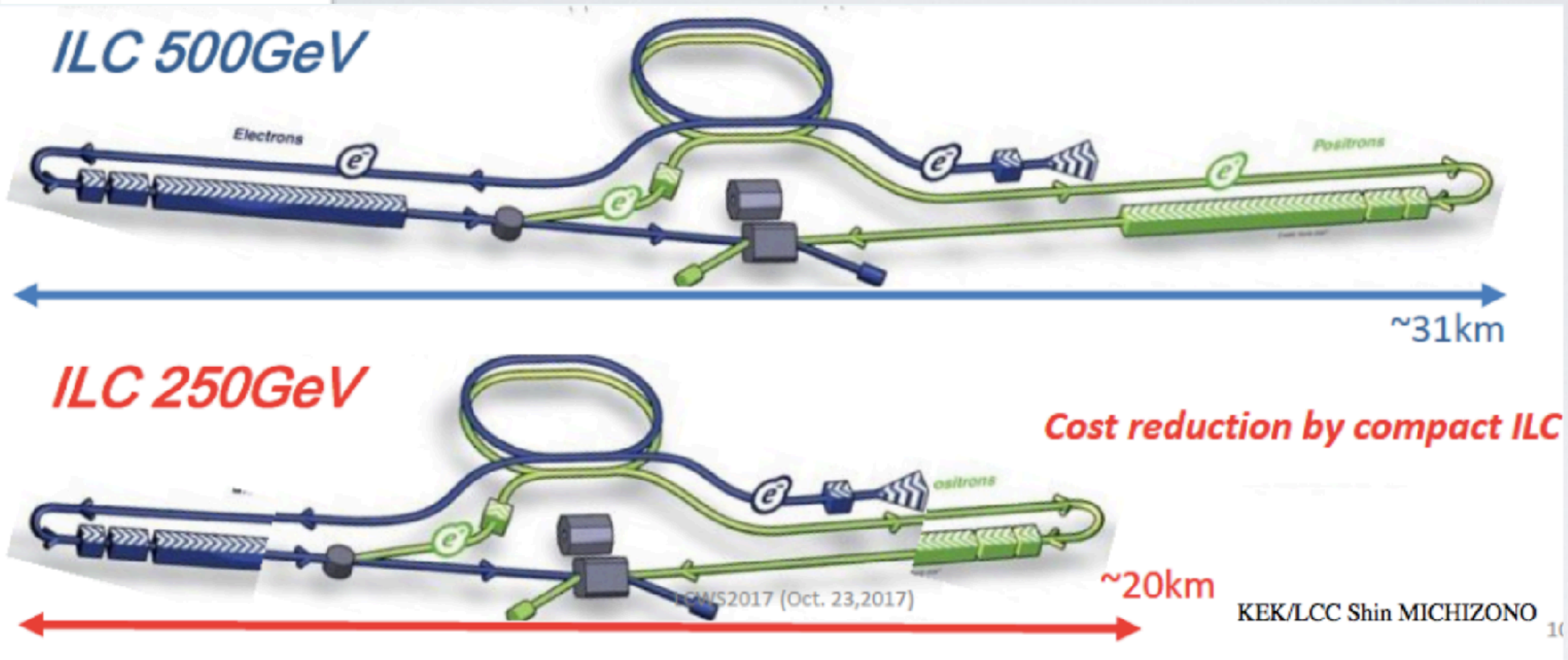
The role of positron polarization for the initial 250 GeV stage of the ILC

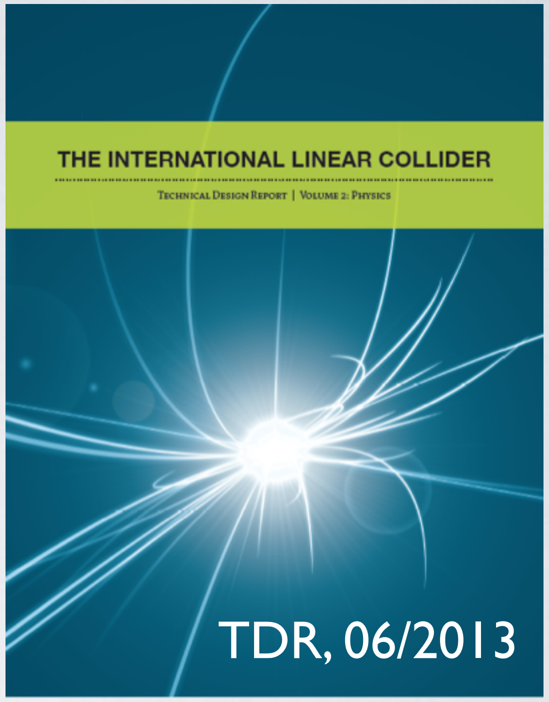
Jürgen R. Reuter, DESY

on behalf of: Physics Working Group of the Linear Collider Collaboration (LCC),

based mostly on: arXiv: 1801.02840

ILC — 250 GeV e^+e^- Linear Collider





- e^+e^- collider, 20.5[–31] km length, c.m. energy: 250 GeV (tunable) [Upgrade: 0.35,0.5,1 TeV]
- Polarisation: 80% e^- and 30% e^+
- Integrated Luminosity: up to 250/fb/yr @ 250 GeV
- Based on superconducting RF cavities, 31.5 MV/m design
- Experimental setup:
  - Well-defined initial state
  - Pure electroweak production (small theory errors)
  - Triggerless operation
- Possible concurrent running with LHC high-luminosity phase

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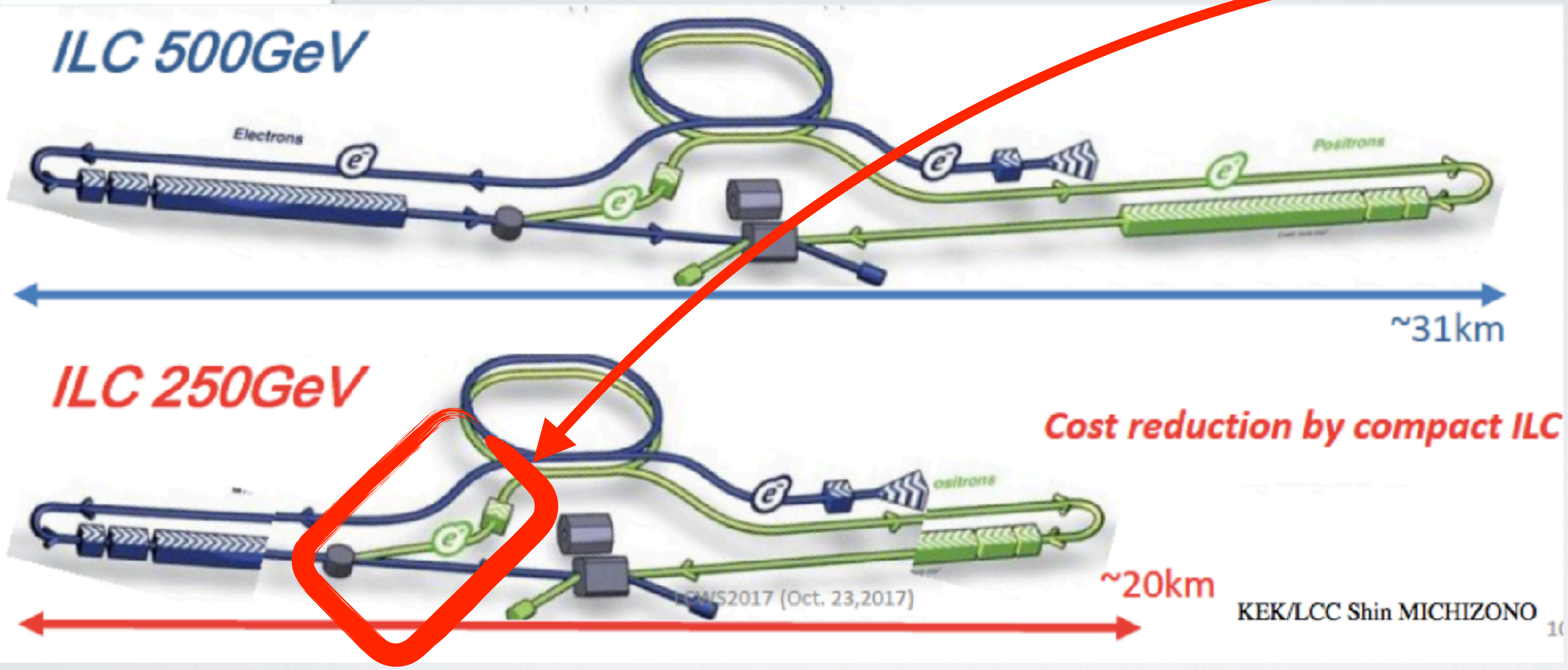
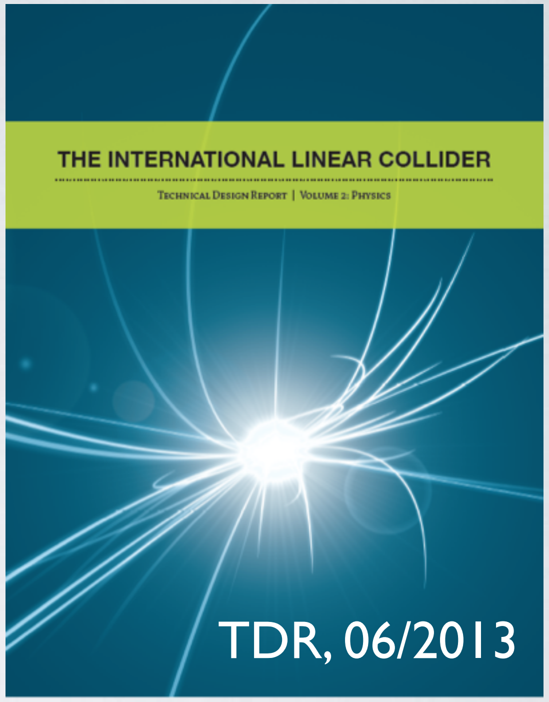
Positron Polarization





