Looking for Light at the End of the LHC Tunnel

The Search for SUSY with Photons at CMS

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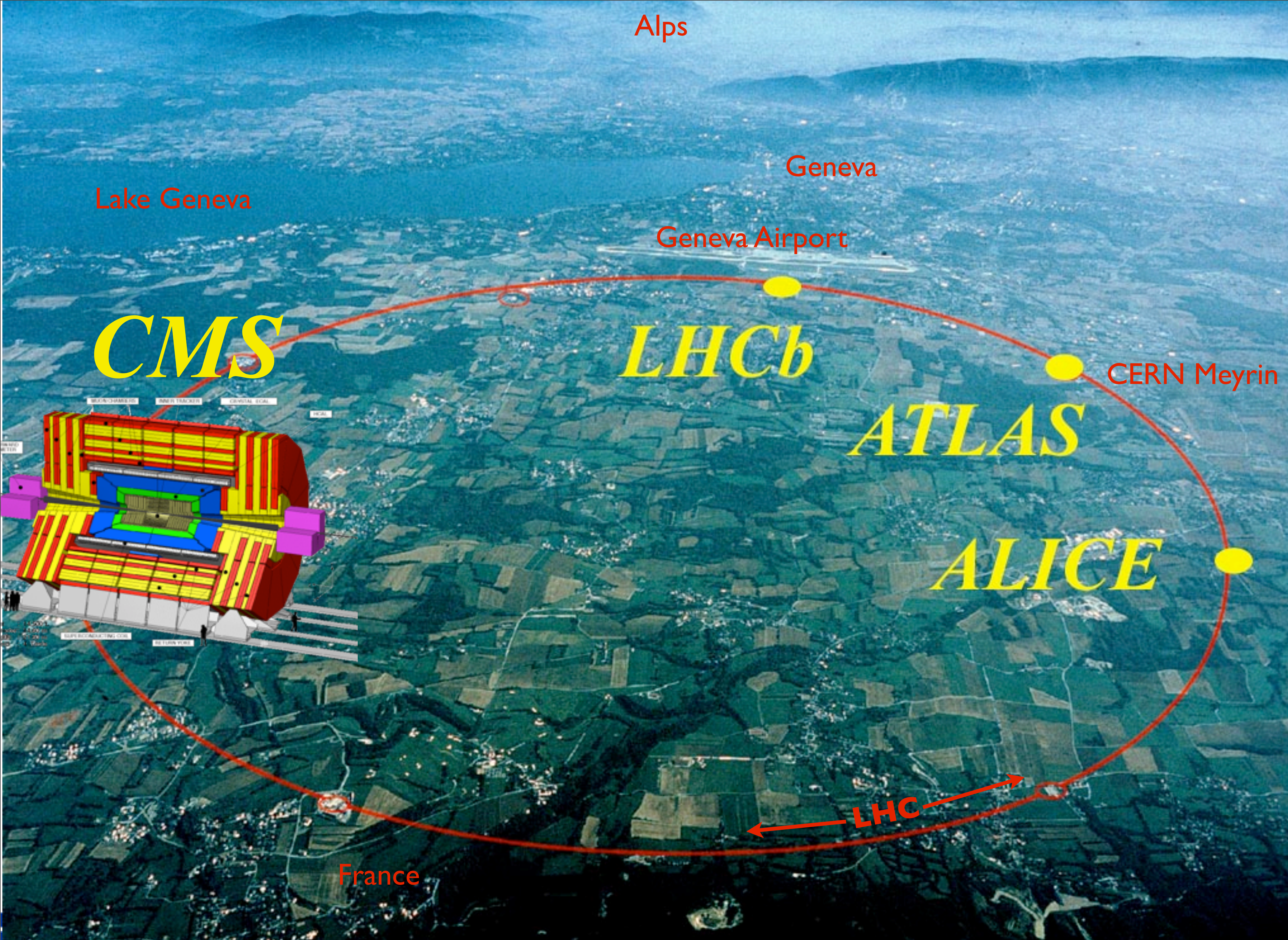
