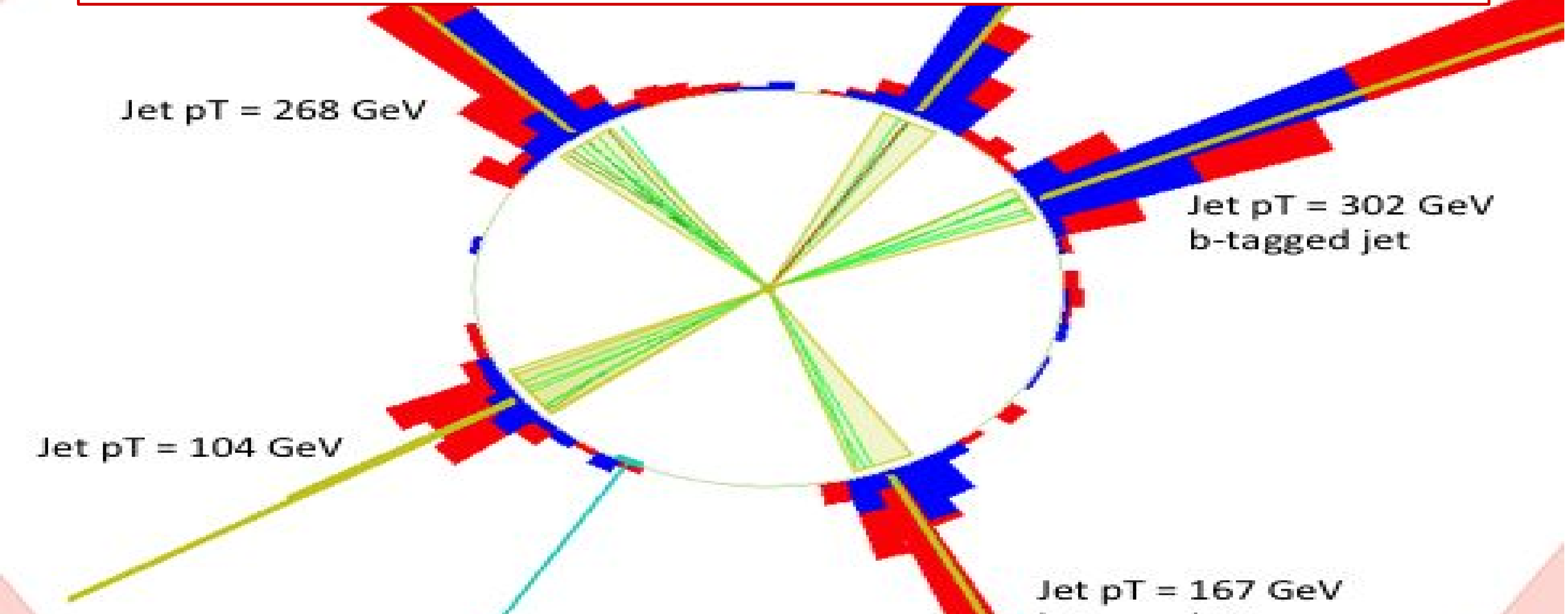
Searches for R-parity conserving SUSY signatures at CMS



Alessandro Gaz,
KMI, Nagoya University

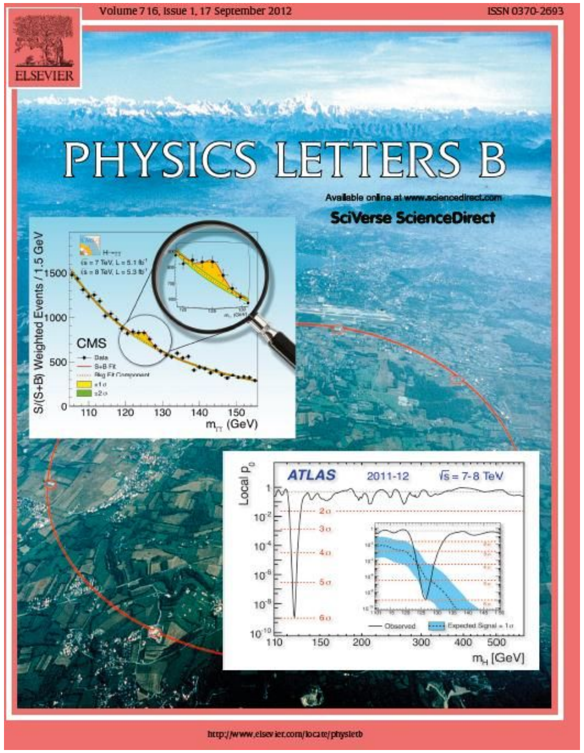
KMI Topics, April 13th 2016

Foreword

- I have been a member of the CMS Collaboration in the period 2009-2014;
- Therefore I have direct experience only of the Run1 data, for Run2, I only participated in the analysis preparation and sensitivity studies.

The Higgs boson exists!

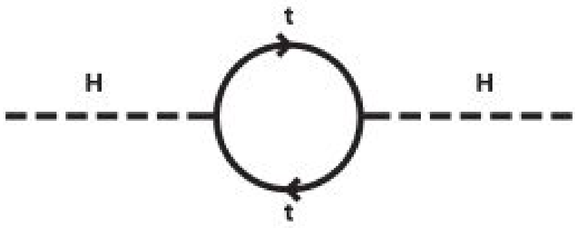
- After decades of searches, finally the Higgs boson is in the bag (and its mass is ~125 GeV);
- It was the last missing piece of the Standard Model, but still many questions to answer:
  - ➔ What is the Dark Matter in the Universe?
  - ➔ What is the origin of the matter/antimatter asymmetry?
  - ➔ Neutrinos seem to be special…
  - ➔ What's the connection between the Cosmic Inflation and Particle Physics?
  - ➔ …



- But also explaining why the Higgs is where we found it is not so trivial...

The Hierarchy problem

- Compared to the other SM particles, the Higgs is "special";
- We know that New Particles must exist, possibly at energy scales of $10^{15} - 10^{19}$ GeV;



- The Higgs couples (possibly indirectly, through loops) with those particles, and its mass receives corrections from the interaction with those particles;

- Unlike the other SM particles, the Higgs is not protected by any symmetry…;
- … thus we would expect its mass to be at the same scale of that of the New Physics particles.

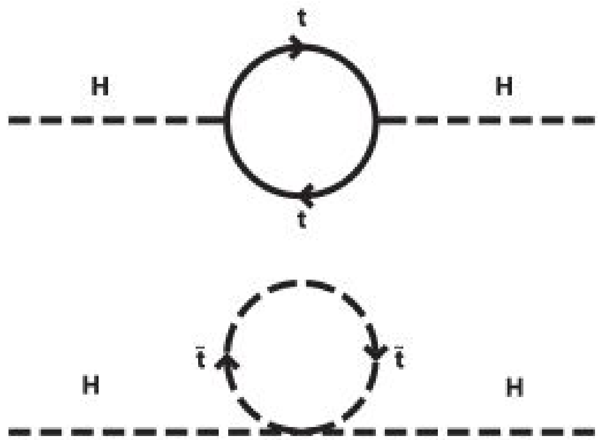
Possible ways out

How can we explain the fact that the Higgs mass is O(100) GeV?

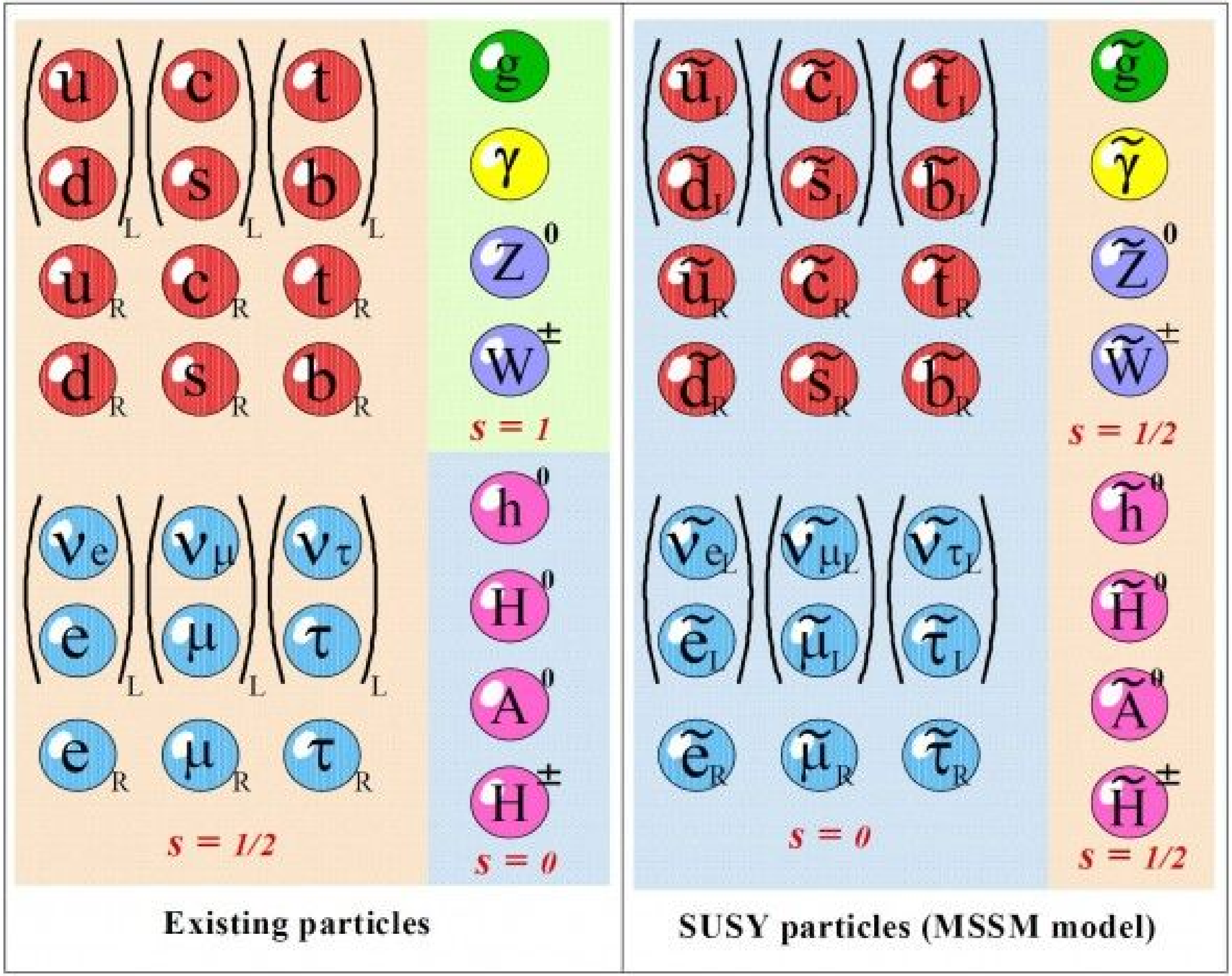
1) There is an extraordinary cancellation among all the corrections to the Higgs mass. "Fine tuning": required precision better than $\sim 1/10^{26}$.

2) There is a mechanism at work so that the sum of all the corrections is reduced to a small value.

Basic idea of Supersymmetry: for each SM particle, associate another particle, with spin differing by ½ a unit. This would give a contribution with opposite sign, and the closer the masses of the two partners, the better the cancellation mechanism.



