Physics at Muon Colliders — SM and Beyond

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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

T. Han/W. Kilian/N. Kreher/Y. Ma/JRR/T. Striegl/K. Xie arXiv: 2108.05362 [JHEP]

P. Bredt, W. Kilian, JRR, P. Stienemeier arXiv: 2208.09438 [JHEP]

K. Korshynska, M. Löschner, M. Marinichenko, K. Mękała/JRR arXiv: 240x.xxxxx

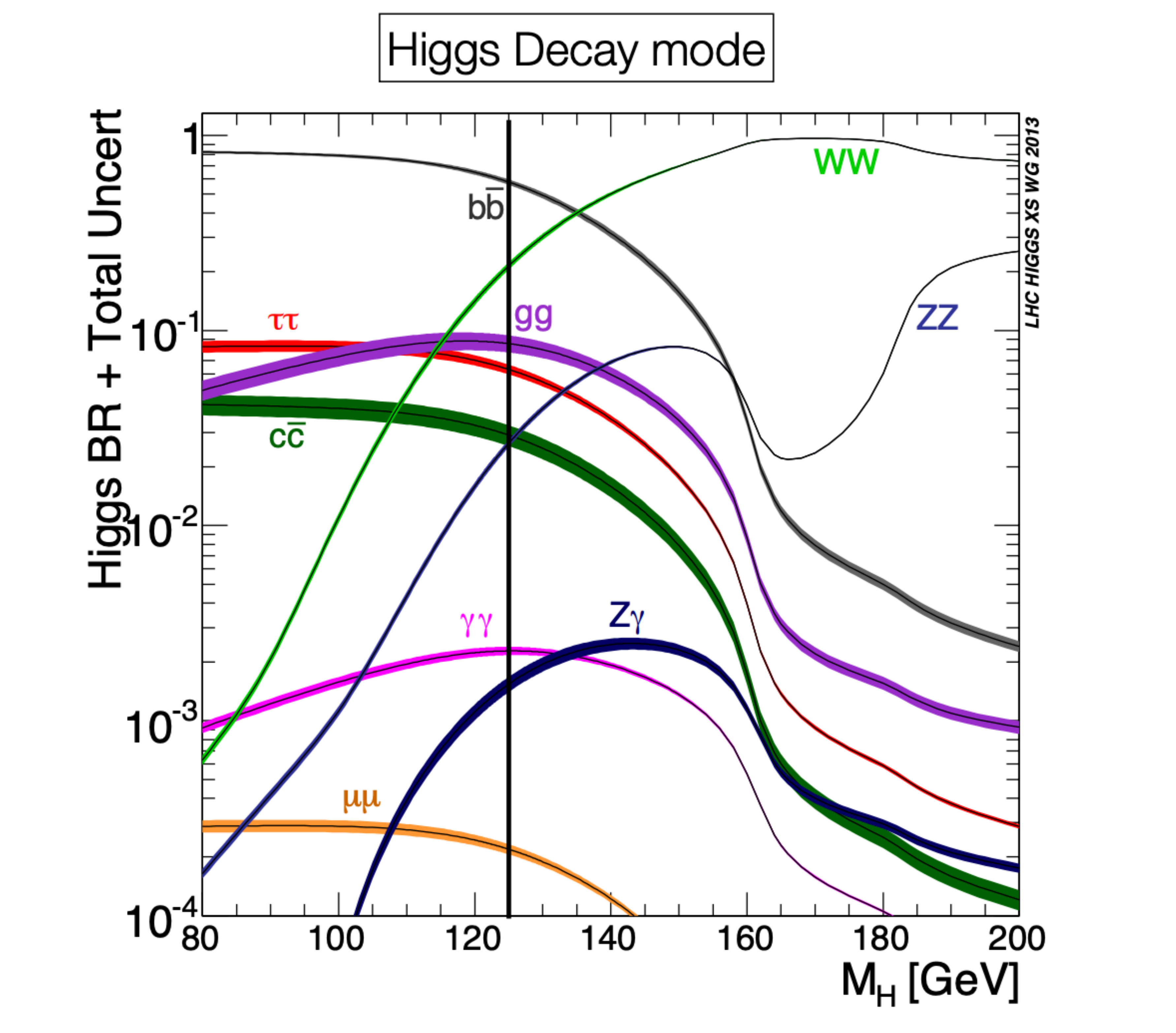
Celada/Han/Kilian/Kreher/Ma/Maltoni/Pagani/JRR/Striegl/Xie, arXiv:231x.xxxx

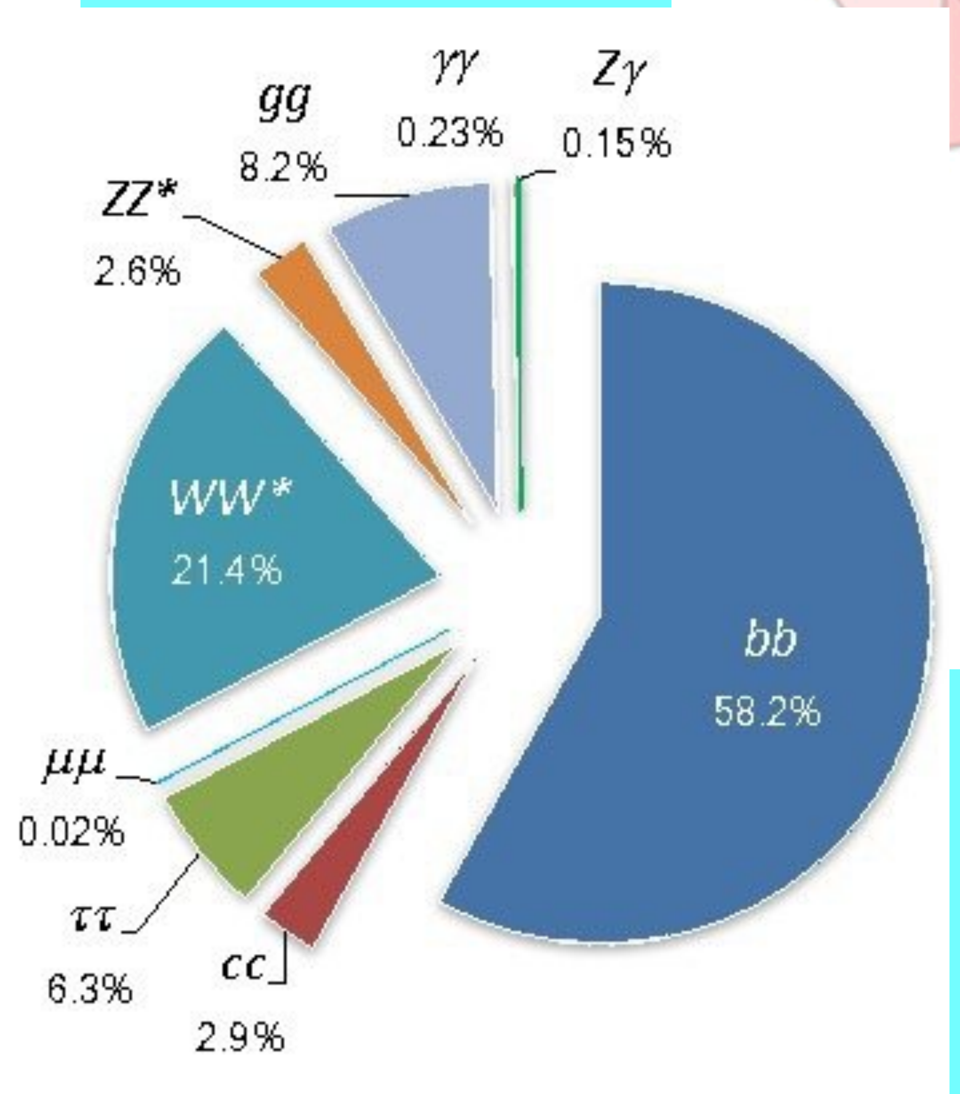
K. Mękała/JRR/A.F. Żarnecki, arXiv: 2301.02602 [PLB] + 231x.xxxxx

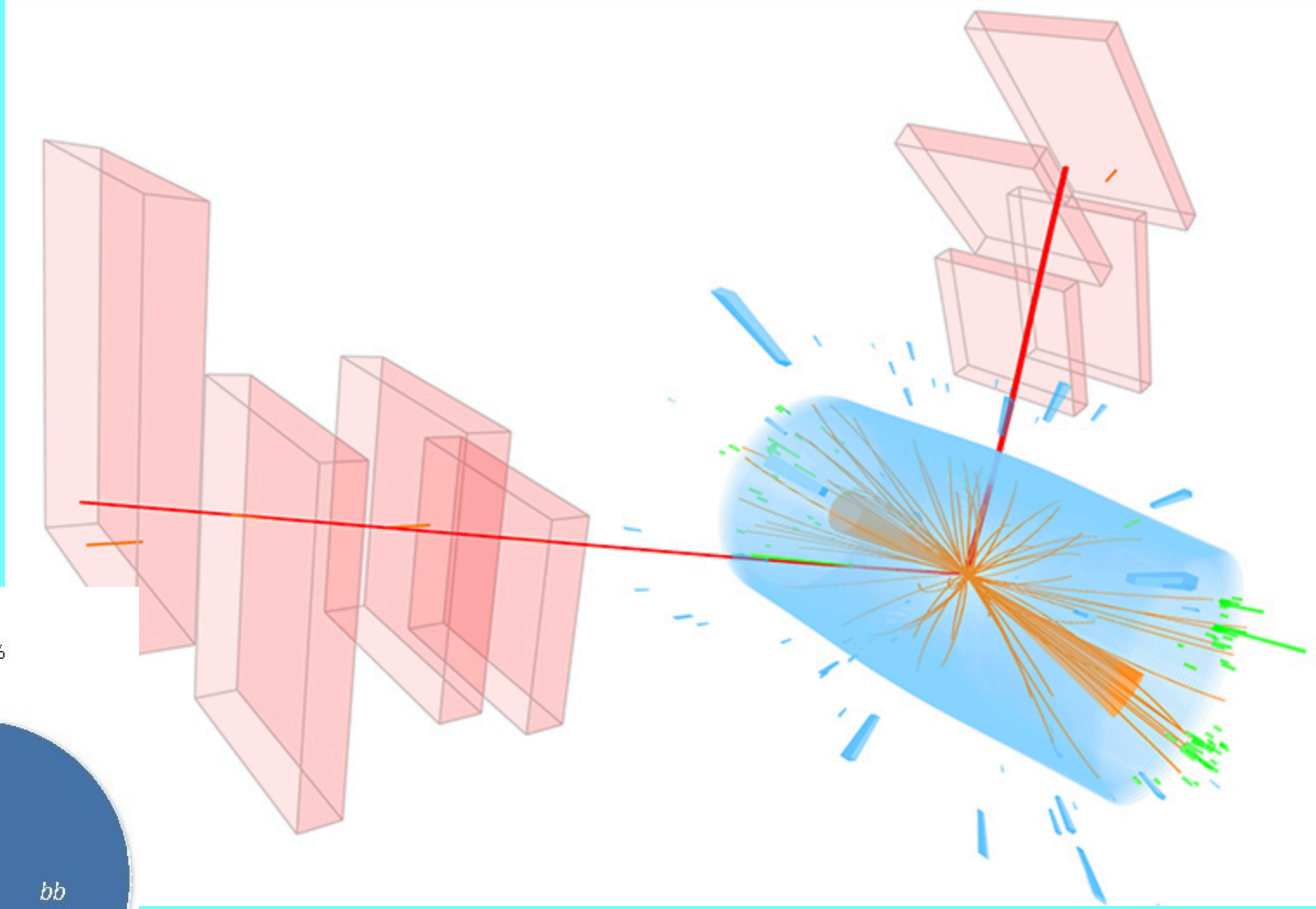
Jürgen R. Reuter

DESY.

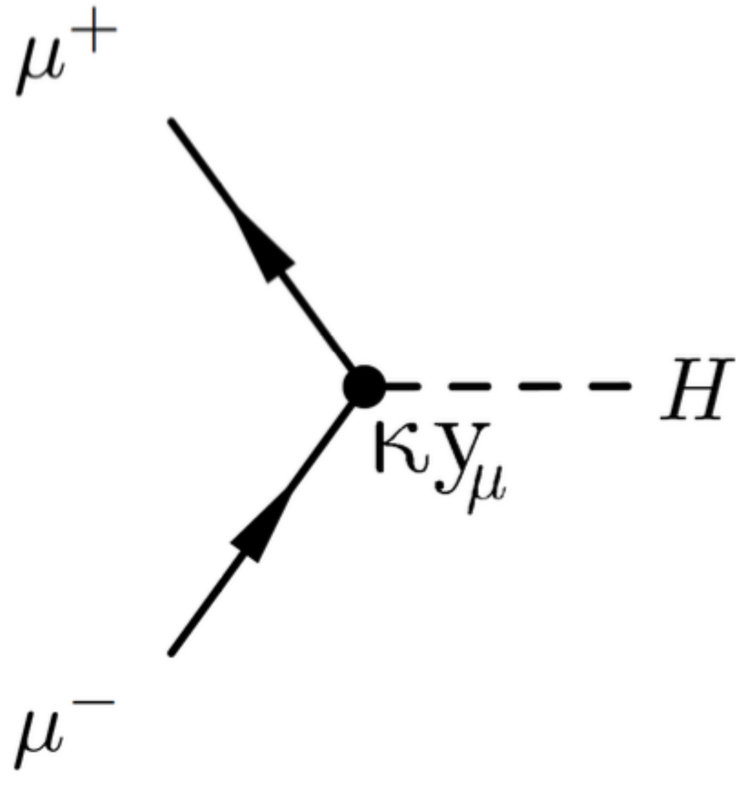
Multi-Bosons: Elusive couplings







Elusive SM couplings

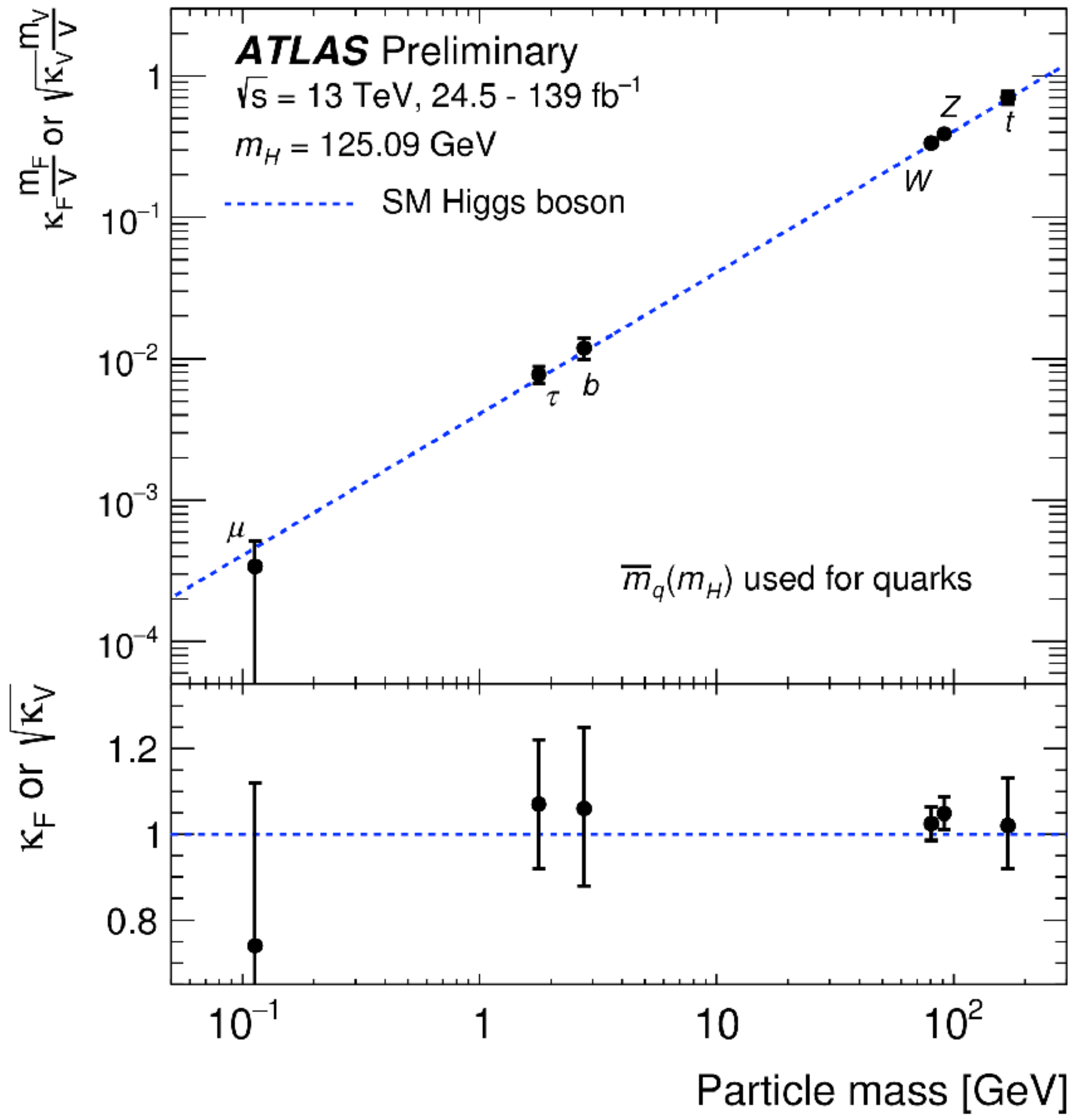


- Higgs properties at high precision utmost priority ⟹ ↪ ESU2020 document
- Higgs potential and Higgs couplings to all SM particles
- Higgs muon Yukawa coupling — connected to muon mass [in the SM!]

SM: $\varkappa = 1$

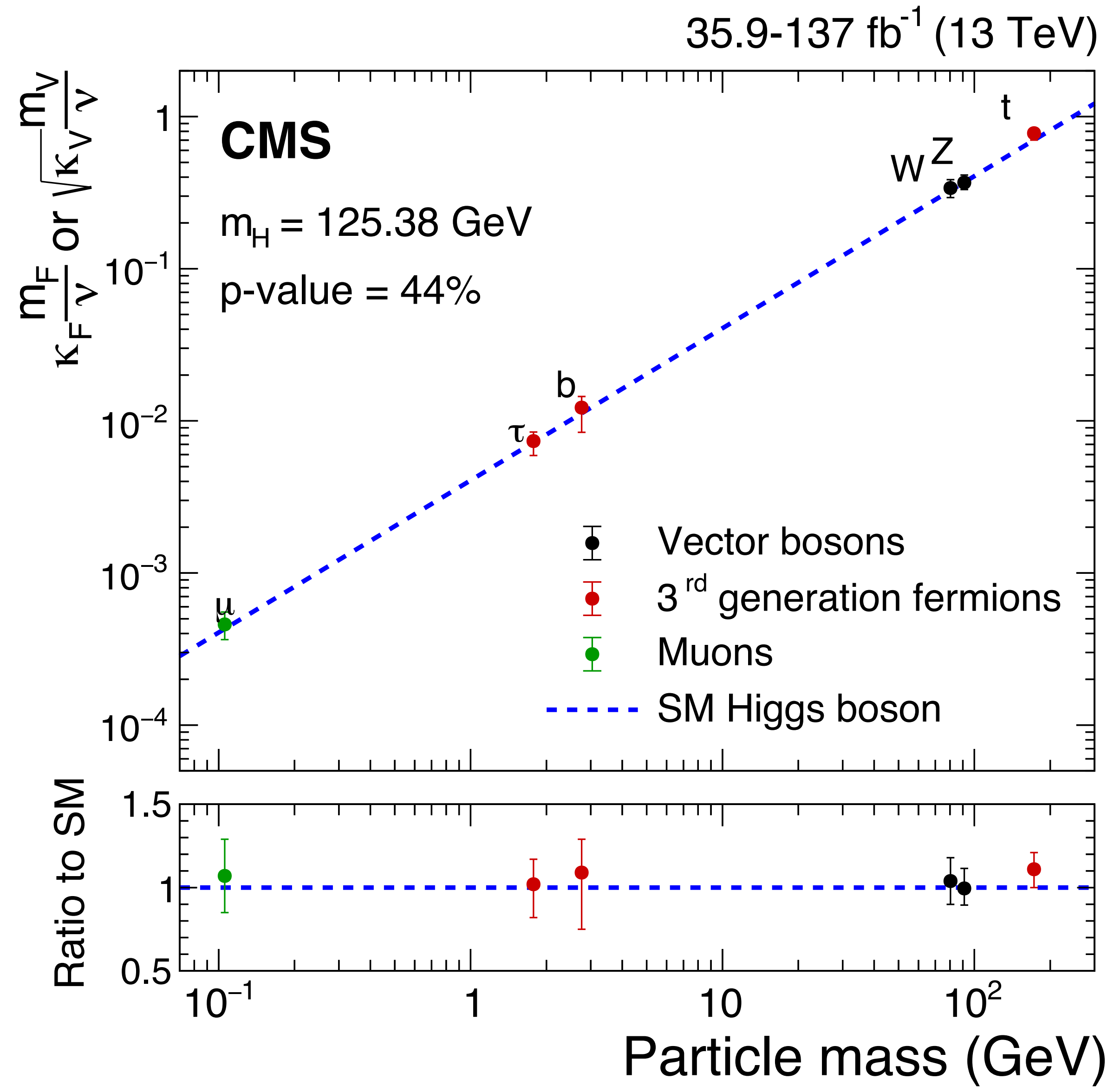
or $\Delta\varkappa = 0$

- Evidence for muon Yukawa coupling 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 5-10% [ATLAS-PHYS-PUB-2014-016]



Challenges / wishlist:

- Model-independent test for this coupling
- Direct access not relying on decays
- Sensitivity to the sign (and maybe phase) of coupling
- ▶ use high-luminosity muon collider



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

Generalized (μ) Yukawa sector

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

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

Linear representation ([truncated] SMEFT)

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

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

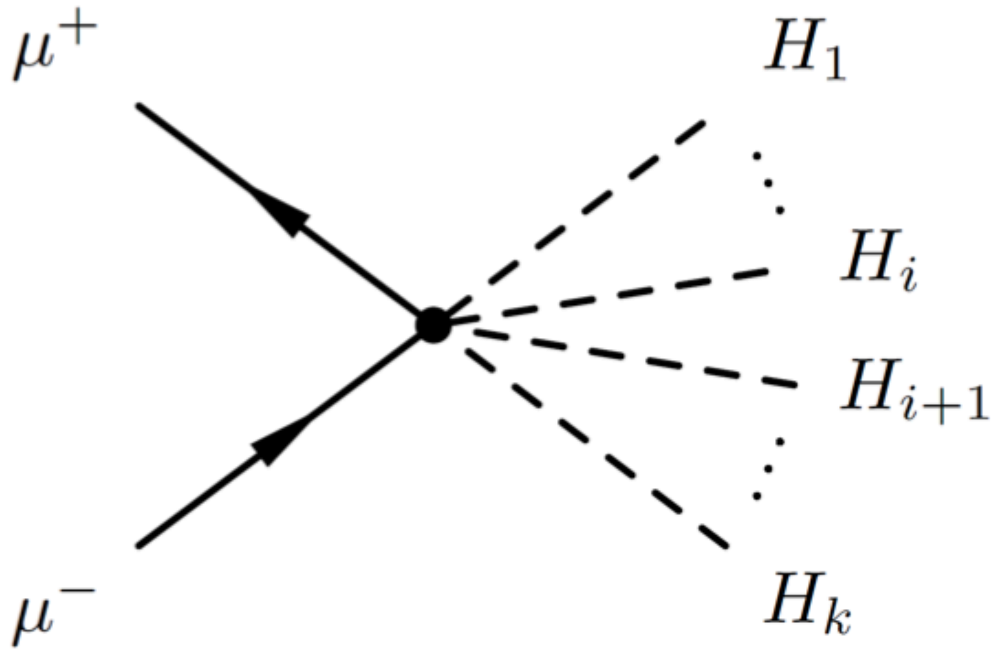
Parameterization of μ mass and Yukawa modifier

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

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

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

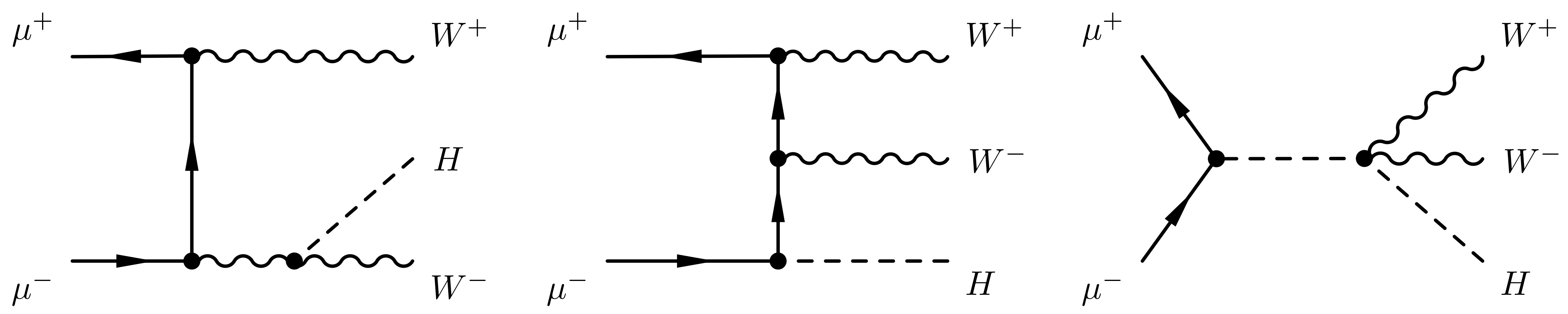
$$-i \frac{k!}{\sqrt{2}} \left[Y_\ell \delta_{k,1} - \sum_{n=n_k}^{M-1} \frac{C_{\mu\varphi}^{(n)}}{\Lambda^{2n}} \binom{2n+1}{k} \frac{v^{2n+1-k}}{2^n} \right] = 0 =$$



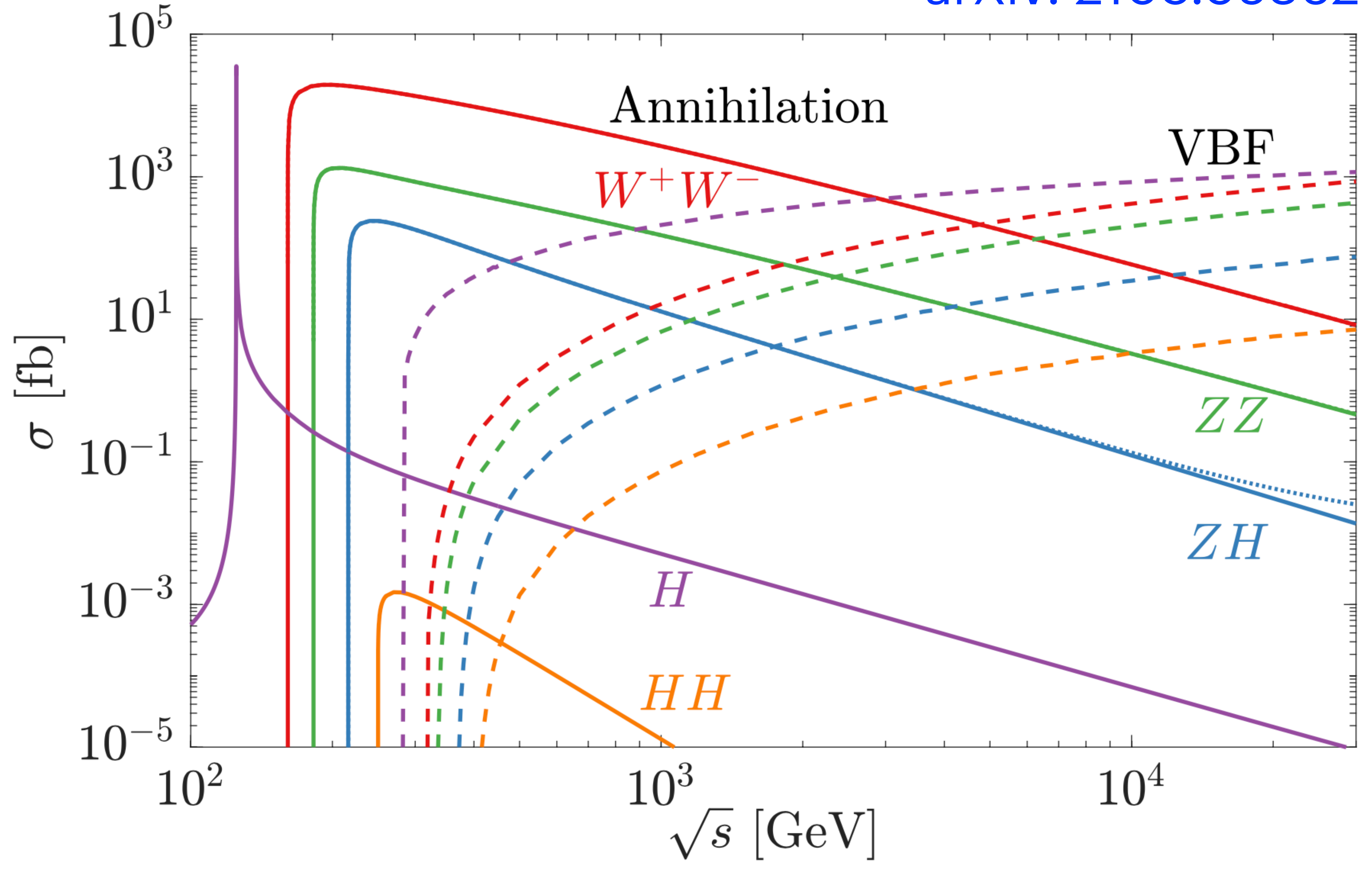
Benchmark scenario: "matched" case

Multi-boson final states

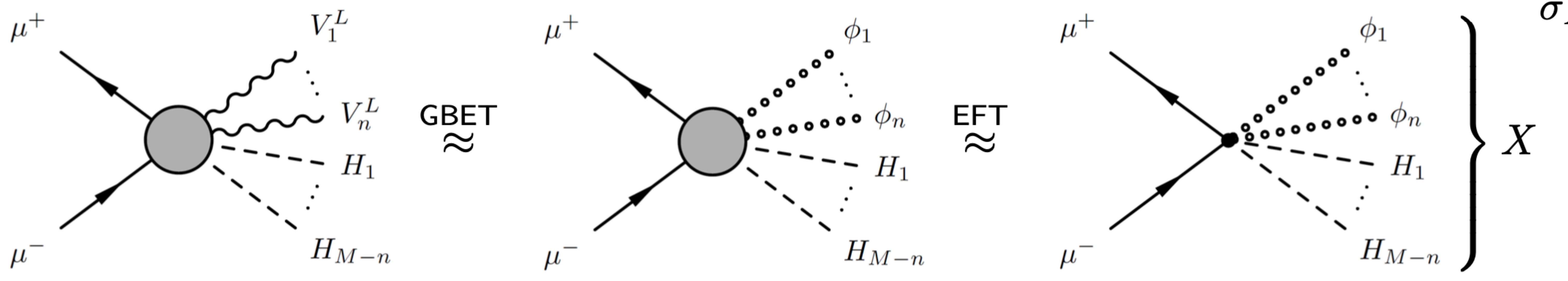
- Subtle cancellation between Yukawa coupling and multi-boson final states [hep-ph/0106281]



arXiv: 2108.05362



- (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)



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

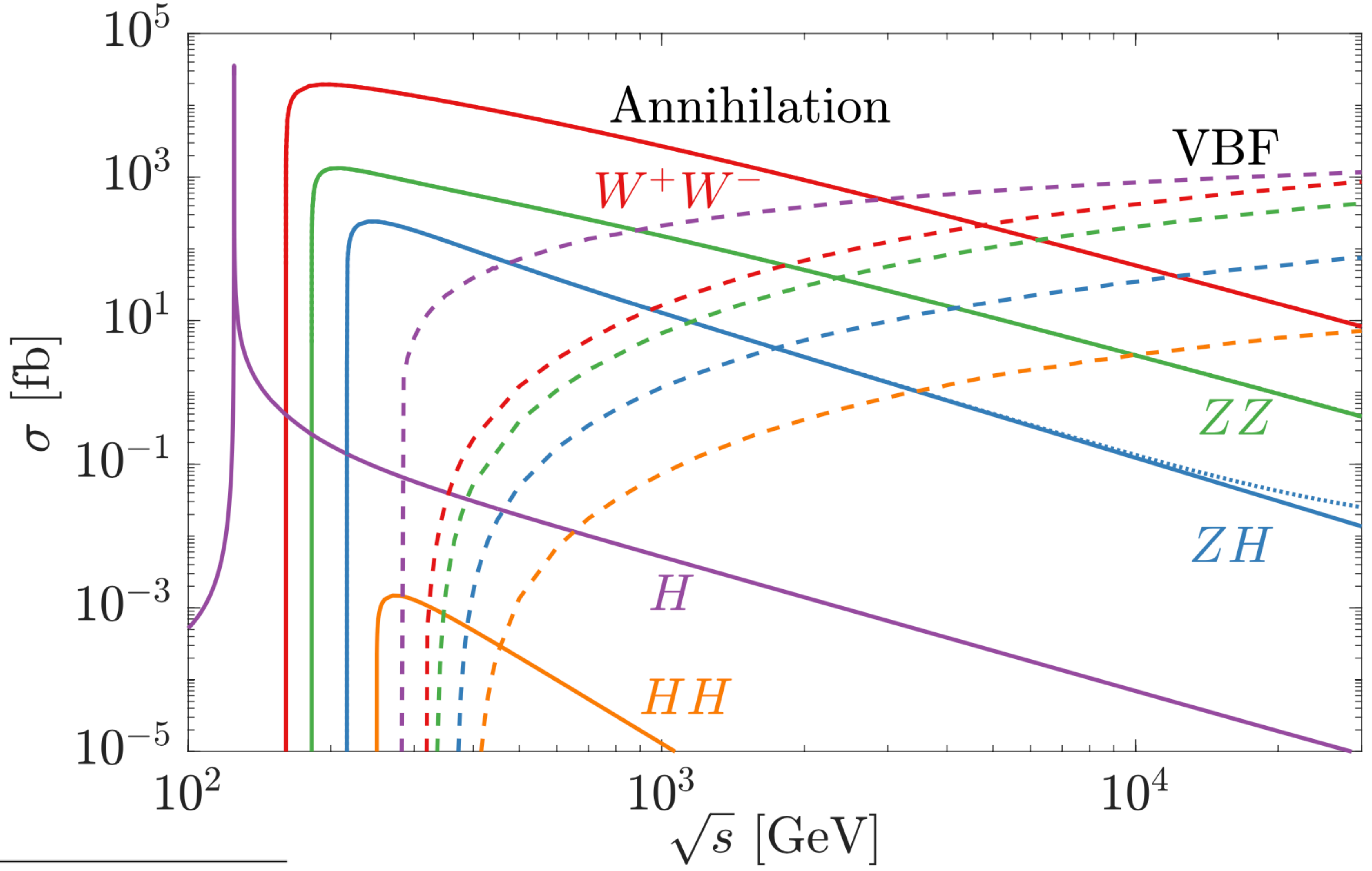
Cross section ratios: $R = \frac{\sigma_X}{\sigma_Y} \approx \frac{|C_X|^2 \left(\prod_{j\in J_X}\frac{1}{n_j!}\right)}{|C_Y|^2 \left(\prod_{j\in J_Y}\frac{1}{n_j!}\right)}$

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	$\dim_6$	$\dim_8$	$\dim_{6,8}$	$\dim_{6,8}^{\text{matched}}$	$\dim_\infty$	$\dim_\infty^{\text{matched}}$
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	$R^{\text{HEFT}}_{(2),1}$	1
HH	9/2	25/2	$R^{\text{SMEFT}}_{(2),1}/2$	0	$2\,R^{\text{HEFT}}_{(2),2}$	0

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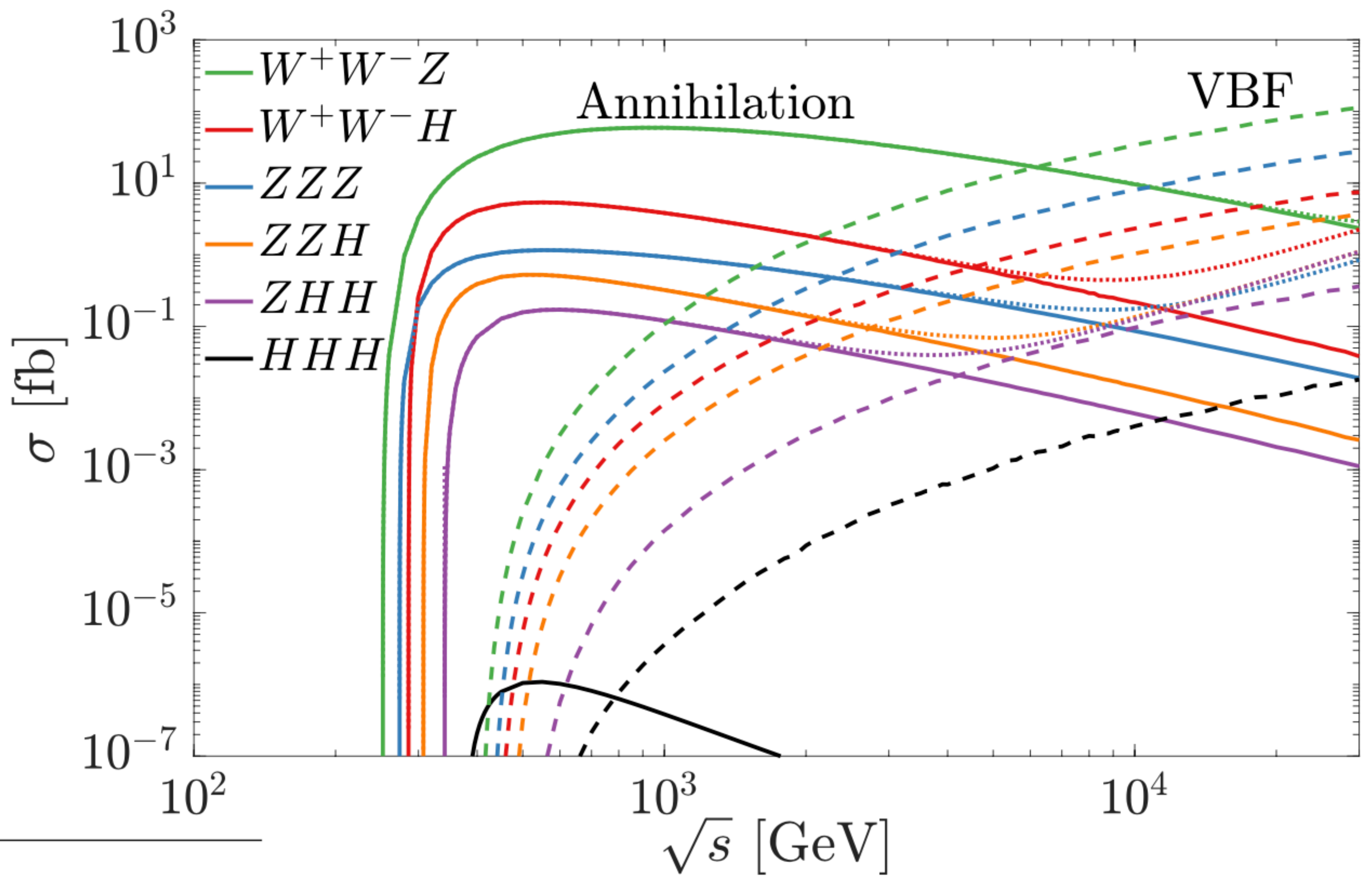
States with multiplicity 3

- 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	$\mathrm{dim}_{6,8}$	$\mathrm{dim}_{6,8}^{\mathrm{matched}}$	dim_∞	$\mathrm{dim}_\infty^{\mathrm{matched}}$
WWZ	1	1/9	$R^{\mathrm{SMEFT}}_{(3),1}$	1/4	$R^{\mathrm{HEFT}}_{(3),1}/9$	1/4
ZZZ	3/2	1/6	$3\,R^{\mathrm{SMEFT}}_{(3),1}/2$	3/8	$R^{\mathrm{HEFT}}_{(3),1}/6$	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	$2\,R^{\mathrm{HEFT}}_{(3),2}$	1/2
HHH	3/2	25/6	$3\,R^{\mathrm{SMEFT}}_{(3),2}/2$	75/8	$6\,R^{\mathrm{HEFT}}_{(3),3}$	0

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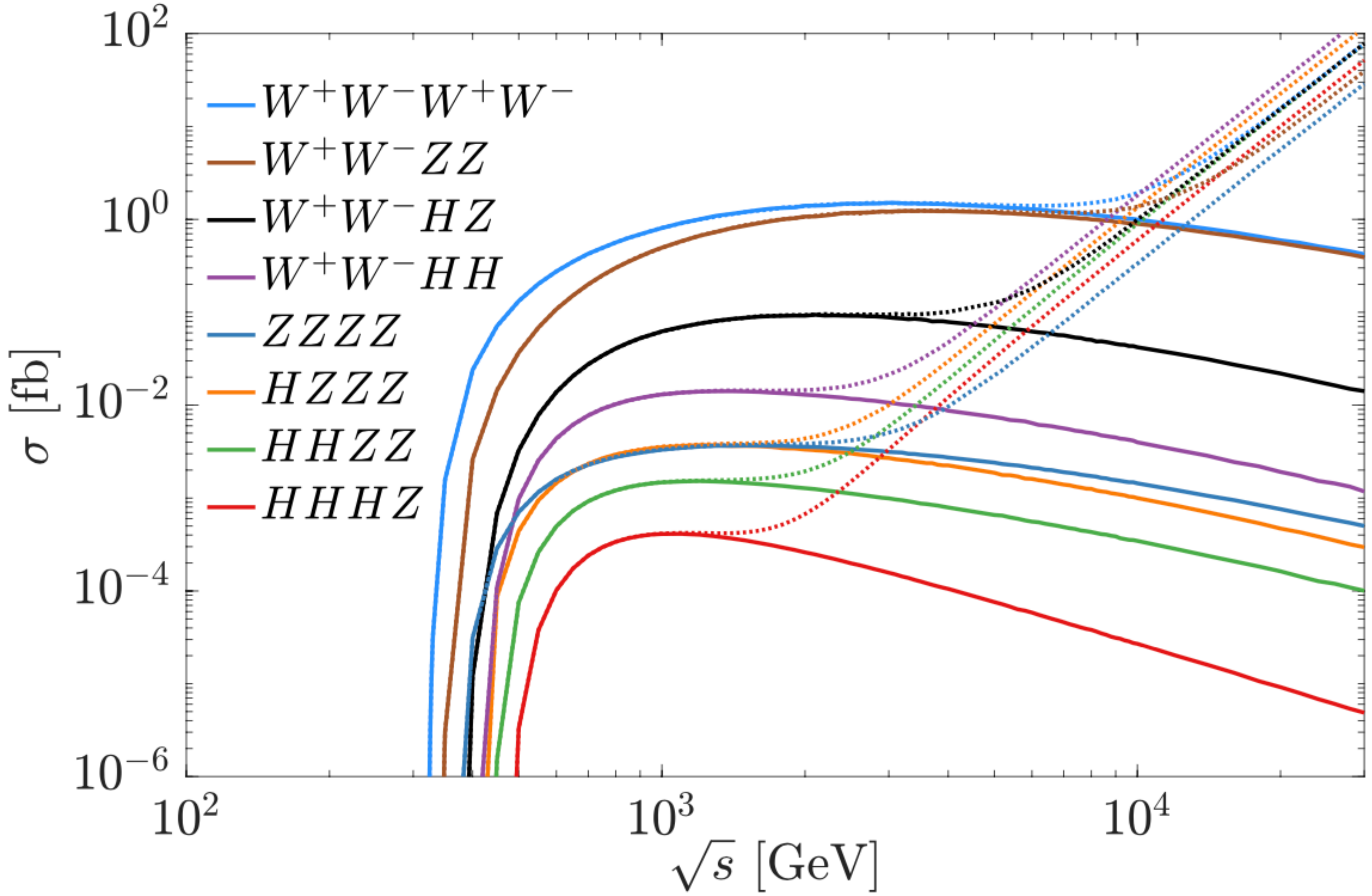
States with multiplicity 4



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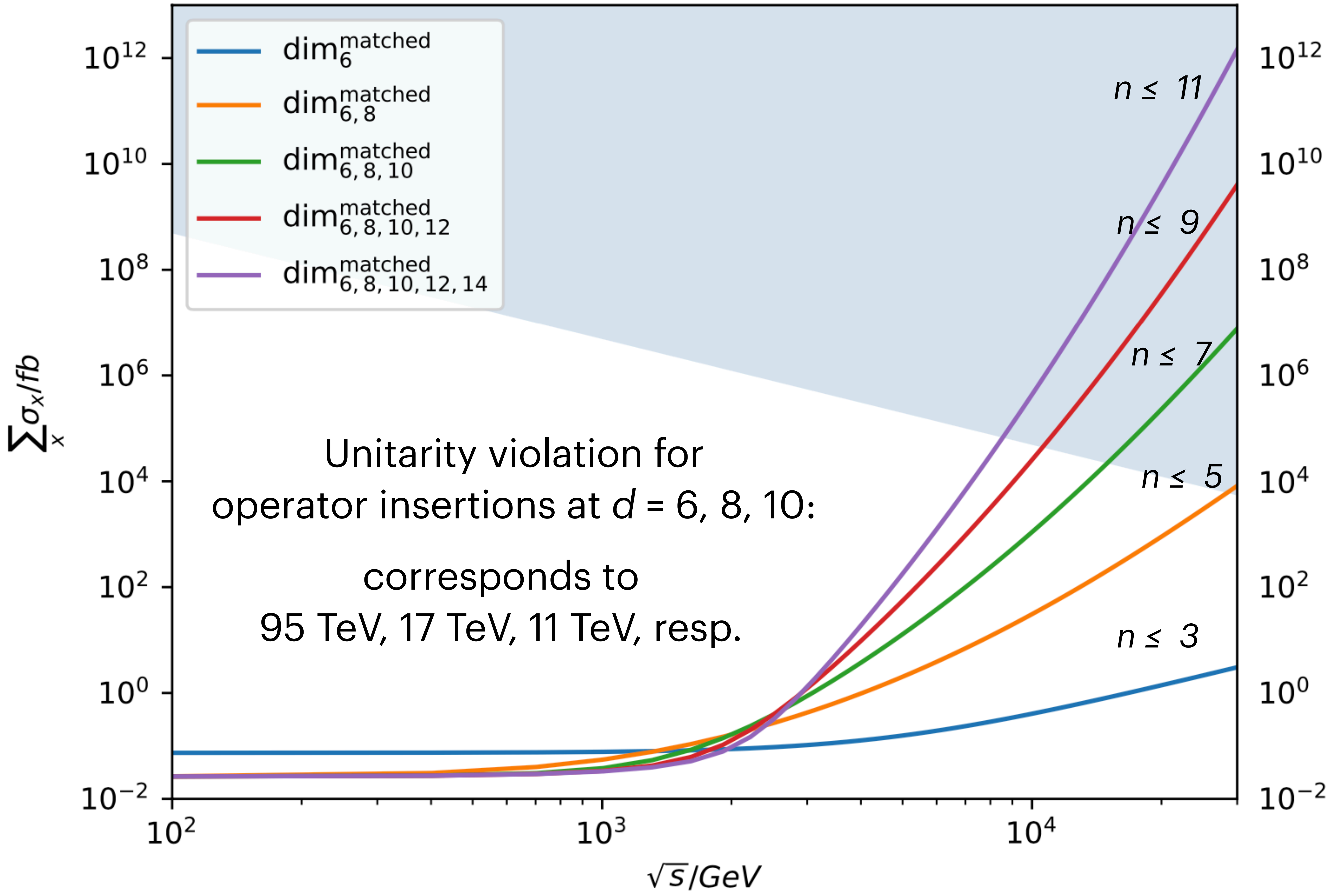
	SMEFT					
$\mu^+\mu^- \to X$	$\text{dim}_{6,8}$	dim_{10}	$\text{dim}_{6,8,10}$	$\text{dim}^{\text{matched}}_{6,8,10}$		
$WWWW$	$2/9$	$2/25$	$2\,R^{\text{SMEFT}}_{(4),1}/9$	$1/2$	R	
$WWZZ$	$1/9$	$1/25$	$R^{\text{SMEFT}}_{(4),1}/9$	$1/4$	R	
$ZZZZ$	$1/12$	$3/100$	$R^{\text{SMEFT}}_{(4),1}/12$	$3/16$	$R^{\text{HEFT}}_{(4),1}/48$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

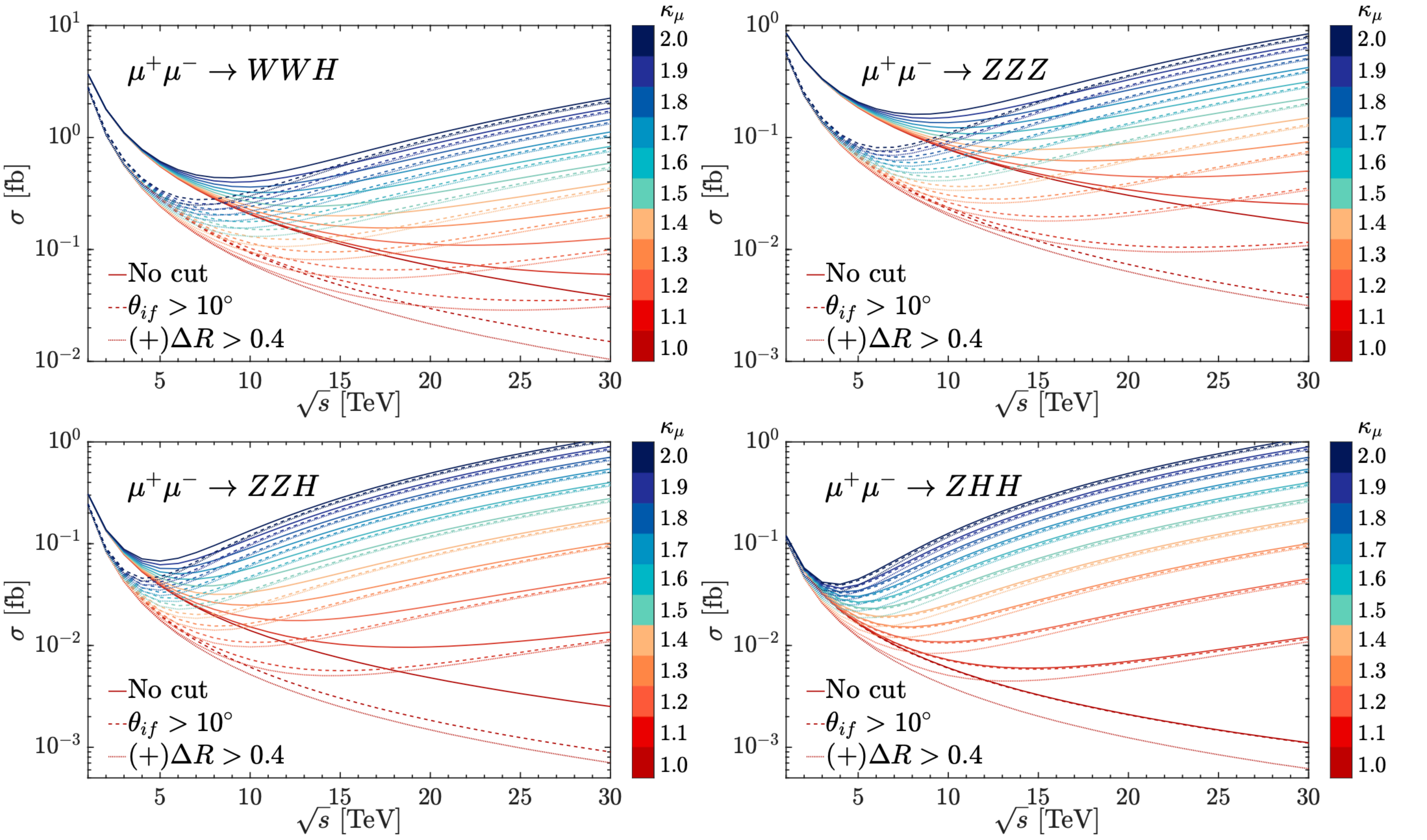


Unitarity bound for final states $X \neq \mu\mu$:

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

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 $\Longrightarrow \Theta_B$
- Separation criterion for final state bosons $\Longrightarrow \Delta R_{BB}$

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		

Results and final projections

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

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: $B = N_{\kappa_\mu=1} + N_{\mathrm{VBF}}$
- Statistical significance of anom. muon Yukawa couplings:

