Higgs Quo Vadis

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Feb. 26, 2013
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Before July 4th we have three types of fundamental particles:

- Spin-1/2 particle (electron)
  --> Relativistic Quantum Field Theory
- Spin-1 particle (photon, W/Z bosons)
  --> Qantum Mechanics (photon), Gauge field theories (W/Z bosons).
- Spin-2 particle (graviton)
  --> Holy Grail of fundamental physics ?

A Higgs boson would be the first (seemingly) fundamental spin-0 particle in Nature!

We expect its discovery to lead to similar revolutions!

The single most important guiding principle for “Higgs” theories is the Naturalness Principle.

Naturalness is best explained by a classic example:

Why isn’t the mass of electron infinite?

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Why isn’t the mass of electron infinite?

The electron has, as part of its rest energy, a Coulomb potential

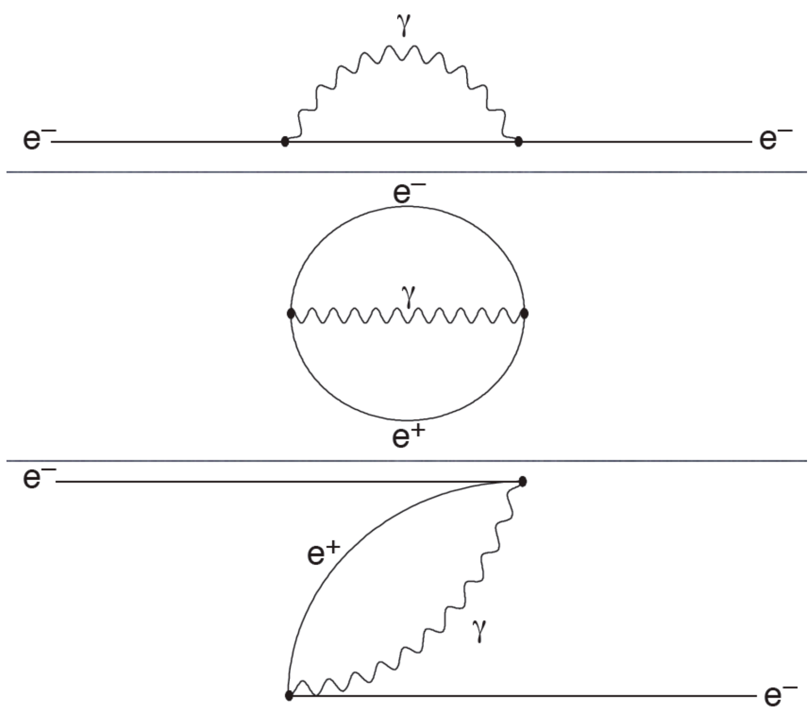
$$m_e \sim \frac{1}{4\pi\epsilon_0}\frac{e}{r}$$

which is infinite for a point particle.

If we use current limit on the size of an electron < 10^{-18} m

$$m_e(r_0) \sim 10\ \mathrm{GeV} \quad \gg \quad m_e^{\mathrm{exp}} = 5 \times 10^{-4}\ \mathrm{GeV}$$

The solution is to introduce new particles, the positron:

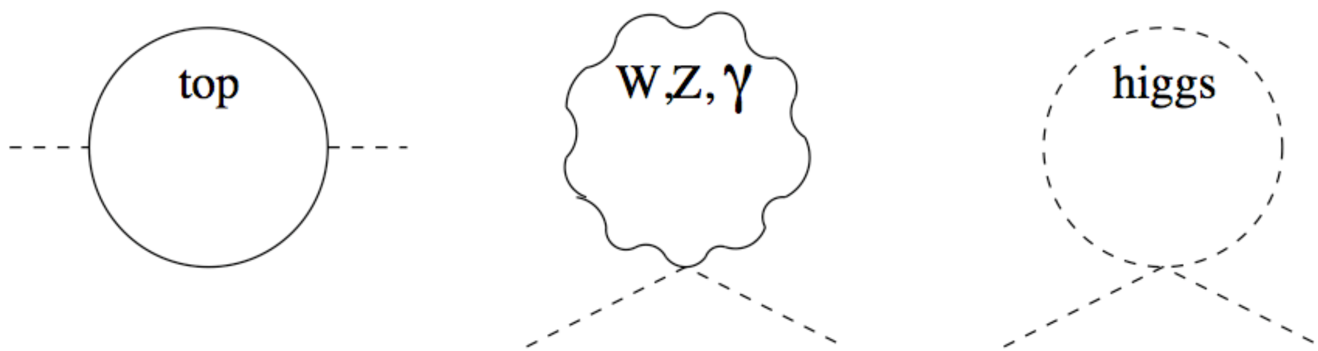


such a cancellation is guaranteed by a new symmetry called the chiral symmetry.

At the same time, the spacetime symmetry is enlarged from rotation to the Lorentz symmetry!

Lesson: Naturalness principle "predicts" new degrees of freedom and new symmetry principles to cancel the infinity in the electron mass!

The Higgs boson has a similar naturalness problem:



Since we have measured the Higgs mass to be at around 126 GeV, naturalness principle would imply new physics at around 1 TeV from

$$\delta m_h^2 = \frac{1}{16\pi^2}\Lambda_{\rm new}^2 \sim \mathcal{O}((100\ \mathrm{GeV})^2)$$

Questions the Higgs program seeks to answer:

- Hints of more dynamic and symmetry princples? Supersymmetry? Compositeness?
- Does the naturalness principle work?
- Are there more new particles out there?

More importantly, there's empirical evidence for "physics beyond the standard model".

Three examples are:

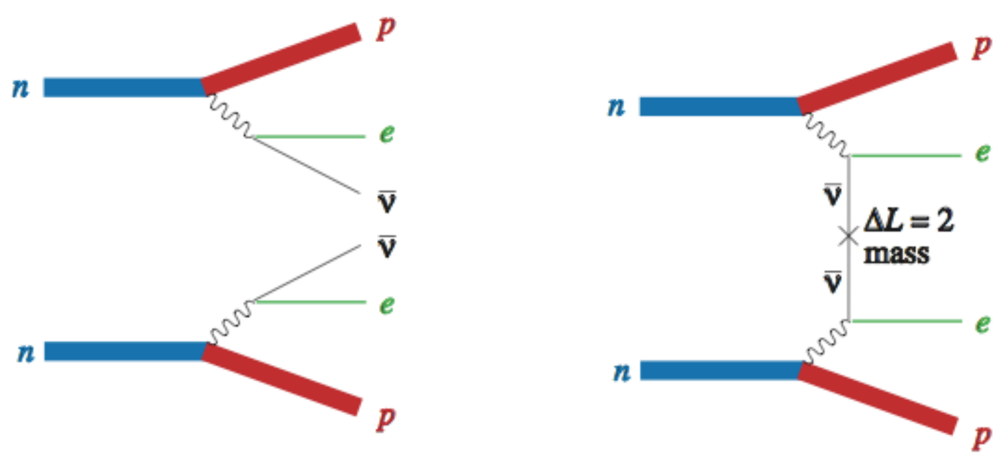
- Compelling evidence for non-baryonic dark matter
- Neutrino oscillations
- Cosmic baryon asymmetry

Majority of models that attempt to address the naturalness problem in the Higgs mass also have far reaching implications for:

- Neutrino masses –

doublet Higgs: $$\frac{\lambda_{ij}}{M}(L_iH)^T(L_jH), \quad i,j=e,\mu,\tau,$$

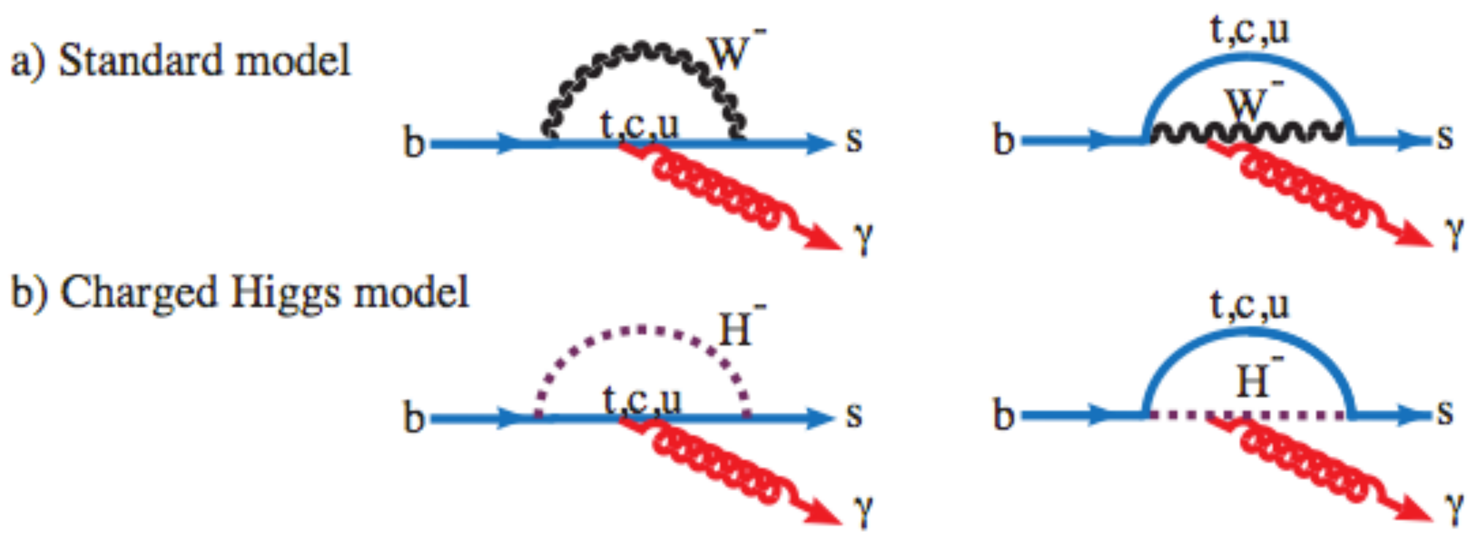
triplet Higgs: $$f_\Delta L^T L\Delta + h.c.$$



Strumia and Vissani:0606054

Majority of models that attempt to address the naturalness problem in the Higgs mass also have far reaching implications for:

- Flavor problems --



Stone:1212.6374

Majority of models that attempt to address the naturalness problem in the Higgs mass also have far reaching implications for:

- Dark matter –

Precision electroweak measurements and the WIMP paradigm:

In order for new physics at TeV scale to be compatible with the precision electroweak measurements, one often need a new "parity" such that all new particles are odd under the new parity and must be pair-produced at colliders. (R-parity in SUSY, KK-parity in extra-dimensions, and T-parity in little Higgs theories.)

The lightest parity-odd particle is then cosmologically stable and, if it is neutral, is a natural dark matter candidate.

Cheng and Low:0308199

The Higgs boson is central to understanding the major problems in particle physics!

We are entering an era of "Precision Higgs measurements!"

"Higgs" boson couplings to SM matters at leading orders:

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

$$+ c_g \frac{\alpha_s}{12\pi v} h \, G_{\mu\nu}^a G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h \, F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w} \, h \, F_{\mu\nu} Z^{\mu\nu}$$

$$+ \sum_f c_f \frac{m_f}{v} h \bar{f} f$$

I will start with the loop-induced couplings and the lessons one could from measuring them precisely.

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

$$+c_g \frac{\alpha_s}{12\pi v} h G_{\mu\nu}^a G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w} h F_{\mu\nu} Z^{\mu\nu}$$

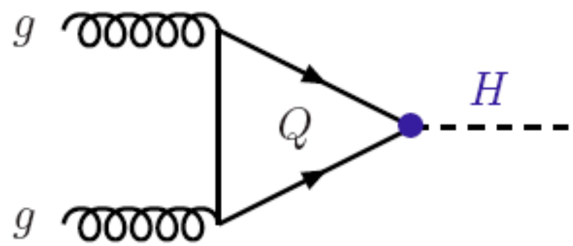
$$+ \sum_f c_f \frac{m_f}{v} h \bar{f} f$$

But in the end we'll see that we need to know many other (tree) couplings as well!

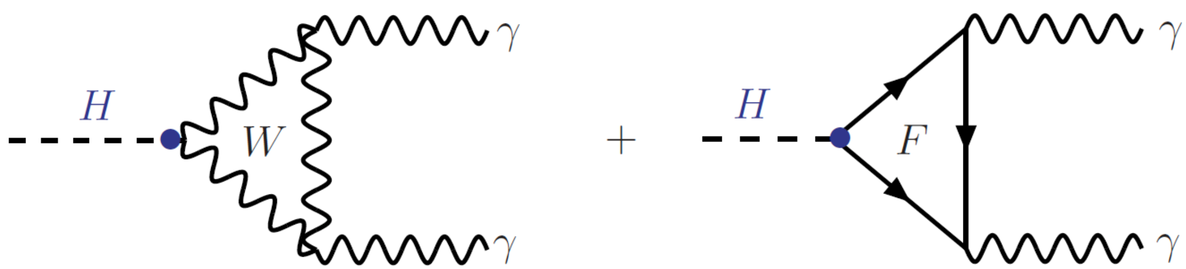
Why loop-induced couplings?

