Theory issues

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Energy frontier issues - LBNL - Jan 9th 2013

The LHC program

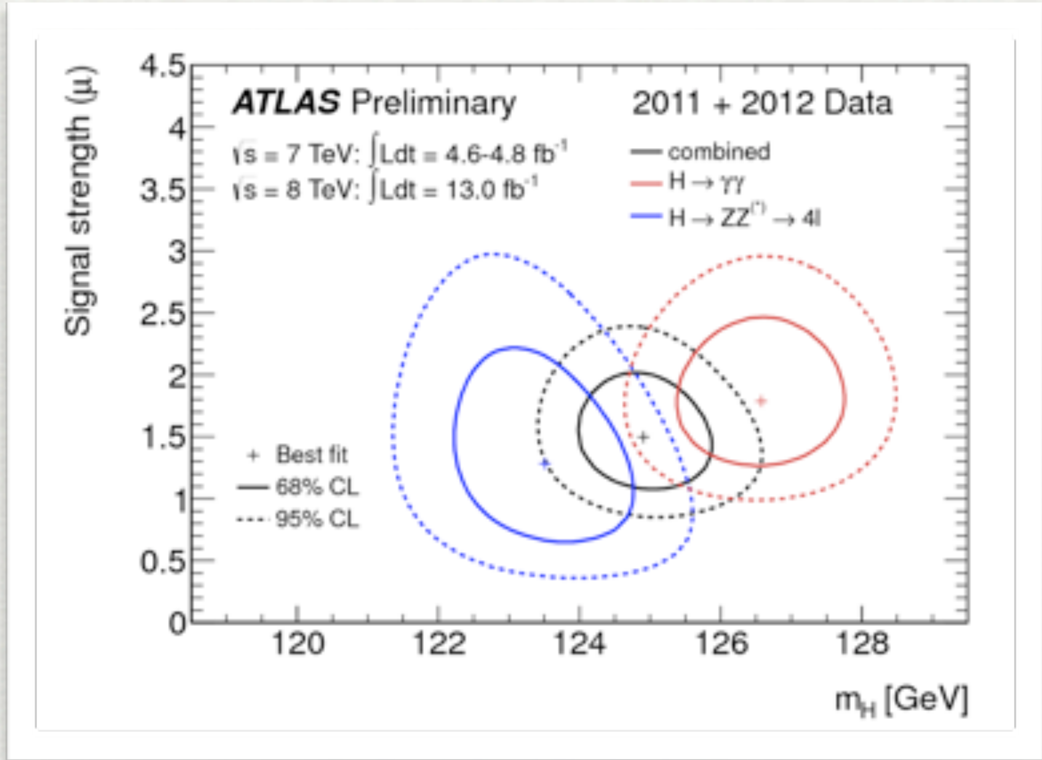
- The primary goal of the LHC is to probe the mechanism of Electroweak Symmetry Breaking
  - existence of Higgs boson(s)? their properties?
  - is the Electroweak scale stabilized by a natural mechanism?
- Other LHC goals
  - Top physics (LHC is a top factory)
  - Physics beyond the Standard Model at the TeV scale
  - weak-scale WIMP dark matter
  - new hidden sectors (valleys)
  - ...

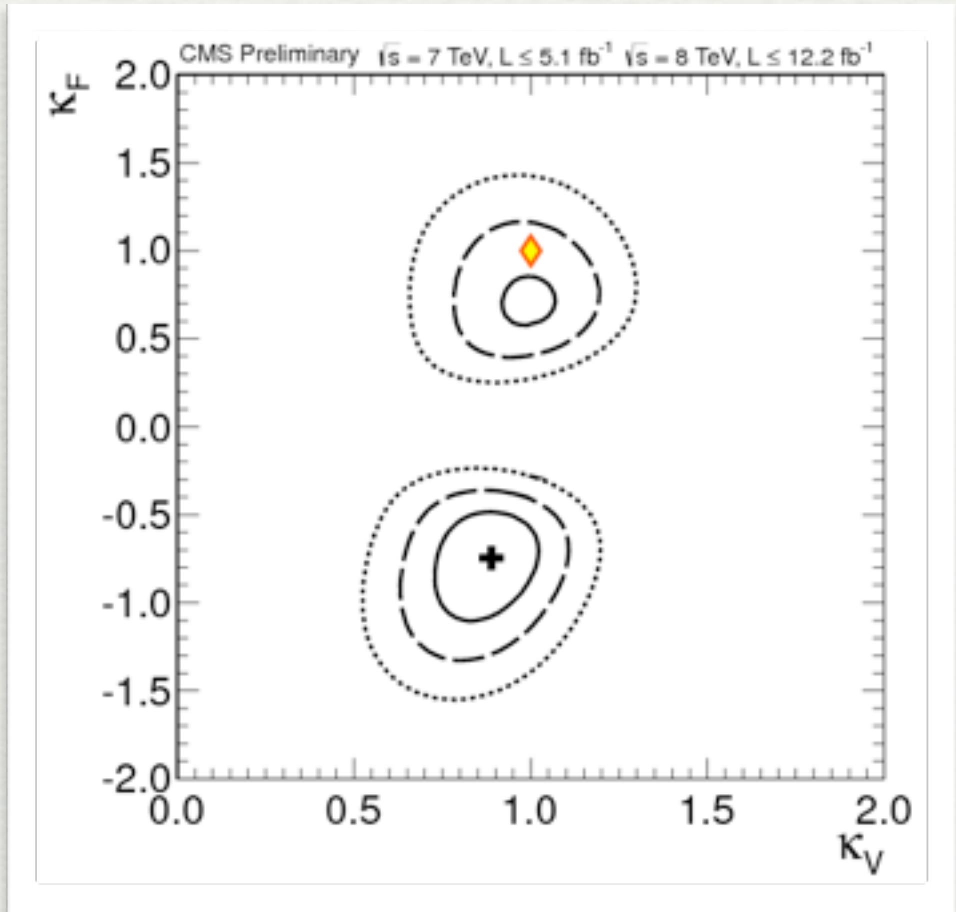
EF issues

- What is left out after 300fb^{-1} @ 14TeV?
  - What can 3000fb^{-1} can add?
  - What can an e^+e^- machine can add? Which energy?
  - (LHC energy upgrade?)

EWSB after 300 fb^{-1}

- Higgs-like boson has been found





- By 300fb^{-1} we may or may not have found other signs of new physics:
  - If new physics is found there will be an extensive (obvious) program for studying it
  - in the following: scenario where no clear signal of BSM physics is present before the end of the 300 fb^{-1} run (besides the Higgs)

EWSB after 300 fb^{-1}

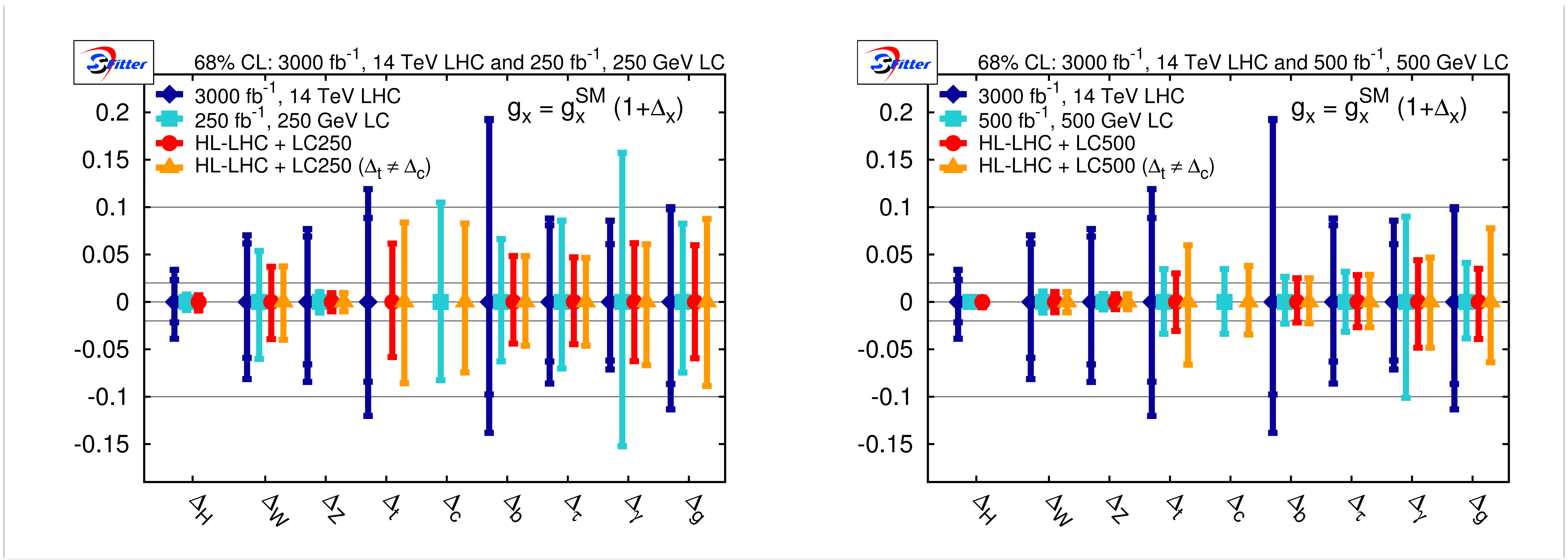
What are the important measurements in the EW sector?

