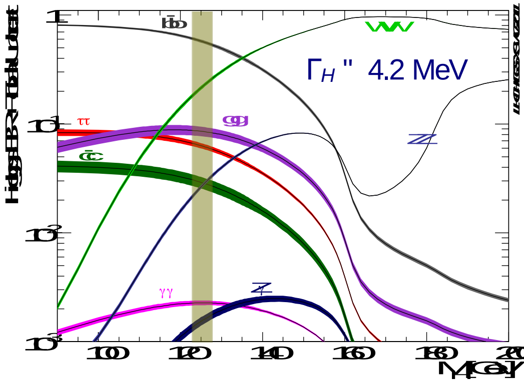
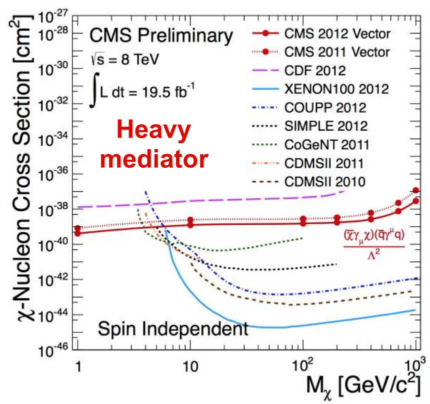
Future Experiments at the Energy Frontier

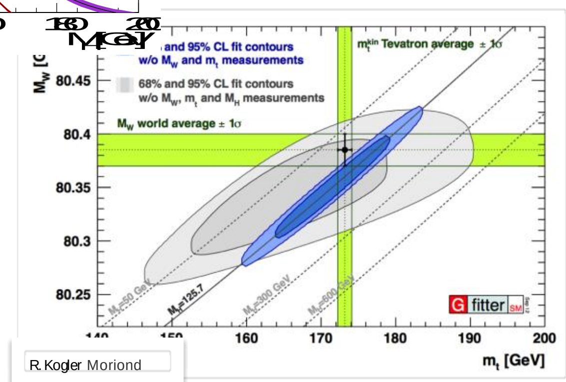
Yuri Gershtein

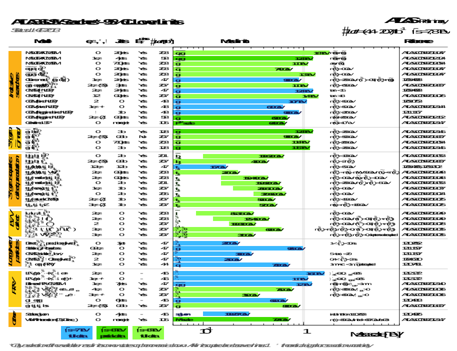
Physics

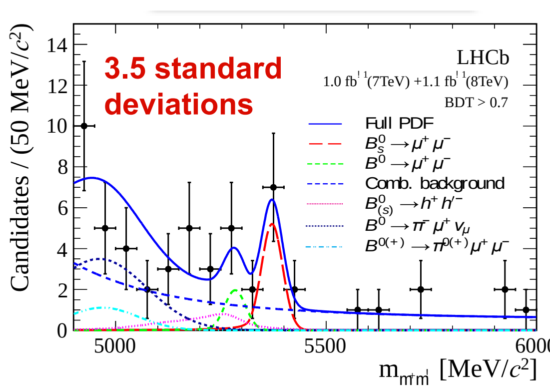
- Higgs
- Precision EWK
- Dark Matter
- Fine tuning and Naturalness
- Flavor











Hadron Collider options

1. *LHC 13 TeV, 300/fb , spacing: 25 ns (50 ns), pileup: 19 (38) events/crossing*
2. *LHC 13 TeV, 3000/fb (HL-LHC) , spacing: 25 ns, pileup: 95 events/crossing*
3. *LHC 30 TeV, 3000/fb (HE-LHC) , spacing: 50 ns, pileup: 225 events/crossing*
4. *VHE-LHC 100 TeV, 3000/fb, spacing: 50 ns, pileup: 263 events/crossing*
5. *VLHC at 100 TeV, 1000/fb , spacing: 19 ns, pileup: 40 events/crossing*

Snowmass '82

HADRON HADRON COLLIDER GROUP*

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1. Introduction

The objective of this group was to make a rough assessment of the characteristics of a hadron-hadron collider which could make it possible to study the 1 TeV mass scale. Since there is very little theoretical guidance for the type of experimental measurements which could illuminate this mass scale, we chose to extend the types of experiments which have been done at the ISR, and which are in progress at the SPS collider to these higher energies. Initially we chose to call these experiments "bellwether experiments" for reasons of convenience. In the absence of any alternative predictions we assumed that the cross sections for these standard experiments could be obtained either by extrapolating perturbative QCD models of hadrons to center of mass energies of 40 TeV or by extrapolating phenomenological parameterization of data obtained from experiments done in the center of mass energy range of 20 to 60 GeV to 40 TeV. For each bellwether we asked up to what mass (or momentum transfer Q) could a significant (> 100) number of events be seen in 10^7 seconds. While it is unlikely

Considering the huge extrapolation of cross sections from 60 GeV to 40 TeV, there was no significant difference between the cross sections for pp or $\bar{p}p$ collisions. The numbers given were calculated for pp interactions.

Before listing the bellwether experiments chosen, it is appropriate to check in Websters to see exactly what a "bellwether" is. "1. a wether, or male sheep, which leads the flock, with a bell on his neck. 2. a leader of a thoughtless crowd." We hope definition 1 applies.

2. The Bellwether Experiments

#1 High Transverse Momentum Jets

This experiment was chosen because it is expected to reveal the dynamics of the interacting constituents. The rate for this process does not depend on the details of constituent hadronization, and it has the largest cross section of the experiments consider-

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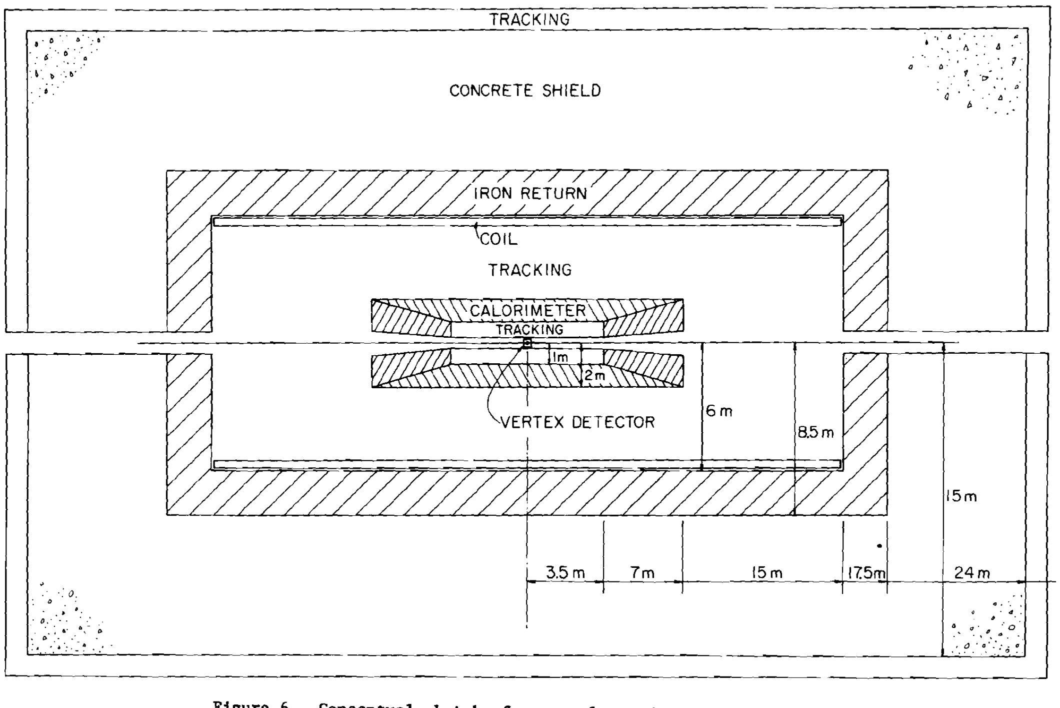
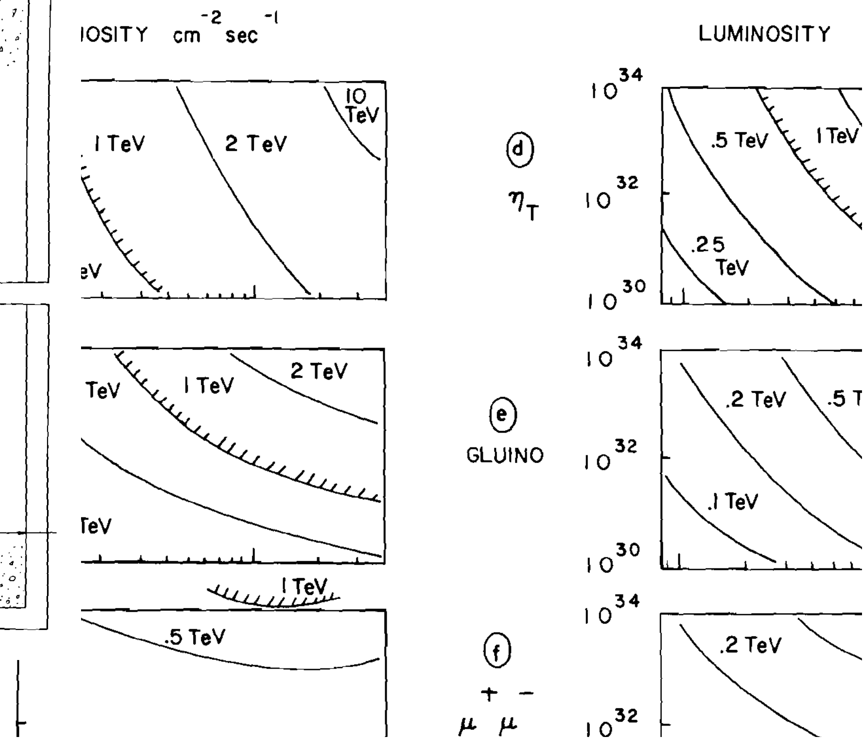




This conclusion can be stated very succinctly by noting that if one must choose between one and two rings in order to reach 10^{32}, then one should choose two rings even at the cost of a modest reduction in

Lepton Colliders

1. *e+e- at 250 GeV (ILC: 500/fb , LEP3: 500/fb, TLEP: 2500/fb), e-/e+ polarization: ILC: 80%/30%, LEP3, TLEP: 0/0*
2. *e+e- at 350 GeV (ILC: 350/fb, CLIC: 350/fb, TLEP: 350/fb) , e-/e+ polarization: ILC: 80%/30%, CLIC: 80%/0, TLEP: 0/0*
3. *e+e- at 500 GeV (ILC: 500/fb), e-/e+ polarization: ILC: 80%/30%*
4. *e+e- at 1000 GeV (ILC: 1000/fb) , e-/e+ polarization: ILC: 80%/20%*
5. *e+e- at 1400 GeV (CLIC: 1400/fb) , e-/e+ polarization: CLIC: 80%/0%*
6. *e+e- at 3000 GeV (CLIC: 3000/fb) , e-/e+ polarization: CLIC: 80%/ 0%*
7. *mu+mu- at 125 GeV 2/fb , 0 polarization*
8. *mu+mu- at 1500 GeV 1000/fb , 0 polarization*
9. *mu+mu- at 3000 GeV 3000/fb , 0 polarization*

PHYSICS WITH LINEAR COLLIDERS IN THE TEV CM ENERGY REGION

Snowmass '82

F. Bulos[†], V. Cook[*], I. Hinchliffe[**], K. Lane[††],
D. Pellet[⊗], M. Perl[†], A. Seiden[Δ], H. Wiedemann[†]

I. Introduction

It may well be that the e^+e^- physics beyond PEP and PETRA and and up to 200 GeV CM energy will deal primarily with the verification of the standard model (SM) of weak and electromagnetic interactions. Various theoretical and experimental studies at workshops for contemplated accelerators[1] (SLC, LEP I, Z^0 at Cornell) have assumed this.

Beyond 200 GeV the picture is less clear. The absence of theoretical models with strong predictions comparable to the SM adds to the difficulty. In addition, the experimental verification of the SM itself is yet to come, and one is forced to make certain assumptions about the outcome.

Here we join some our colleagues in previous studies[2] (in particular J. Ellis and I. Hincliffe) in making the following assumptions:

1) Z^0, $W^\pm$, light higgs (if M_H < 100 GeV) have all been discovered.

2) The t quark has been discovered if its mass is < 100 GeV.

3) QCD is basically the correct theory of the strong interactions.

With these assumptions, we have produced an updated table of possible physics in the TeV region (Table I). This table was used as the basis for the study of specific physics below. It contains best estimates of cross-section, promising signatures for final states. and some helpful comments.

of $10^{33}\text{cm}^{-2}\text{sec}^{-1}$ is attainable with relatively modest AC power, and an energy spread $\Delta E/E < 5\%$.

At this energy and luminosity:

SUMMARY TABLE I. - BEYOND SLC AND LEP

$e^+e^- \to$	R σ/σ_{pnt}	Particle Decay	Jet (Max) Content	REMARKS
W^+W^- Z^0Z^0 $Z^0\gamma$	∿ 25 ∿ 5 ∿ 30	Jet & Leptons	4 4 2 + SHWR	With known W's and Z^0, this constitutes a serious background. However ang. dist. is strongly peaked forward - backward, also Z's, W's can be used as a tag. $Z^0\gamma$ can be easily recognized and eliminated.
Known Quarks $Q(2/3)\bar{Q}$ $Q(-1/3)\bar{Q}$ Total	 ∿ 2 ∿ 1 ∿ 9.0	 Jets "	 2 2	Includes Z^0 contribution as well as γ. They also complicate analysis due to gluons, hence are also a background. However the two jets are back to back.
New Res. $Z^{0\prime}$($M \geq$ 200 GeV)	5000	Like Z^0		Assume coupling similar to Z^0. $\Gamma'/M' = \Gamma/M(Z^0)$ ∿ 3%. To study very well E-beam resol. should be better than 3%.
New Onia $n\ ^3S_1$	1 → 2	ψ, ψ'Like	2 almost b-to-b	Will have substantial weak decay $q' \to W + q$, $H + q$. $\Gamma(q' \to W + q) \approx 6 \times 10^{-3} M_q'$. Separation of two oniums $\approx 5 \times 10^{-3} M_q'$. Hence resonance is broadened.

Photon Colliders

1. *gamma-gamma at 125 GeV, 100/fb ,*
   80% e- polarization to generate the photon beams
2. *gamma-gamma at 200 GeV, gamma-e at 225 GeV, 200/fb ,*
   80% e- polarization to generate the photon beams
3. *gamma-gamma at 800 GeV, gamma-e at 900 GeV, 800/fb ,*
   80% e- polarization to generate the photon beams

Electron-hadron Collider

1. *LHeC 60 GeV e- or e+ on 7 TeV p 50/fb ,*
   90% e- / 0% e+ polarization

Options are familiar

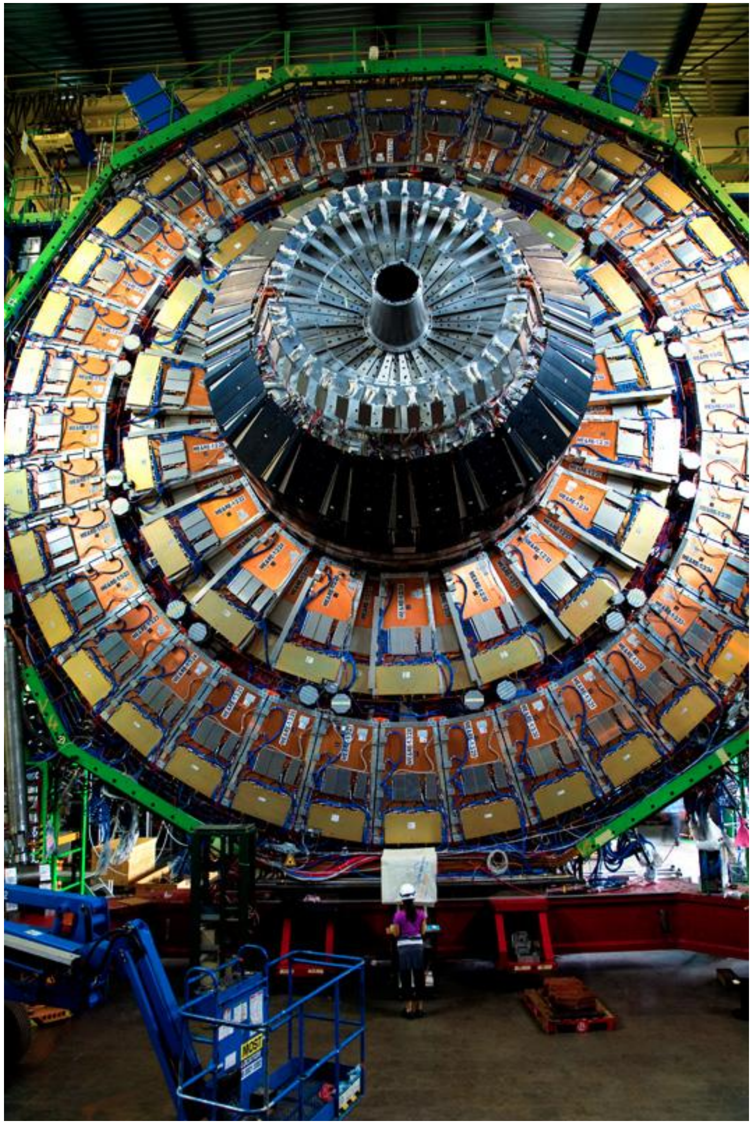
- As is the skepticism about some of them
- In this talk
  - review what we need to measure and the recent progress
  - review (revisit?) the conventional wisdom of what kind of measurements are possible at which machine
  - consider recent developments in regional planning

Higgs


SAY "OFF-SHORE DISCOVERY"
ONE MORE GODDAMN TIME
imgflip.com

NYT Photos in article about the "off-shore" discovery

Most of what you see here is made in the USA



US Spokeperson of an experiment of which US Physicists are the single largest fraction (~35%) reports the Higgs discovery

Not on US soil

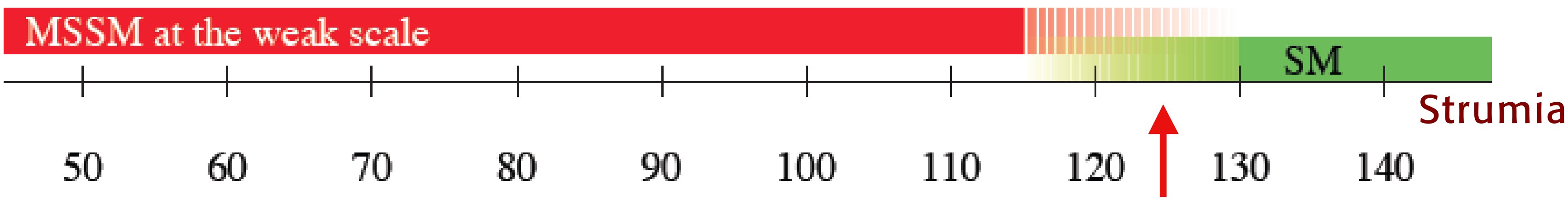
US astronauts and scientists have to travel to Kazakhstan to access the hardware or do work remotely

Higgs @125: malicious?

