BSM theory overview: scalar extensions

Venus Keus

University of Helsinki & Helsinki Institute of Physics

Particle Physics Day, 20 October 2017

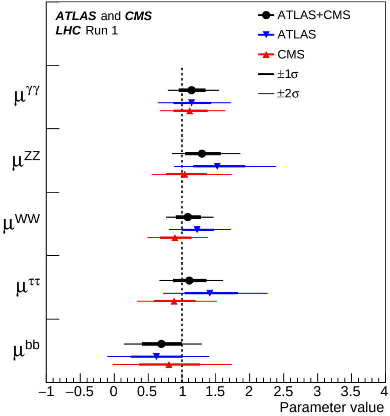
In praise of the Standard Model

Current formulation finalised in the 70's predicted:

- the W & Z (1983)
- the top quark (1995)
- the tau neutrino (2000)
- "a" Higgs boson (2012)

What's up at the LHC?

- Higgs looks SM-like
- No significant deviation from the SM
- No signs of new physics
- Is that all there is?



JHEP 08 (2016) 045

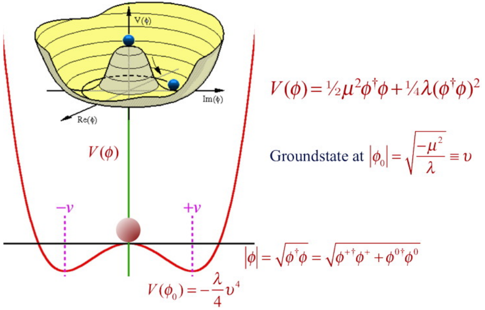
In criticism of the Standard Model

What is missing:

- An explanation for the Femion mass hierarchy
- EW vacuum stability
- Baryon asymmetry in the universe
  - Strongly first order phase transition
  - Sufficient amount of CP-Violation
- No suitable candidate for Dark Matter

Let's focus on the scalar sector

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

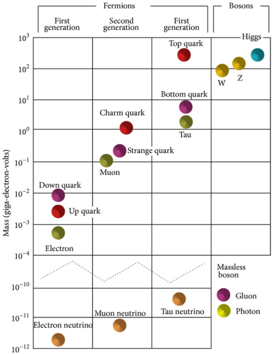


Fermion mass hierarchy

Fermion mass hierarchy

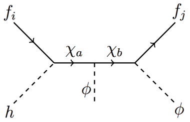
SM: no explanation for

- $m_t/m_e \approx 10^6$
- $m_t/m_\nu \approx 10^{11}$



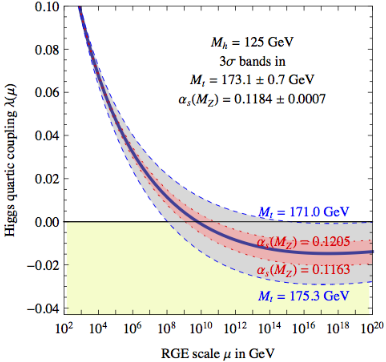
BSM: solutions

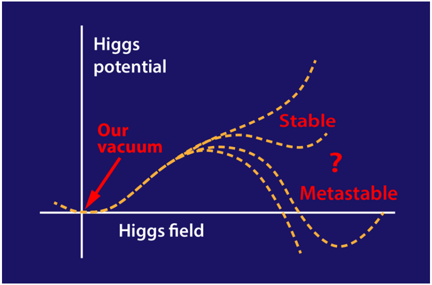
- SM + 2 scalar doublets
  Weinberg's private Higgs model
- SM + singlet scalar +...
  Froggatt-Nielsen mechanism



EW vacuum stability

EW vacuum stability





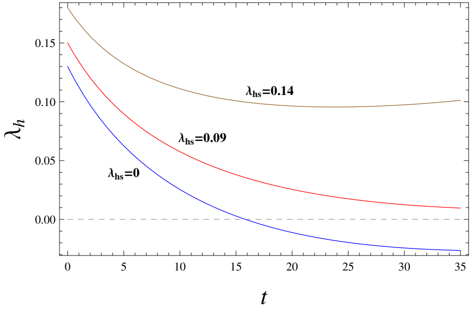
$$V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