- Higgs σ's & BR's
- W,Z self-couplings
- H self-couplings
- high energy behavior of Vector Boson Fusion
- ...

(Many measurements interesting regardless of the presence of the Higgs...)

Studying the Higgs

- We know the projections for Higgs couplings measurements:



Studying the Higgs

- We know the projections for Higgs couplings measurements:

More recent assessments

CMS submission to Strategy Group,
https://indico.cern.ch/contributionDisplay.py?contribId=177&confId=175067

Coupling	Uncertainty (%)			
	$300\ fb^{-1}$		$3000\ fb^{-1}$	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Plus Hμμ coupling to better than 5% at $3000fb^{-1}$

Scenario 1: same systematics as 2012 (TH and EXP)
Scenario 2: half the TH syst, and scale with 1/sqrt(L) the EXP syst

Note: assume no invisible Higgs decay contributing to the Higgs width

Note: results of scenario 1 @ 300/fb are ~ consistent with Peskin's estimates

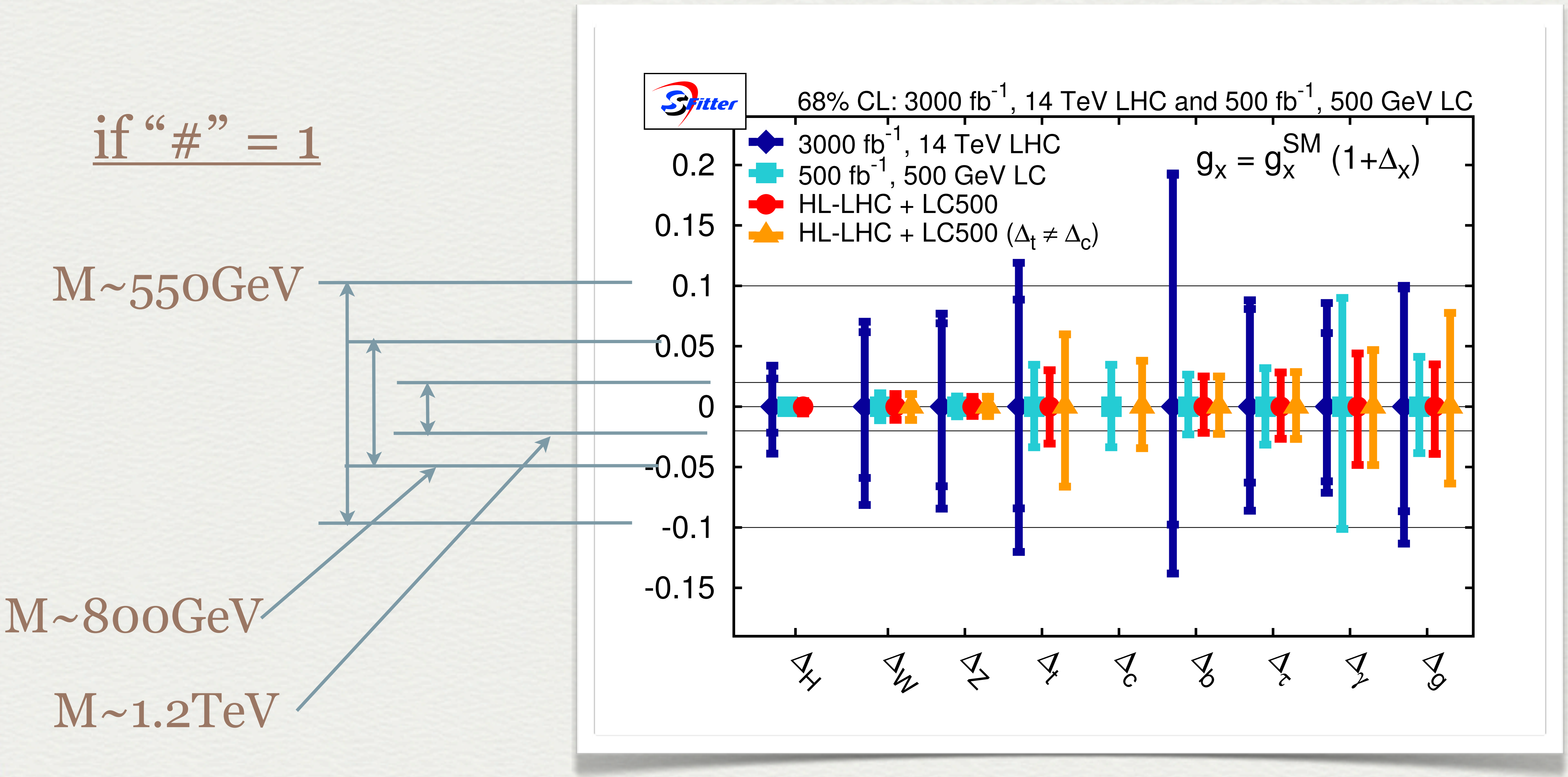
Note: results of scenario 2 @ 3000/fb are almost as powerful as ILC@500GeV !!

M. Mangano, GGI Nov. 2012

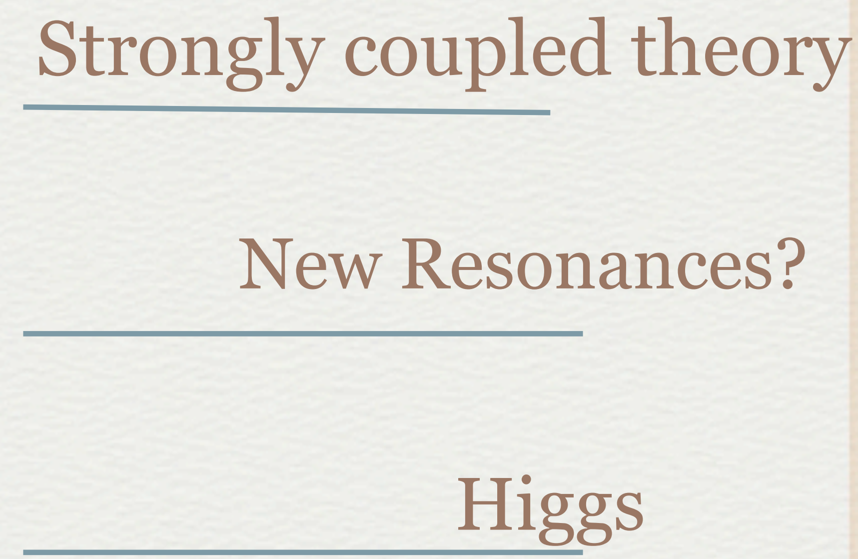
Studying the Higgs

- What does that mean?

New Physics affects Higgs properties → $g/g_{SM}-1 \sim \# * v^2/M^2$



New Physics & Higgs properties



- Higgs is partially composite:
  - # is O(1)-O(10) (recall, $g_{\rho\pi\pi}\sim 6$ in QCD...)
  - new physics affecting Higgs may be quite heavy for LHC14 (and Higgs fine-tuned)
- Extended Higgs sector (2HDM, 2HDM+1singlet, ...)
  - # is due to mixing between Higgs states
  - the more g_W, g_Z are SM-like the more new additional Higgses are not SM-like (→ suppression in LHC production)
  - $H \to hh$ decays possible

New Physics & Higgs properties

- New particles coupling perturbatively and affecting Higgs properties at loop level:
  - $\# \sim 1/16\pi^2$ for W,Z,t,b,..
  - $\# \sim 1$ for g,γ
  - M ~ few hundreds GeV → direct searches @ LHC14?
- Other Higgs decay channels ("exotic" Higgs decays)

New Physics & Higgs properties

- New physics affecting Higgs properties that does not show up directly at LHC14 w/ 300fb^{-1}:
    - may be too heavy (e.g. composite Higgs models with heavy resonances having largish couplings) → HE-LHC
    - may be light but weakly coupled (extra Higgses, new weakly coupled particles, ...) → e^+e^- machines vs. HL-LHC (HE-LHC) depends on their mass
    - may be difficult to find (e.g. invisible Higgs width) → e^+e^- machines

