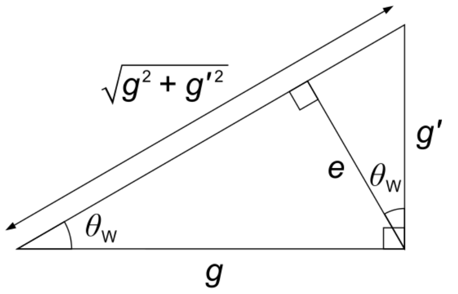
Systematic Uncertainties in measuring the Weinberg angle at SCT

Alex Bondar, Ivan Koop, Alexander Milstein, Alexey Otboev, Vitaly Vorobyev

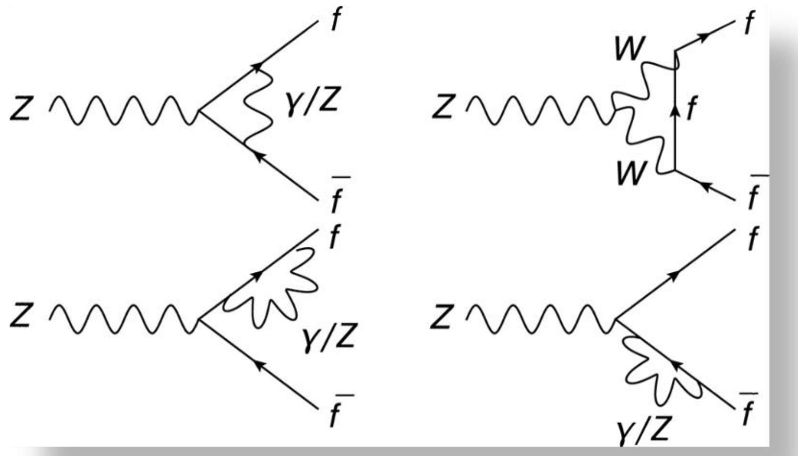
Workshop on future charm-tau factory

November 17th, 2021

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'



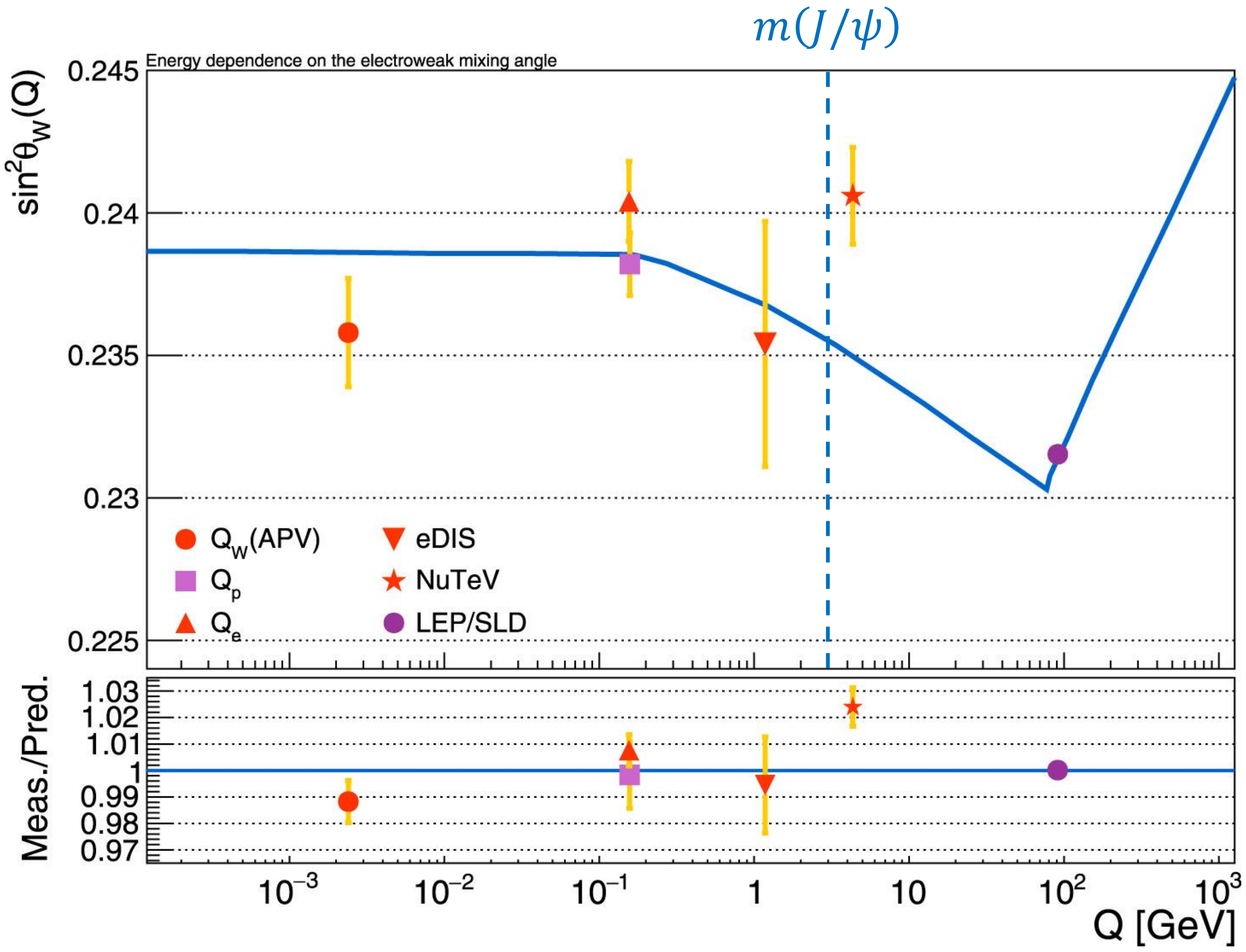
- On-shell definition of the weak mixing angle
$$\sin^2\theta_W \equiv \frac{g'^2}{g^2 + g'^2} = 1 - \frac{m_W^2}{m_Z^2}$$

