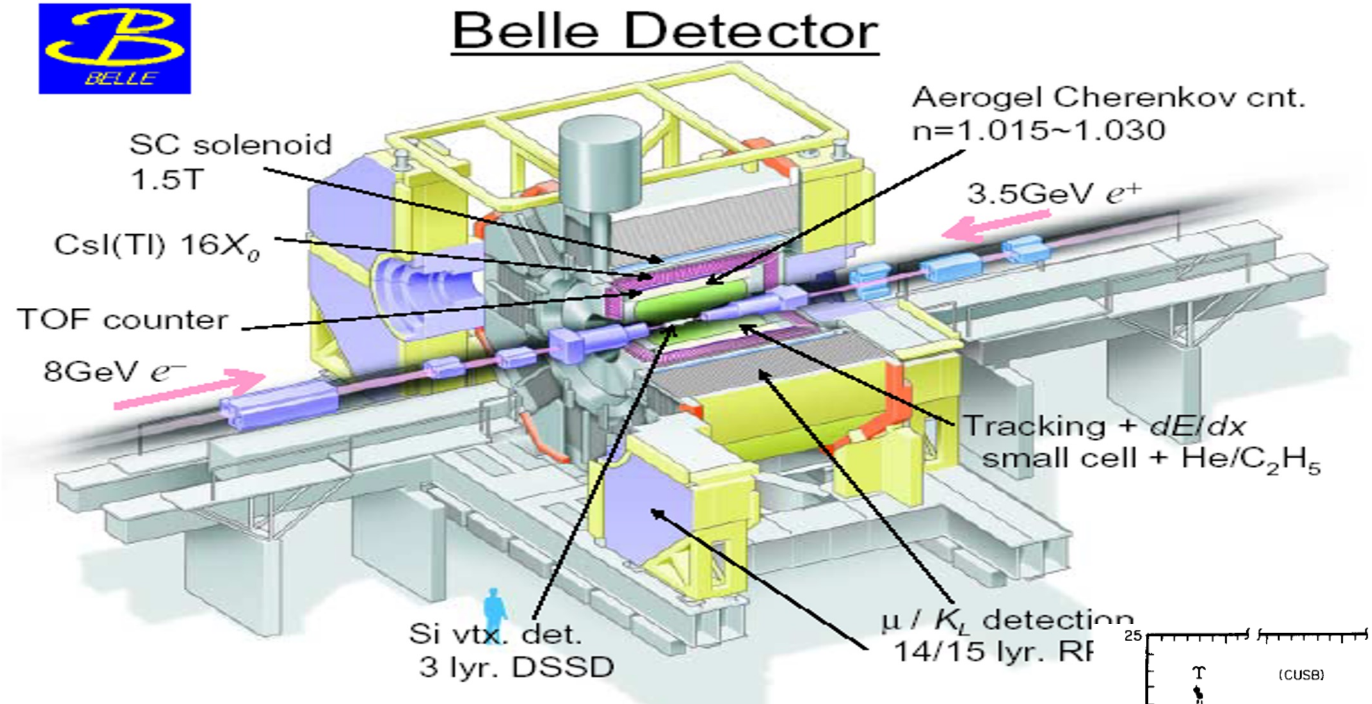
- PETRA at DESY →Discovery of the gluon (shown 1979)



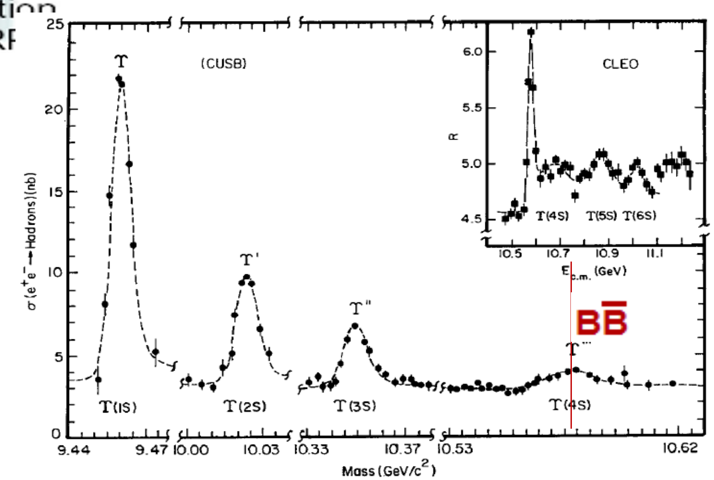
KEK facility



Belle Experiment (1999 - 2010)



Exp.	Scans / Off-res. fb^{-1}	$\Upsilon(5S)$ 10876 MeV fb^{-1}	10^6	$\Upsilon(4S)$ 10580 MeV fb^{-1}	10^6	$\Upsilon(3S)$ 10355 MeV fb^{-1}	10^6	$\Upsilon(2S)$ 10023 MeV fb^{-1}	10^6	$\Upsilon(1S)$ 9460 MeV fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	—	
Belle	100	121	36	711	772	3	12	25	158	6	102



+About $4\text{x}10^6$ events per fb^{-1} off-resonance

From: *PTEP* 2019 (2019) 12, 123C01, *PTEP* 2020 (2020) 2, 029201

The future is now: Next Generation B factory SuperKEKB

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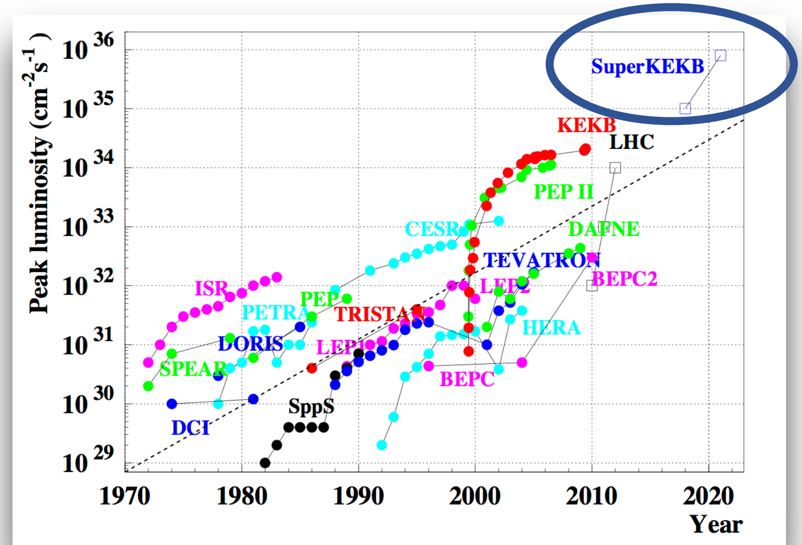
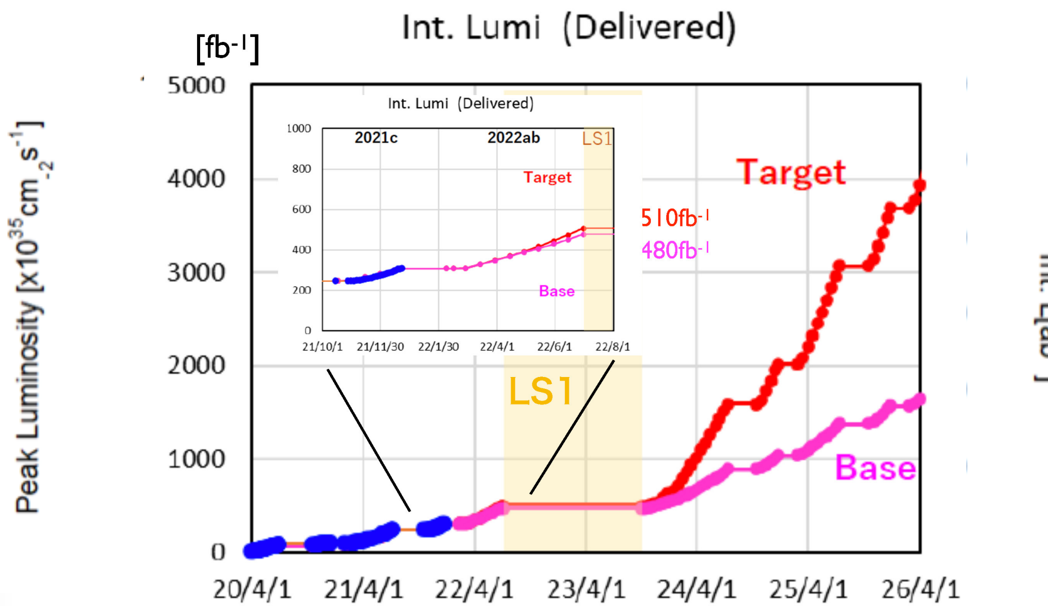




Beam currents *only* a factor of two higher than KEKB (~PEPII)

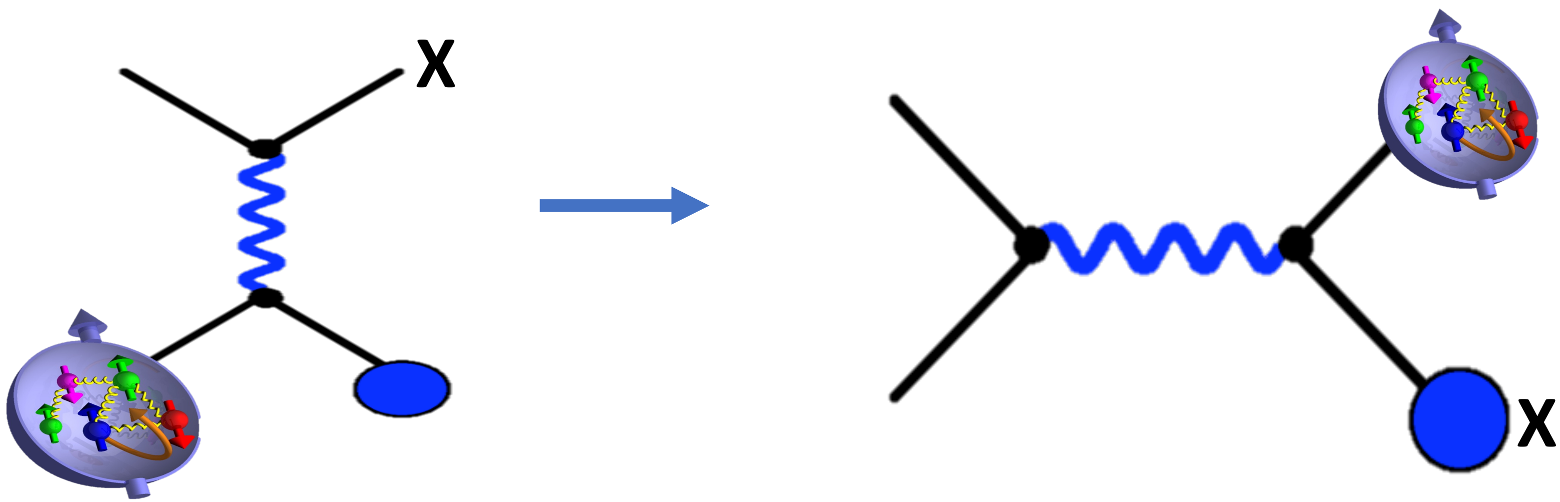
"nano-beams" are the key; vertical beam size is 50nm at the IP

- Belle II already delivered world record luminosity
- Belle II will have 50× Belle luminosity (100 × BaBar)

Study of Fragmentation Functions

PDF in SIDIS ⇔ FF in e^+e^-

- E.g. Sivers ⇔ $\Lambda^{\uparrow}$ production
-

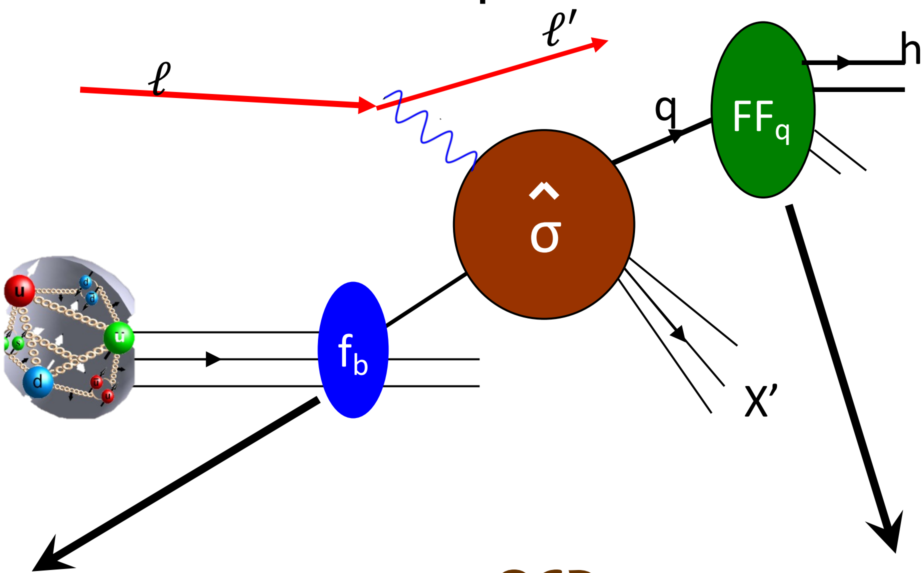


Spacelike SIDIS

Timelike SIA

Fragmentation Functions appear almost always when accessing partonic structure of the nucleon

- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes
- Particular important for transverse spin structure

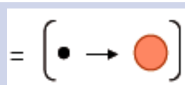
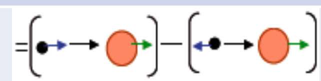
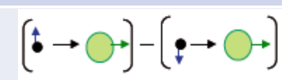
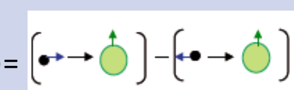
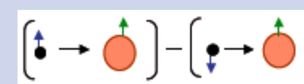


Proton Structure — pQCD — Fragmentation Function

$$\frac{d^2\sigma(ep \to \pi X)}{dx\, dz} \propto \underbrace{q(x, k_T)}_{\text{Proton Structure}} \times \underbrace{\frac{d\sigma^2(e\,q \to e'q')}{dx}}_{\text{pQCD}} \times \underbrace{FF(z, p_T)}_{\text{Fragmentation Function}}$$

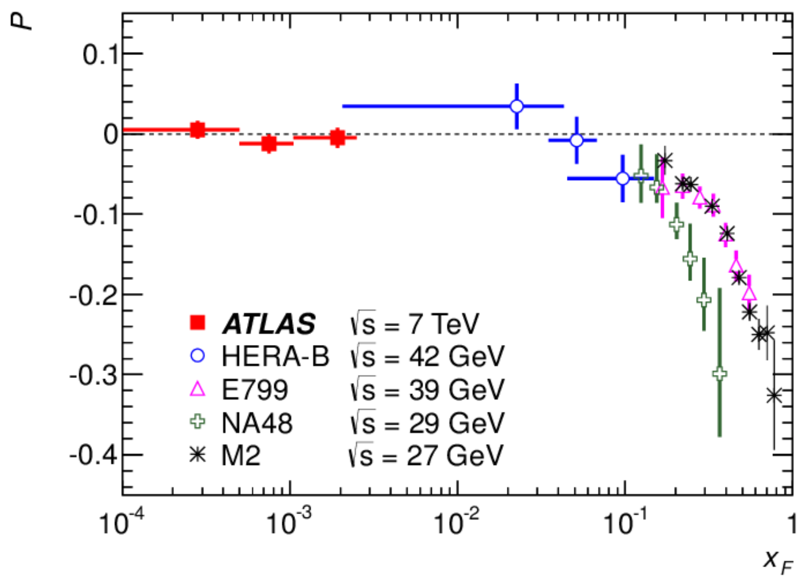
Belle II Strength: Complex Final states.
Example: Polarized Final States

- Similar to PDFs: Encode spin/orbit correlations
- Determining final state polarization needs self analyzing decay (Λ)

Parton polarization → Hadron Polarization ↓	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z, p_T)$ 		$H_1^{\perp h/q}(z, p_T)$ 
longitudinal		$G_1^{\Lambda/q}(z, p_T)$ 	$H_{1L}^{h/q}(z, p_T)$ 
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z, p_T)$ 	$G_{1T}^{h/q}(z, p_T)$= 	$H_1^{\Lambda/q}(z, p_T) =$  $H_{1T}^{\perp\Lambda/q}(z, p_T) =$ 

Polarized Hyperon Production

- Large Λ transverse polarization in unpolarized pp collision PRL36, 1113 (1976); PRL41, 607 (1978)
- Caused by polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^{2})$?
- Polarizing FF is chiral-even, has been proposed PRL105,202001 (2010) as a test of universality.
- FF counterpart of the Sivers function.
- OPAL experiment at LEP has studied transverse Λ polarization, no significant signal was observed. Eur. Phys. J. C2, 49 (1998)

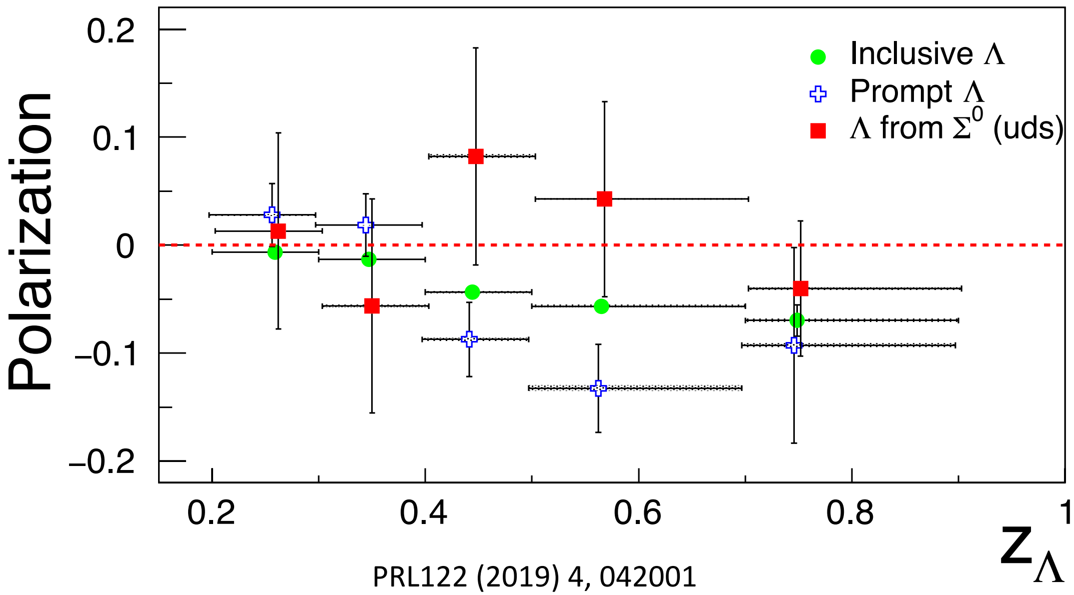


PRD 91, 032004 (2015)

Belle II Makes Precision Λ program possible!

First observation of $\Lambda^{\uparrow}$ at Belle!
(Here feed-down corrected)

Not shown: Associate production in tension with theory prediction→needs to be understood



PRL122 (2019) 4, 042001

- Opportunities at Belle II:
  - Feed down correction for p_T dependence and associated production
    - (currently only for z dependence, introduces large uncertainties)
    - $\Lambda^{\uparrow} - \Lambda^{\uparrow}$ correlations
    - Extension to tensor polarized FFs: e-Print: 2206.11742 [hep-ph]
    - ….
  - Explore low p_T region (not shown here) with higher statistics and better tracking resolution

Belle II Strength: Complex Final states.
Example: Dihadron Fragmentation Functions

Additional Observable:

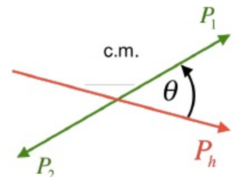
$\vec{R} = \vec{P_1} - \vec{P_2}$:

The relative momentum of the hadron pair is an additional degree of freedom:

the orientation of the two hadrons w.r.t. each other and the jet direction can be an indicator of the quark transverse spin

Parton polarization → Hadron Polarization ⇣	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z,M)$		$H_1^{\perp h/q}(z, p_T M, (Ph), \theta)$ 'Di-hadron Collins'
longitudinal			
Transverse	Type equation here.	**$G_1^{\perp}(z,M,P_h,\theta)$=** T-odd, chiral-even →jet handedness QCD vaccum strucuture	**$H_1^{∢}(z,M,(P_h),\theta)$=.** T-odd, chiral-odd Colinear

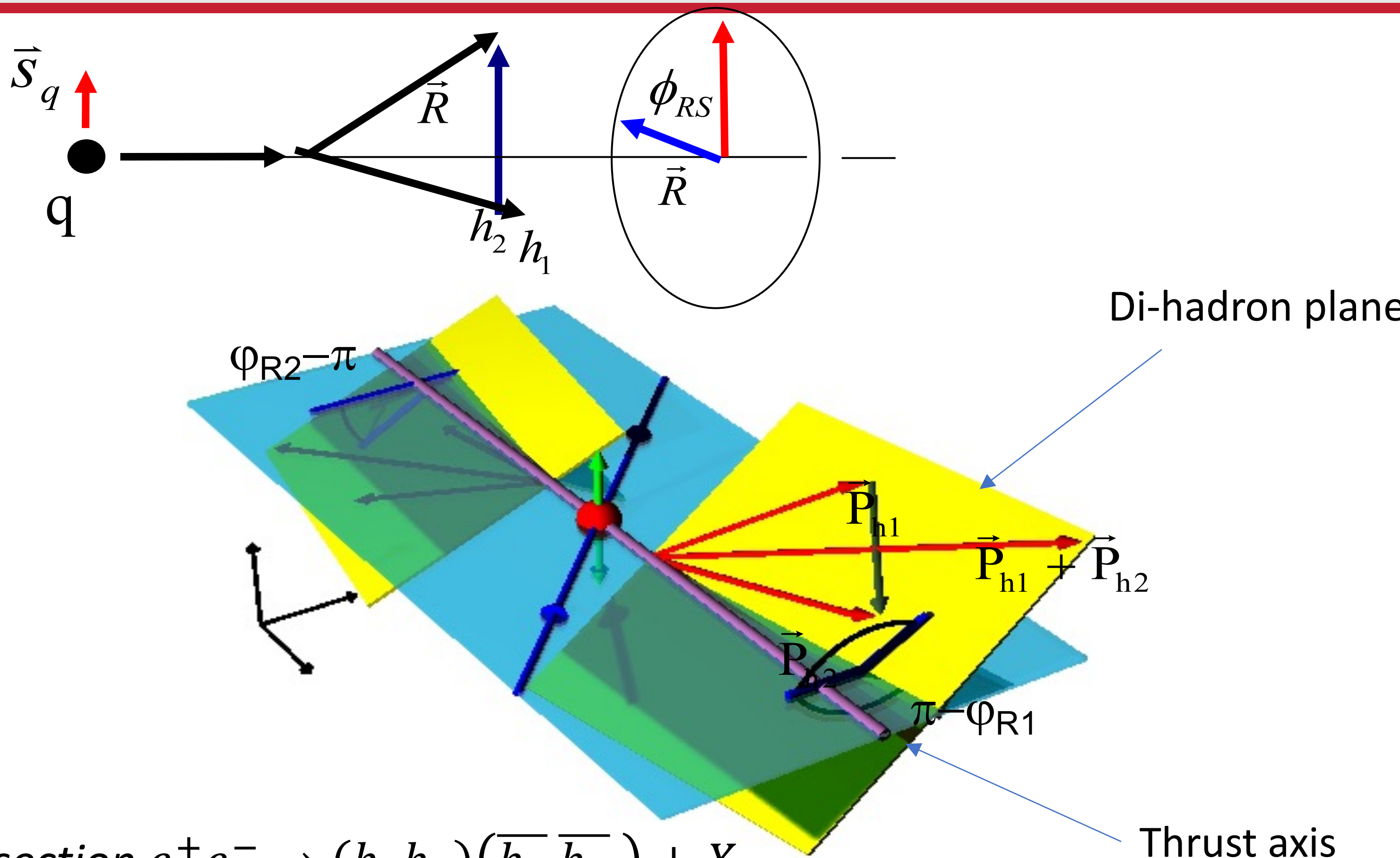
- Relative momentum of hadrons can carry away angular momentum
  - Relative and total angular momentum →In principle endless tower of FFs



More degrees of freedom→More information about correlations in final state

→See e.g. recent extraction of $e(x)$ (e-Print: 2203.14975 [hep-ph])

