Fine Tuning & SUSY Sweet Spot

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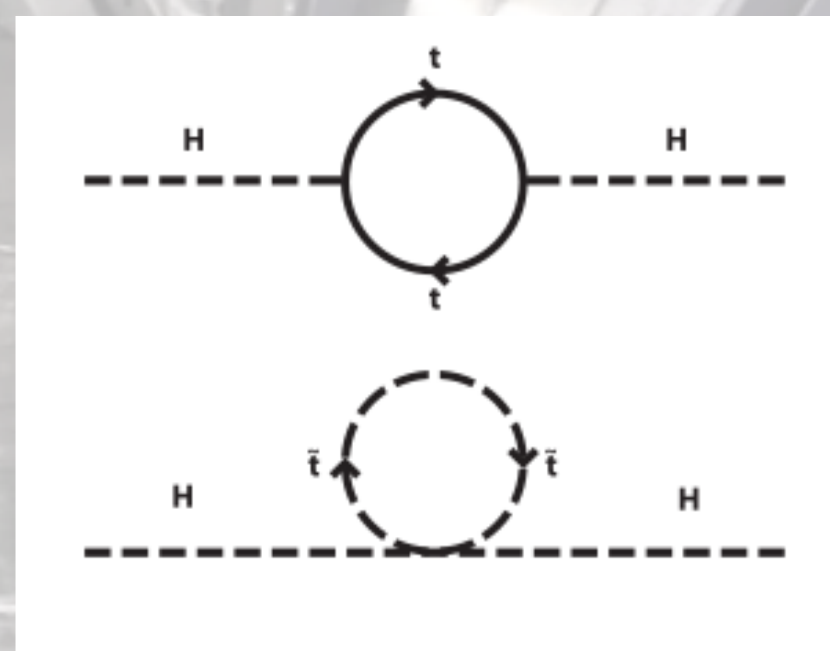
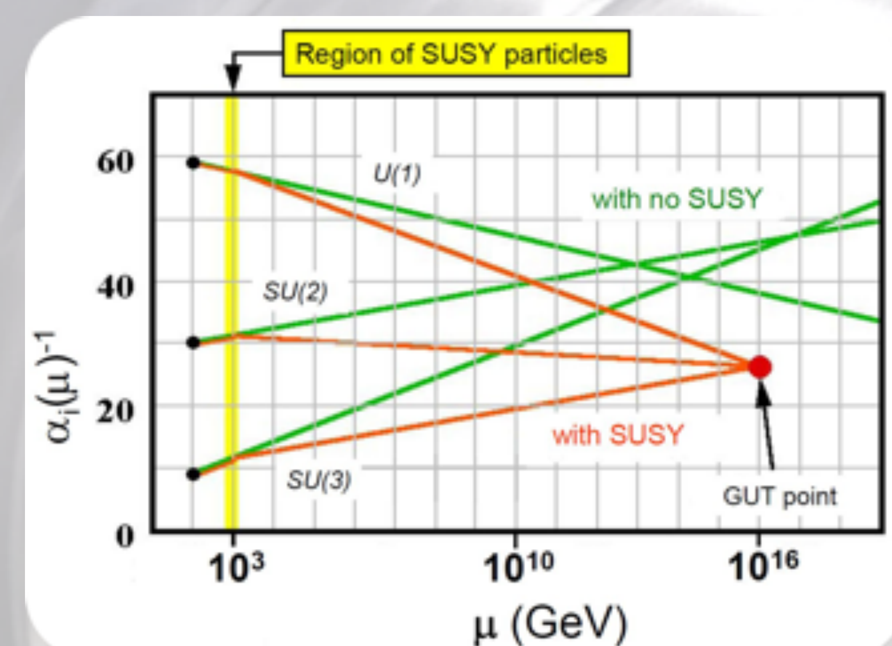
Why we (used to) like SUSY a lot

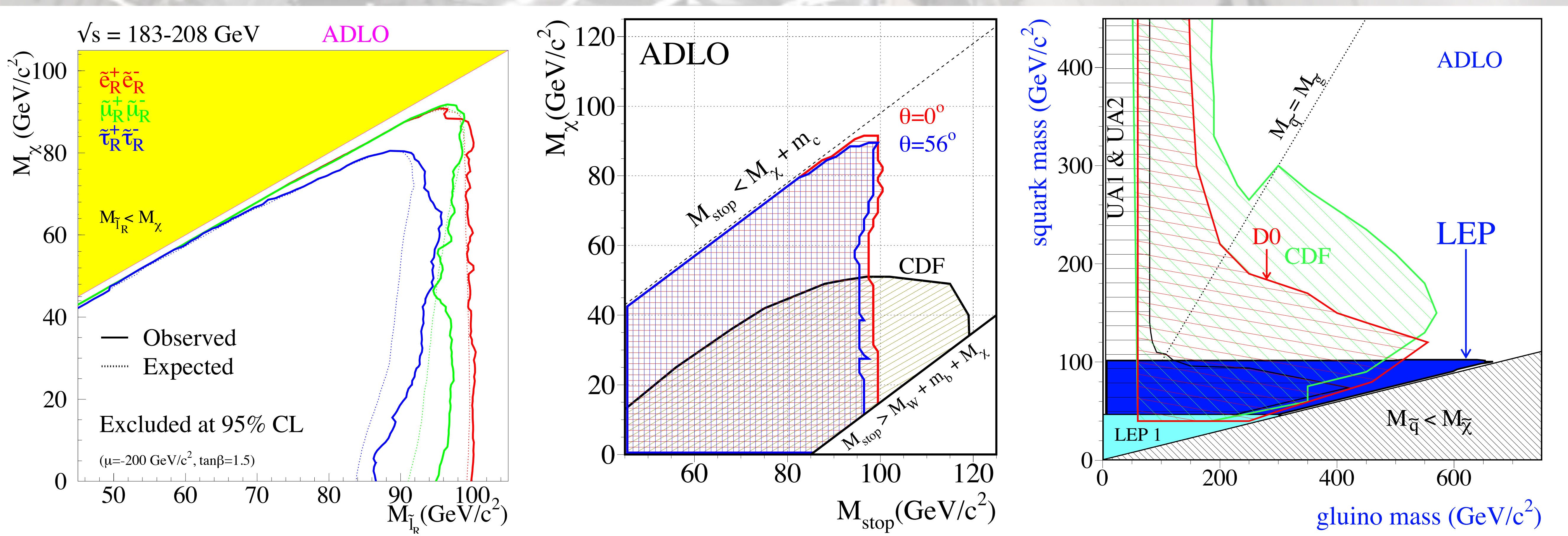
- One solution for three problems:
  - Hierarchy problem: cancellation of quantum corrections to Higgs mass
  - Dark Matter: when R-parity is assumed, the lightest SUSY particle is a DM candidate (DM production in cascade)
  - Unification of gauge interactions: match of the running of the SU(3)/SU(2)/U(1) coupling constants





As you might have noticed...

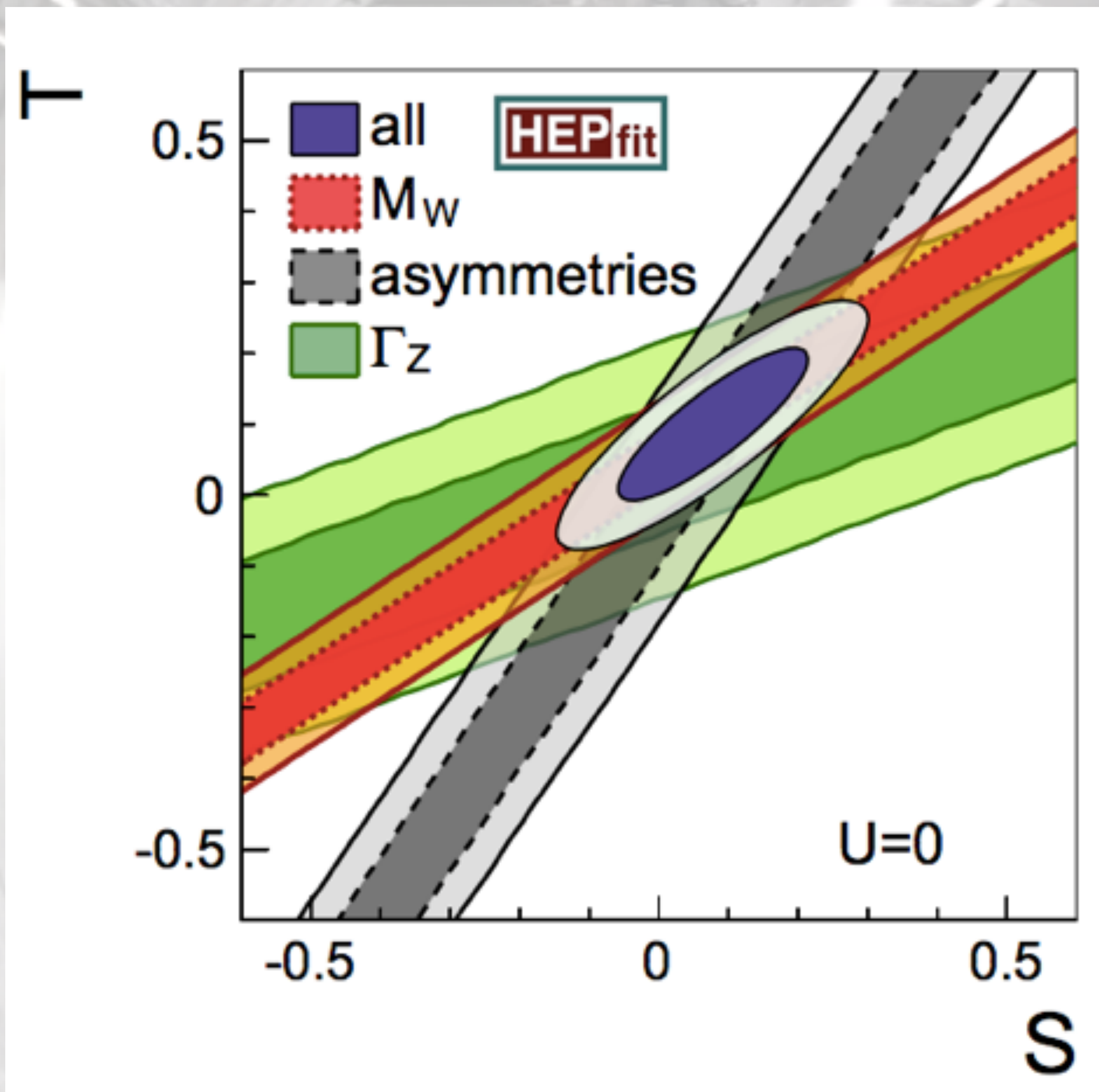
… We didn't discover SUSY at LEP and the Tevatron



R. Barbieri and A. Strumia hep-ph/0007265

As you might have noticed…

… We didn't discover SUSY looking at indirect effects @ EW scale…



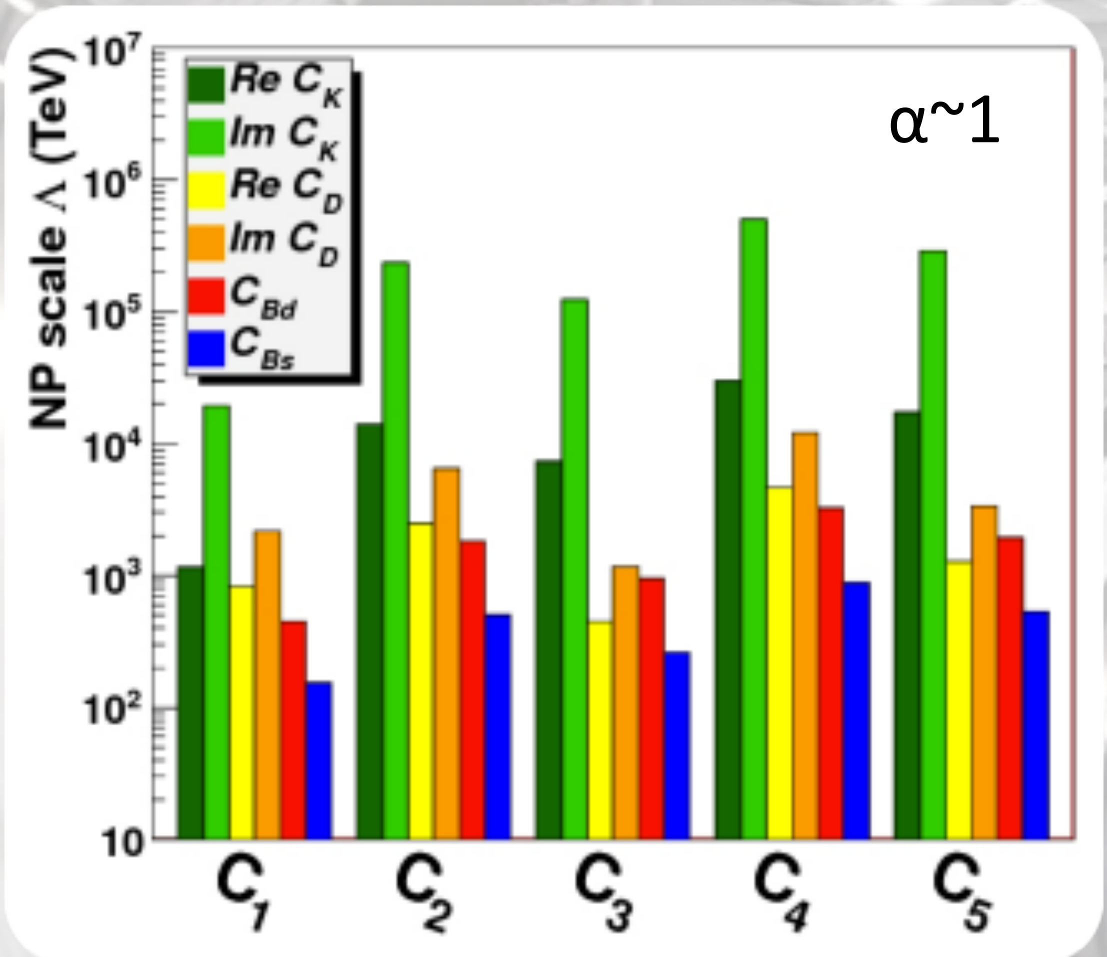
HEPfit http://hepfit.roma1.infn.it

Coefficient	Only EW Λ [TeV] $C_i=-1$	Only EW Λ [TeV] $C_i=1$	Only Higgs Λ [TeV] $C_i=-1$	Only Higgs Λ [TeV] $C_i=1$	EW + Higgs Λ [TeV] $C_i=-1$	EW + Higgs Λ [TeV] $C_i=1$
C_{HG}	—	—	11.4	12.3	11.4	12.3
C_{HW}	—	—	5.1	9.1	5.1	9.1
C_{HB}	—	—	9.6	17.2	9.6	17.2
C_{HWB}	11.1	18.4	12.5	7.1	12.6	15.9
C_{HD}	6.3	15.4	0.5	0.8	6.3	15.5
$C_{H\Box}$	—	—	0.9	0.7	0.9	0.7
$C_{HL}^{(1)}$	14.8	9.2	—	—	14.8	9.2
$C_{HL}^{(3)}$	9.8	14.8	0.9	1.7	9.8	14.9
C_{He}	8.2	12.8	—	—	8.2	12.8
$C_{HQ}^{(1)}$	6.2	5.0	0.2	0.3	6.2	5.0
$C_{HQ}^{(3)}$	9.6	8.7	1.3	0.7	9.7	8.7
C_{Hu}	3.9	3.6	0.4	0.3	3.9	3.6
C_{Hd}	2.7	4.1	0.2	0.3	2.7	4.1
C_{Hud}	—	—	—	—	—	—
C_{eH}	—	—	3.8	6.4	3.8	6.4
C_{uH}	—	—	1.4	1.3	1.4	1.3
C_{dH}	—	—	3.7	3.6	3.7	3.6
C_{LL}	12.0	7.3	1.2	0.6	12.0	7.3

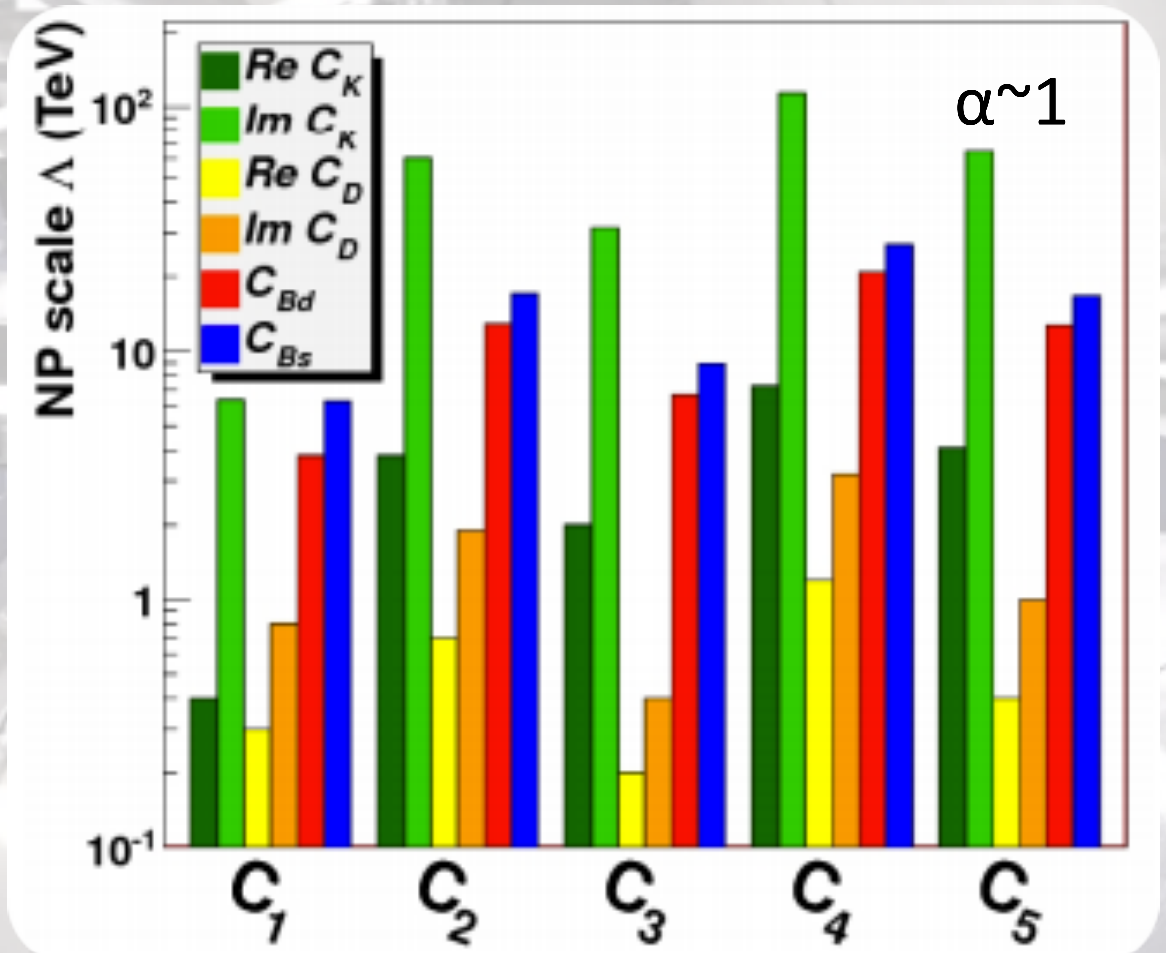
… and we set strong limits on the scale of new physics (under some assumption (e.g., NP through oblique corrections)

As you might have noticed…

… We didn't discover SUSY looking at indirect effects in Flavor…



Generic Flavor structure
for New Physics

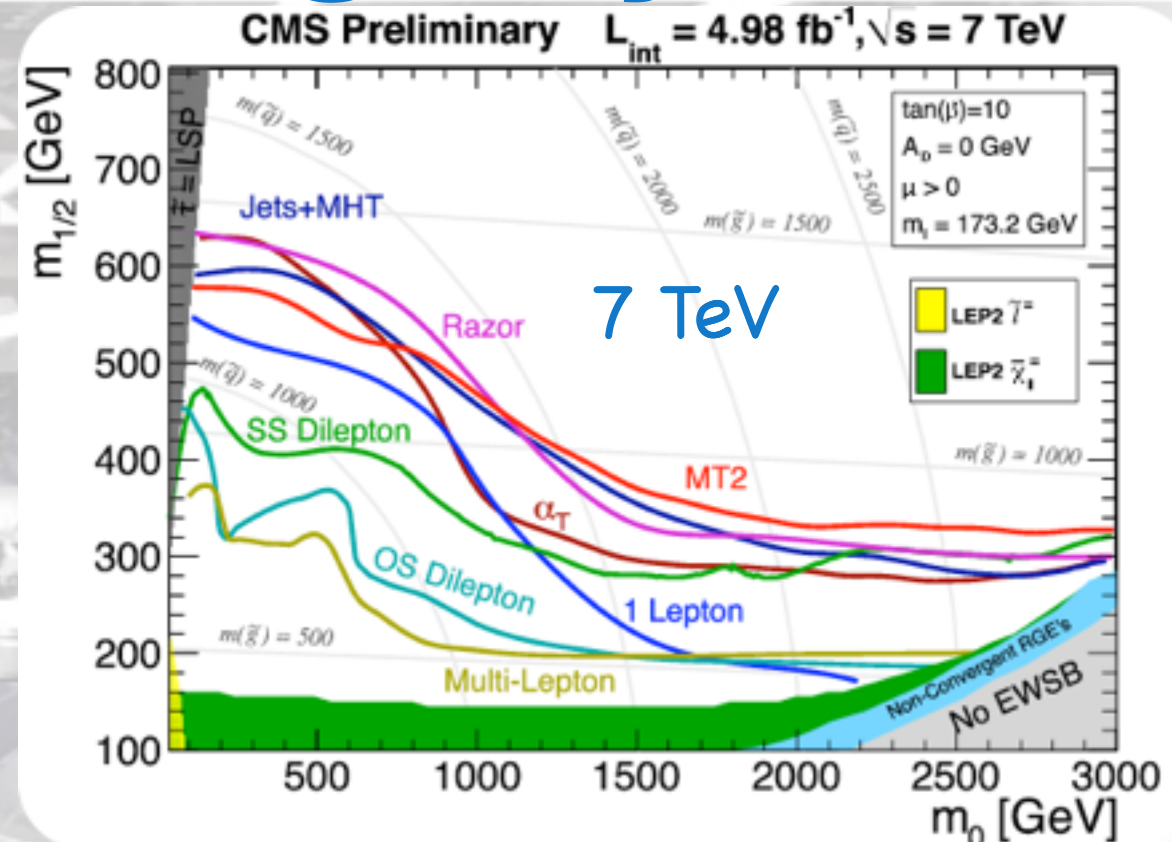


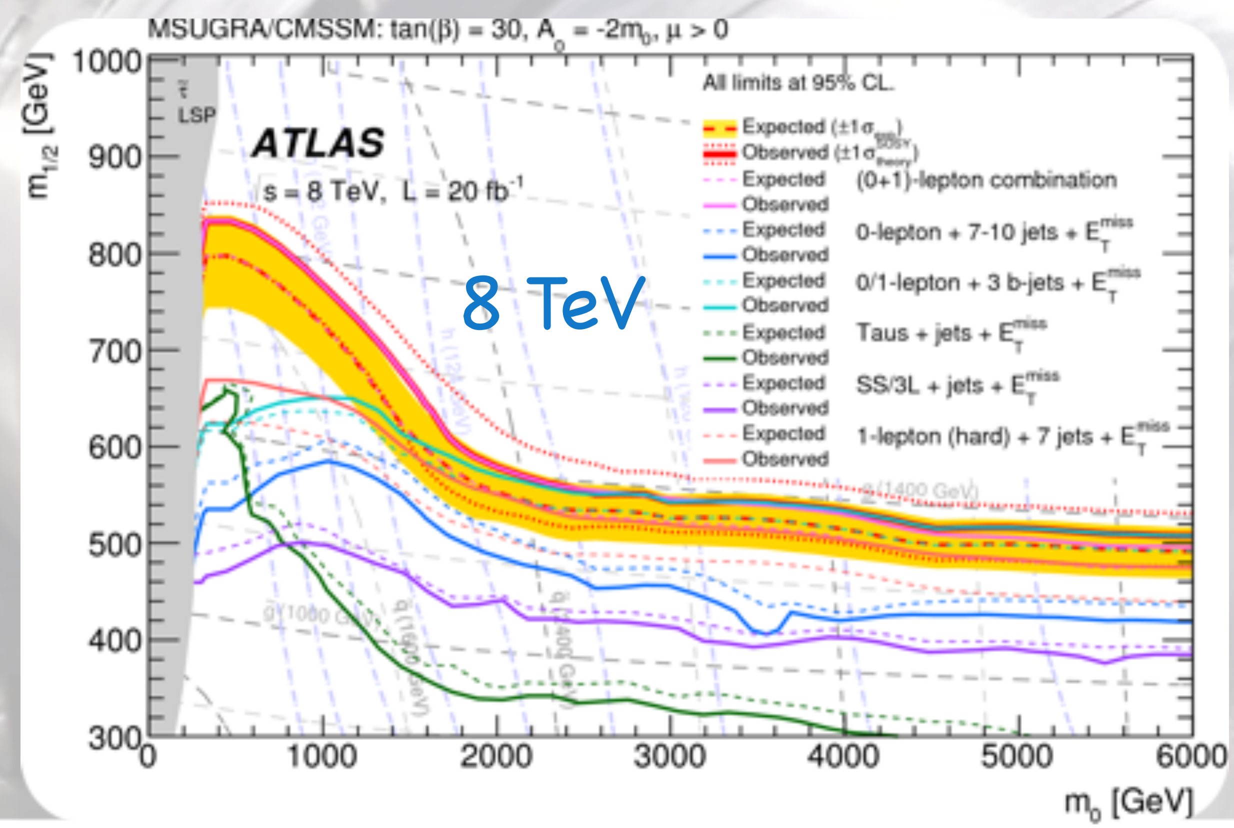
Next To Minimal Flavor
Violation

… and we set strong limits on the scale of new physics (under some assumption (e.g., NP entering mixing processes through DIM6 operators)

