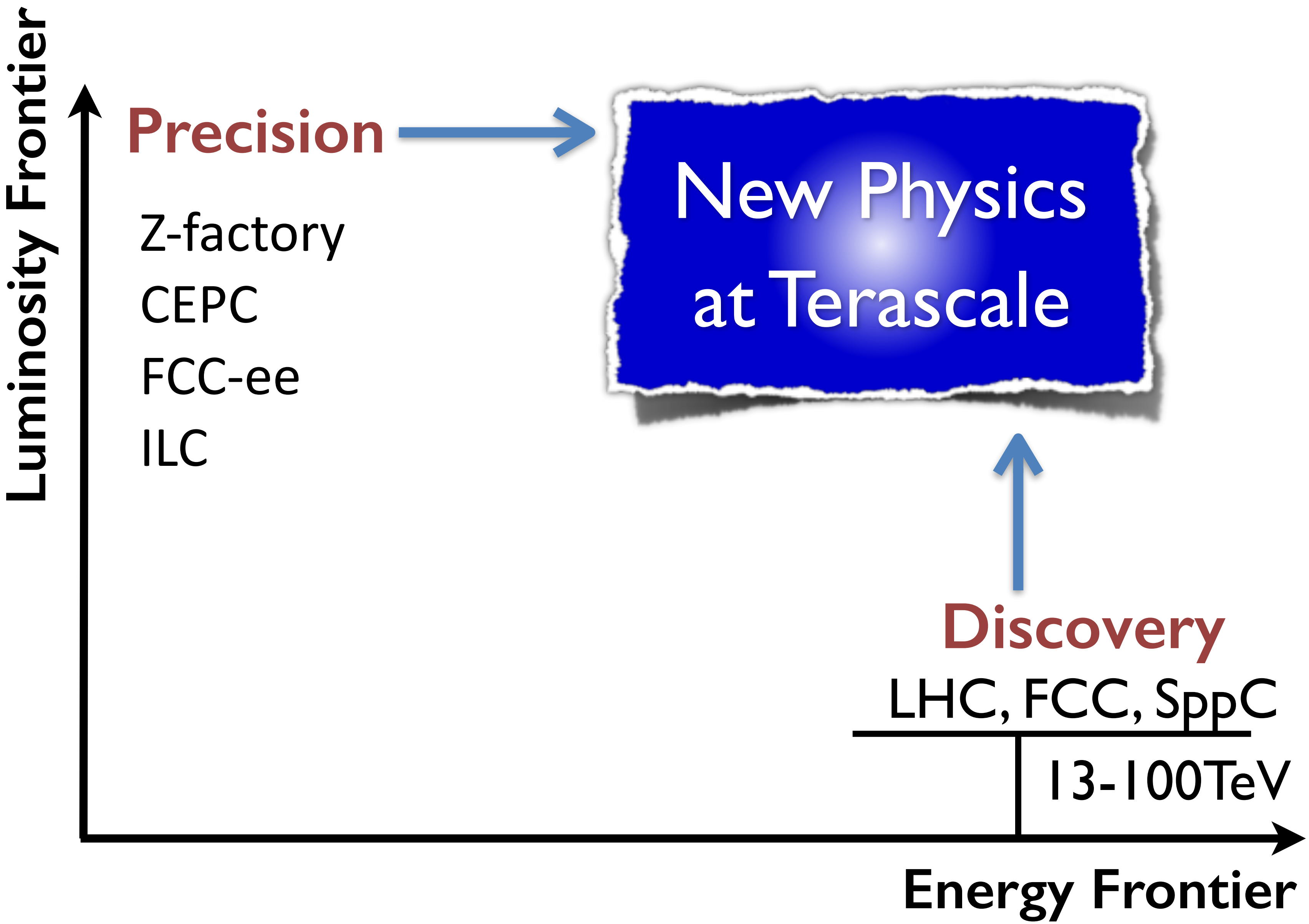
Probing dark particles indirectly at Electron-Positron Colliders

Qing-Hong Cao
Peking University

In collaboration with Yang Li, Bin Yan, Ya Zhang and Zhen Zhang

Nucl. Phys. B909 (2016) 197

Two Frontiers of High Energy Physics



DISCOVERY versus **PRECISION**

DISCOVERY versus PRECISION

New Resonance	SM Parameter values
Excesses (anomaly)	Anomalous couplings

DISCOVERY	versus	**PRECISION**
New Resonance		SM Parameter values
Excesses (anomaly)		Anomalous couplings
Direct search		Indirect search

DISCOVERY versus PRECISION

DISCOVERY	PRECISION
New Resonance	SM Parameter values
Excesses (anomaly)	Anomalous couplings
Direct search	Indirect search
Need good precision of SM backgrounds (mainly QCD)	Need accurate calculation of SM signal processes (mainly EW)

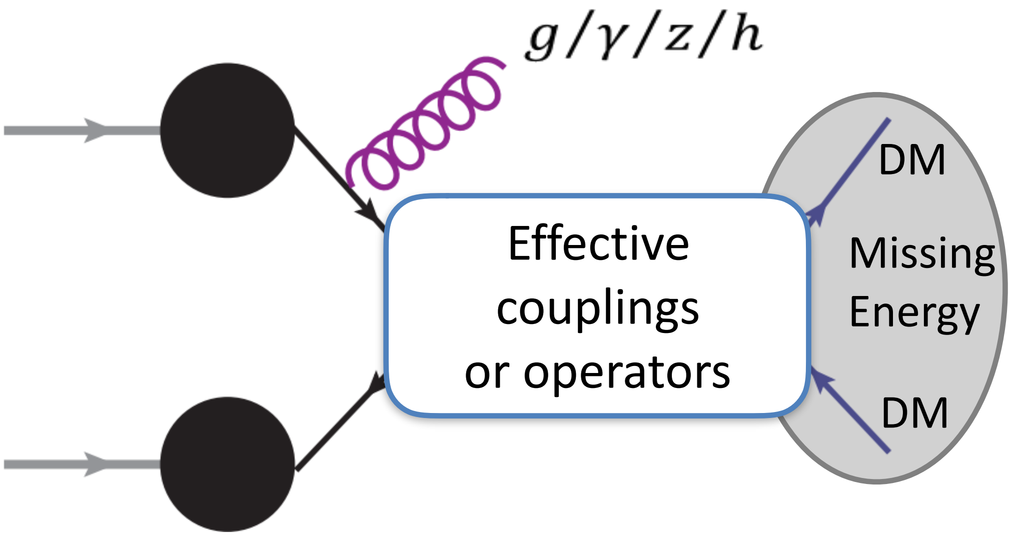
DISCOVERY versus PRECISION

DISCOVERY	PRECISION
New Resonance	SM Parameter values
Excesses (anomaly)	Anomalous couplings
Direct search	Indirect search
Need good precision of SM backgrounds (mainly QCD)	Need accurate calculation of SM signal processes (mainly EW)
SM parameter values? (mainly limits)	

DISCOVERY versus PRECISION

DISCOVERY	PRECISION
New Resonance	SM Parameter values
Excesses (anomaly)	Anomalous couplings
Direct search	Indirect search
Need good precision of SM backgrounds (mainly QCD)	Need accurate calculation of SM signal processes (mainly EW)
SM parameter values? (mainly limits)	
Now	Future

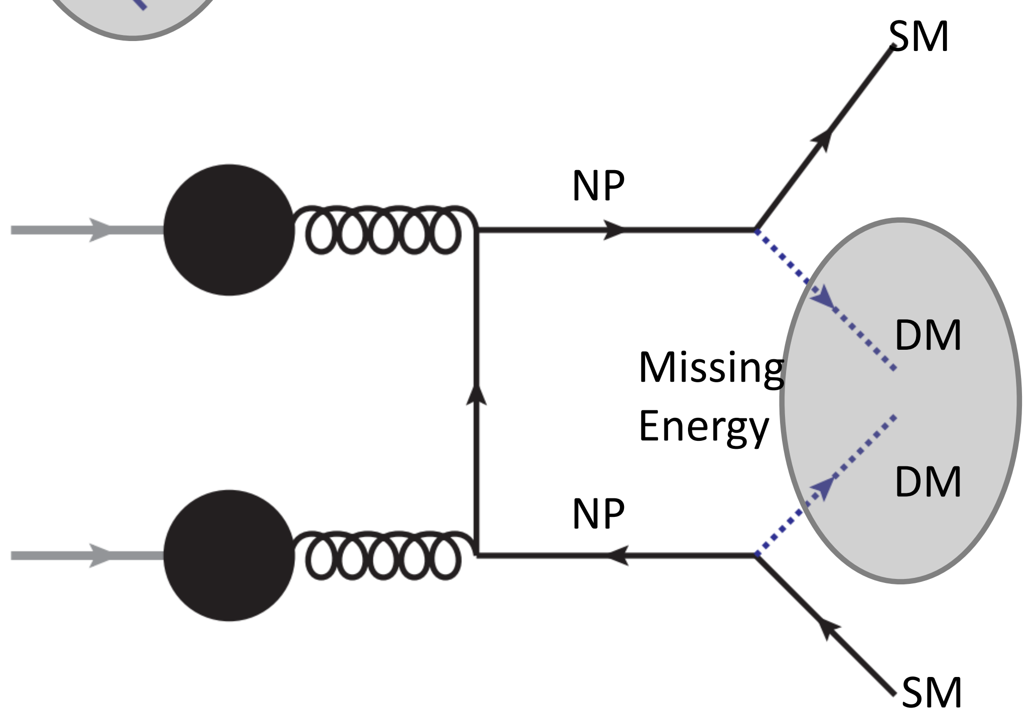
Dark Matter at the LHC



Mono-X plus MET

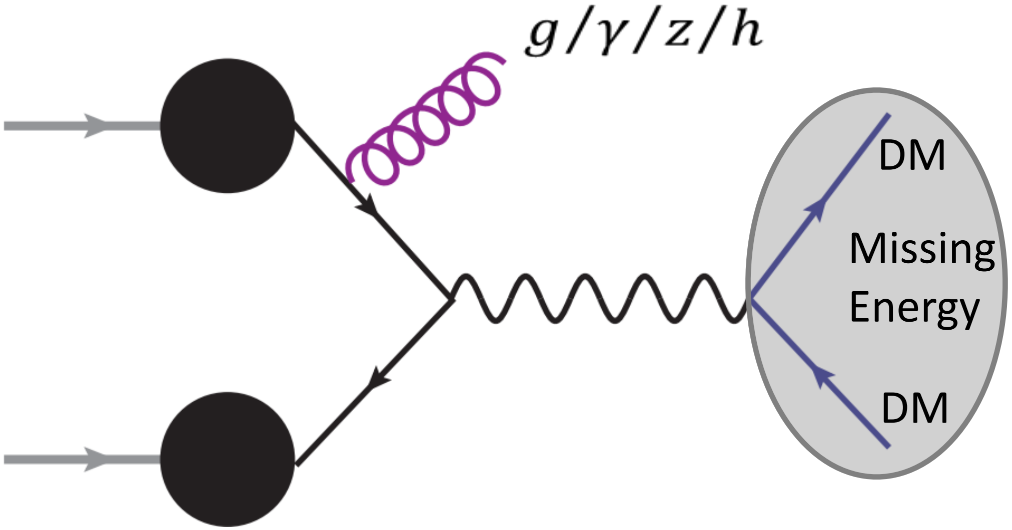
V. Khachatryan et al. (CMS), Eur. Phys. J. C75,235 (2015);
G. Aad et al. (ATLAS), Eur. Phys. J. C75,299 (2015)

SM pair plus MET



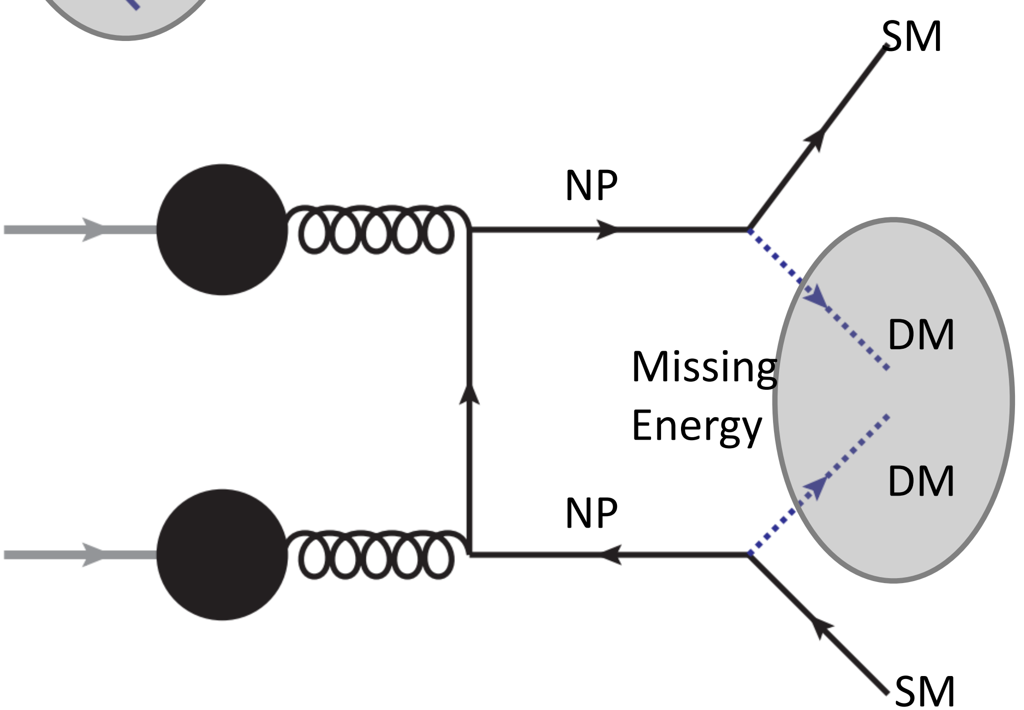
Qing Hong Cao et al. Phys. Rev. Lett.109 (2012) 152004;
Haipeng An et al. Phys. Rev. Lett.115 (2015) 181602;
Qing Hong Cao, Chuan-Ren Chen and Yandong Liu, arxiv:1512.09144

