Precision electroweak measurements at SuperτC with polarised beams

Michael Roney

University of Victoria

LNF SuperB Meeting
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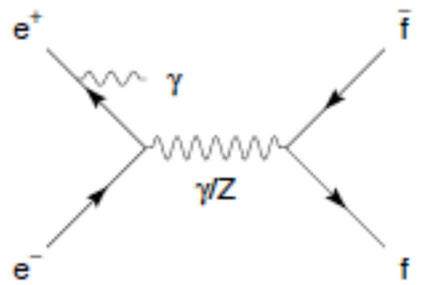
SuperB -> SuperτC:



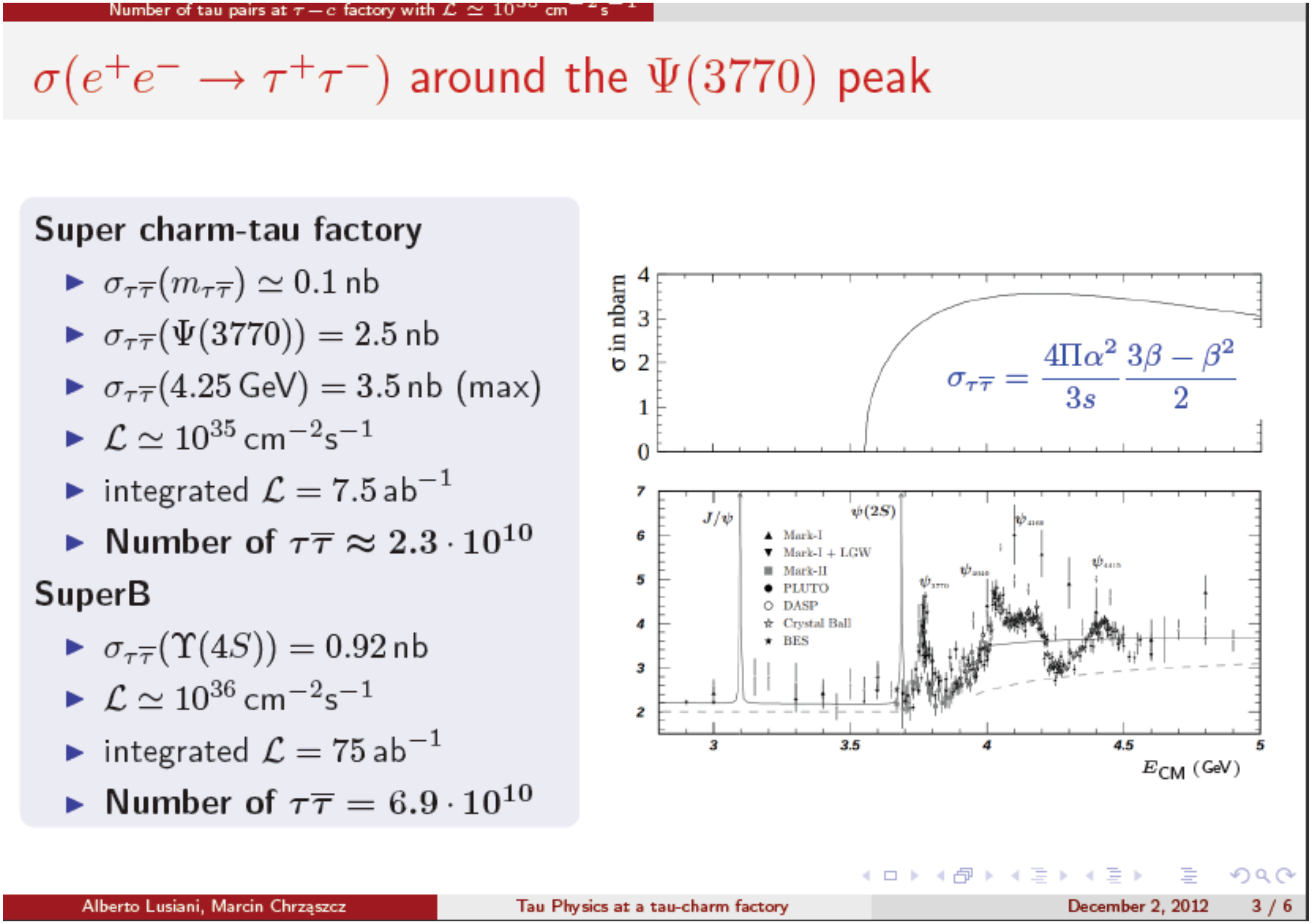
$\mathcal{L}=10^{35}cm^{-2}s^{-1}$, E_{cm}~4GeV, asymmetric e^+e^- collider

- A polarised beam enables an electroweak program:

  caveat –SuperτC numbers are 'rough & new'

- Left-Right Asymmetries (A_{LR}) yield measurements of unprecedented precision of the neutral current vector couplings (g_V) to each of five fermion flavours, f :
  - beauty (D) ← not available at Tau-Charm
  - charm (U)
  - tau
  - muon
  - electron

$$\text{Recall: } g_V^f \text{ gives } \theta_W \text{ in SM} \begin{cases} g_A^f = T_3^f \\ g_V^f = T_3^f - Q_f \sin^2\theta_W \end{cases}$$



Number of tau pairs at $\tau - c$ factory with $\mathcal{L} \simeq 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$

