Summary

Joe Lykken

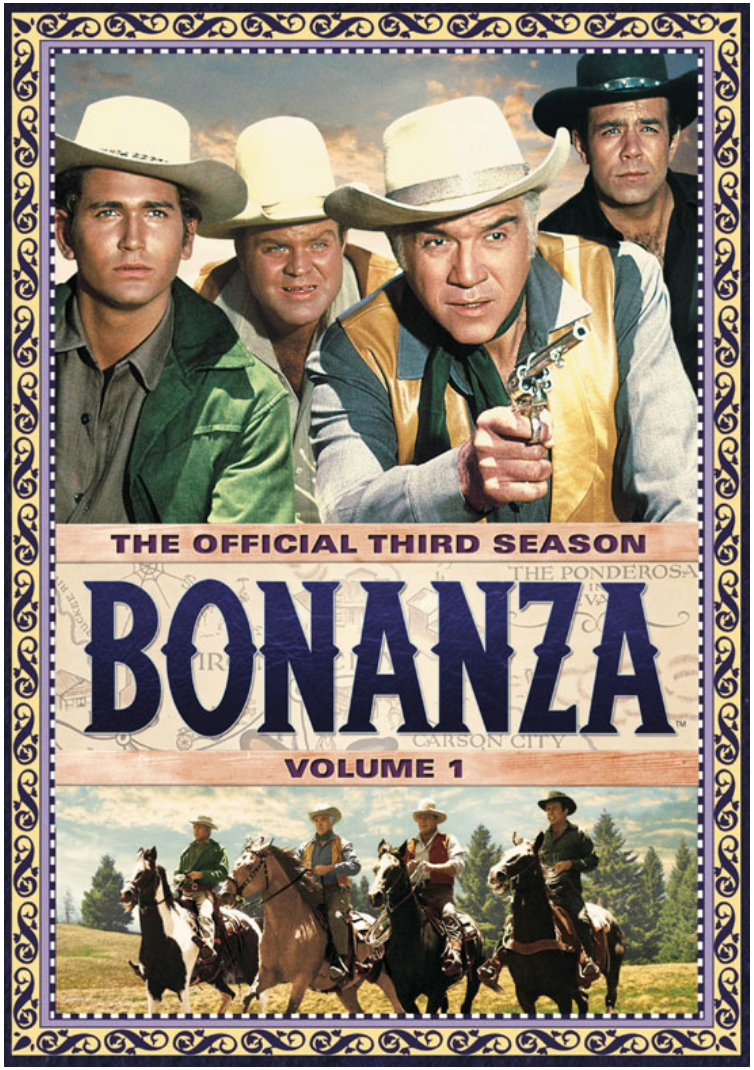
Disclaimer

- This is a “thematic” summary of an action-packed conference
- So I apologize if your talk is not mentioned explicitly

Personal history

When I was a kid growing up on the prairie, one of my favorite TV shows was a western called "Bonanza"

It concerned the adventures of a family of gun-toting cowboys who lived on a 500,000 acre ranch called "The Ponderosa"



Fermilab

Personal history

The opening of the show featured a map showing the exact location of The Ponderosa on the shores of Lake Tahoe

As I grew older I looked forward to some day traveling to Lake Tahoe and visiting The Ponderosa

Fermilab

Personal history

Eventually that day arrived, and I was bitterly disappointed to discover that The Ponderosa did not exist…

The relevance of this story to my talk is left as an exercise for the audience

SUSY and other BSM searches at LHC

Is your glass half full or half empty?

EXECUTIVE SUMMARY

We haven't found it.

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T. Lari, SUSY2015

Fermilab

SUSY and other BSM searches at LHC

$M_{gluino} \approx 1.5$ TeV,

$M_{bino} \approx 450$ GeV,

$M_{wino} \approx 620$ GeV

G. Kane, SUSY2015

Is your glass
half full or
half empty?

For all anybody knows,
a SUSY discovery @ LHC could be imminent

We live in *exciting* times for particle physicists

- The Higgs boson / Higgs field is a completely new kind of beast
  - We have just scratched the surface of the Higgs sector
- LHC 13 TeV has begun!
  - Anything new will be a revolution in particle physics
- Neutrino science is both maturing and ramping up fast
  - Answers to many of our basic questions appear within reach
  - Could confirm anomalies or discover new surprises
- Dark matter direct detection could be just around the corner
  - The most (?) interesting region for WIMPS is being probed soon
  - Could also detect signs of a dark mediator

We live in *exciting* times for particle physicists

Surprises may arise from a variety of experiments that explore the unknown:

- Flavor surprises:
  - charged lepton flavor violation
  - flavor-violating Higgs decays (a hint already?)
  - in B decays at BELLE II or LHCb
  - lepton non-universality (CMS eejj excess, LHCb $B \to K\ell^+\ell^-$)
- Other potential surprises:
  - muon g-2
  - electric dipole moments or other EM anomalies
  - production and decay of heavy neutral leptons
  - proton decay
- And there could be signals from the “unknown unknowns”

Hints from LHC Run 1

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$X \to VV \to JJ \to (qq)(qq)$ [ATLAS]

arXiv:1506.0962

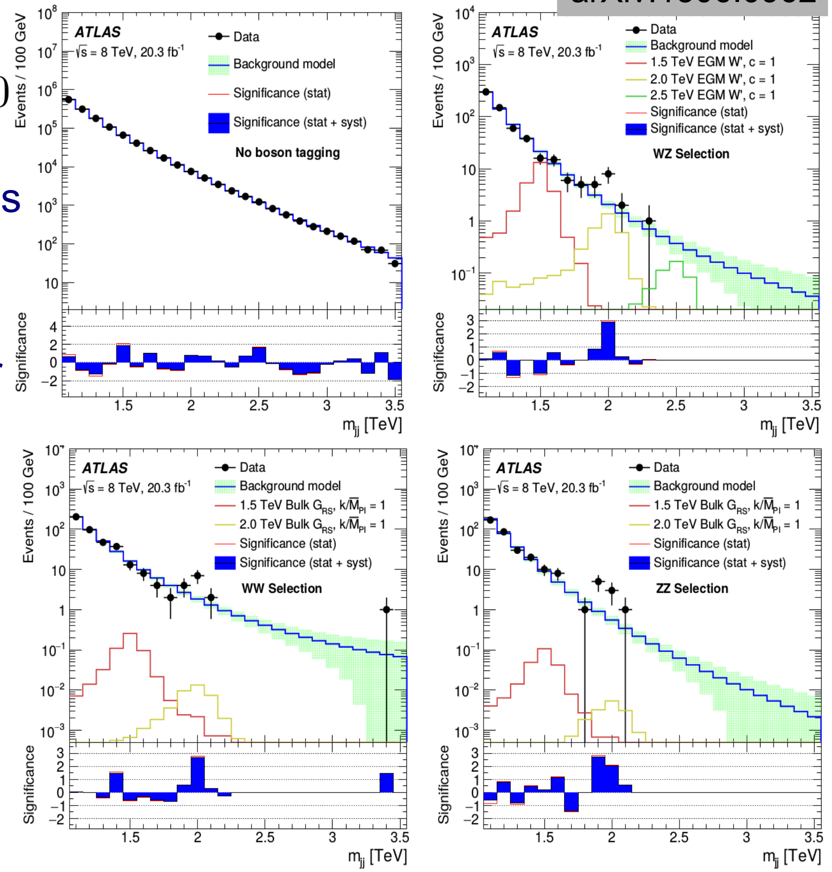
- # of charged tracks in ungroomed jet $n_{\rm trk} < 30$
- Cut on $\sqrt{y_f}$ prefers transversely polarized V's

  (differences wrt CMS)

- Alternative selections for WW, WZ, ZZ

  (not independent!)

- Local significance:
  - WZ : 3.4σ,
  - WW : 2.6σ,
  - ZZ : 2.9σ
- Global significance:
  - WZ : 2.5σ



P. Maksimovic, SUSY2015

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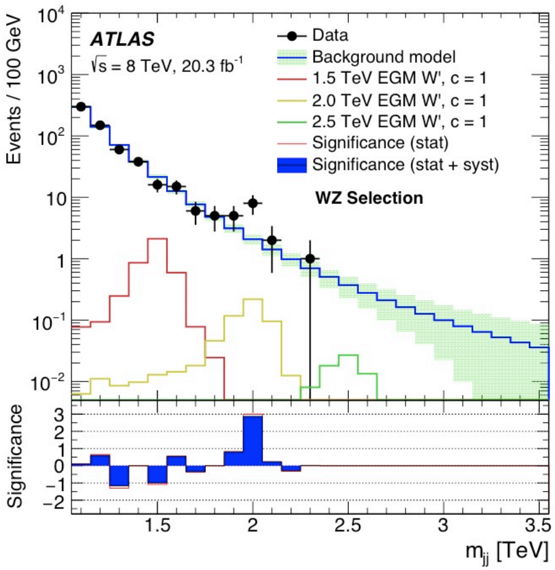
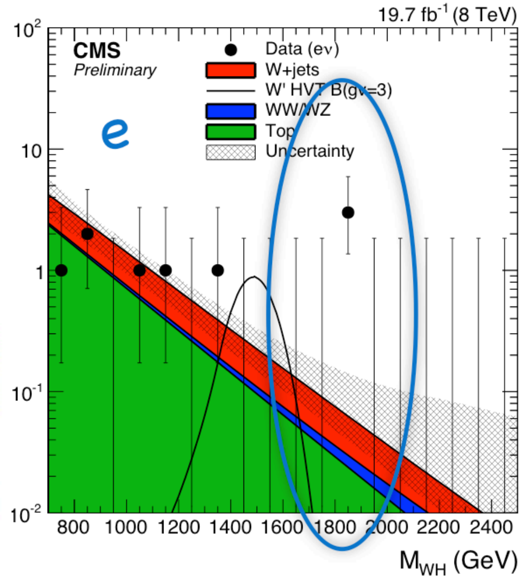
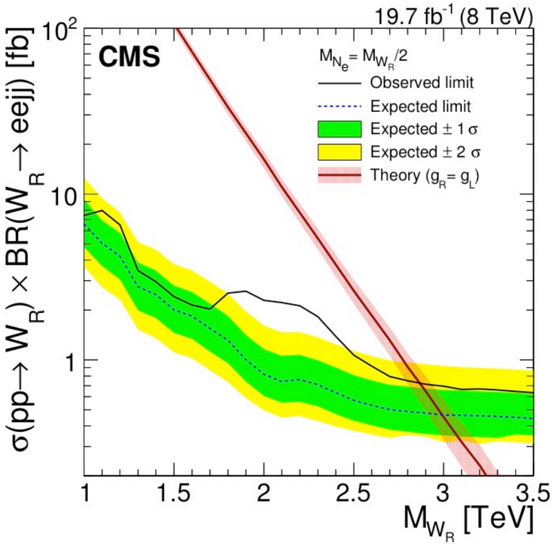
Hints from LHC Run 1







Excesses around 2 TeV in three different channels:

- **Boosted VV -> dijet (ATLAS and CMS)**
- **Boosted HV -> bbenu (CMS only)**
- **W_R -> eejj (CMS only)**

Talk by M. Pierini
Fermilab Users Meeting

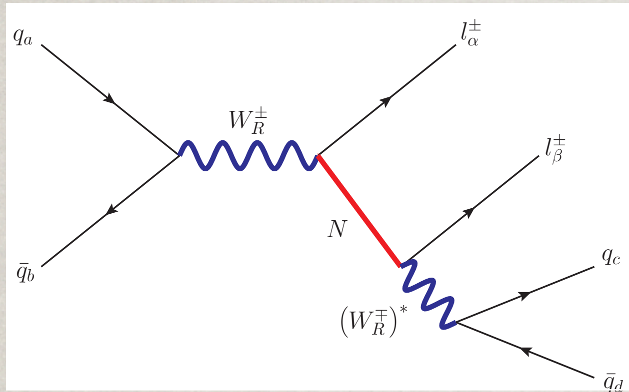
A 2 TeV W_R?

Can't get too excited, since some fluctuations have to be there

On the other hand, you cannot get to 5 sigma without passing through 2.5 sigma on the way…

For an alternate explanation see talk by J. Shu

W_R & N @ ATLAS



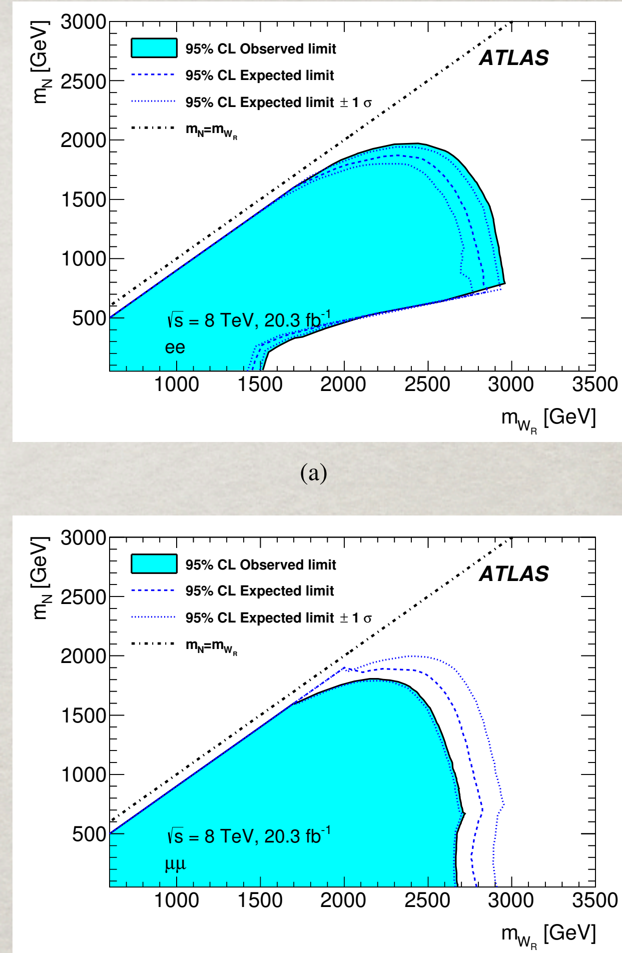
Note: W_R may be the top-candidate to explain the tantalizing excess of di-boson events near 1.8 – 2 TeV!*

So stay tuned …

- J. Hewett, T. Rizzo, J. Kopp, J. Tattersall: arXiv:1507.00013v2;

B. Dobrescu, Z. Liu: arXiv:1507.01923; … …

Keung & Senjanovic, PRL (1983).