The 7 TeV Legacy

- Hoping for an early discovery of CMSSM-like SUSY
  - Full spectrum accessible
  - A lot of signatures
- Quick exclusion of ballpark
  - high energy
  - tricky corners (e.g. degenerate spectra)
  - As we said, not really unexpected
    - EW precision
    - Flavor physics



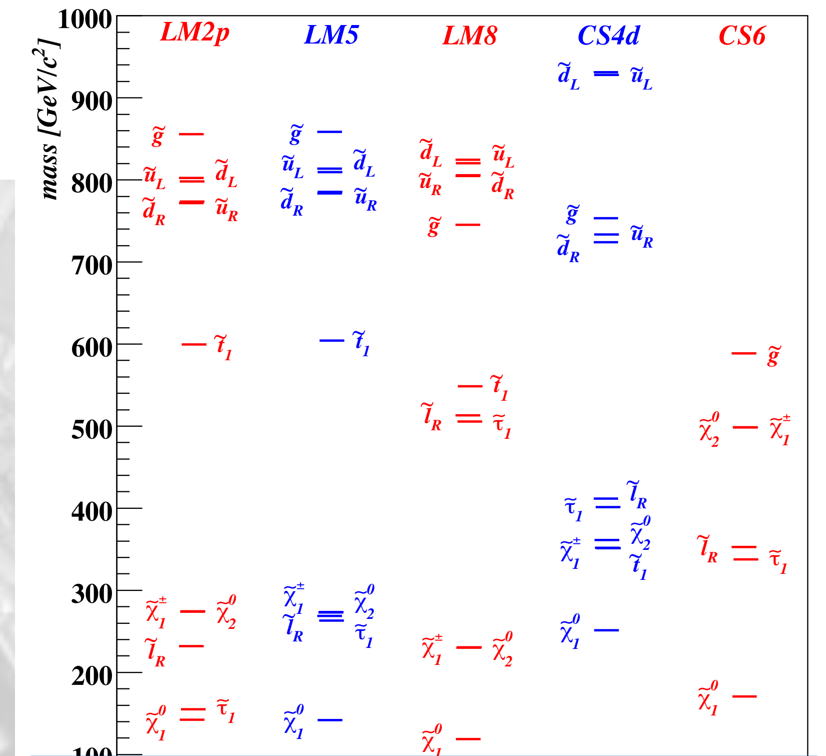


The Natural SUSY paradigm

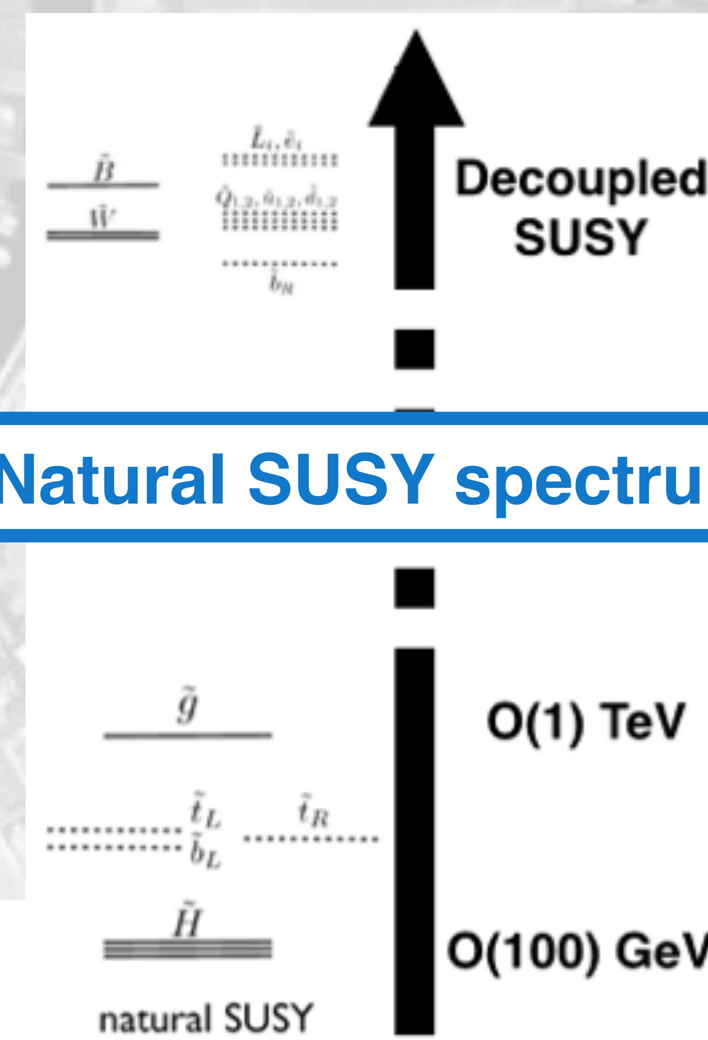
“Natural” SUSY

- Given the existing limits, part of the spectrum has to decouple
- For naturalness, we need part of the spectrum to be light
- Natural SUSY paradigm
  - LHC-accessible spectrum: $\tilde{g}$, $\tilde{t}$, $\tilde{b}$, $\tilde{h}$'s
  - Other particles too heavy

M. Dine et al. arXiv:hep-ph/9304299
P. Pouliot and N. Seiberg, arXiv:hep-ph/9308363
R. Barbieri, L. J. Hall and A. Strumia, arXiv:hep-ph/9504373
S. Dimopoulos, G. F. Giudice hep-ph/9507282
A. Pomarol and D. Tommasini, arXiv:hep-ph/9507462
R. Barbieri, G. R. Dvali and L. J. Hall, arXiv:hep-ph/9512388
A. G. Cohenet al., arXiv:hep-ph/9607394
R. Barbieri, L. J. Hall and A. Romanino, arXiv:hep-ph/9702315
R. Sundrum, arXiv:0909.5430 [hep-th]
R. Barbieri et al. arXiv:1004.2256 [hep-ph]
R. Barbieri et al. arXiv:1011.0730 [hep-ph]
N. Craig, D. Green, A. Katz, arXiv:1103.3708 [hep-ph]
T. Gherghetta, B. von Harling, N. Setzer, arXiv:1104.3171 [hep-ph]
M. Papucci, et al., arXiv:1110.6926 [hep-ph]



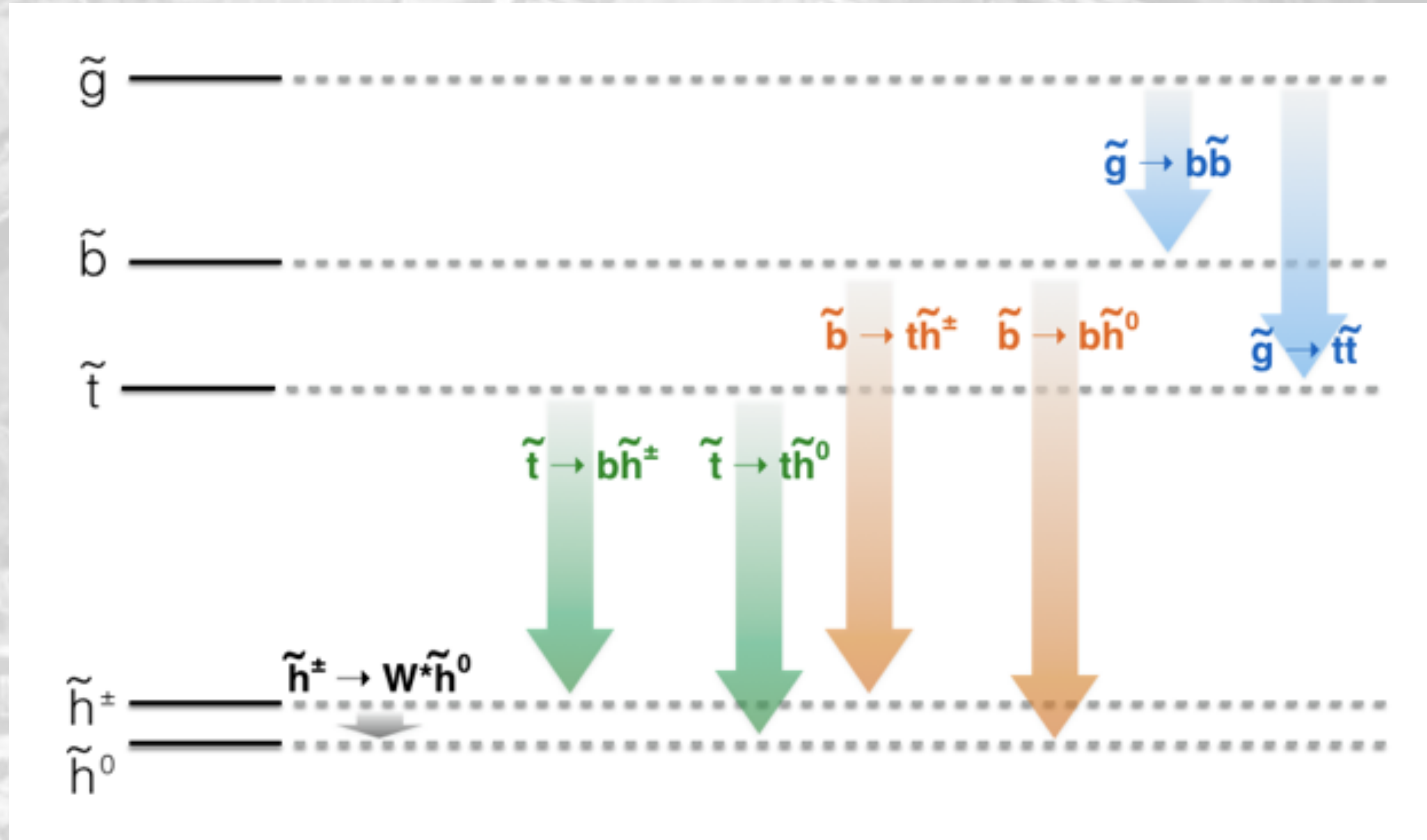
Benchmark SUSY models @ 7TeV



Natural SUSY spectrum

“Natural” SUSY

- Signatures @LHC are still abundant
  - b quarks
  - leptons
  - MET
- Higgsinos almost degenerate [difficult to probe $\tilde{h}^{\pm}$ daughters]



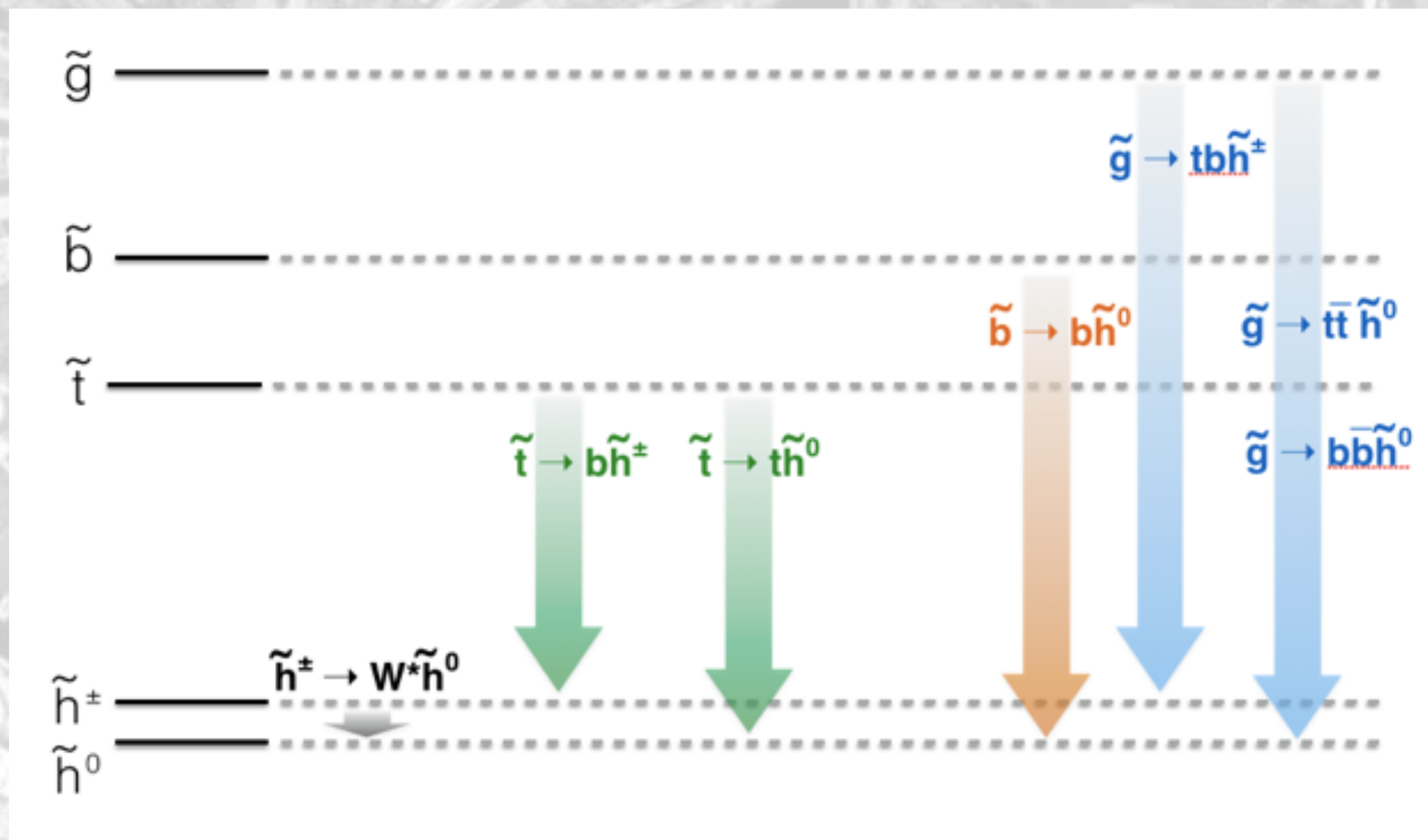
$$\tilde{g}\tilde{g} \to \begin{cases} -\ 4\tilde{t} \\ -\ 3\tilde{t}\ 1\tilde{b} \\ -\ 2\tilde{t}\ 2\tilde{b} \\ -\ 1\tilde{t}\ 3\tilde{b} \\ \quad\ 4\tilde{b} \end{cases} + \tilde{\chi}^0\tilde{\chi}^0 \qquad \tilde{q}\tilde{q} \to \begin{cases} -\ 2\tilde{t} \\ -\ \tilde{t}\ \tilde{b} \\ -\ 2\tilde{b} \end{cases} + \tilde{\chi}^0\tilde{\chi}^0$$

"Natural" SUSY Simplified Models

- Consider gluino-gluino and stop stop pair production
- gluino 3-body decays to Higgsinos
- squark 2-body decays to $b\tilde{h}$ or $t\tilde{h}$
- Consider one production x one or two decay modes

$\tilde{g}\tilde{g} \rightarrow$
- 4t
- 3t 1b
- 2t 2b $+ \tilde{\chi}^0\tilde{\chi}^0$
- 1t 3b
- 4b

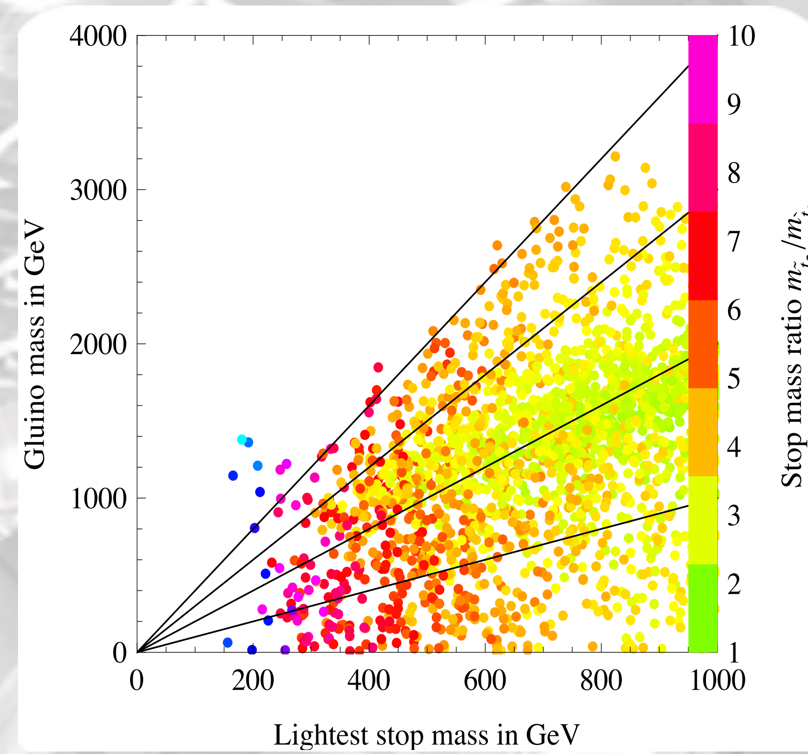
$\tilde{t}\tilde{t} \rightarrow$
- 2t
- t b $+ \tilde{\chi}^0\tilde{\chi}^0$
- 2b

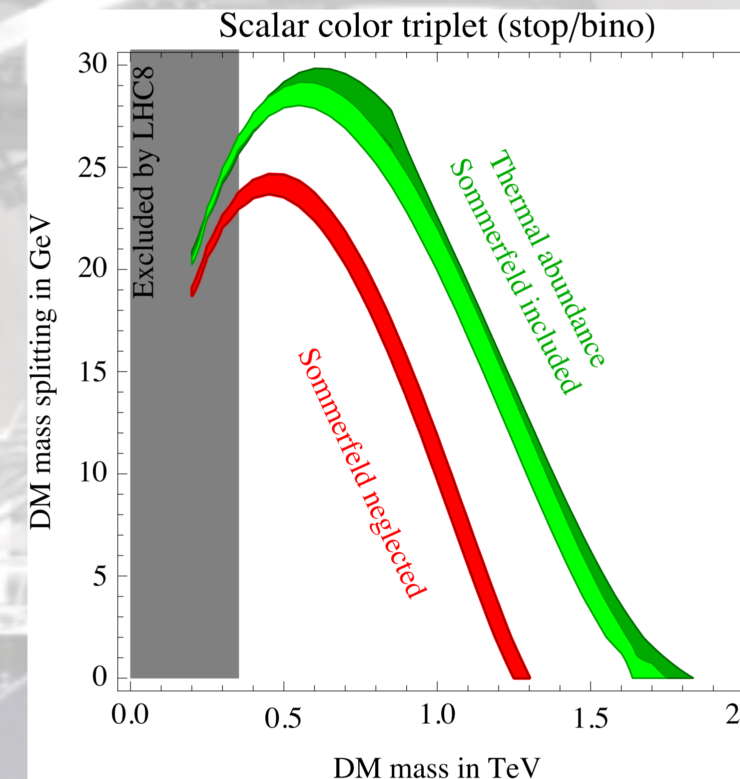


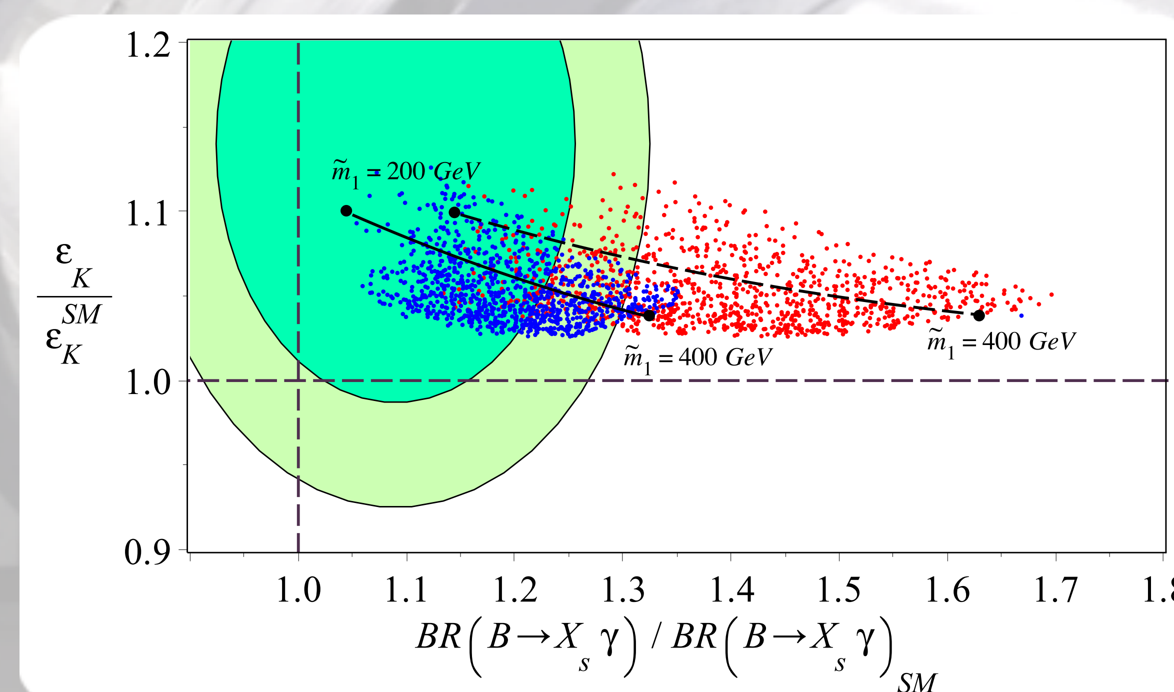
Fine Tuning & Top partners

Natural stop should be light...

- A stop with light mass has many appealing features
  - consistent with collider data & flavor constraints
  - naturally generated by simple RGE evolution of simple UV completions
  - (in compress spectra) offers a co-annihilation mechanism to bring Bino-like DM in agreement with relic density abundance
  - etc etc...