- 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

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

- A_{FB} close to the Z pole
  - $\delta(\sin^2\theta_{\mathrm{eff}}) \approx 0.0006$
  - $Q = m_Z = 91$ GeV
- Atomic parity violation
  - $\delta(\sin^2\theta_{\mathrm{eff}}) \approx 0.002$
  - $Q \sim 10^{-3}$ GeV
- ν and polarized e^- scattering on fixed targets
  - $\delta(\sin^2\theta_{\mathrm{eff}}) \approx 0.0012 - 0.004$
  - $Q \sim 0.1 - 1$ GeV
- Planned experiments
  - P2 at MESA (Mainz)
  - Moller at JLab



Left-right asymmetry at J/ψ

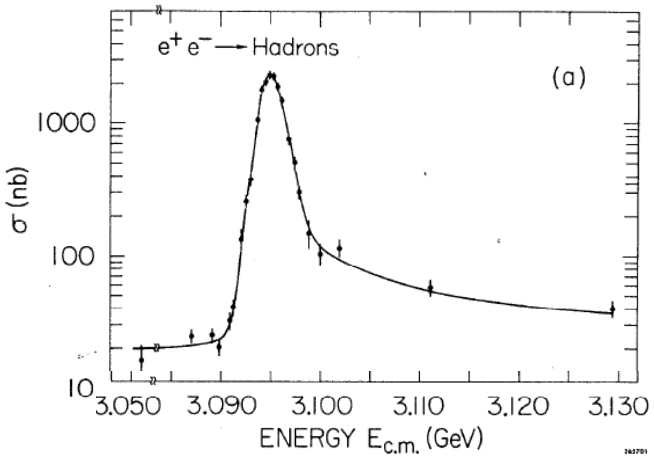
- Interference of γ^* and Z^* annihilation

$$A_{LR} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{3/8 - \sin^2\theta^c_{\text{eff}}}{2\sin^2\theta^c_{\text{eff}}\left(1 - \sin^2\theta^c_{\text{eff}}\right)}\left(\frac{m_{J/\psi}}{m_Z}\right)^2 \boxed{\xi} \approx 4.7\times10^{-4}\xi$$

the average e^- polarization

- Parameters of the SCT experiment
  - Luminosity $L = 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$
  - Cross-section $\sigma(e^+e^- \to J/\psi) \approx 3\times10^{-30}\ \text{cm}^2$
  - One data-taking season $T_{tot} = 10^7$ s
  - Efficiency of J/ψ decays used in the analysis $\varepsilon \approx 0.9$

$$dA_{LR} \approx \frac{1}{\sqrt{L\sigma Ttot\varepsilon}} \sim 10^{-6}$$



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

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

При $\sin^2\theta = {}^1/_4$ [1] эта величина составляет соответственно для ψ- и Υ-пиков

$$\eta_\psi = \frac{\sqrt{2}Gm^2}{16\pi\alpha} \approx 4\cdot10^{-4},\quad \eta_\Upsilon = \frac{\sqrt{2}Gm^2}{4\pi\alpha} \approx 1{,}6\cdot10^{-2}. \qquad (7)$$

$\sin^2(\theta^c_{\text{eff}})$ at J/ψ

$$\frac{d\sin^2\theta^c_{\text{eff}}}{\sin^2\theta^c_{\text{eff}}} \approx -0.44\frac{dA_{LR}}{A_{LR}} \oplus 0.44\frac{d\xi}{\xi} \approx 0.1\%$$

- Ultimate one-year precision

$$\delta(\sin^2\theta^c_{\text{eff}}) \approx 2.5\times10^{-4}$$

- The average electron beam polarization ξ should be controlled with precision better than 10^{-3}
  - On-line laser diagnostics
  - Off-line data-driven approach:

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

JHEP 2020, 76 (2020)

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

Subtleties and difficulties

1. Due to natural radiative polarization the averaged beam polarization $\xi_+ \neq -\xi_-$
2. Beam life time depends on square of polarization degree
3. J/Ψ cross-section depends on beam energy spread. Due to intrabeam scattering the energy spread depends on square of polarization degree
4. Not equal average positive and negative beam polarization $\xi_+ \neq -\xi_-$ may effect on asymmetry measurement
5. Effect of natural polarization of positrons

How to overcome above difficulties?

Experiment at SCT

1. Set beam energy at $\sqrt{s} \approx m(J/\psi)$, about 300 bunches circulate simultaneously
2. Set *random* polarization, ξ_+ or ξ_-, $\xi_+ \approx -\xi_-$, for each e^- bunch
3. During the data taken flip spin of all bunches with high as possible frequency
4. Count numbers of the $J/\psi \to$ hadrons events N_+ and N_- for the polarizations ξ_+ and ξ_-

