Higgs physics at muon colliders

Workshop on UK Contributions to Muon Collider Detector R&D

3/7/24, University of Birmingham

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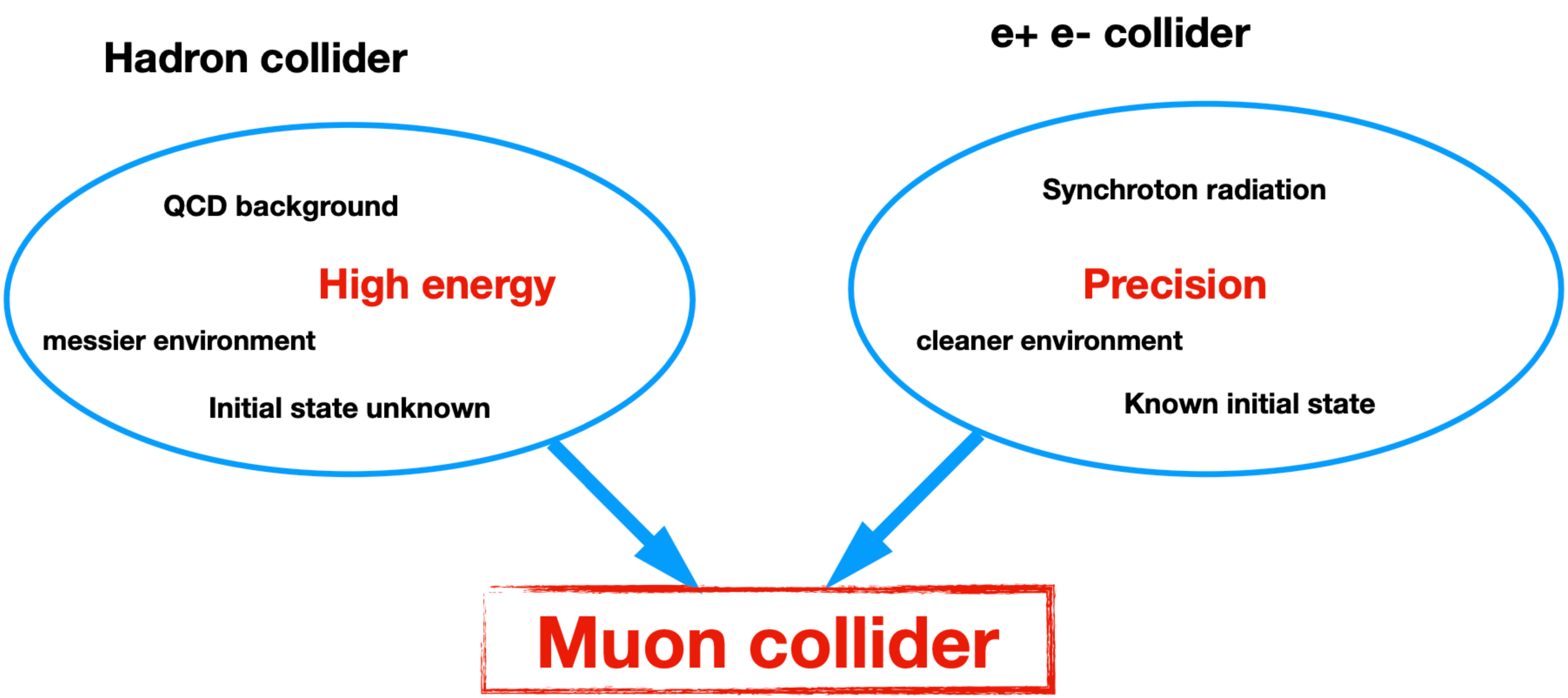
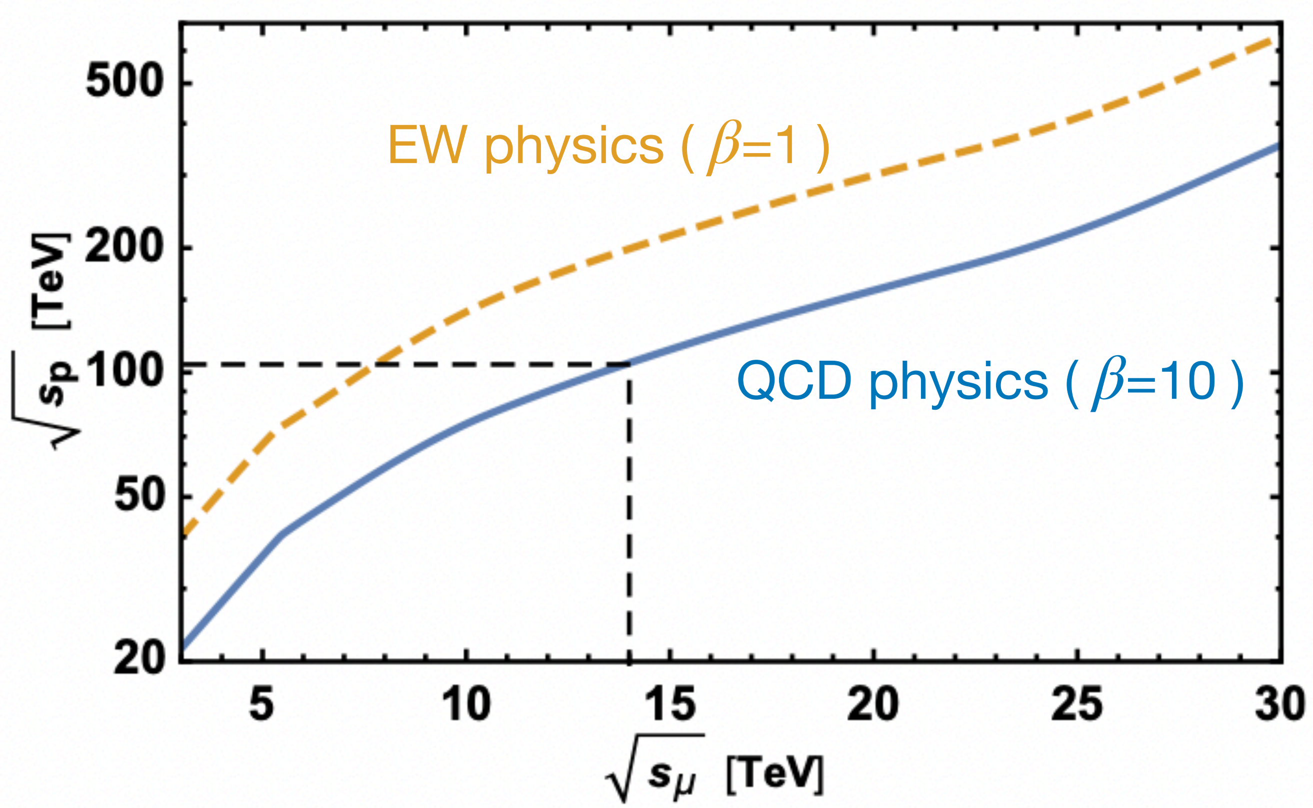
Why a muon collider?

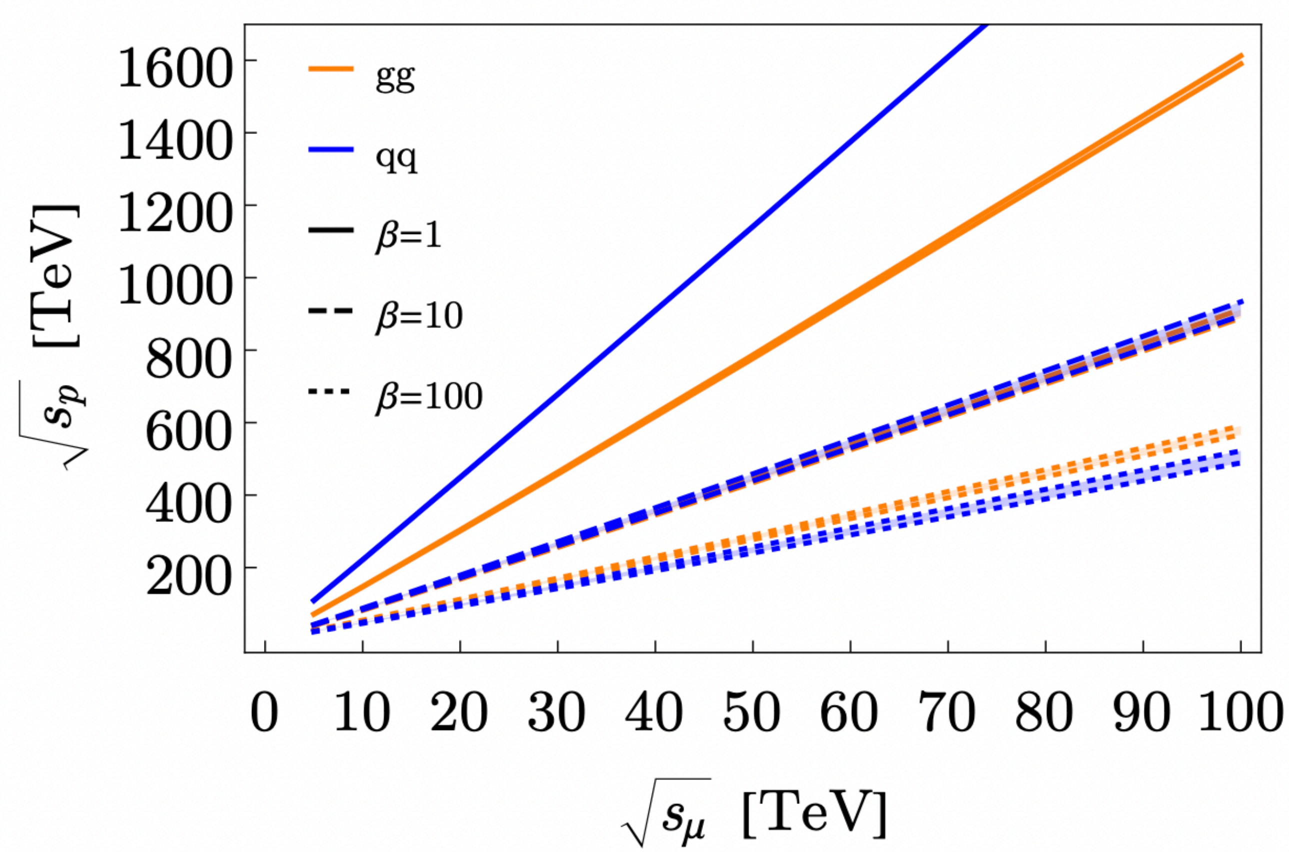


from L. Mantani

Muons vs hadrons

Equivalence of production cross section of heavy pairs at hadron and muon colliders





QCD physics: 14 TeV $\mu\mu$ ~ 100 TeV pp

EW physics: 14 TeV $\mu\mu$ ~ 200 TeV pp

β = relative strength of the heavy particle interactions with the partons / muons

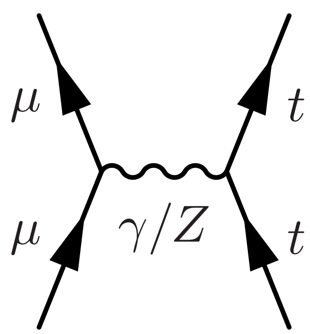
[*Snowmass*; 2203.07256]

Production modes

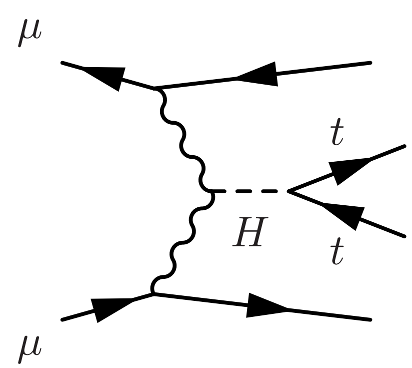
Two main production modes: s-channel and VBF

