New Physics “right off the Z-pole” at Future Lepton Colliders

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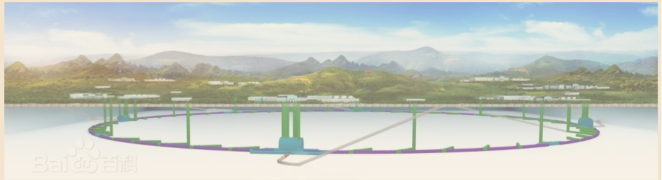
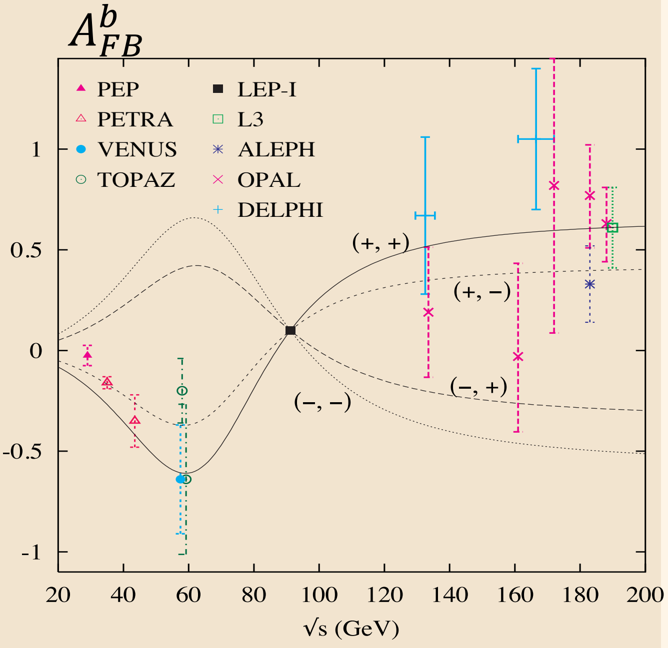




D. Choudhury et. Al (2001)

Off the Z-Pole

1

Precision Measurements

Future lepton colliders offer opportunity for precise measurements of the Z lineshape.

2

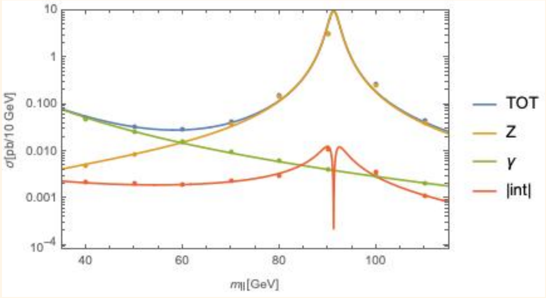
Interference Contribution

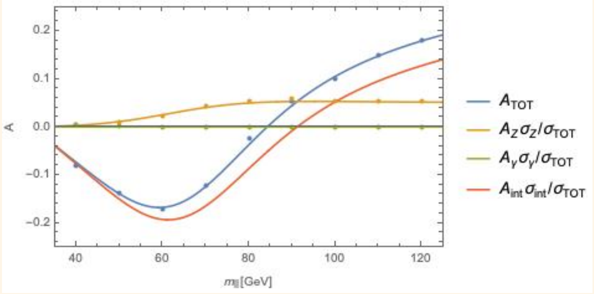
As the SM $Z-\gamma$ interference contribution, shows linearly right off the Z pole scale.

3

Probing New Physics

Line-shape scan from a “humongous” right-off-the Z pole data can be utilized for searching possible NP contribution of interference type.





ZQ, Fady Bishara (2023)

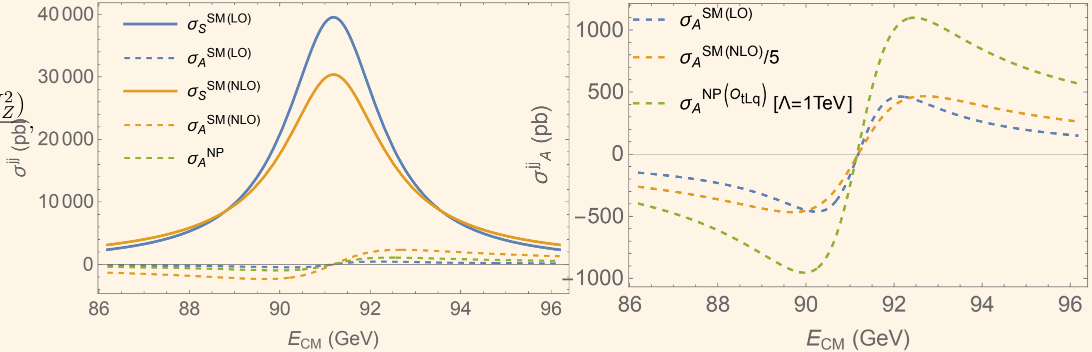
Off the Z-Pole: Observables

$$\sigma_{\mathrm{SM}}^{Z} = \sum_f \frac{N_f}{48\pi}\frac{\left(g_{eL}^2+g_{eR}^2\right)\left(g_{fL}^2+g_{fR}^2\right)s}{\left(s-M_Z^2\right)^2+\Gamma_Z^2M_Z^2},$$