Experimentally

- The dominant Higgs production mode at the LHC is through gluon fusion process, a loop-induced process mediated by the top loop in the standard model:



- Higgs to diphoton decays are also mediated by the W loop and the top loop:



Why loop-induced couplings?

Theoretically

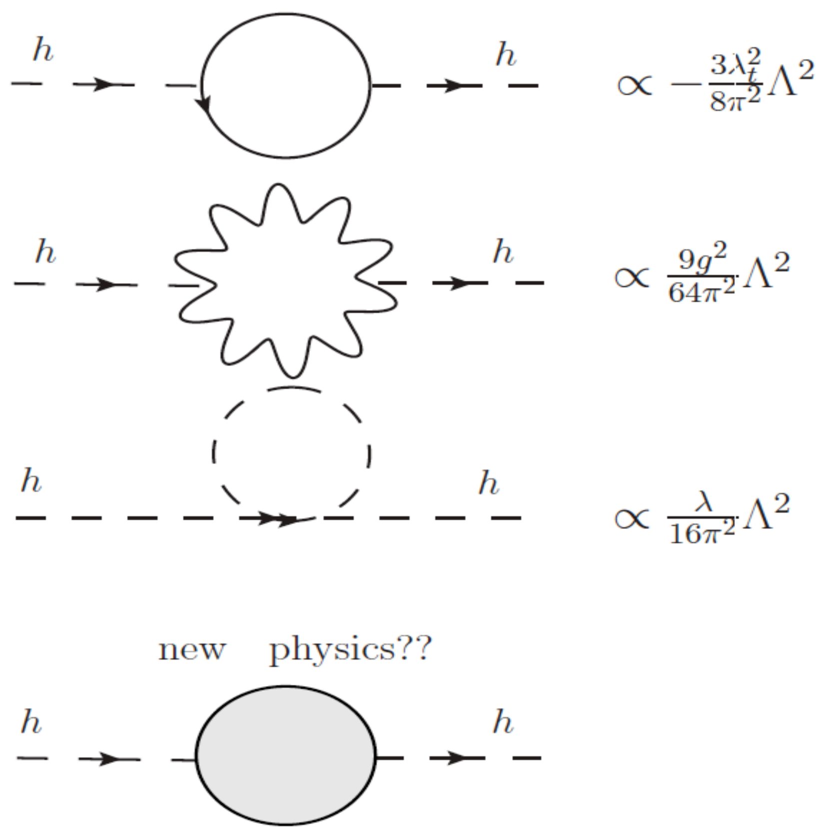
- They are excellent indirect probe to new physics.

- They are intimately connected to the major guiding principle for physics beyond the SM:

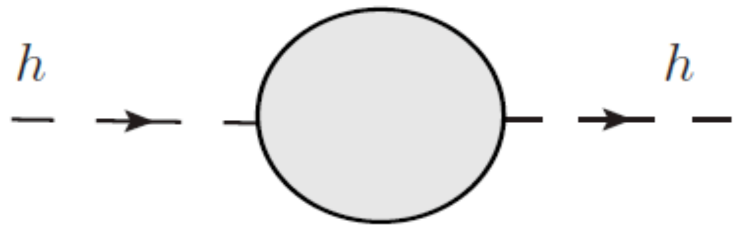
  The naturalness principle.

Naturalness:

one-loop quadratic divergences in the Higgs mass is cut off by some "blob" at the TeV scale:



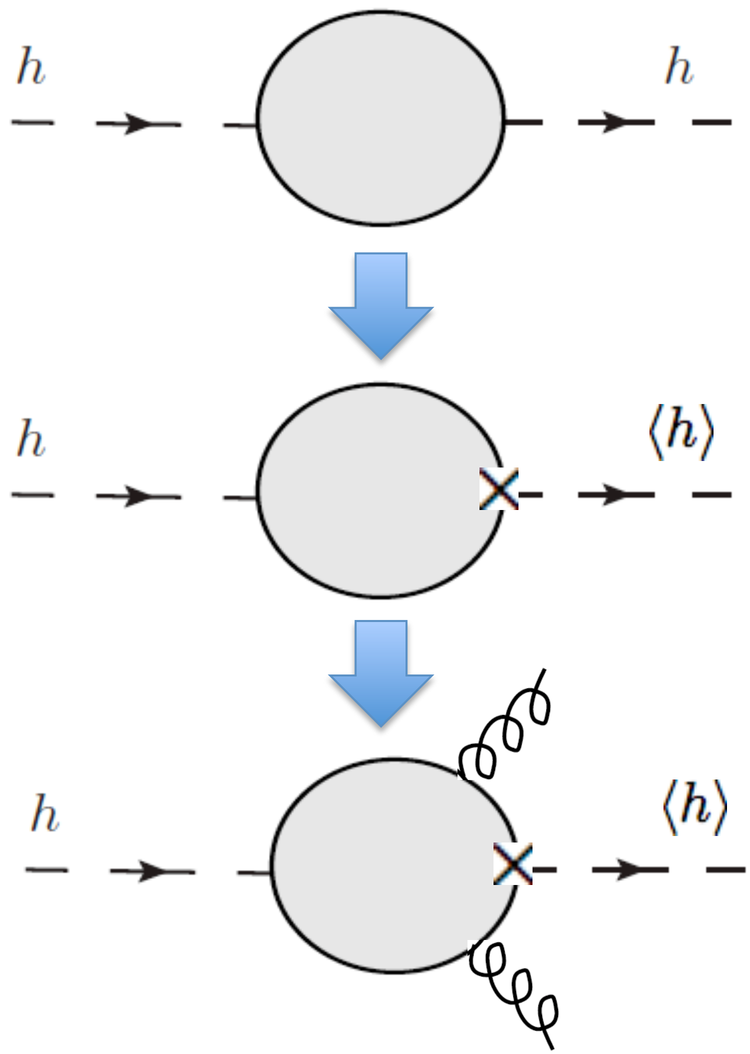
Lock up 10 model-builders in one room and they'll come up with 10^N (N>1) models for the "blob" in no time:



However, no matter what the blob is,

- if it carries QCD color, Higgs-glue-glue coupling will be modified.
- if it carries weak isopsin or hypercharge, Higgs-photon-photon and Higgs-Z-photon couplings will be modified.

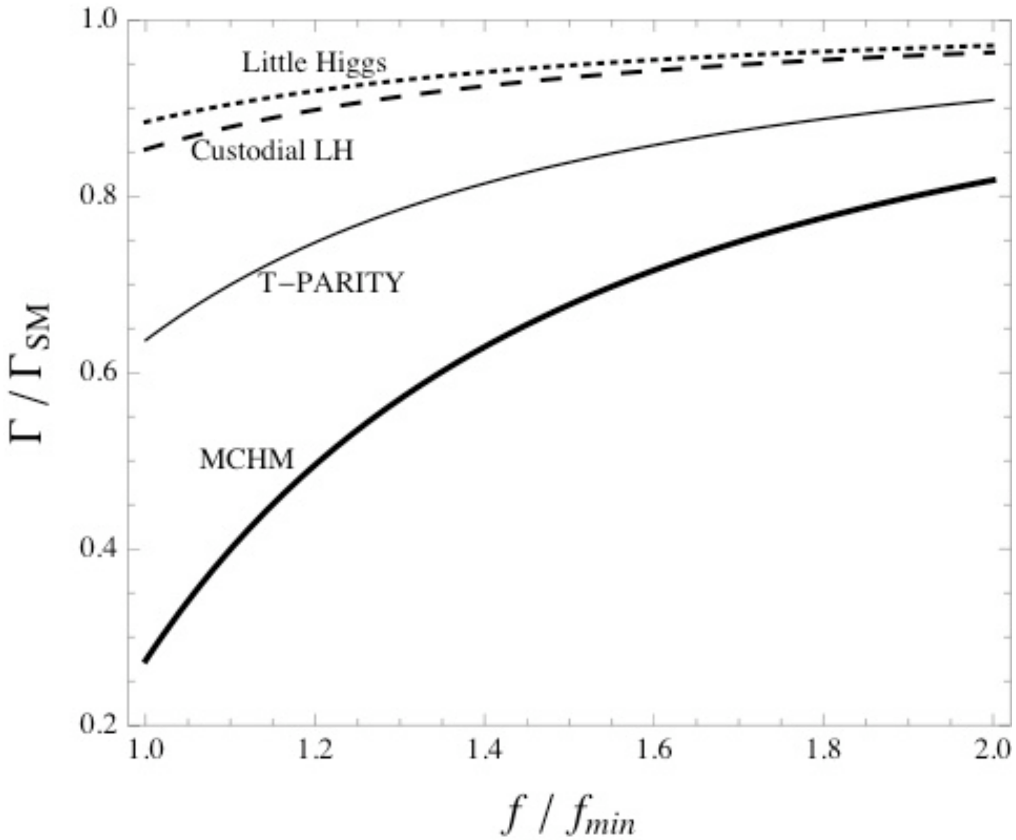
It is simple to see how these statements come about:



Loop-induced Higgs couplings in “natural” EWSB are modified naturally.

Any observed modification in loop-induced couplings is a smoking-gun signal for (un)naturalness.

A “reduced” gluon coupling is a smoking-gun signal for “Naturalness,”



In composite Higgs models
this coupling is always suppressed!

Low, Rattazzi, Vichi:0907.5413
Low and Vichi:1010.2753

A “reduced” gluon coupling is a smoking-gun signal for “Naturalness,” while an “enhanced” gluon coupling may suggest fine-tuned Higgs mass.

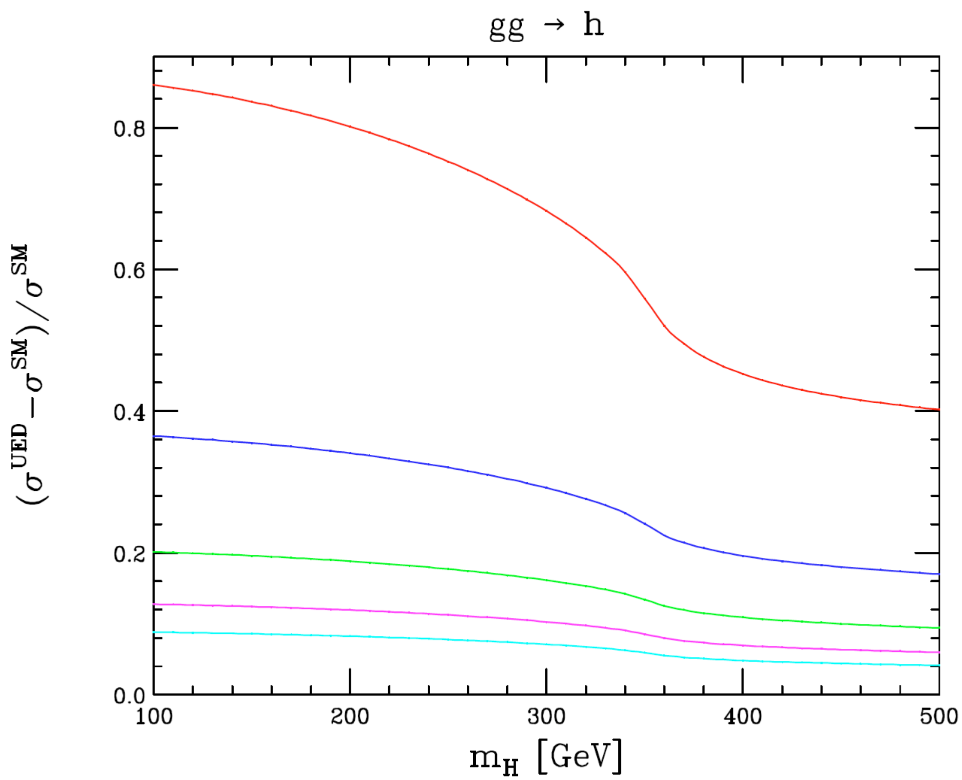
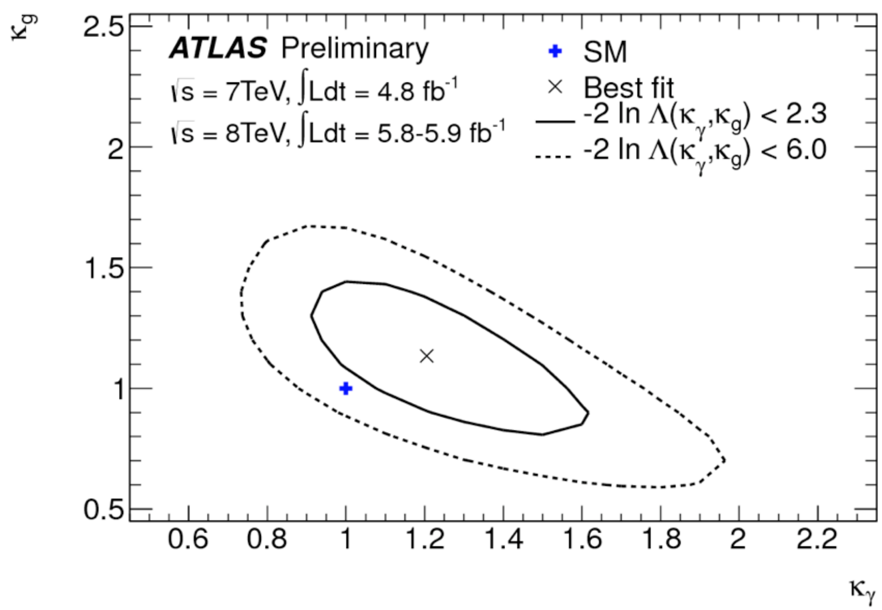
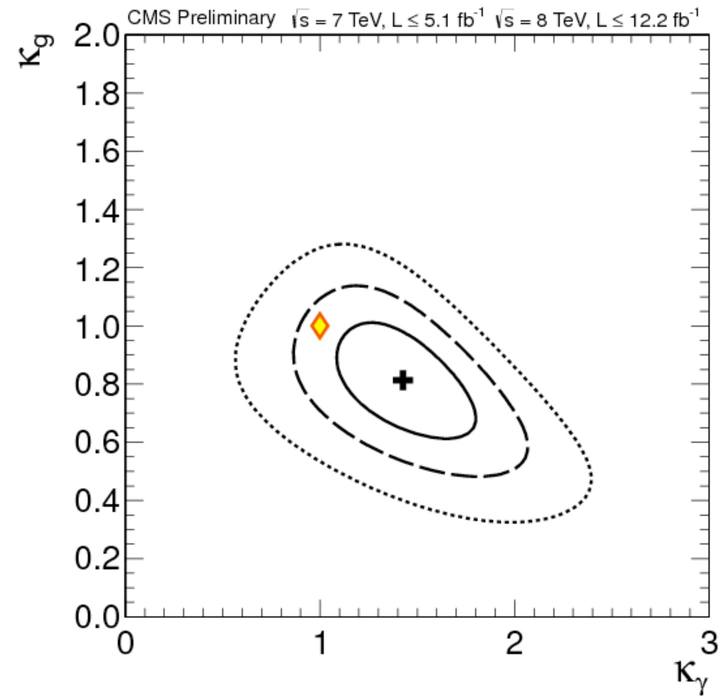


