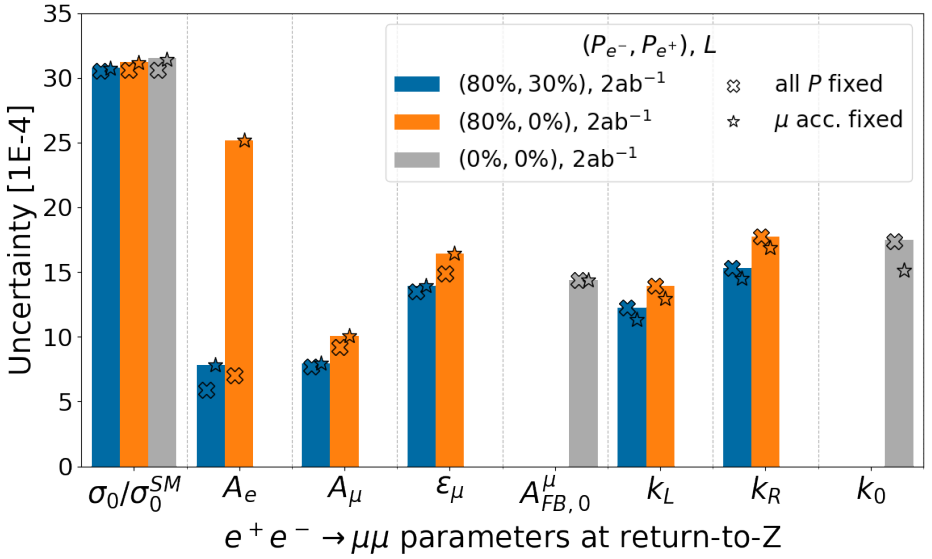
Interplay of beam polarisation and systematic uncertainties at future e^+e^- colliders

Jakob Beyer[1,2], Jenny List[1]
[1]DESY, [2]Universität Hamburg

29.07.2021

EPS-HEP 2021



DESY.

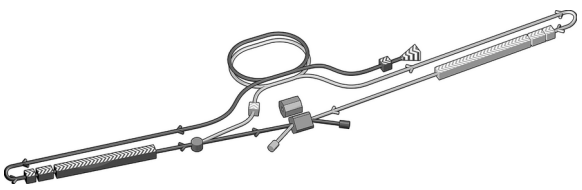
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

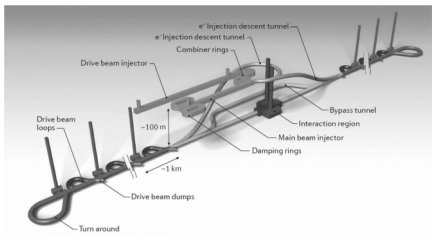
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

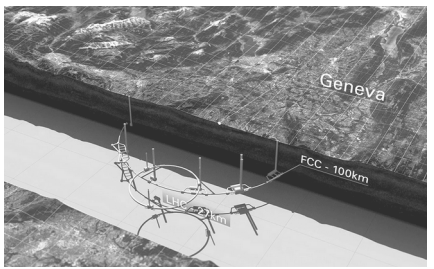
Beam pol. @ future e^+e^- colliders

Linear colliders





Circular colliders



$

$

e^- & e^+ polarised

e^- polarised

both beams unpolarised

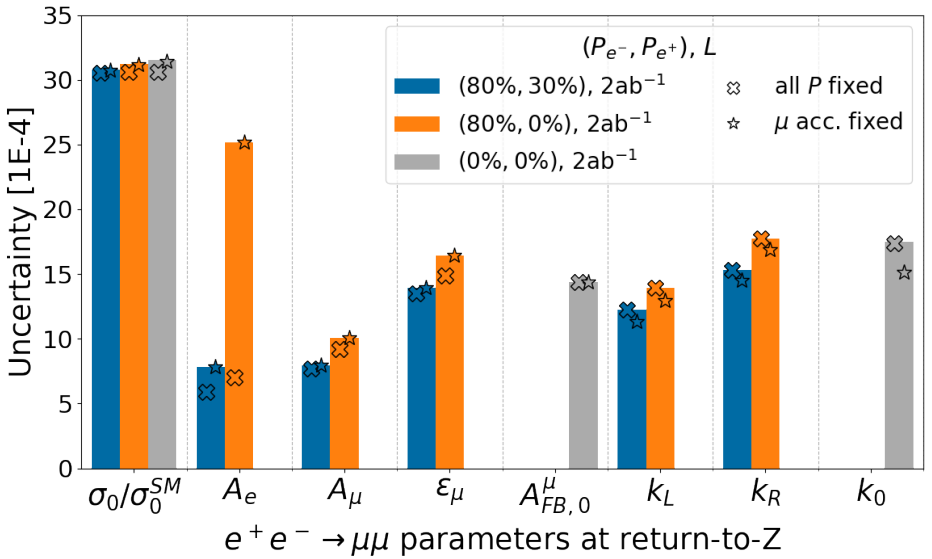
Beam polarisation separates effects by their chiral behaviour

Separation of effects w/ same differential shapes

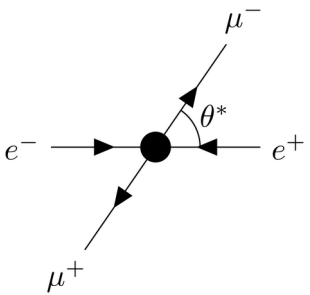
Demonstration in combined $\mu^+\mu^-$ fit

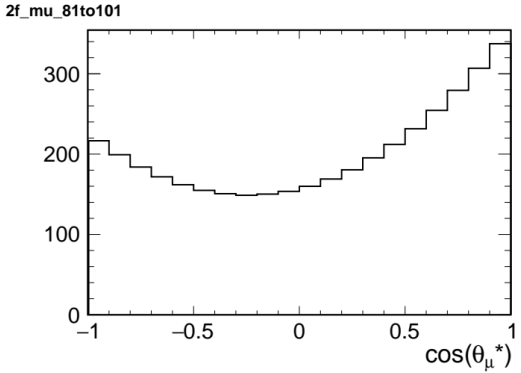
Reducing systematic uncertainties

Demonstration w/ μ acceptance



$\mu^+\mu^-$ @ 250GeV





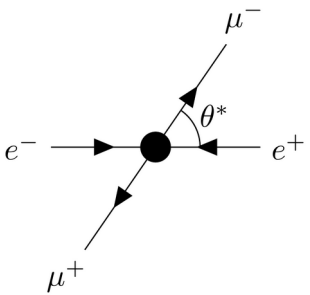
$$e^+e^- \rightarrow Z/\gamma \rightarrow \mu^+\mu^-$$

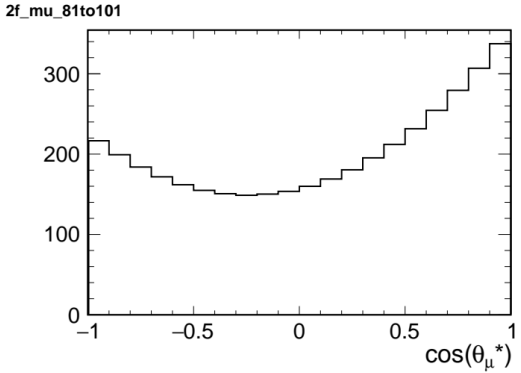
"return-to-Z" $m_{\mu\mu} \sim m_Z$

"high √s*" $m_{\mu\mu} \sim \sqrt{s}$

DESY.

$\mu^+\mu^-$ @ 250GeV





$$e^+e^- \rightarrow Z/\gamma \rightarrow \mu^+\mu^-$$

Focus today

"return-to-Z"

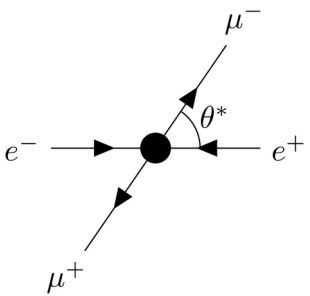
$m_{\mu\mu} \sim m_Z$

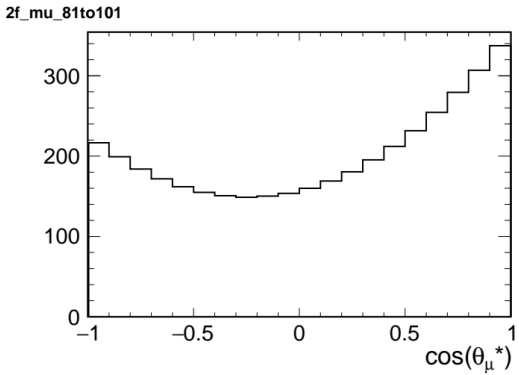
"high √s*"

$m_{\mu\mu} \sim \sqrt{s}$

DESY.

$\mu^+\mu^-$ @ 250GeV





$$e^+e^- \rightarrow Z/\gamma \rightarrow \mu^+\mu^-$$

Focus today

"return-to-Z"

$m_{\mu\mu} \sim m_Z$

"high √s*"

$m_{\mu\mu} \sim \sqrt{s}$

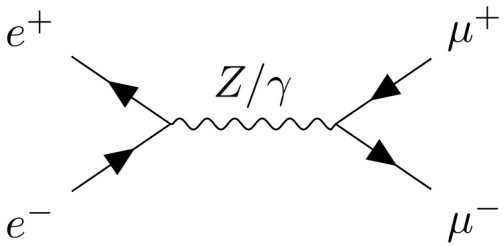
Datasets

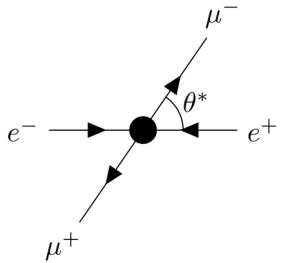
Unpol.	1	00
e^- pol.	2	+0, -0
e^- & e^+ pol.	4	++, +-, -+, --

Combined Fit

Physical and systematic effects

DESY.





