Probing New Physics Through Loops at the CEPC

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Typesetting: slides prepared by Yang Li

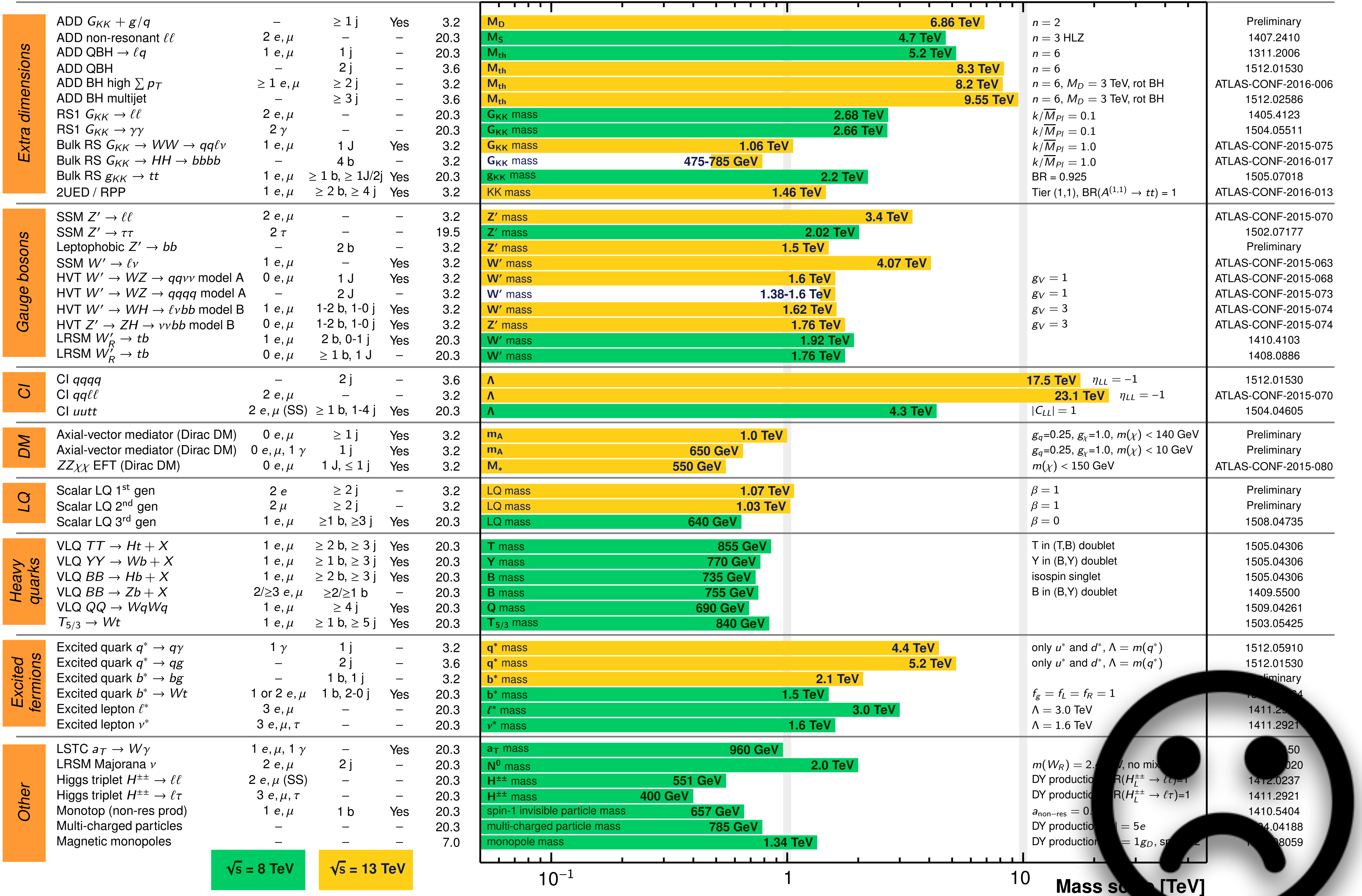
ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8,\ 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	🟨 M_D 6.86 TeV	$n = 2$	Preliminary
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	🟩 M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	3.6	🟨 M_{th} 8.3 TeV	$n = 6$	1512.01530
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	ATLAS-CONF-2016-006
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	🟩 G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	20.3	🟩 G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	3.2	🟨 G_{KK} mass 1.06 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2015-075
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	3.2	🟨 G_{KK} mass 475-785 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-017
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, $\geq$ 1J/2j	Yes	20.3	🟩 g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	🟨 KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	3.2	🟨 Z' mass 3.4 TeV		ATLAS-CONF-2015-070
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	🟩 Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		Preliminary
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	3.2	🟨 W' mass 4.07 TeV		ATLAS-CONF-2015-063
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e, μ	1 J	Yes	3.2	🟨 W' mass 1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-068
	HVT $W' \to WZ \to qqqq$ model A	–	2 J	–	3.2	🟨 W' mass 1.38-1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-073
	HVT $W' \to WH \to \ell\nu bb$ model B	1 e, μ	1-2 b, 1-0 j	Yes	3.2	🟨 W' mass 1.62 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	HVT $Z' \to ZH \to \nu\nu bb$ model B	0 e, μ	1-2 b, 1-0 j	Yes	3.2	🟨 Z' mass 1.76 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	3.6	🟨 Λ 17.5 TeV	$\eta_{LL} = -1$	1512.01530
	CI $qq\ell\ell$	2 e, μ	–	–	3.2	🟨 Λ 23.1 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2015-070
	CI $uutt$	2 e, μ (SS)	≥ 1 b, 1-4 j	Yes	20.3	🟩 Λ 4.3 TeV	$\lvert C_{LL} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	🟨 m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 140$ GeV	Preliminary
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	🟨 m_A 650 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 10$ GeV	Preliminary
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1^{st} gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.07 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2^{nd} gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.03 TeV	$\beta = 1$	Preliminary
	Scalar LQ 3^{rd} gen	1 e, μ	$\geq$1 b, $\geq$3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
	$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	🟩 $T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	🟨 q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	3.6	🟨 q^* mass 5.2 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.01530
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	3.2	🟨 b^* mass 2.1 TeV		eliminary
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1 4
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	🟩 a_T mass 960 GeV		50
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.$ V, no mix	020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	20.3	🟩 $H^{\pm\pm}$ mass 551 GeV	DY productio R($H_L^{\pm\pm} \to \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY productio R($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\mathrm{non-res}} = 0.$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY productio $= 5e$	4.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production $= 1g_D$, sp	08059

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

**Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.*

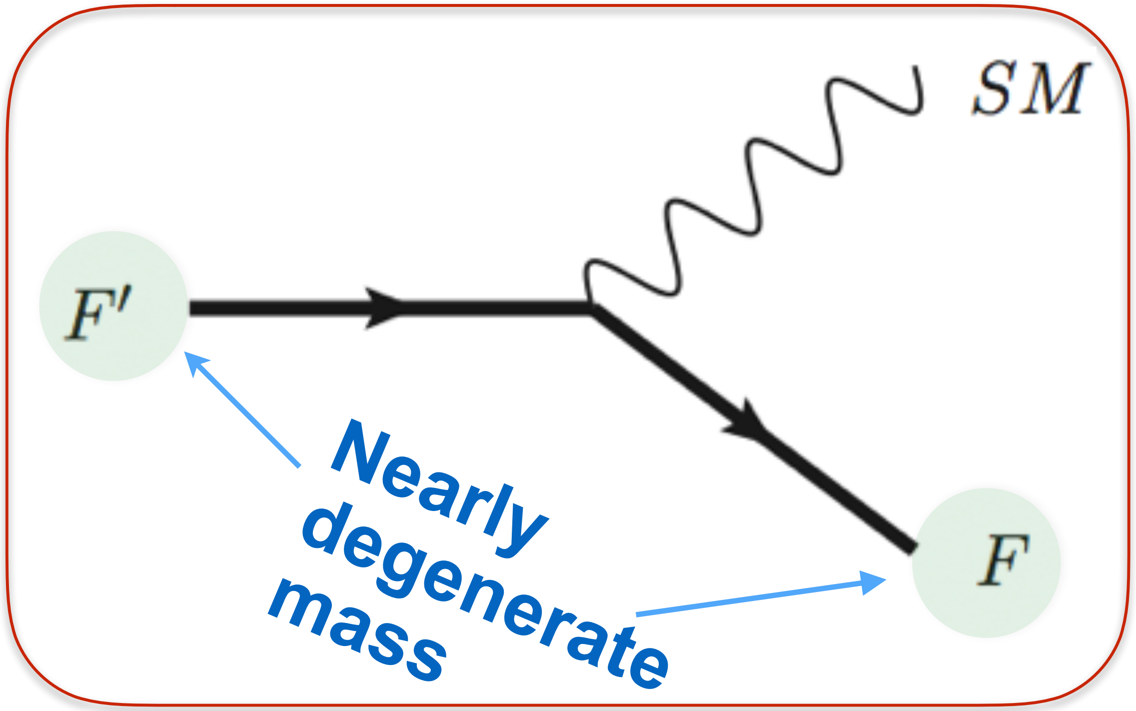
†Small-radius (large-radius) jets are denoted by the letter j (J).

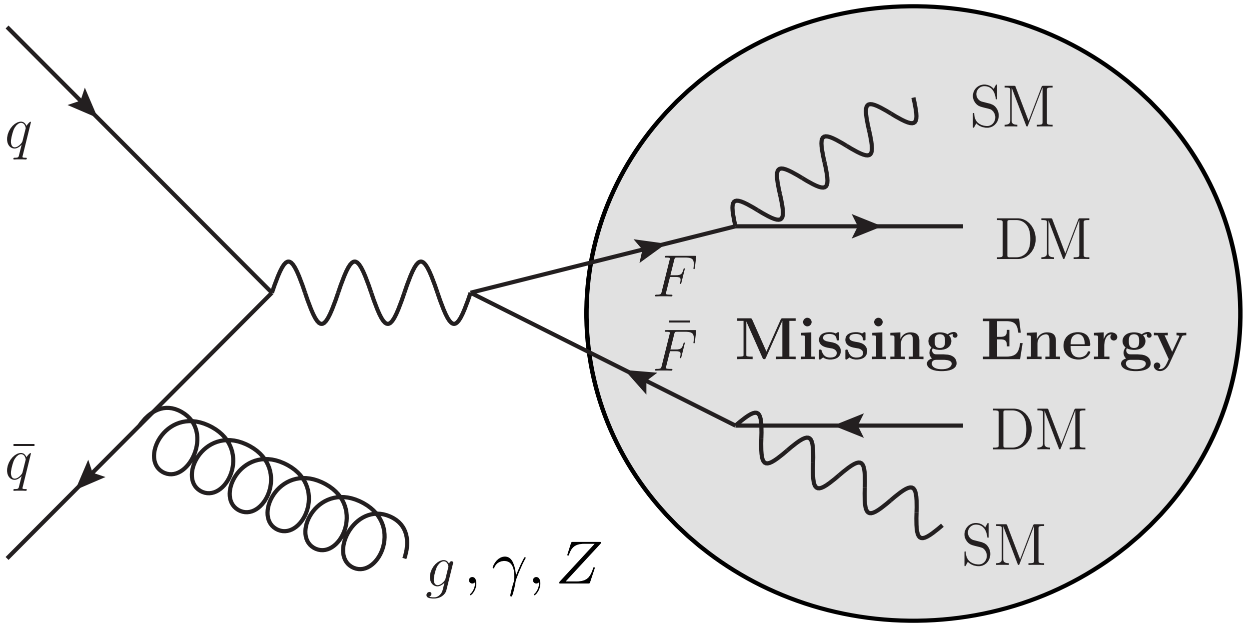
What if no new physics signals were found at the LHC or even at the HL-LHC?

1. What could be possibly missed?

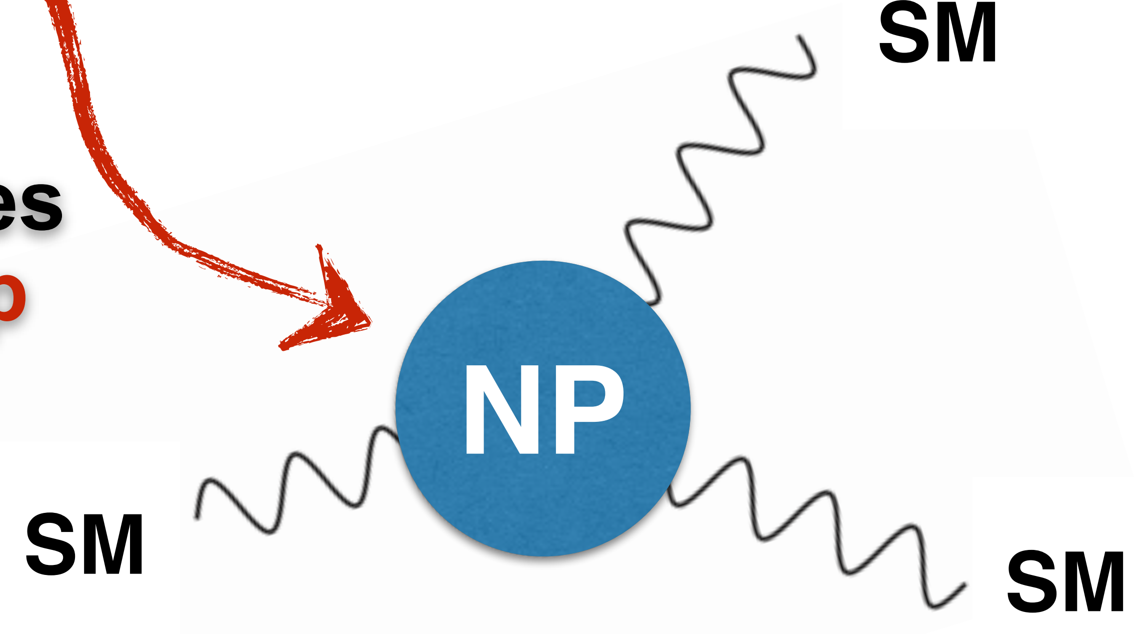
2. Could CEPC say anything about it?

Degenerate Dark Matter Model





NP affects SM processes through loop



Loop does not care about mass split at all, but demands HIGH PRECISION measurements

