BEYOND THE STANDARD MODEL

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on behalf of the BSM working group

OUTLINE

- BSM and naturalness
- existing LHC upgrade and Snowmass 2013 studies
- Plans and activities of the whatsnext BSM subgroup

BSM AND NATURALNESS

- We have a number of reasons to believe the SM is not complete
- For collider searches of new particles, the naturalness argument is crucial, as it requires new physics to exist close to the electroweak scale
- A superheavy particles coupling to the Higgs with strenght g contributes to the Higgs mass as

$$m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2} M^2$$

- To avoid a $(m_H/M)^2$ cancellation with the bare mass we need new phenomena at scale m_{NP}. This reduces the fine tuning to

$$\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 \quad \text{or} \quad \Delta \sim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 \times \log\left(\frac{M^2}{m_{\rm NP}^2}\right)$$

"supersoft" theories — "soft" theories (ex. SUSY)

- Thus $\Delta < 10(100)$ requires $m_{NP} < 1.5(5)$ TeV (and lower if big logarithm)

SOLUTION TO THE FINE TUNING

- There is new physics at a scale m_{NP}
  - We can quantify the future facilities sensitivity to m_{NP} and Δ (for hadron colliders this is often a range reflecting the dependence on model parameters)
  - Eventually we will either find something, or disprove naturalness, which would have a major impact to our understanding of Nature
- The Higgs not an elementary scalar (composite Higgs models). => Compositeness scale should be close to EWK scale, giving top partners (in some models) and new spin-1 bosons at TeV scale.
- Can we build a model without a superheavy scale at all (and still account for gravity, inflation, etc.) ? => Answers to all SM issues should be at low scale
- The Higgs mass might really be fine-tuned (multiverse + anthropic selection?) => need an other guide to NP (Dark Matter, coupling unification, ...)

WHAT'S NEXT ? EXISTING STUDIES

- A substantial amount of studies has been performed in the context of the world-wide efforts of planning for large new facilities (LHC upgrade, higher energy hadron colliders, circular and linear lepton colliders)

- As a general rule, lepton colliders can produce and study very well new particles with mass smaller than $\sqrt{s}/2$.

- The sensitivity of hadron colliders is more model-dependent and also requires more effort to assess.

CAVEAT

- The current projections of LHC experiments makes quite simplifying assumptions and can be expected in general to be conservative

ATLAS uses 14 TeV truth level samples with detector performance parametrizations derived from a few simulated samples.

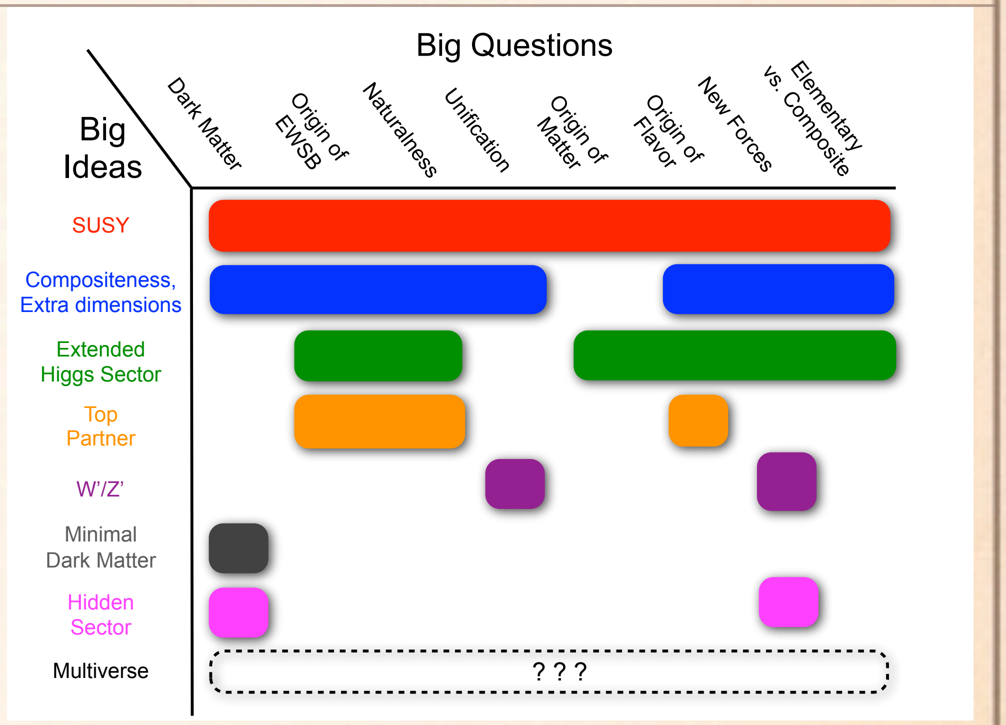
These parameterizations provide rather conservative estimates of the reach and precision of measurements. Except where otherwise noted, they do not include improvements due to new techniques, improved understanding of backgrounds, or reduced theoretical uncertainties.

CMS uses 8 TeV samples scaled according to the 14/8 TeV cross section ratio and luminosity.

higher luminosity and higher pile-up. With this primary assumption, existing public results based on current data are extrapolated to higher energy and luminosities. In most cases, the analyses are assumed to be unchanged, which is a conservative assumption given the fact that all analyses will be reoptimized to maximally exploit the higher energy and luminosity. This

Run-I analyses in many cases have done much better than expected from pre-data studies - see the backup for some examples.

WHICH NEW PHYSICS ?



- I will do an arbitrary sampling of the NP theory space.
  - lepton resonances
  - heavy charged stable particles (HCSP)
  - heavy vector-like quarks
  - supersymmetry (strong and weak production)

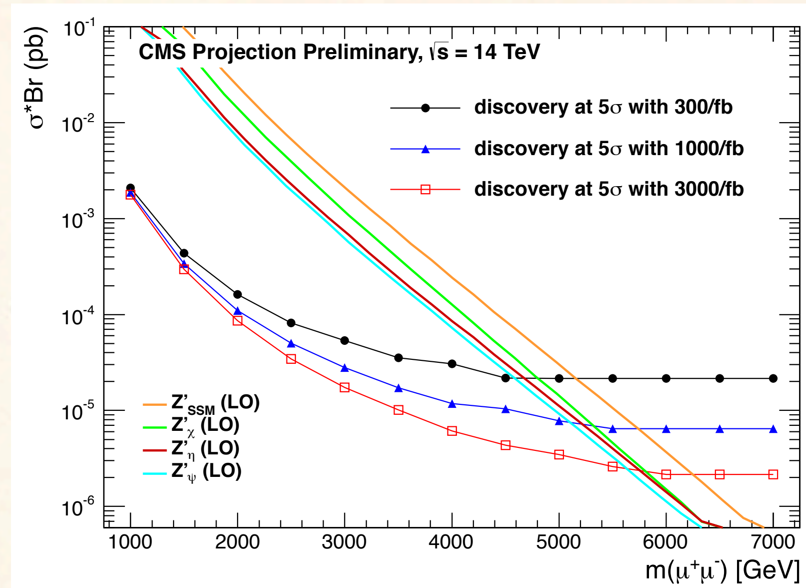
- References: the New Particles working group report of Snowmass 2013 (arXiv:1311.0299v1), the Snowmass input from ATLAS (ATLAS-PHYS-PUB-2013-007,) and CMS (arXiv:1307.7135v2), the update for SUSY searches from ATLAS (ATLAS-PHYS-PUB-2013-011, september 2013)

