Probing Dark Sectors with EDMs

Based on MA, M. Rahat, N. Valori, O. Vives 2407.21100

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Universidad de Valencia & IFIC

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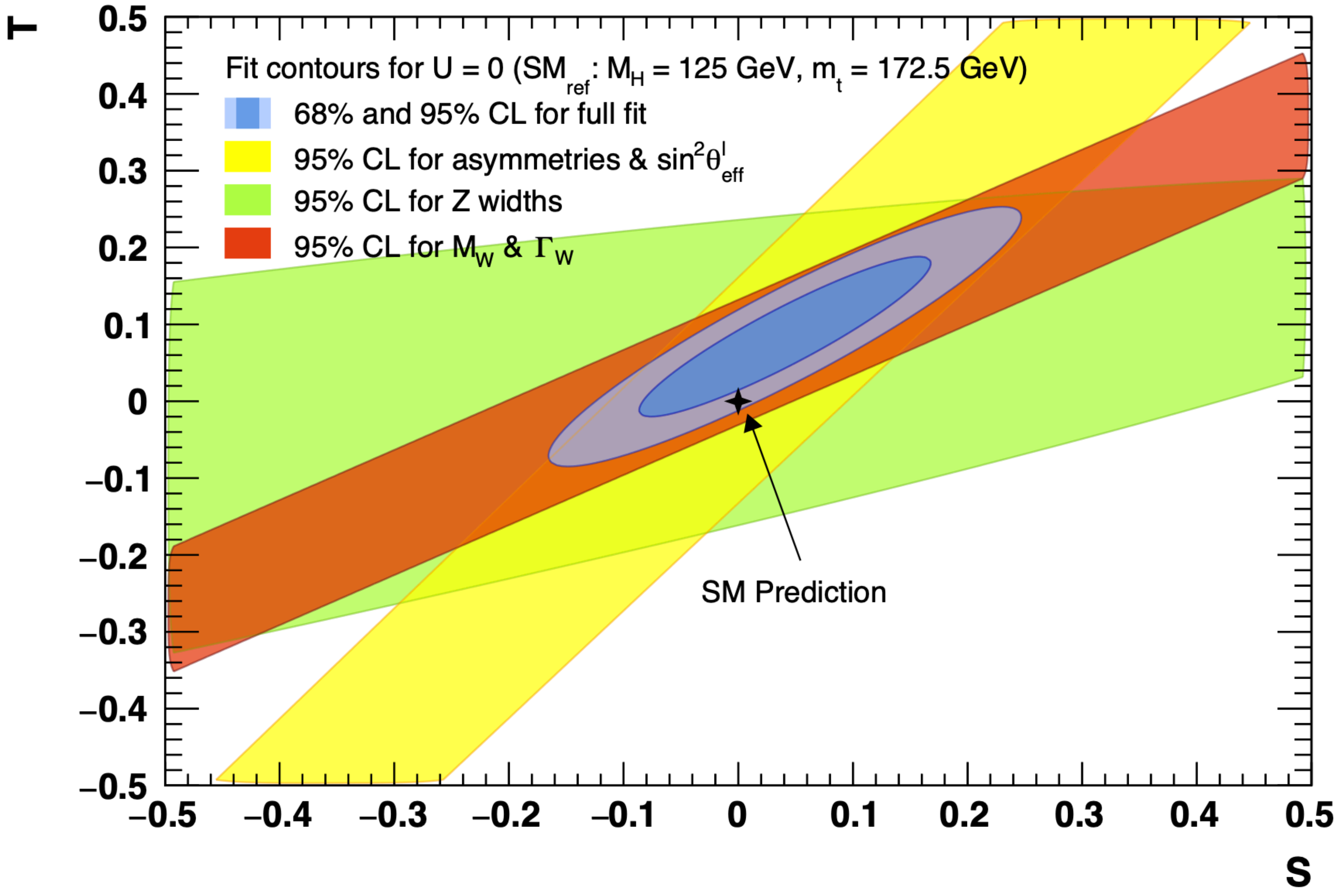

[G-fitter '18]

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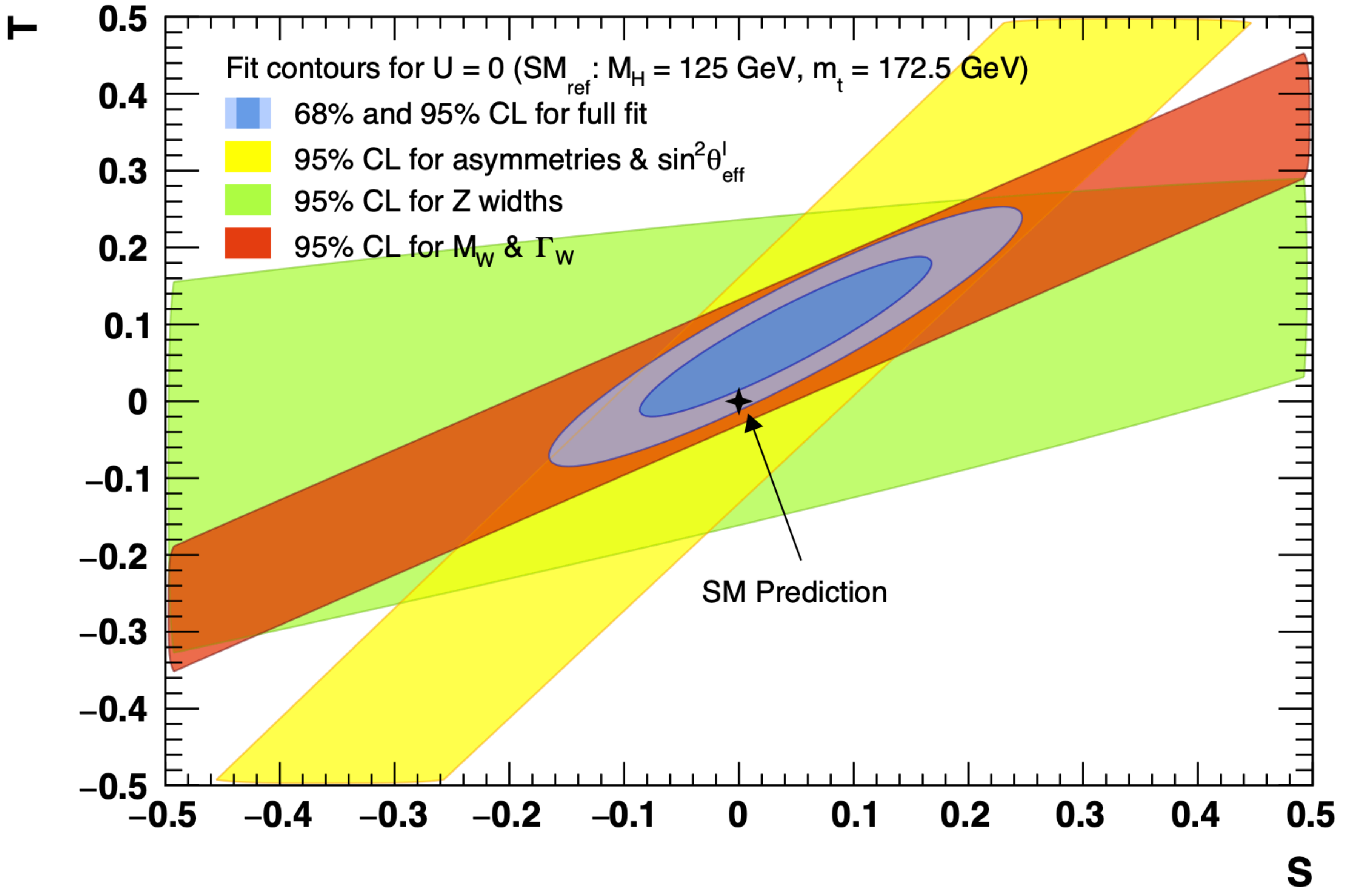

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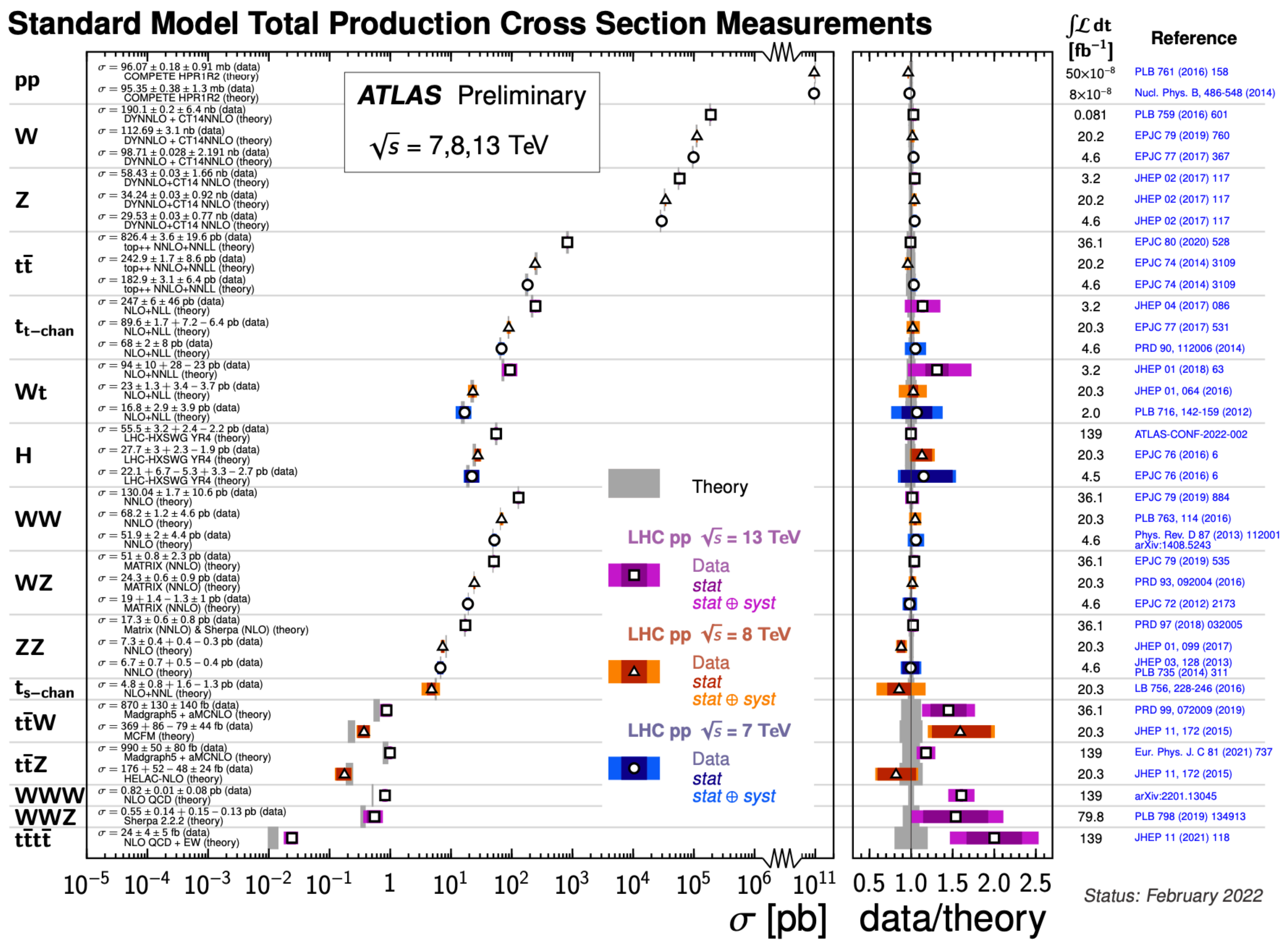

[Atlas Pub2022-009]

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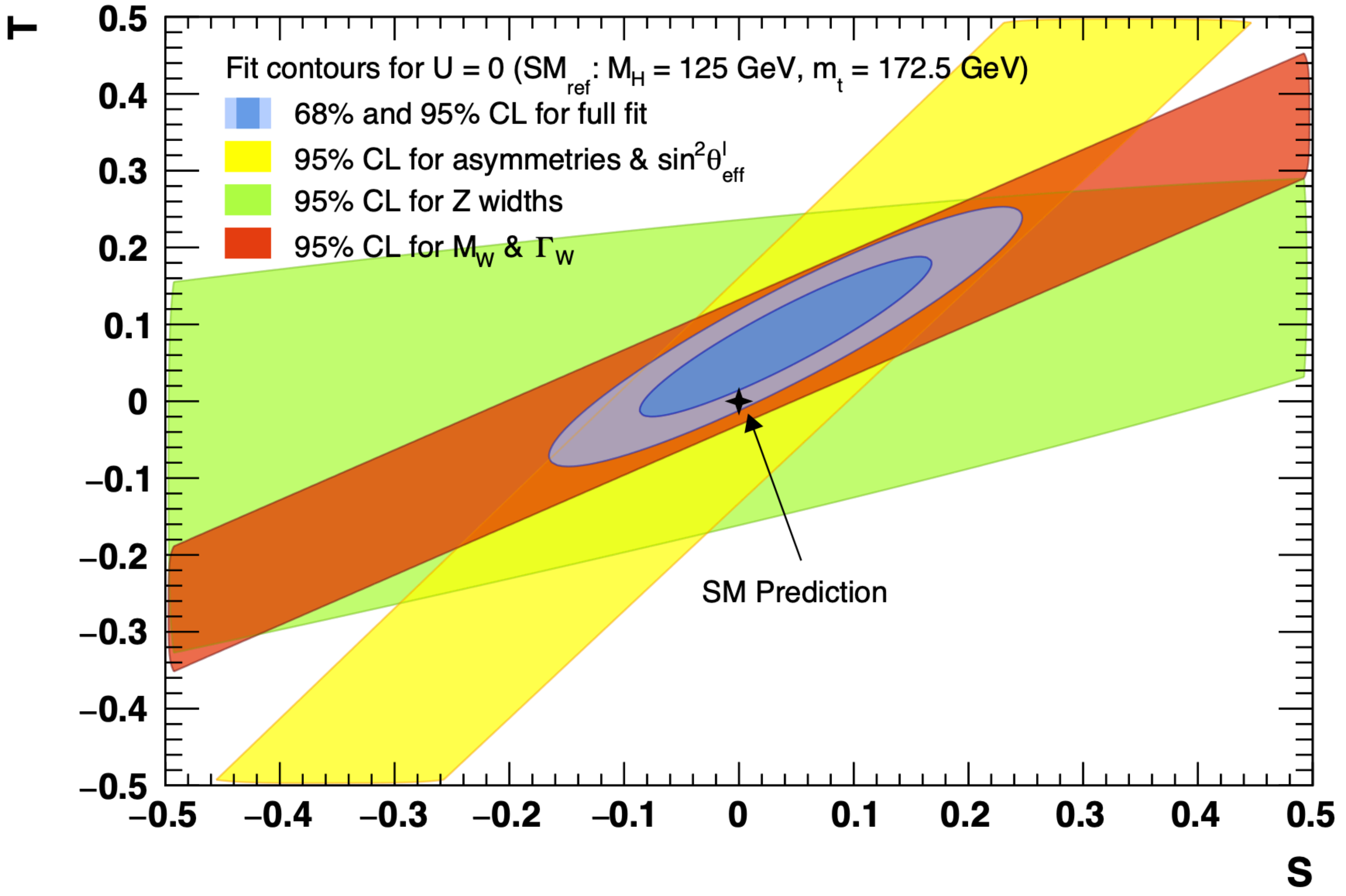