- - - - s-channel ——— VBF

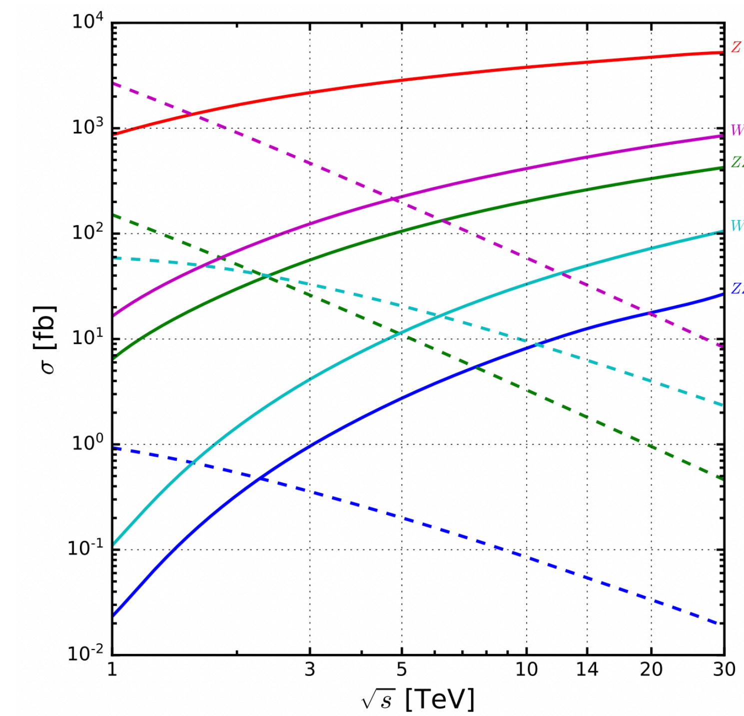
$\sqrt{s} \lesssim$ 1-5 TeV

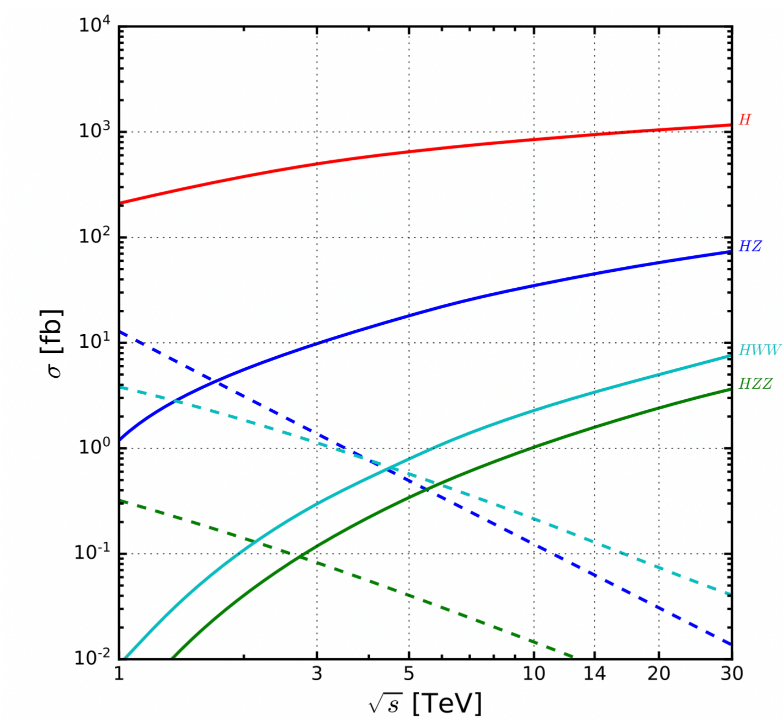


$\sqrt{s} \gtrsim$ 1-5 TeV



VBF takes over at high energies





[*Constantini et al.*; 2005.10289]

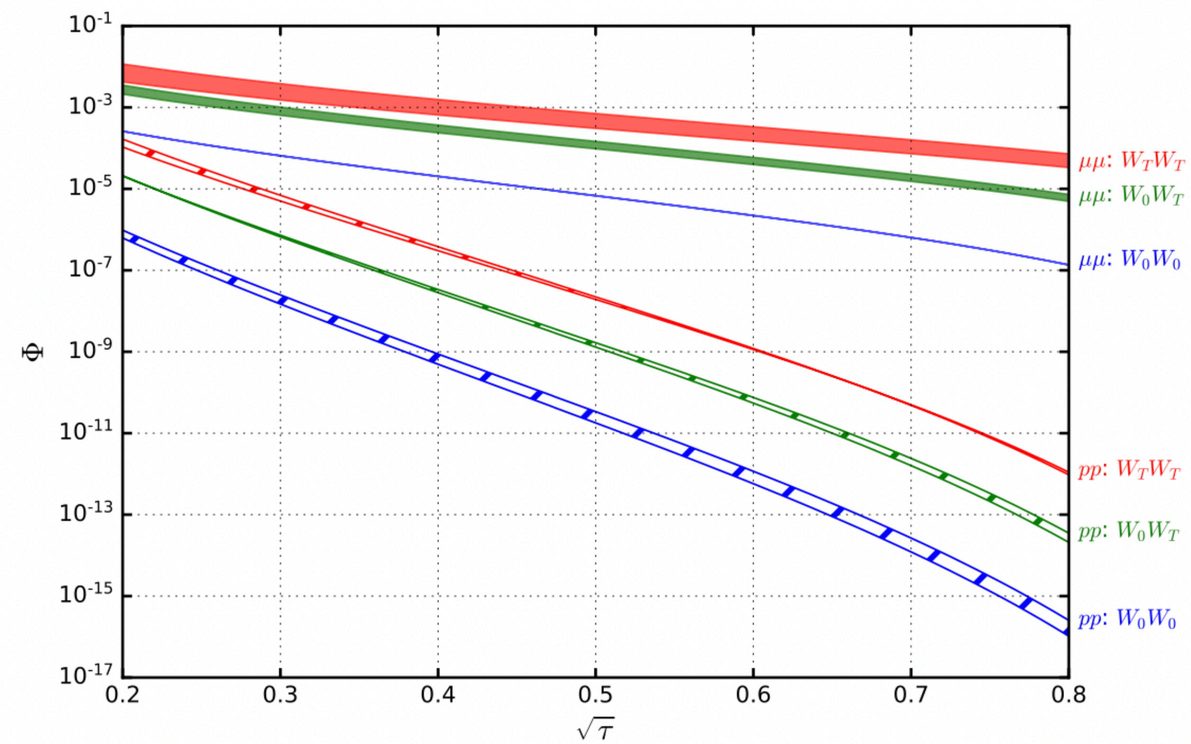
Production modes

Energy at which VBF dominates over s-channel production

	σ [fb]	$\sqrt{s}$ [TeV]		σ [fb]	$\sqrt{s}$ [TeV]
$t\bar{t}$	$8.4 \cdot 10^{0}$	4.5	$t\bar{t}ZZ$	$2.2 \cdot 10^{-2}$	8.4
$t\bar{t}Z$	$5.3 \cdot 10^{-1}$	6.9	$t\bar{t}HZ$	$7.0 \cdot 10^{-3}$	11
$t\bar{t}H$	$7.6 \cdot 10^{-2}$	8.2	$t\bar{t}HH$	$5.9 \cdot 10^{-4}$	13
$t\bar{t}WW$	$1.2 \cdot 10^{-1}$	15	$t\bar{t}t\bar{t}$	$1.6 \cdot 10^{-3}$	22
HZ	$4.3 \cdot 10^{0}$	1.7	$HHWW$	$4.3 \cdot 10^{-3}$	9.2
HHZ	$2.1 \cdot 10^{-2}$	4.2	HZZ	$9.4 \cdot 10^{-2}$	2.7
$HHHZ$	$4.7 \cdot 10^{-5}$	6.9	$HHZZ$	$5.9 \cdot 10^{-4}$	5.7
HWW	$6.6 \cdot 10^{-1}$	4.5			
WW	$2.1 \cdot 10^{2}$	4.8	WWZ	$1.6 \cdot 10^{1}$	6.2
ZZ	$3.9 \cdot 10^{1}$	2.4	ZZZ	$4.8 \cdot 10^{-1}$	2.3

Parton luminosities

$$\sigma_p(s_p) = \int_{\tau_0}^{1} d\tau \sum_{ij} \Phi_{ij}(\tau, \mu_f)\ [\hat{\sigma}_{ij}]_p\, \delta\left(\tau - \frac{M^2}{s_p}\right)$$

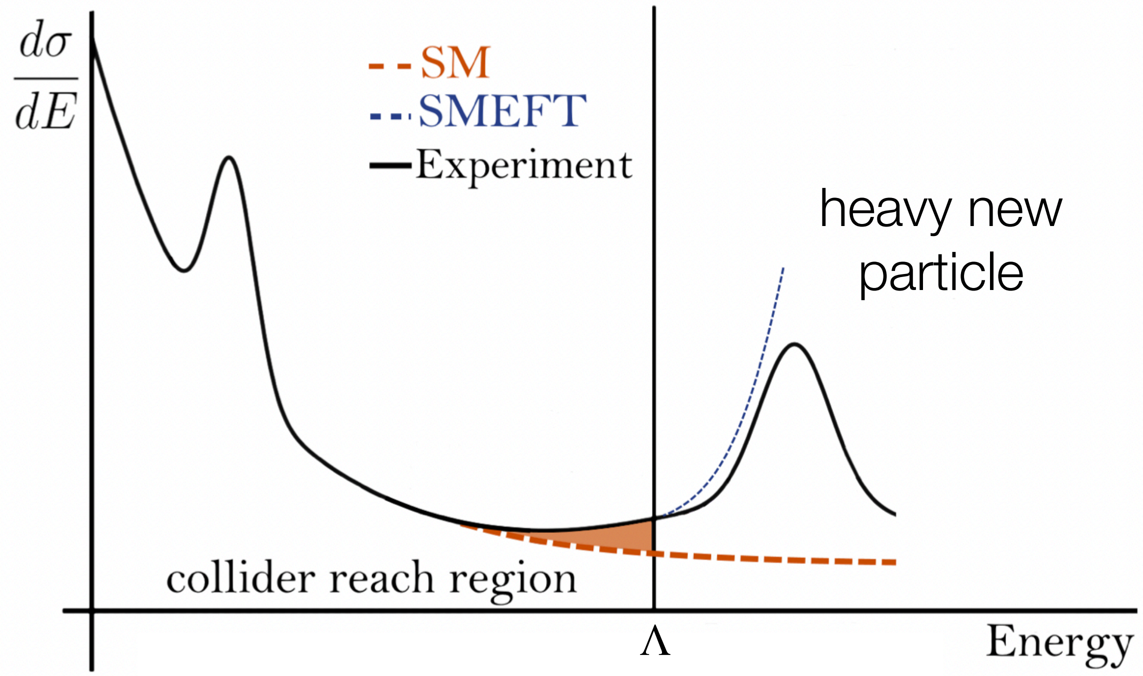


fractional scattering scale $\sqrt{\tau} = M_{VV'}/\sqrt{s}$

A high-energy muon collider is effectively a vector boson collider

[*Constantini et al.;* 2005.10289]