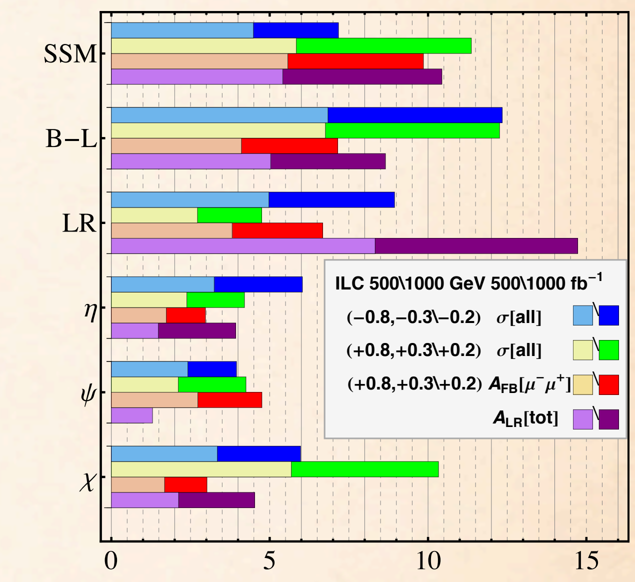
DILEPTON RESONANCES

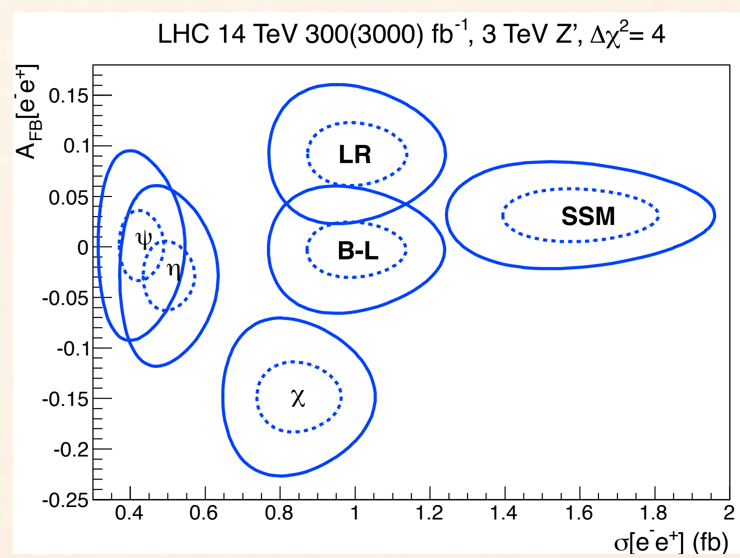
- Foreseen by many SM extensions
- Clean, energy-driven sensitivity at hadron colliders. Accessible with asymmetry measurements at lepton colliders.

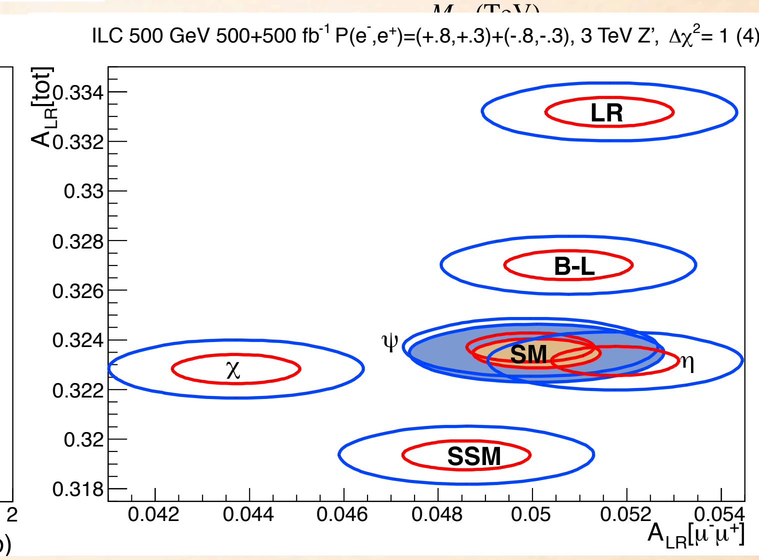
	$\sqrt{s}$ (TeV)	$\int L\,dt(fb^{-1})$	discovery reach
pp	14	300	4.5-5.1
pp	14	3000	5.6-6.2
pp	33	3000	12.1-16
ee	0.5	500	2.7-8.4
ee	1.0	1000	4.7-14.7