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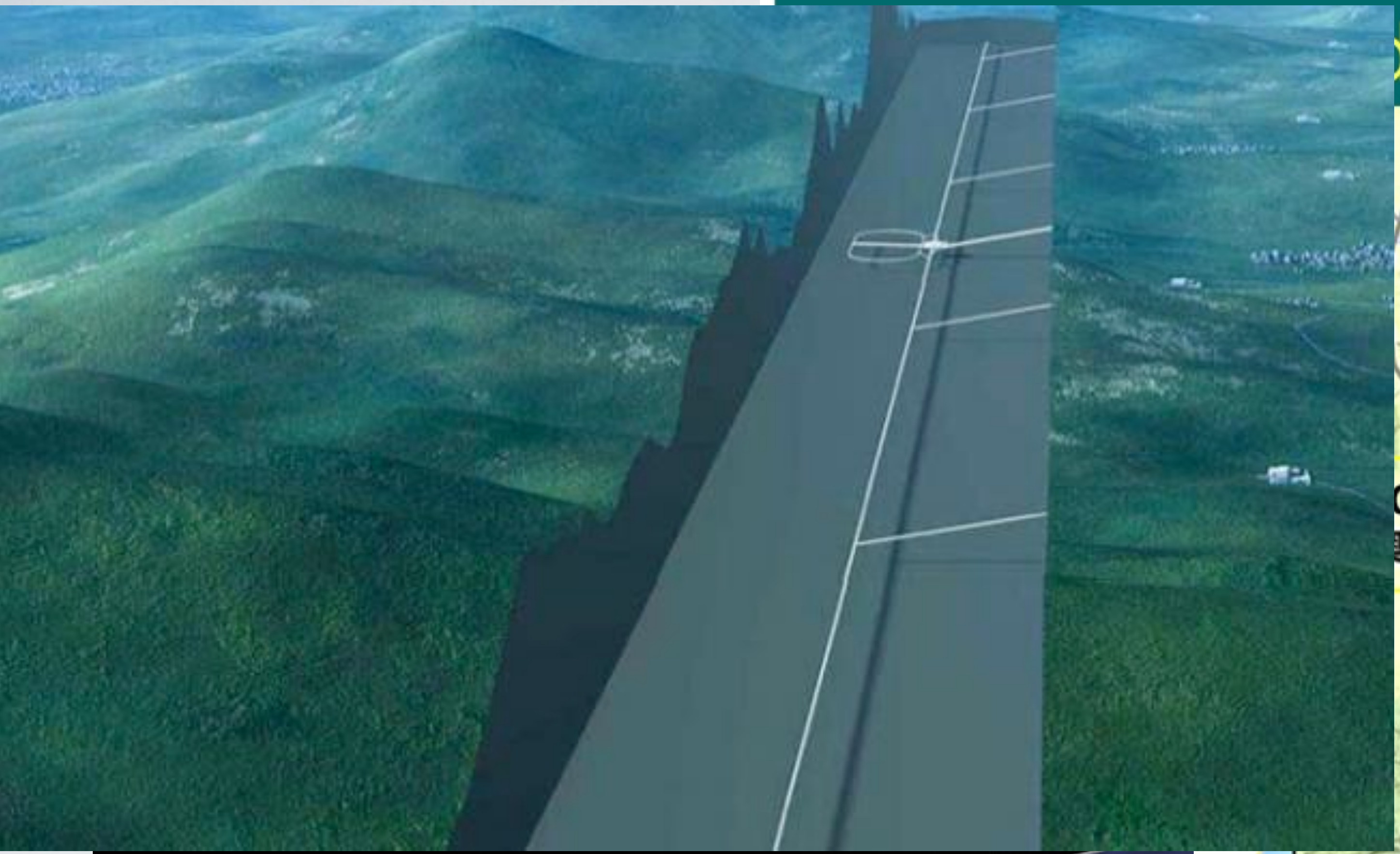
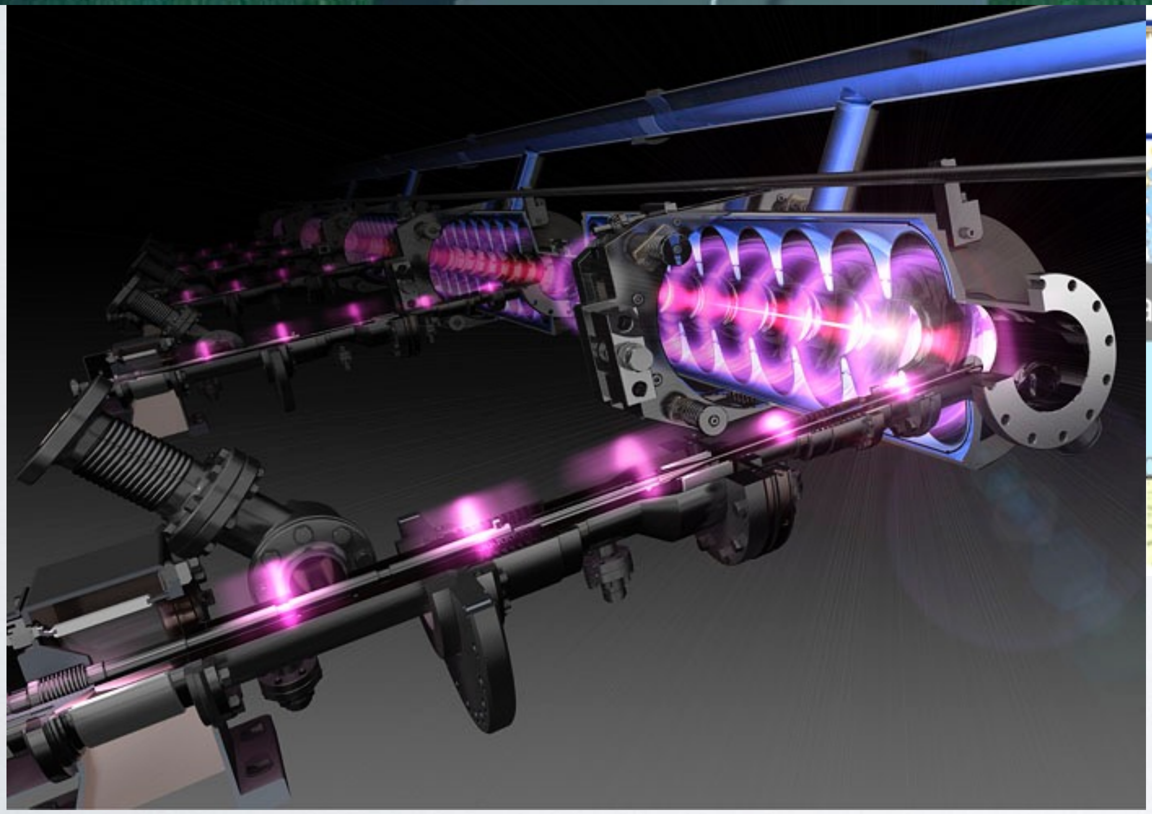
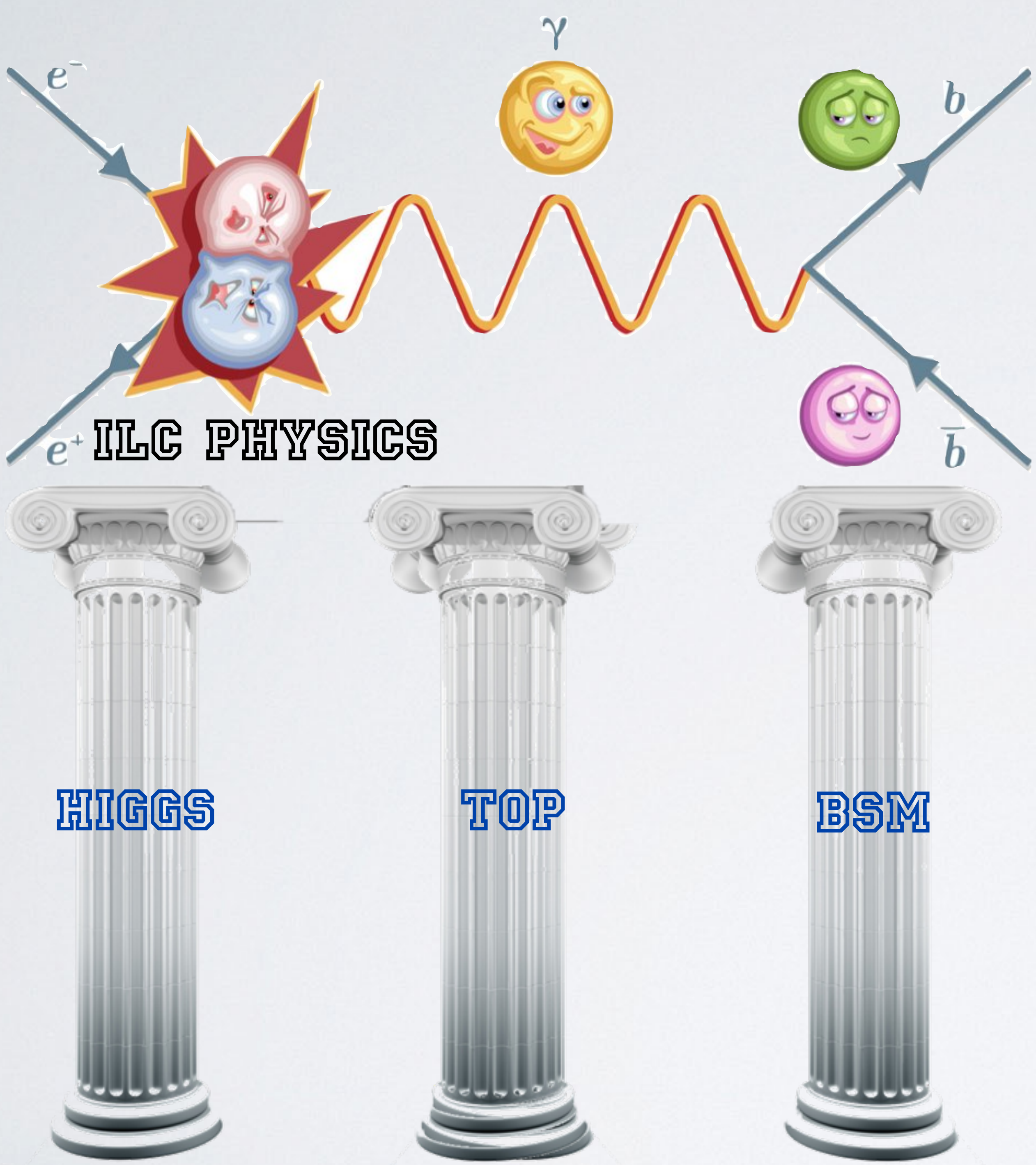
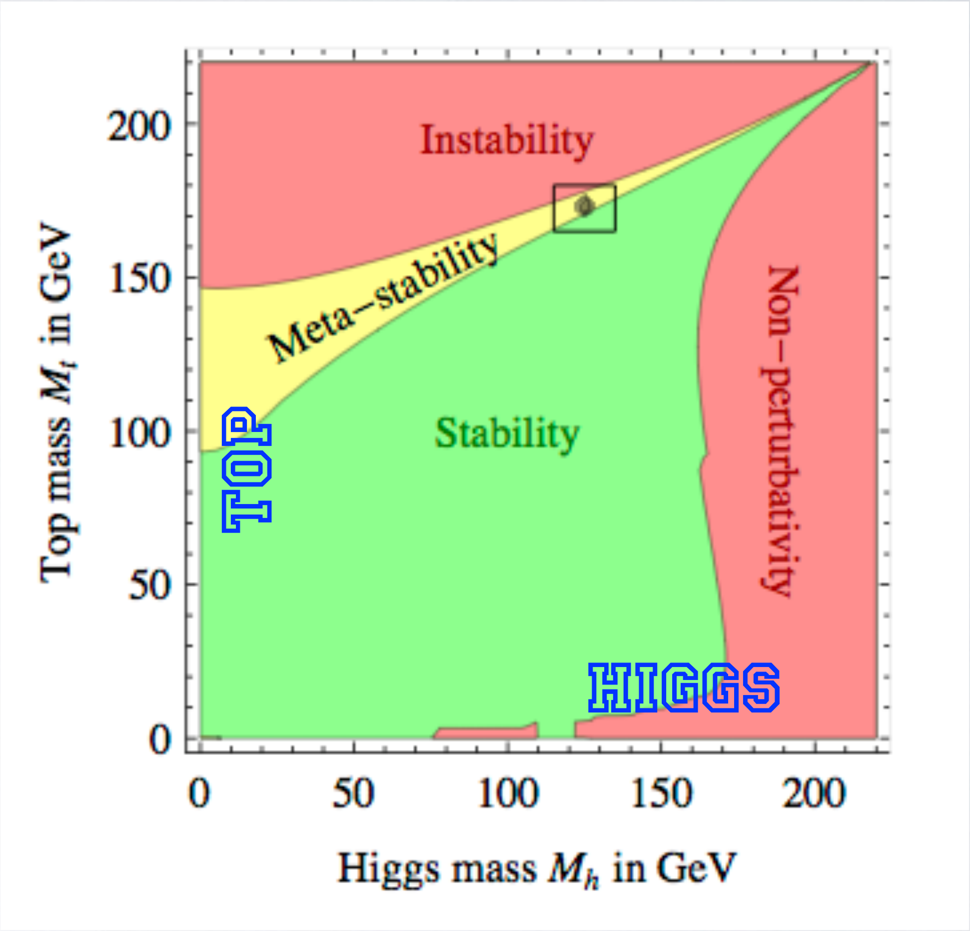




The Pillars of Lepton Physics



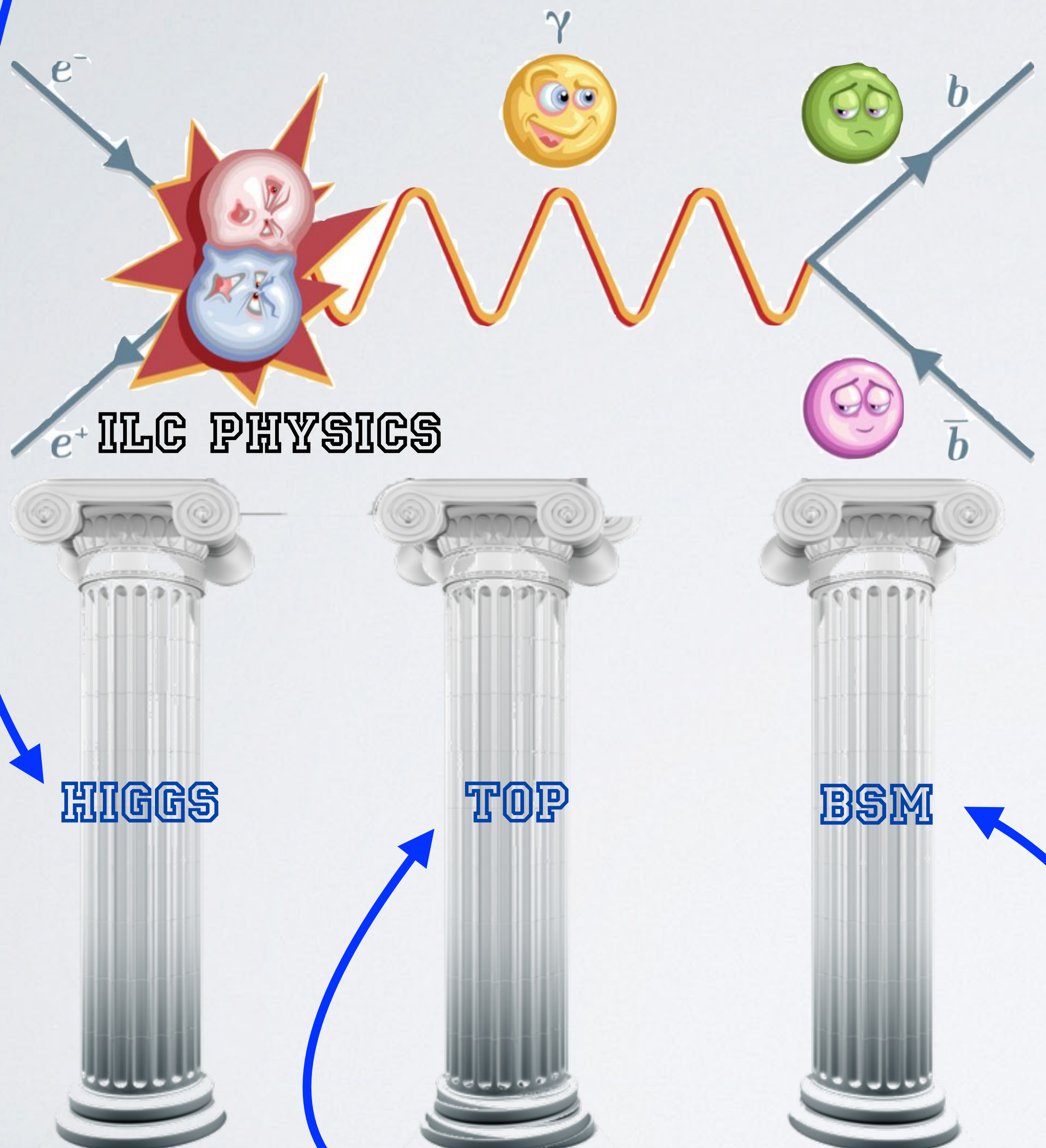
Electroweak vacuum & excitations:



(note: plot under assumptions of NO additional BSM)

The Pillars of Lepton Physics

Talk by Tomohiso Ogawa, 7.7.
Talk by Daniel Jeans, 7.7.



