Measuring the Weinberg angle at SCT

Vitaly Vorobyev (BINP)

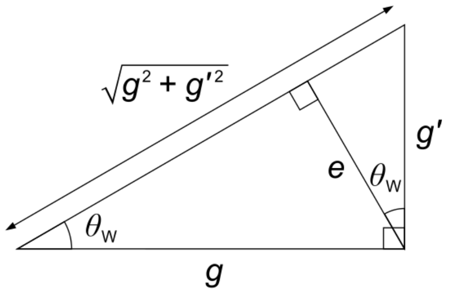
Workshop on future charm-tau factory

November 16th, 2020

JHEP 2020, 76 (2020)

A. Bondar, A. Grabovsky,
A. Reznichenko, A. Rudenko &
V. Vorobyev

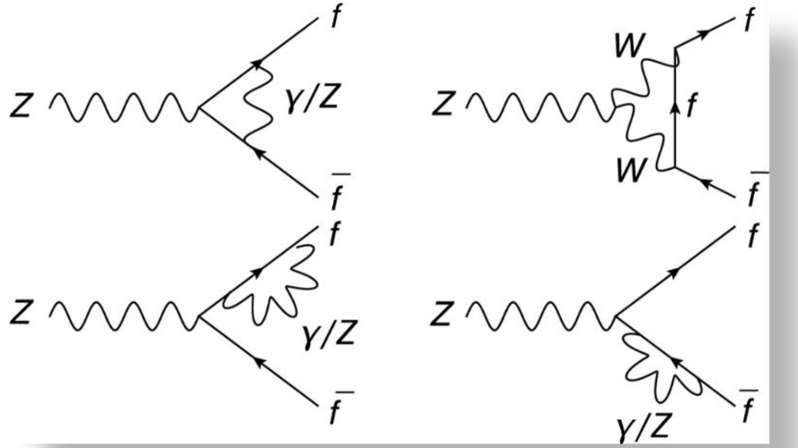
The weak mixing angle



- Electroweak model $SU(2)_L \times U(1)_Y$ (Glashow, 1961)

$$A_\mu = B_\mu^0 \cos\theta_W + W_\mu^0 \sin\theta_W$$
$$Z_\mu = W_\mu^0 \cos\theta_W - B_\mu^0 \sin\theta_W$$

  Two independent coupling constants g and g'



- On-shell definition of the weak mixing angle

$$\sin^2\theta_W \equiv \frac{g'^2}{g^2 + g'^2} = 1 - \frac{m_W^2}{m_Z^2}$$

- Weak neutral current

$$\frac{g}{\cos\theta_W} Z_\mu \bar{f}\gamma^\mu\left(I_3^f - 2Q_f \sin^2\theta_W - I_3^f\gamma_5\right)f, \qquad I_3^f = 0, \pm 1/2$$

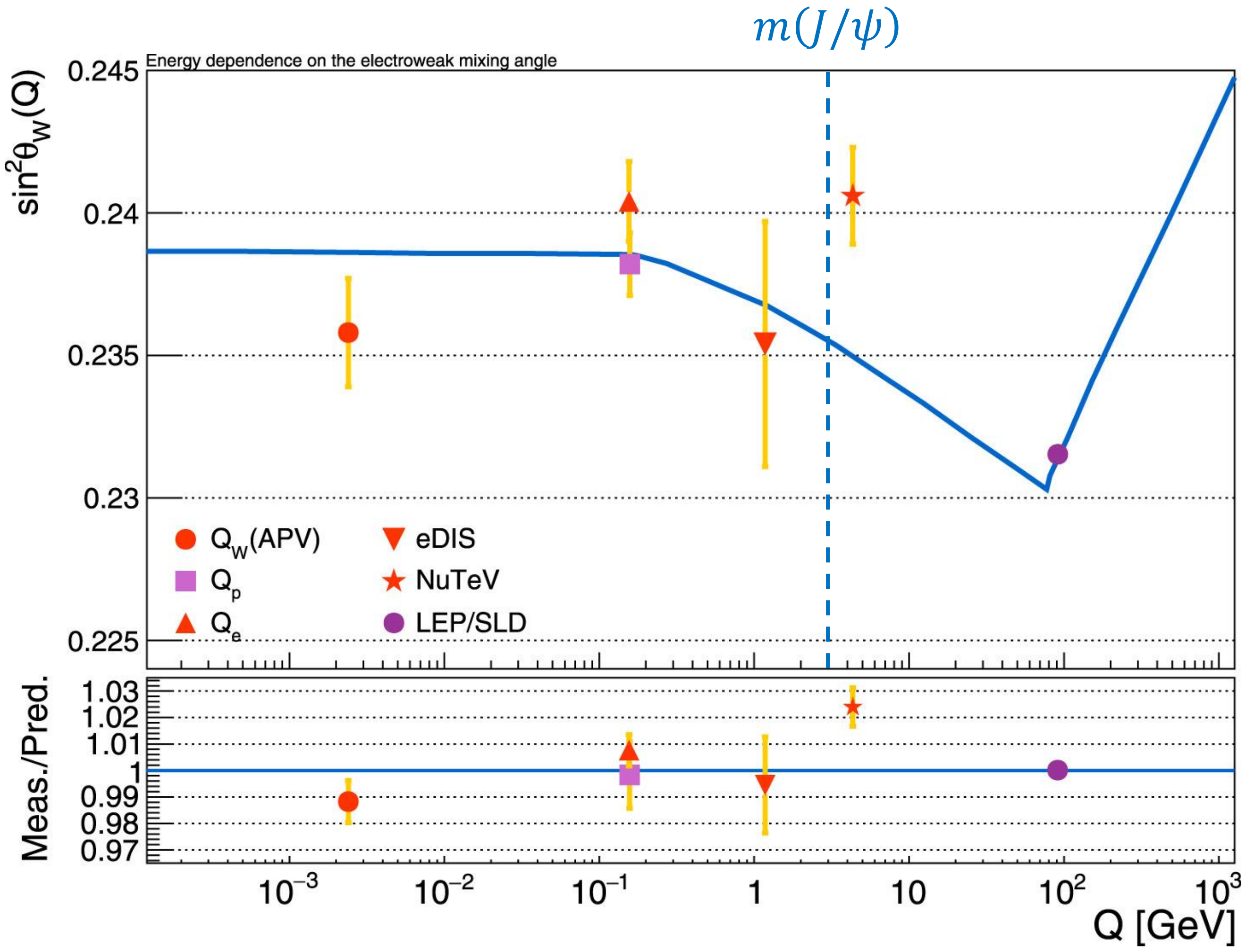
- Effective value due to radiative corrections

$$\sin^2\theta_{\text{eff}}^f \equiv \kappa_Z^f \sin^2\theta_W$$

  Full two-loop EW fermionic and bosonic corrections completed recently

$\sin^2\theta_{\text{eff}}$ measurements

- A_{FB} close to the Z pole
  - $\delta(\sin^2\theta_{\text{eff}}) \approx 0.1\%$
  - $Q = m_Z = 91$ GeV
- Atomic parity violation
  - $\delta(\sin^2\theta_{\text{eff}}) \approx 0.4\%$
  - $Q \sim 10^{-3}$ GeV
- ν and polarized e^- scattering on fixed targets
  - $\delta(\sin^2\theta_{\text{eff}}) \approx 5\%$
  - $Q \sim 1$ GeV
- Planned experiments
  - P2 at MESA (Mainz)
  - Moller at JLab



Left-right asymmetry at J/ψ

- Interference of γ^* and Z^* annihilation

$$A_{LR} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{3/8 - \sin^2\theta_{\text{eff}}^c}{2\sin^2\theta_{\text{eff}}^c\left(1 - \sin^2\theta_{\text{eff}}^c\right)}\left(\frac{m_{J/\psi}}{m_Z}\right)^2 \boxed{\xi} \approx 4.7\times 10^{-4}\xi$$

the average e^- polarization

- Parameters of the SCT experiment
  - Luminosity $L = 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$
  - Cross-section $\sigma(e^+e^- \to J/\psi) \approx 10^{-30}\ \text{cm}^2$
  - One data-taking season $t = 10^7$ s
  - Fraction of J/ψ decays used in the analysis $\varepsilon \approx 0.5$

$$\frac{dA_{LR}}{A_{LR}} \approx \frac{1}{A_{LR}\sqrt{L\sigma t\varepsilon}} \approx 0.5\%$$

СЛАБЫЕ НЕЙТРАЛЬНЫЕ ТОКИ НОВЫХ КВАРКОВ В e^+e^--АННИГИЛЯЦИИ

Ю. И. СКОВПЕНЬ, И. Б. ХРИПЛОВИЧ

ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

(Поступило в редакцию 11 апреля 1979 г.)