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

5. Calculate the cross sections and left-right asymmetry

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

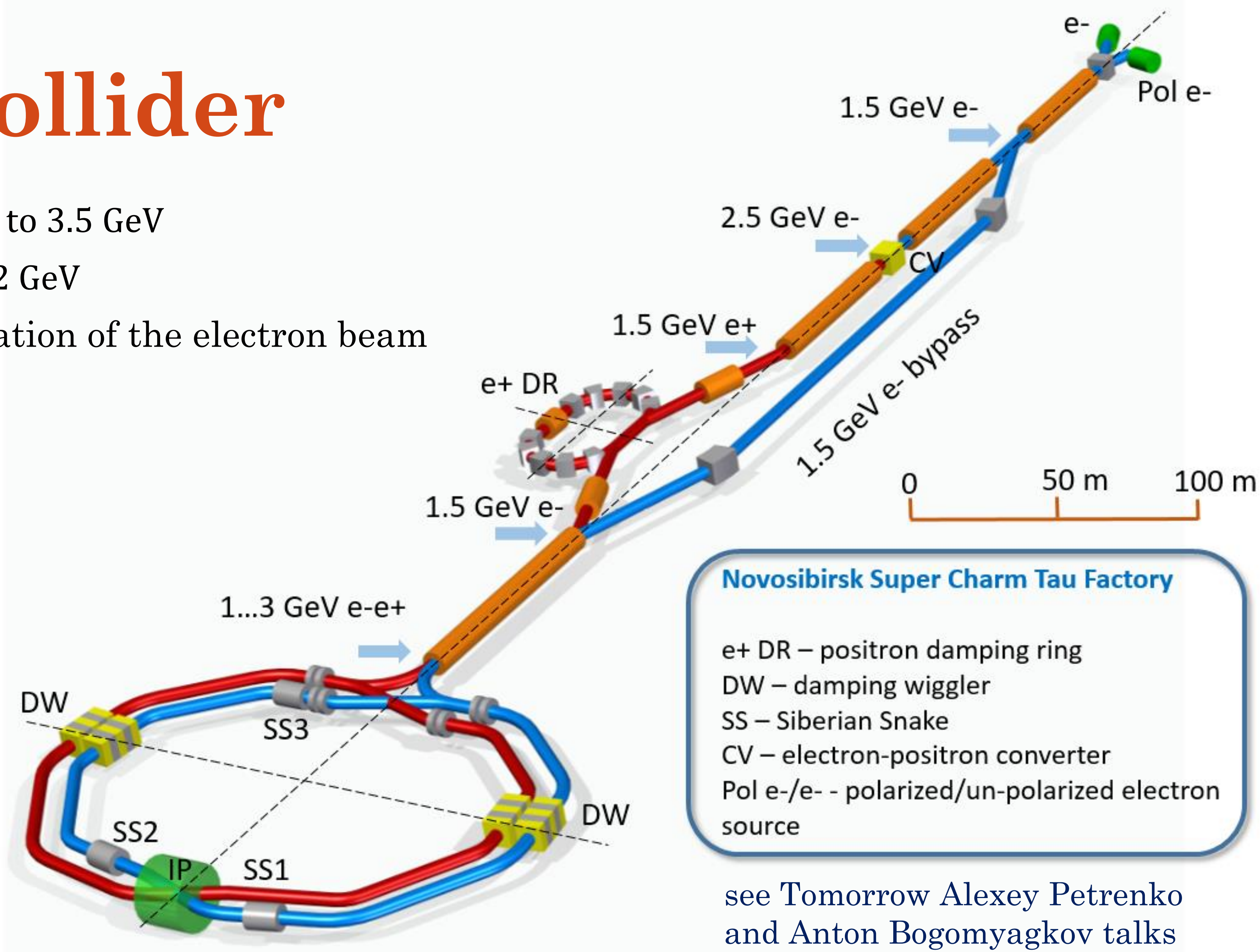
- Luminosity monitoring and backgrounds

  Statistical precision $\sigma_{\mathcal{L}}/\mathcal{L} \sim 10^{-6}$ is needed

SCT collider

- Beam energy: from 1 to 3.5 GeV
- $\mathcal{L} = 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$ @ 2 GeV
- Longitudinal polarization of the electron beam
- Crab-waist collisions

Perimeter	632.94 m		
2θ	60 mrad		
β_x^*/β_y^*	100 mm / 1 mm		
F_{RF}	350 MHz		
E_{beam} (GeV)	**1.5**	**2.5**	**3.5**
I (A)	2	2	2
N_{bunch}	292	328	262
$L_{\text{peak}} \times 10^{35}$ $(\text{cm}^{-2}\text{s}^{-1})$	**0.8**	**1.0**	**1.0**

