New Physics Experimental Results at the LHC

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String Pheno 15

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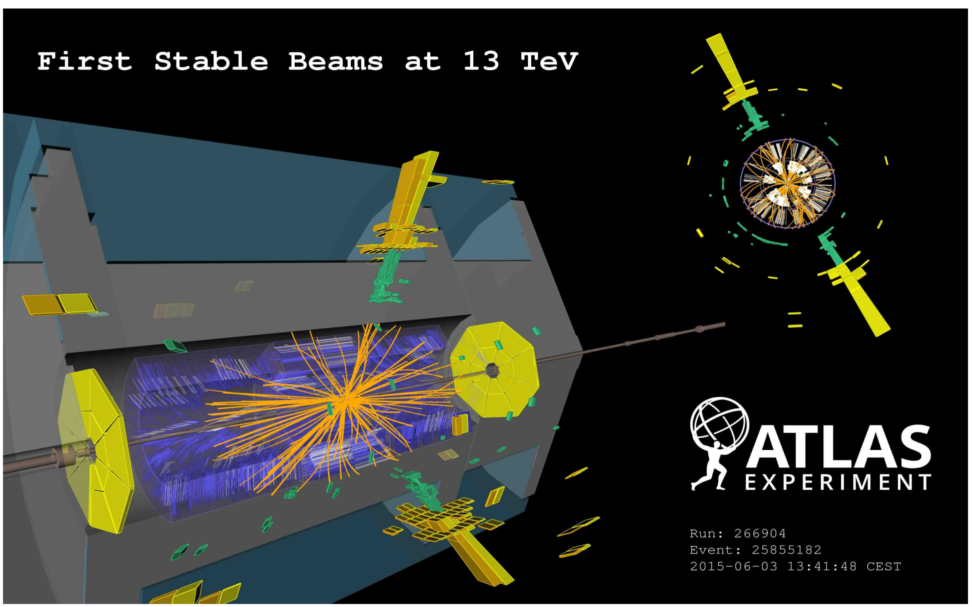
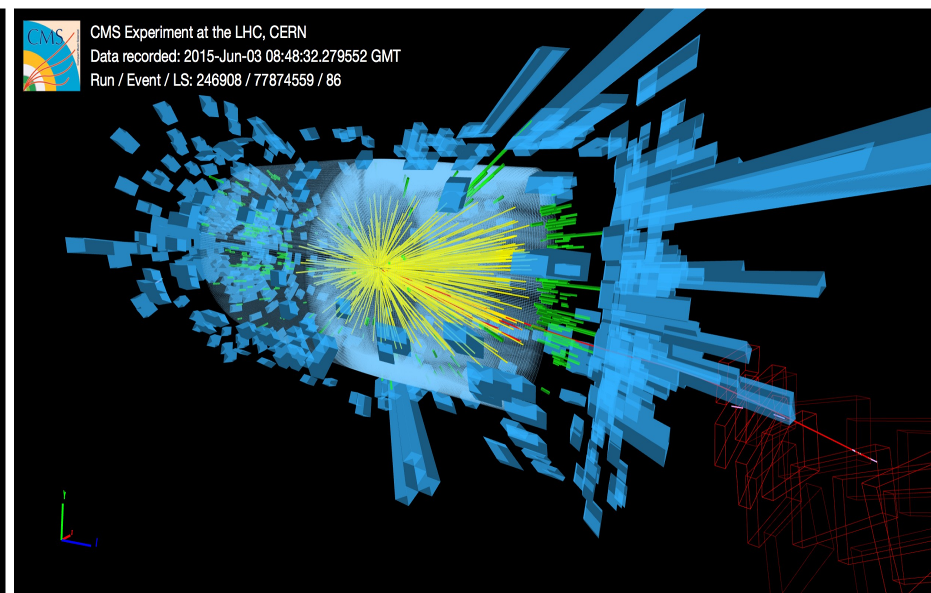
Outline

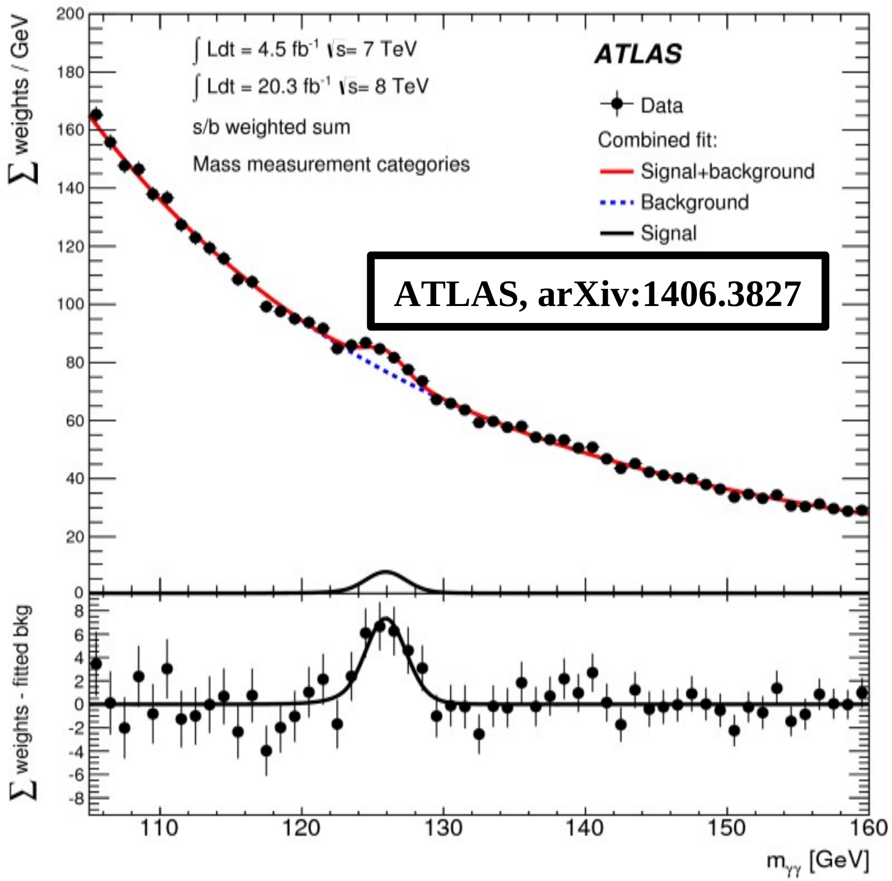
- No time to cover in detail the enormous search program of the LHC in Run1!! I will focus (briefly) on a few areas:
  - Higgs: basic status as of today
  - Supersymmetry: basics and current 'natural' directions
  - Exotics: dark matter + first signatures to search for at Run2 (starting now!)

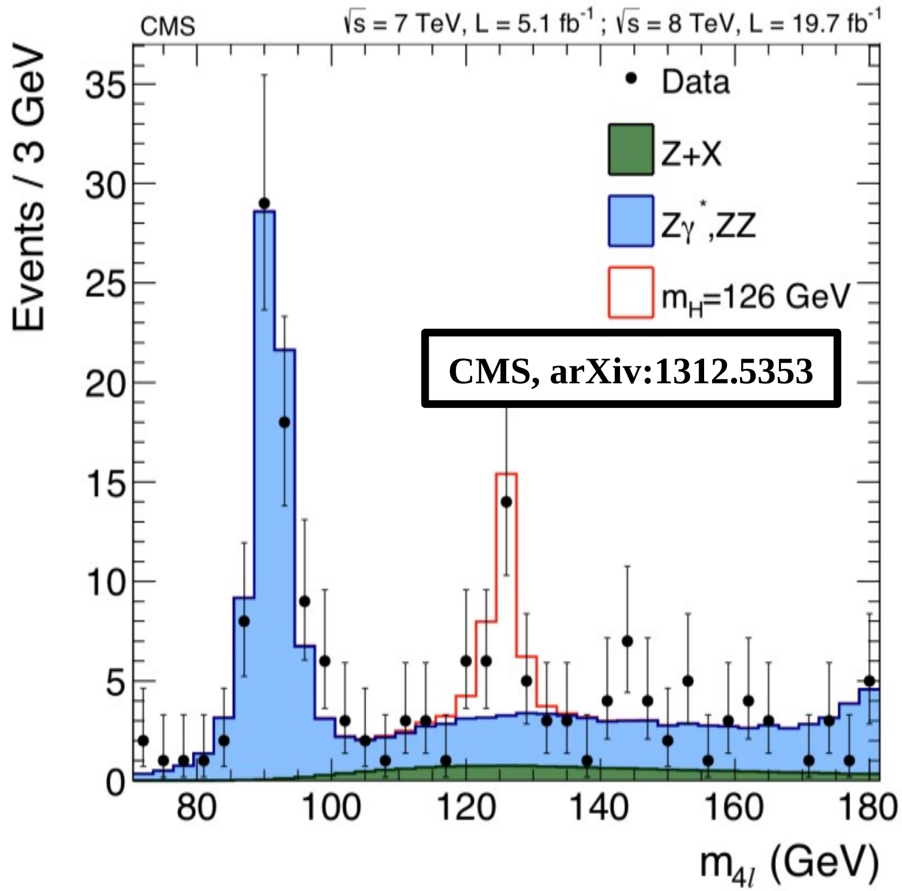




HIGGS

A 'standard' Higgs resonance

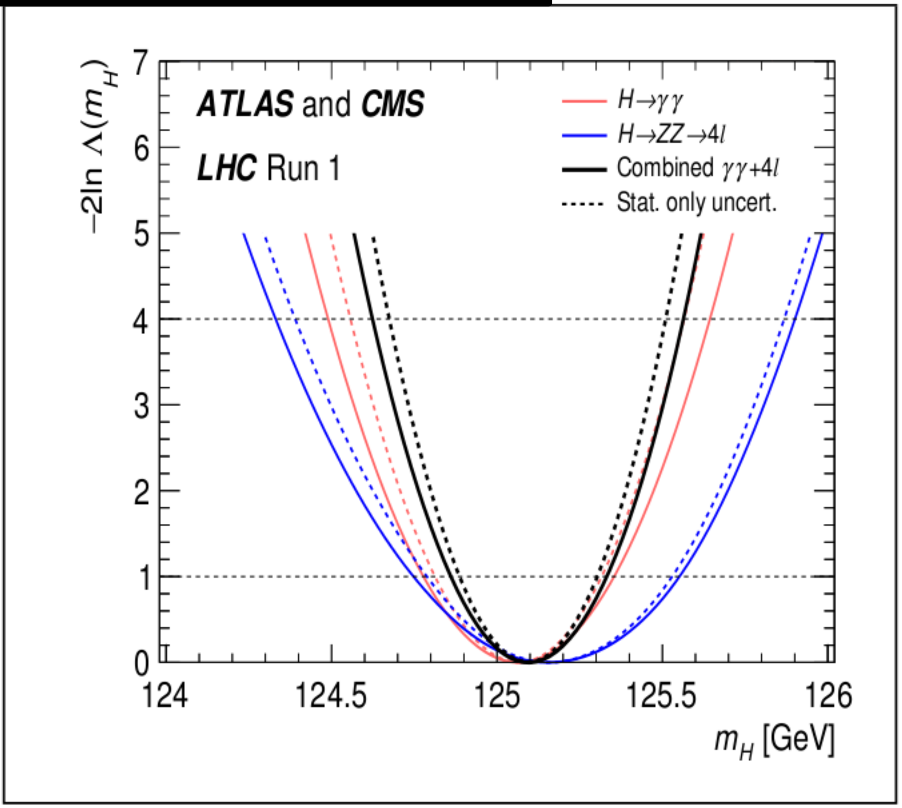


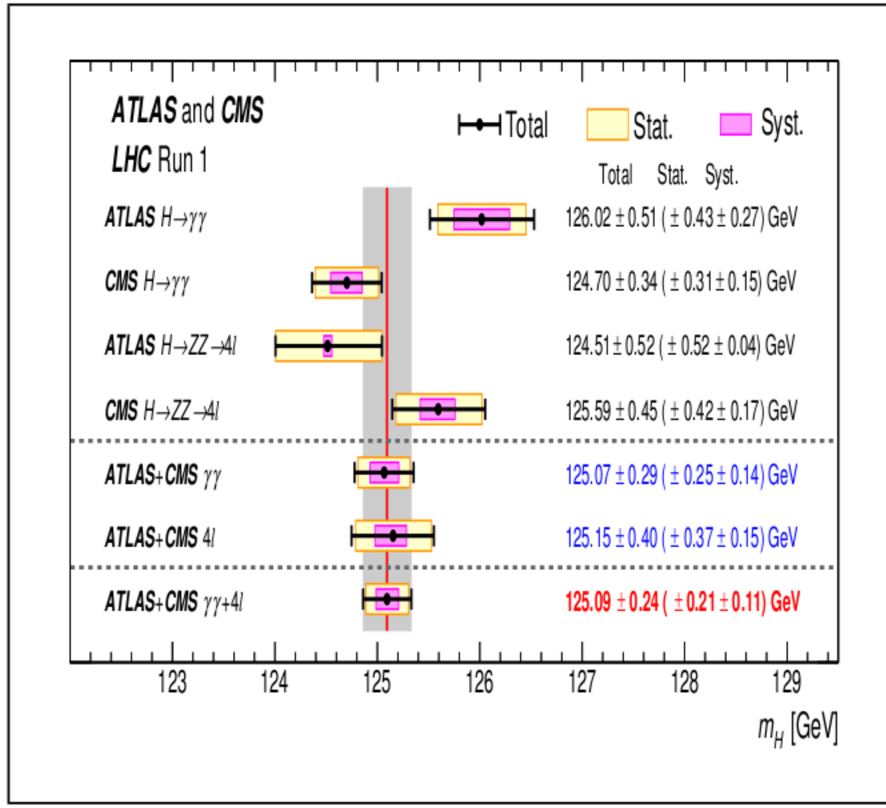


- $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ are the cleanest channels to 'see' the Higgs resonance 'bump'. They are actually the ones used to determine the mass with high precision.