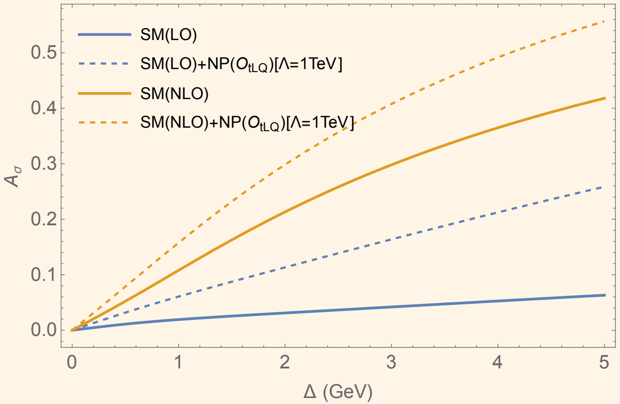
$$\sigma_{\mathrm{SM}}^{Z\gamma} = \sum_f \frac{N_f}{48\pi}\frac{2(4\pi\alpha)Q_eQ_f\left(g_{eL}+g_{fR}\right)\left(g_{fL}+g_{fR}\right)\left(s-M_Z^2\right)}{\left(s-M_Z^2\right)^2+\Gamma_Z^2M_Z^2},$$

$$\sigma_{\mathrm{SM}}^{\gamma} = \sum_f \frac{N_f}{48\pi}\frac{4(4\pi\alpha)^2Q_e^2Q_f^2}{s},$$

$$\sigma_{\mathcal{O}_i}^{\rho\lambda} = \sum_f F\,\frac{N_f}{48\pi}2c_i\left[\frac{g_{e\rho}g_{f\lambda}s\left(s-M_Z^2\right)}{\left(s-M_Z^2\right)^2+\Gamma_Z^2M_Z^2}+4\pi\alpha Q_eQ_f\right].$$

