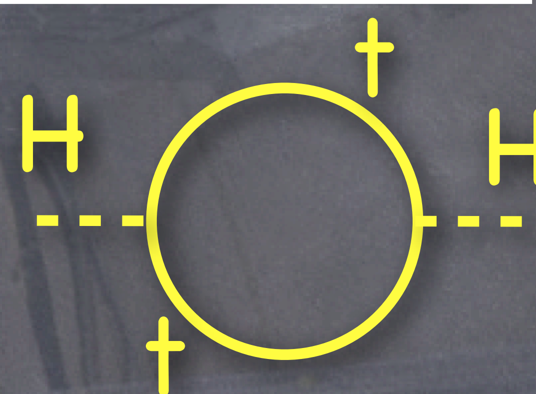
Supersymmetry Searches

Maurizio Pierini

CERN

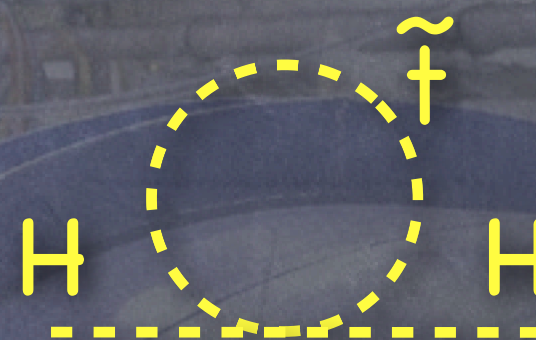
Why SUSY? A solution to three problems

- In the SM the Higgs mass is proportional to the energy scale at which the theory breaks

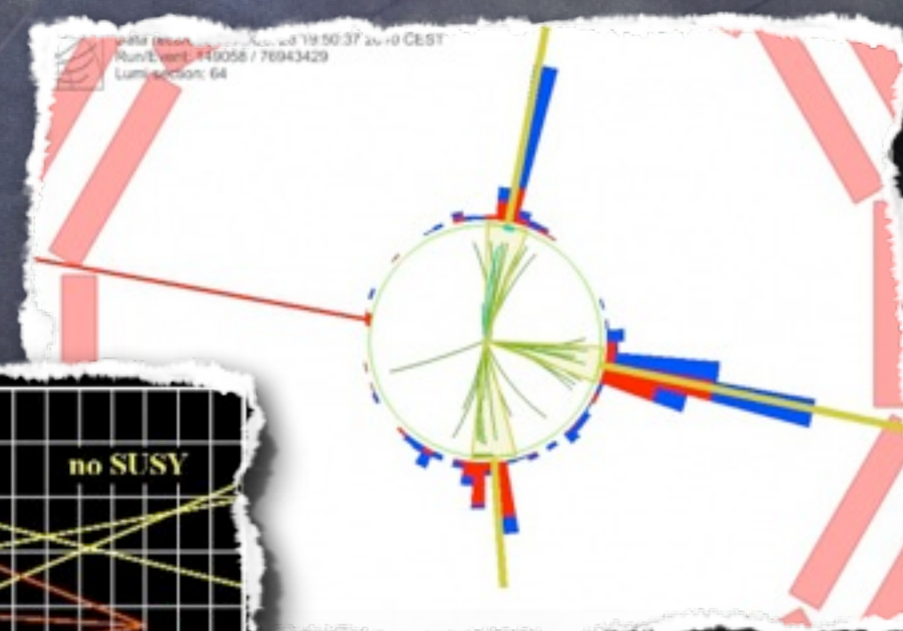


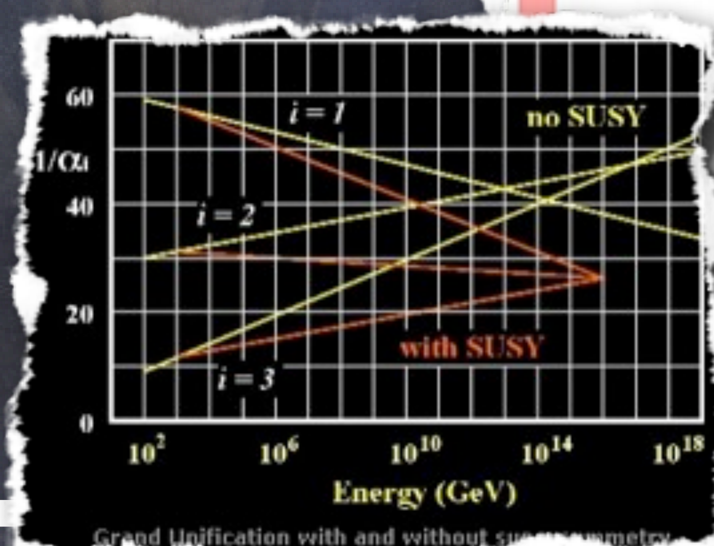
- We measured the Higgs mass to be 125 GeV

- SUSY is the mechanism by which the Higgs stay light without (a large) tuning, canceling each fermion quantum correction by its boson equivalent



- But SUSY can do much more:
  - Provides a Dark Matter candidate (adding R-parity) and MET signatures at colliders
  - Gives unification of QCD and EW forces

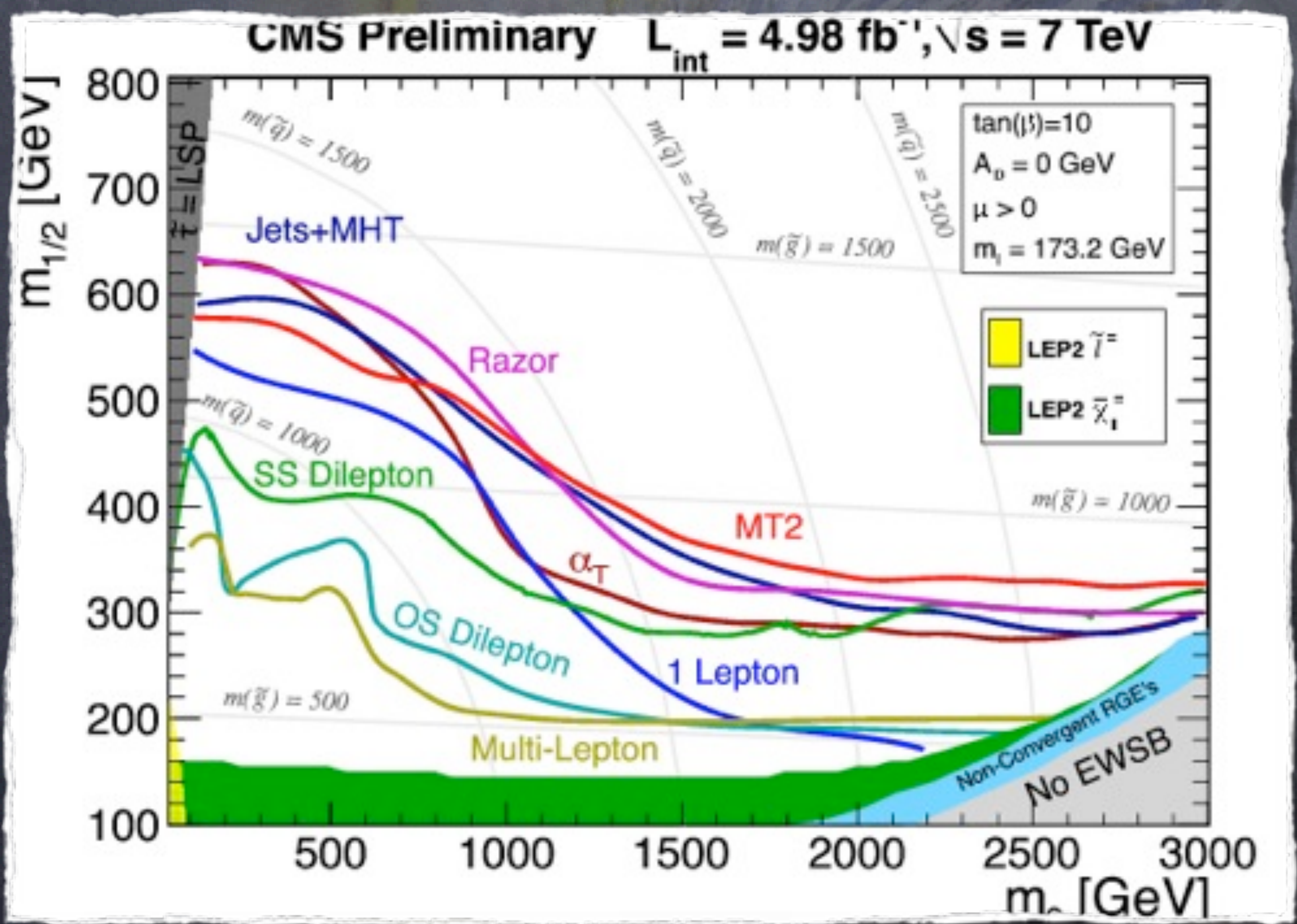




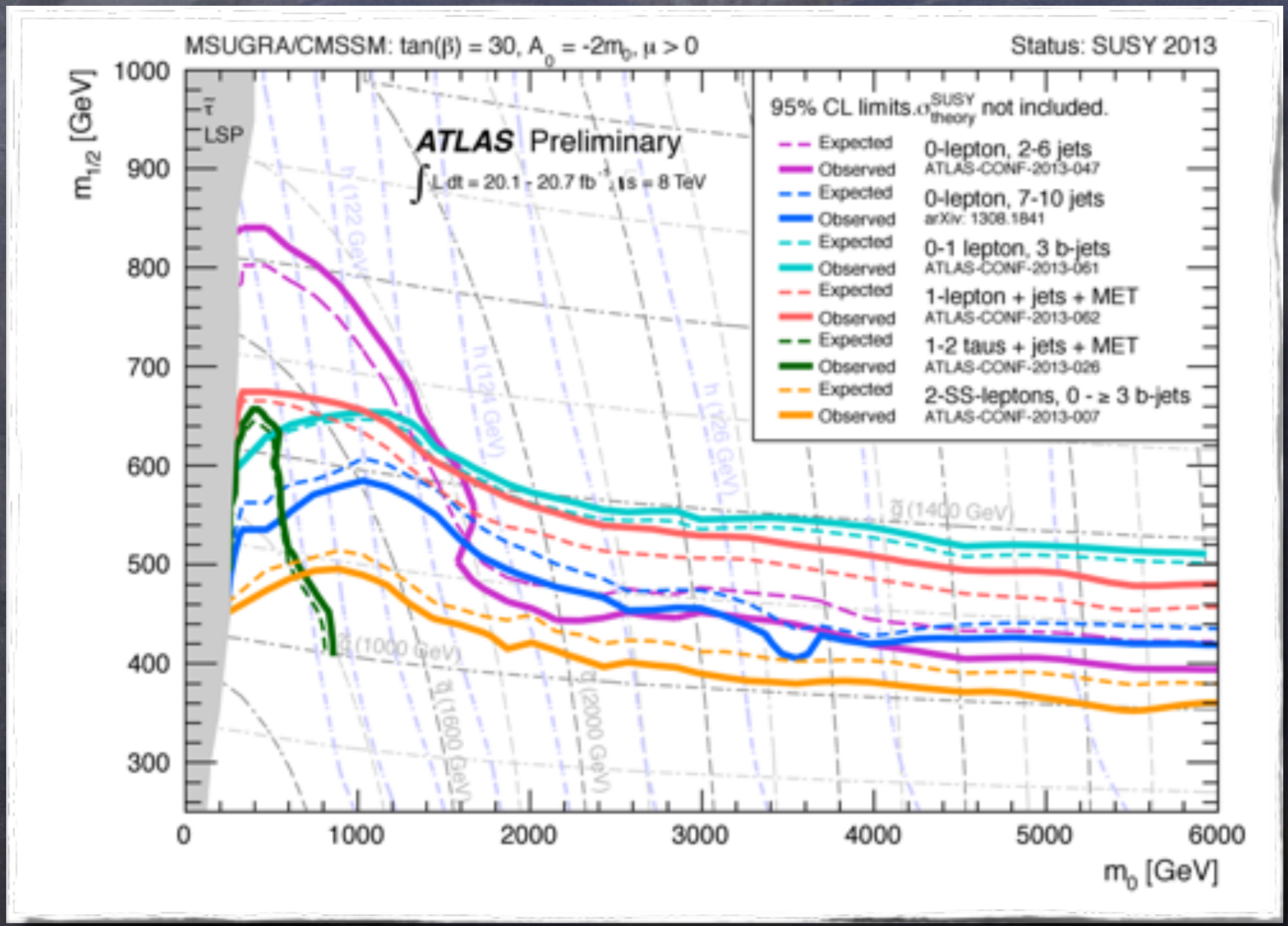
Legacy of 7 TeV Run

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

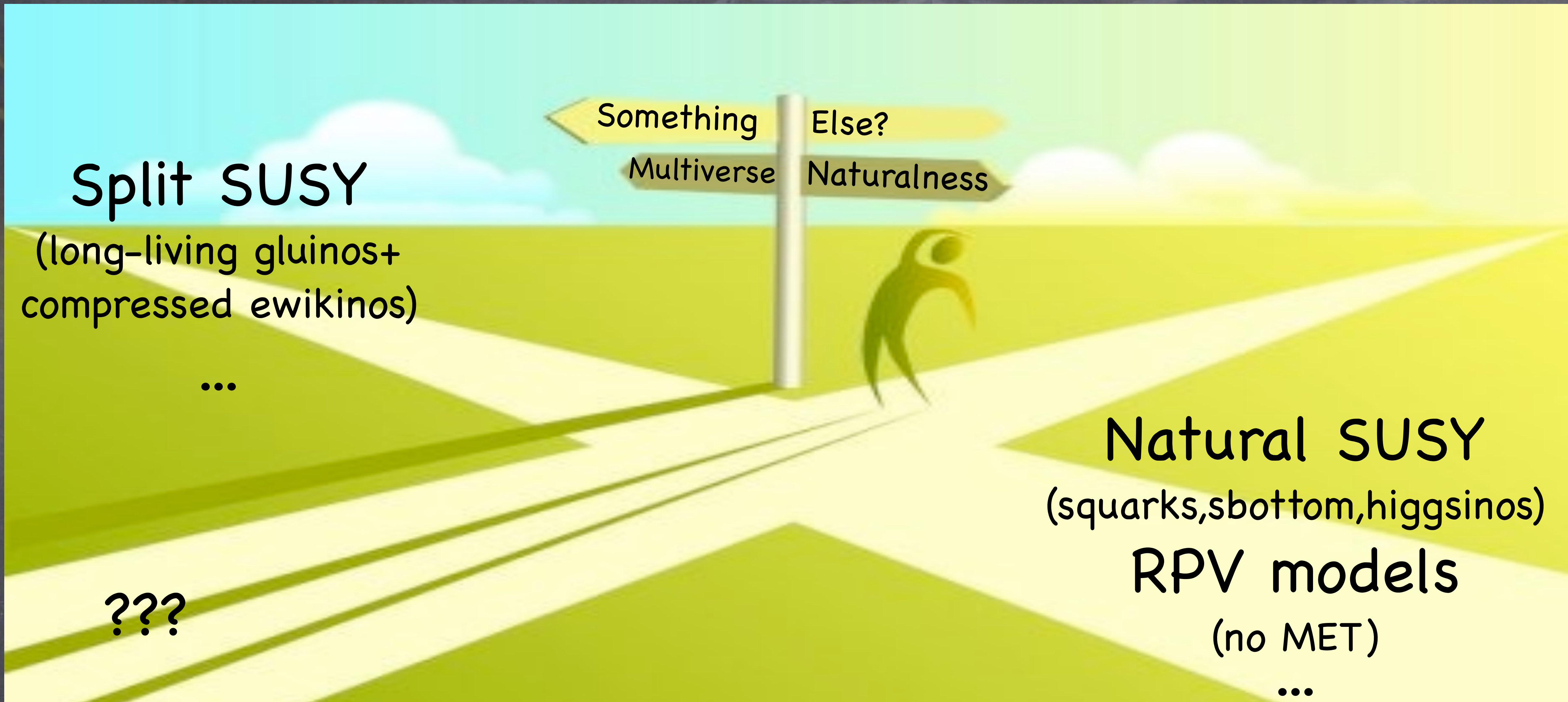
5 fb $^{-1}$ @7 TeV



20 fb^{-1} @8 TeV



New Scenarios

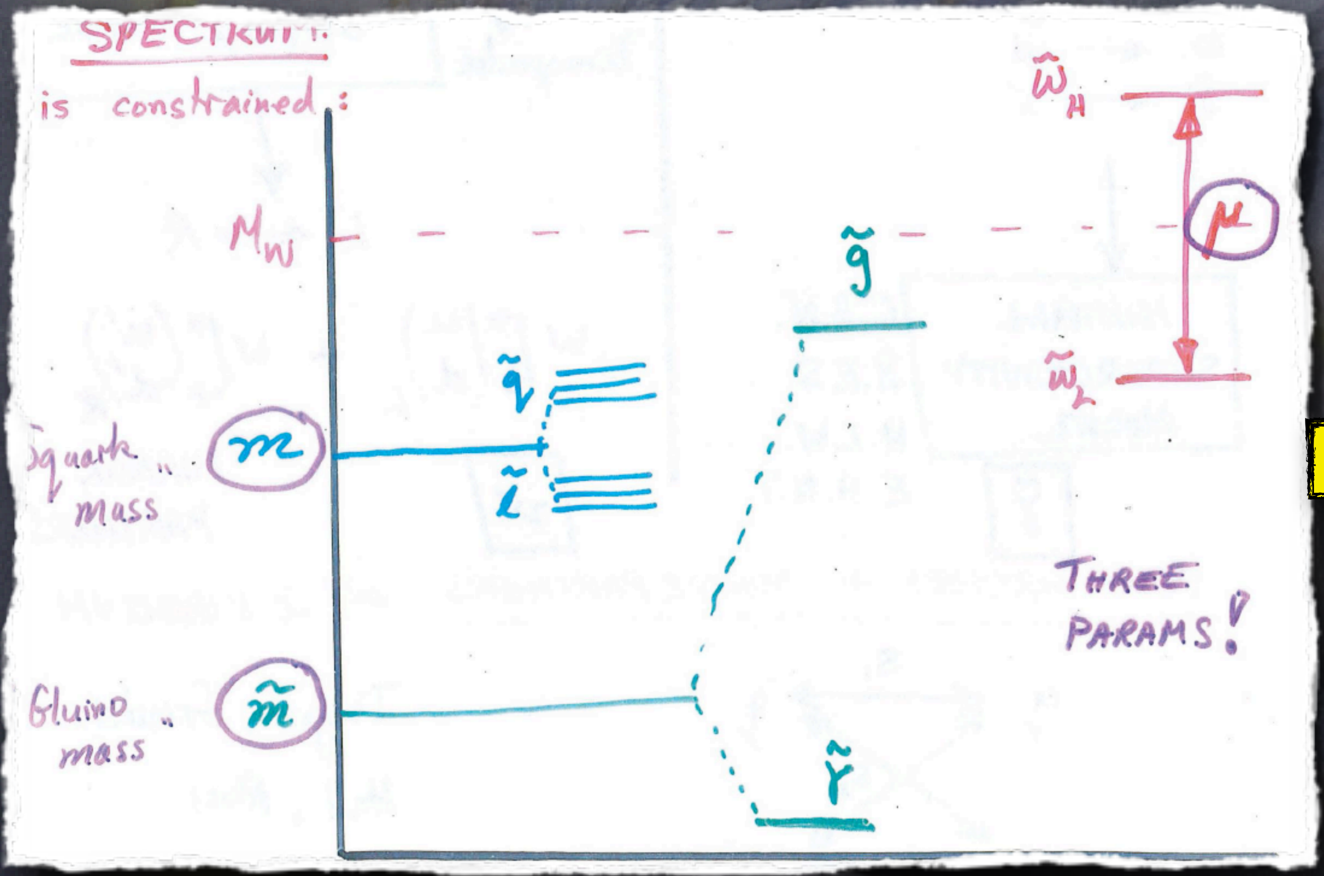


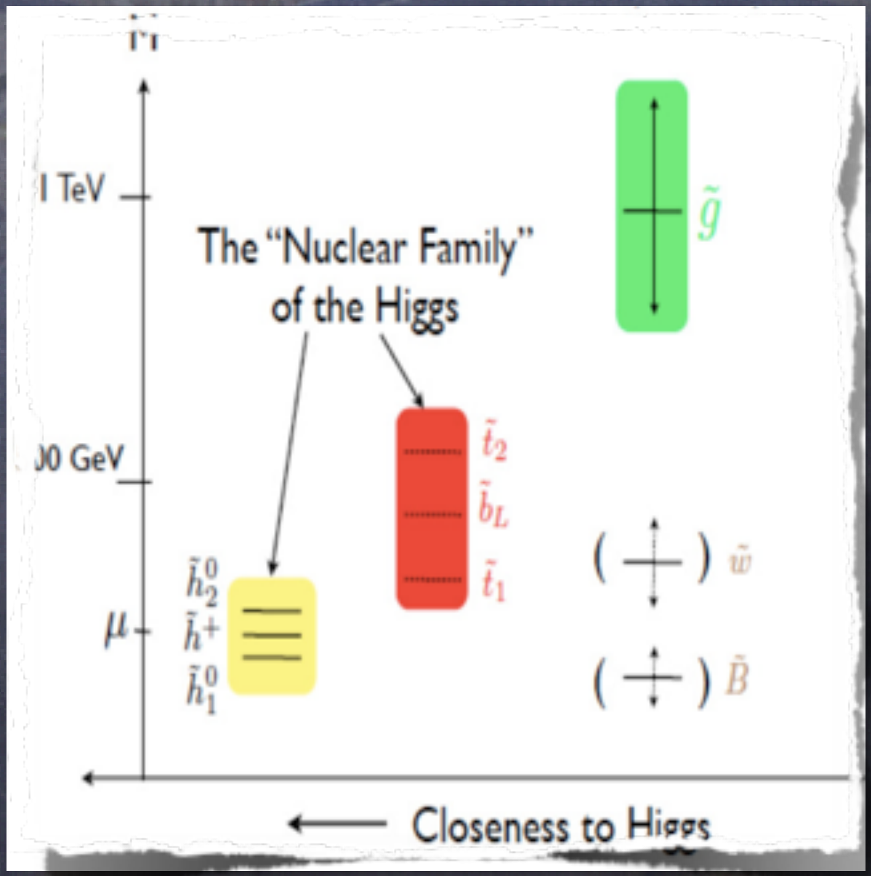
- If we accept that SUSY solves 1/3 (or 2/3) of our problems, SUSY signatures @colliders change drastically
- And we are extensively looking for any direction ...

Natural SUSY Searches

Natural SUSY

- We found the Higgs and it's light
- We would like to stabilize its mass because we are not comfortable with large cancellations
- We don't "need" all the SUSY spectrum. The minimal spectrum to stabilize the Higgs was not probed by experiments yet





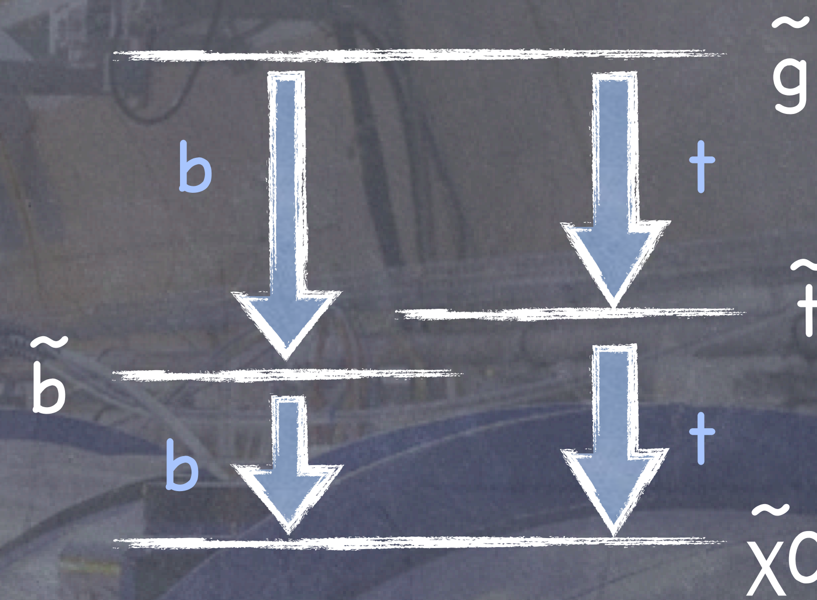
LEP/Tevatron/LHC@7TeV

LHC@8TeV

Natural SUSY with 8 TeV data

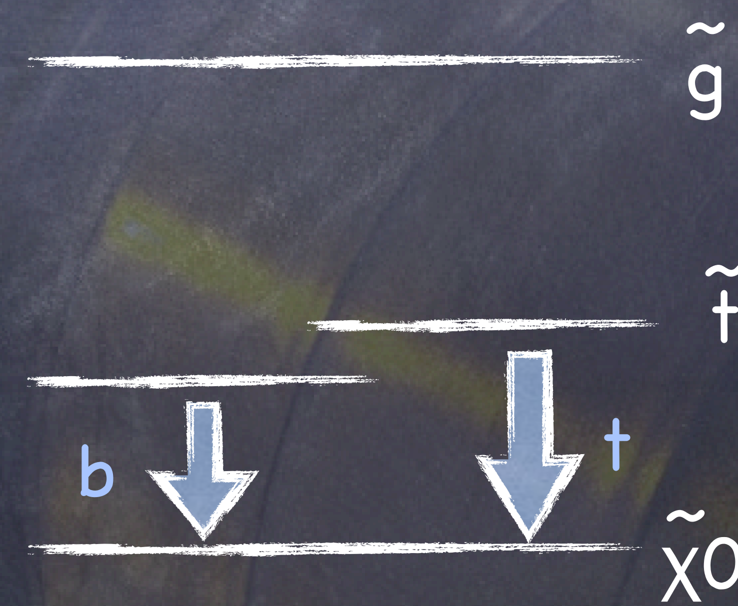
- **Gluino-mediated searches**

  Larger cross section
  4b quarks in the final state, with or w/o leptons
  More handles for bkg discrimination
  Gluinos might be too heavy for these searches to be effective



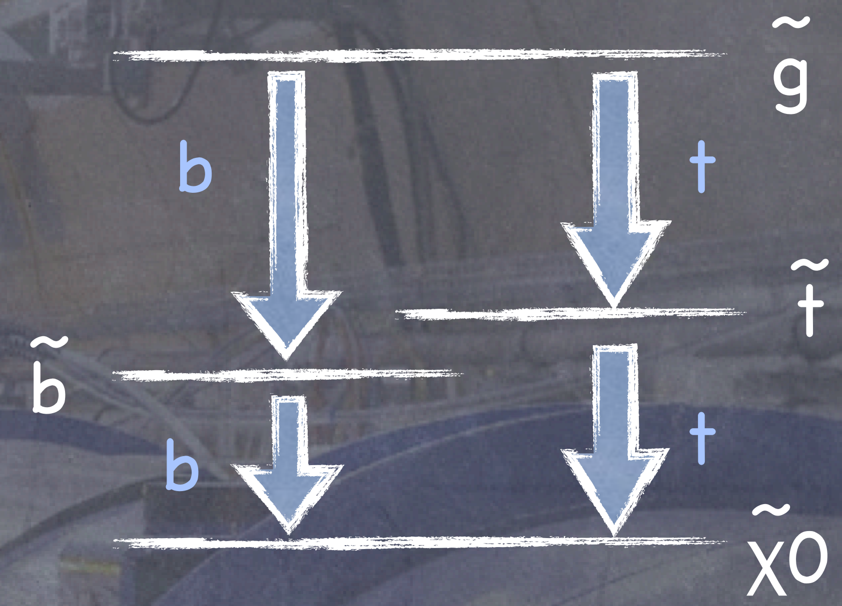
- **Direct squark searches**

  Smaller cross section
  Final state similar to tt in the bulk of the parameter space
  Reduced bkg discrimination power
  Only handle if gluino heavy

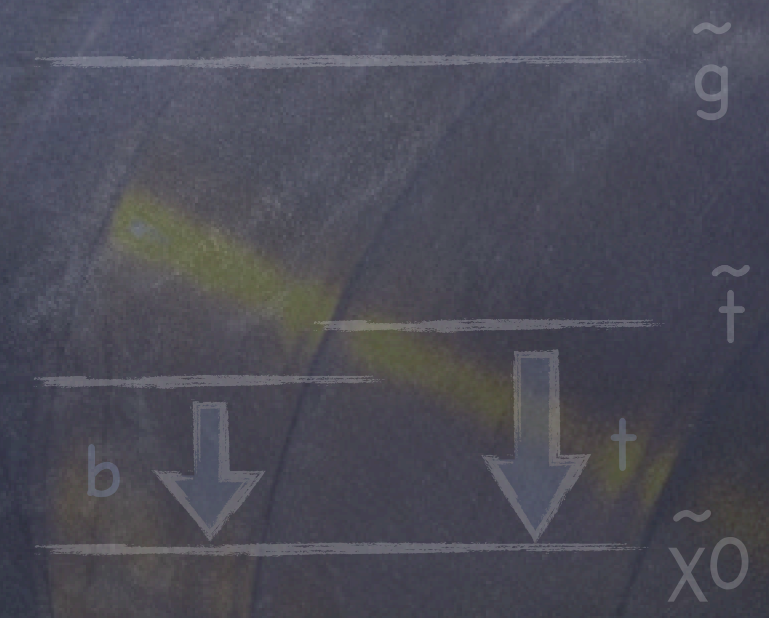


Natural SUSY with 8 TeV data

- Gluino-mediated searches
  Larger cross section
  4b quarks in the final state, with or w/o leptons
  More handles for bkg discrimination
  Gluinos might be too heavy for these searches to be effective



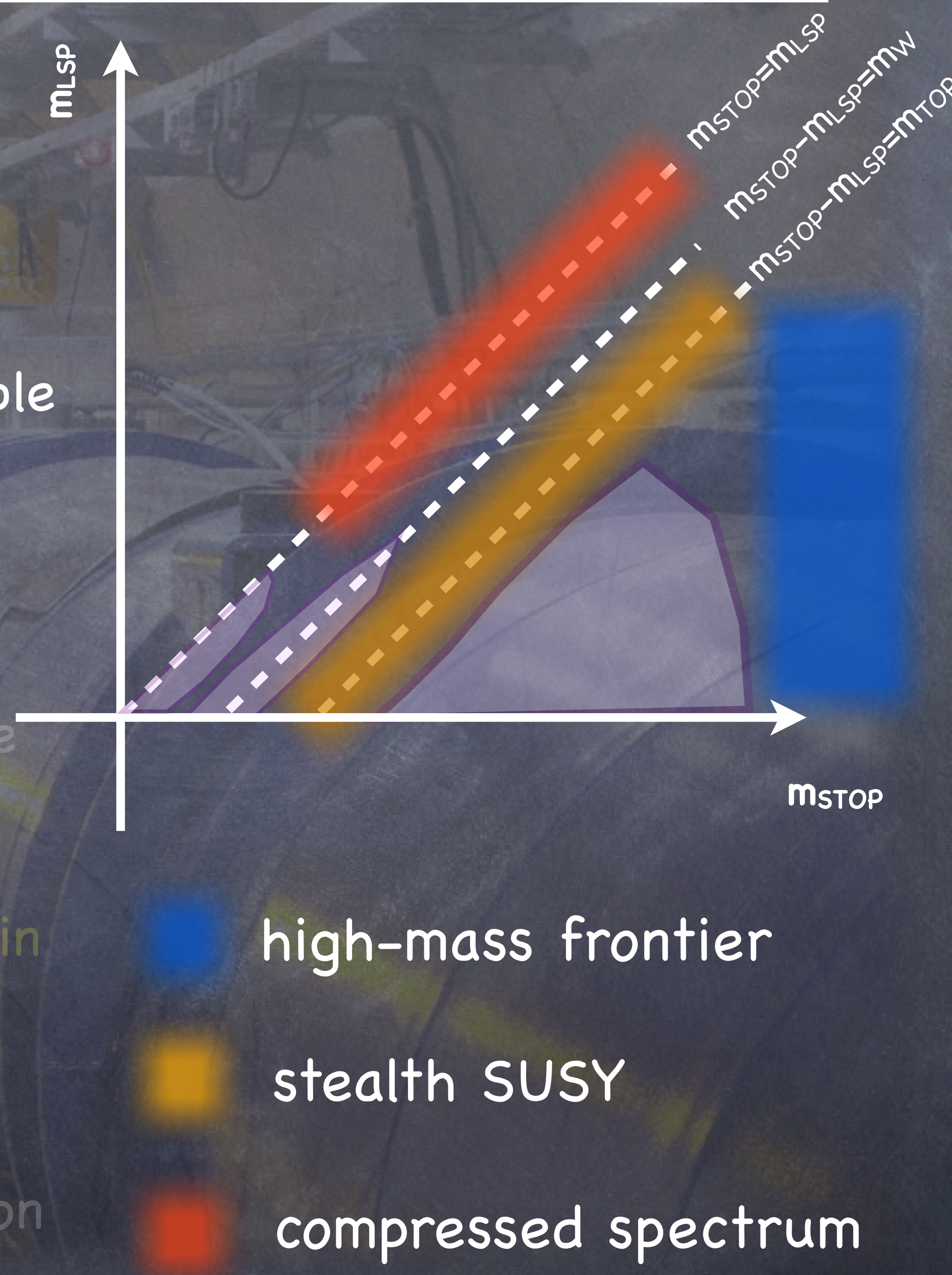
- Direct squark searches
  Smaller cross section
  Final state similar to tt in the bulk of the parameter space
  Reduced bkg discrimination power
  Only handle if gluino heavy