Its mass

ATLAS+CMS, arXiv:1503.07589

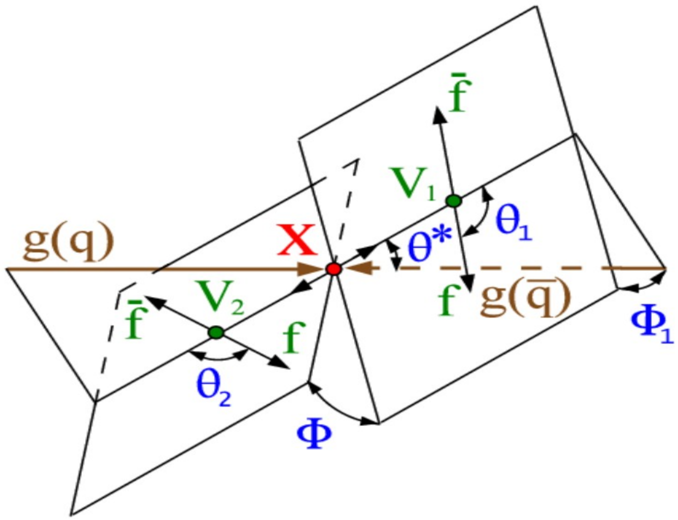


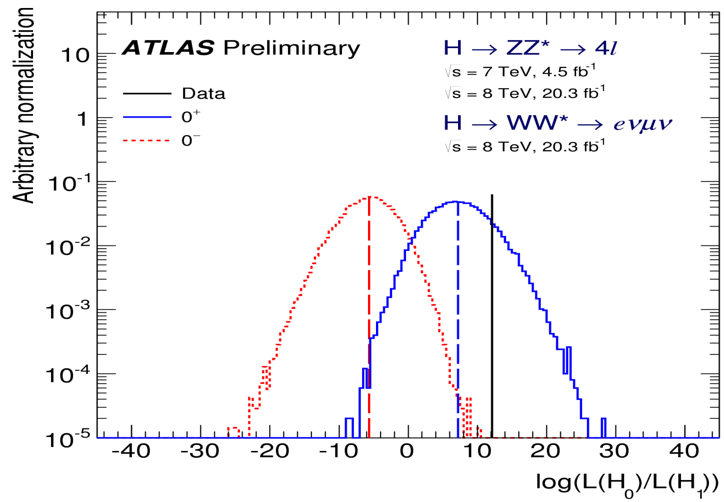


$$m_{\mathrm{H}} = 125.09 \pm 0.21 \; (stat.) \pm 0.11 \; (syst.) \; \mathrm{GeV}$$

- A – very precise - value that can be considered to be “low” or “high”, depending on your preferred theory beyond the SM…

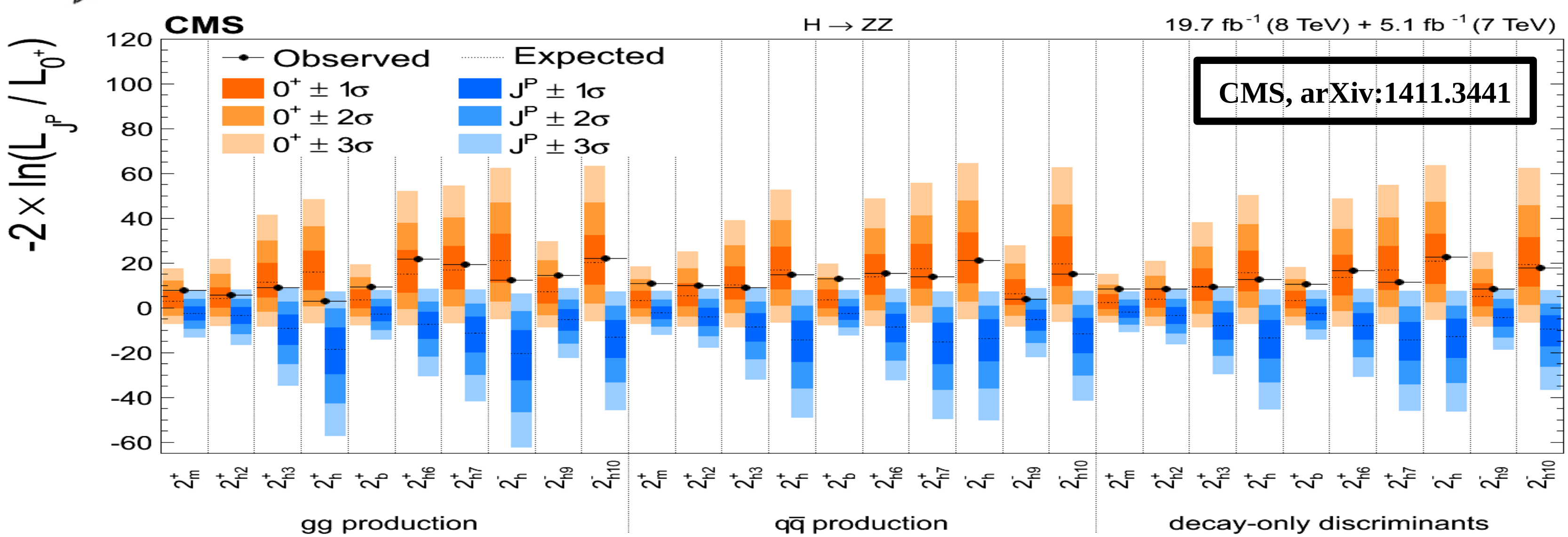
It really looks like a 'scalar'...





- **Scalar (0^+) vs. pseudoscalar (0^-)**

ATLAS-CONF-2015-008

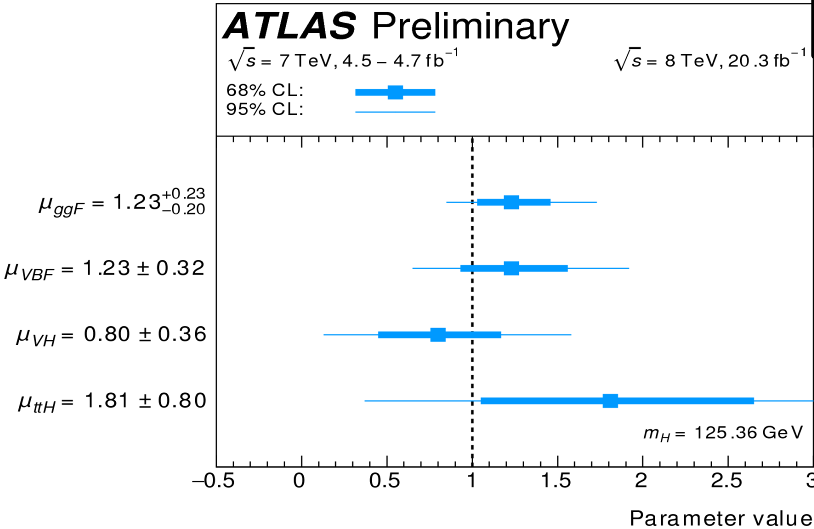


CMS, arXiv:1411.3441

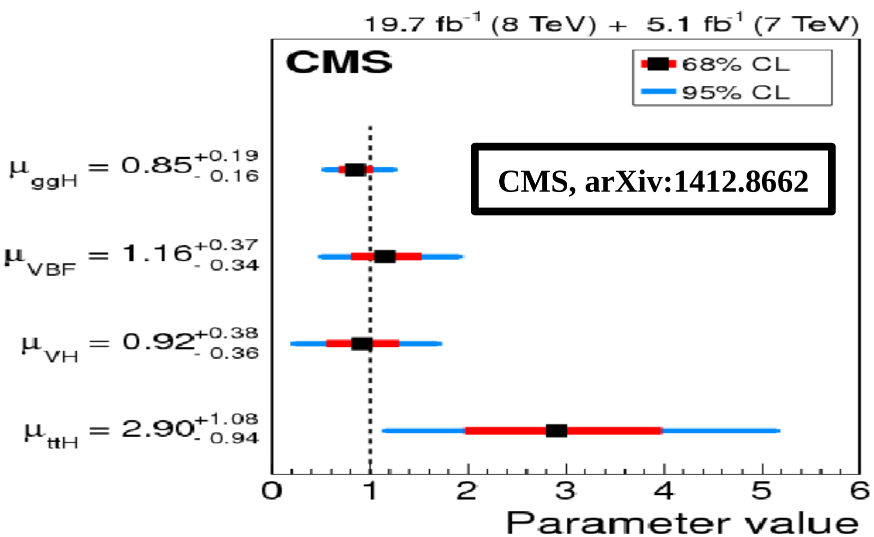
- Likelihood tests in data consistent with a 0^+ hypothesis (orange bands) when tested against different spin 2 coupling hypotheses (blue bands)

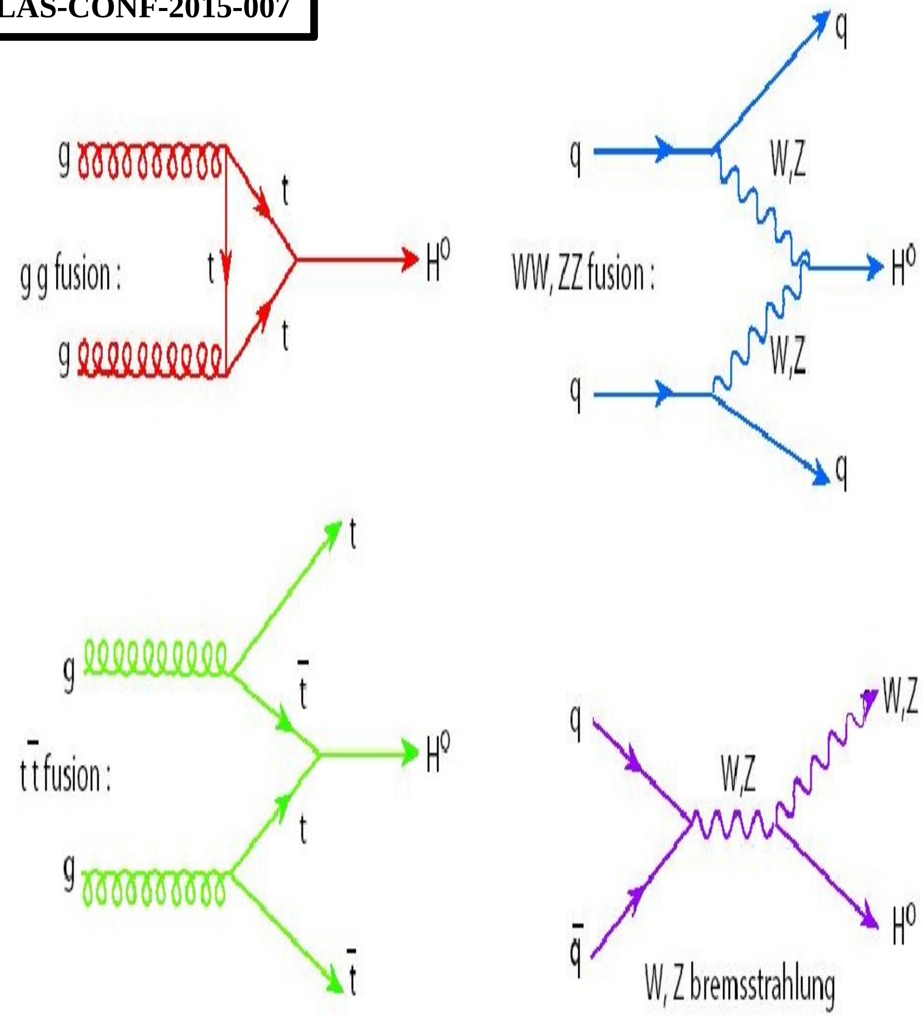
Production properties

ATLAS-CONF-2015-007



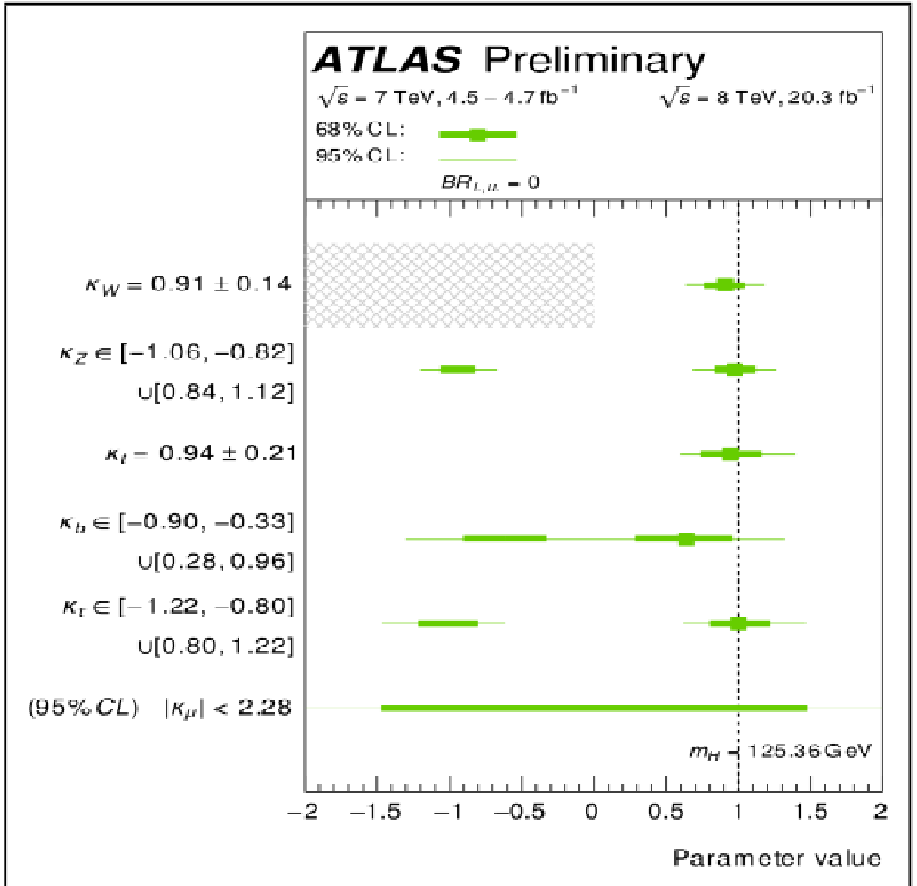
CMS, arXiv:1412.8662

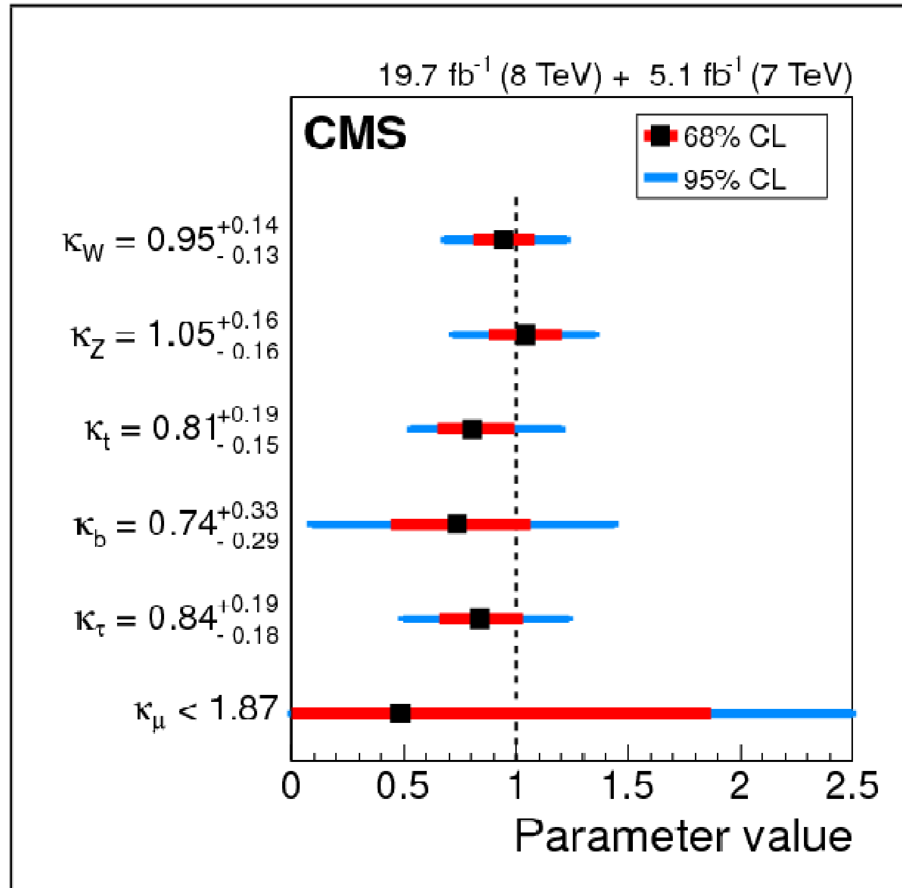




- Only a suggestive deviation in the $t\bar{t}$H case, but with a large uncertainty