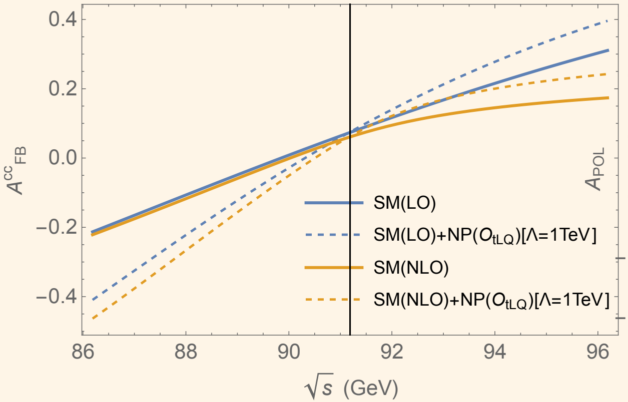


Inclusive Asymmetries



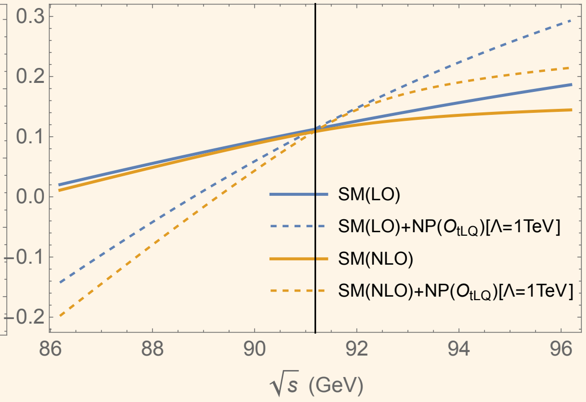
$\Delta_{[\Lambda=1TeV]} > \sim 0.15$

Forward-Backward Asymmetries



$\Delta_{[\Lambda=1TeV]} < \sim 0.1$

Polarization Asymmetries



$\Delta_{[\Lambda=1TeV]} > \sim 0.1$

The Set of 4-fermion Operators

$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i c_i \mathcal{O}_i$		$\mathcal{O}^s_{\ell\ell}$	$\mathcal{O}^t_{\ell\ell}$	$\mathcal{O}^s_{\ell q}$	$\mathcal{O}^t_{\ell q}$	$\mathcal{O}_{\ell e}$	$\mathcal{O}_{qe}$	$\mathcal{O}_{\ell u}$	$\mathcal{O}_{\ell d}$	$\mathcal{O}_{ee}$	$\mathcal{O}_{eu}$	$\mathcal{O}_{ed}$
95% CL	$\lvert c_i \rvert^{\max}$	9.2	1.3	4.3	5.5	5.5	4.5	7.8	8.3	10.1	9.0	6.7
	$\Lambda_i^{\min}/\text{TeV}$	11.7	30.7	17.1	15.1	15.0	16.8	12.7	12.3	11.2	11.8	13.7

Han and W. Skiba (2005)

$\mu^+\mu^-$	$q\bar{q}$
$\mathcal{O}^s_{LL} \equiv \frac{1}{2}(\bar{L}\gamma^\mu L)(\bar{L}\gamma_\mu L)$	$\mathcal{O}^s_{LQ} \equiv (\bar{L}\gamma^\mu L)(\bar{Q}\gamma_\mu Q)$
$\mathcal{O}^t_{LL} = \frac{1}{2}\left(\bar{L}\gamma^\mu \sigma^a L\right)\left(\bar{L}\gamma_\mu \sigma^a L\right)$	$\mathcal{O}^t_{LQ} = \left(\bar{L}\gamma^\mu \sigma^a L\right)\left(\bar{Q}\gamma_\mu \sigma^a Q\right)$
$\mathcal{O}_{L\ell} = \left(\bar{L}\gamma^\mu L\right)\left(\bar{\ell}\gamma_\mu \ell\right)$	$\mathcal{O}_{Q\ell} = \left(\bar{Q}\gamma^\mu Q\right)\left(\bar{\ell}\gamma_\mu \ell\right)$
$\mathcal{O}_{\ell\ell} = \frac{1}{2}\left(\bar{\ell}\gamma^\mu \ell\right)\left(\bar{\ell}\gamma_\mu \ell\right)$	$\mathcal{O}_{Lu} = \left(\bar{L}\gamma^\mu L\right)\left(\bar{q}_u\gamma_\mu q_u\right)$
	$\mathcal{O}_{Ld} = \left(\bar{L}\gamma^\mu L\right)\left(\bar{q}_d\gamma_\mu q_d\right)$
	$\mathcal{O}_{\ell u} = \left(\bar{\ell}\gamma^\mu \ell\right)\left(\bar{q}_u\gamma_\mu q_u\right)$
	$\mathcal{O}_{\ell d} = \left(\bar{\ell}\gamma^\mu \ell\right)\left(\bar{q}_d\gamma_\mu q_d\right)$

The dimension-6 four-fermion operators that interfere with the SM contributions to the $ee \to ff$ processes.

Future lepton colliders: Z-pole options

Experiment	Z-pole Int. Lumi. (pb^{-1})	# of Z's produced
LEP-I + SLC Legacy	160 +20	$\sim 10^7$
ILC-GigaZ	10^5 (100 fb^{-1})	$\sim 4\times10^9$
CEPC	10^8 (100 ab^{-1})	$\sim 4\times10^{12}$
FCC-ee	1.5×10^8 (150 ab^{-1})	$\sim 5\times10^{12}$

Taking CEPC as a blueprint: (Proposed Integrated Luminosity and Main Uncertainties)

$\sqrt{s}$ (GeV)	87.9	90.2	91.2	92.2	94.3
Luminosity (ab^{-1})	1	1	100	1	1

$\delta L/L$ (%)	0.005
$\delta\sqrt{s}$ (MeV)	0.1
$\delta Pol/Pol$ (%)	<1%

$\mathbf{10^{-6}}$ Uncertainties?

Statistical Uncertainties

Decrease significantly with these future large samples of Z pole data $1/\sqrt{N}$. ($\sim\mathbf{10^{-6}}$)

Theoretical Uncertainties

- higher-order corrections
- (input) parametric uncertainty
- modeling of hadronic final states

Experimental Uncertainties

- Luminosity/flux
- beam energy calibration
- Polarization
- background processes

