Alternatives to The Standard Model Higgs Boson

Lake Louise Winter Institute 2015

Ian Lewis
SLAC National Accelerator Laboratory

July 4, 2012

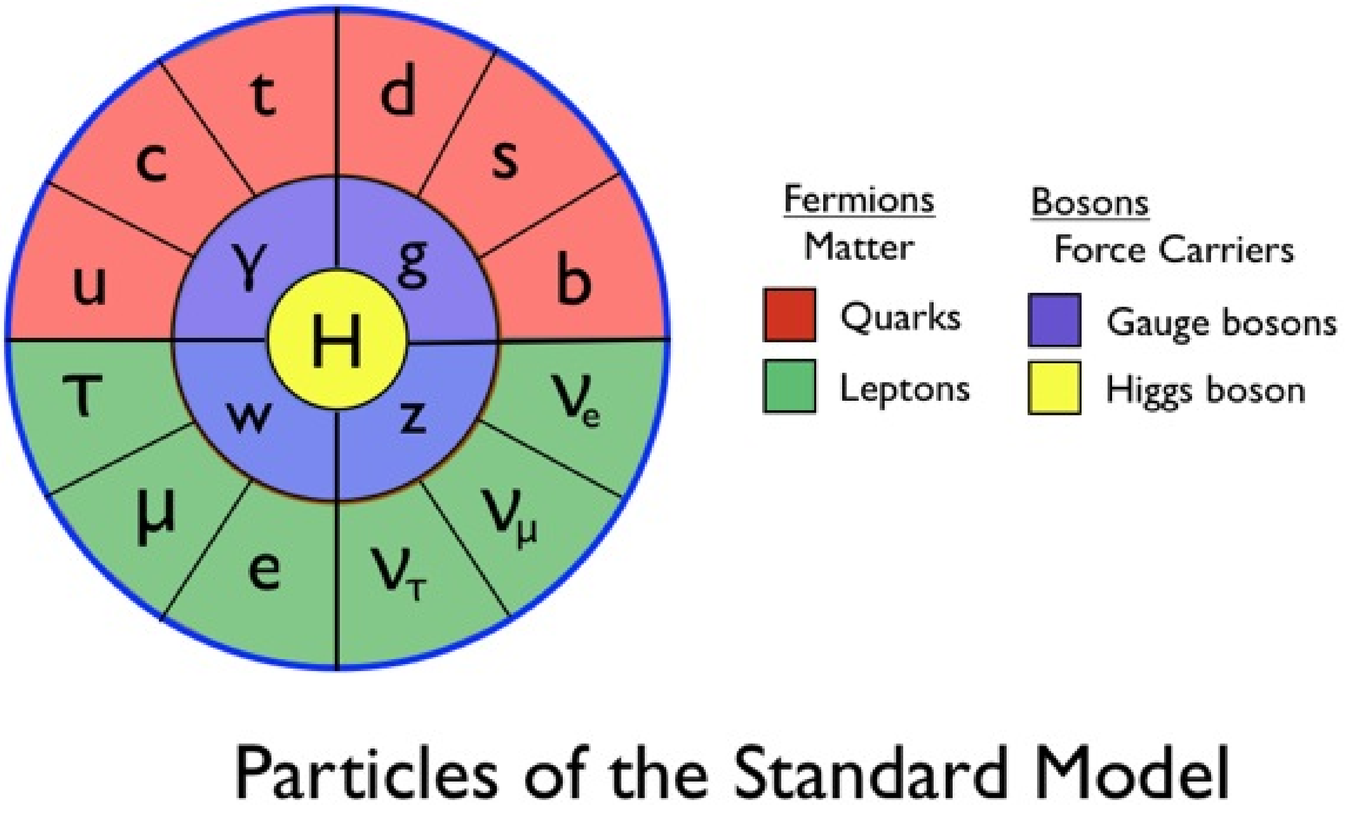
- ATLAS and CMS announce discovery of a new particle.
  - Consistent with long sought-after Higgs boson.

"We have reached a milestone in our understanding of Nature".
--- CERN Director General Rolf Heuer

Long Search

- 50+ years of work by theorists.
- 25+ years of work by thousands of experimentalists.

Standard Model Complete



Quarks: charge +2/3 (up type) and -1/3 (down type)
Leptons: charge -1 and 0

Does Everything

- Gives masses to Gauge Bosons:

$$\left(m_W^2 W^{+\mu} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right)\left(1 + \frac{h}{v}\right)^2$$

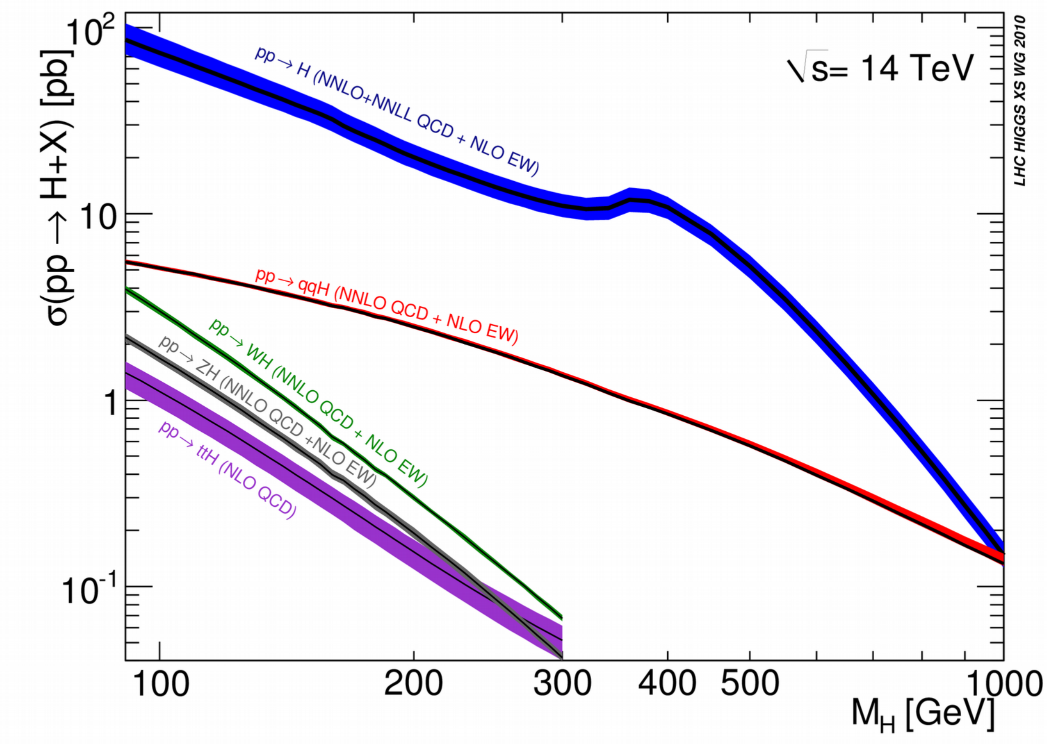
- Give masses to charged fermions:

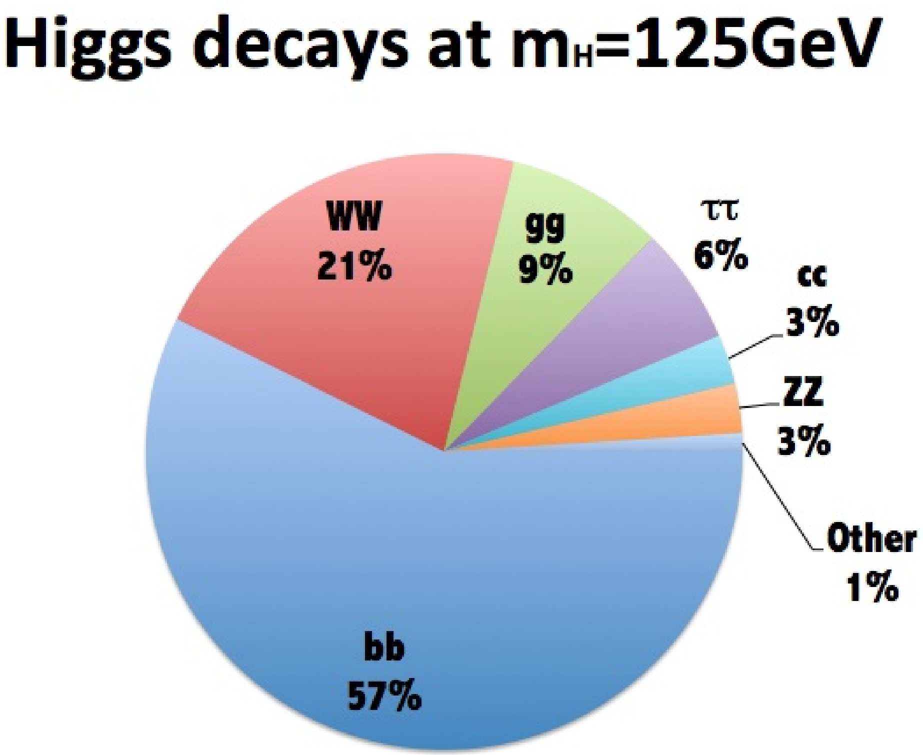
$$m_\psi \left(1 + \frac{h}{v}\right) \overline{\psi}\psi$$

- Completely predictive:
  - Higgs couplings to fermions: $y_\psi \propto m_\psi$
  - Higgs couplings to gauge boson: $g \propto m_V^2$

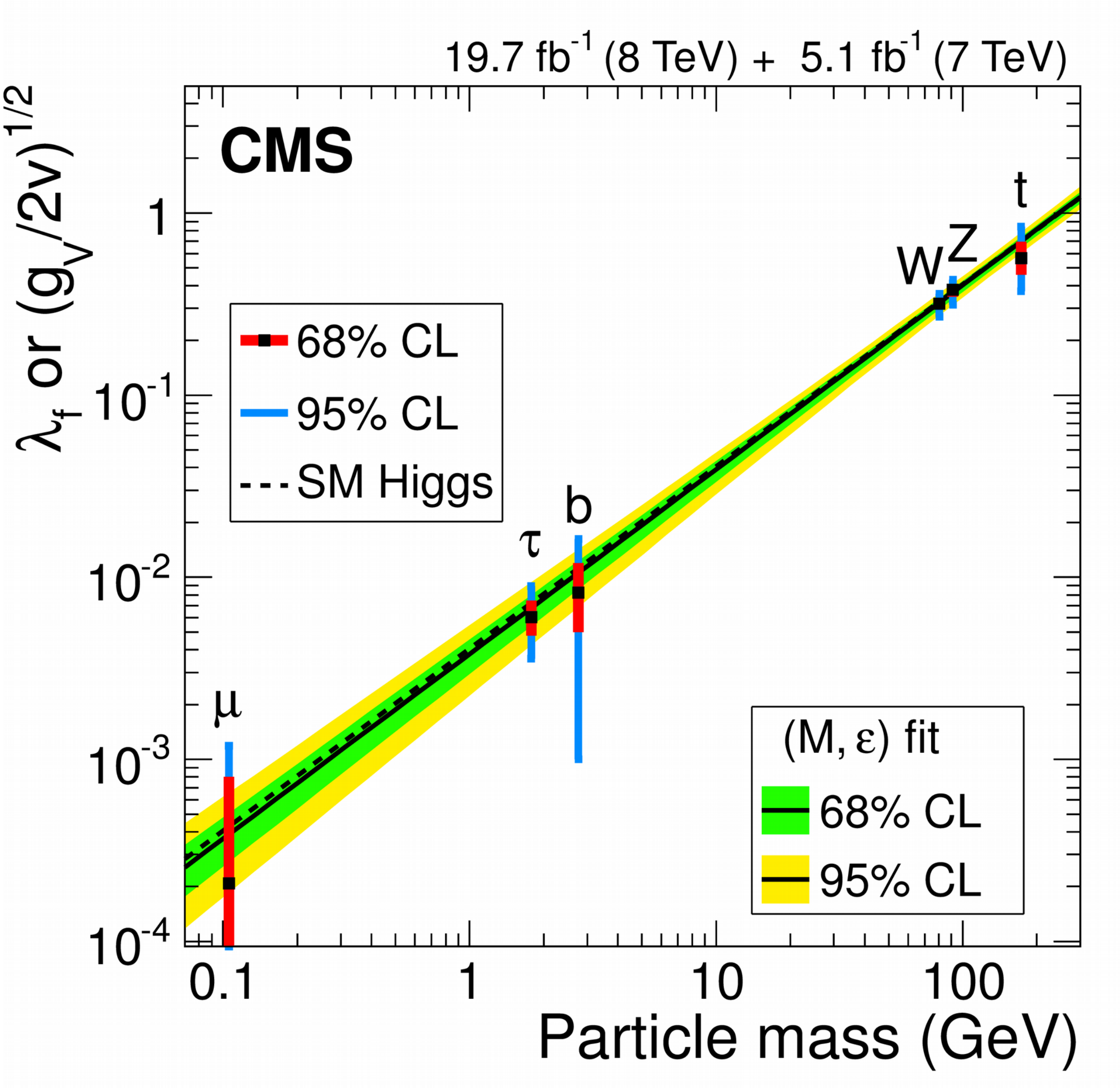
Completely Predictive

- Know everything:

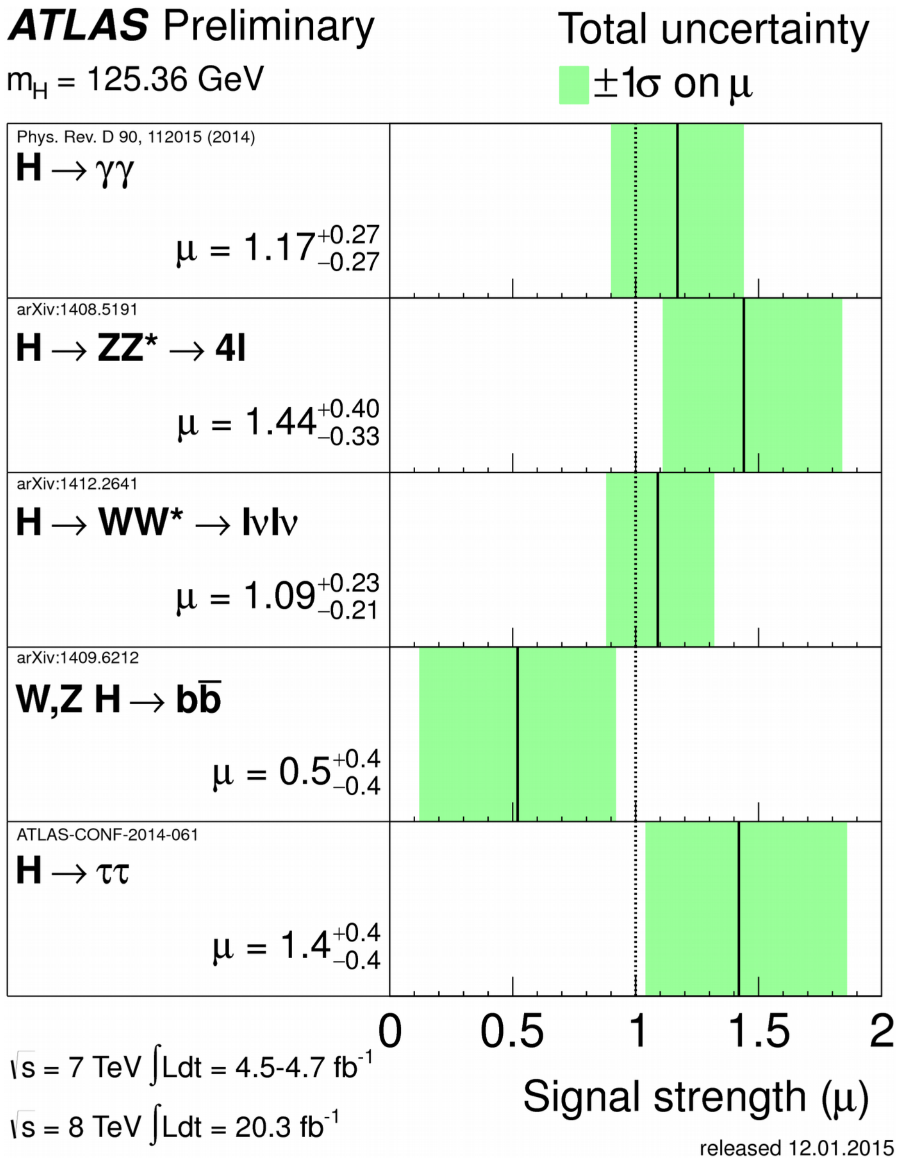


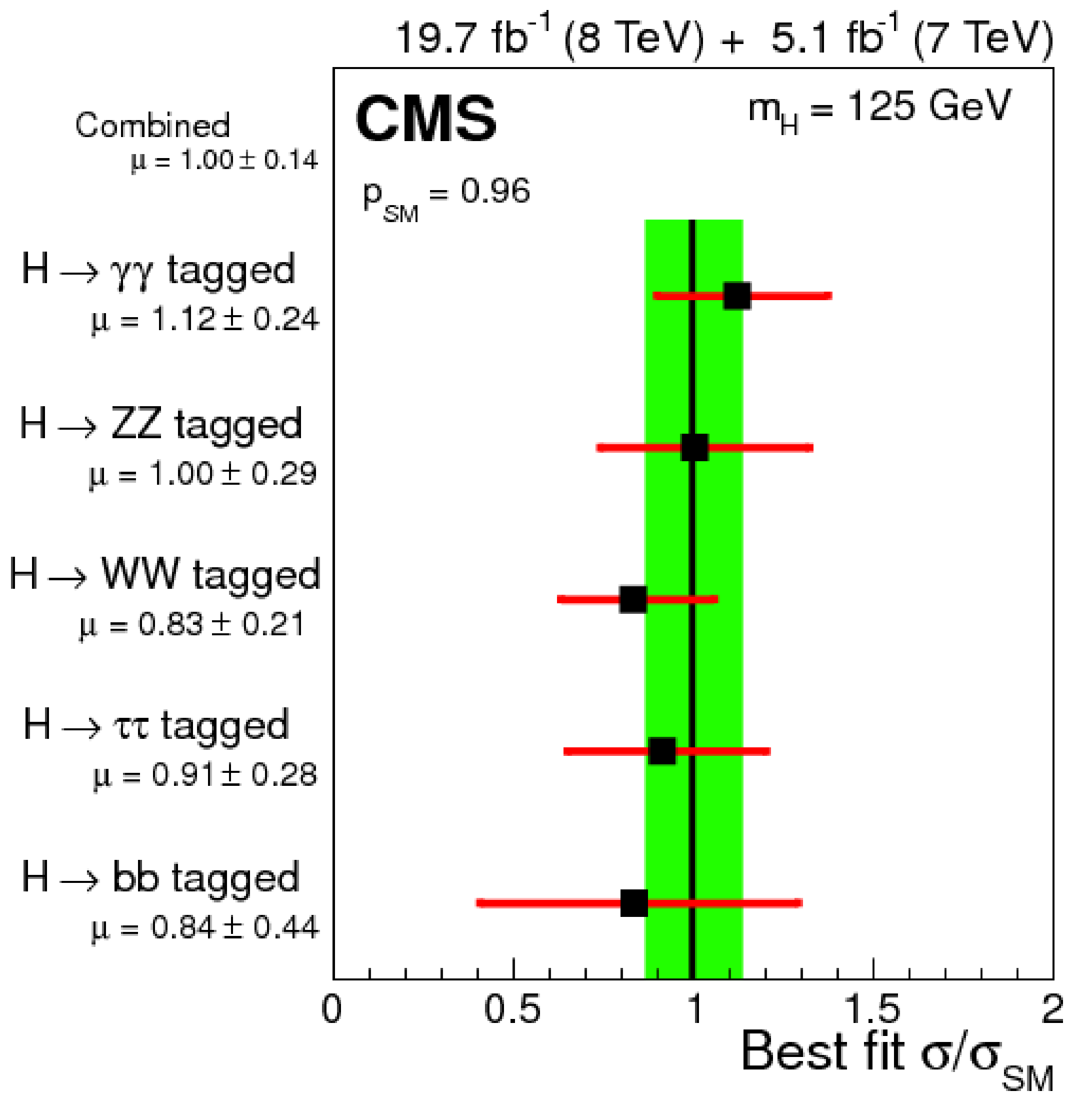


Remarkably Standard Model Like



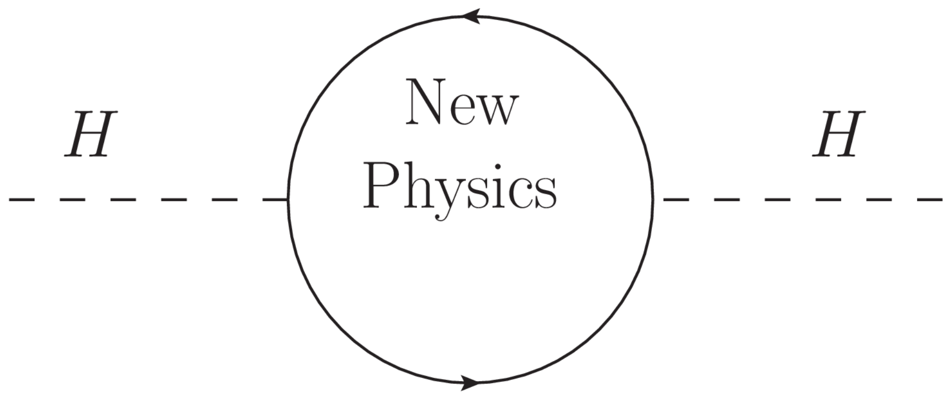
Remarkably Standard Model Like





Why the Discontent?

- Great! Seems we know everything... Hierarchy problem.



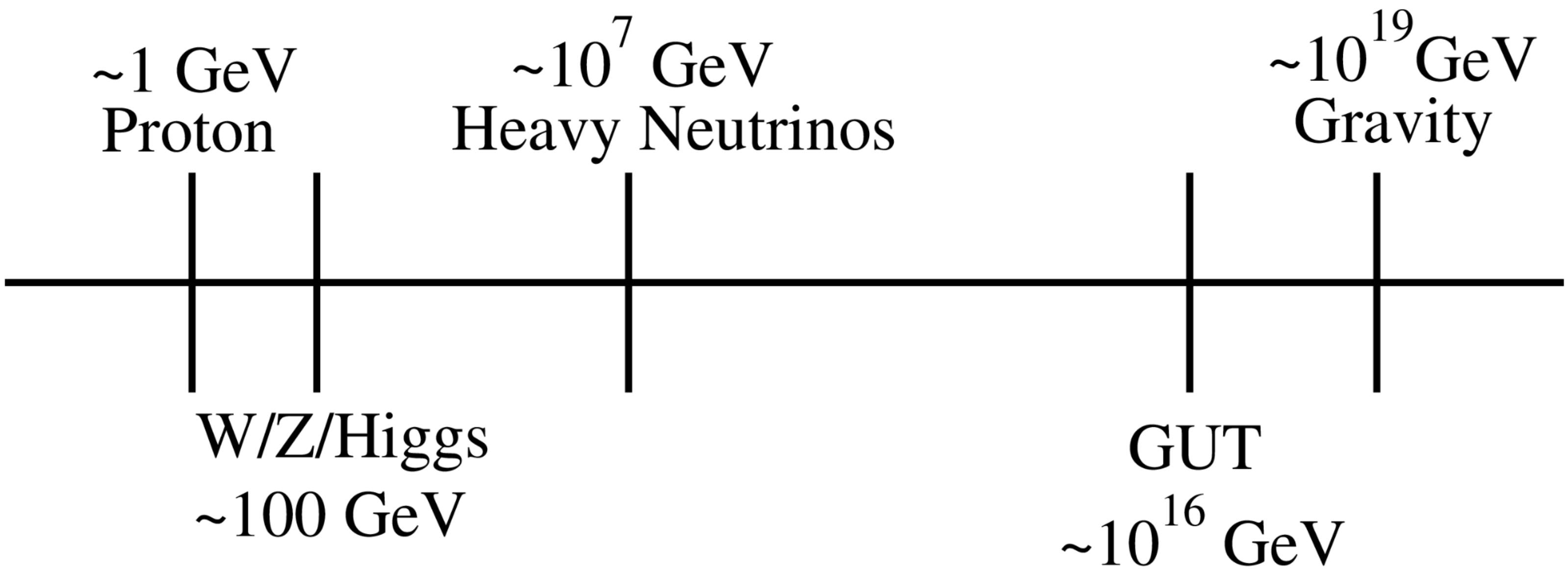
$$\delta m_H^2 \sim \frac{\lambda^2}{16\pi^2} m_{NP}^2$$

- Little to no fine-tuning: $\delta m_H^2 \sim (100 \text{ GeV})^2$

- Scale of New Physics: $\lambda \sim 1 \quad m_{NP} \sim 1 \text{ TeV}$

New Physics Scales

- Expect new physics scales:



The Problem

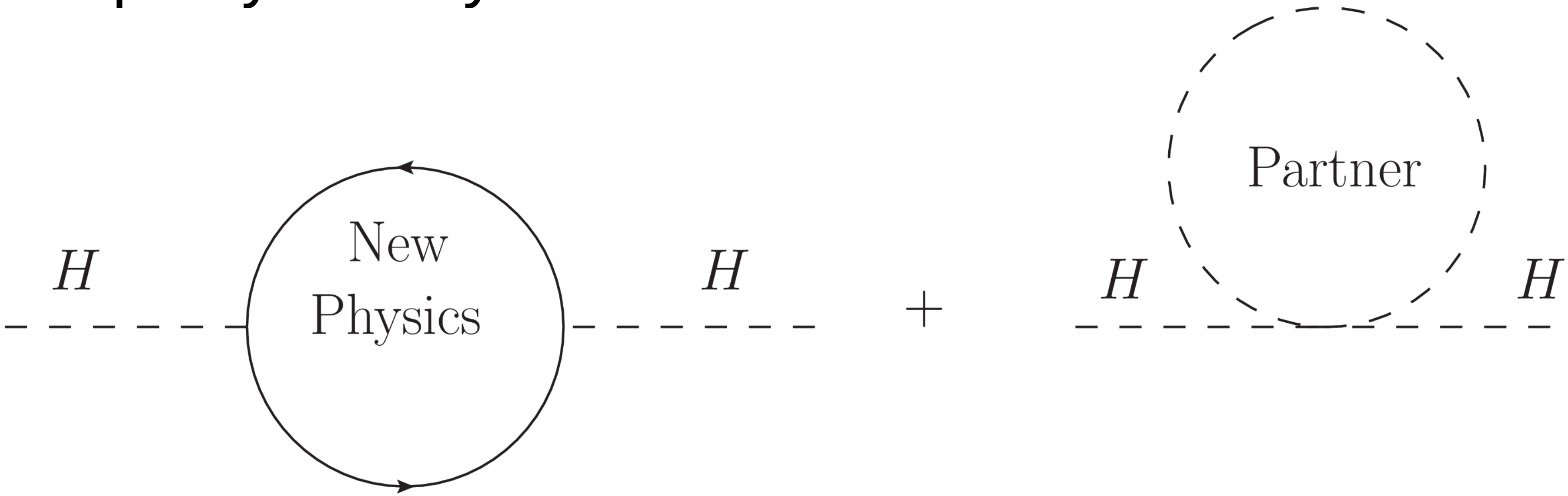
- Fermion masses protected by symmetry.
  - In massless case can transform left and right handed fields separately.
- Gauge bosons protected by gauge symmetry.

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}M_A^2 A_\mu A^\mu \qquad A^\nu \to A^\nu - \partial^\nu \alpha(x)$$

- No symmetry protection for Higgs mass:
- $$\mathcal{L} = (D^\nu H)^\dagger D_\nu H - \mu^2 H^\dagger H$$
- Many models built to construct ways to protect Higgs mass from large contributions.

Solutions to Hierarchy Problem

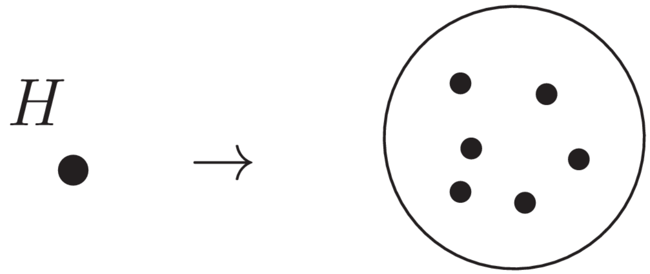
- Supersymmetry:



- Supersymmetry relates mass and couplings of fermion and scalar partners.
  - Loops have opposite signs and cancel.
  - SUSY must be broken, cancellation incomplete.

Composite Models

- Observed Higgs boson is a composite particle:



- No fundamental scalars
  - Hierarchy problem unique to scalars.

Electroweak Symmetry Breaking Sector

- Many of these models contain extended or altered electroweak symmetry breaking sectors.

- Typically have additional new physics associated with this sector.
  - Top partners
  - New resonances

Supersymmetry
(Weakly Interacting Solution)

Supersymmetry

- Supersymmetry has two Higgs doublets.
  - One couples to up type fermions.
  - One couples to down type fermions.
- Special case of a Type II two Higgs doublet model.
- Discuss 2HDMS first.

Generic Two Higgs Doublet Models (Momentary Detour)

Generic Two Higgs Doublet models

- Why have one Higgs that does all the work?
  - Masses to gauge bosons.
  - Masses to up-type and down-type fermions.
  - Masses to quarks are leptons.
- MSSM Higgs sector is a special case of Type II 2HDMs.

Generic 2HDM

- Physical Spectrum:
  - Two neutral scalars: h, H
  - Pseudoscalar: A
  - Charged Higgs: $H^{\pm}$
- Free parameters
  - $\tan\beta = \frac{v_2}{v_1}$
  - Mixing between two neutral scalars: α
  - Higgs masses: $m_h = 126\,\text{GeV}, m_H, m_A, m_{H^{\pm}}$

Higgs Couplings to Fermions

- Generically have FCNCS.
  - Two Higgs doublets, both can couple to fermions.
  - Both Higgs doublets obtain vevs.
  - Fermion masses have two sources:

$$M = \frac{1}{\sqrt{2}}\left(Y^1\langle H_1\rangle + Y^2\langle H_2\rangle\right)$$

  - Yukawa and mass matrices not necessarily simultaneously diagonalized.
  - Leads to tree level flavor changing neutral currents.
  - Can have sever constraints from flavor physics.

Avoiding FCNCs

- Impose parity on one Higgs doublet and subset of right-handed fermions.
- Type II 2HDM:
  - Odd particles: $H_2 \to -H_2,\ d_R \to -d_R,\ \ell_R \to -\ell_R$
  - Odd particle have to couple to other odd parity particles.
  - Yukawa couplings:

$$-\mathcal{L} = Y^U_{ij}\overline{Q^i_L}H_1 u^j_R + Y^D_{ij}\overline{Q^i_L}H_2 d^j_R + Y^\ell_{ij}\overline{E^i_L}H_2 \ell^j_R + \mathrm{h.c.}$$

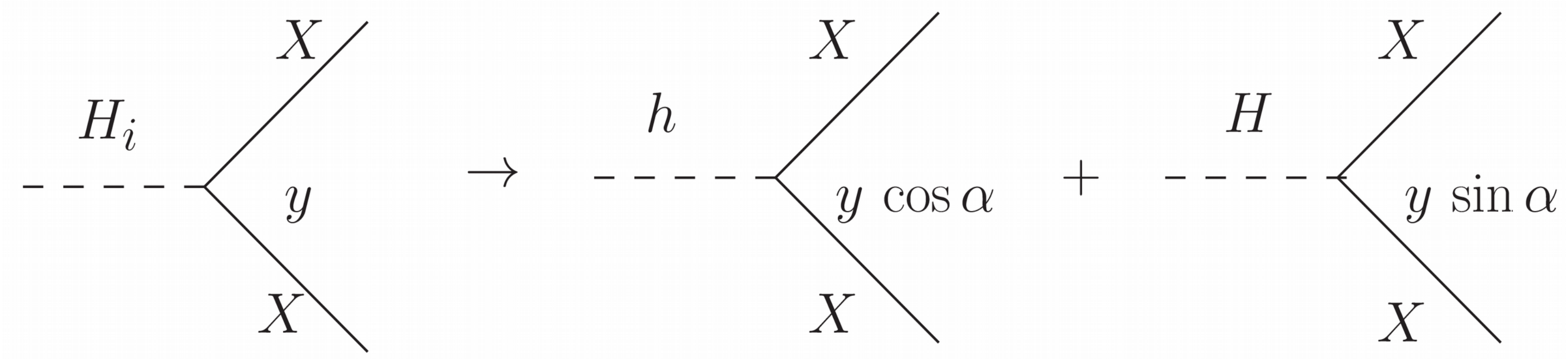
- Fermions get mass from one source.
  - Mass and Yukawa matrices proportional.
  - No tree level FCNCs.

Types of 2HDMS

- Focus on two types:
  - Type I
    - Only one Higgs doublet couples to fermions.
  - Type II
    - One Higgs doublet couples to up-type fermions
    - One Higgs doublet couples to down-type fermions.
- Other popular types
  - Lepton specific:
    - One Higgs doublet couples to leptons.
    - One Higgs doublet couples to quarks.
  - Flipped.
    - One Higgs doublet couples to up-type quark and leptons
    - One Higgs doublet couples to down-type quarks.
- See Branco et al, Phys.Rept. 516 (2012) 1-102 for a review

Couplings to Fermions

- Each fermion type couples to one Higgs doublet.
- Each Higgs doublet has a scalar component.
  - Why there are two scalars in physical spectrum
- Scalar bosons can mix.
  - Both physical neutral scalars couple to all fermions.
  - Changes standard model predictions.

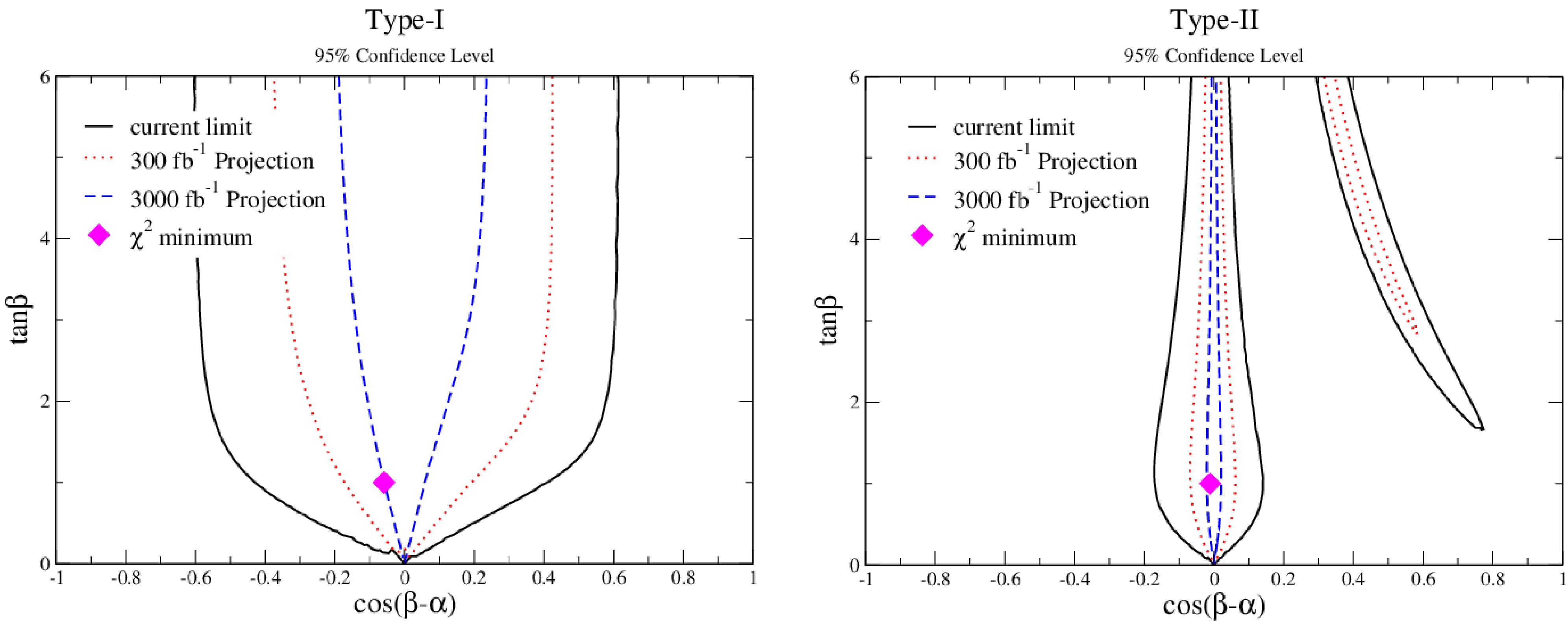


Precision Measurements and Direct Searches

- Precision measurements.
  - Gauge boson and fermion couplings altered from SM values.
  - Precise measurements of observed Higgs boson can limit parameter space.
- Direct Searches
  - Additional Higgs bosons beyond the Standard Model to search for.
- Both important and can give complementary information.