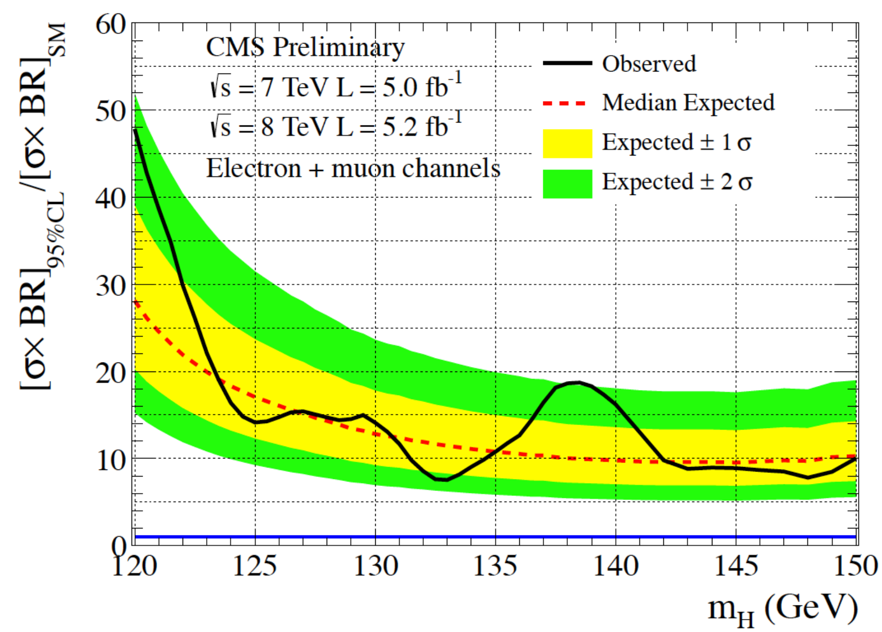
Figure 1: The fractional deviation of the $gg \to h$ production rate in the UED model as a function of m_H; from top to bottom, the results are for $m_1 = 500, 750, 1000, 1250, 1500$ GeV.

F. Petriello, hep-ph/0204067

Where do we stand today?

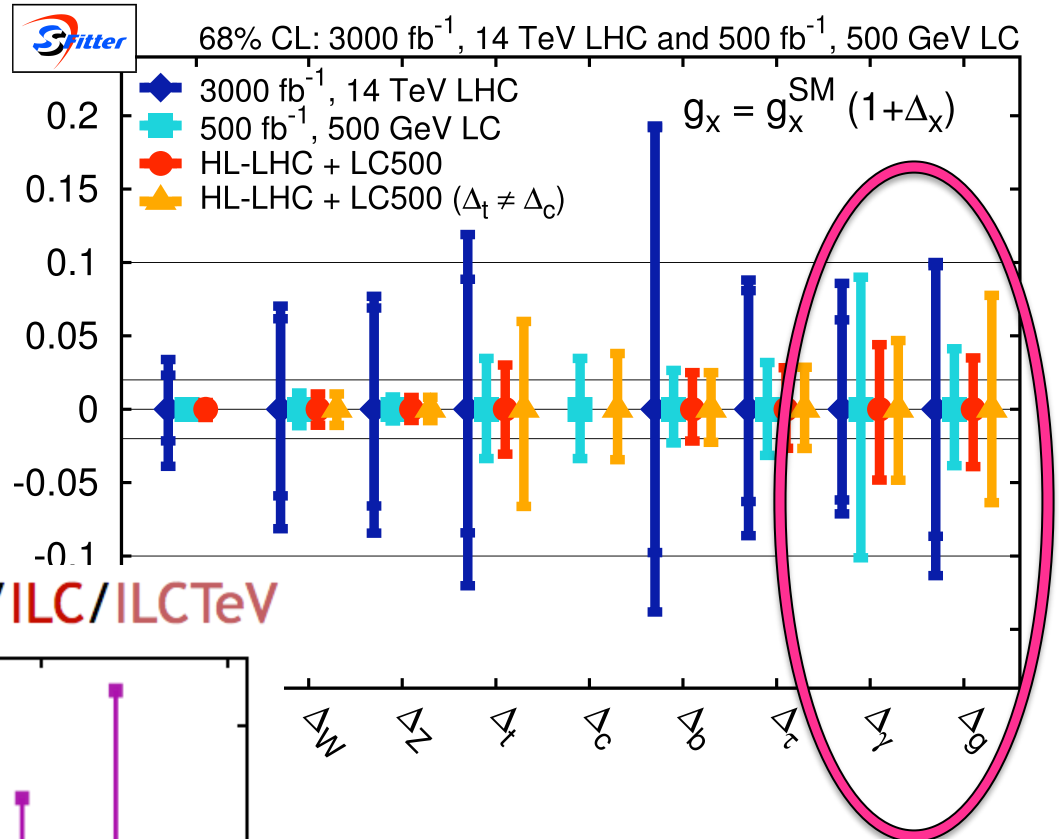






Both ATLAS and CMS presented 2d likelihood fits in glue-glue and $\gamma\ \gamma$ channels, while CMS presented an exclusion limit for Z+γ.

Where we might stand in the future:



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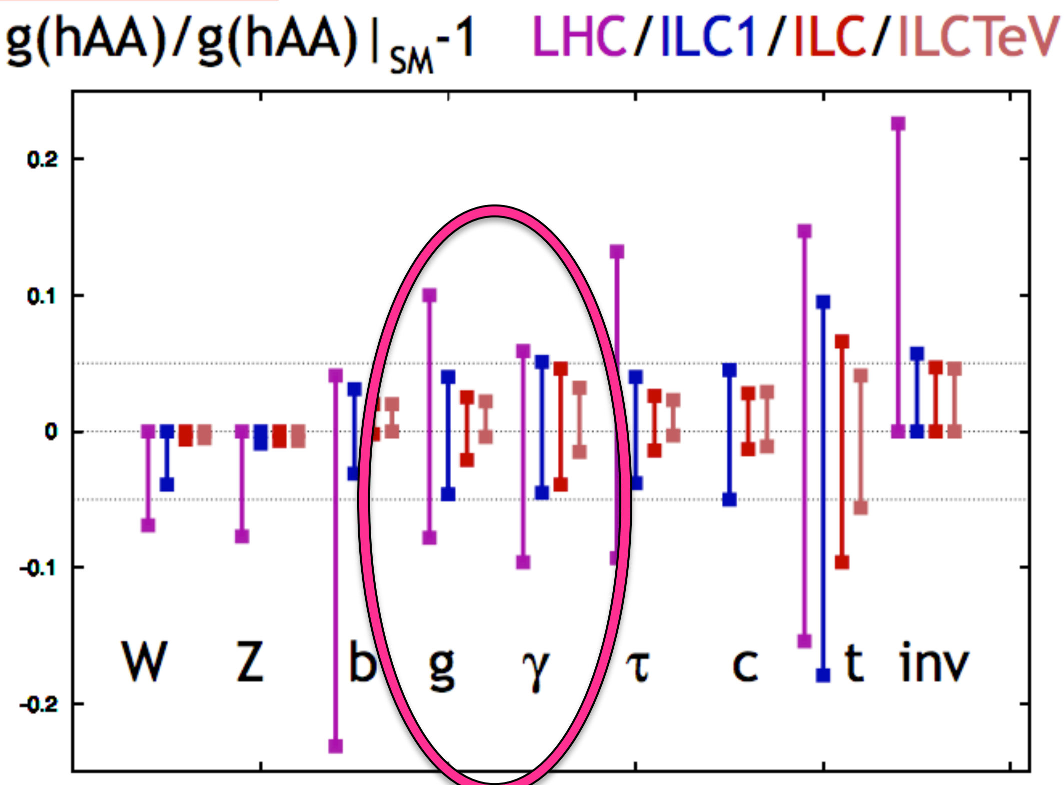
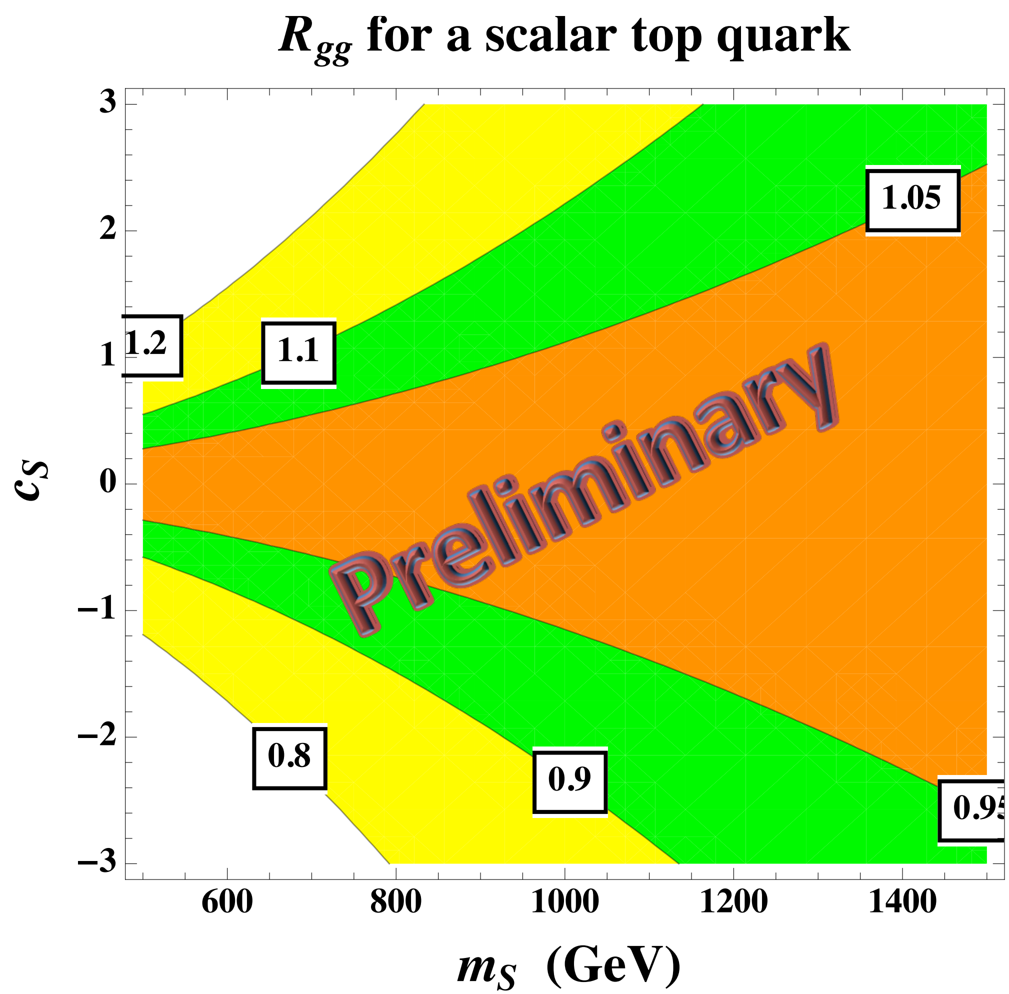


The lack of study on Z+photon coupling need to be remedied!