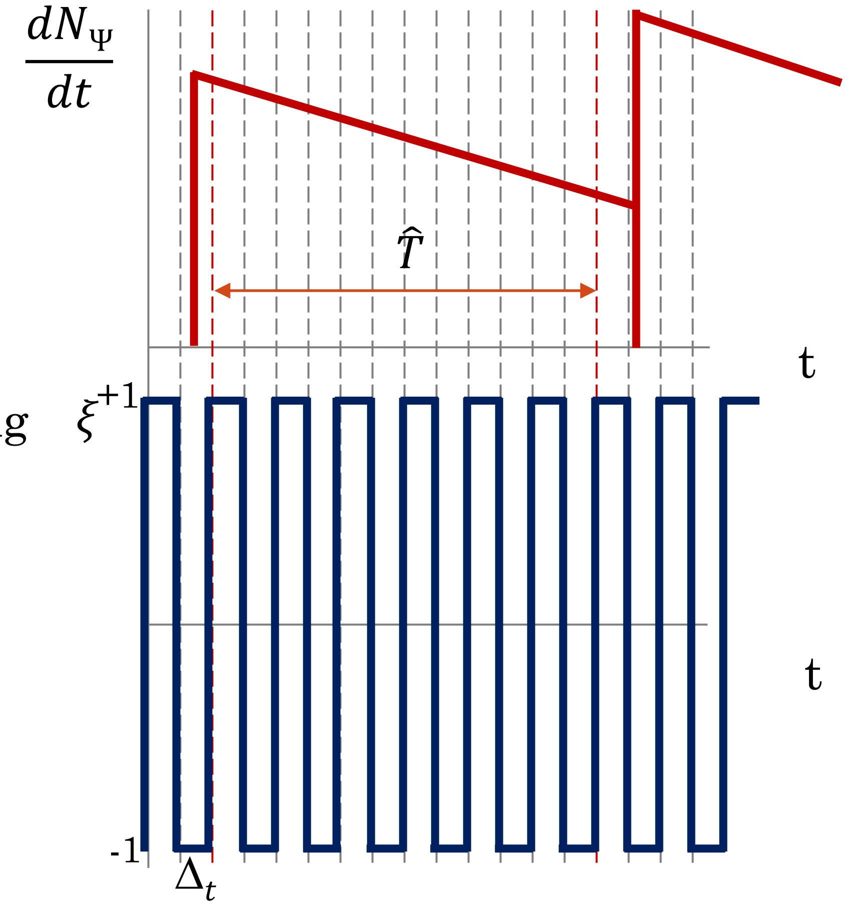


see Tomorrow Alexey Petrenko and Anton Bogomyagkov talks

Systematic errors suppression

A measurement of spin-dependent effects requires periodic reversal of the polarizations of the electron beams. As a rule this procedure does not effect other parameters of the beam.

$$\delta A_{LR}^{Syst} = \frac{\Delta_t}{\tau_L\sqrt{n_B T_{tot}/\hat{T}}} \sim 10^{-6}$$



Δ_t = 5 sec - time interval between spin-flips

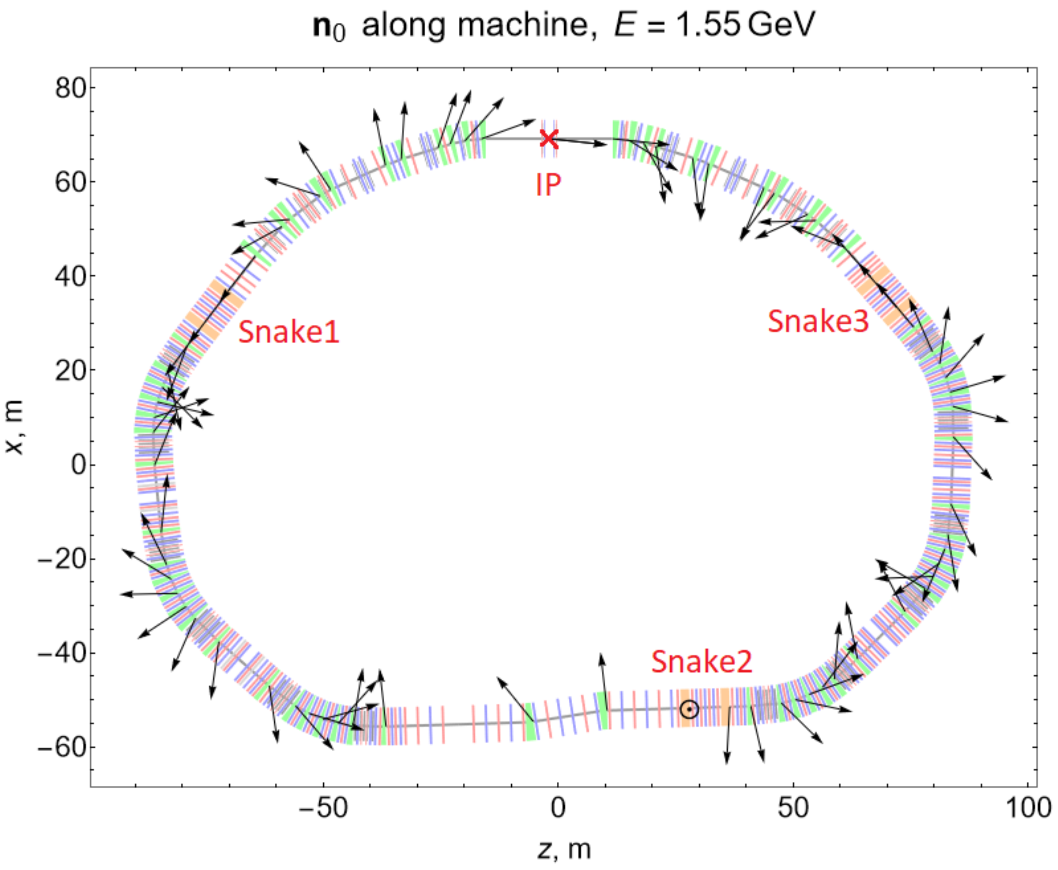
$\hat{T}$ = 300 sec - duration of the single bunch data taking