NEXT TALK

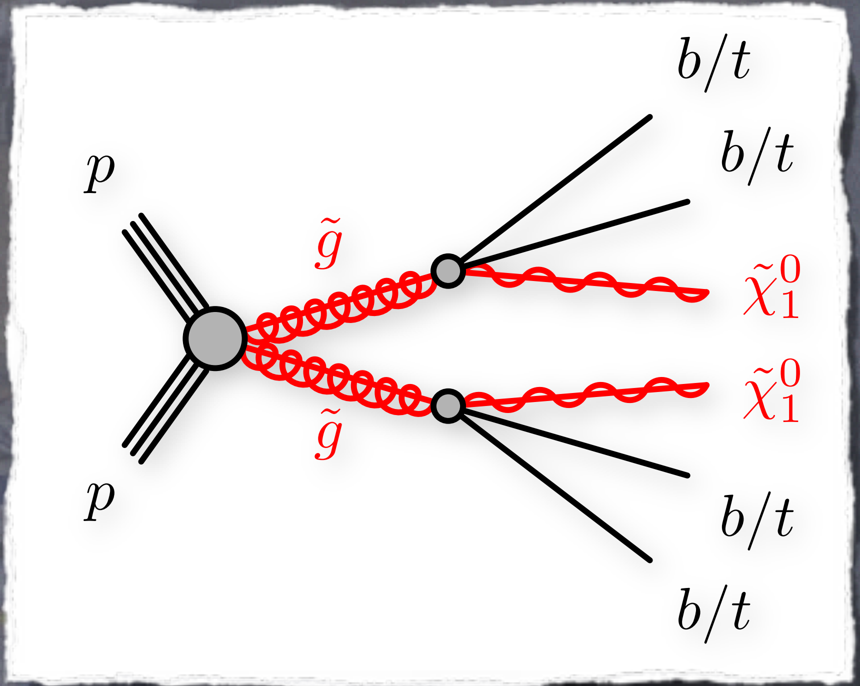
Lesson From Stop/Sbottom Searches

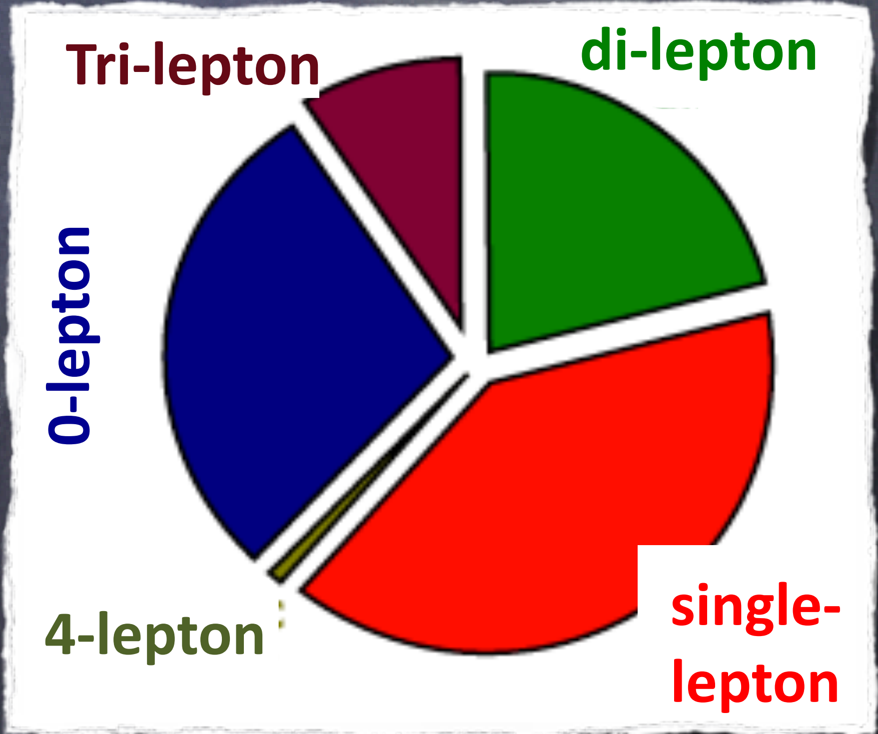
- What we really need is a light stop
- The current stop searches have three blind spots
- As long as the gluino is kinematically accessible @LHC, these blind spots are covered to some extent
- If not, direct stop/sbottom searches are the most powerful probe (but other ways possible with more light sparticles)
- Gluinos are pushed > 1300 GeV and the stop in one of the blind spots, for natural SUSY to survive 8 TeV data
- The main impact of 13 TeV run is the extension of the gluino reach



Gluino-Gluino Searches

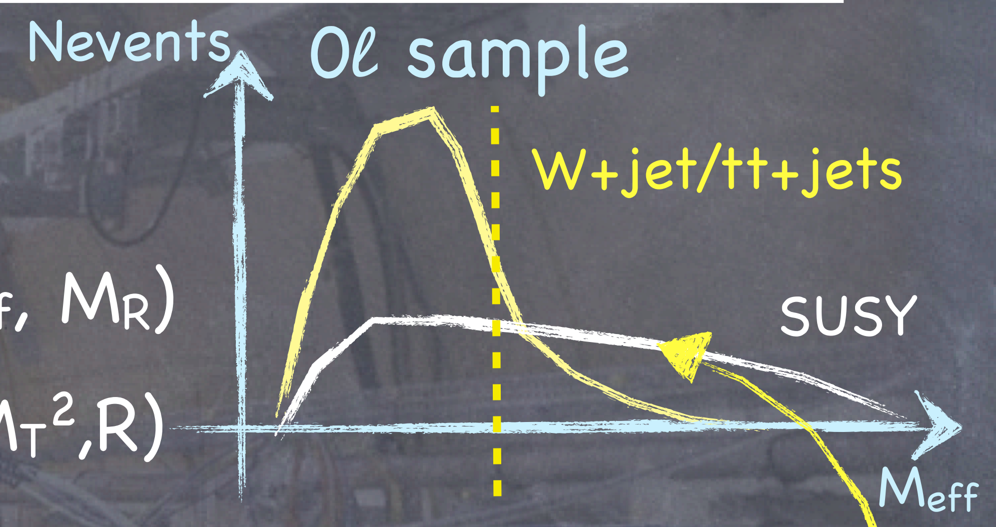
- 4b+MET final state is fully hadronic with large bjet multiplicity (wrt SM backgrounds)
- 4t +MET final state quite unique at the LHC: several final states with different lepton and jet multiplicities
- Other possibilities (3b+1t, 2b+2t, 1b+3t) are between these two extremes
- Could produce same-sign dilepton (low bkg search)
- Ideal territory for inclusive searches combining 0l and 1l final states



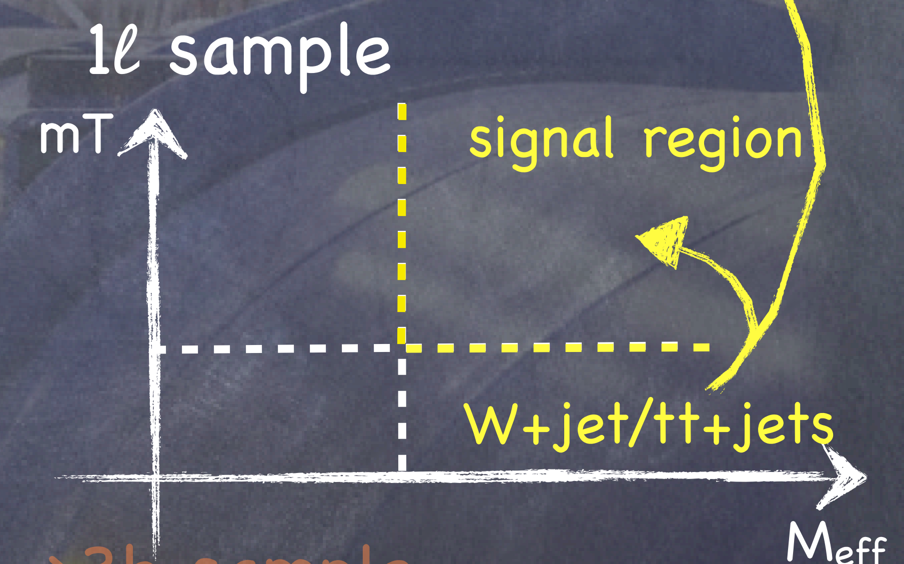


Search Strategy

- 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_{T2},R)

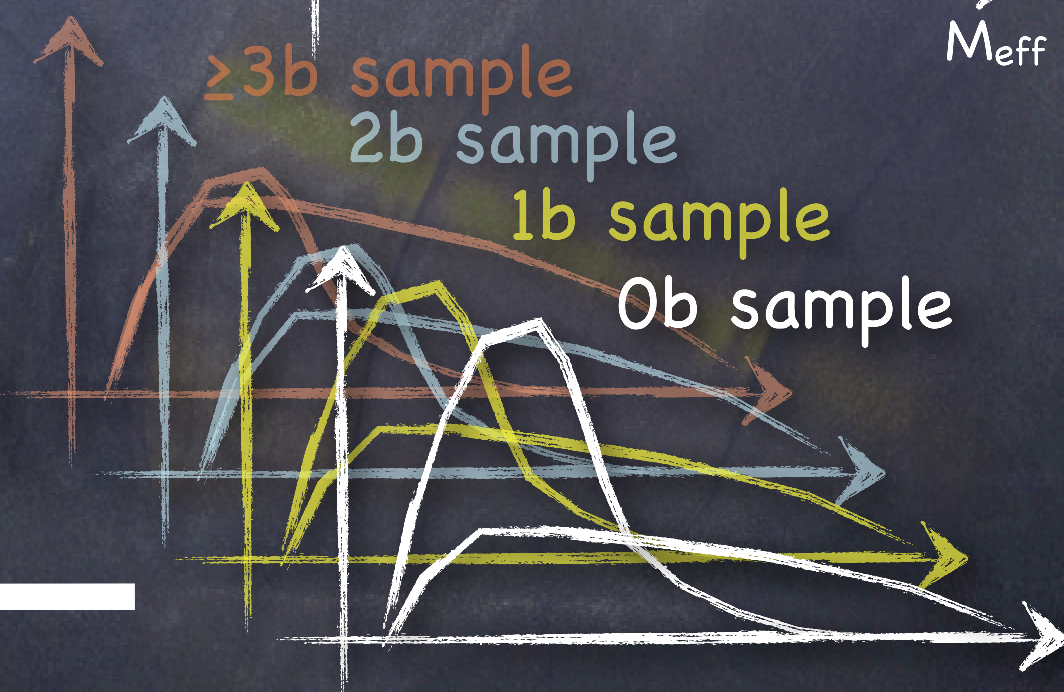


- The background on the tail is measured from the core, using transfer factors from MC



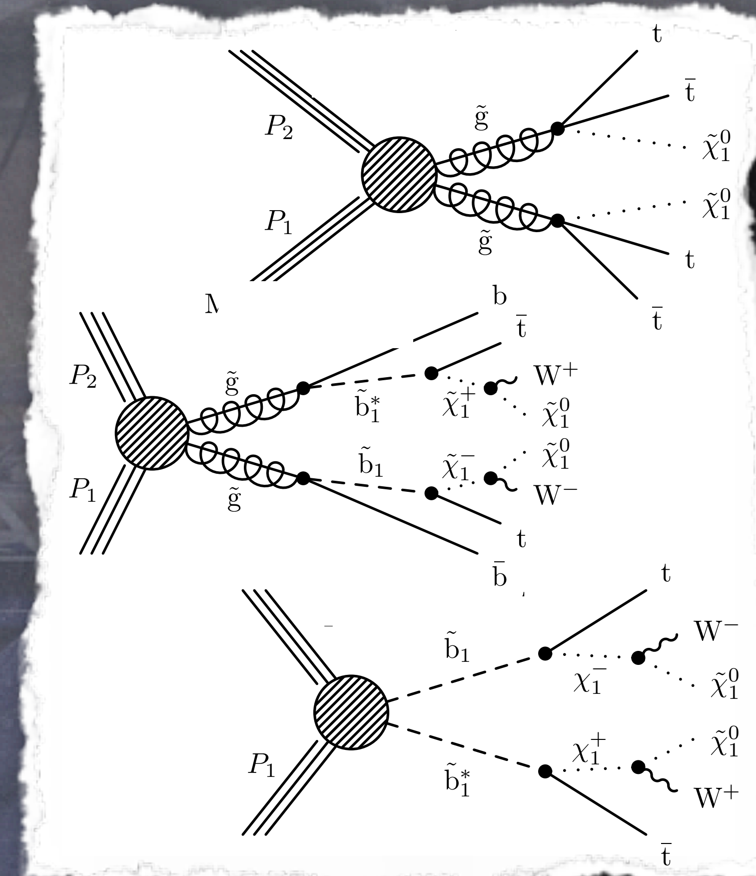
- The searches are repeated for different final states
  - number of jets
  - number of btags
  - number of leptons

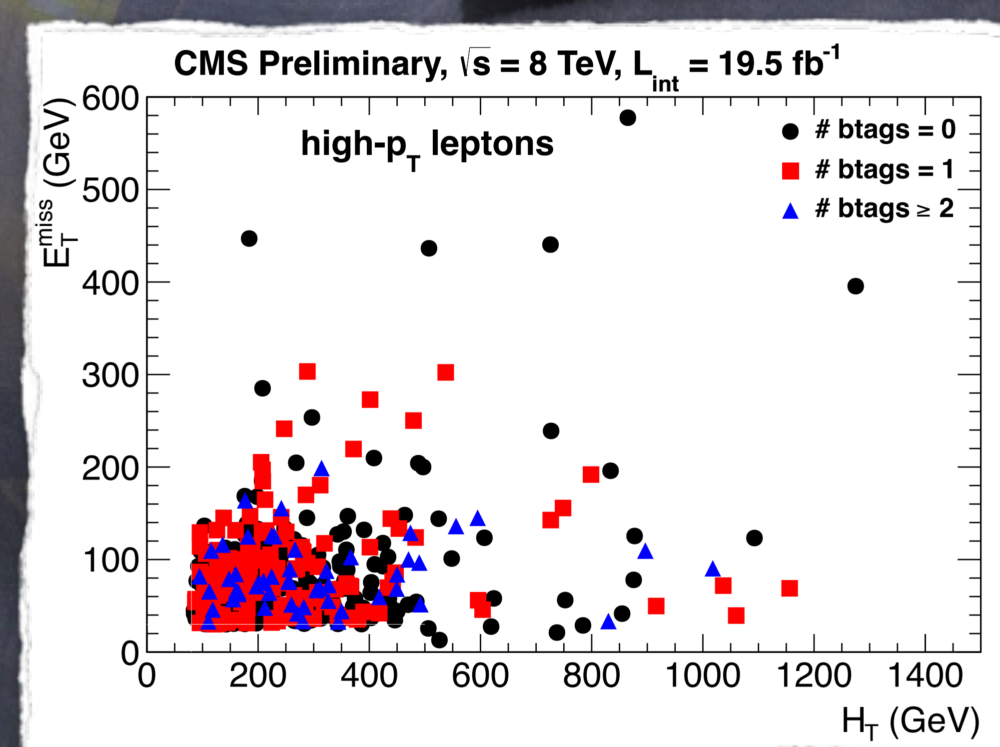
- Searching for specific signals (e.g. stop production) advanced techniques (e.g. BDT) could be used



SS dilepton

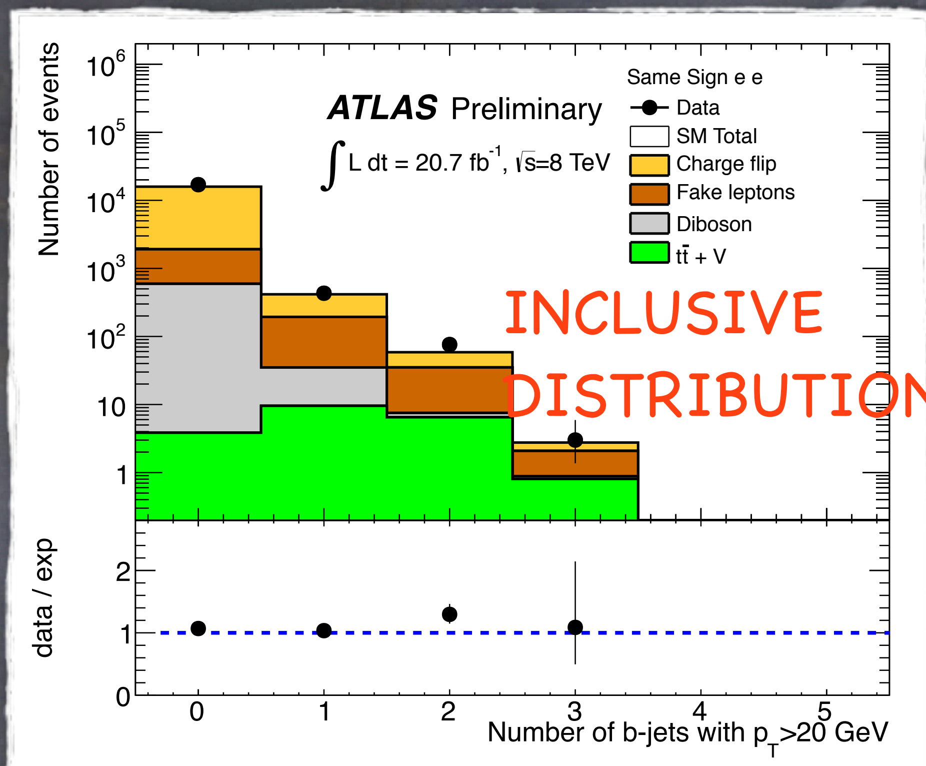
- Low Background to many searches
  - Rare decays (ttW, ttZ, etc) from MC
  - Charge MisID (no muon) from data
  - "Fake" leptons from b decays (from data)
- Sensitive to many SUSY decay chains
  - Same-sign leptons whenever 3W or 4W appear in the final states (long squark cascades)
- Optimal for natural SUSY
  - Loose kinematic cuts (complementary to other searches)
  - Enhance sensitivity with b-tag requirements

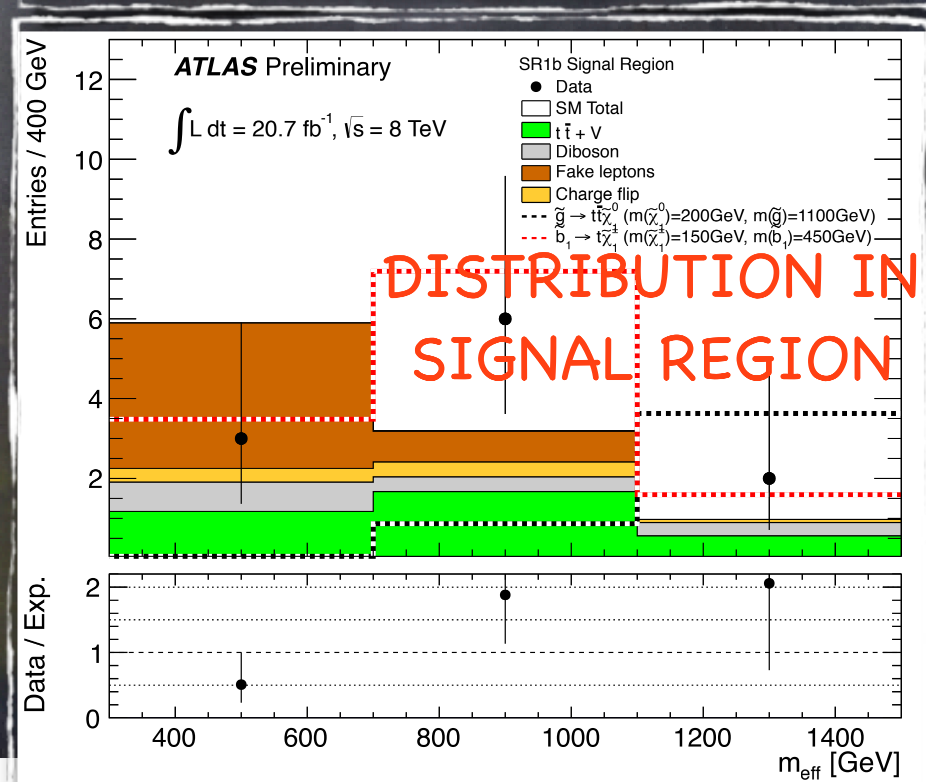




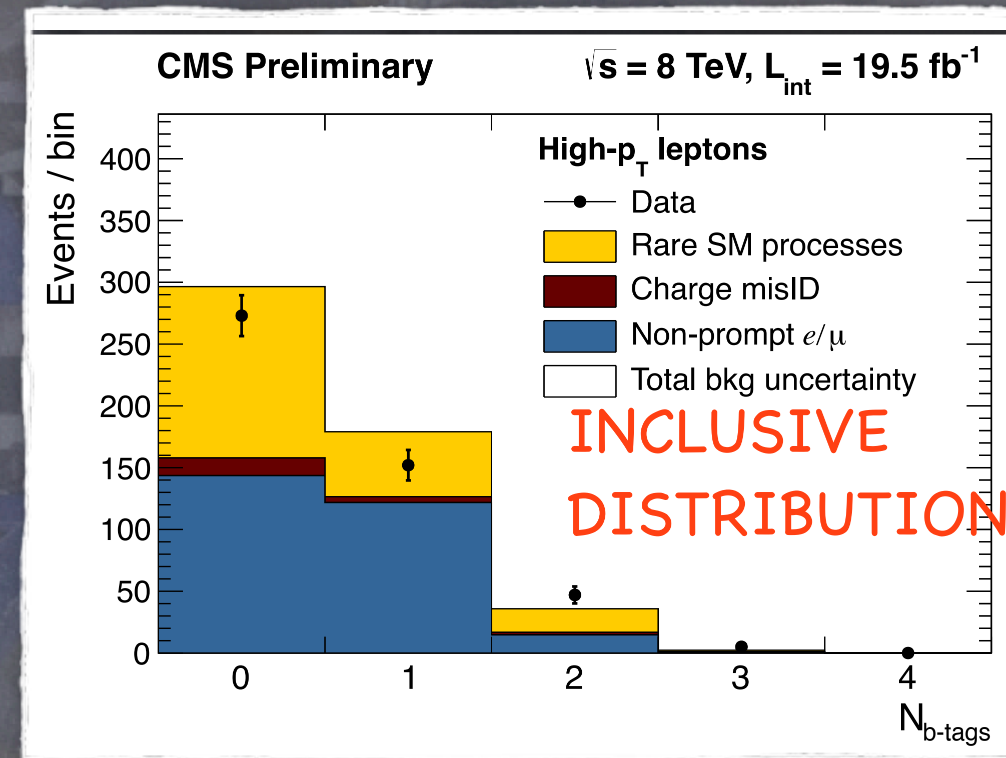
SS dilepton

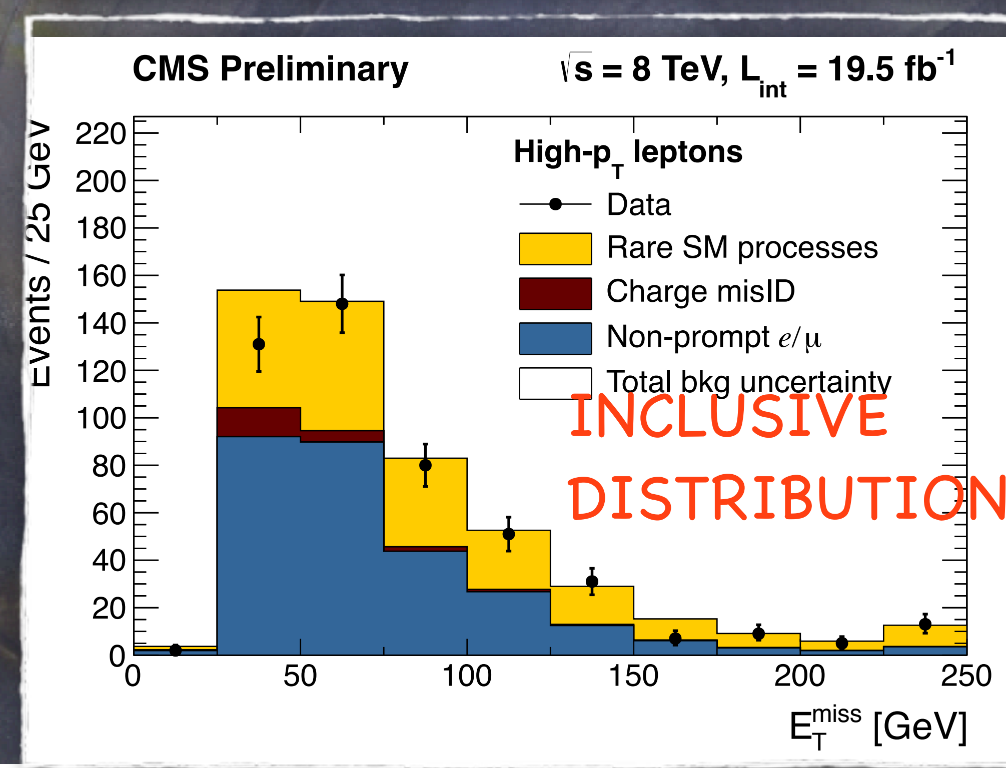
ATLAS-CONF-2013-007





CMS PAS SUS-13-013





ATLAS 0l/1l+3b search

- **Select events with >=3bjets**

  Several search regions depending on njets

  Different final states combined: 0 ℓ or

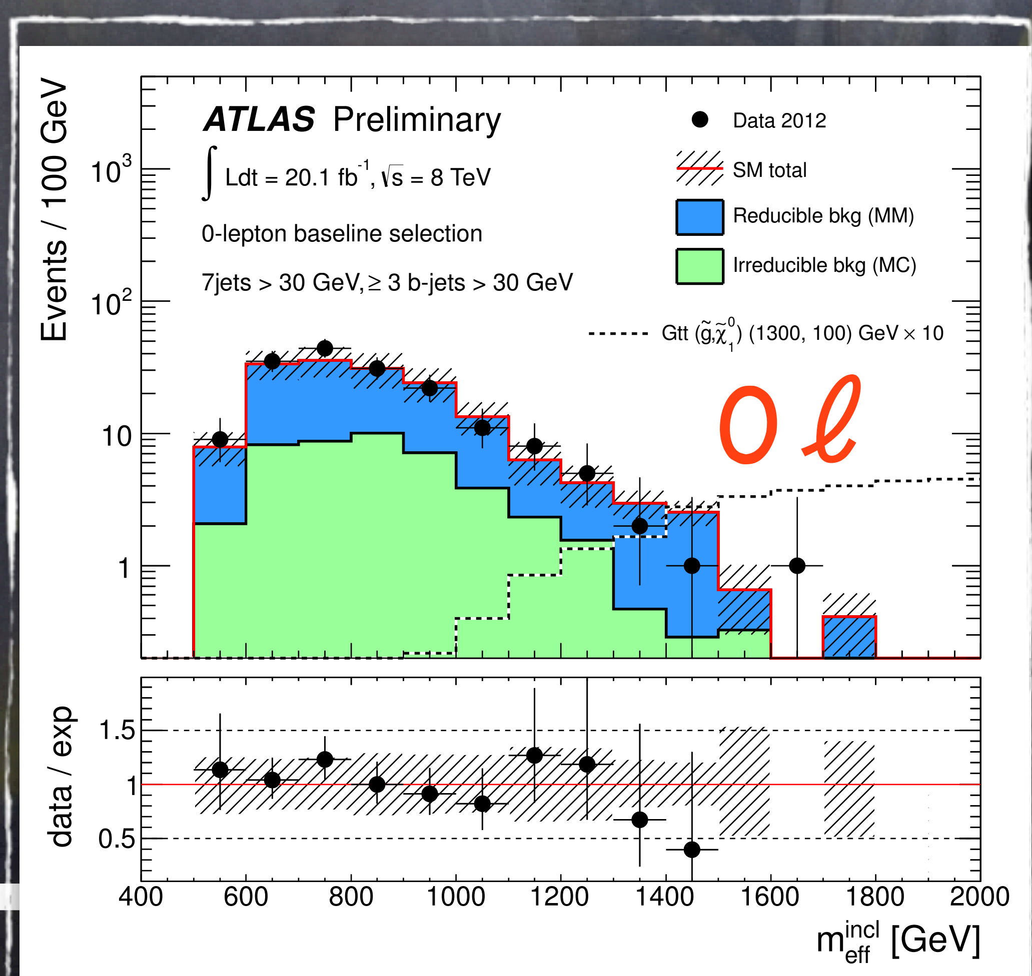
  ≥1 ℓ (e or μ) to get extra sensitivity

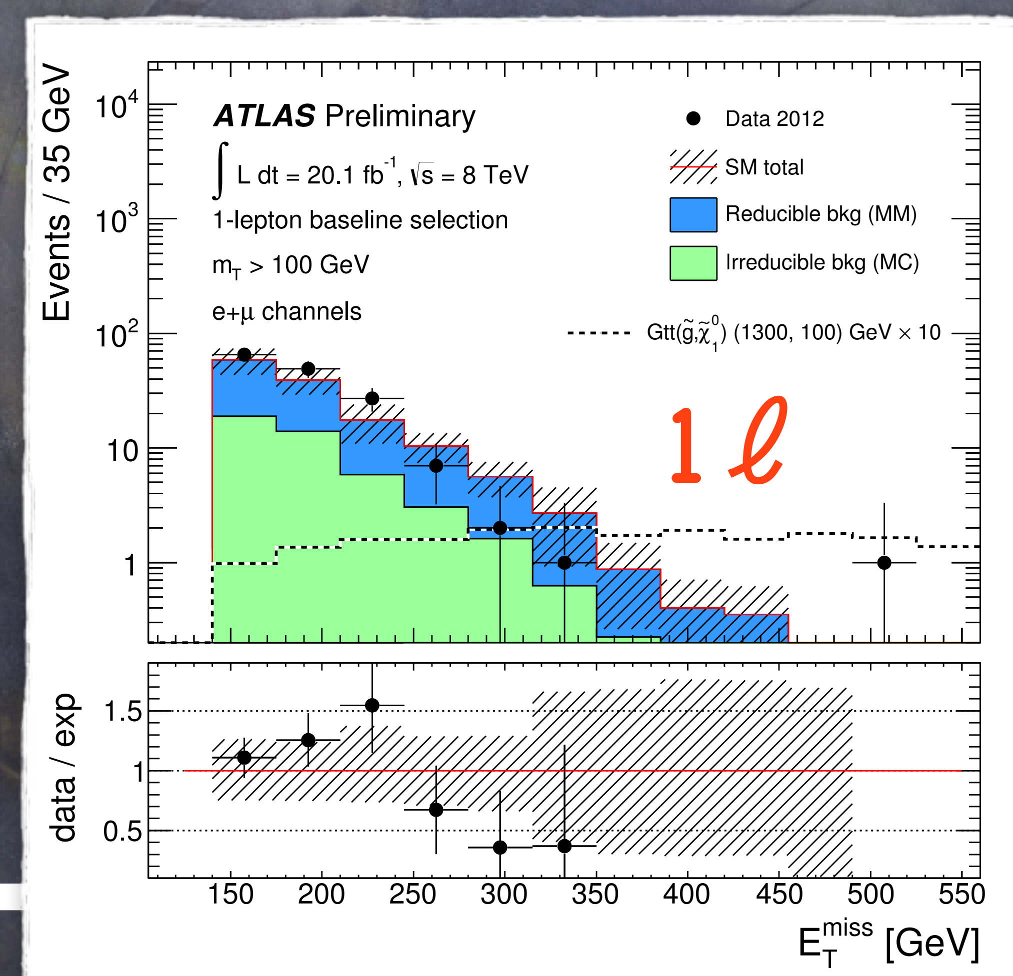
0-ℓ region	N jets	p_T jets [GeV]	E_T^{miss} [GeV]	m_{eff} [GeV]	$E_T^{miss} / \sqrt{H_T^{4j}}$ [GeV$^{\frac{1}{2}}$]
SR-0l-4j-A	≥ 4	> 30	> 200	$m_{eff}^{4j} > 1000$	> 16
SR-0l-4j-B	≥ 4	> 50	> 350	$m_{eff}^{4j} > 1100$	-
SR-0l-4j-C	≥ 4	> 50	> 250	$m_{eff}^{4j} > 1300$	-
SR-0l-7j-A	≥ 7	> 30	> 200	$m_{eff}^{incl} > 1000$	-
SR-0l-7j-B	≥ 7	> 30	> 350	$m_{eff}^{incl} > 1000$	-
SR-0l-7j-C	≥ 7	> 30	> 250	$m_{eff}^{incl} > 1500$	-

- **Search Based on Meff and MET**

  Bkg from tt+jets (data driven estimate) and rare processes (MC)

  Textbook example of the search strategy described before **ATLAS-CONF-2013-061**



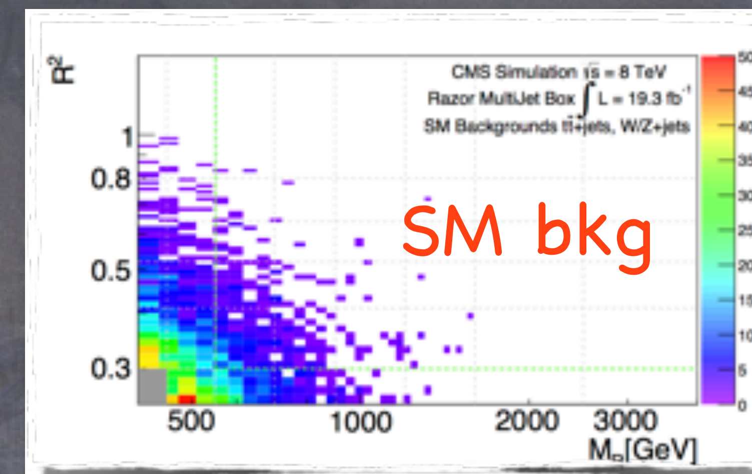


Razor Inclusive Search

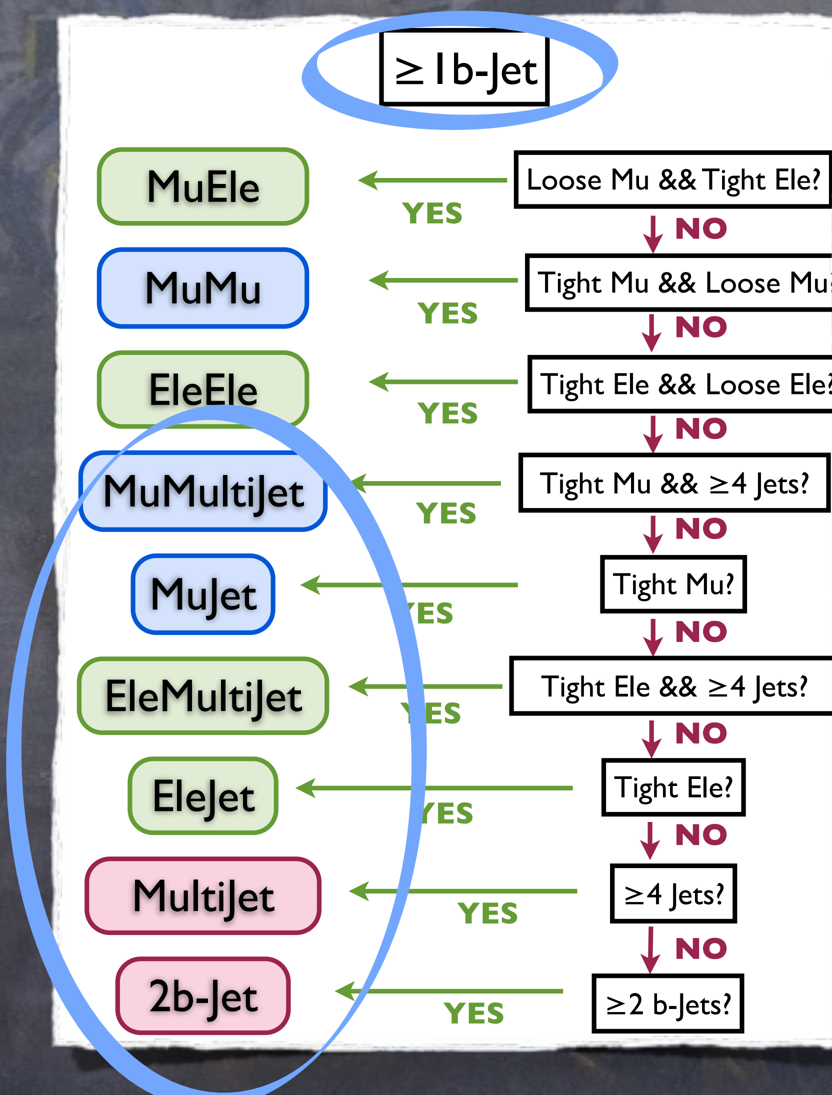
CMS PAS SUS-13-004

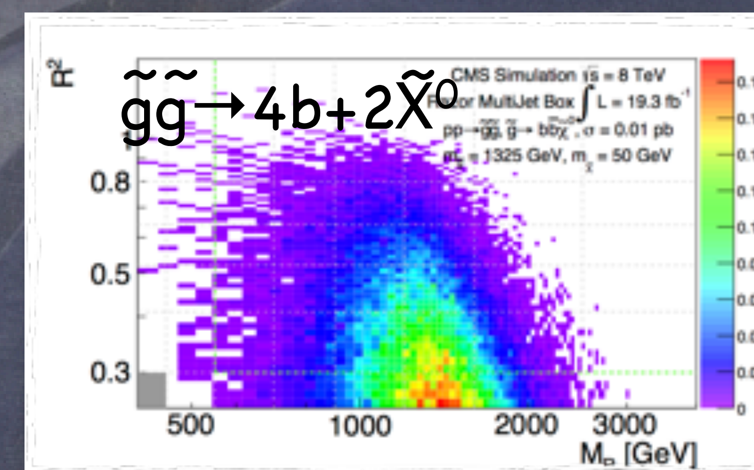
- Suppress QCD cutting on R & exploit peaking behavior of MR (SUSY search as a "resonance" search)

$$R = \frac{M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1}+p_T^{j2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{\,j1}+\vec{p}_T^{\,j2})}{2}}}{M_R \equiv \sqrt{(p_{j_1}+p_{j_2})^2 - (p_z^{j_1}+p_z^{j_2})^2}}$$