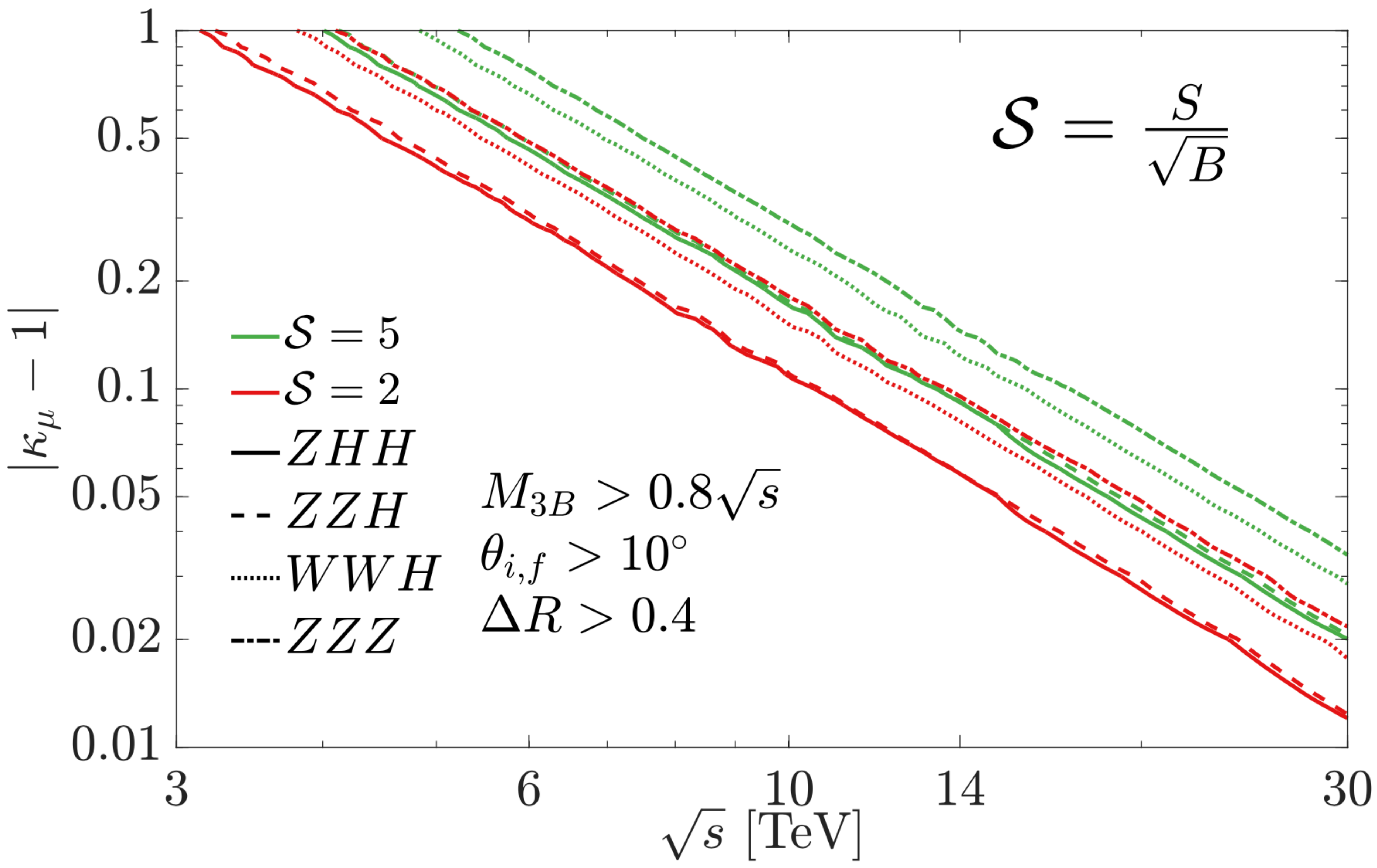
$$\mathcal{S} = \frac{S}{\sqrt{B}}$$

(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

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



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Work in progress: multi-Higgs processes

Celada/Han/Kilian/Kreher/Ma/Maltoni/Pagani/JRR/Striegl/Xie, *to appear soon*

- EFT setup generating multi-boson vertices of higher multiplicity
- Paradigmatic BSM implementations: scalar singlet *S* / vector-like fermions $E_{L/R}$
- Vertex parameterizations (can be expressed by HEFT or SMEFT operators):

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

$$y_{\mu,n} = \frac{\sqrt{2}m_\mu}{v}\alpha_n, \qquad f_{V,n} = \beta_n \lambda$$

$$\alpha_1 = \frac{v}{\sqrt{2}m_\mu} y_{l,1} = 1 + \frac{v^3}{\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{v^5}{\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{3v^7}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_2 = \frac{v}{\sqrt{2}m_\mu} y_{l,2} = \frac{3v^3}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_3 = \frac{v}{\sqrt{2}m_\mu} y_{l,3} = \frac{v^3}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_4 = \frac{v}{\sqrt{2}m_\mu} y_{l,4} = \frac{5v^5}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

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$$\alpha_4 = \frac{v}{\sqrt{2}m_\mu} y_{l,4} = \frac{5v^5}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_5 = \frac{v}{\sqrt{2}m_\mu} y_{l,5} = \frac{v^5}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

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

$\alpha_{1,2}$

$\alpha_{1,2,3}$

$\alpha_{1\ldots4}$

$\alpha_{1\ldots5}$

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- Paradigmatic BSM implementations: scalar singlet S / vector-like fermions $E_{L/R}$
- Vertex parameterizations (can be expressed by HEFT or SMEFT operators):

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

$$y_{\mu,n} = \frac{\sqrt{2} m_\mu}{v} \alpha_n , \qquad f_{V,n} = \beta_n \lambda$$

$$\alpha_1 = \frac{v}{\sqrt{2} m_\mu} y_{l,1} = 1 + \frac{v^3}{\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{v^5}{\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{3 v^7}{4\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_2 = \frac{v}{\sqrt{2} m_\mu} y_{l,2} = \frac{3 v^3}{2\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5 v^5}{2\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21 v^7}{8\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_3 = \frac{v}{\sqrt{2} m_\mu} y_{l,3} = \frac{v^3}{2\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5 v^5}{2\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35 v^7}{8\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

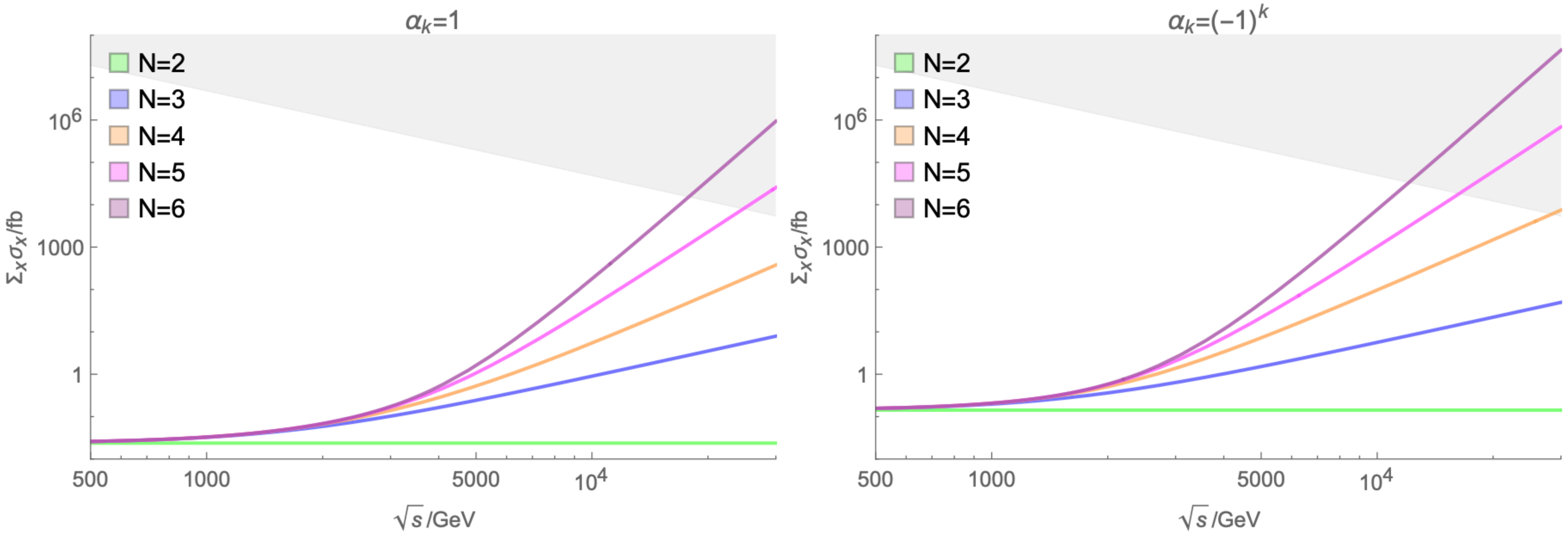
$$\alpha_4 = \frac{v}{\sqrt{2} m_\mu} y_{l,4} = \frac{5 v^5}{4\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35 v^7}{8\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_5 = \frac{v}{\sqrt{2} m_\mu} y_{l,5} = \frac{v^5}{4\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21 v^7}{8\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

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

Perturbative Unitarity bound



Preliminary results for $\mu^+\mu^- \to V^k H^l$

Cut flow: signal and background events

$\sqrt{s}$	3 TeV				10 TeV			
	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF
σ [fb]	$2H$							
No cut	$2.4 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	0.951	$2.4 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.2 \cdot 10^{-4}$	3.80
$M_F > 0.8\sqrt{s}$	$2.4 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	$6.12 \cdot 10^{-4}$	$2.4 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.2 \cdot 10^{-4}$	$6.50 \cdot 10^{-4}$
$\lvert\theta_{iB}\rvert > 10^\circ$	$2.3 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	$1.18 \cdot 10^{-4}$	$2.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.1 \cdot 10^{-4}$	$3.46 \cdot 10^{-5}$
event #	23	–	2.6	0.12	230	–	4.1	0.3
σ [fb]	$3H$							
No cut	$3.1 \cdot 10^{-2}$	$3.0 \cdot 10^{-8}$	$1.1 \cdot 10^{-5}$	$3.69 \cdot 10^{-4}$	$3.7 \cdot 10^{-1}$	$2.3 \cdot 10^{-9}$	$1.7 \cdot 10^{-6}$	$5.52 \cdot 10^{-3}$
$M_F > 0.8\sqrt{s}$	$3.1 \cdot 10^{-2}$	$3.0 \cdot 10^{-8}$	$1.1 \cdot 10^{-5}$	$2.84 \cdot 10^{-6}$	$3.7 \cdot 10^{-1}$	$2.3 \cdot 10^{-9}$	$1.7 \cdot 10^{-6}$	$7.85 \cdot 10^{-5}$
$\lvert\theta_{iB}\rvert > 10^\circ$	$3.0 \cdot 10^{-2}$	$2.8 \cdot 10^{-8}$	$1.1 \cdot 10^{-5}$	$6.82 \cdot 10^{-7}$	$3.5 \cdot 10^{-1}$	$2.2 \cdot 10^{-9}$	$1.7 \cdot 10^{-6}$	$7.37 \cdot 10^{-5}$
$\Delta R_{BB} > 0.4$	$2.9 \cdot 10^{-2}$	$2.7 \cdot 10^{-8}$	$8.1 \cdot 10^{-6}$	$6.07 \cdot 10^{-7}$	$3.4 \cdot 10^{-1}$	$2.1 \cdot 10^{-9}$	$6.8 \cdot 10^{-7}$	$7.22 \cdot 10^{-5}$
event #	29	–	–	–	3400	–	–	0.7

Preliminary results for $\mu^+\mu^- \to V^k H^l$

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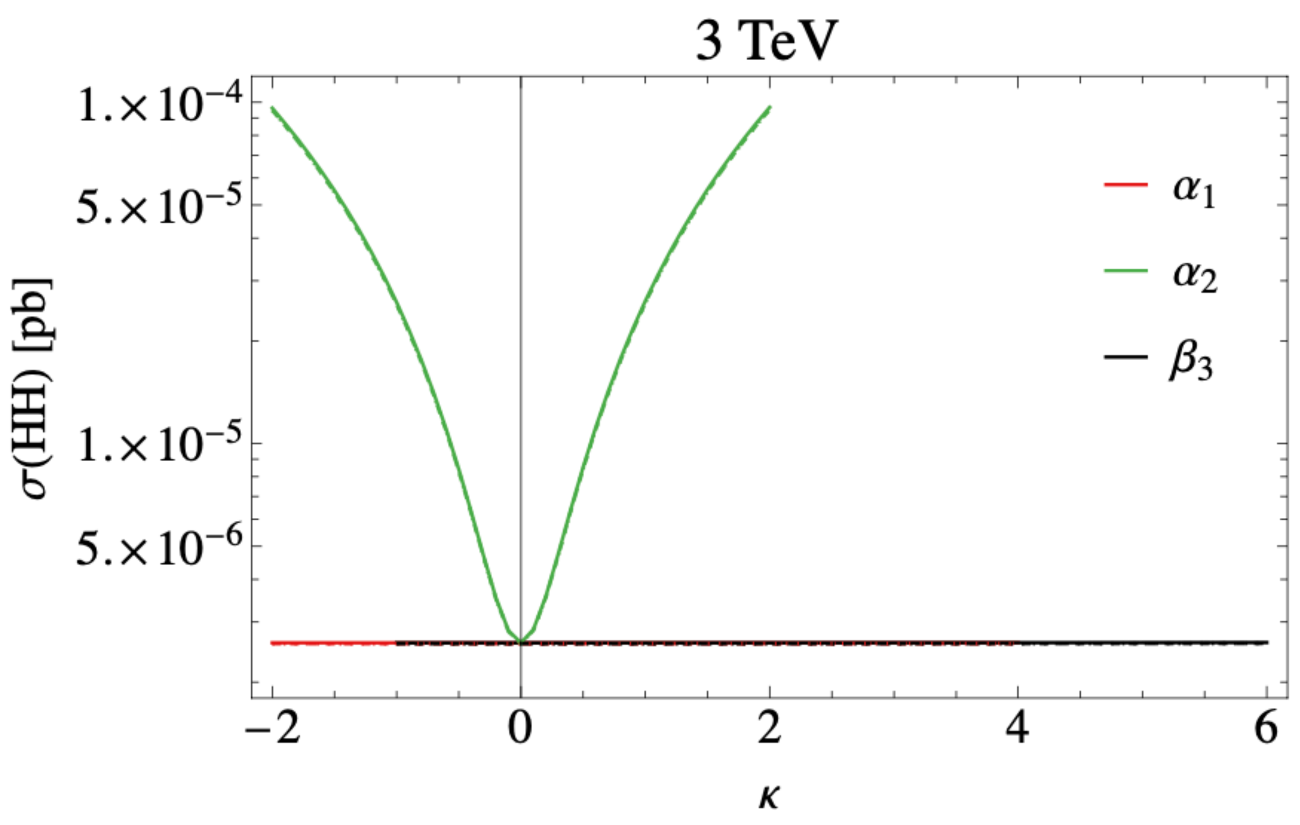

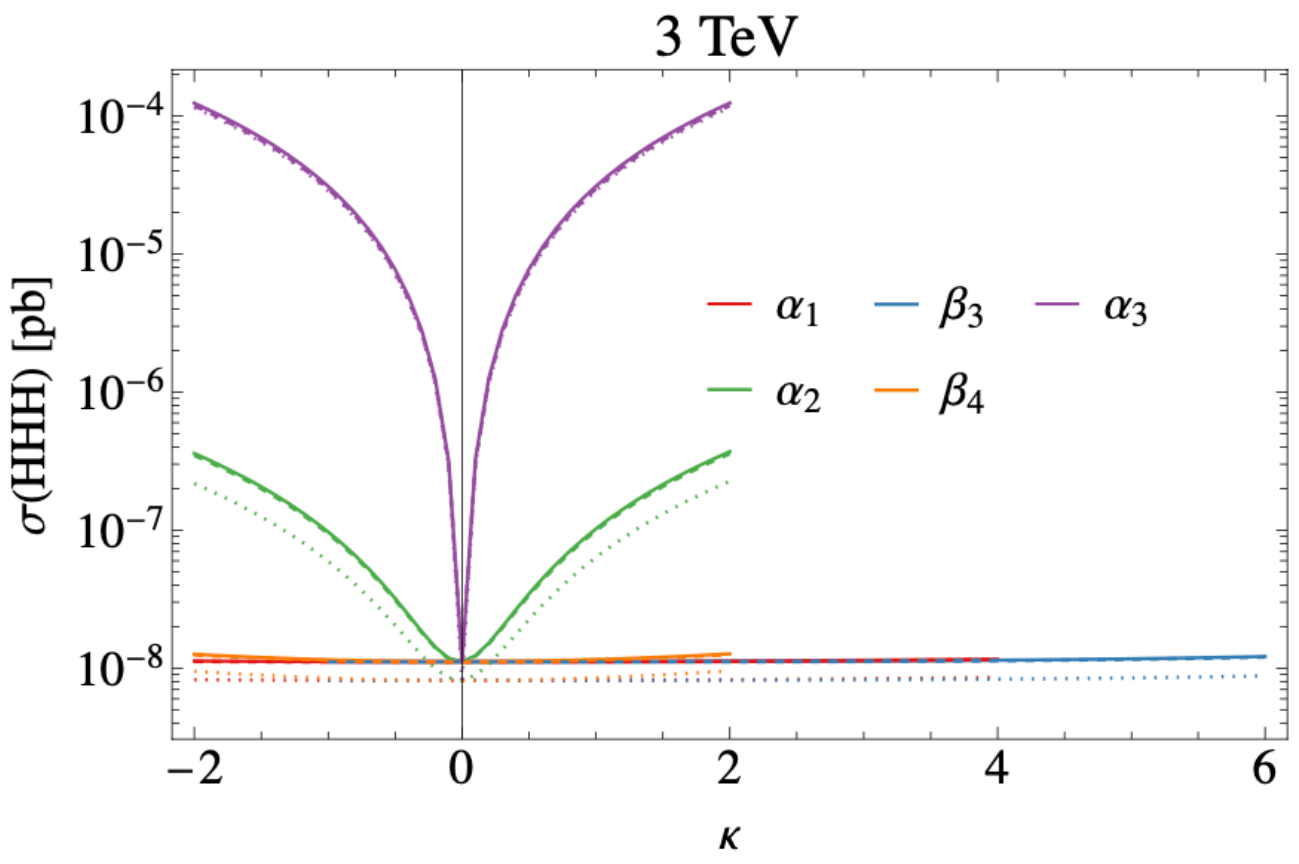

Preliminary results for $\mu^+\mu^- \to V^k H^l$

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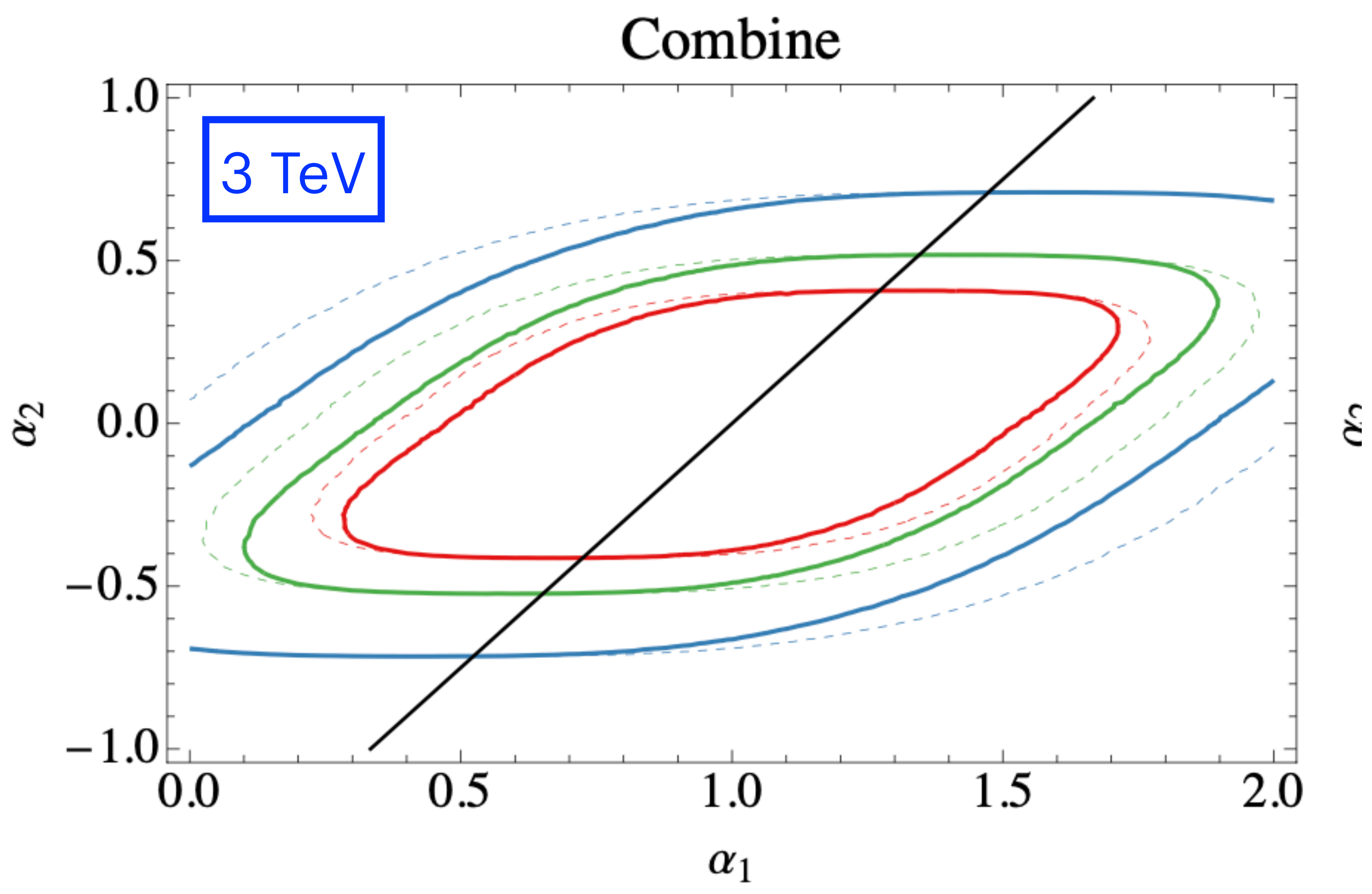
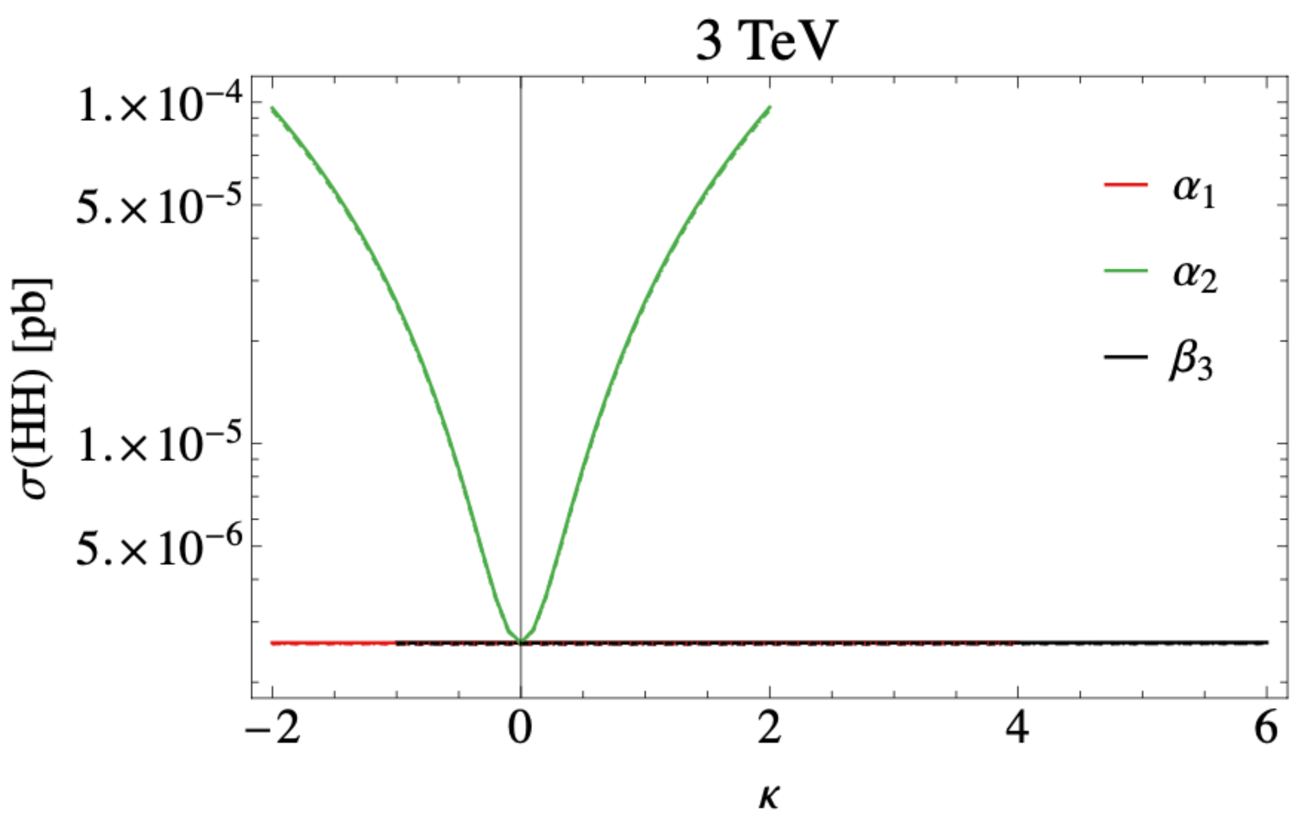
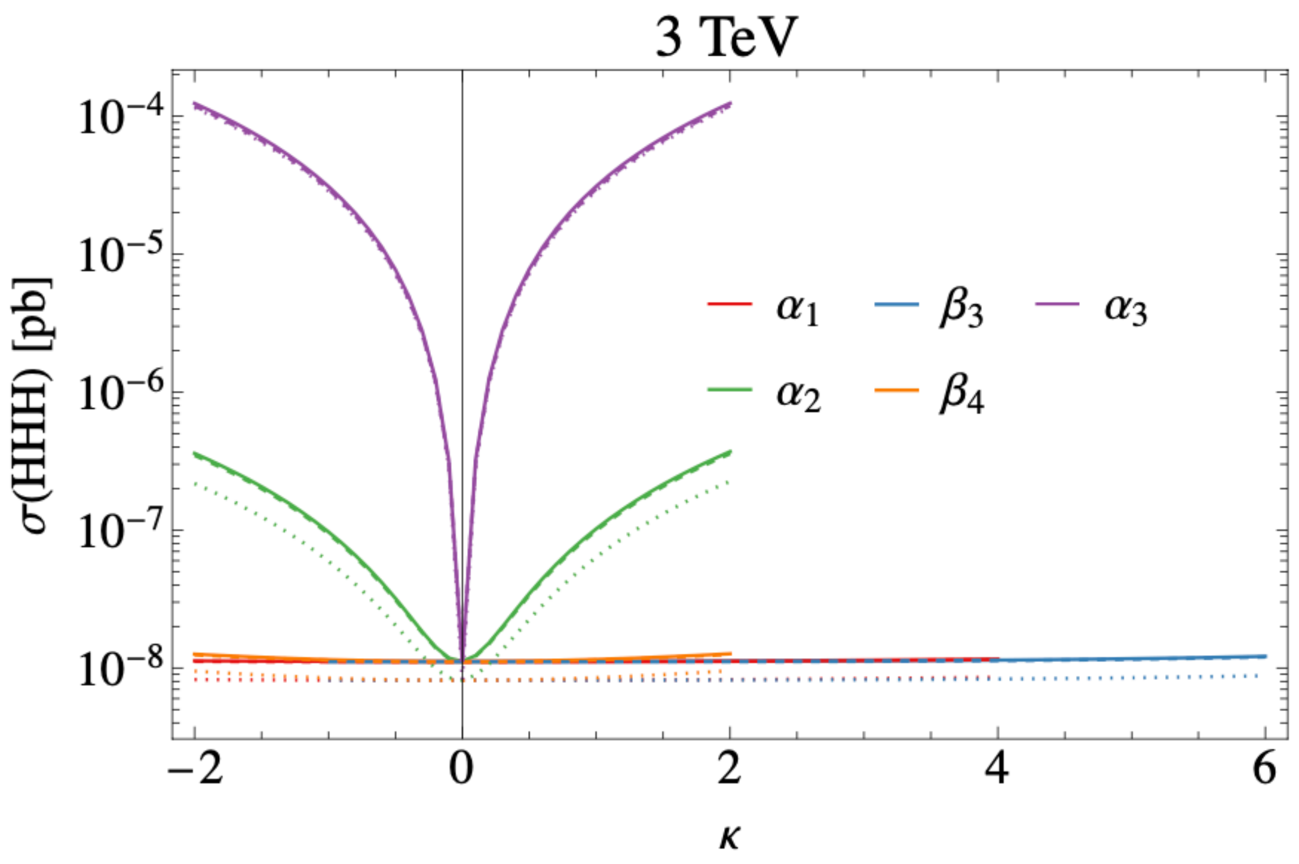
Combination of $\mu\mu \to HH, HVV, V^k$







Preliminary results for $\mu^+\mu^- \to V^k H^l$

Cut flow: signal and background events

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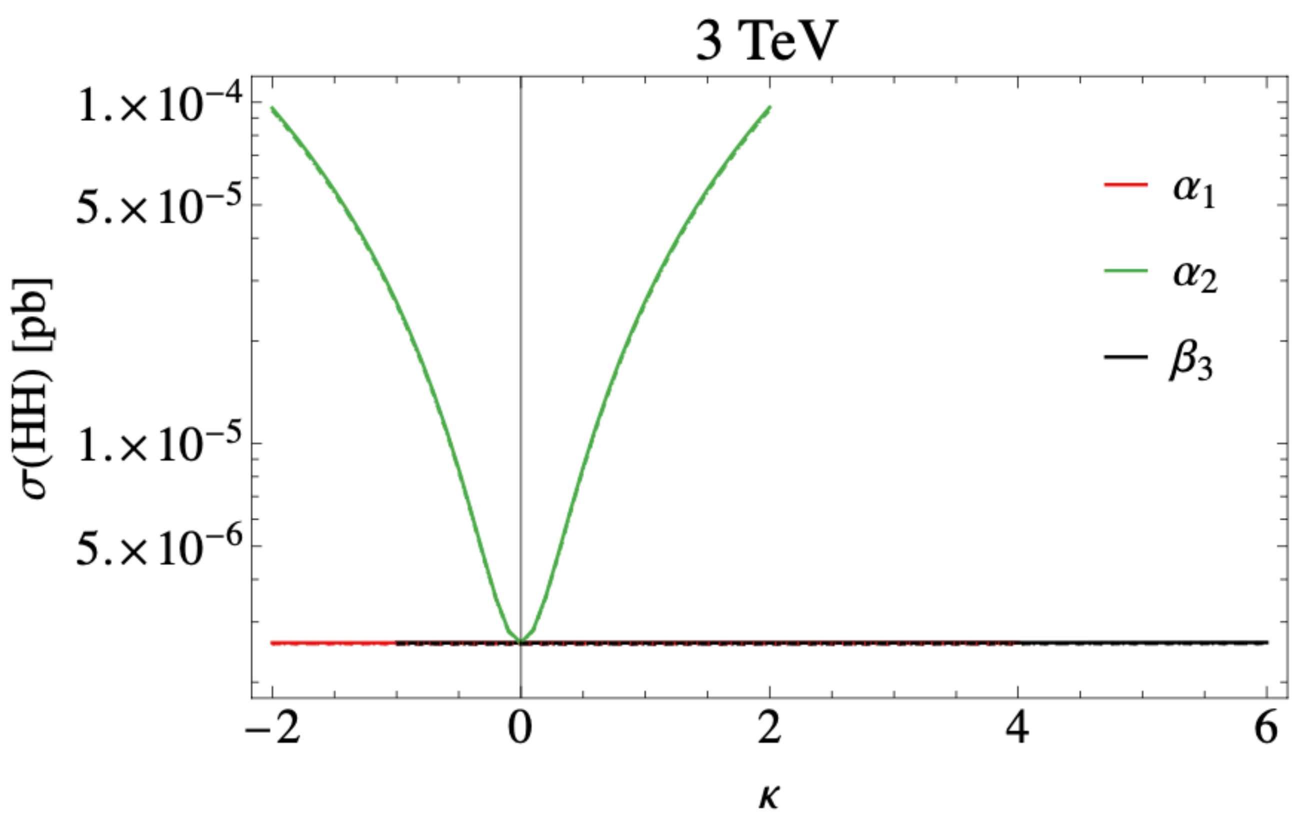
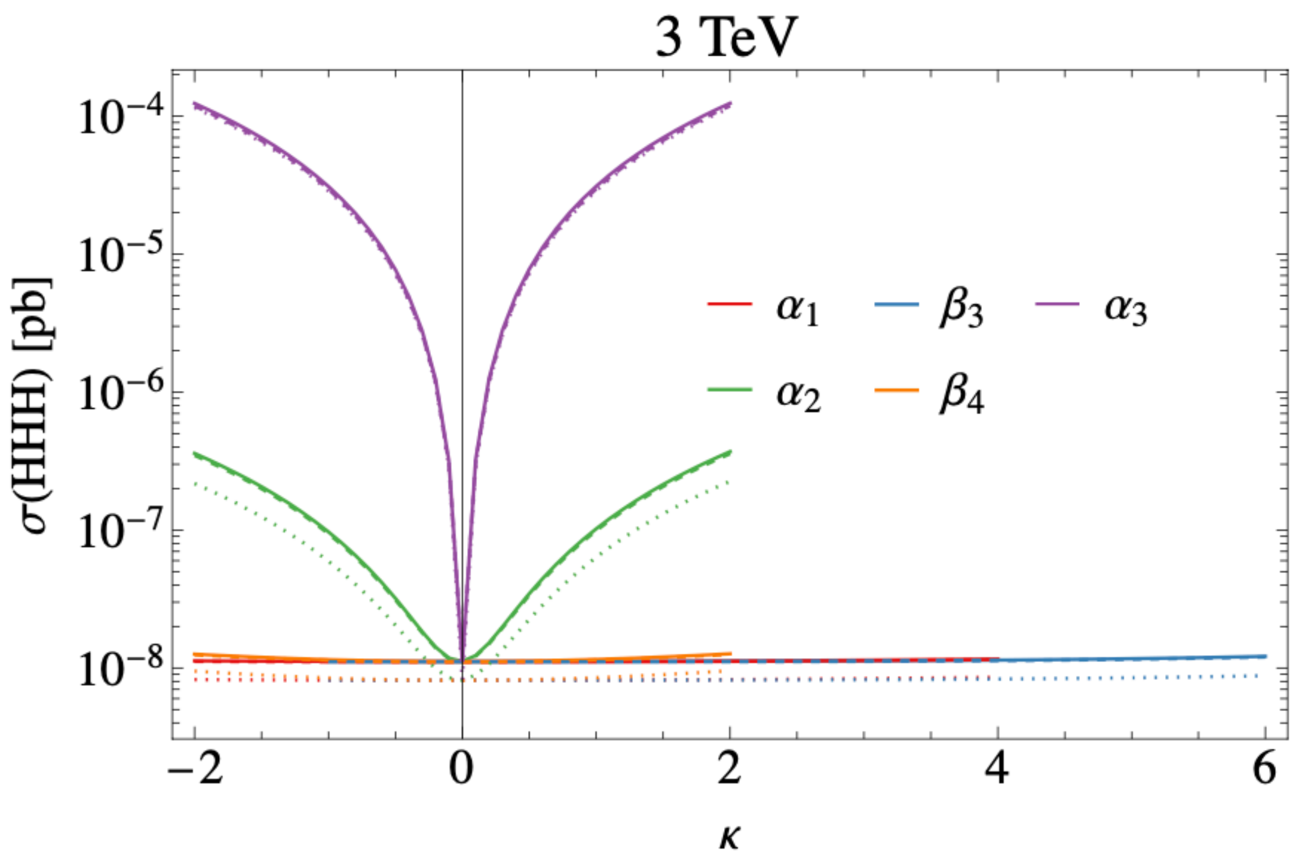
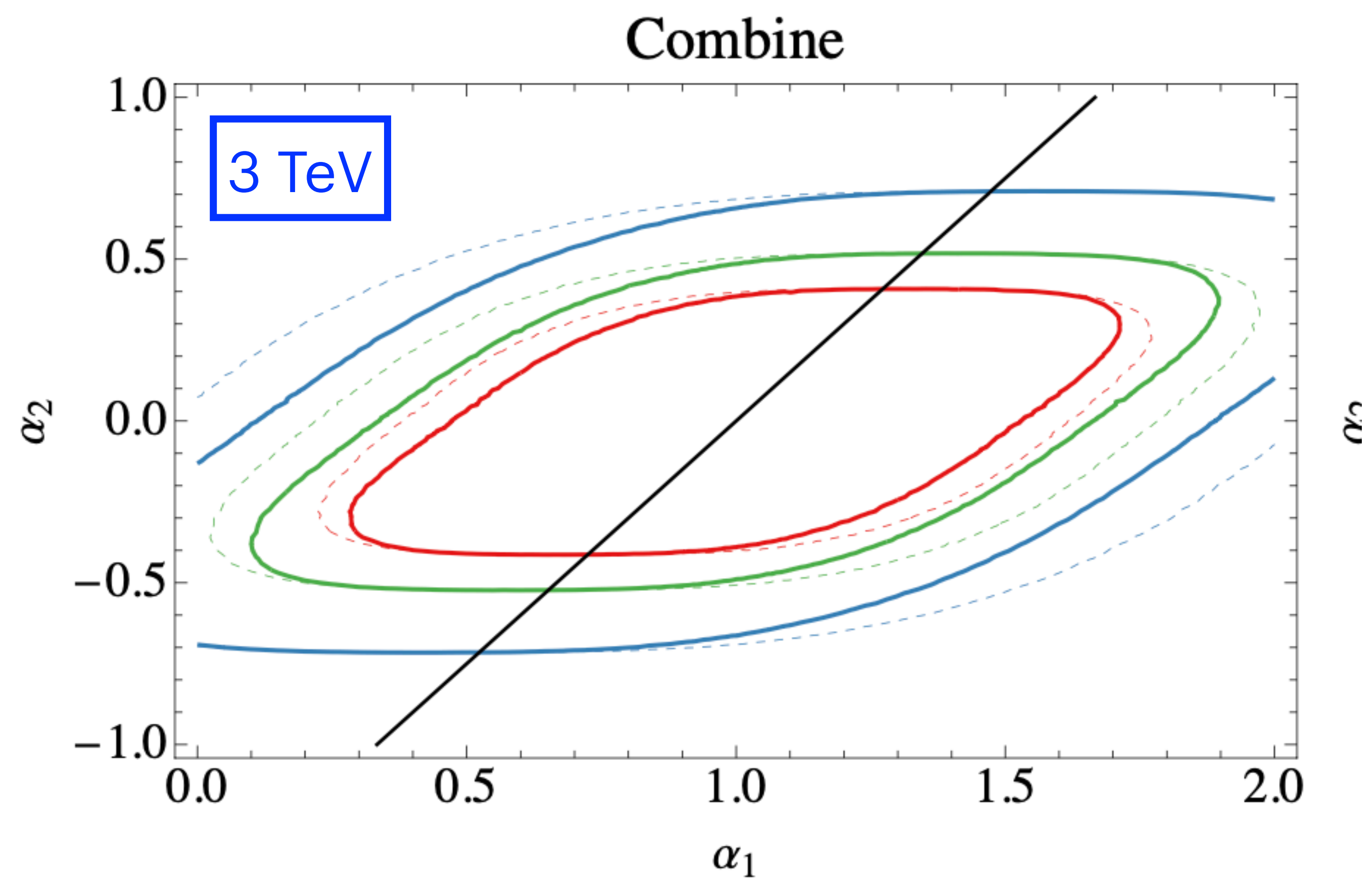
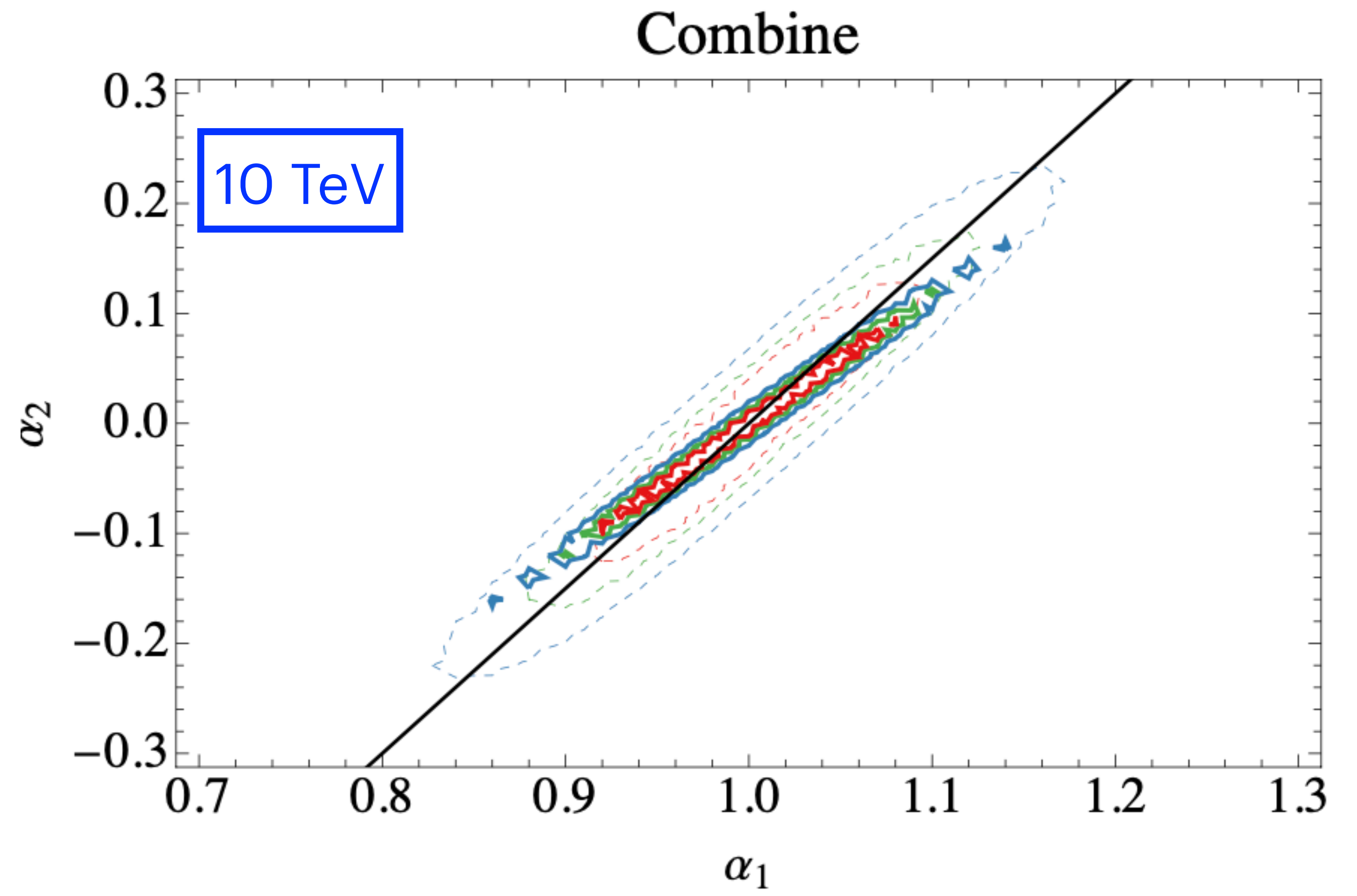


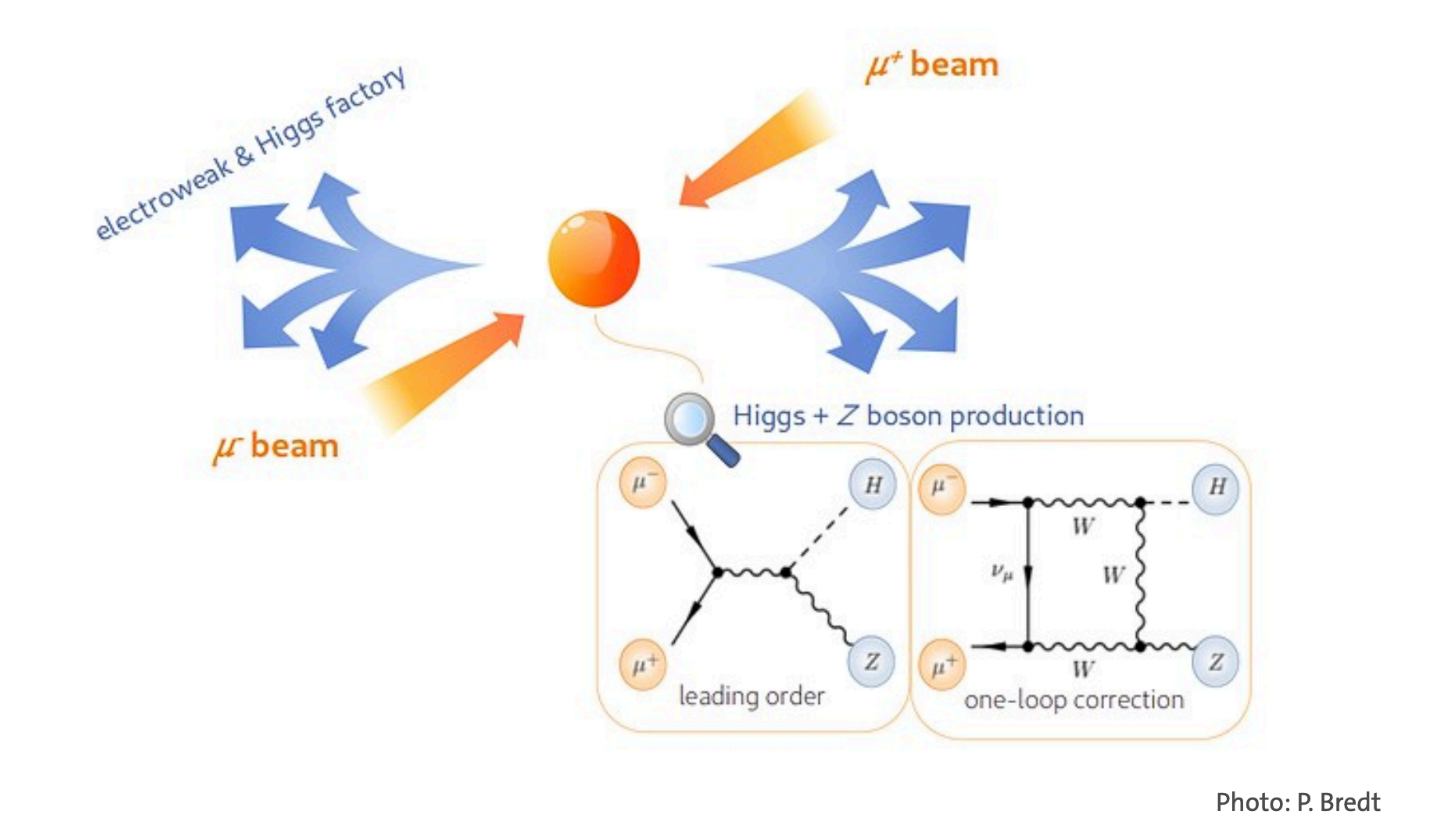


Combination of $\mu\mu \to HH, HVV, V^k$





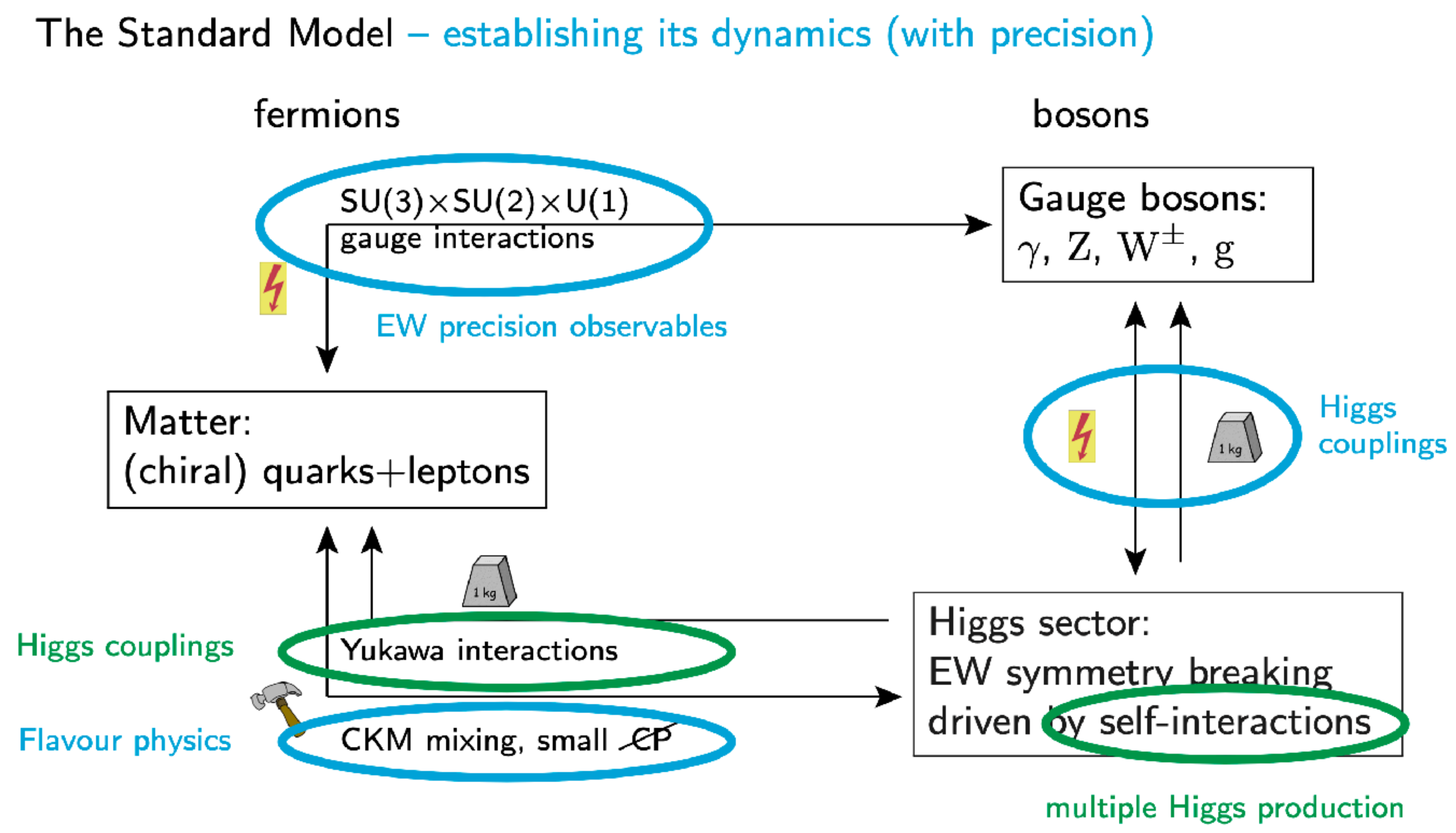
Multi-bosons: SM precision



Precision simulations / EW corrections — e.g. WHIZARD framework

- Detection of BSM physics necessitates understanding SM at high precision

Picture: S. Dittmaier, 2nd ECFA Higgs Factory Workshop, 2023



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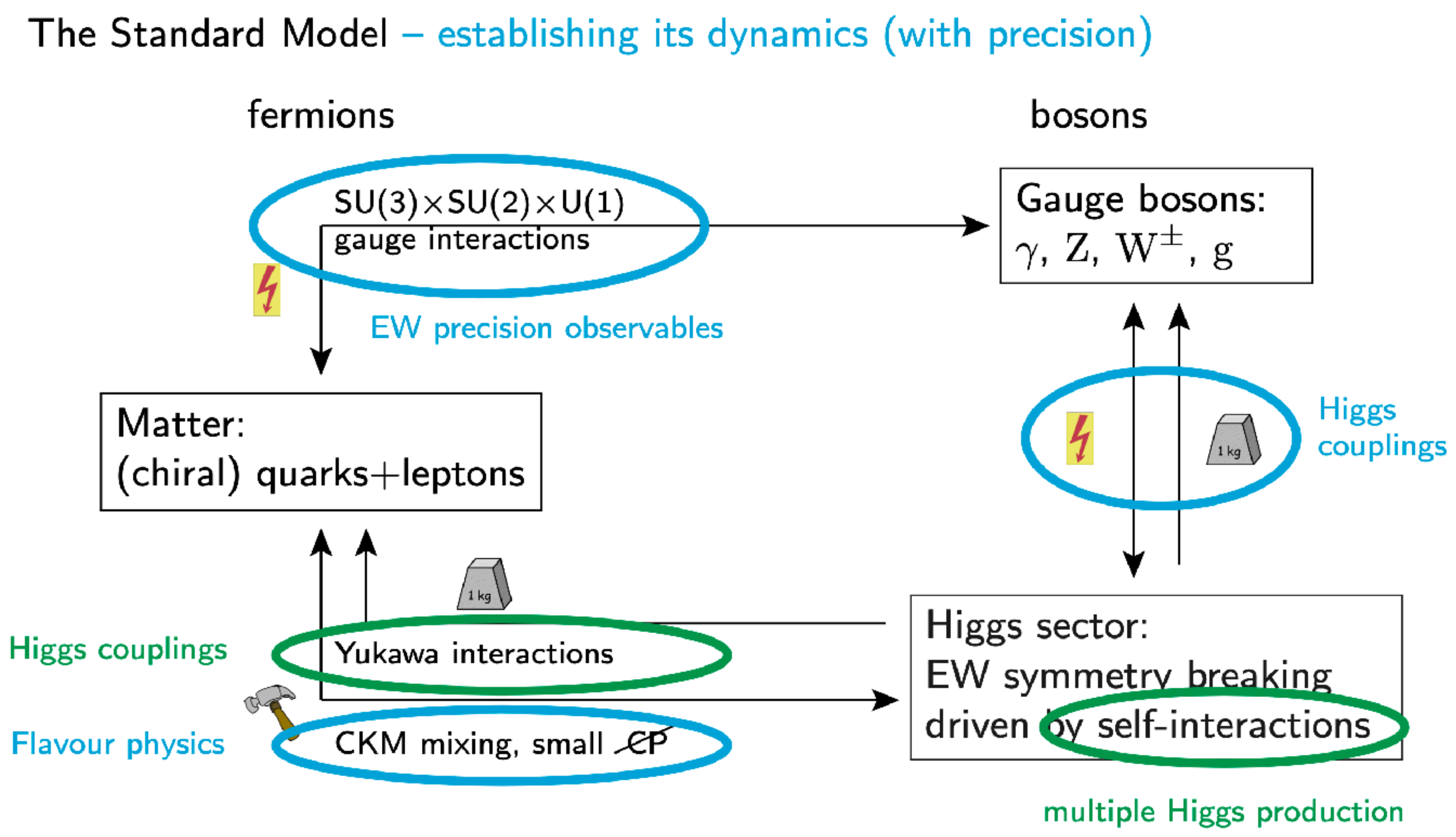
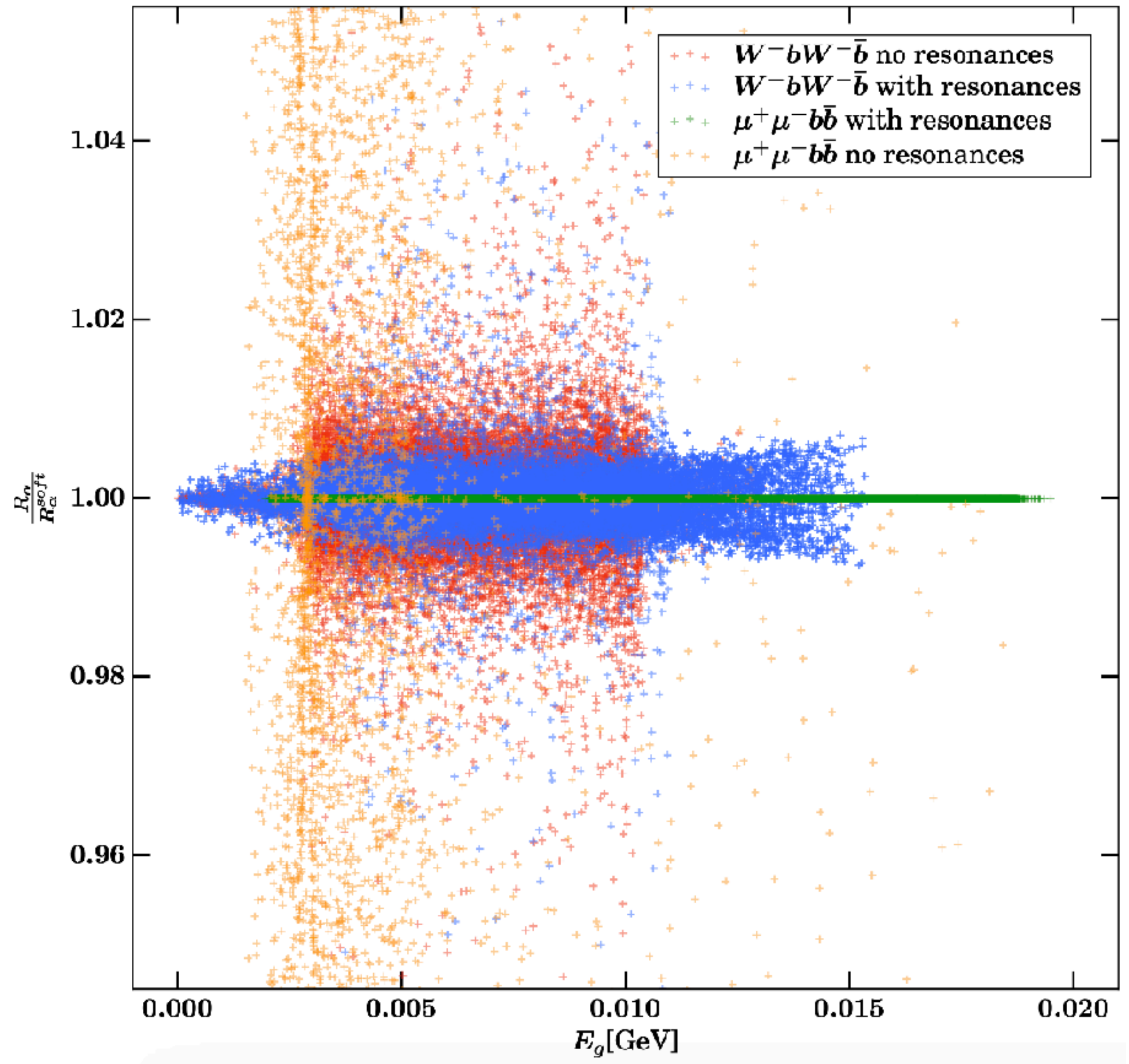