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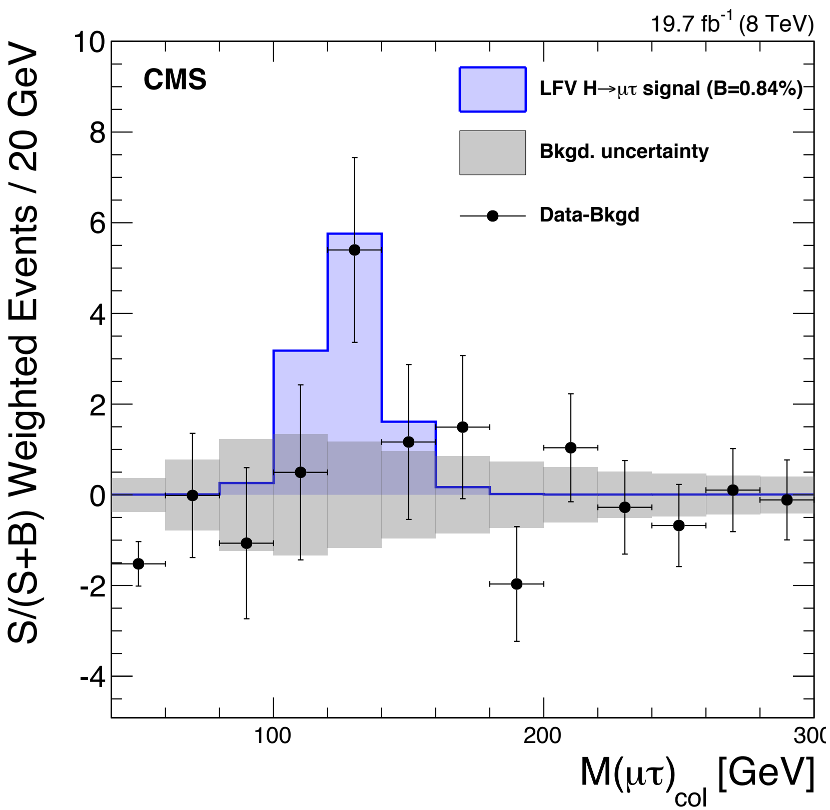
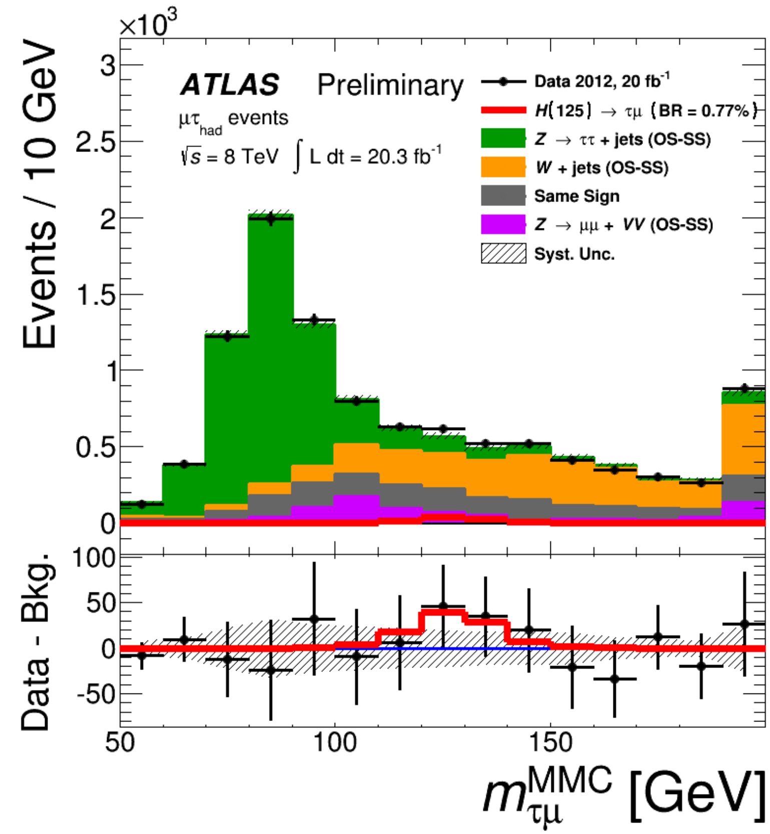
ATLAS collaboration: arXiv:1506.06020v2.

Lepton flavor violating Higgs decays?

H. Okawa and S. Palestini, SUSY2015

Phys. Lett. B 749 (2015) 337, arXiv:1508.03372





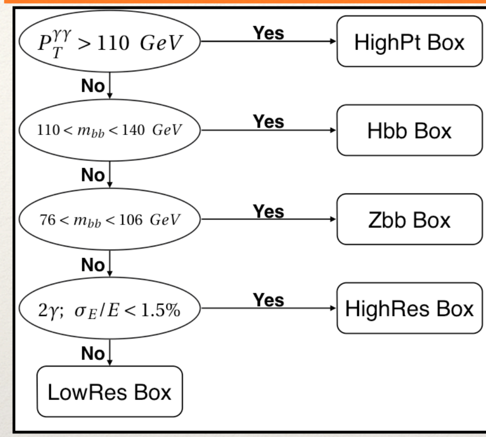
- Slight excess of **2.4σ significance** is observed in CMS (1.3σ in ATLAS).
- **Best fit BR(H→μτ) =** $0.84^{+0.39}_{-0.37}$**% [CMS]**, **0.77±0.62% [ATLAS]**
- Limit: **BR(H→μτ) < 1.51% obs** (0.75% exp) [CMS], **1.85%** (1.24%) [ATLAS]@95%CL

New from CMS Razor: Higgs + MET + jets

Inclusive Higgs-aware Search

CMS-SUS-14-017: New Result

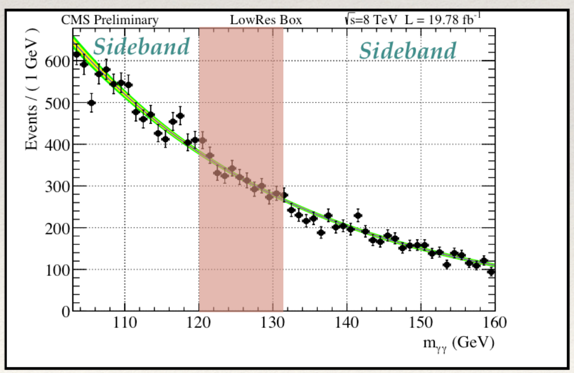
NEW!



Analysis Event Category Workflow

Inclusive Search for SUSY with Higgs

- Selection:
  - Tag higgs using: $h \rightarrow \gamma\gamma$
  - Categorize using higgs P_T and photon resolution
- Discriminating variables: M_R and R^2



- *Background prediction by extrapolating from $m_{\gamma\gamma}$ sidebands.*

$m_{\gamma\gamma} \ni$ [{103-118}, {133-163}] GeV

Thursday, August 27, 2015 18 Cristián Peña, Caltech

C. Peña, SUSY2015

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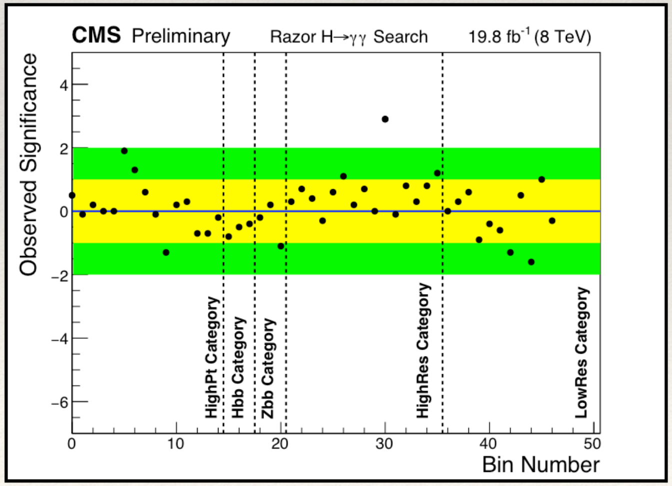
Inclusive Higgs-aware Search

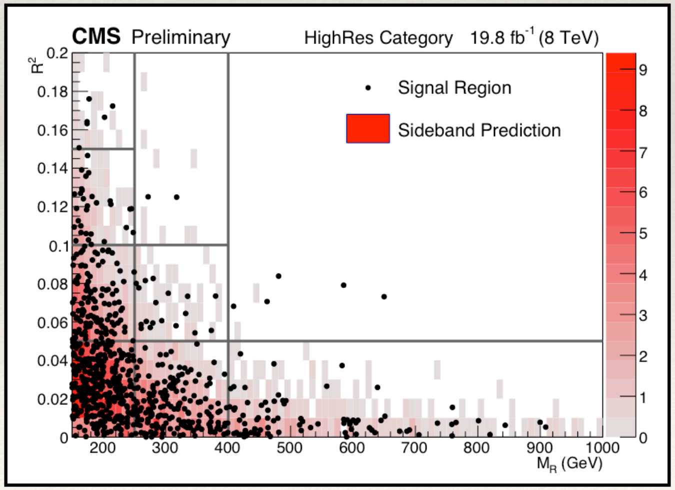
HighRes Event Category Results

M_R region	R^2 region	observed events	expected background	p-value	significance (σ)
150 - 250	0.00 - 0.05	363	$357.6^{+9.6}_{-9.4}$(syst.)	0.40	0.3
150 - 250	0.05 - 0.10	149	$139.4^{+5.6}_{-5.4}$(syst.)	0.23	0.7
150 - 250	0.10 - 0.15	35	$32.5^{+3.4}_{-3.1}$(syst.)	0.34	0.4
150 - 250	0.15 - 1.00	7	$8.0^{+1.7}_{-1.4}$(syst.)	0.40	-0.3
250 - 400	0.00 - 0.05	218	$207.9^{+7.0}_{-6.8}$(syst.)	0.27	0.6
250 - 400	0.05 - 0.10	20	$14.7^{+2.5}_{-2.1}$(syst.)	0.13	1.1
250 - 400	0.10 - 1.00	3	$2.7^{+0.8}_{-0.6}$(syst.)	0.43	0.2
400 - 1400	0.00 - 0.05	109	$101.6^{+5.0}_{-4.8}$(syst.)	0.26	0.7
400 - 1400	0.05 - 1.00	5	$0.5^{+0.4}_{-0.2}$(syst.)	0.002	**2.9**
1400 - 3000	0.00 - 1.00	0	$0.9^{+0.5}_{-0.3}$(syst.)	0.44	-0.1

CMS-SUS-14-017: New Result

excess is 1.6 σ after look elsewhere effect

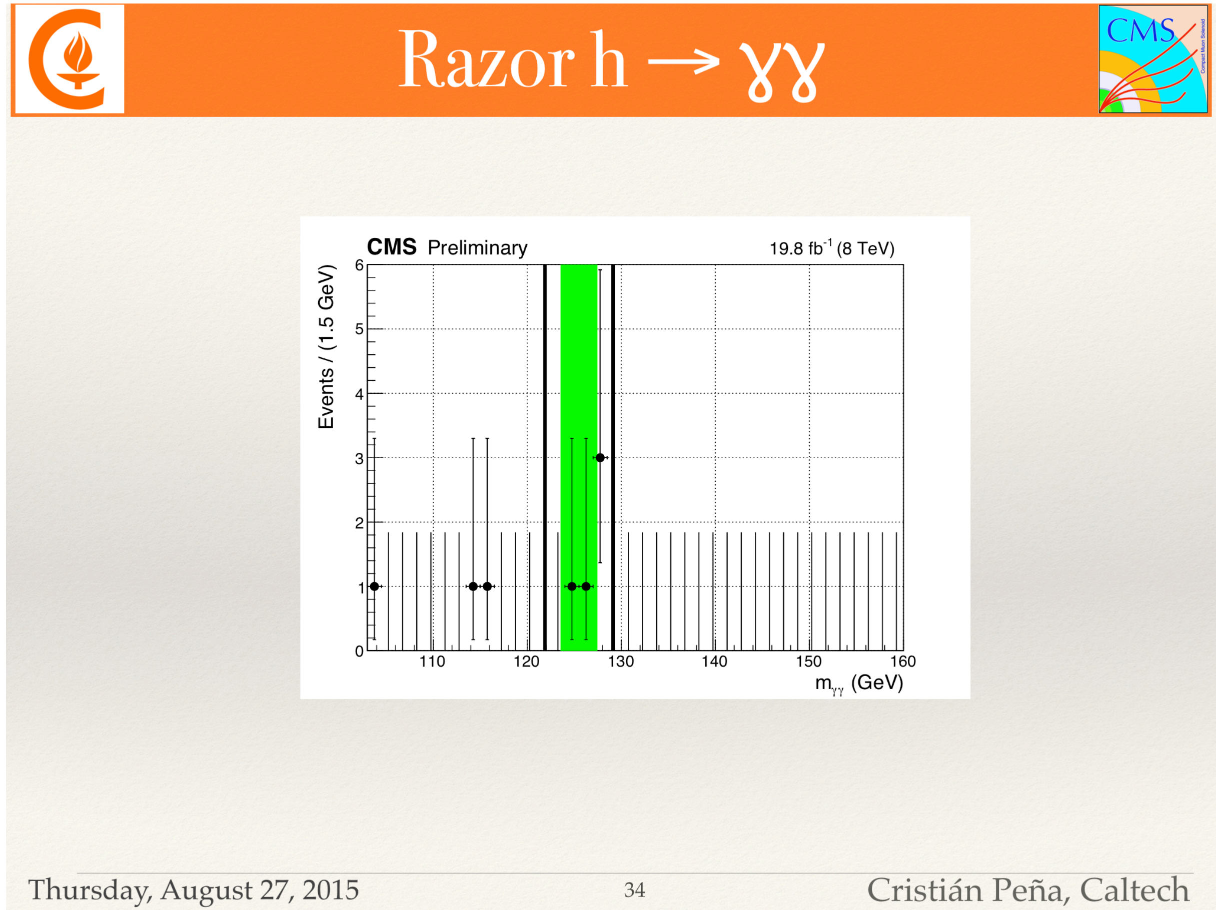




C. Peña, SUSY2015

Prospects for LHC Run 2

If there is a signal of this type in the Run 2 data, should eventually form a clear Higgs diphoton peak



C. Peña, SUSY2015

We live in *confusing* times for particle physicists

For the past 30 years, particle theorists have used the idea of naturalness to argue that a relatively light Higgs boson implies superpartner particles with mass below a TeV

- Light Higgs boson discovered, but no sign of superpartners
- No clear sign of any other new particles at LHC either
- Precision measurements (almost) all agree with Standard Model predictions, with frightening regularity
- Meanwhile the pattern of masses and mixings of Standard Model particles are a total mystery

Today we are confused but nature is surely following some logic

A. Strumia, Moriond 2015

Natural solution: Napoli = Salerno. But not supported by geo data

Anthropic solution: mafia sells signposts. Plausible but untestable

Or think different

The naturalness argument: how far are you willing to go?

$m_H << M_P$?

A. Pomarol, WIN2015

Towards naturalness

No new TeV-physics

reheatons?

"fermionizing" the Higgs

Supersymmetry

"marrying" a fermion:

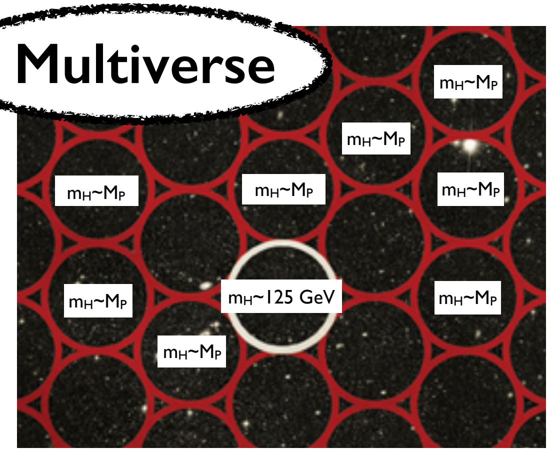
Higgs ⟷ Higgsino

Compositeness

relaxation mechanism?

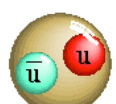
arXiv:1504.07551

Multiverse



The "transvestite" Higgs:

new TeV-physics

H = 

SUSY: a balance between natural and "special"?

Suppose we awaken from a long sleep, and read in the 2040 Review of Particle Properties that:

$$\begin{aligned} M_{\text{Higgsinos}} &= 1200 \text{ GeV} \\ M_{\text{stops}} &= 2000,\ 2500 \text{ GeV} \\ M_{\text{gluino}} &= 3000 \text{ GeV} \\ &\ldots \end{aligned}$$

Which will we then say?

My opinion: there is not, and cannot be, any such thing as an objective measure of fine-tuning.

S. Martin, SUSY2015

SUSY: a balance between natural and “special”?

To get small μ, arrange for cancellation in:

$$m_{H_u}^2 = 1.82\hat{M}_3^2 - 0.21\hat{M}_2^2 + 0.16\hat{M}_3\hat{M}_2 - 0.32\hat{A}_t\hat{M}_3 - 0.07\hat{A}_t\hat{M}_2 - 0.64\hat{m}_{H_u}^2 + 0.36\hat{m}_{Q_3}^2 + 0.28\hat{m}_{u_3}^2 + \ldots$$

Find UV completions in which the cancellation is “natural”.

- Original focus point: Very large $m_0^2 = \hat{m}_{H_u}^2 = \hat{m}_{Q_3}^2 = \hat{m}_{u_3}^2$

  Feng Matchev Moroi 9908309, 9909334.

- FP $M_h = 125$ GeV. $\hat{m}_{H_u}^2 : \hat{m}_{Q_3}^2 : \hat{m}_{u_3}^2 : A_t^2 = 1 : 1{+}x{-}3y : 1{-}x : 9y$

  Feng Matchev Sanford 1112.3021, Feng Sanford 1205.2372

- NUHM $\hat{m}_{H_u}^2 \neq m_0^2 = \hat{m}_{Q_3}^2 = \hat{m}_{u_3}^2$

- . . .

