Higgs Physics at the CEPC-SPPC

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ABSTRACT: In this report, we survey Higgs physics in the SM and beyond, review the current measurements of Higgs physics at the LHC, and present the potential studies of Higgs physics at the CEPC-SPPC.

Higgs Portal into New Physics

- If new physics (NP) manifests itself as SM singlet operators, the 125 GeV Higgs is one of the two fields in the SM which may couple with it via renormalizable couplings [Patt and Wilczek, arXiv:[hep-ph/0605188]]

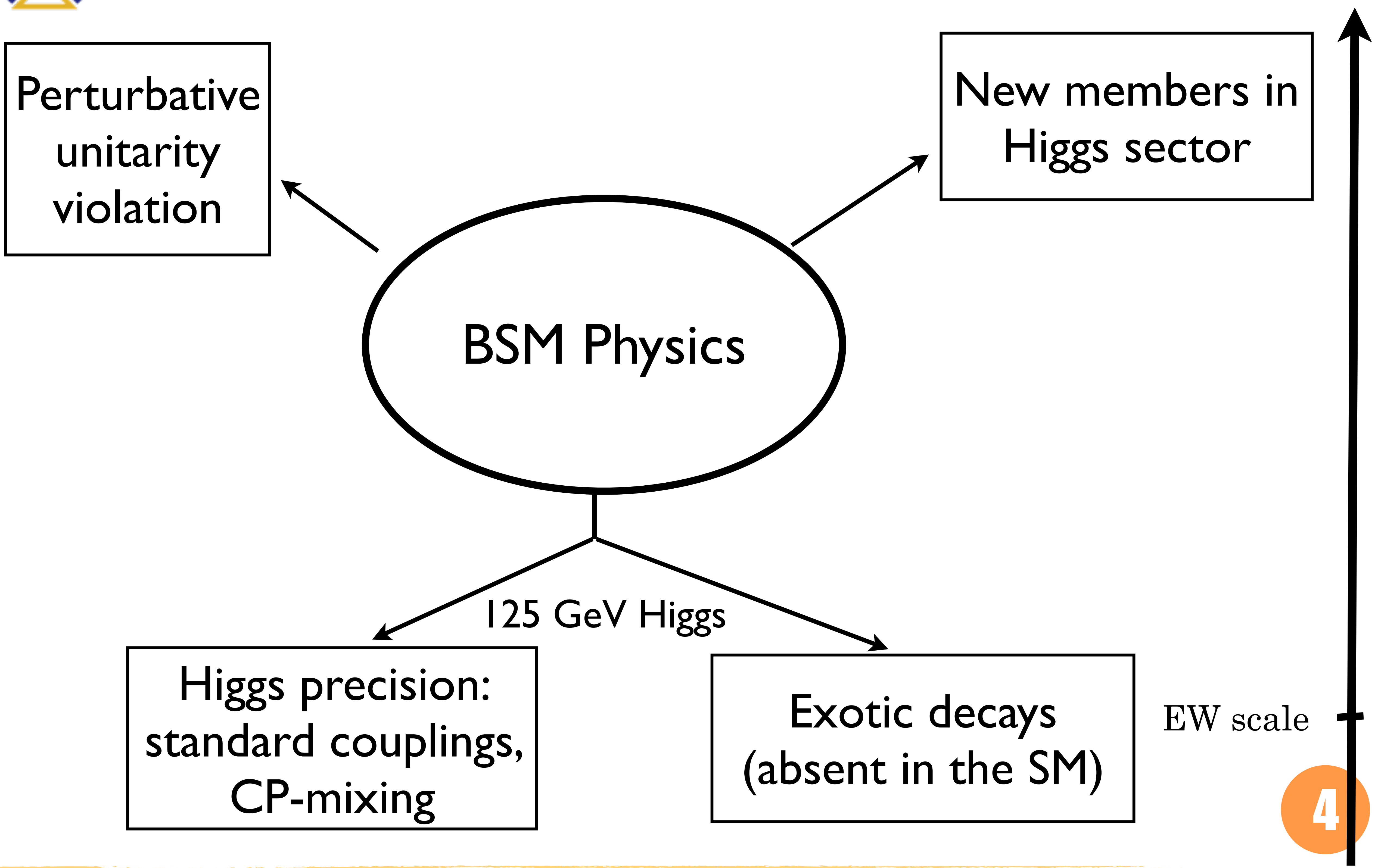
$$\mathcal{L} \supset \lambda H^\dagger H \mathcal{O}_{\rm NP}$$

Lorentz invariant gauge singlet

- If NP serves as a mechanism for stabilizing the 125 GeV Higgs mass (e.g., SUSY), then the Higgs needs to couple with the NP directly

- Both types of couplings can have significant implications for Higgs collider phenomenology.

