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

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SPIN 2021, Matsue & virtual, Oct 18-22 2021

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

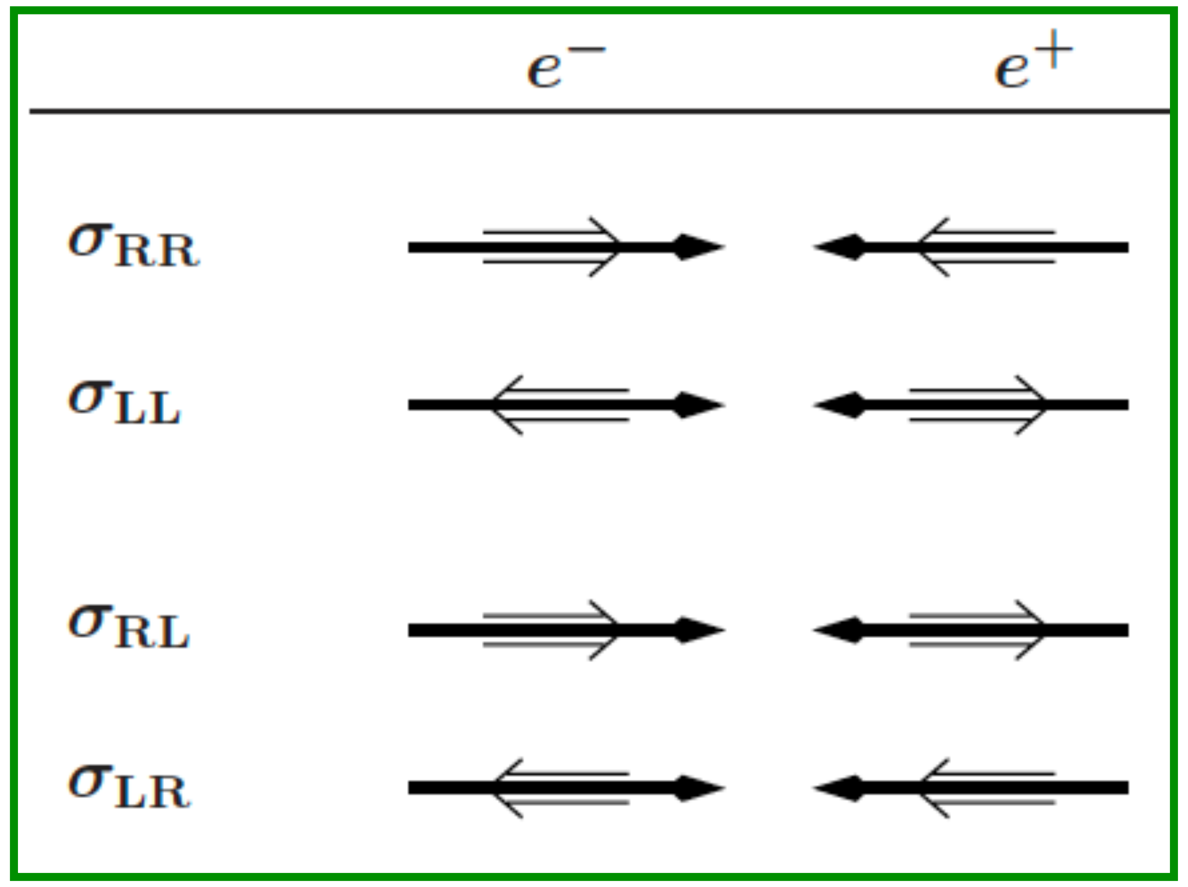
General references on polarised e^+e^- physics:

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

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

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

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

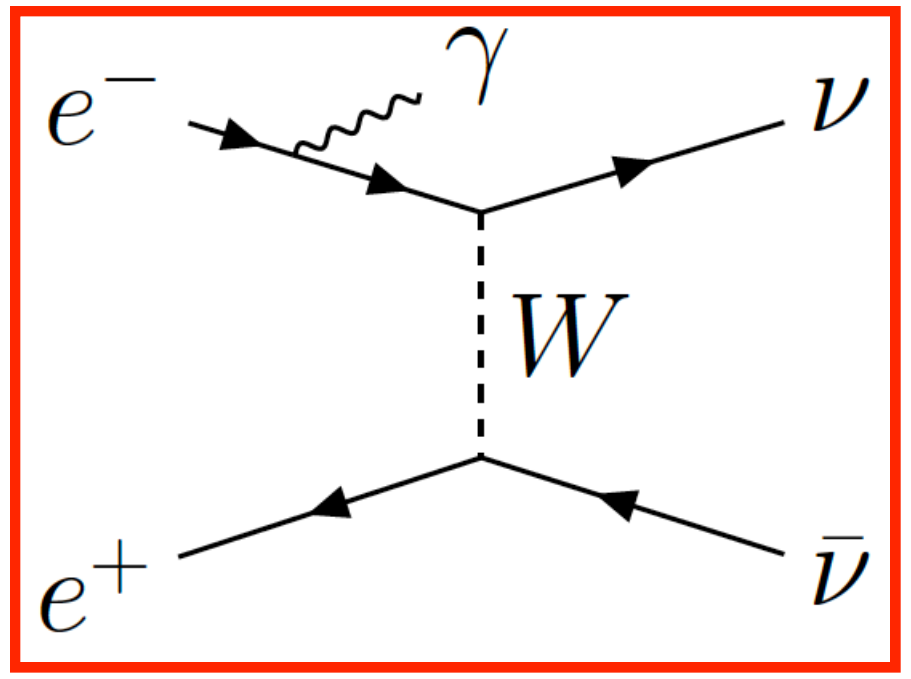


- note: future **circular** Higgs factories offer **no longitudinal beam polarisation**

Physics benefits of polarised beams

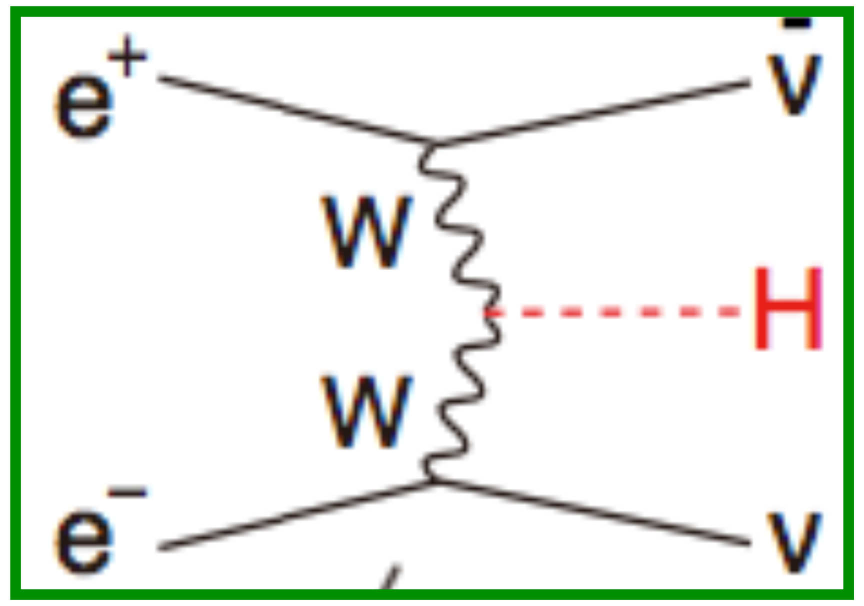
background suppression:

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



signal enhancement:

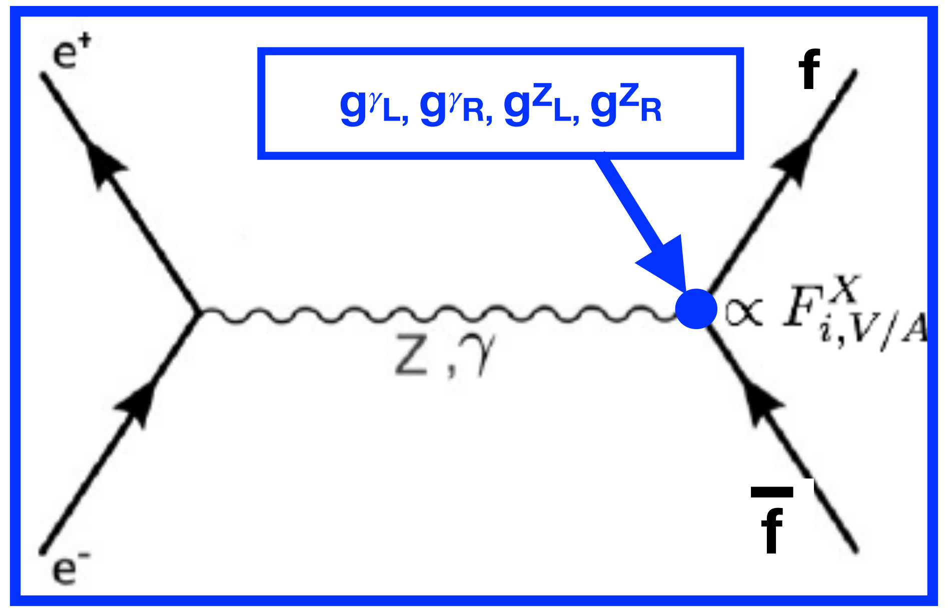
- Higgs production
  in WW fusion
- many BSM processes



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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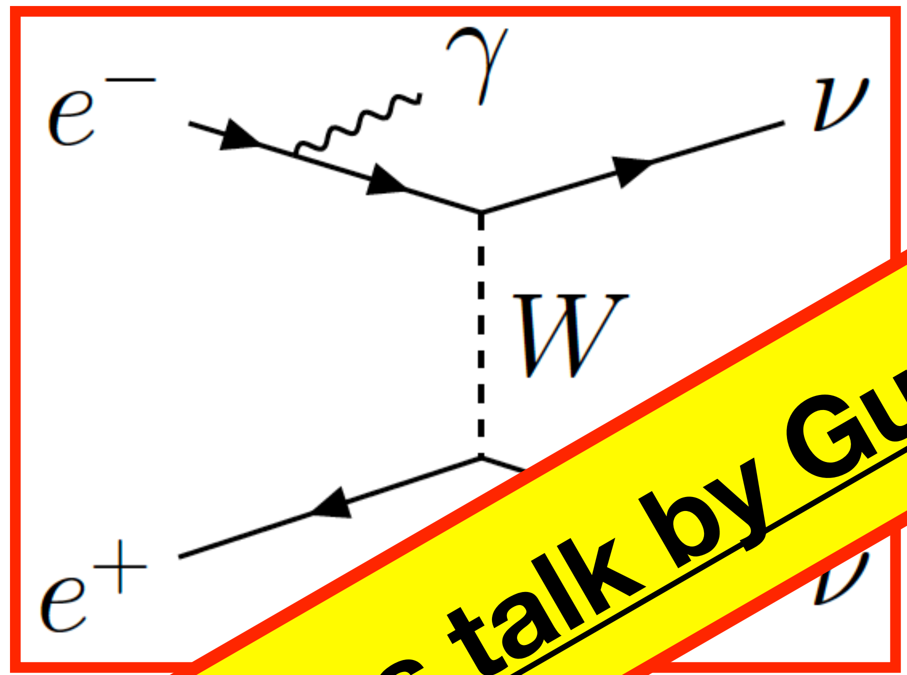

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- … duction
- … W fusion
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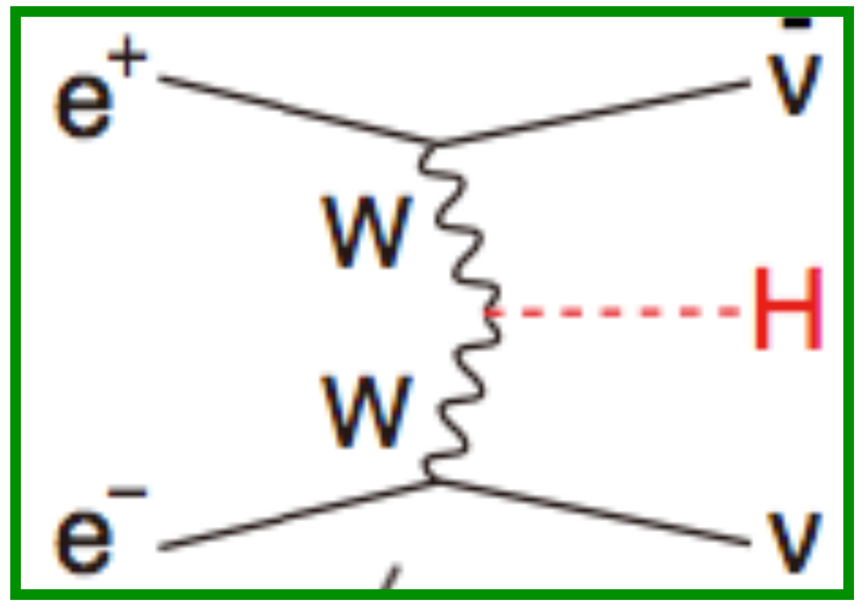

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See previous talk by Gudrid Moortgat-Pick

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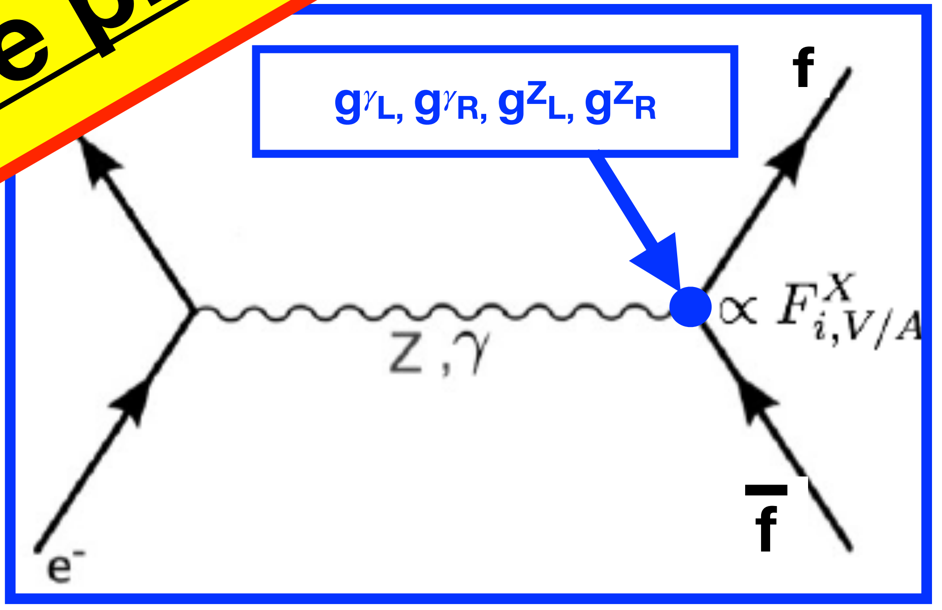

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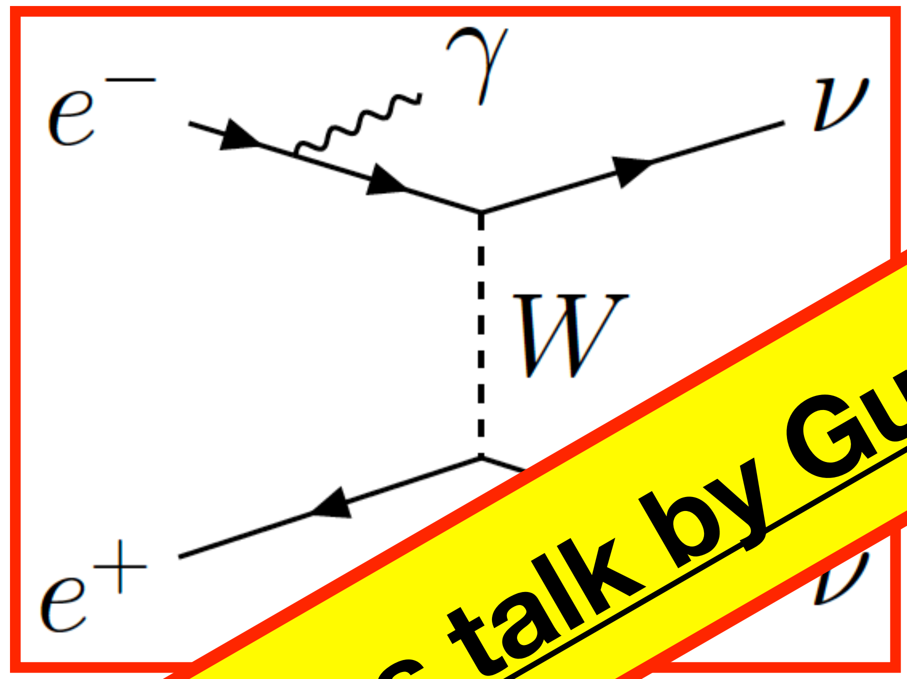