Dark Matter at the LHC



Mono-X plus MET

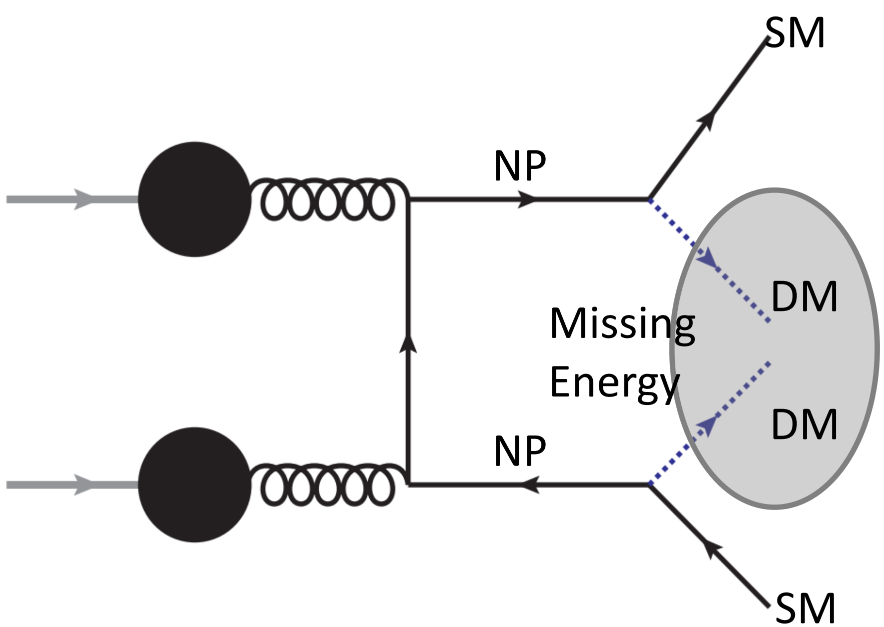
V. Khachatryan et al. (CMS), Eur. Phys. J. C75,235 (2015);
G. Aad et al. (ATLAS), Eur. Phys. J. C75,299 (2015)



SM pair plus MET

Qing Hong Cao et al. Phys. Rev. Lett.109 (2012) 152004;
Haipeng An et al. Phys. Rev. Lett.115 (2015) 181602；
Qing Hong Cao, Chuan-Ren Chen and Yandong Liu, arxiv:1512.09144

Dark Matter at the LHC

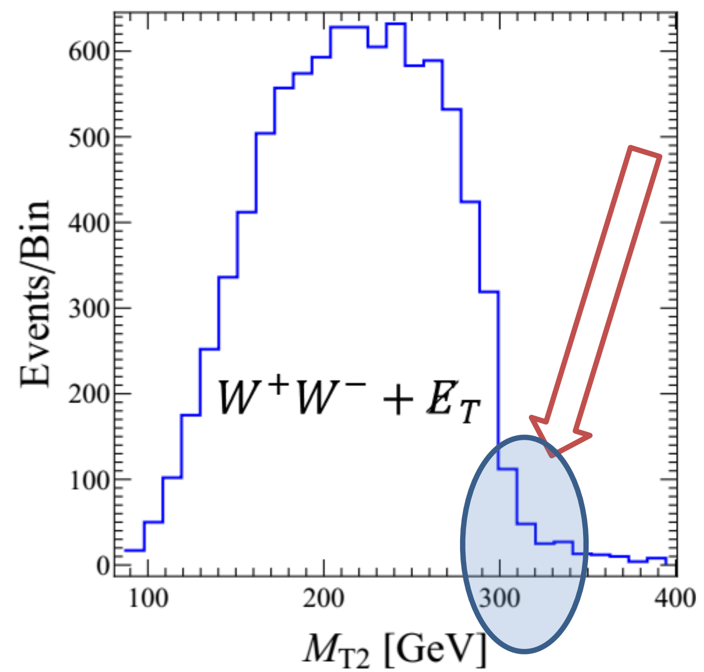


SM pair plus MET

$$M_{NP} \gg M_{DM}$$

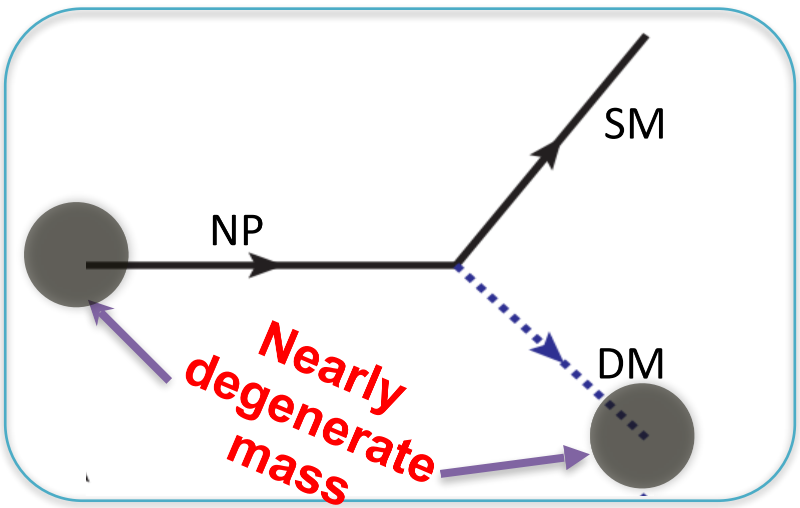
M_{T2} ⟺ mother particle's mass

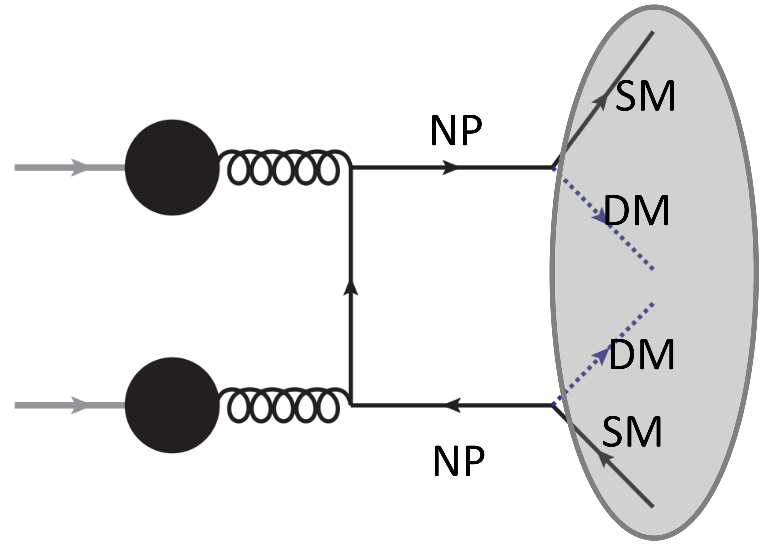
$$M_{NP} = 300\ GeV, \quad M_{DM} = 0$$



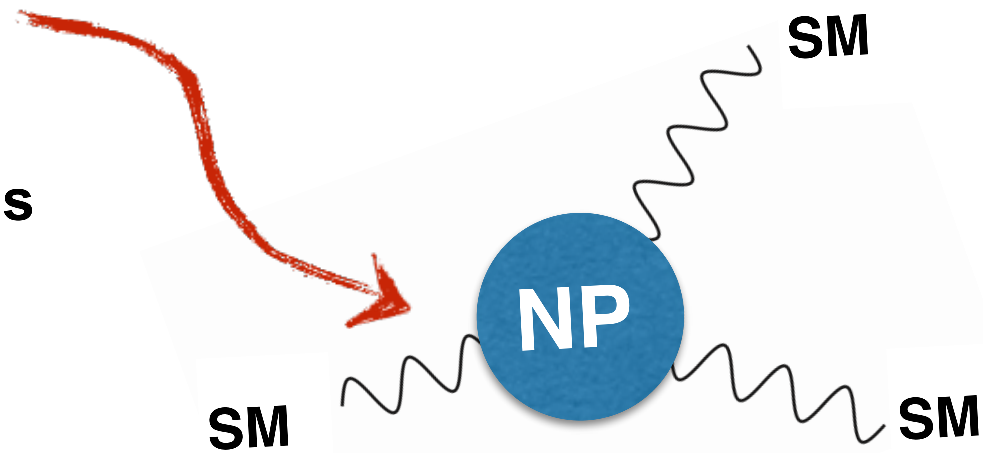
Qing-Hong Cao, Chuan-Ren Chen and Yandong Liu, arxiv:1512.09144

Degenerate Dark Matter Model





NP affects SM processes through loop



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

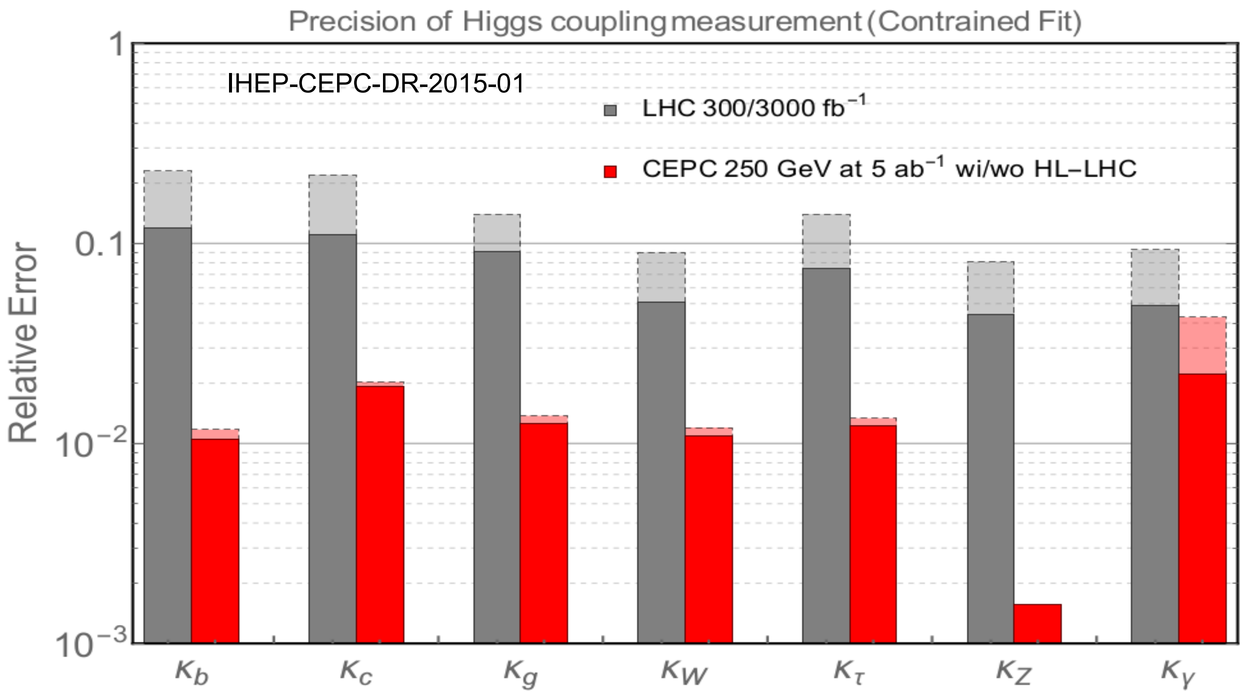
The demand for e^+e^- colliders

high luminosity

clean background

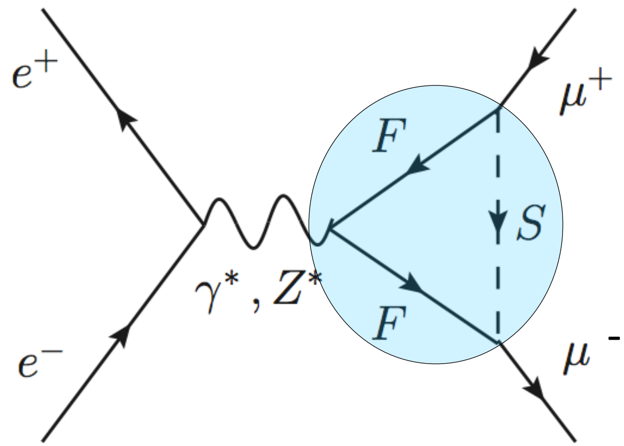
High precision

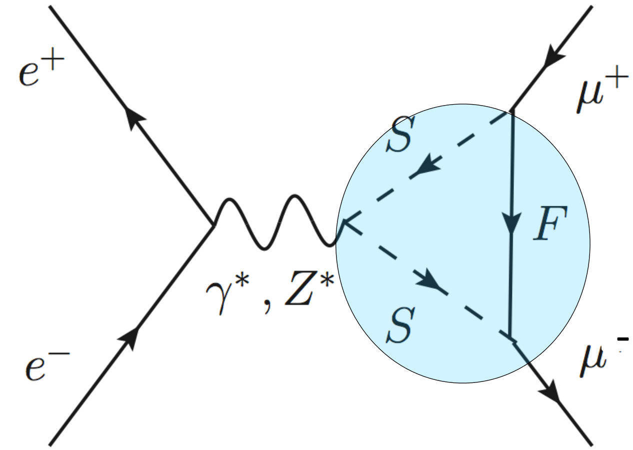
~ 10^{-3} precision

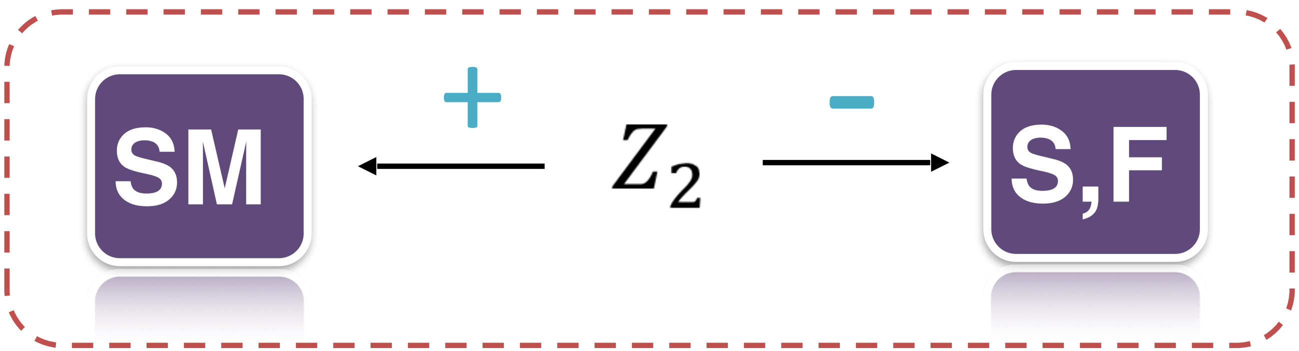


Precisions of a few percents are achievable for some of the couplings.
The CEPC can robustly improve this precision by an order of magnitude.