[JHEP 1312, 089 (2013)]

Economic solution: extend the scalar sector

Simplest case: SM + real singlet scalar

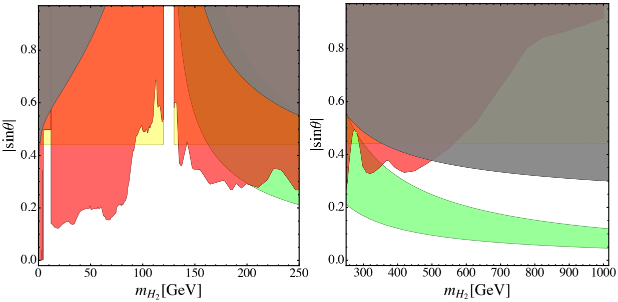
$$V = -\frac{\mu_h^2}{2}\phi^\dagger\phi - \frac{\mu_s^2}{2}S^2 + \frac{\lambda_h}{4}(\phi^\dagger\phi)^2 + \frac{\lambda_s}{4}S^4 + \frac{\lambda_{hs}}{4}(\phi^\dagger\phi)(S^2)$$



[Eur.Phys.J. C72 (2012) 2058]

How much mixing is allowed?

If $\langle S \rangle \neq 0$: $\tan 2\theta = \lambda_{hs} v_h v_s / (\lambda_h v_h^2 - \lambda_s v_s^2)$



Excluded by direct searches (red), precision tests (gray), and H_1 couplings measurements (yellow).

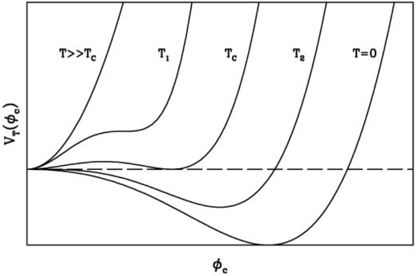
[JHEP 05, 057 (2015)]

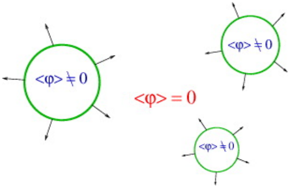
Baryon asymmetry in the Universe

Sakharov's conditions

- B-violation
- C & CP violation
- Departure from thermal equilibrium

Strongly 1^{st} order phase transition





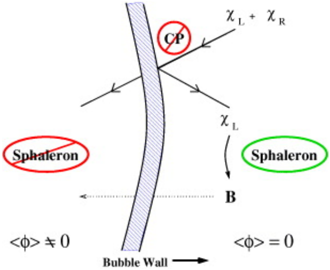
$$V_{eff}(\phi, T) = V_0(\phi) + V_1(\phi) + \Delta V_1^{(T)}(\phi, T)$$

SM scalar potential does not go through a first order phase transition.

$\Rightarrow$ Scalar extensions

[Phys. Rev. Lett. 77 (1996)]

C & CP violation



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ub} \neq V^*_{ub} ; V_{td} \neq V^*_{td} \Rightarrow \textbf{CPV}$$

Observation $\frac{N(B)}{N(\gamma)} \approx 10^{-9} \gg 10^{-20}$ provided by SM

New sources of CPV needed.

$\Rightarrow$ Scalar extensions

Dark Matter

Dark Matter

How we know it exists:

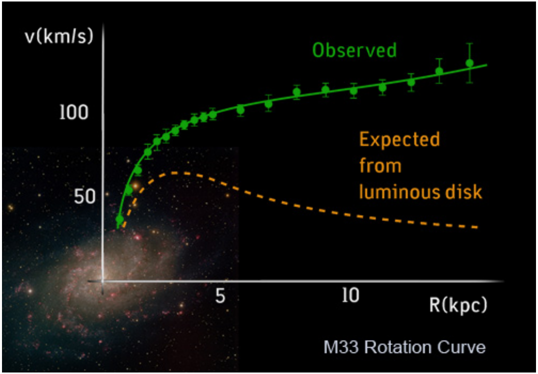
- Galaxy Clusters
- Galactic Rotation Curves
- The CMB
- The Bullet Cluster
- Large-Scale Structure Formation