$\sigma(e^+e^- \to \tau^+\tau^-)$ around the $\Psi(3770)$ peak

Super charm-tau factory

- $\sigma_{\tau\overline{\tau}}(m_{\tau\overline{\tau}}) \simeq 0.1\,\text{nb}$
- $\sigma_{\tau\overline{\tau}}(\Psi(3770)) = 2.5\,\text{nb}$
- $\sigma_{\tau\overline{\tau}}(4.25\,\text{GeV}) = 3.5\,\text{nb}$ (max)
- $\mathcal{L} \simeq 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$
- integrated $\mathcal{L} = 7.5\,\text{ab}^{-1}$
- **Number of $\tau\overline{\tau} \approx 2.3 \cdot 10^{10}$**

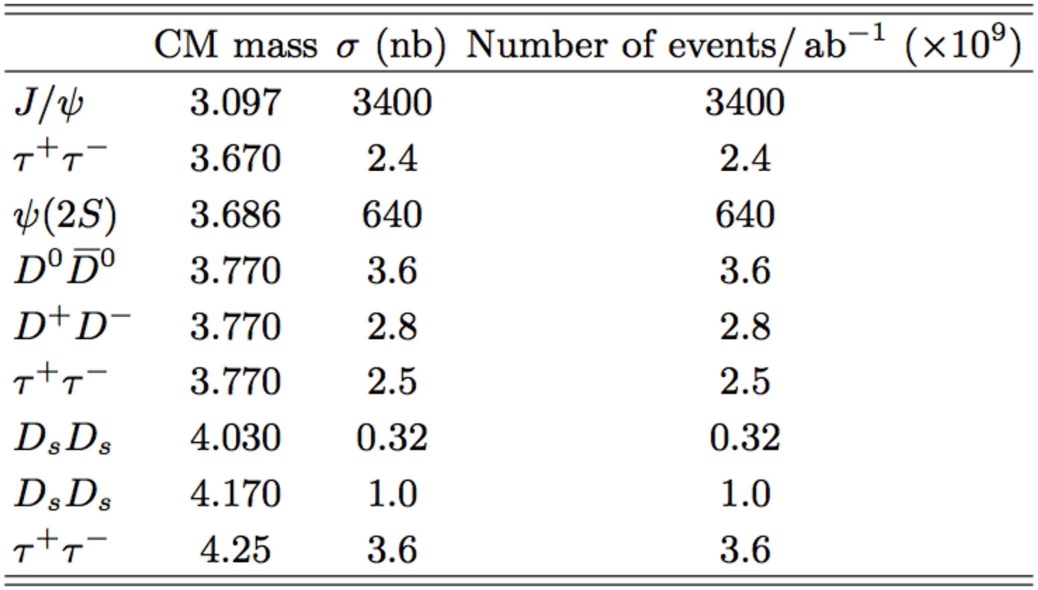
SuperB

- $\sigma_{\tau\overline{\tau}}(\Upsilon(4S)) = 0.92\,\text{nb}$
- $\mathcal{L} \simeq 10^{36}\,\text{cm}^{-2}\text{s}^{-1}$
- integrated $\mathcal{L} = 75\,\text{ab}^{-1}$
- **Number of $\tau\overline{\tau} = 6.9 \cdot 10^{10}$**

$$\sigma_{\tau\overline{\tau}} = \frac{4\Pi\alpha^2}{3s}\,\frac{3\beta - \beta^2}{2}$$

Alberto Lusiani, Marcin Chrząszcz | Tau Physics at a tau-charm factory | December 2, 2012 | 3 / 6

- From Adrian Bevan’s talk:
  - Use physics programme as a guide, starting from the following estimate (BES III Physics Book)
  - ~3ab^{-1} at the ψ(3770)
  - ~4ab^{-1} at other energies (assume 4.03-4.17)



	CM mass	σ (nb)	Number of events/ ab^{-1} ($\times 10^9$)
J/ψ	3.097	3400	3400
$\tau^+\tau^-$	3.670	2.4	2.4
$\psi(2S)$	3.686	640	640
$D^0\overline{D}^0$	3.770	3.6	3.6
D^+D^-	3.770	2.8	2.8
$\tau^+\tau^-$	3.770	2.5	2.5
D_sD_s	4.030	0.32	0.32
D_sD_s	4.170	1.0	1.0
$\tau^+\tau^-$	4.25	3.6	3.6

  - J/ψ and ψ(2S) listed only for completeness
  - Total number of tau pairs taken as: 2.2 x 10^{10}
  - Total number of open charm events taken as: 2.4 x 10^{10}

SuperTC:

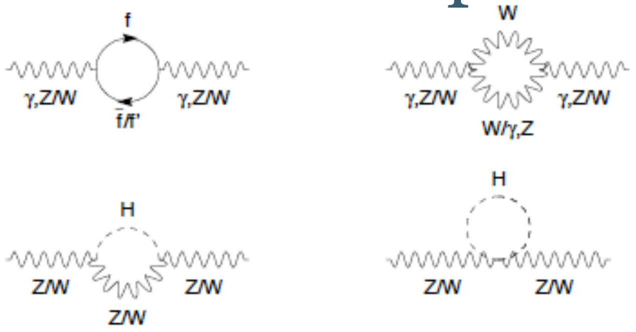
For each of the four fermion flavours

(e, mu, tau, charm) Superτ C provides:

1. determination of the weak mixing angle, vector coupling and from that, $\sin^2\theta_W$
2. study of the running of $\sin^2\theta_W$
3. First-time precision parity violation measurements with e^+e^- $E_{cm}\sim 4$GeV
   - unique probe of potential low energy “dark” (or “hidden”) sector new gauge bosons

At lowest order, the electroweak Standard Model is extensively descriptive with only three input parameters

  - G_F
  - M_Z
  - α
- Can interpret as precision constraints on M_W and the weak mixing angle, $\sin^2\theta_W$
- Deviation from these constraints is a signal for new physics, but higher order corrections need
  - $\Delta\alpha_h^{(5)}$ (hadronic vacuum polarisation corrections)
  - M_{TOP}
  - M_{HIGGS}



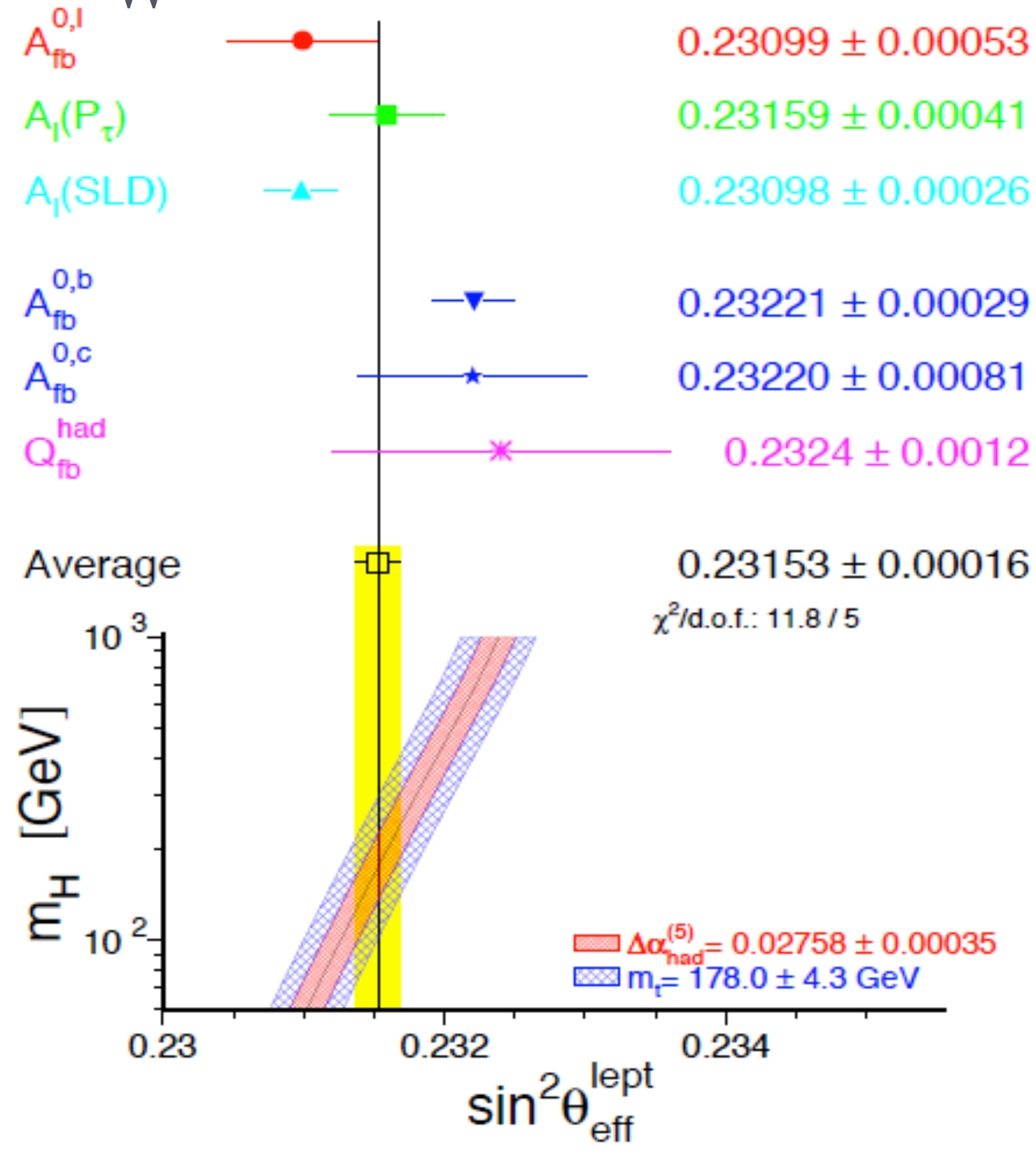
in particular for $\sin^2\theta_W$

$$\sin^2\theta_{\overline{MS}}(M_Z) = 0.23101 + 0.00969\left(\frac{\Delta\alpha_h^{(5)}}{0.02767} - 1\right) - 0.00277\left[\left(\frac{m_t}{178\ \mathrm{GeV}}\right)^2 - 1\right]$$
$$+\ 0.0004908\ \log\left(\frac{m_H}{100\ \mathrm{GeV}}\right)\ +\ 0.0000343\ \left(\log\left(\frac{m_H}{100\ \mathrm{GeV}}\right)\right)^2$$