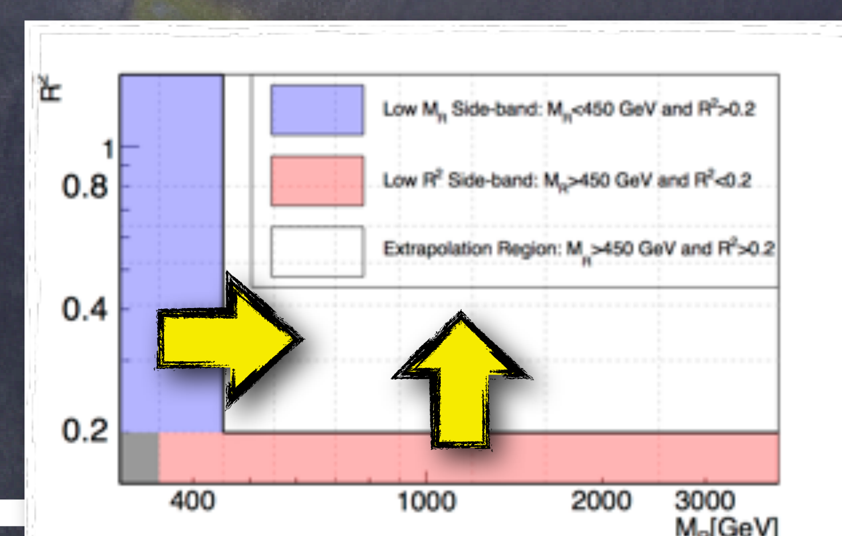
- Combine searches in different final states: overall result is inclusive





- Use b-tag multiplicity to enhance the sensitivity to natural SUSY models

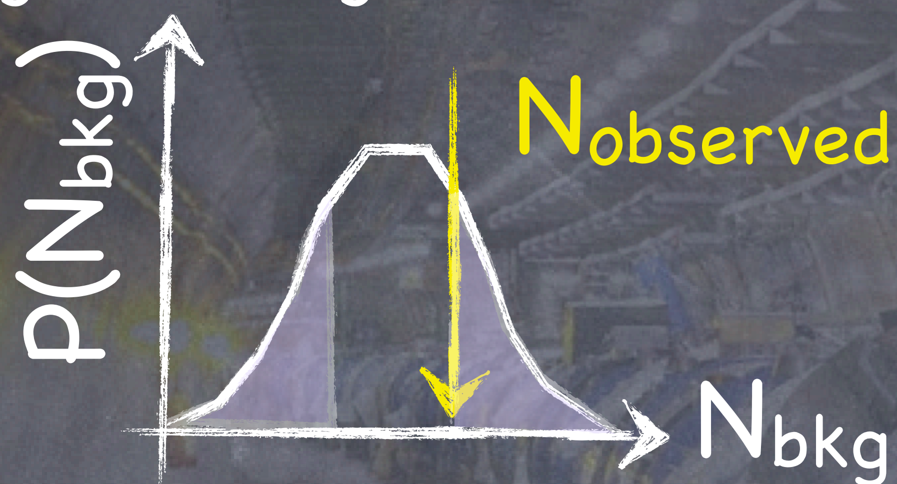
- Determine the bkg with a sideband shape fit+extrapolation

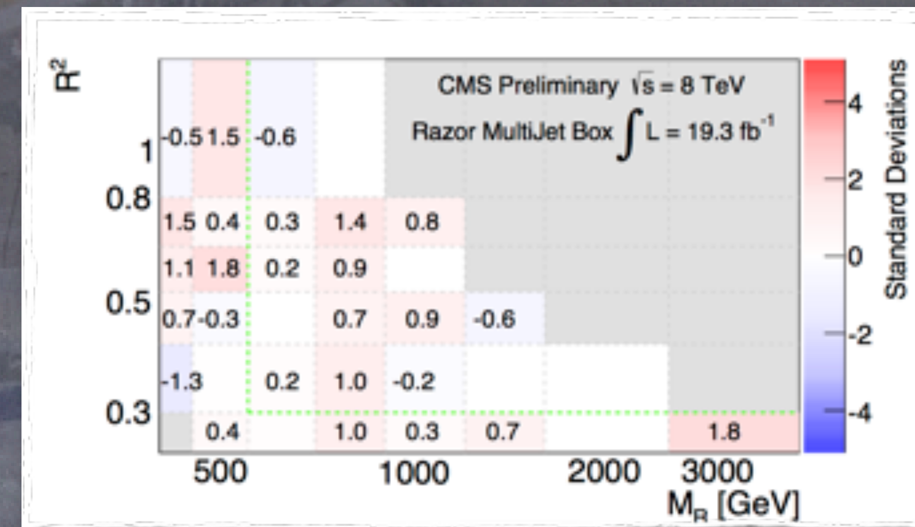


Razor Inclusive Search

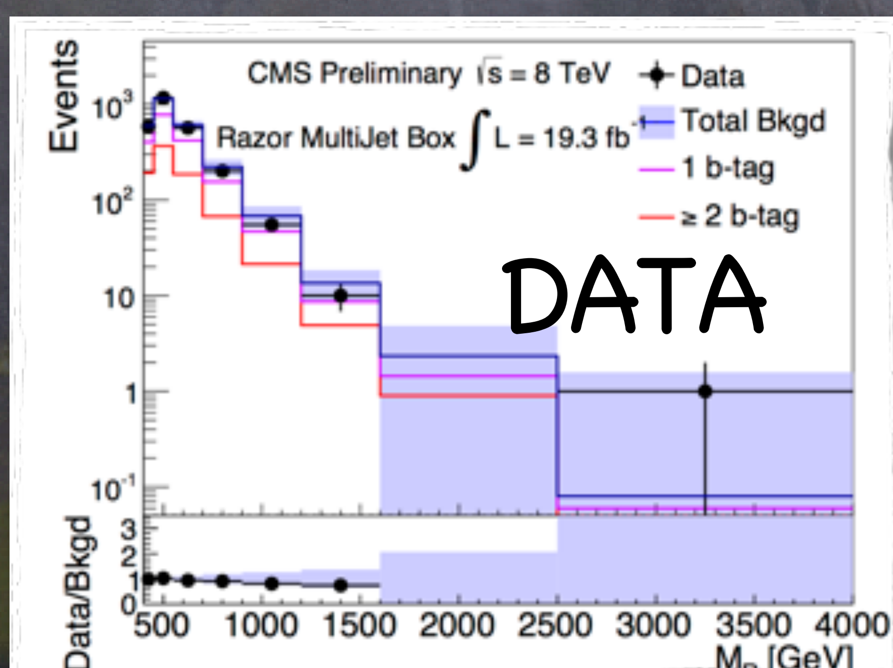
CMS PAS SUS-13-004

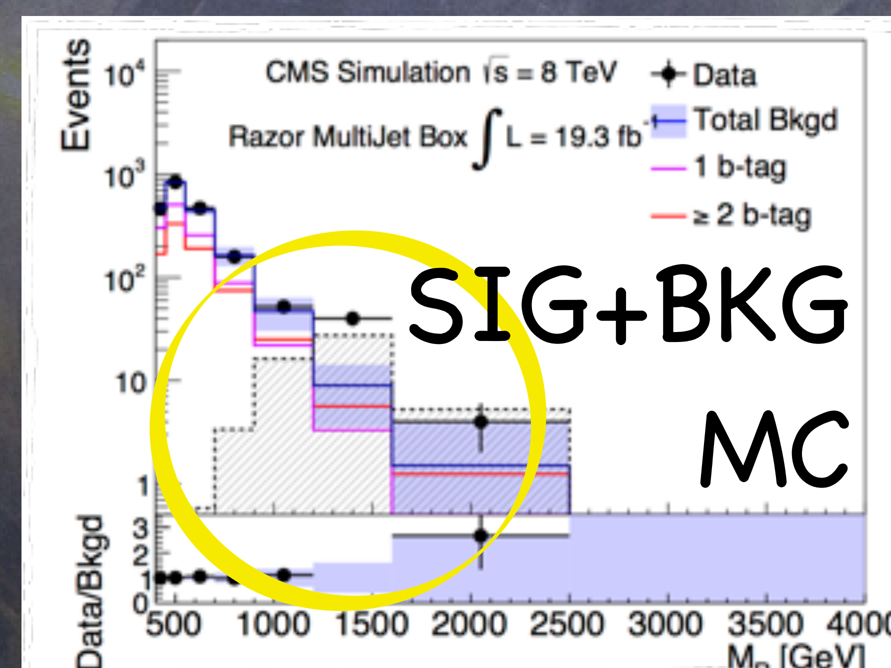
- The extrapolated background prediction is compared to data to evaluate the agreement (given in standard deviations)



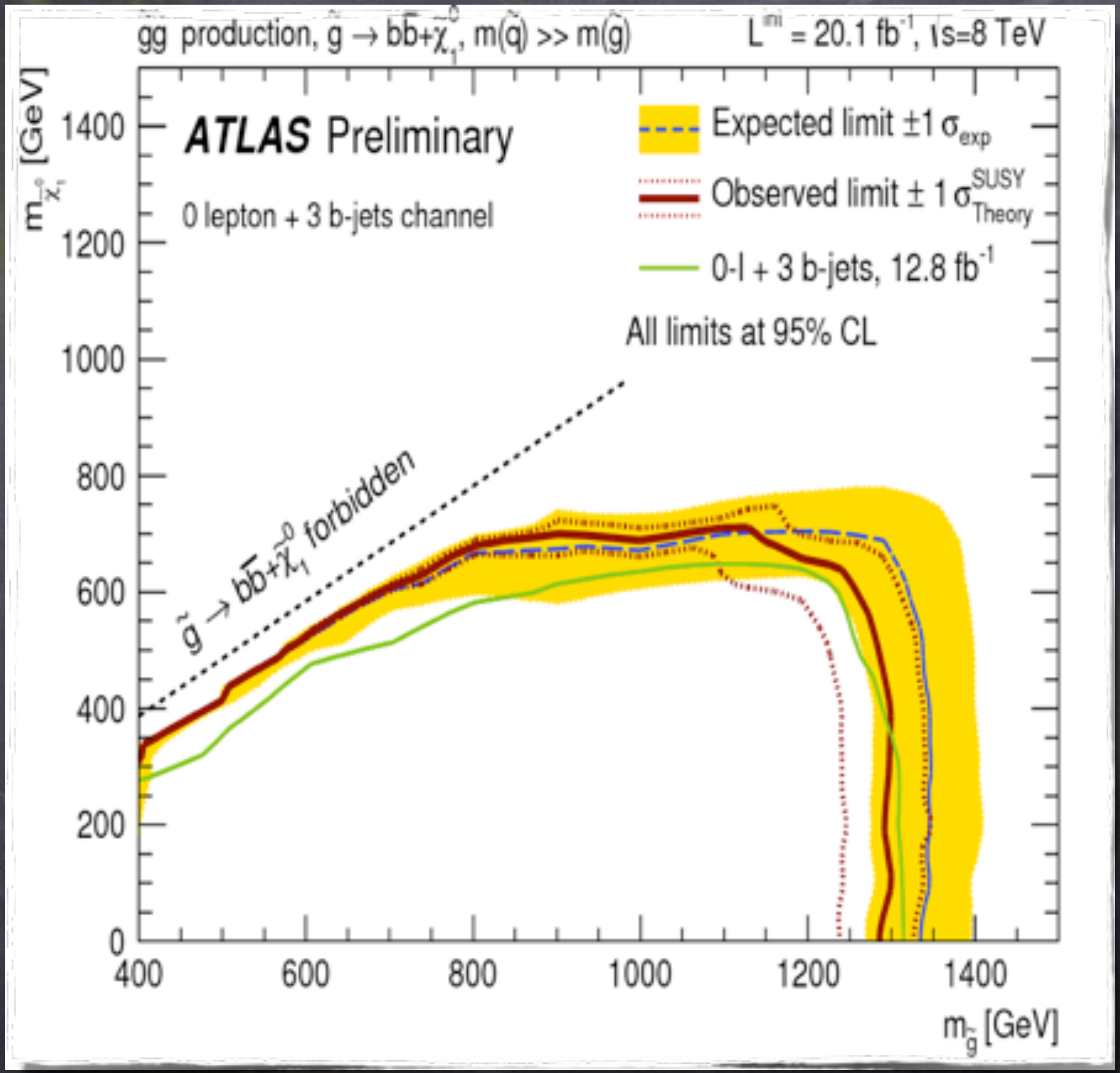


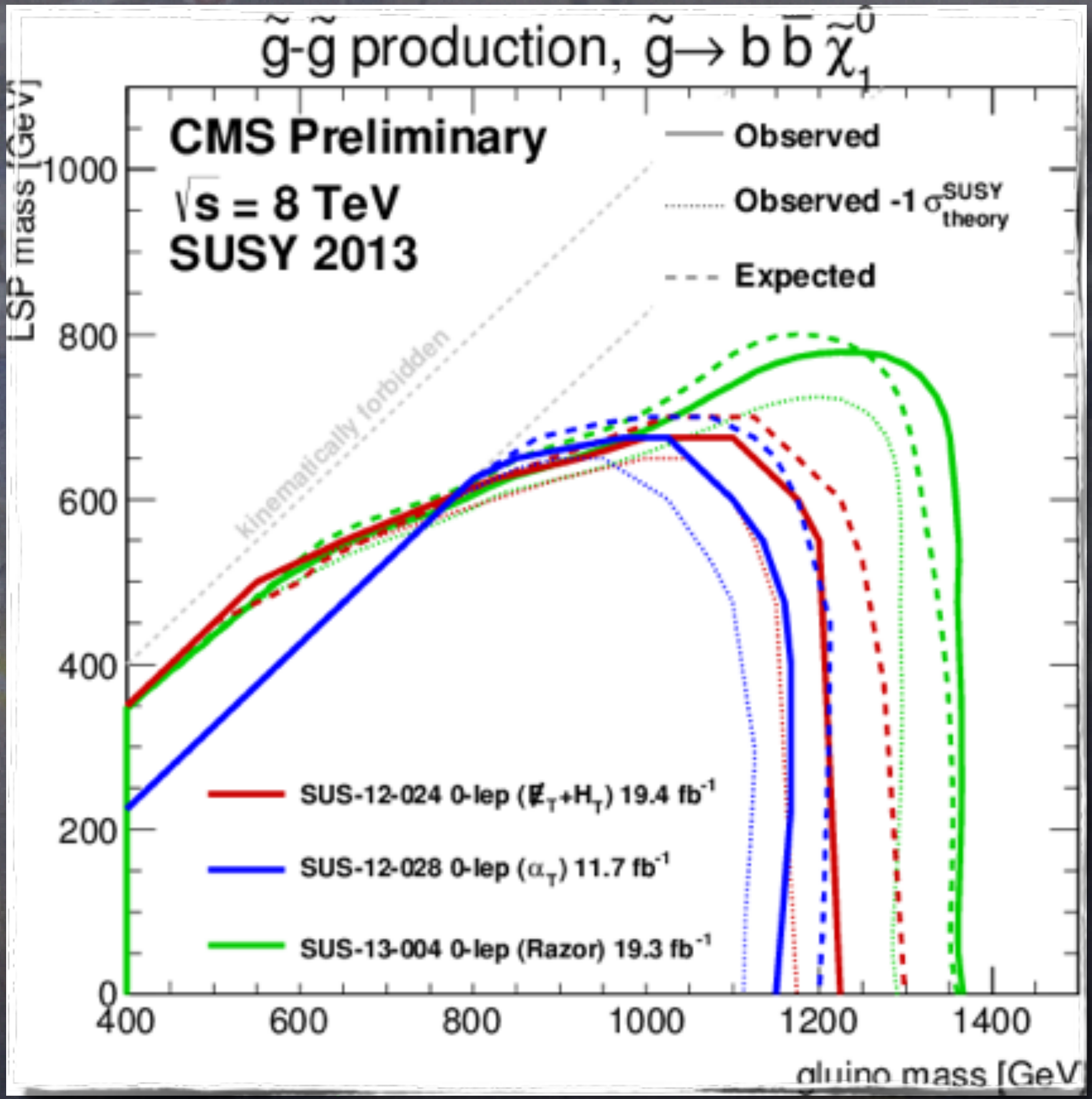
- The projections on M_R and R^2 show now discrepancy. A signal would emerge as a peak in M_R, more significant at large R^2



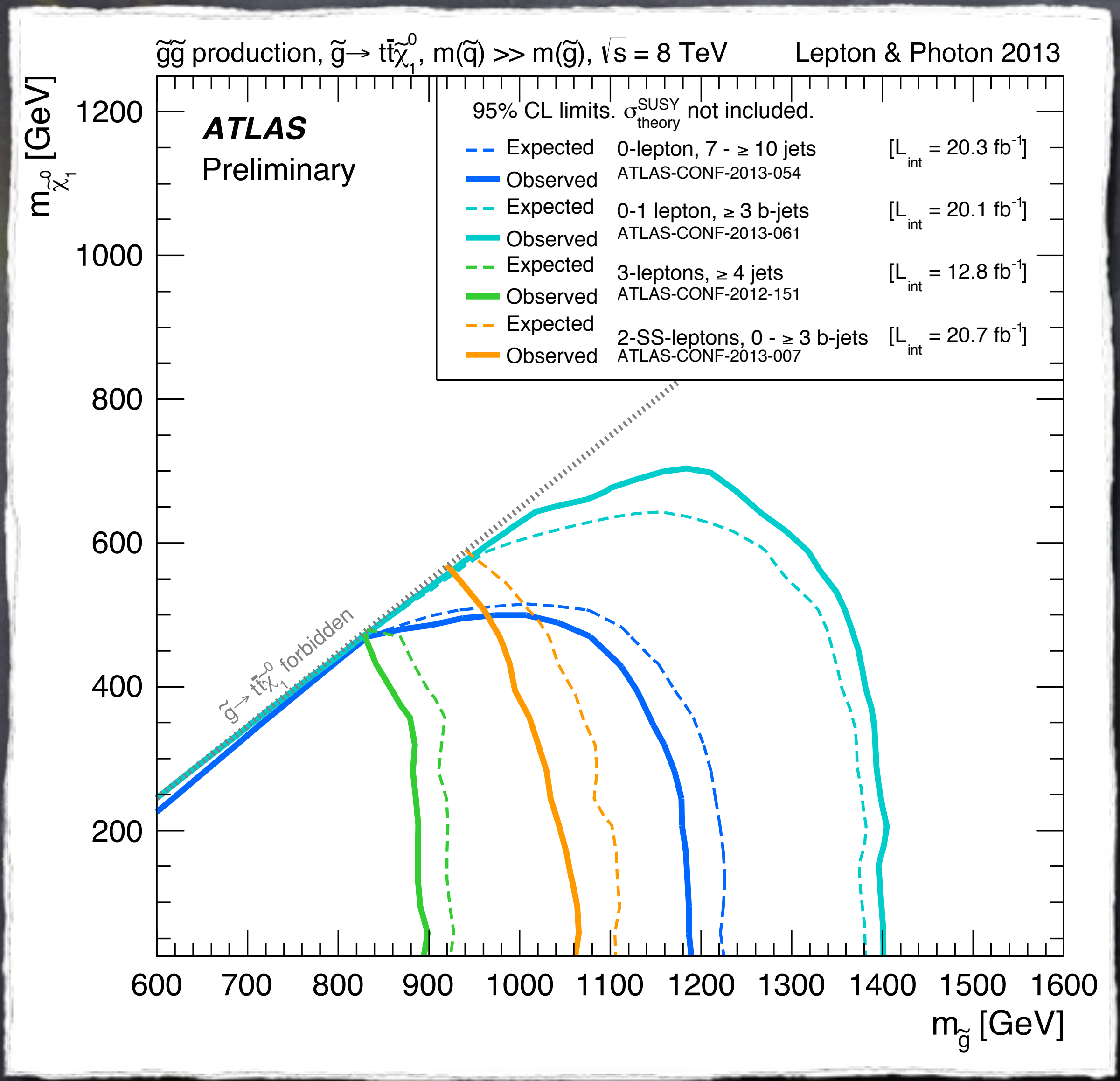


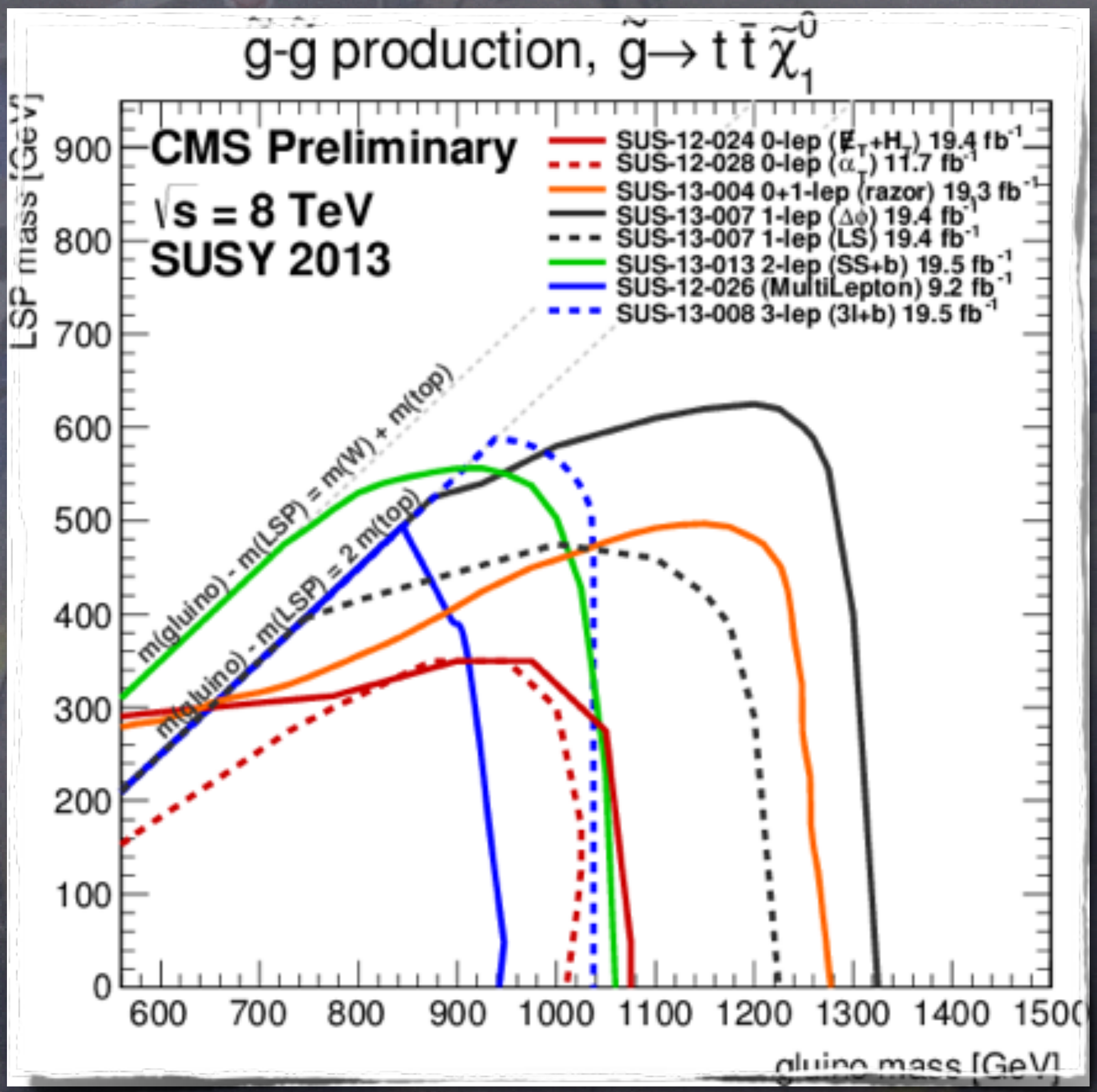
Gluino-Gluino Limits



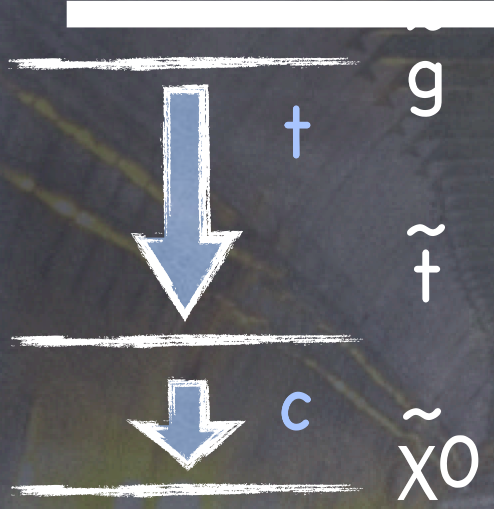


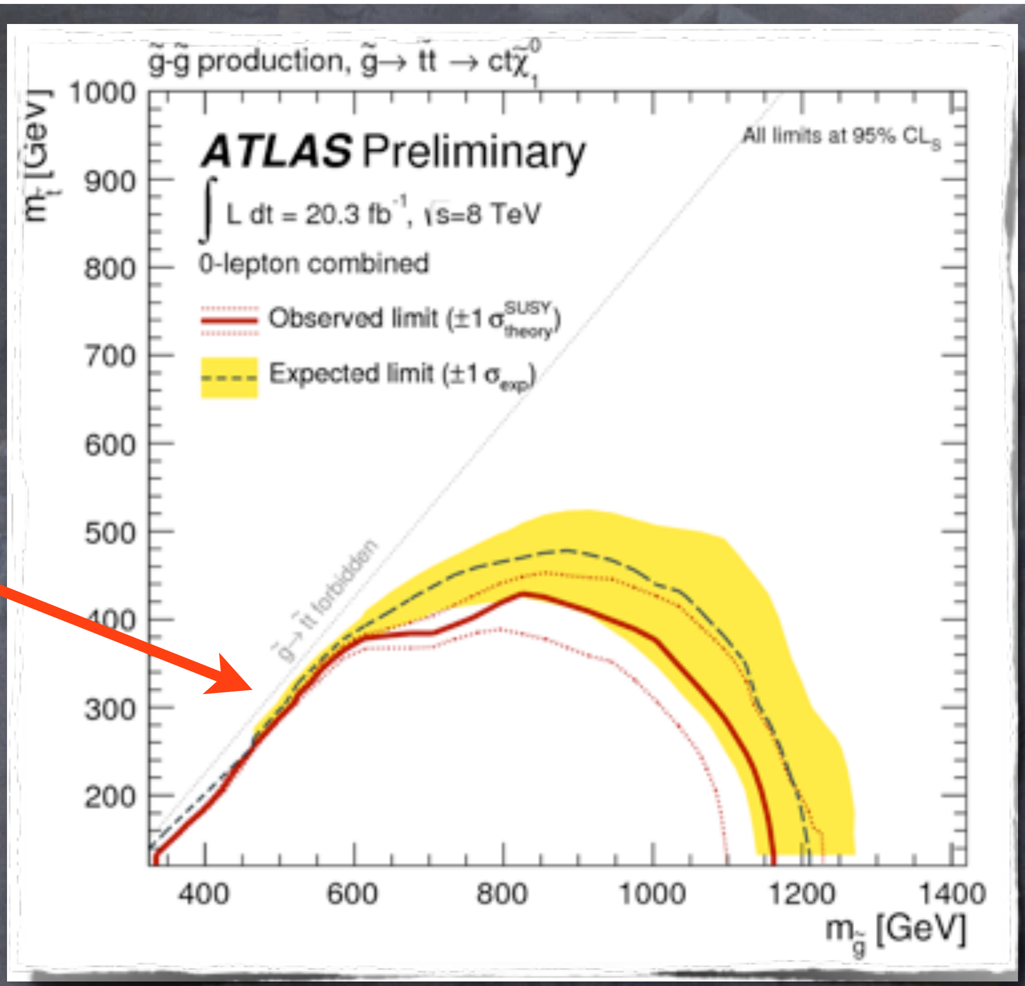
Gluino-Gluino Limits

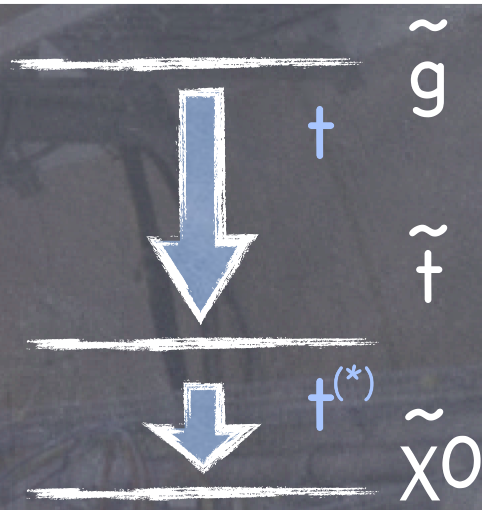


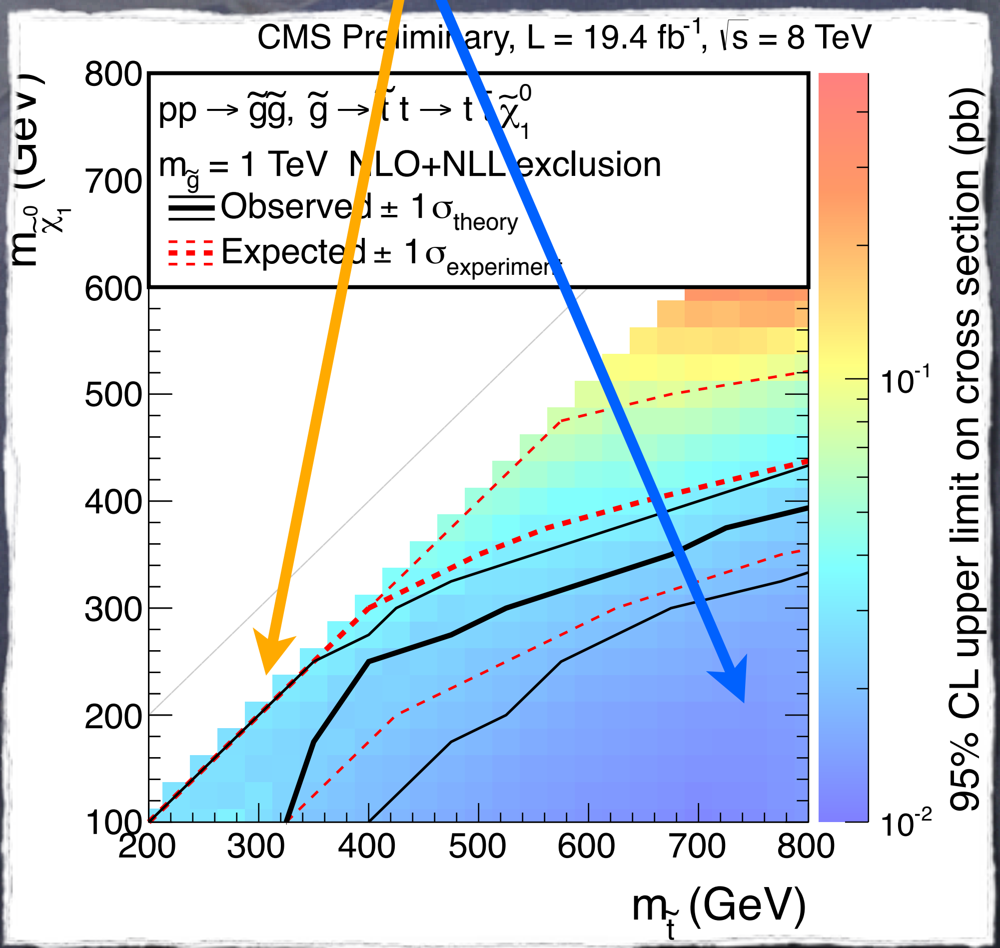


What does it mean for Stop?