Studying the EW Sym' Breaking

- We need to understand whether it's a (partially) composite scalar ("pion") or not

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \left(\frac{1}{2} m_h^2 h^2 + d_3 \left(\frac{m_h^2}{2v}\right) h^3 + d_4 \left(\frac{m_h^2}{8v^2}\right) h^4 + \cdots \right)$$

$$- \left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right)\left(1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \cdots \right)$$

$$- \frac{v}{\sqrt{2}} \left(\bar{u}_L^i \bar{d}_L^i \right) \Sigma \left[1 + c\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \cdots \right] \begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + \text{h.c.}$$

$$\frac{g_s^2}{48\pi^2} G^{\mu\nu\,a} G^a_{\mu\nu} \left(k_g \frac{h}{v} + \frac{1}{2} k_{2g} \frac{h^2}{v^2} + \ldots \right) + \frac{e^2}{32\pi^2} F_{\mu\nu} F^{\mu\nu} \left(k_\gamma \frac{h}{v} + \ldots \right)$$

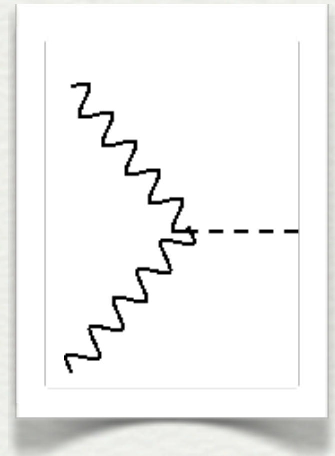
$$+ \frac{g^2}{32\pi^2} \left(k_{WW} W^+_{\mu\nu} W^{-\mu\nu} + k_{ZZ} Z_{\mu\nu} Z^{\mu\nu} + k_{Z\gamma} Z_{\mu\nu} F^{\mu\nu} \right) \frac{h}{v} + \ldots$$

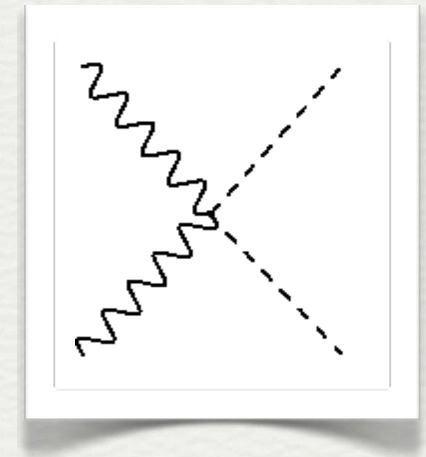
+ $O(p^6)$ terms...

Contino et al. 1002.1011

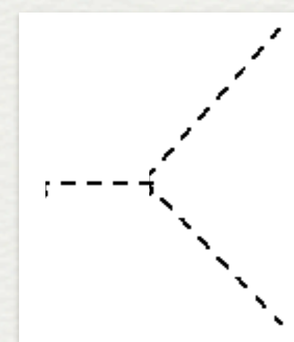
Studying the EW Sym' Breaking

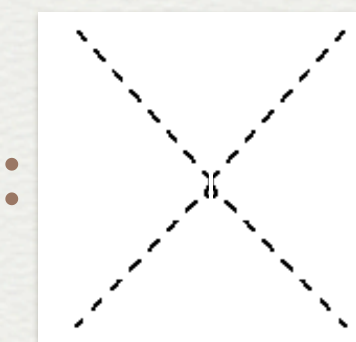
Even at lowest order 2 couplings of Higgs with vector bosons

a: 

b: 

Higgs self-couplings also present

d_3: 

d_4: 

In SM $a=b=d_3=d_4=1$

- If $a\neq1$, $b\neq1$ scattering amplitudes involving W_L,Z_L,h grow with energy (Higgs alone not sufficient to unitarize scattering) → need to map the $s^{1/2}$ behavior

Which Higgs couplings?

often said that measurement of h^3 is a crucial to establish the Higgs mechanism

... beautiful dedicated studies HH→bbWW, bb$\gamma\gamma$

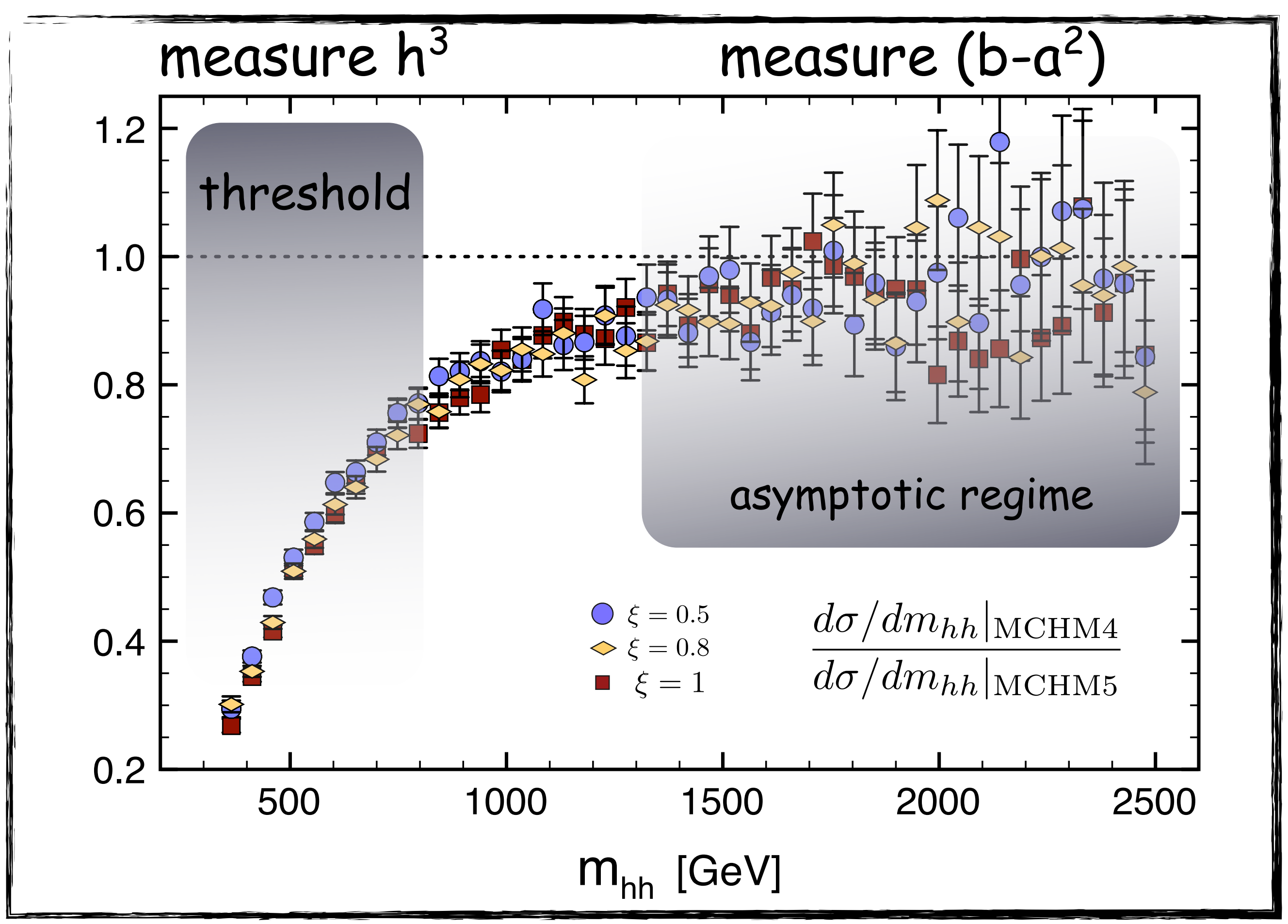
30% sensitivity @ HL-LHC, 20% @ ILC, 20% @CLIC

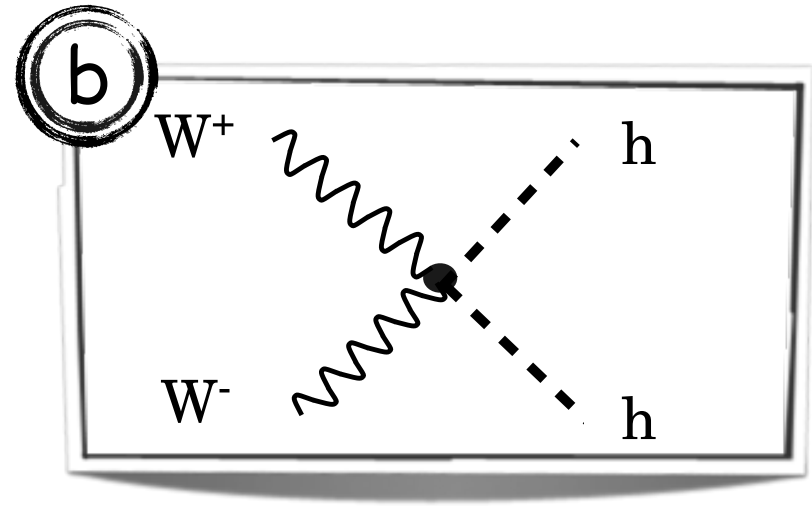
(possible improvement but using additional jet radiation)