Simplified New Physics Model



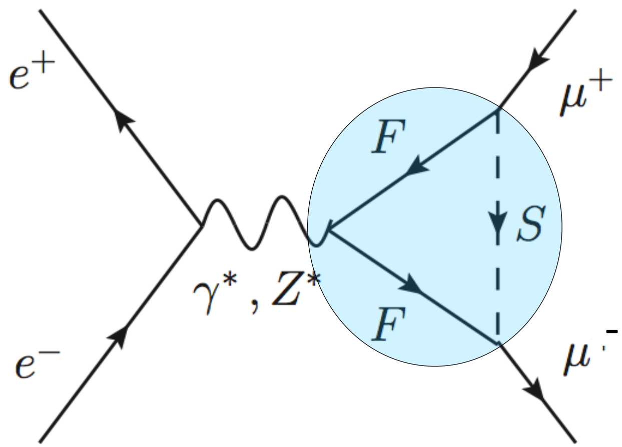


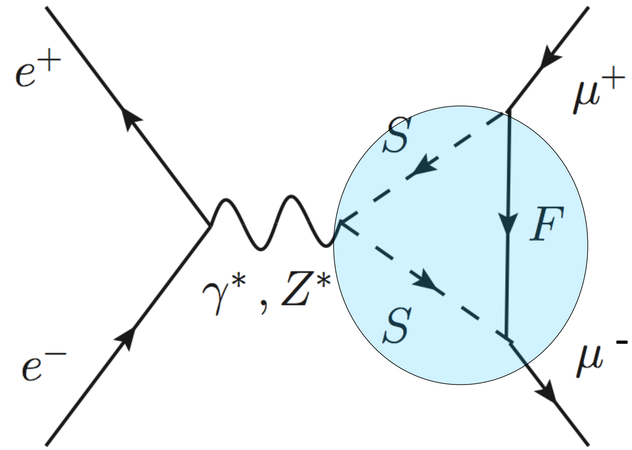


Assuming NP does not talk to electron directly

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

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-handed scenario

$$L_{Yuk} = yC_{ijk}S^i\bar{\mu}_L^k F^j + h.c.$$

$$C_{ijk} = \langle I_{\mu L} k | I_S I_F; ij\rangle$$

$$I_S = I_F \pm 1/2$$

V.S.

Right-handed scenario

$$L_{Yuk} = yC_{ij}S^i\bar{\mu}_R F^j + h.c.$$

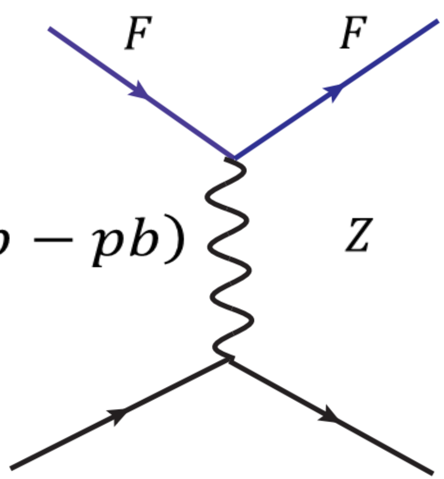
$$C_{ij} = \langle I_{\mu R} 0 | I_S I_F; ij\rangle$$

$$I_S = I_F$$

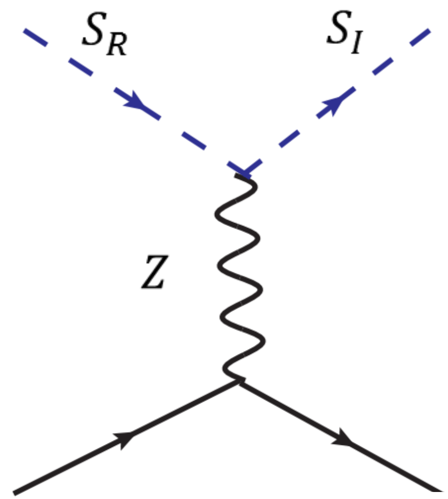
Dark Matter Candidate

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

$\sigma \sim (fb - pb)$



Dark Matter
Direct Detection



$\sigma_{Limit} \sim zb$

$M_{S_R} < M_{S_I}$

Except singlet Fermion

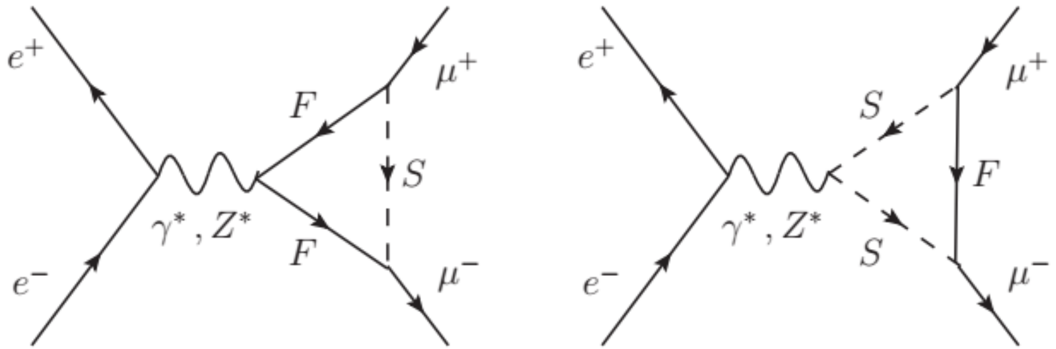
D.S. Akerib et al. (LUX) (2005), Arxiv:1512.03506

Scalar dark matter

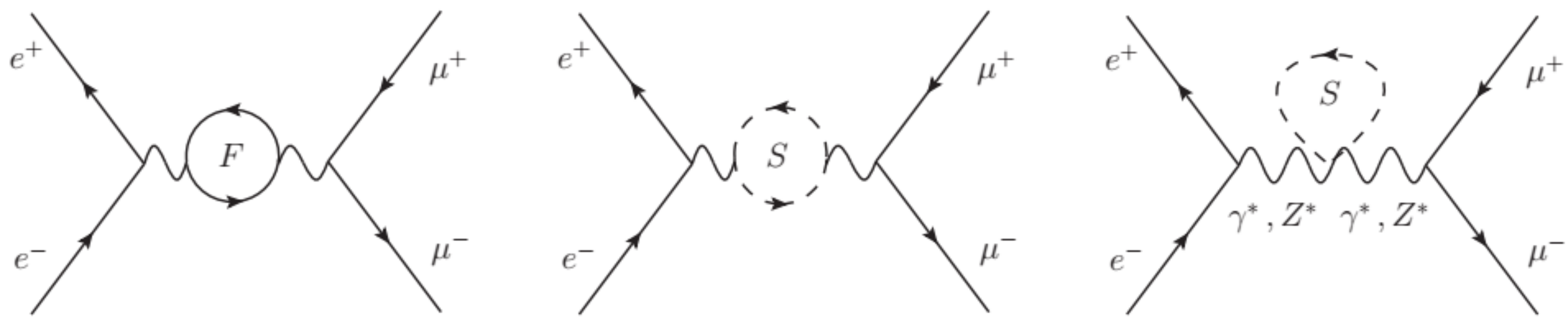
$Y_S \in \{-I_S, -I_S + 1, \ldots, I_S\}$

One-Loop Correction

Yukawa interaction: $\mathcal{O}(y^2)$



Gauge interaction: $\mathcal{O}(e^2)$



Purely Yukawa Interaction

Loop induced effective coupling $V\mu^+\mu^-$

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

On-shell scheme

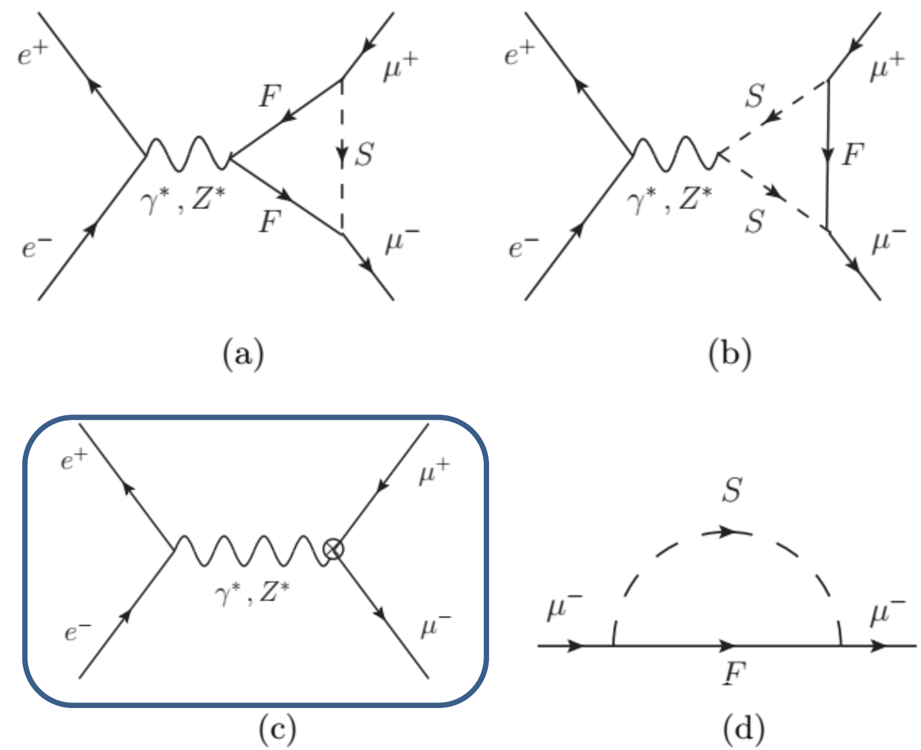
A. Stange and S. Willenbrock, Phys. Rev. D48,2054(1993)
Q.-H.Cao et al, Phys. Rev.D 79,015004(2009)

$$\alpha_V = \alpha_{V,\Delta} + \delta\alpha_V$$

$$\beta_V = \beta_{V,\Delta}$$

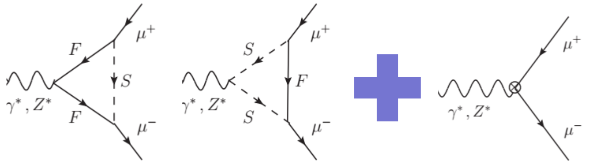
$$\xi_{1,\mathrm{V}} = \xi_{1,V,\Delta} + \delta\xi_{1,\mathrm{V}}$$

$$\xi_{2,\mathrm{V}} = \xi_{2,V,\Delta}$$



Wave function of muon

Purely Yukawa Interaction (Left-Handed Scenario)

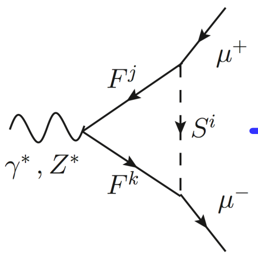


$$V = \gamma, Z$$

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

Stange, Willenbrock, Phys. Rev. D48, 2054 (1993).

$$\alpha_V = \alpha_{V,\triangle} + \delta\alpha_V, \quad \beta_V = \beta_{V,\triangle}, \quad \xi_{1,V} = \xi_{1,V,\triangle} + \delta\xi_{1,V}, \quad \xi_{2,V} = \xi_{2,V,\triangle},$$



$$J_{F3} = \sum_{ijk} C_{ik-\frac{1}{2}} T^3_{F,kj} C^*_{ij-\frac{1}{2}}$$

B_0 and C_0 scalar functions

Dimensional Regularization
On-shell scheme

Aoki, et al, Prog. Theor. Phys. Suppl. 73, 1 (1982).
Passarino, Veltman, Nucl. Phys. B160, 151 (1979).

$$a \equiv \frac{|y|^2}{16\pi^2}\left[a^1 + a^2 B_0(s) + a^3 B_0(m_\mu^2) + a^4 B_0'(m_\mu^2) + a^5 C_0\right].$$

where $a = \alpha_V, \beta_V, \xi_{1,V}, \xi_{2,V}$

$$\sim (a^2 + a^3)\frac{1}{\epsilon} \qquad \epsilon = \frac{4-n}{2}$$

$$\alpha_\gamma^1 = -\frac{s(2Y_S + 2J_{S3} + 1)}{4(s - 4m_\mu^2)}, \qquad \alpha_\gamma^2 = -\alpha_\gamma^3 = \frac{16m_\mu^4 - 2s(6J_{S3} + 6Y_S + 7)m_\mu^2 + s^2}{4(s - 4m_\mu^2)^2},$$

$$\alpha_\gamma^4 = -\frac{m_\mu^2}{2},$$

$$\alpha_\gamma^5 = -\frac{sm_\mu^2\left[s(J_{S3} + Y_S + 1) - 4M^2(2J_{S3} + 2Y_S + 1)\right] + sm_\mu^4(2J_{S3} + 2Y_S - 3) + M^2 s^2(2J_{S3} + 2Y_S + 1) + 8m_\mu^6}{2(s - 4m_\mu^2)^2},$$

$$\beta_\gamma^1 = \frac{m_\mu(2J_{S3} + 2Y_S + 1)}{2(s - 4m_\mu^2)}, \qquad \beta_\gamma^2 = -\beta_\gamma^3 = \frac{m_\mu(2m_\mu^2 + s)(2J_{S3} + 2Y_S + 1)}{2(s - 4m_\mu^2)^2},$$

$$\beta_\gamma^5 = -\frac{m_\mu(2J_{S3} + 2Y_S + 1)\left[m_\mu^4 + m_\mu^2(4M^2 - s) - M^2 s\right]}{(s - 4m_\mu^2)^2},$$

$$\xi_{1,\gamma}^1 = \frac{1}{4}(2J_{S3} + 2Y_S + 1), \qquad \xi_{1,\gamma}^2 = -\xi_{1,\gamma}^3 = -\frac{(4Y_S + 4J_{S3} + 2)m_\mu^2 + s}{4(s - 4m_\mu^2)},$$

$$\xi_{1,\gamma}^5 = -\frac{m_\mu^2\left[s(J_{S3} + Y_S + 1) - m_\mu^2(2J_{S3} + 2Y_S + 1)\right] - M^2(s - 4m_\mu^2)(2J_{S3} + 2Y_S + 1)}{2(s - 4m_\mu^2)},$$

$$\alpha_Z^1 = -\frac{\left[4c_W^2 J_{S3} - 2s_W^2(2Y_S + 1) + 1\right]s}{8c_W s_W(s - 4m_\mu^2)},$$

$$\alpha_Z^2 = -\alpha_Z^3 = \frac{2m_\mu^2 s\left[2s_W^2(6J_{S3} + 6Y_S + 7) - 12J_{S3} - 7\right] + (2s_W^2 - 1)(16m_\mu^4 + s^2)}{8c_W s_W(s - 4m_\mu^2)^2},$$

$\alpha_V, \beta_V, \xi_{1,V}, \xi_{2,V}$

are UV finite

Purely Yukawa Interaction (Left-Handed Scenario)

When M is Large

$$B_0(p^2; M^2, M^2) = B_0(0; M^2, M^2) + \frac{p^2}{6M^2} + \frac{p^4}{60M^4} + \mathcal{O}(M^{-6}),$$