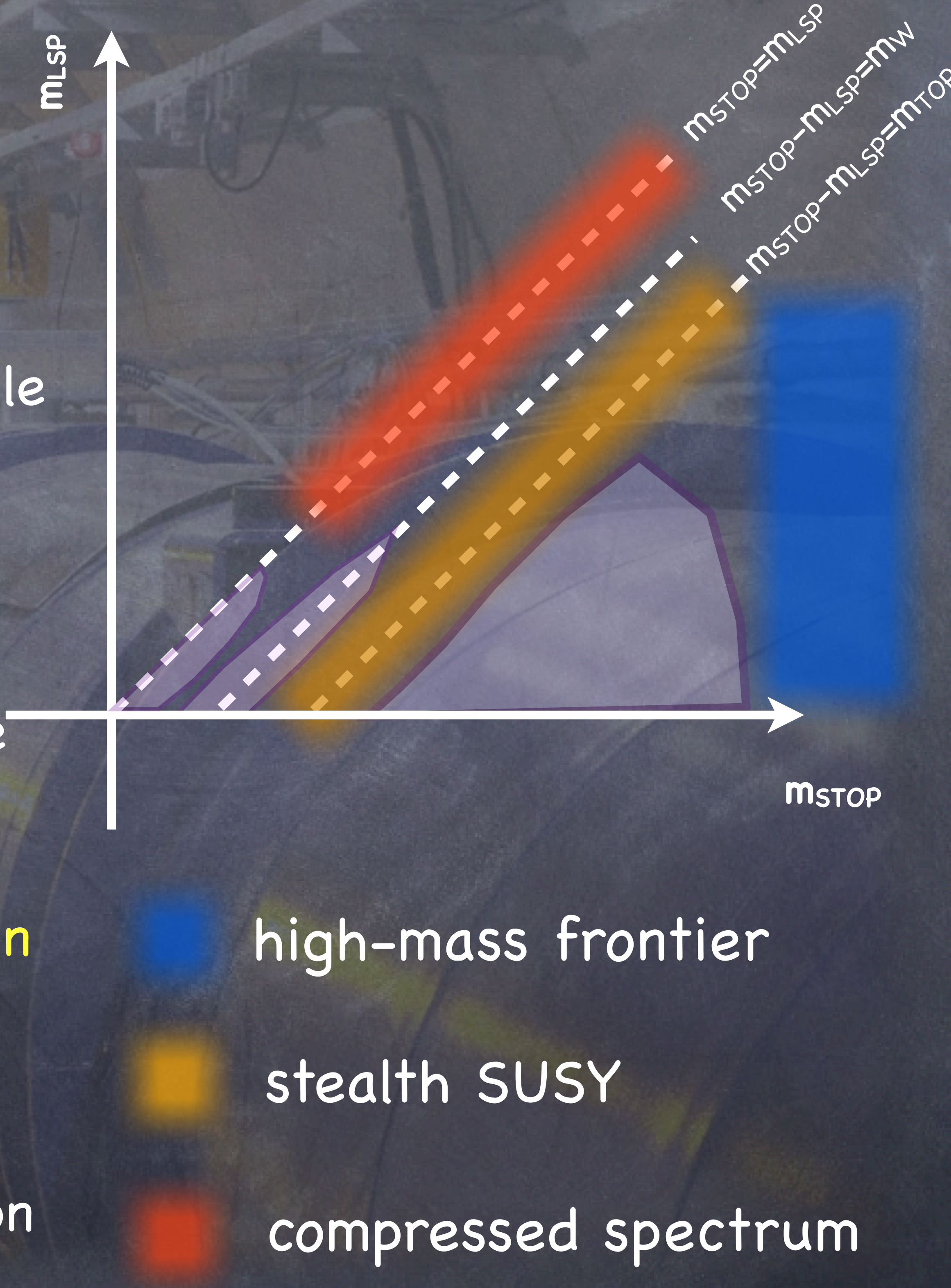




- Through the gluinos we can extend the sensitivity to the blind spot
- This assumes that the gluino is accessible @ LHC
- This will be a must for naturalness only with the next run

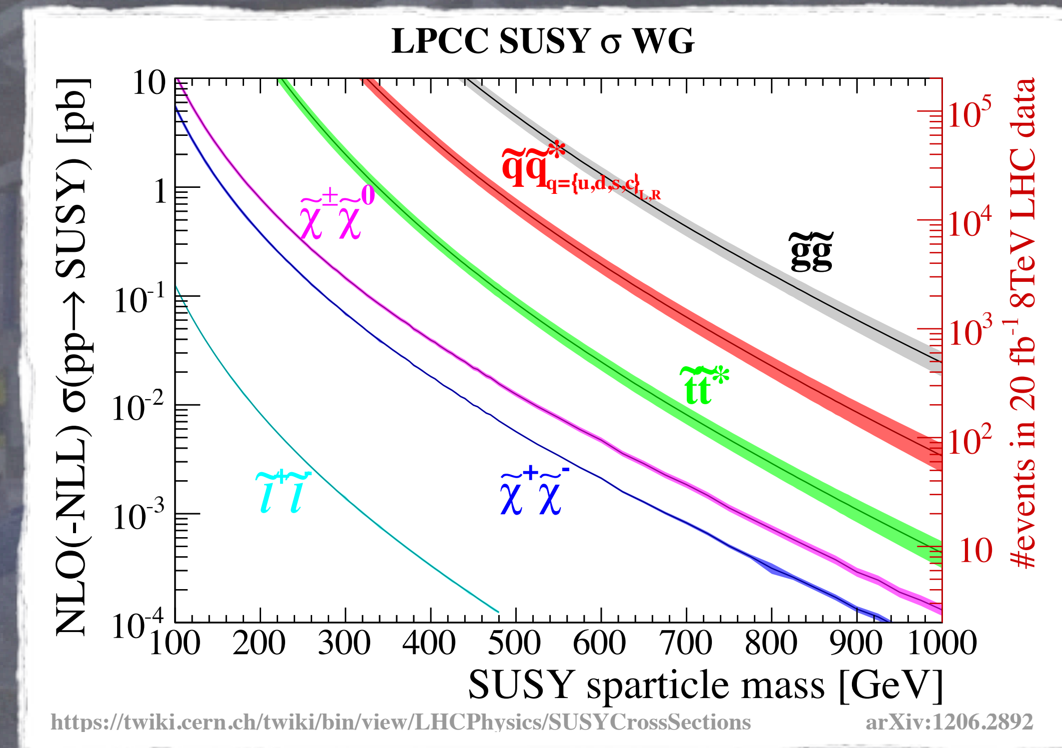
Lesson From Stop/Sbottom/Gluino Searches

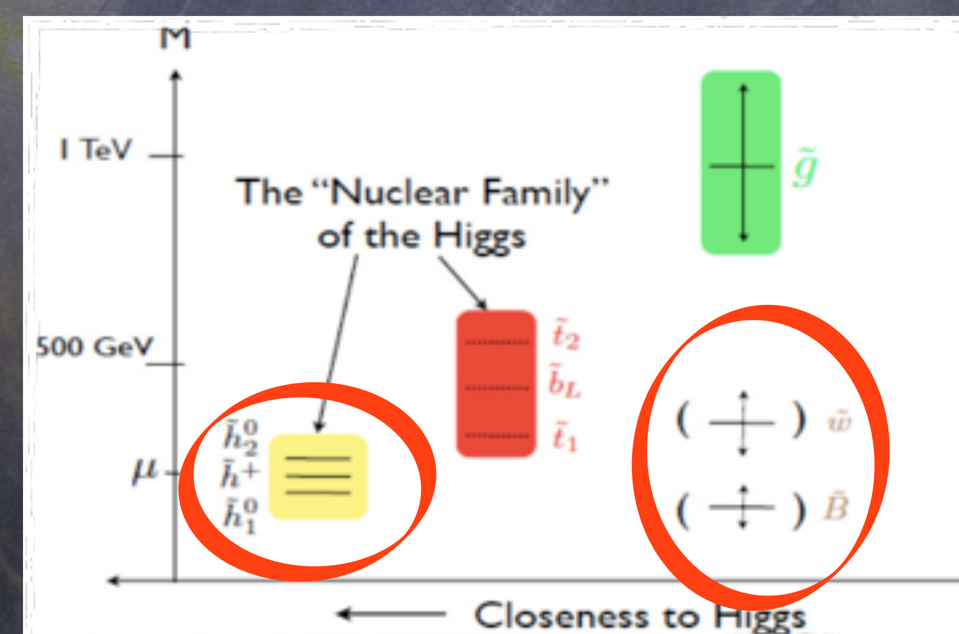
- What we really need is a light stop
- The current stop searches have three blind spots
- As long as the gluino is kinematically accessible @LHC, these blind spots are covered to some extent
- If not, direct stop/sbottom searches are the most powerful probe (but other ways possible with more light sparticles)
- Gluinos are pushed > 1300 GeV and the stop in one of the blind spots, for natural SUSY to survive 8 TeV data
- The main impact of 13 TeV run is the extension of the gluino reach



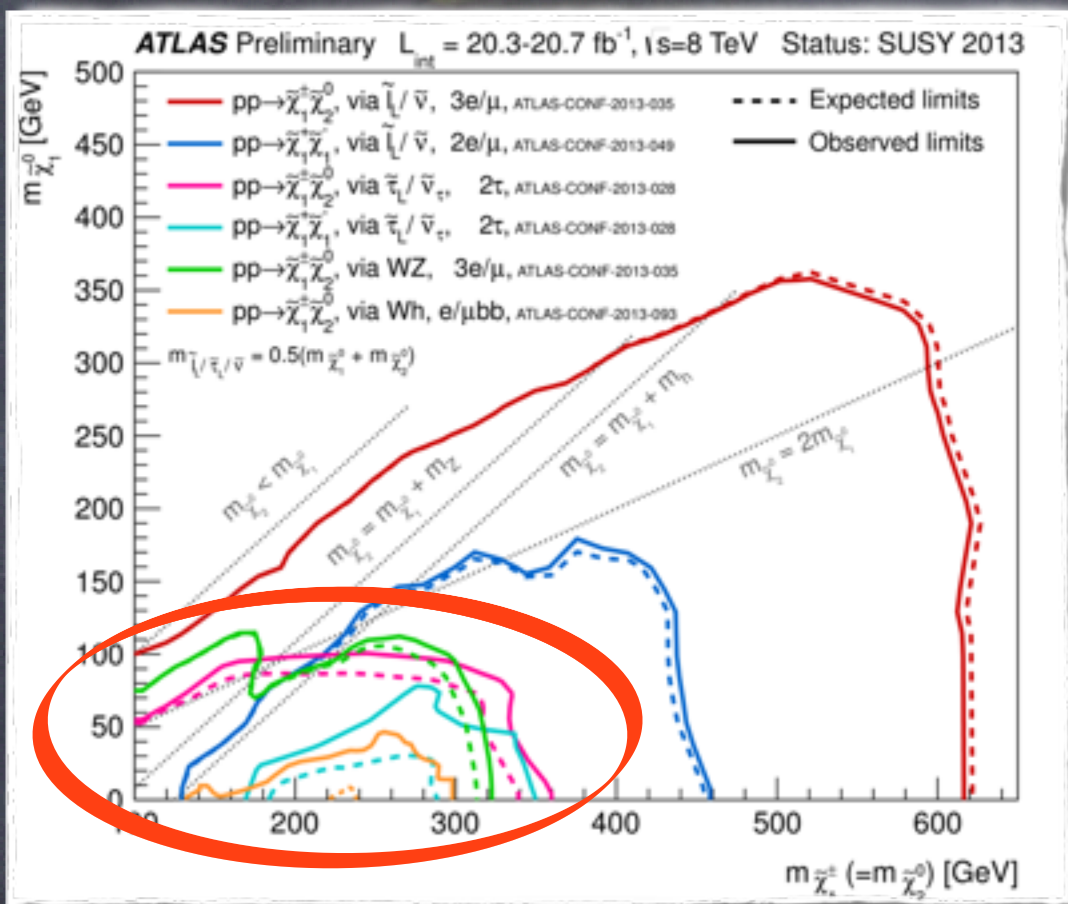
Sleptons/EWino searches

- Searches shown so far concentrate on the production of colored sparticles (higher xsec vs jet background)
- An intense program to search for slepton/chargino/neutralino searches
- The common denominator is multi-lepton events
- Could happen in conjunction with H decays (H-tagging for SUSY searches

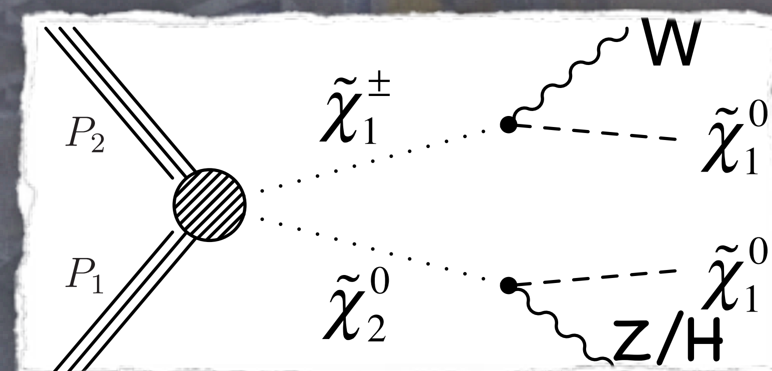


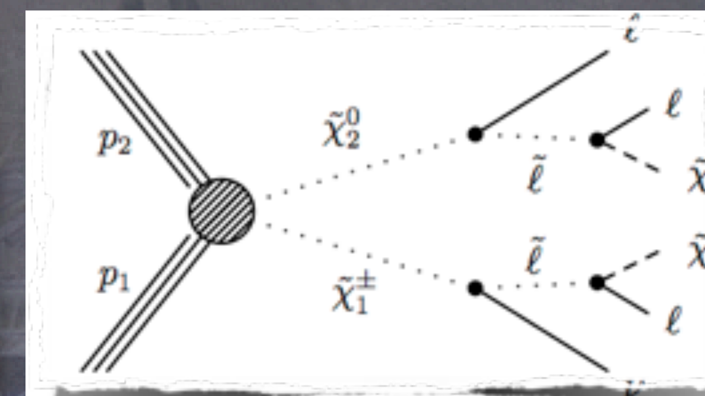


The EWino Limits

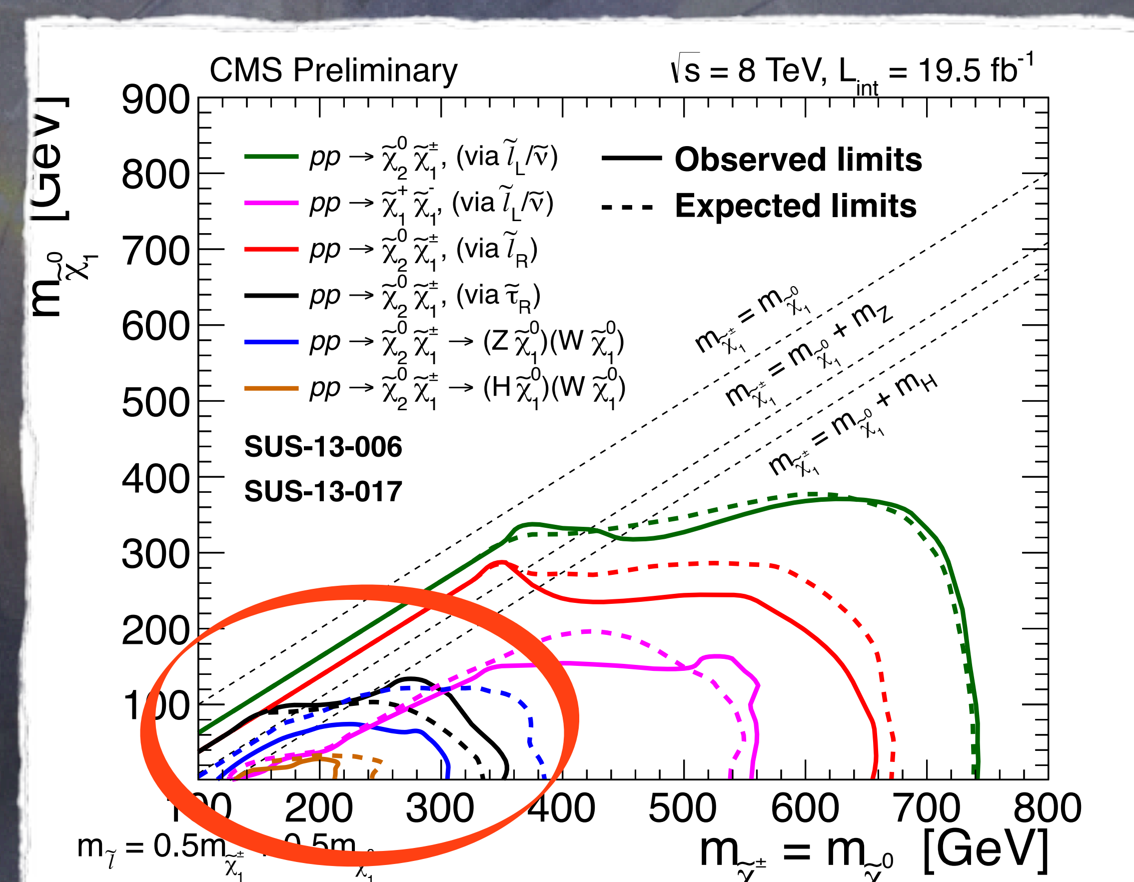


Stringent bounds for EWkinos decaying via a slepton (harder lepton spectrum)





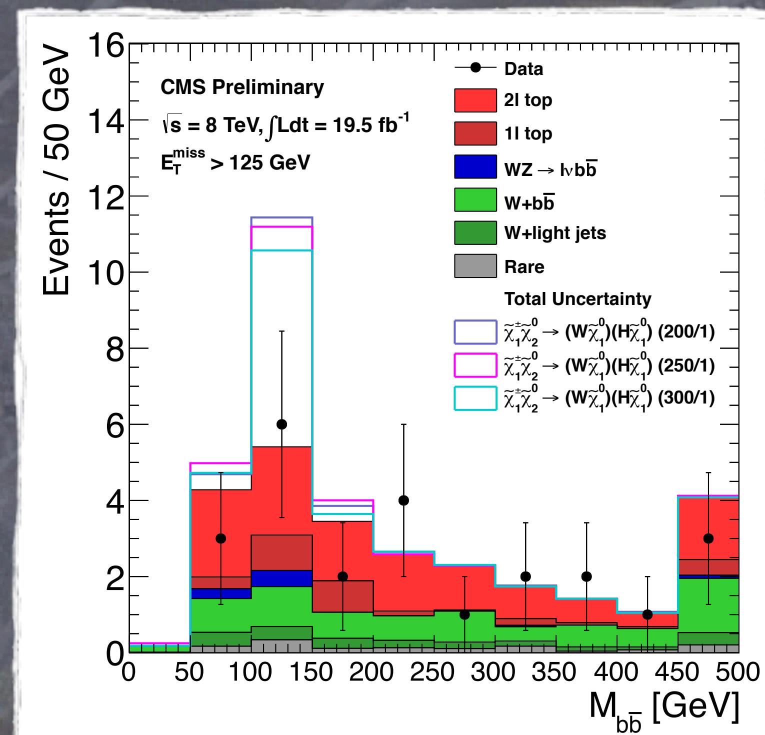
- Limits relaxed to 200-300 GeV when decay via W/Z
- No limit in this case if LSP heavier than 100 GeV

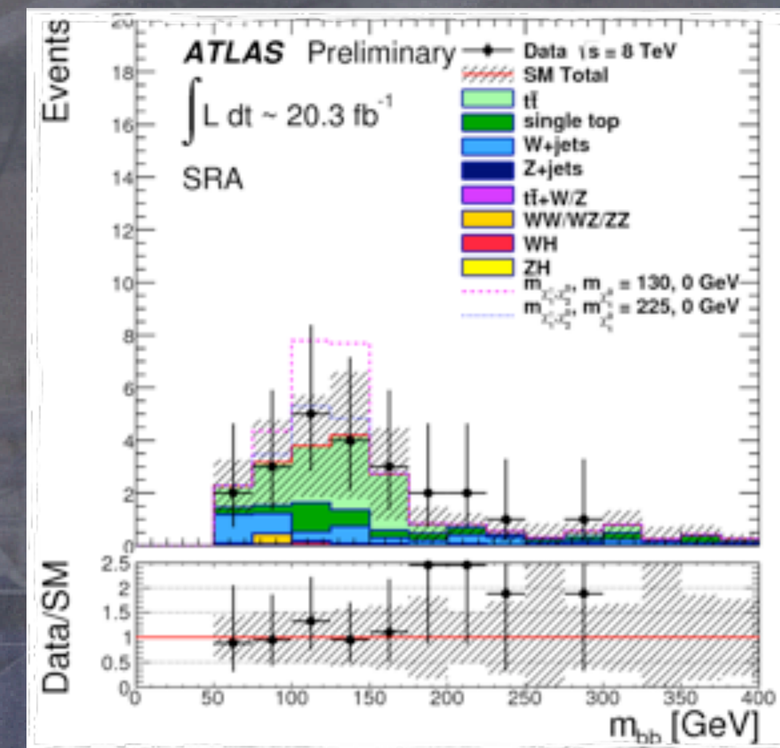


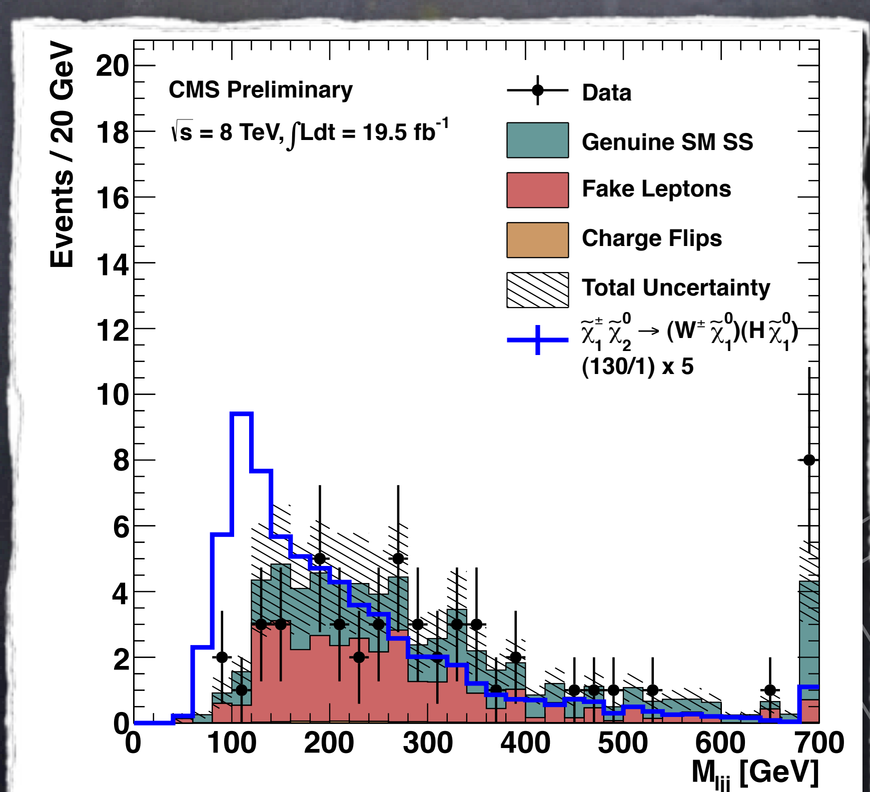
Higgs-tag for SUSY searches

$H \to bb$

- Select events with two bjets. Use m_{bb} to select Higgs-compatible pairs
- Suppress the SM bkg cutting on kinematic variables (MET, M_T, M_{CT})







$H \to WW/ZZ/\tau\tau$

- Exploit multi-lepton signatures (including leptons from other ewikino
- SS dilepton rare in the SM (low bkg)
- For $WW \to jj\nu\ell$ use M_{ljj} to search for a peak

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, talk by K.Black)
- 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 bkgs) 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

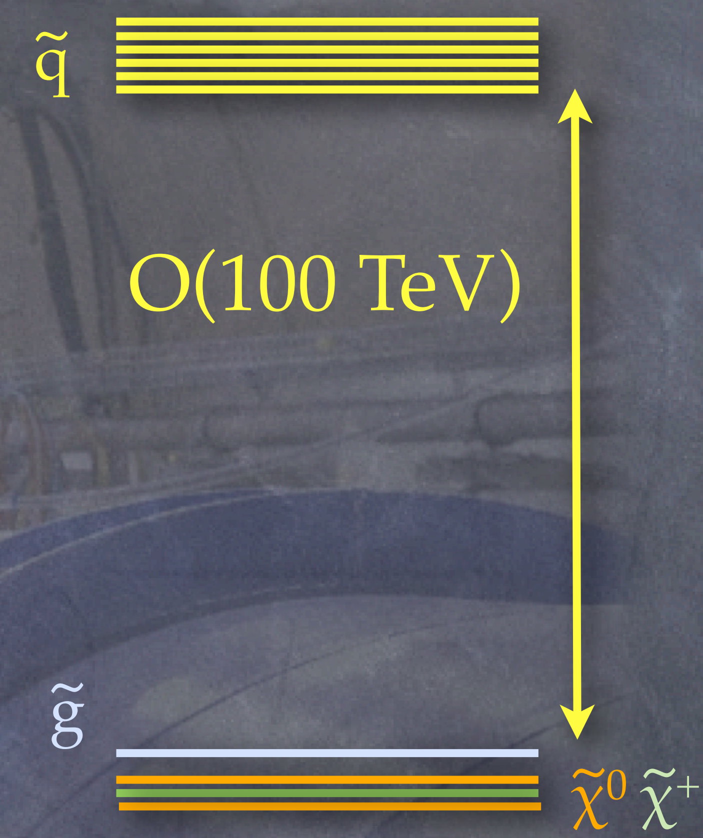
Split SUSY

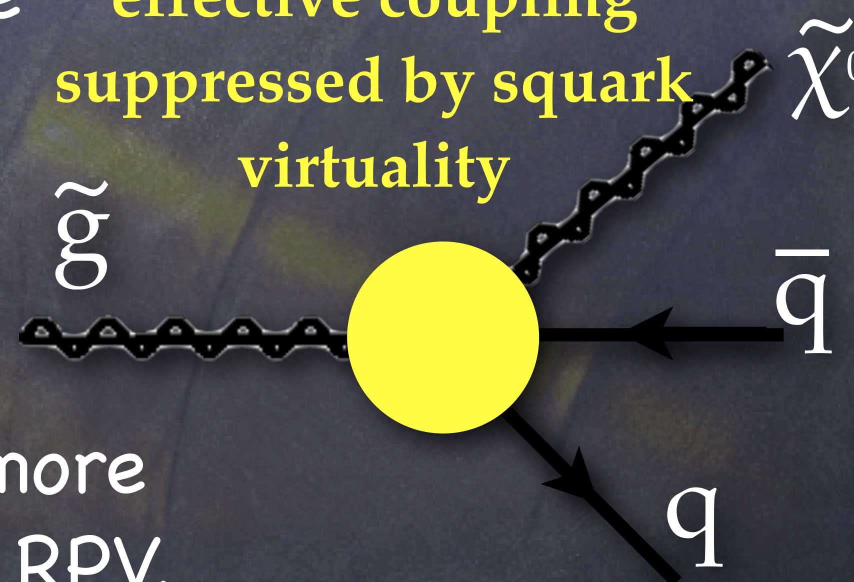
- the accessible sparticles are the gluino and the ewkino sector
- Even in this case, one would need associated jet production
- Even in this case, should look for displaced jets (long-living gluino)

Long-Living Particles

LLP & Split SUSY

- Split SUSY predicts a large mass gap between fermion (light) and scalar (heavy) sparticles
- The gluino travels through the detector as a R-hadron (hadronizing or interacting with the material), with or without electric charge
- We expect a slow particles traveling across the detector
- Could start charged and become neutral (or vice versa) or stay charged all the way through (depending on what the gluon picks when hadronizing)
- Gluinos in split SUSY are only an example of a more general signature (LL sleptons, LL neutralinos in RPV, etc)

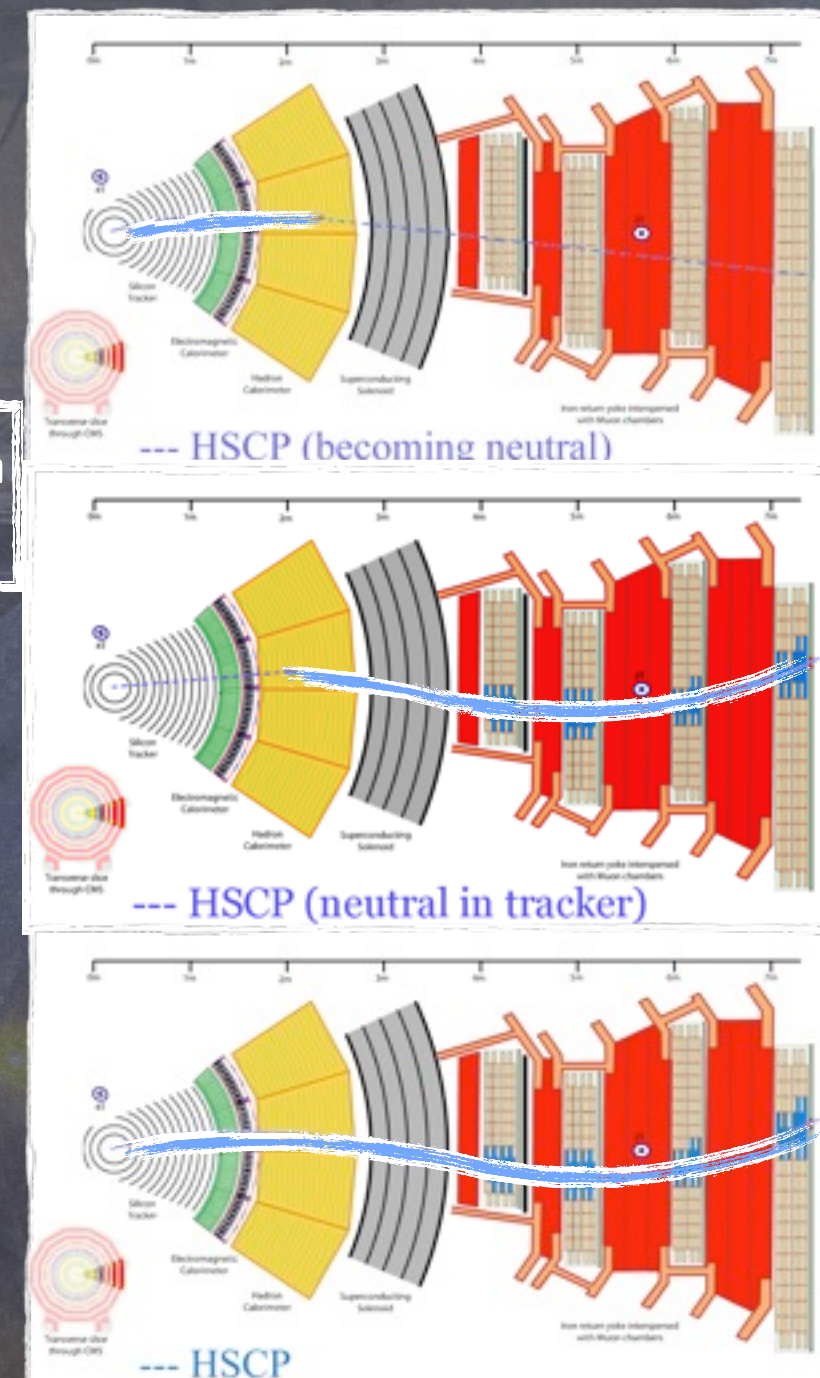


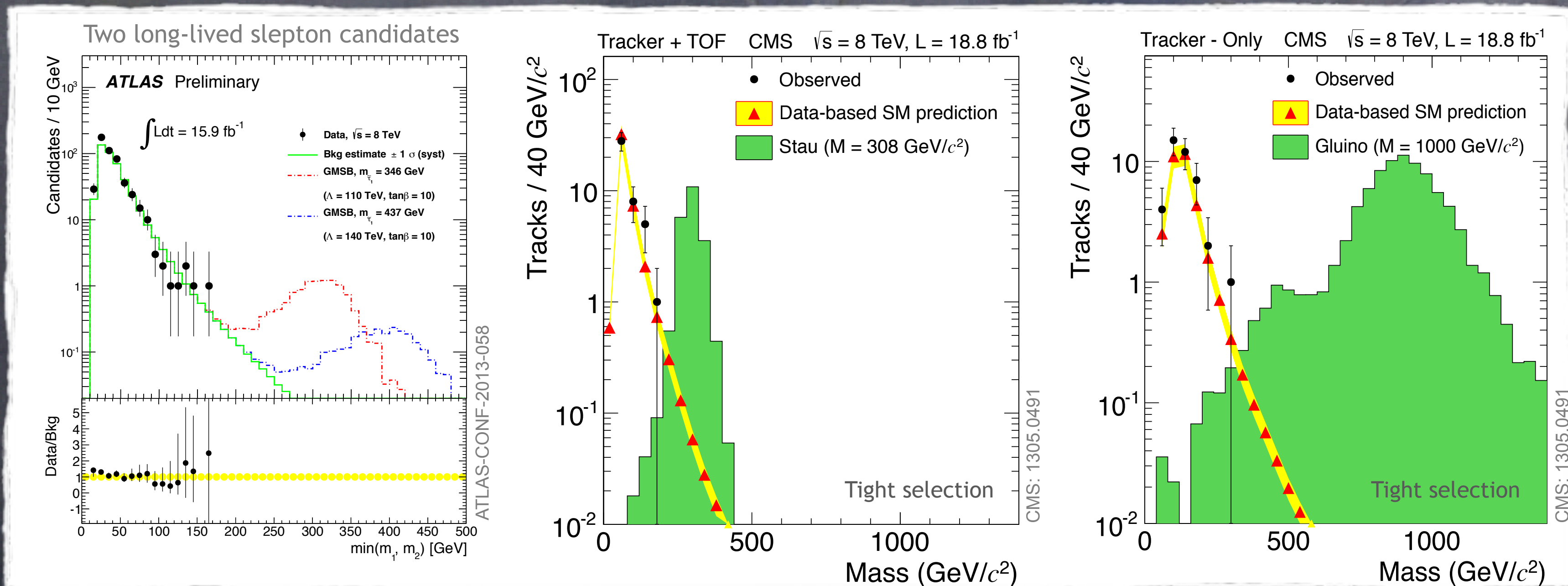


Long-living particles

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)

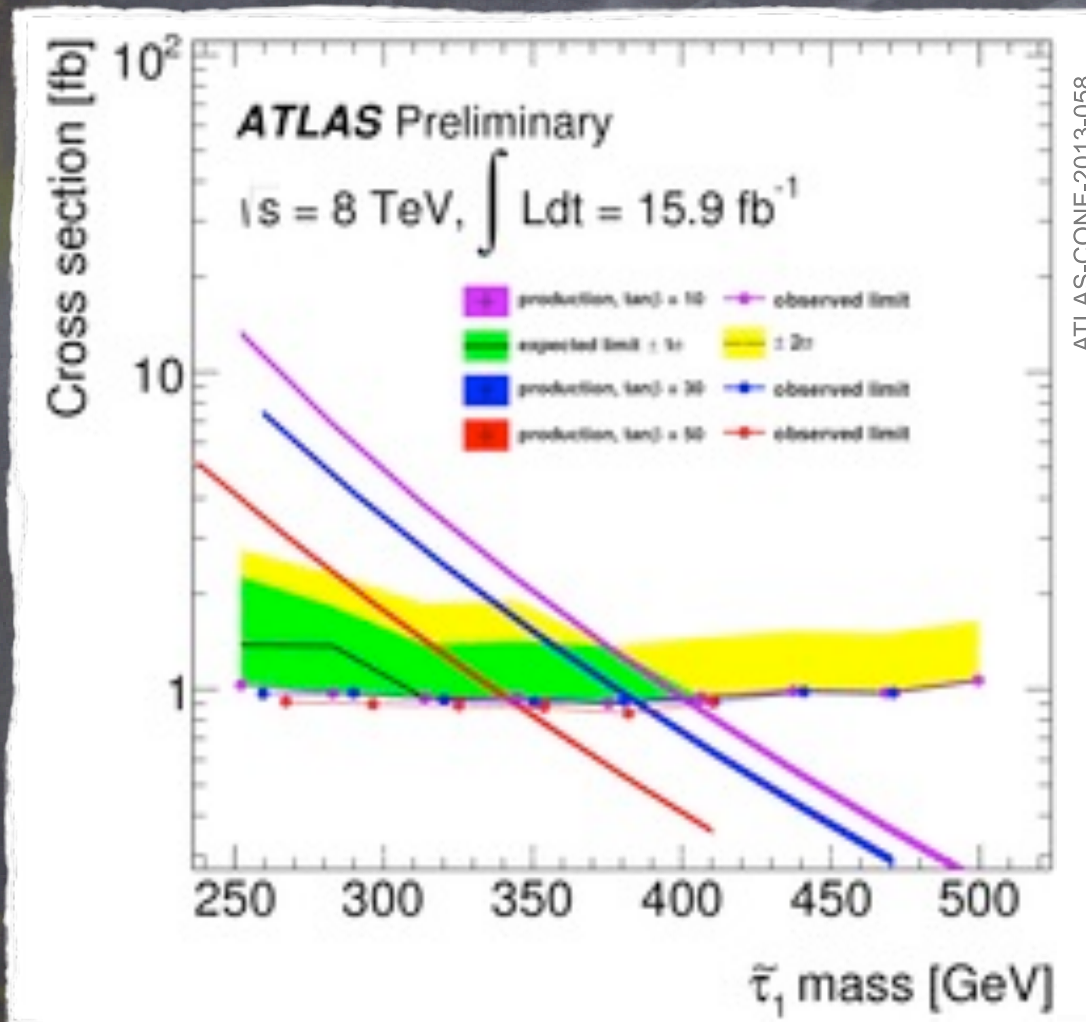


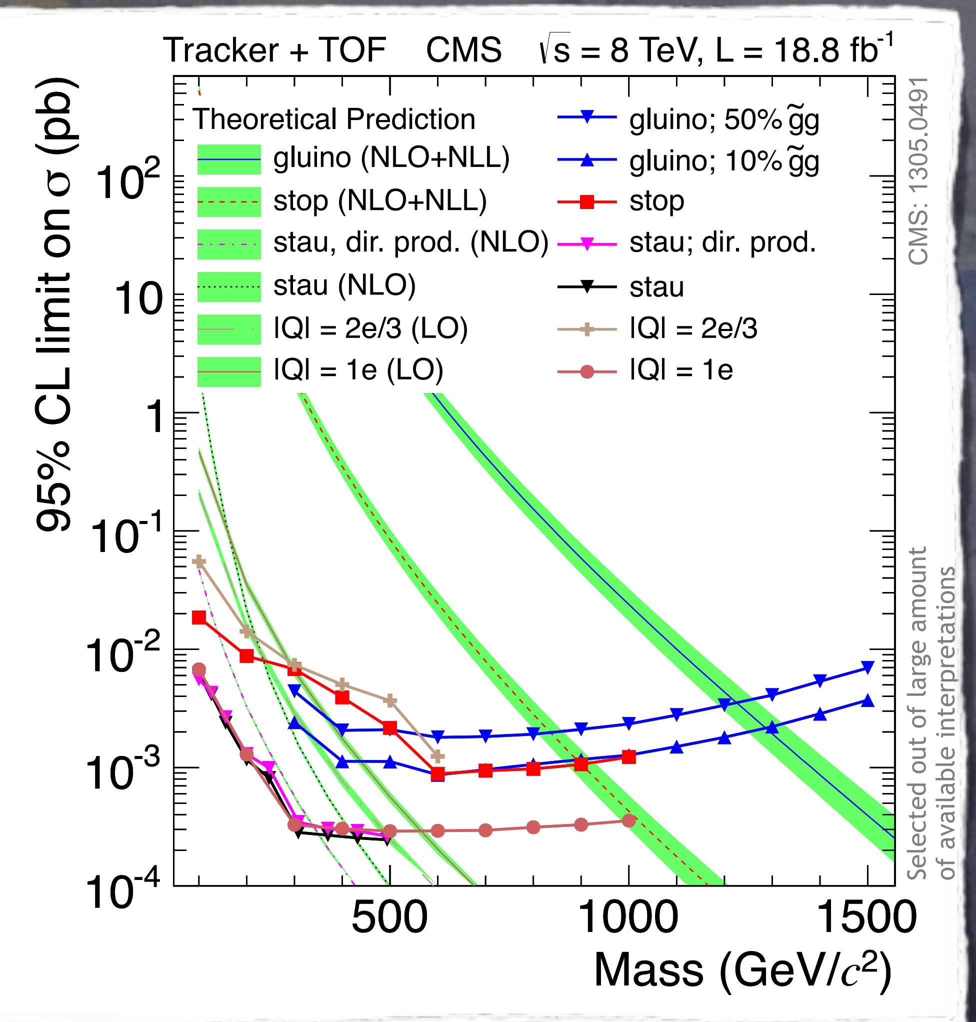


ATLAS-CONF-2013-058 CMS PAS EXO-12-026

Long-living particles

Strong limits on gluino, stop, and stau





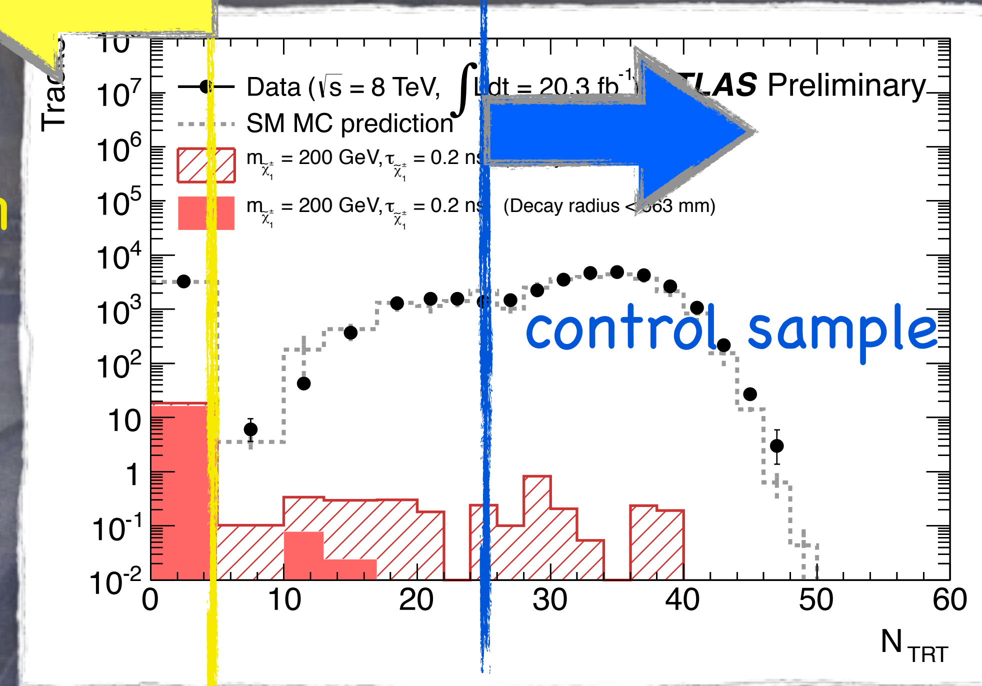
Stopping Tracks

- Look for events with tracks dying in the inner detector (upper cut on TRT hits), recoiling vs ISR jet