G. Altarelli

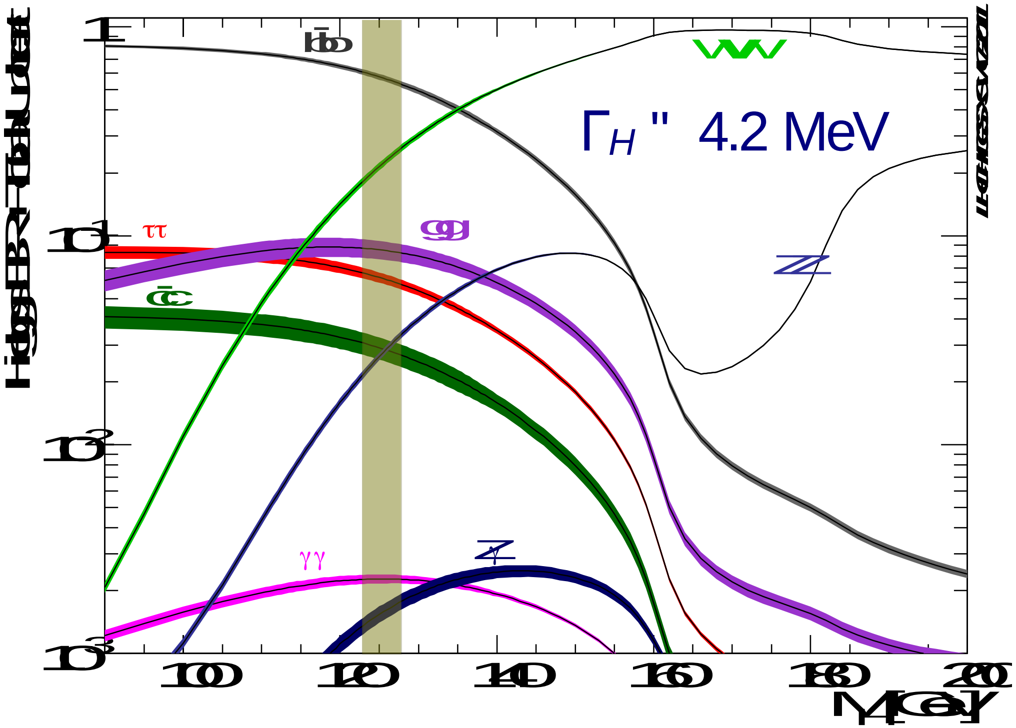
$m_H = 125.6 \pm 0.4$ GeV

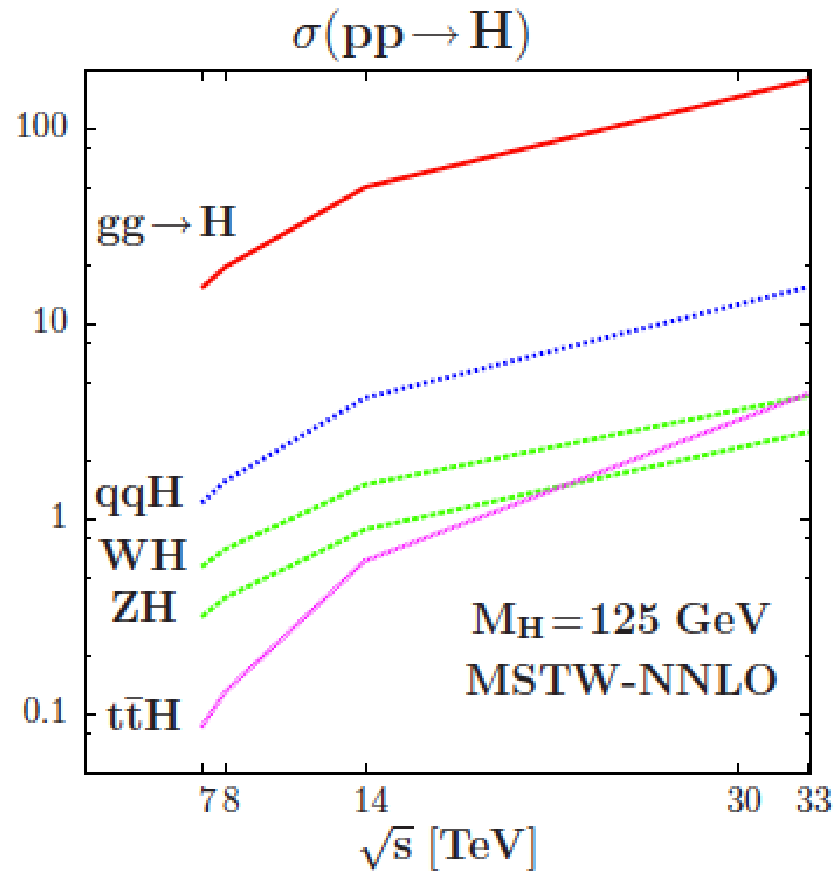
A malicious choice!



m_H ~126 GeV is what you expect from a direct interpretation of EW precision tests: no fancy conspiracy with new physics to fake a light Higgs while the real one is heavy
(in fact no “conspirators” have been spotted: no new physics)

Higgs @125: or lucky?

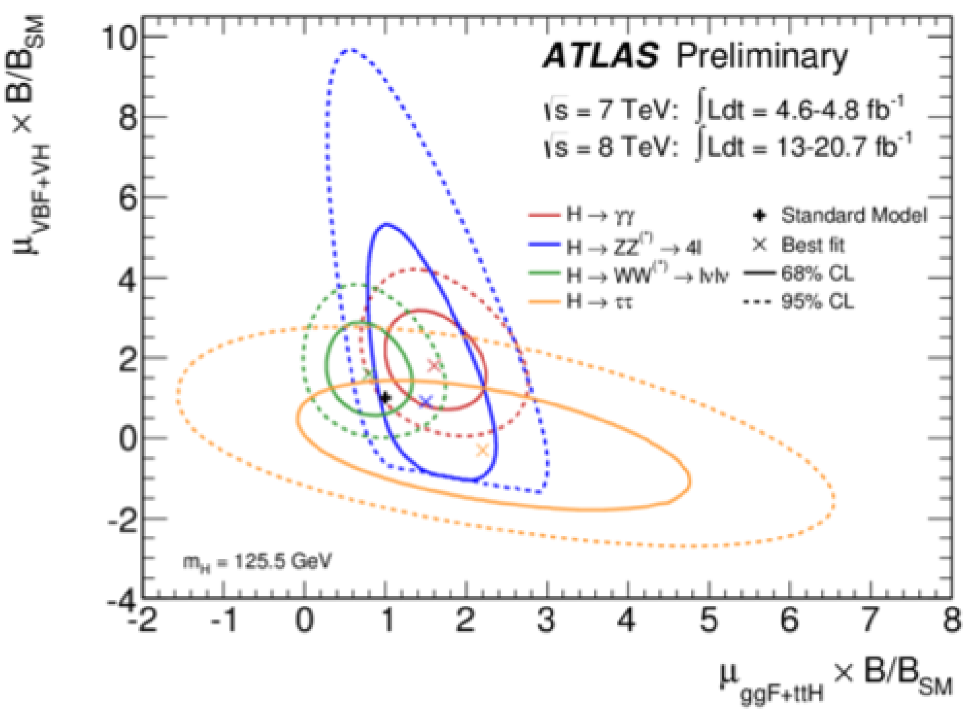


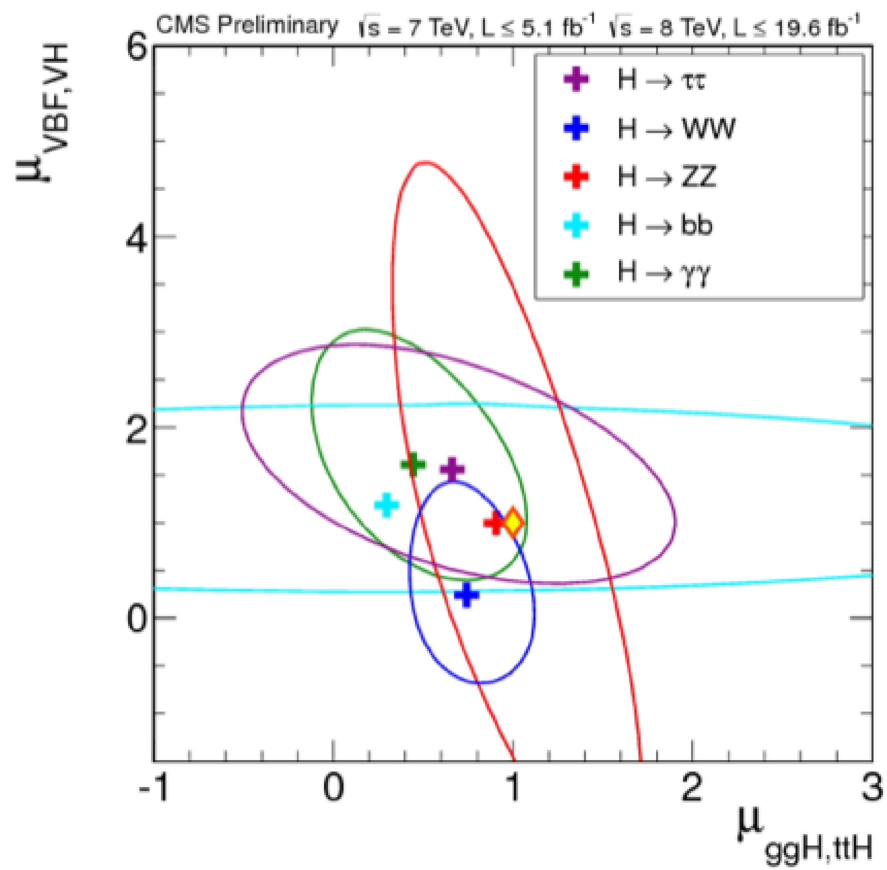


New challenge: what is the *b* quark mass, really?

Higgs: what we know already

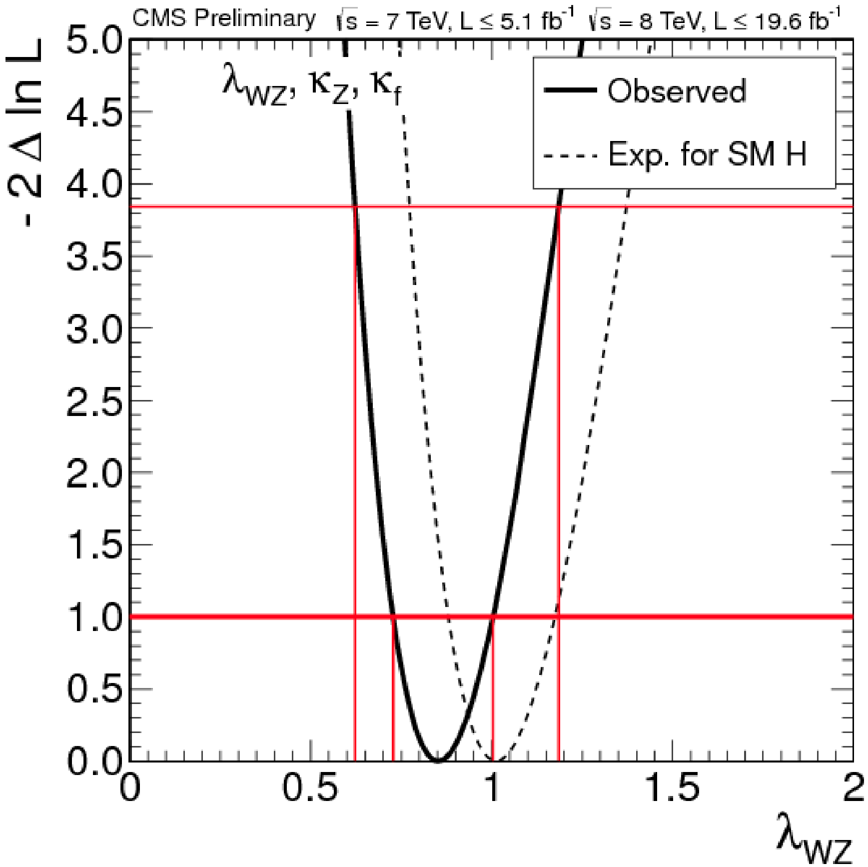
- Combined p-values for h existence are below 10^{-20}
- $>3\sigma$ evidence for $\mu_{VBF+VH} > 0$ in both experiments

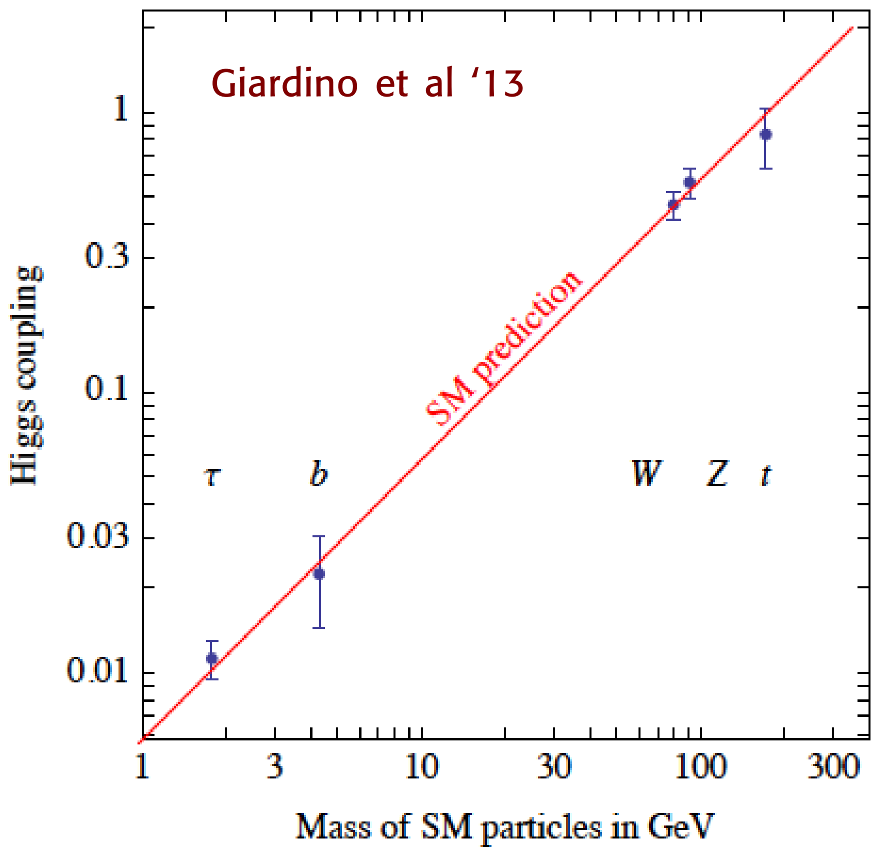




Higgs: what we know already

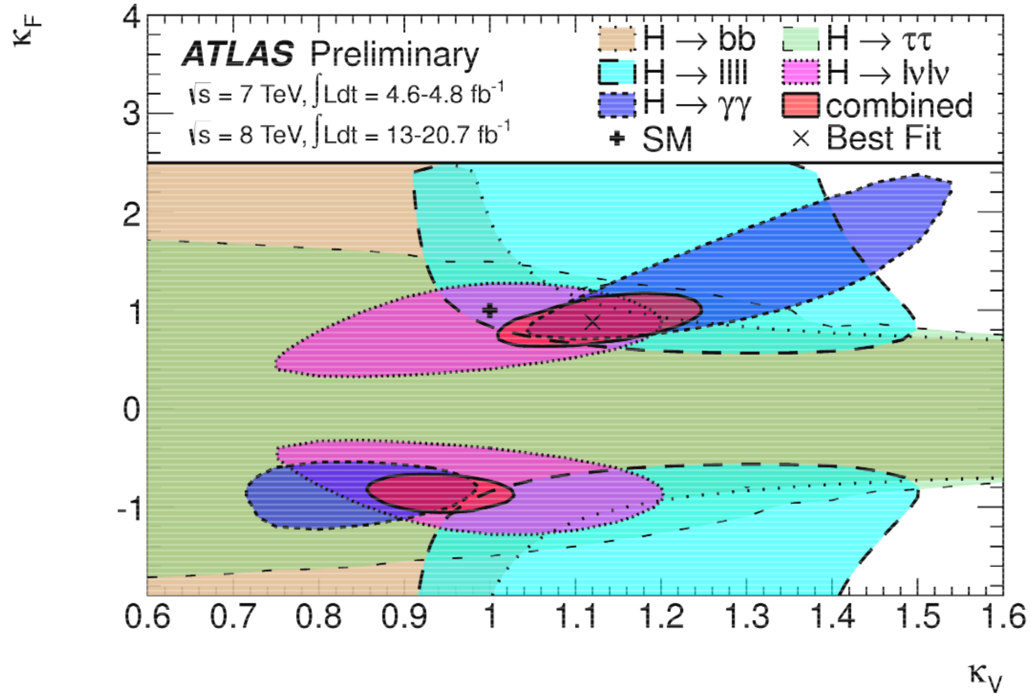
- Relative couplings to W and Z respect custodial symmetry
- Couplings to fermions are in correct proportion to masses

