Precision test of the muon-Higgs coupling at a high-energy muon collider

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QUANTUM UNIVERSE

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arXiv: 2108.05362 [JHEP 12 (2021) 162]

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arXiv: 2208.09438

DESY.

Jürgen R. Reuter

On a personal note

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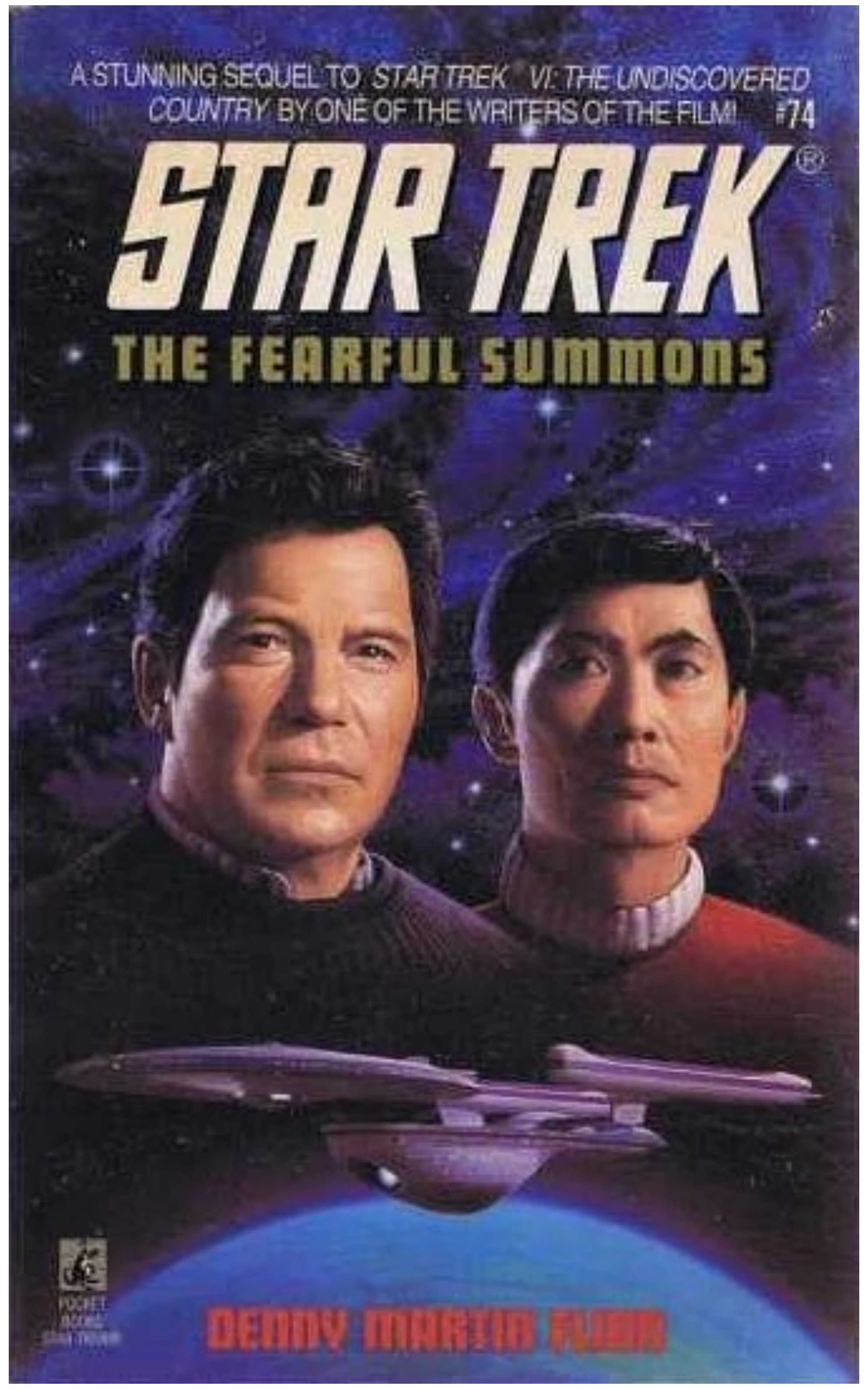

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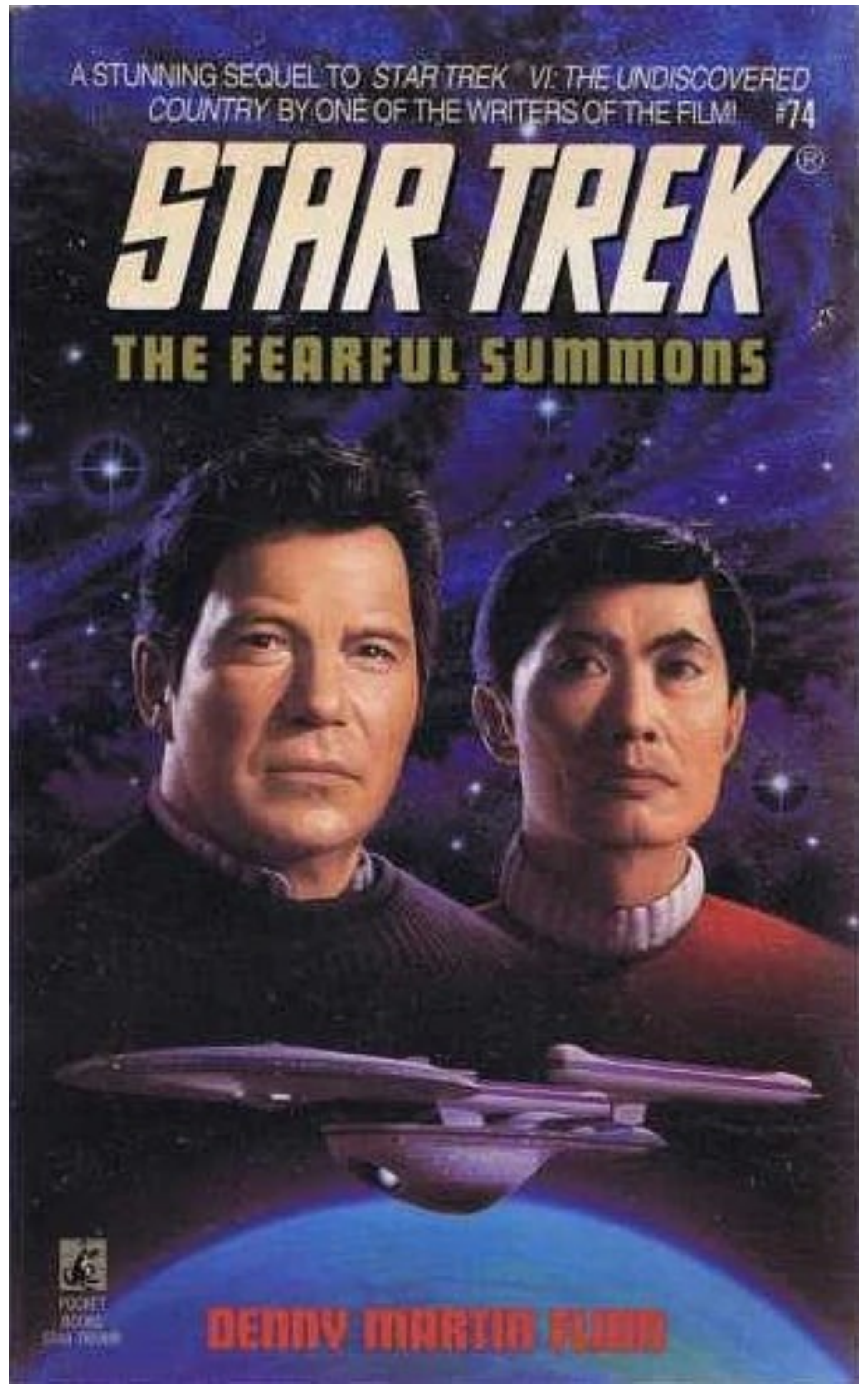
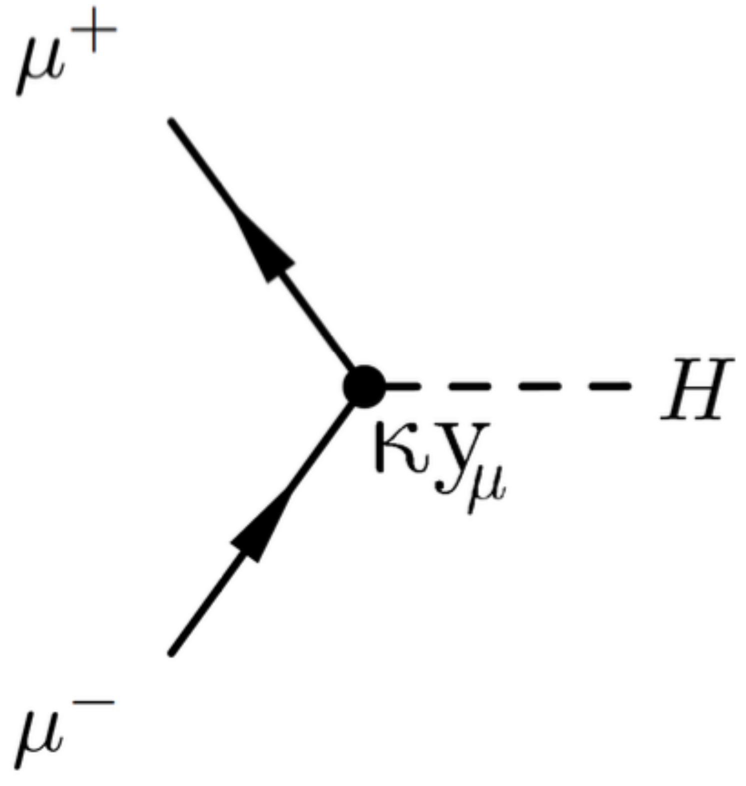


Denny Martin Flinn: *"The fearful summons"* (1990)

It was rumored that the Fleet's Department of Humanoid Resources began some years ago to encourage face-to-face meetings where possible. The department apparently now felt that the failure of electronic dialogue to carry useful nuances and improvised content was a factor in inhibiting the quality of collaborative decision making.

Higgs Precision Paradigm



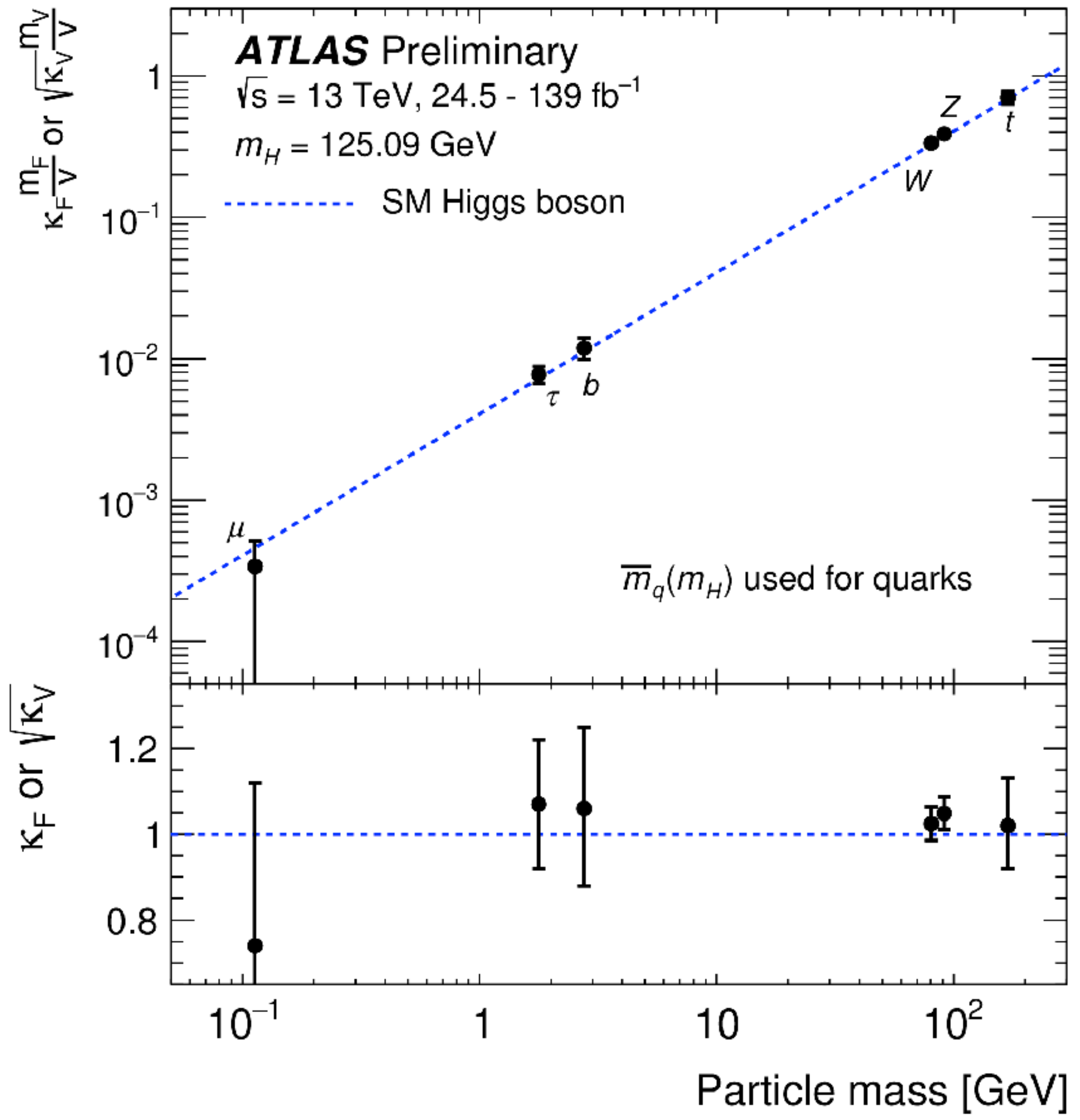
- Higgs properties at high precision utmost priority $\Longrightarrow$ ↪ ESU2020 document
- Higgs potential and Higgs couplings to all SM particles
- Higgs muon Yukawa coupling — connected to muon mass [in the SM!]