SUSY



s = 1
s = 0
s = 1/2
Existing particles
s = 1/2
s = 0
s = 1/2
SUSY particles (MSSM model)

Natural SUSY

- SUSY works well as long as the masses of the s-particles are not much higher than those of the SM particles;
- This is particularly important for the higgsino(s), stop(s), and gluino:

$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m^2_{\underline{gluino}} \left(\log \frac{\Lambda}{m_{gluino}}\right)^2 \qquad \text{two-loops}$$

$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m^2_{\underline{stop}} \log \frac{\Lambda}{m_{stop}} \qquad \text{one-loop}$$

$$\delta m_H^2 \sim |\underline{\mu}|^2 \qquad \text{tree}$$

higgsino

- If the masses of these SUSY particles are way beyond the TeV scale, we still need a lot of fine tuning!

R-parity

- Another ingredient, the multiplicative quantum number:

$$P_R = (-1)^{3B+L+2s}$$

$$P_R(x) = +1$$

$$P_R(\tilde{x}) = -1$$

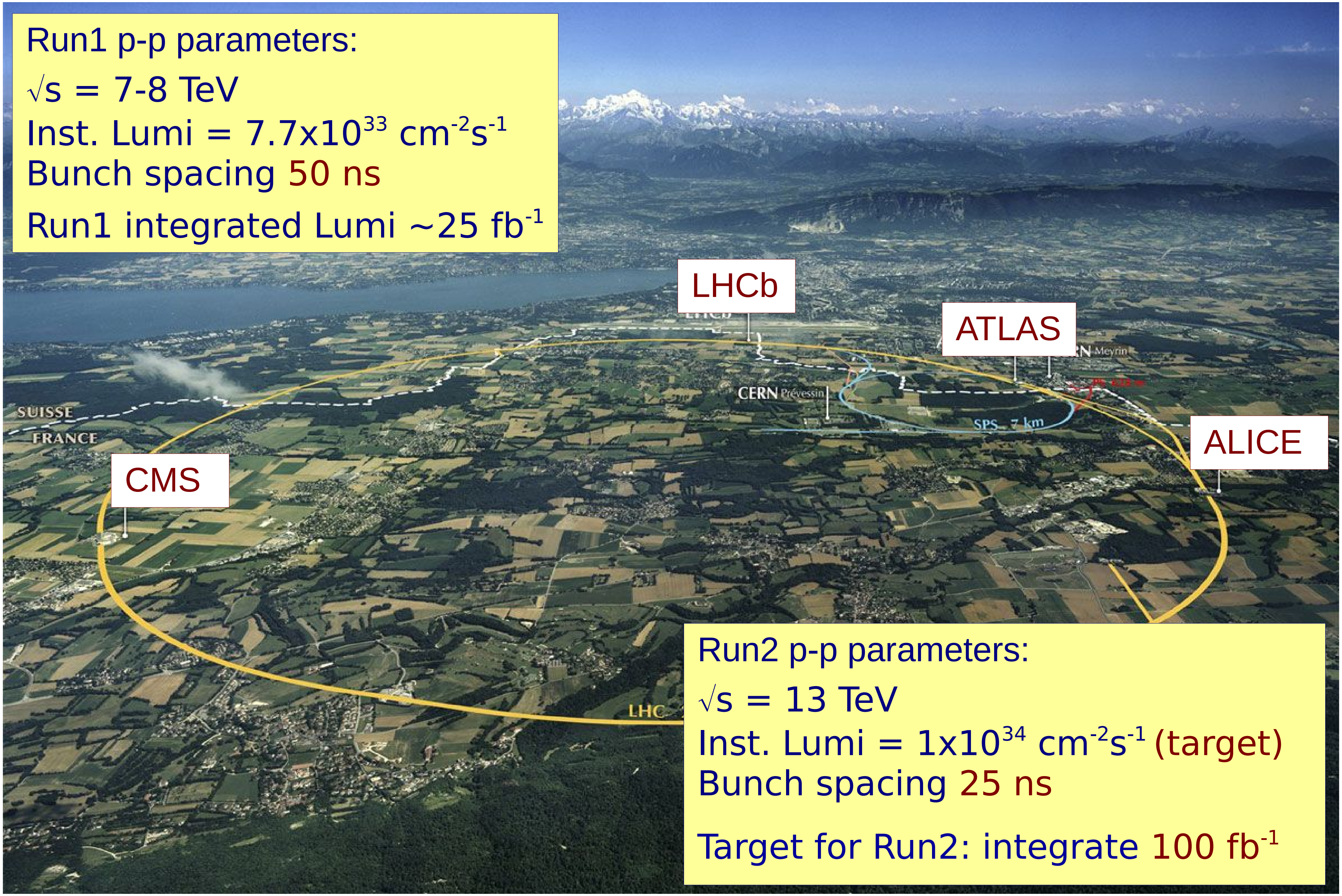
- In most popular SUSY realization this quantum number is conserved (it helps making the proton lifetime compatible with the current limits);
- This has two important consequences:
  1) by colliding SM particles, SUSY particles can only be produced in pairs;
  2) the lightest SUSY particle (LSP) is stable. In most scenarios the LSP is neutral and weakly interacting, so it effectively behaves like a neutrino.

     If its mass is in the 100 GeV – 1 TeV range it is also an interesting candidate for the Dark Matter.

Outline

- The Large Hadron Collider (LHC) and the Compact Muon Solenoid (CMS) experiment;
- Search strategies;
- Some example Run1 analyses:
  - ➔ gluino pair production;
  - ➔ direct stop pair production;
  - ➔ production of electroweakinos decaying to Higgs bosons;
- A look at Run2 data;
- Future prospects.

The LHC



Run1 p-p parameters:

$\sqrt{s}$ = 7-8 TeV

Inst. Lumi = $7.7\text{x}10^{33}$ $cm^{-2}s^{-1}$

Bunch spacing 50 ns

Run1 integrated Lumi ~25 fb^{-1}

Run2 p-p parameters:

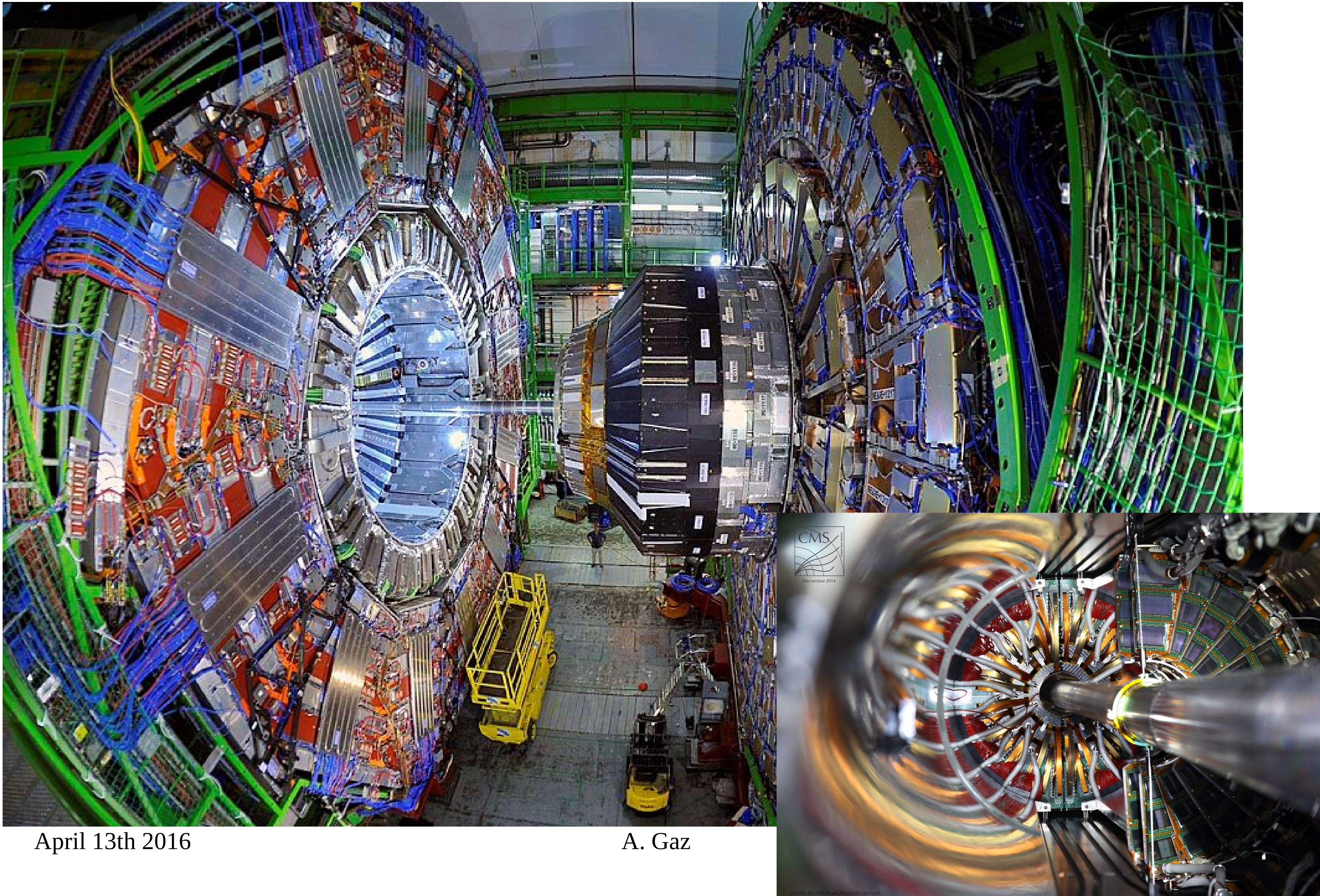
$\sqrt{s}$ = 13 TeV

Inst. Lumi = $1\text{x}10^{34}$ $cm^{-2}s^{-1}$ (target)