Decay and global coupling properties



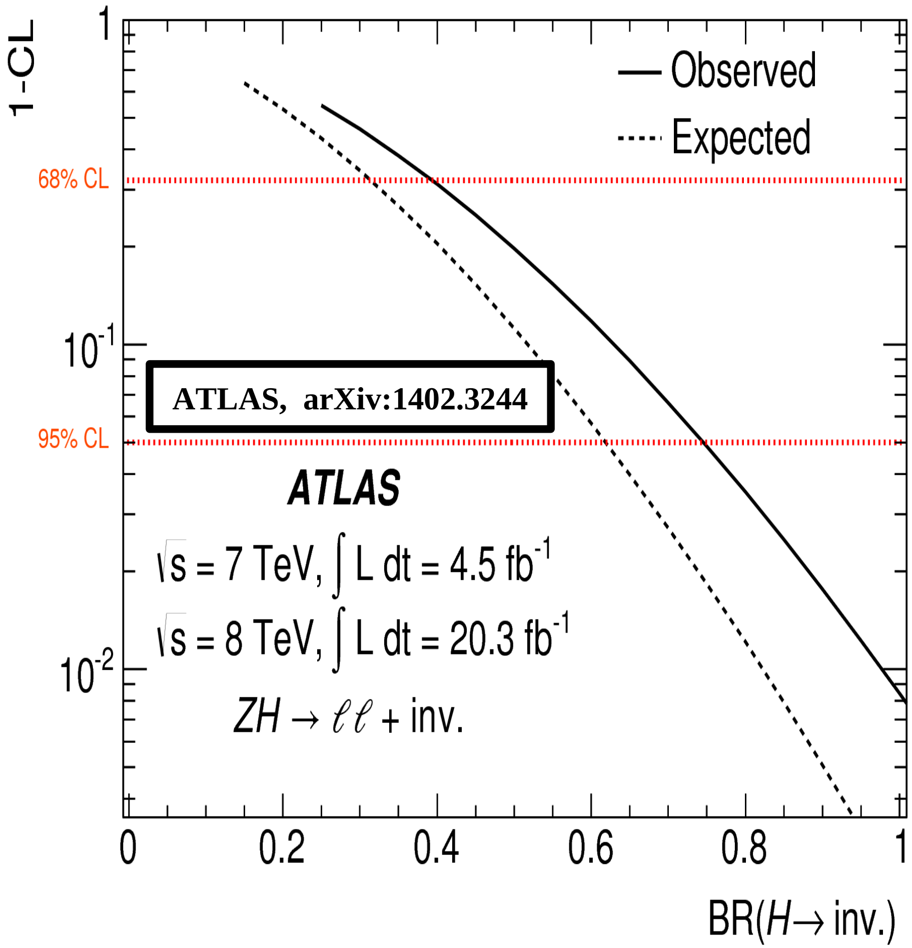


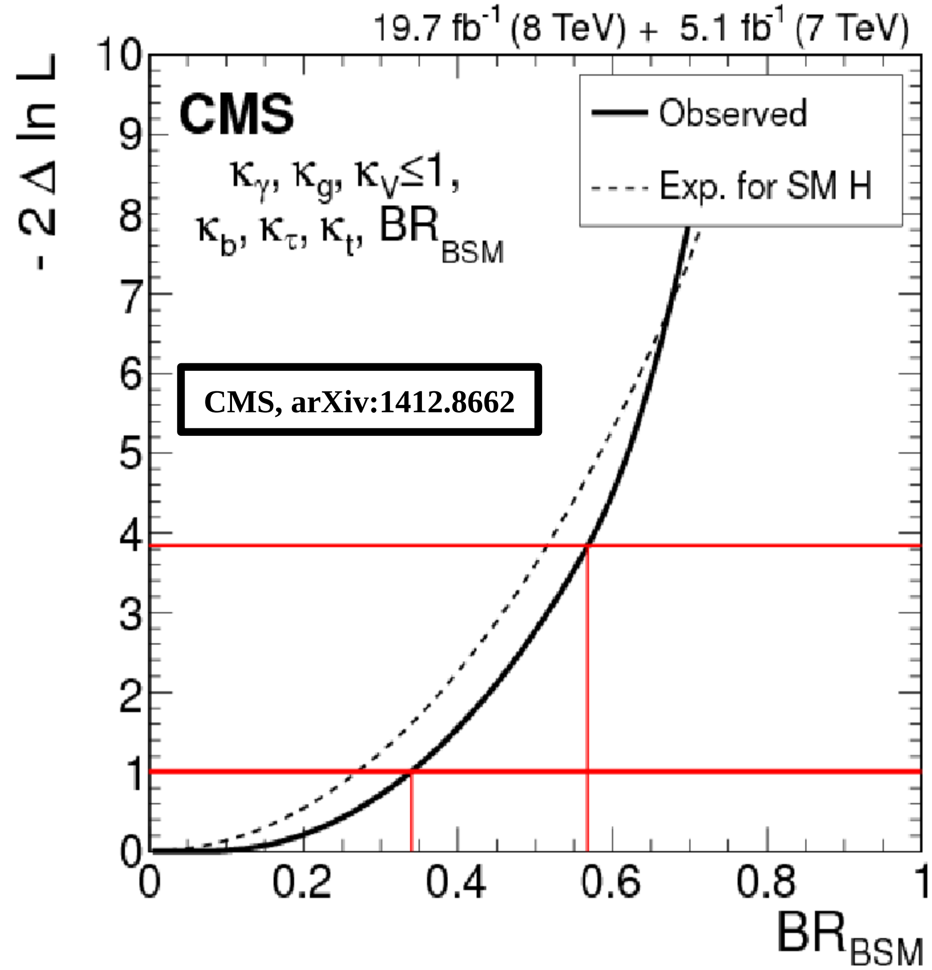
ATLAS-CONF-2015-007

CMS, arXiv:1412.8662

- 6 parameter fit (initial and final state couplings for all channels considered
  - Not so many channels 'observed' (i.e. >5σ), but properties agree remarkably well with SM predictions !

Invisible and BSM decays?



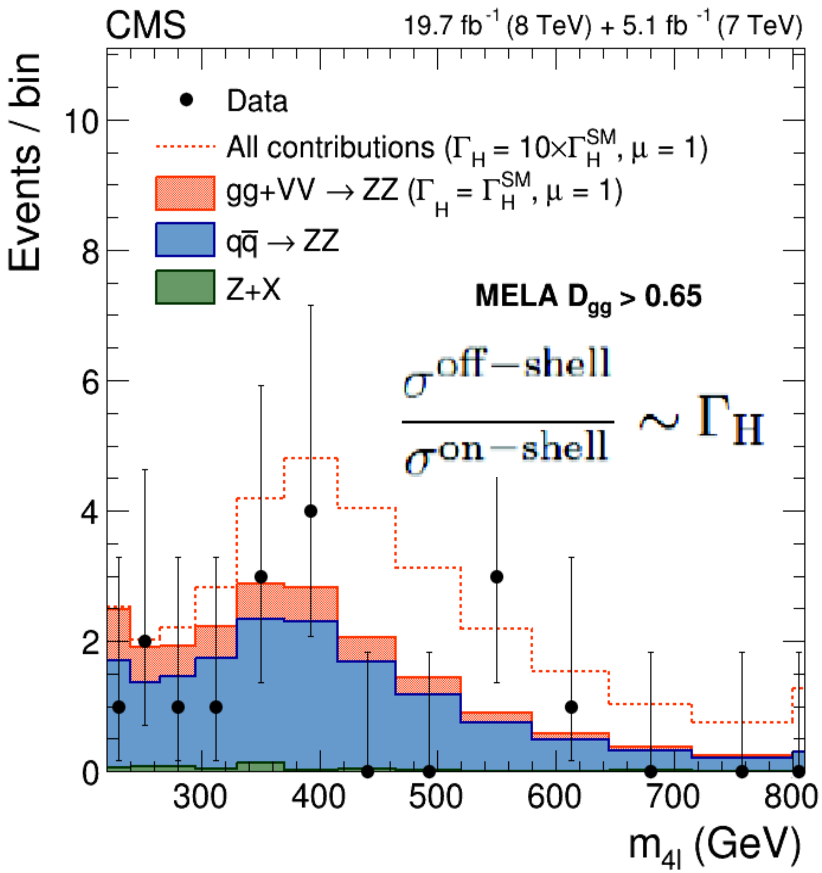


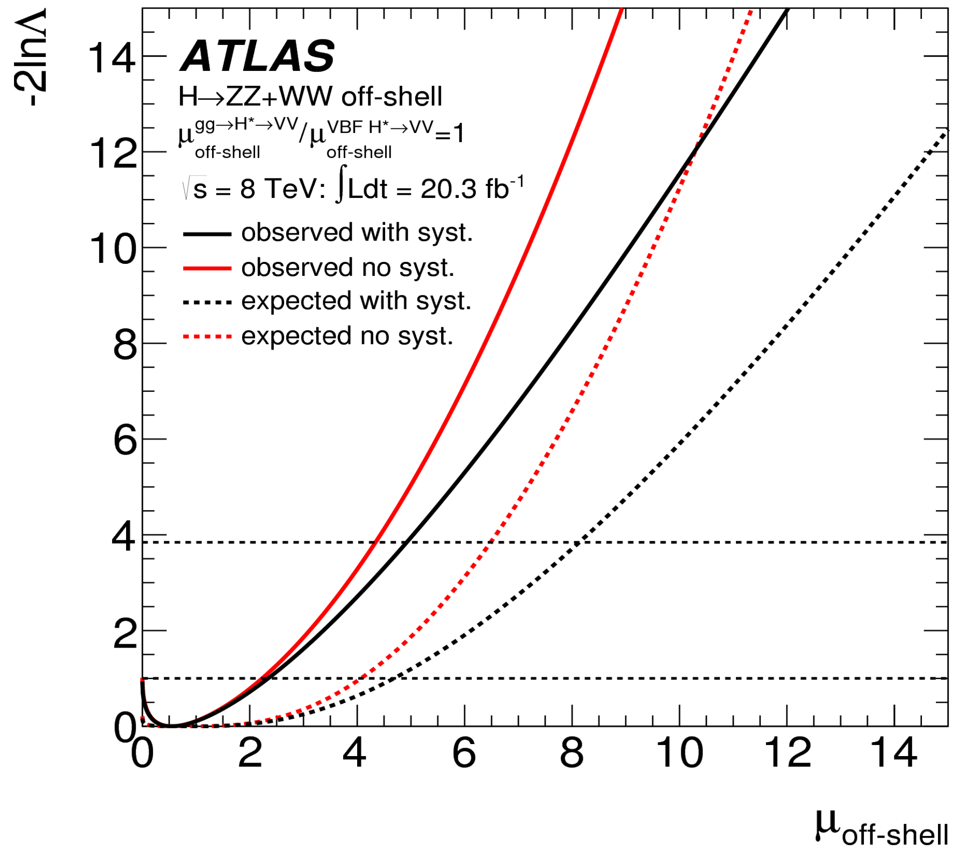
- Branching fraction limits still in the 30% (invisible) - 50% (BSM) range.
- Direct and indirect approaches used to constrain the invisible BR

The Higgs width

CMS, arXiv:1405.3455

ATLAS, arXiv:1503.01060



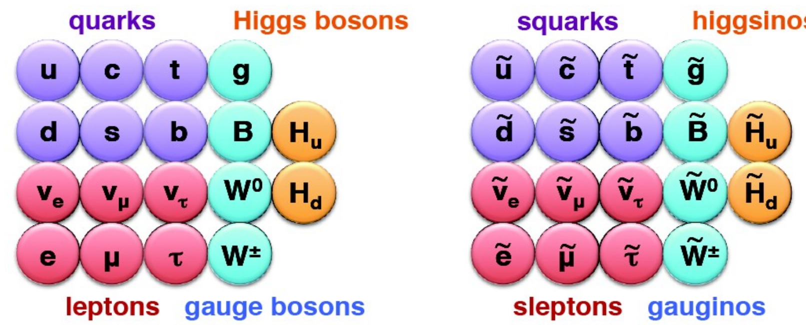


- Higgs production does not vanish so rapidly away from the Higgs resonance region, due to resonant enhancements (ZZ, WW, $t\bar{t}$):
  - Off-shell/on-shell event ratio proportional to Γ_H
  - Not fully model independent, but 'almost': gg→H mode dominating, 0^+ coupling structure, no coupling evolution in 125-400 GeV range, ...

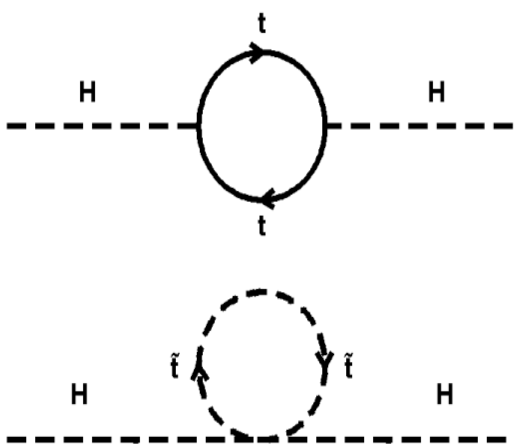
SUSY

SUSY?

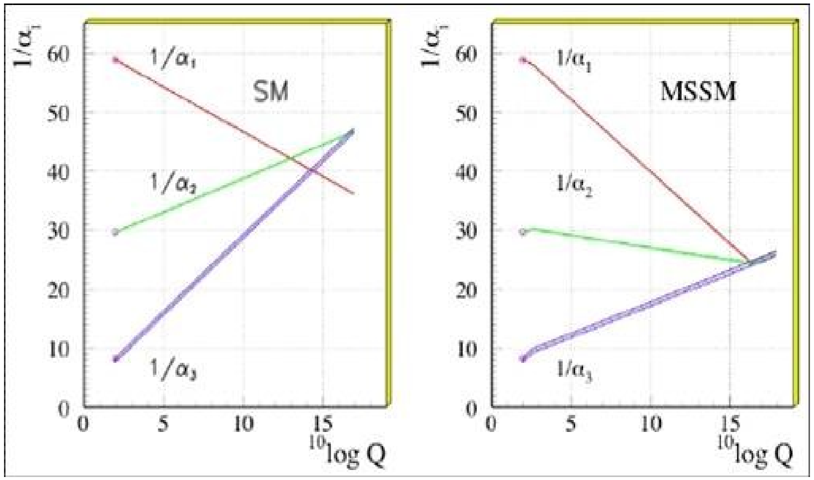
- SUperSYmmetry is a new symmetry relating bosons and fermions. For each known particle, we expect a super-symmetric partner, of spin differing by 1/2



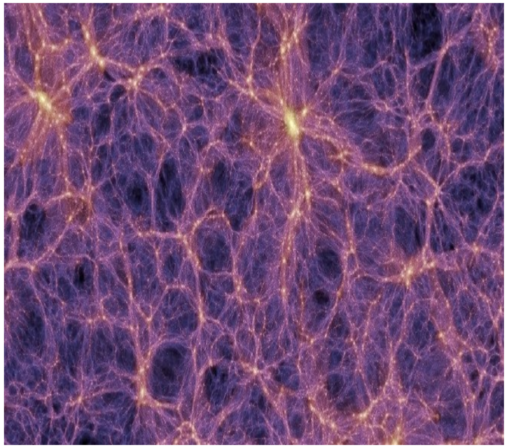
- Reasons to have SUSY realized in nature: maximal possible symmetry, connection with space-time&gravity, nicely consistent with a light Higgs boson, ...
- **But why SUSY at the TeV scale?**