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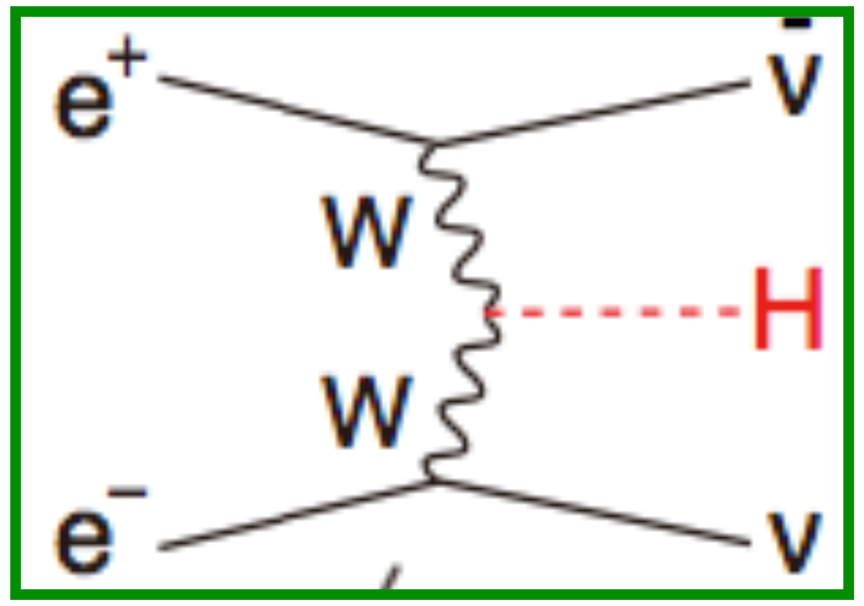

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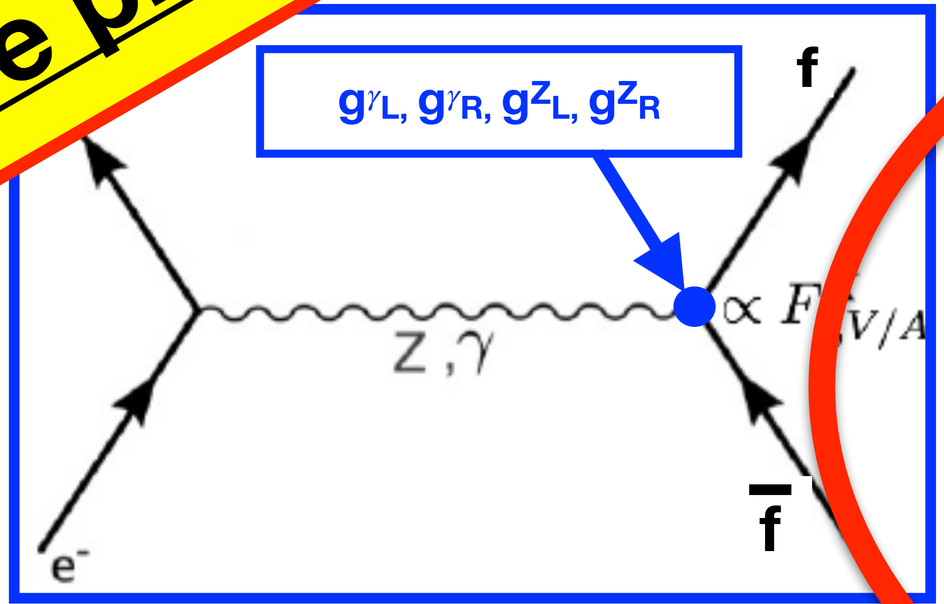

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The general idea

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

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

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

- f's depend on polarisation values:
  $f_{\text{LR}} = (1 - P_{e^-})(1 + P_{e^+}) \times \mathcal{L}$, $f_{\text{RL}} = (1 + P_{e^-})(1 - P_{e^+}) \times \mathcal{L}$
- $\frac{d\sigma(i)}{d\cos\theta_{\mu^-}}$ 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):

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

- n observables vs n+2+N_{shape} unknowns $\Rightarrow$ no overconstraining (even for $N_{\text{shape}} = 0!$)
- $\epsilon(i)$ 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+8 unknowns
  $\Rightarrow$ overconstraining with more than 8 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 $2n{+}8{+}N_{\rm shape}$ unknowns $\Rightarrow$ never overconstrained
  $\Rightarrow$ need additional control regions
- $P(e^-, e^+) = (\pm 80\%, \pm 30\%)$: $4n$ observables vs $2n{+}8{+}N_{\rm shape}$ unknowns $\Rightarrow$ overconstrained when more than $4{+}N_{\rm shape}/2$ 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.

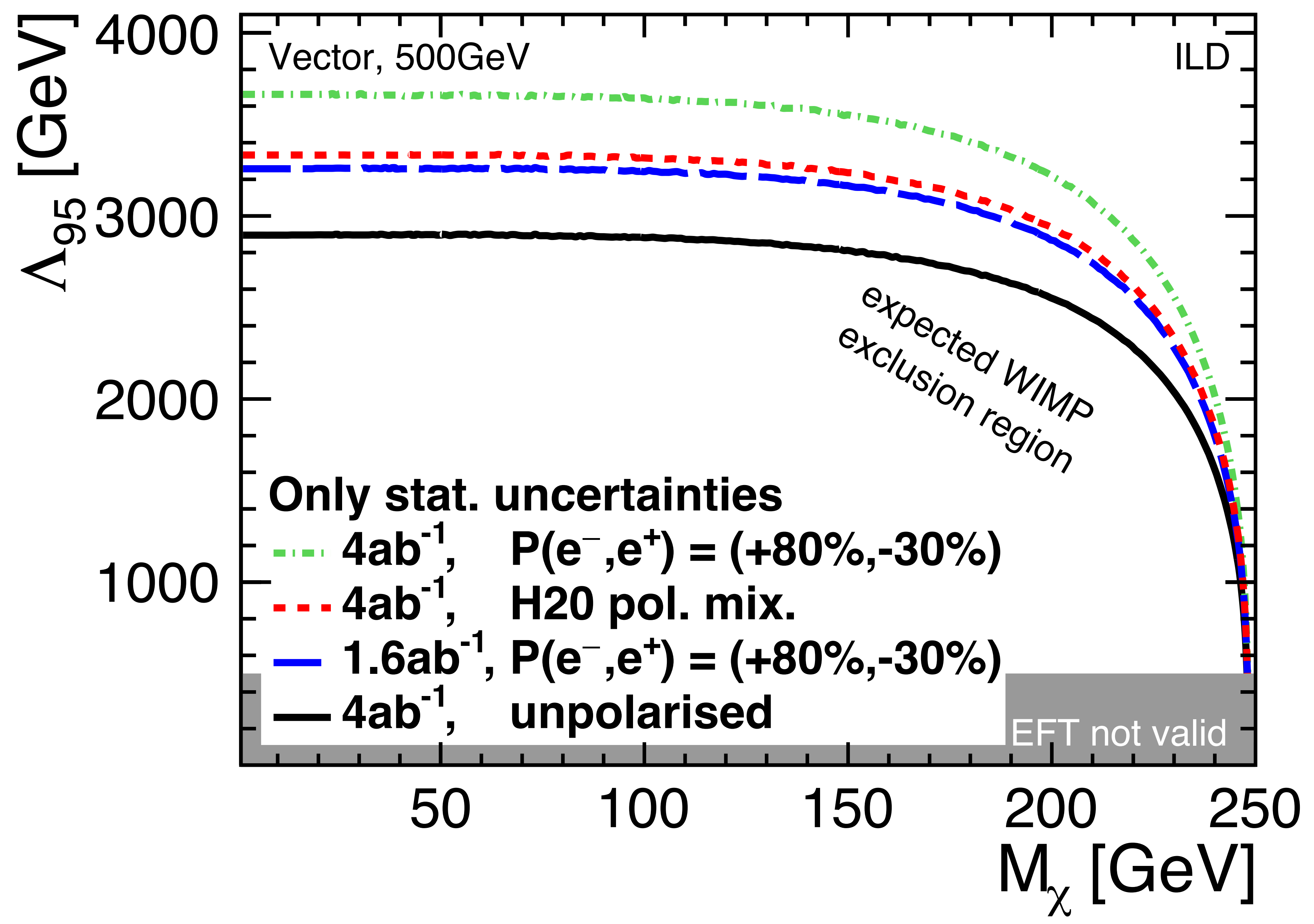
A full analysis example - mono-photon WIMP search

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

⇒ 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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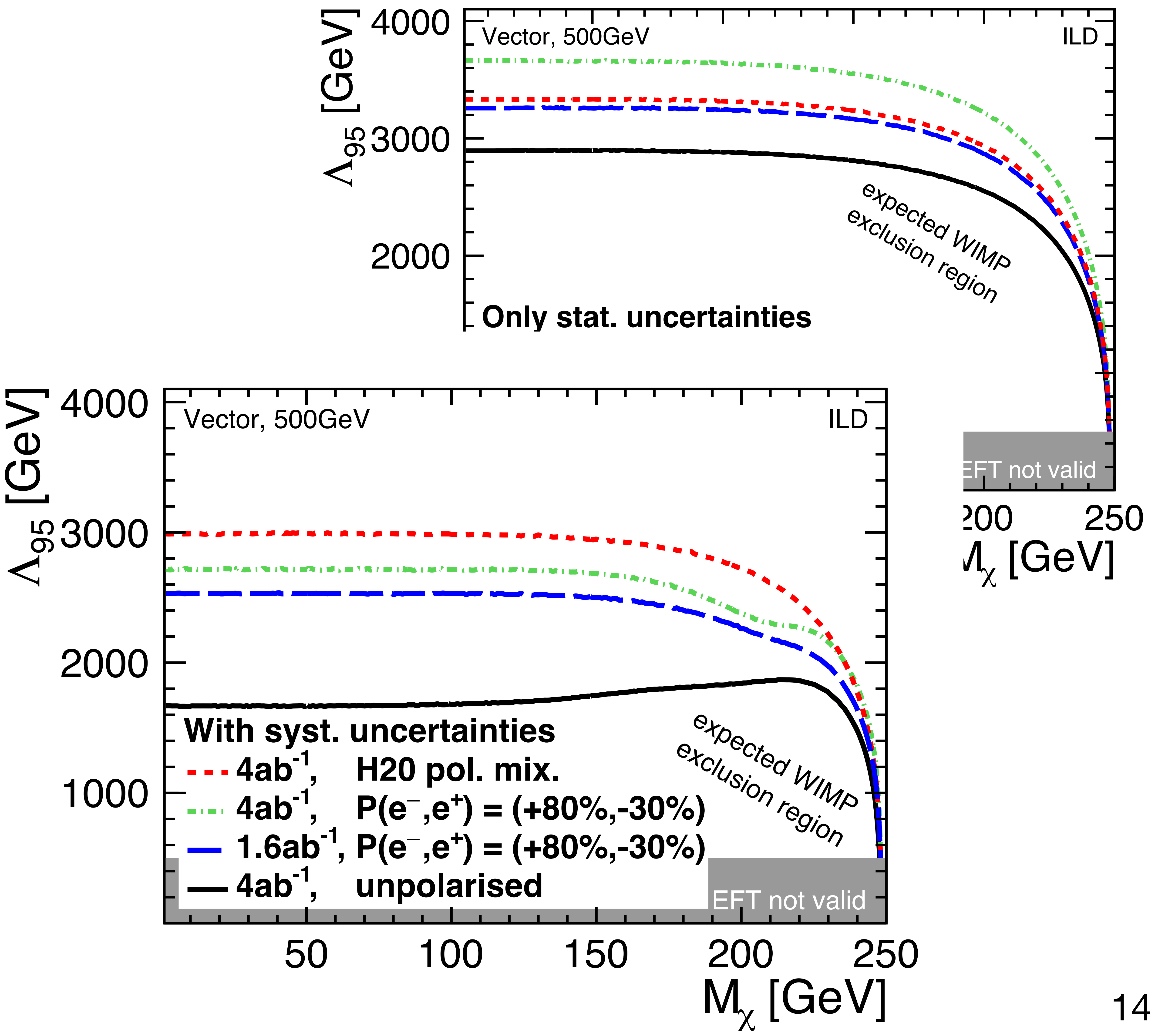

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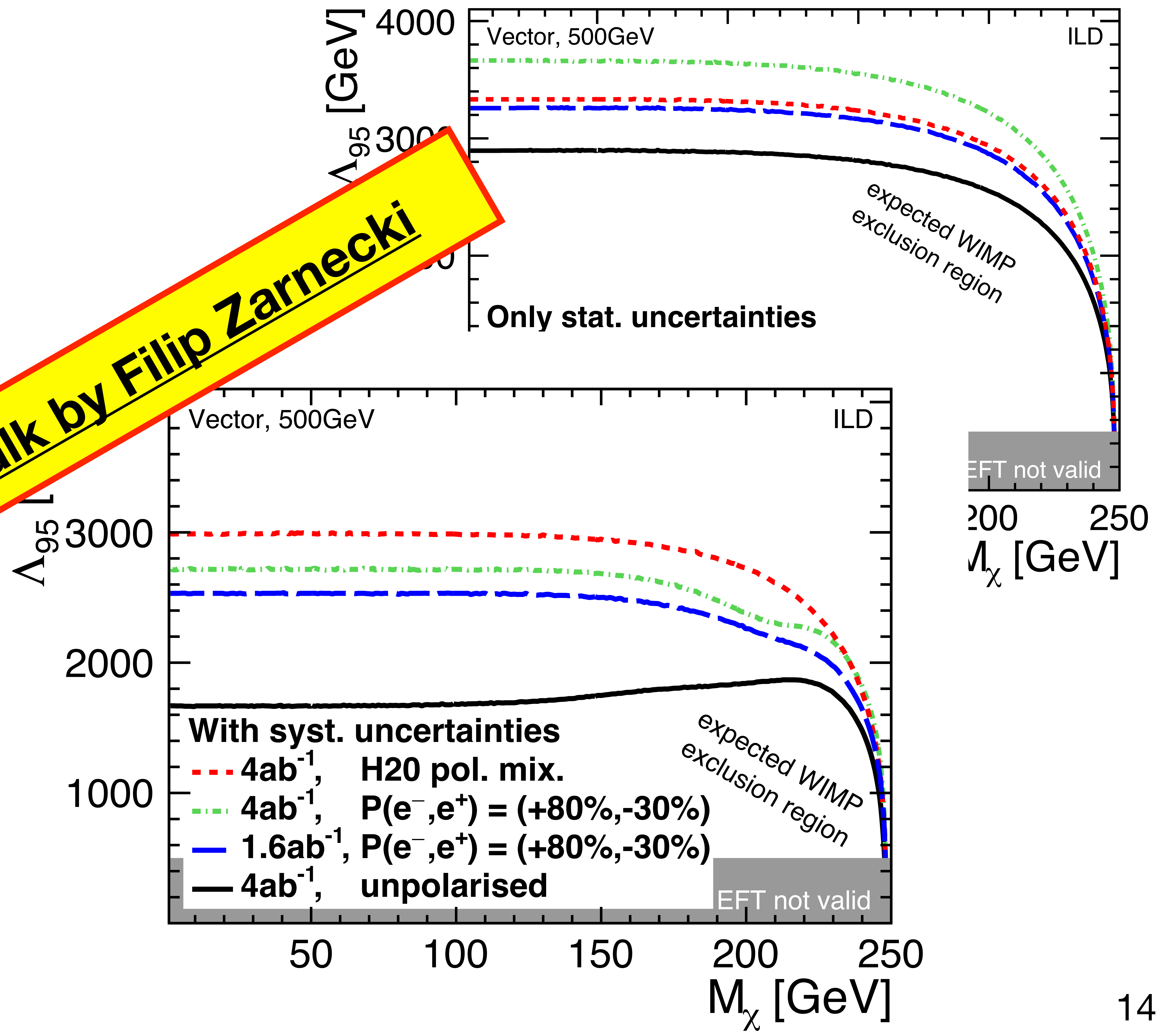
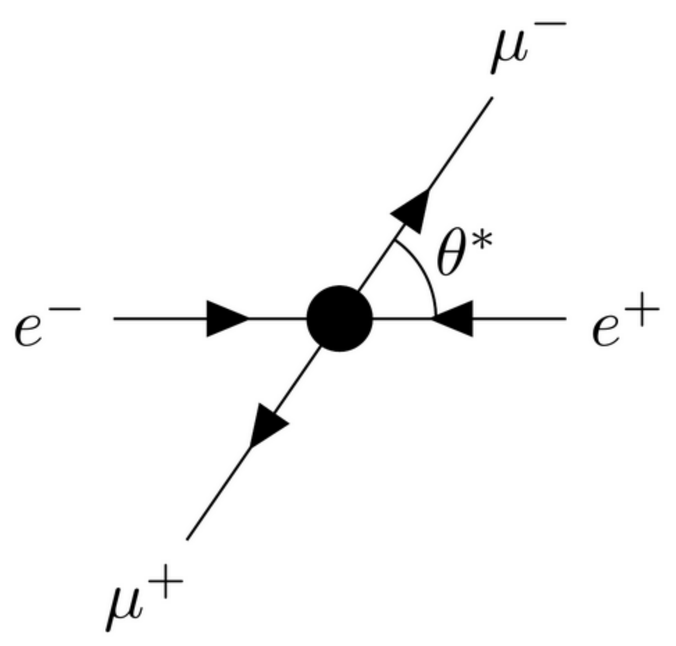
More details later in talk by Filip Zarnecki