- NLO SM lepton-/hadron collider automation completed 2022
  Chokoufé 2017; Weiss 2017; Rothe 2021; Stienemeier 2022; Bredt 2022
- FKS subtraction
- NLO matrix elements from `OpenLoops/Recola/GoSam/`...
- also: resonance-aware FKS subtraction   cf. Ježo/Nason, 1509.09071; Chokoufé, 2017
- Setup for automatic differential fixed-order results (histogrammed distributions)
- Photon isolation, photon recombination, light-, b-, c-jet selection
- LL+NLL QED lepton PDFs, LL EW lepton PDFs (*work in progress*)   ↪Talk Keping Xie



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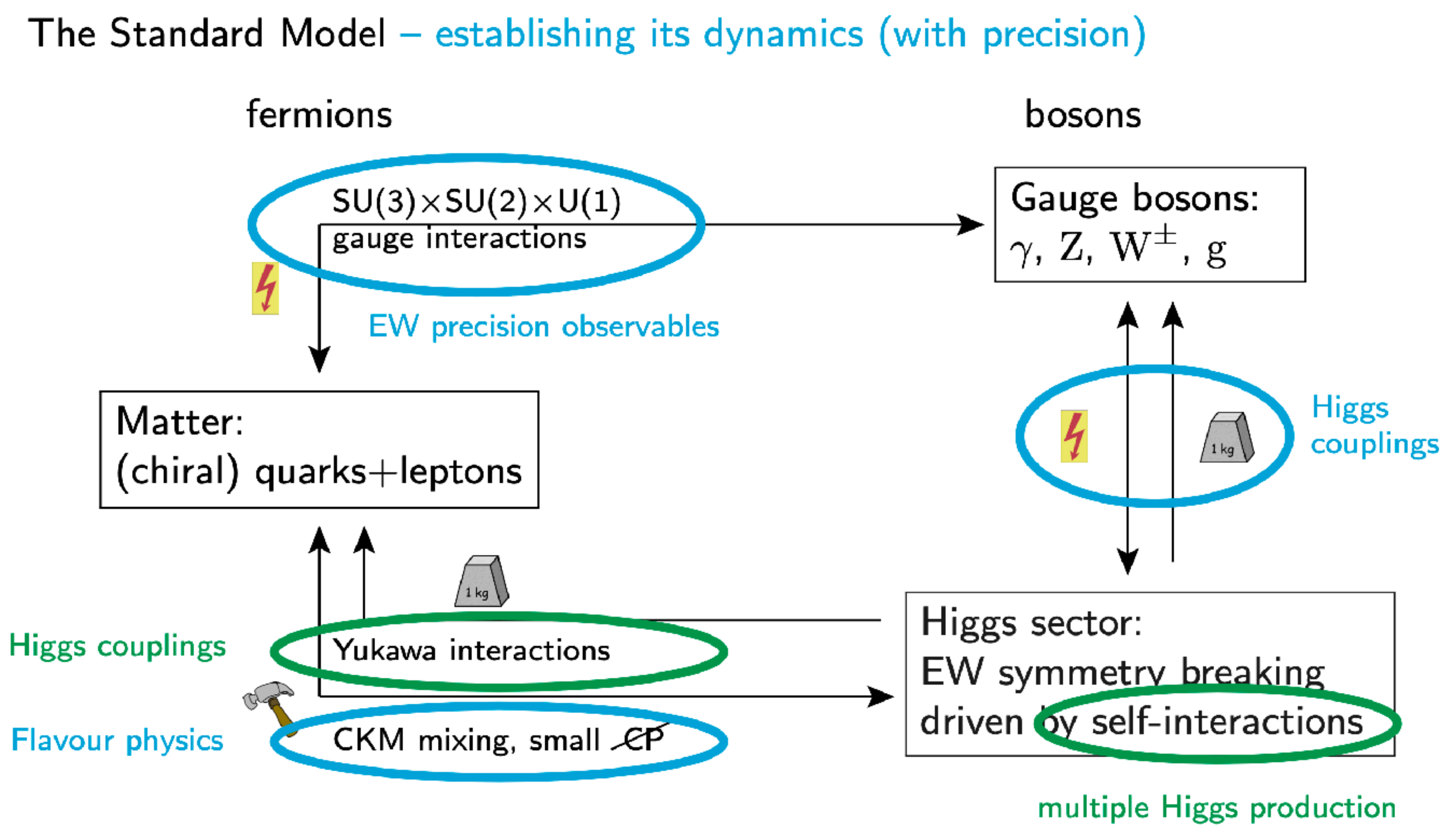

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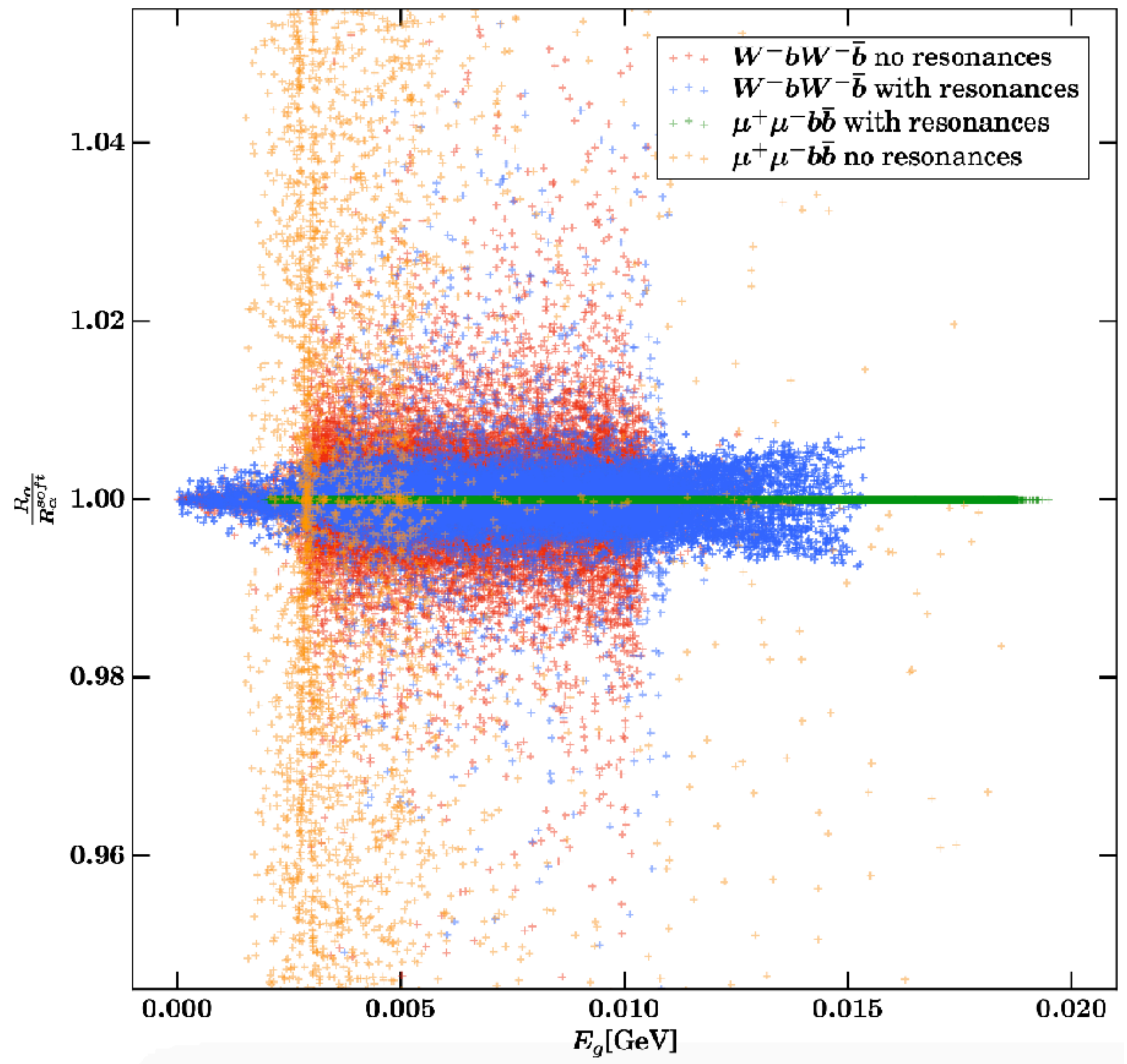


- New: loop-induced processes supported
- Work in progress: NLO (QCD) for BSM processes with UFO models

Some results — some technicalities

ee @ 1 TeV, NLO QCD

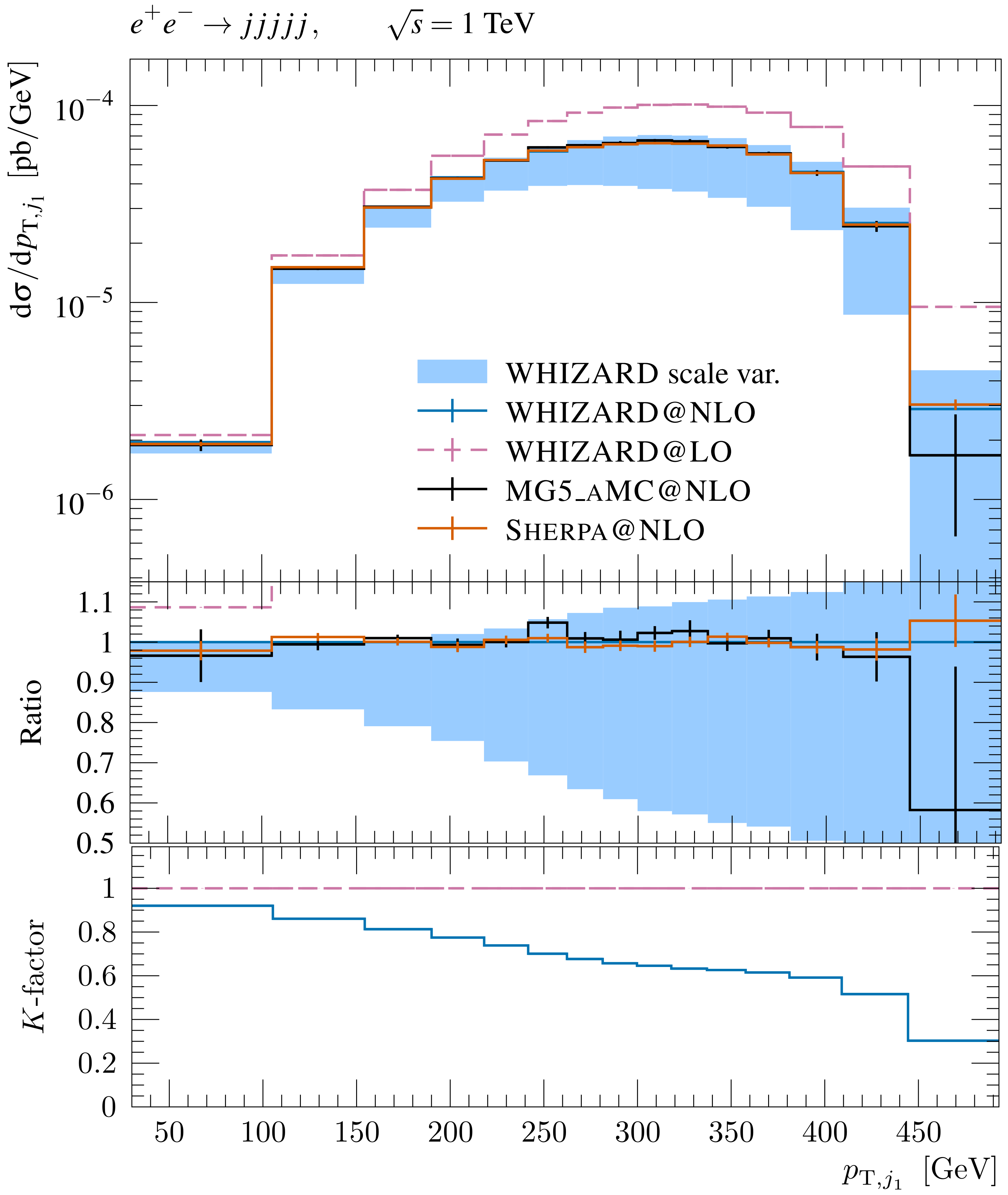
Process	WHIZARD+OpenLoops $\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	K
$e^+e^- \to jj$	622.737(8)	639.39(5)	1.03
$e^+e^- \to jjj$	340.6(5)	317.8(5)	0.93
$e^+e^- \to jjjj$	105.0(3)	104.2(4)	0.99
$e^+e^- \to jjjjj$	22.33(5)	24.57(7)	1.10
$e^+e^- \to t\bar{t}$	166.37(12)	174.55(20)	1.05
$e^+e^- \to t\bar{t}j$	48.12(5)	53.41(7)	1.11
$e^+e^- \to t\bar{t}jj$	8.592(19)	10.526(21)	1.23
$e^+e^- \to t\bar{t}jjj$	1.035(4)	1.405(5)	1.36
$e^+e^- \to t\bar{t}t\bar{t}$	$0.6388(8) \cdot 10^{-3}$	$1.1922(11) \cdot 10^{-3}$	1.87
$e^+e^- \to t\bar{t}t\bar{t}j$	$2.673(7) \cdot 10^{-5}$	$5.251(11) \cdot 10^{-5}$	1.96
$e^+e^- \to t\bar{t}H$	2.020(3)	1.912(3)	0.95
$e^+e^- \to t\bar{t}Hj$	$2.536(4) \cdot 10^{-1}$	$2.657(4) \cdot 10^{-1}$	1.05
$e^+e^- \to t\bar{t}Hjj$	$2.646(8) \cdot 10^{-2}$	$3.123(9) \cdot 10^{-2}$	1.18
$e^+e^- \to t\bar{t}Z$	4.638(3)	4.937(3)	1.06
$e^+e^- \to t\bar{t}Zj$	$6.027(9) \cdot 10^{-1}$	$6.921(11) \cdot 10^{-1}$	1.15
$e^+e^- \to t\bar{t}Zjj$	$6.436(21) \cdot 10^{-2}$	$8.241(29) \cdot 10^{-2}$	1.28
$e^+e^- \to t\bar{t}W^\pm jj$	$2.387(8) \cdot 10^{-4}$	$3.716(10) \cdot 10^{-4}$	1.56
$e^+e^- \to t\bar{t}HZ$	$3.623(19) \cdot 10^{-2}$	$3.584(19) \cdot 10^{-2}$	0.99
$e^+e^- \to t\bar{t}ZZ$	$3.788(6) \cdot 10^{-2}$	$4.032(7) \cdot 10^{-2}$	1.06
$e^+e^- \to t\bar{t}HH$	$1.3650(15) \cdot 10^{-2}$	$1.2168(16) \cdot 10^{-2}$	0.89
$e^+e^- \to t\bar{t}W^+W^-$	$1.3672(21) \cdot 10^{-1}$	$1.5385(22) \cdot 10^{-1}$	1.13

pp @ 13 TeV, NLO QCD

Process	WHIZARD+OpenLoops $\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	K
$pp \to jj$	$1.162(4) \cdot 10^{9}$	$1.601(5) \cdot 10^{9}$	1.38
$pp \to jjj$	$9.01(4) \cdot 10^{7}$	$7.46(9) \cdot 10^{7}$	0.83
$pp \to t\bar{t}$	$4.589(9) \cdot 10^{5}$	$6.740(10) \cdot 10^{5}$	1.47
$pp \to t\bar{t}j$	$3.123(6) \cdot 10^{5}$	$4.087(9) \cdot 10^{5}$	1.31
$pp \to t\bar{t}jj$	$1.360(4) \cdot 10^{5}$	$1.775(7) \cdot 10^{5}$	1.31
$pp \to t\bar{t}t\bar{t}$	4.485(6)	9.070(9)	2.02
$pp \to W^\pm$	$1.3749(8) \cdot 10^{8}$	$1.7696(10) \cdot 10^{8}$	1.29
$pp \to W^\pm j$	$2.046(3) \cdot 10^{7}$	$2.854(5) \cdot 10^{7}$	1.39
$pp \to W^\pm jj$	$6.856(12) \cdot 10^{6}$	$7.814(27) \cdot 10^{6}$	1.14
$pp \to W^\pm jjj$	$1.840(5) \cdot 10^{6}$	$1.978(7) \cdot 10^{6}$	1.07
$pp \to Z$	$4.2541(3) \cdot 10^{7}$	$5.4086(16) \cdot 10^{7}$	1.27
$pp \to Zj$	$7.215(4) \cdot 10^{6}$	$9.733(10) \cdot 10^{6}$	1.35
$pp \to Zjj$	$2.364(5) \cdot 10^{6}$	$2.676(7) \cdot 10^{6}$	1.13
$pp \to Zjjj$	$6.381(23) \cdot 10^{5}$	$6.85(3) \cdot 10^{5}$	1.07
$pp \to W^+W^+jj$	$1.506(5) \cdot 10^{2}$	$2.235(7) \cdot 10^{2}$	1.48
$pp \to W^-W^-jj$	$6.772(24) \cdot 10^{1}$	$9.982(28) \cdot 10^{1}$	1.47
$pp \to ZW^\pm$	$2.780(5) \cdot 10^{4}$	$4.488(4) \cdot 10^{4}$	1.61
$pp \to ZW^\pm j$	$1.609(4) \cdot 10^{4}$	$2.0940(28) \cdot 10^{4}$	1.30
$pp \to ZW^\pm jj$	$8.06(3) \cdot 10^{3}$	$9.02(4) \cdot 10^{3}$	1.12
$pp \to ZZ$	$1.0969(10) \cdot 10^{4}$	$1.4183(11) \cdot 10^{4}$	1.29
$pp \to ZZj$	$3.667(9) \cdot 10^{3}$	$4.807(8) \cdot 10^{3}$	1.31
$pp \to ZZjj$	$1.356(6) \cdot 10^{3}$	$1.684(8) \cdot 10^{3}$	1.24

Some results — some technicalities

ee @ 1 TeV, NLO QCD



pp @ 13 TeV, NLO QCD

WHIZARD+OpenLoops			
Process	$\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	K
$pp \to jj$	$1.162(4) \cdot 10^9$	$1.601(5) \cdot 10^9$	1.38
$pp \to jjj$	$9.01(4) \cdot 10^7$	$7.46(9) \cdot 10^7$	0.83
$pp \to t\bar{t}$	$4.589(9) \cdot 10^5$	$6.740(10) \cdot 10^5$	1.47
$pp \to t\bar{t}j$	$3.123(6) \cdot 10^5$	$4.087(9) \cdot 10^5$	1.31
$pp \to t\bar{t}jj$	$1.360(4) \cdot 10^5$	$1.775(7) \cdot 10^5$	1.31
$pp \to t\bar{t}t\bar{t}$	$4.485(6)$	$9.070(9)$	2.02
$pp \to W^\pm$	$1.3749(8) \cdot 10^8$	$1.7696(10) \cdot 10^8$	1.29
$pp \to W^\pm j$	$2.046(3) \cdot 10^7$	$2.854(5) \cdot 10^7$	1.39
$pp \to W^\pm jj$	$6.856(12) \cdot 10^6$	$7.814(27) \cdot 10^6$	1.14
$pp \to W^\pm jjj$	$1.840(5) \cdot 10^6$	$1.978(7) \cdot 10^6$	1.07
$pp \to Z$	$4.2541(3) \cdot 10^7$	$5.4086(16) \cdot 10^7$	1.27
$pp \to Zj$	$7.215(4) \cdot 10^6$	$9.733(10) \cdot 10^6$	1.35
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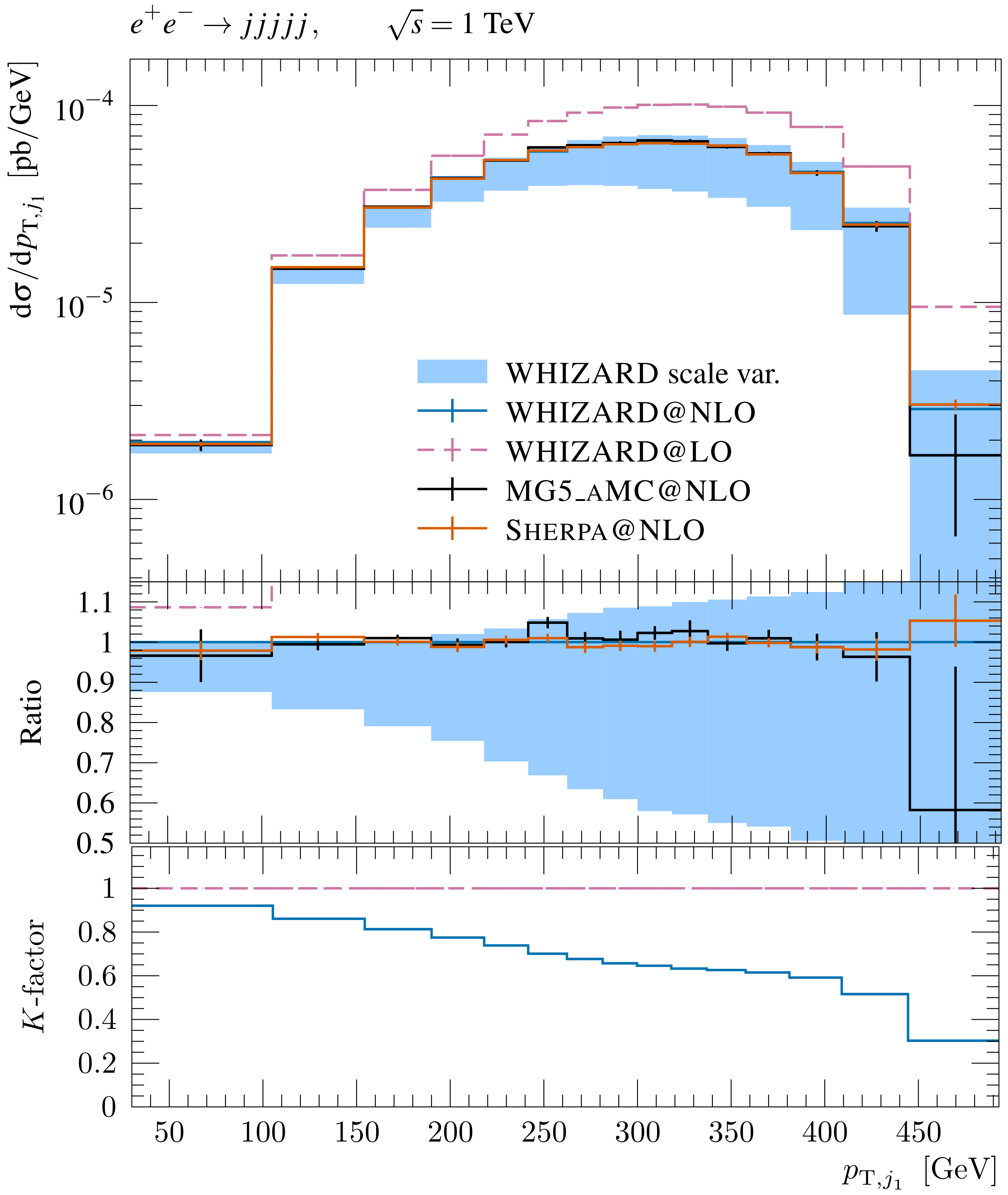
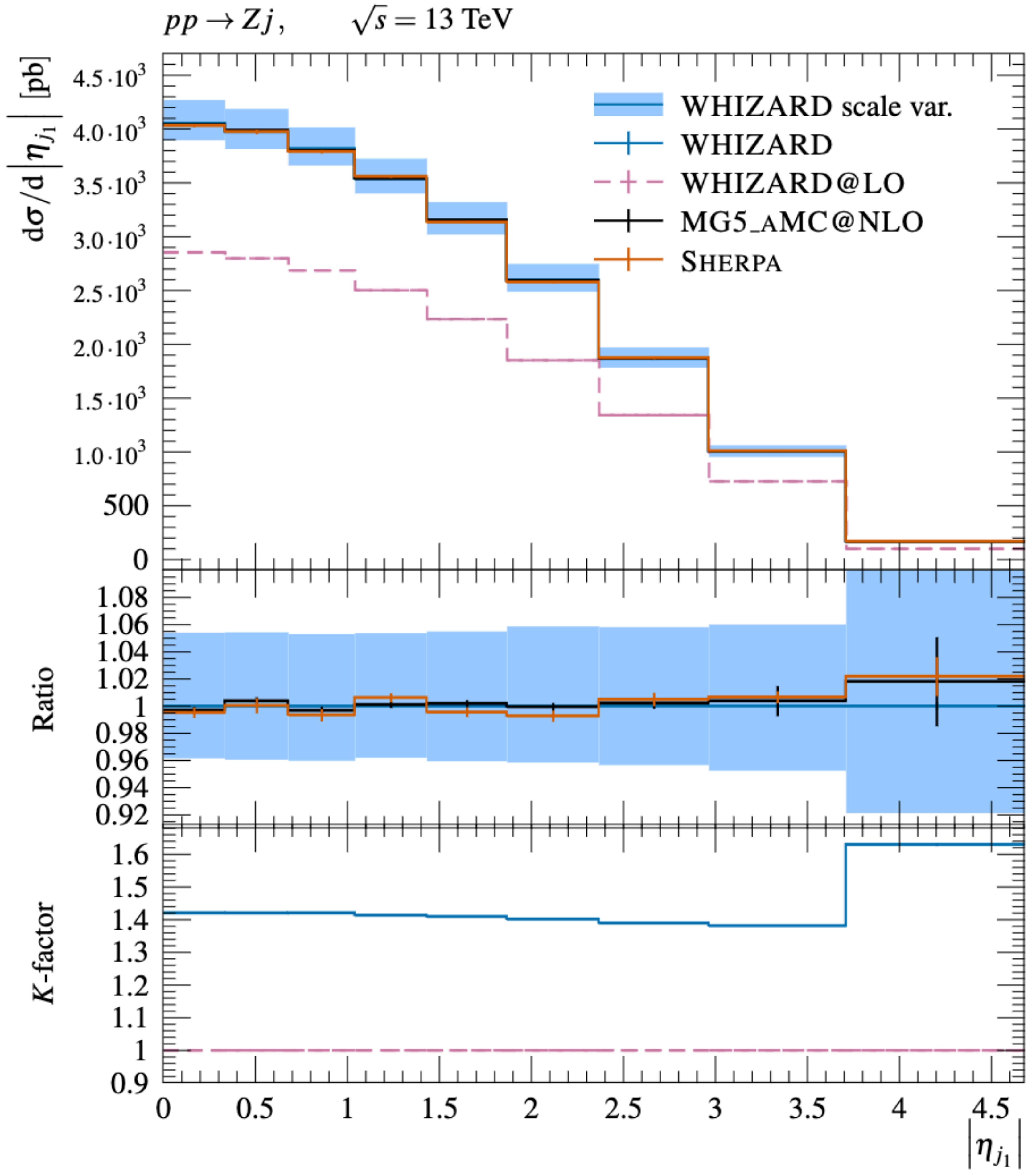
Some results — some technicalities

ee @ 1 TeV, NLO QCD

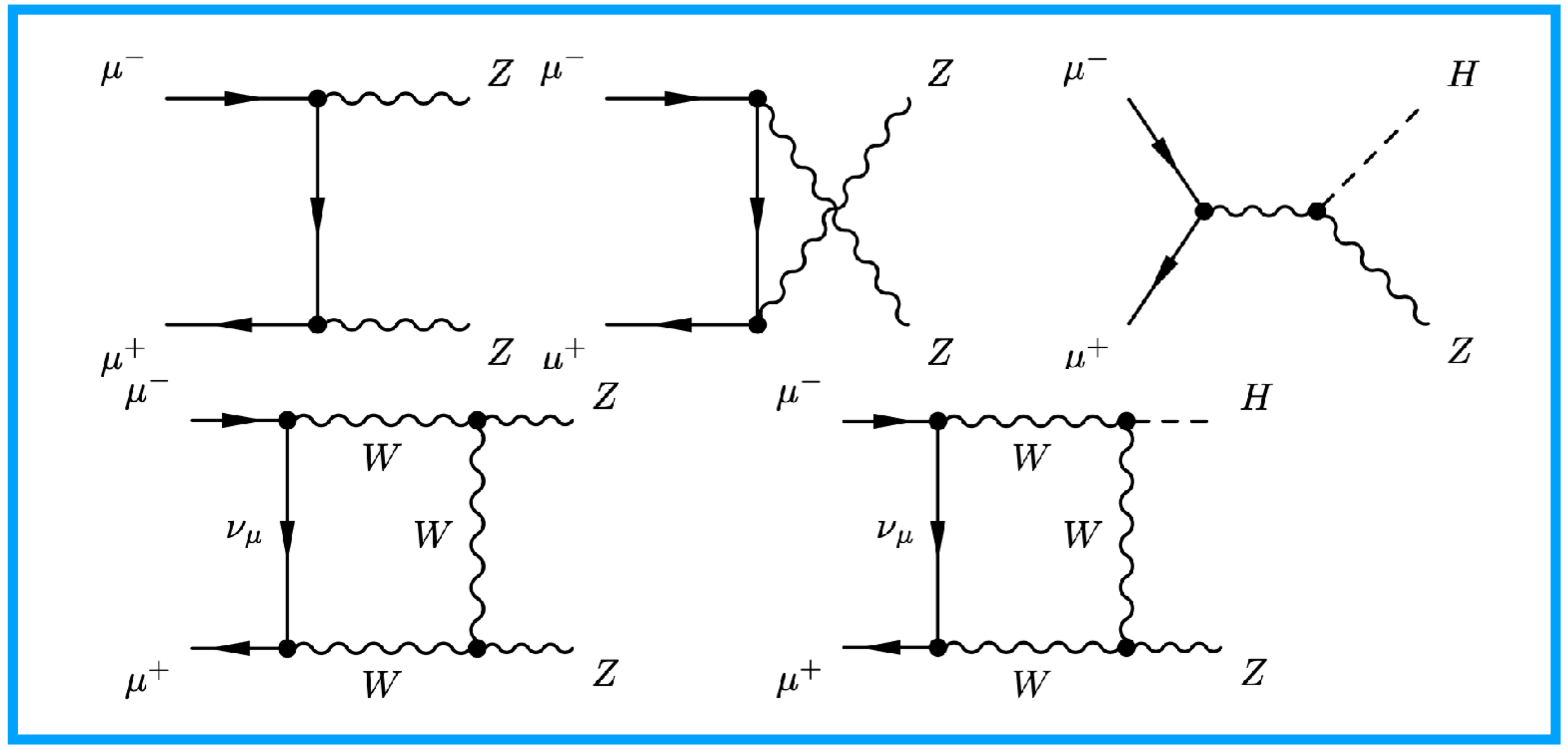


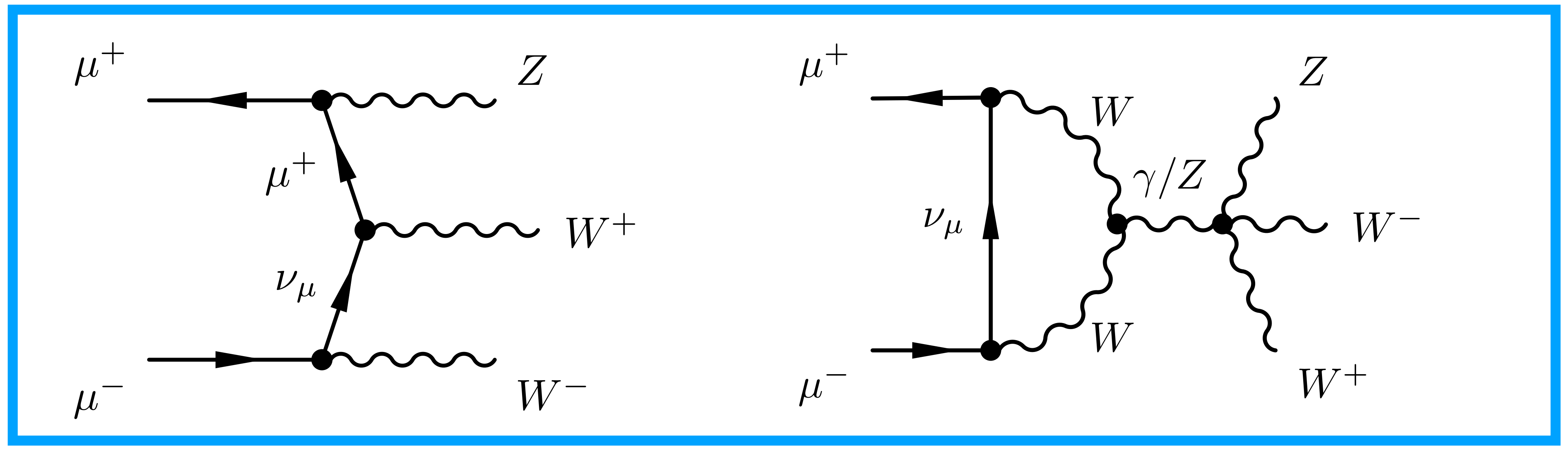
pp @ 13 TeV, NLO QCD

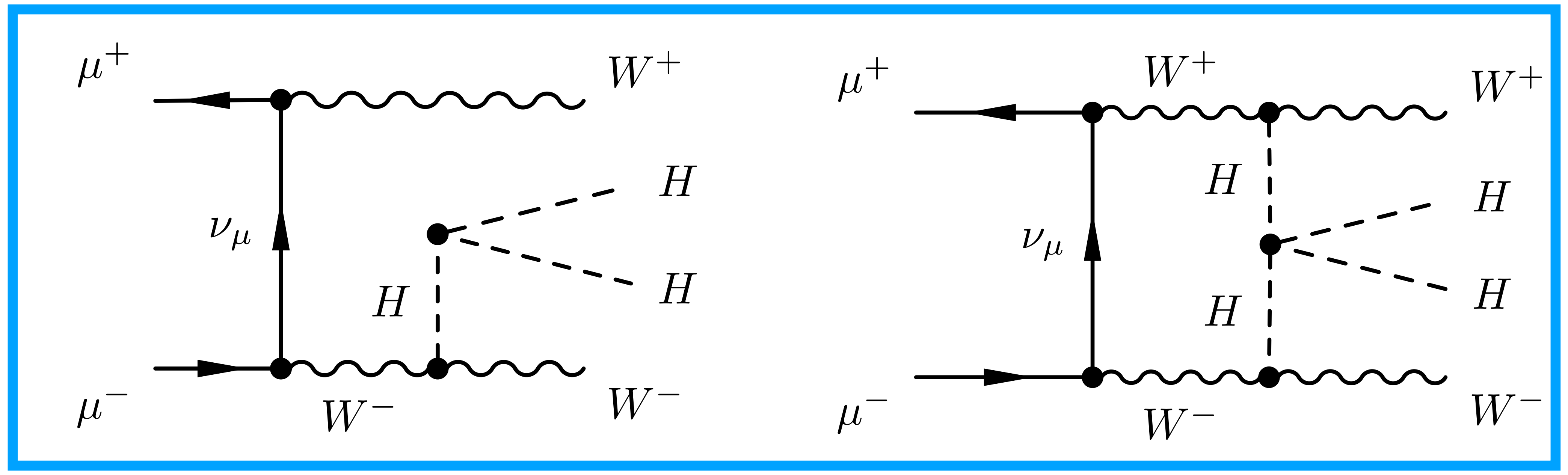


SM EW Corrections to Multi-Bosons

arXiv: 2208.09438







- 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

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

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

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

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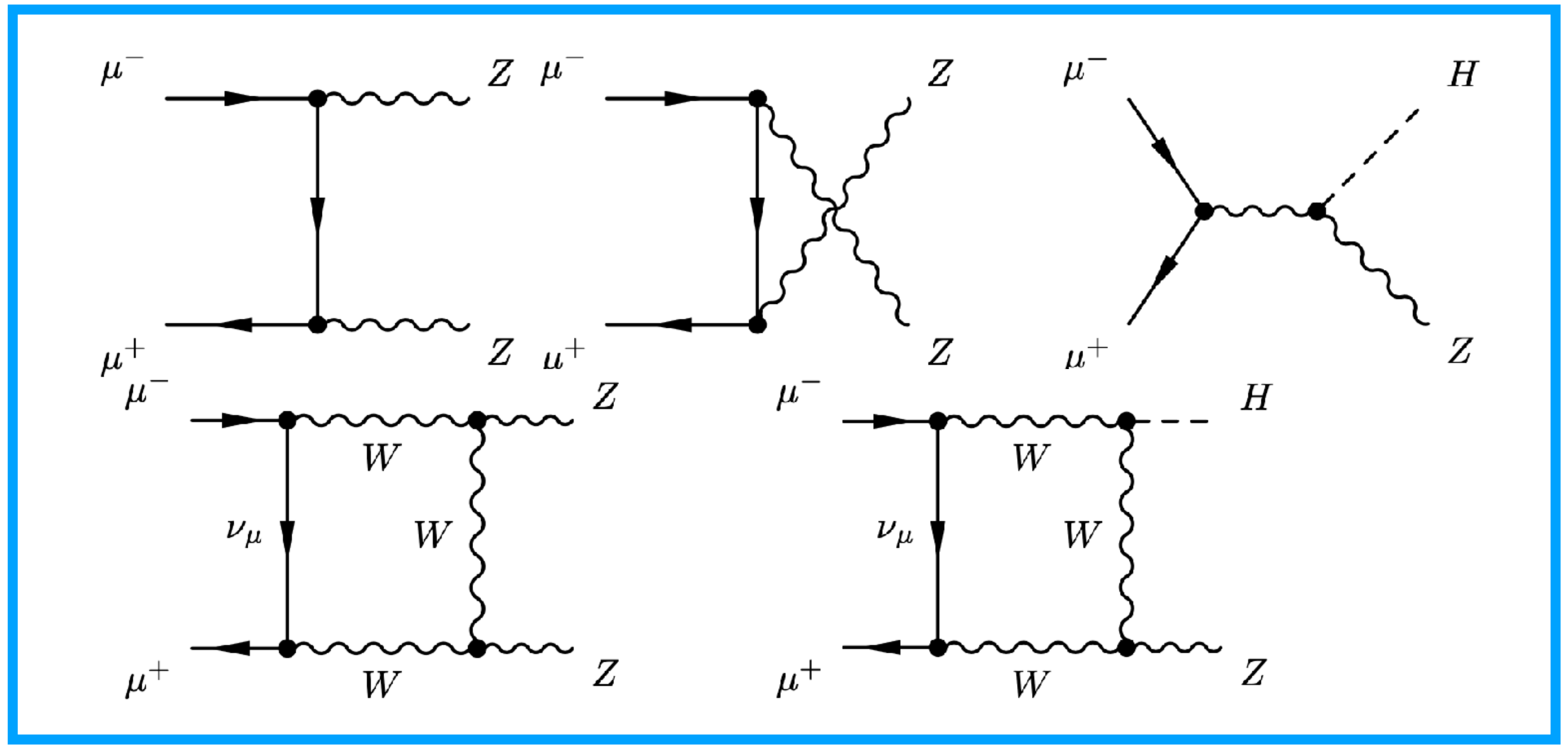
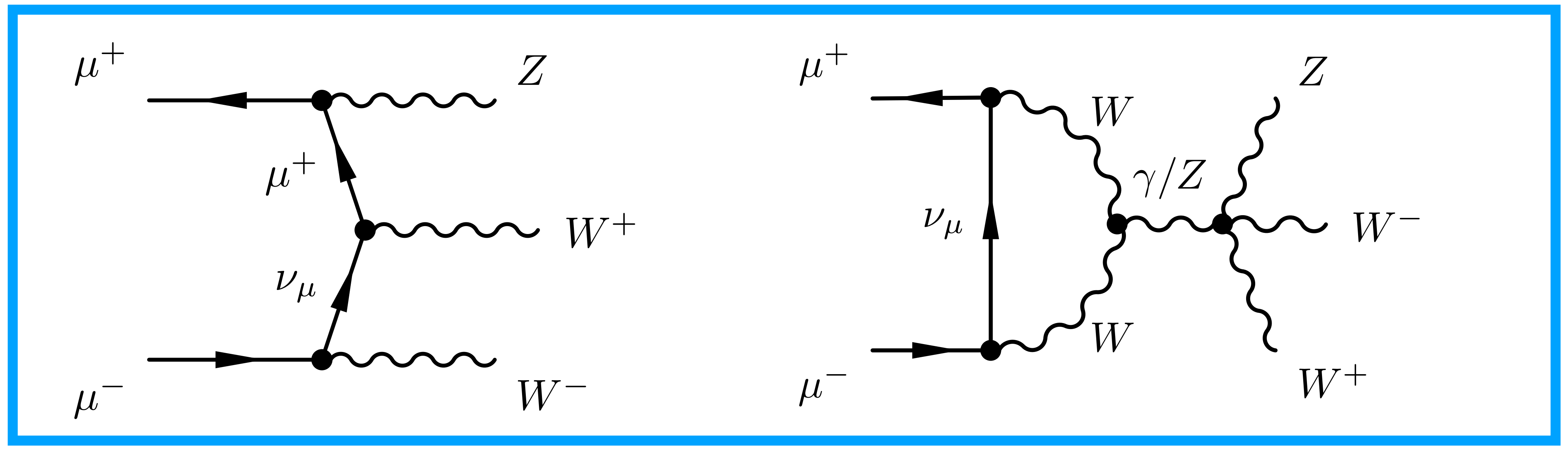
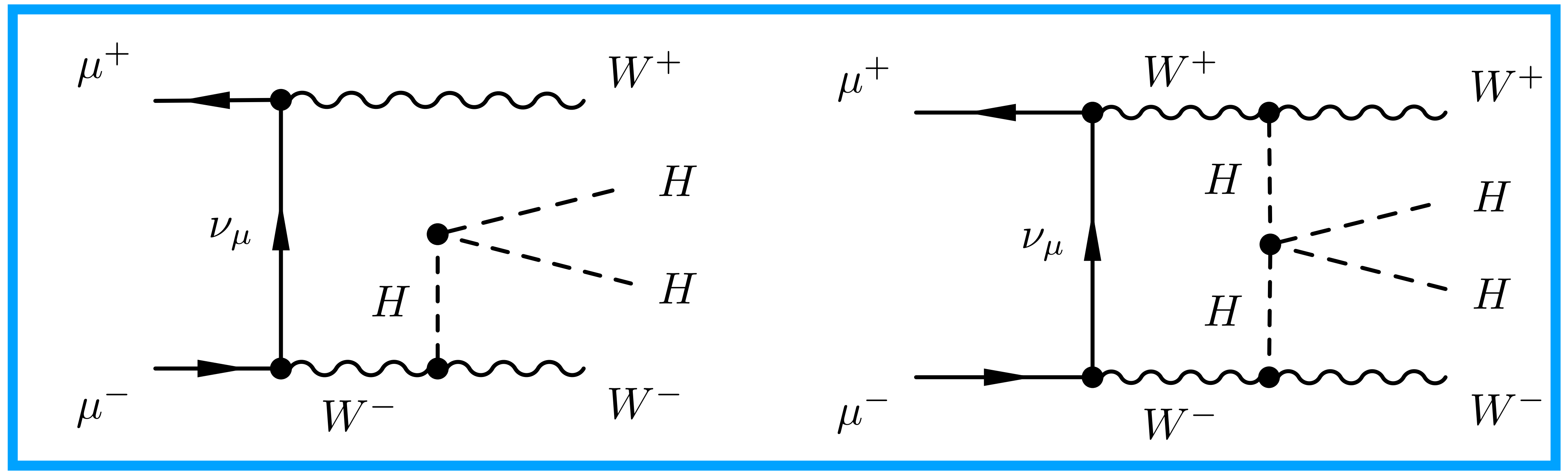






$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma^{\text{incl}}_{\text{LO}}$ [fb]	$\sigma^{\text{incl}}_{\text{NLO}}$ [fb]	δ_{EW} [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$4.847(7) \cdot 10^2$	$+4.0(2)$
ZZ	$2.5988(1) \cdot 10^1$	$2.656(2) \cdot 10^1$	$+2.19(6)$
HZ	$1.3719(1) \cdot 10^0$	$1.3512(5) \cdot 10^0$	$-1.51(4)$
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

