
Review of Searches for New Physics at ATLAS and CMS

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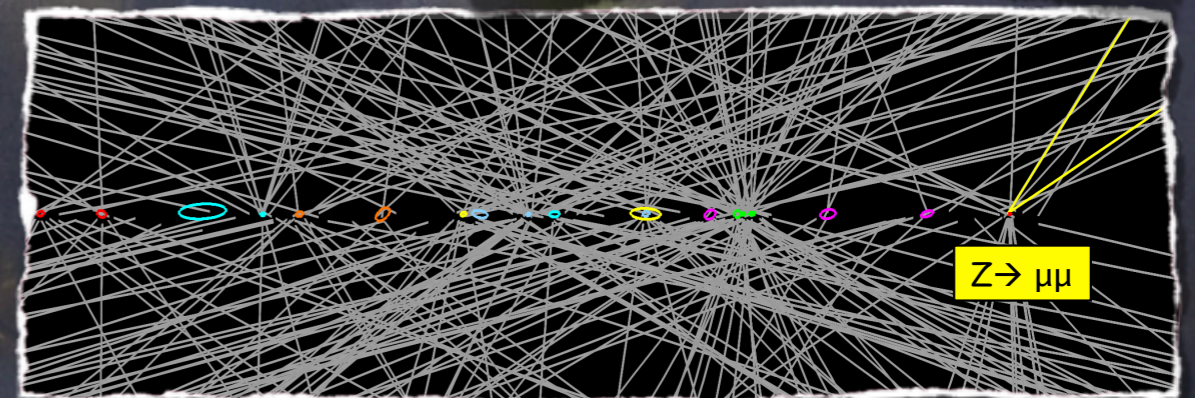
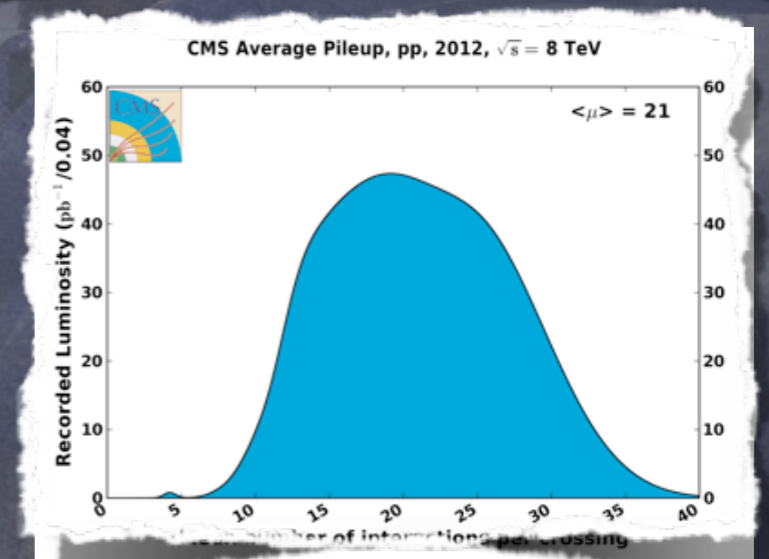
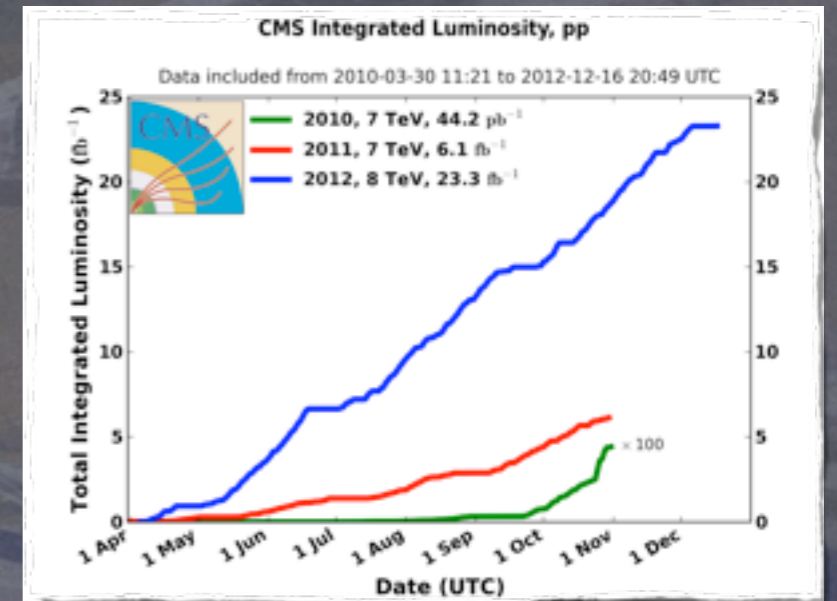


Outline

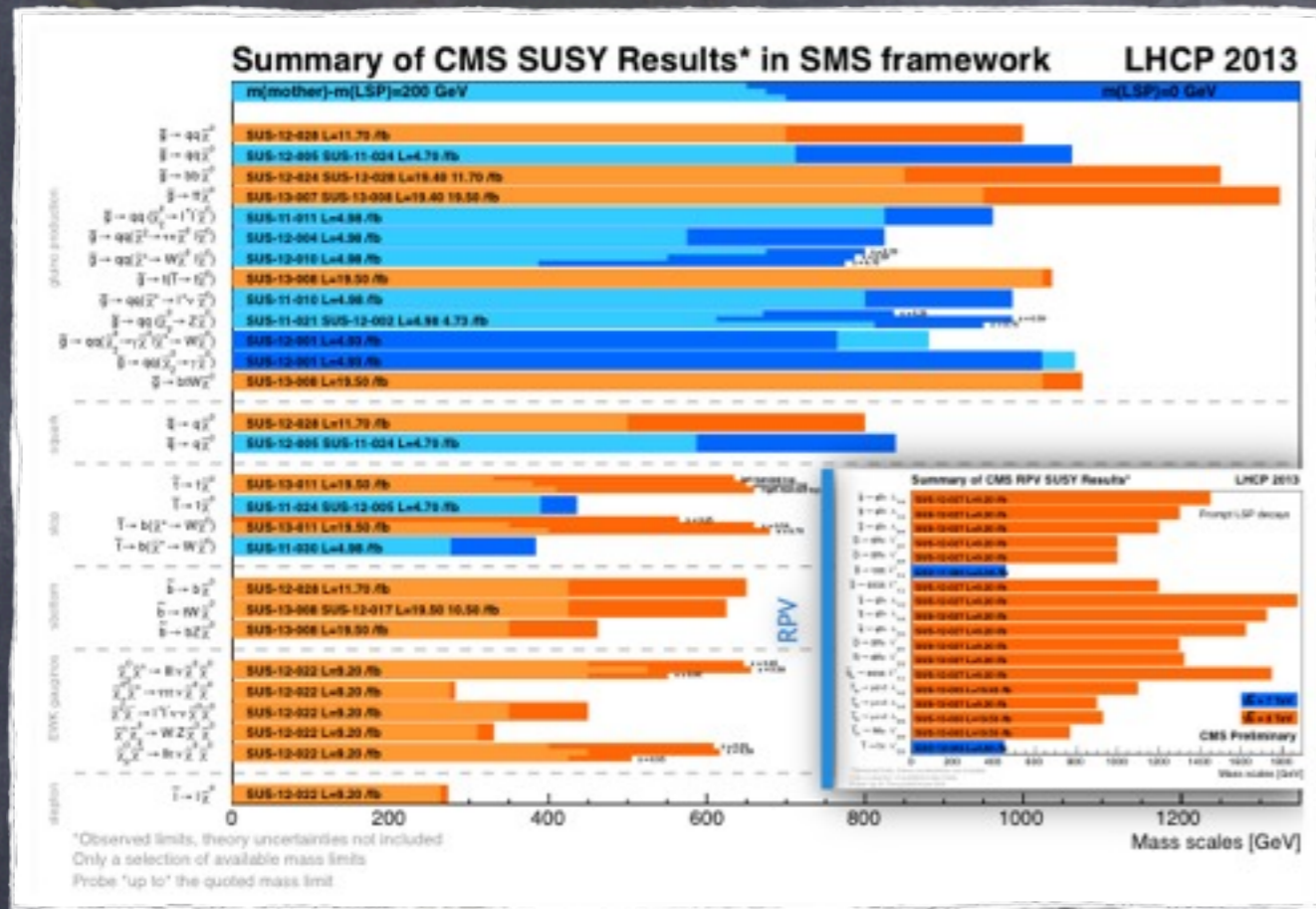
- The global picture
- A few examples
 - Natural SUSY with MET
 - Monojet search
 - Long-living particles
 - New Resonances to boosted V and top
 - Top partners
 - New Resonances to ff
- What Next?

It was a long journey

- The LHC and the detectors behaved incredibly well
- The collected statistics increased constantly, new territories explored every six months
- The environment changed dramatically:
 - Higher rates forced us to use tighter triggers
 - The pileup increase made the object identification (leptons, jets, etc) more challenging
 - Higher luminosity and no new-physics signal made us sensitive to the background from rare processes (e.g. $t\bar{t}V$, $VV+b$ jets, etc)



The Global Picture



ATLAS SUSY Searches - 95% CL Lower Limits
Status: LP 2013

$\int \mathcal{L} dt = (4.4 - 22.9) \text{ fb}^{-1}$ $\sqrt{s} = 7, 8 \text{ TeV}$ ATLAS Preliminary

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches						
MSUGRA/CMSSM	$1 e, \mu$	3-6 jets	Yes	20.3	1.2 TeV	ATLAS-CONF-2013-062
$\tilde{q}\tilde{q}, \tilde{q}\tilde{q}^* \rightarrow \tilde{q}\tilde{q}^*$	0	2-6 jets	Yes	20.3	1.1 TeV	ATLAS-CONF-2013-054
$\tilde{g}\tilde{g} \rightarrow \tilde{q}\tilde{q}^*$	0	2-6 jets	Yes	20.3	740 GeV	ATLAS-CONF-2013-047
$\tilde{g}\tilde{g} \rightarrow \tilde{q}\tilde{q}^* \tilde{q}\tilde{q}^*$	$1 e, \mu$	3-6 jets	Yes	20.3	1.3 TeV	ATLAS-CONF-2013-061
$\tilde{g}\tilde{g} \rightarrow \tilde{q}\tilde{q}^* \tilde{q}\tilde{q}^* \tilde{q}\tilde{q}^*$	$2 e, \mu$ (SS)	3 jets	Yes	20.7	1.18 TeV	ATLAS-CONF-2013-061
GMSB (\tilde{t} NLSP)	$2 e, \mu$	2-4 jets	Yes	4.7	1.24 TeV	ATLAS-CONF-2012-007
GMSB ($\tilde{\tau}$ NLSP)	$1-2 \tau$	0-2 jets	Yes	20.7	1.4 TeV	ATLAS-CONF-2012-021
GGM (bino NLSP)	2γ	0	Yes	4.8	1.07 TeV	ATLAS-CONF-2012-021
GGM (wino NLSP)	$1 e, \mu + \gamma$	0	Yes	4.8	619 GeV	ATLAS-CONF-2012-114
GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	900 GeV	ATLAS-CONF-2012-114
GGM (higgsino NLSP)	$2 e, \mu$ (Z)	0-3 jets	Yes	5.8	590 GeV	ATLAS-CONF-2012-115
Gravitino LSP	0	mono-jet	Yes	10.5	845 GeV	ATLAS-CONF-2012-147
3rd Gen \tilde{g} med.						
$\tilde{g} \rightarrow b\tilde{b}^*$	0	3 b	Yes	20.1	1.2 TeV	ATLAS-CONF-2013-061
$\tilde{g} \rightarrow t\tilde{t}^*$	0	7-10 jets	Yes	20.3	1.14 TeV	ATLAS-CONF-2013-054
$\tilde{g} \rightarrow \tau\tilde{\tau}^*$	0-1 e, μ	3 b	Yes	20.1	1.34 TeV	ATLAS-CONF-2013-061
$\tilde{g} \rightarrow b\tilde{t}^*$	0-1 e, μ	3 b	Yes	20.1	1.3 TeV	ATLAS-CONF-2013-061
gluons direct production						
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{t}^*$	0	2 b	Yes	20.1	100-630 GeV	ATLAS-CONF-2013-053
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{t}^*$	$2 e, \mu$ (SS)	0-3 b	Yes	20.7	430 GeV	ATLAS-CONF-2013-007
$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow Wb\tilde{t}_1^*$	$1-2 e, \mu$	1-2 b	Yes	4.7	167 GeV	ATLAS-CONF-2013-057
$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{t}_1^*$	$2 e, \mu$	0-2 jets	Yes	20.3	220 GeV	ATLAS-CONF-2013-048
$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{t}_1^*$	$2 e, \mu$	0-2 jets	Yes	20.3	150-440 GeV	ATLAS-CONF-2013-048
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{t}_1^*$	0	2 b	Yes	20.1	150-580 GeV	ATLAS-CONF-2013-037
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{t}_1^*$	$1 e, \mu$	1 b	Yes	20.7	200-610 GeV	ATLAS-CONF-2013-037
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{t}_1^*$	0	2 b	Yes	20.5	320-660 GeV	ATLAS-CONF-2013-024
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	$2 e, \mu$ (Z)	1 b	Yes	20.7	500 GeV	ATLAS-CONF-2013-025
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	$3 e, \mu$ (Z)	1 b	Yes	20.7	520 GeV	ATLAS-CONF-2013-025
EW direct						
$\tilde{L}_L \tilde{R}_L^* \rightarrow \tilde{L} \tilde{R}^*$	$2 e, \mu$	0	Yes	20.3	85-315 GeV	ATLAS-CONF-2013-049
$\tilde{X}_1^0 \tilde{X}_1^0 \rightarrow \tilde{\nu} \tilde{\nu}^*$	$2 e, \mu$	0	Yes	20.3	125-450 GeV	ATLAS-CONF-2013-049
$\tilde{X}_1^0 \tilde{X}_1^0 \rightarrow \tilde{\nu} \tilde{\nu}^* (\tilde{\nu} \tilde{\nu}^*)$	2τ	0	Yes	20.7	180-330 GeV	ATLAS-CONF-2013-028
$\tilde{X}_1^0 \tilde{X}_1^0 \rightarrow \tilde{\nu} \tilde{\nu}^* (\tilde{\nu} \tilde{\nu}^*)$	$3 e, \mu$	0	Yes	20.7	600 GeV	ATLAS-CONF-2013-035
$\tilde{X}_1^0 \tilde{X}_1^0 \rightarrow W \tilde{Z} \tilde{X}_1^0$	$3 e, \mu$	0	Yes	20.7	315 GeV	ATLAS-CONF-2013-035
Long-lived particles						
Direct $\tilde{X}_1^0 \tilde{X}_1^0$ prod., long-lived \tilde{X}_1^0	0	1 jet	Yes	4.7	82 GeV	1210.2852
Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	22.9	857 GeV	ATLAS-CONF-2013-057
GMSB, stable \tilde{t}	$1-2 \mu$	0	-	15.9	385 GeV	ATLAS-CONF-2013-058
Direct $\tilde{t}\tilde{t}^*$ prod., stable \tilde{t} or \tilde{t}^*	$1-2 \mu$	0	-	15.9	395 GeV	ATLAS-CONF-2013-058
GMSB, $\tilde{X}_1^0 \rightarrow \gamma \tilde{g}$, long-lived \tilde{X}_1^0	2γ	0	Yes	4.7	230 GeV	1304.6310
$\tilde{X}_1^0 \rightarrow q\tilde{q}$ (RPV)	1μ	0	Yes	4.4	700 GeV	1210.7451
RPV						
LFV $pp \rightarrow \tilde{\nu}_i + X, \tilde{\nu}_i \rightarrow e + \mu$	$2 e, \mu$	0	-	4.6	1.61 TeV	1212.1272
LFV $pp \rightarrow \tilde{\nu}_i + X, \tilde{\nu}_i \rightarrow e(\mu) + \tau$	$1 e, \mu + \tau$	0	-	4.6	1.1 TeV	1212.1272
Bilinear RPV CMSSM	$1 e, \mu$	7 jets	Yes	4.7	1.2 TeV	ATLAS-CONF-2012-140
$\tilde{X}_1^0 \tilde{X}_1^0 \rightarrow W \tilde{Z} \tilde{X}_1^0$	$4 e, \mu$	0	Yes	20.7	760 GeV	ATLAS-CONF-2013-036
$\tilde{X}_1^0 \tilde{X}_1^0 \rightarrow W \tilde{Z} \tilde{X}_1^0$	$3 e, \mu + \tau$	0	Yes	20.7	350 GeV	ATLAS-CONF-2013-036
$\tilde{g} \rightarrow q\tilde{q}$	0	6 jets	-	4.6	666 GeV	1210.4813
$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b\tilde{s}$	$2 e, \mu$ (SS)	0-3 b	Yes	20.7	880 GeV	ATLAS-CONF-2013-007
Other						
Scalar gluon	0	4 jets	-	4.6	100-287 GeV	1210.4826
WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	704 GeV	ATLAS-CONF-2012-147

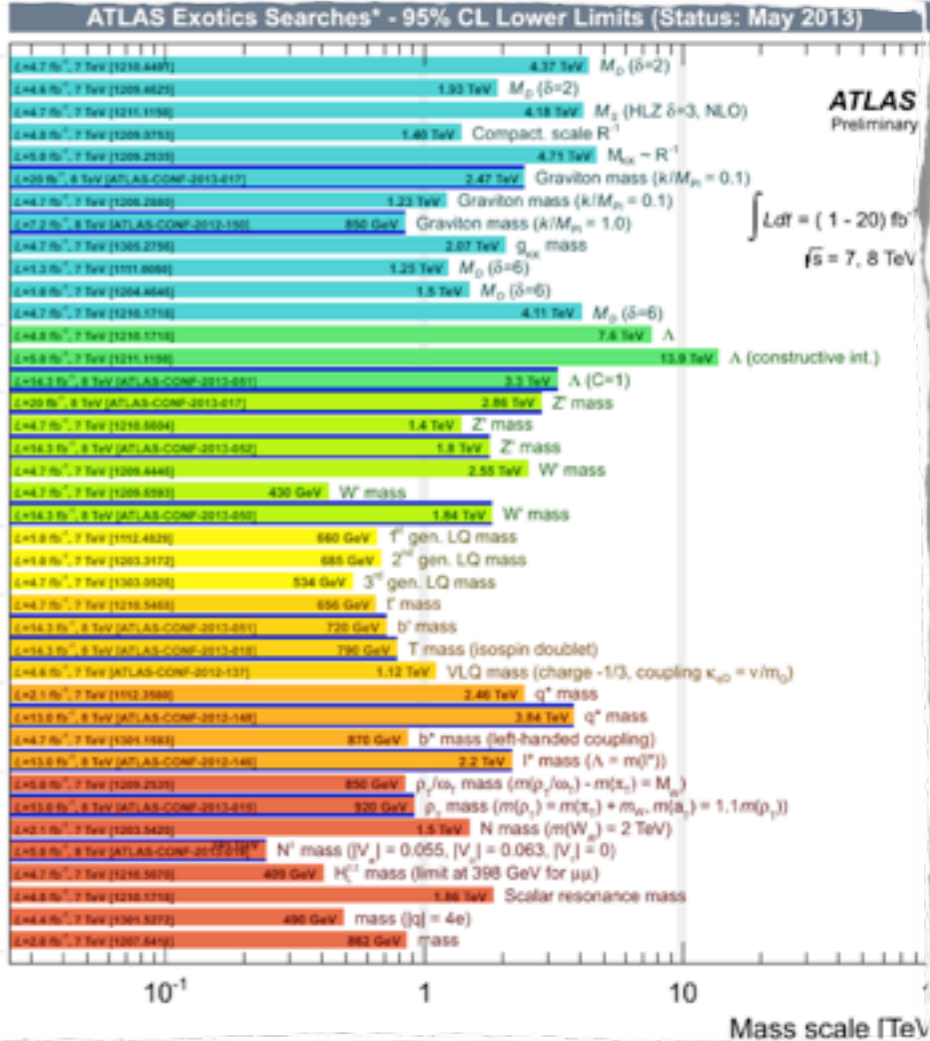
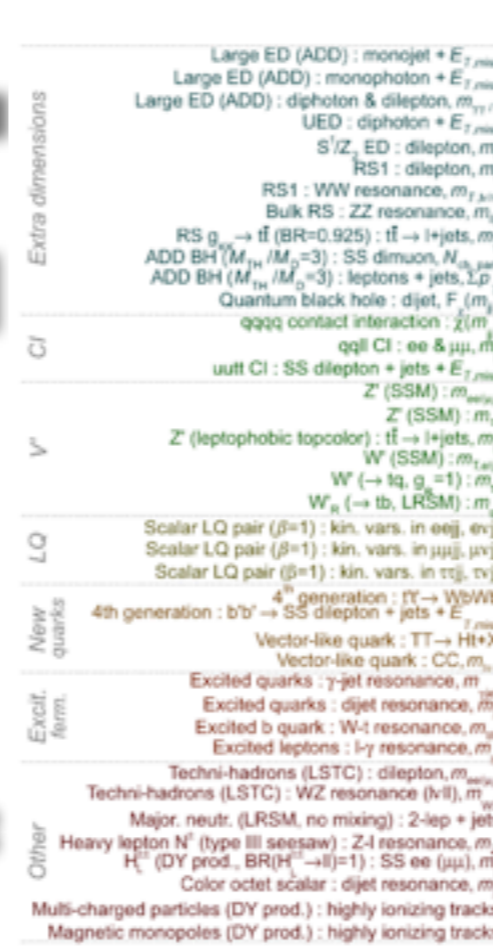
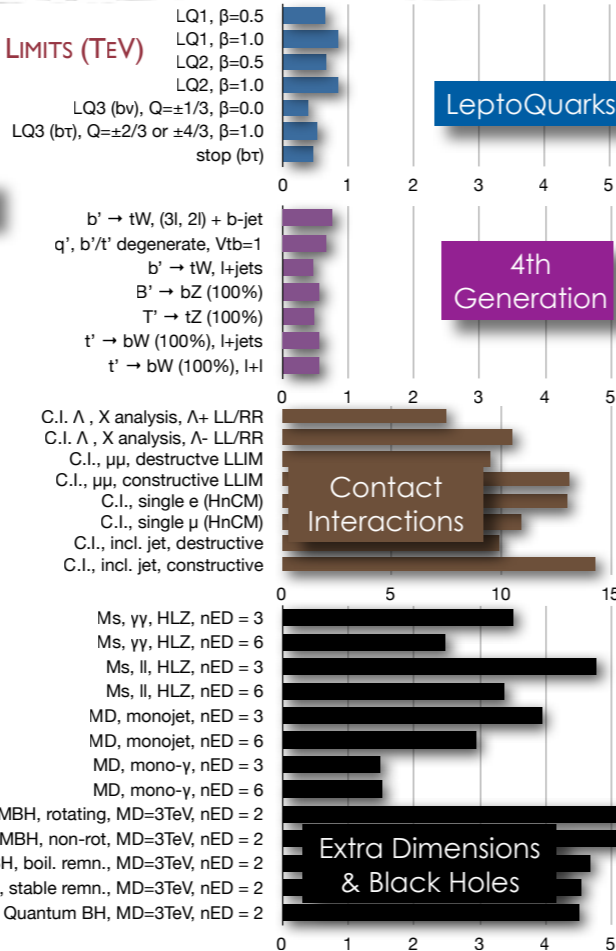
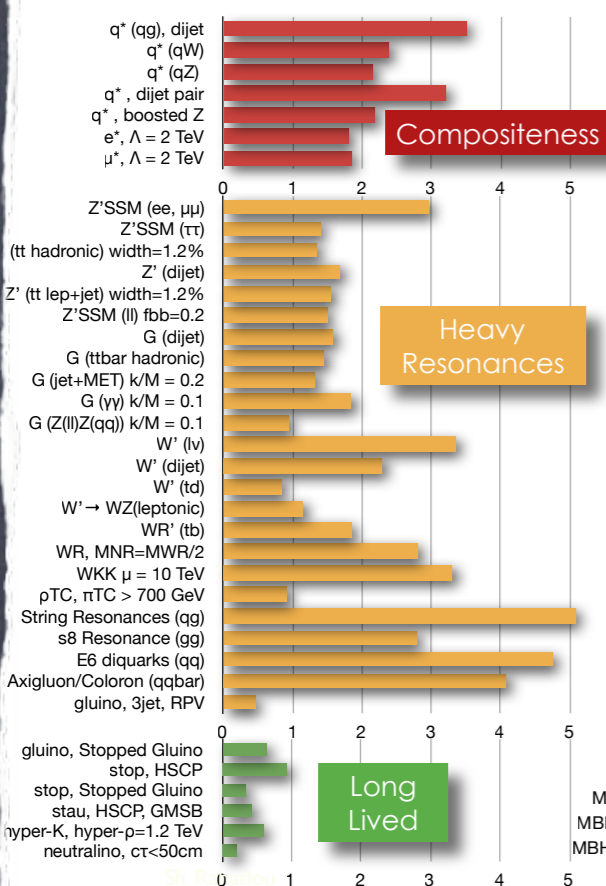
Definitely too much to be covered in one talk

I will try to give you a general idea

You will find more on the ATLAS and CMS twiki pages

The Global Picture

CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)



Definitely too much to be covered in one talk
 I will try to give you a general idea
 You will find more on the ATLAS and CMS twiki pages