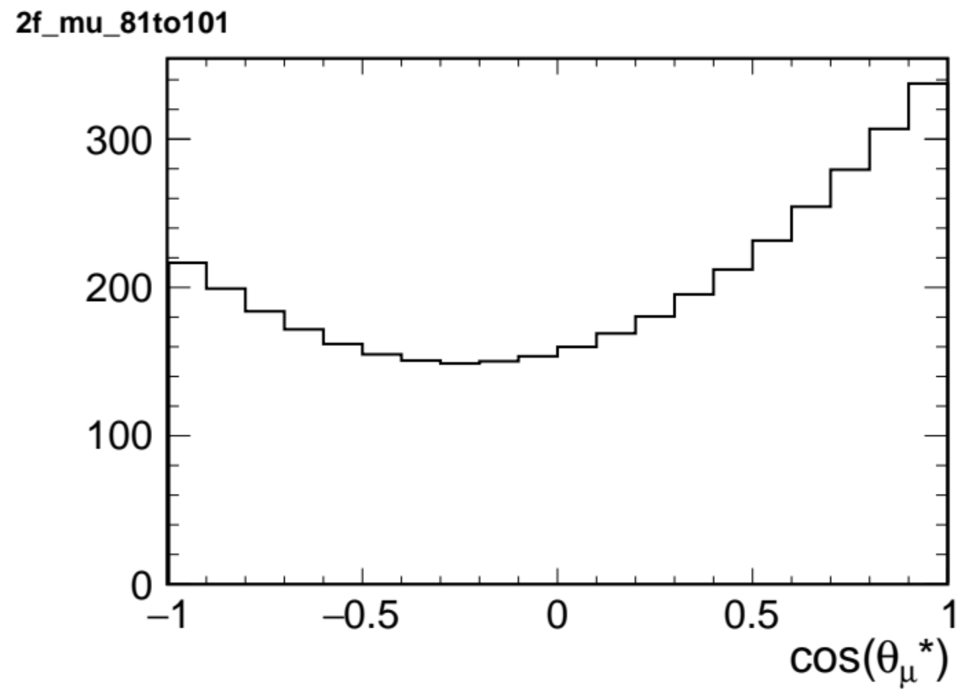


Towards a combined analyses of ee->2f and ee->4f including systematic uncertainties

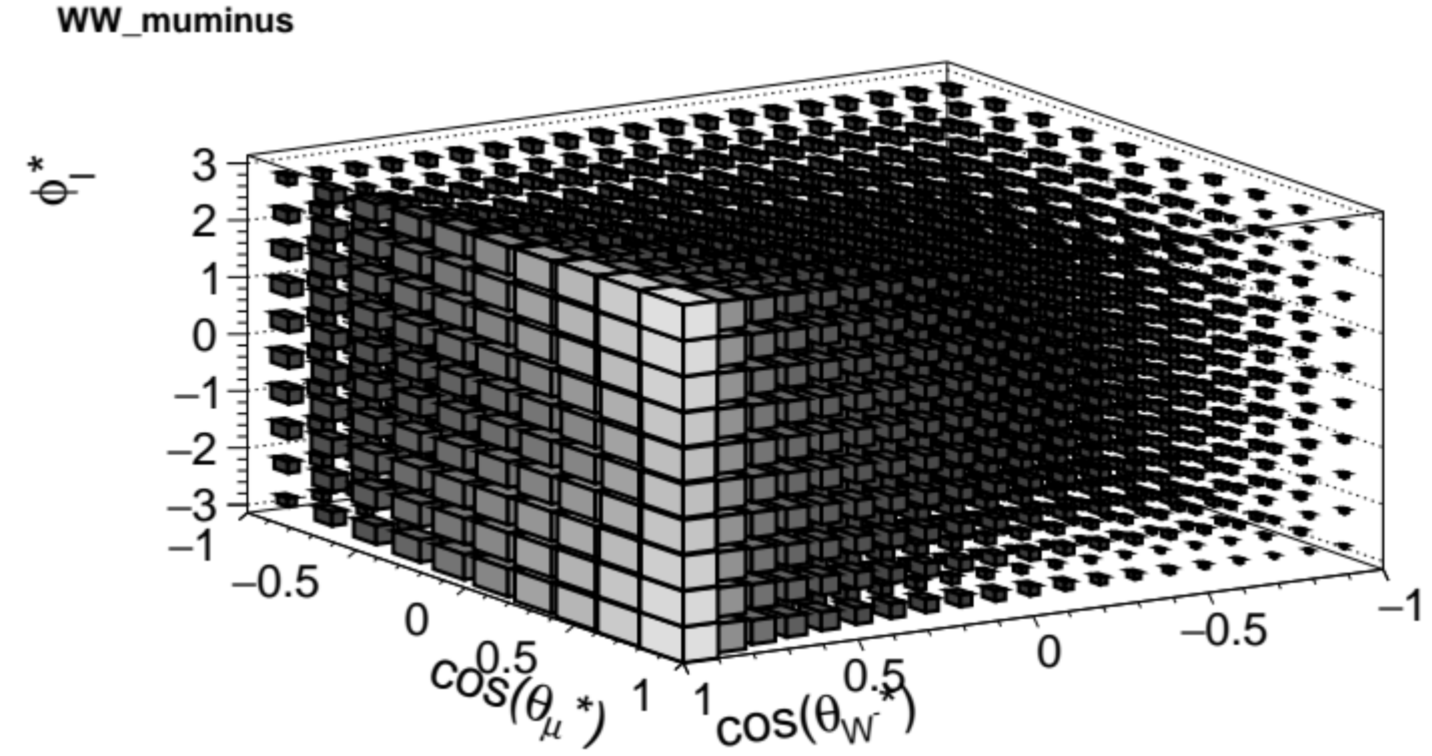
Physics processes & parameters

- **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
      => $Z//\gamma$ interference and initial/final state asymmetries collapse to one parameter (all linear in cosθ*)





- **ee -> 4f example process: ee -> WW -> μνqq**
  - observables: production angle $\cos\theta_W$, decay angles $\cos\theta_l^*$, $\cos\phi_l^*$ [separated into μ^+ and μ^- as preparation for eνqq 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 $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$. 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
$e^+e^- \rightarrow e^+e^- \mu^+\mu^-$	[pb]	–	–	0.1
Cosmic rays	[pb]	0.3	0.3	0.3
Total absolute	[pb]	0.3	0.3	0.3

OPAL

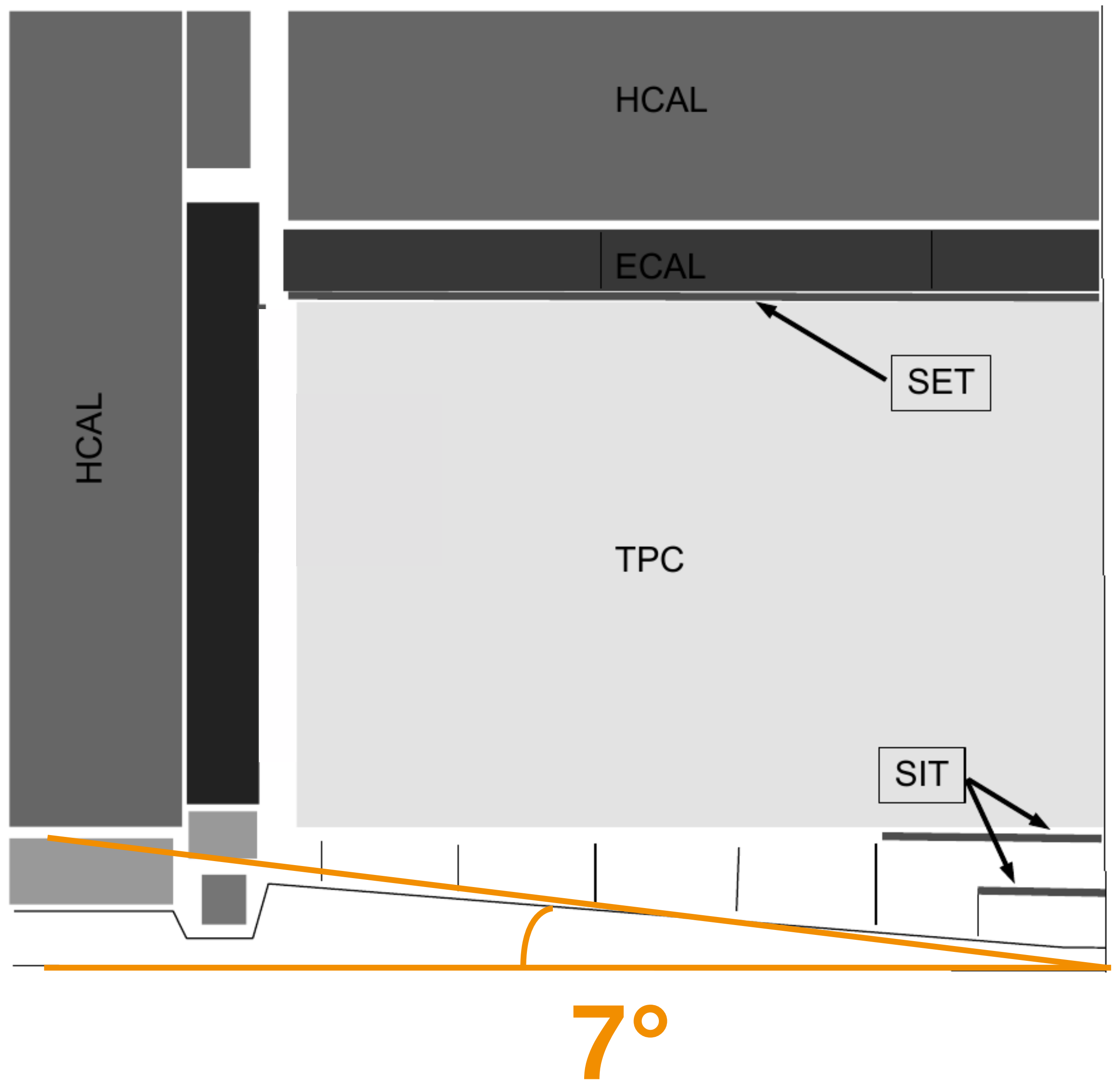
	1993						1994		1995					
	peak−2		peak		peak+2		peak		peak−2		peak		peak+2	
	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)	f	$\Delta f/f$ (%)
Monte Carlo														
$e^+e^- \rightarrow \mu^+\mu^-$ Monte Carlo	1.0995	0.10	1.0955	0.07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

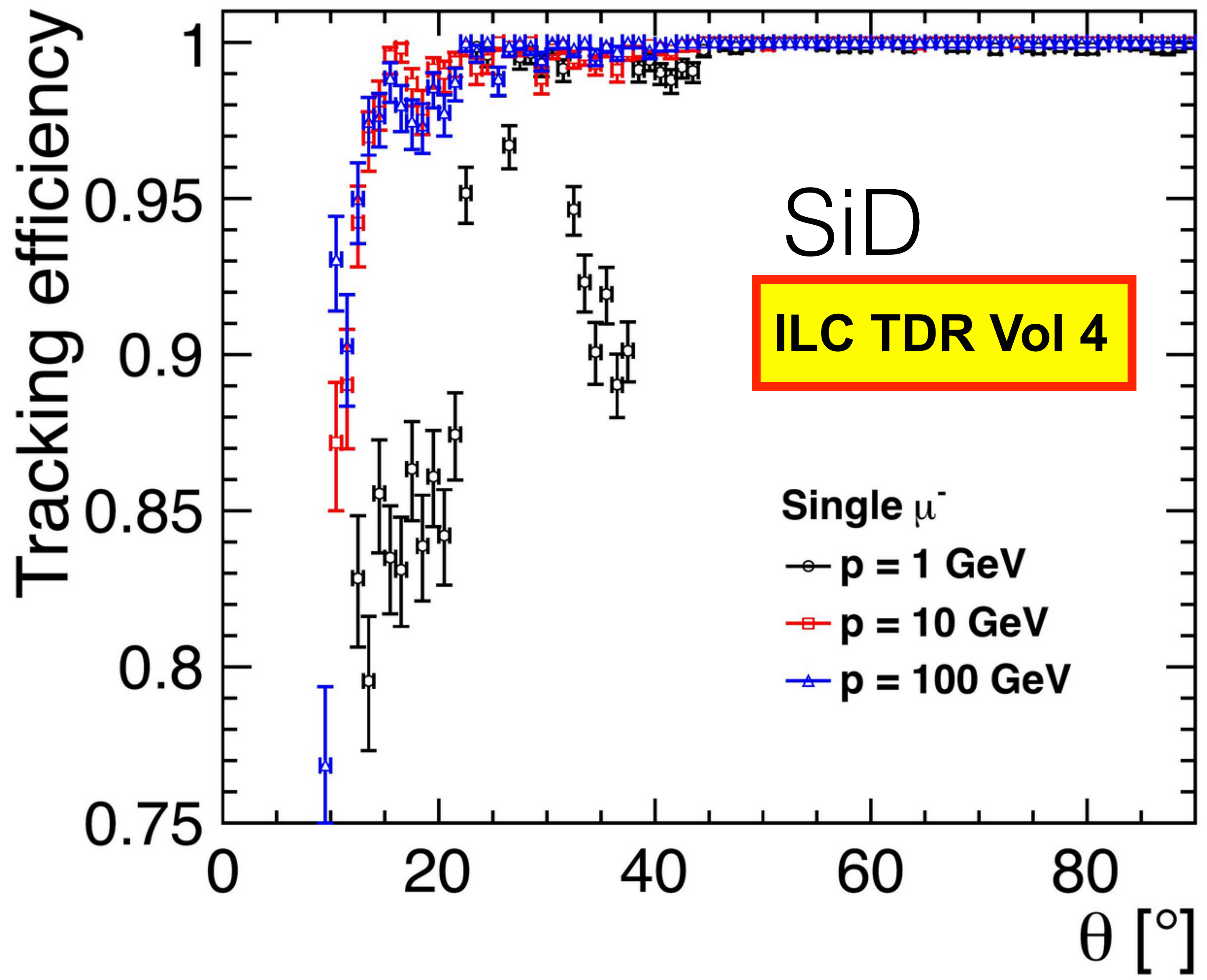
Table 6: Summary of the correction factors, f, and their relative systematic errors, $\Delta f/f$, for the $e^+e^- \rightarrow \mu^+\mu^-$ cross-section measurements. These numbers, when multiplied by the number of events actually selected, give the number of signal events which would have been observed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