Lessons learned by a Pessimist who thinks everything we (will) measure is just SM:

Precision measurements of loop-induced couplings could put constraints on the mass and coupling-to-the-Higgs of new particles.

For example, a “scalar top quark” coupling and mass can be constrained by a precision measurement on the Higgs-glue-glue coupling:

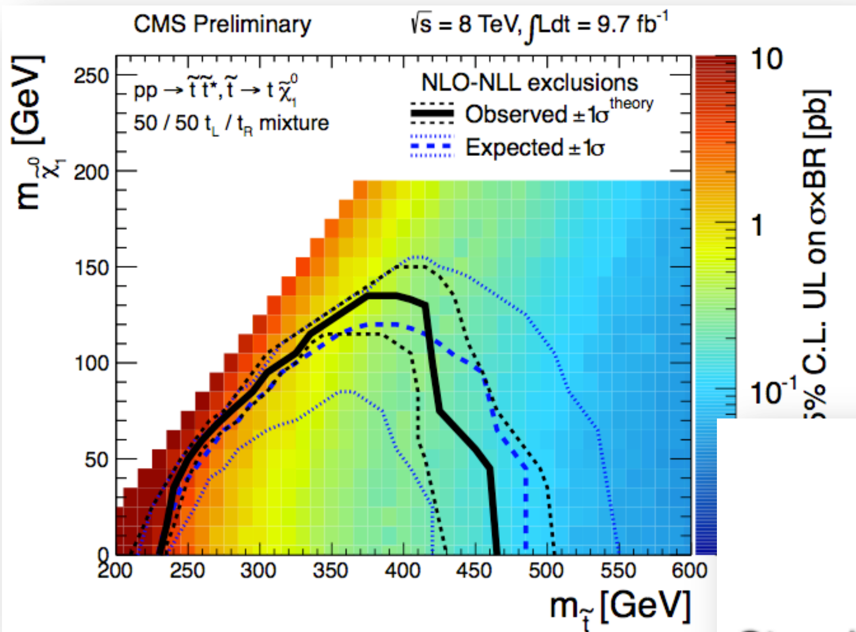


$$\frac{1}{2} c_S \tilde{t}_1 \tilde{t}_1 H^\dagger H$$

A 5% accuracy on hgg coupling translates into a mass bound on the stop of 1 TeV or higher!

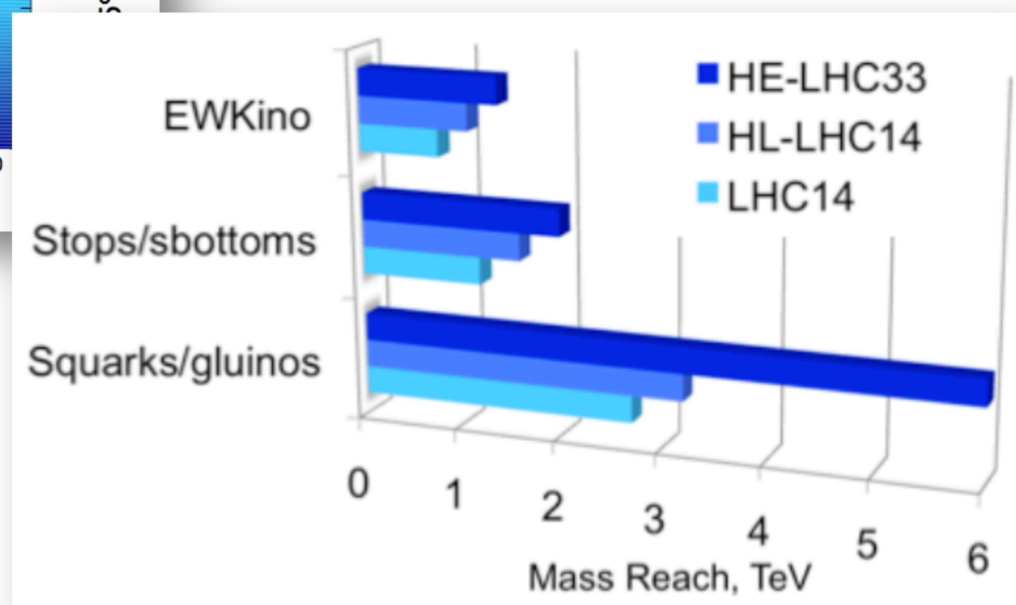
The bound is independent of “the rest of the spectrum”!

It’s interesting to compare the bound from precision Higgs measurements with those from direct searches at the LHC:



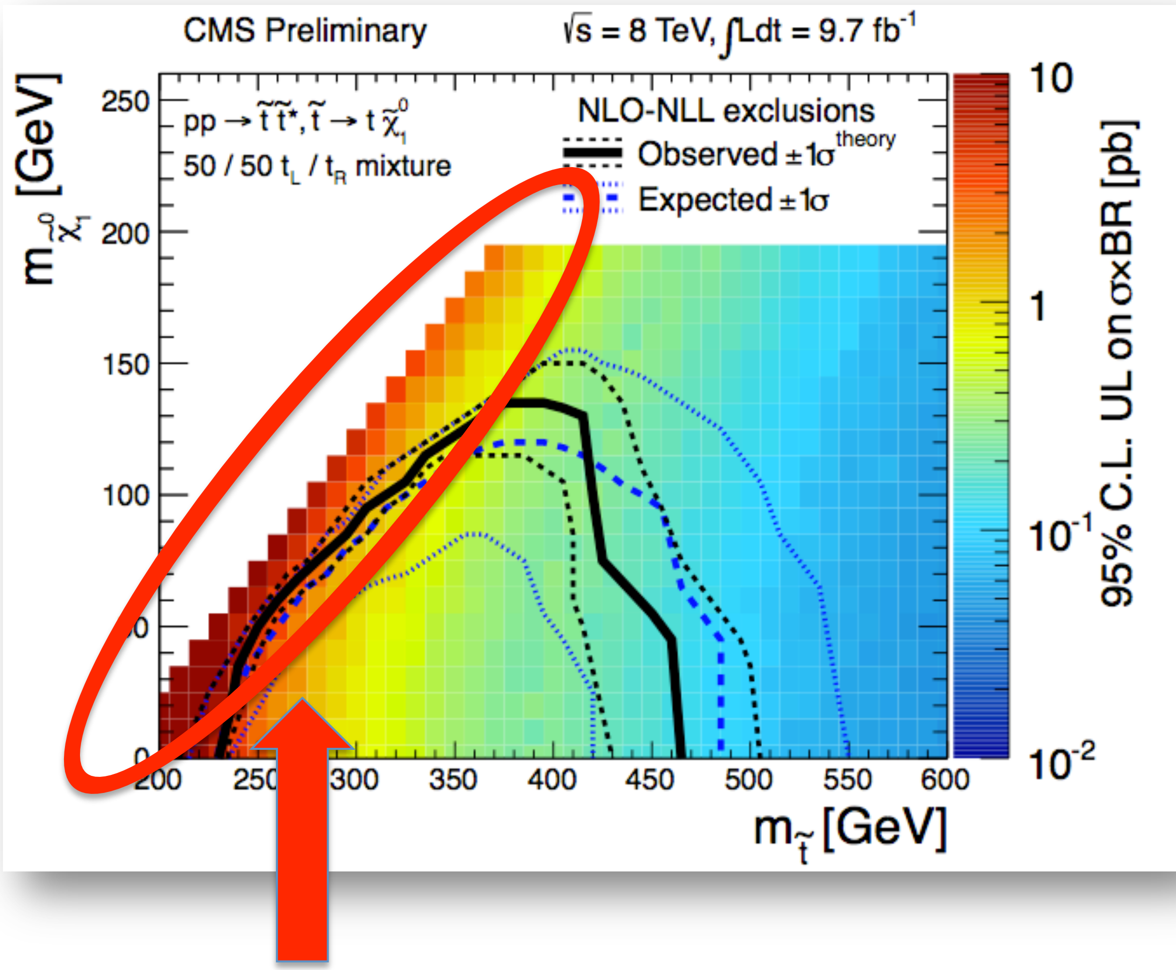
Current bound < 500 GeV

Projection for 14 TeV LHC is about 1.2 TeV!



Physics Briefing Book for “European Strategy for Particle Physics”

It is important to recall that direct searches always depend on the decay final states and the rest of the spectrum:



Direct searches have no sensitivity in this "compressed" region Because the missing E_T is too small to trigger.

We see that precision Higgs measurements and direct searches are very much complementary to each other!

There is even one very important quantity that, given its mass at 125 GeV, is extremely difficult to measure at LHC (or any hadron collider):

The Higgs total decay width Γ = 4 MeV

At a linear collider,

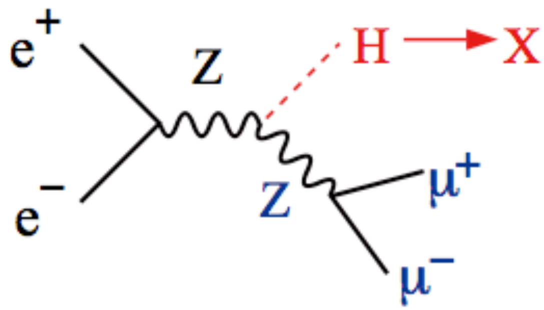
Christian Grefe CERN seminar on Nov.2012

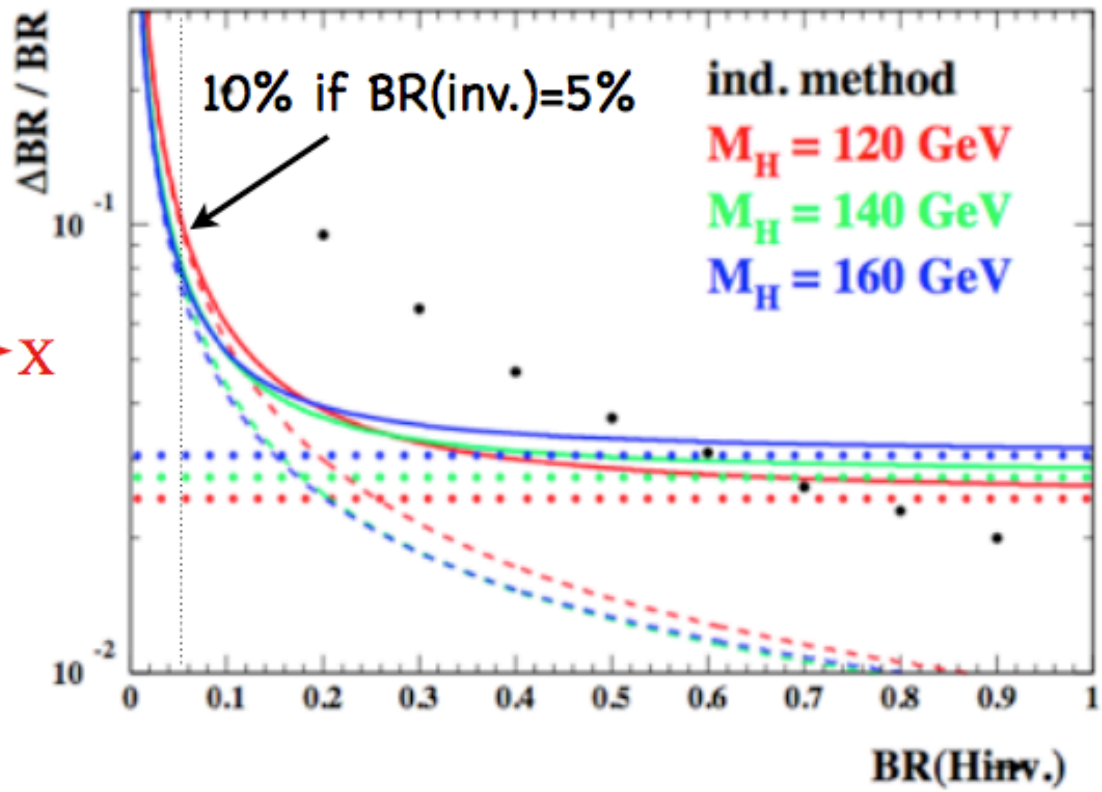
- $\Delta\Gamma_{\mathrm{H}}^{\mathrm{tot}}/\Gamma_{\mathrm{H}}^{\mathrm{tot}} = \sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{H}\nu_e\bar{\nu}_e)/\mathrm{BR}(\mathrm{H} \to \mathrm{WW}^*)$
- For $500\,\mathrm{fb}^{-1}$ at 350 GeV: $\Delta\Gamma_{\mathrm{H}}^{\mathrm{tot}}/\Gamma_{\mathrm{H}}^{\mathrm{tot}} = 6.3\%$

The total width is important because we can constrain the invisible width of the Higgs boson, which may signal the presence of dark matter, or Higgs decays into “soft stuffs” that might have escaped detection.