Polarised

LEP/SLC parameters

σ_0 : total chiral cross section

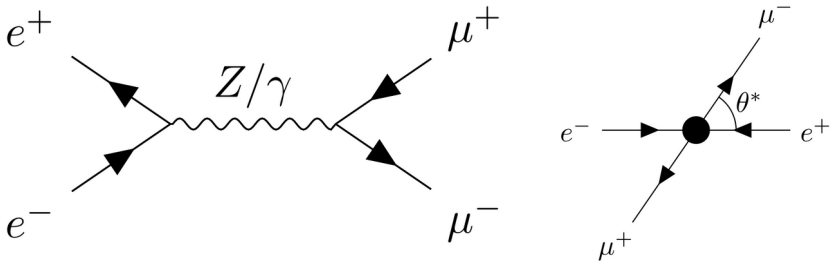
A_e : electron chiral asymmetry

A_μ : final fermion asymmetry

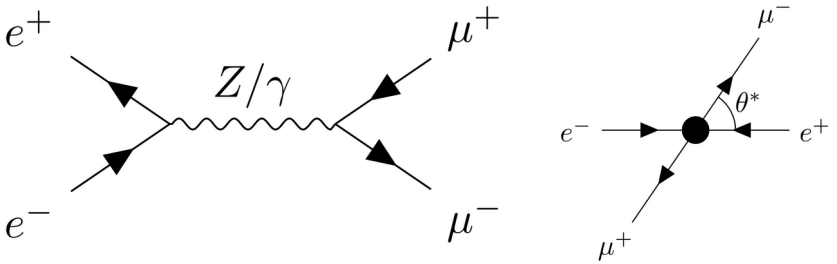
Correction parameters

ε_μ : Z/γ interference correction

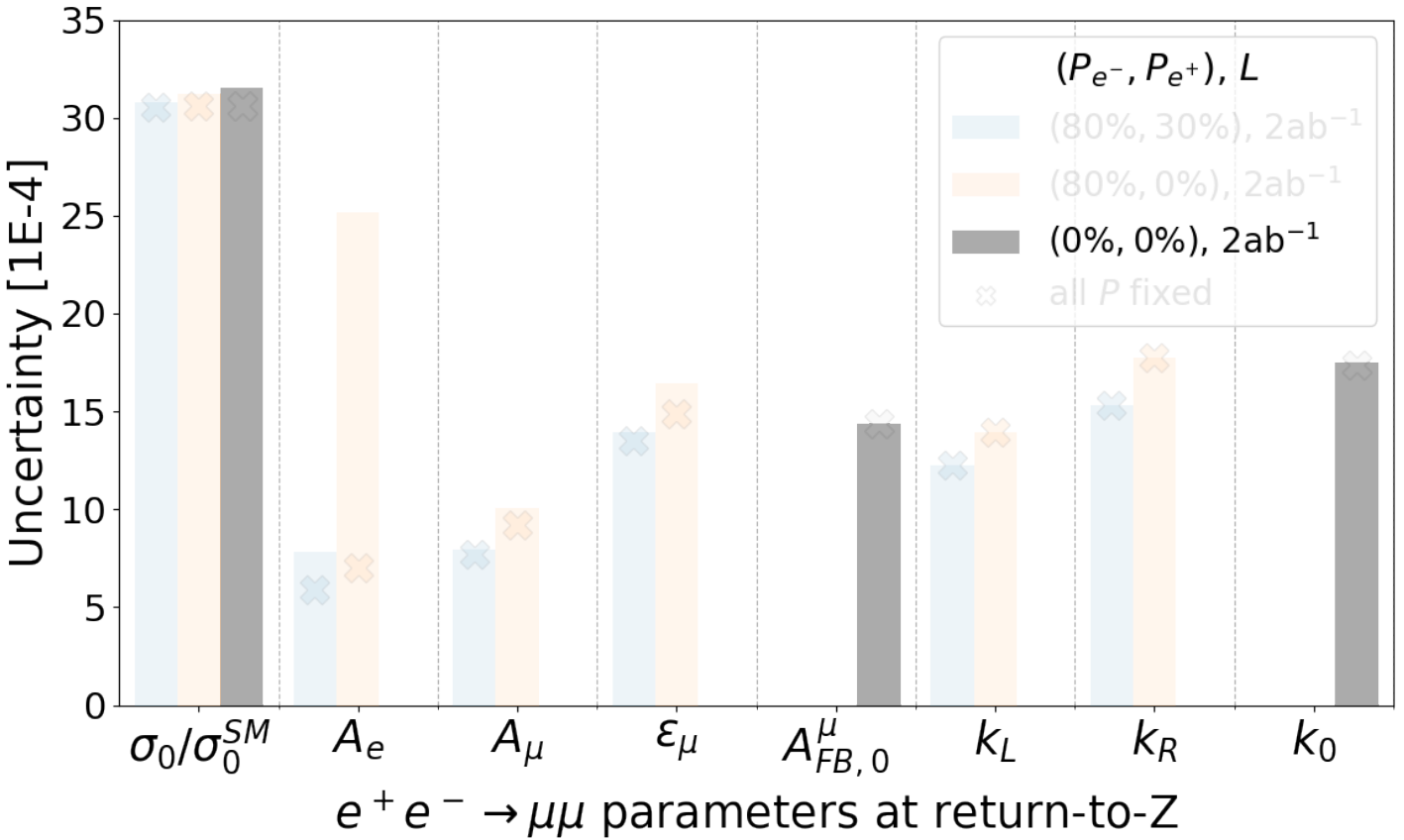
$k_{L/R}$: radiative correction factors

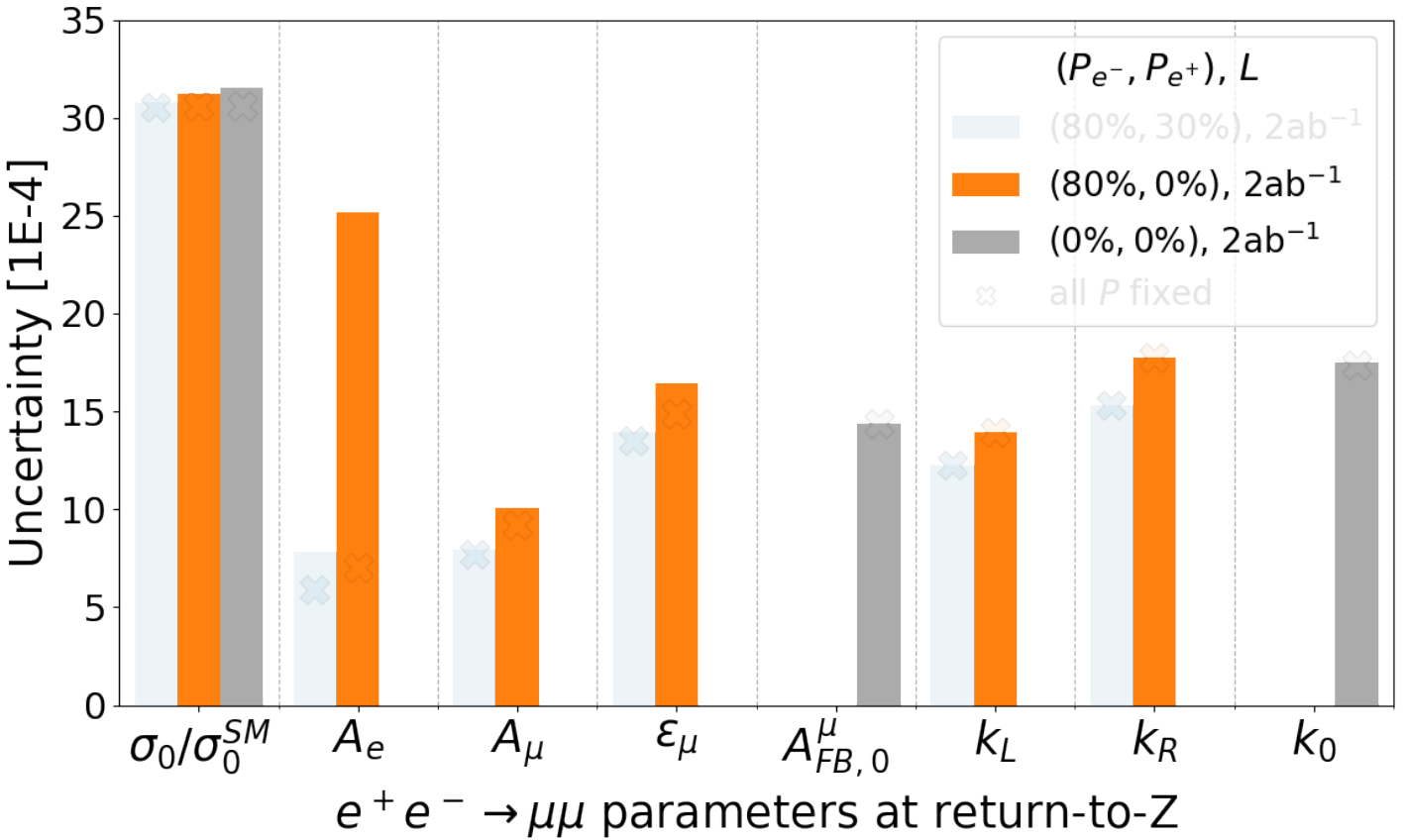


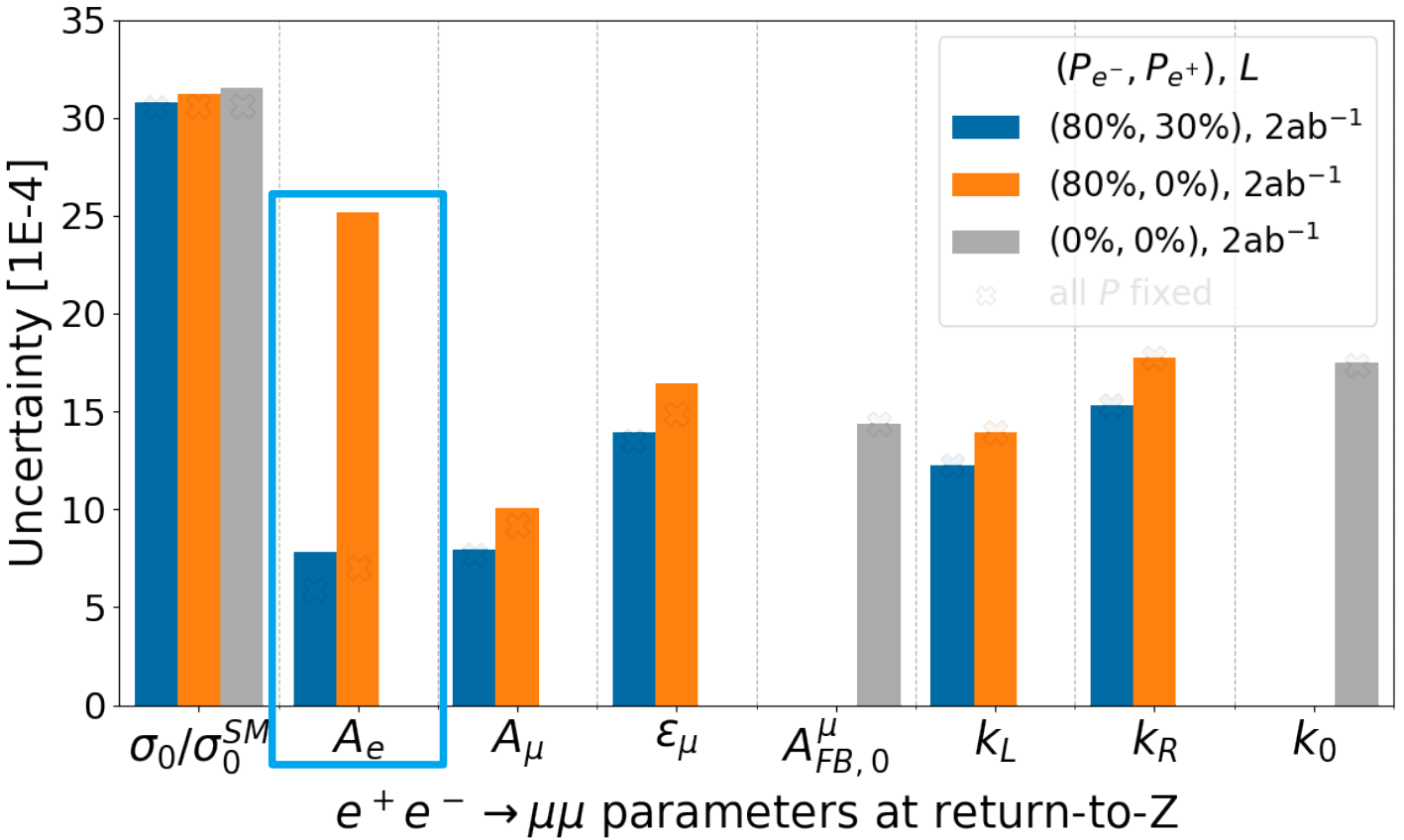
Polarised	Sensitivity loss	**Unpolarised**
LEP/SLC parameters		
σ_0 : total chiral cross section	normalisation →	
A_e : electron chiral asymmetry	→	
A_μ : final fermion asymmetry	→ linear term	
Correction parameters		
ε_μ : Z/γ interference correction	→	
$k_{L/R}$: radiative correction factors	const./quad. term →	



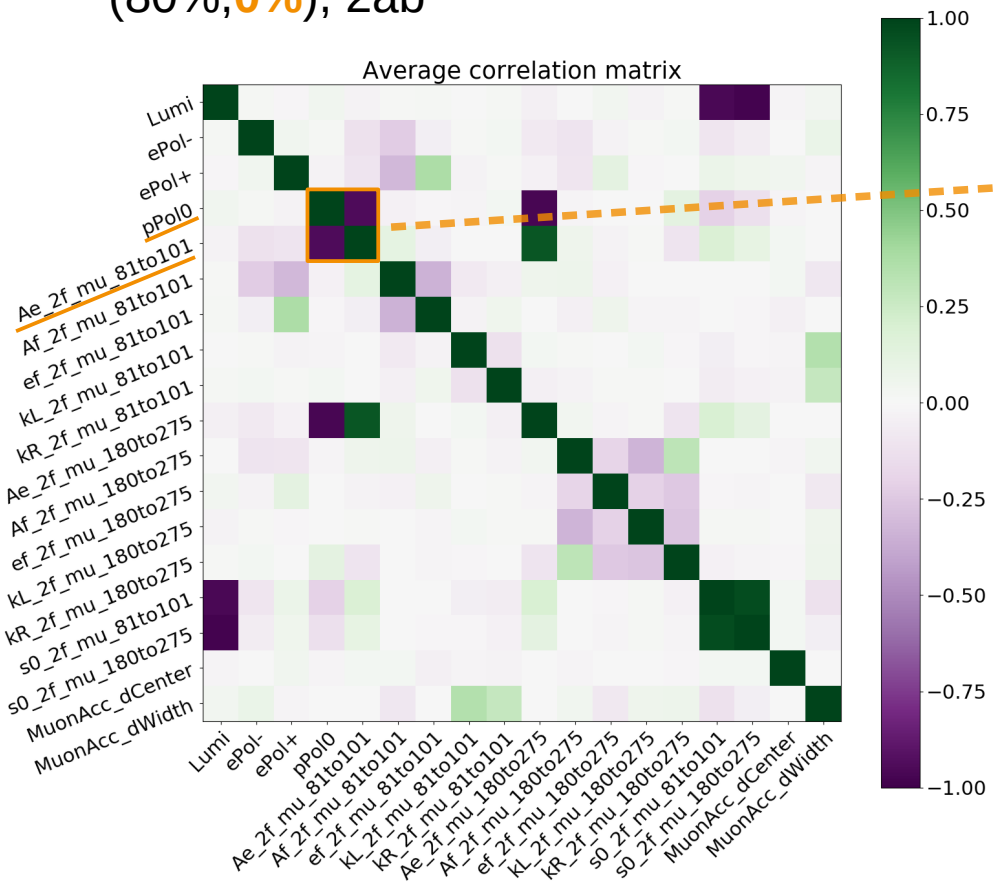
Polarised	Sensitivity loss	**Unpolarised**
LEP/SLC parameters		
σ_0 : total chiral cross section	normalisation →	σ_0 : total chiral cross section
A_e : electron chiral asymmetry	→	
A_μ : final fermion asymmetry	linear term →	$A_{FB,0}$: forward-backward asymmetry
Correction parameters		
ε_μ : Z/γ interference correction	→	
$k_{L/R}$: radiative correction factors	const./quad. term →	k_0 : radiative correction factor


Uncertainty [1E-4]
35
30
25
20
15
10
5
0
(P_{e^-}, P_{e^+}), L
(80%, 30%), 2ab^{-1}
(80%, 0%), 2ab^{-1}
(0%, 0%), 2ab^{-1}
all P fixed
σ_0/σ_0^{SM}
A_e
A_μ
ε_μ
$A_{FB,0}^{\mu}$
k_L
k_R
k_0
$e^+e^- \to \mu\mu$ parameters at return-to-Z

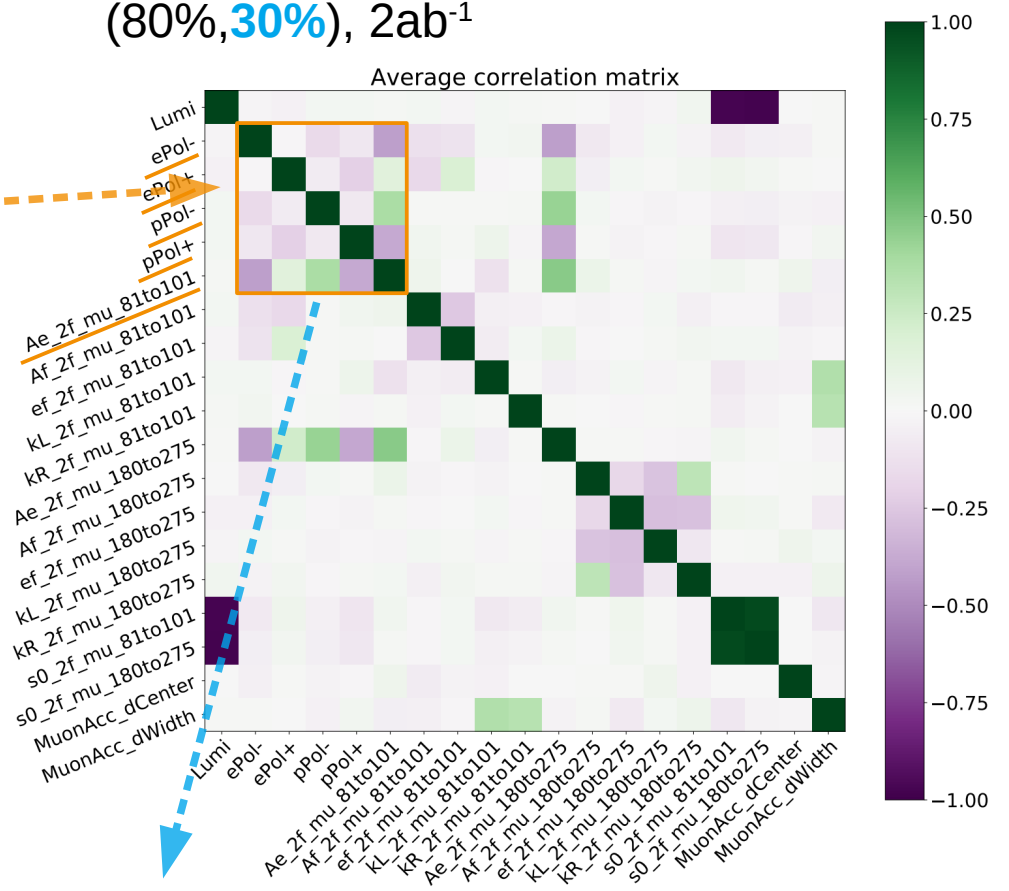

Uncertainty [1E-4]
35
30
25
20
15
10
5
0
(P_{e^-}, P_{e^+}), L
(80%, 30%), 2ab^{-1}
(80%, 0%), 2ab^{-1}
(0%, 0%), 2ab^{-1}
all P fixed
σ_0/σ_0^{SM}
A_e
A_μ
ε_μ
$A_{FB,0}^{\mu}$
k_L
k_R
k_0
$e^+e^- \to \mu\mu$ parameters at return-to-Z


Uncertainty [1E-4]
35
30
25
20
15
10
5
0
(P_{e^-}, P_{e^+}), L
(80%, 30%), 2ab^{-1}
(80%, 0%), 2ab^{-1}
(0%, 0%), 2ab^{-1}
all P fixed
σ_0/σ_0^{SM}
A_e
A_μ
ε_μ
$A_{FB,0}^{\mu}$
k_L
k_R
k_0
$e^+e^- \to \mu\mu$ parameters at return-to-Z