Fermilab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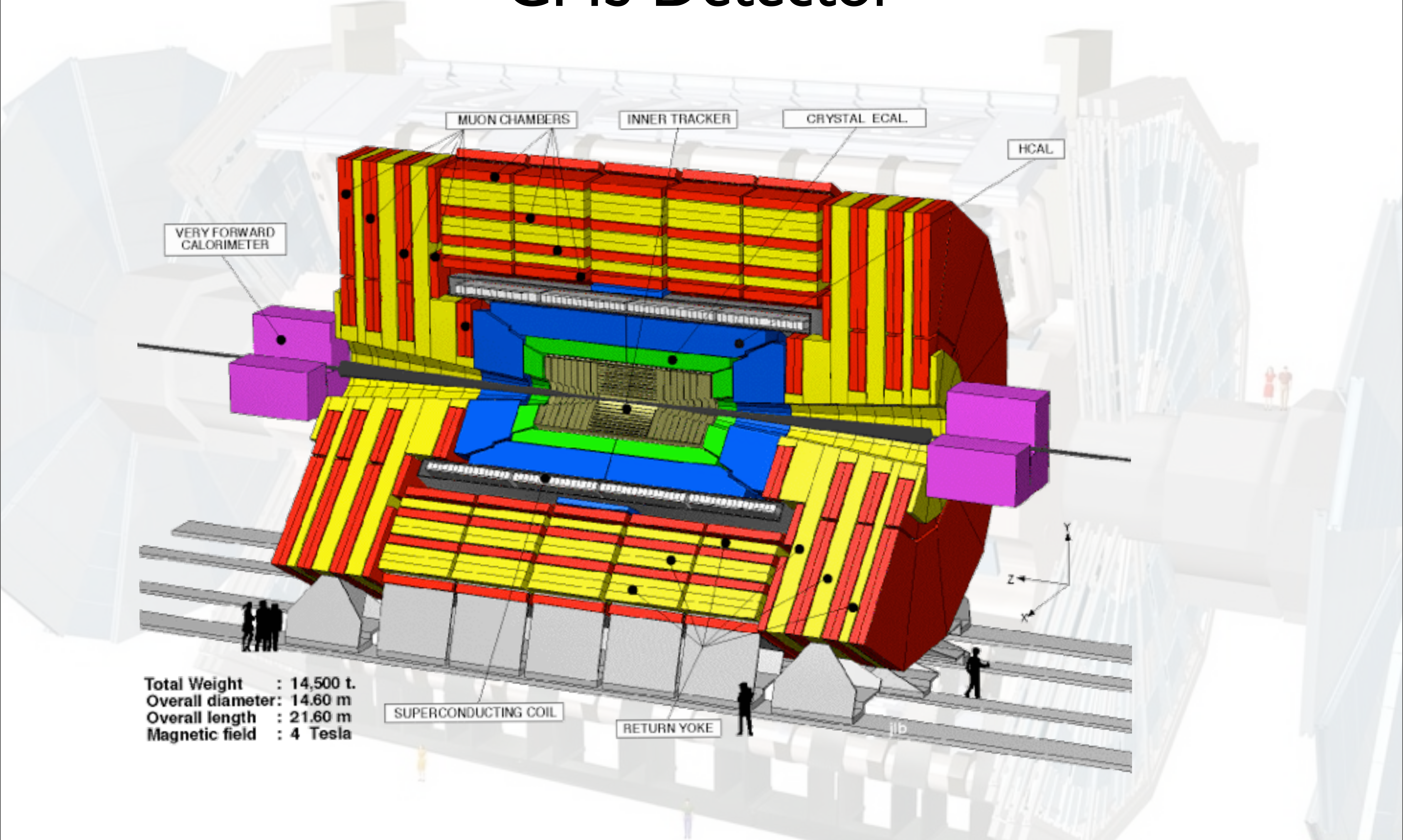