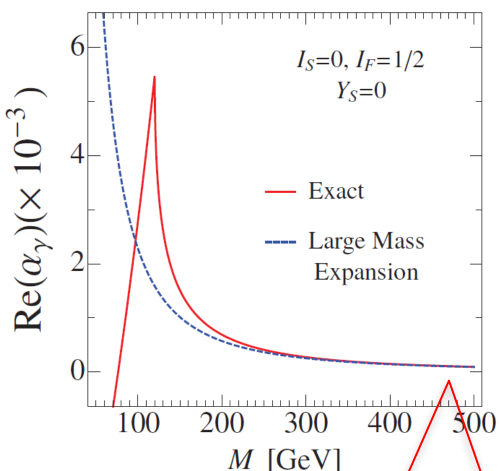
$$C_0(p_1^2, p_2^2, p_3^2; M^2, M^2, M^2) = -\frac{1}{2M^2} - \frac{p_1^2 + p_2^2 + p_3^2}{24M^4} + \mathcal{O}(M^{-6}).$$

$$\alpha_\gamma = +\frac{|y|^2}{768\pi^2}\frac{s}{M^2}(2J_{S3} + 2Y_S + 3) \qquad \alpha_Z = +\frac{|y|^2}{768\pi^2 c_W s_W}\frac{s}{M^2}\left(2c_W^2 J_{S3} - 2s_W^2 Y_S - 3s_W^2 + \frac{3}{2} + \frac{m_\mu^2}{s}\right),$$

$$\beta_\gamma = +\frac{|y|^2}{768\pi^2}\frac{m_\mu}{M^2}(4J_{S3} + 4Y_S + 2) \qquad \beta_Z = +\frac{|y|^2}{768\pi^2 c_W s_W}\frac{m_\mu}{M^2}\left(4c_W^2 J_{S3} - 4s_W^2 Y_S - 2s_W^2 + 1\right),$$

$$\xi_{1,\gamma} = -\frac{|y|^2}{768\pi^2}\frac{s}{M^2}(2J_{S3} + 2Y_S + 3) \qquad \xi_{1,Z} = -\frac{|y|^2}{768\pi^2 c_W s_W}\frac{s}{M^2}\left(2c_W^2 J_{S3} - 2s_W^2 Y_S - 3s_W^2 + \frac{3}{2} - \frac{m_\mu^2}{s}\right),$$

$$\xi_{2,\gamma} = +\frac{|y|^2}{768\pi^2}\frac{m_\mu}{M^2}(4J_{S3} + 4Y_S + 6) \qquad \xi_{2,Z} = +\frac{|y|^2}{768\pi^2 c_W s_W}\frac{m_\mu}{M^2}\left(4c_W^2 J_{S3} - 4s_W^2 Y_S - 6s_W^2 + 3\right).$$



Decoupling

$$\xi_{1,\gamma}\gamma^\nu\gamma_5 + \xi_{2,\gamma}q^\nu\gamma_5 = \xi_{1,\gamma}(\gamma^\nu - 2m_\mu/s\ q^\nu)\gamma_5$$

by $U(1)_{\rm EM}$ symmetry

Anapole Moment

$$(\alpha_\gamma\gamma^\nu + \mathrm{i}\ \beta_\gamma q_\rho\sigma^{\nu\rho} + \xi_{1,\gamma}\gamma^\nu\gamma_5 + \xi_{2,\gamma}q^\nu\gamma_5) \ \to 0$$

in the Thomson limit, i.e., $q^\mu \to 0$

Left-Handed Scenario (Large Mass Expansion)

$$\alpha_\gamma = +\frac{|y|^2}{768\pi^2}\frac{s}{M^2}(2J_{S3}+2Y_S+3)$$

$$\beta_\gamma = +\frac{|y|^2}{768\pi^2}\boxed{\frac{m_\mu}{M^2}}(4J_{S3}+4Y_S+2)$$

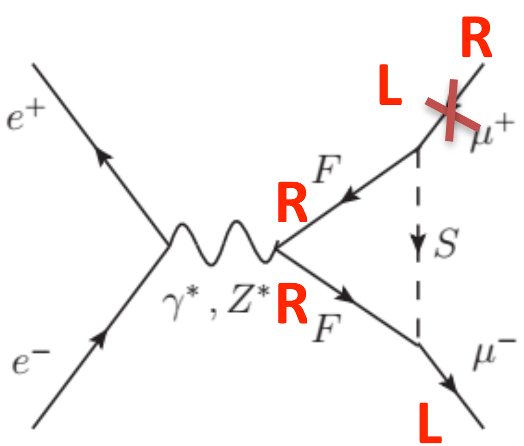
$$\xi_{1,\gamma} = -\frac{|y|^2}{768\pi^2}\frac{s}{M^2}(2J_{S3}+2Y_S+3)$$

$$\xi_{2,\gamma} = +\frac{|y|^2}{768\pi^2}\boxed{\frac{m_\mu}{M^2}}(4J_{S3}+4Y_S+6)$$

$$-ie\bar{u}(k_-)(\alpha_V\gamma^\mu + i\beta_V\sigma^{\mu\nu}q_\nu)v(k_+)$$

$$-ie\bar{u}(k_-)(\xi_{1,V}\gamma^\mu\gamma_5 + \xi_{2,V}q^\mu\gamma_5)v(k_+)$$

$$J_{S3} = \begin{cases} \frac{1}{3}I_S, & \text{for } I_F = I_S + \frac{1}{2}, \\ -\frac{1}{3}(I_S+1), & \text{for } I_F = I_S - \frac{1}{2}. \end{cases}$$



$$\alpha_Z = +\frac{|y|^2}{768\pi^2 c_W s_W}\frac{s}{M^2}\left(2c_W^2 J_{S3} - 2s_W^2 Y_S - 3s_W^2 + \frac{3}{2} + \frac{m_\mu^2}{s}\right),$$

$$\beta_Z = +\frac{|y|^2}{768\pi^2 c_W s_W}\boxed{\frac{m_\mu}{M^2}}\left(4c_W^2 J_{S3} - 4s_W^2 Y_S - 2s_W^2 + 1\right),$$

$$\xi_{1,Z} = -\frac{|y|^2}{768\pi^2 c_W s_W}\frac{s}{M^2}\left(2c_W^2 J_{S3} - 2s_W^2 Y_S - 3s_W^2 + \frac{3}{2} - \frac{m_\mu^2}{s}\right),$$

$$\xi_{2,Z} = +\frac{|y|^2}{768\pi^2 c_W s_W}\boxed{\frac{m_\mu}{M^2}}\left(4c_W^2 J_{S3} - 4s_W^2 Y_S - 6s_W^2 + 3\right).$$

Right-Handed Scenario (Large Mass Expansion)

$$\alpha_\gamma = +\frac{|y|^2}{768\pi^2}\frac{s}{M^2}(2Y_S+3)\,,$$

$$\beta_\gamma = +\frac{|y|^2}{768\pi^2}\frac{m_\mu}{M^2}(4Y_S+2)\,,$$

$$\xi_{1,\gamma} = +\frac{|y|^2}{768\pi^2}\frac{s}{M^2}(2Y_S+3)\,,$$

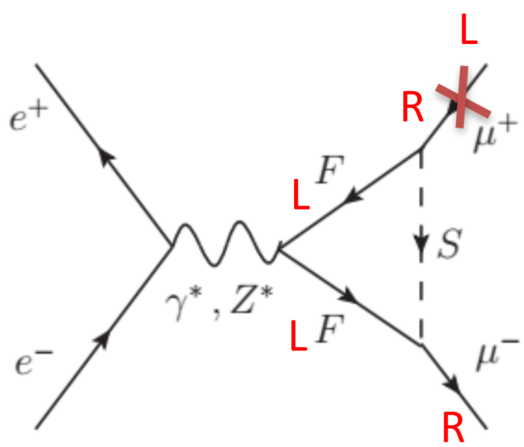
$$\xi_{2,\gamma} = -\frac{|y|^2}{768\pi^2}\frac{m_\mu}{M^2}(4Y_S+6)\,,$$

$$\alpha_Z = +\frac{|y|^2}{768\pi^2 c_W s_W}\frac{s}{M^2}\left(-2s_W^2 Y_S - 3s_W^2 - \frac{m_\mu^2}{s}\right)$$

$$\beta_Z = +\frac{|y|^2}{768\pi^2 c_W s_W}\frac{m_\mu}{M^2}(-4s_W^2 Y_S - 2s_W^2)\,,$$

$$\xi_{1,Z} = +\frac{|y|^2}{768\pi^2 c_W s_W}\frac{s}{M^2}\left(-2s_W^2 Y_S - 3s_W^2 + \frac{m_\mu^2}{s}\right)$$

$$\xi_{2,Z} = -\frac{|y|^2}{768\pi^2 c_W s_W}\frac{m_\mu}{M^2}(-4s_W^2 Y_S - 6s_W^2)\,.$$



$$-ie\bar{u}(k_-)(\alpha_V\gamma^\mu + i\beta_V\sigma^{\mu\nu}q_\nu)v(k_+)$$

$$-ie\bar{u}(k_-)\left(\xi_{1,V}\gamma^\mu\gamma_5 + \xi_{2,V}q^\mu\gamma_5\right)v(k_+)$$

Purely Gauge Interaction

Loop induced effective coupling $V\mu^+\mu^-$

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

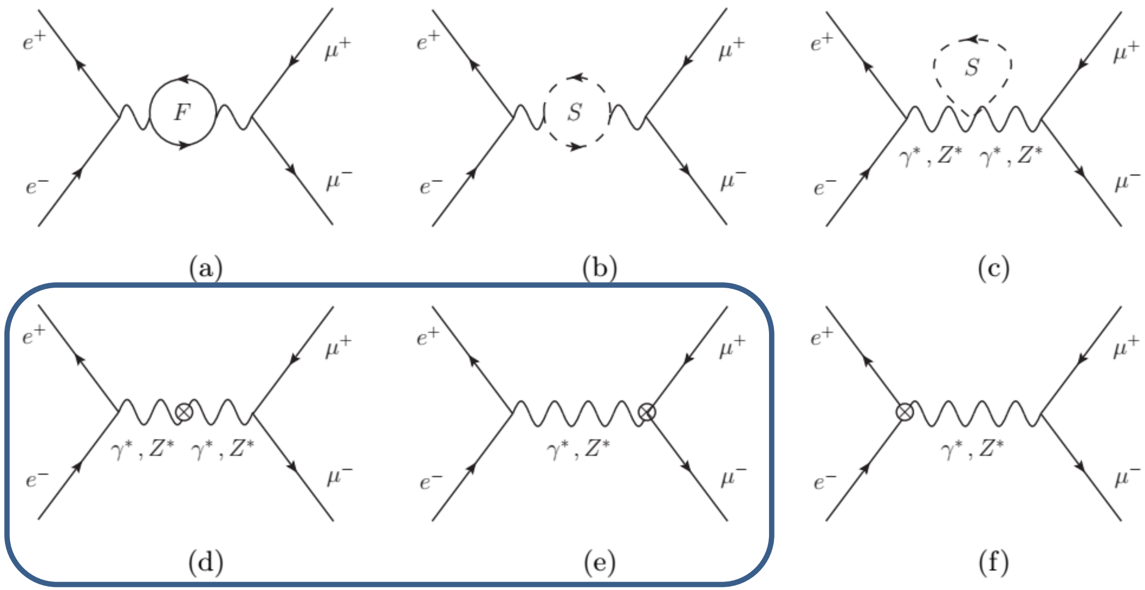
On-shell scheme

$$\alpha_V = \alpha_{V,0} + \delta\alpha_V$$

$$\beta_V = \beta_{V,0}$$

$$\xi_{1,V} = \xi_{1,V,0} + \delta\xi_{1,V}$$

$$\xi_{2,V} = \xi_{2,V,0} + \delta\xi_{2,V}$$



Wave function of gauge boson

Purely Gauge Interaction

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

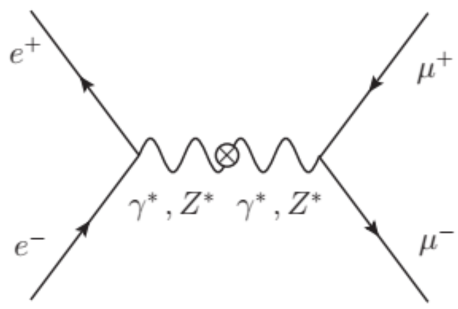
On-shell scheme

$$\alpha_V = \alpha_{V,0} + \delta\alpha_V$$

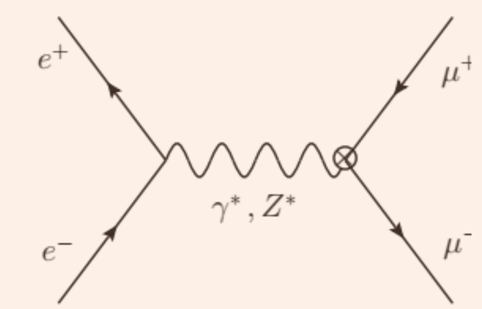
$$\beta_V = \beta_{V,0}$$

$$\xi_{1,V} = \xi_{1,V,0} + \delta\xi_{1,V}$$

$$\xi_{2,V} = \xi_{2,V,0} + \delta\xi_{2,V}$$



(d)



(e)

A. Denner, Fortsch.Phys.41,307(1993),0709.1075

$$\delta\alpha_\gamma = C_v^\gamma + \left(-\frac{g_v}{s-m_Z^2}C_{AZ} + \frac{Q}{s}C_{AA}\right)$$

$$\delta\xi_{1,\gamma} = C_a^\gamma + \left(-\frac{g_a}{s-m_Z^2}C_{AZ}\right)$$

$$\delta\xi_{2,\gamma} = 0 + \left(-\frac{g_a 2m_\mu}{s-m_Z^2}C'_{AZ}\right)$$

$$\delta\alpha_Z = C_v^Z + \left(-\frac{g_v}{s-m_Z^2}C_{ZZ} + \frac{Q}{s}C_{AZ}\right)$$

$$\delta\xi_{1,Z} = C_a^Z + \left(-\frac{g_a}{s-m_Z^2}C_{ZZ}\right)$$

$$\delta\xi_{2,Z} = 0 + \left(-\frac{g_a 2m_\mu}{s-m_Z^2}C'_{ZZ}\right)$$

Numerical Results

- $\Delta\sigma (\equiv \sigma - \sigma_0)$ ~ SM-NP interference

SM tree-level

$$\frac{d\Delta\sigma}{dt} = \frac{\pi\alpha_{\rm EM}^2}{s^2}\sum_{ij}\left[\mathcal{A}_{ij}^L\left(g_i^\gamma + g_L g_i\frac{s}{s-m_Z^2}\right)\left(F_{\gamma,j}^L + F_{Z,j}^L\frac{s}{s-m_Z^2}\right) + (L\to R)\right].$$

$$F_{\gamma,j}^L = 2\Re\left\{\alpha_\gamma + C_L^\gamma,\ \xi_{1,\gamma},\ m_\mu\beta_\gamma\right\}, \qquad F_{Z,j}^L = 2\Re\left\{g_L\alpha_Z + C_L^Z g_v,\ g_L\xi_{1,Z} + C_L^Z g_a,\ g_L m_\mu \beta_Z\right\},$$

$$F_{\gamma,j}^R = 2\Re\left\{\alpha_\gamma + C_R^\gamma,\ \xi_{1,\gamma},\ m_\mu\beta_\gamma\right\}, \qquad F_{Z,j}^R = 2\Re\left\{g_R\alpha_Z + C_R^Z g_v,\ g_R\xi_{1,Z} + C_R^Z g_a,\ g_R m_\mu \beta_Z\right\}.$$

- Input parameters – G_μ scheme:

$$G_\mu = 1.1663787\times 10^{-5}\ {\rm GeV}^{-2}, \qquad \alpha_{\rm EM}(0) = 1/137.035999139,$$

$$m_Z = 91.1876\ {\rm GeV}, \qquad m_W = 80.385\ {\rm GeV}, \qquad m_\mu = 105.6583745\ {\rm MeV},$$