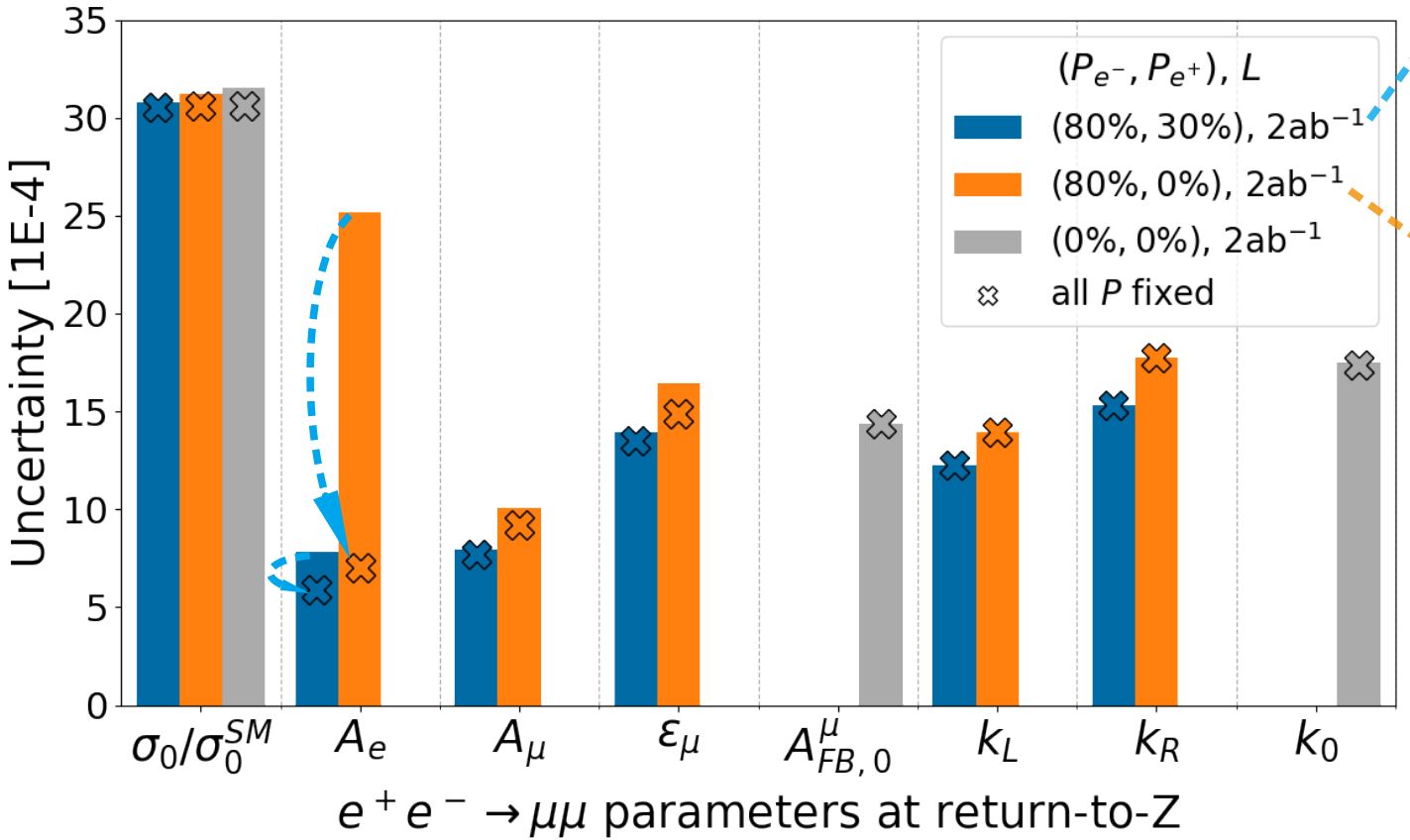
(80%,0%), 2ab^{-1}



(80%,30%), 2ab^{-1}



Enough information / datasets to determine all parameters independently!



All parameters determined independently!

A_e uncertainty determined by polarisation knowledge

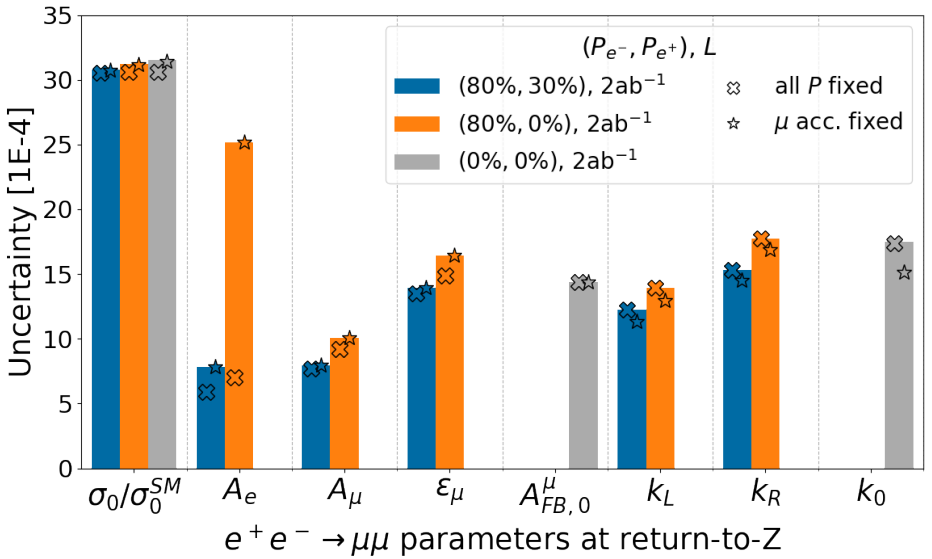
Beam polarisation separates effects by their chiral behaviour

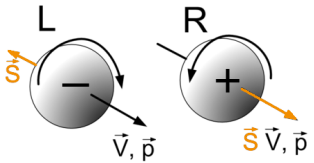
Separation of effects w/ same differential shapes

Demonstration in combined $\mu^+\mu^-$ fit

Reducing systematic uncertainties

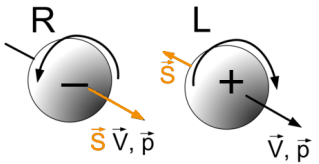
Demonstration w/ μ acceptance

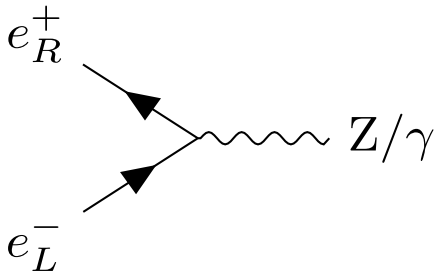




Flipped

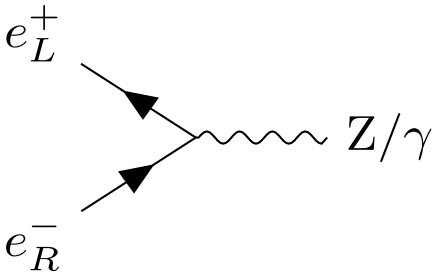
Polarisation

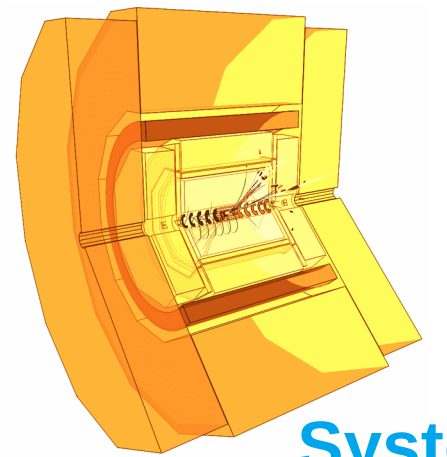




Different

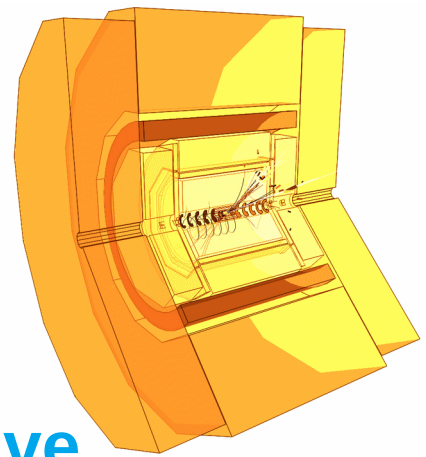
Physics



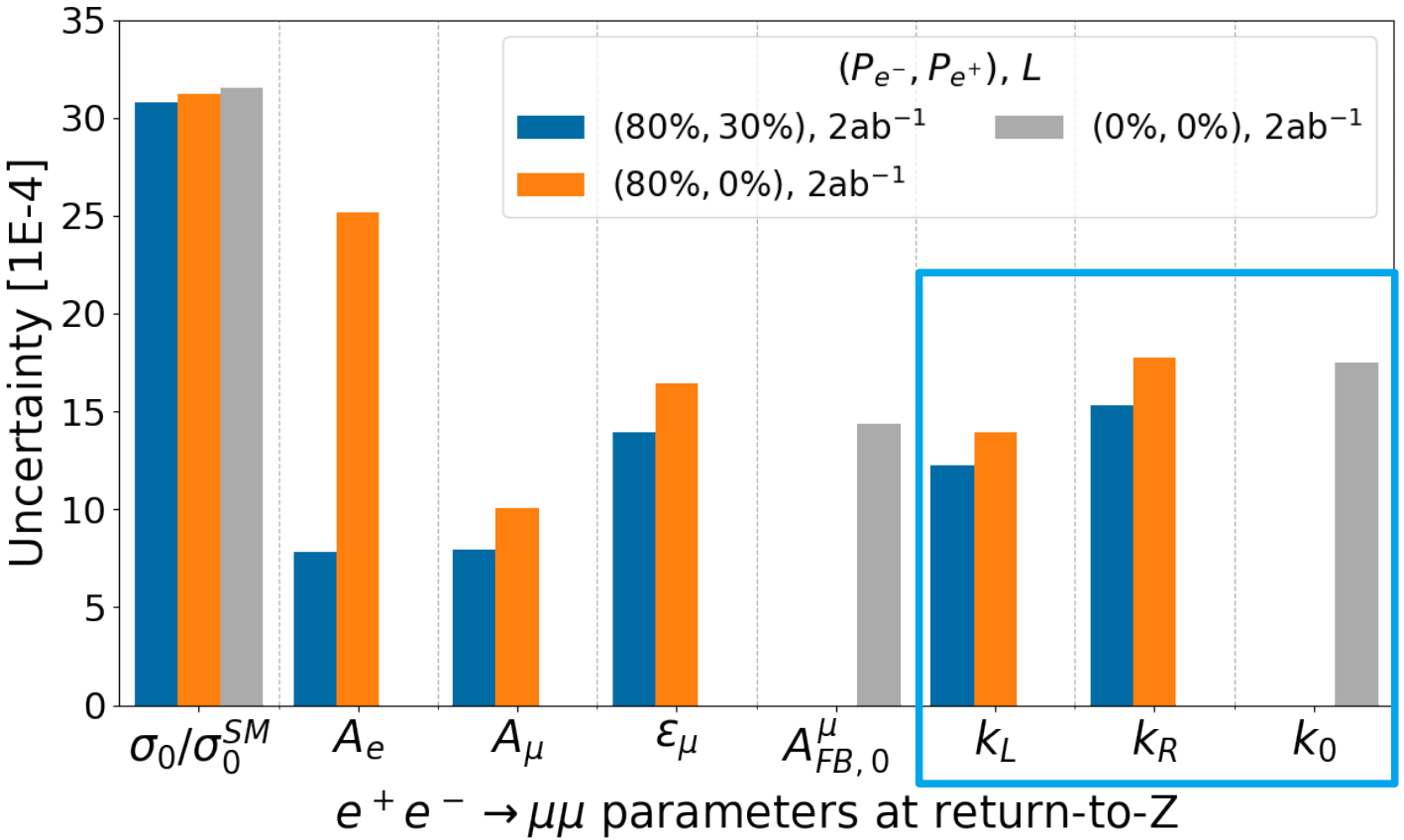


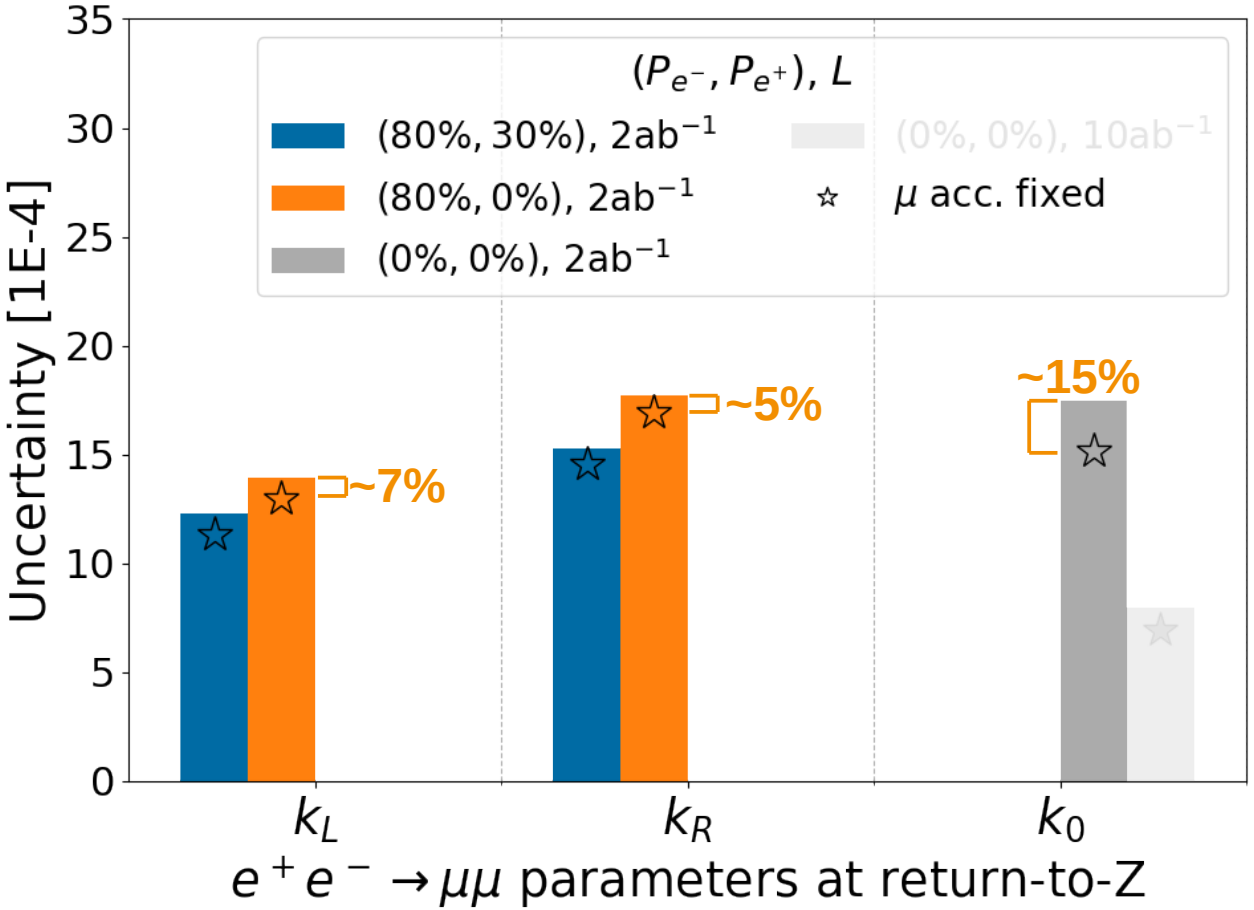
Same

Detector



Systematic effects will have uniquely global signatures if included in combined fit!