The SMEFT



Original fig. by C. Severi, M. Thomas, E. Vryonidou

Dimension-6 operators Warsaw basis

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-3})$$

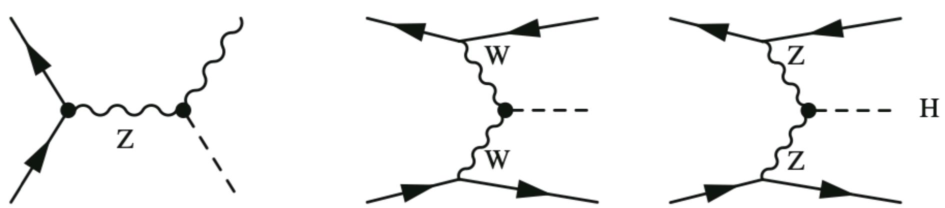
can introduce energy growing effects

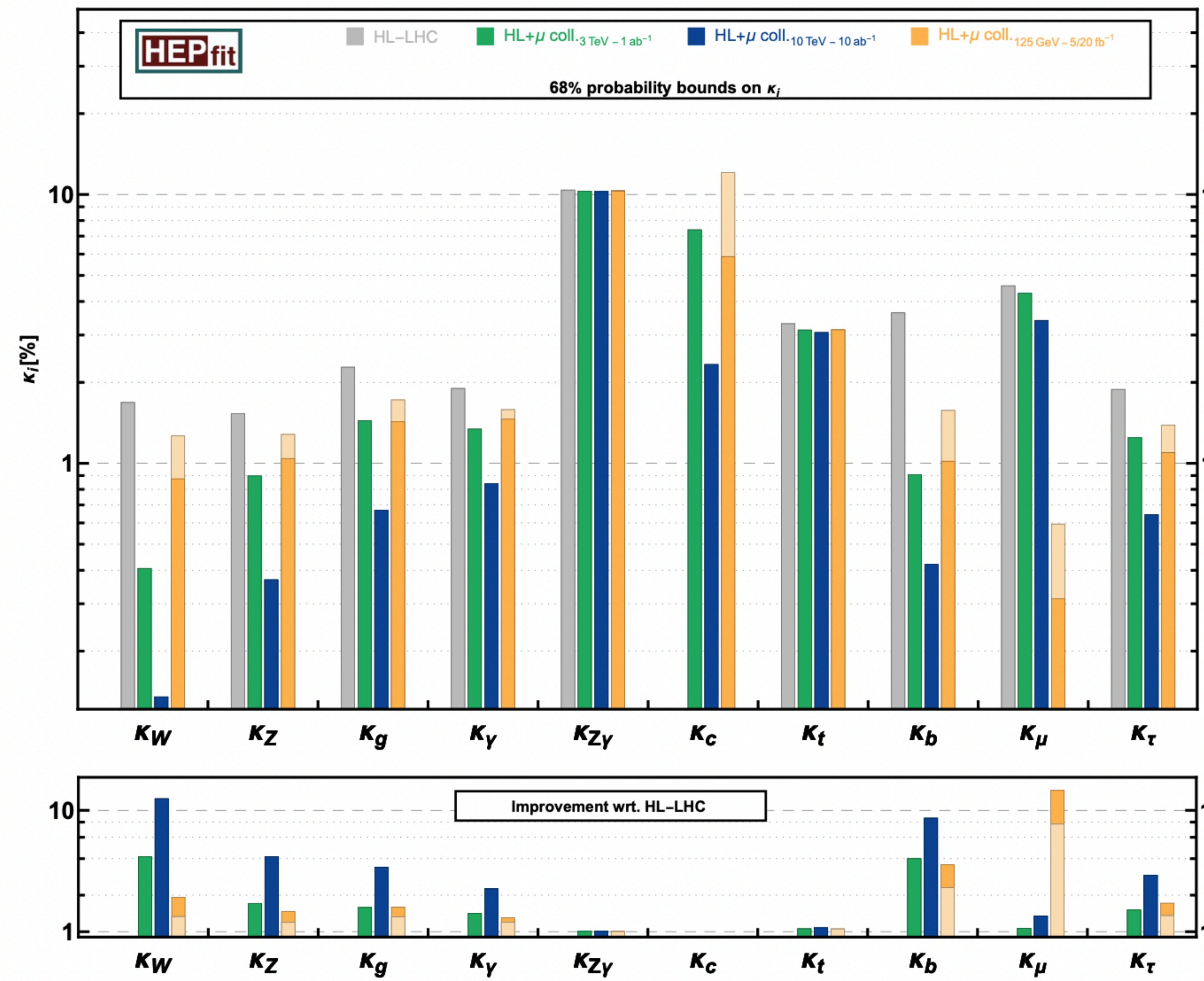
$$\mathcal{M} \sim \mathcal{M}_{SM} \left(1 + C_i \frac{v^2}{\Lambda^2} + C_j \frac{vE}{\Lambda^2} + C_k \frac{E^2}{\Lambda^2}\right)$$

Global SMEFT fits

- Constraints on Higgs effective couplings
- Production channels:

  VBF, s-channels, Higgs decays





- global Higgs&EW fits

up to $\mathcal{O}(10)$ improvements on Higgs couplings at 10 TeV $\mu\mu$ compared to HL-LHC

[Snowmass; 2203.07261]

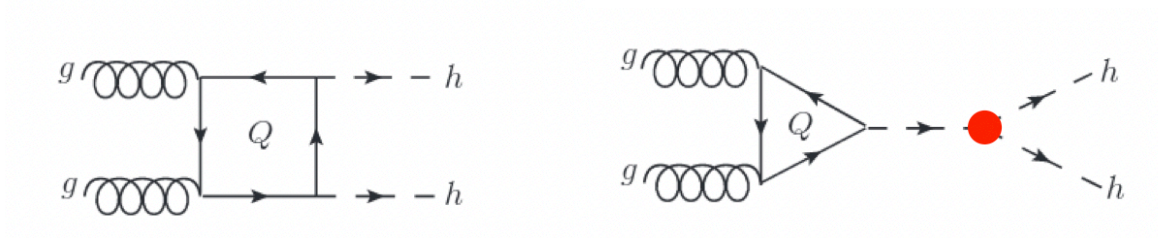
Higgs potential at HL-LHC

- Trilinear interaction: constraints on the shape of the Higgs potential

In the SM: $$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

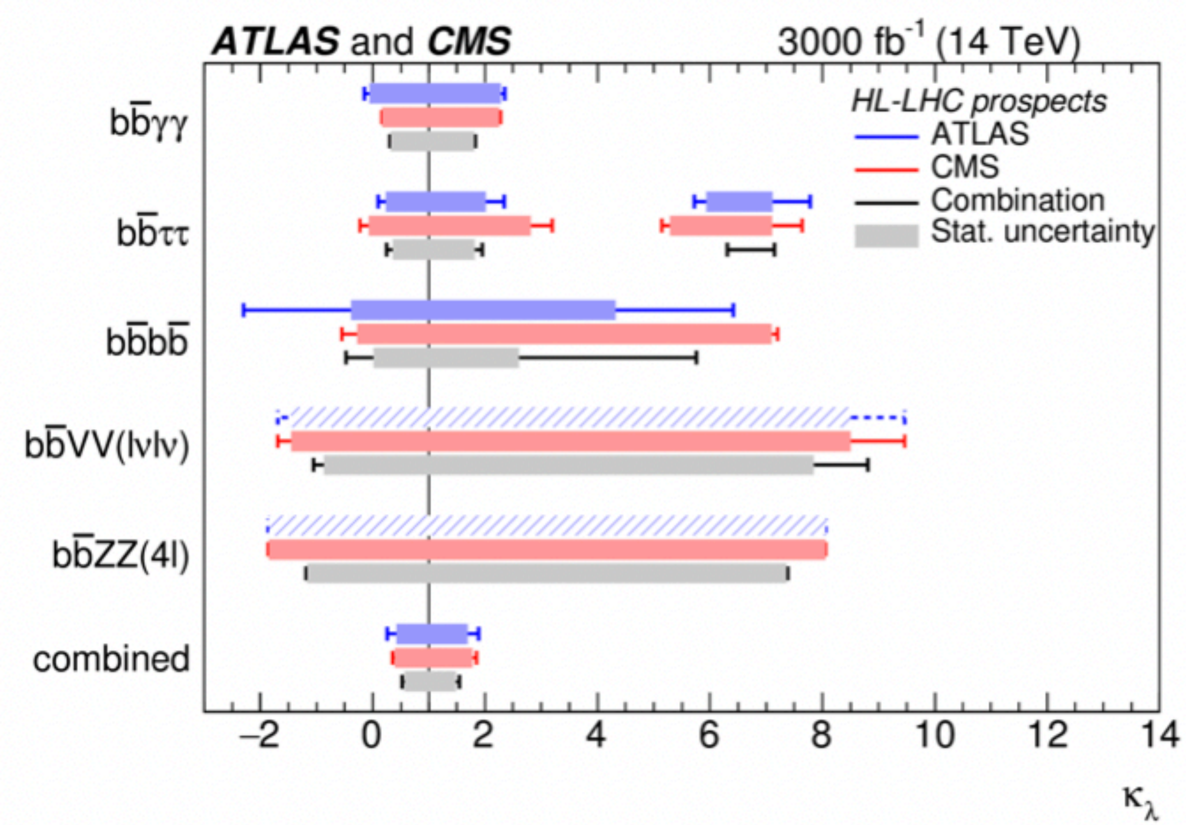
$$\lambda_3 = \lambda_4 = m_H^2/2v^2 \equiv \lambda_{SM}$$

- HH notoriously difficult at LHC ($\sigma \sim 30$ fb)



- HL-LHC expected to reach

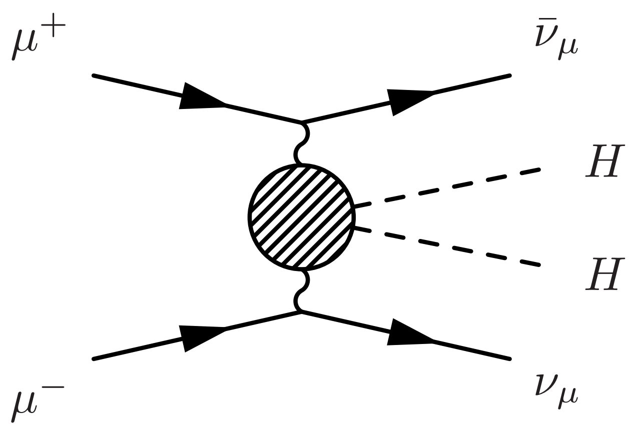
  50% precision on λ_3



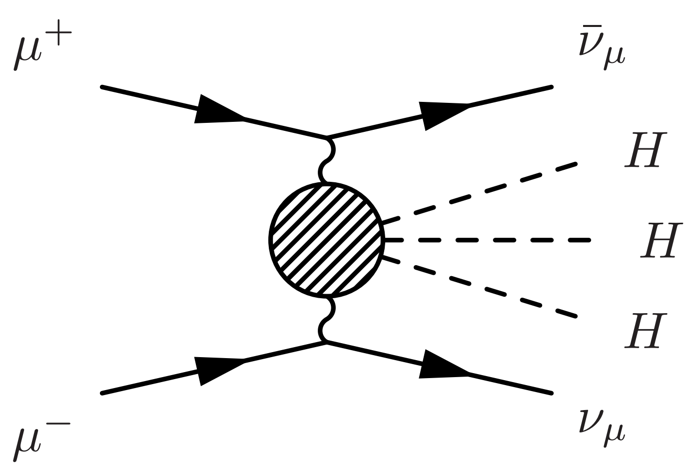
[*Cepeda et al.*; 1902.00134]