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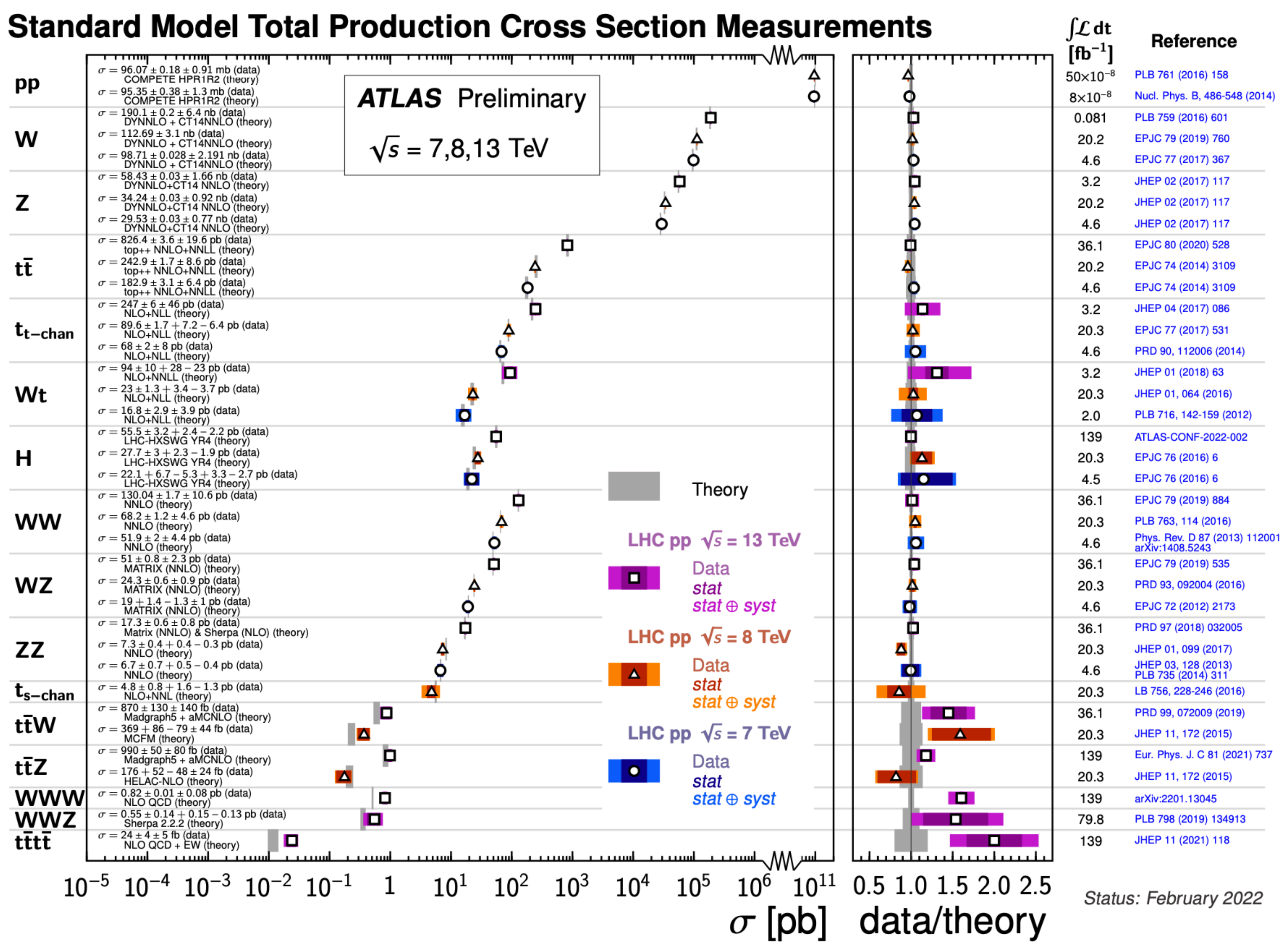

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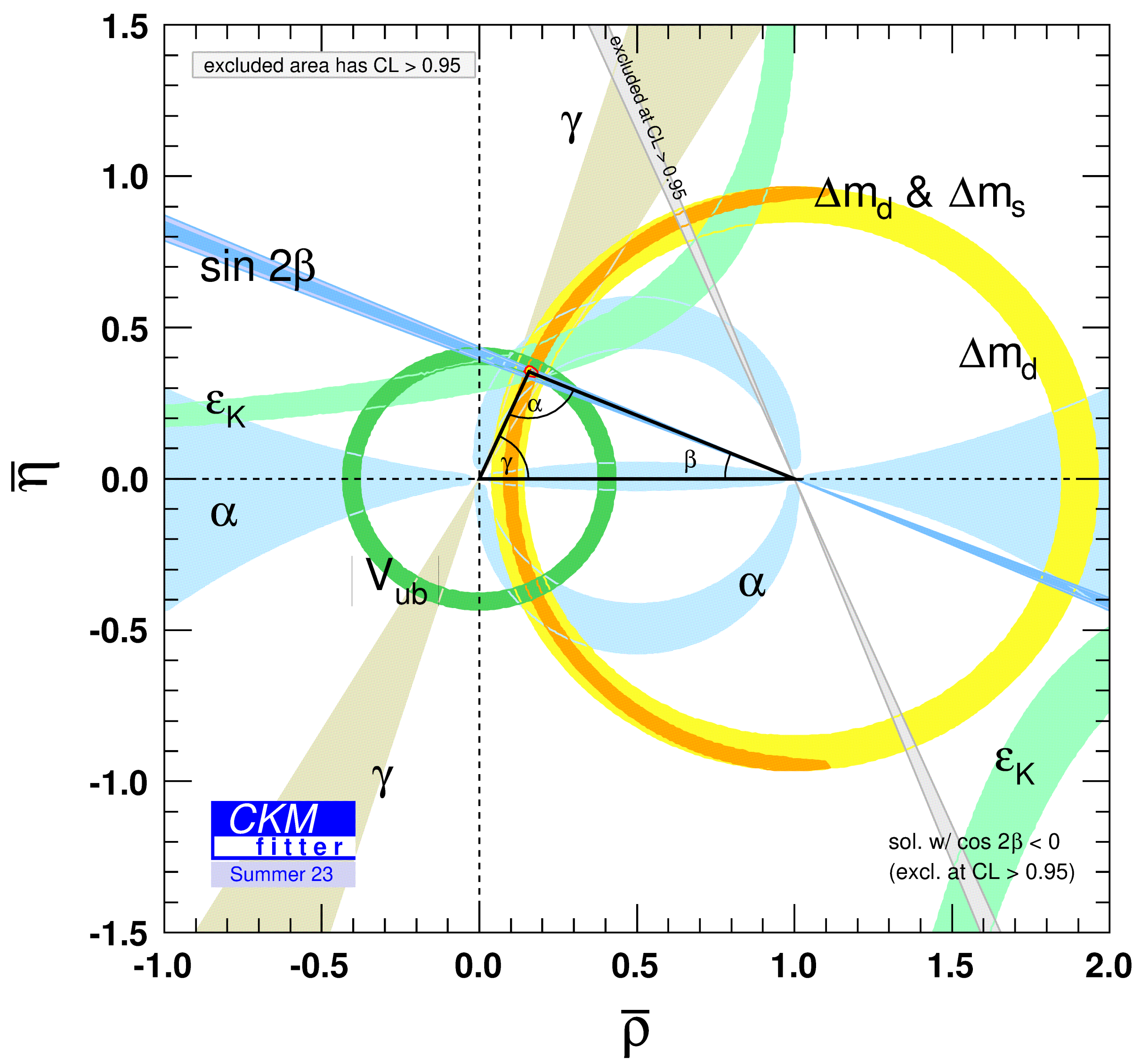

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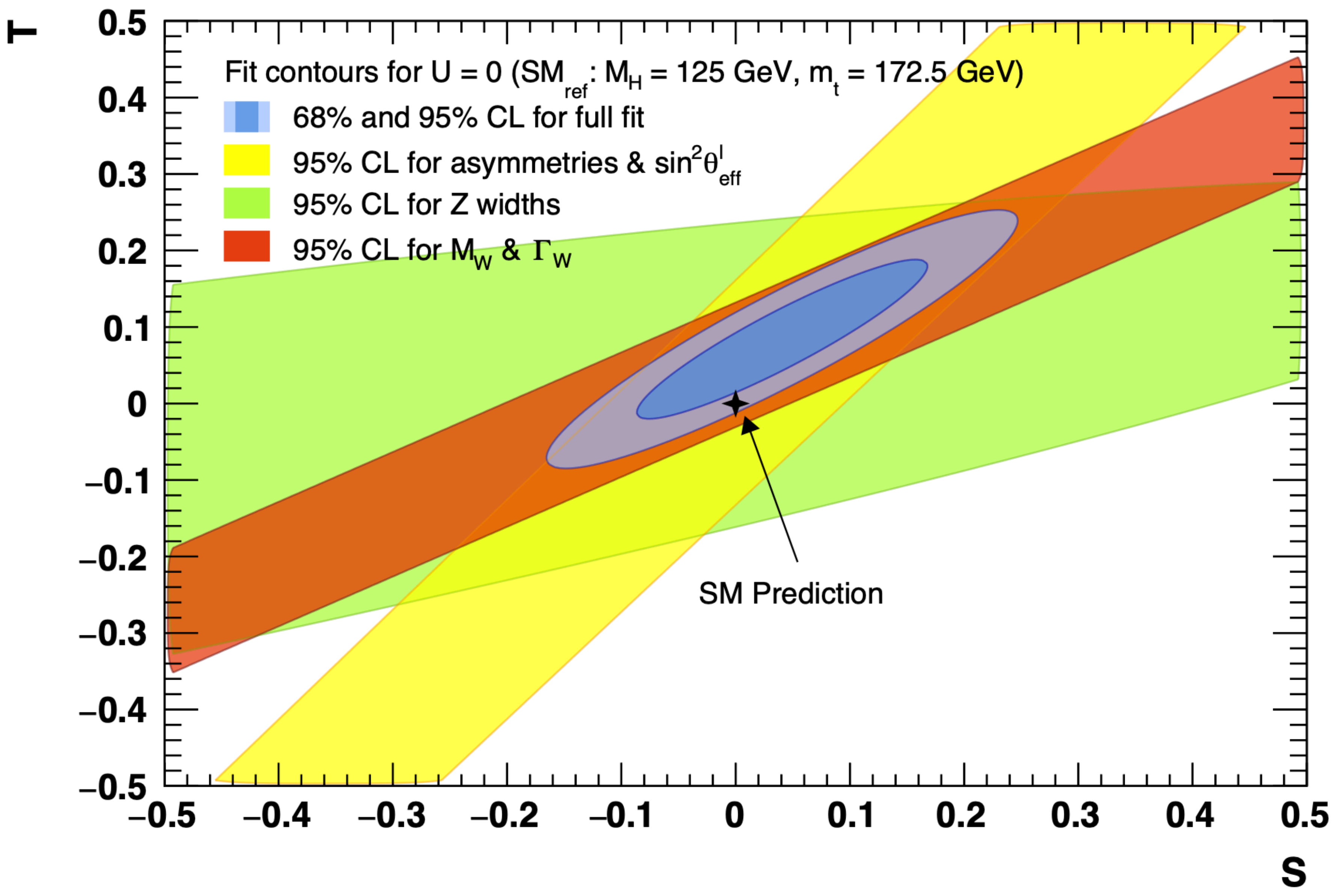