Implications for Higgs Collider Phenomenology

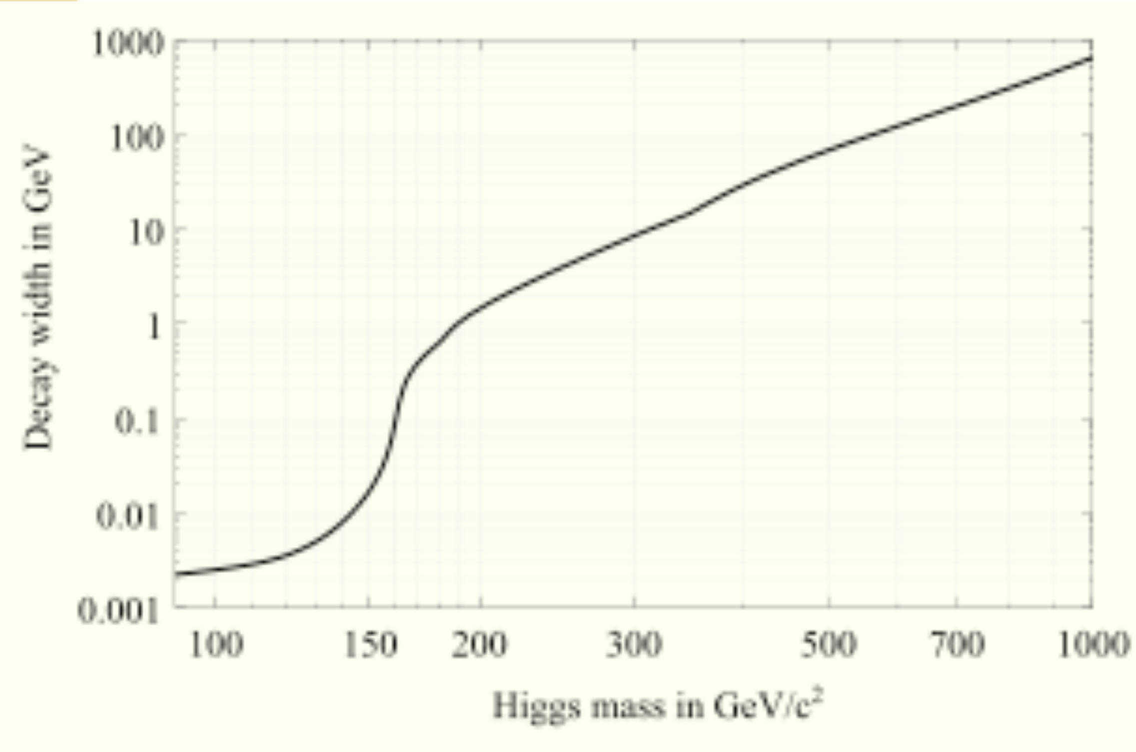


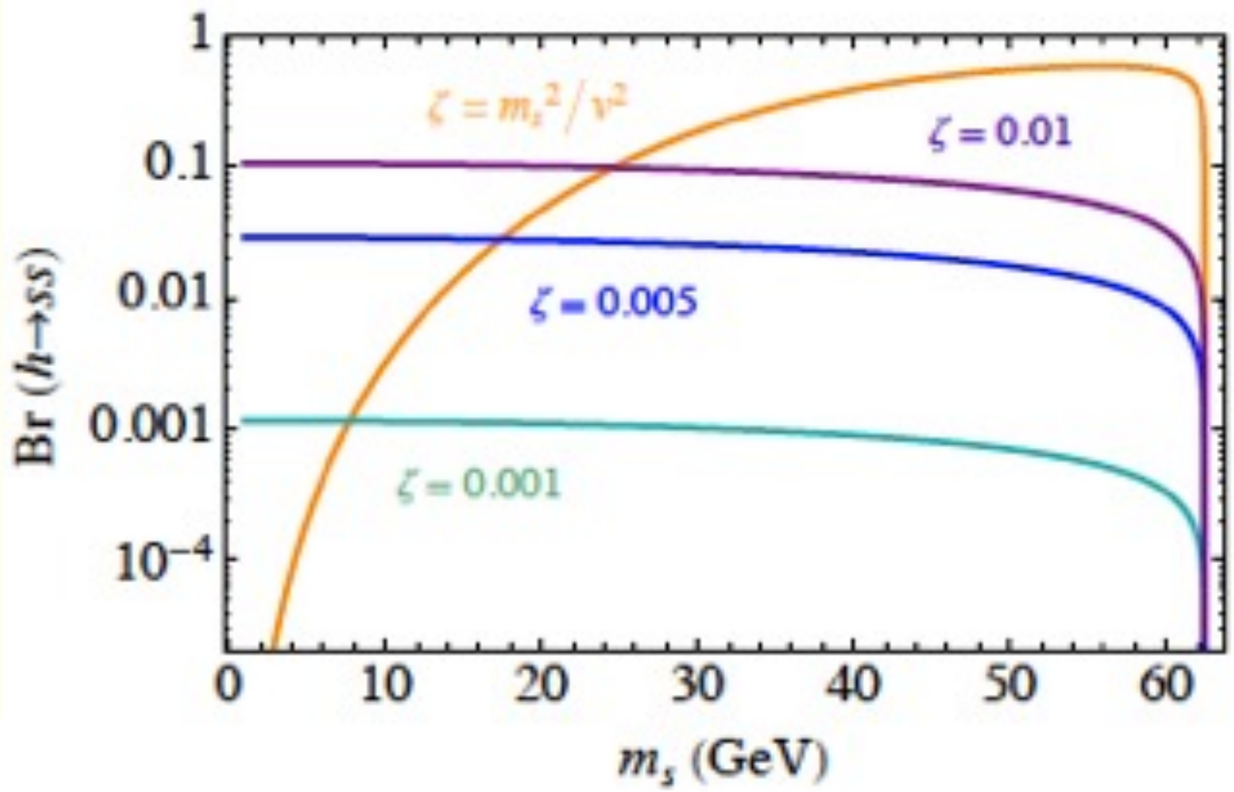
Current Progress on the Report

Current Progress on the Report

Exotic Decays of the 125GeV Higgs Boson

(1) Sensitive to NP





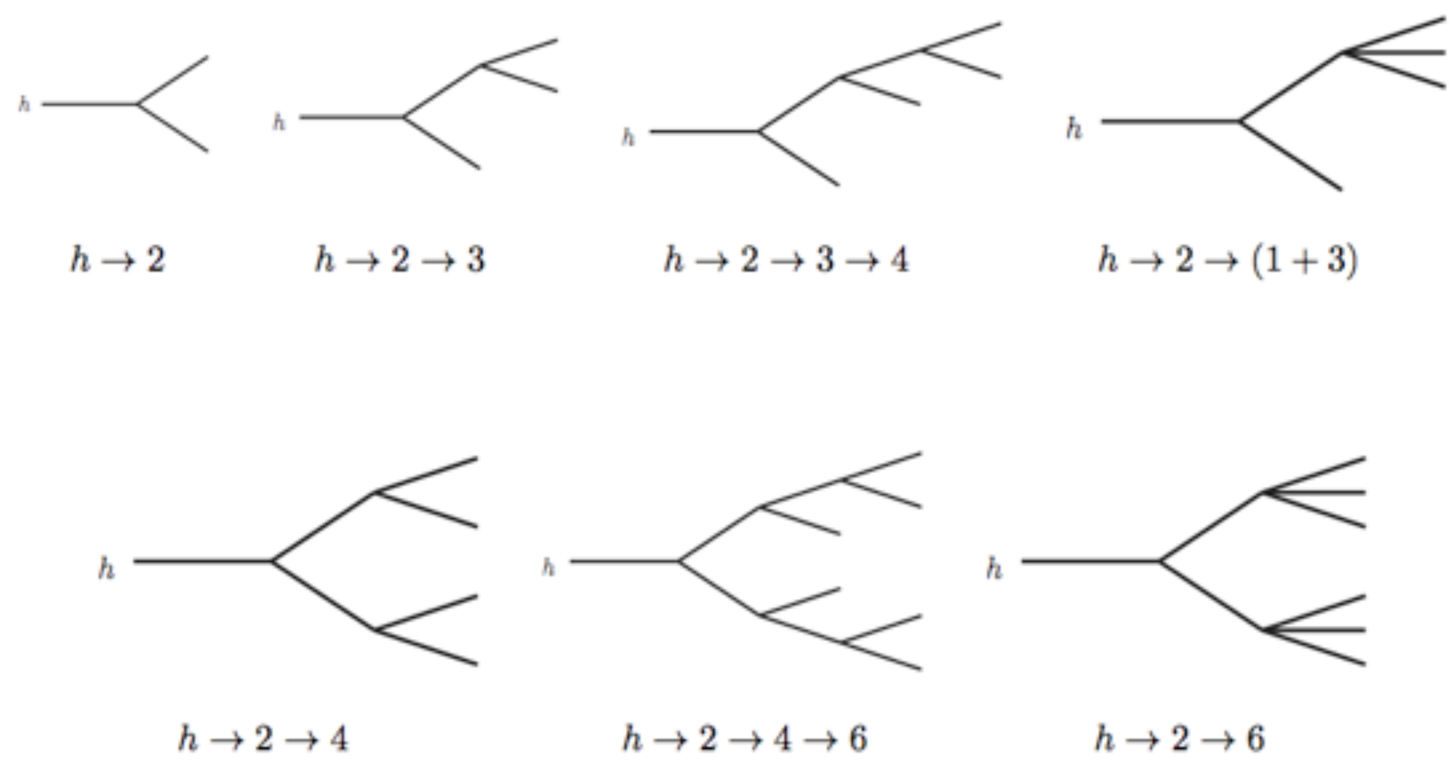
- About three orders smaller than the Z or W widths (~ 4MeV only) !
- A small non-standard Higgs coupling may lead to sizable effect.

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

- So the exotic decays of the 125GeV Higgs are a natural and very efficient way for probing new physics

(2) Many Topologies

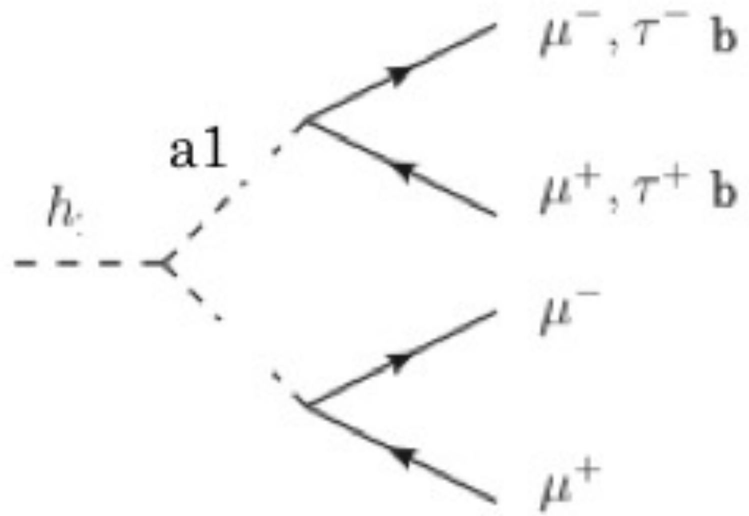
- If the initial exotic decay of the 125 GeV Higgs is 2-body, there are many possibilities
- Collider signature can be classified into three cases: purely invisible, semi-invisible and visible