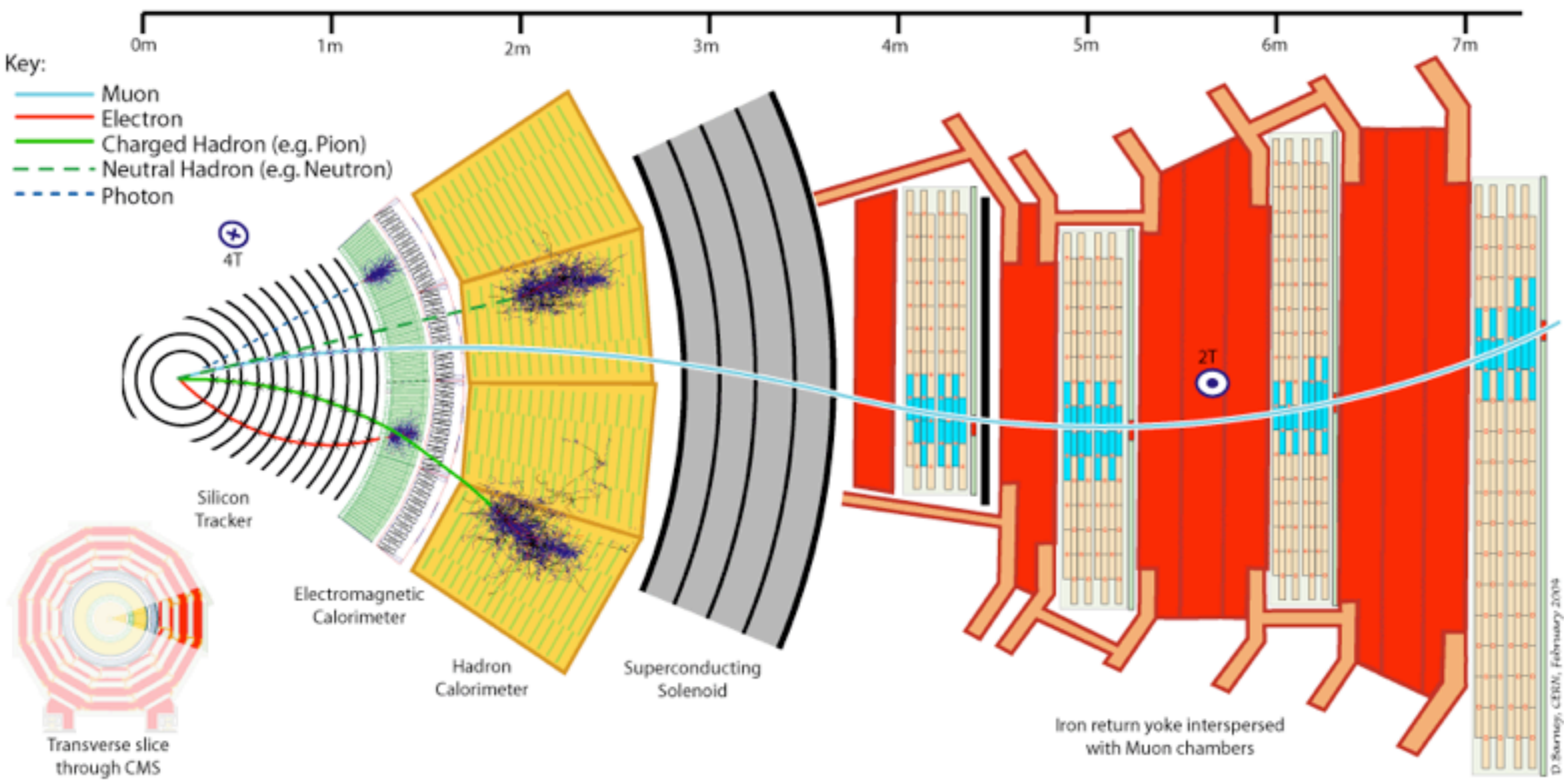
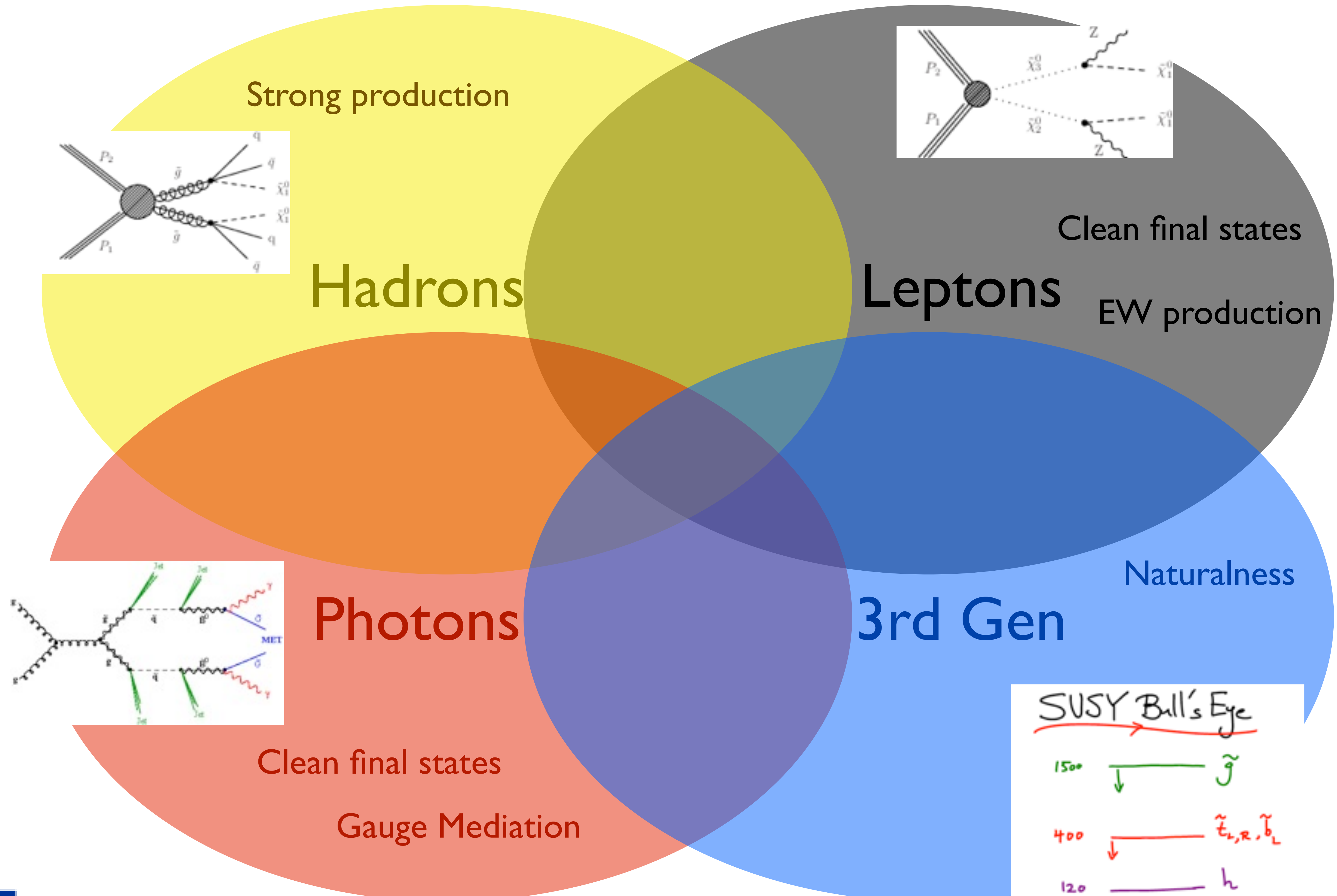
CMS Detector