Hierarchy problem solved

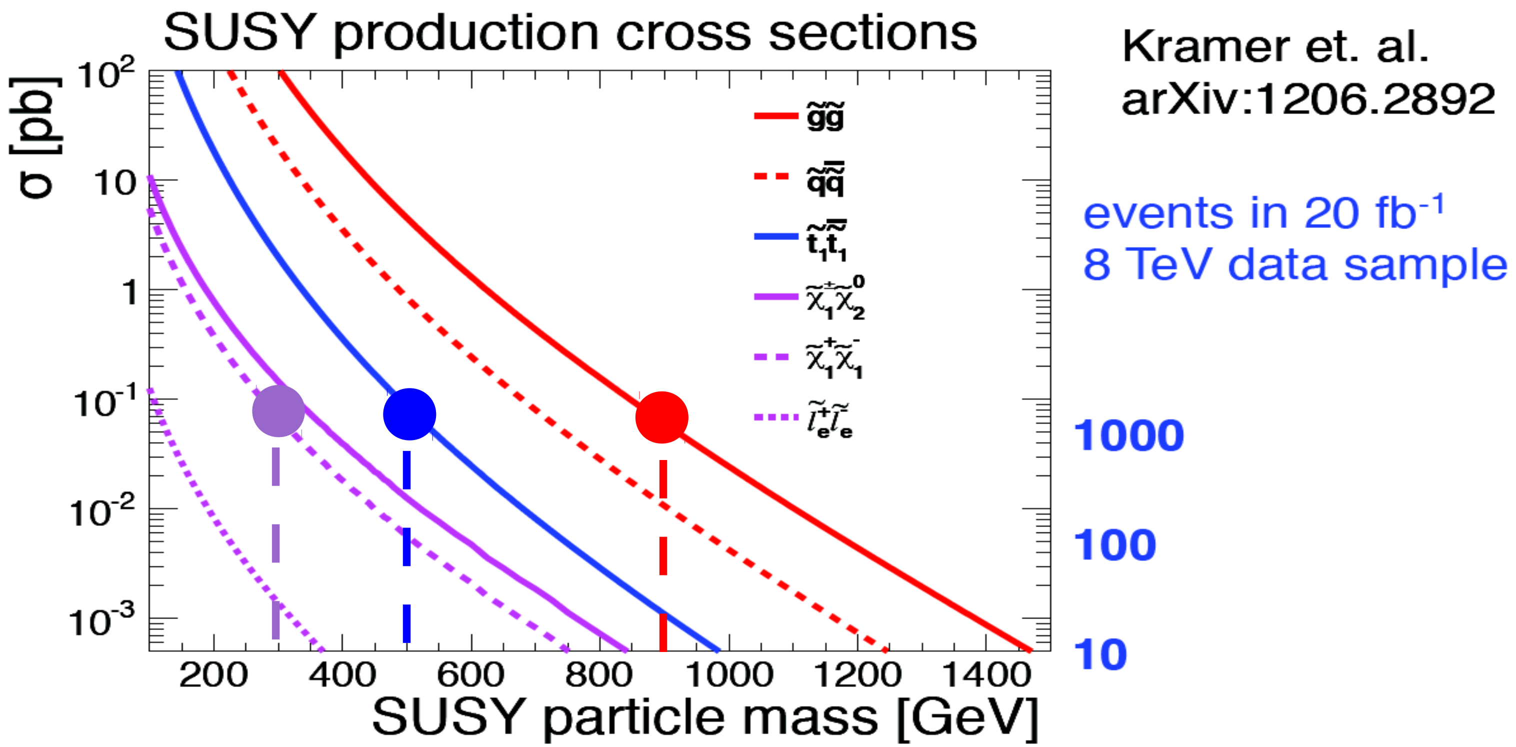


Natural unification of forces



Dark matter candidate

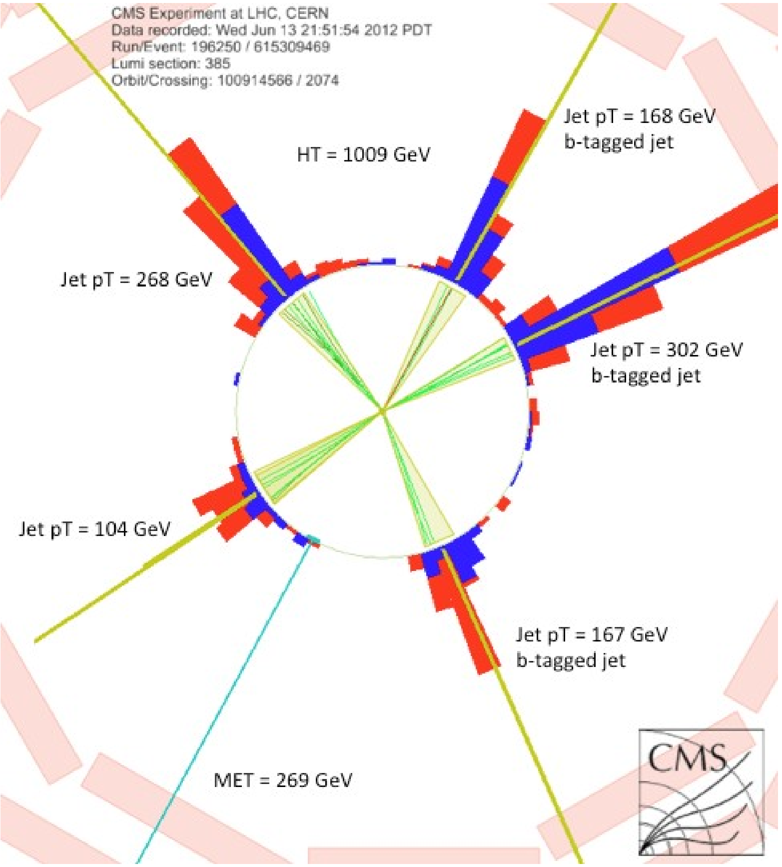
What about SUSY at the LHC?



- Production of SUSY particles fully specified by SM couplings for a mass hypothesis
- Gluino-gluino and squark-squark production: QCD driven (σ>100 pb at m=200 GeV)
- Ewkino and slepton pair production: EWK driven (σ~ 0.1-10 pb at m=100 GeV)

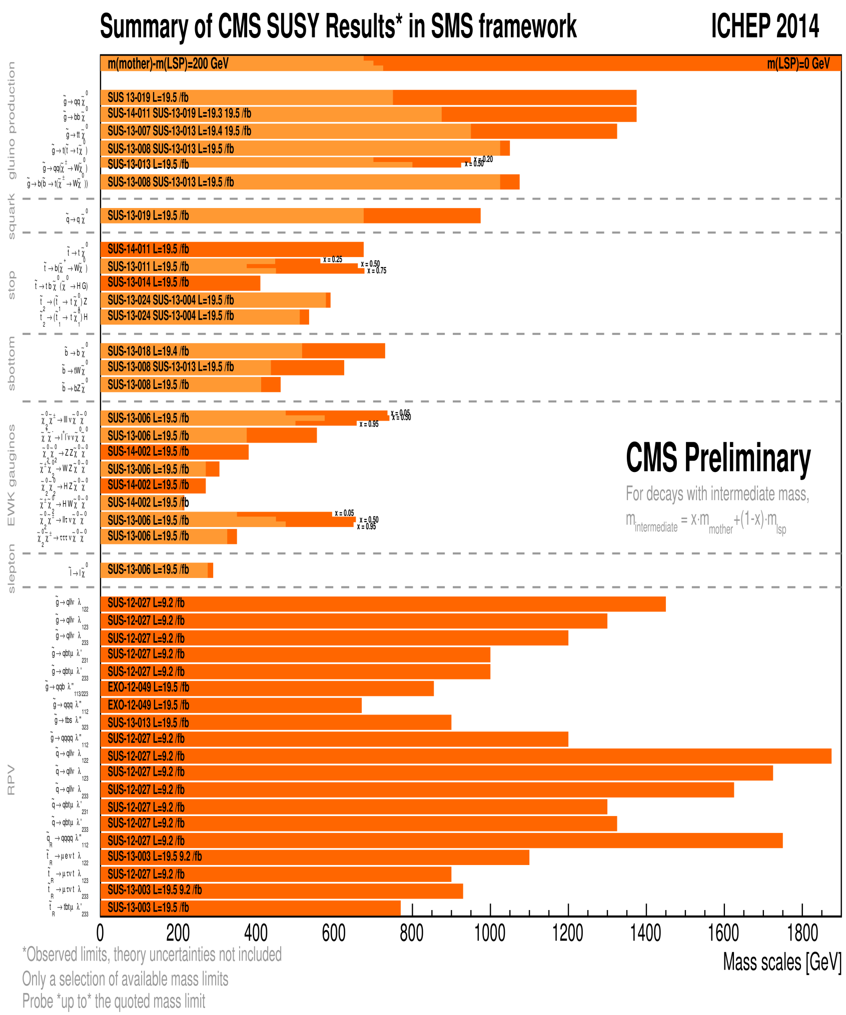
- The most stringent SUSY mass limits at the LHC are obtained by searches for gluino pair production and squark pair production, particularly if all the squarks from the different generations get similar masses.

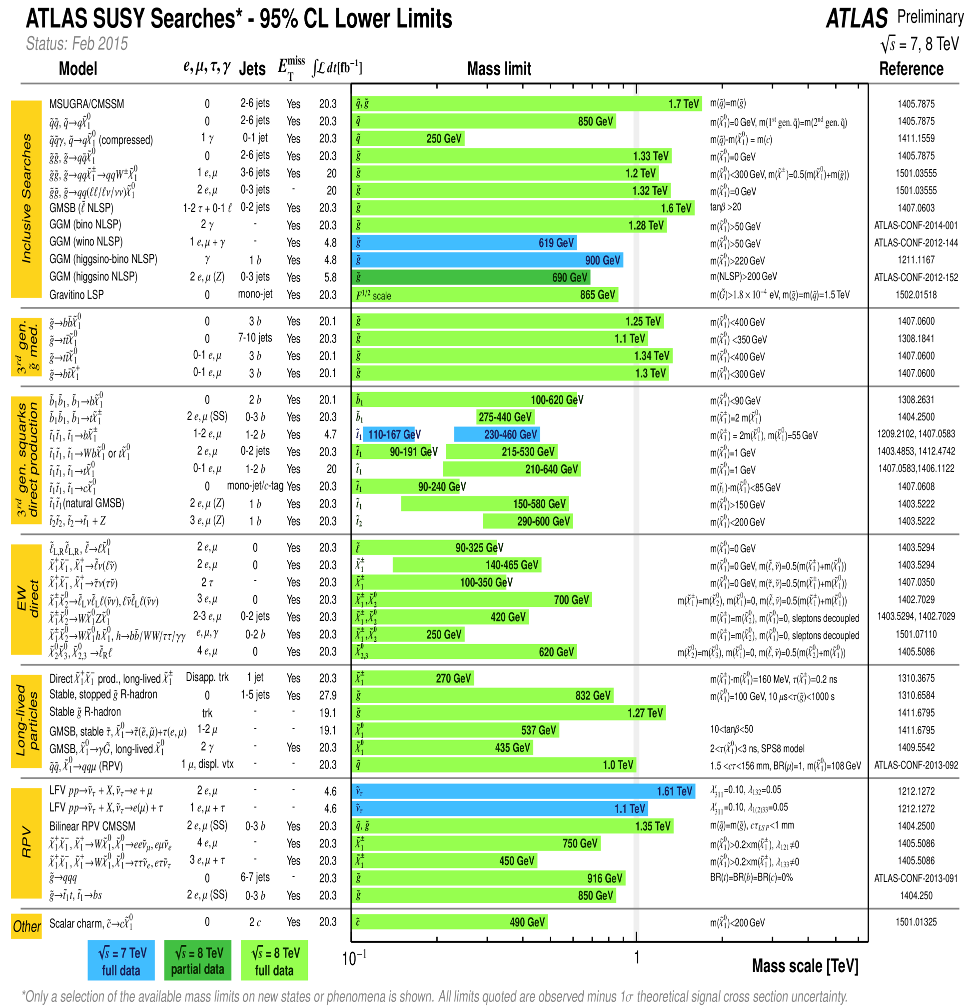
Looking for SUSY at the LHC



- Basic feature of SUSY signals in many scenarios at the largest explored masses:
  - High visible mass
  - High missing transverse energy/masses when there is a neutral lightest stable particle (LSP)
  - B-tagged jets for 3rd generation focused searches
  - Final states with electrons, muons, taus, lepton pairs (same-sign), or even multileptons for searches with ewkinos, sleptons and tops in the final state

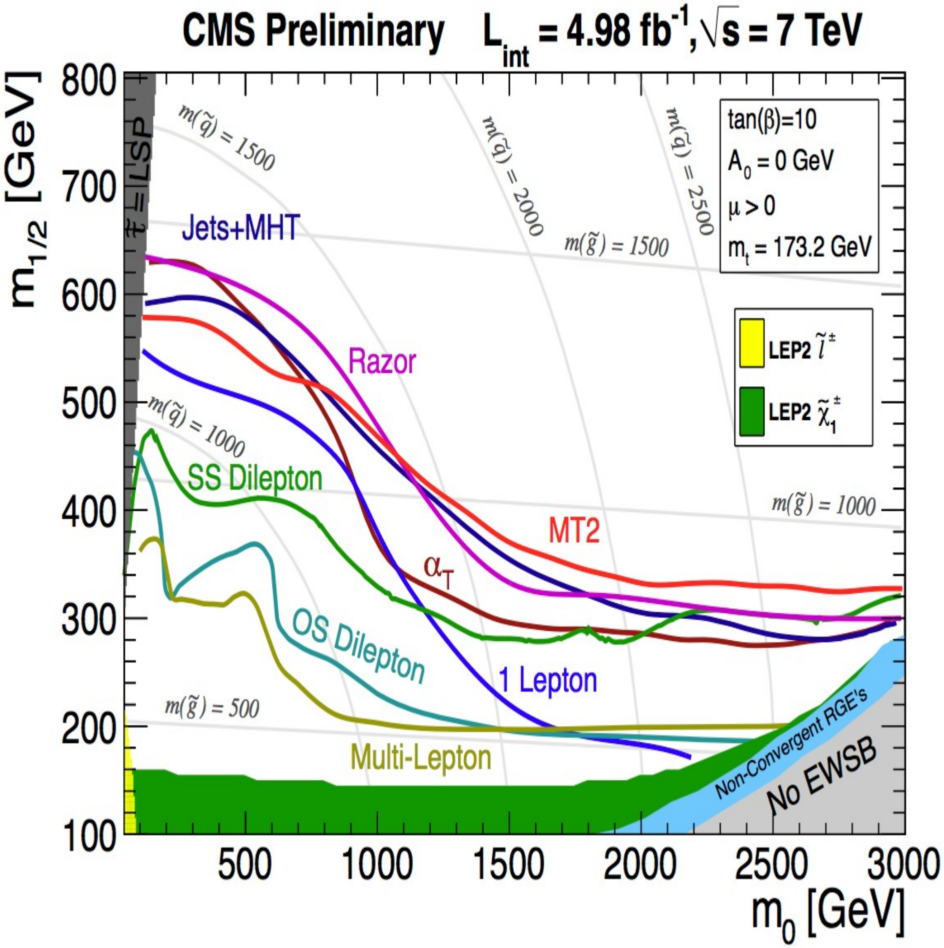
Summary of SUSY searches at the LHC

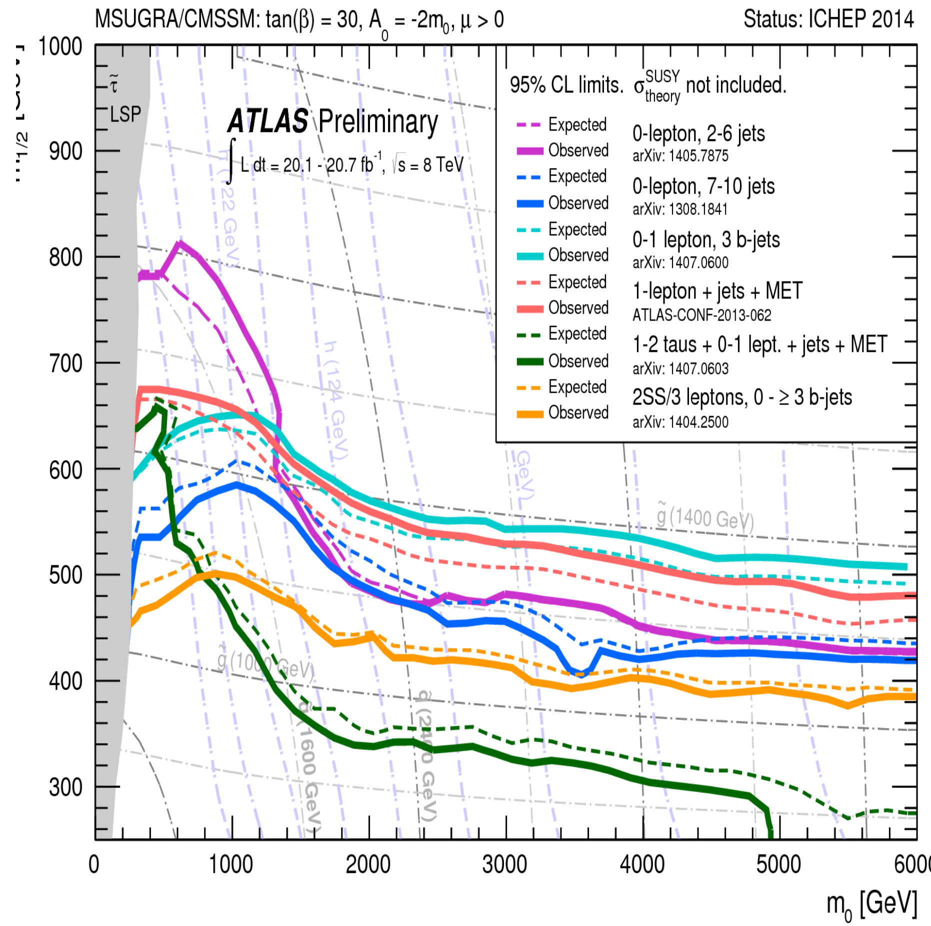




- Many possible signals explored. No evidence of SUSY yet. Several lower limits to masses are already around the TeV.