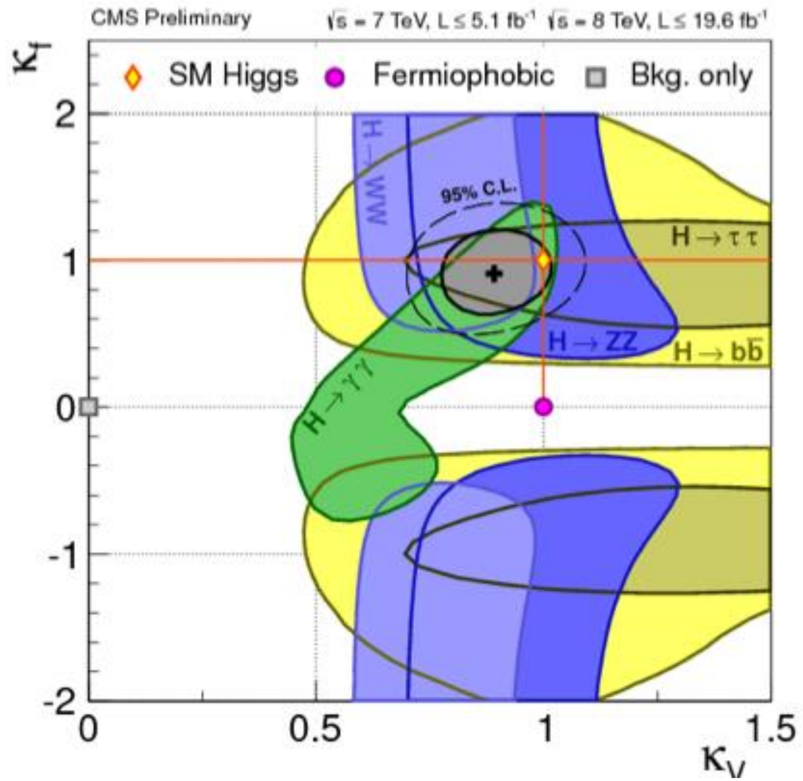




LHC: Couplings

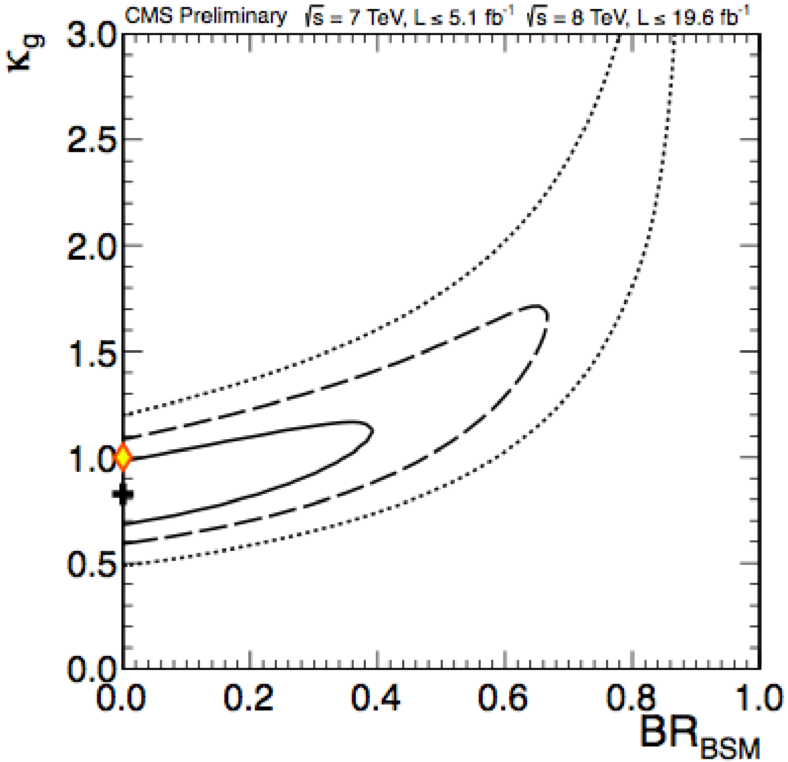
- P(SM) is ~8% in ATLAS and within 1σ in CMS



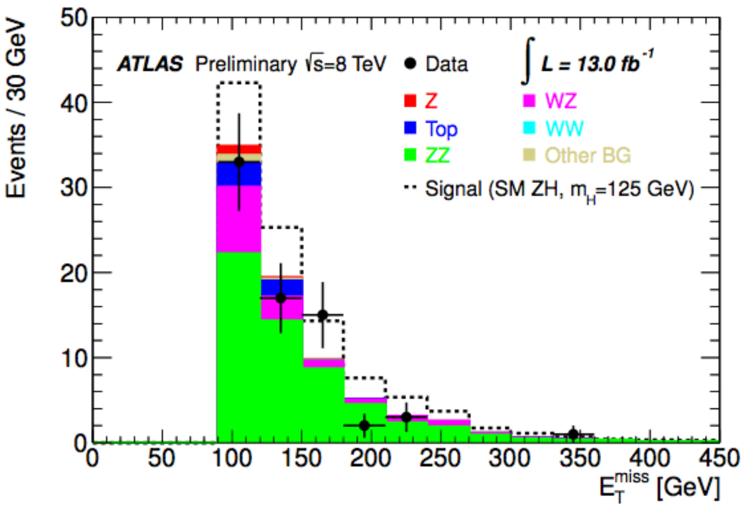


LHC: Extra decays

- BR(BSM) < 0.6 (0.52) in ATLAS (CMS)



- First higgs-tagging analysis from many to come
  - Zh → l^+l^-+MET
  - Br(h → invisible) < 0.65



- VBF-tagged analysis are coming soon
- CMS triggers on VBF with ~10% eff independent on the higgs decay

Coming soon: Rare / Exotic Higgs decays

Essig

How many exotic decays to expect?

assume BR(h→aa) = 10%, LHC8, 20/fb

channel	# events (raw)
ggF	39000
VBF	3150
W(ℓν)+h	280
Z(ℓℓ)+h	55
ttH	260

} Associated Production (AP) — W(ℓν)+h, Z(ℓℓ)+h, ttH

Can always trigger w/ AP… but not many events

Depending on `a` decays, ggF/VBF may be better

- Higgs tagging
  - Get ~all h+V(leptonic)
  - Get ~10% of VBF
- Have 6500 higgses without any trigger bias @LHC8
- If this can be maintained for HL LHC – more tagged higgses then ILC
  - Some decay modes have very small backgrounds – light resonances, long-lived particles, MET, etc

What to measure

- SM couplings
- Total width
- Rare decays
- Quantum numbers
  - already have strong experimental preference for 0^+
- CP admixture

What to measure

- SM couplings
- Total width
- Rare decays
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  - already have strong experimental preference for 0^+
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Where to measure

- Hadron Colliders
  - Real factories – huge numbers of Higgs produced, some of them tagged by VBF or associated W/Z
- Muon colliders
  - precise knowledge of E_{CM}
  - direct measurement of width
- ILC / CLIC
  - Very clean environment
  - $h \rightarrow cc$, $h \rightarrow gg$
- Photon colliders
  - Precise probe of $h\gamma\gamma$ vertex
- Circular e^+e^-
  - Combines clean environment and high luminosity

How precise is too precise?

- Need sub-percent precision to have the full story on higgs and new physics

P. Janot

- **Example : Precision for Higgs couplings**
  - **Maximal deviations with respect to SM couplings, as a function of new physics scale**
    - **SUSY** $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$ **, for tanβ = 5** H. Baer, M. Peskin et al.
    - **Composite Higgs** $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$
    - **Top partners** $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$
    - **Other models may give up to 5% deviations with respect to the Standard Model**
  - **Maximal deviations for the new physics scale still allowed by LHC results**

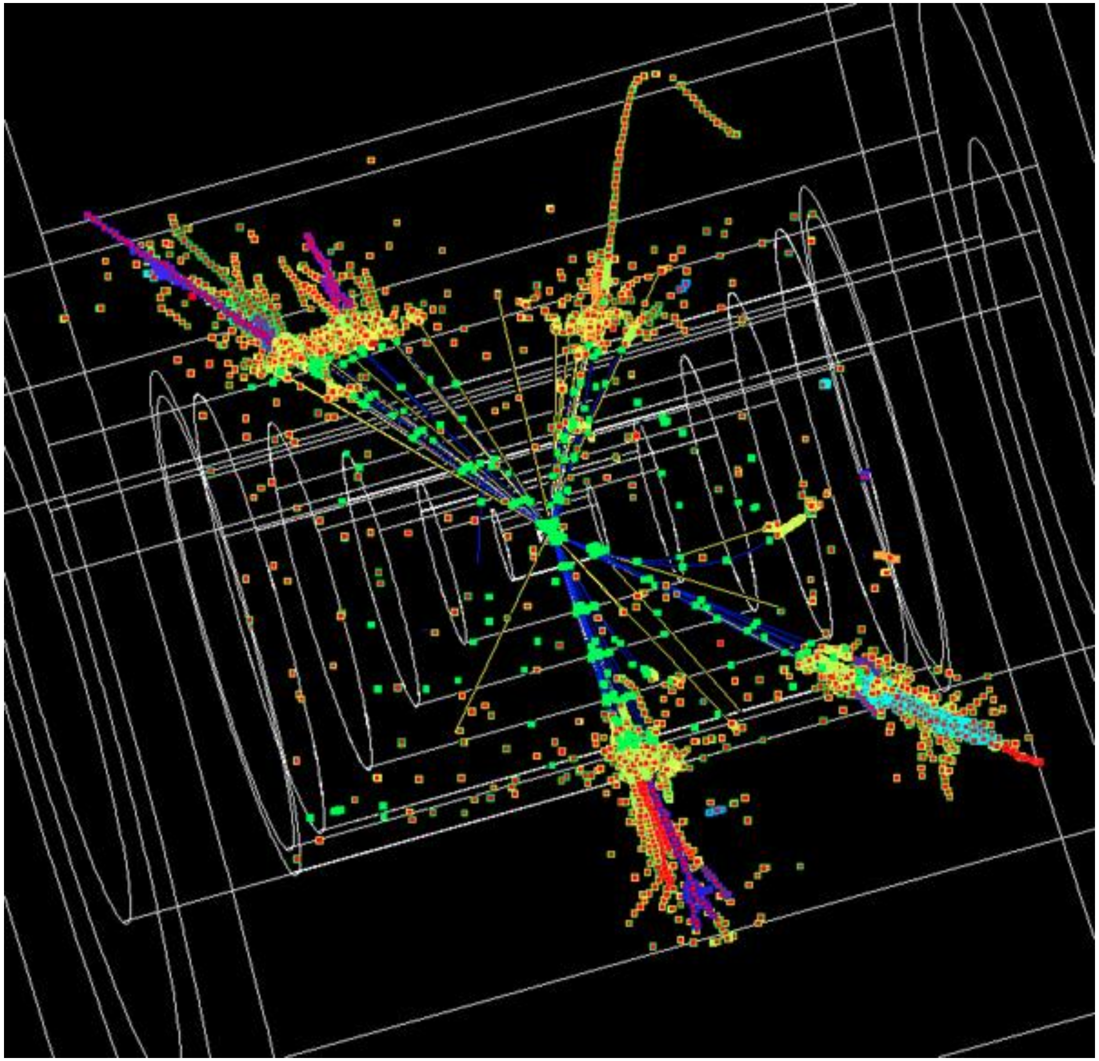
	ΔhVV	$\Delta h\bar{t}t$	Δhbb
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	$10\%^a$, $100\%^b$

J.D. Wells et al.

- **Strongly influences the strategy for Higgs factory projects**
  - **Need at least a per-cent accuracy on couplings for a 5σ "observation"**
    - **And sub-percent precision if new physics is at the (multi-)TeV scale**

Higgs @ e^+e^-

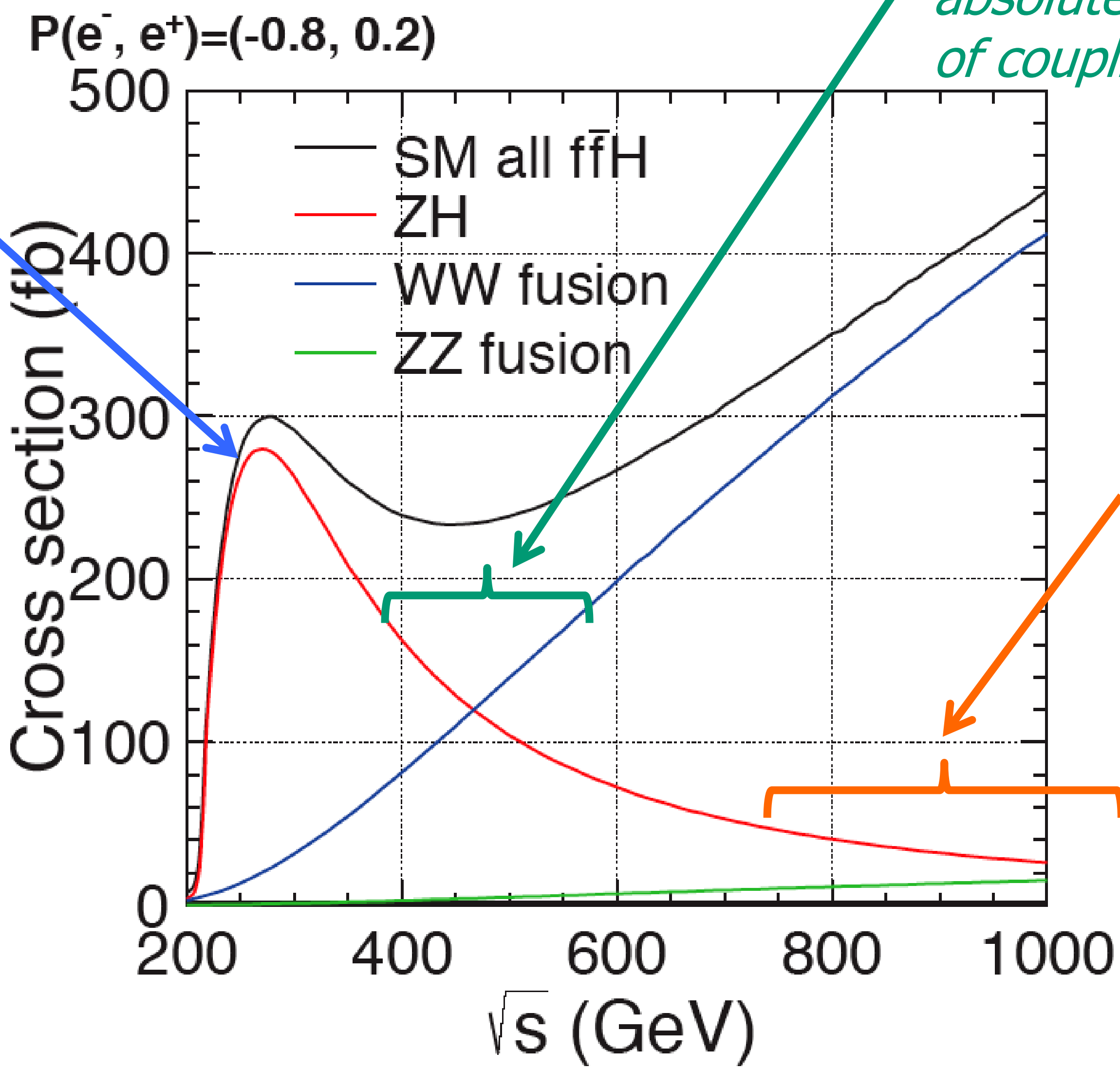
- Zh production, both Z and h decay into jets