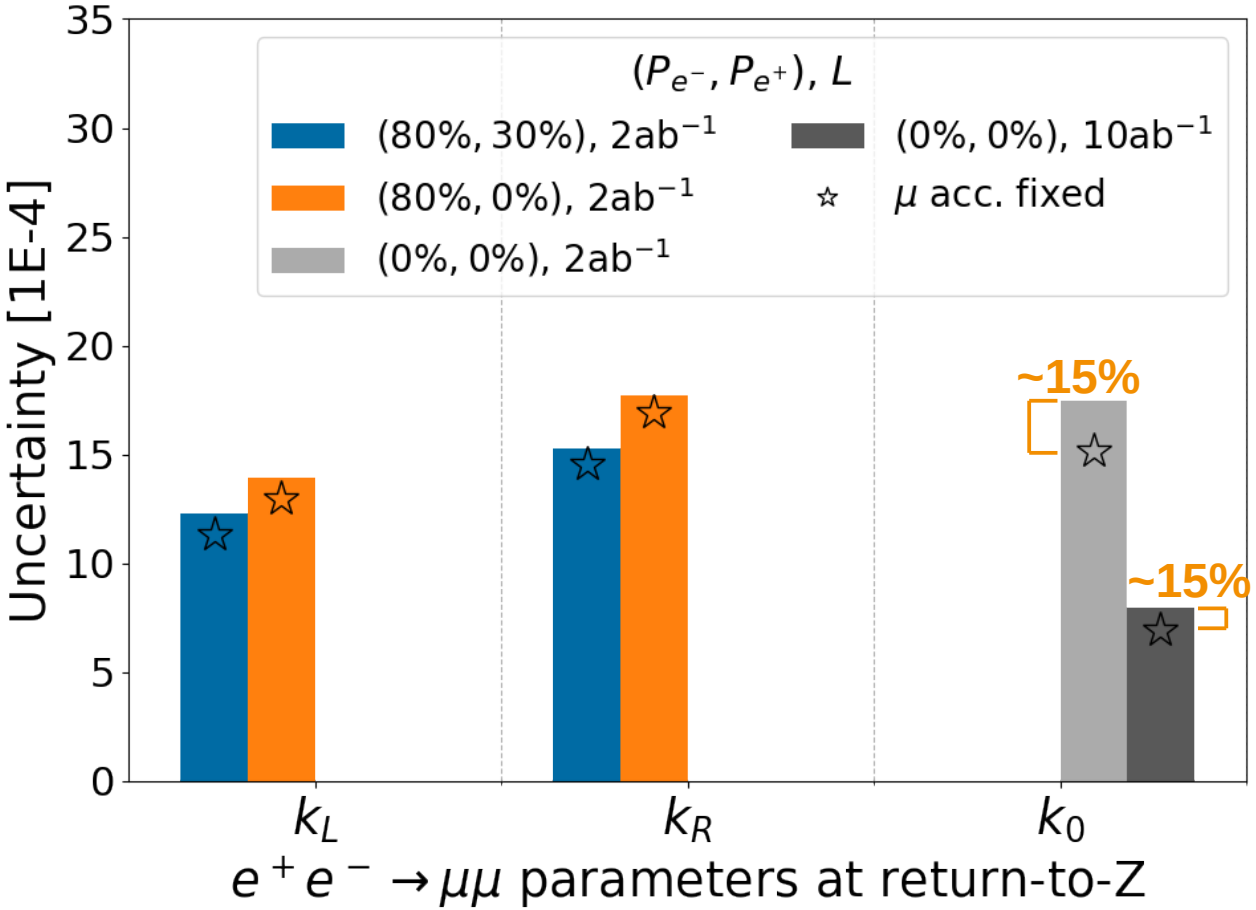

Uncertainty [1E-4]
35
30
25
20
15
10
5
0
(P_{e^-}, P_{e^+}), L
(80%, 30%), 2ab^{-1}
(80%, 0%), 2ab^{-1}
(0%, 0%), 2ab^{-1}
σ_0/σ_0^{SM}
A_e
A_μ
ε_μ
$A_{FB,0}^{\mu}$
k_L
k_R
k_0
$e^+e^- \to \mu\mu$ parameters at return-to-Z



First test:

Geometric μ acceptance

Polarisation allows using chirality dependence to isolate systematic effect



First test:

Geometric μ acceptance

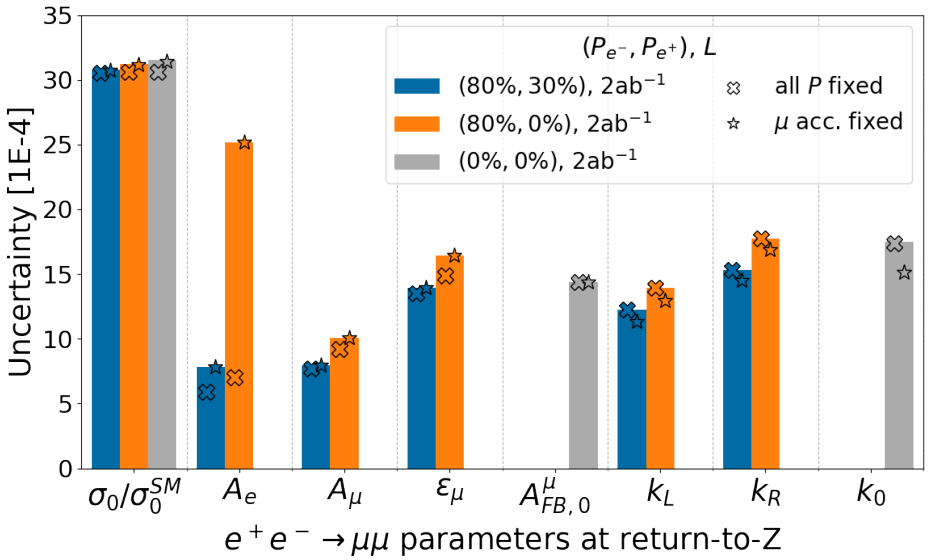
Luminosity also increases knowledge of systematic

Beam polarisation separates effects by their chiral behaviour

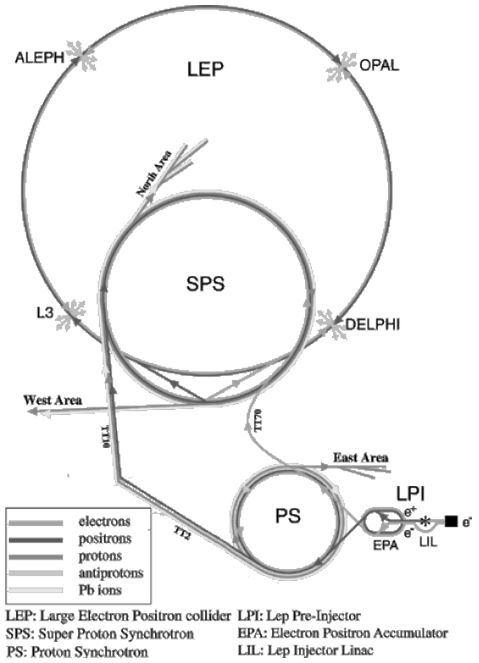
Providing access to chiral structure of interactions

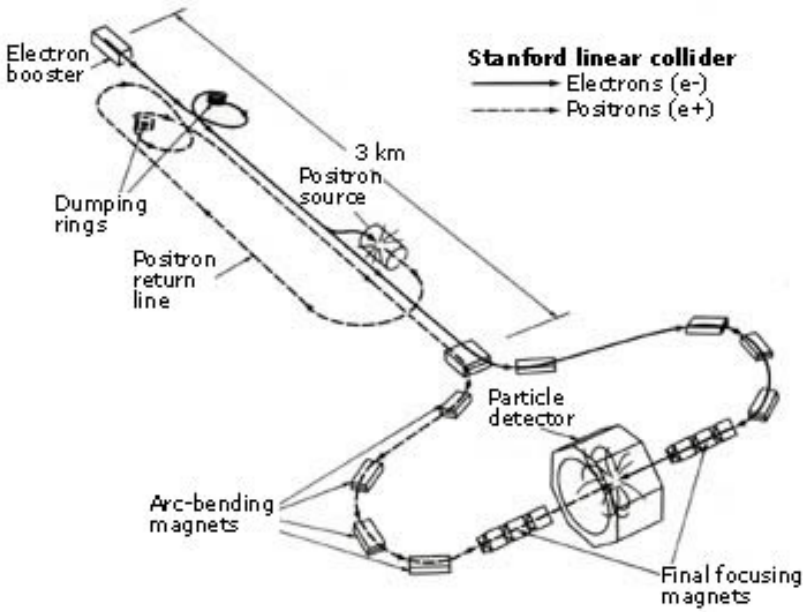
Separating physical from systematic effects

Each additional beam polarisation reduces parameter correlations.



BACKUP



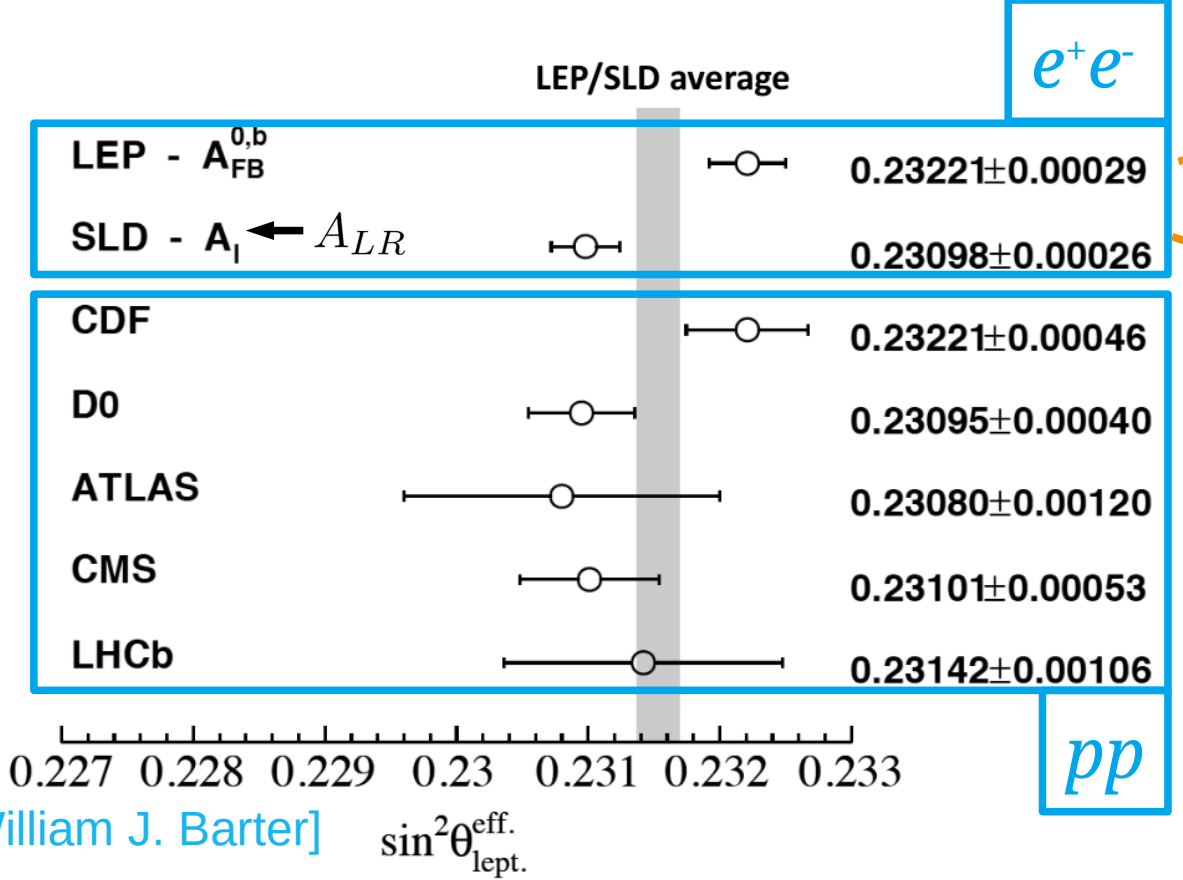


LEP

- Unpolarised
- ~ 17M Z events

SLC

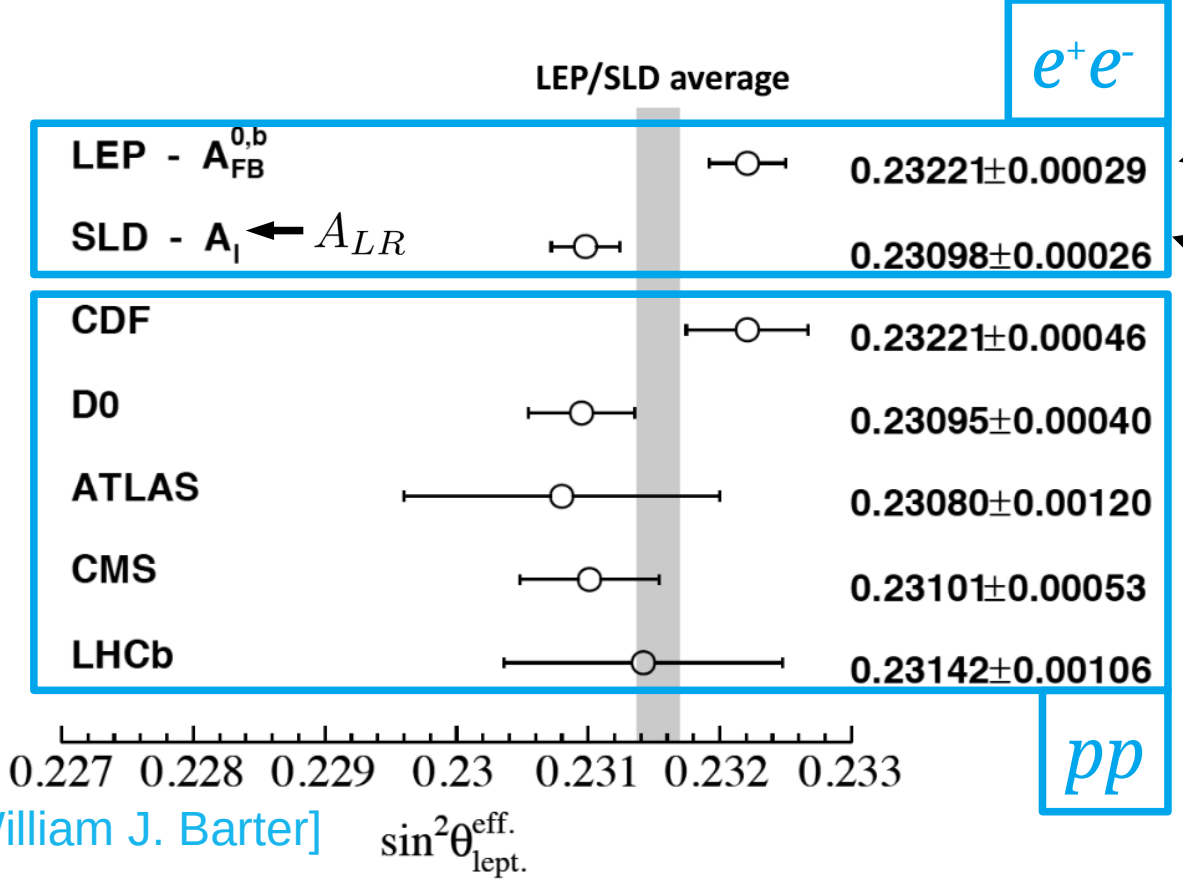
- e^- beam polarised
- ~ 400k Z events



[William J. Barter]