In fact, the Higgs invisible width can also be determined independently:

ILC RDR 2007



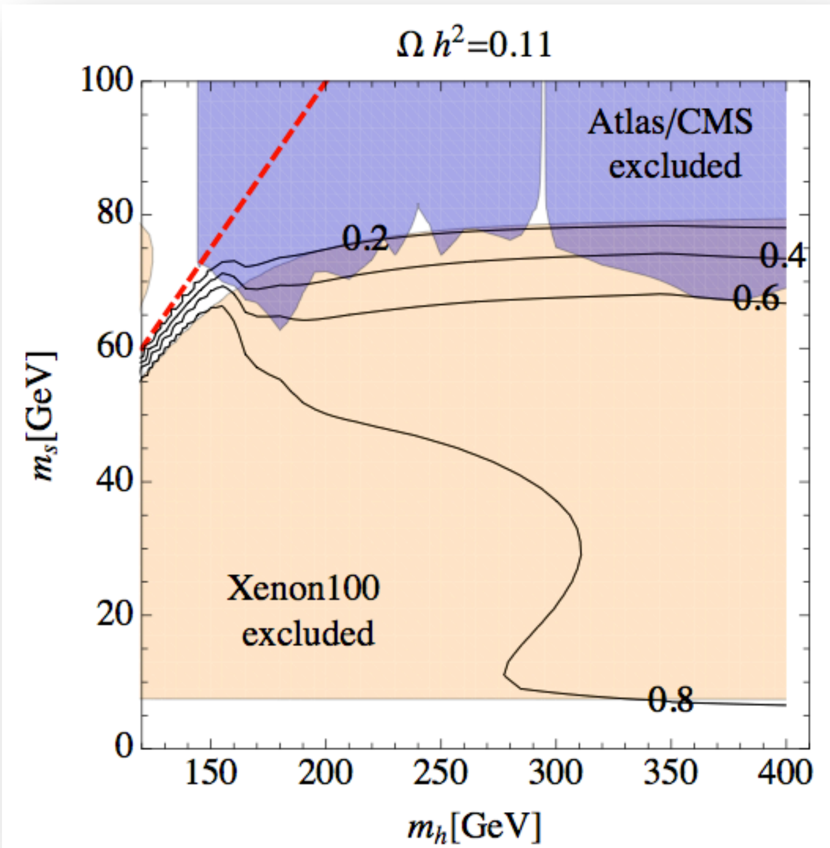


If we assume the dark matter couples to SM only through its couplings to the Higgs (ie the Higgs portal), then

Invisible Width + Relic Density

→ dark matter mass and its coupling to the Higgs

→ (in)direct detection rate is completely predicted



We did this exercise using the Higgs exclusion limit from pre-July 4th data.

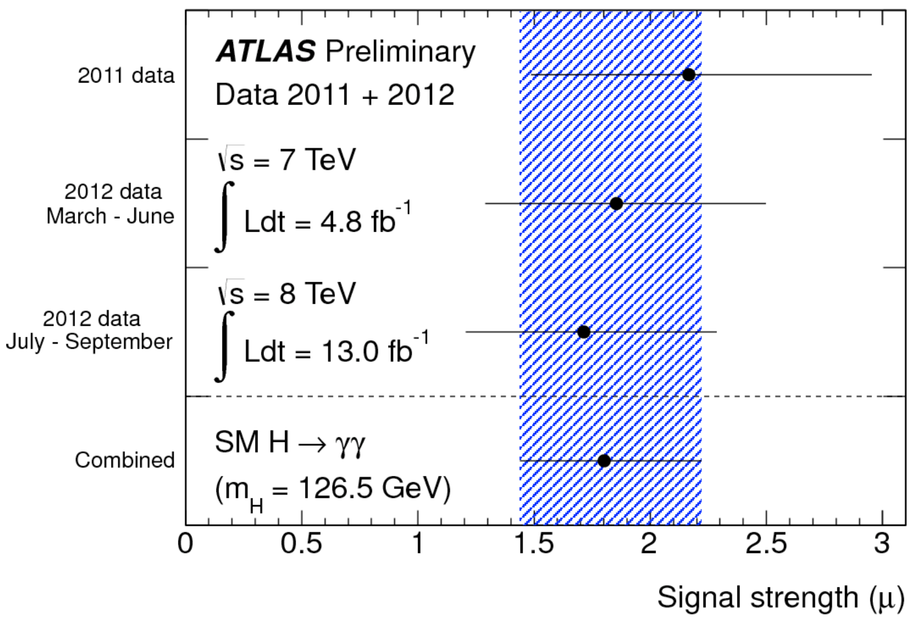
Low, Schwaller, Shaughnessy, Wagner: 1110.4405

An optimist now looks at the same glass half-full:

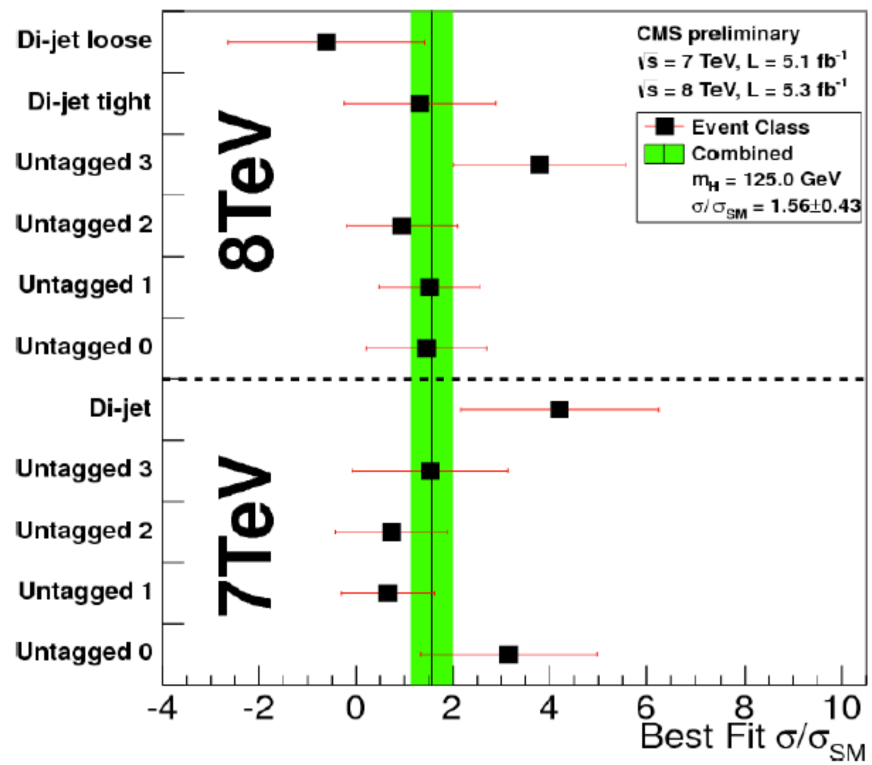
the Higgs-to-diphoton rate seems to be enhanced.

$$\mu = 1.8 \pm 0.3^{+0.29}_{-0.21}$$

(Was 1.8 ± 0.5)



σ/σ_{SM} = 1.56 ± 0.43



Since CMS gives no update, July 4th number stays with us, for now…

If the diphoton excess persists, the Higgs may have a significant decay width into new charged particles mediating the new hγγ coupling:

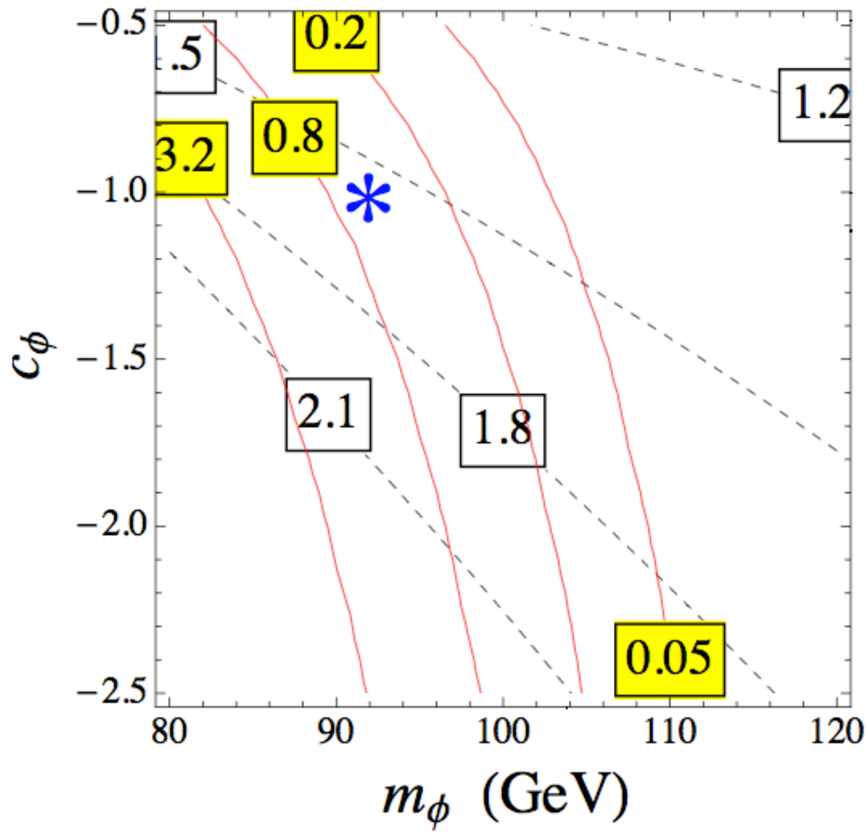


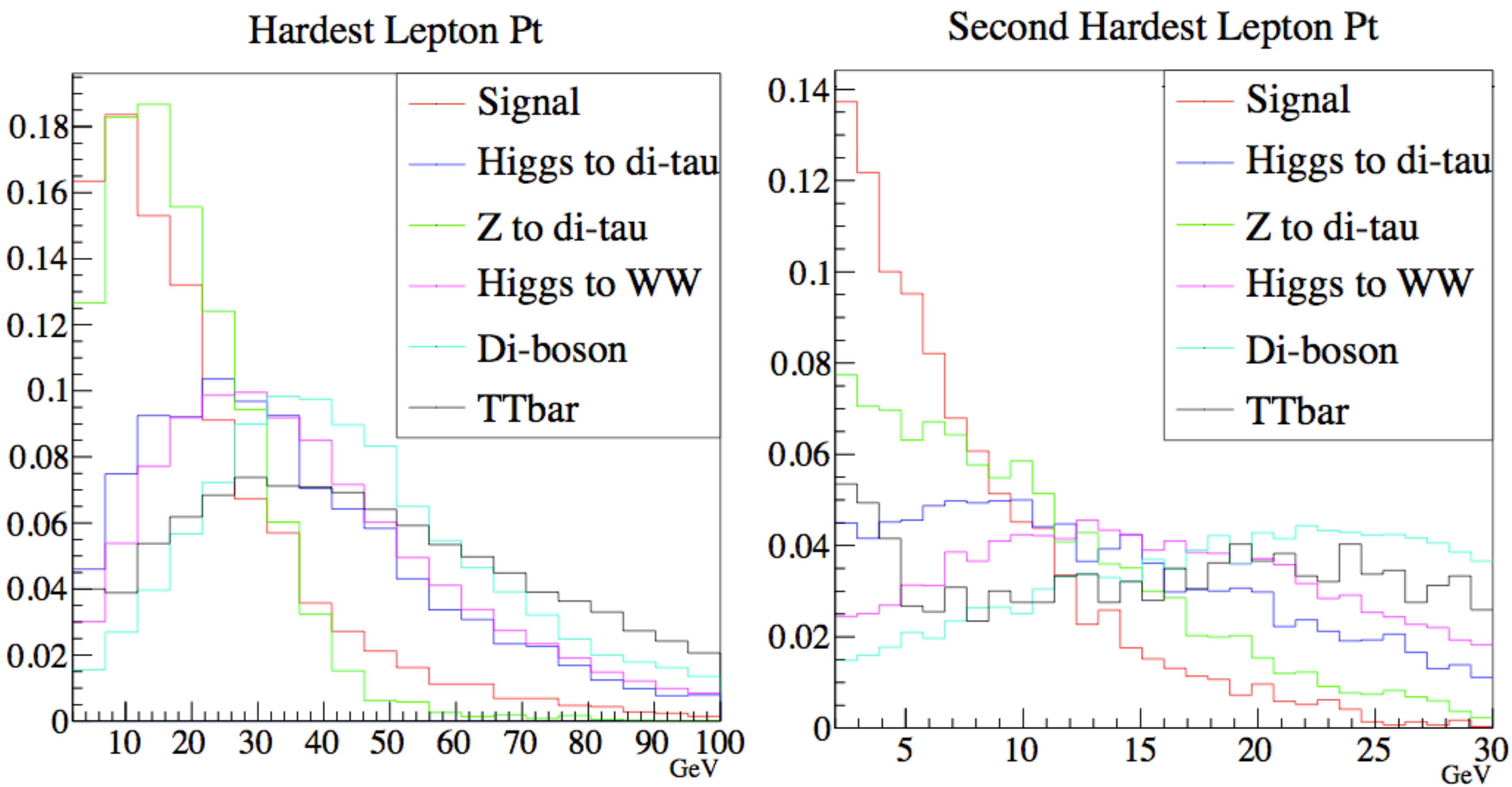
FIG. 1: Contours for $\Gamma_{h\to\phi\phi}/\Gamma^{SM}_{h\to\tau\bar{\tau}}$ (red, solid) and $\Gamma_{h\to\gamma\gamma}/\Gamma^{SM}_{h\to\gamma\gamma}$ (black, dashed).