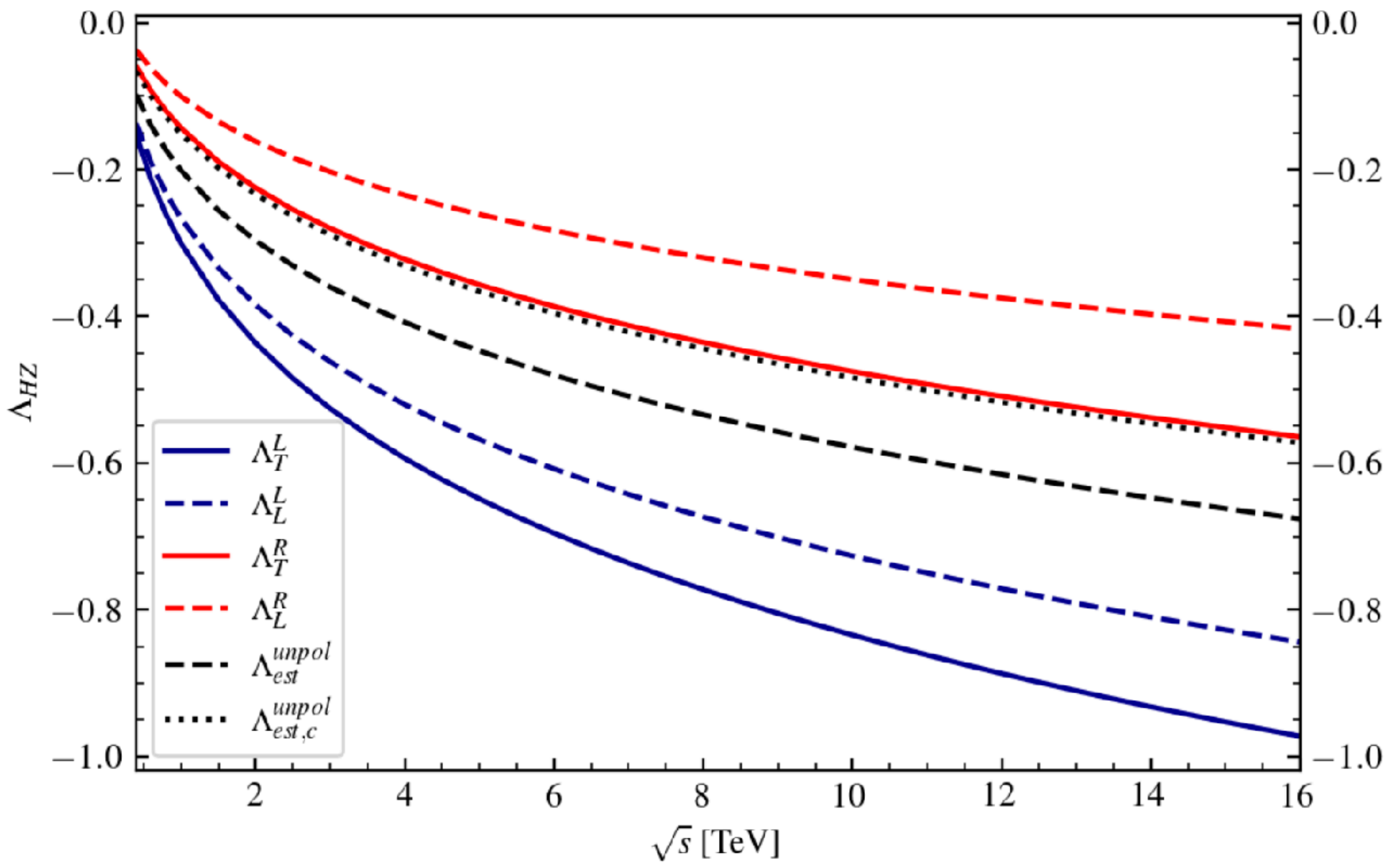
↪ Talk Davide Pagani

- 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

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

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

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



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

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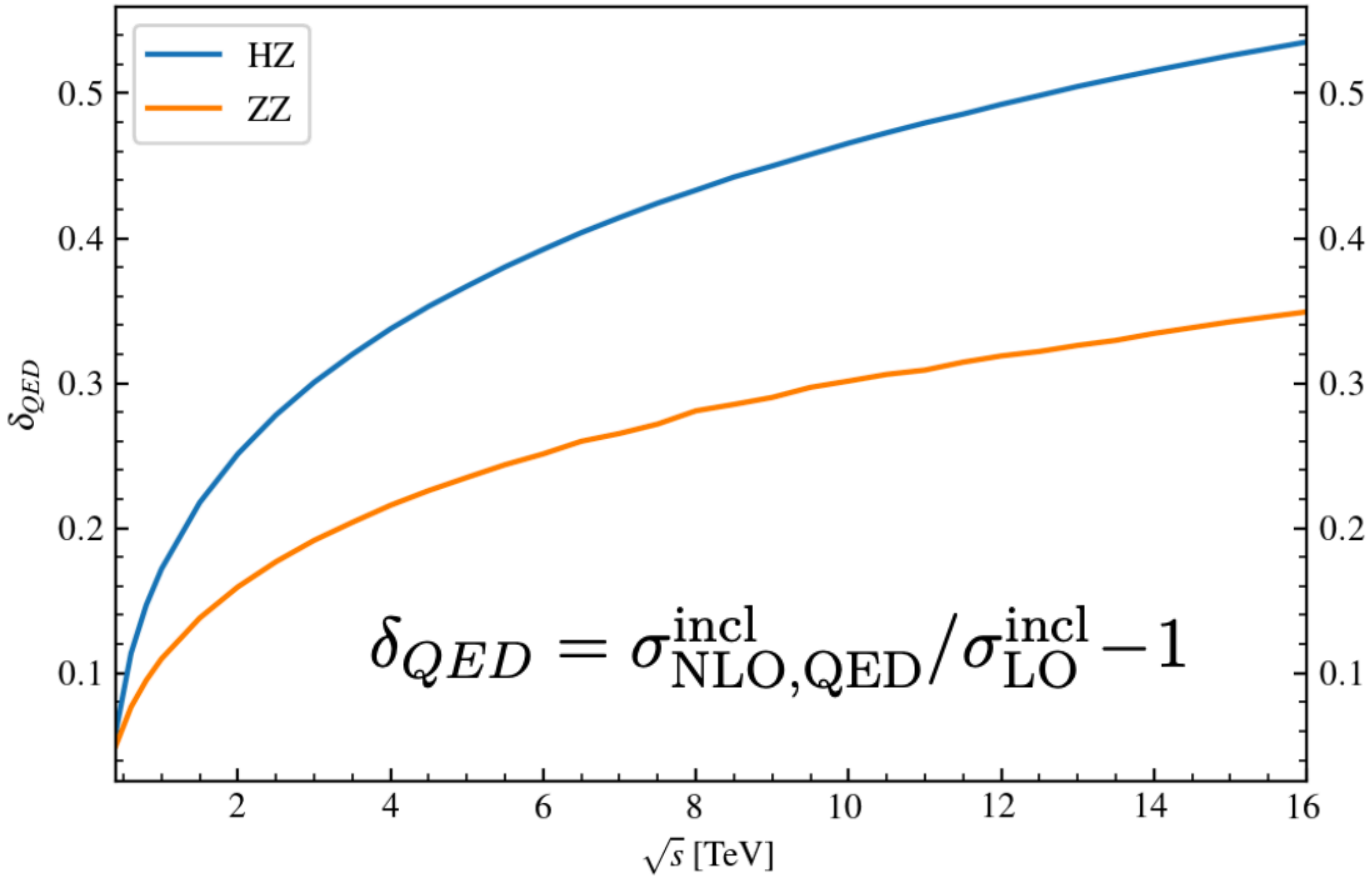

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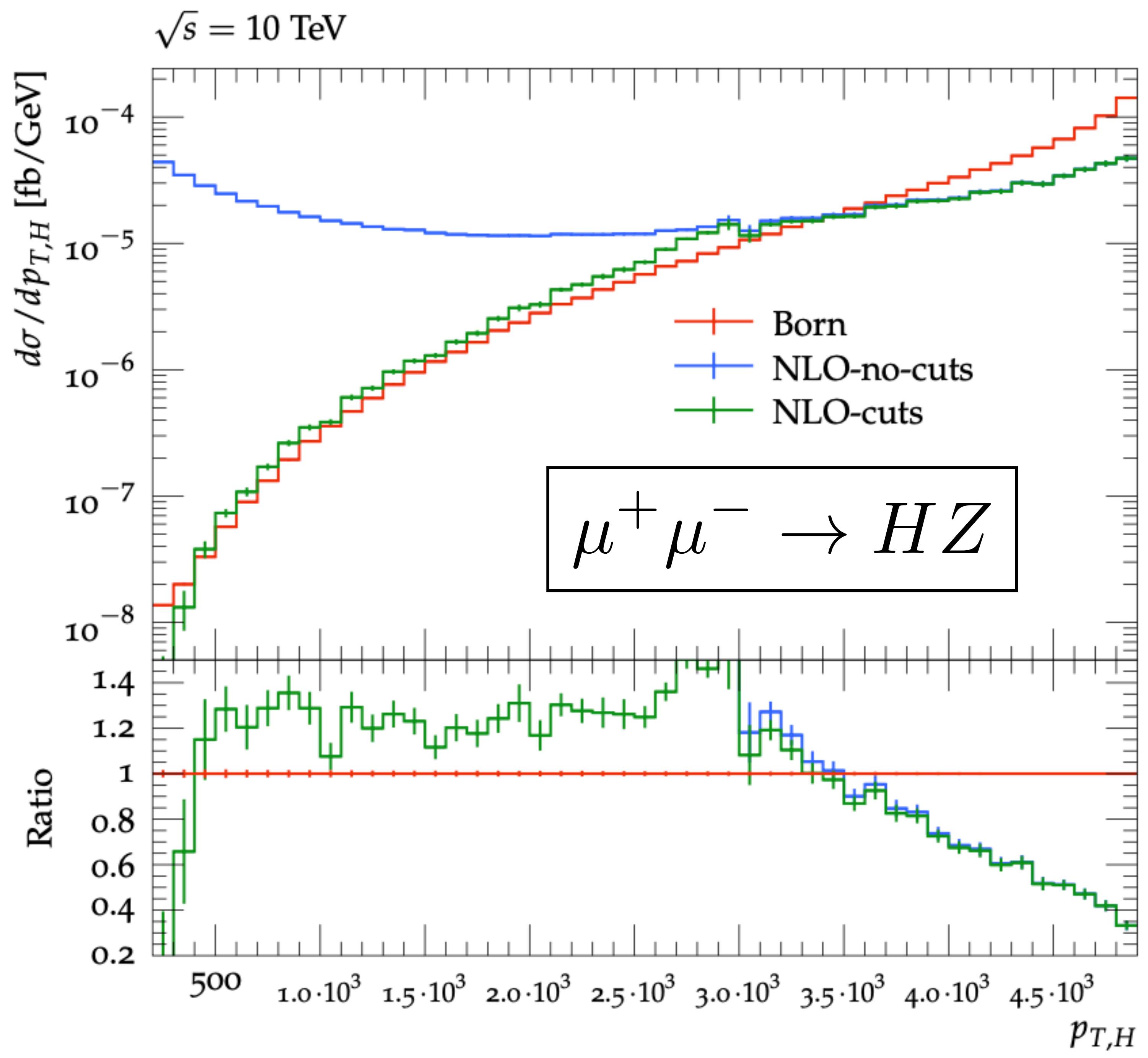
$\mu^+\mu^- \to X, \sqrt{s} = 10$ TeV	$\sigma^{\rm incl}_{\rm LO}$ [fb]	$\sigma^{\rm incl}_{\rm LO+ISR}$ [fb]	$\delta_{\rm ISR}$ [%]
W^+W^-	$5.8820(2) \cdot 10^1$	$7.295(7) \cdot 10^1$	+24.0(1)
ZZ	$3.2730(4) \cdot 10^0$	$4.119(4) \cdot 10^0$	+25.8(1)
HZ	$1.22929(8) \cdot 10^{-1}$	$1.8278(5) \cdot 10^{-1}$	+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)

Differential results

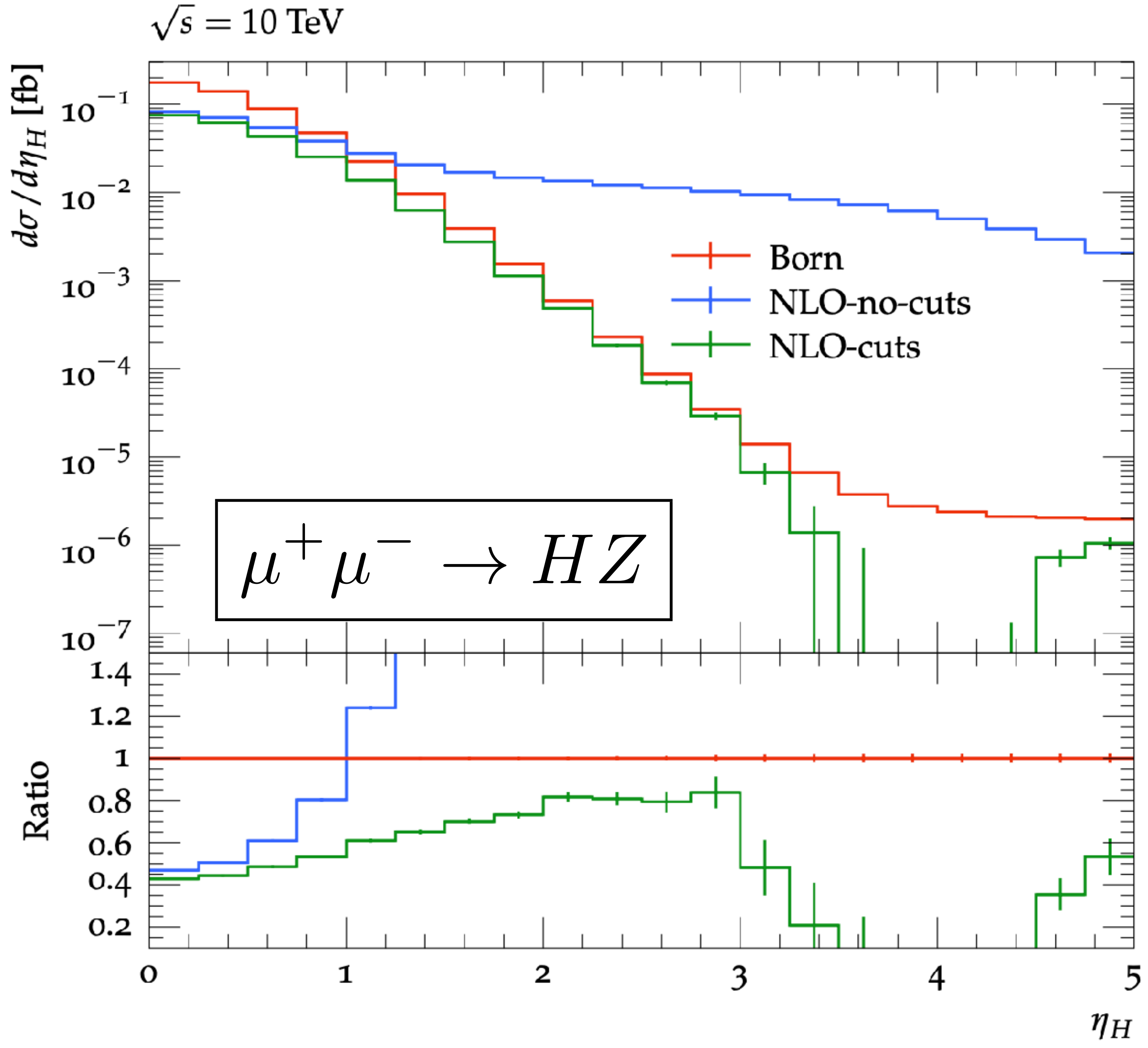
arXiv: 2208.09438

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

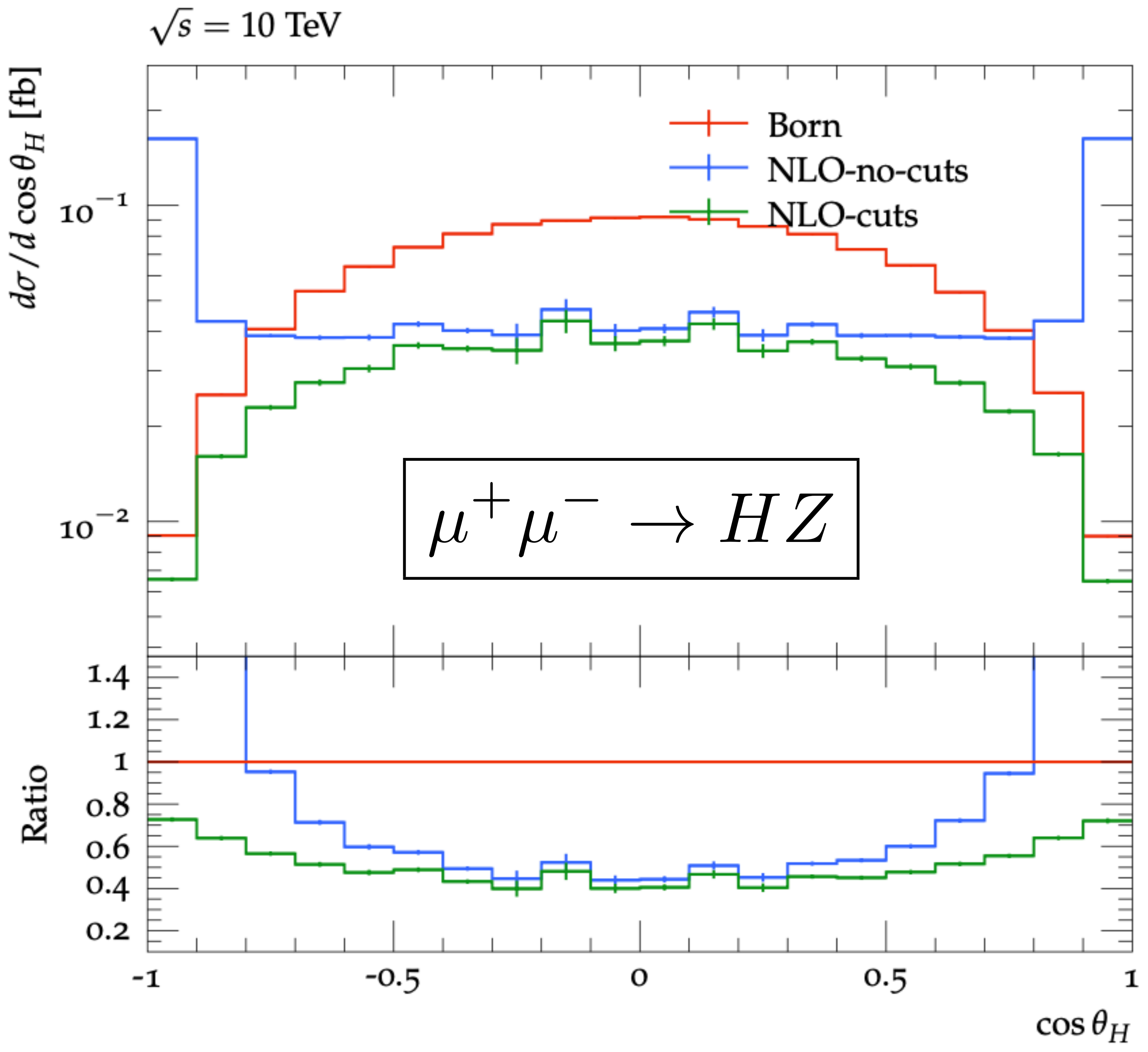
Higgs Transverse Momentum



Higgs rapidity

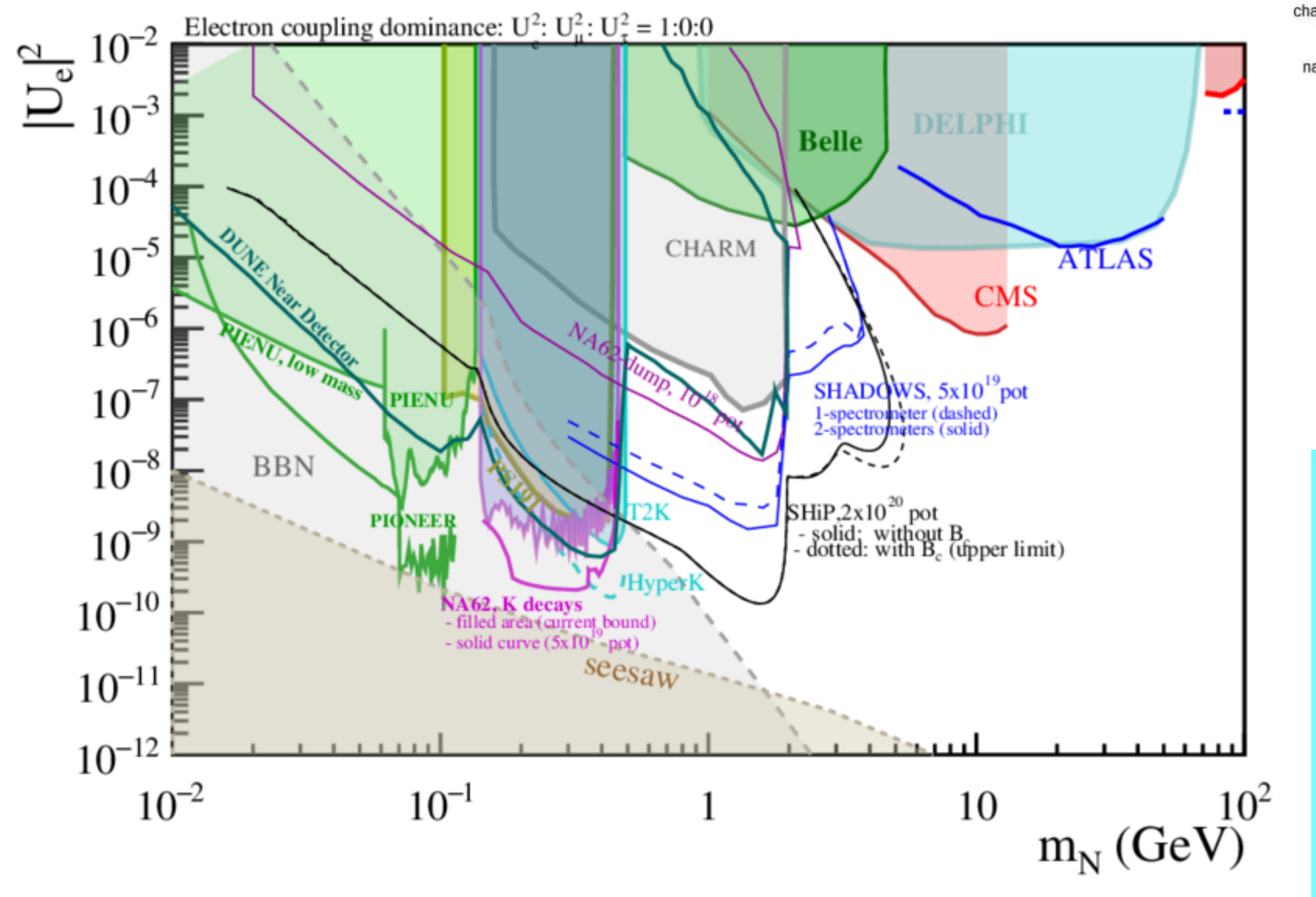


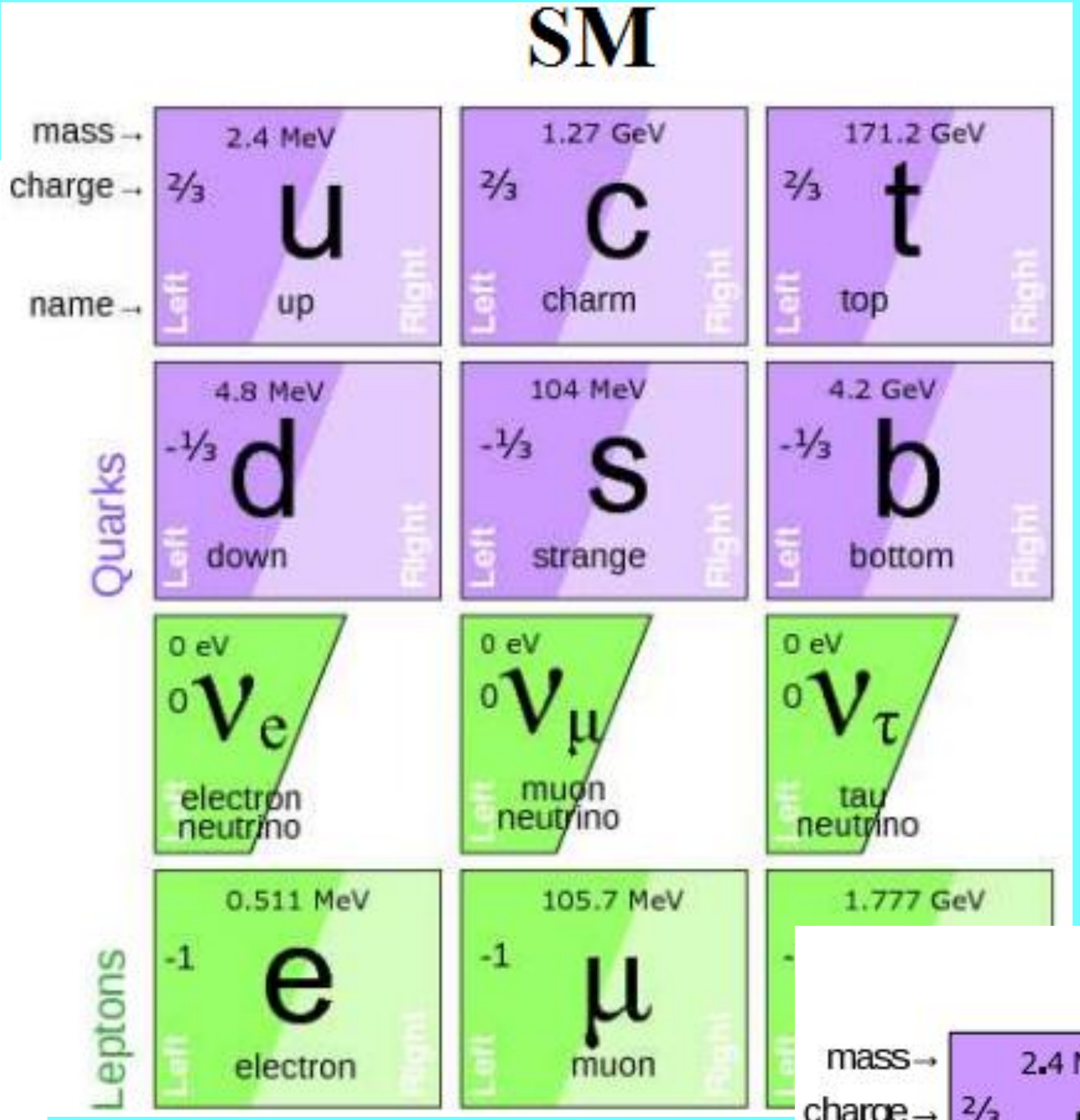
Higgs scattering angle

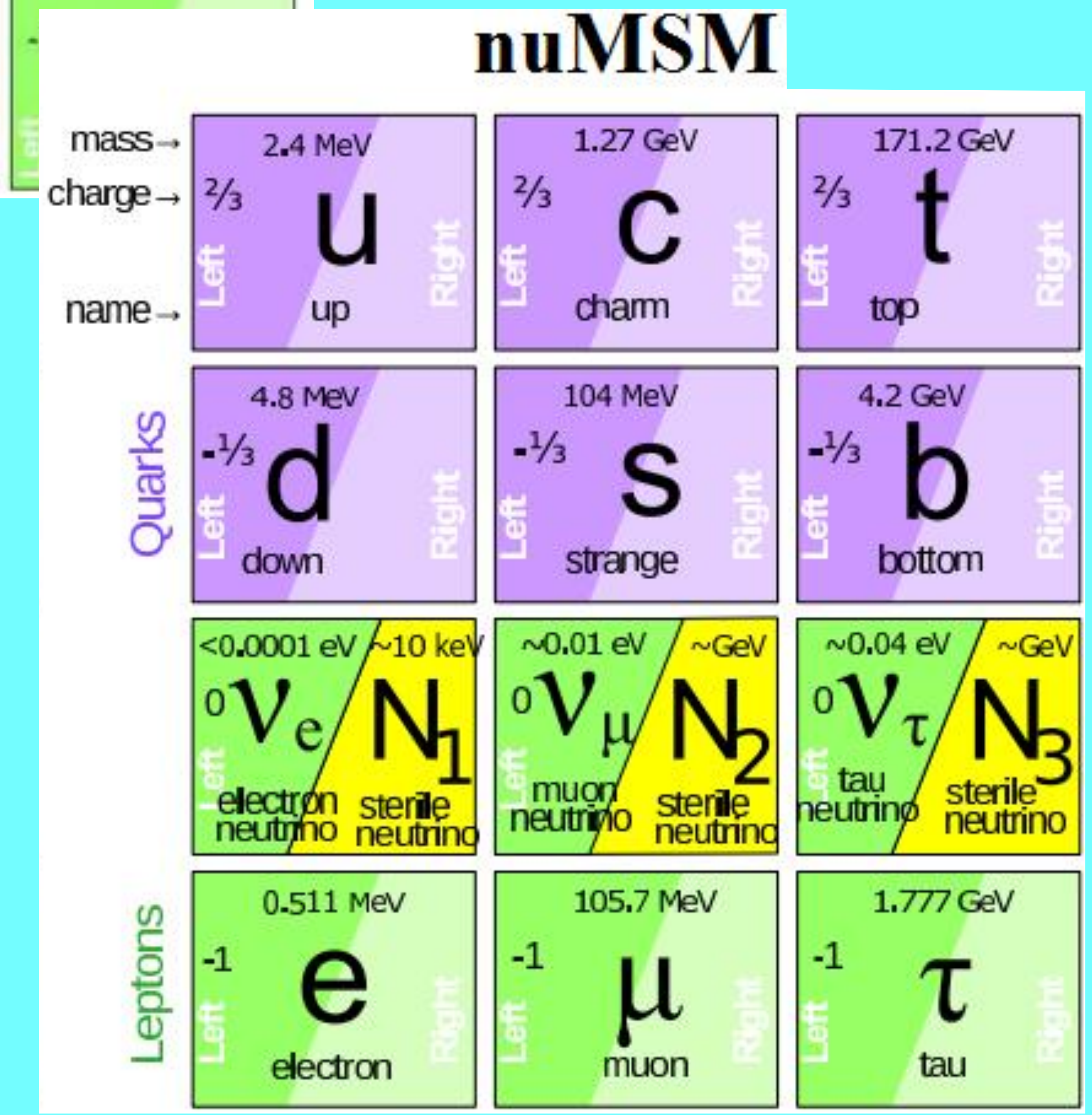


More tasks for even more realistic predictions: exclusive events w/ matching to QED/weak showers, resummation, off-shell processes, separate VBF from VBS

Search for Heavy Neutral Leptons (HNL)



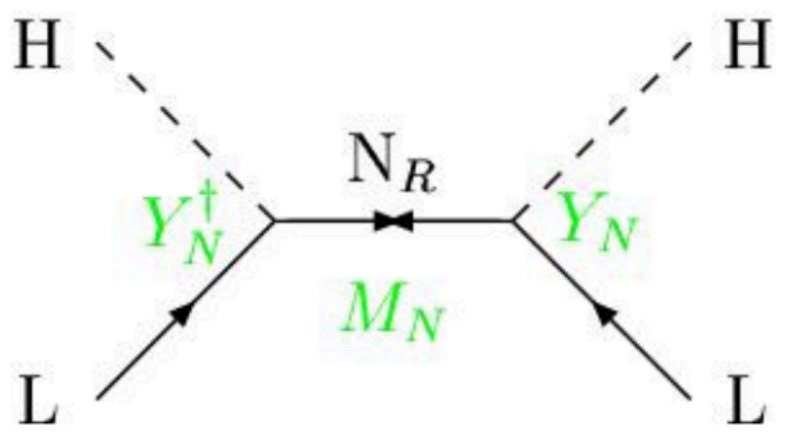




The neutrino mystery

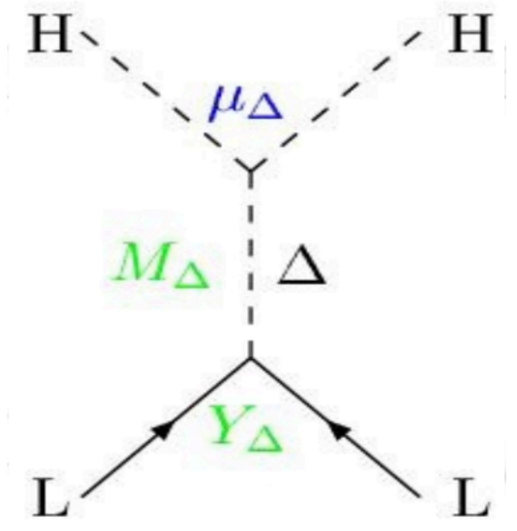
- Neutrinos masses is already physics beyond the standard model
- Simple extension of SM: just add ν_R and Yukawa couplings $\nu_R = (\mathbf{1}, \mathbf{1}, 1)$ $\quad - m_\nu(\overline{\nu}_L \nu_R + h.c.)\left(1 + \frac{h}{v}\right)$
- Singlet allows for a Majorana mass term: $-M_\nu \, \overline{\nu^C} \nu$ [Minkowski, 1977; Mohapatra/Senjanovic, 1980; Yanagida, 1981]
- Dedicated "seesaw" models for neutrino physics: type I (singlet fermion), type II (triplet scalar), type III (triplet fermion)

Right-handed singlet: (type-I seesaw)



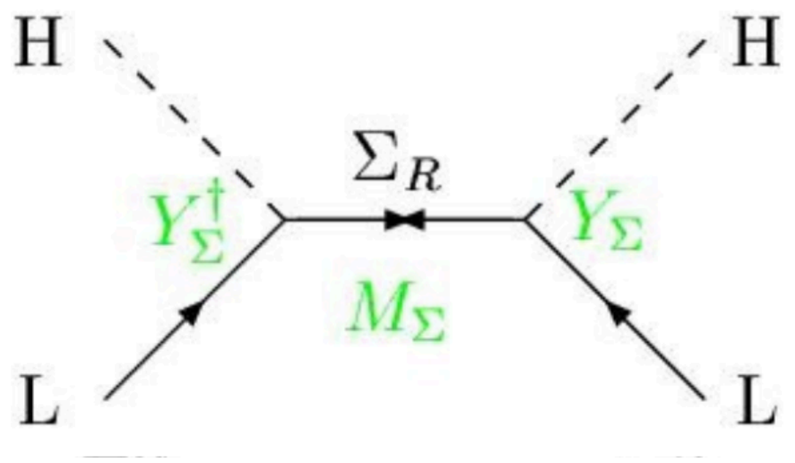
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Scalar triplet: (type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Fermion triplet: (type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

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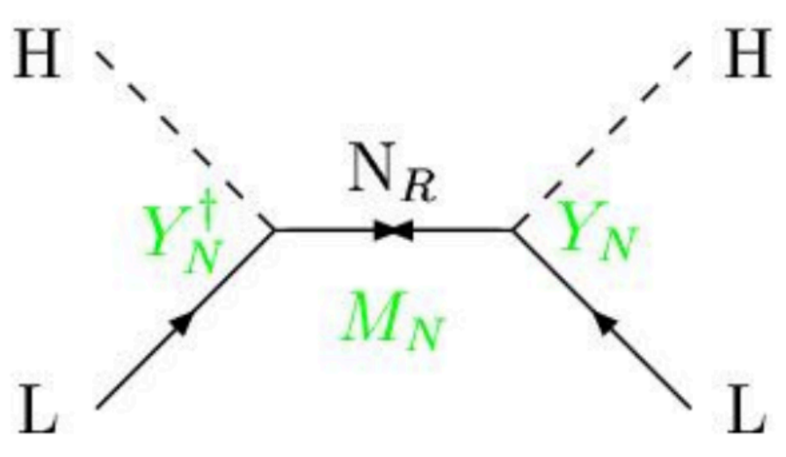

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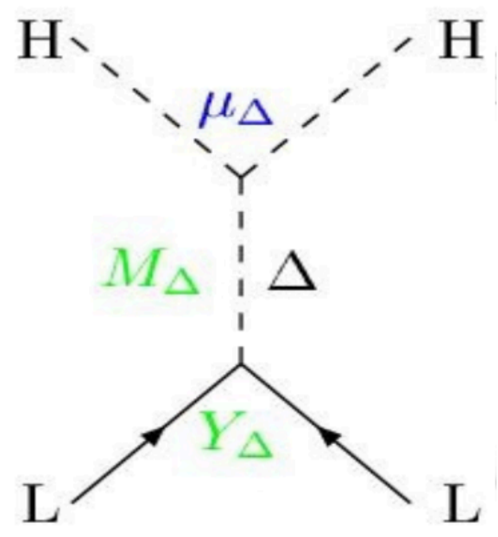

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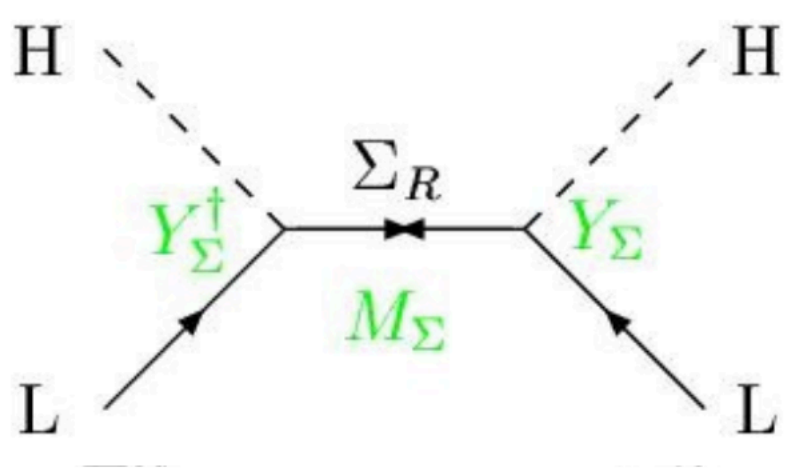


$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

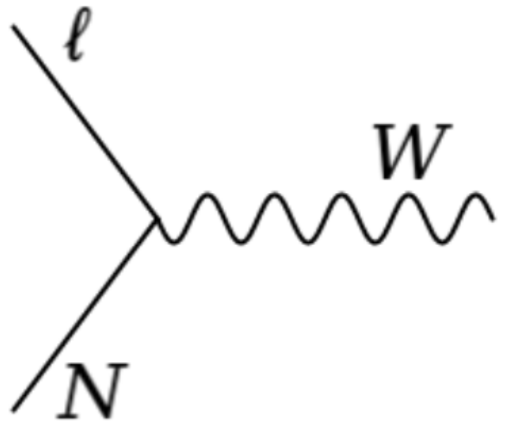
- Pheno of neutrino oscillations, flavor etc.
- Connections to Dark Matter (DM) (?)
- Lepton sector CP violation (?)
- Leptogenesis / Baryogenesis / Baryon Asymmetry of Universe (BAU)
- Lepton Flavor/Number Violation
- Fundamental Majorana Particles (?)

Simplified neutrino model

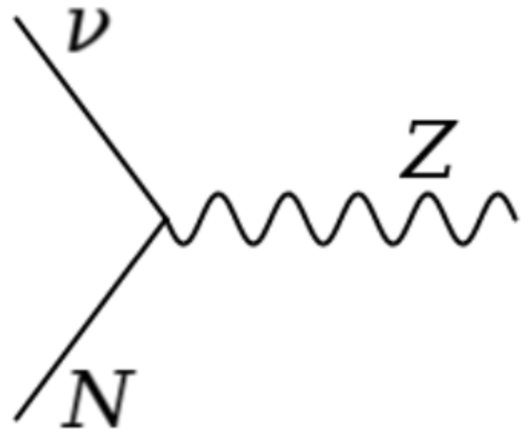
- Simplified model with right-handed (νSM) and sterile neutrinos
- After EWSB heavy (sterile) neutrinos do mix with νSM neutrinos
- Lagrangian: $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{WN\ell} + \mathcal{L}_{ZN\nu} + \mathcal{L}_{HN\nu}$

$$\mathcal{L}_N = \xi_\nu \cdot \left(\bar{N}_k i\partial\!\!\!/ N_k - m_{N_k}\bar{N}_k N_k\right) \qquad \text{for } k = 1,\, 2,\, 3$$

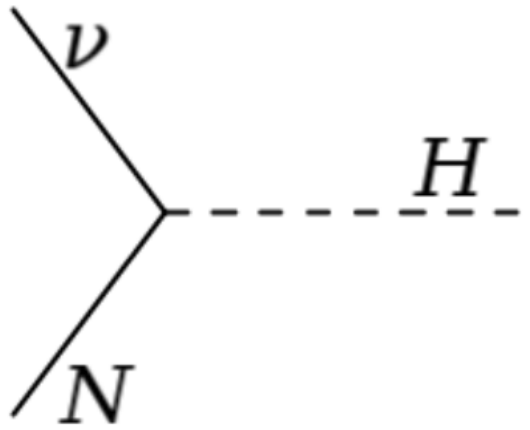
$$\mathcal{L}_{WN\ell} = -\frac{g}{\sqrt{2}} W^+_\mu \sum_{k=1}^{3} \sum_{l=e}^{\tau} \bar{N}_k V^*_{lk} \gamma^\mu P_L \ell^- + \text{ h.c.},$$



$$\mathcal{L}_{ZN\nu} = -\frac{g}{2\cos\theta_W} Z_\mu \sum_{k=1}^{3} \sum_{l=e}^{\tau} \bar{N}_k V^*_{lk} \gamma^\mu P_L \nu_l + \text{ h.c.}$$



$$\mathcal{L}_{HN\nu} = -\frac{g m_N}{2M_W} h \sum_{k=1}^{3} \sum_{l=e}^{\tau} \bar{N}_k V^*_{lk} P_L \nu_l + \text{ h.c.}$$



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Incomplete literature:

Aguilar-Saavedra ea., hep-ph/0502189; hep-ph/0503026; Shaposhnikov, 0804.4542; Das/Okada, 1207.3734; Banerjee ea., 1503.05491; Antusch, Cazzato, Fischer, 1612.0272; Cai, Han, Li, Ruiz, 1711.02180; Pascoli, Ruiz, Weiland, 1812.08750

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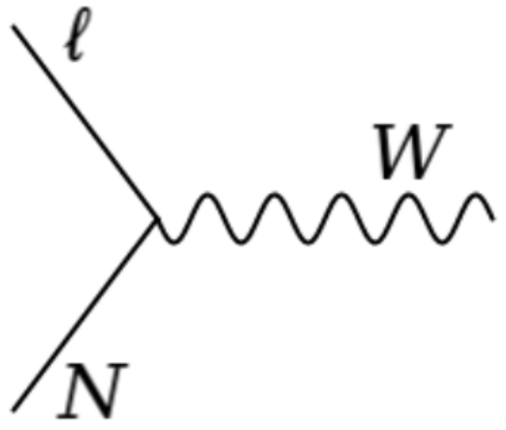
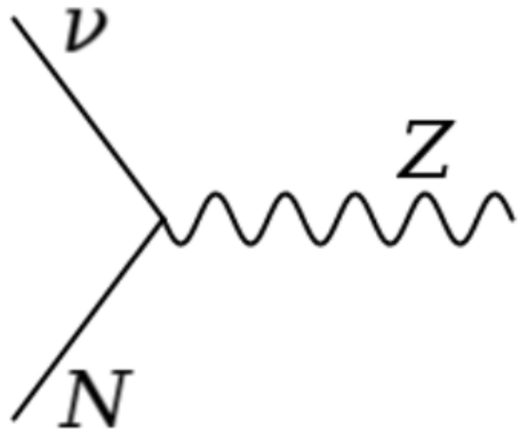
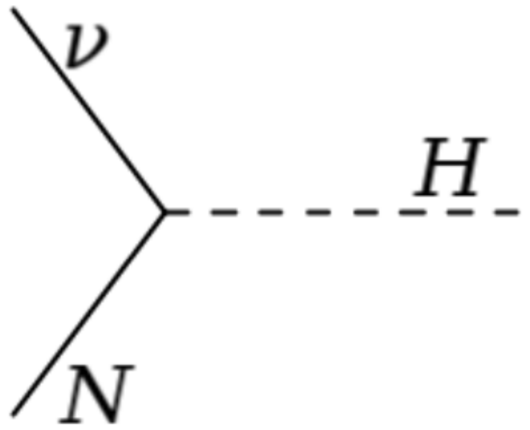
$$\mathcal{L}_{WN\ell} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{k=1}^{3}\sum_{l=e}^{\tau} \bar{N}_k V_{lk}^* \gamma^\mu P_L \ell^- + \text{ h.c.},$$



$$\mathcal{L}_{ZN\nu} = -\frac{g}{2\cos\theta_W} Z_\mu \sum_{k=1}^{3}\sum_{l=e}^{\tau} \bar{N}_k V_{lk}^* \gamma^\mu P_L \nu_l + \text{ h.c.}$$



$$\mathcal{L}_{HN\nu} = -\frac{g m_N}{2M_W} h \sum_{k=1}^{3}\sum_{l=e}^{\tau} \bar{N}_k V_{lk}^* P_L \nu_l + \text{ h.c.}$$

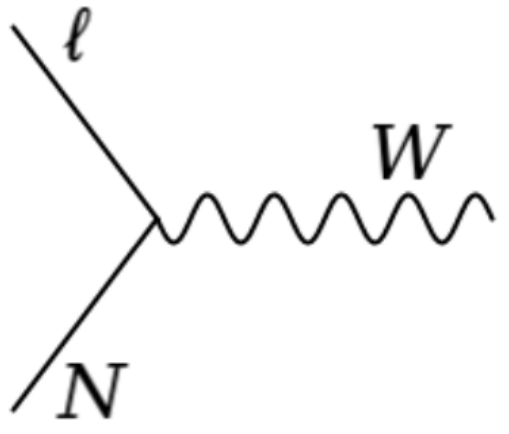


Simplified neutrino model

- Simplified model with right-handed (νSM) and sterile neutrinos
- After EWSB heavy (sterile) neutrinos do mix with νSM neutrinos
- Lagrangian: $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{WN\ell} + \mathcal{L}_{Z N\nu} + \mathcal{L}_{HN\nu}$

$$\mathcal{L}_N = \xi_\nu \cdot \left(\bar{N}_k i \partial\!\!\!/ N_k - m_{N_k} \bar{N}_k N_k \right) \qquad \text{for } k = 1,\, 2,\, 3$$

$$\mathcal{L}_{WN\ell} = -\frac{g}{\sqrt{2}} W^+_\mu \sum_{k=1}^{3} \sum_{l=e}^{\tau} \bar{N}_k V^*_{lk} \gamma^\mu P_L \ell^- + \text{ h.c.},$$



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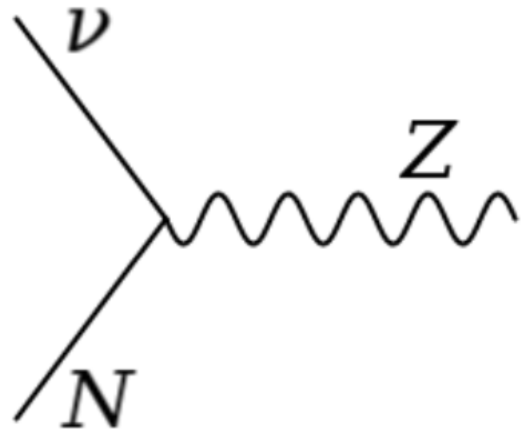

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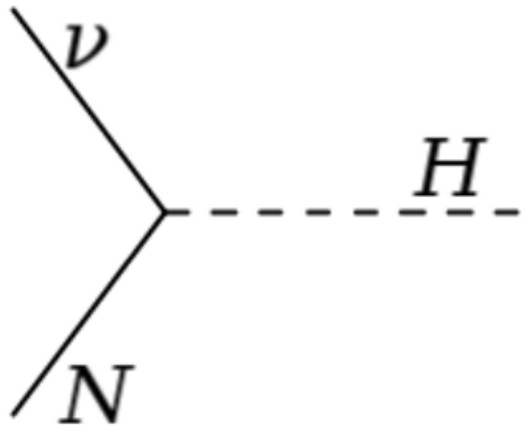


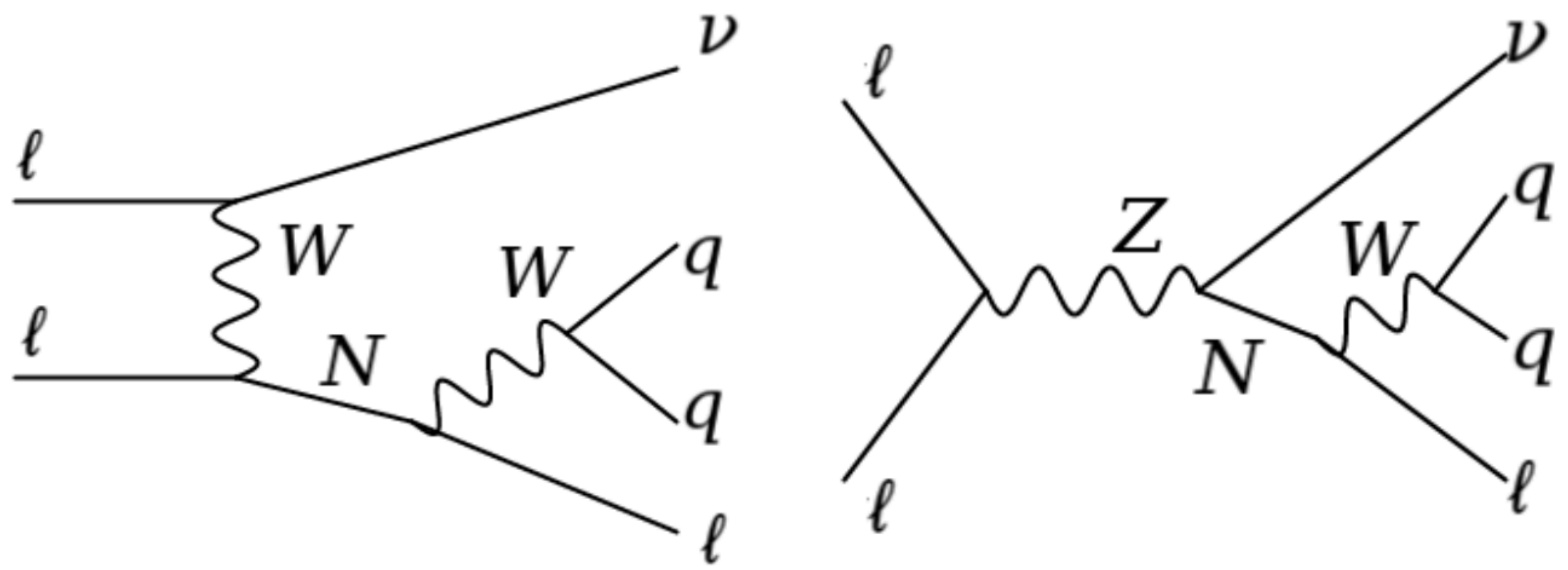
Incomplete literature:

Aguilar-Saavedra ea., hep-ph/0502189; hep-ph/0503026; Shaposhnikov, 0804.4542; Das/Okada, 1207.3734; Banerjee ea., 1503.05491; Antusch, Cazzato, Fischer, 1612.0272; Cai, Han, Li, Ruiz, 1711.02180; Pascoli, Ruiz, Weiland, 1812.08750

- ☑ At lepton colliders, single production possible
- ☑ Associated production: $\ell^+\ell^- \to \nu N$
- ☑ Vector boson fusion: $\ell^+\ell^- \to \bar{\nu}\nu N + \ell^+\ell^- N$
- ☑ Three neutrino masses: $M_{N_1}, M_{N_2}, M_{N_3}$
- ☑ Nine real mixing parameters: $V_{\ell k}$, $\ell = e, \mu\, \tau, k = N_1, N_2, N_3$
- ☑ Three neutrino widths: $\Gamma_{N_1}, \Gamma_{N_2}, \Gamma_{N_3}$

Signal, simulation, selection

- At lepton colliders: optimal channel single production with decay to $N \to jj\ell$
- In that case: full reconstruction of *N* (incl. mass peak) possible
- Study for ILC250, ILC500, ILC1000, CLIC 3 TeV, MuC 3+10 TeV
- Simulation with `Whizard 3.0` (first paper!) + `Pythia6 + Delphes`
- Using UFO model `HeavyN`



K. Mękała/JRR/A.F. Żarnecki, 2202.06703; 2301.02602

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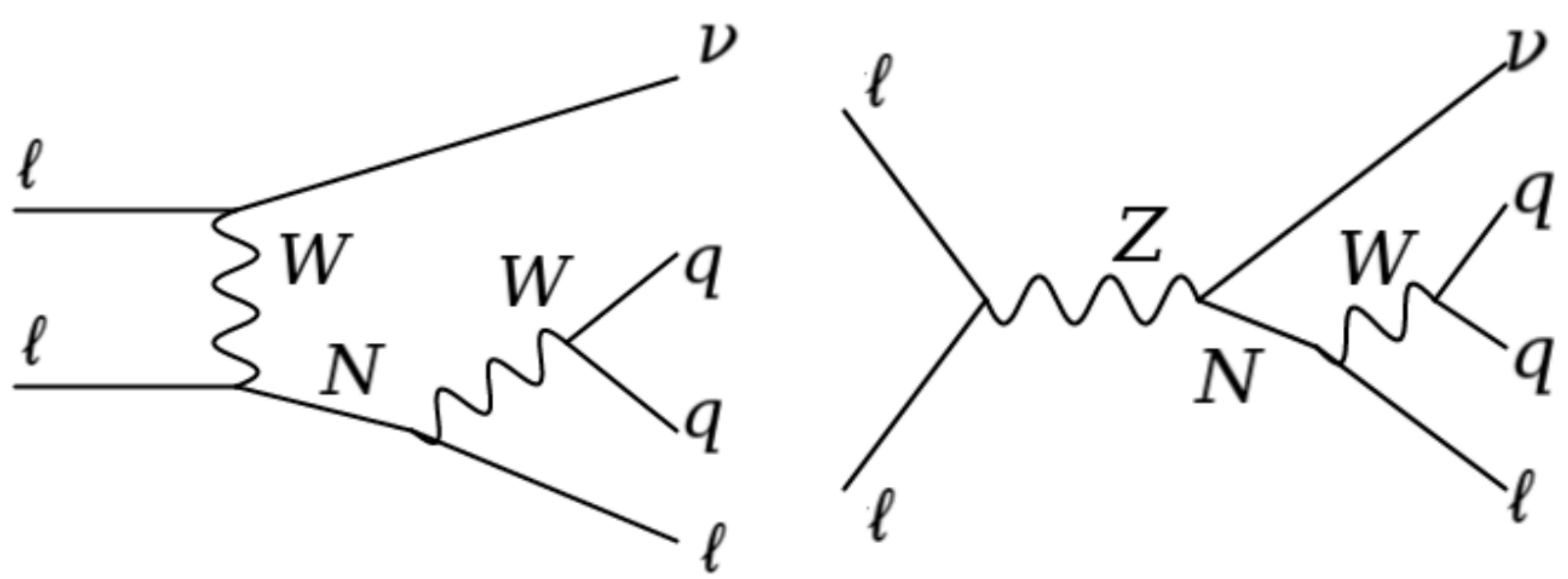