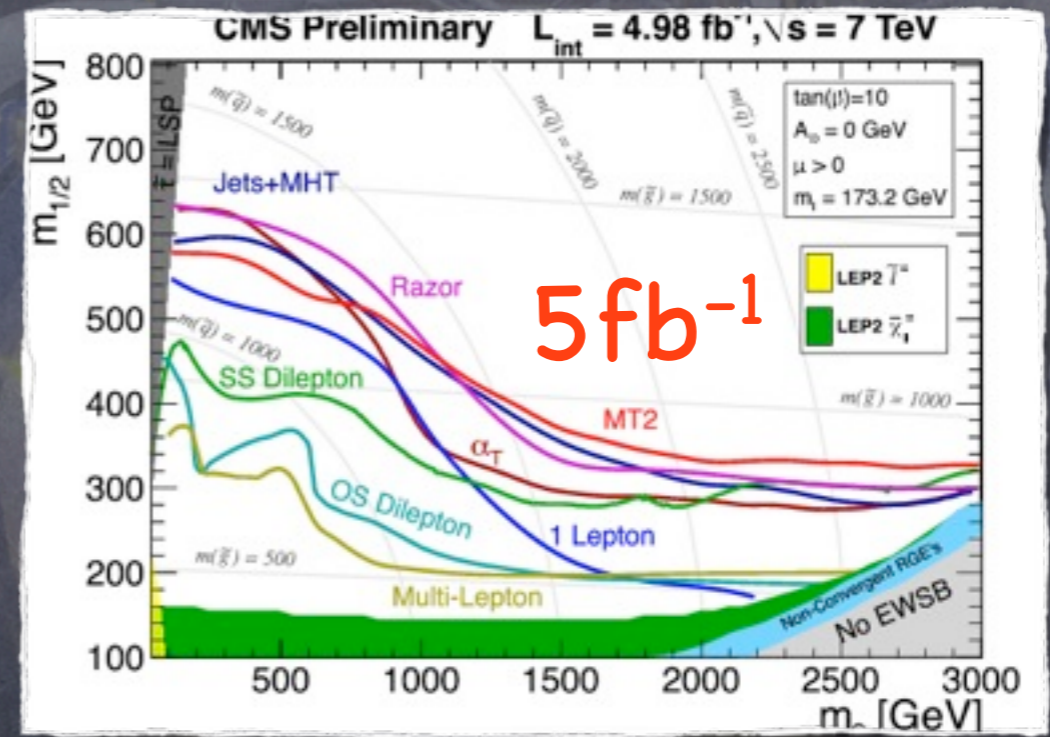
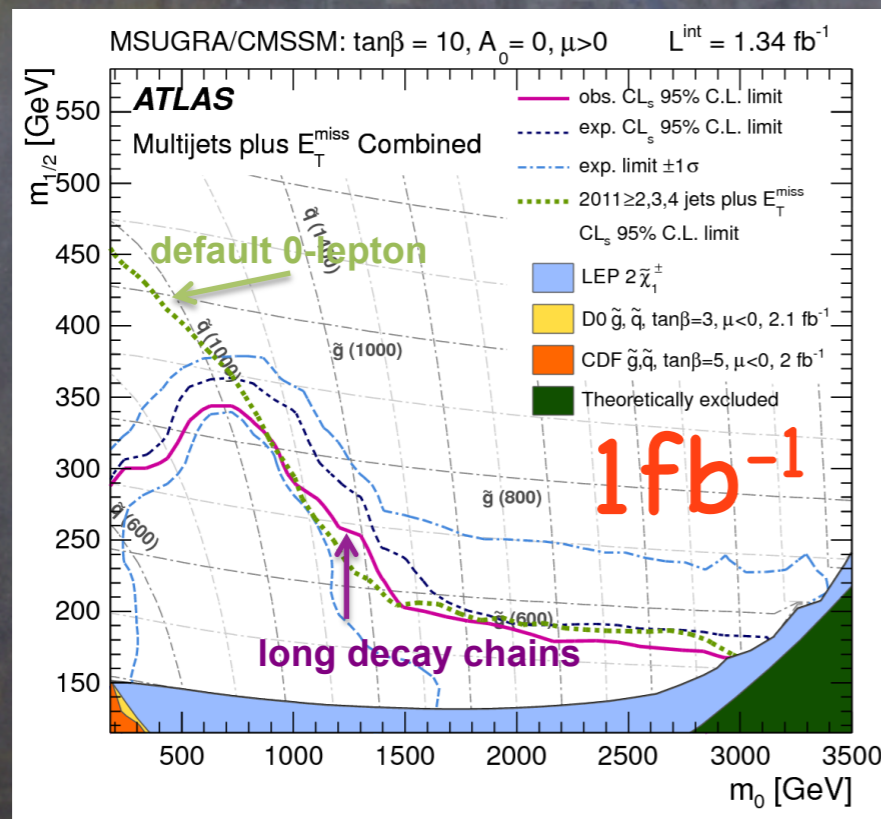
Legacy of the 7 TeV run

Already with 1fb^{-1} the exclusion curve removed a large fraction of the accessible parameter space

Adding statistics moved the limit by ATLAS and CMS more in the unexplored territory

After this, any improvement on the high-mass front became adiabatic

This was not true anymore if one changes the SUSY paradigm



The ballpark of what we could discover was gone quite quickly

The Higgs was found

We turned our attention to some special kind of SUSY

Natural SUSY with 8 TeV data

Direct squark searches

Smaller cross section

Final state similar to $t\bar{t}$ in the bulk of the parameter space

Reduced bkg discrimination power

Only handle if gluino heavy

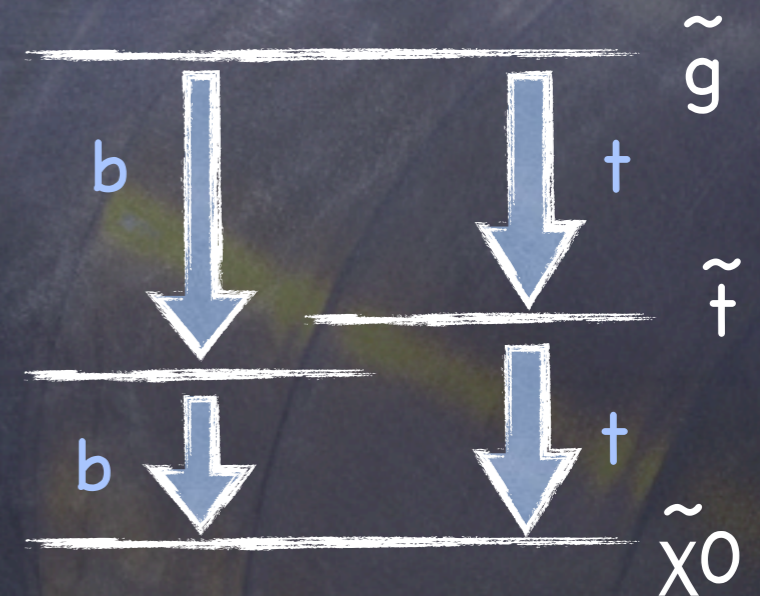
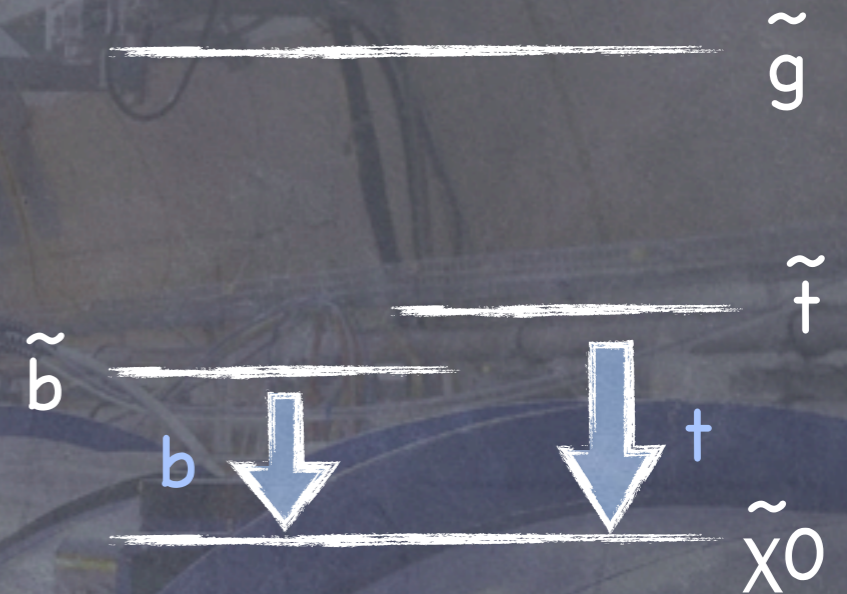
Glauino-mediated searches

Larger cross section

4b quarks in the final state, with or w/o leptons

More handles for bkg discrimination

Glauinos might be too heavy for these searches to be effective



The Search Strategy

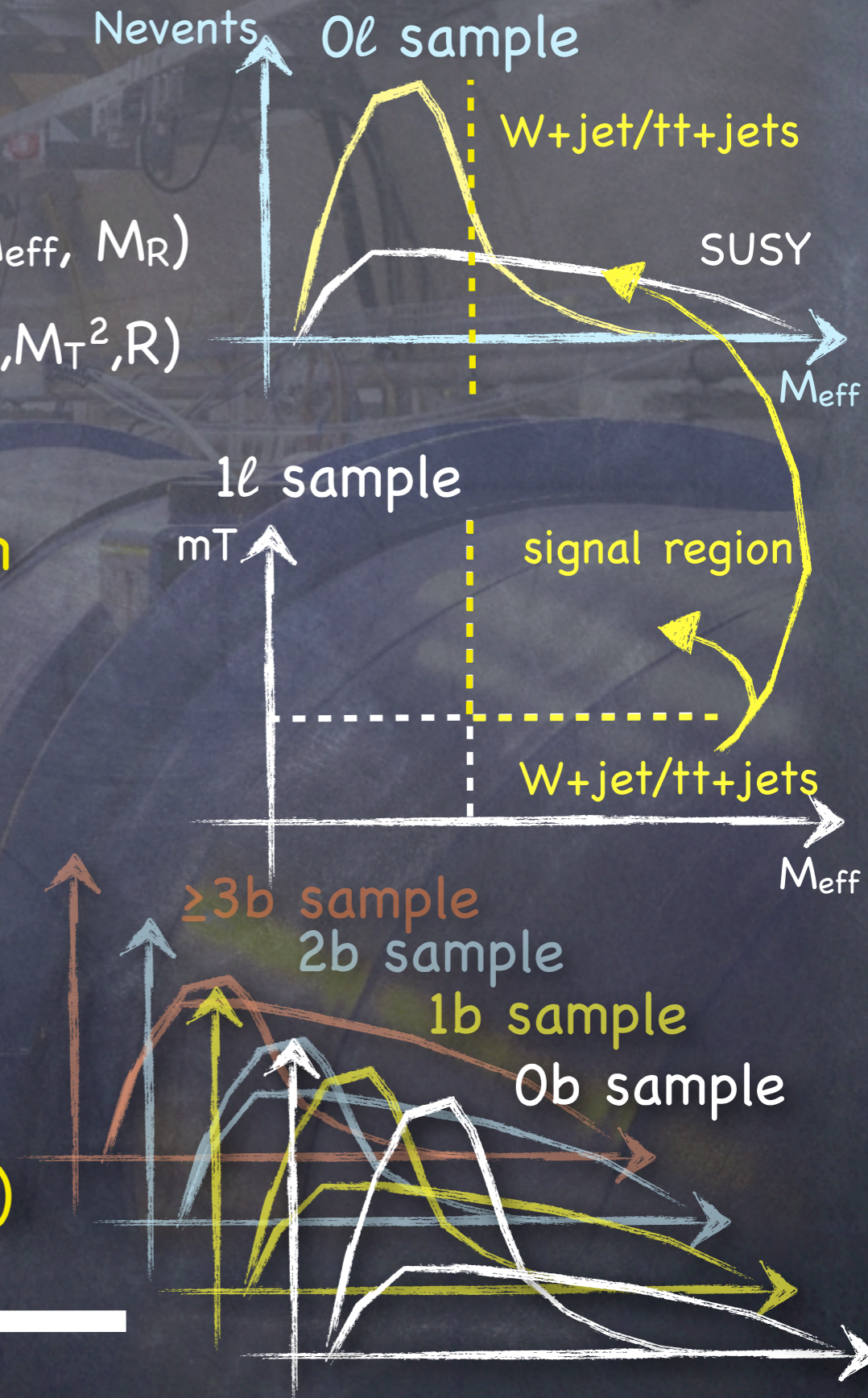
- The main ingredient to the search is a kinematic plane.
- A measurement of the event energy (HT , M_{eff} , M_R)
- A measurement of the unbalancing (MET , α_T , M_T^2 , R)

- The background on the tail is measured from the core, using transfer factors from MC

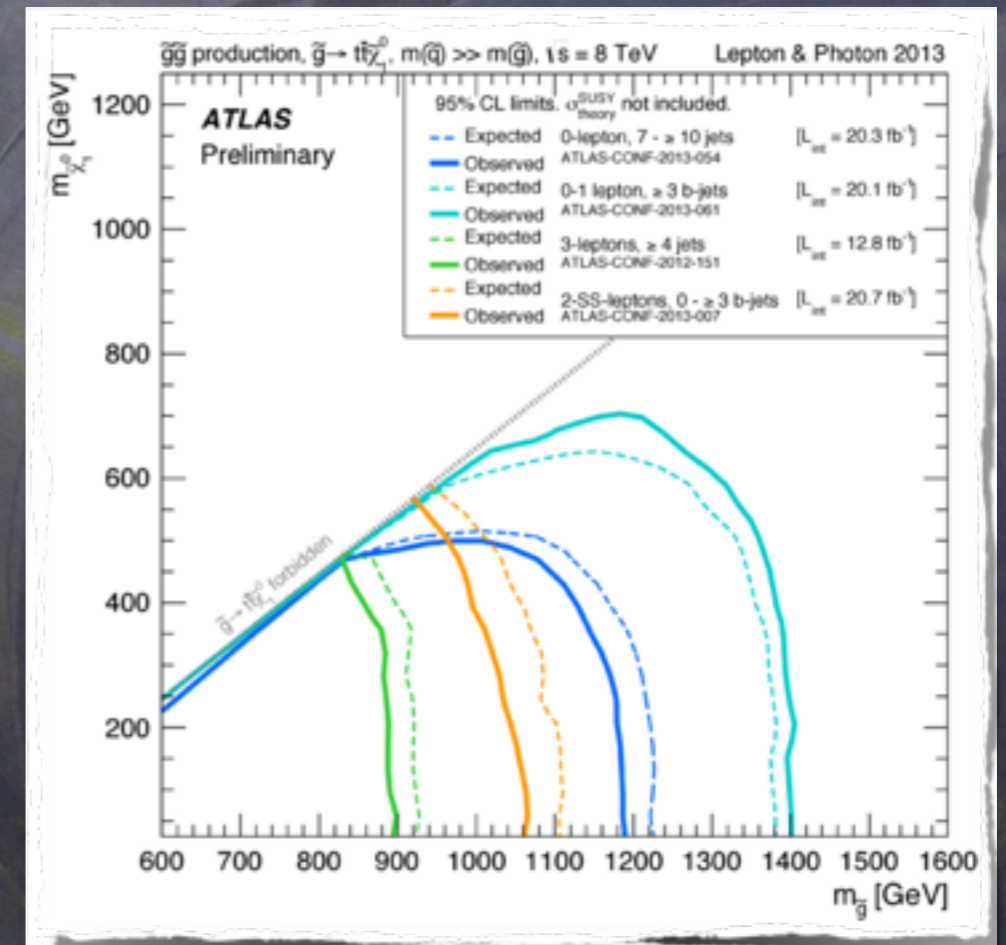
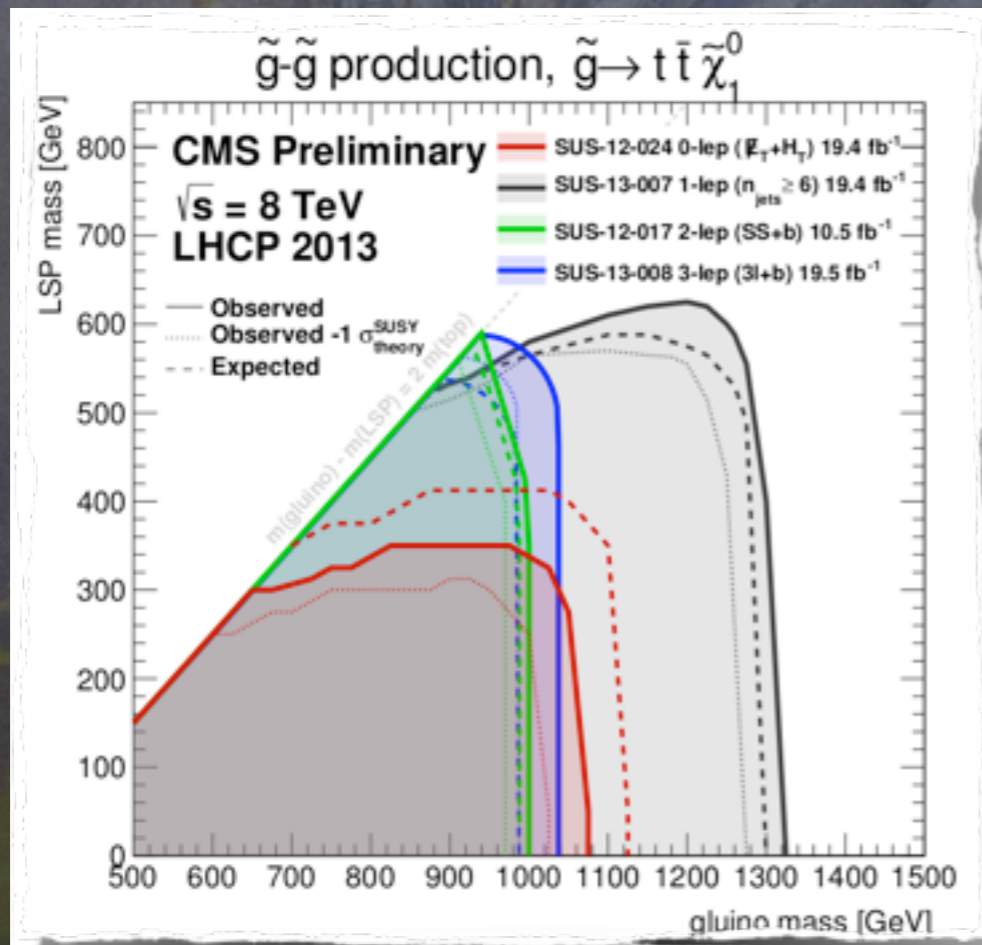
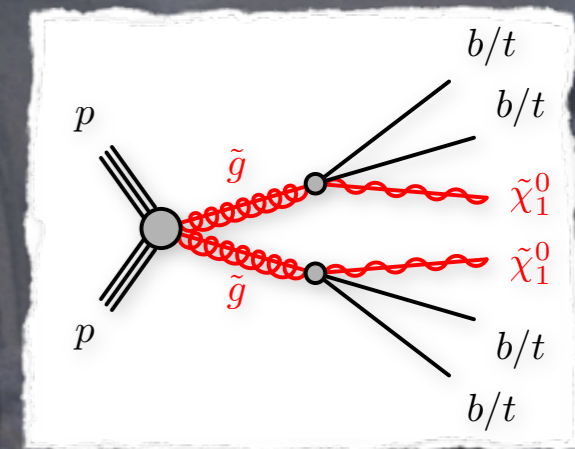
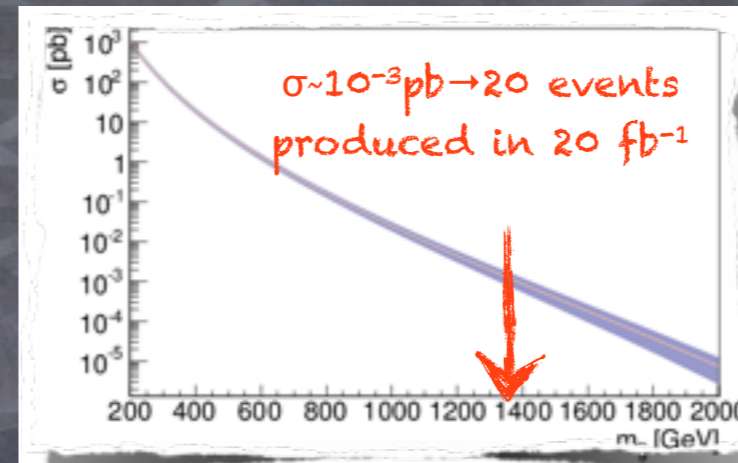
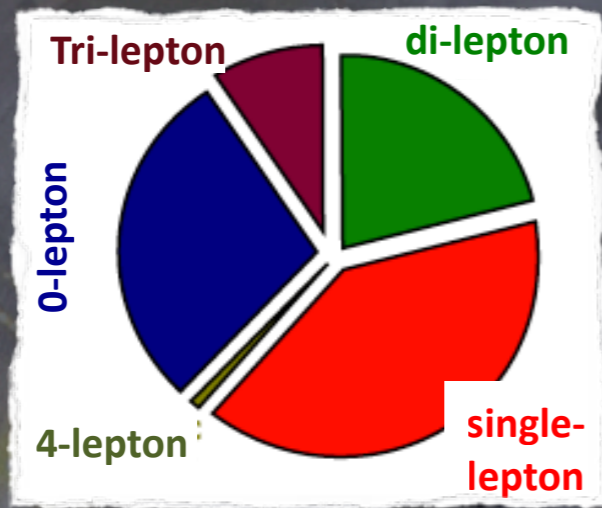
- The searches are repeated for different final states

- number of jets
- number of btags
- number of leptons

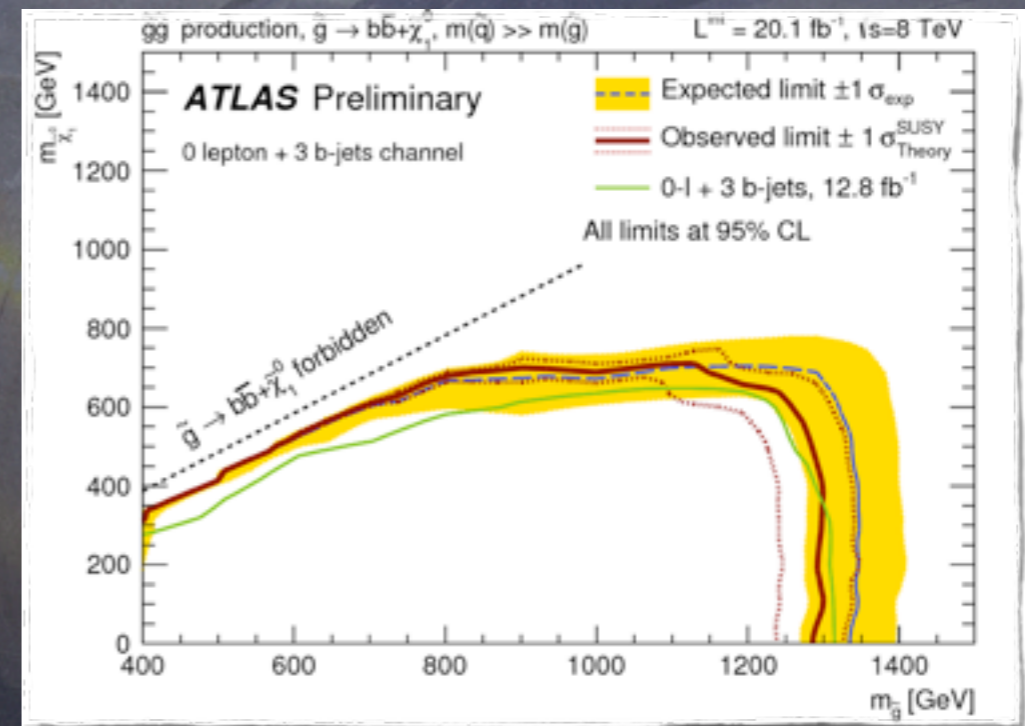
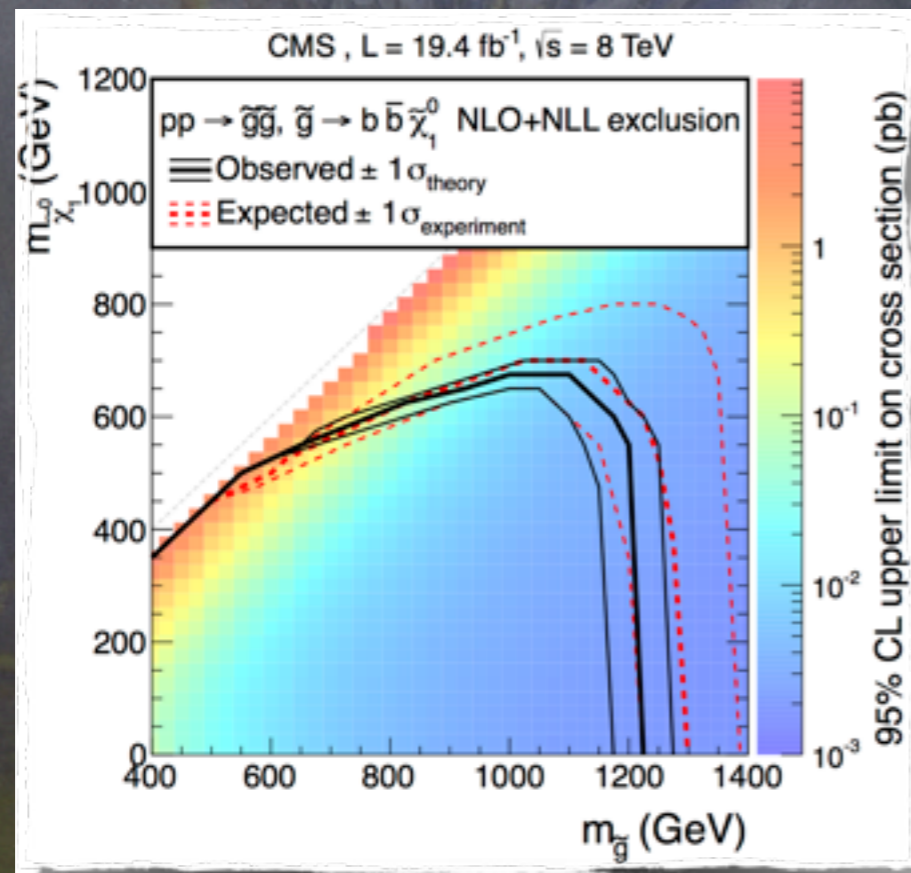
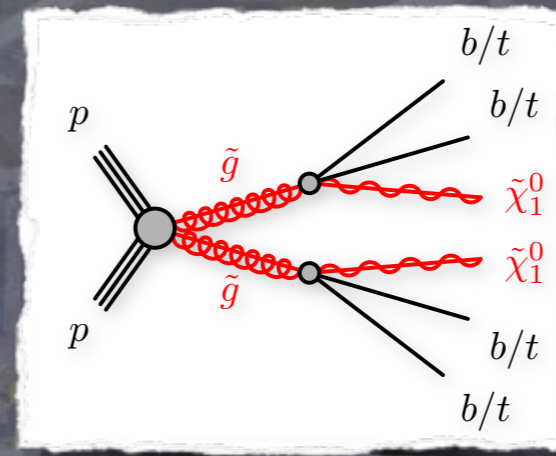
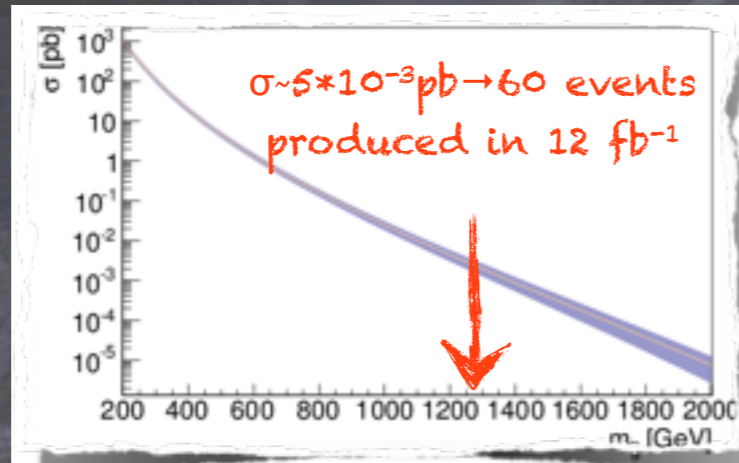
- Searching for specific signals (e.g. stop production) advanced techniques (e.g. BDT) could be used