Current limits on SSM Z' are 2.9 TeV
The range is the model dependence



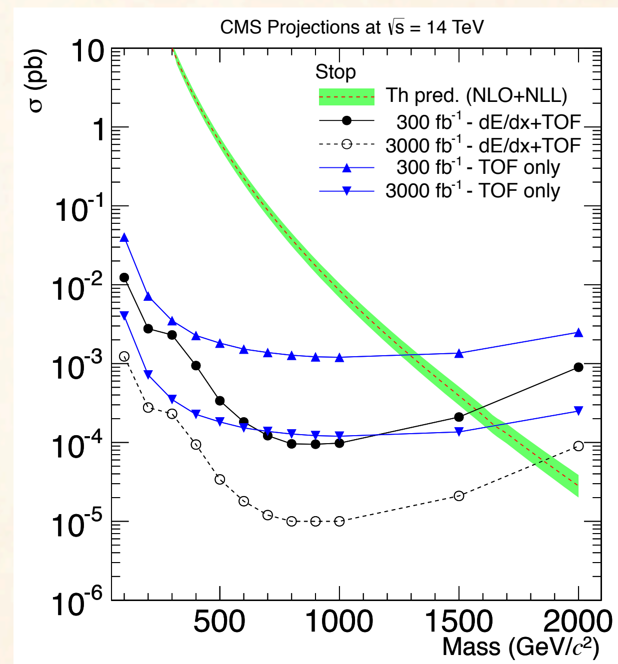


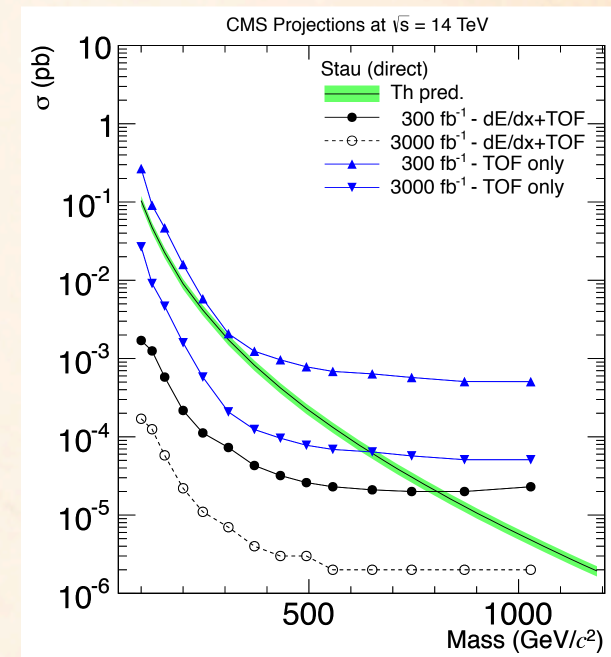




HCSP

- Some of the non-SM particles might easily be stable on detector time of flight scales
- This kills backgrounds and dependence on decay mode !
- Energy driven and hadron collider driven sensitivity for benchmark scenarios (but beware of HCSP with reduced couplings)





Secondly, the current dE/dx measurement relies on analog readout of the CMS Tracker, which will almost certainly not be possible after the CMS Tracker is upgraded during LS3. To account for this, the sensitivity with 3000 fb^{-1} is presented based on the combination of long time-of-flight and highly ionizing signatures, corresponding to an assumption that the dE/dx performance remains unchanged, and the sensitivity using the long time-of-flight signature alone, corresponding to an assumption that dE/dx measurements cannot be performed with the upgraded CMS Tracker.

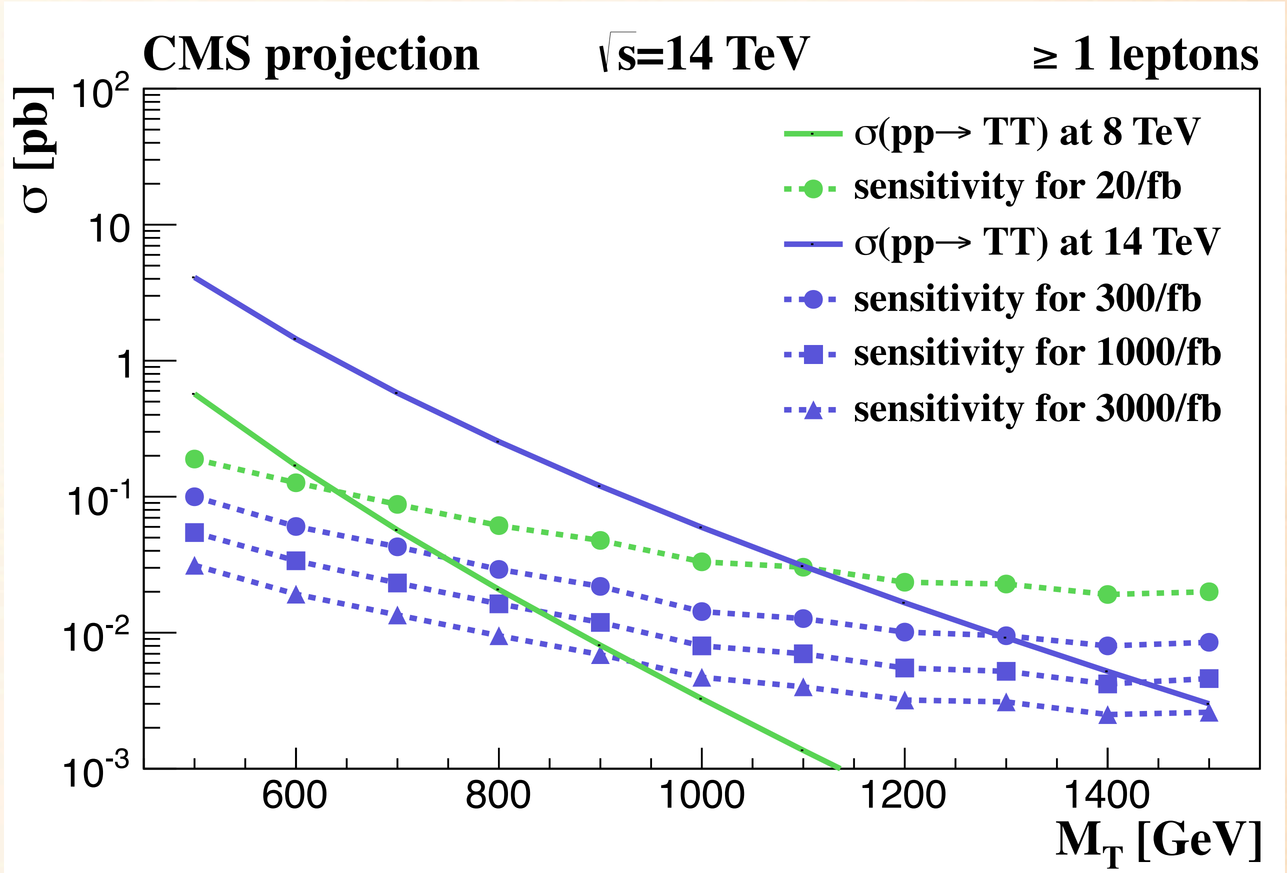
	$\sqrt{s}$ (TeV)	$\int L\,dt(fb^{-1})$	charged	scalar quark	color octet
current limits	8	20	0.34 TeV	0.9 TeV	1.3 TeV
discovery reach	14	300	0.8 TeV	1.6 TeV	2.0 TeV
discovery reach	33	3000	2 TeV ?	4.5 TeV ?	7 TeV ?