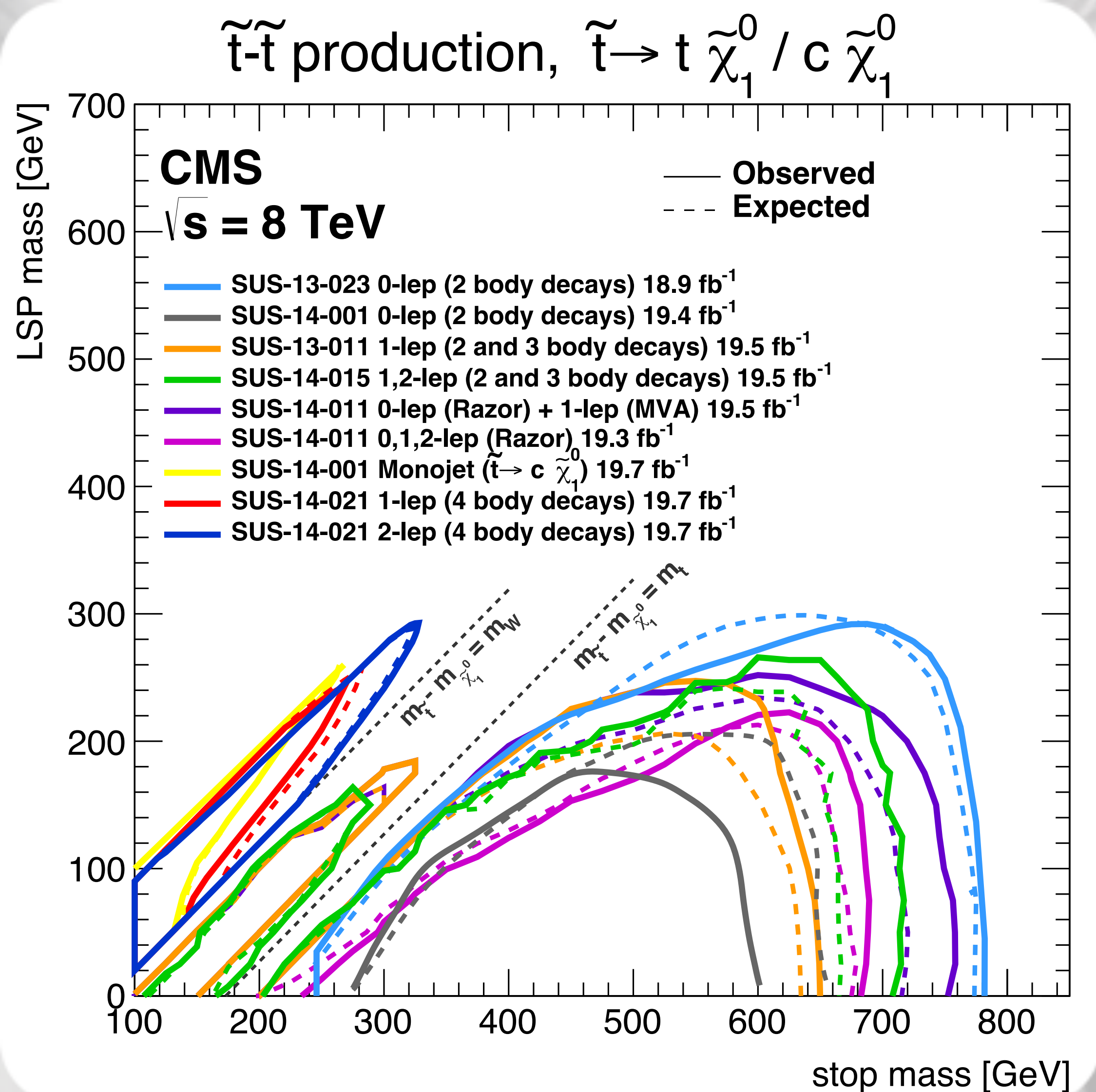


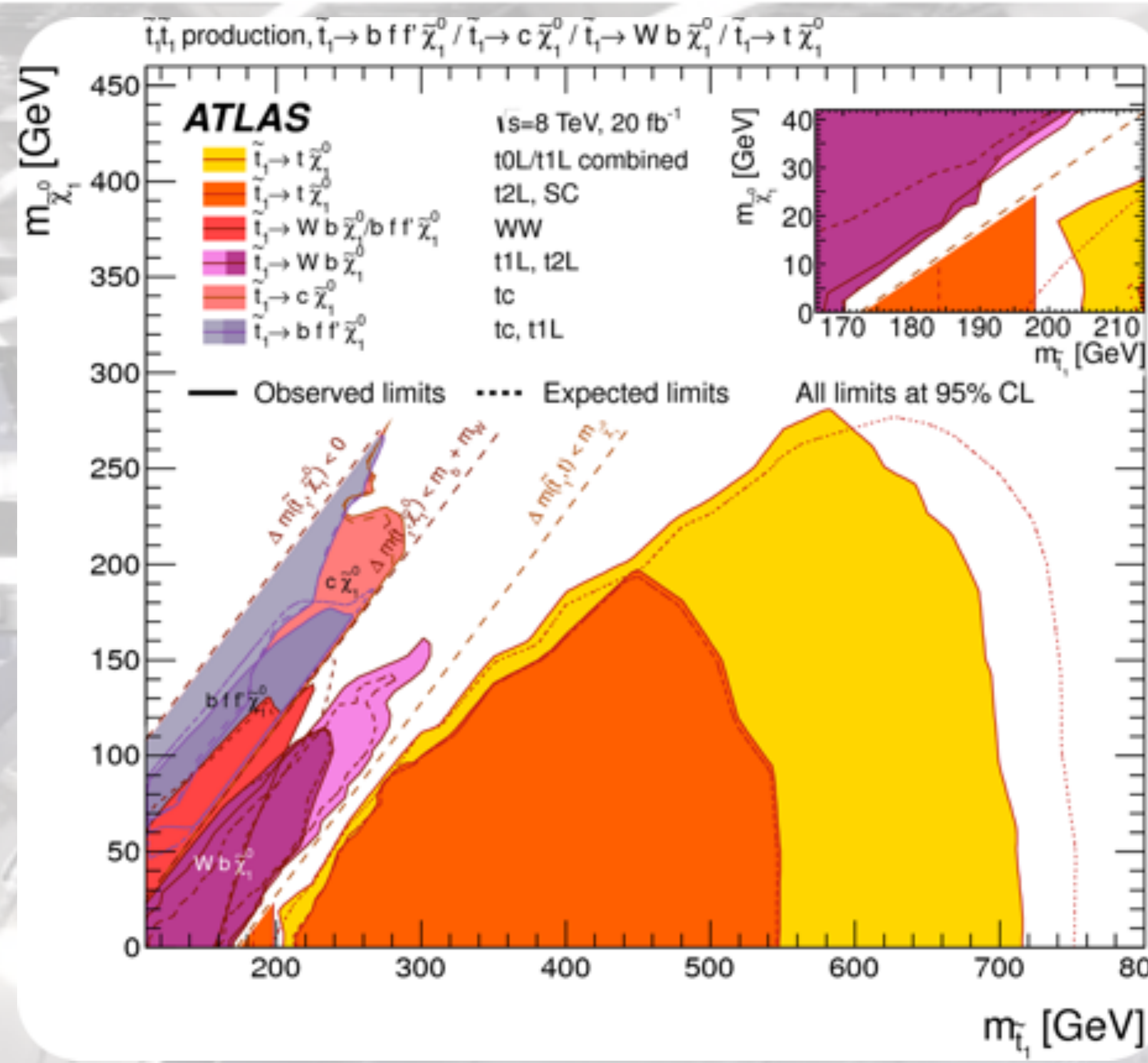




arxiv:1212.6847

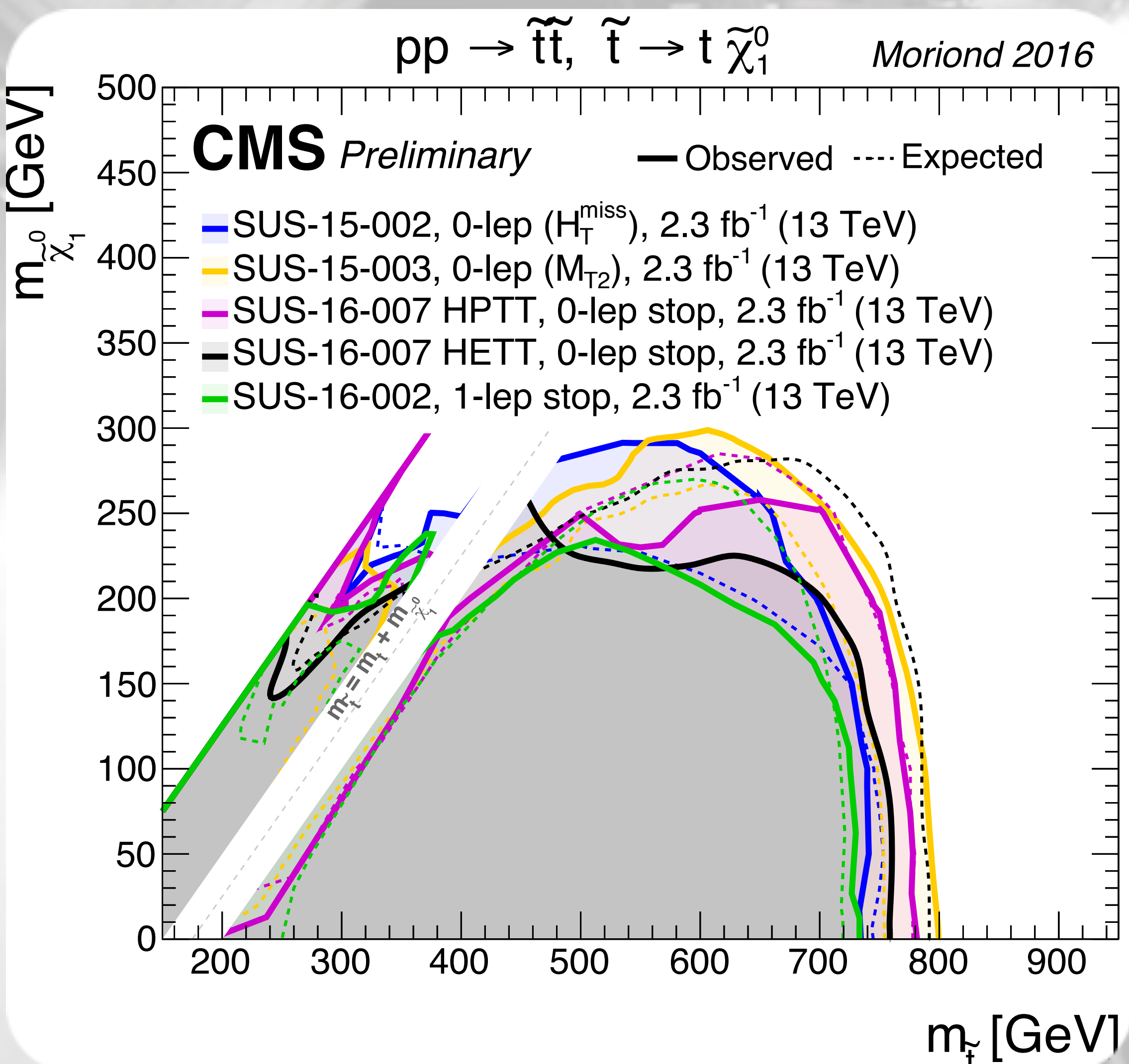
... so we looked for it in Run I





- Searched for decays to top+LSP
- All top final states explored (0l,1l,2l)
- Excluded large portion of mass plane, with two notable "degeneracy" exceptions:
  - stealthy-stop valley (tt pair with small MET)
  - compressed spectrum (soft particles from stop decays)

... so we looked for it in Run II



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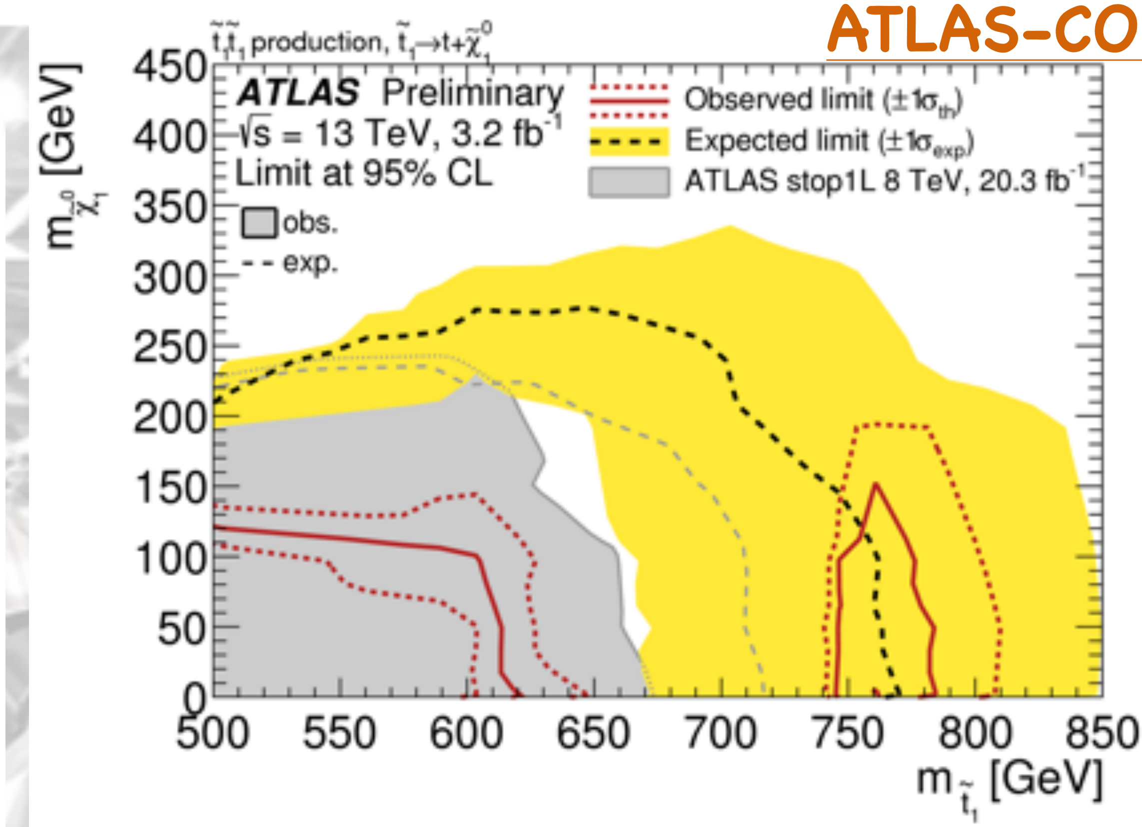

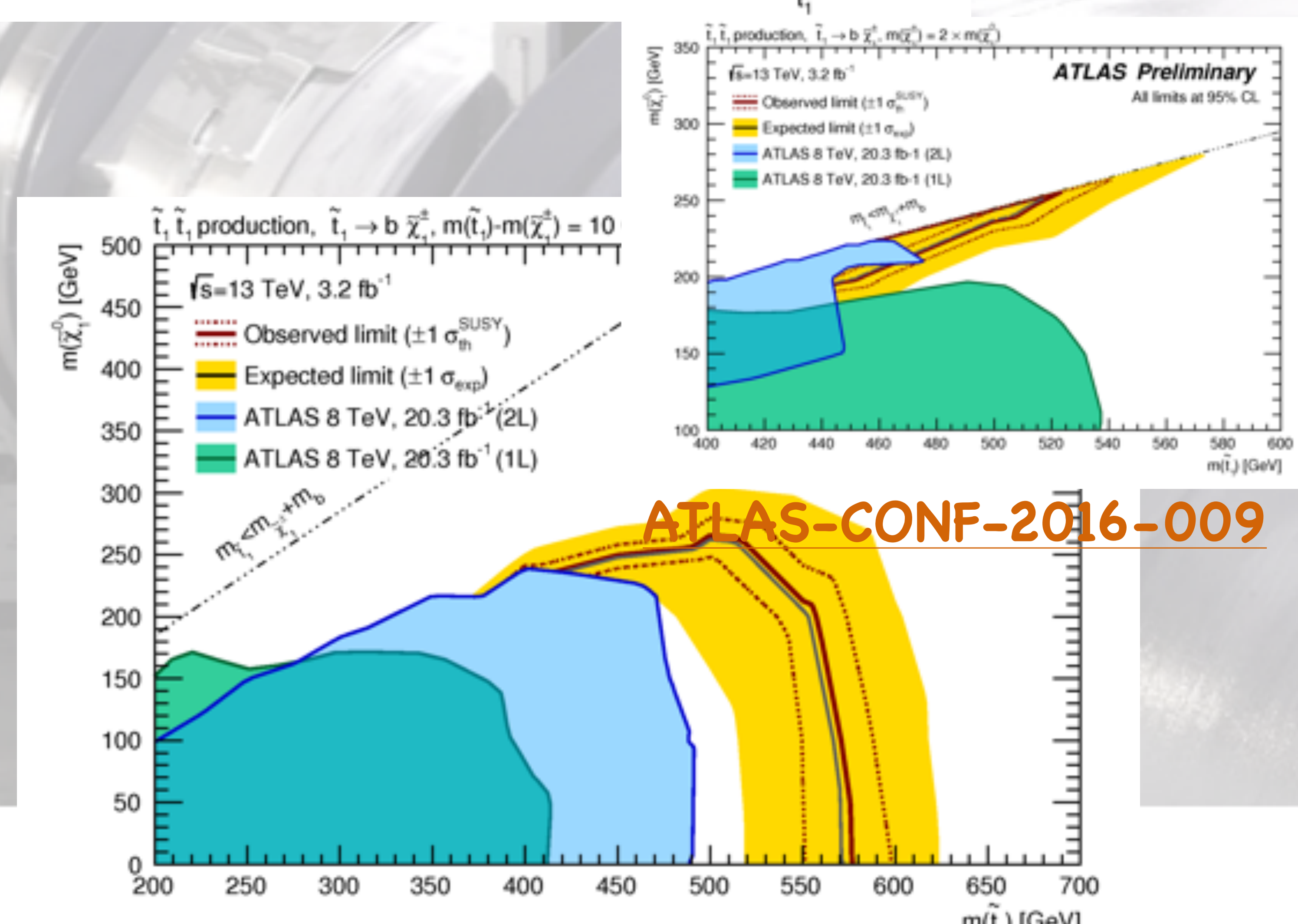

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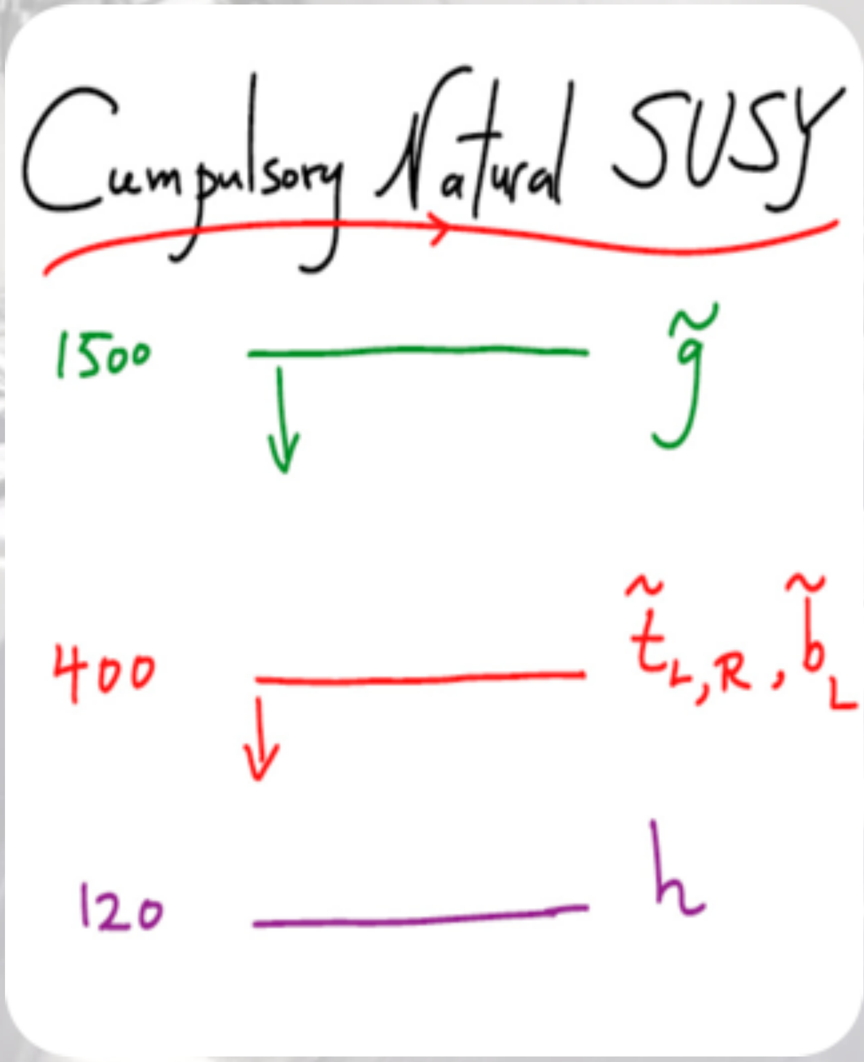
- Already with a few fb-1 of data, Run I precision matched
- Confirmed findings from Run I
- More data needed to explore new territory

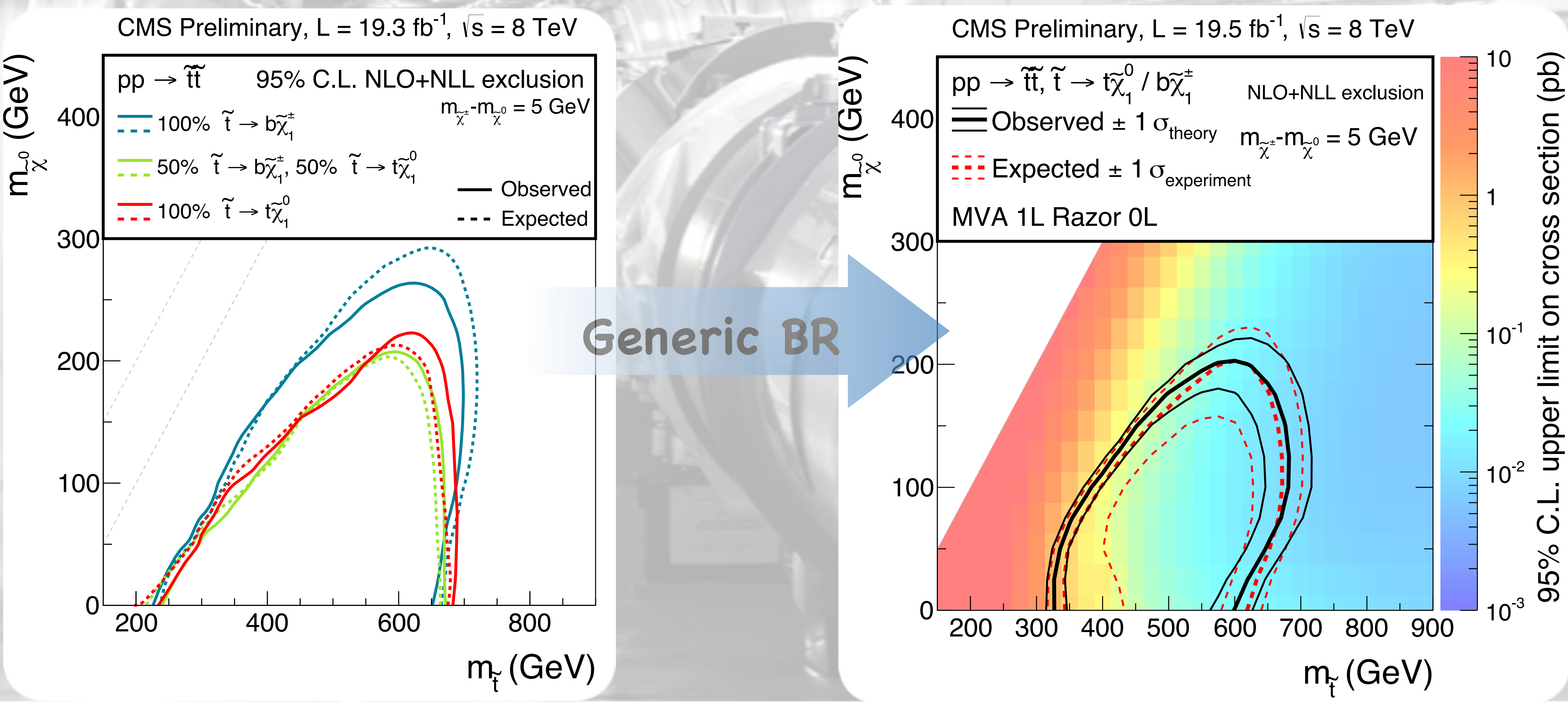
Is natural SUSY in danger?