Access to polarization dependent di-hadron FFs in di-hadron back-to-back correlations



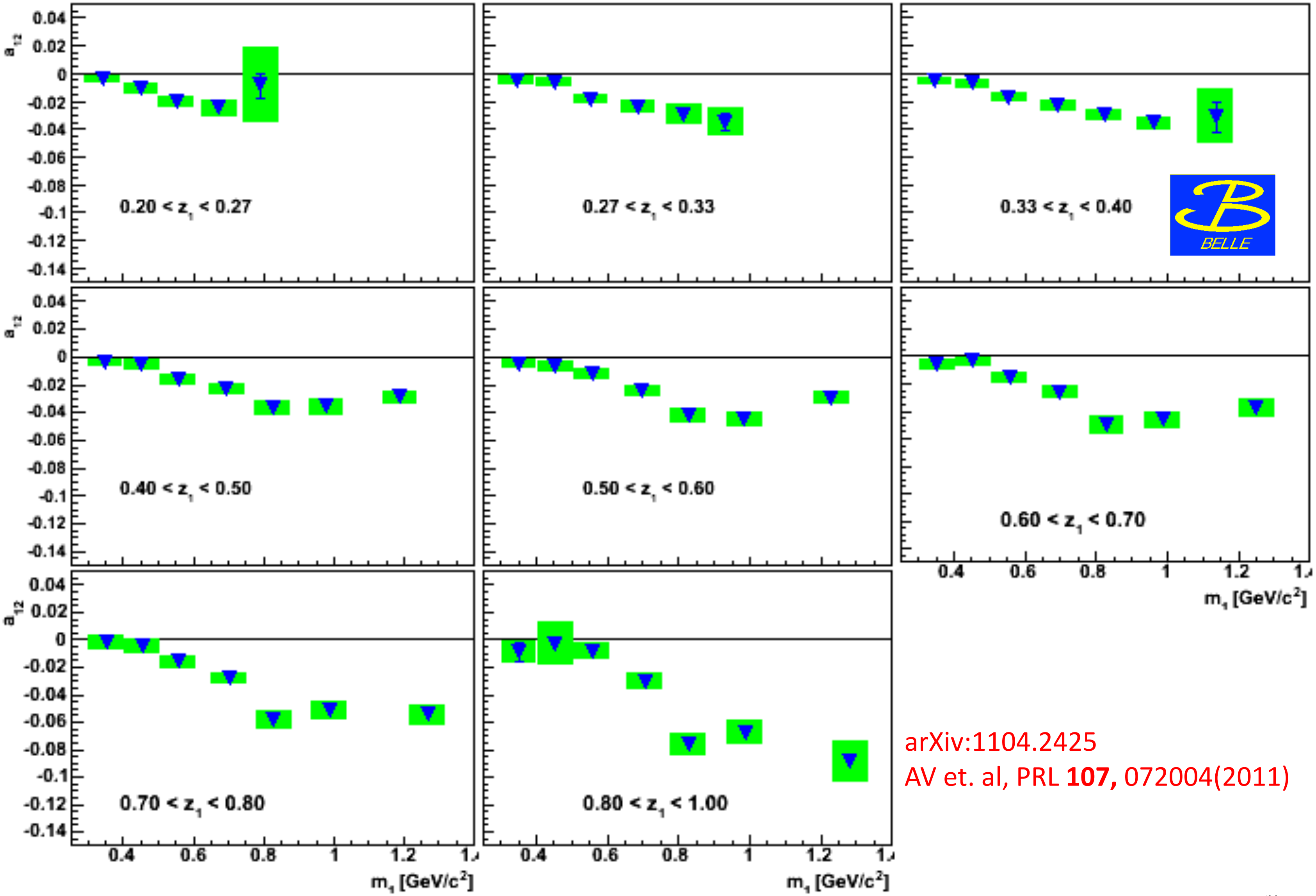
Cross-section $e^+e^- \rightarrow (h_1 h_2)(\overline{h_1}\,\overline{h_2}) + X$

$$\propto D_1^{\perp}\,\overline{D_1^{\perp}} + H_1^{\perp}\,\overline{H_1^{\perp}}\cos(\phi_{R1}+\phi_{R2})$$

- Statistics Hungry, only possible at B-factories

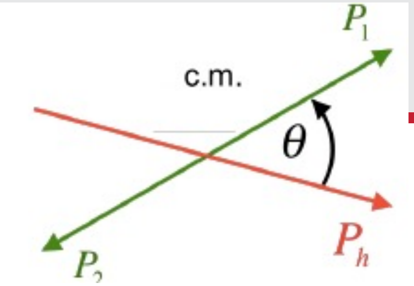
First measurement of Interference Fragmentation Function

$a_{12} \propto H_1^{<} * H_1^{<}$

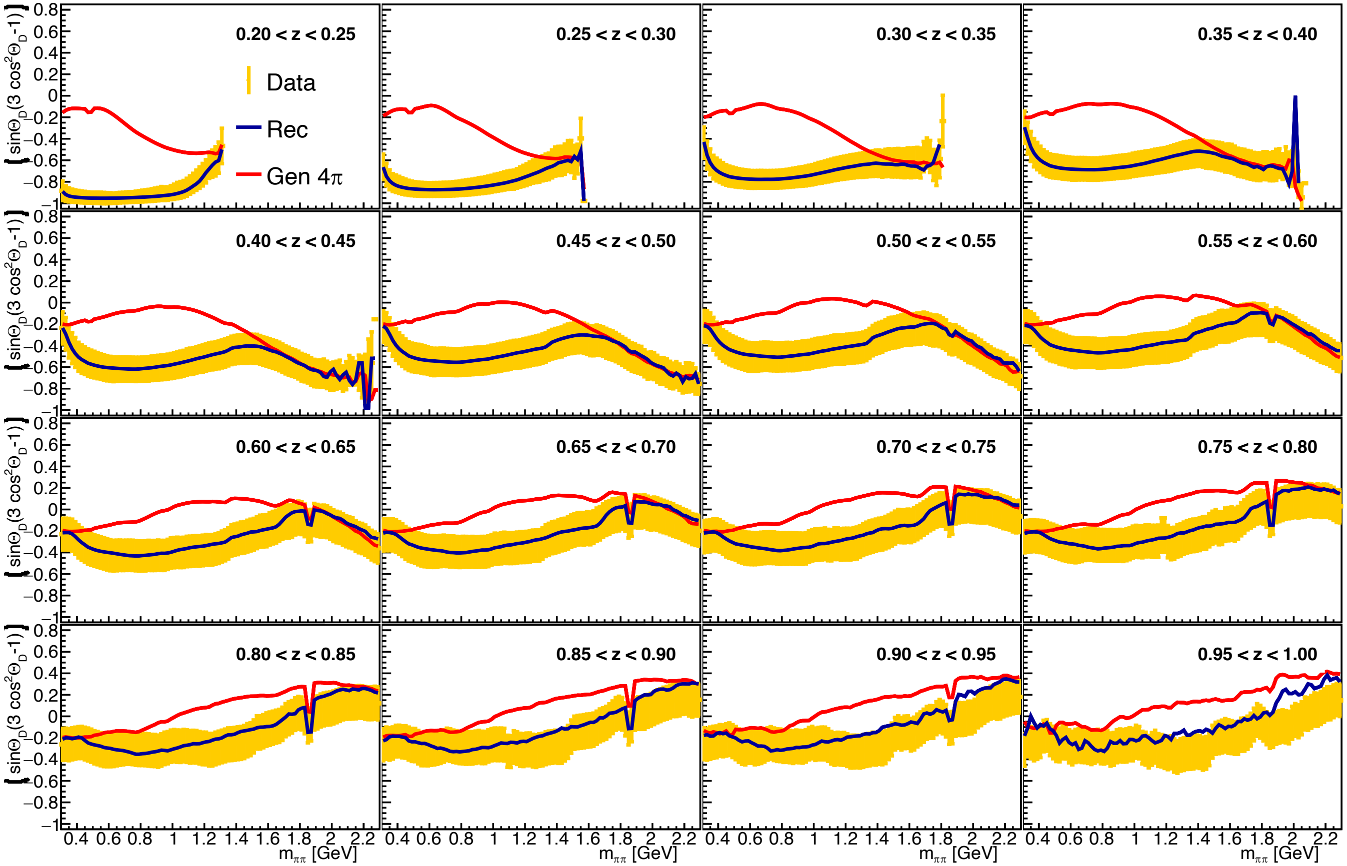


arXiv:1104.2425
AV et. al, PRL **107,** 072004(2011)

Acceptance Impact on Partial Wave composition



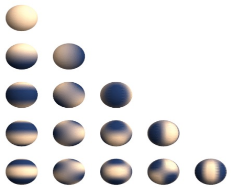
- Consider dependence of FFs on decay angle θ
- Higher order PWs lead to different moments in θ and ϕ
  → These are different FFs that are mixed by the acceptance



Belle Collaboration Phys.Rev. D96 (2017) no.3, 032005

- Belle II prospects: Sufficient statistics for full partial wave decomposition

Belle II prospects

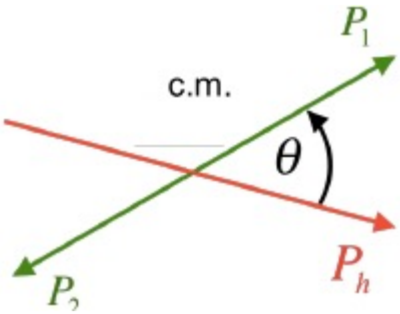


- Higher order PWs lead to different moments in θ and ϕ
- In models, evolution of the different PWs different
- Important to have a full picture to understand mixing effects in ratios/partial integrals/acceptance
- Missing info from partial wave estimated to have effects up to 10% e.g. on extraction of transversity

- Full partial wave decomposition ➔full description of two-particle correlations in hadronization

➔Describe hadronization dynamics

➔Bridge between FFs and MCEGs



Relation to Monte Carlo Event Generators (MCEGs)

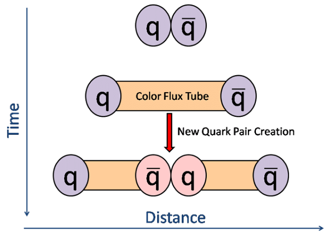
Fragmentation Functions

- Focus on more '**inclusive**' measurements → factorization holds
- Recent activity in more exclusive measurements (in particular jets)
- Needs MCEGs for experimental extraction
- Very precise extractions→Benchmark for MCEGs