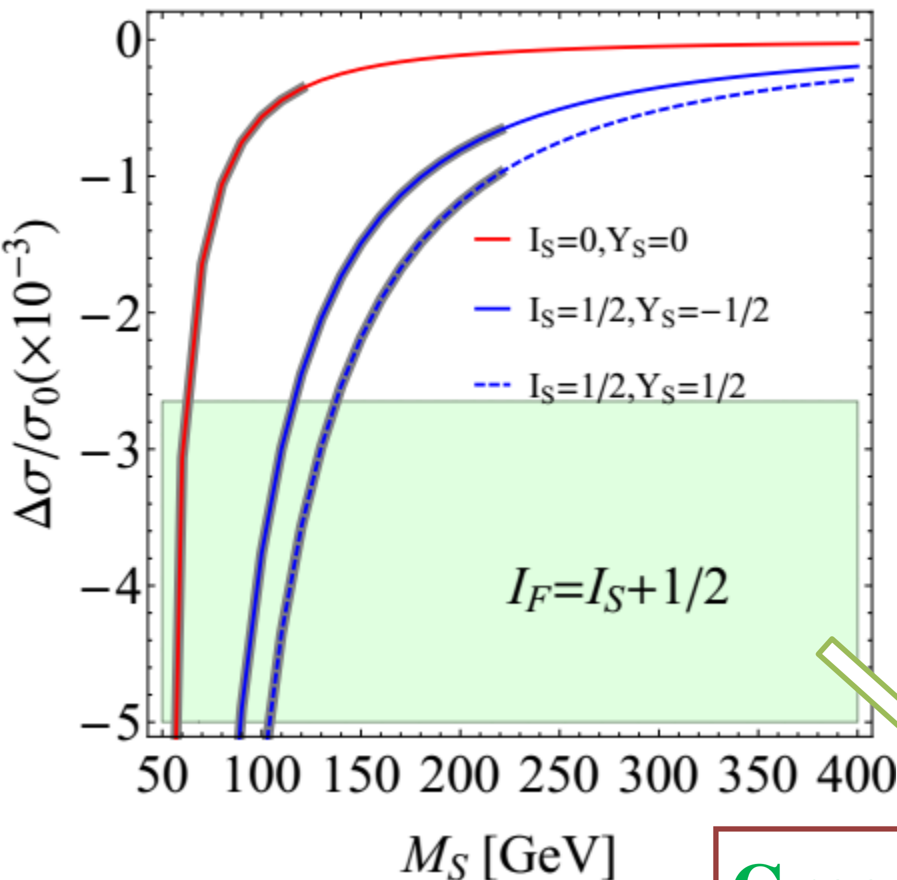
$$c_W = m_W/m_Z$$

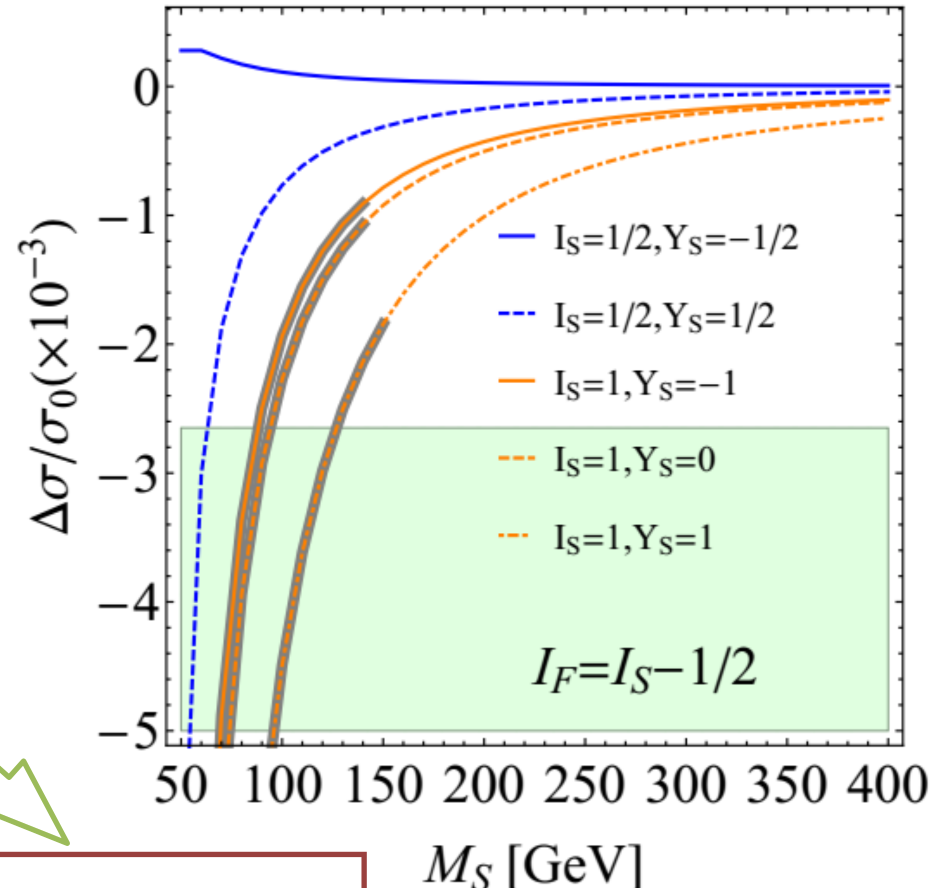
P. J. Mohr, D. B. Newell, and B. N. Taylor (2015)

- LoopTools for the evaluation of the scalar functions.

LEP-I Constraint (Left-handed Scenario)

$\sqrt{s} = 91\ GeV$ y=1





Green region:
Excluded by Z-peak data at LEP-I

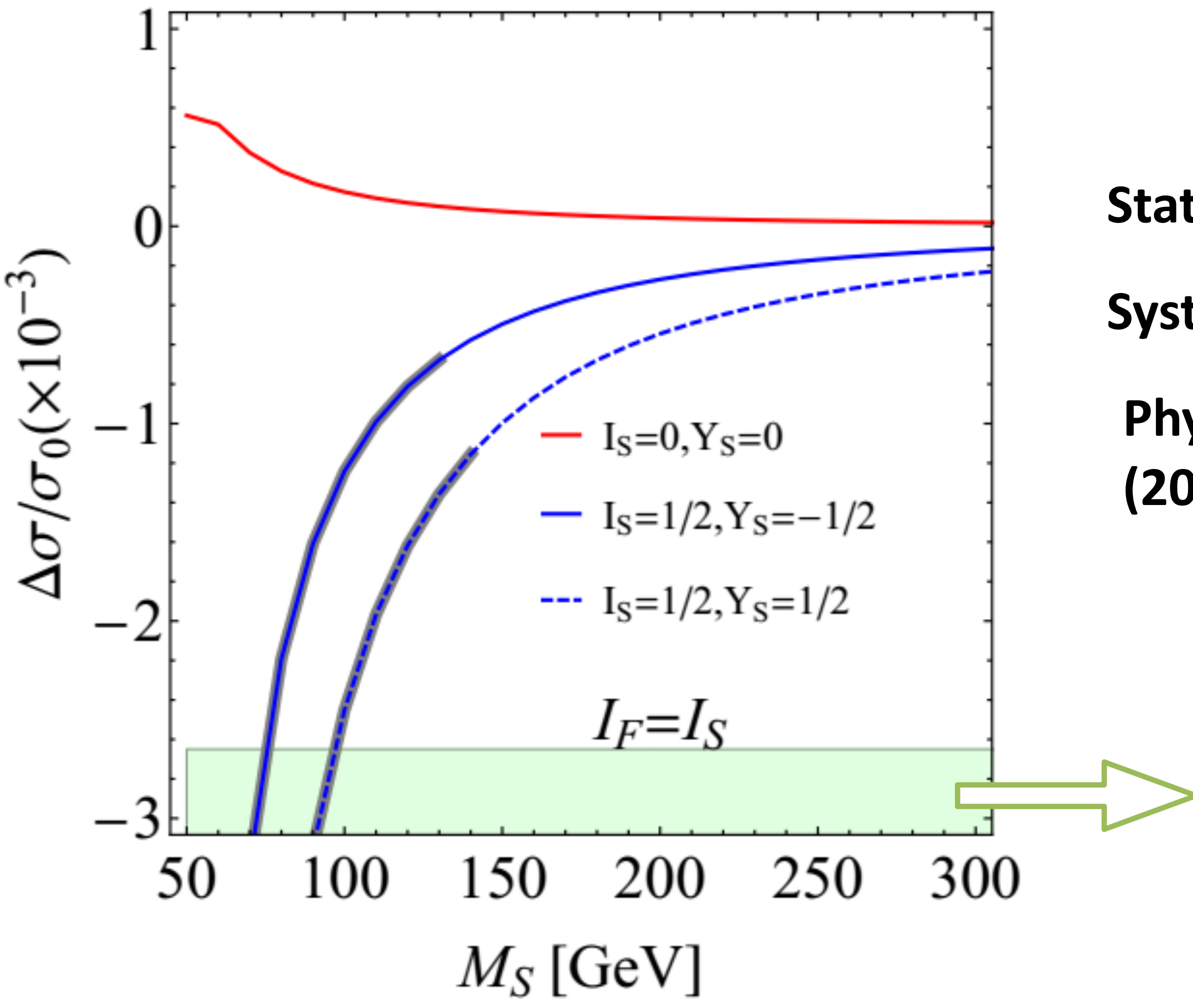
Gray shaded bands:

excluded by Mono-jet + MET data

Statistical error: 0.5%
Systematic error: 0.09%
Physics Reports 427 (2006)257-454

LEP-I constraint (Right-handed Scenario)

$\sqrt{s} = 91\ GeV$



y=1

Statistical error: 0.5%

Systematic error: 0.09%

Physics Reports 427 (2006)257-454

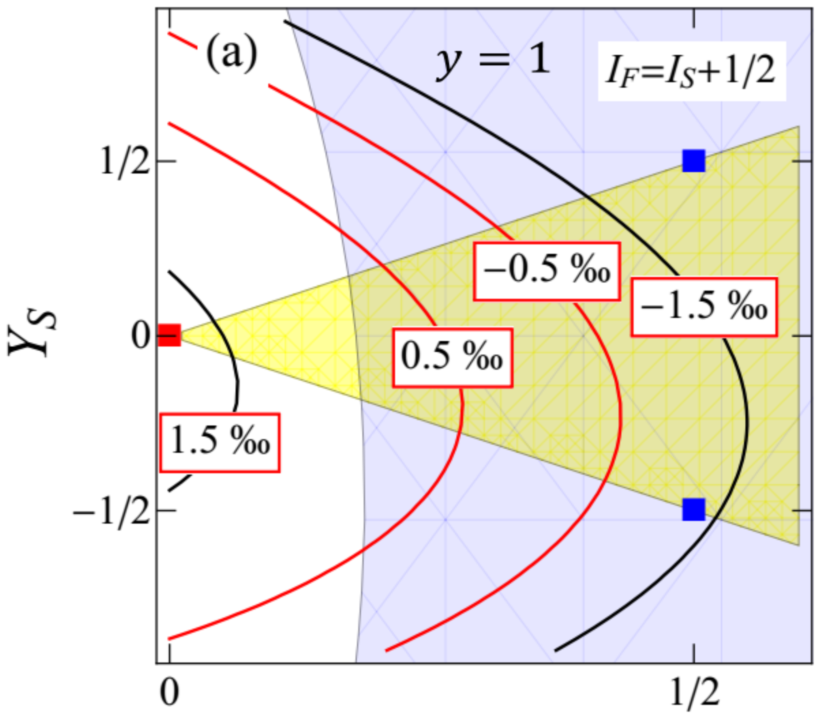
Green region :
Excluded by Z-peak data at LEP-I

Gray shaded bands:
excluded by Mono-jet + MET data

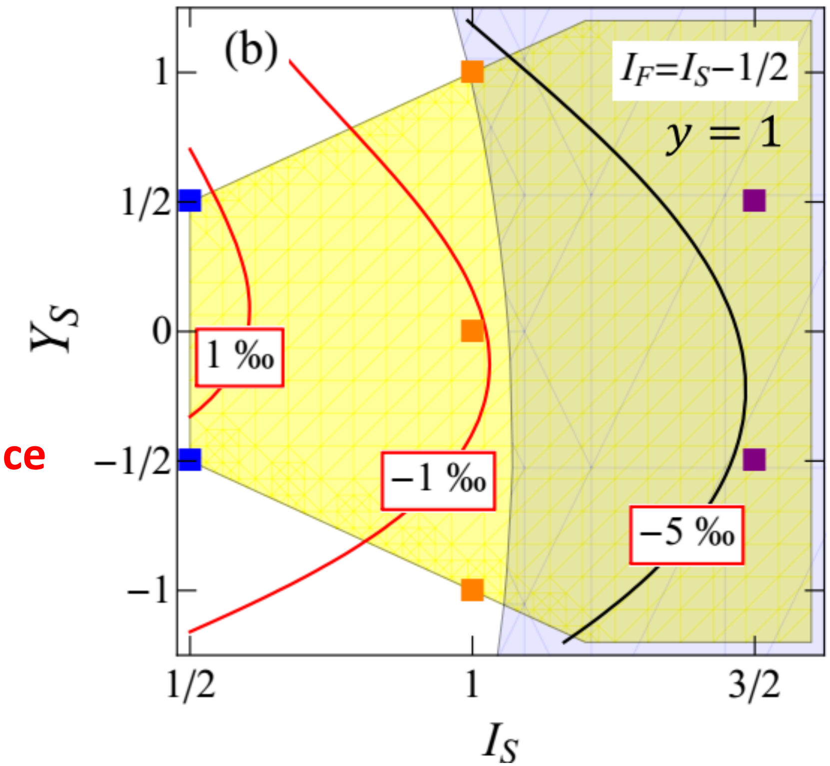
Left-Handed Scenario (E_{cm}=240GeV)

$\Delta\sigma/\sigma_0$ contours

$M = 150\ GeV$



SM-NP interference



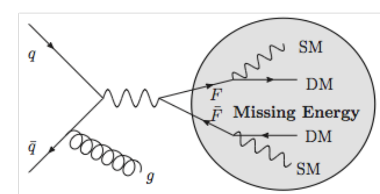
Yellow region:

Representations with DM candidates

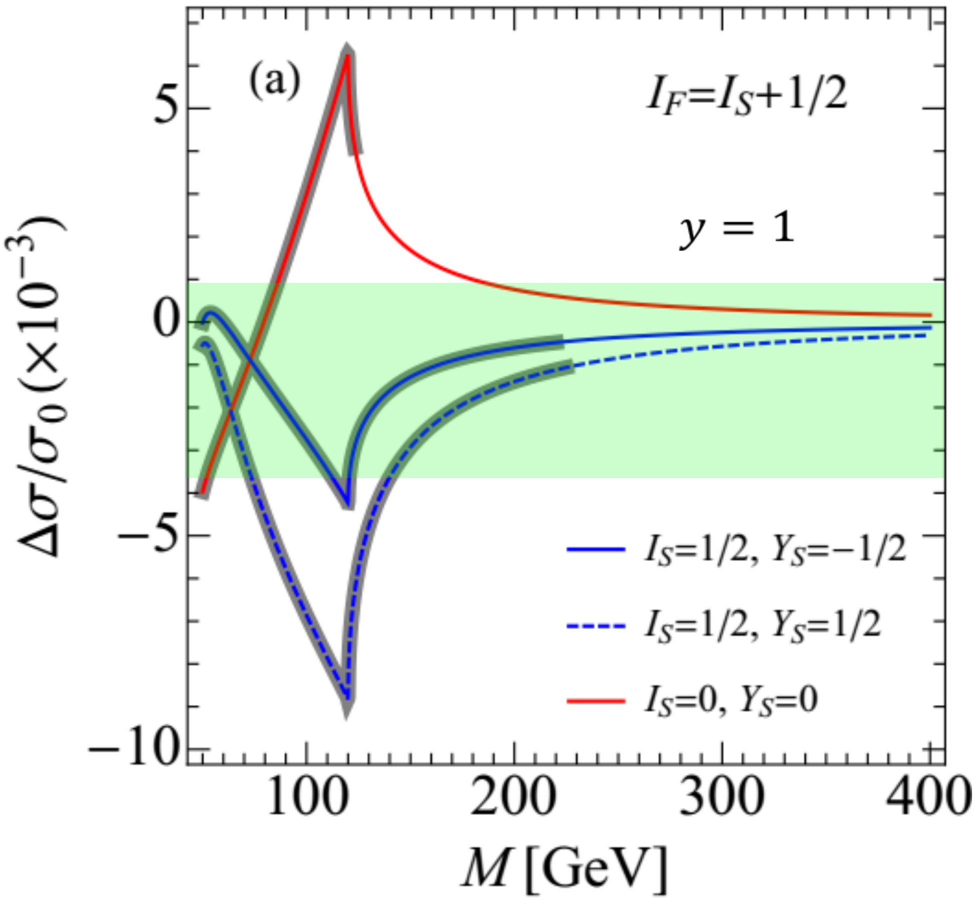
$$Y_S \in \{-I_S, -I_S + 1, \ldots, I_S\}$$

Blue region :

Higher Reps excluded by mono-jet + MET data

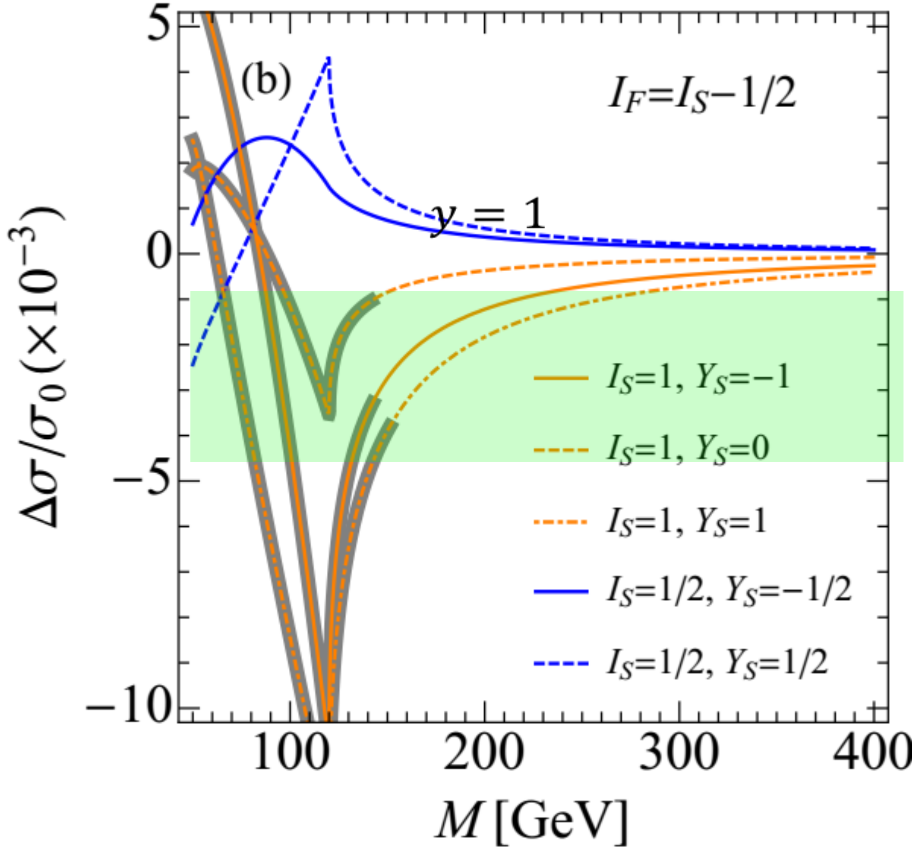


Left-Handed Scenario (E_{cm}=240GeV)



y=1

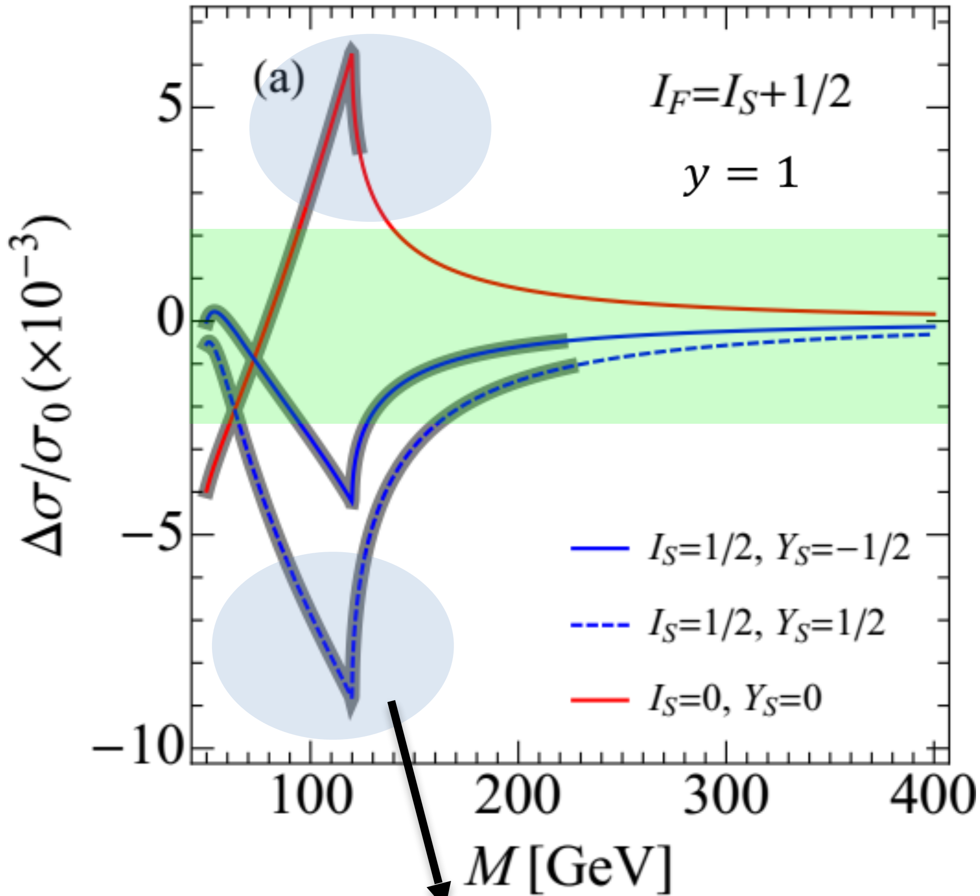
CEPC 0.2%

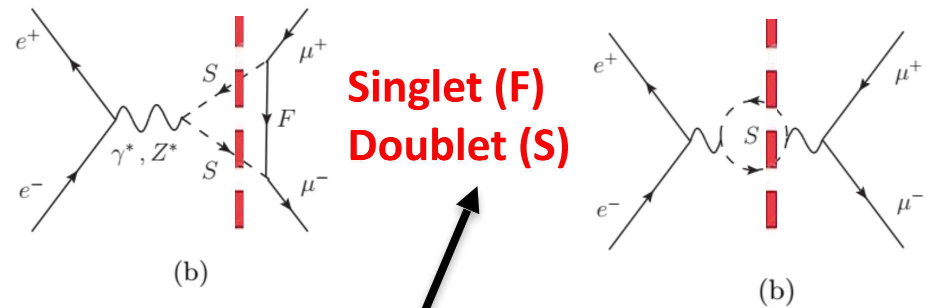


Gray shaded bands:

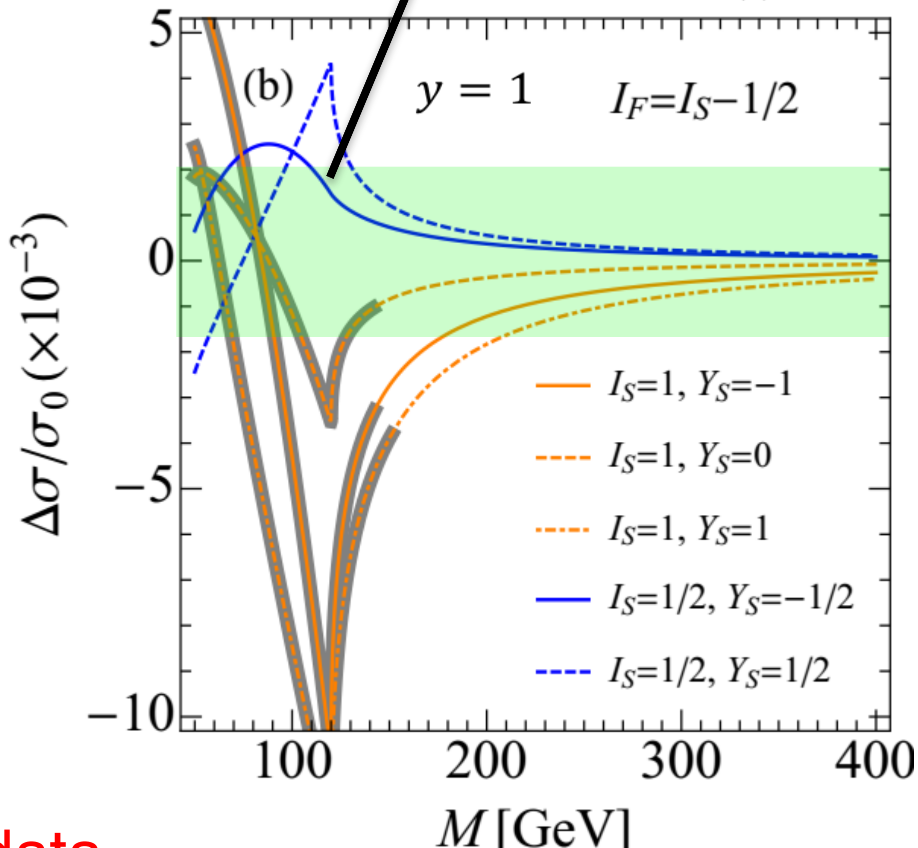
excluded by Mono-jet + MET data

Left-Handed Scenario (E_{cm}=240GeV)





Singlet (F)
Doublet (S)



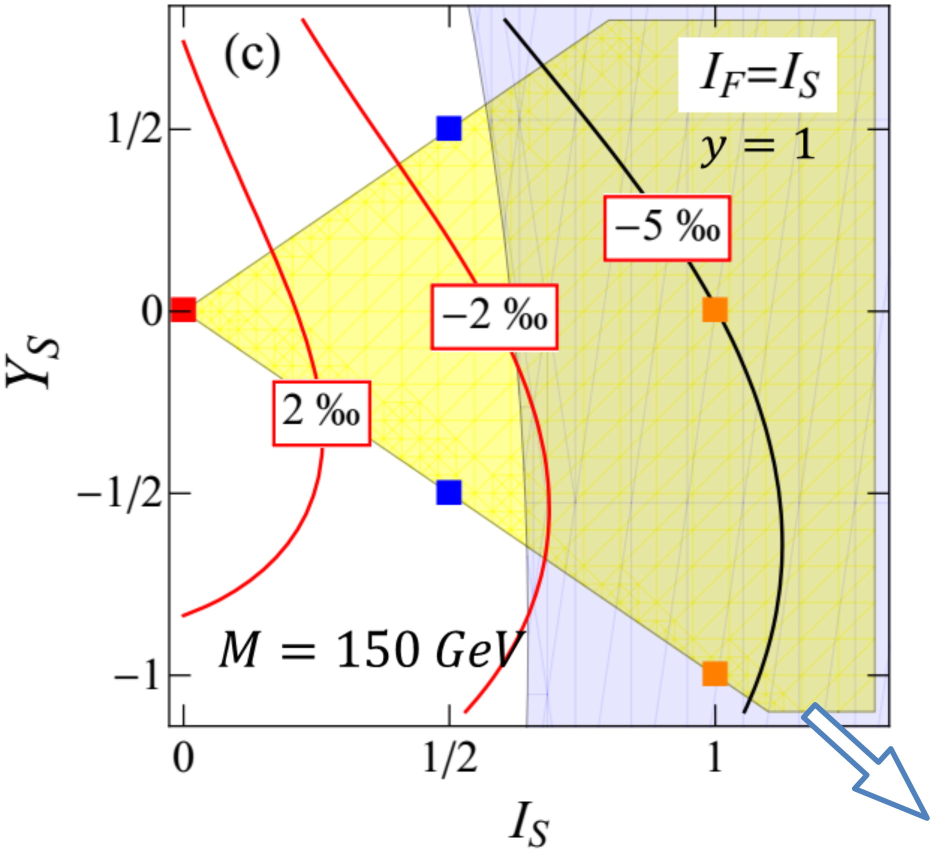
Threshold effect

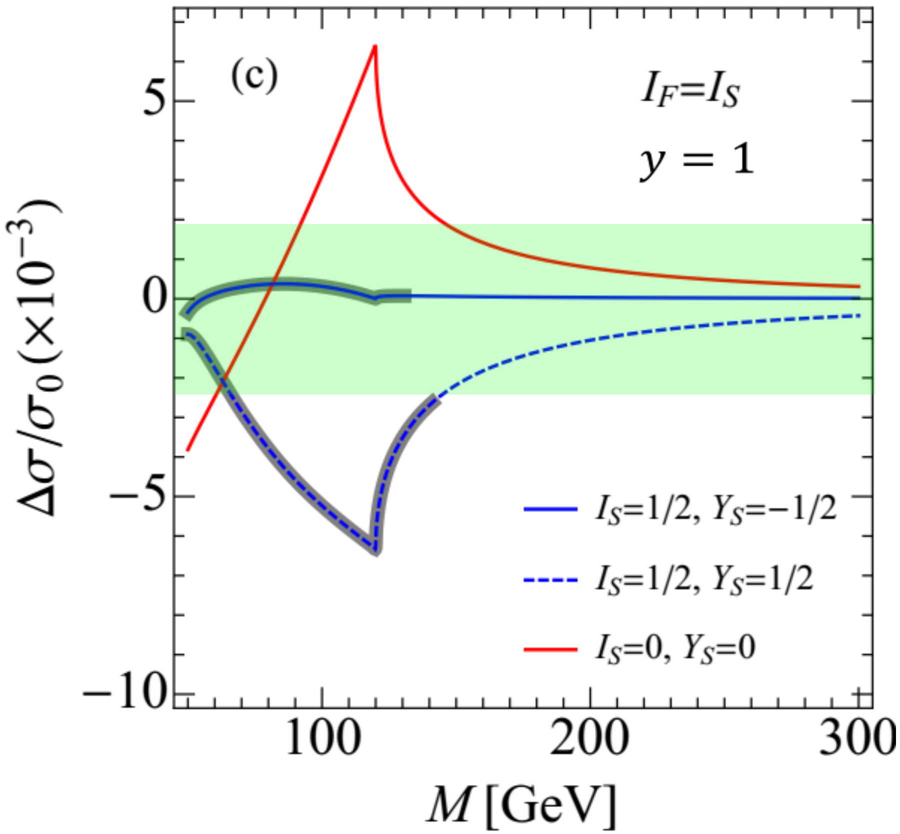
Gray shaded bands:

excluded by Mono-jet + MET data

Right-Handed Scenario (E_{cm}=240GeV)