Higgs @ e^+e^-

250 GeV:
(tagged h)
branching fractions

350-500 GeV:
(WW fusion)
absolute normalization of couplings

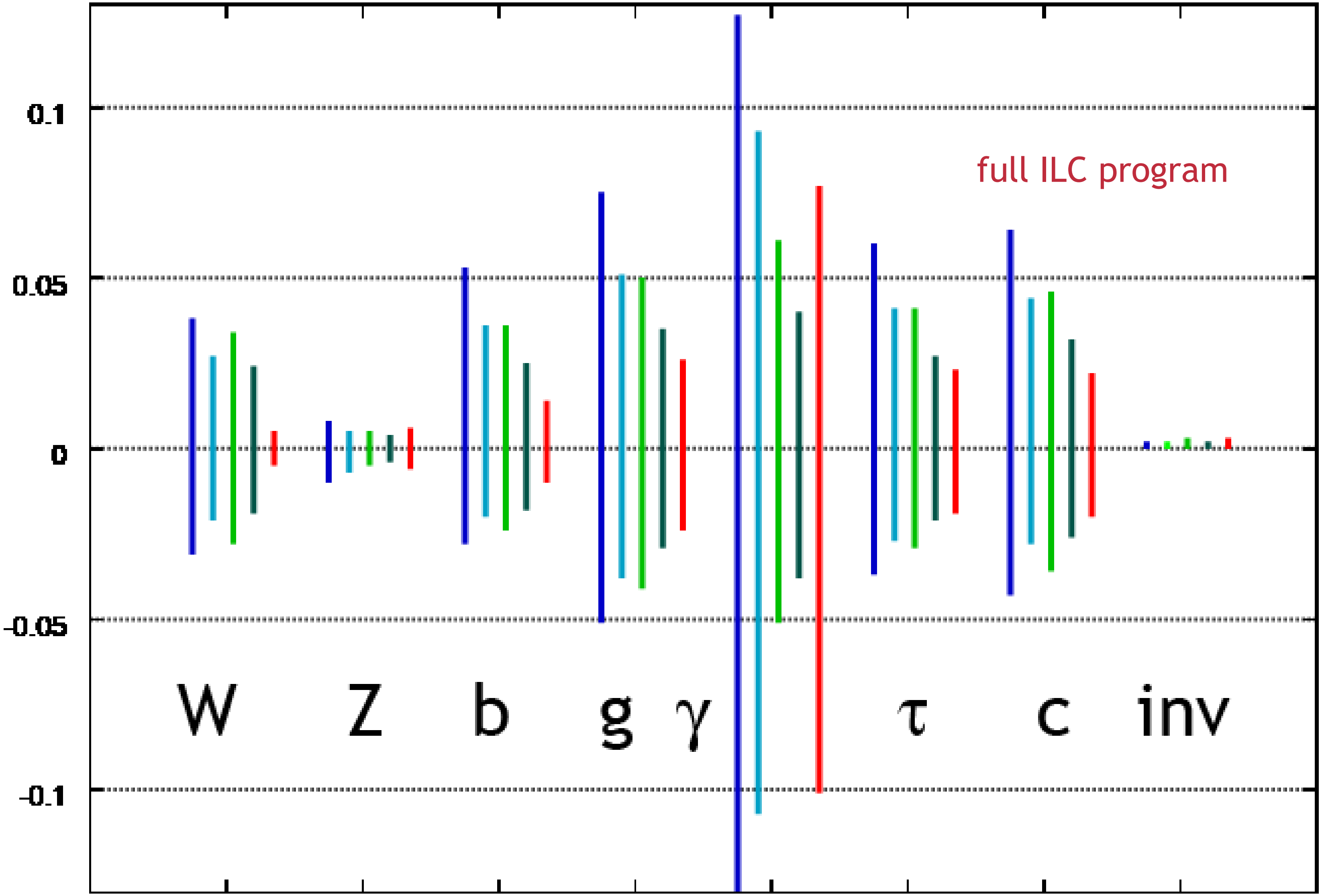


>700 GeV:
Self-coupling
top coupling

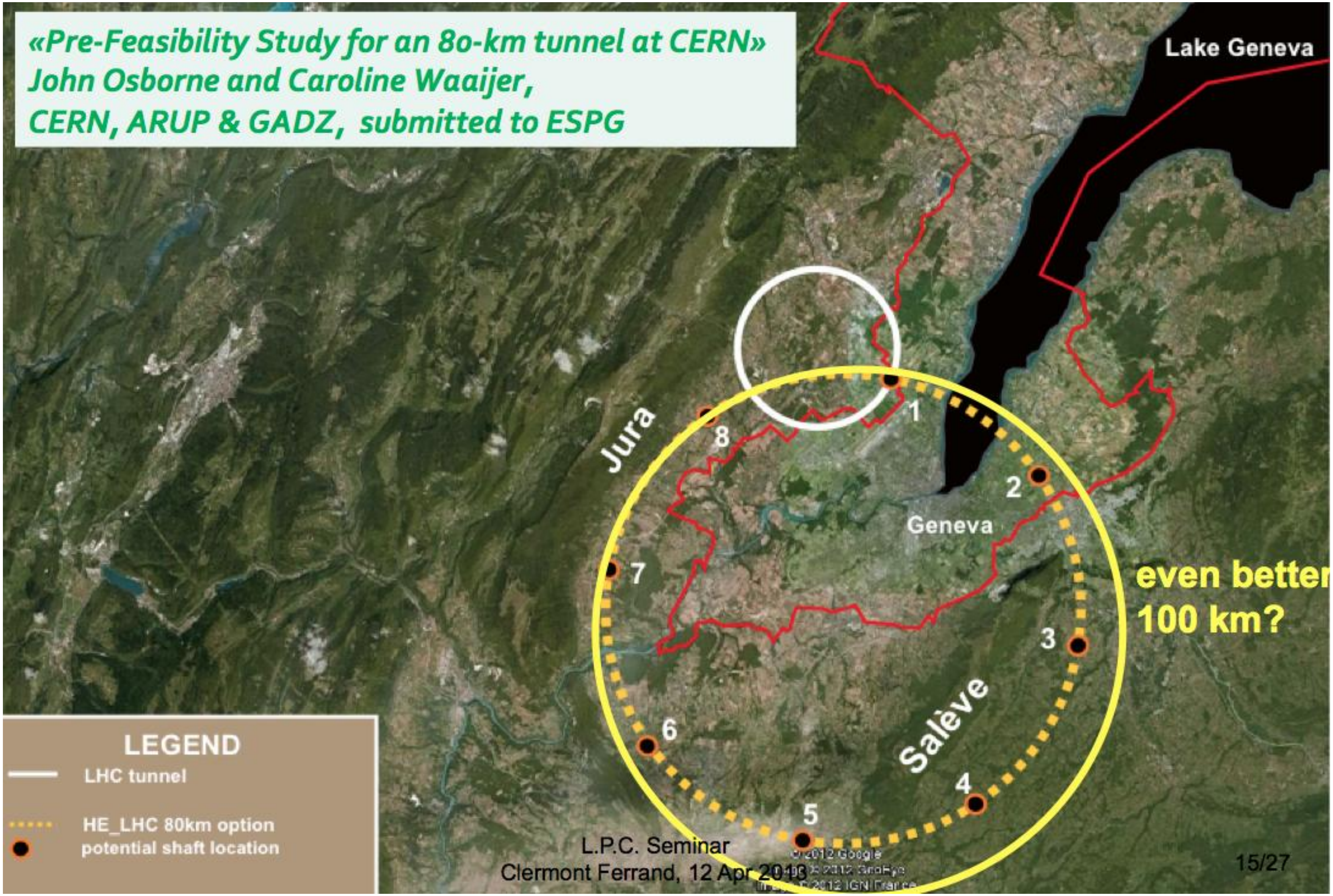
15% @
3 TeV CLIC

Peskin

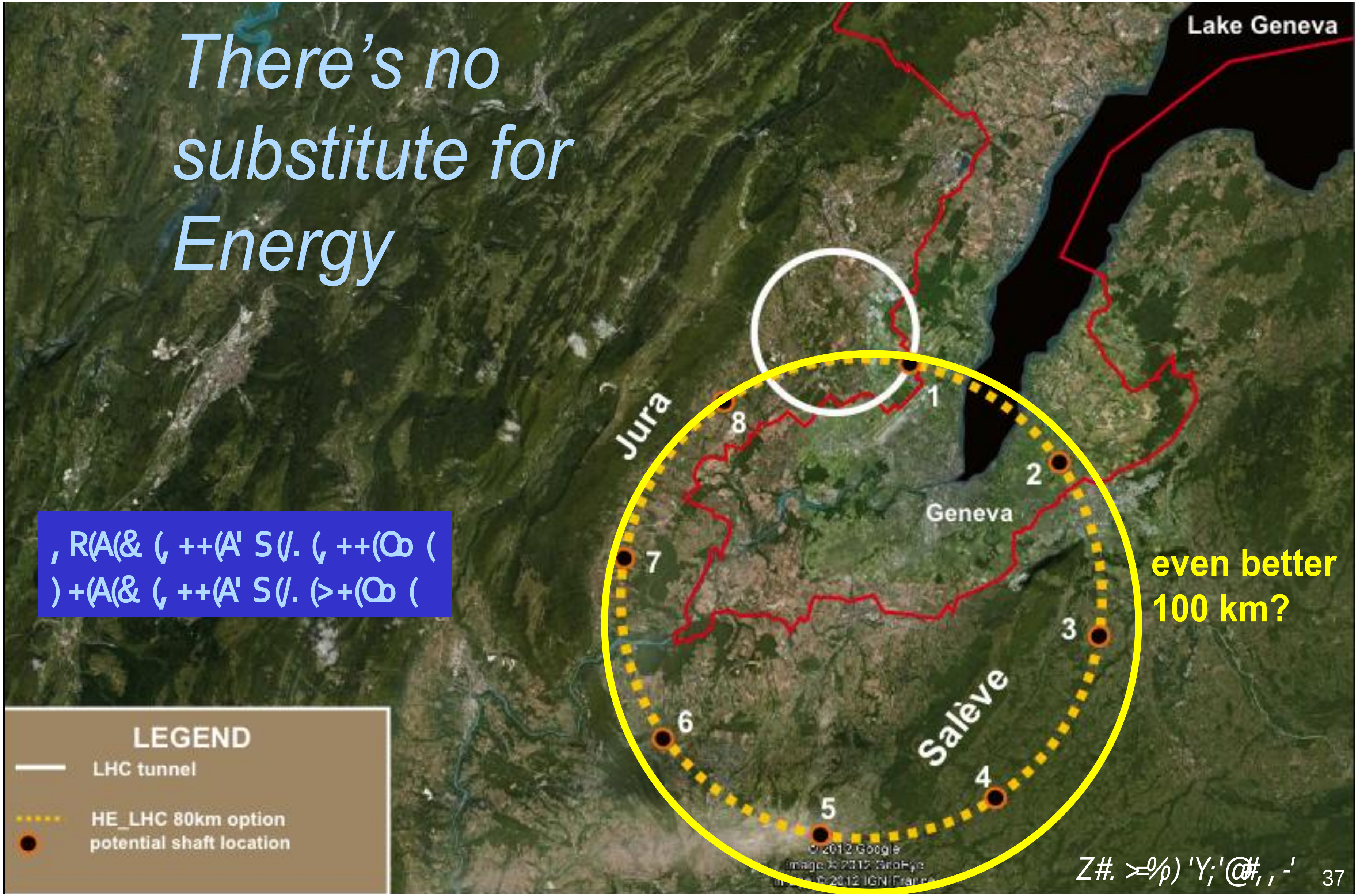
$g(hAA)/g(hAA)|_{SM}-1$ ILC/ILC/LEP3/LEP3/ILC



Circular e^+e^- in a New Tunnel



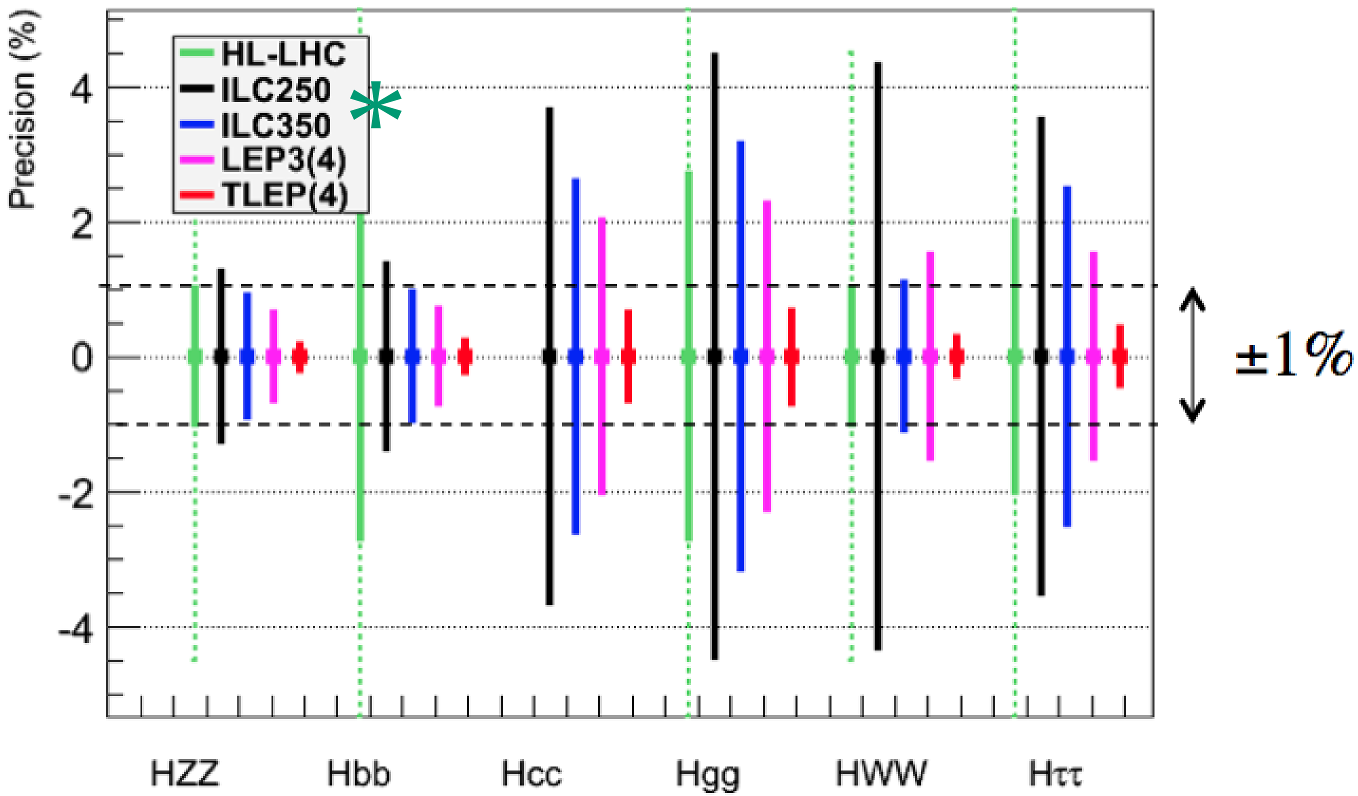
The only hope for VLHC?



