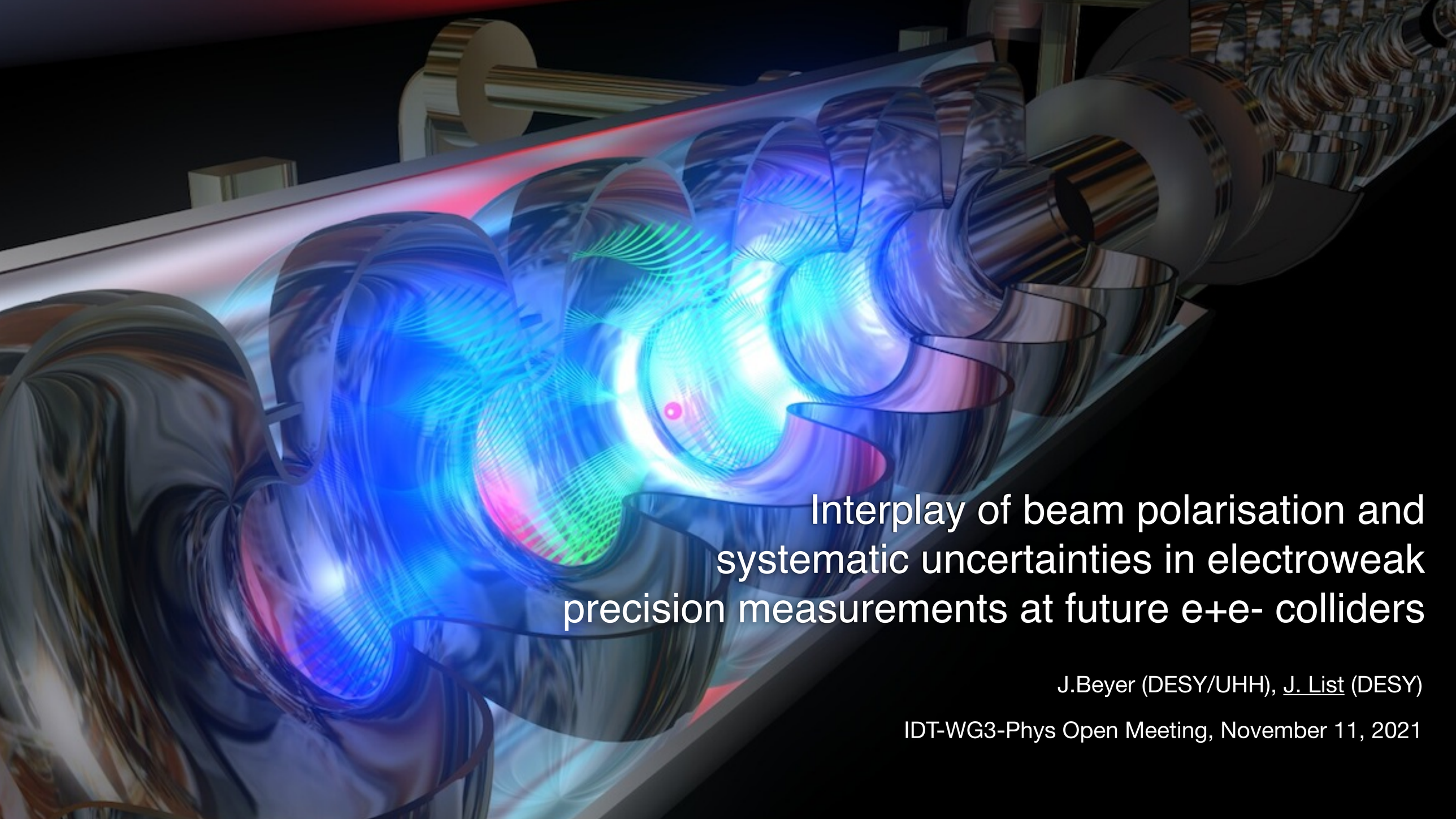


Interplay of beam polarisation and systematic uncertainties in electroweak precision measurements at future e+e- colliders

J.Beyer (DESY/UHH), J. List (DESY)

IDT-WG3-Phys Open Meeting, November 11, 2021

Future e^+e^- Colliders and (longitudinally) Polarised Beams

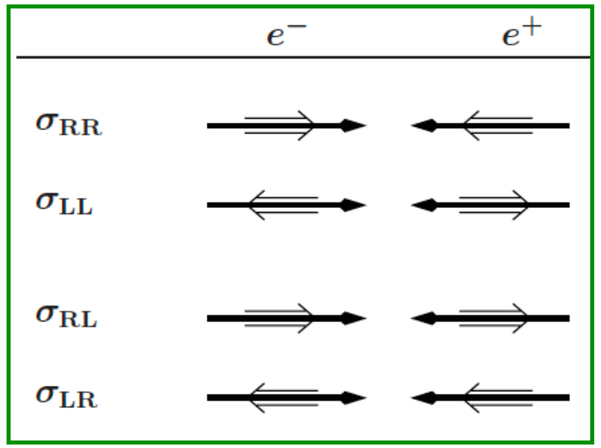
General references on polarised e^+e^- physics:

- **arXiv:1801.02840**
- **Phys. Rept. 460 (2008) 131-243**

- Longitudinally **polarised beams** are a special feature of **Linear e^+e^- Colliders**:
  - SLC: P(e^-) = ± 80%, P(e^+) = 0%
  - ILC: P(e^-) = ± 80%, P(e^+) = ± 30% (upgrade 60%)
  - CLIC: P(e^-) = ± 80%, P(e^+) = 0%

$$P = \frac{N_R - N_L}{N_R + N_L}$$

- Electroweak interactions highly sensitive to chirality of fermions: $SU(2)_L$ x U(1)
  - every cross section depends on beam polarisations
  - **with both its beams polarised, ILC is "four colliders in one":**

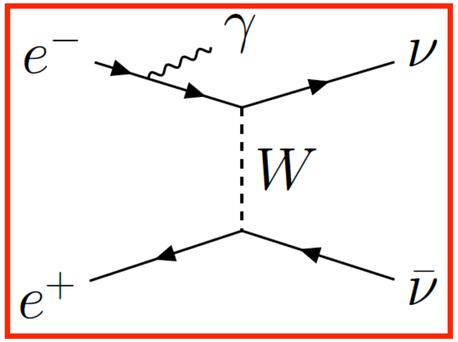


- note: future **circular** Higgs factories offer **no longitudinal beam polarisation**

Physics benefits of polarised beams

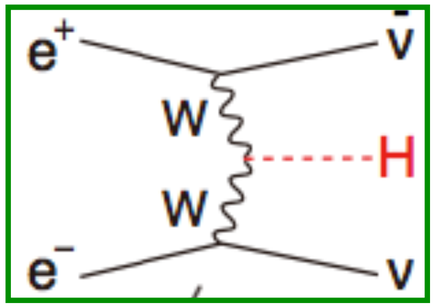
background suppression:

- $e^+e^- \rightarrow WW$ / $\nu_e\nu_e$
  strongly P-dependent
  since t-channel only
  for $e^-_L e^+_R$



signal enhancement:

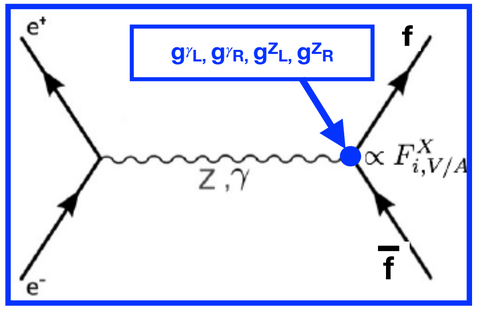
- Higgs production
  in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in
  couplings to left- and
  right-handed fermions



- BSM:
  chiral structure unknown, needs to be determined!

redundancy & control of systematics:

- "wrong" polarisation yields "signal-free" control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

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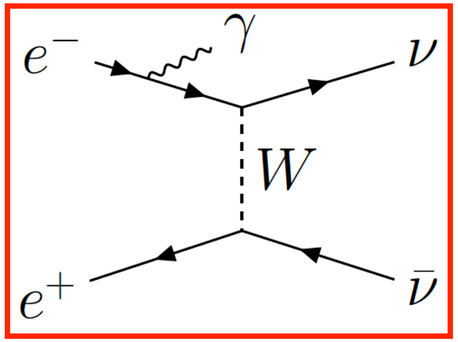

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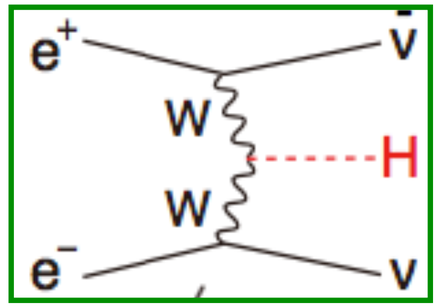

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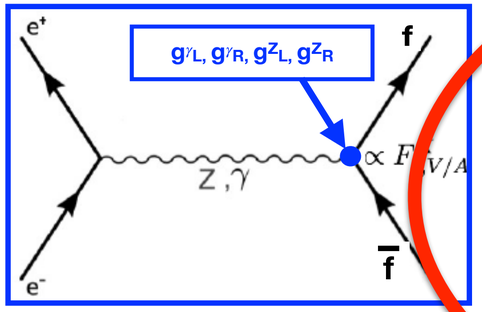

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The general idea

Polarisation & Systematics: what we start from

Processes and their polarisation dependence

- s-channel: exchange of vector particles $\Rightarrow \sigma_{\mathrm{LL}} = \sigma_{\mathrm{RR}} = 0$
- t-channel W or ν exchange: $\Rightarrow \sigma_{\mathrm{LL}} = \sigma_{\mathrm{RR}} = \sigma_{\mathrm{RL}} = 0$
- t-channel γ, Z or e exchange: all chiral cross sections > 0

Time-dependent experimental uncertainties

- originate from drifts in calibrations, changes in detector configuration, alignment, machine parameters, ...
- change slowly w.r.t. to flipping of polarisation signs
- $\Rightarrow$ data sets with different polarisation signs are collected "quasi-concurrently"
- $\Rightarrow$ time-dependent systematic effects are strongly correlated between such data sets!

A simplified example - consider....

.. one signal and one background process

- signal: s-channel process, e.g. $\mu^+\mu^-$, or $\mu^+\mu^- h$: σ^S_{LR}, σ^S_{RL}
- background: dominantly t-channel ν exchange, e.g. $W^+W^- \to \mu^+\nu\mu^-\nu$: σ^B_{LR}, σ^B_{RL}

... one uncertainty depending on one kinematic variable

- e.g. reconstruction efficiency for isolated μ^-: $\epsilon(\cos\theta_{\mu^-})$
- can change with time e.g. due to change of beam spot position, detector alignment w.r.t. machine, ..
- important: at any time and $\cos\theta_{\mu^-}$, the efficiency is the same for each isolated muon, regardless of process or polarisation.

Target quantities and nuisance parameters

- σ^S_{LR}, σ^S_{RL}, σ^B_{LR}, σ^B_{RL} (or, equivalently, σ^S_0, A^S_{LR}, σ^B_0, A^B_{LR})
  $\Rightarrow$ note: this assumes differential cross-sections perfectly known — in practice additional N_{shape} "shape" parameters, e.g. A_{FB}, TGCs, ...
- $\epsilon(i)$ in each of n bins in $\cos\theta_{\mu^-}$
- optionally $P^-_{e^-}$, $P^+_{e^-}$, $P^-_{e^+}$, $P^+_{e^+}$

$\Rightarrow$ between n+4 ($+N_{\mathrm{shape}}$) and n+8 ($+N_{\mathrm{shape}}$) "unknowns"

This is a very simple example designed to illustrate the basic mechanisms!

Observables (still in our simple example)

for each data set:

- event count in bin i

$$\frac{dN(i)}{d\cos\theta_{\mu-}} = f_{\mathrm{LR}}\sigma^S_{\mathrm{LR}}\frac{d\sigma^S_{\mathrm{LR}}(i)}{d\cos\theta_{\mu-}}\epsilon(i) + f_{\mathrm{RL}}\sigma^S_{\mathrm{RL}}\frac{d\sigma^S_{\mathrm{LR}}(i)}{d\cos\theta_{\mu-}}\epsilon(i) \quad (1)$$

$$+ f_{\mathrm{LR}}\sigma^B_{\mathrm{LR}}\frac{d\sigma^B_{\mathrm{LR}}(i)}{d\cos\theta_{\mu-}}\epsilon(i) + f_{\mathrm{RL}}\sigma^B_{\mathrm{RL}}\frac{d\sigma^B_{\mathrm{LR}}(i)}{d\cos\theta_{\mu-}}\epsilon(i) \quad (2)$$

- f's depend on polarisation values:
  $f_{\mathrm{LR}} = (1-P_{e-})(1+P_{e+})\times\mathcal{L}$, $f_{\mathrm{RL}} = (1+P_{e-})(1-P_{e+})\times\mathcal{L}$
- $\frac{d\sigma(i)}{d\cos\theta_{\mu-}}$ denotes differential cross section in bin i; normalised to $\int = 1$ (shape only)

$\Rightarrow$ n, $2n$ or $4n$ "observables" for one, two or four data sets

The unpolarised case (still in our simple example)

$P(e^-, e^+)$=(0,0):

$$\frac{dN(i)}{d\cos\theta_{\mu-}} = (\sigma_0^S \frac{d\sigma_0^S(i)}{d\cos\theta_{\mu-}} + \sigma_0^B \frac{d\sigma_0^B(i)}{d\cos\theta_{\mu-}}) \cdot \epsilon(i) \cdot \mathcal{L} \quad (3)$$

- n observables vs n+2+N_{shape} unknowns $\Rightarrow$ no overconstraining (even for $N_{\mathrm{shape}} = 0$!)
- $\epsilon(i)$ and σ_0^B need to be known from other measurements / control samples / MC
- or systematic effect (μ efficiency) needs to be described with much less parameters than 1 per bin

Polarised beams (still in our simple example)

$P(e^-, e^+) = (\pm 80\%, 0)$, N_{shape}=0:

- assume polarisations known: $2n$ observables vs n+4 unknowns
  $\Rightarrow$ overconstraining with more than 4 bins
- polarisations as nuisance parameters: $2n$ observables vs $n+7$ unknowns
  $\Rightarrow$ overconstraining with more than 7 bins
- this can still be combined with additional knowledge from other measurements / control samples / MC

$P(e^-, e^+) = (\pm 80\%, \pm 30\%)$, N_{shape}=0:

- assume polarisations known: $4n$ observables vs n+4 unknowns
  $\Rightarrow$ overconstraining with at least 2 bins
- polarisations as nuisance parameters: $4n$ observables vs n+8 unknowns
  $\Rightarrow$ overconstraining with more than 2 bins
- again, this can still be combined with additional knowledge from other measurements / control samples / MC

Some discussion - part 1

What about “common modes”?