Selection requirement	Observed events	Expected signal events (efficiency [%])
Quality requirements and trigger	20479553	1873 (8.8)
Jet cleaning	18627508	1867 (8.8)
Lepton veto	12485944	1827 (8.6)
Leading jet $p_{\mathrm{T}} > 90$ GeV	10308840	1571 (7.4)
$E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV	6113773	1484 (7.0)
$\Delta\phi_{\mathrm{min}}^{\mathrm{jet}-E_{\mathrm{T}}^{\mathrm{miss}}} > 1.5$	5604087	1444 (6.8)
High-p_{T} isolated track selection	34379	21.9 (0.10)
Disappearing-track selection	3256	18.4 (0.087)

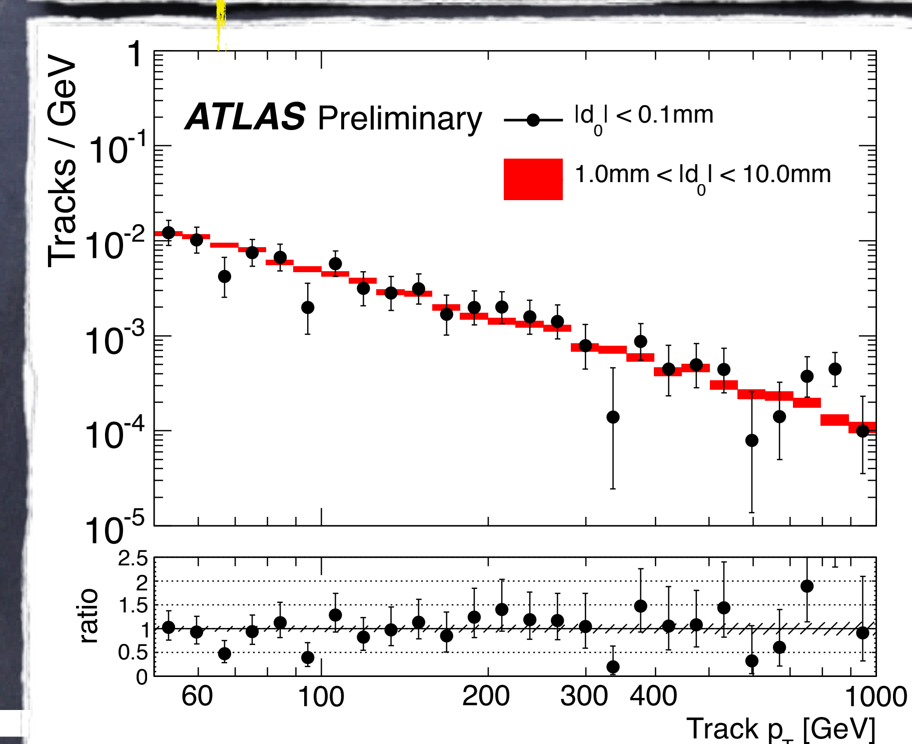
ATLAS-CONF-2013-069

signal region



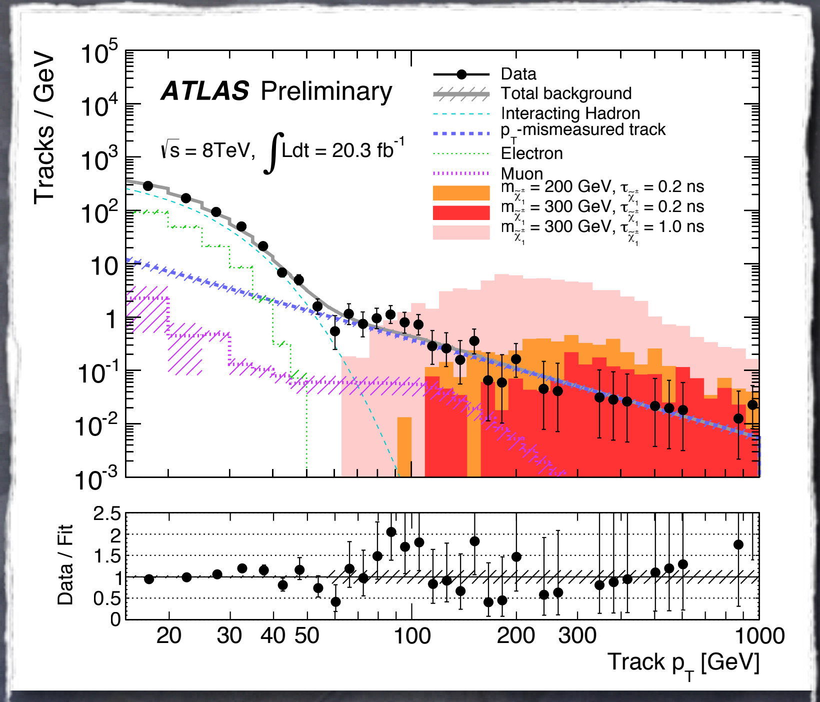
- Three main bkg sources, measured with data control samples

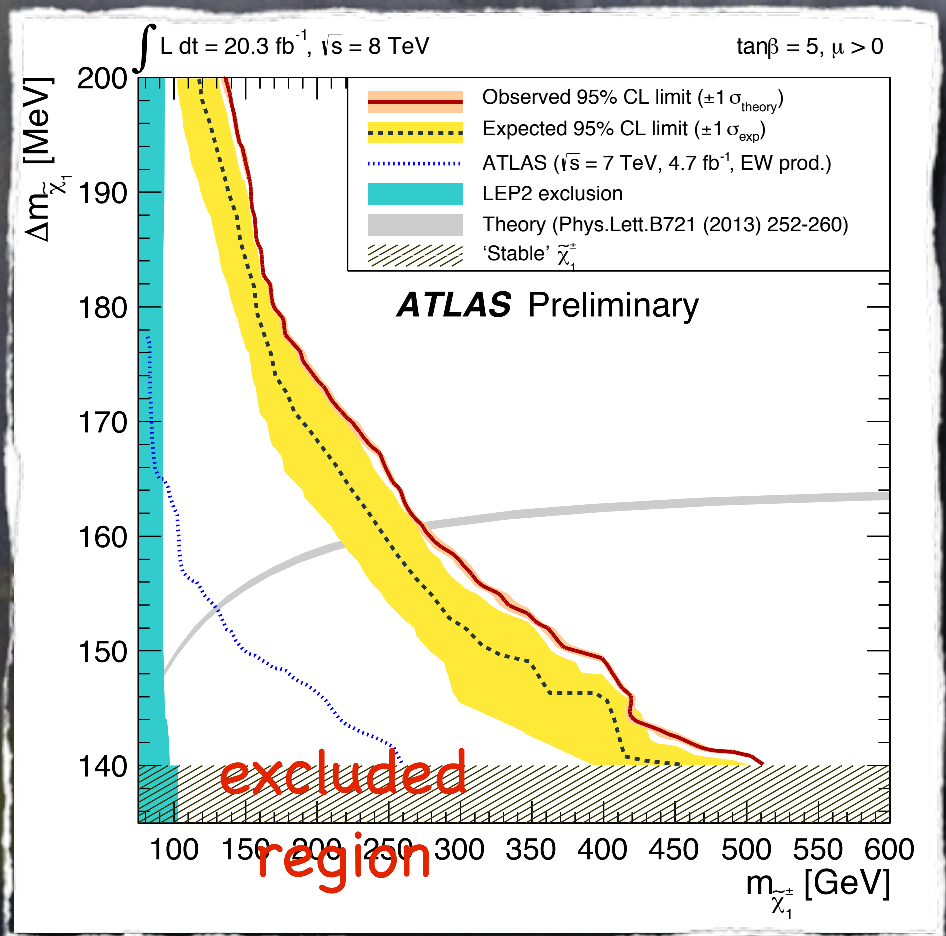
charged hadrons interacting with material (from NTRT>25 tracks)
not identified leptons (from identified leptons)
mismeasured low-pT tracks (from large impact parameter tracks in multijet samples)

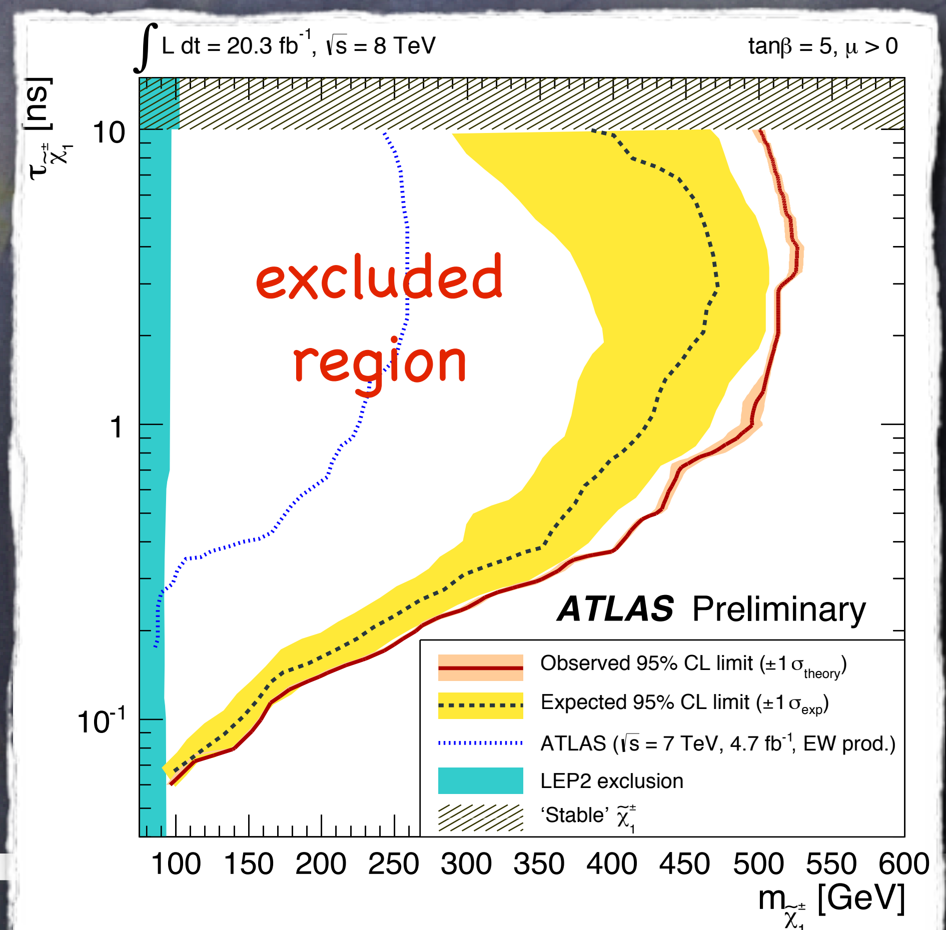


Stopping Tracks

No excess observed
derived limit on lifetime
(and mass split) for
chargino/neutralino
compressed spectrum

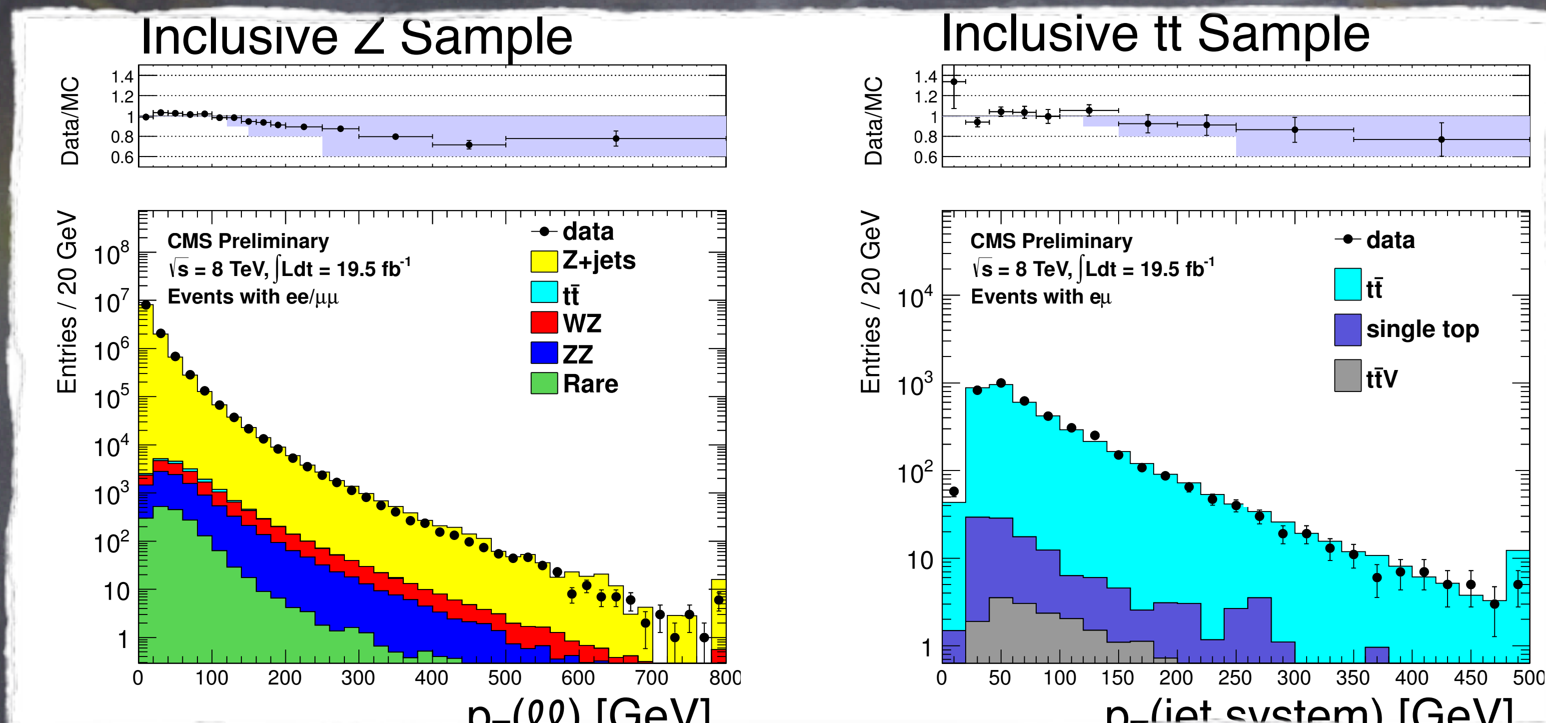


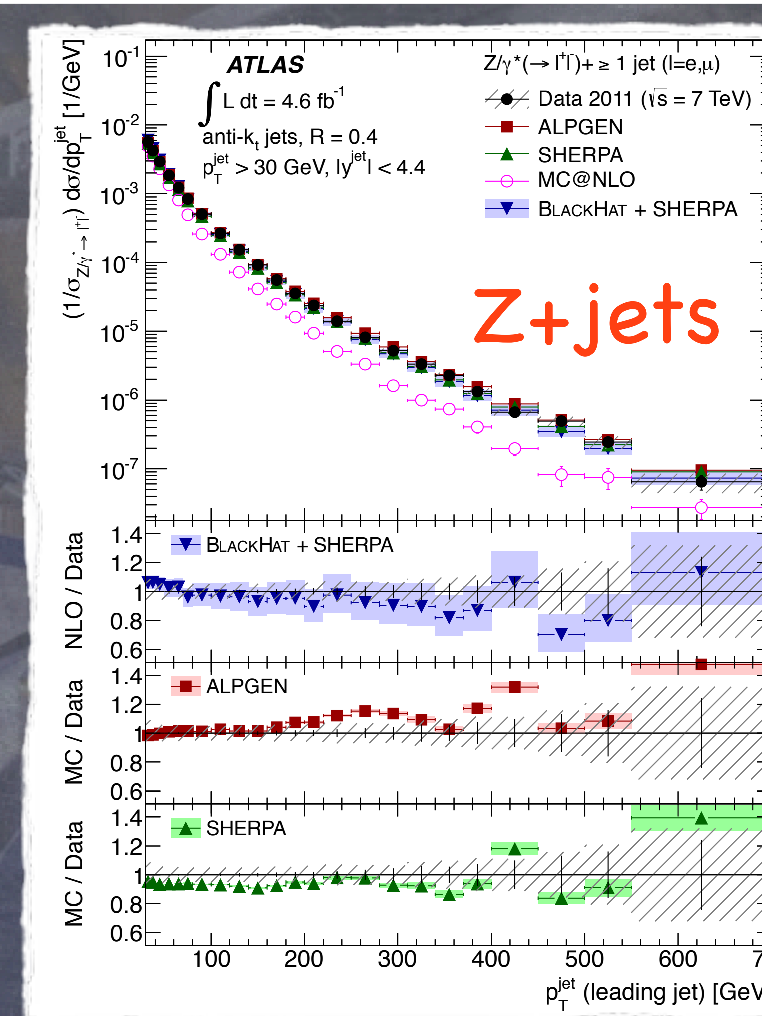




A Side Remark on ISR

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

Relevant for inclusive searches and searches with dedicated ISR selection

R-Parity Violation

Leptonic & Hadronic RPV SUSY

Once R-parity is broken, new kinds of couplings give new processes (and signatures @LHC)

Leptonic RPV **Mixed RPV** **Hadronic RPV**

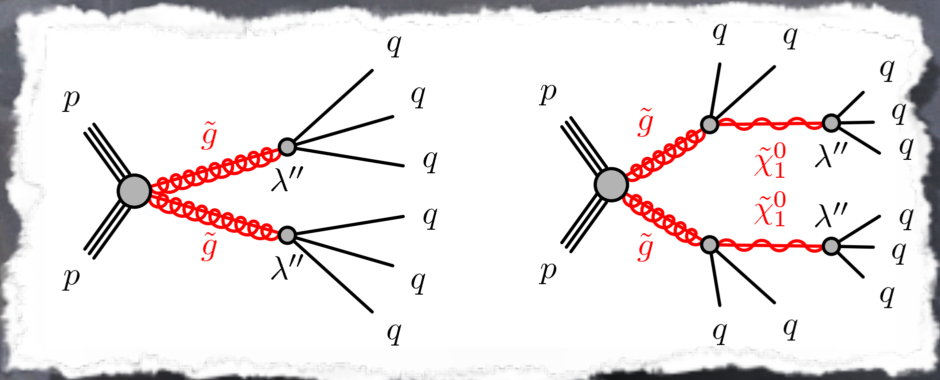
$$W_{RPV} = \tfrac{1}{2}\,\lambda_{ijk} L_i L_j \overline{E}_k + \lambda^{`}_{ijk} L_i Q_j \overline{D}_k + \tfrac{1}{2}\,\lambda^{``}_{ijk} U_i D_j \overline{D}_k + \kappa_i L_i H_2$$

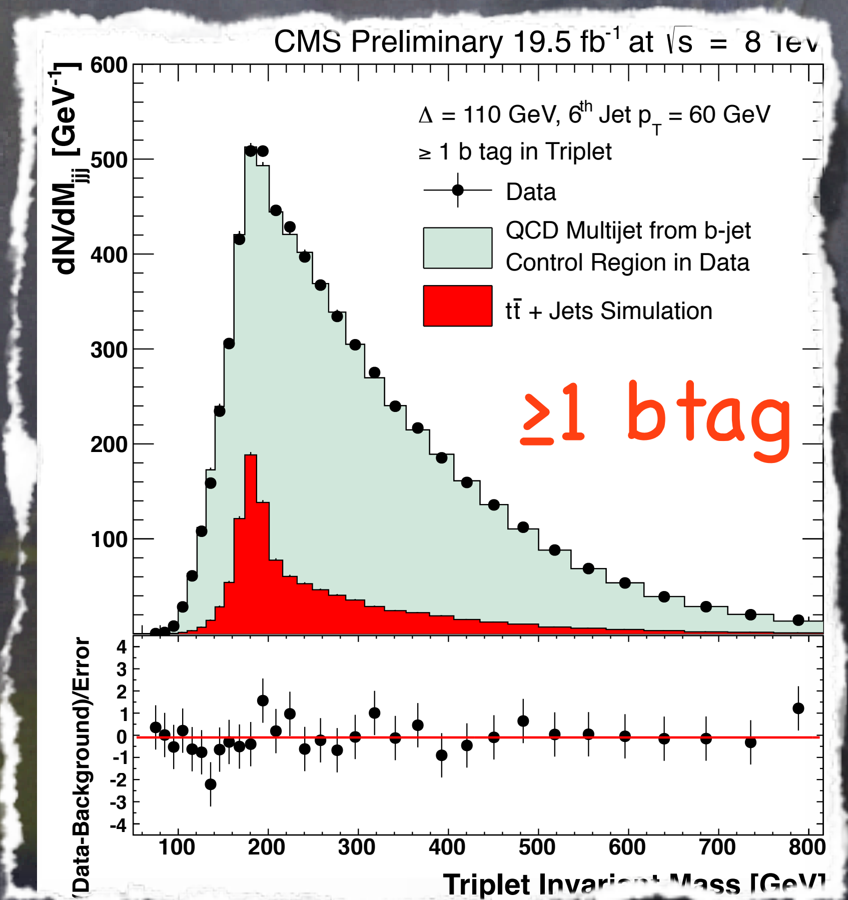
- RPV couplings can violate **lepton and baryon number conservation**
- Can result in **two, three and four body decays** of supersymmetric particles to Standard Model particles
- Couplings chosen to have **prompt decay**, and to satisfy constraints from neutrino mass and proton decay.

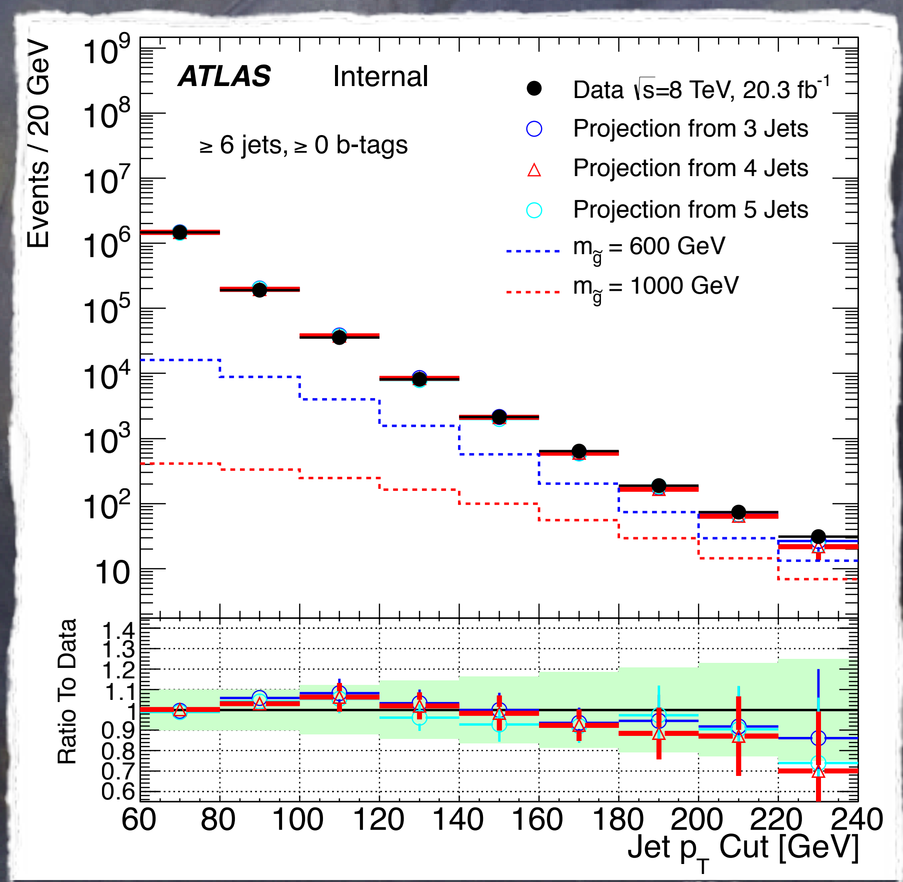
- In general, one needs a mechanism by which these couplings are small
- Leptonic SUSY is easier to find (leptons in final state)
- Hadronic RPV has appealing theoretical aspects (trade R-parity for MFV explains the small couplings) but it is more difficult to search for

Multijet Search for Hadronic RPV

- Pair-produced gluinos give multijet final states
- Background from QCD. No MET to suppress it. Estimated with lower-njet data (ATLAS) or with a shape analysis (CMS)
- Study final states with b-jets (enhanced sensitivity to 3rd generation)
- Could probe more complicated cascades



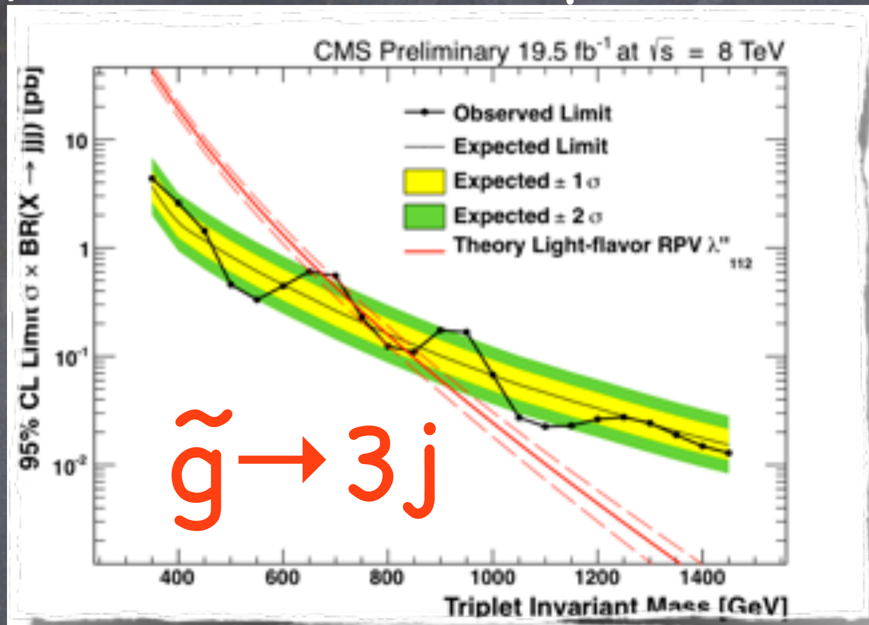


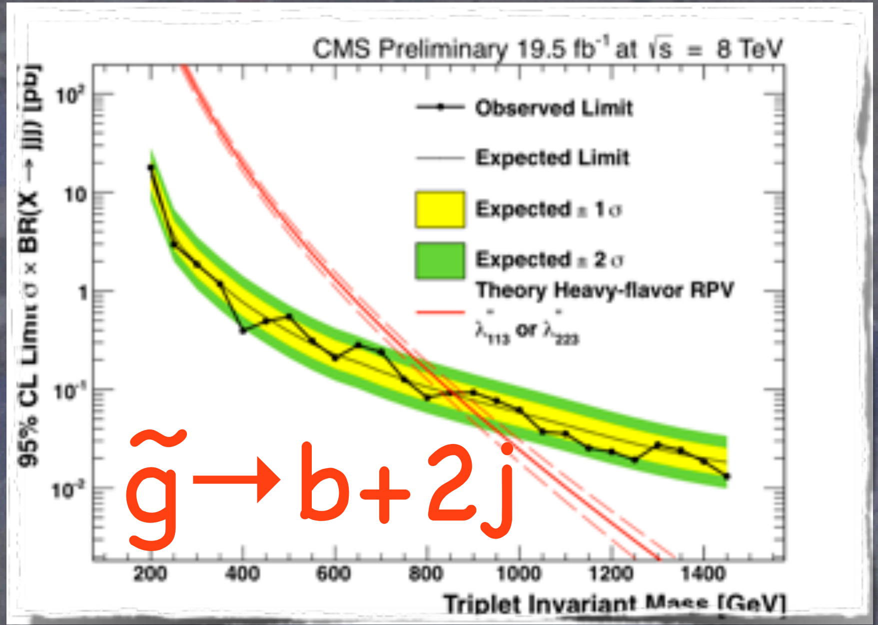


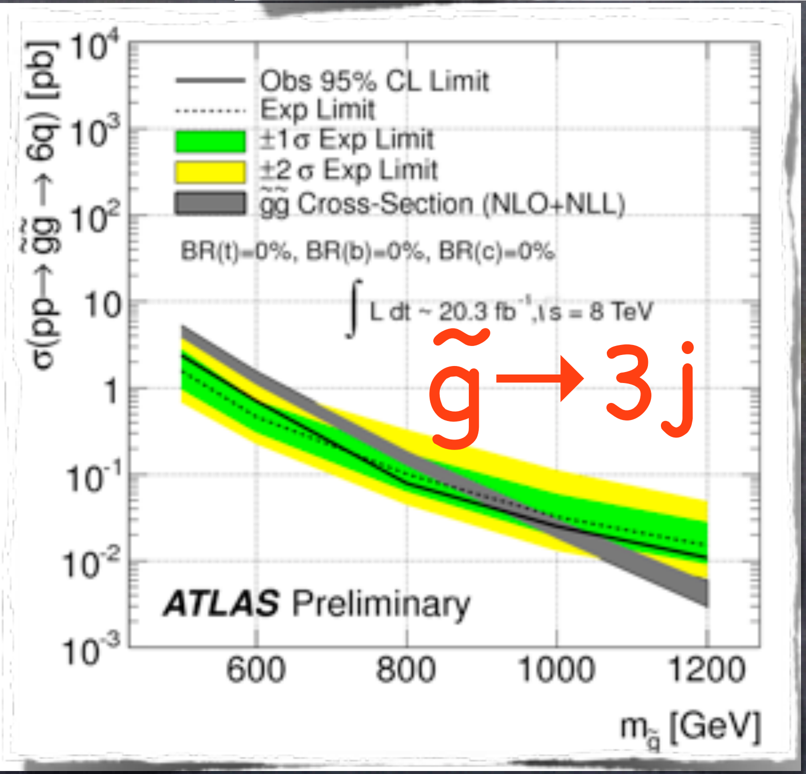
Data/Bkg vs pT cut on the jets

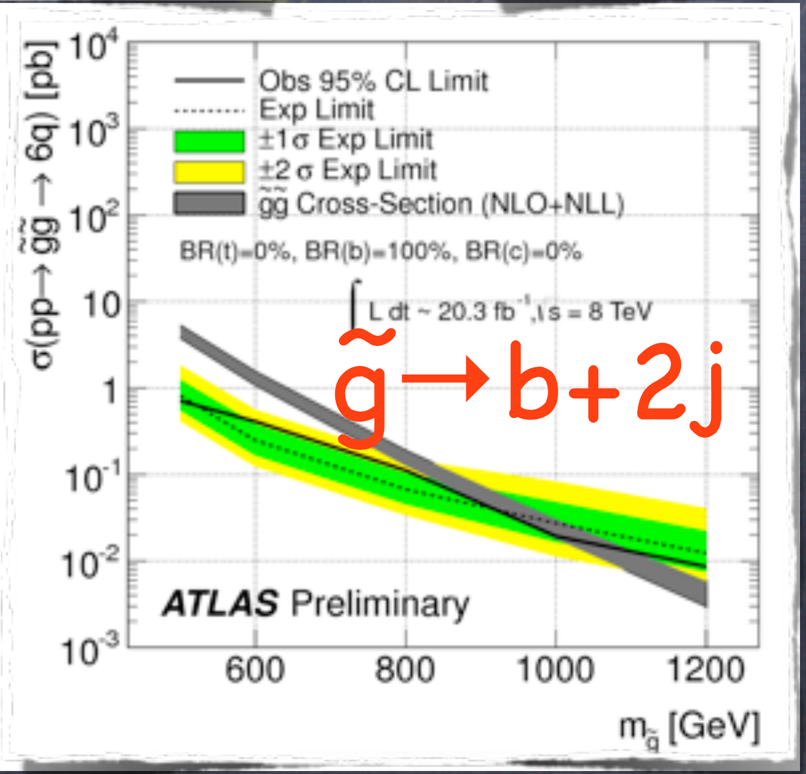
Multijet Search for Hadronic RPV

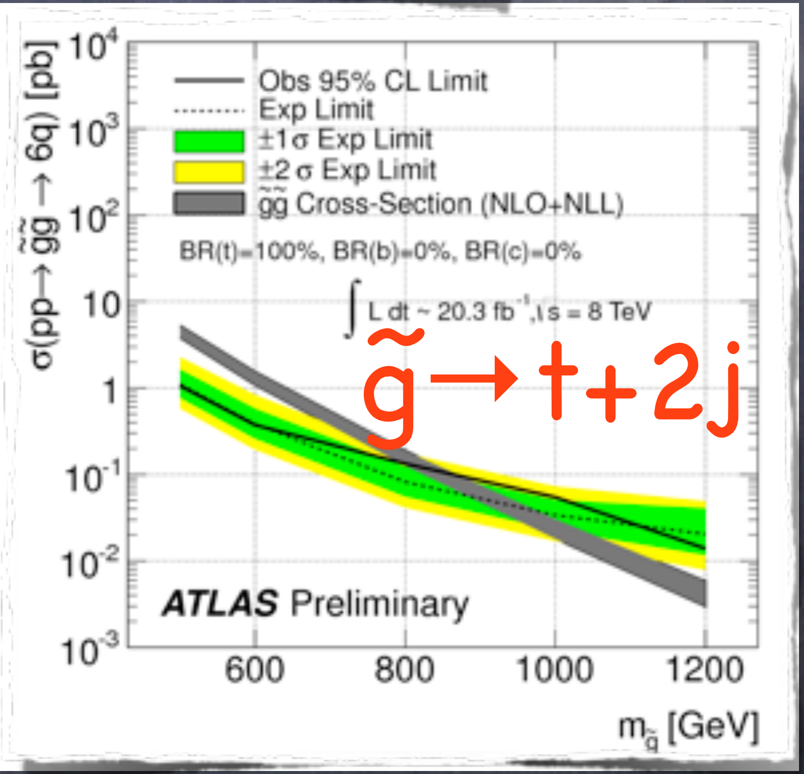
- Gluino masses around 900 GeV probed
- Analyses sensitive up to low gluino masses (~200/400 GeV)