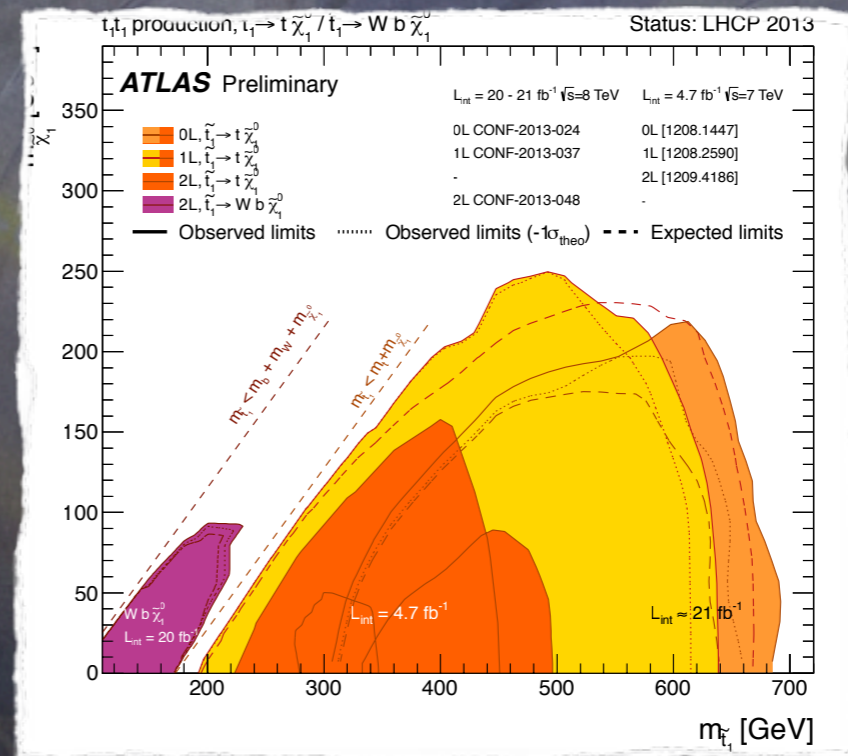
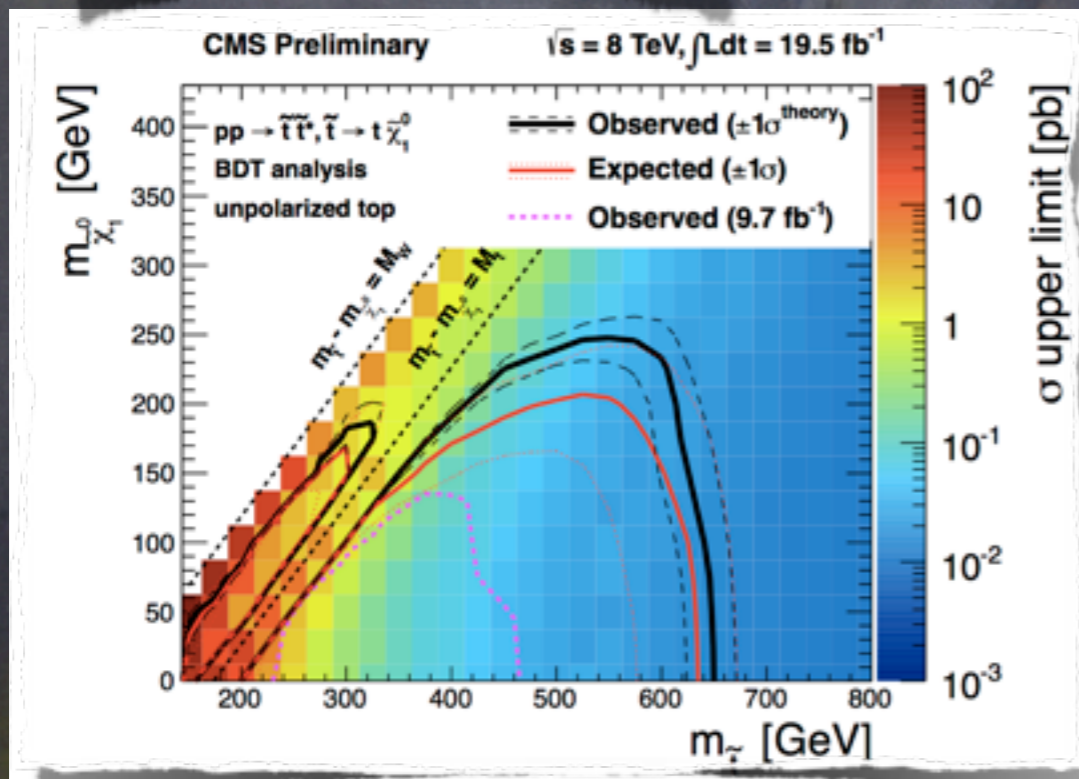
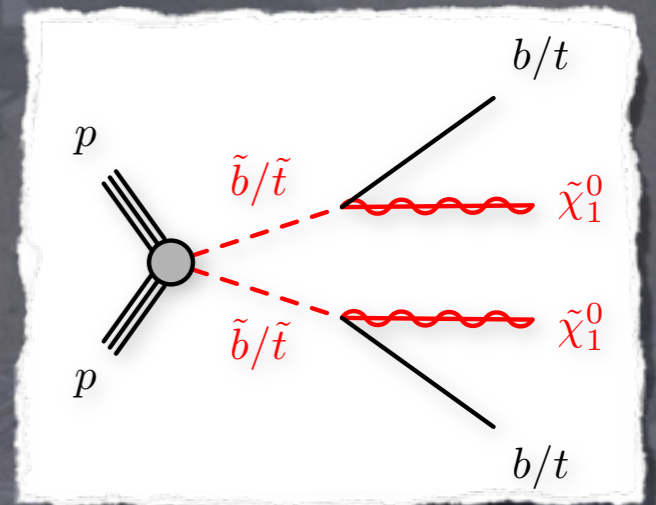
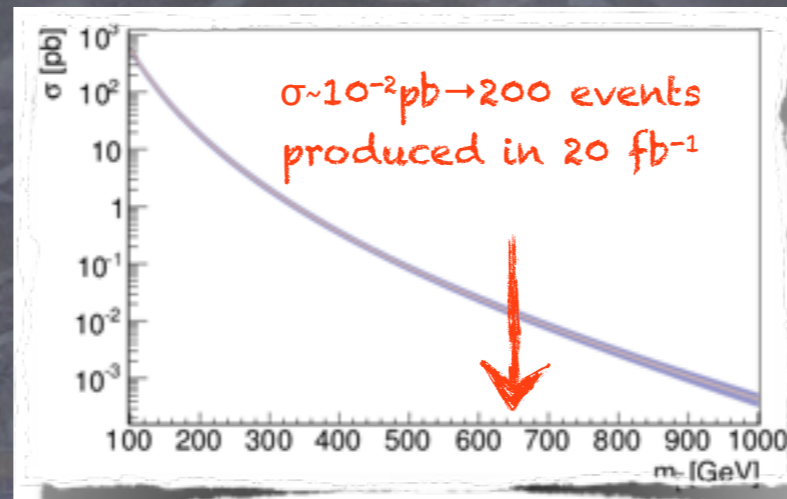
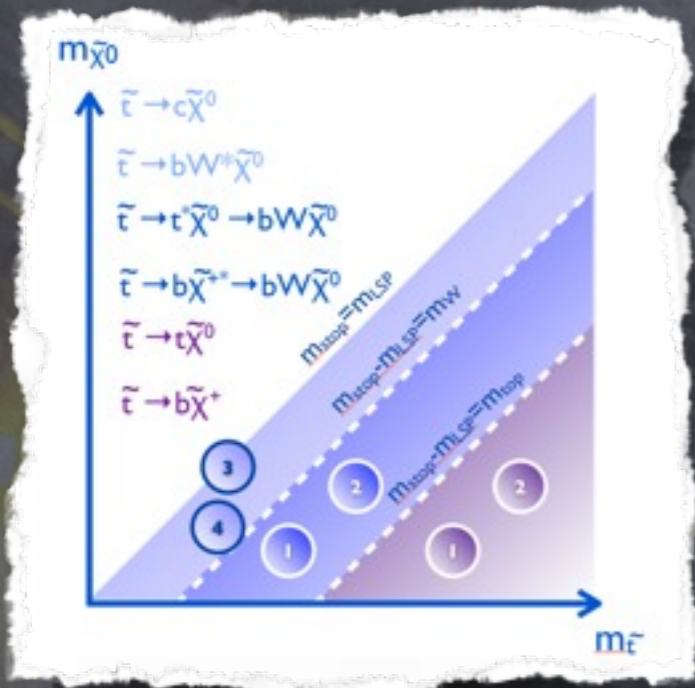
Glauino-Gluino Search: 4t+MET



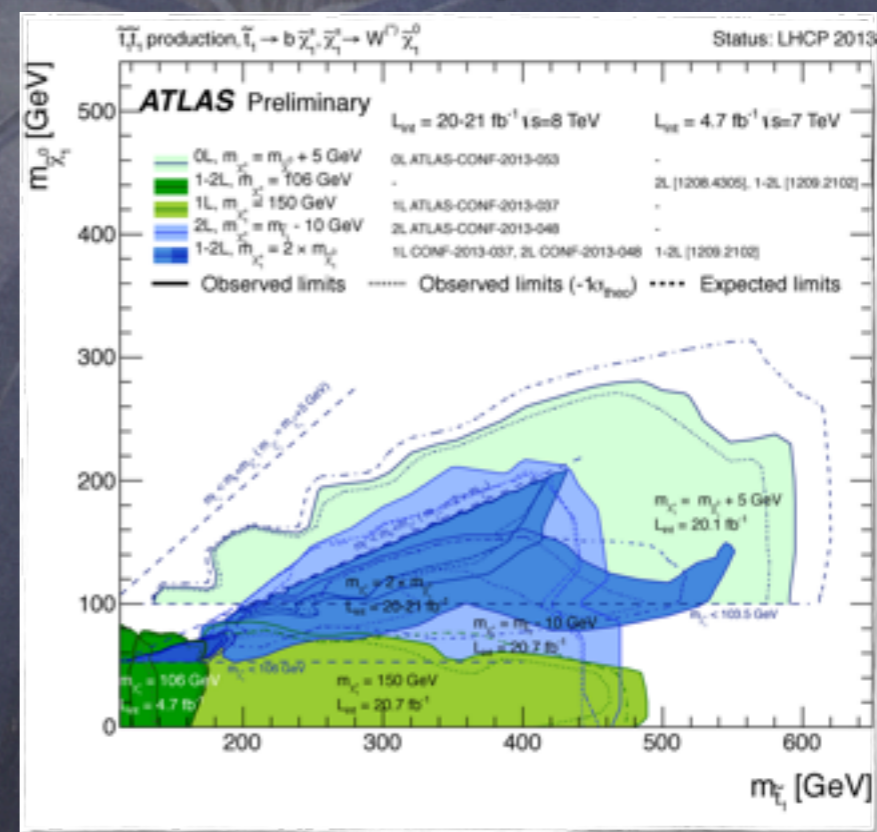
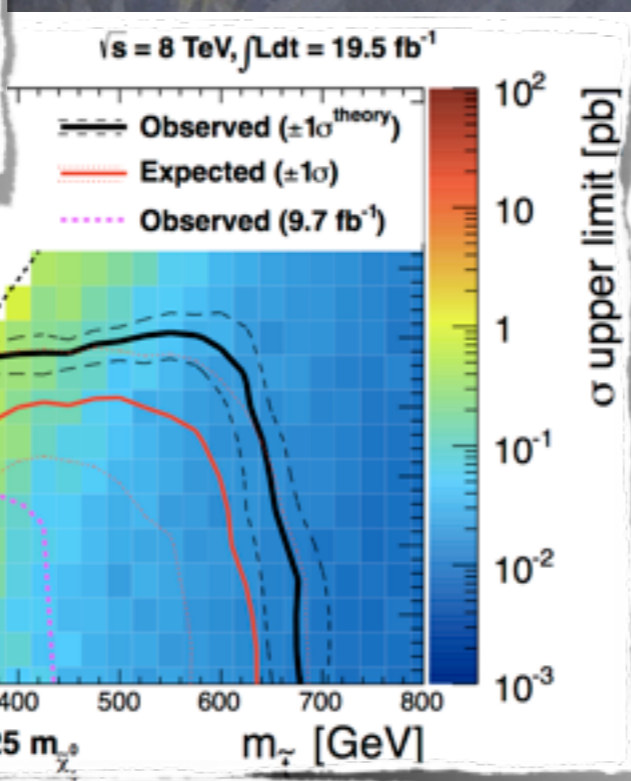
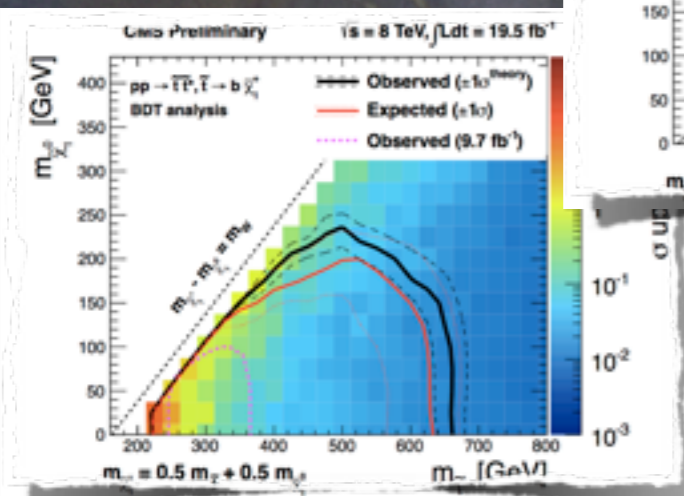
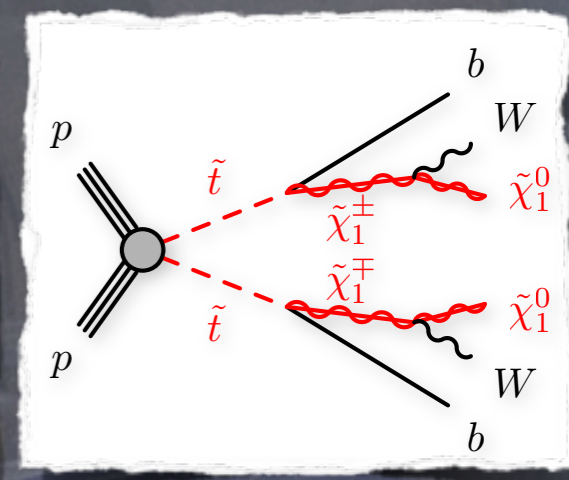
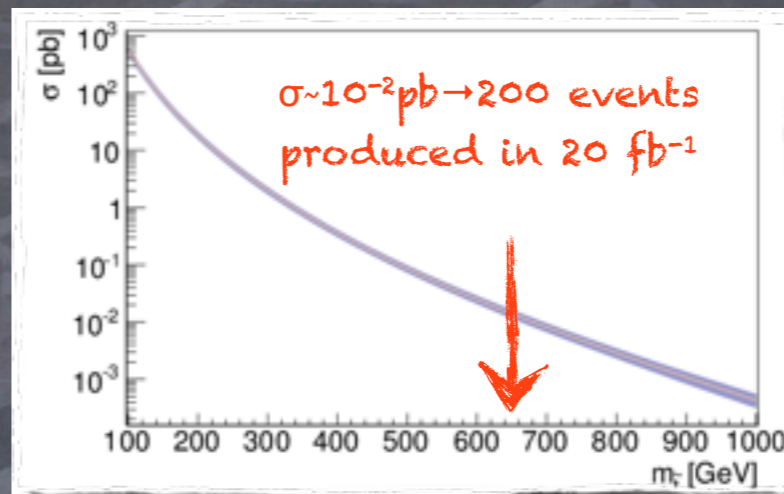
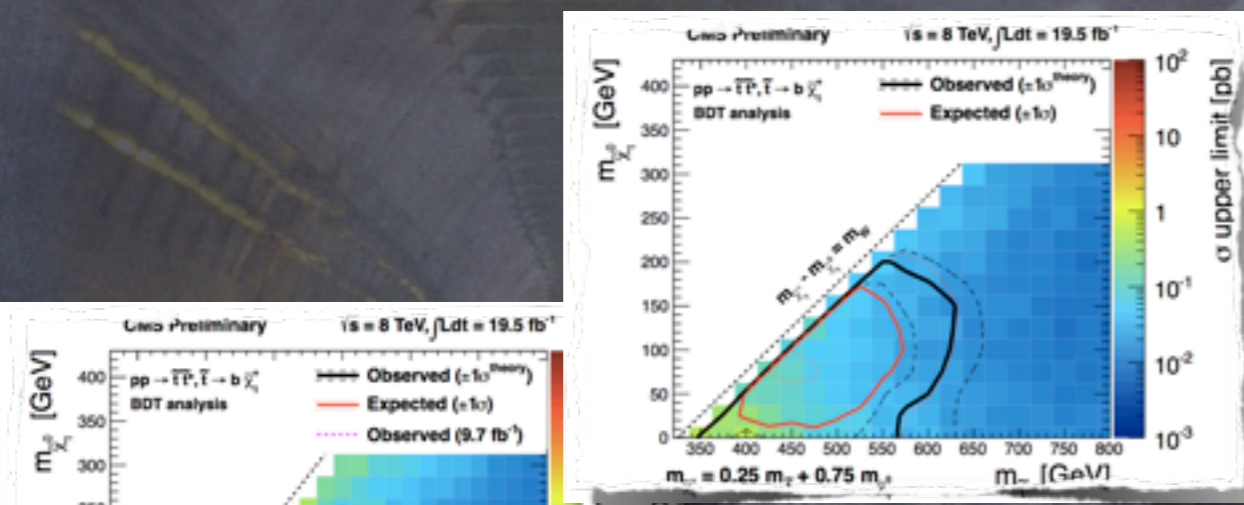
Glino-Glino Search: $4b+MET$



Stop-Stop Search: $t\bar{t} + \text{MET}$

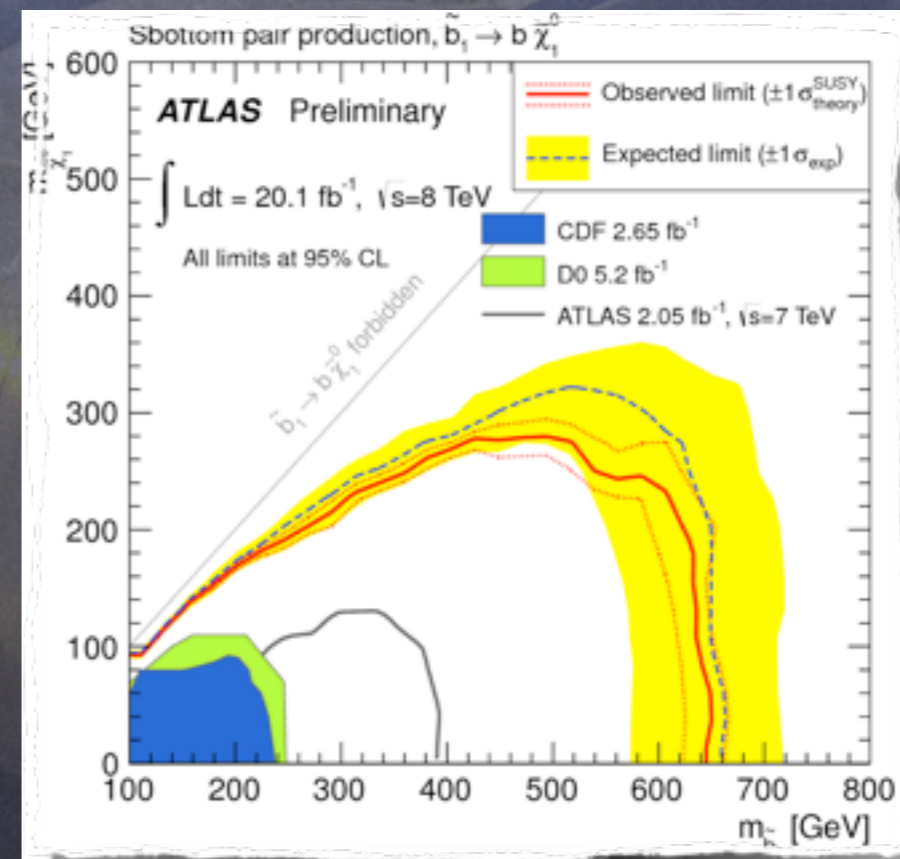
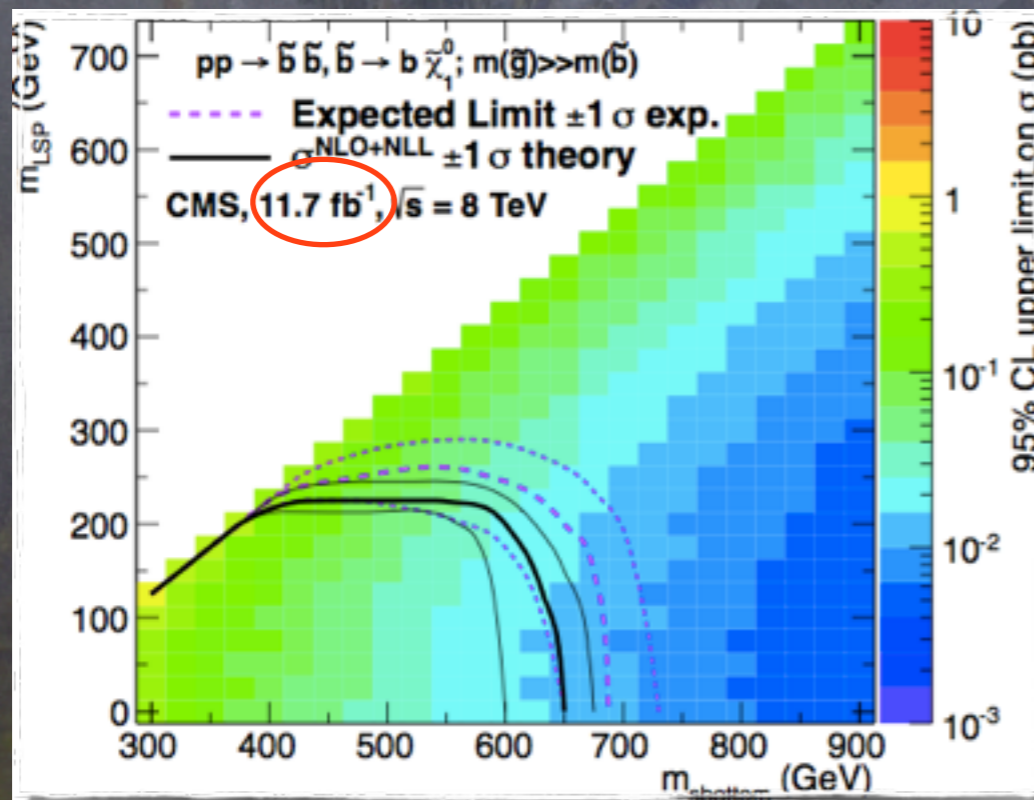
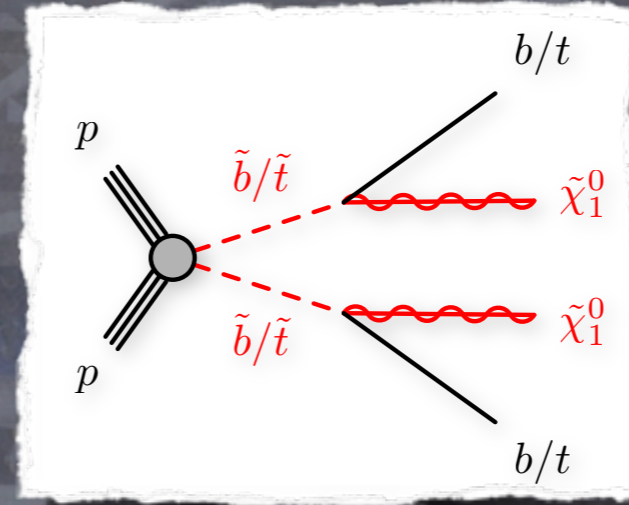
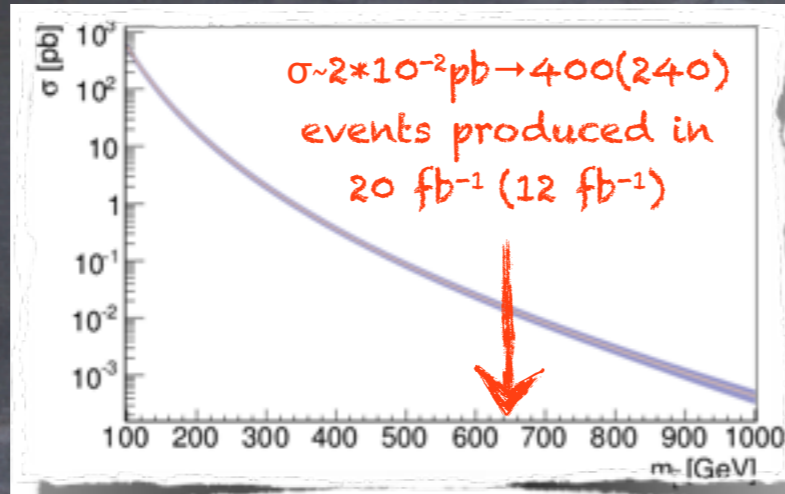