~ 40 x more events

e^- polarisation



[William J. Barter]

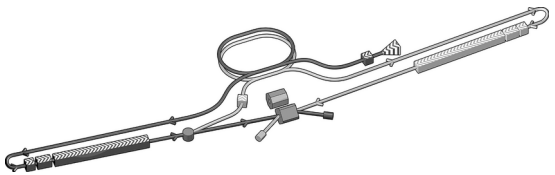
$\Delta_{syst} \approx \frac{1}{2} \Delta_{stat}$

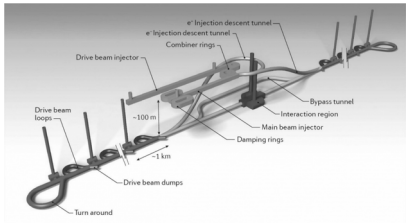
$\Delta_{syst} \approx \frac{1}{2} \Delta_{stat}$

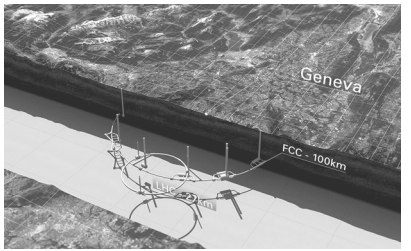
Δ_{syst} → **LEP:** τ charge, ℓ/γ ID, MC statistics, bkg estimation

Δ_{syst} → **SLC:** polarimeter, EW corrections

250GeV test scenarios





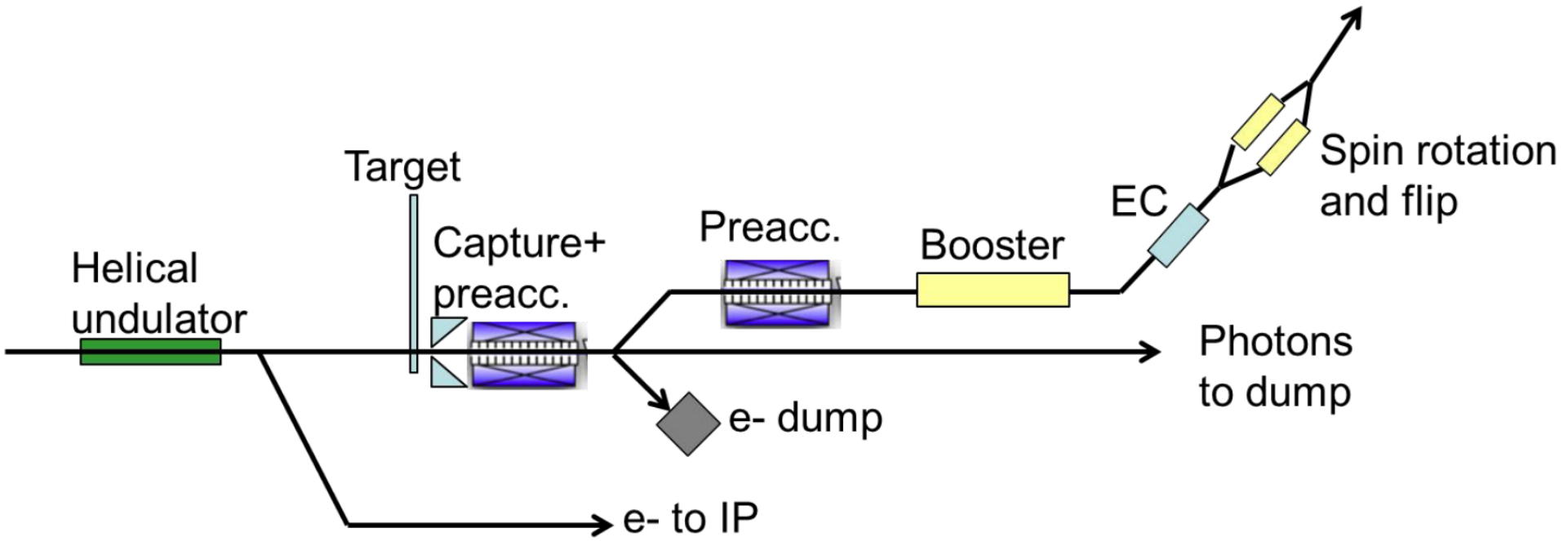


Pol.:	**(80%,30%)**	**(80%,0%)**	**(0%,0%)**
Sharing:	+- : -+ : ++ : --	+0 : -0	00
	45 : 45 : 5 : 5	50 : 50	

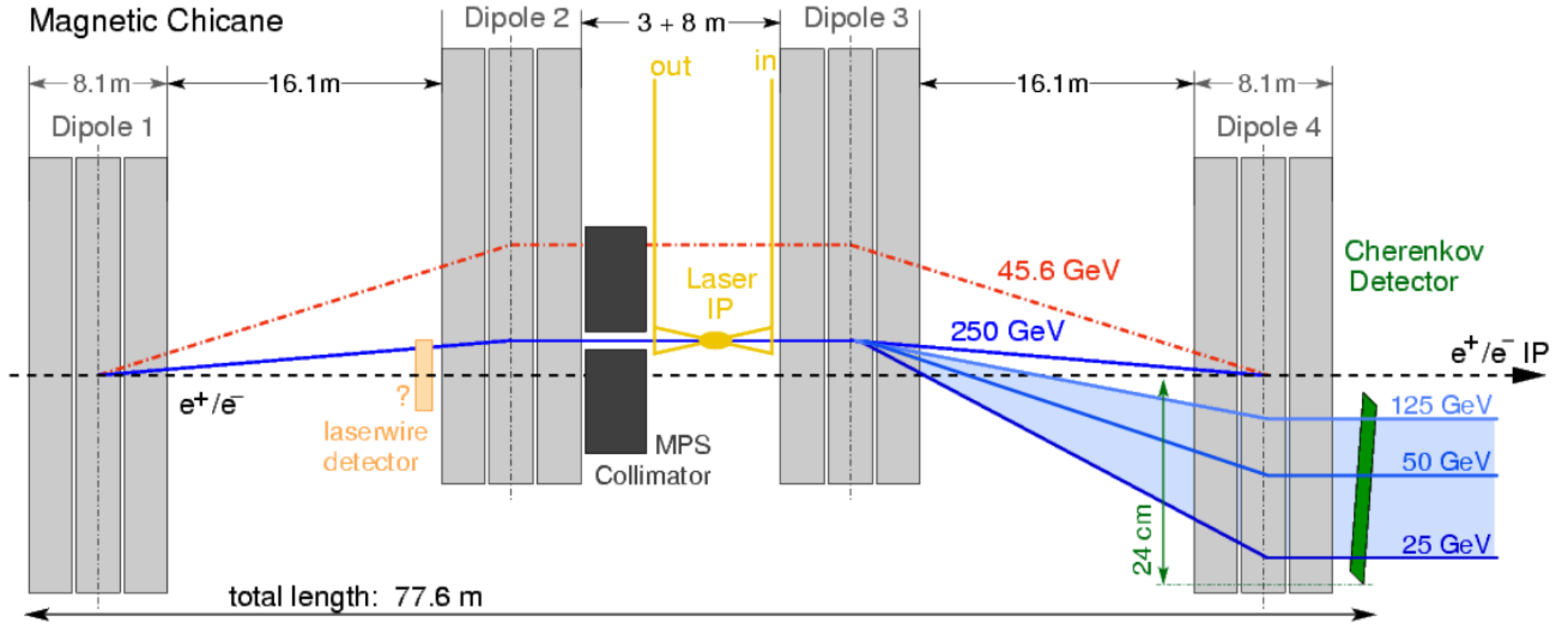
- **L**: **2ab^{-1}** , **10ab^{-1}**
- **Constraints**: $\Delta L/L$ = 3e-3, $\Delta P/P$ = 2.5e-3 (= ΔP_0)

[arXiv:1304.4082] [arXiv:0902.3221]

Polarised positron source:



External polarisation measurement

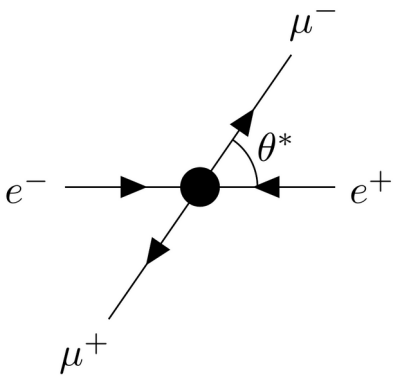


$f\bar{f}$ parametrisation

6 parameters: LEP/SLC parameters

σ_0^f ... total chiral cross section sum

$A_{e/f}$ ... initial / final fermion chiral asymmetry



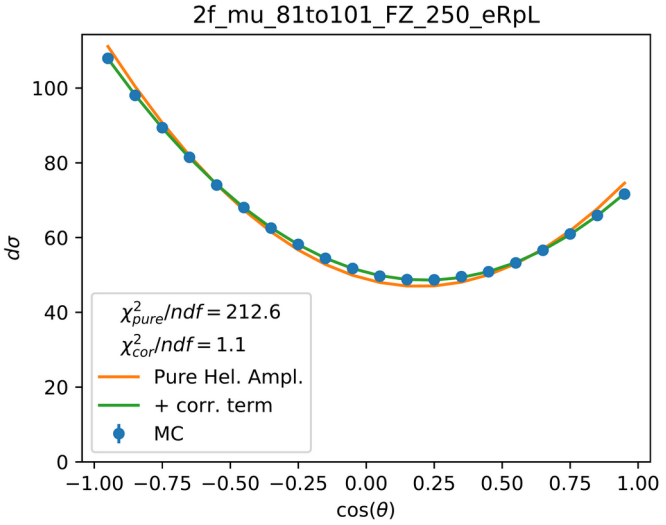
$$\frac{d\sigma^f_{LR}}{d\cos\theta} = \frac{3}{8}\sigma_0^f \frac{1+A_e}{2}\left[(1+k_L)+(\epsilon_f+2A_f)\cos\theta+(1-3k_L)\cos^2\theta\right]$$

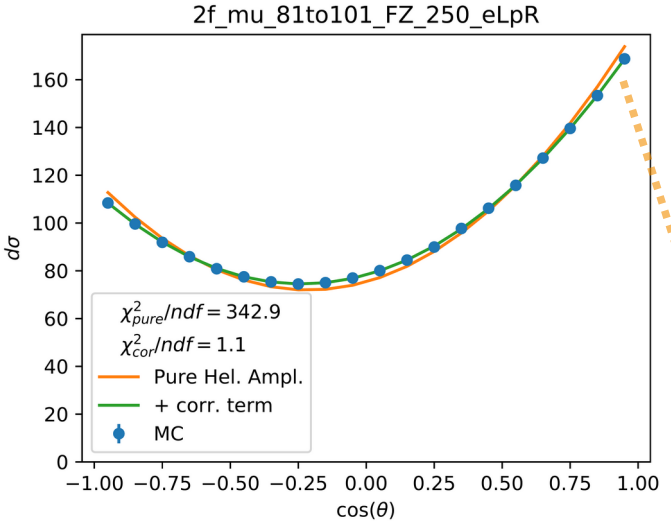
$$\frac{d\sigma^f_{RL}}{d\cos\theta} = \frac{3}{8}\sigma_0^f \frac{1-A_e}{2}\left[(1+k_R)+(\epsilon_f-2A_f)\cos\theta+(1-3k_R)\cos^2\theta\right]$$

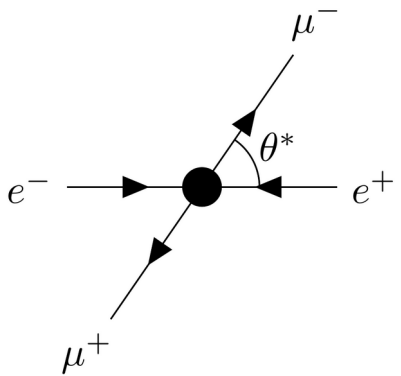
Correction parameters

ε_f ... Z/γ interference correction

$k_{L/R}$ ... radiative correction factors







$$\frac{d\sigma^f_{LR}}{d\cos\theta} = \frac{3}{8}\boldsymbol{\sigma_0^f}\frac{1+\boldsymbol{A_e}}{2}\left[(1+\boldsymbol{k_L}) + (\boldsymbol{\epsilon_f} + 2\boldsymbol{A_f})\cos\theta + (1-3\boldsymbol{k_L})\cos^2\theta\right]$$

$$\frac{d\sigma^f_{RL}}{d\cos\theta} = \frac{3}{8}\boldsymbol{\sigma_0^f}\frac{1-\boldsymbol{A_e}}{2}\left[(1+\boldsymbol{k_R}) + (\boldsymbol{\epsilon_f} - 2\boldsymbol{A_f})\cos\theta + (1-3\boldsymbol{k_R})\cos^2\theta\right]$$

Correction parameters

ε_f ... Z/γ interference correction

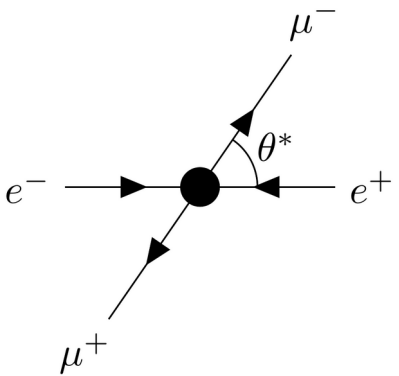
$k_{L/R}$ ... radiative correction factors

$f\bar{f}$ parametrisation - unpolarised

3 parameters: LEP/SLC parameters

σ_0^f ... total chiral cross section sum

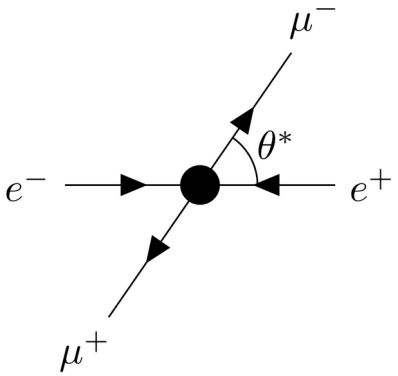
$A^f_{FB,0}$ ... forward-backward asymmetry



$$\frac{d\sigma_0^f}{d\cos\theta} = \frac{3}{8}\boldsymbol{\sigma_0^f}\mathcal{P}_{eff}\left(\mathcal{P}^0_{e^+},\mathcal{P}^0_{e^-}\right)\left[(1+\boldsymbol{k_0}) + \boldsymbol{A^f_{FB,0}}\cos\theta + (1-3\boldsymbol{k_0})\cos^2\theta\right]$$