CEPC 0.2%

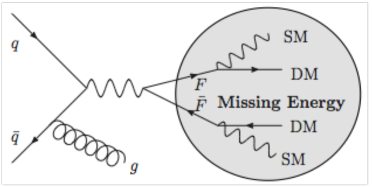




Yellow region: Representations with DM candidates

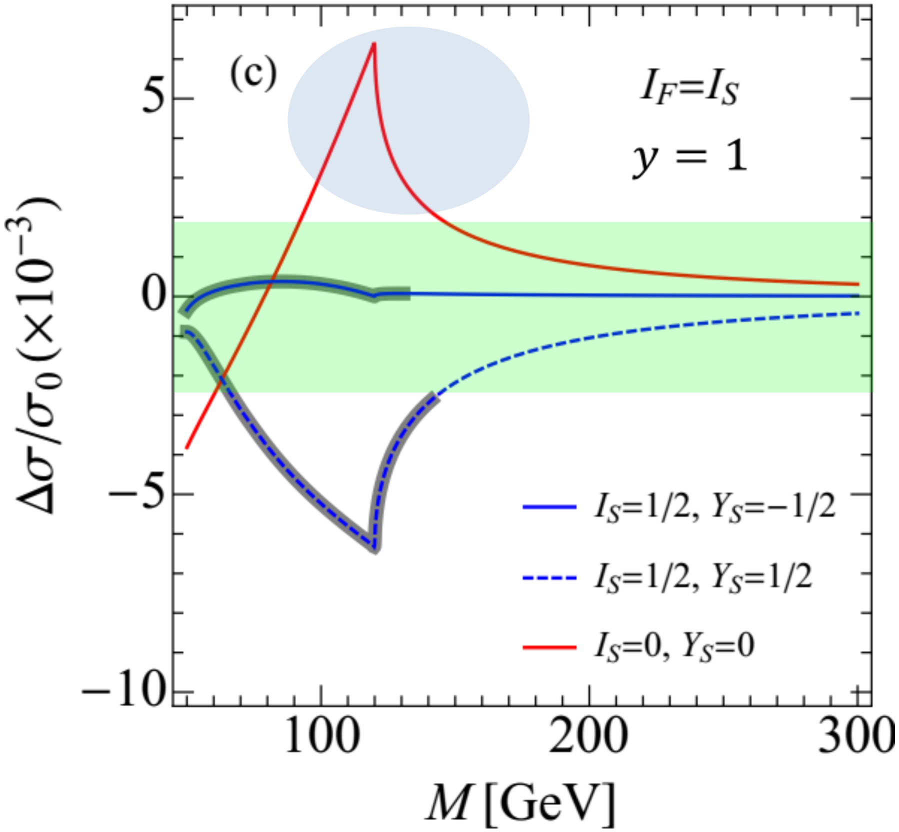
Blue region :

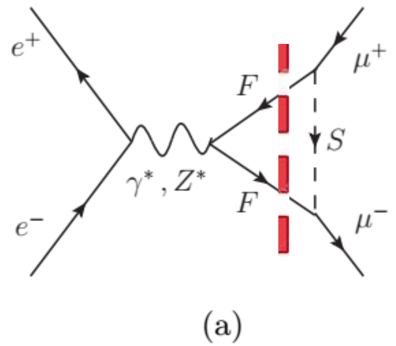
Higher Reps excluded by mono-jet + MET data

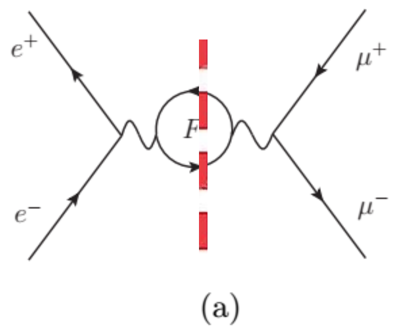


Right-Handed Scenario (E_{cm}=240GeV)