Stop-Stop Search: $bbWW+MET$



The limit depends on how close the χ^+ and χ^0 masses are

Sbottom-Sbottom Search: $b\bar{b} + MET$



Hunting in the corners

• Compressed Spectra

- The decay products of the produced sparticles are too soft to be detected
- Could trigger the events only through associated jet production (e.g. **monojet**)
- For very compressed spectra, the decay products could become **long living** (e.g. ewikinos)

• RPV models

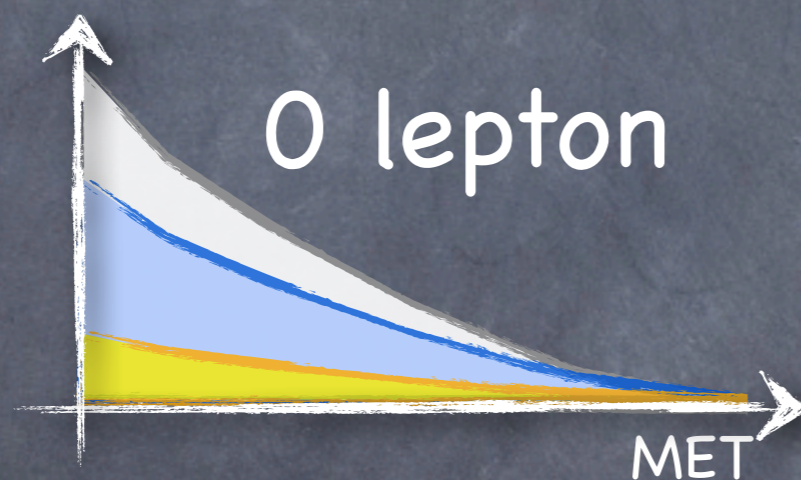
- searches for leptonic RPV in place since the beginning of the run
- hadronic RPV more challenging (no MET to kill SM bkg) but not impossible (can use the resonance peak)
- MFV SUSY offers special opportunities (bjet excess). Some bound from existing searches (e.g. 3l+b or 2l+b). More to come

• Split SUSY

- the accessible sparticles are the gluino and the ewkino sector
- Even in this case, one would need **associated jet production**
- Even in this case, should look for displaced jets (**long-living gluino**)

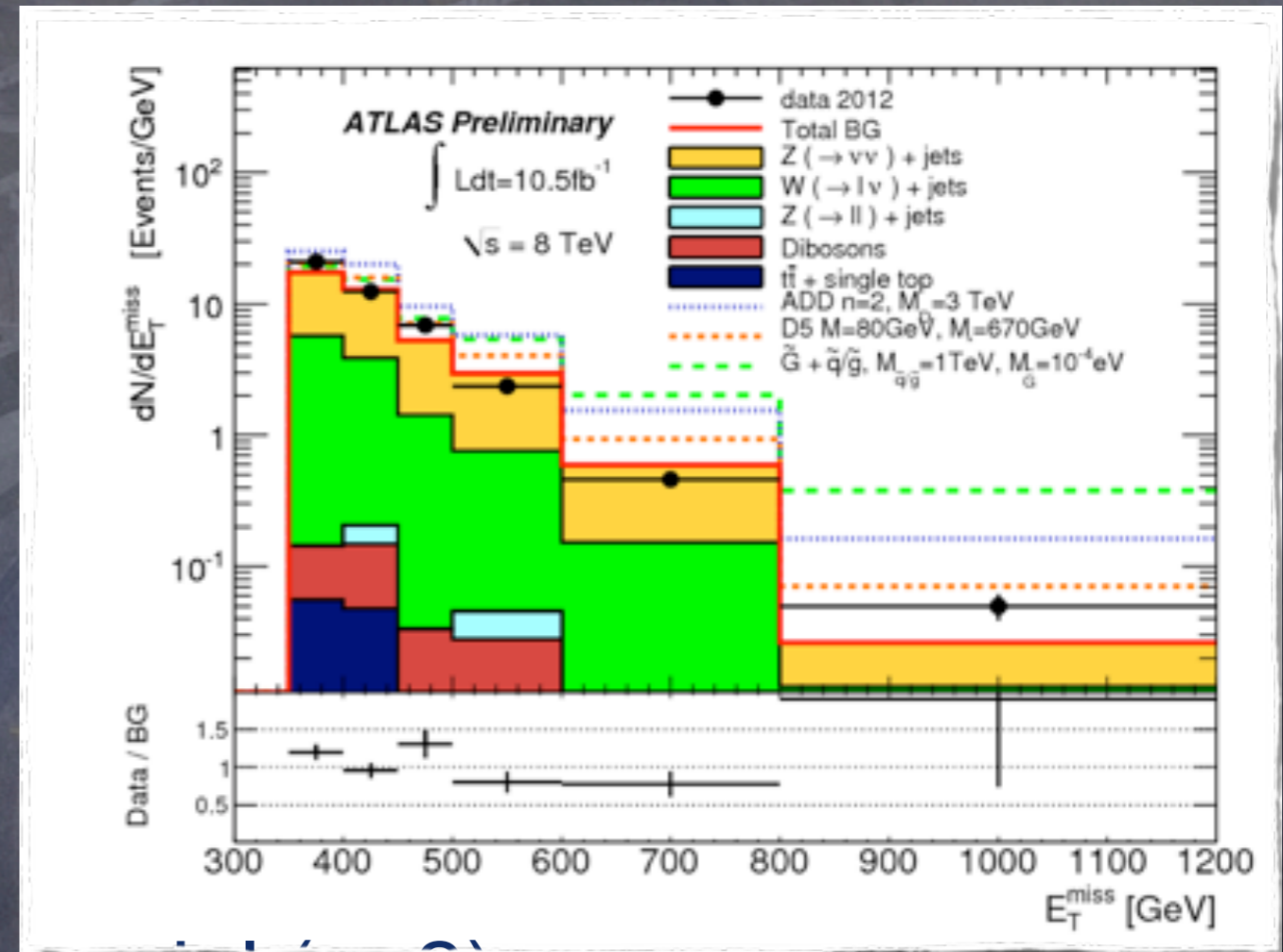
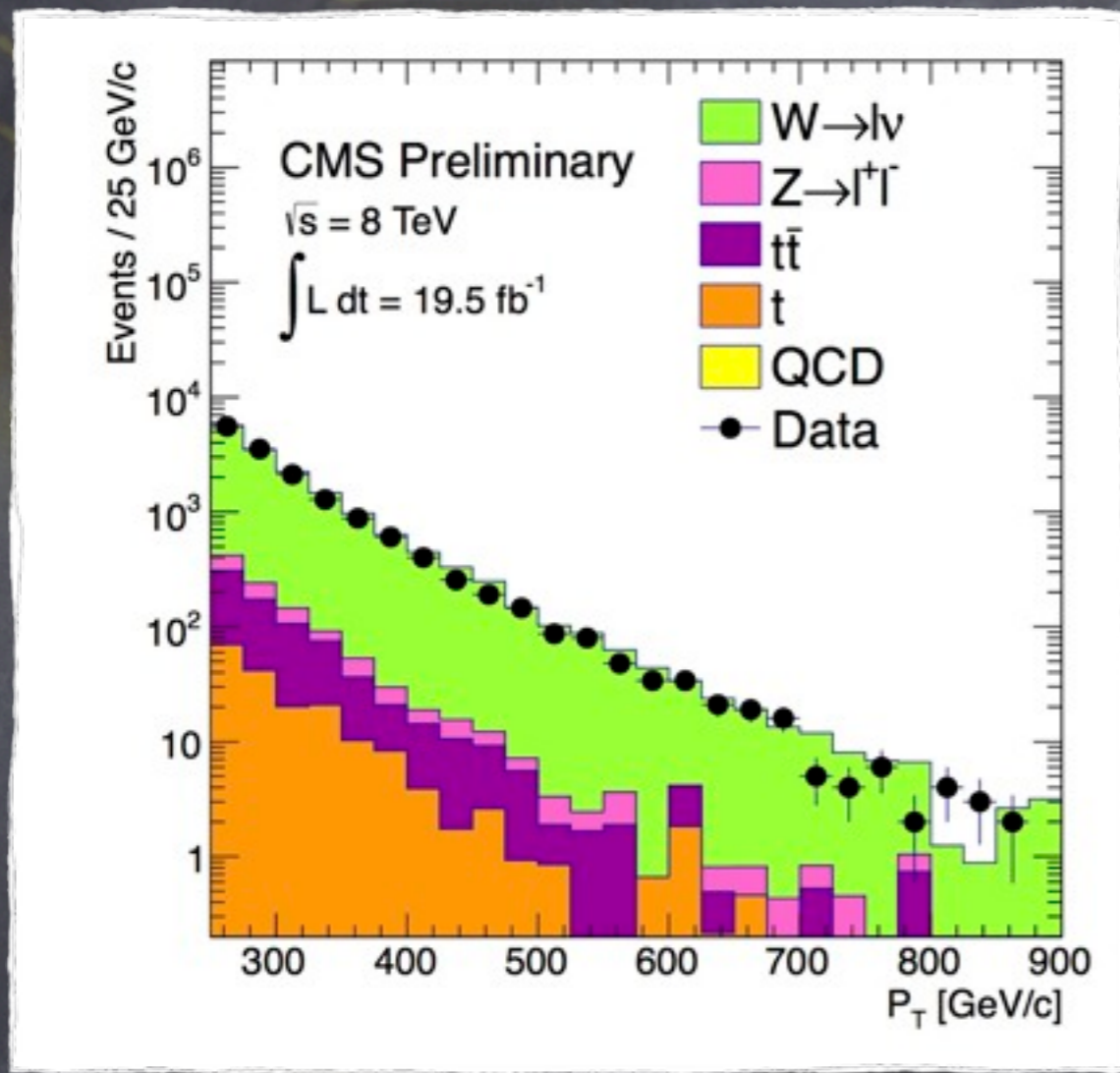
The Monojet Search

MET spectrum from data
control samples and MC
scale factors



No need to different
kinematic cuts (eg mT)
for bkg control samples
(no signal contamination)

The Monojet Search

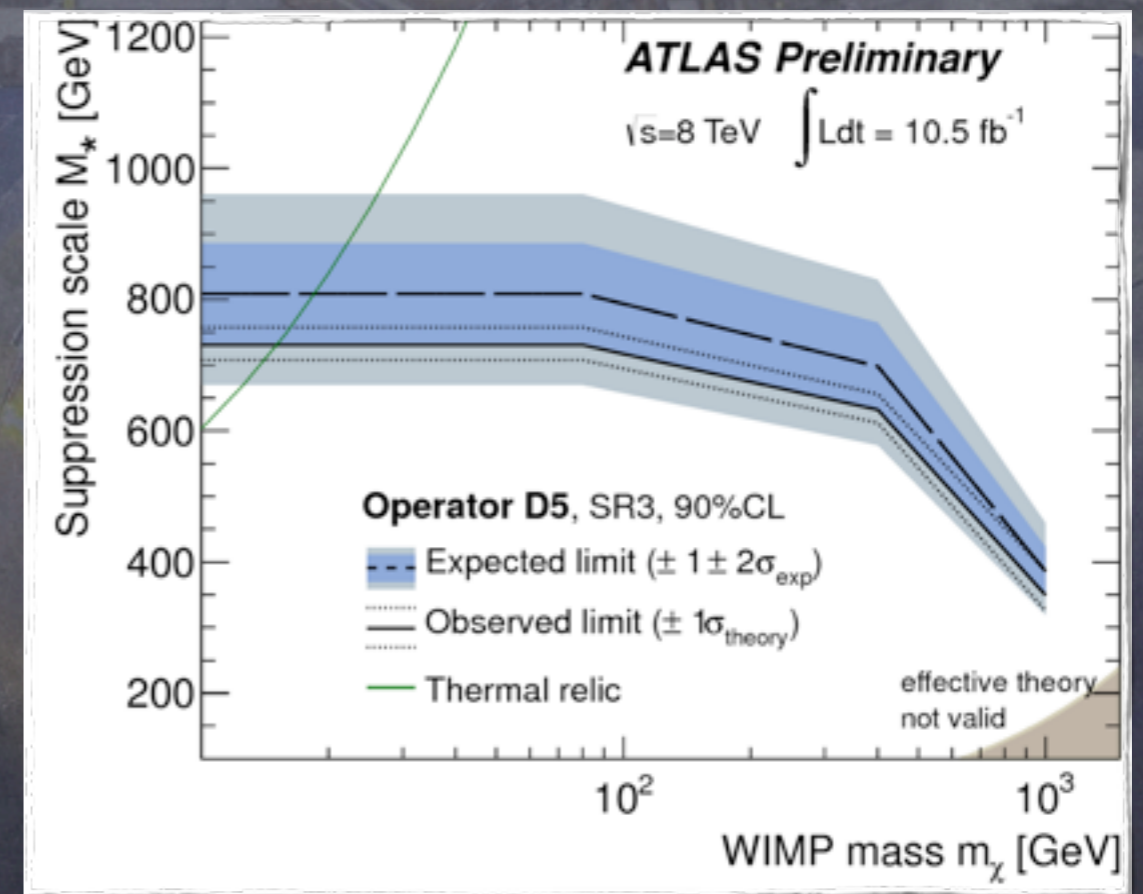
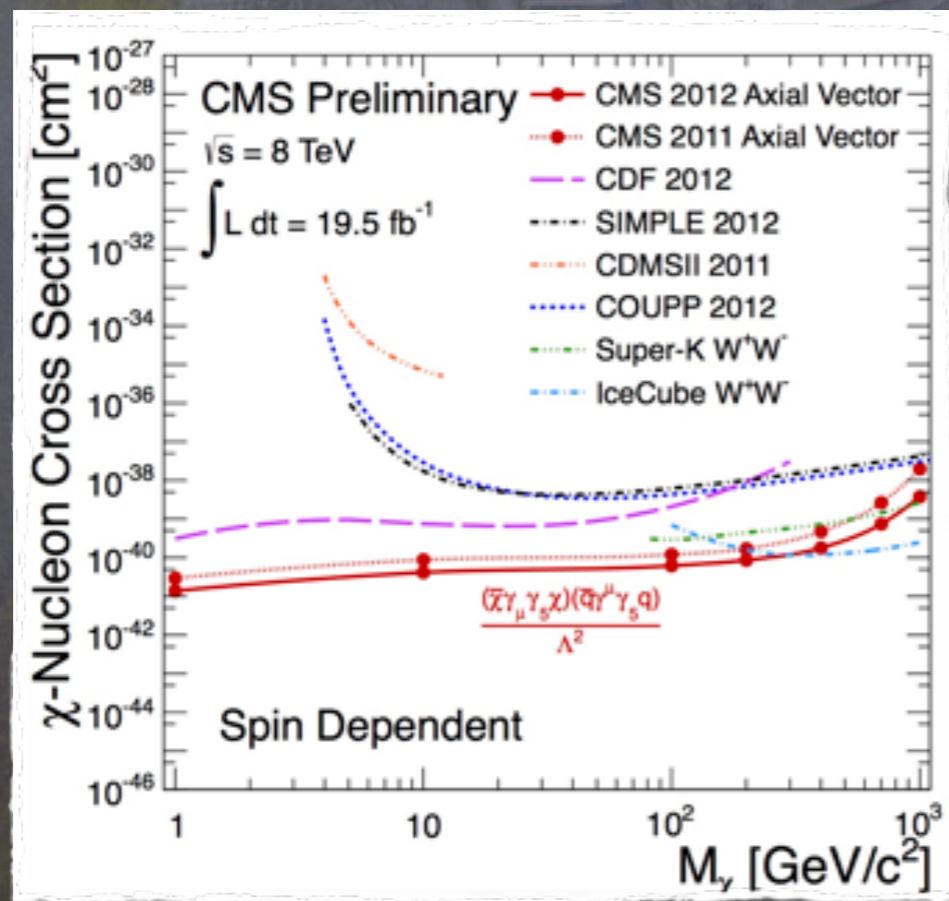


Good control over the kinematic variables
 MC prediction OK
 Large sensitivity to NP on the MET tail
 No evidence for a deviation from SM

The Monojet Search

Result translated in a limit using effective operators ,
suppressed by M^*

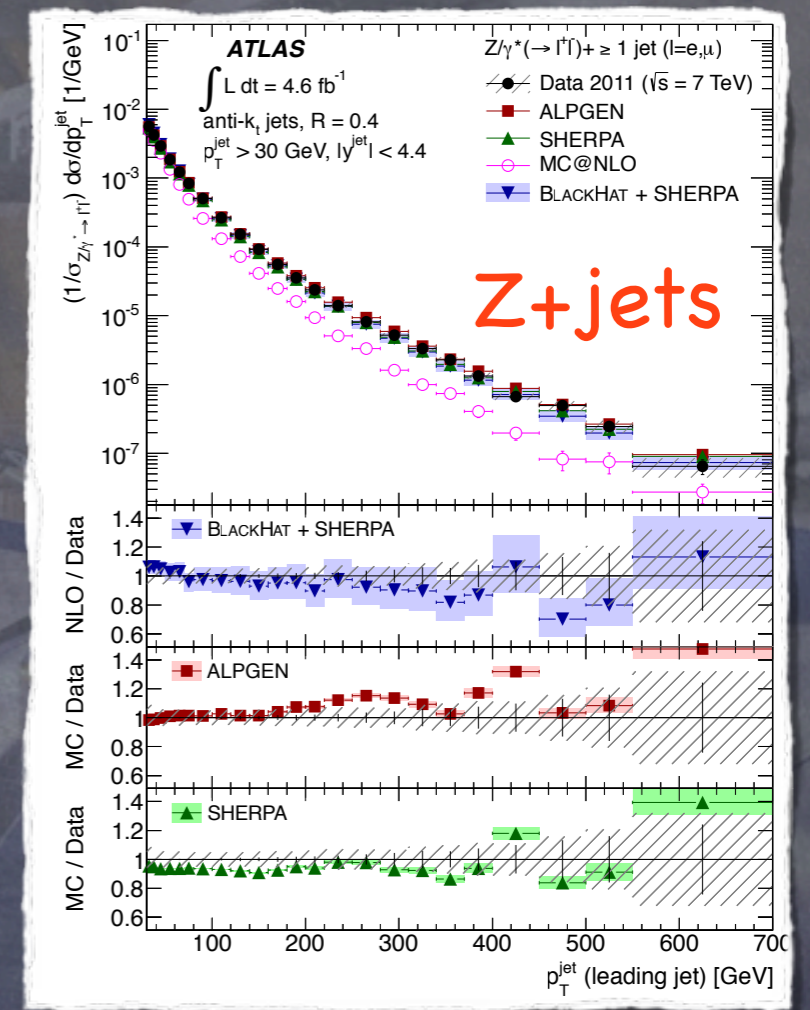
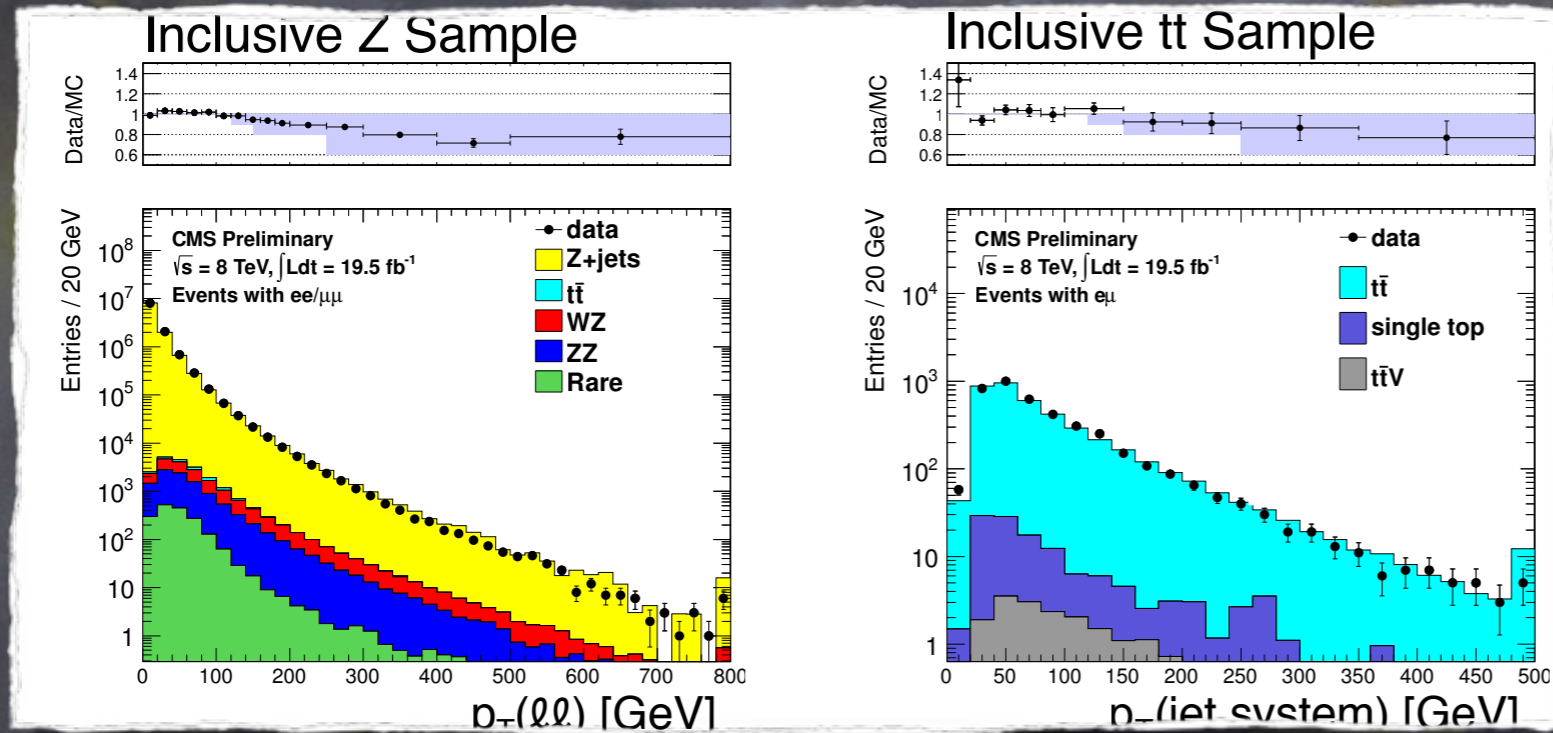
Results can be compared to direct DM searches under the
assumptions implicit in the effective-operators approach



Also limits from ADD models (n=2): 4.2 TeV (ATLAS) ; 5 TeV (CMS)

Do we control the jet radiation?