Precision Higgs Measurements

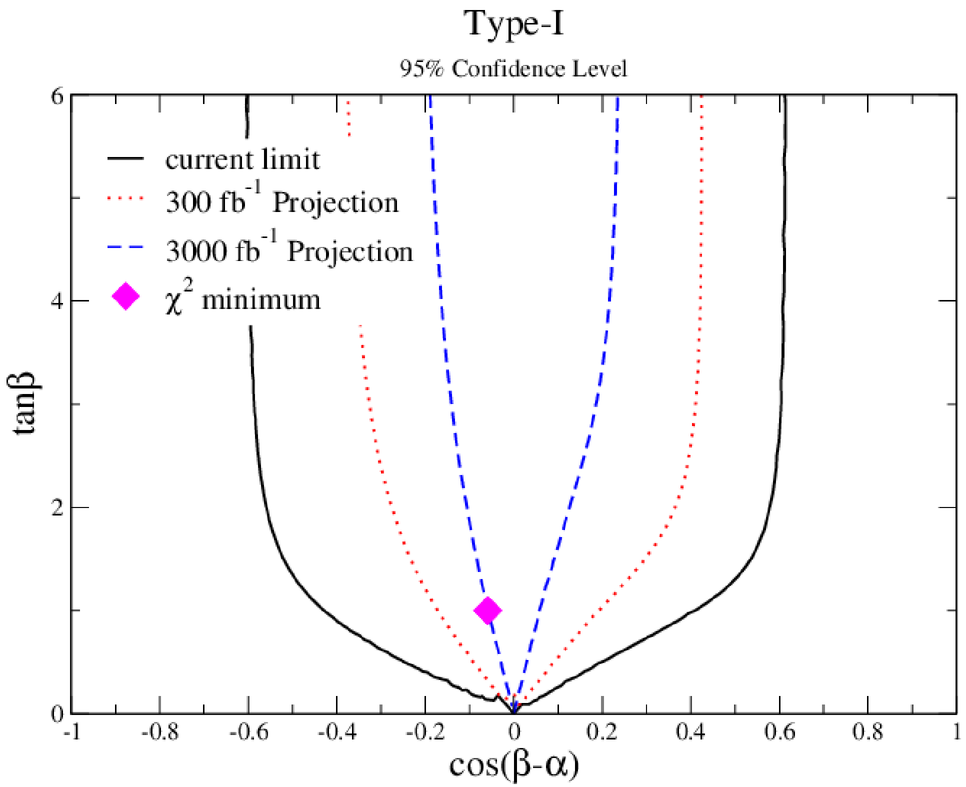
- Higgs Precision Measurements:

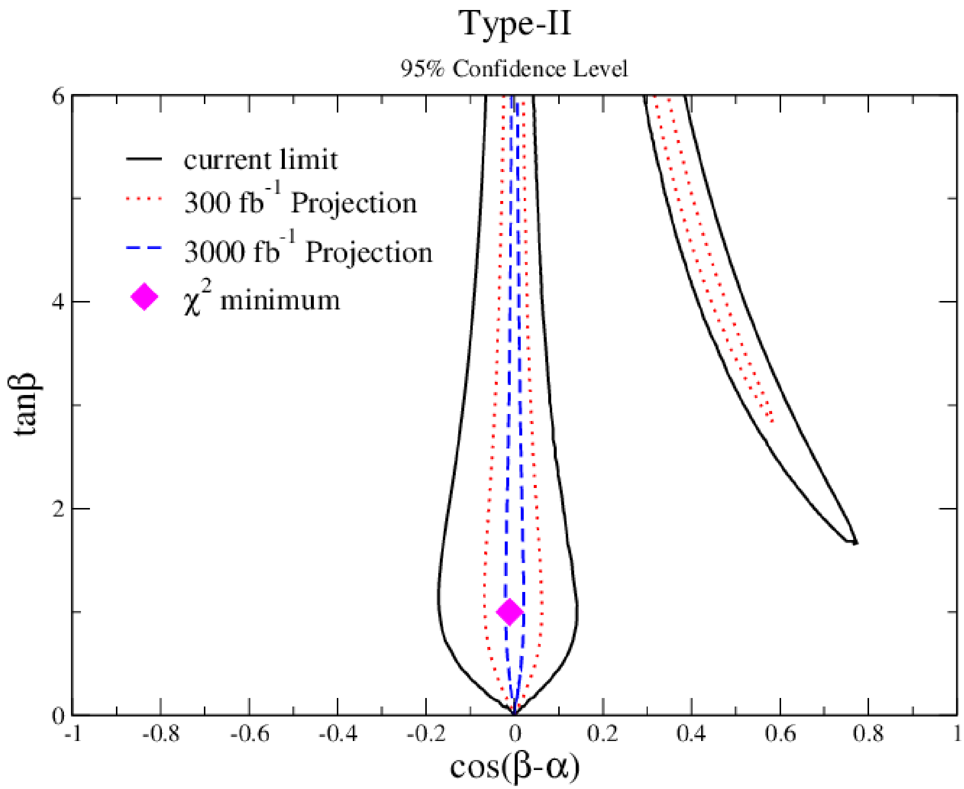


Chen, Dawson, Sher Phys.Rev. D88 (2013) 015018

Alignment Limit $\beta - \alpha = \frac{\pi}{2}$

Light Higgs	Type I	Type II
Gauge Bosons	1	1
Down Type Fermions	$1 - \cot\beta(\beta - \alpha - \pi/2)$	$1 + \tan\beta(\beta - \alpha - \pi/2)$
Up Type Fermions	$1 - \cot\beta(\beta - \alpha - \pi/2)$	$1 - \cot\beta(\beta - \alpha - \pi/2)$





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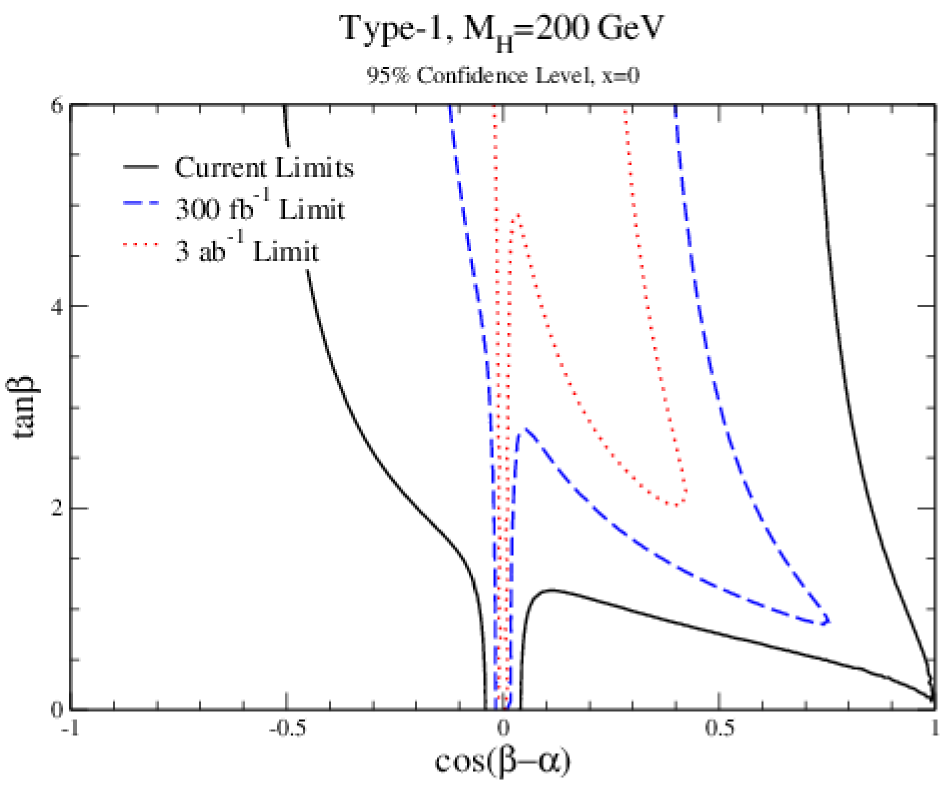
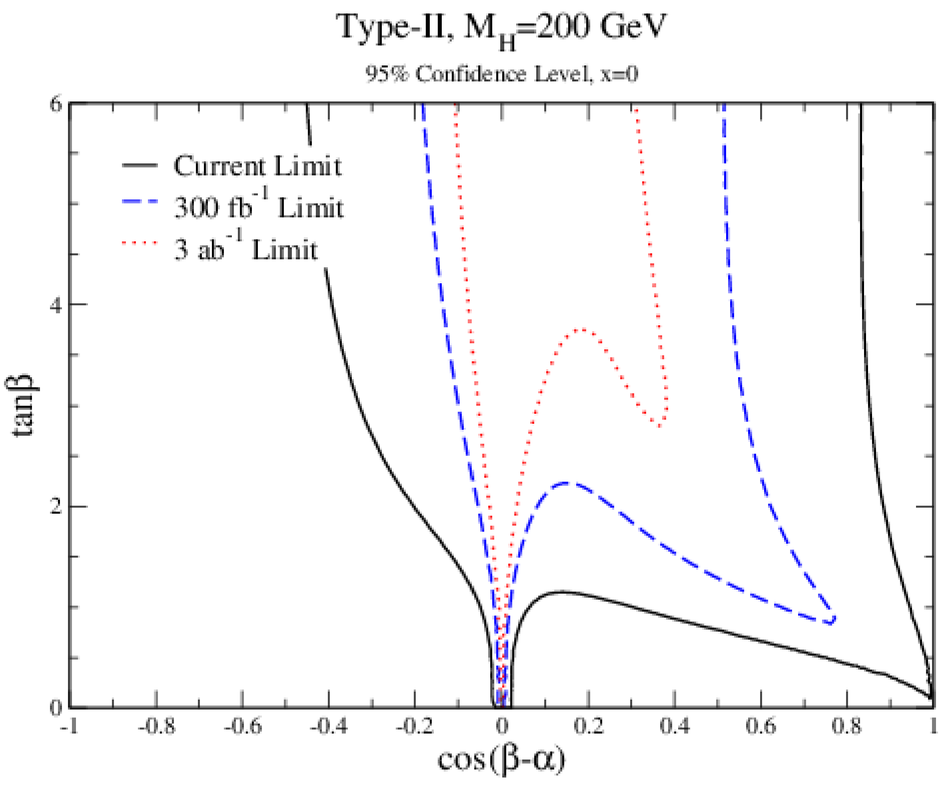
Search For Heavy Neutral Higgs





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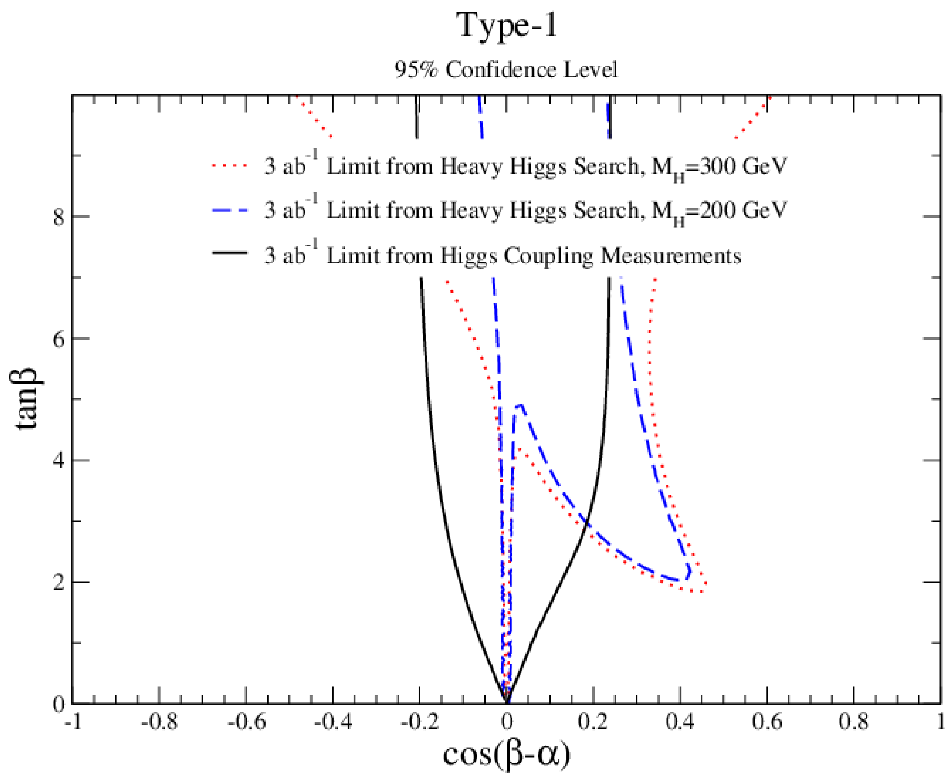
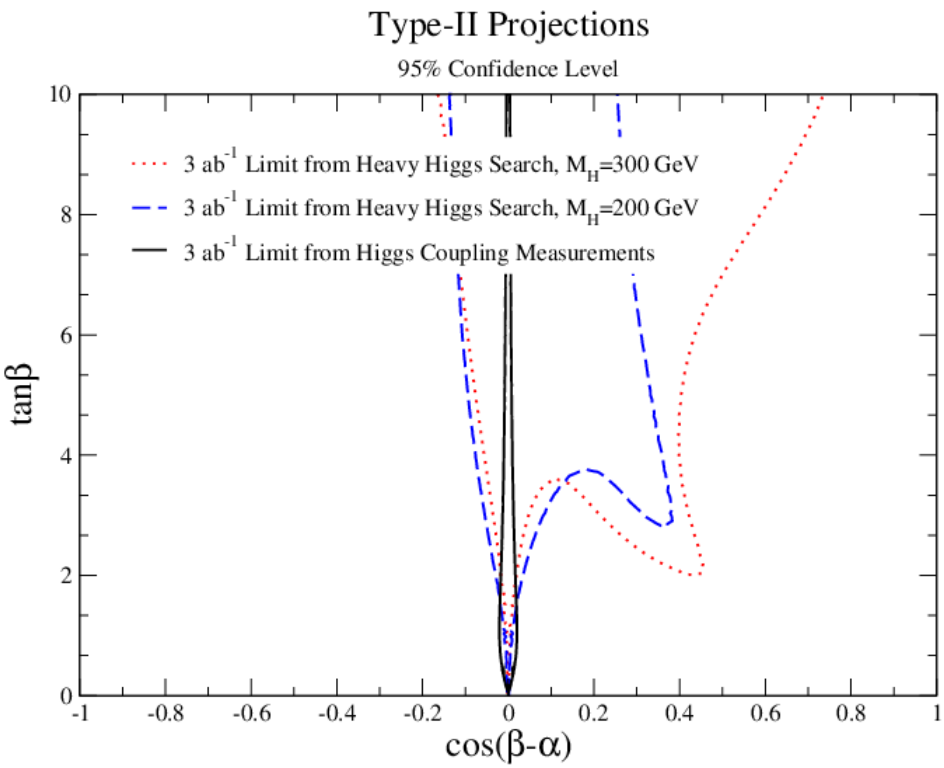
Comparison

- Direct searches and precision measurements give complementary information.





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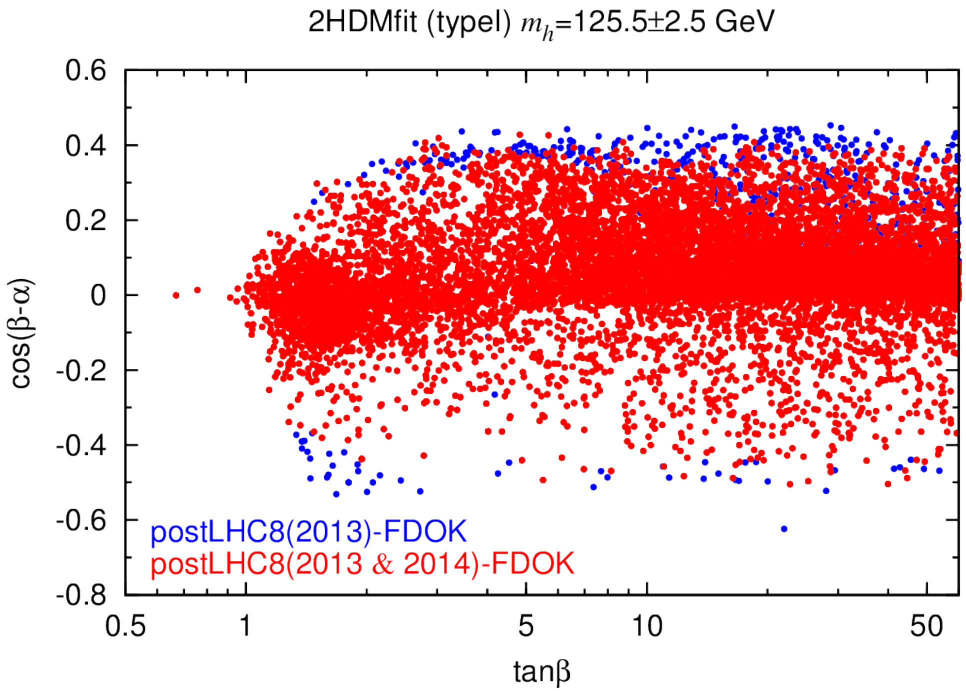
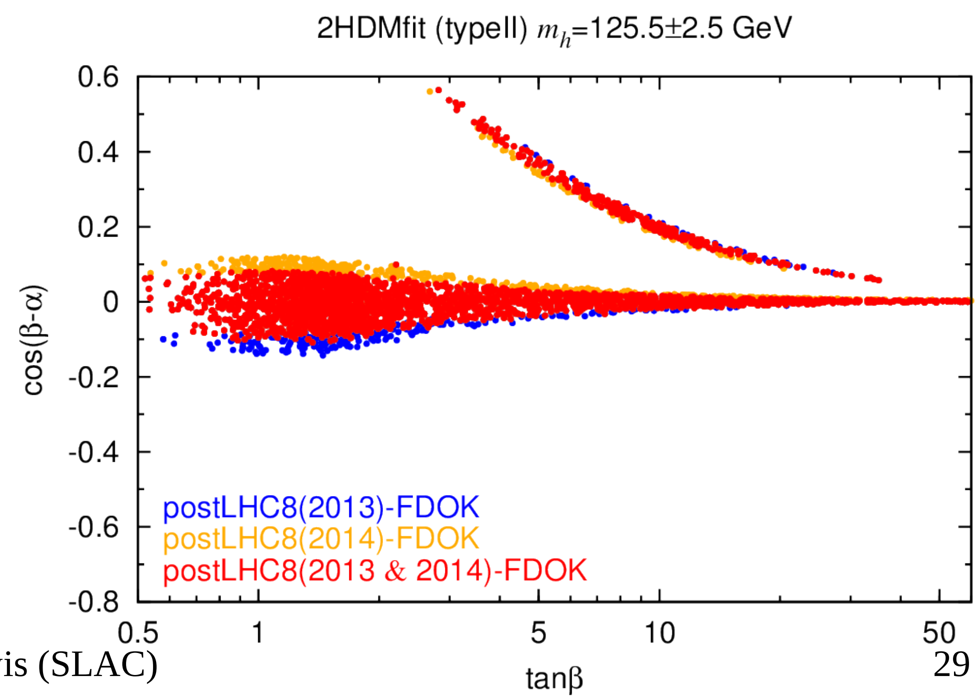
Recent Bounds