VBF as a probe of Higgs couplings

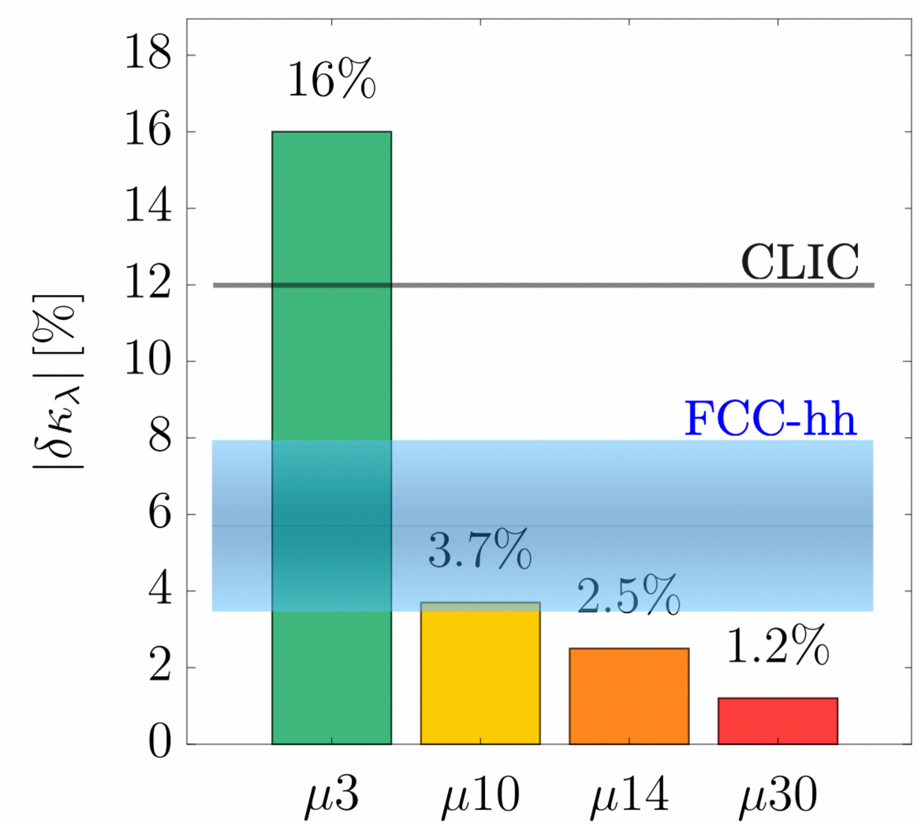
Precise determination only possible at high-energy machines



Sensitivity to Higgs trilinear (λ_3)



Sensitivity to Higgs trilinear (λ_3) and quartic (λ_4)



[Snowmass; 2203.07256]

Higgs potential in the SMEFT

Relevant SMEFT operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-3})$$

$$\mathcal{O}_\varphi = \left(\varphi^\dagger \varphi - \frac{v^2}{2}\right)^3 \supset v^3 H^3 + \frac{3}{2} v^2 H^4,$$

$$\mathcal{O}_{\varphi d} = \left(\varphi^\dagger \varphi\right) \Box \left(\varphi^\dagger \varphi\right) \supset 2v \left(H \Box H^2 + H^2 \Box H\right) + H^2 \Box H^2,$$

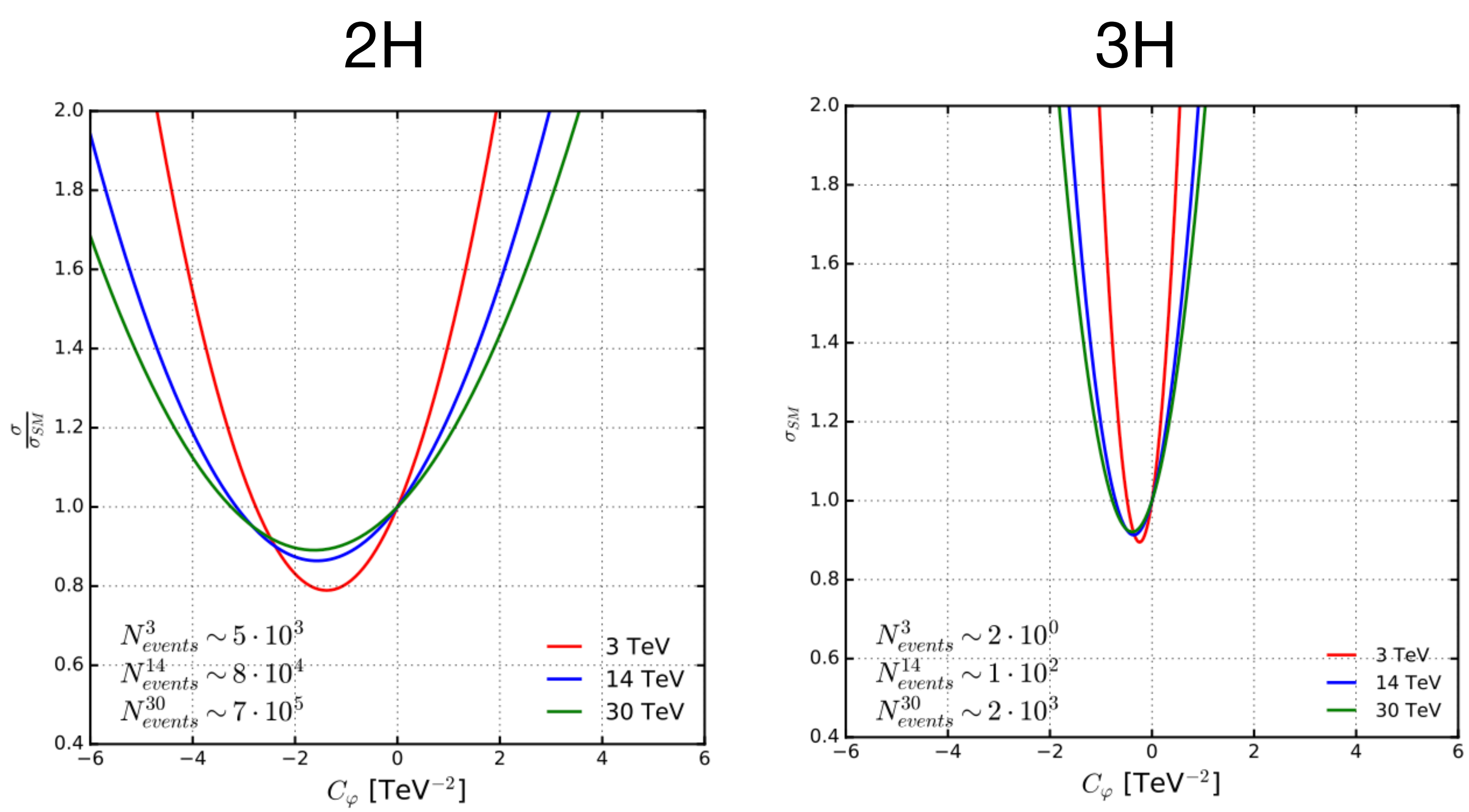
$$\mathcal{O}_{\varphi D} = \left(\varphi^\dagger D_\mu \varphi\right)^\dagger \left(\varphi^\dagger D^\mu \varphi\right) \supset \frac{v}{2} H \partial_\mu H \partial^\mu H + \frac{H^2}{4} \partial_\mu H \partial^\mu H.$$

No additional E dependence

Max sensitivity near threshold

3H vs 2H

- more sensitivity
- smaller rates (irrelevant at 3 TeV)



[Constantini et al.; 2005.10289]

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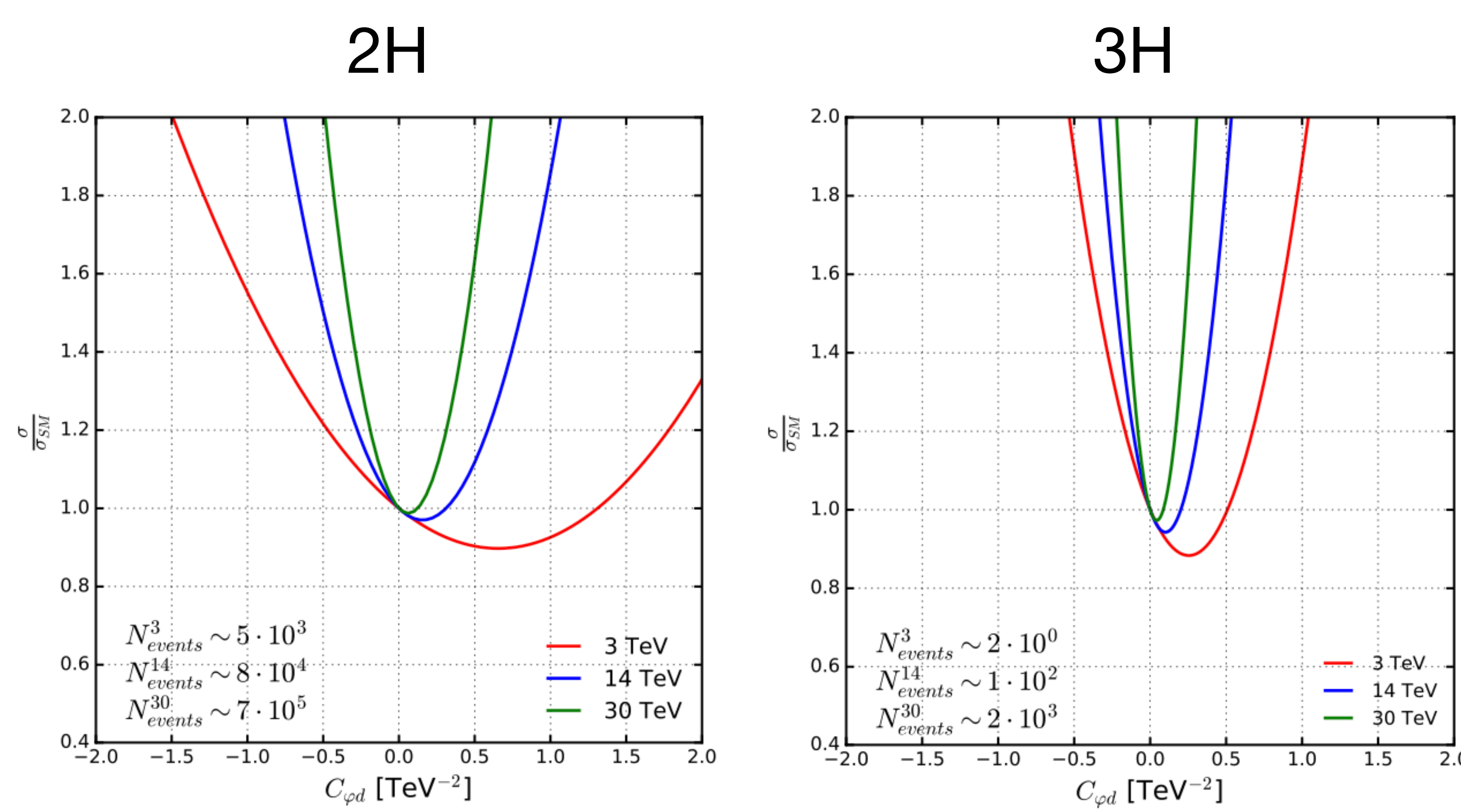
Additional p^2 dependence

Gain in sensitivity with E

O_ϕ and $O_{\phi d}$ sensitivities are driven by complementary PS regions



[Constantini et al.; 2005.10289]