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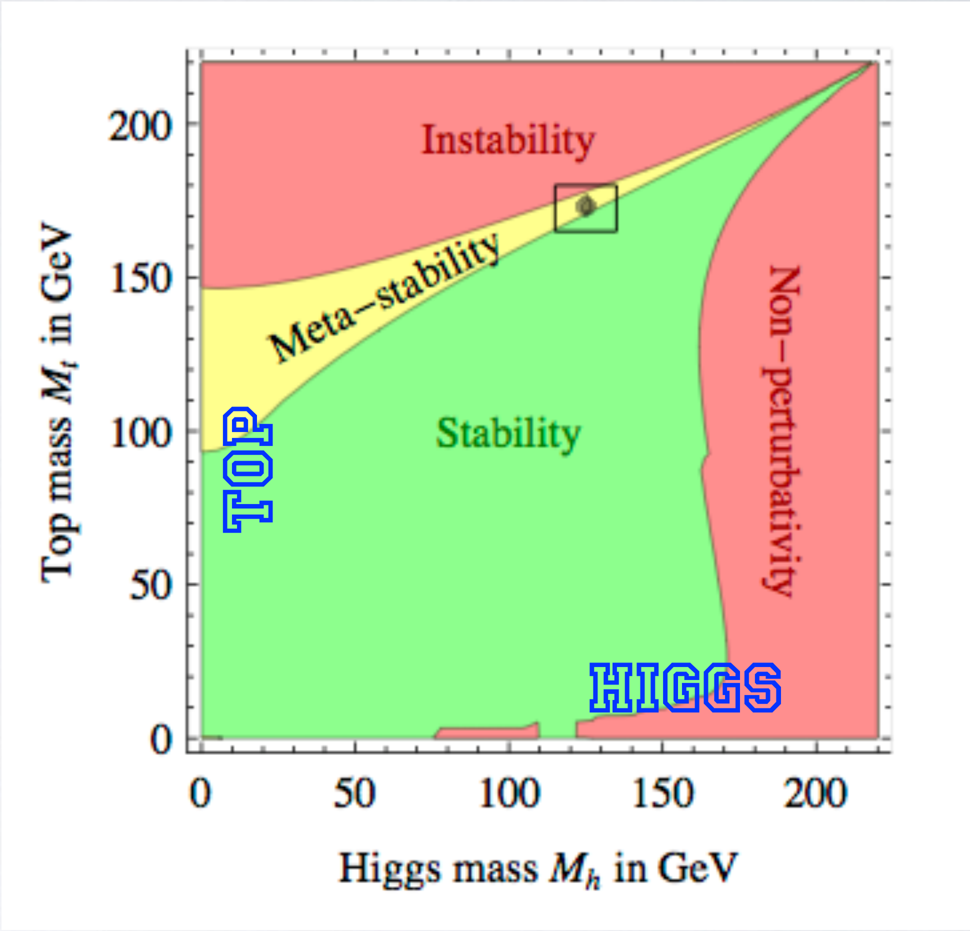

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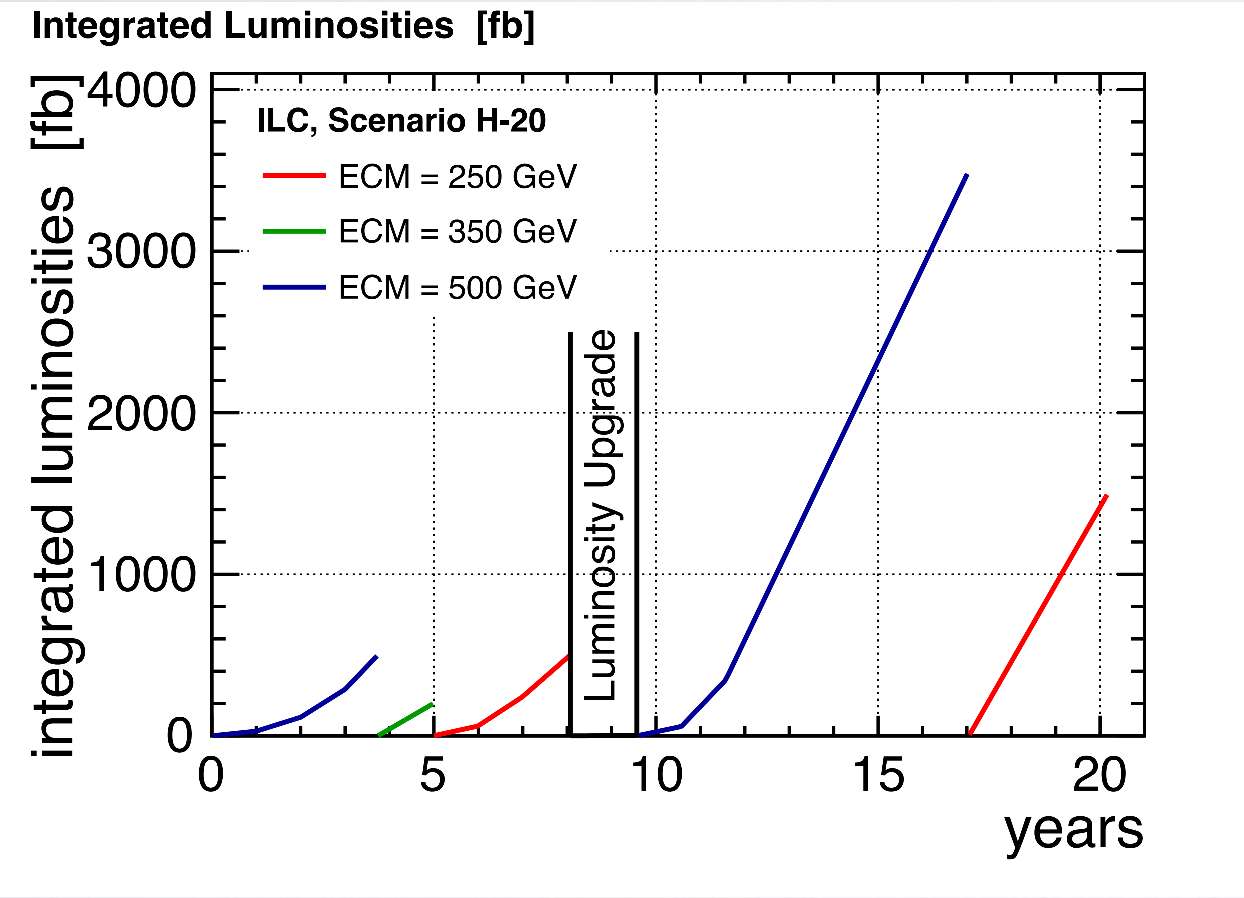
Talk by JRR, 6.7.

Talk by Mikael Berggren, 7.7.
Talk by Yan Wang, 7.7.

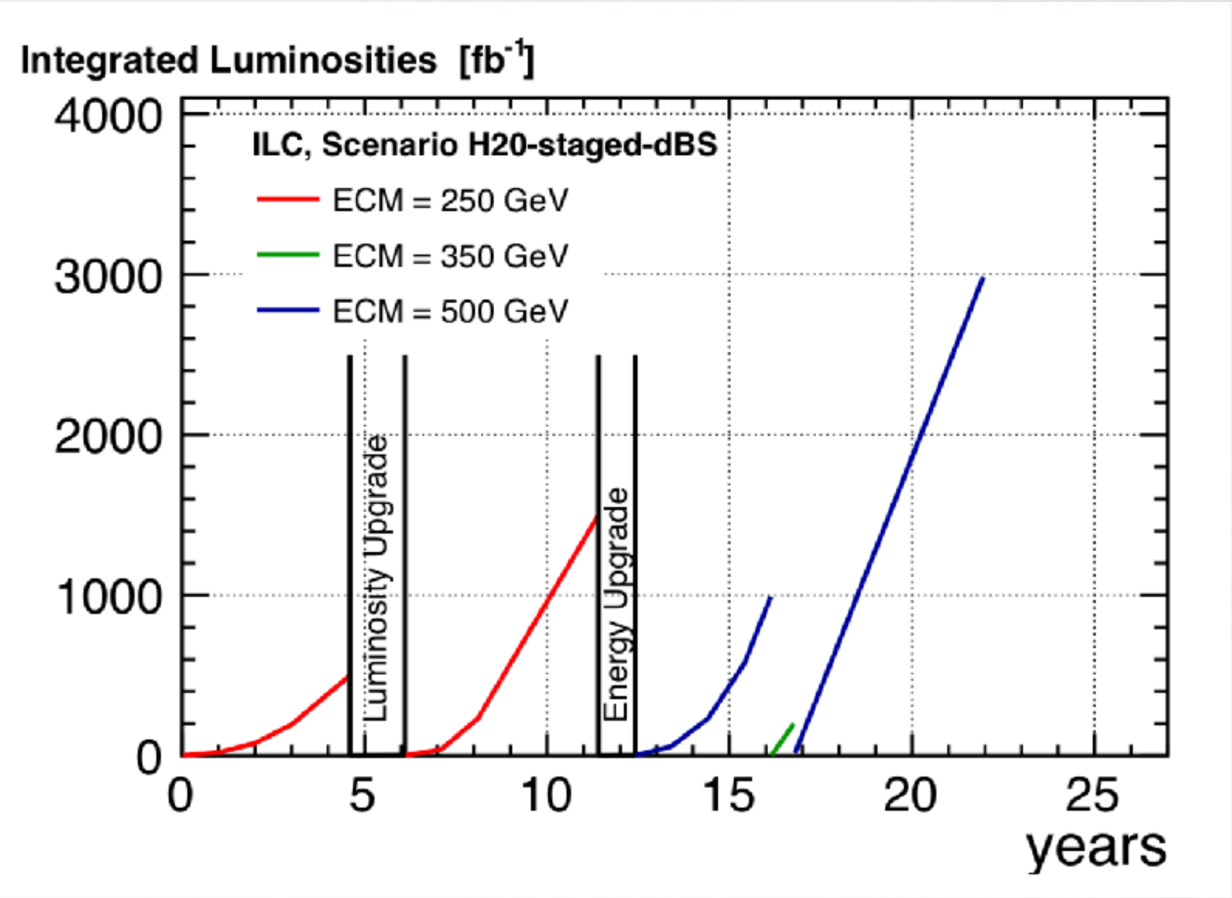
ILC Running scenarios

- Updated physics case by LCC Physics WG: 1506.05992 & 1702.05333 & 1710.07621
- 'Official' running scenarios proposed by LCC Parameter Group: 1506.07830

Original H20 Running scenario



Staged H20 Running scenario



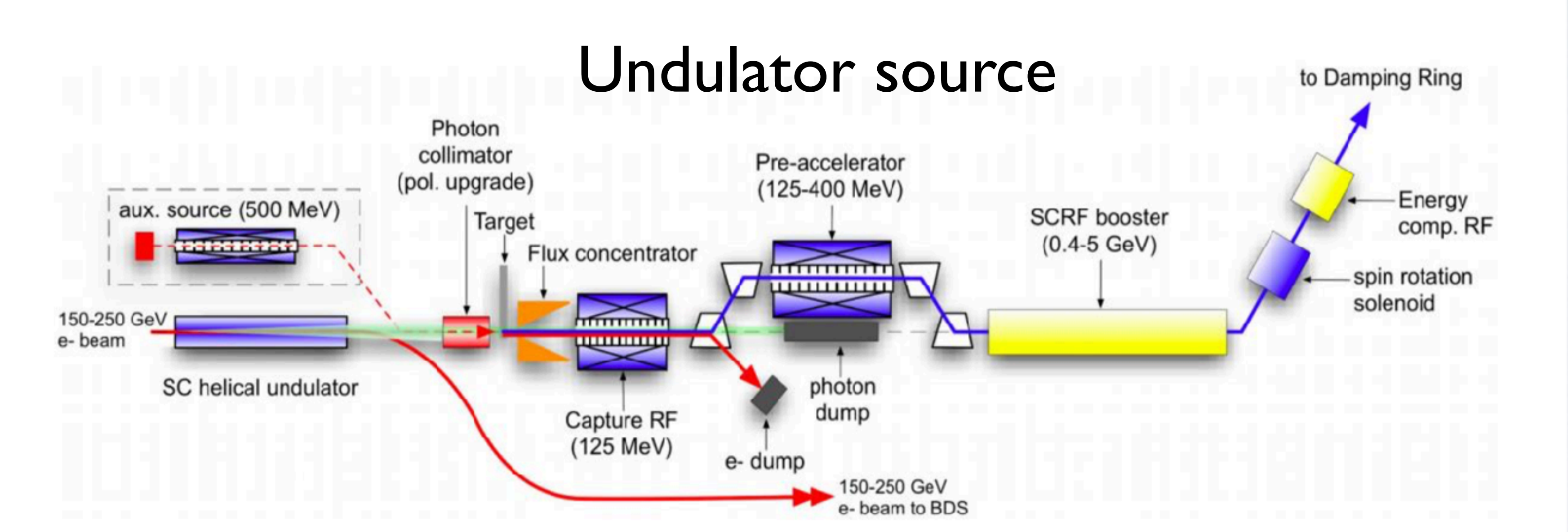
80% electron polarization ✓

What is the impact of positron pol.?

Positron Undulator vs. Conventional Source

Staging Report: 1711.00568

- **TDR Baseline Design:** polarized positron source with SC helical undulator
- Undulator length: 231 m [125 GeV e^- beam]
- Needs full energy electron beam



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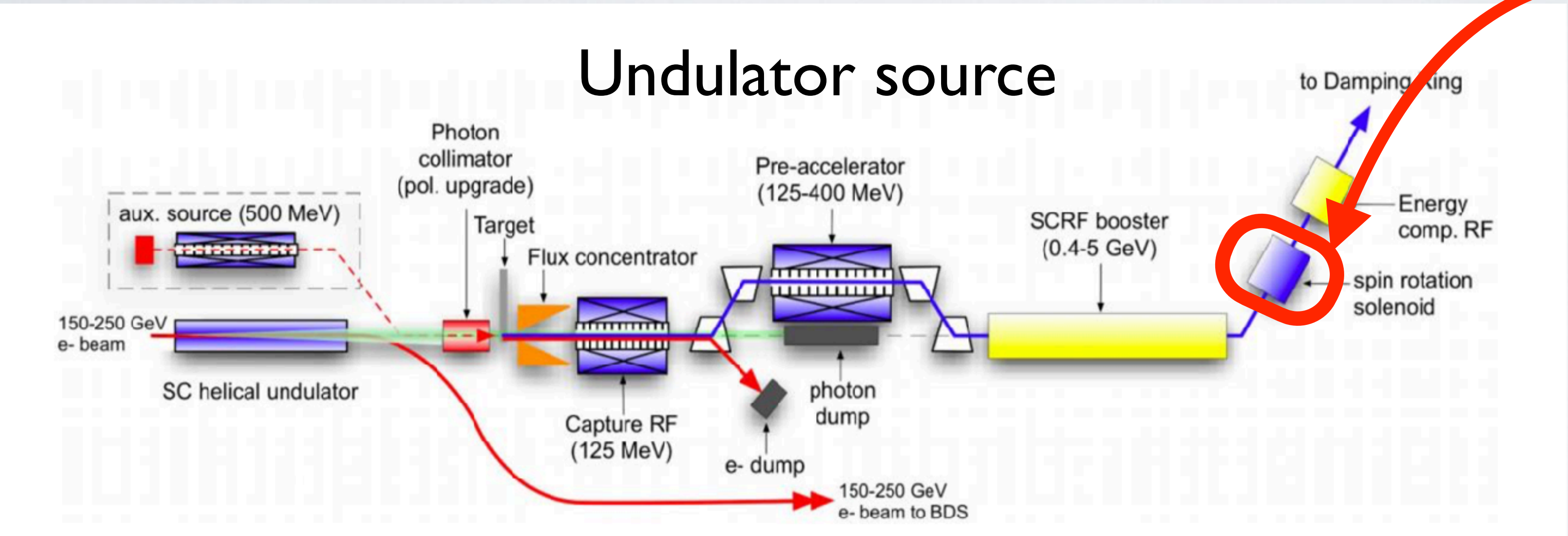