Correlation Pattern	$\delta N_\pm$ (stat)	$\delta N_\pm(\text{para})$	$\delta N_\pm(\text{higher})$	$\delta N_\pm(\delta L)$	$\delta N_\pm(\delta\sqrt{s})$	$\delta N_\pm$ (Pol)
A_σ	×	✓	✓	×	×	
A_{FB}	×	✓	✓		✓	
A_{pol}	×	✓	✓	×	×	×

$$\delta A^2_{\text{uncorr}} \equiv \frac{4N_-^2(\delta N_+)^2}{(N_+-N_-)^4} + \frac{4N_+^2(\delta N_-)^2}{(N_+-N_-)^4},$$

$$\delta N_\pm \equiv \frac{\partial N_\pm}{\partial X_\pm}\delta X_\pm,$$

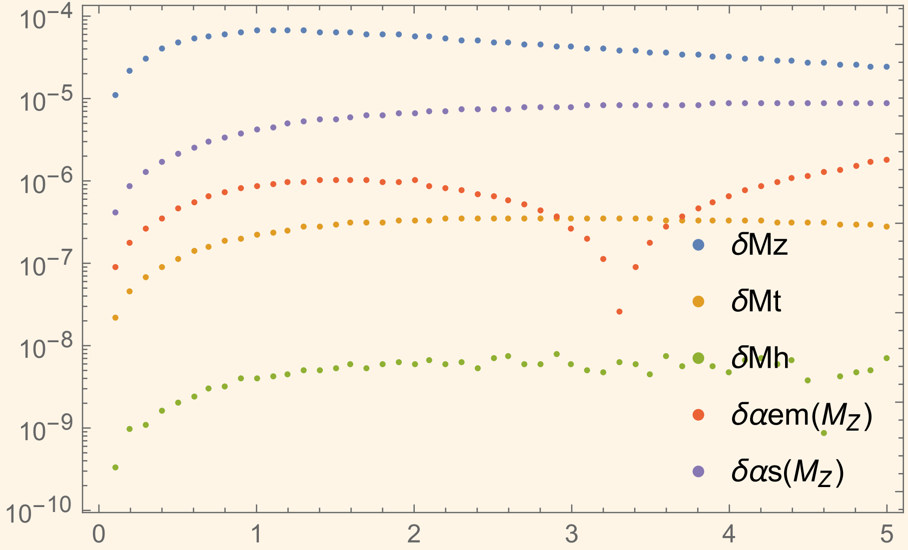
$$\delta A_{\text{corr}} = \frac{\partial A}{\partial X}\delta X = \frac{2\,\delta X}{(N_+-N_-)^2}\left(N_-\frac{\partial N_+}{\partial X} + N_+\frac{\partial N_-}{\partial X}\right)$$

Input Parameter (/Parametric) Uncertainties

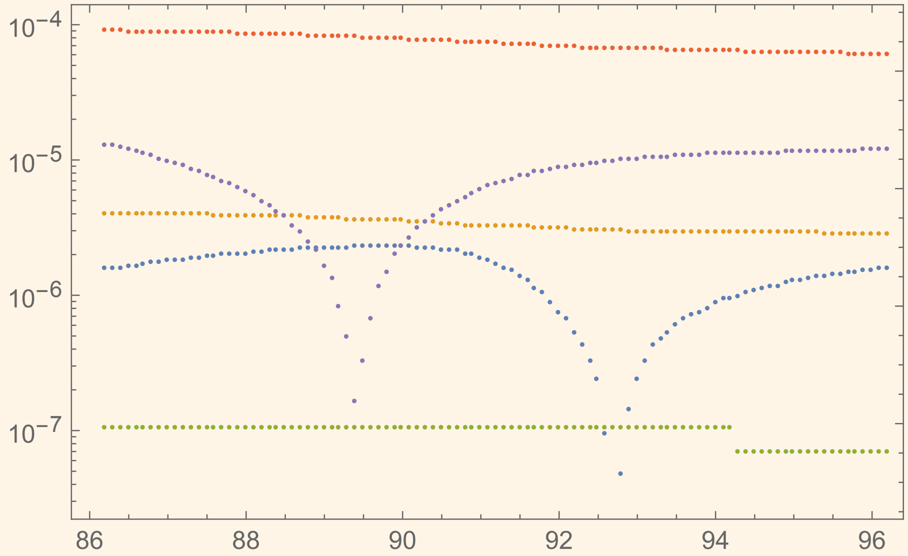
	Current	**CEPC**	**Improvement***
δM_Z	2.1 MeV	0.1 MeV	Z-pole scan
$\delta\alpha_s(M_Z)/\alpha_s(M_Z)$	$\sim 0.76\%$	$\sim 0.13\%$	Z hadronic decay
$\delta\alpha_{EM}(M_Z)\ /\alpha_{EM}(M_Z)$	$\sim 10^{-4}$	$\sim 5 * 10^{-5}$	Low c.o.m *ee* collision data; Z-pole scan
δM_t	300 MeV	25 MeV	$t\bar{t}$ threshold scan
δM_h	170 MeV	~ 5 MeV	Zh Higgs factory
Overall Effect	$\delta(M_Z) > 10^{-4}$ @ A_σ $\delta\alpha(M_Z) > 10^{-4}$ @ $A_{FB,Pol}$	$\delta(M_Z) > 10^{-5}$ @ A_σ $\delta\alpha(M_Z)\ > few\ 10^{-5}$ @ $A_{FB,Pol}$	