SM: $\kappa = 1$

or $\Delta\kappa = 0$

- Muon Yukawa coupling established at LHC (not yet 5σ)
  [ATLAS: 2007.07830 ; CMS: 2009.04363]

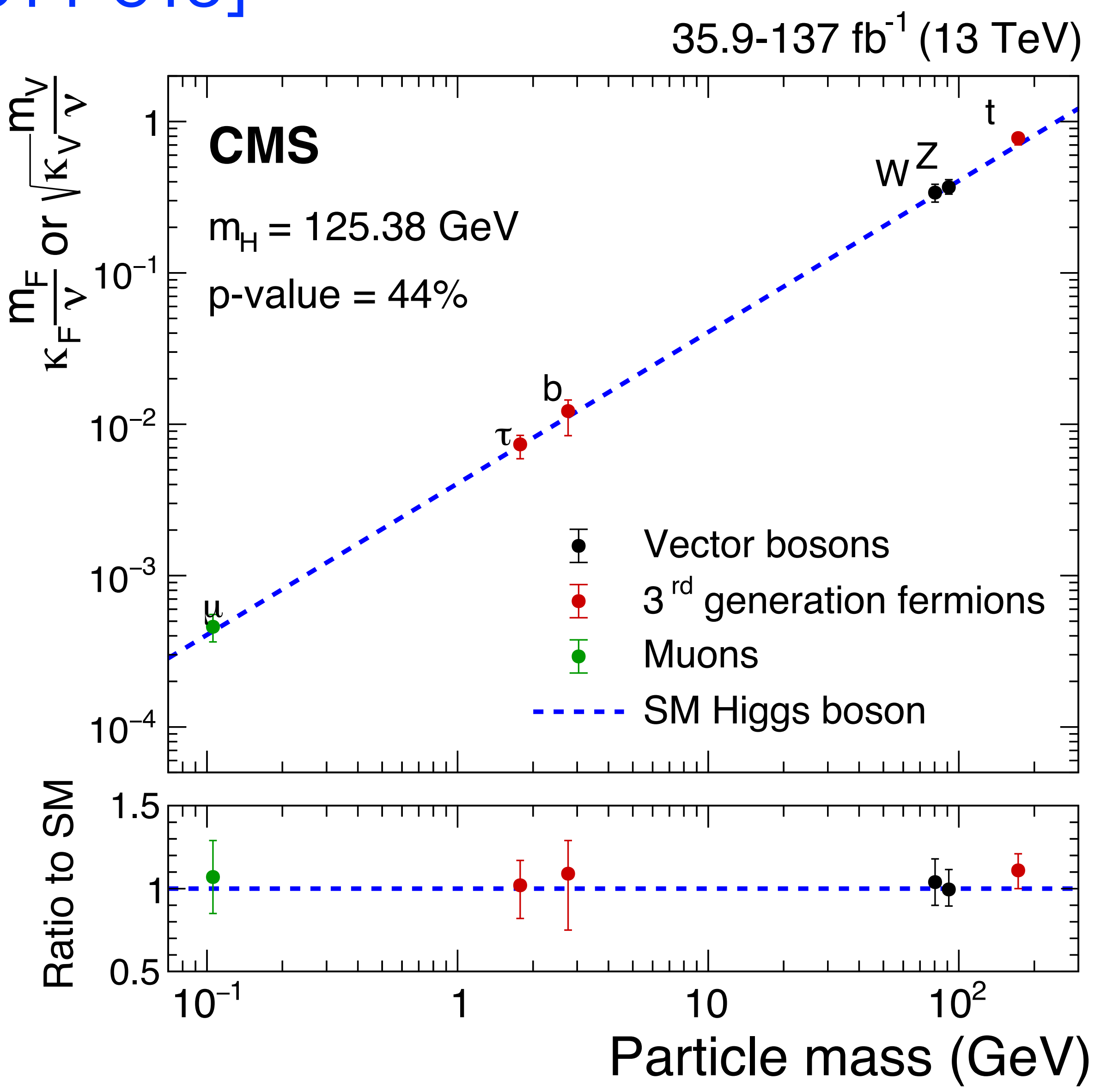
- Projections for the high-luminosity LHC (HL-LHC): (model-dependent) sensitivity with precision of (several) 10% [ATLAS-PHYS-PUB-2014-016]



Challenges / wishlist:

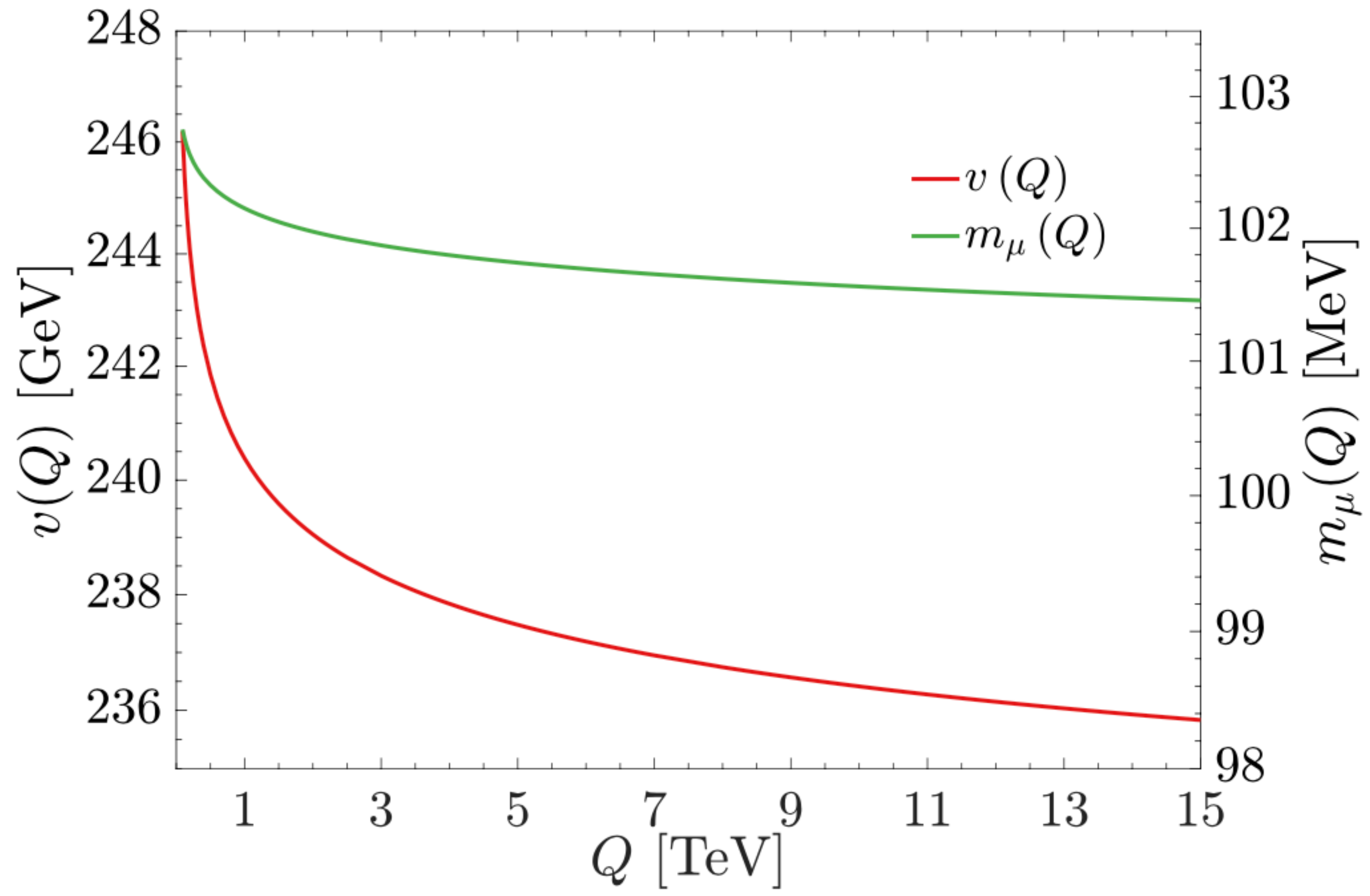
- (very) small coupling needs (very) large luminosity
- Model independence I: Separate production/decay
- Model independence II: sensitivity to many BSM models

➤ use high-luminosity lepton (muon) collider



Running of muon Yukawa

VeV and muon mass in the SM



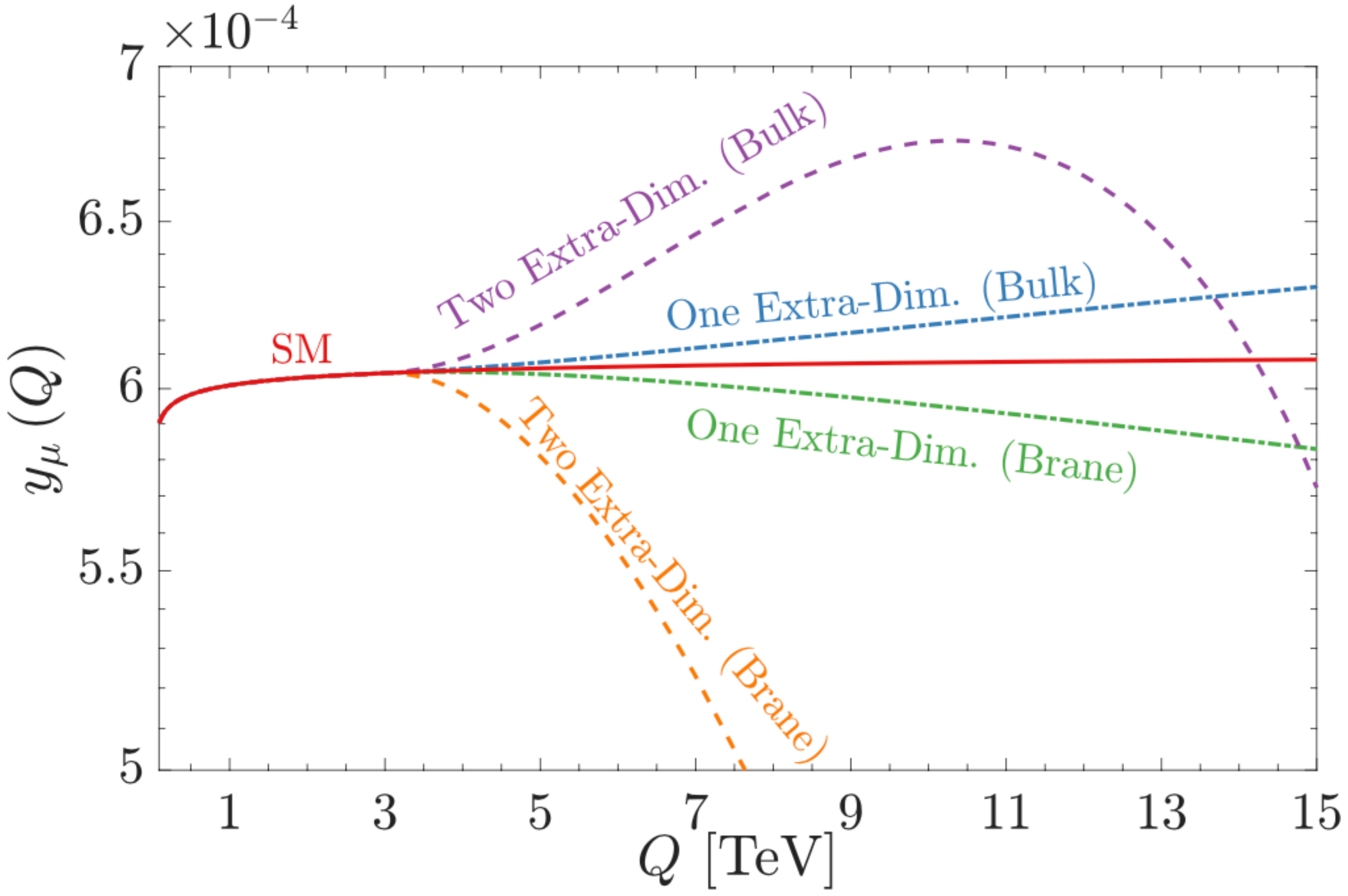
$$\beta_{y_t} = \frac{dy_t}{dt} = \frac{y_t}{16\pi^2}\left(\frac{9}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right),$$

$$\beta_{y_\mu} = \frac{dy_\mu}{dt} = \frac{y_\mu}{16\pi^2}\left(3y_t^2 - \frac{9}{4}(g_2^2 + g_1^2)\right),$$

$$\beta_v = \frac{dv}{dt} = \frac{v}{16\pi^2}\left(\frac{9}{4}g_2^2 + \frac{9}{20}g_1^2 - 3y_t^2\right),$$

$$\beta_{g_i} = \frac{dg_i}{dt} = \frac{b_i g_i^3}{16\pi^2}, \qquad b_i^{\rm SM} = (41/10, -19/6, -7)$$

Muon Yukawa in different BSM models



$$\frac{dy_t}{dt} = \beta_{y_t}^{\rm SM} + \frac{y_t}{16\pi^2}2(S(t)-1)\left(\frac{3}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right), \qquad \text{5D Brane,}$$

$$\frac{dy_\mu}{dt} = \beta_{y_\mu}^{\rm SM} - \frac{y_\mu}{16\pi^2}2(S(t)-1)\left(\frac{9}{4}g_2^2 + \frac{9}{4}g_1^2\right), \qquad \text{5D Brane,}$$

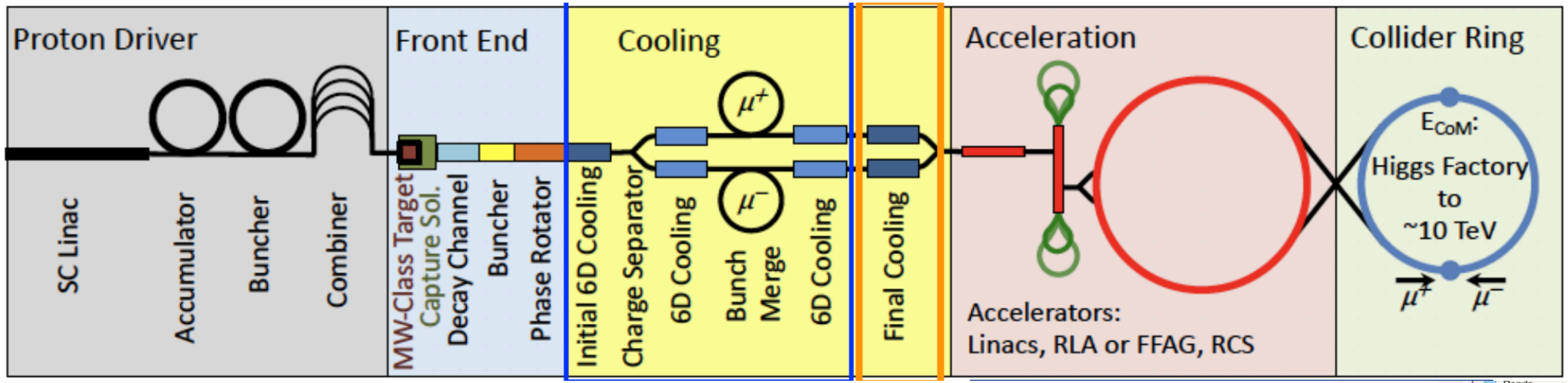
$$\frac{dy_t}{dt} = \beta_{y_t}^{\rm SM} + \frac{y_t}{16\pi^2}(S(t)-1)\left(\frac{15}{2}y_t^2 - \frac{28}{3}g_3^2 - \frac{15}{8}g_2^2 - \frac{101}{120}g_1^2\right), \qquad \text{5D Bulk,}$$

$$\frac{dy_\mu}{dt} = \beta_{y_\mu}^{\rm SM} + \frac{y_\mu}{16\pi^2}(S(t)-1)\left(6y_t^2 - \frac{15}{8}g_2^2 - \frac{99}{40}g_1^2\right), \qquad \text{5D Bulk.}$$

arXiv: 1110.1942; 1209.6239; 1306.4852

The (high-energy) muon collider

cf. also talk by David Marzocca



$m_\mu = 0.1056\,\mathrm{GeV} \approx 207 \cdot m_e$

$\Gamma_\mu = 3 \cdot 10^{-19}\,\mathrm{GeV} \qquad \tau_\mu = 2.2\,\mu\mathrm{s}$