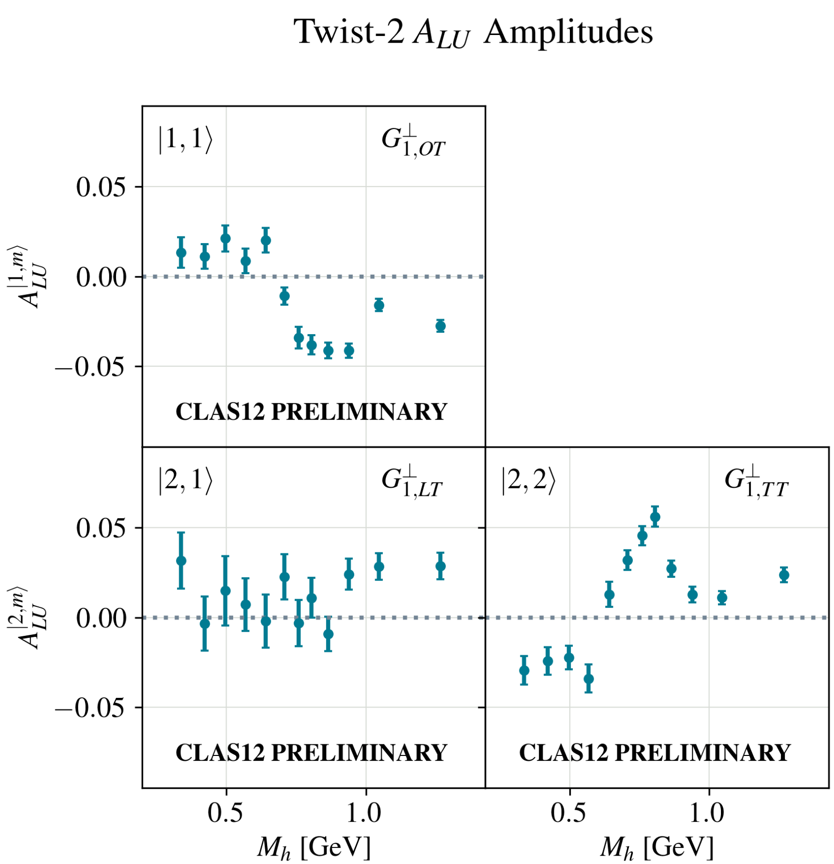
Hadronization Model in MCEG

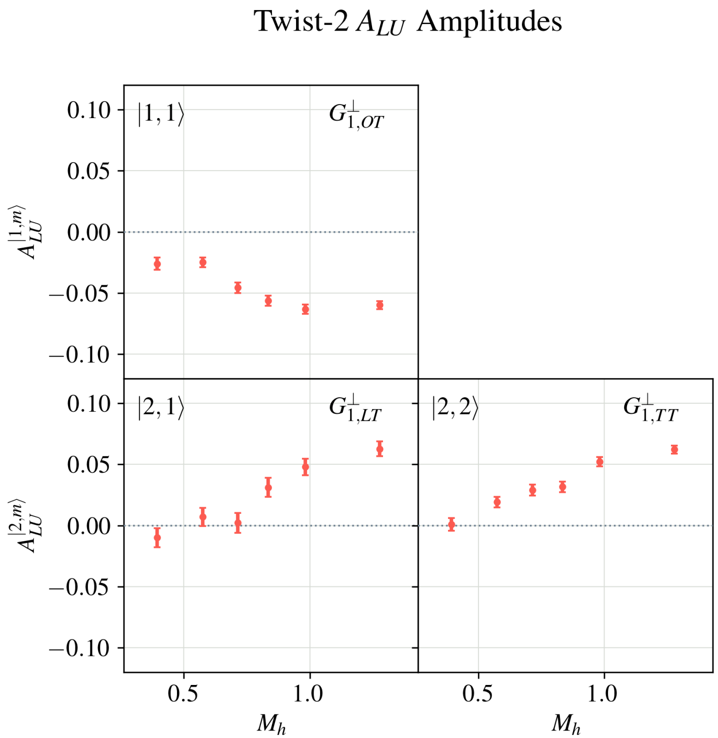
- Exclusive final states
- "Hard" subprocesses well constrained by theory
- Measurements focusing on MCEG improvement different from measurements extracting hard physics (grooming) or FFs (more exclusive)

Compare Partial Wave Decomposition in MC and Data



- Comparing to Polarized Lund model here (StringSpinner, A. al, *Comput.Phys.Commun.* 272 (2022))





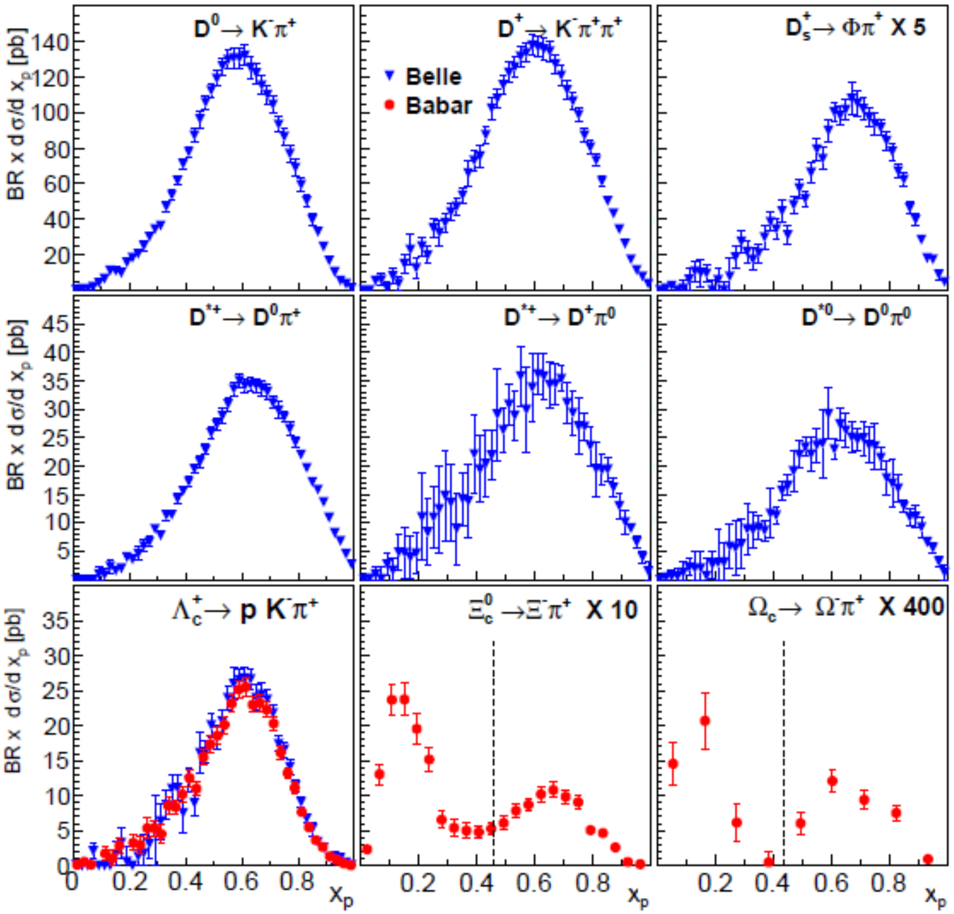
MC tuning studies

- Event Shapes
- Jet rates vs resolution, hemisphere,
- Event rates relative to event plane (and z, p_T), including baryons
- Multiplicities of resonance production ($\rho, \omega, K^*, \phi, \Lambda, \Sigma, \Xi, \Omega$)
  - Ratios between pseudo-scalar and vector mesons (also important for cosmic events)
- Charge/strangeness/baryon number compensation along event axis

Current Status of HF FFs from Belle, BaBar

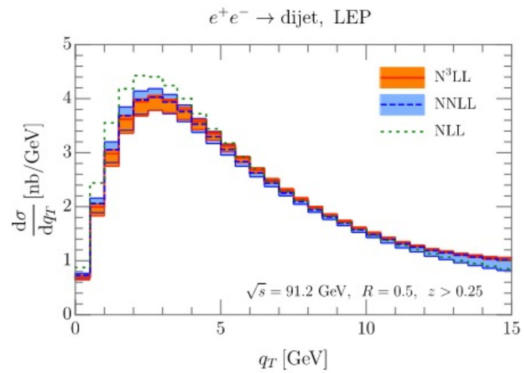
PRL.95, 142003 (2005)(Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007)(Babar)
PRL 99, 062001 (2007)(Babar)

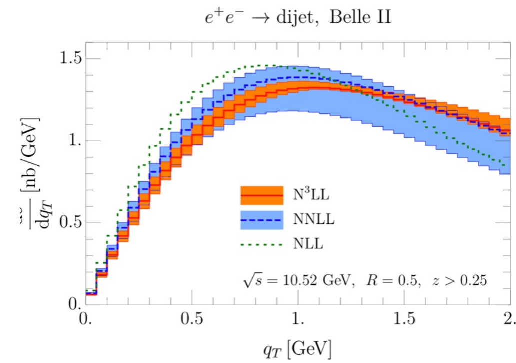
- Single hadron differential cross sections for Λ, Σ, Ξ, Ω, Λ_c, Σ_c, Ξ_c, Ω_c (etc) vs x_p available
- Heavier particles generally plotted vs normalized momentum
- Unlike light hadrons charmed hadrons contain large fraction of charm quark momentum
  ➔peaked at larger x_p
- Belle II prospects: Multidimensional extraction, p_T dependence

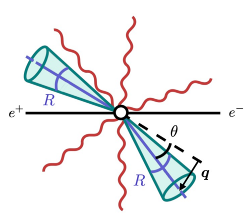


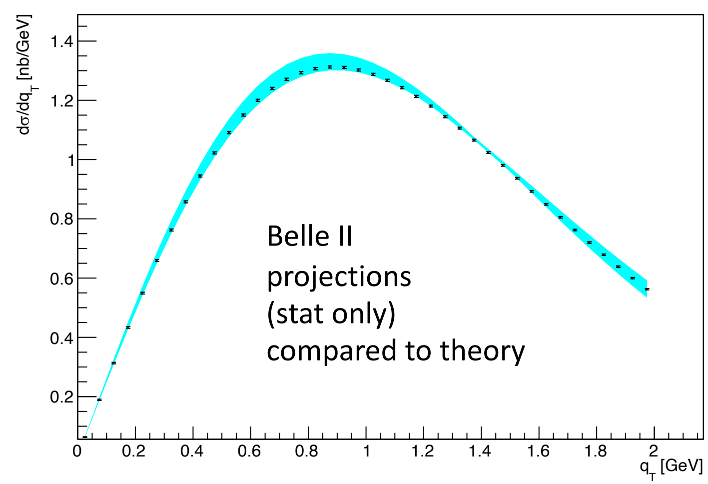
Brand New Opportunities at Belle II: Precision Jet Physics in e^+e^-

- Jet physics (will) play an important role at the EIC and LHC
- Precision measurements in e^+e^- annihilation will test current theoretical understanding
- Lower energies like Belle in particular sensitive to hadronization effects
- Example: Transverse Momentum Imbalance ← → TMD framework









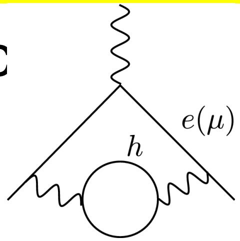
Using $R = 1.0, E_{jet} > 3.75\ GeV$,

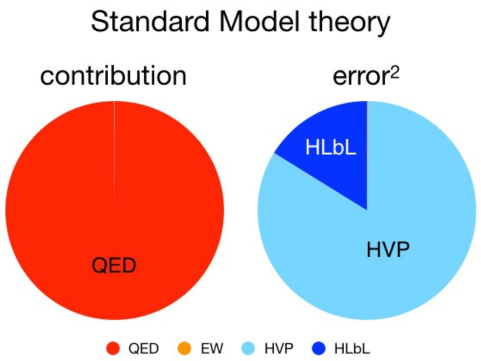
Motivation: Belle II needed to reduce uncertainty on Muon anomalous magnetic moment $a_\mu = \frac{g_\mu - 2}{2}$

- Currently: $a_\mu^{exp} - a_\mu^{SM} \triangleq 4.2\sigma$ with uncertainty on a_μ^{exp}, a_μ^{SM} comparable
- Plan to reduce $\sigma_{a_\mu^{exp}}$ by a factor 4:

→Discovery potential of experiment limited if $\sigma_{a_\mu^{SM}}$ is not reduced as well.