- Non-universal gaugino masses: $\hat{M}_3 \sim 0.3\hat{M}_2$. Compressed spectrum, small $|\mu|$. e.g. SPM 0703097, 1312.0582

S. Martin, SUSY2015

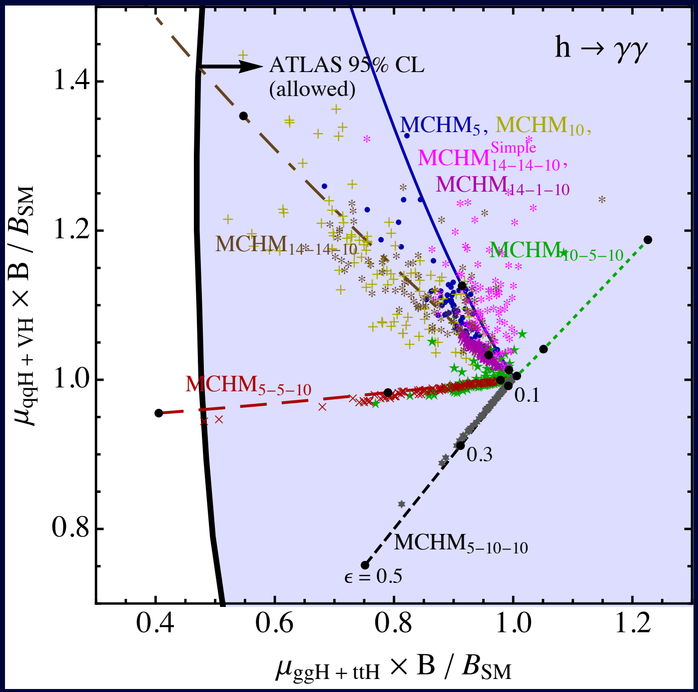
Composite PNGB Higgs: well motivated and predictive

- PNGB-Higgs can naturally be light and narrow
- Decoupling limit v/f —> infty where SM is recovered
- Fine-tuning worsens with larger f and g*
- Predictions and largest effects:
  - strong double H production
  - 10% corrections to tree-level Higgs couplings
  - small h—> gluons and photons but (possibly large) h—> Z gamma
  - light vector-like coloured partners expected below 1.5 TeV

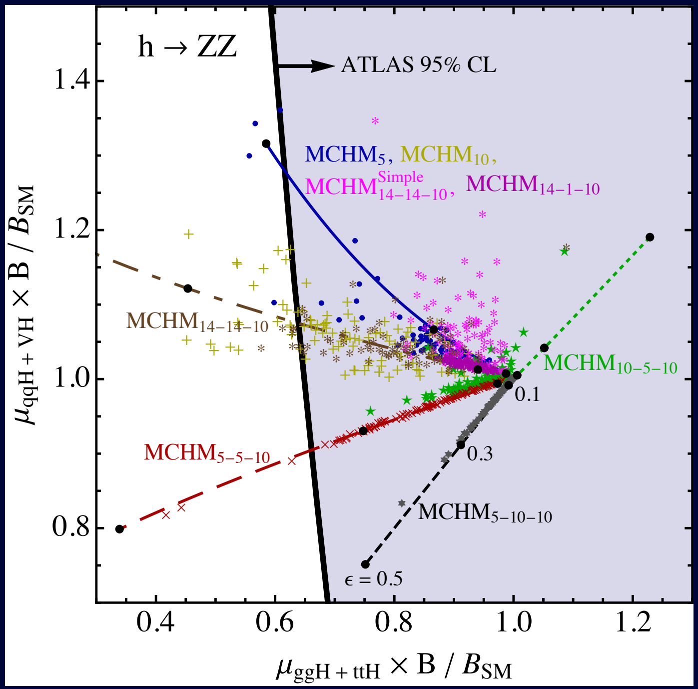
B. Bellazzini, SUSY2015

Minimal Composite Higgs models confronting data

h to di-photons



h to ZZ



Talk by M. Carena

M.C., Da Rold, Ponton'14

After EWSB: $\varepsilon = v_{SM}/f$ and precision data demands f > 500 GeV

More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

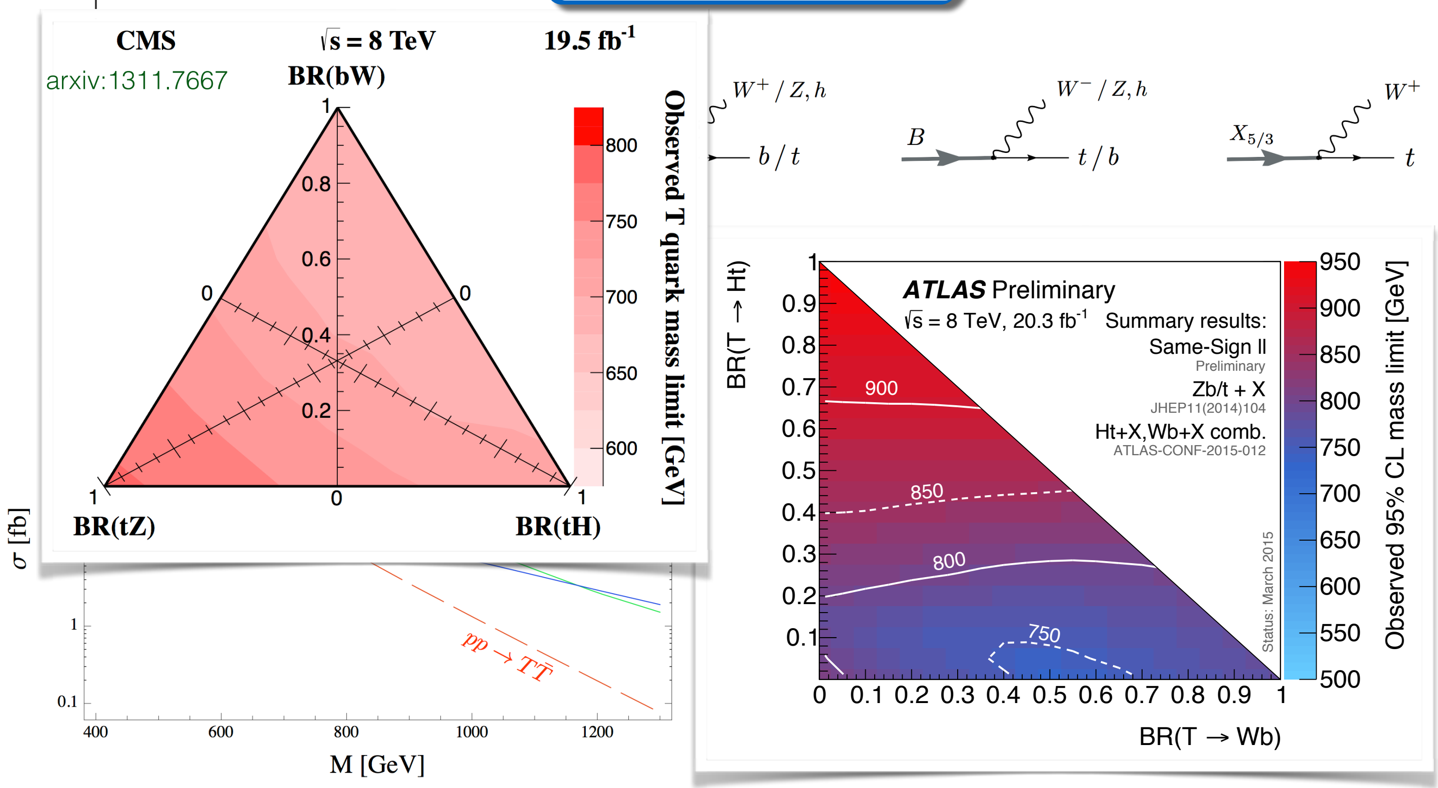
Other global symmetry patterns allow for additional Higgs Bosons in the spectrum

Composite Higgs predicts new vector-like quarks

SPIN-1/2 RESONANCES

$$m_T \gtrsim 800\ \mathrm{GeV}$$

B. Bellazzini, SUSY2015



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Is the Standard Model (almost) all there is?

Maybe the naturalness argument applied to the Higgs is just wrong (well, it was apparently wrong for the vacuum energy too)

- The Standard Model plus some TeV scale renormalizable additions (like dark matter) might be all there is
- The Standard Model itself, or with such modest additions, *is completely natural* (EW scale is not a prediction)
- Usual counterargument involves the putative Planck scale and unification thresholds, but this is speculative
- An unsatisfying scenario, leaving many questions unanswered, but has a certain minimalist appeal

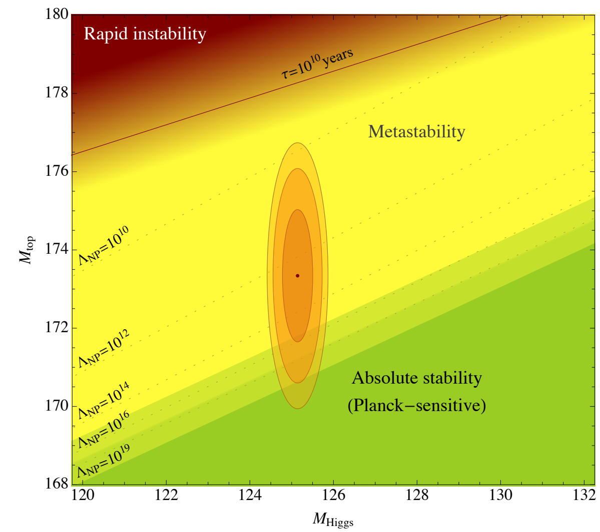
Why are we so close to the edge of SM stability?

$M_H \approx 125$ GeV is close to the boundary between the stability and metastability regions

If you believe in weak scale SUSY then you are forced to claim that this is a ~1% accident

Making such claims has historically not been a winning strategy in our field

[Rearranging the Goldstone contribution to $V_{\rm eff}$, to cure the gauge dependence of the stability bound order-by-order]



Andreassen *et al.*, 1408.0292

Stability condition:

$M_H > (129.4 \pm 1.5)$ GeV for $M_t^{\rm pole} = (173.34 \pm 0.76_{\rm exp} \pm 0.3_{\rm th})$ GeV

$M_t^{\rm pole} < (171.22 \pm 0.42)$ GeV for $M_H = (125.15 \pm 0.24)$ GeV

NOTE: questions on the identification of $M_t^{\rm pole}$ with the " $M_t^{\rm MC}$ " provided by the experiments

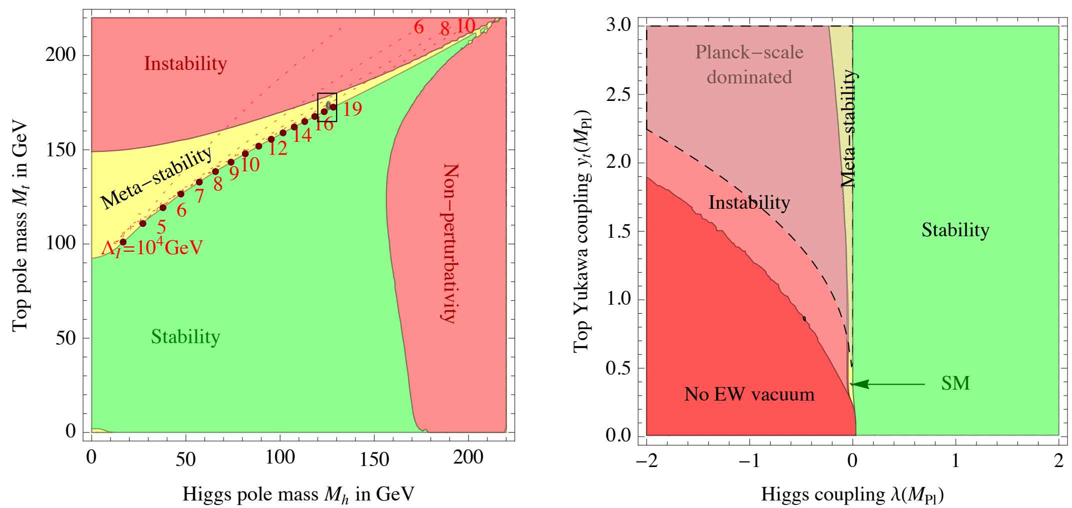
Alternative determinations from $\sigma_{t\bar{t}}$, e.g. $M_t^{\rm pole} = (171.2 \pm 2.4)$ GeV [Alekhin *et al.*, 1310.3059]

P. Slavich, SUSY2015

Why are we so close to the edge of SM stability?

Nature appears to have made rather special choices for the SM parameters

On the other hand trying to explain this as NOT an accident leads down a confusing road…



Buttazzo *et al.*, 1307.3536

- Speculation #1: *metastability as a critical phenomenon* [Buttazzo *et al.*, 1307.3536]
  [the multiverse pushes for small λ, but the universes where it is too small don't survive]
- Speculation #2: *metastability required by quantum gravity* [Espinosa *et al.*, 1505.04825]
  [QG cannot be consistently defined in a (dS) vacuum with positive cosmological constant; the decay to another (AdS) vacuum with negative cosmological constant offers a way out]

All these "conclusions" can be altered if we introduce any New Physics below the Planck scale

[see also Branchina+ Messina, 1307.5193 and 1507.08812]

P. Slavich, SUSY2015

The Twin Higgs

[Z. Chacko, H.-S. Goh, R. Harnik '05]

electroweak constraints are satisfied by construction. These models demonstrate that, contrary to the conventional wisdom, stabilizing the weak scale does not require new light particles charged under the Standard Model gauge groups.

Symmetry is $SM_A \times SM_B \times Z_2$

Twin Higgs

hep-ph/0506256 Chacko, Goh, Harnik
1411.3310 Burdman, Chacko, Harnik, de Lima, Verhaaren

SM_A x SM_B (mirror sector) particle content with Z_2 symmetry

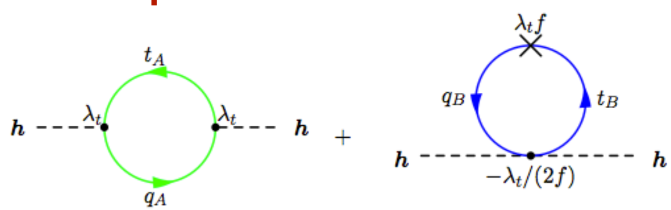
SU(4) Higgs sector with gauged $SU(2)_A$ x $SU(2)_B$ subgroup.

Gauge + Yukawa interactions break SU(4) and generate mass for goldstone boson (Higgs). **But...**

$$\Delta V = \frac{3}{8\pi^2}\Lambda^2\left(\lambda_A^2 H_A^\dagger H_A + \lambda_B^2 H_B^\dagger H_B\right) \quad \longrightarrow \quad \Delta V = \frac{3\lambda^2}{8\pi^2}\Lambda^2\left(H_A^\dagger H_A + H_B^\dagger H_B\right) = \frac{3\lambda^2}{8\pi^2}\Lambda^2 H^\dagger H$$

$$\lambda_A = \lambda_B \equiv \lambda$$

Z_2 symmetry protects pGB mass at 1-loop.



Spectrum:
A-sector: SM fermions
B-sector: mirror fermions, charged under their own $SU(3)_B$x$SU(2)_B$x$U(1)_B$

vacuum alignment: $\langle H_A \rangle = v \ll \langle H_B \rangle = f$.
Higgs mixing shifts couplings by ~ v^2/f^2 ~ Tuning

D. Curtin, SUSY2015

5

Twin Higgs: what to look for at LHC

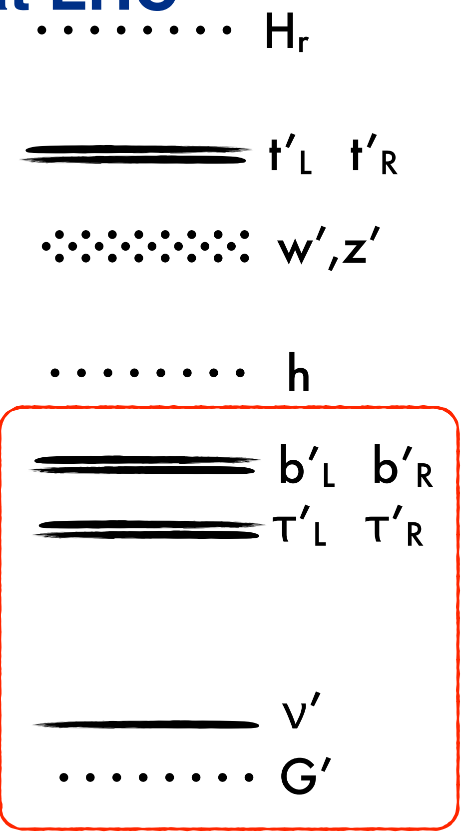
Decays into the hidden sector may come back to the Standard Model on interesting scales.

