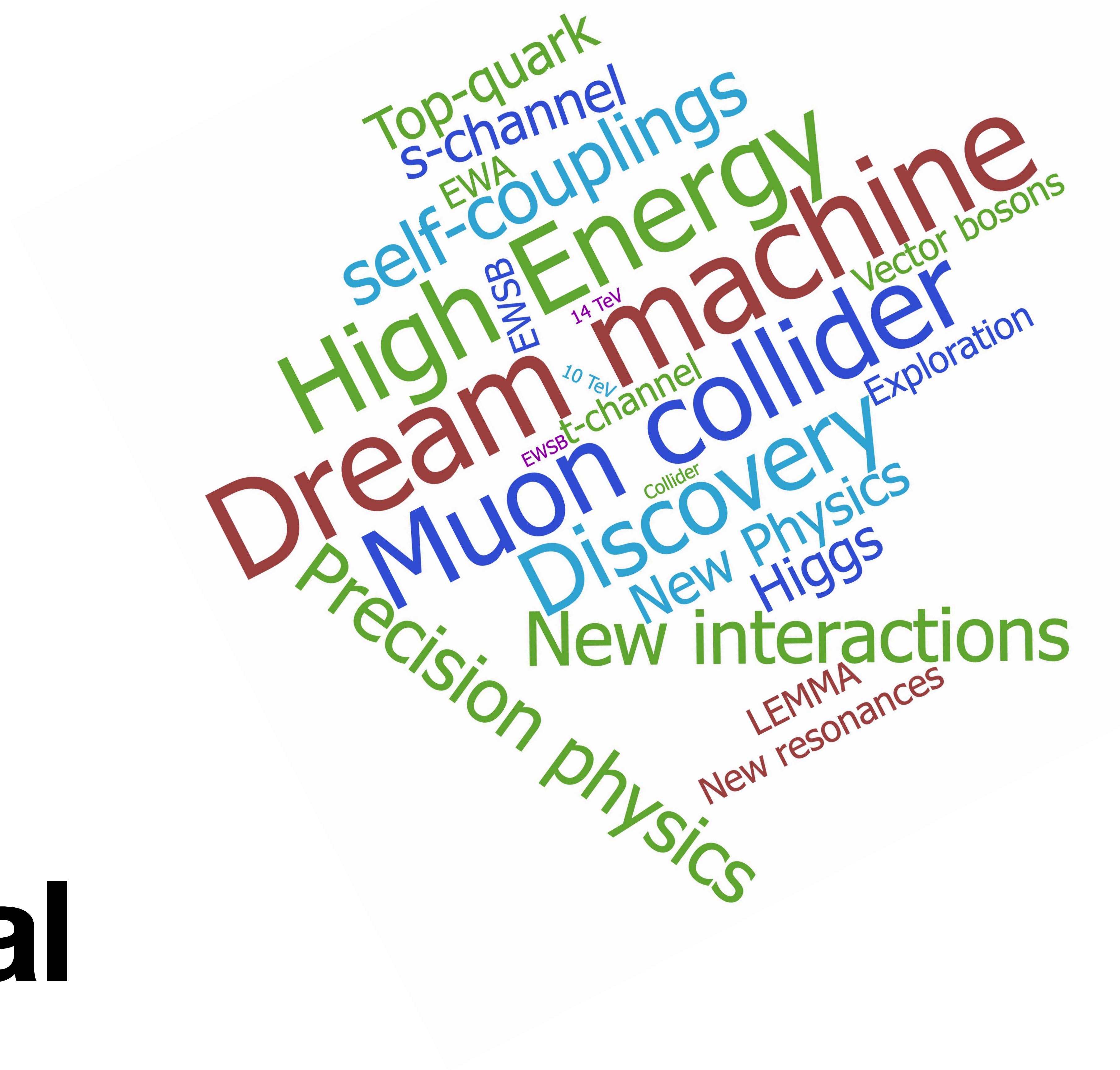


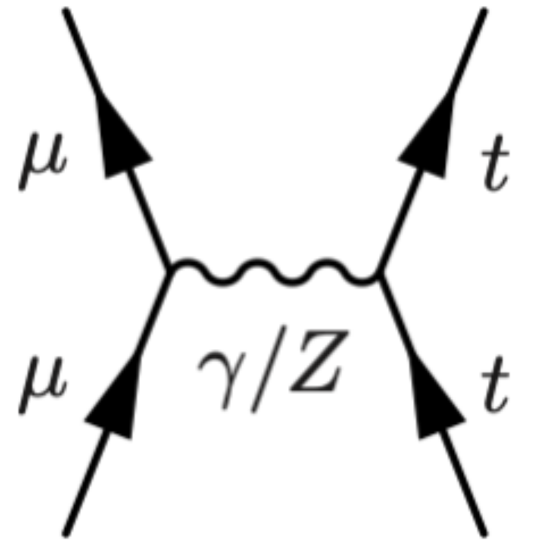
Muon Collider Physics Potential

Fabio Maltoni
Univ/INFN Bologna

Multi-TeV muon collider physics

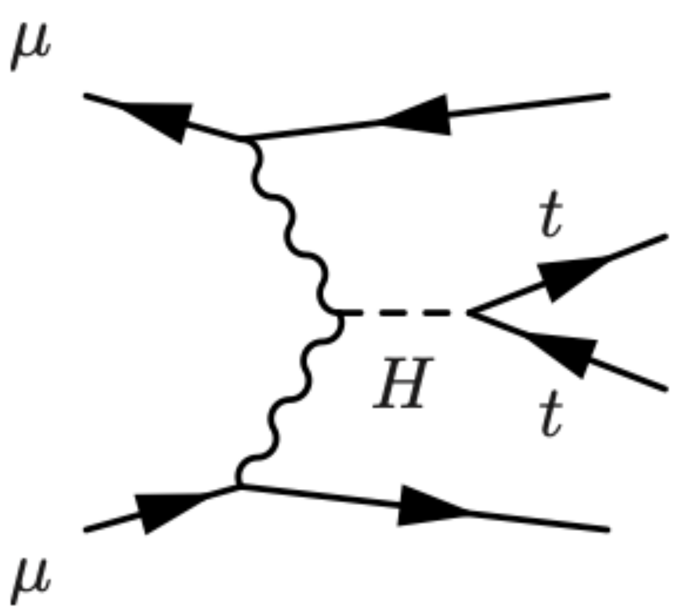
Exploration+Intensity=Two colliders in one

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



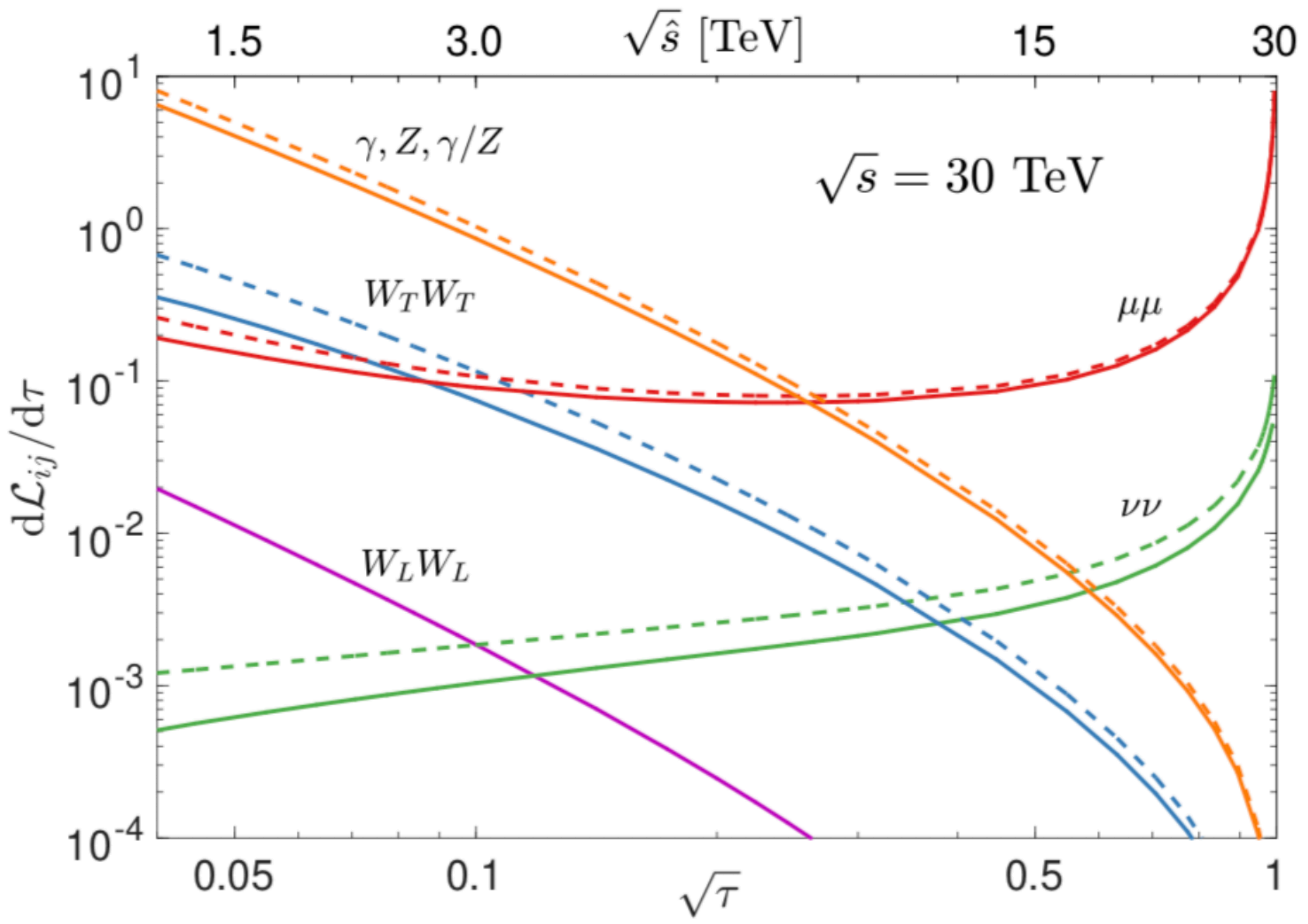
$$\sigma_s \sim \frac{1}{s} \quad \Longleftrightarrow \quad \sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$

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



$\mu^+\mu^-$- annihilation

- "All energy in" at disposal ⇒ ENERGY FRONTIER $M_X = \sqrt{s}/2$
- Needs $\mathscr{L}$ to increase with s



[Han et al. , 2007.14300]

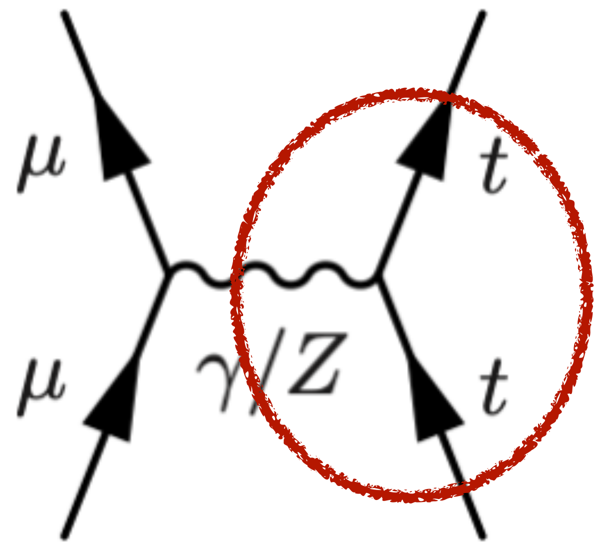
V V - fusion

- Vector PDFS limit the energy < $\sqrt{s}$
- Cross sections increase with energy, become important for PRECISION measurements