- Type I:



- Type II:



Dumont et al arXiv: 1409.4088

Supersymmetry (Weakly Interacting Solution to Hierarchy Problem)

SUSY

- Minimal Supersymmetric Standard Model (MSSM):
  - Two Higgs Doublets: H_u, H_d
    - H_u gives masses to up-type fermions.
    - H_d gives masses to down-type fermions.
  - So called Type-II Two Higgs Doublet Model (2HDM).

$$\mathcal{L} = -y_u \overline{Q_L} H_u u_R - y_d \overline{Q_L} H_d d_R - y_\ell \overline{L} H_d e_L + \mathrm{h.c.}$$

MSSM Higgs

- Five Higgses:.
  - Two scalars: h, H
  - Pseudoscalar: A
  - Charged Higgs: $H^{\pm}$
- Supersymmetry more constraining than parity, two free parameters:
  - $$\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$$
  - Pseudoscalar mass: m_A

Mass, Mixing, and Couplings to other SM particles

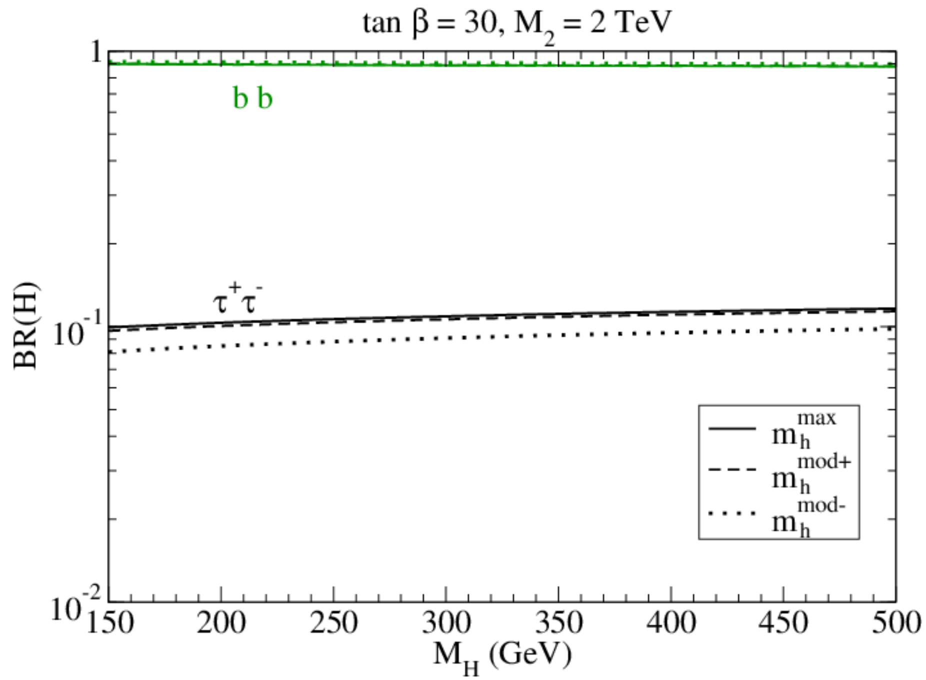
- At tree level have upper bound on Higgs mass:

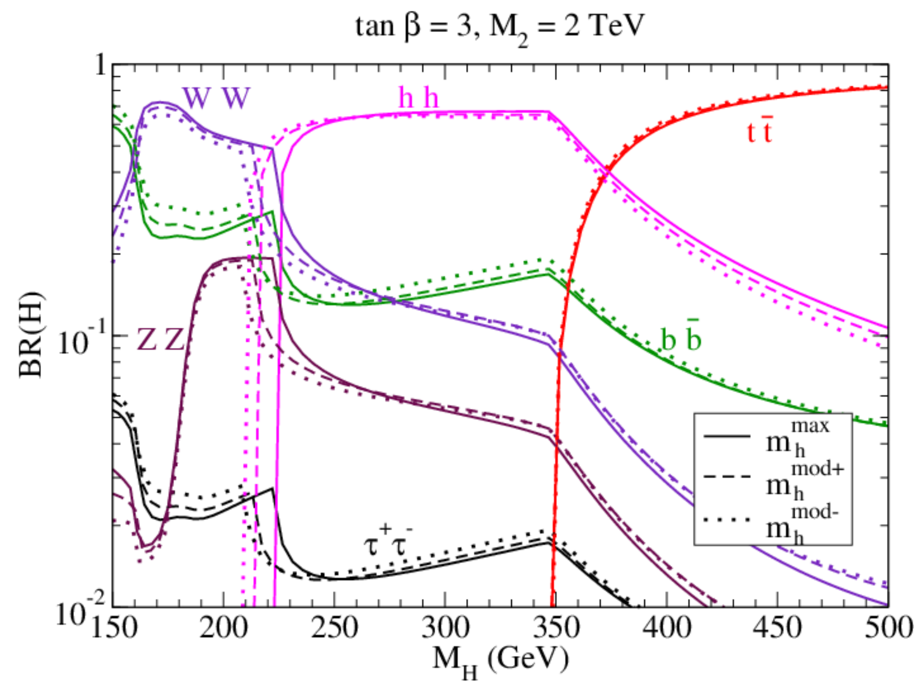
$$m_h^2 \leq m_Z^2 \cos 2\beta$$

- Stop squark can raise mass to observed level.
  - Higgs mass sensitive to highest scale in the theory.
  - Stop squark couples strongly.

Decays of Heavy Scalar

- Branching ratio depends greatly on $\tan\beta$
- For large $\tan\beta = \dfrac{\langle H_u \rangle}{\langle H_d \rangle}$
  - Down type fermions get mass from $\langle H_d \rangle$
  - Smaller $\langle H_d \rangle$, larger coupling
- For small $\tan\beta$
  - Many possible decay channels
  - Depends greatly on mass

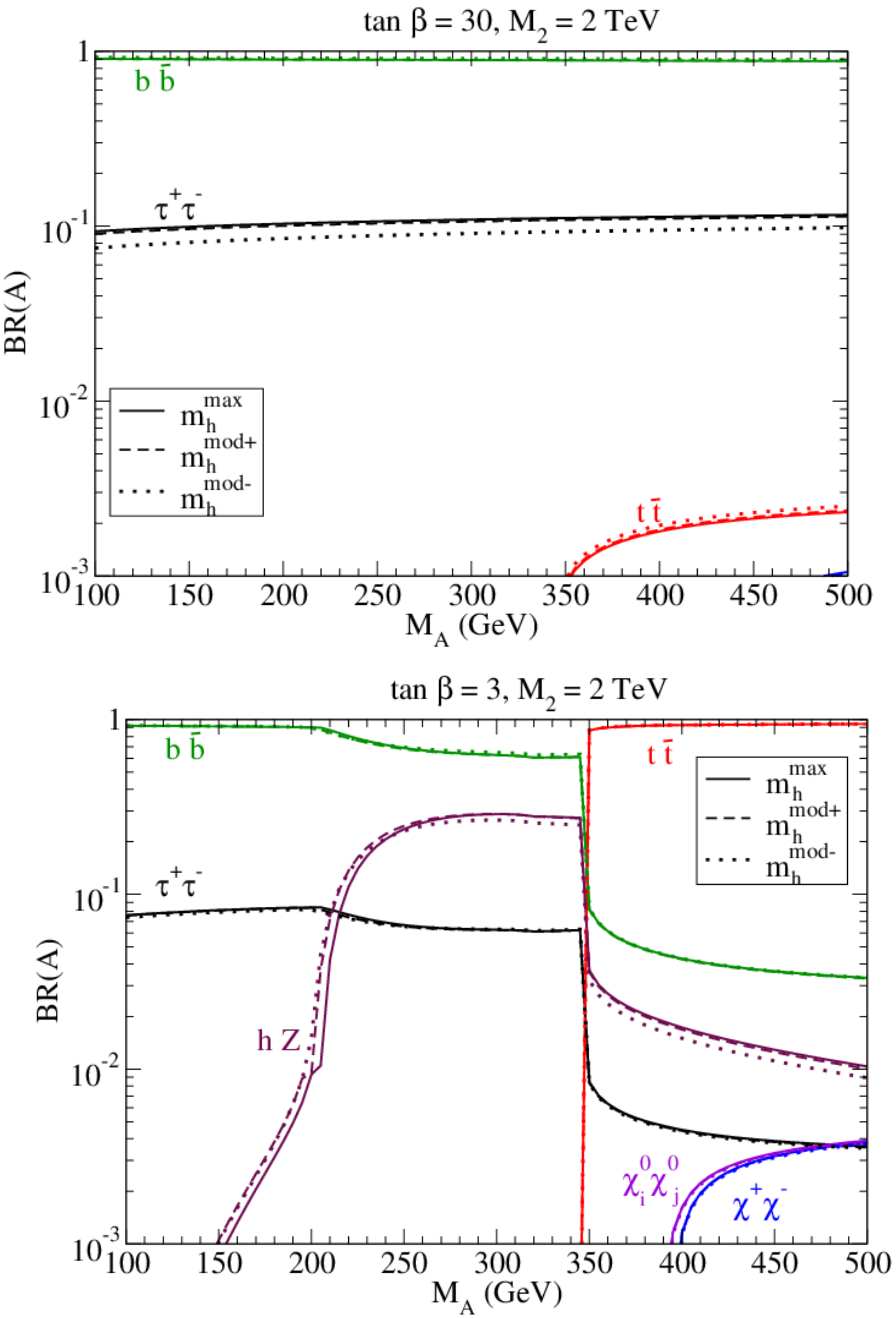




IL arXiv:1308.1742, Snowmass

Decays of Pseudscalar

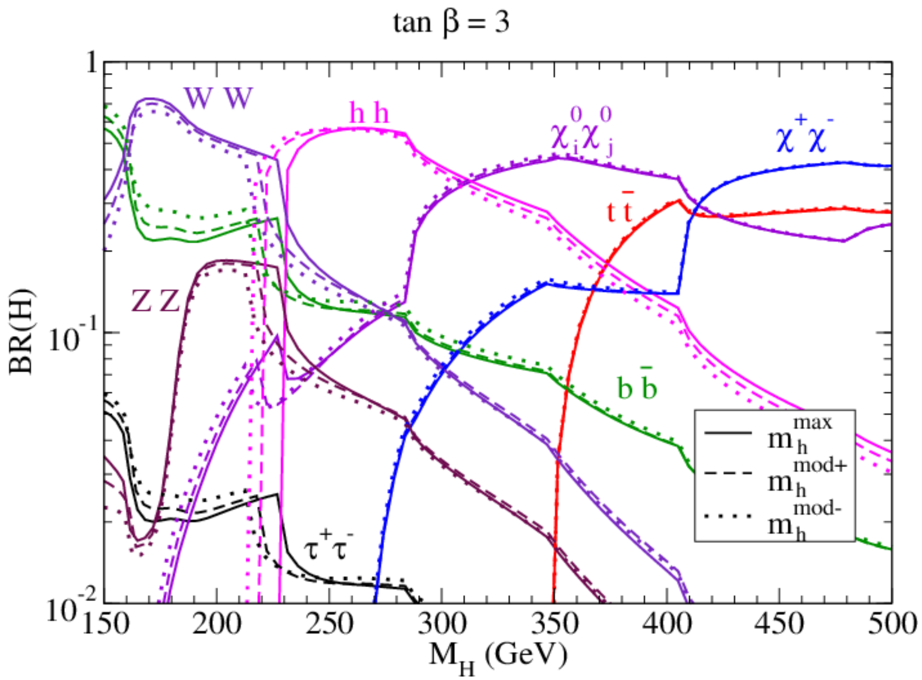
- Branching ratio depends greatly on $\tan\beta$
- For large $\tan\beta$
  - Decays to down-type fermions
- For small $\tan\beta$
  - Many possible decay channels
  - Exotic decay channels open up
  - Depends on thresholds

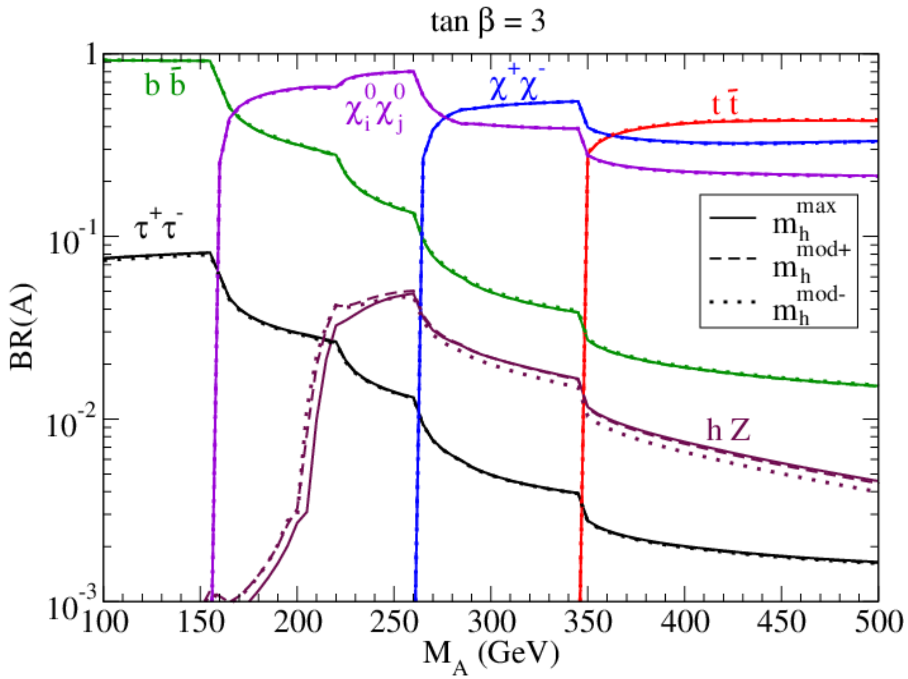


IL arXiv:1308.1742, Snowmass

SUSY Spectrum Matters

- At low $\tan\beta$ spectrum of SUSY particles matters
- For large $\tan\beta$
  - Branching ratios largely the same.
- For small $\tan\beta$
  - Open up neutralino decay channels.
  - Depends on mass thresholds.