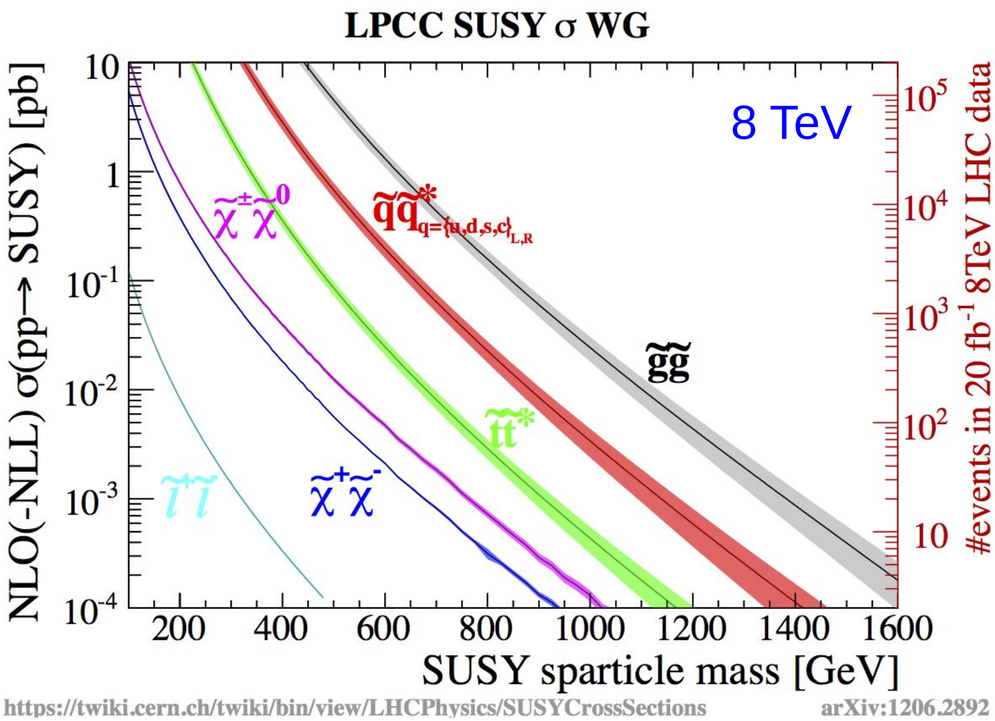
Bunch spacing 25 ns

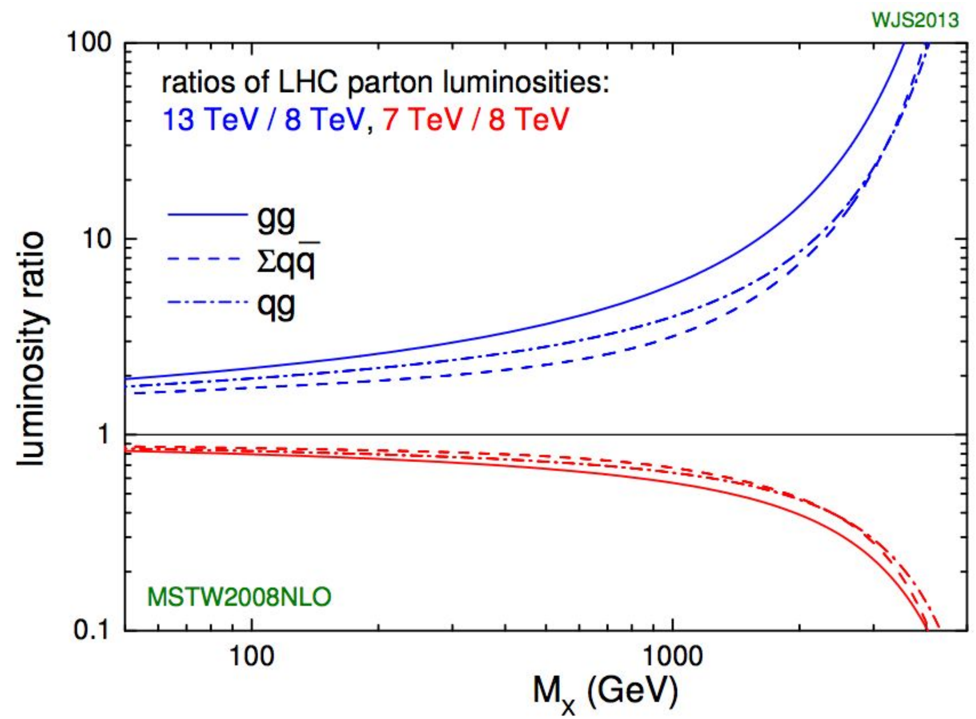
Target for Run2: integrate 100 fb^{-1}

The CMS Experiment



SUSY production at LHC

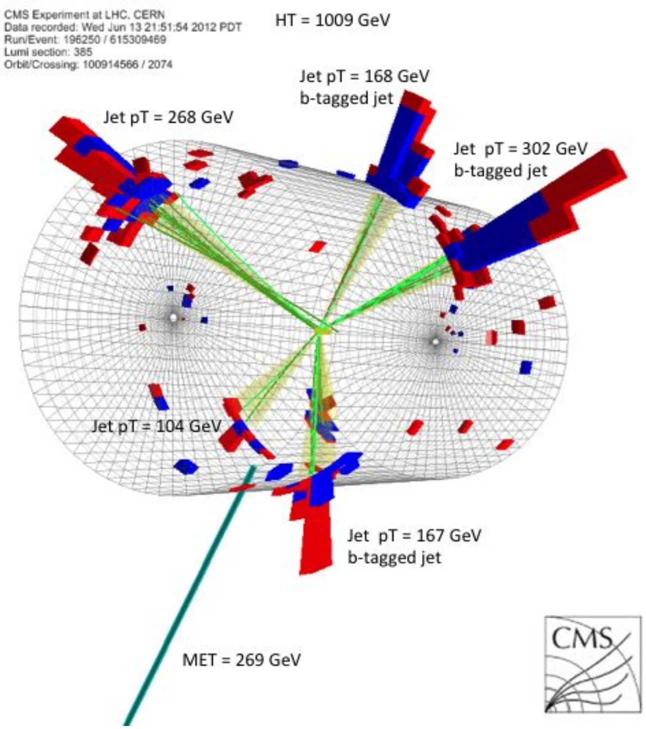




- Production of colored (i.e. strongly interacting) particles clearly favored at a hadron collider...
- … still neutralinos are expected to be among the lightest SUSY particles, so the production could be significant!

Search strategies

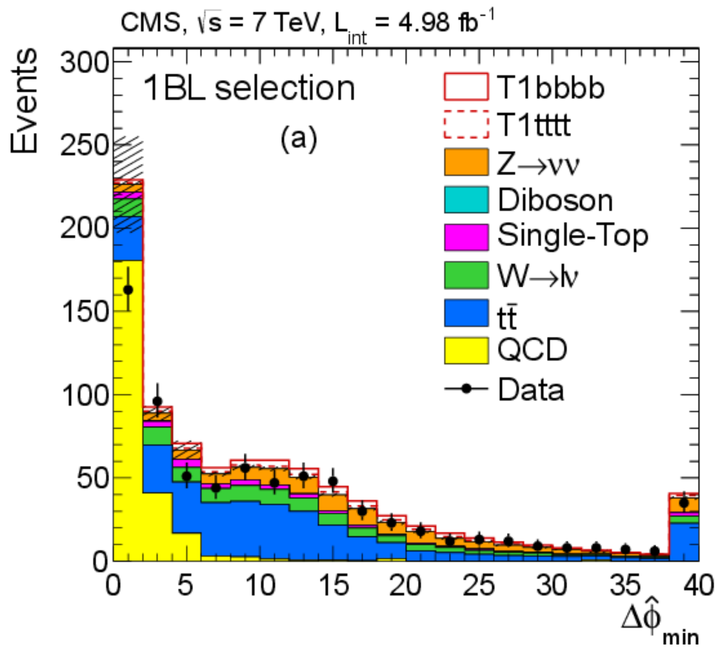
- I will focus on RP-conserving scenarios: the LSP is neutral, weakly interacting, and stable. So it behaves like a (possibly heavy) neutrino;



- The common feature for these events is the presence of large missing transverse energy (MET);
- Together with MET, other selection criteria are applied, to increase sensitivity to specific topologies and reduce the impact of SM backgrounds:
  - presence or absence of (τ) leptons;
  - presence of vector bosons, Higgs, …;
  - total energy in the event;
  - …

Standard Model backgrounds

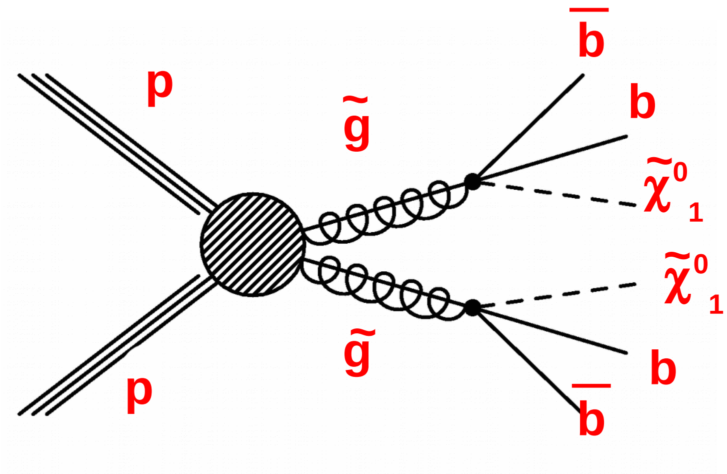
- Missing transverse energy is not exclusively a signature for SUSY (or other New Physics), many SM processes can mimic SUSY events;
- Examples:
  - multijet events, in which MET arises from incorrectly measured jet energy;
  - $t\bar{t}$ events, with one top decaying semileptonically ($t \to b\ l\ \nu$)
  - $Z \to \nu\nu$ events;

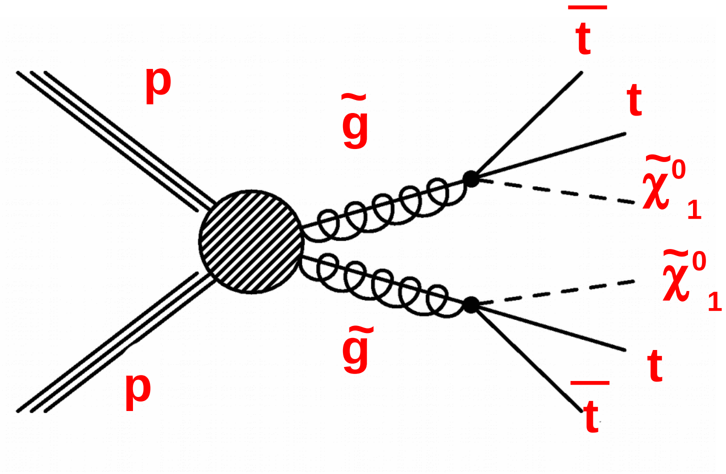


- A large fraction of the analysis effort is devoted to carefully estimating the SM backgrounds (from data control samples, as much as possible);
- The hope is to observe some topology in which the event yields are incompatible with the SM background predictions.

Search for gluino pair production

- Target topologies:

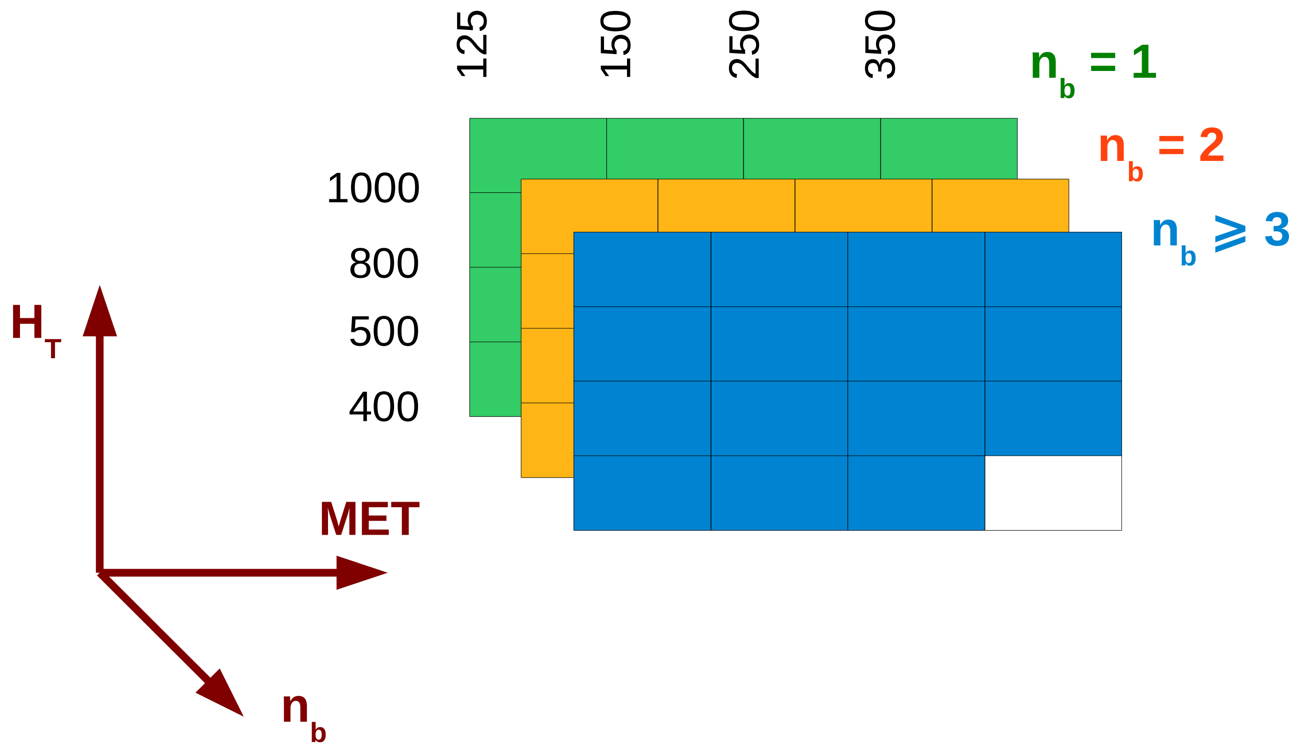


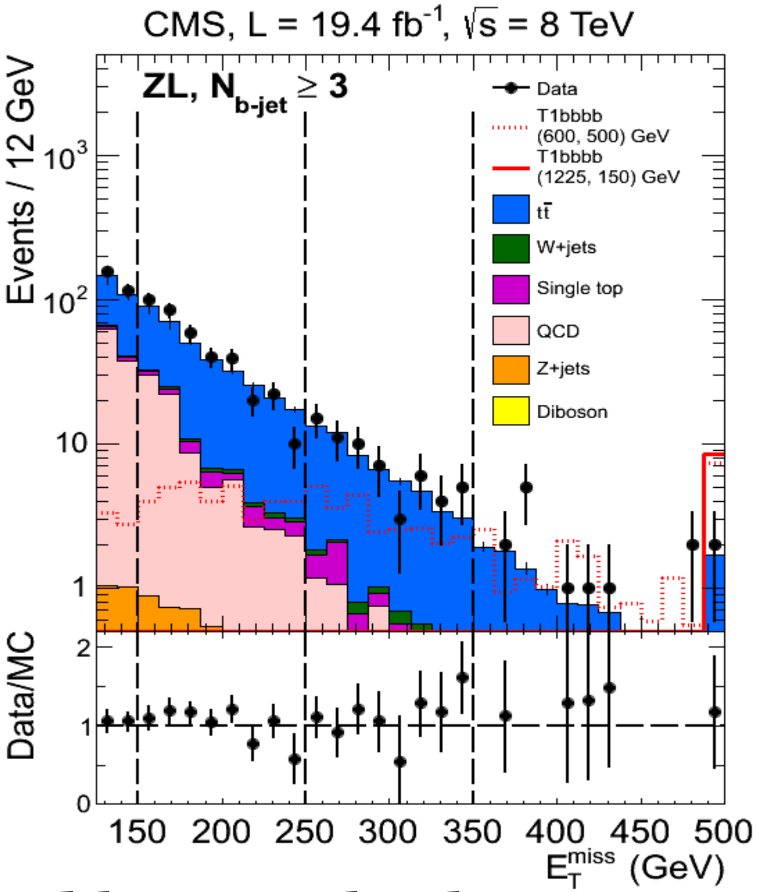


- In Natural SUSY scenarios, s-tops and s-bottoms are expected to be relatively light, so searches with "3rd generation" particles are particularly important;
- Main signatures:
  - ➔ large MET and hadronic energy;
  - ➔ high b-jet multiplicity.

arXiv: 1305.2390 [hep-ex], Phys. Lett. **B725** 243 (2013)

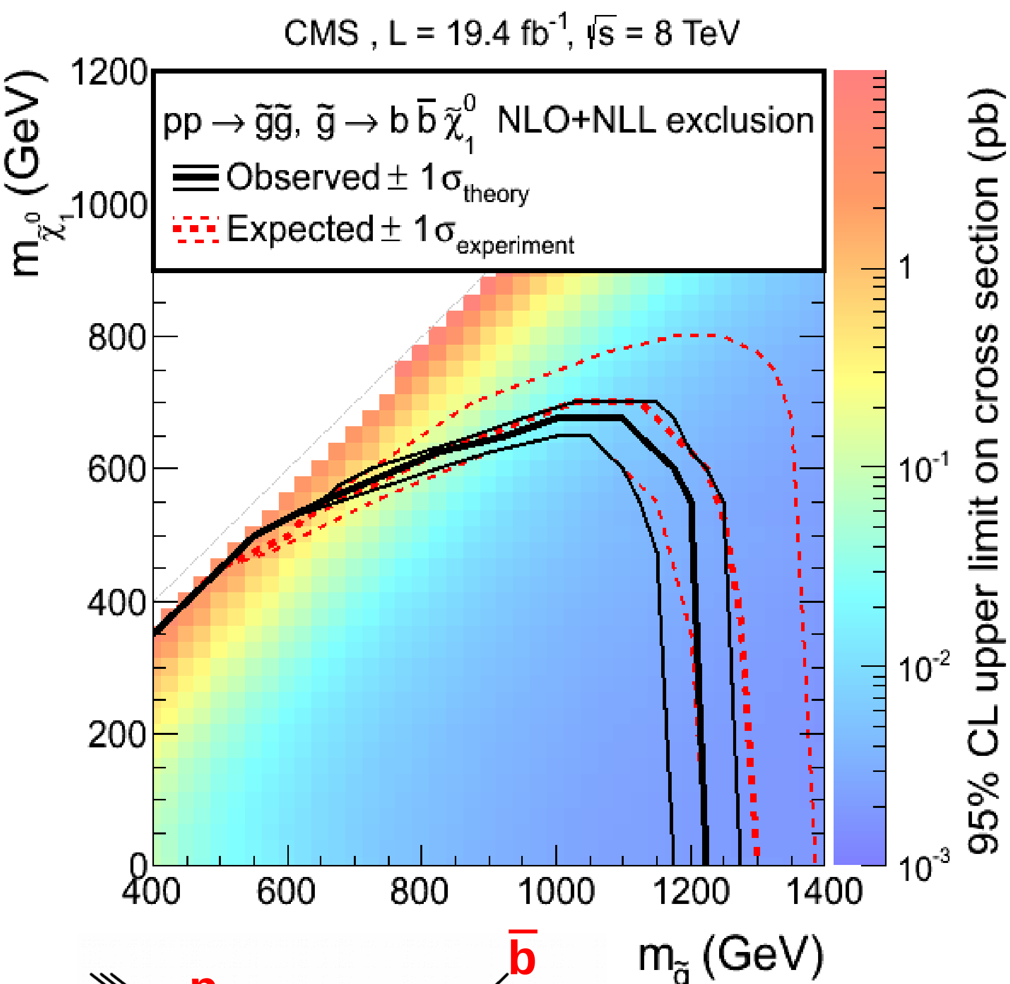
Search for gluino pair production

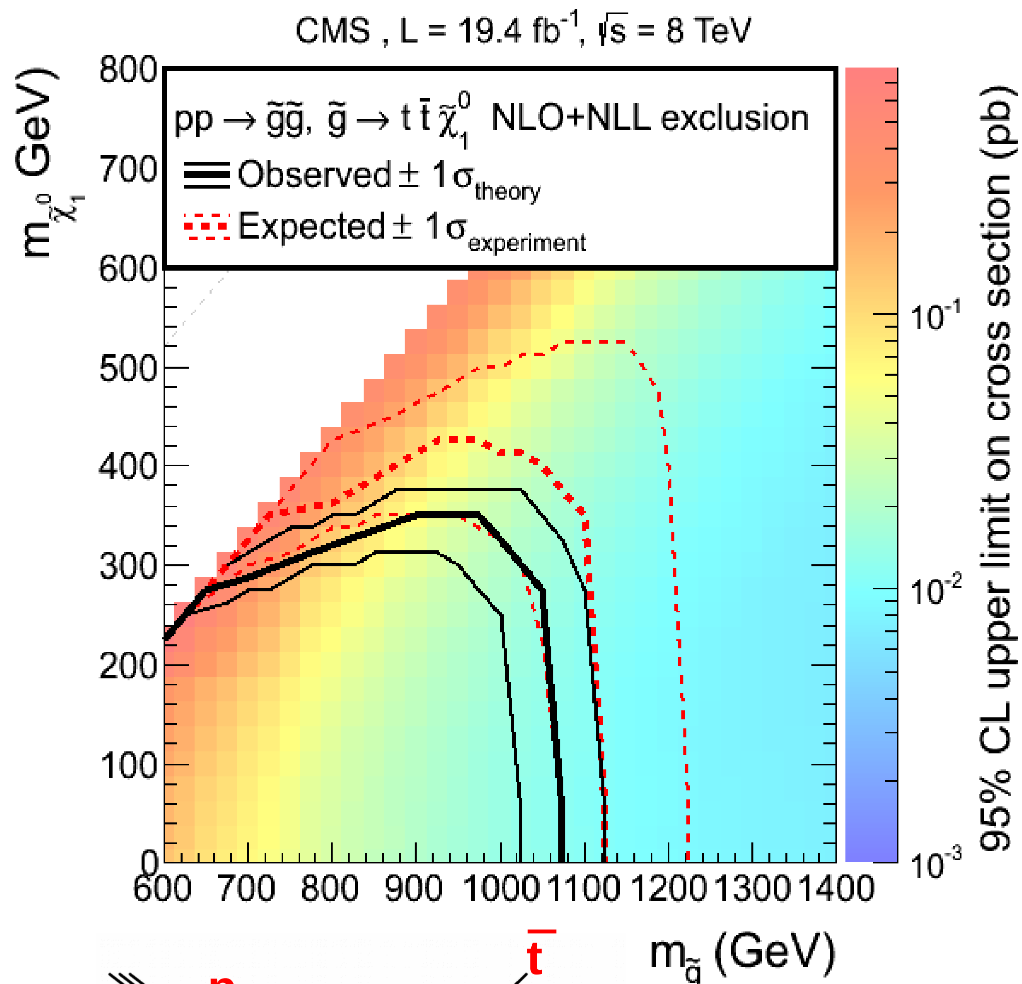


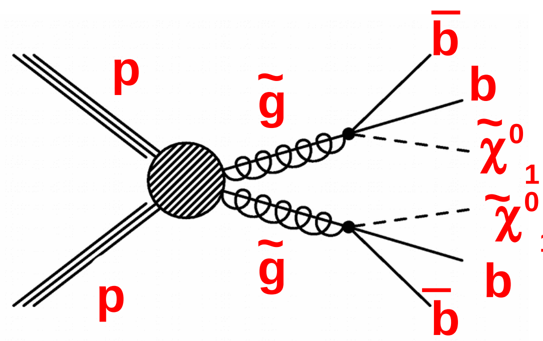


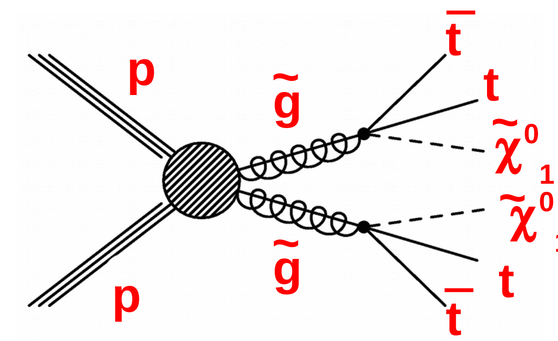
- 3-dimensional analysis on the variables MET, scalar sum of jet momenta (HT), and b-jet multiplicity;
- 45 independent signal regions, correlations from nuisance parameters taken into account;
- No excess wrt SM background predictions...