Correction parameters

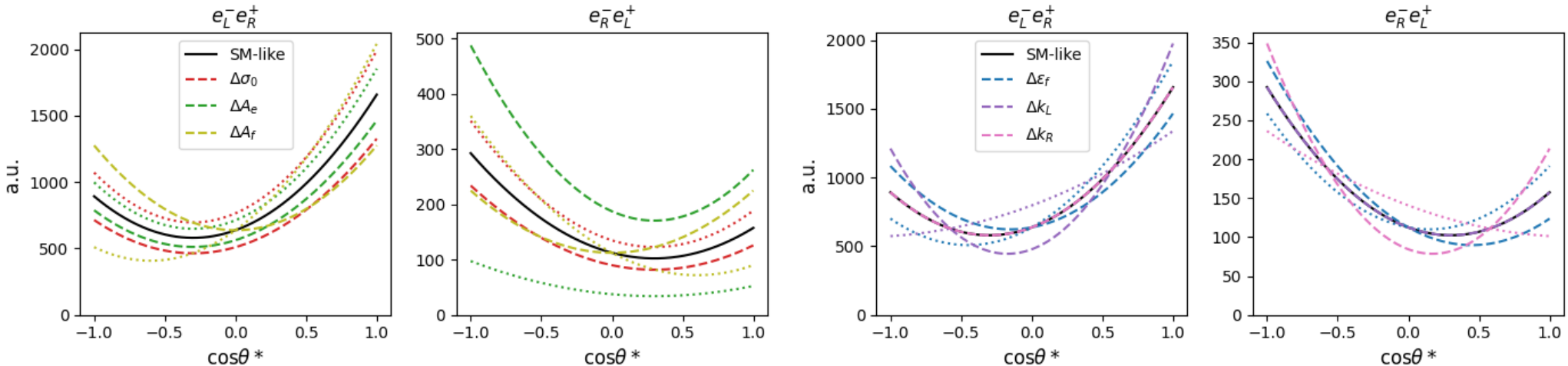
k_0 ... radiative correction factor



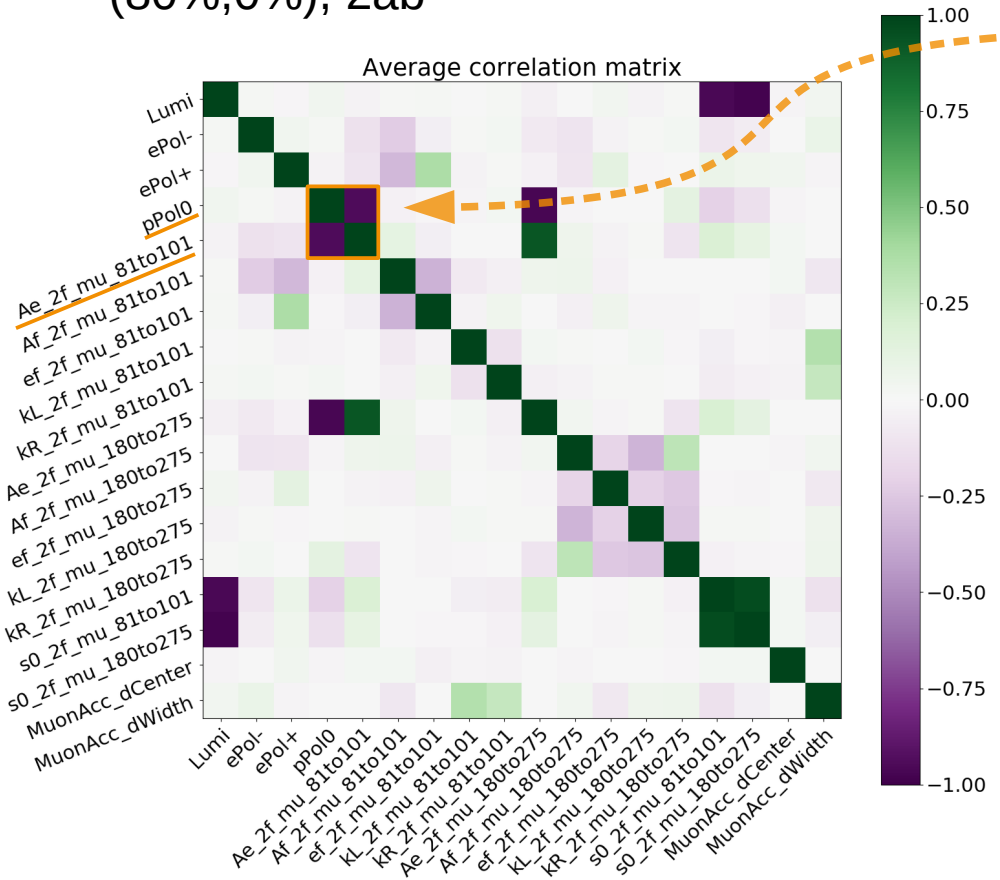
$$\frac{d\sigma^f_{LR}}{d\cos\theta} = \frac{3}{8}\sigma_0^f \frac{1+A_e}{2}\left[(1+k_L)+(\epsilon_f+2A_f)\cos\theta+(1-3k_L)\cos^2\theta\right]$$

$$\frac{d\sigma^f_{RL}}{d\cos\theta} = \frac{3}{8}\sigma_0^f \frac{1-A_e}{2}\left[(1+k_R)+(\epsilon_f-2A_f)\cos\theta+(1-3k_R)\cos^2\theta\right]$$

Example with meaningless values / deviations

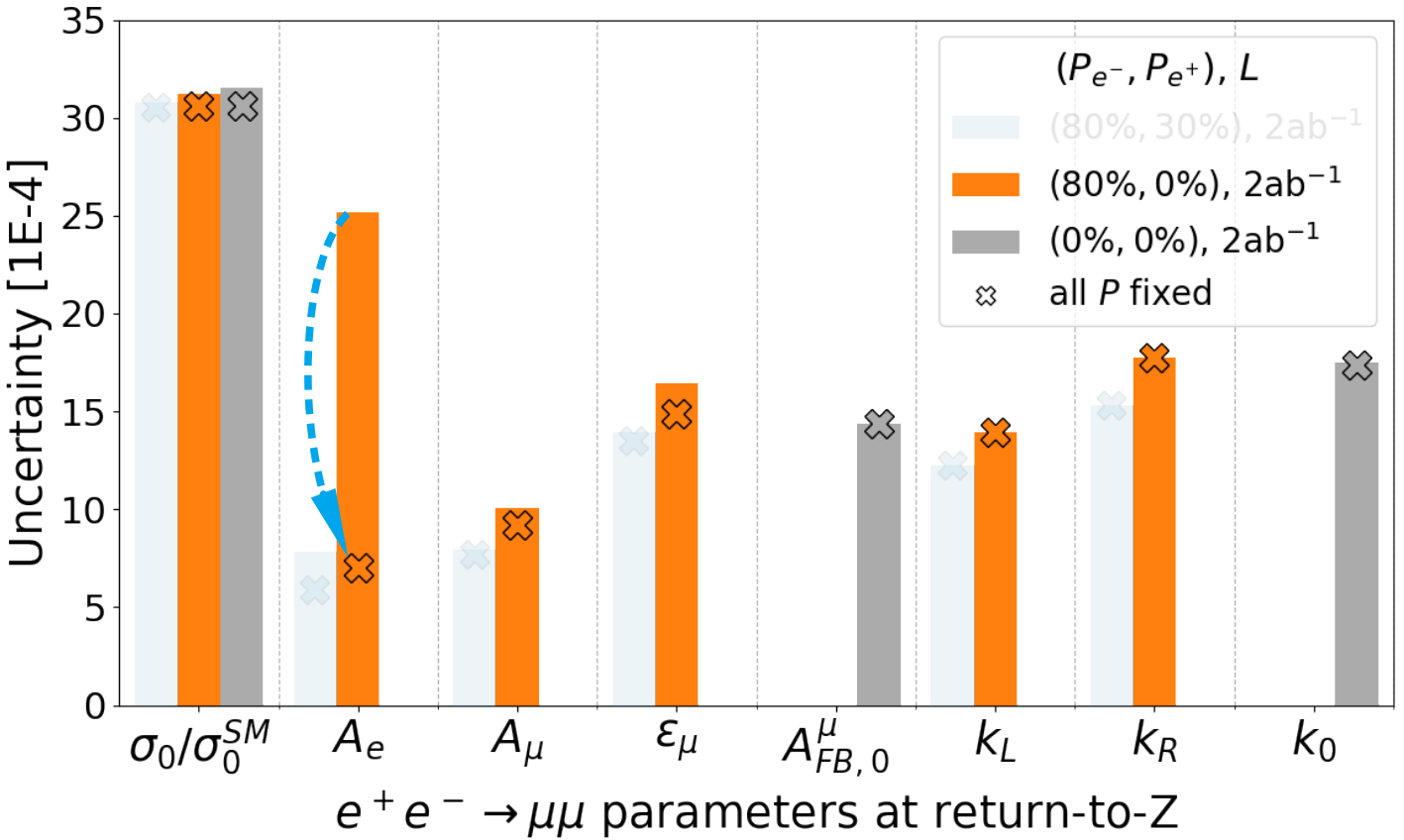


(80%,0%), 2ab^{-1}

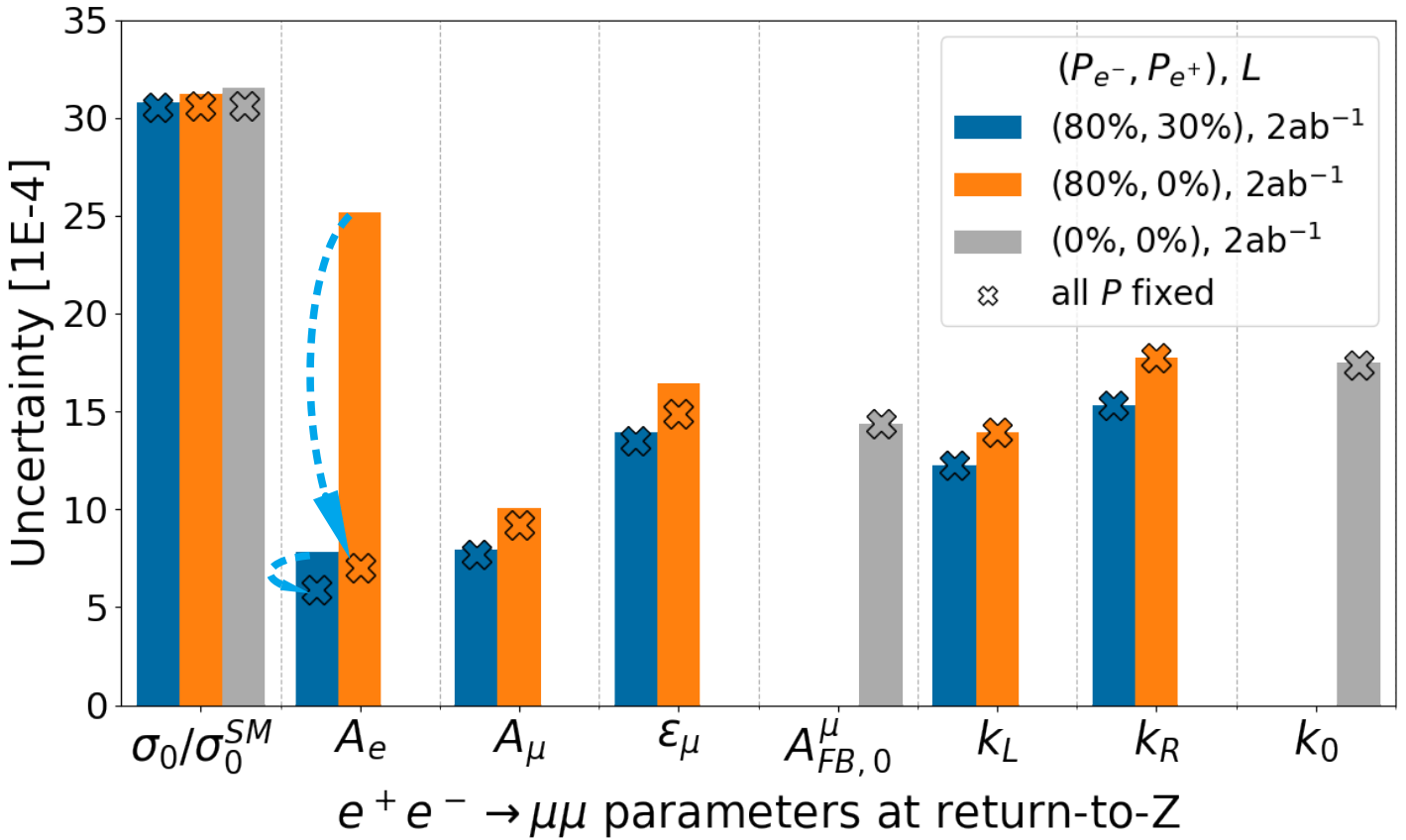


Not enough information

A_e uncertainty determined by polarisation knowledge



A_e uncertainty determined by polarisation knowledge



A_e uncertainty determined by polarisation knowledge

Solved by e^+ polarisation

Which systematic for μμ̄?