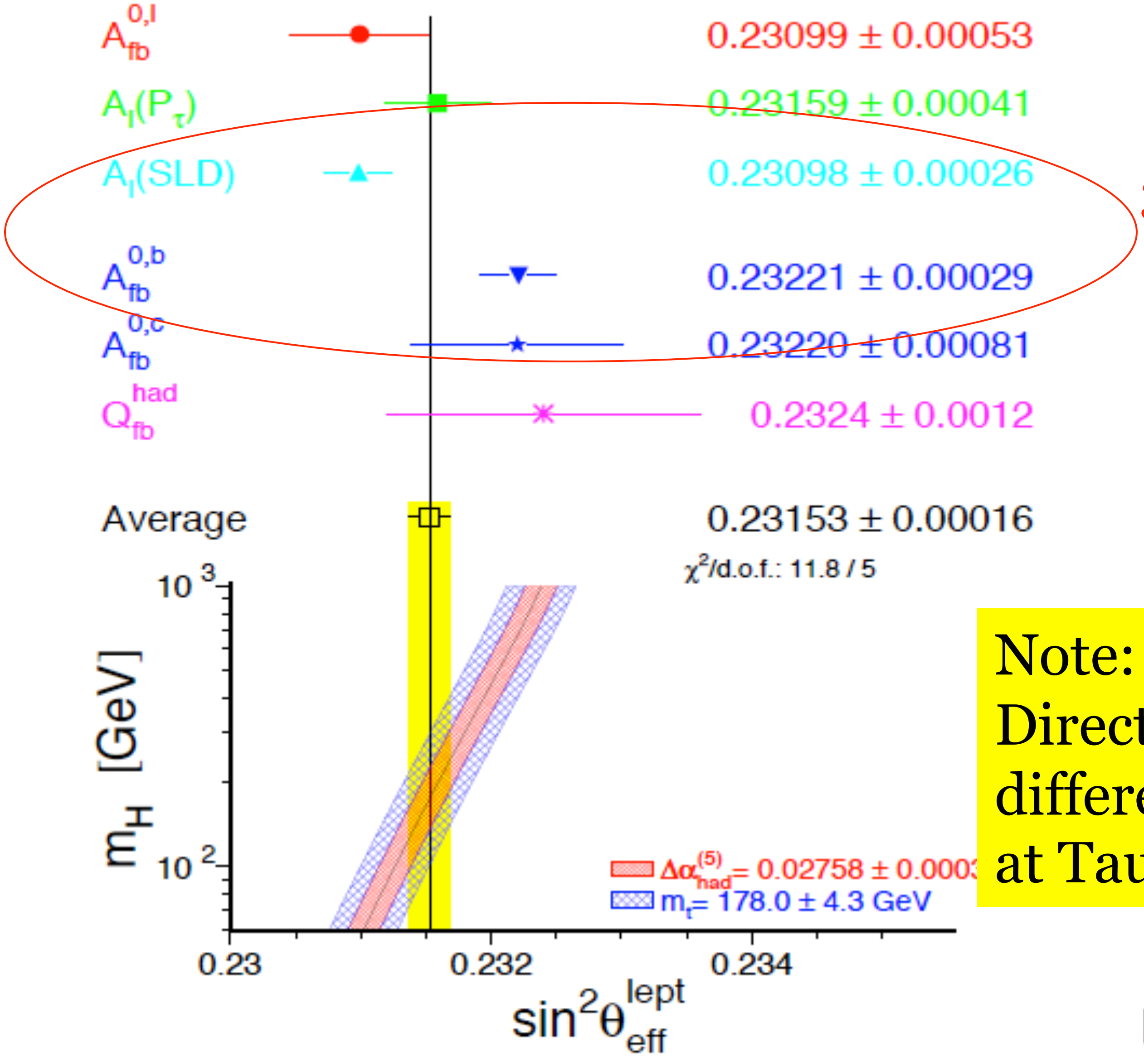
(using parameterization of hep-ph/0203224, hep-ph/0411179 for the MSbar renormalization scheme)

Note LEP/SLC use: $\sin^2\theta^{lept}_{eff} = \sin^2\theta_{\overline{MS}}(M_Z) + 0.00028$

$\sin^2\theta_W$ measurements on the Z-Pole:



Existing tension in data on the Z-Pole:



3.2σ comparing only A_{LR} (SLC) and $A^{o,b}_{fb}$(LEP)

Note:
Directly addressing this difference is not an option at TauCharm

Left-Right Asymmetries

- Measure difference between cross-sections with left-handed beam electrons and right-handed beam electrons
- At ~4GeV, polarised e- beam yields product of the neutral axial-vector coupling of the electron and vector coupling of the final-state fermion via Z-γ interference:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle Pol \rangle$$

$$\propto T_3^f - 2Q_f \sin^2\theta_W$$

$$\langle Pol \rangle = 0.5\left\{\left(\frac{N_R^{e-} - N_L^{e-}}{N_R^{e-} + N_L^{e-}}\right)_R - \left(\frac{N_R^{e-} - N_L^{e-}}{N_R^{e-} + N_L^{e-}}\right)_L\right\}$$

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Left-Right Asymmetries

- Same technique as A_{LR} measurement performed by SLD at the Z-pole used to get the single most precise measurement of $\sin^2\theta_{eff}^{lepton} = 0.23098 \pm 0.00026$
- SuperB would have had a $\sin^2\theta_{eff}^{lepton}$ error of ±0.0002 with 70% electron beam polarisation and 75 ab^{-1} of data assuming lepton universality and 0.5% uncertainty on <*Pol*>