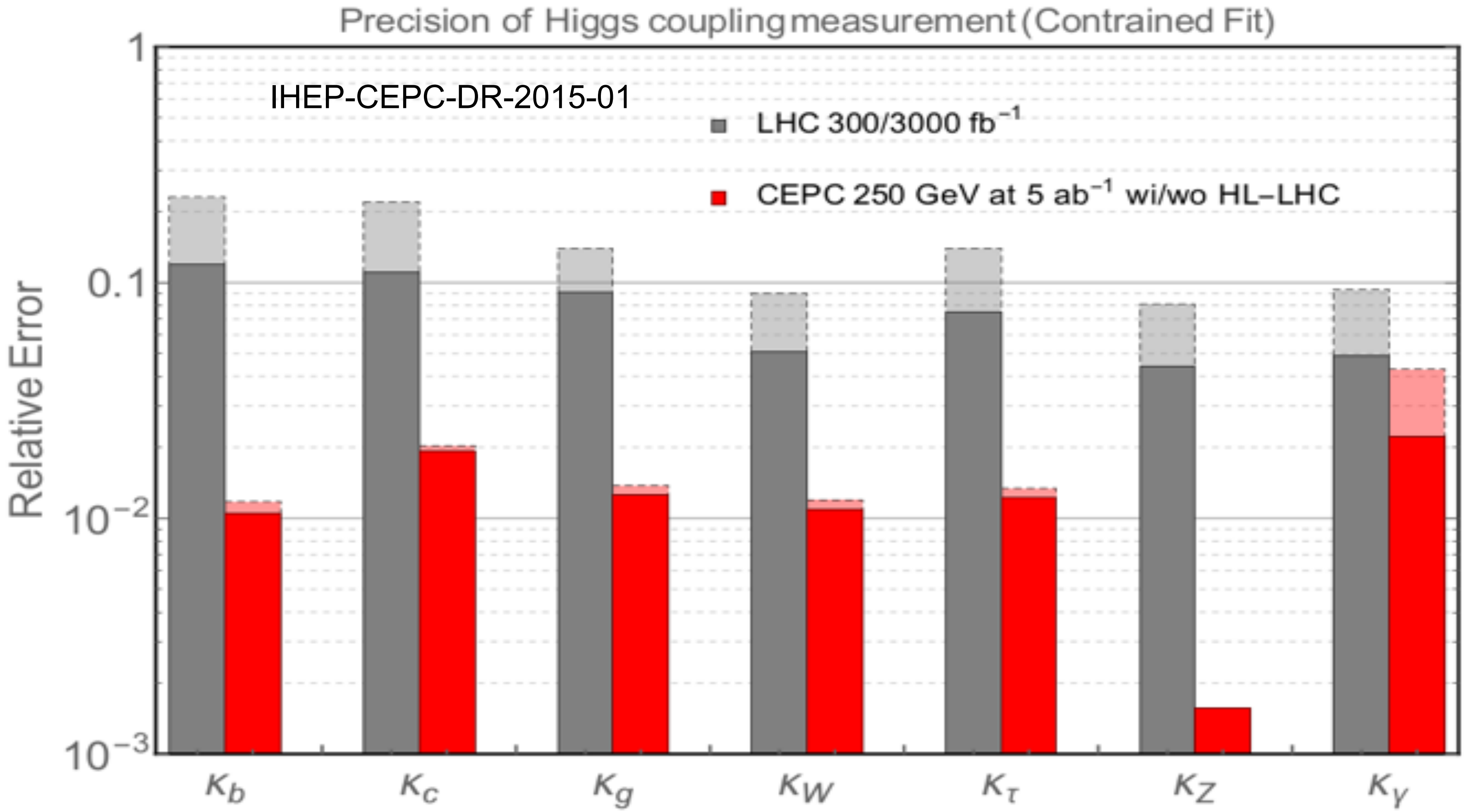
The demand for an e$^+$e$^-$ collider

~ 10^{-3} precision

high luminosity

clean background

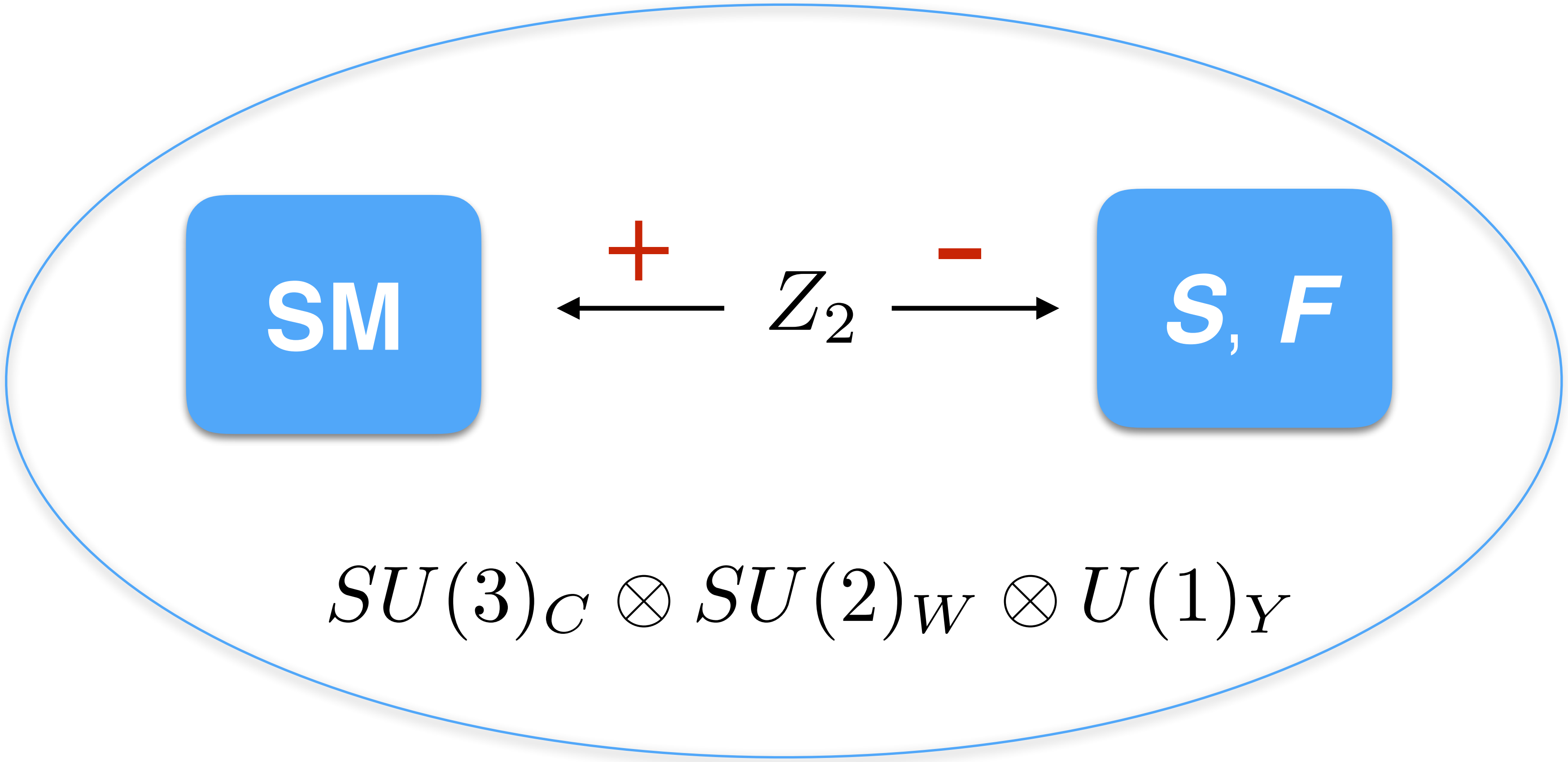
High precision



Precisions of a few percents are achievable for some of the couplings.
The CEPC can robustly improve this precision by an order of magnitude.

Our Framework

Add NP scalar *S* and/or vector-like fermion *F* to the SM



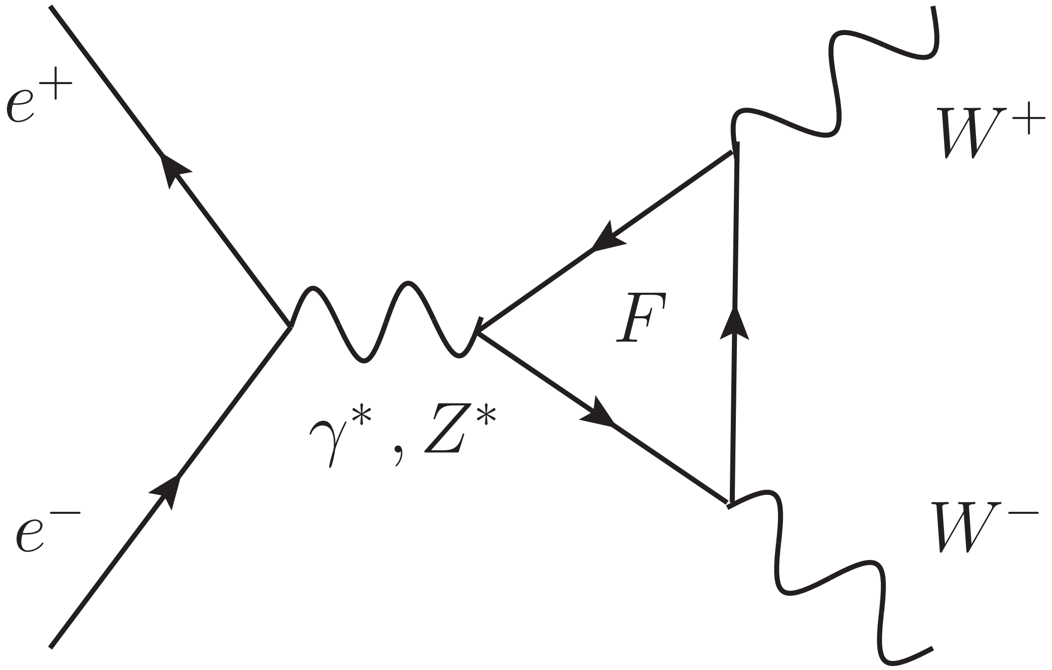
$$e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$$

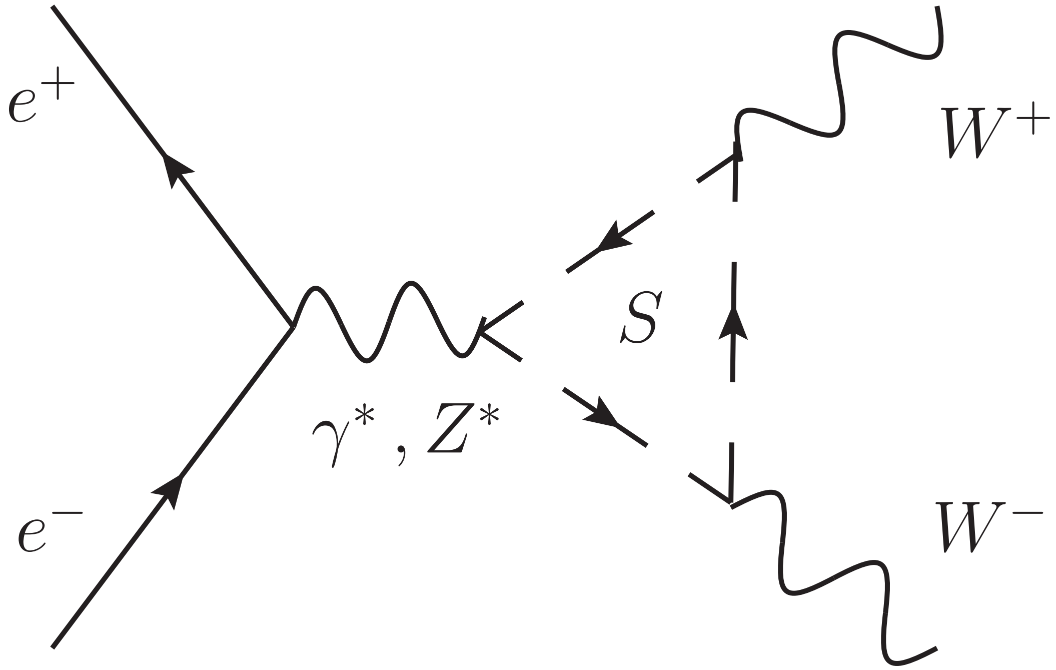
$$e^+e^- \to W^+W^-, \cancel{ZZ}$$

$$e^+e^- \to ZH$$

Assuming NP does not talk to electron directly

1) $e^+e^- \to W^+W^-$





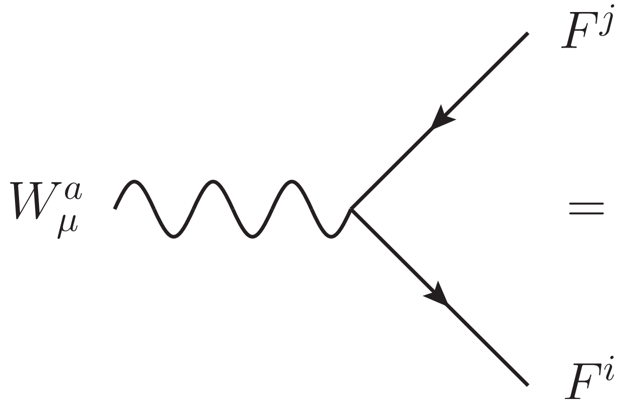
Severely constrained by DM direct detection

Big savior:

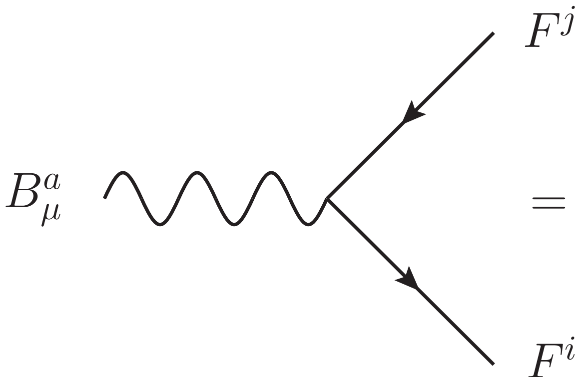
Small mass split between real and imaginary components of neutral DM scalar