Naive approaches already exhausted





- A significant fraction of the available phase space in the “Constrained” Minimal Supersymmetric Standard Model (CMSSM) was already excluded with 7 TeV data, and also in the post-Higgs era for scenarios consistent with m_H≈126 GeV

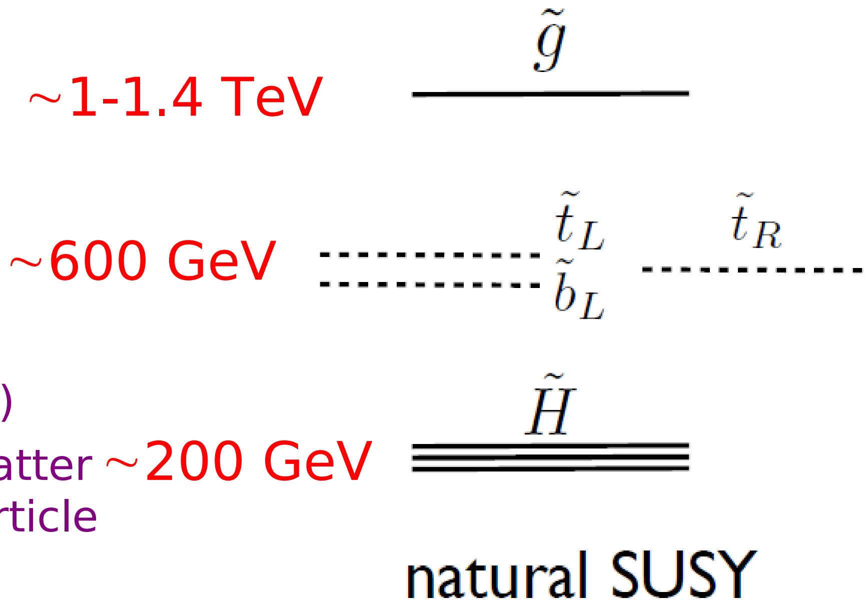
Still 'natural' SUSY?

- Minimal conditions to be satisfied:
  - The MSSM imposes tight constraints on the masses of Higgsinos and stop sector, since they are directly related to the EWK scale:

Stop, gluino

Higgsino

$$M_Z^2 = -2\mu^2 + 2\,\frac{m_{H_d}^2 - t_\beta^2\, m_{H_u}^2}{t_\beta^2 - 1}$$

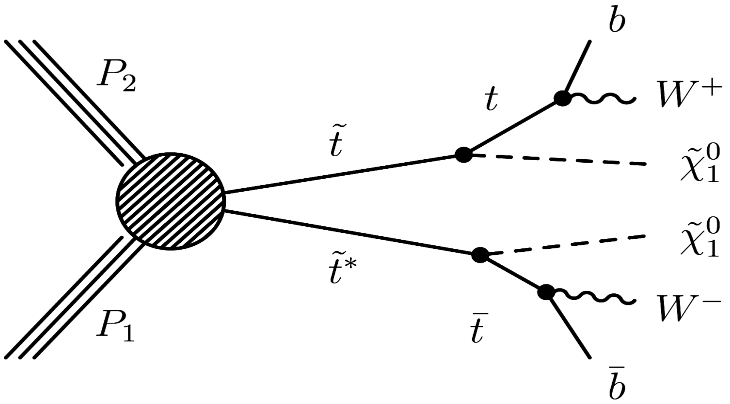


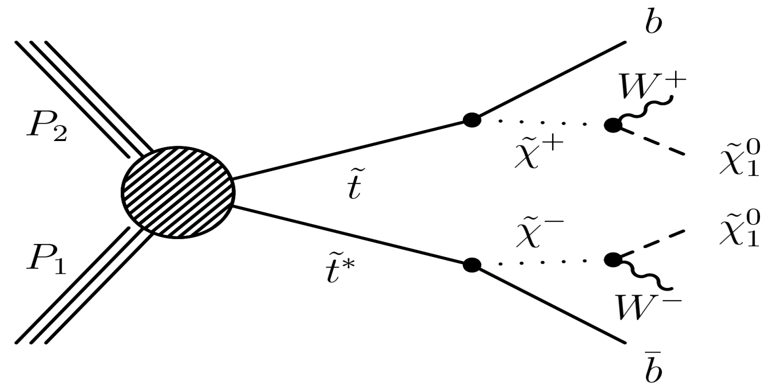
(example from arXiv:1110.6926)

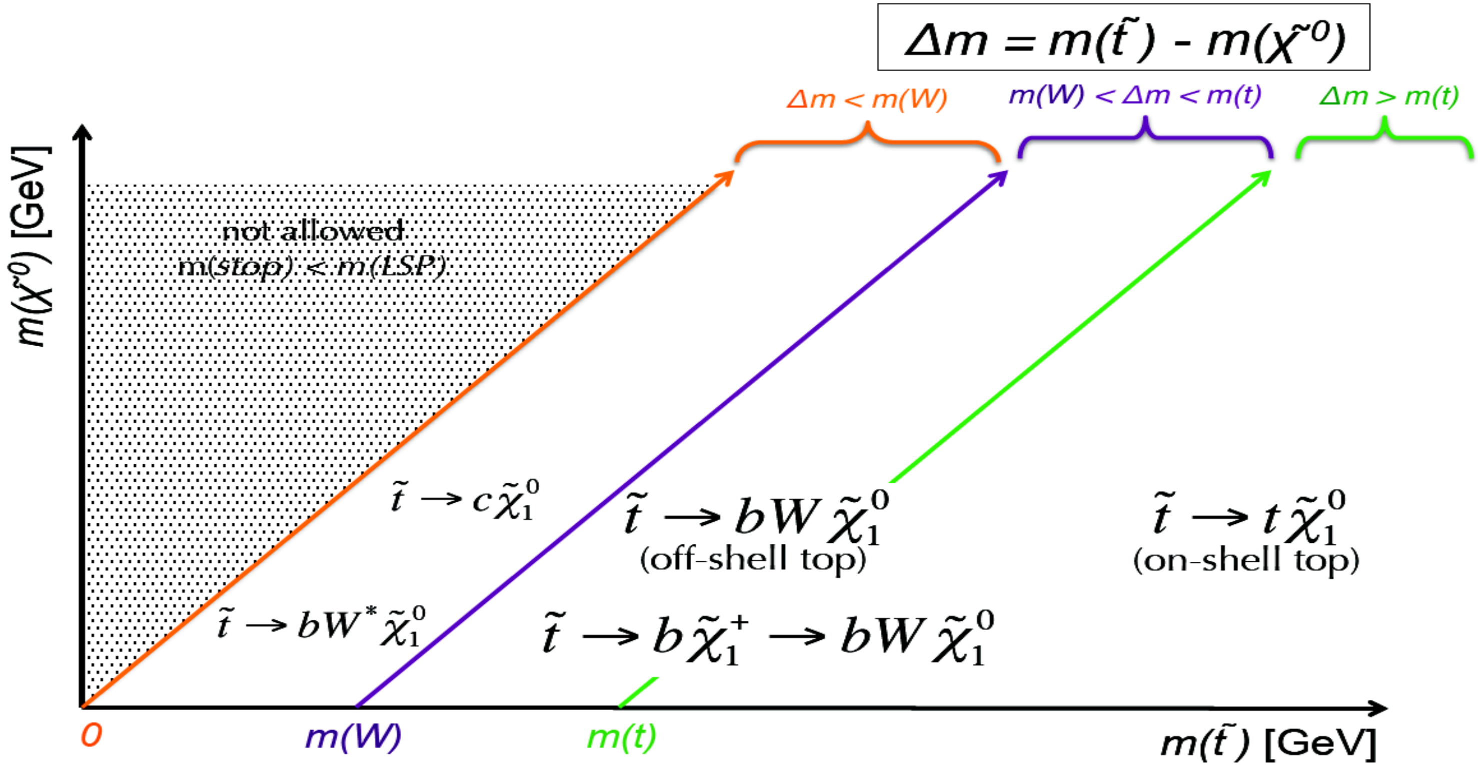
  - The gluino can not be too massive (it contributes to the stop mass via loops)
  - One of the Higgsinos can be a dark matter candidate if it is the lightest stable particle (LSP).
  - The sbottom-left and the stop-left masses are related

- The rest of the SUSY spectrum can be decoupled (=>much higher masses) without being in contradiction with low energy physics constraints

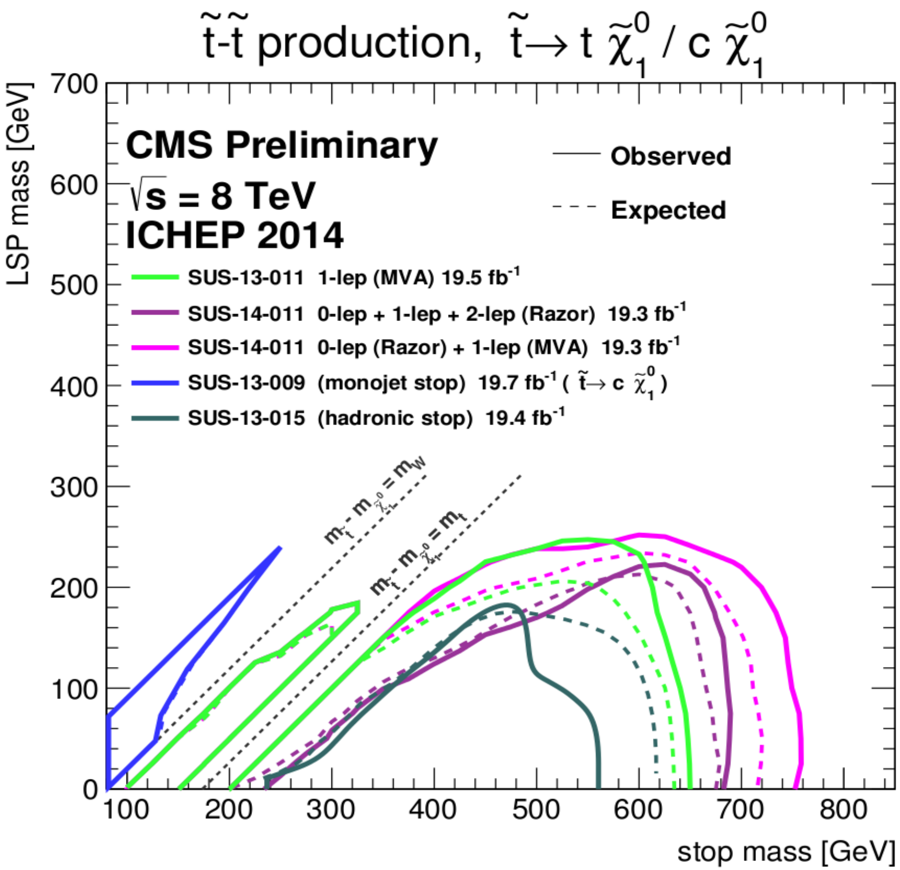
Direct scalar top searches

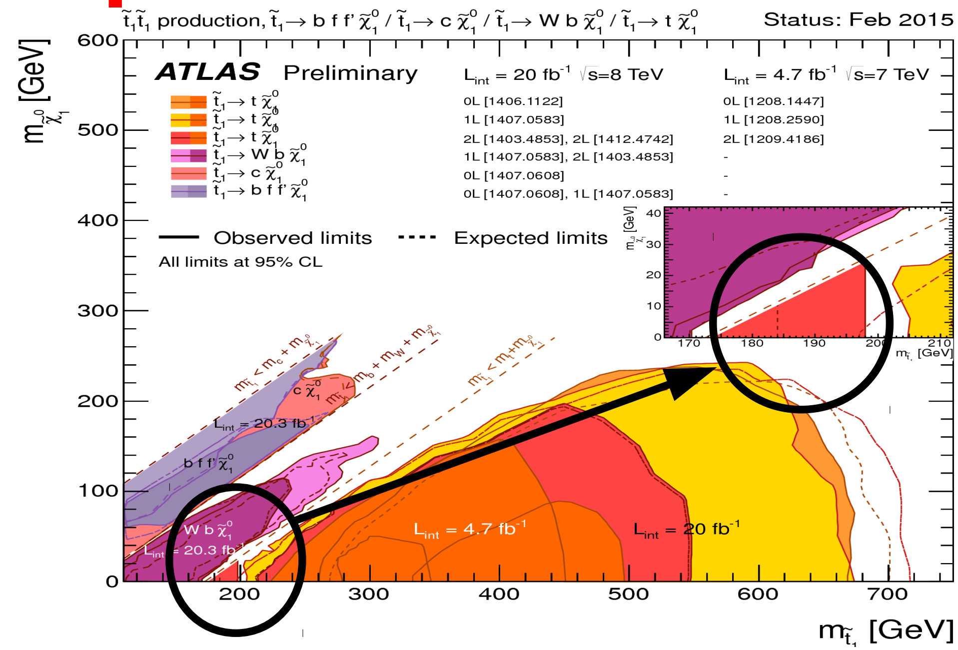


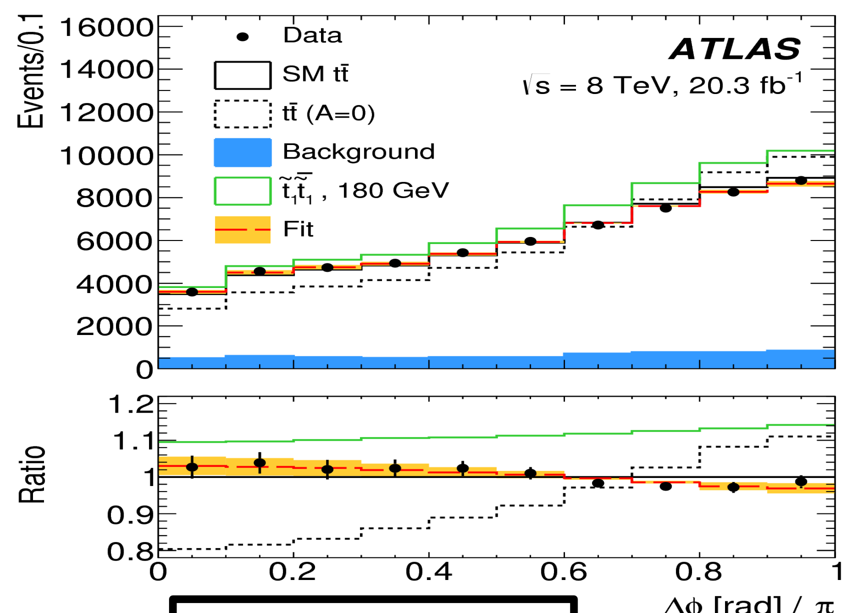




Direct scalar top searches







- Maximal reach at Run1 ~ 750 GeV
- Looking for stop->t+X even in regions where it can be hardly distinguished from pure $t\bar{t}$ production (helicity studies)

ATLAS, arXiv:1412.4742

What do we expect this year?