LO ME+PS generators model the associated jet production in a fair way



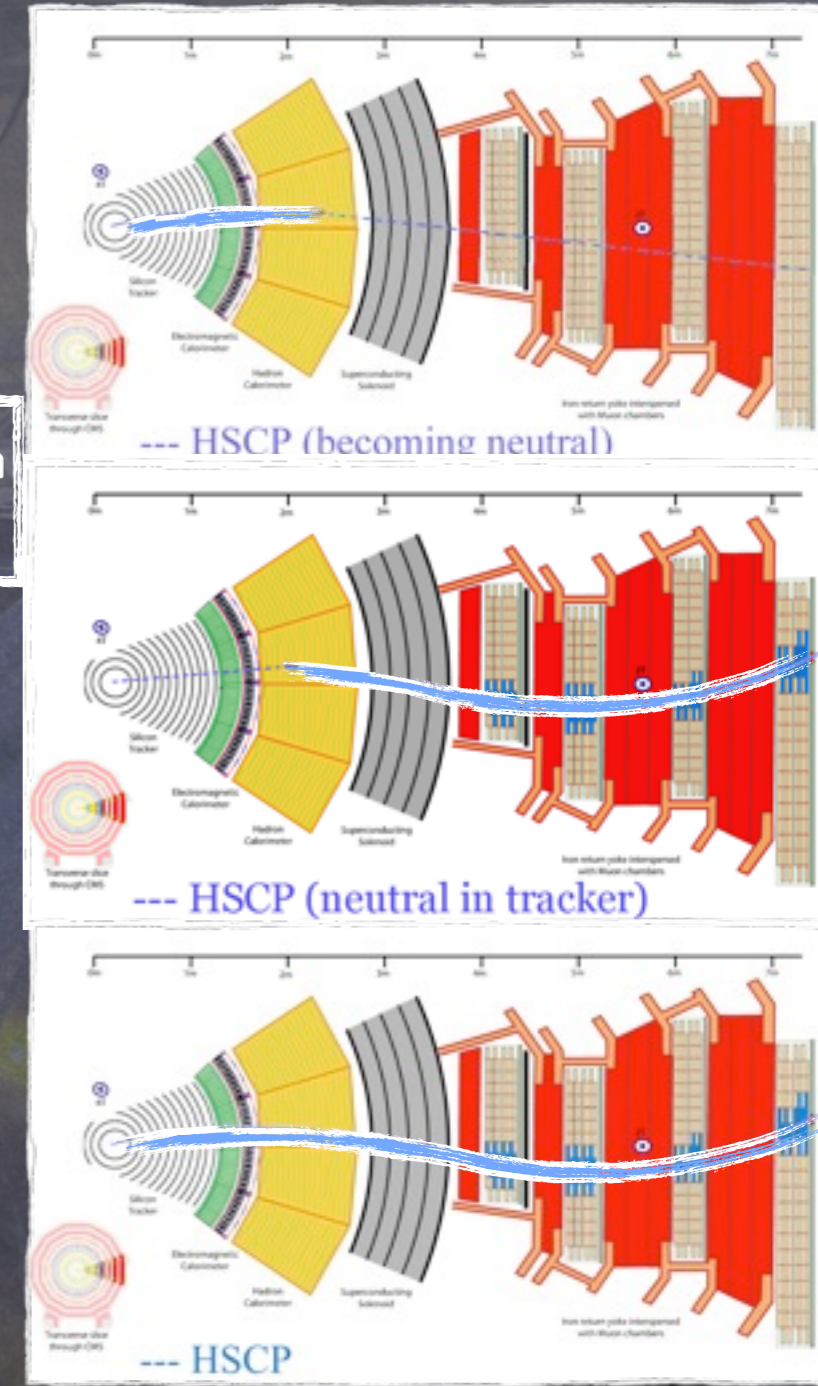
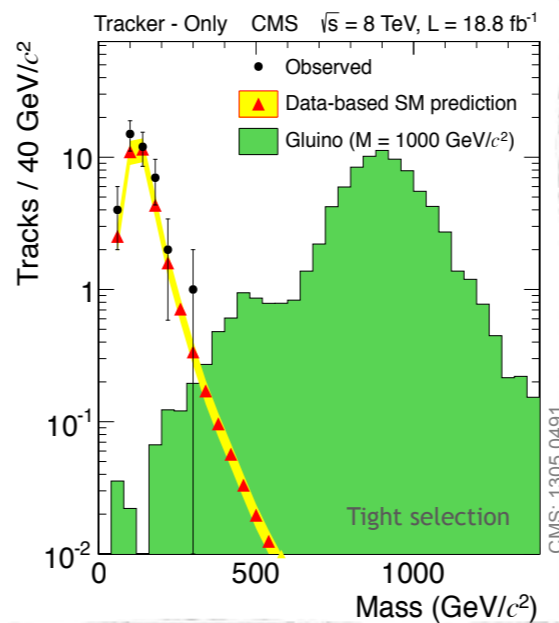
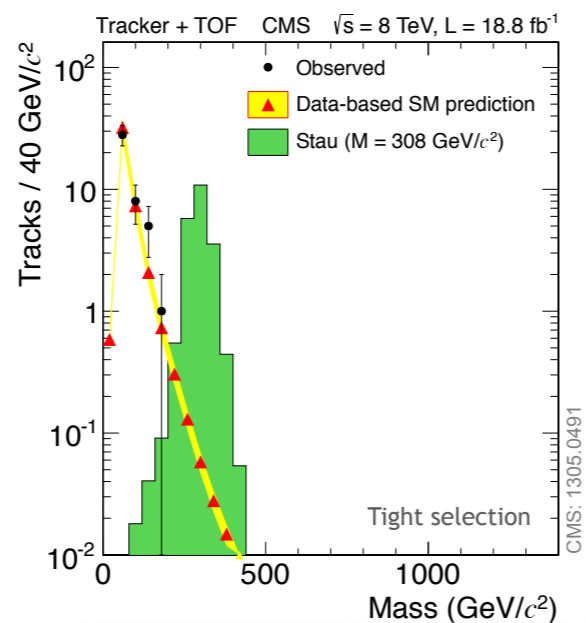
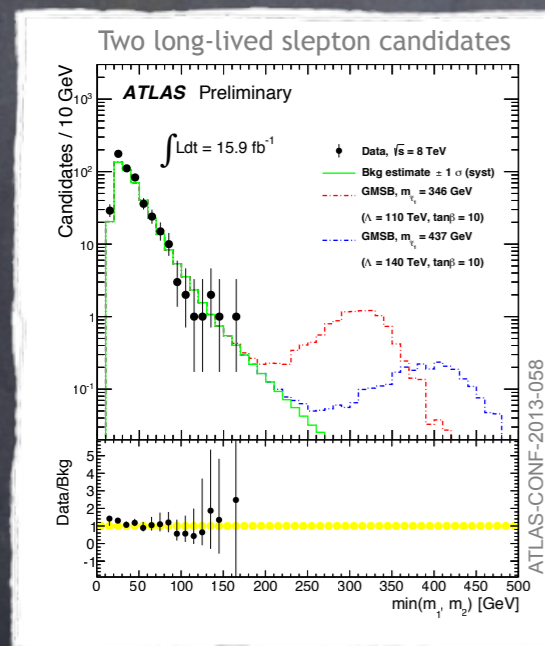
The study of SM processes (e.g. V+jets or tt+jets):

- make us confident that we control the signal efficiency for monojet-like signatures
- provide us with a measurement of the systematic error (and a MC weight) to correct the signal Monte Carlo

Long-living particles

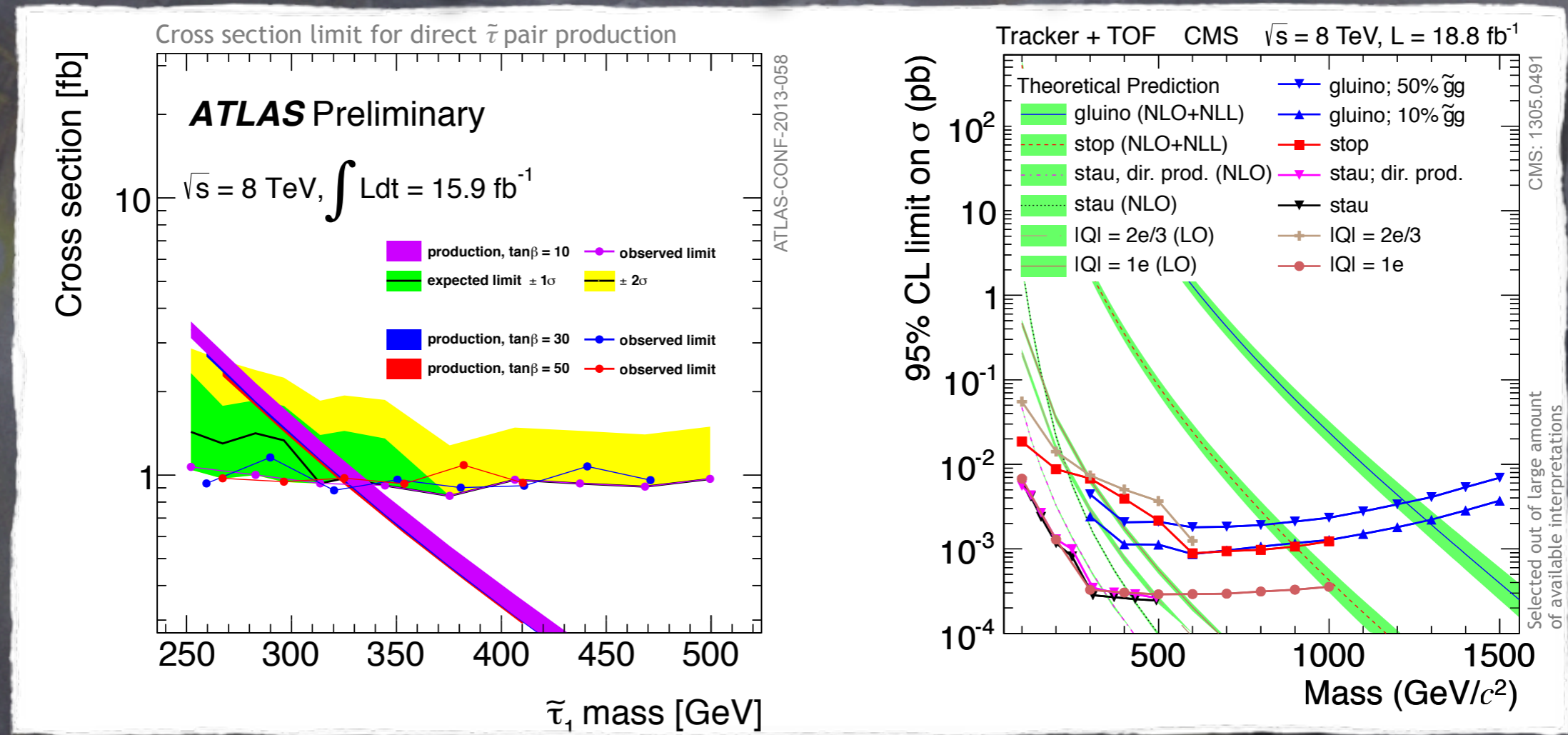
Long-living particles are detected measuring the **ionization**, the **time of flight**, and the **momentum**

Different parts of the detector are used, together (to improve the precision) or individually (to be sensitive to different NP scenarios): tracker / calorimeter / muon system (ATLAS only)



Long-living particles

Strong limits on gluino, stop, and stau



If Not SUSY

• New Resonances to ff

*what was planned
before data*

• New Resonances to $VV/VH/HH$

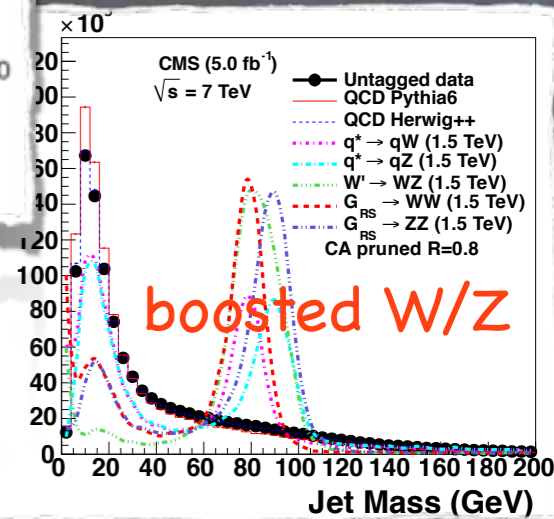
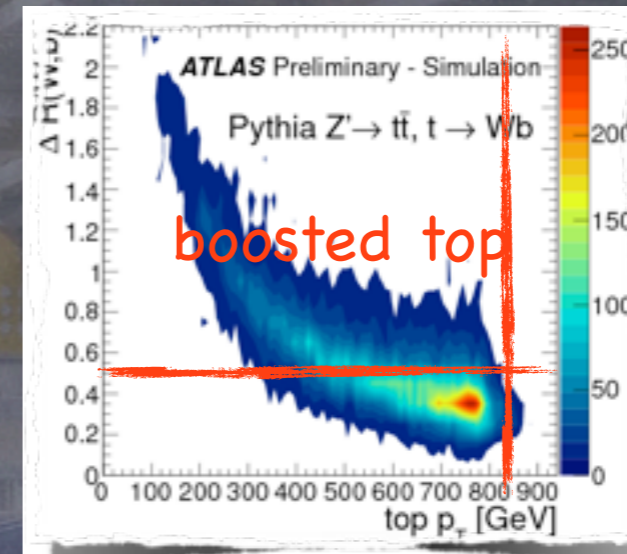
• New Partners of Top and Bottom

*the substructure
revolution*

• Many other possibilities I have no time to cover

The Substructure Revolution

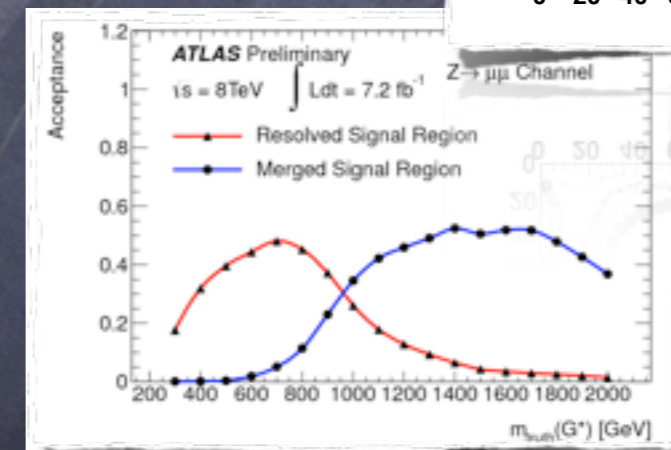
- Pushing the searches to higher mass values, we are confronting ourselves with W,Z,H, and top produced at large boost
- After a mass-dependent threshold, the particles acquire enough mass to look like a single fat jet once they decay hadronically



$$p^\mu = (E, \vec{p})$$

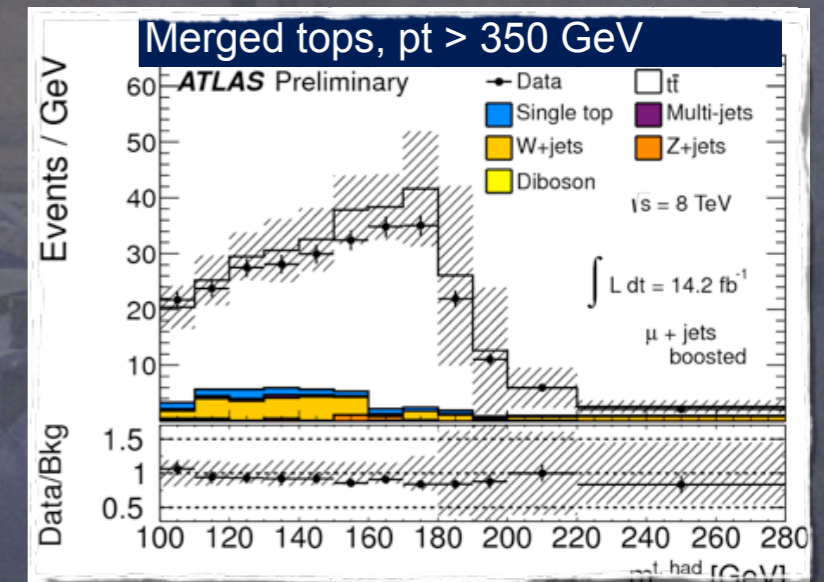
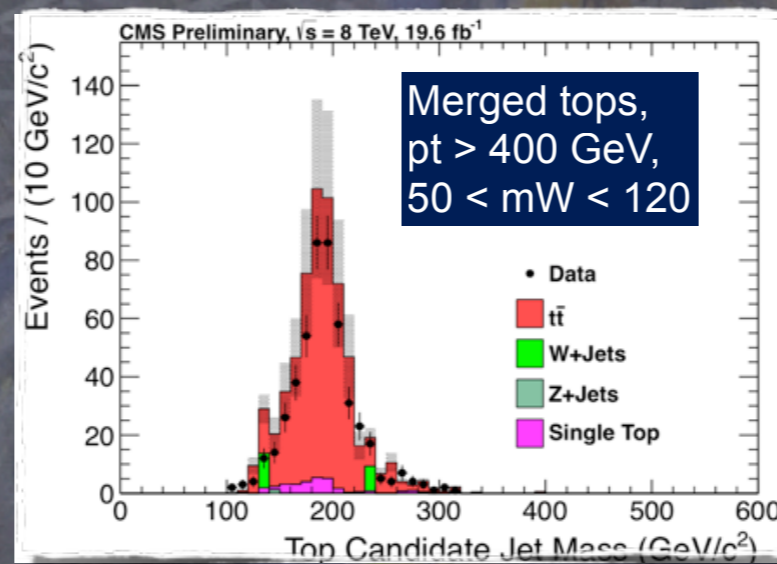
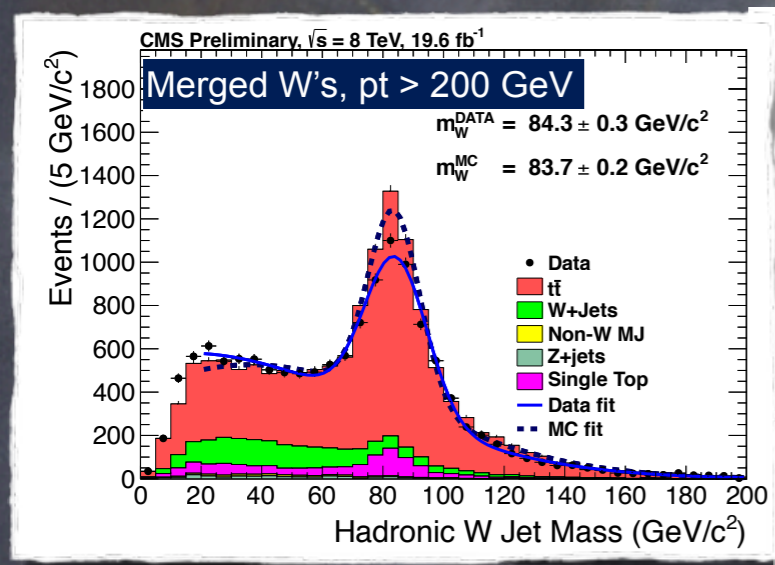
$$\theta \approx 2 \frac{m}{E}$$

- In this case, we don't reconstruct them anymore from jets, but as a single massive jet
- The jet mass becomes a powerful discriminator against ordinary backgrounds
- We can then look inside the jet to see if it looks more like more jets merging (massdrop, subjettiness, etc)



The Substructure Revolution

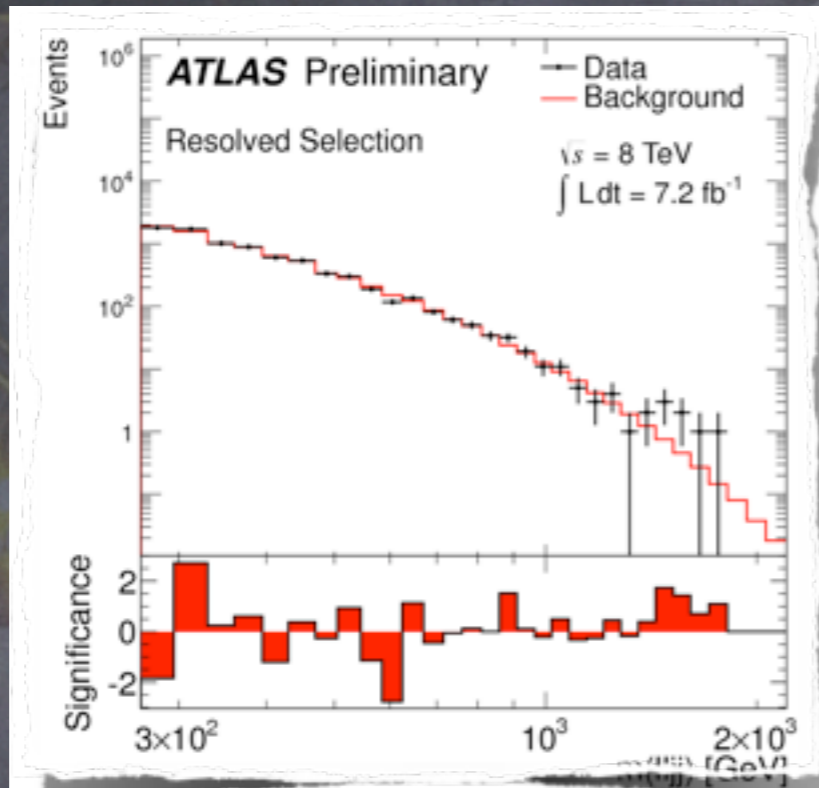
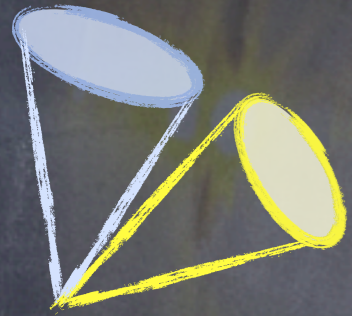
- The technique is tested on data control samples (e.g. boosted Ws and tops in $t\bar{t}$ events)



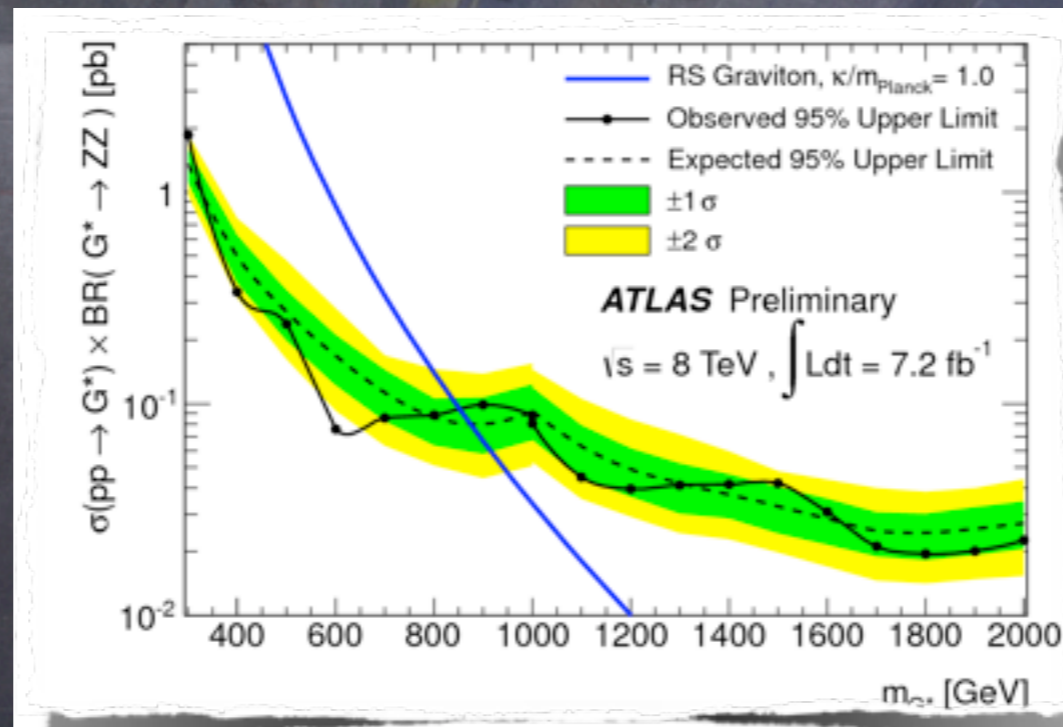
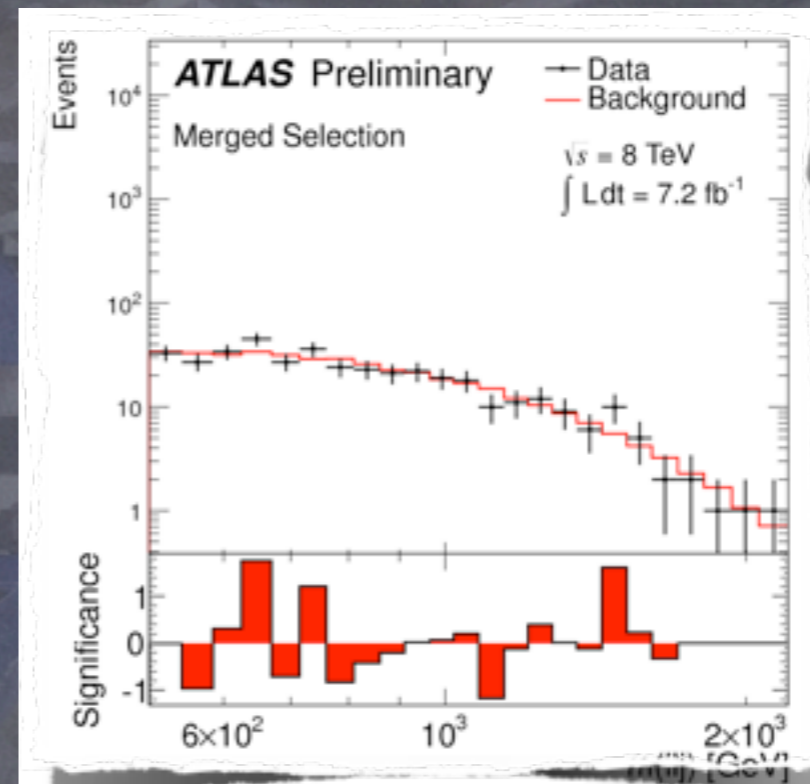
- These studies allow to check and correct the MC simulation of the signals
- This allows to optimize the V-tagging, H-tagging, and t-tagging to improve the searches
- A new domain of jet physics which will be more important with 13 TeV collisions