- A global bias in efficiency can mathematically not be distinguished from a global bias in all polarised cross sections
- How likely is it that all polarised cross sections of all processes (in reality combine many more than 2!) are off from the SM in exactly the same way?
  $\Rightarrow$ in a global fit: include a-priori knowledge from theory as additional constraint with reasonable uncertainty
  $\Rightarrow$ compensating μ efficiency by changing all cross sections will give χ^2 penalty for each included process

Some discussion - part 2

Add a "reducible" background, e.g. with non-prompt μ's:

- determine in addition fake rates $\epsilon_f(i)$
  note: this is a brute-force approach, assuming one independent parameter for "fakes" for each bin, for the sake of the argument.
- $P(e^-, e^+) = (\pm 80\%, 0)$: $2n$ observables vs $2n{+}8{+}N_{\mathrm{shape}}$ unknowns $\Rightarrow$ never overconstrained
  $\Rightarrow$ need additional control regions
- $P(e^-, e^+) = (\pm 80\%, \pm 30\%)$: $4n$ observables vs $2n{+}8{+}N_{\mathrm{shape}}$ unknowns $\Rightarrow$ overconstrained when more than $4{+}N_{\mathrm{shape}}/2$ bins
  $\Rightarrow$ data sets with different polarisations – thus different S/B – act as "control samples" here.

Some discussion - part 3

Improvement with luminosity?

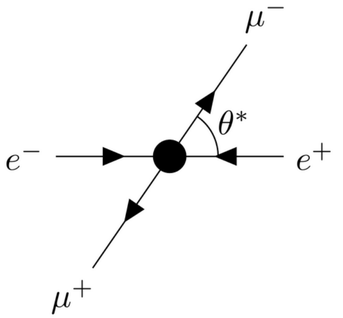
- For all time-dependent effects, more data taken at another time (a month later, a year later, ...) does not help anymore, because the exact change with time can only determined with limited precision.
- In the long-term average, the “jitter” of time-dependent systematic effects leads to a finite minimum of the systematic uncertainties.
- Concurrently taken data sets with different polarisation will push this minimum further down.

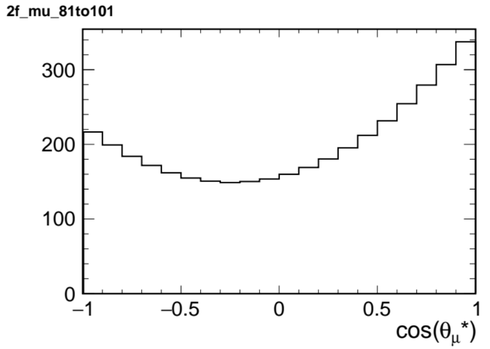
Towards a combined analyses of ee->2f and ee->4f including systematic uncertainties

Physics processes & parameters

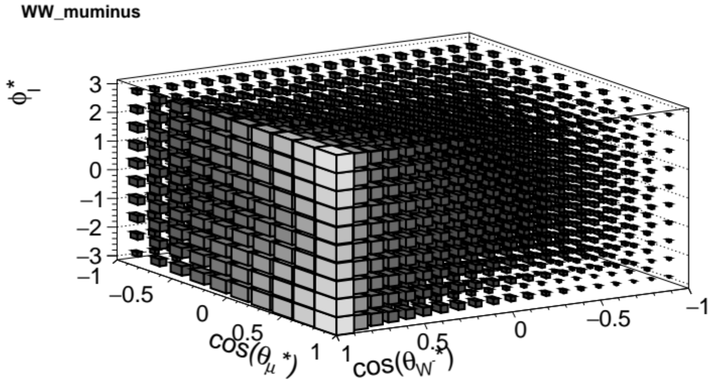
here: Whizard LO ME + PS + ISR
future: many generators work on improved ISR / NLO, see eg recent MC WS of ECFA Higgs Factory Study

- **E_{CM} = 250 GeV, L=2 ab^{-1}, P(e^-,e^+)=(±80%,±30%), (±80%,0%), (0%,0%)**
  - nuisance parameters: polarisations, luminosity, with constraints from polarimeters & lumi measurement
- **ee->2f example process: ee->μμ**
  - observable: cosθ* in restframe;
    separated into "high-Q^2" and "return to Z"
  - physics parameters:
    - polarised: σ_0, A_e, A_μ; ε_μ (Z/γ interference), $k_{L/R}$ (ISR)
    - unpolarised: σ_0, $A_{FB,0}$; k_0
      => Z//γ interference and initial/final state asymmetries collapse to one parameter (all linear in cosθ*)





- **ee -> 4f example process: ee -> WW -> μνqq**
  - observables: production angle cosθ$_W$, decay angles cosθ$_l$*, cosϕ$_l$*
    [separated into μ^+ and μ^- as preparation for evqq including single-W]
  - physics parameters: σ_0(W), A_{LR}(W), 3 charged TGCs



Which experimental systematics to test?

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

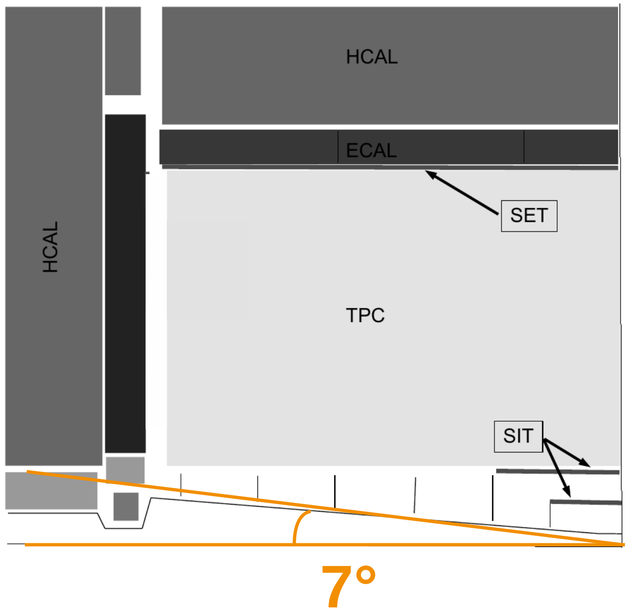
	1993						1994		1995					
	peak−2		peak		peak+2		peak		peak−2		peak		peak+2	
	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)
Monte Carlo														
$e^+e^- \to \mu^+\mu^-$ Monte Carlo	1.0995	0.10	1.0955	0.07	1.0986	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

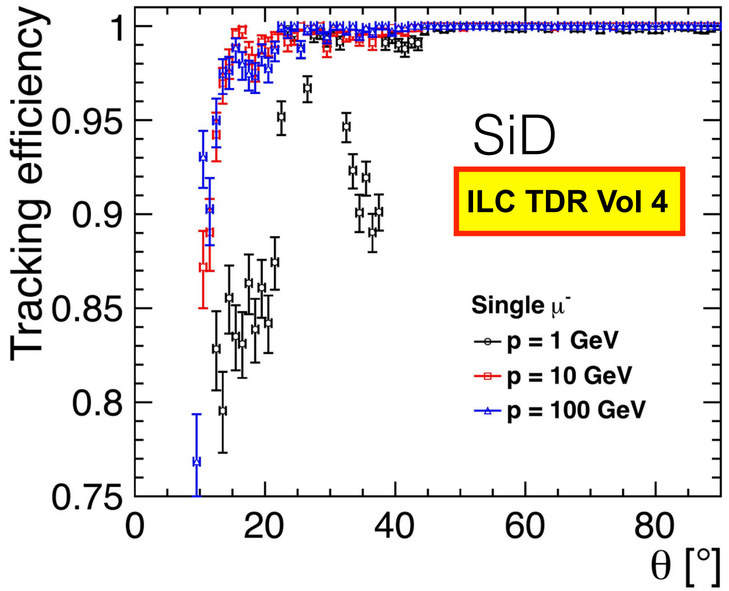
Table 6: Summary of the correction factors, f, and their relative systematic errors, $\Delta f/f$, for the $e^+e^- \to \mu^+\mu^-$ cross-section measurements. These numbers, when multiplied by the number of events actually selected, give the number of signal events which would have been observed in the 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**

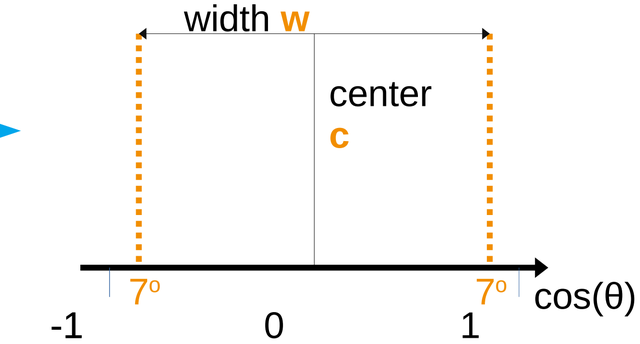
Parametrising the muon acceptance for an ILC detector

ILD tracking down to:





Simplified picture:
Event passes if all μ's inside box

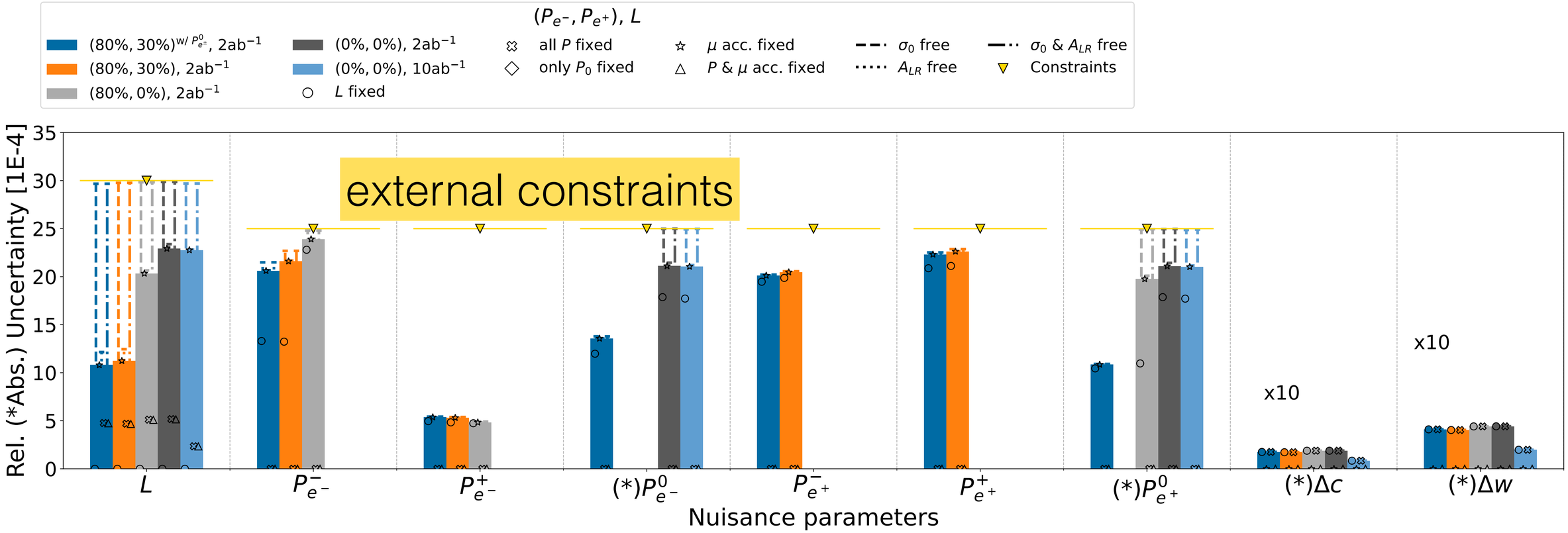


Fit parameters: Δc, Δw

notabene: according to previous considerations,
an acceptance described by 2 parameters can be determined in all cases
- only a first conceptual step here
also: all inputs on generator-level…