$c\tau_\mu \approx 660\,\mathrm{m}$

- ☑ Muons pointlike objects: cleaner environment than hh
- ☑ Much less synchrotron radiation than electrons
- ☑ Much smaller beam energy spread: *ΔE ≈ 0.1 — 0.001%*
- ☐ Complicated production: protons → target → π → μ
- ☐ Short lifetime: difficult to get high-quality/lumi beams
- ☐ Difficult cooling of beams
- ☐ Beam-induced bkgds (BIP) from decay @ IP
- ☐ Radiation hazard from beam dump (neutrinos)

➢**Largest Radius is ~2.65 km**

- **~16.5 km Circumference**
  - **~2/3 LHC**

~RCS accelerator

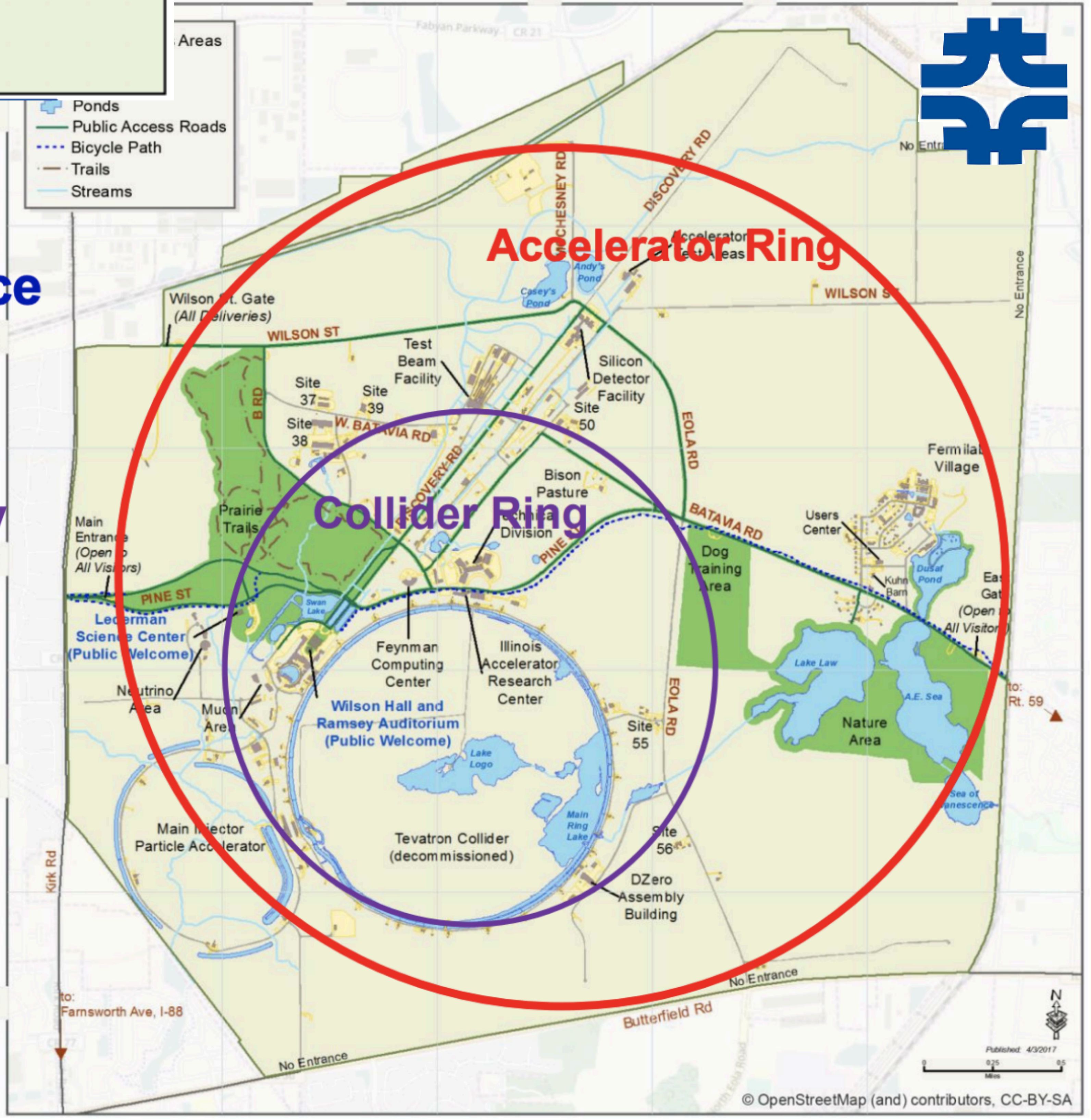
If B_{ave} = 3 T → E_μ = 2.4 TeV
(B_{max} = 8T, B_{pulse} =±2T)

Doubled ?

B_{ave} = 6.3 T → E_μ = 5 TeV
(B_{max} = 16T, B_{pulse} =±4T)

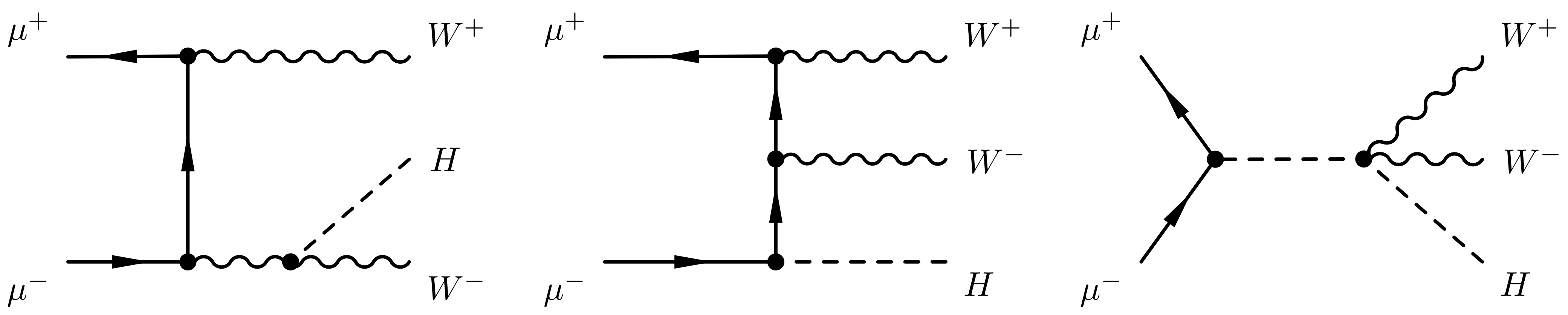
10 TeV collider

Collider Ring ~10 km
B_{ave} = 10 T
τ_μ = 0.104 s



Multi-boson final states

- Subtle cancellation between Yukawa coupling and multi-boson final states [hep-ph/0106271]



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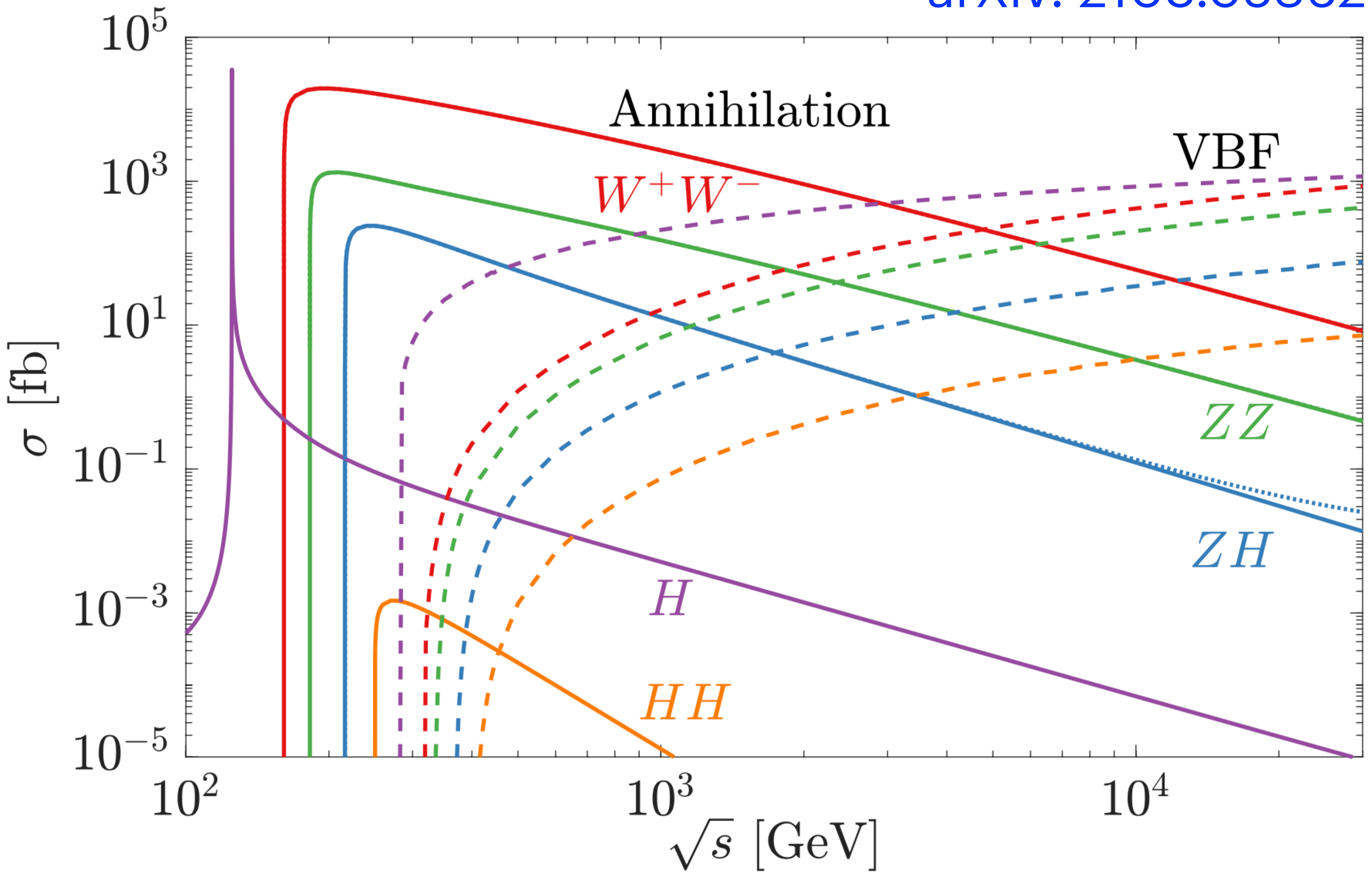
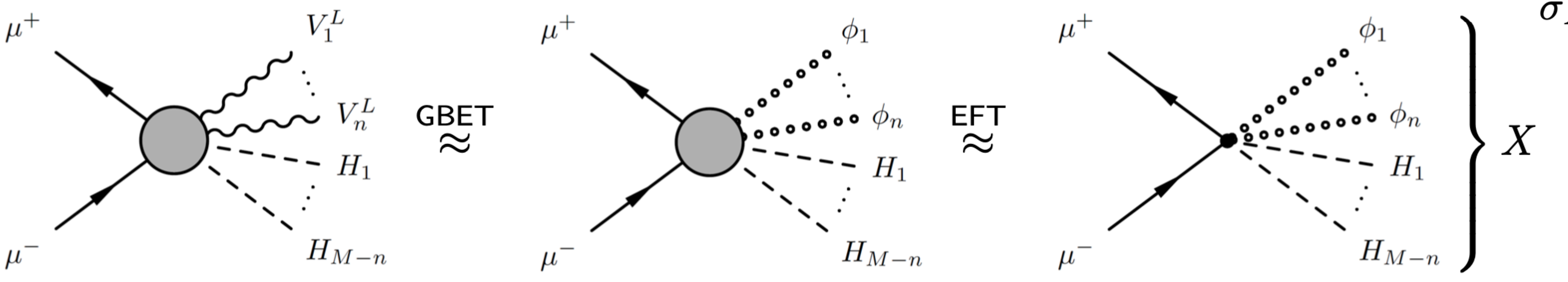


- (Multi-) boson final states: longitudal polarizations dominate high energies
- Analytic calculations can be approximated by Goldstone-boson Equivalence Theorem (GBET) [NPB261(1985) 379; PRD34(1986) 379]
- New physics parameterized by EFT operator insertions (Wilson coeff. C_X)



$$\sigma_X \approx \frac{1}{4}\left(\frac{\pi}{2(2\pi)^4}\right)^{M-1} \frac{s^{M-2}}{\Gamma(M)\Gamma(M-1)}|C_X|^2 \left(\prod_{j\in J_X}\frac{1}{n_j!}\right)$$

Cross section ratios: $$R = \frac{\sigma_X}{\sigma_Y} \approx \frac{|C_X|^2 \left(\prod_{j\in J_X}\frac{1}{n_j!}\right)}{|C_Y|^2 \left(\prod_{j\in J_Y}\frac{1}{n_j!}\right)}$$

EFT modelling of SM deviations

$$F_U(H) = 1 + \sum_{n\geq 1} f_{U,n} \left(\frac{H}{v}\right)^n$$

Non-linear representation (HEFT)

Scalar H NGB $U = e^{i\phi^a \tau_a / v}$ $\phi^a \tau_a = \sqrt{2} \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix}$

Linear representation ([truncated] SMEFT)

H doublet $\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + H + i\phi^0 \end{pmatrix}$

Generalized (μ) Yukawa sector

$$\mathcal{L}_{UH} = \frac{v^2}{4} \mathrm{tr}[D_\mu U^\dagger D^\mu U] F_U(H) + \frac{1}{2} \partial_\mu H \partial^\mu H - V(H)$$
$$- \frac{v}{2\sqrt{2}} \left[\sum_{n\geq 0} y_n \left(\frac{H}{v}\right)^n (\bar{\nu}_L, \bar{\mu}_L) U (1 - \tau_3) \begin{pmatrix} \nu_R \\ \mu_R \end{pmatrix} + \text{h.c.} \right]$$

$$\mathcal{L}_\varphi = \left[-\bar{\mu}_L y_\mu \varphi \mu_R + \sum_{n=1}^{N} \frac{C_{\mu\varphi}^{(n)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^n \bar{\mu}_L \varphi \mu_R + \text{h.c.} \right]$$