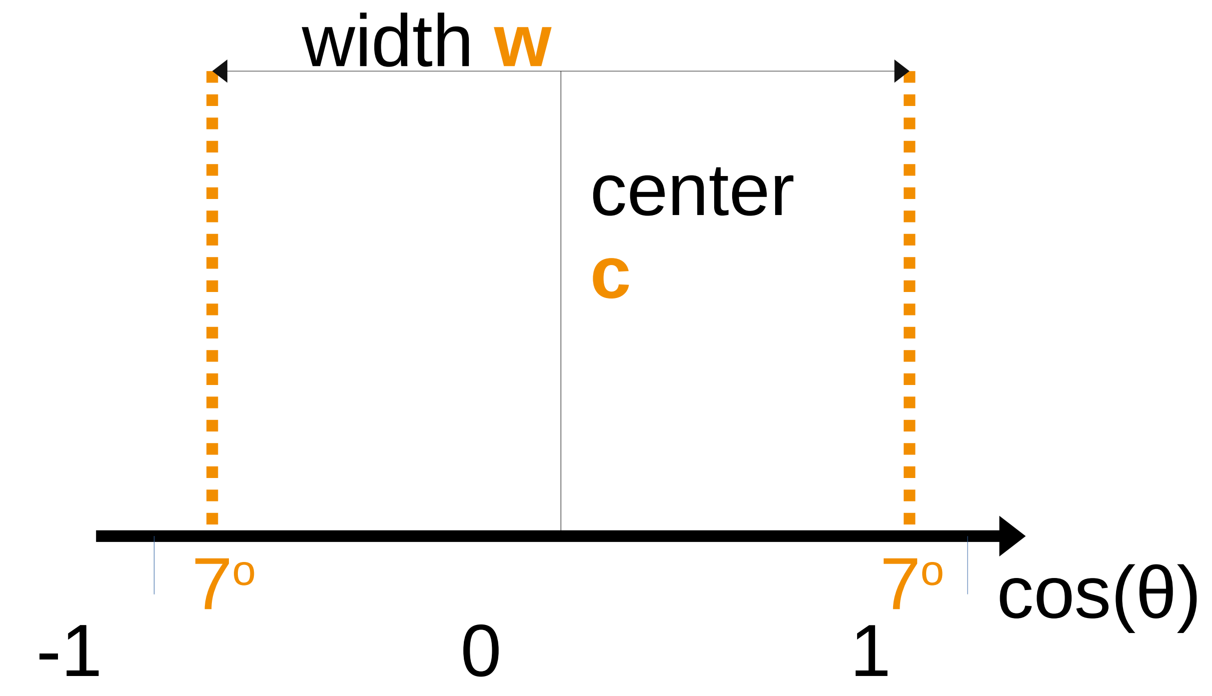
Parametrising the muon acceptance for an ILC detector

ILD tracking down to:





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

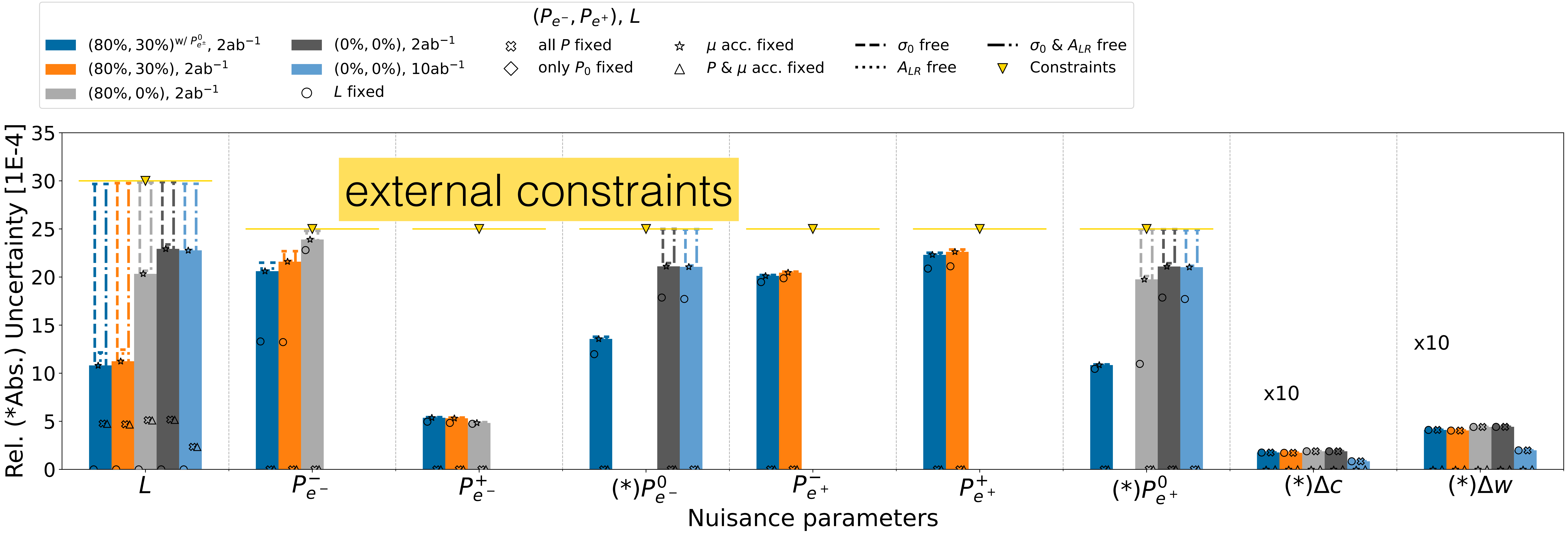


Fit parameters: Δc, Δw

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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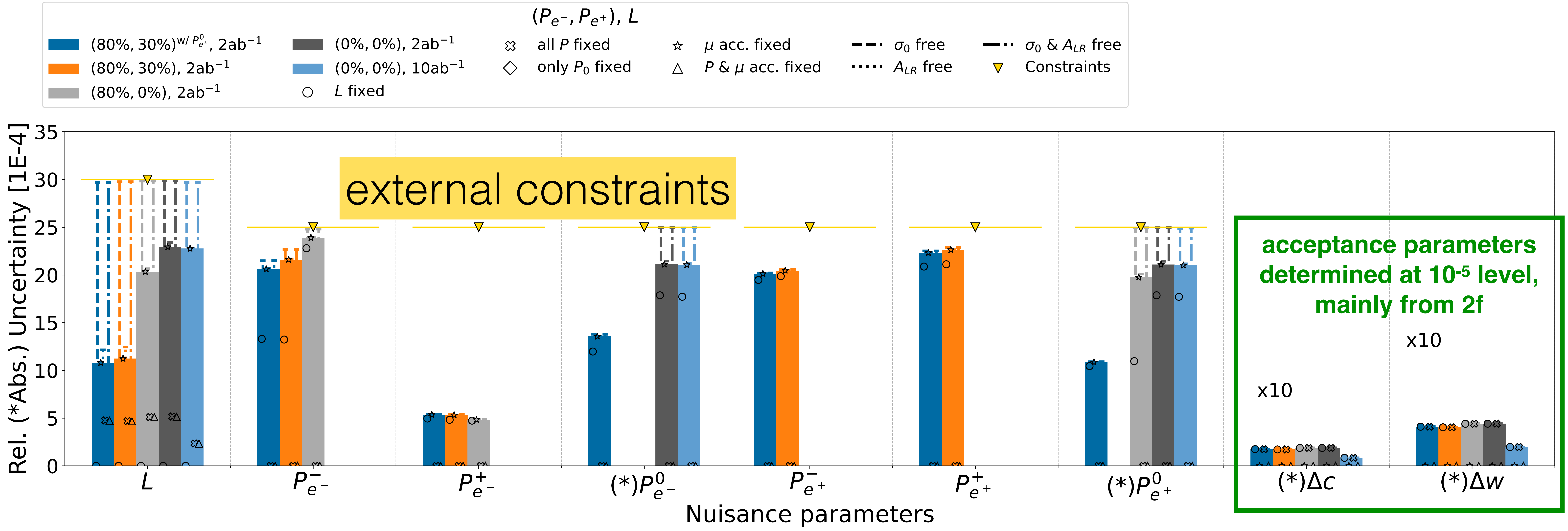

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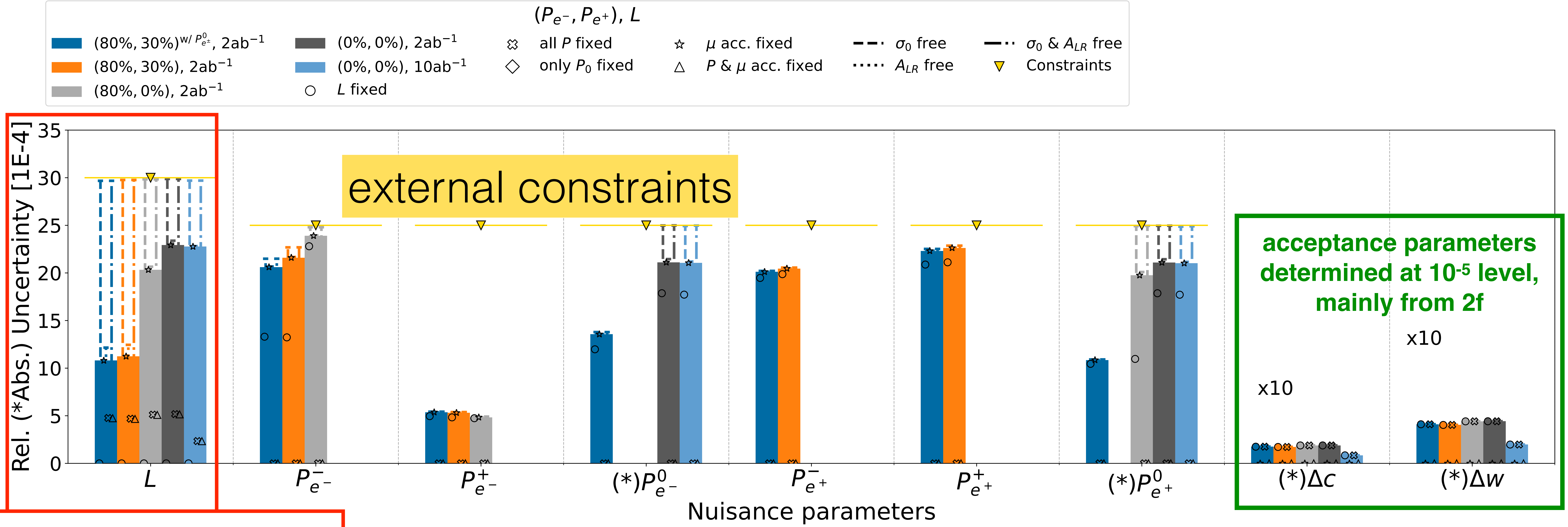

if one σ_0 were known better than lumi measurement, luminosity could be better constrained => academic ?

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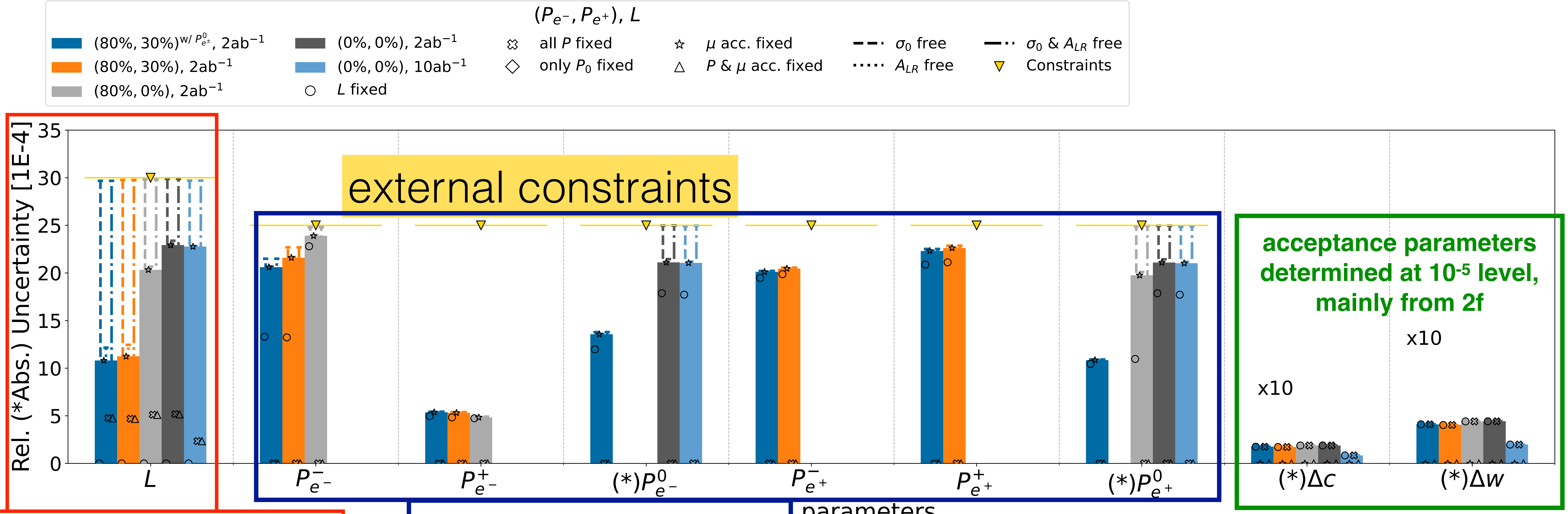

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polarisations determined to 0.05…0.2%, almost exclusively from WW

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

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

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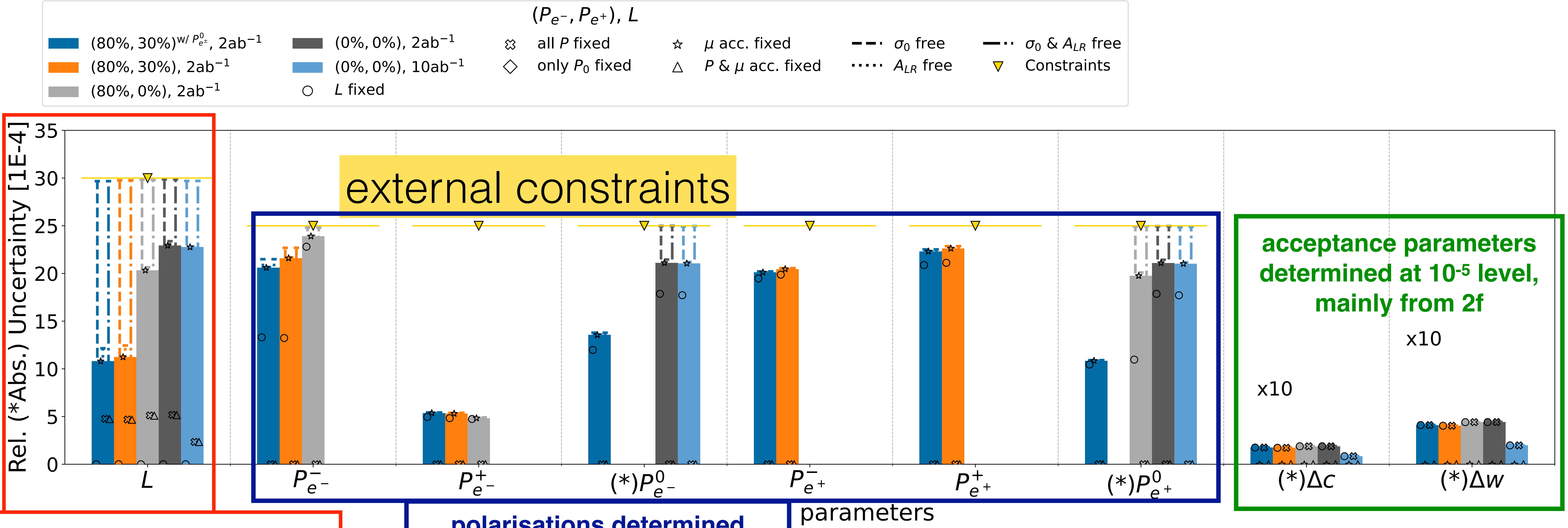

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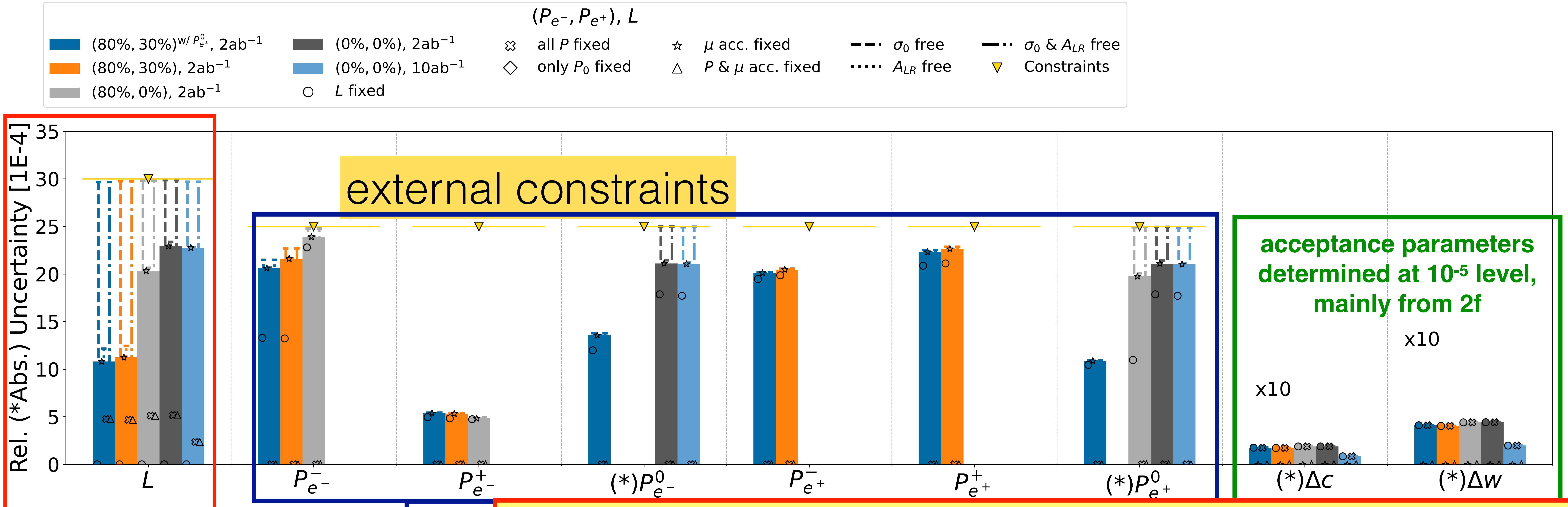