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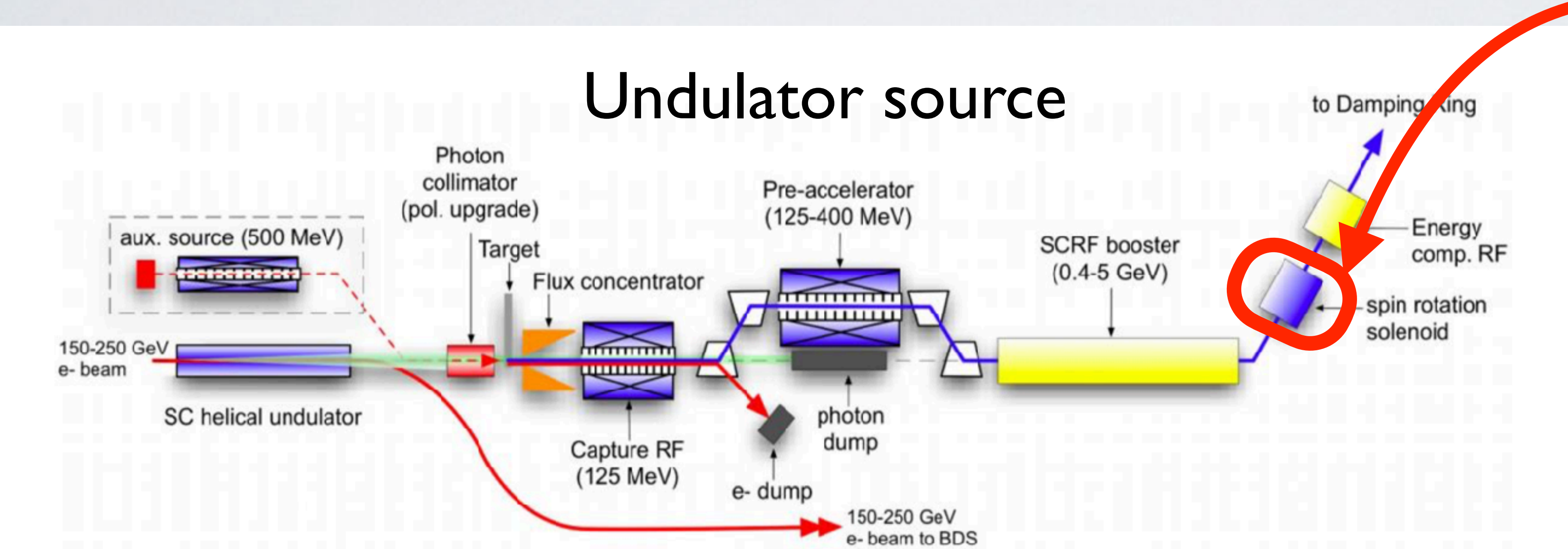

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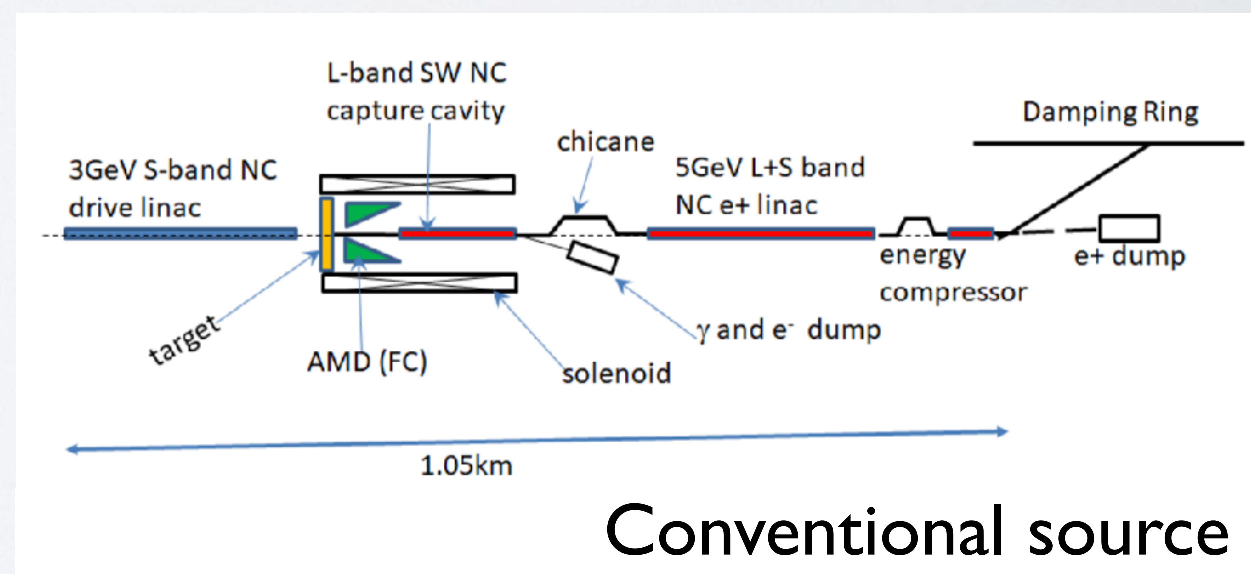
- **Alternative design:** no e^+ polarization, then: no ~100 GeV e^- beam necessary
- NC linacs: More complicated bunch structure
- Possible need for 2nd positron damping ring



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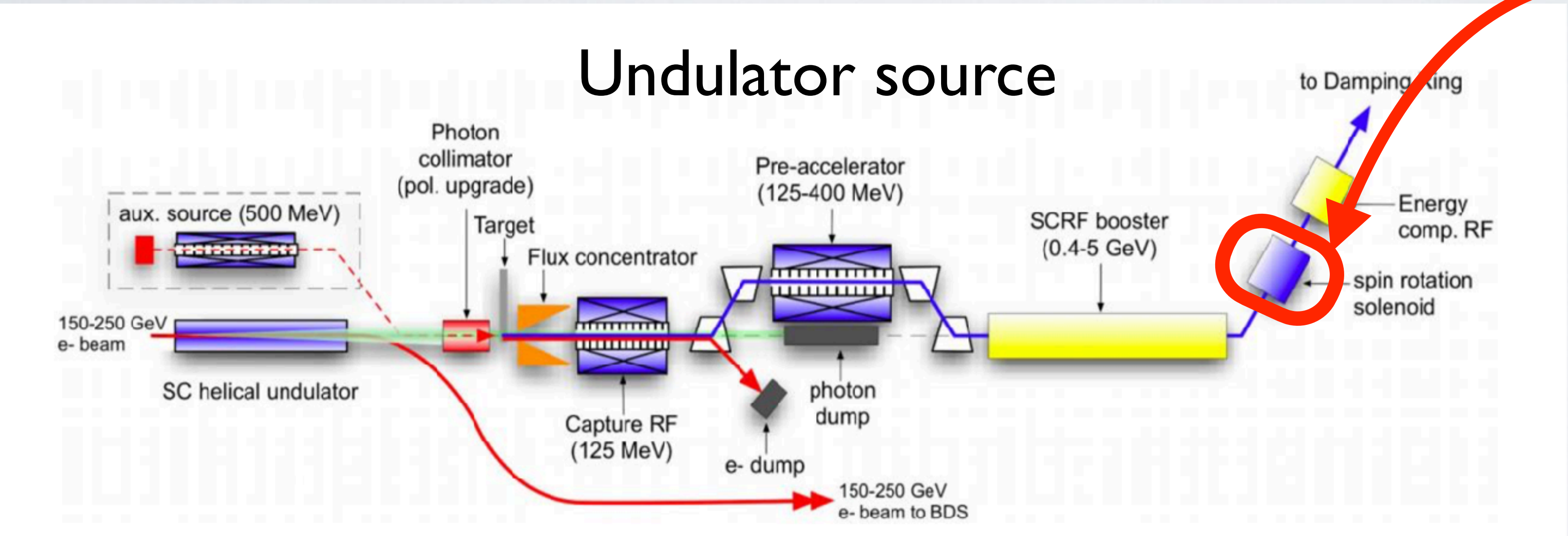
Final technology decision after approval:
Provide input for the physics case of positron polarization



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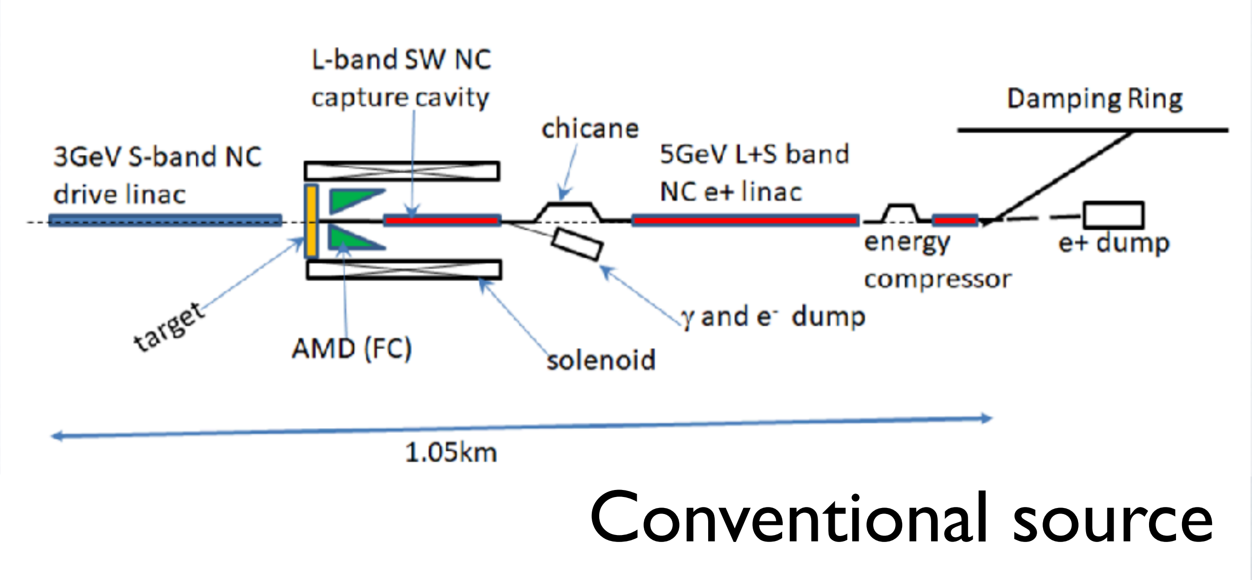

Polarization at the ILC

- Definition of longitudinal beam polarization: $\mathcal{P} = \frac{N_R - N_L}{N_R + N_L}$
- Use the e⁻ and e⁺ beam polarization fractions: $\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$

> ❑ **Polarization allows higher rates for signal samples** [saves on running time]
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> ❑ **Enhances signal-to-background ratios by simultaneously suppressing bkgds**

- Unpolarized cross section: $\sigma_0 = \frac{1}{4}\{\sigma_{\rm RR} + \sigma_{\rm LL} + \sigma_{\rm RL} + \sigma_{\rm LR}\}$
- Left-right asymmetry: $A_{\rm LR} = \frac{\sigma_{\rm LR} - \sigma_{\rm RL}}{\sigma_{\rm LR} + \sigma_{\rm RL}}$

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- Effective luminosity: $\mathcal{L}_{\rm eff.} = \frac{1}{2}(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})\mathcal{L} \longrightarrow 0.62\,\mathcal{L}$ $[0.5\,\mathcal{L}]$
- Effective polarization: $\mathcal{P}_{\rm eff.} = \frac{\mathcal{P}_{e^-} - \mathcal{P}_{e^+}}{1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+}} \longrightarrow -0.89$ $[\mathcal{P}_{e^-}]$

$\mathcal{P}_{e^-} = -0.8 \quad \mathcal{P}_{e^+} = +0.3$ $\qquad$ $\mathcal{P}_{e^+} = 0$

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24% lumi loss

10% loss of analyzing power of A_{LR}

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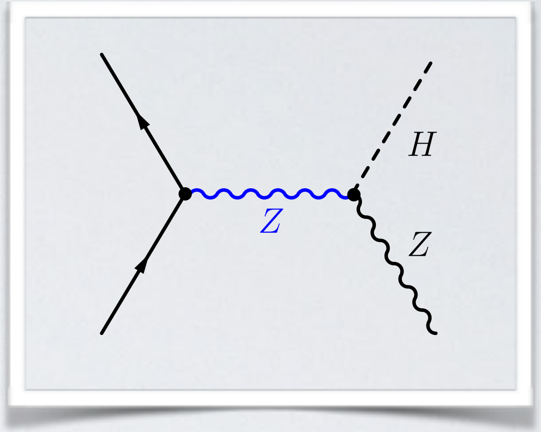
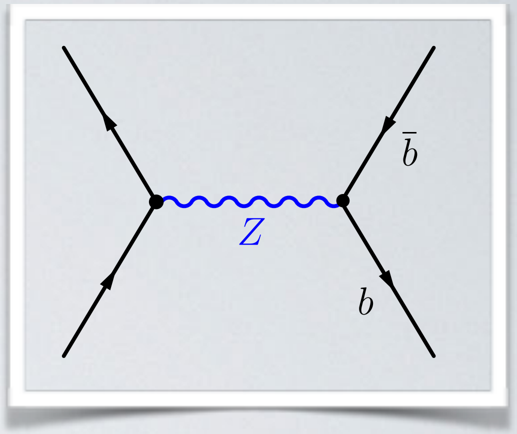
Physics Effects of Polarization

s-channel γ/Z exchange:

spin-1 exchange
only σ_{LR} and $\sigma_{RL} \neq 0$

$$\sigma(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = 2\sigma_0 \frac{\mathcal{L}_{\text{eff.}}}{\mathcal{L}} \left[1 - \mathcal{P}_{\text{eff.}} A_{\text{LR}}\right]$$





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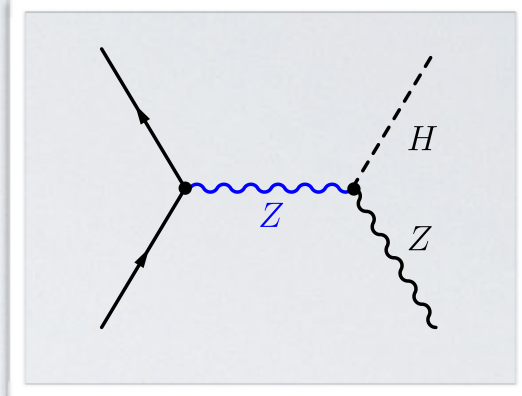