Input Parameter (/Parametric) Uncertainties

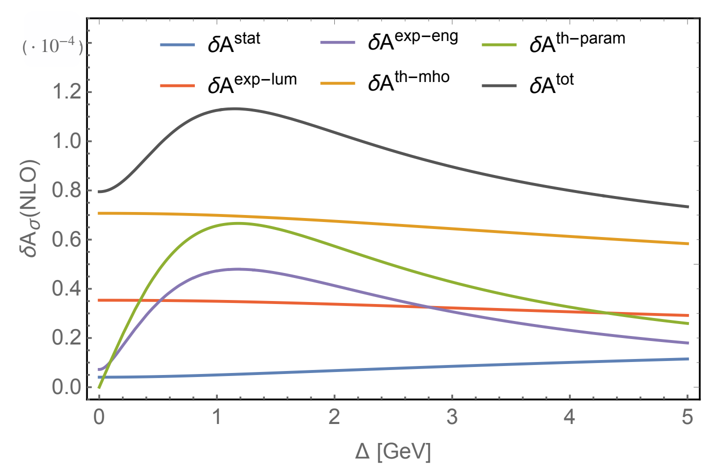
Contribution to δA_σ



Contribution to δA_{FB}



Uncertainties for Cross section Asymmetry A_σ



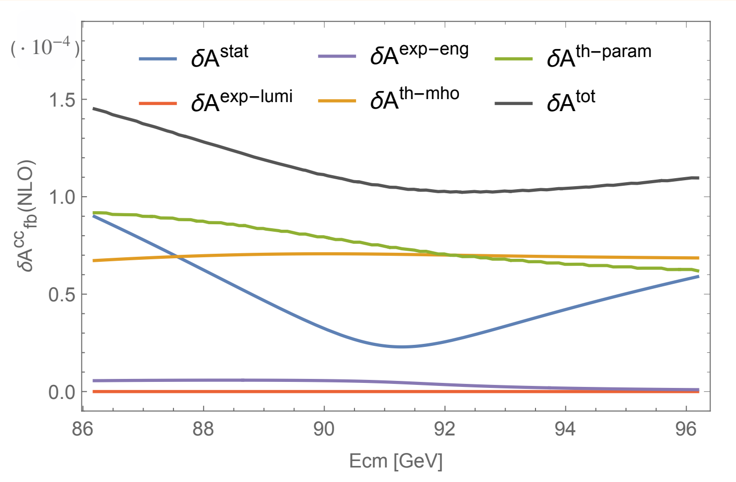
Uncertainties reaching $\mathcal{O}(10^{-4})$

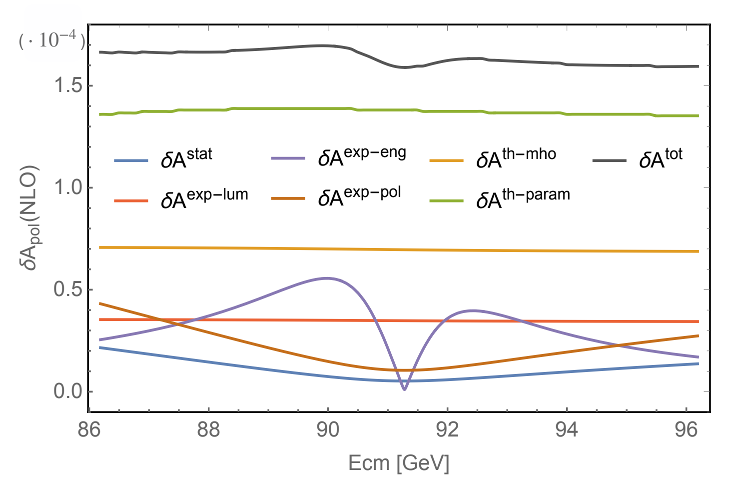
- Theory Uncertainty: Missing higher Order $\mathcal{O}(\alpha^3, \alpha^2\alpha^s)$ _[1,2]
- Theory Uncertainty: Input Parameter (δM_Z)
- Experimental Uncertainty: Luminosity and Energy

❖ Statistical Uncertainty: rises with decrease of σ (negligible)

1. Theory Uncertainty estimated with a relative 10^{-4} uncorrelated uncertainty on the ± cross sections
2. A. Freitas, “Theory Needs for Future e+e− Colliders,” Acta Phys. Polon. B 52 no. 8, (2021) 929–946.