Fritz Zwicky in 1933 using the Virial theorem

Dark Matter

How we know it exists:

- Galaxy Clusters
- Galactic Rotation Curves
- The CMB
- The Bullet Cluster
- Large-Scale Structure Formation

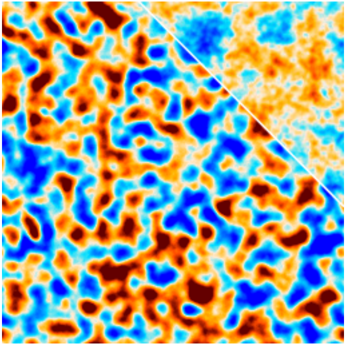


Vera Rubin & Kent Ford in 1960s

Dark Matter

How we know it exists:

- Galaxy Clusters
- Galactic Rotation Curves
- The CMB
- The Bullet Cluster
- Large-Scale Structure Formation



Planck CMB simulator

Dark Matter

How we know it exists:

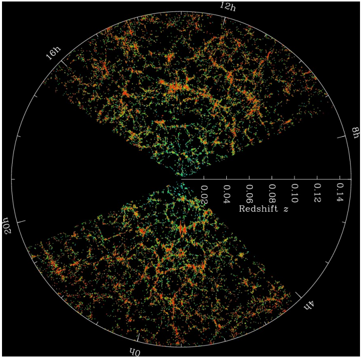
- Galaxy Clusters
- Galactic Rotation Curves
- The CMB
- The Bullet Cluster
- Large-Scale Structure Formation

Two galaxies collide (2006)

Dark Matter

How we know it exists:

- Galaxy Clusters
- Galactic Rotation Curves
- The CMB
- The Bullet Cluster
- Large-Scale Structure Formation

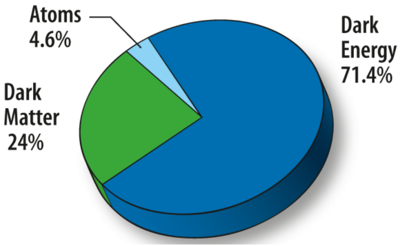


Sloan Digital Sky Survey (2013)

WIMP Dark Matter

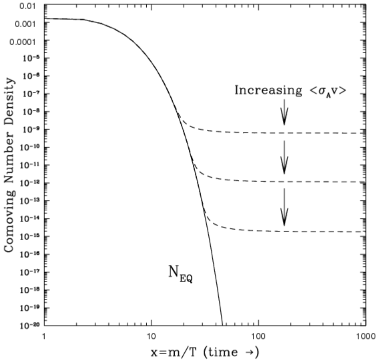
Characteristics:

- Cold (non-relativistic at the onset of galaxy formation)
- Non-baryonic
- Neutral & weakly interacting
- Stable due to a discrete symmetry



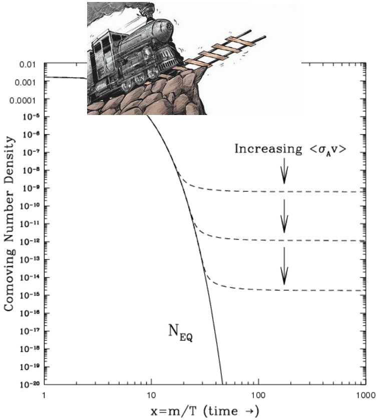
$$\underbrace{\text{DM DM} \to \text{SM SM},}_{\text{pair annihilation}} \quad \underbrace{\text{DM} \not\to \text{SM}, \ldots}_{\text{stable}}$$