- Run I and Run II results cover the ballpark of the “natural” stop mass
- But we should keep in mind that we are looking at Simplified Models
  - BR always fixed to 100% (not true in a full model)
- What would be a more realistic model?
  - a pMSSM-like scan with sbottom, stop, chargino and neutralino. Much easier than pMSSM!!!
  - more final states, less BR for each final state
  - SIDE REMARK: in a realistic scenario, tt+MET and bb+MET are the final states with the smallest BR. Why did we start with those?

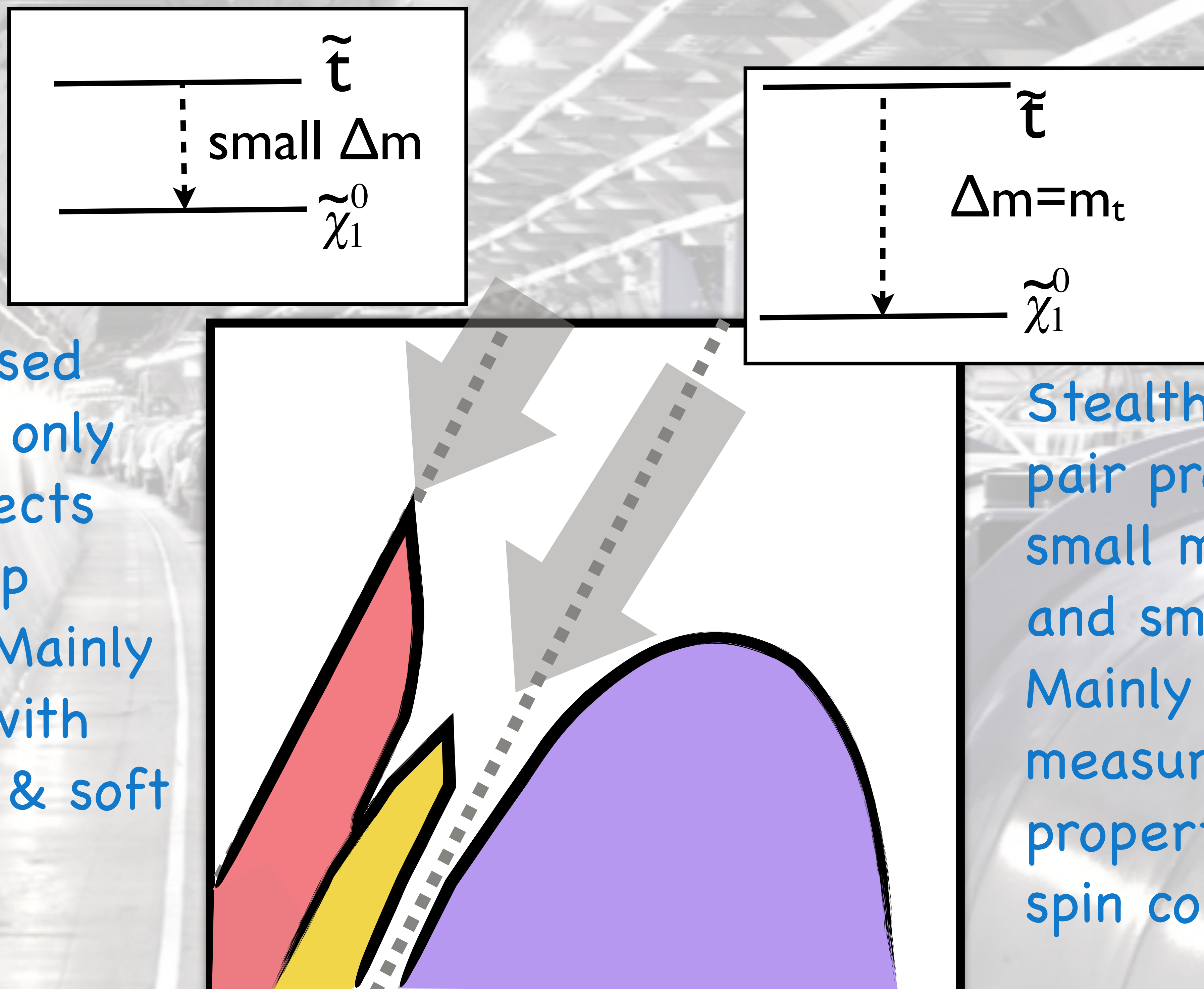


The natural SUSY paradigm is challenged

- How do we go around the limitations of Simplified models?
  - combining analyses or designing an inclusive search
  - deriving results for generic Branching Ratios
- Plenty of place for SUSY to hide. 13 TeV data will tell us



The tricky spots...



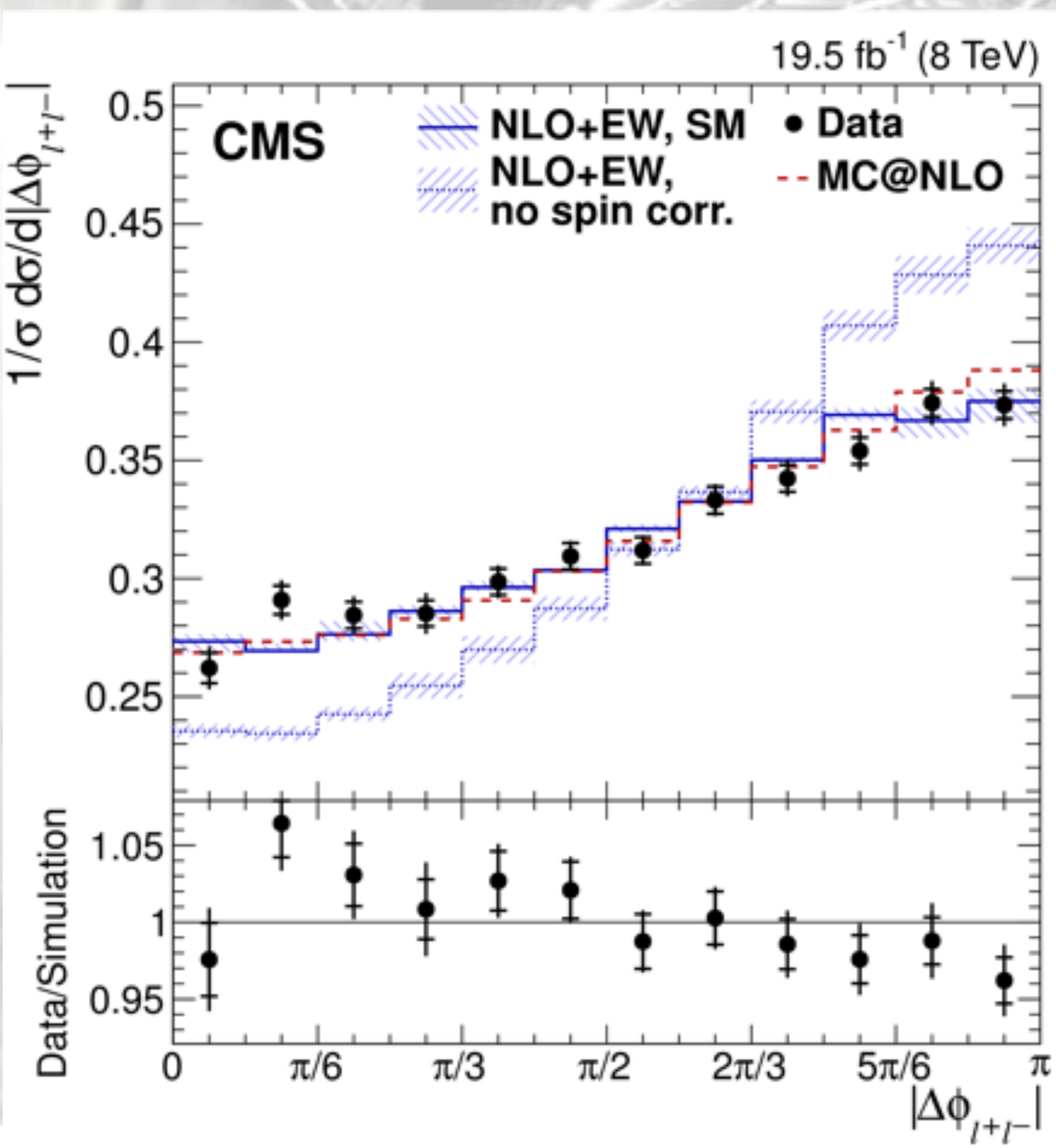
Compressed spectra: only soft objects from stop decays. Mainly probed with monojet & soft leptons

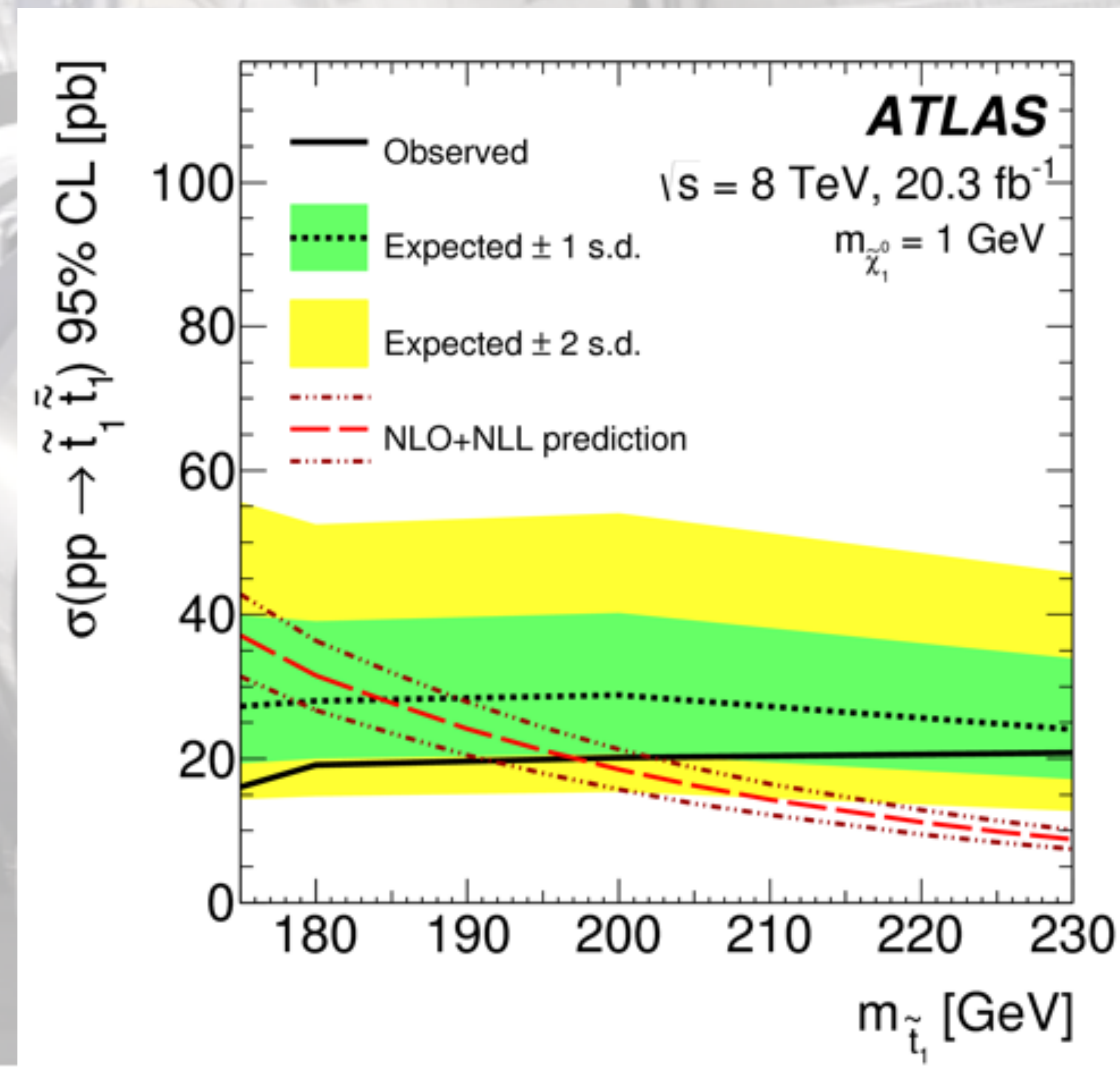
Stealthy stop: tt pair produced with small momentum and small MET. Mainly probed measuring tt properties (e.g. spin correlations)

In both scenarios, probing the region of interest for naturalness (the light stop window) is complicated

Are the tricky spots so tricky?

- In the stealthy-stop valley ($\Delta M \sim m_t$), difficult to directly see the stop
- tt production cross section enhanced within the theory and experimental uncertainty
- spin correlation modified (stop is a scalar)





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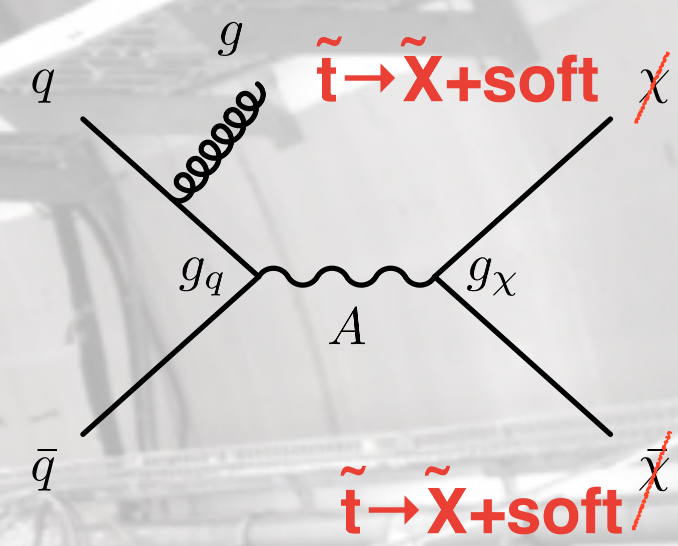
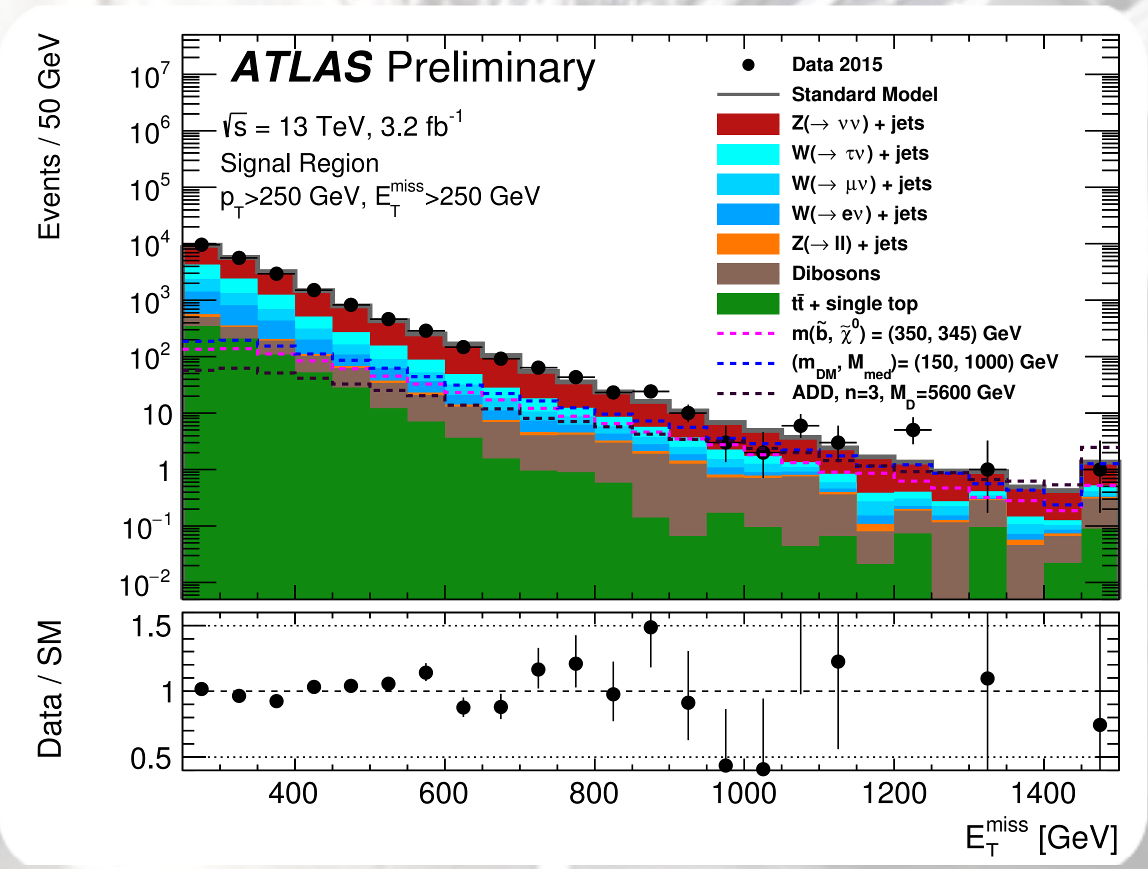
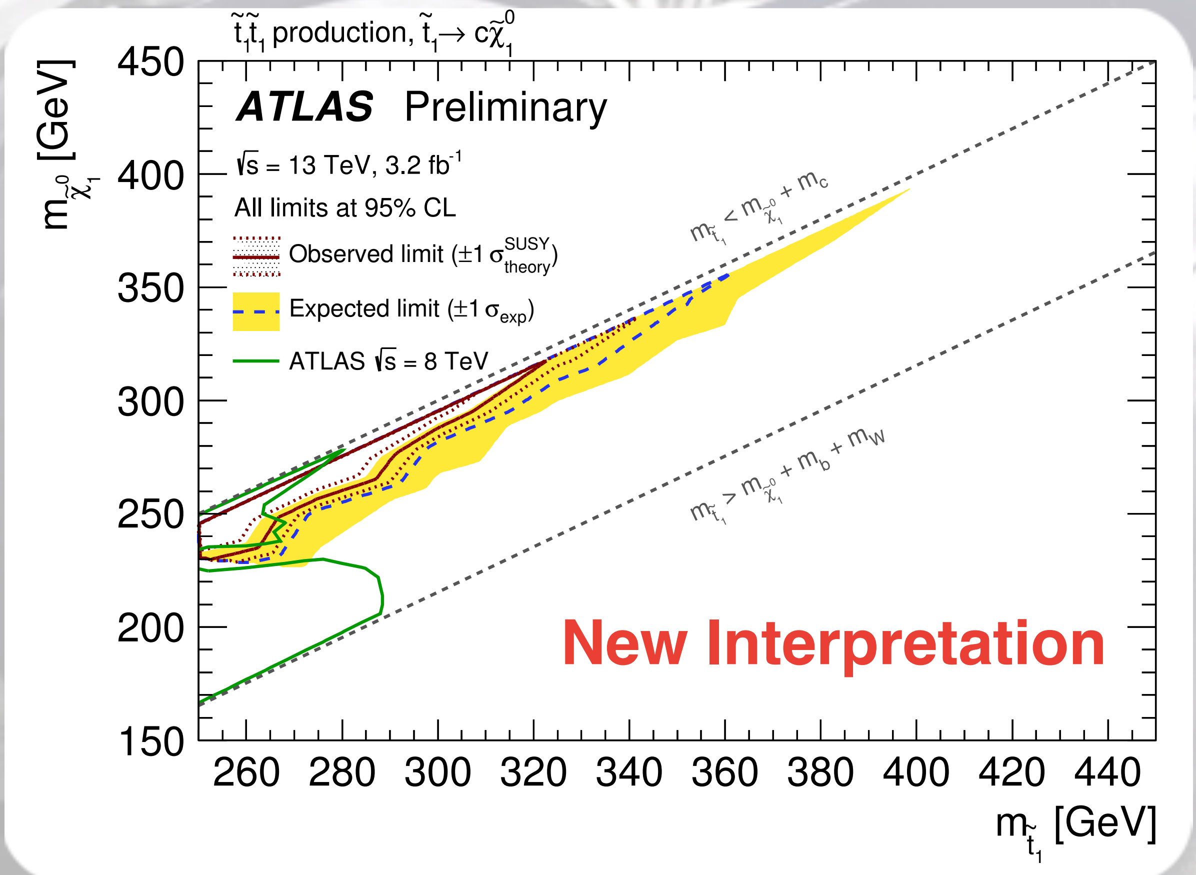
ATLAS-TOPQ-2014-07

Are the tricky spots so tricky?