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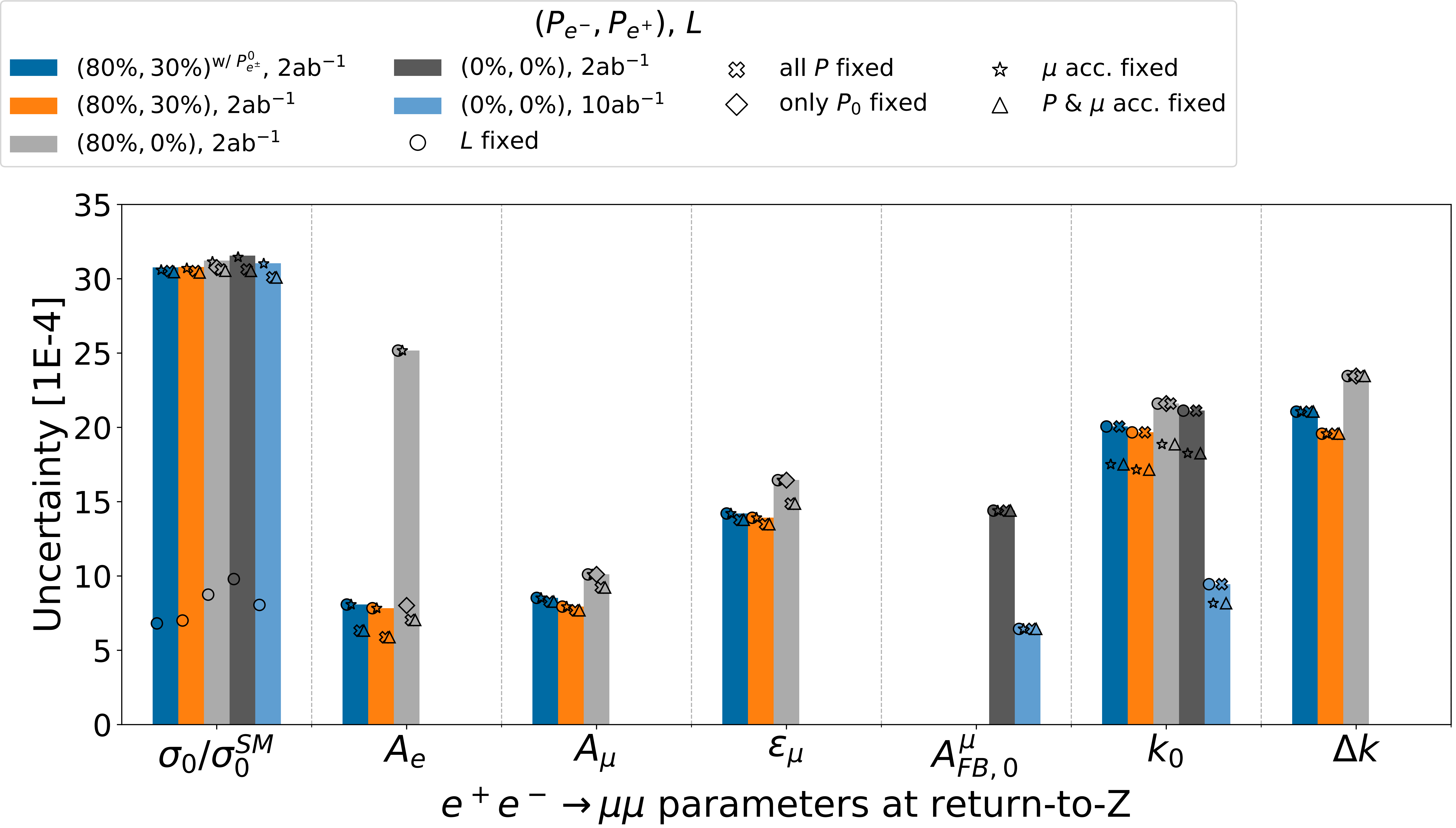
pola... to... ex...

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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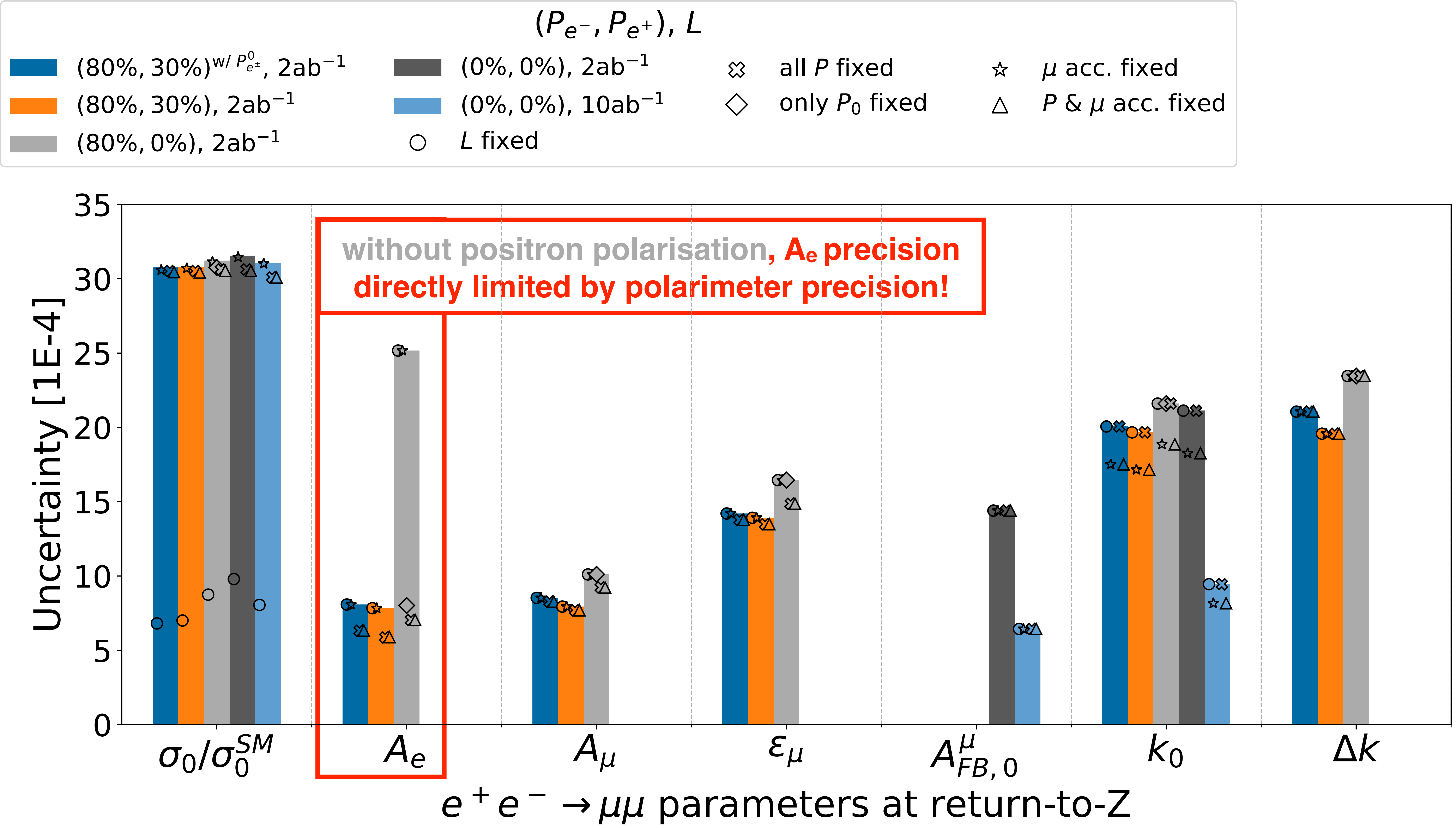

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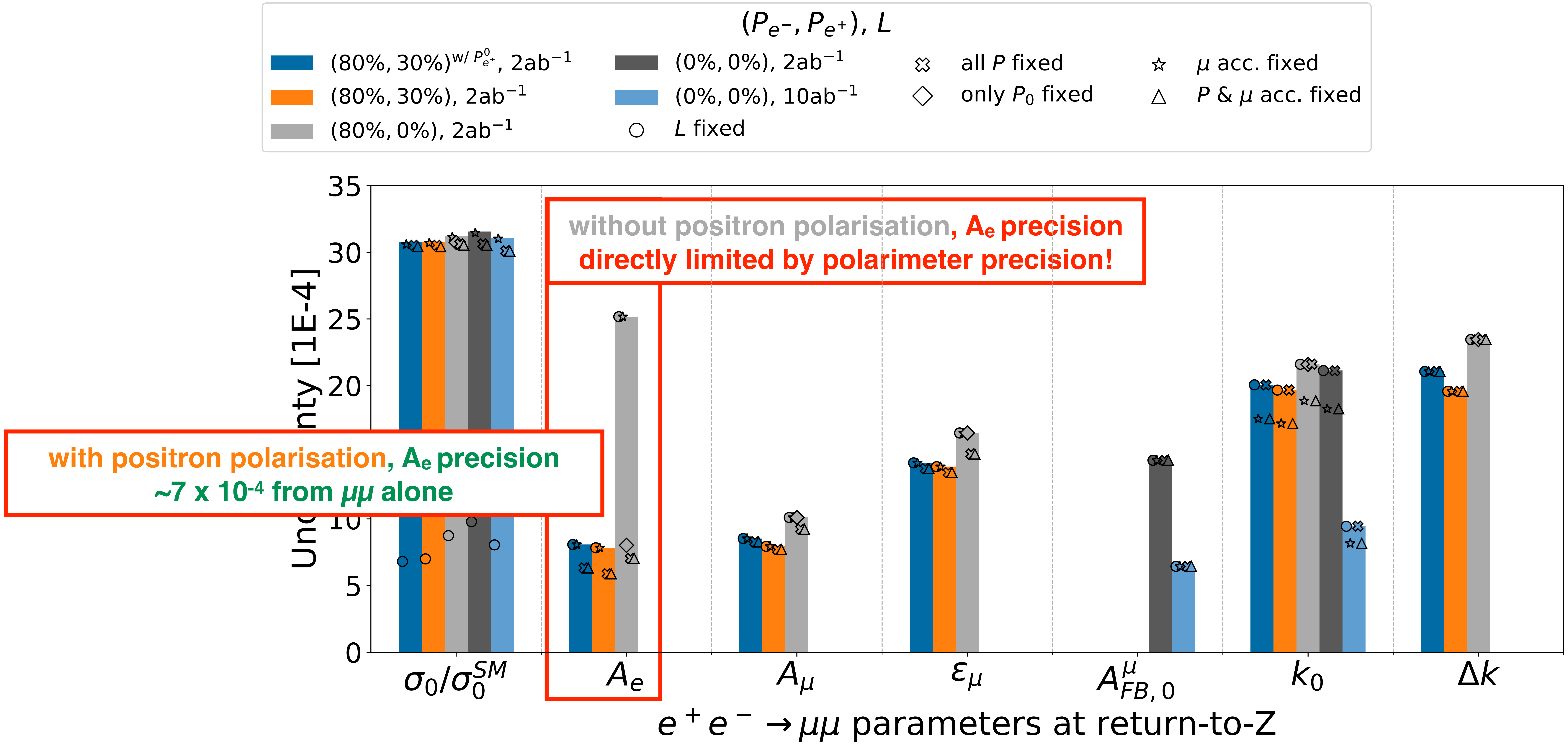

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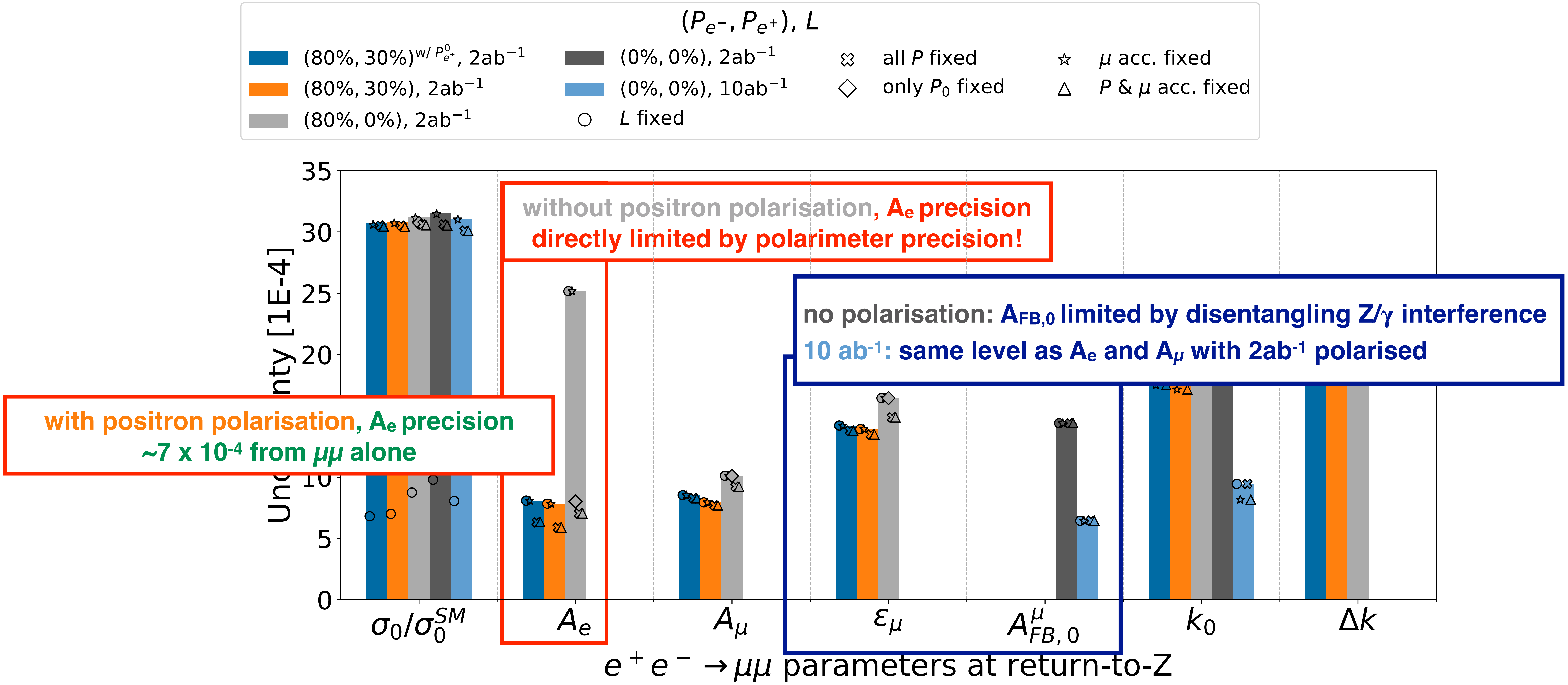
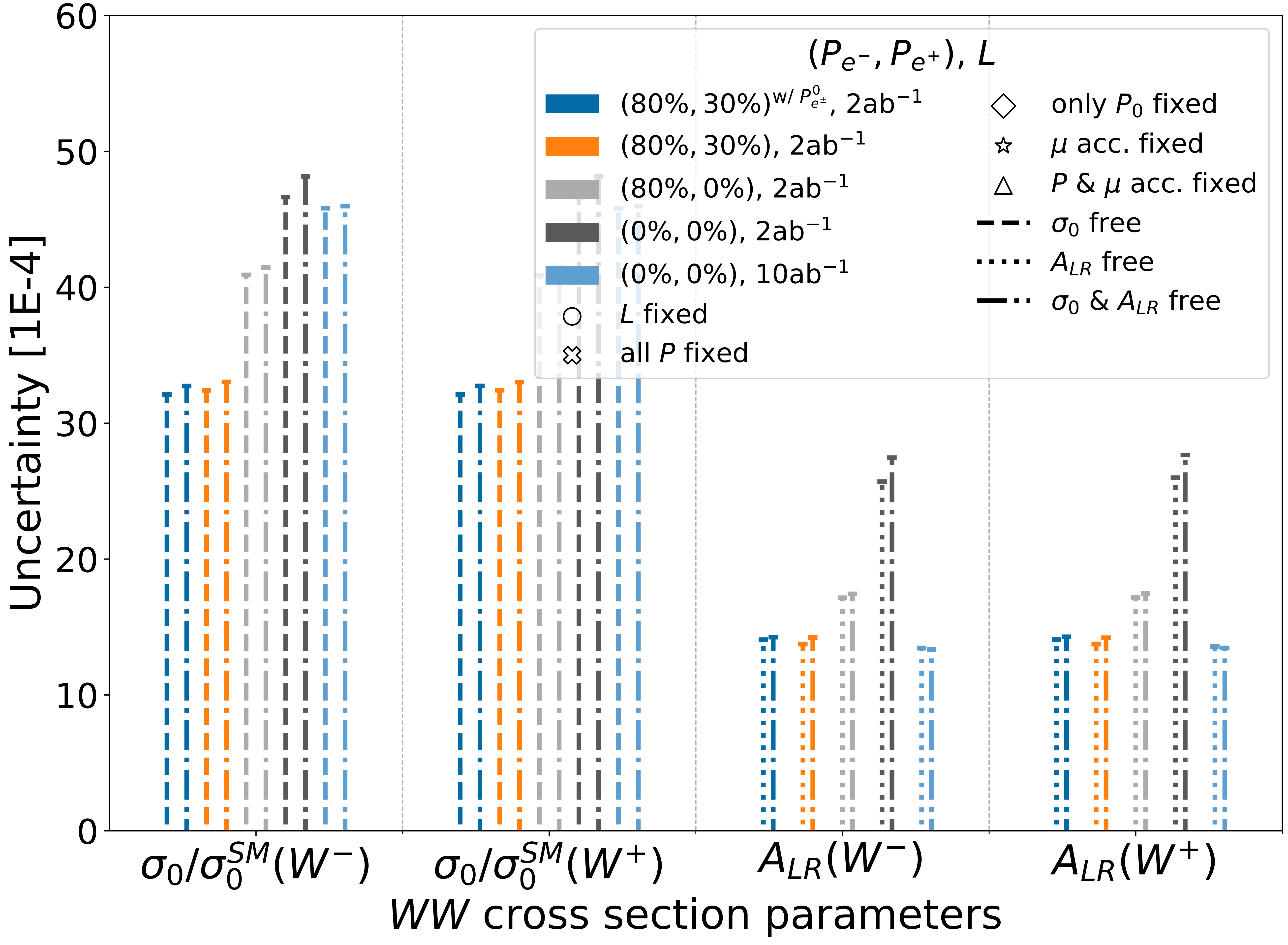