K. Mękała/JRR/A.F. Żarnecki, 2202.06703; 2301.02602

- [x] Assumption on couplings: $|V_{eN_1}|^2 = |V_{\mu N_1}|^2 + |V_{\tau N_1}|^2 \equiv |V_{\ell N_1}|^2$
- [x] Reference signal sample with $|V_{\ell N_1}| = 0.0003$, N_2, N_3 couplings set to zero
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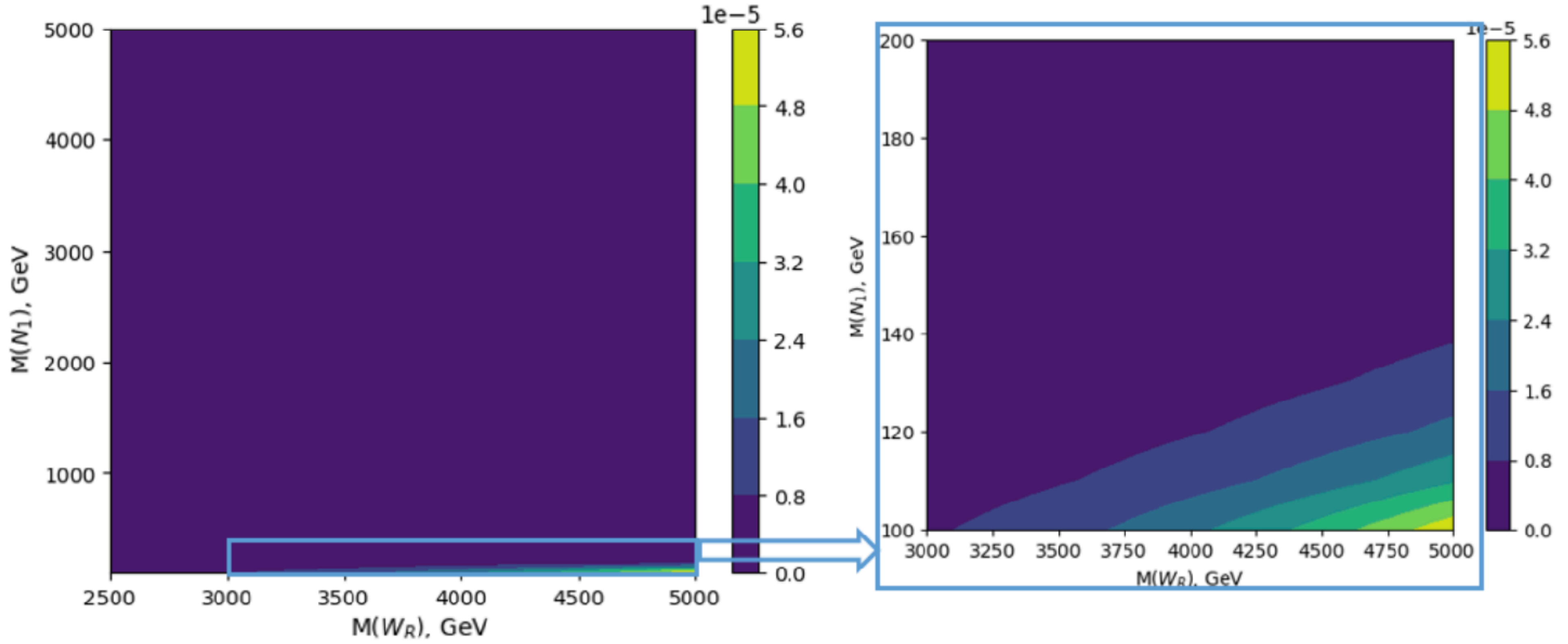

K. Korshynska/M. Löschner/M. Marinichenko/
JRR/K. Mękała, Febr. 2023

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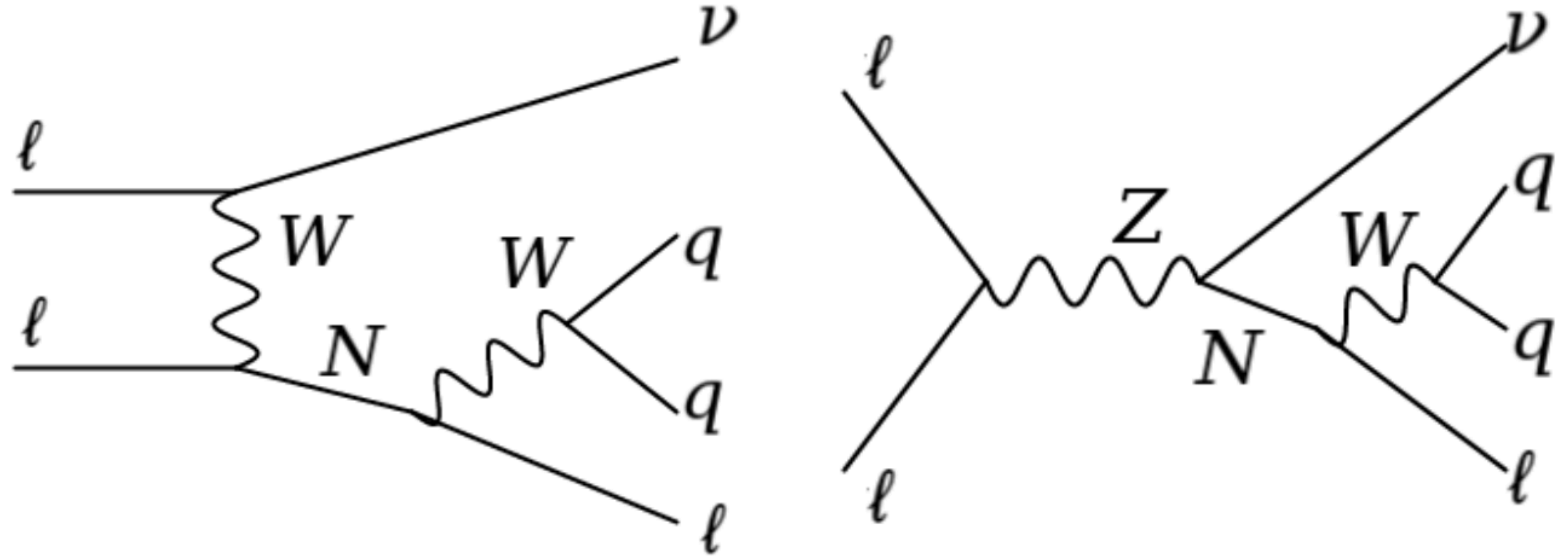

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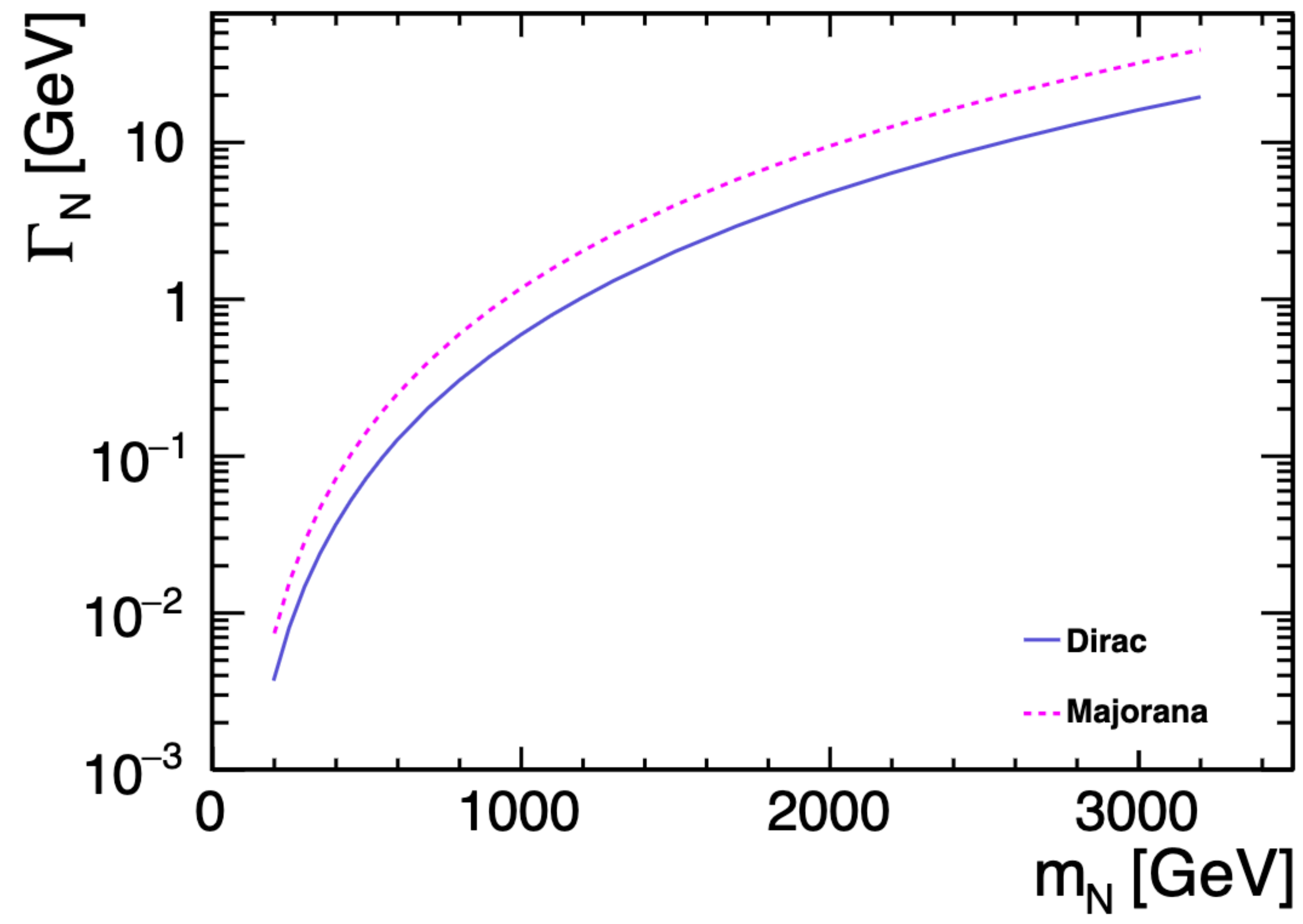

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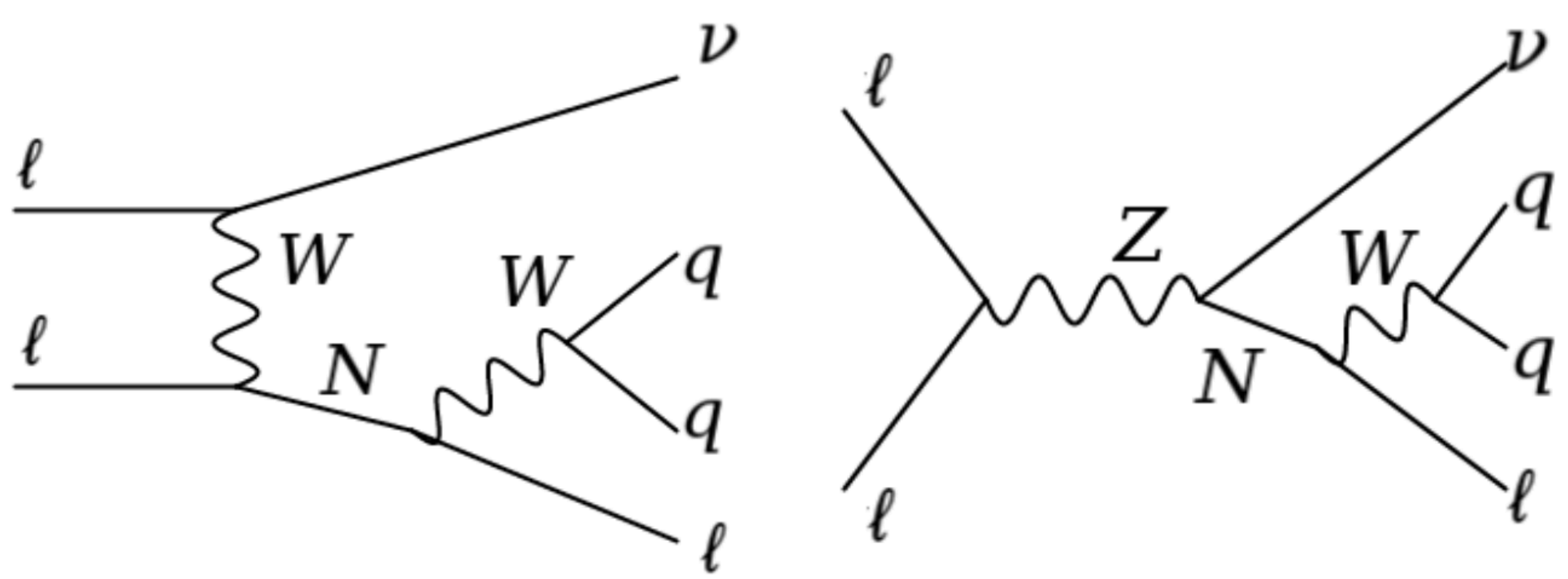

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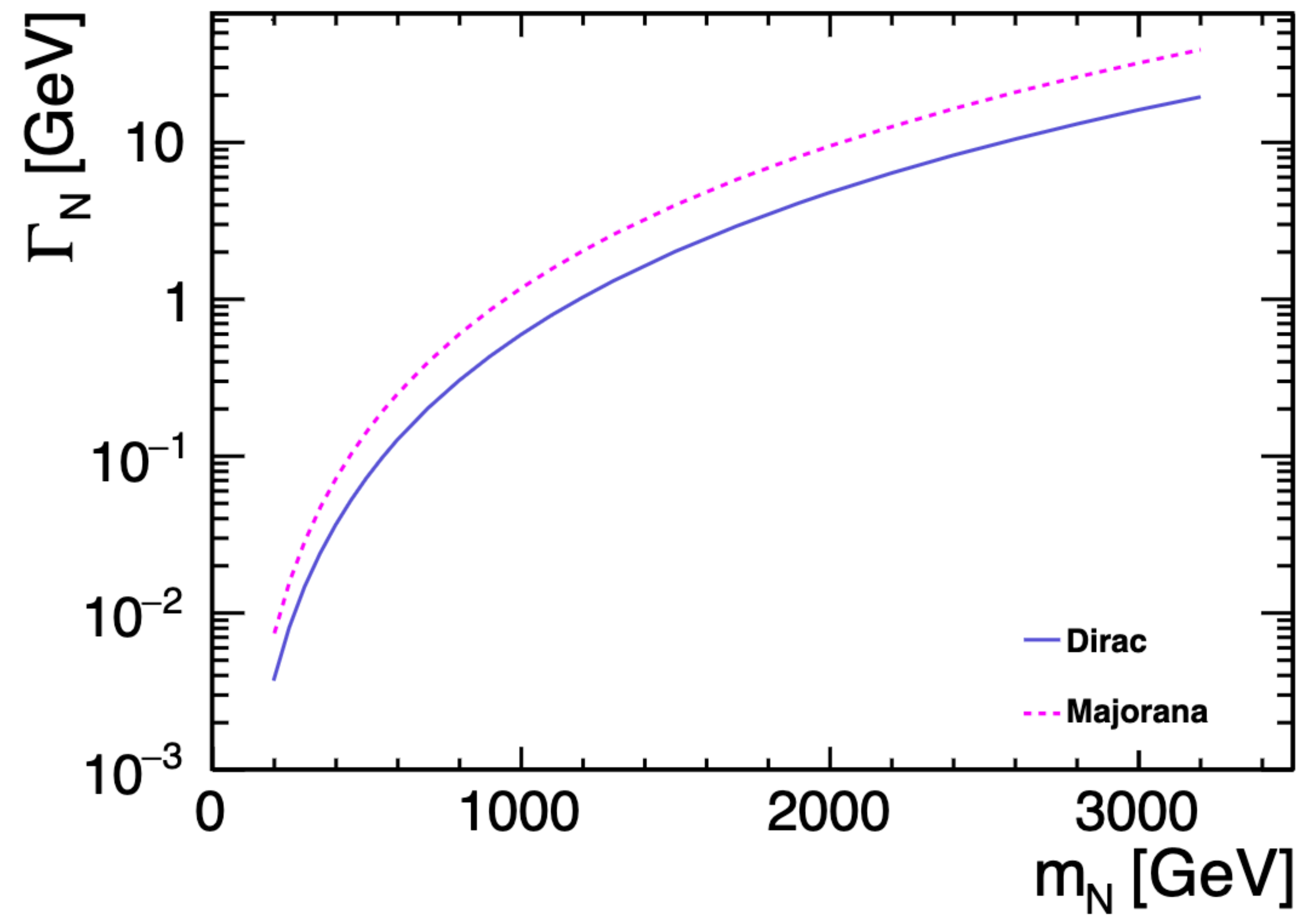

  - Background simulation: without N propagators ("background")
  - Signal simulation: $\ell\ell \to N\nu \to \ell jj\nu$ ("signal")
  - $S/B \sim 10^{-3}$ e.g. ILC500: $jj\ell\nu$ bkgd. ~ 10 pb, signal ~ 10 fb
  - Preselection on signal topology: exactly 1 lepton and 2 jets
  - BDT training; CLs method to get final results

Event selection & analysis

Bkgd processes with at least one lepton

- $\mu^+\mu^- \to jj\ell^\pm\nu$
- $\mu^+\mu^- \to jj\ell^+\ell^-$
- $\mu^+\mu^- \to \ell^+\ell^-\ell'^+\ell'^-$
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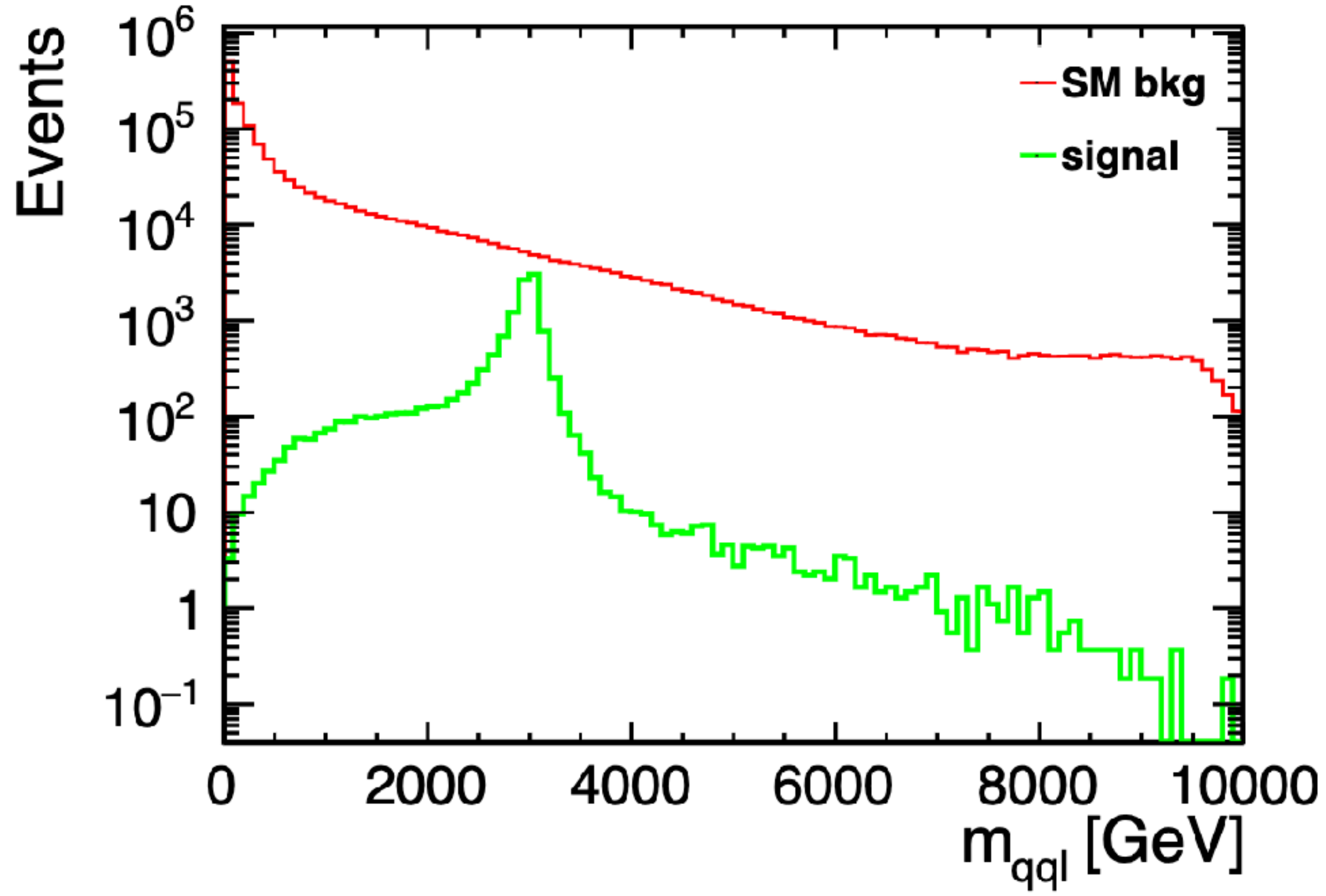

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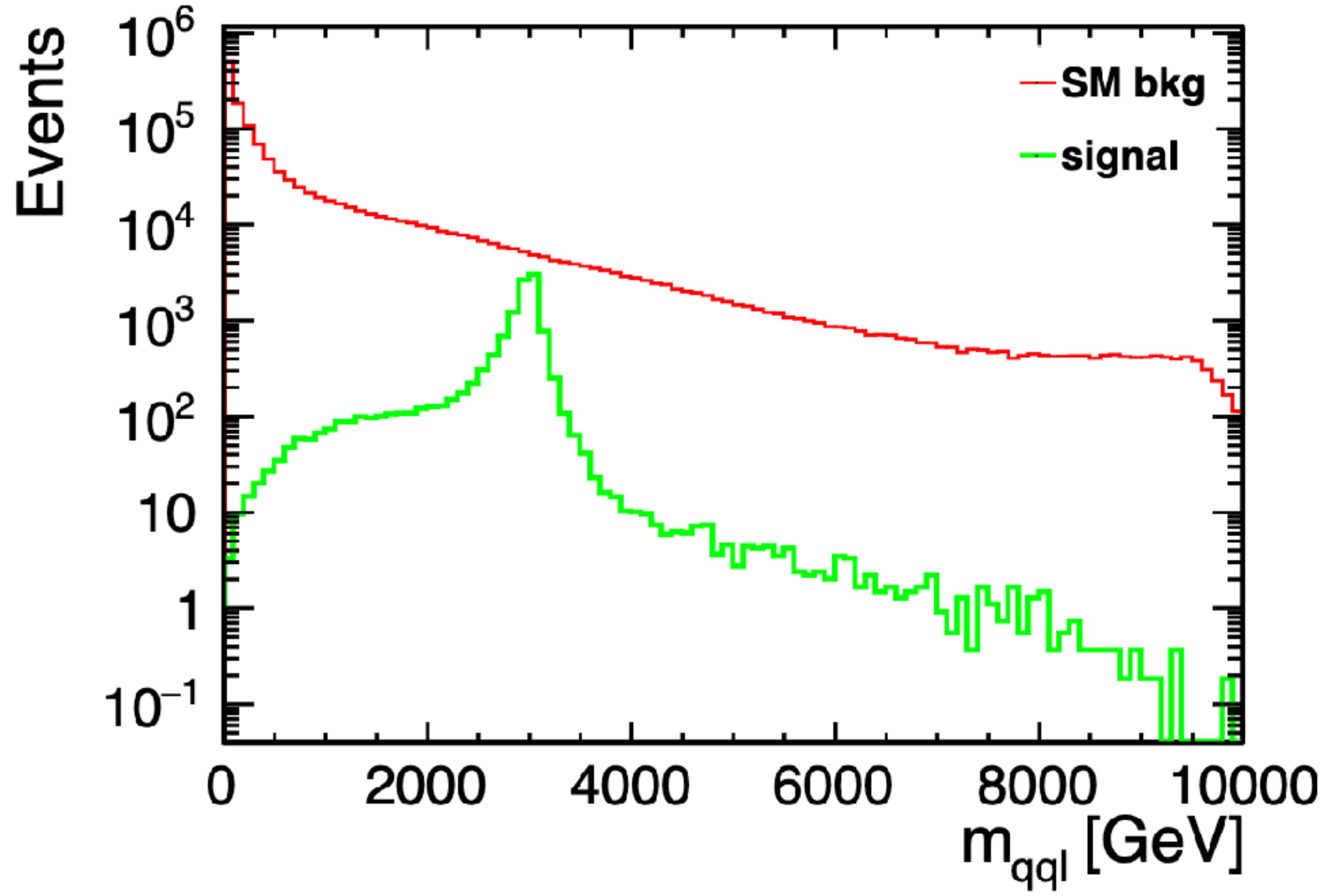

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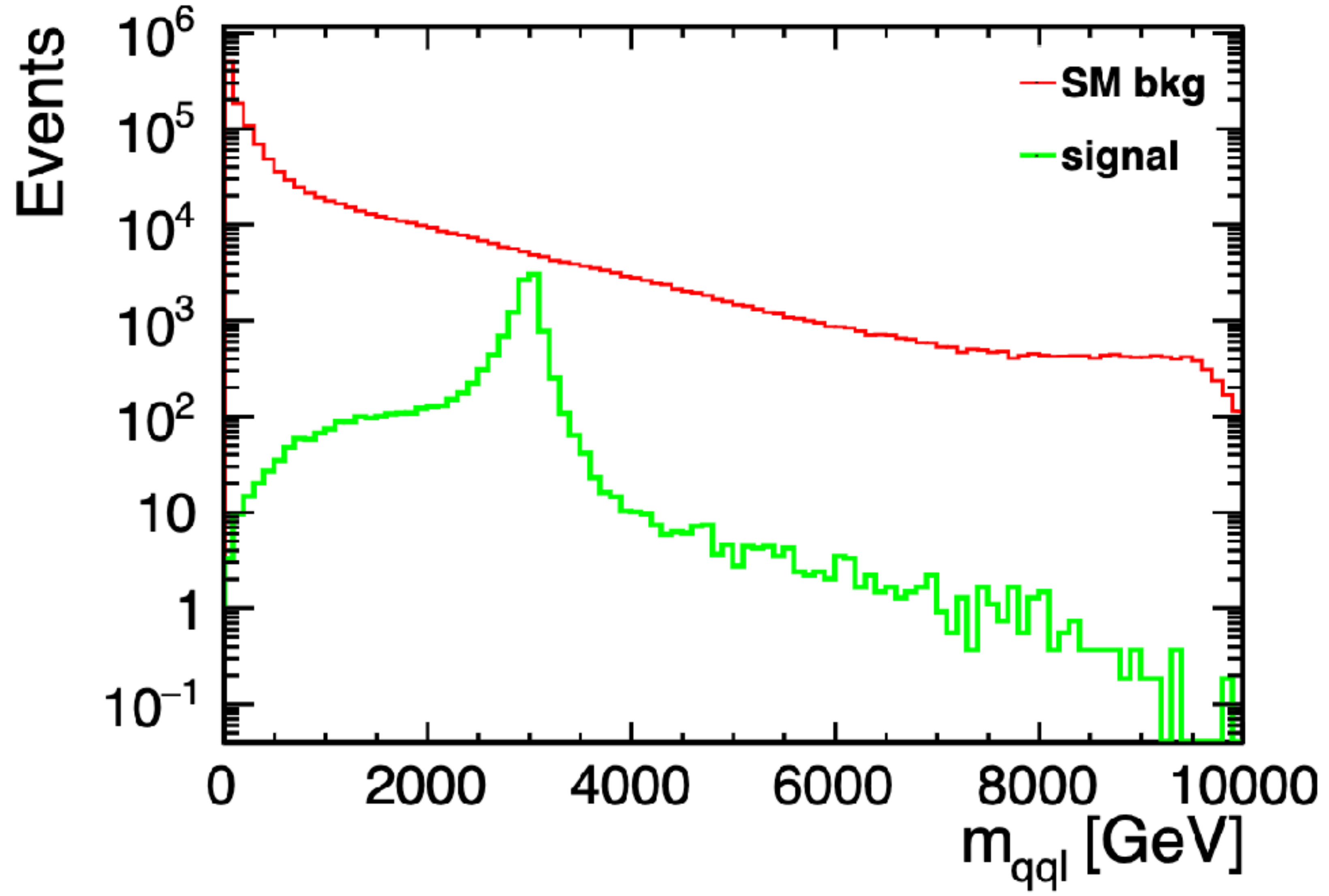

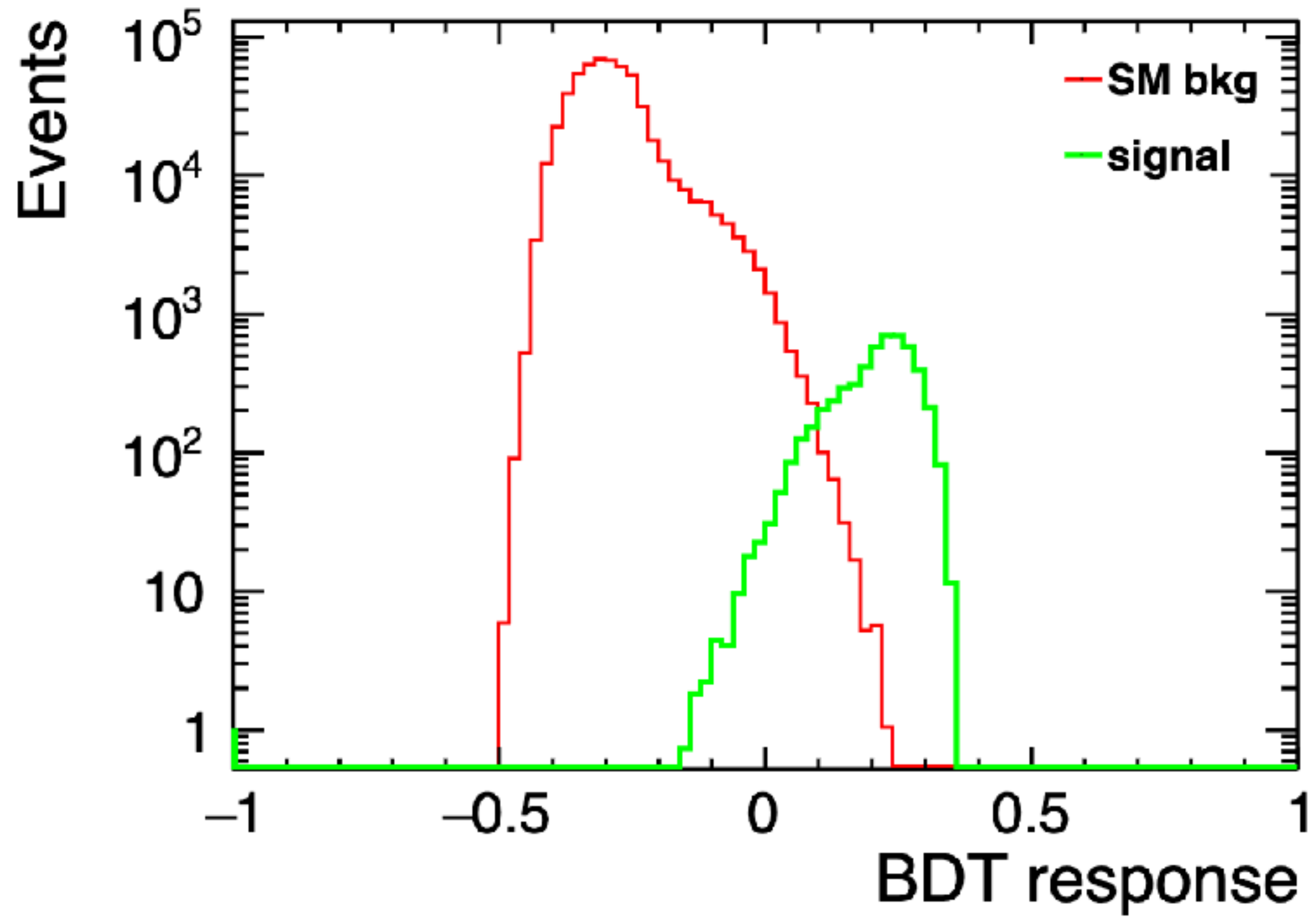

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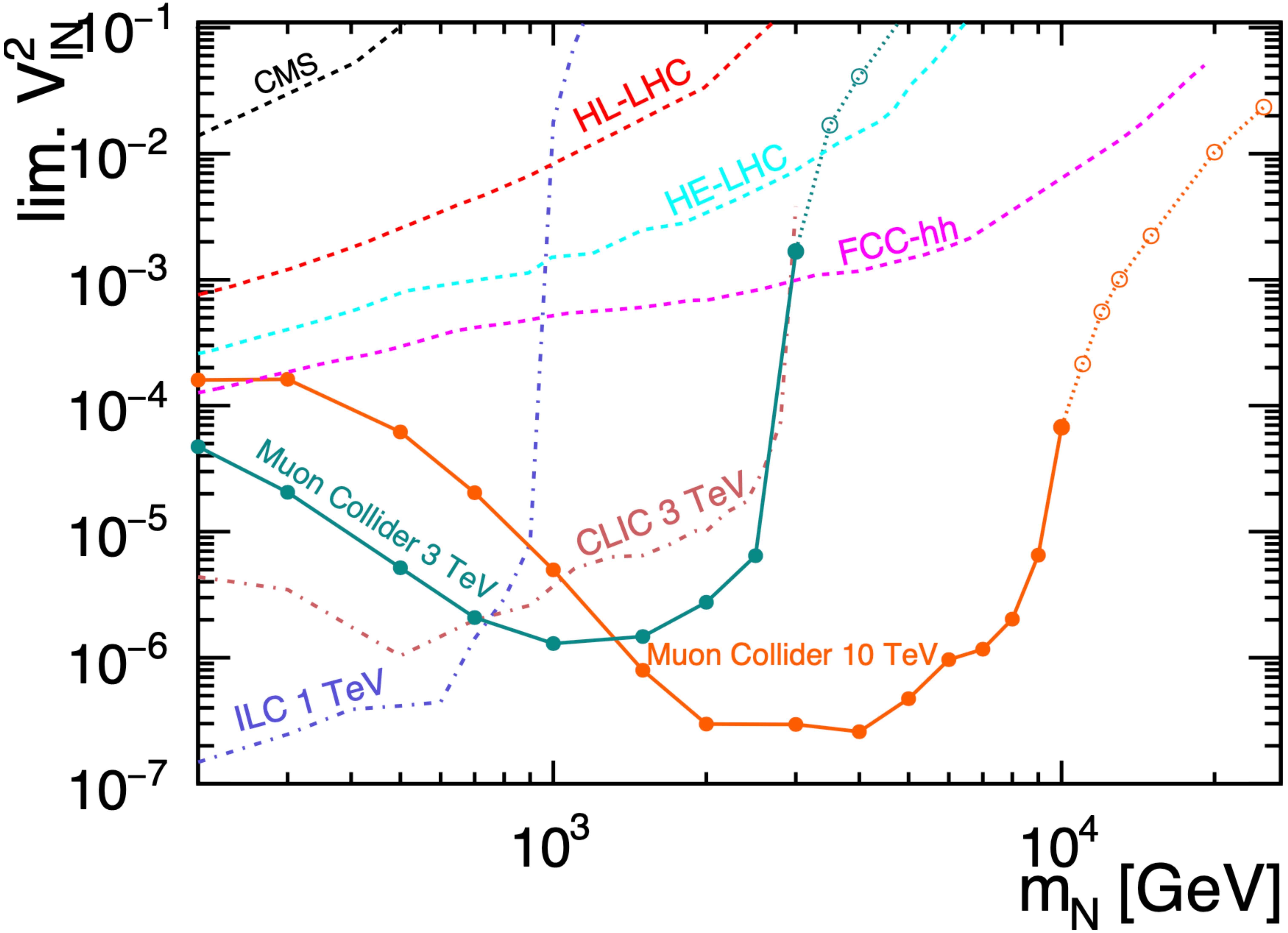
BDT response for model in `RooStats`, CLs method to set cross section limits
Combination of $e^\pm$ and $\mu^\pm$ channels

8 variables considered in BDT

- $m_{qq\ell}$ – invariant mass of the dijet-lepton system,
- α – angle between the dijet-system and the lepton,
- α_{qq} – angle between the two jets,
- E_ℓ – lepton energy,
- $E_{qq\ell}$ – energy of the dijet-lepton system,
- p^T_ℓ – lepton transverse momentum,
- p^T_{qq} – dijet transverse momentum,
- $p^T_{qq\ell}$ – transverse momentum of the dijet-lepton system.

Reach for HNLs



K. Mękała/JRR/A.F. Żarnecki, 2301.02602

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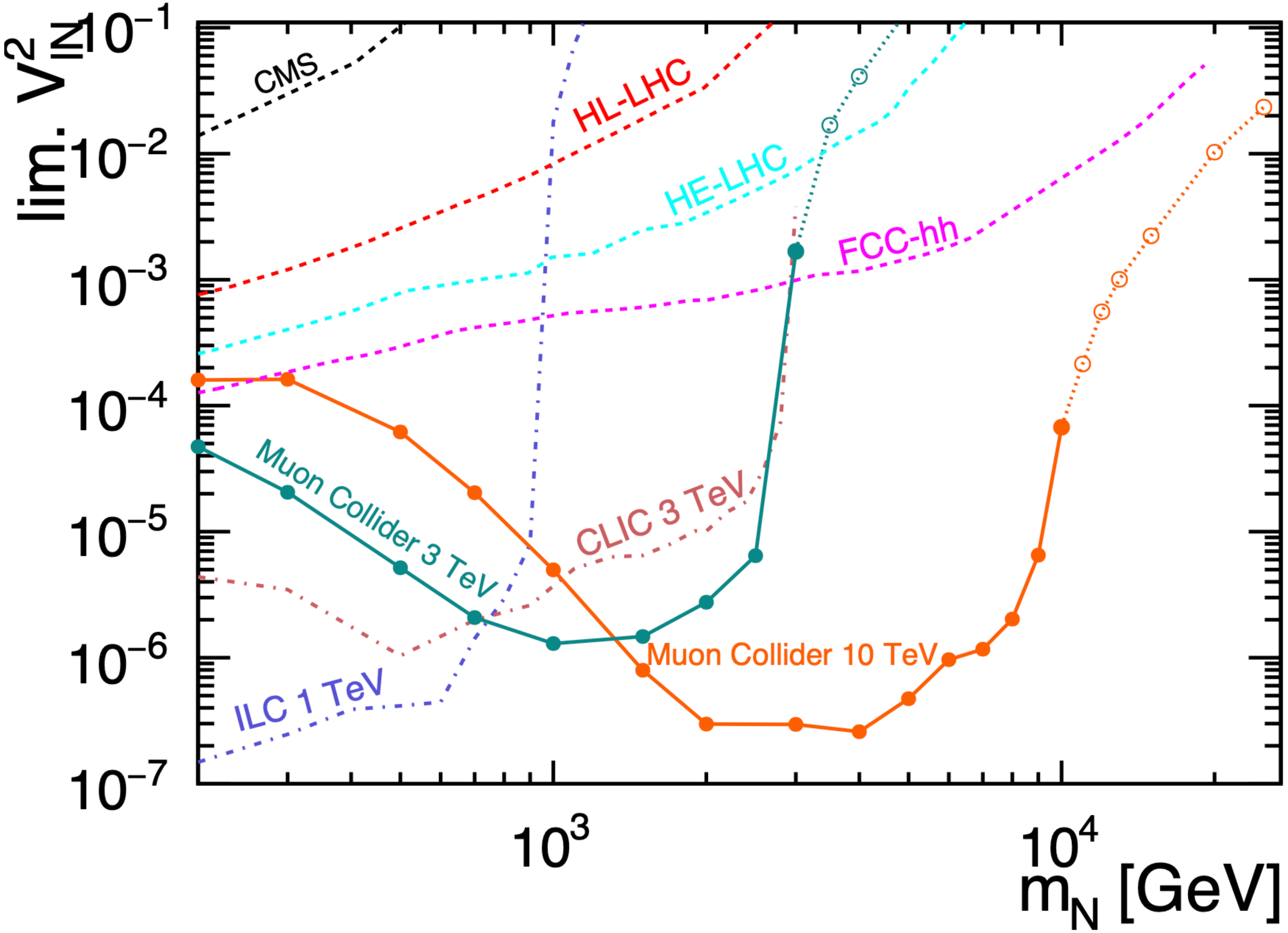

K. Mękała/JRR/A.F. Żarnecki, 2301.02602

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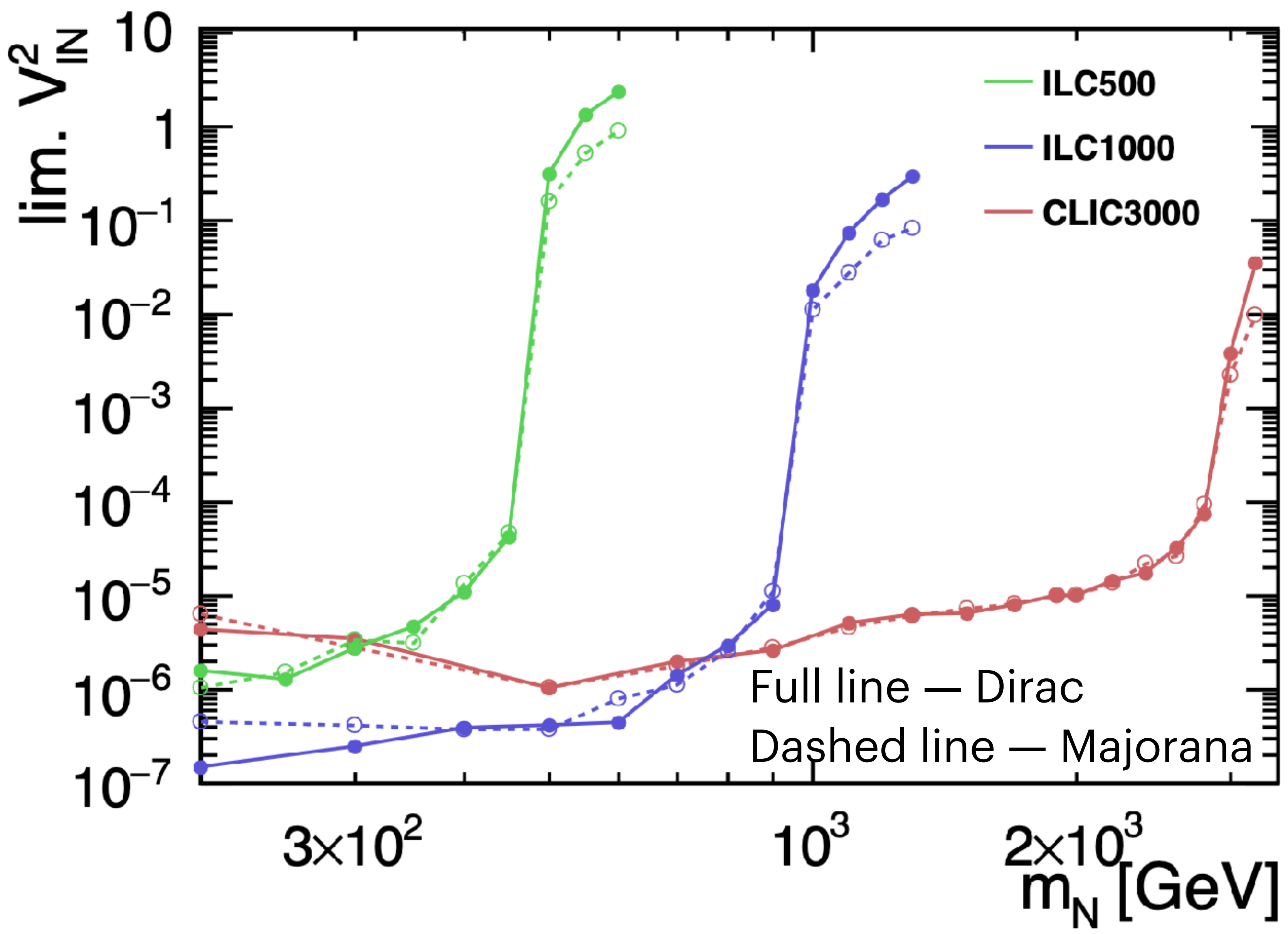
MuC-10 outperforms FCC-hh-100
over the whole mass range!

Discrimination of Dirac vs. Majorana

- Exclusion limit very similar for Dirac & Majorana neutrino (except: off-shell production)
- Possible discriminant: lepton emission angle in *N* rest frame



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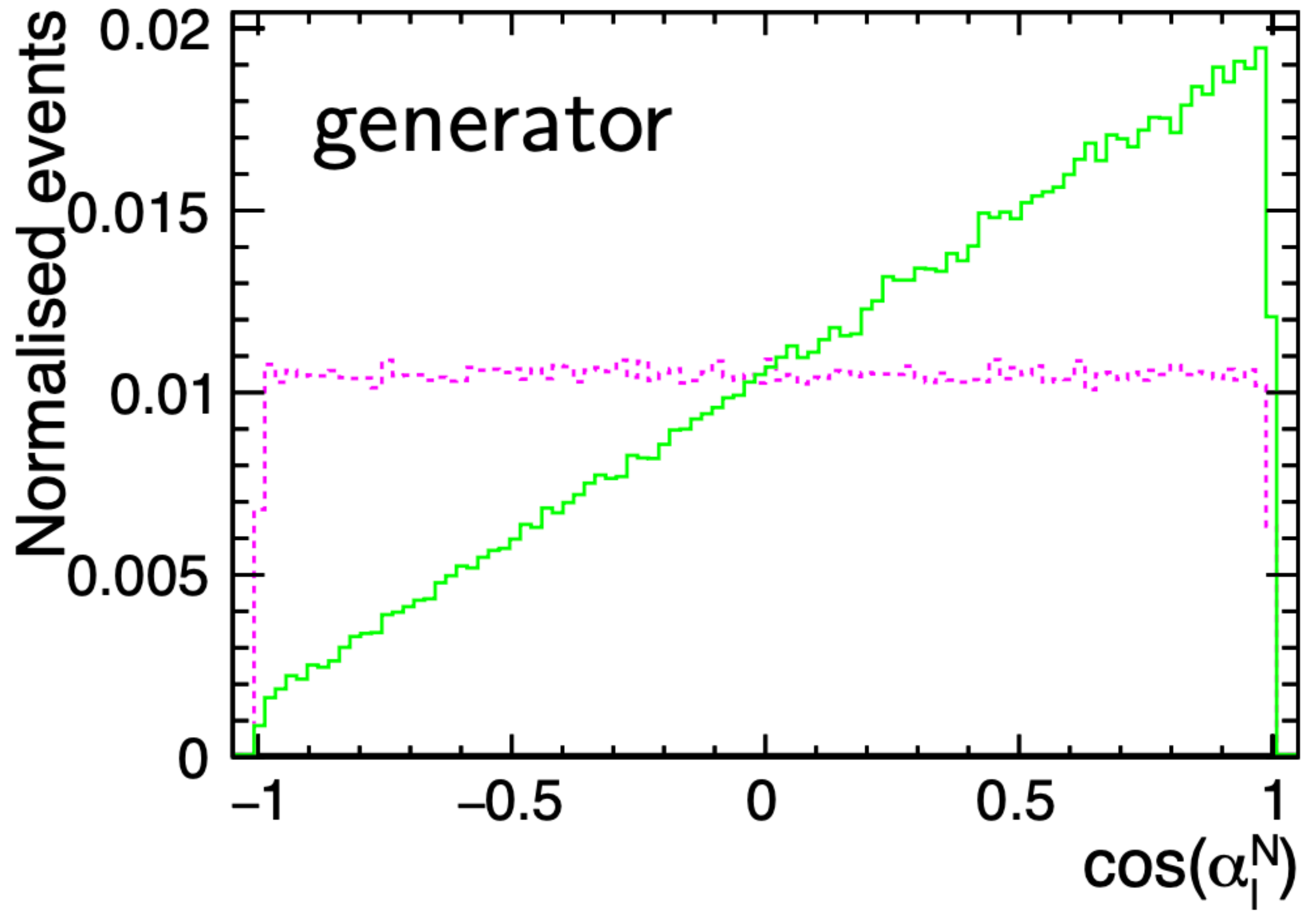

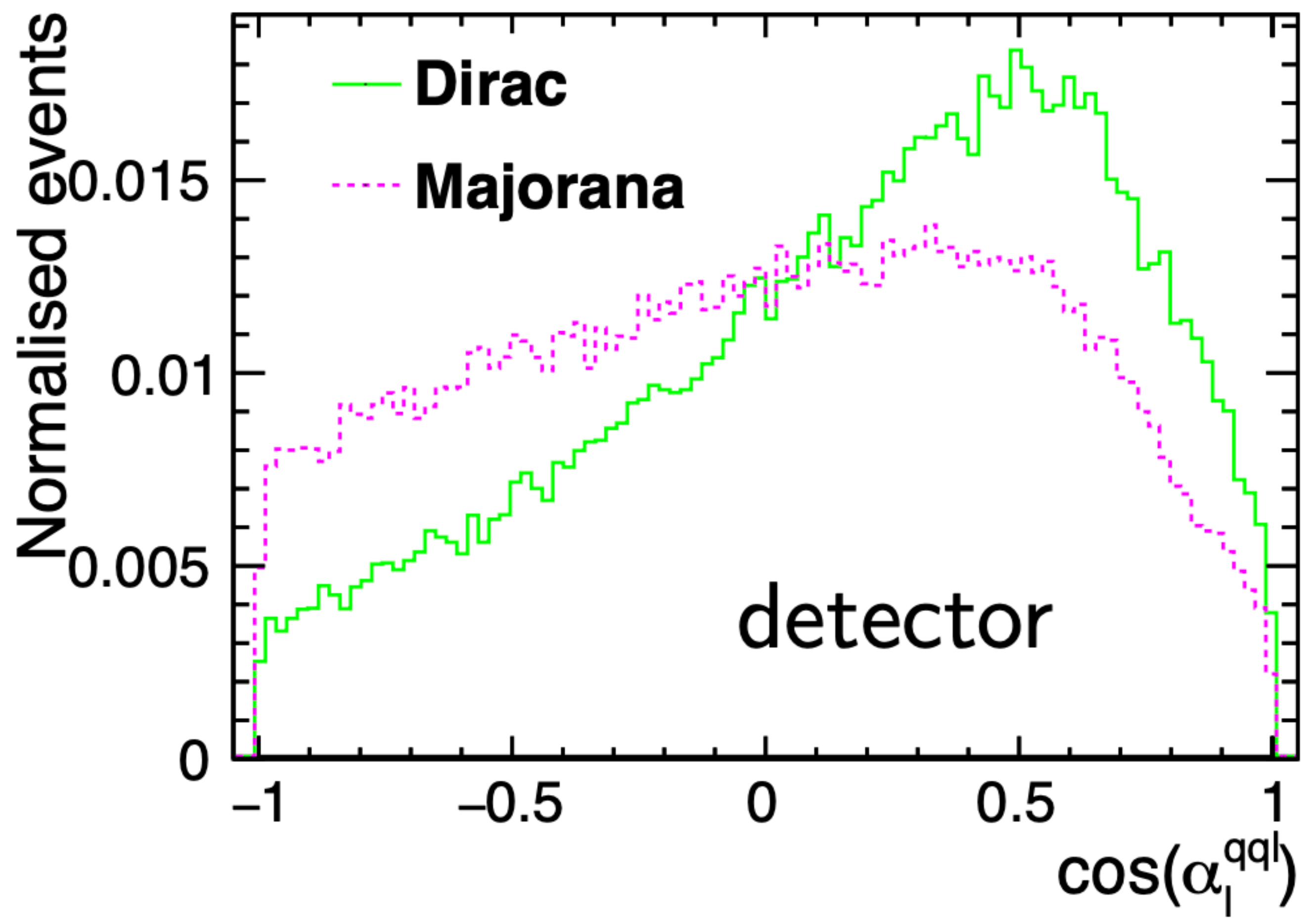

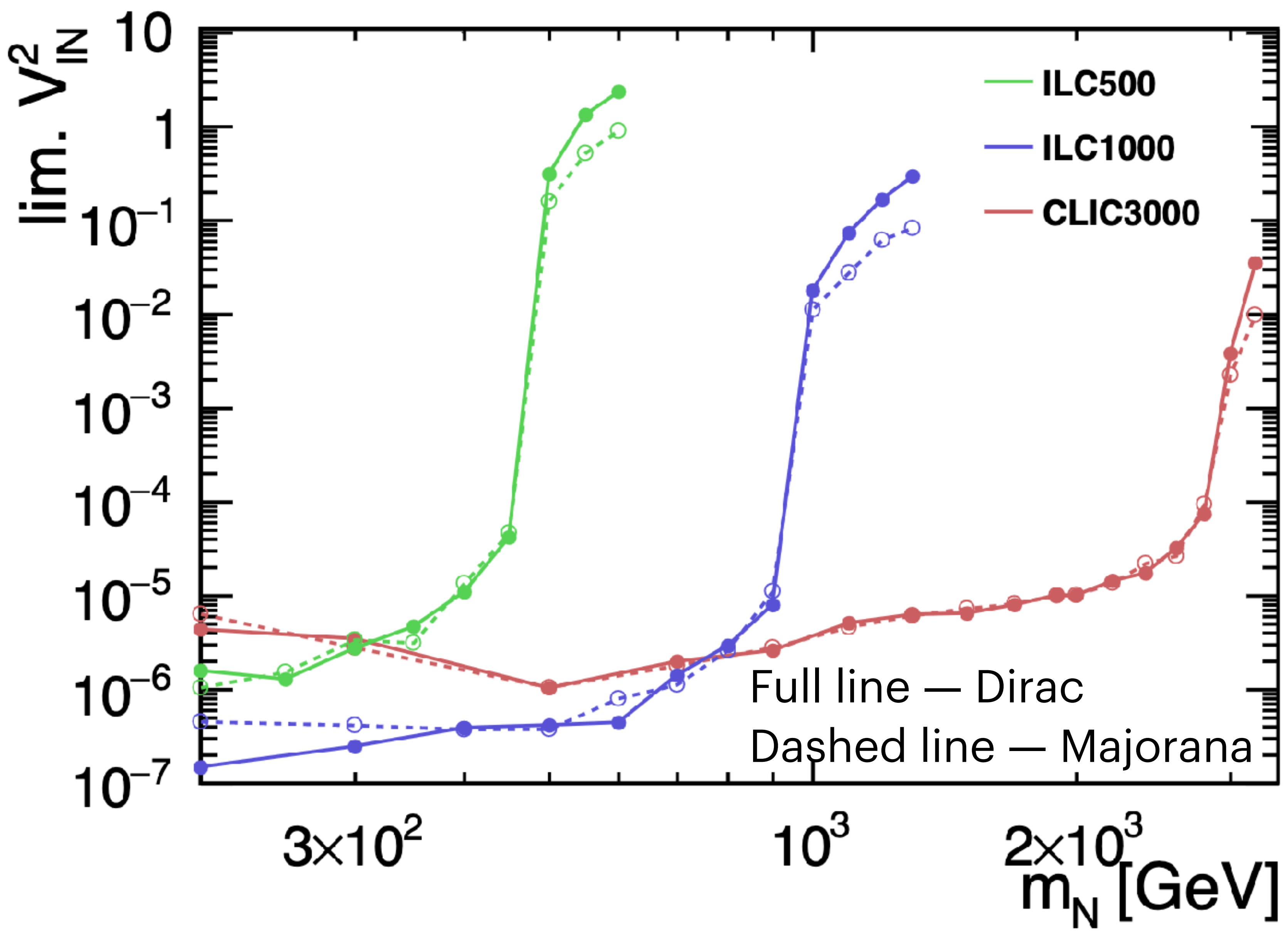

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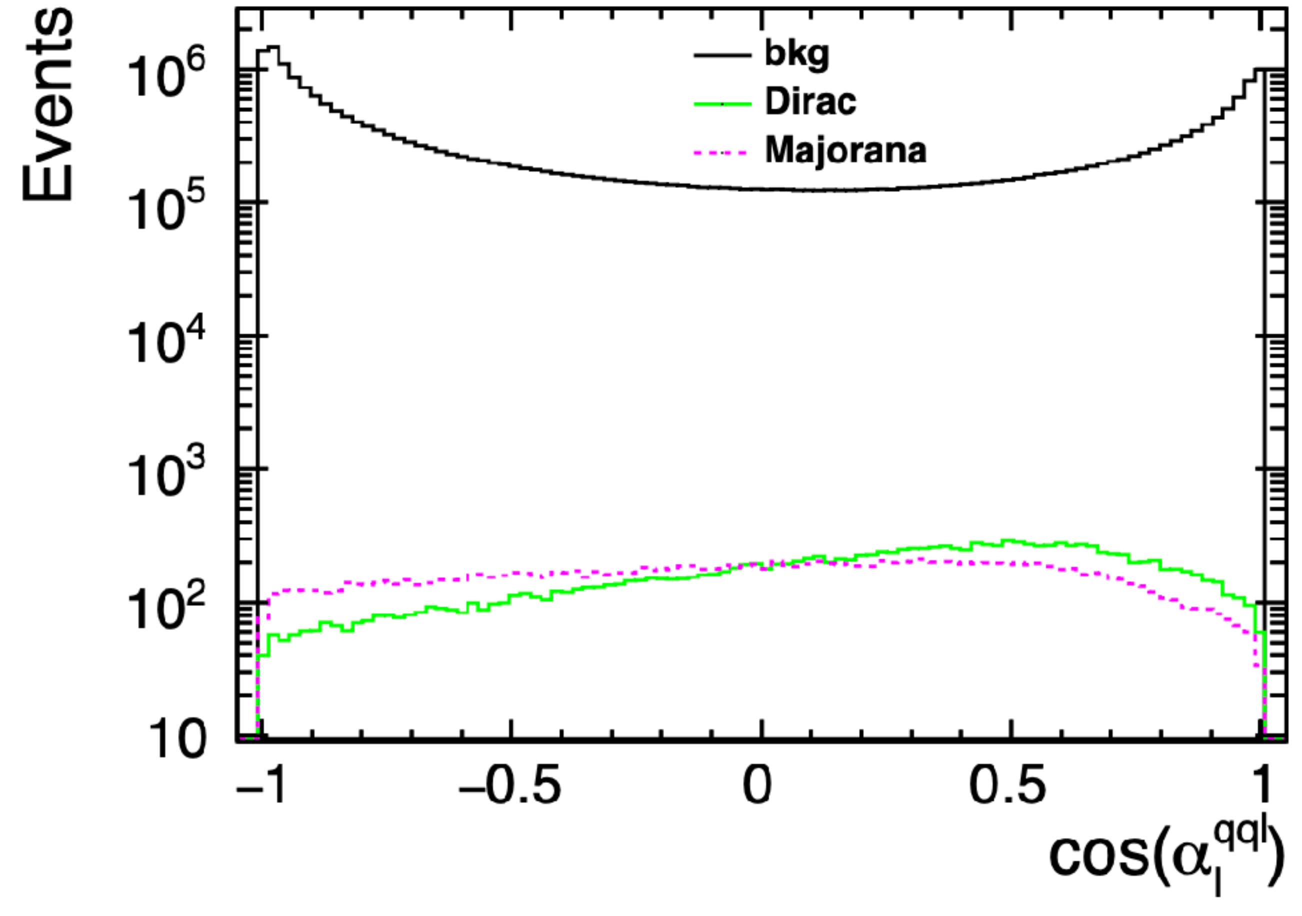