Multi-TeV muon collider physics

Two colliders in one

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

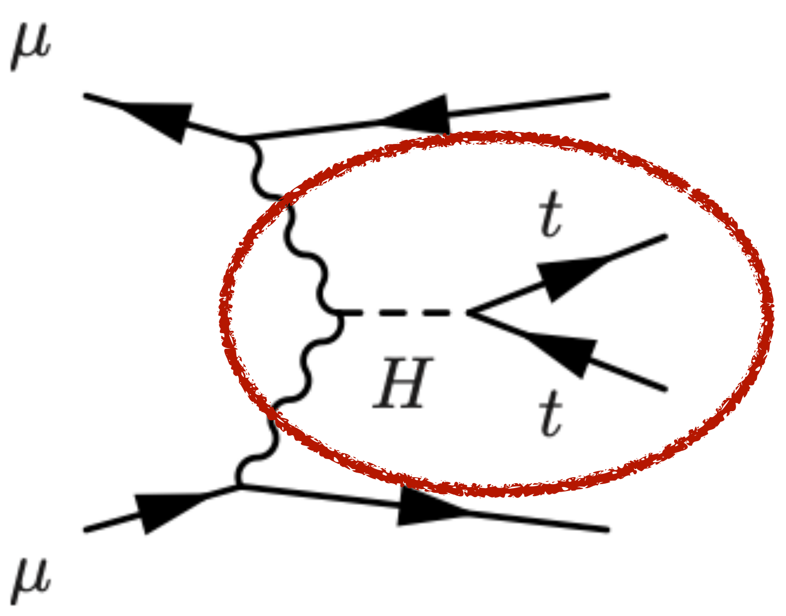


$$\sigma_s \sim \frac{1}{s}$$

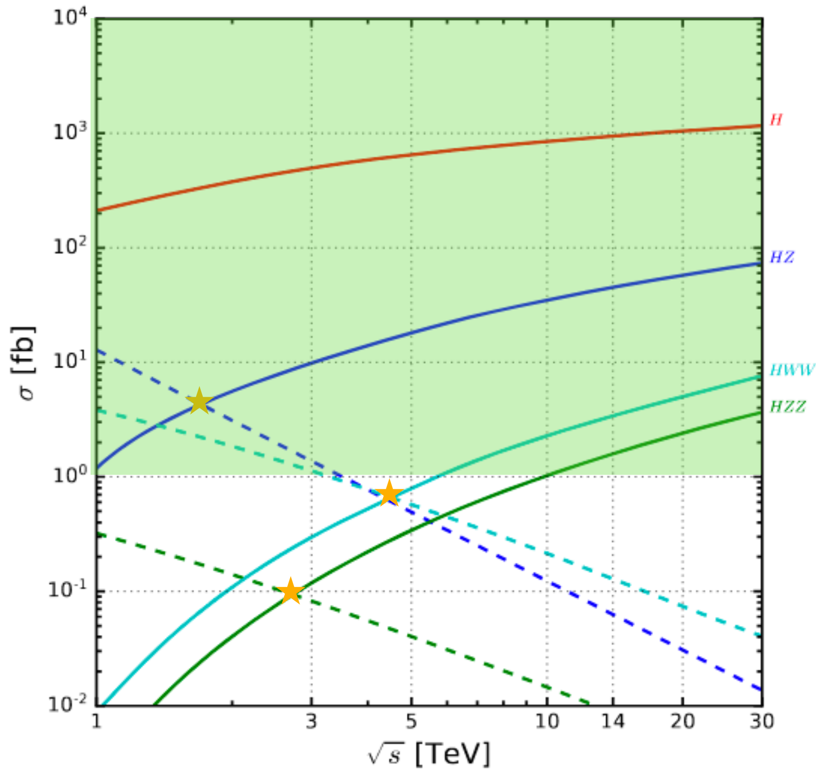
↔

$$\sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$

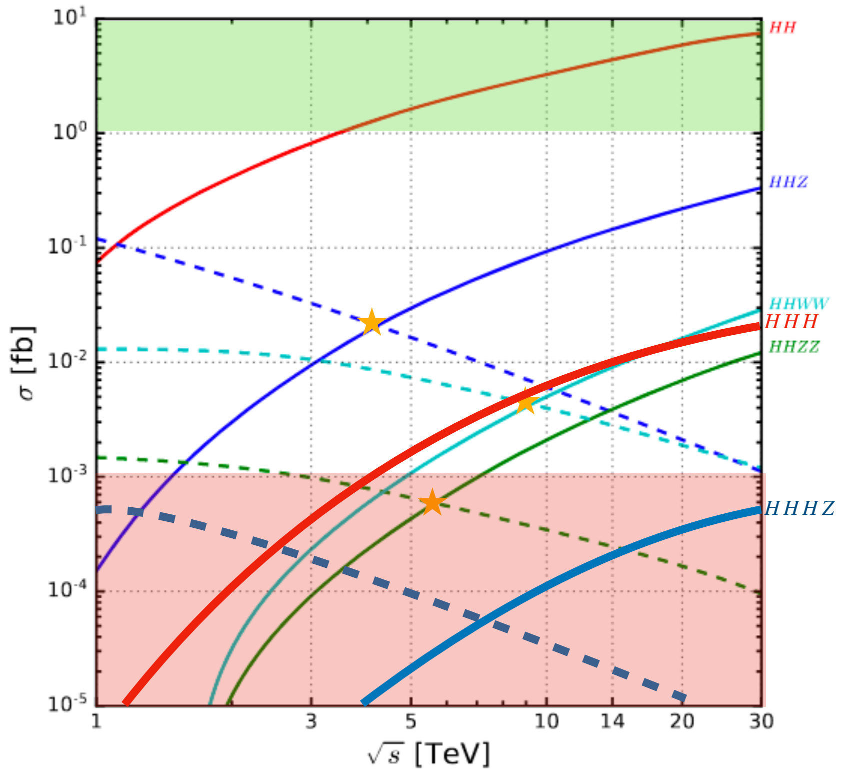
$\sqrt{s} \gtrsim 1\text{-}5\,\text{TeV}$



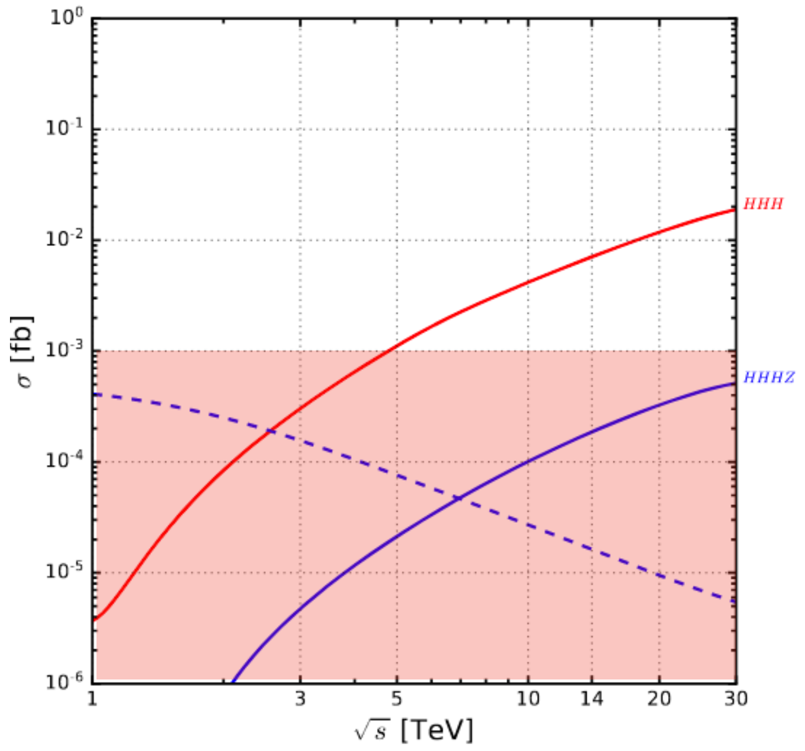
[Costantini et al. 2005.10289]



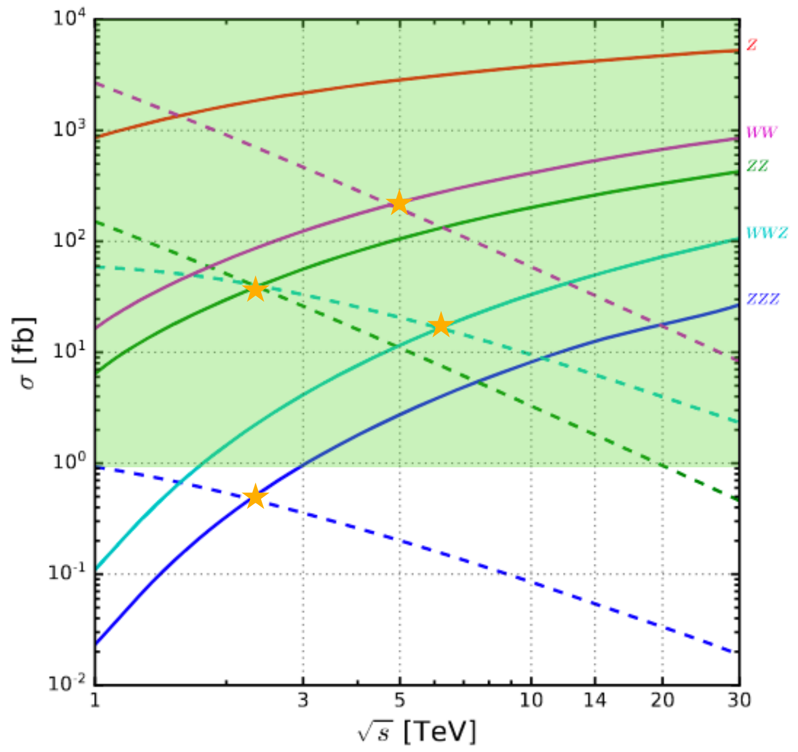
1 Higgs



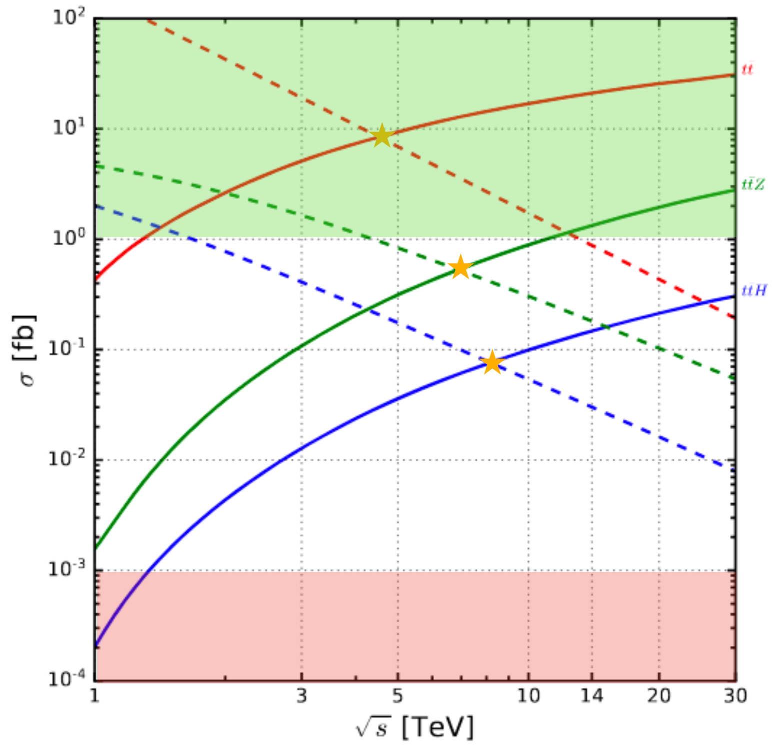
2 Higgs



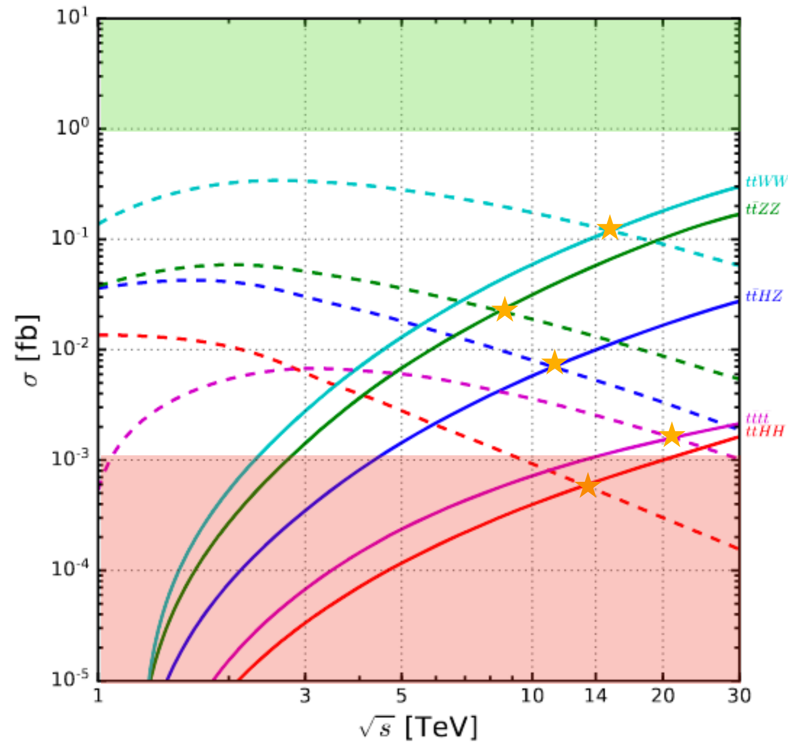
3 Higgs



Vectors



tt(+B)



tt+BB

Fast growing theory interest

Papers

Fusing Vectors into Scalars at High Energy Lepton Colliders

Dario Buttazzo (INFN, Pisa), Diego Redigolo (Princeton, Inst. Advanced Study and Tel Aviv U. and Weizmann Inst.), Filippo Sala (DESY), Andrea Tesi (INFN, Florence) (Jul 12, 2018)