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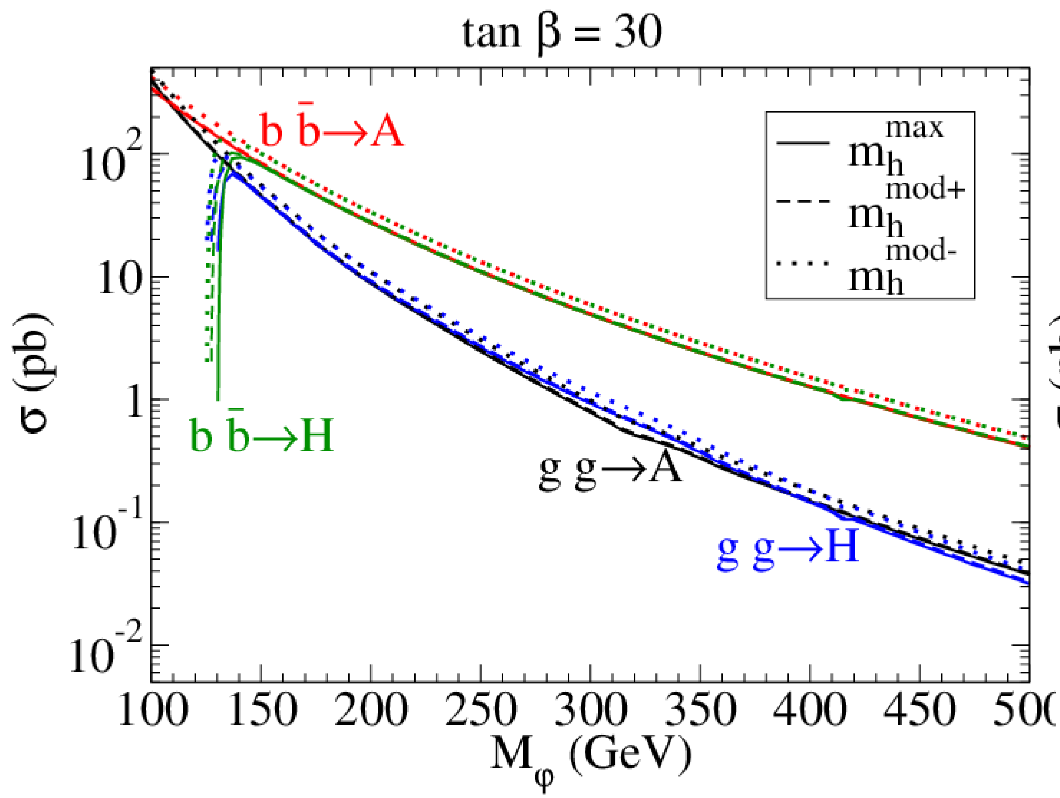
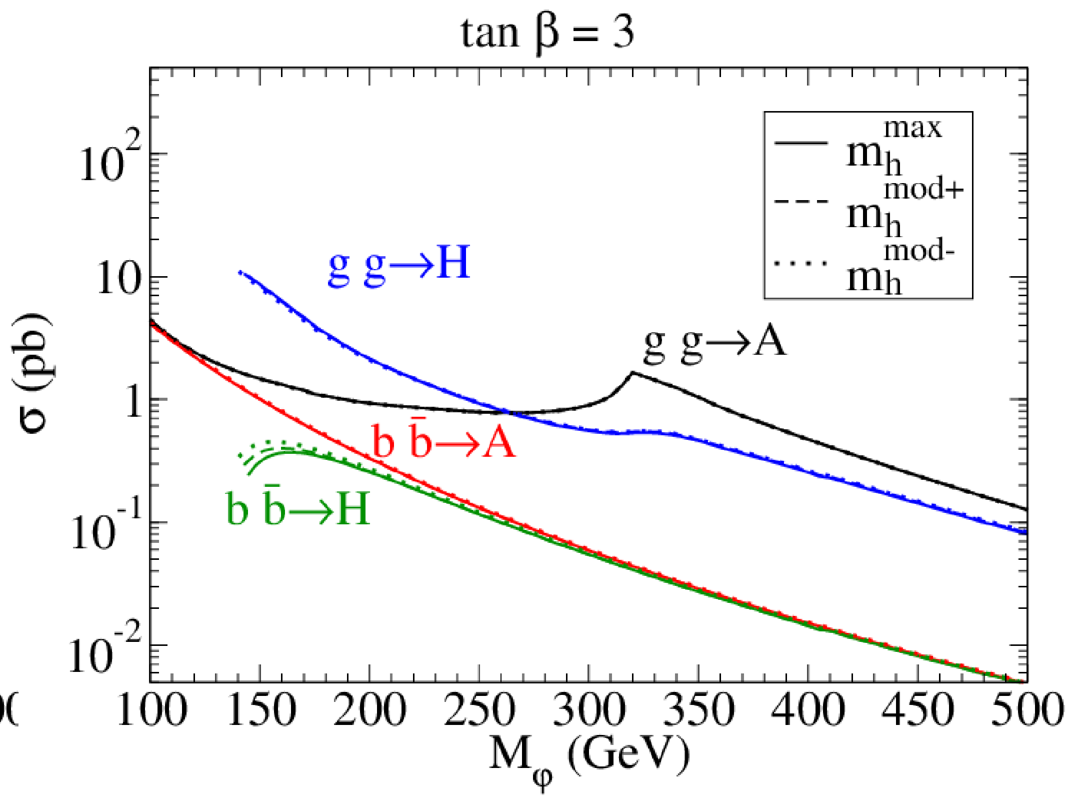
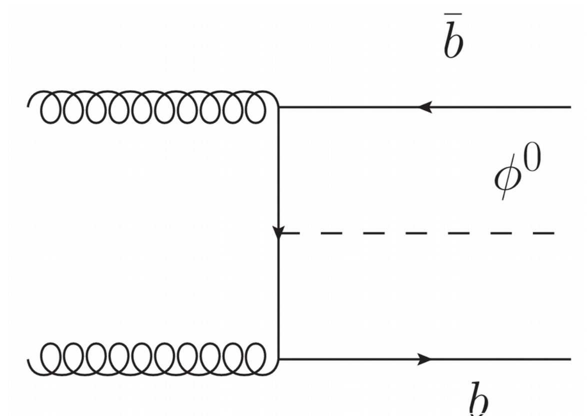
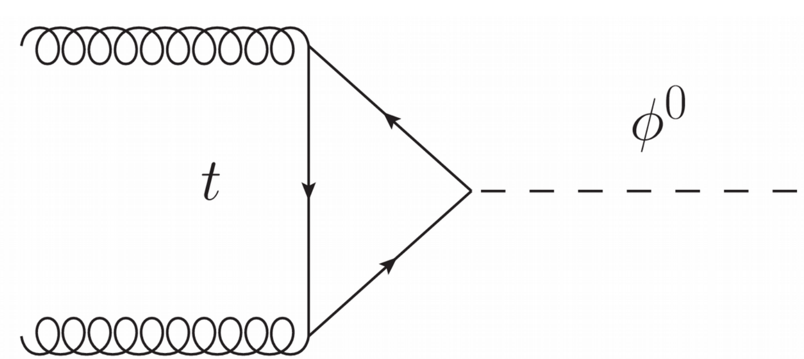
Production of Neutral Scalars

- Production mechanism depends on $\tan\beta$



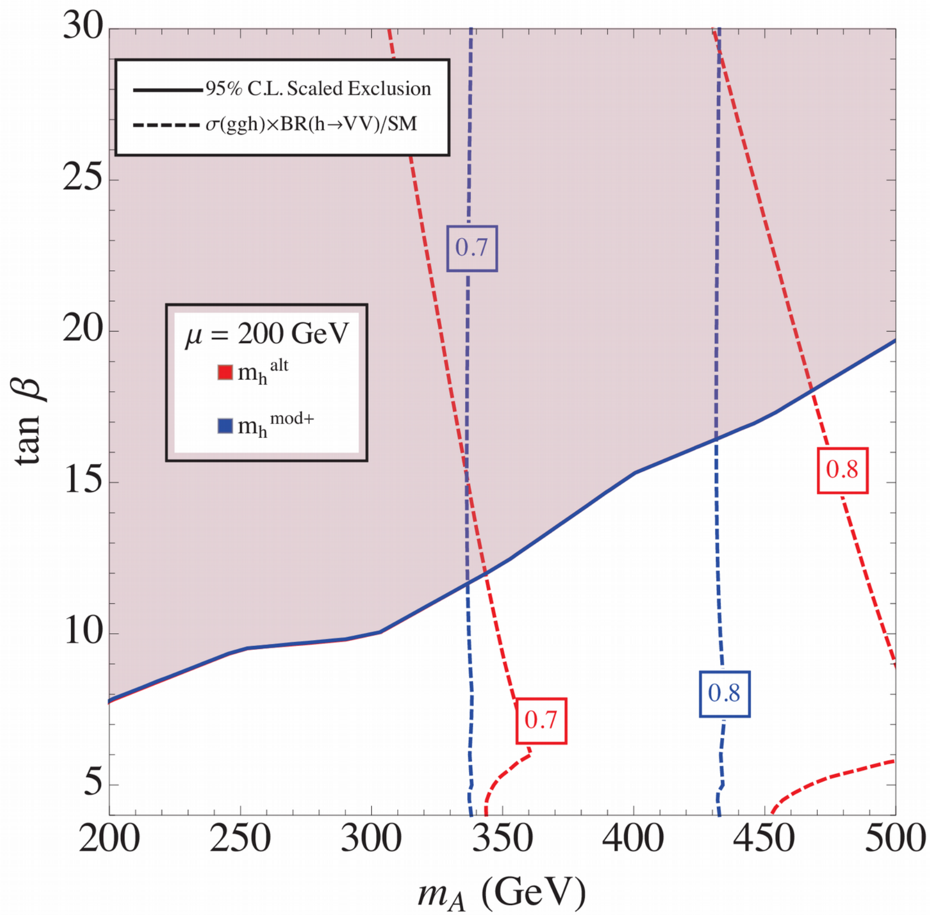


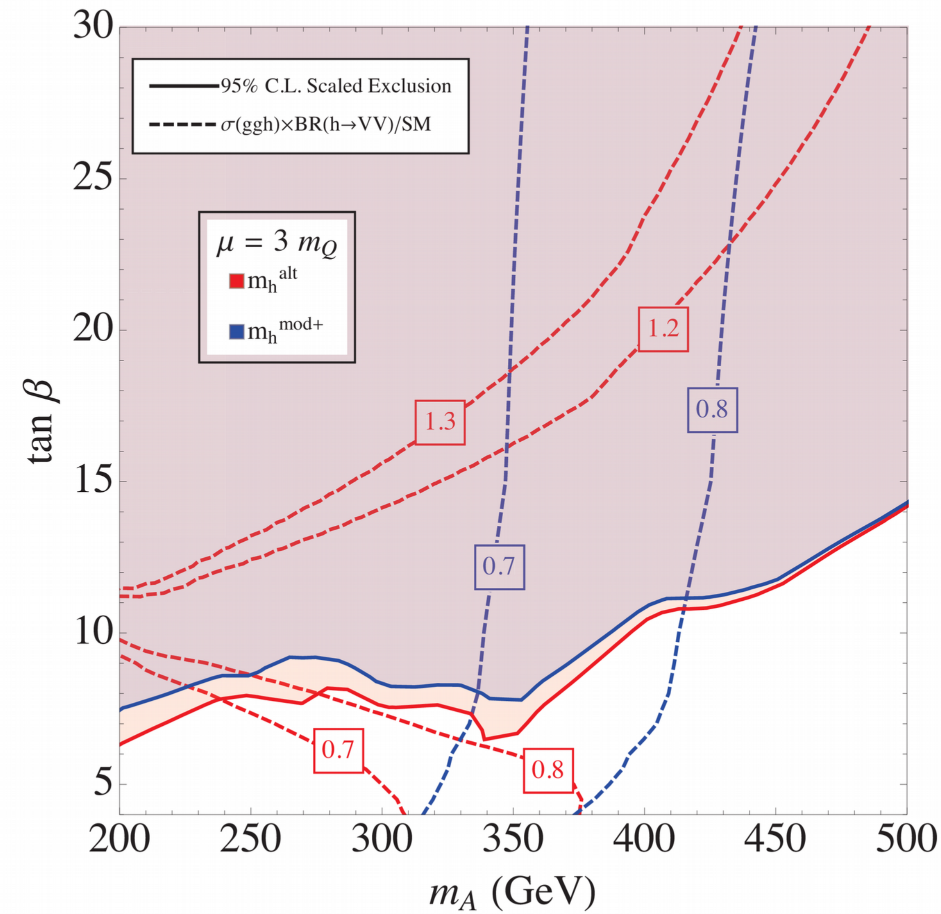




IL arXiv:1308.1742, Snowmass

Direct Searches and Precision Measurements





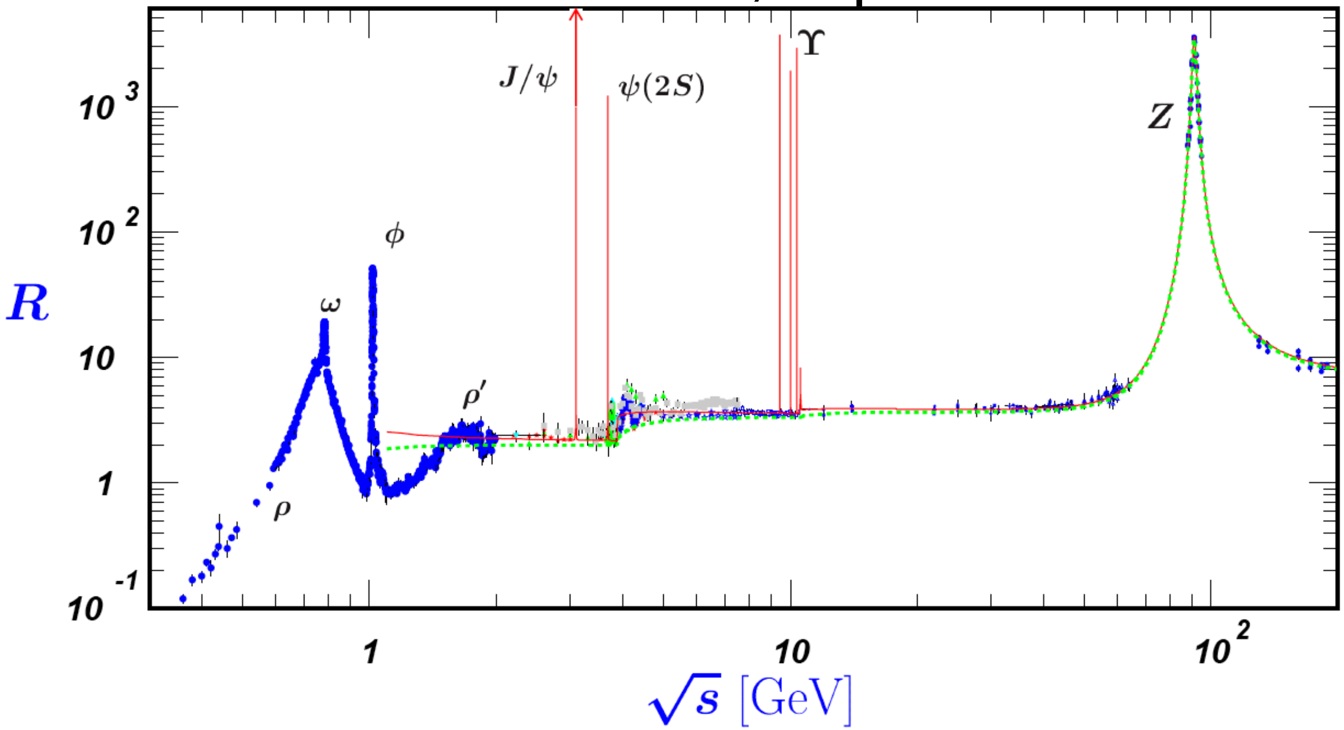
- Solid line: recast searches for ττ resonances.
- Dotted lines: precision Higgs measurements.
- Limits depend on SUSY spectrum.

Carena et al Phys.Rev. D91 (2015) 3, 035003

Composite Models
(Strongly Interacting Solution)

Technicolor

- Most basically: scaled up QCD
  - Electroweak symmetry broken by strong interactions, similar to pions.
  - Strong scale is electroweak scale, expect resonances.



  - Separate strong interaction from electroweak scales.

Pseudo Nambu-Goldstone Boson Higgs

- Make Higgs a Nambu-Goldstone boson of some symmetry breaking.
  - Massless at tree level.
  - Natural to be much lighter than other resonances in the strongly interacting sector.
  - Use loops to give Higgs mass.

$$v_{EW} \quad \ll \quad m_\rho = g_\rho f \quad \ll \quad 4\pi f \to \text{UV completion}$$

Parameterize Via EFT

- Do not necessarily know dynamics of strongly interacting sector.

$$\mathcal{L}_{eff} = -c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + m_W^2 W_\mu^+ W^{-\mu}\left(1 + 2c_W \frac{h}{v} + \cdots\right) + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \left(1 + 2c_Z \frac{h}{v} + \cdots\right)$$

$$-\sum_{\psi=u,d,\ell} m_\psi \overline{\psi}\psi \left(1 + c_\psi \frac{h}{v} + \cdots\right) + \cdots$$

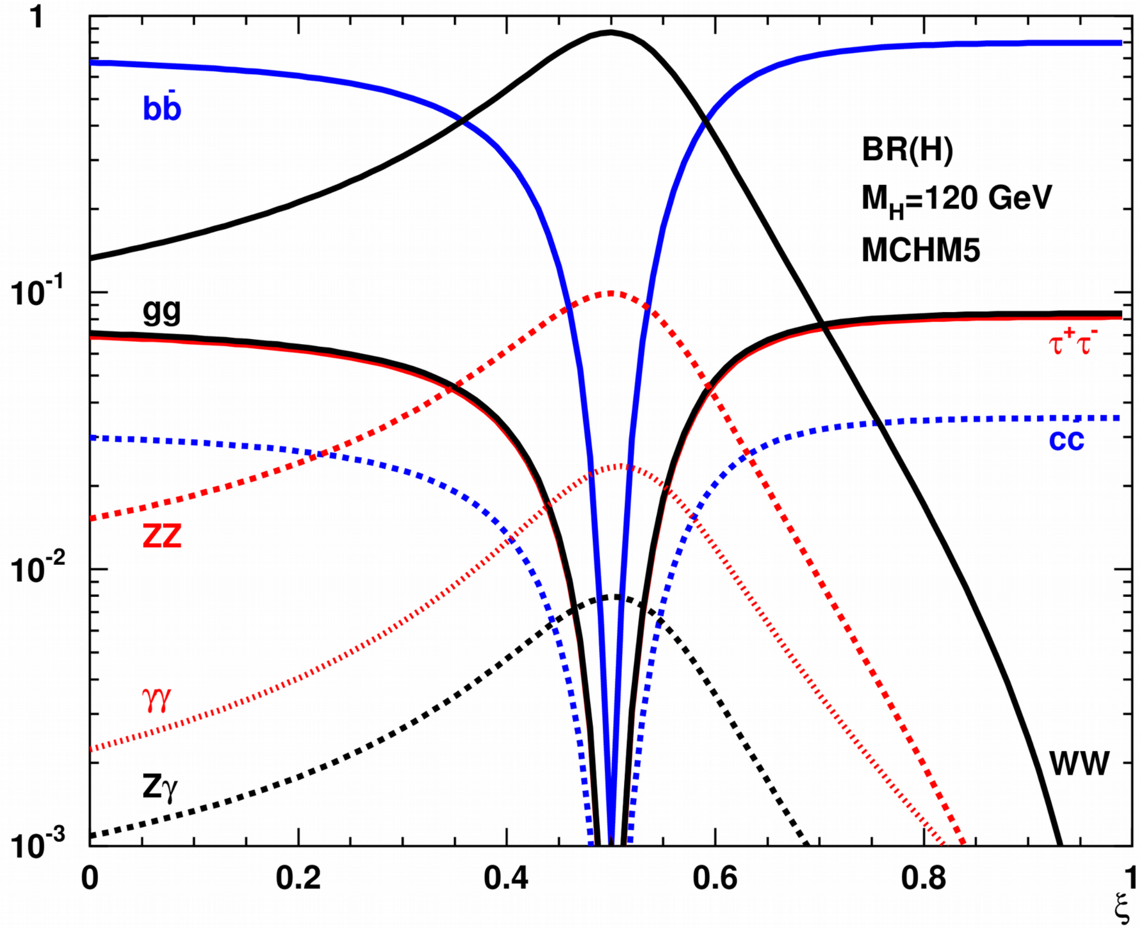
- Standard Model Limit: $c_W = c_Z = c_\psi = 1$
- Changes couplings from Standard Model, expect corrections of order

$$\xi = \frac{v^2}{f^2} \sim \frac{(\text{Electroweak scale})^2}{(\text{Strongly interacting scale})^2}$$

Minimal Composite Models

- Specific models $\Rightarrow$ specific predictions:
  - MCHM5: $c_W = c_Z = \sqrt{1-\xi}, \quad c_3 = c_\psi = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

Agashe, Contino, Pomarol, Nucl.Phys. B719 (2005) 165-187



Espinosa, Grojean, Muhlleinter, JHEP 1005 (2010) 065

Precision Higgs Measurements

- Precise Higgs signal rates:

ξ	LHC	HL-LHC	LC	HL-LC	HL-LHC+HL-LC
universal	0.076	0.051	0.008	0.0052	0.0052
non-universal	0.068	0.015	0.0023	0.0019	0.0019
f [TeV]					
universal	0.89	1.09	2.82	3.41	3.41
non-universal	0.94	1.98	5.13	5.65	5.65

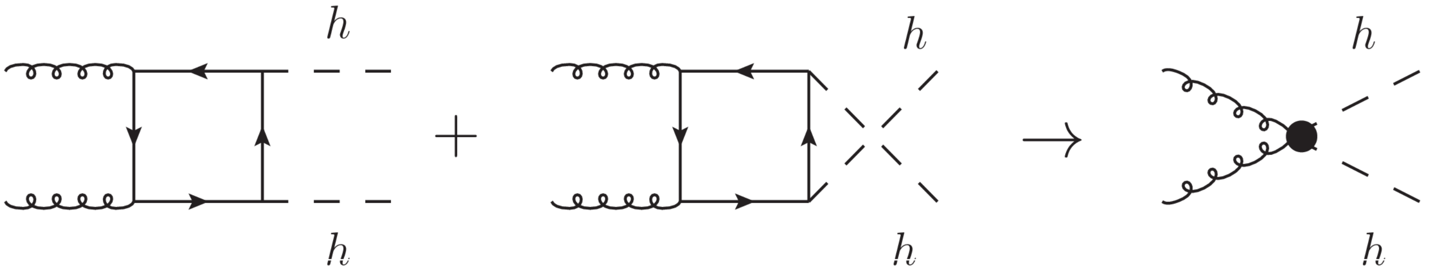
Englert et al J.Phys. G41 (2014) 113001

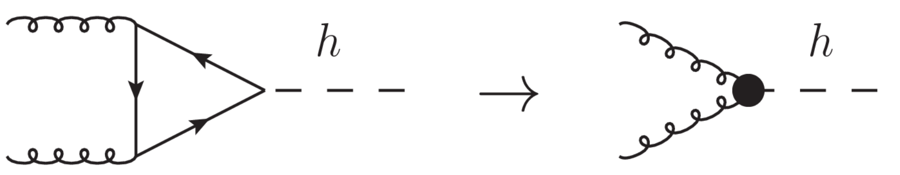
- For moderate fine tuning, generically expect top partners in TeV range.