Sensitivity to mass, in GeV. In parenthesis, the corresponding fine tuning in supersymmetry (see slide 12)

VECTOR LIKE QUARKS

- Strong link with naturalness, as most solutions of the hierarchy problems feature top partners

- Wb, tZ and tH decays occur in most models (often with a 2:1:1 ratio at high mass)



	$\sqrt{s}$ (TeV)	$\int L\,dt (fb^{-1})$	mass (TeV)	fine tuning
current limits	8	20	0.7-0.8	~2
discovery reach	14	300	1.3	~7
discovery reach	14	3000	1.5	~10
discovery reach	33	3000	3.2	~40

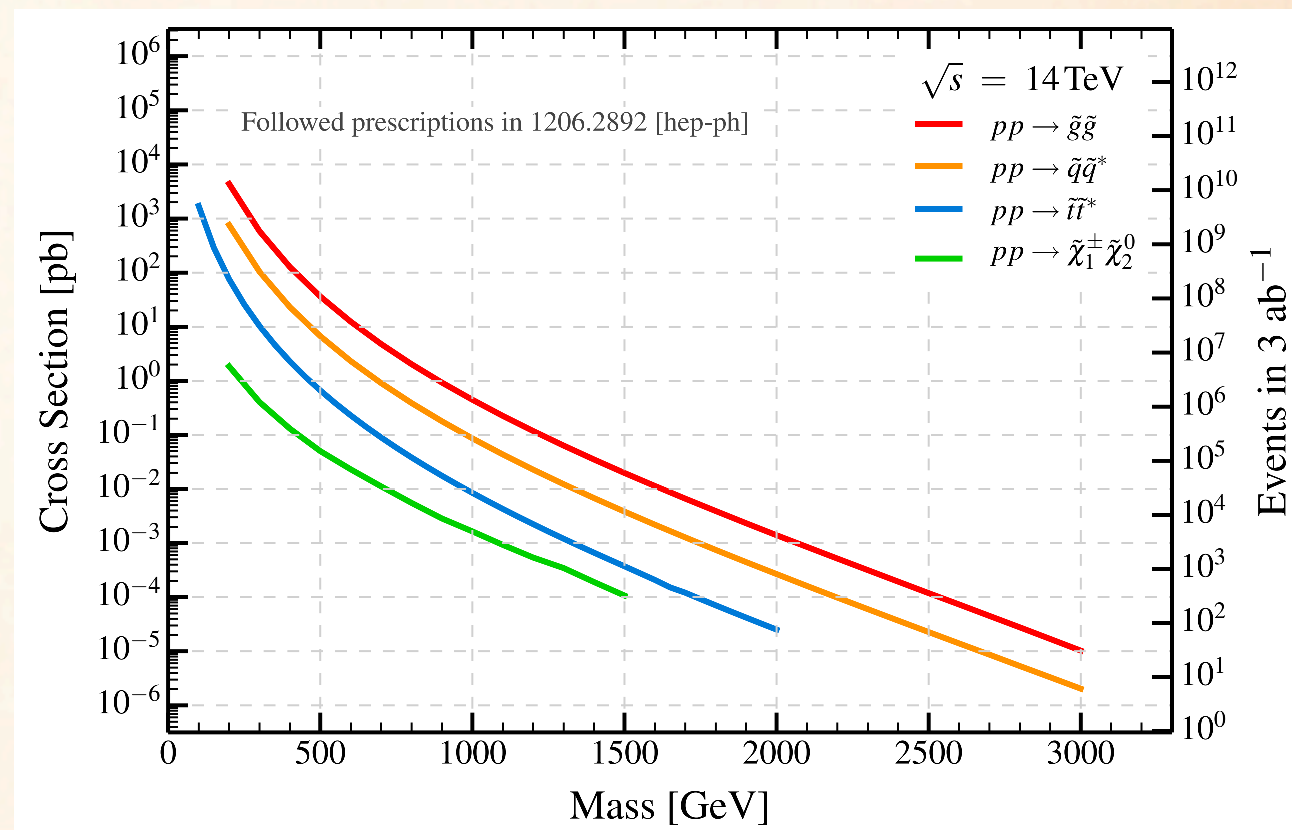
SUPERSYMMETRY

- At hadron colliders we can classify SUSY processes in:

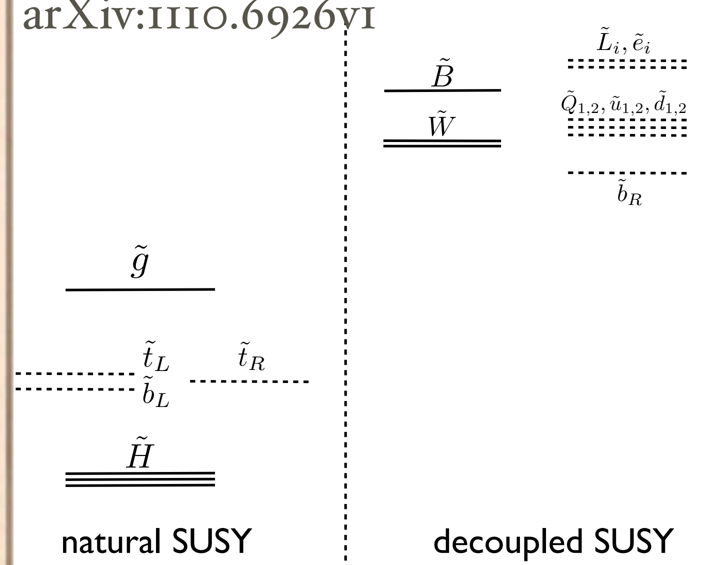
u/d/c/s squarks and gluinos pair production
Highest cross section
Signature: jets+MET(+X)

stop and sbottom pair production
Intermediate cross section
Signature: jets+MET(+X)

gaugino and slepton pair production
lowest cross section
Signature: Leptons+MET(+no jets)



arXiv:1110.6926v1



The higgsinos, stop and gluinos are related to the Higgs mass at tree level, 1 loop, 2 loop respectively and thus are constrained to be light by naturalness.