Nuisance parameters from combined ee->μμ & ee->μνqq fit

full bars: σ_0(WW), A_{LR}(WW) fixed - dash-dotted bars: all free



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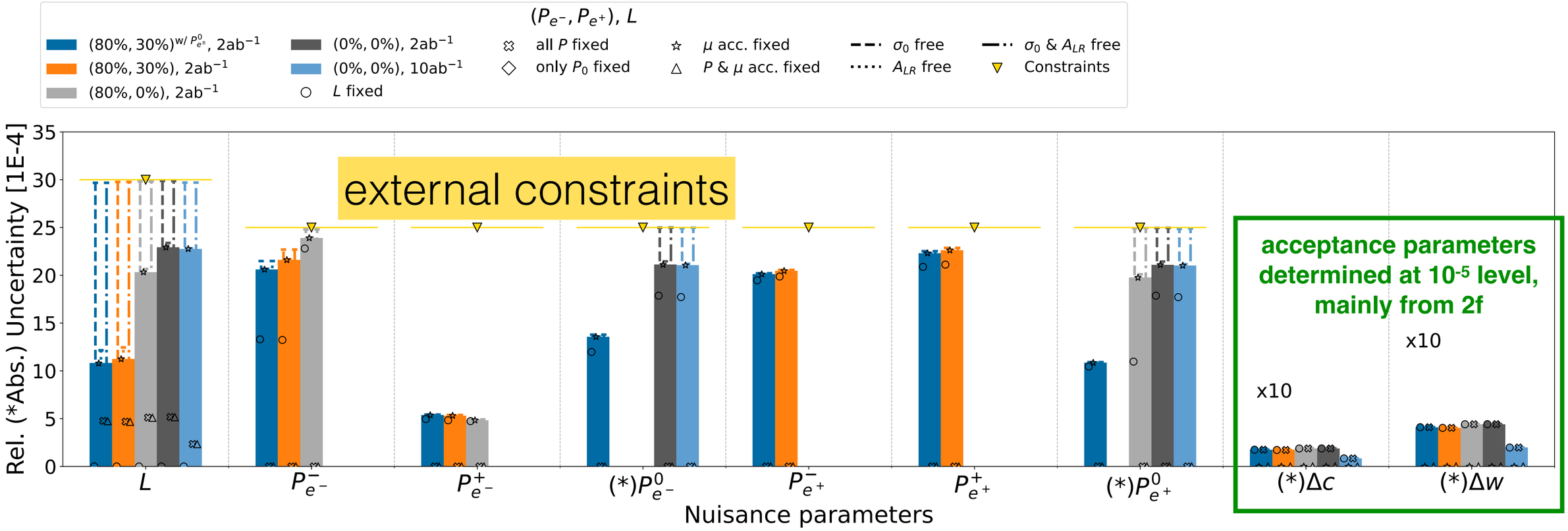

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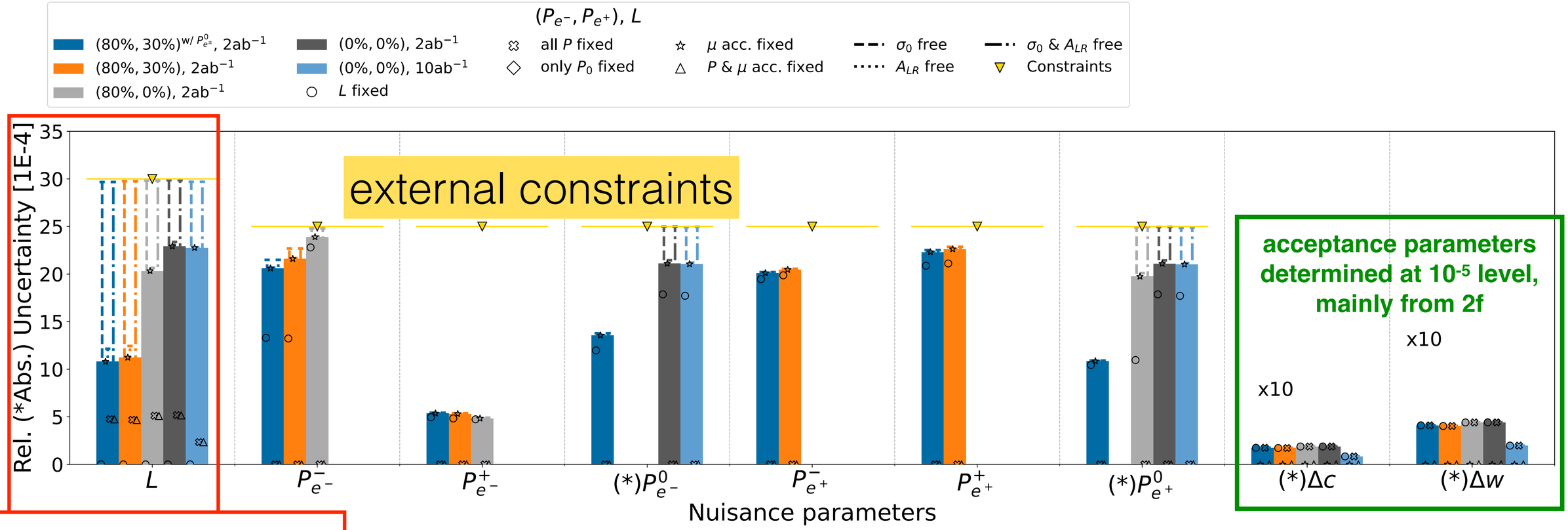

if one σ_0 were known better than lumi measurement, luminosity could be better constrained => academic ?

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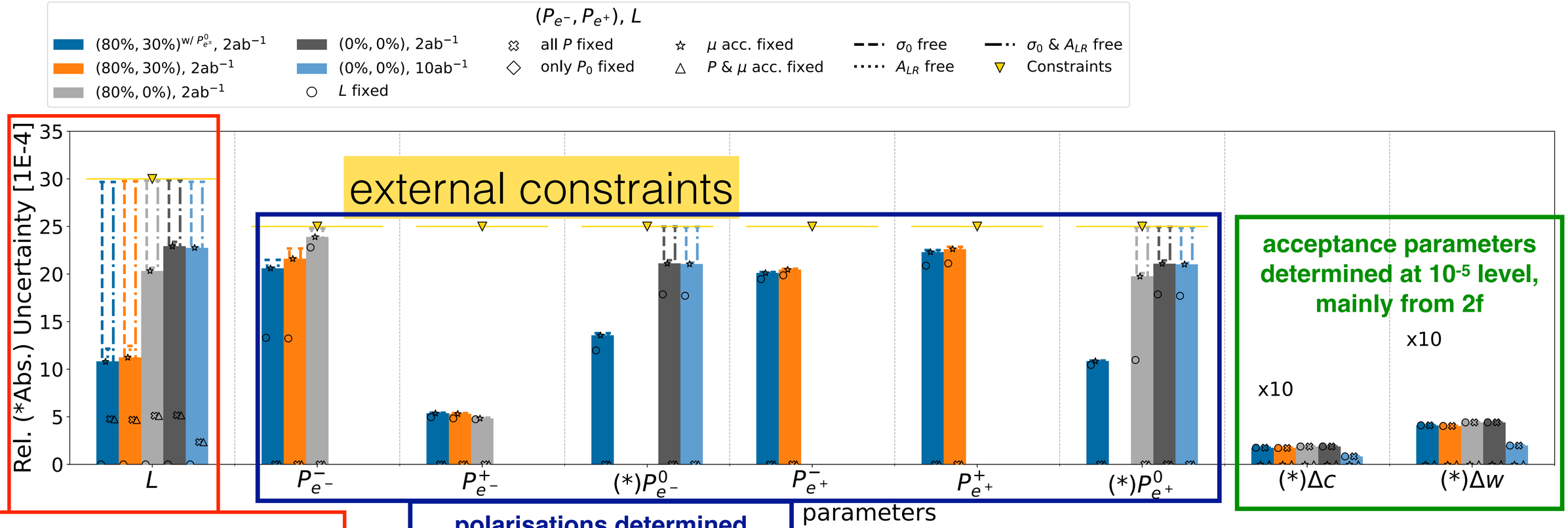

acceptance parameters determined at 10^{-5} level, mainly from 2f

polarisations determined to 0.05…0.2%, almost exclusively from WW

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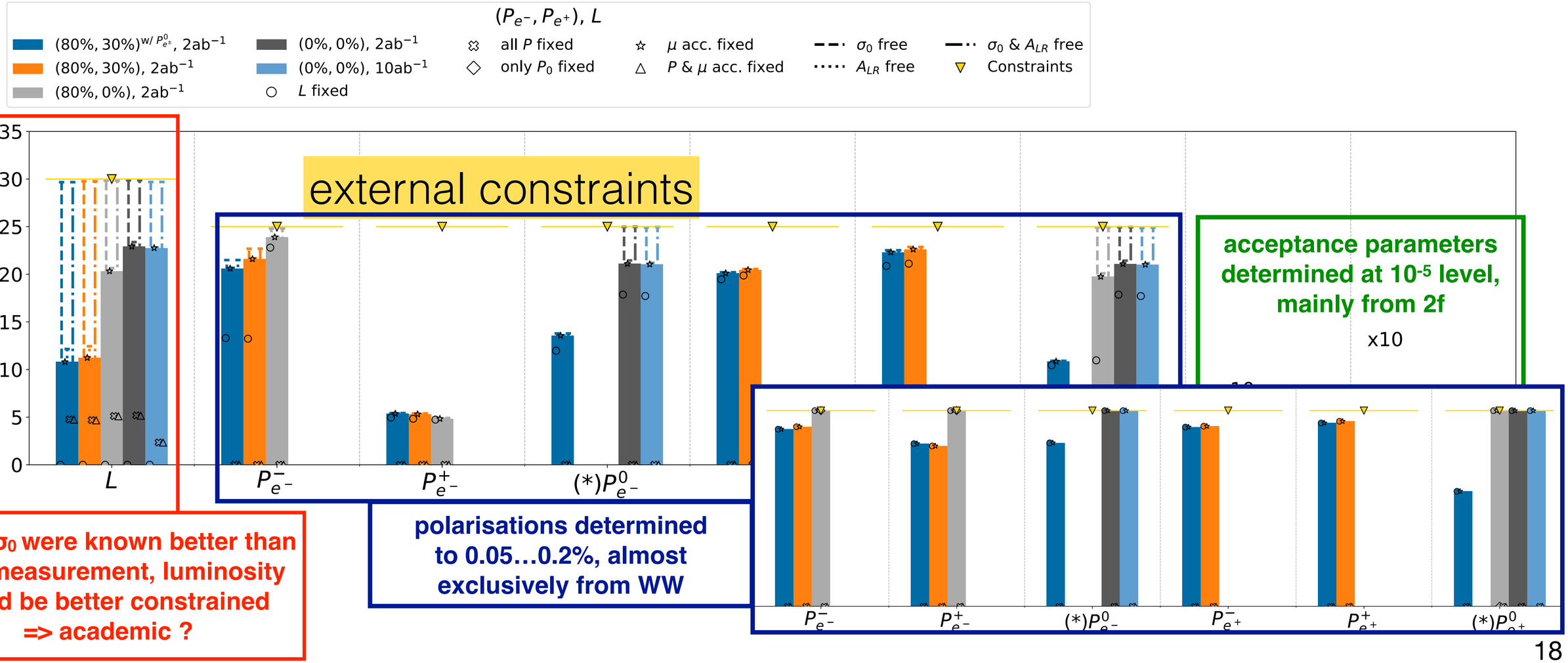

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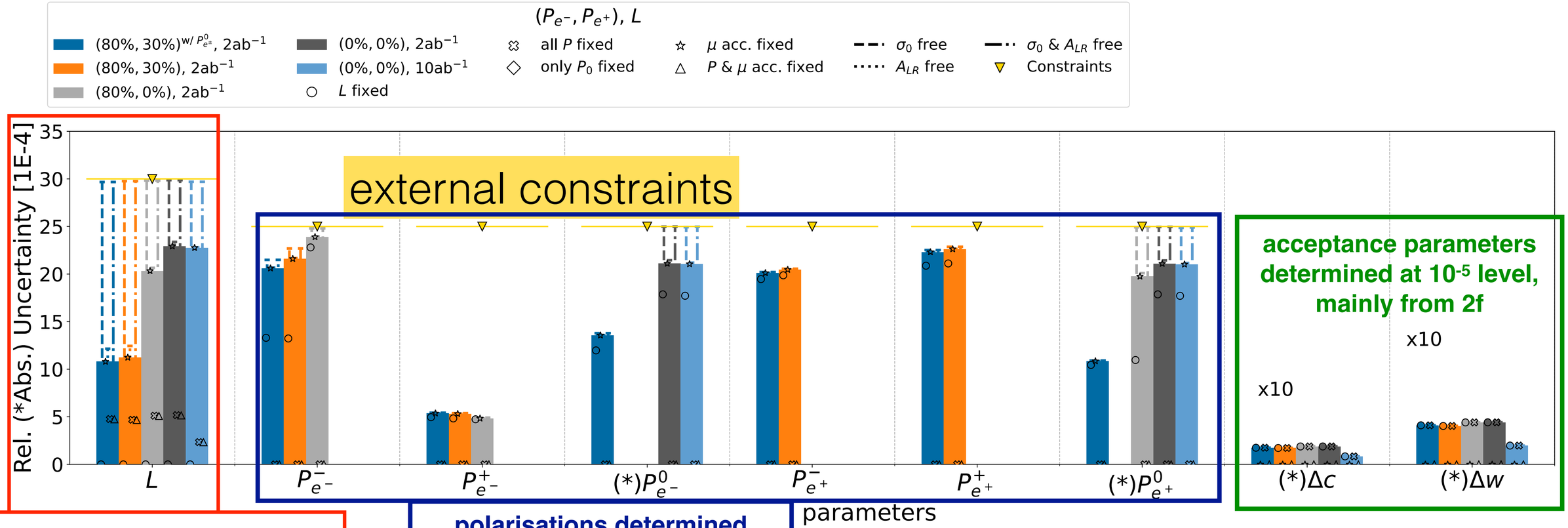