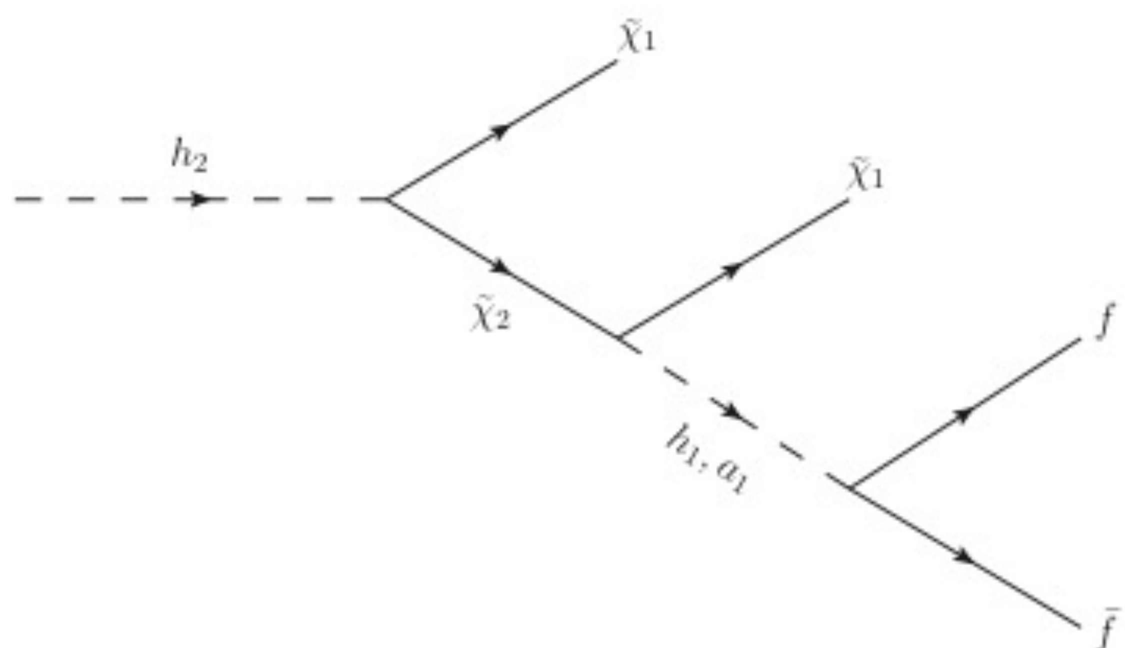
$h \to$ MET	$h \to Z_D Z_D \to 4l$
$h \to 4b$	$h \to \gamma$+MET
$h \to 2b2\tau$	$h \to 2\gamma$+MET
$h \to 2b2\mu$	$h \to 4l$+MET
$h \to 4\tau, 2\tau 2\mu$	$h \to 2l$+MET
$h \to 4j$	$h \to$ one lepton jet
$h \to 2\gamma 2j$	$h \to$ two lepton jets
$h \to 4\gamma$	$h \to bb$+MET
$h \to Z Z_D \to 4l$	$h \to \tau\tau$+MET

(3) Good Motivation in Theory

- SM+S, 2HDM+S
  - gives h -> 2a -> 2f 2f'
  - include R-symmetry limit of the NMSSM
- SM + one or two fermions
  - gives h -> invisible or semi-visible
  - included PQ-limit of the NMSSM
- SM + dark vector boson



[Dobrescu et al., Phys. Rev. D 63 (2001); Dermisek, Gunion, Phys. Rev. Lett. 95 (2005)]



[Draper, TL, Wagner, Wang and Zhang, Phys. Rev. Lett. 106 (2011);

J. Huang, TL, L.T.Wang and F. Yu, arXiv: 1309.6633]

(4) Potentially Large Number of Events

Production	$\sigma_{7\ \text{TeV}}$ (pb)	$N_{\text{ev}}^{10\%}$, 5 fb^{-1}	$\sigma_{8\ \text{TeV}}$ (pb)	$N_{\text{ev}}^{10\%}$, 20 fb^{-1}	$\sigma_{14\ \text{TeV}}$ (pb)	$N_{\text{ev}}^{10\%}$, 300 fb^{-1}
ggF	15.13	7,600	19.27	38,500	49.85	1.5×10^6
VBF	1.22	610	1.58	3,200	4.18	125,000
$hW^\pm$	0.58	290	0.70	1,400	1.5	45,000
$hW^\pm(\ell^\pm\nu)$	$0.58 \cdot 0.21$	62	$0.70 \cdot 0.21$	300	$1.5 \cdot 0.21$	9,600
hZ	0.34	170	0.42	830	0.88	26,500
$hZ(\ell^+\ell^-)$	$0.34 \cdot 0.067$	11	$0.42 \cdot 0.067$	56	$0.88 \cdot 0.067$	1,800
$t\bar{t}h$	0.086	43	0.13	260	0.61	18,300

- Exotic kinematics, dedicated analyses are generally required
- If we don't look for them, we will not find them

The Article

arXiv.org > hep-ph > arXiv:1312.4992

Search or

High Energy Physics – Phenomenology

Exotic Decays of the 125 GeV Higgs Boson

David Curtin, Rouven Essig, Stefania Gori, Perit Jaiswal, Andrey Katz, Tao Liu, Zhen Liu, David McKeen, Jessie Shelton, Matthew Strassler, Ze'ev Surujon, Brock Tweedie, Yi-Ming Zhong

(Submitted on 17 Dec 2013)

We perform an extensive survey of non-standard Higgs decays that are consistent with the 125 GeV Higgs-like resonance. Our aim is to motivate a large set of new experimental analyses on the existing and forthcoming data from the Large Hadron Collider (LHC). The explicit search for exotic Higgs decays presents a largely untapped discovery opportunity for the LHC collaborations, as such decays may be easily missed by other searches. We emphasize that the Higgs is uniquely sensitive to the potential existence of new weakly coupled particles and provide a unified discussion of a large class of both simplified and complete models that give rise to characteristic patterns of exotic Higgs decays. We assess the status of exotic Higgs decays after LHC Run 1. In many cases we are able to set new nontrivial constraints by reinterpreting existing experimental analyses. We point out that improvements are possible with dedicated analyses and perform some preliminary collider studies. We prioritize the analyses according to their theoretical motivation and their experimental feasibility. This document is accompanied by a website that will be continuously updated with further information: this http URL

Comments: 172 pages + references and appendices, 34 figures, 20 tables. Enjoy!
Subjects: **High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex)
Cite as: arXiv:1312.4992 [hep-ph]
(or arXiv:1312.4992v1 [hep-ph] for this version)

It is not a pure review, but contains many new inputs !

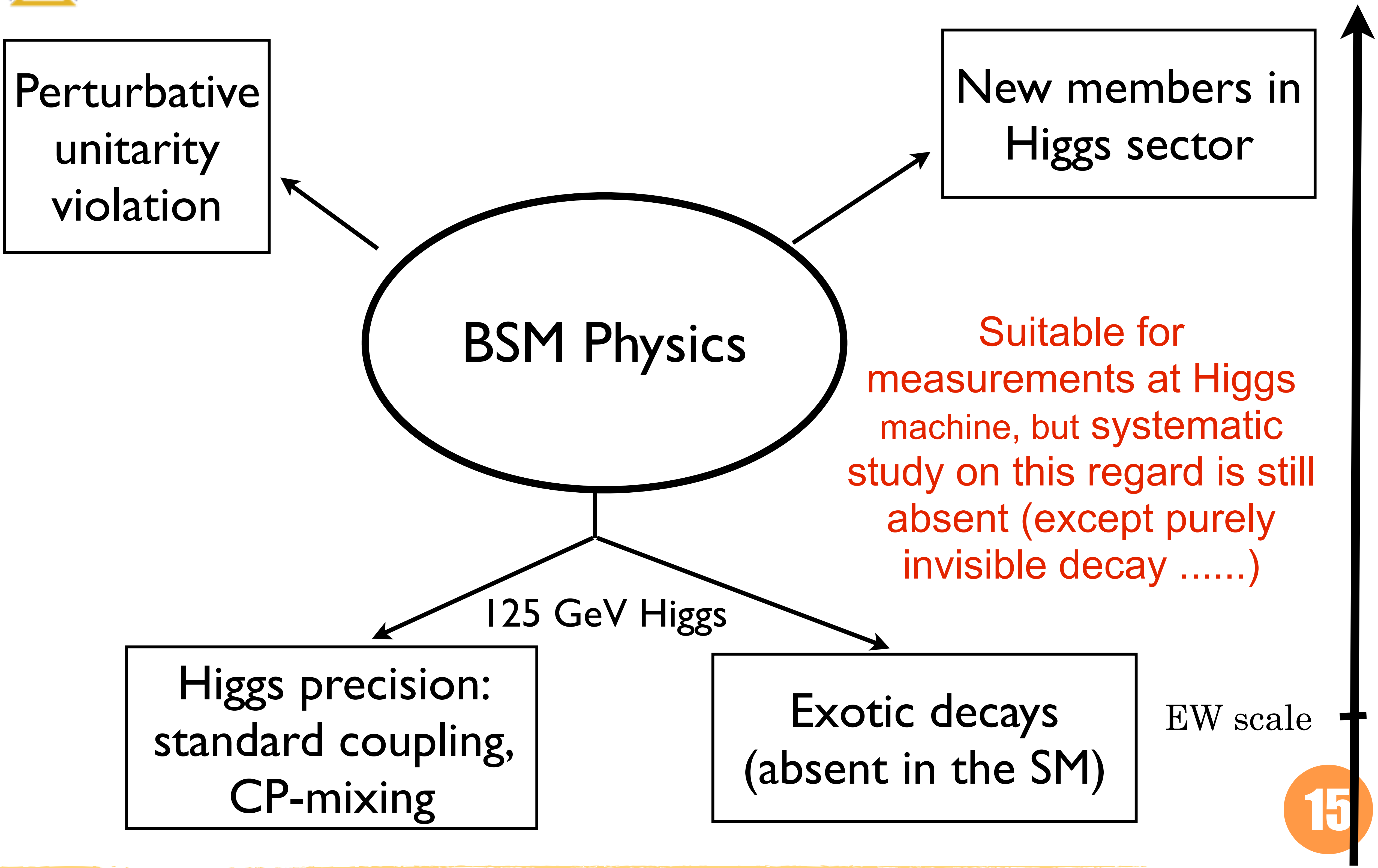
Highly Motivated Searches at LHC7 + LHC8 + LHC14