2018 Published in: *JHEP* 11 (2018) 144 • e-Print: 1807.04743 [hep-ph]

2020 Measuring the quartic Higgs self-coupling at a multi-TeV muon collider

Mauro Chiesa (Annecy, LAPTH), Fabio Maltoni (Louvain U., CP3 and U. Bologna, DIFA and INFN, Bologna), Luca Mantani (Louvain U., CP3 and U. Heidelberg, ITP), Barbara Mele (INFN, Rome), Fulvio Piccinini (INFN, Pavia) et al. (Mar 30, 2020)

Published in: *JHEP* 09 (2020) 098 • e-Print: 2003.13628 [hep-ph]

Vector boson fusion at multi-TeV muon colliders

Antonio Costantini (INFN, Bologna), Federico De Lillo (Louvain U., CP3), Fabio Maltoni (Louvain U., CP3 and Bologna U. and INFN, Bologna), Luca Mantani (Louvain U., CP3 and U. Heidelberg, ITP), Olivier Mattelaer (Louvain U., CP3) et al. (May 20, 2020)

Published in: *JHEP* 09 (2020) 080 • e-Print: 2005.10289 [hep-ph]

High energy leptonic collisions and electroweak parton distribution functions

Tao Han (Pittsburgh U.), Yang Ma (Pittsburgh U.), Keping Xie (Pittsburgh U.) (Jul 28, 2020)

Published in: *Phys.Rev.D* 103 (2021) 3, L031301 • e-Print: 2007.14300 [hep-ph]

Electroweak couplings of the Higgs boson at a multi-TeV muon collider

Tao Han (Pittsburgh U.), Da Liu (UC, Davis, QMAP), Ian Low (Northwestern U. and Argonne), Xing Wang (UC, San Diego) (Aug 27, 2020)

Published in: *Phys.Rev.D* 103 (2021) 1, 013002 • e-Print: 2008.12204 [hep-ph]

WIMPs at High Energy Muon Colliders

Tao Han (Pittsburgh U.), Zhen Liu (Maryland U.), Lian-Tao Wang (Chicago U., EFI and Chicago U., KICP), Xing Wang (UC, San Diego) (Sep 23, 2020)

e-Print: 2009.11287 [hep-ph]

Two Paths Towards Precision at a Very High Energy Lepton Collider

Dario Buttazzo (INFN, Pisa), Roberto Franceschini (INFN, Rome3 and Rome III U.), Andrea Wulzer (CERN and EPFL, Lausanne, LPTP and U. Padua, Dept. Phys. Astron.) (Dec 21, 2020)

e-Print: 2012.11555 [hep-ph]

Probing the muon g-2 anomaly at a Muon Collider

Dario Buttazzo (INFN, Pisa), Paride Paradisi (Padua U. and INFN, Padua) (Dec 4, 2020)

e-Print: 2012.02769 [hep-ph]

Heavy Higgs Bosons in 2HDM at a Muon Collider

Tao Han (Pittsburgh U.), Shuailong Li (Arizona U.), Shufang Su (Arizona U.), Wei Su (Adelaide U.), Yongcheng Wu (Carleton U. and Oklahoma State U.) (Feb 16, 2021)

e-Print: 2102.08386 [hep-ph]

2020

2021

Hunting wino and higgsino dark matter at the muon collider with disappearing tracks

Rodolfo Capdevilla (Toronto U. and Perimeter Inst. Theor. Phys.), Federico Meloni (DESY), Rosa Simoniello (CERN), Jose Zurita (Valencia U.) (Feb 22, 2021)

e-Print: 2102.11292 [hep-ph]

Quark and Gluon Contents of a Lepton at High Energies

Tao Han (Pittsburgh U.), Yang Ma (Pittsburgh U.), Keping Xie (Pittsburgh U.) (Mar 17, 2021)

e-Print: 2103.09844 [hep-ph]

Probing the $R_{K^{(*)}}$ Anomaly at a Muon Collider

Guo-Yuan Huang (Heidelberg, Max Planck Inst.), Sudip Jana (Heidelberg, Max Planck Inst.), Farinaldo S. Queiroz (IIP, Brazil and Rio Grande do Norte U.), Werner Rodejohann (Heidelberg, Max Planck Inst.) (Mar 2, 2021)

e-Print: 2103.01617 [hep-ph]

The Muon Smasher's Guide (+)

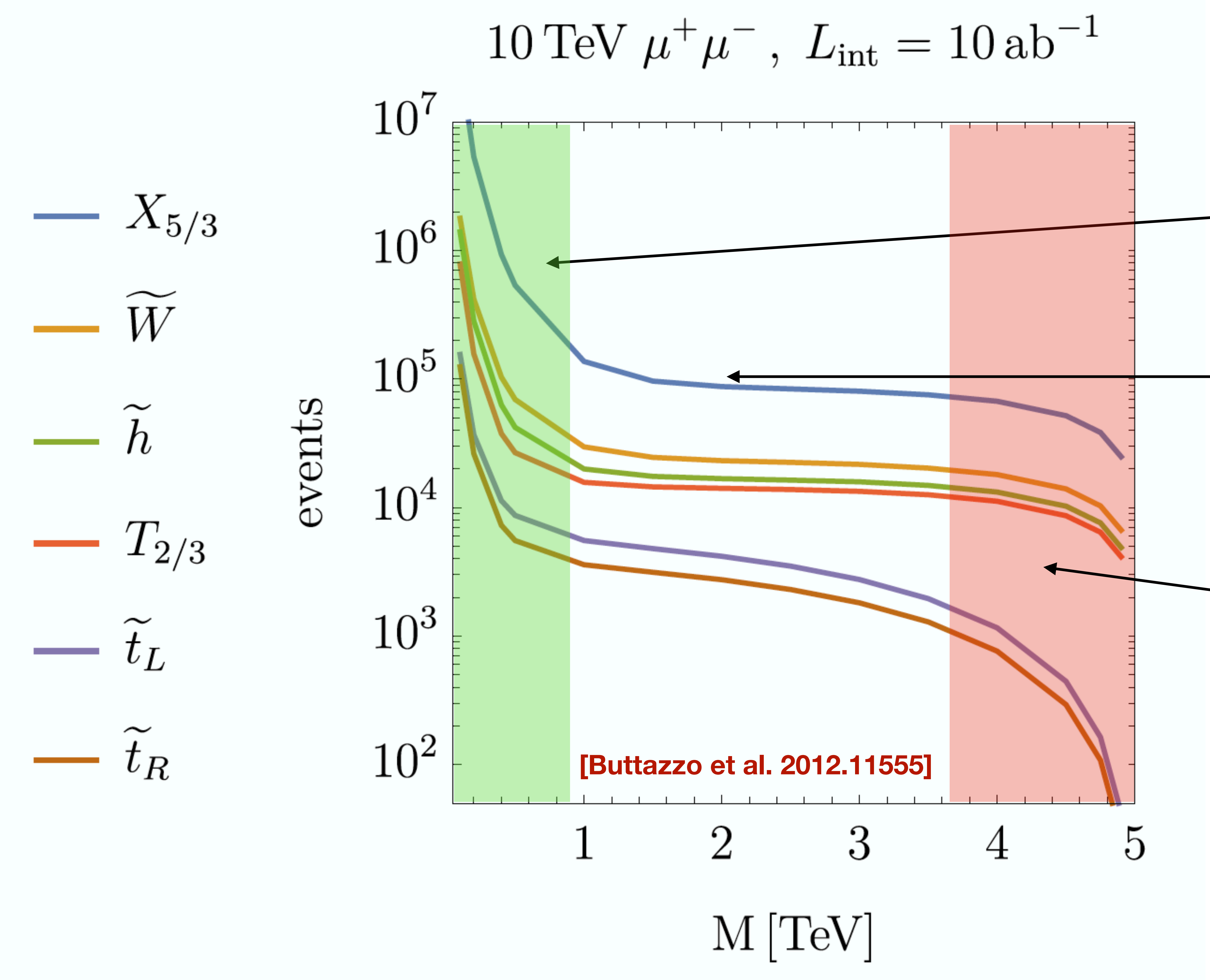
Hind Al Ali, Nima Arkani-Hamed, Ian Banta, Sean Benevedes, Dario Buttazzo, Tianji Cai, Junyi Cheng, Timothy Cohen, Nathaniel Craig, Majid Ekhterachian, JiJi Fan, Matthew Forslund, Isabel Garcia Garcia, Samuel Homiller, Seth Koren, Giacomo Koszegi, Zhen Liu, Qianshu Lu, Kun-Feng Lyu, Alberto Mariotti, Amara McCune, Patrick Meade, Isobel Ojalvo, Umut Oktem, Diego Redigolo, Matthew Reece, Filippo Sala, Raman Sundrum, Dave Sutherland, Andrea Tesi, Timothy Trott, Chris Tully, Lian-Tao Wang, Menghang Wang

105 pages

e-Print: 2103.14043 [hep-ph]

New Physics: direct reach

Pair production of new states



VBF : $\rightarrow \sigma \sim 1/M^2$

s – channel $\rightarrow \sigma \sim 1/s = \text{const}.$

$M^2/s \lesssim 1 \rightarrow \begin{array}{l} \sigma_S \sim \beta^3/s \\ \sigma_F \sim \beta/s \end{array}$

Indirect effects vs direct reach in SUSY

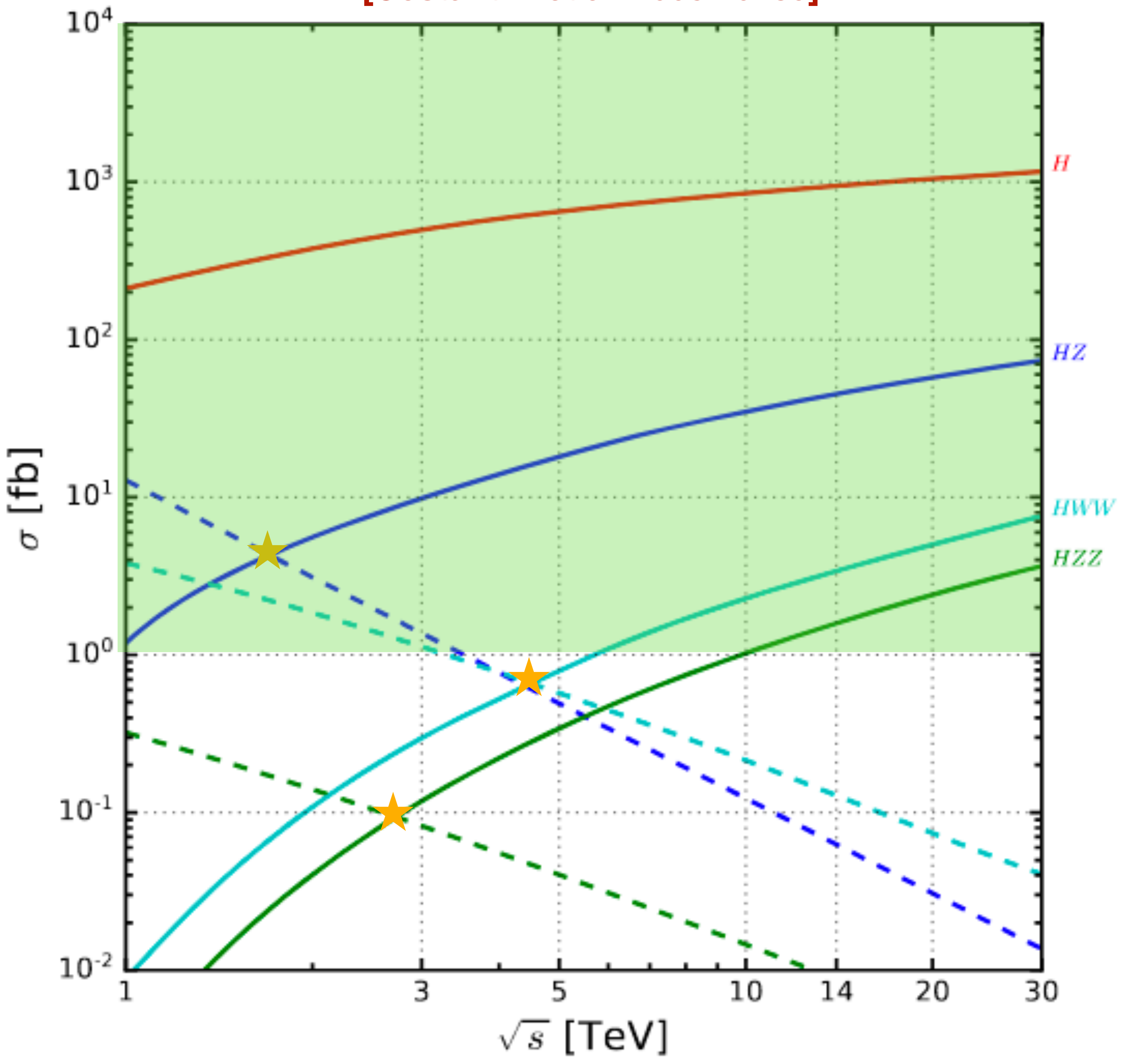
Targets by fine tuning: indirect vs direct