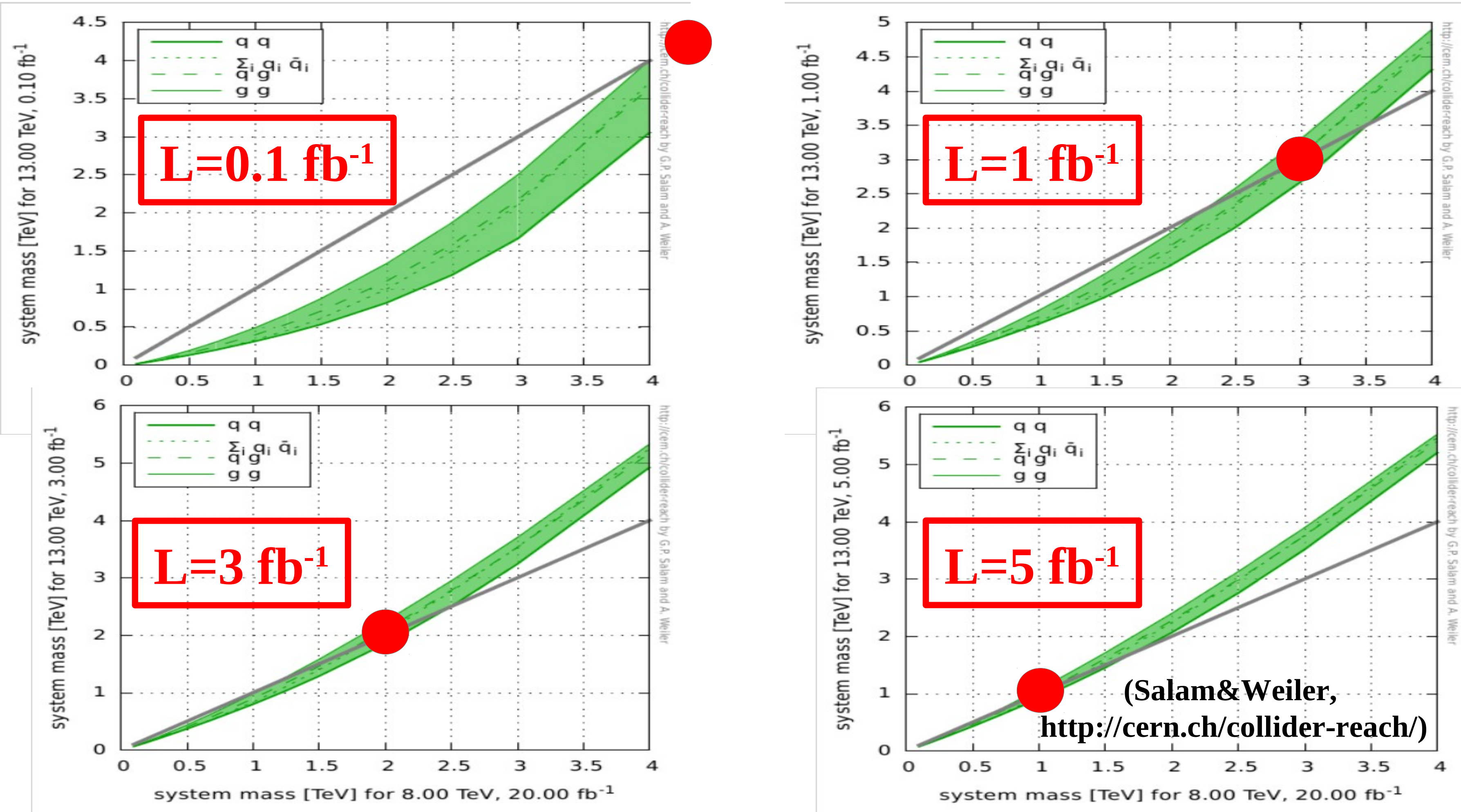
2015 commissioning strategy

- **Low intensity commissioning of full cycle – 8 weeks**
- Pilot physics – low number of bunches
- Special physics run: LHCf and luminosity calibration
- Scrubbing for 50 ns
- Intensity ramp-up with 50 ns
  - Characterize vacuum, heat load, electron cloud, losses, instabilities, UFOs, impedance
- Scrubbing for 25 ns
- Ramp-up 25 ns operation with relaxed beta*
- Possibly commission lower beta*
- 25 ns operation

- Basic target in 2015:
  - 1 fb^{-1} of integrated luminosity with 50 ns bunch spacing
  - 5-10 fb^{-1} of integrated luminosity with 25 ns bunch spacing

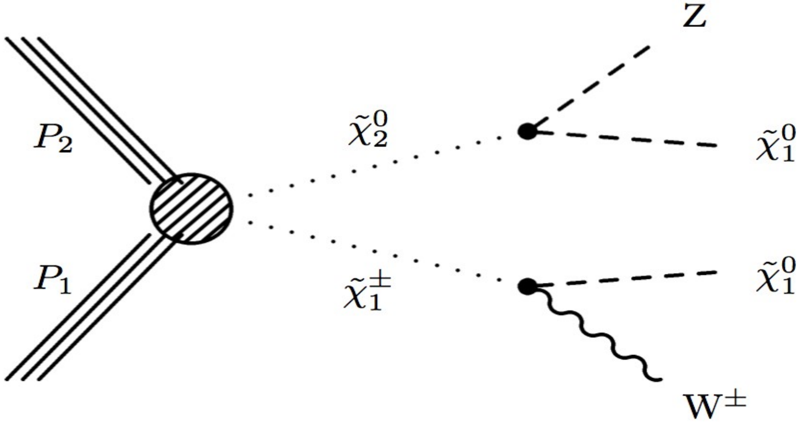
Enough to improve over all existing LHC Run1 searches for masses/scales > 1 TeV

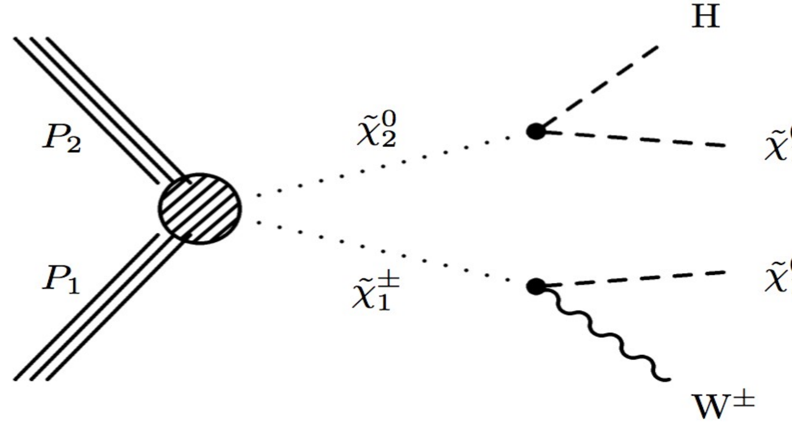
LHC reach in 2015

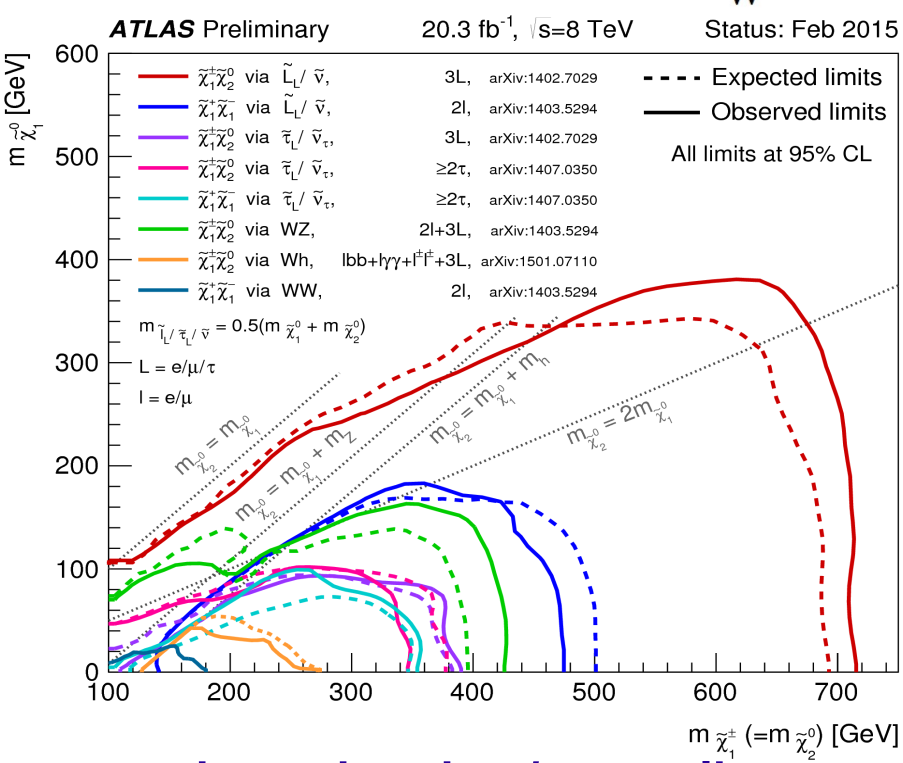


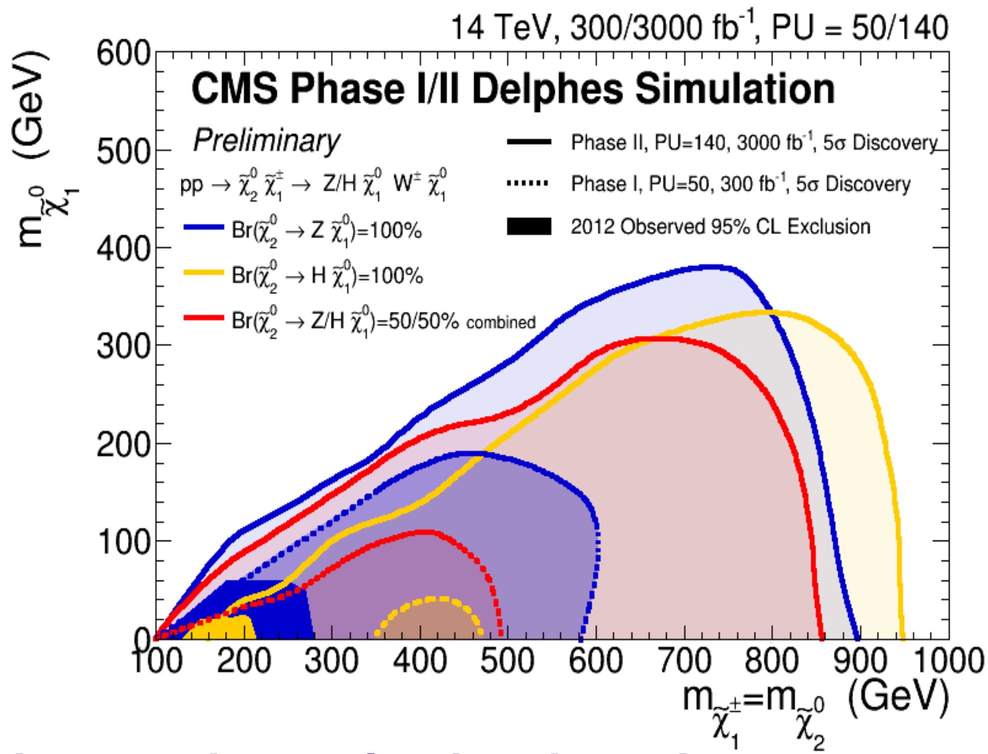
- More sensitive than Run1 to masses ≳3 TeV with just 1 fb^{-1} in Run2
- Essentially better than Run1 for most searches with 5 fb^{-1}:
  - Improved sensitivity to gluinos and stops already in 2015.

SUSY reach in LHC for ewkinos





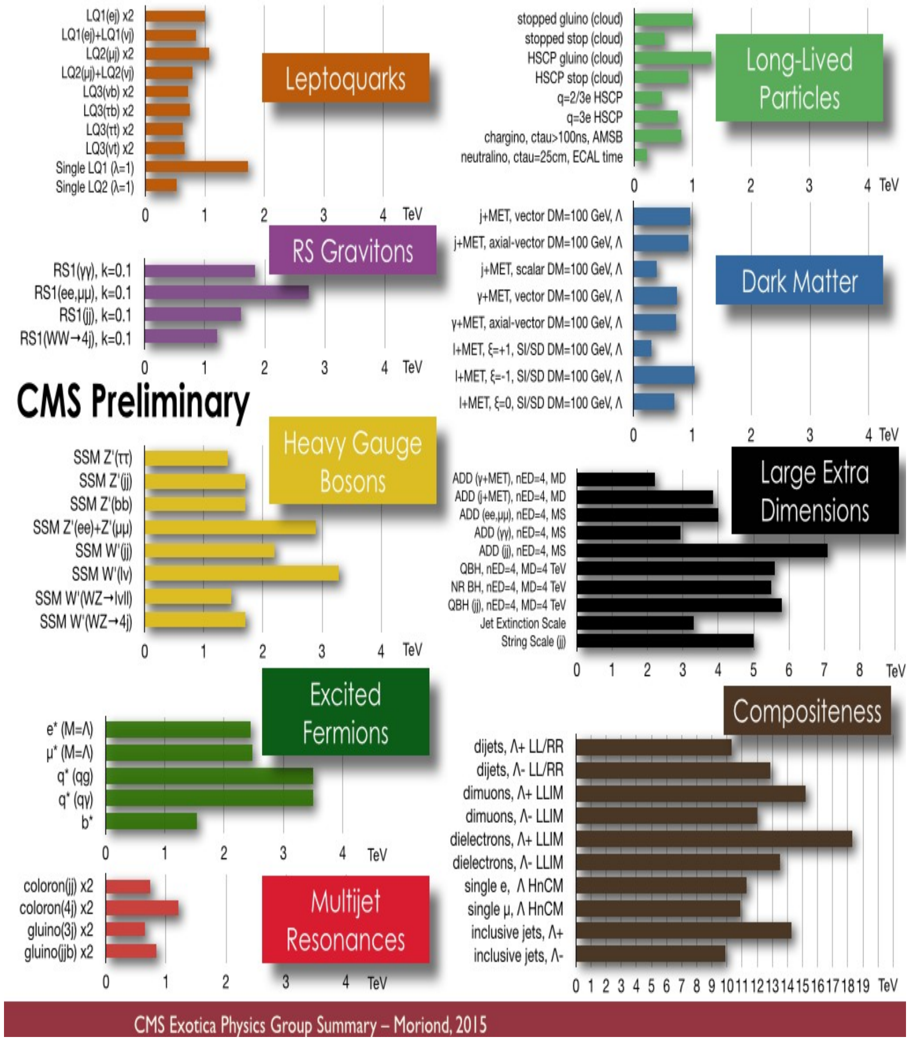


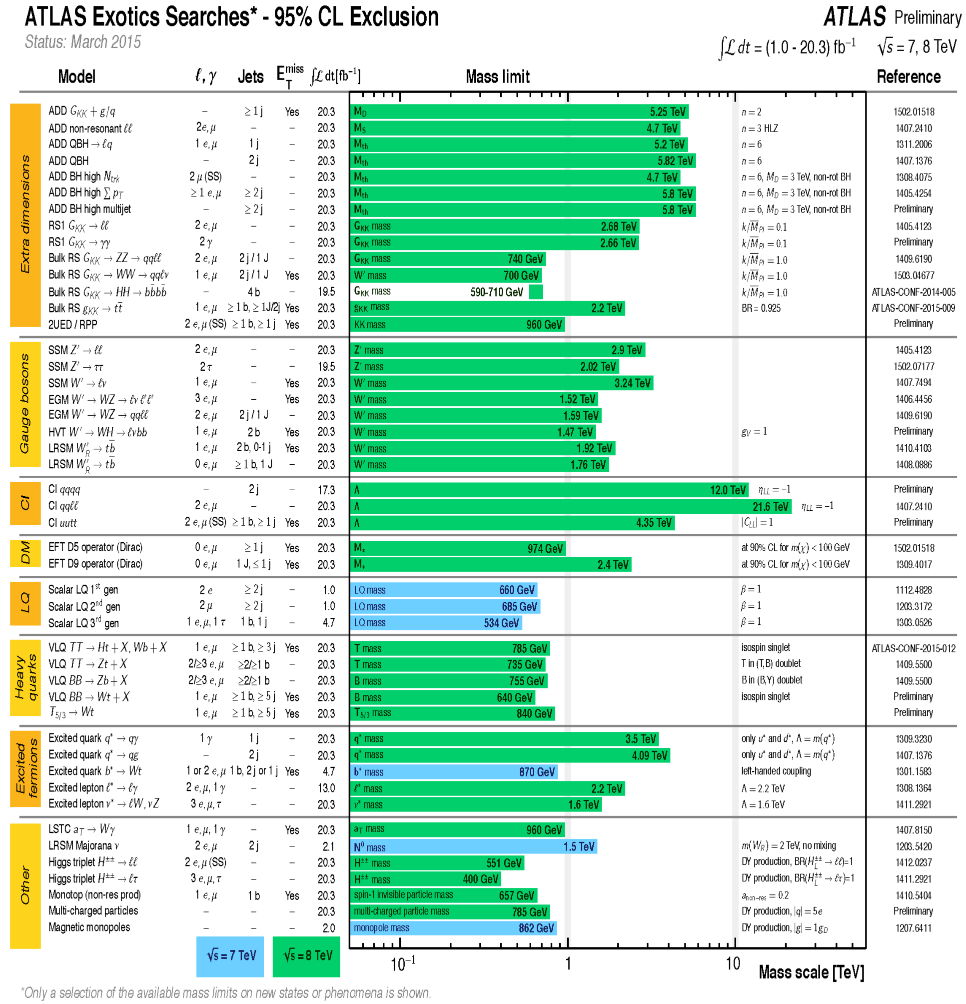


- **Direct chargino / neutralino searches need more luminosity to improve**

EXOTICA

Exotica as alternative

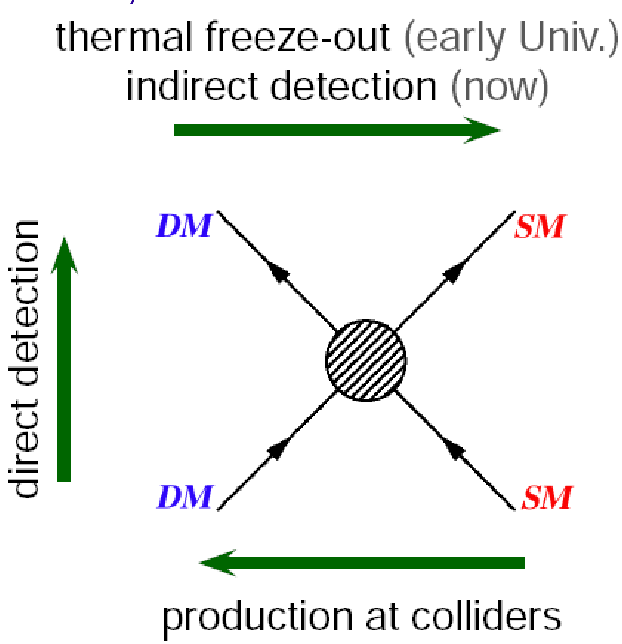


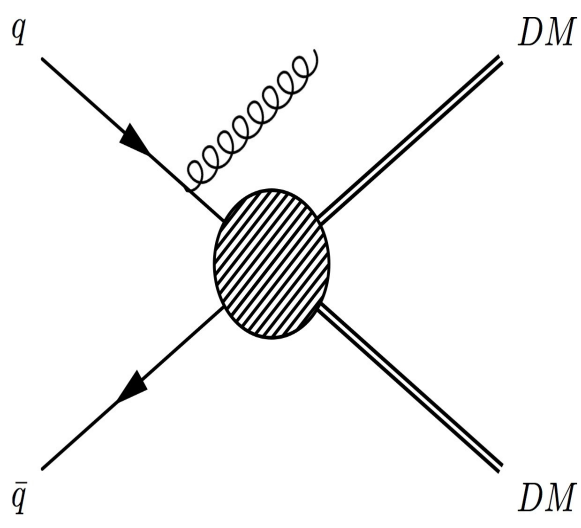


- No evidence (yet) for alternative solutions to the BSM puzzle. Nevertheless, we keep looking for new effects. This talk is just giving a very brief overview of the most relevant search strategies today and next plans.