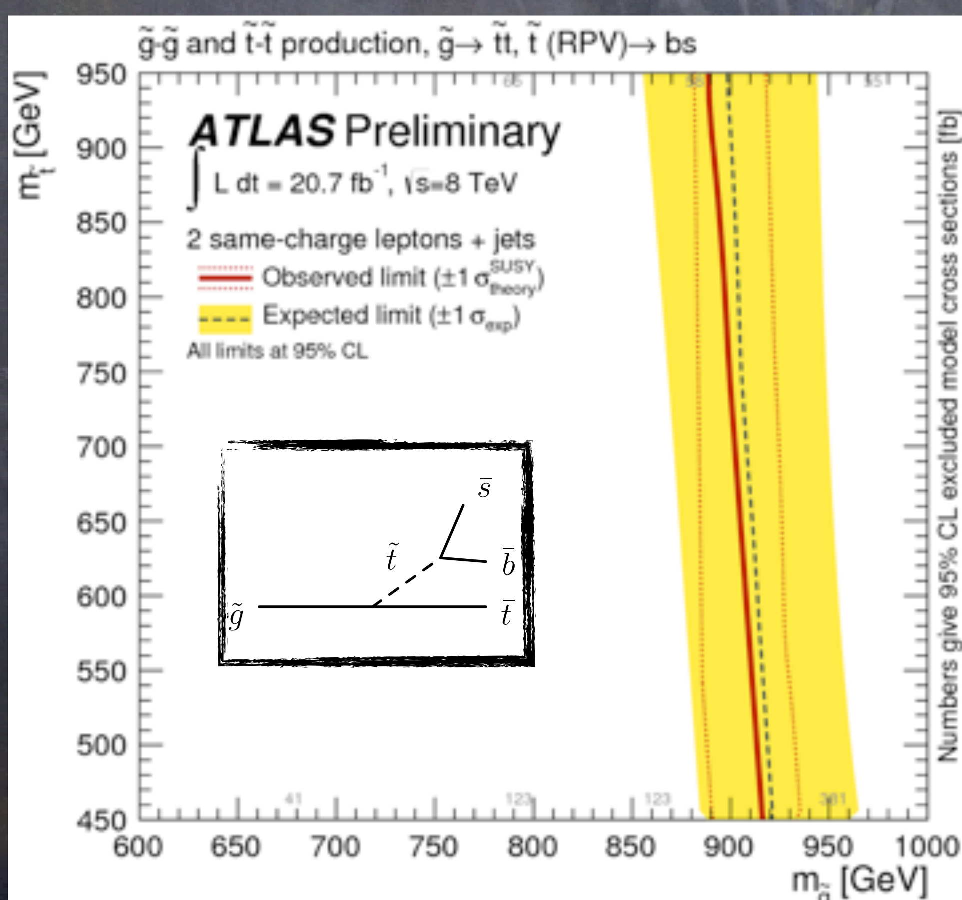


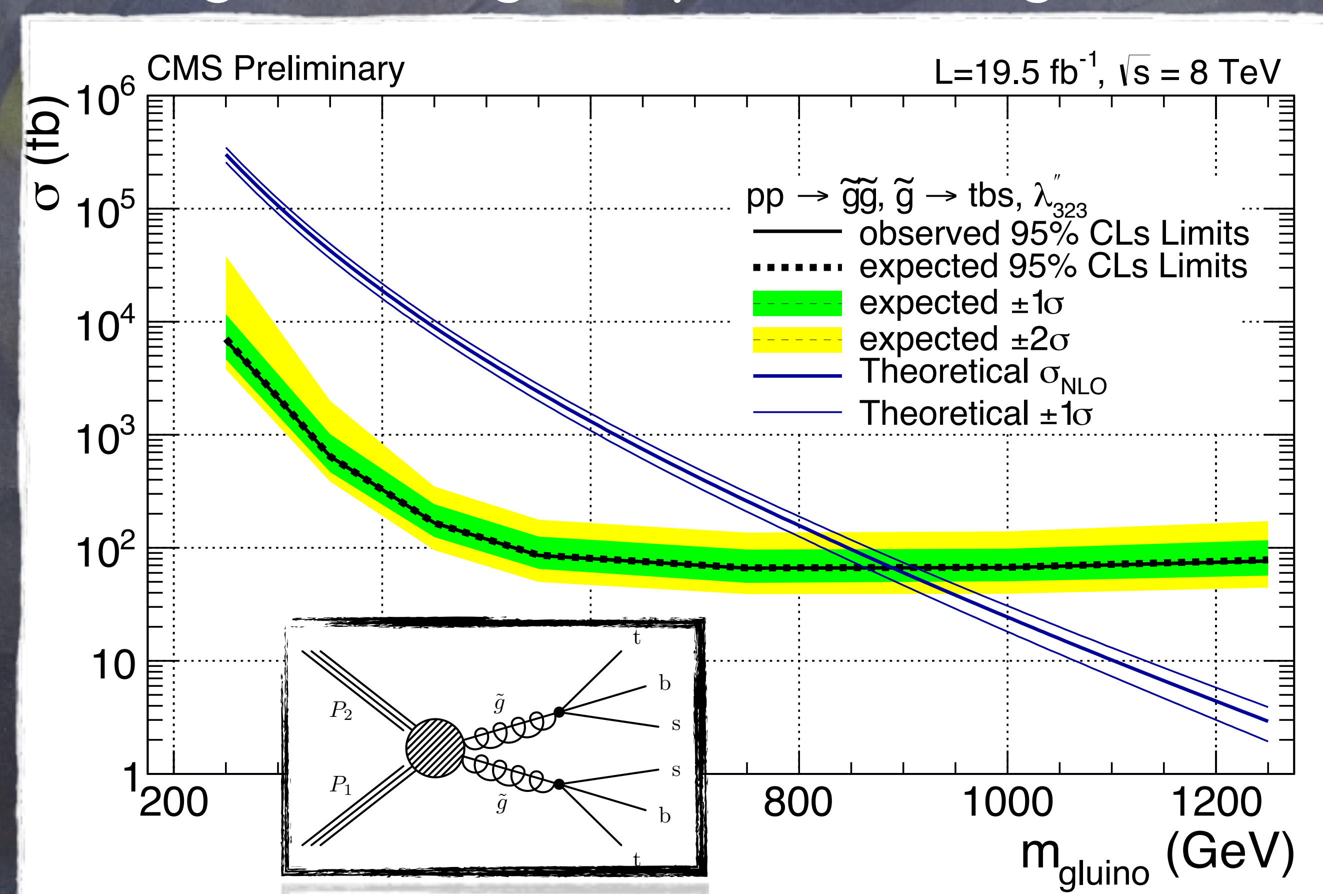




Gluinos in MFV SUSY

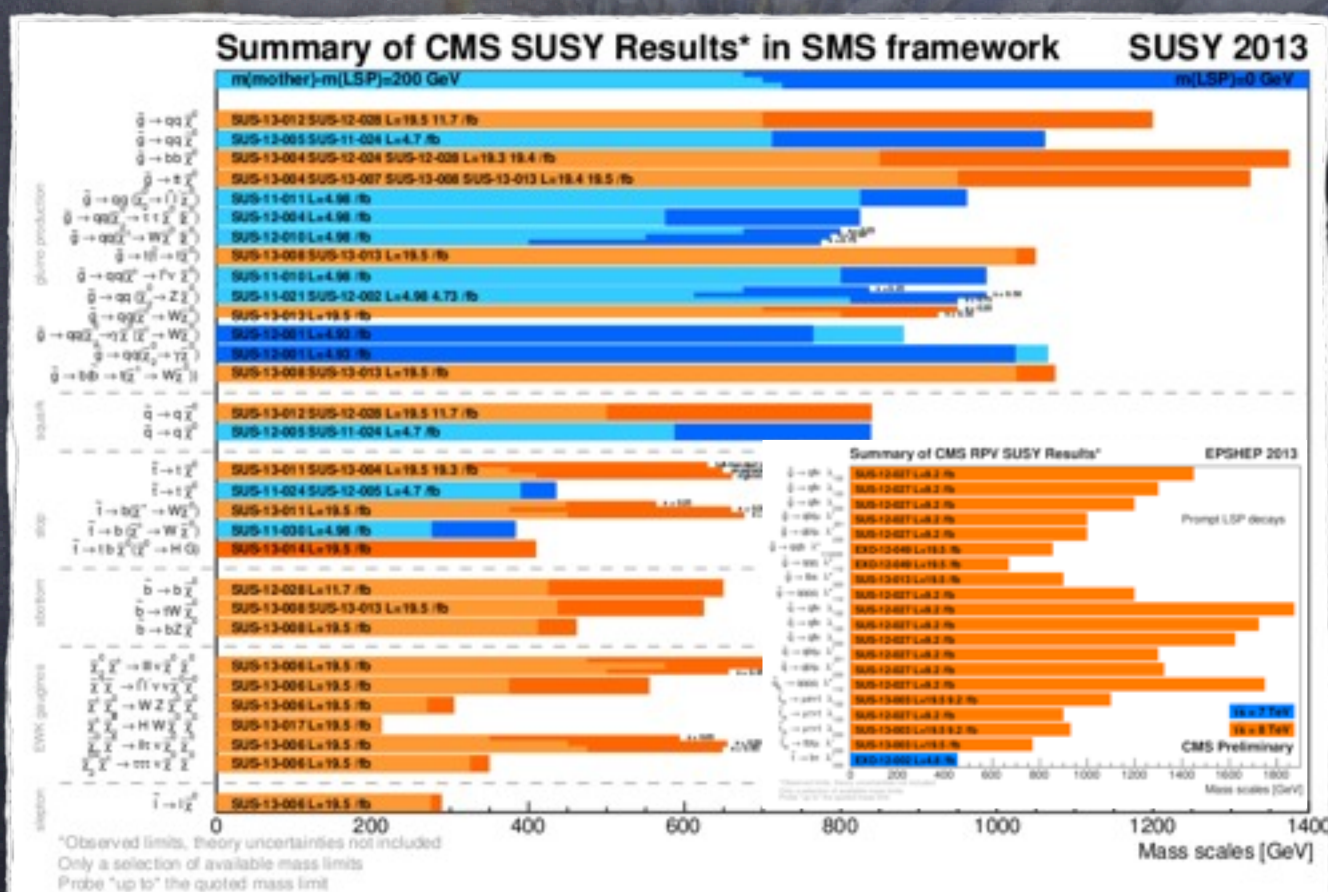
- Appealing RPV scenario: the CKM couplings save us from proton decay
- Gluinos are pair produced and decay to tt+2bjet+2j
- SS dilepton (if gluino is a Majorana particle) excludes gluinos lighter than ~900 GeV
- As for natural SUSY, the lack of a gluino signal puts stringent bounds

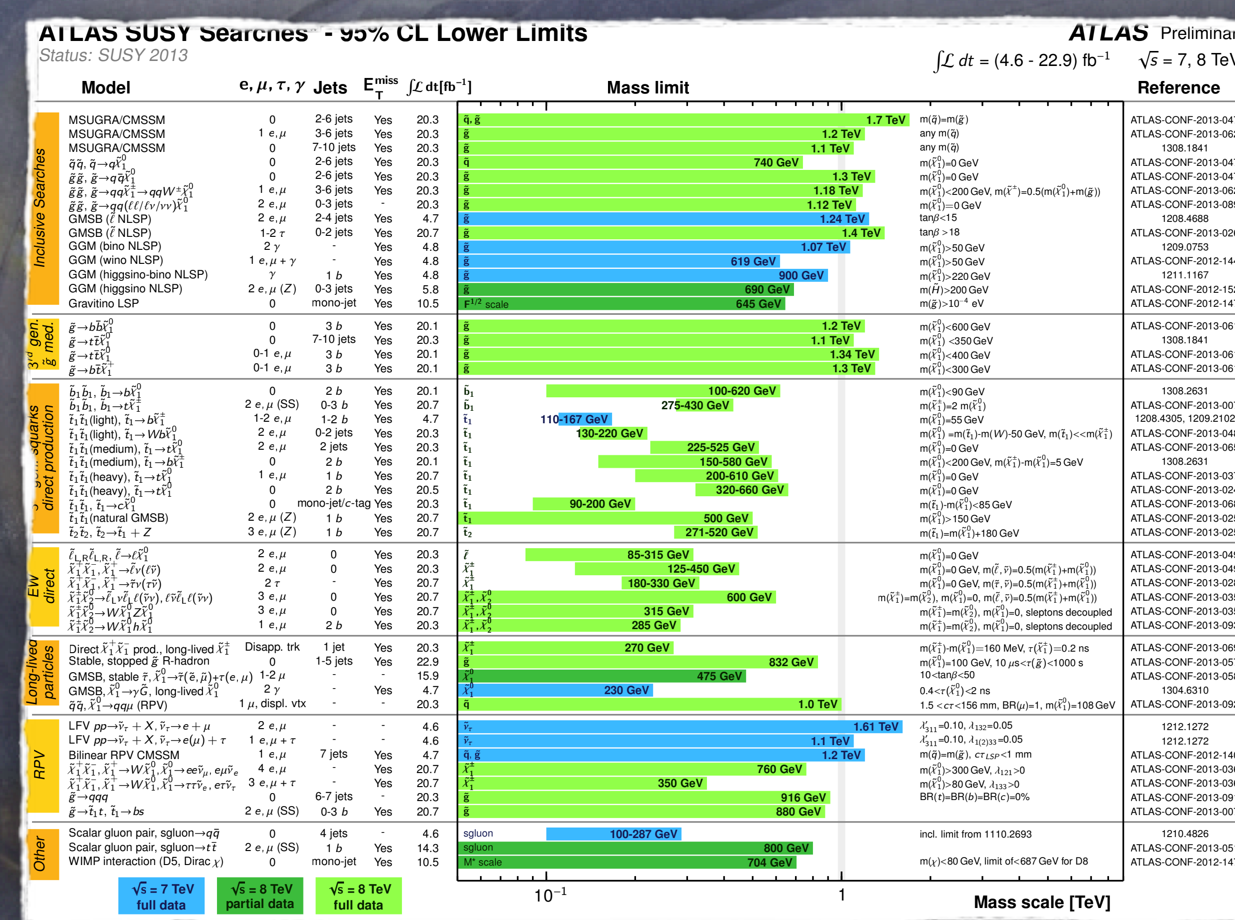




And Much More

- Many other topics I could not cover (for lack of time)
  - search for 1st/2nd generation squarks (direct and gluino-mediated production)
  - leptonic RPV (mainly from SS dilepton and multilepton)
  - other searches for LLP
  - Search for GMSB susy in events with photons
  - Other exotic signatures: stopping gluinos, disappearing tracks, etc
  - ...





The Next Run

What Next?

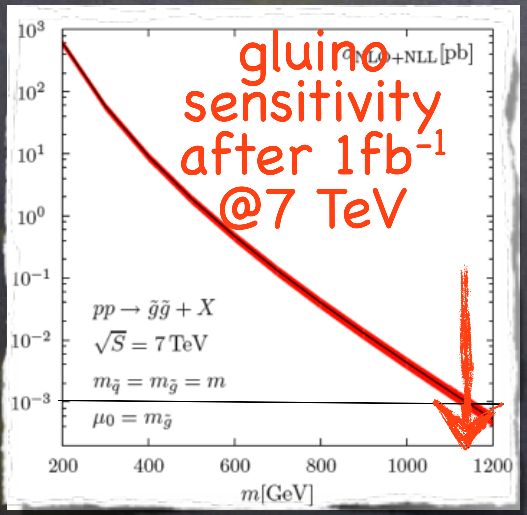
For the restart

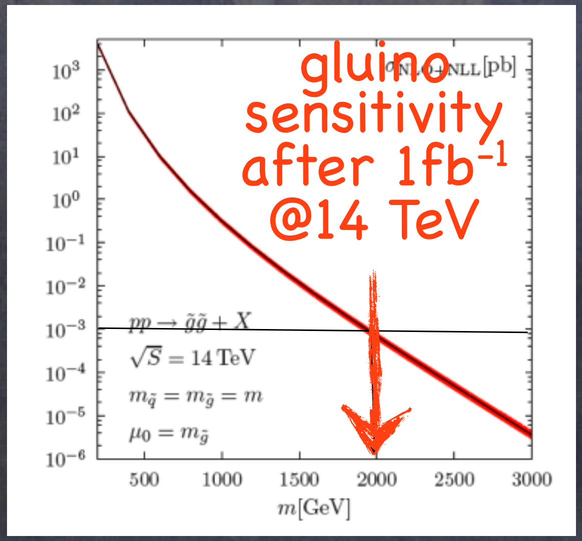
We will most likely have a rump-up as fast as for Run-I (experienced gained operating the LHC and the detectors)

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

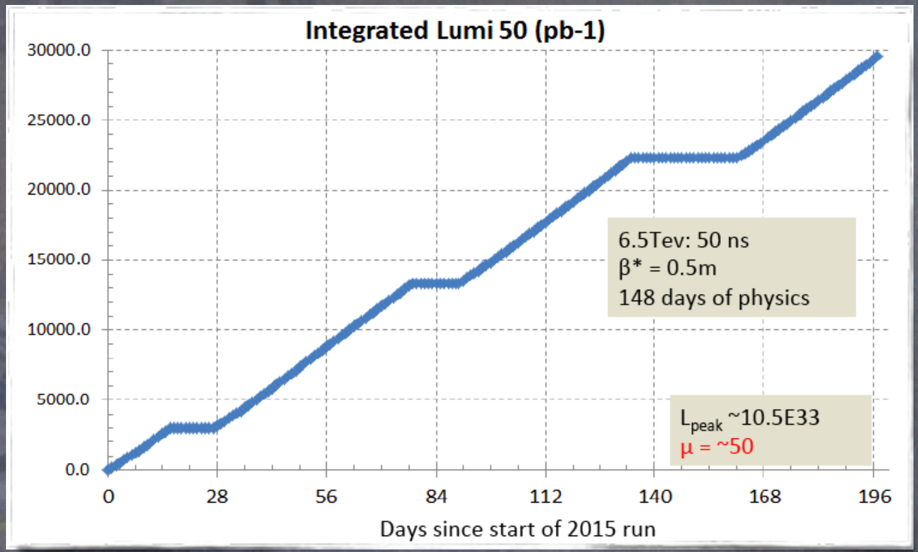
Cumulating more data on the longer term we will also improve the intermediate mass range

We will get to the sensitivity of Run-I after the first 1-3 fb^{-1}

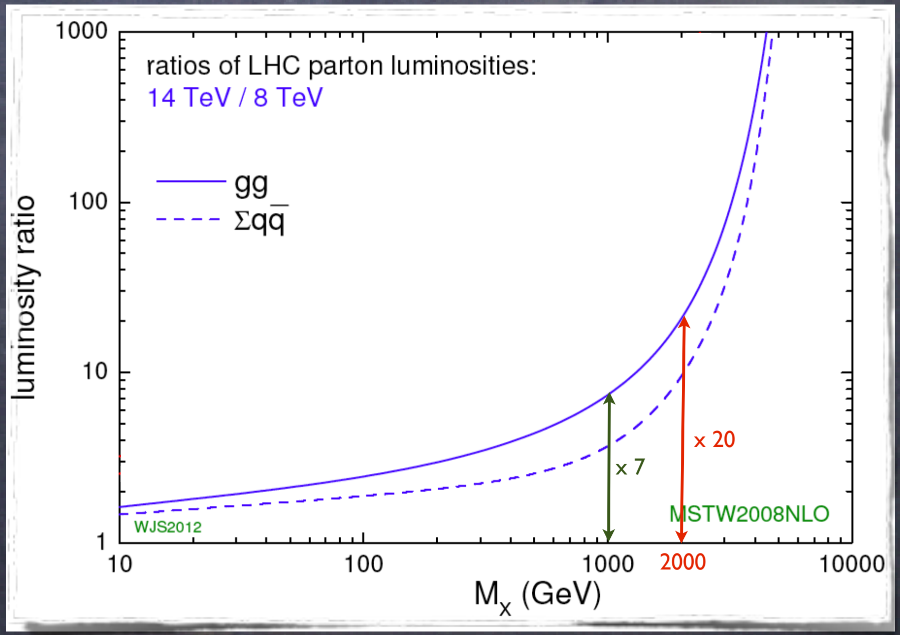




estimated performances for 50 ns collisions@13 TeV



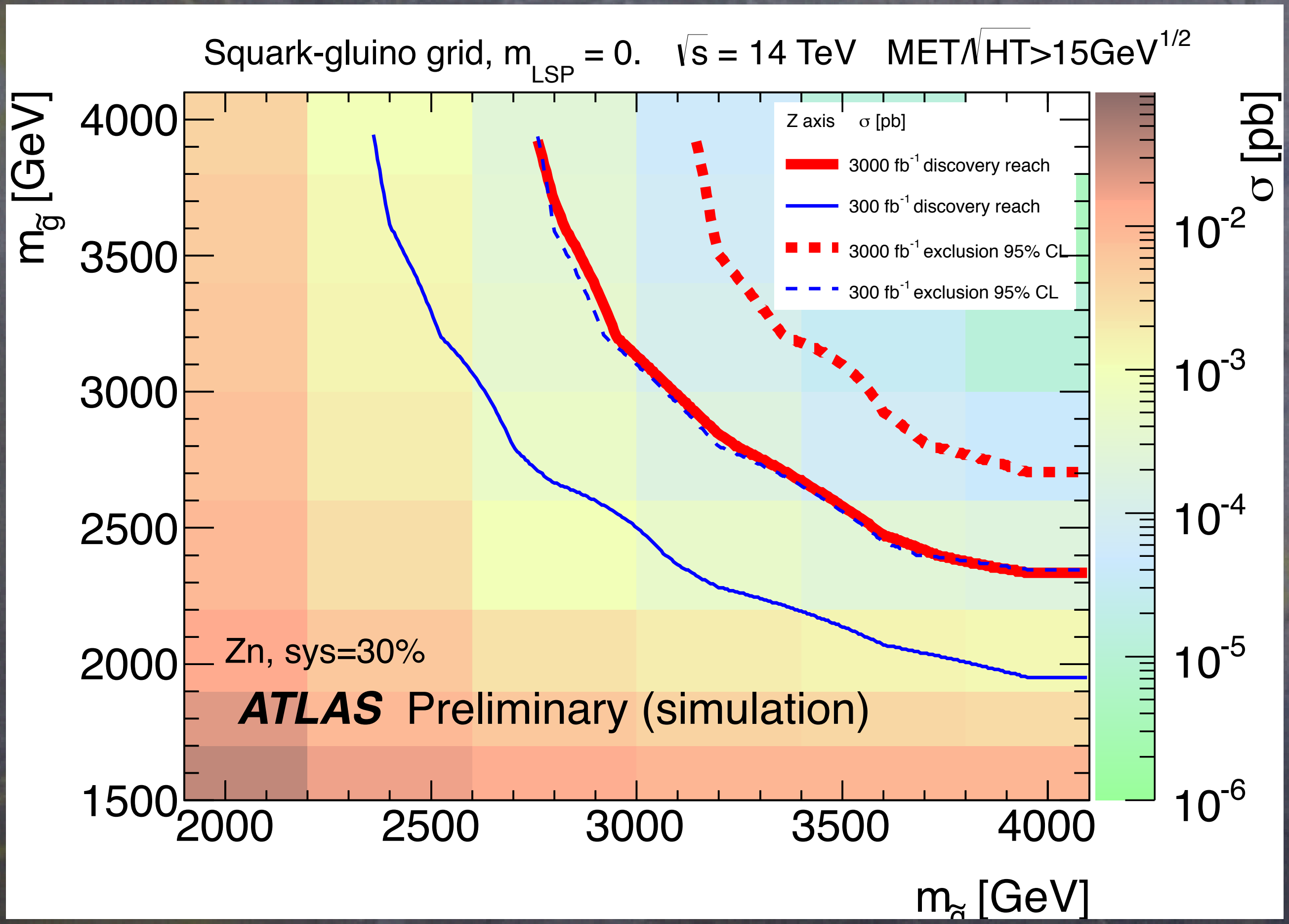
The gain in energy is particularly pronounced for heavy objects

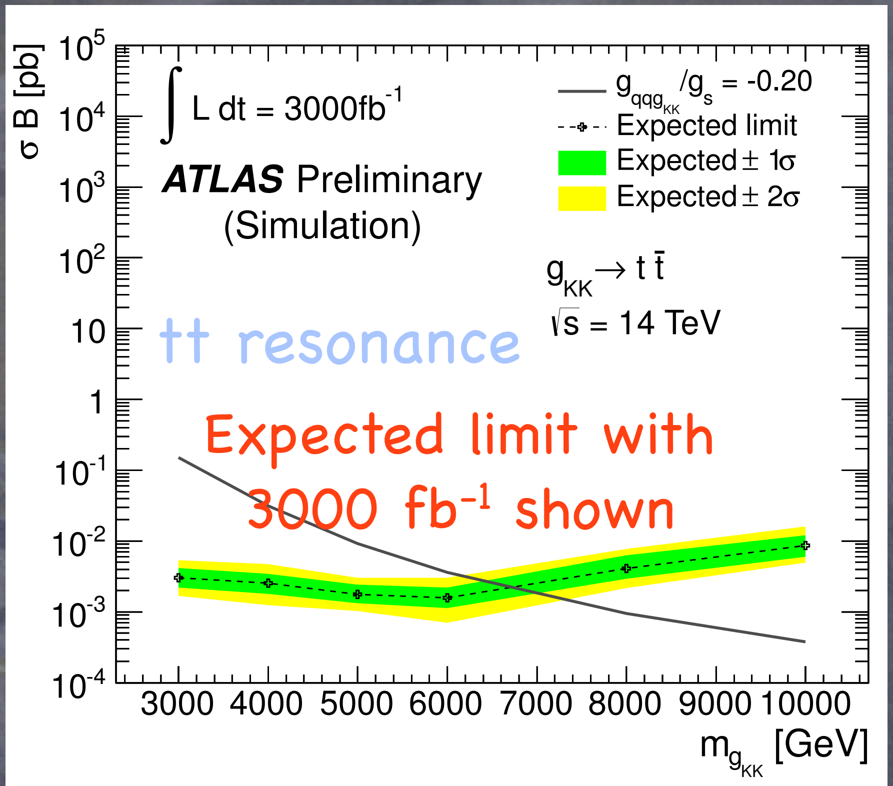


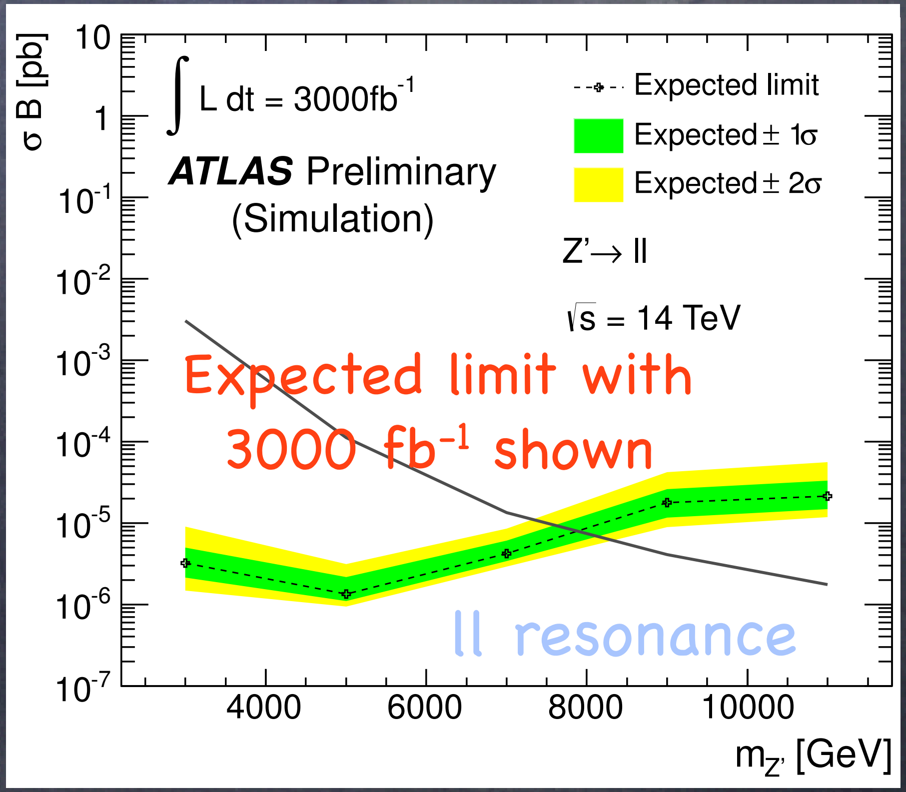
G. Rolandi BrunoFest@Berkeley

Snowmass Extrapolations

- Dominated by physics backgrounds Z(νν)+jets and top pairs
- Large missing energy requirement robust against pileup



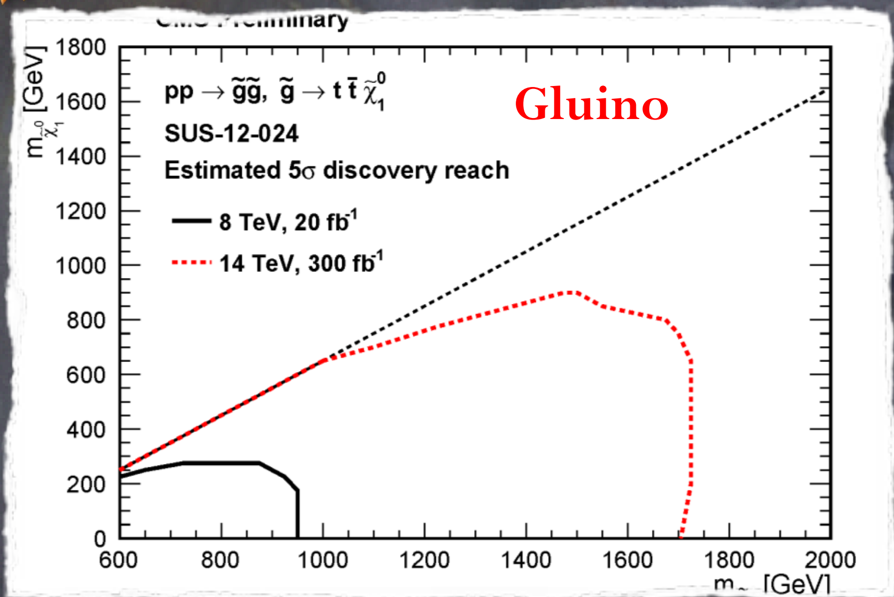


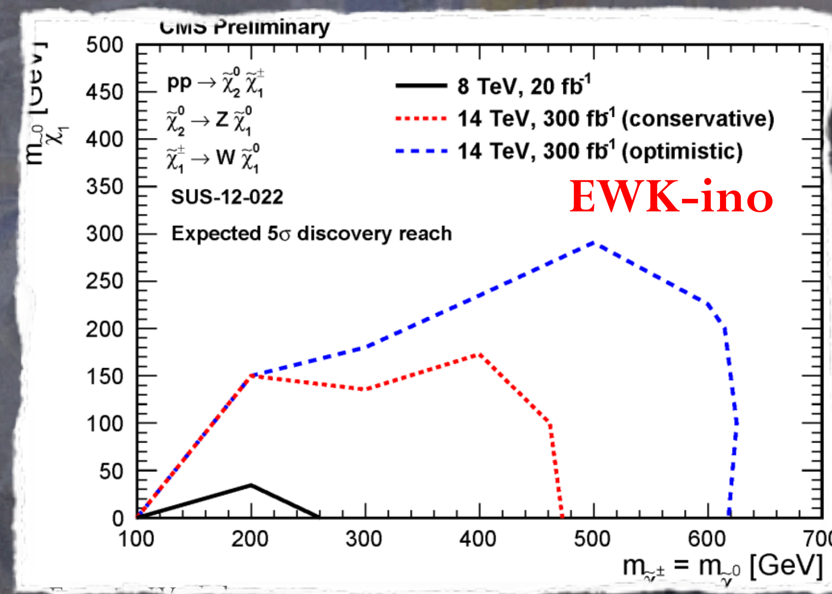


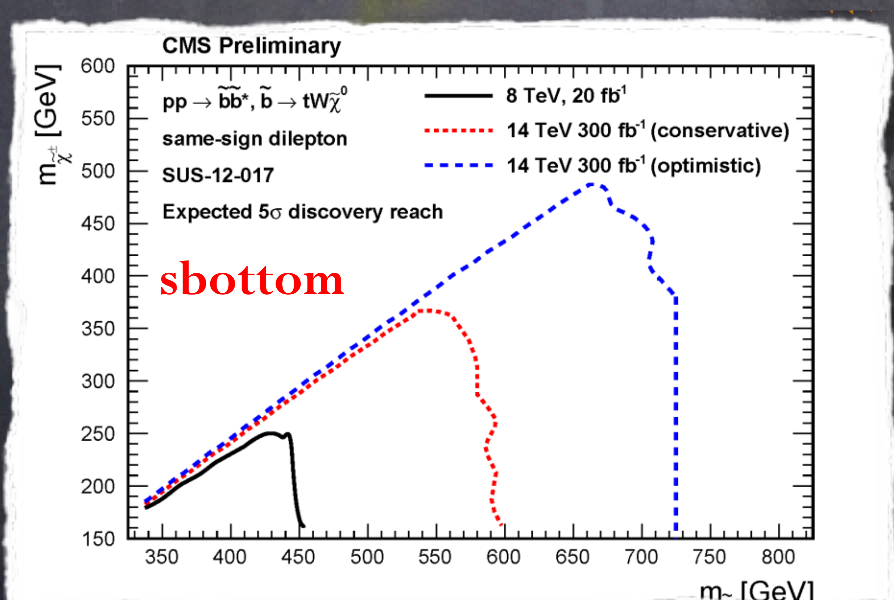
Similar extrapolations from CMS

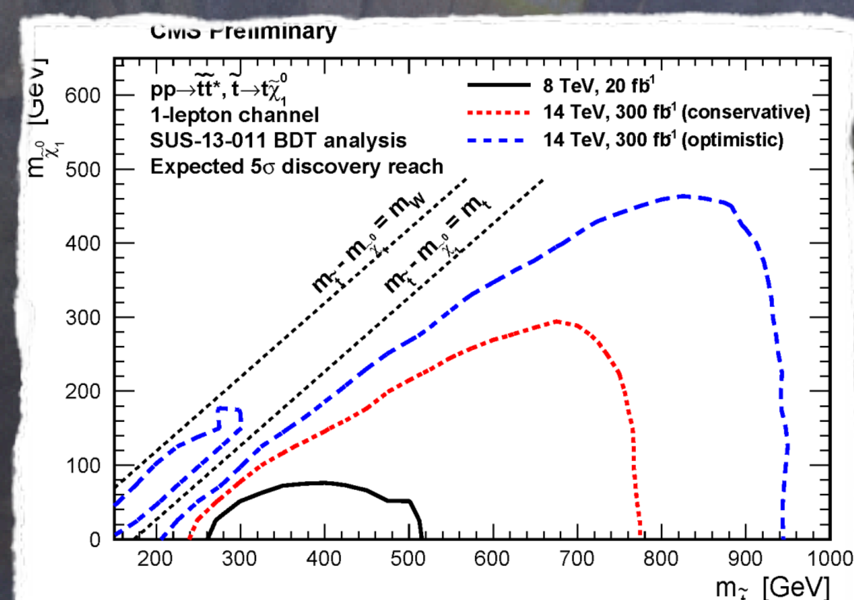
Snowmass Extrapolations

- 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 1.7 TeV
- Sbottom: ~600 – 700 GeV
- EWK-ino: ~500 – 600 GeV