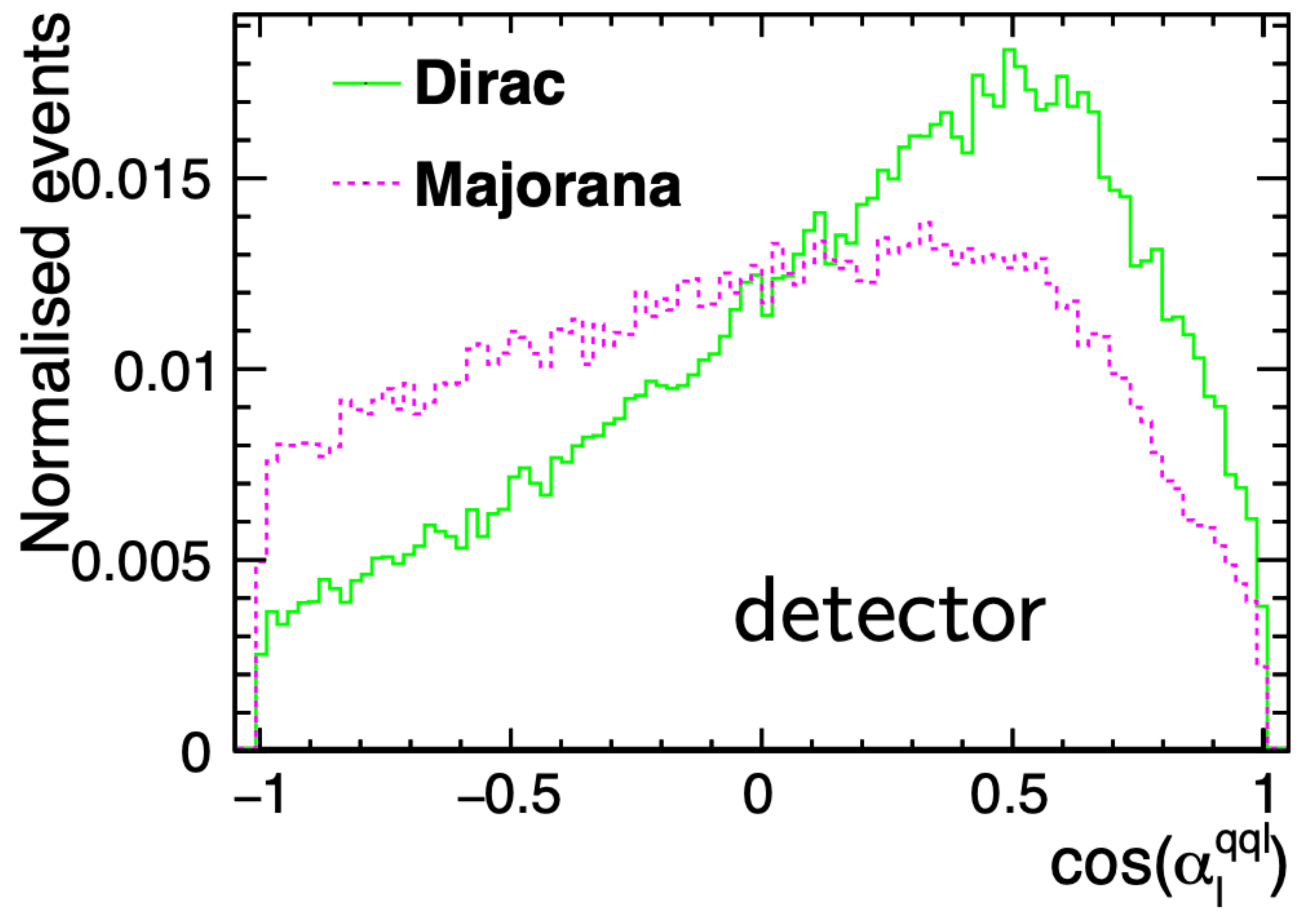

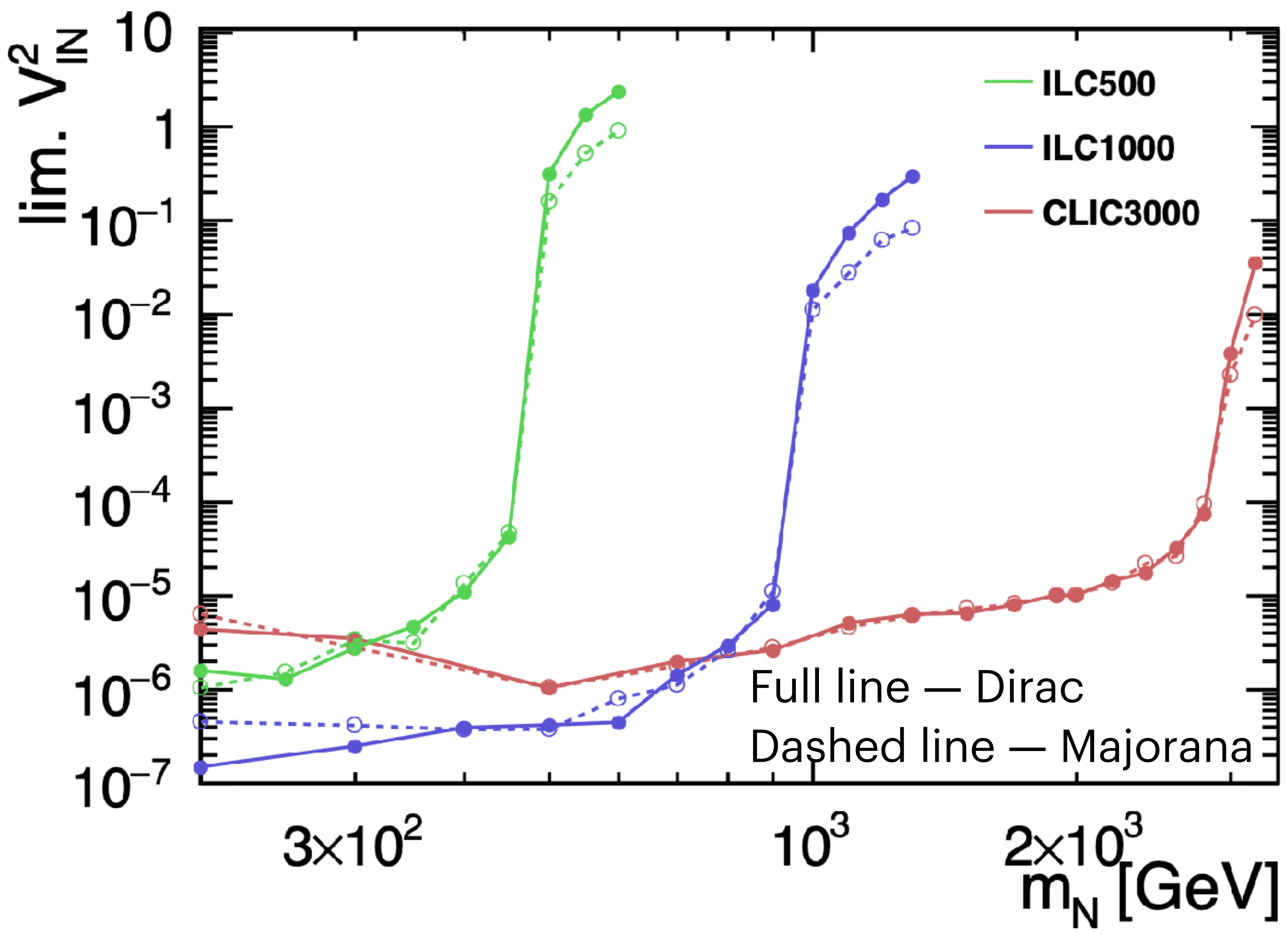

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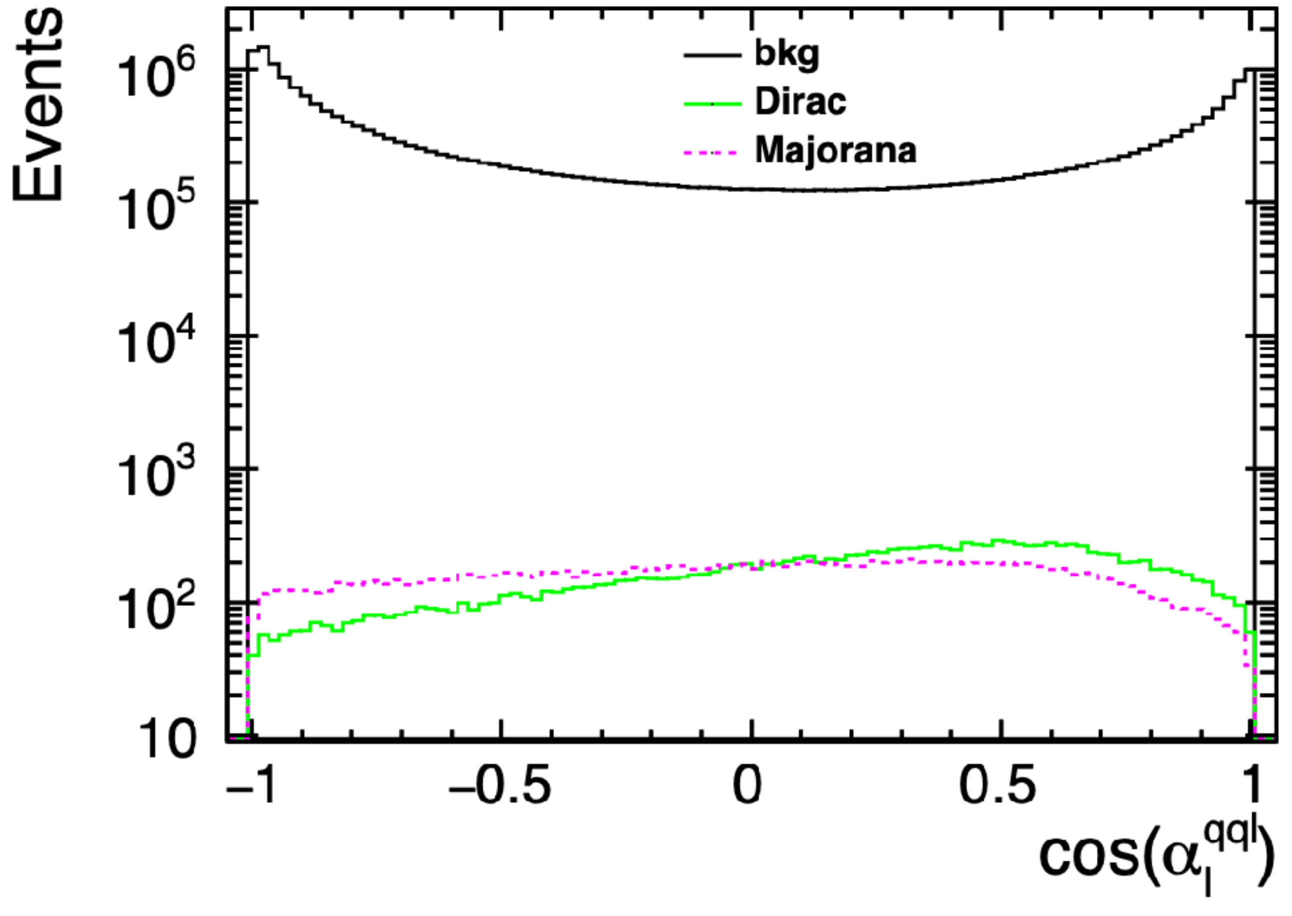
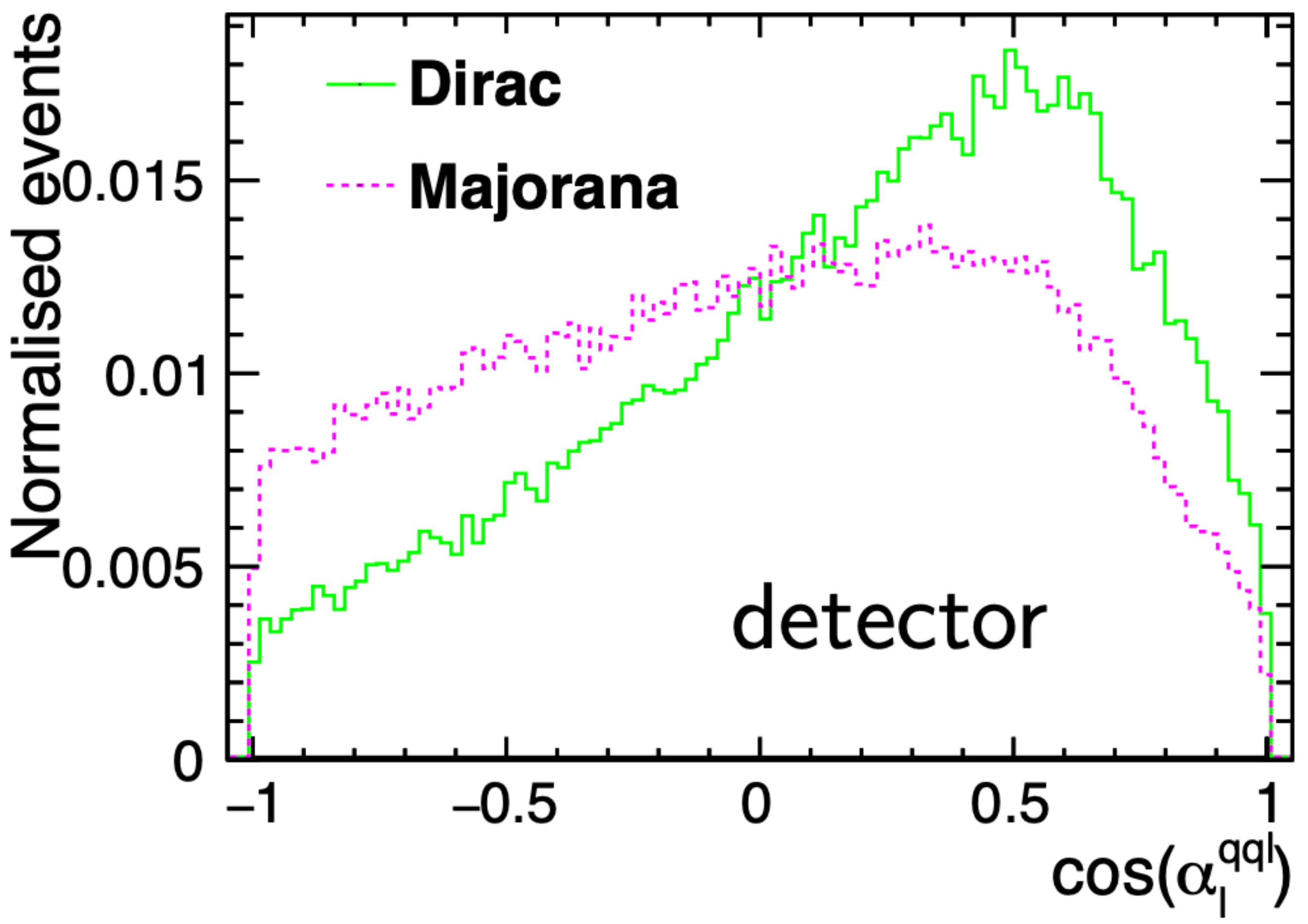
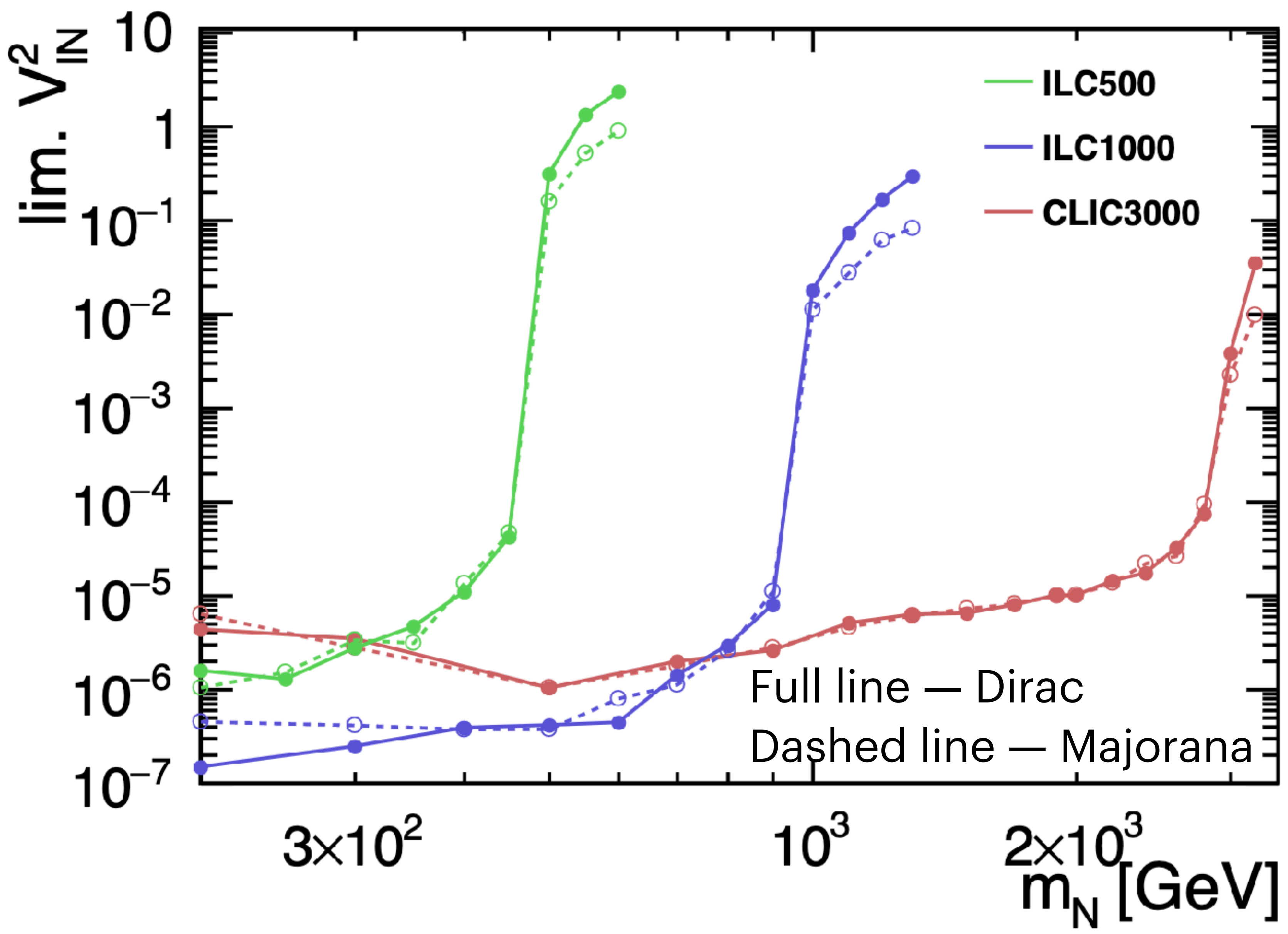
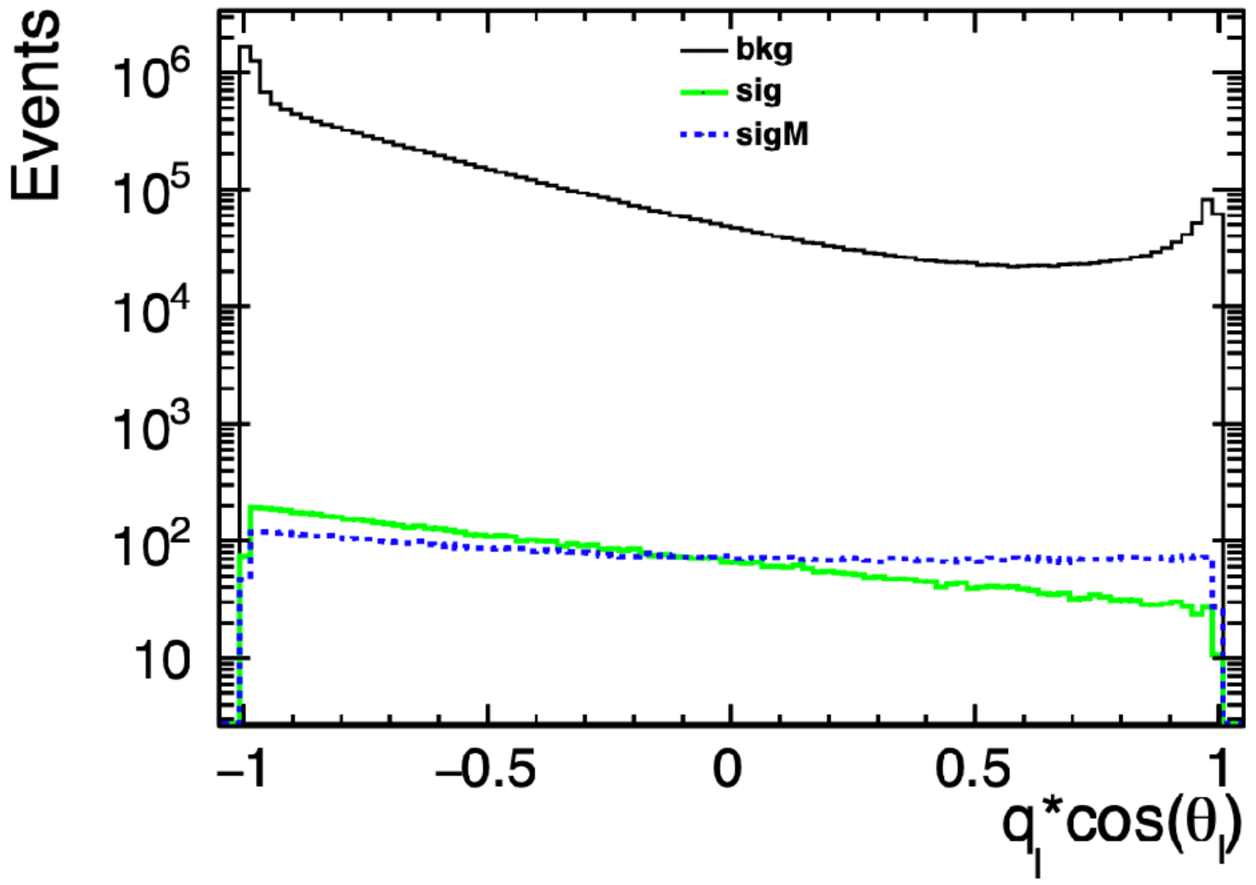


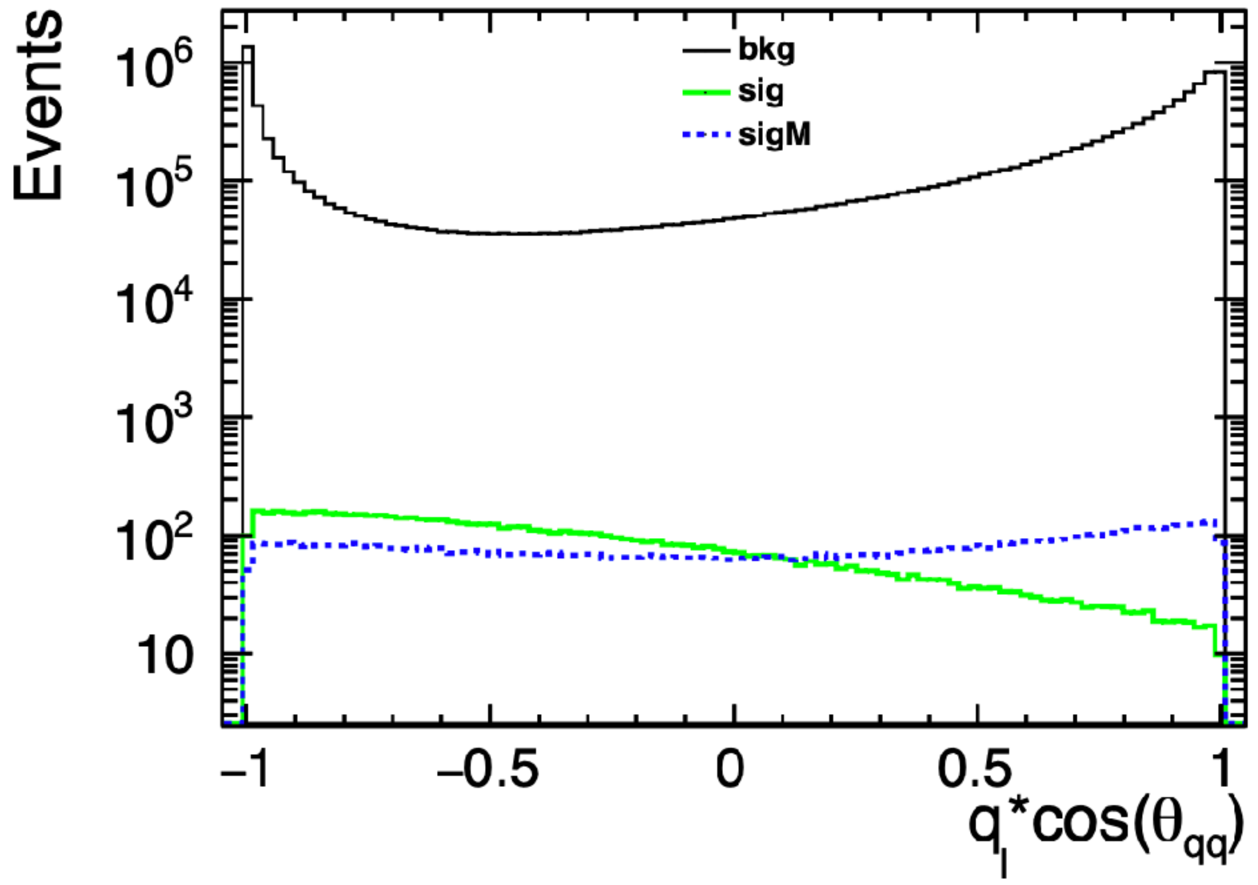




- More sophisticated variable: lepton and dijet angles relative to beam weighted by the lepton charge q_ℓ

ILC 250 GeV, $m_N = 150$ GeV

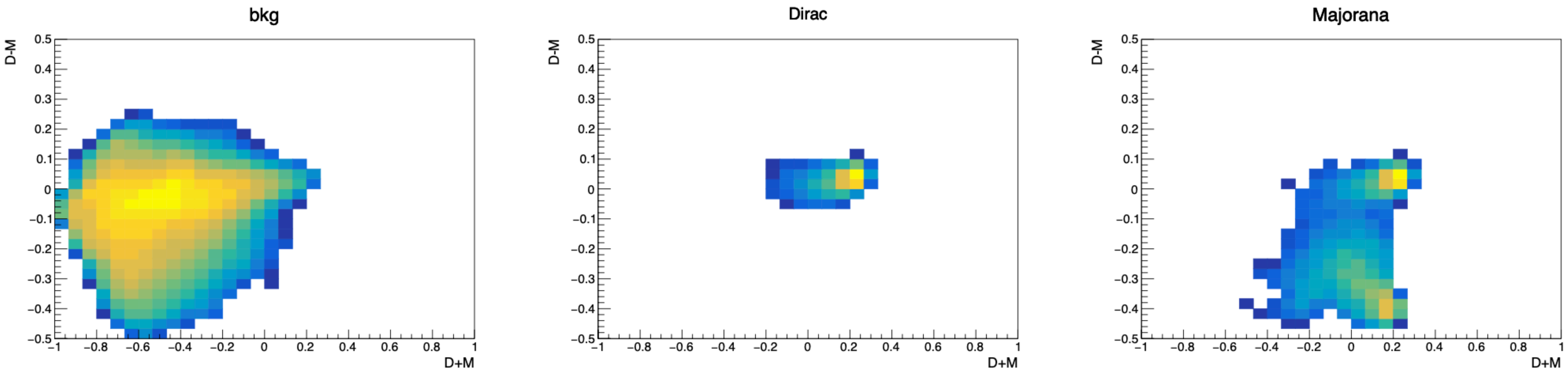




BDT framework for model discrimination

- 2 independent BDT trainins: Dirac vs. (α_{BDT} · Majorana + Bkgd.) & Majorana vs. (α_{BDT} · Dirac + Bkgd.)
- χ^2-like statistics: $T' = \sum_{bins} \frac{[(B+D)-(B+M)]^2}{\frac{1}{2}[(B+D)+(B+M)]} + \#\,\text{DOF} = \sum_{bins} \frac{(D-M)^2}{B+\frac{D+M}{2}} + \#\,\text{DOF}$ $\quad T' \longrightarrow T'(\alpha_{lim}) = \sum_{bins} \frac{\alpha_{lim}^2 (D-M)^2}{B + \alpha_{lim}\cdot\frac{D+M}{2}}$
- Statistical test: $T \geq \chi^2_{crit}(\text{DOF}) \implies$ signal hypotheses distinguishable
- 2D histograms: $\text{BDT}_D + \text{BDT}_M$, $\text{BDT}_D - \text{BDT}_M$
- Technical procedure:

1. Train BDT for different values α_{BDT}
2. For each α_{BDT}: calculate 95% CL limit
   α_{lim} such that $T(\alpha_{lim}) = \chi^2_{crit}(\text{DOF})$
3. Select the best limit: $\alpha_{min} = \min\left\{\alpha_{lim}\right\}$
4. Set final limit as $V^{\text{lim}}_{\ell N} = \alpha_{min} \cdot V^{ref}_{\ell N}$



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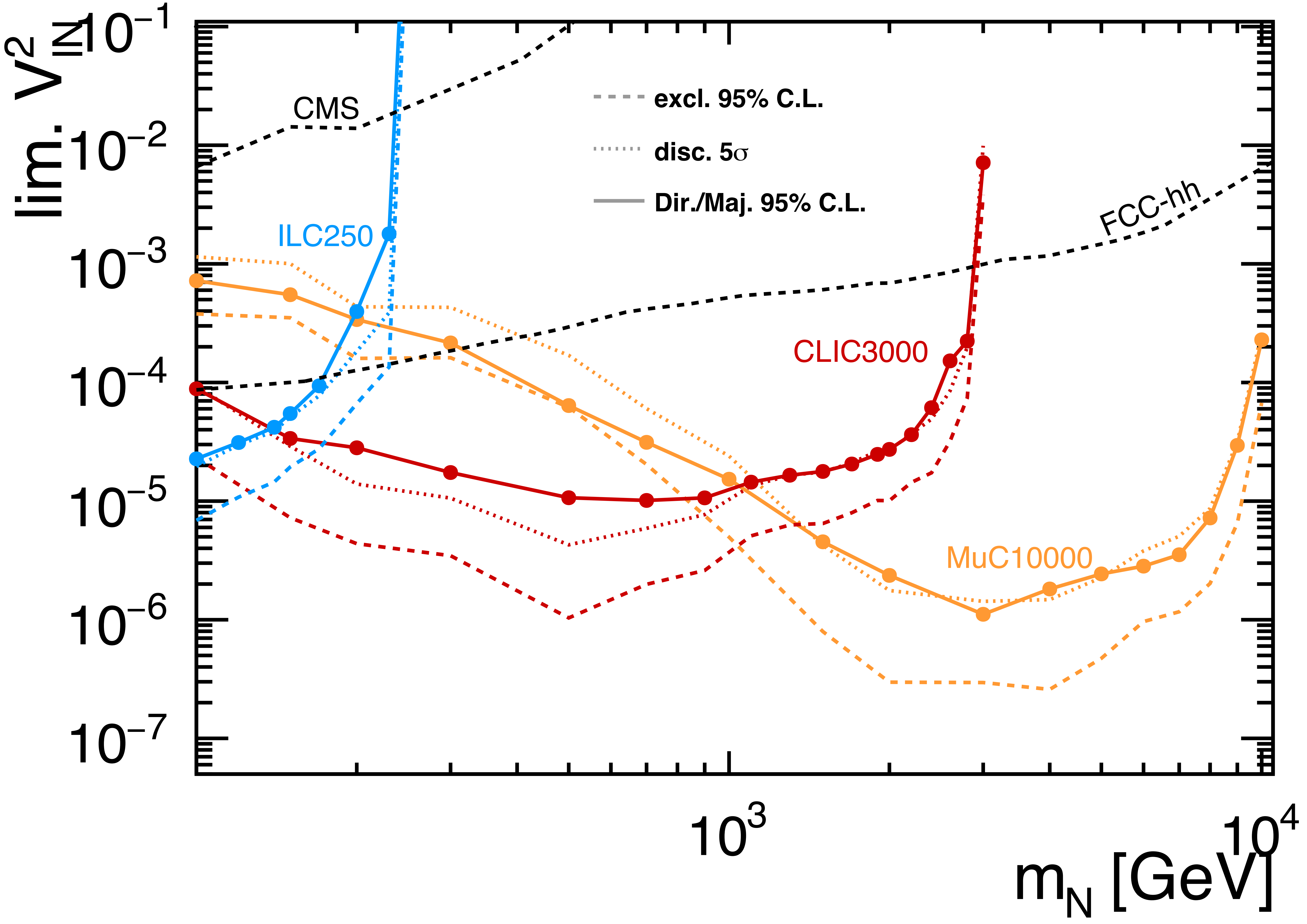

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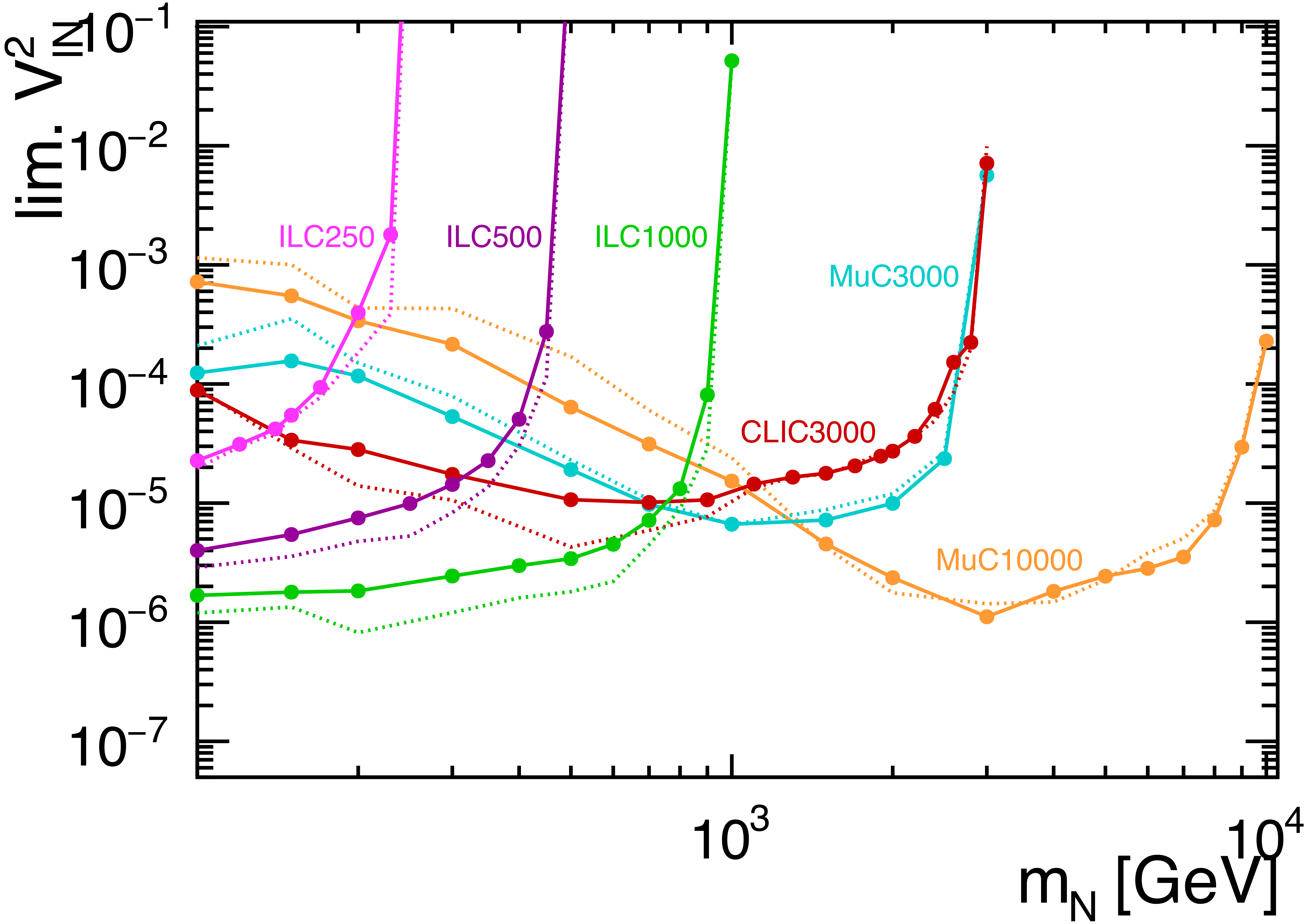
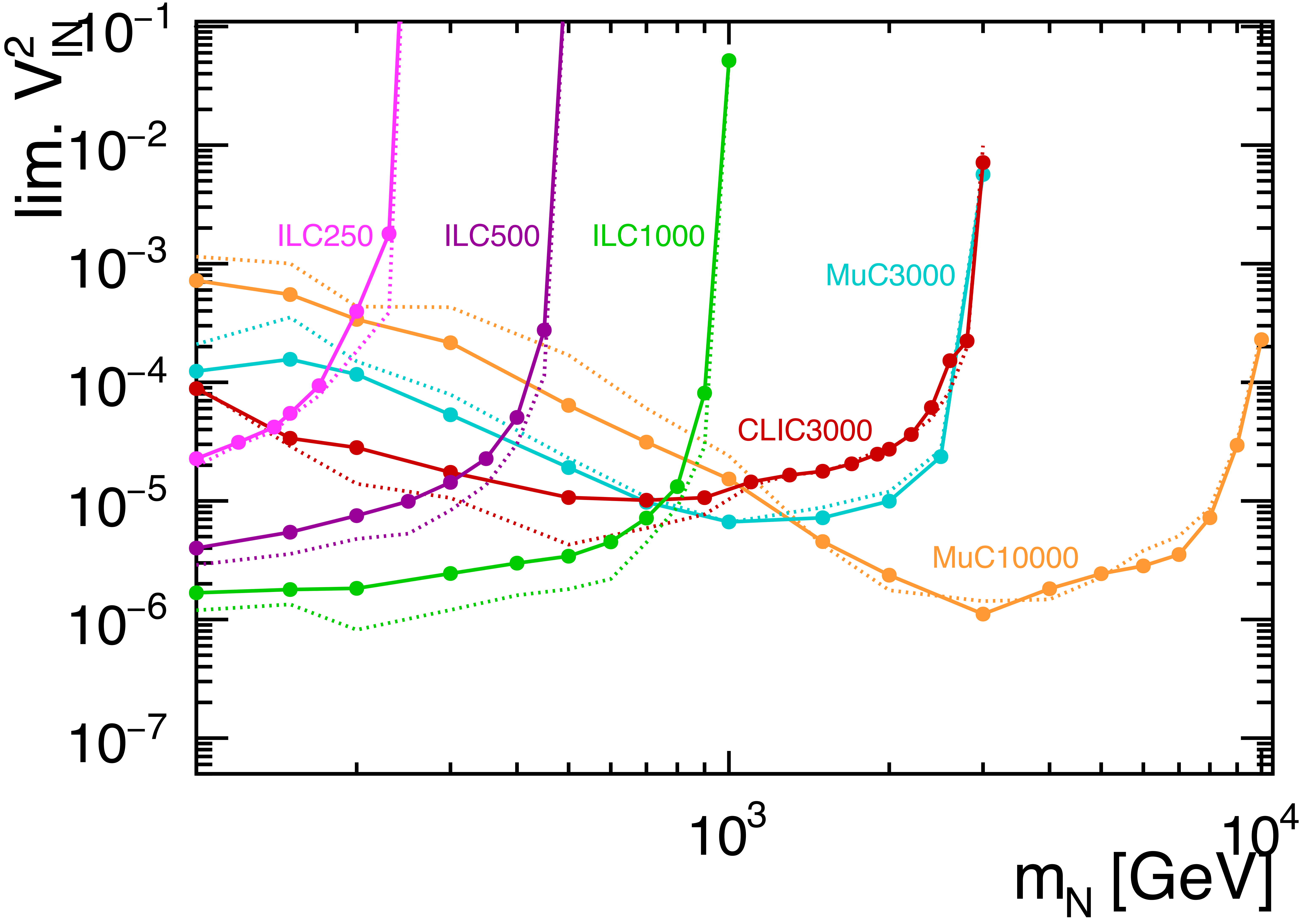


Almost immediately with a discovery a Majorana vs. Dirac discrimnation possible!

Dirac vs. Majorana discrimination



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More difficult, but possible for off-shell case!