As a "simplified model," assume ϕ is a new charged scalar that decays to tau leptons + tau neutrinos:

$$\phi \to \tau + \nu_\tau$$

Giddings, Liu, Low, and Mintun: 1301.2324

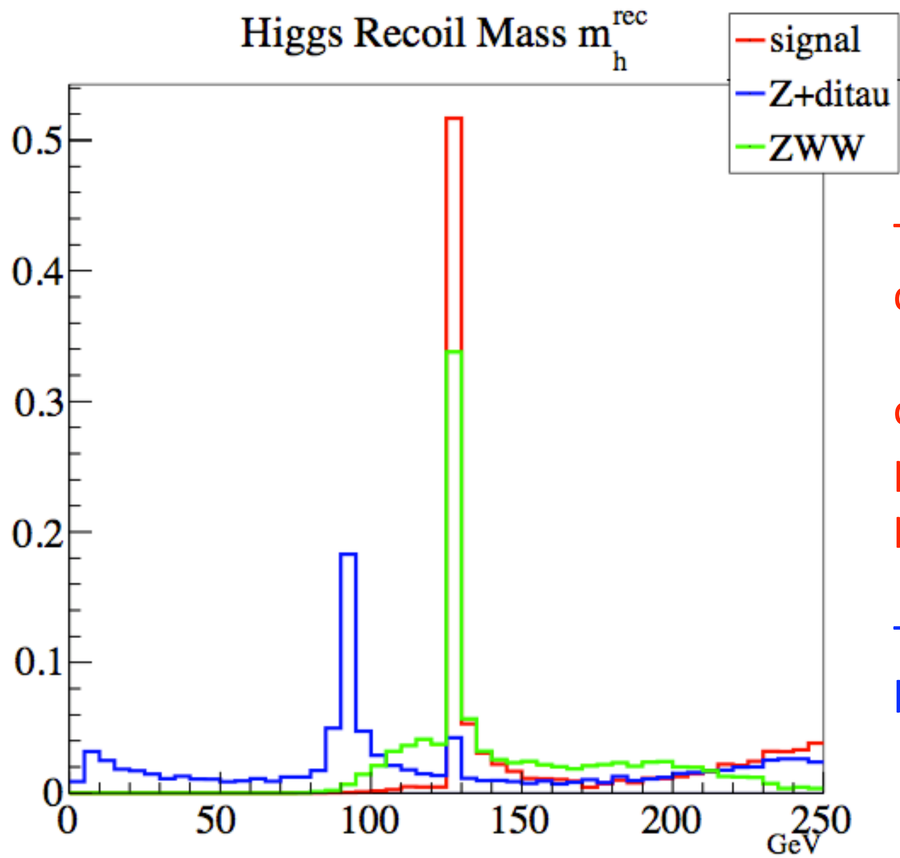
However, the Higgs mass is only 125 GeV, so one of the “mediators” is far off-shell and its decay products extremely soft:



Very difficult to do this search at the LHC….

However, this search seems like an easy shot for a Higgs factory.

$$e^+e^- \rightarrow Z + h \rightarrow (Z \rightarrow 2l) + (h \rightarrow 2\tau 2\nu_\tau)$$



The beauty of knowing the center-of-mass energy:

one can reconstruct a nice Higgs mass peak although there're two missing particles!!

This allows to cut away the major background from diboson production.

FIG. 3: Normalized distributions of the Higgs recoil mass.

Here is the comparison between LHC and ILC:

Cut 1	Two jets with $p_T > 20$ GeV each, $m_{jj} > 650$ GeV, $\vert\Delta\eta\vert > 3.5$, and $\eta_1\eta_2 < 0$. Total jet $H_T > 80$ GeV, and no additional jets with $p_T > 30$ GeV between forward jets.
Cut 2	Two opposite-sign leptons, harder with 10 GeV $< p_T < 20$ GeV, softer with 10 GeV $< p_T < 15$ GeV $\vert\eta\vert < 2.3$ for electrons; $\vert\eta\vert < 2.1$ for muons.
Cut 3	Invariant lepton mass $m_{ll} < 20$ GeV, $\not{p}_T > 40$ GeV .

TABLE I: Cuts for the LHC analysis.

Cut 1	Three leptons l_i ($i = 1, 2, 3$), with $\vert\cos\theta_{l_i}\vert < 0.99$, $E_{l_i} > 3$ GeV and $E_{l_3} < 20$ GeV. Fourth-lepton (with $\vert\cos\theta_{l_4}\vert < 0.99$ and $E_{l_4} > 10$ GeV) veto.
Cut 2	$m_{l_1 l_2} = 91.2 \pm 5$ GeV, $\vert\cos\theta_{l_1 l_2}\vert < 0.8$
Cut 3	$\not{p}_T > 70$ GeV
Cut 4	125 GeV $< m_h^{\rm rec} <$ 150 GeV

14 TeV	Signal	$h \to \tau_l\tau_l$	$h \to WW$	$Z \to \tau_l\bar{\tau}_l$	$t\bar{t}$	Di-boson
σ (pb)	0.06	0.11	0.27	0.72	8.0	0.17
Cut 1	1539	3041	6393	24757	9377	4421
Cut 2	33	66	74	327	11	13
Cut 3	16	2	16	40	2	4
$S/\sqrt{B}$	$\sim 2\sigma$					

$\sqrt{s} = 250$ GeV	signal	$Z\tau\bar{\tau}$	ZWW
Xsection (fb)	0.93	27.81	0.02
Events	10000	10000	10000
Cut 1	2420	1854	1404
Cut 2	1272	575	329
Cut 3	821	93	258
Cut 4	820	3	255
$S/\sqrt{B}$	$\sim 5.2\sigma$		

14 TeV and 100 /fb

250 GeV and 40/fb

Again we see that complementarity between a Higgs factory and the LHC!

Last but not least, I'd like to show one example of a dark matter particle arising out of a model attempting to address the naturalness issue of the Higgs boson, since Sam Ting and AMS seem to be ready to release something:

NATURE NEWS BLOG

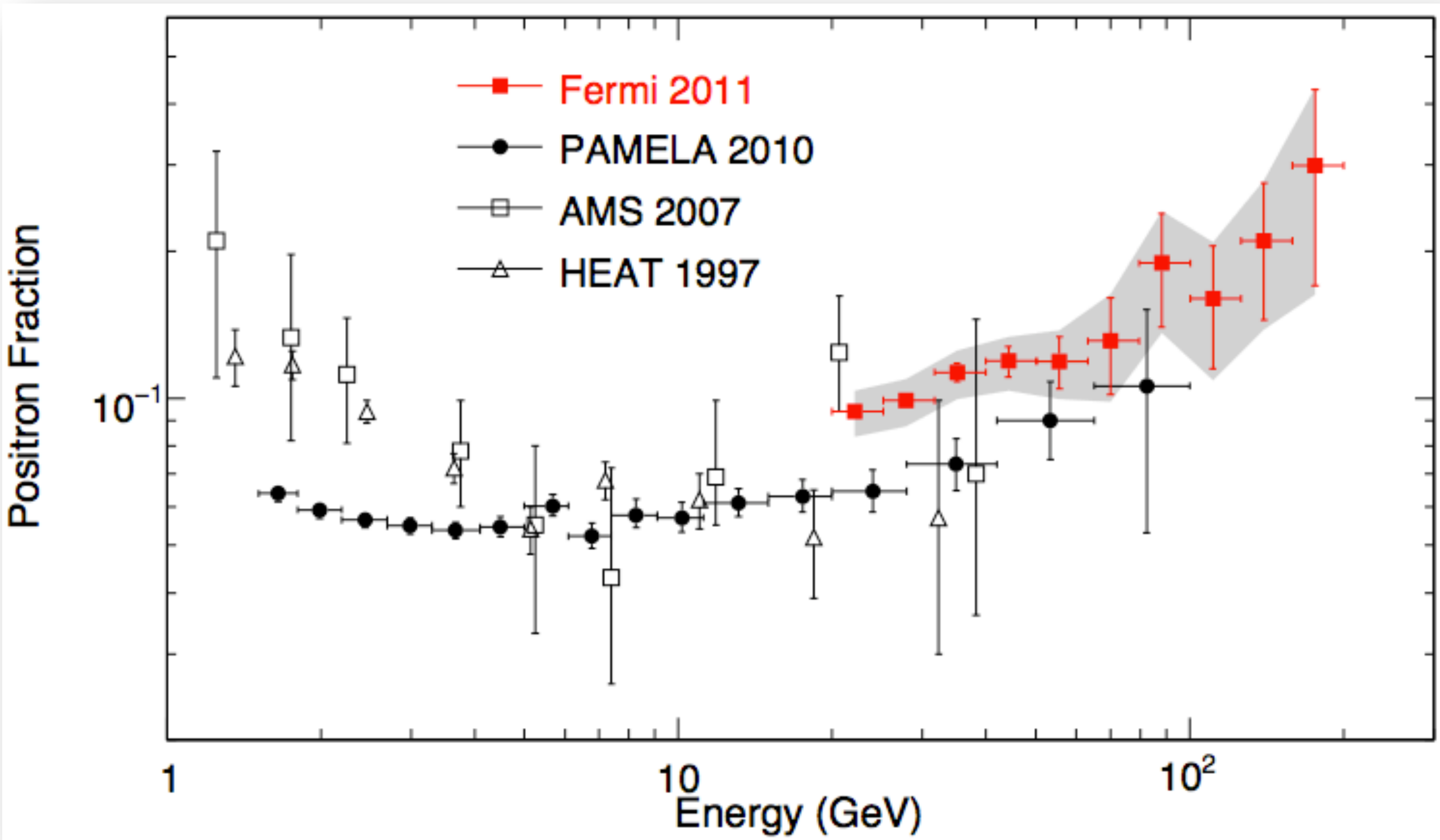
Dark-matter search from the space station continues to tease

17 Feb 2013 | 22:54 GMT | Posted by Eugenie Samuel Reich | Category: Physics & Mathematics

Nobel prize winner Samuel Ting (pictured) likes to keep people guessing. Nowhere was this more true than at his press conference this morning at the American Association for the Advancement of Science (AAAS) meeting in Boston, Massachusetts. The AAAS had suggested that Ting would be ready to present the first dark matter results from his brainchild, the US$1.5 billion Alpha Magnetic Spectrometer (AMS), basically a giant magnet and antimatter detector fixed to the outside of the International Space Station. Ting was prefaced by a line-up of physicist colleagues who described themselves as "very excited". But Ting ended up only disappointing them and around 100 reporters who had gathered for the press conference. Ting said that he wasn't ready to make an announcement yet. "In two to three weeks, we should be ready," he said.

Ting did say that he is on the verge of releasing a paper showing how the ratio of positrons (the antimatter counterpart of electrons) to electrons passing through the space station's near-Earth orbit varies with energy.