How Different Particles Appear in CMS



4 corners of the CMS SUSY search strategy



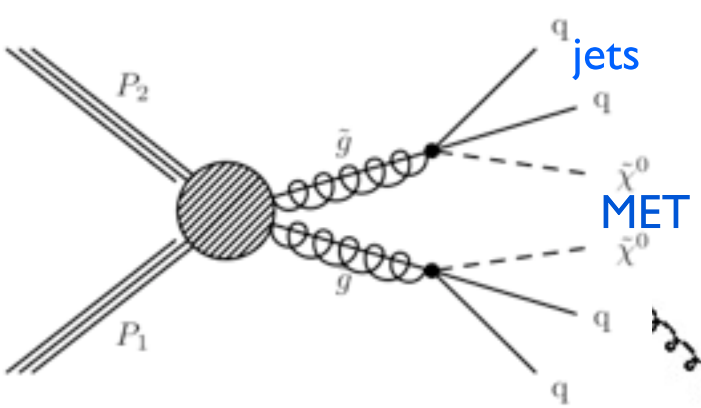
Why SUSY?

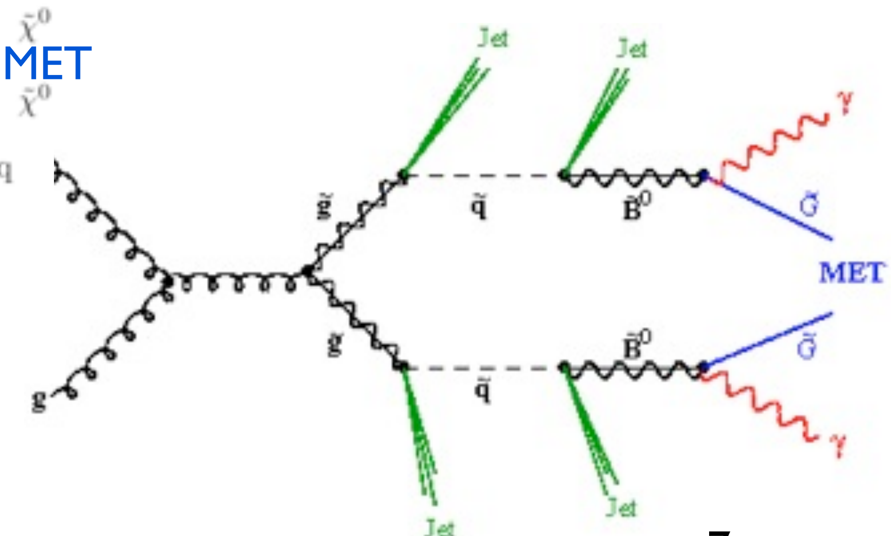
- Having likely seen results out of the LHC this past year you may ask this question for a different reason ("Why SUSY Still?") -- but quickly some of the standard motivational arguments...

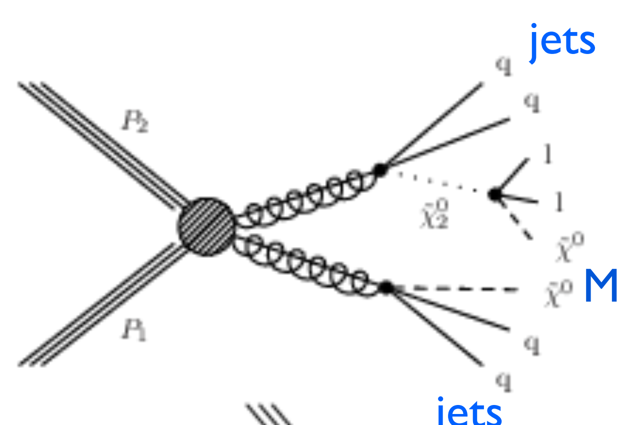
- Unifies the SM gauge couplings
- Helps solve the "hierarchy problem" -- introduces a new symmetry between fermions and bosons which helps cancel divergences in radiative corrections to the Higgs mass
  - We don't see SUSY particles everywhere, so this symmetry is broken -- sparticles would need to be massive not to have been seen yet
  - But needs to be around the TeV scale...
- Lightest SUSY particle can be a viable dark matter candidate.
- But also from the experimental perspective, SUSY provides a rich menagerie of new physics signatures on which to frame more general searches for new physics

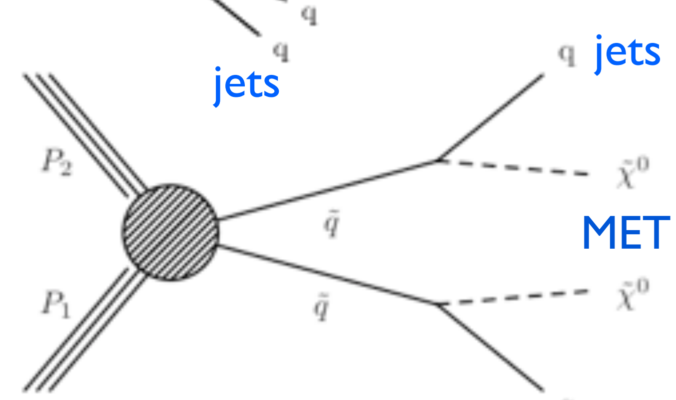
How SUSY might manifest...

- R (matter) parity conservation -- SUSY particles produced in pairs, lightest (LSP) can't decay
    - Have LSP interact weakly -- stable dark matter candidate.
- Stable LSP not detected -- manifests in an apparent nonconservation of momentum in an event -- Missing E_T or "MET"
- Strongly produced sparticles, as have been expected at the LHC, can have long decay chains emitting jets and SM particles along the way
- Mass spectra and choice of LSP / "Next to" LSP (NLSP) defines the topology one looks for in the detector.