Simplified New Physics Models

New fermion multiplet

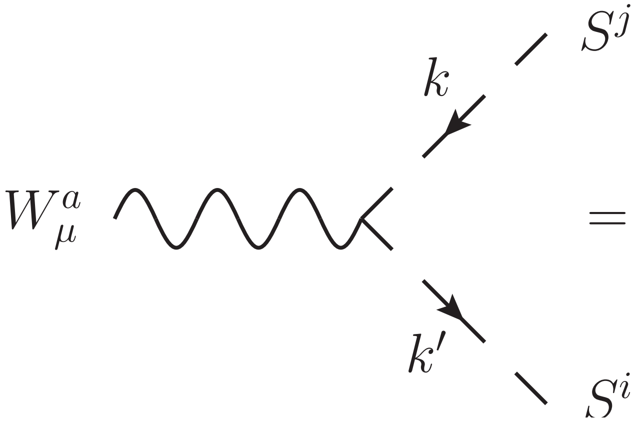


$= ig\gamma^\mu T^a_{ij}$

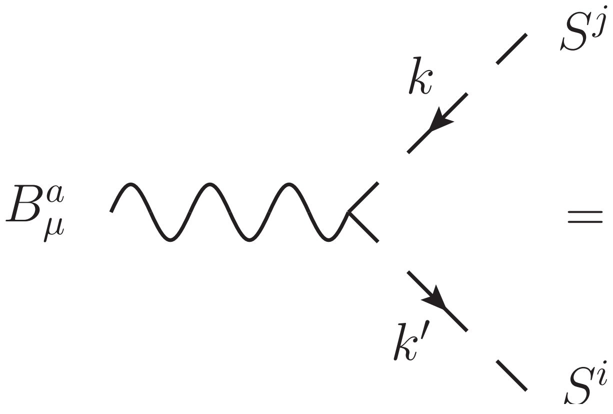


$= ig'\gamma^\mu Y\delta_{ij}$

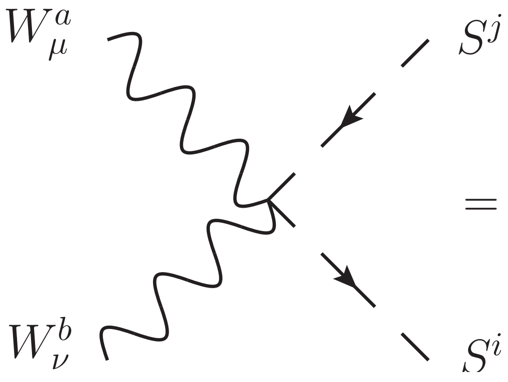
New scalar multiplet



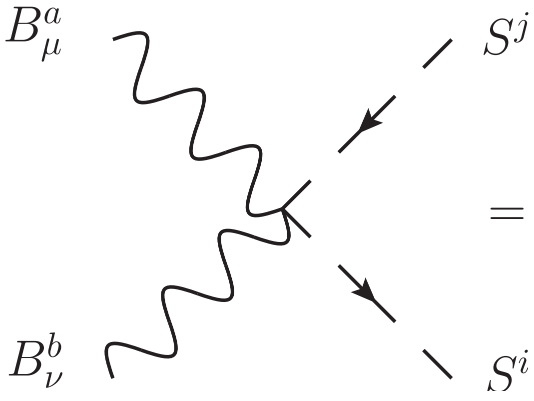
$= ig(k+k')^\mu T^a_{ij}$



$= ig(k+k')^\mu Y\delta_{ij}$

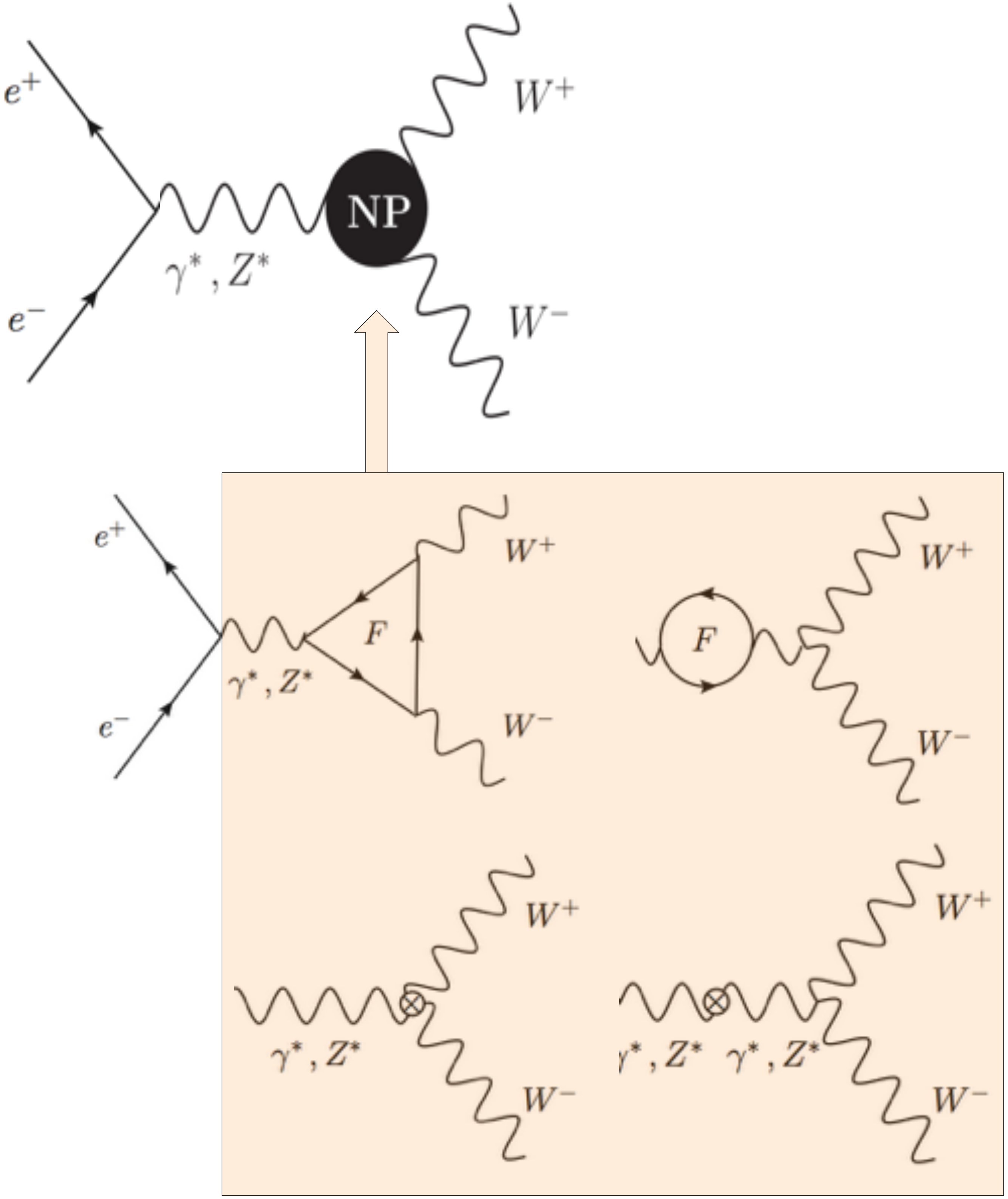


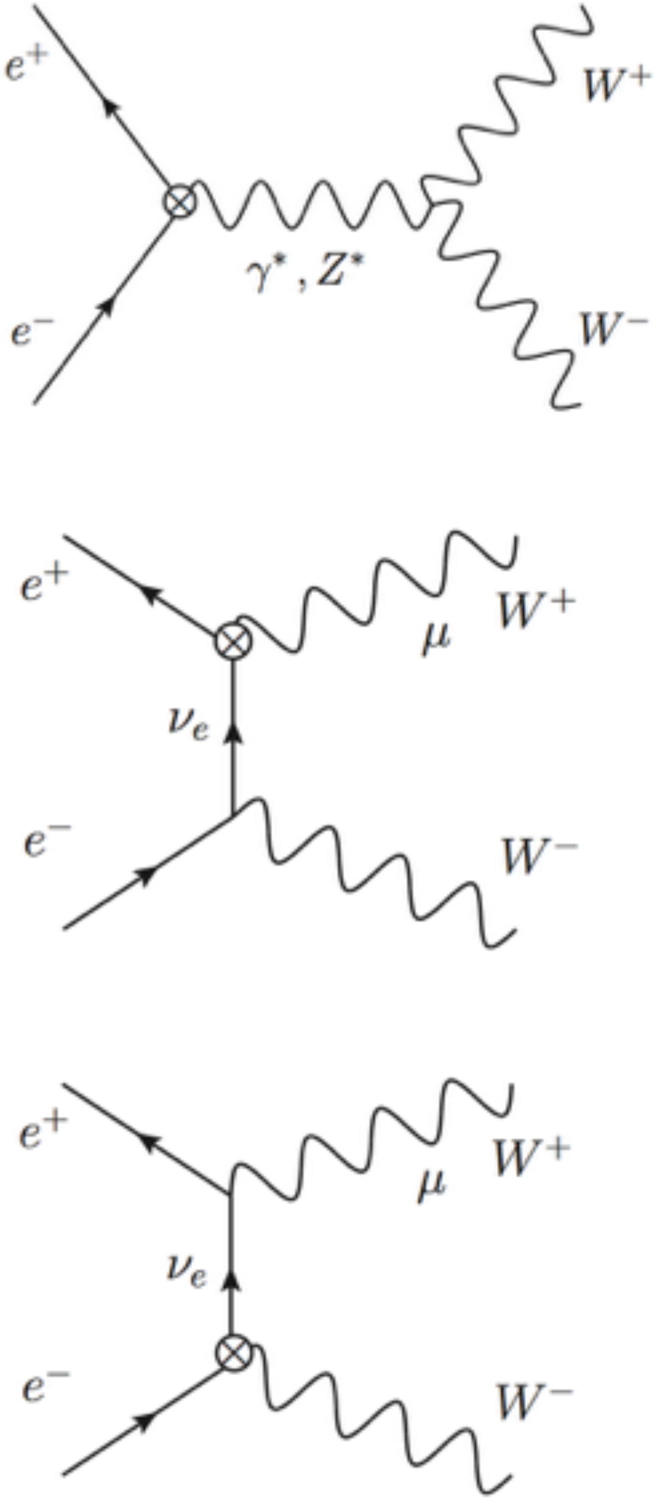
$= ig^2 g^{\mu\nu}(T^aT^b+T^bT^a)_{ij}$

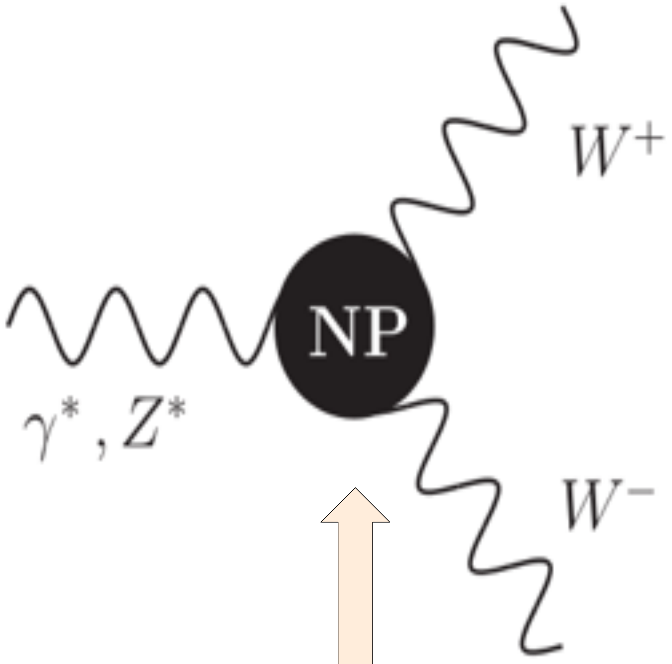


$= ig'^2 g^{\mu\nu} 2Y\delta_{ij}$

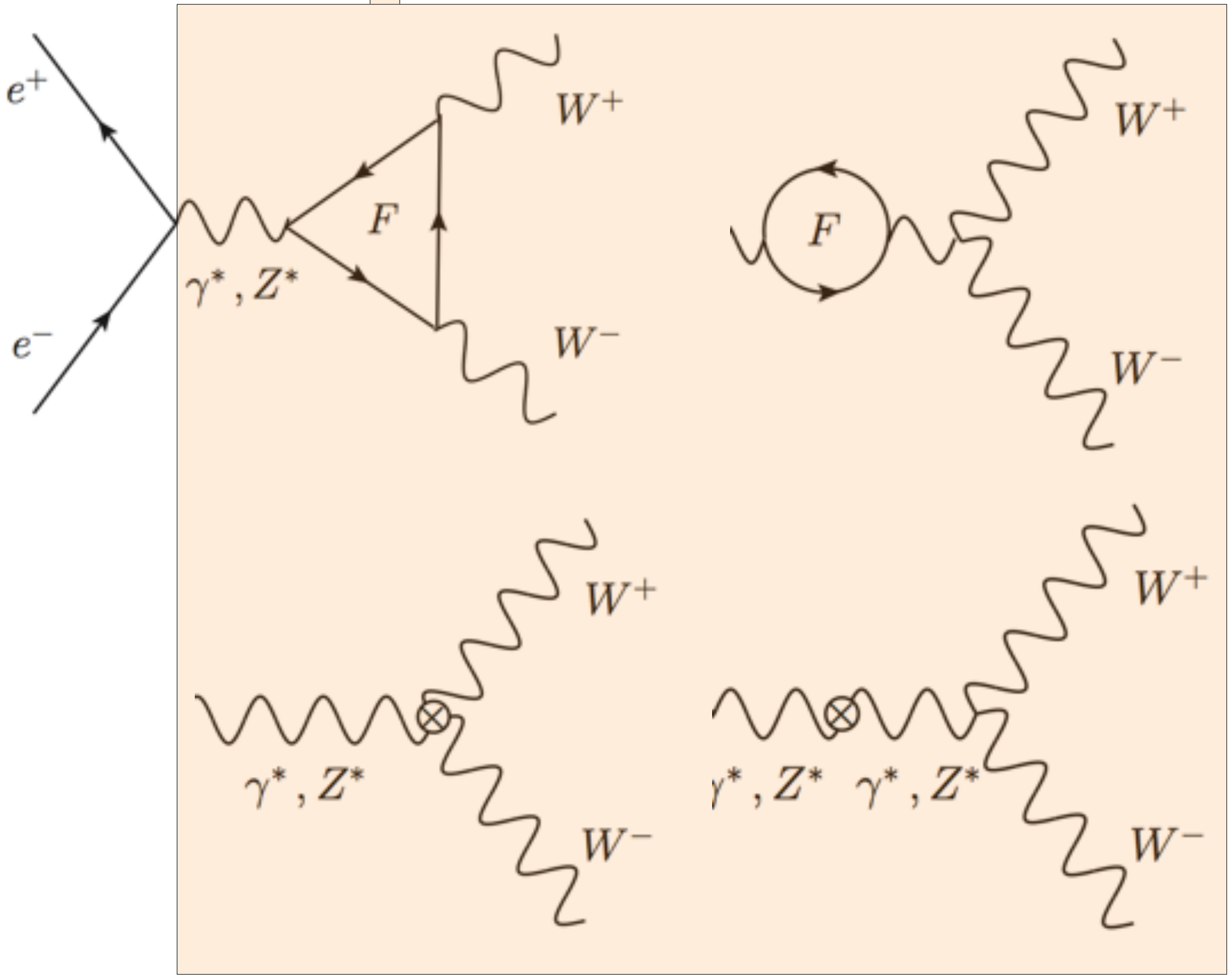
One Loop Corrections to $e^+ e^- \rightarrow W^+W^-$



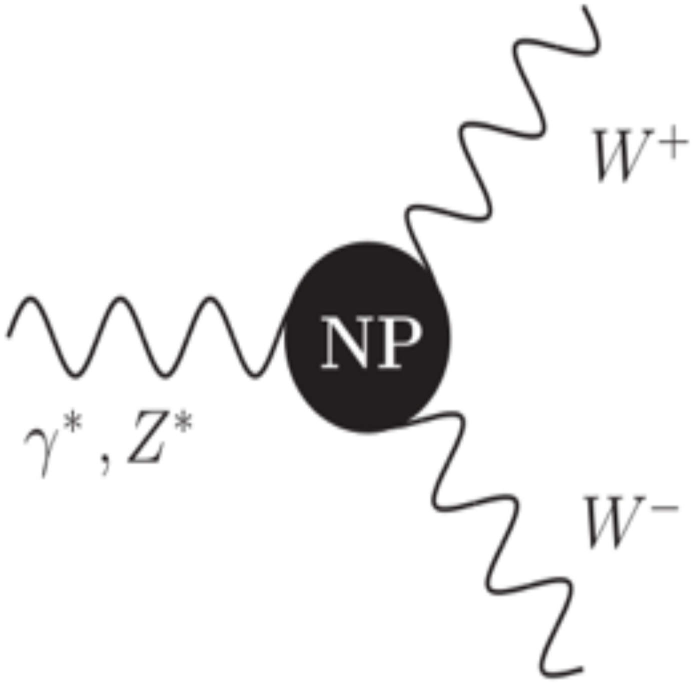




$$
\begin{aligned}
\mathcal{L}_{\rm TGC}/g_{WWV} = & \; ig_{1,V}\left(W^+_{\mu\nu}W^-_{\mu}V_\nu - W^-_{\mu\nu}W^+_{\mu}V_\nu\right) \\
& + i\kappa_V W^+_\mu W^-_\nu V_{\mu\nu} \\
& + \frac{i\lambda_V}{m_W^2} W^+_{\lambda\mu}W^-_{\mu\nu}V_{\nu\lambda}
\end{aligned}
$$



$$
\begin{aligned}
g_{1,V} &= g_{1,V,\triangle} + g_{1,V,\bigcirc} + \delta g_{1,V} \\
\kappa_V &= \kappa_{V,\triangle} + \kappa_{V,\bigcirc} + \delta\kappa_V \\
\lambda_V &= \lambda_{V,\triangle} + \lambda_{V,\bigcirc}
\end{aligned}
$$



$$
\begin{aligned}
\mathcal{L}_{\mathrm{TGC}}/g_{WWV} = {} & i g_{1,V}\left(W^+_{\mu\nu}W^-_{\mu}V_{\nu} - W^-_{\mu\nu}W^+_{\mu}V_{\nu}\right) \\
& + i\kappa_V W^+_{\mu}W^-_{\nu}V_{\mu\nu} \\
& + \frac{i\lambda_V}{m_W^2}W^+_{\lambda\mu}W^-_{\mu\nu}V_{\nu\lambda}
\end{aligned}
$$

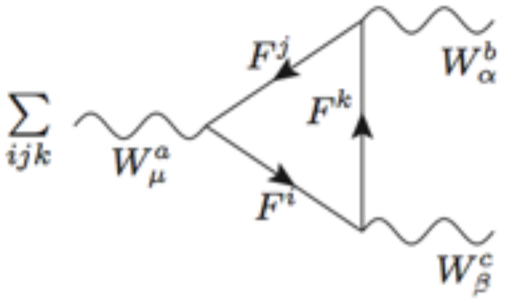
$$
\begin{aligned}
g_{1,V} &= g_{1,V,\triangle} + g_{1,V,\bigcirc} \boxed{+\,\delta g_{1,V}} \\
\kappa_V &= \kappa_{V,\triangle} + \kappa_{V,\bigcirc} + \boxed{\delta\kappa_V} \\
\lambda_V &= \lambda_{V,\triangle} + \lambda_{V,\bigcirc}
\end{aligned}
$$

Sirlin's definition

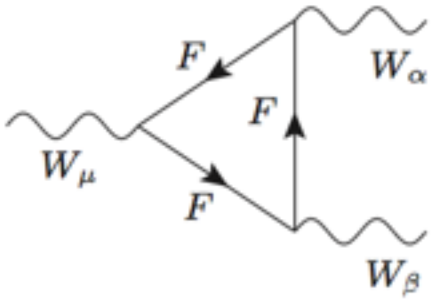
$$s_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

$$
\begin{aligned}
\delta m_W^2 &= \Re\,\Sigma_T^W(m_W^2), \\
\delta Z_W &= -\Re\left.\frac{\partial\Sigma_T^W(k^2)}{\partial k^2}\right|_{k^2=m_W^2}
\end{aligned}
$$

$$
\begin{aligned}
\delta g_{1,\gamma} &= \delta\kappa_\gamma = \left[\frac{\delta \mathrm{Z}_{\mathrm{AA}}}{2} + \frac{c_W\delta\mathrm{Z}_{\mathrm{ZA}}}{2s_W} + \delta\mathrm{Z}_e + \delta\mathrm{Z}_W\right] + \left[-\delta\mathrm{Z}_{\mathrm{AA}} - \frac{c_W\left(s\delta\mathrm{Z}_{\mathrm{AZ}} + \delta\mathrm{Z}_{\mathrm{ZA}}\left(s-m_Z^2\right)\right)}{2s_W\left(s-m_Z^2\right)}\right] \\
\delta g_{1,Z} &= \delta\kappa_Z = \left[\frac{\delta\mathrm{Z}_{\mathrm{AZ}}s_W}{2c_W} - \frac{\delta\mathrm{s}_W}{c_W^2 s_W} + \delta\mathrm{Z}_e + \delta\mathrm{Z}_W + \frac{\delta\mathrm{Z}_{\mathrm{ZZ}}}{2}\right] \\
&\quad + \left[\frac{\delta\mathrm{Z}_{\mathrm{ZZ}}\left(m_Z^2 - s\right) + \delta\mathrm{m}_Z^2}{s-m_Z^2} - \frac{s_W\left(s\delta\mathrm{Z}_{\mathrm{AZ}} + \delta\mathrm{Z}_{\mathrm{ZA}}\left(s-m_Z^2\right)\right)}{2sc_W}\right]
\end{aligned}
$$



$= \mathrm{Tr}[T^a_R T^b_R T^c_R] \times$



$$\begin{aligned}\mathcal{L}_{\mathrm{TGC}}/g_{WWV} = & \, i g_{1,V}\left(W^+_{\mu\nu} W^-_\mu V_\nu - W^-_{\mu\nu} W^+_\mu V_\nu\right) \\ & + i\kappa_V W^+_\mu W^-_\nu V_{\mu\nu} \\ & + \frac{i\lambda_V}{m_W^2} W^+_{\lambda\mu} W^-_{\mu\nu} V_{\nu\lambda}\end{aligned}$$

Large Mass Expansion

Effective Field Theory

$$\begin{aligned} g_{1,Z} &= -\frac{e^2}{120\pi^2 s_W^2}\frac{m_W^2}{M^2}\frac{s_W^2}{c_W^4} D_R Y_R^2, \\ \lambda_Z &= +\frac{e^2}{240\pi^2 s_W^2}\frac{m_W^2}{M^2} C_R, \\ \kappa_Z &= -\frac{e^2}{120\pi^2 s_W^2}\frac{m_W^2}{M^2}\frac{s_W^2}{c_W^4} D_R Y_R^2 \end{aligned}$$

$$\begin{aligned} g_{1,\gamma} &= 0, \\ \lambda_\gamma &= +\frac{e^2}{240\pi^2 s_W^2}\frac{m_W^2}{M^2} C_R, \\ \kappa_\gamma &= 0 \end{aligned}$$

$$\begin{aligned} g_{1,V} &= g_{1,V,\triangle} + g_{1,V,\bigcirc} + \delta g_{1,V} \\ \kappa_V &= \kappa_{V,\triangle} + \kappa_{V,\bigcirc} + \delta\kappa_V \\ \lambda_V &= \lambda_{V,\triangle} + \lambda_{V,\bigcirc} \end{aligned}$$

$$\begin{aligned} c = \frac{e^2}{16\pi^2}\{ & c^1 + c^2 B_0(0) + c^3 B_0(s) + c^4 B_0(m_W^2) \\ & + c^5 B_0(m_Z^2) + c^6 B_0'(0) + c^7 B_0'(m_W^2) \\ & + c^8 B_0'(m_Z^2) + c^9 C_0\} \end{aligned}$$

where $c \in \{g_{1,z}, \lambda_z, \kappa_z, g_{1,\gamma}, \lambda_\gamma, \kappa_\gamma\}$.

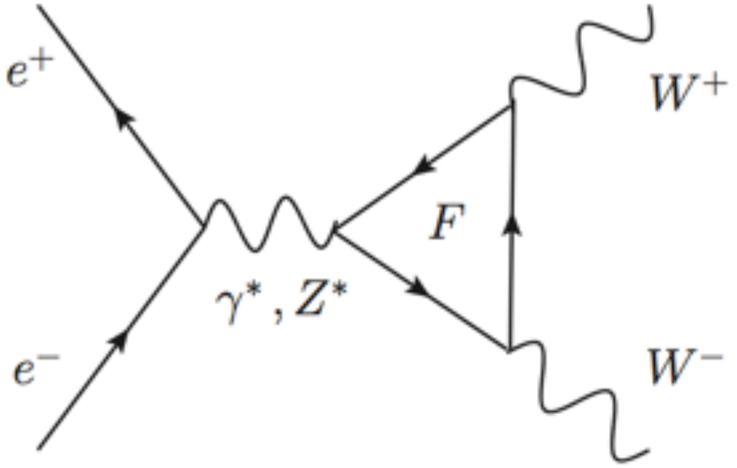
$$g_{1,z}{}^1 = \frac{8 C_R m_W^2 (m_W^2 + s)}{3(s - 4m_W^2)^2 s_W^2}$$

$$\ldots$$

$$\ldots$$

$$\kappa_\gamma{}^9 = -\frac{16 C_R m_W^2 \left(-2m_W^8 + (8M^2 + 11s) m_W^6 + 6(M^2 - s) s m_W^4 + s^2 (s - 6M^2) m_W^2 + M^2 s^3\right)}{s(s - 4m_W^2)^3 s_W^2}$$

Differential cross section of $e^+e^- \to W^+W^-$



$$\mathcal{L}_{\mathrm{TGC}}/g_{WWV} = i g_{1,V}\left(W^+_{\mu\nu}W^-_{\mu}V_{\nu} - W^-_{\mu\nu}W^+_{\mu}V_{\nu}\right) + i\kappa_V W^+_{\mu}W^-_{\nu}V_{\mu\nu} + \frac{i\lambda_V}{m_W^2}W^+_{\lambda\mu}W^-_{\mu\nu}V_{\nu\lambda}$$