			Indirect	Direct [Smasher's guide: 2103.14043]
Tree-level	$\Delta_{\tilde{h}} \simeq \frac{2m_{\tilde{h}}^2}{m_h^2}$	$\Rightarrow$	$10\,\% \to m_{\tilde{h}} = 300\,\mathrm{GeV}$	*
			$1\,\% \to m_{\tilde{h}} = 900\,\mathrm{GeV}$	*
			$0.1\,\% \to m_{\tilde{h}} = 2.8\,\mathrm{TeV}$	>10 TeV w/ 10 iab
One-loop	$\Delta_{\tilde{t}} \simeq \frac{3y_t^2}{4\pi^2}\frac{m_{\tilde{t}}^2}{m_h^2}\log\frac{\Lambda}{m_{\tilde{t}}}$	$\Rightarrow$	$10\,\% \to m_{\tilde{t}} = 1\,\mathrm{TeV}$	*
			$1\,\% \to m_{\tilde{t}} = 3\,\mathrm{TeV}$	>10 TeV w/ 10 iab
			$0.1\,\% \to m_{\tilde{t}} = 10\,\mathrm{TeV}$	*
Two-loop	$\Delta_{\tilde{g}} \simeq \frac{\alpha_s y_t^2}{\pi^3}\frac{m_{\tilde{g}}^2}{m_h^2}\log^2\frac{\Lambda}{m_{\tilde{g}}}$	$\Rightarrow$	$10\,\% \to m_{\tilde{g}} = 3\,\mathrm{TeV}$	>10 TeV w/ 10 iab
			$1\,\% \to m_{\tilde{g}} = 10\,\mathrm{TeV}$	*
			$0.1\,\% \to m_{\tilde{t}} = 30\,\mathrm{TeV}$	*

Higgs couplings

A first look at the sensitivity with the kappa's

[Costantini et al. 2005.10289]



Higgs:

@ FCC-ee 240 GeV: (sigma=200 fb) * 5 iab = 1M (ZH production)

@ μ-C 10 TeV: (sigma=10^3 fb) * 10 iab = 10M (via WW/ZZ→H)

@ FCC-hh 100 TeV: (sigma=1 nb) * 30 iab = 30G (via gg→H)

Higgs couplings

A first look at the sensitivity with the kappa’s

10 parameter fit. The simplest one. No BR_{BSM} .

[Higgs European Strategy Group: 1905.03764]

kappa-0	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 15000	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

[Smasher’s guide: 2103.14043]

	muon collider @ 10 TeV w/ 10 iab only	muon collider @ 10 TeV w/ 10 iab + HL-LHC	muon collider @ 10 TeV w/ 10 iab + HL-LHC + Higgs factory
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27

Very preliminary

mostly better/equivalent

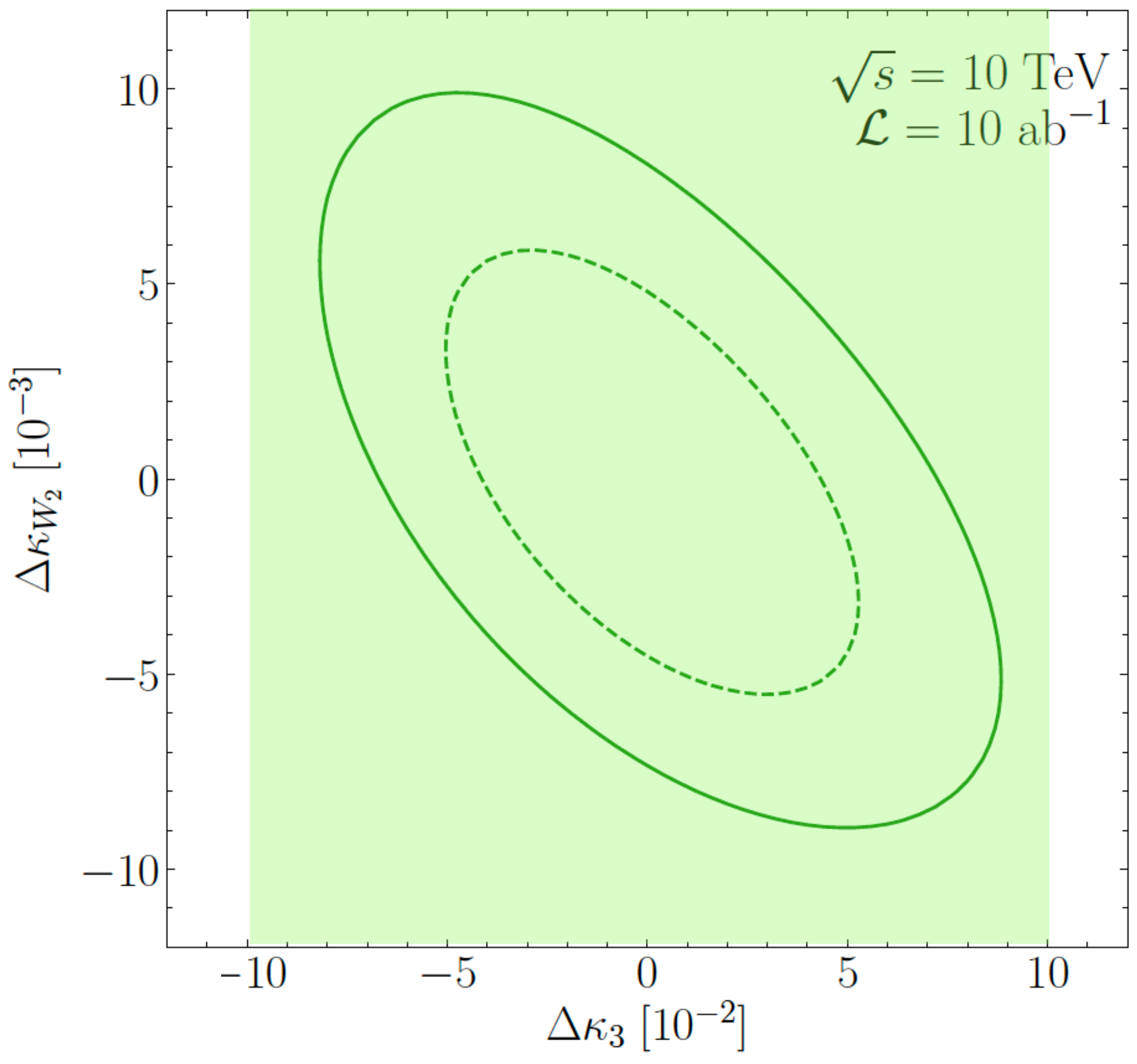
always better

Higgs couplings

Sensitivity to the Higgs self-interactions

λ_3

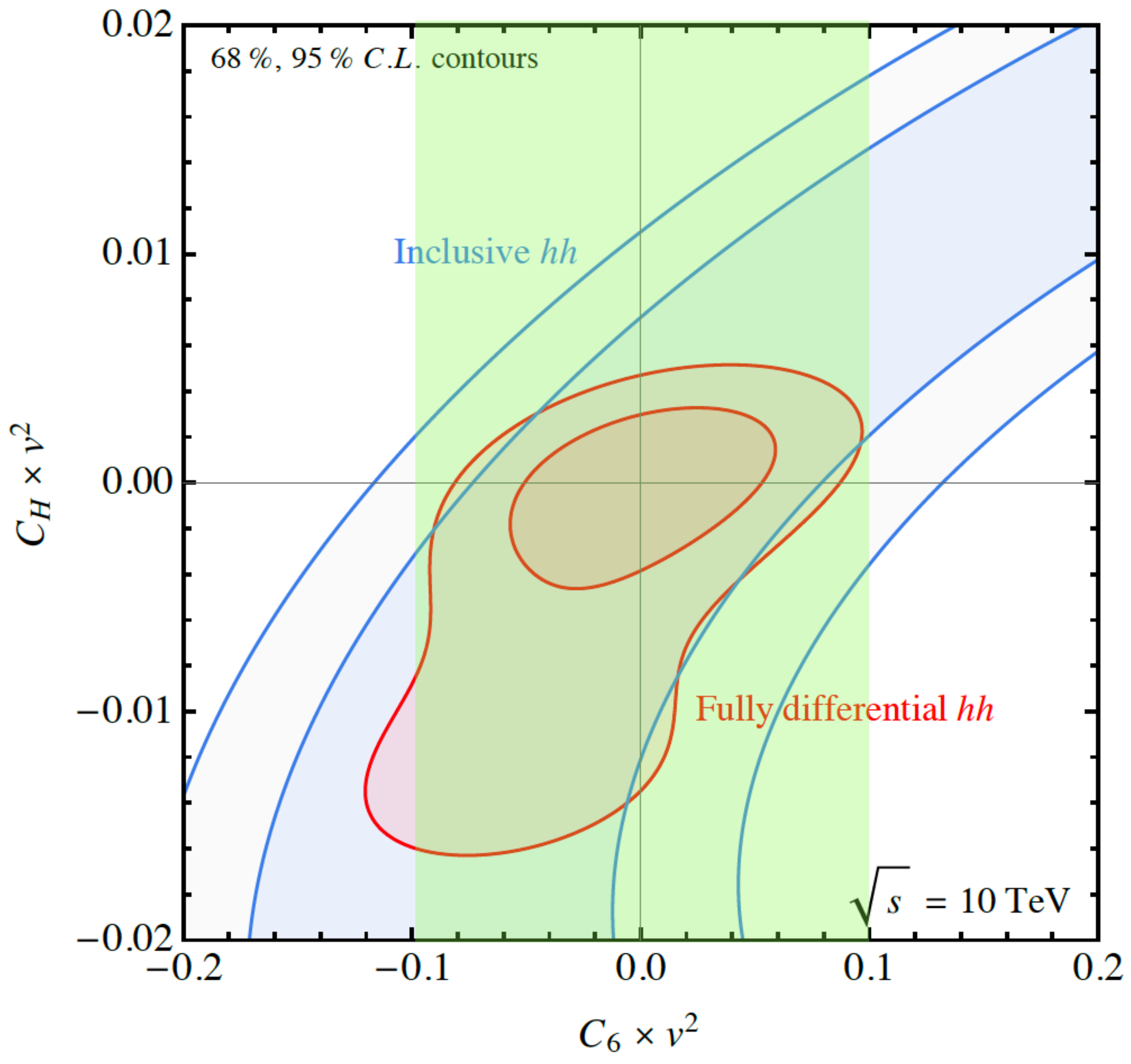
[Han et al. 2008.12204]



(HH+WW prod only)