- Light fermions in the hidden sector: form light hadrons. Look for invisible decays of the Higgs.
- Light U(1) in the hidden sector: look for hidden photon phenomena.
- Light glueballs in the hidden sector…

Intriguing lifetime!

$$c\tau \approx 18\ \text{m}\ \times \left(\frac{10\ \text{GeV}}{m_0}\right)^7 \left(\frac{f}{500\ \text{GeV}}\right)^4$$

Strong dependence (7th power) on glueball mass → decays scan rapidly over LHC length scales.



N. Craig, SUSY2015
See also talks by
C. Verhaaren
E. Salvioni
O. Telem

Glueballs decay back to the SM through an off-shell SM higgs

$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f} G'^{a}_{\mu\nu} G'^{\mu\nu}_{a} \rightsquigarrow 0^{++} \rightarrow h^* \rightarrow \dots$$

Many motivations for extended Higgs sectors

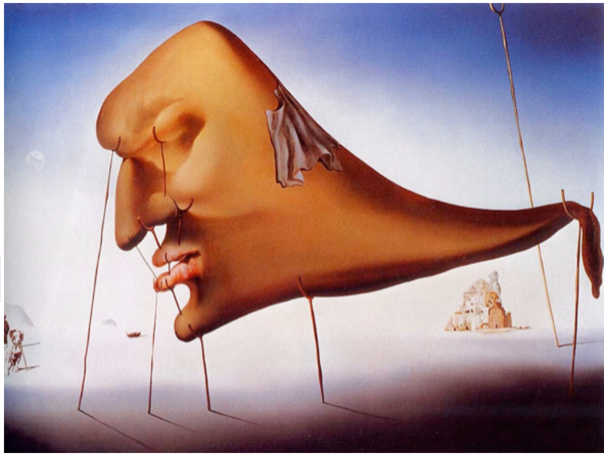
- Extended Higgs sectors: SM + s, MSSM + S, composite models, ...
  - simplest realization of Higgs portal coupling: $|S|^2|H|^2$
  - NMSSM: dynamically generate μ, relax phenomenological constraints on $V(H)$, neutralino dark matter
  - electroweak phase transition: baryogenesis, cosmological history of the SM

J. Shelton, SUSY2015

We wish to explore a third possibility in which one fine-tuning is required to obtain the EWSB scale and the Higgs mass of 125 GeV. But, additional Higgs scalars are also light due to an approximate symmetry that links their mass scale to the scale of EWSB. We call a two Higgs doublet model (2HDM) of this type *partially natural*, in which one fine-tuning is sufficient to obtain the entire Higgs spectrum with masses of $\mathcal{O}(v)$.

H. Haber, SUSY2015

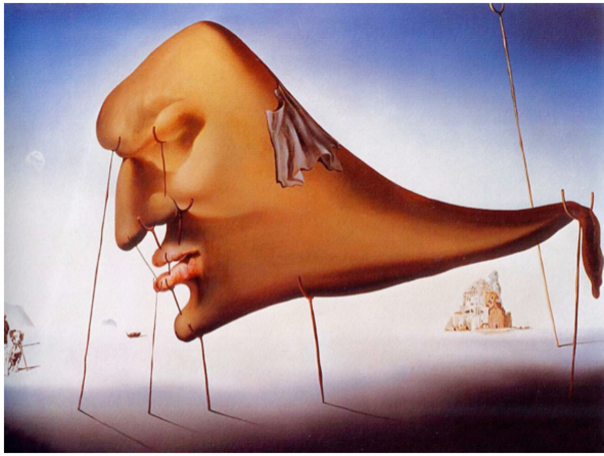
The canonical Beyond the Standard Model paradigm



- Superpartners at the LHC
- Dark matter from supersymmetry, axions
- “Grand” or similar unification of matter and gauge forces somewhere around 10^{16} or 10^{17} GeV
- Tiny neutrino masses from a see-saw related to the new physics at superhigh energies
- Superstrings at the Planck scale with lots of extra structure to explain flavor structure, primordial inflation, etc.

There are (still) lots of good arguments for this picture!

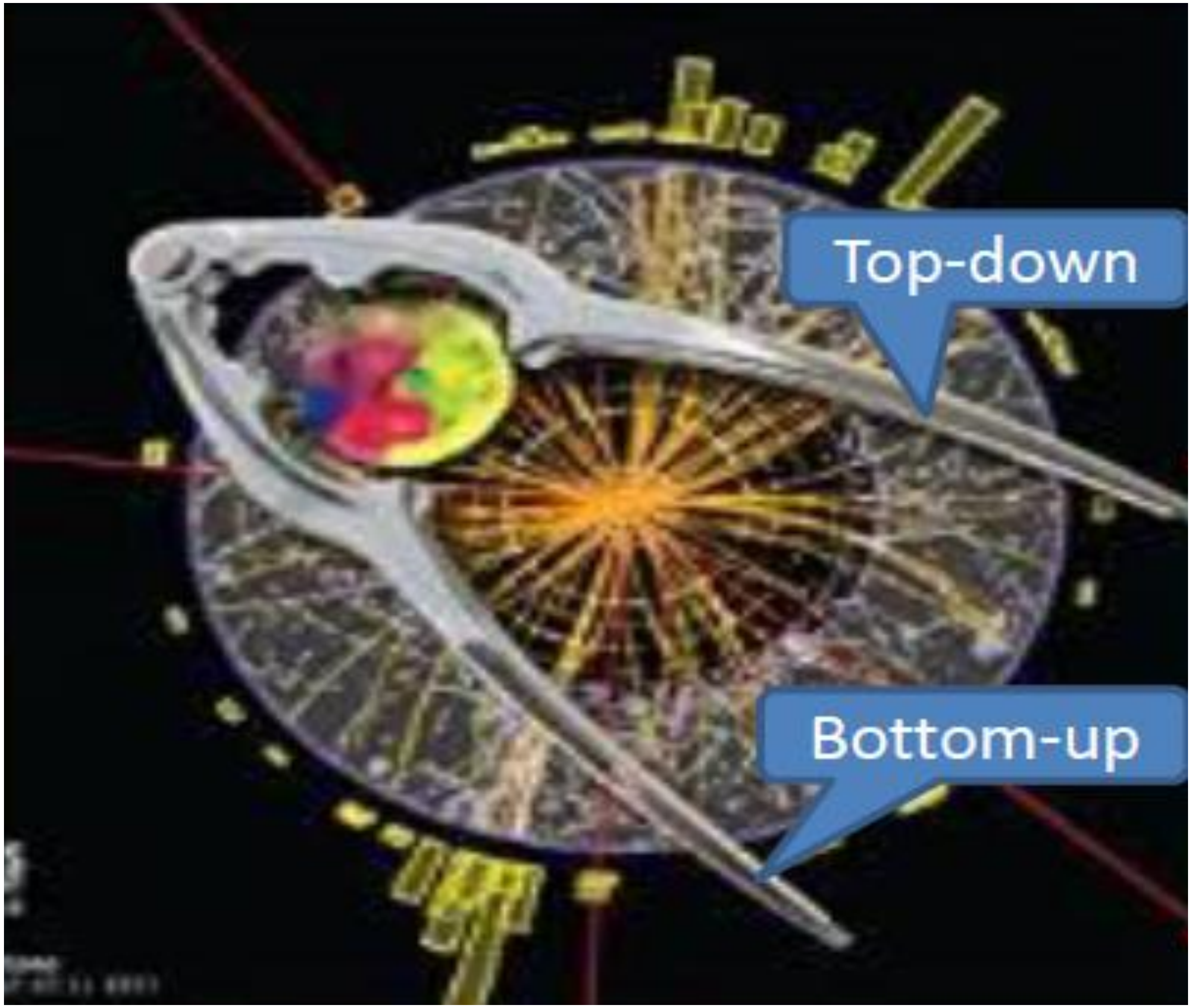
The canonical Beyond the Standard Model paradigm



The experimental program that goes with this paradigm is pretty clear:

- Find superpartners, map properties
- Nail down the physics of the Higgs
- Close the circle of dark matter between direct detection, indirect detection, LHC production, and large scale structure
- Nail down the neutrino sector including CP violation and Majorana mass
- Find proton decay and possibly charged lepton flavor violation
- Cosmic Microwave Background probes primordial inflation
- **Use all these clues to extract a more concrete picture of the unified theory at superhigh energies**

A hard nut to crack



G. Kane, SUSY2015

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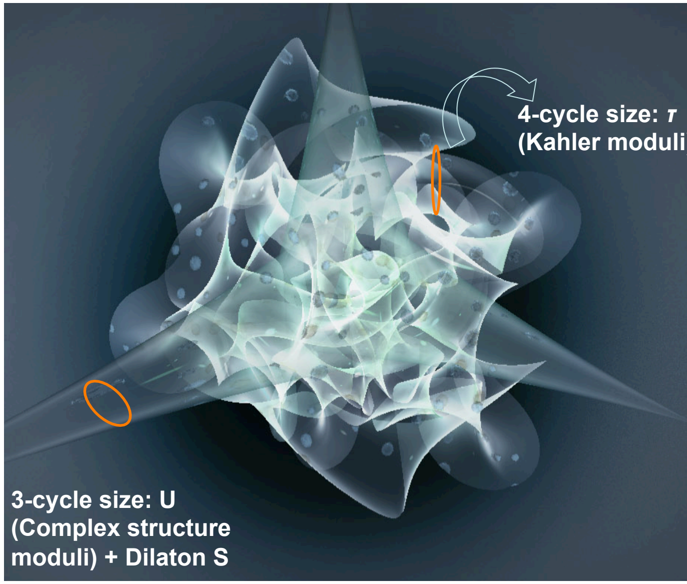
SUSY Challenges for String Scenarios

F. Quevedo, SUSY2015

- **Explicit *N*=1 Compactification**
- **Concrete SUSY breaking mechanism**
- **Moduli Stabilisation (small cc)**
  (+ avoid CMP (plus gravitino+ dark radiation excess,etc!))
- **Chiral visible sector**
- **Computable soft terms**

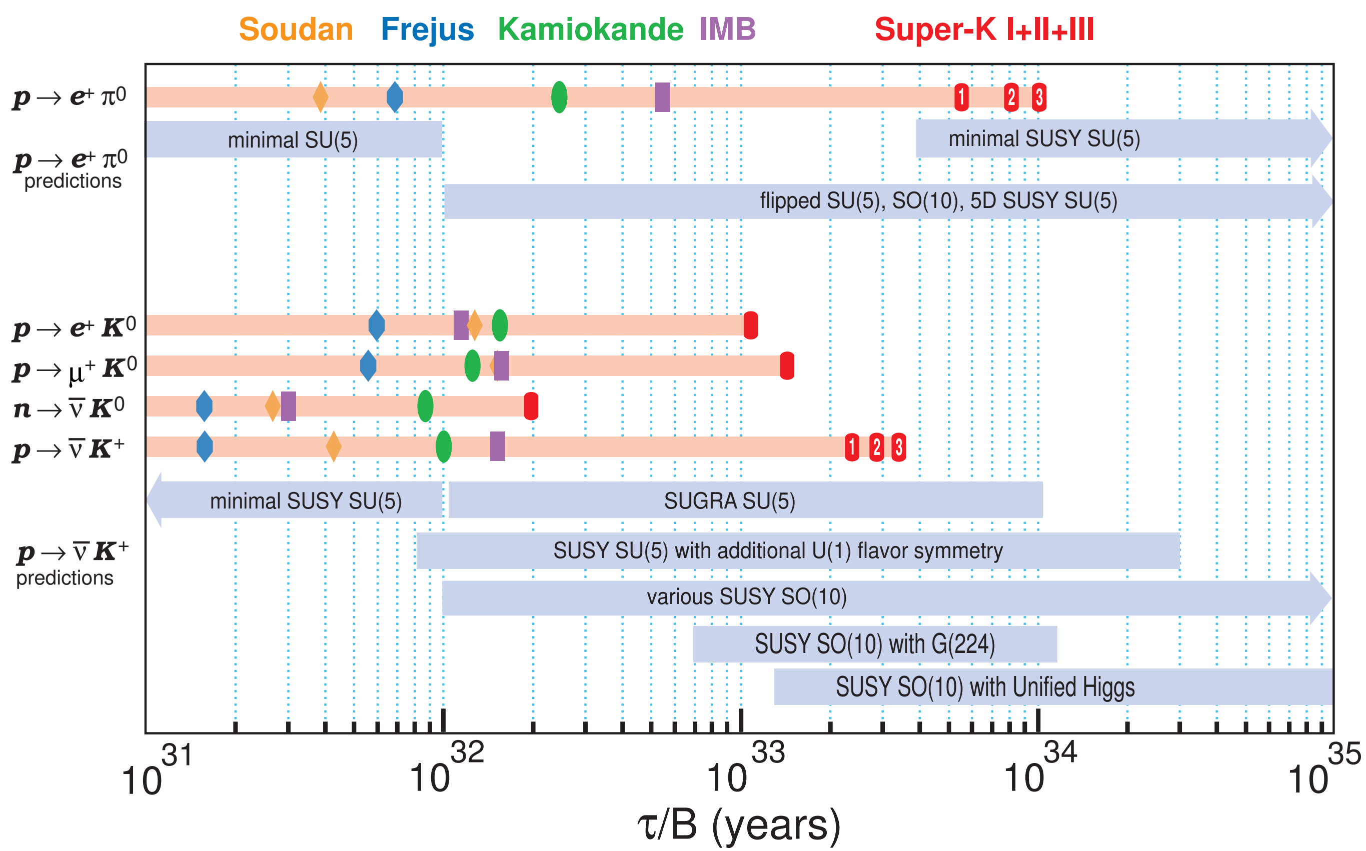


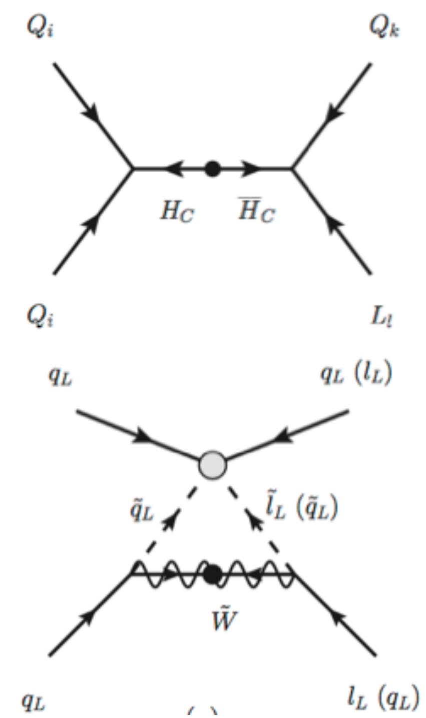
➢ **String/M-theory too important to be left to string theorists**

G. Kane, SUSY2015

SUSY and proton decay

- Long known to be trouble for minimal supersymmetric SU(5): lower limits on the proton are already very strong!