Resonances to VV

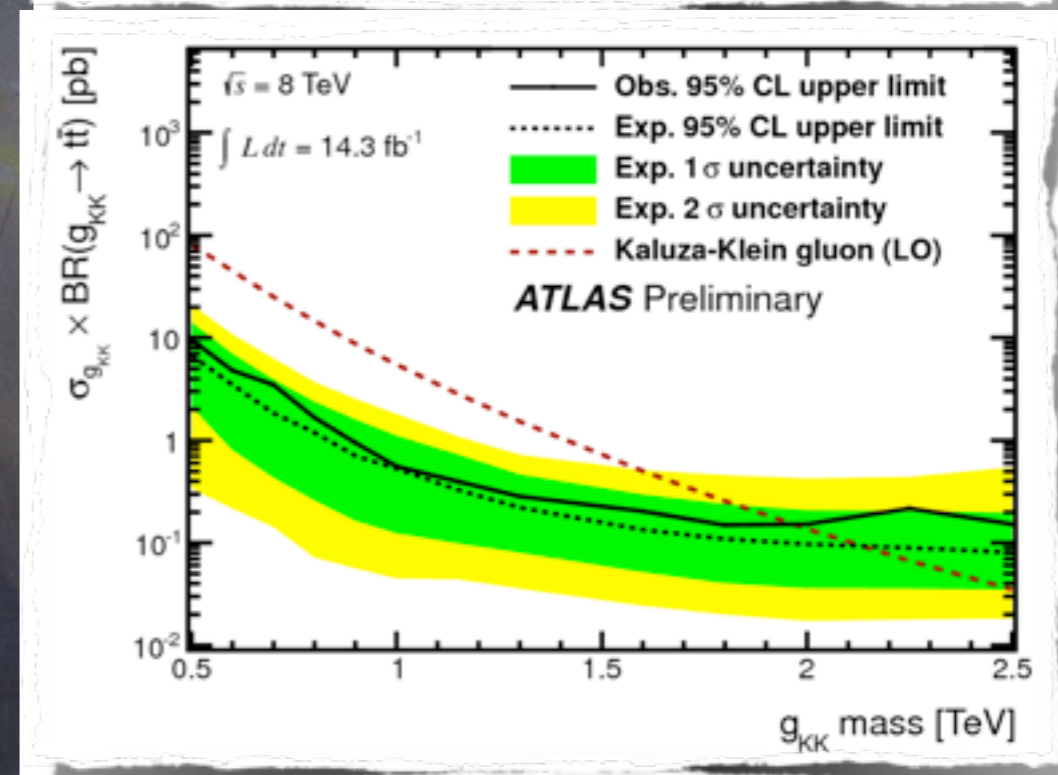
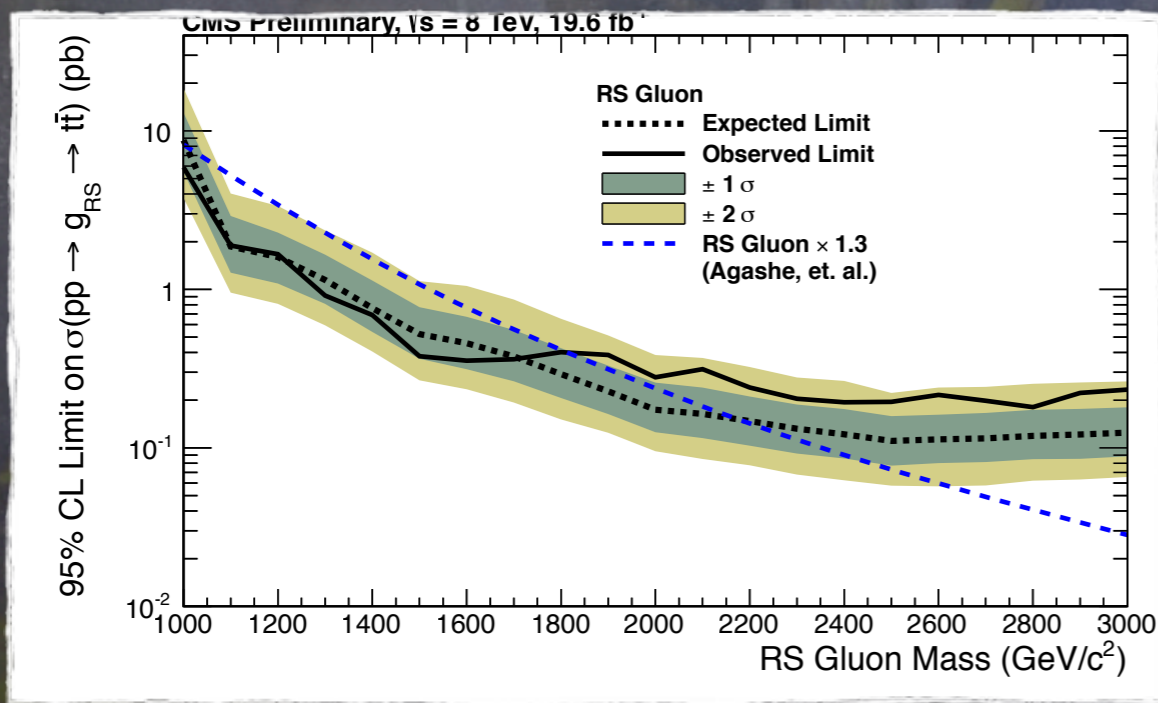
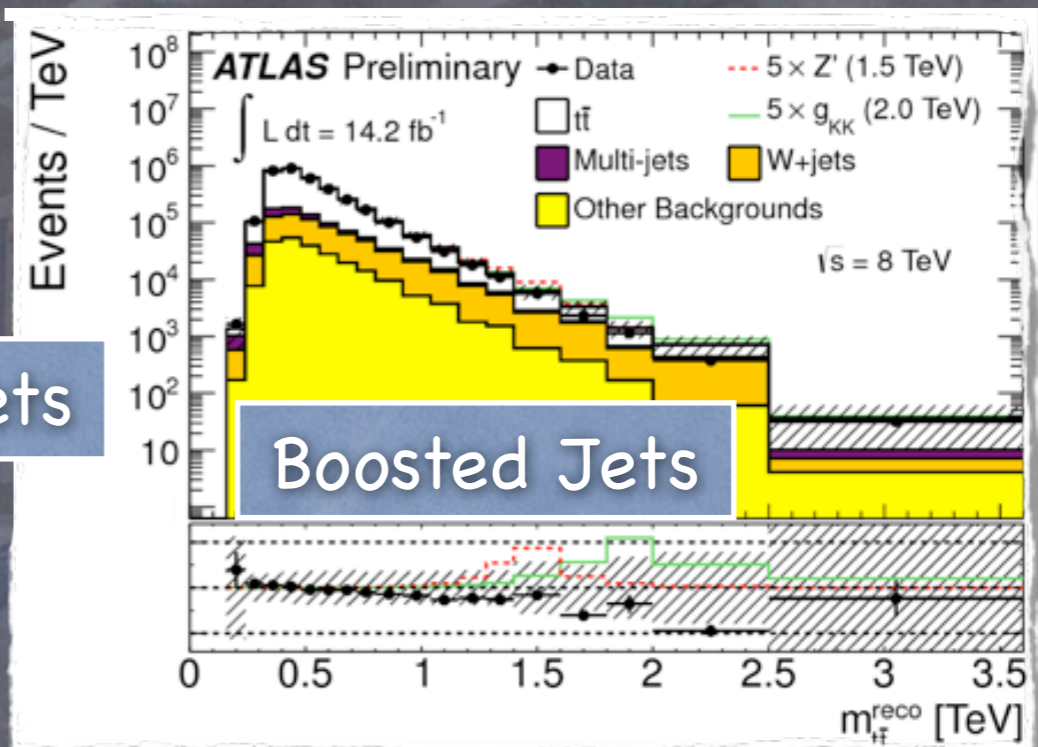
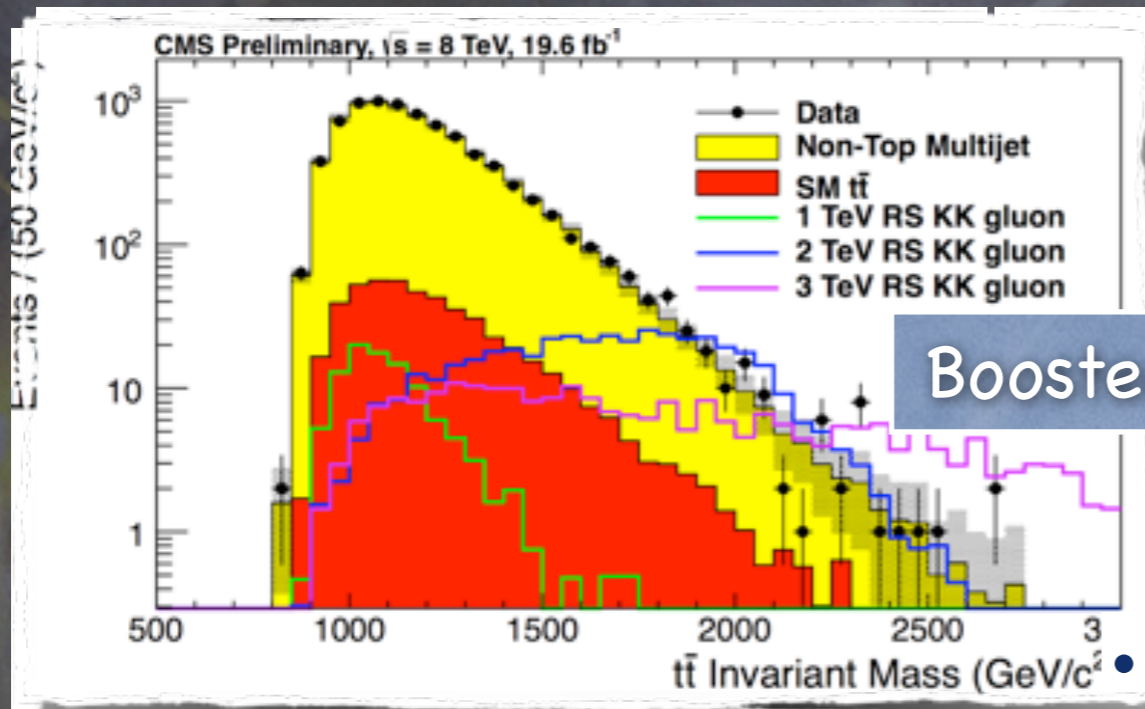
resolved topology (small masses)



merged topology (large masses)

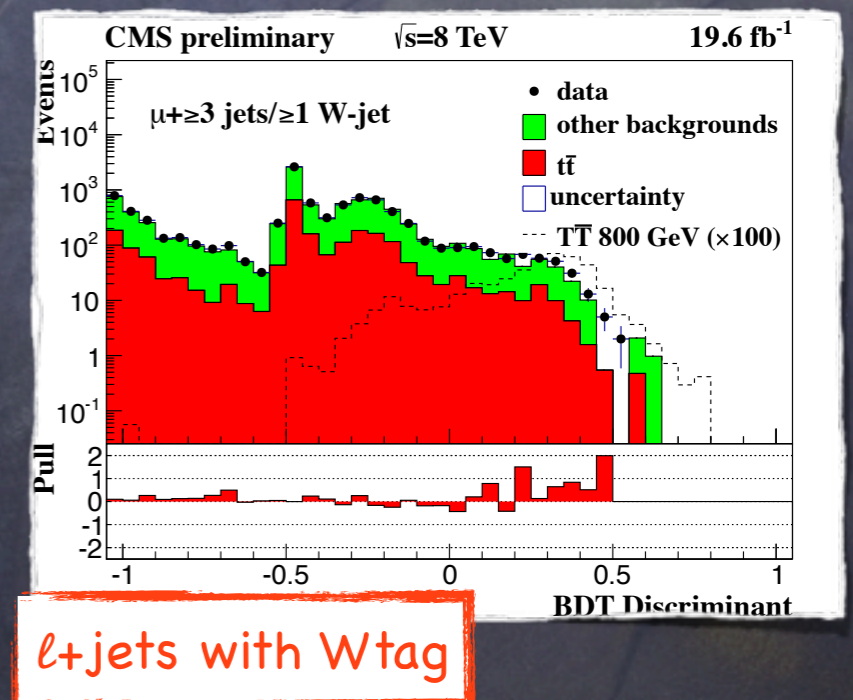
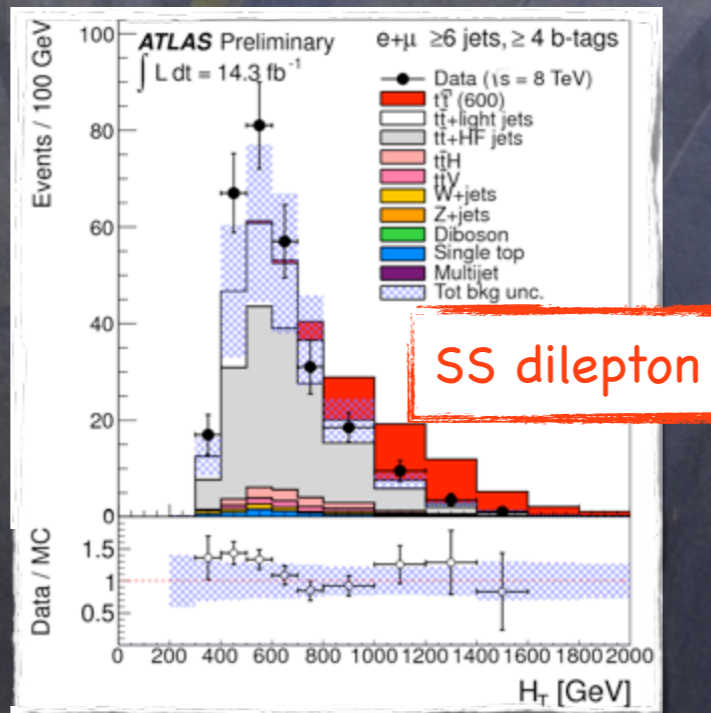
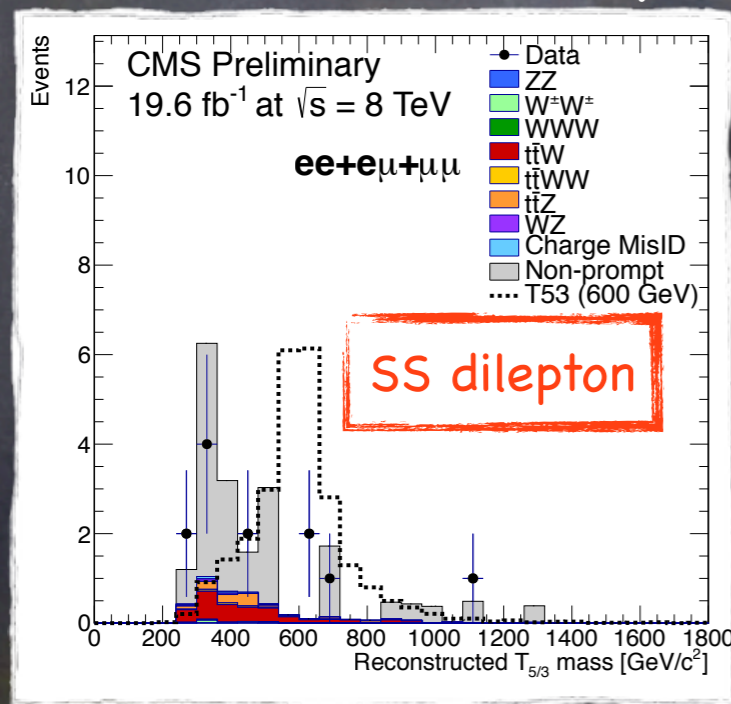
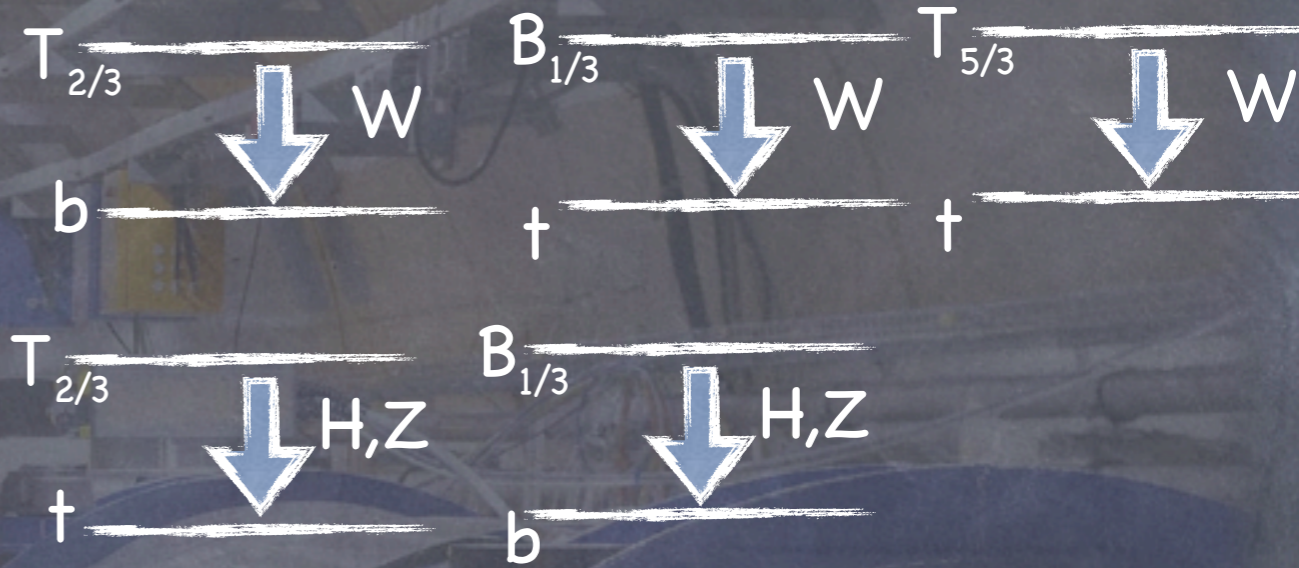


Resonances to $t\bar{t}$



Top&Bottom Partners

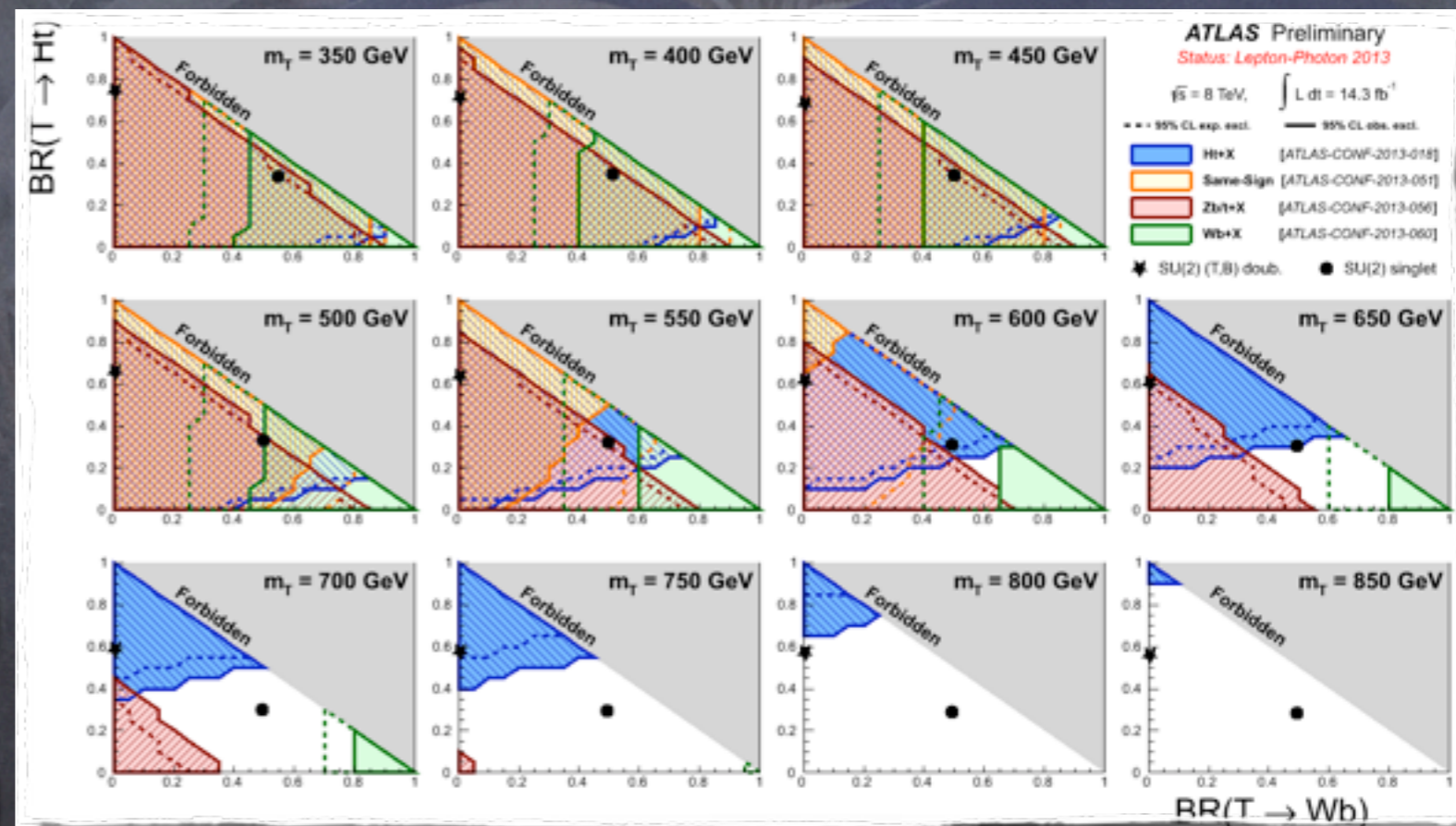
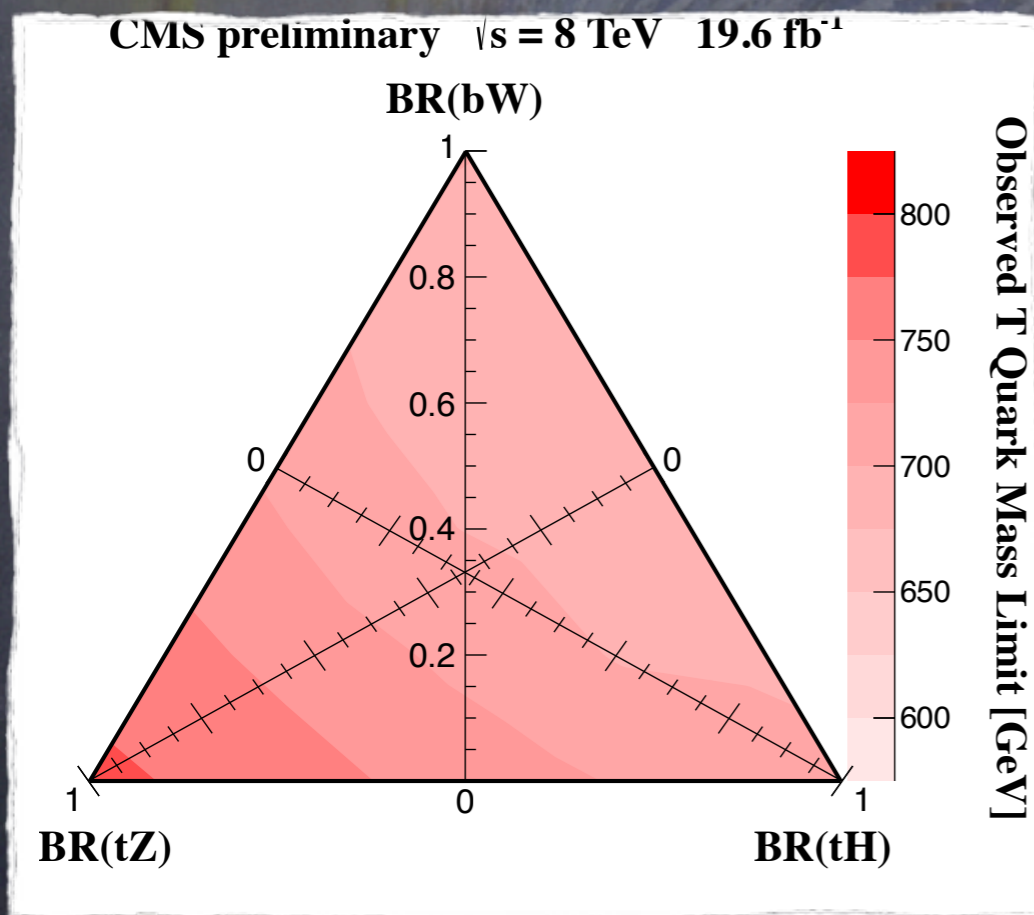
- New heavy colored objects decaying to a b or t + one boson (W,Z,H)
- Searched for mainly in pair production, with both merged or resolved decay products
- Different techniques (exclusive vs inclusive vs multivariate analyses)