Parameterization of μ mass and Yukawa modifier

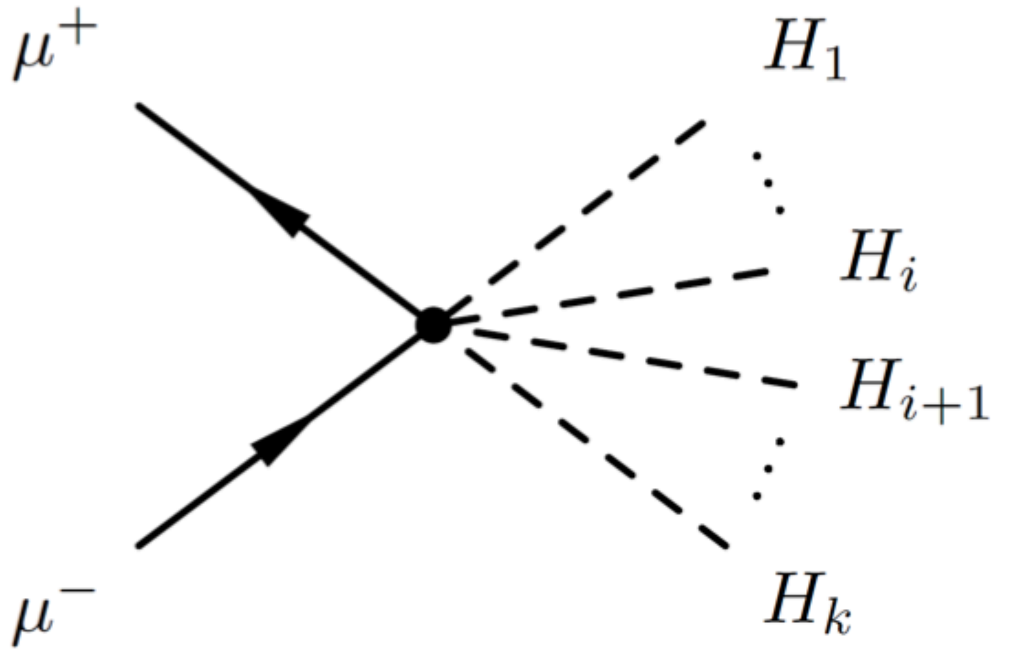
$$m_\mu = \frac{v}{\sqrt{2}} y_0 \qquad \kappa = \frac{v}{\sqrt{2} m_\mu} y_1$$

$$m_\mu = \frac{v}{\sqrt{2}} \left[y_\mu - \sum_{n=1}^{N} \frac{C_{\mu\varphi}^{(n)}}{\Lambda^{2n}} \frac{v^{2n}}{2^n} \right]$$

$$\kappa = 1 - \frac{v}{\sqrt{2} m_\mu} \sum_{n=1}^{N} \frac{C_{\mu\varphi}^{(n)}}{\Lambda^{2n}} \frac{n v^{2n}}{2^{n-1}}$$

Extreme case: vanishing μ Yukawa: no pure Higgs final states at tree-level !

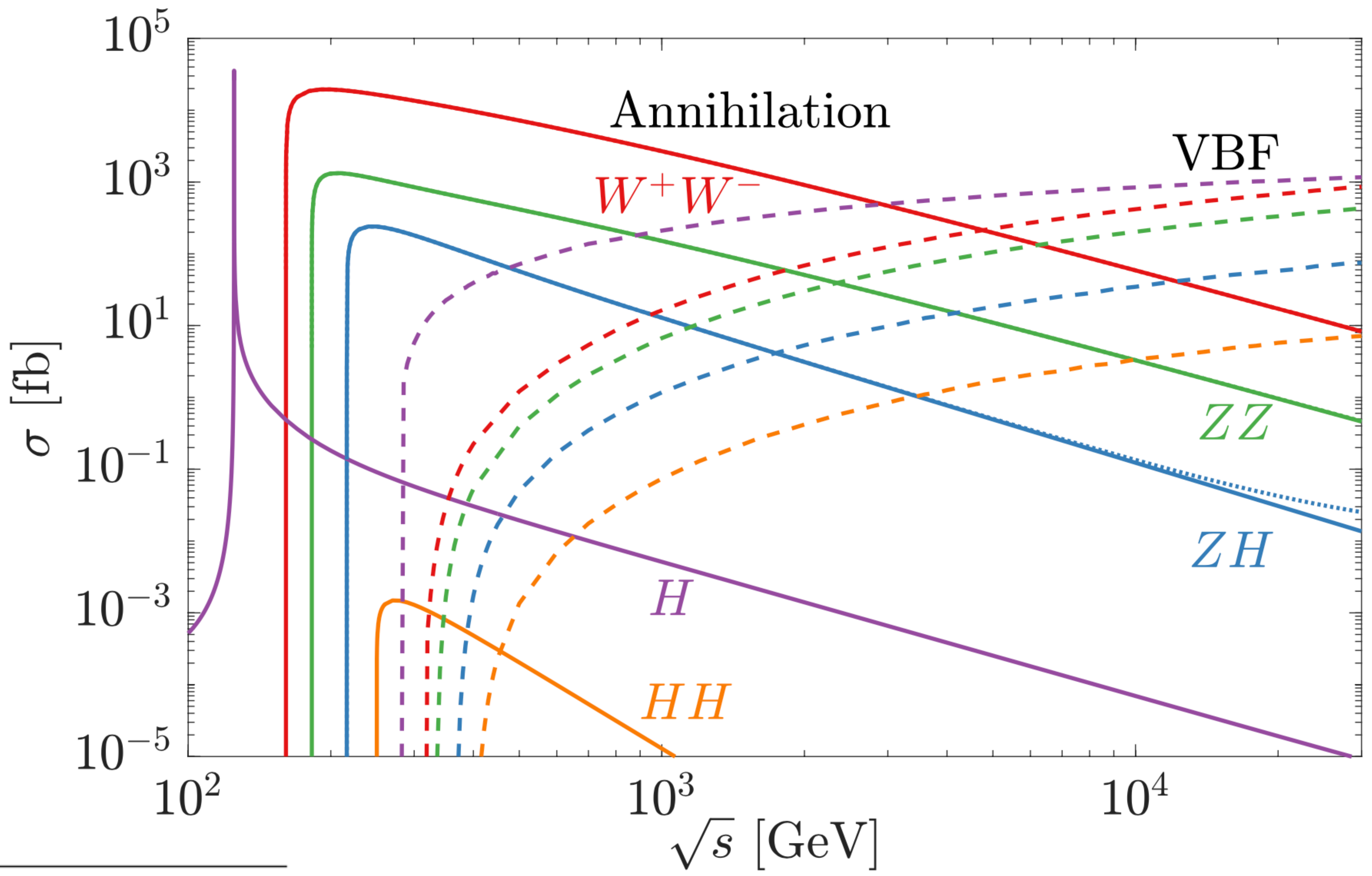
$$-i \frac{k!}{\sqrt{2}} \left[Y_\ell \delta_{k,1} - \sum_{n=n_k}^{M-1} \frac{C_{\mu\varphi}^{(n)}}{\Lambda^{2n}} \binom{2n+1}{k} \frac{v^{2n+1-k}}{2^n} \right] = 0 \quad =$$



Benchmark scenario: “matched” case

Simulation, Consistency, Unitarity & Cross Sections

- ☑ Analytical calculations checked independently by 3 groups
- ☑ Validation of analytic calculation with 2 different MCs
- ☑ Final simulation: using UFO files in `WHIZARD`



States with multiplicity 2

- Different cases: dim 6 alone, dim 8 alone, dim 6+8 combined
- Matched case: combination such that Yukawa coupling is zero
- HEFT contains in principle all orders: matched is zero Yukawa

	$\Delta\sigma^X/\Delta\sigma^{W^+W^-}$					
	SMEFT				HEFT	
X	dim_6	dim_8	$\mathrm{dim}_{6,8}$	$\mathrm{dim}_{6,8}^{\mathrm{matched}}$	dim_∞	$\mathrm{dim}_\infty^{\mathrm{matched}}$
W^+W^-	1	1	1	1	1	1
ZZ	1/2	1/2	1/2	1/2	1/2	1/2
ZH	1	1/2	1	1	$R^{\mathrm{HEFT}}_{(2),1}$	1
HH	9/2	25/2	$R^{\mathrm{SMEFT}}_{(2),1}/2$	0	$2\,R^{\mathrm{HEFT}}_{(2),2}$	0

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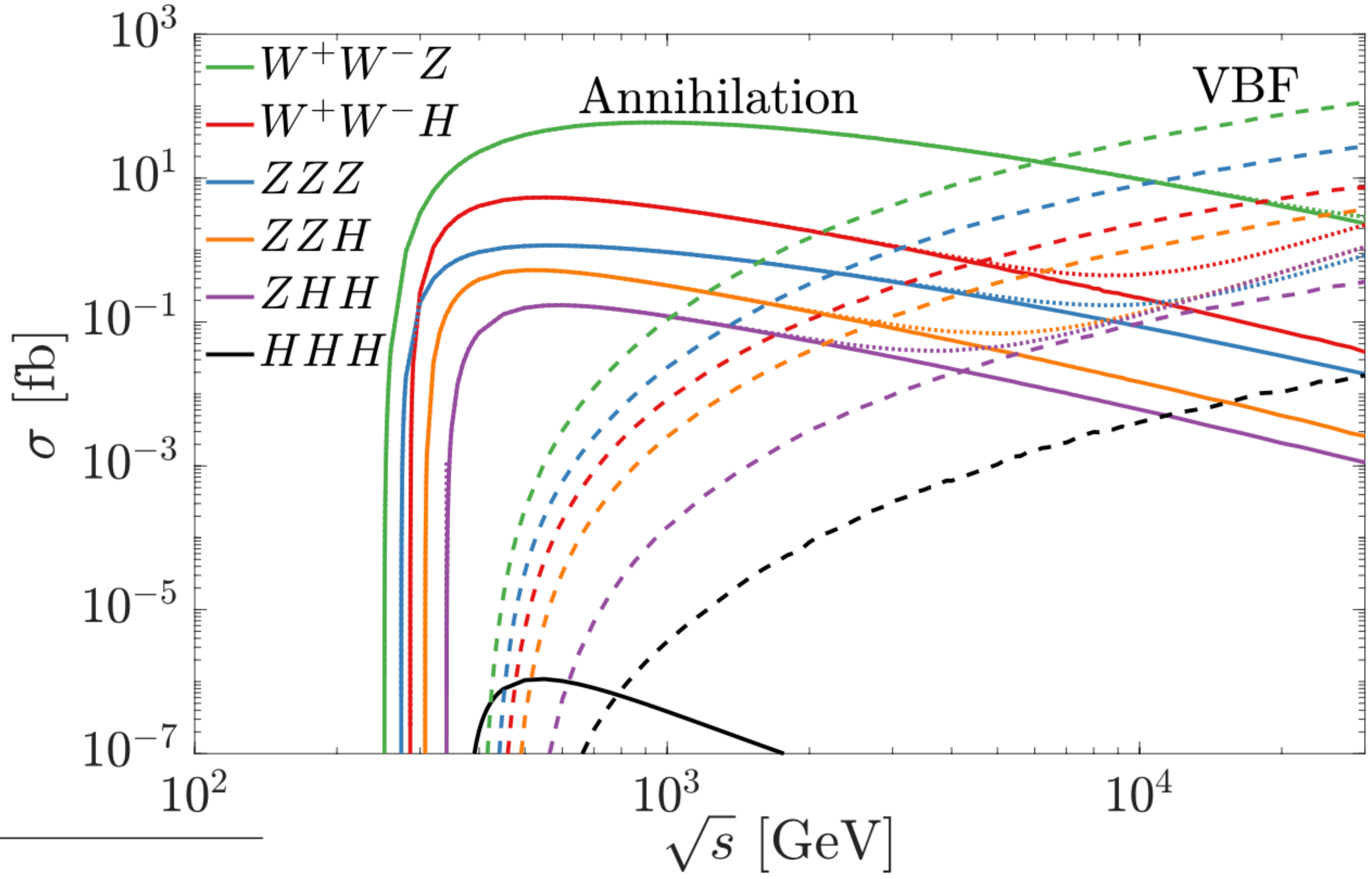
States with multiplicity 3

- Different cases: dim 6 alone, dim 8 alone, dim 6+8 combined
- Matched case: combination such that Yukawa coupling is zero
- HEFT contains in principle all orders: matched is zero Yukawa



	$\Delta\sigma^X/\Delta\sigma^{W^+W^-H}$					
	SMEFT				HEFT	
$\mu^+\mu^- \to X$	$\dim_6$	$\dim_8$	$\dim_{6,8}$	$\dim_{6,8}^{\text{matched}}$	$\dim_\infty$	$\dim_\infty^{\text{matched}}$
WWZ	1	1/9	$R^{\text{SMEFT}}_{(3),1}$	1/4	$R^{\text{HEFT}}_{(3),1}/9$	1/4
ZZZ	3/2	1/6	$3\,R^{\text{SMEFT}}_{(3),1}/2$	3/8	$R^{\text{HEFT}}_{(3),1}/6$	3/8
WWH	1	1	1	1	1	1
ZZH	1/2	1/2	1/2	1/2	1/2	1/2
ZHH	1/2	1/2	1/2	1/2	$2\,R^{\text{HEFT}}_{(3),2}$	1/2
HHH	3/2	25/6	$3\,R^{\text{SMEFT}}_{(3),2}/2$	75/8	$6\,R^{\text{HEFT}}_{(3),3}$	0

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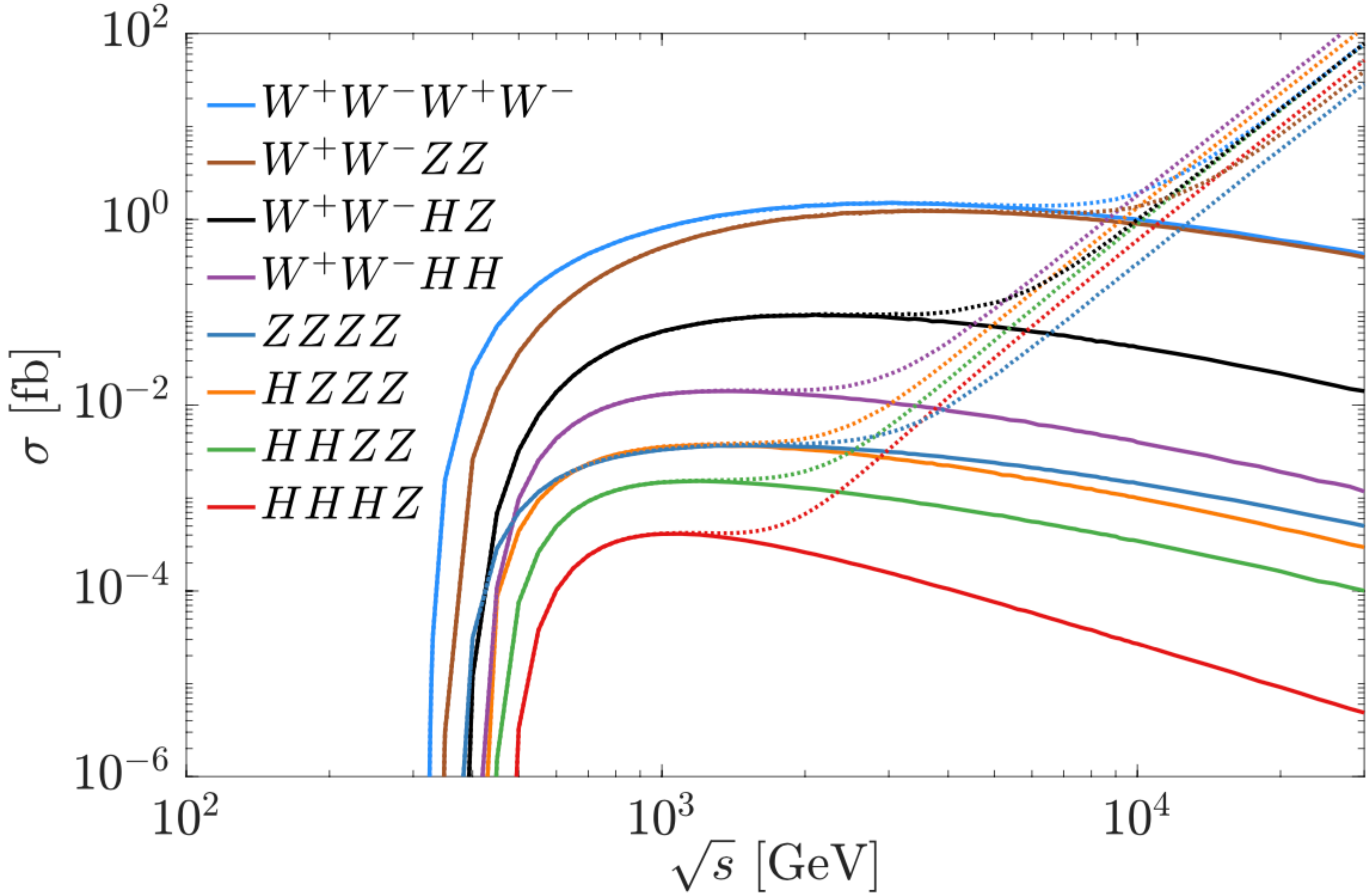