- In the compressed region, stop decay products are too soft to be seen
- The stop "looks" like an invisible particle, but with a strong production xsec
- One can then "recycle" DM searches (monojet etc)







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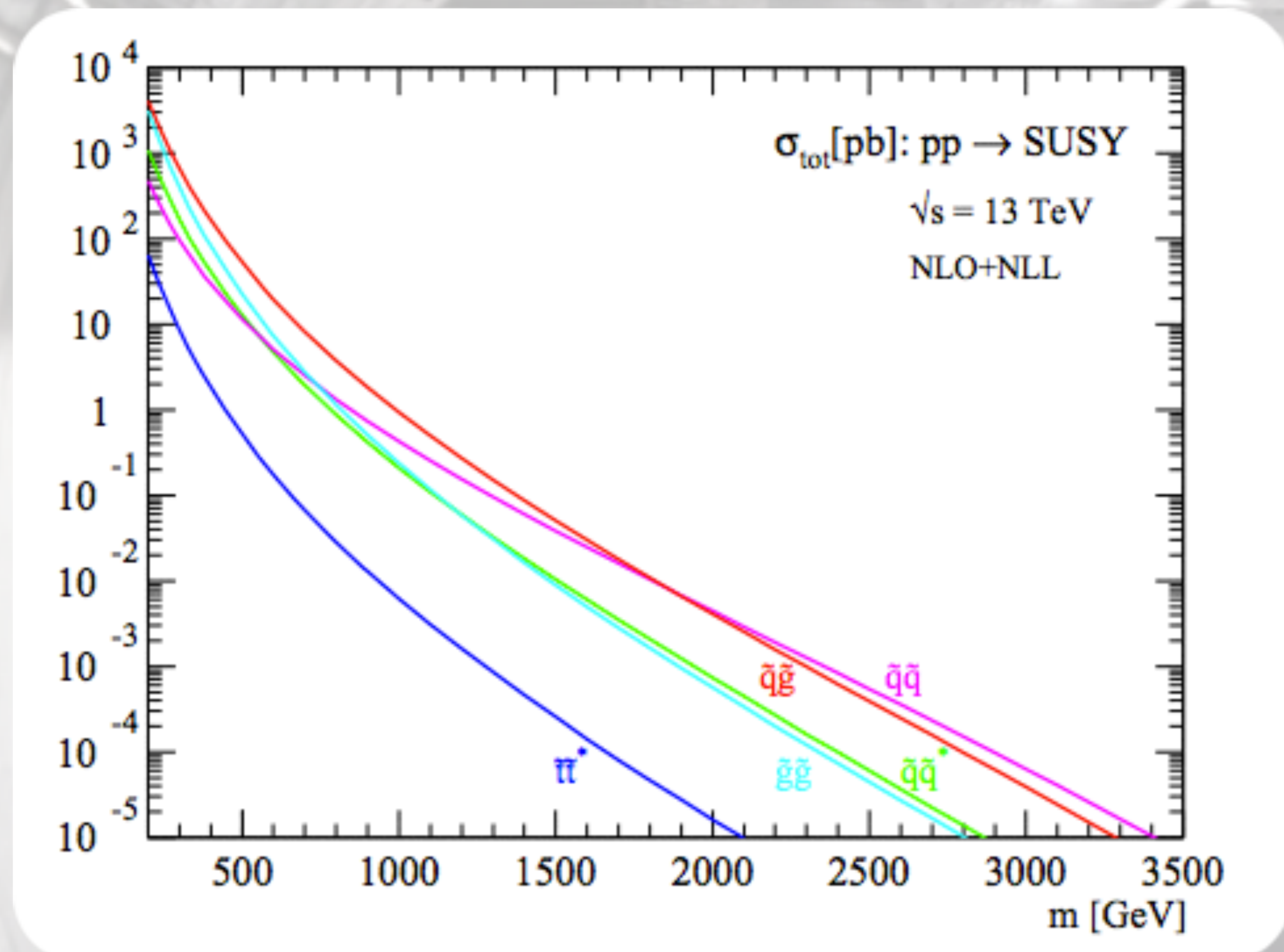
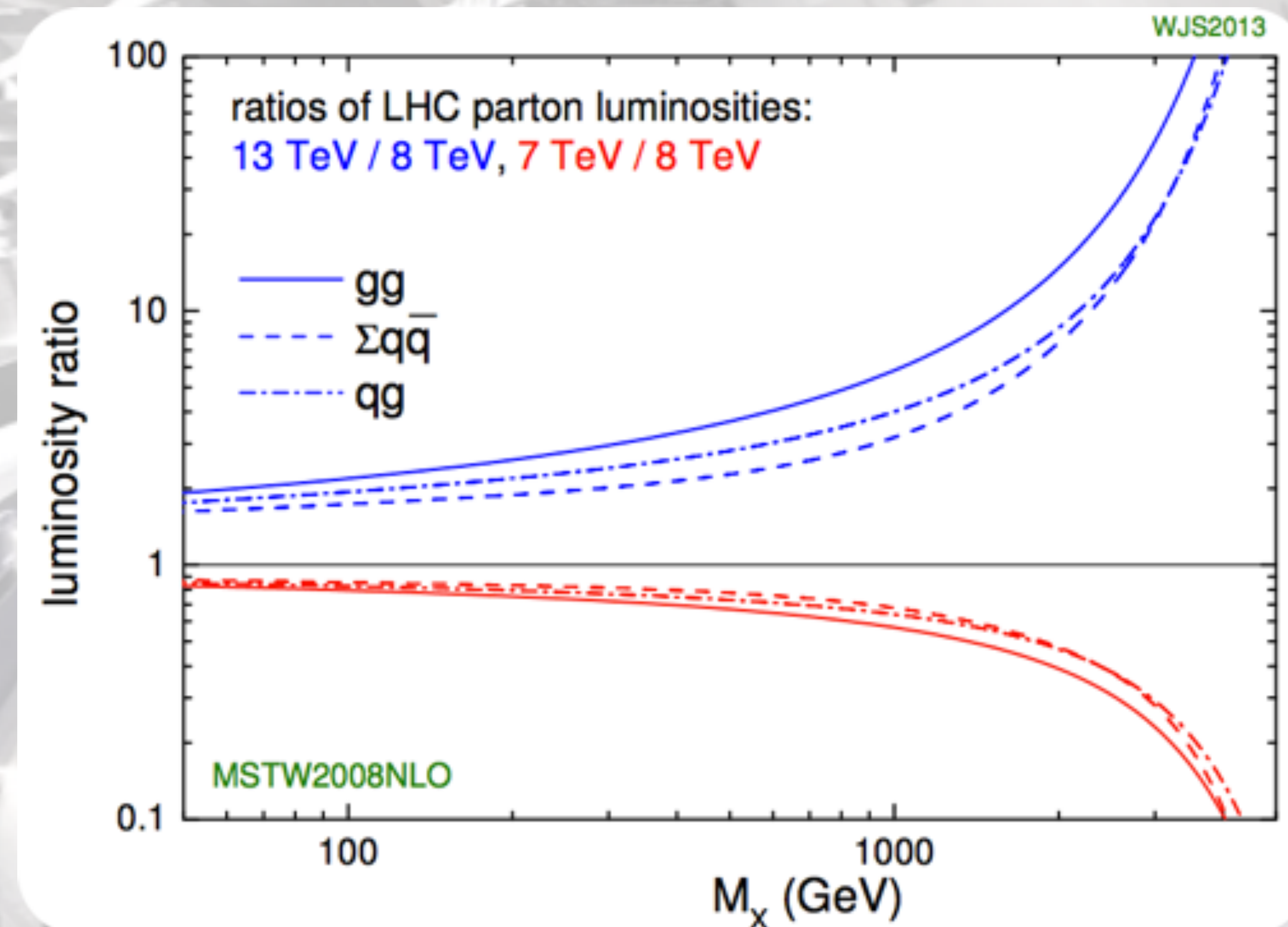
The Elephant in SUSY's room: gluino

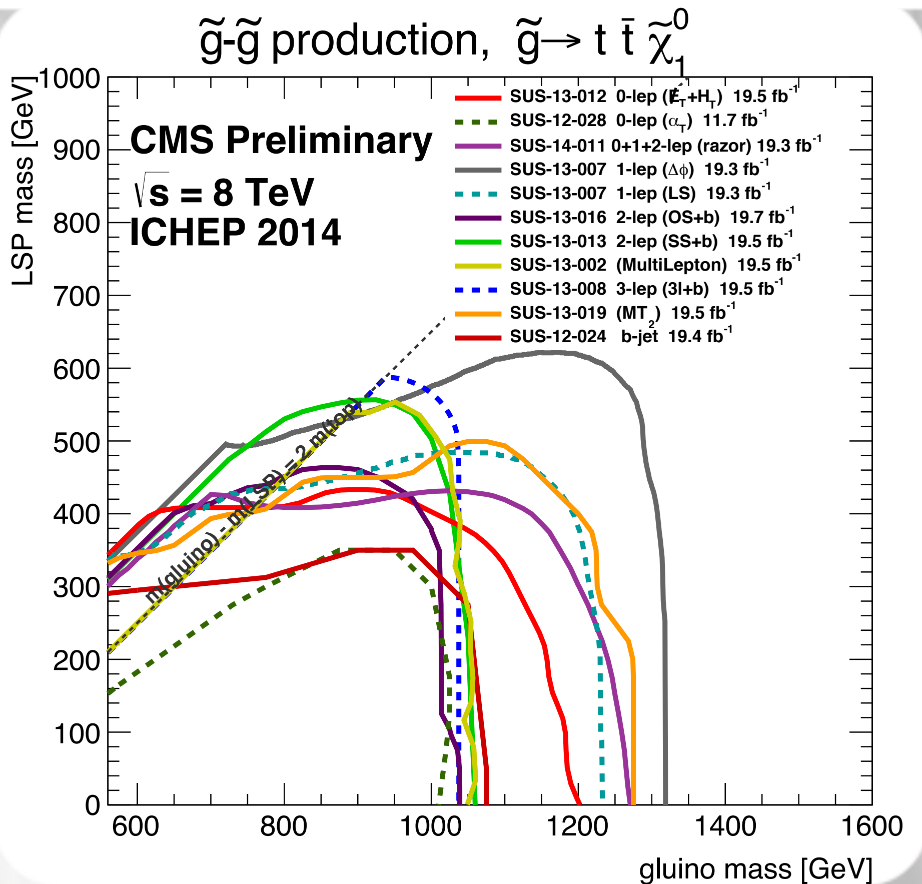
The LHC should be a gluino factory

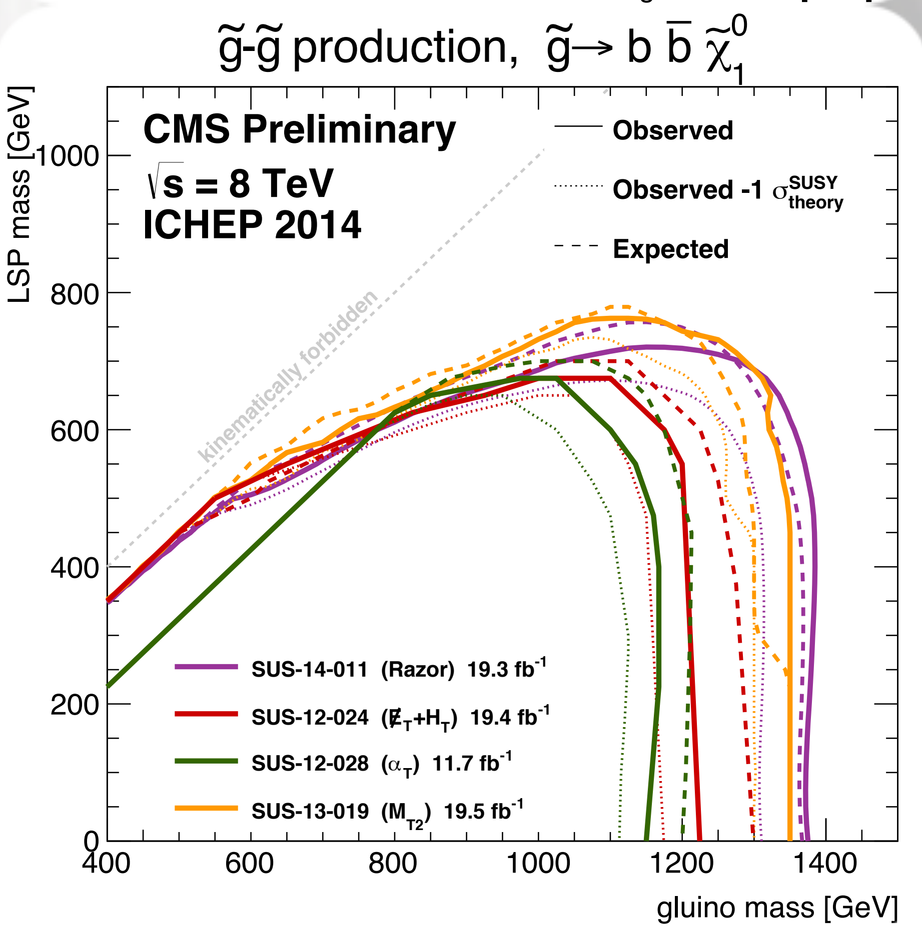


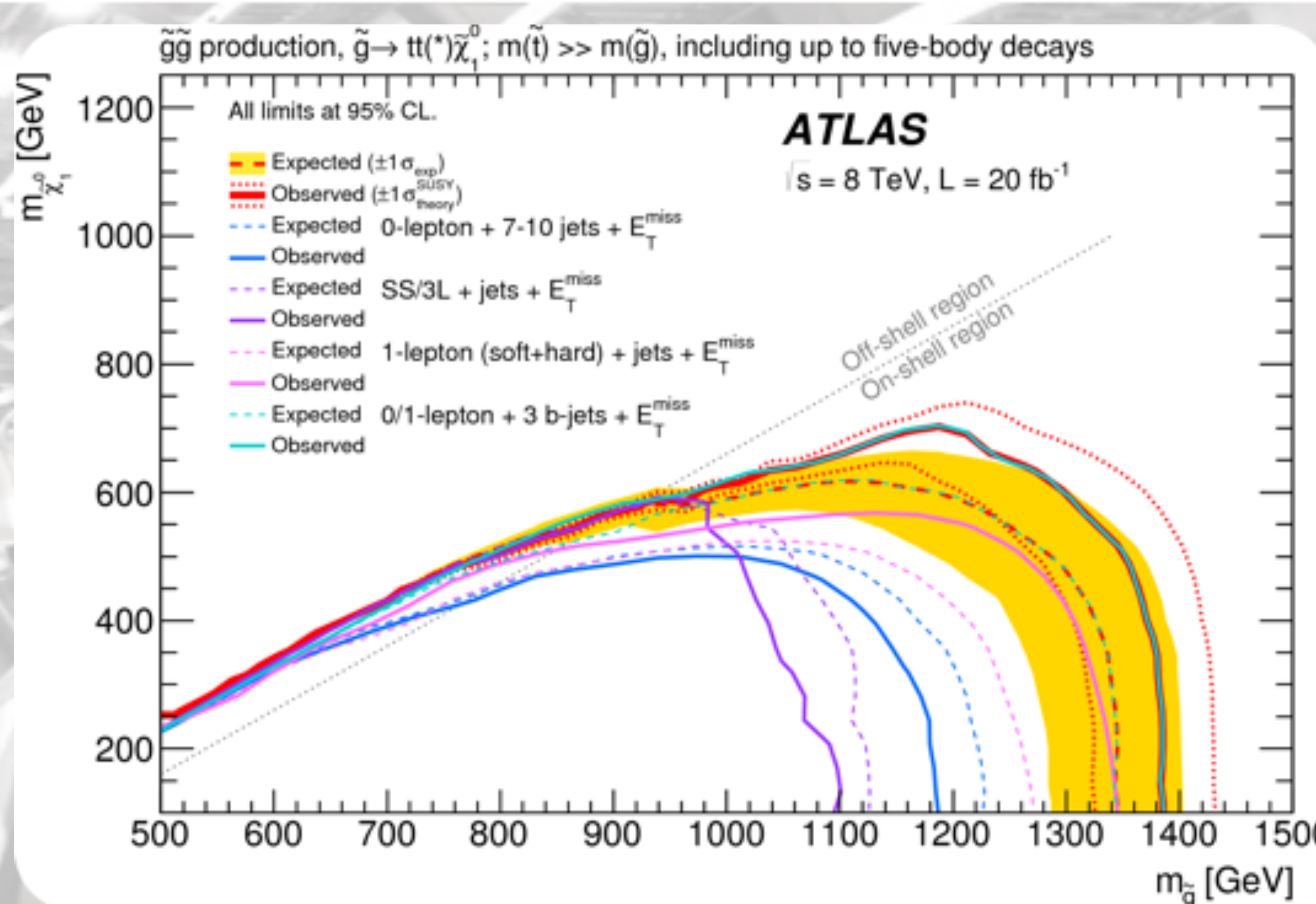


- Largest pair-production rate for one SUSY particle
- Largest gain in the energy increase
  - Unlike for squarks, we are already exploring new territory