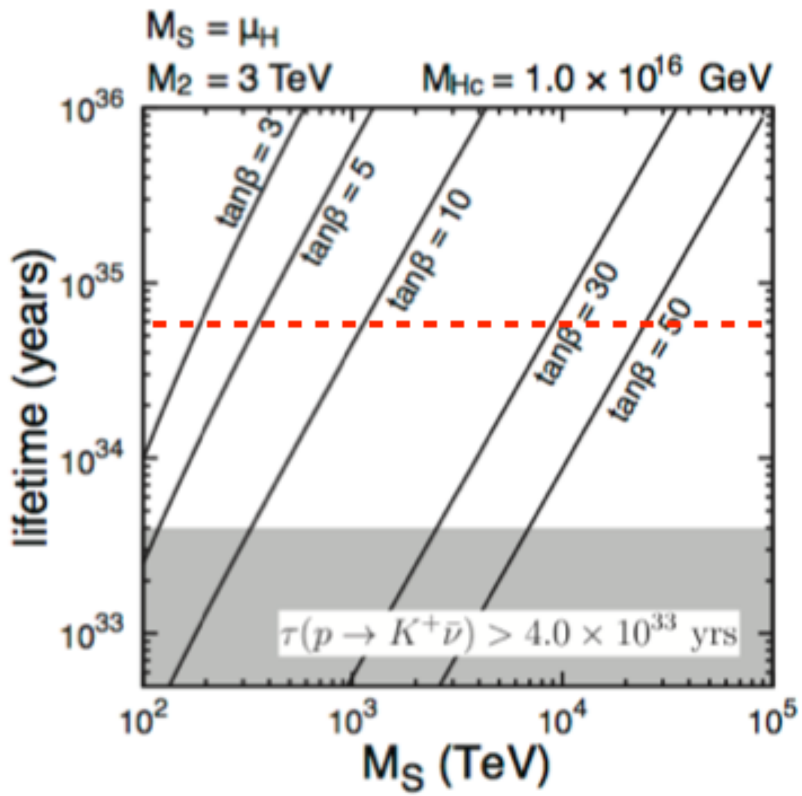




SUSY and proton decay

- Lifting squark masses to ~100 TeV or higher gives an extra suppression that revives minimal supersymmetric SU(5)
- Also works in classes of SUSY SO(10) models with ~20 TeV squark masses

J. Pati, PPC2015



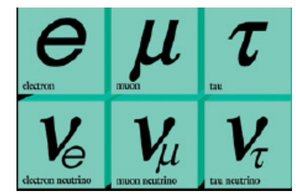
Even better, such models will actually produce a proton decay signal at DUNE and HyperK

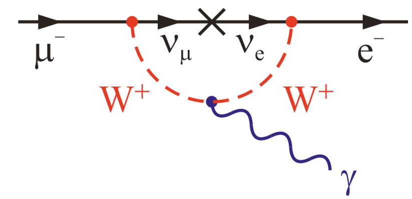
Another window to BSM: charged LFV

Y. Kolomensky, SUSY2015

Charged Lepton Flavor Violation

- Charged Lepton flavor: accidental symmetry in the Standard Model
  - Lepton flavor violation forbidden if neutrinos are massless
    - ☞ Very small SM effect due to finite neutrino mass: *BR*($\mu \to e\gamma$) ~ 10^{-52}





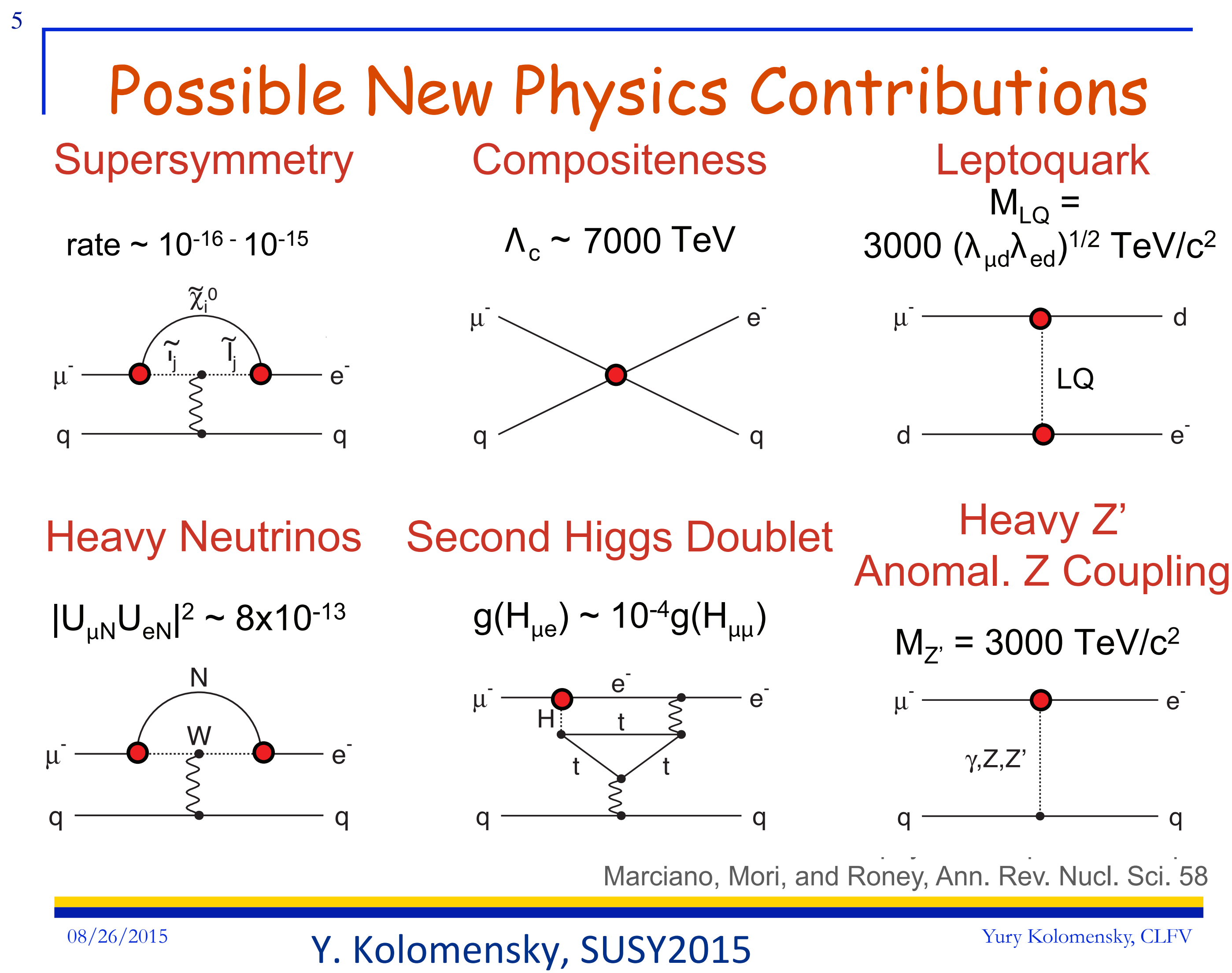
- CLFV: an unambiguous signature of new physics
  - ☞ Sensitivity to mass scales far beyond the reach of direct searches
  - ☞ Window into TeV physics and beyond
  - ☞ Next generation experiments will have sensitivity to directly test predictions of many BSM theories, e.g. SUSY

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

08/26/2015 Yury Kolomensky, CLFV

Fermilab

Another window to BSM: charged LFV



Muon CLFV and Muon g-2

The dipole effective operators that mediate $\mu \to e\gamma$ and contribute to a_μ are virtually the same:

$$\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma^{\mu\nu}\mu F_{\mu\nu} \qquad \times \qquad \theta_{e\mu}\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma^{\mu\nu}eF_{\mu\nu}$$

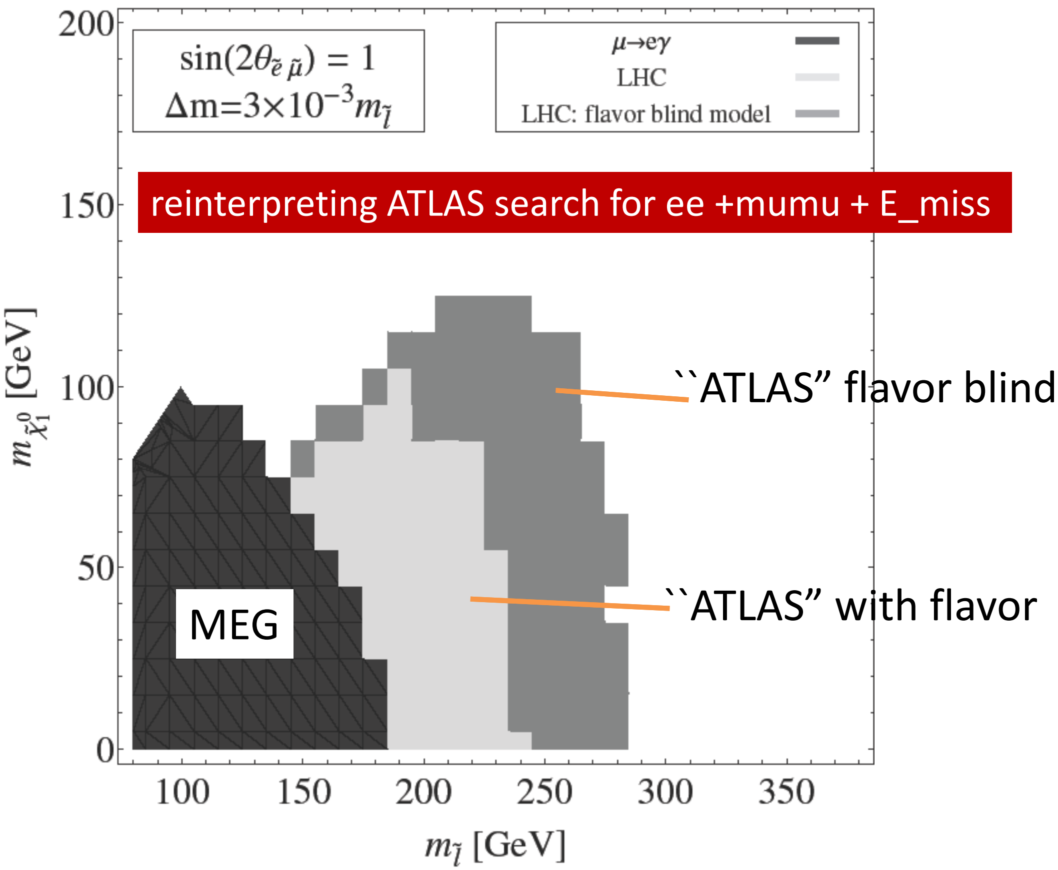
$g-2$	CLFV	What Does it Mean?
YES	YES	New Physics at the TeV Scale; Some Flavor Violation
YES	NO	New Physics at the TeV Scale; Tiny Flavor Violation
NO	YES	New Physics Above TeV Scale; Some Flavor Violation – How Large?
NO	NO	No New Physics at the TeV Scale; CLFV only way forward?

A. de Gouvea, PPC2015

Muon campus at Fermilab

- Muon g-2 ring is cold and almost fully powered
- Will get beam in 2017
- Mu2e starts in 2020/21

CLFV and LHC SUSY searches



Y. Shadmi, SUSY2015

Keep looking for new physics in quark flavor

Summary of "Traditional Flavour"

- No sign of NP in "golden" SUSY channel $B_s \to \mu^+\mu^-$
- Run 2 LHC ➜$B_d \to \mu^+\mu^-$
- NA62 and KOTO ➜$K \to \pi\nu\bar{\nu}$
- Tensions in $B \to K^*\mu^+\mu^-$, R_K
  power corrections? statistical fluctuations?
  NP with very special structure?

Current Flavour data do not favour SUSY signals

E. Stamou, SUSY2015

Fermilab

Neutrino mass: what seesaw?

- Small neutrino mass -> heavy neutrino (N_R) by "SeeSaw"
- Several models predict TeV scale heavy neutrinos.

- If heavy neutrinos exist at TeV scale we should be able to see them at the LHC.
- CMS and ATLAS have performed searches for heavy neutrinos in a number of models.

- Type 1: weak-singlet fermion (N)
  EXO-12-057 EXO-14-014
- Left-Right Symmetric Model (LRSM): $SU(2)_R$ symmetry to the SM: N, W_R, Z'
  EXO-13-008 LRSM In Back Up slides
- Type 3 : weak-triplet fermion ($\Sigma^0\Sigma^{+/-}$)
  EXO-14-001 Type 3 In Back Up slides

J. Almond, SUSY2015; see also talks by X. Marcano, B. Shakya

To-do list for BSM theorists, 2015

- If we have missed/screwed up on some major aspect of BSM physics at observable scales: explore effects (good or bad) on the experimental program
- Can we exclude entire scenarios rather than just blobs of parameter spaces?
- Getting our act together for the LHC era:
  - Shrinking theory uncertainties
  - Even better simulation tools
  - Benchmarks: Simplified models vs “Complete models” vs EFT
  - New physics objects, new kinematic variables, validation
  - Relating LHC results to other experimental results (DM direct and indirect searches, precision EW, heavy flavor, g-2, etc)

Can we rule out electroweak baryogenesis?

Just based on scales and the fact that we already see the Higgs at LHC, it seems like we should be able to conclusively test this scenario generically

- Charged under SM group: (MSSM stops, 2HDM, etc: LHC Higgs global fits, direct searches on S, etc) A
- Higgs mixture (NMSSM, etc, LHC non-Standard Higgs searches, EW precision, etc) B
- Hidden (EW & Higgs precision, SPPC direct search) C

J. Shu, SUSY2015

But there are many, many possible realizations, related to all the possibilities for the Higgs sector and related BSM physics

Can we rule out electroweak baryogenesis?

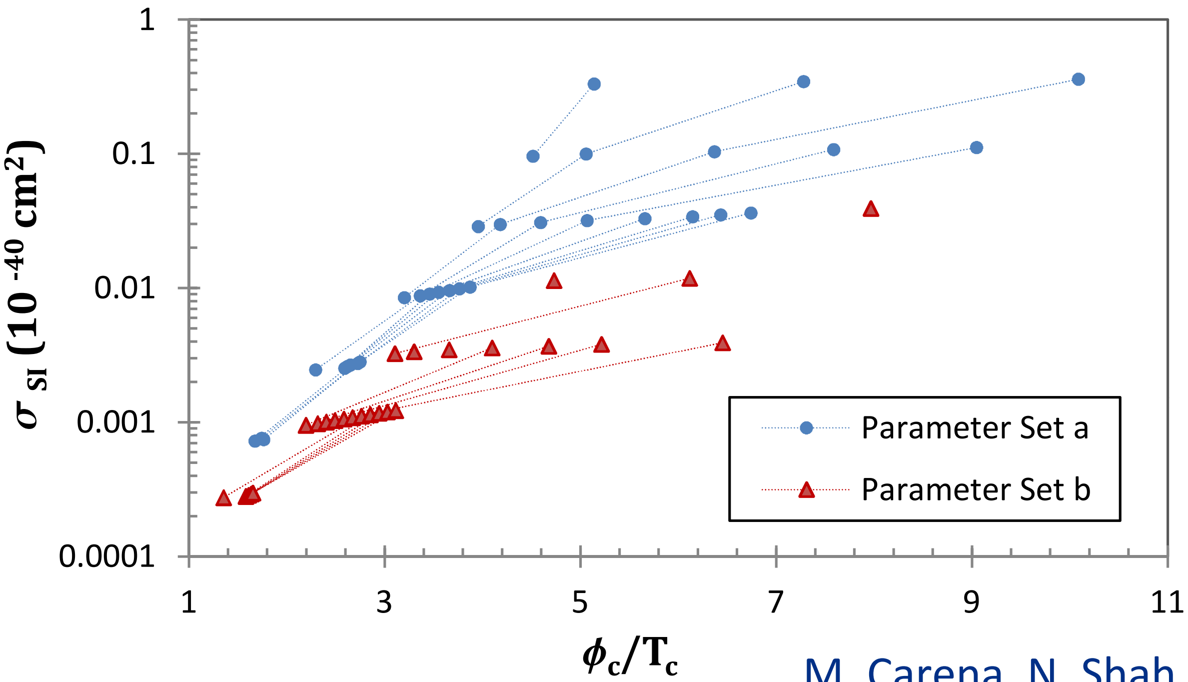
- Increase the thermal cubic term E term (E is the coefficient of $\phi^3 T$)

J. Shu, SUSY2015

- Decrease the T=0 energy difference ΔV (Increase the fine tuning of the Higgs potential)

- Can make a lot of progress by concentrating on the key physics required to make EWBG work
- Still a difficult experimental challenge, e.g. need to measure Higgs self coupling

Can we rule out electroweak baryogenesis?