τ_L = 2000 sec - luminosity life time

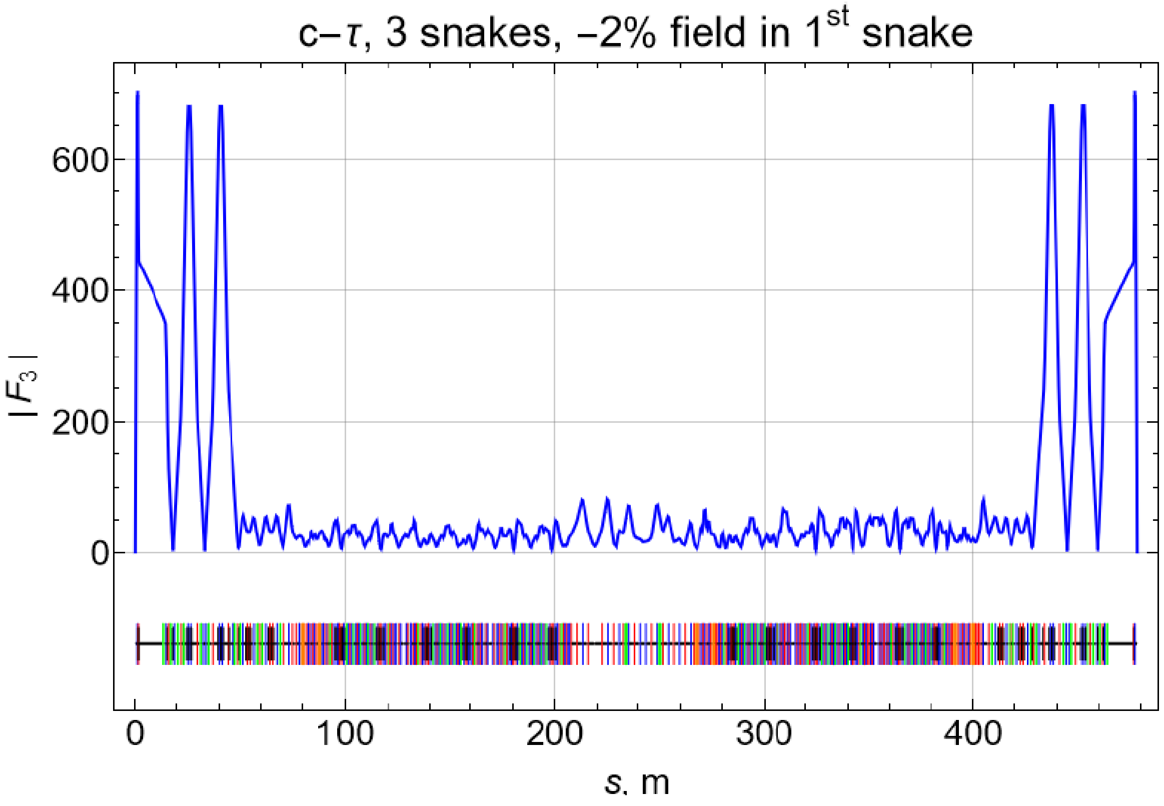
n_B = 300 - number of bunches

T_{tot} = 10^7 sec - time of measurement

Spin motion in the storage ring

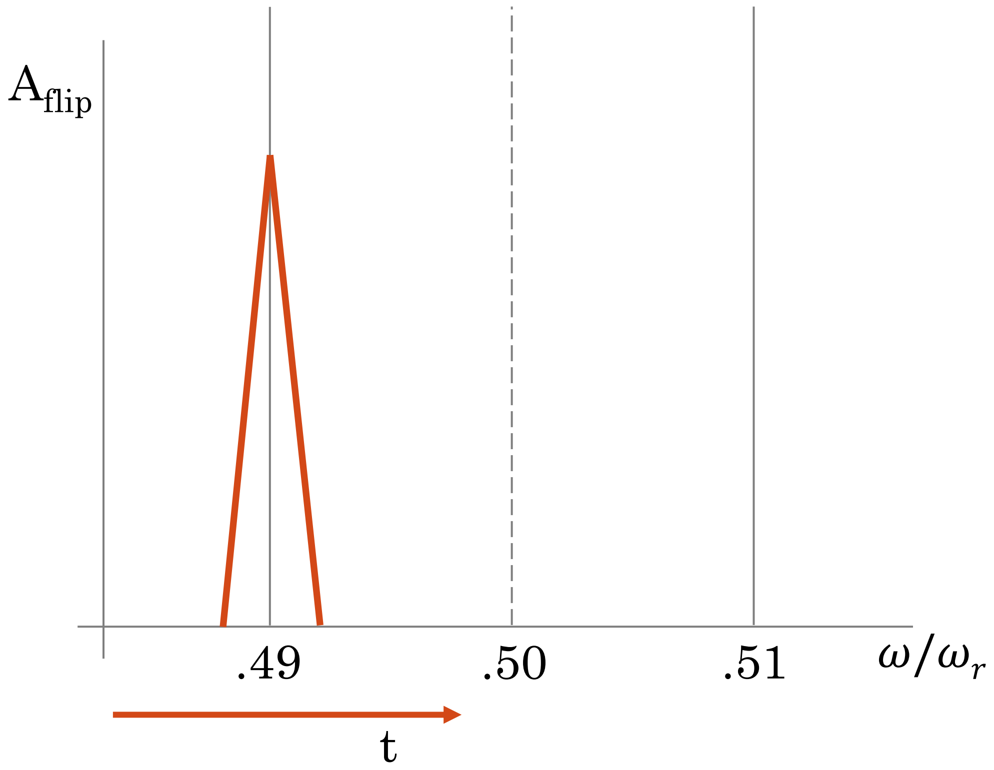


Equilibrium spin direction along the ring. The spin turn is equal to half integer number.