Matsedonskyi, Panico, Wulzer JHEP 1301 (2013) 164; Panico, Redi, Tesi, Wulzer JHEP 1303 (2013) 051

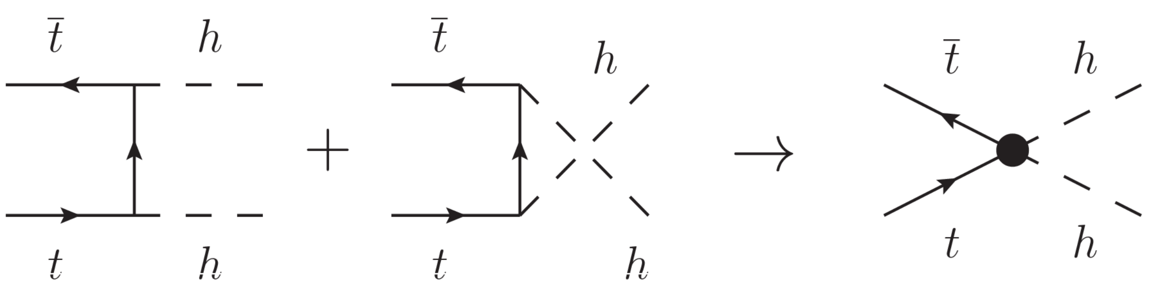
Double Higgs Production

- Need to expand effective field theory:
  - New resonances introduce new Higgs couplings:



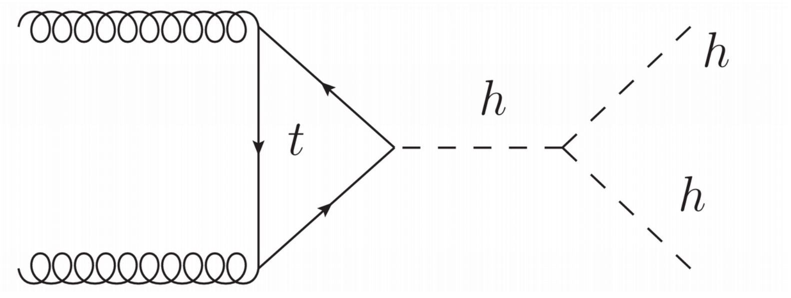


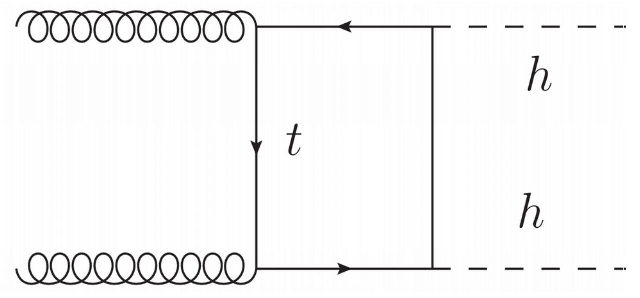
  - New four point interaction:

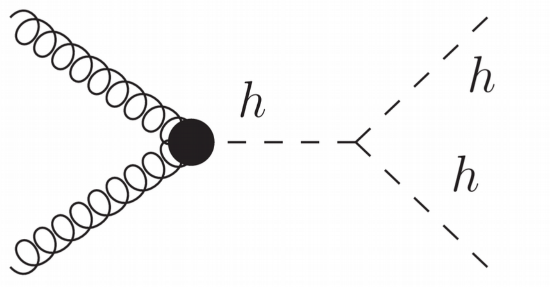


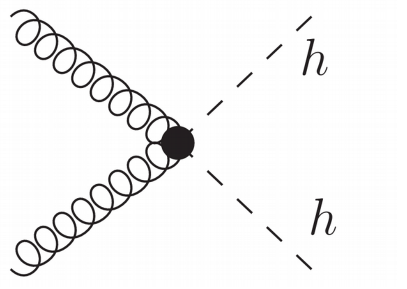
Double Higgs Production

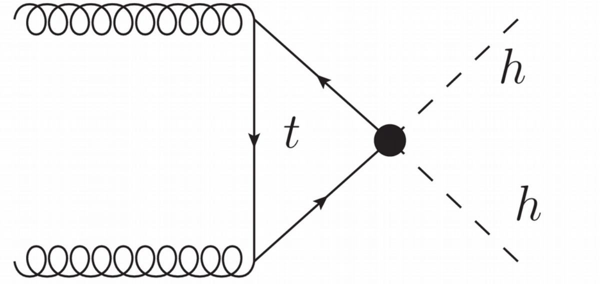
- Representative Diagrams:





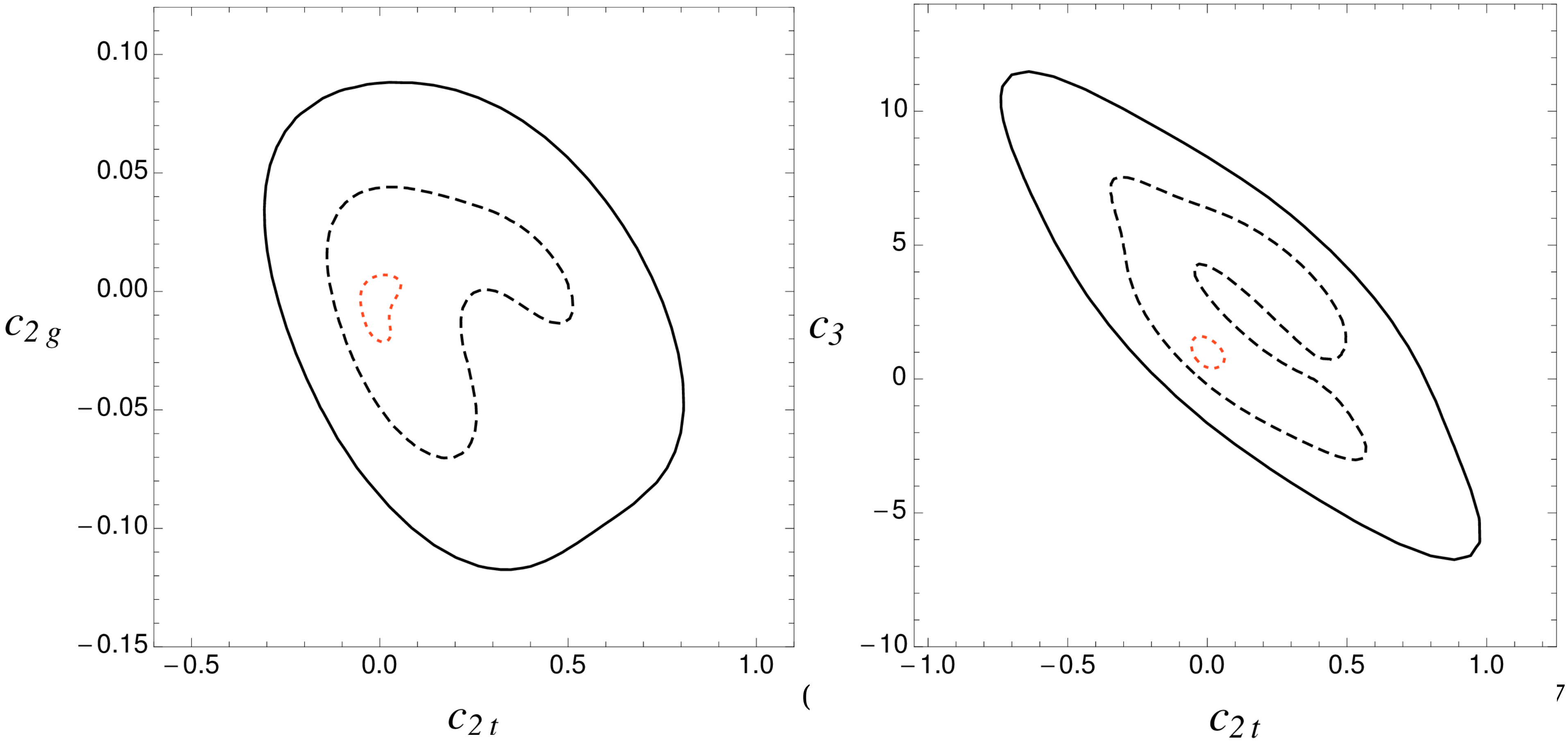






Double Higgs Production

- Search for double Higgs production via $gg \to hh \to b\bar{b}\gamma\gamma$
  - Solid: LHC 14 TeV 300 fb^{-1}, Dashed: 14 TeV 3 ab^{-1}
    Red: 100 TeV 3 ab^{-1} Azatov, Contino, Panico, Son arXiv:1502.00539
  - c_{2g}: g-g-h-h c_{2t}: t-t-h-h c_3: h-h-h



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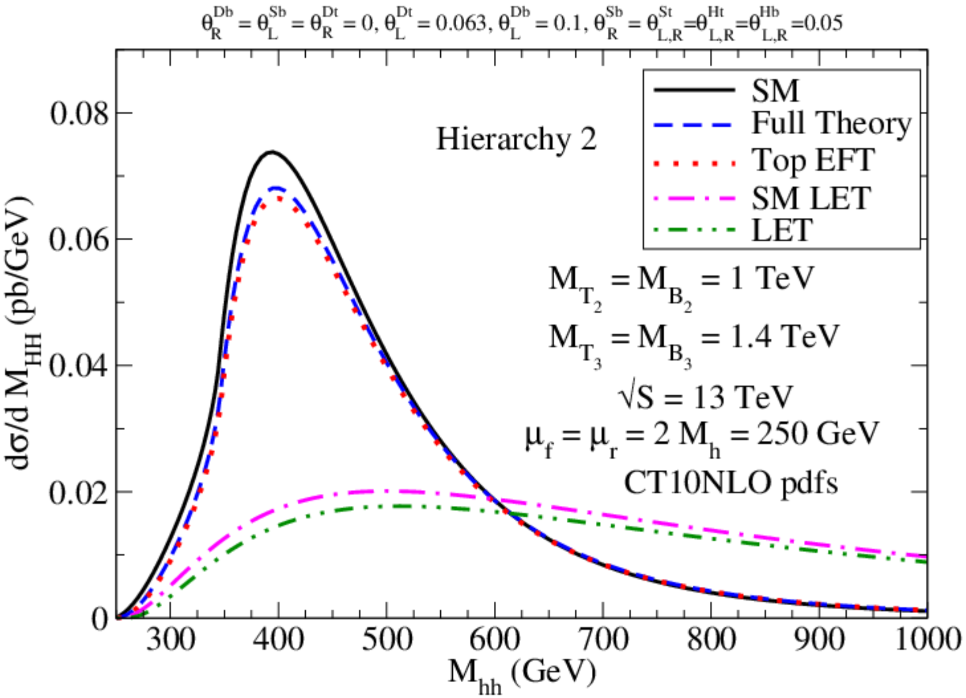
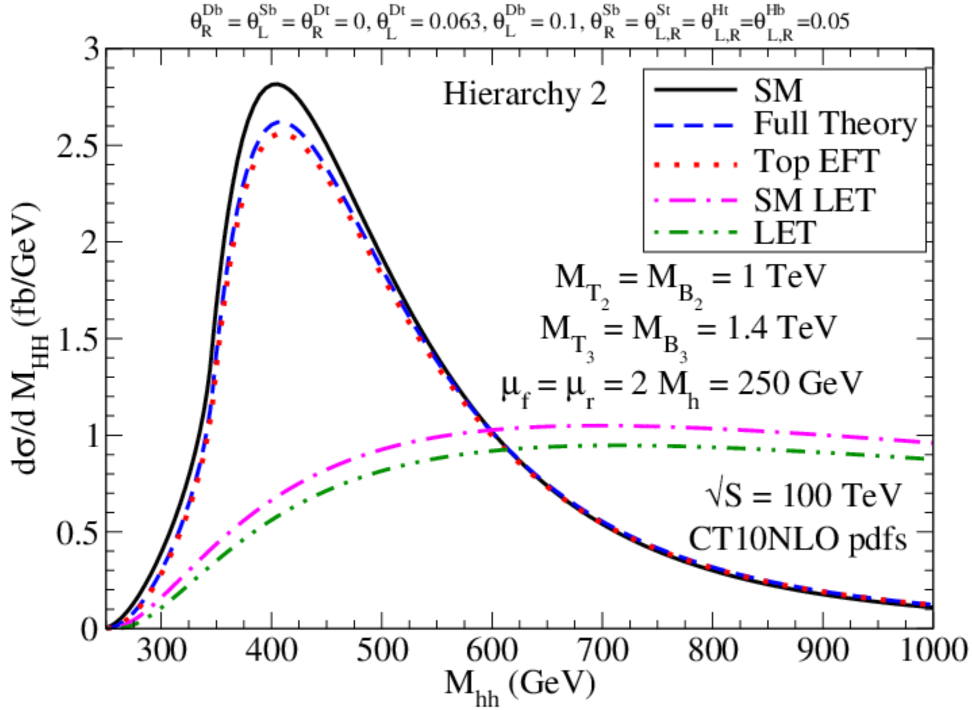
Validity of EFT





13 TeV

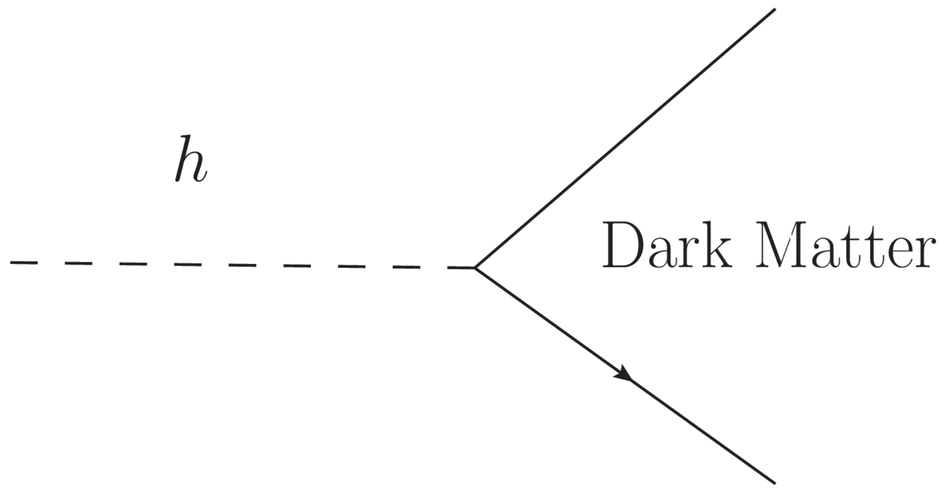
100 TeV

Chen, Dawson, IL Phys.Rev. D90 (2014) 3, 035016

Higgs and the Dark Sector

Invisible Higgs Decays

- Higgs decays to Dark Matter:



- Heard about yesterday.
- Possible for Higgs processes to probe dark sector in other ways.

Higgs and Dark Matter Sector

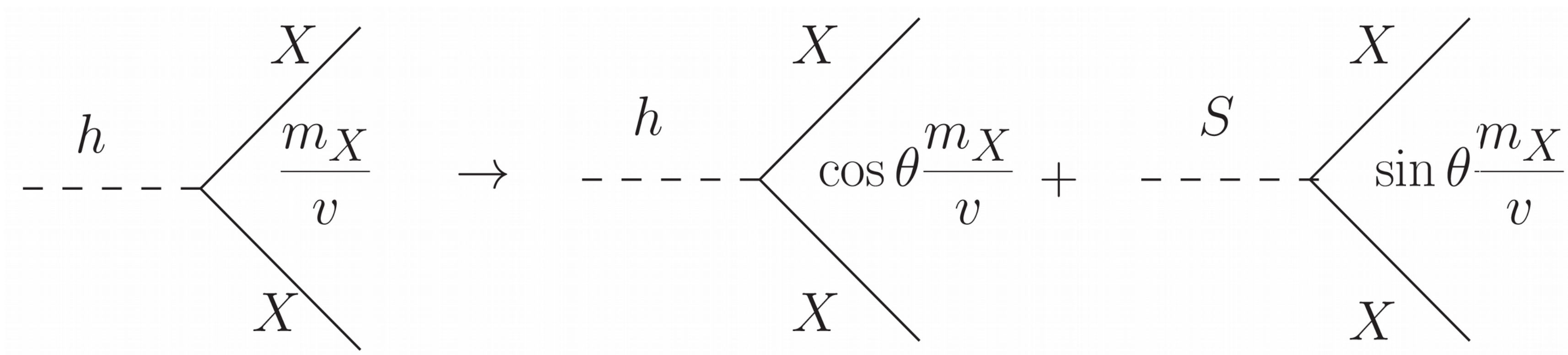
- Higgs can serve as portal to other particles of the dark sector.