Higgs potential in the SMEFT

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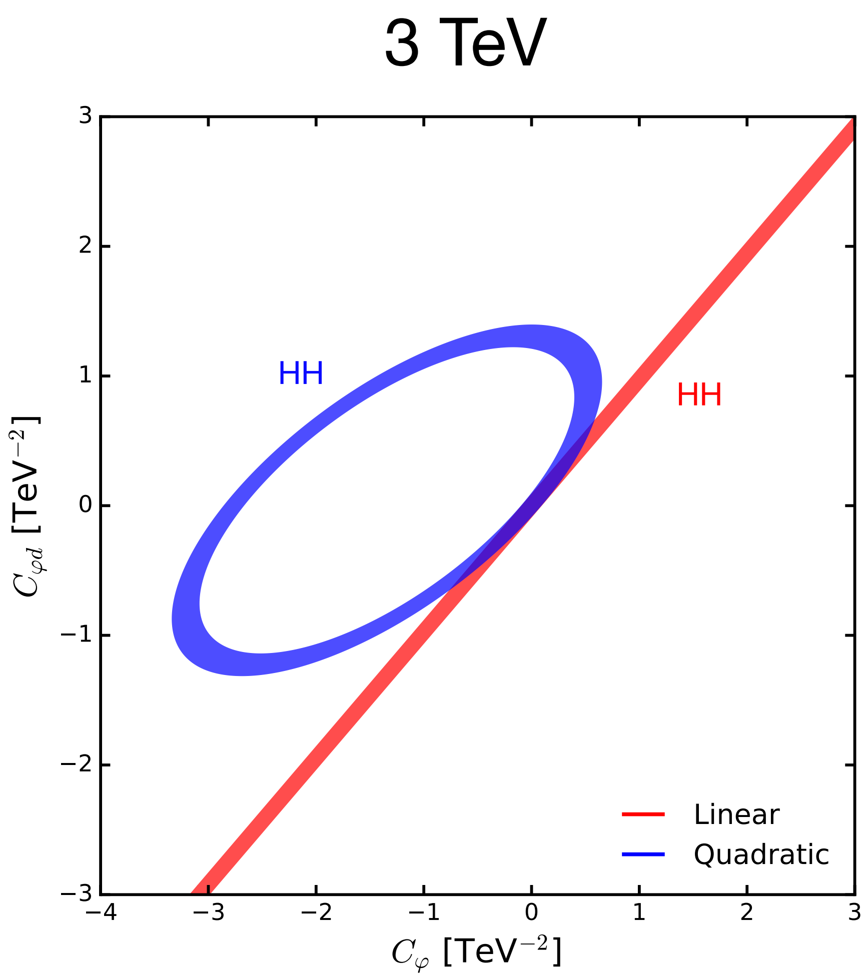
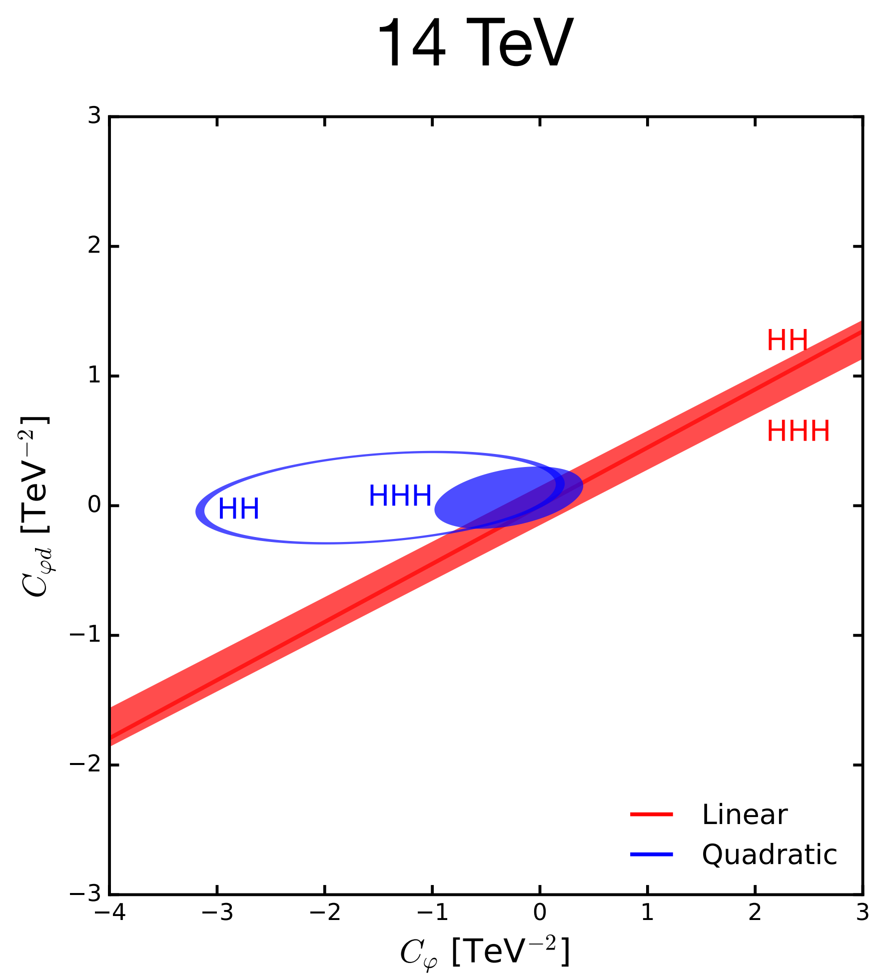
constrained by EWPO

Higgs potential in the SMEFT





95% CL:

$$\frac{S}{\sqrt{B}} = \frac{|\mathcal{L} \cdot (\sigma - \sigma_{SM})|}{\sqrt{\mathcal{L} \cdot \sigma_{SM}}} \leq 2$$

	3 TeV	14 TeV
C_φ	[-3.33, 0.65]	[-0.66, 0.23]
$C_{\varphi d}$	[-1.31, 1.39]	[-0.17, 0.30]

Individual bounds (68% CL)

FCC combination $C_\varphi \sim [-0.79, 0.79]$ TeV^{-2} and $C_{\varphi d} \sim [-0.03, 0.03]$ TeV^{-2}

14 TeV muon collider $C_\varphi \sim [-0.02, 0.02]$ TeV^{-2} and $C_{\varphi d} \sim [-0.002, 0.002]$ TeV^{-2}

$O_{\phi d}$ constrained in single Higgs: only O_ϕ relevant

[*Constantini et al.*; 2005.10289]

Decorrelating λ_3 and λ_4

$$\lambda_3 = \lambda_{SM}(1+\delta_3) = \kappa_3 \lambda_{SM}$$

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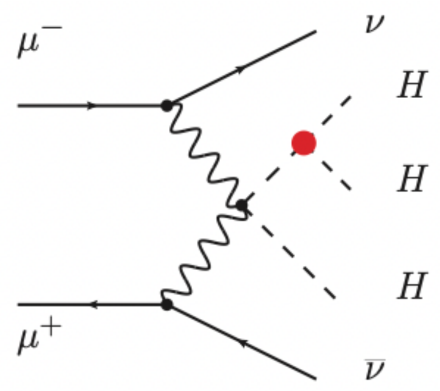
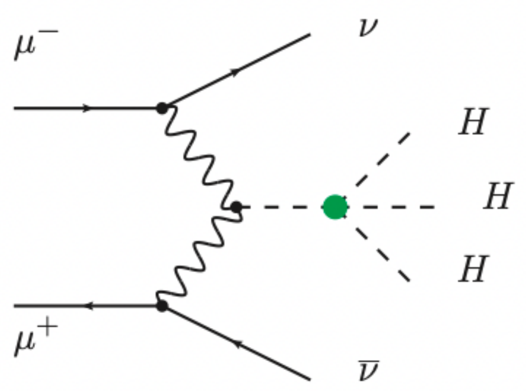
can be correlated in the SMEFT at dim 6

$$\mathcal{O}_\varphi = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3 \quad \Rightarrow \quad \delta_4 = 6\,\delta_3$$





Need to measure λ_4 independently

- sensitivity at tree level in HHH

  $\lambda_4/\lambda_4^{\mathrm{SM}} \in [-2, +13]$ at 2σ at FCC-hh

- at loop-level in HH

  $\lambda_4/\lambda_4^{\mathrm{SM}} \in [-2.3, +4.3]$ at 1σ at FCC-hh

[Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao; 2003.13628]

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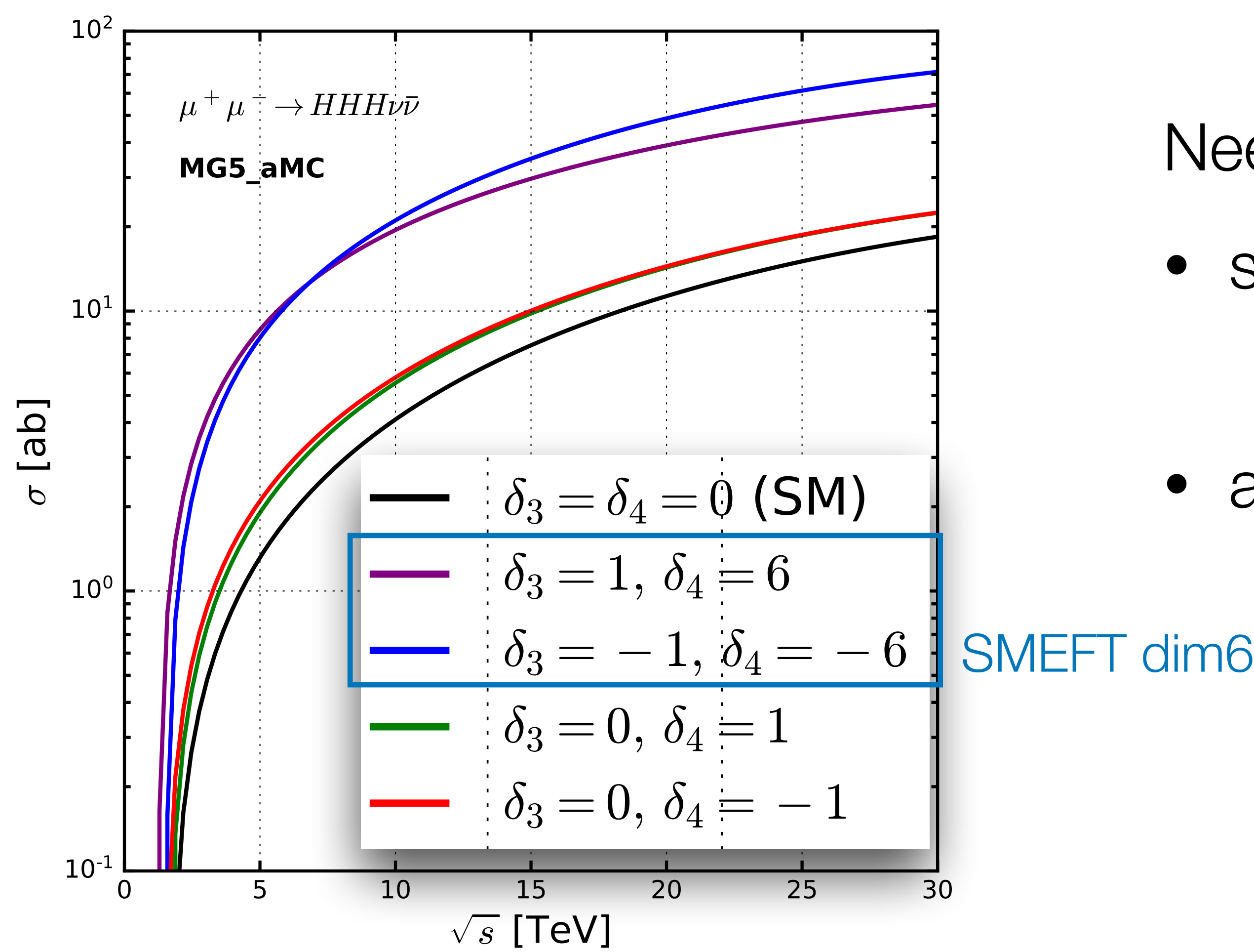