WW cross section and left-right asymmetry



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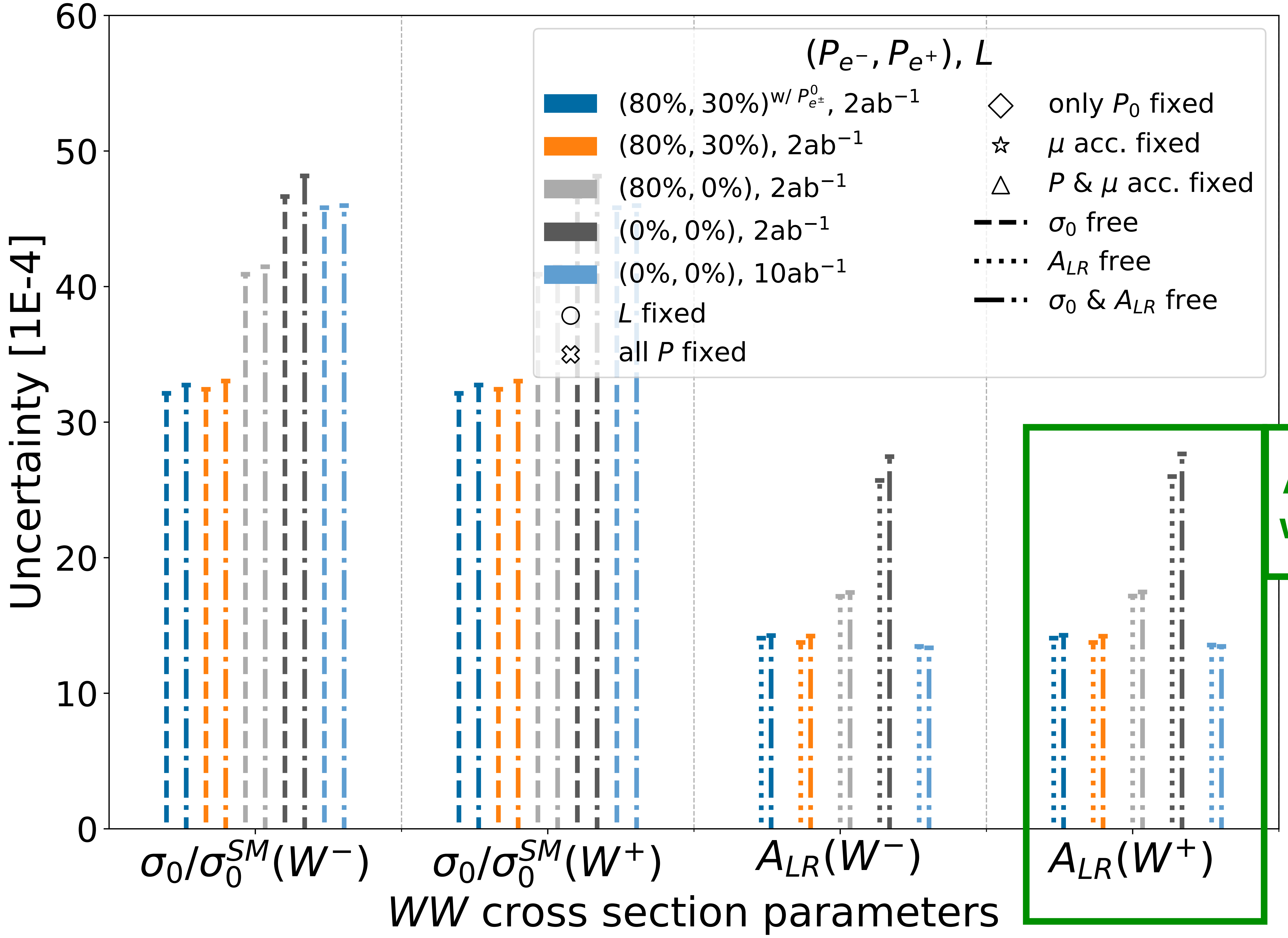

A_{LR}(WW) determined to 0.015% with polarised beams or 10 ab^{-1}

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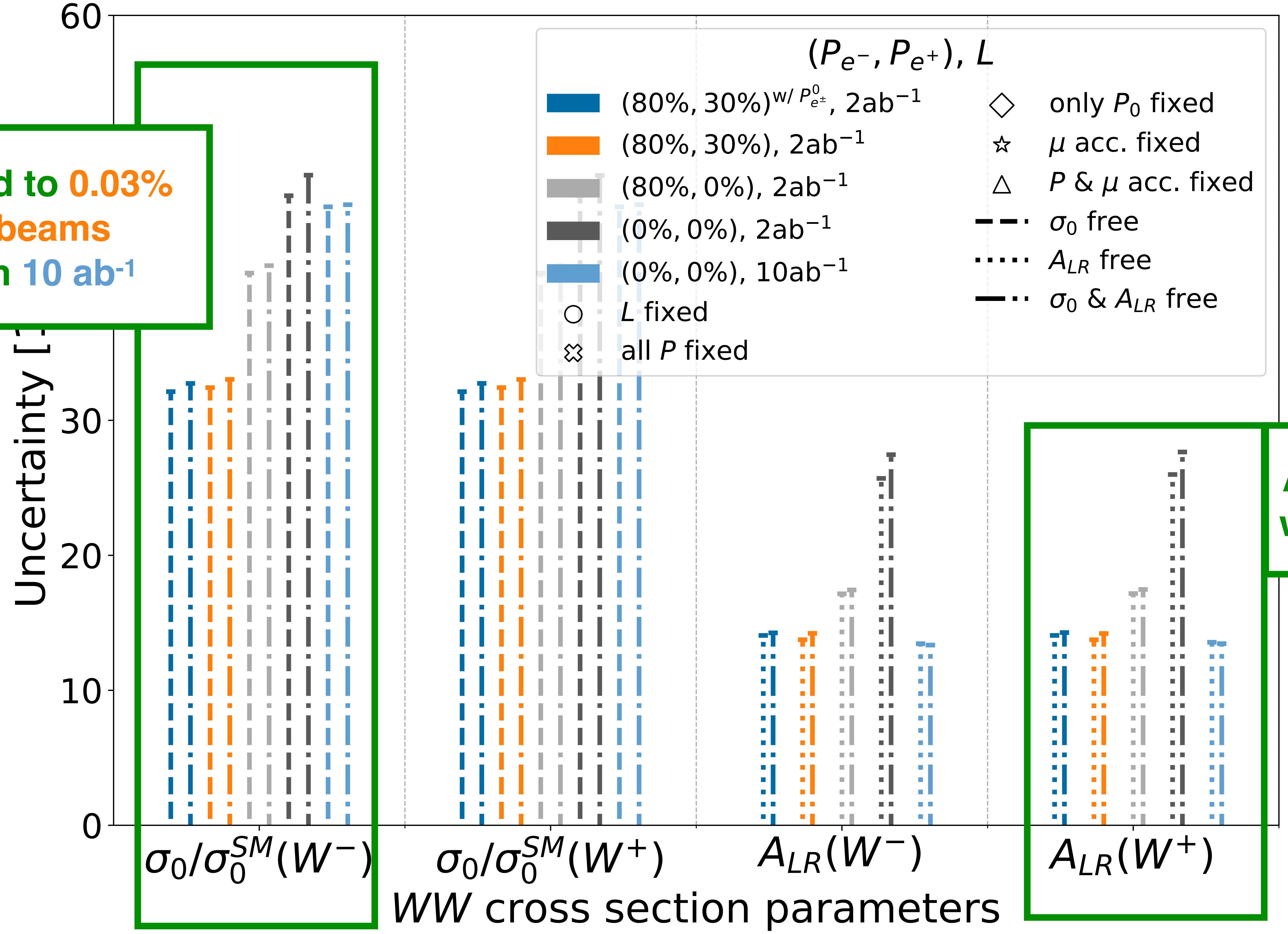
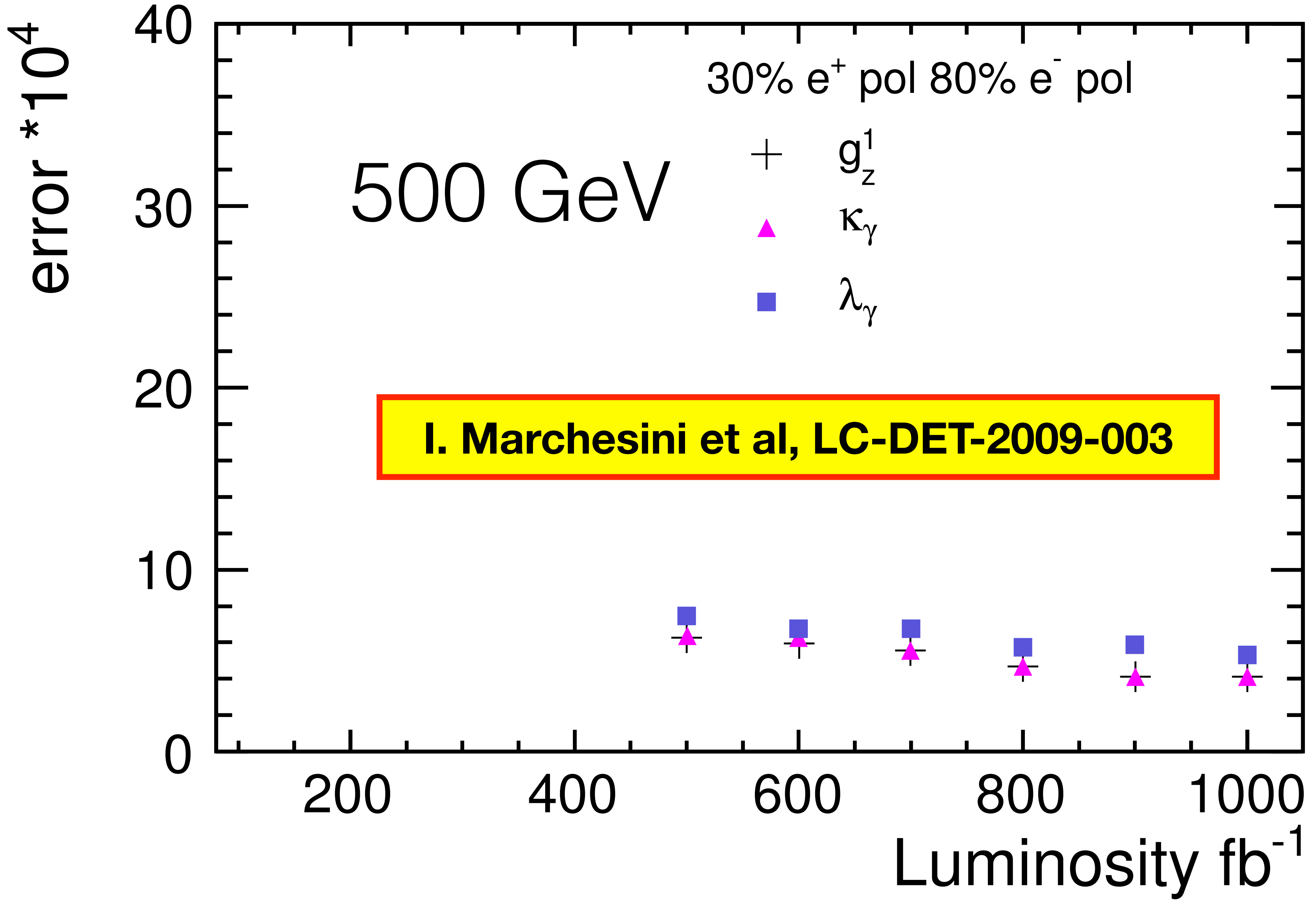


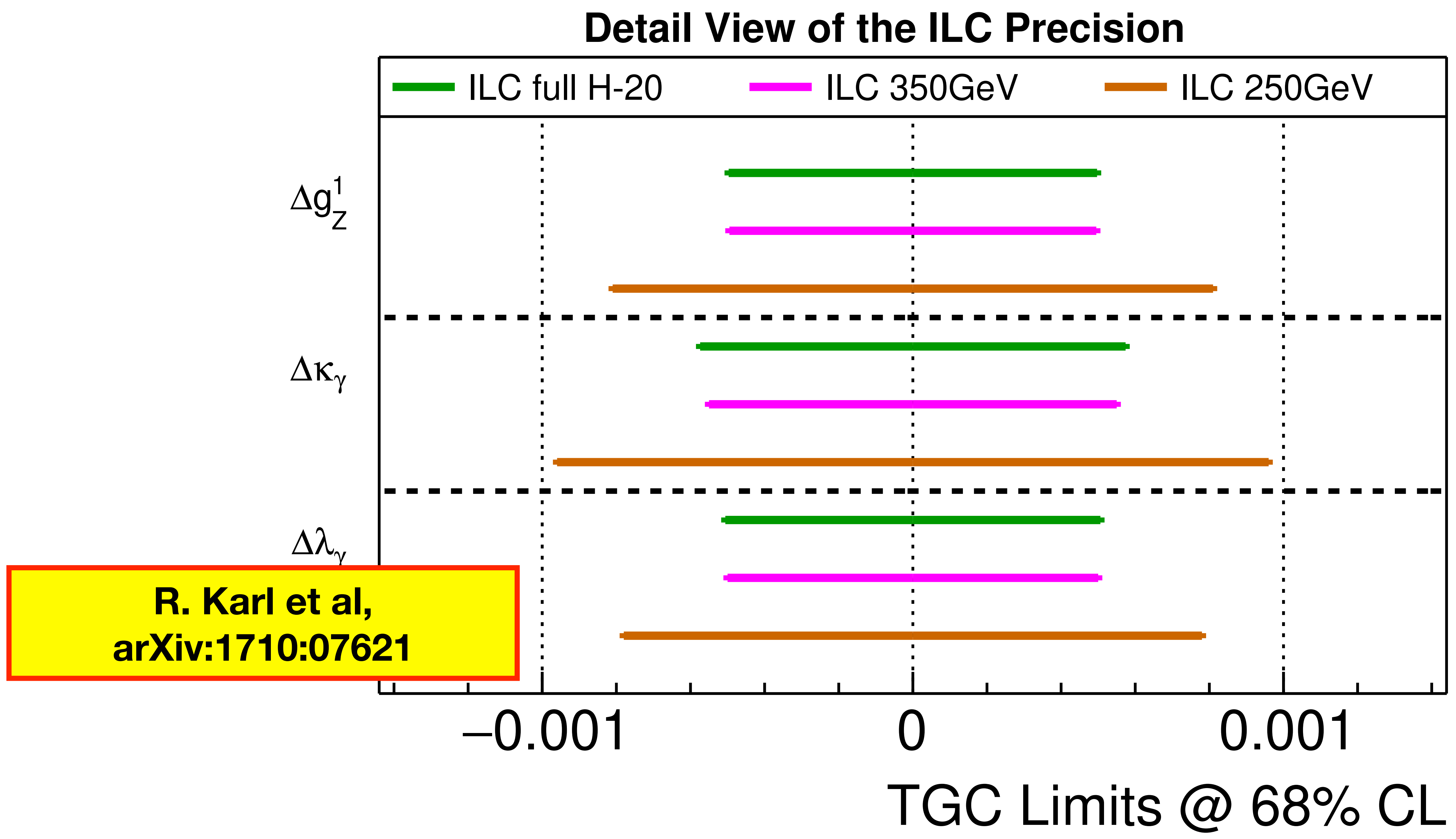
σ_0(WW) determined to 0.03% with polarised beams or to 0.045% with 10 ab^{-1}