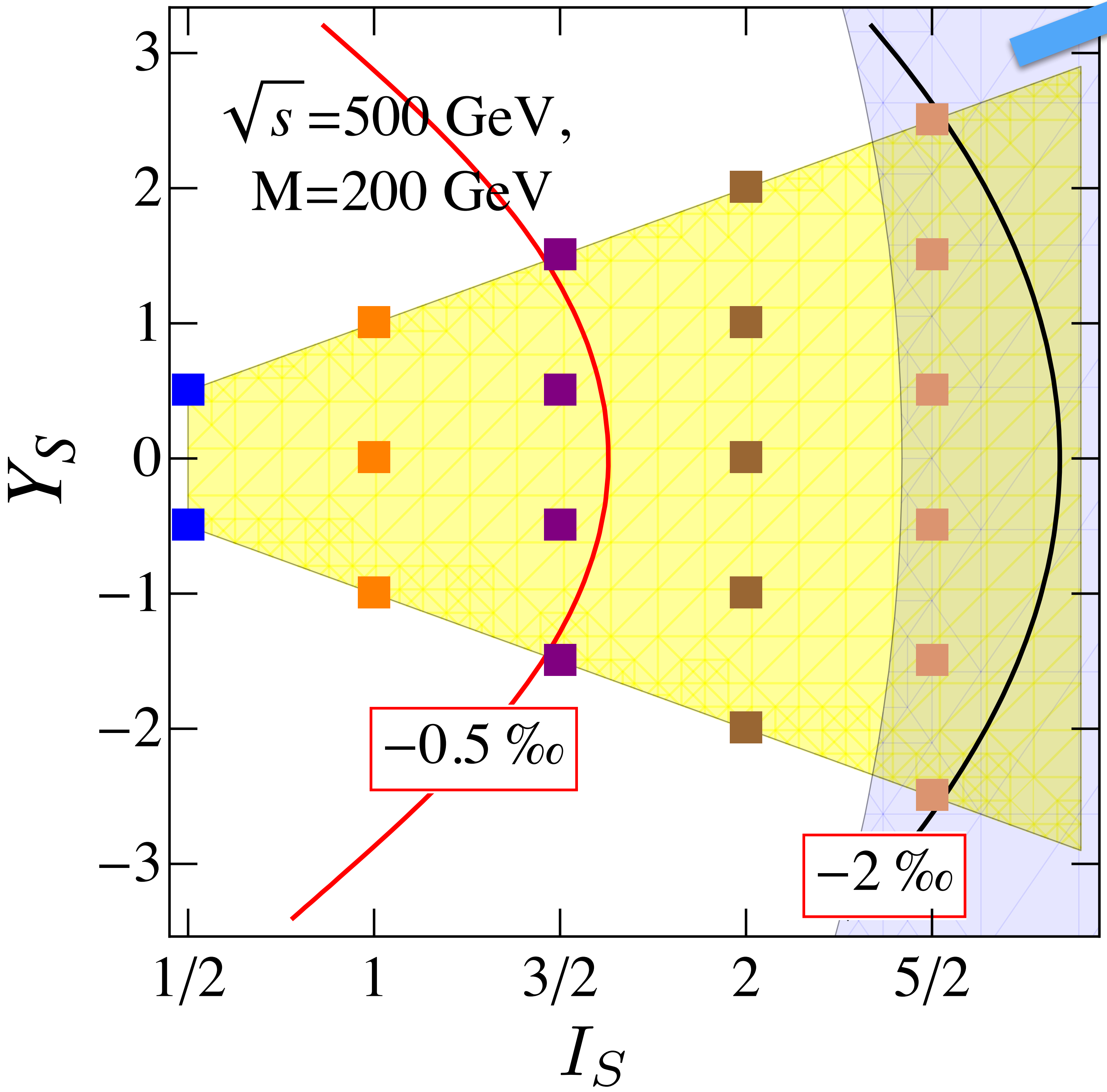
Deviation from the SM contribution

$$\frac{d\Delta\sigma}{dt} = \frac{\pi\alpha^2}{s^2}\sum_i\left\{\mathcal{A}_i\left[\left(Q + \frac{g_L}{s_W^2}\frac{s}{s-m_Z^2}\right)\left(Qc^{\mathcal{A},L}_{\gamma,i} + \frac{g_L}{s_W^2}\frac{s}{s-m_Z^2}c^{\mathcal{A},L}_{Z,i}\right) + (L \to R)\right] + \mathcal{I}_i\frac{1}{2s_W^2}\left(Qc^{\mathcal{I},L}_{\gamma,i} + \frac{g_L}{s_W^2}\frac{s}{s-m_Z^2}c^{\mathcal{I},L}_{Z,i}\right)\right\} + \frac{\pi\alpha^2}{s^2}\mathcal{E}\frac{1}{4s_W^2}c^{\mathcal{E}}$$

$$c^{\mathcal{A},L}_{\gamma} = 2\Re\left\{g_{1,\gamma} + c^L_{e\gamma},\ \kappa_\gamma + c^L_{e\gamma},\ \lambda_\gamma\right\},$$

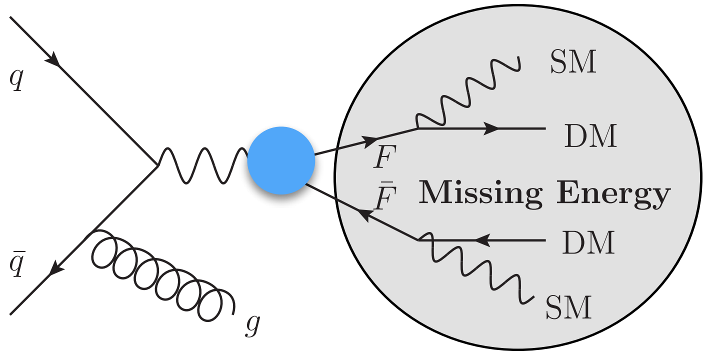
Weak and Hypercharge Quantum Numbers of S

$$Y_S \in \{-I_S, -I_S+1, \cdots, I_S\}$$



Blue region :

Higher Reps excluded by mono-jet + MET data



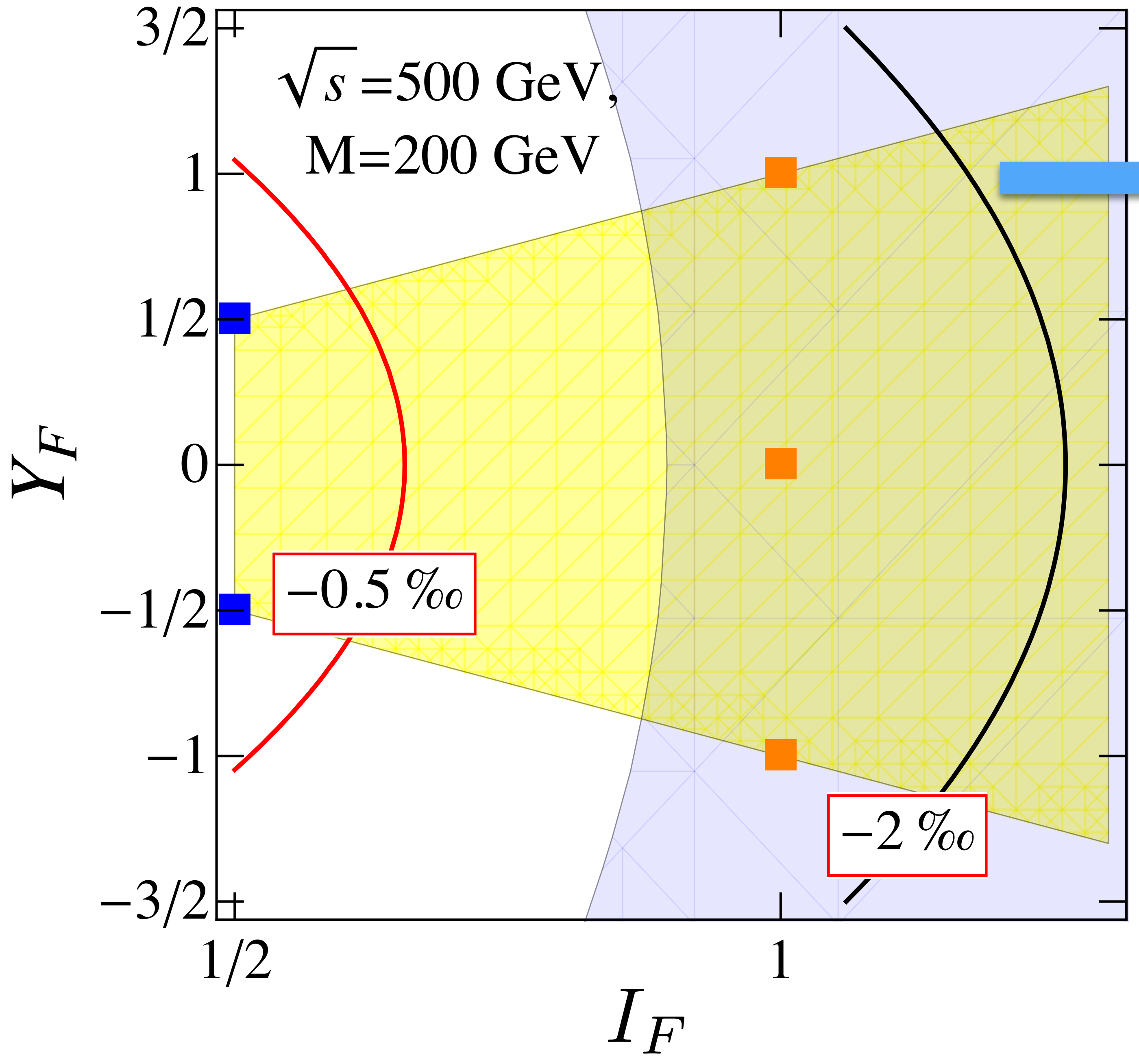
Yellow region:

Representations with DM candidate

Doublet, Triplet, Quartet, Quintet allowed

Weak and Hypercharge Quantum Numbers of F

$$Y_F \in \{-I_F, -I_F+1, \cdots, I_F\}$$



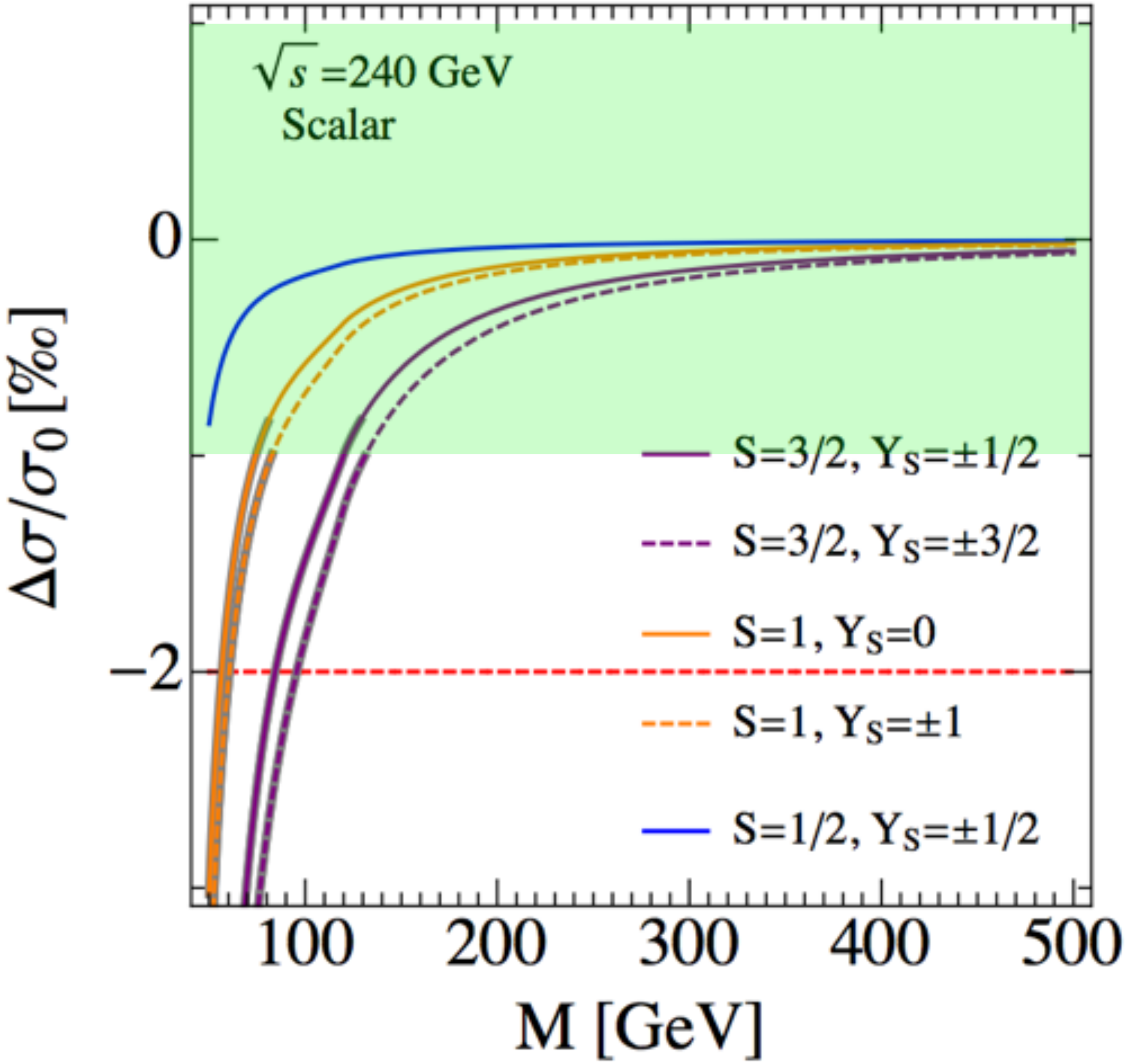
Blue region :
exclusion by
mono-jet + MET

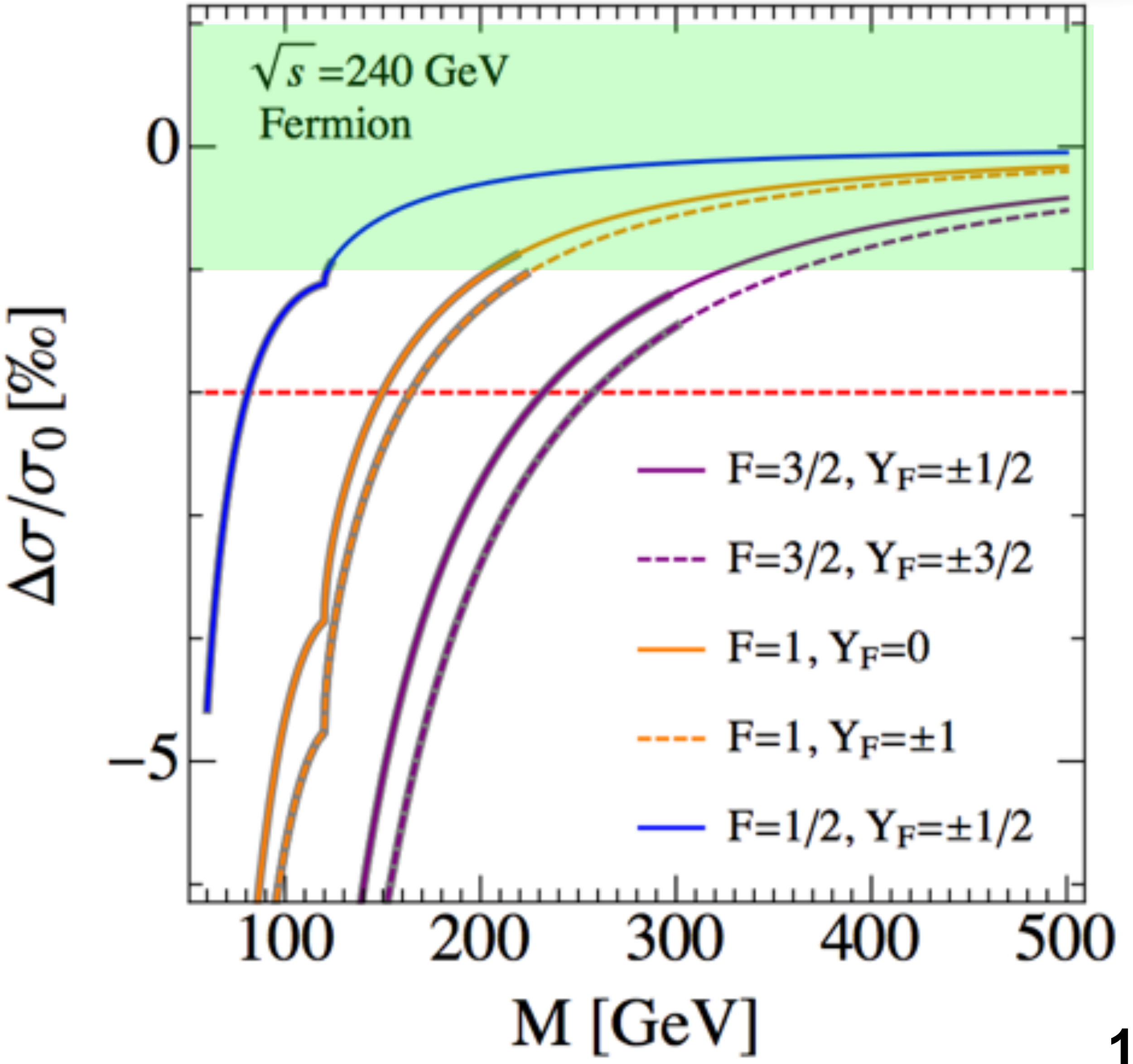
Yellow region:
Representations
with DM candidate

Only fermion doublet allowed

Deviation of $e^+e^-\rightarrow W^+W^-$ at the CEPC (240GeV)

$$g_{1,Z} = -\frac{e^2}{120\pi^2 s_W^2}\frac{m_W^2}{M^2}\frac{s_W^2}{c_W^4}D_R Y_R^2,$$
$$\lambda_Z = +\frac{e^2}{240\pi^2 s_W^2}\frac{m_W^2}{M^2}C_R,$$
$$\kappa_Z = -\frac{e^2}{120\pi^2 s_W^2}\frac{m_W^2}{M^2}\frac{s_W^2}{c_W^4}D_R Y_R^2$$