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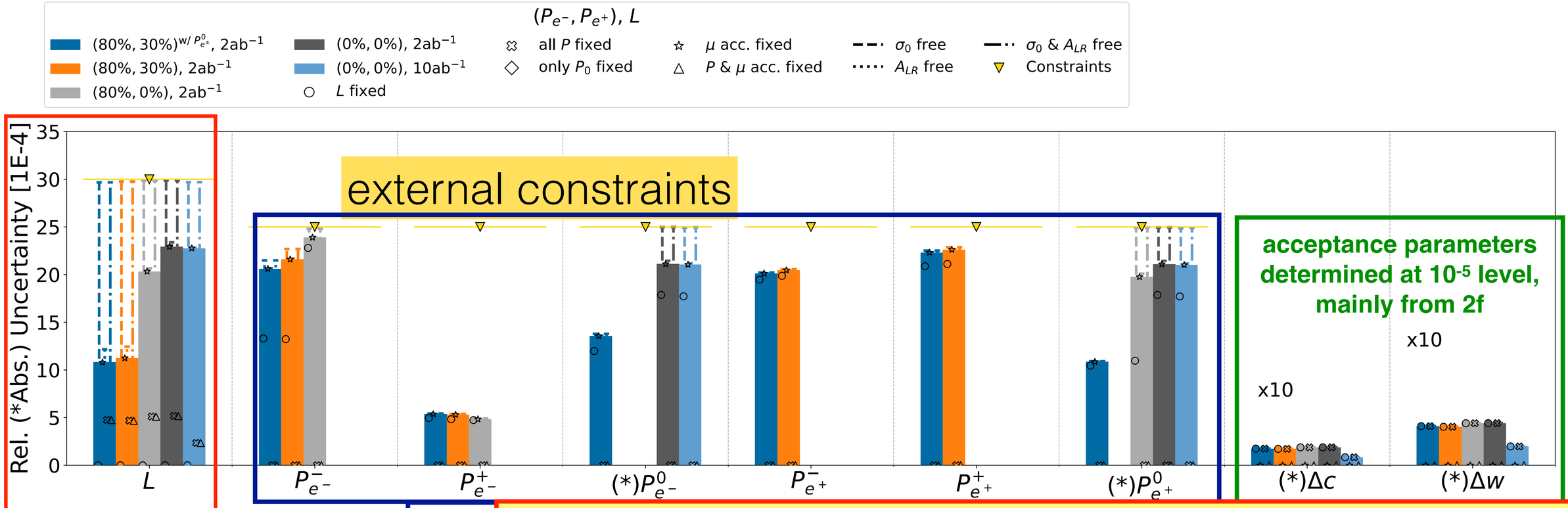
Nuisance parameters from combined ee->μμ & ee->μνqq fit

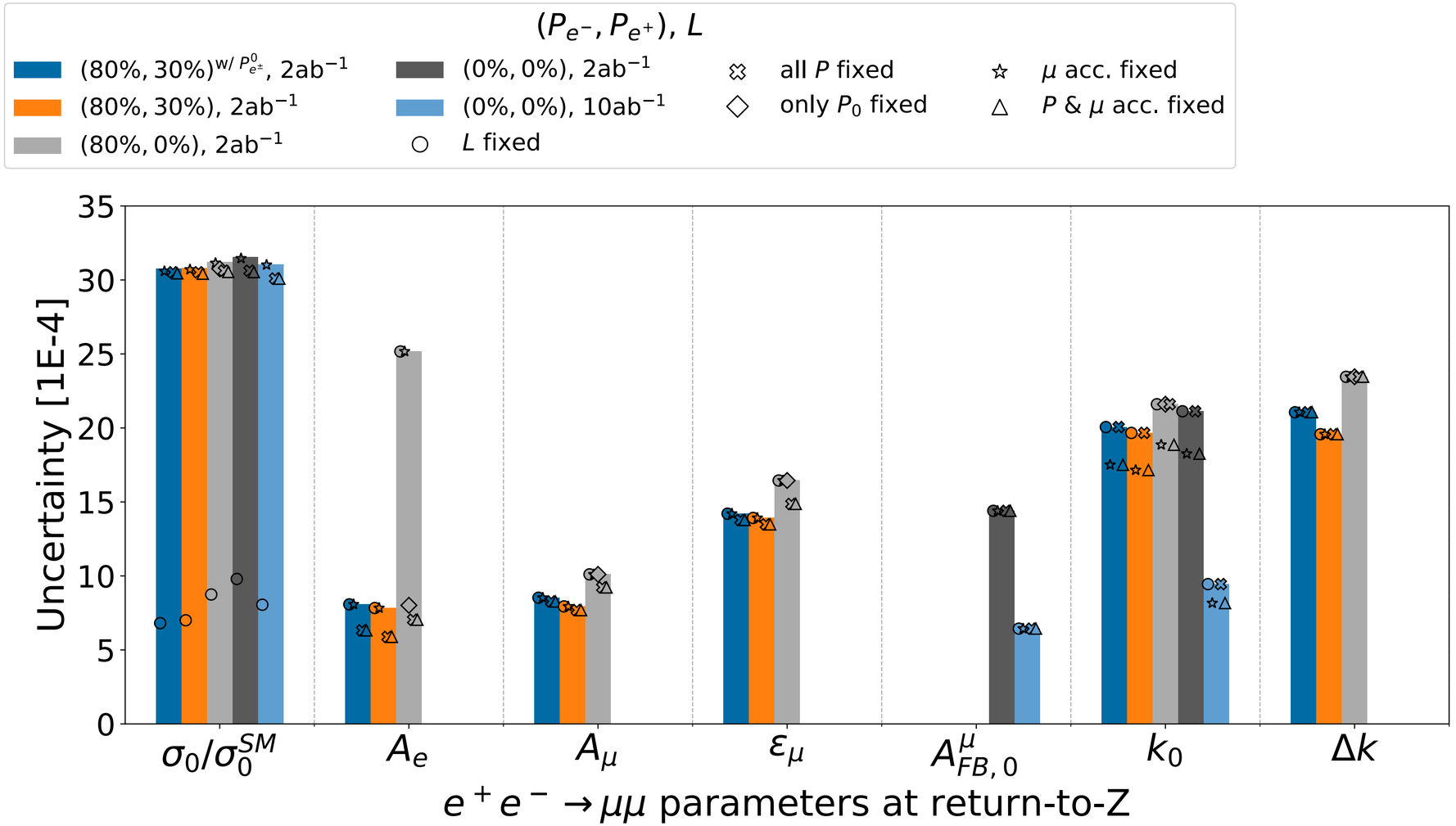
full bars: σ_0(WW), A_{LR}(WW) fixed - dash-dotted bars: all free



if one σ_0 were known better than lumi measurement, luminosity could be better constrained => academic ?

Note: more polarisation parameters for polarised beams (obviously) — but each of them better constrained than P=0 ! — and better than polarimeter measurements alone

2f parameters - return-to-Z (very similar picture for high-E)



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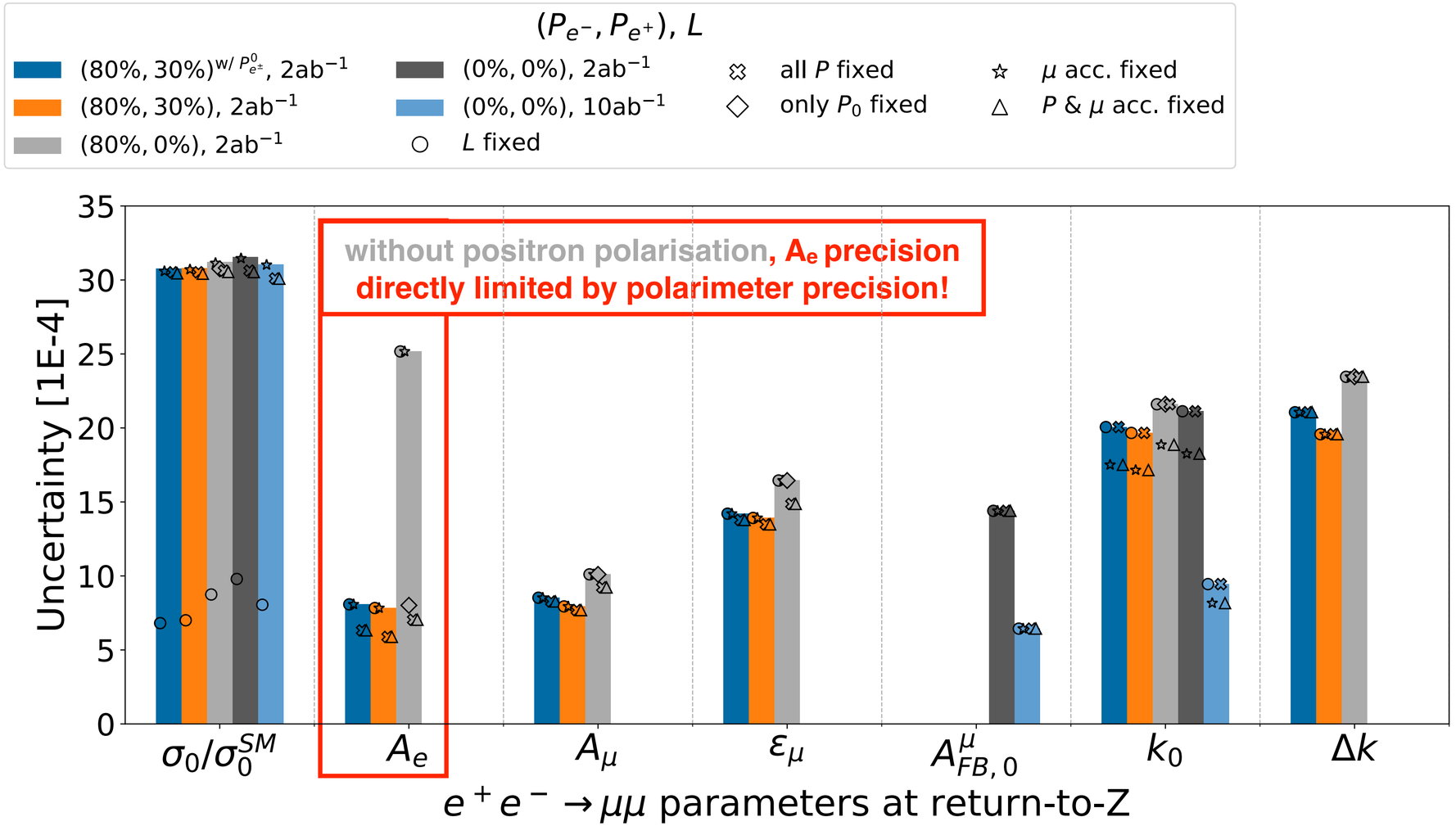

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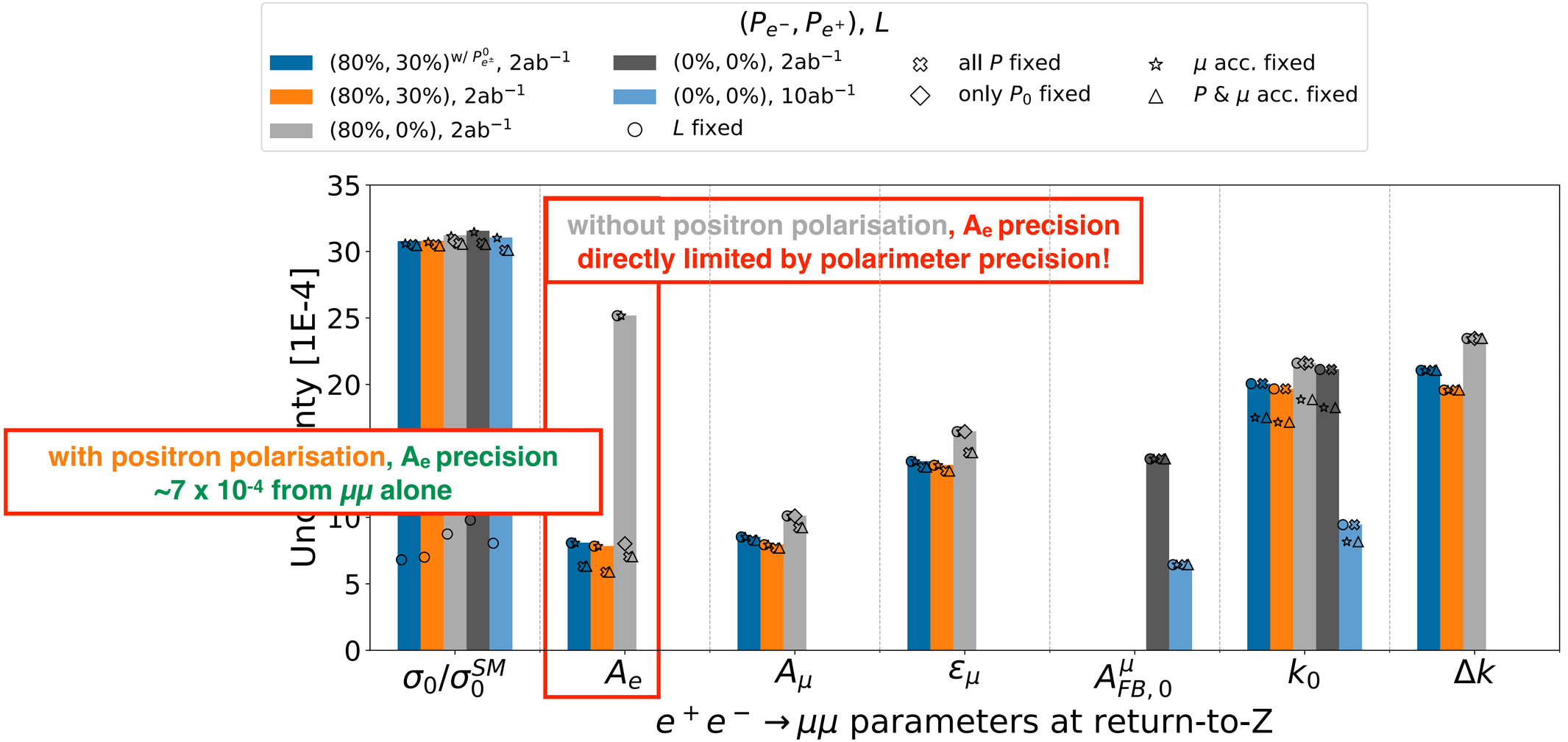