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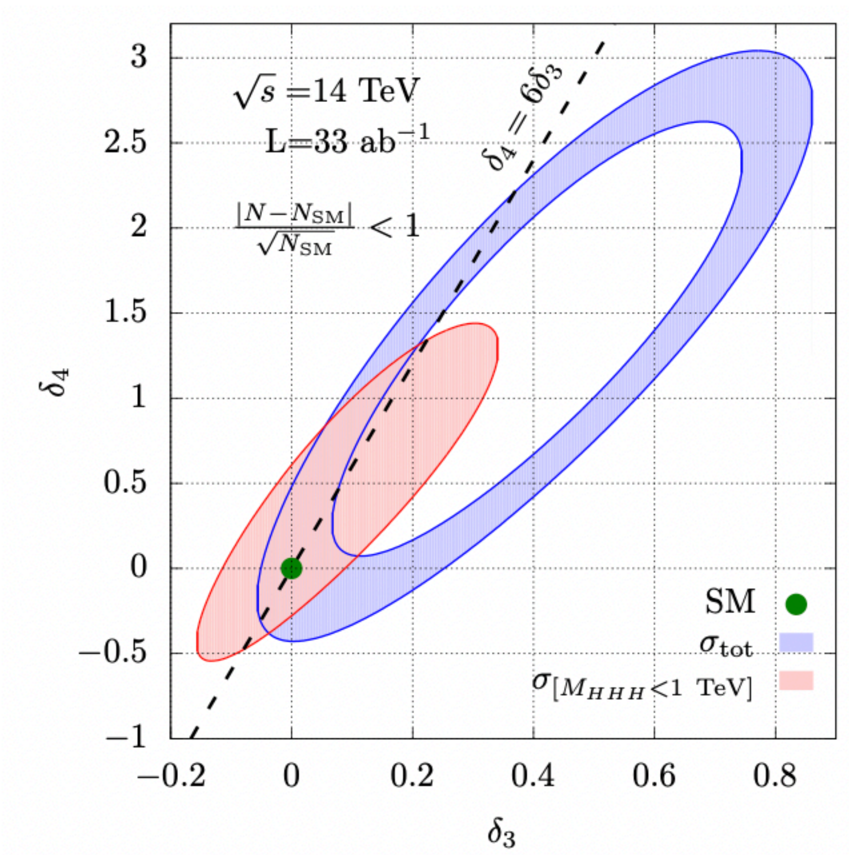
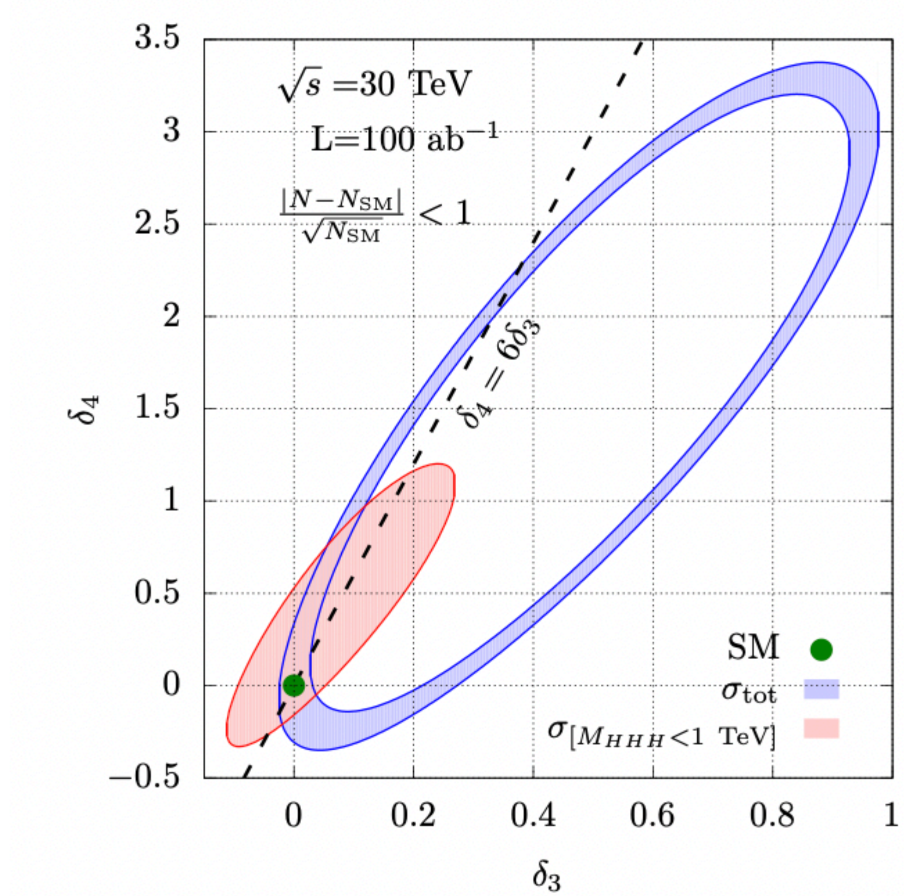




1σ exclusion plots

At other colliders

- ILC $\sim [-10, +10]$
- CLIC $\sim [-5, +5]$
- FCC-hh $\sim [-2, +4]$

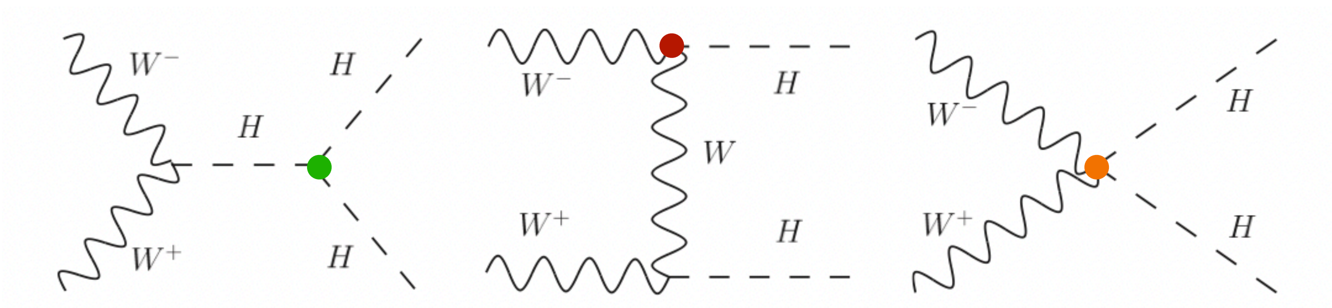
$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	Constraints on δ_4 (with $\delta_3 = 0$) x-sec only 1 σ	x-sec only 2 σ	threshold + $M_{HHH} > 1$ TeV 1 σ
6	12	$[-0.60, 0.75]$	$[-0.90, 1.00]$	$[-0.55, 0.85]$
10	20	$[-0.50, 0.55]$	$[-0.70, 0.80]$	$[-0.45, 0.70]$
14	33	$[-0.45, 0.50]$	$[-0.60, 0.65]$	$[-0.35, 0.55]$
30	100	$[-0.30, 0.35]$	$[-0.45, 0.45]$	$[-0.20, 0.40]$
3	100	$[-0.35, 0.60]$	$[-0.50, 0.80]$	$[-0.45, 0.65]$

$\mathcal{O}$(10%) precision at a muon colliders

[Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao; 2003.13628]

HH as a probe of VVHH

HH depends on κ_3 but also on κ_V, κ_{V2}

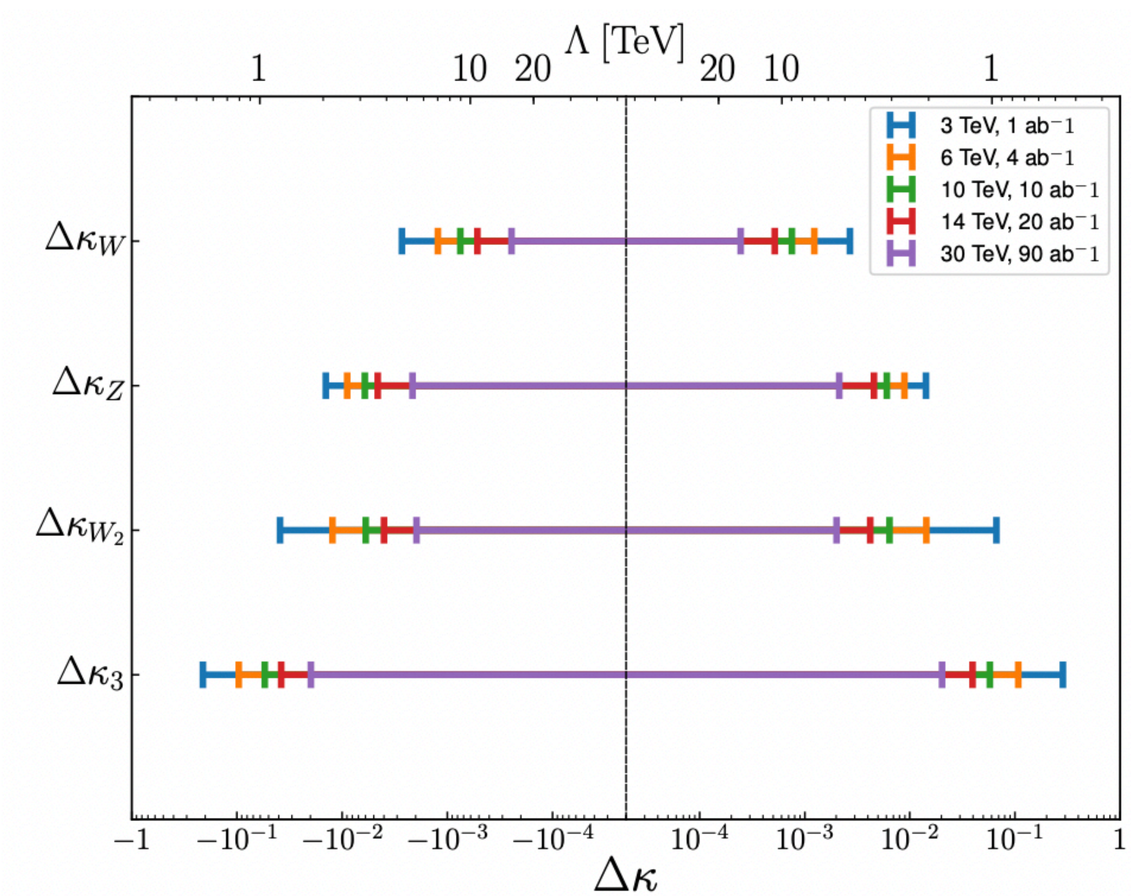


$$\mathcal{L} \supset \left(M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)\left(\kappa_V \frac{2H}{v} + \kappa_{V_2}\frac{H^2}{v^2}\right) - \frac{m_H^2}{2v}\left(\kappa_3 H^3 + \frac{1}{4v}\kappa_4 H^4\right)$$

$$\Delta\kappa_V = -\frac{C_{\varphi d}}{2}\frac{v^2}{\Lambda^2} \quad \Delta\kappa_{V2} = -2C_{\varphi d}\frac{v^2}{\Lambda^2}$$

correlated in the SMEFT

Expected 95% CL bounds at muon colliders:



} ~5% at LHC
<1% at ee Higgs factories

~1% at FCC-hh (100 TeV)

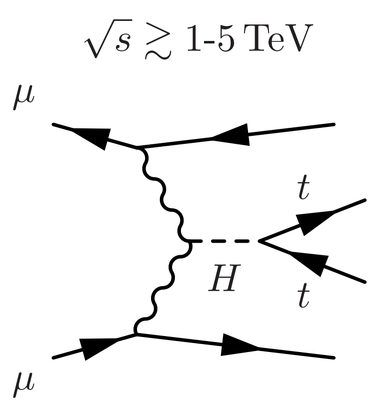
~5% at FCC-hh (100 TeV)

[Han, Liu, Wang; 2008.12204]