- "The dominant sources of theory error are by far the hadronic contributions, in particular, the $\mathcal{O}(\alpha^2)$HVP term and the $\mathcal{O}(\alpha^3)$ HLbL term"





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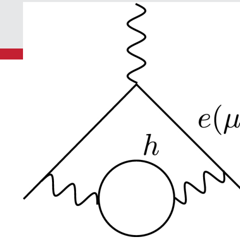

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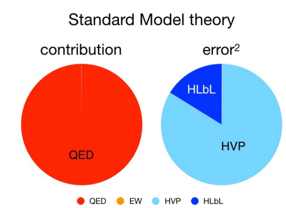
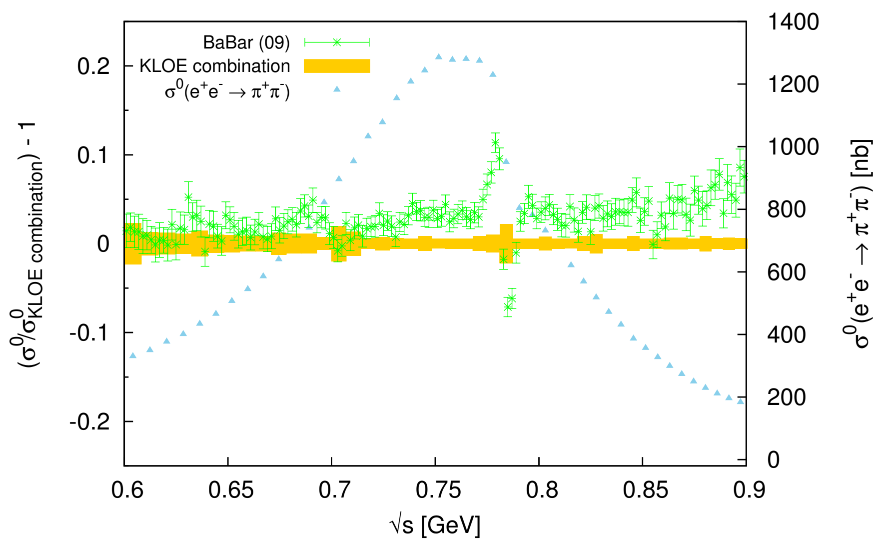
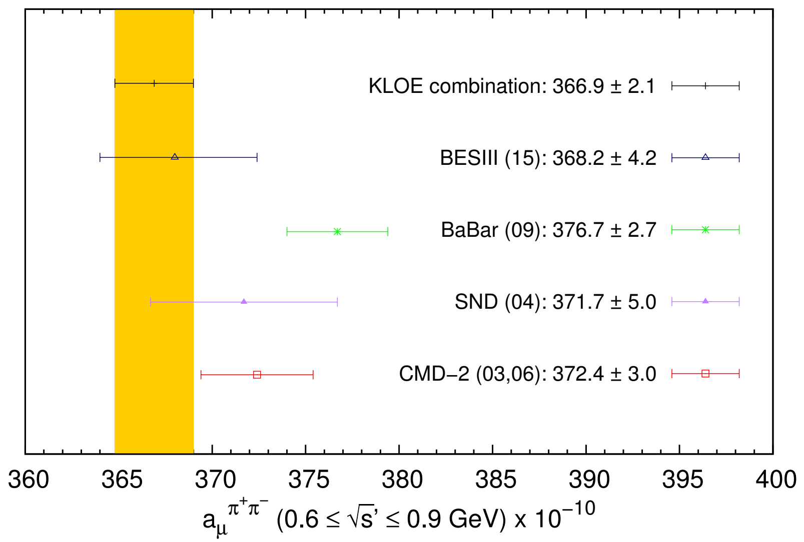


- Gold Standard for HVP determination: Experimental measurement of e^+e^- hadronic cross-section (R measurement)
  - E.g. New lattice calculations (Nature 593, 51–55 (2021)) reduce tension to 2σ
  - But: Tension between KLOE/BaBar measurement make up ~1/3rd of HVP uncertainty

Tension in existing KLOE/BaBar measurements

Need to be resolved !





Figures from JHEP 03, 173 (2018), arXiv:1711.03085 [hep-ex]

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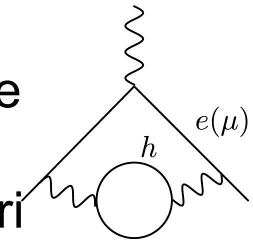

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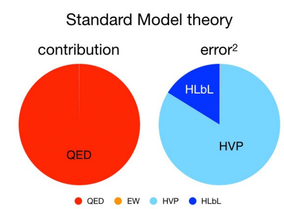

- Belle II will provide new input to resolve current tensions and work on reducing uncertainties on R measurements ➔ Crucial for discovery potential of g-2 experiment
- A host of other measurements possible to reduce subdominant uncertainties and provide complementary information on HVP, Hlbl →more confidence in results

α_S (and test of QCD calculations)

- Measurements of α_S generally also test QCD calculation framework
- $\alpha_S = 0.1179 \pm 0.0009$, ($Z$ pole) ➔ $\frac{\delta\alpha_S}{\alpha_S} \approx 0.8\%$:

  ➔ Order of magnitude larger than QED, weak, gravitational coupling uncertainties!
- Need reduction of $\delta\alpha_S$ to improve uncertainties on all pQCD observables

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- e^+e^- event shapes, EEC (currently few percent α_S uncertainty)
  - Advances in theory to NNLL, progress to reduce dependence on hadronization uncertainties (e.g. groomed jet)
- FFs
  - From MLLA
  - From scaling violations combining FFs at Belle II with FFs at higher energies

α_S (and test of QCD calculations)

- Measurements of α_S generally also test QCD calculation framework
- $\alpha_S = 0.1179 \pm 0.0009$, ($Z$ pole) ➔ $\frac{\delta\alpha_S}{\alpha_S} \approx 0.8\%$:
  ➔ Order of magnitude larger than QED, weak, gravitational coupling uncertainties!
- Need reduction of $\delta\alpha_S$ to improve uncertainties on all pQCD observables

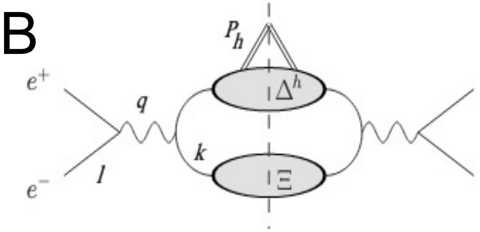
Belle II can contribute to reduce uncertainties on α_S through

- τ spectral functions (currently $\approx 1.6\%$ uncertainty on α_S extraction)
  - In particular some $2{,}4\,\pi$ final states still dominated by LEP
- e^+e^- R ratio ($\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$)
  - Belle II could provide independent R measurement from $\sqrt{s} \approx 2 - 10$ through radiative return technique
- e^+e^- event shapes, EEC (currently few percent α_S uncertainty)
  - Advances in theory to NNLL, progress to reduce dependence on hadronization uncertainties (e.g. groomed jet)
- FFs
  - From MLLA
  - From scaling violations combining FFs at Belle II with FFs at higher energies

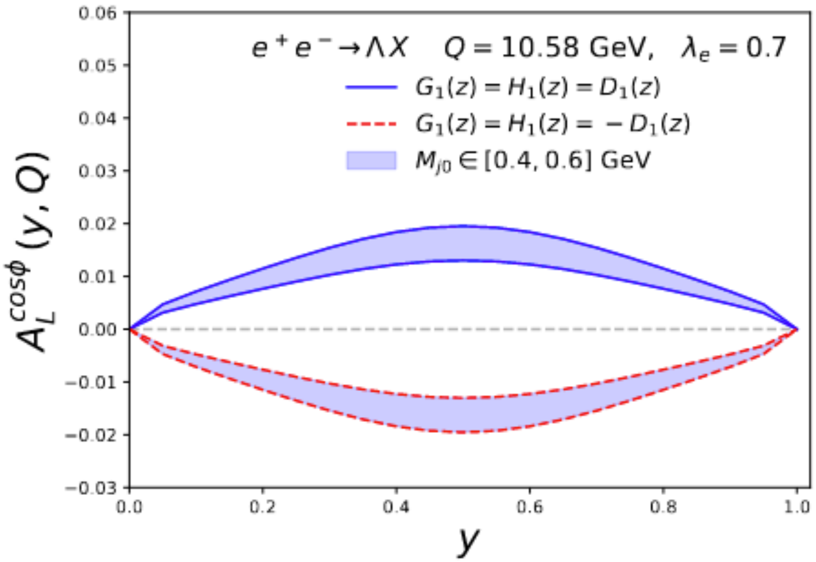
Jet mass

- Proposal to polarize electron beam at SuperKEKB

→ Whitepaper: e-Print: 2205.12847



- Can access jet mass
- ”QCD Higgs mechanism”



$$\frac{d\sigma^L}{d\Omega dz} \propto \lambda_e \sum_a \left\{ \frac{1}{2} C(y) G_1^{a\to\Lambda}(z,Q) + 2D(y)|S_T|\cos(\phi)\frac{M_\Lambda}{Q}\left(\frac{1}{z}G_T^{a\to\Lambda}(z,Q) + \frac{m_a^{dyn}}{M_\Lambda}H_1^{a\to\Lambda}(z,Q)\right)\right\}$$

See also A. Accardi, A. Signori, *Phys.Lett.B* 798 (2019) 134993

Summary and Outlook

- e^+e^- annihilation allow for precision studies of QCD
- Belle II will provide world record statistics for
  - Precision measurements of fragmentation functions with complex final states
  - Tune MC generators
  - Probe Jet calculations at low scales where hadronization effects play a significant role
  - Constrain HVP, Hlbl contributions to g-2
  - Constrain α_S
  - Test QCD calculations of event shapes
  - …

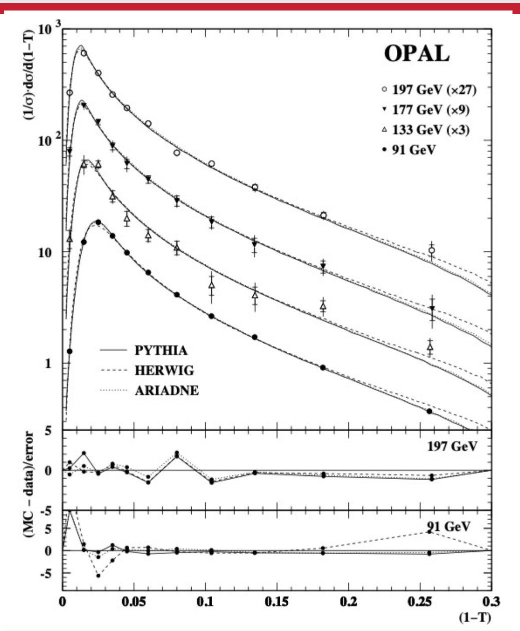
Save the Date

25th International Symposium on Spin Physics will be hosted by Duke University in Durham, NC

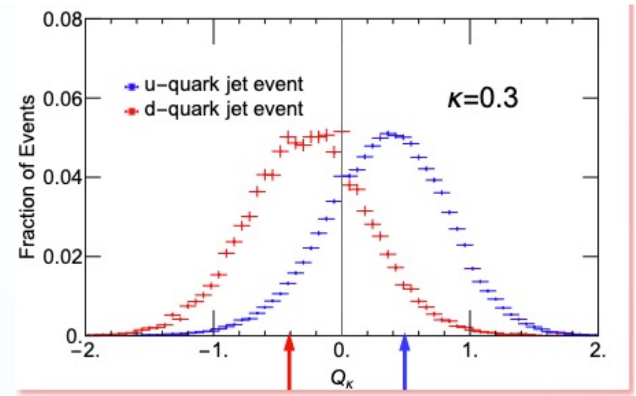
September 24-29 2023

Future measurement to study hadronization in e^+e^-

- Back-to-back hadrons to explore k_T spectrum
- Event shapes
  – Rich topic at LEP
  – LEP did flavor tagged/$q/\bar{q}$
  →can this be done with jet charge?
  – Energy-Energy Correlations



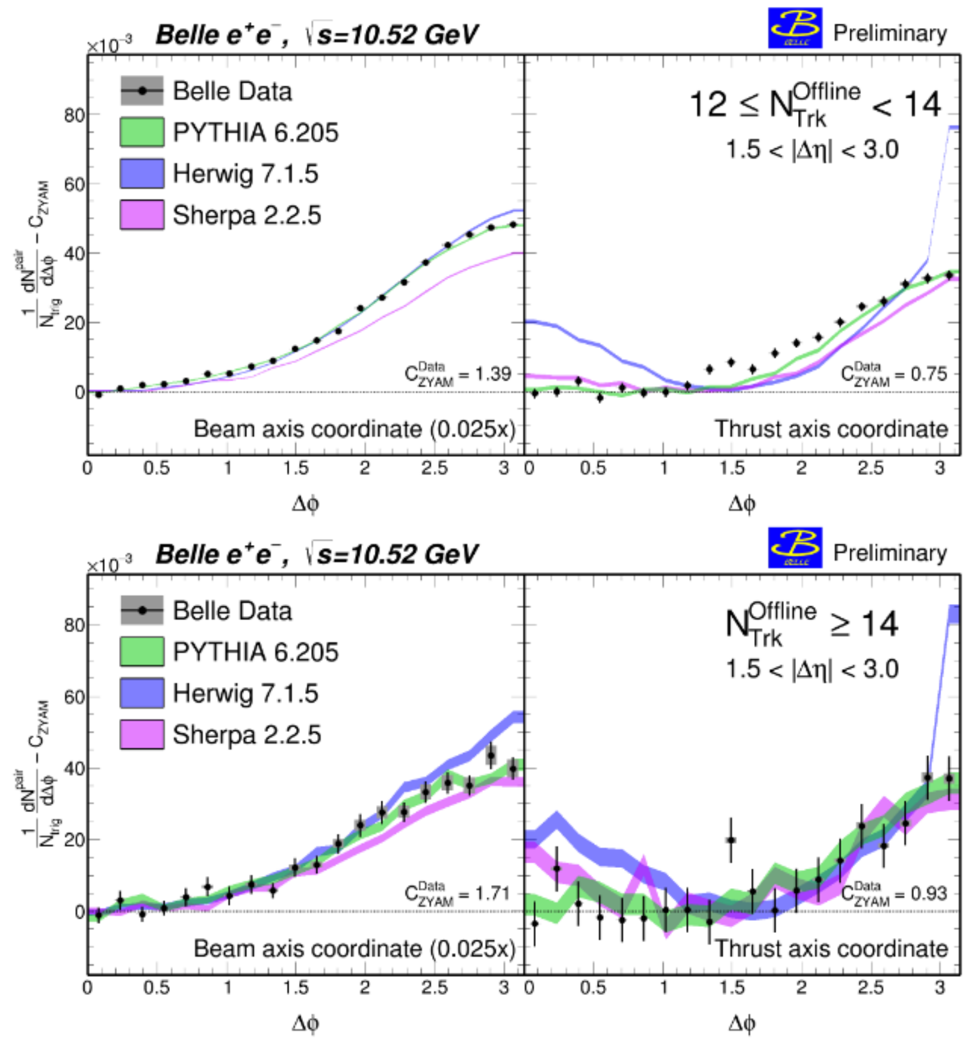
- Jet topic still to be explored further in e^+e^-
  – Reanalysis of ALPEH data (MITHIG-MOD-NOTE-21-001)
  – Start of program at Belle
    - Initially focused on
      – q_T distributions in di-jets, jet-hadron correlations,
      – T-odd jets
      – WTA vs standard jet axis
      – …