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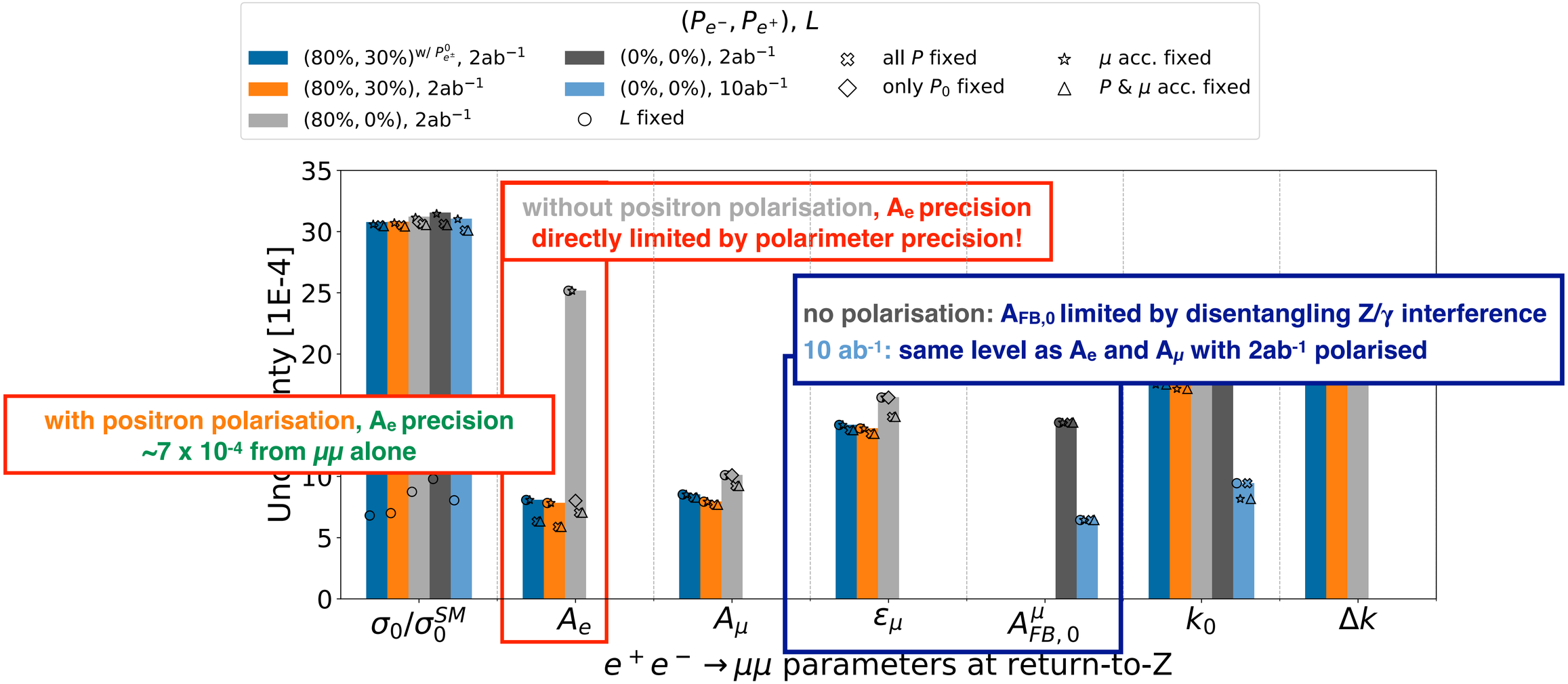
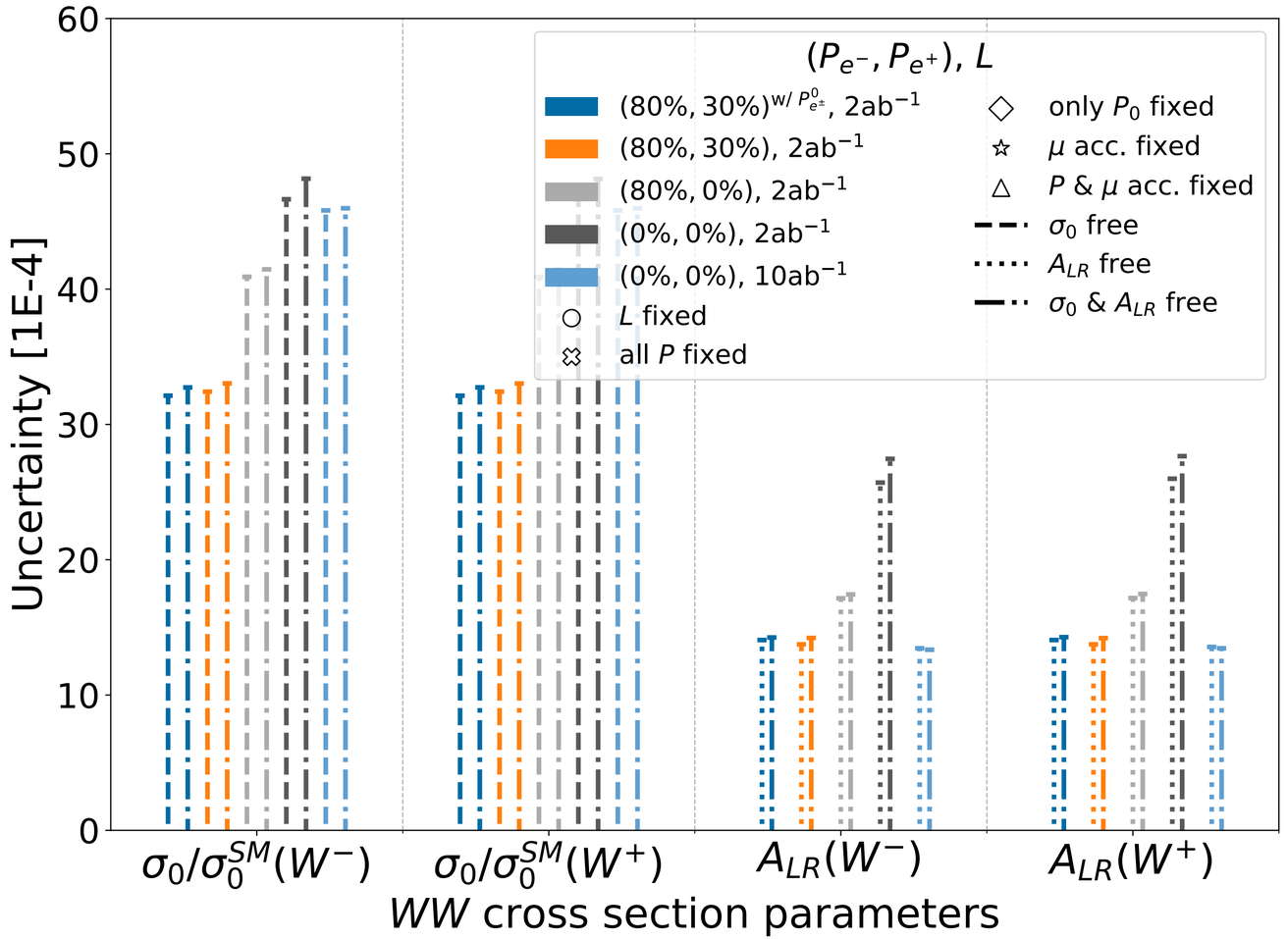


WW cross section and left-right asymmetry



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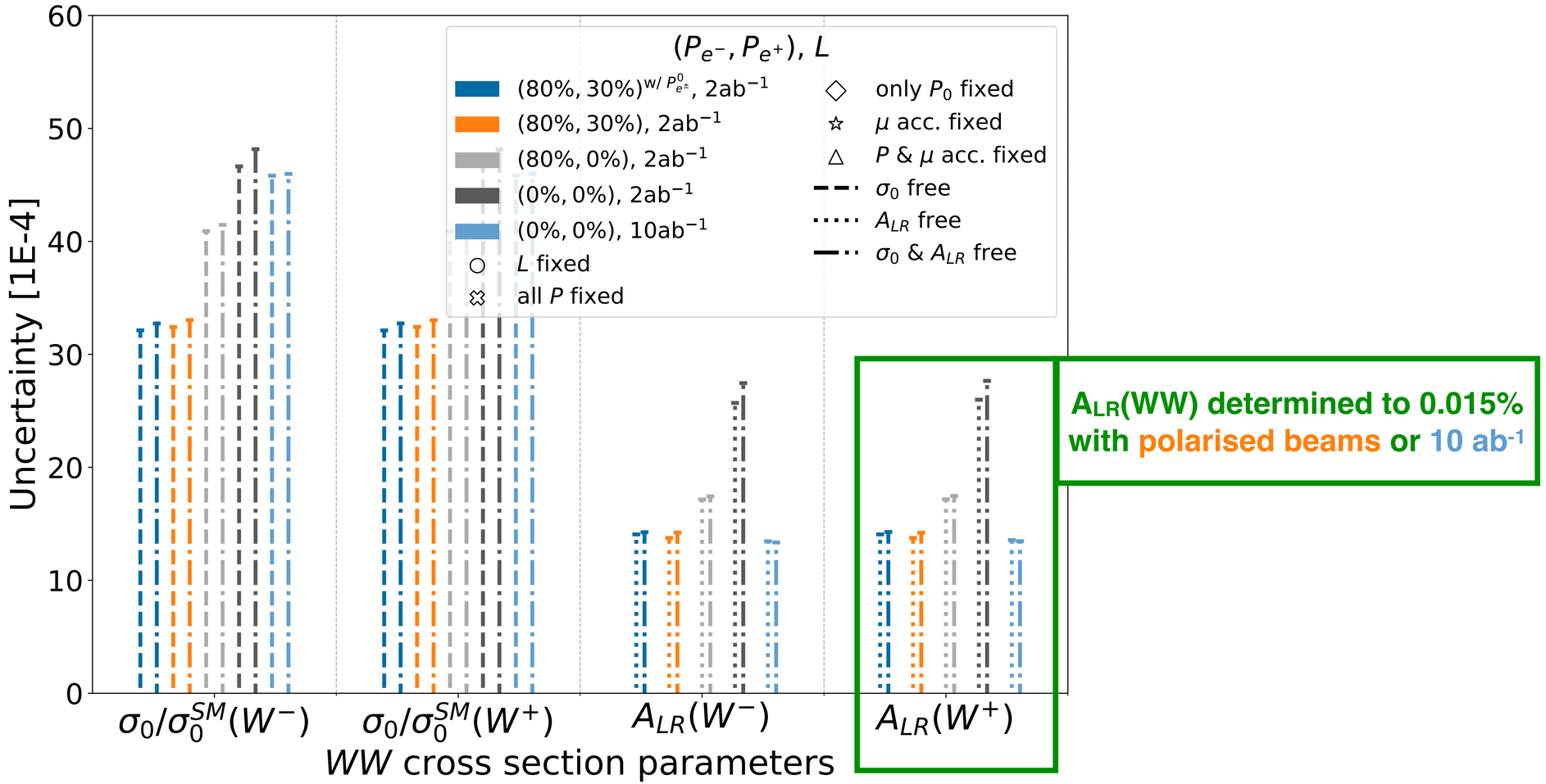
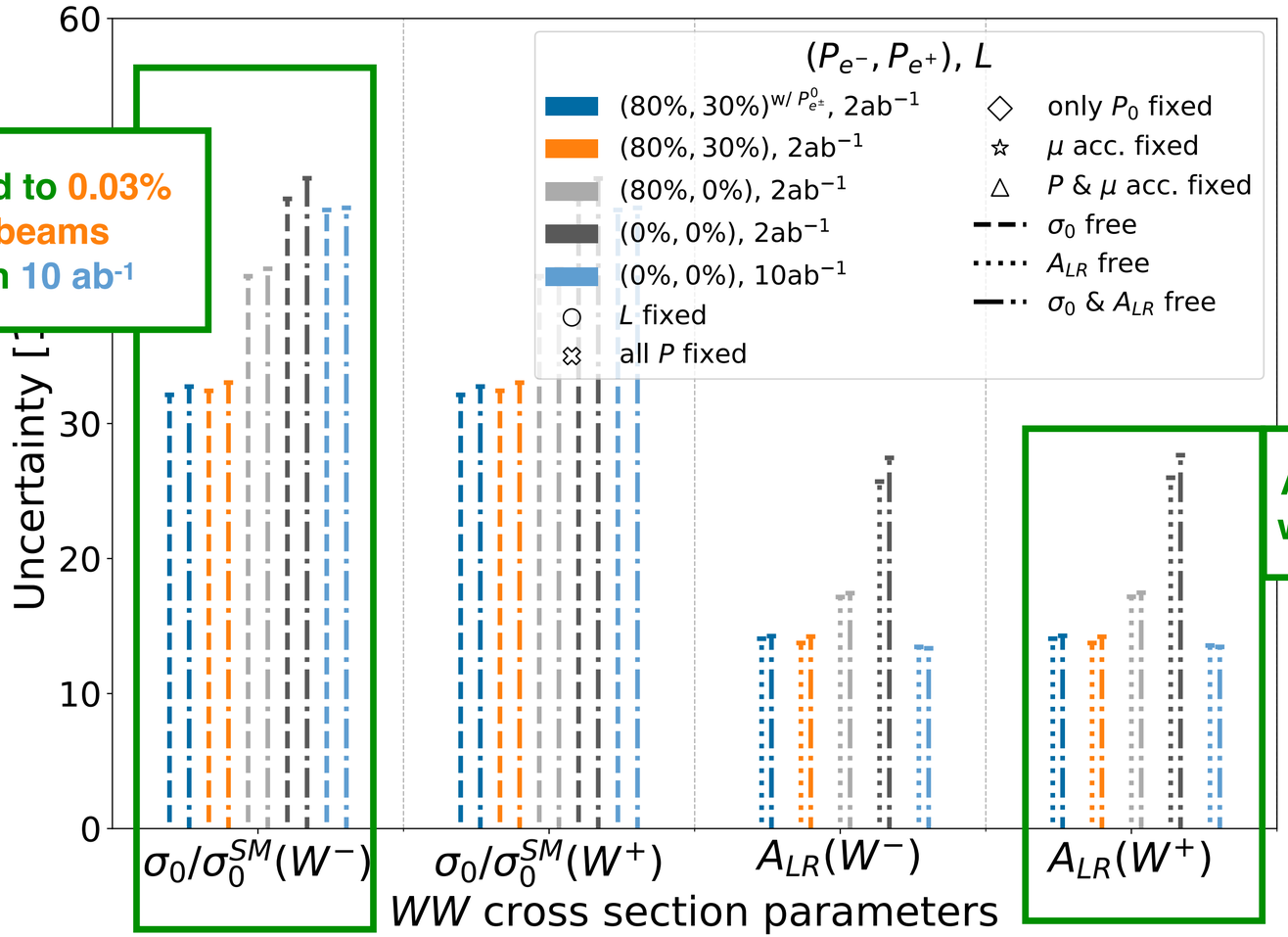