Search for gluino pair production



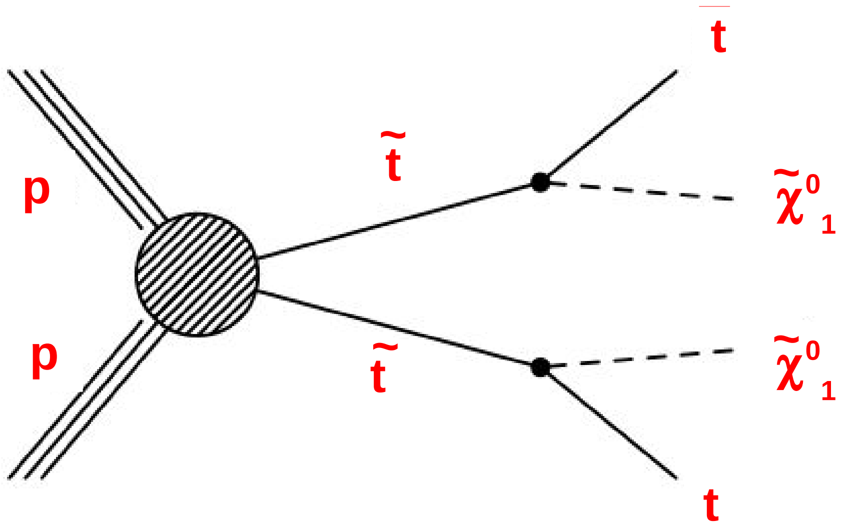






Search for direct stop pair production

- The stop is expected to be light, in order to keep the fine tuning reasonably low;
- Expect cross section for direct production to be reasonably high, but…;

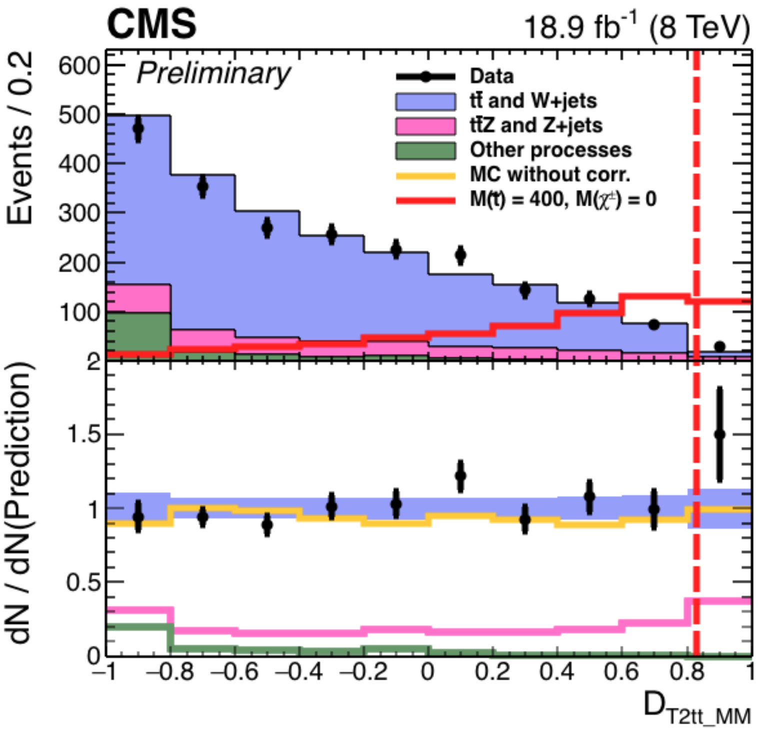


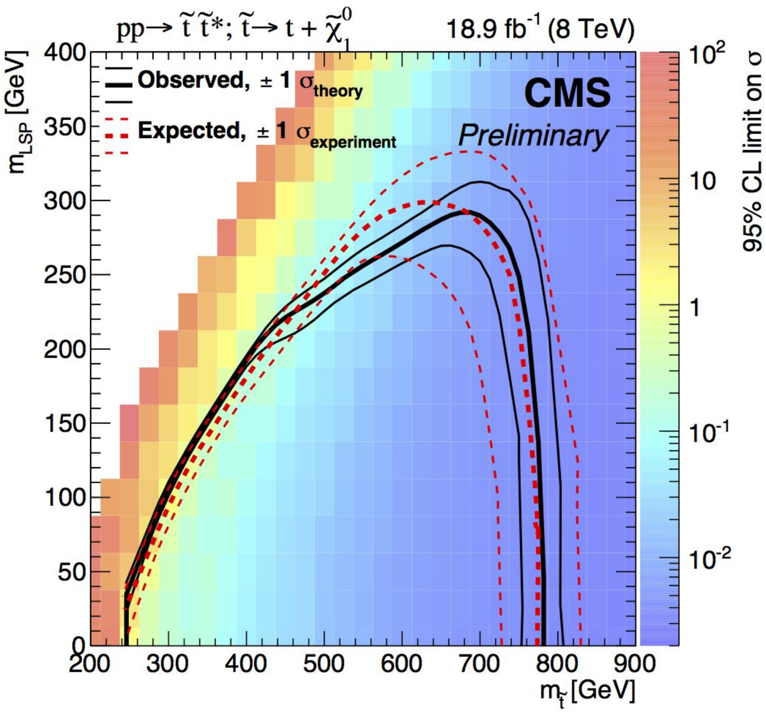
- The signature is similar to that of a $t\bar{t}$ event, the only difference is the presence of MET;
- If $m(\tilde{t}) \sim m(t) + m(\tilde{\chi}^0_1)$, the neutralinos carry little momentum (and the events will look like SM $t\bar{t}$);
- Need a strategy to cover also the "blind spots" of the phase space: maybe the stop is there but we haven't been able to see it yet.

Search for direct stop pair production

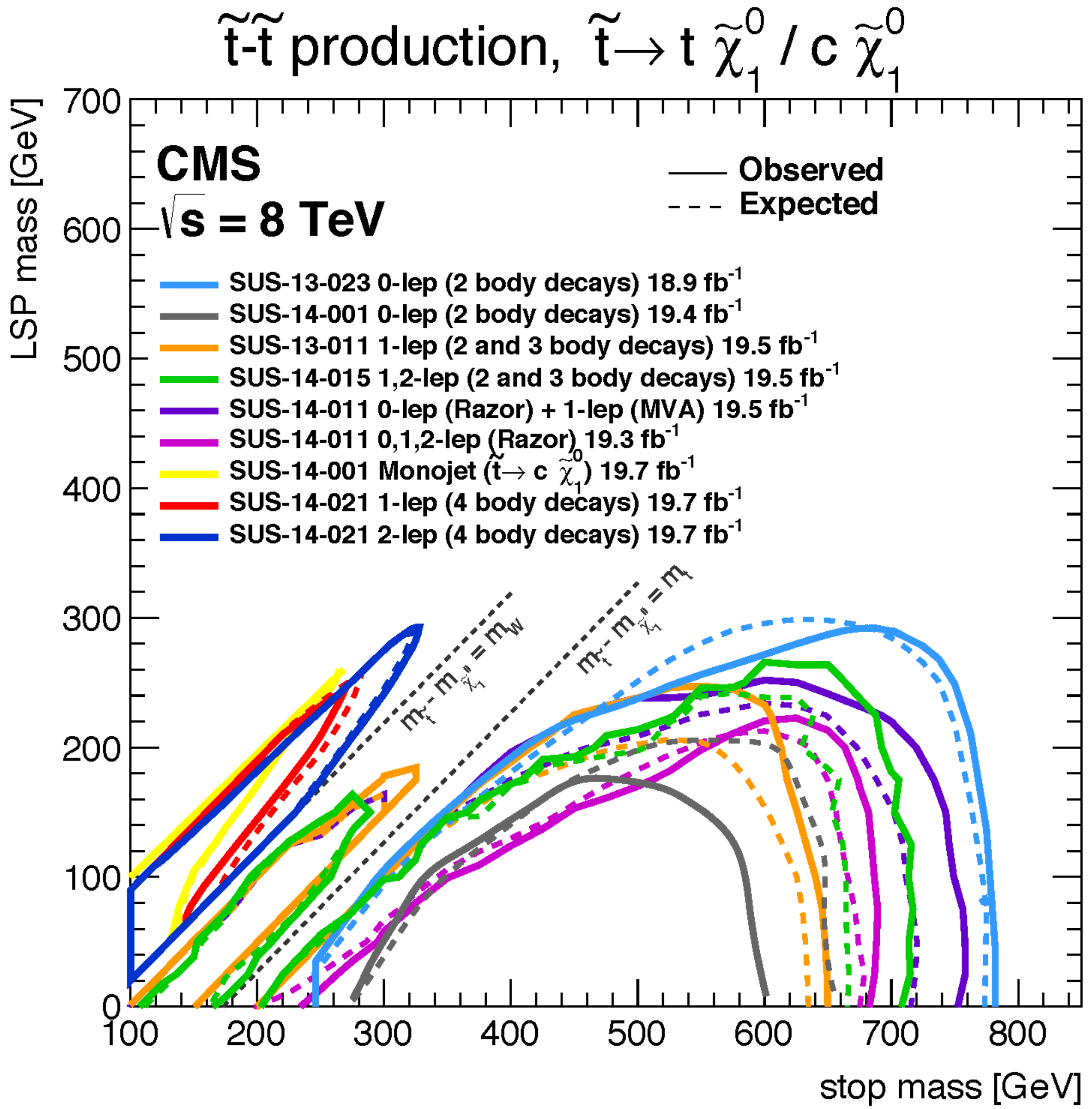
- Search performed on fully hadronic final states;
- Variable-cone jet reconstruction to optimize top selection;
- Multivariate BDT discriminant to enhance the potential signal from the dominant $t\bar{t}$ background.

CMS-SUS-13-023



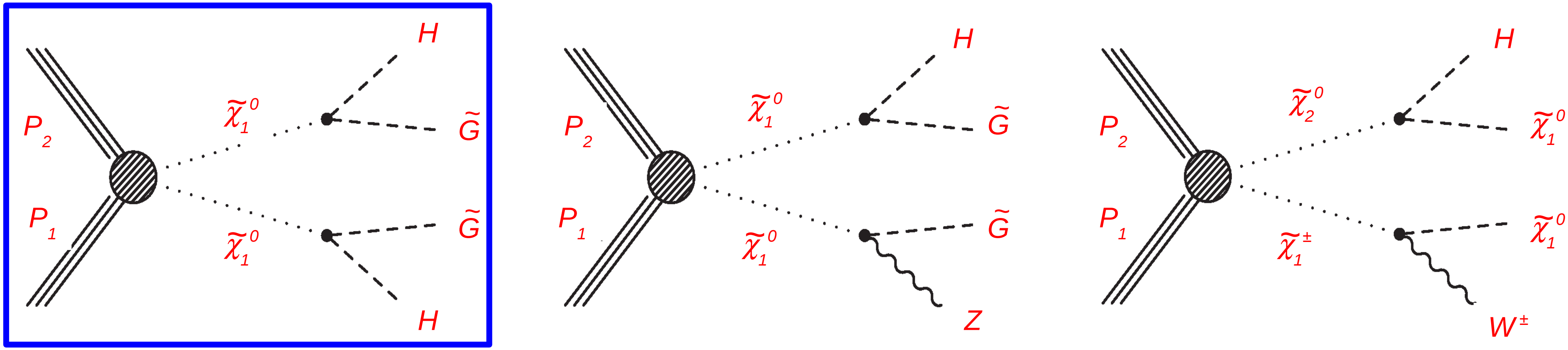


Search for direct stop pair production



Ewkino production with Higgs in the final state

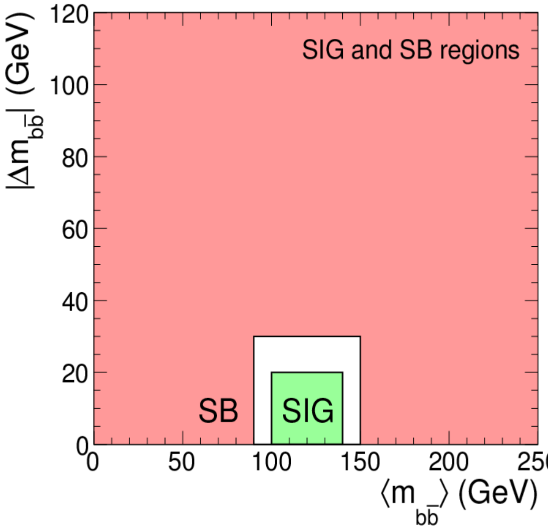
- Ewkinos (neutralinos and charginos) are expected to be light and couple naturally to the Higgs and the vector bosons;
- Several topologies are possible:

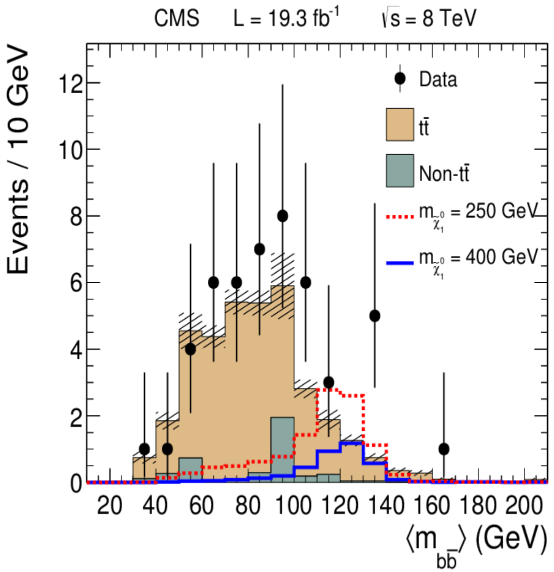


- Basically we search for events containing Higgs (or W and Z) bosons, associated with a non SM source of MET;
- Today I will cover only the topology with two Higgs's in the final state, both of them decaying to a $b\bar{b}$ pair.

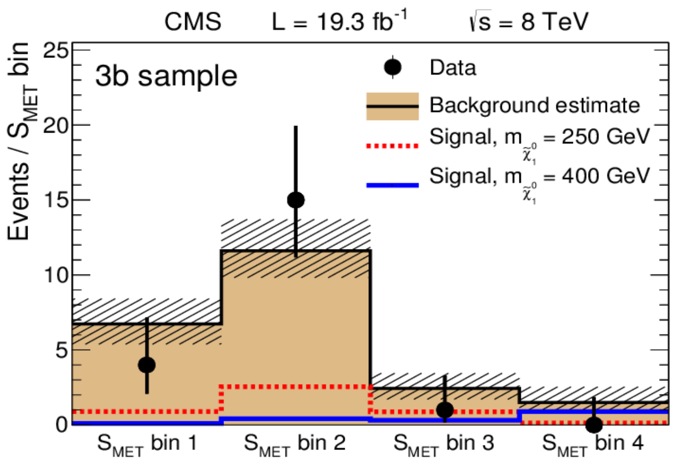
Ewkino production with Higgs in the final state

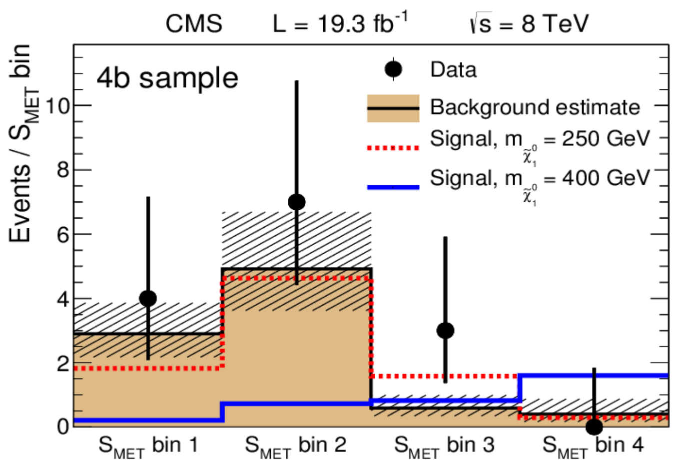
- Search for events with 4 b-jets, and combine them to make two Higgs candidates;
- Dominant background is from $t\bar{t}$ events;
- Discriminating variable: MET significance.





Again, good agreement between data and expected SM backgrounds

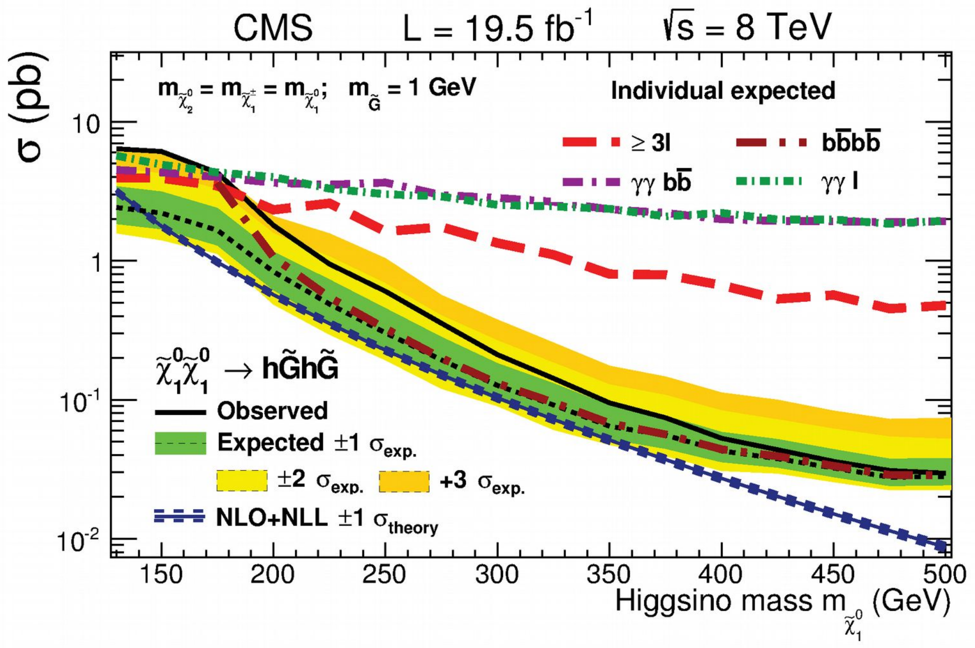


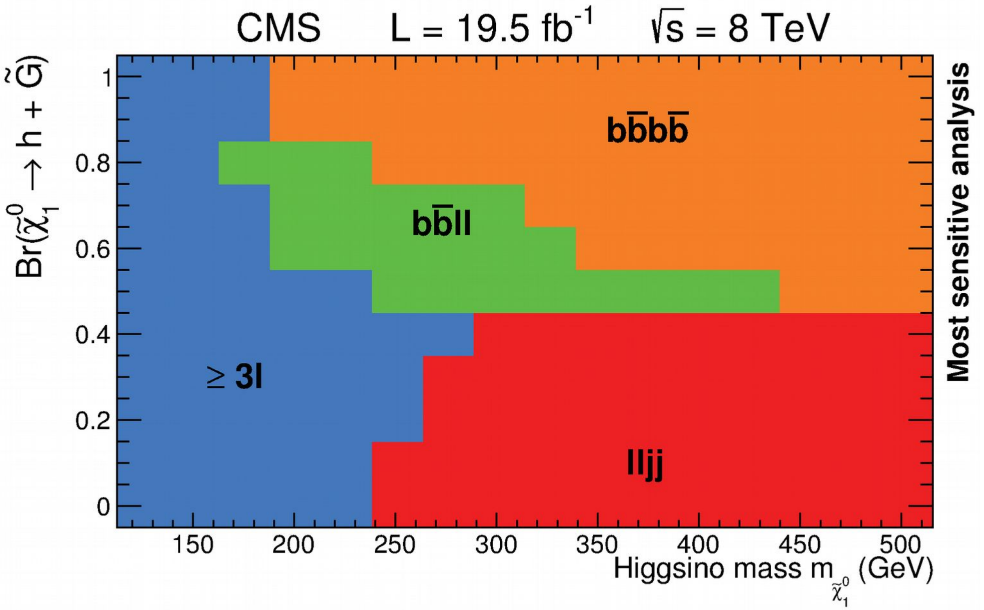


Phys. Rev. **D90** 092007 (2014)

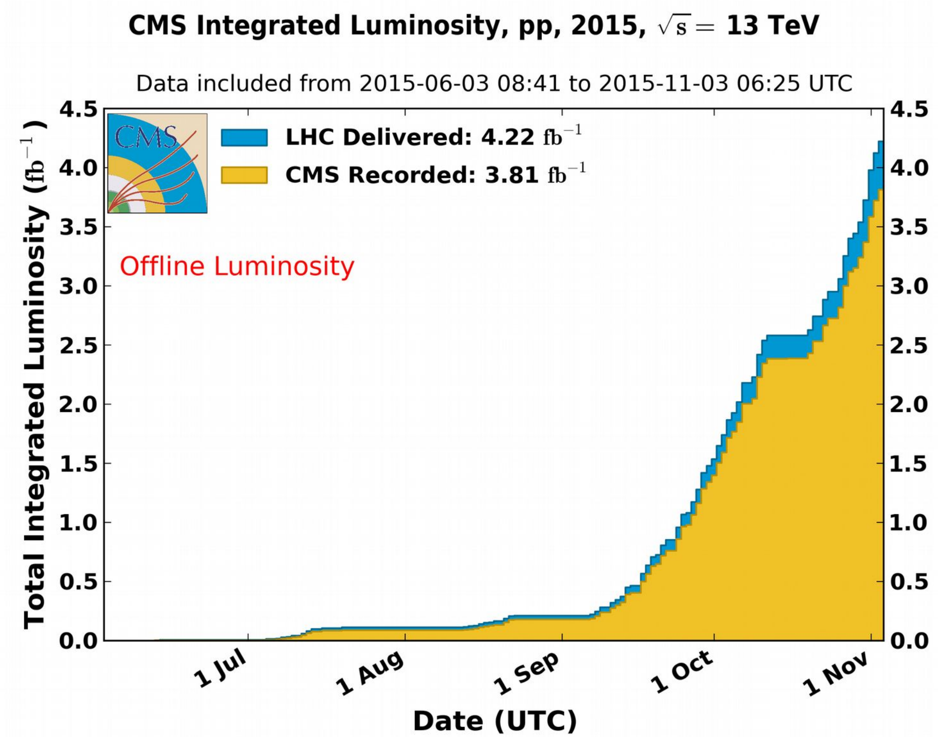
Ewkino production with Higgs in the final state

- Not yet able to get significant exclusion with Run1 data, but we are getting really close…