и при полной продольной поляризации обеих или хотя бы одной из начальных частиц находим для $q\bar{q}$-резонанса

$$\eta(1,-1) = \eta(1,0) = \eta(0,-1) = \frac{\sqrt{2}Gm^2}{8\pi\alpha|Q|}(1-4|Q|\sin^2\theta). \quad (6)$$

При $\sin^2\theta = 1/4$ [1] эта величина составляет соответственно для ψ- и Υ-пиков

$$\eta_\psi = \frac{\sqrt{2}Gm^2}{16\pi\alpha} \approx 4\cdot 10^{-4},\quad \eta_\Upsilon = \frac{\sqrt{2}Gm^2}{4\pi\alpha} \approx 1{,}6\cdot 10^{-2}. \quad (7)$$

$\sin^2(\theta_{\text{eff}}^c)$ at J/ψ

$$\frac{d\sin^2\theta_{\text{eff}}^c}{\sin^2\theta_{\text{eff}}^c} \approx -0.44\frac{dA_{LR}}{A_{LR}} \oplus 0.44\frac{d\xi}{\xi} \approx 0.3\%$$

- Ultimate one-year precision

$$\sigma(\sin^2\theta_{\text{eff}}^c) \approx 5 \times 10^{-4}$$

- The average electron beam polarization ξ should be controlled with precision of 10^{-3}
  - On-line laser diagnostics
  - Off-line data-driven approach (this talk):

$$e^+e^- \to J/\psi \to [\Lambda \to p\pi^-][\bar{\Lambda} \to \bar{p}\pi^+]$$

$e^+e^- \to J/\psi \to [\Lambda \to p\pi^-][\bar{\Lambda} \to \bar{p}\pi^+]$

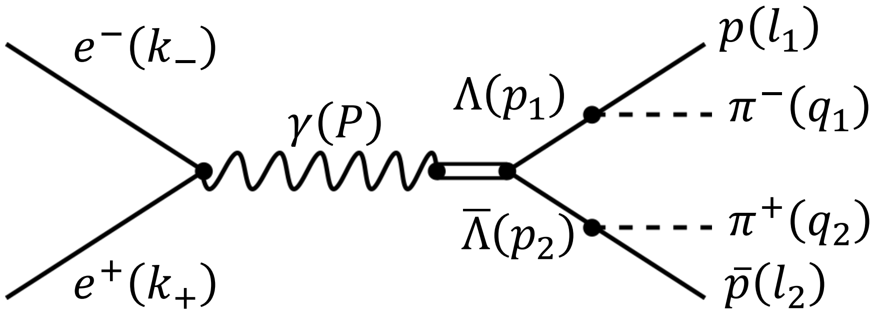
- Leptonic current (z axis along Λ momentum)

$$j_e^\mu \equiv \bar{v}_{-\xi}\gamma^\mu u_\xi = \sqrt{s}(0, \xi\cos\theta\,, i, -\xi\sin\theta)$$

- The $J/\psi \to \Lambda\bar{\Lambda}$ vertex

$$-ie_g\bar{u}_\Lambda(p_1)\left[G_M^\psi\gamma^\mu - \frac{2m_\Lambda}{Q^2}\left(G_M^\psi - G_E^\psi\right)Q^\mu\right]v_{\bar{\Lambda}}(p_2),$$

$$Q \equiv p_1 - p_2$$



- The $\Lambda \to p\pi^-$ ($\bar{\Lambda} \to \bar{p}\pi^+$) vertex

$$\bar{u}_p[\,A + B\gamma^5]u_\Lambda, \qquad (\bar{v}_{\bar{\Lambda}}[\,A' + B'\gamma^5]v_{\bar{p}}), \qquad |A| \sim |B|$$

- Four real form-factors

$$\alpha \equiv \frac{s\left|G_M^\psi\right|^2 - 4m_\Lambda^2\left|G_E^\psi\right|^2}{s\left|G_M^\psi\right|^2 + 4m_\Lambda^2\left|G_E^\psi\right|^2}, \qquad \Delta\Phi \equiv \arg\left(\frac{G_E^\psi}{G_M^\psi}\right), \qquad \alpha_1, \alpha_2$$

Λ and $\bar{\Lambda}$ decay form-factors. CP symmetry implies $\alpha_1 = -\alpha_2$

Leptonic and hadronic tensors

- Leptonic tensor

$$L^{\mu\nu} \equiv (j_e^{\nu})^{\dagger} j_e^{\mu} = k_+^{\mu} k_-^{\nu} + k_-^{\mu} k_+^{\nu} - \frac{s}{2} g^{\mu\nu} - \boxed{\xi i \varepsilon^{\mu\nu\alpha\beta} k_{-\alpha} k_{+\beta}}$$

- Hadronic tensor: separate symmetric and anti-symmetric parts

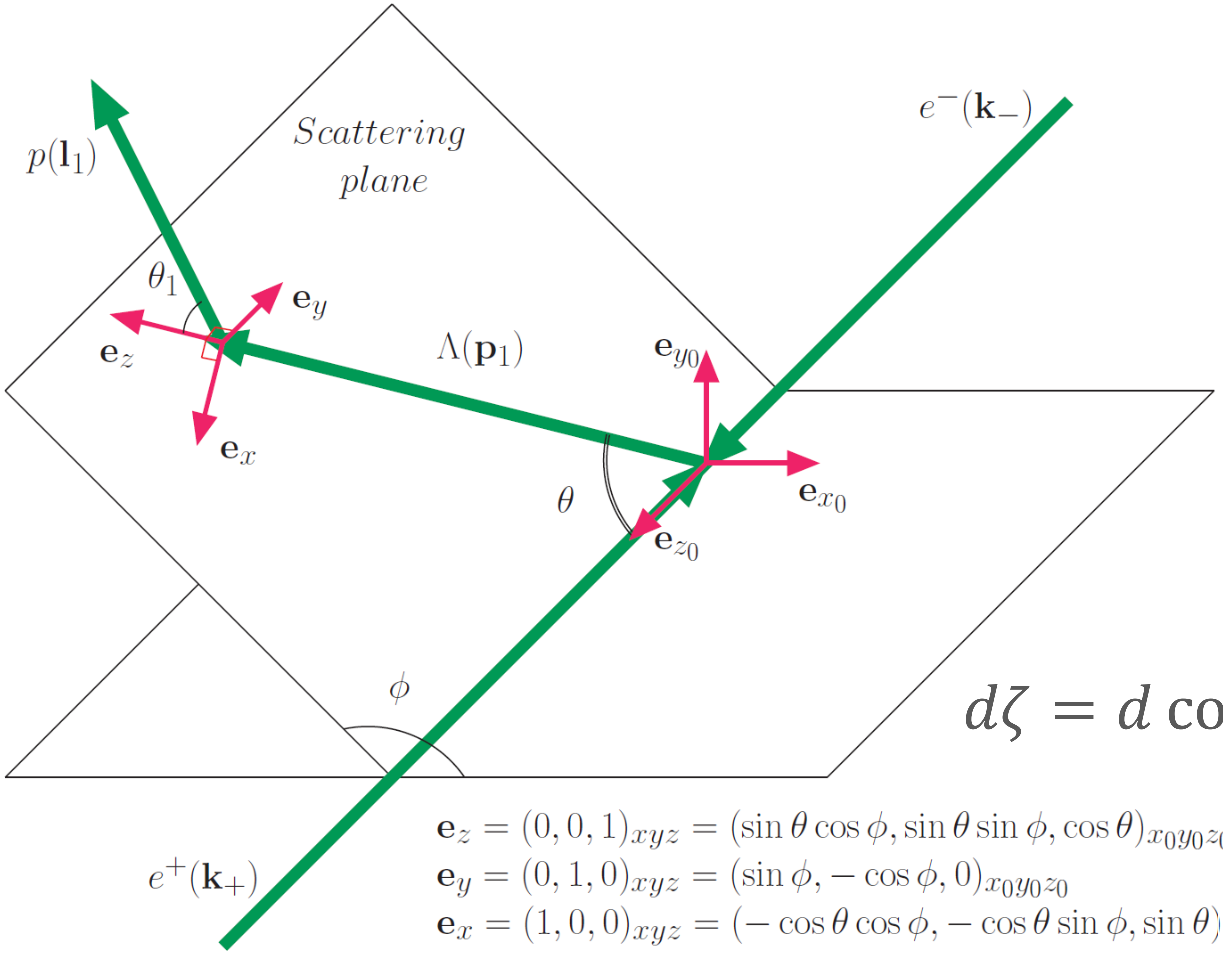
$$H_{\nu\mu} \equiv \widetilde{H}_{\nu\mu} + \overline{H}_{\nu\mu}, \qquad \widetilde{H}_{\nu\mu} \equiv \frac{H_{\nu\mu} + H_{\mu\nu}}{2}, \qquad \overline{H}_{\nu\mu} \equiv \frac{H_{\nu\mu} - H_{\mu\nu}}{2}$$