WIMP Dark Matter freeze-out



Observed relic density: $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$

WIMP Dark Matter freeze-out



Observed relic density: $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$

BSMs to the rescue

Focusing on DM and CPV

SM + singlet scalar extension

DM, ~~CPV~~

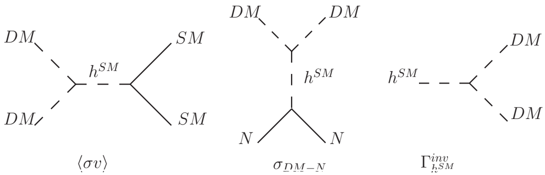
SM+RS: scalar DM

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 + \frac{1}{2} m_{DM}^2 S^2 - \lambda_{DM} S^4 - \lambda_{hDM} \phi_{SM}^2 S^2$$

$$S \to -S, \quad \text{SM fields} \to \text{SM fields}$$

Higgs-portal interaction:

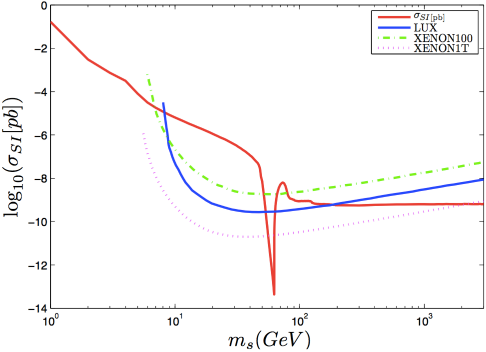
$$\text{SM sector} \overset{\text{Higgs}}{\longleftrightarrow} \text{DM sector}$$



given by the same coupling

SM+RS: scalar DM

Relic density + direct detection constraints:



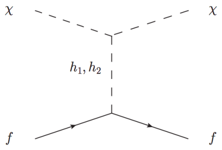
+ Higgs decays + SM vacuum stability + purturbativity constraints:

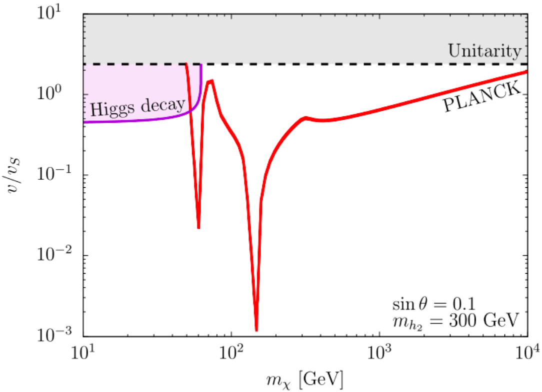
$$1.1 \text{ TeV} \leq m_{DM} \leq 2.0 \text{ TeV}$$

[JHEP 12, 044 (2015)]

SM+CS: scalar DM

$S = (v_s + s + i\chi) \rightarrow Z_2$-symmetry broken, CP conserves DM





[arXiv:1708.02253]

Further singlet extensions

SM+ 2 singlet scalars:

$S_1 \to -S_1, \quad S_2 \to -S_2, \quad \text{SM fields} \to \text{SM fields}$

- Introducing coannihilation channels
- DM: the lightest particle from the dark sector
- CPV: in the dark sector
- CPV not transferable to fermions → ~~EWBG~~

[Phys.Rev.D. 83 (2011)]

2 Higgs doublet model

DM, ~~CPV~~

~~DM~~, CPV

2HDM with CP-violation (~~DM~~)

The general scalar potential

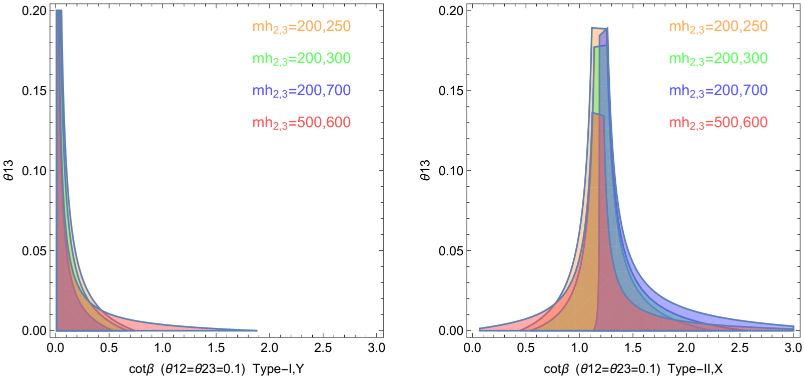
$$
\begin{aligned}
V &= -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) - \left[\mu_3^2(\phi_1^\dagger\phi_2) + h.c.\right] \\
&+ \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\
&+ \left[\frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + h.c.\right].
\end{aligned}
$$