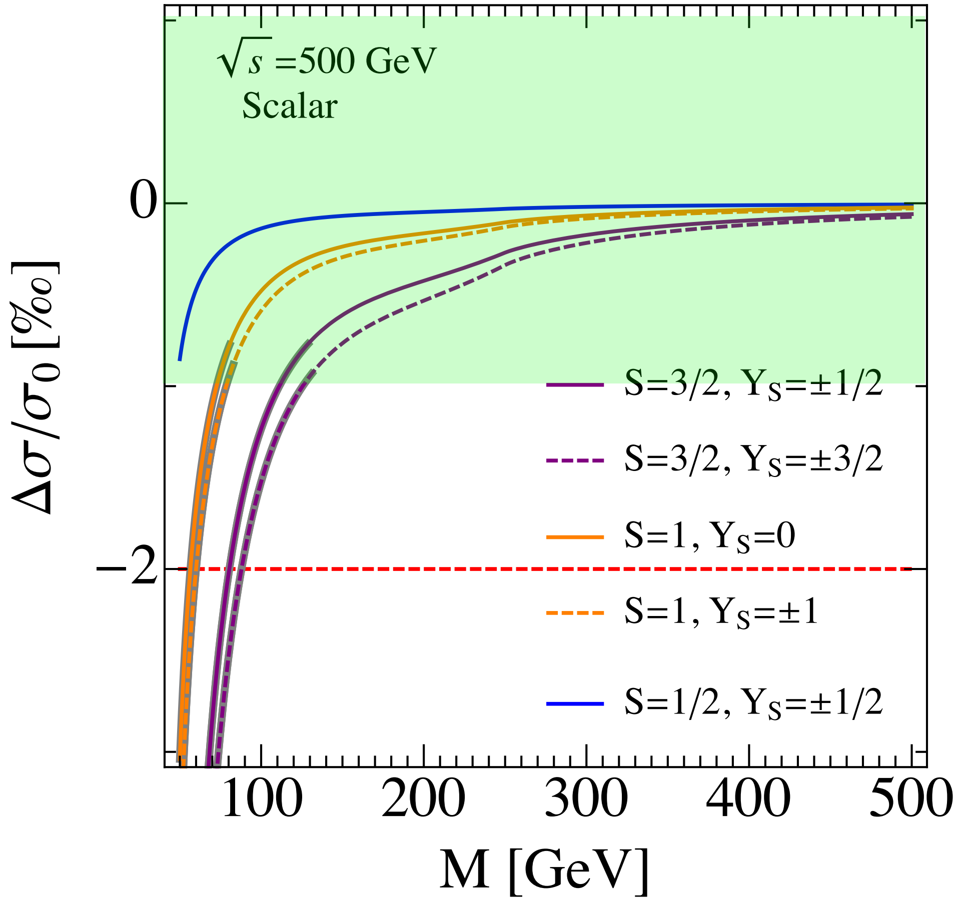


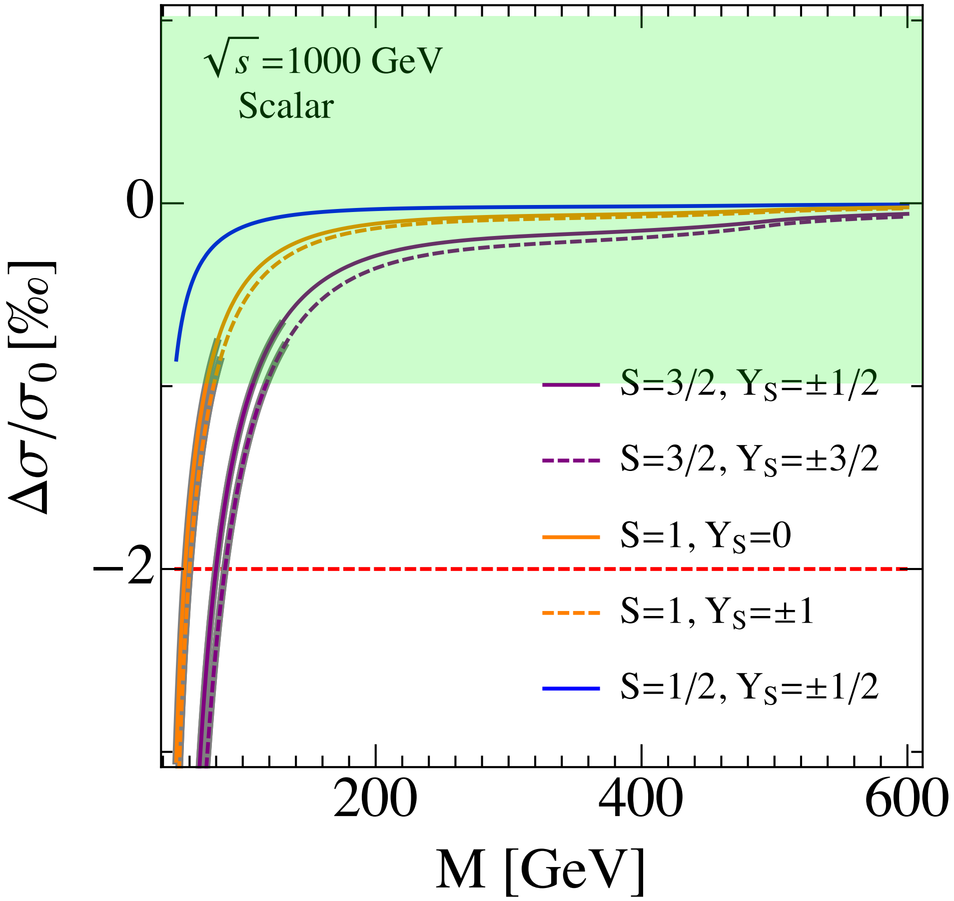


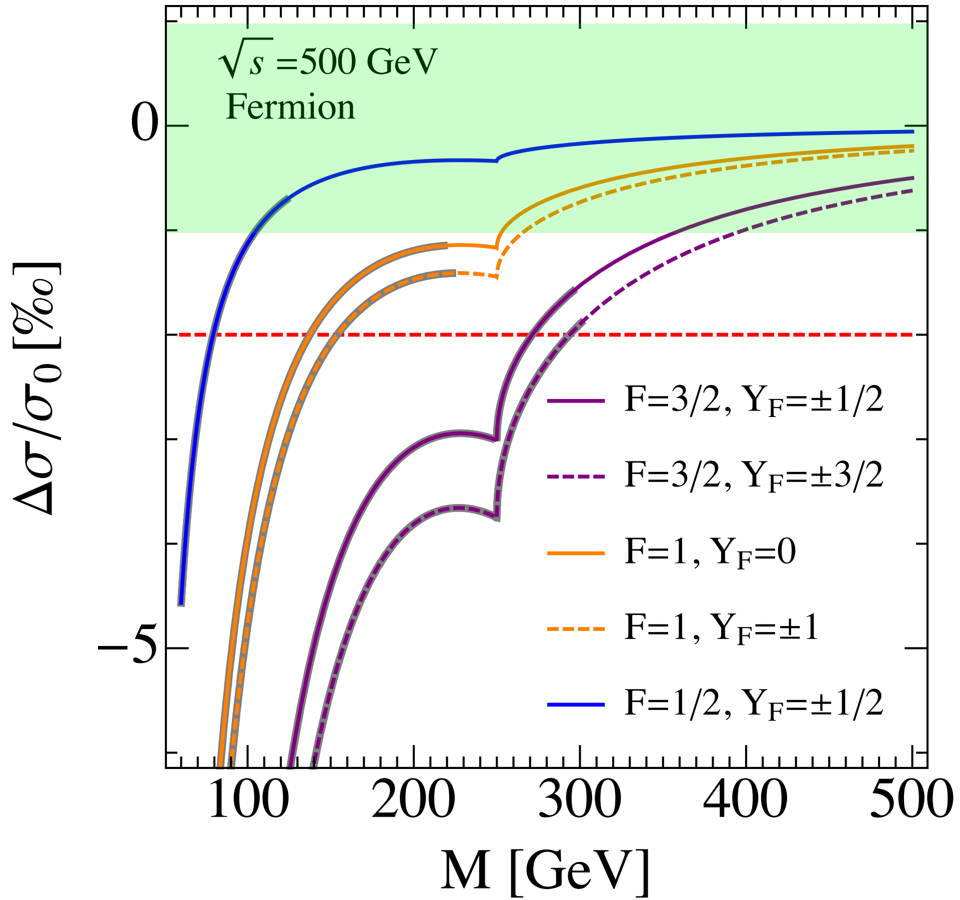
Gray shaded bands:

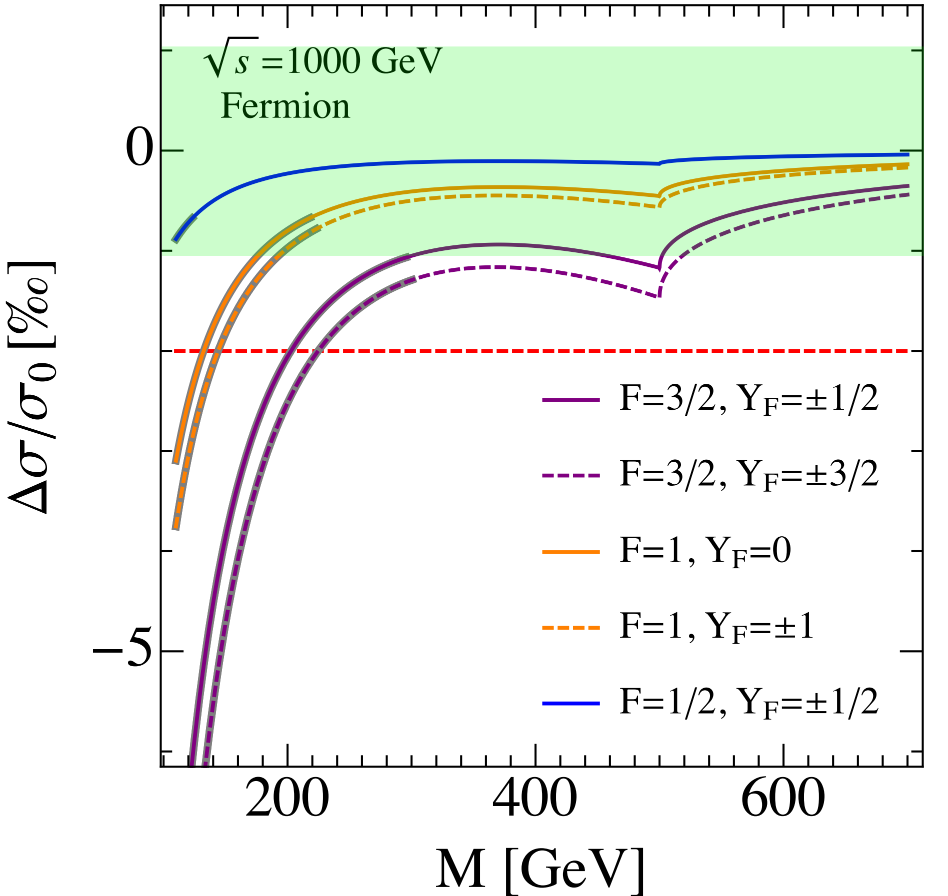
excluded by
Mono-jet + MET data

Electron-Positron Colliders (500GeV and 1TeV)

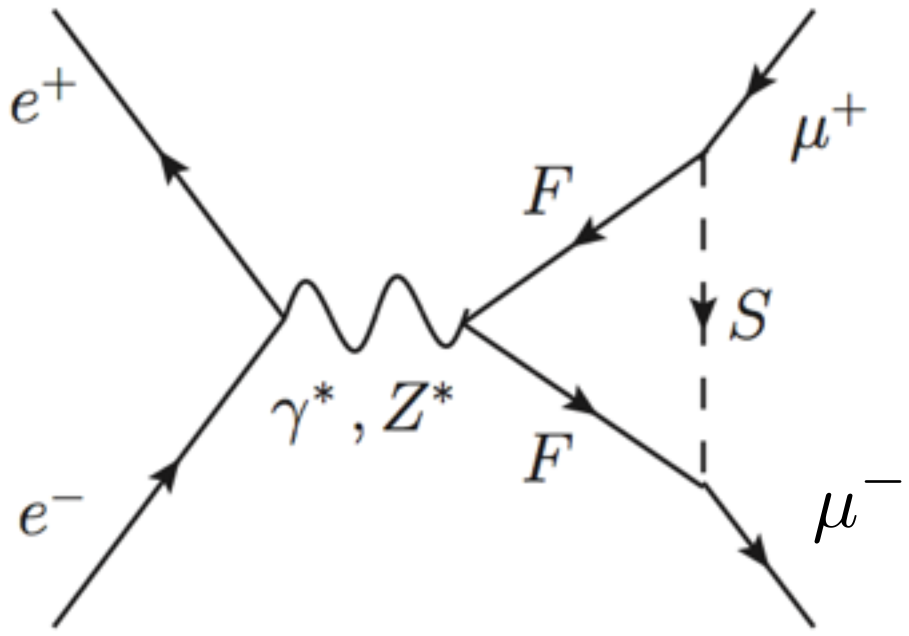


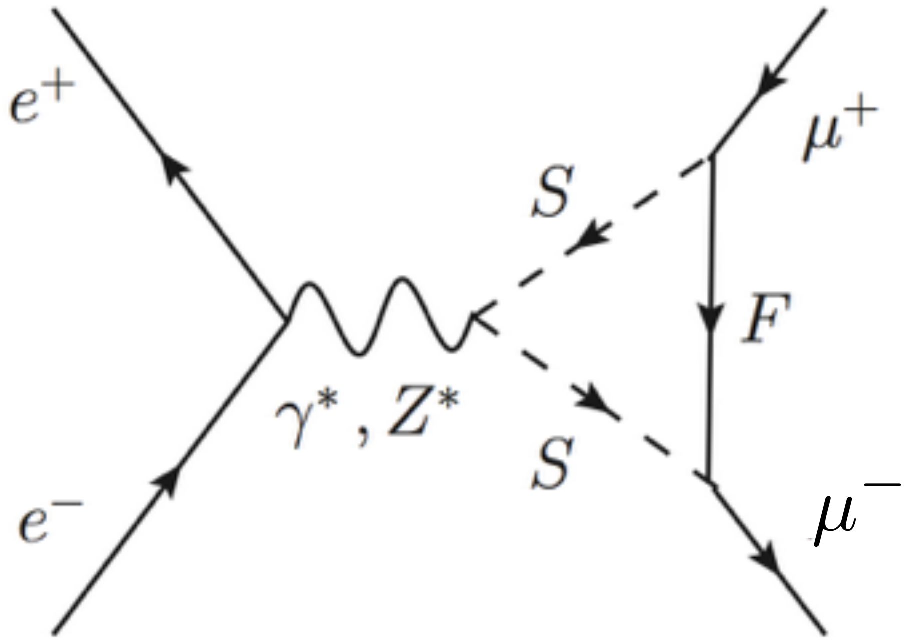






2) $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$

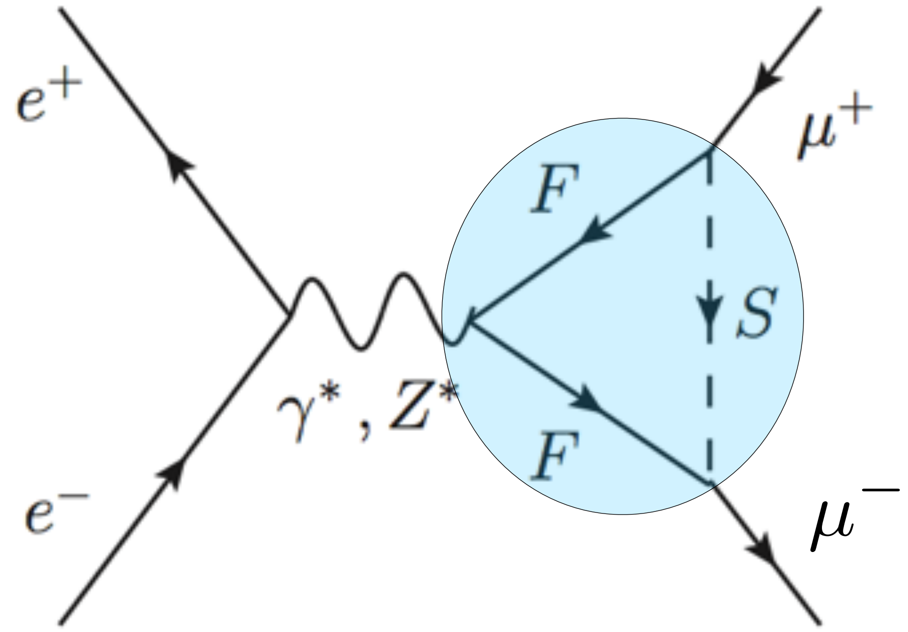


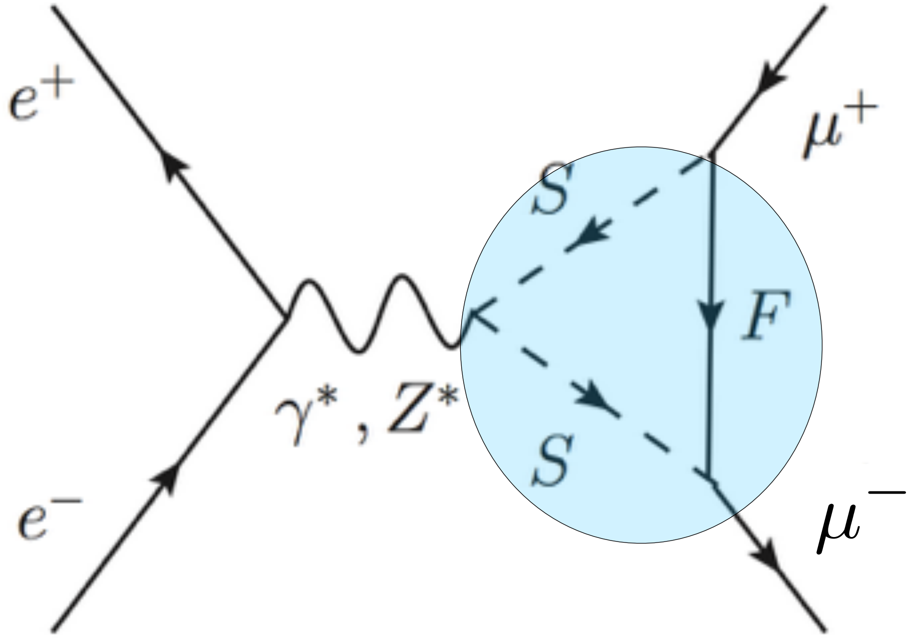


Simplified new physics model

$$\Delta\mathcal{L} = \bar{F}(i\not{D} - M_F)F + |D_\mu S|^2 - M_S^2 S^\dagger S - V(S,H)$$

$$+ \left\{ \begin{array}{l} yC_{ijk}S^i\bar{\mu}_L^k F^j + h.c. \\ yC_{ij}S^i\bar{\mu}_R F^j + h.c. \end{array} \right.$$