Threshold effects

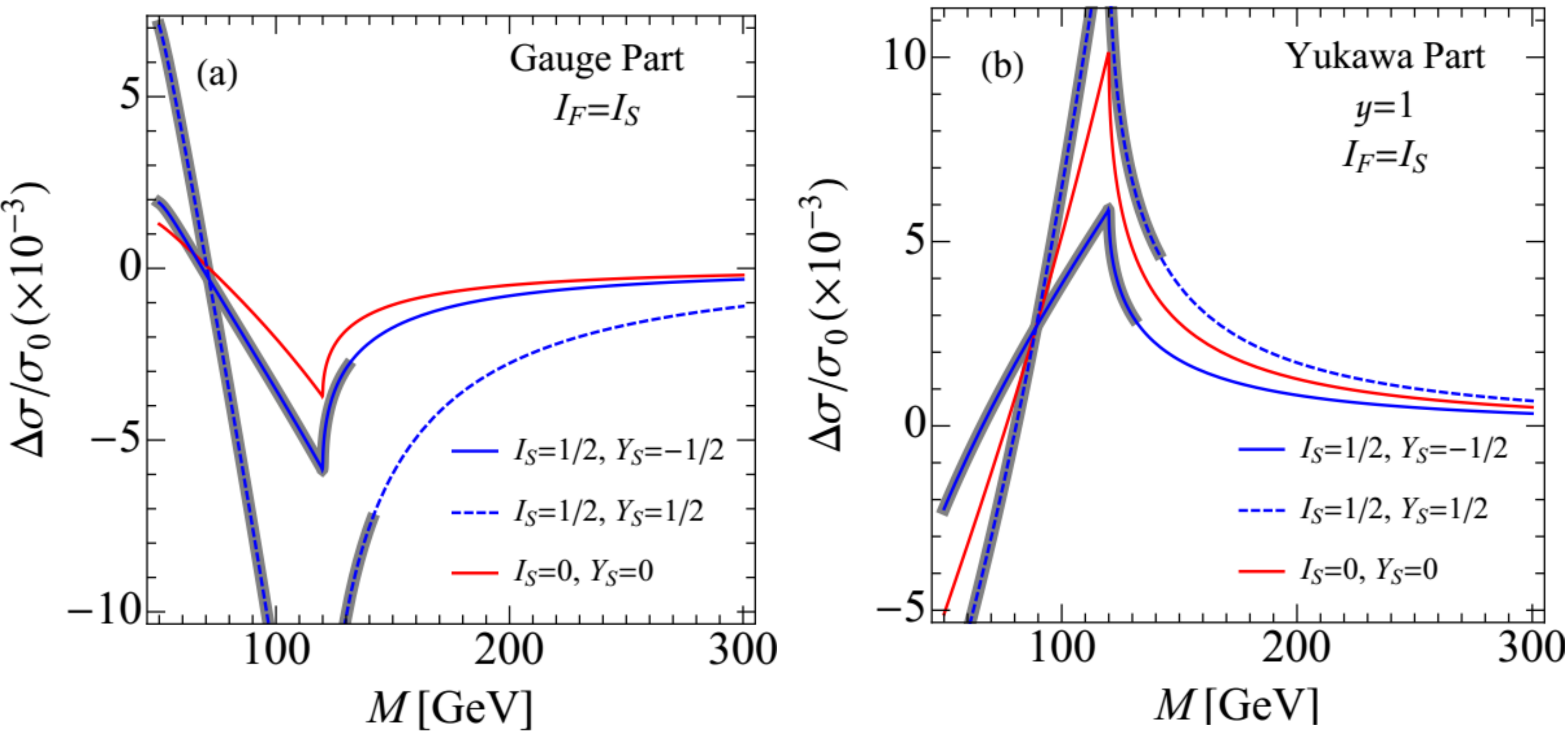






$M = 150\ GeV$

Right-Handed Scenario

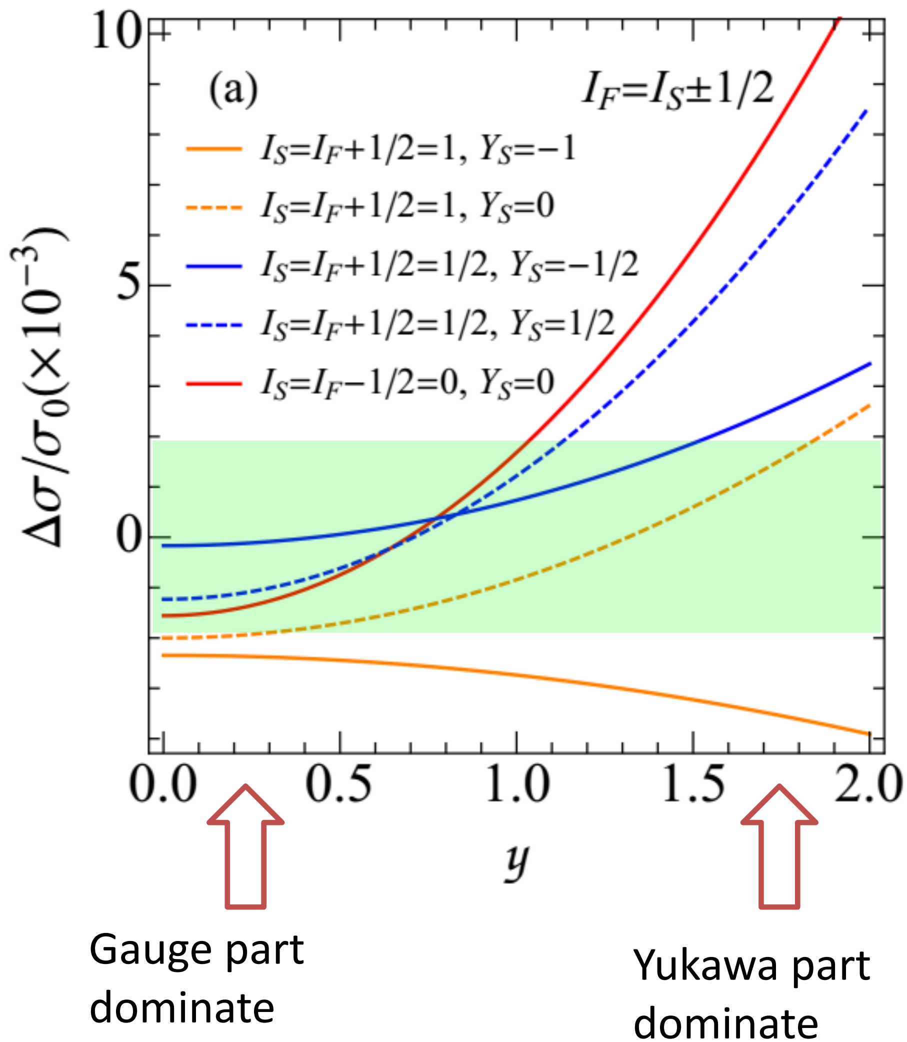


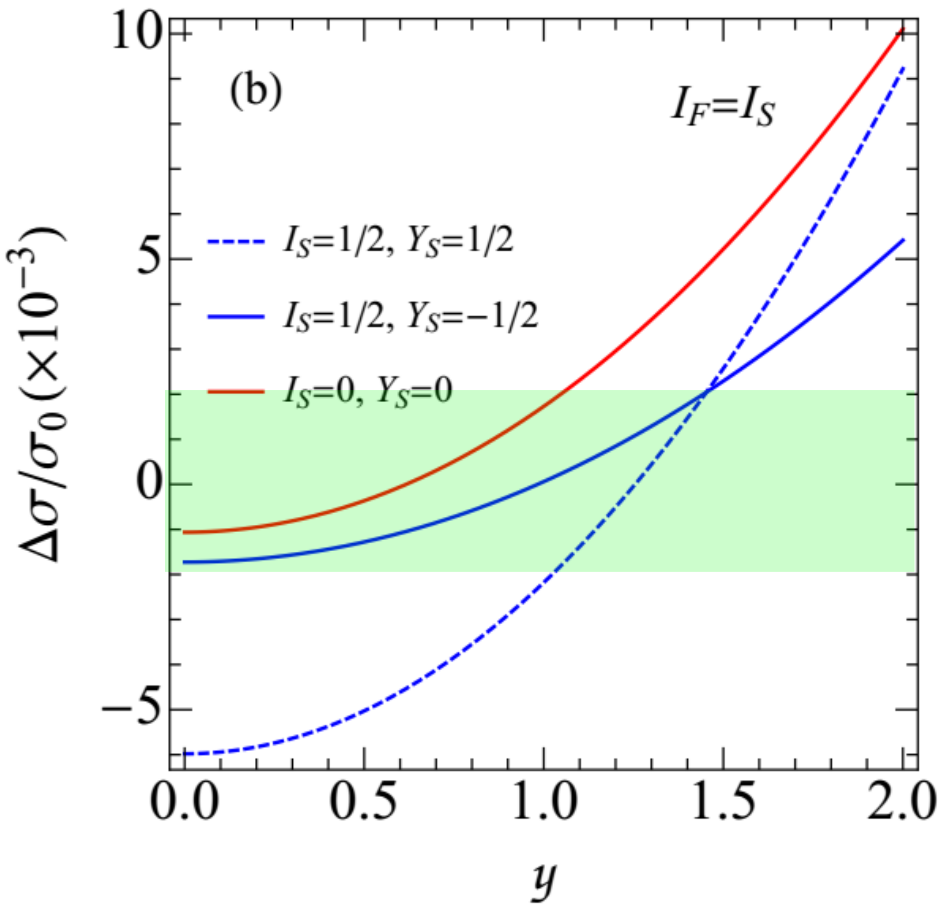
Negative

Positive

Large cancelation between gauge part and Yukawa part

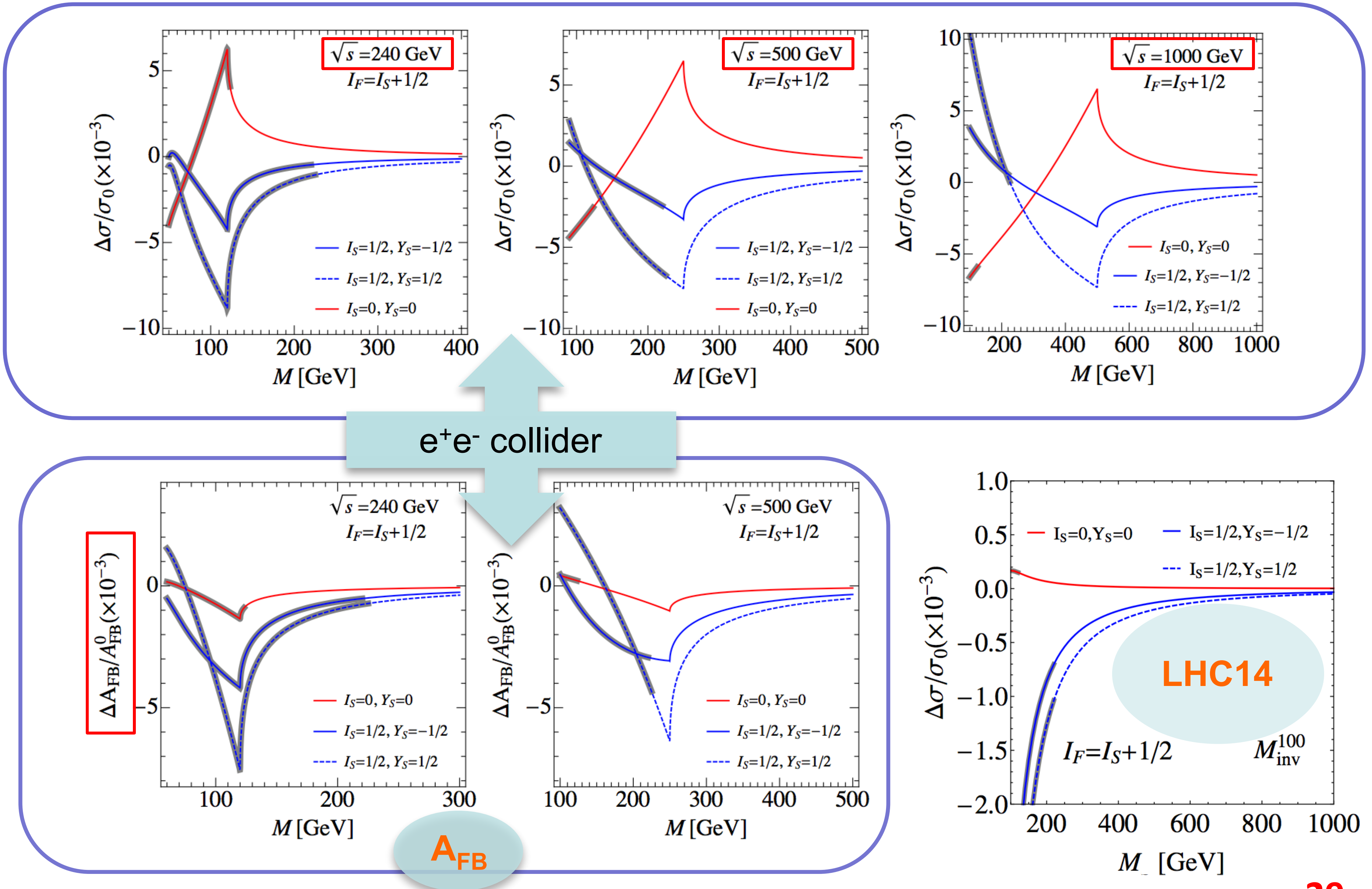
Yukawa Coupling





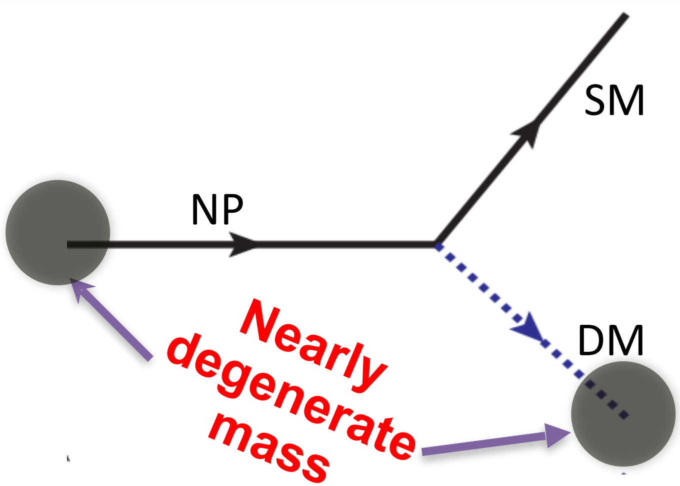
$M = 150\ GeV$

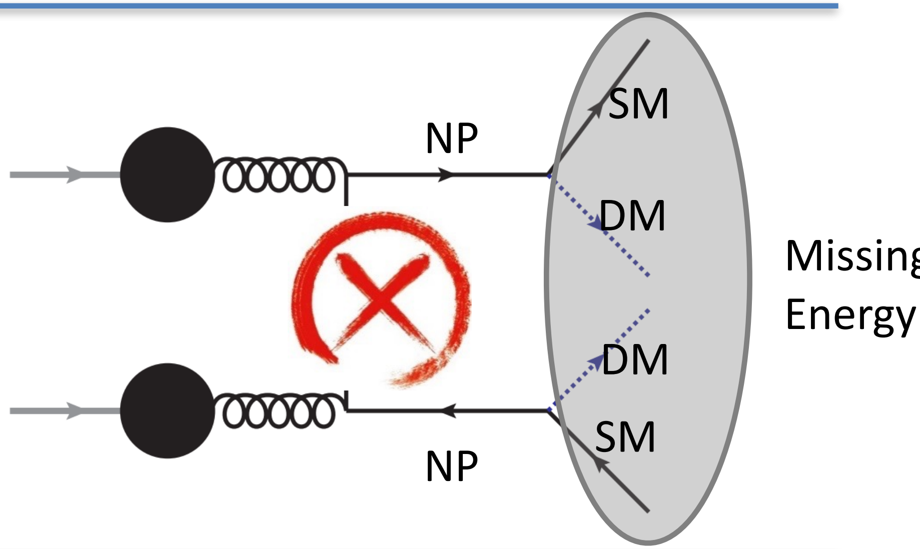
Other collision energies, A_{FB}, pp collider

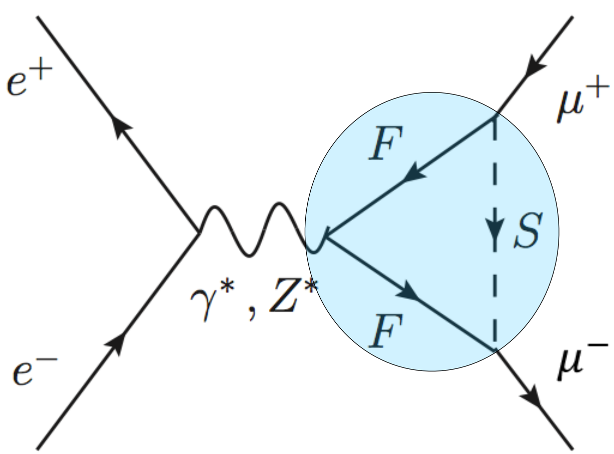


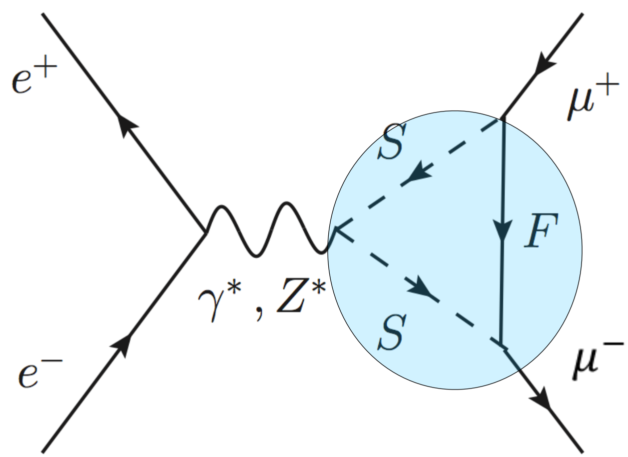
Summary

Nearly degenerate DM models, which are hard to be probed directly at the LHC, can be tested at electron-positron colliders potentially.









Backup slides

$$M_{T2}\left(p_{vis}^{(1)}, p_{vis}^{(2)}, \not{E}_T; m_{inv}\right) = \min_{\not{E}_T = \not{E}_T^{(1)} + \not{E}_T^{(2)}} \left[\max\left\{M_T\left(p_{vis}^{(1)}, \not{E}_T^{(1)}; m_{inv}\right), M_T\left(p_{vis}^{(2)}, \not{E}_T^{(2)}; m_{inv}\right)\right\}\right]$$

$$M_T\left(p_{vis}^{(i)}, \not{E}_T^{(i)}; m_{inv}\right) = \sqrt{m_{inv}^2 + m_{vis}^2 + 2\left(E_T^{vis} \not{E}_T^{(i)} - \vec{p}_{vis}^{\,i} \vec{\not{E}}_T^{\,i}\right)}$$

$$J_{S3} = \begin{cases} \frac{1}{3} I_S, & \text{for } I_F = I_S + \frac{1}{2}, \\ -\frac{1}{3}(I_S + 1), & \text{for } I_F = I_S - \frac{1}{2}. \end{cases}$$

Input parameters

G_μ Scheme:

$G_\mu = 1.1663787 \times 10^{-5} GeV^{-2}$

$\alpha_{EM}(0) = 1/137.035999138$

$m_Z = 91.1876 GeV$

$m_W = 80.385 GeV$

$m_\mu = 105.6583745 MeV$

$c_W = m_W / m_Z$

Renormalization Constant

Yukawa interaction:

$$\delta\alpha_\gamma = -\frac{1}{2}Q\left(\delta Z_\mu^R + \delta Z_\mu^L\right), \qquad \delta\alpha_Z = \frac{1}{2}\left(g_R\delta Z_\mu^R + g_L\delta Z_\mu^L\right),$$

$$\delta\xi_{1,\gamma} = -\frac{1}{2}Q\left(\delta Z_\mu^R - \delta Z_\mu^L\right), \qquad \delta\xi_{1,Z} = \frac{1}{2}\left(g_R\delta Z_\mu^R - g_L\delta Z_\mu^L\right),$$

$$\Sigma(\not p) = \not p\left[\Sigma_L\left(p^2\right)P_L + \Sigma_R\left(p^2\right)P_R\right] + m_\mu\Sigma_S\left(p^2\right),$$

$$\delta Z_\mu^{L,R} = -m_\mu^2\frac{\partial}{\partial p^2}\Re\left[\Sigma_L(p^2) + \Sigma_R(p^2) + 2\Sigma_S(p^2)\right]\Big|_{p^2=m_\mu^2} - \Re\,\Sigma_{L,R}(m_\mu^2).$$

Gauge interaction:

$$\mathcal{C}_{L/R}^\gamma = -Q\left(\frac{1}{2}\delta Z_{AA} + \delta Z_e\right) + g_{L/R}\frac{1}{2}\delta Z_{ZA}, \qquad \mathcal{C}_{L/R}^Z = g_{L/R}\left(\frac{\delta g_{L/R}}{g_{L/R}} + \frac{1}{2}\delta Z_{ZZ}\right) - Q\frac{1}{2}\delta Z_{AZ},$$

$$\mathcal{C}_{AA} = s\delta Z_{AA}, \qquad \mathcal{C}_{AZ} = \delta Z_{ZA}\left(s - m_Z^2\right) + s\delta Z_{AZ}, \qquad \mathcal{C}_{ZZ} = \delta Z_{ZZ}\left(s - m_Z^2\right) - \delta m_Z^2,$$

$$\mathcal{C}'_{AZ} = \frac{1}{2}\left(\delta Z_{AZ} + \delta Z_{ZA}\right), \qquad \mathcal{C}'_{ZZ} = \delta Z_{ZZ},$$

$$\delta g_L = \frac{T^3}{-c_W s_W}\left[\frac{\delta s_W\left(s_W^2 - c_W^2\right)}{c_W^2 s_W} + \delta Z_e\right] + \delta g_R, \qquad \delta g_R = \frac{s_W}{c_W}Q\left[\frac{\delta s_W}{c_W^2 s_W} + \delta Z_e\right],$$

Feynman Rules

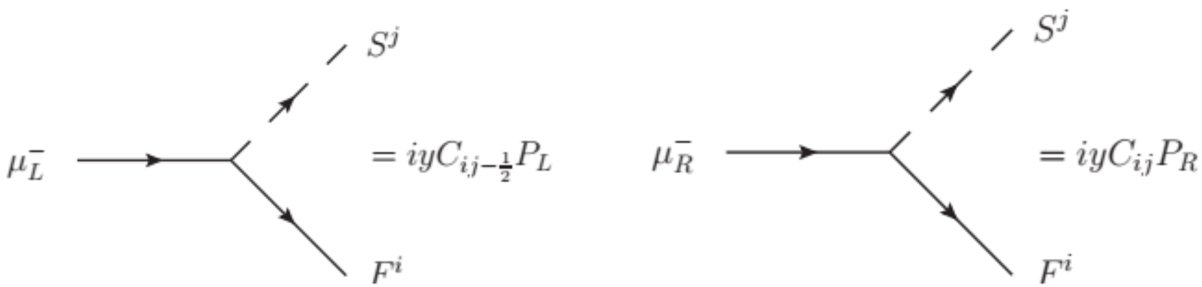
Appendix A: Feynman rules

The Feynman rules for the Yukawa couplings in Eq. 3 and Eq. 13 are displayed in Fig. 7 (a) and (b), respectively. The CG coefficients are given explicitly as follows,

$$C_{ij-\frac{1}{2}} = \begin{cases} (-1)^{I_S-i}\sqrt{\dfrac{I_S+i+1}{2I_S^2+3I_S+1}}\,\delta_{i+j,-\frac{1}{2}}, & \text{for } I_F = I_S+\dfrac{1}{2}, \\ (-1)^{I_S-i-1}\sqrt{\dfrac{I_S-i}{I_S(2I_S+1)}}\,\delta_{i+j,-\frac{1}{2}}, & \text{for } I_F = I_S-\dfrac{1}{2}, \end{cases} \tag{A1}$$

and

$$C_{ij} = (-1)^{I_S-i}\frac{1}{\sqrt{2I_S+1}}\delta_{i+j,0} \quad . \tag{A2}$$



(a) (b)

FIG. 7: Feynman rules of the $S\bar{\mu}_L F$ (a) and $S\bar{\mu}_R F$ (b) couplings in Eq. 3 and 13 respectively.