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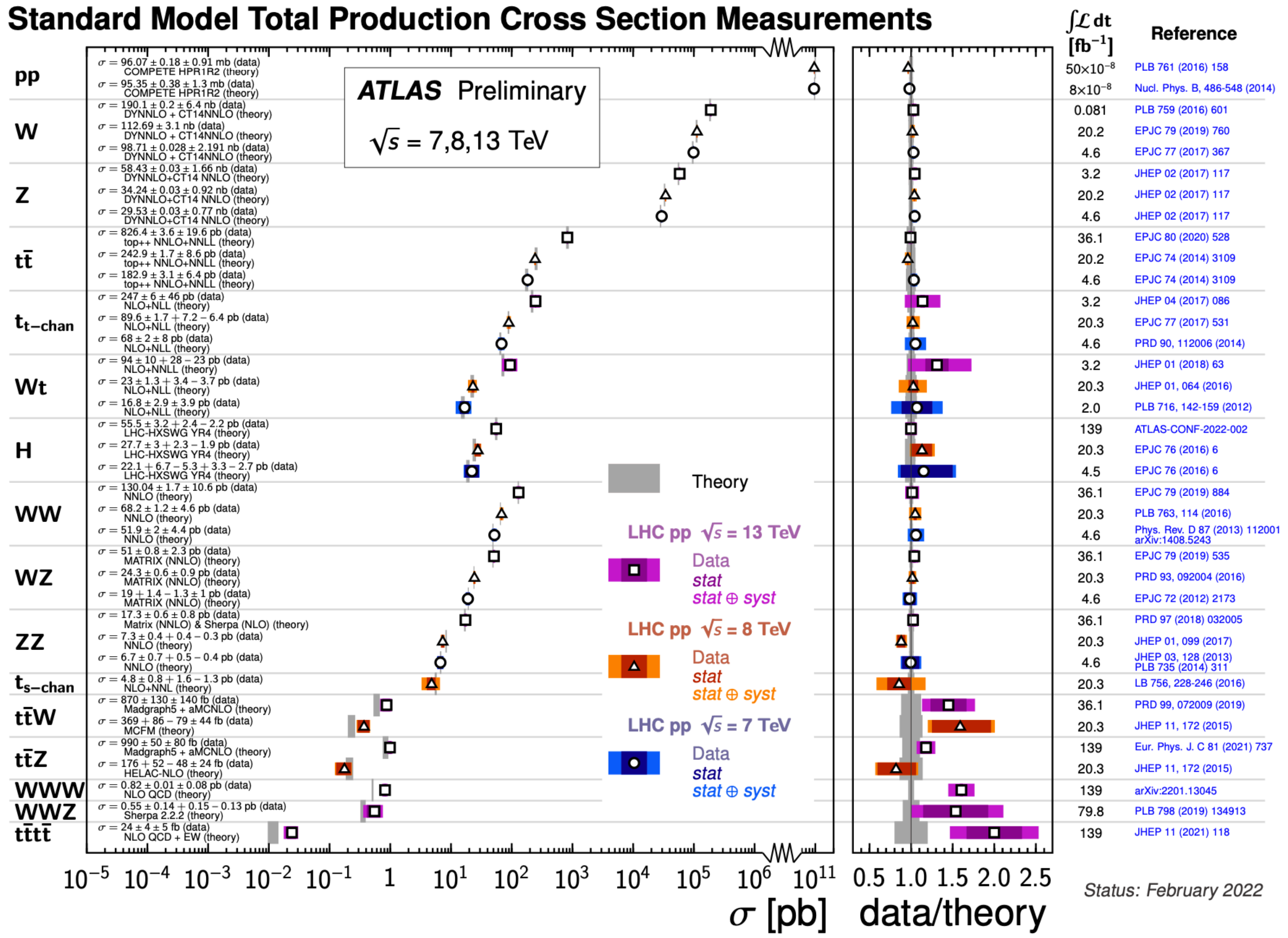

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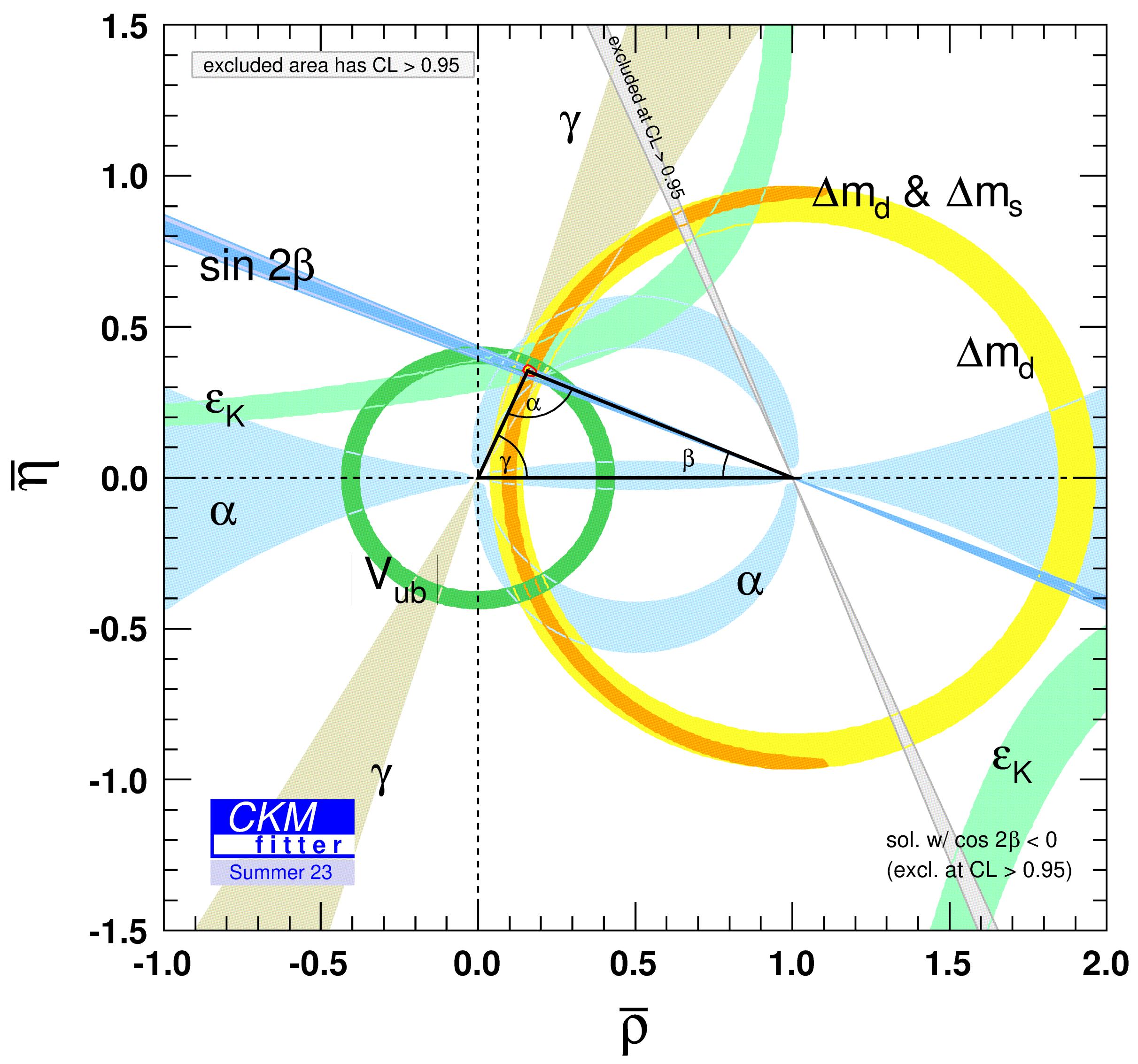
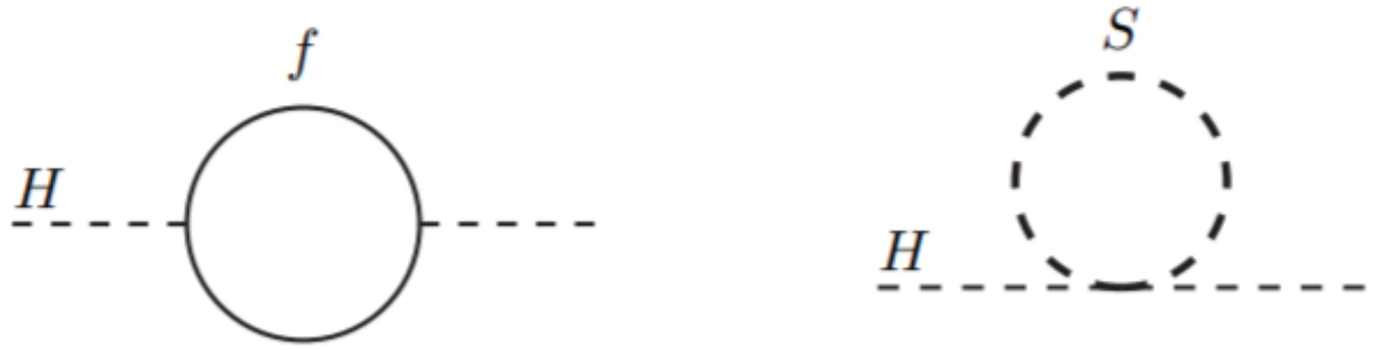


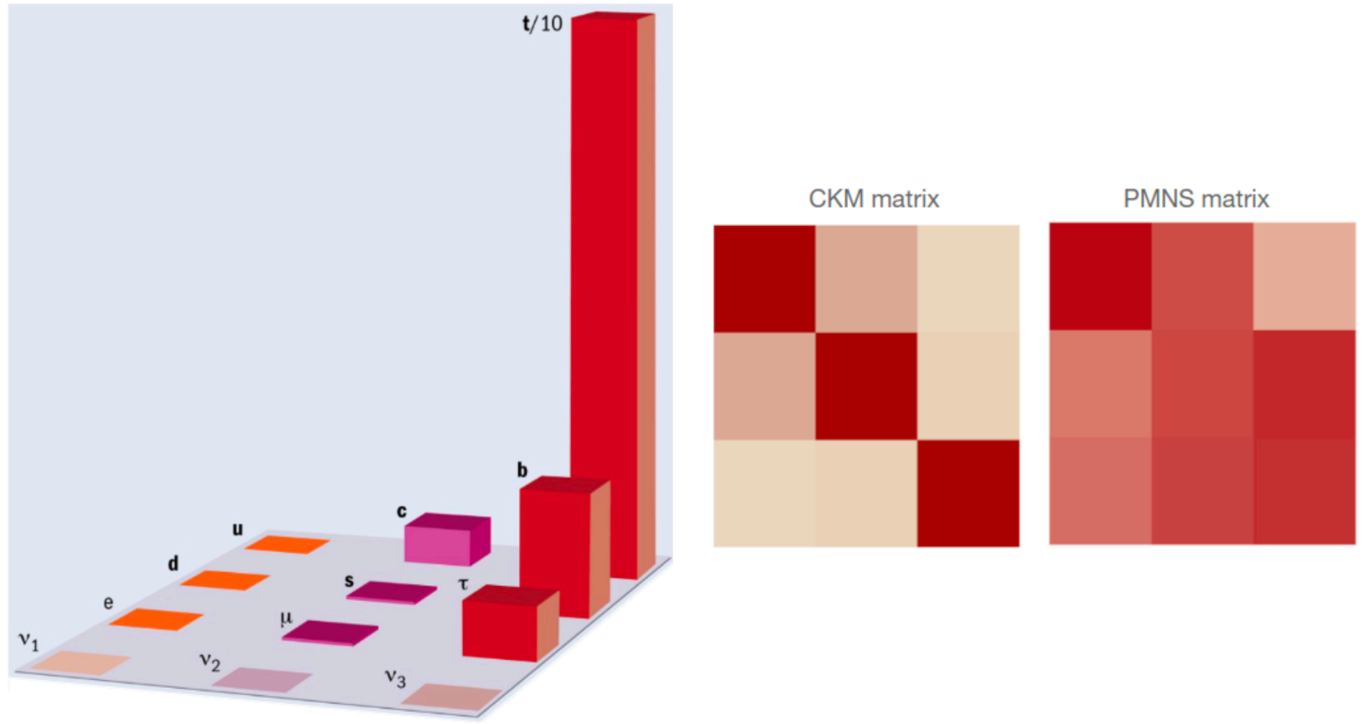
[CKM-fitter '23]

- The Standard Model of Particle Physics is extremely successful in explaining a wide variety of phenomena
- No evidence of new states
- **Yet we know that it cannot be the full story…**