P. Janot

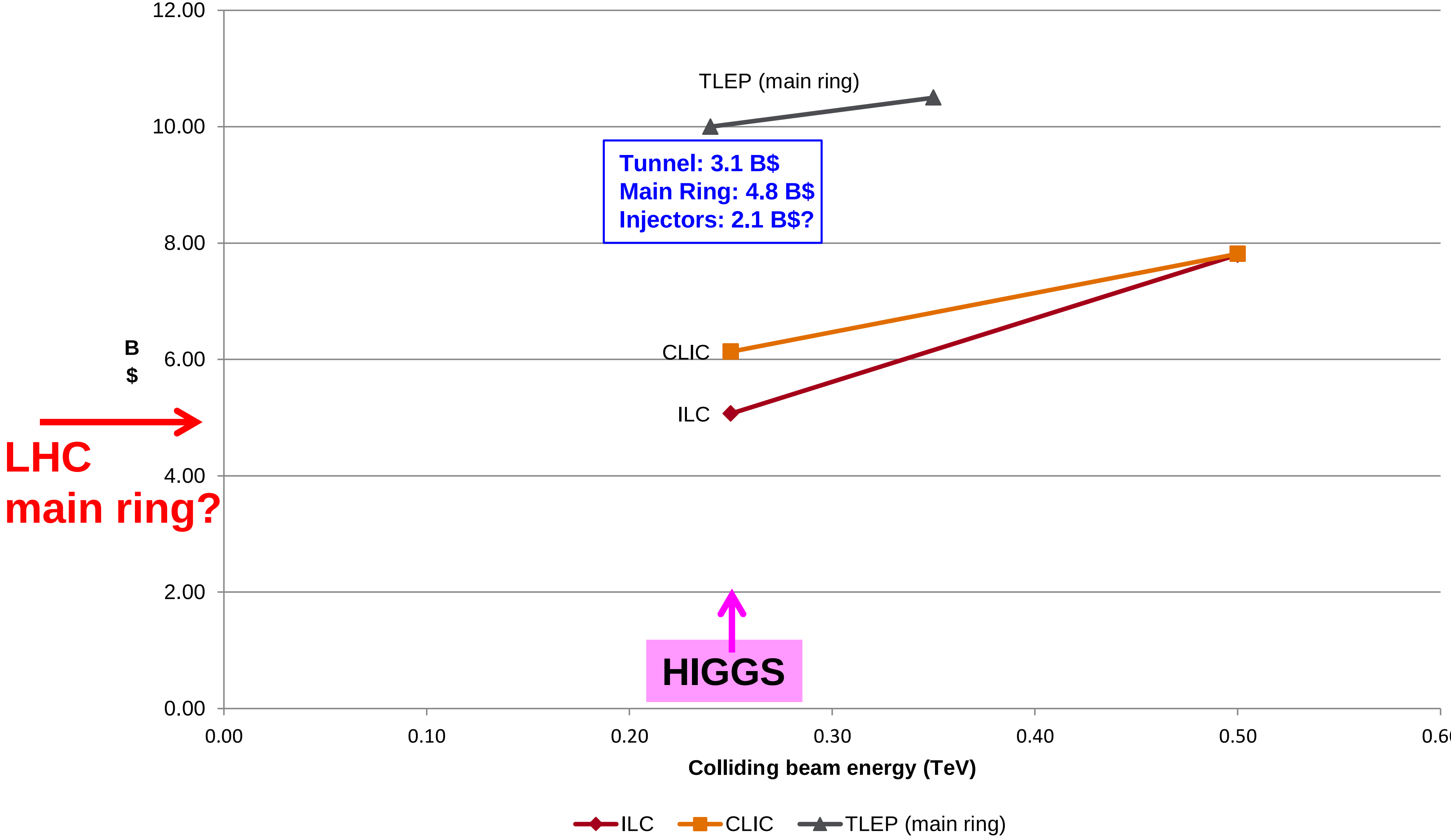
- **Same assumptions as for HL-LHC for a sound comparison**
  - **Total width fixed to the sum of the visible partial widths + correction** (Δg/g ~ 1/2 ΔBR/BR)

$$\sigma_{HZ} \propto g^2_{HZZ}, \text{ and } \sigma_{HZ} \times \mathrm{BR}(H \to XX) \propto g^2_{HZZ} g^2_{HXX} / \Gamma_H$$

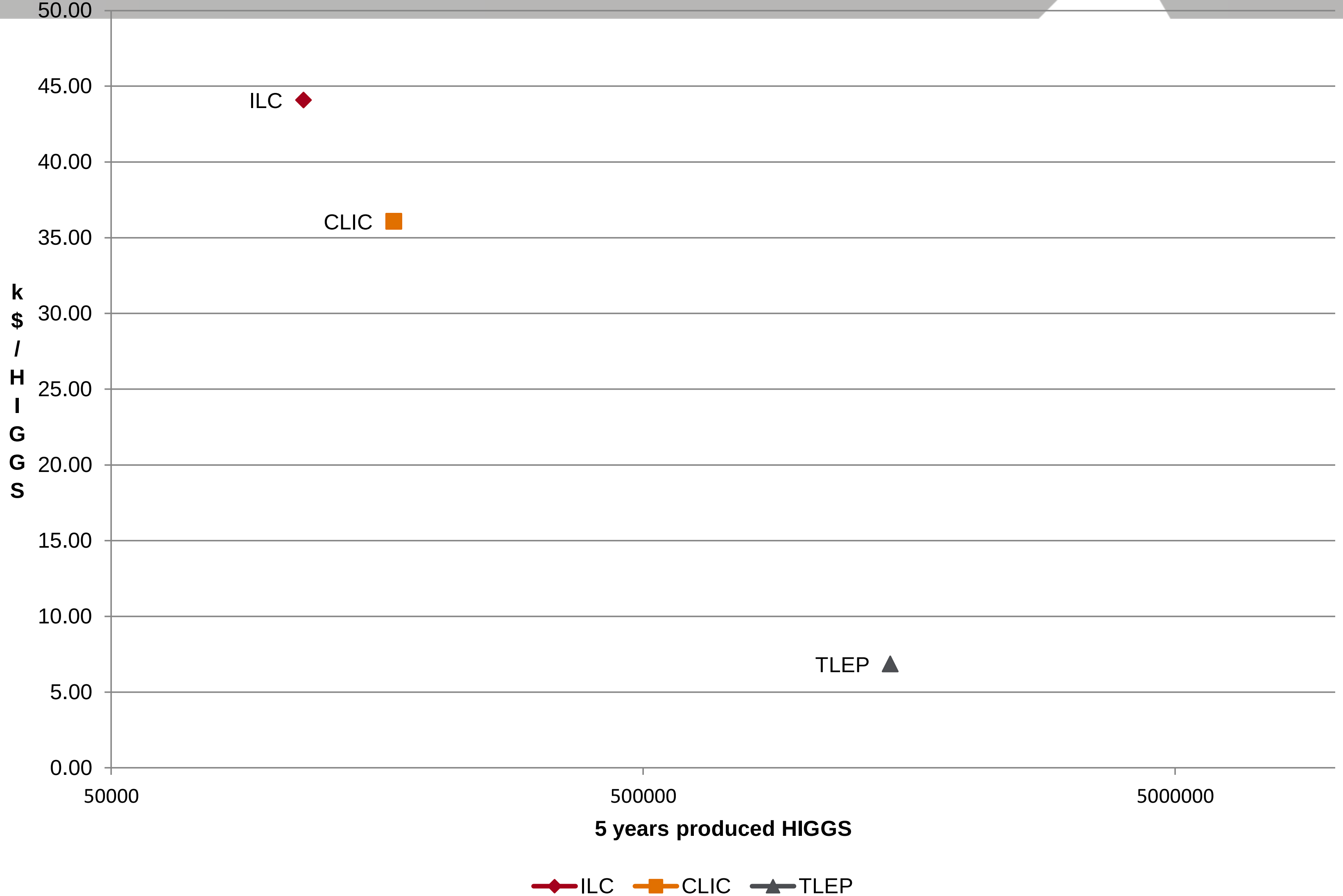


* HL-LHC projections are discussed later

Capital cost

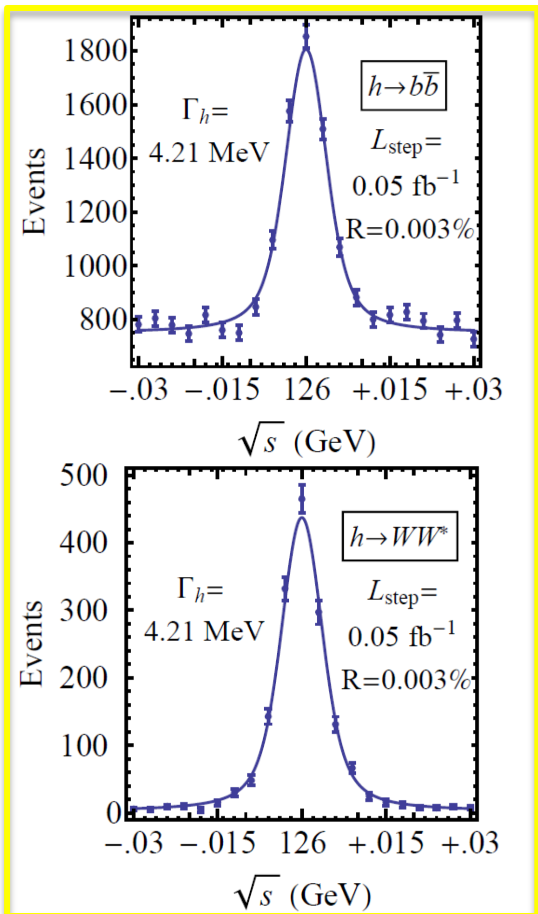


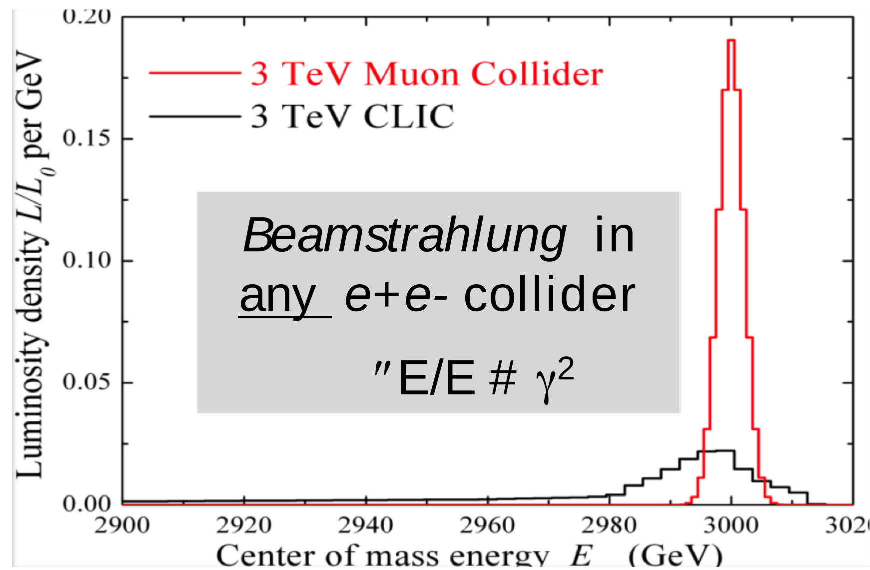
Capital cost per 5 years produced HIGGS



Muon Collider

- Synergetic with high intensity neutrino program
- Precisely known E_{CM} allows for direct Higgs width measurement
- $h\mu\mu$



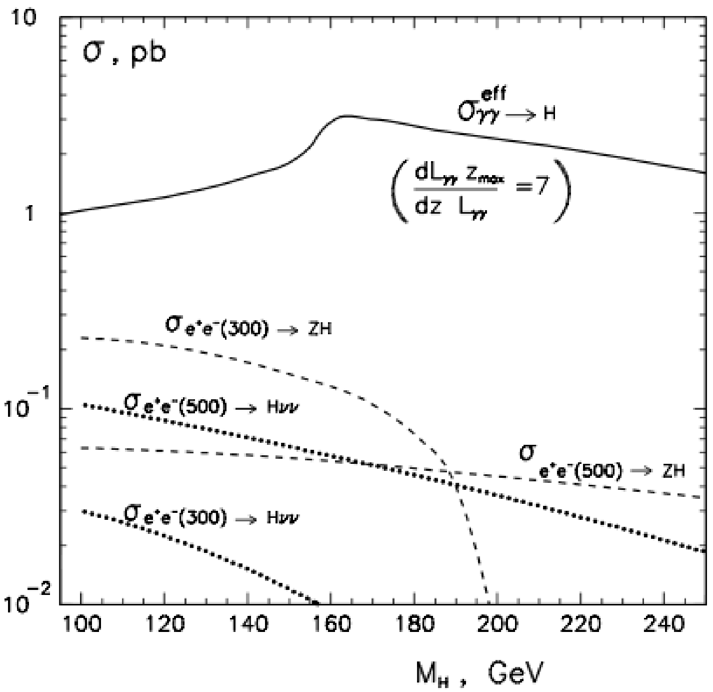


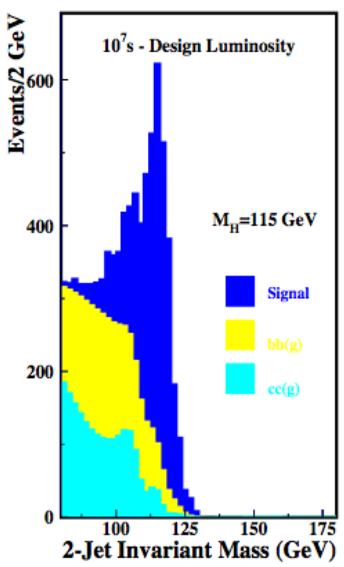
Han and Liu
hep-ph 1210.7803

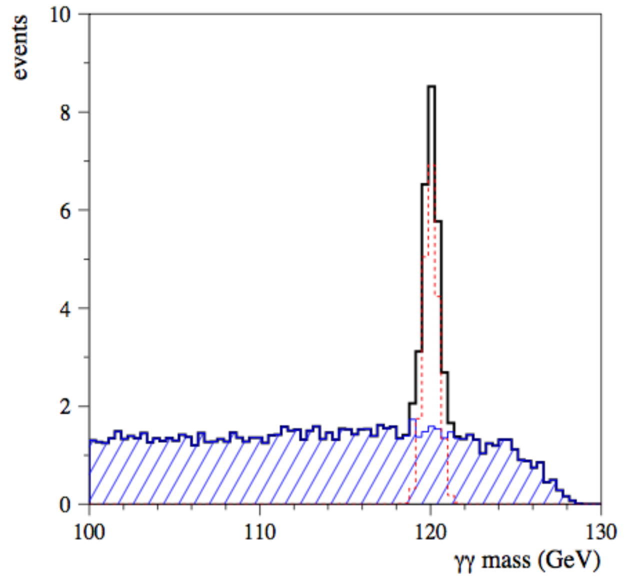
Photon Colliders

Addition to e^+e^- to get to $h\gamma\gamma$ coupling

$h^0 \to b\bar{b}$ **and** $h^0 \to \gamma\gamma$ hep-ex/0110056







2% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to b\bar{b})\}$ within a year!

M. Velasco

What about MELA-style analysis of $h \rightarrow Z\gamma^* \rightarrow Z\, l^+l^-$?

Only with

γγC

ζ_2 is the degree o

(ζ_3, ζ_1) are the degrees of linear polarization

In s-channel production of Higgs:

$$\overline{|\mathcal{M}^{H_i}|^2} = \overline{|\mathcal{M}^{H_i}|_0^2}\left\{[1+\zeta_2\tilde{\zeta}_2] + \mathcal{A}_1\left[\zeta_2+\tilde{\zeta}_2\right] + \mathcal{A}_2\left[\zeta_1\tilde{\zeta}_3+\zeta_3\tilde{\zeta}_1\right] - \mathcal{A}_3\left[\zeta_1\tilde{\zeta}_1-\zeta_3\tilde{\zeta}_3\right]\right\}$$

== 0 if CP is conserved

== +1 (-1) for CP is conserved for A CP-Even (CP-Odd) Higgs

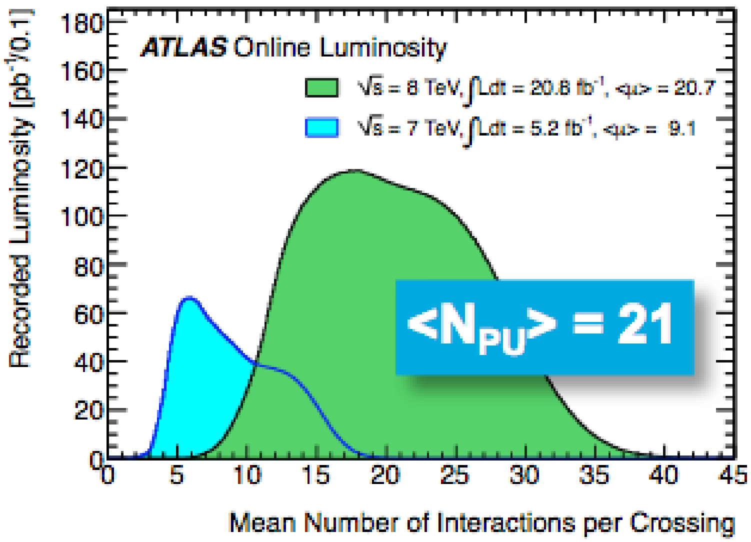
If $A_1 \neq 0$, $A_2 \neq 0$ and/or $|A_3| < 1$, the Higgs is a mixture of CP-Even and CP-Odd states

Possible to search for CP violation in gg → H → fermions without having to measure their polarization