Top Yukawa in tt VBF

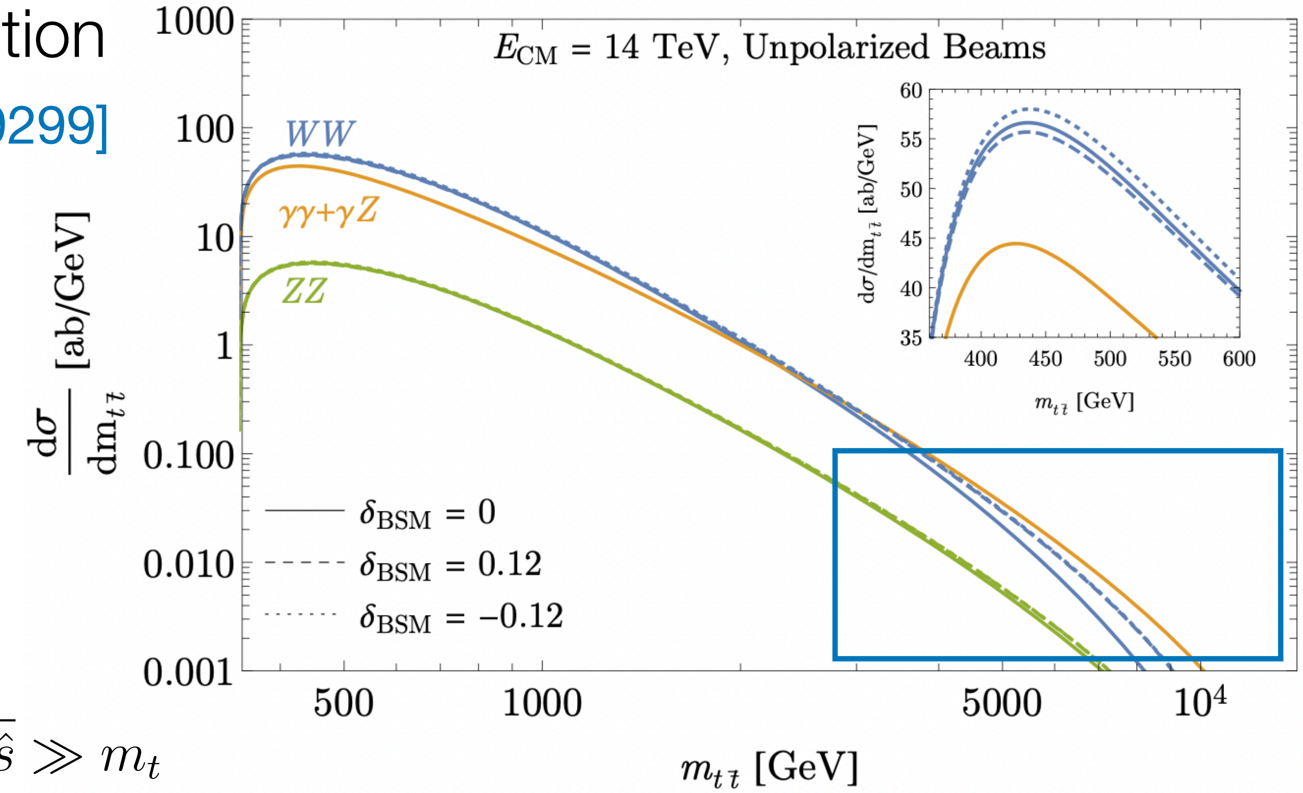
Higgs without the Higgs: off-shell H production

[*Henning et al.*; 1812.09299]



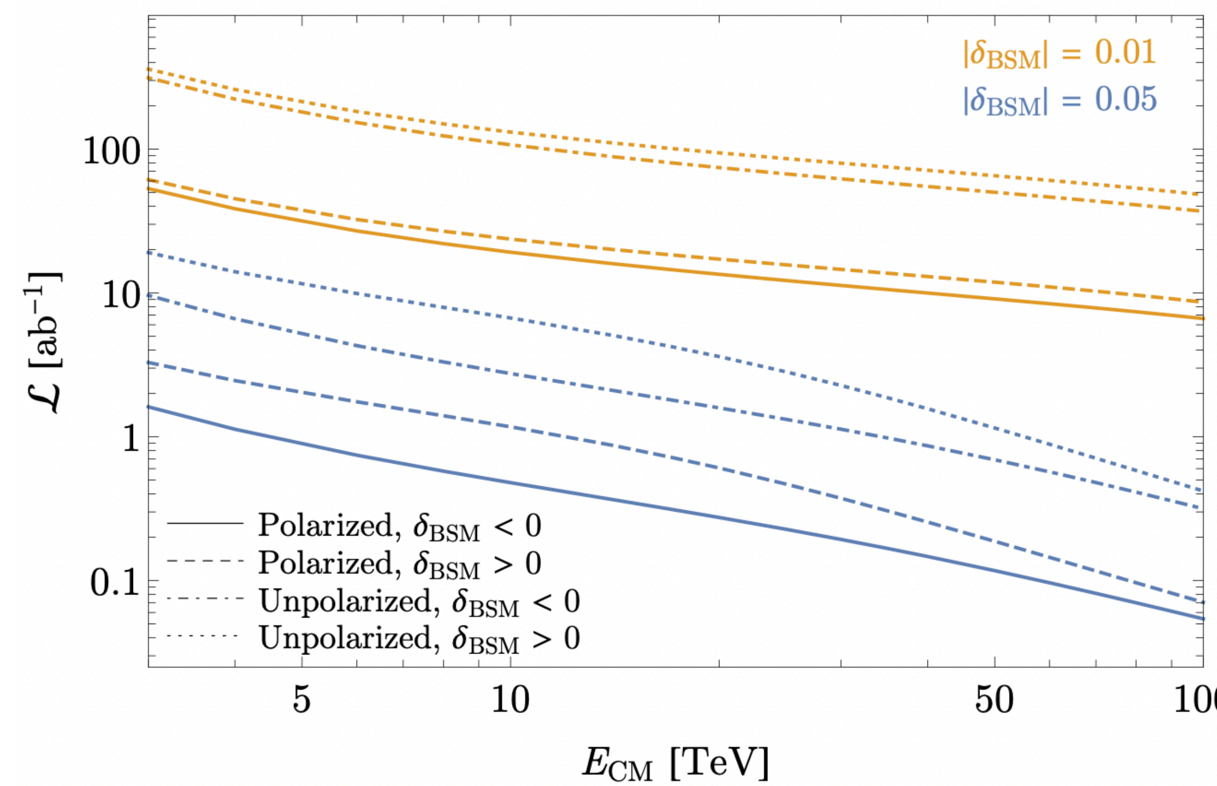
$$y_t \mapsto y_t(1 + \delta_{\rm BSM})$$

$$\mathcal{M}(W_L^+ W_L^- \to t\bar{t}) \simeq -\frac{m_t}{v^2}\delta_{\rm BSM}\sqrt{\hat{s}}\,, \qquad \text{with} \qquad \sqrt{\hat{s}} \gg m_t$$



95% CL bounds:

- HL-LHC: $|\delta_{\rm BSM}| \leq 0.06$
- 14 TeV μC: $|\delta_{\rm BSM}| \leq 0.01$ with $\mathscr{L} \sim 100$ ab^{-1}



[*Muon Smasher's Guide*; 2103.14043]

Muon Yukawa

- Yukawa couplings of the second generation are still poorly measured

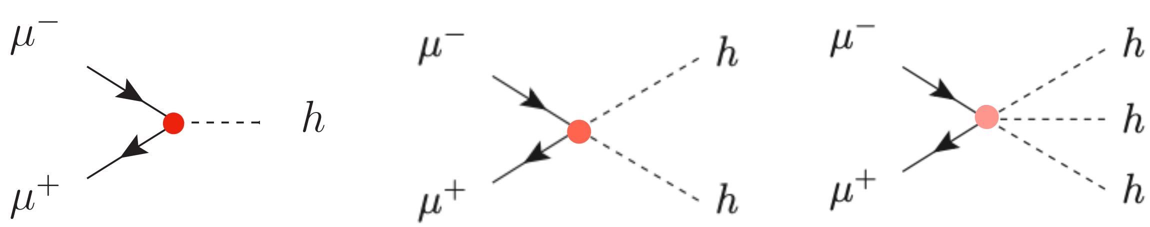
Anomalous muon-Higgs couplings in HEFT

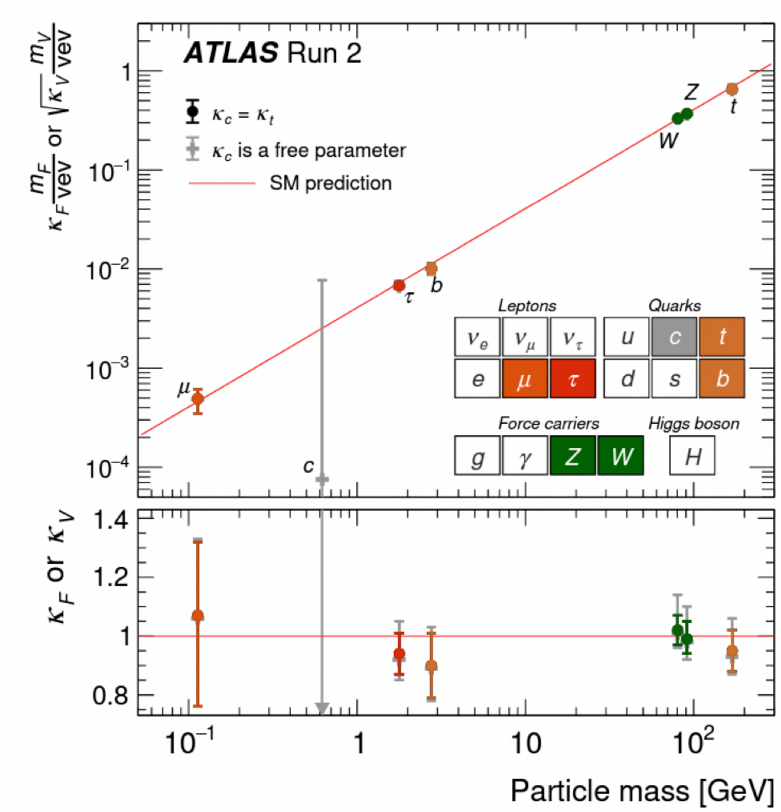
$$\mathcal{L} \supset -\frac{m_H^2}{2}H^2 - m_\mu \bar{\mu}\mu - \sum_{n=3}^{\infty} \beta_n \frac{\lambda}{v^{n-4}} H^n - \boxed{\sum_{n=1}^{\infty} \alpha_n \frac{m_\mu}{v^n} \bar{\mu}\mu H^n}$$

…and in SMEFT at dim 6

$$\boxed{\frac{c_{\ell\varphi}^{(6)}}{\Lambda^2}(\varphi^\dagger\varphi)(\bar{\ell}_L \varphi \mu_R + \text{h.c.})}$$

$$\frac{c_{\ell\varphi}^{(6)}}{\Lambda^2} = -\frac{35 m_\mu}{4\sqrt{2}v^3} + \boxed{\frac{35 m_\mu}{4\sqrt{2}v^3}\alpha_1} - \boxed{\frac{5 m_\mu}{\sqrt{2}v^3}\alpha_2} + \boxed{\frac{3 m_\mu}{2\sqrt{2}v^3}\alpha_3}$$





Muon Yukawa

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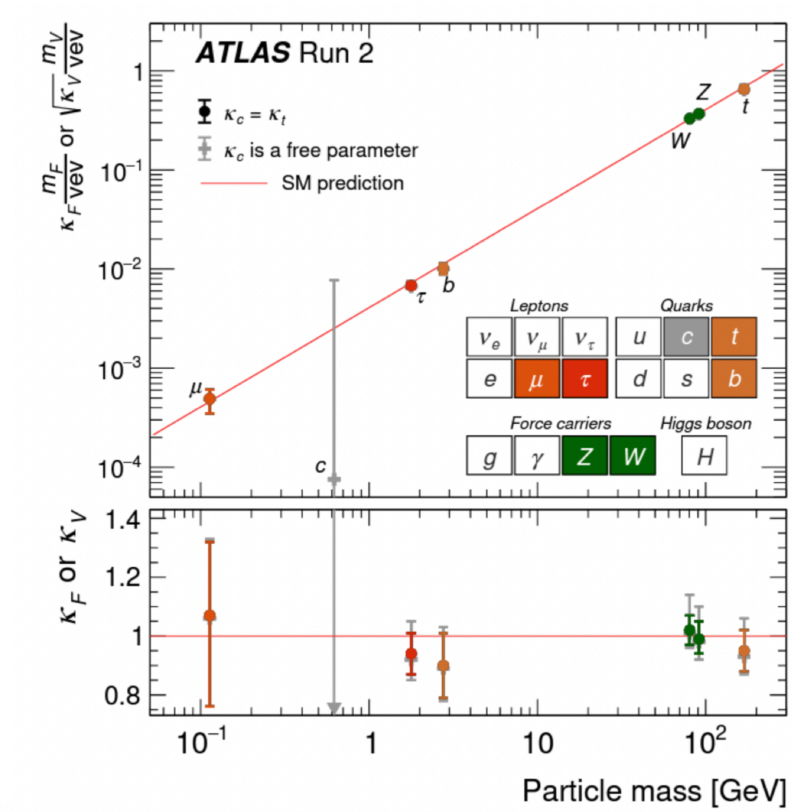