Uncertainties for Cross section Asymmetry A_{FB}, A_{Pol}





$\sim \mathcal{O}(10^{-4})$

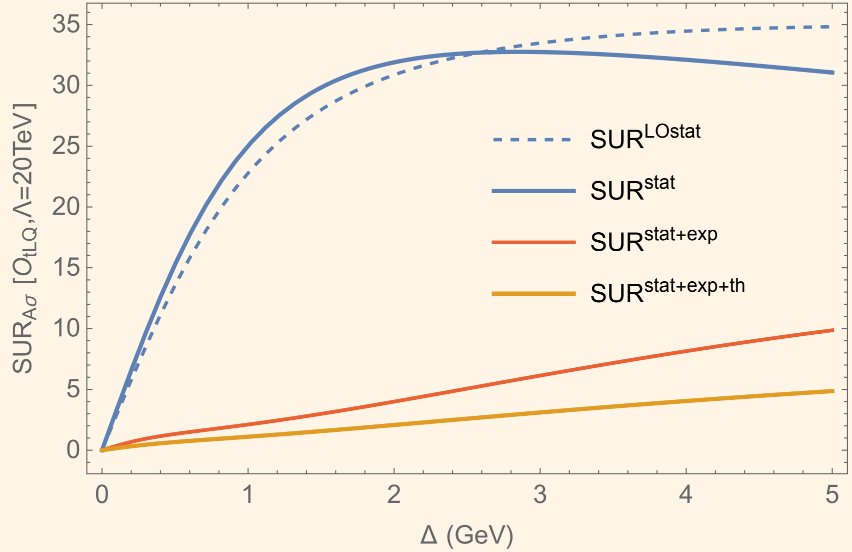
- Parametric ($\delta\alpha_{EM}$)
- Missing Higher Order
- Statistics : $\mathcal{O}(\text{few } 10^{-5})$

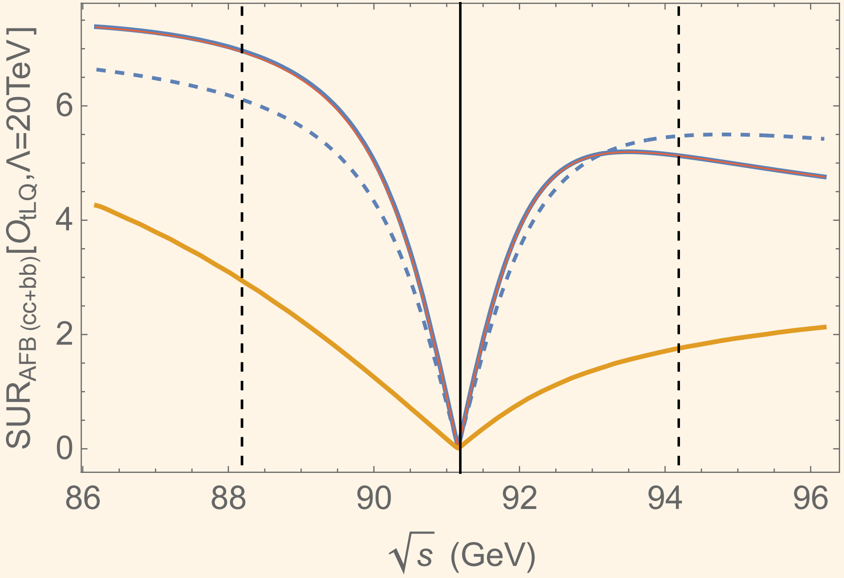
$\sim \mathcal{O}(10^{-4})$

- Parametric ($\delta\alpha_{EM}$) : $\mathcal{O}(10^{-4})$
- Higher Order ($\alpha^3, \alpha^2\alpha^s$):$\mathcal{O}(10^{-5})$
- 3 Experimentals: $\mathcal{O}(\text{few } 10^{-5})$