λ_3

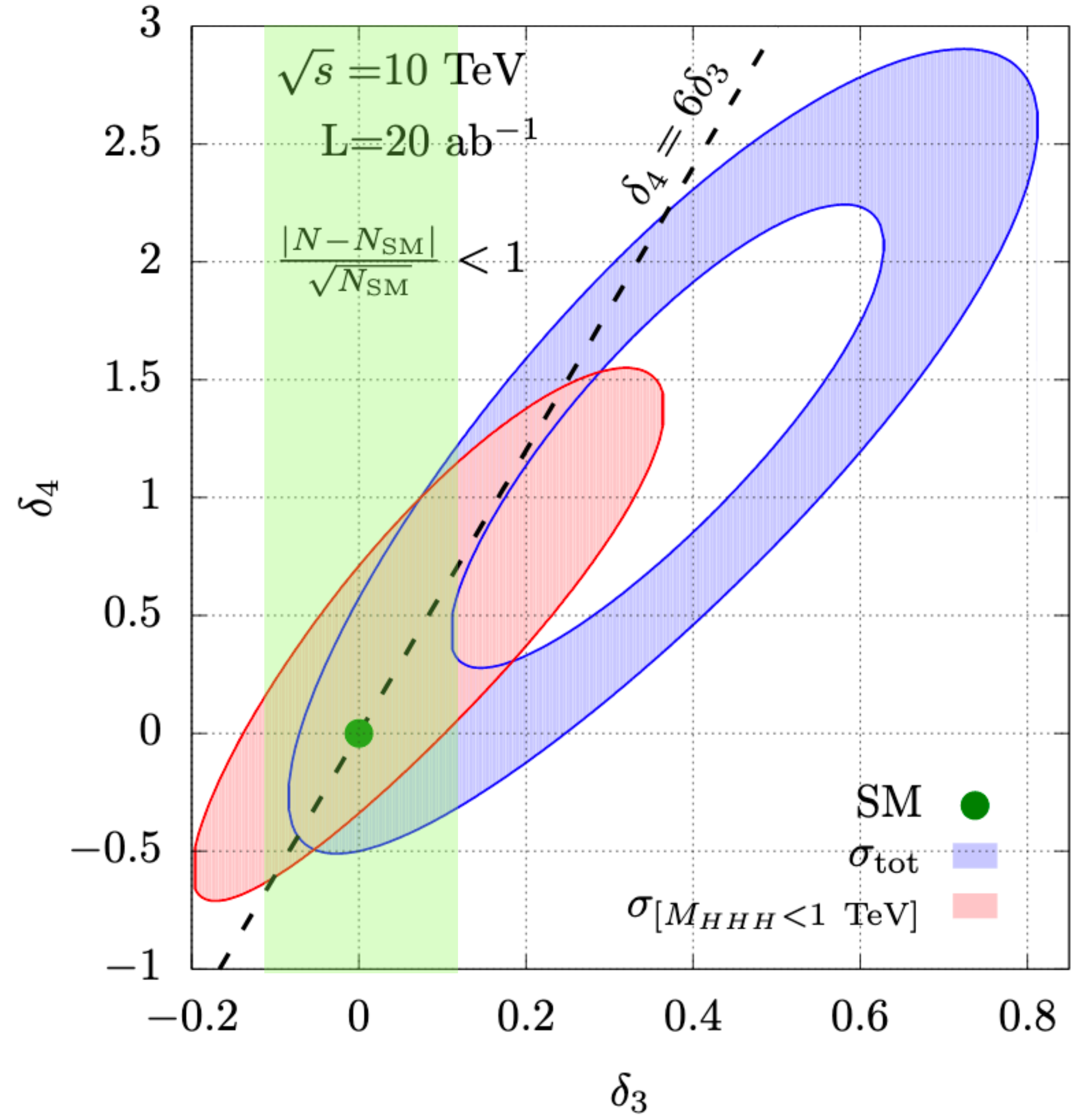
[Buttazzo et al. 2012.11555]



(HH prod only)

λ_4

[Chiesa et al. 2003.13628]



(HHH prod only)

Interplay with precision physics

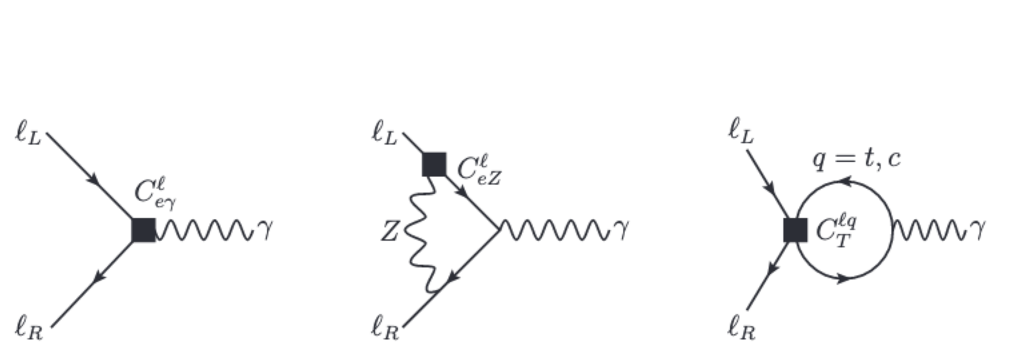
(g-2)μ

Δa_μ **discrepancy at** $\sim 3.7\,\sigma$ **level:**

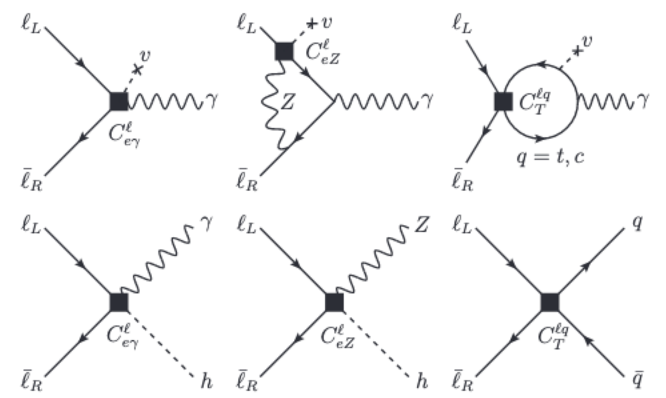
$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = (2.79 \pm 0.76) \times 10^{-9}$$

$$\Delta a_\mu \equiv a_\mu^{\rm NP} \approx (a_\mu^{\rm SM})_{weak} \approx \frac{m_\mu^2}{16\pi^2 v^2} \approx 2 \times 10^{-9}$$

- A weakly interacting NP at $\Lambda \approx v$ can naturally explain $\Delta a_\mu \approx 2 \times 10^{-9}$.
- $\Lambda \approx v$ favoured by the *hierarchy problem* and by a WIMP DM candidate.



$$\frac{\Delta a_\mu}{3\times 10^{-9}} \approx \left(\frac{250\ {\rm TeV}}{\Lambda}\right)^2 \left(C^\mu_{e\gamma} - 0.2 C_T^{\mu t} - 0.002 C_T^{\mu c} - 0.05 C^\mu_{eZ}\right).$$



$$\sigma^{\rm cut}_{\mu\mu\to h\gamma} \approx 0.5\,{\rm ab} \left(\frac{\sqrt{s}}{30\ {\rm TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2$$

$$\sigma_{\mu\mu\to Zh} \approx 38\,{\rm ab} \left(\frac{\sqrt{s}}{10\ {\rm TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2$$

$$\sigma_{\mu\mu\to t\bar{t}} \approx 58\,{\rm ab} \left(\frac{\sqrt{s}}{10\ {\rm TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2$$

$$\sigma_{\mu\mu\to c\bar{c}} \approx 100\,{\rm fb} \left(\frac{\sqrt{s}}{3\ {\rm TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2$$

[Buttazzo and Paradisi, 2012.02769]

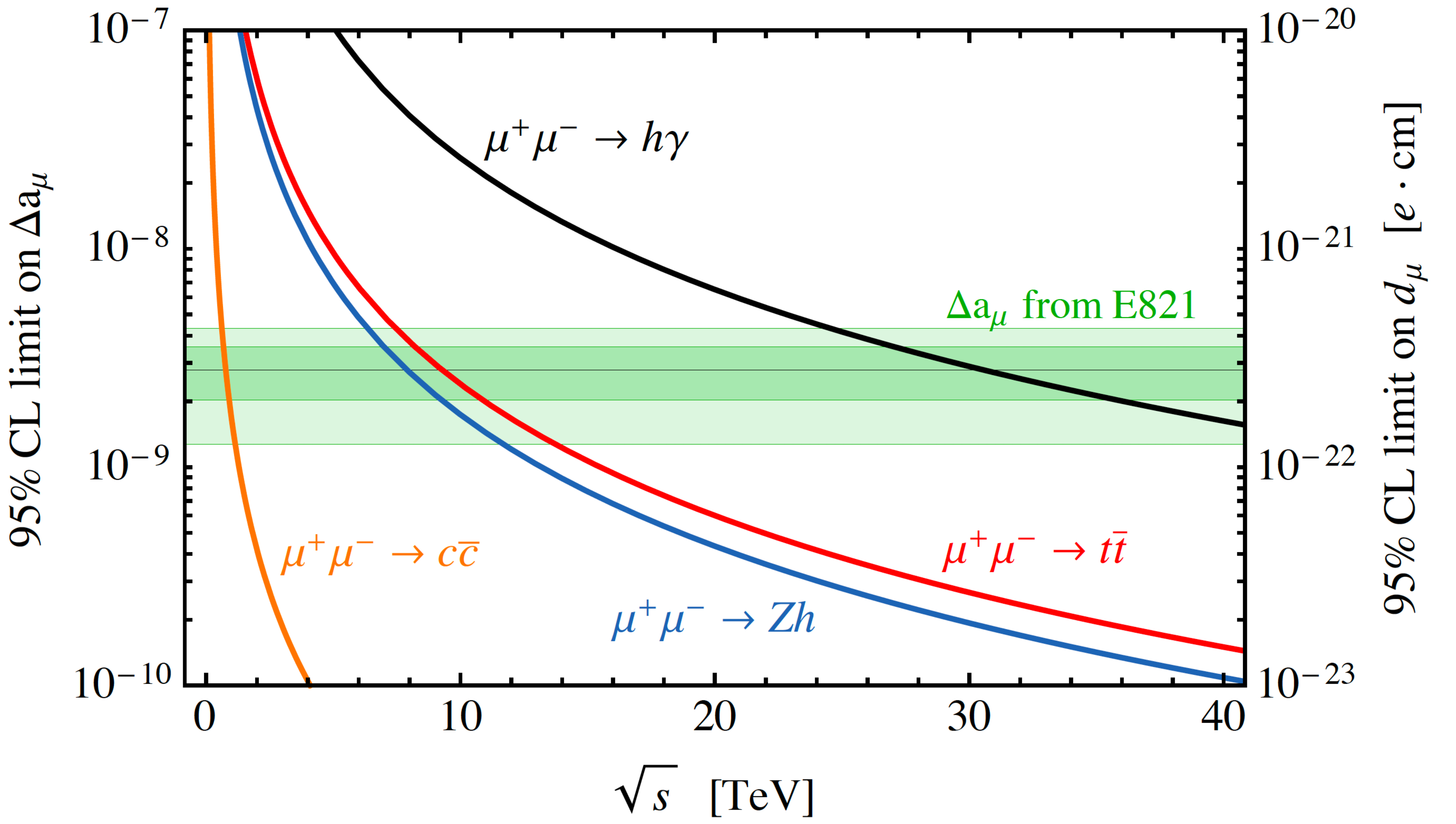


Figure: 95% C.L. reach on the muon anomalous magnetic moment Δa_μ, as well as on the muon EDM d_μ, as a function of the center-of-mass energy $\sqrt{s}$ from various processes.

People
Theory/Phenomenology

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Mauro Moretti (INFN-FE)

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Andrea Wulzer (PD)

…

+

Collaborating post-docs and PhD students:

Mauro Chiesa: PD (Pavia)

Clara del Pio: PhD (Pavia)

Antonio Costantini: PD (Bologna -> Louvain (now))

Richard Ruiz: PD (Louvain -> PAN)

Luca Mantani: PhD (Louvain (now)) ->PD (Cambridge)

Xiaoran Zhao: PhD (Louvain) -> PD (RM3 (now))

⇒

Message:

Italian theory community uniquely placed in this endeavour (SM, BSM, Simulations/MC) and with significant interest.

Close collaborations with the experimental efforts with mutual benefit.

Having the INFN support for HR in the TH exploration would allow our community to keep the leadership while the US and the rest of the world are gaining momentum!

The known unknowns

Fundamentals

- Predictions for both Precision and HE behaviors
- EW physics at high energy: Soft vs collinear resummation.
- MC's for $\mu - C$'s
- Resummation vs power corrections: matching
- EW and QCD NLO computations + PS
- "QCD" Backgrounds to Higgs analyses
- Multi boson production
- Precision Higgs/Top/EW physics
- ....

NP Reach

- Dark Matter
- SUSY
- Multi-Higgs
- UV complete models
- Composite models
- SMEFT : precision vs HE
- Leptogenesis
- Leptophilic physics
- EW charged new physics states
- Majorana/Dirac neutrinos
- ....

Interplay

- Flavour physics
- Flavour anomalies
- $(g-2)_\mu$
- SMEFT
- HL-LHC feedback information
- Linking HE and bulk measurements within the $\mu - C$
- Lepton flavour
- …

Ex: Assegno 2 years | Assegno 2 years | Assegno 2 years

Summary

* Theorist's pow: A multi-TeV collider is a dream machine

* Energy exploration together with intensity/precision at the same time.

* With a reference 10 TeV/10 iab setup, very first studies already show great potential => much more work to nail it!