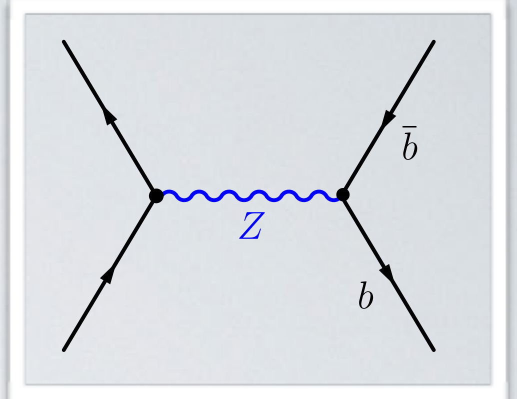

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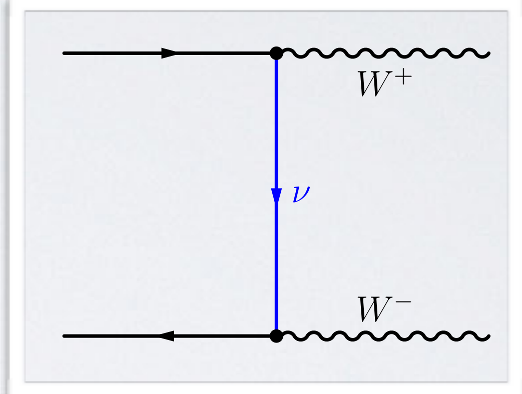
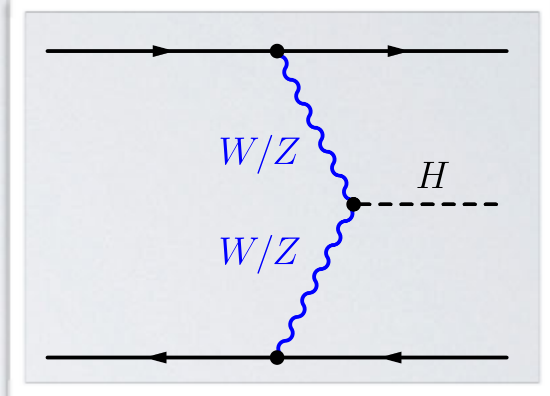
30% less bkgd.





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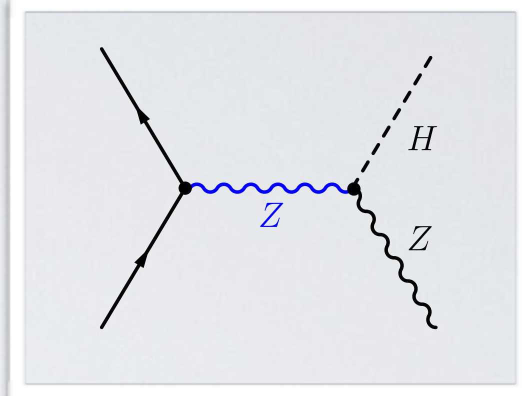

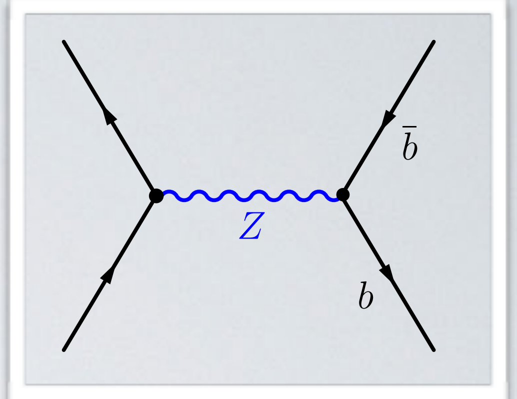

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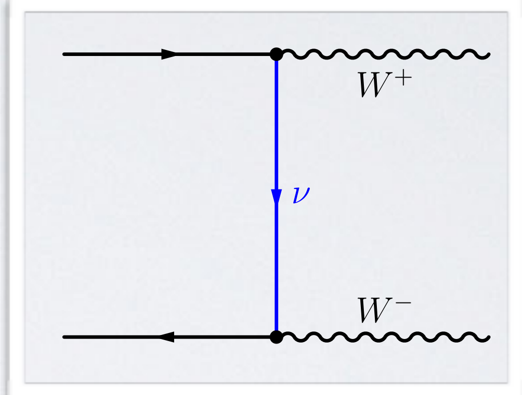
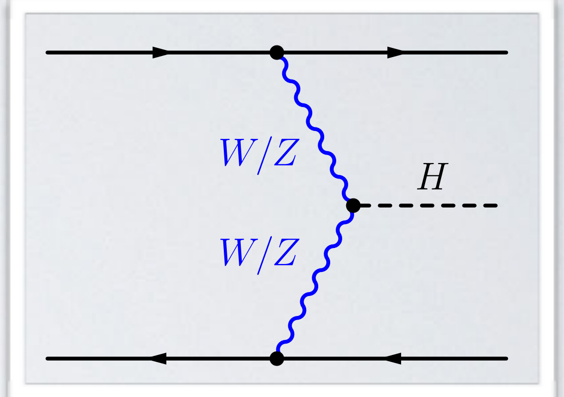
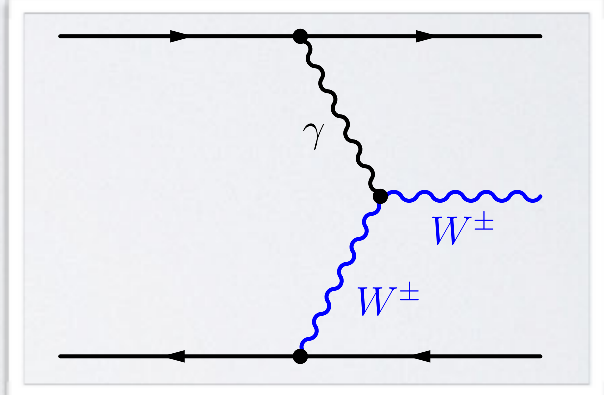




single W production:

$$A_{\text{RR/LL}} = \frac{\sigma_{\text{LR}} - \sigma_{\text{RR/LL}}}{\sigma_{\text{LR}} + \sigma_{\text{RR/LL}}}$$

$$\sigma_W^{\pm}(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = \sigma_0 (1 \pm \mathcal{P}_{e^{\pm}}) \left[1 - \mathcal{P}_{e^{\mp}} A_{\text{RR/LL}}\right]$$



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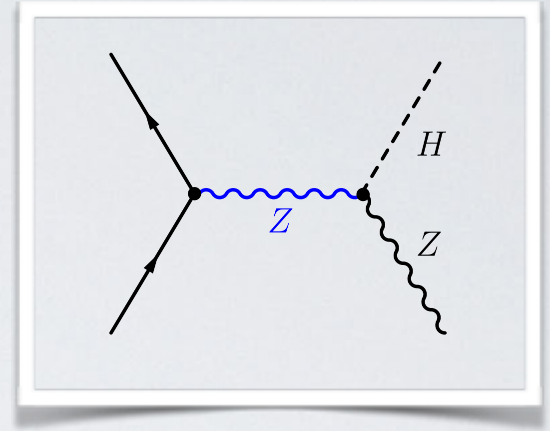

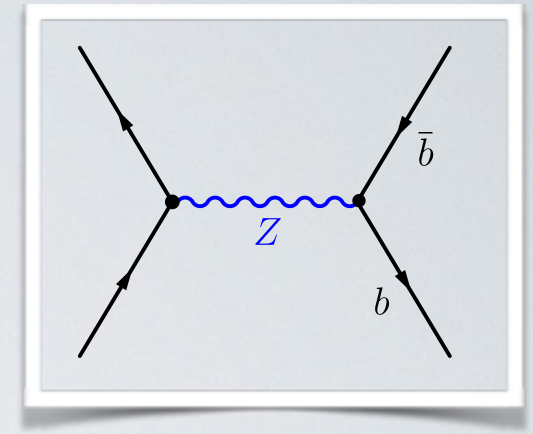

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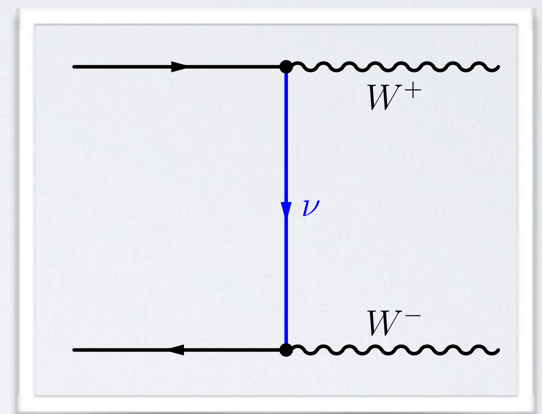

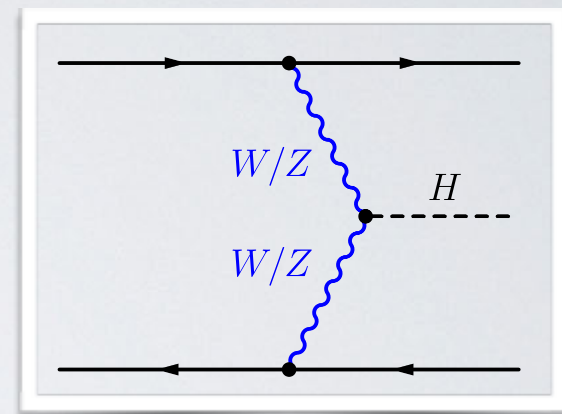

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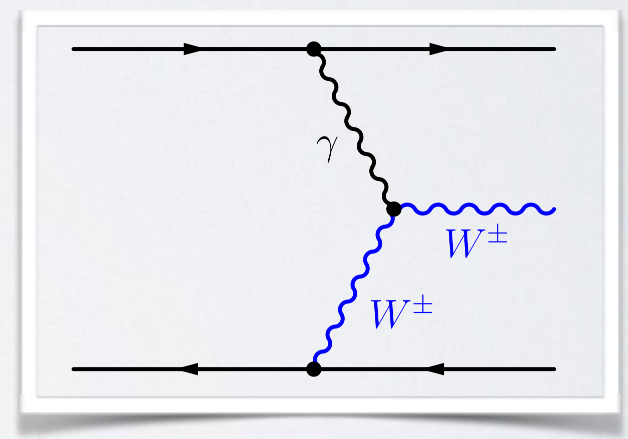

BSM searches:

all four combinations can contribute:

different cases: dark matter searches, heavy leptons, contact interactions

Physics Effects of Polarization

Consider two different scenarios 250 GeV 2 ab^{-1}

Scenario "e⁺ Pol."		Scenario "no e⁺ pol."	
45% (+,−)	45% (−,+)	50% (+, ·)	50% (−, ·)
5% (+,+)	5% (−,−)		
$\vert\mathcal{P}_{e^-}\vert = 80\%$	$\vert\mathcal{P}_{e^+}\vert = 30\%$	$\vert\mathcal{P}_{e^-}\vert = 80\%$	$\vert\mathcal{P}_{e^+}\vert = 0\%$

studied in 1710.07621

- Combination of samples w/ different polarizations gives higher sensitivity than single sample
- Allows to study like-sign polarization sets
- In total 4 different data sets (including transversal polarizations: 9 different data sets)
- Samples with different positron polarization allow reduction of systematic uncertainties

e^+ Pol. & SM Precision Measurements

Systematics of cross section and asymmetry measurements

- Total xsec., LR asymmetry, beam polarization fits: Minimization of systematic uncertainties crucial
- Electron polarization can always be determined to sub-permil level R. Karl, 2018, thesis
- No positron polarization ⇒ up to factor 5 larger Higgs systematic uncertainties
- Even using positron polarimeters: factor 2-3 larger uncertainties on single-W and WW, $ee \to ff$
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EFT global fits and determination of Wilson coefficients

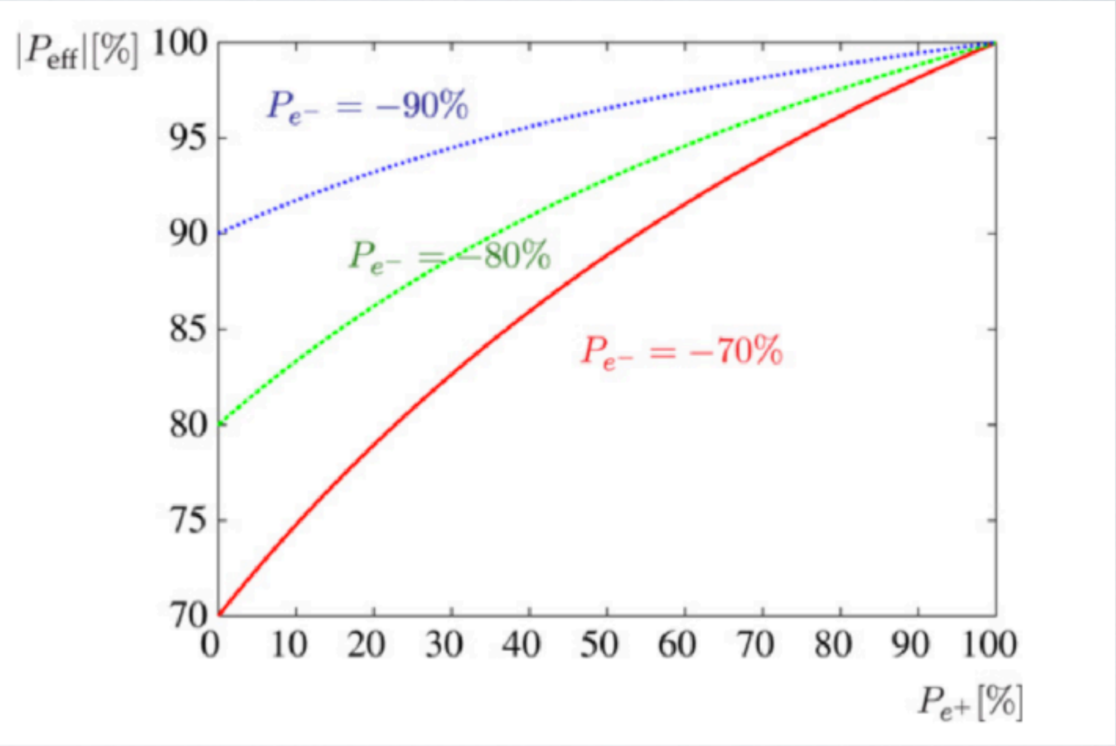
- Most simple EFT parameterizations for $e^+e^- \to W^+W^-$ can be measured w\ e^+ polarization
- Most general EFT w/ 14 complex parameters: only e^+ pol. allows to extract Wilson coefficients
- EFT coefficient extraction of trilinear couplings in $e^+e^- \to Z\gamma$ needs e^+ polarization
- Measurements of Wilson coefficients of general EFTs only possible with e^+ pol