States with multiplicity 4

- Different cases: dim 6 alone, dim 8 alone, dim 6+8 combined
- Matched case: combination such that Yukawa coupling is zero
- HEFT contains in principle all orders: matched is zero Yukawa

	SMEFT				HEFT	
$\mu^+\mu^- \to X$	$\text{dim}_{6,8}$	dim_{10}	$\text{dim}_{6,8,10}$	$\text{dim}^{\text{matched}}_{6,8,10}$	dim_{∞}	$\text{dim}^{\text{matched}}_{\infty}$
$WWWW$	$2/9$	$2/25$	$2\,R^{\text{SMEFT}}_{(4),1}/9$	$1/2$	$R^{\text{HEFT}}_{(4),1}/18$	$1/2$
$WWZZ$	$1/9$	$1/25$	$R^{\text{SMEFT}}_{(4),1}/9$	$1/4$	$R^{\text{HEFT}}_{(4),1}/36$	$1/4$
$ZZZZ$	$1/12$	$3/100$	$R^{\text{SMEFT}}_{(4),1}/12$	$3/16$	$R^{\text{HEFT}}_{(4),1}/48$	$3/16$
$WWZH$	$2/9$	$2/25$	$2\,R^{\text{SMEFT}}_{(4),1}/9$	$1/2$	$R^{\text{HEFT}}_{(4),2}/8$	$1/2$
$WWHH$	1	1	1	1	1	1
$ZZZH$	$1/3$	$3/25$	$R^{\text{SMEFT}}_{(4),1}/3$	$3/4$	$R^{\text{HEFT}}_{(4),2}/12$	$3/4$
$ZZHH$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$
$ZHHH$	$1/3$	$1/3$	$1/3$	$1/3$	$3\,R^{\text{HEFT}}_{(4),3}$	$1/3$
$HHHH$	$25/12$	$49/12$	$25\,R^{\text{SMEFT}}_{(4),2}/12$	$1225/48$	$12\,R^{\text{HEFT}}_{(4),4}$	0

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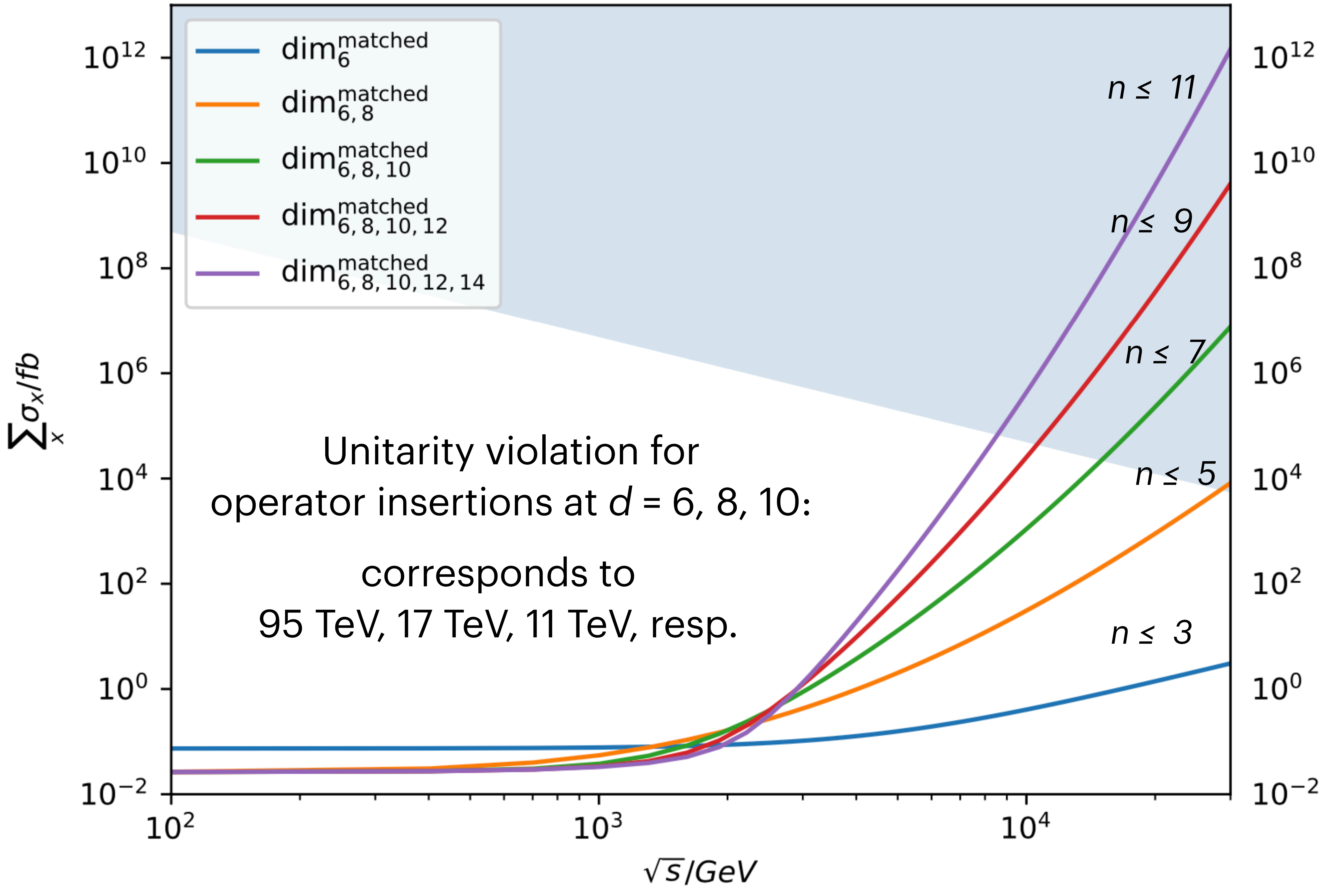

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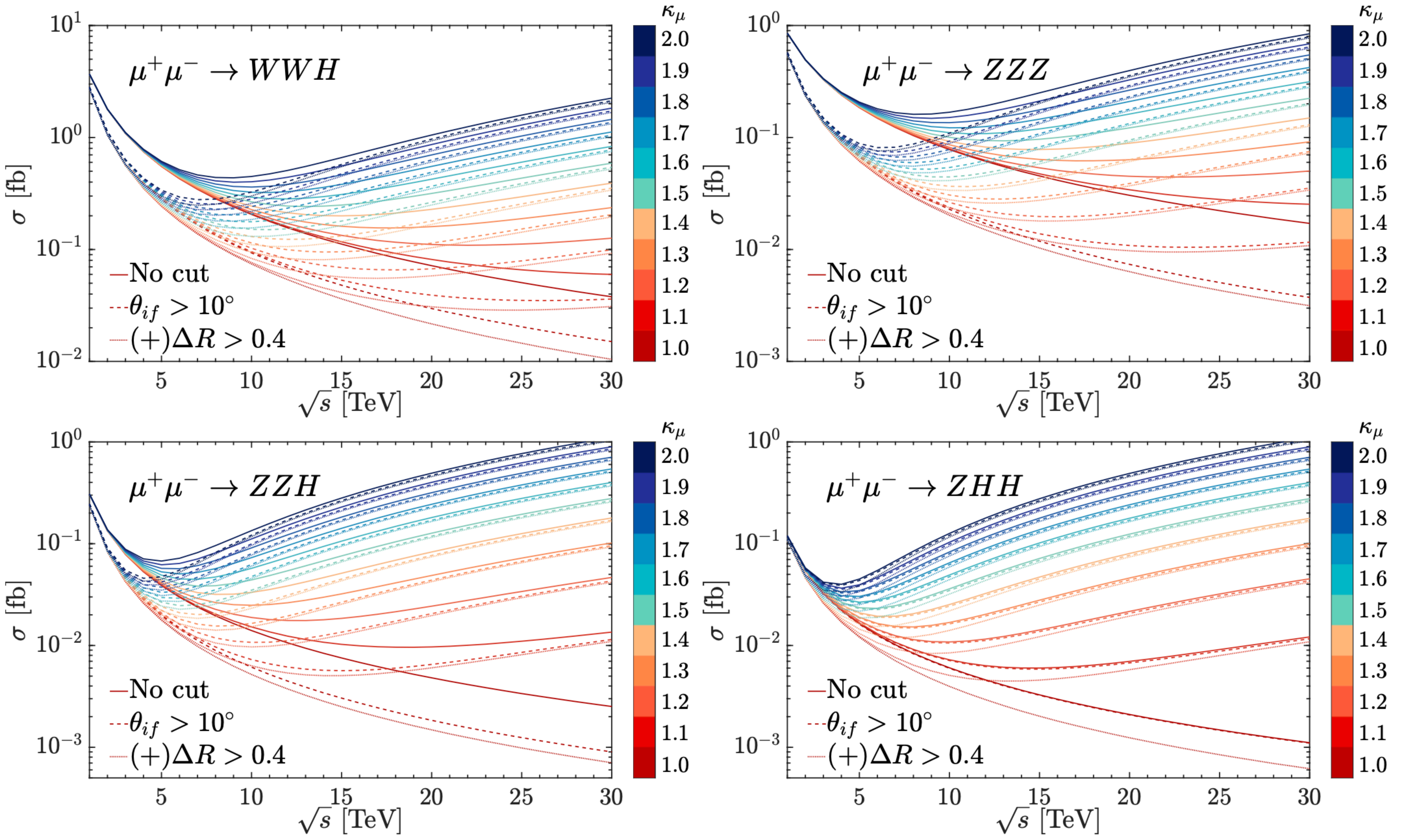
	SMEFT					
$\mu^+\mu^- \to X$	$\dim_{6,8}$	$\dim_{10}$	$\dim_{6,8,10}$	$\dim_{6,8,10}^{\text{matched}}$		
$WWWW$	$2/9$	$2/25$	$2\,R^{\text{SMEFT}}_{(4),1}/9$	$1/2$	R	
$WWZZ$	$1/9$	$1/25$	$R^{\text{SMEFT}}_{(4),1}/9$	$1/4$	R	
$ZZZZ$	$1/12$	$3/100$	$R^{\text{SMEFT}}_{(4),1}/12$	$3/16$	$R^{\text{HEFT}}_{(4),1}/48$	$3/16$
$WWZH$	$2/9$	$2/25$	$2\,R^{\text{SMEFT}}_{(4),1}/9$	$1/2$	$R^{\text{HEFT}}_{(4),2}/8$	$1/2$
$WWHH$	1	1	1	1	1	1
$ZZZH$	$1/3$	$3/25$	$R^{\text{SMEFT}}_{(4),1}/3$	$3/4$	$R^{\text{HEFT}}_{(4),2}/12$	$3/4$
$ZZHH$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$
$ZHHH$	$1/3$	$1/3$	$1/3$	$1/3$	$3\,R^{\text{HEFT}}_{(4),3}$	$1/3$
$HHHH$	$25/12$	$49/12$	$25\,R^{\text{SMEFT}}_{(4),2}/12$	$1225/48$	$12\,R^{\text{HEFT}}_{(4),4}$	0

Unitarity bound for final states $X \neq \mu\mu$:

$$\sum_X \sigma_{\mu^+\mu^-\to X}(s) \le \frac{4\pi}{s}$$

hep-ph/0106281

Variations of cross sections with κ



Kinematic separation of signal

$\mu^+\mu^- \to W^+W^-H$

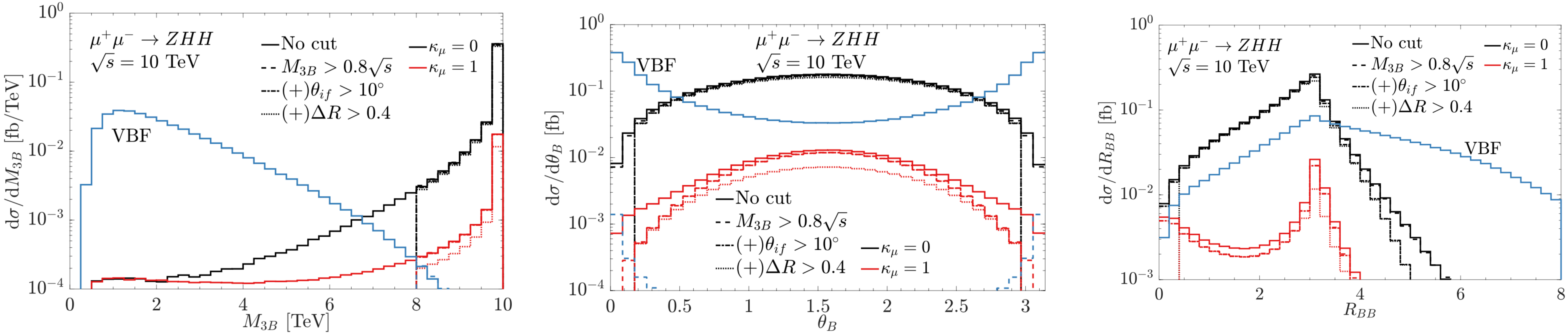
Kinematic separation between multi-boson direct production and VBF, e.g. 10 TeV: arXiv: 2108.05362