M. Carena, N. Shah, C. Wagner, to appear

- Certain classes of models, e.g. NMSSM, provide other handles for experimental tests, e.g. connections between EWBG and dark matter

Progress on PDF uncertainties for LHC

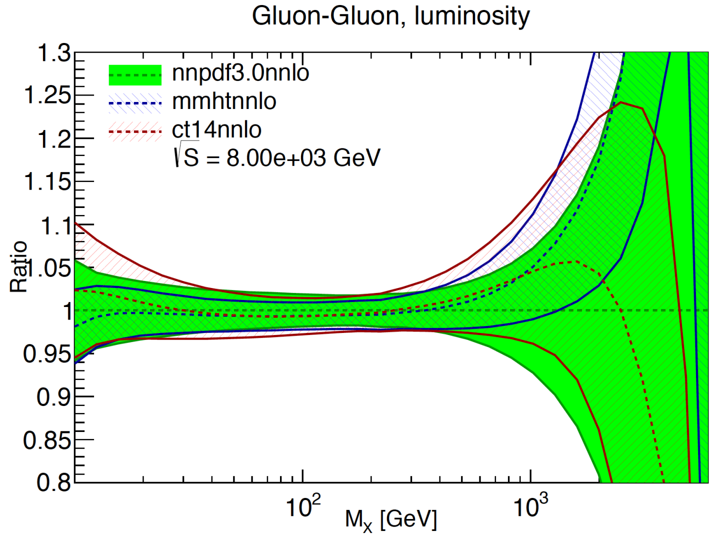
σ [pb]	√s=7 TeV	√s=8 TeV	Uncertainty at 8 TeV [%] QCD scale	PDF+α_S
ggH	15.1	19.2	+7.2 -7.8(**)	+7.5 -6.9
VBF	1.22	1.58	±0.2	+2.6 -2.8
WH	0.577	0.703	±1.0	±2.3
ZH	0.334	0.414	±3.1	±2.5
ttH(*)	0.086	0.129	+3.8 -9.3	±8.1
bbH(*)	0.156	0.203	+10.3 -14.8	±6.2

A. Andreazza, SUSY2015

Progress on PDF uncertainties for LHC

NNLO PDF uncertainties

NEW 2015



- Much nicer convergence for new generations of PDFs (updated HERA data included).
- PDF uncertainty on Higgs production down to about 2%
- New recommendations: conservative envelope no longer needed, PDF and α_s uncertainties to be kept separate (combine in quadrature if needed), PDFs delivered for each value of α_s.

Radja Boughezal, ANL 31 Precision Higgs Physics

R. Boughezal, SUSY2015

For LHC Run 2: boosted analyses

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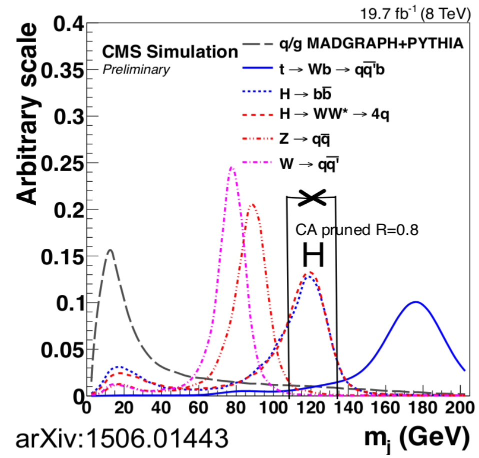
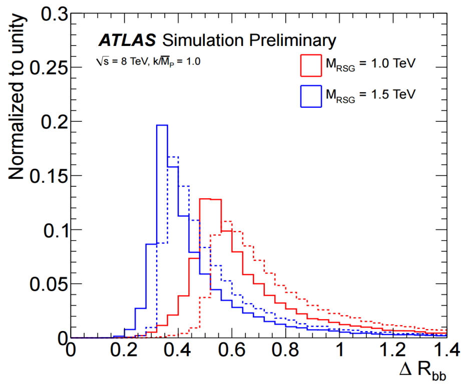
Boosted H → bb tagging

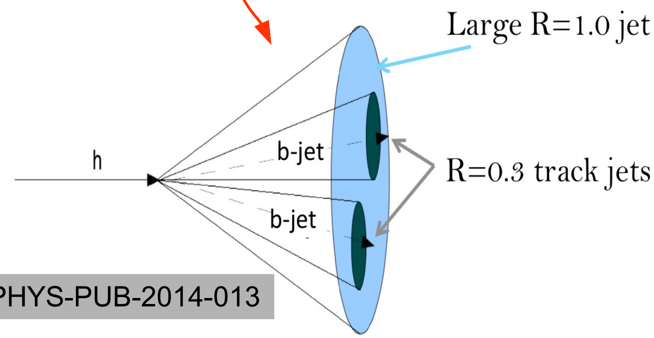
arXiv:1506.01443

- Discriminants:
  - large R jet (ATLAS: anti-k_T R=1.0, CMS: CA R=0.8)
  - groomed jet mass (trimmed for ATLAS, pruned for CMS)
  - “subjet b tagging”
    - track jets R=0.3 for ATLAS
    - pruned subjets for CMS



arXiv:1506.01443





ATL-PHYS-PUB-2014-013

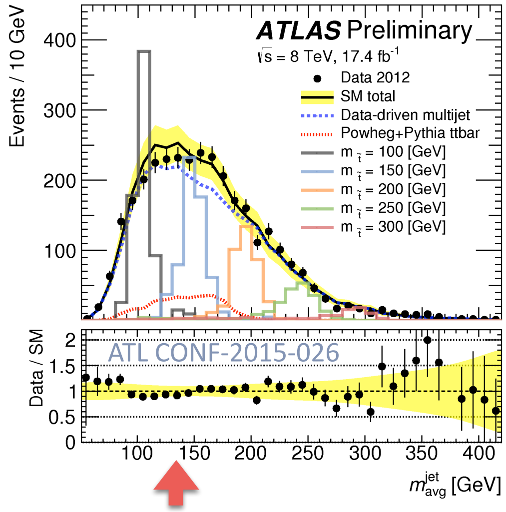
P. Maksimovic, SUSY2015

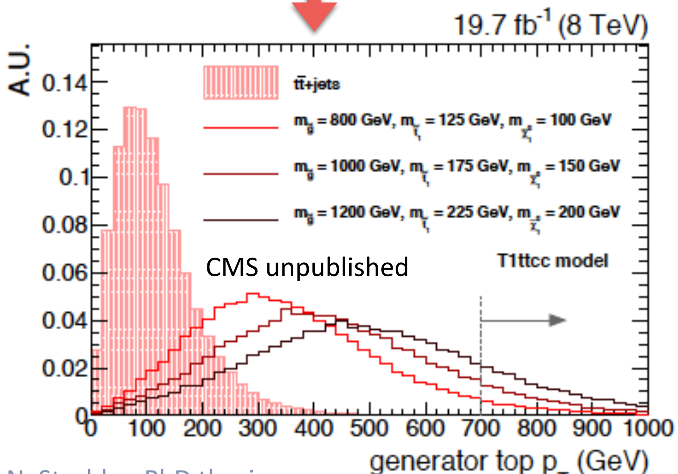
For LHC Run 2: boosted analyses

Boosted SUSY: analyses

S. Sekmen, SUSY2015

- Boosted Ws from top decays used in CMS in a search with razor variables to probe $\tilde{g} \to \tilde{t}_1 t$ where $m_{\tilde{g}} - m_{\tilde{t}_1}$ is large, and direct stop production for heavy stops (CMS SUS-14-007).
- Becomes important for completing Naturalness searches. Already pursued for Run2 in with flavors of boosted tops.





N. Strobbe, PhD thesis

- RPV SUSY leads to no E_T^{miss} signatures: build sparticles from visible decay products.
- ATLAS studied $\tilde{g} \to qqq$ (SUSY-2013-07) and $\tilde{t} \to bs$ (CONF-2015-026).
- Used M_{jet}^{Σ} for $\tilde{g}$; jet mass and substructure for $\tilde{t}$. Substructure for RPV can be further optimized.

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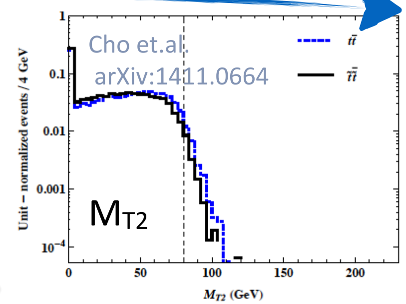
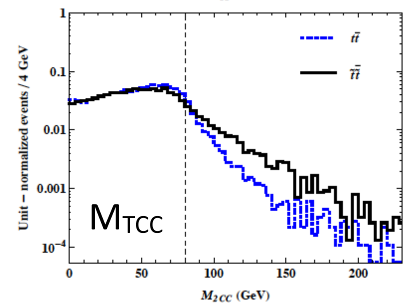
For LHC Run 2: clever kinematic variables

New variables and methods: Kinematics

As signal and background become similar, make most of the subtle kinematic differences.

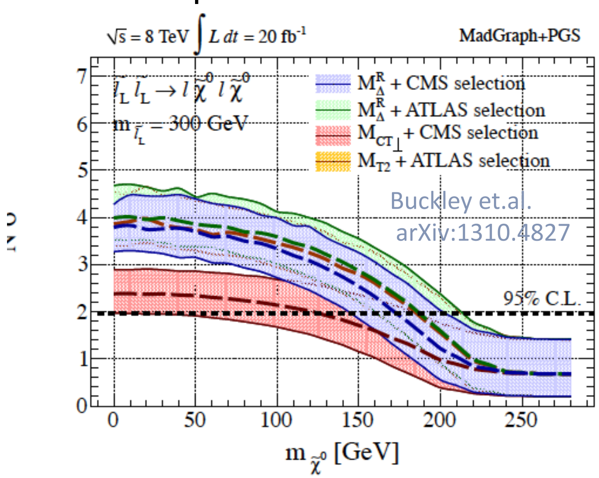
- M_2, the on-shell constrained invariant mass variables minimize some parent mass wrt p of invisible daughers. 3+1 generalizations of M_{T2}, and improve signal-background discrimination.
- Recent study with stops promising, there is a lot to explore.





Also see OPTIMASS, package to minimize kinematic mass functions with constraints (arXiv:1508.00589)

Talks by L. Lee, P. Jackson,



- Recent super-razor variables improve sensitivity to EWK gaugino pair production.
- Recursive jigsaw reconstruction extends super-razor: recipe to assign 4-vectors to the invisible particles to constrain system at each step of decay.

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S. Sekmen, SUSY2015

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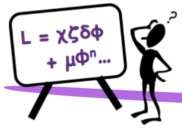
LHC Run 2: what experiments want from theorists



New models

In Run1, ATLAS and CMS used simplified models to model signatures. In Run2, full models will be more focused on. What models could be interesting / motivated / relevant?

- pMSSM was extensively used, and will continue to be used.
- Flavor violating models?
- Extensions of the MSSM:
  - NMSSM and studies in its rich Higgs sector; models with sneutrino/ axino/… LSP, extended gauge groups (U(1), left-right, E6, …); …
- Run2 will probably say the final word on Naturalness with light stop. Complete Naturalness scans?
  - Different ways of achieving Naturalness? neutral naturalness?
- Relations with dark matter? Effective field theories?

We need guidance from theorists!

S. Sekmen, SUSY2015

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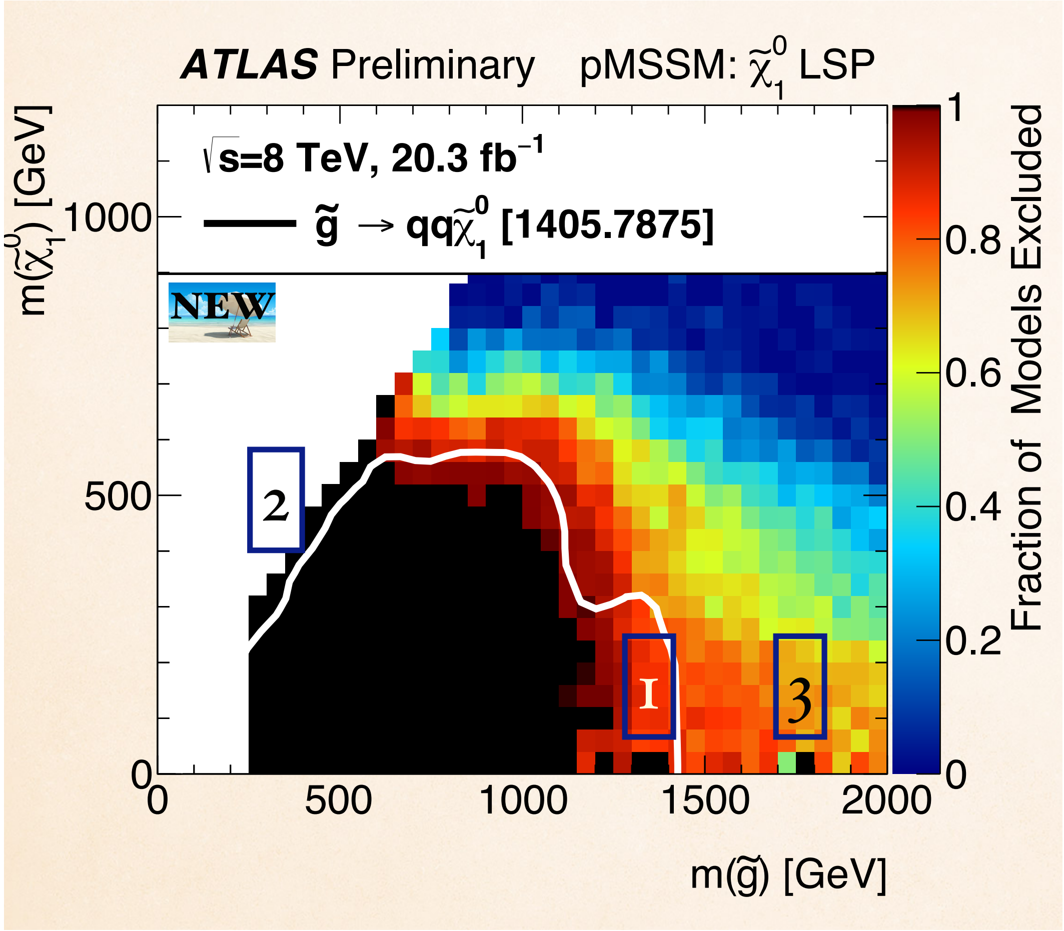
LHC Run 2: how to present exclusion results?