Dolan, Englert, Spannowsky '12

however h^3 affects threshold physics only and doesn't modify asymptotic behavior

hh invariant mass distribution





non-standard "b" coupling could also modify the sensitivity on h^3

two models with same asymptotic regime but different higgs-self-coupling

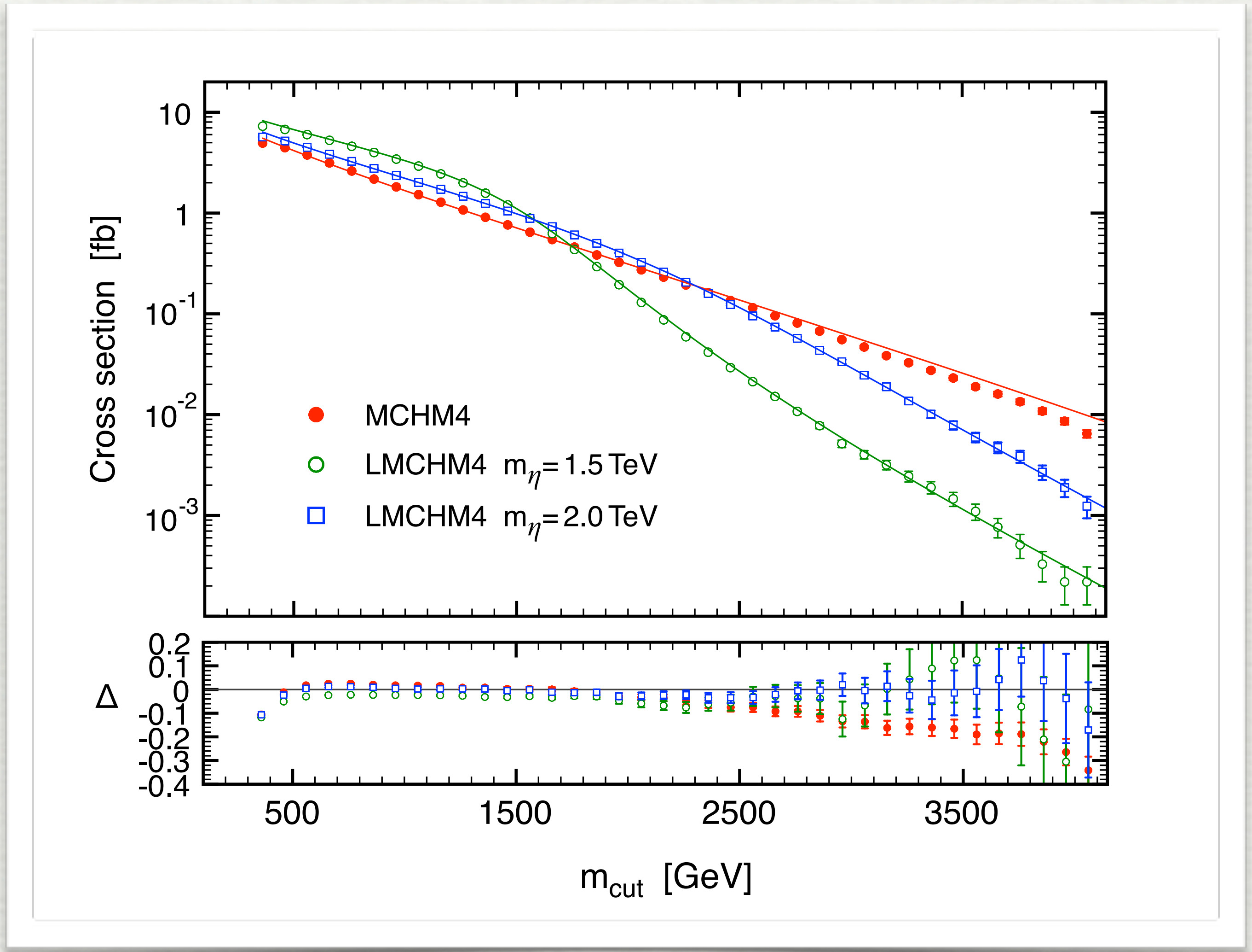
Looking for VBF

- "Unitarization" models in MC introduce model dep' (ok for sensitivity studies but in the end we will need $d\sigma/dm_{VV}$ ...)
- Challenges for forward jet tagging and jet veto in high luminosity environment due to pile-up
- Challenges for theoretical calculations → the central jet veto introduces logs more difficult to deal with (various ongoing efforts)
- Focusing on the high energy regime, W's, Z's and h's tend to be boosted → benefit by recent progress in boosted objects reconstruction (performance w/ high pile-up?)
- publicly available collider studies after Higgs discovery?

Studying the EW Sym' Breaking

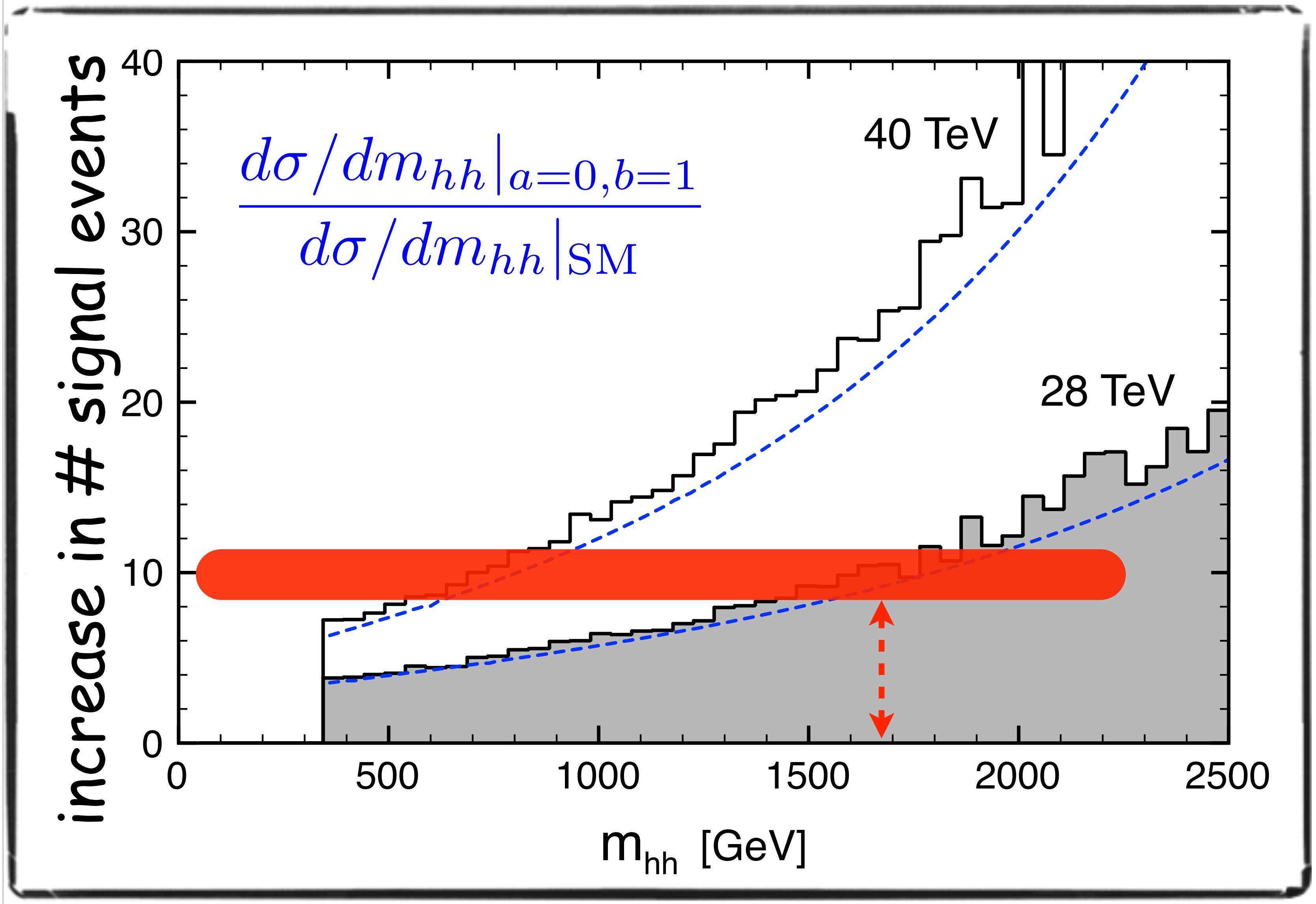
- Cross sections for VBF diboson larger than di-Higgs: start to be accessible before 300 fb^{-1}