A lot of the excitement recently came from the PAMELA excess in cosmic positron flux below 100 GeV region, which was subsequently confirmed and extended by Fermi-LAT:



Fermi-LAT: 1109.0521

There are two possibilities for such an excess:

1. Positrons from WIMPs annihilating into 2 or 4 charged leptons in the galactic halo.

$$\mathrm{DM} \to \ell^+\ell^- \quad \mathrm{or} \quad \mathrm{DM} \to 2\phi \to (\ell^+\ell^-)(\ell^+\ell^-)$$

2. Positrons from near-by Pulsars.

WIMPs annihilations could explain the data, but it requires

$$\langle \sigma v \rangle_{ann} \gg \langle \sigma v \rangle_{freeze} \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

A ``boost factor'' of O(100) is introduced in order to give a large enough annihilation cross-section. (Refs: 0809.1683; 0809.2409)

Where does the boost factor come from?

- Astrophysical source: clumpiness in the dark matter halo profile??
- Particle physics source: Sommerfeld enhancement due to long-range attraction between dark matter particles??

- Alternatively, if the dark matter decays with a long lifetime, the annihilation cross-section (which sets the relic density) would be decoupled from the flux (due to decays) measured by PAMELA.

- The large flux required by PAMELA positron excess translates into a decay lifetime of $O(10^{26})$ seconds. No boost factor is needed!

Where does this number come from??

A dark matter decaying through GUT-suppressed dim-6 operators happens to give (Ref: 0811.4153)

$$\tau \sim 8\pi \frac{M_{\rm GUT}^4}{m_{\rm DM}^5} = 3 \times 10^{27}\ {\rm s} \left(\frac{\rm TeV}{m_{\rm DM}}\right)^5 \left(\frac{M_{\rm GUT}}{2 \times 10^{16}\ {\rm GeV}}\right)^4$$

In SUSY the LSP could be the decaying dark matter if R-parity is violated by a small amount.

The only problem is, for both annihilation or decays into 2 or 4 charged leptons, the resulting synchrotron radiation tend to produce too much diffuse galatic diffuse gammay ray that was not consistent with Fermi-LAT observations.

2/4-body DM annihilations:

(Dated: February 24, 2010)

Abstract

The first published Fermi large area telescope (Fermi-LAT) measurement of the isotropic diffuse gamma-ray emission is in good agreement with a single power law,

In reasonable background and dark matter structure scenarios (but not in all scenarios we consider) it is possible to exclude models proposed to explain the excess of electrons and positrons measured by the Fermi-LAT and PAMELA experiments.

ferent available results of matter structure formation we assess these uncertainties. We also quantify how the dark matter constraints depend on the assumed conventional backgrounds and on the Universe's transparency to high-energy gamma-rays. In reasonable background and dark matter structure scenarios (but not in all scenarios we consider) it is possible to exclude models proposed to explain the excess of electrons and positrons measured by the Fermi-LAT and PAMELA experiments. Derived limits also start to probe cross sections expected from thermally produced relics (e.g. in minimal supersymmetry models) annihilating predominantly into quarks. For the monochromatic gamma-ray signature, the current measurement constrains only dark matter scenarios with very strong signals.

Fermi-LAT: 1002.4415

The only problem is, for both annihilation or decays into 2 or 4 charged leptons, the resulting synchrotron radiation tend to produce too much diffuse galatic diffuse gammay ray that was not consistent with Fermi-LAT observations.

2/4-body DM decays:

We derive new bounds on decaying Dark Matter from the gamma ray measurements of (i) the isotropic residual (extragalactic) background by Fermi and (ii) the Fornax galaxy cluster by H.E.S.S.. We find that those from (i) are among the most stringent constraints currently available, for a large range of DM masses and a variety of decay modes, excluding half-lives up to $\sim 10^{26}$ to few 10^{27} seconds. In particular, they rule out the interpretation in terms of decaying DM of the $e^{\pm}$ spectral features in PAMELA, Fermi and H.E.S.S., unless very conservative choices are adopted. We also

Cirelli et al: 1205.5283

So the message is clear:

conventional 2/4-body final states of DM decays/annihilations

$$\mathrm{DM} \to \ell^+\ell^- \quad \text{or} \quad \mathrm{DM} \to 2\phi \to (\ell^+\ell^-)(\ell^+\ell^-)$$

are having difficulty with existing diffuse gamma-ray measurements!

Our proposal is to alleviate the tension with 3-body decays with a missing particle (the LSP),

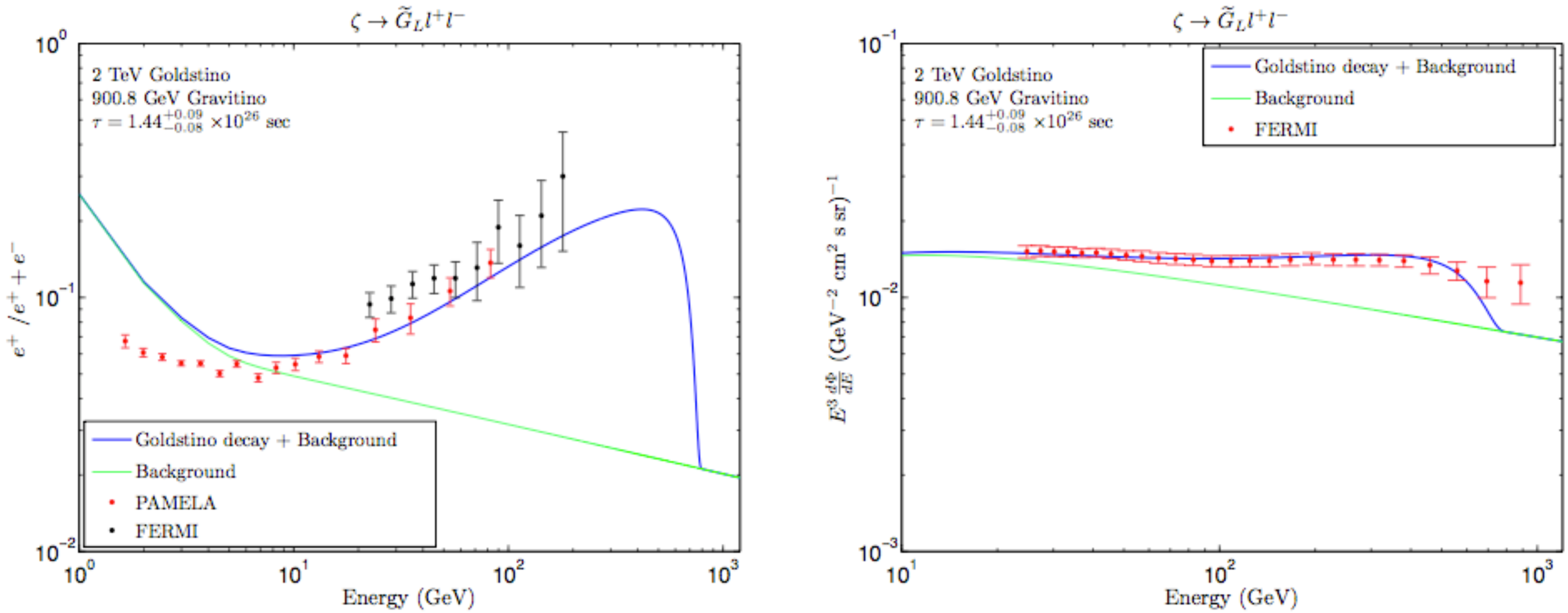
$$\zeta \to \widetilde{G}_L + \ell^+ + \ell^-$$

which occurs naturally in R-parity preserving supersymmetric theories with multiple SUSY-breaking sectors, the goldstini model. (Cheung, Nomura, and Thaler: 1002.1967)

The physics behind is very simple:

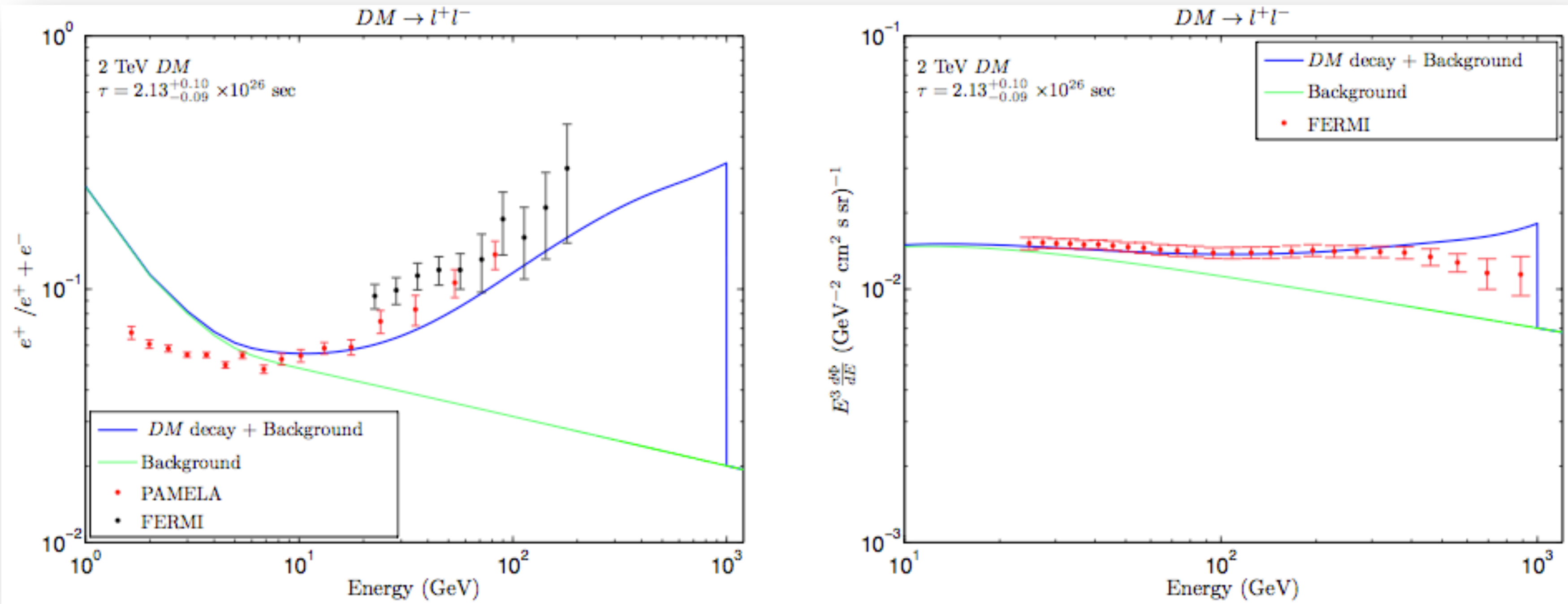
Three-body decay kinematics with a missing particle give a softer energy spectrum for the charged leptons and, as a result, softer synchrotron radiation.

We can fit both the positron fraction and total e^++e^- spectra:



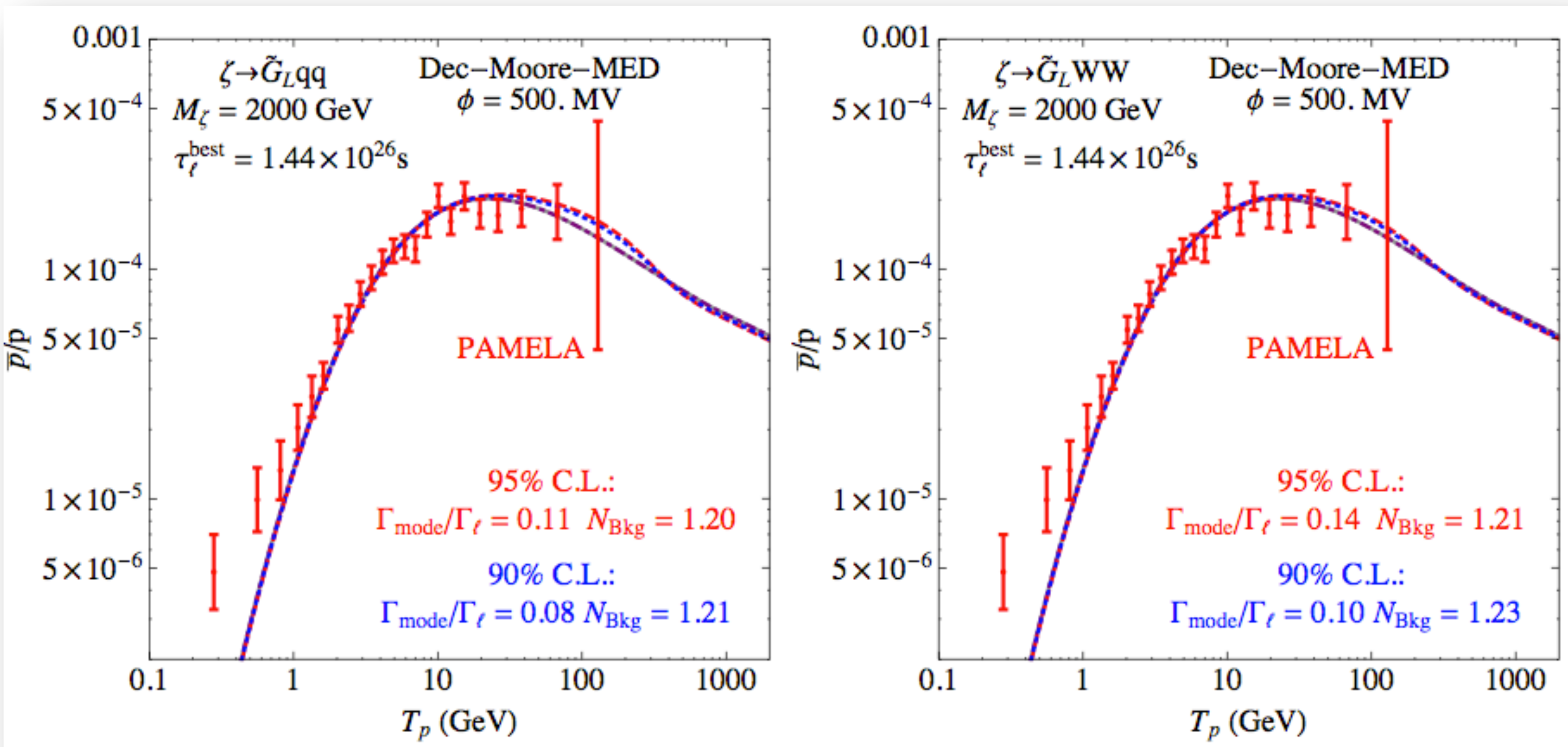
Cheng, Huang, Low, and Menon: 1012.5300
Cheng, Huang, Low, and Shaughnessy: 1205.5270