Higgs Portal

- Add new scalar no couplings to SM
  - S could be part of a dark sector, generically couples to Higgs.
- New potential

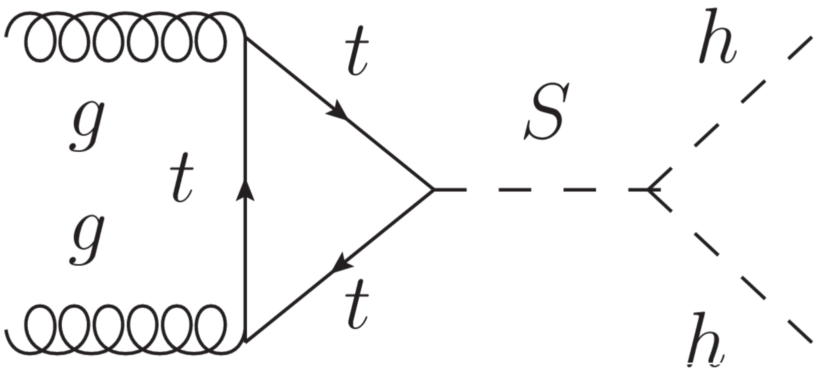
$$V(H,S) = V_h(H) + V_{hS}(H,S) + V_S(S)$$

  - New Higgs Interactions: $V_{hS}(h,S) = a_1 H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2$
  - Mixing with Higgs introduces new interactions:



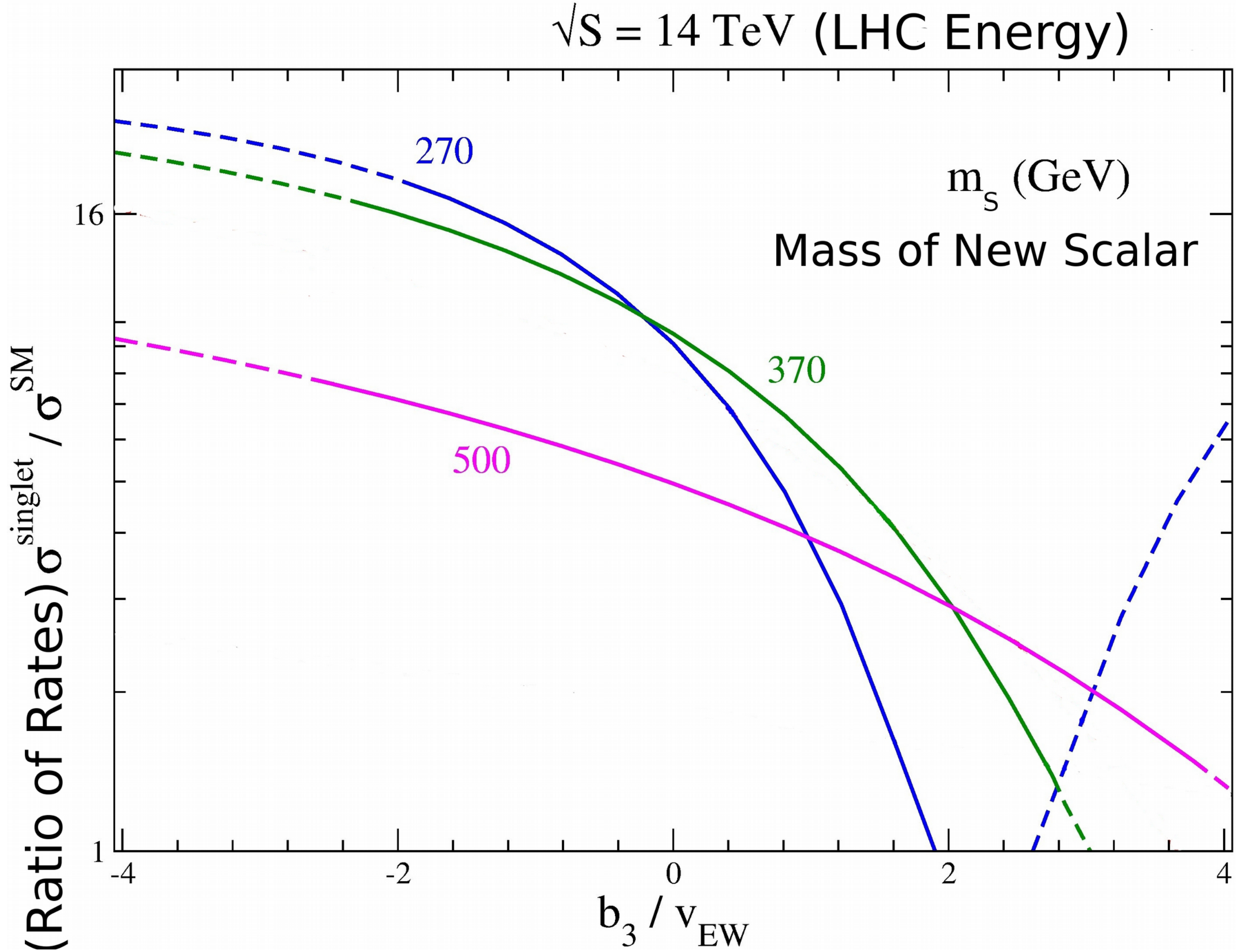
Double Higgs Resonance

- New Higgs process.
- Potential has many minima now
  - Vacuum expectation value of S cannot give mass to W/Z.
  - Require minimum with Standard Model Higgs vacuum expectation value is global minimum.
  - Affect S-h-h coupling



Large Enhancements

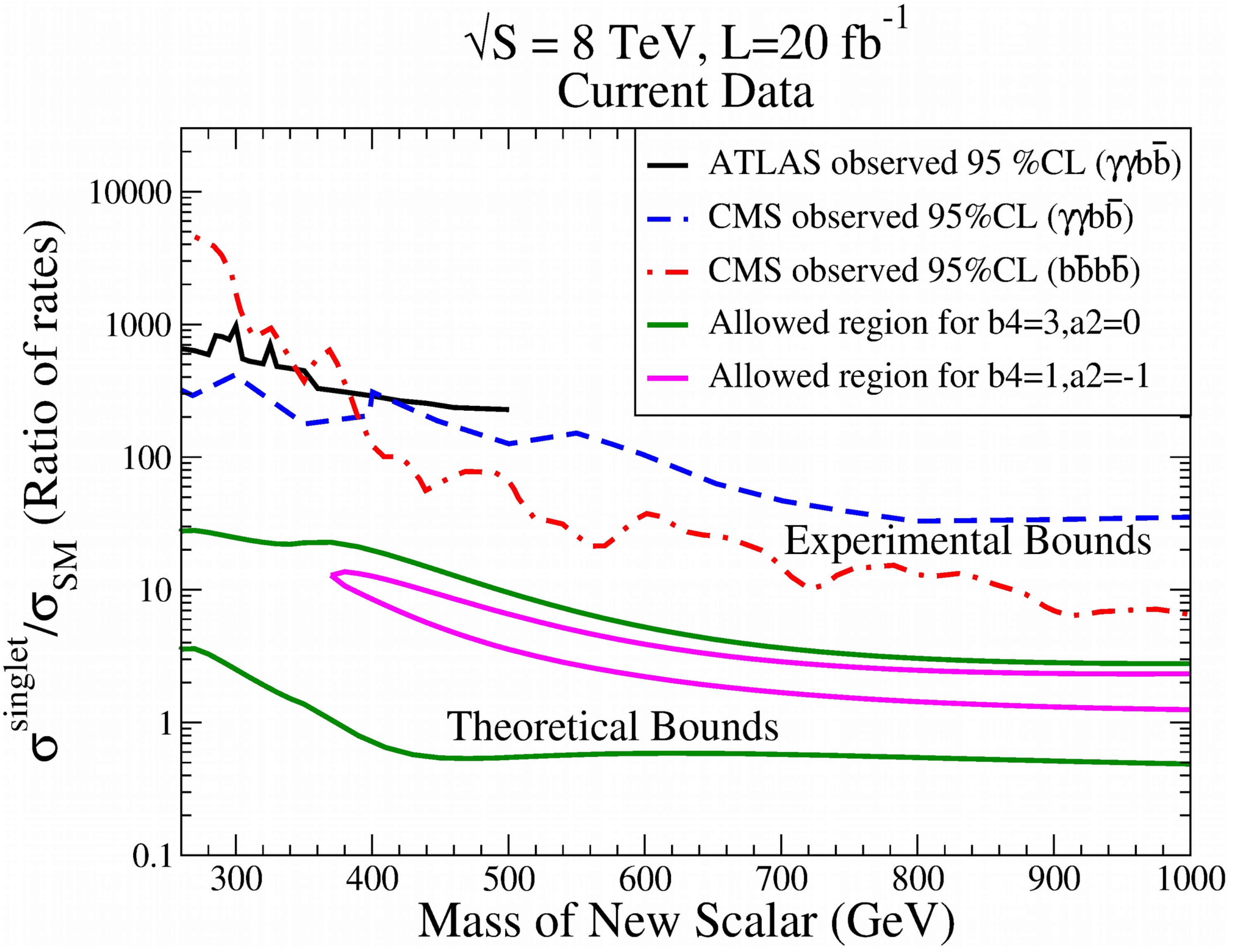
- Ratio of double Higgs rate with S included to double Higgs rate in Standard Model
- Dashed lines have incorrect vacuum expectation value for Higgs.



Chen, Dawson, IL arXiv:1410.5488 [hep-ph]

Bounds With Current Data

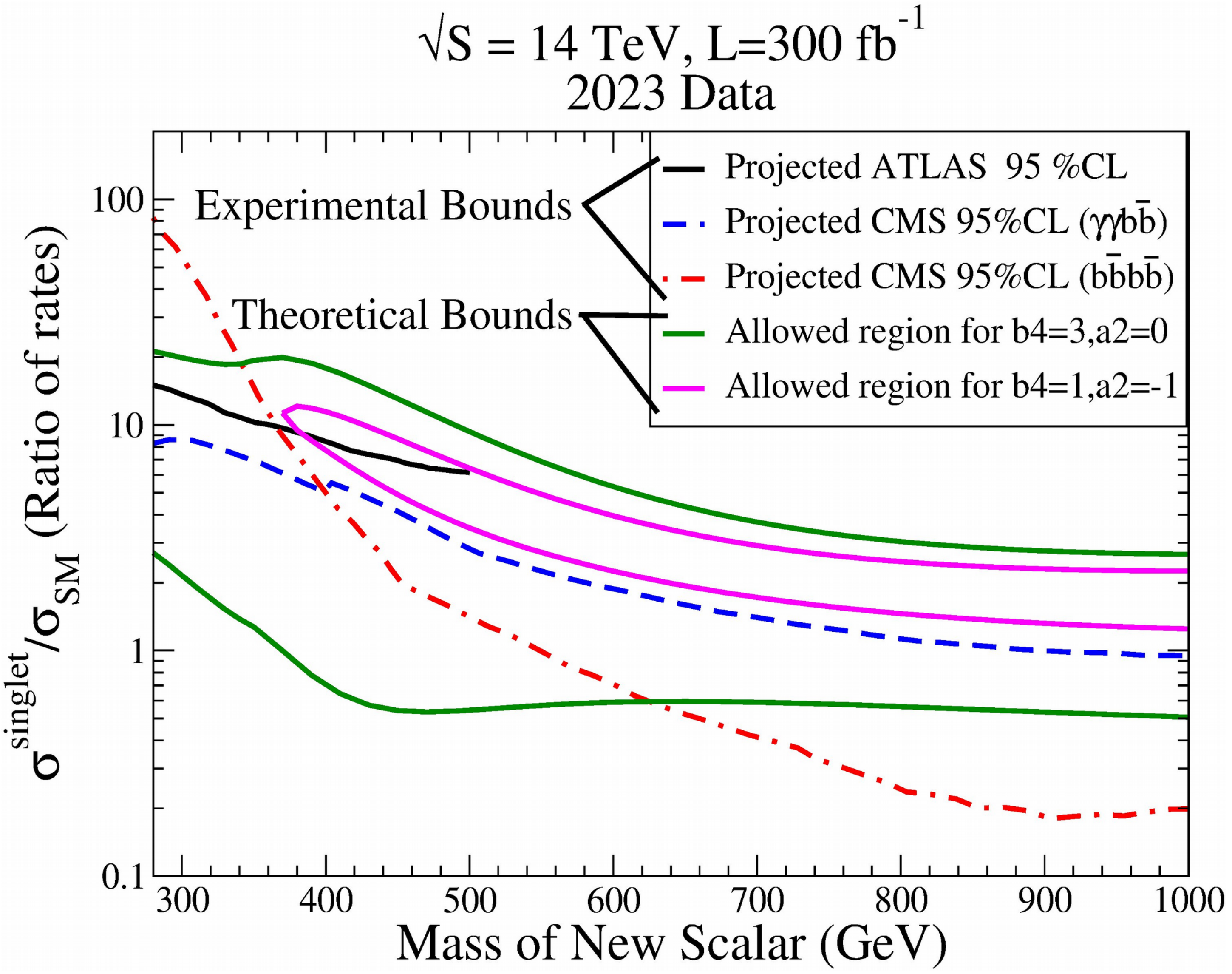
- Ratio of double Higgs rate with S to Standard Model prediction.
  - Area within green and magenta curves are theoretical bounds.
- Current bounds not enough



Chen, Dawson, IL arXiv:1410.5488 [hep-ph]

Extrapolated bounds

- Ratio of double Higgs rate with S to Standard Model prediction.
  - Area within green and magenta curves are theoretical bounds.
- Need 2023 data
- Scenario where scalar only has couplings through Higgs.



Chen, Dawson, IL arXiv:1410.5488 [hep-ph]

U(1) Symmetry in 2HDM

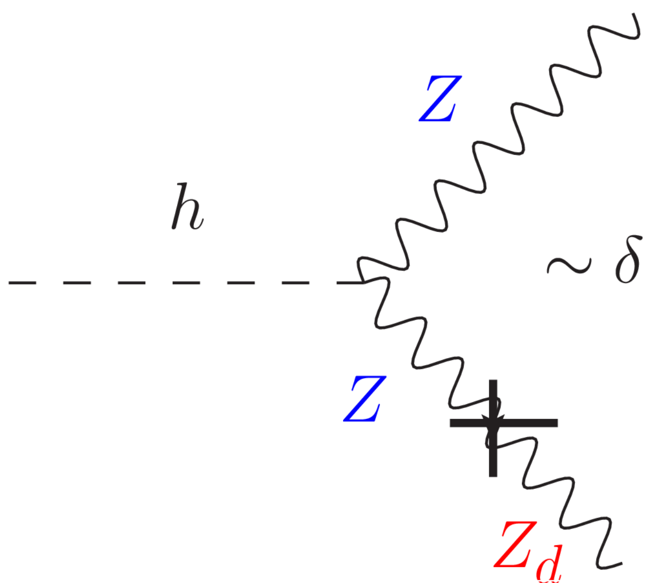
- Previously used parity to constrain Higgs fermion couplings.
- Possible to also charge second Higgs doublet under a U(1) gauge symmetry
  - Both Higgses get vevs
  - New massive gauge boson, Dark Z (Z_d)
- New light gauge bosons motivated.
  - Interacting dark matter.