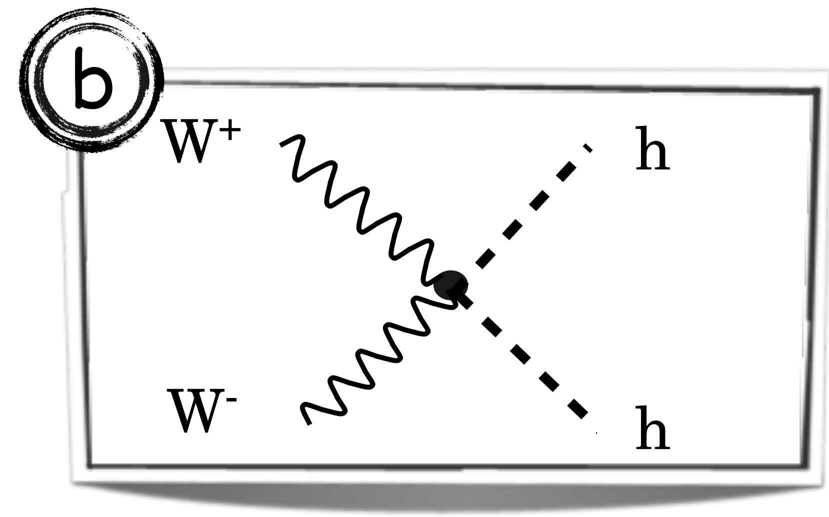
- Di-Higgs is 3000 fb^{-1} realm:



Which Higgs couplings?

'b' is a high energy quantity:
question to address is very different than measurement of h^3.
Need LHC results to know which question to ask!





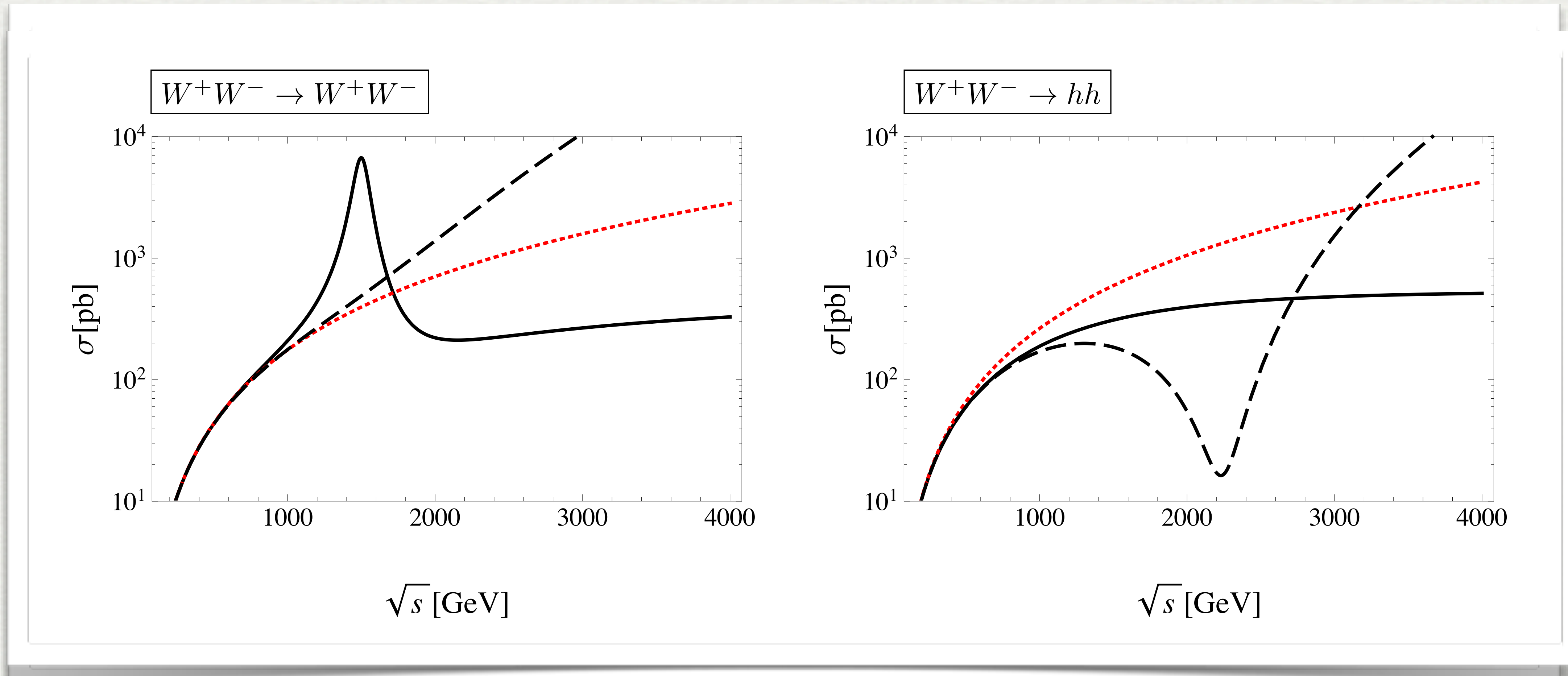
HL-LHC vs. HE-VLHC

10 x lum ≈ 10 x events

2 x √s = 10 x events
iif m_{hh} > 1.6TeV

Studying the EW Sym' Breaking

- High energy behavior depends on "what's next" (UV completions)
- Resonances likely to be present but maybe heavy or wide. Even when present may induce very different behaviors:

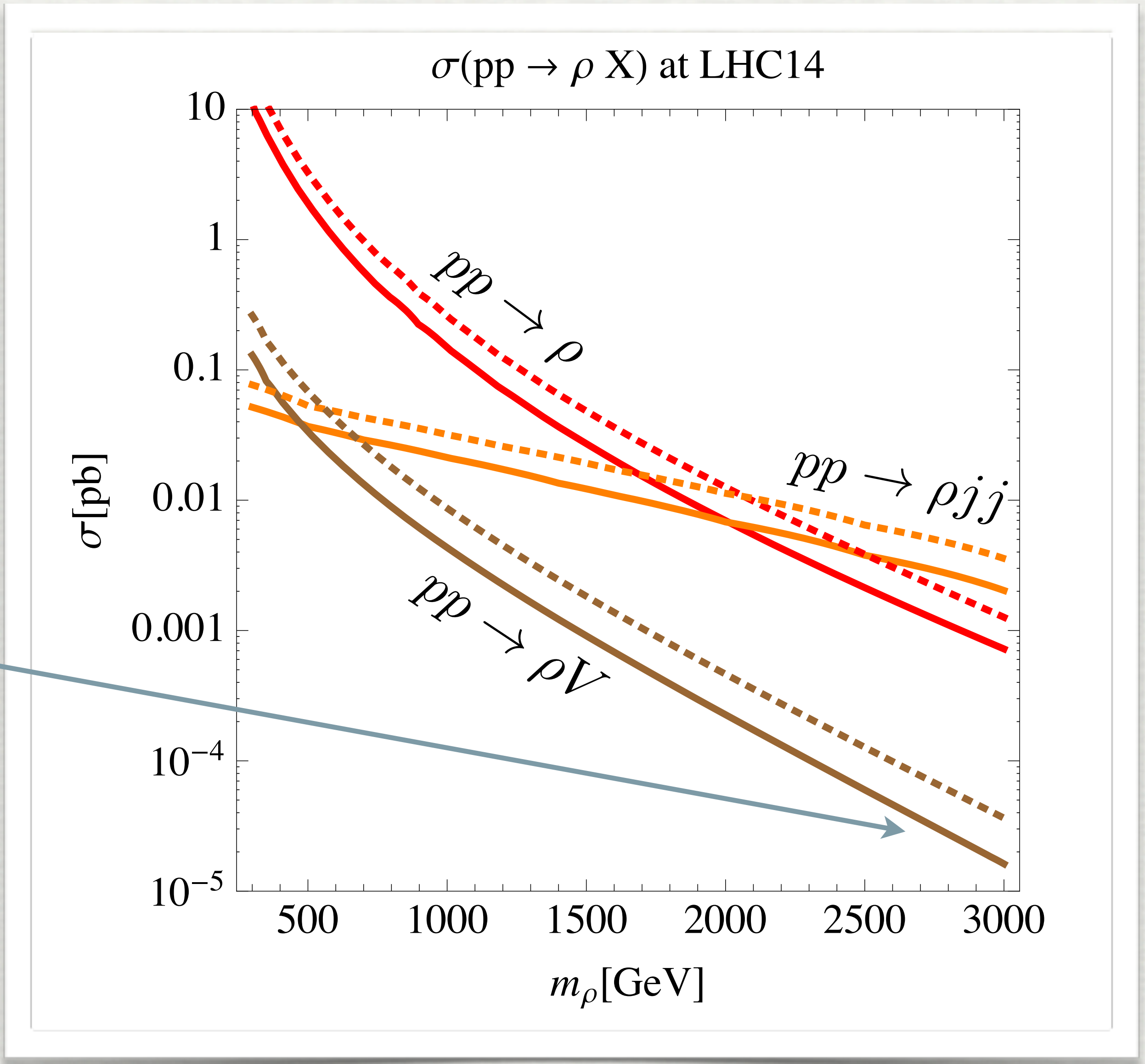


Contino et al. 1109.1570

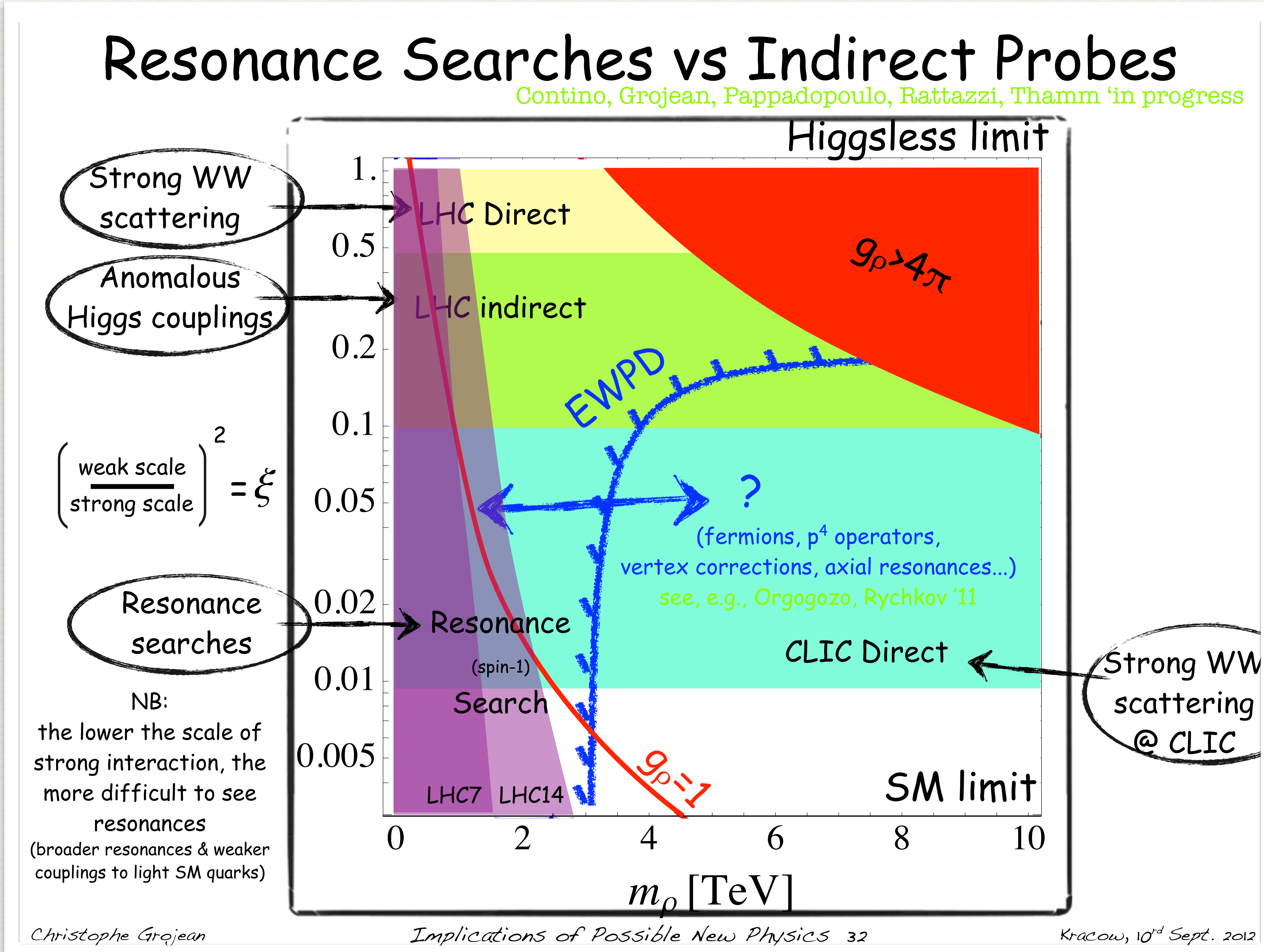
Direct resonance searches

- If Higgs is partially composite resonances are very likely to be present and can also be searched directly in other channels

Some xsec large enough to start exploring with 300fb^{-1}, full program likely to need 3000 fb^{-1}



Falkowski et al. 1108.1183



In this plot 500GeV e^+e^- is only marginally better than HL-LHC

Vector Boson self-couplings

- Triple and quartic gauge couplings measurements via di- and tri-boson production is also complementary to Higgs studies:

Heavy resonance can generate deviations:

$$g_1^Z = \frac{m_Z^2}{m_\rho^2} c_W \qquad \kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW} + c_{HB}) \qquad \kappa_Z = g_1^Z - \kappa_\gamma \tan^2\theta_W$$

Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g_1^Z	0.0038	0.0024	0.0023	0.0007	0.0050

ph/0204087

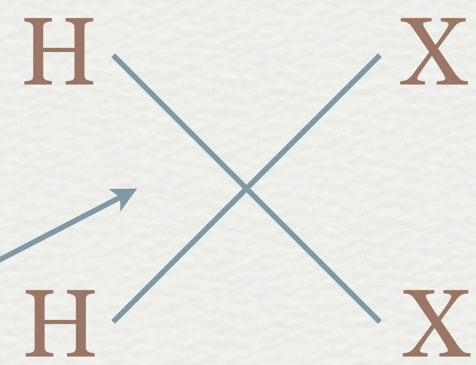
need per-mille sensitivity to beat LEP bounds on resonances

Coupling	Indirect Limits (1σ) ($\times 10^{-3}$)	LHC, 100 fb^{-1} (1σ) ($\times 10^{-3}$)	LHC, 6000 fb^{-1} (1σ) ($\times 10^{-3}$)	LHC, 6000 fb^{-1} 95% C.L. ($\times 10^{-3}$)
α_4	$-120. \leq \alpha_4 \leq 11.$	$-1.1 \leq \alpha_4 \leq 11.$	$-0.67 \leq \alpha_4 \leq 0.74$	$-0.92 \leq \alpha_4 \leq 1.1$
α_5	$-300. \leq \alpha_5 \leq 28.$	$-2.2 \leq \alpha_5 \leq 7.7$	$-1.2 \leq \alpha_5 \leq 1.2$	$-1.7 \leq \alpha_5 \leq 1.7$
α_6	$-20. \leq \alpha_6 \leq 1.8$	$-9.6 \leq \alpha_6 \leq 9.1$	$-3.5 \leq \alpha_6 \leq 3.2$	$-4.3 \leq \alpha_6 \leq 3.9$
α_7	$-19. \leq \alpha_7 \leq 1.8$	$-10. \leq \alpha_7 \leq 7.4$	$-4.4 \leq \alpha_7 \leq 2.2$	$-5.4 \leq \alpha_7 \leq 2.8$
α_{10}	$-21. \leq \alpha_{10} \leq 1.9$	$-24. \leq \alpha_{10} \leq 24.$	$-4.1 \leq \alpha_{10} \leq 4.1$	$-4.8 \leq \alpha_{10} \leq 4.8$

$\sigma_{WWW} \sim O(50$ fb$) \to \sigma < 1$ fb xsec incl' BR's

“Precision” Higgs?