A_{LR}(WW) determined to 0.015% with polarised beams or 10 ab^{-1}

WW cross section and left-right asymmetry

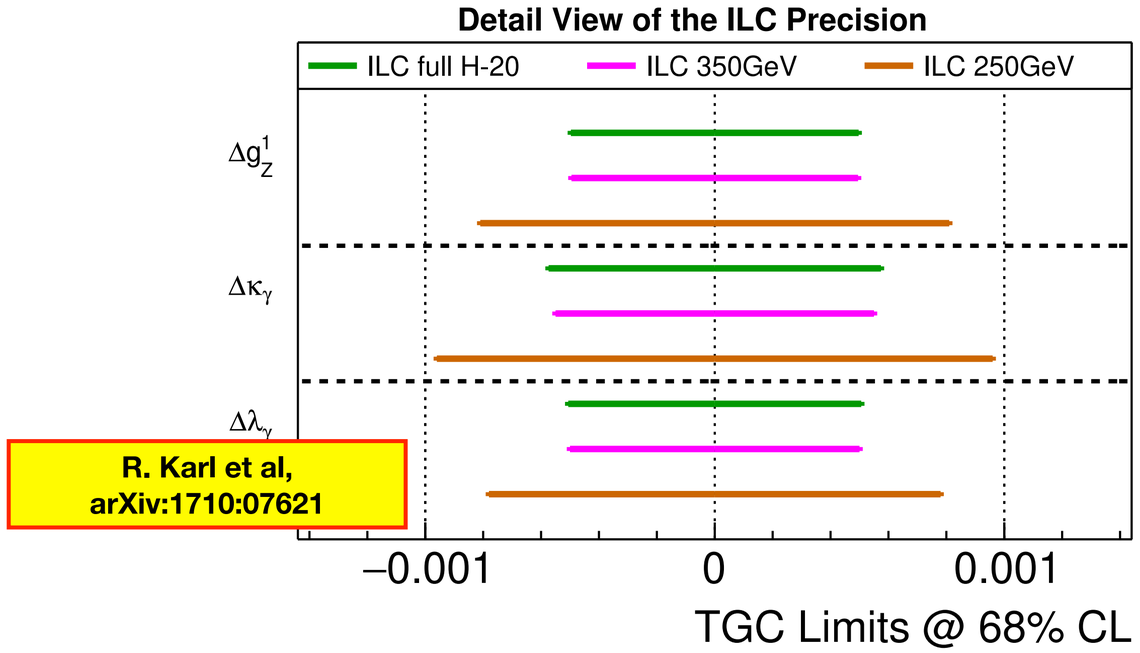
σ_0(WW) determined to 0.03% with polarised beams or to 0.045% with 10 ab^{-1}

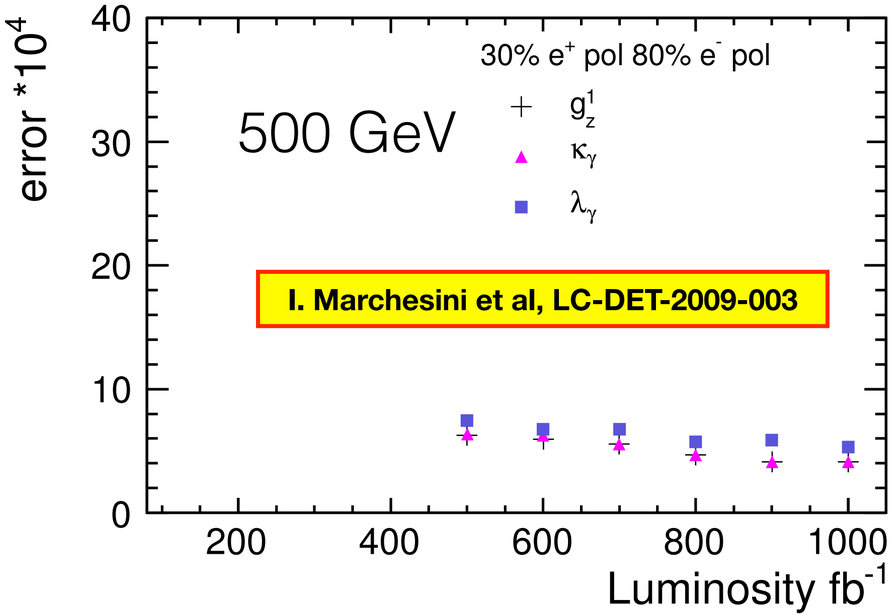


A_{LR}(WW) determined to 0.015% with polarised beams or 10 ab^{-1}

WW - charged triple gauge couplings - previous studies

- **I. Marchesini, 500 GeV**
  - full Geant4-based simulation of ILD
  - free pars: 3 cTGCs, polarisations
    => i.e. σ_0(WW), A_{LR}(WW) fixed
- **R.Karl, extrapolation to 250 GeV**

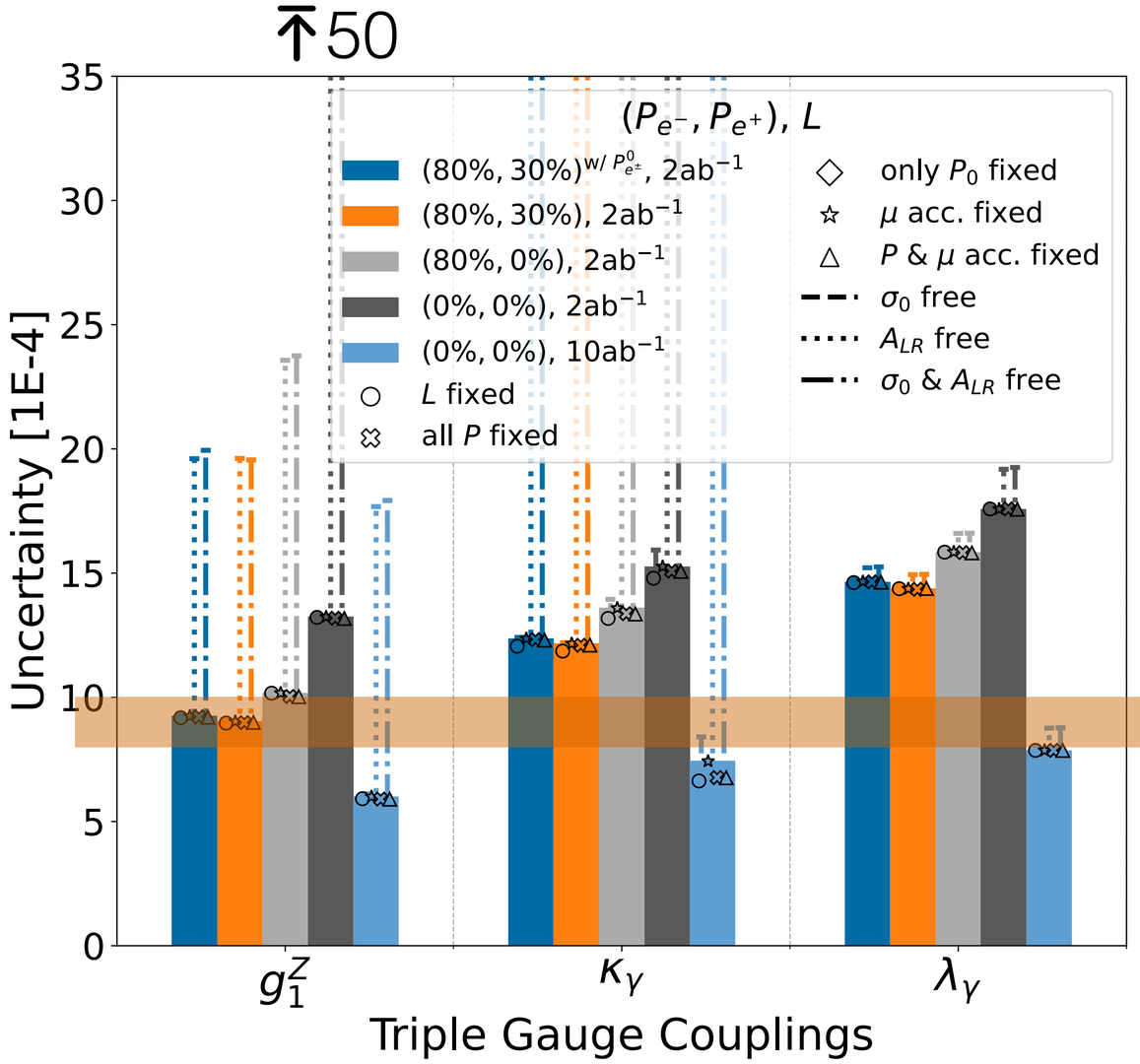




expect 8..10 x 10^{-4} at 250 GeV

WW -> evqq & μvqq,
detector effects somewhat pessimistic,
σ_0(WW), A_{LR}(WW) fixed

WW - charged triple gauge couplings - this study



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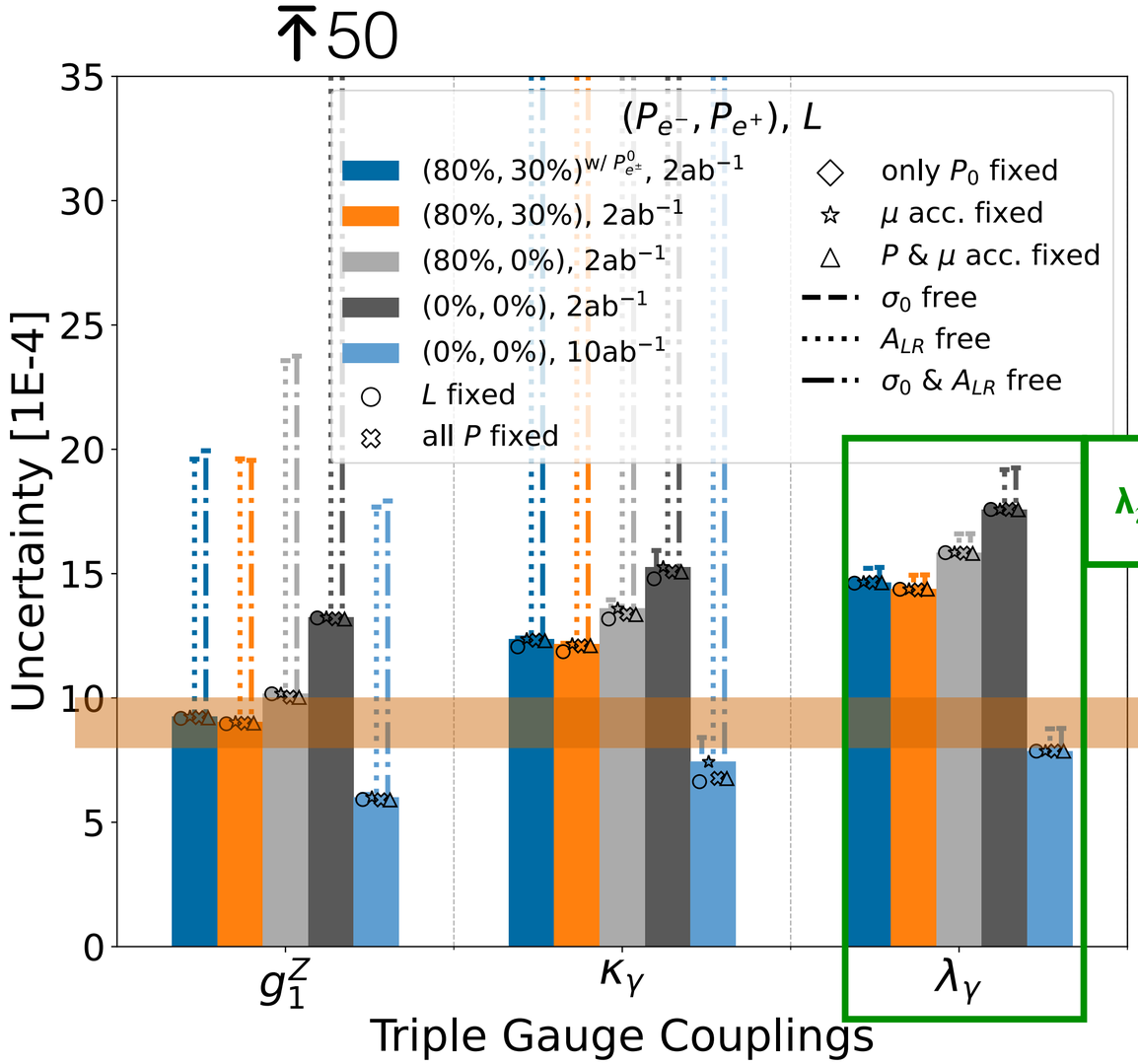