Z. Kang at INT FF worskhop 2021

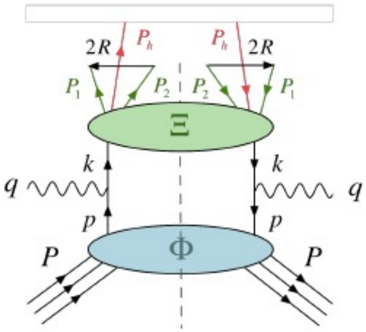
"Ridge" Correlations

- Example of QCD correlation analysis 'off the beaten path'
- Makes use of clean e^+e^- environment

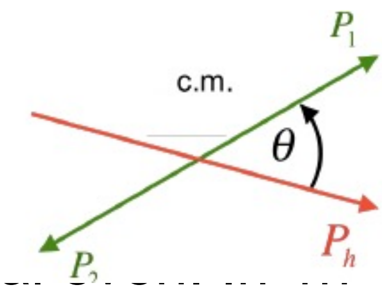


hep-ex:2008.04187

Di-hadron fragmentation functions

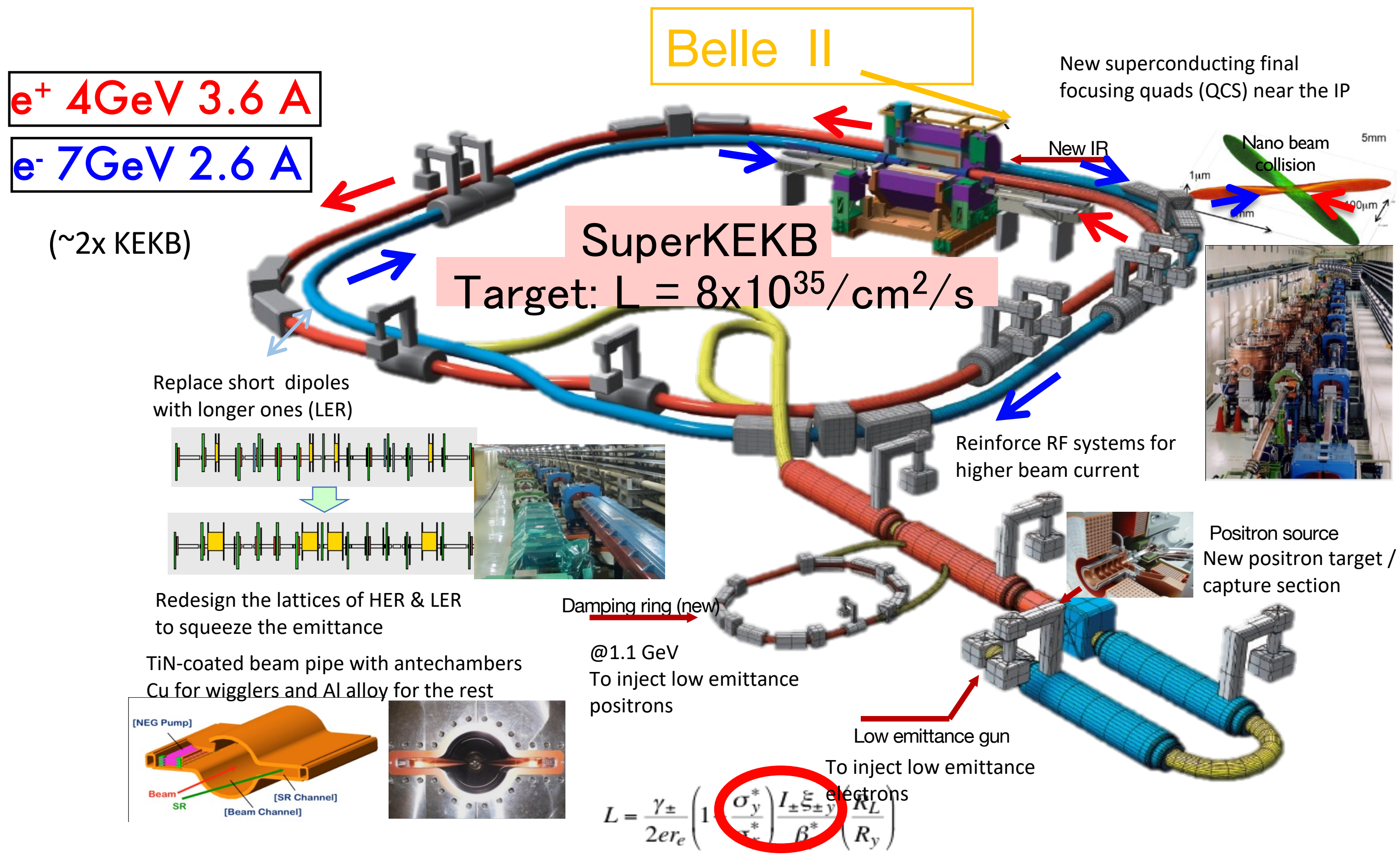


- Additional degree of freedom ($\vec{R} = \overrightarrow{P_1} - \overrightarrow{P_2}$)
  - Plus z, P_T
- Relative momentum of hadrons can carry away ang momentum
  - Partial wave decomposition in θ
  - Relative and total angular momentum →In principle endless tower of FFs
  - Analogue of 1h production with spin in final state



- Transverse polarization dependence in collinear fra
- Makes 'new' FFs possible, such as $G_1^{\perp}$: T-odd chir case, this needs polarized hadron in the final state
- **Similar to Λ FF,chiral-even, T-odd: Import[illegible] t[illegible]heck factorization**

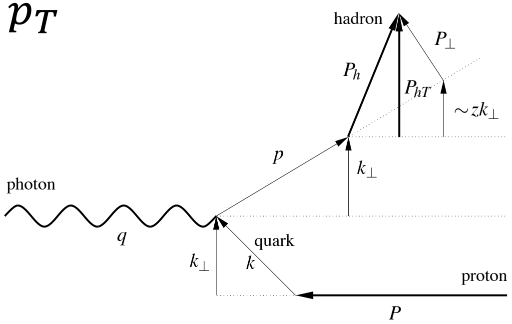
KEKB →SuperKEKB: Deliver Instantaneous Luminosity x 40



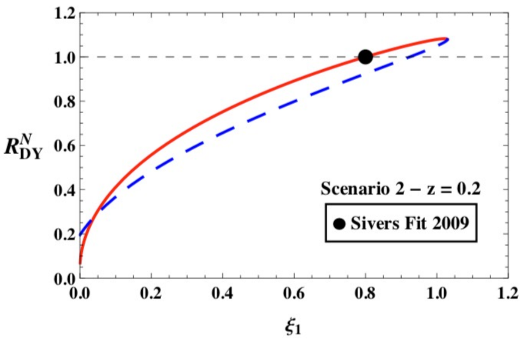
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

Need for precise extraction of TMD FFs to extract TMD PDFs

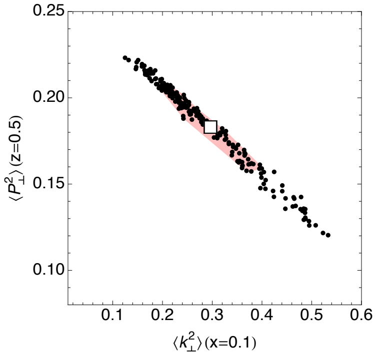
- Example: variation in Sivers effect varying $\xi = \frac{k_T}{p_T}$



- SIDIS necessary to extract flavor dependence of FFs but cannot disentangle source of pT

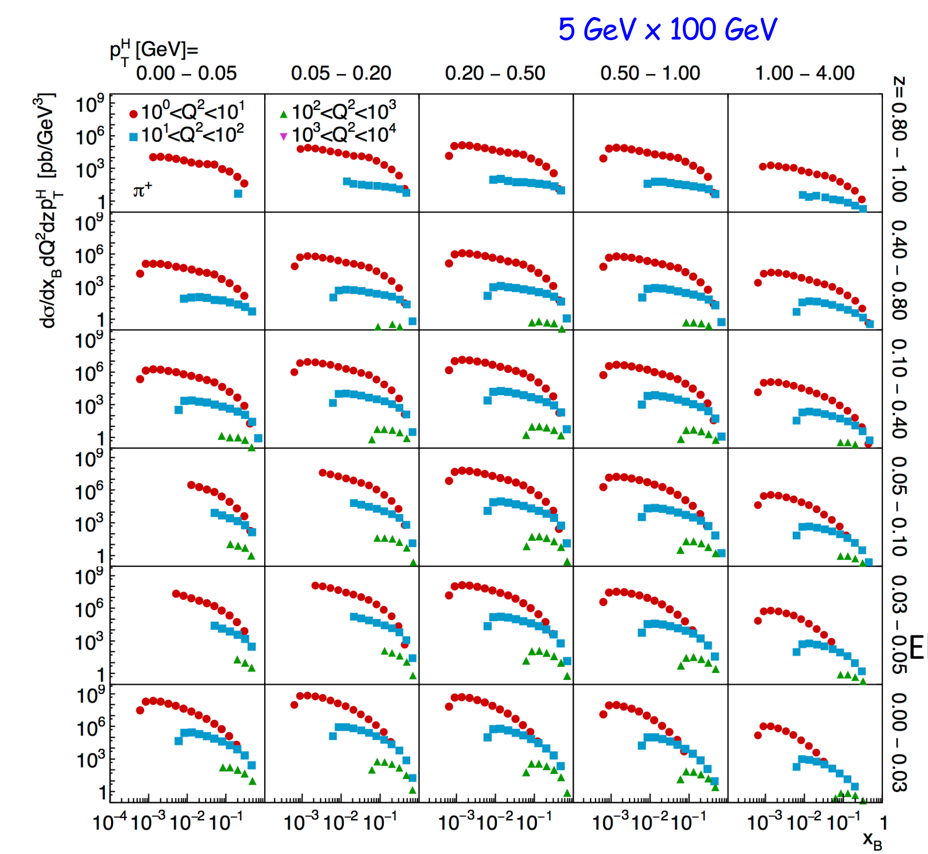


Phys.Rev. D98 (2018) no.9, 094023



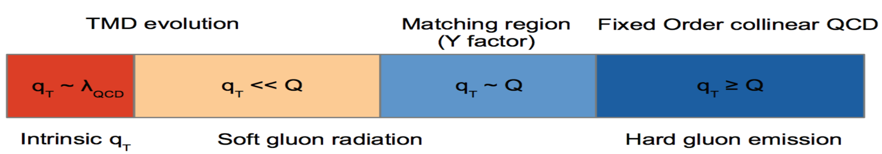
JHEP 1311 (2013) 194

Unpolarized SIDIS@EIC



Elke Aschenauer at

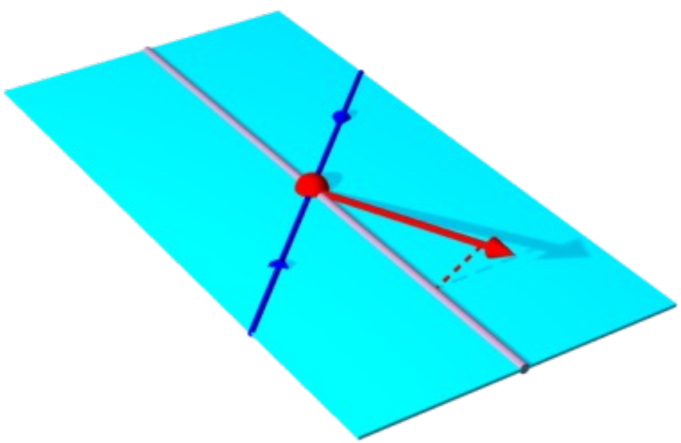
Same precision and kinematic coverage for π±, K±, p± should provide great input to **simultaneously** constrain TMD PDFs and FFs