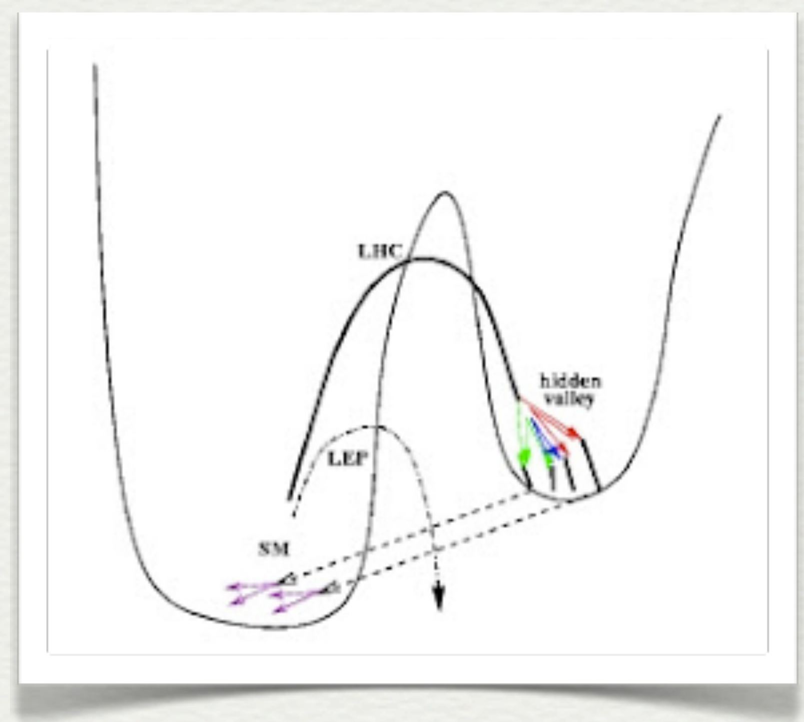
- ideally one would like to measure as many Higgs BR’s as possible
- Well known BR’s targets: γZ, $\mu\mu$, invisible, but there is more…
- Higgs is special:



$H \to XX$

Allowed, with X completely neutral under SM interactions!

window on possible new sectors → “Higgs portal”



important to look for rare non-SM Higgs decays!!

"Precision" Higgs?

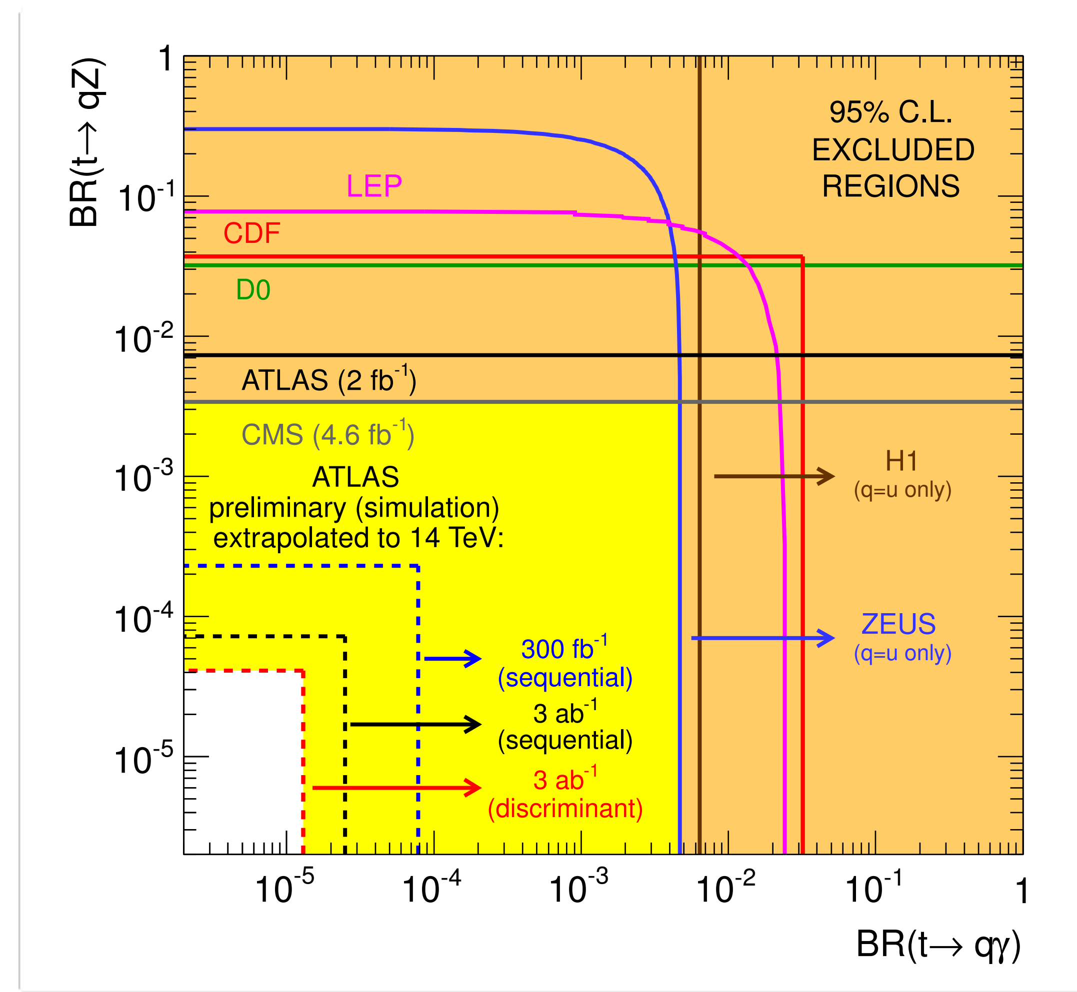
Fox, Weiner, Chang, Dermisek, Yavin, Cranmer, Falkowski, Volansky, Strassler, Zurek, ...

- X stable: invisible Higgs width (hard), relevant for Dark Matter searches
- X decays back to known particles: 4-body Higgs decays (but also multibody like "lepton jets", etc.):
  - final states of X can be any SM pair (μμ,ττ,ee,bb,γγ,jj), some easier to look for
  - angular separation depends on X mass (if light → boosted pair)
  - pT is soft ~ 30-40GeV, but multiplicity or ΔR closeness may help to keep trigger rates small?

Challenge for high luminosity trigger at LHC!!

Non-Higgs physics

Top physics

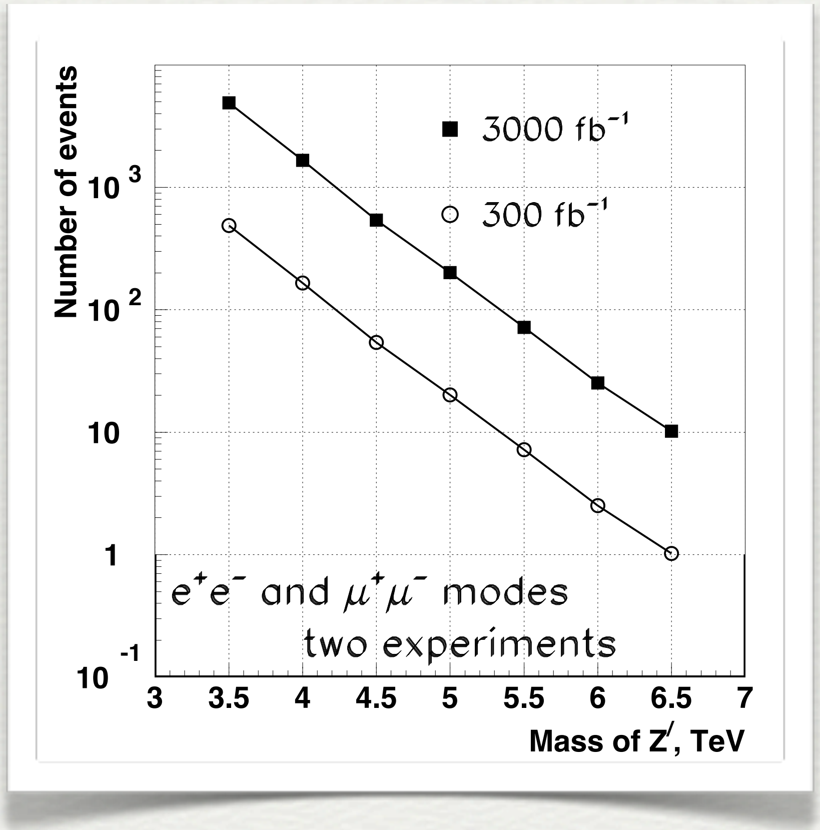


- LHC is a top factory: high lumi → tons of tops
- Precision measurement of top properties and differential xsec will constrain new physics
- Rare top decays (FCNCs): $t \to qZ$, $q\gamma$, qg, qh
  - Interesting region for models with non-trivial flavor structure at the TeV (e.g. Randall-Sundrum, ...) mostly @ (10^{-4})10^{-5}
  - constraints from B-factories still play a role below 10^{-4} → interesting interplay if signal is observed

Resonance searches

ph/0204087

- Moving from 300fb^{-1} to 3000fb^{-1} at the same energy will not significantly extend the mass range of the searches: O(20%) more mass reach