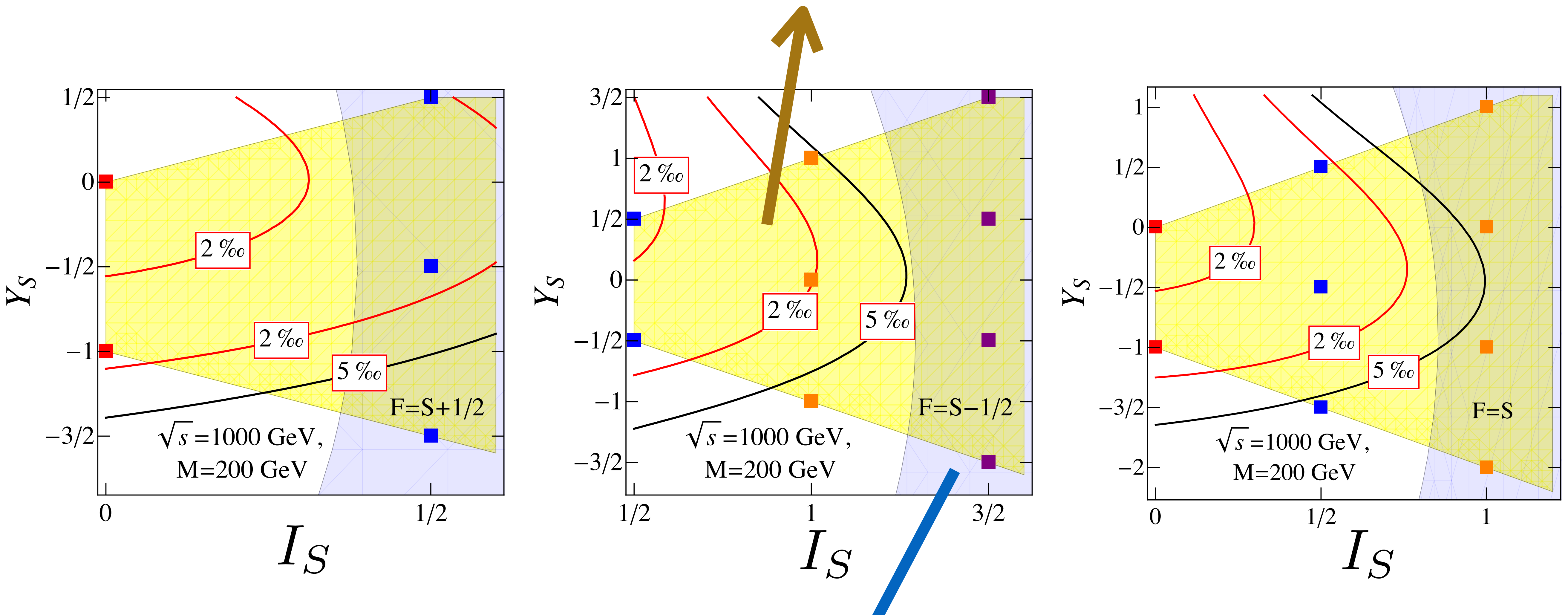


Effective couplings of $Z\mu^+\mu^-/\gamma\mu^+\mu^-$

$$-ie\bar{u}(k_-)\left(\alpha_V\gamma^\mu + \mathrm{i}\beta_V\sigma^{\mu\nu}q_\nu + \xi_{1,V}\gamma^\mu\gamma_5 + \xi_{2,V}q^\mu\gamma_5\right)v(k_+)$$

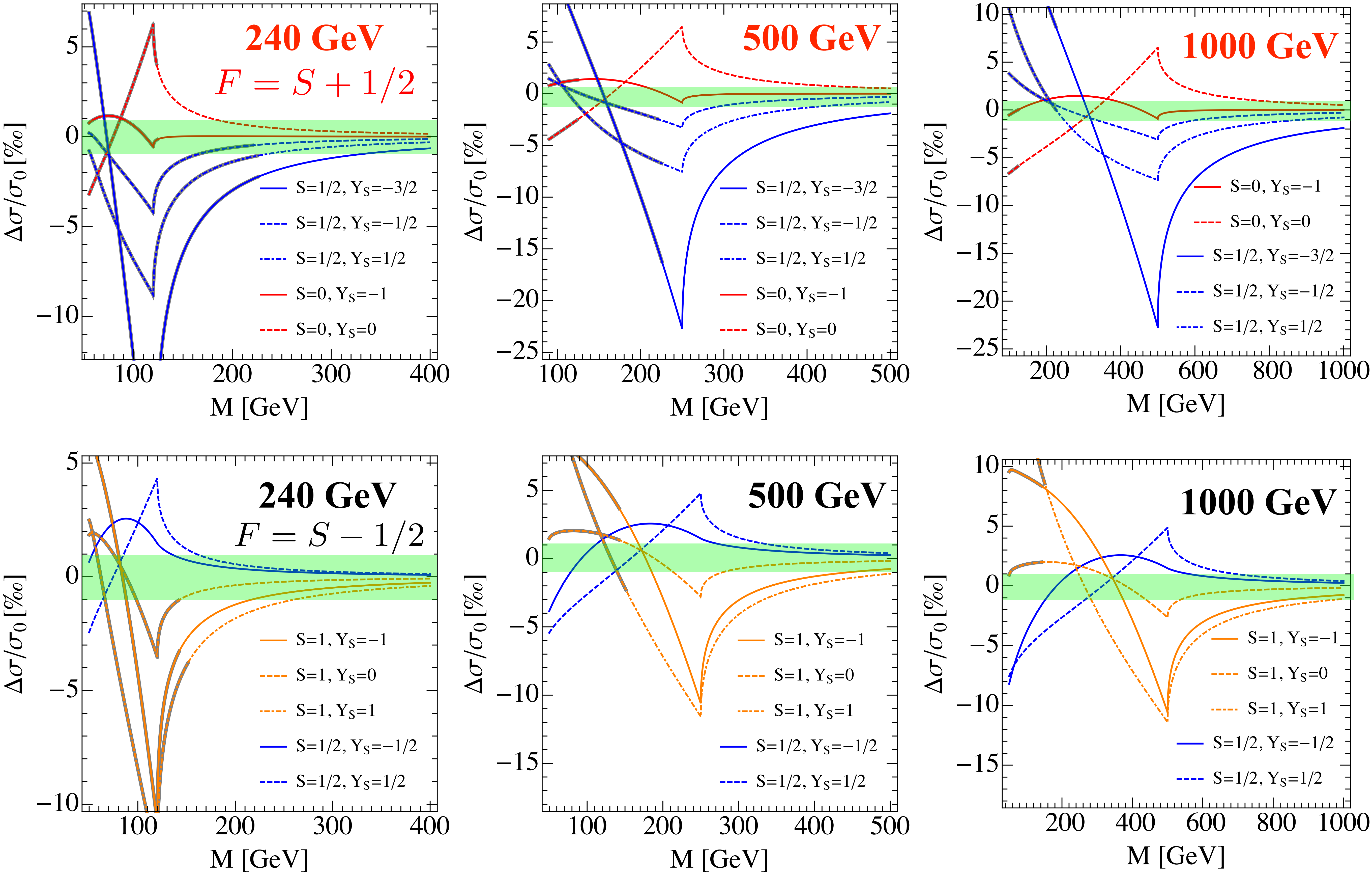
Weak and Hypercharge Quantum Numbers of S and F

Yellow region:
Representations with DM candidate



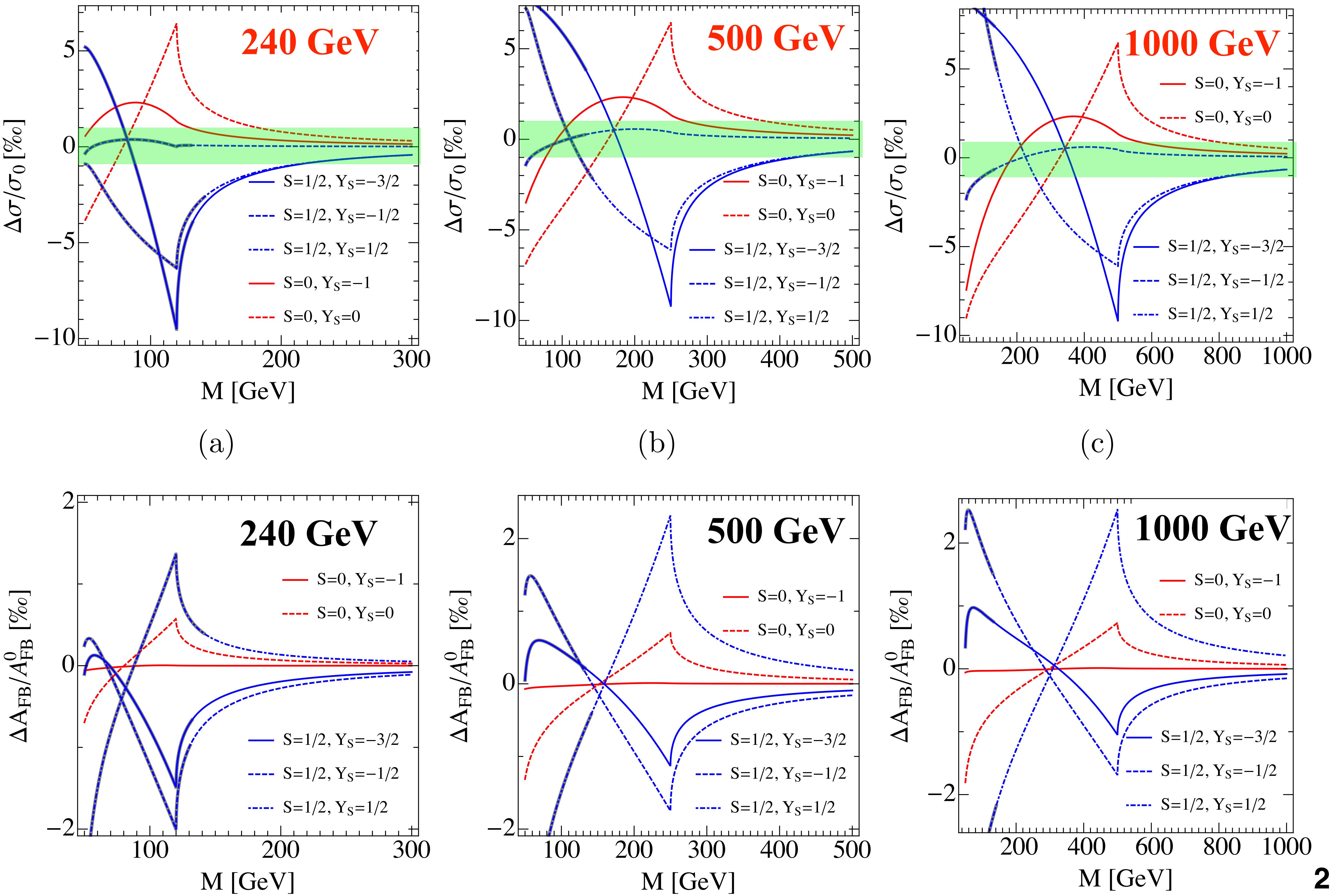
Blue region :
Higher Reps excluded by
mono-jet + MET data

Deviation of cross section of $e^+e^-\rightarrow\mu^+\mu^-$



The e^+e^- collider with 10^{-3} precision can probe certain parameter space

$e^+e^- \longrightarrow \mu^+\mu^-$: $F = S$ (μ_R)

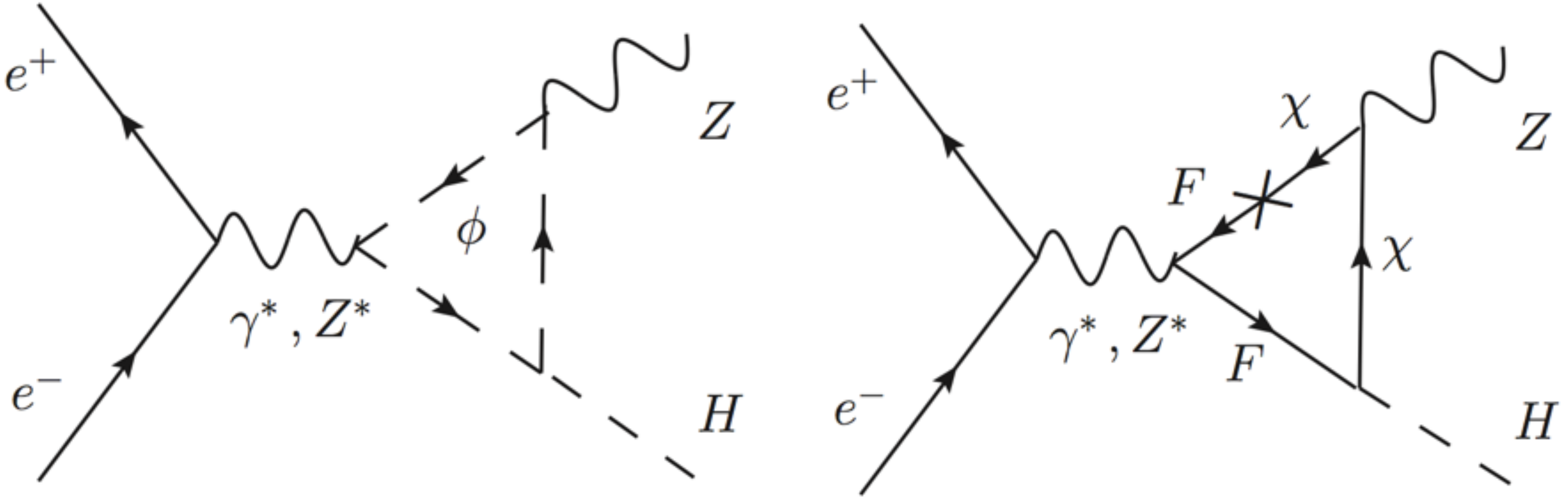


(a)

(b)

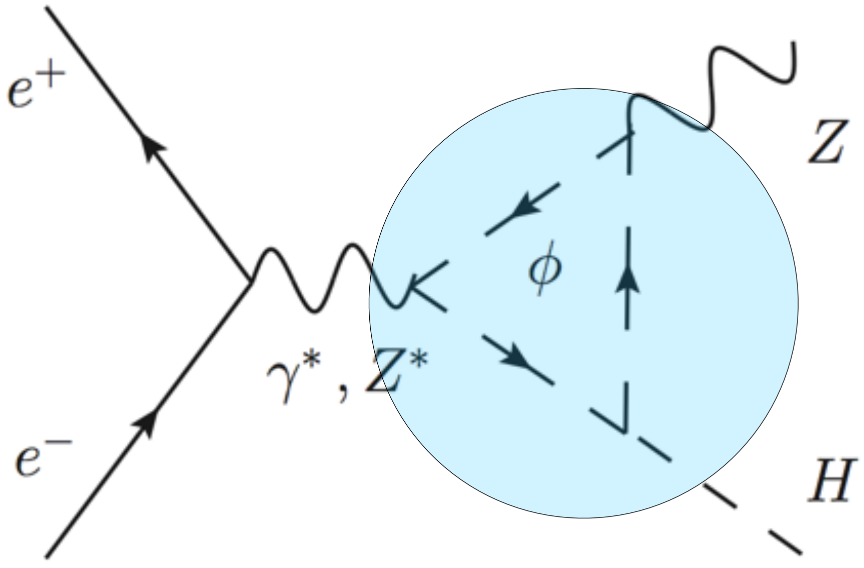
(c)

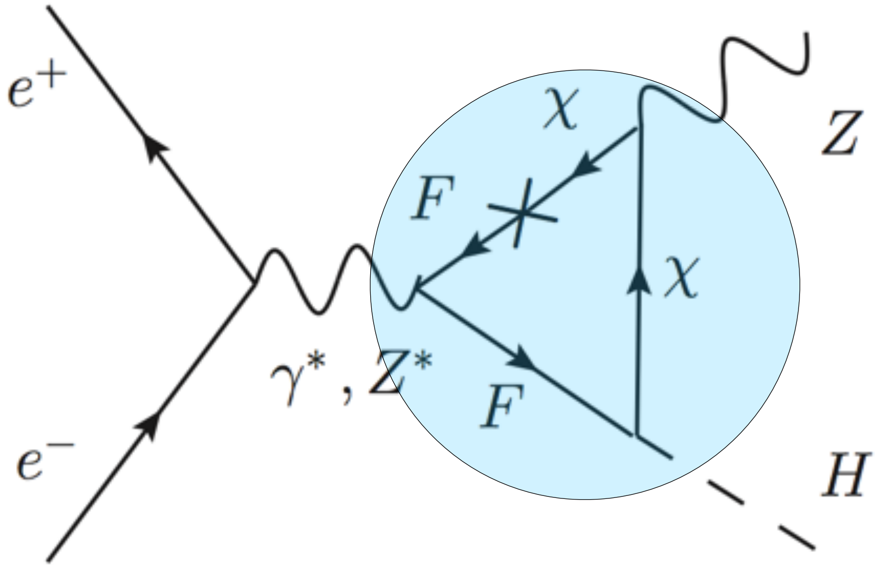
3) $e^+e^- \to ZH$



Simplified new physics model

New scalars and fermions





Effective $HZZ/HZ\gamma$ couplings

$$ig_Z m_Z[c_{1,V} g^{\mu\alpha} - \frac{c_{2,V}}{m_Z^2}(-g^{\mu\alpha}k\cdot q + k^\mu q^\alpha)]$$

Simplified new physics model

New scalar

$$\begin{aligned} V(\phi, H) = {} & \lambda_1 C^1_{ijkl} \left(H^i H^{\dagger j}\right) \left(\phi^k \phi^{\dagger l}\right) + \lambda_2 C^2_{ijkl} \left(\phi^{\dagger l} H^i\right) \left(\phi^k H^{\dagger j}\right) + \lambda_3 C^3_{ijkl} \left(\phi^{\dagger l} H^{\dagger j}\right) \left(\phi^k H^i\right) \\ & + \lambda_4 C^4_{ijkl} \left(\phi^l H^j\right) \left(\phi^k H^i\right) + \lambda_5 C^5_{ijkl} \left(H^i H^j\right) \left(\phi^l \phi^k\right) \\ & + \lambda_6 C^6_{ijkl} \left(\phi^l H^{\dagger j}\right) \left(\phi^k H^i\right) + \lambda_7 C^7_{ijkl} \left(\phi^{\dagger l} H^j\right) \left(\phi^k H^i\right) \\ & + \lambda_8 C^8_{ijkl} \left(H^i H^{\dagger j}\right) \left(\phi^k \phi^l\right) + \lambda_9 C^9_{ijkl} \left(H^i H^j\right) \left(\phi^k \phi^{\dagger l}\right) \\ & + \lambda_{10} C^{10}_{ijkl} \left(H^{\dagger i} H^{\dagger j}\right) \left(\phi^k \phi^l\right) + h.c. \ + \cdots . \end{aligned}$$