* ….and of course muons are the stars of the day…!!

$$R_{K^{(*)}} = \left. \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)} \right|_{q^2 \in [q^2_{\rm min}, q^2_{\rm max}]} \quad \& \quad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$$

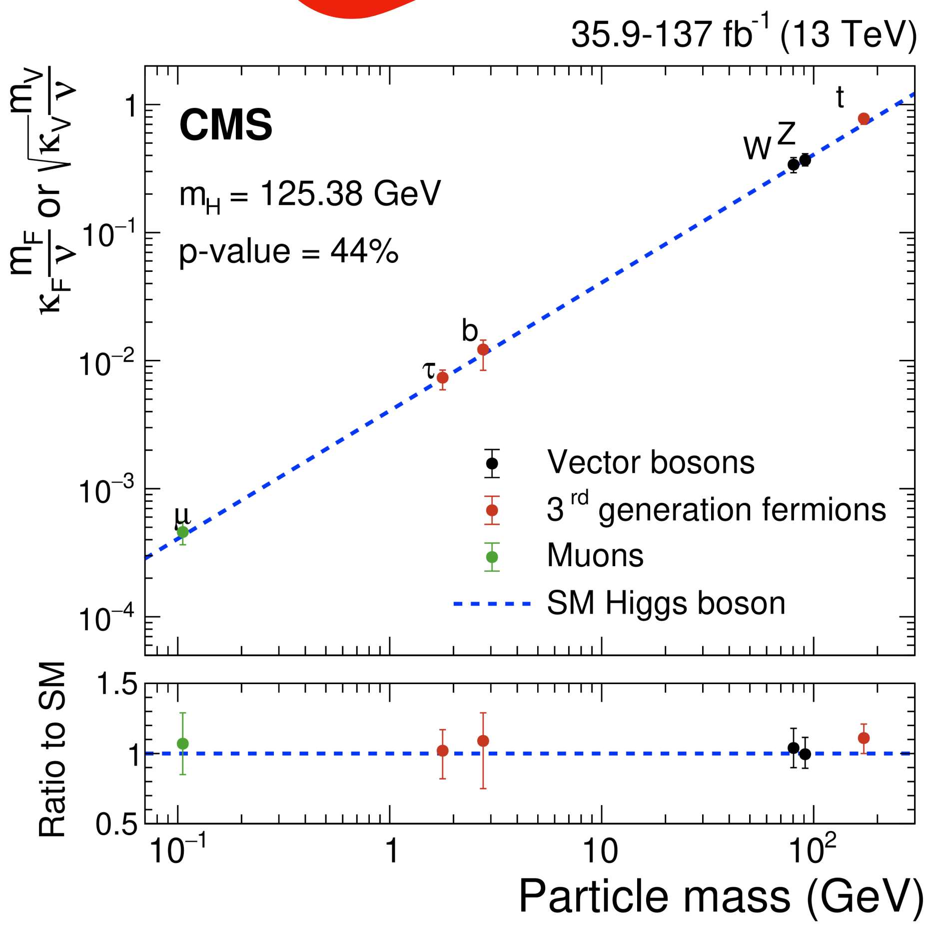
$$R_K^{[1.1,6]} = 0.847(42)^{\rm LHCb} \quad {\rm vs} \quad R_K^{[1,6]} = 1.00(1)^{\rm SM}$$

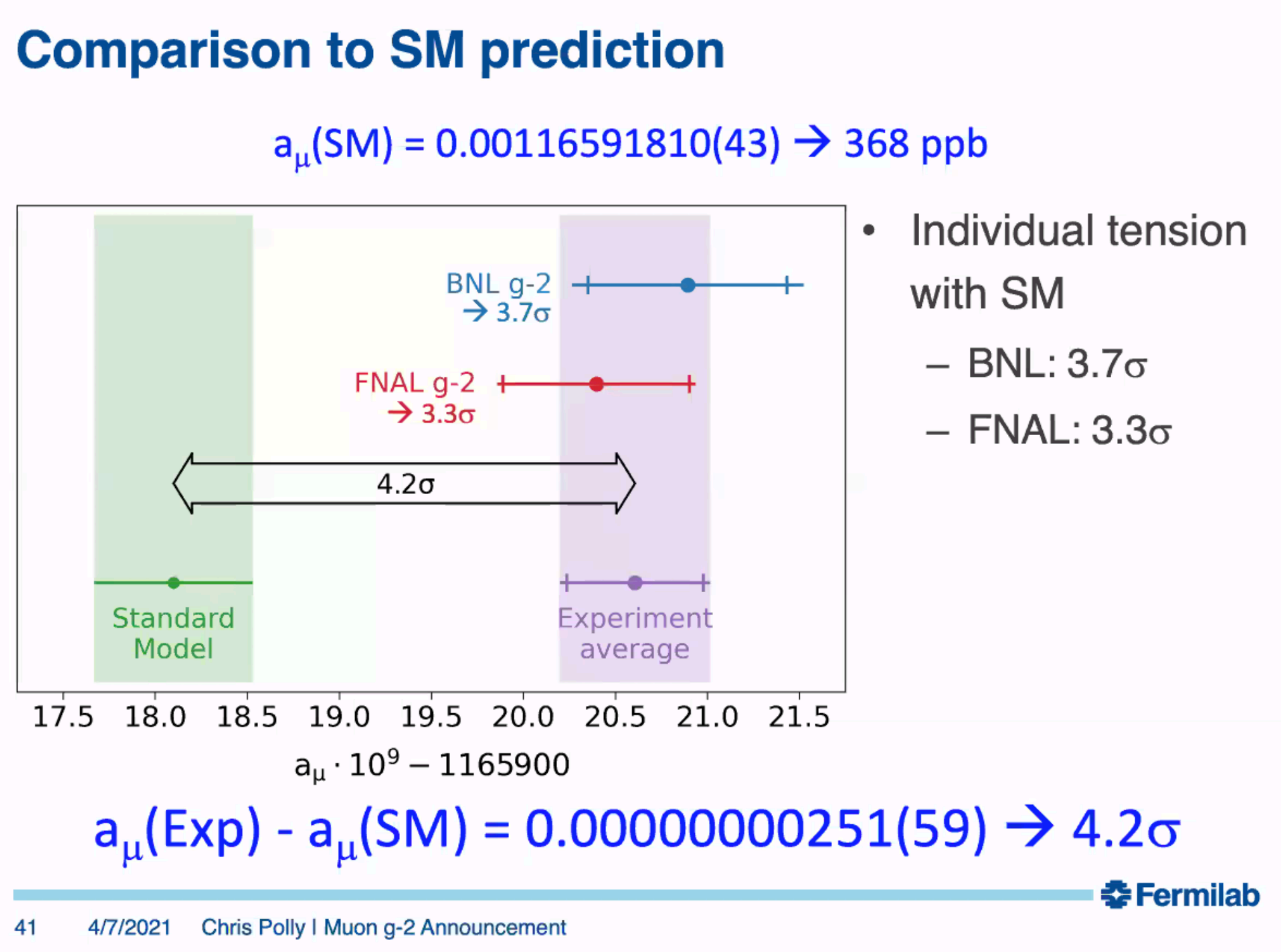
$$R_{K^*}^{[1.1,6]} = 0.71(10)^{\rm LHCb} \quad {\rm vs} \quad R_{K^*}^{[1,6]} = 1.00(1)^{\rm SM}$$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar\nu)}{\mathcal{B}(B \to D^{(*)}\ell\bar\nu)}_{\ell \in (e,\mu)} \quad \& \quad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$

$$\text{Exp}: \quad R_D = 0.340 \pm 0.030\,, \quad R_{D^*} = 0.295 \pm 0.014$$

$$\text{SM}: \quad R_D^{\rm SM} = 0.293 \pm 0.008\,, \quad R_{D^*}^{\rm SM} = 0.257 \pm 0.003$$





Supplemental material

Proton-proton vs muon-muon

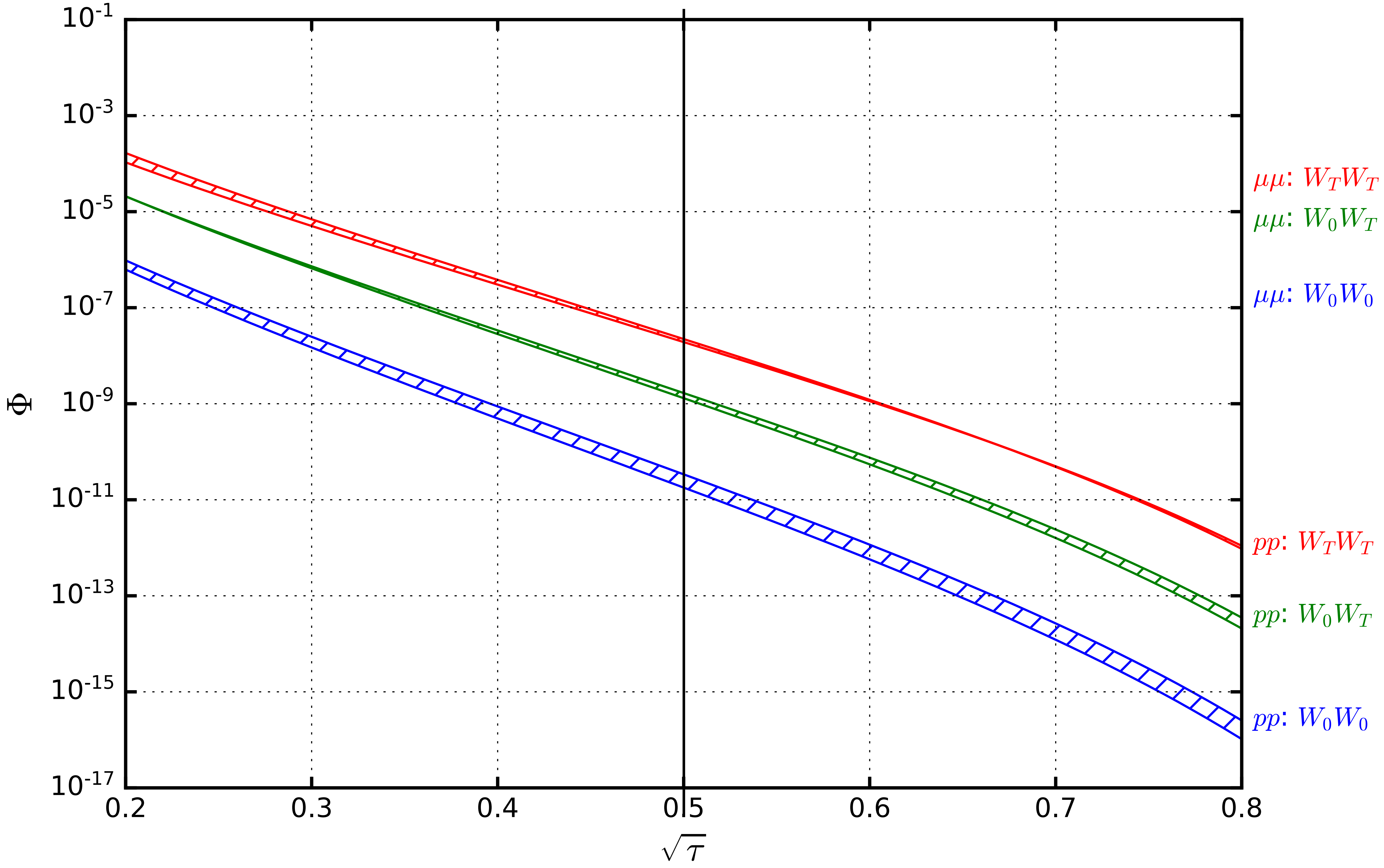
$$\Phi_{W^+_{\lambda_1} W^-_{\lambda_2}}(\tau, \mu_f) = \int_\tau^1 \frac{d\xi}{\xi}\; f_{W_{\lambda_1}/\mu}\left(\xi, \mu_f\right) f_{W_{\lambda_2}/\mu}\left(\frac{\tau}{\xi}, \mu_f\right)$$

This plot can be used in any case, but it is particularly simple when considering a muon-collider in the same ring of a proton collider, $\sqrt{s}_{\mu\mu} = \sqrt{s}_{pp}$.

For 2->1, let's take for example $\sqrt{\tau} = \frac{M}{\sqrt{s}} = \frac{1}{2}$

the luminosity ratio $\mu\mu/pp$ is larger than 10^4 !

[Costantini et al. 2005.10289]



MonteCarlos

- Event generation at LO based on matrix elements available (e.g. MadGraph and Whizard) for s-channel

 - $\mu^+\mu^- \to X$

 and t-channel (MadGraph and Whizard)

 - $\mu^+\mu^- \to X + \nu_\mu \bar{\nu}_\mu$ W·W fusion
 - $\mu^+\mu^- \to X + \nu_\mu \mu$ W·Z/γ* fusion
 - $\mu^+\mu^- \to X + \mu \bar{\mu}$ Z/γ*·Z/γ* fusion

Recent Examples:

- 2006.16277 * Capdevilla et al. (MadGraph)
- 2005.10289 * Costantini et al. (MadGraph)
- 2003.13628 * Chiesa et al (MadGraph and Whizard)
- 2002.12218 * Kumar et al. (MadGraph)
- 2001.04431 * Bartosik et al. (Pythia8)
- 1810.10993 * Di Luzio et al. (by hand)
- 1807.04743 * Buttazzo et al. (MadGraph)
- more…

- EWA/EZA(/EPA) LL implementations being validated in MadGraph to be compared with available resummed results.