- Search for $h \to Z_D Z_D \to (\ell^+\ell^-)(\ell^+\ell^-)$ ......
- Search for $h \to Z Z_D \to (\ell^+\ell^-)(\ell^+\ell^-)$ ......
- Search for $h \to \ell^+\ell^- +$ MET ......
- Search for $h \to \ell^+\ell^-\ell^+\ell^- +$ MET ......
- Search for $h \to aa \to (b\bar{b})(\mu^+\mu^-)$ ......
- Search for $h \to aa \to (\tau^+\tau^-)(\mu^+\mu^-)$ ......
- Search for $h \to aa \to (\gamma\gamma)(\gamma\gamma)$ ......
- Search for $h \to \gamma\gamma +$ MET ......

Future Studies

- $h \to 2 \to 6$ e.g. decays of the Higgs to neutralinos that decay via R-parity violation to three jets, etc.
- h to > 4 leptons, τs, bs; decays such as $h \to 6\tau$ or $8b$ have been suggested in the literature.
- h to complex lepton jets (*i.e.* with > 2 tracks), including both purely electronic, purely muonic, purely leptonic with a mix of muons and electrons, and mixed leptonic/hadronic jets.
- Decays to one or more photonic jets (consisting of ≥ 2 collimated photons) need more experimental study.
- h decaying to long-lived particles with decays in flight.
- It is urgent that further studies be done on the more difficult channels, such as $b\bar{b}\tau\tau$, $b\bar{b}+$ MET, $\tau\tau+$ MET, $jj\gamma\gamma$, in the context of VBF production. If such studies reveal VBF can yield significant improvements in sensitivity, then developing triggers for 2015 aimed at these final states may be crucial.
- ... ...

Role of a Higgs Machine



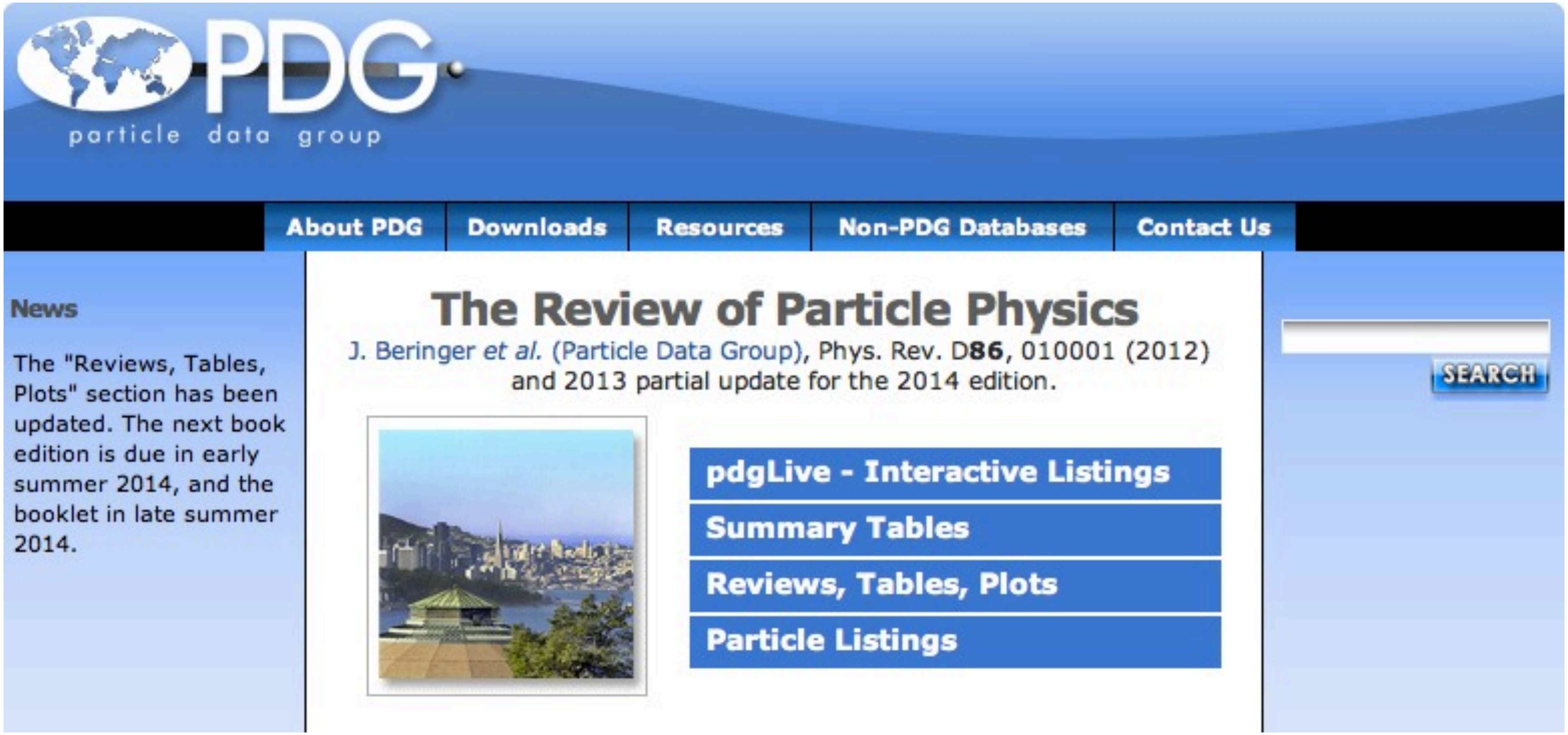
Z Boson Measurements (from PDG)

Z DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
e^+e^-		(3.363 ± 0.004) %		45594
$\mu^+\mu^-$		(3.366 ± 0.007) %		45594
$\tau^+\tau^-$		(3.370 ± 0.008) %		45559
$\ell^+\ell^-$	[b]	(3.3658 ± 0.0023) %		–
invisible		(20.00 ± 0.06) %		–
hadrons		(69.91 ± 0.06) %		–
$(u\overline{u}+c\overline{c})/2$		(11.6 ± 0.6) %		–
$(d\overline{d}+s\overline{s}+b\overline{b})/3$		(15.6 ± 0.4) %		–
$c\overline{c}$		(12.03 ± 0.21) %		–
$b\overline{b}$		(15.12 ± 0.05) %		–
$b\overline{b}b\overline{b}$		$(3.6 \pm 1.3) \times 10^{-4}$		–
ggg		< 1.1 %	CL=95%	–
$\pi^0\gamma$		$< 5.2 \times 10^{-5}$	CL=95%	45594
$\eta\gamma$		$< 5.1 \times 10^{-5}$	CL=95%	45592
$\omega\gamma$		$< 6.5 \times 10^{-4}$	CL=95%	45590
$\eta'(958)\gamma$		$< 4.2 \times 10^{-5}$	CL=95%	45589
$\gamma\gamma$		$< 5.2 \times 10^{-5}$	CL=95%	45594
$\gamma\gamma\gamma$		$< 1.0 \times 10^{-5}$	CL=95%	45594
$\pi^\pm W^\mp$	[h]	$< 7 \times 10^{-5}$	CL=95%	10162
$\rho^\pm W^\mp$	[h]	$< 8.3 \times 10^{-5}$	CL=95%	10136
$J/\psi(1S)X$		$(3.51 {}^{+0.23}_{-0.25}) \times 10^{-3}$	S=1.1	–
$\psi(2S)X$		$(1.60 \pm 0.29) \times 10^{-3}$		–
$\chi_{c1}(1P)X$		$(2.9 \pm 0.7) \times 10^{-3}$		–
$\chi_{c2}(1P)X$		$< 3.2 \times 10^{-3}$	CL=90%	–
$\Upsilon(1S)X + \Upsilon(2S)X + \Upsilon(3S)X$		$(1.0 \pm 0.5) \times 10^{-4}$		–
$\Upsilon(1S)X$		$< 4.4 \times 10^{-5}$	CL=95%	–
$\Upsilon(2S)X$		$< 1.39 \times 10^{-4}$	CL=95%	–
$\Upsilon(3S)X$		$< 9.4 \times 10^{-5}$	CL=95%	–
$(D^0/\overline{D}^0)X$		(20.7 ± 2.0) %		–
$D^\pm X$		(12.2 ± 1.7) %		–
$D^*(2010)^\pm X$	[h]	(11.4 ± 1.3) %		–
$D_{s1}(2536)^\pm X$		$(3.6 \pm 0.8) \times 10^{-3}$		–
$D_{sJ}(2573)^\pm X$		$(5.8 \pm 2.2) \times 10^{-3}$		–
$D^{*\prime}(2629)^\pm X$		searched for		–
B^+X	[i]	(6.08 ± 0.13) %		–
B^0_sX	[i]	(1.59 ± 0.13) %		–
B^+_cX		searched for		–
Λ^+_cX		(1.54 ± 0.33) %		–
Ξ^0_cX		seen		–
Ξ_bX		seen		–
b-baryon X	[i]	(1.38 ± 0.22) %		–
anomalous γ+ hadrons	[j]	$< 3.2 \times 10^{-3}$	CL=95%	–
$e^+e^-\gamma$	[j]	$< 5.2 \times 10^{-4}$	CL=95%	45594
$\mu^+\mu^-\gamma$	[j]	$< 5.6 \times 10^{-4}$	CL=95%	45594
$\tau^+\tau^-\gamma$	[j]	$< 7.3 \times 10^{-4}$	CL=95%	45559
$\ell^+\ell^-\gamma\gamma$	[k]	$< 6.8 \times 10^{-6}$	CL=95%	–
$q\overline{q}\gamma\gamma$	[k]	$< 5.5 \times 10^{-6}$	CL=95%	–
$\nu\overline{\nu}\gamma\gamma$	[k]	$< 3.1 \times 10^{-6}$	CL=95%	45594
$e^\pm\mu^\mp$	LF [h]	$< 1.7 \times 10^{-6}$	CL=95%	45594
$e^\pm\tau^\mp$	LF [h]	$< 9.8 \times 10^{-6}$	CL=95%	45576
$\mu^\pm\tau^\mp$	LF [h]	$< 1.2 \times 10^{-5}$	CL=95%	45576
pe	L,B	$< 1.8 \times 10^{-6}$	CL=95%	45589
$p\mu$	L,B	$< 1.8 \times 10^{-6}$	CL=95%	45589