Example: uncertainties for LR asymmetries

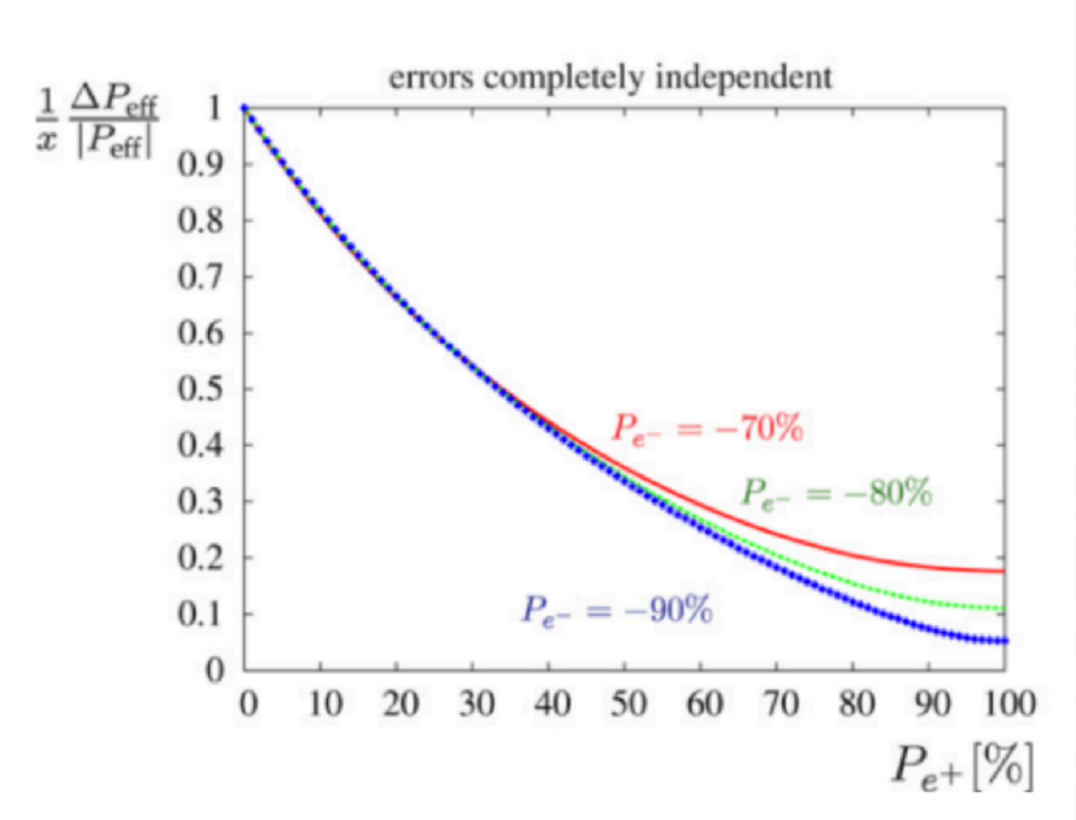
- Positron polarization increases $|P_{eff}|$
- Errors on A_{LR} decrease, because

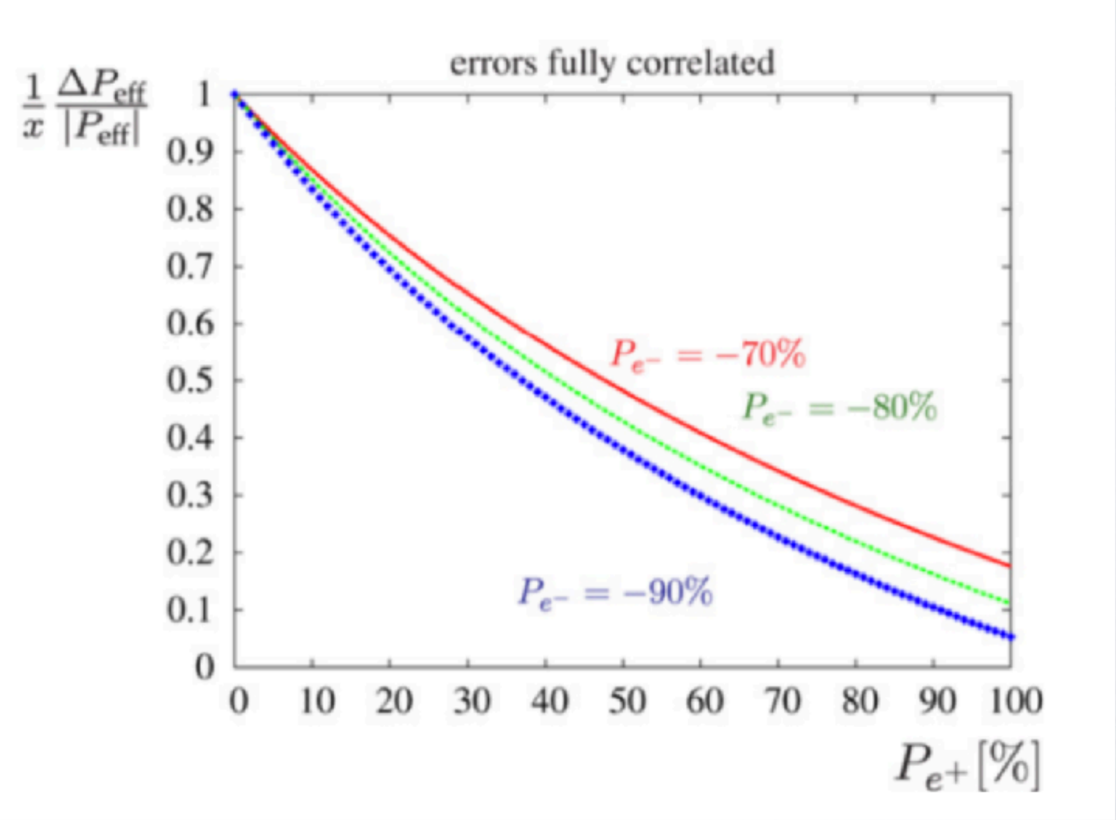
  (1) $|P_{eff}|$ is larger

  (2) $|P_{eff}|$ less sensitive to beam pol. uncertainties if positrons polarized



[G. Moortgat-Pick et al.]

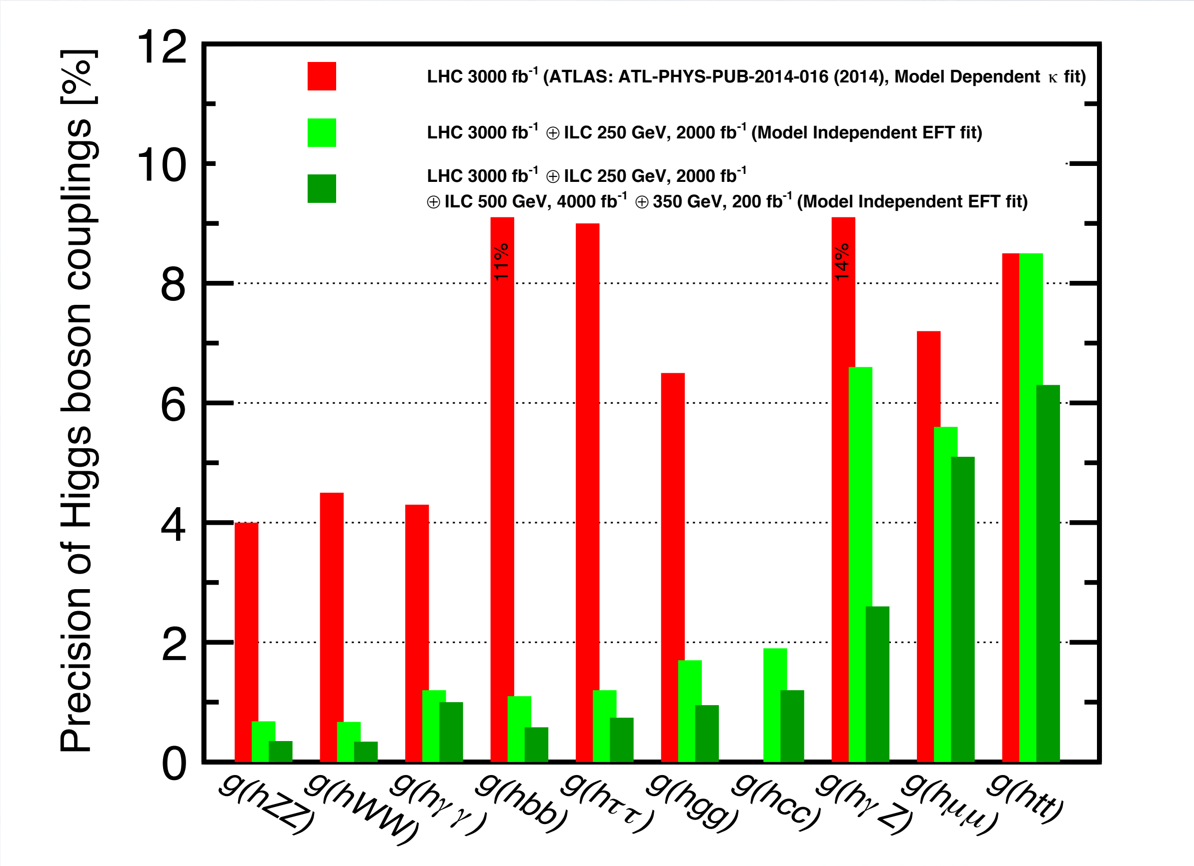




e^+ Pol & Higgs Precision Measurements

- e⁺ pol. enhances *ZH* cross section: 420,000 → 500,000 Higgs bosons
- Reduces running costs by ≈19%
- EFT Higgs coupling fit: degradation of extraction of up to 6% [mainly statistics]
- Several systematics were considered on same footing, however:

based on: Barklow/Fujii/Jung/Karl/List/Ogawa/Peskin/Tian, 1708.08912



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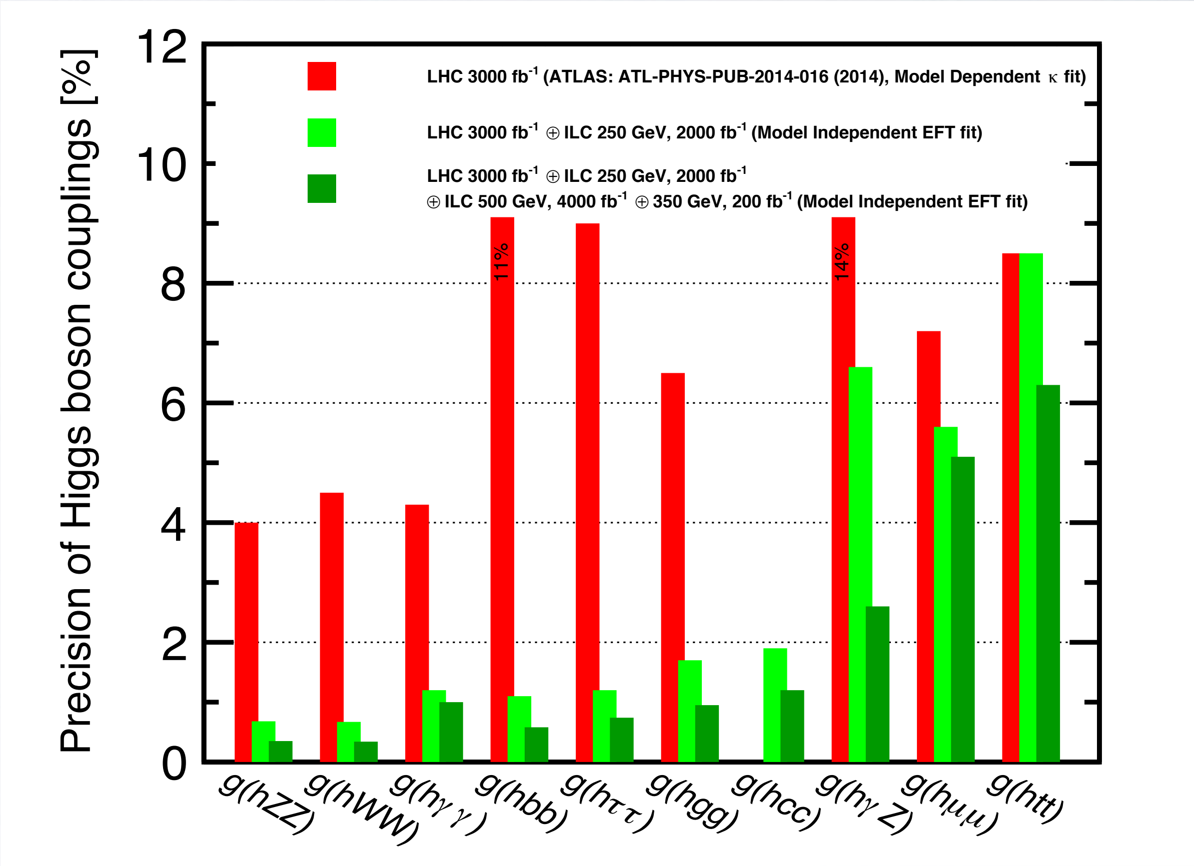
- **Luminosity uncertainty:** depends much on e^+ pol.
- **Polarization uncertainty:** bias from polarimeter
- **Background uncertainty:** different polarization samples allow *in-situ* background reduction (Bkgd. determination from signal-disfavored combo)