Signal-Uncertainty Ratio

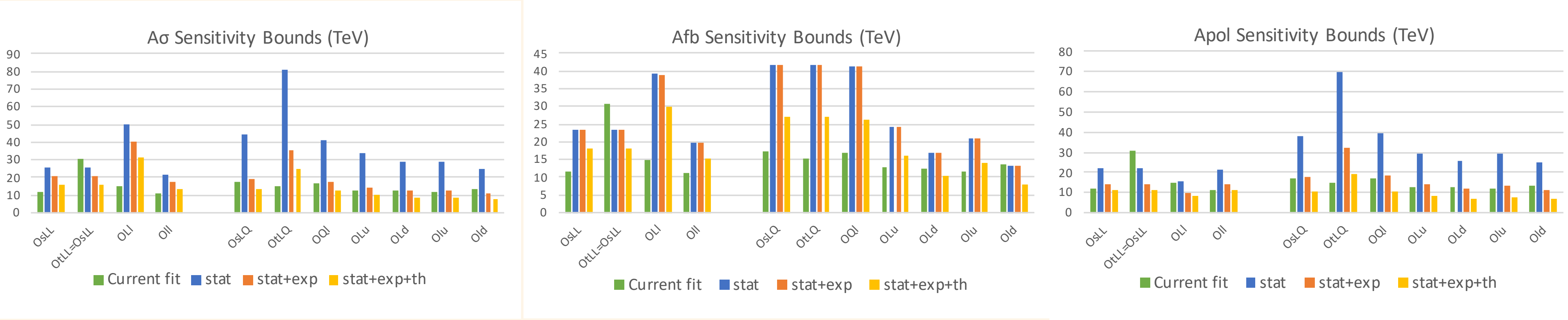
Representative Benchmark O_{tLQ} (Λ_{NP} = 20 TeV)





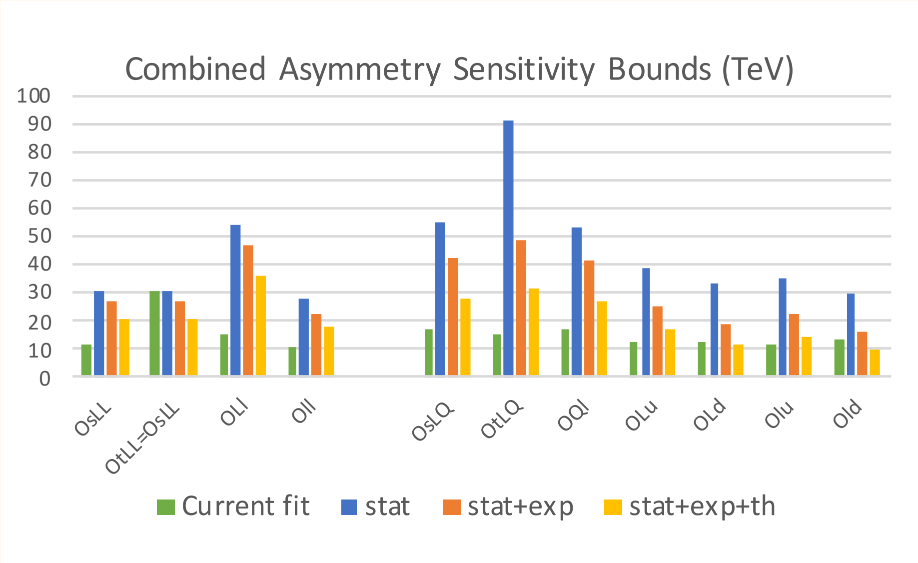
Offset Δ= ±3 GeV taken as decent choice, could extend further.

Projected Sensitivity



- A_{FB} reaches overall better bounds
- A_{σ} reaches with overall biggest bounds before experimental error (lumi)
- A_{FB} has controlled Experimental Uncertainty and best reach before theory
- A_{Pol} gives minor improvement

Combined Sensitivity and Last Slide

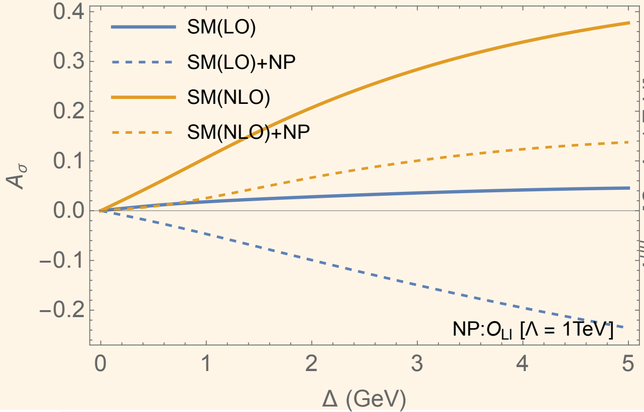


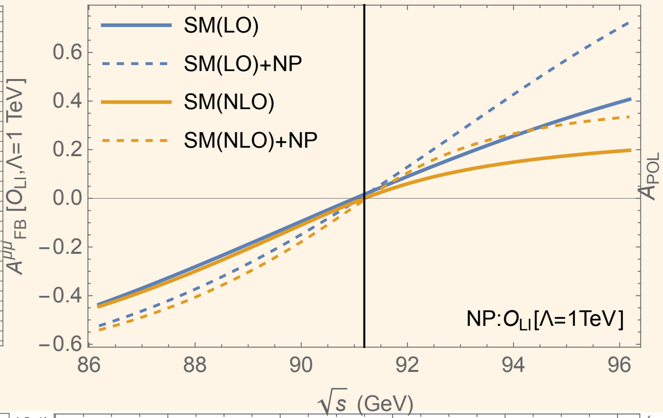
- Off-Z-pole asymmetry signals alone reach 10 ~ 30 TeV for the 4f-operators.
- Sensitivities reduced significantly by theory uncertainties.