SM decays

Rare and non-standard decays

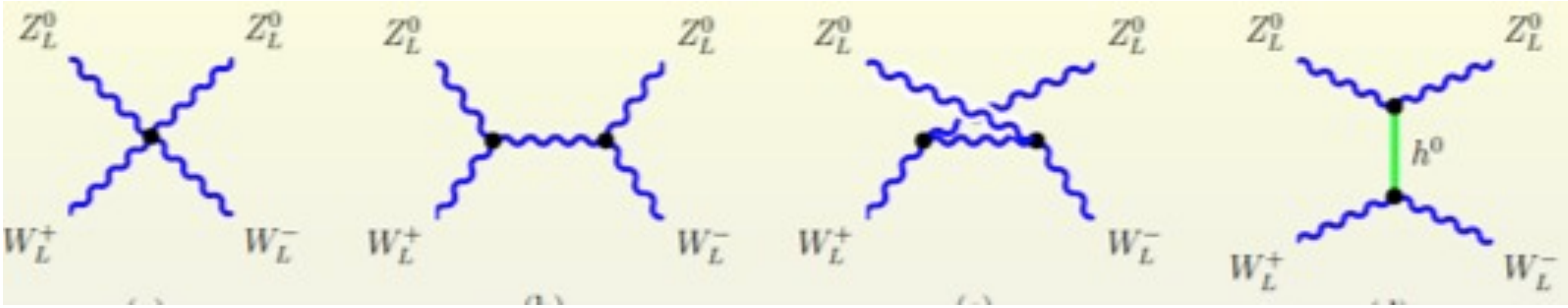
Particle Data Group



Hopefully in the near future similar entries will be created for the 125GeV Higgs boson

Perturbative Unitarity Bound

Unitarity in VLVL Scattering



- In the SM, perturbative unitarity requires that s terms be cancelled exactly
- Such a cancellation is ensured by the SM Higgs boson
- However, Higgs couplings with gauge bosons might be modified due to new physics effects (e.g., in the MSSM). Such a modification can re-introduce unitarity violation

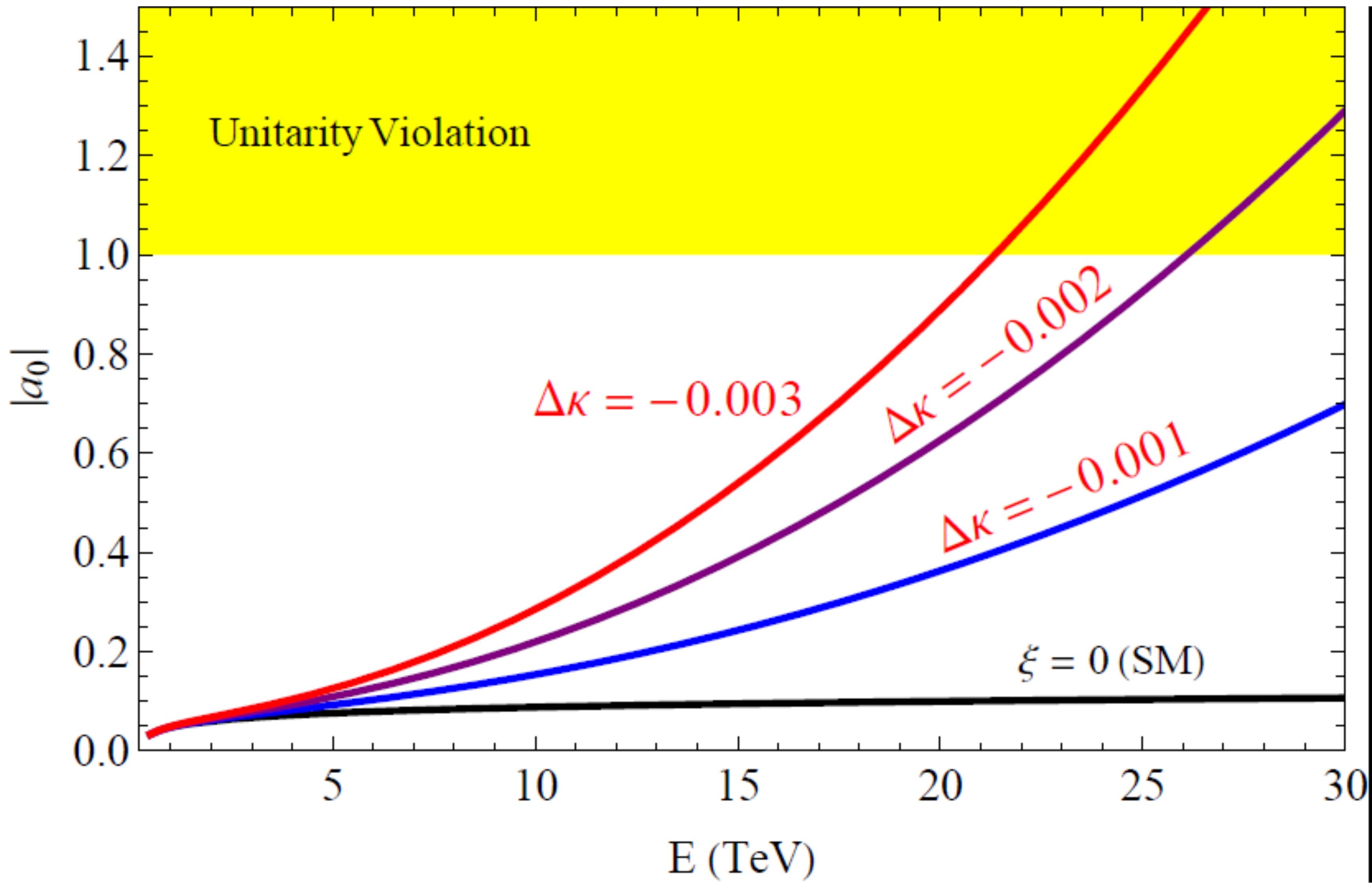
$$\Delta\mathscr{L}_H = \left(\Delta\kappa\, vh + \tfrac{1}{2}\Delta\kappa'\, h^2\right)\left[\frac{2M_W^2}{v^2}W_\mu^+W^{-\mu} + \frac{M_Z^2}{v^2}Z_\mu Z^\mu\right].$$