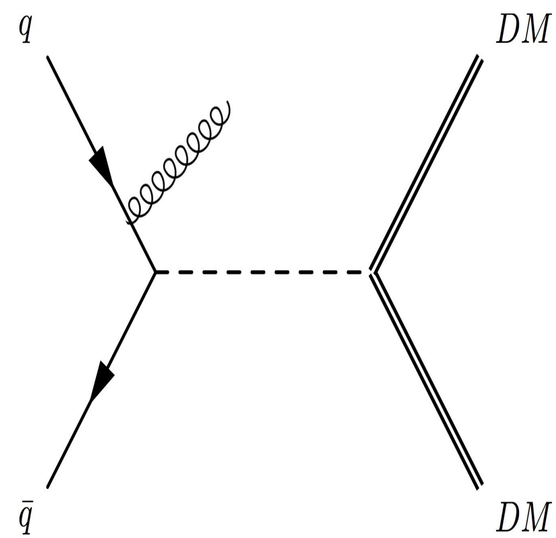
Dark matter (DM) fever

- Lots of interest and hope to find evidence of dark matter production in LHC Run2 !!
- LHC approach is complementary to direct/indirect searches:
  - Main signature exploited at the LHC: missing transverse energy associated to visible jets, EWK bosons, ...
  - Recent developments in the theory front to improve the theoretical description and to better match direct detection interpretations:
    - Effective Lagrangians -> Simplfied Models -> True Models (SUSY, ...)
- Not necessarily the next hint of dark matter connections at the LHC. We can get first an observation in SUSY decay chains, or the discovery of a new mediator in dijet or dilepton final states, ...





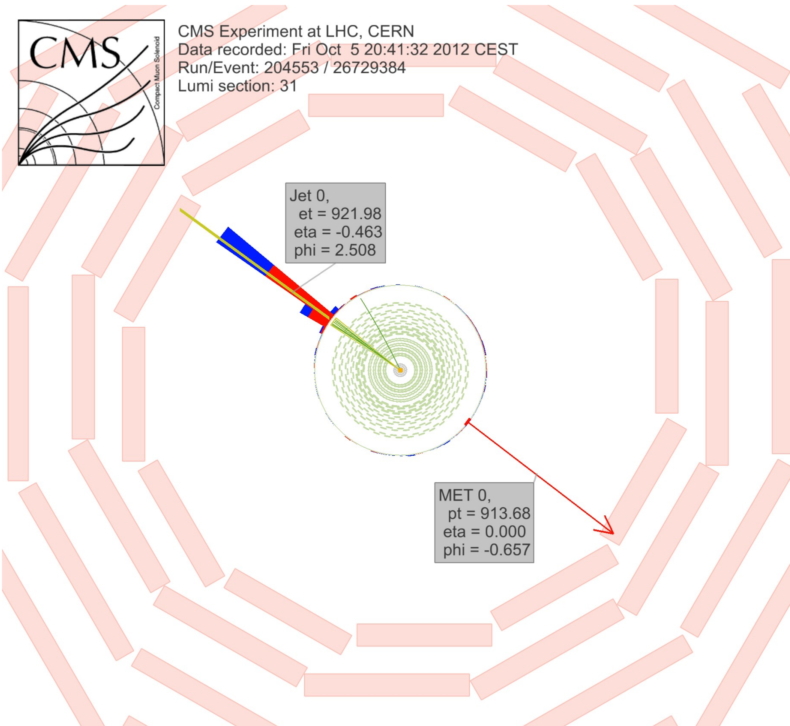
Effective Interaction at LHC



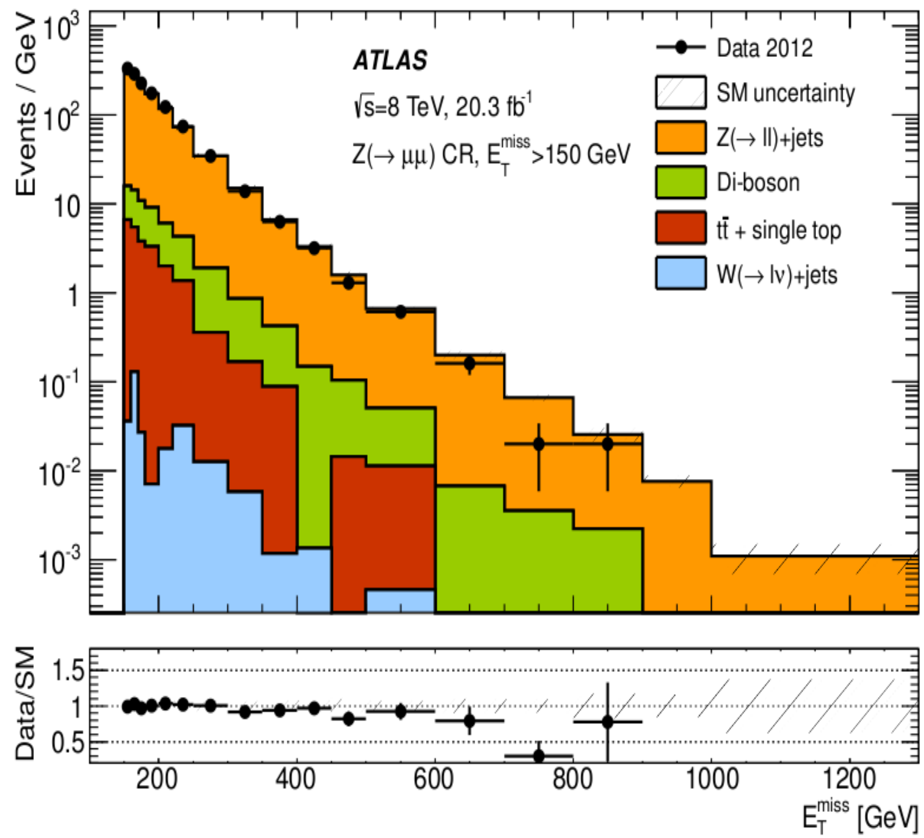
Simplified Model at LHC

DM searches at Run1: monojet signature

- Most sensitive channel in most scenarios (sizable ISR QCD radiation):
  - Large missing transverse energy recoiling against a high p_T jet
  - Critical points: trigger thresholds, missing E_T tails, controlling backgrounds (jets+$Z(\nu\bar{\nu})$, ...)

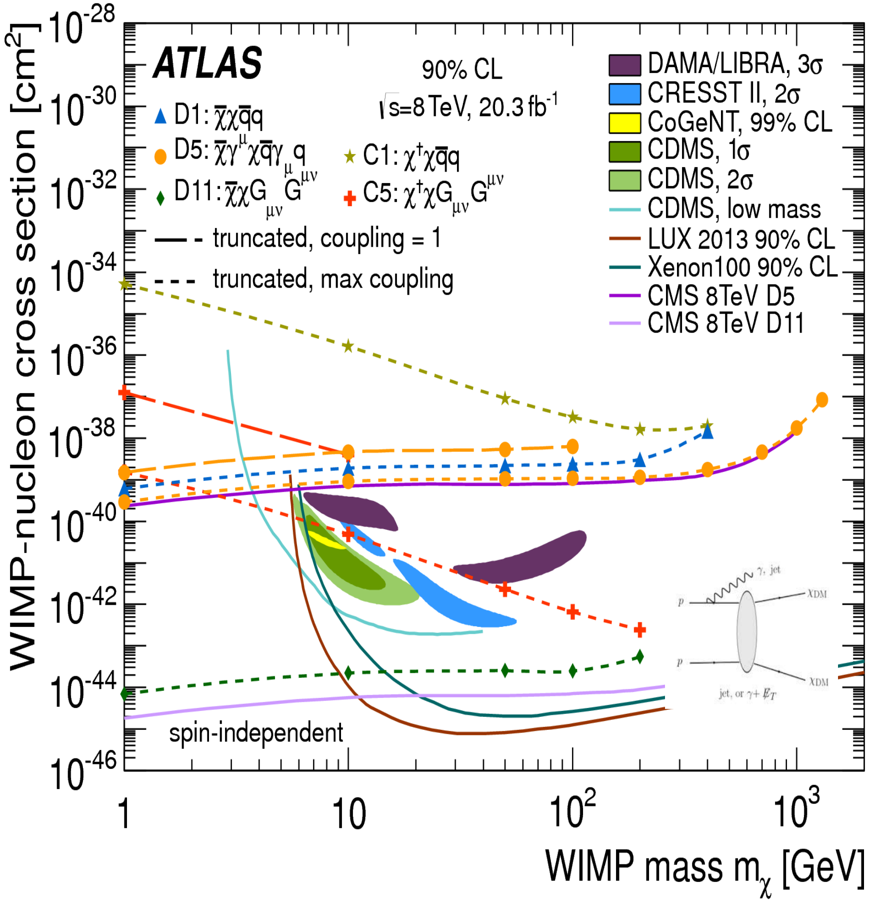


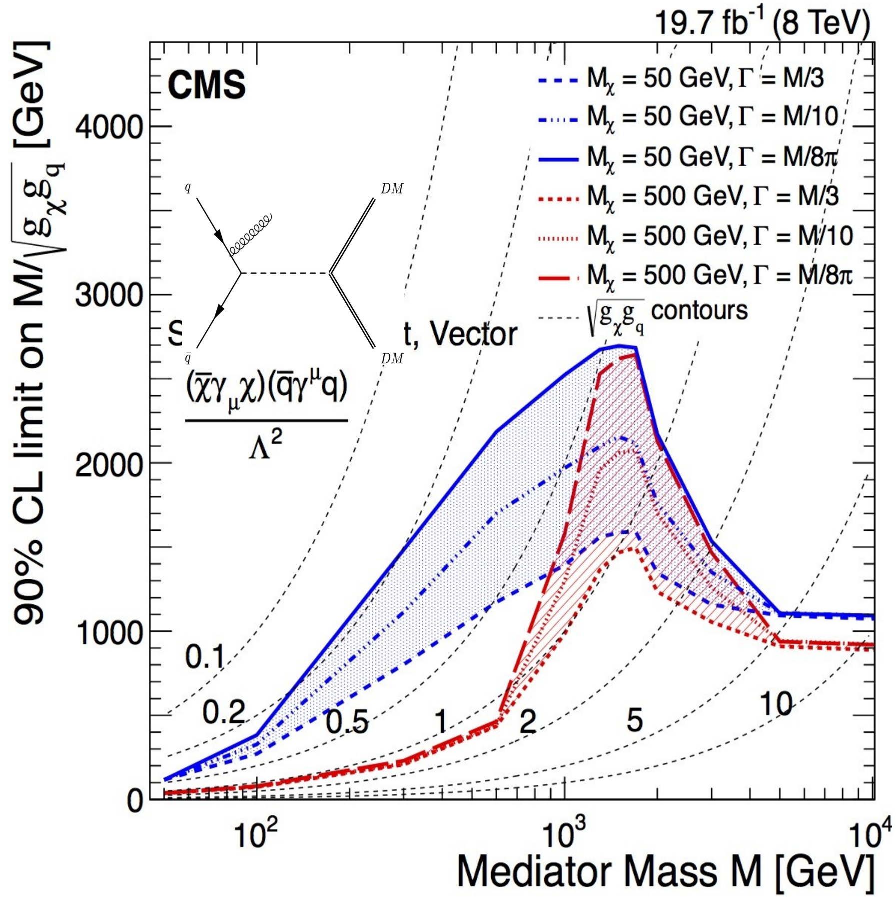
CMS, arXiv:1408.3583



ATLAS, arXiv:1502.01518

DM searches at Run1: monojet signature





Effective Model (truncated at Q=mediator mass => conservative for comparisons with direct detection limits)

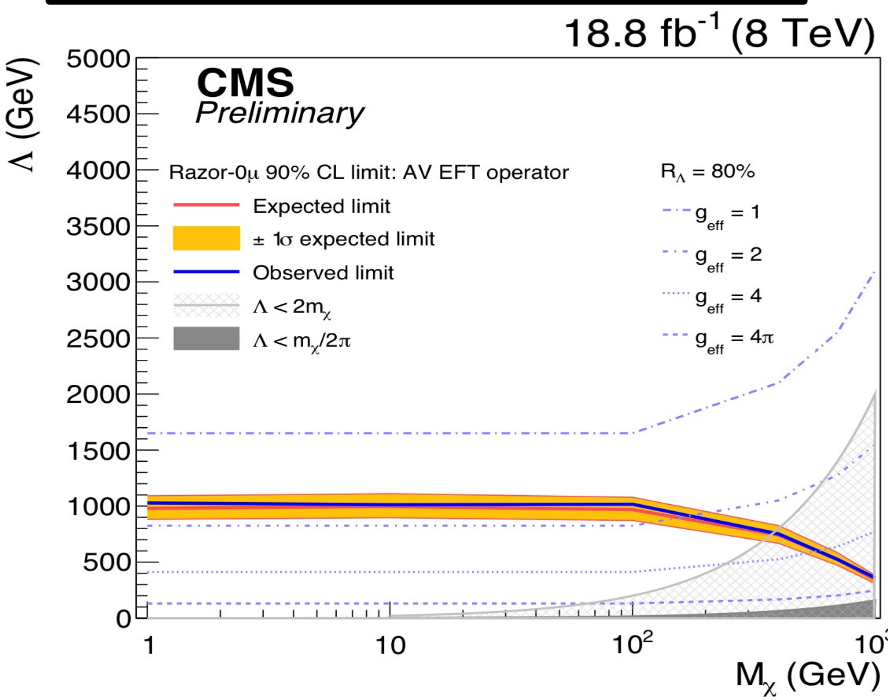
Simplified Model (closer to a real scenario with a dominant mediator resonance) More free parameters to play with: M, Γ

- Current limits on scale/mediator mass: ≳ 1 TeV.
- Improving limits in Run2 already with 5 fb^{-1} of integrated luminosity.