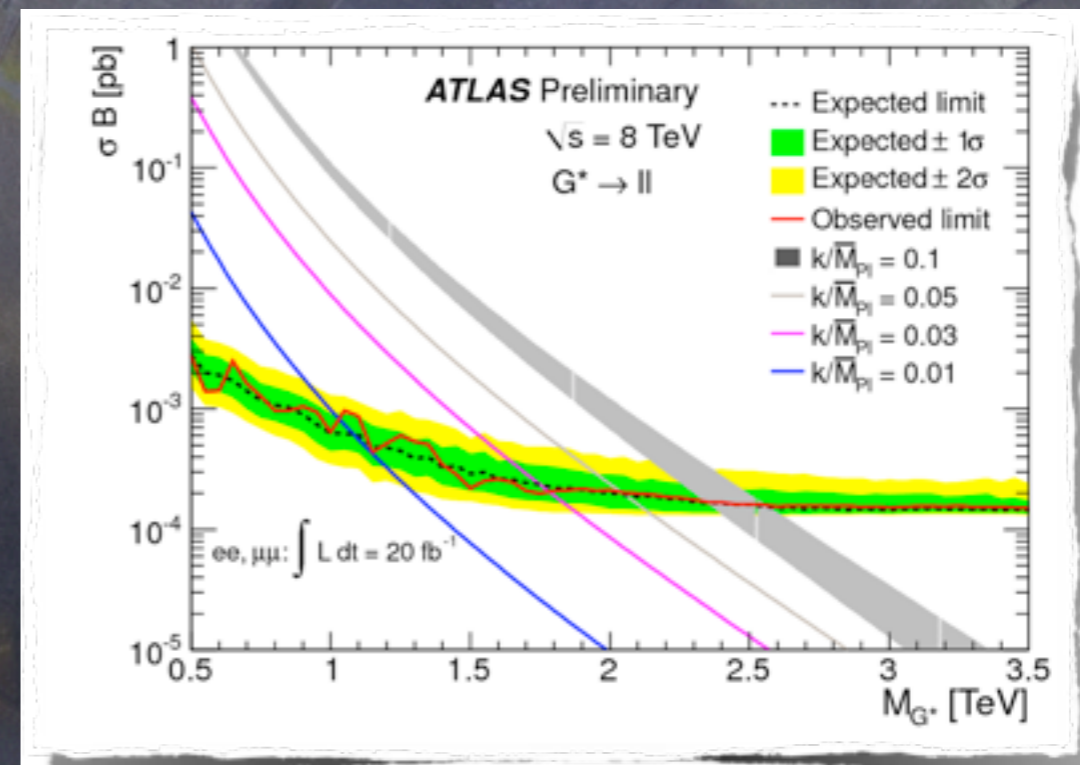
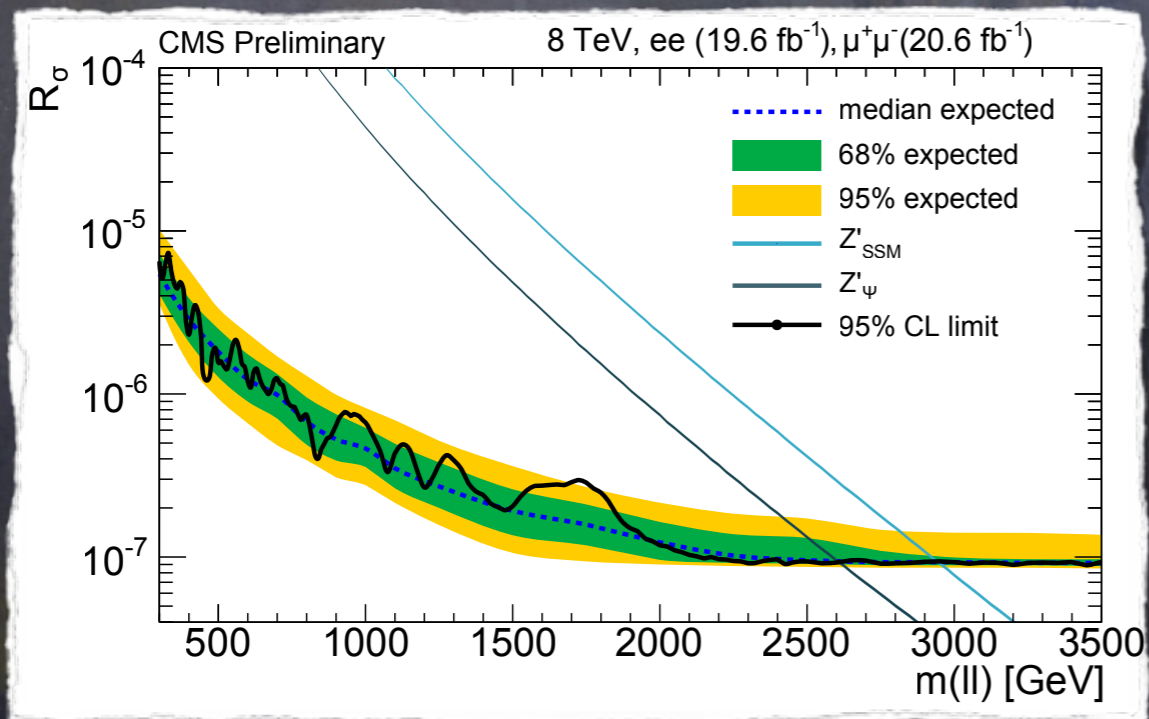
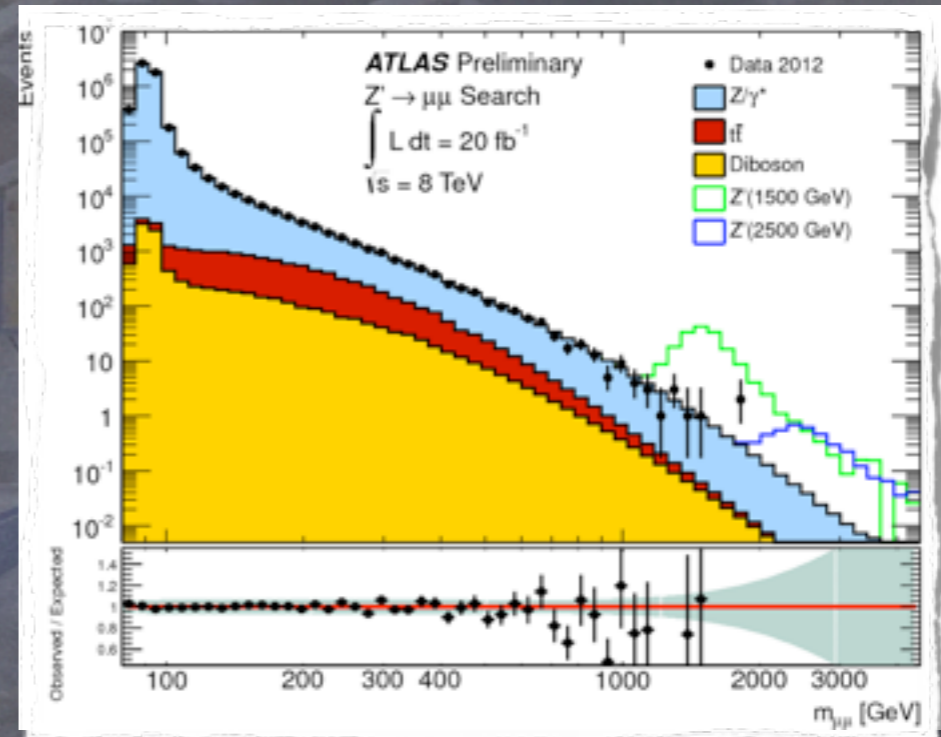
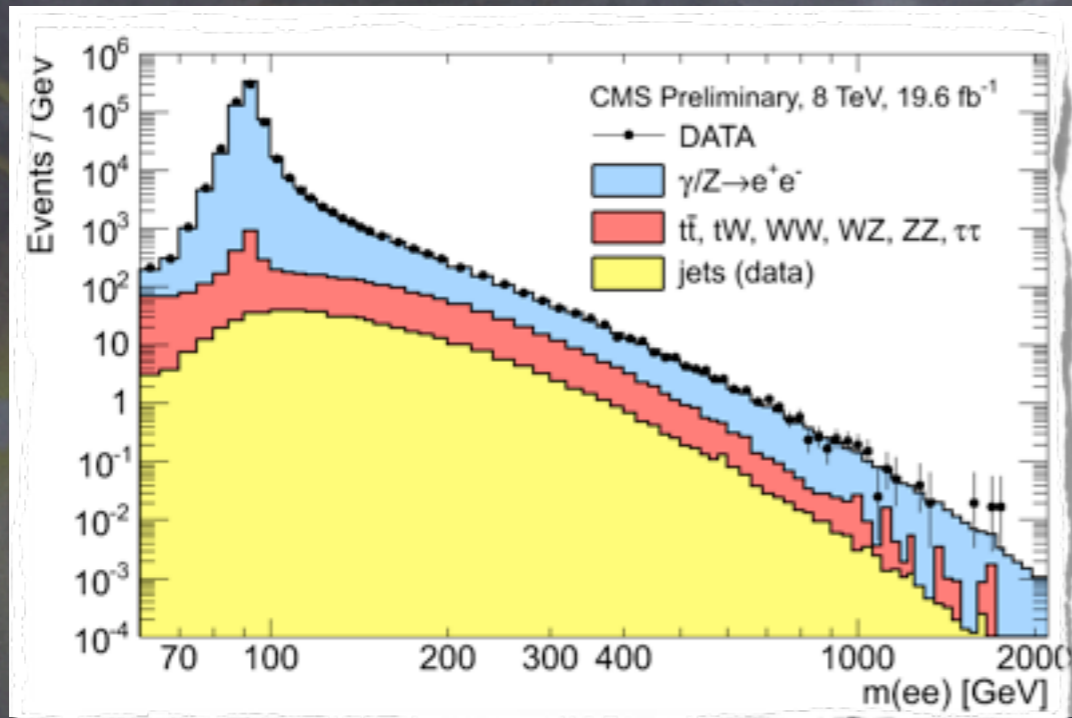
- When possible, exploit number of btags to suppress SM backgrounds

Top&Bottom Partners

The limit is studied vs the BR to the three open channels
 Plane fully explored for masses ~ 600 GeV
 Masses up to 800 GeV excluded for some BR choice

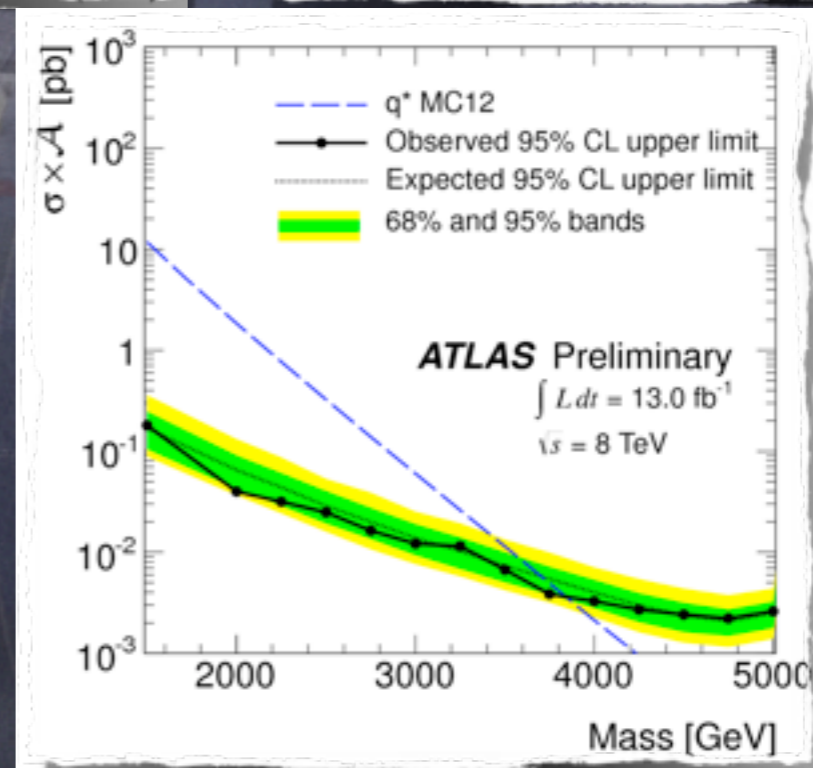
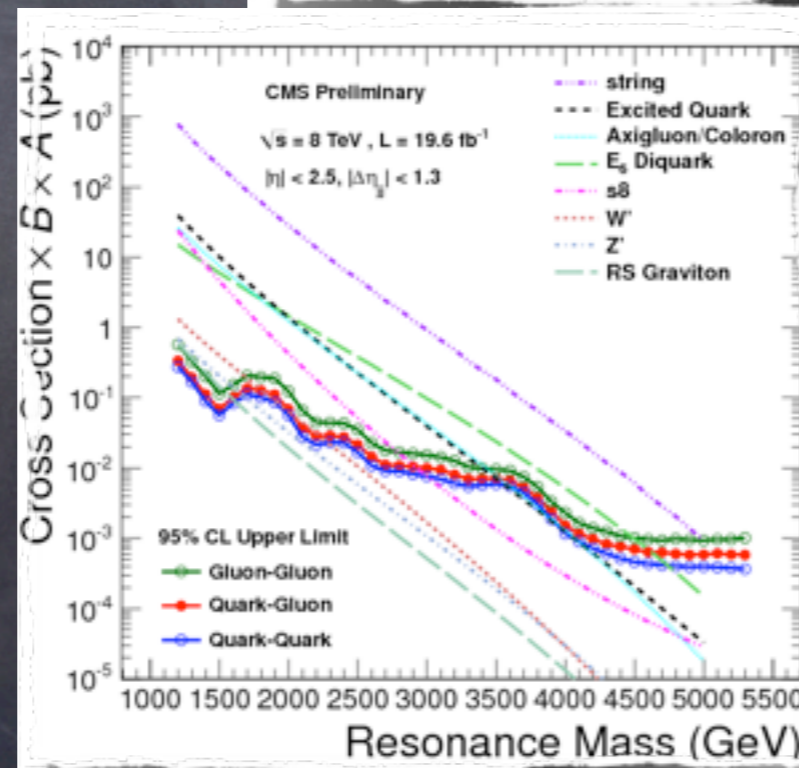
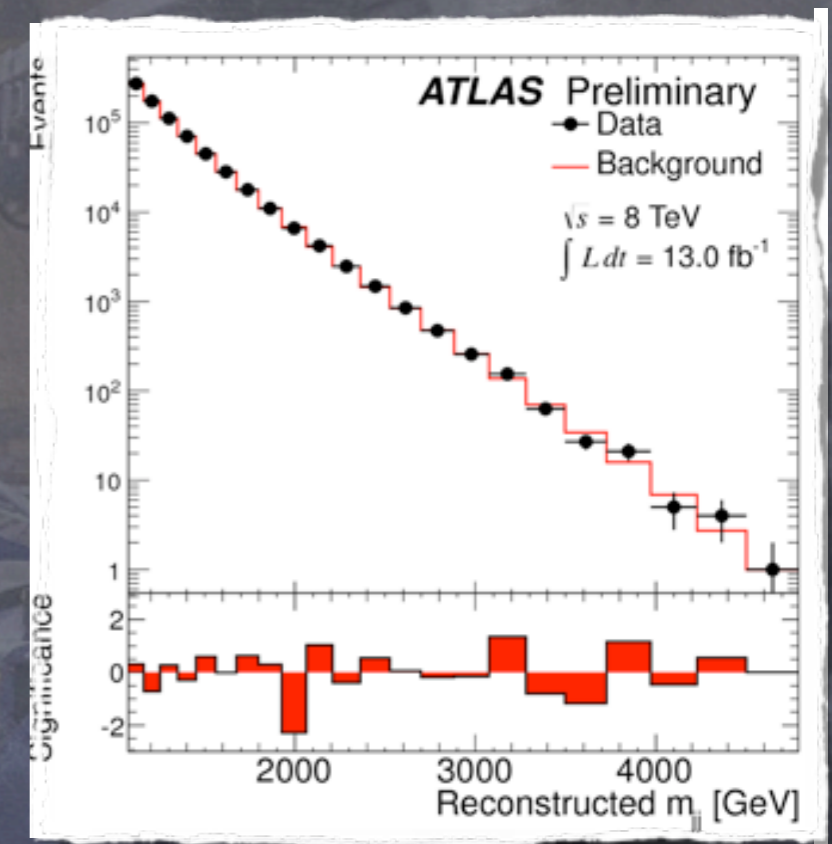
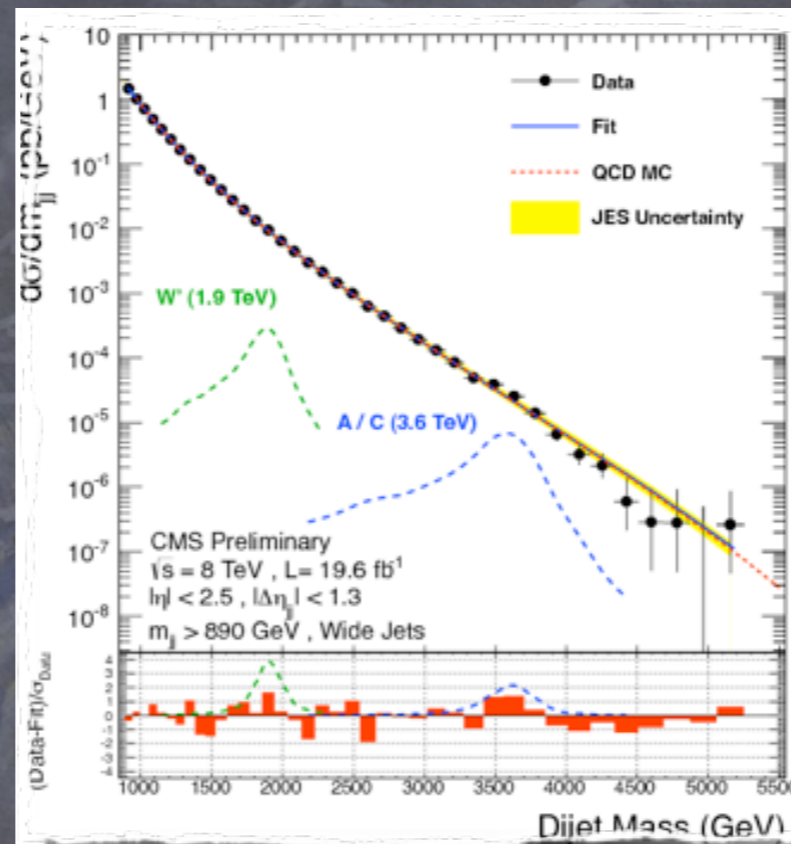


Resonances to ll



Resonances to dijet

Results in agreement with SM until 5 TeV (highest explored energy)





The Next Run

What Next?

For the restart

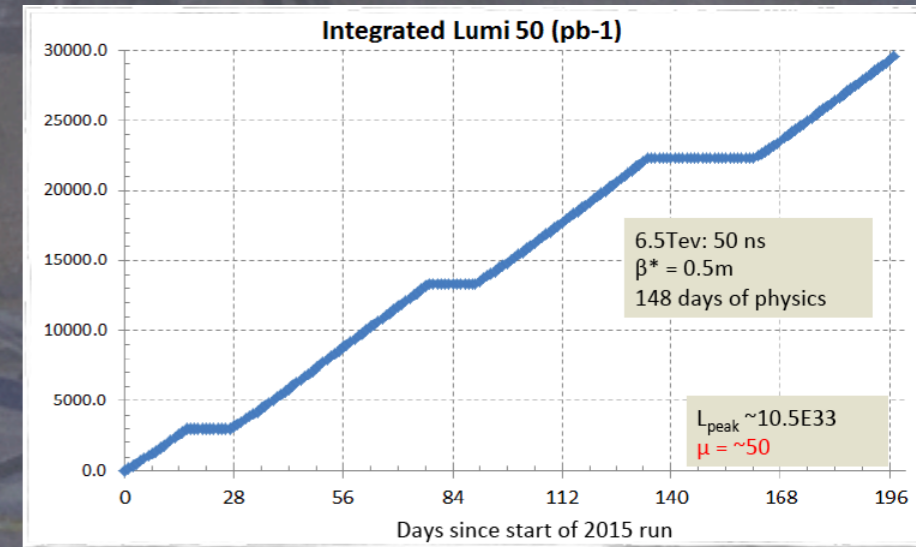
We will most likely have a rump-up as fast as for Run-I (experienced gained operating the LHC and the detectors)

We will benefit immediately of the higher energy to probe the existence of heavy objects

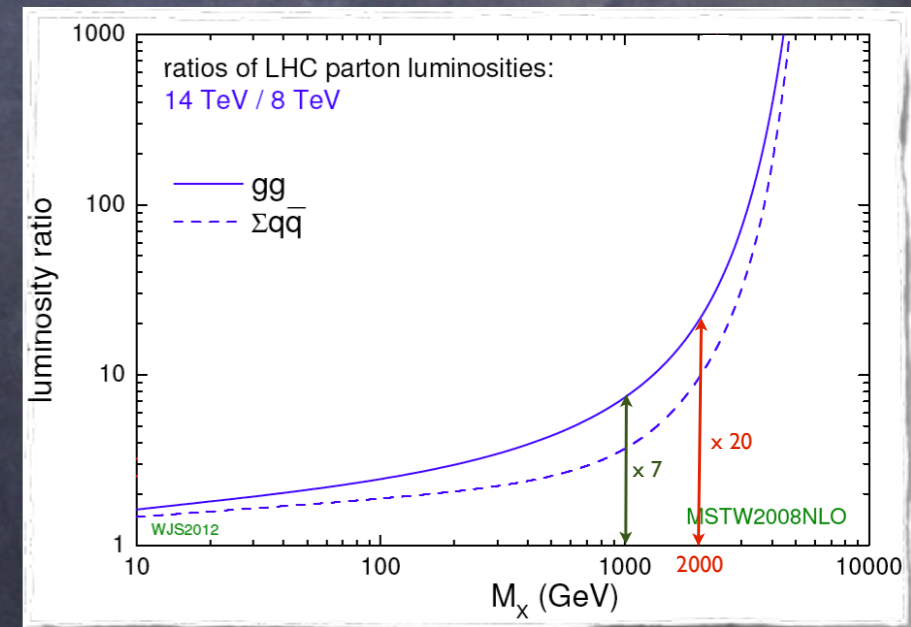
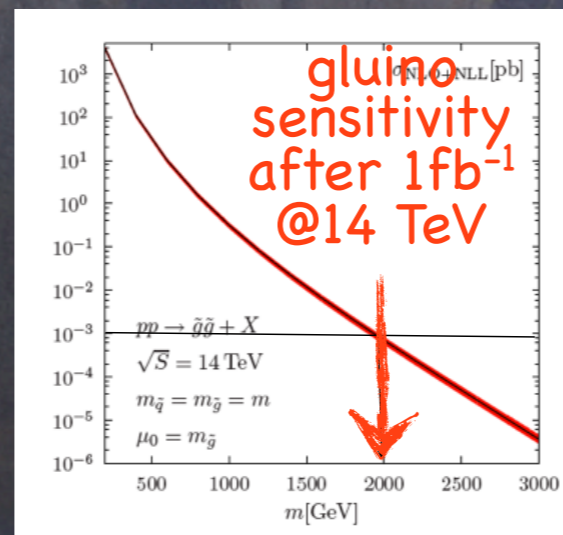
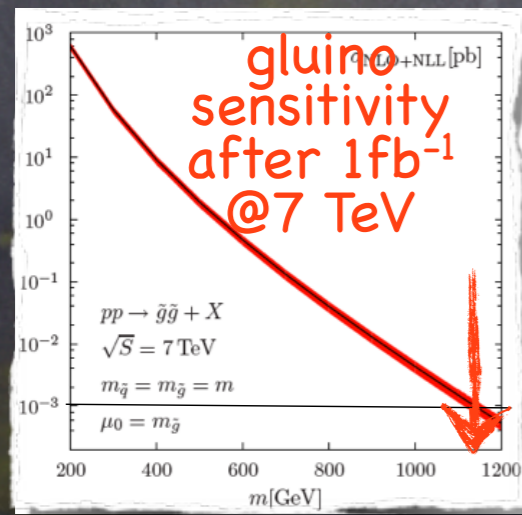
Cumulating more data on the longer term we will also improve the intermediate mass range