- Differential cross-section (5D)

$$d\sigma \propto W(\zeta) d\cos\theta \, d\Omega_1 d\Omega_2, \qquad W(\zeta) \propto L^{\mu\nu} H_{\nu\mu} = a + \xi b$$

- Symmetric part calculated in G. Fäldt, Eur. Phys. J. A 51 (2015) 74

Combined reference frame



$$\mathbf{e}_z = (0,0,1)_{xyz} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)_{x_0y_0z_0}$$
$$\mathbf{e}_y = (0,1,0)_{xyz} = (\sin\phi, -\cos\phi, 0)_{x_0y_0z_0}$$
$$\mathbf{e}_x = (1,0,0)_{xyz} = (-\cos\theta\cos\phi, -\cos\theta\sin\phi, \sin\theta)_{x_0y_0z_0}$$

$$e_z = \frac{p}{|p|}$$

$$e_y = \frac{1}{\sin\theta}\left(\frac{p}{|p|} \times \frac{k}{|k|}\right)$$

$$e_x = e_y \times \frac{p}{|p|}$$

$$d\zeta = d\cos\theta\, d\cos\theta_1\, d\varphi_1 d\cos\theta_2\, d\varphi_2$$

Angular distribution

$$W(\zeta) = a + \xi b$$

$$a = F_0 + \alpha F_5 + \alpha_1\alpha_2\left(F_1 + \sqrt{1-\alpha^2}\cos(\Delta\Phi)\,F_2 + \alpha F_6\right) + \sqrt{1-\alpha^2}\sin(\Delta\Phi)\,(\alpha_1 F_3 + \alpha_2 F_4)$$

$$b = (1+\alpha)(\alpha_1 G_1 + \alpha_2 G_2) + \sqrt{1-\alpha^2}\cos(\Delta\Phi)\,(\alpha_1 G_3 + \alpha_2 G_4) + \sqrt{1-\alpha^2}\alpha_1\alpha_2\sin(\Delta\Phi)\,G_5$$

$$\begin{aligned}
\mathcal{F}_0 &= 1,\\
\mathcal{F}_1 &= \sin^2\theta\sin\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 + \cos^2\theta\cos\theta_1\cos\theta_2,\\
\mathcal{F}_2 &= \sin\theta\cos\theta\left(\sin\theta_1\cos\theta_2\cos\phi_1 + \cos\theta_1\sin\theta_2\cos\phi_2\right),\\
\mathcal{F}_3 &= \sin\theta\cos\theta\sin\theta_1\sin\phi_1,\\
\mathcal{F}_4 &= \sin\theta\cos\theta\sin\theta_2\sin\phi_2,\\
\mathcal{F}_5 &= \cos^2\theta,\\
\mathcal{F}_6 &= \cos\theta_1\cos\theta_2 - \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2,
\end{aligned}$$

$$\begin{aligned}
\mathcal{G}_1 &= \cos\theta\cos\theta_1,\\
\mathcal{G}_2 &= \cos\theta\cos\theta_2,\\
\mathcal{G}_3 &= \sin\theta\sin\theta_1\cos\phi_1,\\
\mathcal{G}_4 &= \sin\theta\sin\theta_2\cos\phi_2,\\
\mathcal{G}_5 &= \sin\theta\left(\sin\theta_1\cos\theta_2\sin\phi_1 + \cos\theta_1\sin\theta_2\sin\phi_2\right).
\end{aligned}$$

New!

BESIII analysis

- $1.31 \times 10^9\ J/\psi$ events
- $J/\psi \to [\Lambda \to p\pi^-][\bar{\Lambda} \to \bar{p}\pi^+]$ signal yield 0.42×10^6 (with 400 background events)
- The results

$$\Delta\Phi = (42.4 \pm 0.6 \pm 0.5)^\circ$$
$$\alpha = 0.461 \pm 0.006 \pm 0.007$$
$$\alpha_1 = +0.750 \pm 0.009 \pm 0.004$$
$$\alpha_2 = -0.758 \pm 0.010 \pm 0.007$$


nature > nature physics > letters > article

nature physics

Letter | Published: 06 May 2019

Polarization and entanglement in baryon–antibaryon pair production in electron–positron annihilation

The BESIII Collaboration

Nature Physics **15**, 631–634 (2019) | Download Citation

3334 Accesses | **8** Citations | **45** Altmetric | Metrics

Feasibility study: the procedure

1. Generate phase-space distributed events with EvtGen
2. Accept-reject algorithm with the probability density function $W(\zeta)$
3. Simple detection efficiency (min $p_t = 60\ MeV$, min $\theta = 10°$), perfect momentum resolution and perfect particle identification
4. Maximum likelihood fit with likelihood function

$$-2\ln\mathcal{L} = -2\sum_{i=1}^{N}\ln W(\zeta_i) + 2N\ln\sum_{j=1}^{M}\ln W\left(\tilde{\zeta}_j\right), \qquad M \gg N$$

Signal events

PHSP normalization sample

5D Fit

Setup	SCT one-year σ (10^{-4})			
	ξ	α	$\Delta\Phi$ (rad)	α_i
$\xi = 0$	Fixed	1.5	3.1	2.8
$\xi = 0.8$	1.3	1.2	1.6	0.9