$$Z_2 \text{ symmetry} \Rightarrow \lambda_6 = \lambda_7 = 0$$

The doublets composition with $\tan\beta = v_2/v_1$

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + h_1^0 + i a_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + h_2^0 + i a_2^0}{\sqrt{2}} \end{pmatrix}$$

How much CPV is allowed?



[work in progress]

The Inert Doublet Model (~~CPV~~)

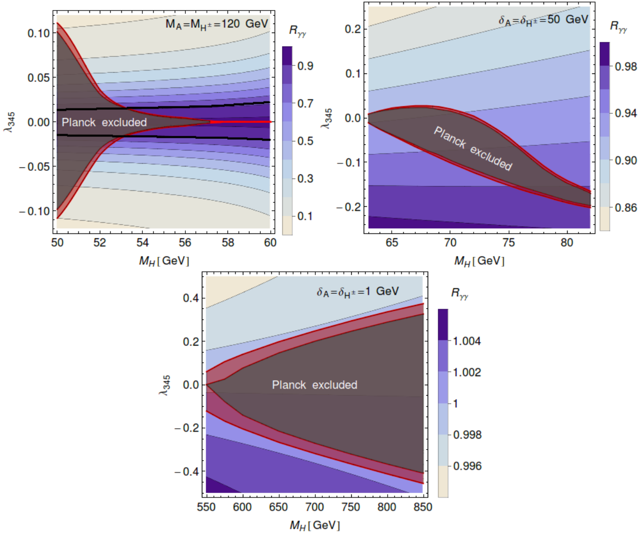
Scalar potential invariant under a Z_2-transformation:

$$Z_2 : \quad \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}$$

$$\begin{aligned} V &= -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) + \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 \\ &+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 \end{aligned}$$

- All parameters are real $\to$ no CP violation
- $\langle\phi_1\rangle = v$, $\langle\phi_2\rangle = 0$

All constraint taken into account



[JHEP 09, 055 (2013)]

To explain:

DM, CPV, EWBG, Stability

$$\Downarrow$$

beyond simple singlet/doublet extensions

Summary

Scalar extensions with or without a Z_2 symmetry:

- SM + scalar singlet(s)
  - $\phi_{SM},\ S \quad \Rightarrow \quad$ DM, ~~CPV~~
  - $\phi_{SM},\ S_1,\ S_2 \quad \Rightarrow \quad$ DM, ~~CPV~~
- 2HDM: SM + scalar doublet
  - Type-I, Type-II, ...: $\phi_1,\ \phi_2 \quad \Rightarrow \quad$ CPV, ~~DM~~
  - IDM - I(1+1)HDM: $\phi_1,\ \phi_2 \quad \Rightarrow \quad$ DM, ~~CPV~~
- 3HDM: SM + 2 scalar doublets
  - Weinberg model: $\phi_1,\ \phi_2,\ \phi_3 \quad \Rightarrow \quad$ CPV, ~~DM~~
  - I(1+2)HDM: $\phi_1,\ \phi_2,\ \phi_3 \quad \Rightarrow \quad$ DM, CPV
  - I(2+1)HDM: $\phi_1,\ \phi_2,\ \phi_3 \quad \Rightarrow \quad$ CPV, DM