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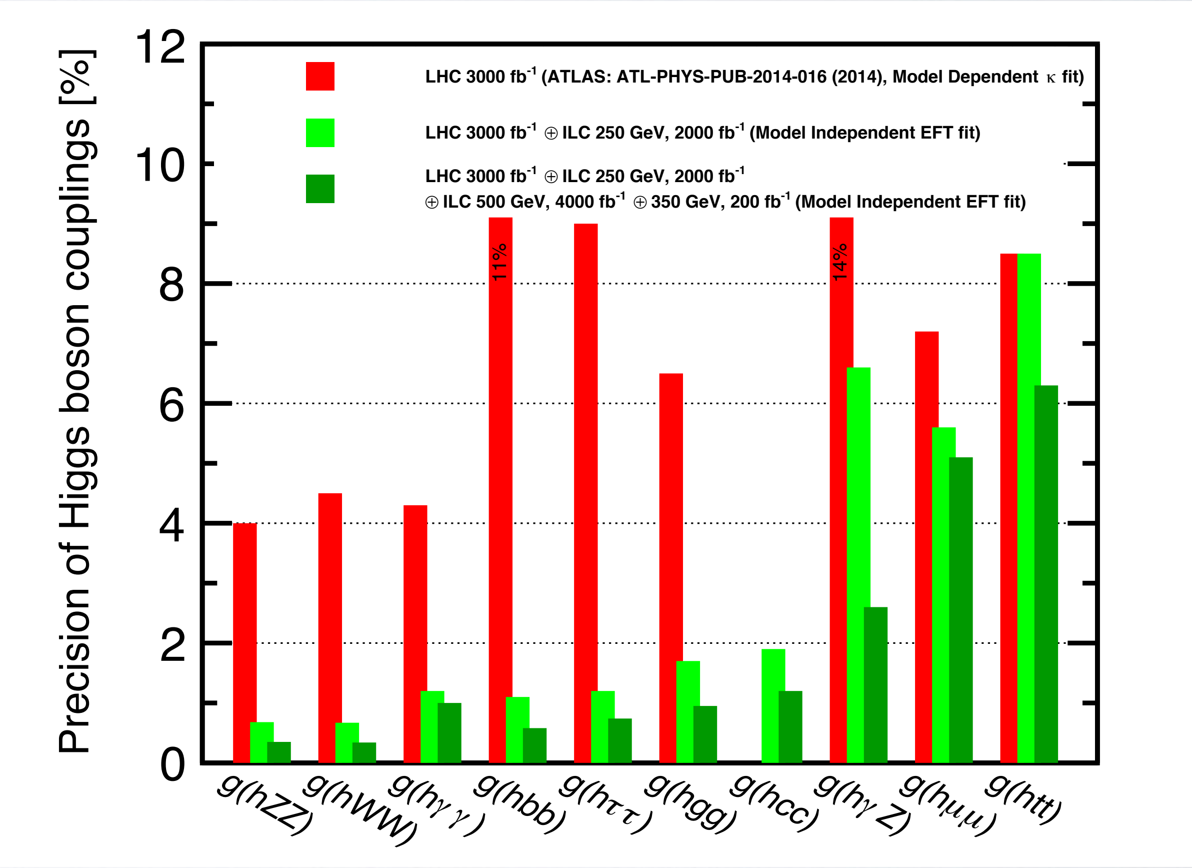
- ☑ Reduces running costs by ≈19%
- ☑ EFT Higgs coupling fit: degradation of extraction of up to 6% [mainly statistics]
- ☑ Several systematics were considered on same footing, however:

based on: Barklow/Fujii/Jung/Karl/List/Ogawa/Peskin/Tian, 1708.08912

- Luminosity uncertainty: depends much on e^+ pol.
- Polarization uncertainty: bias from polarimeter
- Background uncertainty: different polarization samples allow *in-situ* background reduction (Bkgd. determination from signal-disfavored combo)



e^+ pol. allows new tests of EFT framework by overconstraining setup

Positron Polarization in BSM searches

- General paradigm: polarized source could be built in *after* a possible discovery
- Separation ***not*** necessarily possible:
- Most likely: Large data set needed to establish 3σ–5σ evidence or discovery
- Positron polarization would very early on provide handle on significance
- Discoveries could even be missed without positron polarization:

Invisible particles

- LR/RL vs. LL/RR: allows to separate signal / background
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- profits immensely from presence of 4 different pol. samples
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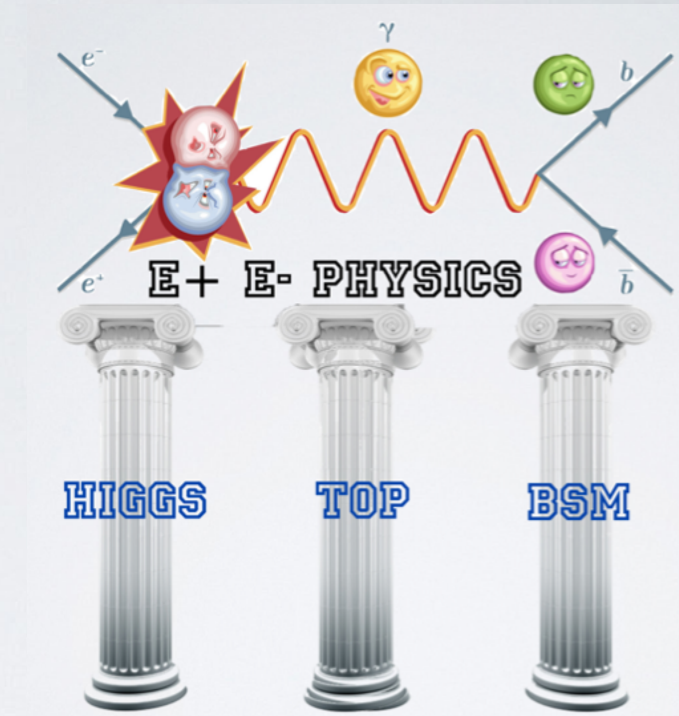
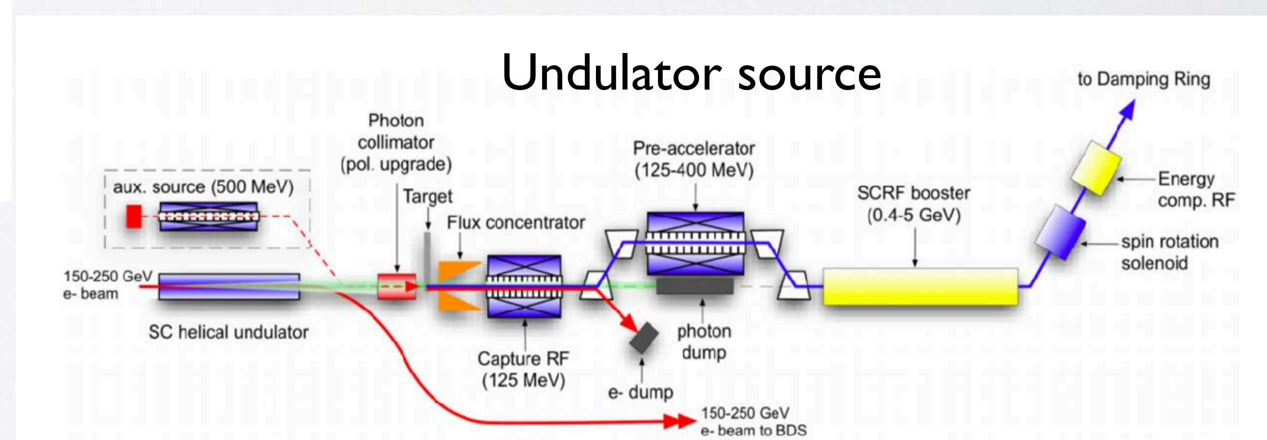
Light pNGBs
- Searches for light pseudo-Nambu-Goldstone bosons in $e^+e^- \to bb\phi$
- Posipol: determination of quantum numbers [Kilian/JRR/Rainwater, '04—'06]

Conclusions and Outlook

- ILC offers indispensable physics program e.g. 1506.05992
- Model-independent high-precision Higgs program
- Model-independent electroweak searches
- Dark Matter direct searches
- Positron polarization crucially enhances physics potential
- Improvement on signal-to-background ratios
- Safeguard against systematic uncertainties
- Much higher sensitivity (combination of different data sets)

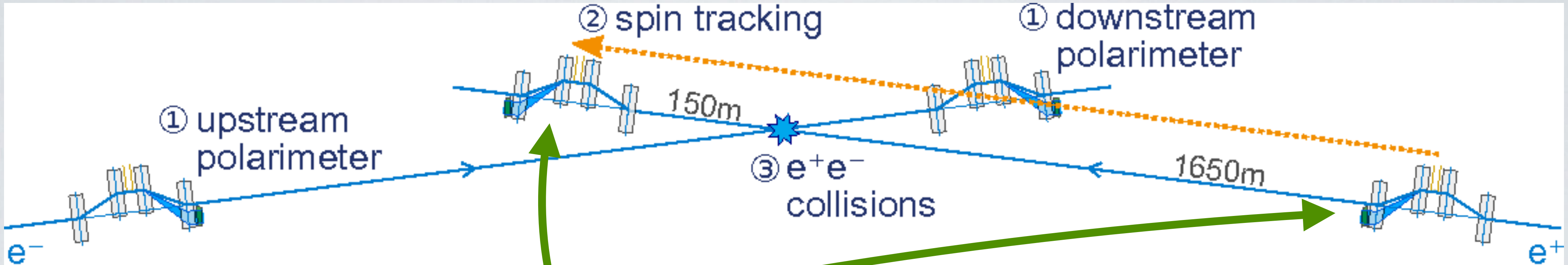




… may there be polarized anti-leptons at the end of the tunnel …

BACKUP

Measurement of Polarization: Uncertainties



- Polarimeter 1.7 km before and 150 m behind the IP
- Measurement with precision of 0.25 %
- Luminosity-weighted average polarization can differ: spin transport & depolarization effects
- Can be measured with 0.1 % precision in case of positron polarization
- Problem: in case of significant deviation $\Rightarrow$ how to proof that it is a polarization effect?
- Historical example: 3σ discrepancy for weak mixing angle via SLD $A_{LR}(e)$ and LEP $A_{FB}(b)$
- *A posteriori* measurement of positron polarization to proof positron polarization
- Positron polarization should be treated as nuisance parameter even for zero e^+ polarization
- Positron polarimeters essential part of physics program

Non-standard running stages

Recommendations for other energies outside official running scenario:

- 90 GeV: 100 fb^{-1} ("GigaZ")
- 160 GeV: 500 fb^{-1} (M_W to ~2 MeV by WW threshold scan)
- 1 TeV: 8 ab^{-1} (tth, vvH, BSM)

	integrated luminosity with $\mathrm{sgn}(P(e^-),P(e^+)) =$			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]
1 TeV	3200	3200	800	800
90 GeV	40	40	10	10
160 GeV	340	110	25	25

	Staged ILC		TDR			TDR
ECM [GeV]	**250**	**250**	**500**	**250**	**500**	**1000**
rep. rate [Hz]	5	10	**5**	10	5	**5**
N_{bunch}	1315	1315	**1315**	2625	2625	**2625**
inst. lumi [10^{34} / cm^2 / s]	0.75	1.5	**1.8**	3	3.6	**3.6-4.9**
total power [MW]	**100**	**160**	**160**	**190**	**200**	**300**

- Different physics prefers different helicity fractions (“beam helicities”)

Original H20 scenario

	fraction with $\mathrm{sgn}(P(e^-),P(e^+)) =$			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[%]	[%]	[%]	[%]
250 GeV	67.5	22.5	5	5
350 GeV	67.5	22.5	5	5
500 GeV	40	40	10	10

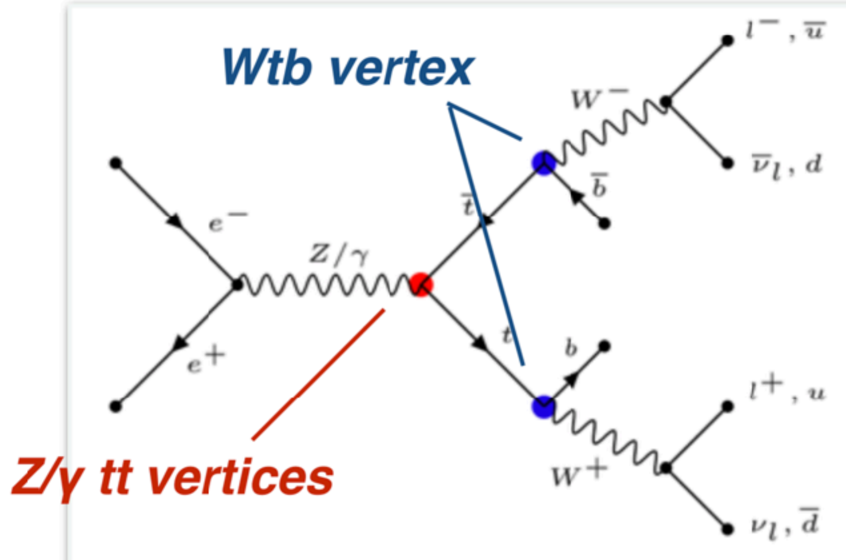
General cross section with e^+ / e^- polarization

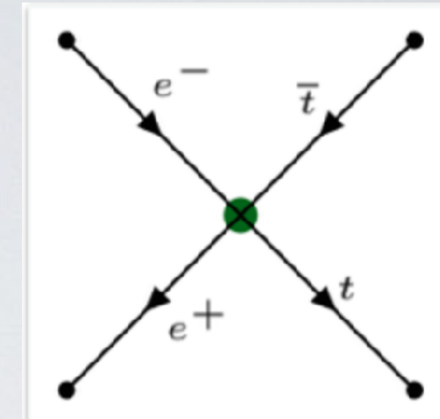
$$\sigma(\mathcal{P}_{e^-},\mathcal{P}_{e^+}) = \frac{1}{4}\Big\{ (1+\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\mathrm{RR}} + (1-\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\mathrm{LL}} + (1+\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\mathrm{RL}} + (1-\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\mathrm{LR}} \Big\}$$

Positron Polarization in Top Measurements

$$
\begin{aligned}
O^{1}_{\varphi q} &\equiv \tfrac{y_t^2}{2} \quad \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \\
O^{3}_{\varphi q} &\equiv \tfrac{y_t^2}{2} \quad \bar{q}\tau^I\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi \\
O_{\varphi u} &\equiv \tfrac{y_t^2}{2} \quad \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \\
O_{\varphi ud} &\equiv \tfrac{y_t^2}{2} \quad \bar{u}\gamma^\mu d \quad \varphi^T \epsilon\, i D_\mu \varphi
\end{aligned}
$$

$$
\begin{aligned}
O_{uG} &\equiv y_t g_s \quad \bar{q}T^A\sigma^{\mu\nu}u \quad \epsilon\varphi^* G^A_{\mu\nu} \\
O_{uW} &\equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}u \quad \epsilon\varphi^* W^I_{\mu\nu} \\
O_{dW} &\equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}d \quad \epsilon\varphi^* W^I_{\mu\nu} \\
O_{uB} &\equiv y_t g_Y \quad \bar{q}\sigma^{\mu\nu}u \quad \epsilon\varphi^* B_{\mu\nu}
\end{aligned}
$$





- Strong handle on BSM (e.g. compositeness)
- Excellent top reconstruction in e+e-
- Study of CP properties possible (!)