- *WWZ* largest cross section, but small deviation
- *WWH* large cross section and considerable deviation
- *ZZH* smaller/-ish cross section, but largest (relative) deviation
- Direct production has almost full energy (except for ISR) $\Longrightarrow$ M_{3B}
- VBF generates mostly forward bosons $\Longrightarrow$ Θ_B
- Separation criterion for final state bosons $\Longrightarrow$ ΔR_{BB}

Cut flow	$\kappa_\mu = 1$	w/o ISR	$\kappa_\mu = 0$ (2)	CVBF	NVBF
σ [fb]			WWH		
No cut	0.24	0.21	0.47	2.3	7.2
$M_{3B} > 0.8\sqrt{s}$	0.20	0.21	0.42	$5.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-2}$
$10° < \theta_B < 170°$	0.092	0.096	0.30	$2.5 \cdot 10^{-4}$	$2.7 \cdot 10^{-4}$
$\Delta R_{BB} > 0.4$	0.074	0.077	0.28	$2.1 \cdot 10^{-4}$	$2.4 \cdot 10^{-4}$
# of events	740	770	2800	2.1	2.4
S/B			2.8		

Kinematic separation of signal

$\mu^+\mu^- \to ZZH$



σ [fb]	ZHH				
No cut	$6.9 \cdot 10^{-3}$	$6.1 \cdot 10^{-3}$	0.119	$9.6 \cdot 10^{-2}$	$6.7 \cdot 10^{-4}$
$M_{3B} > 0.8\sqrt{s}$	$5.9 \cdot 10^{-3}$	$6.1 \cdot 10^{-3}$	0.115	$1.5 \cdot 10^{-4}$	$7.4 \cdot 10^{-6}$
$10° < \theta_B < 170°$	$5.7 \cdot 10^{-3}$	$6.0 \cdot 10^{-3}$	0.110	$8.8 \cdot 10^{-6}$	$7.5 \cdot 10^{-7}$
$\Delta R_{BB} > 0.4$	$3.8 \cdot 10^{-3}$	$4.0 \cdot 10^{-3}$	0.106	$8.0 \cdot 10^{-6}$	$5.6 \cdot 10^{-7}$
# of events	38	40	1060	–	–
S/B	27				

Results and final projections

Muon collider with energy range $1 < \sqrt{s} < 30$ TeV and luminosity $\mathcal{L} = \left(\frac{\sqrt{s}}{10 \text{ TeV}}\right)^2 10 \text{ ab}^{-1}$

1901.06150; 2001.04431; PoS(ICHEP2020)703; Nat.Phys.17, 289-292

- Sensitivity to (deviations of) the muon Yukawa coupling
- Definition of # signal events: $S = N_{\kappa_\mu} - N_{\kappa_\mu=1}$
- Definition of # background events: $B = N_{\kappa_\mu=1} + N_{\text{VBF}}$
- Statistical significance of anom. muon Yukawa couplings:

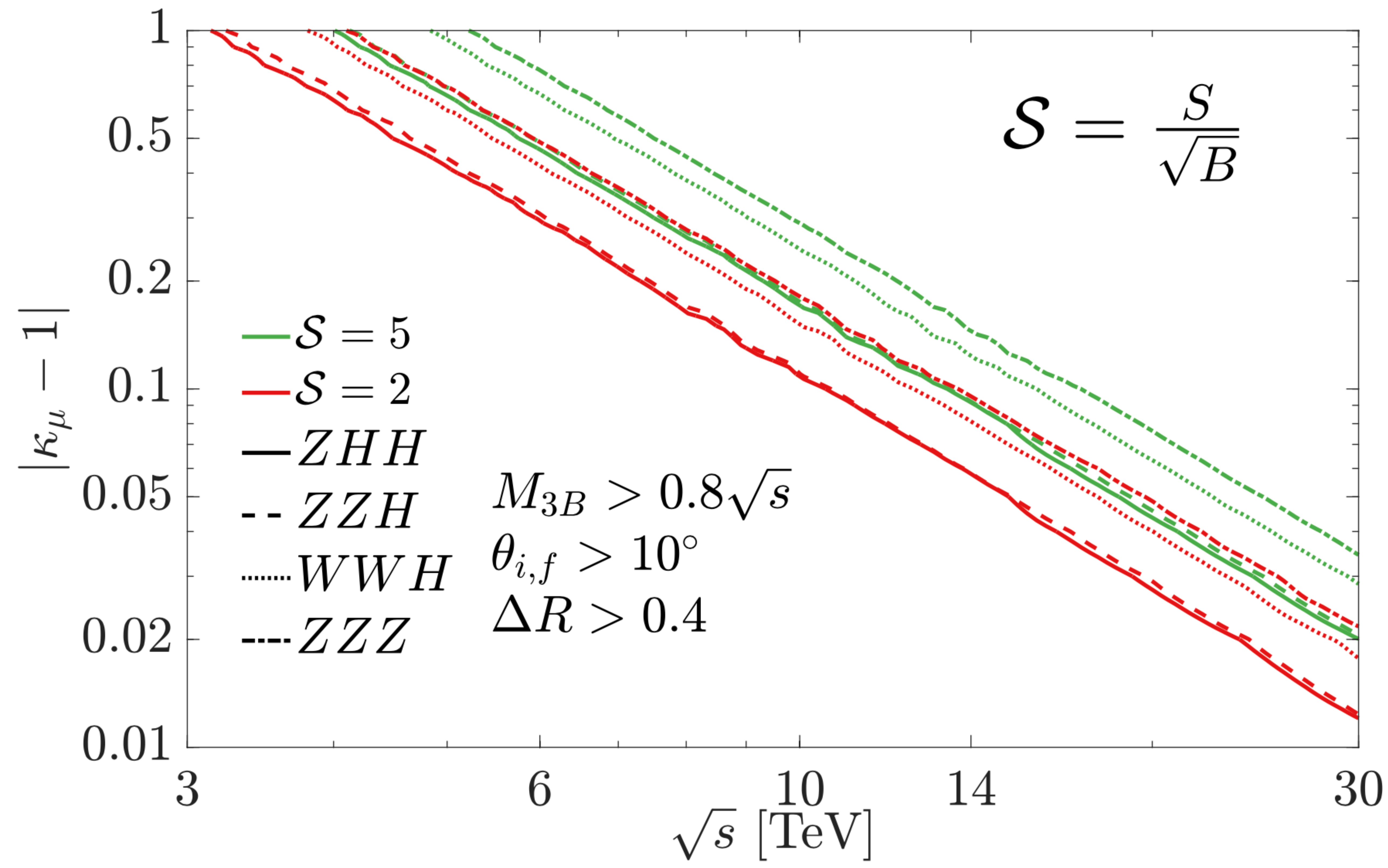
$$\mathcal{S} = \frac{S}{\sqrt{B}}$$

(note that always: $N_{\kappa_\mu} \geq N_{\kappa_\mu=1}$)

$$\sigma|_{\kappa_\mu=1+\delta} = \sigma|_{\kappa_\mu=1-\delta} \quad \Longrightarrow \quad \mathcal{S}|_{\kappa_\mu=1+\delta} = \mathcal{S}|_{\kappa_\mu=1-\delta}$$

- 5σ sensitivity to 20% @ 10 TeV .... 2% @ 30 TeV
- Sensitivity to κ translates to new physics scale Λ

$$\Lambda > 10 \text{ TeV} \sqrt{\frac{g}{\Delta\kappa_\mu}}$$



arXiv: 2108.05362

SM tails — watch out for EW corrections

- EW corrections at high energies dominated by EW double and single Sudakov logarithms
- Relevant in kinematic region of Sudakov limit $r_{kl} = (p_k + p_l)^2 \sim s \gg M_W^2$
- Infrared quasi-divergencies of virtual corrections not cancelled by real EW radiation
- Both initial and final states no EW "color" singlets
- Relevant in kinematic region of Sudakov limit
- Leading double logarithms and single (angular-dependent) logarithms

$$L(s, M_W^2) = \frac{\alpha}{4\pi} \log^2 \frac{s}{M_W^2} \overset{10\text{ TeV}}{\sim} 6\%$$

$$l(s, M_W^2) = \frac{\alpha}{4\pi} \log \frac{s}{M_W^2} \overset{10\text{ TeV}}{\sim} 0.6\%$$

- Quadratic Casimir operators rather large, for longitudinal / left-handed degrees $\sim 1/\sin^2\theta_W$

$$\Lambda^\kappa_{T,L} = A^\kappa_{T,L}\, L(s, M_W^2) + B^\kappa_{T,L}\, \log \frac{M_Z^2}{M_W^2} l(s, M_W^2) + C_{T,L}$$

$$G_\mu = 1.166379 \cdot 10^{-5}\ \text{GeV}^{-2}$$

$$\begin{aligned} m_u &= 0.062\ \text{GeV} & m_d &= 0.083\ \text{GeV} \\ m_c &= 1.67\ \text{GeV} & m_s &= 0.215\ \text{GeV} \\ m_t &= 172.76\ \text{GeV} & m_b &= 4.78\ \text{GeV} \end{aligned}$$

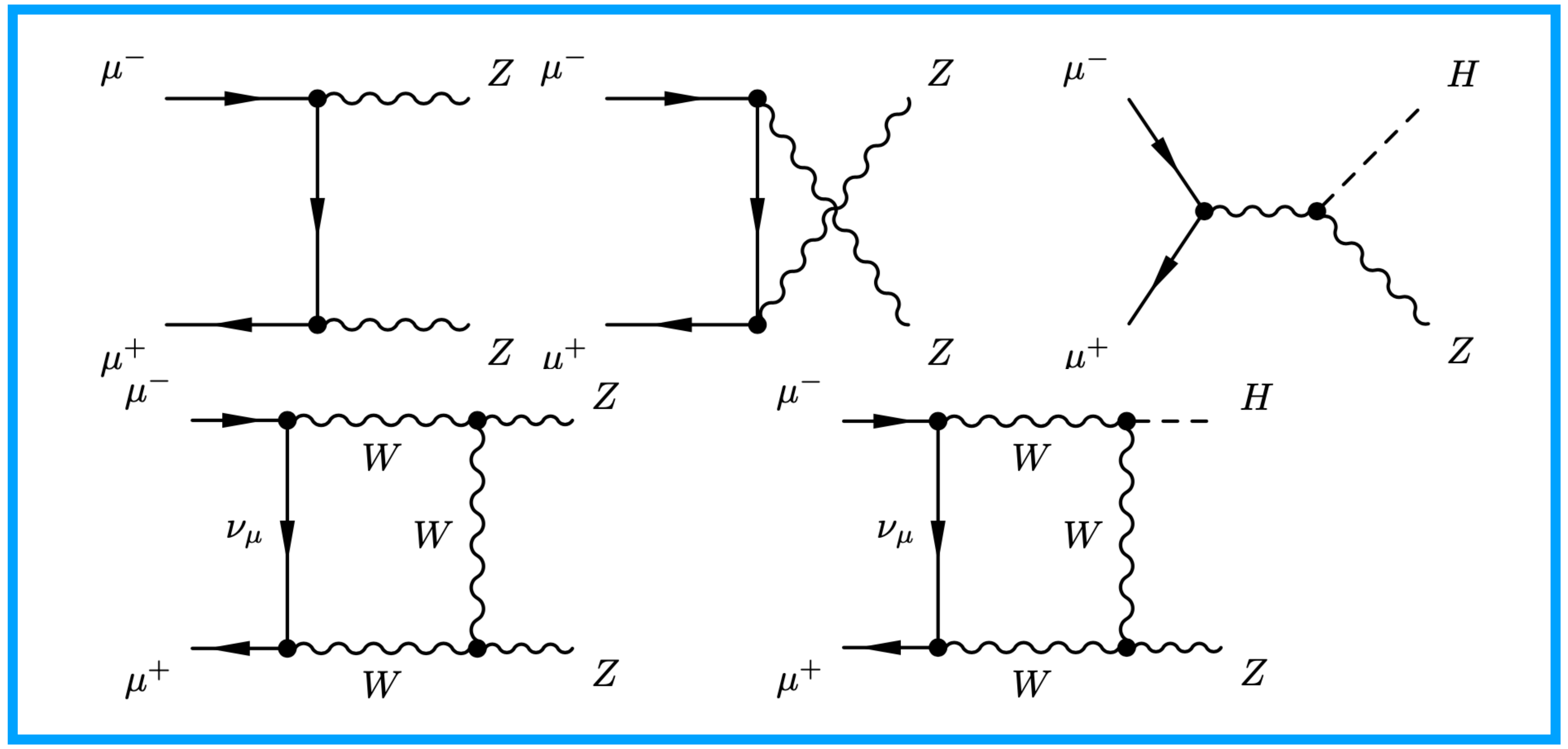
$$\begin{aligned} M_W &= 80.379\ \text{GeV} & m_e &= 0.0005109989461\ \text{GeV} \\ M_Z &= 91.1876\ \text{GeV} & m_\mu &= 0.1056583745\ \text{GeV} \\ M_H &= 125.1\ \text{GeV} & m_\tau &= 1.77686\ \text{GeV} \end{aligned}$$

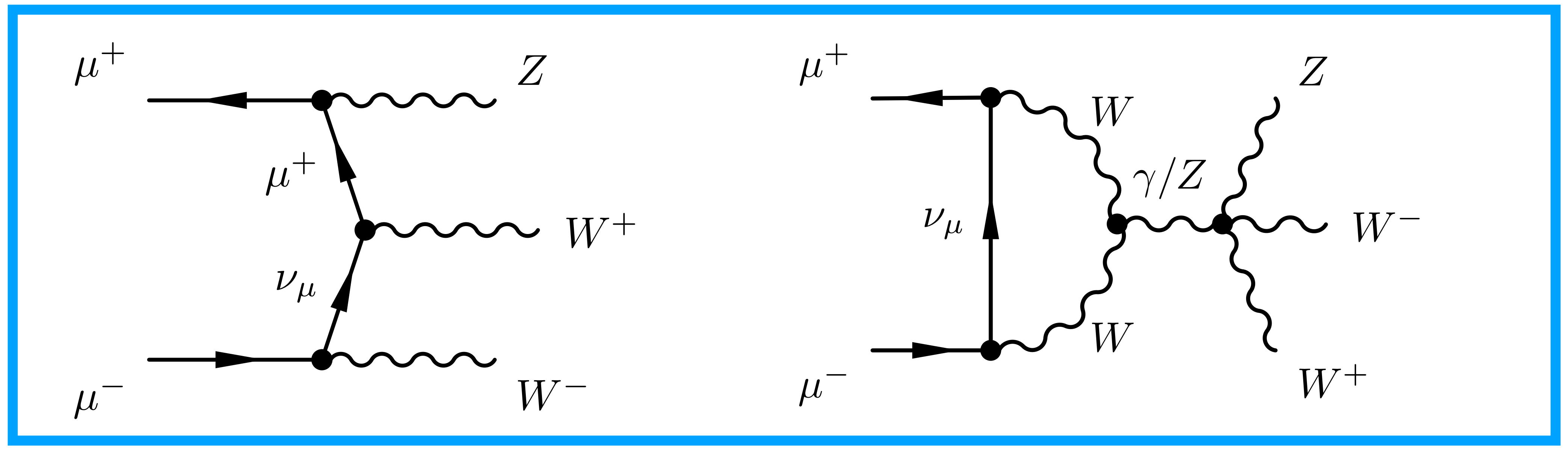
- EW corrections for massive initial state muons
- Alternatively: collinear lepton NLL PDF, 1909.03886, 1911.12040, 2207.03265
- WHIZARD NLO SM Automation Framework with FKS subtraction
- Massive eikonals need special treatment at high energies
- Validation against MCSANC-ee ; analytic Sudakov comparison
- Extraction of pure QED corrections