Similar extrapolations from ATLAS

Summary

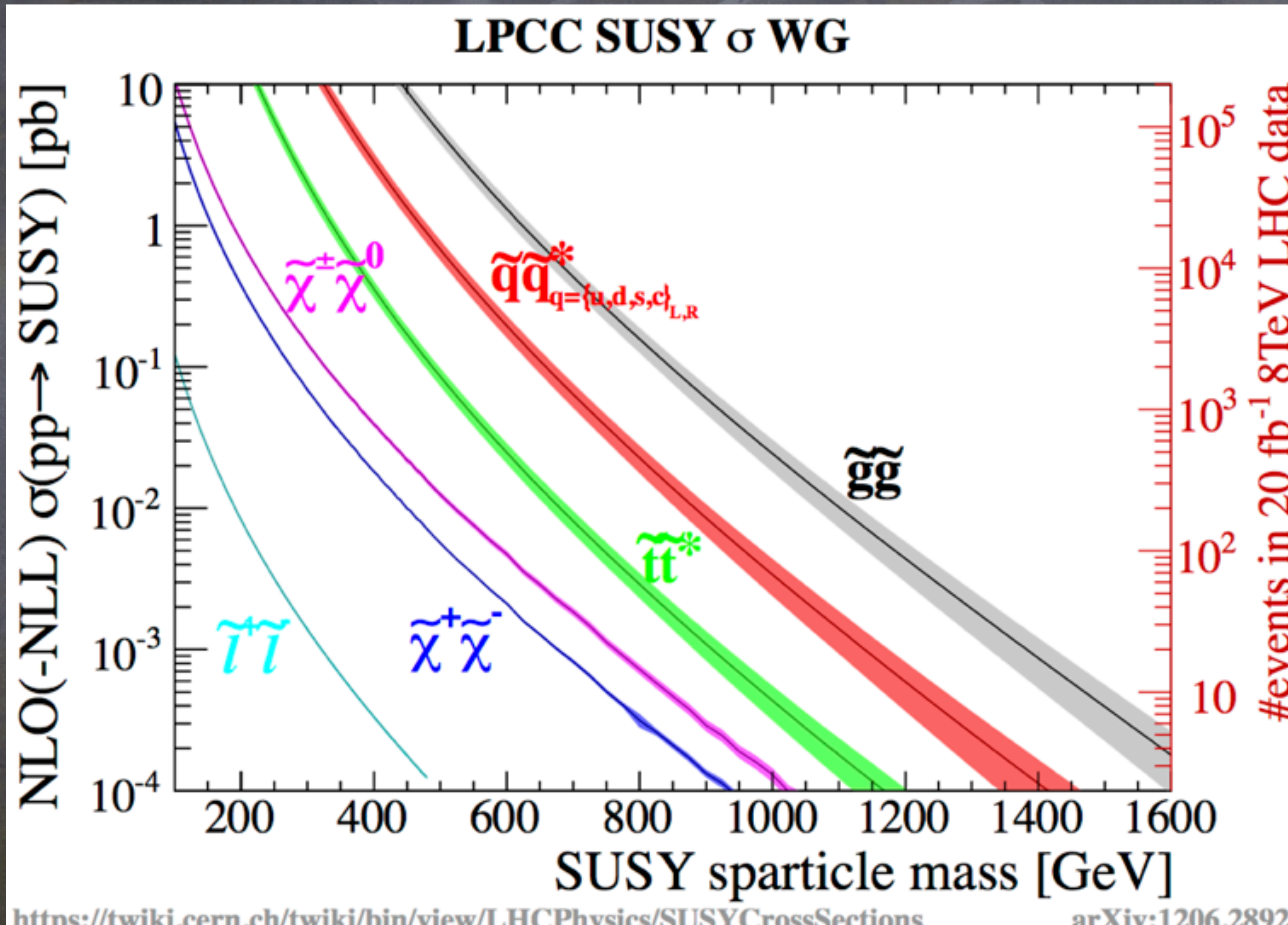
- No evidence of new physics so far
- We improved the techniques and we learned a lot. It was a good training exercise for the next run (and we got the Higgs discovery "for free")
- We are still looking at the 8 TeV data extending the searches to the unexplored (and more difficult) corners
- We will have 1 year to plan in advance the analysis of the first few fb^{-1} of ~13TeV 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/AtlasPublic/SupersymmetryPublicResults

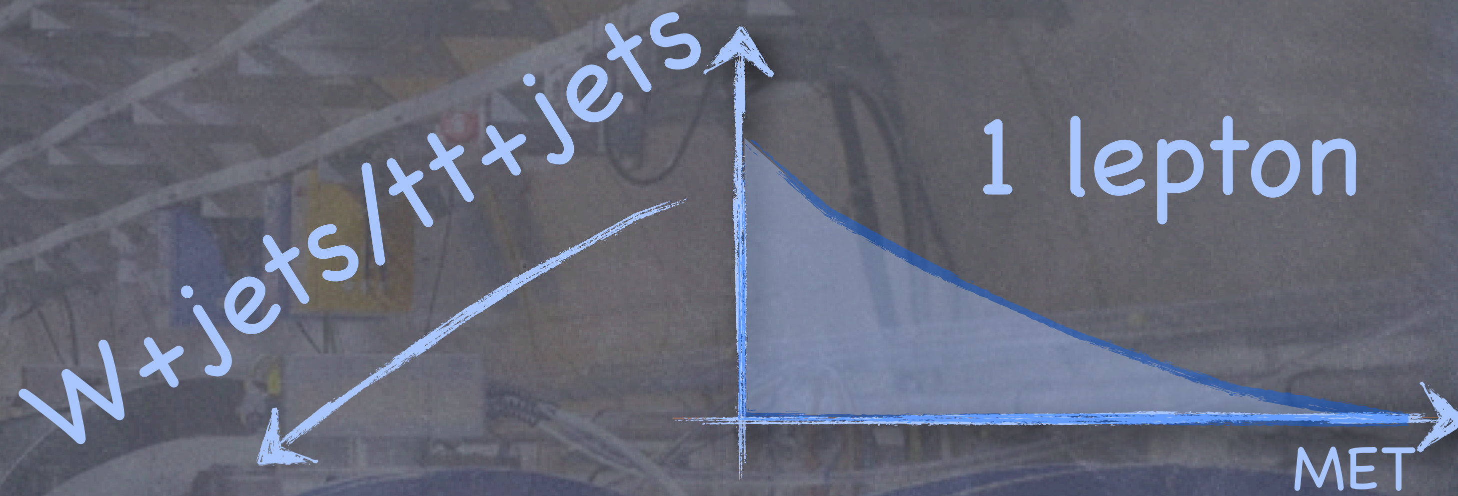
Backup

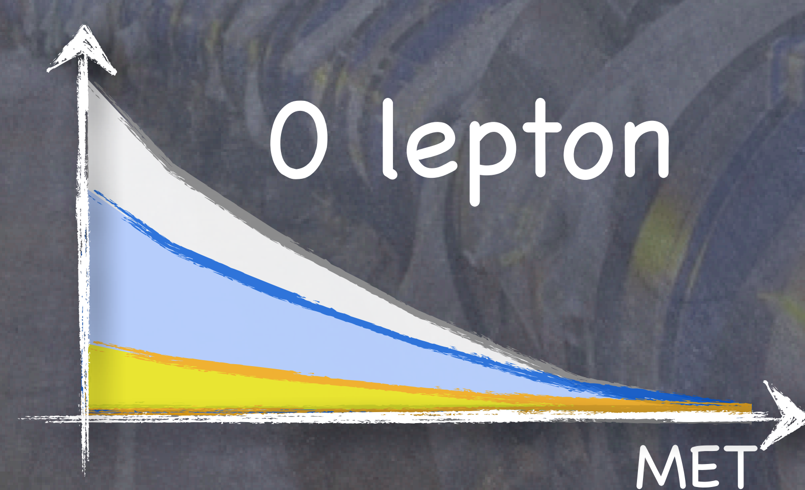
SUSY Cross Section

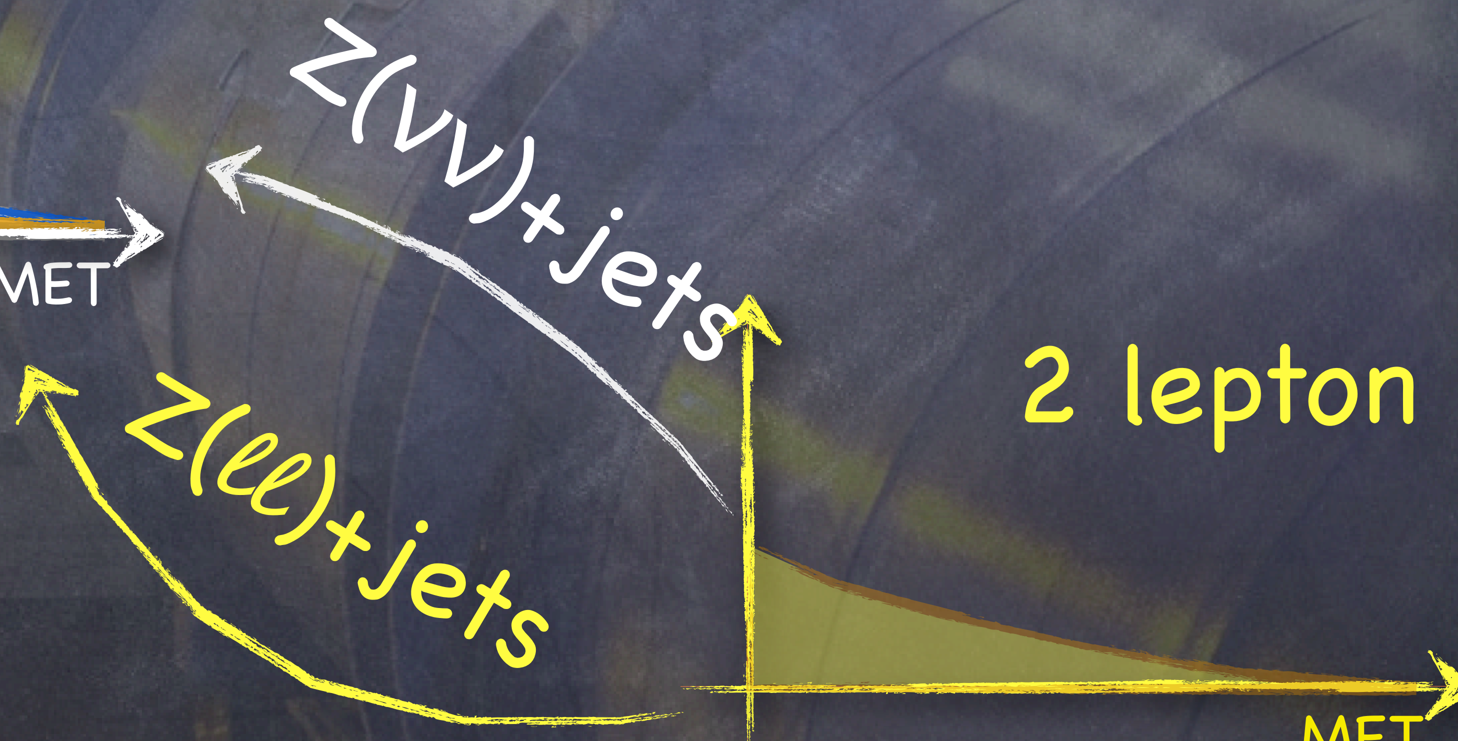


The Monojet Search

MET spectrum from data control samples and MC scale factors

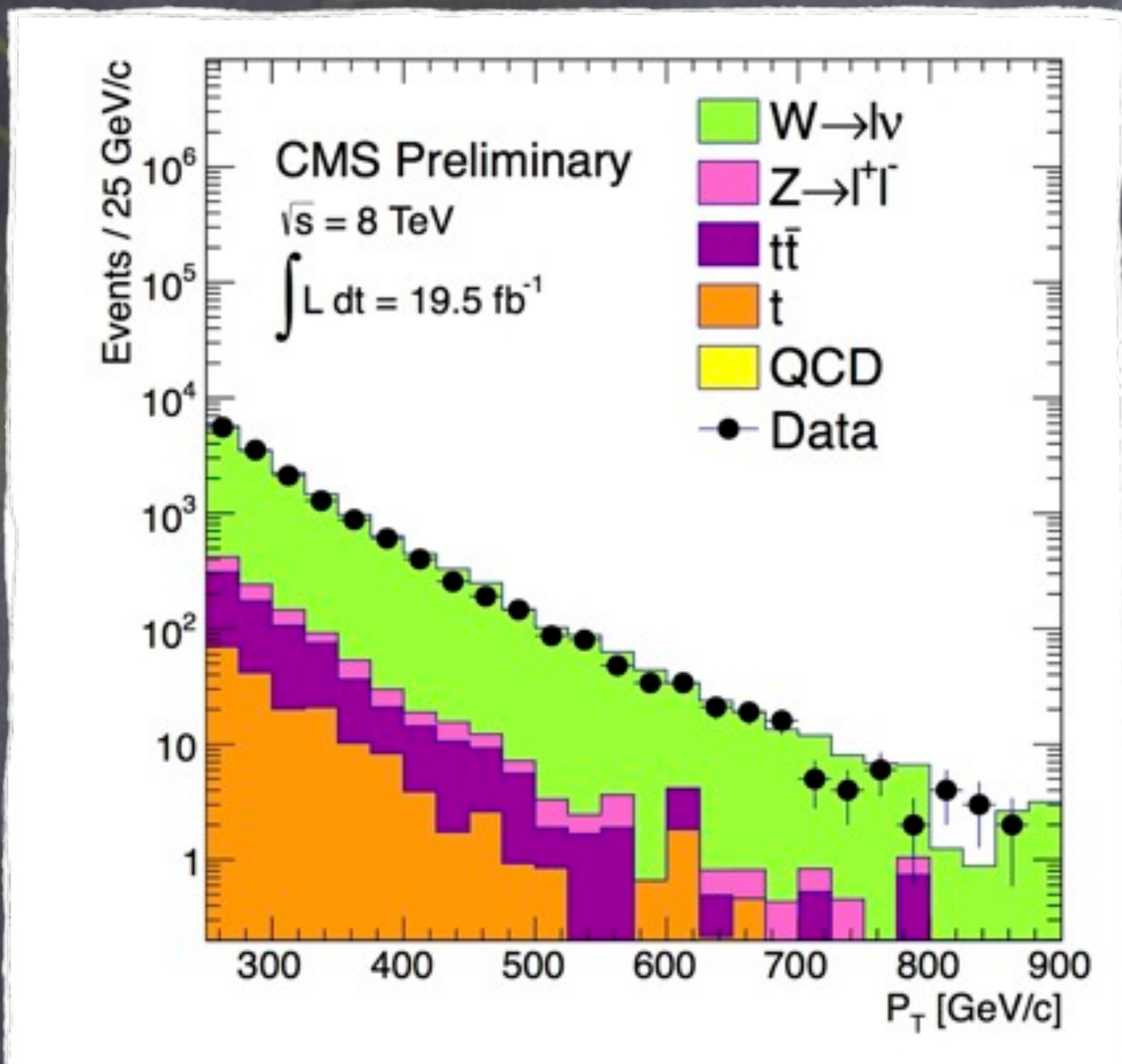


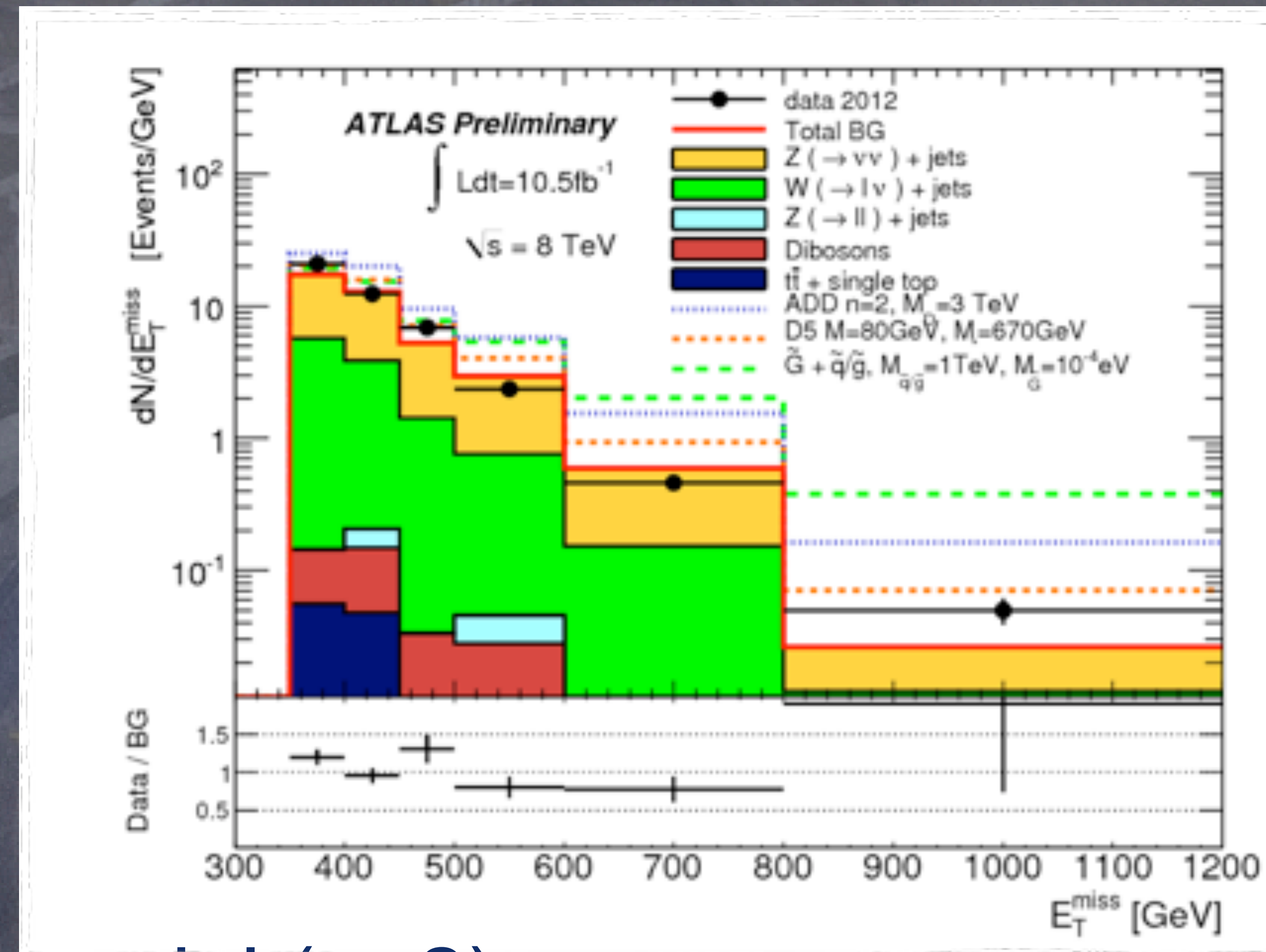




No need to different kinematic cuts (eg mT) for bkg control samples (no signal contamination)

The Monojet Search



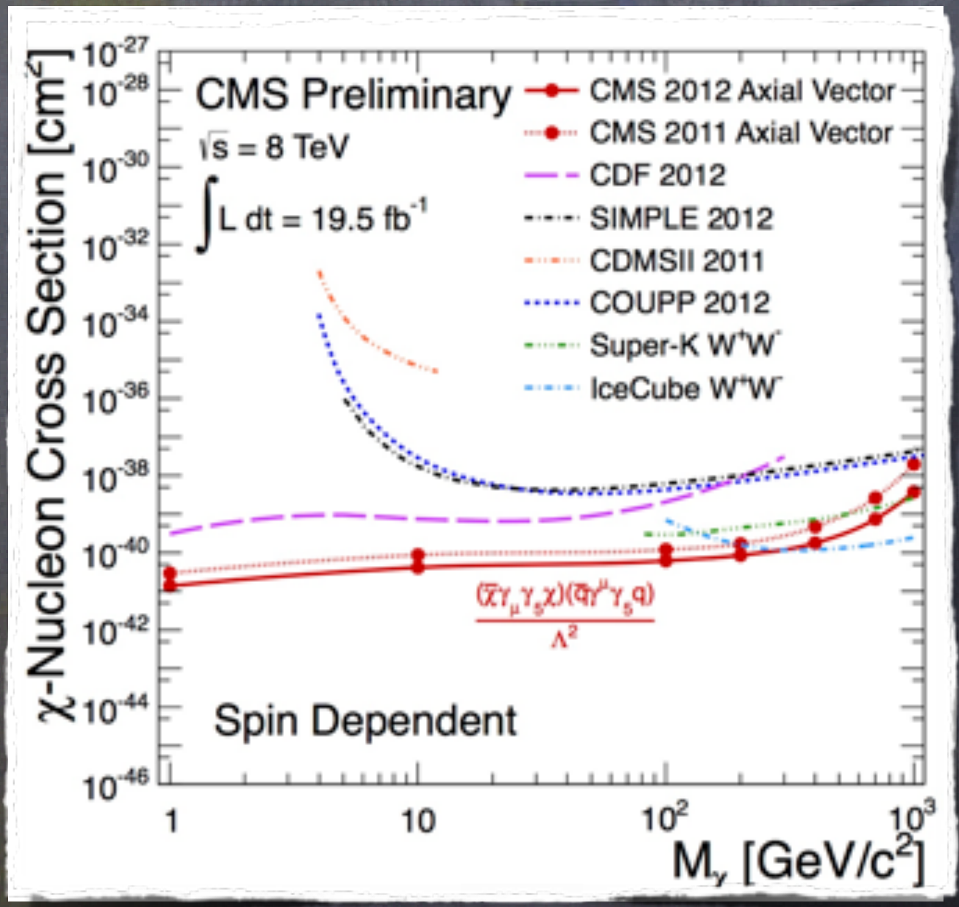


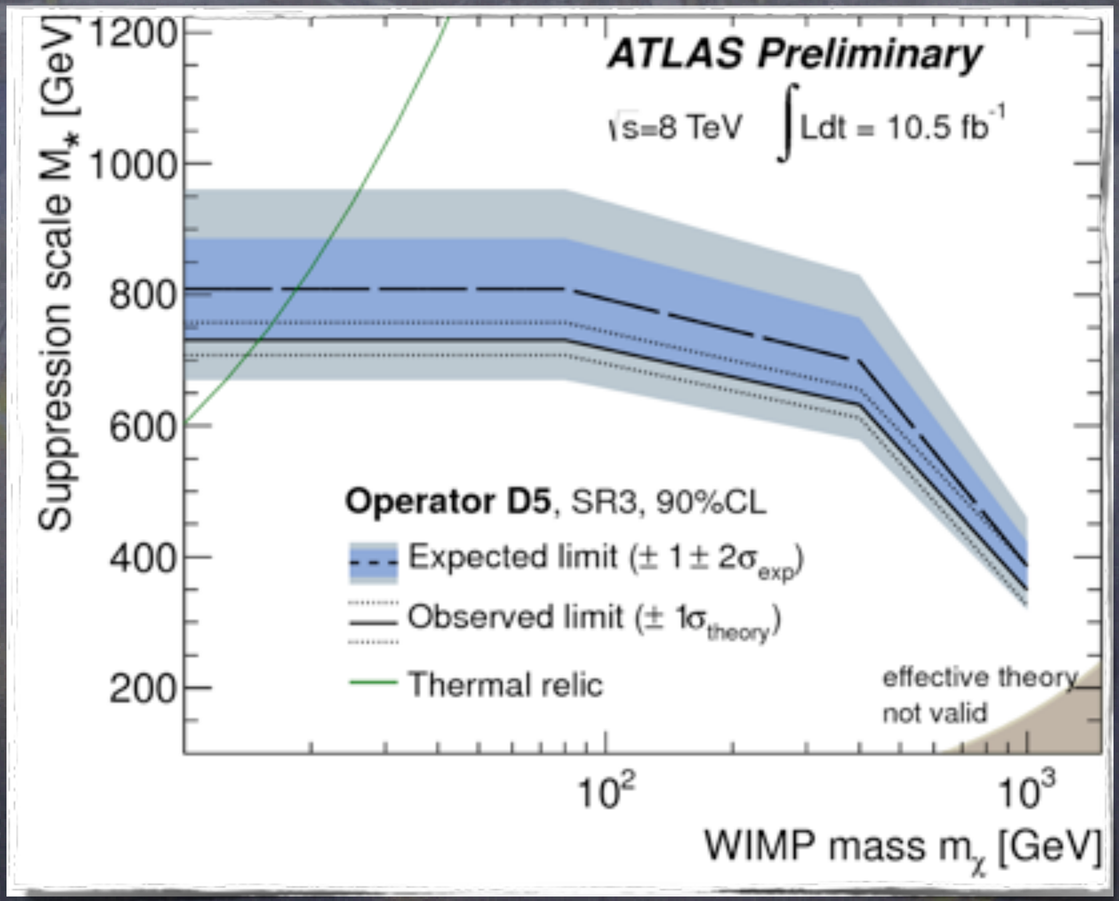
- Good control over the kinematic variables
- MC prediction OK
- Large sensitivity to NP on the MET tail
- No evidence for a deviation from SM

Limits from Monojet

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





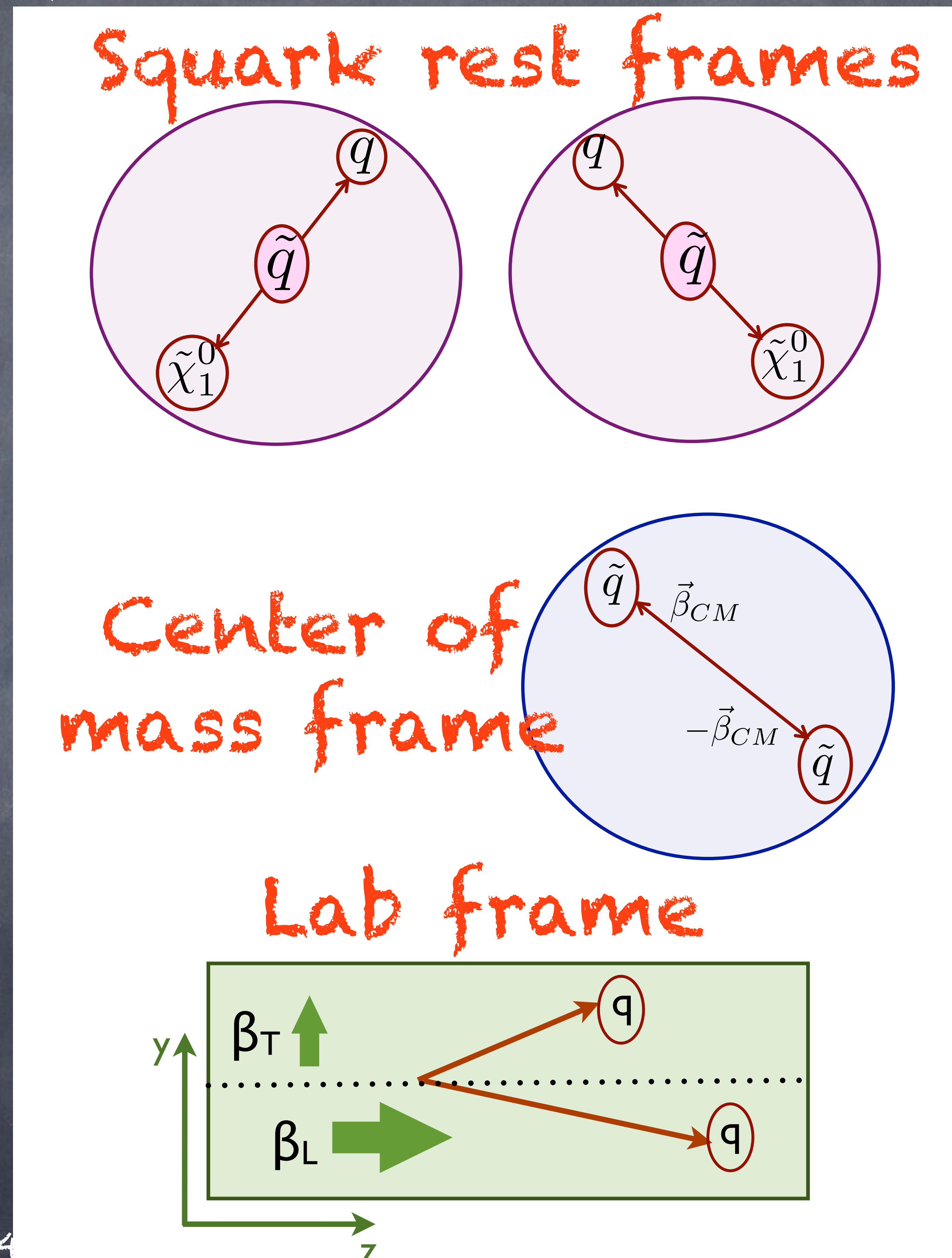
Also limits from ADD models (n=2): 4.2 TeV (ATLAS) ; 5 TeV (CMS)

The Razor

- The prototype process is squark-squark -> jj + 2 LSP
- If we could put the squarks in their rest frames, we would see two jest with same |p|

$$M_\Delta \equiv \frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2}{M_{\tilde{q}}} = 2M_{\tilde{\chi}}\gamma_\Delta\beta_\Delta$$

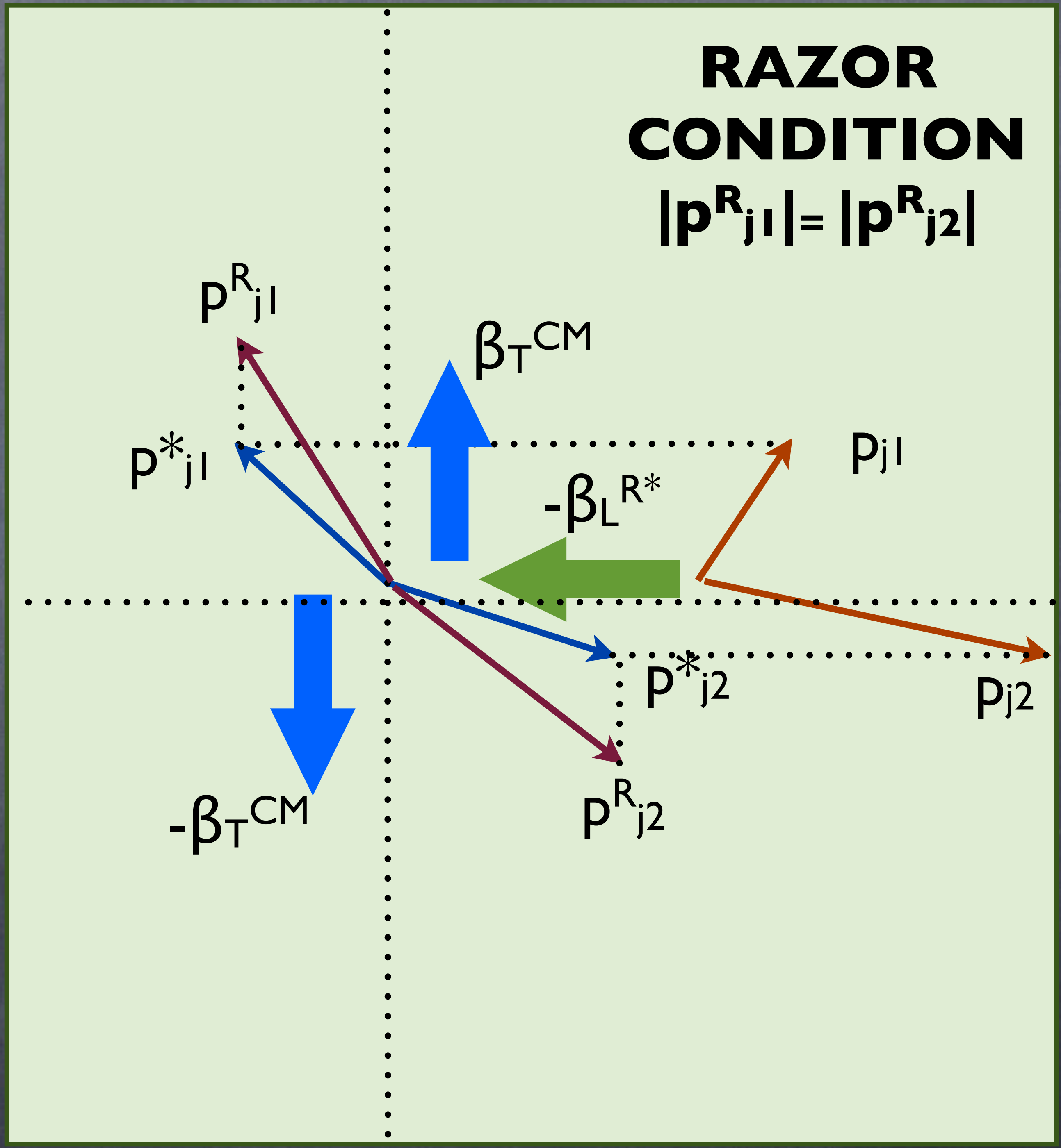
- We observe the jets in the lab frame, boosted by relative squark momentum and partons boost
- We would like to undo the two boosts