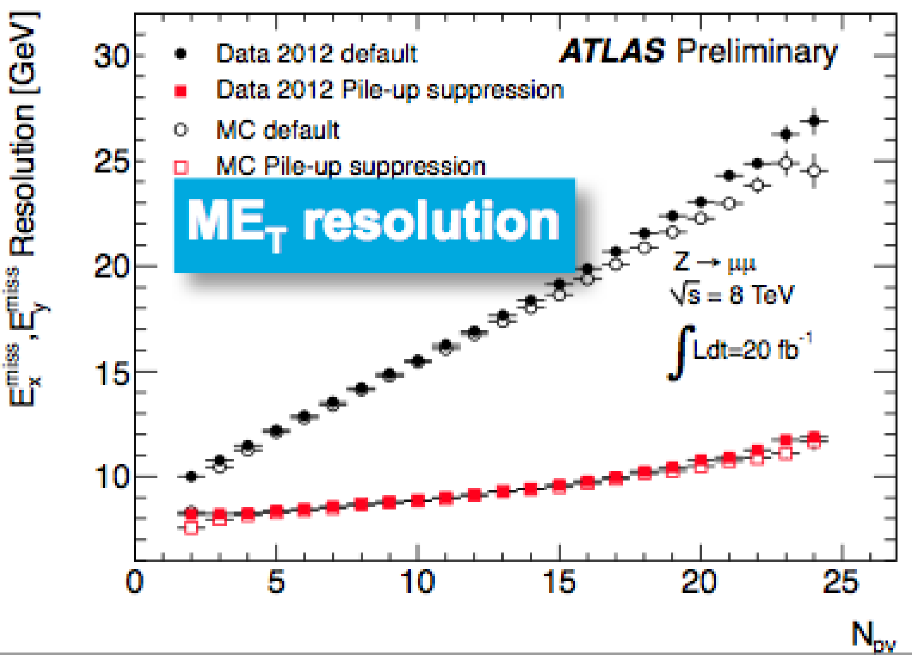
In bb, a < 1% asymmetry can be measure with 100 fb^{-1} that is, in 1/2 years

arXiv:0705.1089v2

LHC Projections

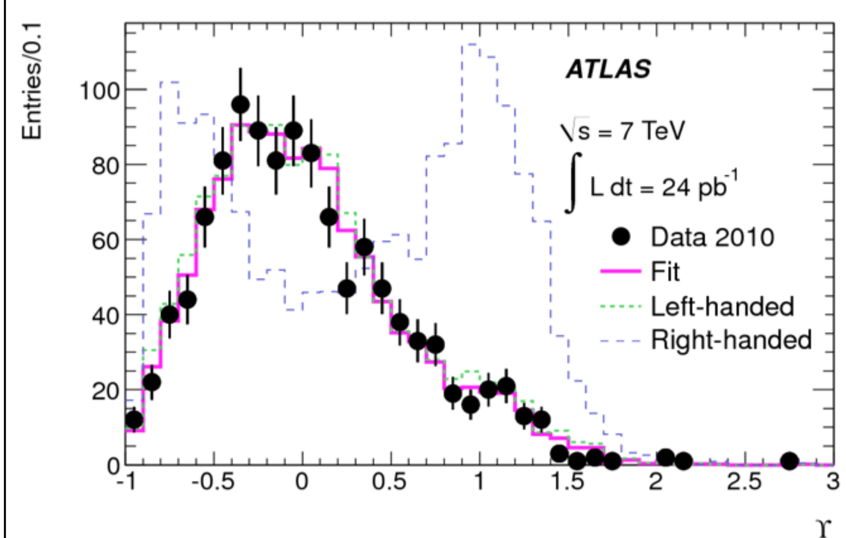


- Very messy environment
- Very well-segmented detectors
- Lots and lots of data



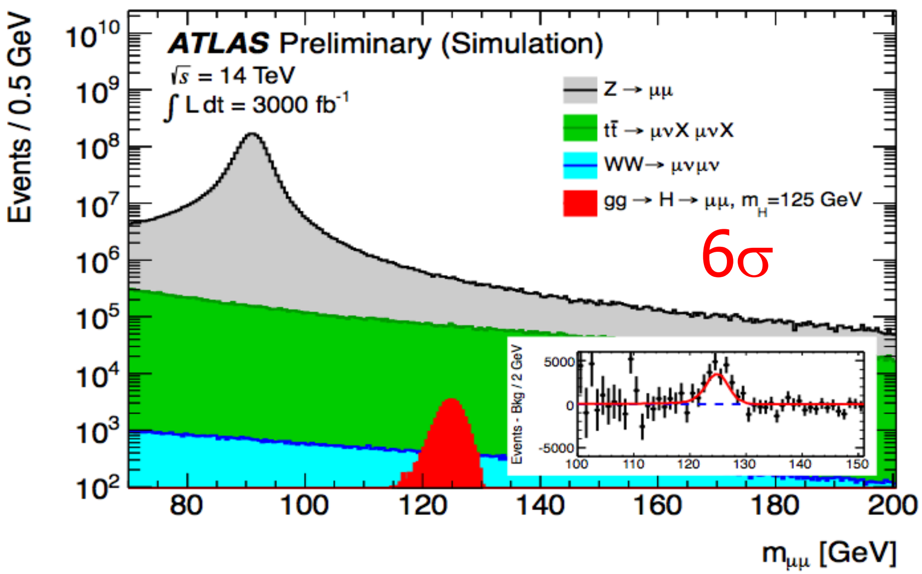
S. Demers

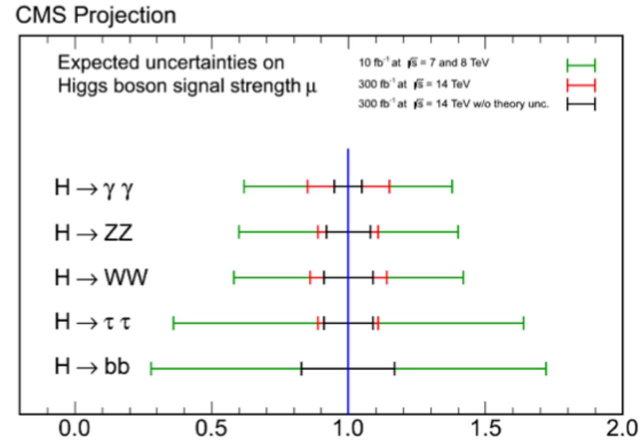
Measurements that rely on
tau polarization CAN be done at hadron colliders

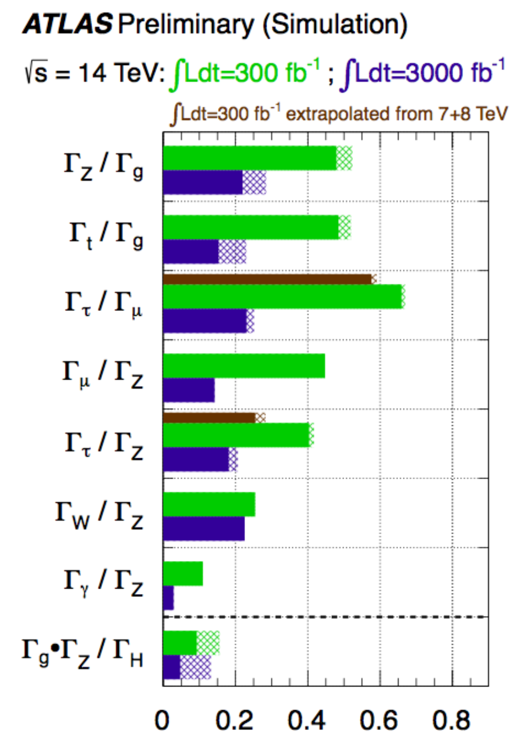


$$P_\tau = -1.06 \pm 0.04\ (stat)\ ^{+0.05}_{-0.07}\ (syst)$$

LHC Higgs Projections







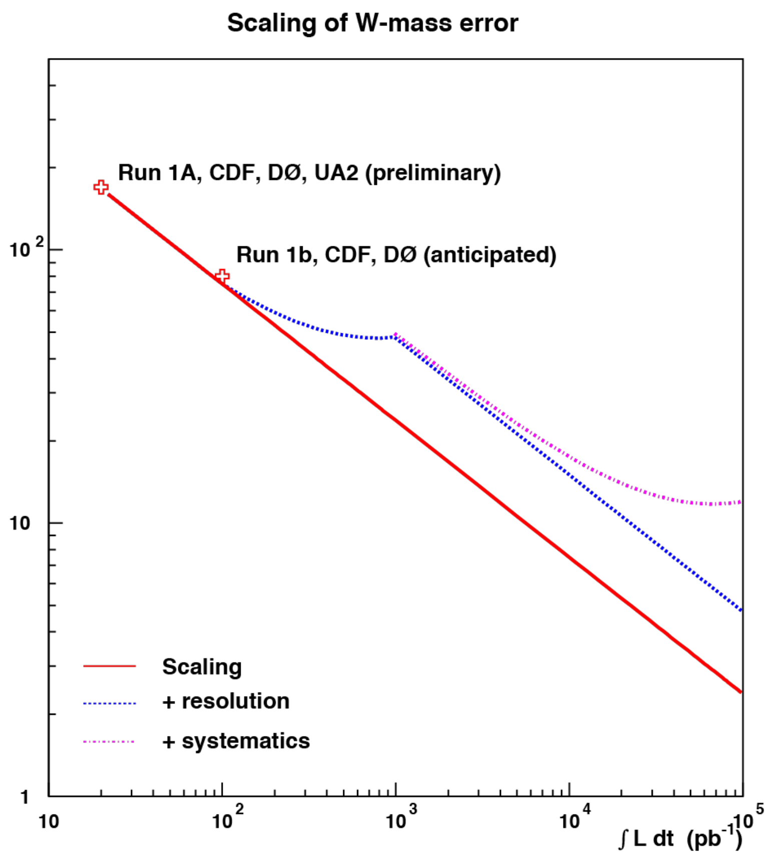
$$\frac{\Delta(\Gamma_X/\Gamma_Y)}{\Gamma_X/\Gamma_Y} \sim 2\frac{\Delta(\kappa_X/\kappa_Y)}{\kappa_X/\kappa_Y}$$

CMS Projection

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

Past Experience: W mass

- A plot from 1996 report from TeV-2000
- Extrapolations without exact knowledge of upgraded detector performance, how to deal with pile-up, how will the theory errors evolve, etc…



Report of the TeV-2000 Study Group:
SLAC-REPRINT-1996-085, FERMILAB-PUB-96-082

Past Experience: W mass

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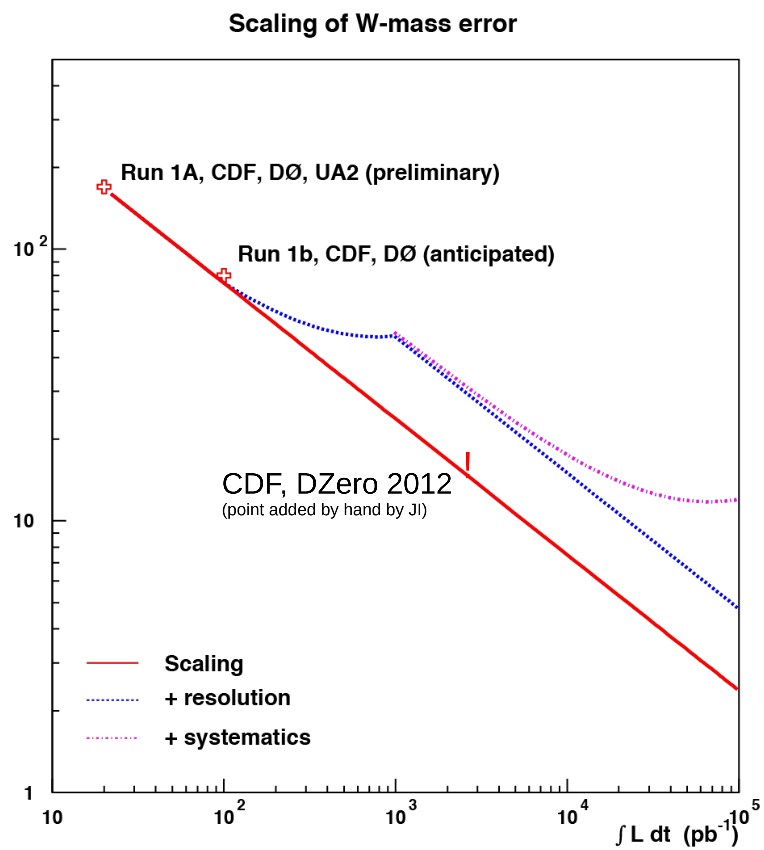


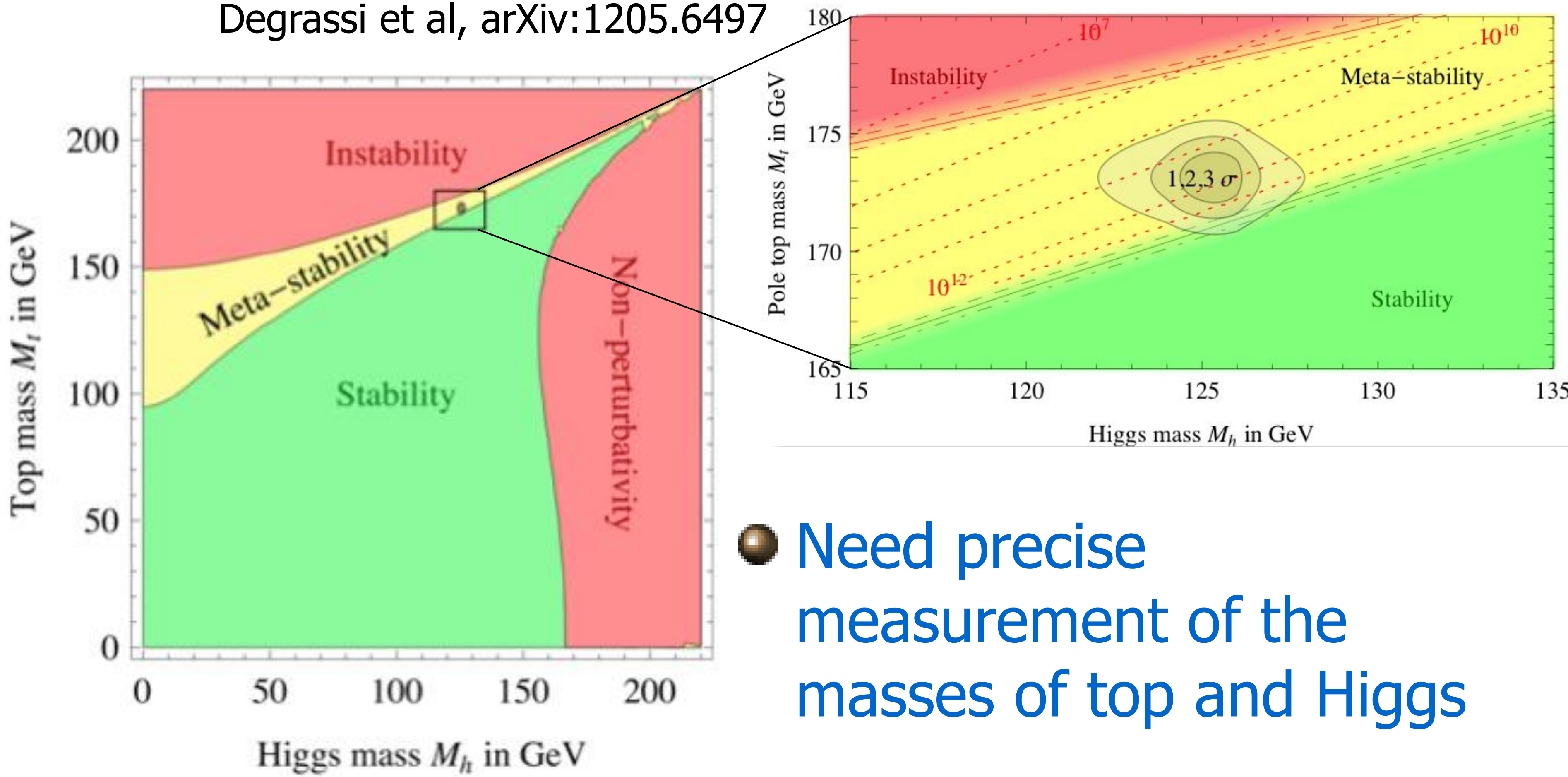
Report of the TeV-2000 Study Group:
SLAC-REPRINT-1996-085, FERMILAB-PUB-96-082

Tevatron EWWG: arXiv:1204.0042 [hep-ex]

Goldilocks Higgs

- Is it a Ragged Edge of Doom or the Nature is just trying to tell us something?