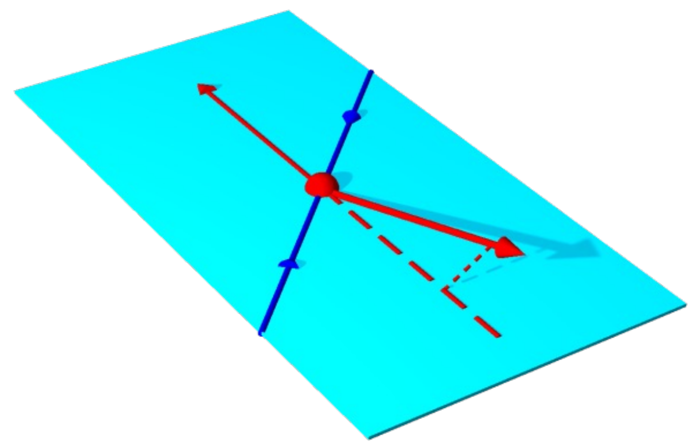


From M Boglione
PoS QCDEV2016 (2017) 026

Transverse momentum dependence

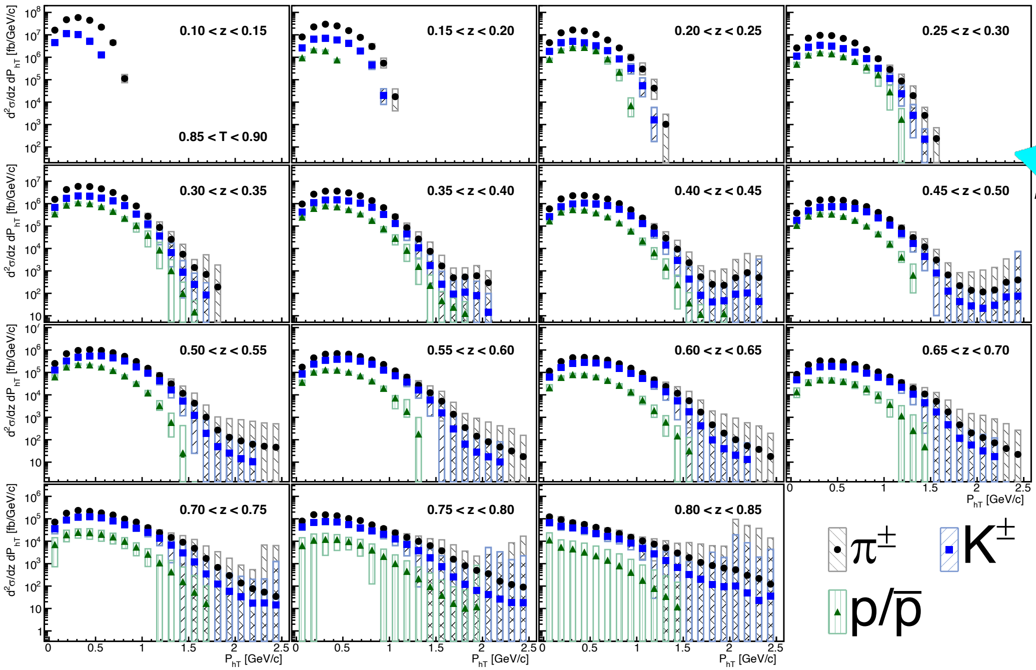
- Goal: Extract $D(z, k_T)$
- Several ways to be sensitive to k_T
  - Vs thrust or jet direction → Have to relate measured p_T to k_T
  - Relative in back-to-back hadrons→sensitive to $D(z_1, k_{Tt}) \otimes D(z_2, k_{T2})$

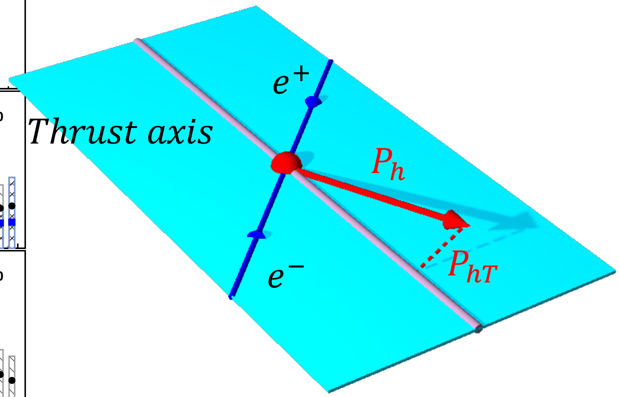


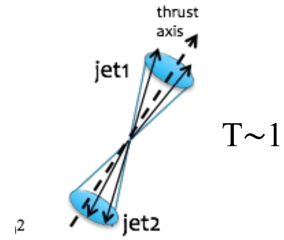


Transverse momentum distributions

- 0.85< Thrust T < 0.9
  - Transverse momenta mostly Gaussian
  - Possible deviations for large P_{hT} tails, but also large uncertainties
  - →TMD evolution



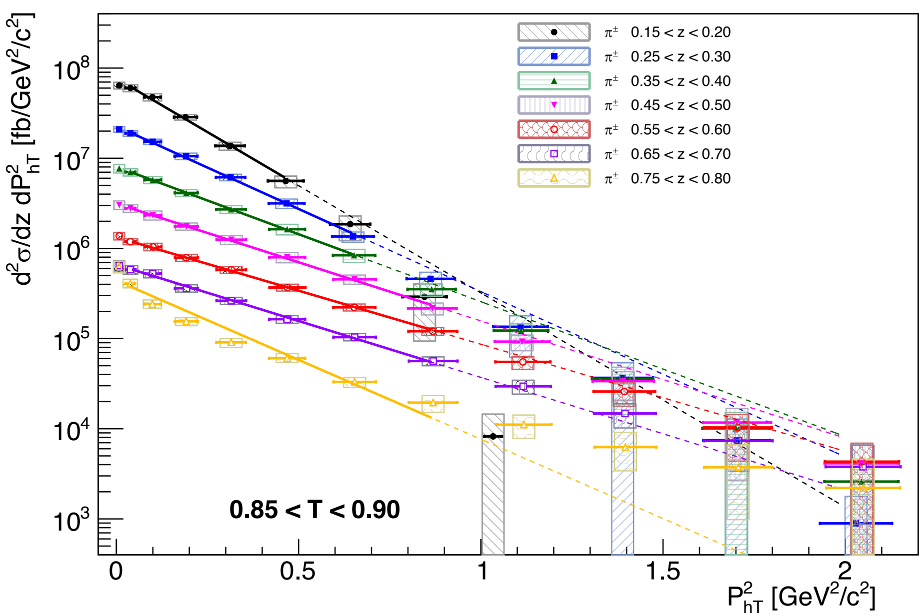


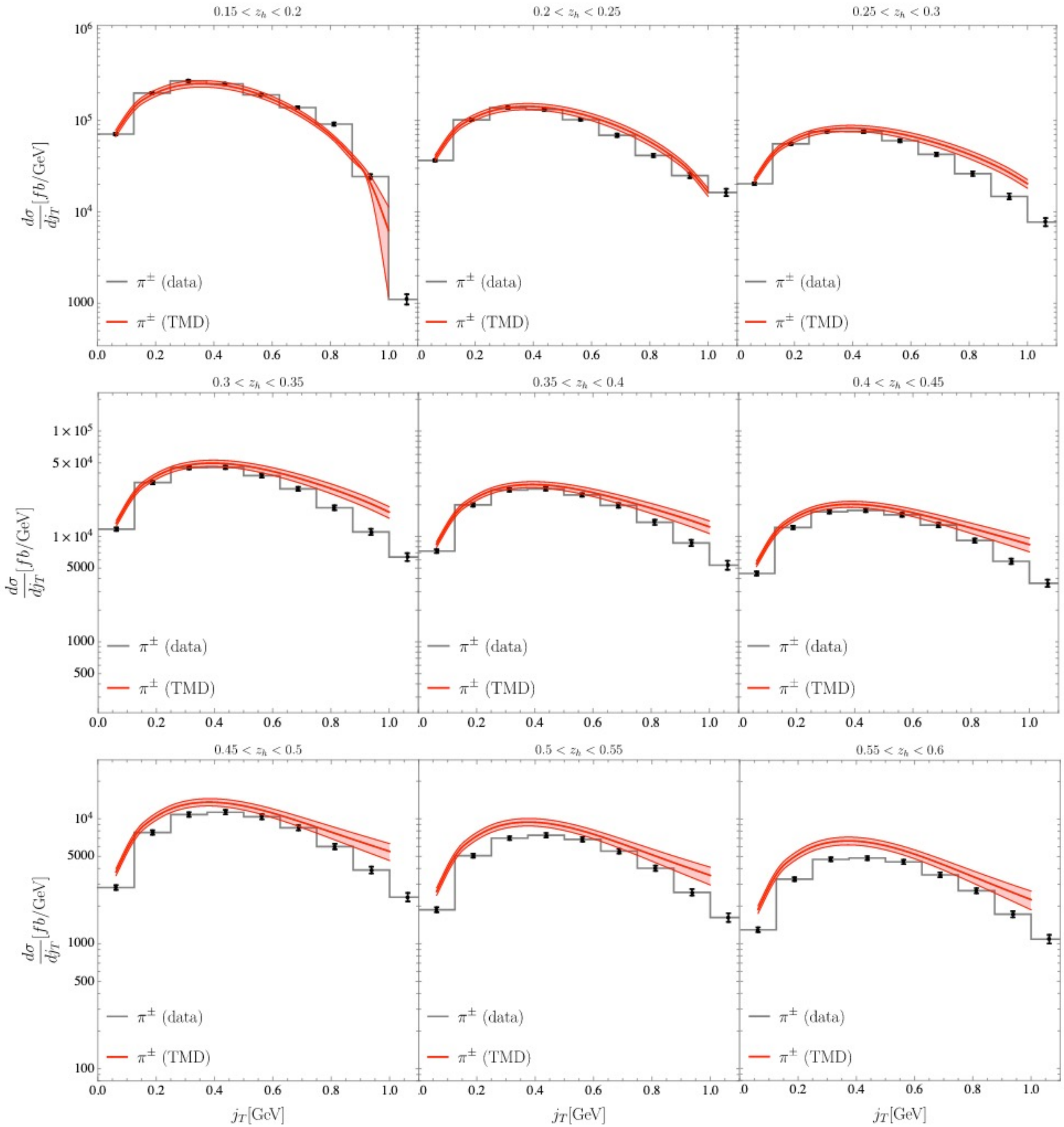


Phys.Rev.D 99 (2019) 11, 112006

Transverse Momentum: Gaussian widths

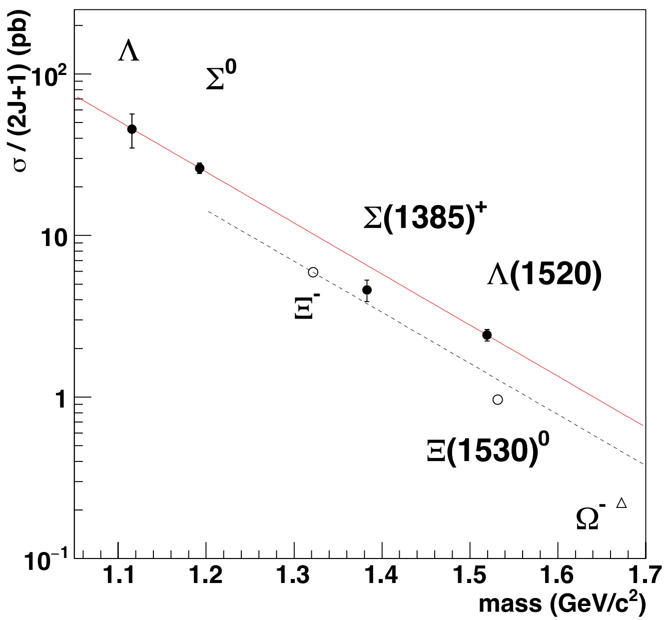
- $0.85 < T < 0.9$
  - Fit Gauss to low P_{hT} data
  - Mostly well described with possible exception at high z
  - Deviation from Gauss at large P_{hT}
  - Clear increase in width with z for low values of z