We will get to the sensitivity of Run-I after the first 1-3 fb⁻¹

estimated performances for 50 ns collisions@13 TeV



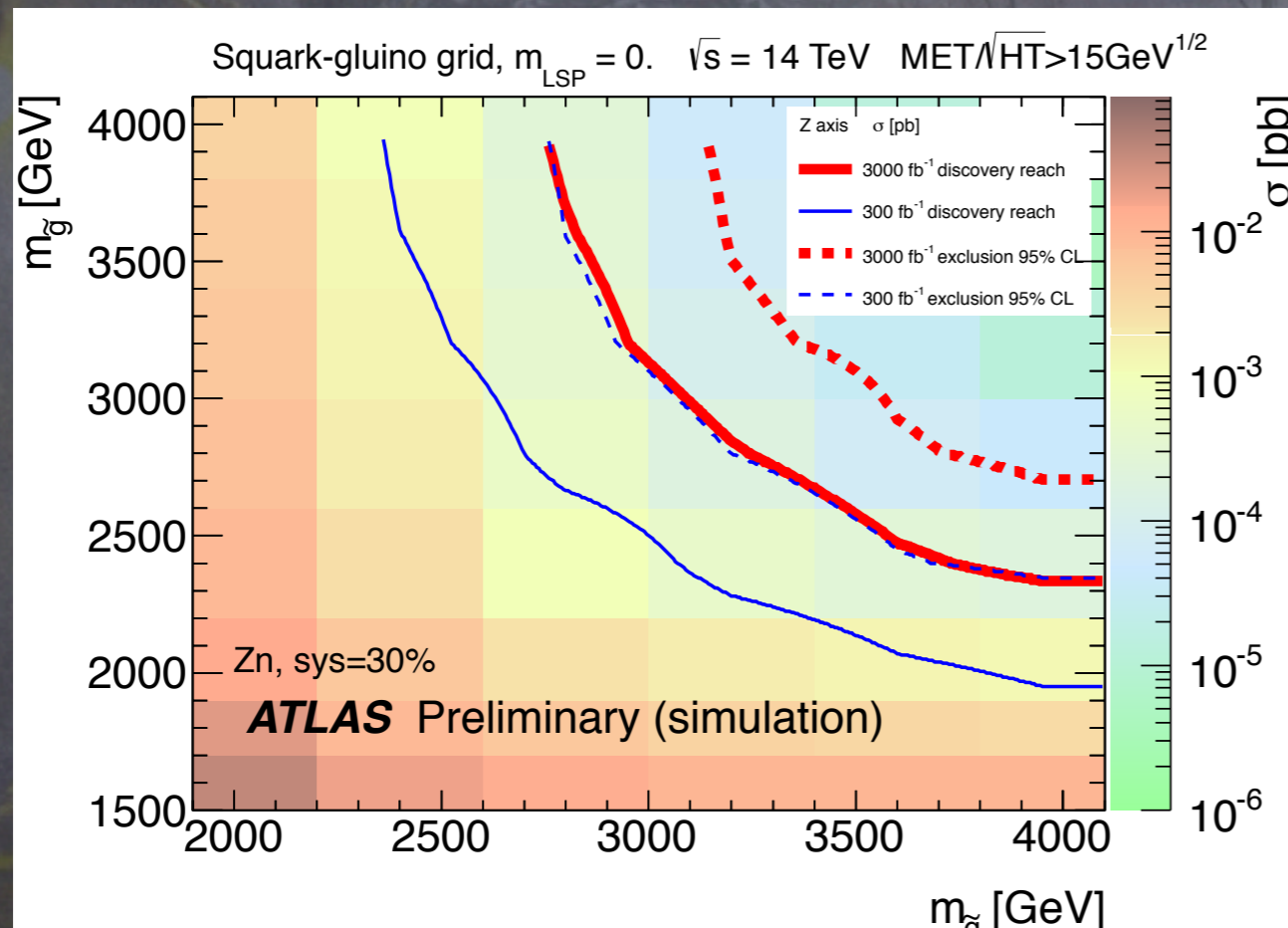
The gain in energy is particularly pronounced for heavy objects



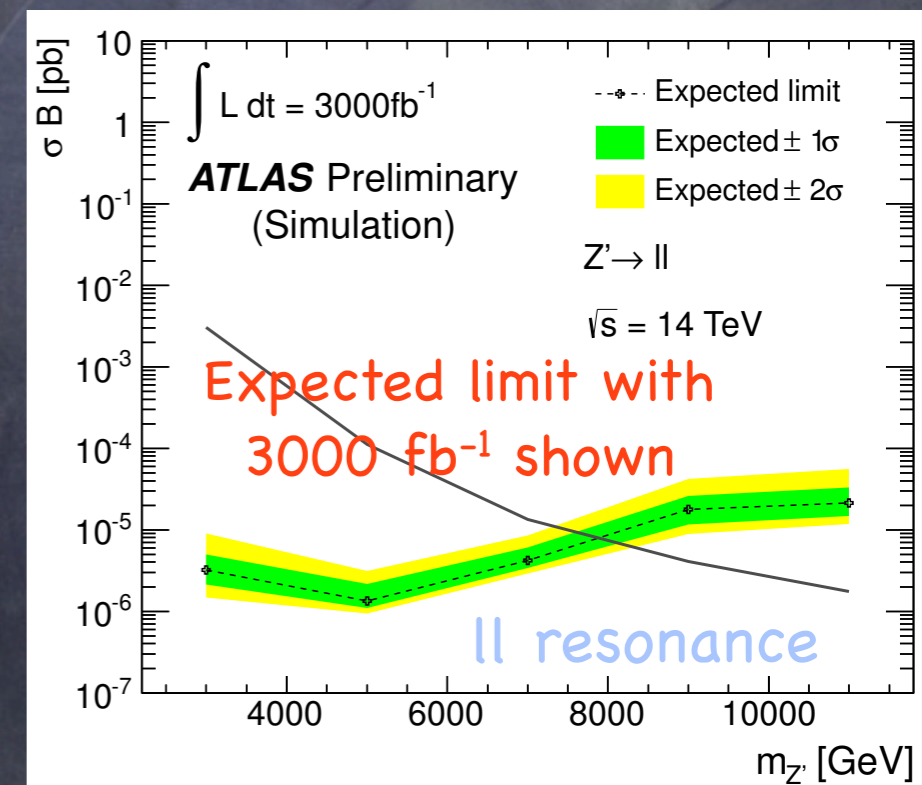
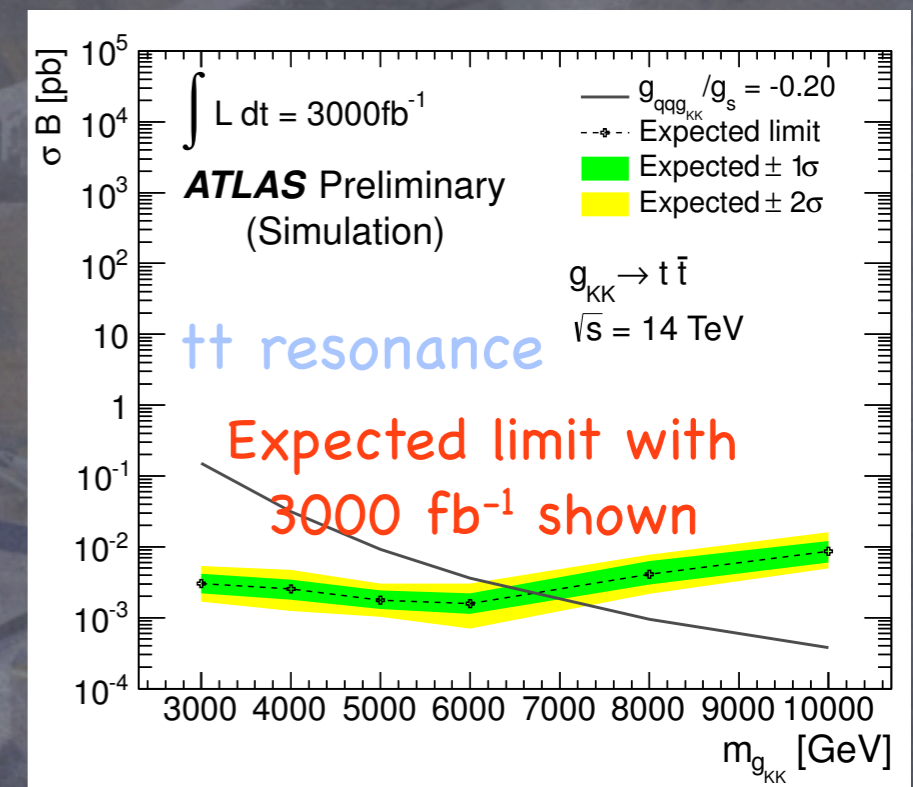
G. Rolandi BrunoFest@Berkeley

Snowmass Extrapolations

- Dominated by physics backgrounds $Z(\nu\nu)+\text{jets}$ and top pairs
- Large missing energy requirement robust against pileup

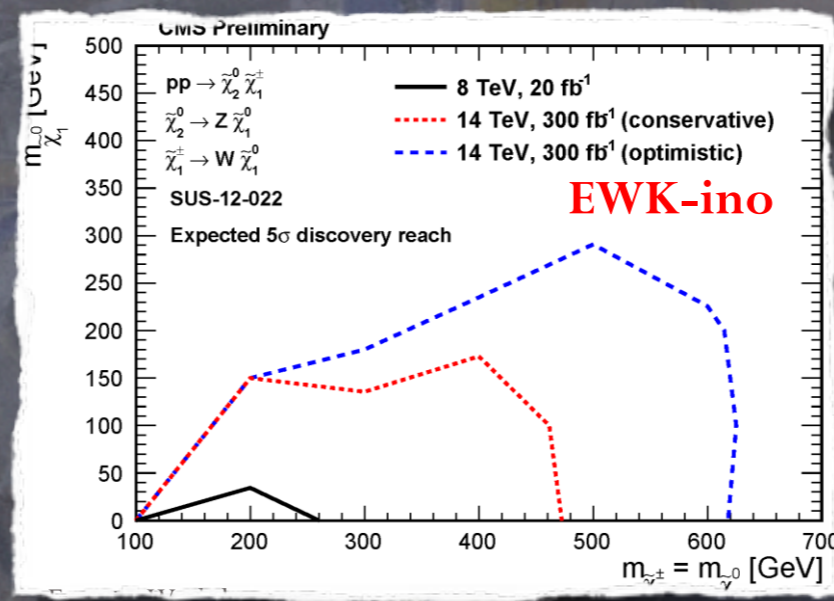
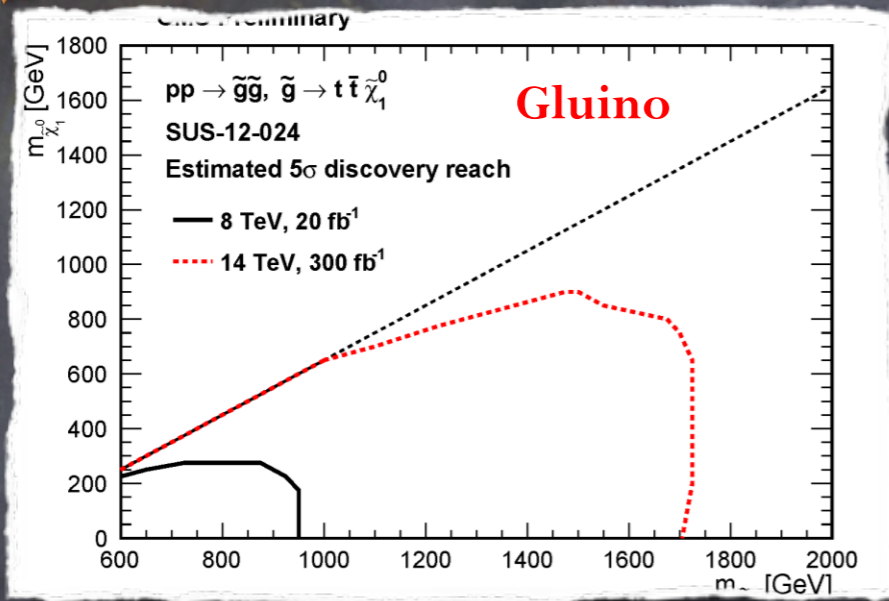


Similar extrapolations from CMS



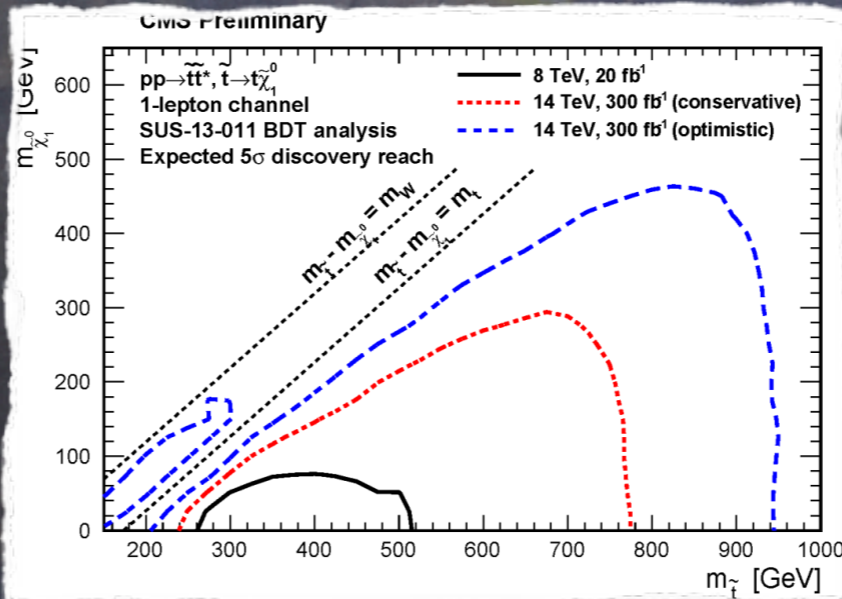
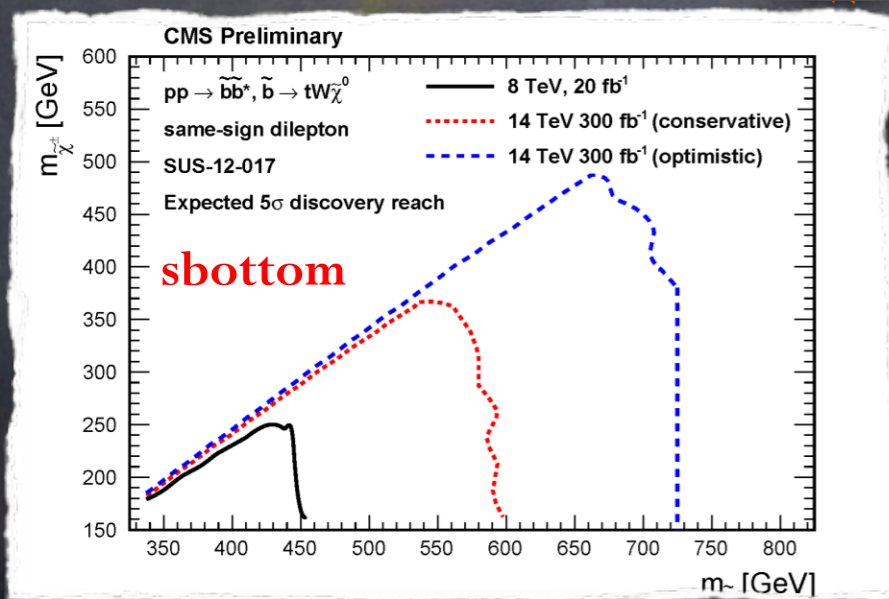
Snowmass Extrapolations

- Extrapolated with pessimistic (same systematics as now) and optimistic (scale systematics with luminosity) models
- The true value should be in the middle
- 5σ discovery reach shown



5σ discovery reach

- **Guino: up to 1.7TeV**
- **Sbottom: ~600 – 700 GeV**
- **EWK-ino: ~500 – 600 GeV**



Similar extrapolations from ATLAS

Summary

- No evidence of new physics so far
- We improved the techniques and we learned a lot. It was a good training exercise for the next run (and we got the Higgs “for free”)
- We are still looking at the 8 TeV data extending the searches to the unexplored (and more difficult) corners
- We will have 1 year to plan in advance the analysis of the first fb⁻¹ of 13 (?) TeV collisions and then the long term high-statistics analyses

References

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>



Backup

dE/dX IN THE TRACKER

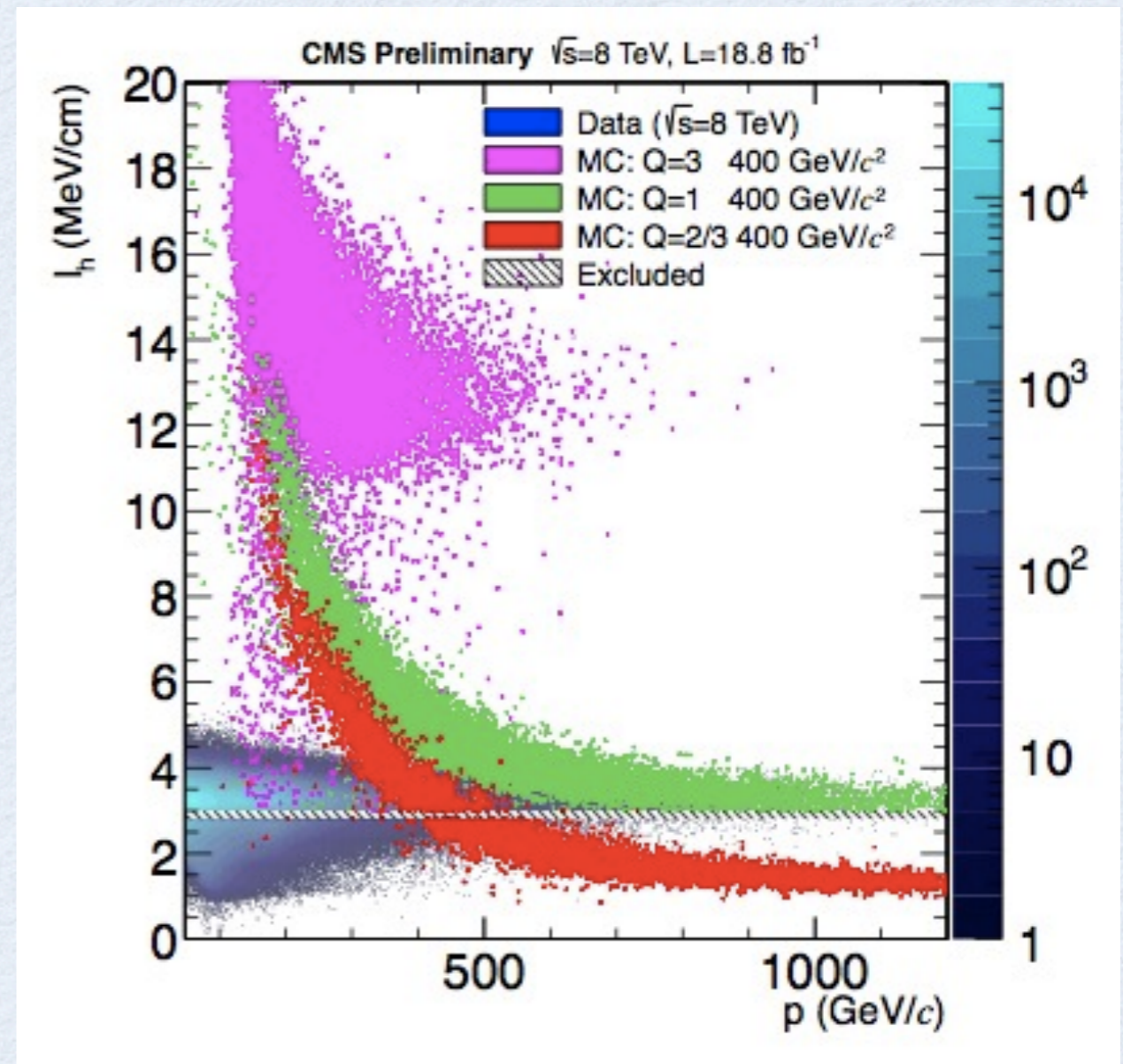
- Measure the charge released in the tracker
- Compute ionization, which gives a measurement of p/m through charge-dependent empirical coefficients

charge / unit path (fixed k=2)

$$I_h = \left(\frac{1}{N} \sum_i c_i^k \right)^{1/k} = K \frac{m^2}{p^2} + C$$

empirical coefficients

**I_h vs p_T distributions
provides S vs B
discrimination**



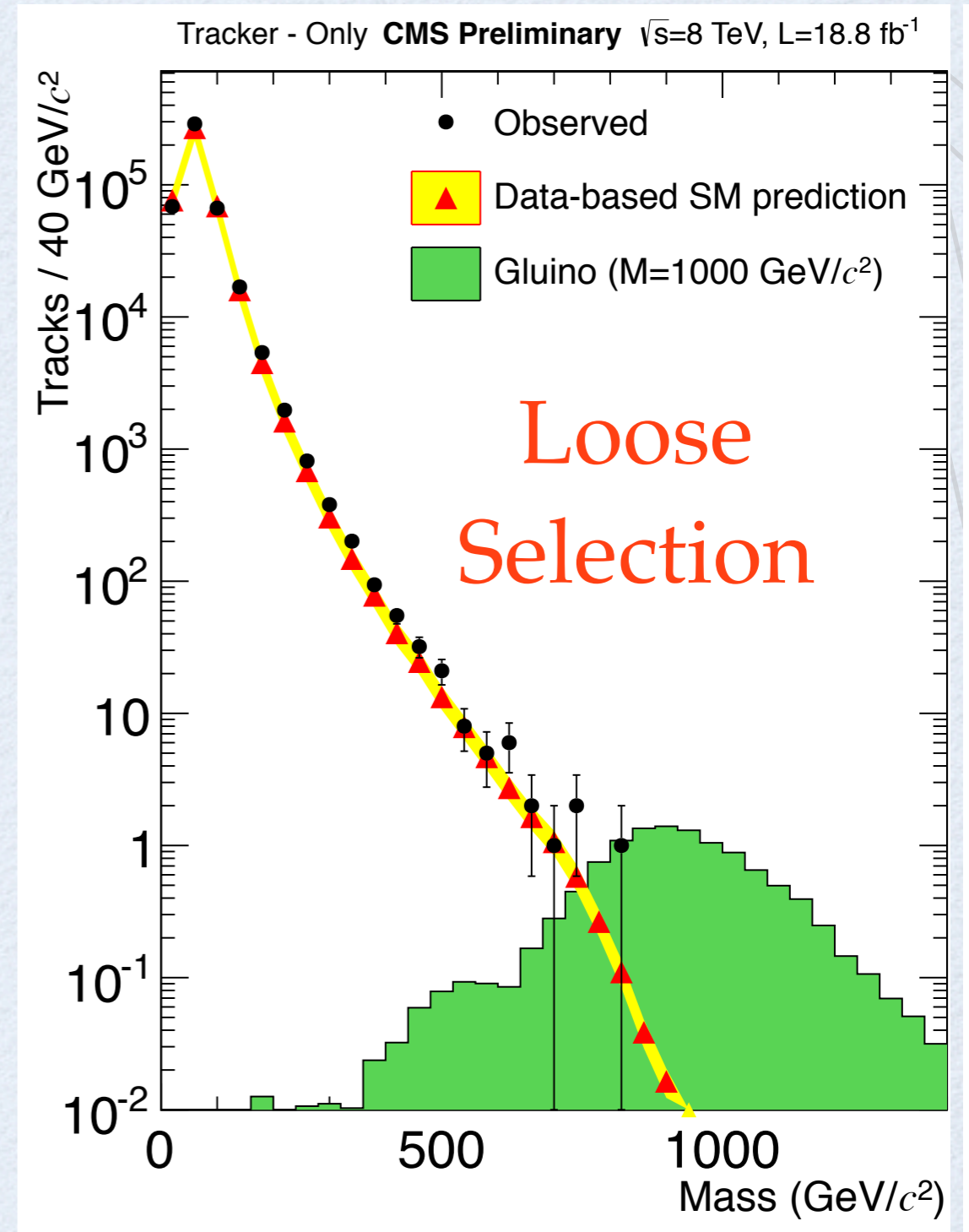
dE/dX IN THE TRACKER

- Additional discrimination from p-value of MIP-ionization pdf (for data-driven BKG determination)

probability MIP to produce \leq observed ionization

$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^N \left[P_i \times \left(P_i - \frac{2i-1}{2N} \right)^2 \right] \right)$$

- Measurement of mass from the knowledge of $I_h(p)$ [measured on data sideband]



TIME OF FLIGHT

- Use arrival time in the muon chambers to measure the TOF
- For a single hit determines β^{-1}

$$\beta^{-1} = 1 + \frac{c\delta_t}{L}$$

- For a track, weighted average of the single hits

$$w_i = \frac{(n-2)}{n} \frac{L_i^2}{\sigma_{DT}^2}$$

DTs ($\sigma \sim 3$ ns)

~~$$w_i = \frac{L_i^2}{\sigma_i^2}$$~~

CSCs ($\sigma \sim 7$ ns for cathode, 9 ns for anode)

For both $\sigma(\beta^{-1}) \sim 0.07$