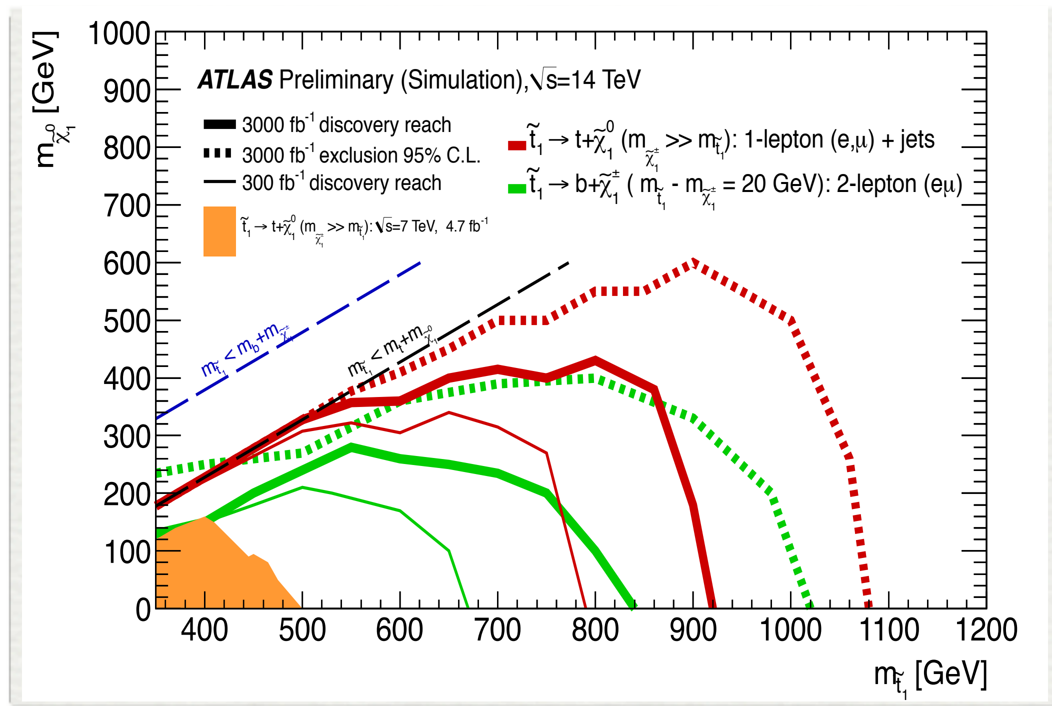
- Improvement for M.Peskin's "no boson left behind"*: keep improving limits on cross section of lower mass resonances

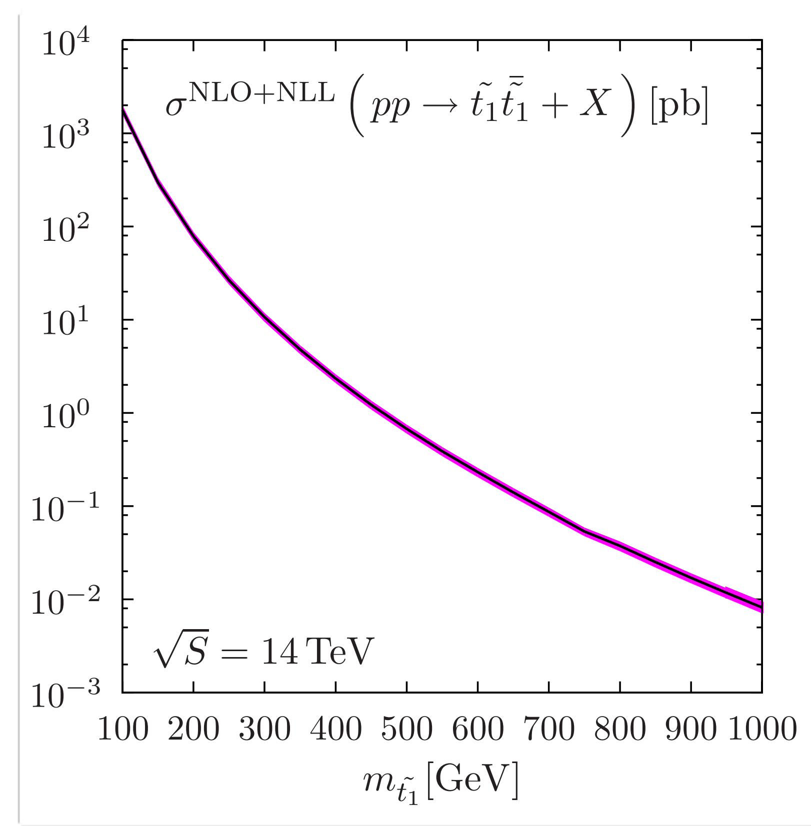
Limit in multi-TeV region → boosted techniques for decays to W's,Z's,h's, tops: high pileup effects?

*SEARCH workshop, Maryland, 2011

SUSY (example for new phys' relevant for stabilizing the weak scale)

- "Naturalness" of SUSY (=no large cancelations in the Higgs potential from different quantum corrections) during HL-LHC?
- for 1 in 100 cancelation (~what LEP did to the CMSSM):
- stops below ~2-2.5TeV,
- gluino below 4TeV,
- (some) charginos and neutralinos below 800 GeV...





Beenakker et al. 1006.4771

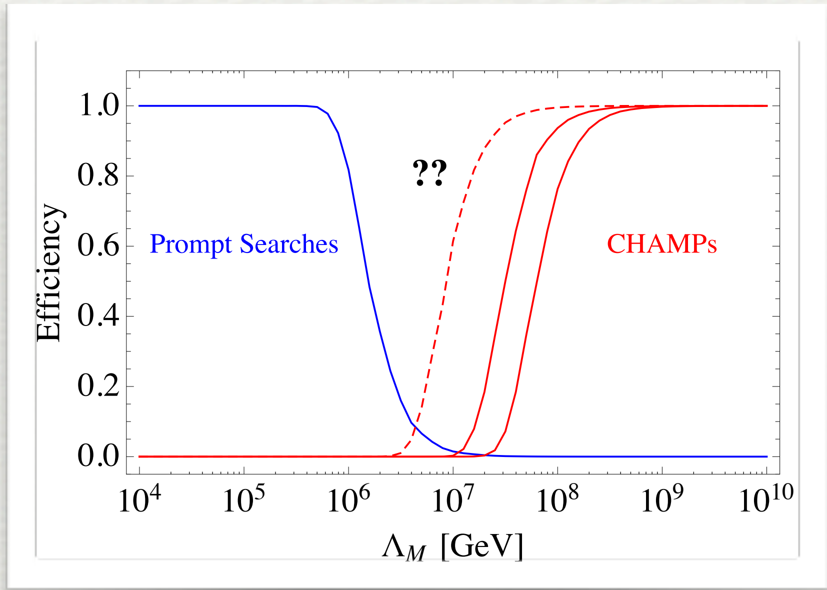
New non-colored particles

- DY production of non-colored particles (e.g. neutralinos and charginos in SUSY) naturally small at the LHC
- if decays dominated by bosons (W,Z,h), further suppressions to get to final states with better S/B
- Direct production limits will benefit from high statistics
- Relevant for SUSY EW sector (charginos/neutralinos), but also for WIMP Dark Matter models

$\sigma \sim O(\text{few fb})$ for 500 GeV particle

High lumi challenges

- Many new physics scenarios (including SUSY) have long-lived particles
- Various signatures, from HSCP to displaced vertices, to decays in outer detector, to disappearing tracks
- Higher occupancy render some of these searches more challenging to reconstruct. How much?
- Searches are still relevant at high luminosity (prod xsec can be small, mass can be higher, ...)
- Efficiency hit easily $O(10^{-1} - 10^{-2})$ to be picked up by standard searches (prompt, MET, HSCP), in many cases too much price...



Conclusions

- Various options for what's next if nothing is found at LHC14 besides the Higgs
- probing VBF di-boson production at high energy necessary irrespective of the discovery of the Higgs (if Higgs present then also Zh, Wh, and hh) → distinguish "pion" from fundamental scalar
- Precision tests of EW interactions with di and tri- boson production
- Some Higgs-related new physics may be too heavy for LHC14
- e+e- sub-TeV machines will improve Higgs couplings. HL-LHC may or may not be competitive with them on many couplings depending on future systematics
- e+e- sub-TeV machines may not provide a clear advantage over HL/HE-LHC for the question of Higgs compositeness → WW scattering @ ILC/CLIC would be needed

Conclusions

- HL-LHC relevant
  - precision top physics & top FCNCs
  - Exploration of BSM models with low rates:
    - resonances with suppressed couplings
    - pushing the limits on top partners down to 1% tuning
    - exploring heavier DY-produced new electroweak particles
- Long lived particles / exotics searches would benefit from higher statistics, but challenge for reconstruction/cleanliness @ LHC? (HL-LHC vs e+e-?)