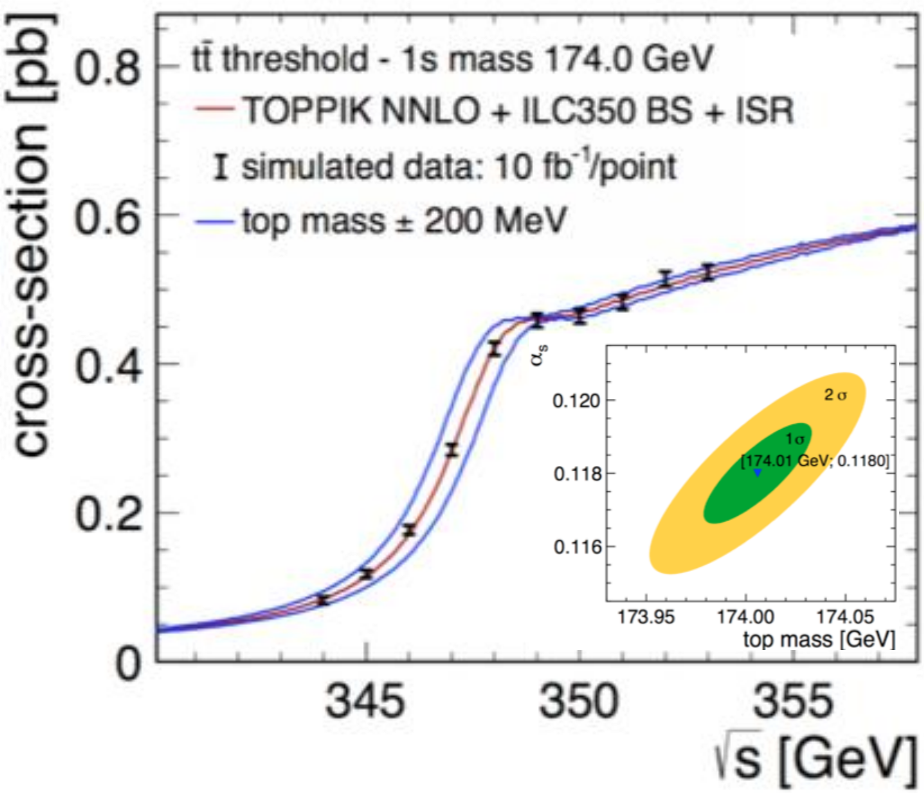
Degrassi et al, arXiv:1205.6497

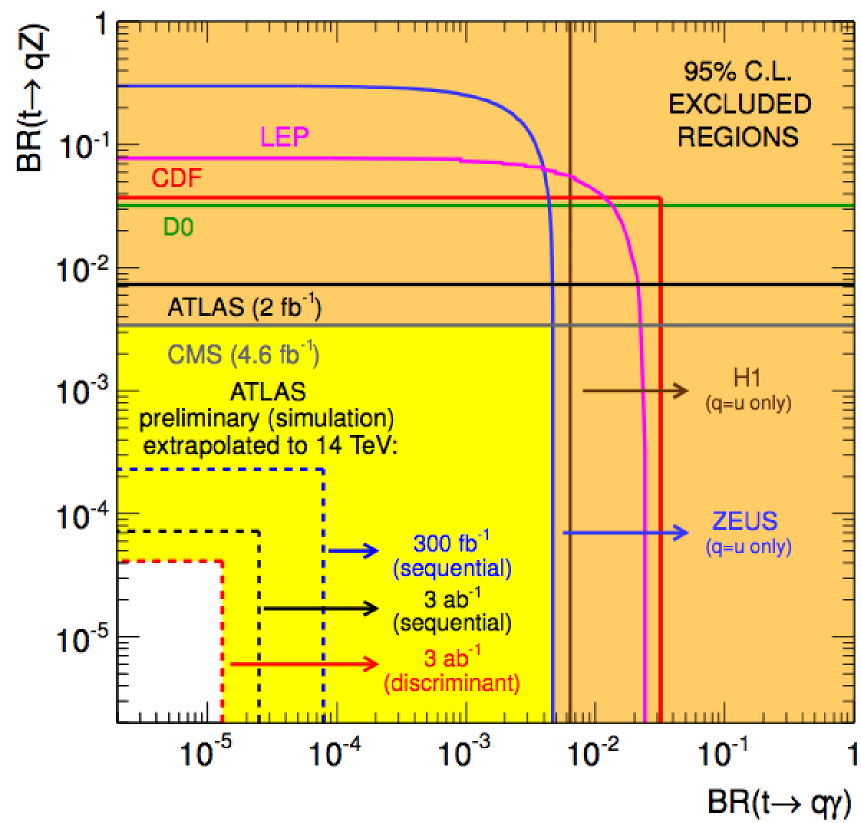


- Need precise measurement of the masses of top and Higgs

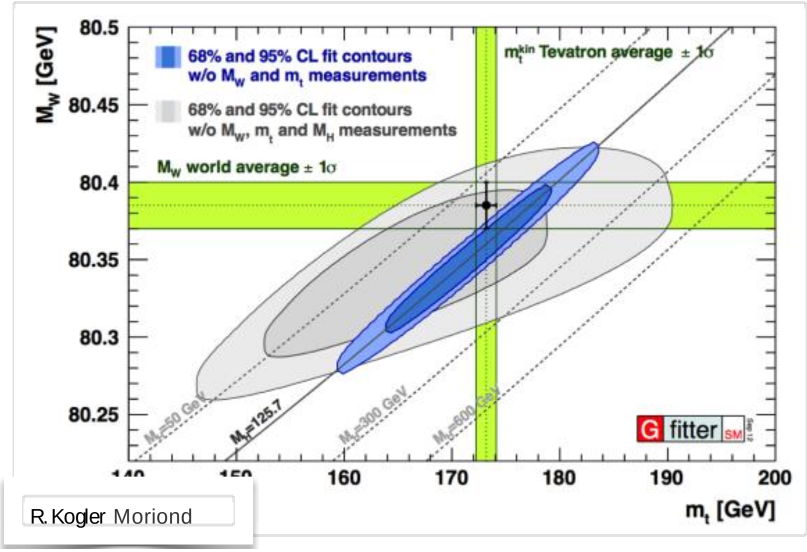
Top

- Lepton colliders can measure top "mass" to 0.1 GeV
- Hadron colliders lead on rare decays (i.e. FCNC)

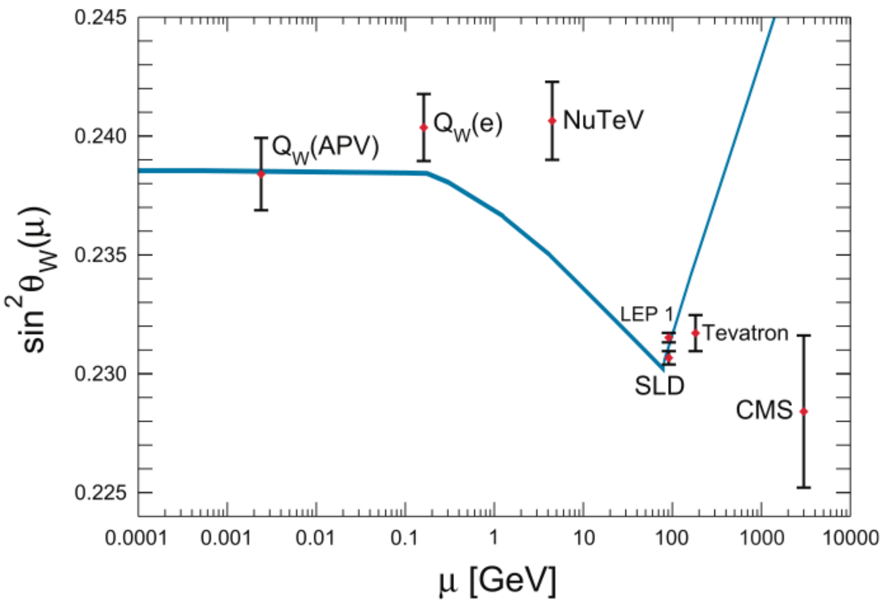


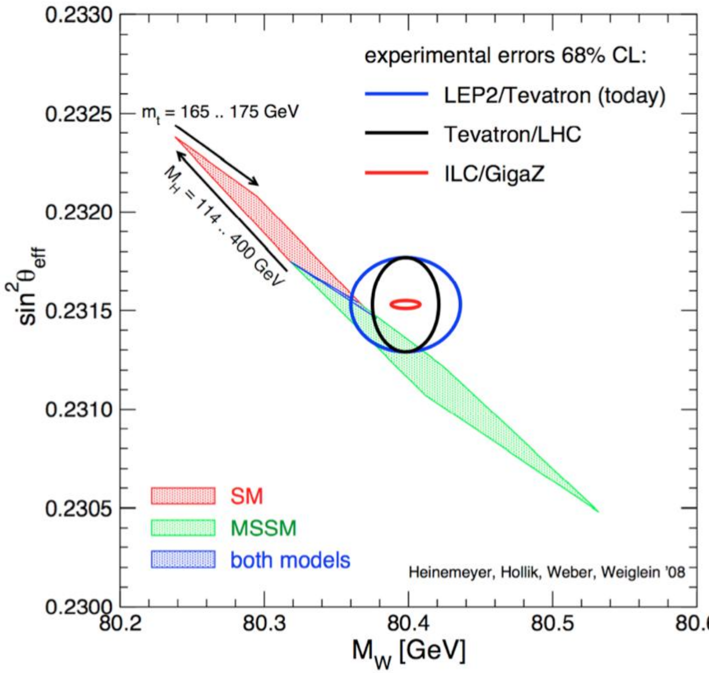


W mass and precision EWK



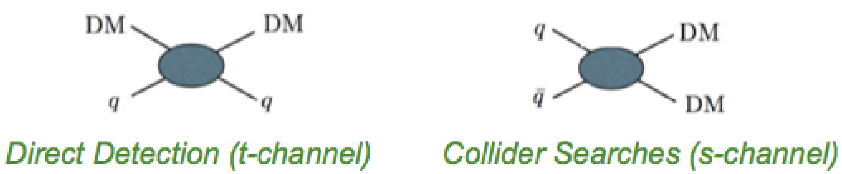
- With the Higgs discovery the SM is over-constrained
- Precise consistency tests are needed – and may indirectly indicate new physics

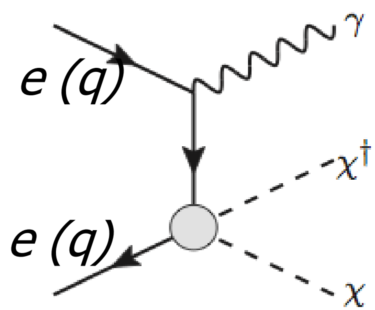


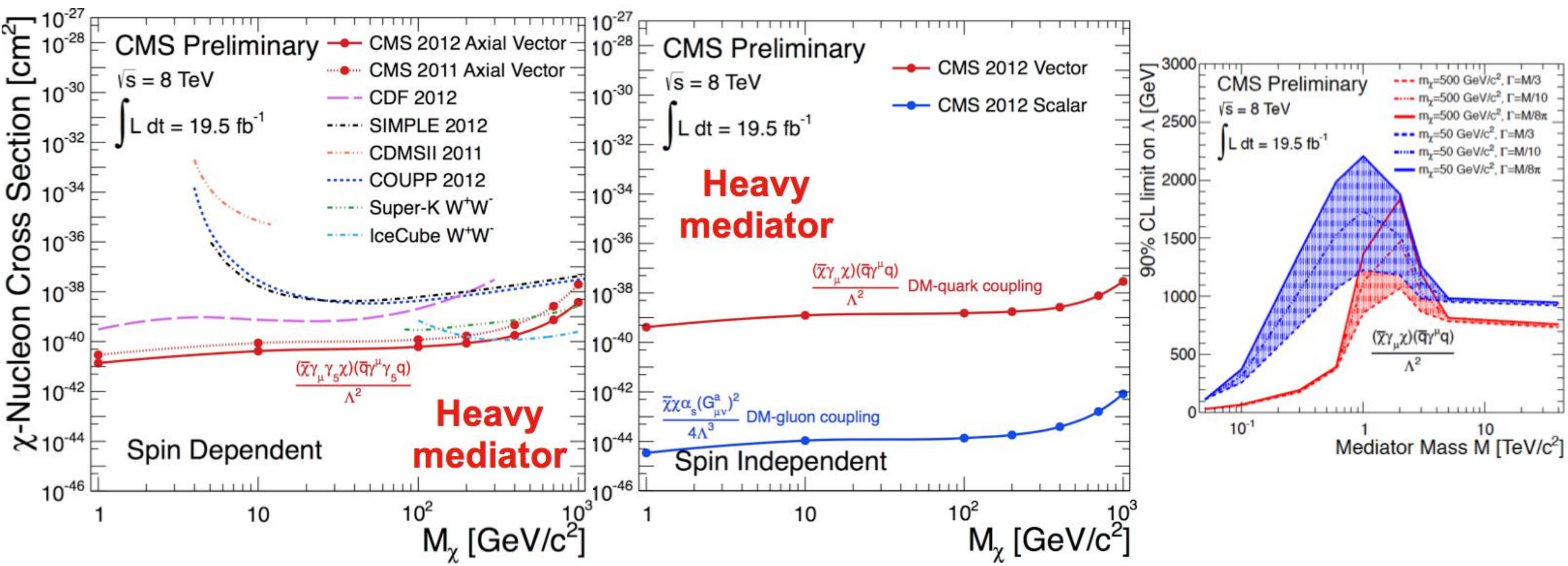


Dark Matter

- If DM is particle(s) interacting more then gravitationally, we can create DM with accelerators just as any other matter
  - Complementarity with direct searches





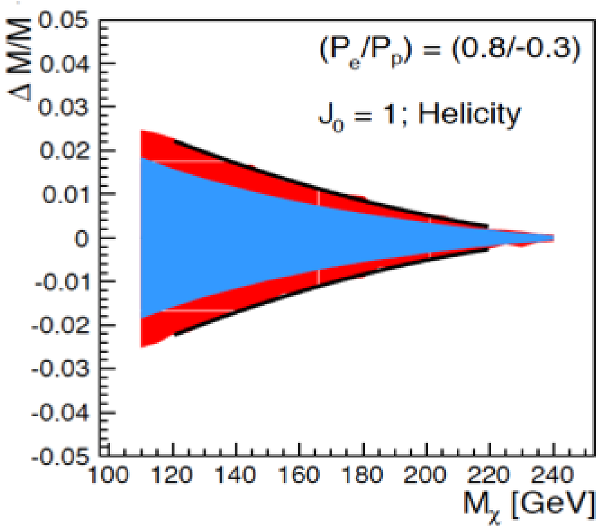


Dark Matter @ ILC

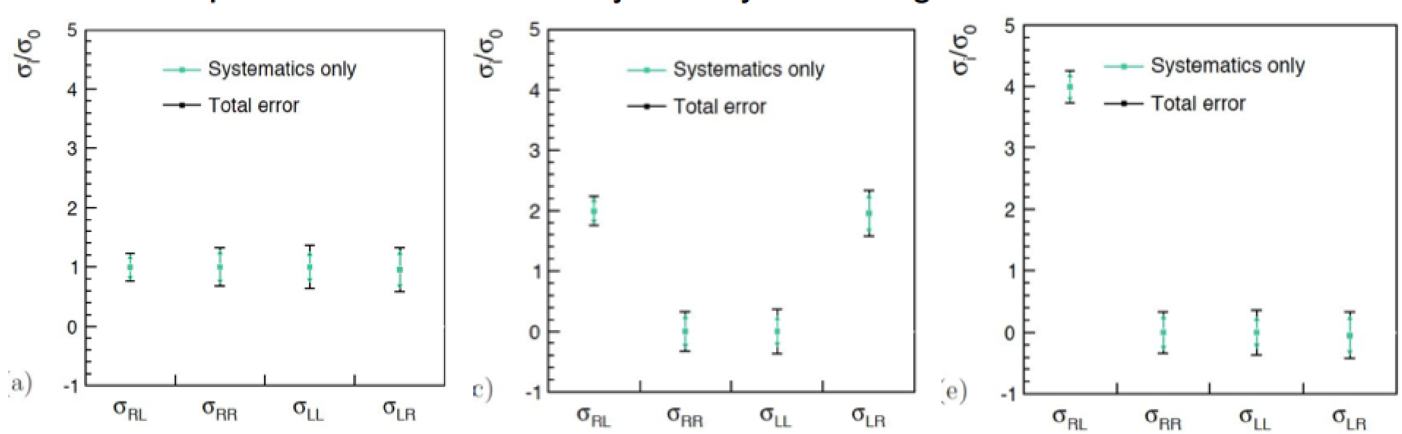
- Can measure mass and quantum numbers and helicity structure of fermion interaction

1206.6639 [hep-ex], Bartels et al

- Mass resolution
  eg ILC @ 500 GeV, 500fb^{-1},
  P(e^+,e^-) = (-30%,80%)
  - 1-2% level
    - Dominated by conservative assumption on knowledge of beam energy spectrum



- Three examplatory coupling scenarios:



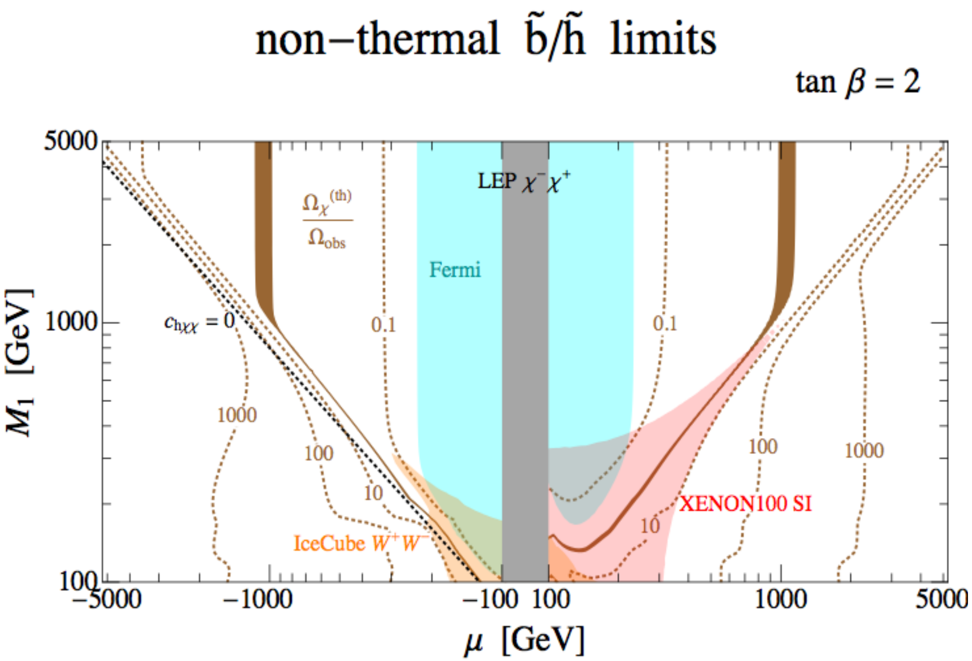
J. List

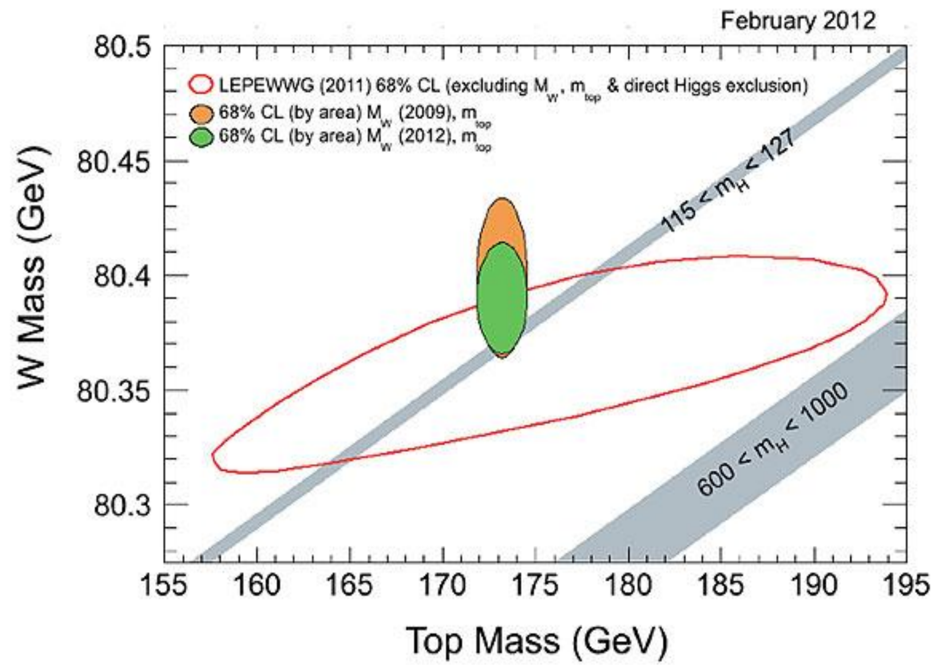
SUSY Dark Matter

- "Almost wiped out" or …
- "Now we know where it is?"