T. Lari, SUSY2015
C. Wanatotaroj, SUSY2015

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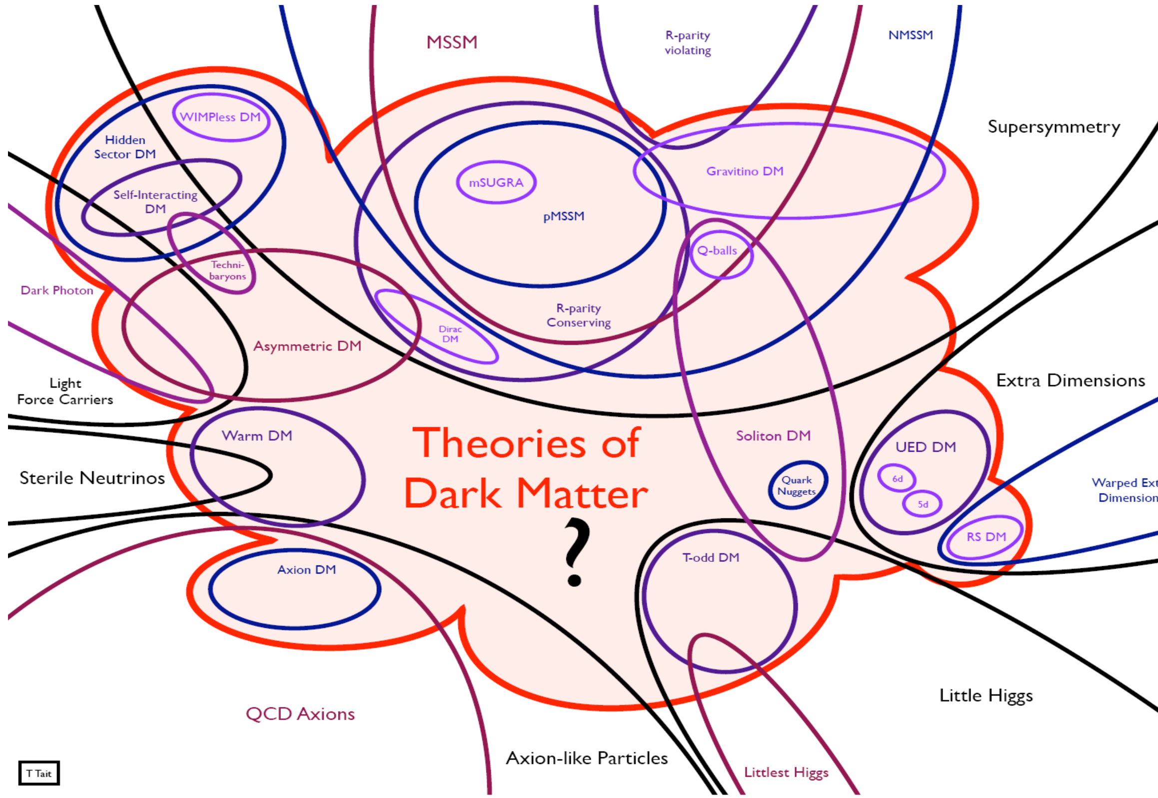
Dark matter bestiary

- Superpartner particles: Wino, Bino, Higgsino, sneutrino, …
- Axions
- Kaluza-Klein particles from extra dimensions
- Sterile neutrinos
- Asymmetric dark matter
- SuperWIMPS
- Hidden sector particles
- WIMPzillas (don't ask…)



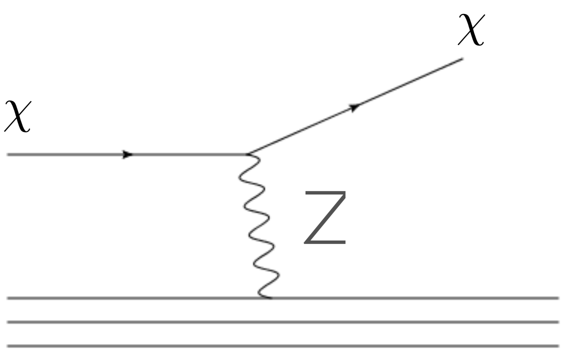
Three Vignettes

	Current Status	Future Prospects
Direct Detection	Probing Higgs-exchange region	Exploring MeV-GeV dark matter
Collider Searches	Missing energy searches	Probing non-minimal dark sectors
Indirect Detection	Probing weak-scale annihilation cross sections	Clarifying GC anomaly

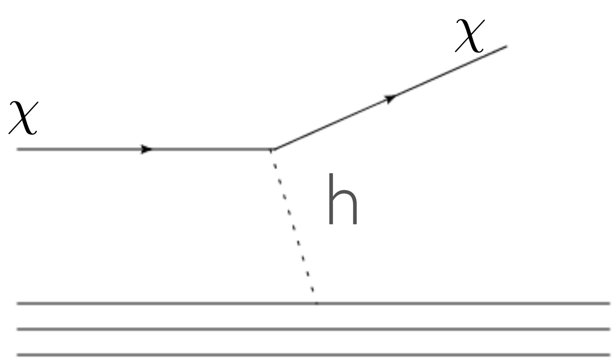
M. Lisanti, SUSY2015

How does dark matter interact with ordinary matter?

via gravity we know



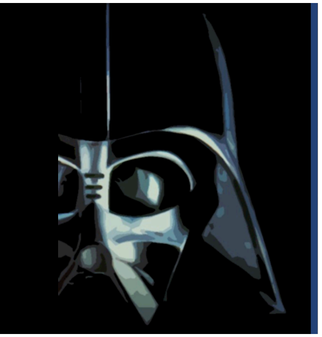
via the known weak interactions, like neutrinos?



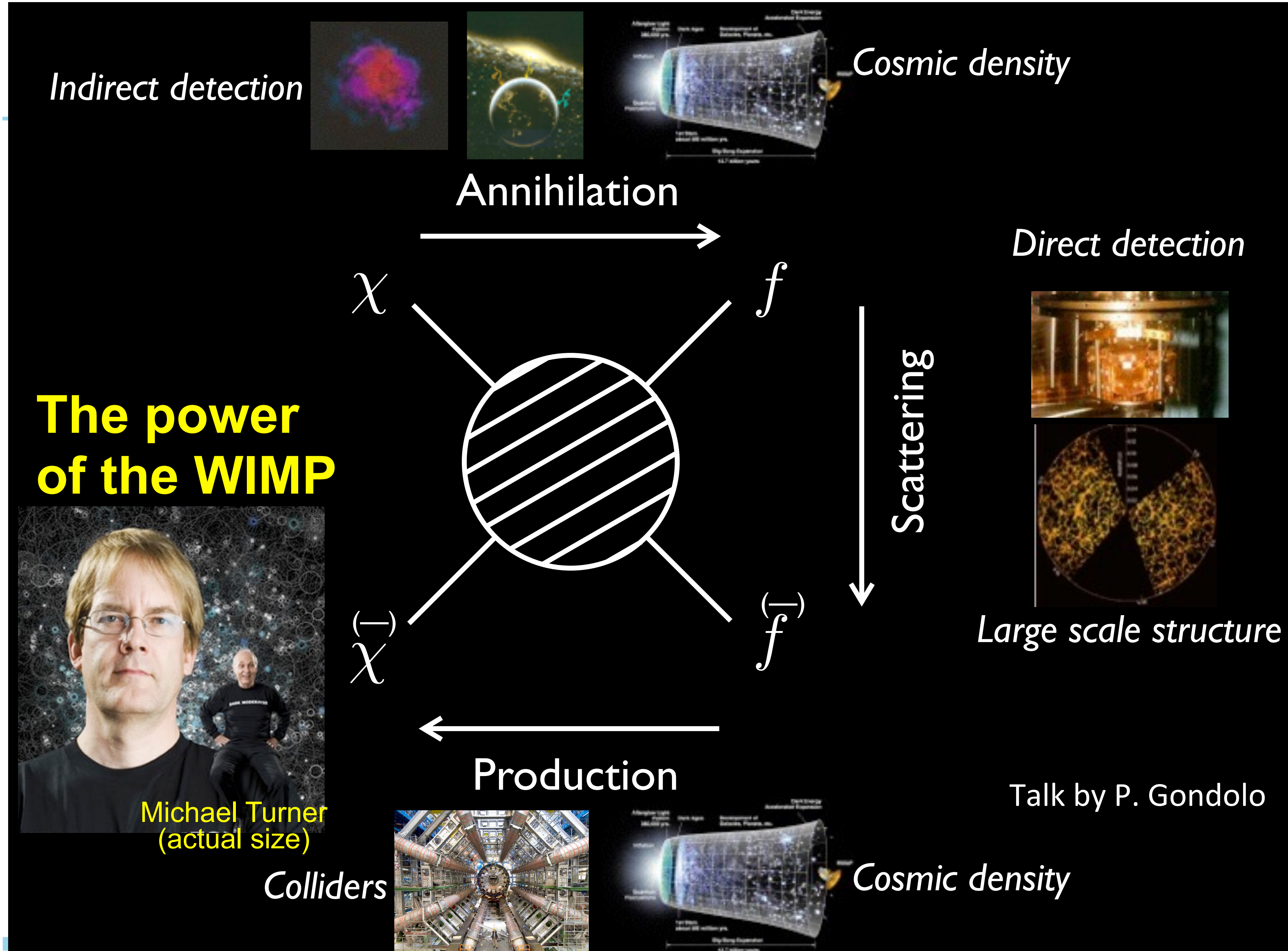
via the Higgs boson?

$$\mathcal{L} \sim L H \nu_R + \nu_D \eta \nu_R + M \nu_R \nu_R$$

via a neutrino portal?



Or: via some exotic unknown “dark forces”?

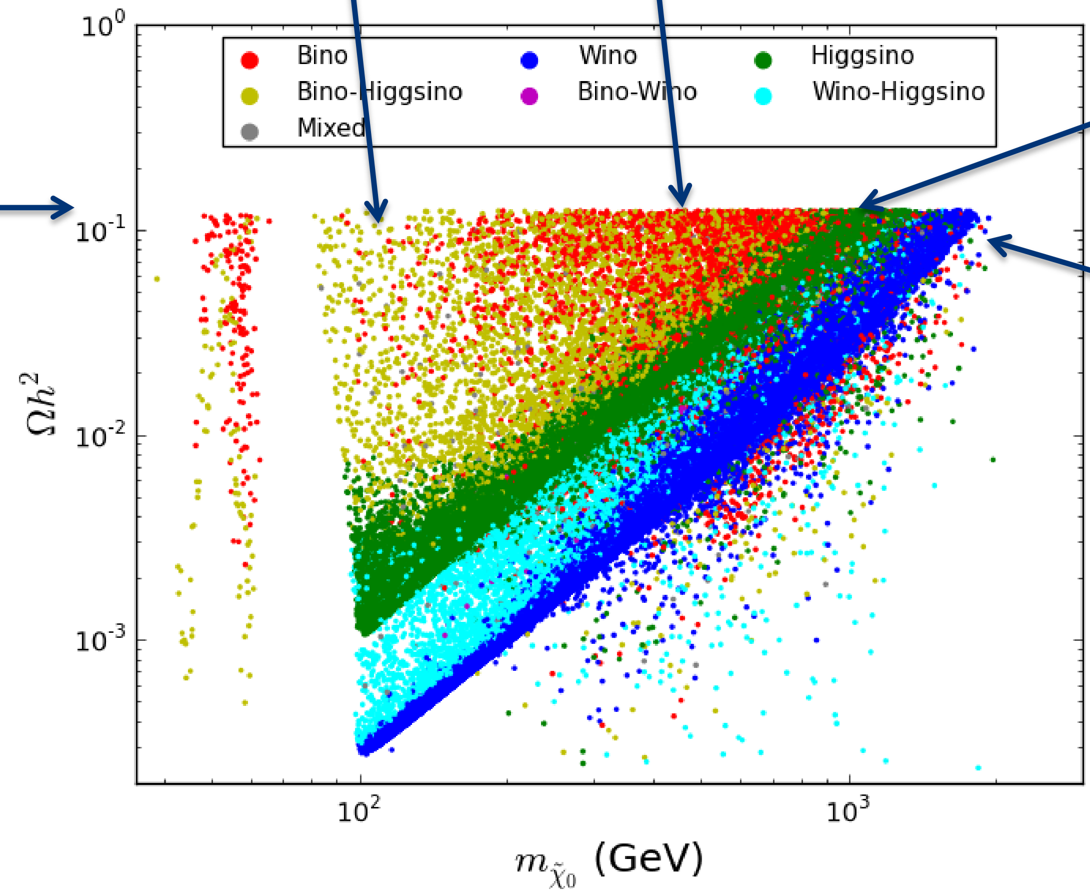

Indirect detection
Cosmic density
Annihilation
Direct detection
χ
f
Scattering
The power of the WIMP
$\overset{(-)}{\chi}$
$\overset{(-)}{f}$
Large scale structure
Production
Talk by P. Gondolo
Michael Turner
(actual size)
Colliders
Cosmic density