- SuperτC: a $\sin^2\theta_{eff}^{lepton}$ error of ±0.0014 with 70% electron beam polarisation and 7 ab^{-1} of data assuming lepton universality and 1% uncertainty on <*Pol*>

Estimates of Polarisation Systematic errors from Compton Polarimeter… arXiv:1009.6178

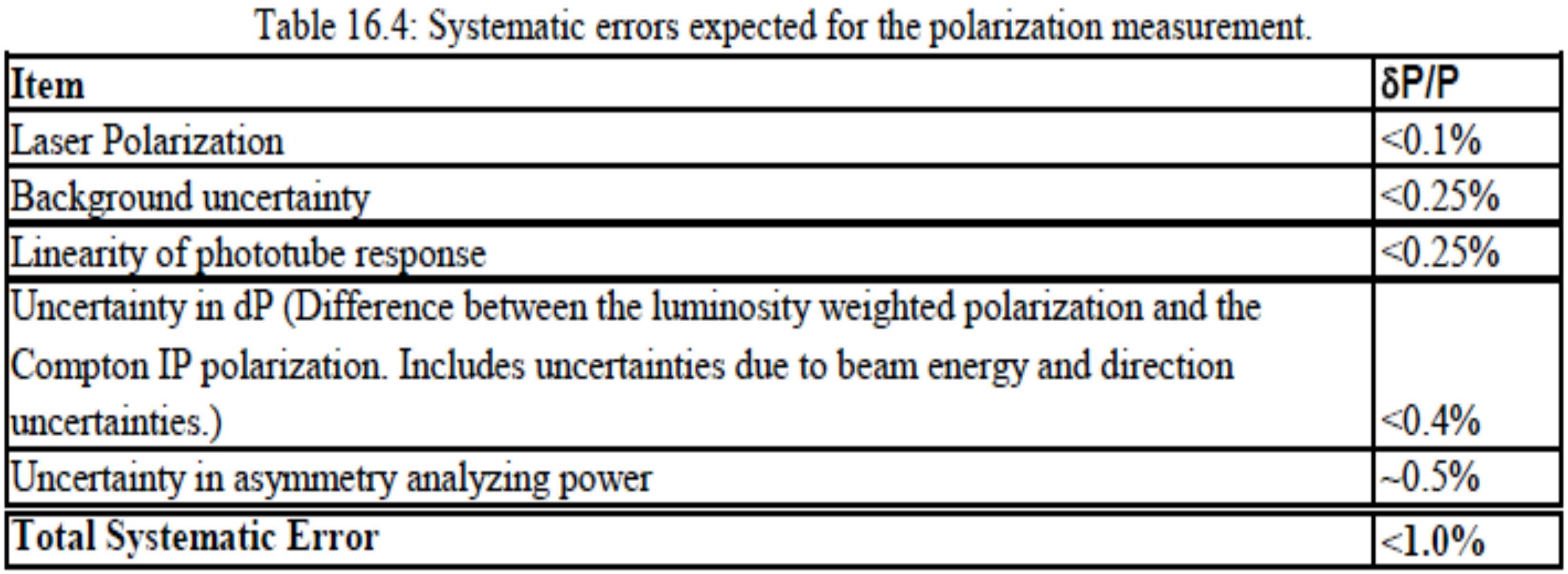


Table 16.4: Systematic errors expected for the polarization measurement.

Item	**δP/P**
Laser Polarization	<0.1%
Background uncertainty	<0.25%
Linearity of phototube response	<0.25%
Uncertainty in dP (Difference between the luminosity weighted polarization and the Compton IP polarization. Includes uncertainties due to beam energy and direction uncertainties.)	<0.4%
Uncertainty in asymmetry analyzing power	~0.5%
Total Systematic Error	<1.0%

Tau Polarisation as Beam Polarimeter

$$P_{z'}^{(\tau-)}(\theta,P_e) = -\frac{8G_F s}{4\sqrt{2}\pi\alpha}\mathrm{Re}\left\{\frac{g_V^l - Q_b g_V^b \Upsilon_{1S,2S,3S}(s)}{1+Q_b^2 \Upsilon_{1S,2S,3S}(s)}\right\}\left(g_A^\tau \frac{|\vec{p}|}{p^0} + 2g_A^e \frac{\cos\theta}{1+\cos^2\theta}\right)$$

$$+ P_e \frac{\cos\theta}{1+\cos^2\theta}$$

- Dominant term is the polarisation forward-backward asymmetry (A^{pol}_{FB}) whose coefficient is the beam polarisation
- Measure tau polarisation as a function of θ for the separately tagged beam polarisation states
- Because it’s a forward-backward asymmetry it doesn’t use information we’d want to use for new physics studies & note EW contribution is small

Tau Polarisation as Beam Polarimeter

- Advantages:
  - Measures beam polarisation at the IP: biggest uncertainty in Compton polarimeter measurement is likely the uncertainty in the transport of the polarisation from the polarimeter to the IP.
  - It automatically incorporates a luminosity-weighted polarisation measurement
  - If positron beam has stray polarisation, it's effect is automatically included
- Experience from OPAL (at LEP) indicates a 0.2% on systematic error on the A^{pol}_{FB} is achievable, translates into 0.5% error on the beam polarisation
- Need to assess if statistical error on A^{pol}_{FB} still significantly smaller than this systematic error at SuperτC