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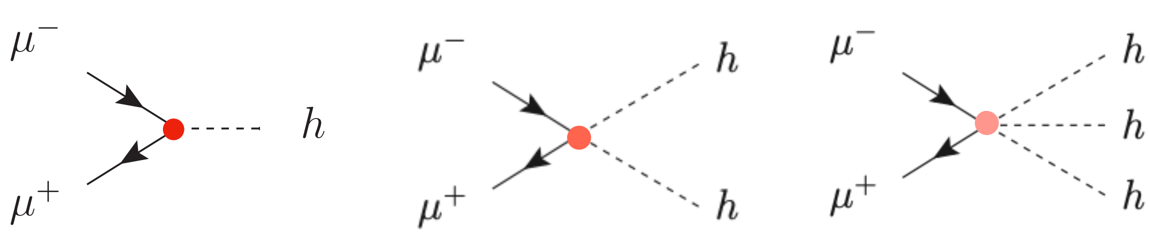
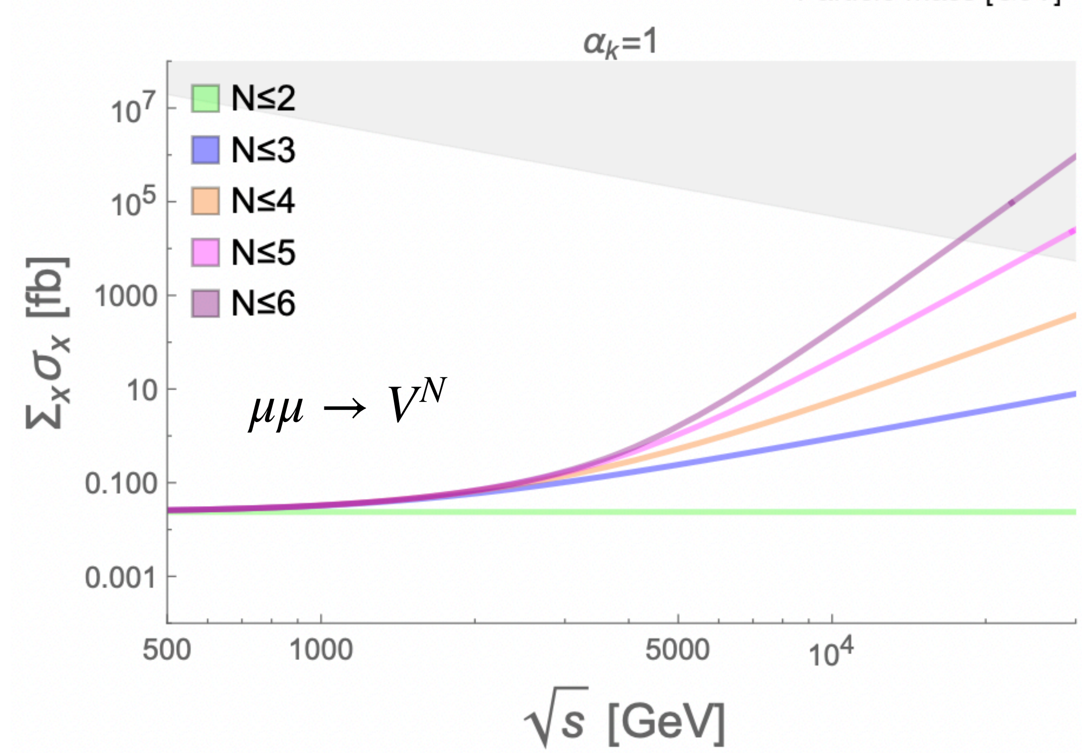




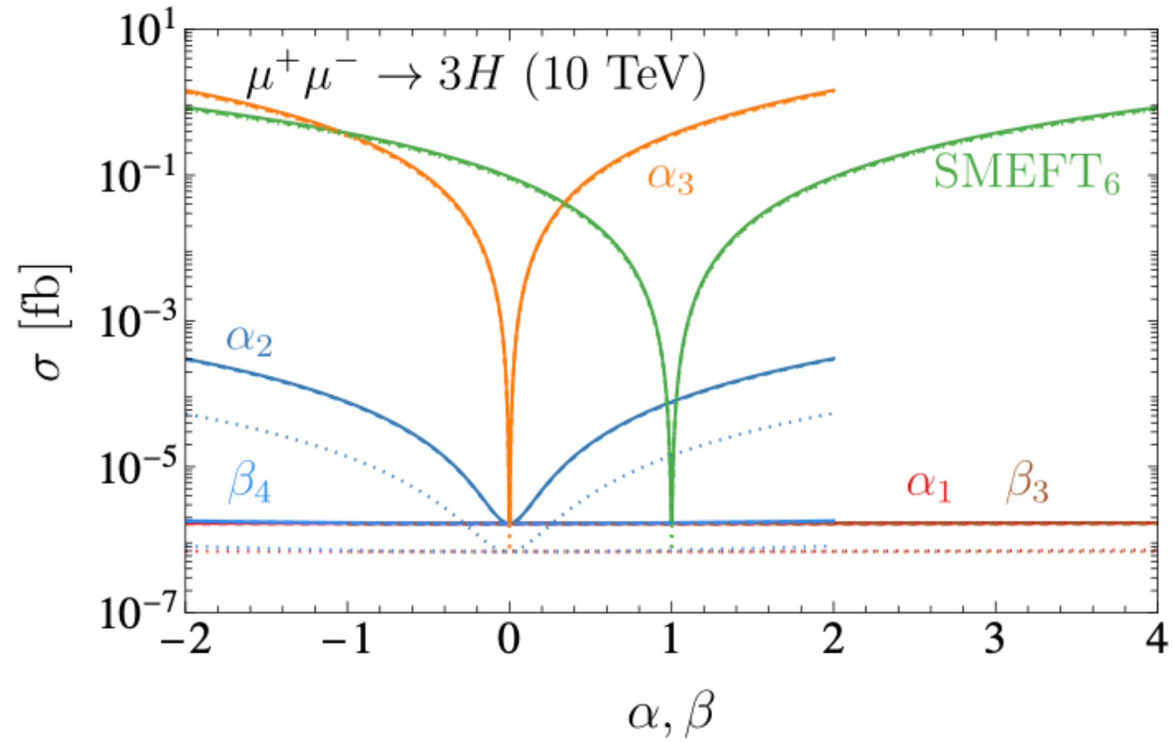
- An anomalous Yukawa coupling in $\mu\mu \to V^N$ leads to unitarity breaking effects

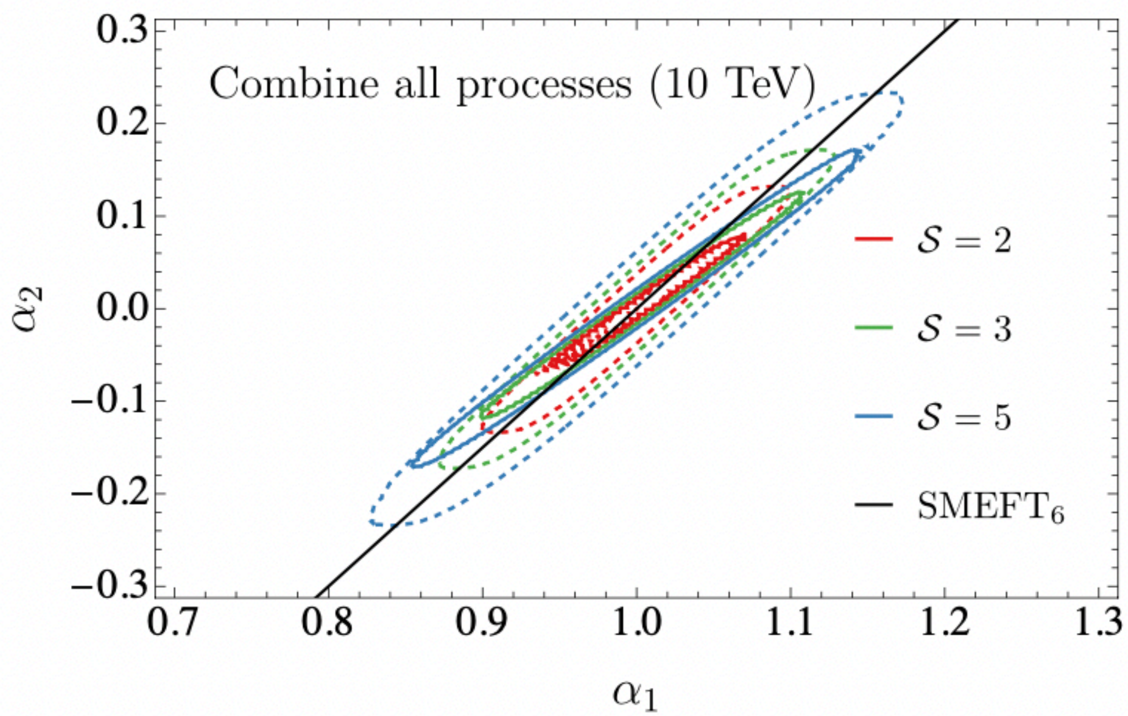
[EC, T. Han et al.; 2312.13082]

Muon Yukawa

H \ V	0	1	2	3	4	5
0	-	Z	Z^2,W^2	Z^3 W^2Z	Z^4, W^4 W^2Z^2	Z^5,W^2Z^3 W^4Z
1	H	ZH	W^2H Z^2H	W^2ZH Z^3H	W^4H, Z^4H W^2Z^2H	-
2	H^2	ZH^2	W^2H^2 Z^2H^2	W^2ZH^2 Z^3H^2	-	-
3	H^3	ZH^3	W^2H^3 Z^2H^3	-	-	-
4	H^4	ZH^4	-	-	-	-
5	H^5	-	-	-	-	-

α_1
$\alpha_{1,2}$
$\alpha_{1,2,3}$
$\alpha_{1\ldots4}$
$\alpha_{1\ldots5}$





Great potential for a 10 TeV muon collider!

- current bounds at LHC: $|\Delta\alpha_1| \in [-0.2, 0.4]$
- SMEFT: $\mu\mu \to HHH$ constrains $|\Delta\alpha_1| \leq 0.05$
- HEFT: $|\Delta\alpha_1| \leq 0.1$ (combination)
- sign determination in HH, HHH, ZZZ
- simultaneous constraints in (α_1, α_2) contour plots

[EC, T. Han et al.; 2312.13082]

Summary & conclusions

- A high energy muon collider is a vector boson collider

- probe Higgs interactions via VBF and longitudinal scattering amplitudes

- promising results for
  - *triple & quartic Higgs self coupling*: better than FCC-hh already at 6 TeV
  - *HHVV*: competitive with FCC-hh at ~ 6 TeV
  - *top Yukawa*: %-level precision at $\sqrt{s} \geq 14$ TeV and $\mathscr{L} \sim 100$ ab^{-1}
  - *muon Yukawa*: 5% precision at a 10 TeV collider

Great prospects for Higgs physics motivate further studies