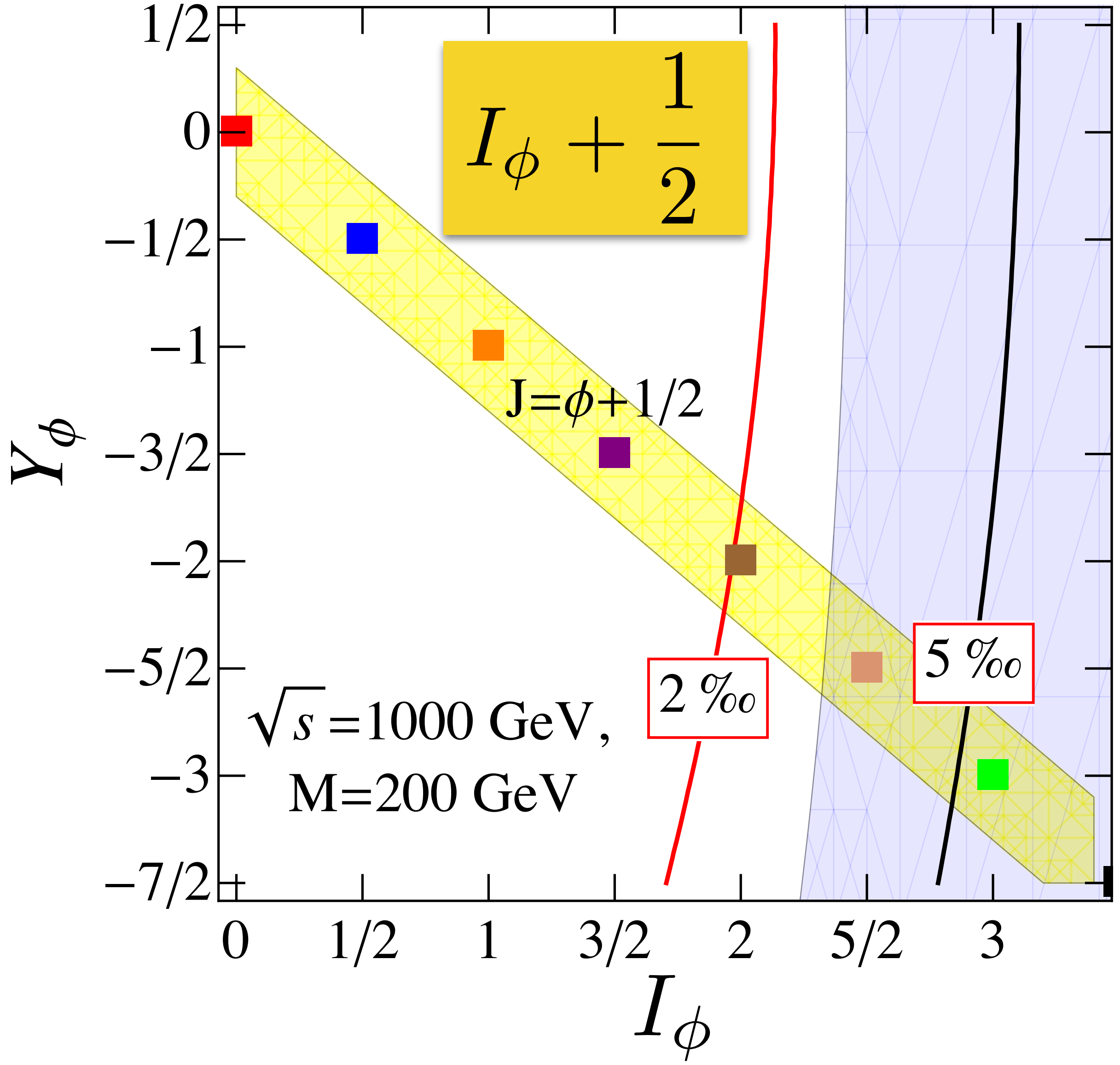
Focusing on

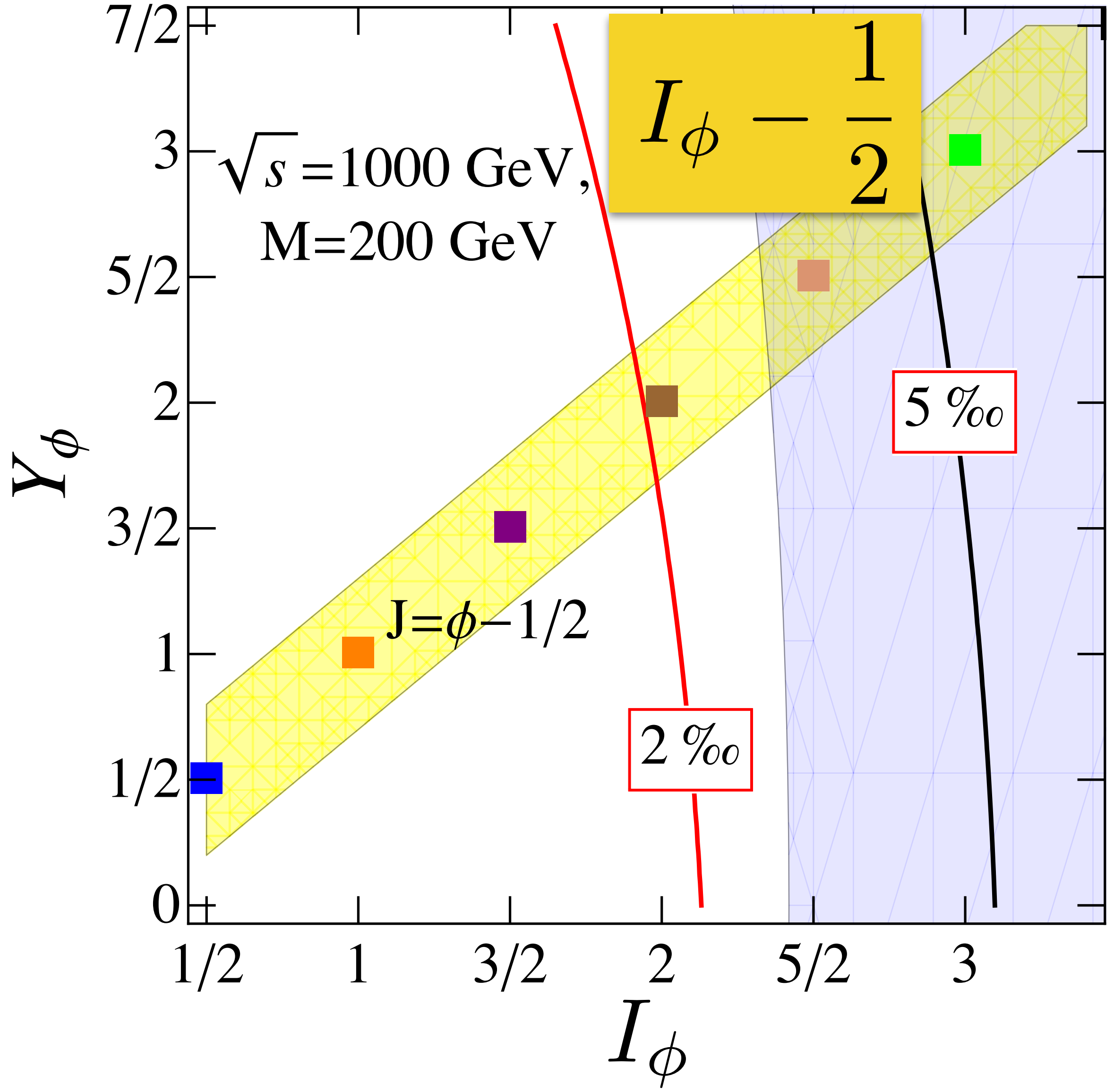
$$\lambda C_{ijkl} \left(\phi^{\dagger l} H^i\right) \left(\phi^k H^{\dagger j}\right)$$

New vector fermions

$$\Delta \mathcal{L} = \bar{F}(i\not{D} - M_F)F + \bar{\chi}(i\not{D} - M_\chi)\chi + y C_{ijk} \bar{F}^i \chi^j H^k + h.c.$$

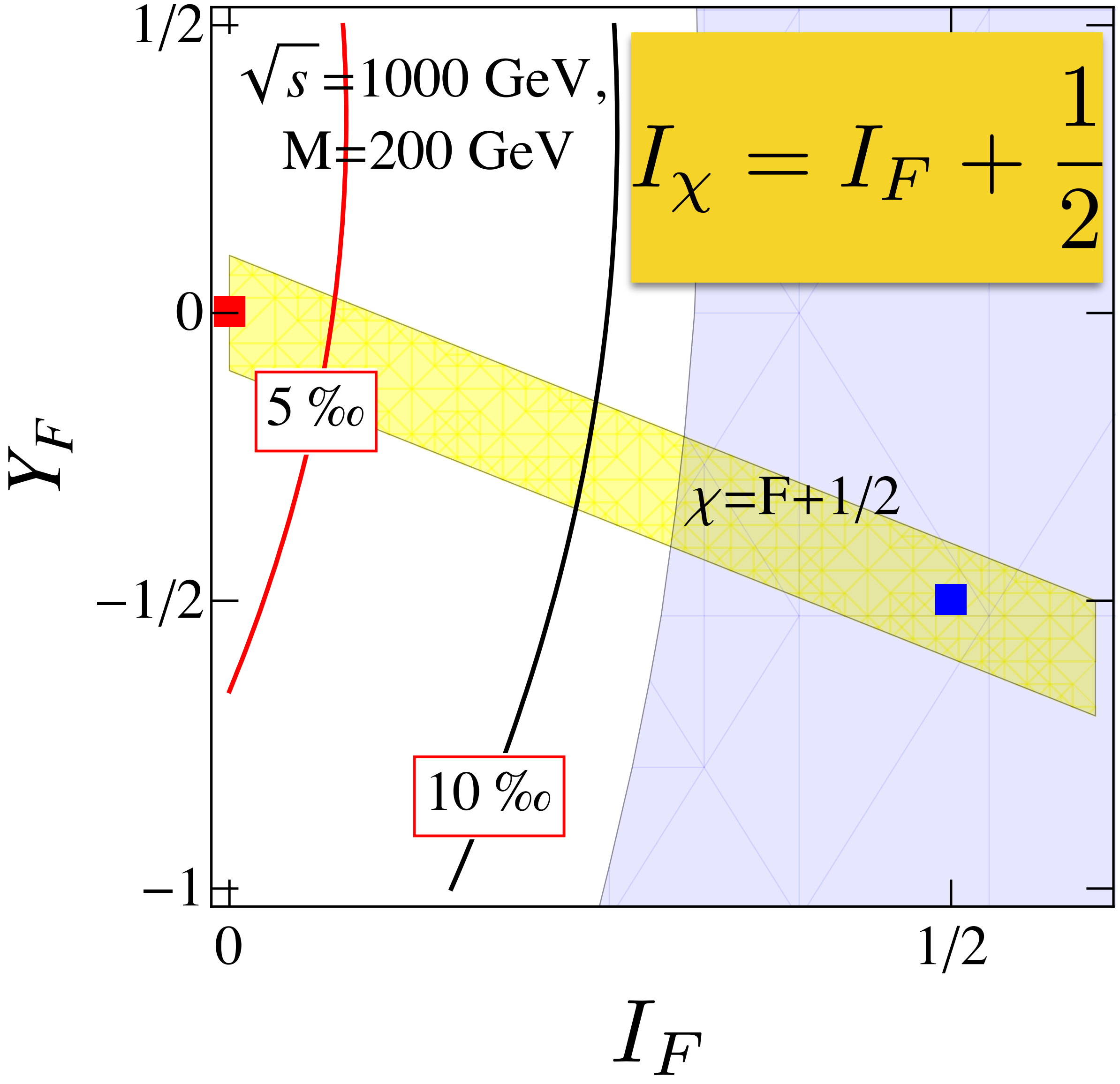
Weak and Hypercharge Quantum Numbers of ϕ

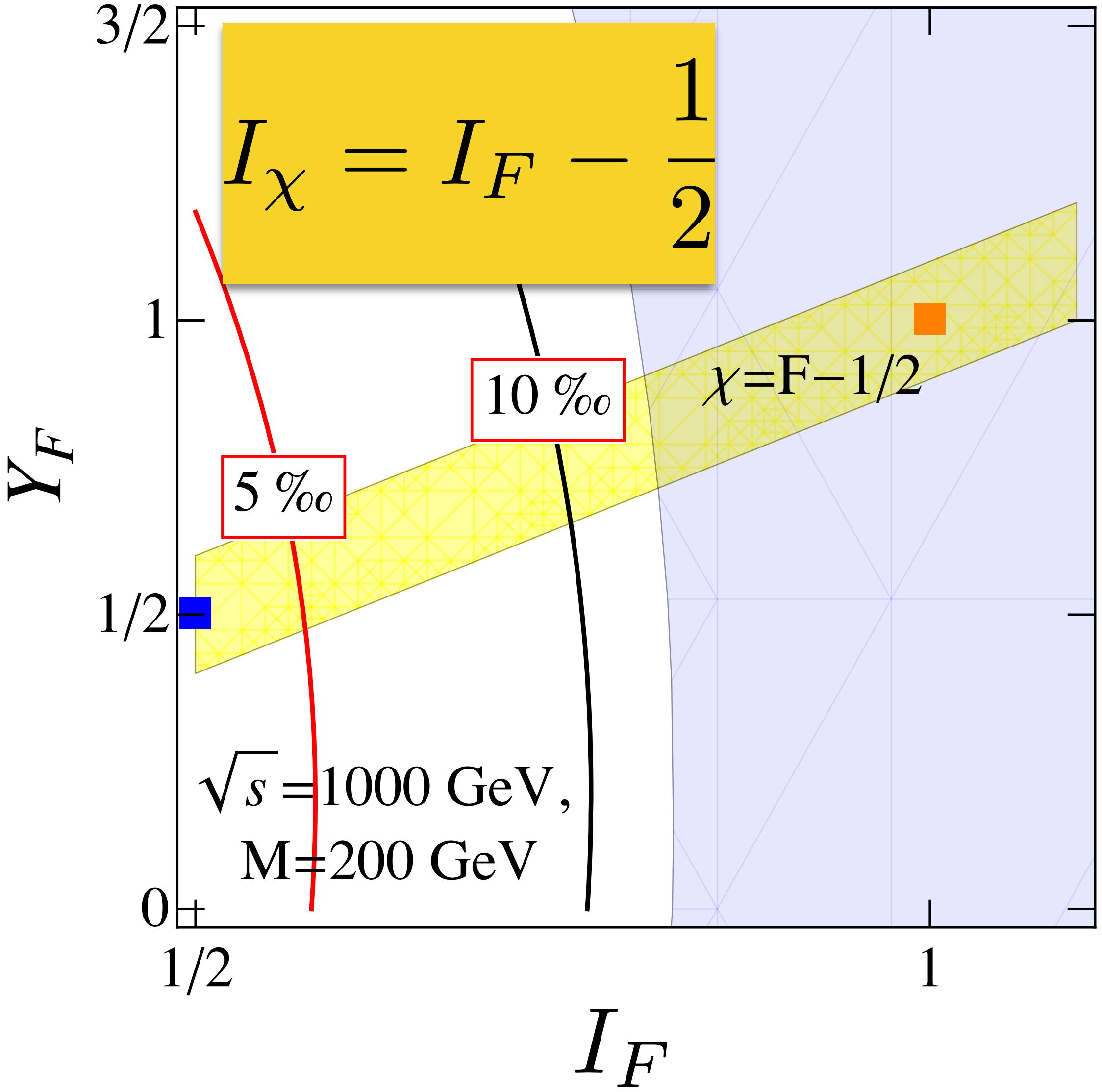


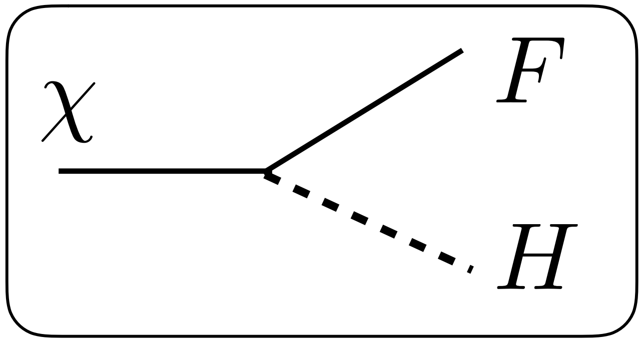


$$M_k^2 - M_\phi^2 = \begin{cases} -\dfrac{\phi+1+k}{(\phi+1)(2\phi+1)}\dfrac{\lambda v^2}{2}, & \text{for } J = \phi + \dfrac{1}{2} \\[2ex] -\dfrac{\phi-k}{\phi(2\phi+1)}\dfrac{\lambda v^2}{2} & \text{for } J = \phi - \dfrac{1}{2} \end{cases}$$