Flavor complementarity

- Dominant *t*-channel production (*W* exchange):
- On-shell production
- Off-shell more difficult: need to scan each parameter point

$$\sigma \propto \frac{|V_{\ell_{in}N}|^2 \cdot |V_{\ell_{out}N}|^2}{|V_{eN}|^2 + |V_{\mu N}|^2}$$

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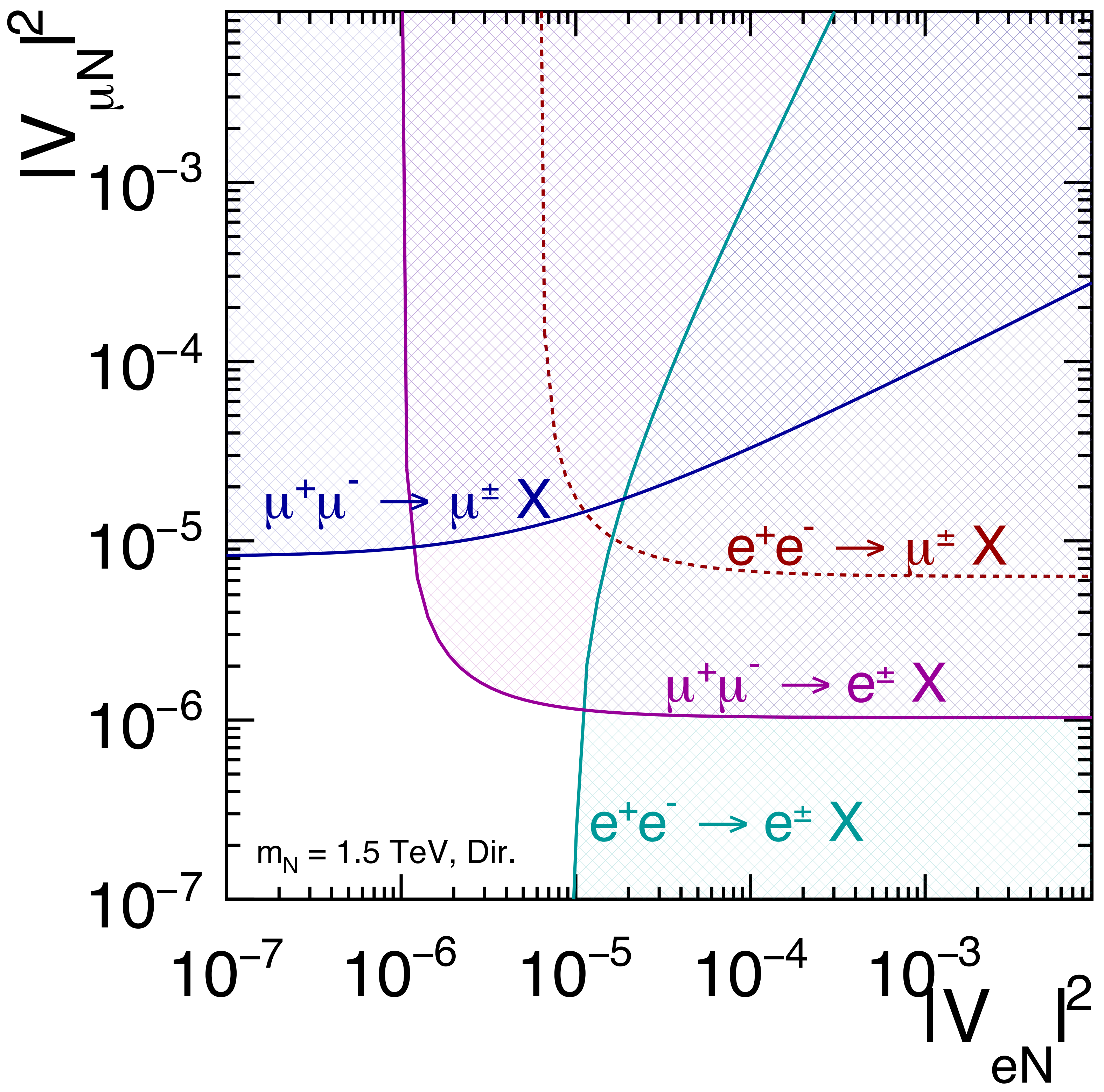

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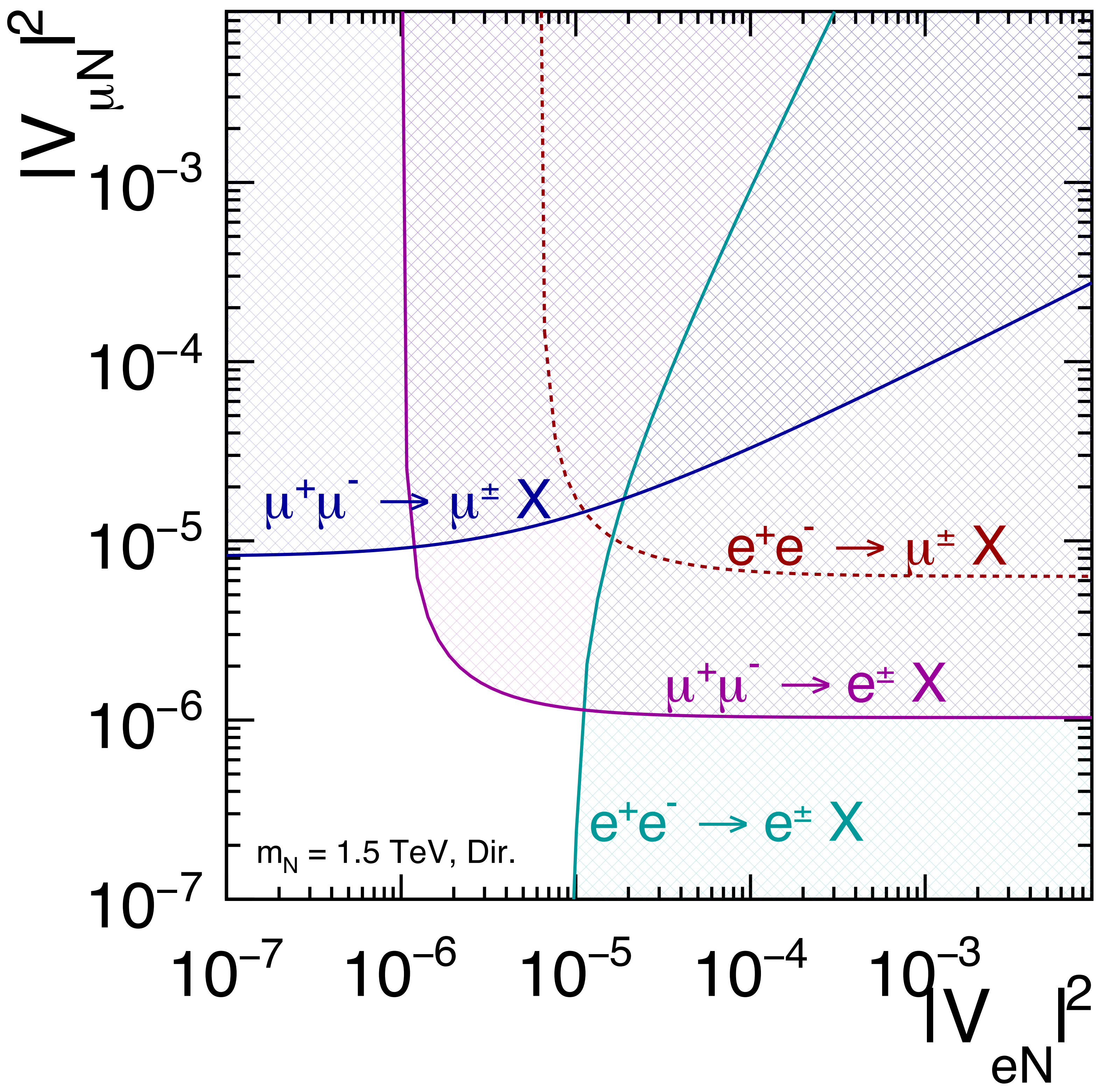

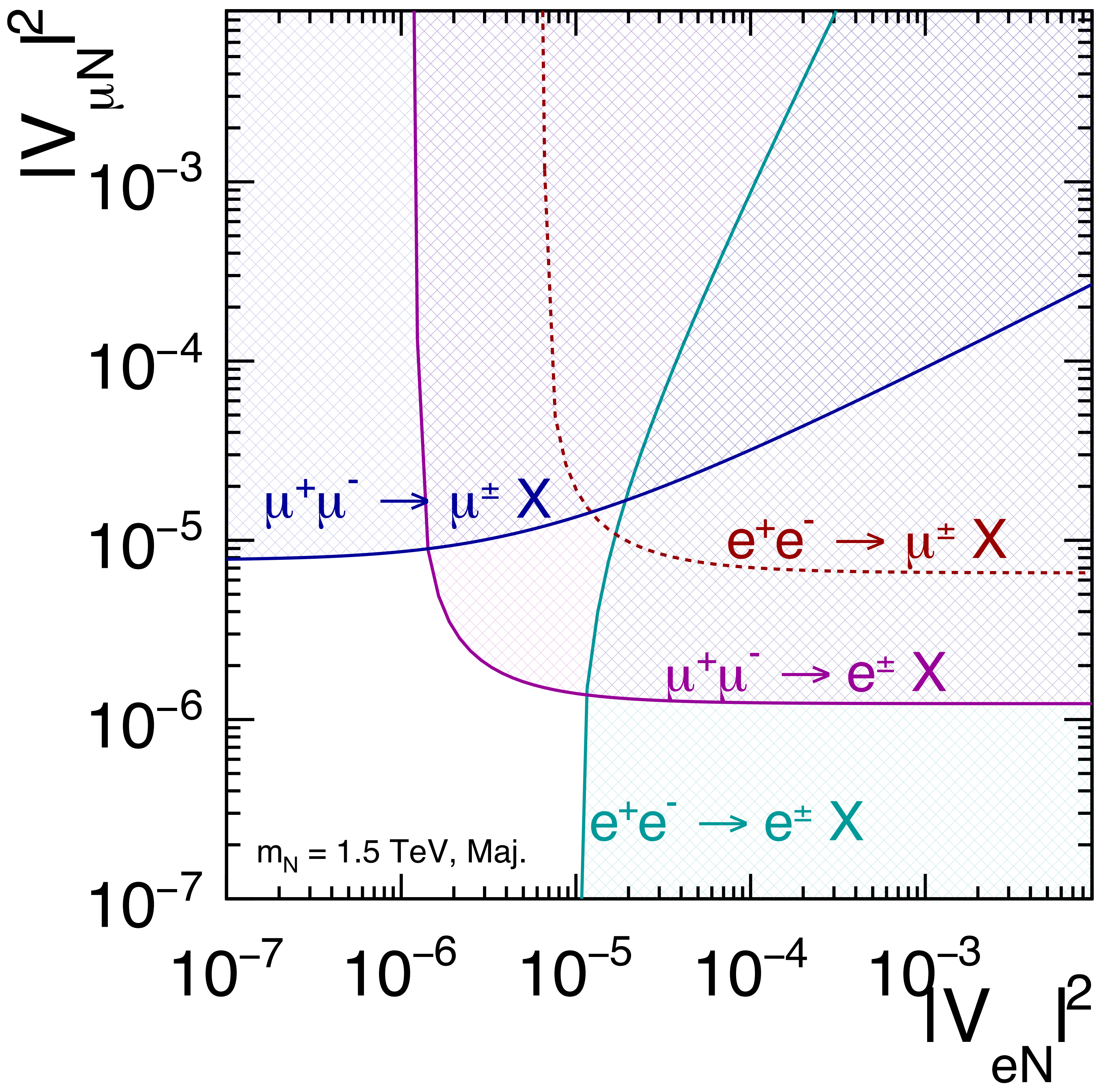

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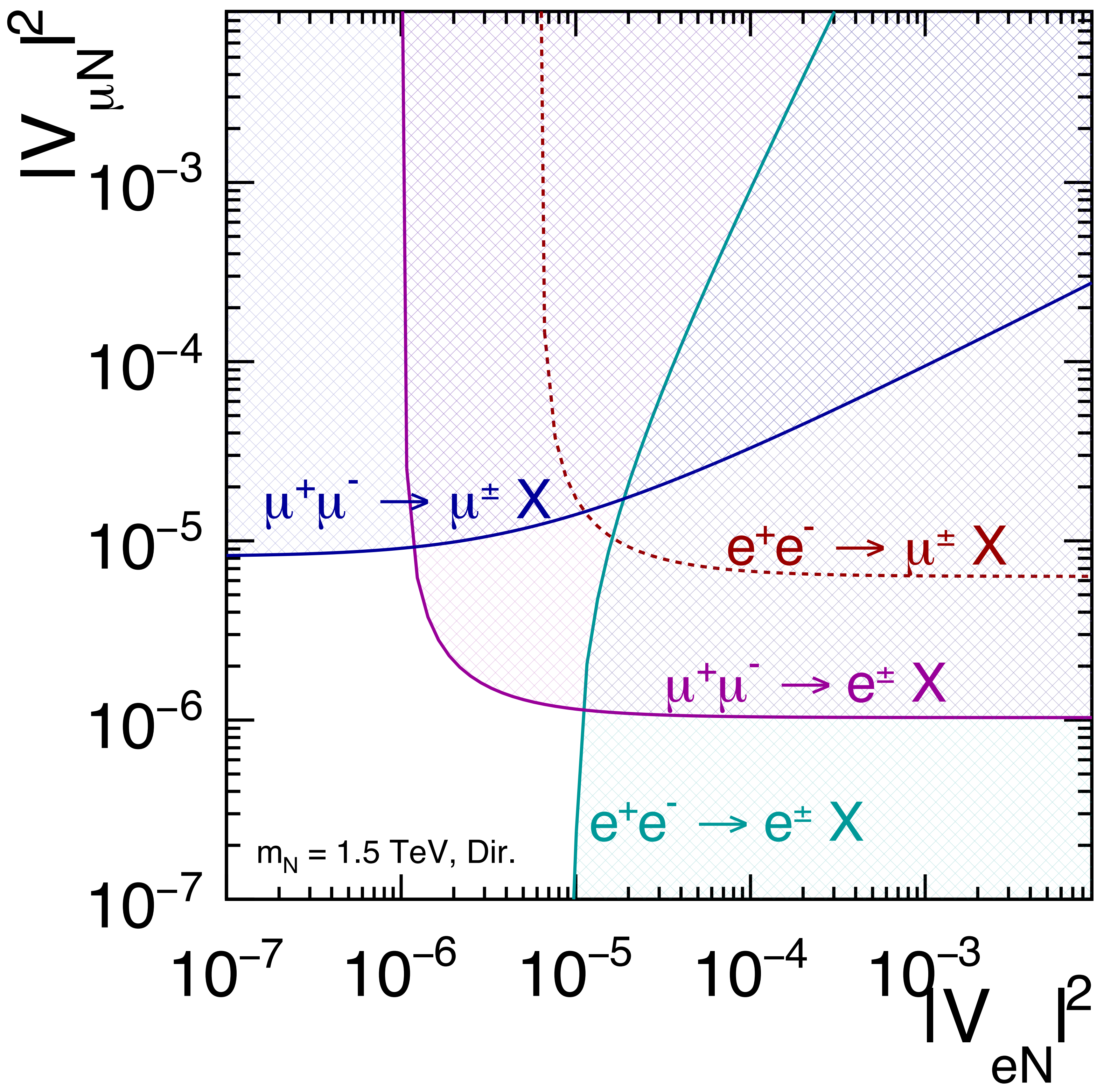
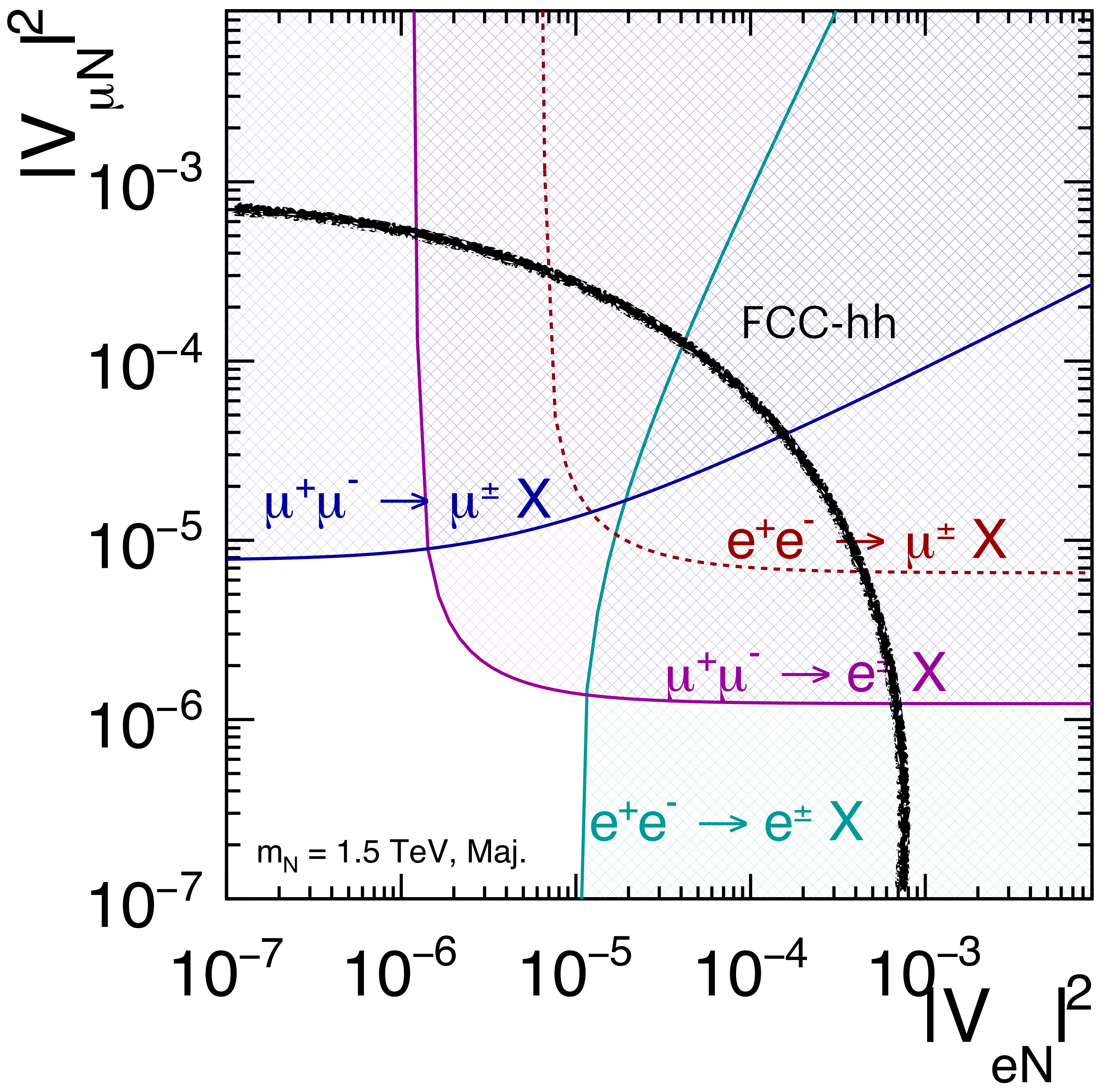
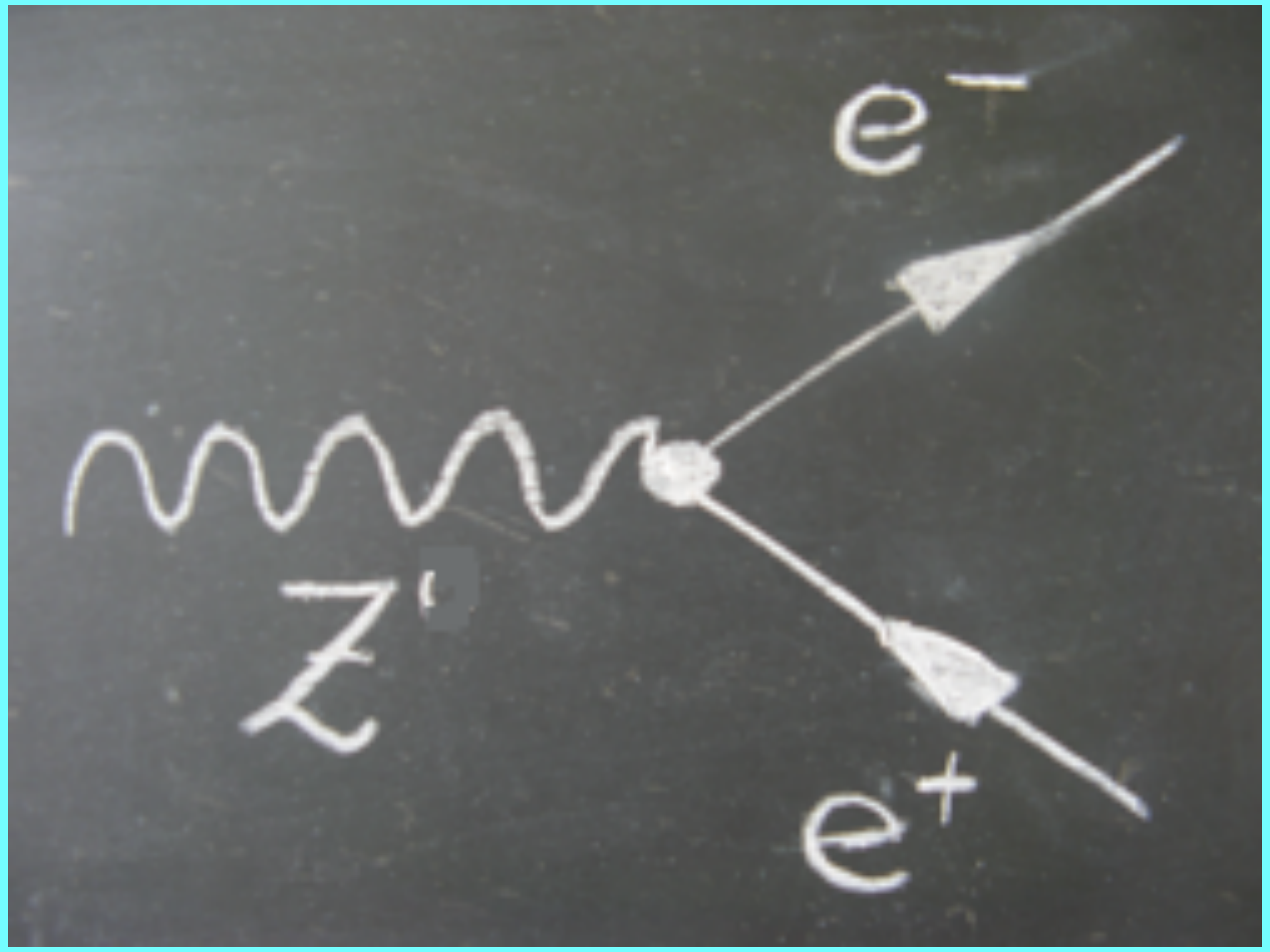
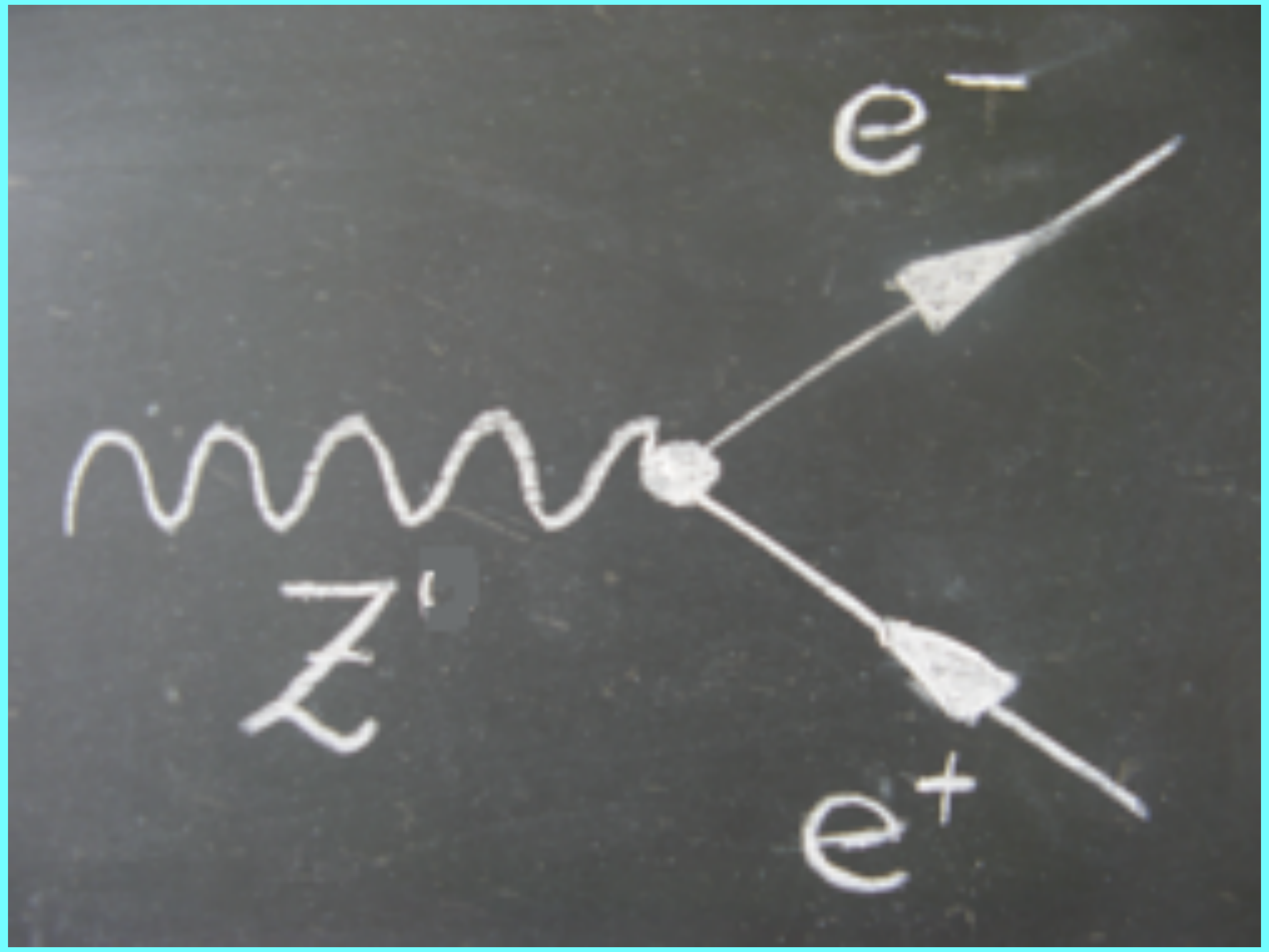




Search for Heavy Neutral Currents





Rationale and search processes

- Many different motivations for Z': GUTs, gauge composite models, gauged flavor symmetries
- (Remember: global symmetries are difficult in string theory)
- Most basic processes: $\mu^+\mu^- \to f\bar{f} \qquad f = e, \mu, \tau, j, c, b, (t)$
- Very simple event topologies
- Discovery & discrimination of models, many observables:

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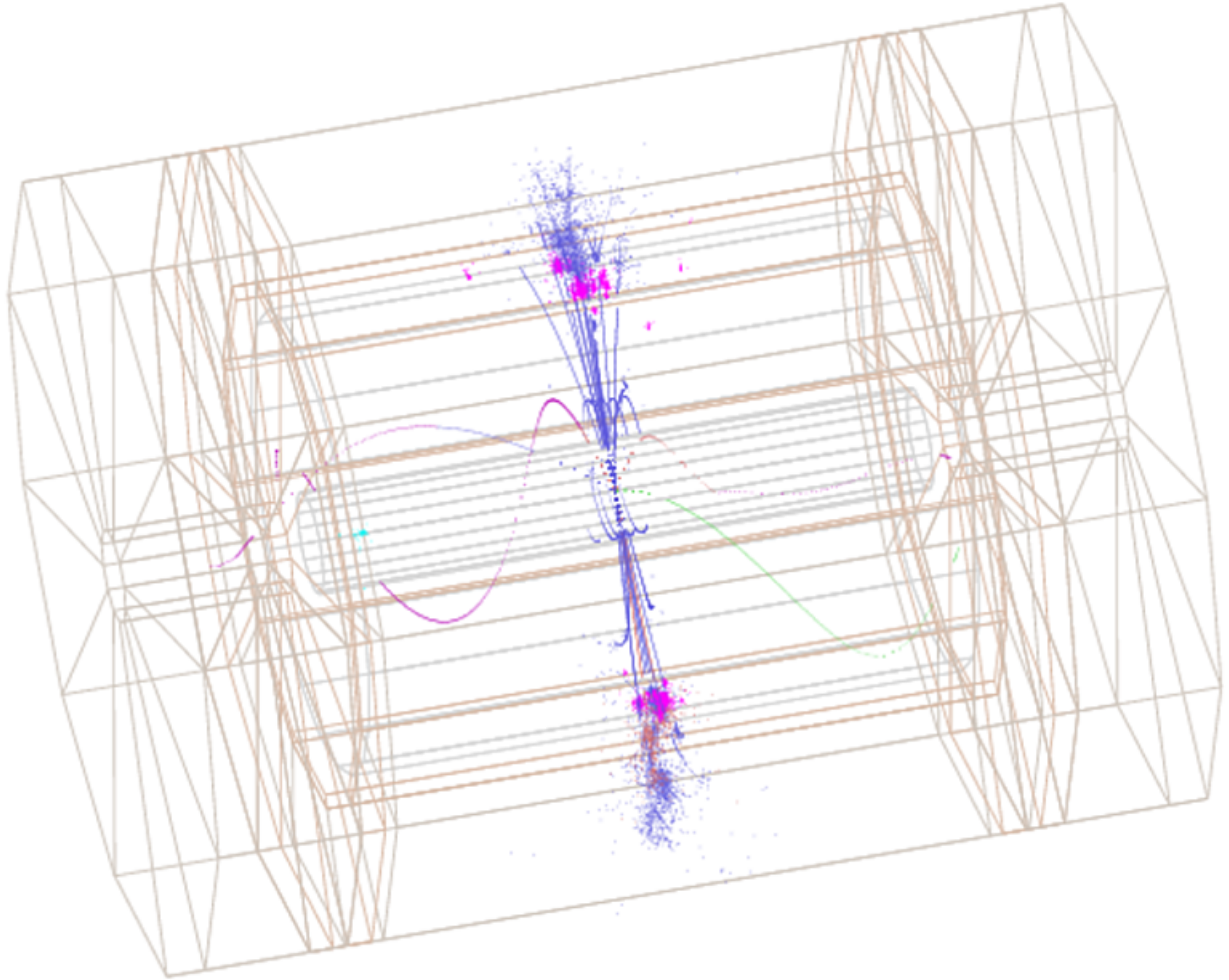

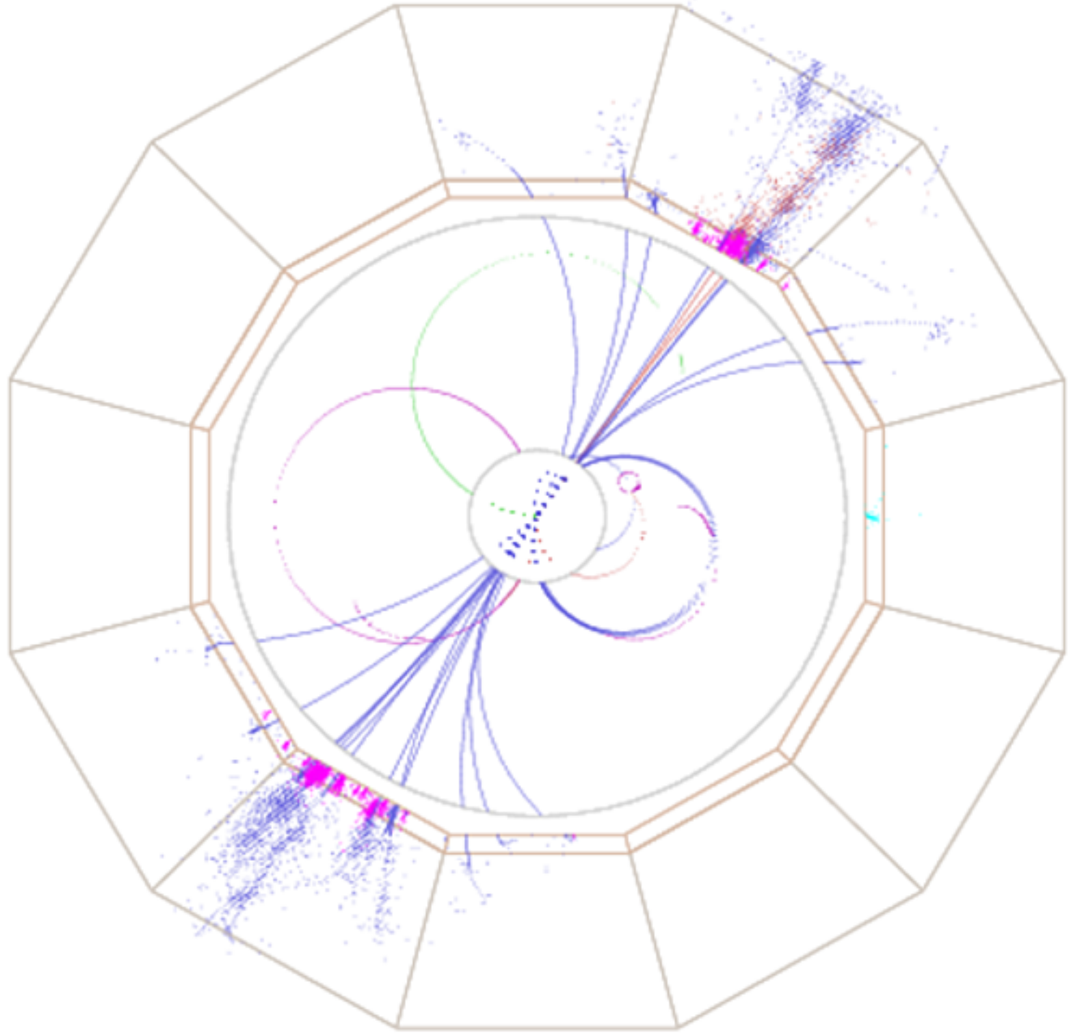

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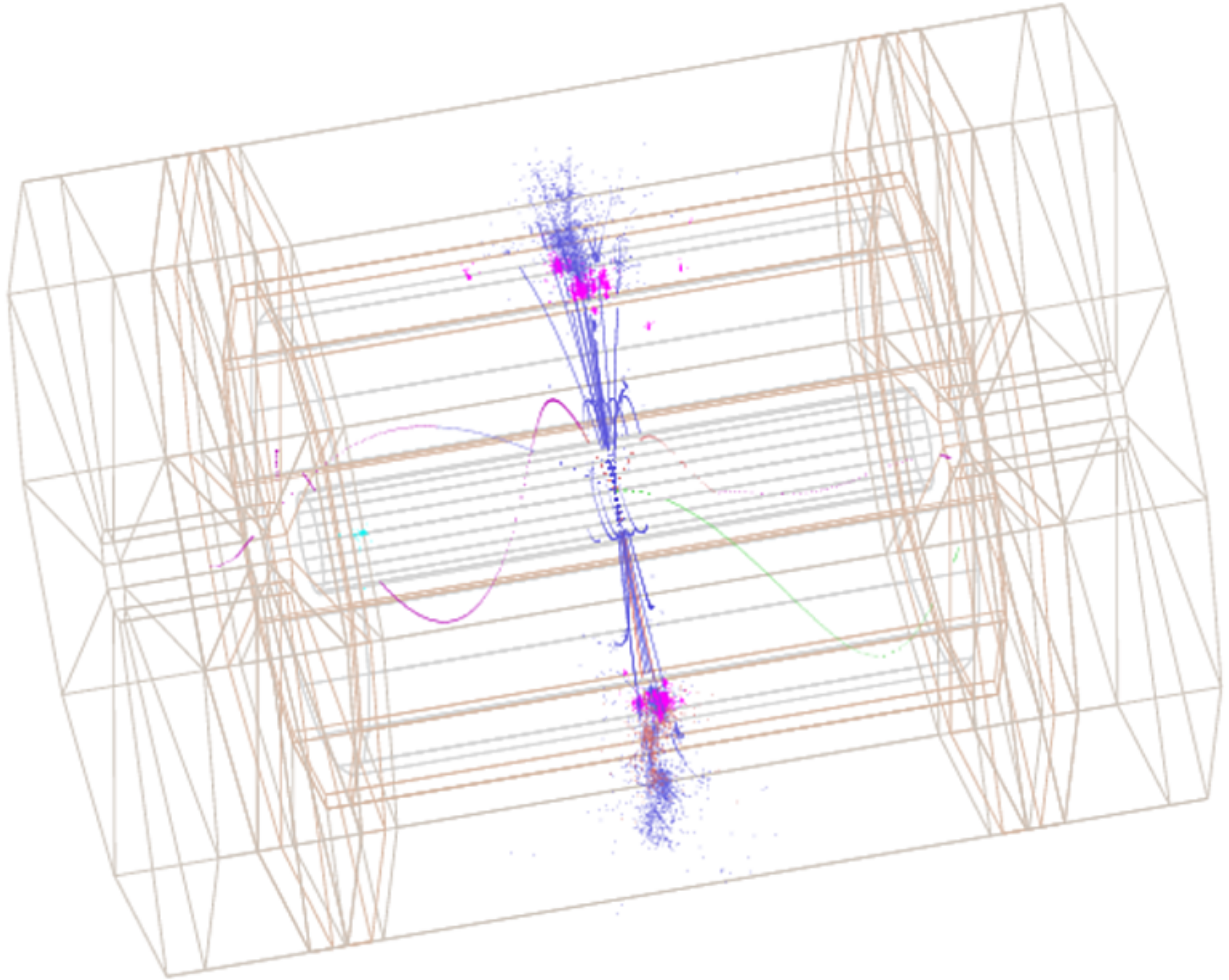

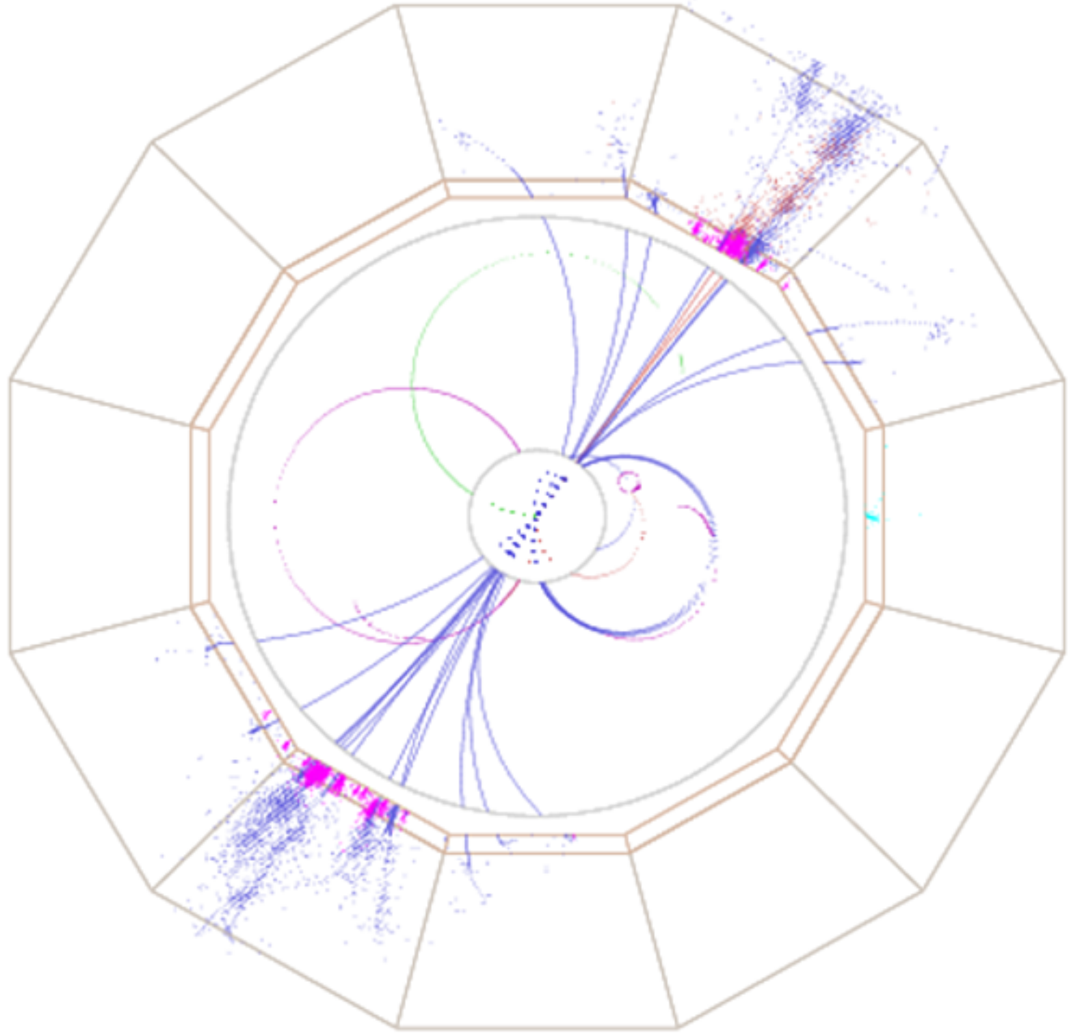

- ☑ Forward-backward asymmetries: $A^f_{FB}(\mu^+\mu^- \to f\bar{f})$
- ☑ Tau polarization asymmetries: $A^\tau_{pol.}(\mu^+\mu^- \to \tau^+\tau^-)$
- ☑ Binned angular distributions
- ☑ Left-right asymmetries: $A^f_{LR}(\mu^+\mu^- \to f\bar{f})$ (needs beam polarization)
- ☑ Spin-sensitive processes $(\mu^+\mu^- \to W^+W^-, t\bar{t})$

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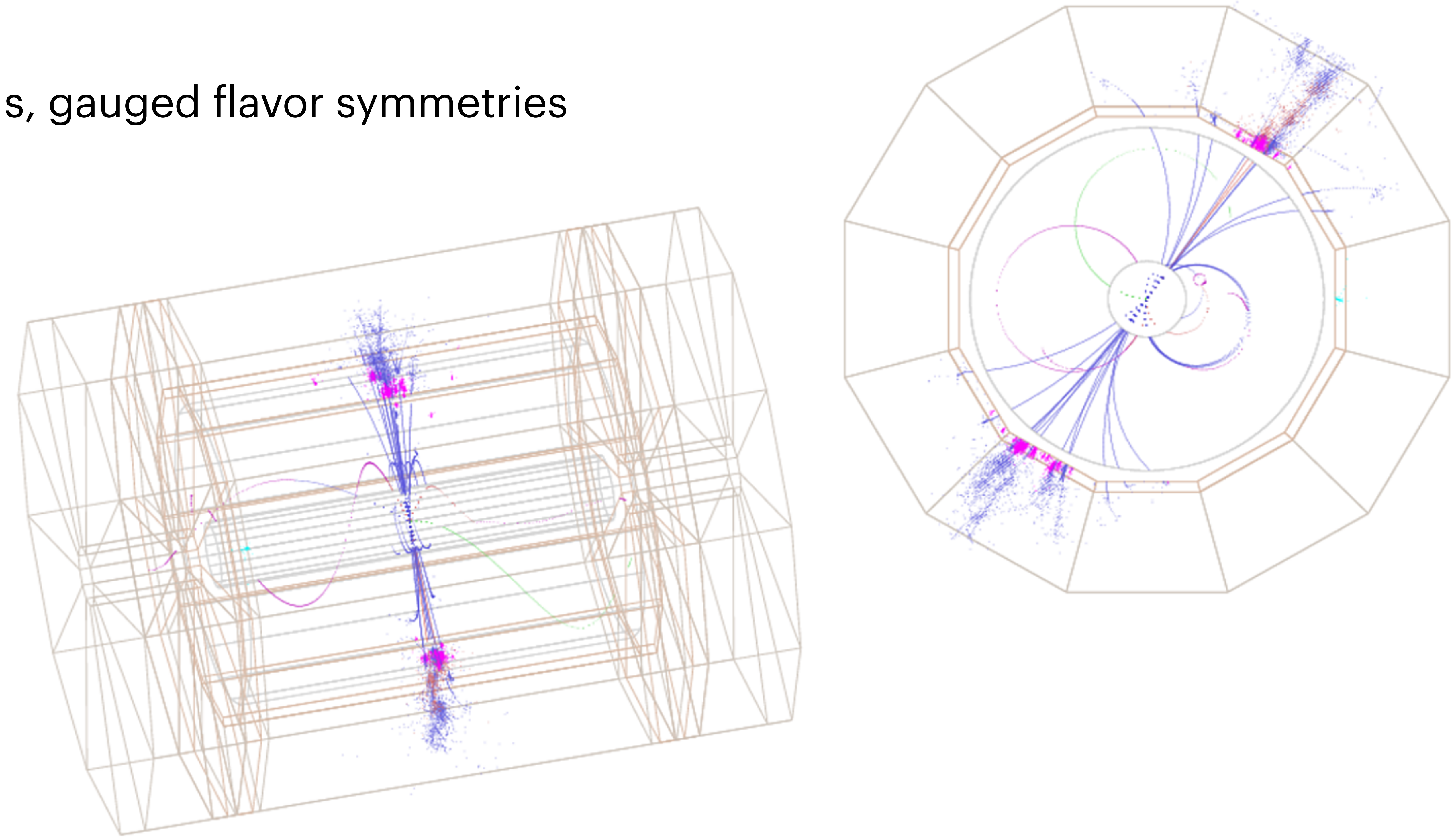

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Investigated Z' models:
(1) Sequential SM (SSM)
(2) E_6, $SU(2)_L \otimes SU(2)_R$ (LR)
(3) Littlest Higgs (LH), Simplest Little Higgs (SLH)
(4) $U(1)_X$ model
(5) many more

Resolving power for Z'

Normalization of couplings:

	$g_{Z'}$
SSM	$e/(s_W c_W)$
E_6, LR	e/c_W
ALR	$e/(s_W\, c_W \sqrt{1-2s_W^2})$
LH	e/s_W
USLH, AFSLH	$e/(c_W \sqrt{3-4s_W^2})$
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- Model parameters to be determined: vector and axial vector couplings *v, a*
- Observables: $\mathcal{O}_i \in \left\{ \sigma_{tot}, A_{FB}^f, A_{LR}^f \right\}$
- Resolving power: $\chi^2_{model} = \sum_{i=1}^{n_{ob}} \left(\frac{\mathcal{O}_i^{model} - \mathcal{O}_i(v,a)}{\Delta \mathcal{O}_i(v,a)} \right)^2 < 5.99$ for 95% CL
- Statistical uncertainties: $\frac{\Delta\sigma_{tot}}{\sigma_{tot}} = \frac{1}{\sqrt{N}}, \qquad \Delta A_{FB} = \sqrt{\frac{1-A_{FB}^2}{N}}, \qquad \Delta A_{LR} = \sqrt{\frac{1-(PA_{LR})^2}{NP^2}}$
- Collider luminosity: $\mathcal{L}_{int}(E_{CM}) = 10\ \text{ab}^{-1} \cdot E_{CM}/10\,\text{TeV}$

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f	ν	e	u	d
		SSM		
$2v'_f$	$\frac{1}{2}$	$2s_W^2 - \frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}s_W^2$	$\frac{2}{3}s_W^2 - \frac{1}{2}$
$2a'_f$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$
		E$_6$		
$2v'_f$	$3A+B$	$4A$	0	$-4A$
$2a'_f$	$3A+B$	$2(A+B)$	$2(B-A)$	$2(A+B)$
		LR		
$2v'_f$	$\frac{1}{2\alpha}$	$\frac{1}{\alpha} - \frac{\alpha}{2}$	$\frac{\alpha}{2} - \frac{1}{3\alpha}$	$-\frac{1}{3\alpha} - \frac{\alpha}{2}$
$2a'_f$	$\frac{1}{2\alpha}$	$\frac{\alpha}{2}$	$-\frac{\alpha}{2}$	$\frac{\alpha}{2}$

		ALR		
$2v'_f$	$s_W^2 - \frac{1}{2}$	$\frac{5}{2}s_W^2 - 1$	$\frac{1}{2} - \frac{4}{3}s_W^2$	$\frac{1}{6}s_W^2$
$2a'_f$	$s_W^2 - \frac{1}{2}$	$-\frac{1}{2}s_W^2$	$s_W^2 - \frac{1}{2}$	$-\frac{1}{2}s_W^2$
		LH		
$2v'_f$	$\frac{c}{4s}$	$-\frac{c}{4s}$	$\frac{c}{4s}$	$-\frac{c}{4s}$
$2a'_f$	$\frac{c}{4s}$	$-\frac{c}{4s}$	$\frac{c}{4s}$	$-\frac{c}{4s}$
		USLH		
$2v'_f$	$\frac{1}{2} - s_W^2$	$\frac{1}{2} - 2s_W^2$	$\frac{1}{2} + \frac{1}{3}s_W^2$	$\frac{1}{2} - \frac{2}{3}s_W^2$
$2a'_f$	$\frac{1}{2} - s_W^2$	$\frac{1}{2}$	$\frac{1}{2} - s_W^2$	$\frac{1}{2}$

		AFSLH		
$2v'_f$	$\frac{1}{2} - s_W^2$	$\frac{1}{2} - 2s_W^2$	$-\frac{1}{2} + \frac{4}{3}s_W^2$	$\frac{1}{3}s_W^2 - \frac{1}{2}$
$2a'_f$	$\frac{1}{2} - s_W^2$	$\frac{1}{2}$	$-\frac{1}{2}$	$s_W^2 - \frac{1}{2}$
		U(1)$_X$		
$2v'_f$	$-x_H - x_\Phi$	$-3x_H - x_\Phi$	$\frac{5}{3}x_H + \frac{1}{3}x_\Phi$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
$2a'_f$	$-x_H$	x_H	$-x_H$	x_H

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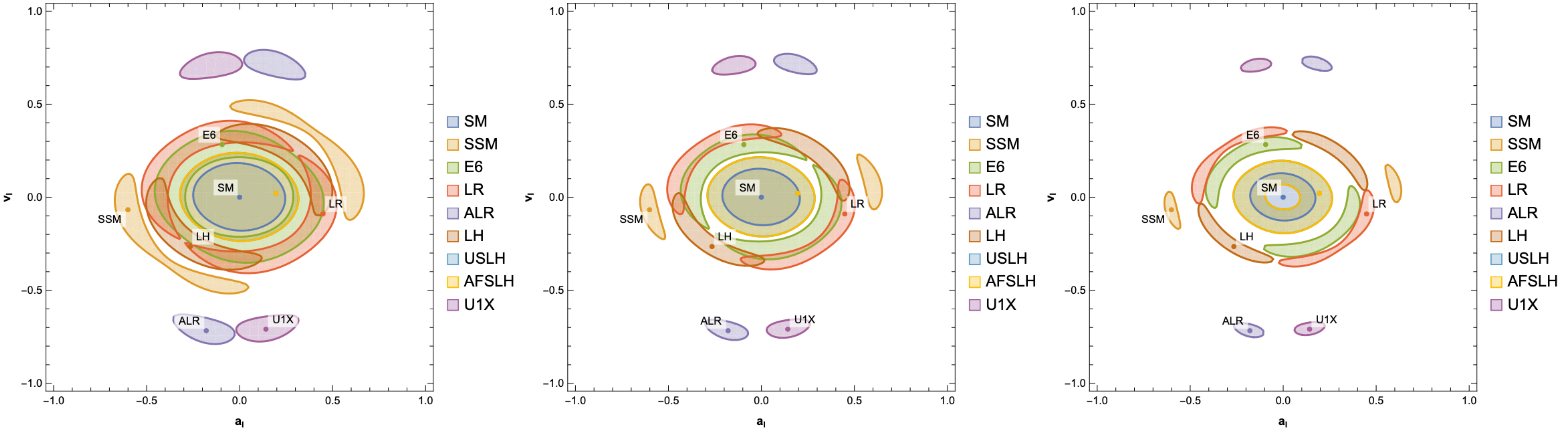
Preliminary Results



(a) $L_{\text{int}} = 5\,\text{ab}^{-1}$ (b) $L_{\text{int}} = 10\,\text{ab}^{-1}$ (c) $L_{\text{int}} = 20\,\text{ab}^{-1}$

$E_{CM} = 10$ TeV, $P = 1$, $M_{Z'} = 30$ TeV

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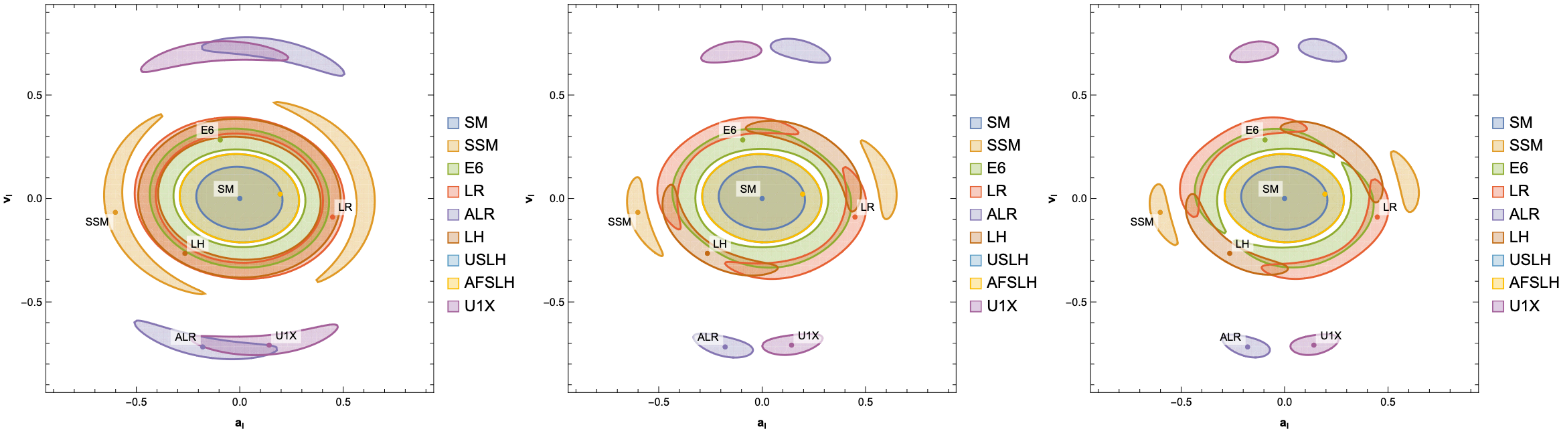
Preliminary Results



(a) $P = 0.3$ (b) $P = 0.8$ (c) $P = 1$

$E_{CM} = 10\,\text{TeV}, \quad \mathscr{L} = 10\,\text{ab}^{-1}, \quad M_{Z'} = 30\,\text{TeV}$

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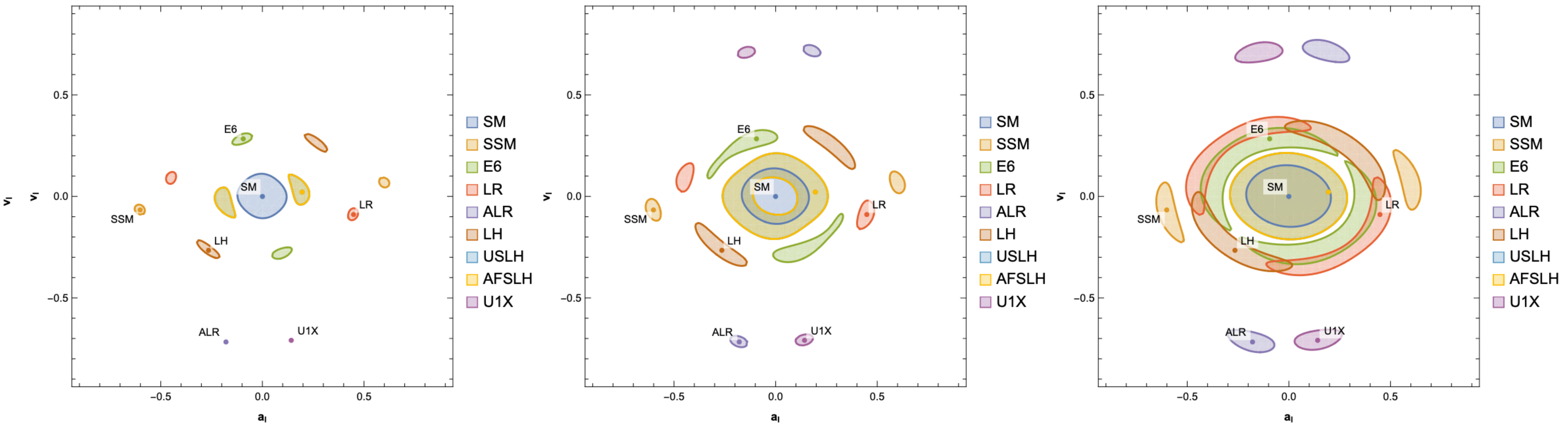

(a) $M_{Z'} = 15\,\text{TeV}$ (b) $M_{Z'} = 20\,\text{TeV}$ (c) $M_{Z'} = 30\,\text{TeV}$

$E_{CM} = 10\,\text{TeV}, \quad \mathscr{L} = 10\,\text{ab}^{-1}, \quad P = 1$

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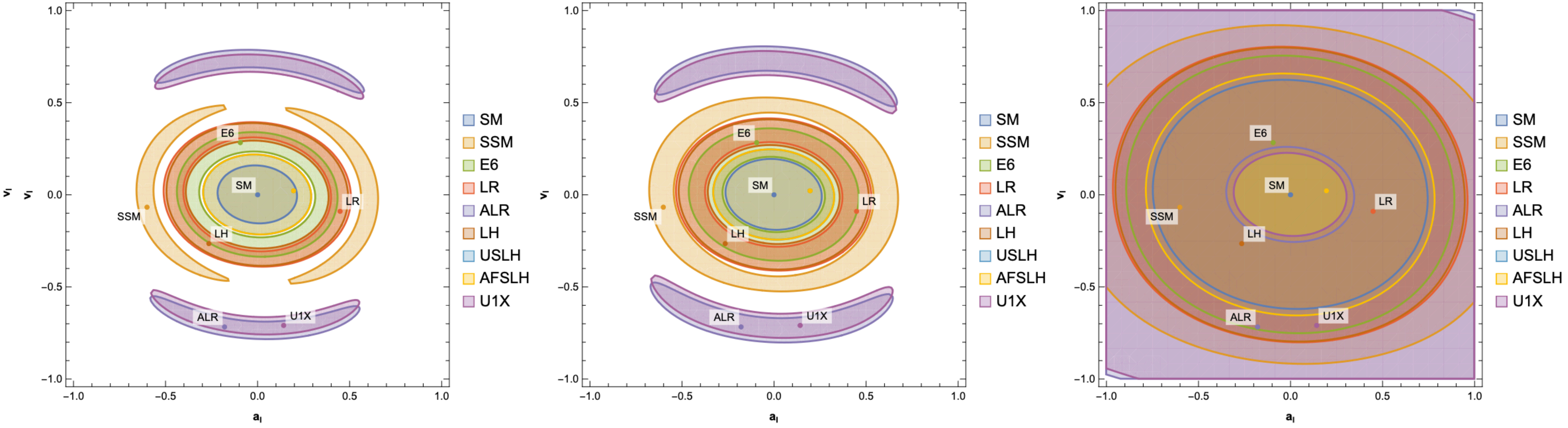


(a) $\Delta O_{\mathrm{sys}} = 0.1\%$ (b) $\Delta O_{\mathrm{sys}} = 1\%$ (c) $\Delta O_{\mathrm{sys}} = 10\%$

Systematic uncertainties should be tuned down to the level of ~ 1 per cent

Conclusions & Outlook

- Muon collider fantastic Energy Frontier option
- Huge potential for Higgs and electroweak physics as well as BSM sensitivity
- Three prime examples: anomalous muon-Higgs couplings, heavy neutral leptons, heavy Z'
- $\mu - H$ **coupling testable with 20% @ 10 TeV .... 2% @ 30 TeV,** i.e. BSM sensitivity to $\Lambda \sim 20 - 70$ TeV