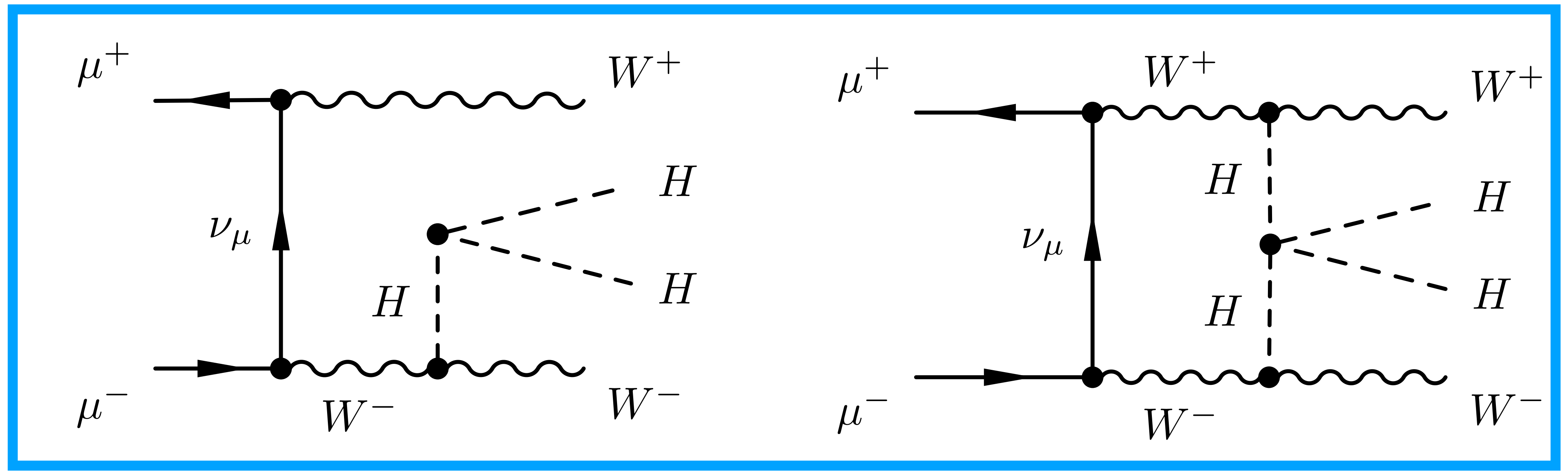
arXiv: 2208.09438

SM EW Corrections to Multi-Bosons

arXiv: 2208.09438



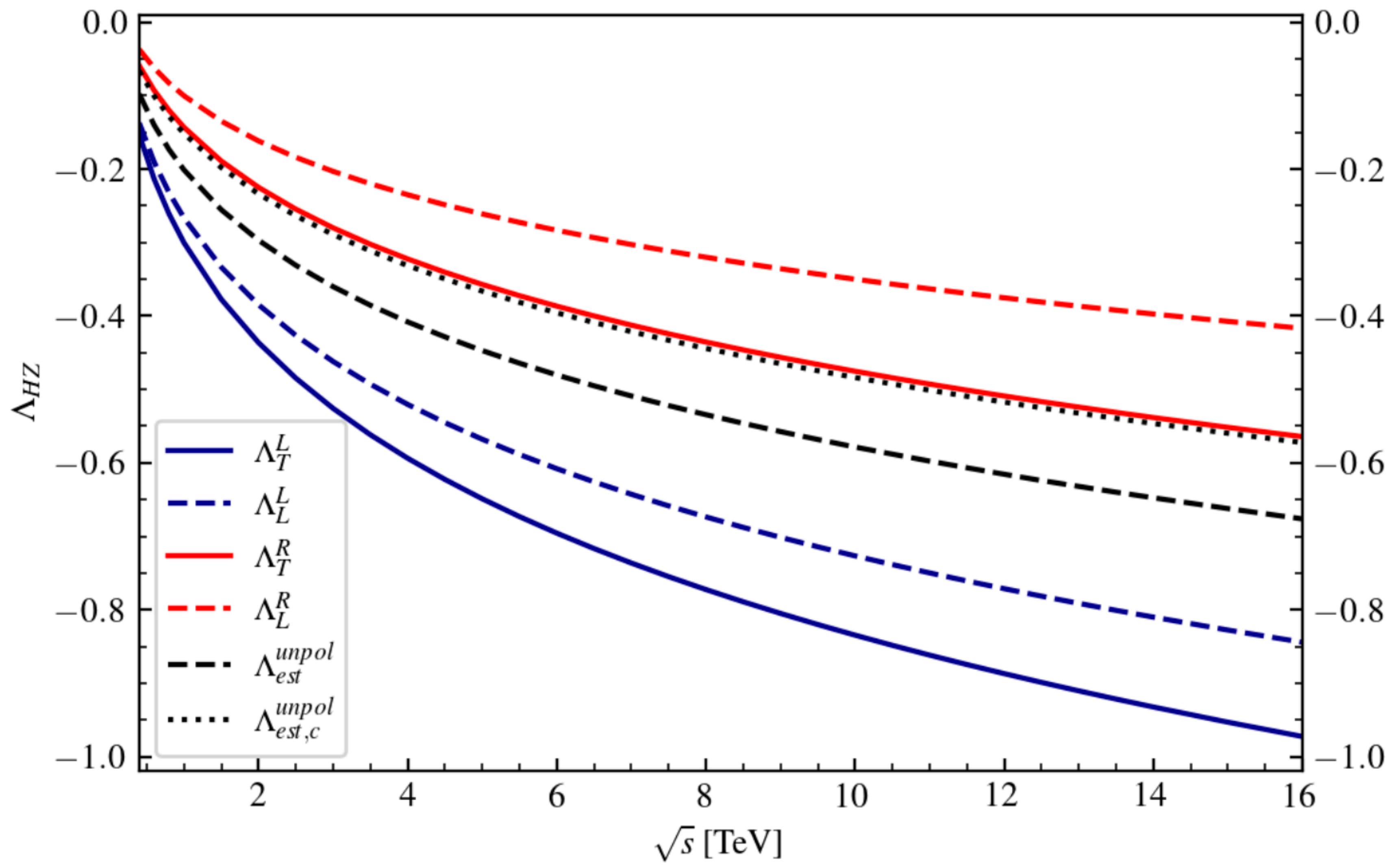


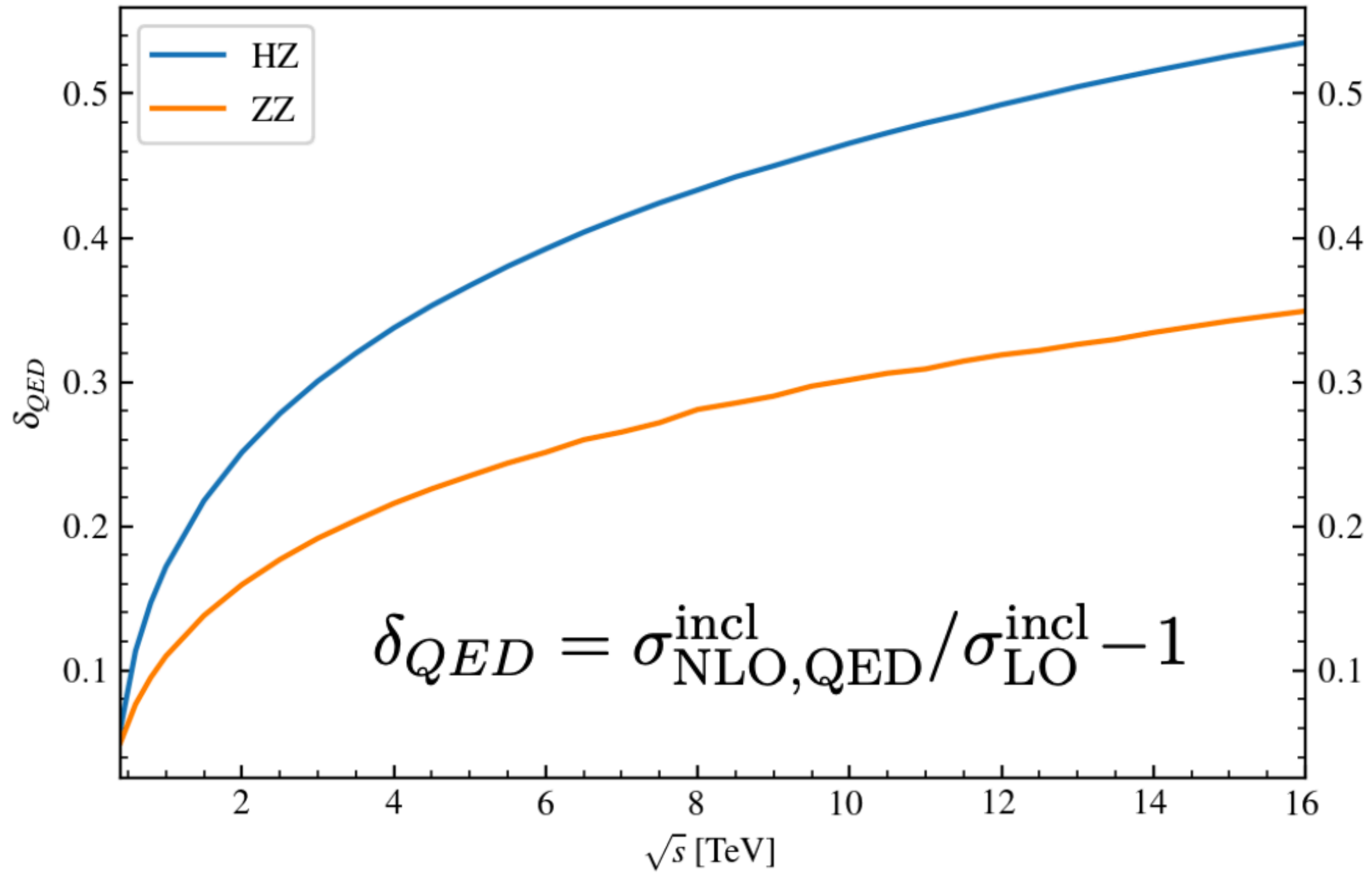


$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma^{\text{incl}}_{\text{LO}}$ [fb]	$\sigma^{\text{incl}}_{\text{NLO}}$ [fb]	δ_{EW} [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$4.847(7) \cdot 10^2$	$+4.0(2)$
ZZ	$2.5988(1) \cdot 10^1$	$2.656(2) \cdot 10^1$	$+2.19(6)$
HZ	$1.3719(1) \cdot 10^0$	$1.3512(5) \cdot 10^0$	$-1.51(4)$
HH	$1.60216(7) \cdot 10^{-7}$	$5.66(1) \cdot 10^{-7}$ *	
W^+W^-Z	$3.330(2) \cdot 10^1$	$2.568(8) \cdot 10^1$	$-22.9(2)$
W^+W^-H	$1.1253(5) \cdot 10^0$	$0.895(2) \cdot 10^0$	$-20.5(2)$
ZZZ	$3.598(2) \cdot 10^{-1}$	$2.68(1) \cdot 10^{-1}$	$-25.5(3)$
HZZ	$8.199(4) \cdot 10^{-2}$	$6.60(3) \cdot 10^{-2}$	$-19.6(3)$
HHZ	$3.277(1) \cdot 10^{-2}$	$2.451(5) \cdot 10^{-2}$	$-25.2(1)$
HHH	$2.9699(6) \cdot 10^{-8}$	$0.86(7) \cdot 10^{-8}$ *	
$W^+W^-W^+W^-$	$1.484(1) \cdot 10^0$	$0.993(6) \cdot 10^0$	$-33.1(4)$
W^+W^-ZZ	$1.209(1) \cdot 10^0$	$0.699(7) \cdot 10^0$	$-42.2(6)$
W^+W^-HZ	$8.754(8) \cdot 10^{-2}$	$6.05(4) \cdot 10^{-2}$	$-30.9(5)$
W^+W^-HH	$1.058(1) \cdot 10^{-2}$	$0.655(5) \cdot 10^{-2}$	$-38.1(4)$
$ZZZZ$	$3.114(2) \cdot 10^{-3}$	$1.799(7) \cdot 10^{-3}$	$-42.2(2)$
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$1.766(6) \cdot 10^{-3}$	$-34.4(2)$
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$6.24(2) \cdot 10^{-4}$	$-36.5(2)$
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$1.165(4) \cdot 10^{-4}$	$-25.7(2)$

Validation of the Sudakov regime

$\mu^+\mu^- \to X, \sqrt{s} = 10$ TeV	$\sigma^{\text{incl}}_{\text{LO}}$ [fb]	$\sigma^{\text{incl}}_{\text{NLO}}$ [fb]	δ_{EW} [%]
W^+W^-	$5.8820(2) \cdot 10^1$	$6.11(1) \cdot 10^1$	$+3.9(2)$
ZZ	$3.2730(4) \cdot 10^0$	$3.401(4) \cdot 10^0$	$+3.9(1)$
HZ	$1.22929(8) \cdot 10^{-1}$	$1.0557(8) \cdot 10^{-1}$	$-14.12(7)$
HH	$1.31569(5) \cdot 10^{-9}$	$42.9(4) \cdot 10^{-9}$ *	
W^+W^-Z	$9.609(5) \cdot 10^0$	$5.86(4) \cdot 10^0$	$-39.0(2)$
W^+W^-H	$2.1263(9) \cdot 10^{-1}$	$1.31(1) \cdot 10^{-1}$	$-38.4(5)$
ZZZ	$8.565(4) \cdot 10^{-2}$	$5.27(8) \cdot 10^{-2}$	$-38.5(9)$
HZZ	$1.4631(6) \cdot 10^{-2}$	$0.952(6) \cdot 10^{-2}$	$-34.9(4)$
HHZ	$6.083(2) \cdot 10^{-3}$	$2.95(3) \cdot 10^{-3}$	$-51.6(5)$
HHH	$2.3202(4) \cdot 10^{-9}$	$-1.0(2) \cdot 10^{-9}$ *	