… so we looked for it in Run I

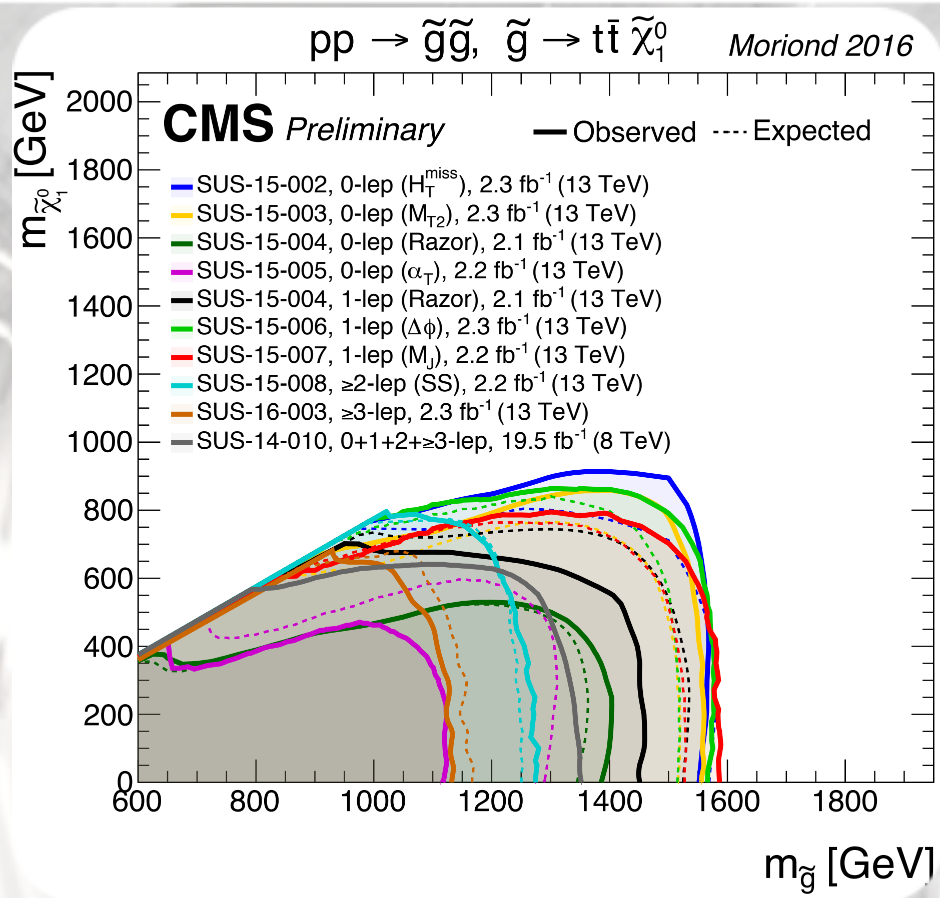


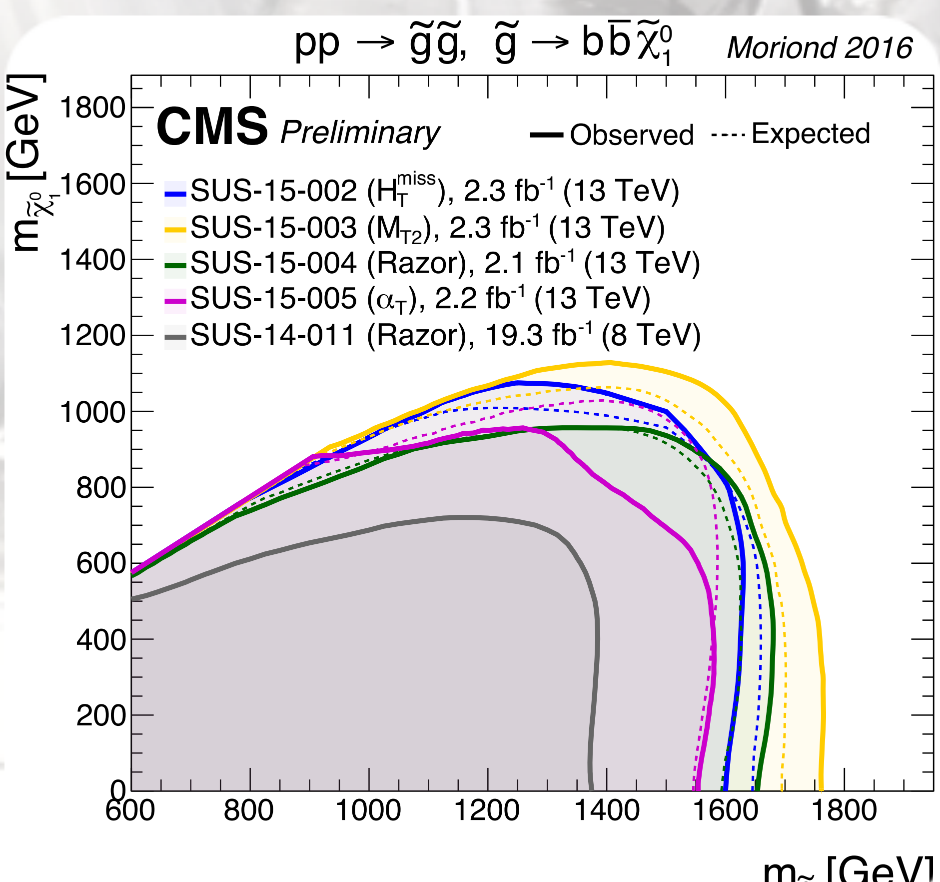


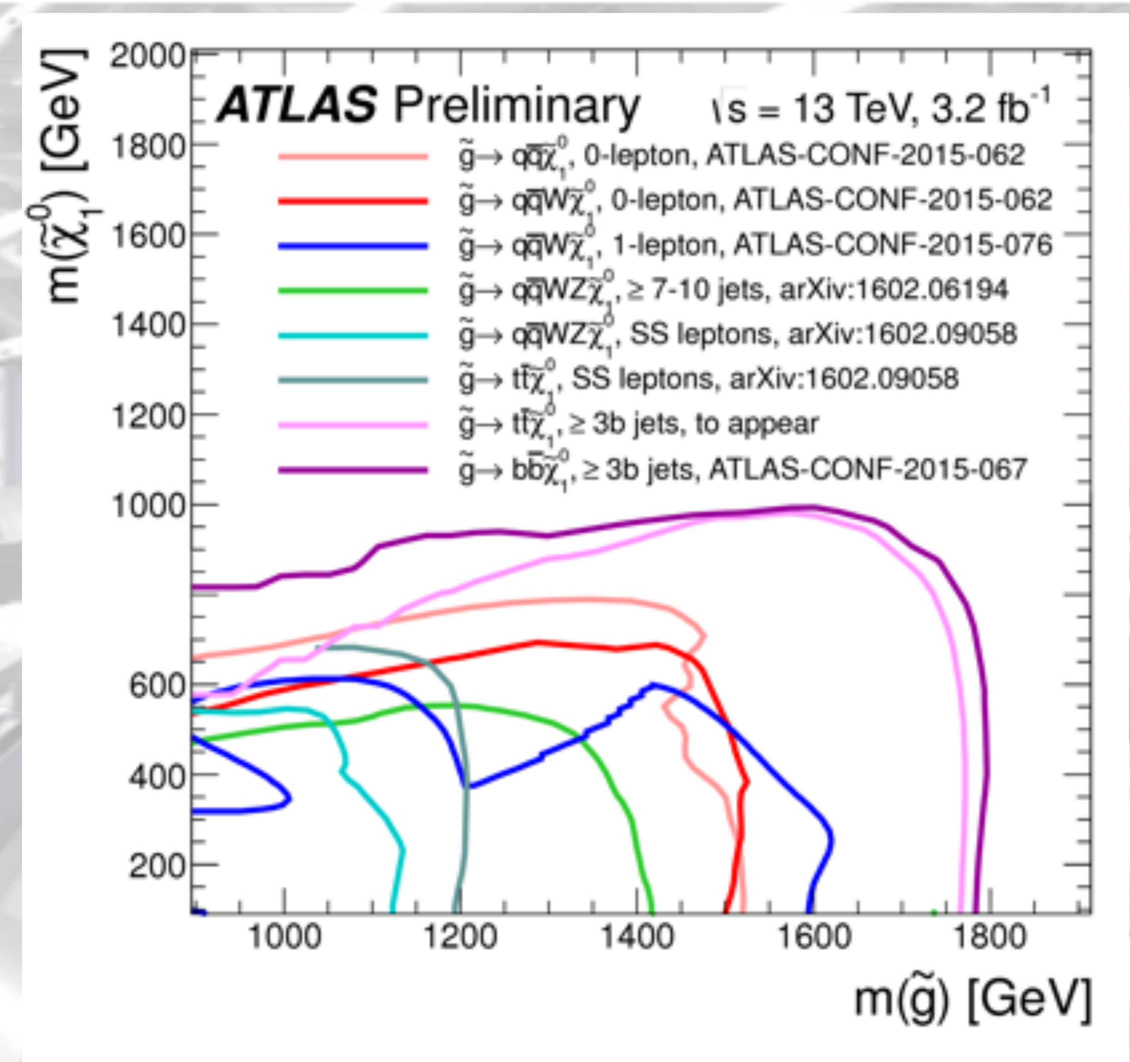


Very large mass limit reached, thanks to the large production cross section

… so we looked for it in Run II



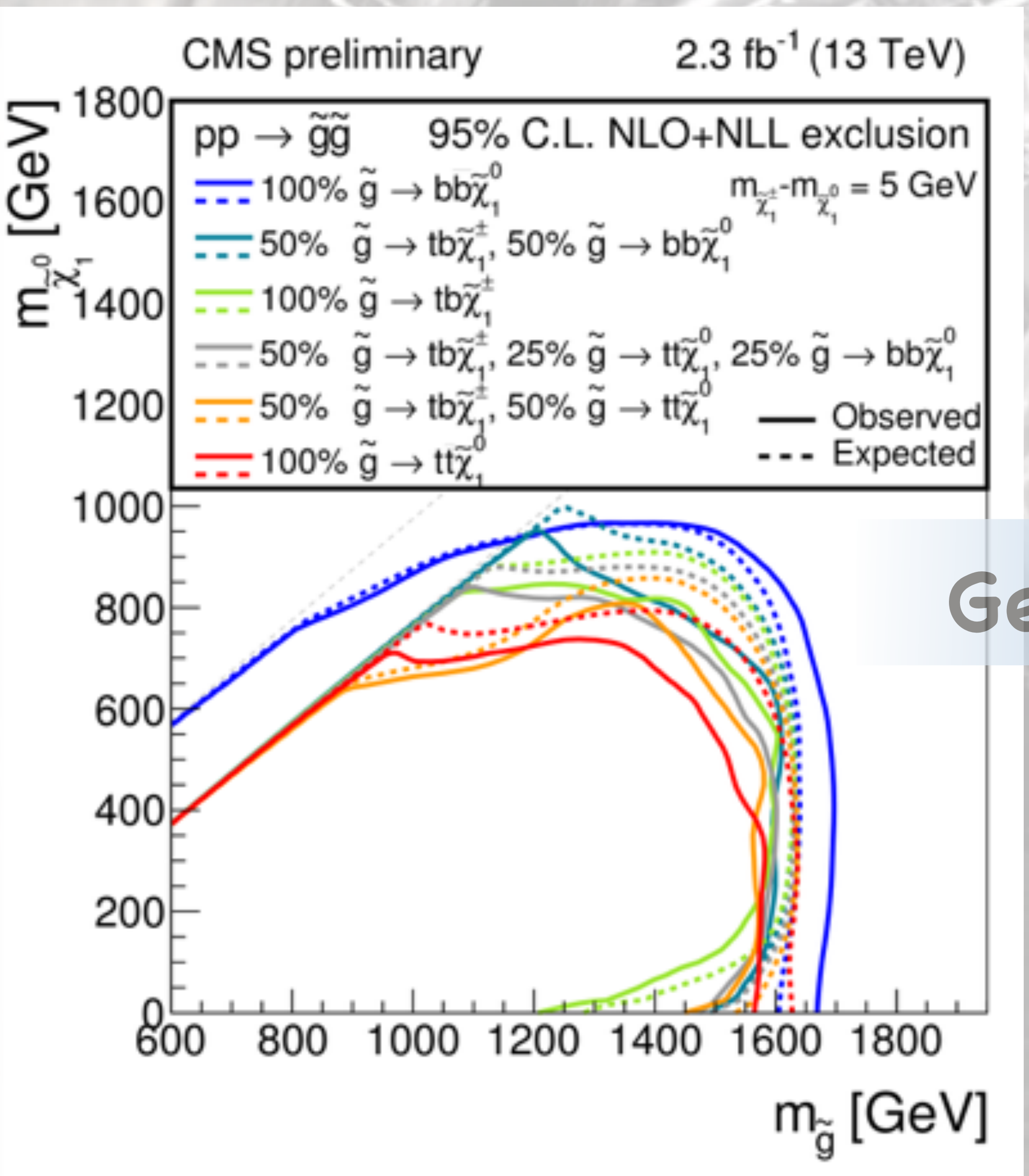


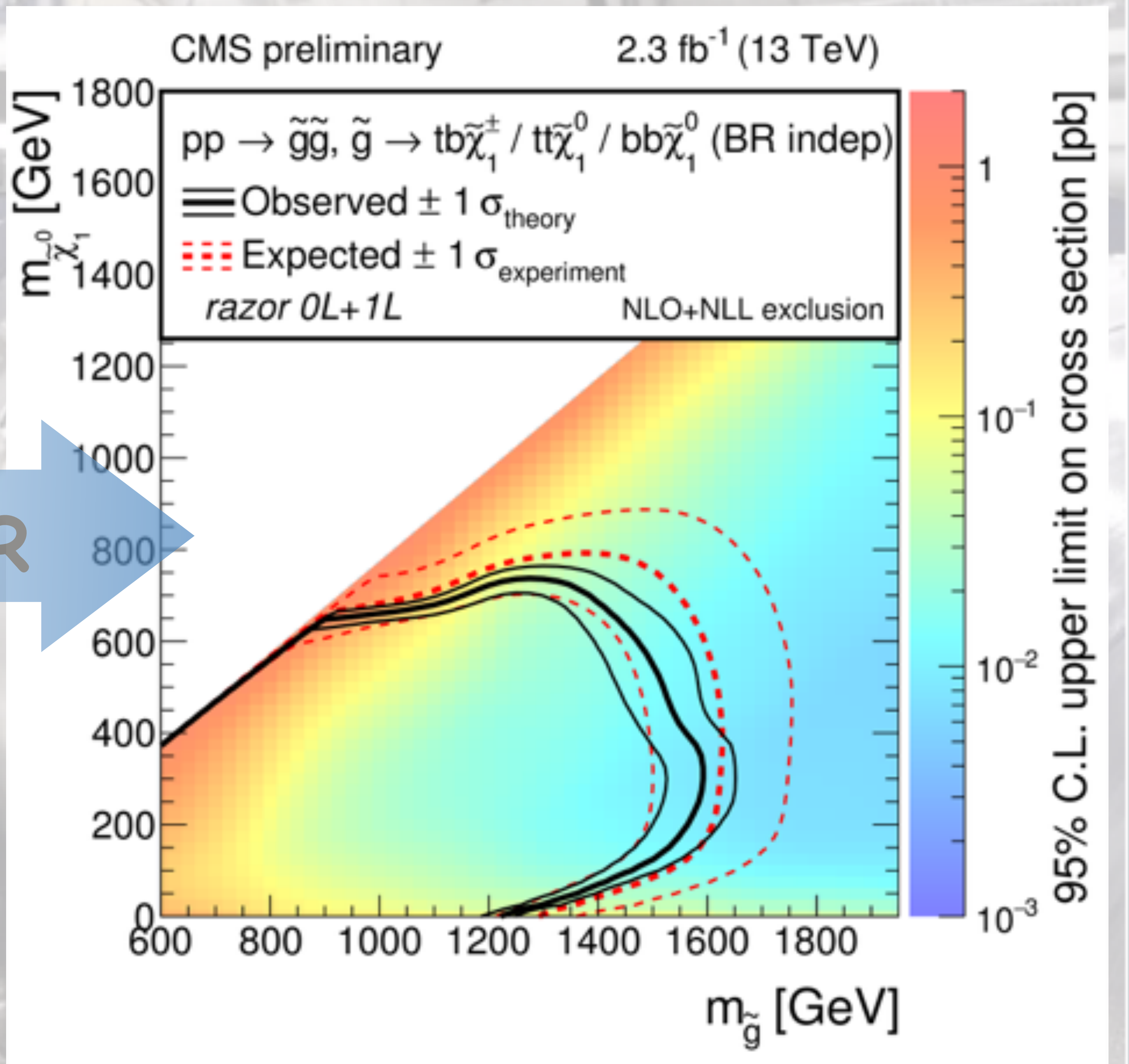


Maximal (among SUSY particles) benefit from energy increase, since large cross section allows to probe quickly the large-mass region

Is natural SUSY in danger?

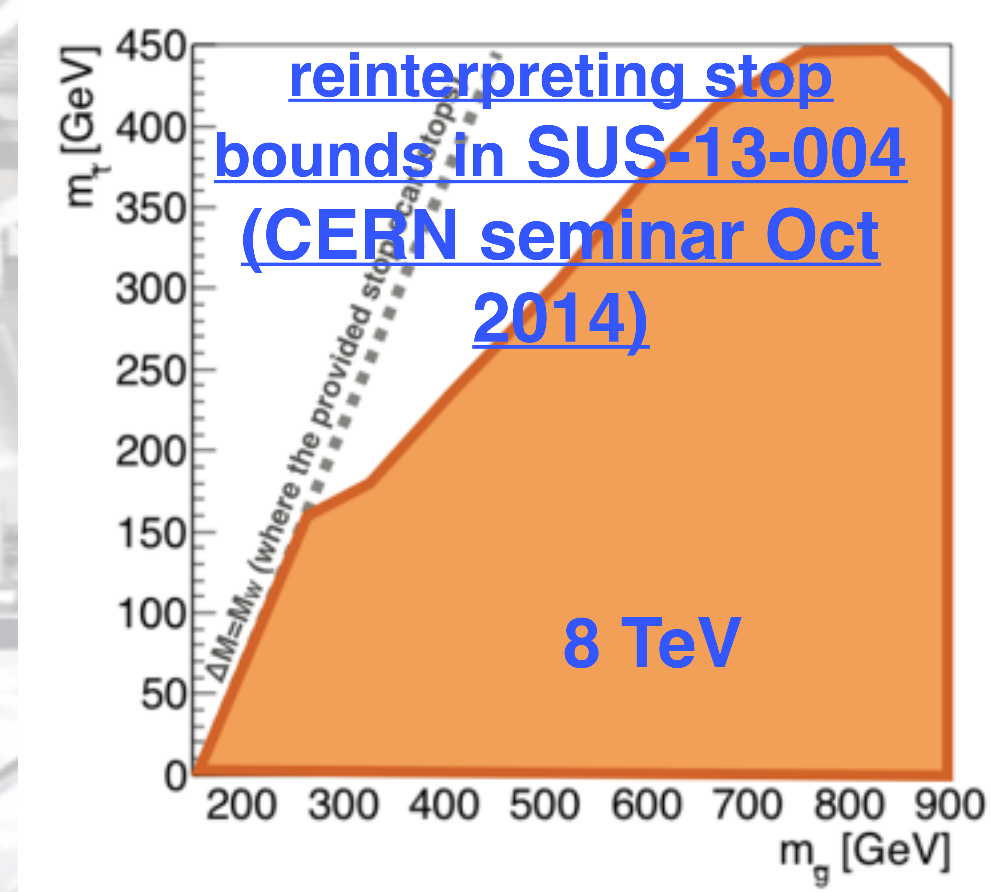
- How do we go around the limitations of Simplified models?
  - combining analyses or designing an inclusive search
  - deriving results for generic Branching Ratios

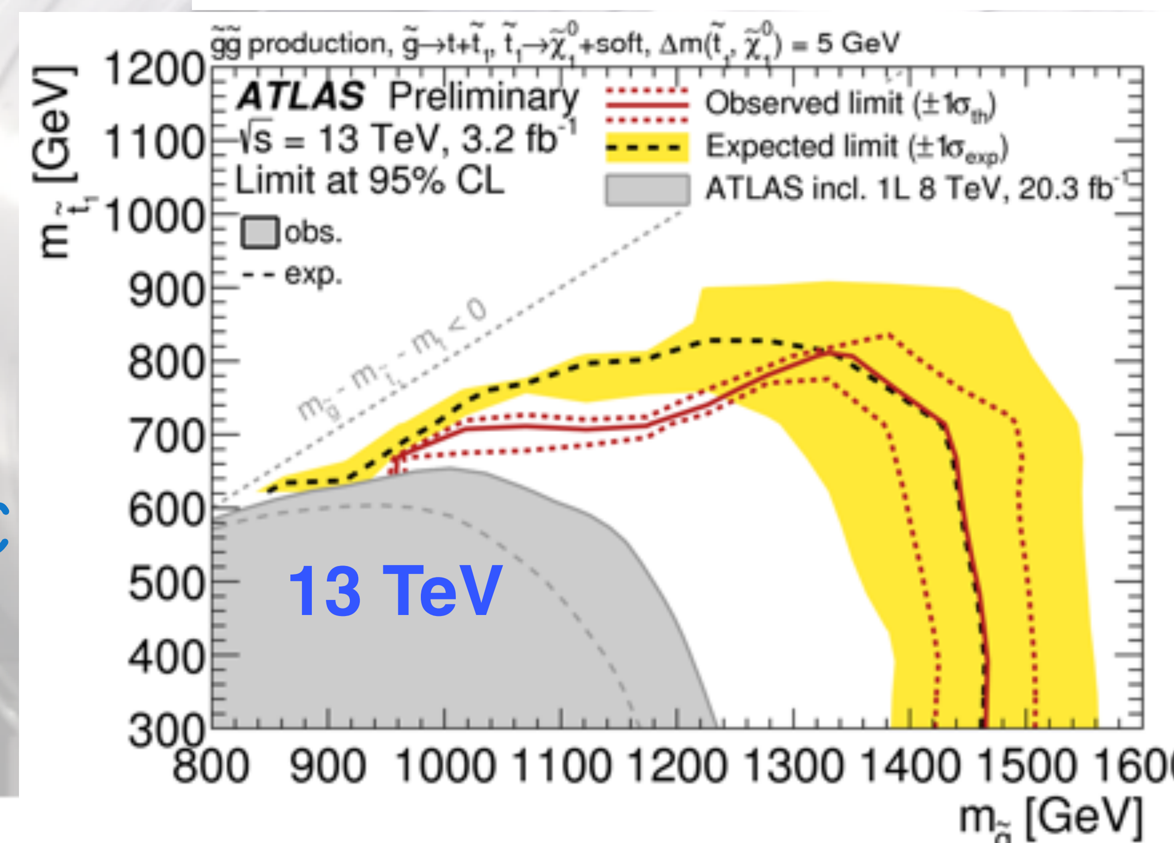




Are the tricky spots so tricky?

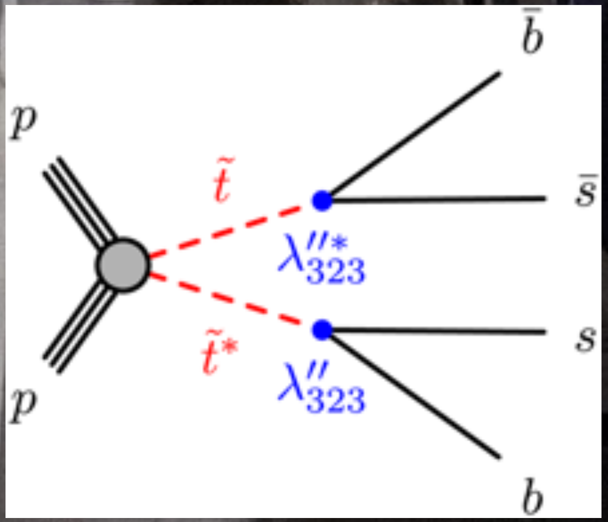
- If stop produced from gluino decay, it comes with a top
- For compressed spectra, difficult to see particles from stop decays
- Production from gluino cascade gives tt +soft particles + MET (similar to stop searches)
- One can recast stop searches with x10 larger cross section
- Gluino production @LHC is unique opportunity: if kinematically accessible, SUSY is (typically) observable at the LHC through gluino decay, regardless of the final state

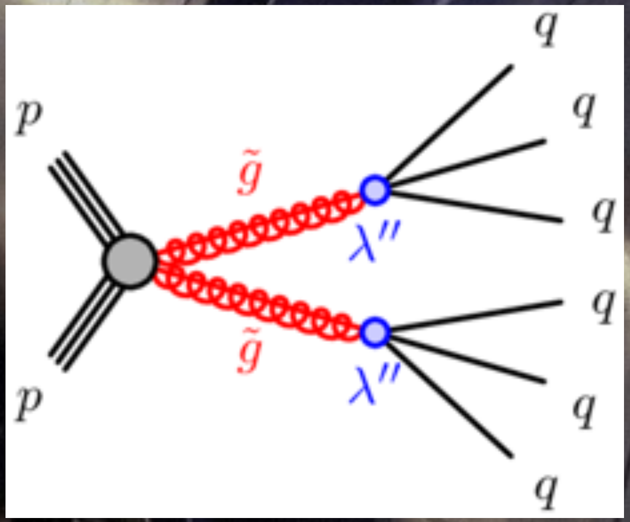




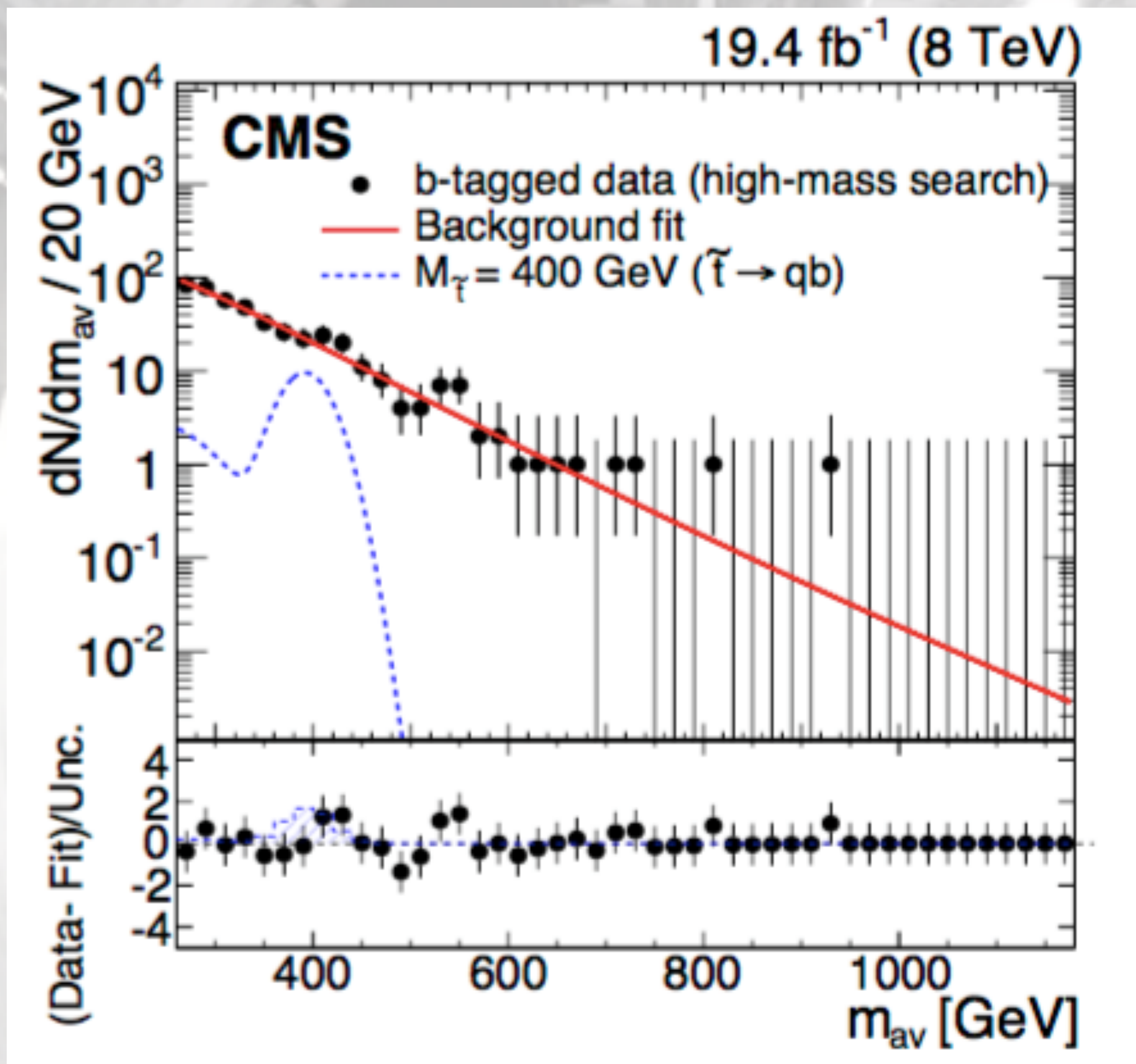
ATLAS-CONF-2016-007

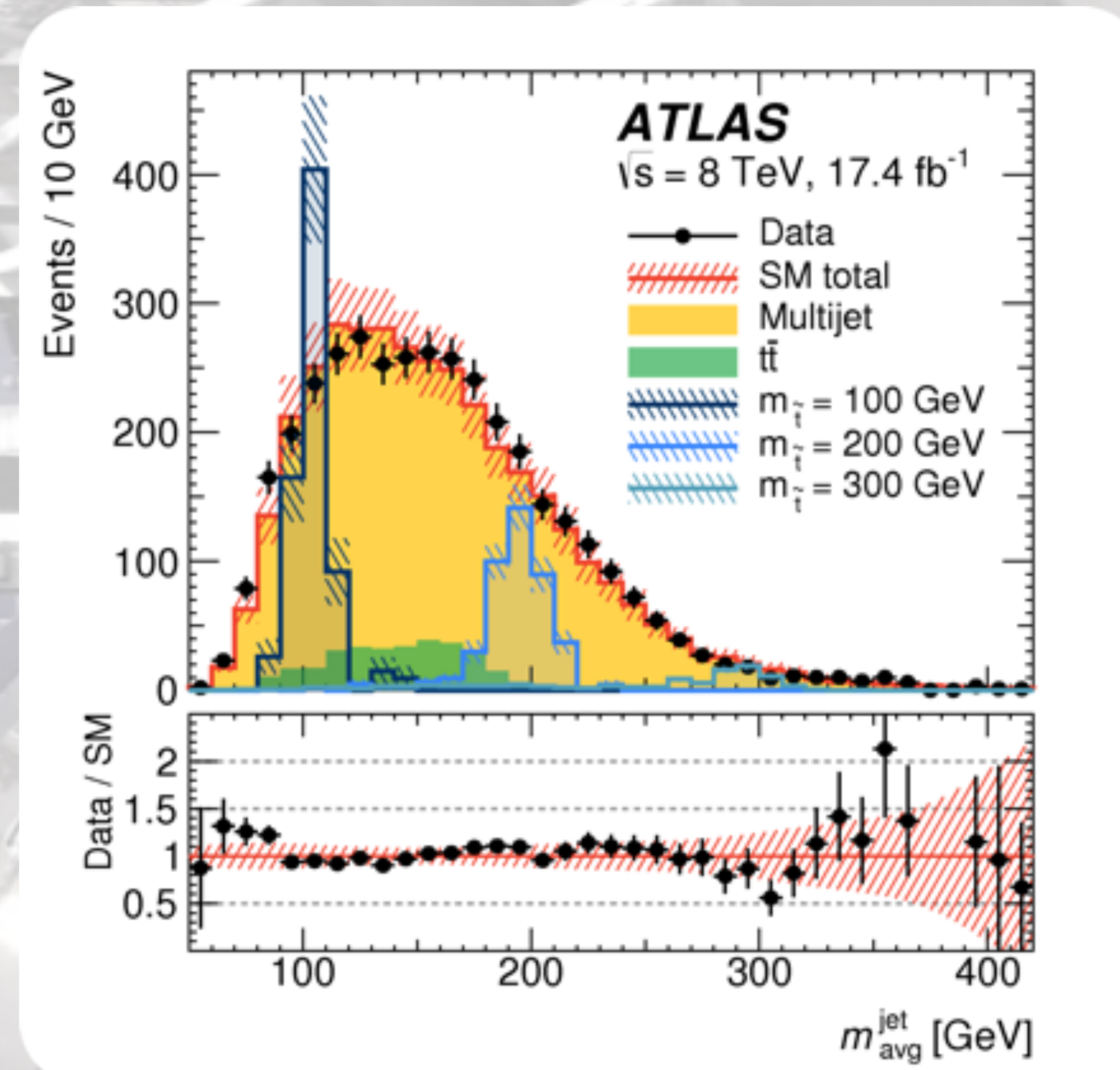
What if SUSY has nothing to do with Dark Matter? RPV Stop decays