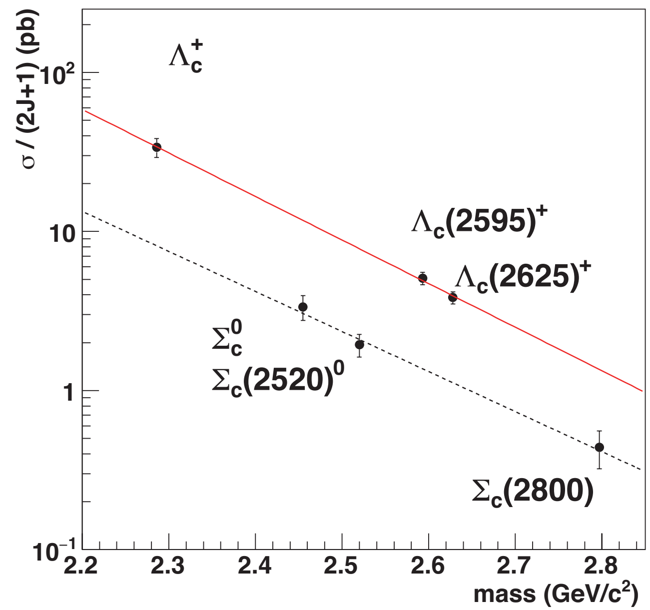




M. Boglione, A. Simonelli, "Factorization of $e^+e^- \to HX$ cross section, differential in z_h, P_T and thrust, in the 2-jet limit", 2011.07366 [hep-ph]

Mass Dependence of σ →test hadronization model



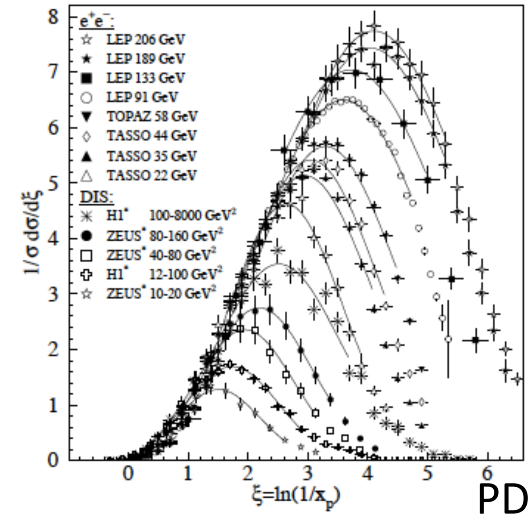


- Found consistent with di-quark model

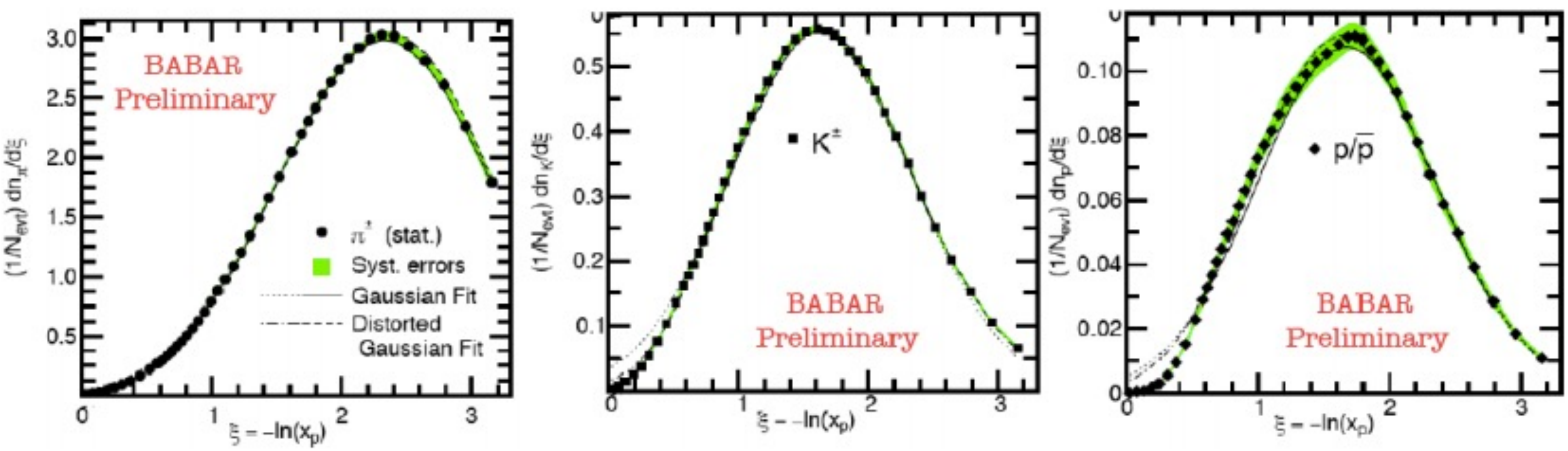
PRD 97, 072005 (2018)

Perturbative QCD tests

- Time like splitting functions have singulari
  like important for DIS)
- MLLA → test for resummation
- Observed shape consistent with QCD calc
- FCC-ee might go to lower z. Impact?

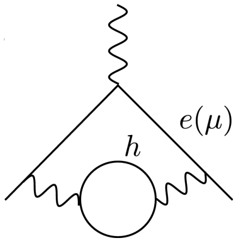


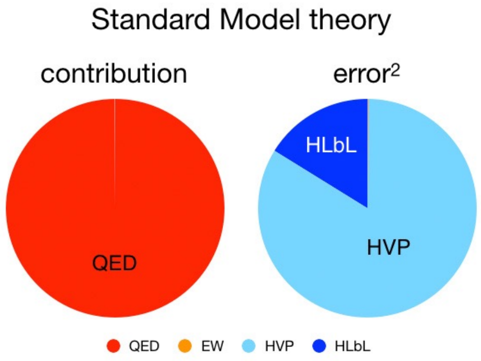
PDG



Motivation: Belle II needed to reduce uncertainty on a_μ

- Muon anomalous magnetic moment $a_\mu = \frac{g_\mu - 2}{2}$
- Currently: $a_\mu^{exp} - a_\mu^{SM} \mathrel{\widehat{=}} 4.2\sigma$ with uncertainty on a_μ^{exp}, a_μ^{SM} comparable
- Plan to reduce $\sigma_{a_\mu^{exp}}$ by a factor 4:
  → Discovery potential of experiment limited if $\sigma_{a_\mu^{SM}}$ is not reduced as well.
- "The dominant sources of theory error are by far the hadronic contribution in particular, the $\mathcal{O}(\alpha^2)$HVP term and the $\mathcal{O}(\alpha^3)$ HLbL term"





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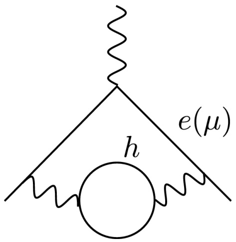
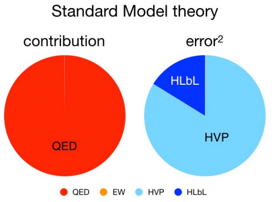
- "The dominant sources of theory error are by far the hadronic contributions, in particular, the $\mathcal{O}(\alpha^2)$HVP term and the $\mathcal{O}(\alpha^3)$ HLbL term"
- Gold Standard for HVP determination: Experimental measurement of e^+e^- hadronic cross-section (R measurement)
  - E.g. New lattice calculations (Nature 593, 51–55 (2021)) reduce tension to 2σ
  - But: Tension between KLOE/BaBar measurement make up ~1/3rd of HVP uncertainty





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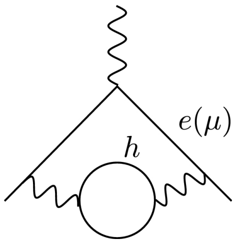
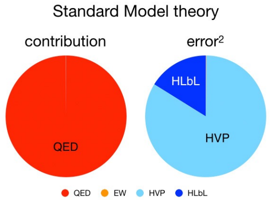
- **Belle II will provide new input to resolve current tensions and work on reducing uncertainties on R meausurements ➔ Crucial for discovery potential of g-2 experiment**
- A host of other measurements possible to reduce subdominant uncertainties and provide complementary information on HVP, Hlbl →more confidence in results





How to measure HVP in e^+e^-

- Use dispersion relation

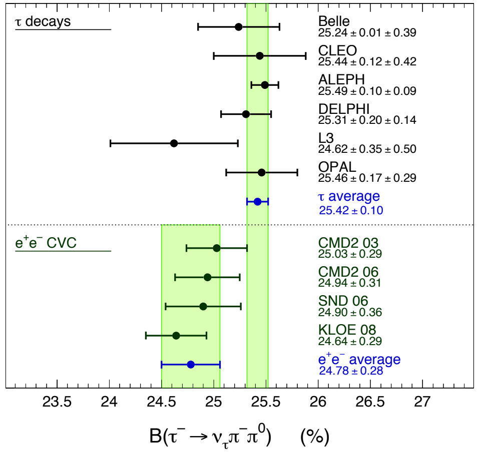
$$a_\mu^{HVP,LO} = \frac{\alpha^2}{2\pi^2}\int_{M_\pi^2}^{\infty}\frac{K(s)}{s}R(s)ds$$

- R: hadronic R ratio: $R(s) = \frac{3s}{4\pi\alpha^2}\sigma_h(e^+e^- \to hadrons)$

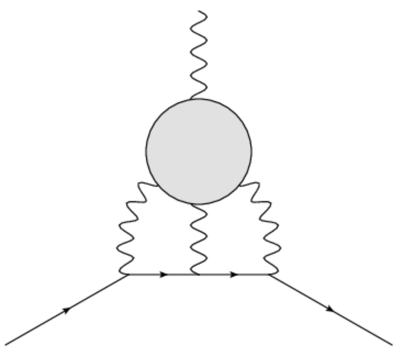
- R is dominated by
  low s region
  → $e^+e^- \to \pi\pi$ (70%)
  →resonance region around ρ, ω
  Fixed energy B factories: ISR technique
- E.g. at BaBar effectively the ratio $\frac{\sigma(e^+e^- \to \pi\pi)}{\sigma(e^+e^- \to \mu\mu)}$ is measured
  →dominant systematic cancel
  →remaining systematics dominated by PID, ISR calculations

Additional Measurements related to g-2

- Conserved vector current (CVC): $\tau \rightarrow \pi^0 \pi \nu_\tau \leftrightarrow e^+e^- \rightarrow \pi\pi$
  - However: isospin breaking effects not fully understood
    →tension between τ decay and CVC e^+e^-
    →Future theory developments could bring this channel into play again
  - Belle II will provide further input



- Hadronic Light-by-Light (HLbL)
  - HLbL is $\mathcal{O}(\alpha^3)$ →needs to be known to within $\approx 10\%$
  - 4-point function →significantly more complex than HVP
    →experimental input is needed to validate theory models
    →See whitepaper for measurements validating different aspects of the calculations



Summary and Take away message

- a_μ measurements among the most sensitive to New Physics

BUT:

Discovery potential needs experimental input from e^+e^- to reduce theory uncertainty to same level as expected experimental uncertainties

Need:

→HVP from $e^+e^- \to \pi\pi$

→HLbL from form factors and $\gamma\gamma \to$hadrons

Belle II is a second generation B-factory

- State of the art detector optimized for precision physics with identified hadrons
- Will reduce systematics by resolving current experimental tension in HVP
- Excellent opportunity to reduce systematics to expected precision of a_μ^{exp}
- Must do experiment to validate theory calculations for HVP and HLbL

Details in "Opportunities for precision QCD physics in hadronization at Belle II -- a snowmass whitepaper" (2204.02280 [hep-ex])

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