Tau Polarisation as Beam Polarimeter

- Major Question:
    - At 3770MeV, the CM momentum of a tau is 630MeV
    - Is this sufficient for the tau's to still yield a sufficiently precise measurement of A^{pol}_{FB}?
    - This would have to be studied but a Compton Polarimeter is more important at SuperτC factory;
        - Could limit systematic error on A_{LR} to 1% (below expected statistical error)

SuperTC Left-Right Asymmetries

Fermion flavour	**No. events** (billions) **(assumed eff %)**	**No. selected events (billions)**	**SM g_V^f (M_Z)**	**A_{LR} 70% Pol**	**A_{LR} Rel. Stat error (%)**	**g_V^f Total Error**	**$\mathrm{Sin}^2\theta_W(M_Z)$ Total Error (LEP/SLC values)**
charm	24 (30%??)	7.2	+0.1920 ±.0002	-5×10^{-4}	2.6%	0.005	±0.004 (0.2355±0.0059)
tau	22 (25%)	5.5	-0.0371 ±.0003	-6×10^{-5}	28%	0.010	±0.005
muon	56 (54%)	30	-0.0371 ±.0003	-6×10^{-5}	12%	0.004	±0.002
electron		~30	-0.0371 ±.0003	-6×10^{-5}	12%	0.004	±0.002
leptons			-0.0371 ±.0003	-6×10^{-5}	7%	0.003	±0.0016 (0.23128±0.00019)
all							±0.0014

Comparisons with present neutral current vector coupling uncertainties

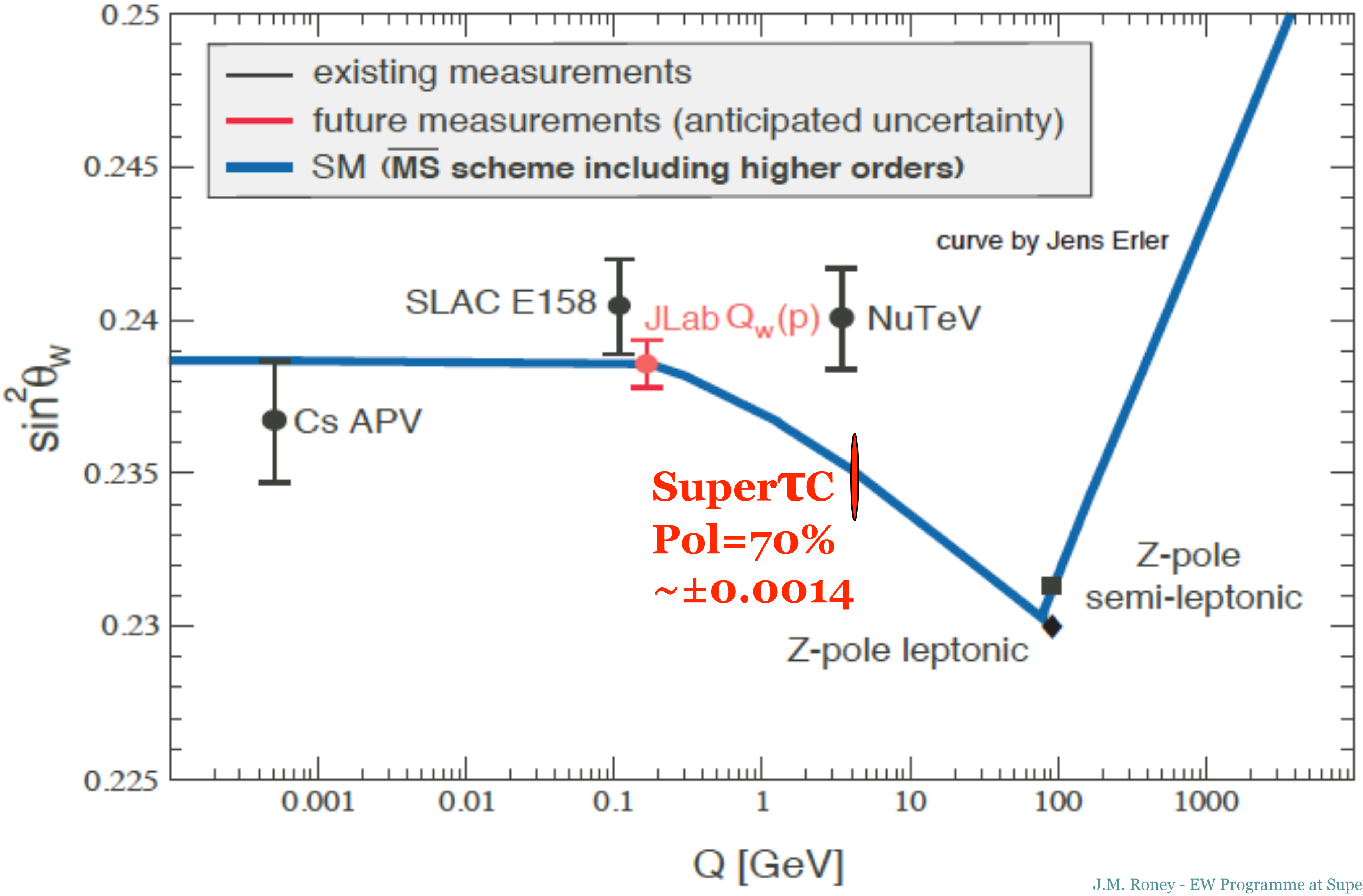
Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

charm:	+0.1873±0.0070	cf SuperτC ±0.005
tau:	−0.0366±0.0010	cf SuperτC ±0.010
muon:	−0.0367±0.0023	cf SuperτC: ±0.004
electron:	−0.03816±0.00047	cf SuperτC: ±0.004