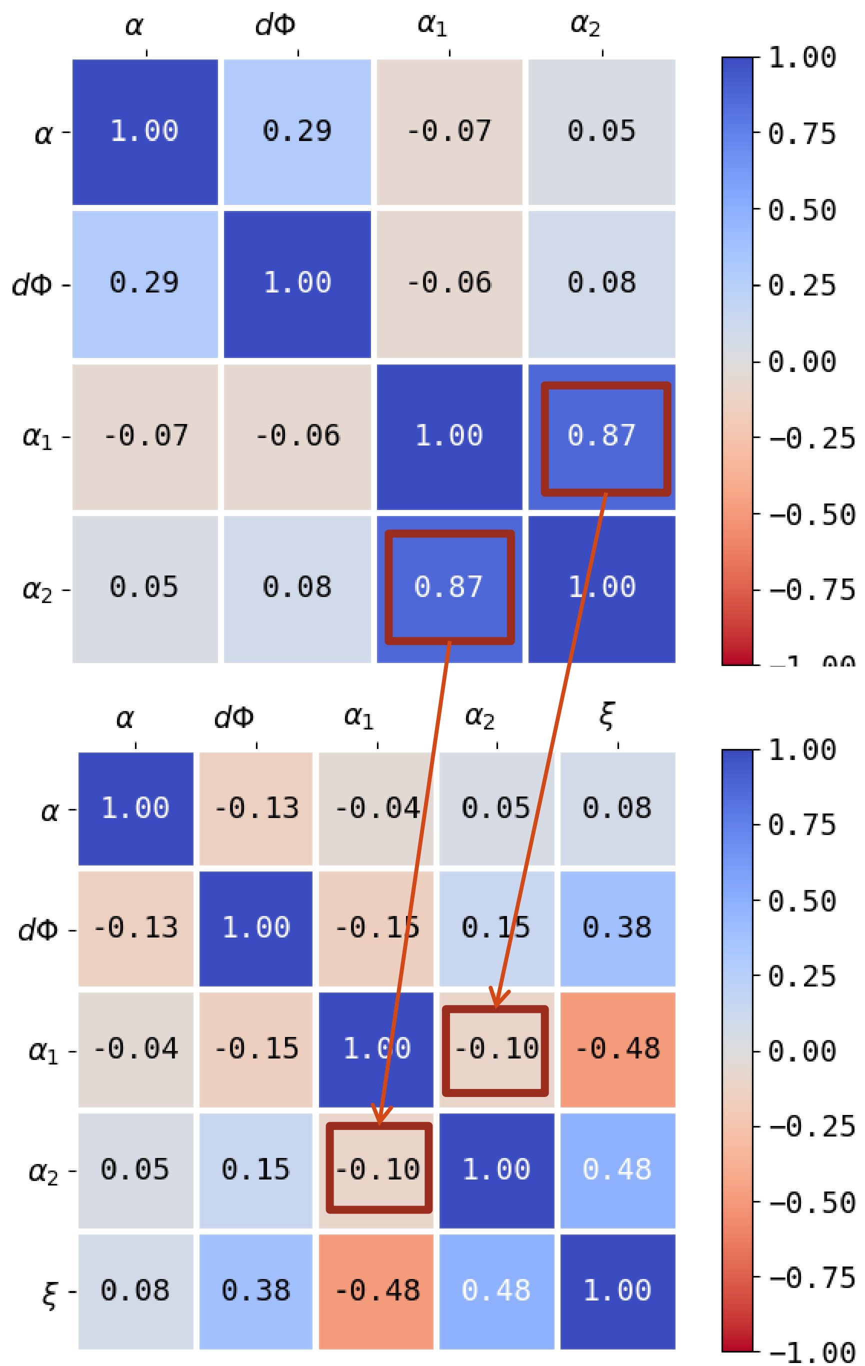
- The expected one-year signal yield at SCT

$$N_{\text{sig}} = 0.8 \times 10^9 \varepsilon_{\text{det}}$$

- ξ_+ and ξ_- are independent fit parameters
- Sensitivity to the *CP*-violating combination $\alpha_1 + \alpha_2$ is increased dramatically due to the beam polarization
  - SM expectation

$$A_\Lambda \equiv \left|\frac{\alpha_1 + \alpha_2}{\alpha_1 - \alpha_2}\right| \lesssim 5 \times 10^{-5}$$

Expected precision: $\sigma(A_\Lambda) = 1.2 \times 10^{-4}$



Single-side observables

- 3D single-side angular distribution

$$\frac{d\sigma}{d\cos\theta \; d\Omega_1} \propto a + \xi b$$

$$a = 1 + \alpha\cos^2\theta + \alpha_1\sqrt{1-\alpha^2}\sin\Delta\Phi\sin\theta\cos\theta\sin\theta_1\sin\phi_1$$

$$b = (1+\alpha)\alpha_1\cos\theta\cos\theta_1 + \alpha_1\sqrt{1-\alpha^2}\cos\Delta\Phi\sin\theta\sin\theta_1\cos\phi_1$$

- The form factors and average beam polarization can be measured using single-side reconstructed events

Setup	SCT one-year σ (10^{-4})			
	ξ	α	$\Delta\Phi$ (rad)	α_i
5D $\xi = 0$	Fixed	1.5	3.1	2.8
5D $\xi = 0.8$	1.3	1.2	1.6	0.9
3D $\xi = 0.8$	4.3	1.2	2.4	3.4

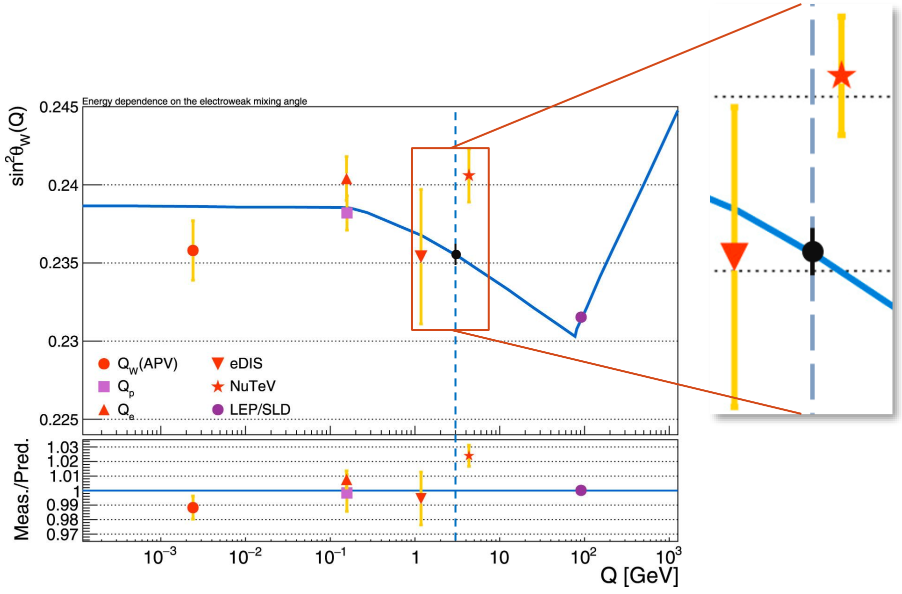
Feasibility study: conclusions

1. The process $e^+e^- \to J/\psi \to [\Lambda \to p\pi^-][\bar{\Lambda} \to \bar{p}\pi^+]$ can be used to control the average beam polarization precisely enough for measurement of the $\sin^2\theta_{\text{eff}}^c$

$$\sigma_{\text{stat}}(\xi) \sim 10^{-4}$$

Systematic uncertainty is to be considered

2. Longitudinal polarization of the electron beam
   - improves Λ baryon formfactors measurement accuracy
   - improves sensitivity to the CP symmetry breaking in Λ decays
   - enriches physics of charmed baryons at SCT (this item is to be further developed)



Subtleties and difficulties

1. Luminosity monitoring
2. Effect of the detector magnetic field
3. Effect of the bunch magnetic field
4. Effect of (non-zero) bunch crossing angle
5. Not equal average positive and negative beam polarization $\xi_+ \neq -\xi_-$
6. Accounting the $e^+e^- \to Z \to J/\psi \to \Lambda\bar{\Lambda}$ amplitude contribution
7. Effect of natural polarization of positrons
8. ???