Contact interactions

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O_{eq} &\equiv \bar{q}\gamma_\mu q \quad \bar{e}\gamma^\mu e \\
O_{eu} &\equiv \bar{u}\gamma_\mu u \quad \bar{e}\gamma^\mu e
\end{aligned}
$$

$$O^{T}_{lequ} \equiv \bar{q}\sigma^{\mu\nu}u \;\epsilon\; \bar{l}\sigma_{\mu\nu}e$$

$$
\begin{aligned}
O^{S}_{lequ} &\equiv \bar{q}u \;\epsilon\; \bar{l}e \\
O_{ledq} &\equiv \bar{d}q \quad \bar{l}e
\end{aligned}
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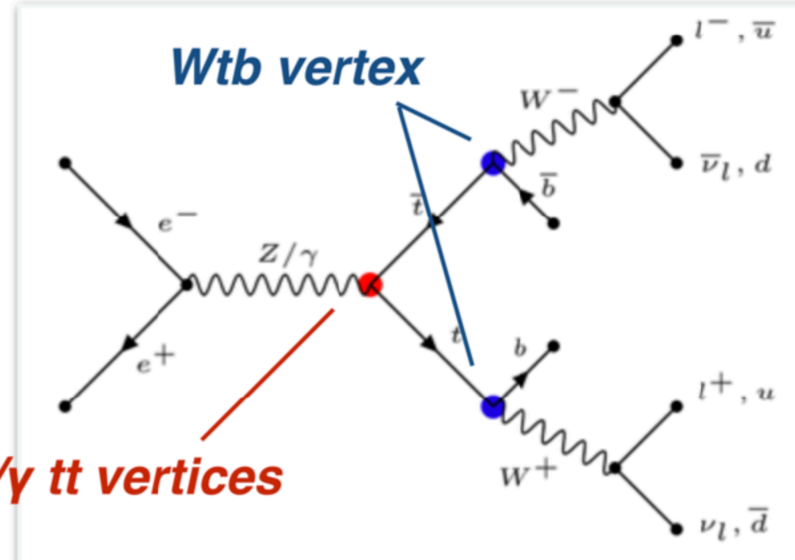

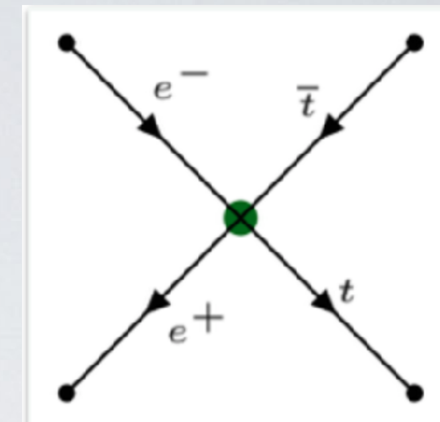

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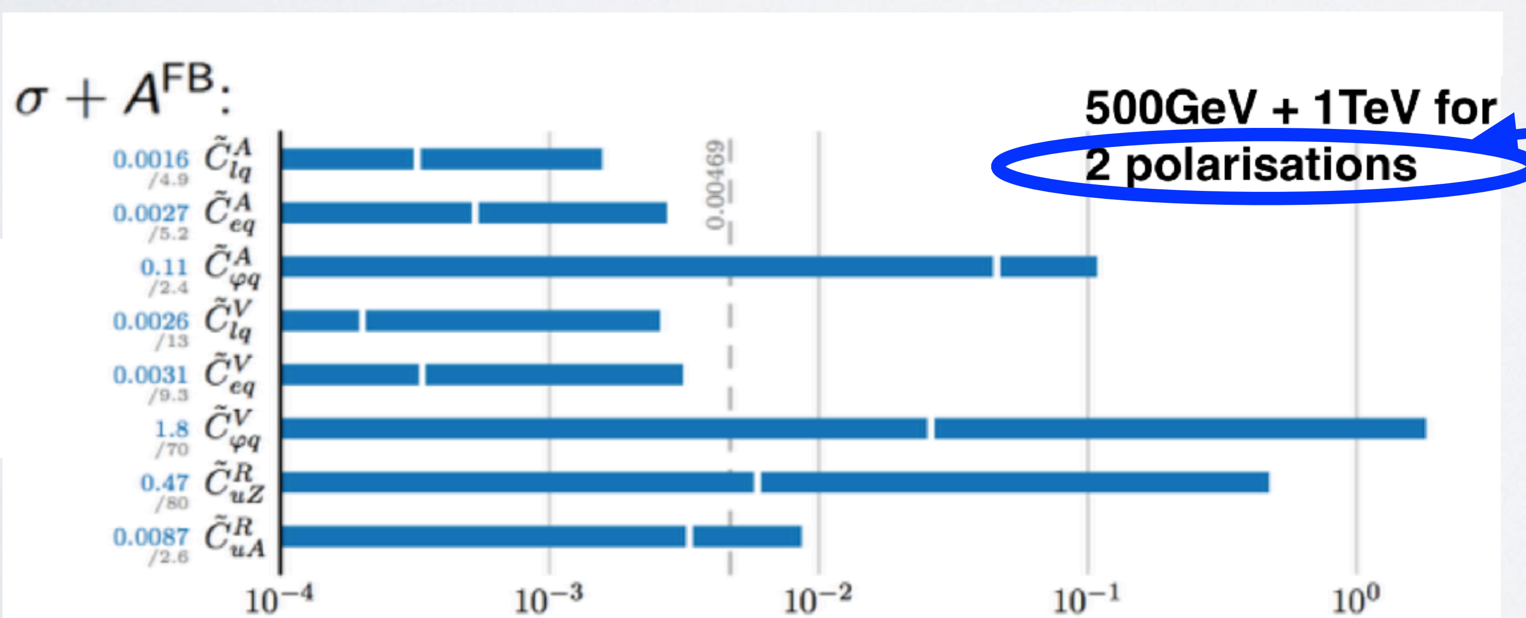


Positron polarization crucial for global fit on Wilson coefficients

Example: uncertainties for LR asymmetries

"e⁺ Pol."

$$A_{LR} = \frac{1}{|\mathcal{P}_{e^-}|}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

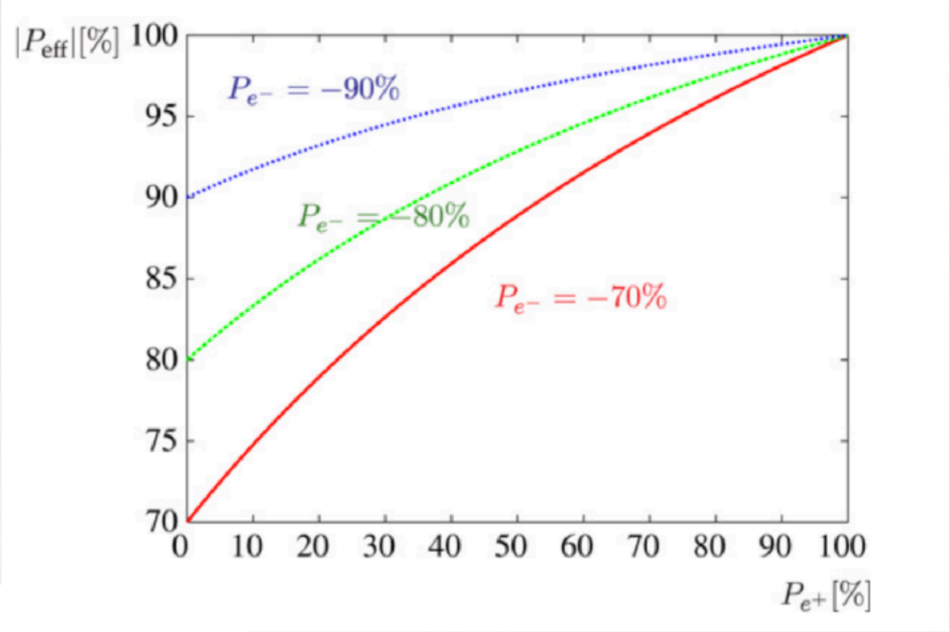
$$\Delta A_{LR} = \frac{\Delta \mathcal{P}_{e^-}}{\mathcal{P}_{e^-}} A_{LR} \oplus \frac{\sqrt{1 - A_{LR}^2 \mathcal{P}_{e^-}^2}}{P\sqrt{N}}$$

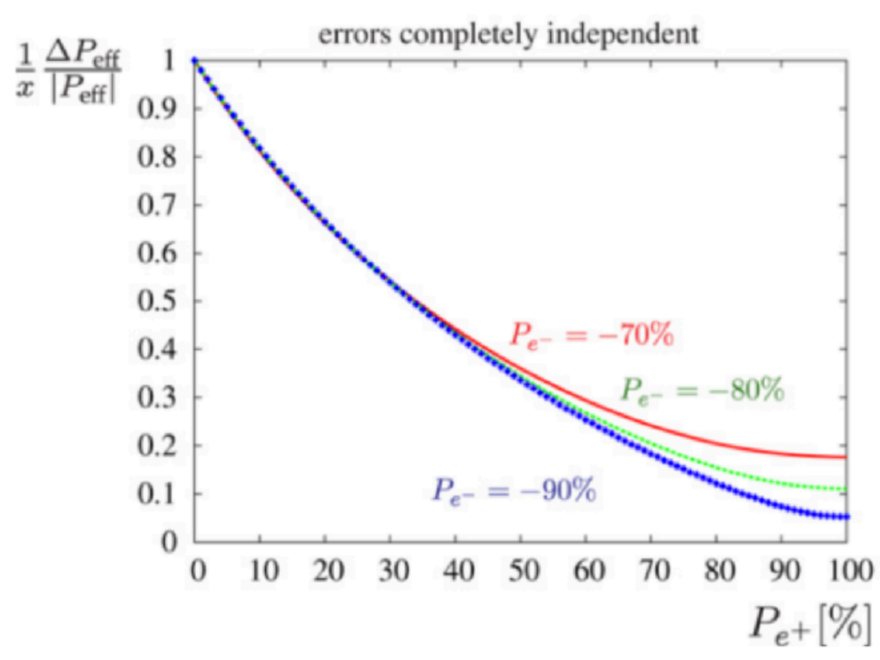
"no e⁺ Pol."

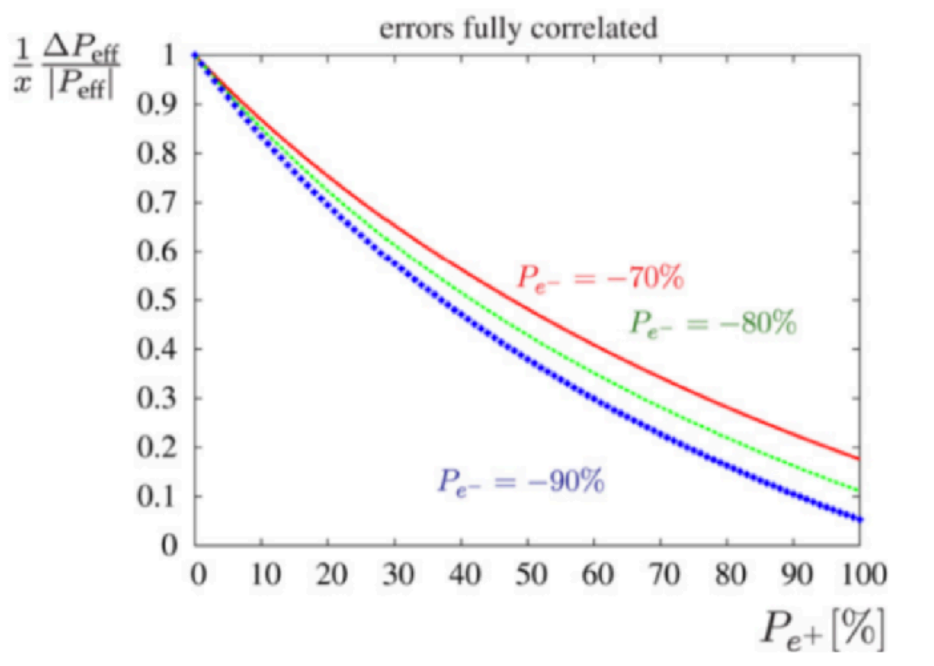
$$A_{LR} = \frac{1}{|\mathcal{P}_{\text{eff.}}|}\frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}}$$

$$\Delta A_{LR} = \frac{\Delta \mathcal{P}_{\text{eff.}}}{\mathcal{P}_{\text{eff.}}} A_{LR} \oplus \frac{\sqrt{1 - A_{LR}^2 \mathcal{P}_{\text{eff.}}^2}}{P\sqrt{N}}$$

- Posipol increases $|P_{\text{eff}}|$
- Errors on A_{LR} decrease, because
  - (1) $|P_{\text{eff}}|$ is larger
  - (2) $|P_{\text{eff}}|$ less sensitive to beam pol. uncertainties if positrons polarized







[G. Moortgat-Pick et al.]

e^+ Pol & Higgs Precision Measurements

Barklow/Fujii/Jung/Karl/
List/Ogawa/Peskin/Tian, 1708.08912

	no pol.	80%/0%	80%/30%
$g(hbb)$	1.33	1.13	1.09
$g(hcc)$	2.09	1.97	1.88
$g(hgg)$	1.90	1.77	1.68
$g(hWW)$	0.978	0.683	0.672
$g(h\tau\tau)$	1.45	1.27	1.22
$g(hZZ)$	0.971	0.693	0.682
$g(h\gamma\gamma)$	1.38	1.23	1.22
$g(h\mu\mu)$	5.67	5.64	5.59
$g(h\gamma Z)$	14.0	6.71	6.63
$g(hbb)/g(hWW)$	0.911	0.909	0.861
$g(h\tau\tau)/g(hWW)$	1.08	1.08	1.02
$g(hWW)/g(hZZ)$	0.070	0.067	0.067
Γ_h	2.93	2.60	2.49
$BR(h \to inv)$	0.365	0.327	0.315
$BR(h \to other)$	1.68	1.67	1.58