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**

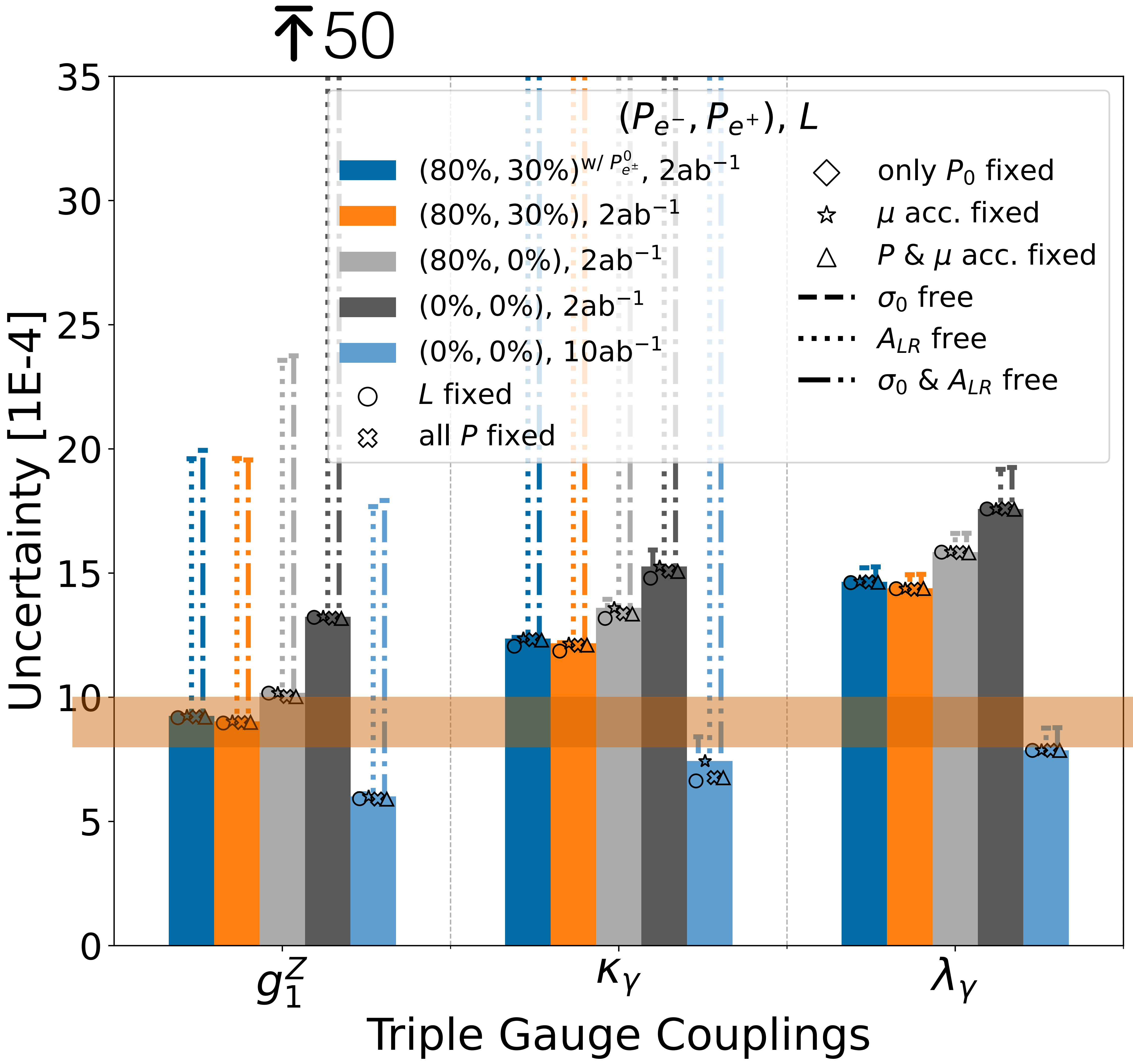




expect 8..10 x 10^{-4} at 250 GeV

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

WW - charged triple gauge couplings - this study



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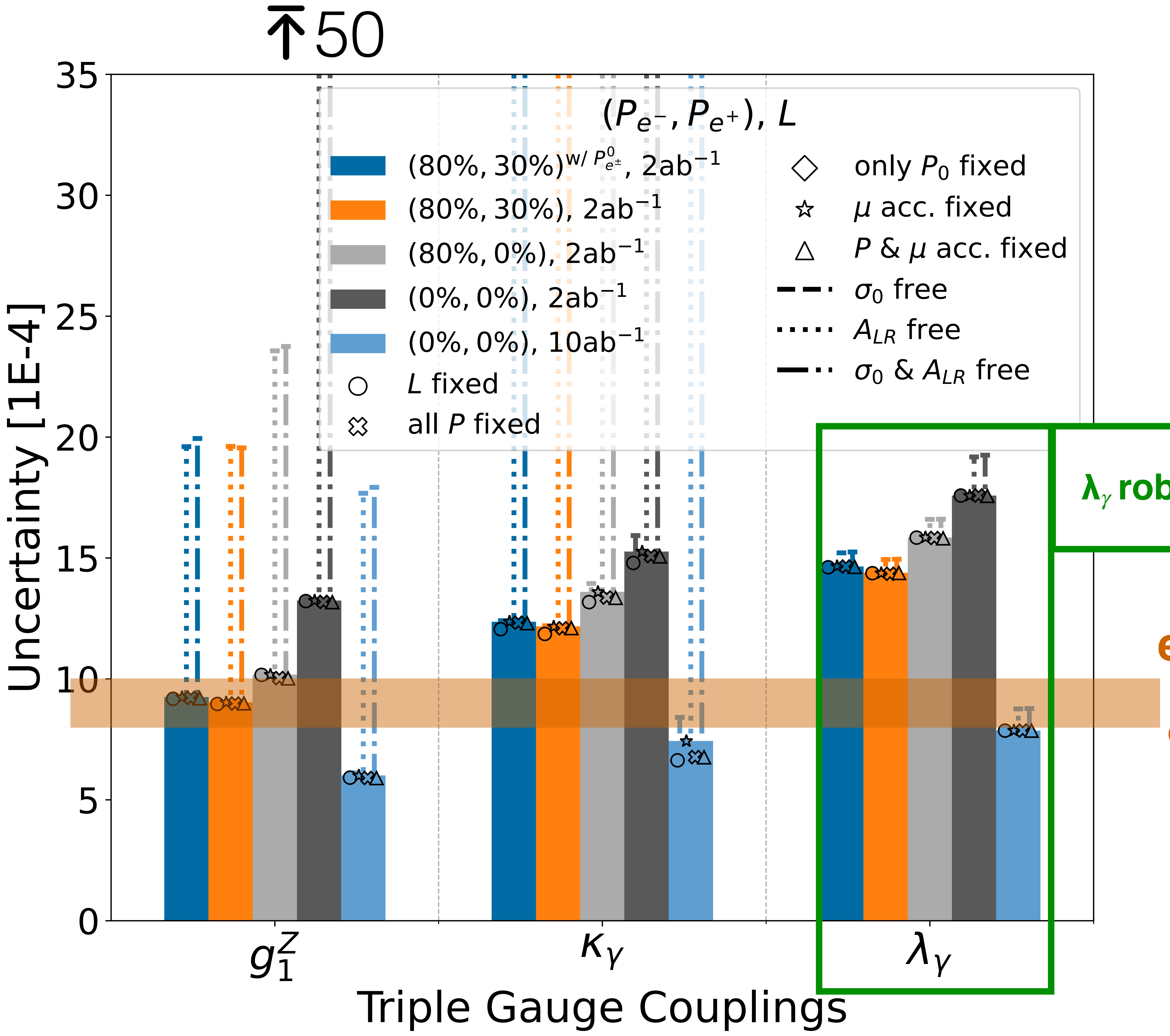

λ_γ robust against free σ_0(WW), A_{LR}(WW)

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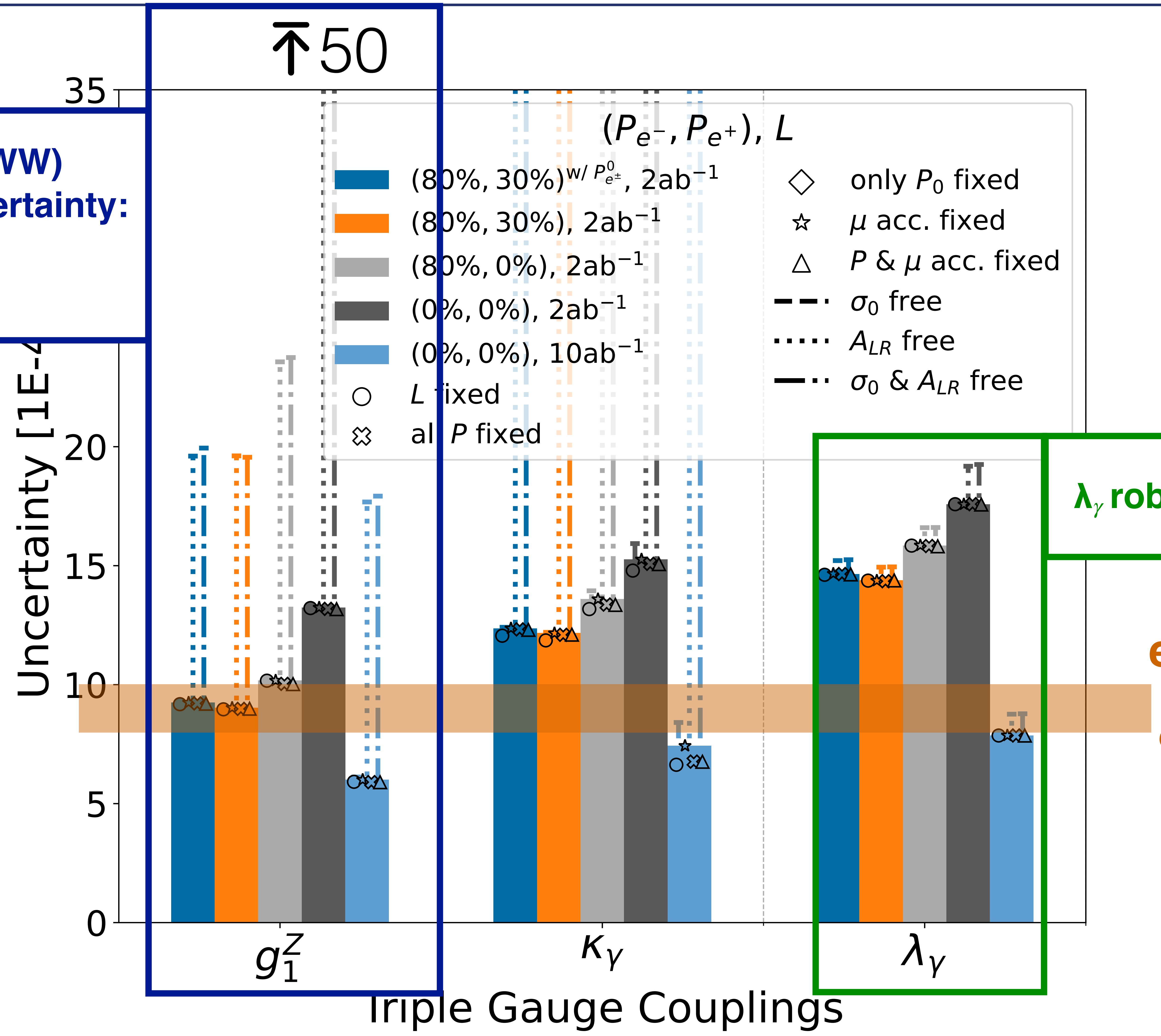
g_1^Z robust against freeing σ_0(WW)
BUT: free A_{LR}(WW) increases uncertainty:
x2 polarised
x3 unpolarised



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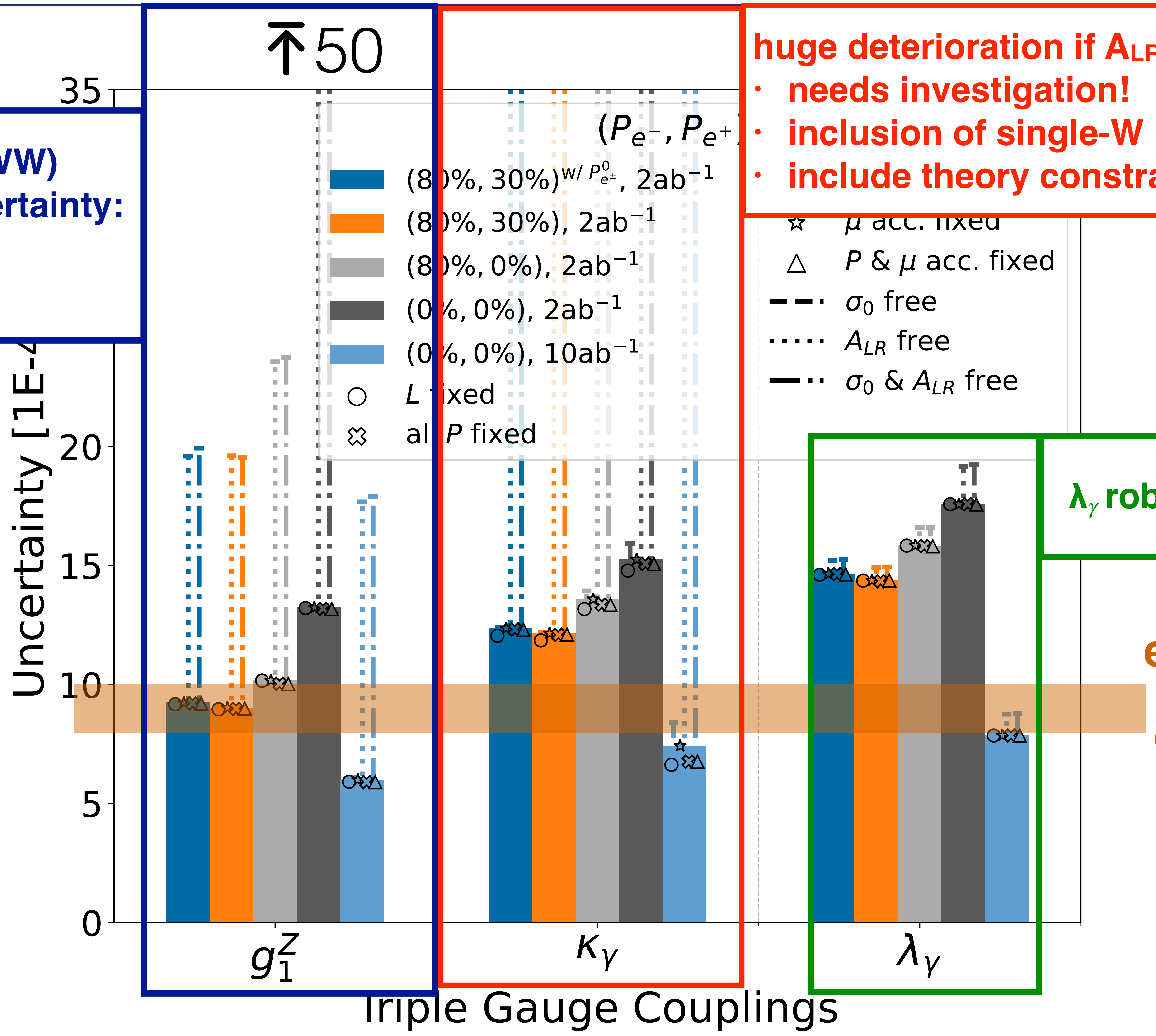


huge deterioration if A_{LR}(WW) free ?