Effects of TeV-scale New Physics

Recall: TeV scale new physics typically indicates % level deviation

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

EW Symmetry Breaking



Ren & He

- WW have a cm energy ~ 10-30 TeV for 50-100 TeV pp collider, so we may expect a sensitivity to probe a coupling deviation as small as

$$\Delta\kappa \sim \mathcal{O}(10^{-3})$$

EW Symmetry Breaking

He et.al 2003

Number of events at the LHC (300 fb^{-1}) for $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$ $(\ell = e, \mu)$

$\Delta\kappa =$	−0.40	−0.30	−0.24	−0.21	−0.18	0.00	0.18	0.21	0.23	0.30	0.40
$m_H = 115$	34(4.9)	27(3.1)	23(2.1)	21(1.5)	19(1.0)	15	23(2.1)	25(2.6)	27(3.1)	37(5.7)	58(11)
130	34(4.9)	27(3.1)	23(2.1)	21(1.5)	19(1.0)	15	23(2.1)	25(2.6)	27(3.1)	37(5.7)	57(11)
200	35(5.2)	28(3.4)	24(2.3)	23(2.1)	21(1.5)	15	20(1.3)	23(2.1)	25(2.6)	33(4.6)	52(9.6)
300	36(5.0)	30(3.5)	26(2.5)	24(2.0)	23(1.8)	16	19(0.8)	22(1.5)	23(1.8)	29(3.3)	43(6.8)

- As a comparison, at 14 TeV with 300/fb, we can only probe

$$\Delta\kappa \sim \mathcal{O}(10^{-1})$$

Origins of Fermion Mass

- If new physics enters the generation of fermion mass, then Yukawa couplings will be modified

$$Y_f = \frac{\sqrt{2}}{v} M_f (1 + \Delta\kappa_f)$$

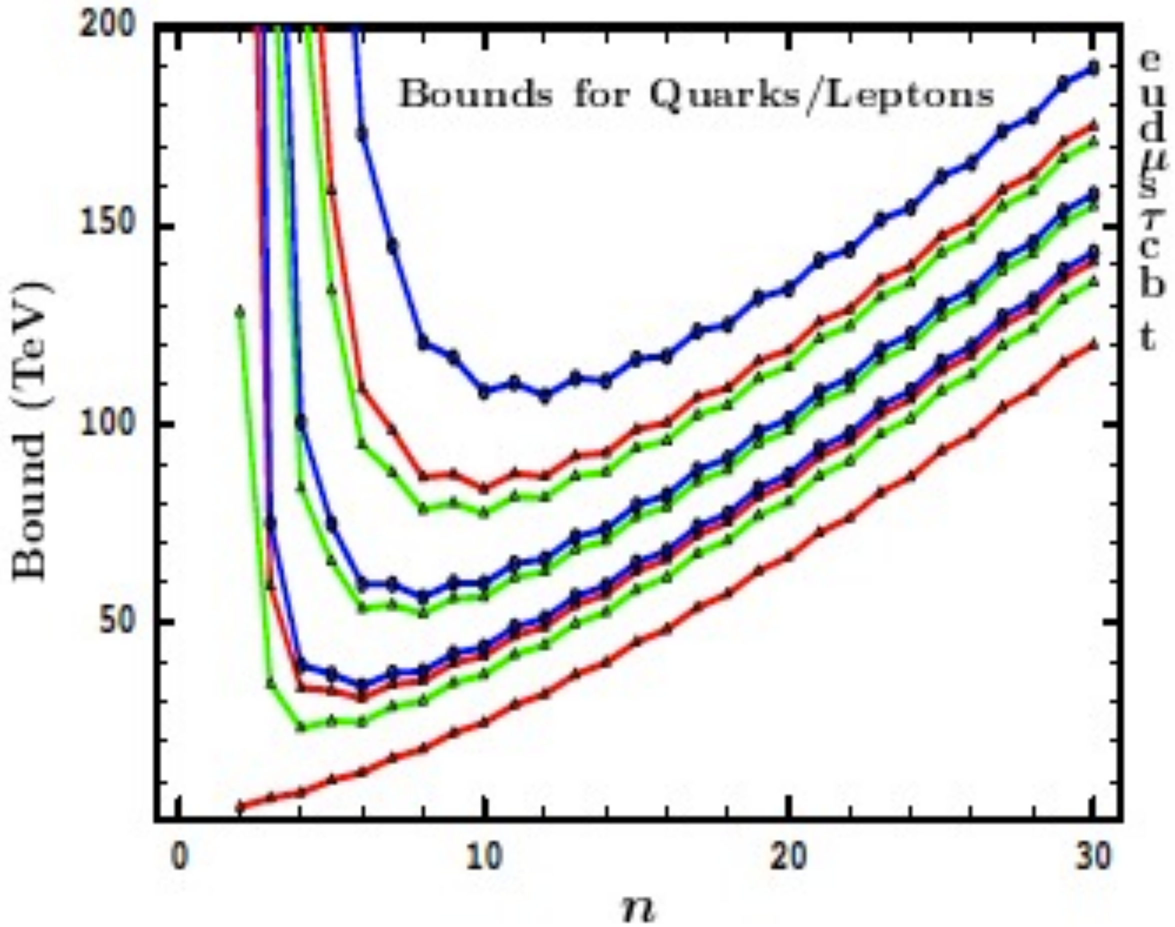
- This is possible, since there is no fundamental principle which requires the Higgs and the SM fermions couple with each other in a standard way.

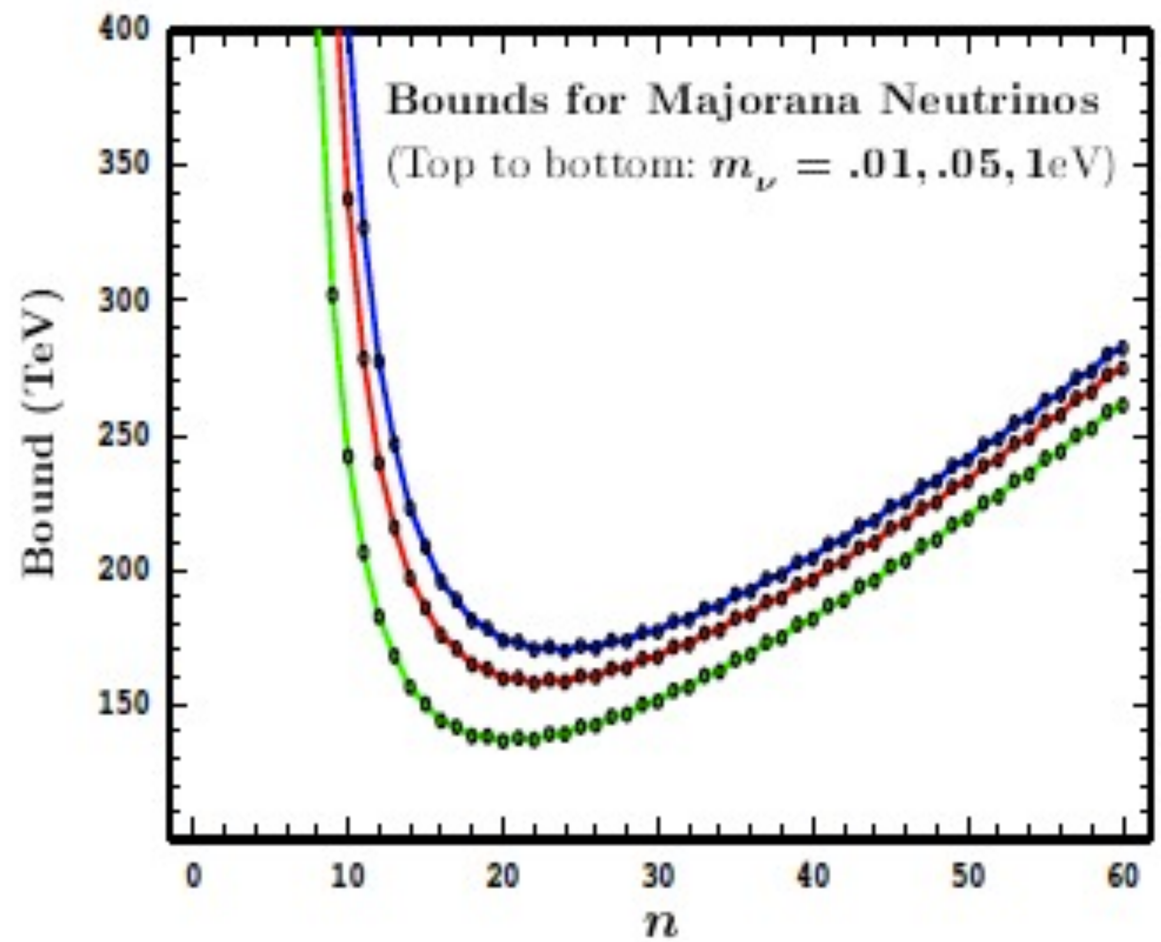
- Unitarity can be violated and be directly probed at high-energy scattering

$$f\bar{f} \to nV_L \qquad (n \geq 2)$$

Dependence of Unitarity Bound on ``n''