ALEPH

Table 13. Exclusive $\mu^+\mu^-$ selection: examples of relative systematic uncertainties (in %) for the 1994 (1995) peak points

Source	$\Delta\sigma/\sigma$ (%)
Acceptance	0.05
Momentum calibration	0.006 (0.009)
Momentum resolution	0.005
Photon energy	0.05
Radiative events	0.05
Muon identification	$\simeq$ 0.001 (0.02)
Monte Carlo statistics	0.06
Total	0.10 (0.11)

L3

Table 8. Contributions to the systematic uncertainty on the cross section $e^+e^- \to \mu^+\mu^-(\gamma)$. Except for the contribution from Monte Carlo statistics, all errors are fully correlated among the data sets yielding a correlated scale error of $\delta^{cor} = 3.1^0/_{00}$ for 1993–94 data. For the 1995 data this error is estimated to be $3.6^0/_{00}$ and it is taken to be fully correlated with the other years

Source		1993	1994	1995
Monte Carlo statistics	$[^0/_{00}]$	0.9 – 1.5	0.4	1.7 – 2.4
Acceptance	$[^0/_{00}]$	2.7	2.7	3.2
Selection cuts	$[^0/_{00}]$	1.3	1.3	1.4 – 2.2
Trigger	$[^0/_{00}]$	0.6	0.6	0.5 – 0.7
Resonant background	$[^0/_{00}]$	0.3	0.3	0.3
Total scale	$[^0/_{00}]$	3.2 – 3.4	3.1	3.9 – 4.6
$e^+e^- \to e^+e^-\,\mu^+\mu^-$	[pb]	–	–	0.1
Cosmic rays	[pb]	0.3	0.3	0.3
Total absolute	[pb]	0.3	0.3	0.3

OPAL

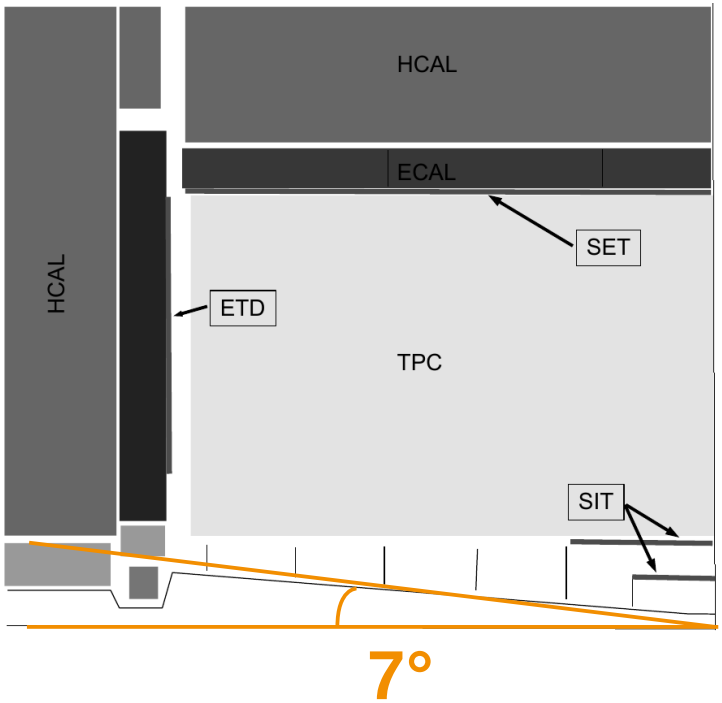
	1993						1994		1995					
	peak−2		peak		peak+2		peak		peak−2		peak		peak+2	
	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)
Monte Carlo														
$e^+e^- \to \mu^+\mu^-$ Monte Carlo	1.0995	0.10	1.0955	0.07	1.0986	0.10	1.0948	0.04	1.1032	0.12	1.0970	0.05	1.1001	0.10
s' cut correction	0.9971	–	0.9990	–	0.9980	–	0.9990	–	0.9971	–	0.9990	–	0.9980	–
Initial/final state interference	1.0003	–	1.0002	–	1.0001	–	1.0002	–	1.0003	–	1.0002	–	1.0001	–
Acceptance Correction														
Tracking losses	1.0046	0.06	1.0046	0.06	1.0046	0.06	1.0042	0.04	1.0043	0.06	1.0043	0.06	1.0043	0.06
Track multiplicity cuts	0.9999	0.05	1.0007	0.04	1.0000	0.04	1.0004	0.02	1.0007	0.09	1.0010	0.04	1.0013	0.08
Muon identification	1.0000	0.05	1.0000	0.05	1.0000	0.05	1.0015	0.04	1.0000	0.06	1.0000	0.06	1.0000	0.06
Acceptance definition	1.0000	0.10	1.0000	0.10	1.0000	0.10	1.0000	0.05	1.0000	0.05	1.0000	0.05	1.0000	0.05
Other Corrections														
Trigger efficiency	1.0006	0.02	1.0006	0.02	1.0006	0.02	1.0005	0.02	1.0002	0.02	1.0002	0.02	1.0002	0.02
Four-fermion events	1.0009	0.01	1.0011	0.01	1.0011	0.01	1.0011	0.01	1.0009	0.01	1.0011	0.01	1.0011	0.01
Signal Correction	1.1032	0.17	1.1022	0.15	1.1034	0.17	1.1024	0.09	1.1071	0.18	1.1034	0.12	1.1056	0.16
Backgrounds														
$e^+e^- \to \tau^+\tau^-$	0.9914	0.02	0.9914	0.02	0.9914	0.02	0.9903	0.04	0.9905	0.02	0.9905	0.02	0.9905	0.02
$e^+e^- \to e^+e^-\mu^+\mu^-$	0.9988	0.01	0.9995	0.01	0.9991	0.01	0.9996	0.01	0.9987	0.01	0.9995	0.01	0.9990	0.01
Cosmic rays	0.9998	0.02	0.9998	0.02	0.9998	0.02	0.9998	0.02	0.9997	0.02	0.9997	0.02	0.9997	0.02
Background Correction	0.9900	0.03	0.9907	0.03	0.9903	0.03	0.9897	0.05	0.9889	0.03	0.9897	0.03	0.9892	0.03
Total Correction Factor	1.0922	0.17	1.0920	0.16	1.0927	0.17	1.0910	0.10	1.0948	0.18	1.0920	0.12	1.0937	0.17

Table 6: Summary of the correction factors, f, and their relative systematic errors, $\Delta f/f$, for the $e^+e^- \to \mu^+\mu^-$ cross-section measurements. These numbers, when multiplied by the number of events actually selected, give the number of signal events which would have been observed in the ideal acceptance described in Table 2. The effects tracking losses, track multiplicity cuts and muon identification were, in principle, simulated by the Monte Carlo. The quoted corrections were introduced to take into account the observed discrepancies between the data and Monte Carlo for these effects. The error correlation matrix is given in Table 19.

→ First test of systematic effect: **μ acceptance**

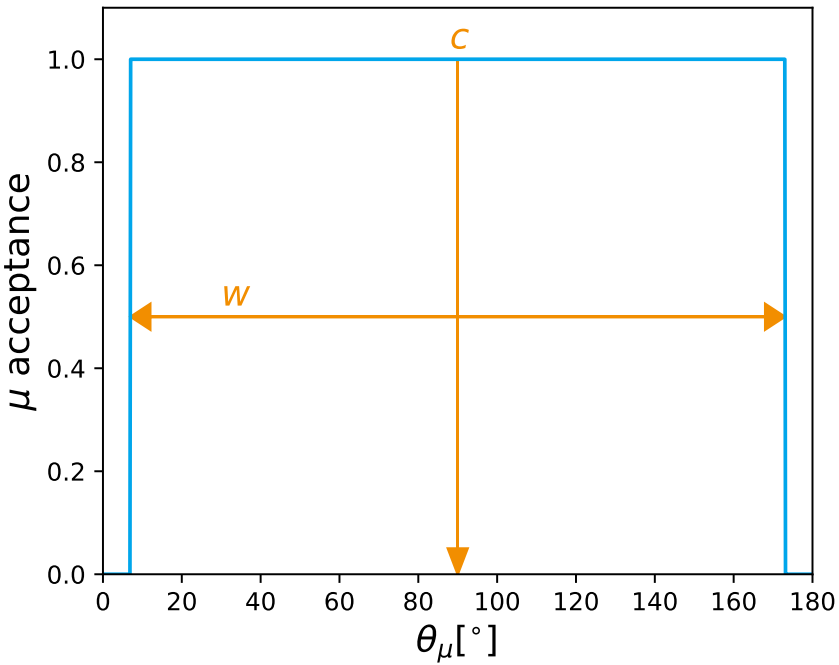
μ acceptance

ILD tracking down to:

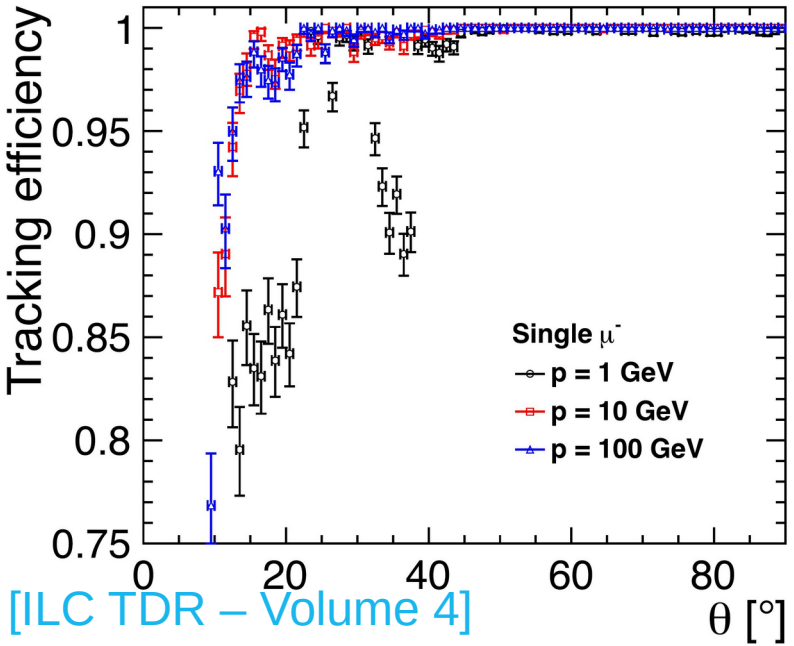


Simplified μ acceptance

→ 2 Parameters: Δc, Δw



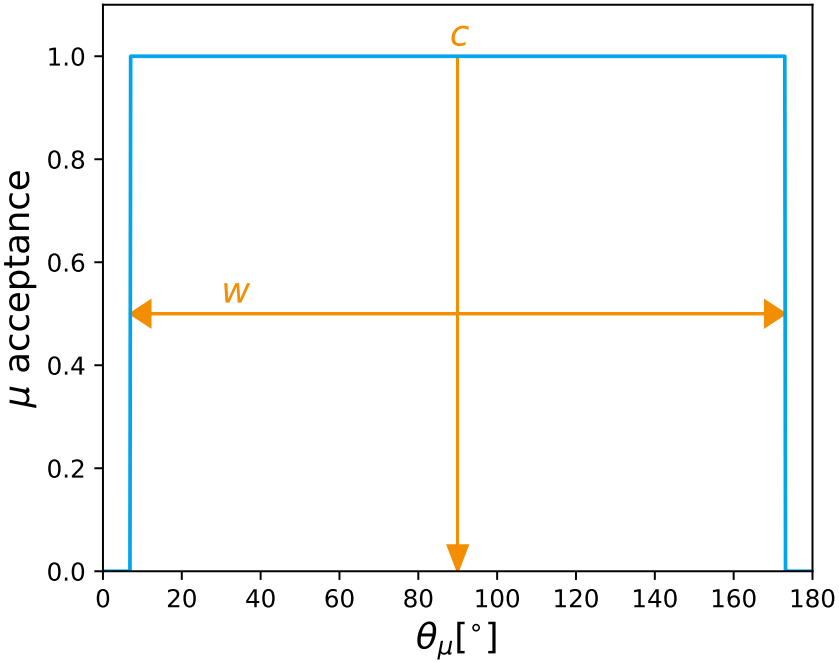
μ acceptance



[ILC TDR – Volume 4]

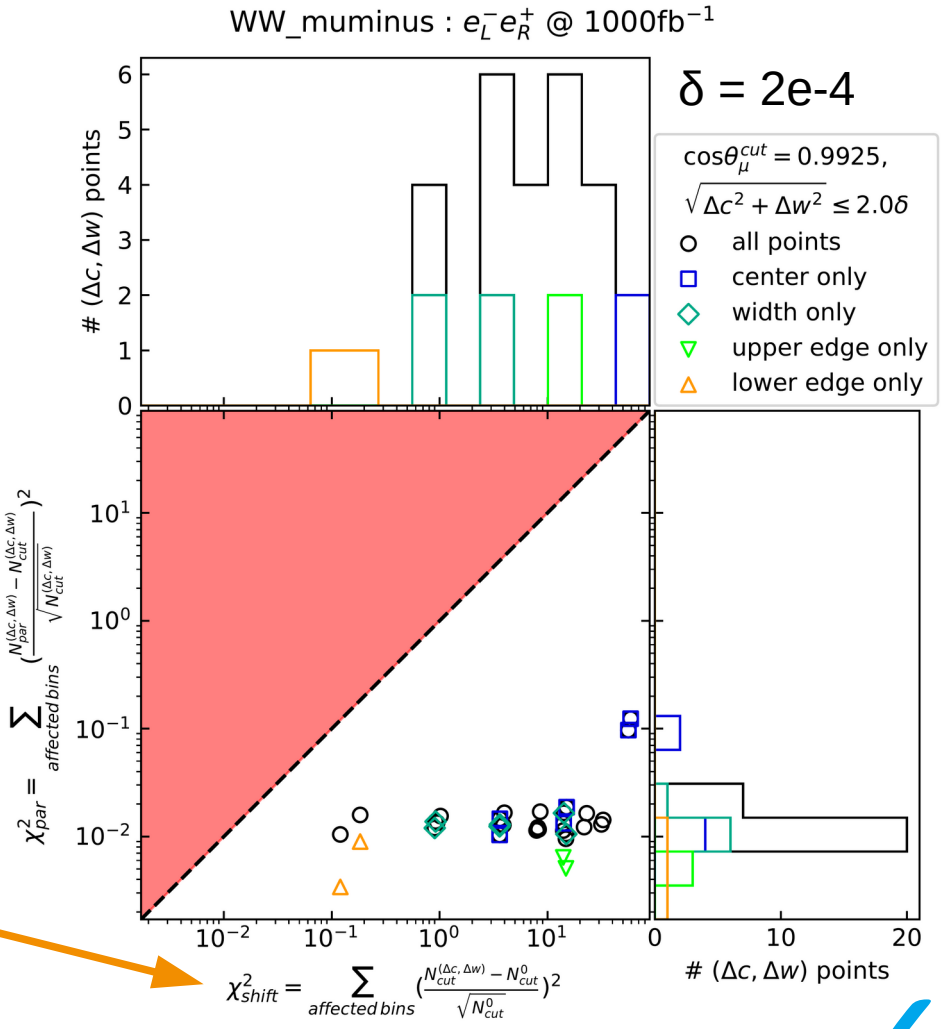
Simplified μ acceptance

→ 2 Parameters: Δc, Δw



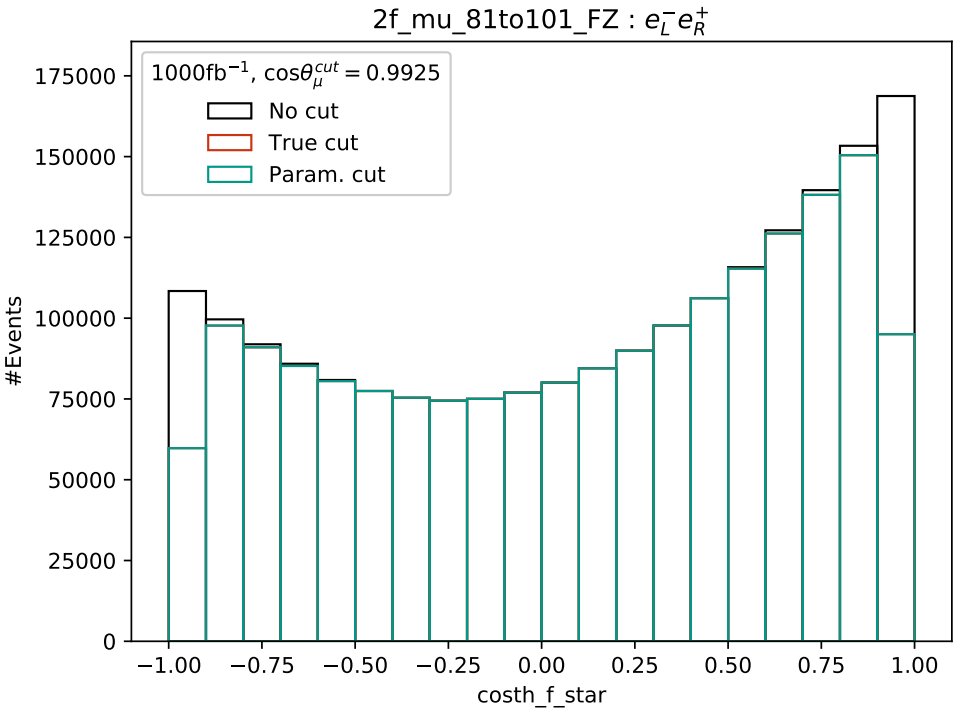
Validation of the parametrisation:

How relevant is:
- **mistake made by parametrisation**
vs.
- **effect of deviation** ?