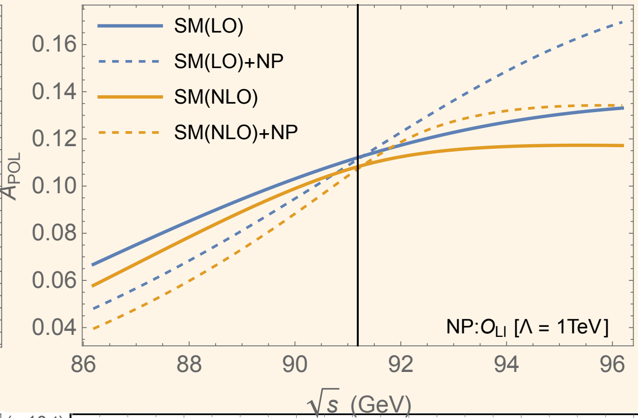
❖ Complementary bounds from higher c.o.m data considering all realistic uncertainties will be interesting for further comparison and discussed.

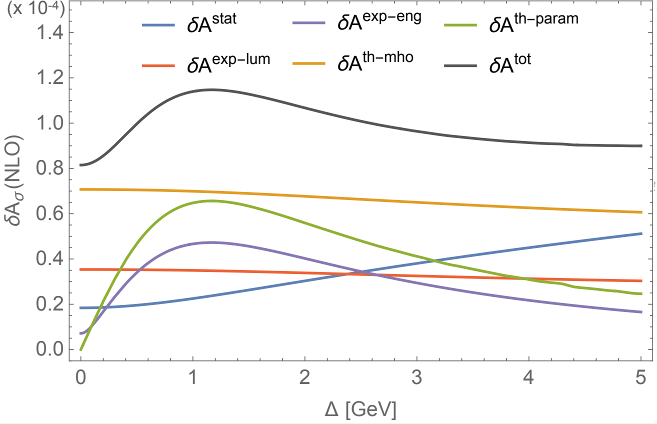
Thank you for listening!

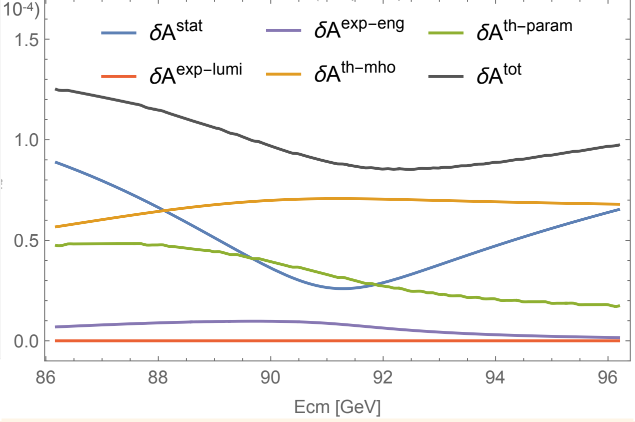
More Information on the $ee \to \mu\mu$ observable

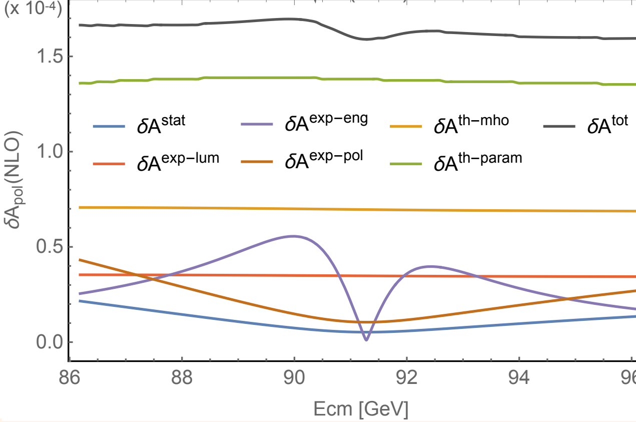












More Information on the $ee \to \mu\mu$ observable