More DM + X searches at Run1

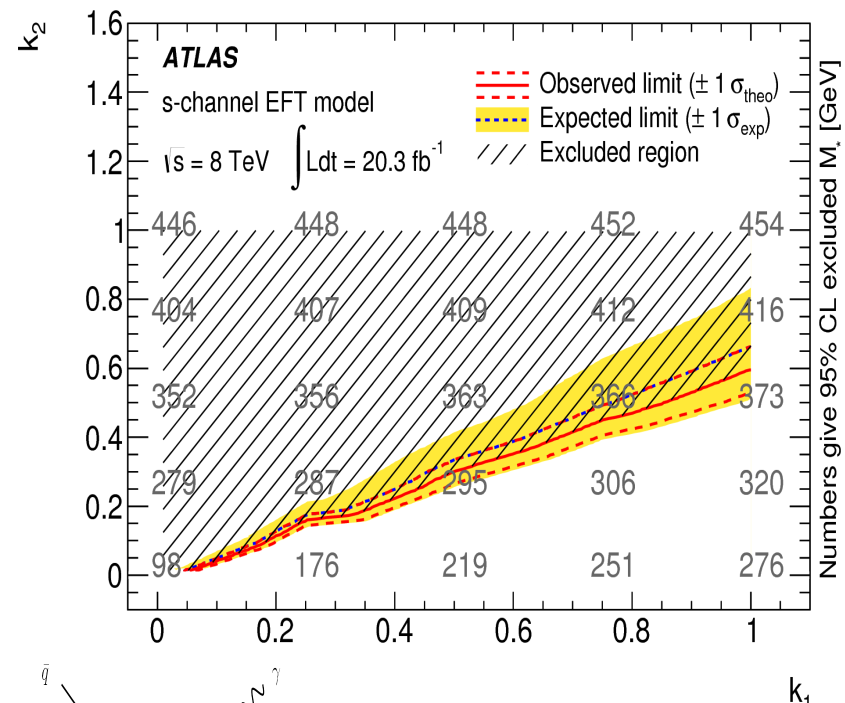
- Similar production mechanisms when compared to the monojet case, but :
  - Dijets + DM production (recycling multijets+missing energy SUSY searches, for instance)
  - Different coupling strength to u and d quarks in the W/Z/γ + DM case
  - Special connections with 3rd generation? $t\bar{t}$+DM, $b\bar{b}$+DM, FCNC leading to t+DM, b+DM, ...
  - Higgs to DM ? Dark sector connection? ...

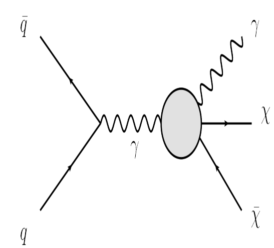
Razor 2j+DM: CMS-PAS-EXO-14-004



Sensitivity similar to monojet+DM analysis

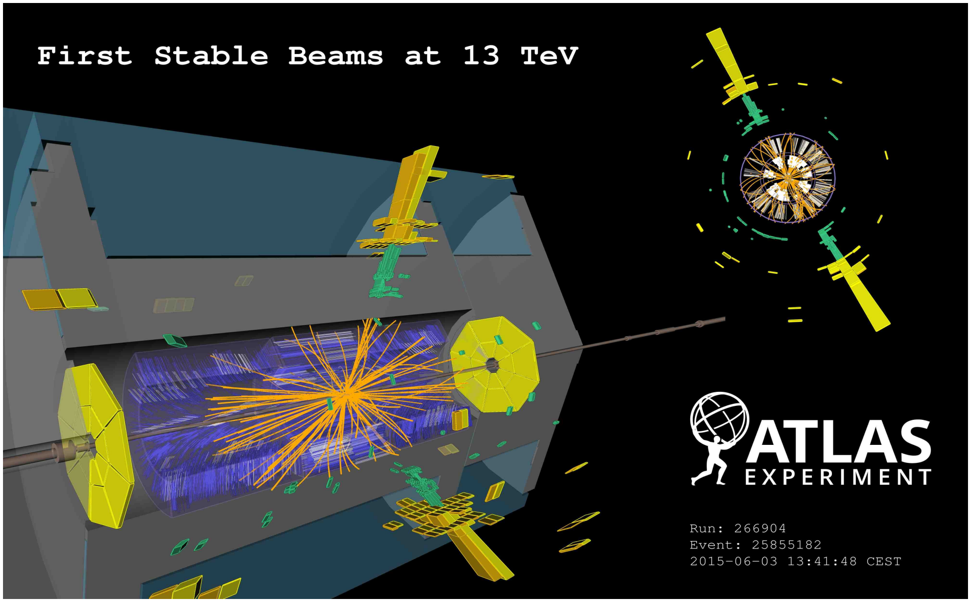
ATLAS γ+DM: arXiv:1411.1559

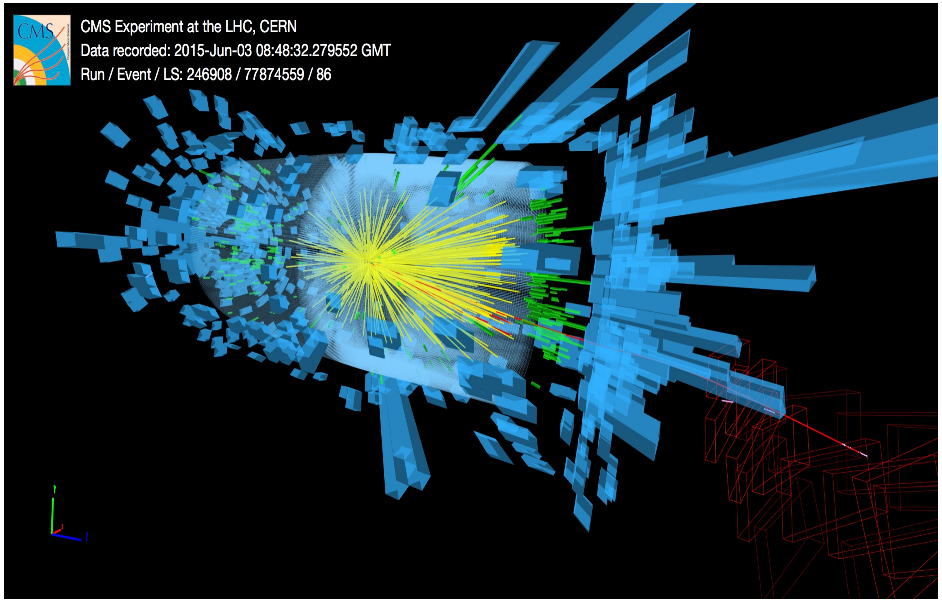




Probing γγχχ interactions too (Fermi-LAT motivated)

VERY EARLY SEARCHES

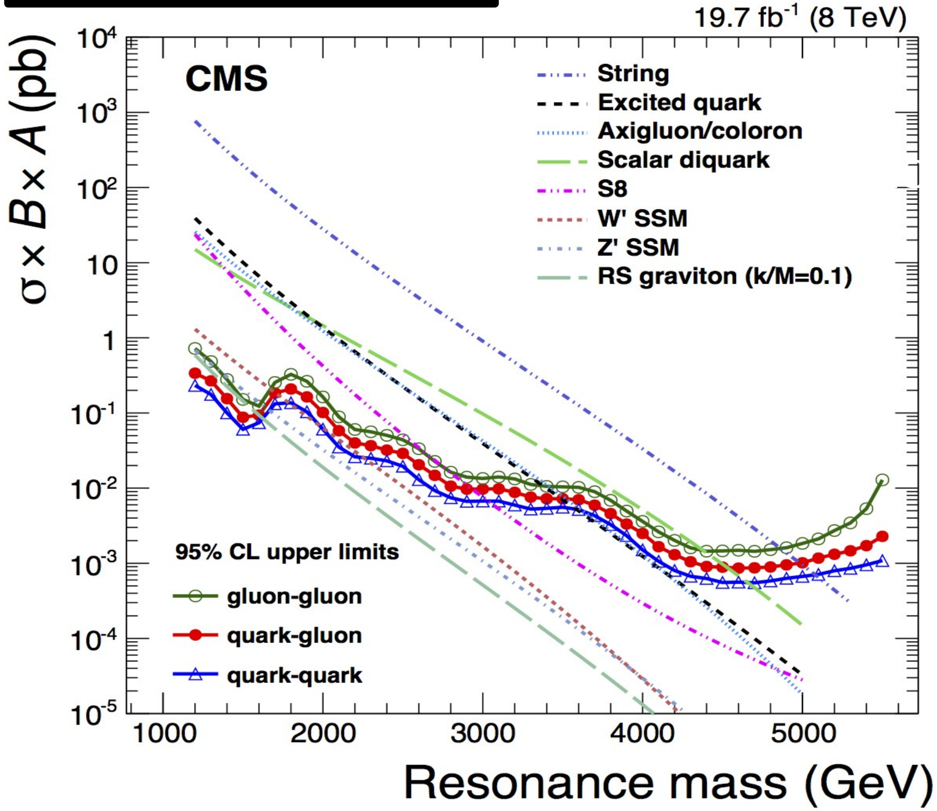




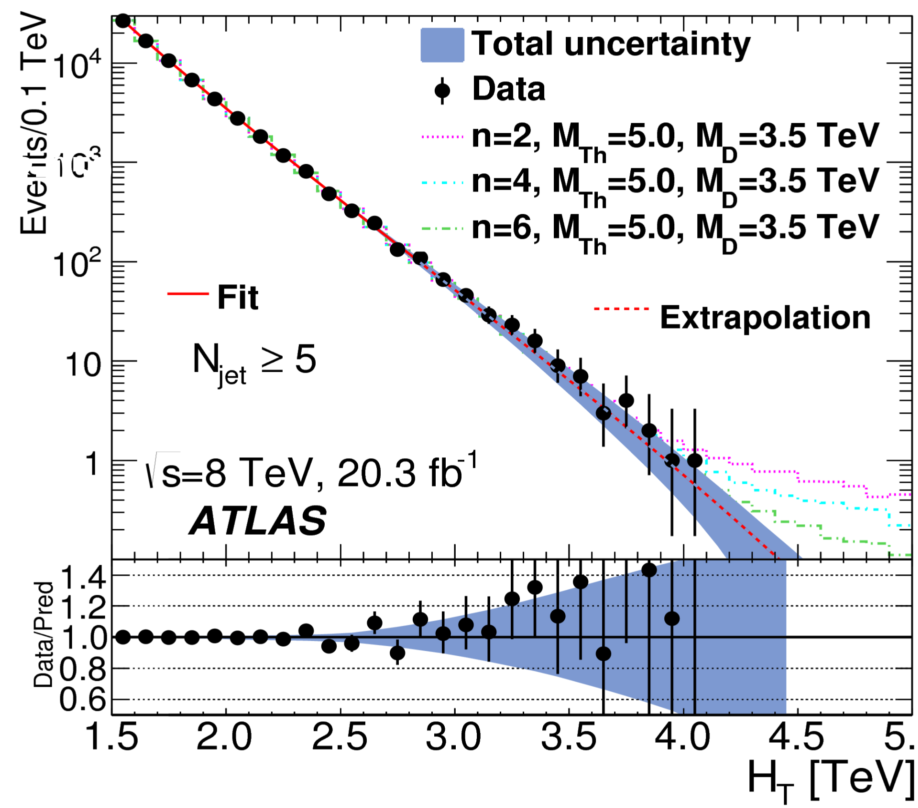
Classic Exotics: pure hadronic, highest scales

- Hadronic (relatively) narrow resonances and black hole searches:
  - Cross sections may be huge: far reach in terms of physics scales/masses
  - Almost fully data driven: assume a smooth background and then look for bumps or excesses at the highest transverse energies/multiplicities

CMS: arXiv:1501.04198



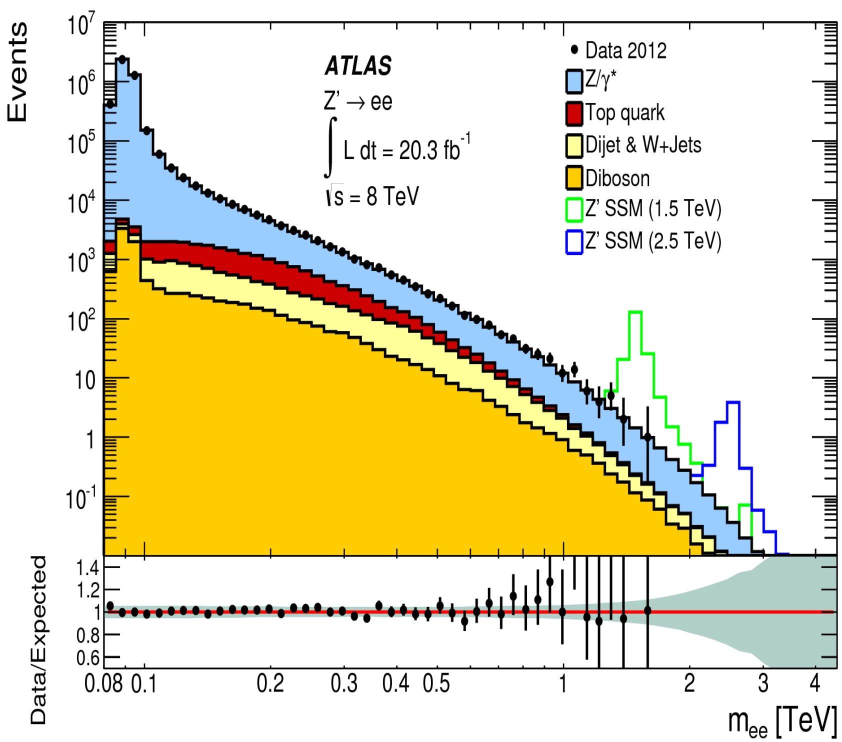
ATLAS, arXiv:1503.08988



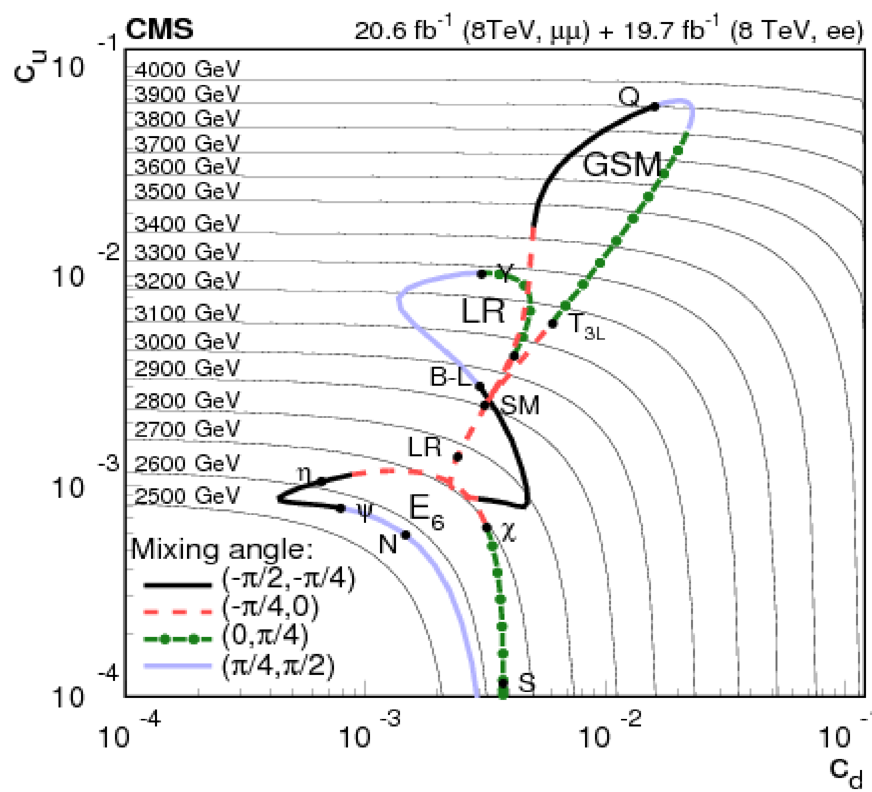
Classic Exotics: narrow resonances

- Dilepton resonances:
  - Clean, excellent resolution even at higher masses (but a delicate business to get there)
  - Non-resonant background: EWK corrections to DY and $\gamma^*\gamma^* \to ll$ matter at high mass
  - Many possible theory scenarios (different group extensions → different couplings)

ATLAS, arXiv:1405.4123



CMS, arXiv:1412.6302



Summary

- No evidence for new physics beyond the SM in Run1:
  - A few interesting excesses here and there to be followed, as expected, although not very significant
- Huge physics program covered already in Run1:
  - Characterization of the recently discovered scalar: no significant deviations observed.
  - SUSY being explored in new corners, trying to keep it 'natural' at the TeV scale.
  - Many BSM excluded models, most of them at masses/scales in the 1-3 TeV range.
- The energy jump of LHC Run2 may lead to early discoveries:
  - We will surpass the Run1 sensitivity soon (2015) in most searches
  - Likely the biggest jump in new physics reach in the next years.

EXCITING TIMES AHEAD!