Dicus & He, arXiv:hep-ph/0409131





- Perturbative unitarity bound is dependent on the number of longitudinal gauge bosons in final state
- Typically the strongest unitarity bounds are not from the case with ``n=2''

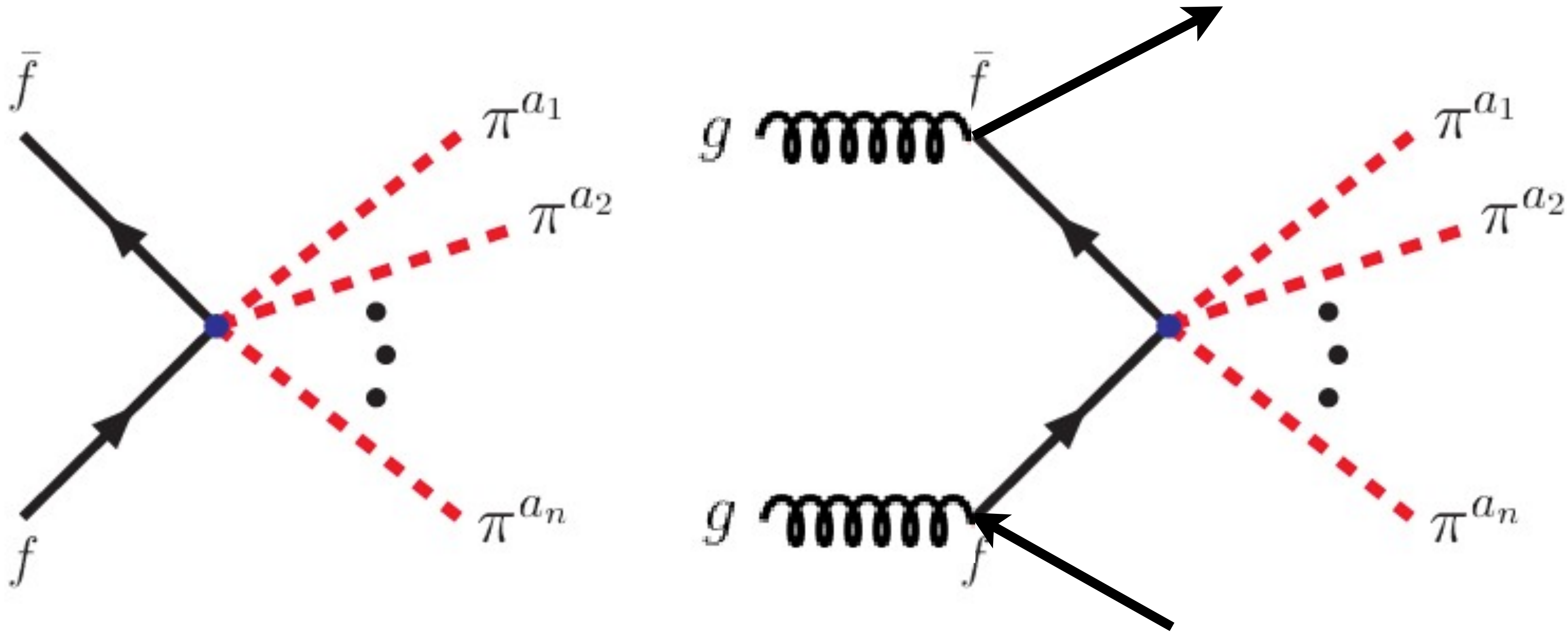
Origins of Fermion Mass

Dicus & He, arXiv:hep-ph/0409131

$\xi_1\xi_2$	V_LV_L	$t\bar{t}$	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$d\bar{d}$	$u\bar{u}$	$\tau^-\tau^+$	$\mu^-\mu^+$	e^-e^+	$\nu_L\nu_L$
Mass (GeV)	80.4	178	4.85	1.65	0.105	0.006	0.003	1.777	0.106	5.11×10^{-4}	5×10^{-11}
n_s	2	2	4	6	8	10	10	6	8	12	22
$E^{\star(\min)}_{2\to n}$ (TeV)	1.2	3.49	23.4	30.8	52.1	77.4	83.6	33.9	56.3	107	158
$E^\star_{2\to 2}$ (TeV)	1.2	3.49	128	377	6×10^3	10^5	2×10^5	606	10^4	2×10^6	1.1×10^{13}

- 2-> n scattering put upper bounds on scales of mass generations of the last two generation of quarks and leptons within 3.5-56 TeV and the third one within 77-107 TeV
- Given this fact, high-energy collider like the SPPC may play an important and even crucial role in probing the mass origin of the SM fermions.

Relevant Processes at High-energy Machine



- This can be tested via the topologies illustrated above
- The collider analysis is progress

Short Comments on Other Topics

Measurements of Standard Higgs Couplings

Snowmass-Higgs-Rept, arXiv:1310.8361

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%
κ_μ	91%	91%	16%	10%	6.4%	6.2%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42[illegible]
κ_t	–	14%	3.2%	2.0%	–	13%
BR_{inv}	0.9%	$<$ 0.9%	$<$ 0.9%	0.4%	0.19%	$<$ 0.19%

CP Properties of the 125 GeV Higgs Boson

- The measurements of CP-properties at the LHC have been suggested in a couple of channels: ZZ, di-photon, di-tau, tt, ...
- Typically challenging at the LHC. But at the e+e- collider, the story is relatively simple. For example,

Measuring CP Violation in $h \to \tau^+\tau^-$ at Colliders

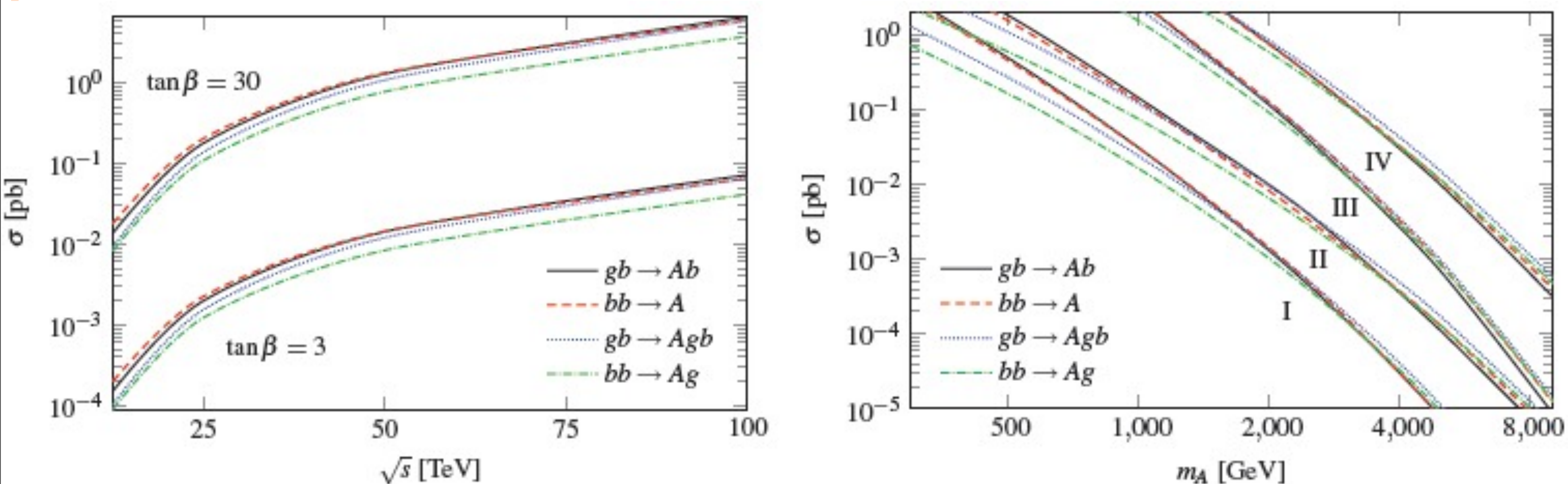
Roni Harnik,[1] Adam Martin,[2,3] Takemichi Okui,[4] Reinard Primulando,[5] and Felix Yu[1]

We investigate the LHC and Higgs Factory prospects for measuring the CP phase in the Higgs-τ-τ coupling. Currently this phase can be anywhere between 0° (CP even) and 90° (CP odd). A new, ideal observable is identified from an analytic calculation for the $\tau^\pm \to \rho^\pm \nu \to \pi^\pm \pi^0 \nu$ channel. It is demonstrated to have promising sensitivity at the LHC and superior sensitivity at the ILC compared to previous proposals. Our observable requires the reconstruction of the internal substructure of decaying taus but does not rely on measuring the impact parameter of tau decays. It is the first proposal for such a measurement at the LHC. For the 14 TeV LHC, we estimate that about 1 ab^{-1} data can discriminate CP-even versus CP-odd at the 5σ level. With 3 ab^{-1}, the CP phase should be measurable to an accuracy of $\sim 11°$. At an e^+e^- Higgs Factory, we project that a 250 GeV run with 1 ab^{-1} luminosity can measure the phase to $\sim 4.4°$ accuracy.