The need for Beyond SM physics

- Strong CP Problem
- Hierarchy Problem
- Flavour puzzle
- …





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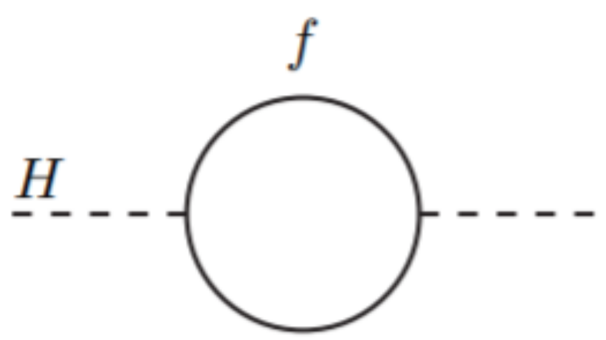
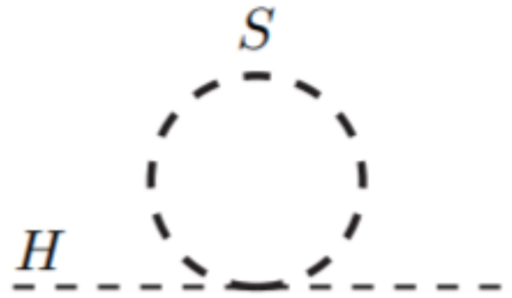
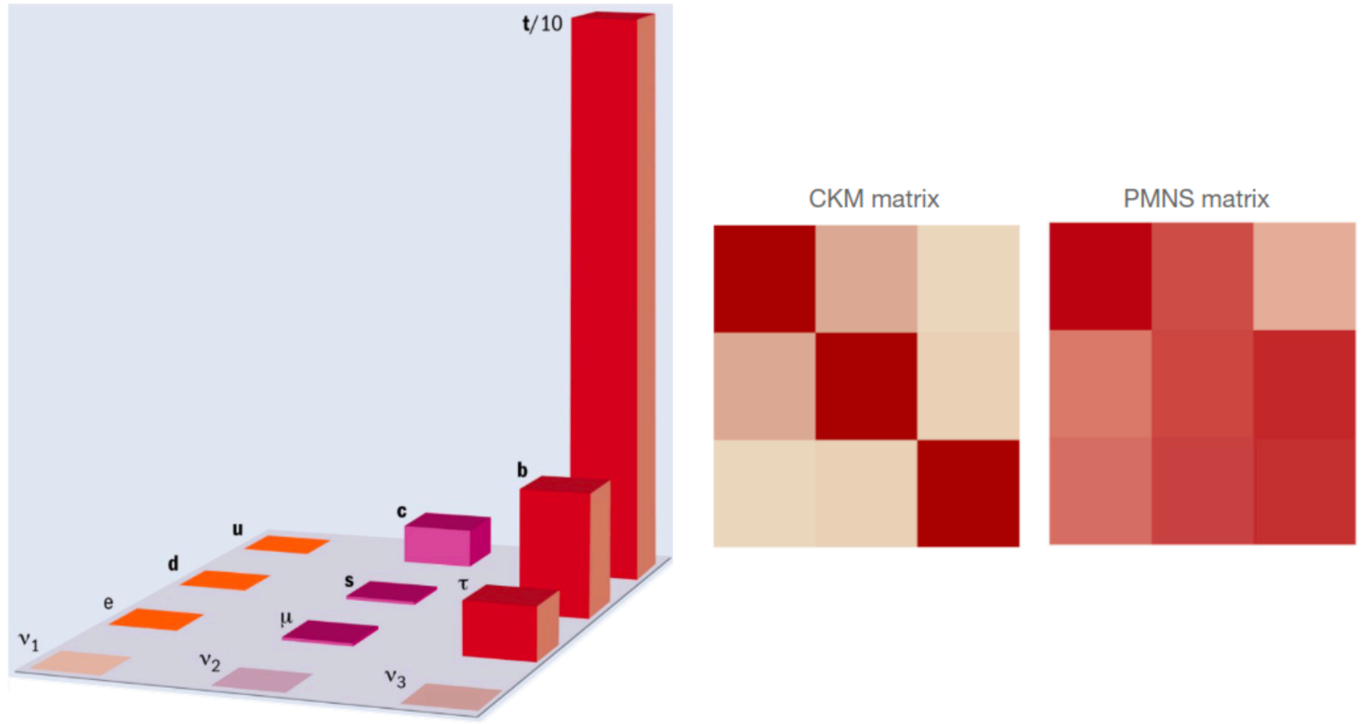
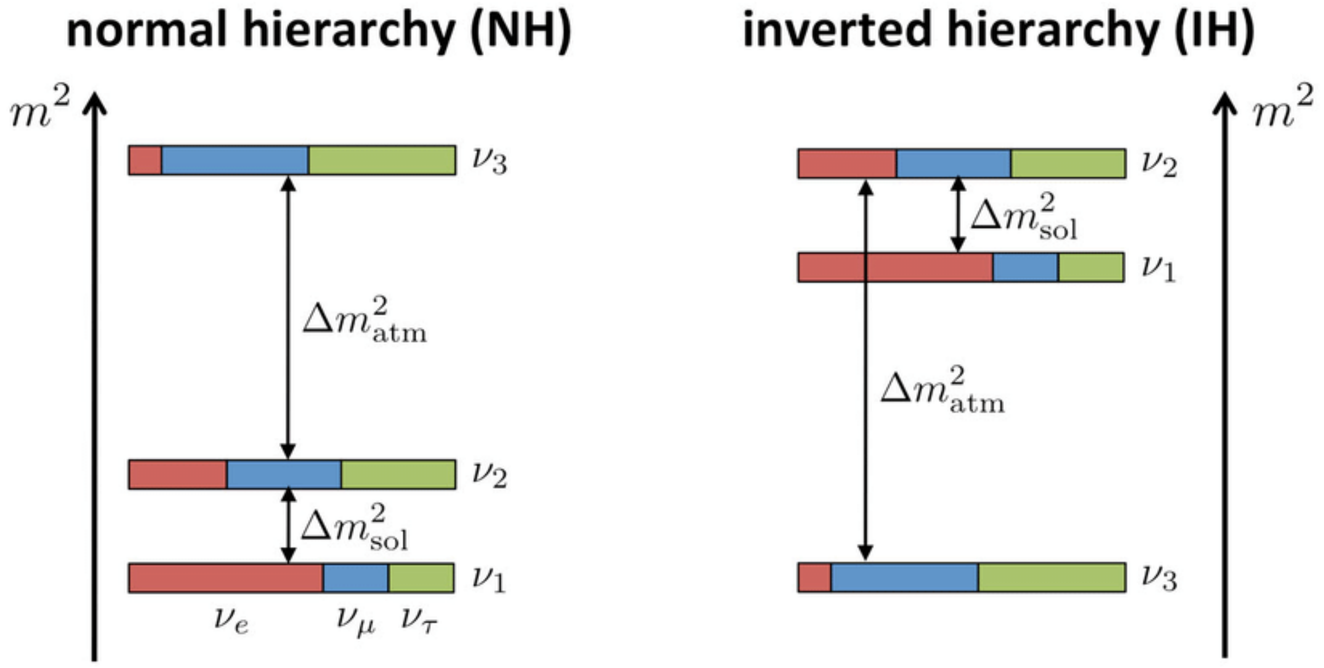
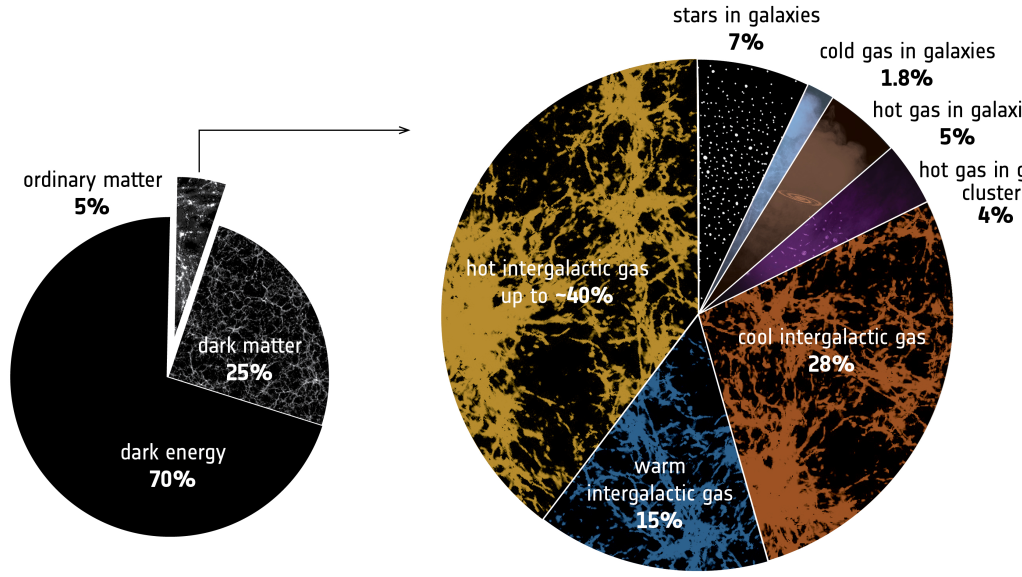






- Neutrino masses
- Dark matter
- Baryon asymmetry of the Universe





$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

Dark Sector (DS)

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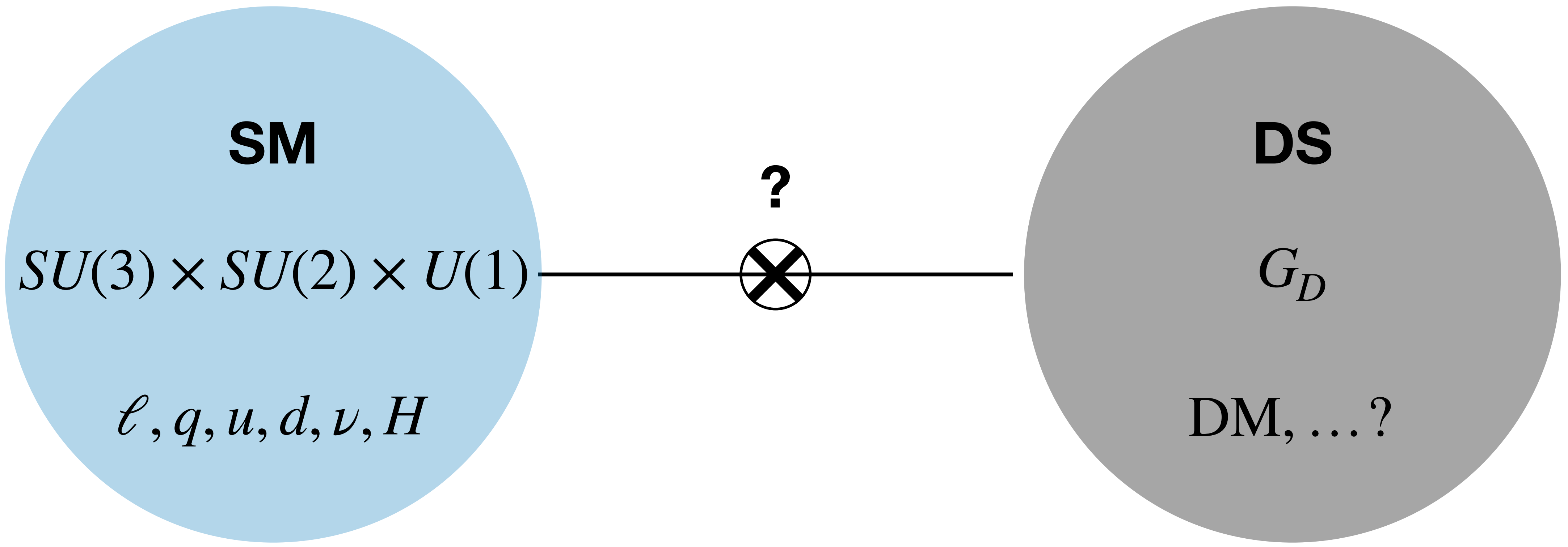
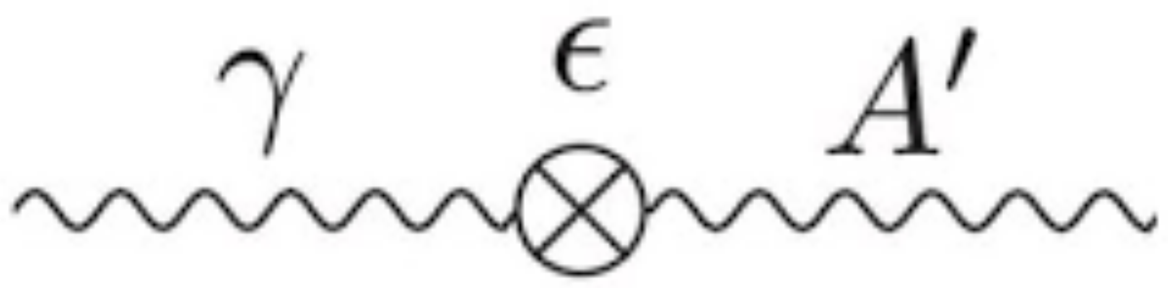


Vector portal to the DS: simplest case

- The SM and DS gauge bosons could mix kinetically

$$G_D = U(1)_D$$

[Holdom '86]



$$U(1)_Y \qquad U(1)_D$$

$$\epsilon B_{\mu\nu} X^{\mu\nu}$$

$$\square_{\mu\nu} = \partial_\mu \square_\nu - \partial_\nu \square_\mu$$

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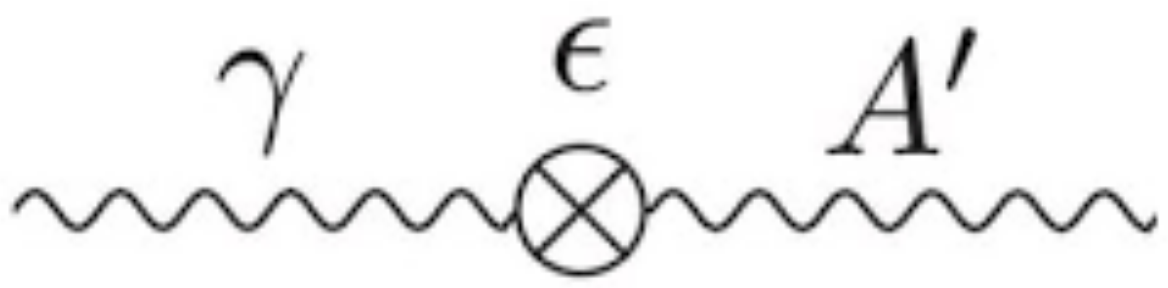

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- The **kinetic mixing for two $U(1)$ is renormalizable** (ϵ is dimensionless)

- If the $U(1)$ is not embedded in a larger group at higher energies, ϵ is just another tree-level Lagrangian coupling

- To make the **dark sector feebly interacting** with the SM we have to take $\epsilon \ll 1$

Vector portal to the DS: Non-abelian dark sectors

$$G_D = SU(N)_D$$

- The vector bosons of the dark sector carry an adjoint index A: $X^A_{\mu\nu}$.

$\Rightarrow$ Vector mixing is only possible at the non-renormalizable level!