- BSM scenarios including EFT available in FeynRules/MadGraph

The size of the Higgs

$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$

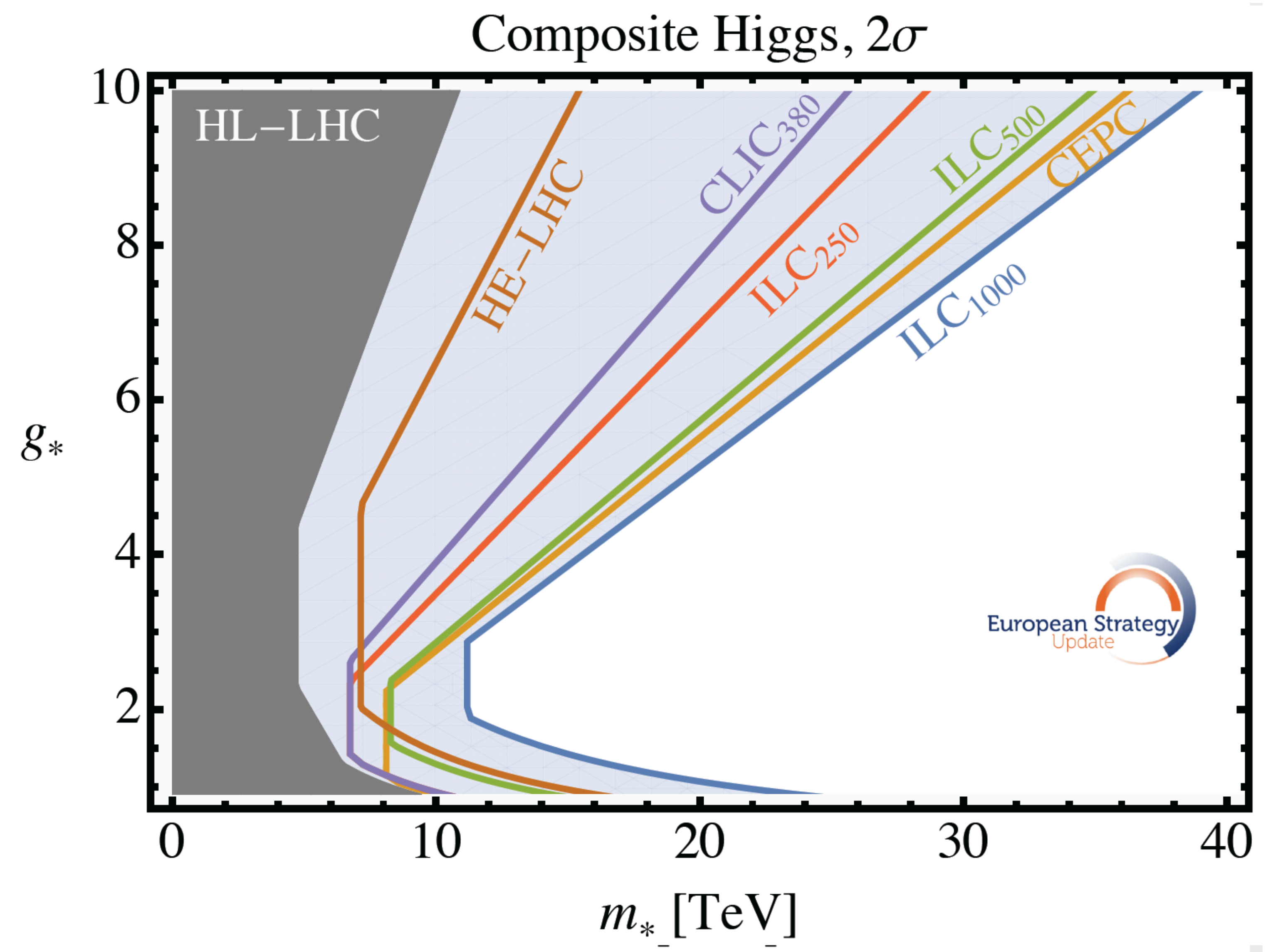
$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

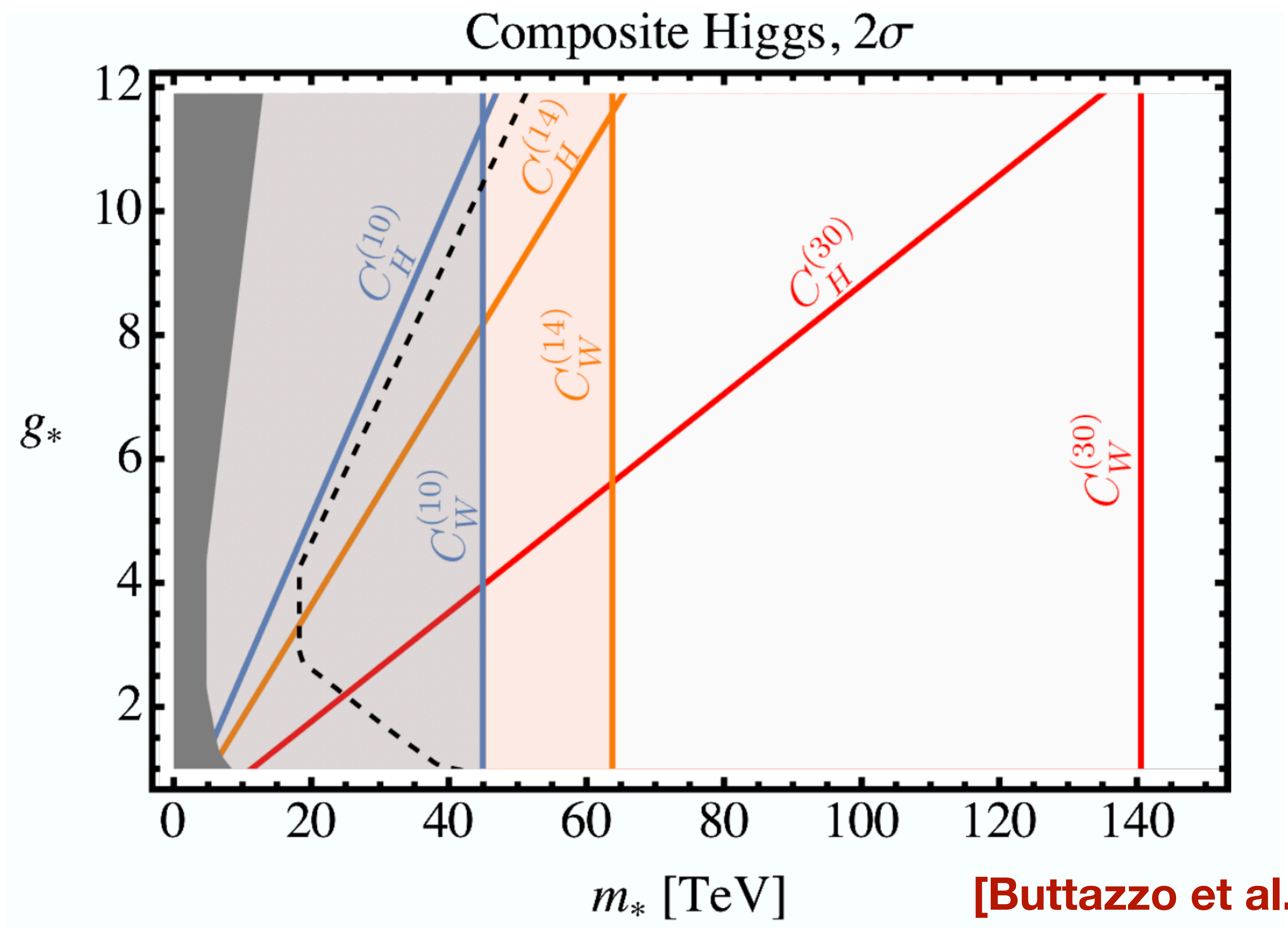
$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

$1/f \sim g_\star/m_\star$

$1/(g_\star f) \sim 1/m_\star$

$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

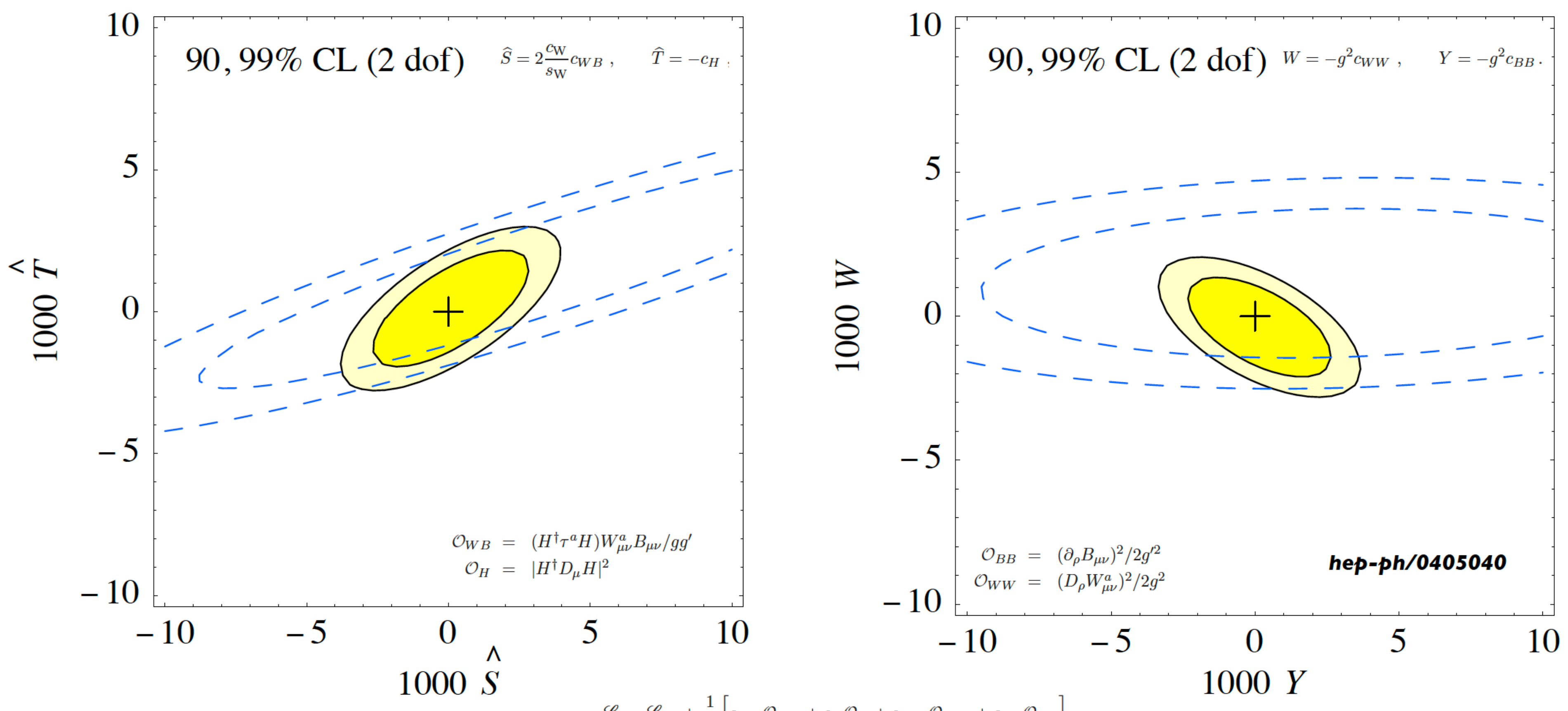




[Buttazzo et al. 2012.11555]