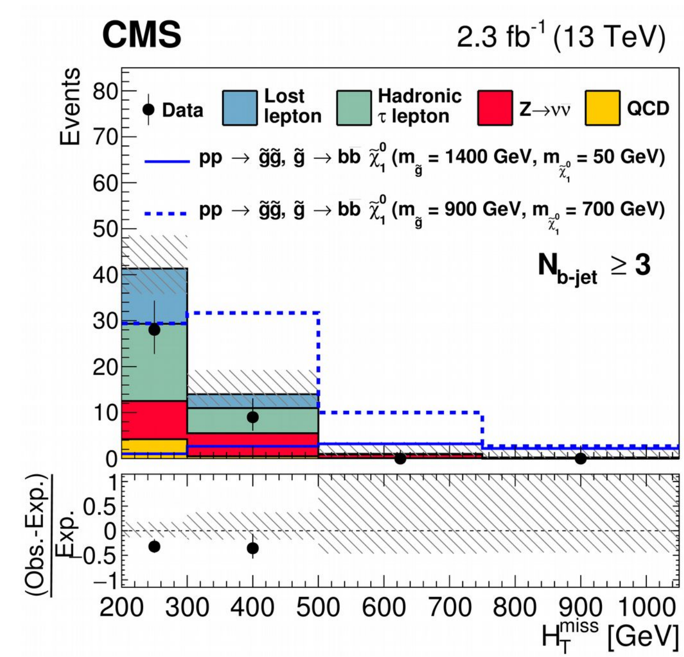
LHC Run2

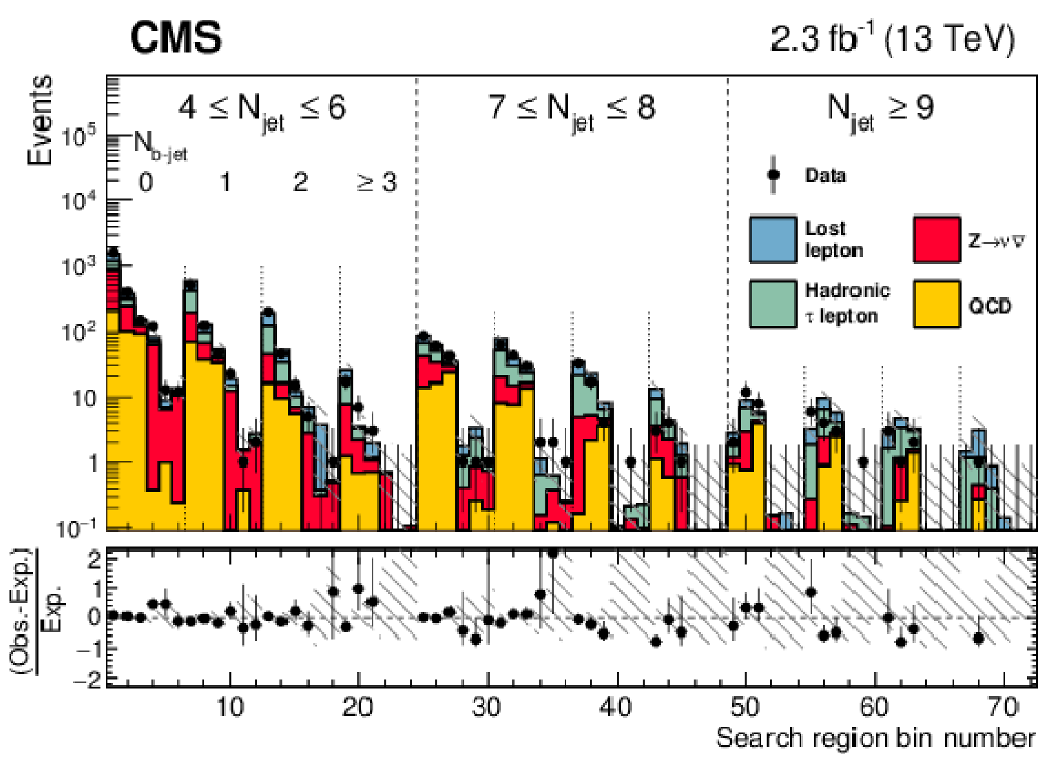


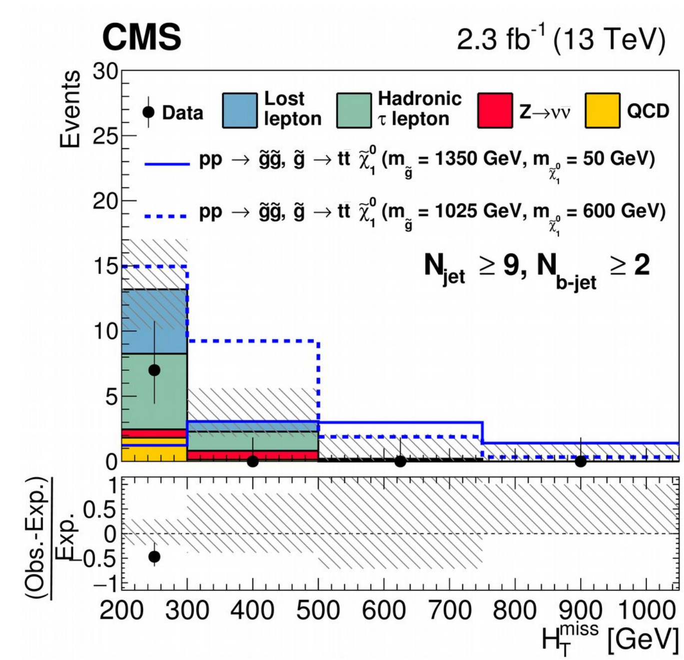
- What I have shown so far is based on the ~20 fb^{-1} of the 8 TeV 2012 Run;
- After a long shutdown, the LHC resumed operations in 2015, raising the collision energy to 13 TeV;
- The LHC delivered ~4.2 fb^{-1}, which, after accounting for data-taking inefficiency, data quality requirements, and the problem with the magnet, reduce to ~2.3 fb^{-1} available for analysis;
- Anyway, thanks to the higher cross-sections this data sample is sufficient to increase the sensitivity of many Run1 analyses.

Searches for gluino pair production

- 4-dimensional analysis in missing H_T, H_T, jet multiplicity and b-jet multiplicity;
- 72 search regions in total.





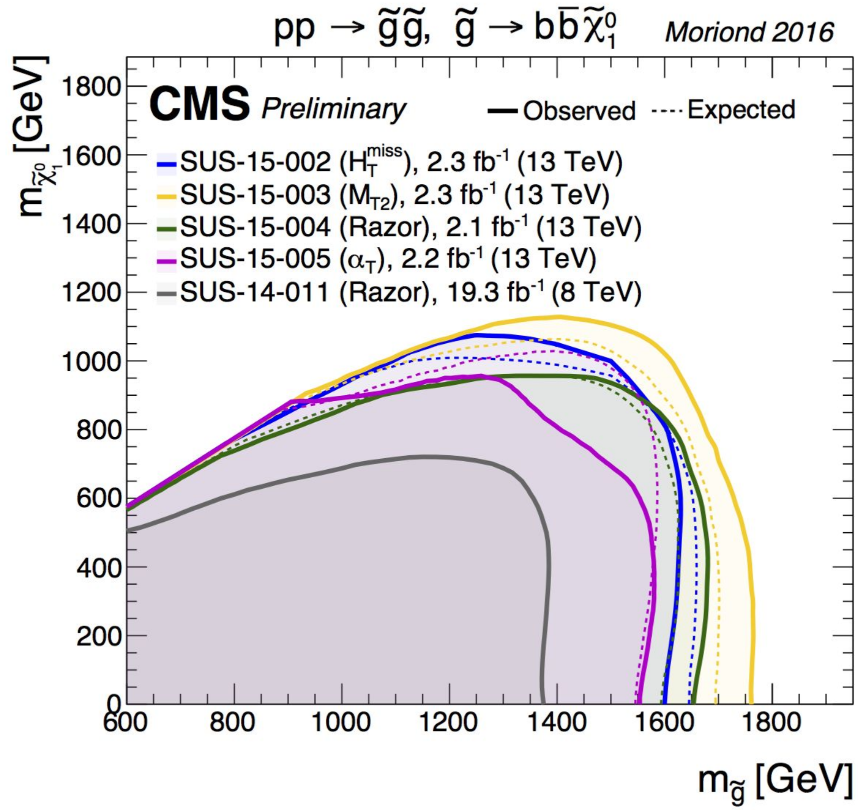


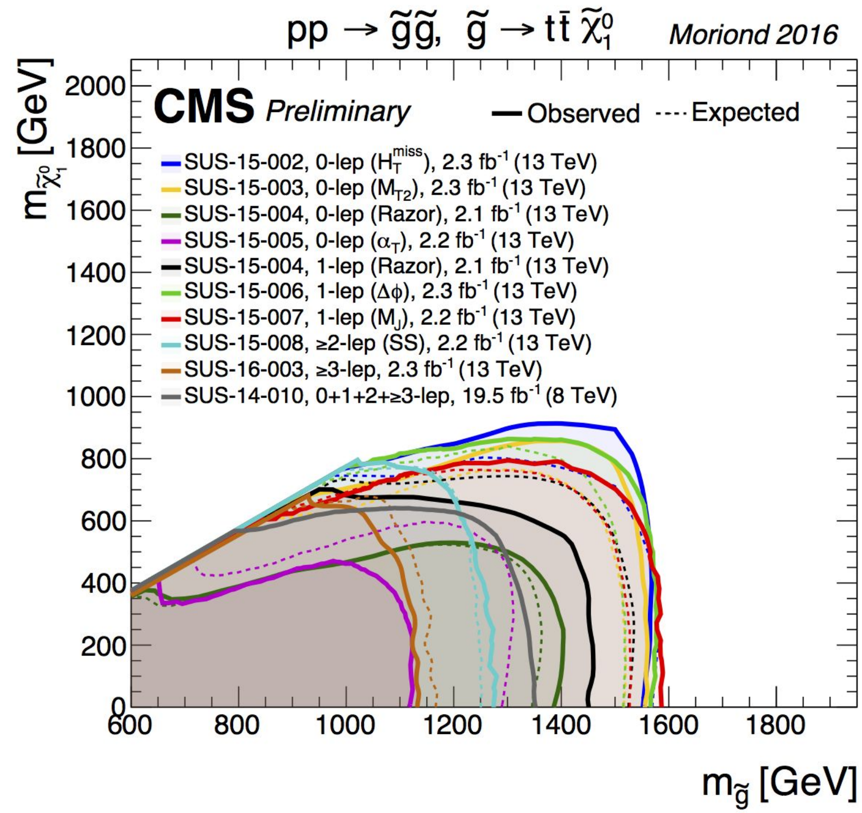
April 13th 2016

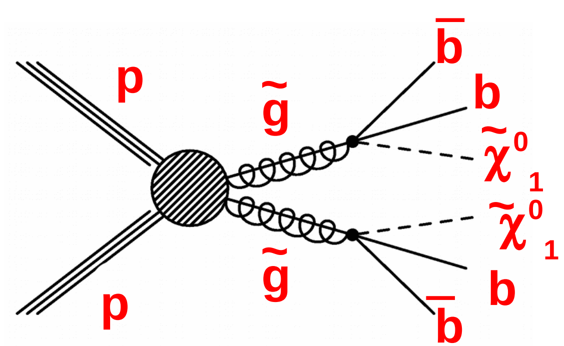
arXiv:1602.06581 [hep-ex]

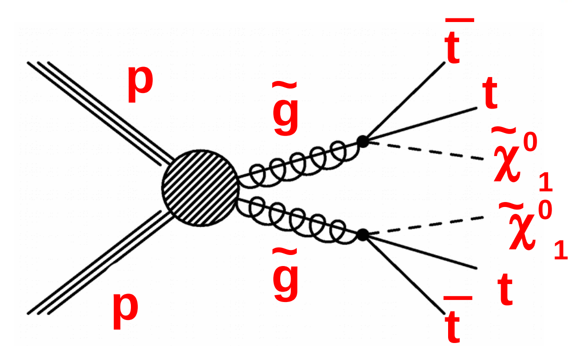
Searches for gluino pair production

Run1 limits are already superseded!