Luminosity monitoring

$$\sigma_{\pm} = \frac{N_{\pm}}{\mathcal{L}_{\pm}\varepsilon_{\text{eff}}}$$

- Statistical precision $\sigma_{\mathcal{L}}/\mathcal{L} \sim 10^{-6}$ is needed
  - Multiplicative biases vanish in asymmetry
- $\mathcal{L}$ monitoring with Bhabha events

$$\sigma(e^+e^- \to e^+e^-)_{\theta>10^\circ} \approx 1 \times 10^{-30}\ \text{cm}^2 \approx \sigma(e^+e^- \to J/\psi)$$

  - Bhabha events statistics will limit precision
- $\mathcal{L}$ monitoring with dedicated device at low angle
  - Would provide good support for the $\sin^2\theta_{\text{eff}}$ measurement
  - The device should be able to measure bunch-by-bunch luminosity

Detector magnetic field

- $c\tau(\Lambda) = 7.90$ mm
- Λ spin rotation in magnetic field

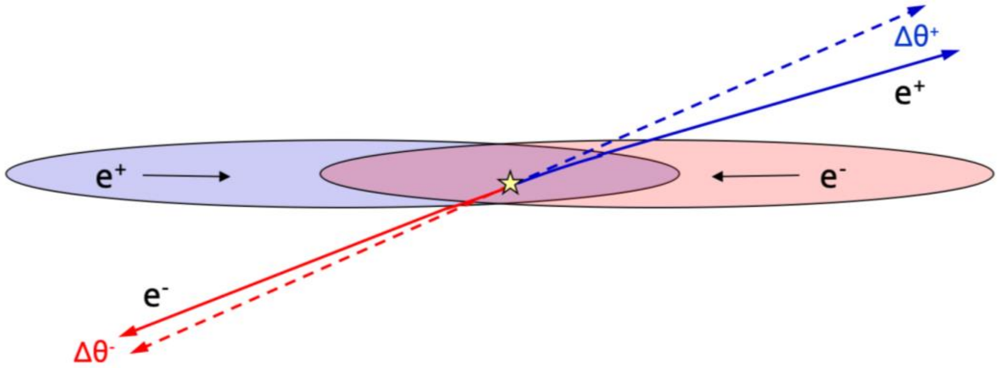
$$\omega = \frac{-2B\mu_\Lambda \mu_N}{\hbar}, \qquad \mu_\Lambda = -0.613$$

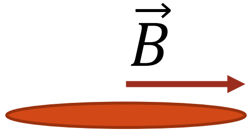
- Λ spin rotation in 1.5 T magnetic field is about 30 mrad
  - A $\sim 10^{-3}$ effect, probably should be taken into account
- Λ flight length-dependent correction
  - Requirements for the spatial and vertex resolution

[H.-B. Li, X.-X. Ma, PRD 100 (2019) 076007]

Bunch magnetic field at SCT

- Bunch current 4.2 mA
- Beam size 0.178μm × 17.8μm × 10mm
- Magnetic field at bunch surface is about 0.01 T
- Correction for the effect of bunch magnetic field should be considered in the Bhabha-measured luminosity

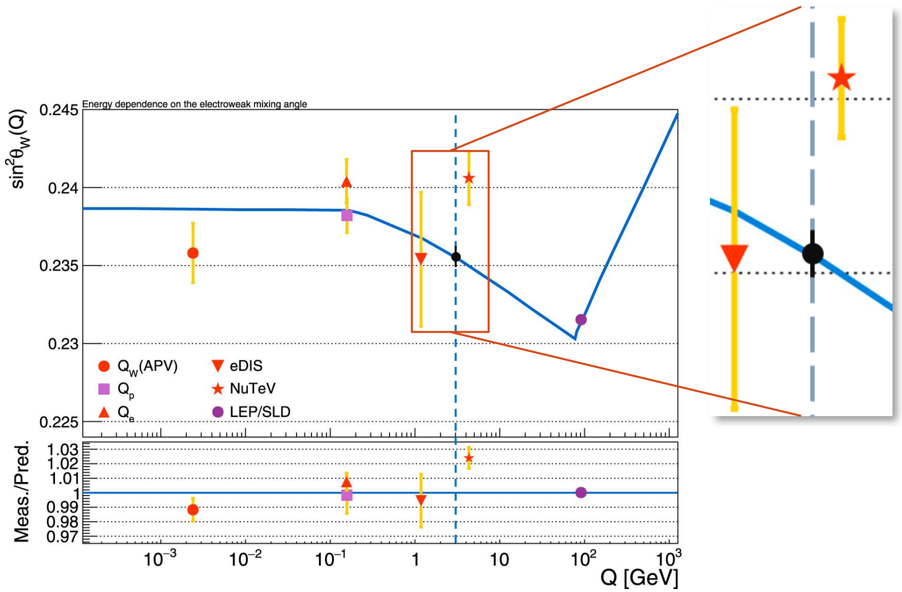




[G. Voutsinas et al., JHEP 10 (2019) 225]

Conclusions

1. SCT with polarized electron beam is a unique experiment to study neutral weak coupling of the charm quark and to measure $\sin^2\theta^c_{\text{eff}}$
2. The decay $J/\psi \to \Lambda\bar{\Lambda}$ can be used as a precise monitor of the average polarization of electrons
3. Baryon physics at SCT with polarized electrons is attractive and needs to be considered in detail
4. Reaching new precision frontiers implies facing new subtle effects



Backup

Experiment at SCT

1. Set beam energy at $\sqrt{s} \approx m(J/\psi)$, about 400 bunches circulate simultaneously
2. Set *random* polarization 0, ξ_+ or ξ_-, $\xi_+ \approx -\xi_-$, for each e^- bunch
3. Count numbers of the $J/\psi \to$ hadrons events N_+ and N_- for the polarizations ξ_+ and ξ_-

$$N_\pm \sim 10^{12}, \qquad \text{event rate} \approx 100\,\text{kHz}$$

4. Calculate the cross sections and left-right asymmetry

$$\sigma_\pm = \frac{N_\pm}{\mathcal{L}_\pm \varepsilon_{\text{det}}}, \qquad A_{LR} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

- Luminosity monitoring and backgrounds
  - Statistical precision $\sigma_\mathcal{L}/\mathcal{L} \sim 10^{-6}$ is needed
  - Biases:
    - Multiplicative bias $\mathcal{L}'_\pm = (1+\kappa)\mathcal{L}_\pm$ vanishes
    - Additive bias δN should be controlled at the level of 10^{-3}

Lambda decay form factor

- $\Lambda \to p\pi^-$ decay with Λ polarization $\boldsymbol{\omega}$ and π^- momentum $\boldsymbol{q}$:
$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_1 \boldsymbol{\omega} \cdot \boldsymbol{q}$$
- $\bar{\Lambda} \to \bar{p}\pi^+$:
$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_2 \boldsymbol{\omega} \cdot \boldsymbol{q}$$
- CP symmetry implies $\alpha_1 = -\alpha_2$. CP asymmetry
$$A_\Lambda \equiv \frac{\alpha_1 + \alpha_2}{\alpha_1 - \alpha_2}$$
is about 5×10^{-5} within the standard model

1D Distributions

- Proton azimuth angle ϕ_1 in Λ frame

$$\frac{d\sigma}{d\phi_1} \propto 1 + \frac{\alpha}{3} + \xi \frac{\pi^2}{16} \alpha_1 \sqrt{1-\alpha^2} \cos\Delta\Phi \cos\phi_1$$

  - Corresponding integral asymmetry

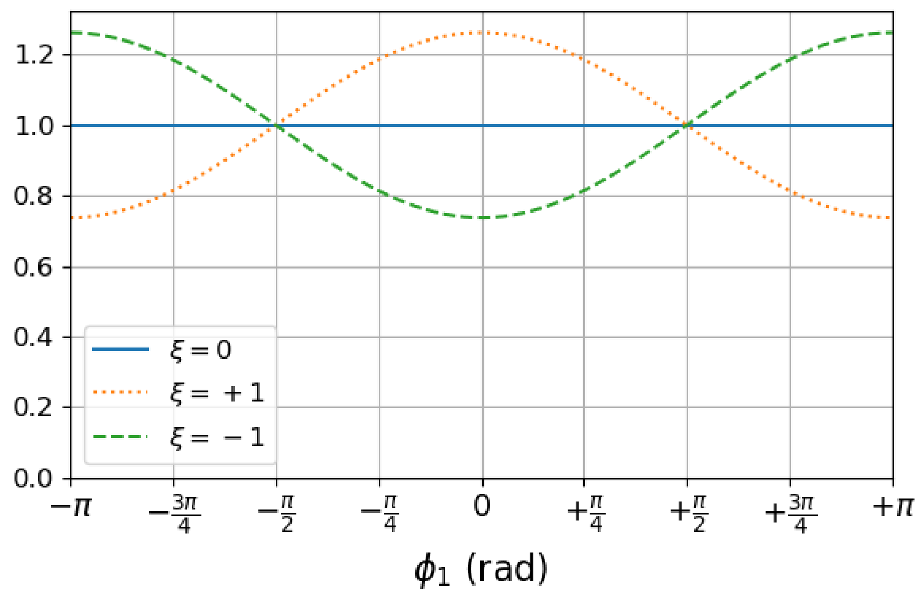
$$A_{\mathrm{LR}} = \xi \frac{3\pi}{8} \frac{\sqrt{1-\alpha^2}}{\alpha+3} \alpha_1 \cos\Delta\Phi \approx 0.17\xi$$