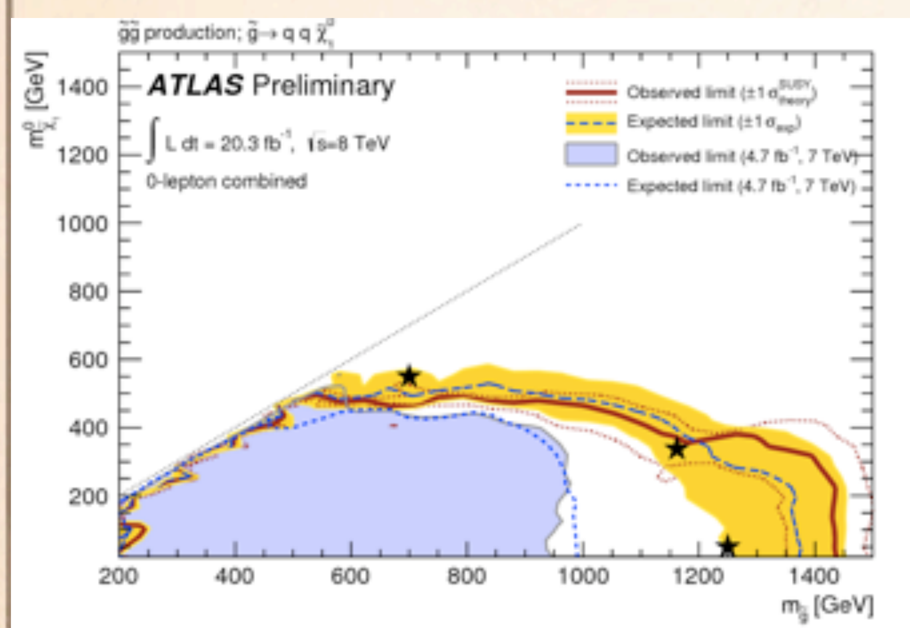
$$\frac{m_H^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2 \quad \Rightarrow \quad \Delta \sim 5\left(\frac{\mu}{200GeV}\right)^2$$

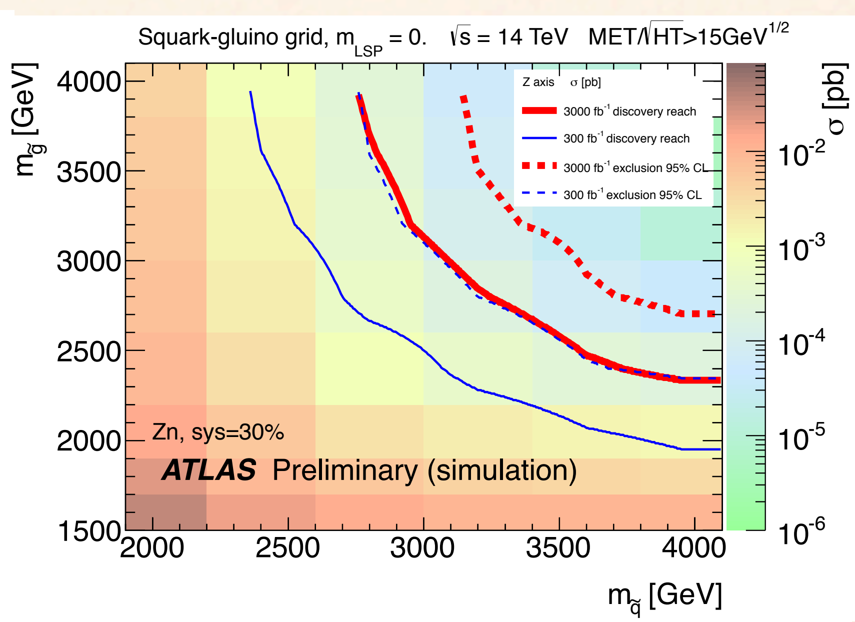
$$\delta m_H^2\Big|_{stop} \cong -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{TeV}\right) \quad \Rightarrow \quad \Delta \geq 30\left(\frac{m(\tilde{t}_1)}{TeV}\right)^2\left(\frac{\log(\Lambda/TeV)}{3}\right)$$

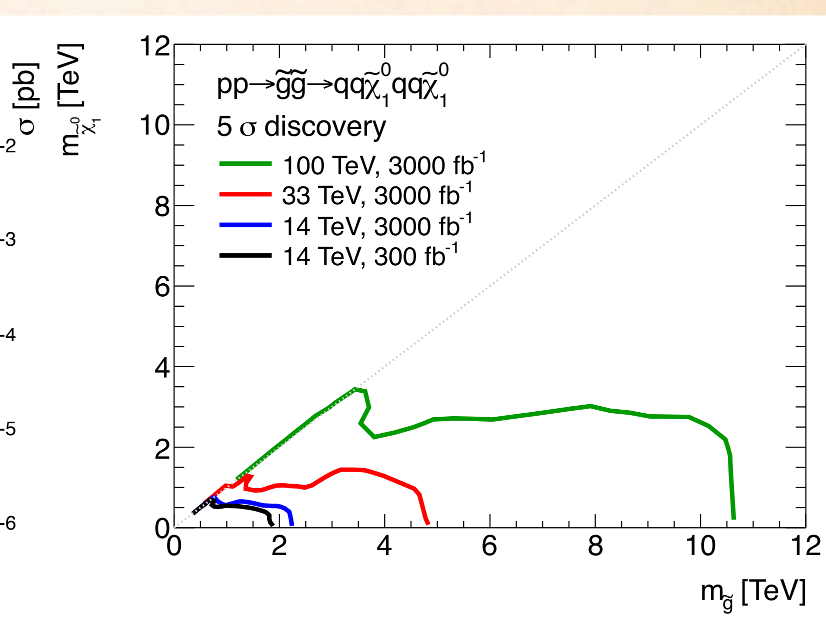
$$\delta m_H^2\Big|_{gluino} \cong -\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2\ln^2\left(\frac{\Lambda}{TeV}\right) \quad \Rightarrow \quad \Delta \sim 5\left(\frac{m(\tilde{g})}{TeV}\right)^2\left(\frac{\log(\Lambda/TeV)}{3}\right)^2$$

GLUINO SEARCHES

- Current limits on the gluino mass are between 0.6 TeV (nearly degenerate gluino and LSP) and 1.4 TeV (massless LSP)
- Expected discovery reach in the massless LSP scenario is 1.9(2.3) TeV for 300(3000) fb^{-1}
- Snowmass study provides the reach for higher energy collider and also for the degerate case (not sure if the analysis is really optimized for the latter). Notice how the reach scales roughly with collision energy.
- Run 2+3 improves the reach by about 50% in mass (2x in fine tuning) compared to run 1.
- For low SUSY breaking scale the gluino might be quite heavy and still natural. For Λ= 10 TeV I get Δ =10(100) for 4(13) TeV mass...