$\mu^+\mu^- \to X, \sqrt{s} = 10$ TeV	$\sigma^{\text{incl}}_{\text{LO}}$ [fb]	$\sigma^{\text{incl}}_{\text{LO+ISR}}$ [fb]	δ_{ISR} [%]
W^+W^-	$5.8820(2) \cdot 10^1$	$7.295(7) \cdot 10^1$	$+24.0(1)$
ZZ	$3.2730(4) \cdot 10^0$	$4.119(4) \cdot 10^0$	$+25.8(1)$
HZ	$1.22929(8) \cdot 10^{-1}$	$1.8278(5) \cdot 10^{-1}$	$+48.69(4)$
W^+W^-Z	$9.609(5) \cdot 10^0$	$10.367(8) \cdot 10^0$	$+7.9(1)$
W^+W^-H	$2.1263(9) \cdot 10^{-1}$	$2.410(2) \cdot 10^{-1}$	$+13.3(1)$
ZZZ	$8.565(4) \cdot 10^{-2}$	$9.431(7) \cdot 10^{-2}$	$+10.1(1)$
HZZ	$1.4631(6) \cdot 10^{-2}$	$1.677(1) \cdot 10^{-2}$	$+14.62(8)$
HHZ	$6.083(2) \cdot 10^{-3}$	$6.916(3) \cdot 10^{-3}$	$+13.68(6)$

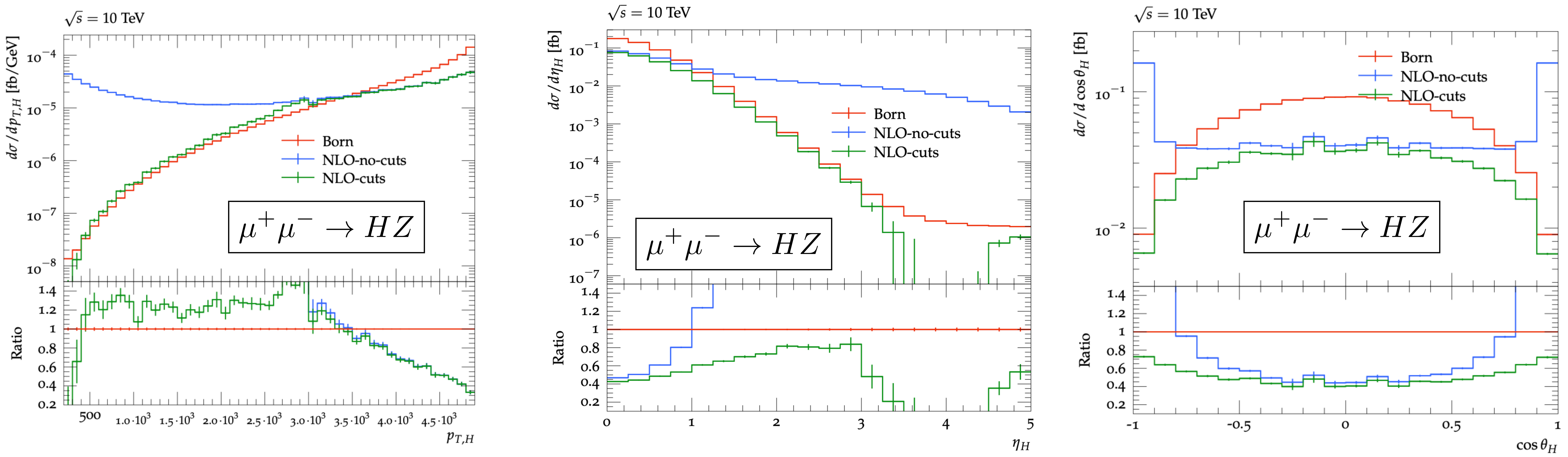
arXiv: 2208.09438

Differential results

Experimentally motivated photon veto in hard radiation: $E_\gamma < 0.7 \cdot \sqrt{s}/2$

arXiv: 2208.09438

Higgs Transverse Momentum — Higgs rapidity — Higgs scattering angle



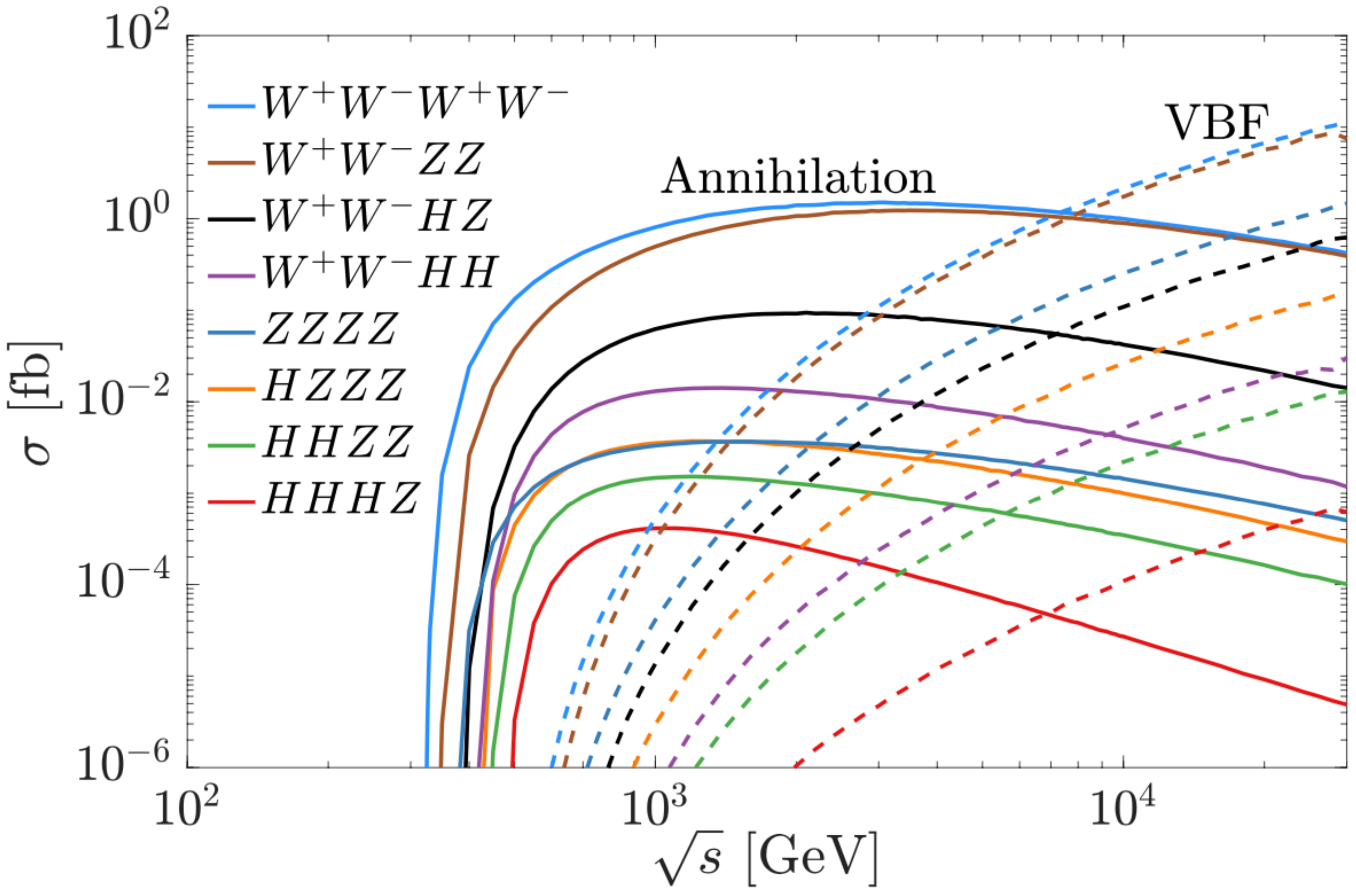
More tasks for even more realistic predictions: exclusive events w/ matching to QED/weak showers, resummation, off-shell processes, separate VBF from VBS

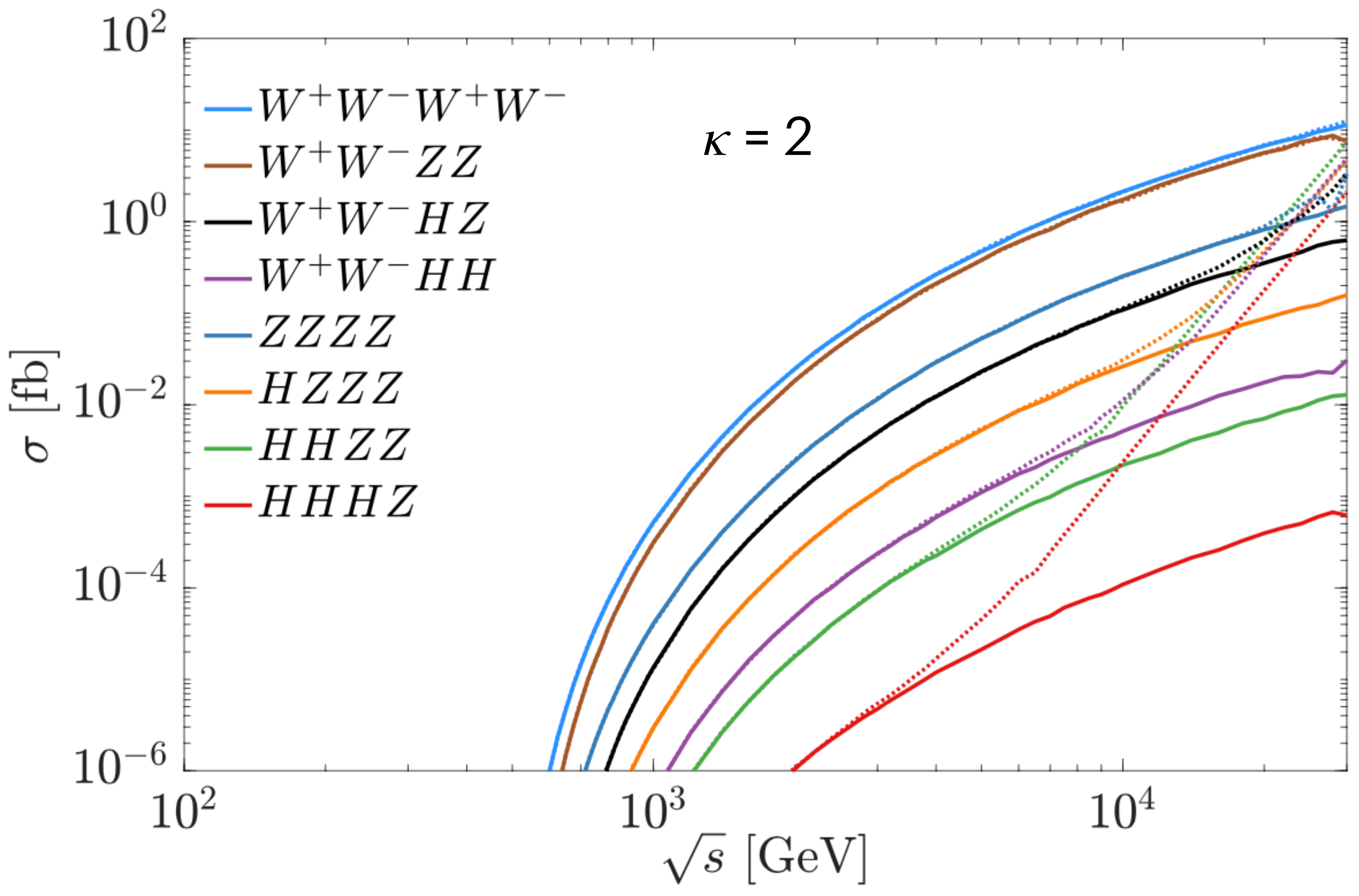
Conclusions & Outlook

- Muon collider highly interesting Energy Frontier option
- Recent technological progress: muon cooling, beam dump etc. .... still a long way to go
- Huge potential for Higgs and electroweak physics as well as BSM sensitivity (multi bosons)
- Example: sensitivity to anomalous muon Yukawa couplings
- Deviations grow with number of final state (EW/Higgs) bosons
- Optimal: tri-boson processes (diboson less sensitivity, quartic bosons smaller xsec.)
- Separation direct production from VBF: *BBB* invariant mass and *B* angular cuts
- **Muon Yukawa coupling testable with sensitivity 20% @ 10 TeV .... 2% @ 30 TeV**
- Translates to 5σ sensitivities to new physics of $\Lambda \sim 20 - 70$ TeV
- Thorough understanding of SM EW corrections: available in well automated way
- Sudakov regimes necessitates resummation
- Work in progress: multi-Higgs final states & trilinear/quartic Higgs coupling

BACKUP

Additional cross sections





Collection of useful formulæ

Unitarity violation for operator insertions at d = 6, 8, 10: corresponds to 95 TeV, 17 TeV, 11 TeV, respectively

$$\Lambda_d = 4\pi\kappa_d \left(\frac{v^{d-3}}{m_\mu}\right)^{1/(d-4)}, \quad \text{where} \quad \kappa_d = \left(\frac{(d-5)!}{2^{d-5}(d-3)}\right)^{1/(2(d-4))}$$

$$R^{\text{SMEFT}}_{(3),1} = \left(\frac{v^2 c^{(2)}_{\ell\varphi} + c^{(1)}_{\ell\varphi}}{3v^2 c^{(2)}_{\ell\varphi} + c^{(1)}_{\ell\varphi}}\right)^2, \qquad R^{\text{SMEFT}}_{(3),2} = \left(\frac{5v^2 c^{(2)}_{\ell\varphi} + c^{(1)}_{\ell\varphi}}{3v^2 c^{(2)}_{\ell\varphi} + c^{(1)}_{\ell\varphi}}\right)^2$$

$$m^{(8)}_\mu = \frac{v}{\sqrt{2}}\left(y_\mu - \frac{v^2}{2}c^{(1)}_{\ell\varphi} - \frac{v^4}{4}c^{(2)}_{\ell\varphi}\right),$$

$$\lambda^{(8)}_\mu = \left(y_\mu - \frac{3v^2}{2}c^{(1)}_{\ell\varphi} - \frac{5v^4}{4}c^{(2)}_{\ell\varphi}\right),$$

$$R^{\text{HEFT}}_{(3),1} = \left(\frac{y_\mu}{y_1}\right)^2, \qquad R^{\text{HEFT}}_{(3),2} = \left(\frac{y_2}{y_1}\right)^2, \qquad R^{\text{HEFT}}_{(3),3} = \left(\frac{y_3}{y_1}\right)^2$$

$$R^{\text{SMEFT}}_{(4),1} = \left(\frac{3v^2 c^{(3)}_{\ell\varphi} + 2c^{(2)}_{\ell\varphi}}{5v^2 c^{(3)}_{\ell\varphi} + 2c^{(2)}_{\ell\varphi}}\right)^2, \qquad R^{\text{SMEFT}}_{(4),2} = \left(\frac{7v^2 c^{(3)}_{\ell\varphi} + 2c^{(2)}_{\ell\varphi}}{5v^2 c^{(3)}_{\ell\varphi} + 2c^{(2)}_{\ell\varphi}}\right)^2$$

$$R^{\text{HEFT}}_{(4),1} = \left(\frac{y_\mu}{y_2}\right)^2, \quad R^{\text{HEFT}}_{(4),2} = \left(\frac{y_1}{y_2}\right)^2, \quad R^{\text{HEFT}}_{(4),3} = \left(\frac{y_3}{y_2}\right)^2, \quad R^{\text{HEFT}}_{(4),4} = \left(\frac{y_4}{y_2}\right)^2$$