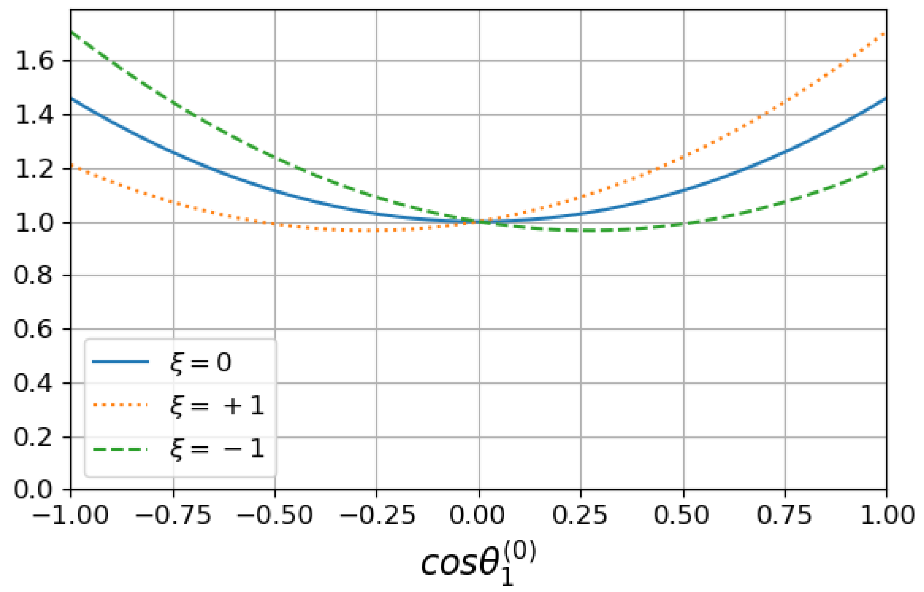
- Proton polar angle in the lab frame

$$\frac{d\sigma}{d\cos\theta_1^{(0)}} \propto 1 + \alpha\cos^2\theta_1^{(0)} + \xi\alpha_1\cos\theta_1^{(0)}\,[0.203(1+\alpha)$$
$$+0.054\sqrt{1-\alpha^2}\cos\Delta\Phi + \mathcal{O}(10^{-2})]$$

  - Integral asymmetry $A_{\mathrm{FB}}^{(0)} \approx 0.11\xi$

can be improved





2D Distribution

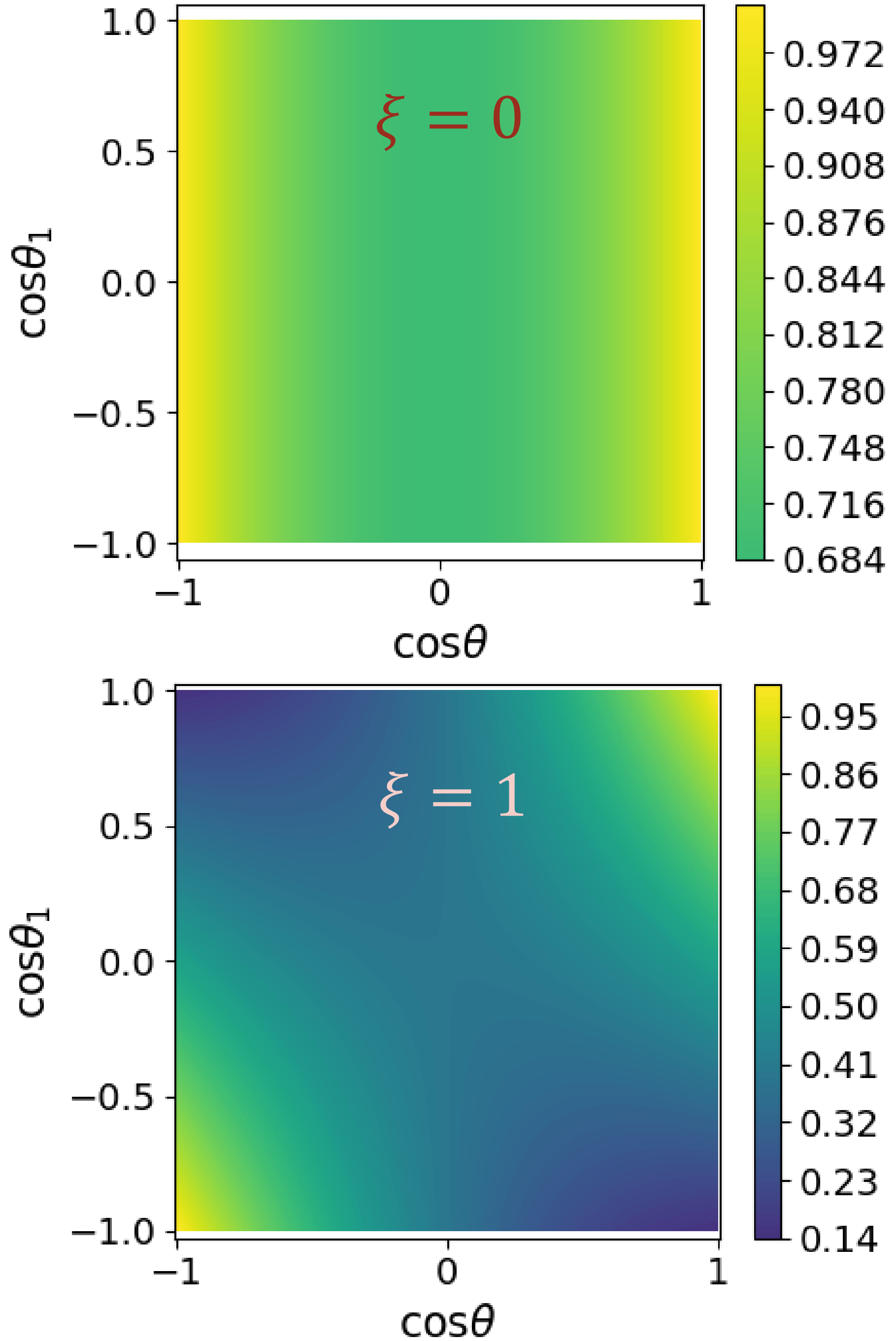
$$\frac{d\sigma}{d\cos\theta\, d\cos\theta_1} \propto 1 + \alpha\cos^2\theta + \xi(1+\alpha)\alpha_1\cos\theta\cos\theta_1$$

- Polarization makes $\cos\theta$ and $\cos\theta_1$ correlated
- Asymmetry can be formed

$$A_{\mathrm{FB}} \equiv \frac{\sigma_{\mathrm{fwd}} - \sigma_{\mathrm{bwd}}}{\sigma_{\mathrm{fwd}} + \sigma_{\mathrm{bwd}}} = \xi\frac{3\alpha_1}{4}\frac{\alpha+1}{\alpha+3} \approx 0.24\xi$$

$$\sigma_{\mathrm{fwd}} \equiv \int_{\cos\theta\cos\theta_1>0} \frac{d\sigma}{d\cos\theta\, d\cos\theta_1} d\cos\theta\, d\cos\theta_1$$

$$\sigma_{\mathrm{bwd}} \equiv \int_{\cos\theta\cos\theta_1<0} \frac{d\sigma}{d\cos\theta\, d\cos\theta_1} d\cos\theta\, d\cos\theta_1$$