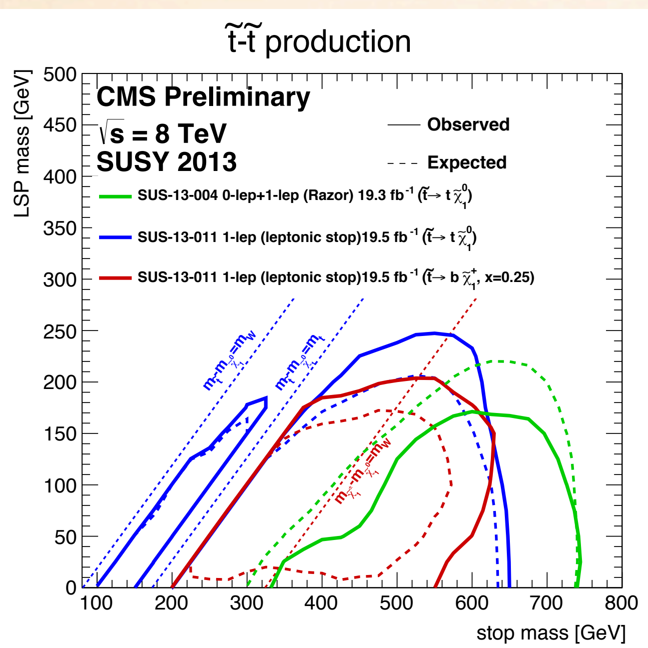
STOP SEARCHES

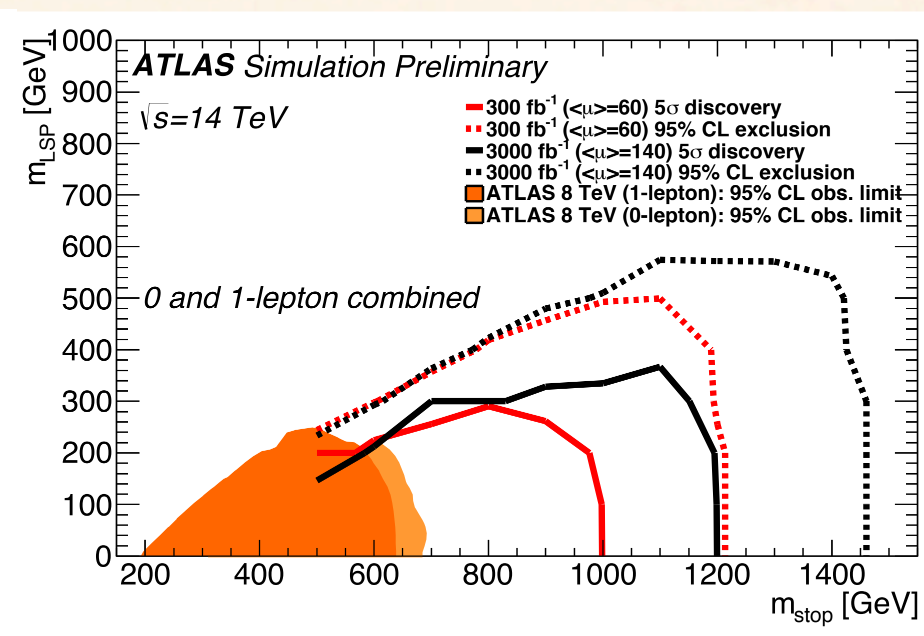
- Currents limits are 740 GeV for decays to a top and massless LSP, ~250 GeV for small stop-LSP mass differences.

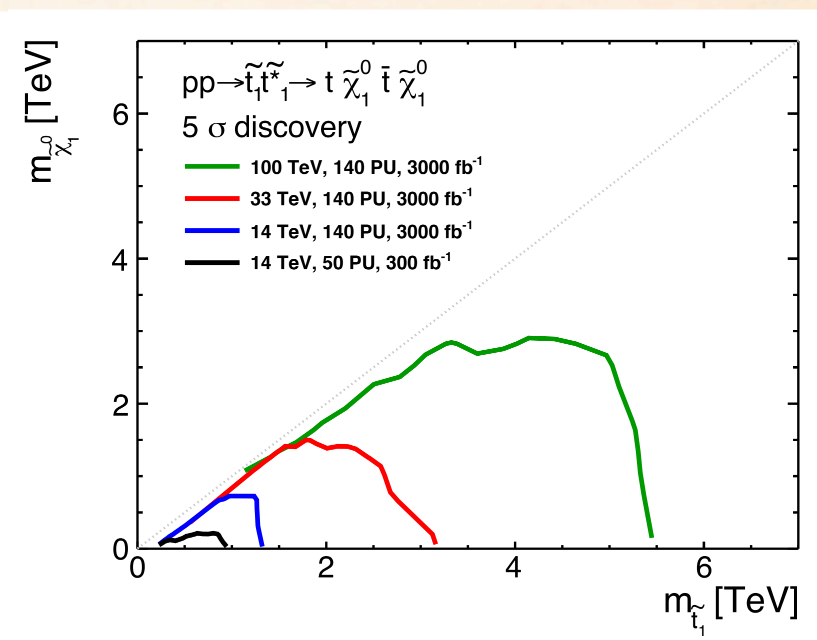
- Even below 250 GeV, loopholes exist for long decay chains and particular masses of the particles in the decay chain (so in principle a discovery is still possible at ILC500)

- Future sensitivity studies are optimized for the easy case, giving discovery reach to 1000(1200) GeV with 300(3000) fb-1 of LHC data, and 3.2/5.5 TeV with a 33/100 TeV hadron collider. It would be interesting to evaluate the sensitivity to the worst (for hadron colliders) cases

- For Λ= 10 TeV, Δ can get as low as 10(100) for 1(3) TeV mass...