Multi-boson

Oblique parameters

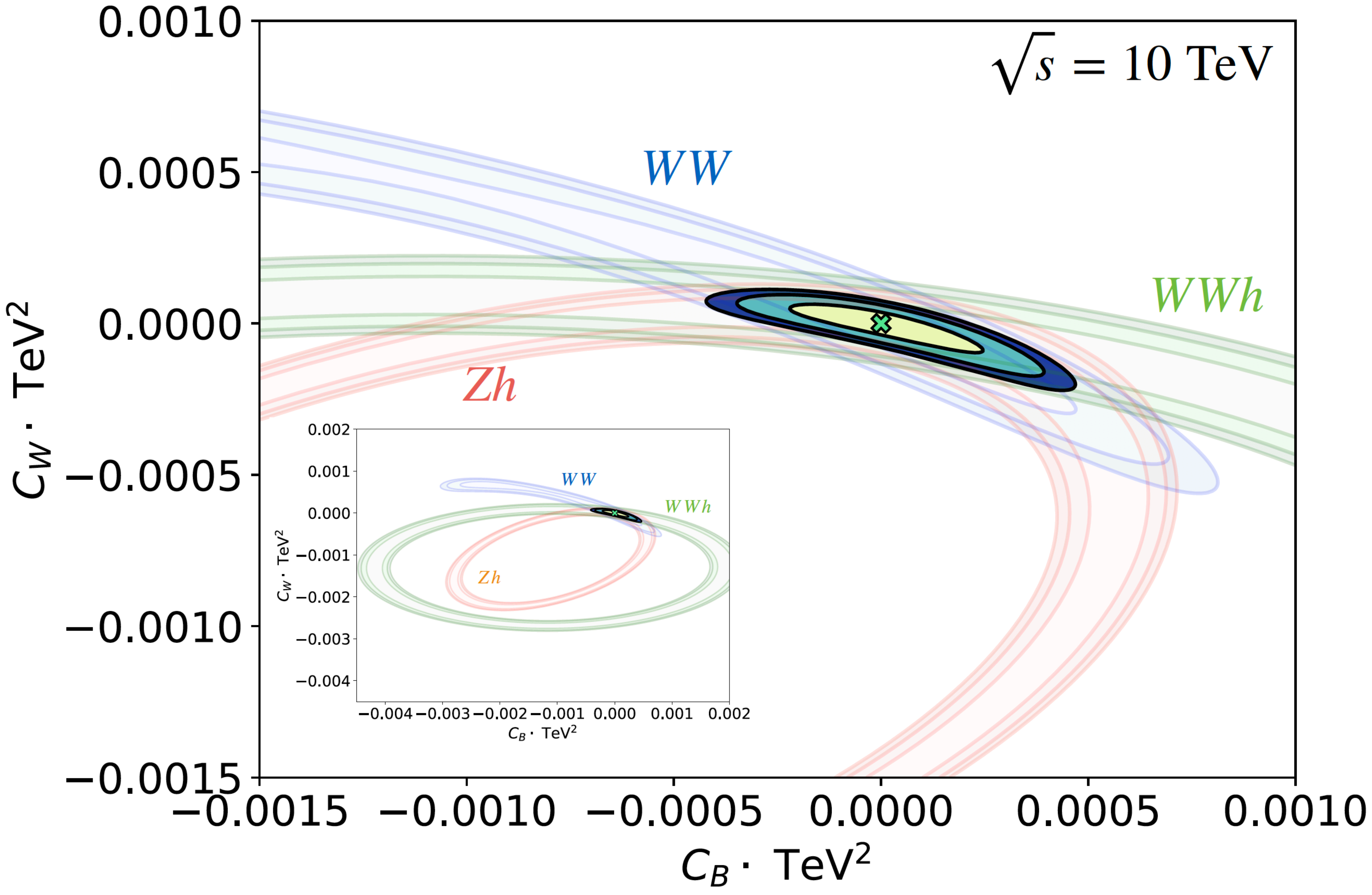


$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{v^2}\left[c_{WB}\mathcal{O}_{WB} + c_H\mathcal{O}_H + c_{WW}\mathcal{O}_{WW} + c_{BB}\mathcal{O}_{BB}\right]$$

$$S = \frac{4 s_W^2}{\alpha_{em}} \cdot \hat{S} \simeq 119 \cdot \hat{S} < O(0.1)$$

$$M_{NP} > O(30 \cdot m_W)$$

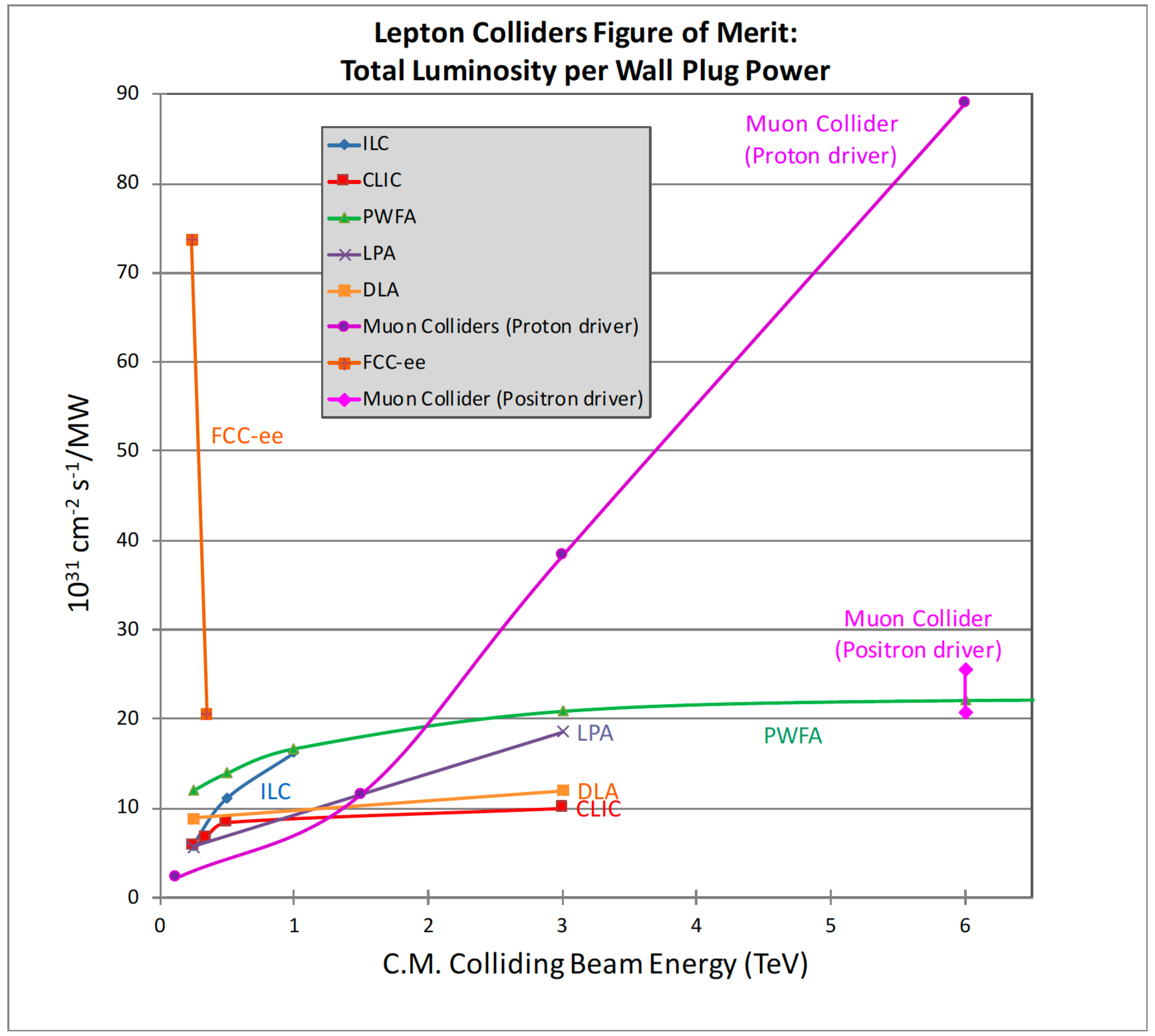
[Buttazzo et al. 2012.11555]

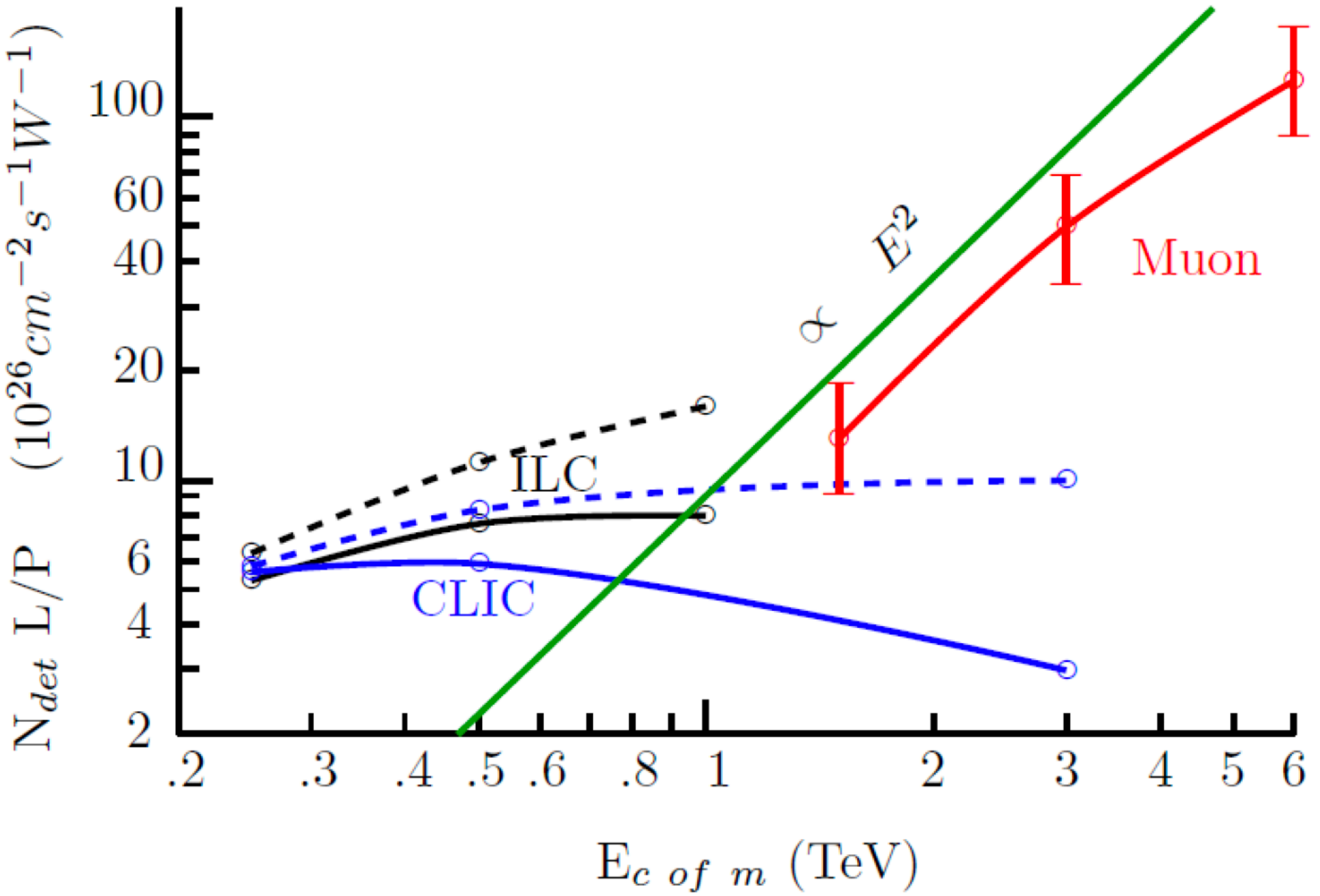


- **A MC offers a new way to probe NP which is complementary both to:**
  - Direct searches for new particles at high-energy particle colliders.
  - Indirect searches at low energy through high-precision experiments.
- **A MC running at $\sqrt{s} \gg 1\,\text{TeV}$ provides a unique opportunity to probe new physics effects in the muon *g*-2 in a model-independent way:**
  - Direct determination of NP, not hampered by the hadronic uncertainties of $a_\mu^{\rm SM}$.
  - A high-energy measurement with $\mathcal{O}(1)$ precision is sufficient to probe $\Delta a_\mu \sim 10^{-9}$.
- **Extraction of the tau $g-2$ through:** [Buttazzo & Paradisi, in progress]
  - Rare Higgs decays $h \to \ell^+\ell^-\gamma$ and $h \to \ell^+\ell^- Z$
  - Drell-Yan process $\mu^+\mu^- \to \tau^+\tau^-$
  - VBF process $\mu^+\mu^- \to \mu^+\mu^-\tau^+\tau^-(\bar{\nu}\nu\tau^+\tau^-)$
  - Expected sensitivity: $10^{-5} \lesssim |\Delta a_\tau| \lesssim 10^{-4}$
- **B-physics anomalies and leptonic $g-2$ at a MC**
  - Leptoquarks –favoured by B-physics anomalies– generate semileptonic operators which contribute also to leptonic $g-2$ and can be tested at a MC.
- . . . .

Luminosity

Collider wall power





[Boscolo et al arXiv:1808.01858v2]

[Palmer, 2014]