$\sin^2\theta_{\text{eff}}$ at colliders

1. LEP
   - Unpolarized e^+e^- beams near the Z pole, 17×10^6 Zs
   - Forward-backward asymmetry
2. SLAC Large Detector (SLD)
   - Polarized e^+e^- beams near the Z pole, 50×10^3 Zs
   - Average beam polarization of 60%
   - Combinations of the forward-backward and left-right asymmetries
3. LHC: ATLAS, CMS, LHCb
   - Unpolarized proton beams
   - Tests of the $Z \to l\bar{l}$ couplings and measurement of the $\sin^2\theta_{\text{eff}}^l$
   - Model-dependent

A_{FB} at LEP

- Annihilation process $e^+e^- \to Z \to f\bar{f}$, unpolarized cross-section

$$\frac{d\sigma}{d\cos\theta} \propto A(1+\cos^2\theta) + B\cos\theta$$

- Forward-backward asymmetry

$$A_{FB}^f \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f,$$

$$A_f \equiv \frac{2 g_v^f g_a^f}{\left(g_a^f\right)^2 + \left(g_v^f\right)^2} = \frac{1 - 4|Q_f|\sin^2\theta_{\text{eff}}^f}{1 - 4|Q_f|\sin^2\theta_{\text{eff}}^f + 8|Q_f|\sin^4\theta_{\text{eff}}^f}$$

- Counting experiment

SLC Experiment

- Polarized beam gives access to the left-right asymmetry

$$A_{LR} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = A_e \xi$$

  ξ is the average polarization of the electron beam

- Forward-backward asymmetry with polarized beam

$$A_{FB}^{f} = \frac{3}{4} A_f \frac{A_e + \xi}{1 + A_e \xi}$$

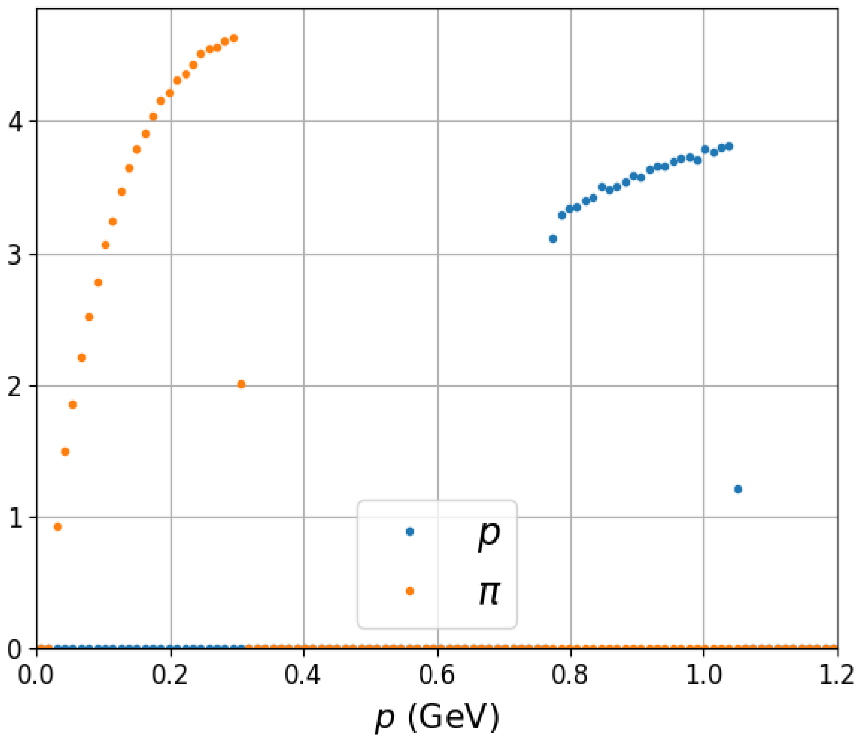
- Left-right forward-backward cross-section ratio

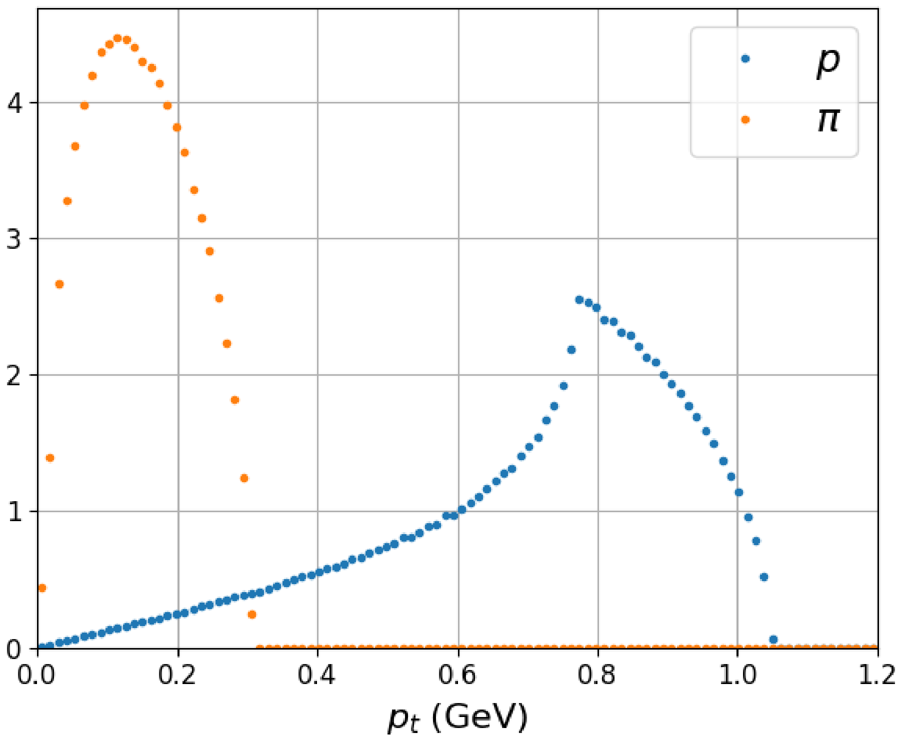
$$A_f = \frac{4}{3} \frac{\sigma_{LF}^{f} + \sigma_{RB}^{f} - \sigma_{LB}^{f} - \sigma_{RF}^{f}}{\sigma_{LF}^{f} + \sigma_{RB}^{f} + \sigma_{LB}^{f} + \sigma_{RF}^{f}}$$

  Counting experiment with direct measurement of A_f

Signal yield and Detection efficiency

$J/\psi \to [\Lambda \to p\pi^-][\overline{\Lambda} \to \bar{p}\pi^+]$





- $p_t > 60$ MeV and $\theta > 10°$ give
  - Double-side detection efficiency $\varepsilon_{\text{det}} = 0.72$
  - Single-side detection efficiency $\varepsilon_{\text{det}}^{\text{ss}} = 0.84$

- $\mathcal{B}_1 \equiv \mathcal{B}(J/\psi \to \Lambda\overline{\Lambda}) = 1.9 \times 10^{-3}$
- $\mathcal{B}_2 \equiv \mathcal{B}(\Lambda \to p\pi^-) = 0.64$
- $N_{\text{sig}}^0 = 10^{12} \times \mathcal{B}_1 \times \mathcal{B}_2^2 \approx 0.8 \times 10^9$

Table 3.8
Overview of the measured asymmetries at the Z pole from the LEP and SLD experiments [19]. The values are compared to the SM prediction and a pull value for each observable, $(\mathcal{O}_{\text{measured}} - \mathcal{O}_{\text{predicted}})/\Delta\mathcal{O}$, is calculated. In addition, the corresponding effective weak mixing angle $\sin^2\theta^l_{\text{eff}}$ is given. The values indicated with an asterisk have been derived within this work.