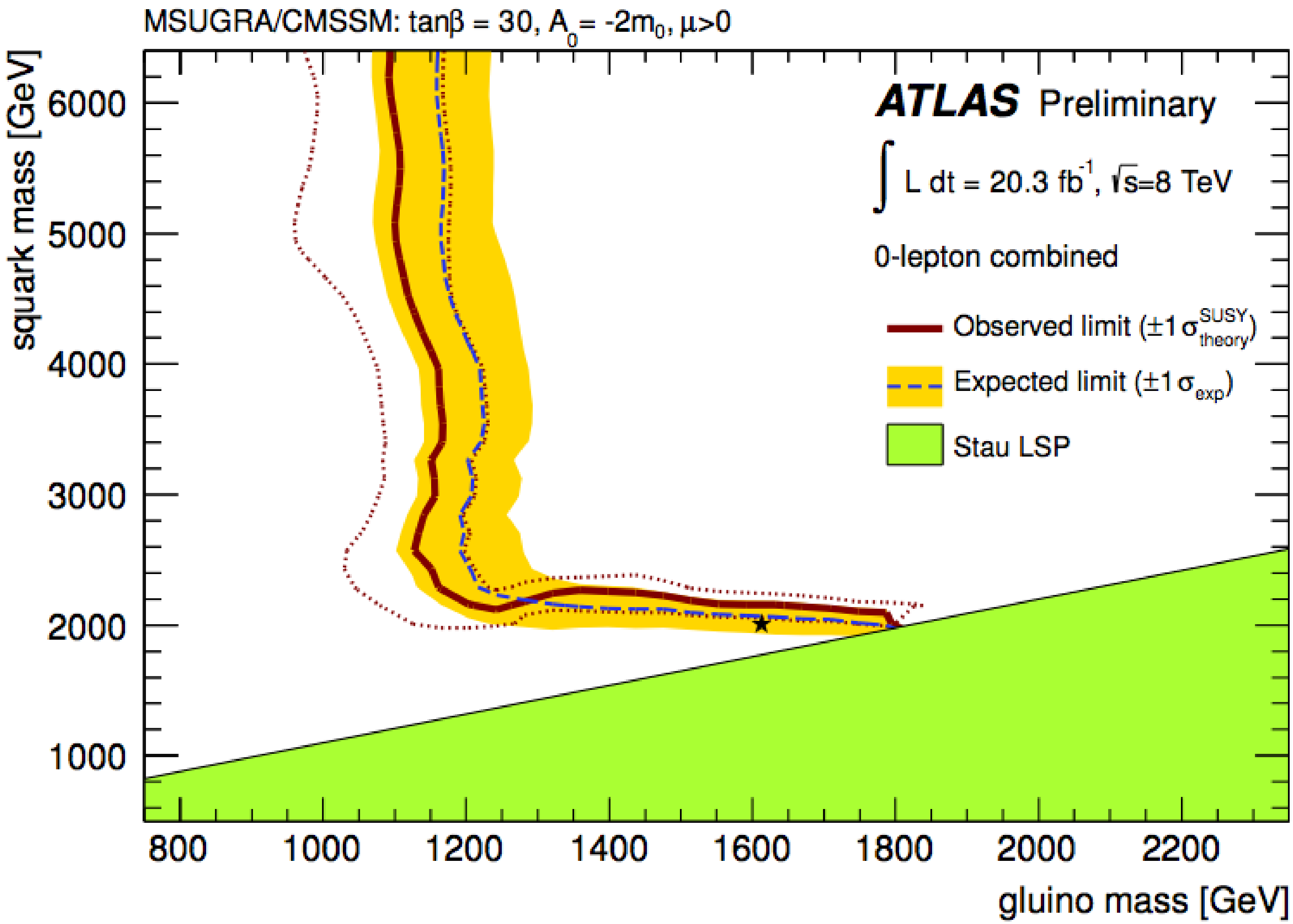
need to be acutely aware of our biases

arXiv:1211.4873





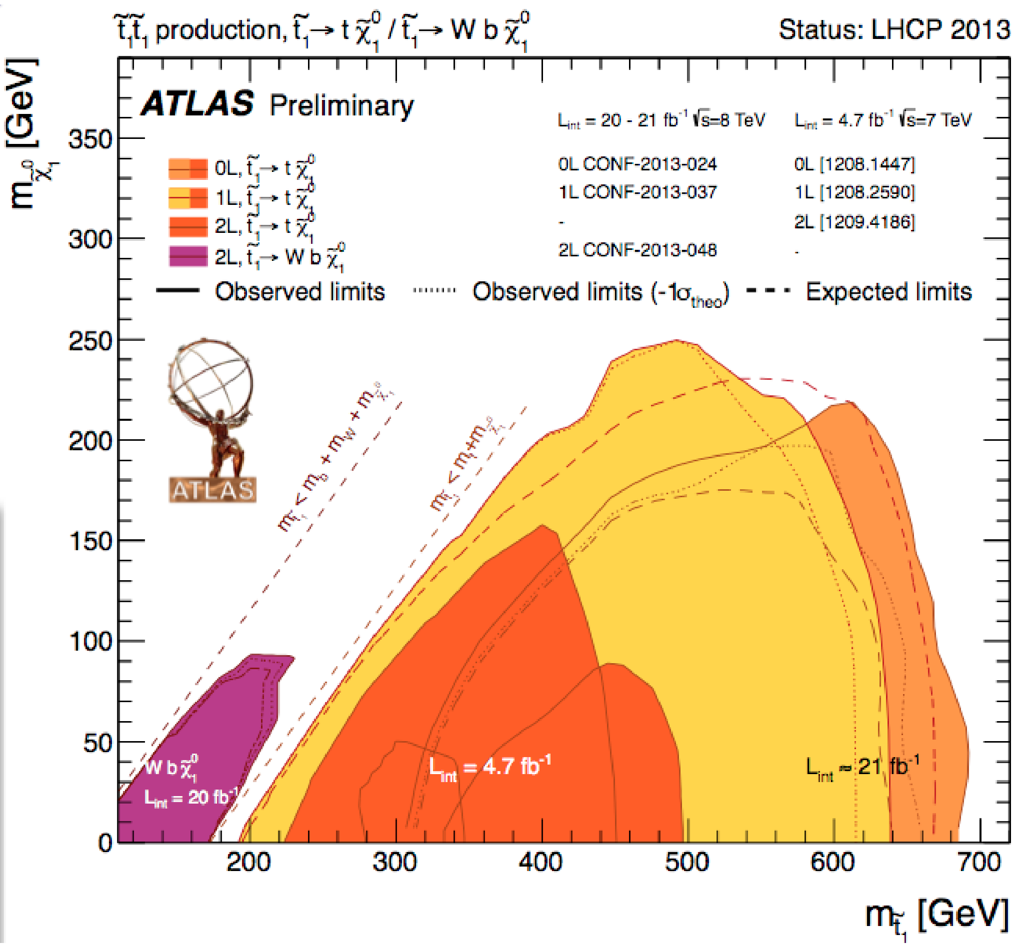
An Inconvenient SUSY

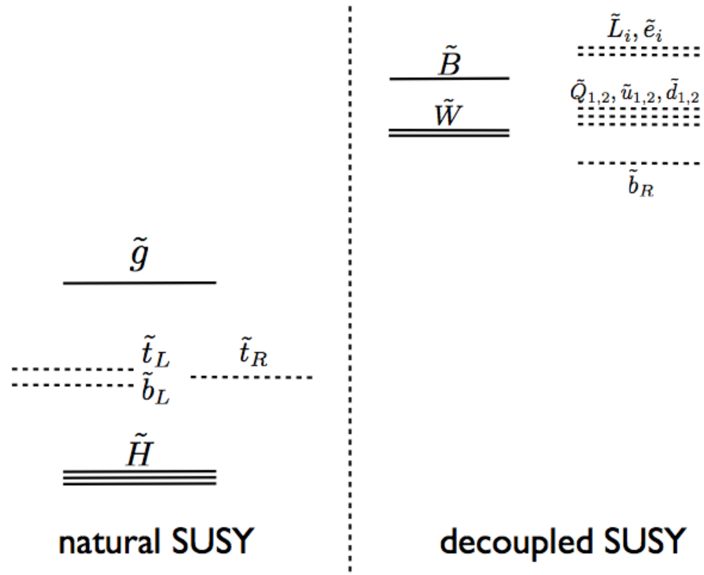


Light Stops

- Only starting to bite into "Natural" MSSM

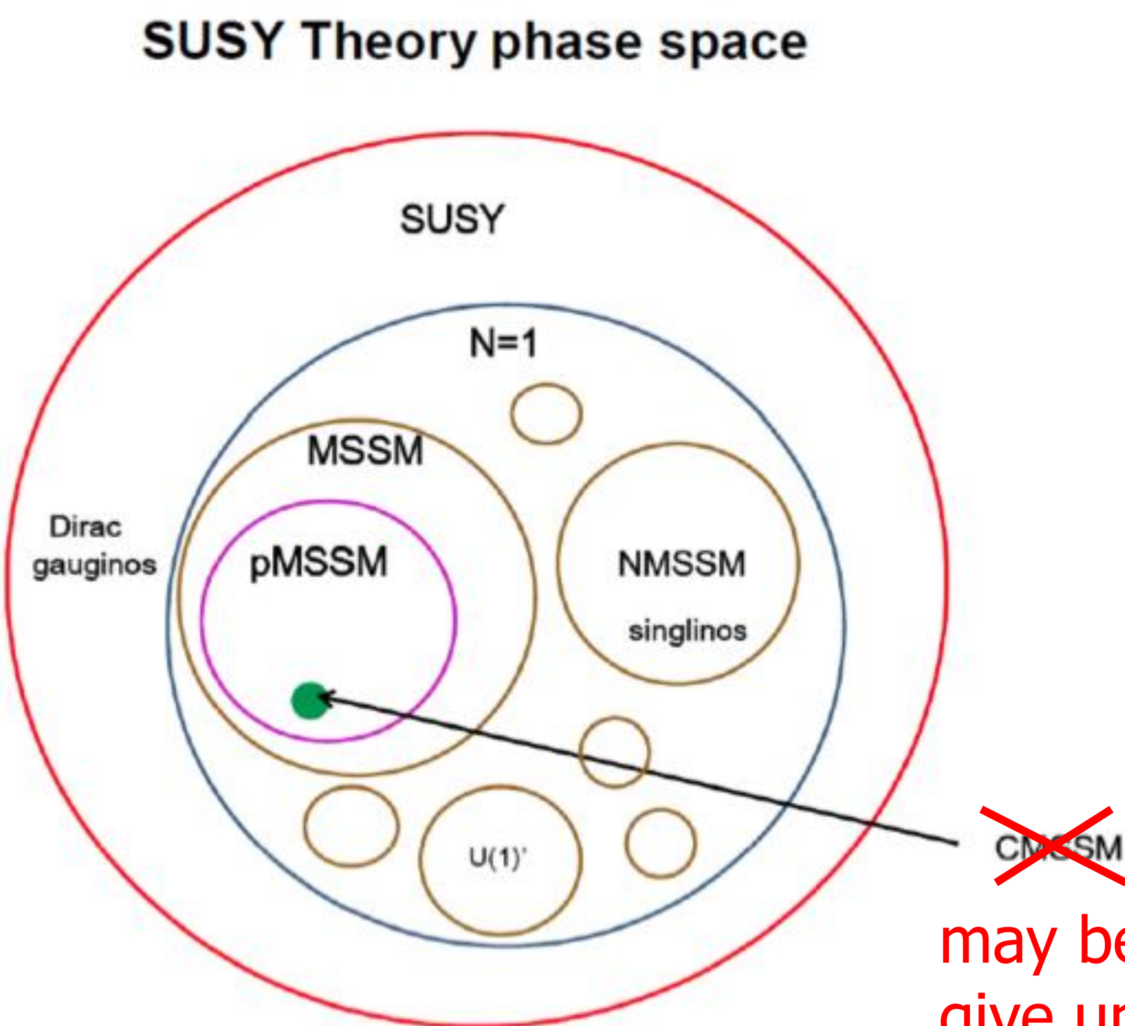
Papucci, Ruderman, Weiler
arXiv:1110.6926





Even smaller sensitivity so far if GMSB or RPV

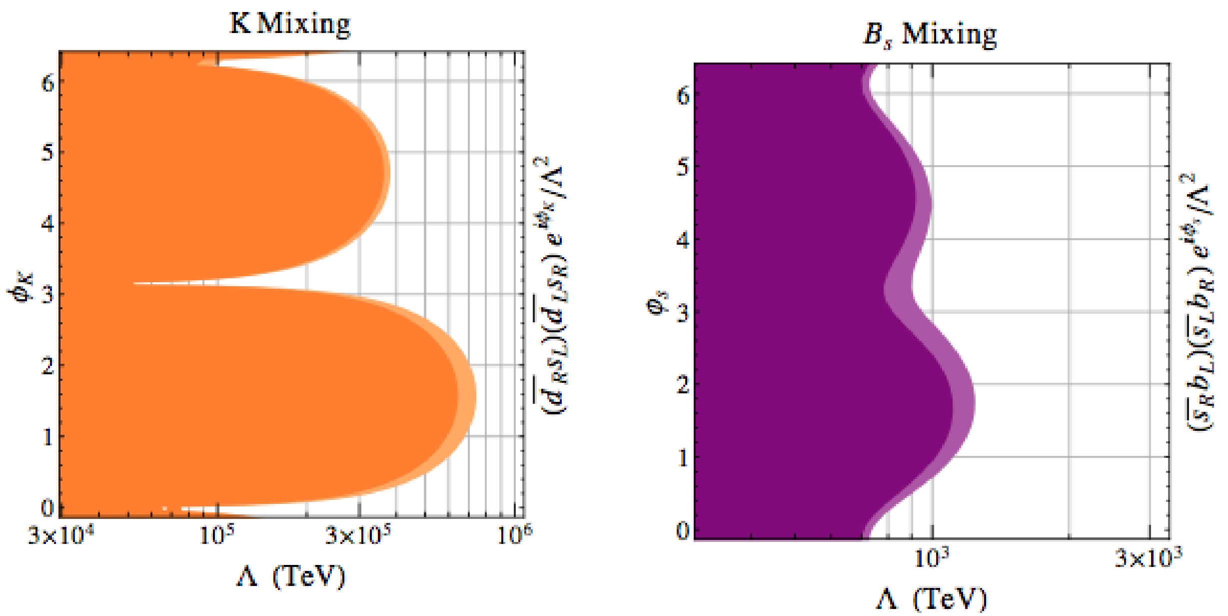
Far from the end of “Natural”



may be should give up on that

T. Rizzo (SLAC Summer Institute, 01-Aug-12)

Flavor as a guide



$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} + \sum_i \frac{c_i}{\Lambda_{\rm NP}^2}\mathcal{O}_i$$

- We can explore high scales with high precision flavor measurements, EDM's, etc.
- If we make a discovery in precision measurements we'd want to go study the energy scale that it predicts

Summary

- LHC is just at the start of a 20+ year well motivated program
  - High luminosity and energy upgrades planned
    - *and cost non-trivial amount of money*
  - Will US continue to be a major player?
- Multitude of options for electron-positron colliders
  - Linear or circular?
  - What is the main motivation – Higgs or BSM?
  - What is the future – grow energy of the ILC or switch back to protons?
  - Is US interested in participating?
- Photon collider
  - CP measurements are very important – what kind of statistics one would need to do competitive measurements at LHC / ILC / TLEP?
- Muon collider
  - Compact machine, synergetic with neutrino program
  - Direct measurement of Higgs width
  - Also can do a lot of what ILC can do (at higher technical risk)

J.P. Delahaye

Timelines of Higgs Factory projects

Approximate dates, uncertainty increases with time