  Remember: model-independent test (production, separate from BRs), can determine sign
- MuC outperforms *all* energy frontier machines in searches for heavy neutral leptons (neutrinos)
- Hugh discriminate power for new gauge interactions up to 10s of TeV, determination of axial structure
- Thorough understanding of dominant SM EW corrections: available in well automated way
- Sudakov regimes rules at the MuC: partially necessitates resummation

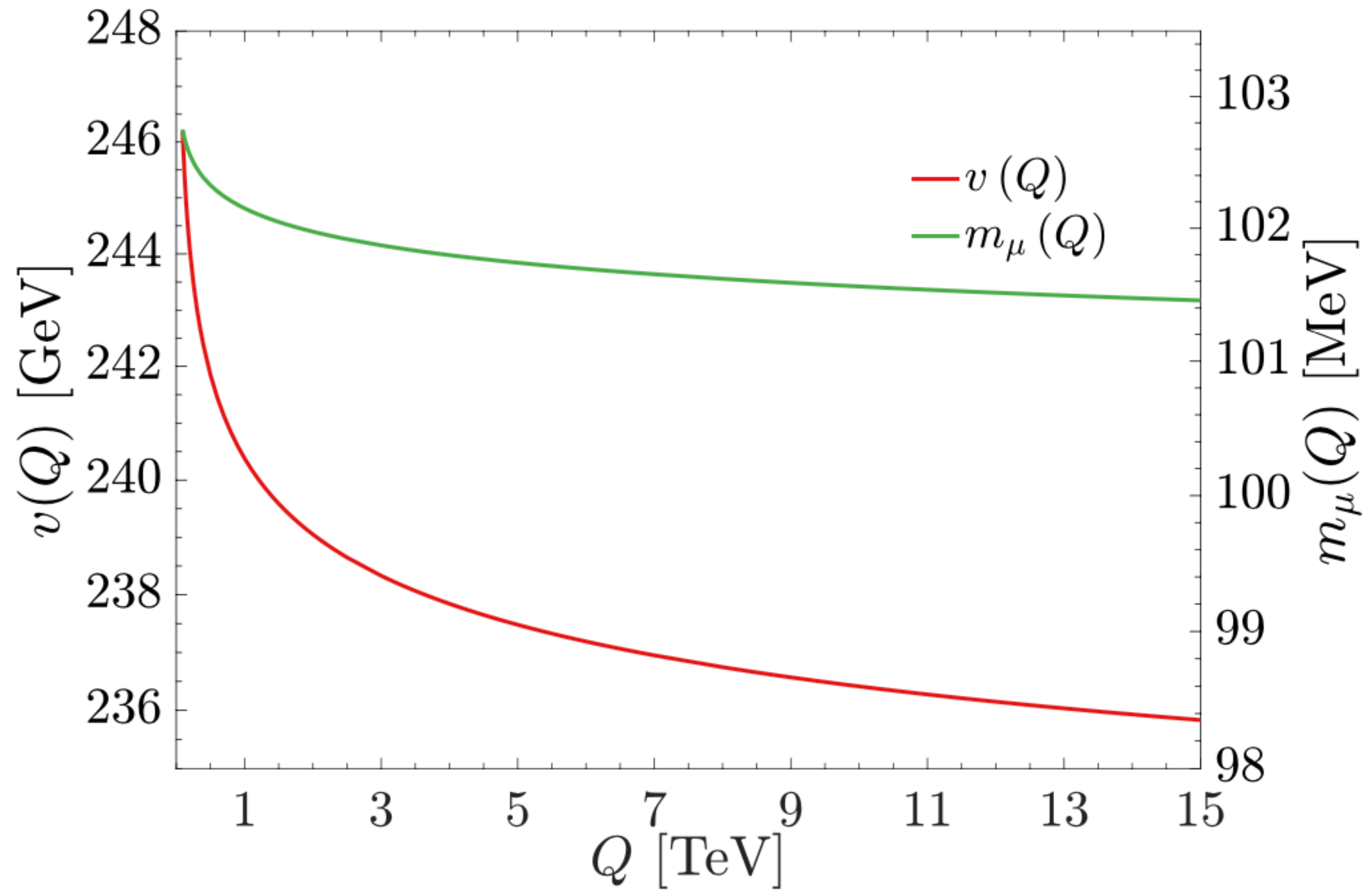
Dig deep and ....you find the unexpected

Dig deep and ....you find the unexpected

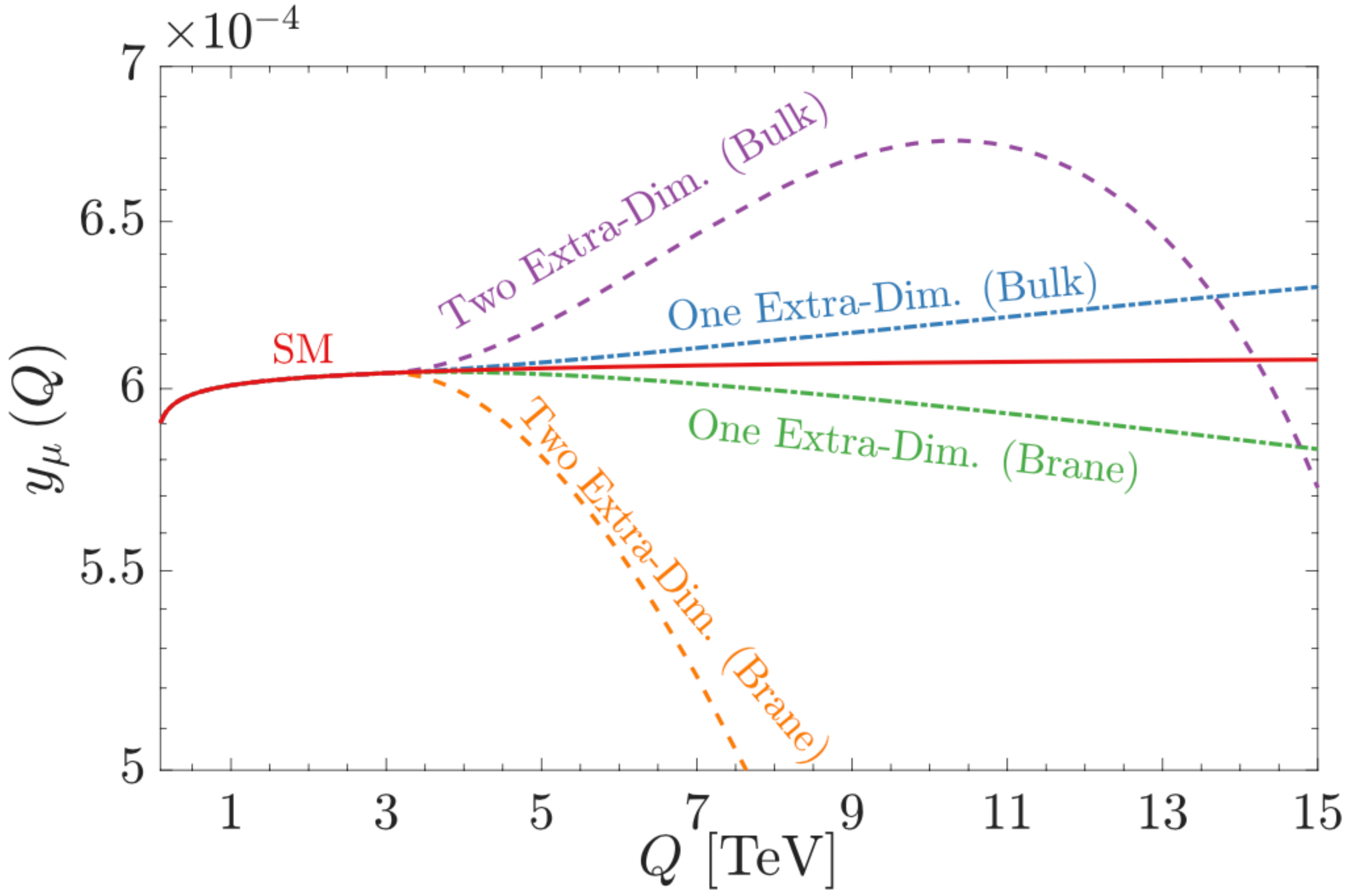
BACKUP

Running of muon Yukawa

VeV and muon mass in the SM



Muon Yukawa in different BSM models



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

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

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

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

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

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

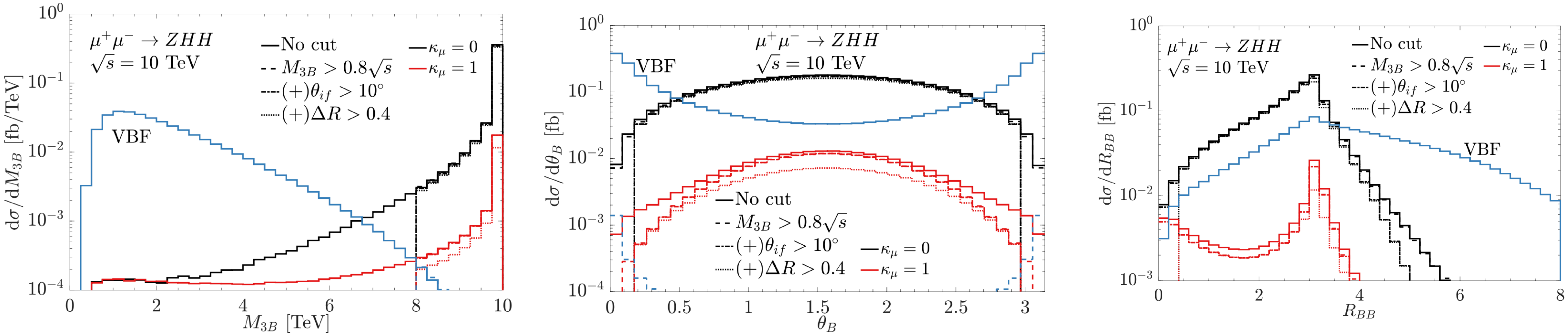
$$\frac{dy_t}{dt} = \beta_{y_t}^{\mathrm{SM}} + \frac{y_t}{16\pi^2}(S(t)-1)\left(\frac{15}{2}y_t^2 - \frac{28}{3}g_3^2 - \frac{15}{8}g_2^2 - \frac{101}{120}g_1^2\right), \qquad \text{5D Bulk,}$$

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

arXiv: 1110.1942; 1209.6239; 1306.4852

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				

Collection of useful formulæ

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

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

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

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

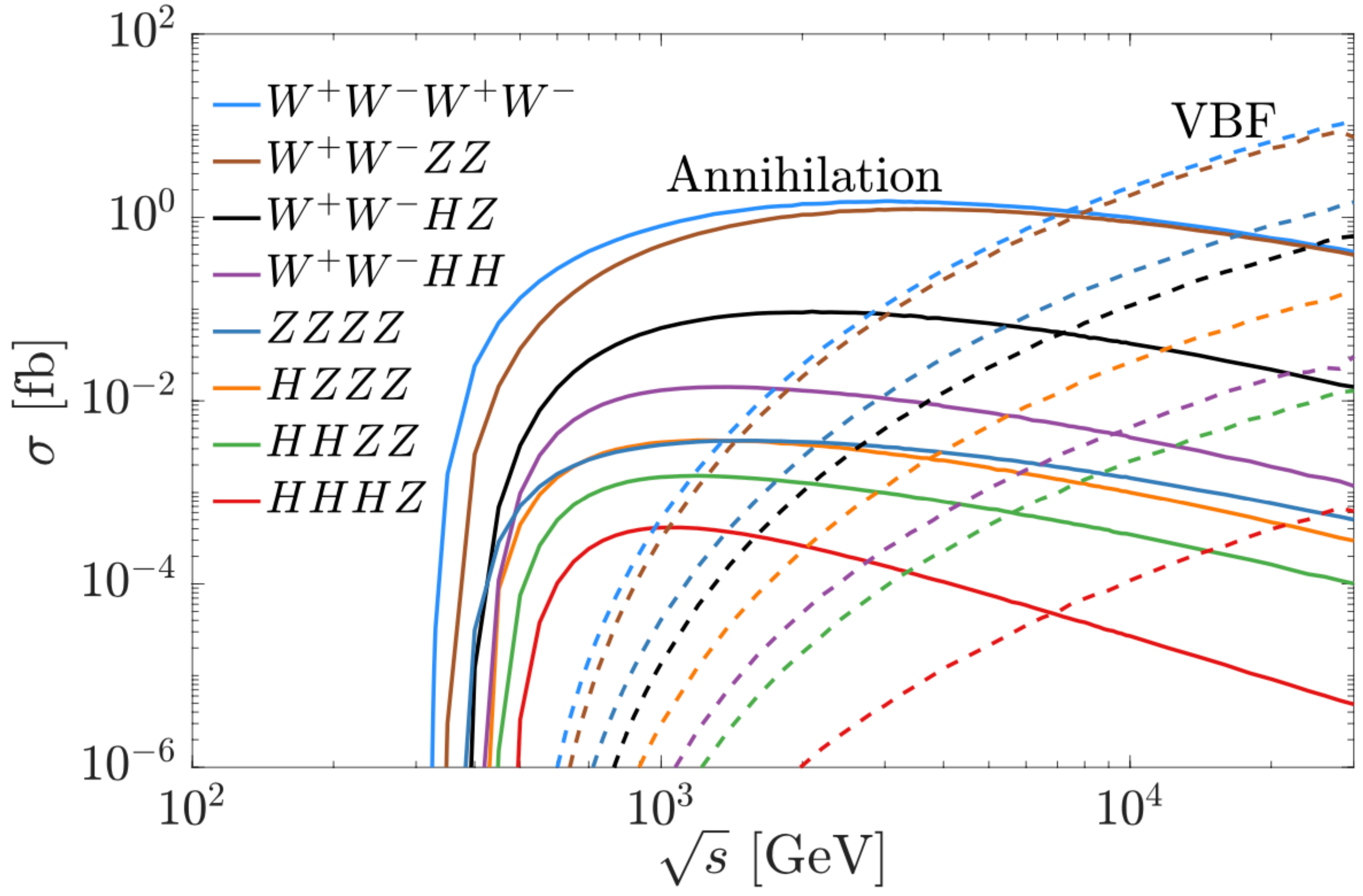
$$\lambda^{(8)}_\mu = \left(y_\mu - \frac{3v^2}{2} c^{(1)}_{\ell\varphi} - \frac{5v^4}{4} c^{(2)}_{\ell\varphi}\right) ,$$

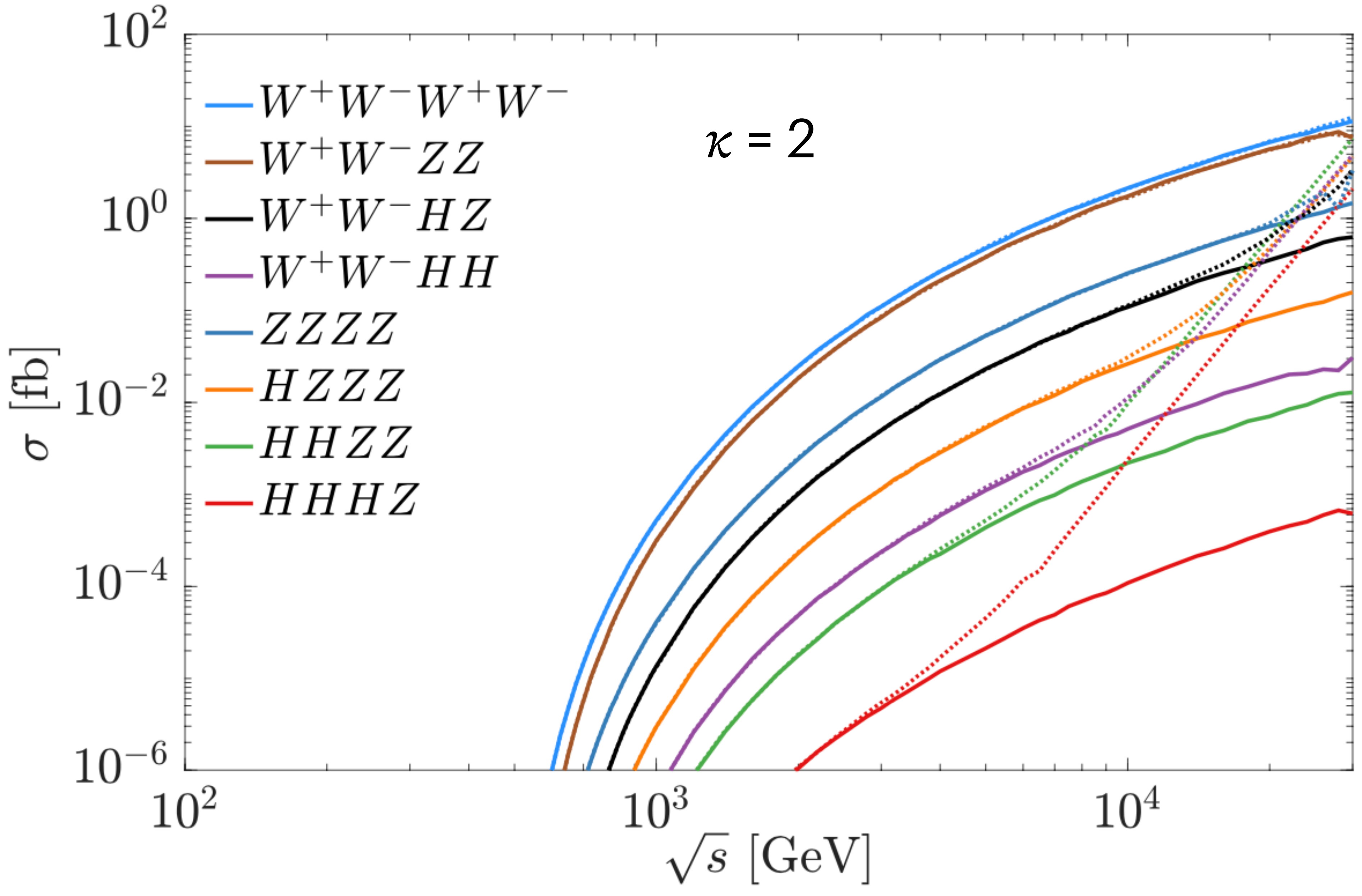
$$R^{\text{HEFT}}_{(3),1} = \left(\frac{y_\mu}{y_1}\right)^2 , \qquad R^{\text{HEFT}}_{(3),2} = \left(\frac{y_2}{y_1}\right)^2 , \qquad R^{\text{HEFT}}_{(3),3} = \left(\frac{y_3}{y_1}\right)^2$$

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

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

Additional cross sections





NLO matching to parton shower

- Matching between NLO real emission from hard ME and parton shower (PS)
- Perturbative α_s : $\left|\mathcal{M}_{\text{soft}}\right|^2 \sim \frac{1}{k_T^2} \longrightarrow \log \frac{k^T_{\text{max}}}{k^T_{\text{min}}}$
- POWHEG method: hardest emission first [Frixione/Nason et al.]
- Process-independent NLO matching in WHIZARD
- Massive/massless emitters, back-to-pack kinematics, running α_s
- Real partitioning of phase space into singular and finite regions
- Resonance-aware subtraction: Intermediate resonances handled
- At the moment: NLO QCD; straightforward EW generalization

- Complete NLO events

$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\text{rad}} R(\Phi_{n+1})$$

- POWHEG generate events according to the formula:

$$d\sigma = \overline{B}(\Phi_n) \left[\Delta_R^{\text{NLO}}(k_T^{\text{min}}) + \Delta_R^{\text{NLO}}(k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\text{rad}} \right]$$

- Uses the modified Sudakov form factor:

$$\Delta_R^{\text{NLO}}(k_T) = \exp\left[- \int d\Phi_{\text{rad}} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \theta(k_T(\Phi_{n+1}) - k_T) \right]$$

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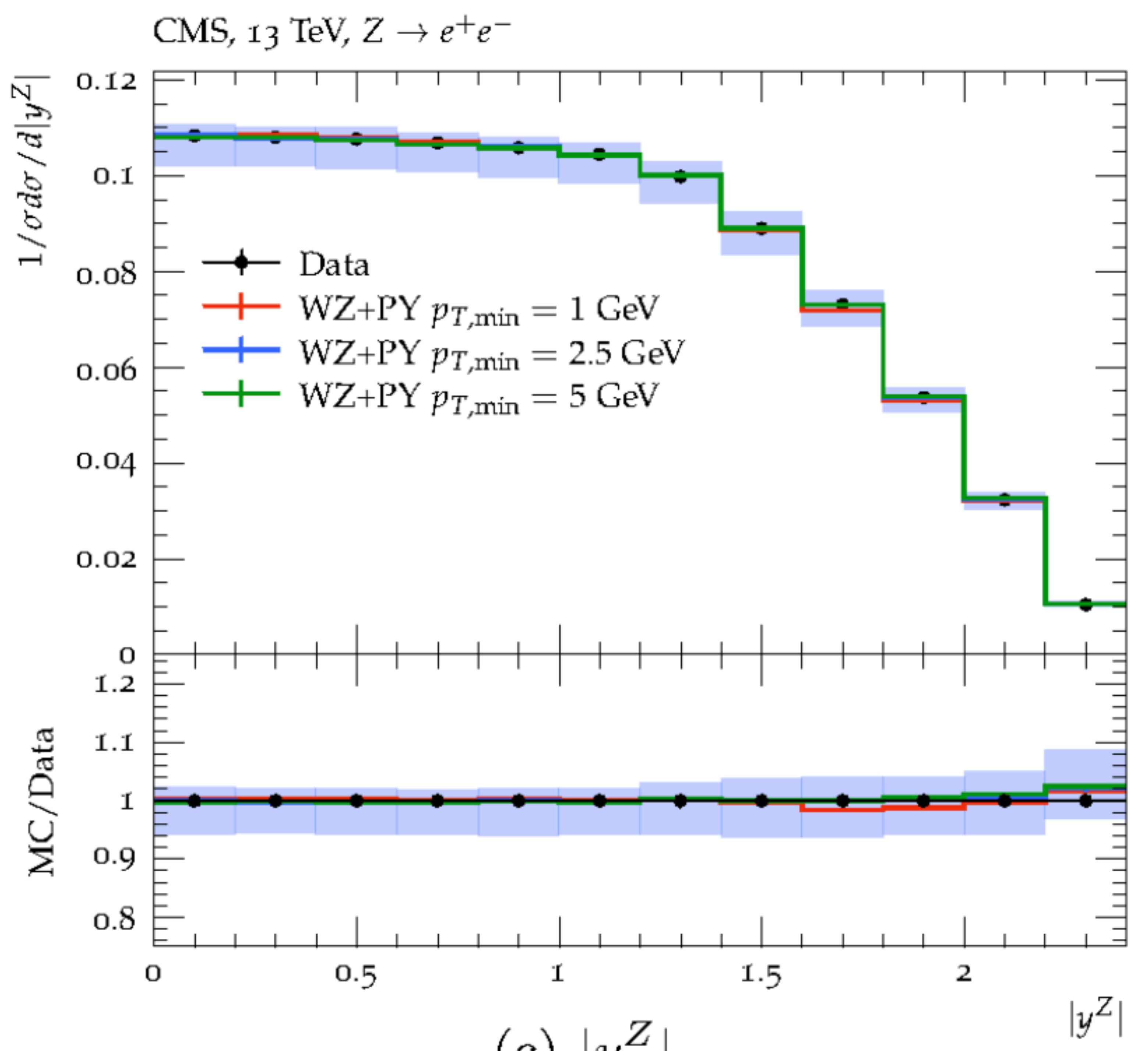
LHC 13 TeV: Drell-Yan $pp \to \ell^+\ell^-$
compared to CMS data



(c) $|y^Z|$

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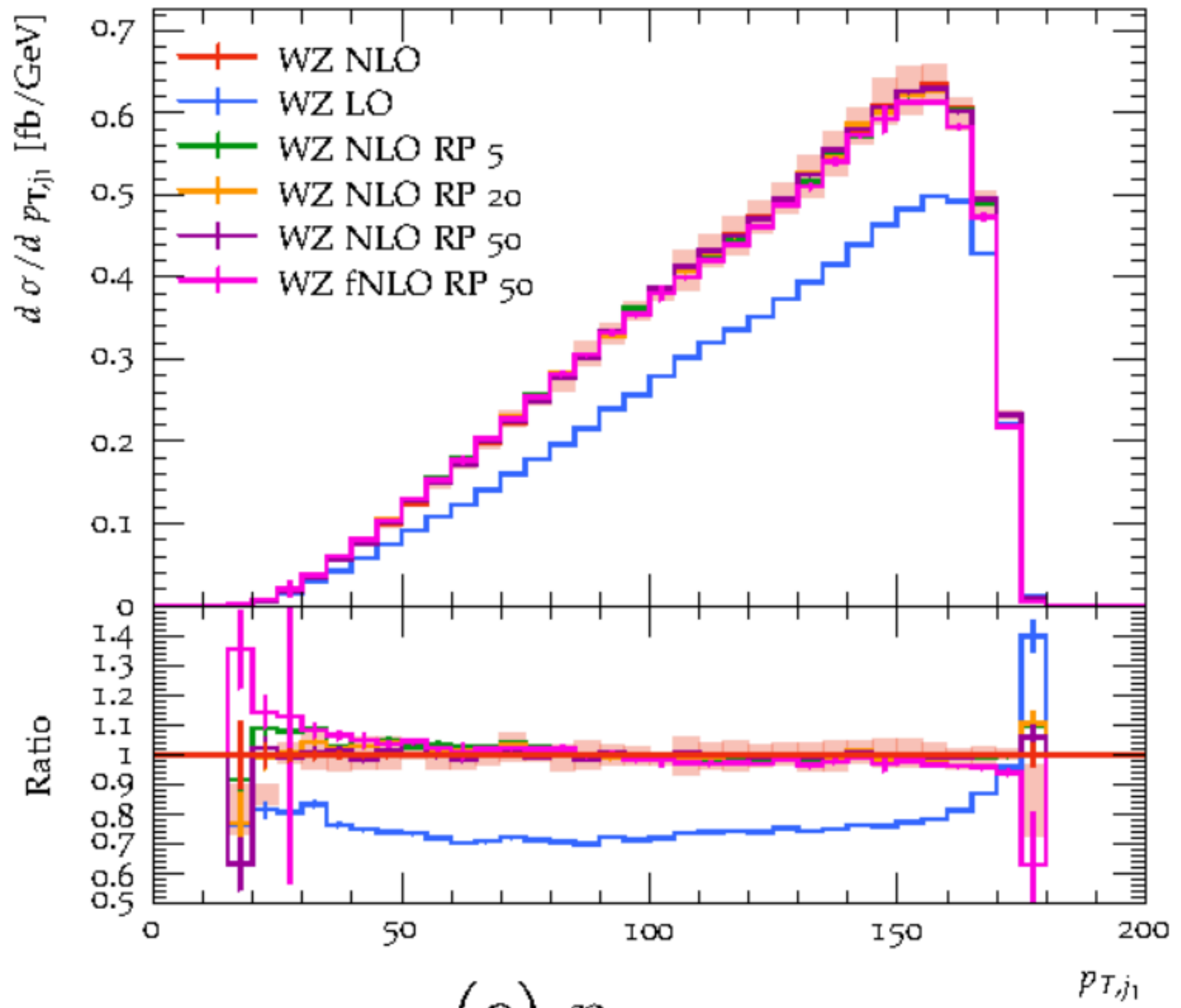
NLO matching to parton shower

- Matching between NLO real emission from hard ME and parton shower (PS)
- Perturbative α_s : $\left|\mathcal{M}_{\text{soft}}\right|^2 \sim \frac{1}{k_T^2} \longrightarrow \log \frac{k^T_{\text{max}}}{k^T_{\text{min}}}$
- POWHEG method: hardest emission first [Frixione/Nason et al.]
- Process-independent NLO matching in WHIZARD
- Massive/massless emitters, back-to-pack kinematics, running α_s
- Real partitioning of phase space into singular and finite regions
- Resonance-aware subtraction: Intermediate resonances handled
- At the moment: NLO QCD; straightforward EW generalization

ILC 500: $e^+e^- \to t\bar{t}j$

$$\mu_R = {}^{H_T}/_2 \quad \text{with} \quad H_T := \sum_i \sqrt{p_{T,i}^2 + m_i^2}$$



(c) p_{T,j_1}

- Complete NLO events

$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\text{rad}} R(\Phi_{n+1})$$

- POWHEG generate events according to the formula:

$$d\sigma = \overline{B}(\Phi_n)\left[\Delta_R^{\text{NLO}}(k_T^{\text{min}}) + \Delta_R^{\text{NLO}}(k_T)\frac{R(\Phi_{n+1})}{B(\Phi_n)}d\Phi_{\text{rad}}\right]$$

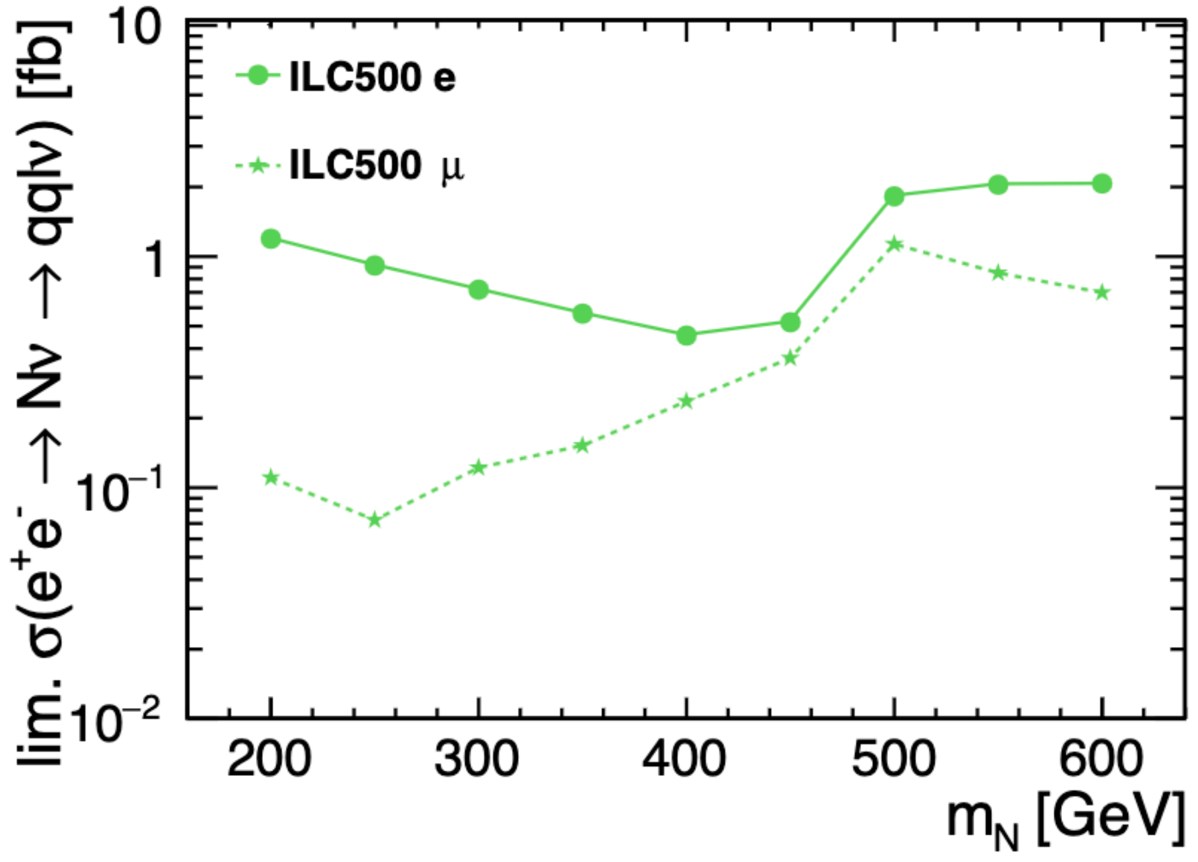
- Uses the modified Sudakov form factor:

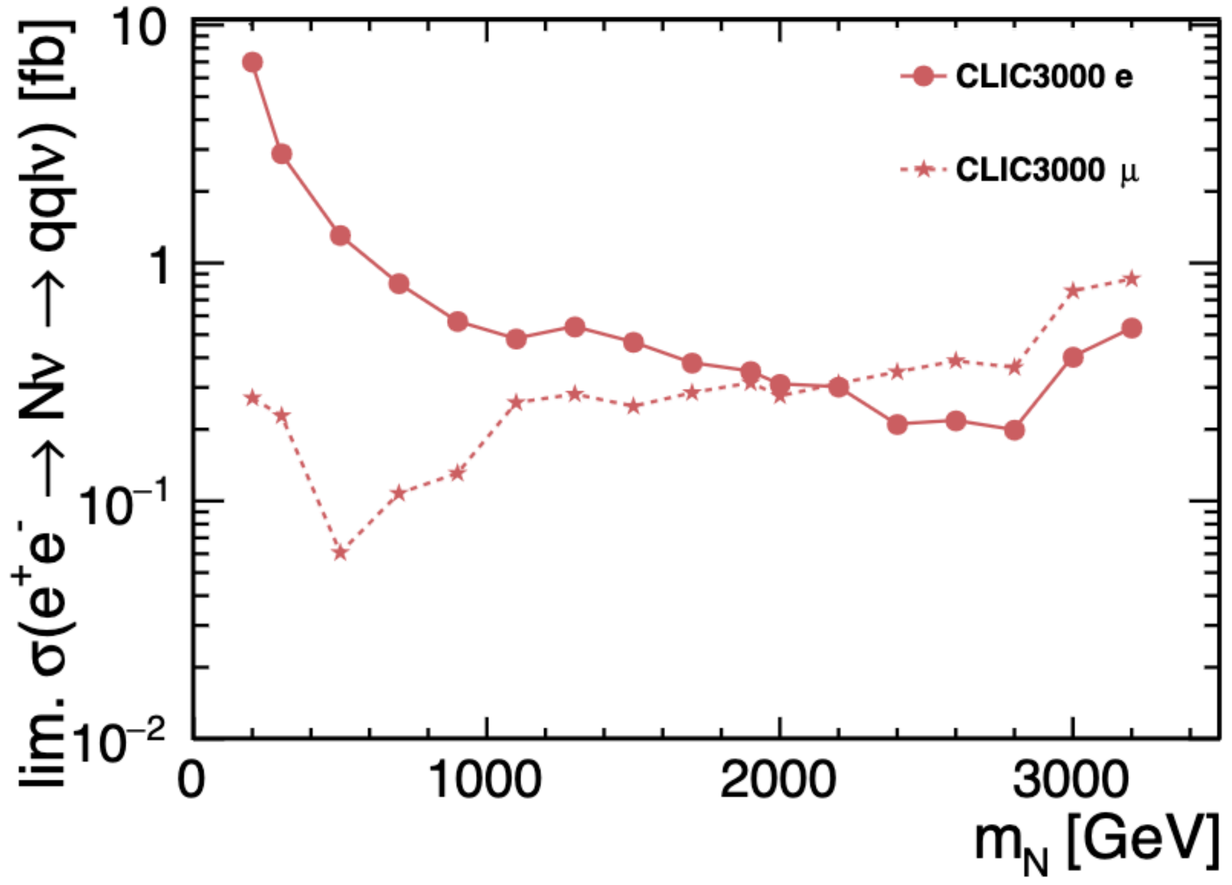
$$\Delta_R^{\text{NLO}}(k_T) = \exp\left[-\int d\Phi_{\text{rad}}\frac{R(\Phi_{n+1})}{B(\Phi_n)}\theta(k_T(\Phi_{n+1}) - k_T)\right]$$

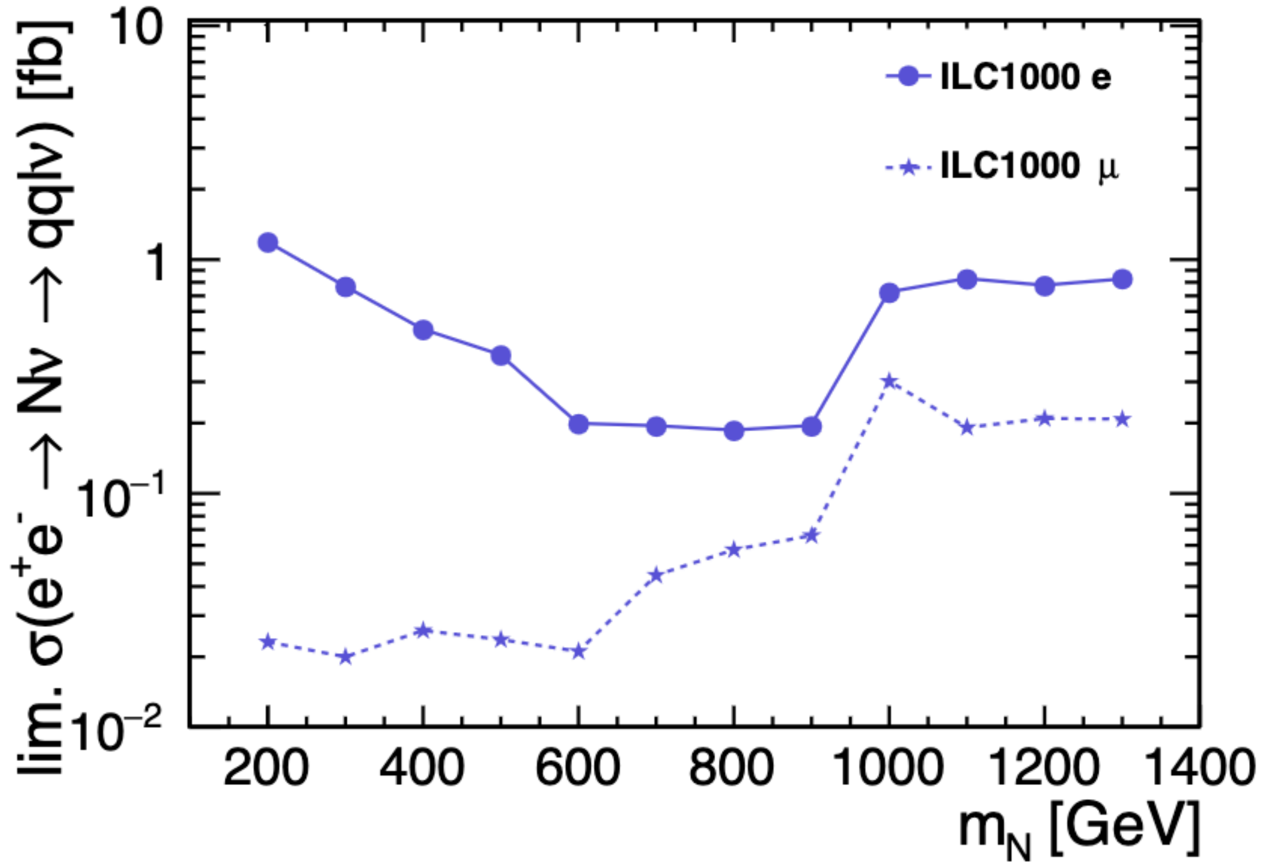
BDT CLs cross section limits

BDT response used to build model in `RooStats` to use CLs method to set limits on cross sections:

Combination of $e^{\pm}$ and $\mu^{\pm}$ channels







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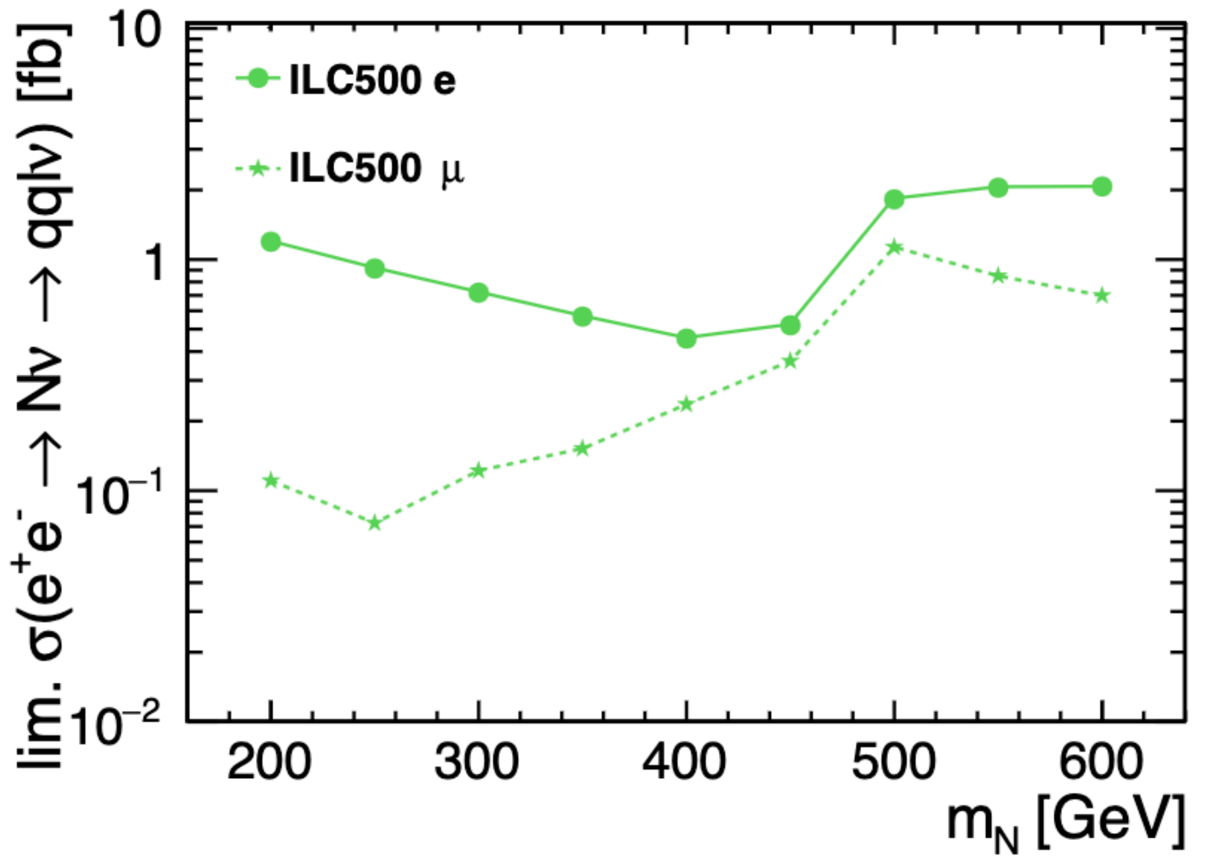
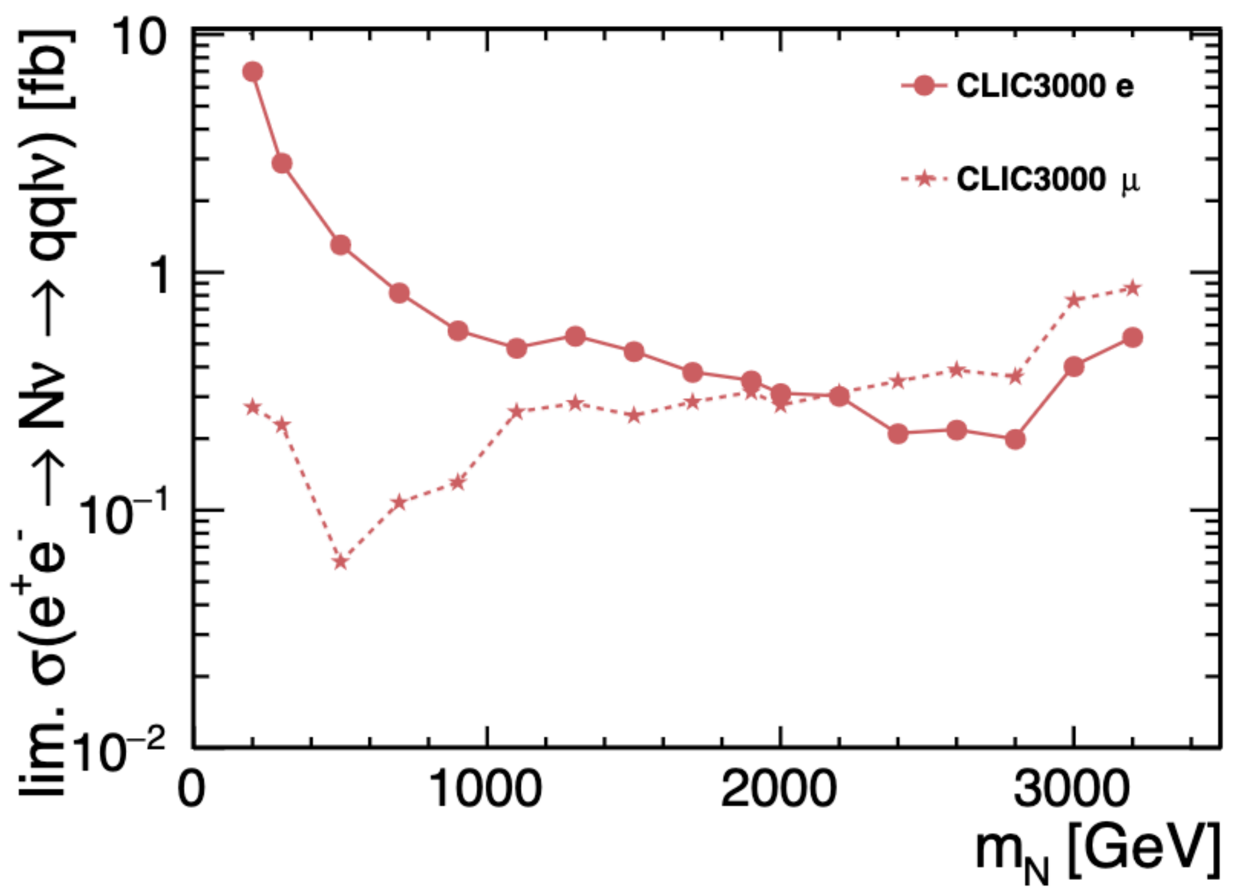
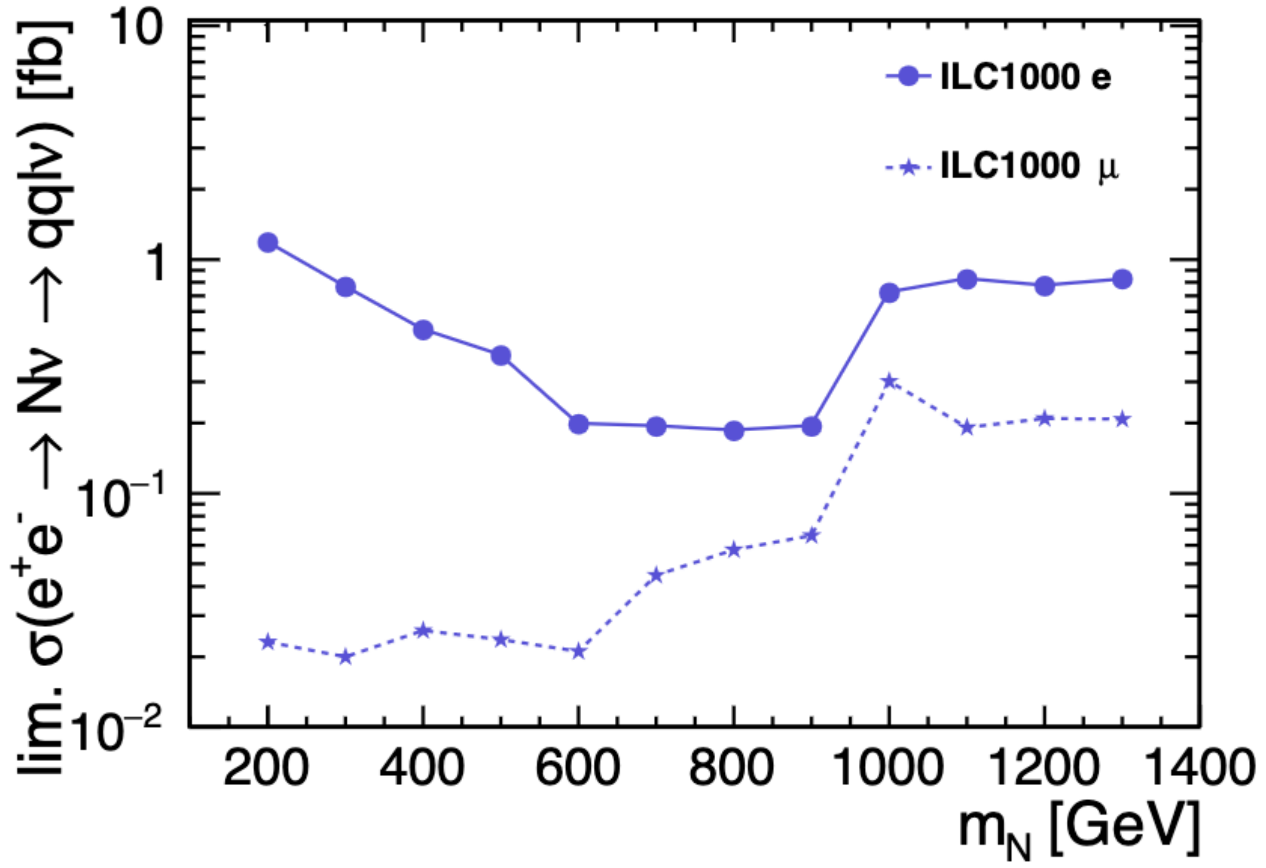
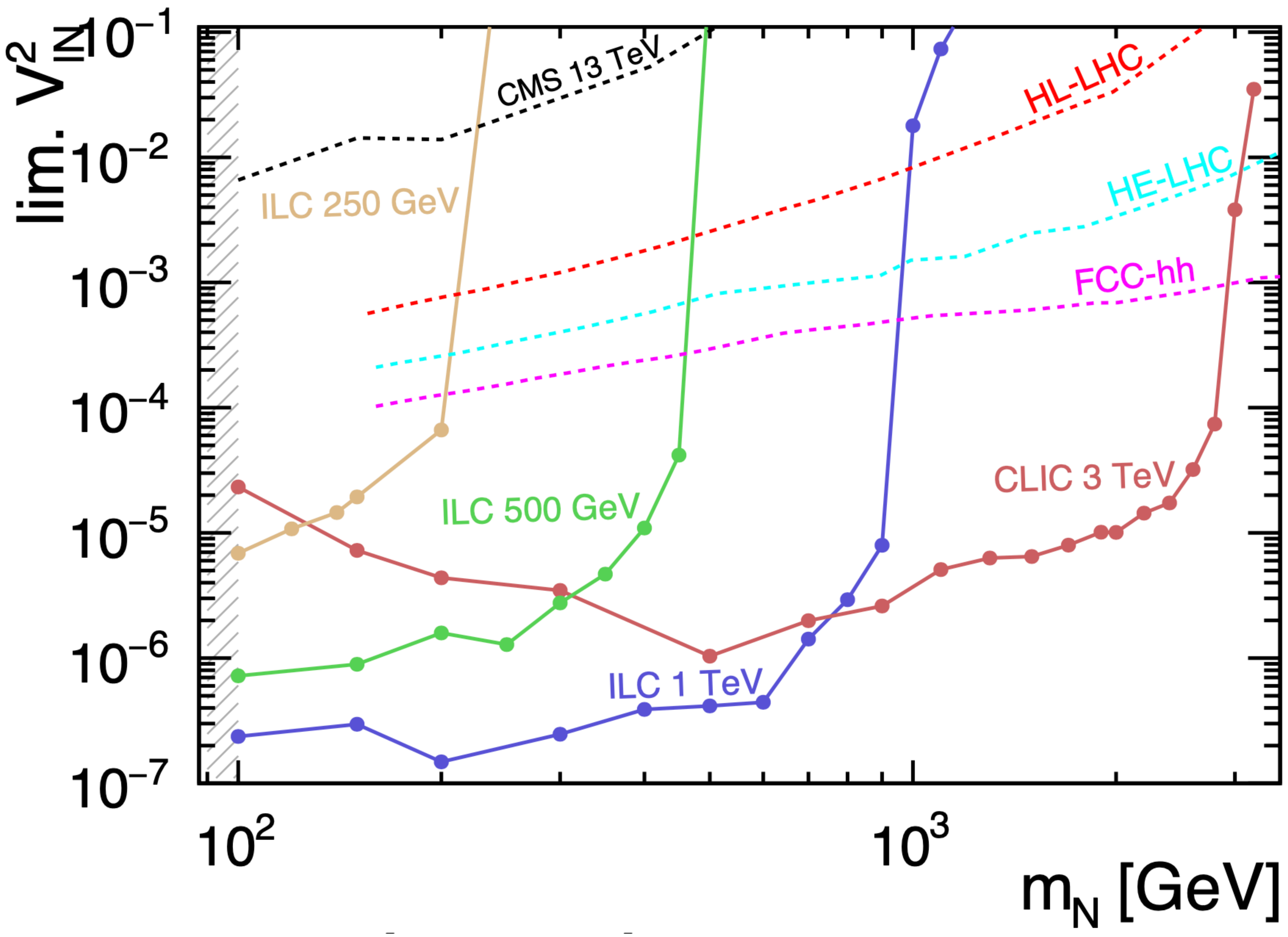






Typical hadron/lepton duality:
masses vs. coupling reach!



LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$