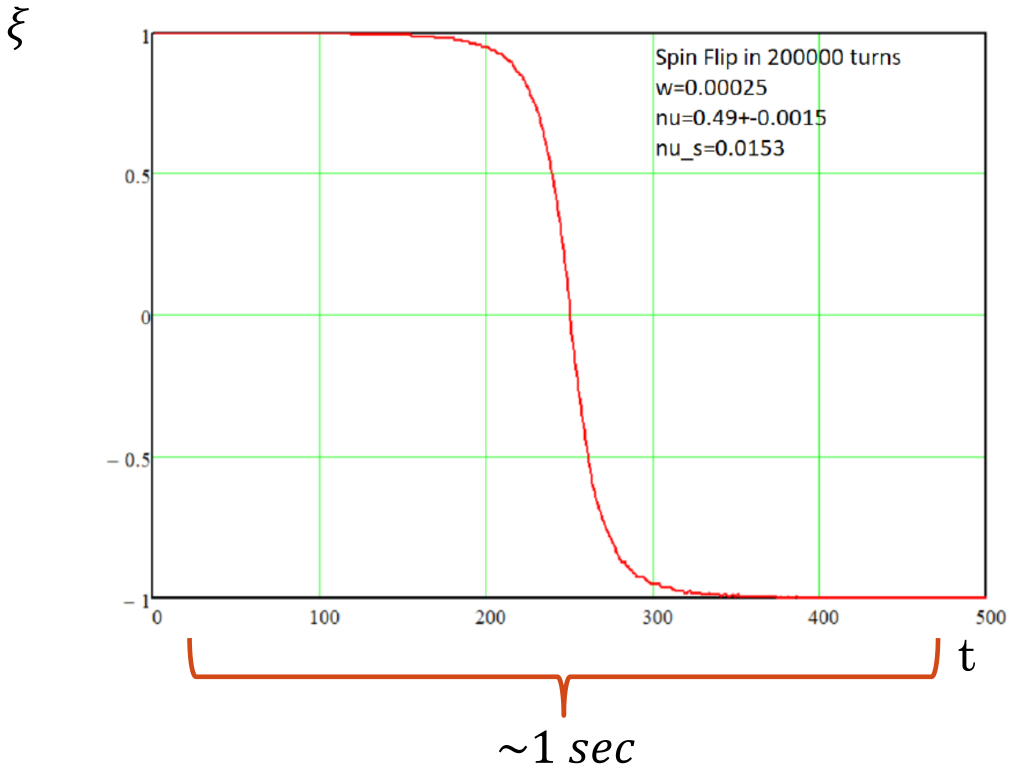


Spin response function to the flipper transverse magnetic field along the ring

Spin flip



Spin Flipper RF-field amplitude variation with field frequency for adiabatic resonant spin flip



Result of the adiabatic resonant spin flip simulation

Requirements to Detector

1. Event time resolution is better than 1 nsec
2. High rate (>100 kHz) event record capability
3. High rate luminosity measurement at small angles

Requirements to Collider

1. High luminosity
2. Electron beams with high degree of longitudinal polarization
3. Fast control bunch by bunch polarization
4. Adiabatic spin flip
5. Flexible beams injection
6. Guaranty depolarization of the positrons ($\xi_{||}<10^{-6}$ at the IP)

Forward - Backward asymmetry

- Annihilation process $e^+e^- \to f\bar{f}$

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

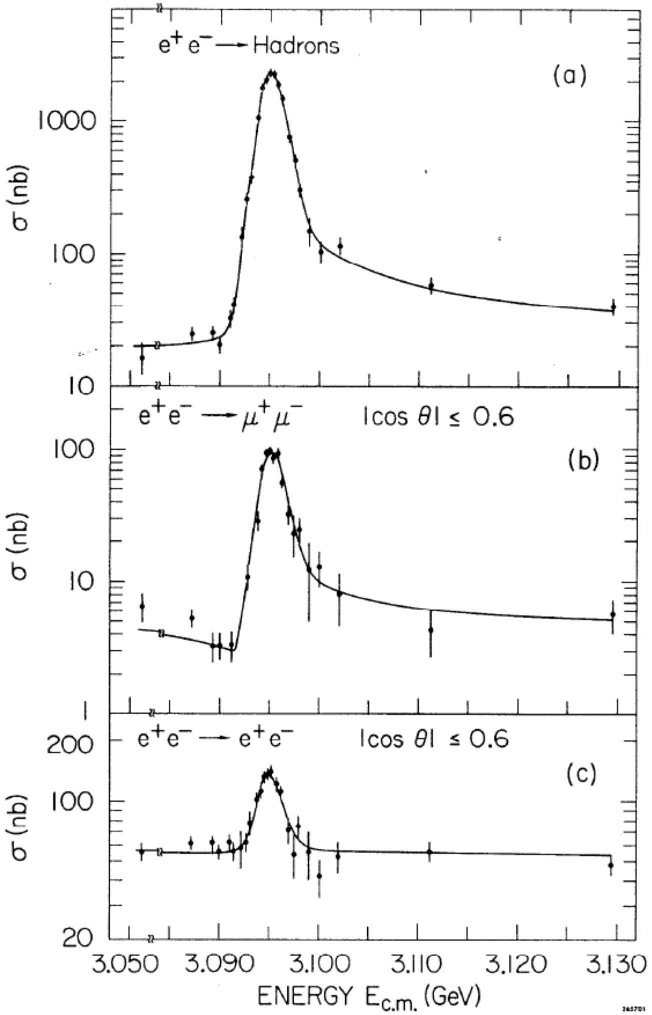
- Forward-backward asymmetry

$$A_{FB}^f \equiv \frac{(\sigma_{LF}-\sigma_{LB})-(\sigma_{RF}-\sigma_{RB})}{(\sigma_{LF}+\sigma_{LB})+(\sigma_{RF}+\sigma_{RB})} = \frac{3}{4}|\xi|A_f,$$

$$A_f \equiv \frac{2g_v^f g_a^f}{\left(g_a^f\right)^2+\left(g_v^f\right)^2} = \frac{1-4|Q_f|\sin^2\theta_{\mathrm{eff}}^f}{1-4|Q_f|\sin^2\theta_{\mathrm{eff}}^f+8|Q_f|\sin^4\theta_{\mathrm{eff}}^f}\left(\frac{m_{J/\psi}}{m_Z}\right)^2$$