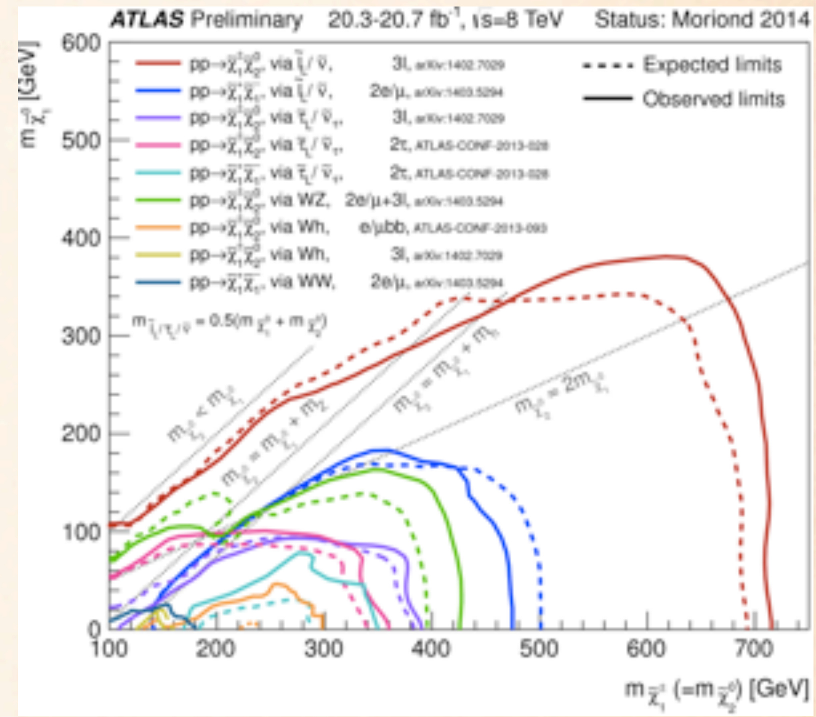


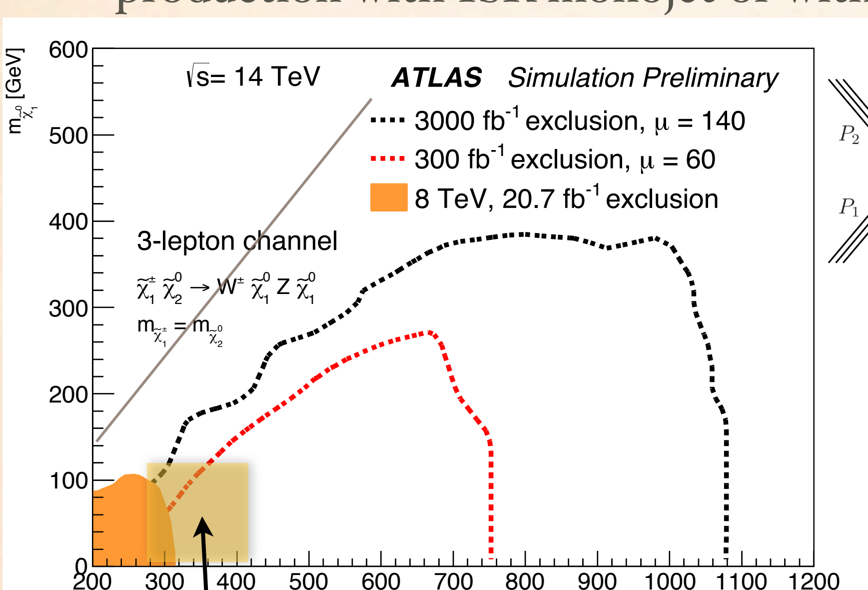
DIRECT EWKINO SEARCHES

- Dark Matter requires a weakly interacting **lightest** supersymmetric particle. Natural models have light higgsinos (related to Higgs mass at tree level).

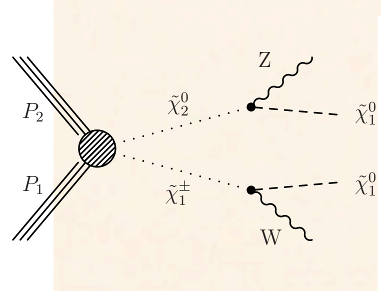
- Hadron collider can look for neutralino to gravitino + X, with X=Z, h, or γ. If neutralino LSP, they can see heavier ewkinos decay, like N2C1 to WZN1N1 or hZN1N1. Luminosity significantly extends the reach

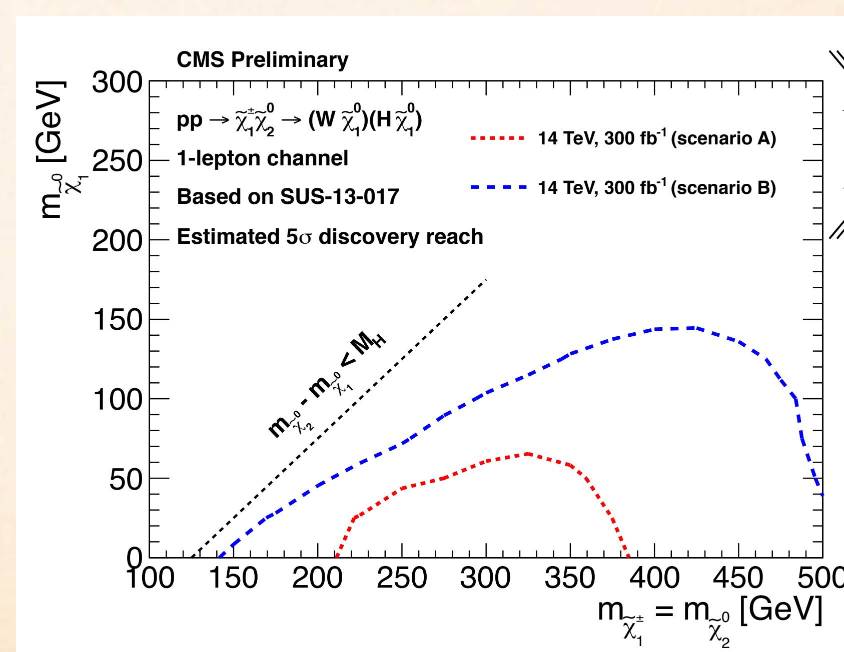
- For the natural spectrum with light Higgsinos (nearly degenerate N1,N2,C1) and out-of-reach heavier winos/zinos lepton colliders would be best. With high luminosity, theory papers suggest LHC should have sensitivity to higgsino production with ISR monojet or with VBF production for 100-200 GeV

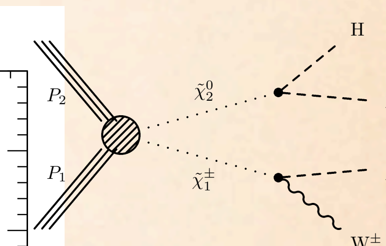




excluded by improved analysis in paper w.r.t. the preliminary results







WHATSNEXT BSM GROUP ACTIVITIES

- Composite Higgs models
- Natural supersymmetry
- Connections to other WGs

COMPOSITE HIGGS

- Two classes of models: 1) the Higgs is a pseudo-Goldstone model from a broken symmetry 2) a specific mechanism is introduced to generate the fermion masses (partial compositeness)