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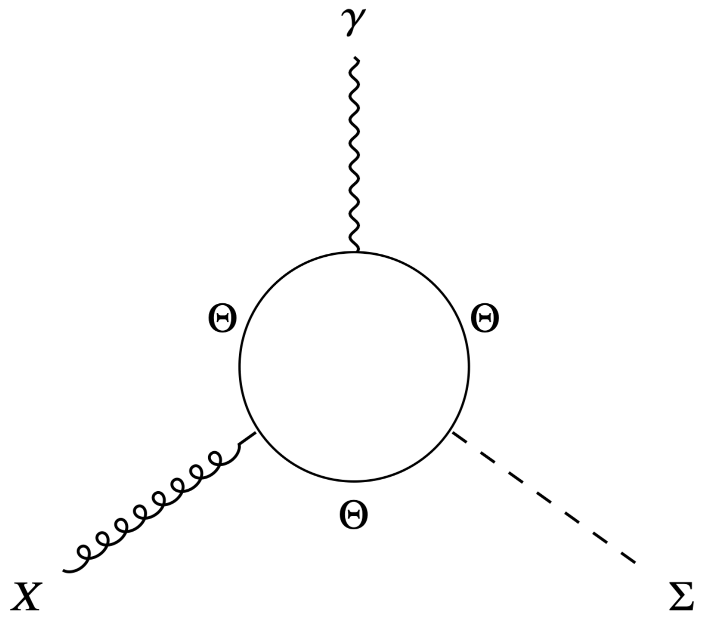

$$\frac{\Sigma^A}{\Lambda} B^{\mu\nu} X^A_{\mu\nu} \qquad \frac{(\phi^\dagger T^A \phi)}{\Lambda^2} B^{\mu\nu} X^A_{\mu\nu} \qquad \cdots$$

$T^A \equiv$ generator

$\Sigma^A \equiv$ adjoint scalar

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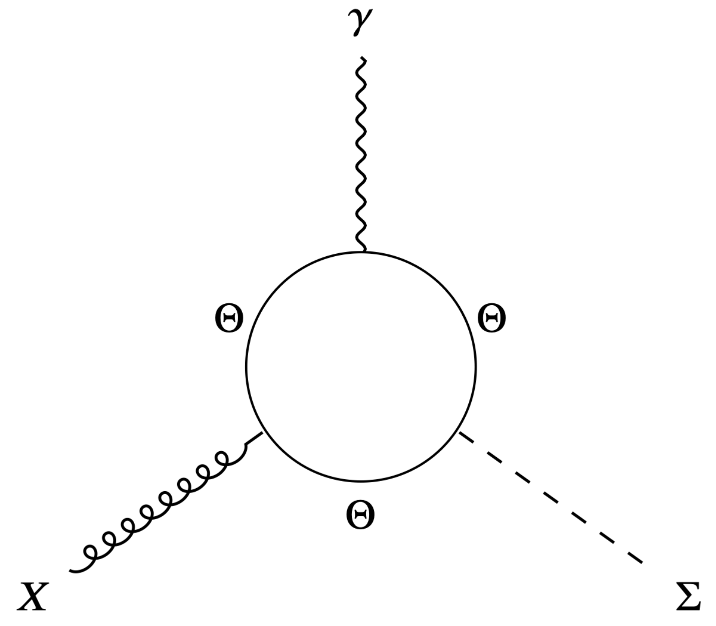

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- Kinetic mixing possible if scalar gets vevs (or group confines) and is naturally suppressed if Λ is large:

[Alonso-Alvarez et al '23]

$$\frac{\langle \Sigma^A \rangle}{\Lambda} B^{\mu\nu} X^A_{\mu\nu} \equiv \epsilon^A B^{\mu\nu} X^A_{\mu\nu}$$

Intermezzo: CP violation

- **CP** distinguishes matter and anti-matter $\Rightarrow$ **CP violation necessary to explain baryon and anti-baryon asymmetry**!

[Sakharov '67]

$$i \xrightarrow{\Delta B} f \quad \overset{\hat{C}\hat{P}}{\Rightarrow} \quad \bar{i} \xrightarrow{-\Delta B} \bar{f}$$

It must be $\Gamma(i \to f) \neq \Gamma(\bar{i} \to \bar{f})$

- All CP violation in the SM is parametrised by the Jarlskog invariant $J \simeq 10^{-5}$ [Jarlskog '85] [PDG RPP '22]
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No way to define a C charge for Σ that make both CP even: CP is violated

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Probing non-abelian DS with EDMs

[Buttazzo et al ’19,’20]
[Landini, Wang ’20]
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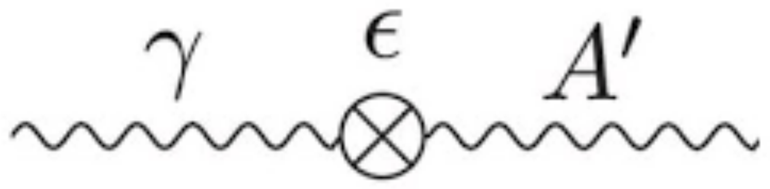

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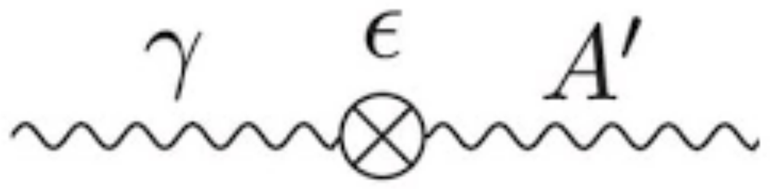

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Higgs-Dark scalar mixing

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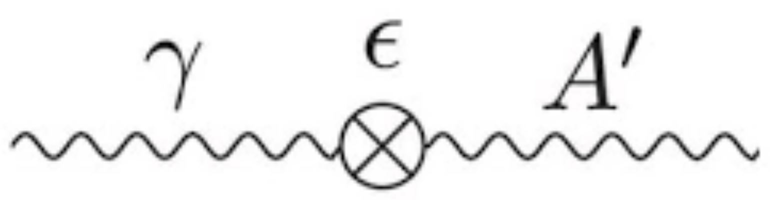

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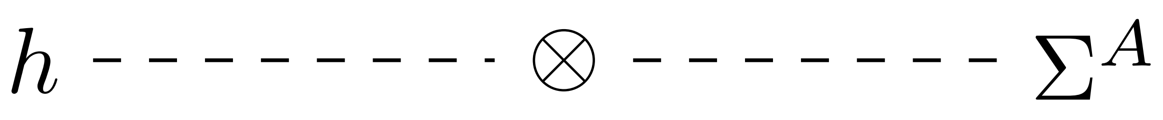

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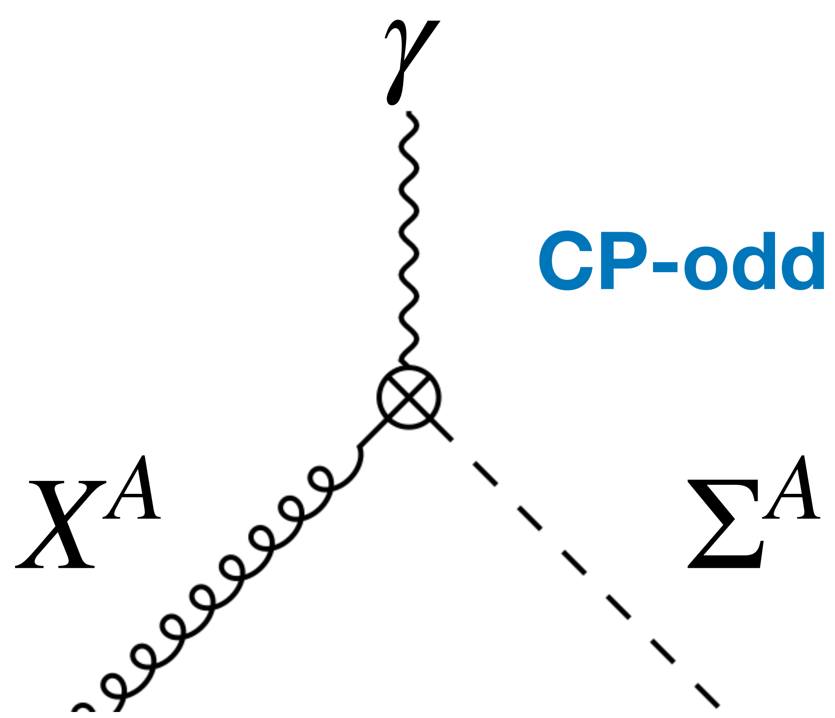

CP-odd triple vertex

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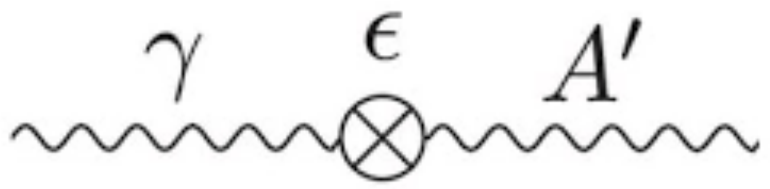

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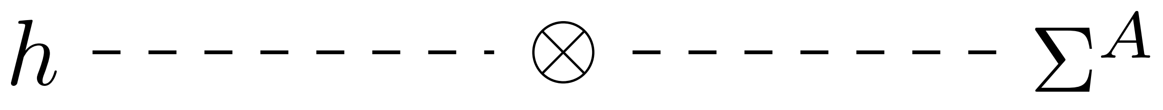

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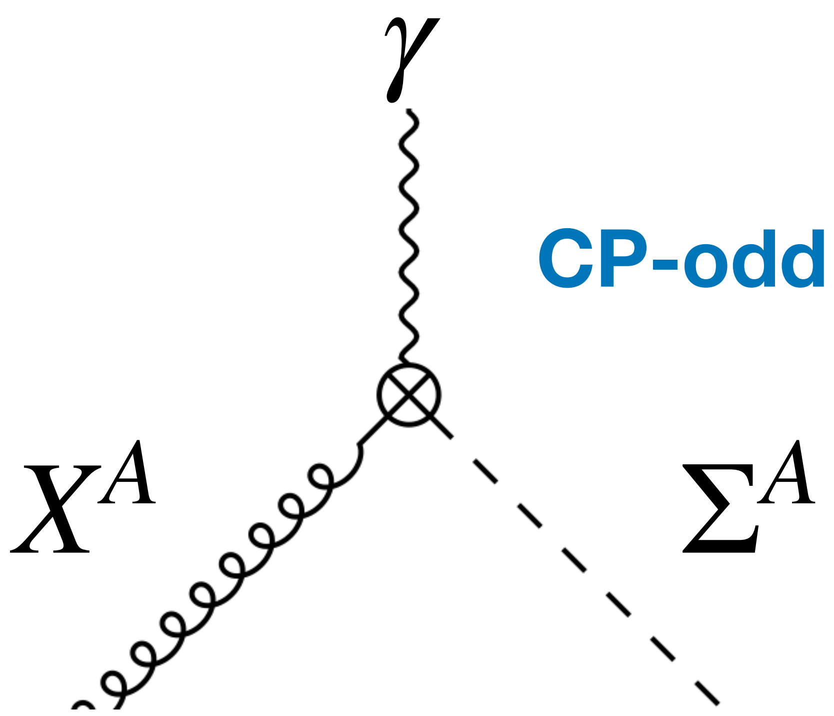
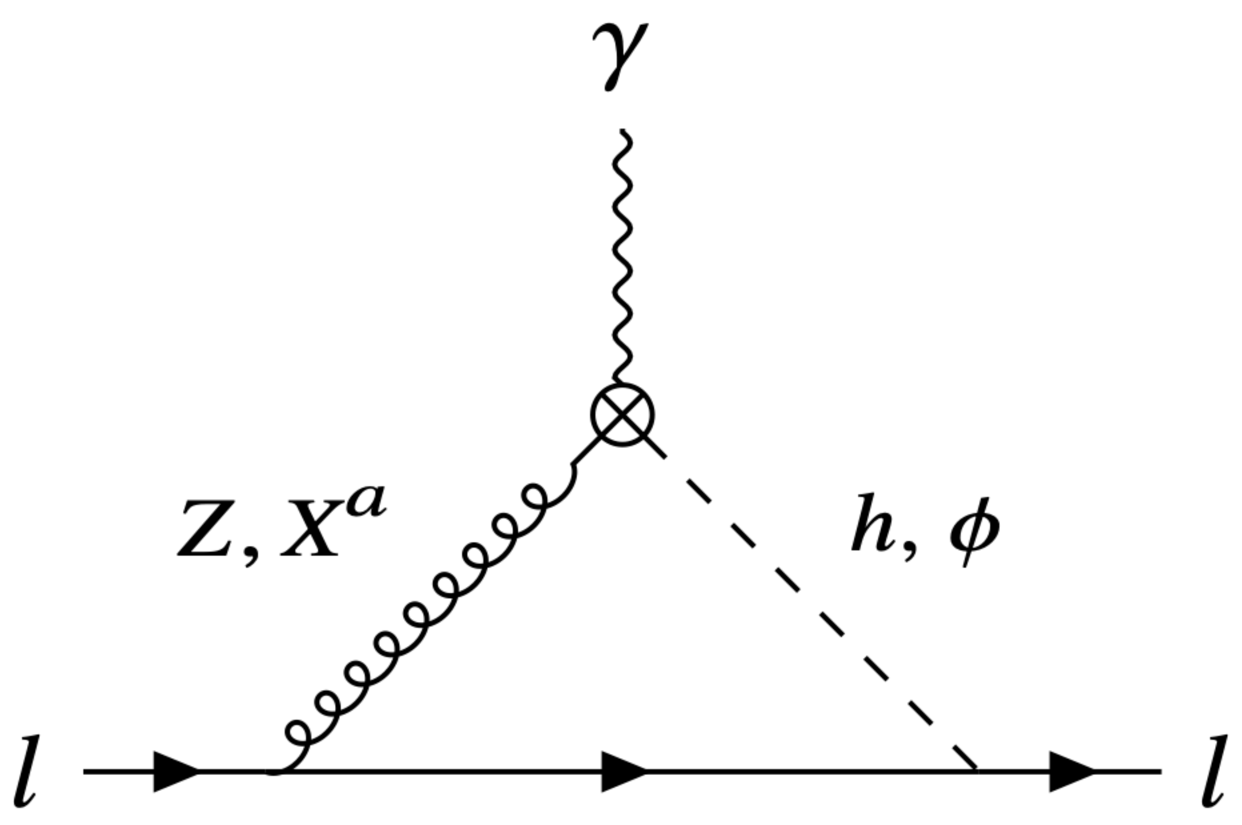


CP-odd triple vertex

- Contribution to the EDMs:



$$\mathscr{L}_{\text{EDM}} = -\frac{i}{2} d_f \left(\bar{\psi}_f \sigma_{\mu\nu} \gamma_5 \psi_f\right) F^{\mu\nu}$$