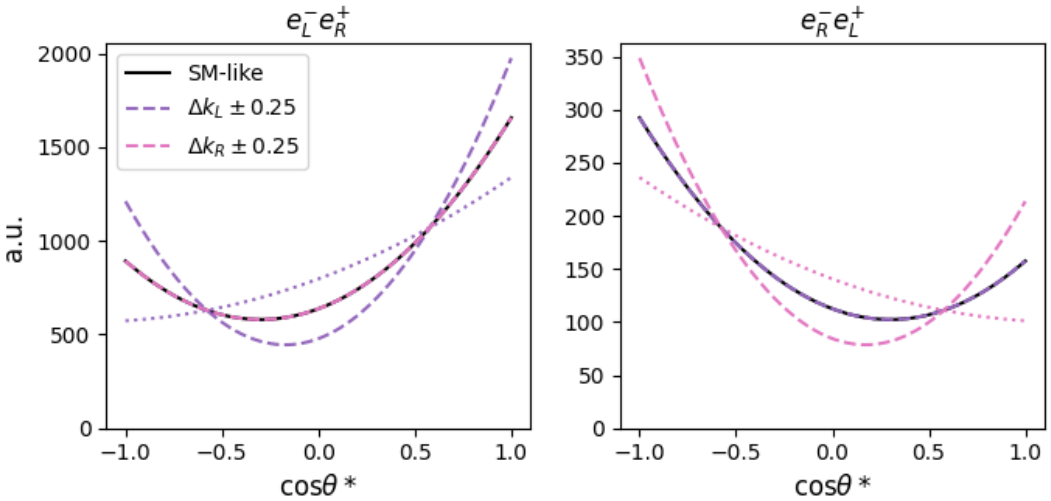


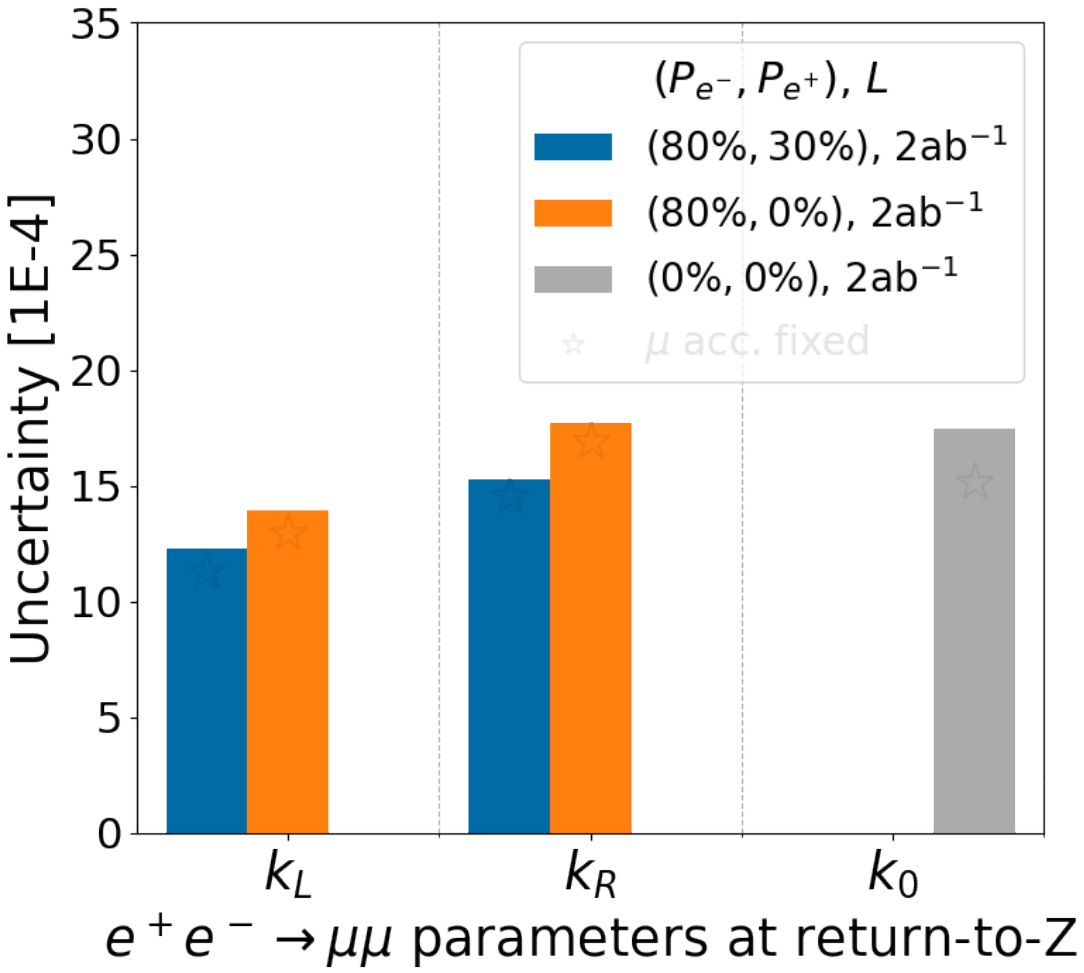
Safe to use ✓

Acceptance @ return-to-Z



Correction factors





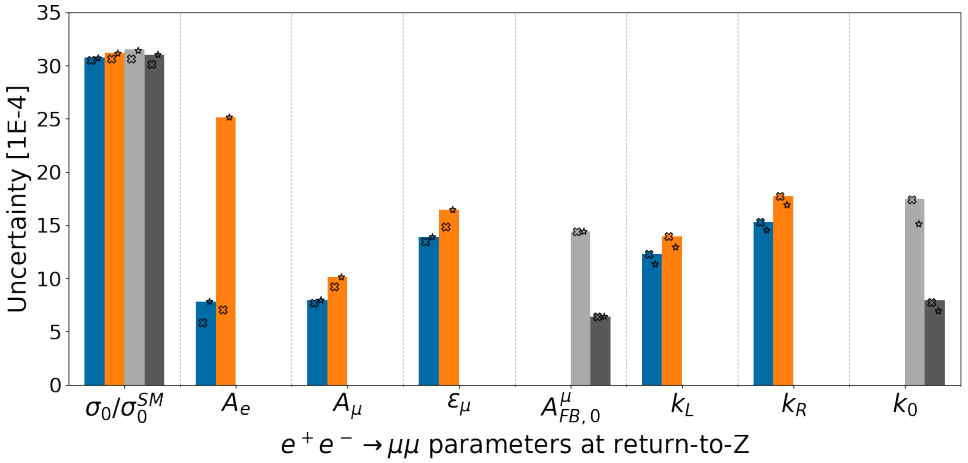
First test:

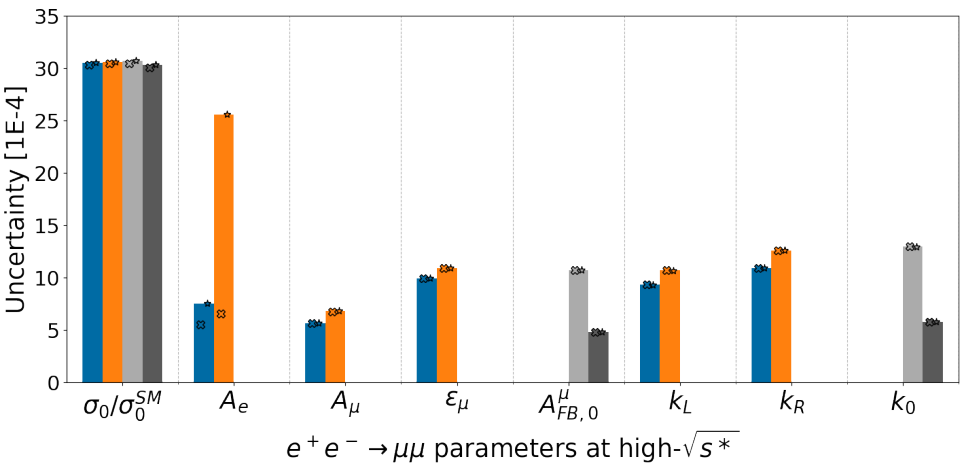
Geometric μ acceptance

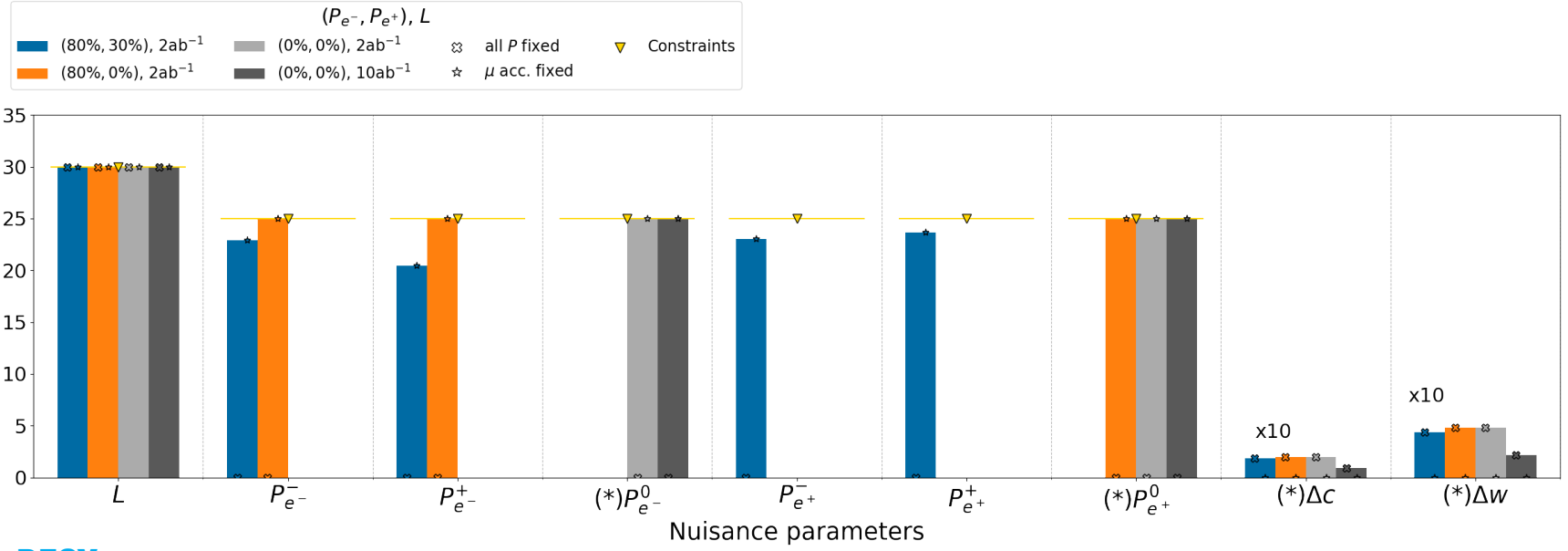
k parameters forward-sensitive

↓

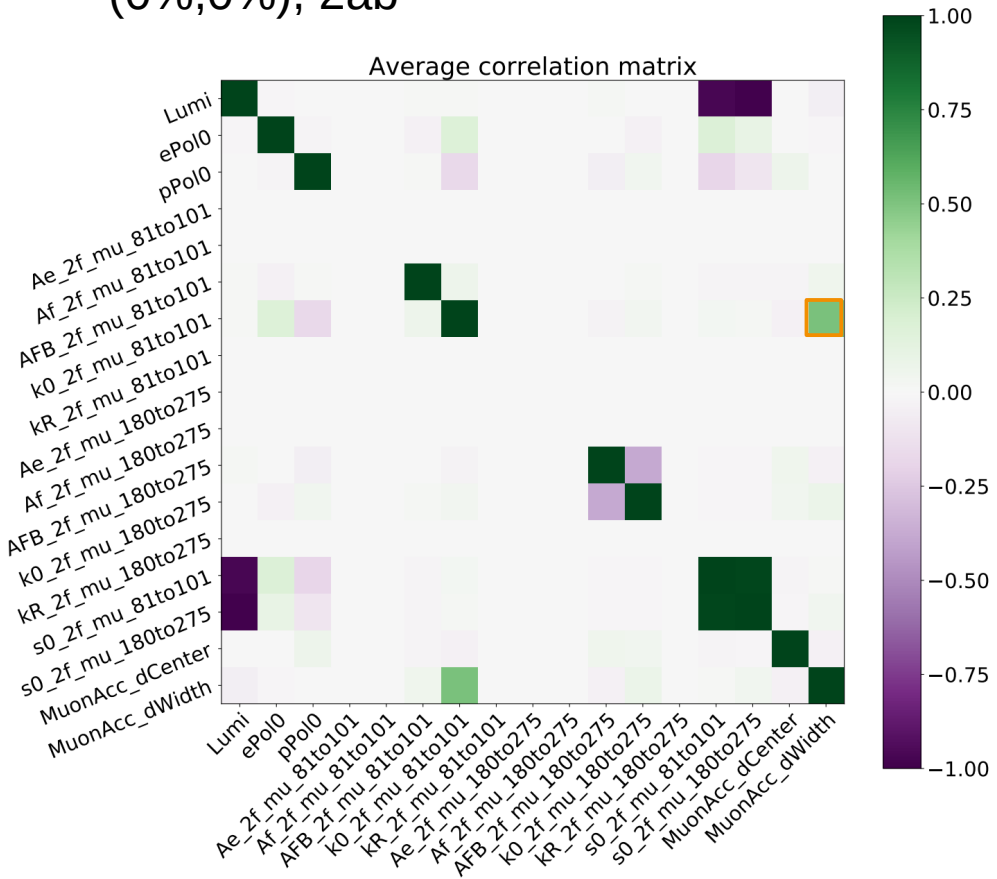
Need precise knowledge of μ acceptance edge


Uncertainty [1E-4]
σ_0/σ_0^{SM}
A_e
A_μ
ε_μ
$A^{\mu}_{FB,0}$
k_L
k_R
k_0
$e^+e^- \to \mu\mu$ parameters at return-to-Z


Uncertainty [1E-4]
σ_0/σ_0^{SM}
A_e
A_μ
ε_μ
$A^{\mu}_{FB,0}$
k_L
k_R
k_0
$e^+e^- \to \mu\mu$ parameters at high-$\sqrt{s*}$


(P_{e^-}, P_{e^+}), L
(80%, 30%), 2ab^{-1}
(80%, 0%), 2ab^{-1}
(0%, 0%), 2ab^{-1}
(0%, 0%), 10ab^{-1}
all P fixed
μ acc. fixed
Constraints
Rel. (*Abs.) Uncertainty [1E-4]
L
$P^-_{e^-}$
$P^+_{e^-}$
$(*)P^0_{e^-}$
$P^-_{e^+}$
$P^+_{e^+}$
$(*)P^0_{e^+}$
$(*)\Delta c$
$(*)\Delta w$
x10
x10
Nuisance parameters

(0%,0%), 2ab^{-1}



(80%,30%), 2ab^{-1}