- Counting experiment

Forward - Backward asymmetry



- Interference of γ^* and Z^* annihilation
- $A^f_{FB} \equiv \frac{(\sigma_{LF}-\sigma_{LB})-(\sigma_{RF}-\sigma_{RB})}{(\sigma_{LF}+\sigma_{LB})+(\sigma_{RF}+\sigma_{RB})} = \frac{3/8-\sin^2\theta^c_{\text{eff}}}{2\sin^2\theta^c_{\text{eff}}(1-\sin^2\theta^c_{\text{eff}})}\left(\frac{m_{J/\psi}}{m_Z}\right)^2 \xi$ (A.Milstein)

Parameters of the SCT experiment

- Luminosity $L = 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$
- Cross-section $\sigma(e^+e^- \to J/\psi \to \mu^+\mu^-) \approx 0.2\ \times 10^{-30}\ \text{cm}^2$
- One data-taking season $T_{tot} = 10^7$ s

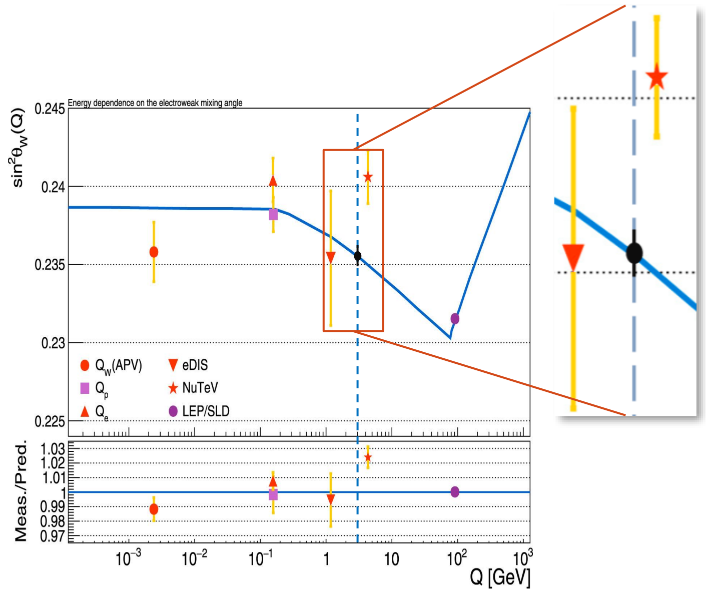
$$dA^f_{FB} \approx \frac{2}{\sqrt{L\sigma Ttot}} \sim 5\ \times dA_{LR} = 5 \times 10^{-6}$$

$$\delta(\sin^2\theta^c_{\text{eff}}) \approx 1.25 \times 10^{-3}$$

5 times less statistical sensitivity, but much less systematic error

Conclusions

1. SCT with polarized electron beam is a unique experiment to study neutral weak coupling of the charm quark and to measure $\sin^2\theta^f_{\text{eff}}$
2. The decay $J/\psi \to \Lambda\bar{\Lambda}$ can be used as a precise monitor of the average polarization of electrons
3. Spin "gymnastics" radically suppresses systematic uncertainties in measuring asymmetry of A_{LR}
4. Measurement of forward backward asymmetry in the $J/\psi \to \mu\bar{\mu}$ even more free from possible systematic errors



Thus, it can be conclude that precision measurement of $\sin^2\theta_W$ at Super C-Tau factory could be feasible

Backup

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

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

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

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

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.