EDM=most sensitive probe of CP violation

- Experiments are sensitive to EDMs much larger than what the SM predicts

[Chupp et al, 1710.0250]

SUSY
CPV Two Higgs Doublet Model
Left-Right Symmetric Model
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⇒ **They still provide stringent constraint on CP violating New Physics**

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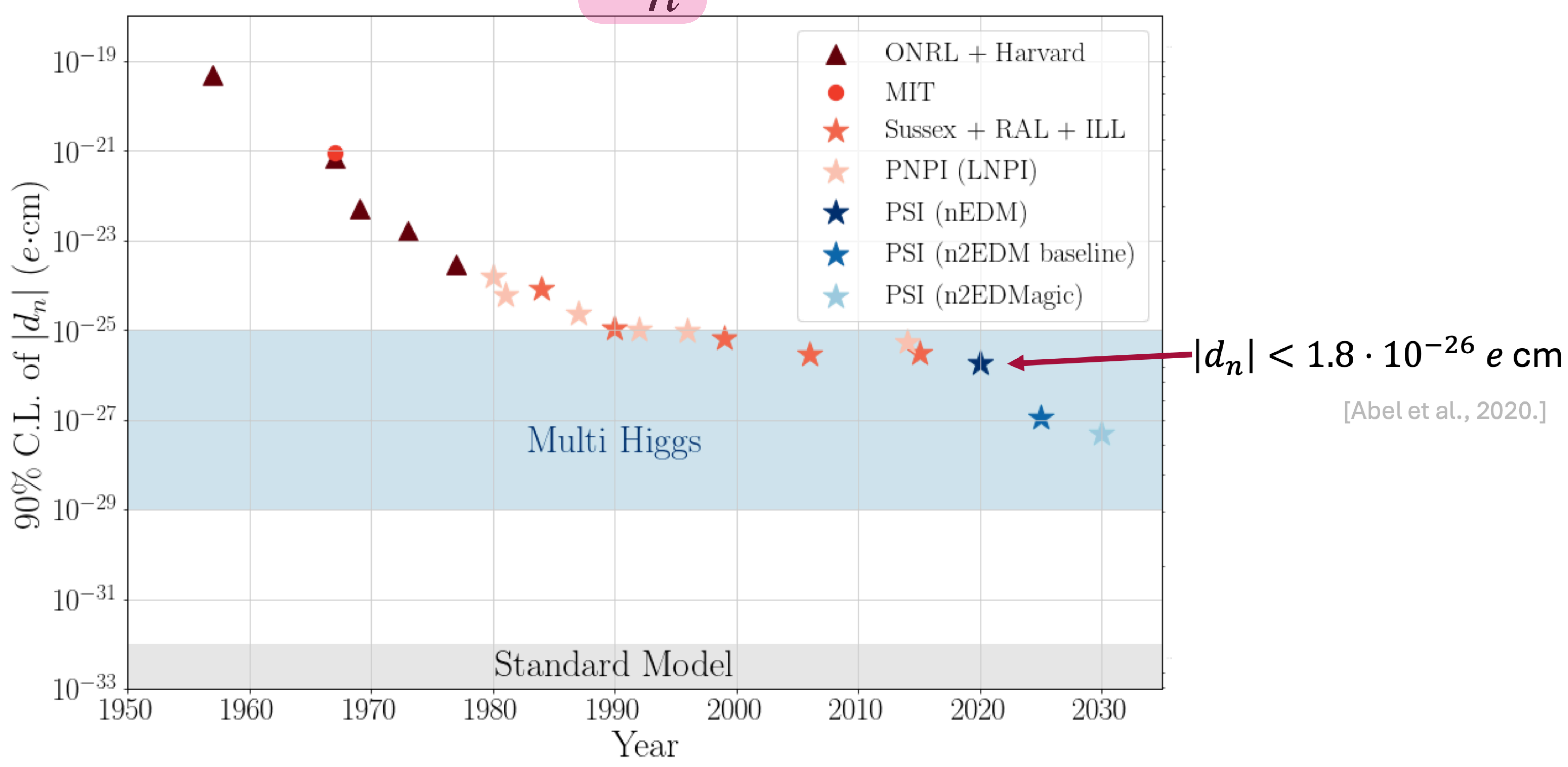

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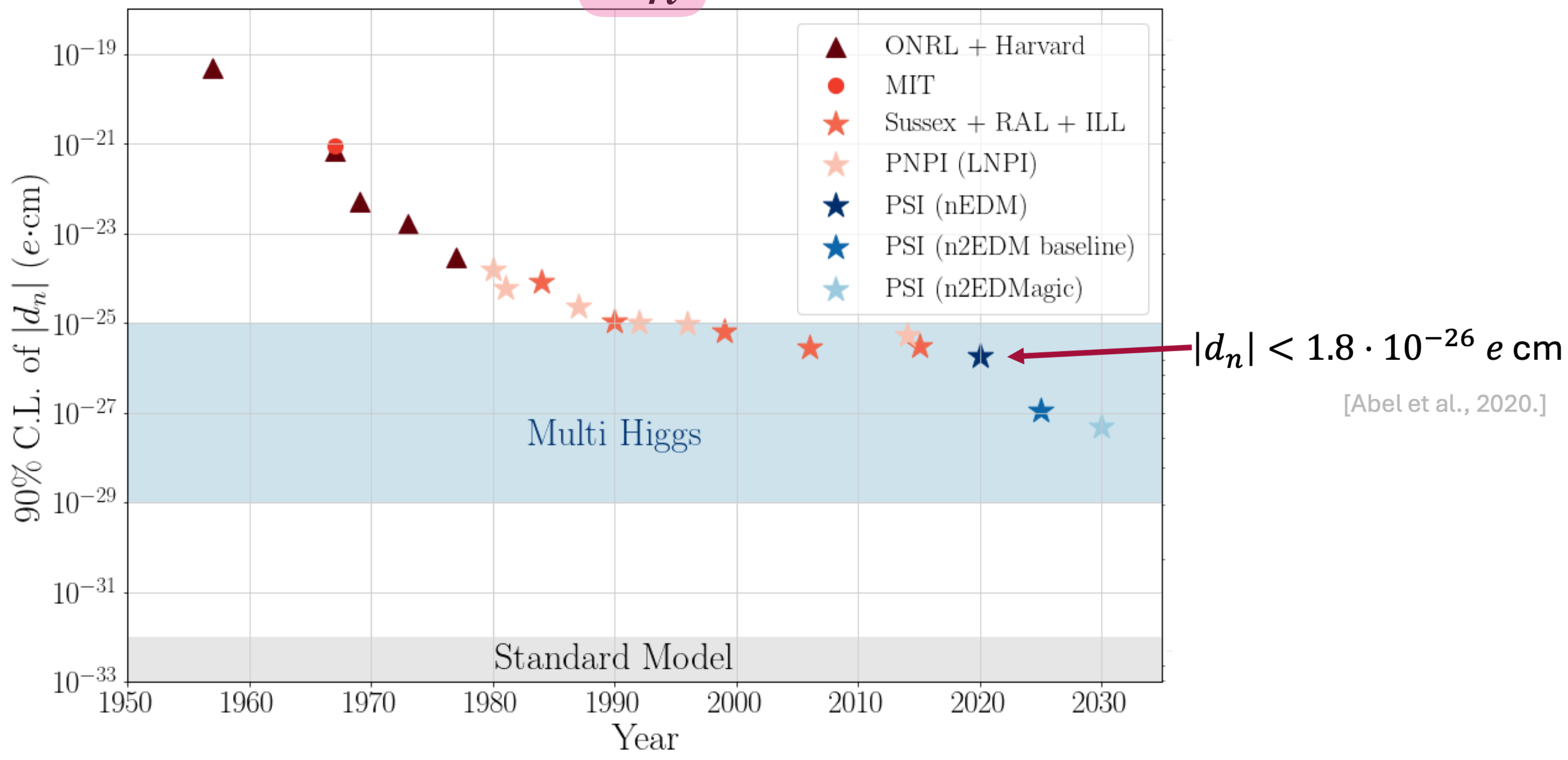
d_n



$$d_\mu < 1.8 \times 10^{-19}\ e \cdot \mathrm{cm} \rightarrow 6 \times 10^{-23}\ e \cdot \mathrm{cm}$$

[muEDM, 2201.06561]

EDM=most sensitive probe of CP violation

- Experiments are sensitive to EDMs much larger than what the SM predicts

  ⇒ **They still provide stringent constraint on CP violating New Physics**

[Chupp et al, 1710.0250]

SUSY
CPV Two Higgs Doublet Model
Left-Right Symmetric Model
…

- **Next generation of experiments expect to improve their sensitivities of orders of magnitude**

d_e

Experiment	Current bound/Upcoming sensitivity
JILA eEDM	$< 4.1 \times 10^{-30}$ e cm
ACME III	$\sim 1 \times 10^{-30}$ e cm
YBF	$\sim 1 \times 10^{-31}$ e cm
BaF	$\sim 1 \times 10^{-33}$ e cm

- In flavour blind models, the electron EDM is the most constraining

eEDM vs Dark Photon searches

- Assume that CP-even and CP-odd operators have a similar coefficient

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$$\frac{\epsilon}{v_D}\Sigma B^{\mu\nu}X_{\mu\nu}$$

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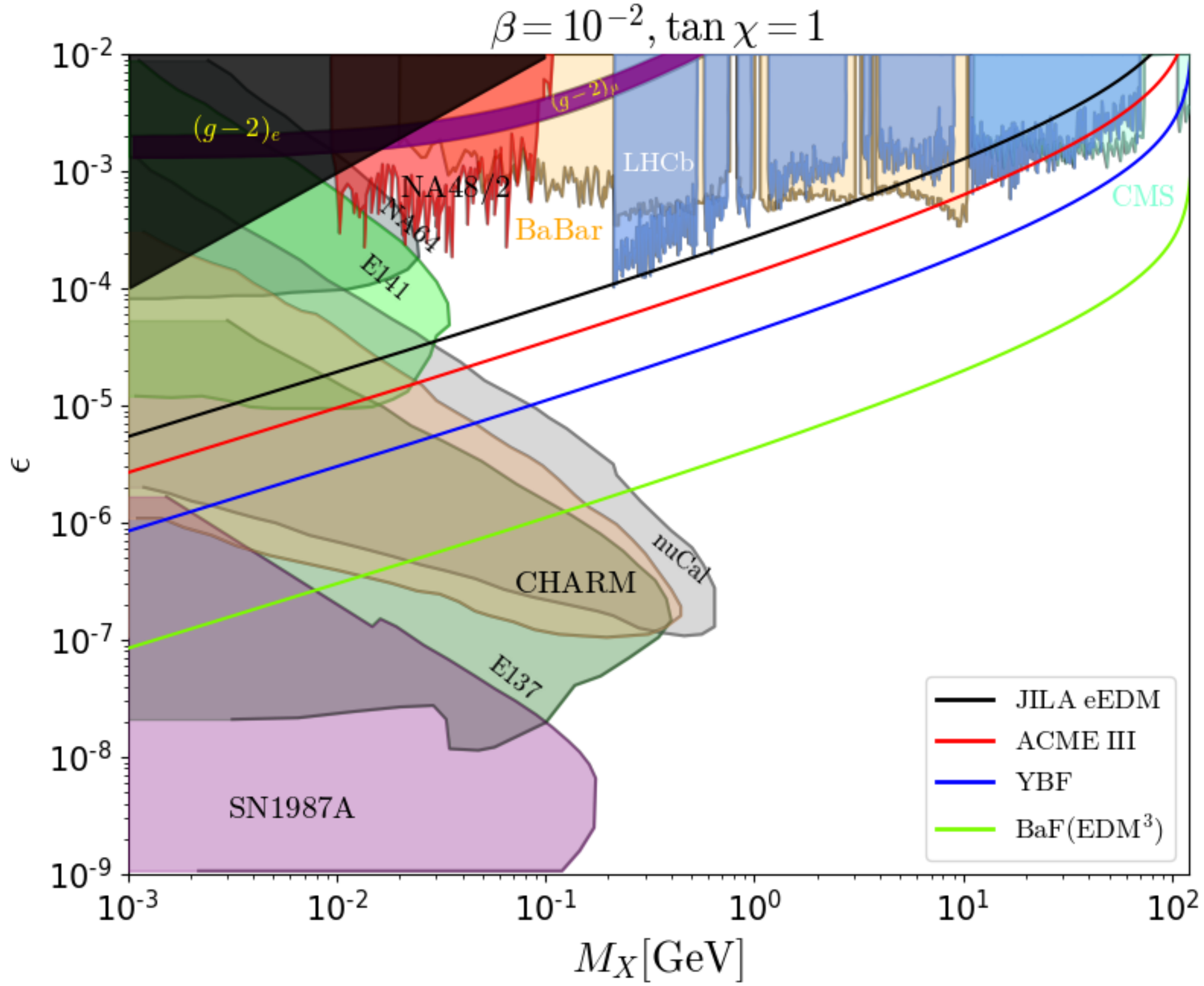
- Assume that the dark photon acquire a mass $M_X \sim v_D$ and the scalar mass is also $m_\Sigma \sim v_D$