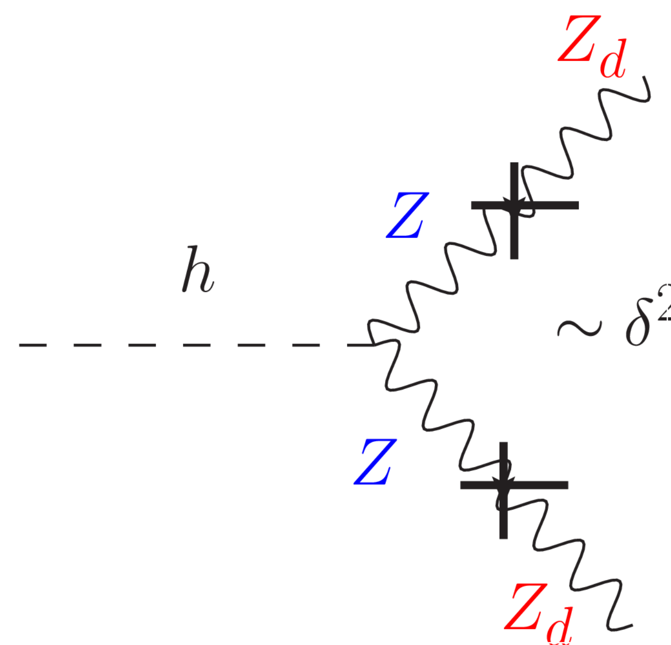
Exotic Higgs Decays

- H_2 charged under U(1) and Standard Model.
  - Mass mixing between SM Z-boson and new Z_d

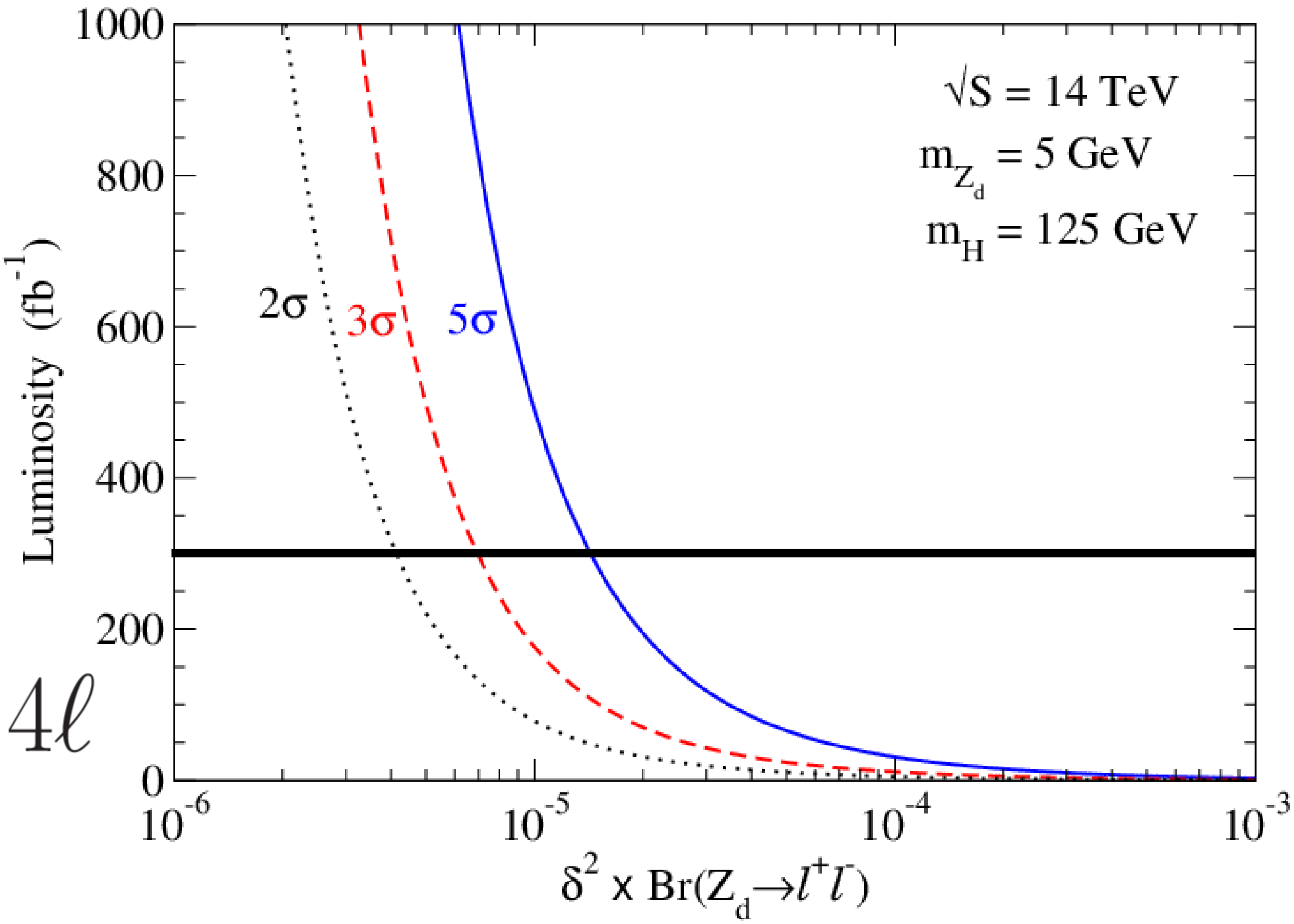
$$\sim (Z^\mu,\ Z_d^\mu) \begin{pmatrix} g_Z^2(v_1^2+v_2^2) & g_d g_Z v_2^2 \\ g_d g_Z v_2^2 & g_d^2 v_2^2 \end{pmatrix} \begin{pmatrix} Z_\mu \\ Z_{d,\mu} \end{pmatrix}$$

- If Z_d light exotic Higgs decay:





LHC Search



$$h \to ZZ_{dark} \to 4\ell$$

- With 300 fb^{-1}:
  - Exclusion: $\delta^2 \,\mathrm{Br}(Z_d \to \ell^+\ell^-) \gtrsim 4 \times 10^{-6}$
  - Discovery: $\delta^2 \,\mathrm{Br}(Z_d \to \ell^+\ell^-) \gtrsim 1.5 \times 10^{-5}$
- Stronger than current bounds.

Davoudiasl, Lee, IL, Marciano Phys. Rev. D88 (2013) 015022

Search for $h \to ZZ_{dark} \to 4\ell$

Mass of Dark Z	2 σ (Exclusion)	3 σ (Observation)	5 σ (Discovery)
5 GeV	78 fb^{-1}	180 fb^{-1}	490 fb^{-1}
10 GeV	100 fb^{-1}	230 fb^{-1}	640 fb^{-1}

Davoudiasl, Lee, IL, Marciano Phys. Rev. D88 (2013) 015022

- Complementary to low energy searches.
- Observable within next decade.
- Looked for in other exotic decays as well.

Davoudiasl, Marciano, Ramos, Sher Phys.Rev. D89 (2014) 11, 115008
Curtin et al arXiv:1412.0018

Conclusions

- Discovered a Higgs boson!
  - Not end of story, hierarchy problem still there.
  - Two major solutions:
    - Strong interactions: composite Higgs
    - Weak interactions: SUSY
  - Precision Higgs measurements and direct searches can shed light on situation.
- Higgs measurements sensitive to new physics.
  - Test the origin of the fundamental masses of particles.
  - Help us search for new sources or changes in the breaking of gauge invariance.
  - Search for sector decoupled from rest of the Standard Model.
  - Interesting new physics scenarios probed in next run.

Extra Slides

The Problem

- Fermions protected via chiral symmetry:

$$\mathcal{L} = \overline{\psi_L} i \not{D} \psi_L + \overline{\psi_R} i \not{D} \psi_R + m_\psi (\overline{\psi_L} \psi_R + \text{h.c.})$$

$$\psi_L \to e^{iQ_L} \psi_L, \ \psi_R \to e^{iQ_R} \psi_R$$

  - Without fermion mass: $Q_L \neq Q_R$

- Gauge boson masses protected via gauge symmetry.

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} M_A^2 A_\mu A^\mu \qquad A^\nu \to A^\nu - \partial^\nu \alpha(x)$$

- No symmetry protection for Higgs mass:

$$\mathcal{L} = (D^\nu H)^\dagger D_\nu H - \mu^2 H^\dagger H$$

Higgs as Pseudo-Nambu Goldstone Boson.

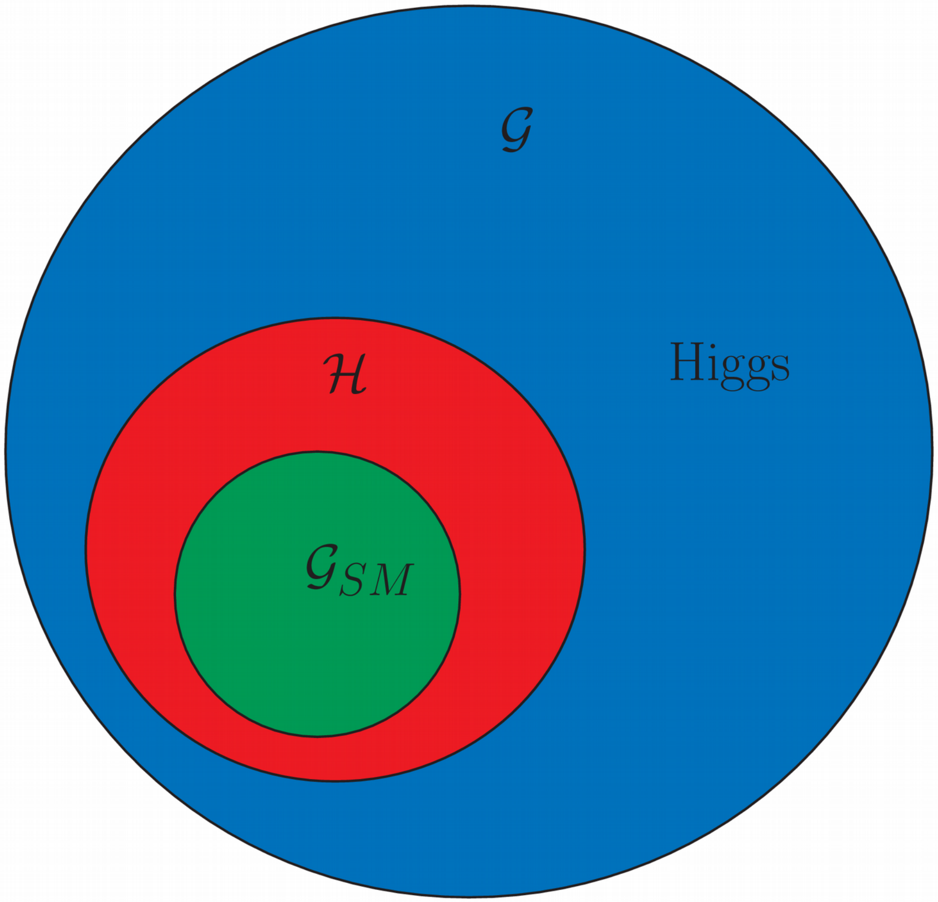
- Symmetry breaking pattern:

$$\mathcal{G} \to \mathcal{H}_1 \supset G_{SM}$$

- Have set of massless Nambu-Goldstone bosons associated with broken generators of

$$\mathcal{G}/\mathcal{H}_1$$

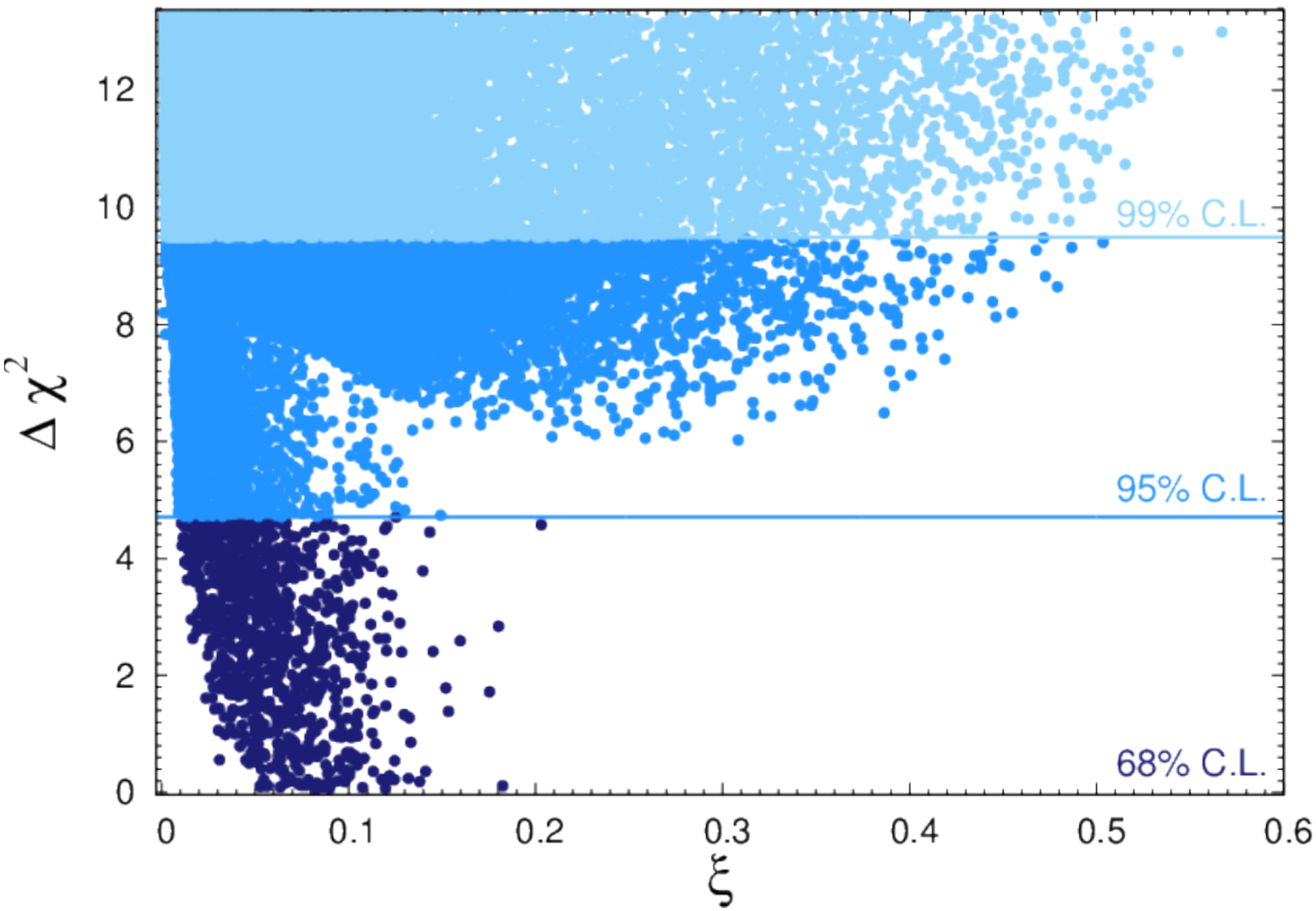
- Gauge SM such that Nambu-Goldstone bosons gain mass at loop level.
  - Higgs is one of these PNG bosons.



Electroweak Precision

- EWPT with |Vtb|>0.92

Gillioz, Grober, Kapuvari, Muhlleitner JHEP 1403 (2014) 037



Composite Models

- Single flavor strongly interacting sector:

$$\mathcal{L} = \overline{\psi_L} i \not{D} \psi_L + \overline{\psi_R} i \not{D} \psi_R$$

- Becomes strongly interacting, have scalar composite states of fermions:

$$\langle \overline{\psi} \psi \rangle \sim \langle \overline{\psi_L} \psi_R \rangle + \langle \overline{\psi_R} \psi_L \rangle$$

- Two flavor QCD more complicated, breaks non-Abelian chiral symmetry:

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

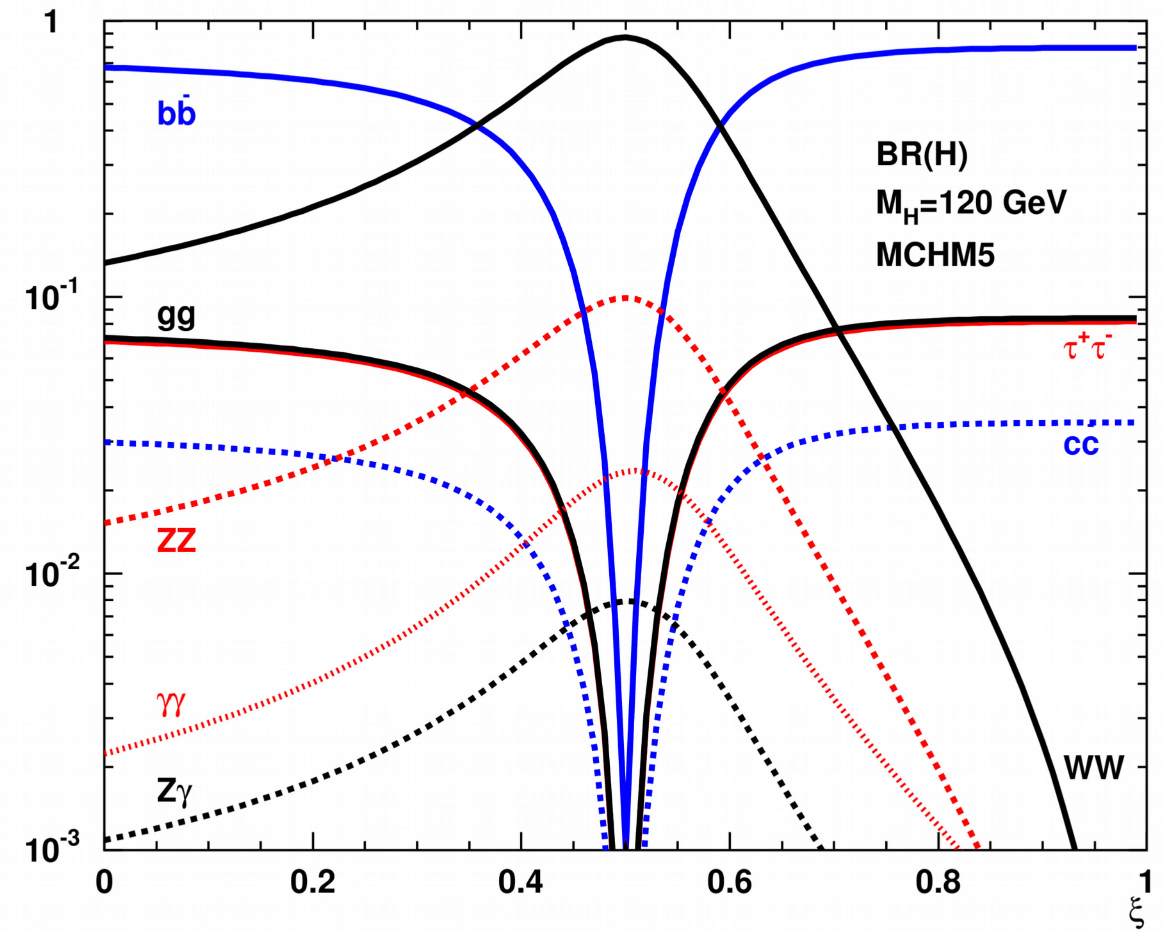
- Breaks electroweak symmetry.

Minimal Composite Models

- Specific models ⇒ specific predictions:
  - MCHM5: $c_W = c_Z = \sqrt{1-\xi}, \quad c_3 = c_\psi = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

    Agashe, Contino, Pomarol, Nucl.Phys. B719 (2005) 165-187
  - MCHM4: $c_W = c_Z = c_3 = c_\psi = \sqrt{1-\xi}$

    Contino, Da Rold, Pomarol, Phys. Rev. D75, 055014 (2007)



Espinosa, Grojean, Muhlleinter, JHEP 1005 (2010) 065

Couplings to Gauge Bosons and Fermions

- Mixing a neutral scalars introduce couplings to all fermions.

$\mathrm{h\,Couplings}$	$\mathrm{Type\,I}$	$\mathrm{Type\,II}$
Gauge Bosons	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
Down Type Fermions	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Up Type Fermions	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$

$\mathrm{H\,Couplings}$	$\mathrm{Type\,I}$	$\mathrm{Type\,II}$
Gauge Bosons	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
Down Type Fermions	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$
Up Type Fermions	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$

Search For Heavy Neutral Higgs

- Alignment limit

Heavy Higgs	Type I	Type II
Gauge Bosons	$-(\beta-\alpha-\pi/2)$	$-(\beta-\alpha-\pi/2)$
Down Type Fermions	$-\cot\beta-(\beta-\alpha-\pi/2)$	$\tan\beta-(\beta-\alpha-\pi/2)$
Up Type Fermions	$-\cot\beta-(\beta-\alpha-\pi/2)$	$-\cot\beta-(\beta-\alpha-\pi/2)$