Confronting the WIMP miracle in SUSY

Bino-Higgsino mixture, closest case to the WIMP Miracle

Pure Bino needs co-annihilation with other quasi-degenerate superpartners

"correct" thermal relic density

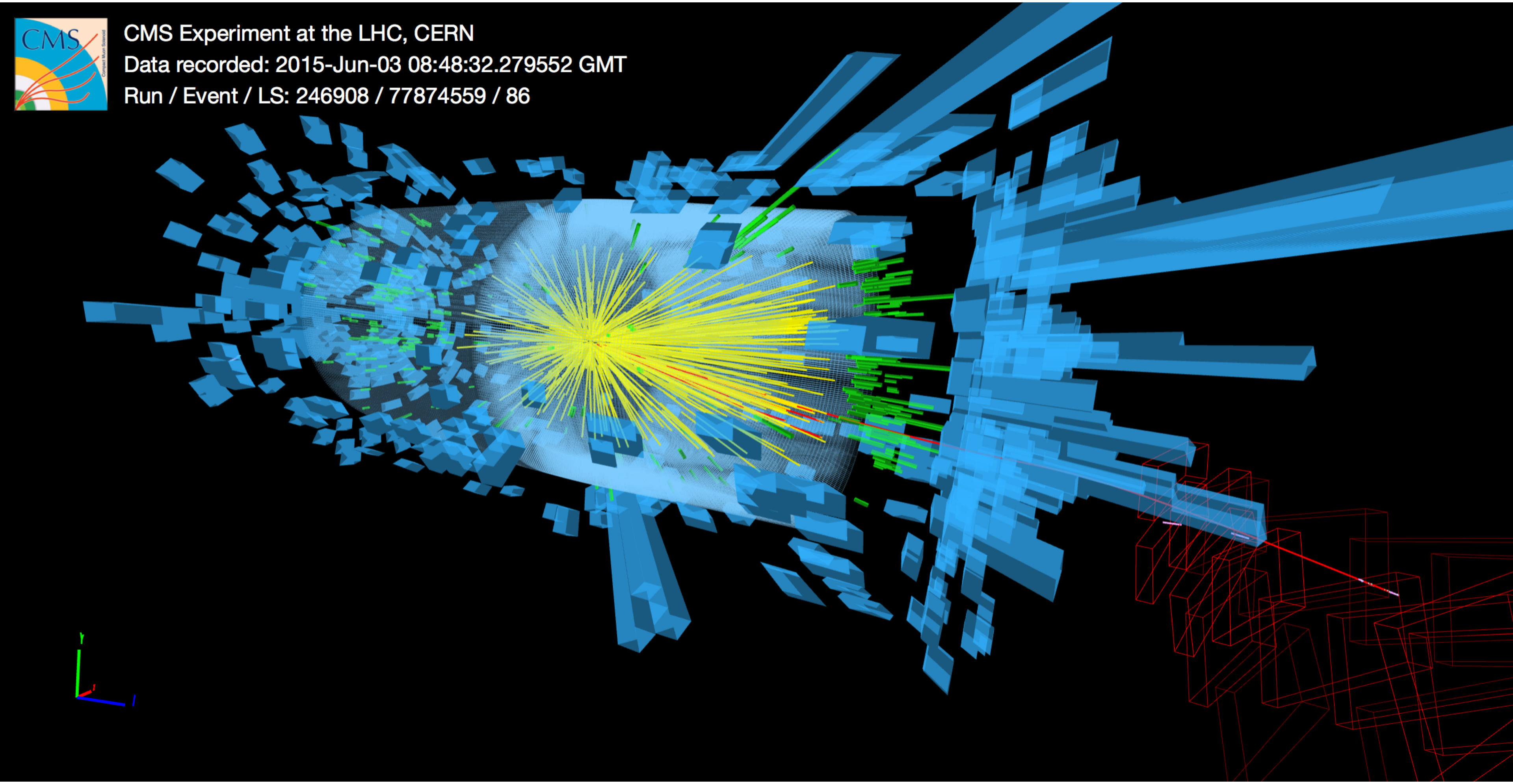


Higgsino, ~ 1.5 TeV

Wino, ~ 3 TeV

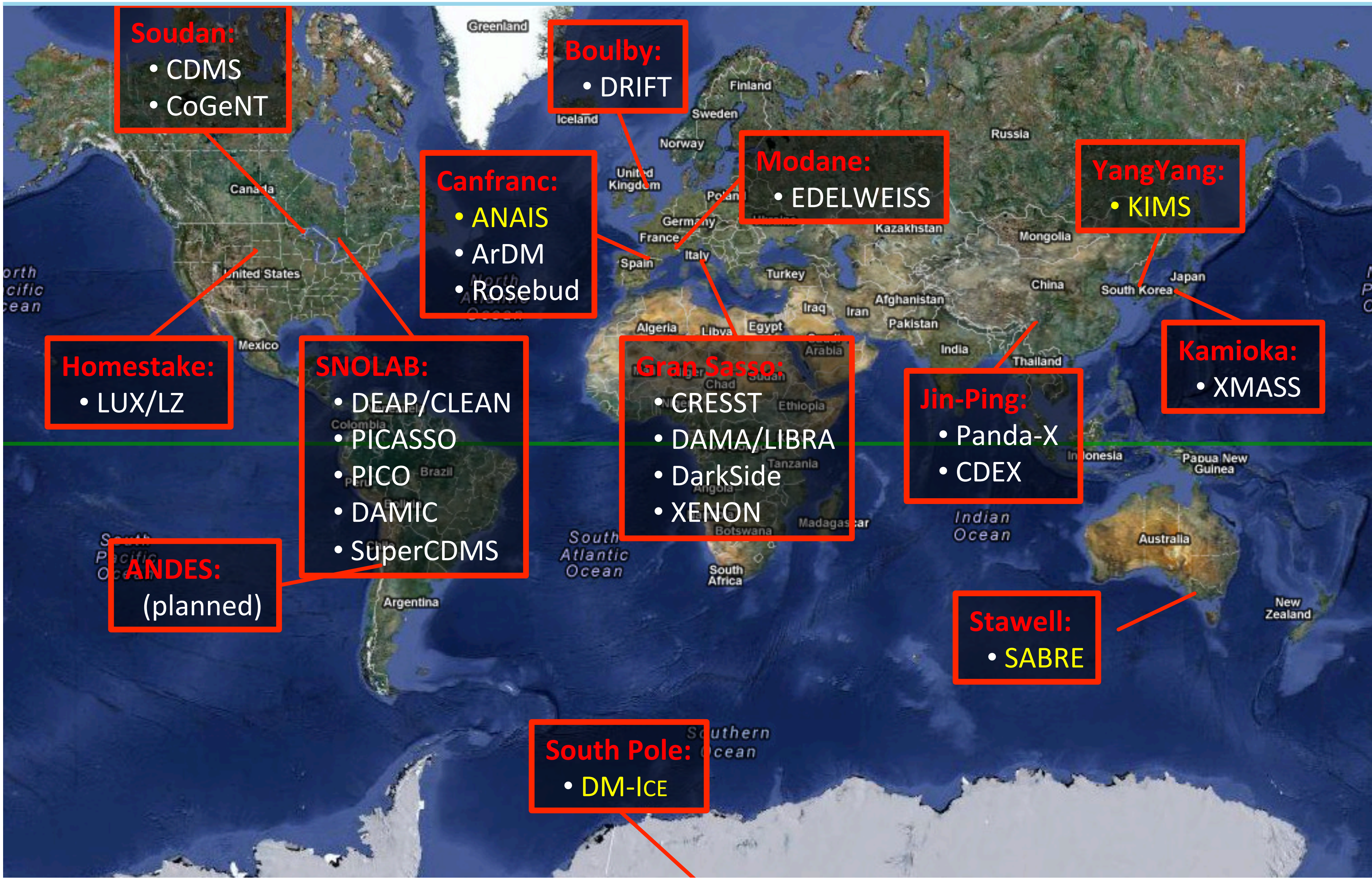
M. Cahill-Rowley et al, 1405.6716

Dark matter at the 13 TeV LHC



Talks by P. Pani, B. Gomber, P. Srimanobhas, J. Piedra Gomez, V. Ippolito, SUSY 2015

Dark matter direct detection experiments



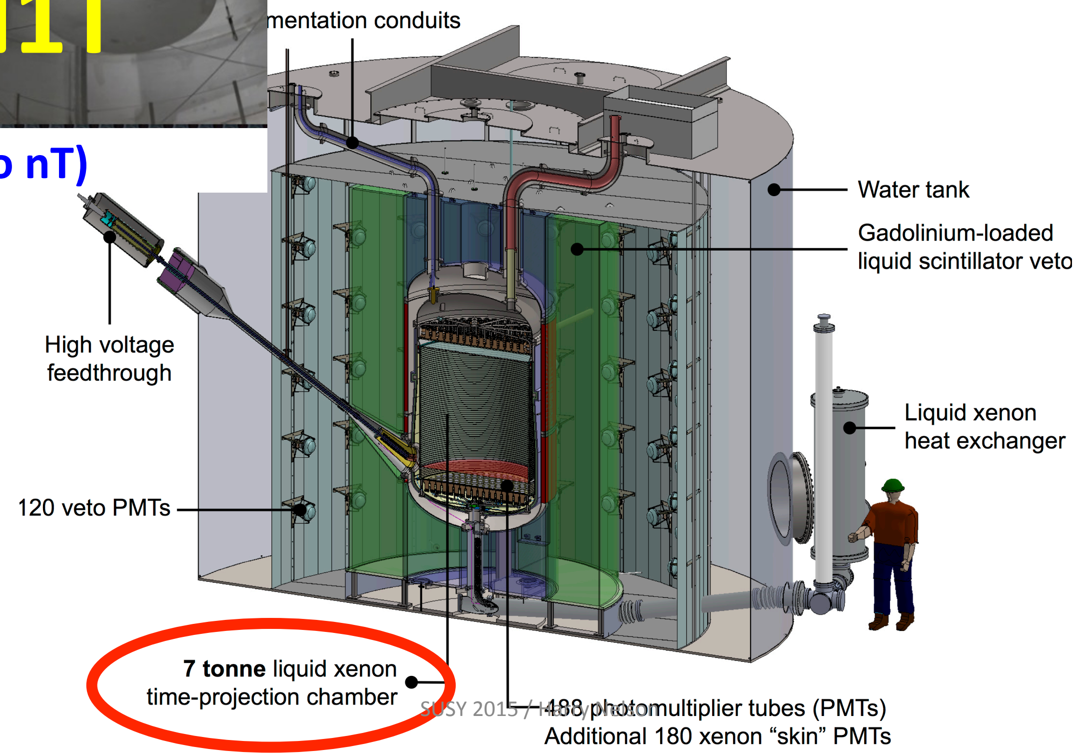
Fermilab

Noble liquids for Nobel prizes?

From Laura Baudis

(upgradable to nT)

The LZ Dark Matter Experiment

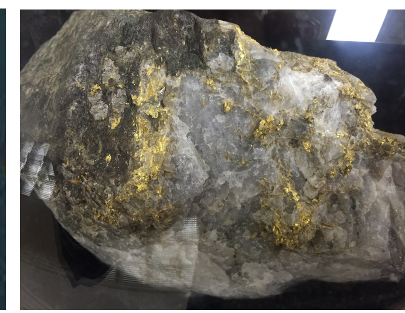


Talks by H. Nelson, M. Monzani, C. Tunnell, M. Szydagis SUSY2015

Prospecting for gold at Homestake

4,850-foot-level (overburden of 4,300 m.w.e.) for shielding LUX against cosmic rays

- Already one Nobel prize awarded for an experiment in the Homestake mine
- Why not more?



Is dark matter like visible matter?

- why should the dark sector be any simpler than the visible sector?
- the visible sector has 5 different massive stable particles (6 if you count the neutron)
- the abundance of visible matter is *not* a thermal relic abundance, it is set by the *unknown* process of baryogenesis or leptogenesis

Is dark matter like visible matter?

MODIFYING FREEZE-OUT - ASYMMETRIC DM

- ONE VERY POPULAR OPTION – ASYMMETRIC DM χ (SCALAR OR FERMION)

Nussinov '85; Gelmini, Hall, Lin '87; Barr '91; Kaplan '92;Thomas '95; Hooper, March-Russell, SW '04; Kitano and Low '04, Kaplan, Luty Zurek'09 ; R. Foadi, Frandsen, F. Sannino '09+...

VISIBLE SECTOR

$$q, e, W, Z, H, \tilde{q}, \ldots$$

$$\chi, \overline{\chi}$$

- DYNAMICS GENERATE DARK MATTER POSSESSING A MATTER-ANTIMATTER ASYMMETRY

$$n_\chi - n_{\overline{\chi}} \neq 0$$

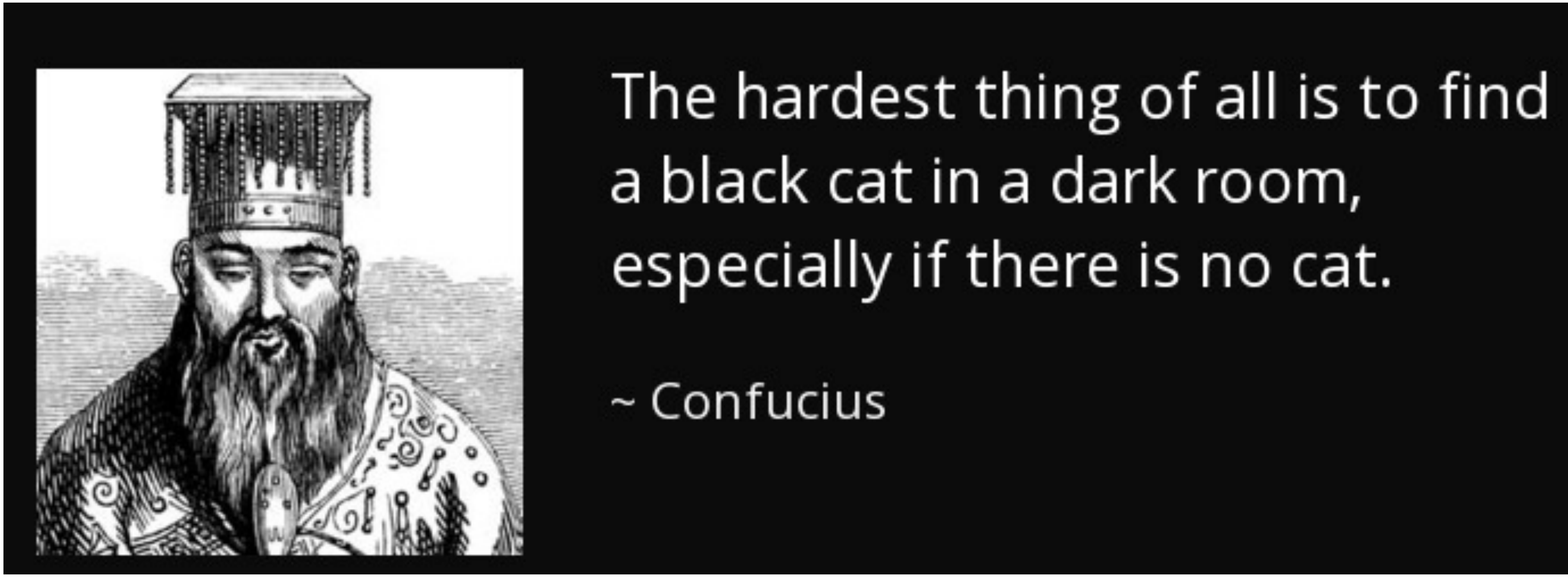
- FOR SUFFICIENTLY LARGE DM ANNIHILATION – DM ABUNDANCE IS DETERMINE BY ASYMMETRY

- MOTIVATION TO LINK TO THE BARYON ASYMMETRY TO EXPLAIN RELATIVE ABUNDANCES

$$\frac{\Omega_{\rm dm}}{\Omega_{\rm b}} = \frac{\eta_{\rm dm} m_{\rm dm}}{\eta_{\rm b} m_{\rm b}} \sim 5$$

S. West SUSY2015

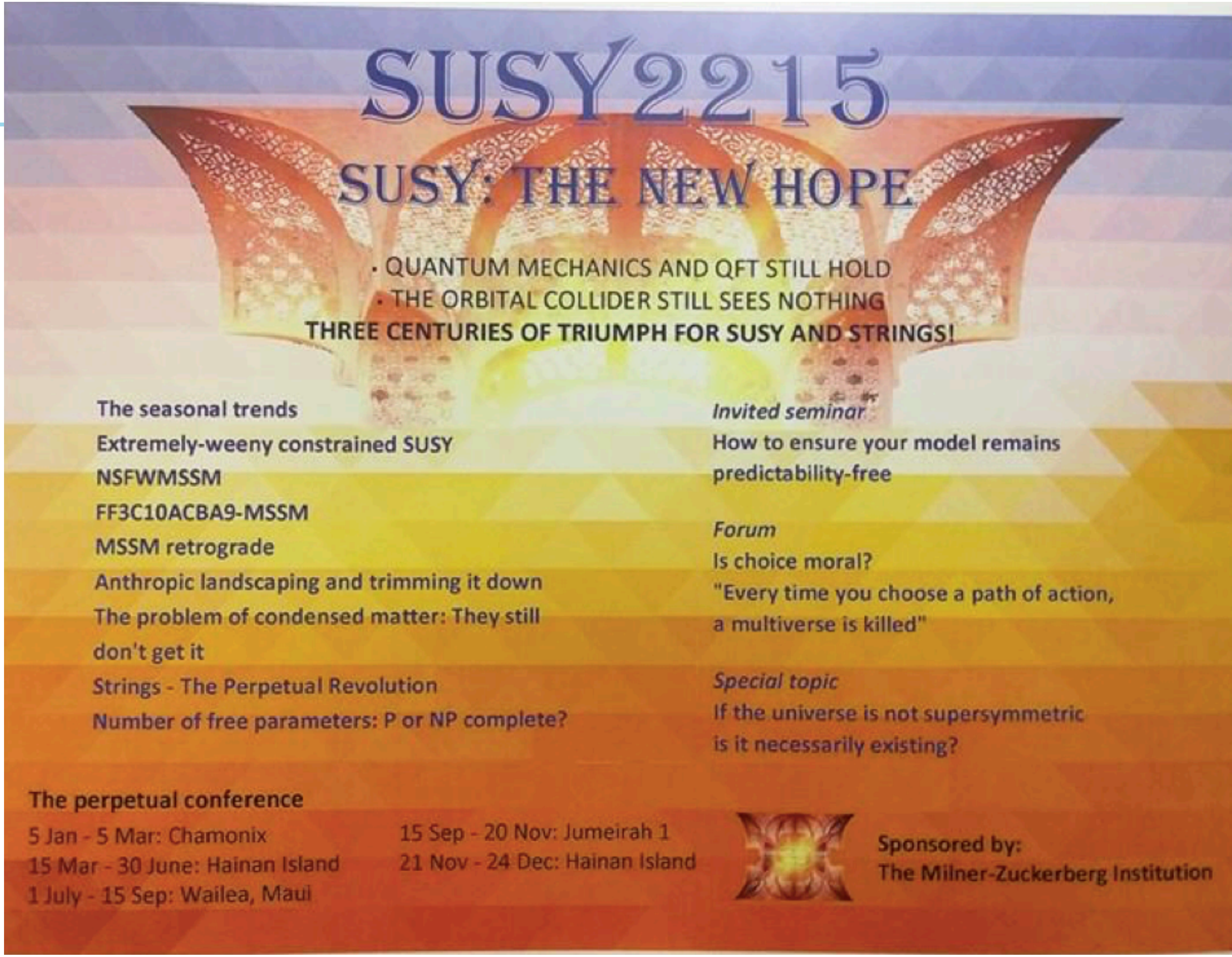
Executive Summary



Y. Kolomensky, SUSY2015

Preview of SUSY 2016

Preview of SUSY 2215


SUSY2215
SUSY: THE NEW HOPE
· QUANTUM MECHANICS AND QFT STILL HOLD
· THE ORBITAL COLLIDER STILL SEES NOTHING
THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!
The seasonal trends
Extremely-weeny constrained SUSY
NSFWMSSM
FF3C10ACBA9-MSSM
MSSM retrograde
Anthropic landscaping and trimming it down
The problem of condensed matter: They still don't get it
Strings - The Perpetual Revolution
Number of free parameters: P or NP complete?
Invited seminar
How to ensure your model remains predictability-free
Forum
Is choice moral?
"Every time you choose a path of action, a multiverse is killed"
Special topic
If the universe is not supersymmetric is it necessarily existing?
The perpetual conference
5 Jan - 5 Mar: Chamonix
15 Mar - 30 June: Hainan Island
1 July - 15 Sep: Wailea, Maui
15 Sep - 20 Nov: Jumeirah 1
21 Nov - 24 Dec: Hainan Island
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Thanks to Jack, Robin, and all the organizers