- β is the mixing angle between Higgs and the dark scalar



$SU(2)_D \to U(1)_D$

- **SU(2) spontaneously broken by an adjoint scalar Σ: unbroken $U(1)_D$**

$$\langle \Sigma^3 \rangle = v_D \qquad M_{X_3} = 0,\ M_{X_{1,2}} = g_D v_D$$

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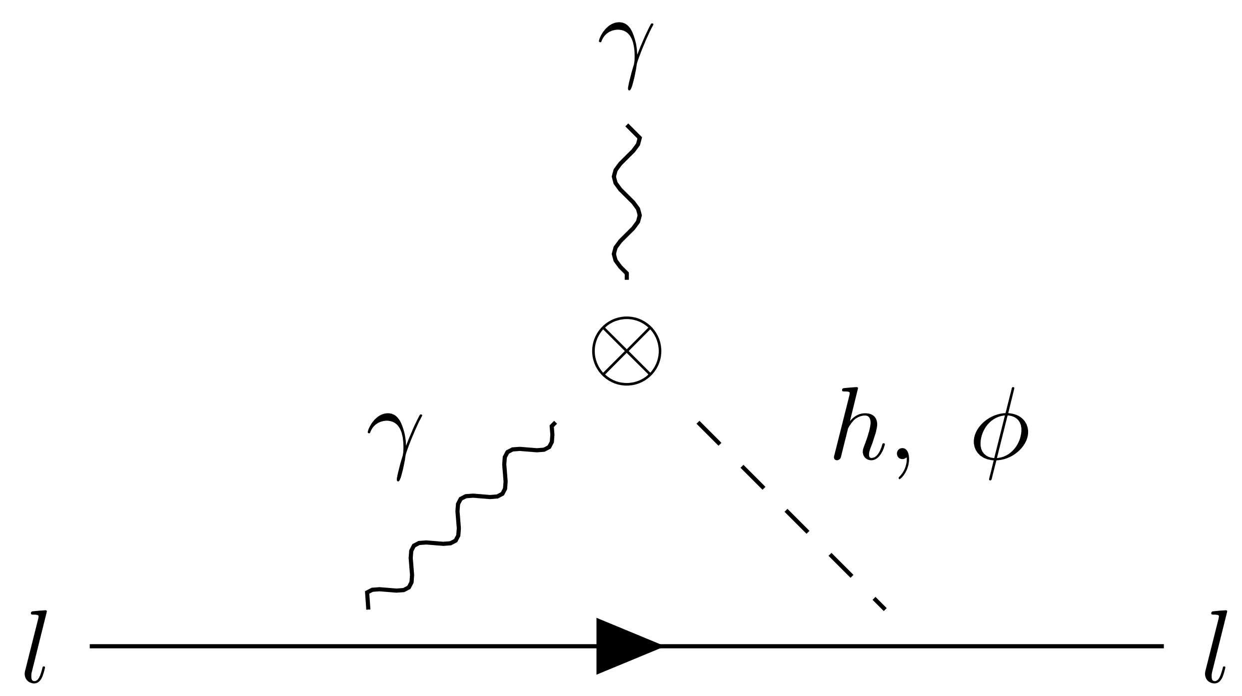

$$\Leftarrow \frac{\tilde{\epsilon}}{v_D}\, \epsilon^{\mu\nu\rho\sigma}\, \Sigma^A B_{\mu\nu} X^A_{\rho\sigma}$$

EDMs vs millicharged particles searches

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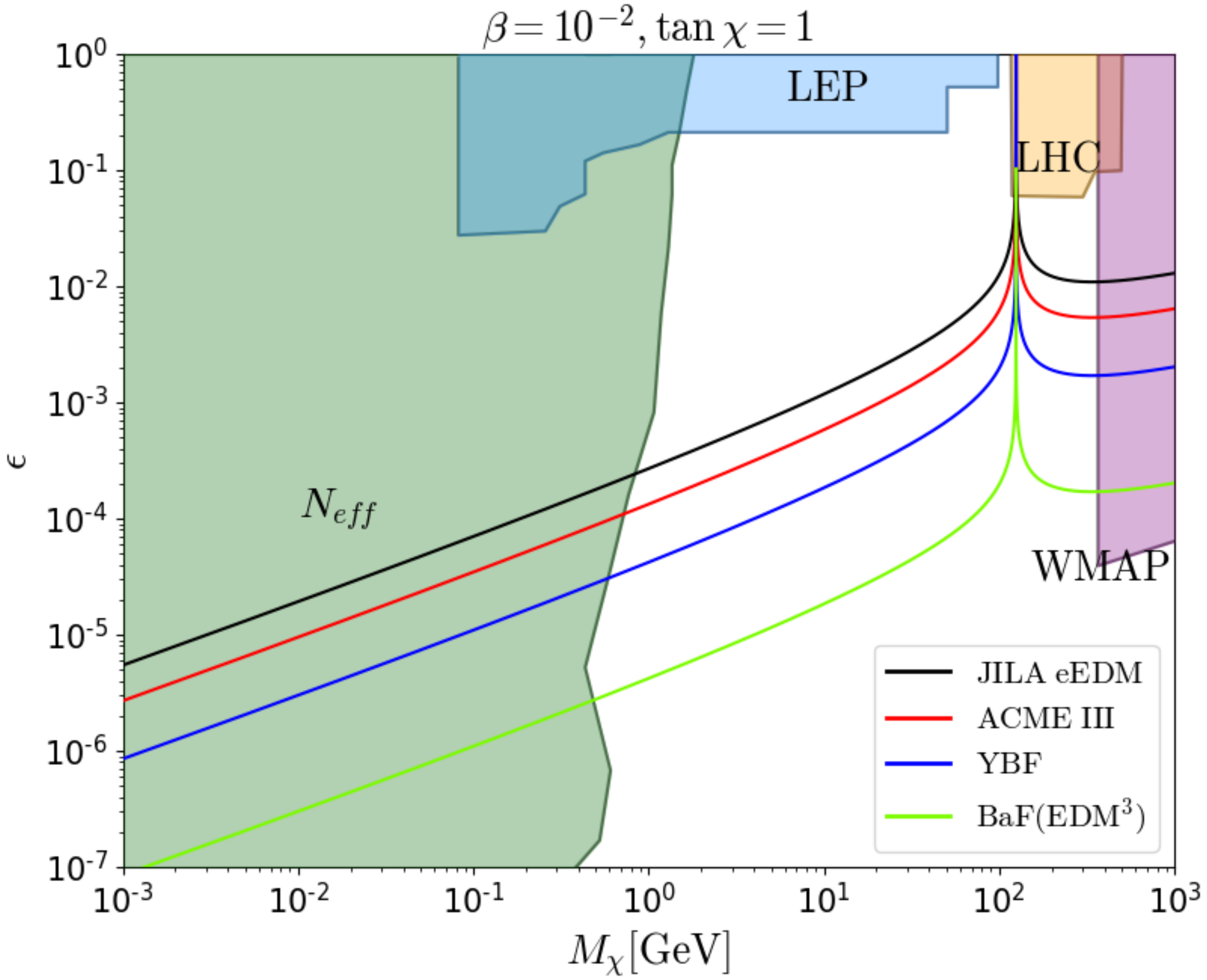
- The massive gauge boson X_1, X_2 combine into $U(1)_D$ charged states $W_D^{\pm}$ which are also **millicharged under $U(1)_{\rm em}$**. The x axis correspond to the vector masses

- β is the mixing angle between Higgs and the dark scalar



M. Ardu

DM in a $SU(2)_D \to 0$ model

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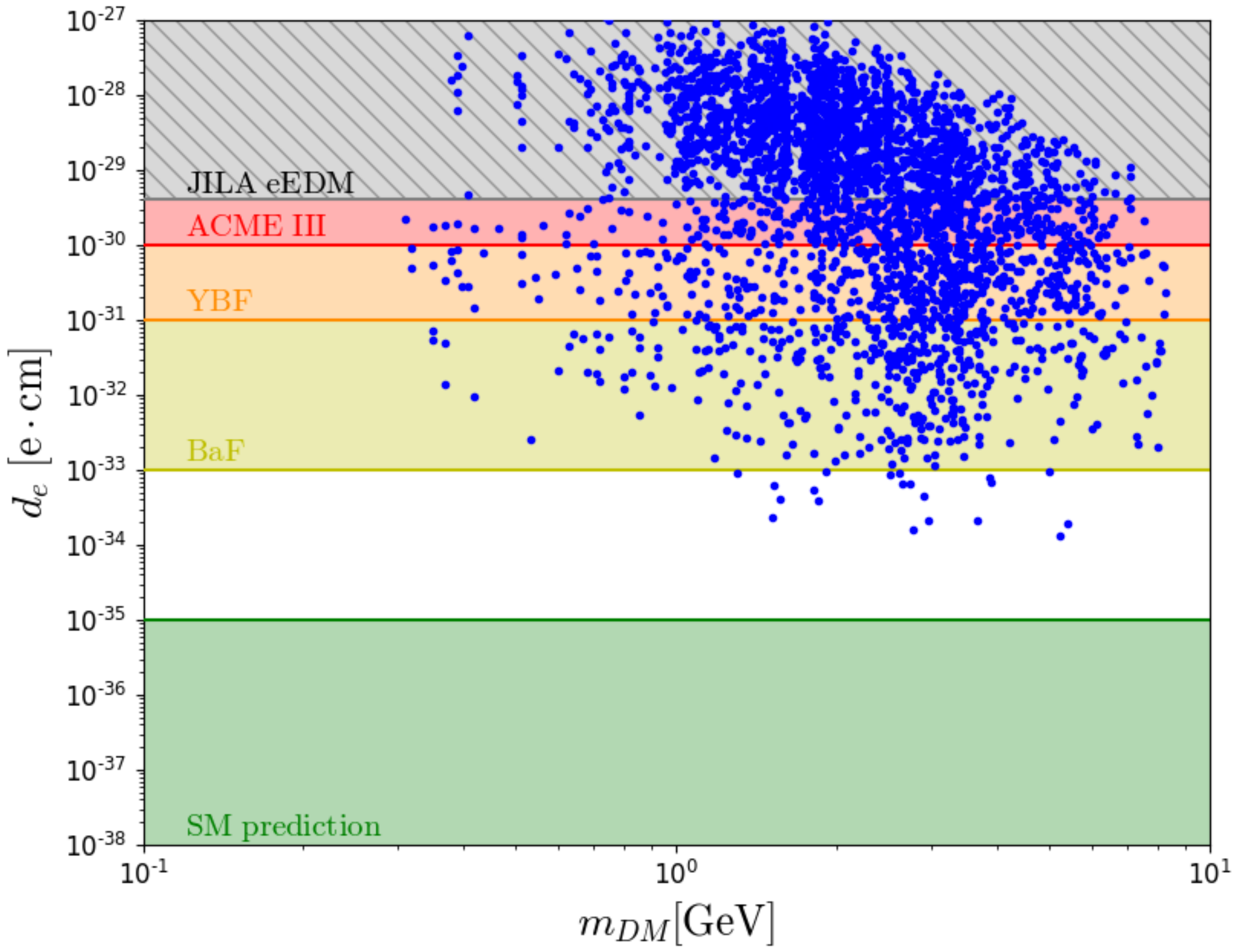


Conclusions

- **The Standard Model must be extended to address various unresolved puzzles**
- **CP violating New Physics is motivated by the observed baryon-antibaryon asymmetry**
- **EDM are exceptionally sensitive observables to CP violation**
- **The EDM could indirectly probe Dark Sectors that respect a non-abelian gauge symmetry**
- **If CP violation is large in the Dark Sector, EDM can have a better sensitivity to kinetic mixing parameters than other experimental probes (dark photon searches, millicharged particles)**

Back-up Slides

CP violation in the SM

- Where does CP violation in the SM come from?

$$-\mathscr{L}_{W^\pm} = \frac{g}{\sqrt{2}}\overline{u_{Li}}\gamma^\mu \left(V_{\mathrm{CKM}}\right)_{ij} d_{Lj} W^+_\mu + h.c. \quad \overset{\hat{C}\hat{P}}{\Rightarrow} \quad \frac{g}{\sqrt{2}}\overline{u_{Li}}\gamma^\mu \left(V^*_{\mathrm{CKM}}\right)_{ij} d_{Lj} W^+_\mu + h.c.$$

$\Rightarrow$ If $V_{\mathrm{CKM}} \neq V^*_{\mathrm{CKM}}$, CP is violated

Possible only with at least three flavours

[Kobayashi, Maskawa '73]

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- But observables don't care about the basis/parametrization, so **CP violation must be proportional to an invariant**

$$\mathrm{Im}\left(V_{ij}V_{kl}V^*_{il}V^*_{kj}\right) = J \times \sum_{m,n} \varepsilon_{ikm}\varepsilon_{jln}$$

Repeated indices are not summed

Jarlskog invariant

[Jarlskog '85]

$$J = s_{12}s_{23}s_{31}c_{12}c_{23}c_{31}^2 \sin\delta = \left(3.08^{+0.15}_{-0.13}\right) \times 10^{-5}$$

[PDG RPP '22]

Electric dipole moments (EDMs)

- A particle with spin $\vec{S}$ can have a **magnetic** and an **electric** dipole moment

$$H = -(\mu\,\vec{S}\cdot\overrightarrow{B} + d\,\vec{S}\cdot\overrightarrow{E})/S$$

- $\vec{S}$ and $\overrightarrow{B}$ are axial vectors, while $\overrightarrow{E}$ is a vector $\Rightarrow$ $\vec{S}\cdot\overrightarrow{B}$ and $\vec{S}\cdot\overrightarrow{E}$ are P and CP even and odd respectively

- In a quantum field theory, the electric dipole moment of a fermion is given by the CP-odd operator