The Razor

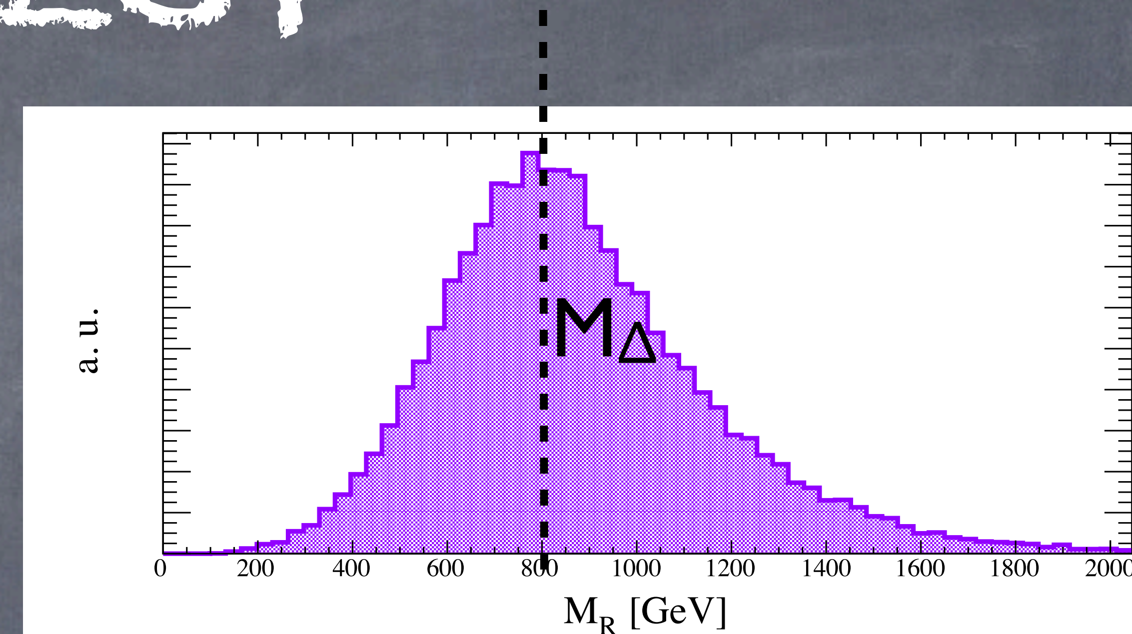
- In reality, the best we can do is to compensate the missing degrees of freedom with assumptions on the boost direction
  - The parton boost is forced to be longitudinal
  - The squark boost in the CM frame is assumed to be transverse
- We require that the two jets have the same momentum after the transformation, and we solve for the boost
- The transformed momentum defines the M_R variable

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$



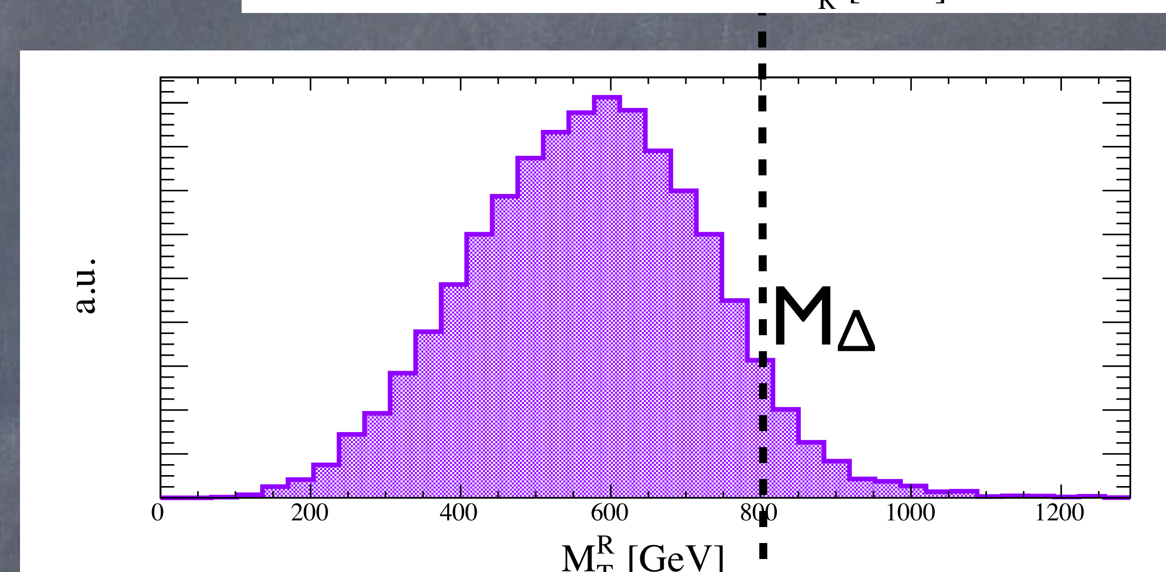
The Razor

- M_R is boost invariant, even if defined from 3D momenta
- No information on the MET is used
- The peak of the M_R distribution provides an estimate of M_Δ



- M_Δ could be also estimated as "edge" of $M_T{}^R$

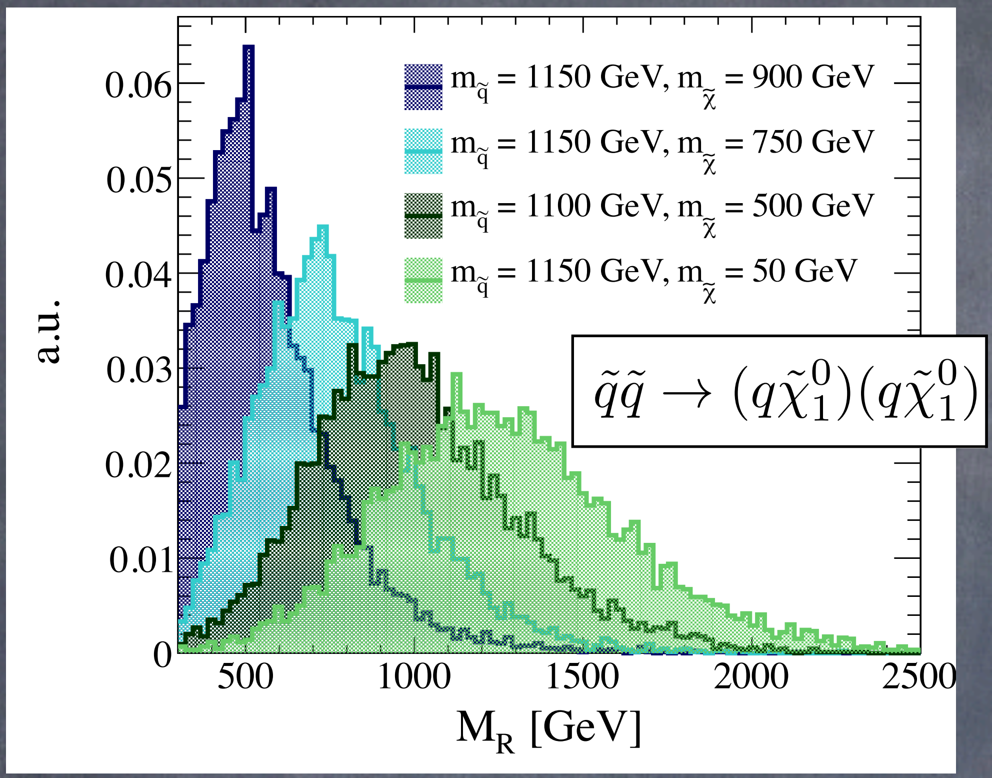
$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

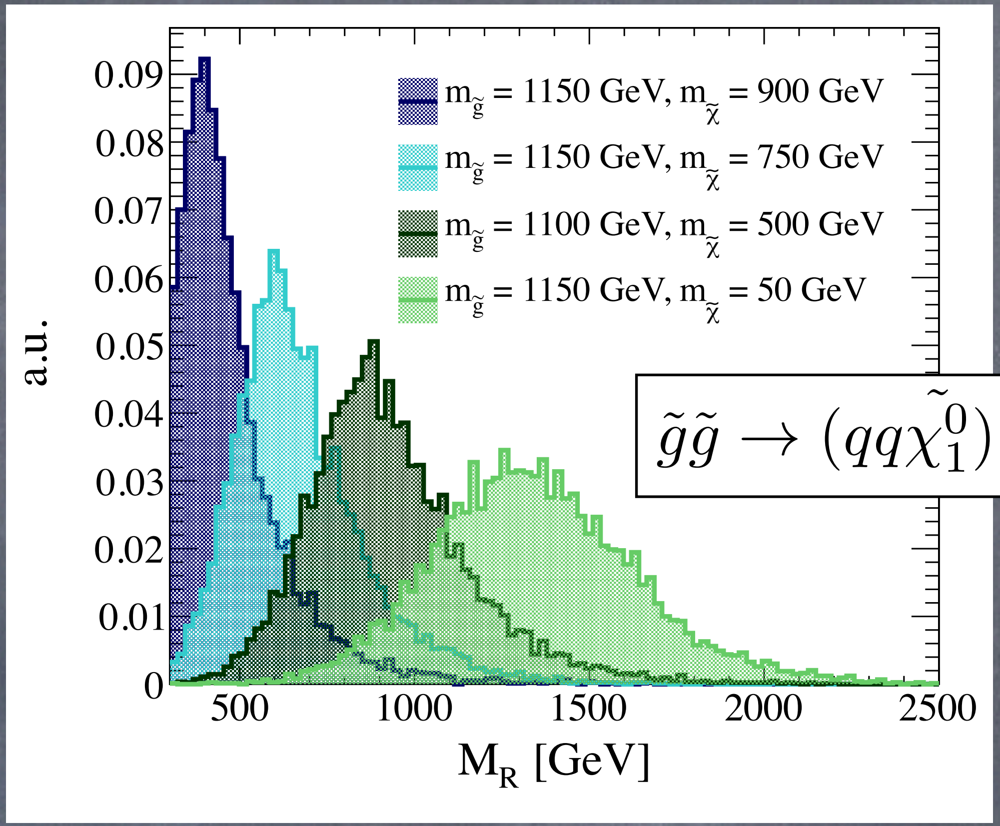


- $M_T{}^R$ is defined using transverse quantities and it is MET-related
- The Razor (aka R) is defined as the ratio of the two variables

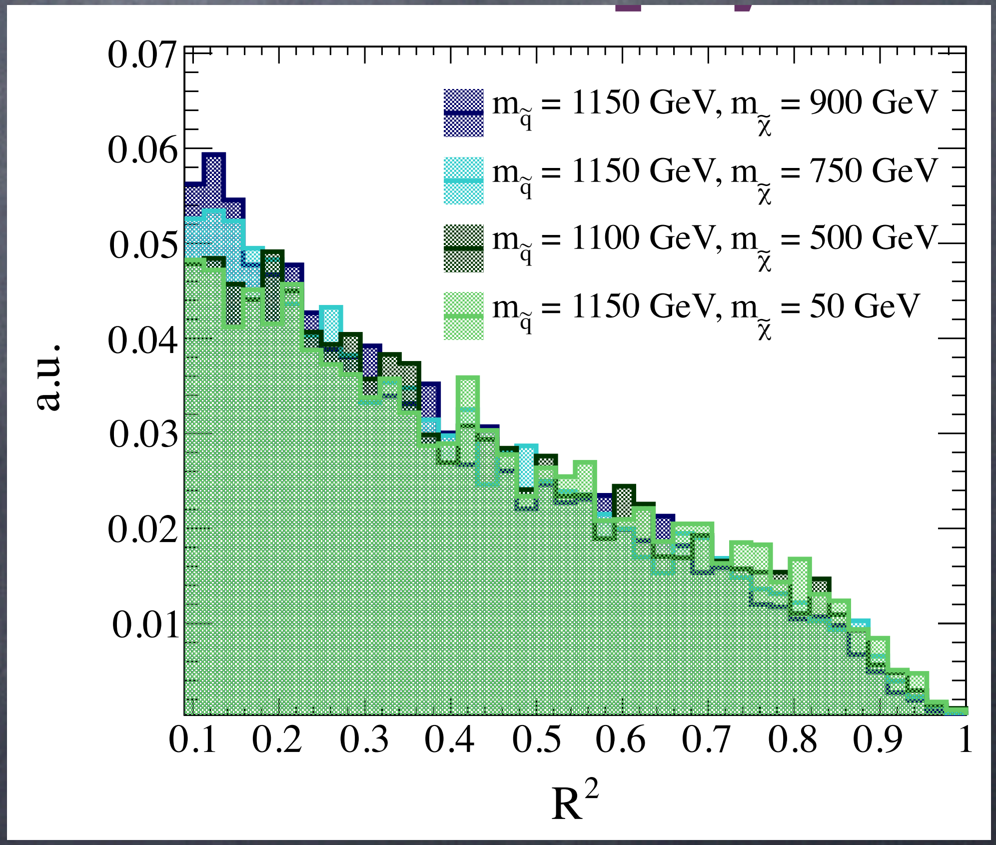
$$R \equiv \frac{M_T^R}{M_R}$$

SUSY Search As a Bump Hunting





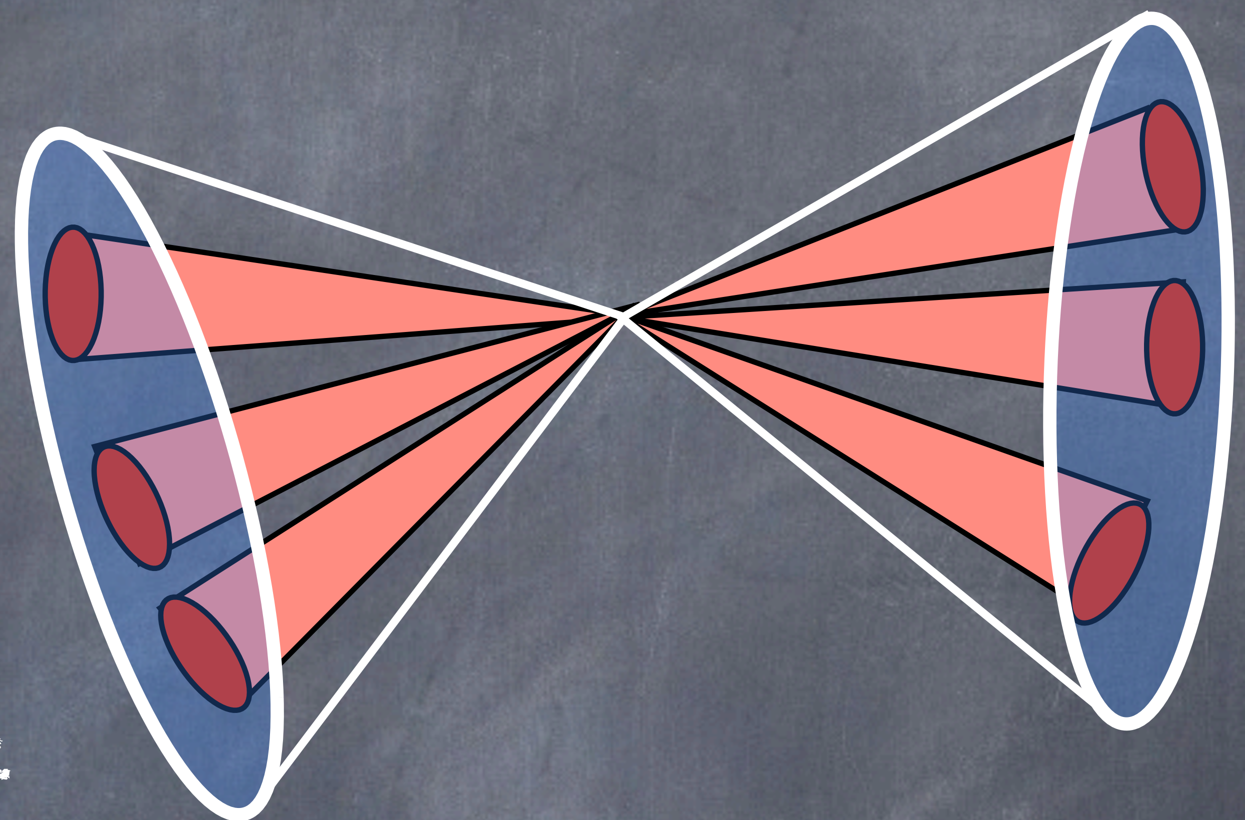
- Peaking signal at $M_R \sim M_\Delta$ (discovery and characterization)
- R^2 is determined by the topology, but not changes too much vs particle masses



Megajets

We target a multijet +MET topology

We built a framework for dijet+MET decays



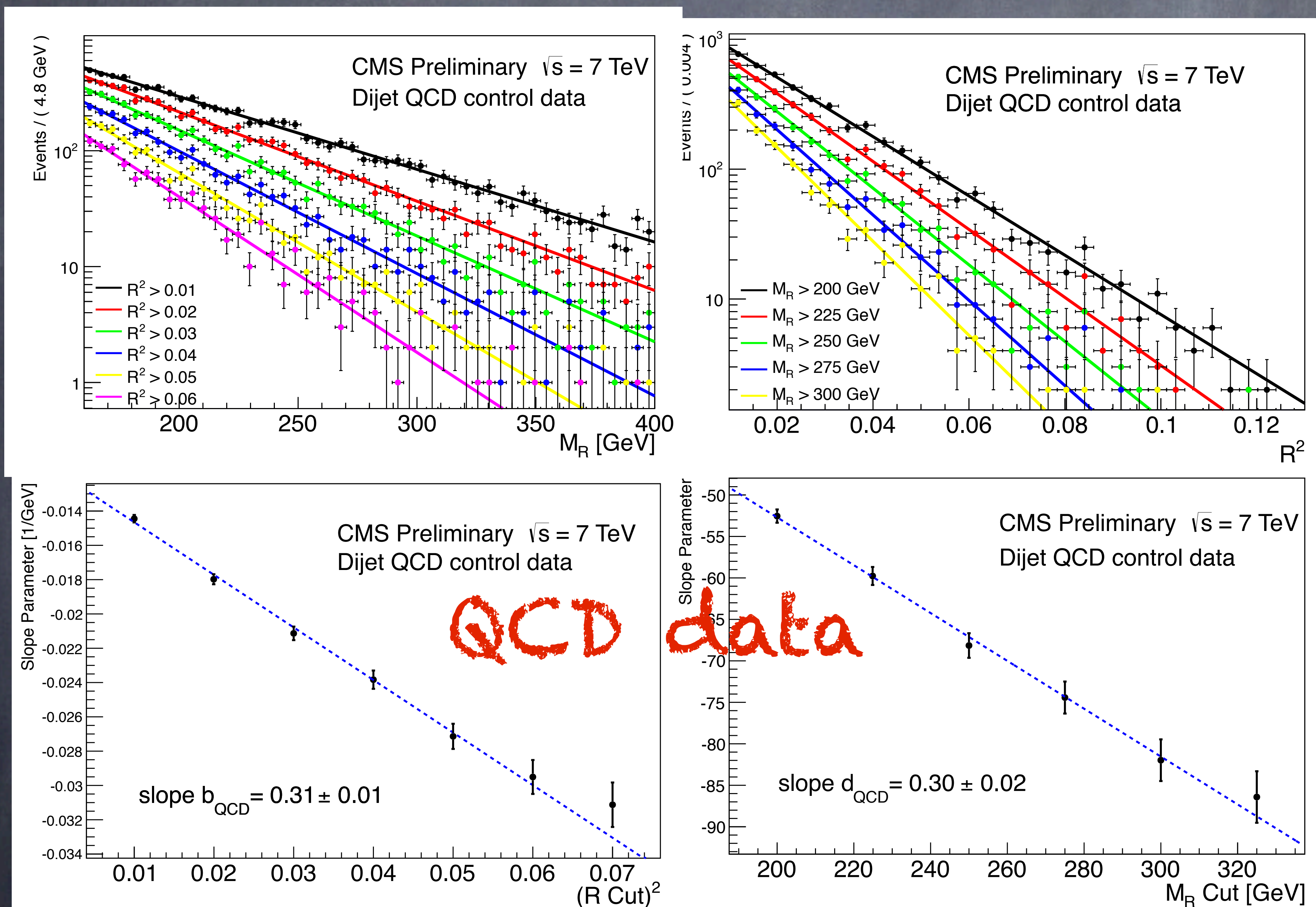
We consider all the possible ways to separate the jets in two "megajets"

We compute the four-momentum of one megajet as the sum of the fourmomenta of jets it contains

We take the configuration for which the megajets give the smallest sum of inv. masses

1D Background Model

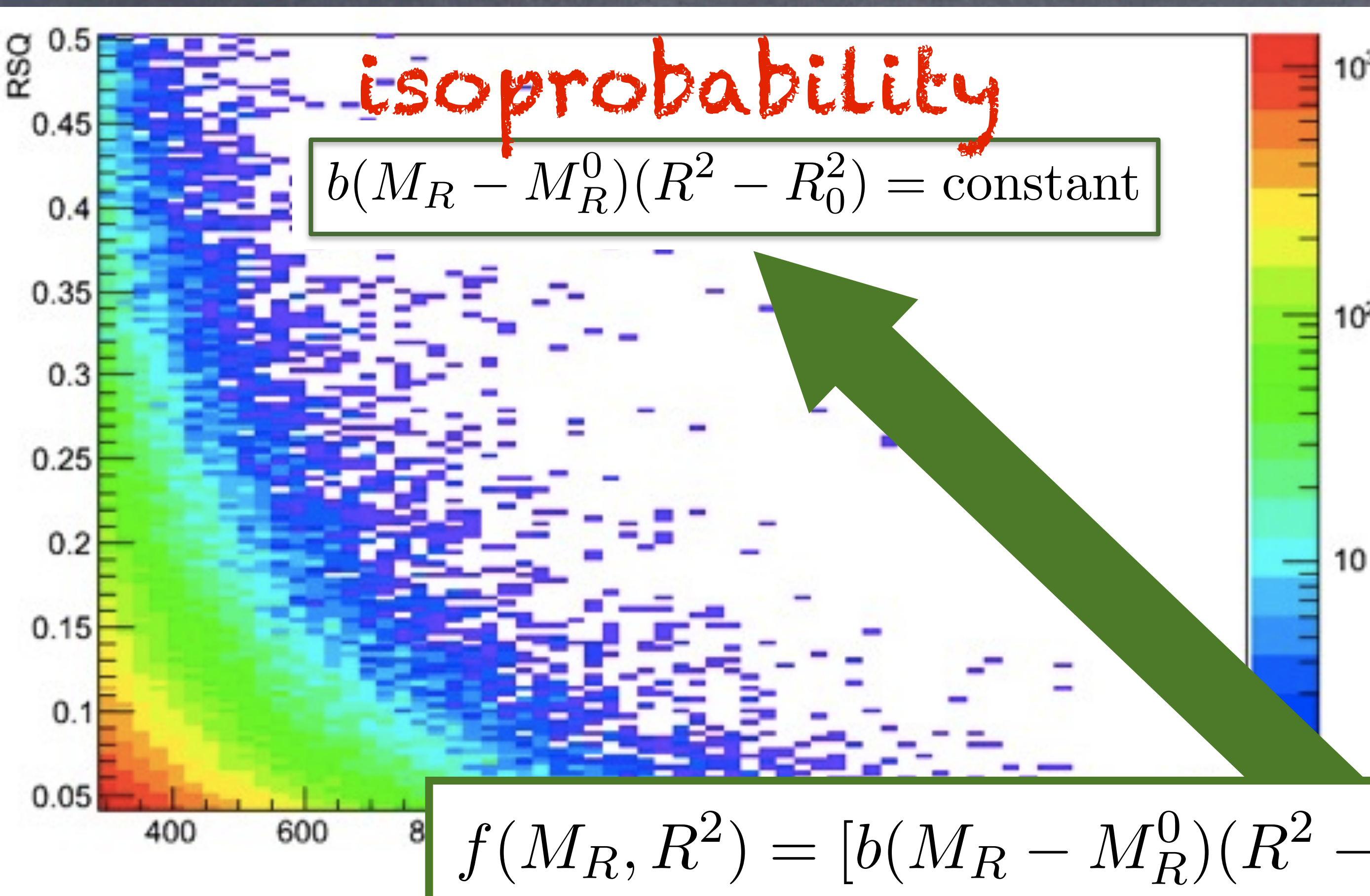
$f(M_R) \sim e^{-kM_R} \quad k = a + b\, R^2_{cut}$



QCD data

$f(R^2) \sim e^{-kR} \quad k = c + b\, M_R^{cut}$

From 1D to 2D

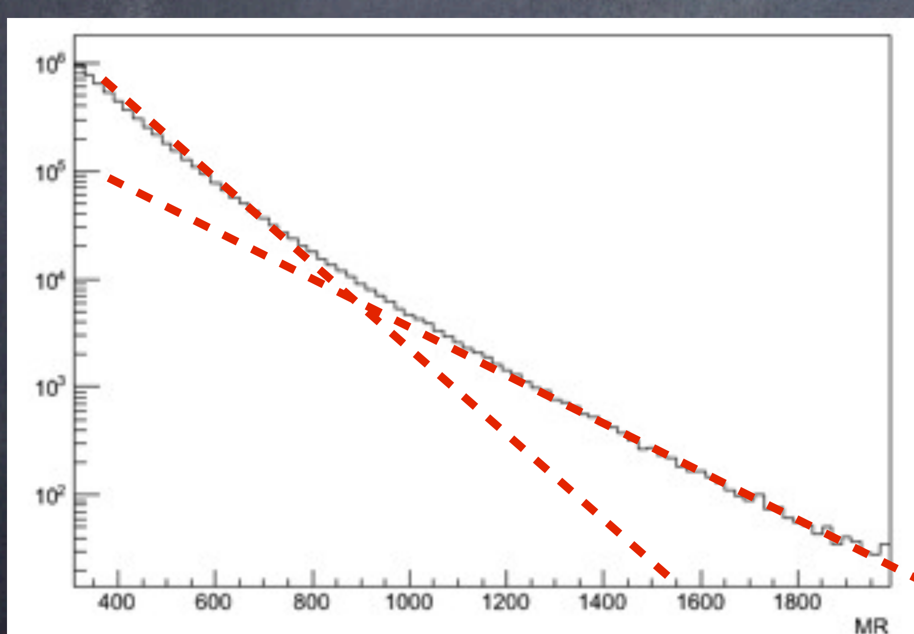


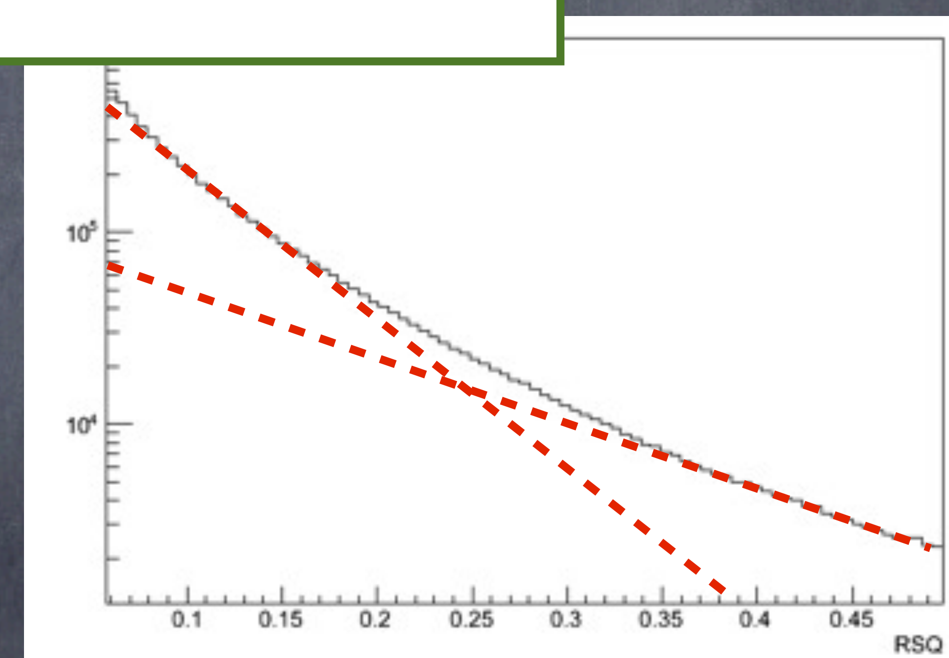
isoprobability

$$b(M_R - M_R^0)(R^2 - R_0^2) = \text{constant}$$

Each Bkg components (Z+jets, W+jets, tt+jets) well described by the sum of two of these pdfs

$$f(M_R, R^2) = [b(M_R - M_R^0)(R^2 - R_0^2) - 1]e^{-b(M_R - M_R^0)(R^2 - R_0^2)}$$





$$\int_{R^2_{cut}}^{+\infty} f(M_R, R^2)dR^2 \sim e^{-(a+bR^2_{cut})M_R}$$

$$\int_{M_R^{cut}}^{+\infty} f(M_R, R^2)dM_R \sim e^{-(c+bM_R^{cut})R^2}$$

dE/dx in the tracker

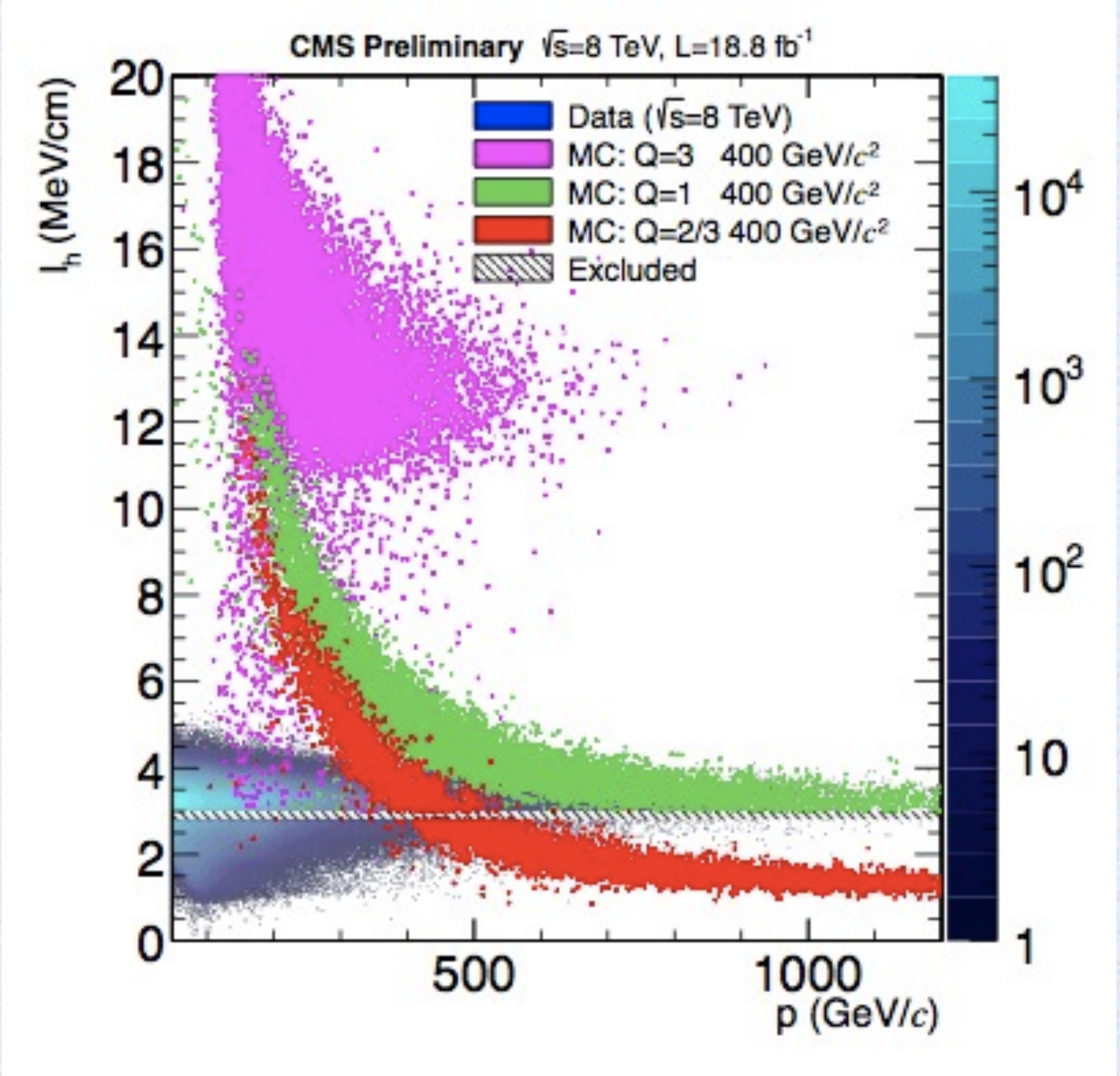
- Measure the charge released in the tracker
- Compute ionization, which gives a measurement of p/m through charge-dependent empirical coefficients

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

Ih vs pT distributions provides S vs B discrimination



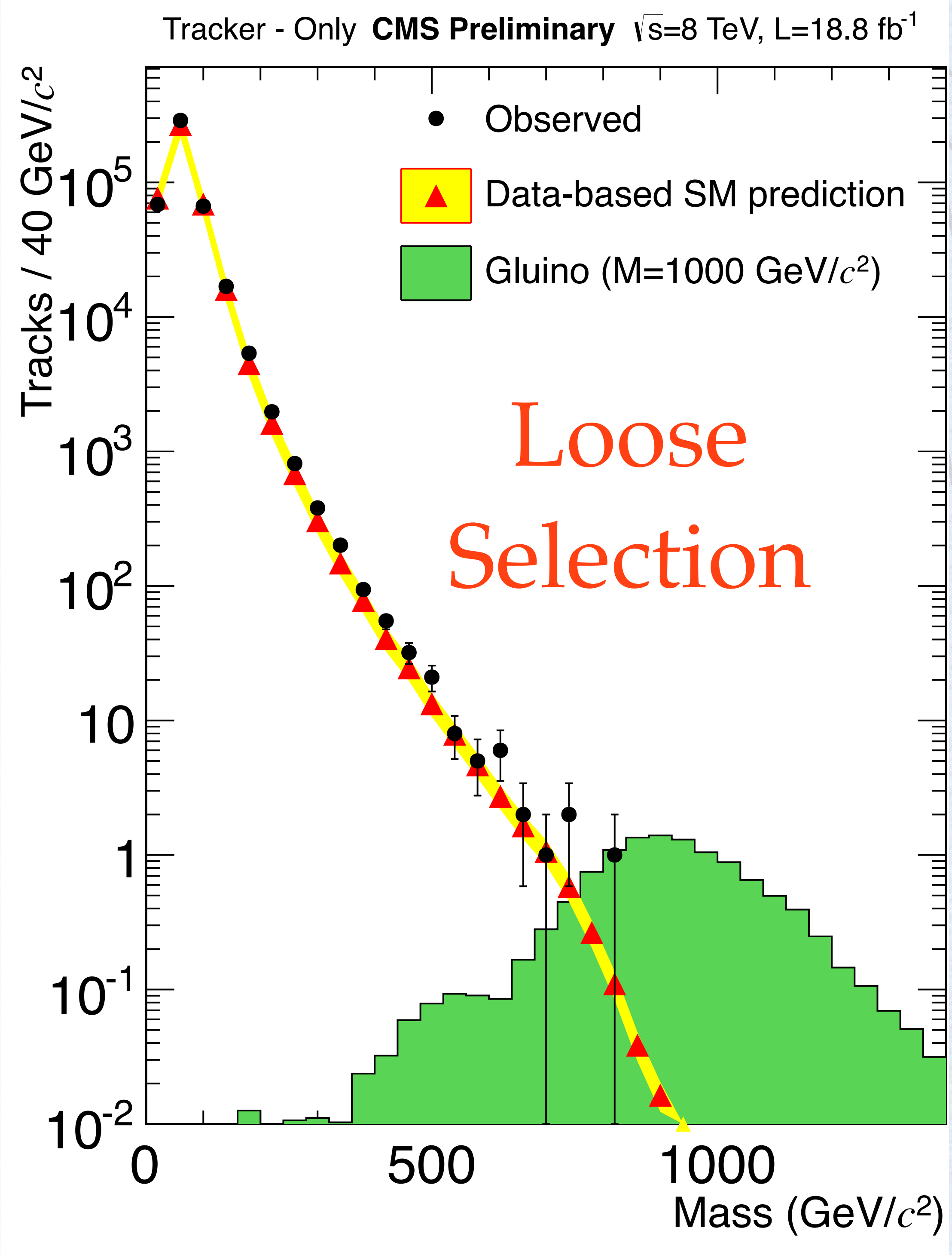
dE/dx in the tracker

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

probability MIP to produce <= 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

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

DTs (σ ~ 3 ns)

CSCs (σ ~ 7 ns for cathode, 9 ns for anode)

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