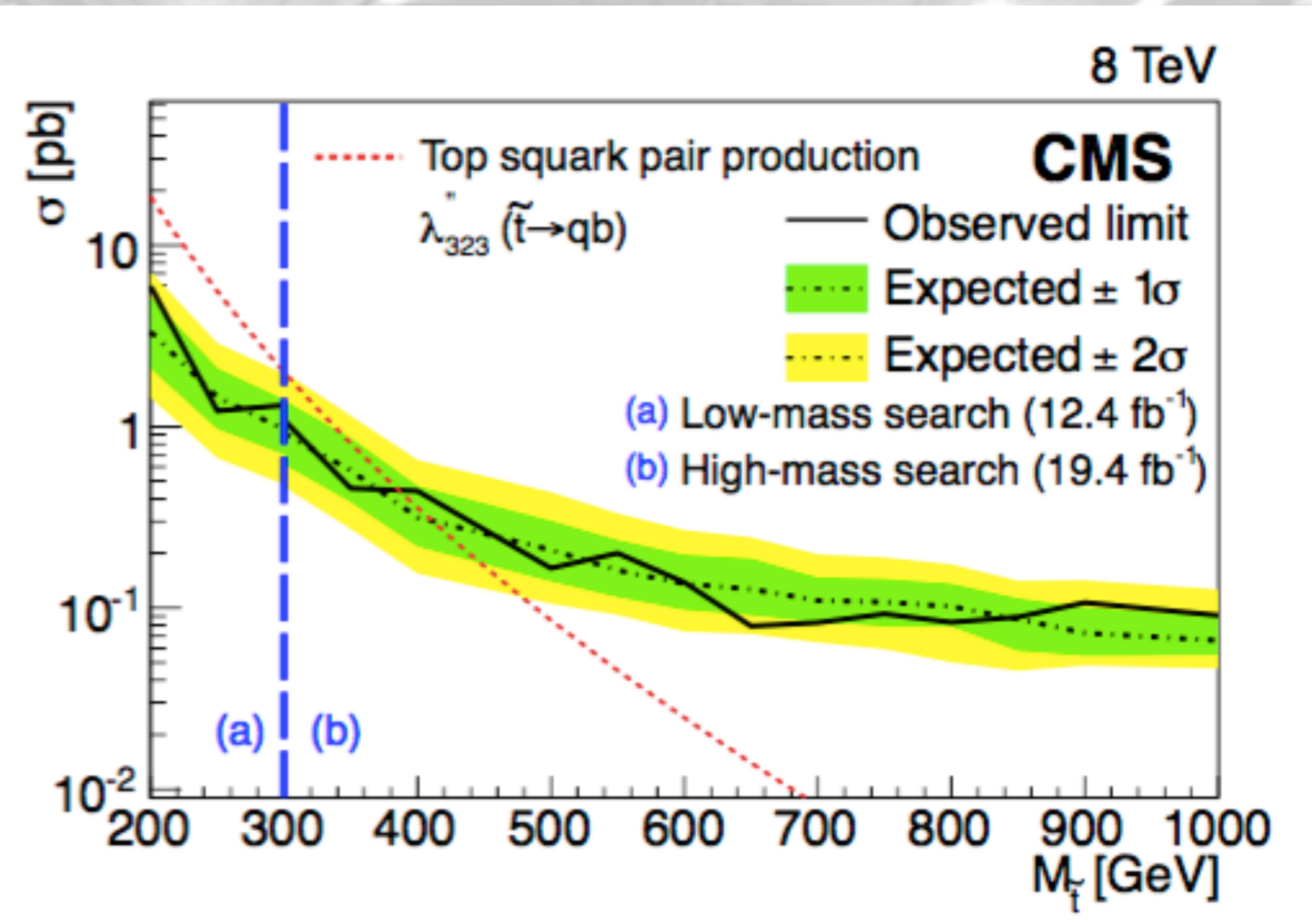
RPV Stop decays: di-dijet

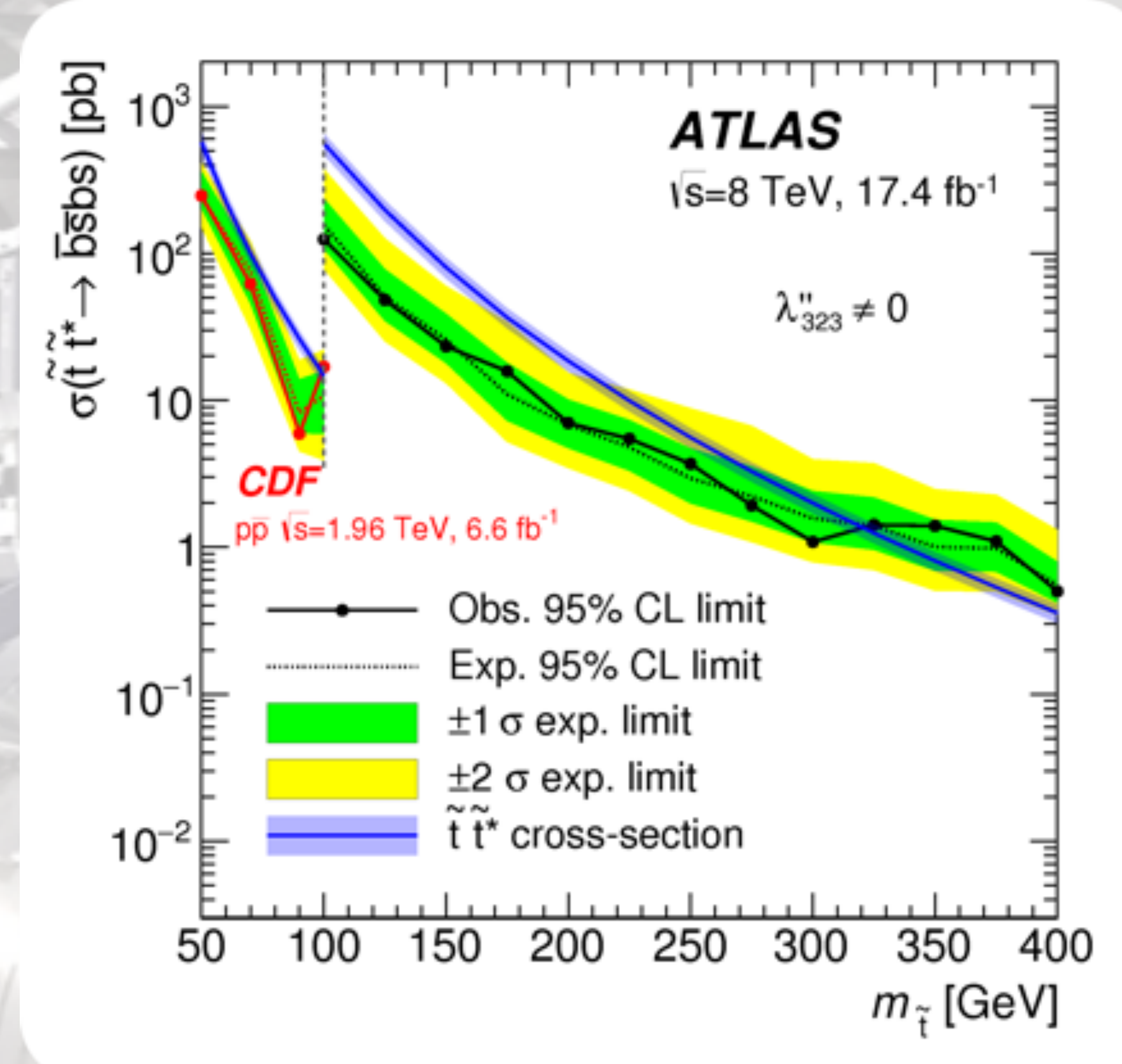




- Search for two jet pairs (with and w/o b-tag) with similar mass
- Analysis similar to dijet resonance search, with less background
- Explored the "natural" range of stop masses above m_t
- For smaller mass values, main limitation from trigger

RPV Stop decays: di-dijet





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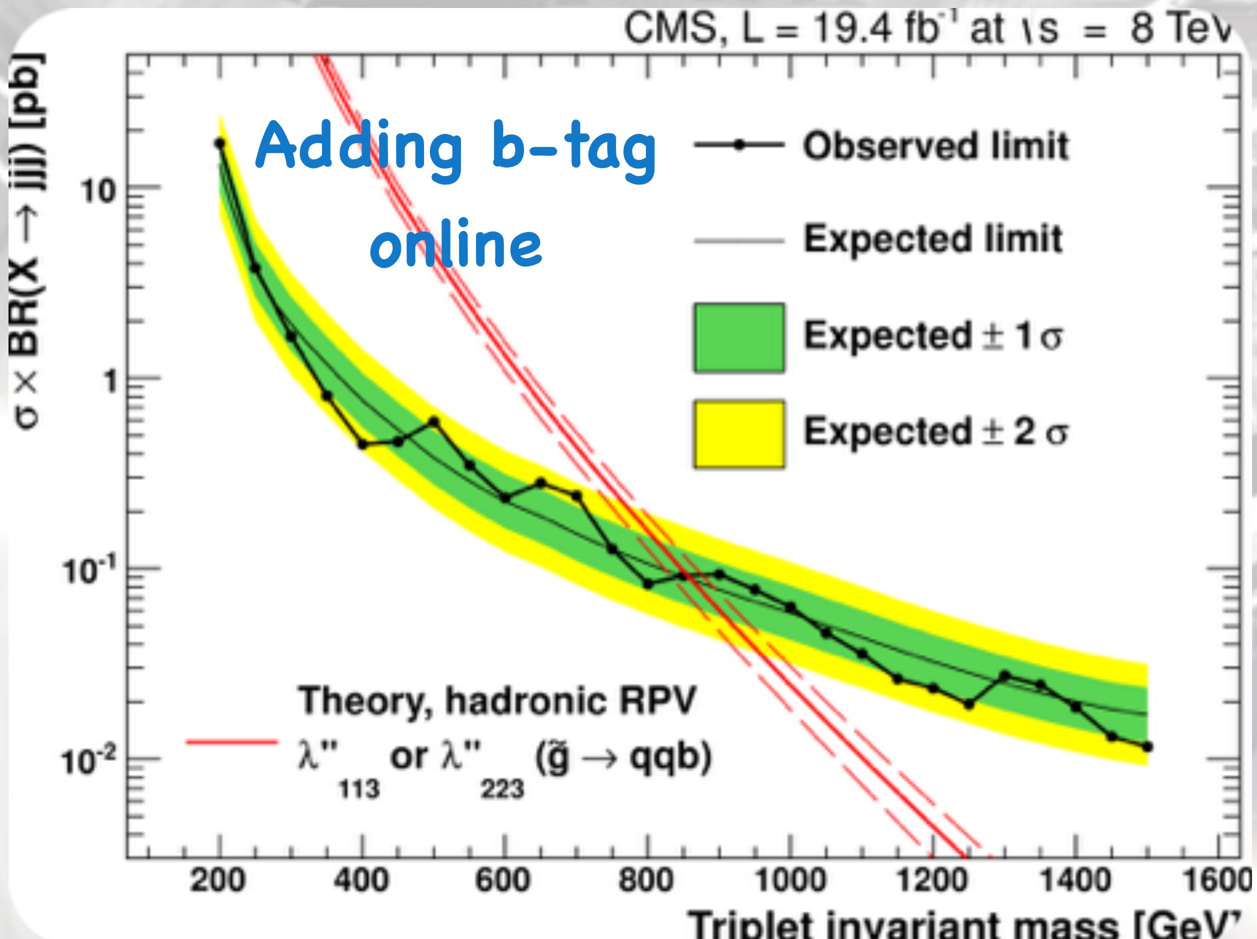
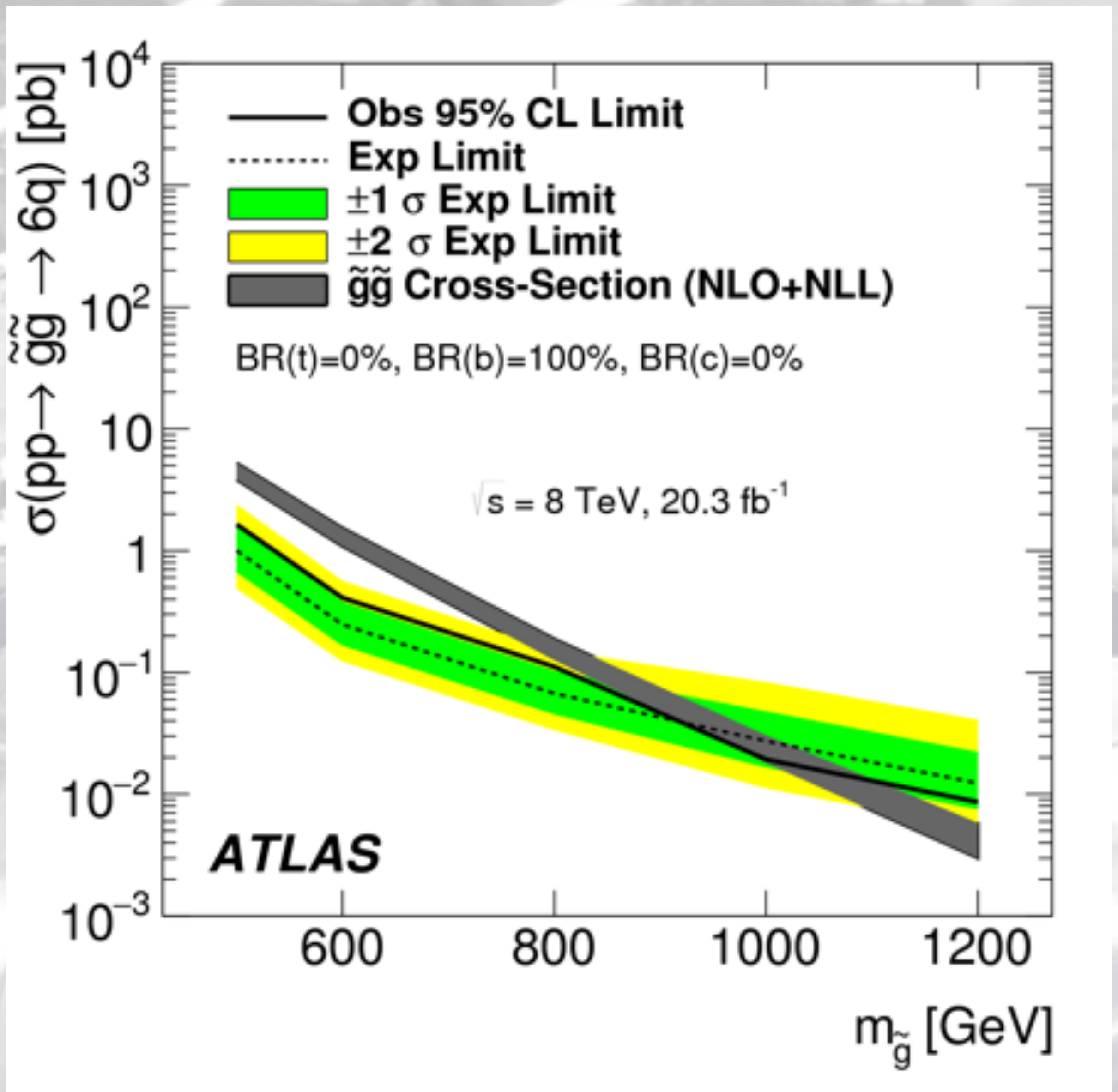
RPV gluino decays: di-trijet

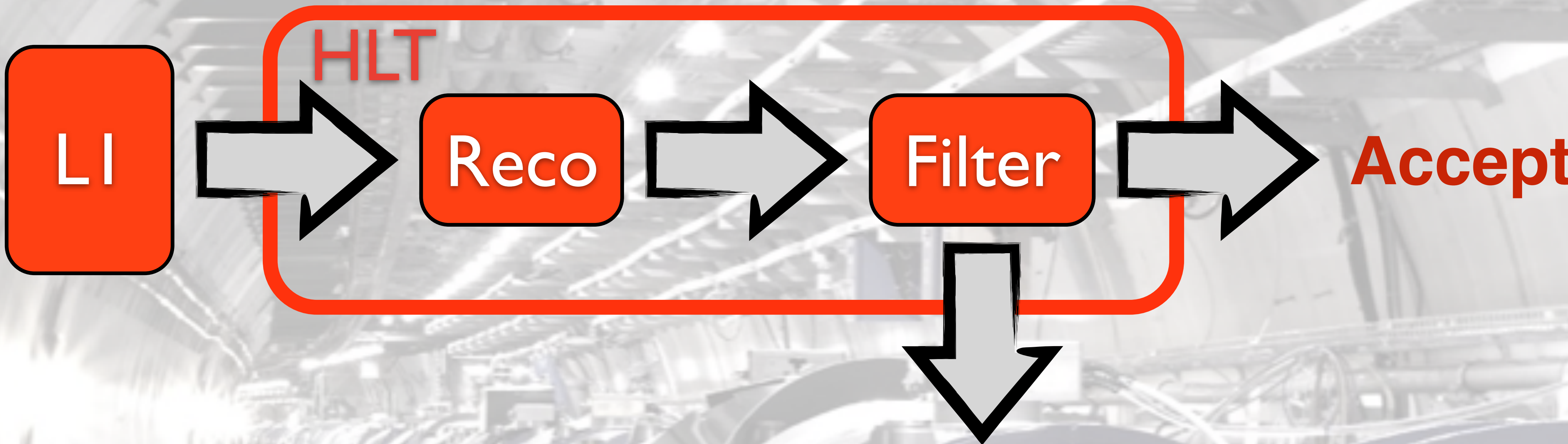




- More jets in the final state: easier signature
- Larger production xsec
- More combinatoric (problematic to associate jets to two triplets)
  - jet substructure techniques will play a major role here

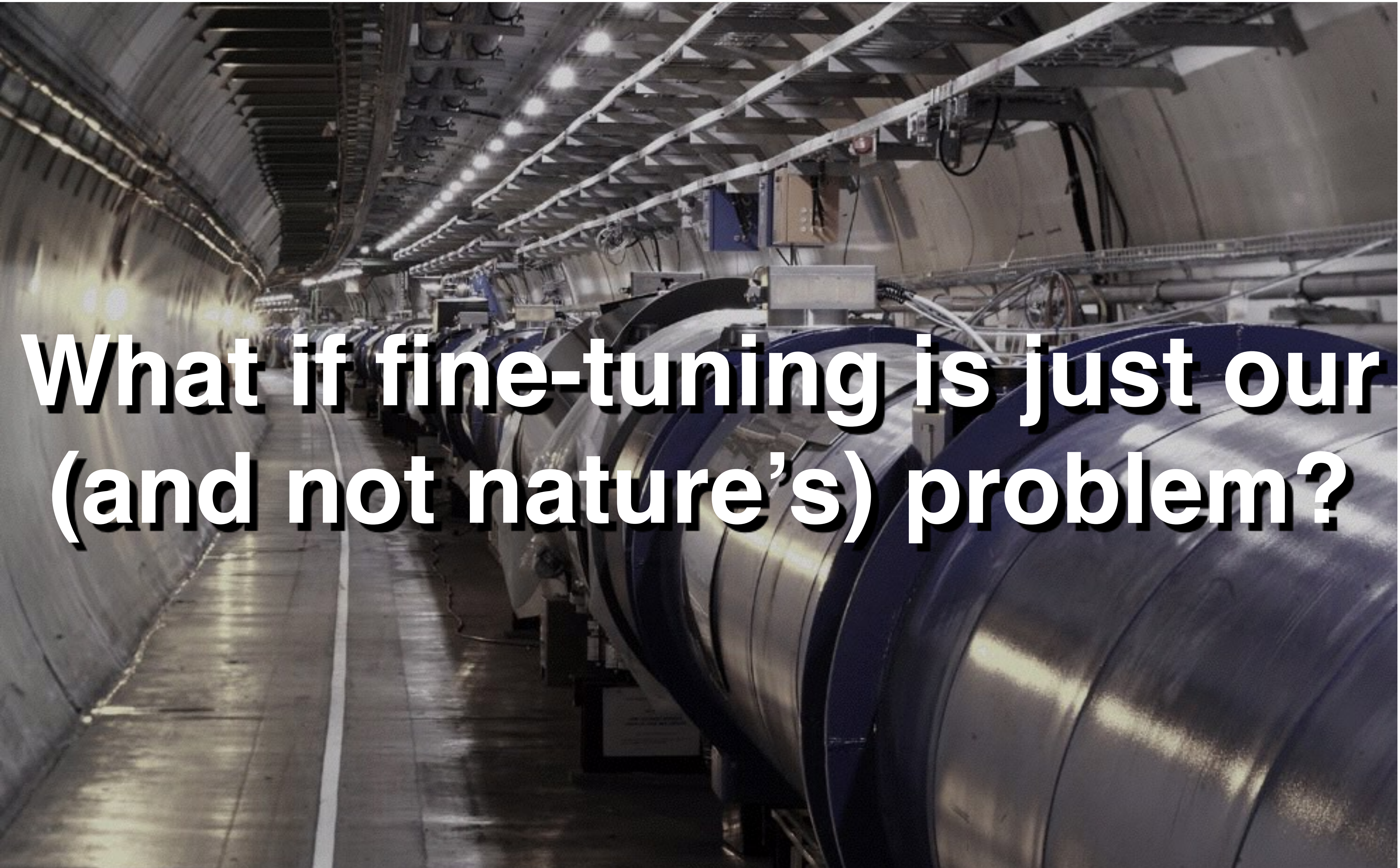
CMS-EXO-12-049 ATLAS-SUSY-2013-07

Staying sensitive to low masses: data scouting



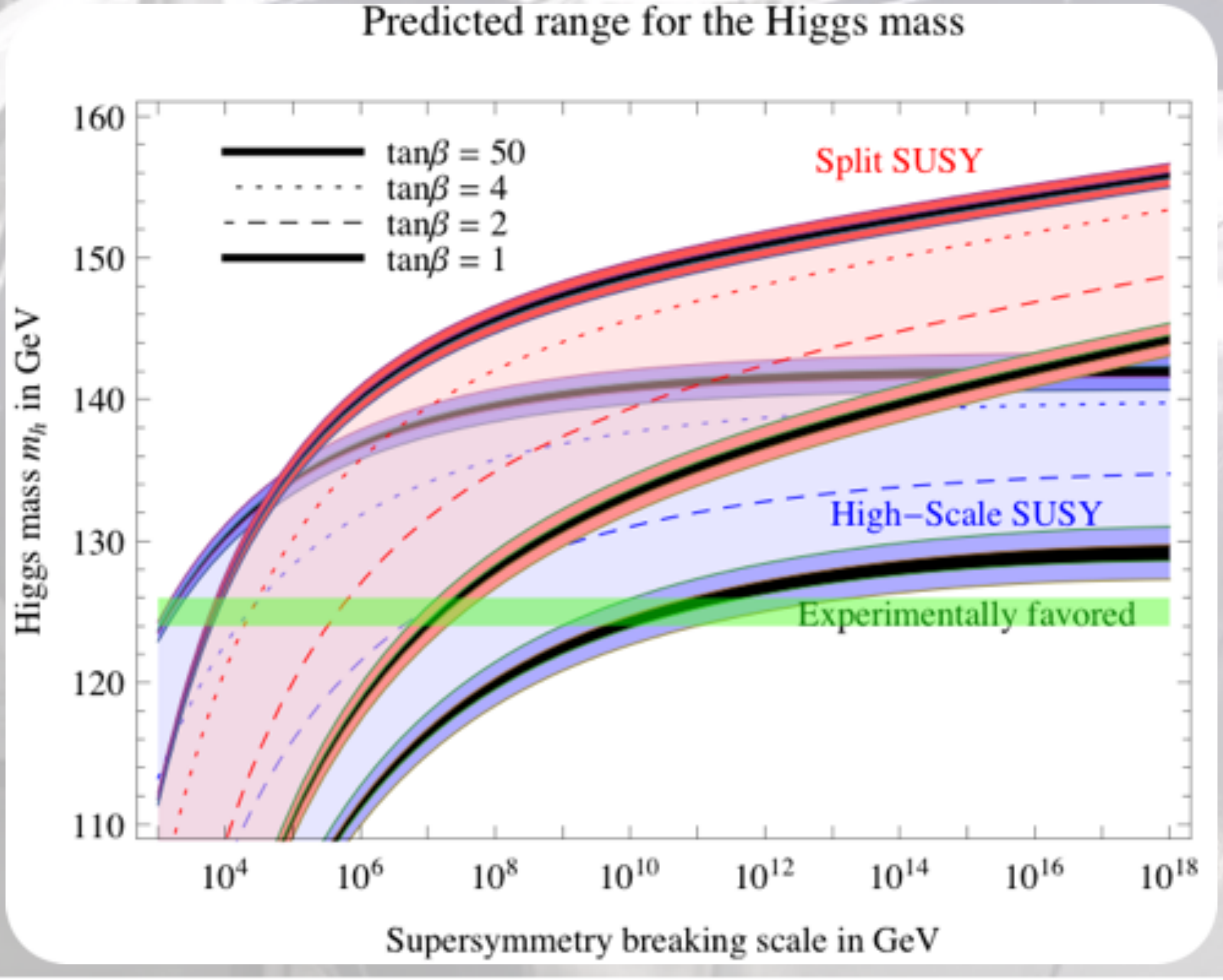
scouting: save 4momenta of jets@HLT

- Instead of dropping events, save limited information (jet 4-mom)
  - ~5 kB/evt rather than ~500 kB/evt [these are CMS numbers]
  - @ 1 kHz, take same disk/evt than ordinary 10 Hz [these are CMS numbers]
- PRO: can go beyond the trigger/processing limitations
- CON: limited info in case debug is needed (e.g., no event display)