BACKUP SLIDES

Detailed summary

- Both DM and CPV from scalar sector $\rightarrow$ beyond 2HDM
- CP-Violation in I(1+2)HDM
  - IDM-like inert sector: CPC DM
  - CPV in the active sector: $\tilde{H}_1, \tilde{H}_2, \tilde{H}_3$
  - EWBG possible
- CP-Violation in I(2+1)HDM
  - SM-like active sector: $H_3 \equiv h^{SM}$
  - CPV in the inert sector: $H_{1,2}, A_{1,2} \rightarrow S_{1,2,3,4}$ CPV DM
  - EWBG possible

LHC bounds on CPV DM

Higgs invisible branching ratio and total decay

From ATLAS and CMS

$$\mathrm{Br}(h \to \mathrm{inv}) < 0.23 - 0.36$$

for $m_{i,j} < m_h/2$ if long lived

$$\mathrm{BR}(h \to \mathrm{inv}) = \frac{\sum_{i,j} \Gamma(h \to S_i S_j)}{\Gamma_h^{\mathrm{SM}} + \sum_i \Gamma(h \to S_i S_j)}$$

The total decay signal strength

$$\mu_{tot} = \frac{\mathrm{BR}(h \to XX)}{\mathrm{BR}(h_{\mathrm{SM}} \to XX)} = \frac{\Gamma_{tot}^{SM}(h)}{\Gamma_{tot}^{SM}(h) + \Gamma^{inert}(h)}$$

We use $\mu_{tot} = 1.17 \pm 0.17$ at 3σ level.

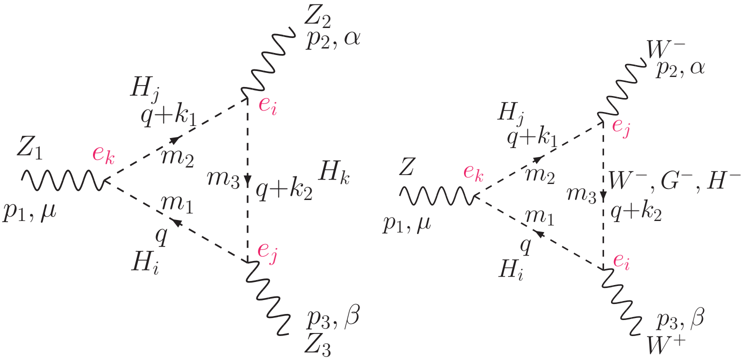
LHC signatures

$E_{miss}^{T} + e^+e^-$ cross section at the LHC

- Higgs-strahlung at tree level:
  $q\bar{q} \to Z \to S_1 S_{2,3,4} \to S_1 S_1 Z^* \to S_1 S_1 e^+ e^-$ with $\sigma \sim 10^{-2}$ pb
- Higgs-strahlung at loop level:
  $q\bar{q} \to Z \to S_1 S_{2,3,4} \to S_1 S_1 \gamma^* \to S_1 S_1 e^+ e^-$ with $\sigma \sim 10^{-3}$ pb
- Gluon-fusion at tree level:
  $pp \to h \to S_1 S_{2,3,4} \to S_1 S_1 Z^* \to S_1 S_1 e^+ e^-$ with $\sigma \sim 10^{-5}$ pb

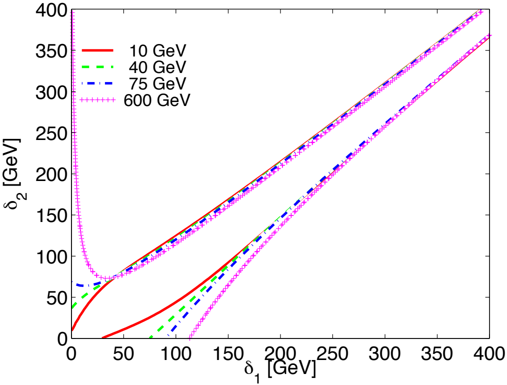
Other CPV observables

ZZZ and ZWW vertices



S, T, U parameters

(Phys.Rev. D80 (2009) 055012)



$\delta_1 = m_{H^\pm} - m_{DM}$ and $\delta_2 = m_A - m_{DM}$