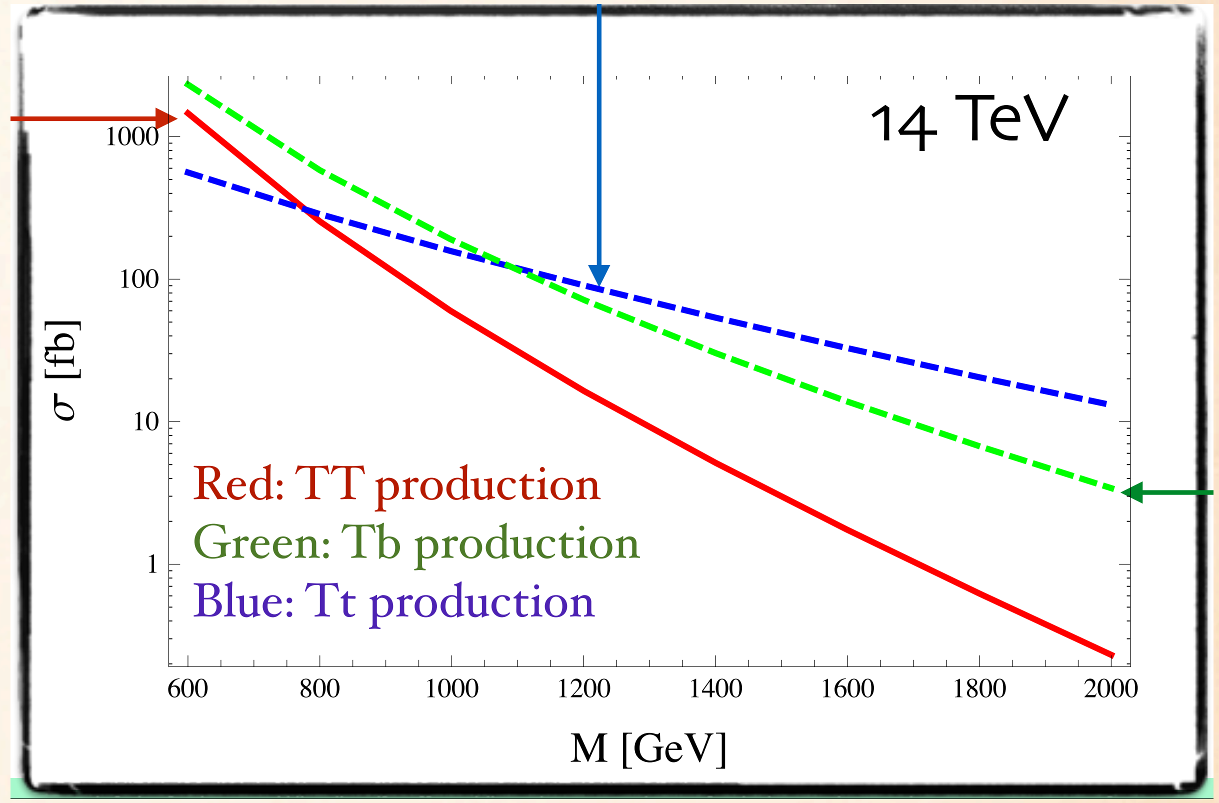
- Both foresee spin-1 states at the compositeness scale M. EWPT imply M > 2.5 TeV. Decays to leptons are suppressed, best sensitivity would be from VV and VH decays.

- In (2) there is a vector-like top parner as well. If lighter than M, allows a reduced fine tuning, and in this case $\delta m_H^2 \approx \left(\frac{m_{NP}}{0.5\,\mathrm{TeV}}\right)^2 \log\left(\frac{M^2}{m_{NP}^2}\right)$

- Currents limits are of the order of 0.7 TeV, which does not constrain naturalness much yet .

COMPOSITE HIGGS DETAILS

- Existing studies deal with pair production of top partners
- In the composite Higgs model, the dominant process at high mass is single production, which could give much better sensitivity
- Evaluation of the sensitivity is in progress, but seems promising. See the talks of Matsedonsky and Panizzo in the parallel session yesterday



Fine tuning is of the order of 20%(5%) for 1.2(2.4) TeV mass

NATURAL SUPERSYMMETRY

- Define a realistic model with small fine tuning as possible
  - In the MSSM an Higgs mass of 125 GeV can only be obtained with relatively heavy stop quarks, which imply high fine tuning. Adding a singlet (NMSSM) allows the correct Higgs mass with light stop quarks.
  - Have symmetry breaking at relatively low scale, to minimize the logarithm, and split the third and first two generation masses
- Consider mass spectra/decays which allow light stop and gluinos (i.e. difficult to see at LHC) and evaluate the sensitivity of future data. Since existing studies focus on easier cases, generate MC samples with public codes and evaluate the sensitivity ourselves.
- See the presentations of Romanino and Polesello at the parallel session yesterday

INTERACTIONS WITH OTHER WGS

- Dark Matter: for models which include DM candidates and can be explored at colliders, evaluate the complementarity of direct, indirect and collider searches
- SM: define a framework to parametrize the effect of New Physics on the Higgs couplings - define a set of higher dimensional operators motivated by new physics scenarios ?

CONCLUSIONS

- Naturalness points to the presence of new physics near the EWK scale
- The run-1 results have eaten some part of the natural theory space, but by no means all of it. >10% fine tuning and direct searches constraints can be reconciled for example for
  - 0.3-1.0 TeV stop and 0.6-fewTeV gluinos in SUSY
  - 0.7-1.8 TeV top partners in composite Higgs models
- run 2/3 will cover much, but not all, of available space, as documented by existing studies in some benchmark scenarios
- The BSM group is planning to adress future facilities sensitivity for some well motivated scenarios not adressed by the Snowmass/ECFA studies

BACKUP

SUSY FINE TUNING FORMULAS

- The derivation of upper bounds on the different SUSY particles from naturalness was first discussed in a paper of Barbieri and Giudice in 1987 (Nucl. Phys. B306, 63)

- After the 2011 LHC results pushed limits on squark and gluinos around 1 TeV, lots of discussion on naturalness-based susy spectra. In this talk I started from the formulas in Papucci, Rudermann and Weiler, arXiv:1110.6926v1

$$\mu \lesssim 200\,\mathrm{GeV}\left(\frac{m_h}{120\,\mathrm{GeV}}\right)\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

Tree-level Higgs mass relation to Higgsinos. Very simple, just solve for delta.

$$\delta m^2_{H_u}|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{Q_3} + m^2_{u_3} + |A_t|^2\right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

$$\sqrt{m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}} \lesssim 600\,\mathrm{GeV}\frac{\sin\beta}{(1+x_t^2)^{1/2}}\left(\frac{\log(\Lambda/\,\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{m_h}{120\,\mathrm{GeV}}\right)\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

One loop Higgs mass relation to stops. The **minimum** fine tuning for a given lightest stop mass occurs for sinb =1, no mixing, and mt1 = mt2. I put these conditions and solved for delta.

$$\delta m^2_{H_u}|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right)|M_3|^2 \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

$$M_3 \lesssim 900\,\mathrm{GeV}\sin\beta\left(\frac{\log(\Lambda/\,\mathrm{TeV})}{3}\right)^{-1}\left(\frac{m_h}{120\,\mathrm{GeV}}\right)\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

Two loop contribution from gluinos. The **minimum** fine tuning for a given gluino mass occurs for sinb =1. I put these conditions and solved for delta.