LEP/SLC:
Lepton g_V= -0.03753± 0.00037

SuperτC error = ±0.003 (SuperB: ± 0.00038)

$\sin^2\theta_W$


existing measurements
future measurements (anticipated uncertainty)
SM (MS scheme including higher orders)
curve by Jens Erler
SLAC E158
JLab Q_w(p)
NuTeV
Cs APV
SuperτC
Pol=70%
~±0.0014
Z-pole
semi-leptonic
Z-pole leptonic
0.25
0.245
0.24
0.235
0.23
0.225
0.001
0.01
0.1
1
10
100
1000
Q [GeV]
sin²θ_W

Some comments…

These estimates base on some assumptions on event selection efficiency that need to be evaluated with detailed studies (i.e. 30% efficiency for selecting charm events just an assumption)

Also, they have assumed a polarisation of 70%

- the relative errors on the couplings are linearly dependent on the polarisation – so 80% polarisation will decrease uncertainties by 7/8.

What if both beams are polarised ?

(possibility suggested by Marica Biagini on Wednesday…)

- If both beams are polarised, the effective value for the polarisation (P_{eff}=P(e-)- P(e+)/(1-P(e-)*P(e+))) is higher
- Also, cross-section $\sigma \sim (1-P(e-)*P(e+))\,\sigma_0$
  e.g. P(e-)=0.8; P(e+)=-0.8 increase σ by ~1.64

Uncertainties on A_{LR} and therefore on couplings scale as:

$P(e-)/P_{eff}\sqrt{(1-P(e-)*P(e+))}$ cf single polarised beam

e.g. P(e-)=0.8; P(e+)=-0.8 -> uncertainties decrease by 0.56 cf to values for P(e-)=0.7; P(e+)=0

Comparisons with present neutral current vector coupling uncertainties with P(e-)=0.8; P(e+)=-0.8

Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

charm: +0.1873±0.0070 cf SuperτC ±0.003

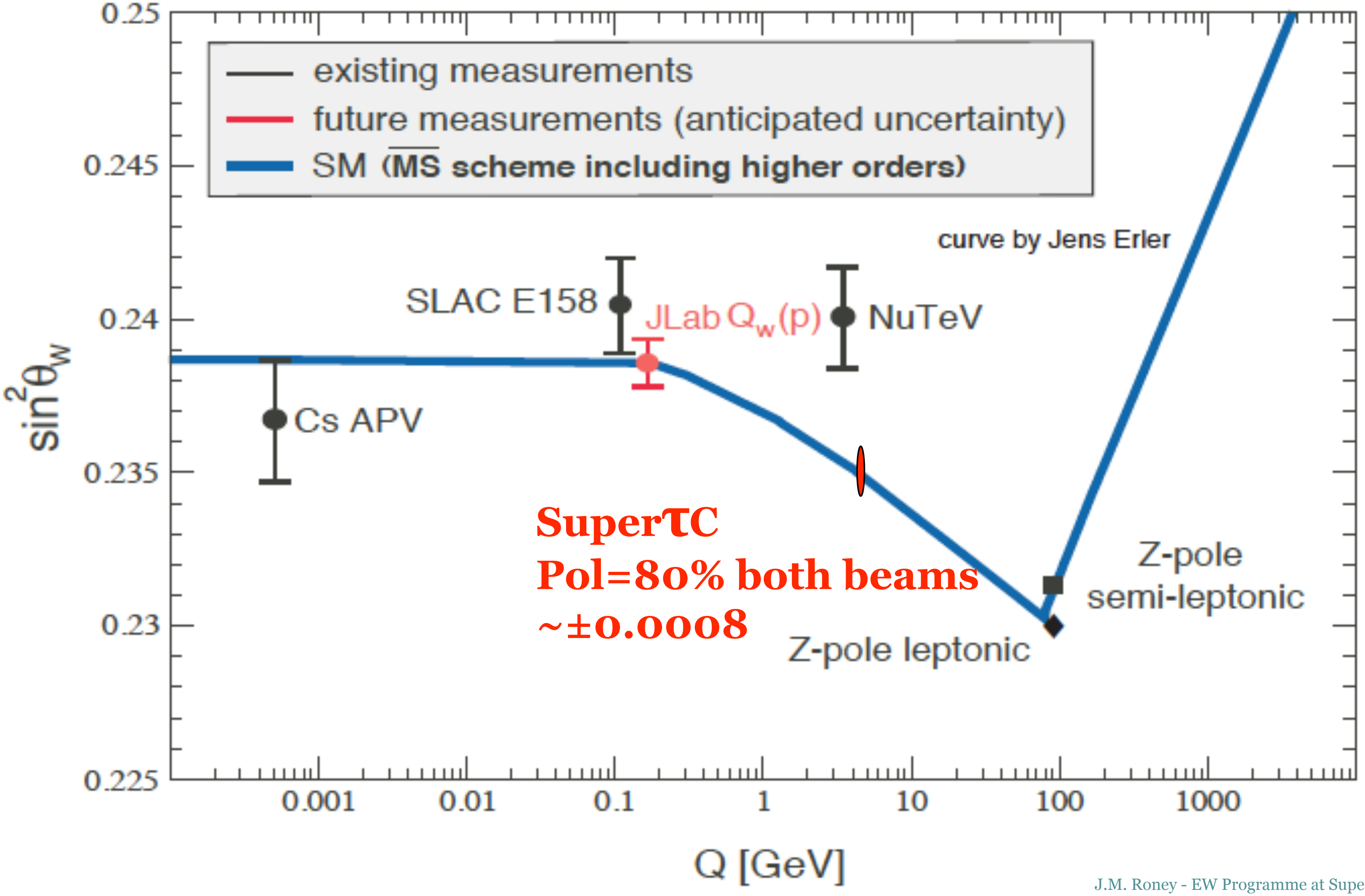
tau: −0.0366±0.0010 cf SuperτC ±0.006

muon: −0.0367±0.0023 cf SuperτC: ±0.002

electron: −0.03816±0.00047 cf SuperτC: ±0.002

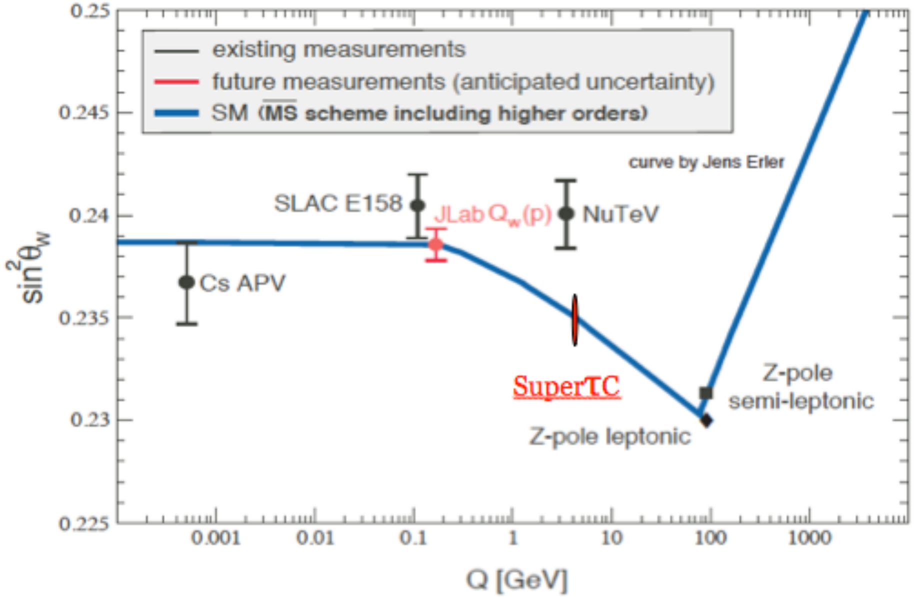
error on $\sin^2\theta_W$ using all channels: ±0.0008

$\sin^2\theta_W$



SuperτC
Pol=80% both beams
~±0.0008

SuperTC probes both high and low energy scales



- Sensitivity to Dark Sector light neutral gauge bosons in 4GeV regime
    - Because couplings are small, this sector would have been hidden

Summary

SuperτC with $\mathcal{L}=10^{35}\text{cm}^{-2}\text{s}^{-1}$, ~3ab^{-1} at the ψ(3770)

~4ab^{-1} at other energies and electron beams with 70% polarisation

- unique window on electroweak physics
  - SuperτC is the only place where the charm, tau, muon, and electron couplings will be measured at 4GeV
  - uncertainty on charm and perhaps muon vector coupling competitive with that from the Z-pole, but measured at 4GeV.
- Provides measurements complementary with those at the Z-pole but at 4GeV centre-of-mass:
  - will probe new physics at TeV scale complementary to LHC
  - will probe ‘Dark Sector’

Summary

- Because $A_{LR} \propto s$ we lose ~$10.58^2/4^2$ in relative precision cf SuperB even if the number of events is the same
- Because relative errors are larger than SuperB's projected errors, the demands on the beam polarisation systematic uncertainties are relaxed cf SuperB
- Higher polarisation and/or polarisation of both beams will improve uncertainties on couplings
- Polarising both beams increases cross sections
- Still need to see if tau polarisation forward-backward asymmetry determination of the beam polarisation is sufficient on its own; 1% Compton Polarimeter is sufficient.

Additional slides

SuperB Left-Right Asymmetries

Fermion flavour	σ (nb) eff %	Number Selected events (billions)	SM g_V^f (M_Z)	A_{LR} 70% Pol	g_V^f Total Error (%)	$\sin^2\theta_W(M_Z)$ Total Error
beauty	1.1 (95%)	38	-0.3437 ± .0001	-0.013	0.5	0.0026
charm	1.3 (30%)	29	+0.1920 ±.0002	-0.003	0.5	0.00076
tau	0.92 (25%)	17	-0.0371 ±.0003	-3×10^{-4}	2.2	0.00043
muon	1.15 (54%)	46	-0.0371 ±.0003	-3×10^{-4}	1.5	0.00027
electron	40 (1.5%)	40	-0.0371 ±.0003	-3×10^{-4}	1.5	0.00027
leptons			-0.0371 ±.0003	-3×10^{-4}	1.0	0.00019