To show you the contrast with 2-body DM decays:

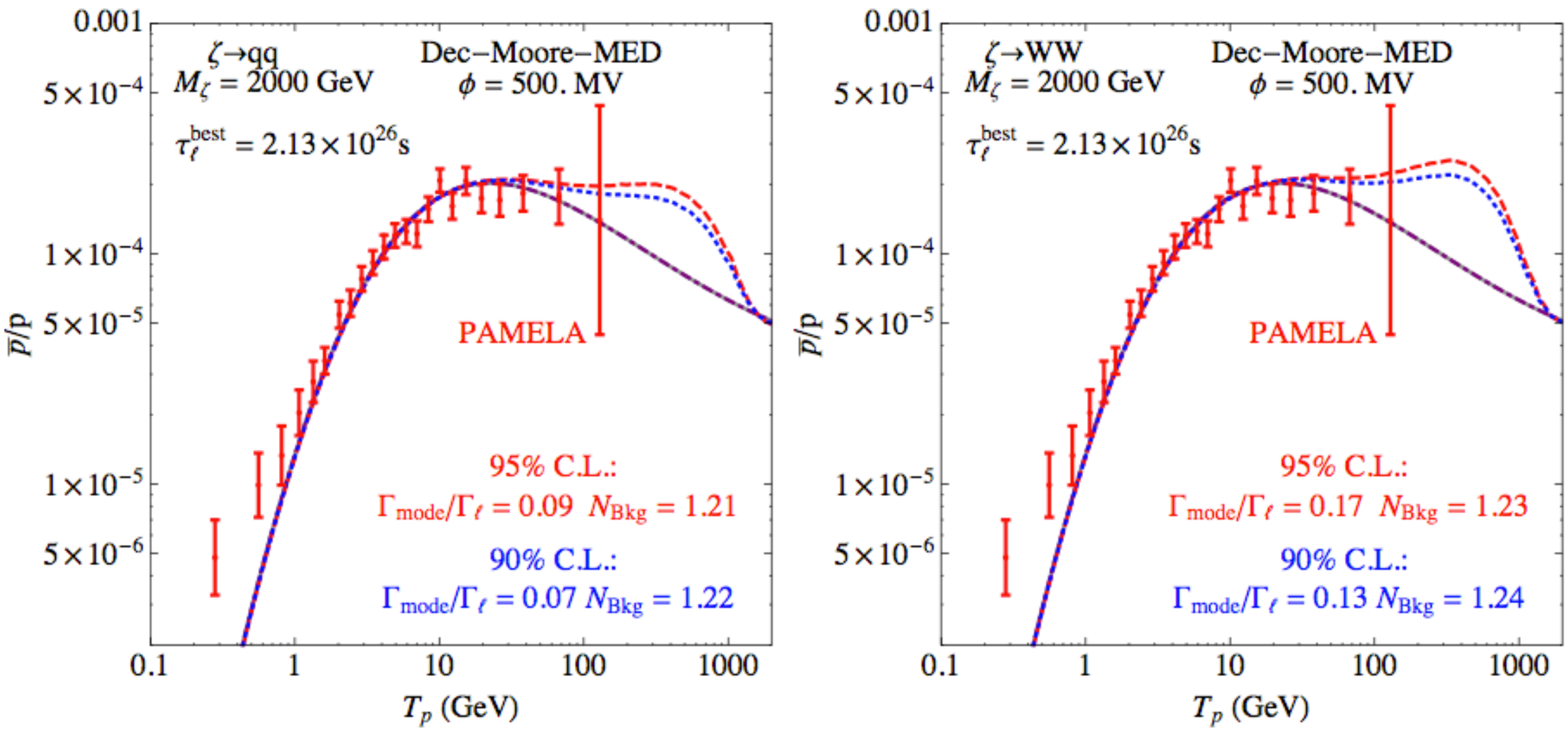


Both diffuse and prompt gamma ray constraints can be satisfied.

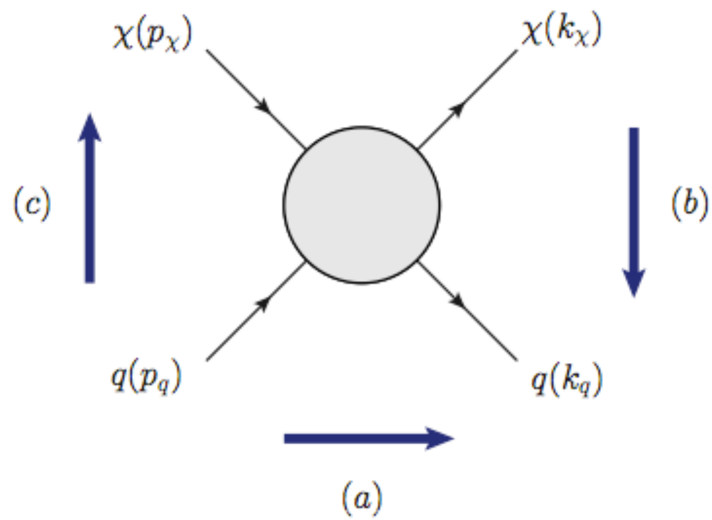
The 3-body case could also open up some hadronic decay channels without running afoul with the anti-proton measurements:



Again, to show you the contrast with 2-body DM decays:



Finally, there are interplays between DM direct detection, indirect detection, and collider searches:



$$(\mathrm{a}): \quad \chi(p_\chi) + q(p_q) \to \chi(k_\chi) + q(k_q)$$

$$(\mathrm{b}): \quad \chi(p_\chi) + \chi(k_\chi) \to q(p_q) + \bar{q}(k_q)$$

$$(\mathrm{c}): \quad q(p_q) + \bar{q}(k_q) \to \chi(p_\chi) + \chi(k_\chi)$$

In particular,

a signal in direct detection

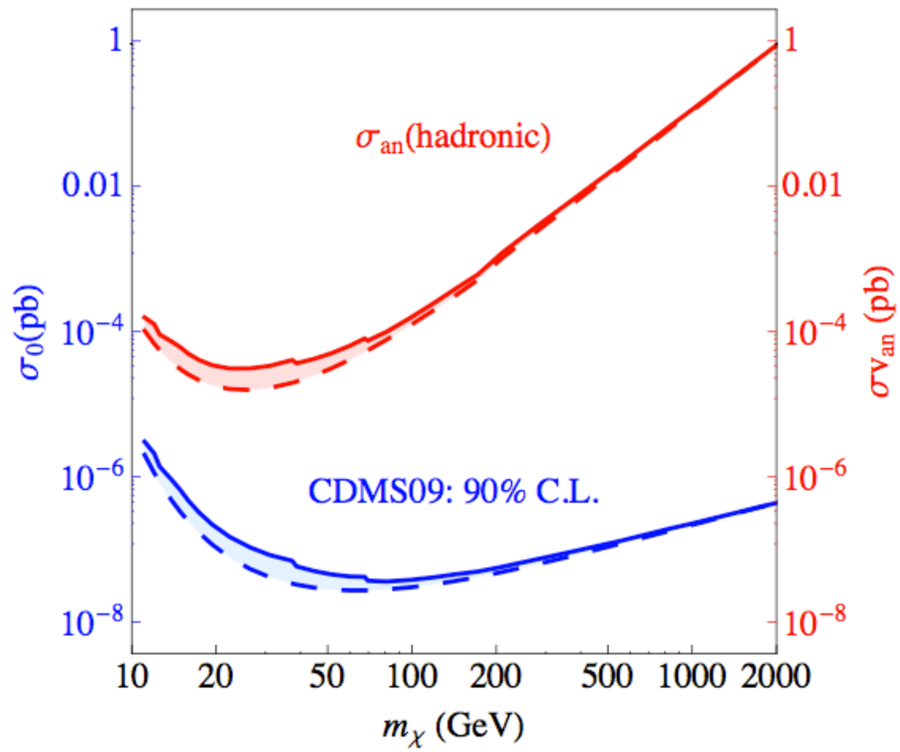
→ DM coupling to quarks

→ DM annihilations into hadronic final states

→ anti-proton measurement in indirect detection

We did this exercise using the "limit" at CDMS in '09, using a simple model of fermionic DM coupling to quarks through a Z-prime mediator.

Cao, Low, Shaughnessy:0912.4510



In particular,

a signal in direct detection

→ DM coupling to quarks

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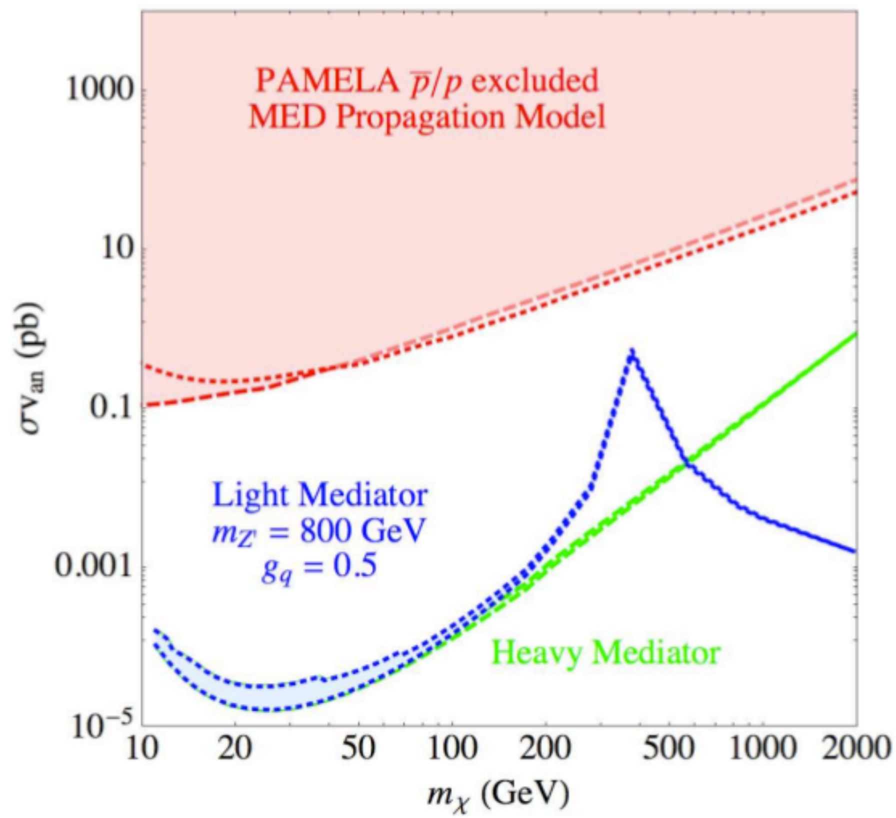
→ anti-proton measurement in indirect detection

As the precision gets better in indirect detection in the future, this exercise should be repeated!

Cao, Low, Shaughnessy:0912.4510



Concluding Remarks:

In the next two decades, three areas of particle physics would be rich in data:

- Precision Higgs measurements
- Dark Matter Detection
- Mass and CP violation in Neutrinos
- Flavor Physics

All these areas are interconnected. We need an all-out effort to come up with a global picture that would tie up all frontiers together!