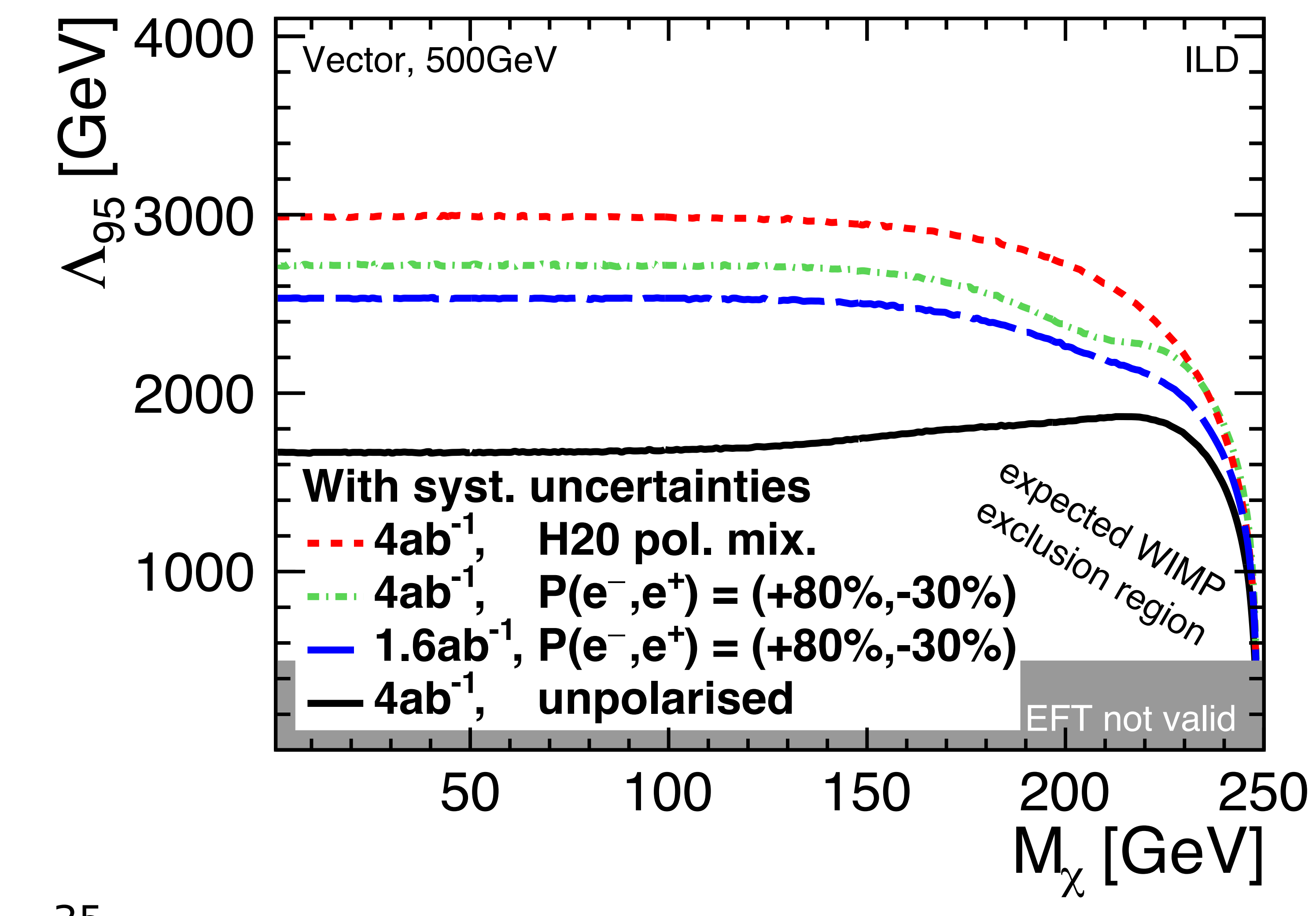
- **needs investigation!**
- **inclusion of single-W proceses?**
- **include theory constraints / search limits (ν_R)?**

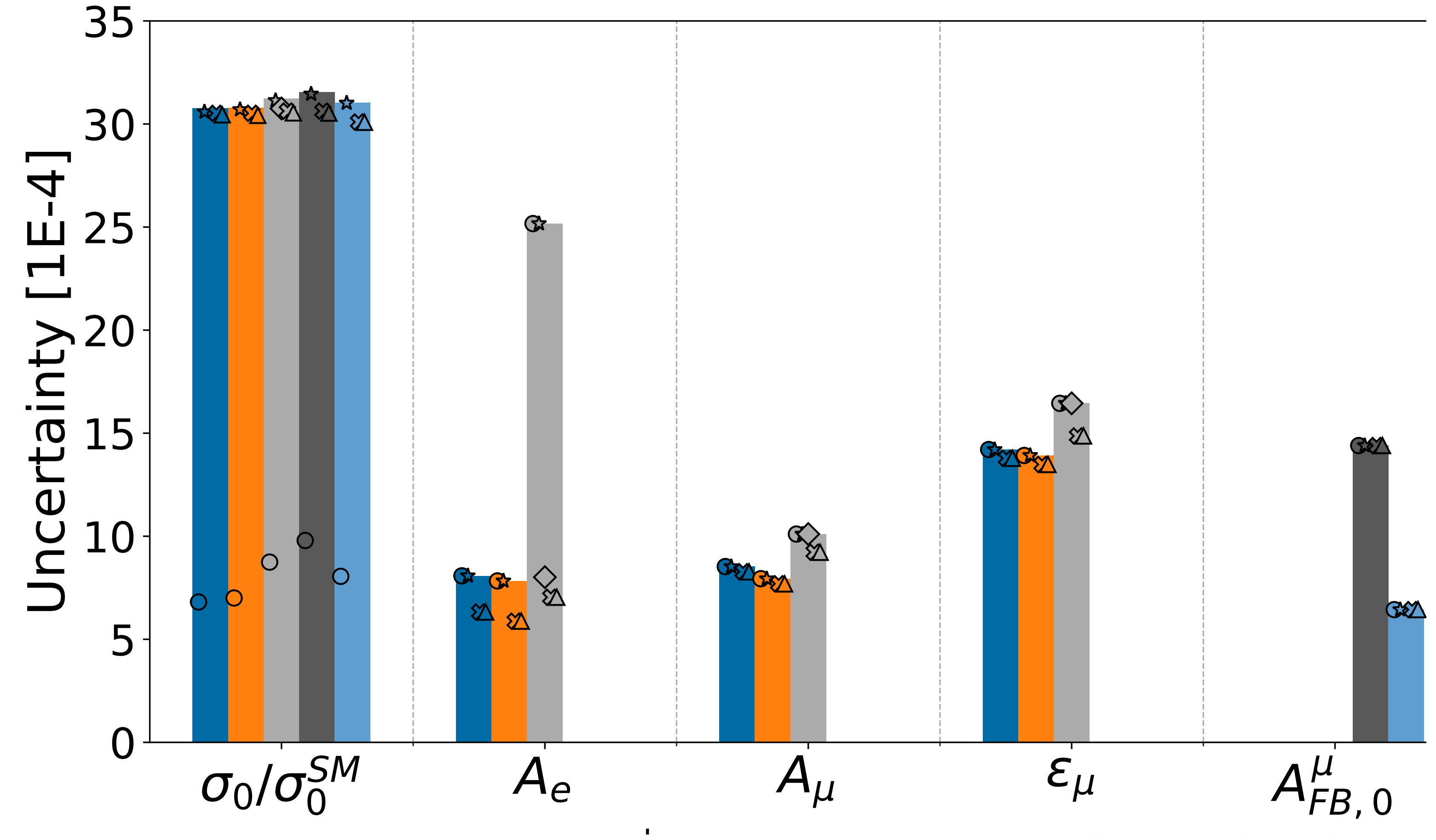
λ_γ robust against free σ_0(WW), A_{LR}(WW)

expect 8..10 x 10^{-4} at 250 GeV
WW -> eνqq & μνqq,
detector effects somewhat pessimistic,
σ_0(WW), A_{LR}(WW) fixed

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**
- **combination of data-sets with different polarisation configurations helps significantly to reduce the impact of systematic uncertainties**
- **first steps have been undertaken to apply the same principles to a combined fit of ee->2f and ee->4f processes**
- **impact of polarisation seen in various places:**
- **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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- role of beam polarisation for chiral analysis, signal-to-background ratio, effective luminosity at future e+e- collider well studied since years
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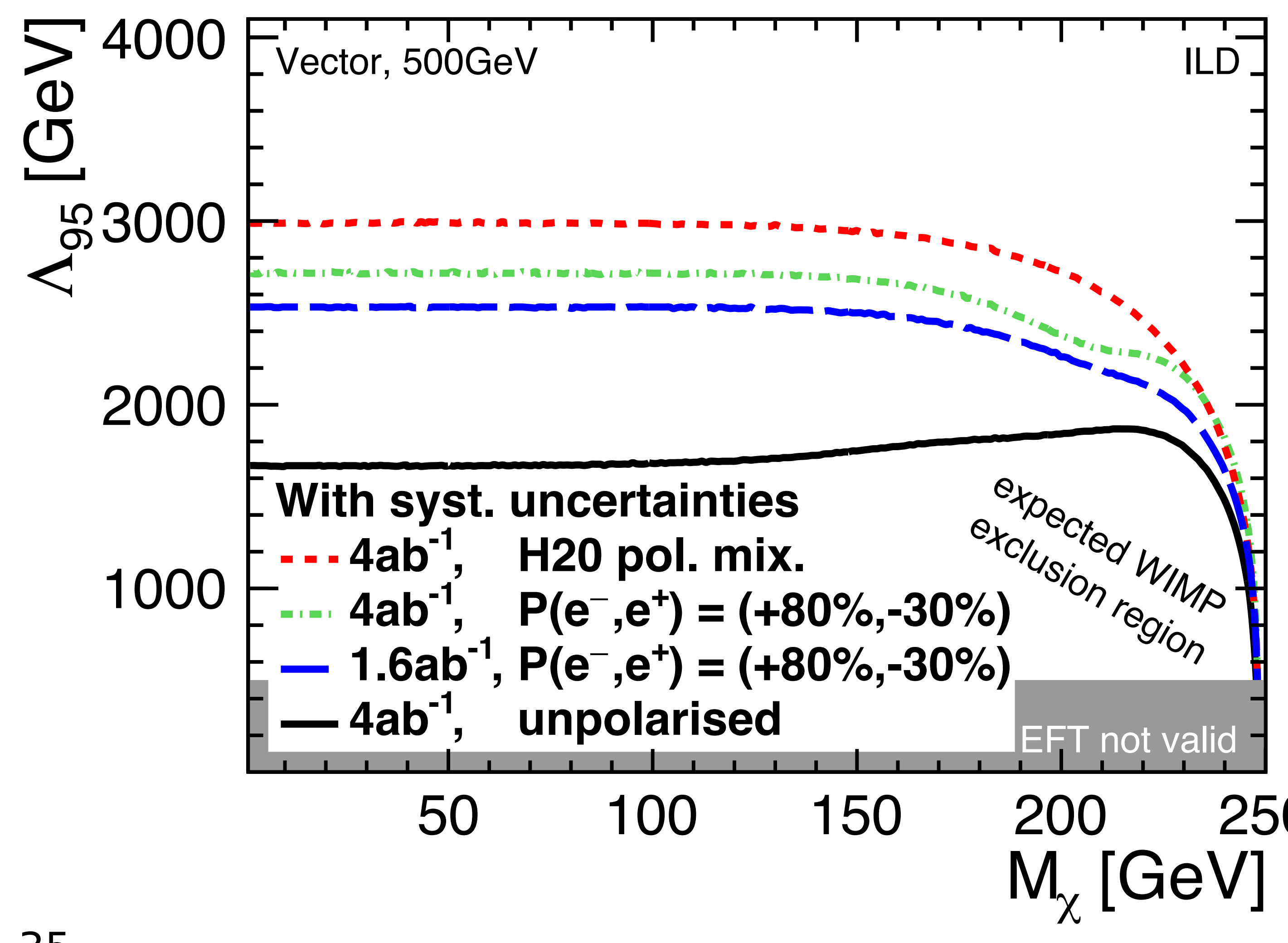
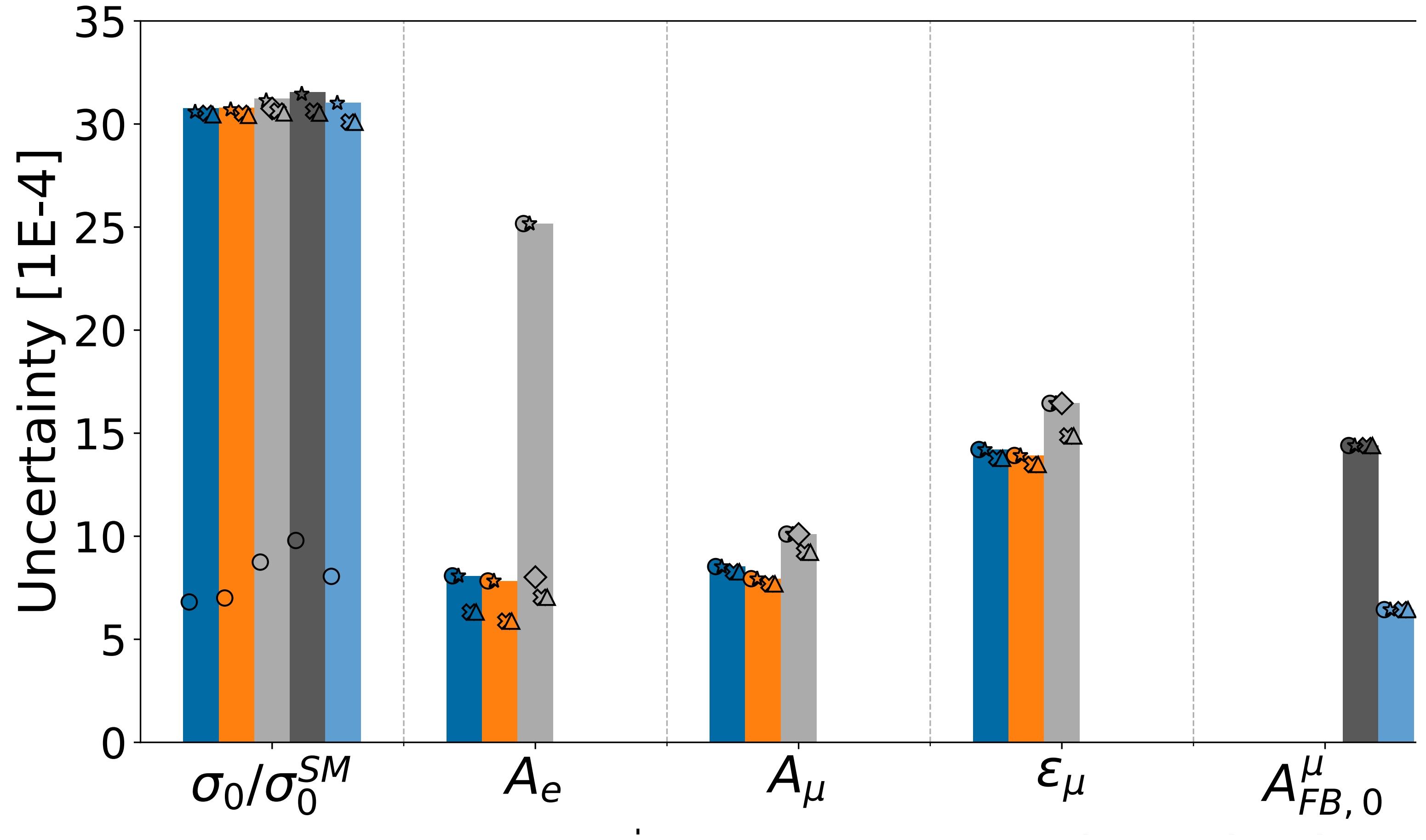
- first steps have been undertaken to apply the same principles to a combined fit of ee->2f and ee->4f processes
- impact of polarisation seen in various places:

4 polarisation sign 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

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} /cm² /s
  - upgrade 2.7×10^{34} /cm² /s
- **beam polarisation**
  - $P(e^-) \geq 80\%$
  - $P(e^+) = 30\%$, at 500 GeV upgradable to 60%
- total length (250 GeV): 20.5 km