- Can the e+e- collider help probe CP-violating couplings in some difficult cases, e.g., hbb ?

Nonstandard Higgs Search

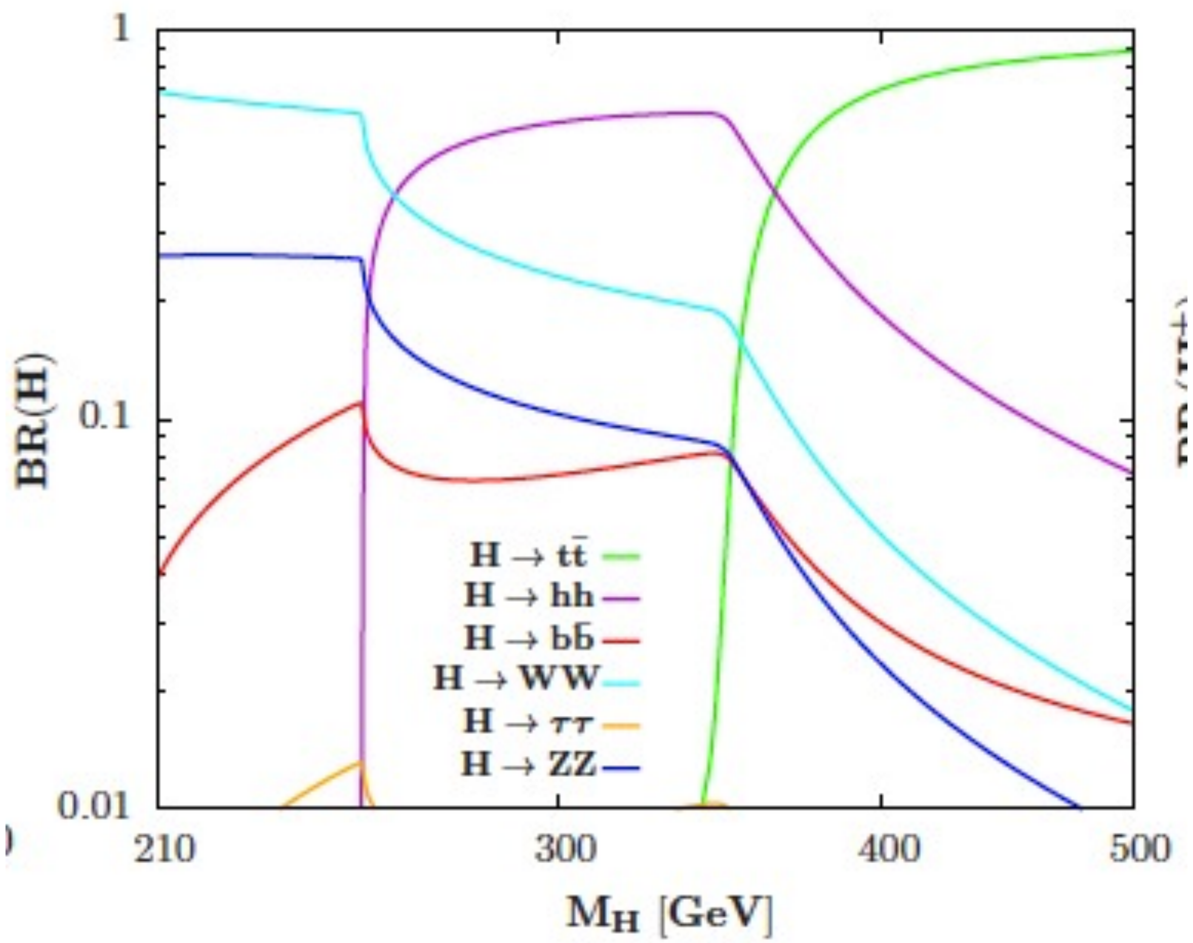
- Can be electrically neutral, singly charged, doubly charged. The SPPC can play a role in performing searches over larger possible mass range!
- Using the MSSM as an example, the production cross section of the CP-odd Higgs boson is enhanced by roughly two orders at the SPPC, compared with the LHC.

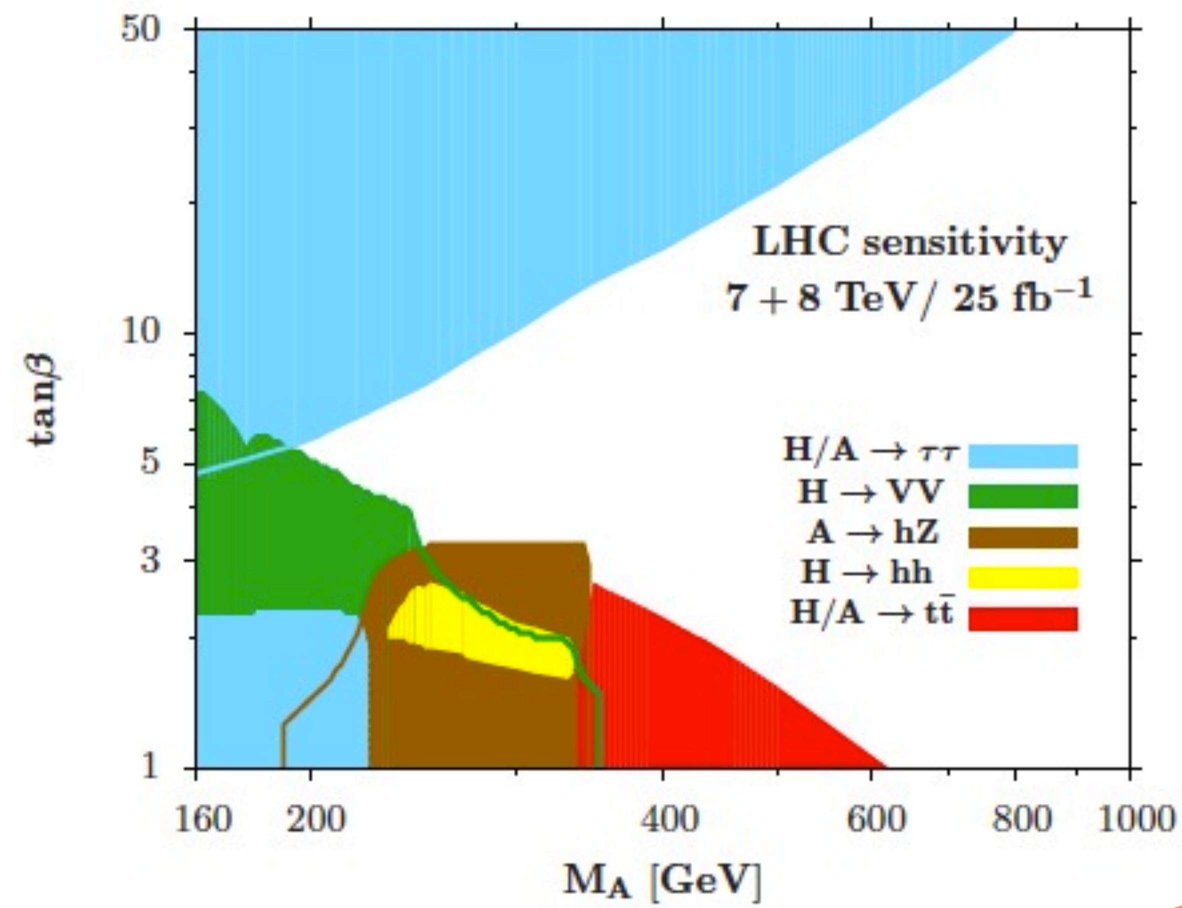


Hajar, Liu

Nonstandard Higgs Search

- tt channel may play a crucial role in searching for such a heavy non-standard Higgs boson as well as probing its CP-properties





A. Djouadi, 2013

Questions to Address

- CP properties of the 125 GeV Higgs: systematic asses potential for their measuring at the ILC
- Exotic decay of 125 GeV Higgs: systematic assess potential for discovery at the ILC
- Higgs unitarity: assess potential for probing it at the SPPC
- Nonstandard Higgs boson: new search strategies, CP-violation