λ_γ robust against free σ_0(WW), A_{LR}(WW)

expect 8..10 x 10^{-4} at 250 GeV

WW -> evqq & μvqq,
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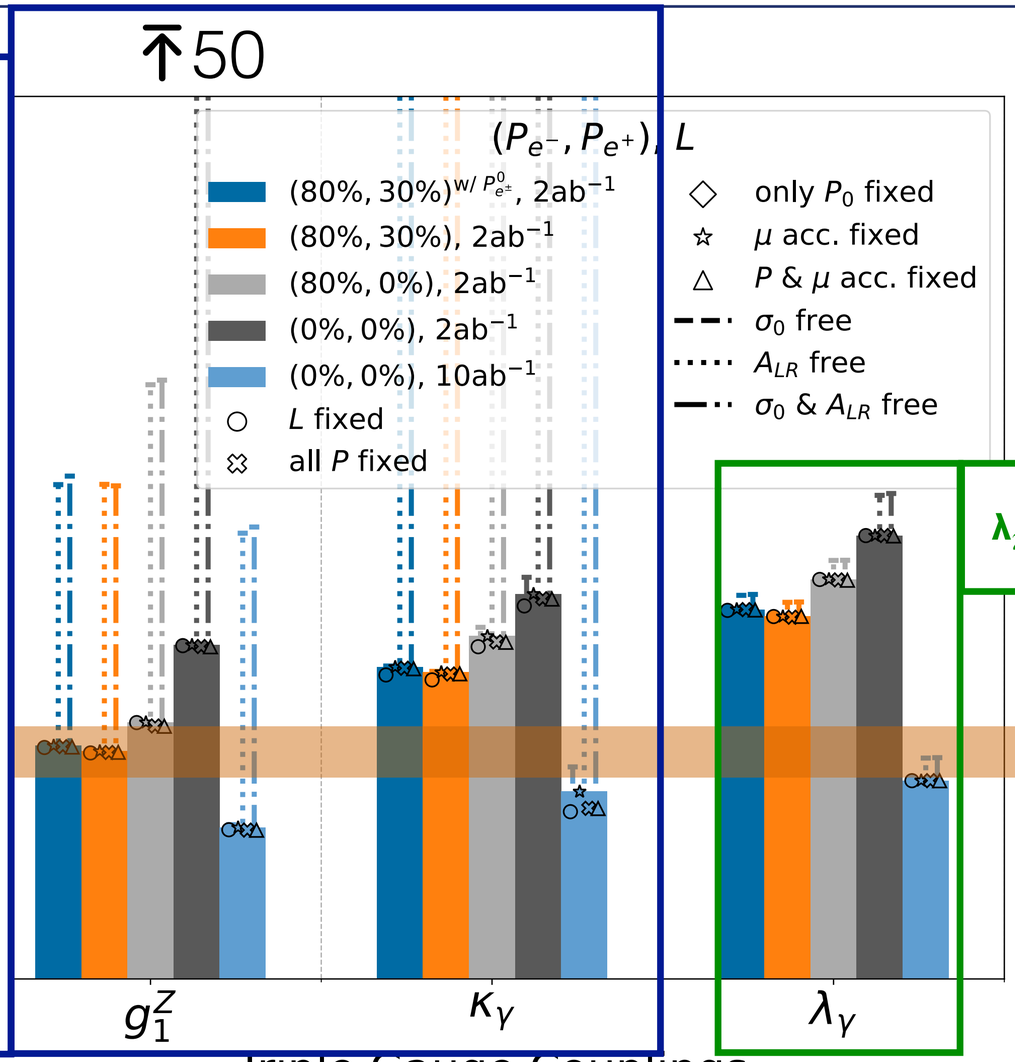
σ_0(WW), A_{LR}(WW) fixed

WW - charged triple gauge couplings - this study

- g_1^Z & κ_γ robust against freeing σ_0(WW)
- freeing A_{LR}(WW) increases uncertainty by factor 2 (pol) or 3 (unpol)
- also seen in LHC studies (cf backup)
- effect due to significant correlations of A_{LR}(WW) with g_1^Z and κ_γ
- correlations can be lifted by
  - adding single-W processes or
  - in full SMEFT via A_e

=> better control of A_e with positron polarisation will be important also for TGCs

=> this effect has so far been neglected in previous ILC TGC studies



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Triple Gauge Couplings

Conclusions

- **role of beam polarisation for chiral analysis, signal-to-background ratio, effective luminosity at future e+e- collider well studied since years**
- **only more recently studied: role of beam polarisation for constraining experimental systematics**
- **first steps have been undertaken to consider experimental systematics in combined fit of ee->2f and ee->4f processes**
- **positron polarisation essential to avoid A_e measurement being limited by polarimeter precsion**
- **precise A_e (250 GeV) will be crucial for precise TGC determination**
- **study needs to be deepened / extended in other places to obtain complete picture, e.g. wrt role of some of the leading uncertainties in the corresponding analyses at LEP**

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4 polarisation configurations better than 2 or just 1

- **study needs to be deepened / extended in other places to obtain complete picture, e.g. wrt role of some of the leading uncertainties in the corresponding analyses at LEP**

Backup

Impact of $A_{LR}(WW)$

- same effect seen in HL-LHC projections
- effect even stronger for HE-LHC

=> will require A_q's from lepton collider!

arXiv:1902.04070

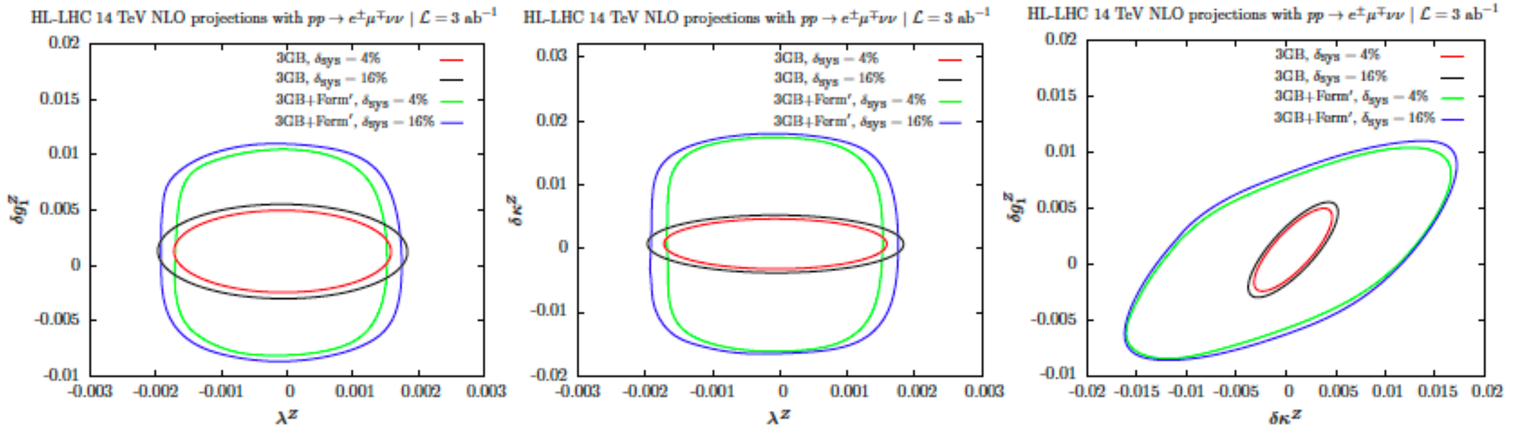


Fig. 40: Projections for 14 TeV with 3 ab^{-1}. $p_{T,cut} = 750$ GeV, corresponding to $\delta_{stat} = 16\%$ with $\delta_{sys} = 4\%$ and $\delta_{sys} = 16\%$. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.

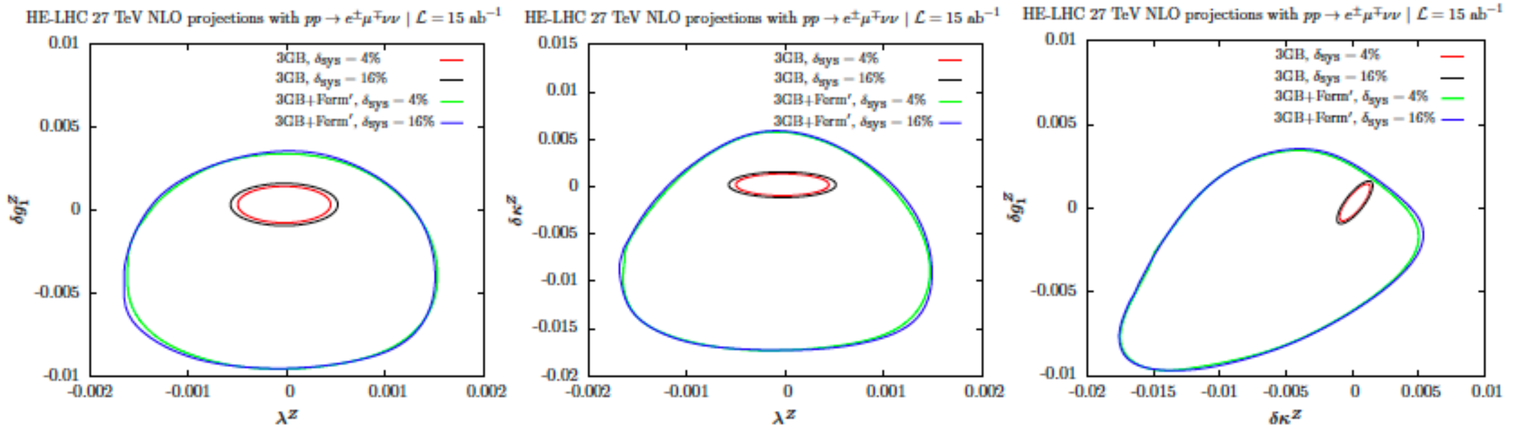


Fig. 41: Projections for 27 TeV with 15 ab^{-1}. $p_{T,cut} = 1350$ GeV, corresponding to $\delta_{stat} = 16\%$ with $\delta_{sys} = 4\%$ and $\delta_{sys} = 16\%$. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.

Impact of $A_{LR}(WW)$

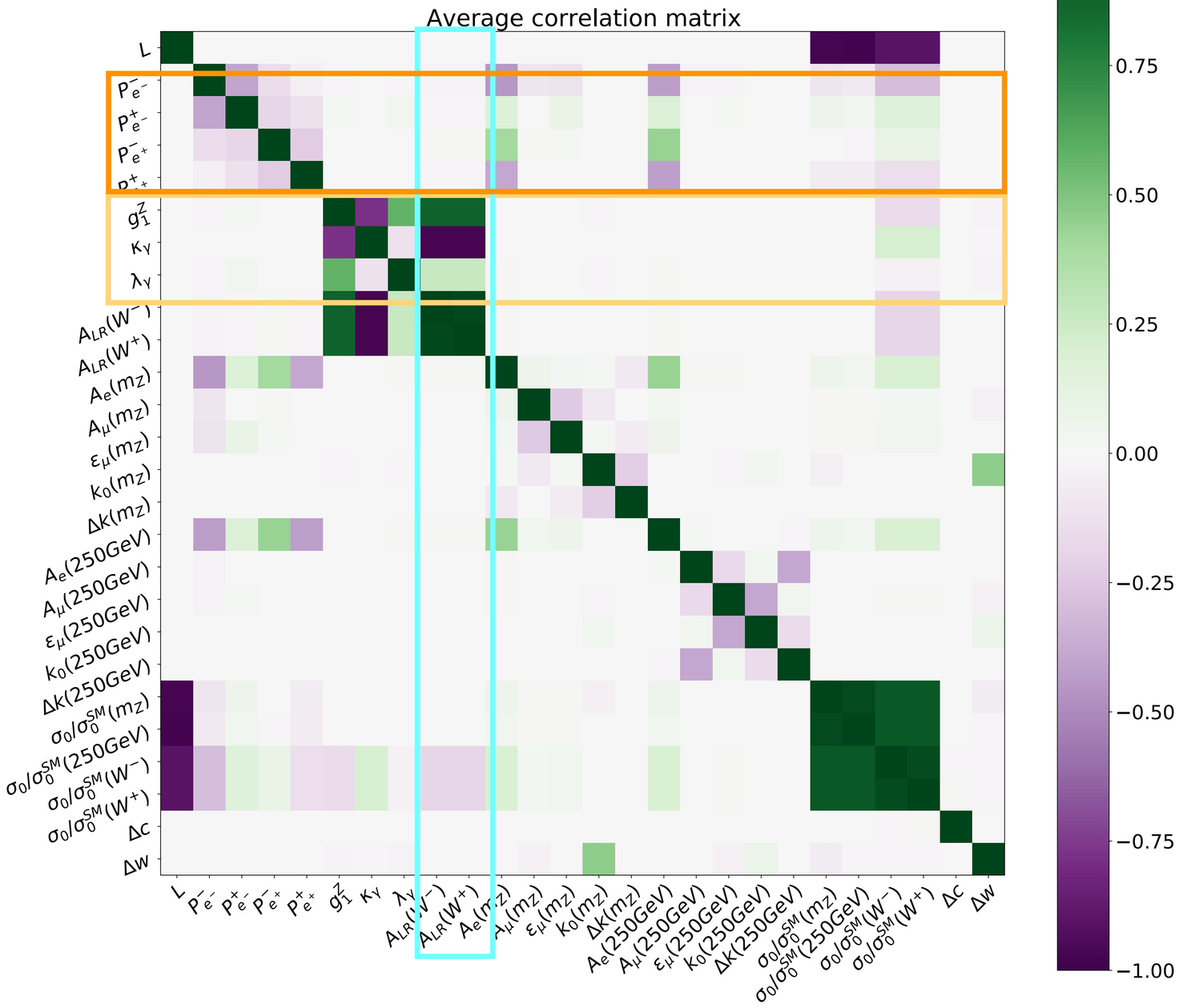
both beams polarised:

- strong correlation $A_{LR}(WW)$ - g_1^Z and $\boldsymbol{\kappa_\gamma}$
- no correlation with P's
  => TGC-**in**dependent t-channel asymmetry (e-nu-W vtx) well determined

=> TGC-**de**pendent s-channel asymmetry (e-e-Z/$\boldsymbol{\gamma}$ vtx) creates correlation

=> will be lifted by

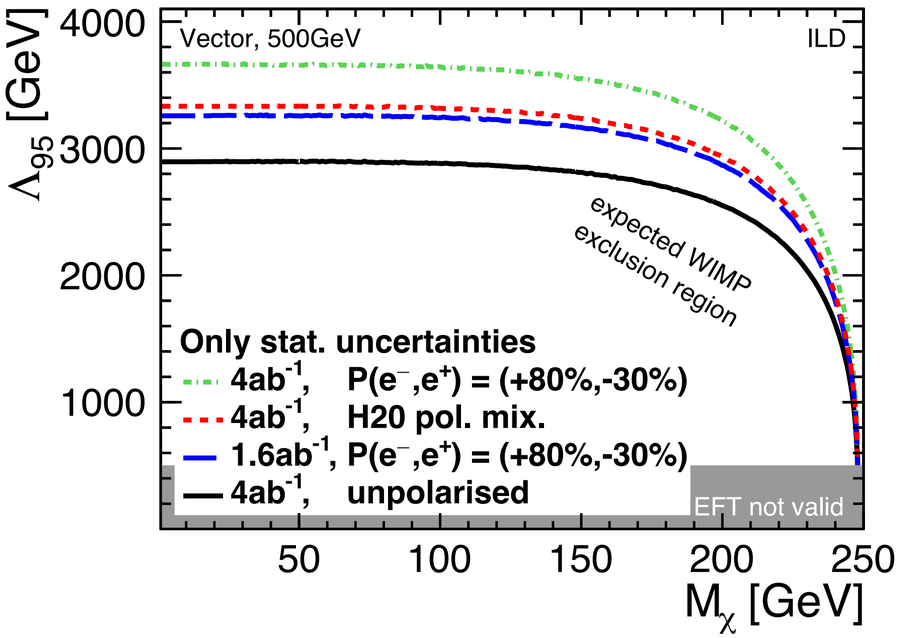
- full SMEFT since A_e is much better constrained
- addition of single-W processes (depend on TGCs but not on A_e)



A full analysis example - mono-photon WIMP search

Phys. Rev. D 101 (2020) 7

- Large background from SM $\nu\bar{\nu}\gamma$
- Limit calculation by fractional event counting, weight optimisation includes systematic uncertainties
- Many systematic uncertainties included (luminosity, polarisation, beam energy spectrum, photon efficiency etc pp) in lower plot
- assumed to be correlated to a large degree between data sets with different polarisations



$\Rightarrow$ Combination of several data sets "H20 pol mix" is significantly more robust against systematics than individual data sets!

Here: only global scaling systenatics, no shape-dependency

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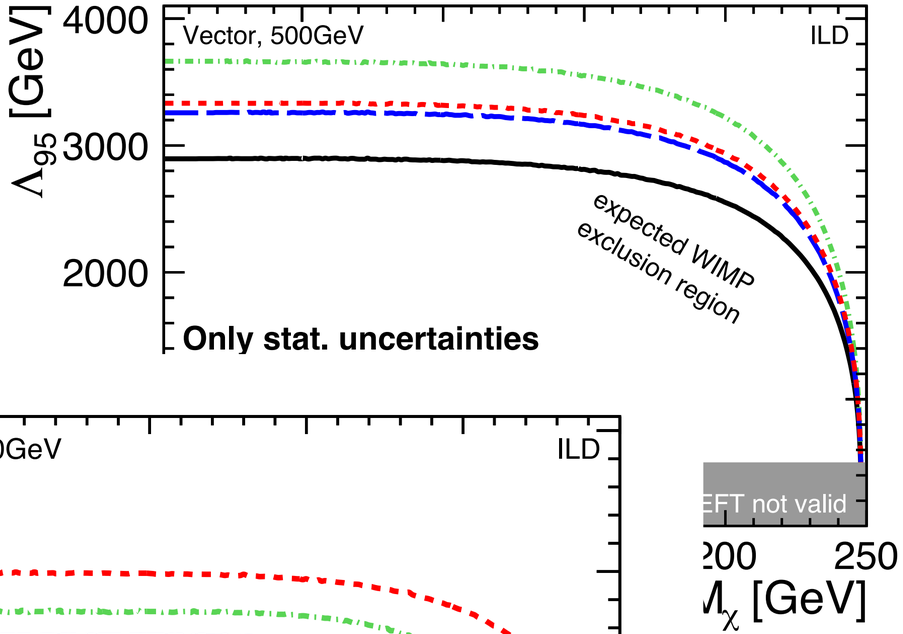
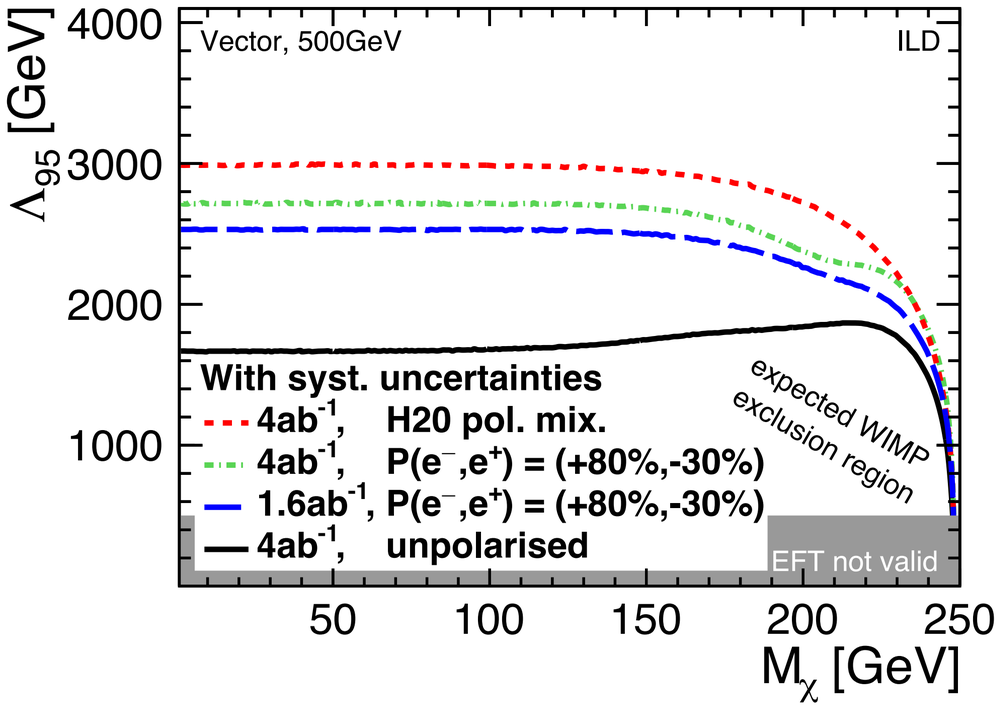
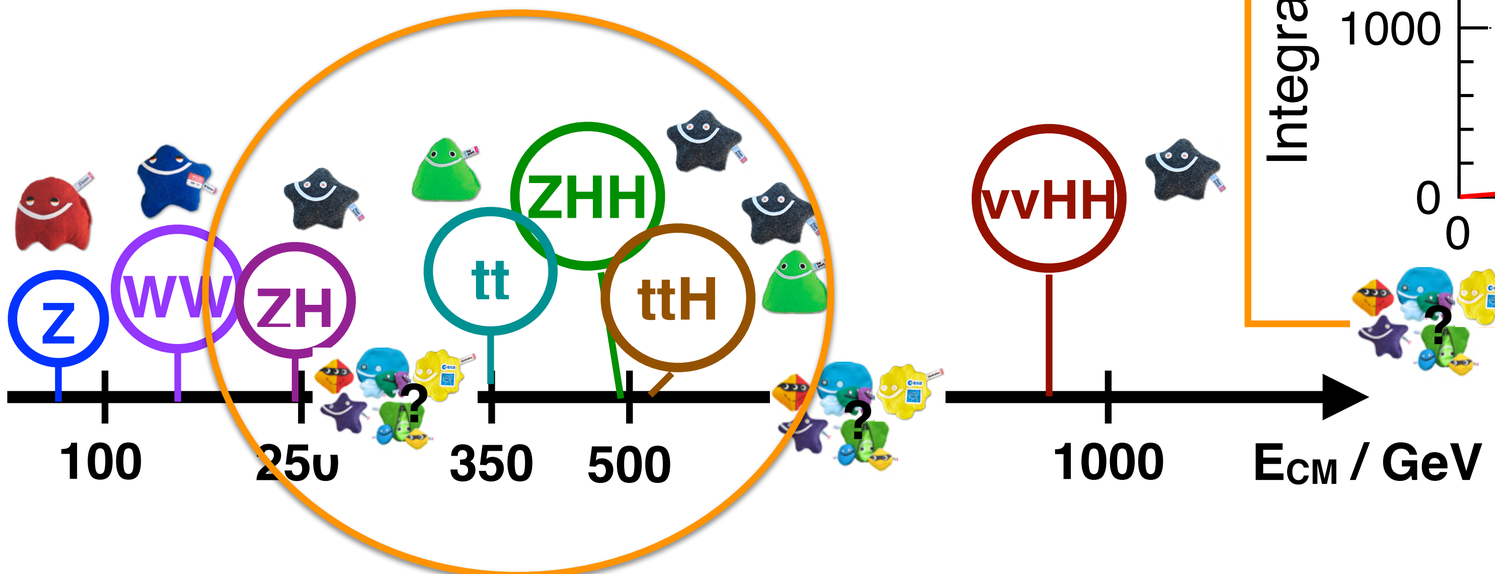
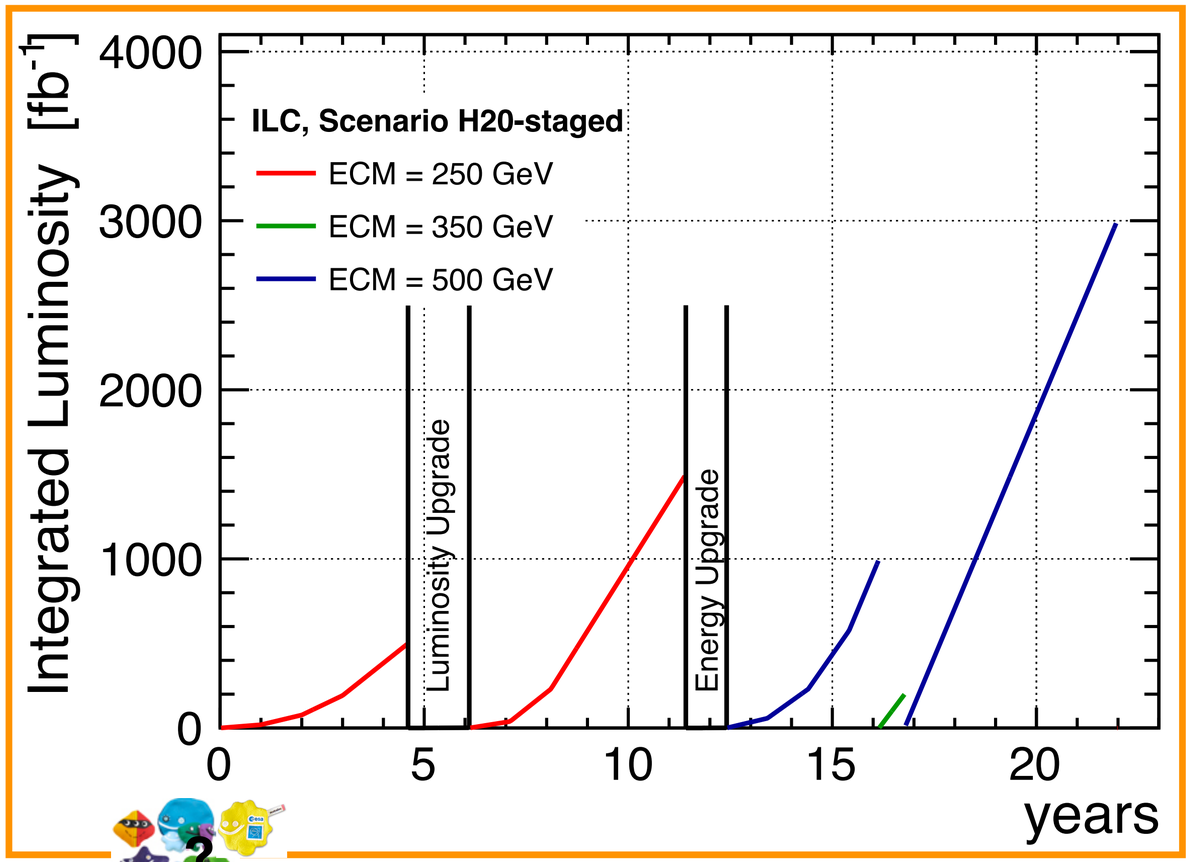




The International Linear Collider in a nutshell

all up-to-date numbers in ILC ESU Document

- **e^+e^- centre-of-mass energy**
  - first stage: 250 GeV
  - tunable
  - upgrades: **500 GeV, 1 TeV, 91 /161 GeV**
- **luminosity** at 250 GeV:
  - 1.35×10^{34} /cm^2 /s
  - upgrade 2.7×10^{34} /cm^2 /s
- **beam polarisation**
  - $P(e^-) \geq 80\%$
  - $P(e^+) = 30\%$, at 500 GeV upgradable to 60%
- total length (250 GeV): 20.5 km