Weak and Hypercharge Quantum Numbers of F

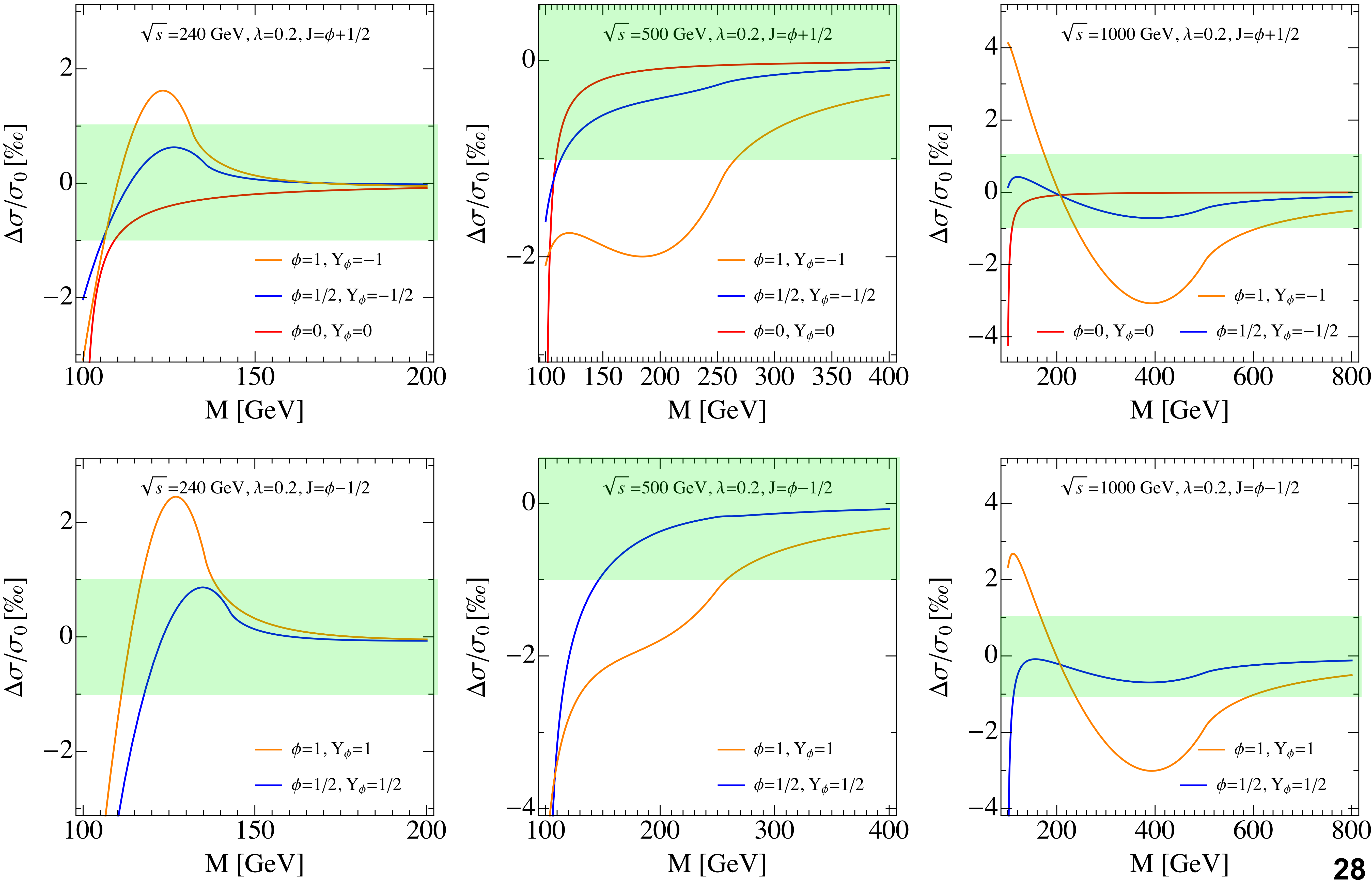




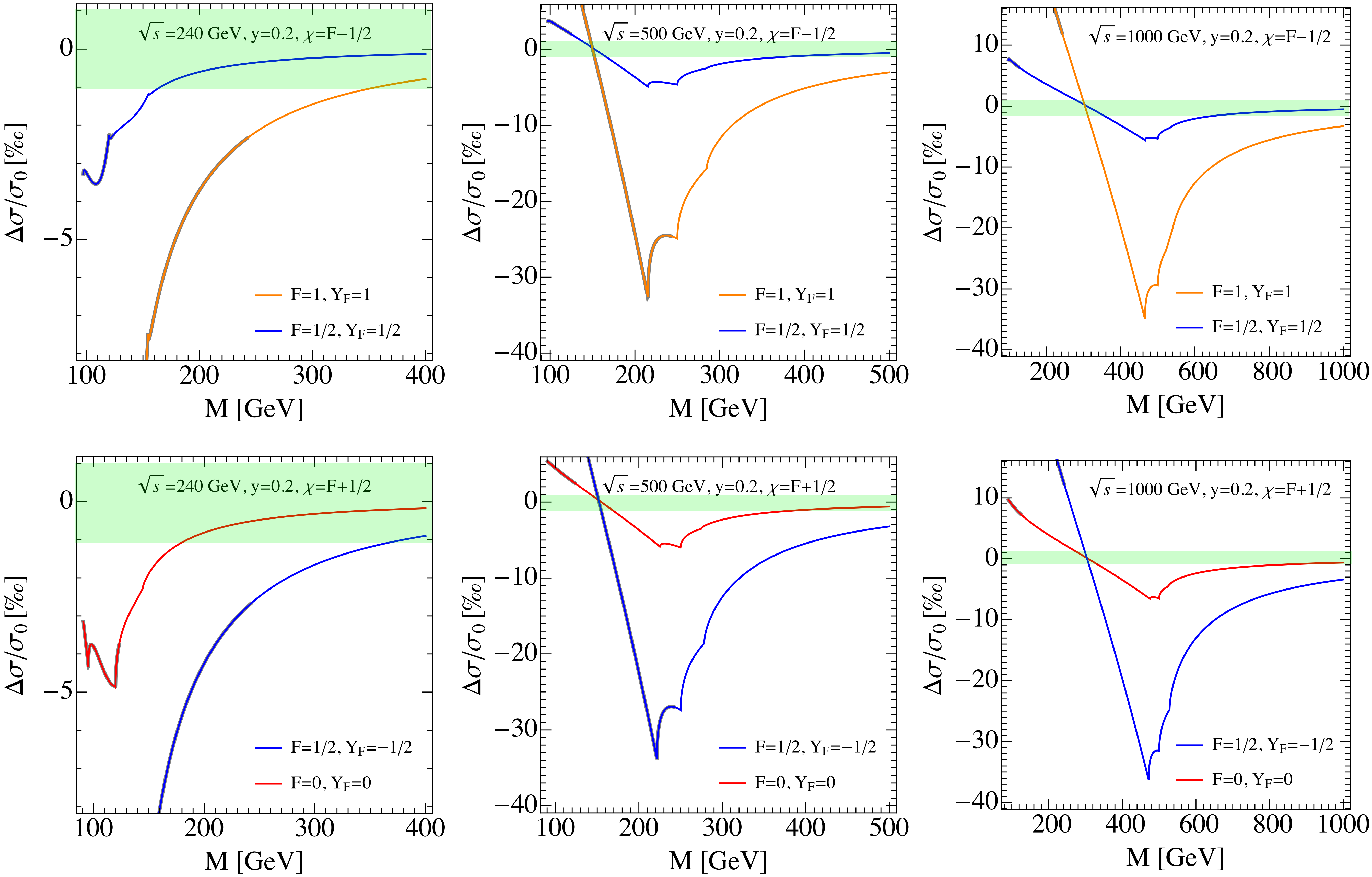


$$M_i - M_F = \begin{cases} \pm \frac{yv}{\sqrt{2}} \sqrt{\frac{F-i}{2F}}, & \text{for } \chi = F - \frac{1}{2} \\ \pm \frac{yv}{\sqrt{2}} \sqrt{\frac{F+1+i}{2F+2}}, & \text{for } \chi = F + \frac{1}{2} \end{cases}$$

$e^+e^- \to ZH$: Scalar Loop

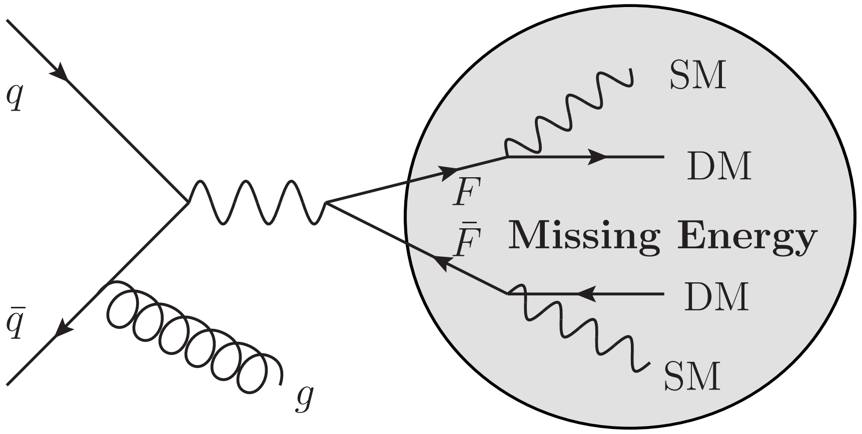


$e^+e^- \to ZH$: Fermion Loop



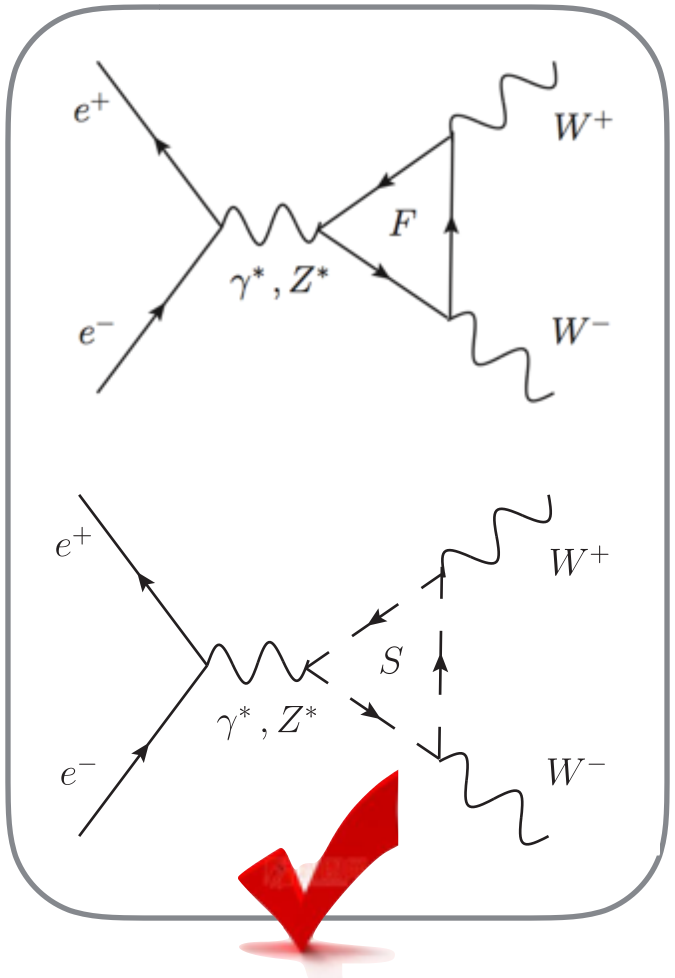
Summary

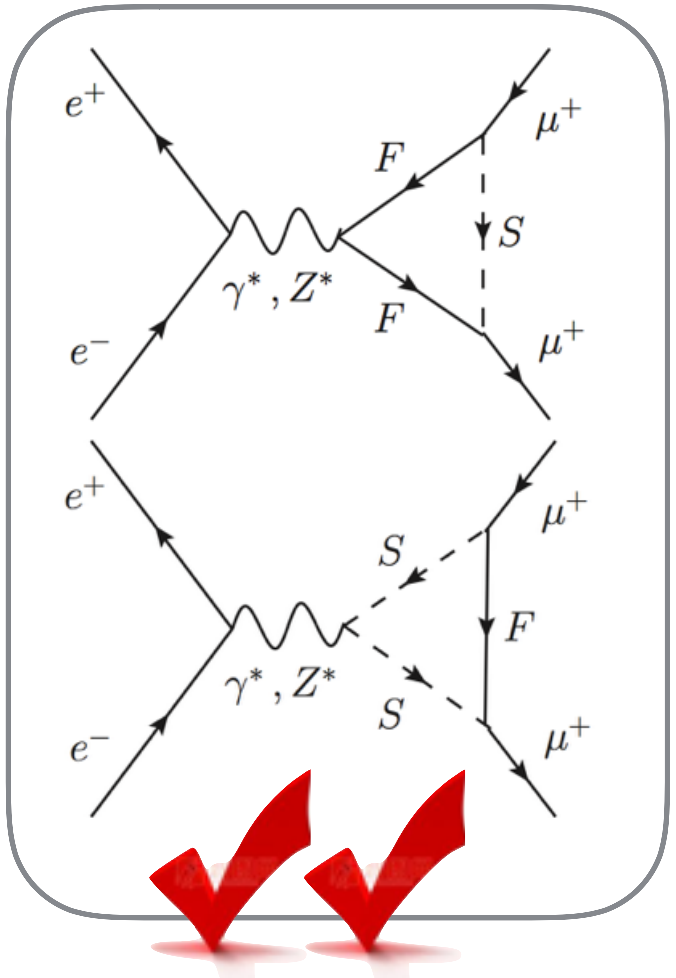
It is hard to probe DM models with nearly degenerate mass spectrum

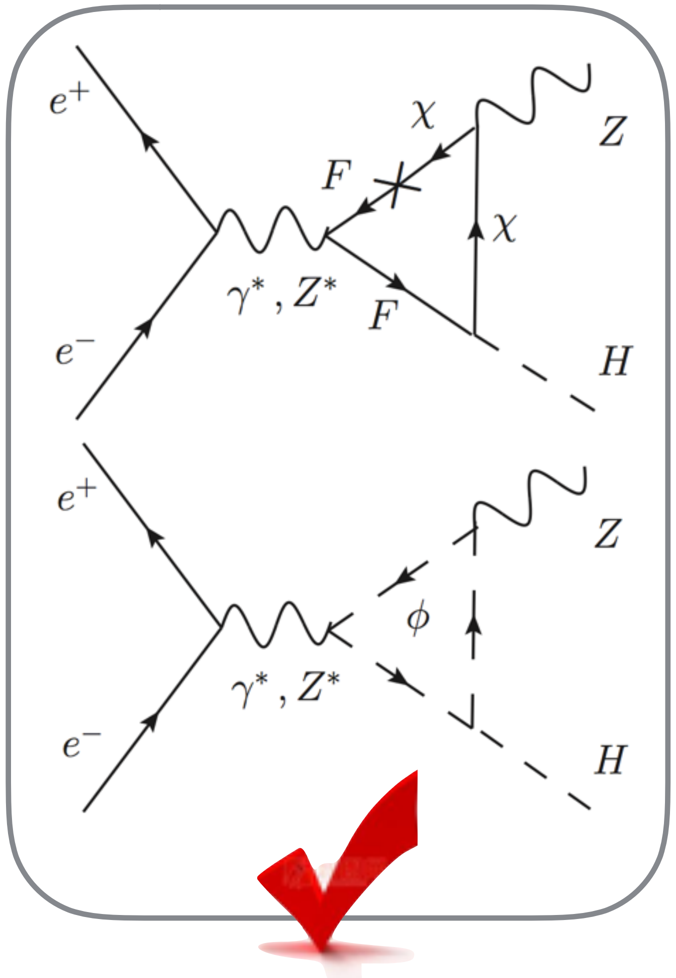


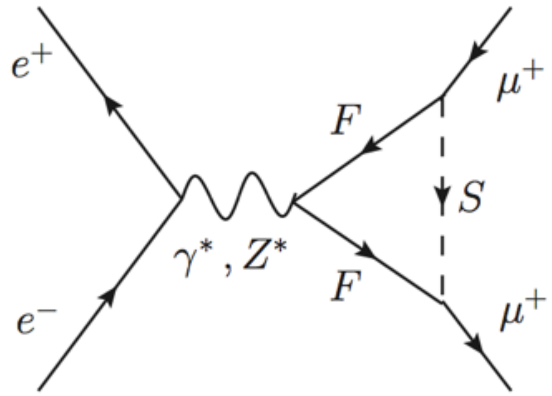
Mono-jet (photon) + MET

One could probe the loop effects of light NP particles, e.g.



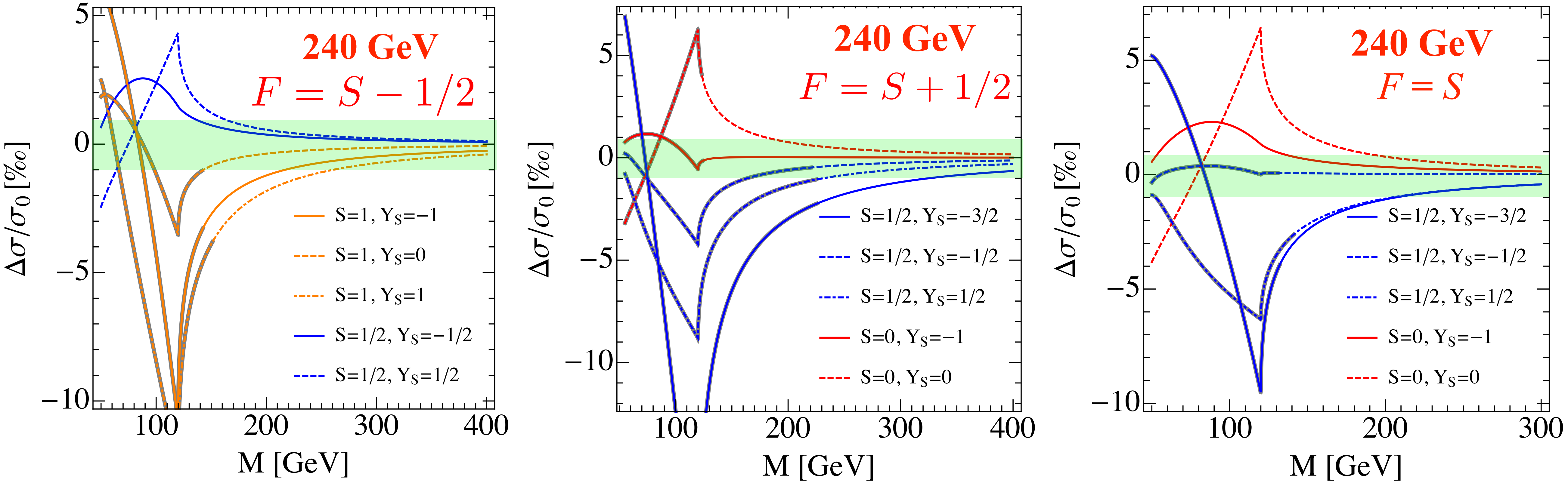






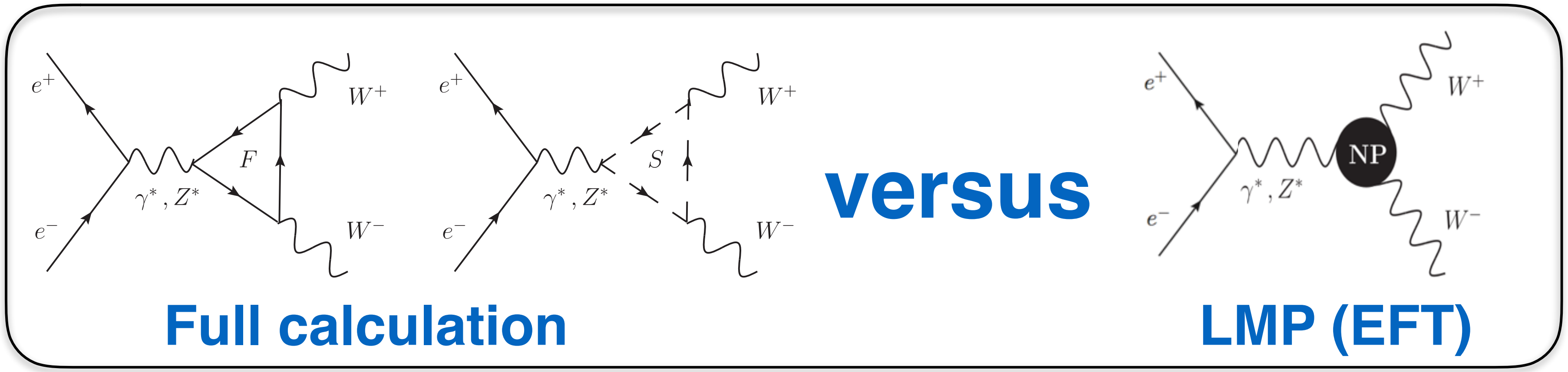
$F = S \pm 1/2$ $\quad$ $yC_{ijk}S^i\bar{\mu}_L^kF^j + h.c.$

$F = S$ $\quad$ $yC_{ij}S^i\bar{\mu}_RF^j + h.c.$



The e^+e^- collider with 10^{-3} Precision can probe certain parameter spaces of NP models

Increasing c.m. energy would improve the sensitivity significantly



Full calculation

versus

LMP (EFT)

$$M \gtrsim 2\sqrt{S}$$