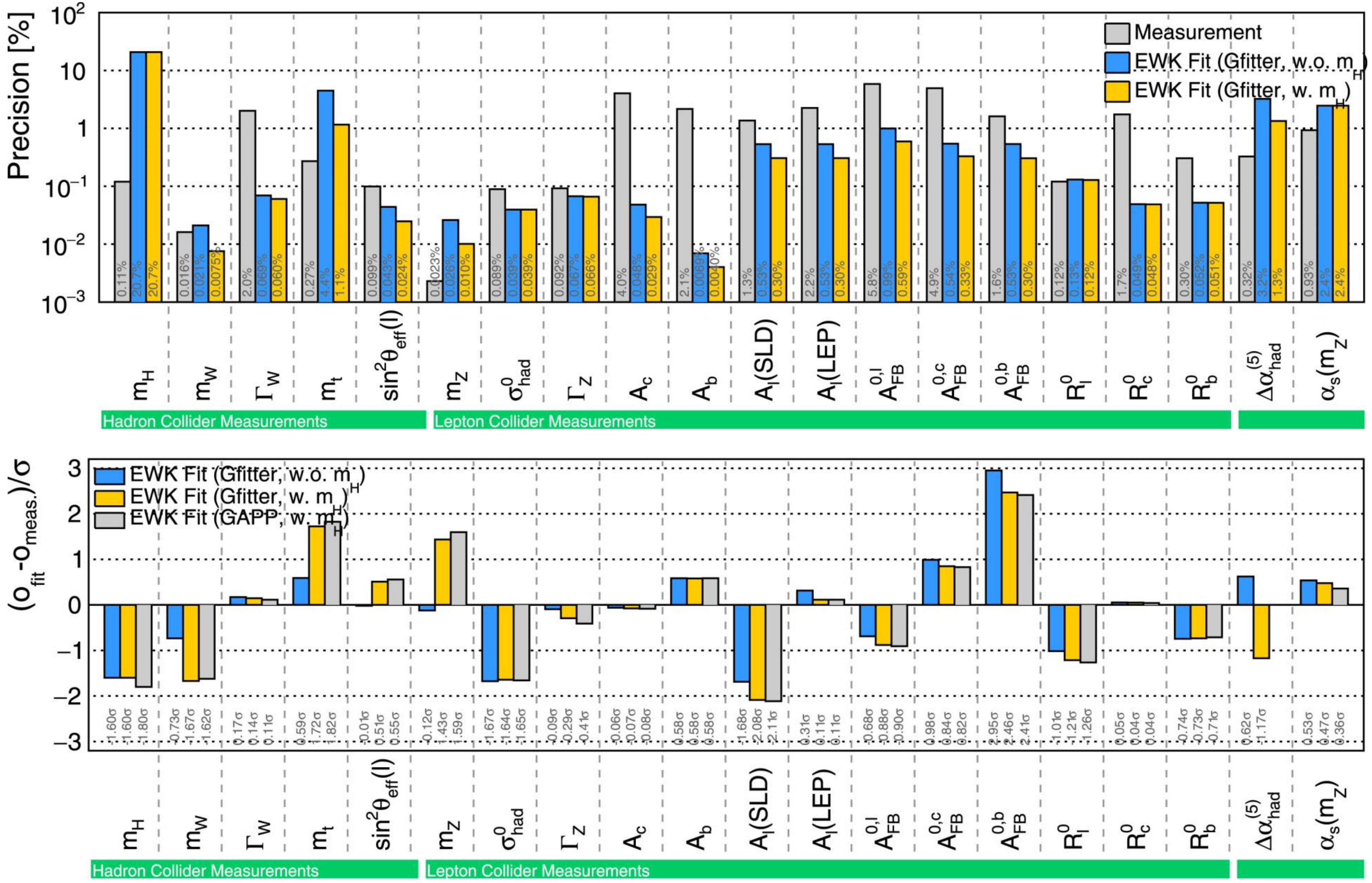
Observable	Collider	Value	Total unc.	SM expectation	Pull	Corresponding $\sin^2\theta^l_{\text{eff}}$
A_e	LEP	0.1498	0.0049	0.1473 ± 0.0012	0.5	$0.23117 \pm 0.00062^*$
A_τ	LEP	0.1439	0.0043	0.1473 ± 0.0012	−0.8	0.23192 ± 0.00055
$A_{FB}^{0,e}$	LEP	0.0145	0.0025	0.01627 ± 0.00027	−0.7	$0.23254 \pm 0.0015^*$
$A_{FB}^{0,\mu}$	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

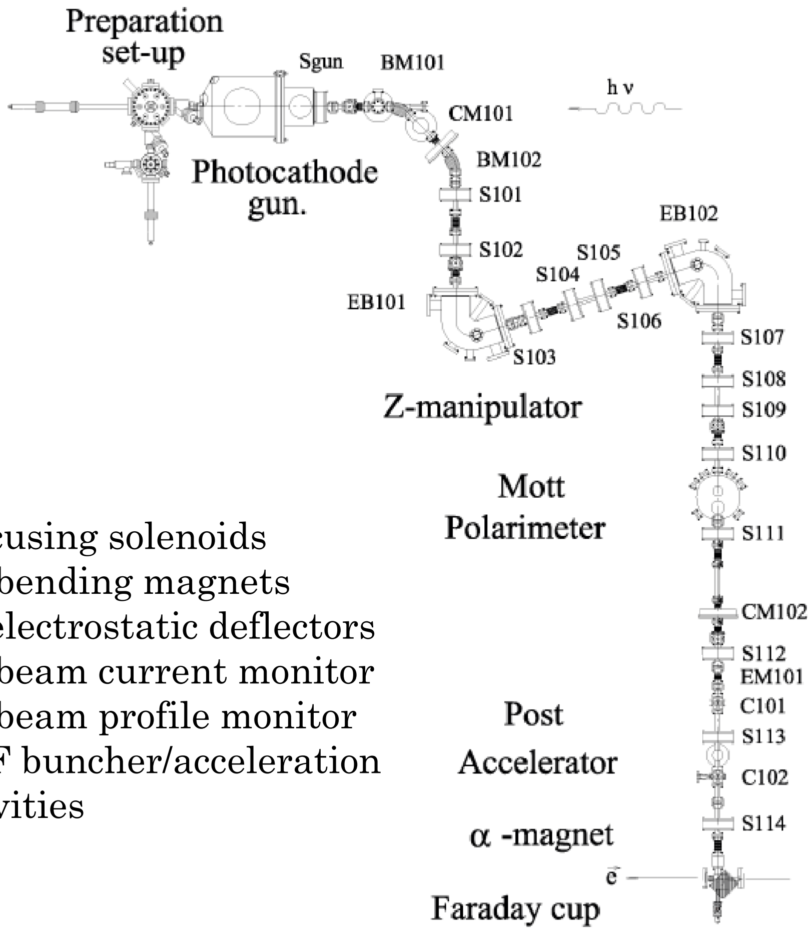
p-value is 0.24

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

Polarized electron source

- Beam polarization 80 %
- Cathode voltage (pulsed) -100 kV
- Photocathode type Strained InGaAsP
- Laser type Ti – Sapphire
- Light wavelength 700 – 850 nm
- Laser power in a pulse 200 W
- Pulse duration 2.1 µs
- Repetition rate 1 Hz
- Maximum current from a gun 150 mA
- Operational current 15 – 20 mA
- Photocathode recesiation time

  (depends on laser power) 190 – 560 hours



S – focusing solenoids
BM – bending magnets
EB – electrostatic deflectors
CM – beam current monitor
EM – beam profile monitor
C – RF buncher/acceleration cavities