Observable	Collider	Value	Total unc.	SM expectation	Pull	Corresponding $\sin^2\theta^l_{\text{eff}}$
A_e	LEP	0.1498	0.0049	0.1473 ± 0.0012	0.5	$0.23117 \pm 0.00062^*$
A_τ	LEP	0.1439	0.0043	0.1473 ± 0.0012	−0.8	0.23192 ± 0.00055
$A_{FB}^{0,e}$	LEP	0.0145	0.0025	0.01627 ± 0.00027	−0.7	$0.23254 \pm 0.0015^*$
$A_{FB}^{0,\mu}$	LEP	0.0169	0.0013	0.01627 ± 0.00027	0.5	$0.23113 \pm 0.0007^*$
$A_{FB}^{0,\tau}$	LEP	0.0188	0.0017	0.01627 ± 0.00027	1.5	$0.23000 \pm 0.0009^*$
$A_{FB}^{0,l}$	LEP	0.0171	0.001	0.01627 ± 0.00027	0.8	0.23099 ± 0.00053
$A_{FB}^{0,c}$	LEP	0.0699	0.0036	0.07378 ± 0.00068	−1.1	0.23220 ± 0.00081
$A_{FB}^{0,b}$	LEP	0.0992	0.0017	0.10324 ± 0.00088	−2.4	0.23221 ± 0.00029
A_e	SLD	0.1516	0.0021	0.1473 ± 0.0012	2.0	$0.23094 \pm 0.00027^*$
A_μ	SLD	0.142	0.015	0.1473 ± 0.0012	−0.4	$0.23216 \pm 0.002^*$
A_τ	SLD	0.136	0.015	0.1473 ± 0.0012	−0.8	$0.23259 \pm 0.002^*$
A_l	SLD	0.1513	0.0021	0.1473 ± 0.0012	1.9	0.23098 ± 0.00026
A_c	SLD	0.67	0.027	0.66798 ± 0.00055	0.1	$0.231 \pm 0.008^*$
A_b	SLD	0.923	0.02	0.93462 ± 0.00018	−0.6	$0.25 \pm 0.03^*$

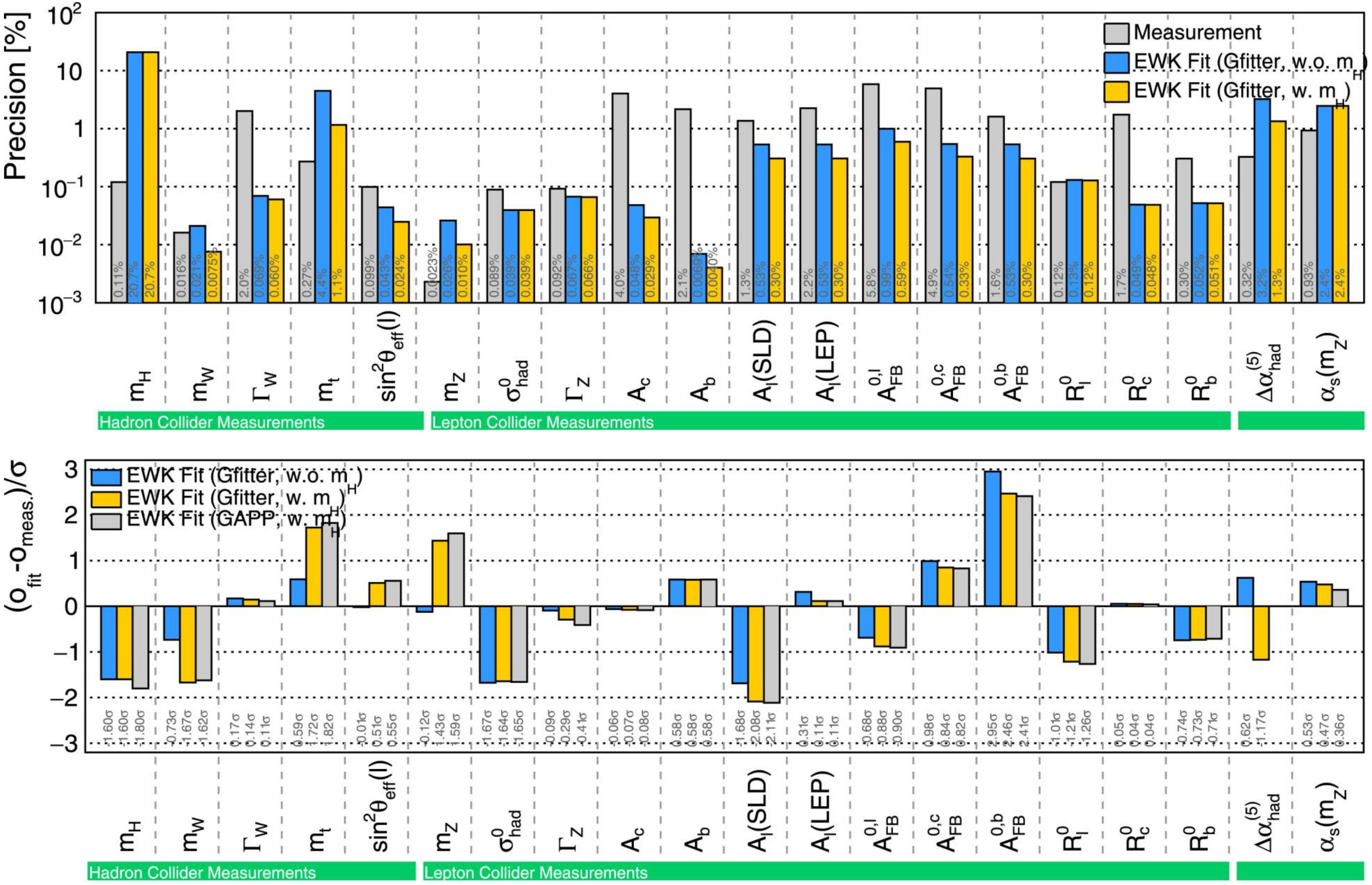
https://doi.org/10.1016/j.ppnp.2019.02.007

Table 3.9
Overview of selected measurements at LEP, SLD, Tevatron and the LHC of the effective leptonic electroweak mixing angle $\sin^2\theta^l_{\text{eff}}$ using different observables including a breakdown of different sources of uncertainties. Values which are indicated with an asterisk have not been published and hence only estimated within this work.

$\sin^2\theta^l_{\text{eff}}$	Value	Stat. unc.	Syst. unc.	PDF unc.	Model unc.	Total unc.	Reference
DØ	0.23095	0.00035	0.00007	0.00019	0.00008	0.00047	[223]
CDF	0.23221	0.00043	0.00003	0.00016	0.00006	0.00046	[224]
Tevatron (combined)	0.23148	0.00027	0.00005	0.00018	0.00006	0.00033	[225]
CMS	0.23101	0.00036	0.00018	0.00030	0.00016	0.00053	[226]
ATLAS (central)	0.23119	0.00031	0.00018	0.00033	0.00006	0.00049	[227]
ATLAS (forward)	0.23166	0.00029	0.00021	0.00022	0.00010	0.00043	[227]
ATLAS (combined)	0.23140	0.00021	0.00014	0.00024	0.00007	0.00036	[227]
LHCb	0.23142	0.00073	0.00052	0.00043*	0.00036*	0.00106	[228]
A_{FB}^{had} (LEP)	0.23240	0.00070	0.00100	–	–	0.00120	[19]
A_l (LEP)	0.23099	0.00042*	0.00032*	–	–	0.00053	[19]
$A_\tau + A_e$ (LEP)	0.23159	0.00037*	0.00018*	–	–	0.00041	[19]
A_{FB}^b (LEP)	0.23221	0.00023*	0.00017*	–	–	0.00029	[19]
A_l (SLD)	0.23098	0.00024	0.00013	–	–	0.00026	[19]

https://doi.org/10.1016/j.ppnp.2019.02.007

Global EW fit



p-value is 0.24

https://doi.org/10.1016/j.ppnp.2019.02.007