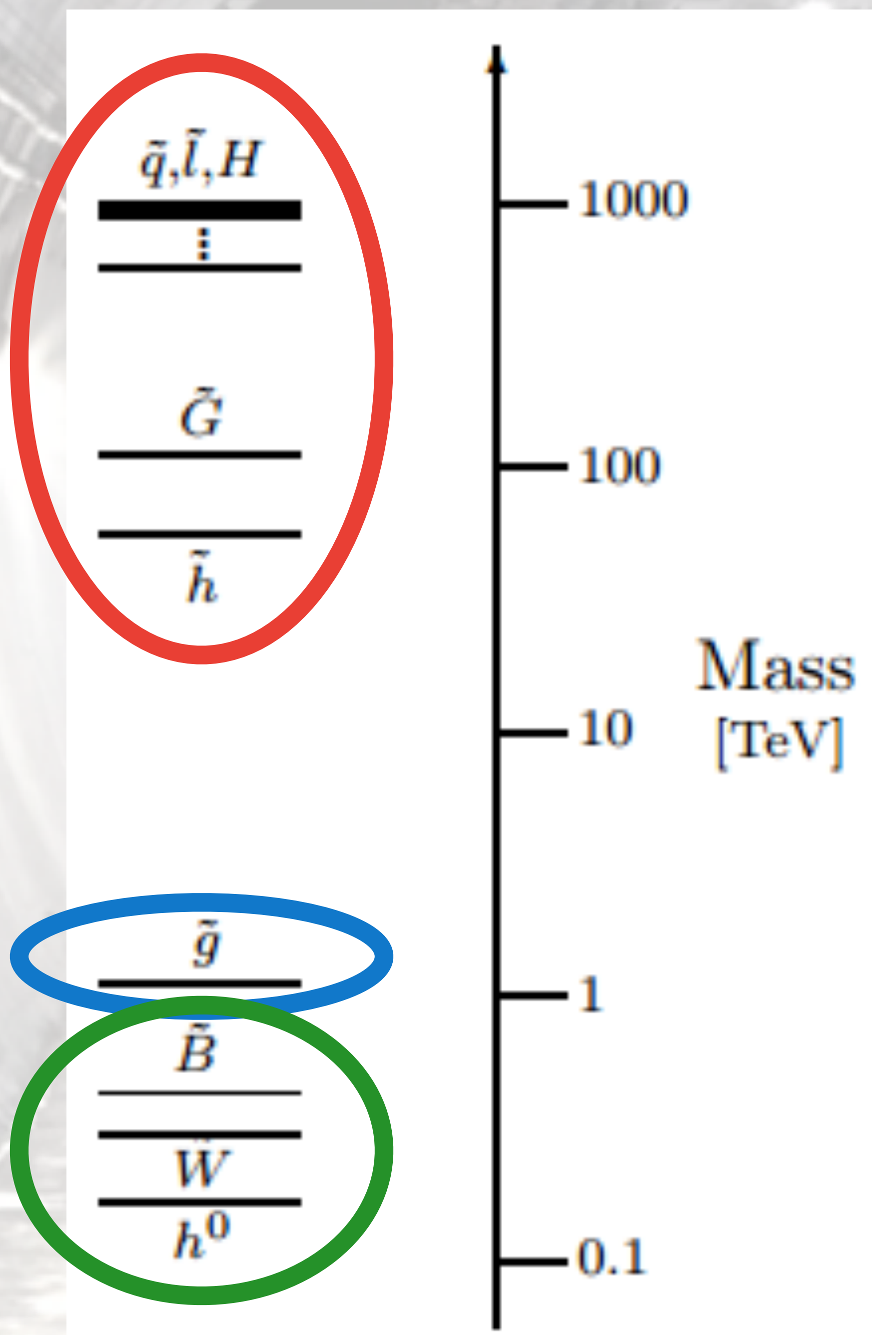

What if fine-tuning is just our
(and not nature's) problem?

Split SUSY in the time of Higgs discovery

- Split SUSY in a nutshell:
  - All scalars decoupled
  - Gauginos light (good enough for unification)
  - SUSY to explain DM -> Stable LSP
  - Naturalness is not a real issue in nature (cosmology, etc)
- The discovery of the Higgs boson puts a bound on the scale of SUSY scalars
- Low enough to probe it with future colliders?
- Meanwhile, we can search for gauginos @LHC



A Typical Split-SUSY spectrum

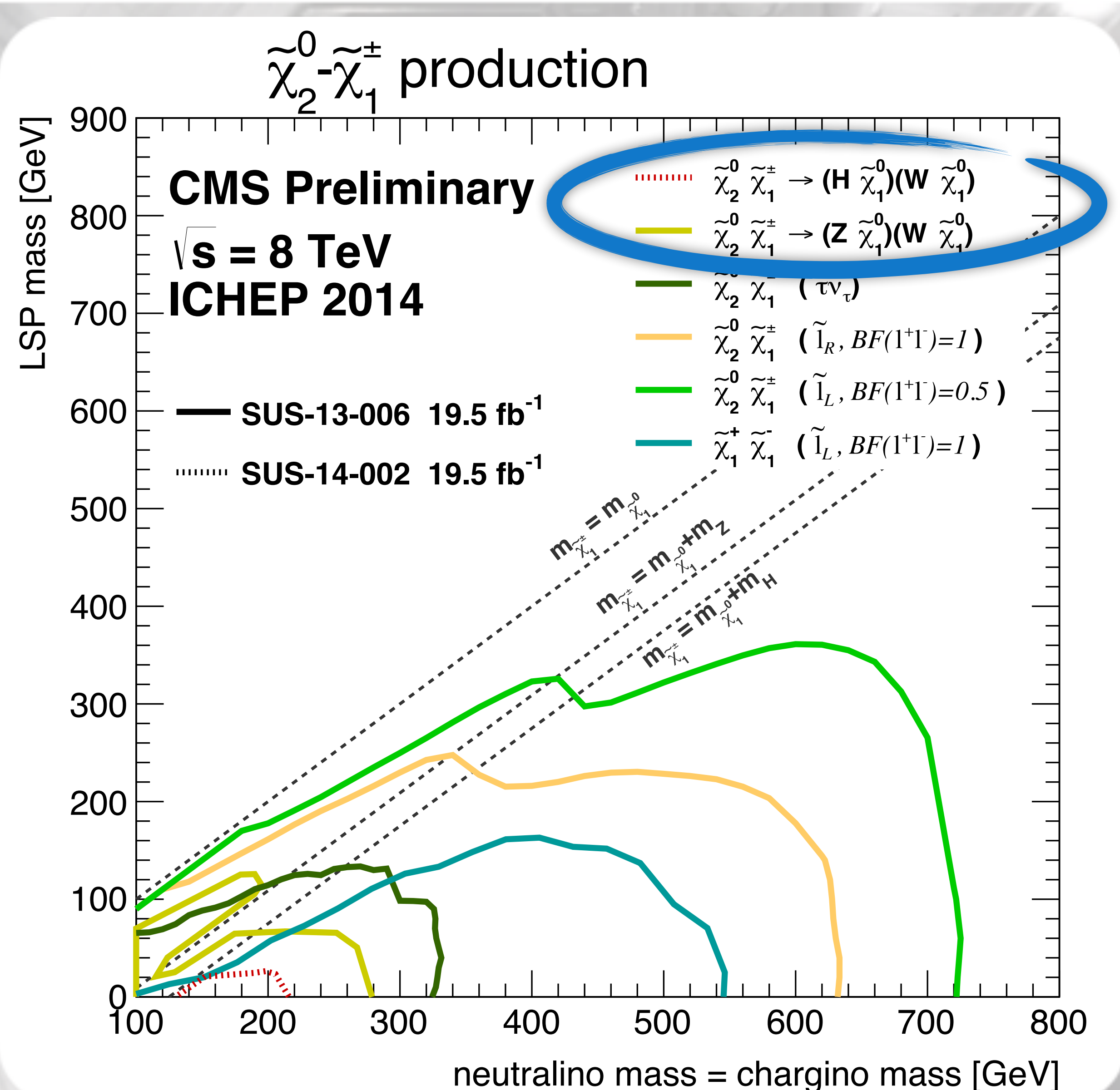


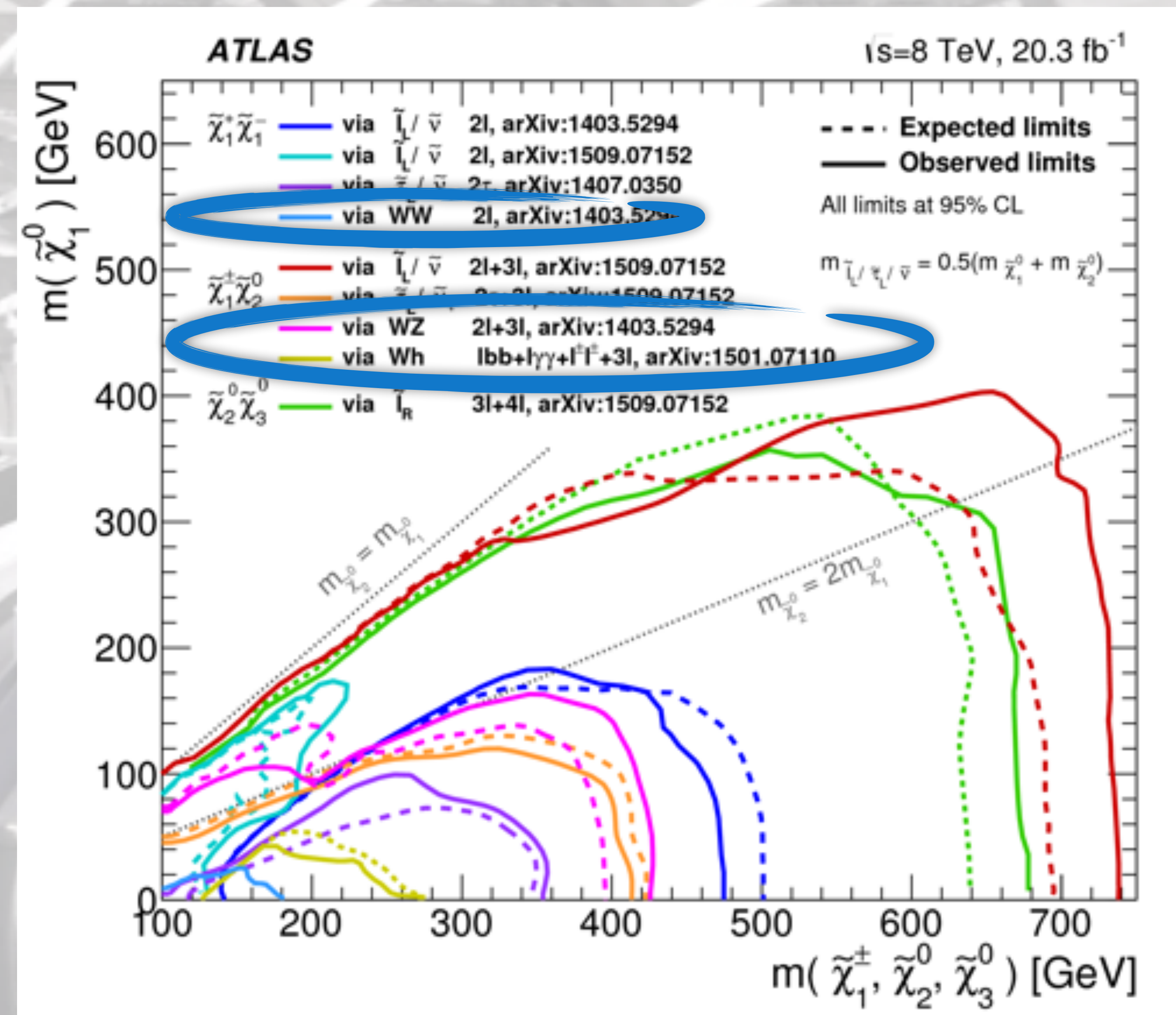
These are beyond reach @LHC (and a 100 TeV collider?

These are the "usual" EWkino searches. We know what to do with those, and we know that it's complicated

This is special: a long living gluino

Search for EWkinos



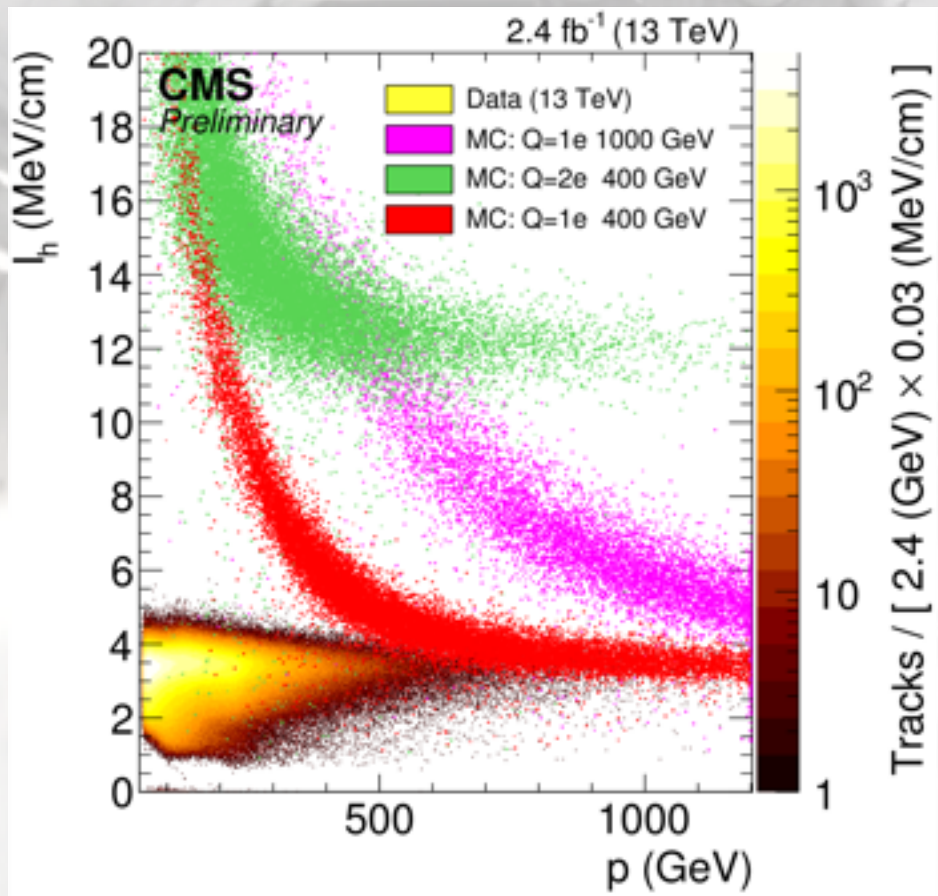


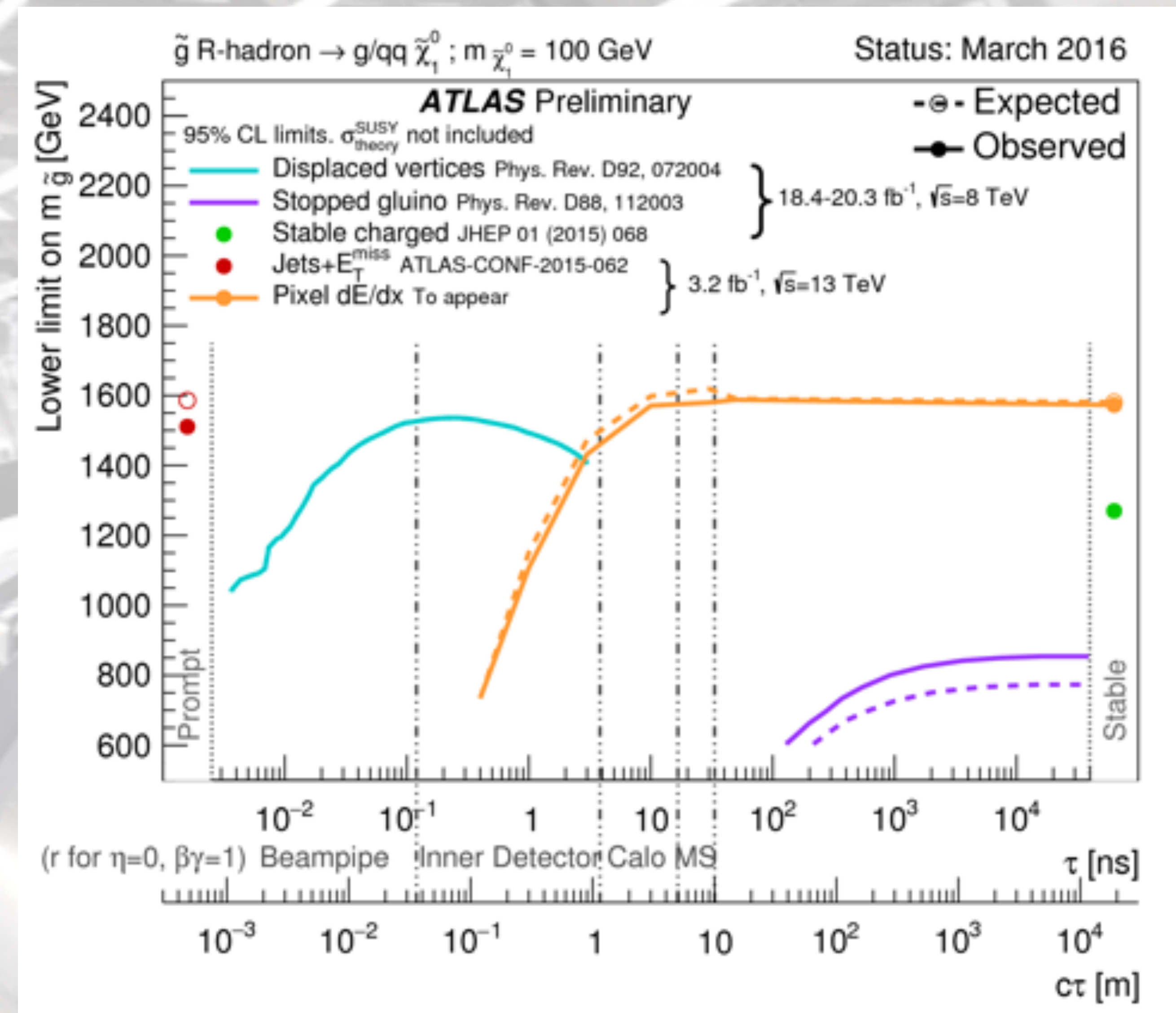
- Strong bounds are derived if one postulates the existence of light sleptons (decay through sleptons make lepton spectra different than for bkg)
- In the minimal scenario, signal quite similar to diboson production → weaker limits
- Run II will be crucial to extend these searches

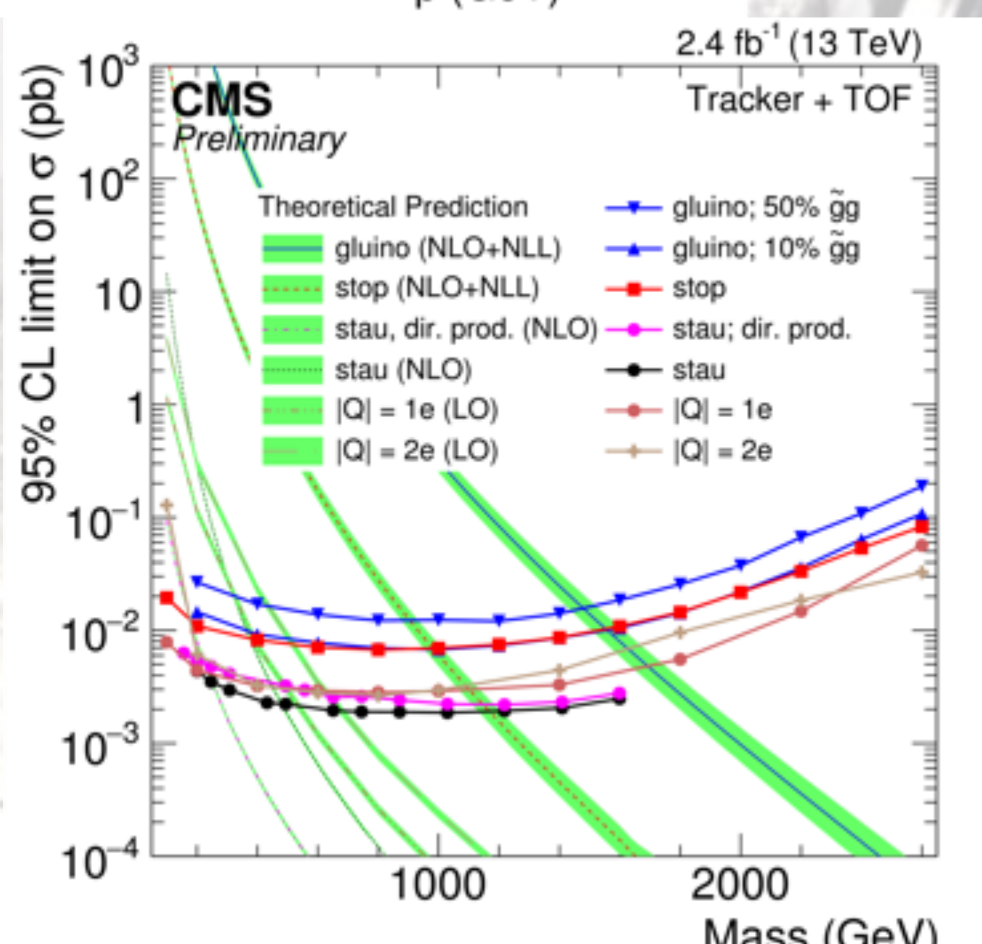
Exotic gluino signatures

- In this scenario, gluinos are long living, resulting in exotic experimental signatures
    - gluinos stopping in the detector and decaying when there are no beams
    - R-hadrons traveling in the detector as heavy stable charged particles
    - gluino/gluon balls + decays to displaced jets
- These signatures extensively studied during Run I
- More effort (and more data) needed in Run II

Exotic gluino signatures







Conclusions

- Our vision of what light SUSY looks like evolved with year
  - we buried the super-natural SUSY we looked for @LEP time
  - we now focus on a minimal SUSY spectrum
- LHC data are challenging this scenarios, but bounds on plots look stronger than what they are (mind the assumptions)
- Still room for SUSY to hide, but no place look prohibitive with enough data
- Run II will be the crucial time to answer many questions about SUSY vs naturalness, hopefully with some surprise


Backup Slides