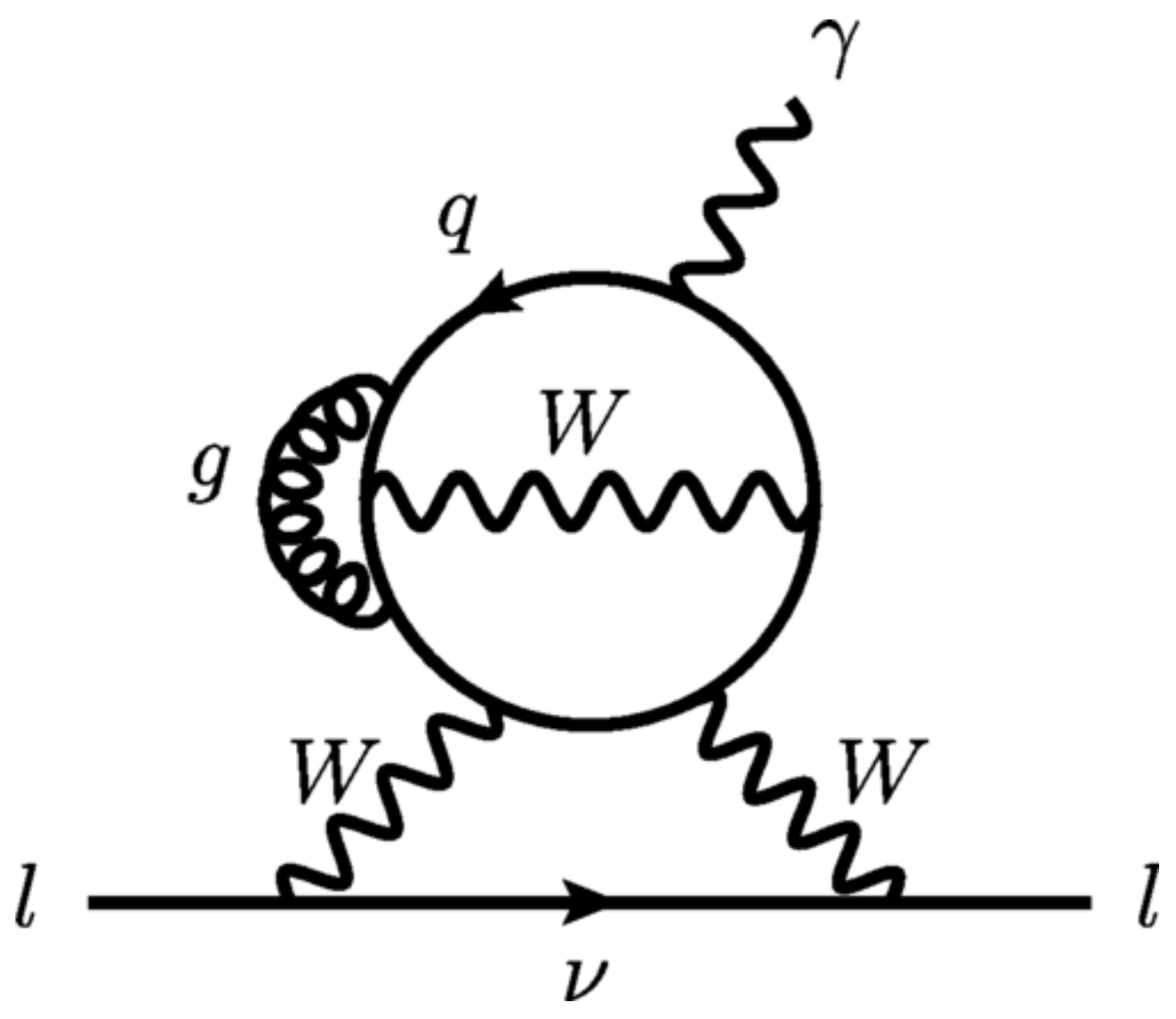
$$\boxed{\mathscr{L}_{\rm EDM} = -\frac{i}{2}\, d_f\, (\bar{\psi}_f \sigma_{\mu\nu}\gamma_5 \psi_f)\, F^{\mu\nu}}$$

$$[\psi] = 3/2,\ [F_{\mu\nu}] = 2,\ [\mathscr{L}] = 4 \ \Rightarrow\ [d_f] = -1$$

- **d_f can only be non-zero if CP is not conserved**

EDM in the SM vs exp. searches

- EDMs are predicted to be very small in the SM



Lepton EDMs appear at four or higher-loops

Back-of-the-envelope: $d_l \lesssim \frac{m_l}{m_e} \times 10^{-44}\ e \cdot \mathrm{cm}$

[Pospelov, Ritz ’14]

Quark EDMs appear at three or higher-loops

Back-of-the-envelope: $d_{u,d} \lesssim 10^{-34}\ e \cdot \mathrm{cm}$

For an up-to-date estimate see: [Yamanaka, Yamaguchi ’20]

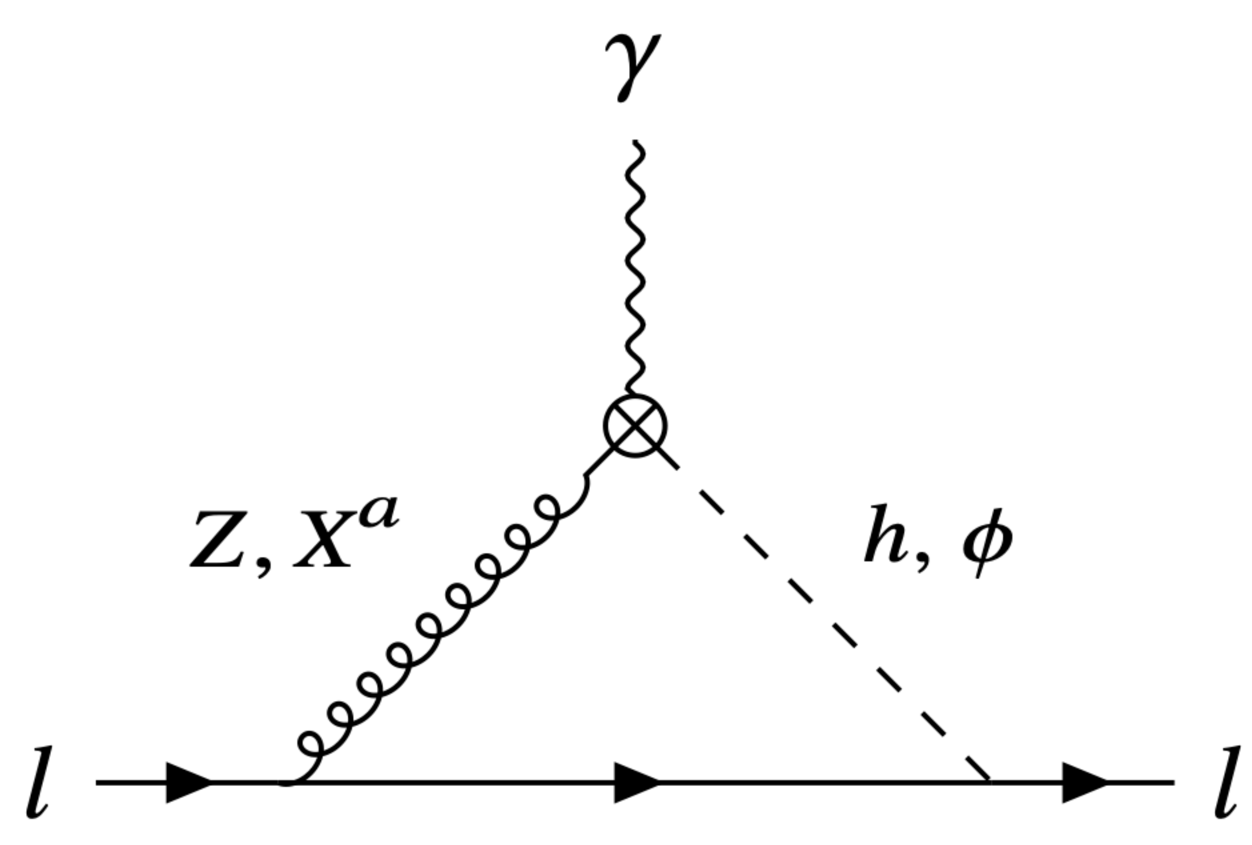
- Experiments are sensitive to much larger values

$$d_e^{(\mathrm{exp})} \lesssim 4 \times 10^{-30}\ e \cdot \mathrm{cm}$$ [JILAeEDM - Roussy et al ’23]

$$\boxed{d_n^{(\mathrm{exp})} \lesssim 2 \times 10^{-26}\ e \cdot \mathrm{cm}}$$ [Abel et al ’20, PRL 124-081803]

Upper limit on neutron EDM severely constraint CP violation in strong interactions (why so small? = Strong CP problem)

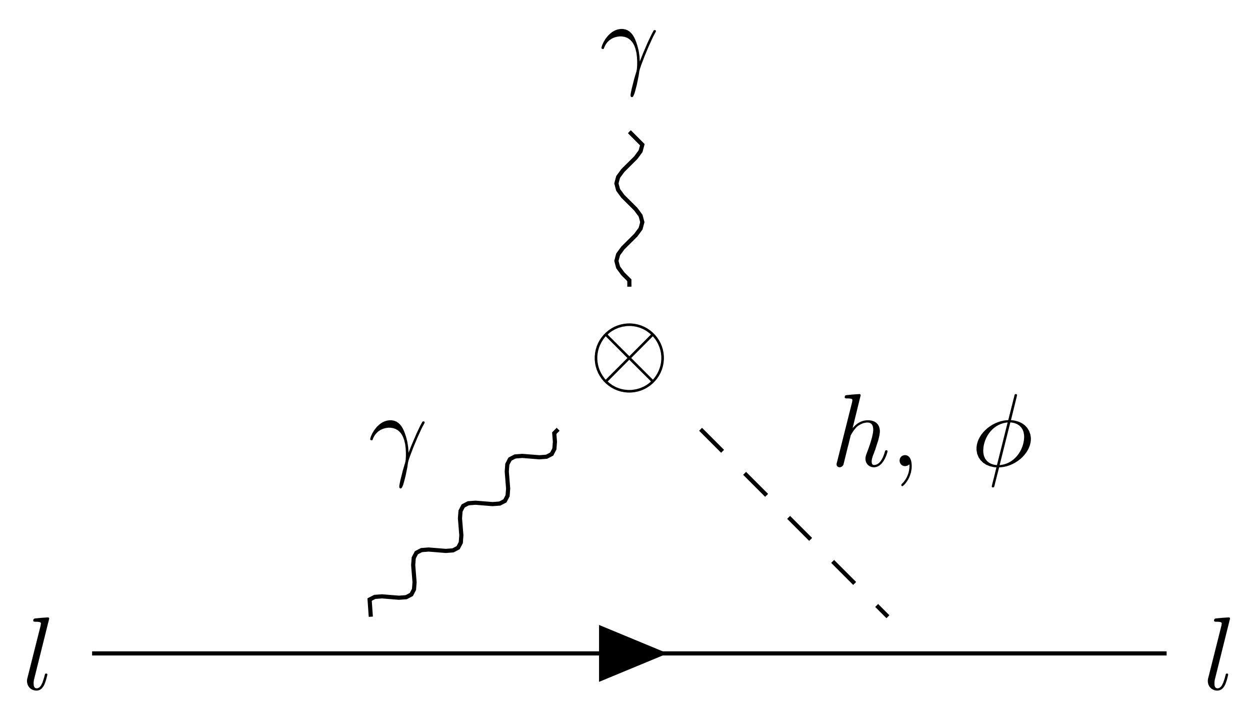
EDM prediction dark sector



$$d_l \simeq \frac{Y_l}{8\pi^2 v_D}\epsilon\tilde{\epsilon}\beta c_\theta^2\, e \left(\frac{\log(x_{X\phi})}{x_{X\phi}-1} - \frac{\log(x_{Xh})}{x_{Xh}-1}\right)$$

$$x_{ij} = m_i^2/m_j^2$$

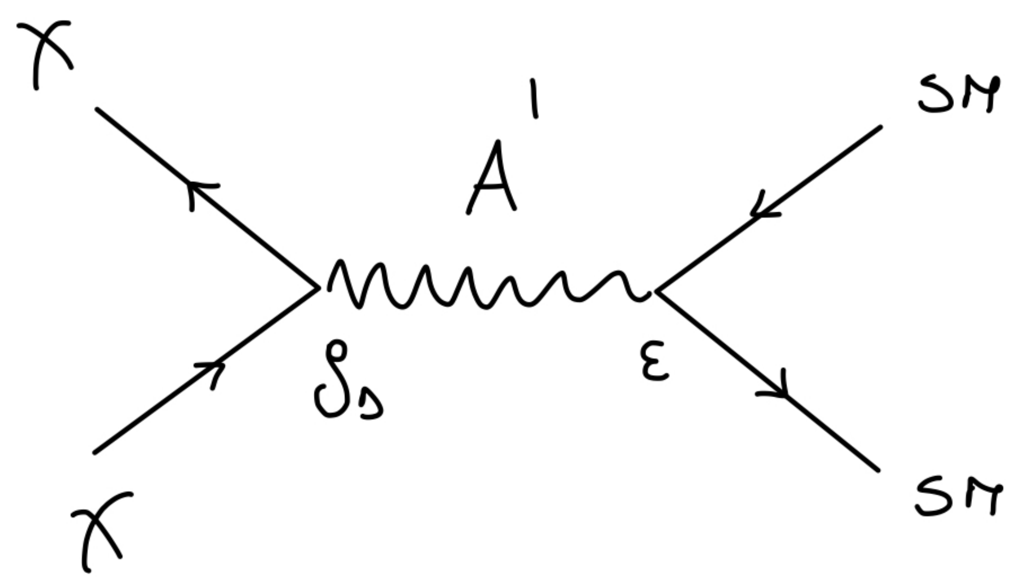
$$\tan\chi = \tilde{\epsilon}/\epsilon$$



$$d_l \simeq e\left(\frac{Y_l}{8\pi^2 v_D}\right)\epsilon^2 \tan\chi\ \beta c_\theta^2 \log\left(\frac{m_h^2}{m_\phi^2}\right)$$

Why inelastic DM?

- Correct relic abundance for thermal freeze-out require $\langle \sigma v_{\rm rel} \rangle \sim 1.7 \times 10^{-9}$ GeV^{-2}



- Requires $\epsilon \sim 10^{-4}$, $M_X \sim \text{few} \times m_\chi$ and $m_\chi \lesssim 1$ GeV to have the correct DM abundance and respect laboratory constraints

- But then it conflicts with indirect detection that place constraints on s-wave annihilation $m_\chi \gtrsim 30$ GeV, a region severely constrained by direct detection too

- In the inelastic DM scenario, there are two DM states χ_H, χ_S with a small mass splitting

- If only inelastic scattering is allowed $\chi_H \chi_S \to SM$ (which sets the relic abundance), one can avoid the indirect detection bound because χ_H would have decayed in χ_S by then, and $\chi_S \chi_S \to SM$ is forbidden