Searches for direct stop pair production

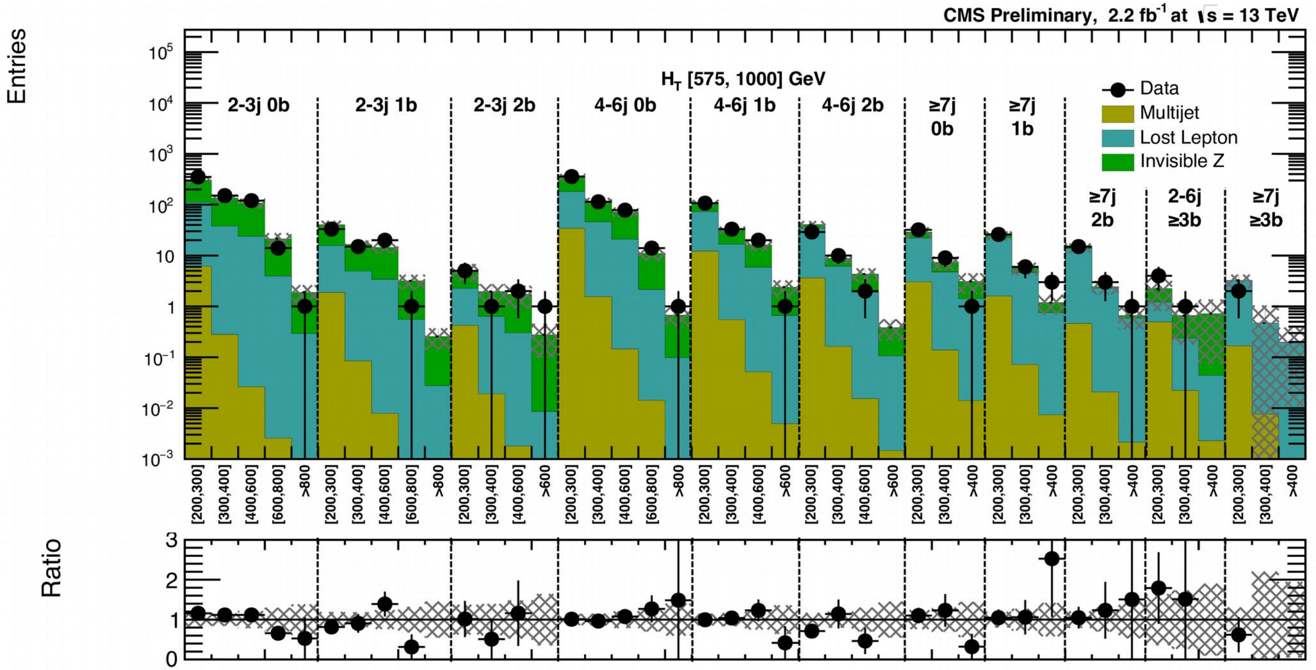
- Analysis exploiting the M_{T2} variable, designed to be robust against jet p_T mismeasurements:

$$M_{T2}(m_{\tilde{\chi}}) = \min_{\vec{p}_T^{\tilde{\chi}(1)} + \vec{p}_T^{\tilde{\chi}(2)} = \vec{p}_T^{\text{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

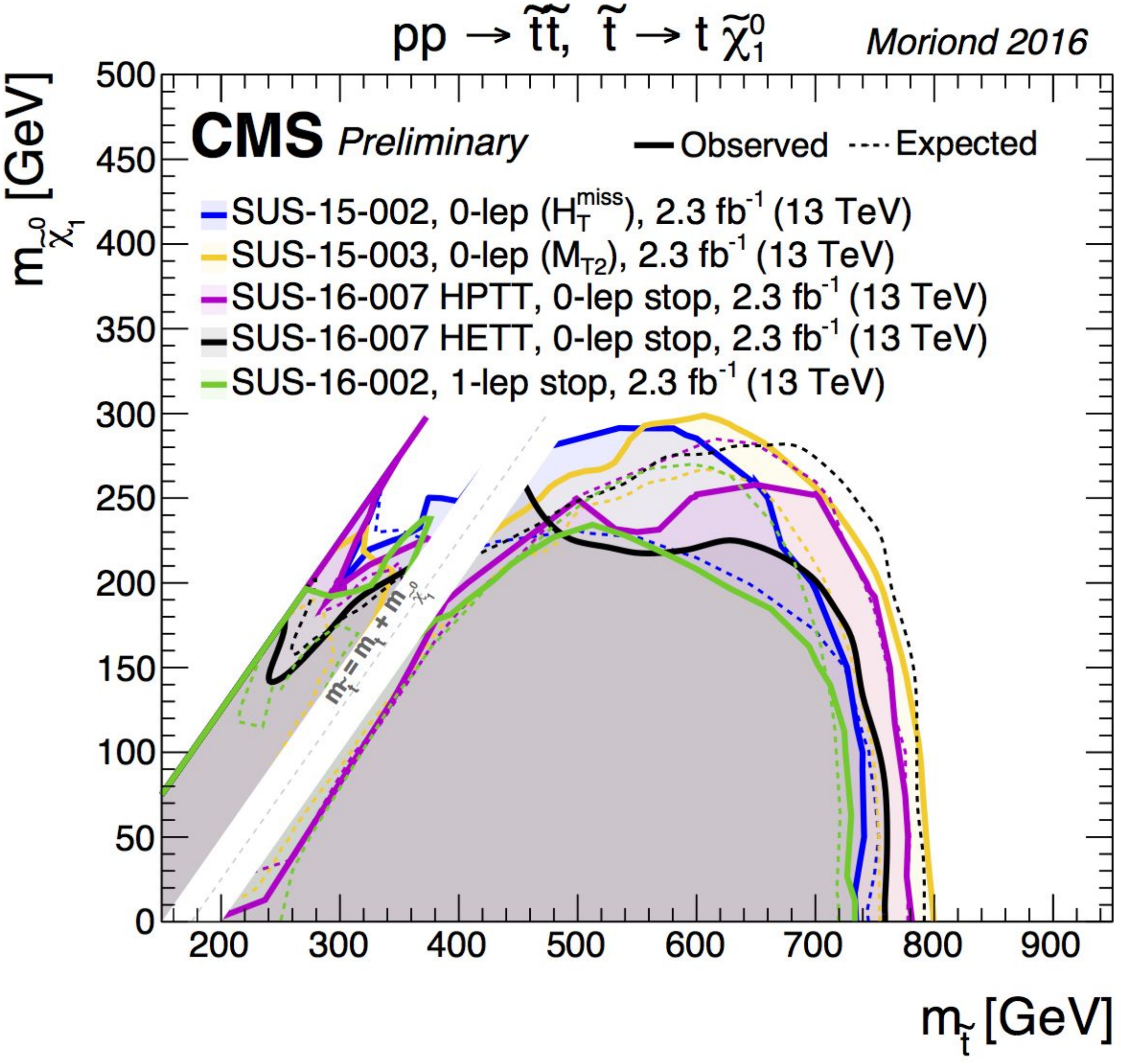
$$(M_T^{(i)})^2 = (m^{\text{vis}(i)})^2 + m_{\tilde{\chi}}^2 + 2\left(E_T^{\text{vis}(i)} E_T^{\tilde{\chi}(i)} - \vec{p}_T^{\text{ vis}(i)} \cdot \vec{p}_T^{\tilde{\chi}(i)} \right)$$

- Very powerful for signatures with two (pseudo-)jets;

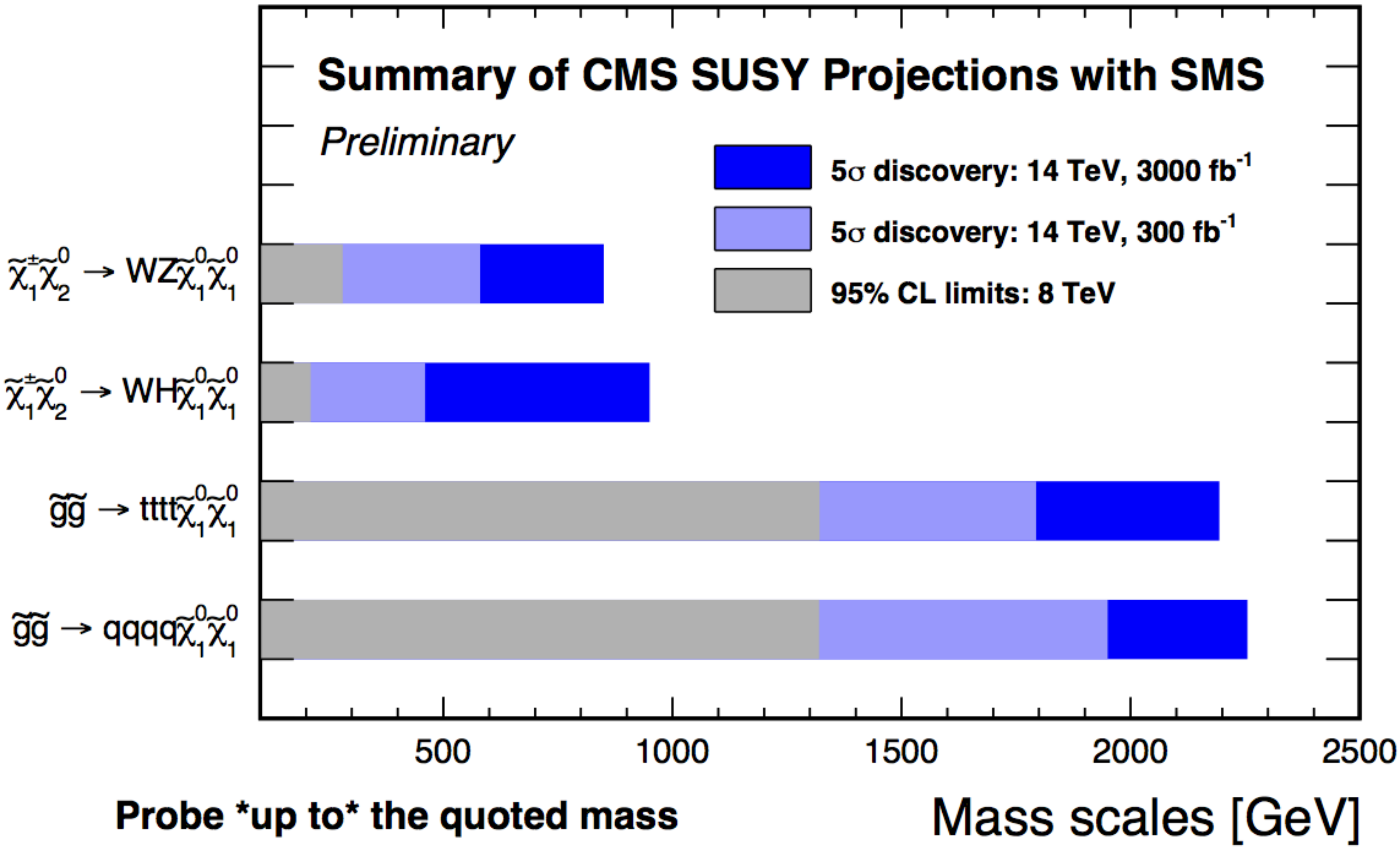
CMS-SUS-15-003



Searches for direct stop pair production



Ultimate LHC sensitivity



Probe *up to* the quoted mass

Conclusions

- Run1 of the LHC has greatly extended our sensitivity to discoveries of SUSY signatures, I covered only a tiny part of all the searches;
- Unfortunately no evidence so far, the Natural SUSY paradigm is under a lot pressure;
- Still high hopes to find SUSY, but probably we will have to give up/relax something (minimality, naturalness, R-parity conservation, …);
- LHC Run2 and HL LHC will extend our sensitivity even further, hopefully some of the excesses we have seen in the recent past will stay;
- And we should not forget that SUSY might show up somewhere else (Flavor Physics, $(g\text{-}2)_\mu$, direct DM searches…).