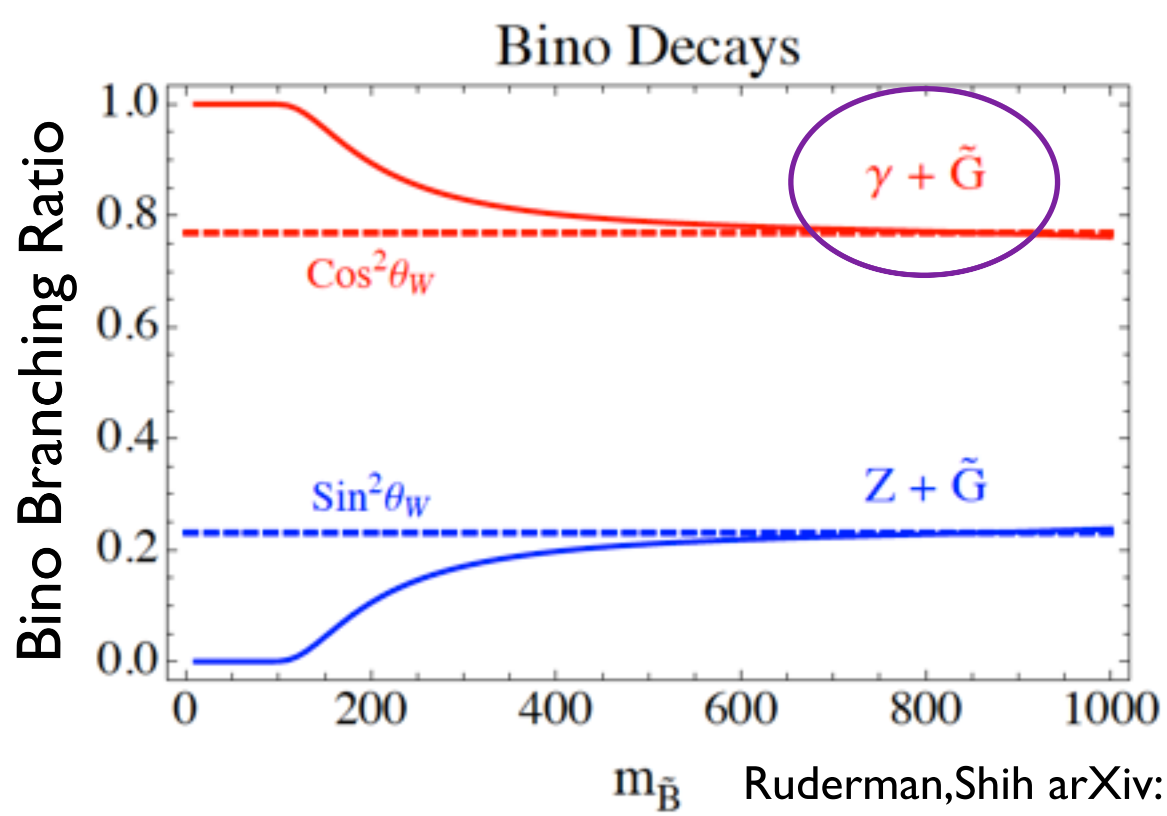




How SUSY manifests on Google

Why look for SUSY using Photons?

- We will discuss several CMS searches utilizing photons in the final state, motivated by General Gauge Mediated SUSY and Universal Extra Dimensions
  - In GGM SUSY the lightest SUSY particle is the stable gravitino (undetected, resulting in missing transverse energy)
  - If the NLSP is a neutralino, especially if bino like:

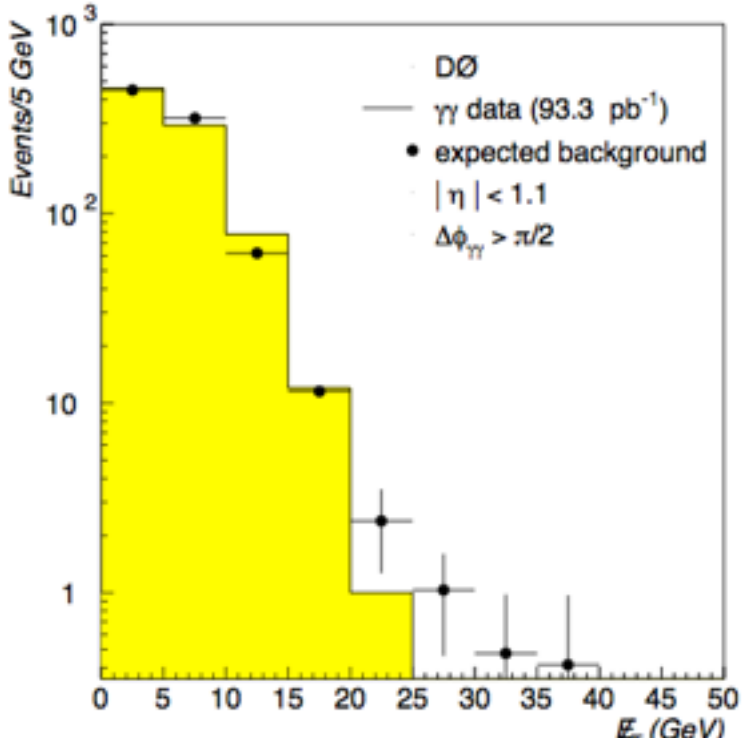


Ruderman,Shih arXiv:1103.6083

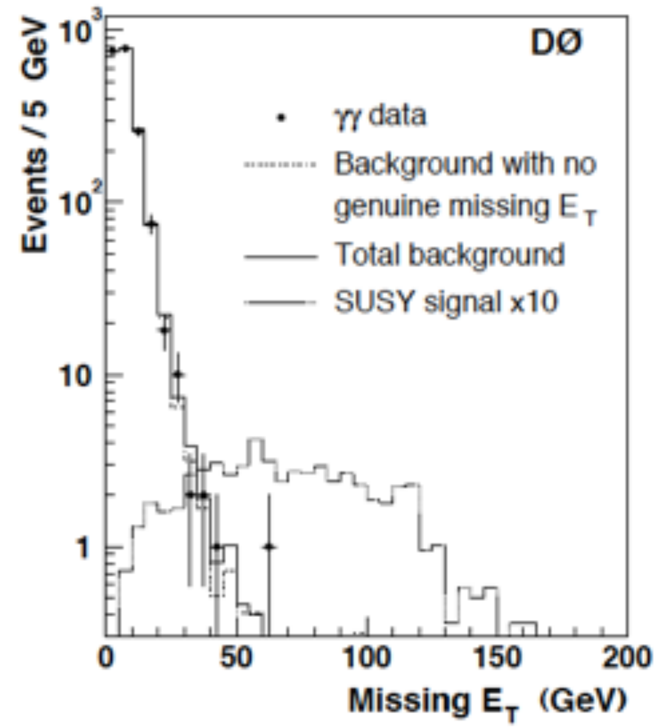
  - We would expect SUSY production to result in signatures containing photons + missing E_T

And Here “We” has not been just CMS...

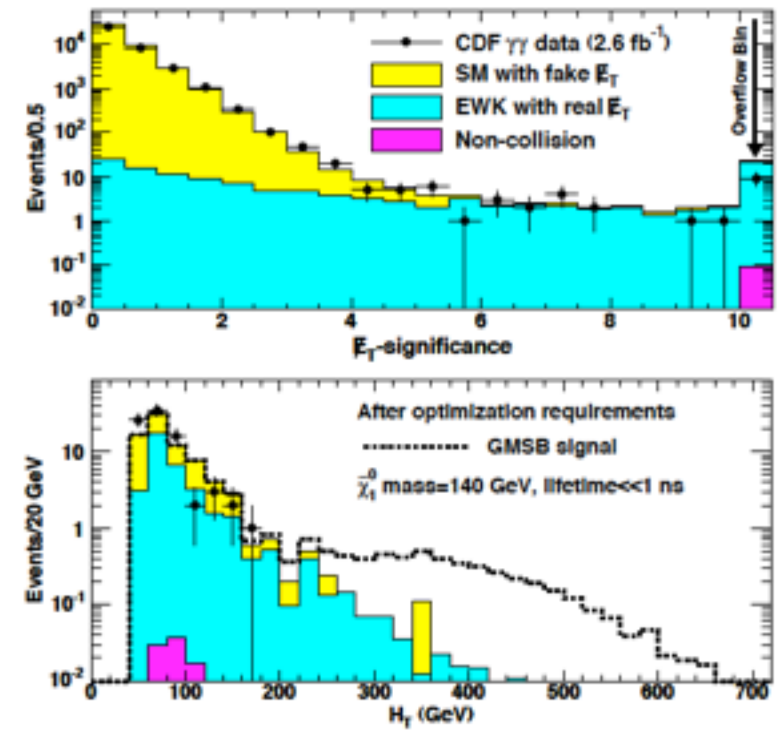
Past photon based SUSY searches:



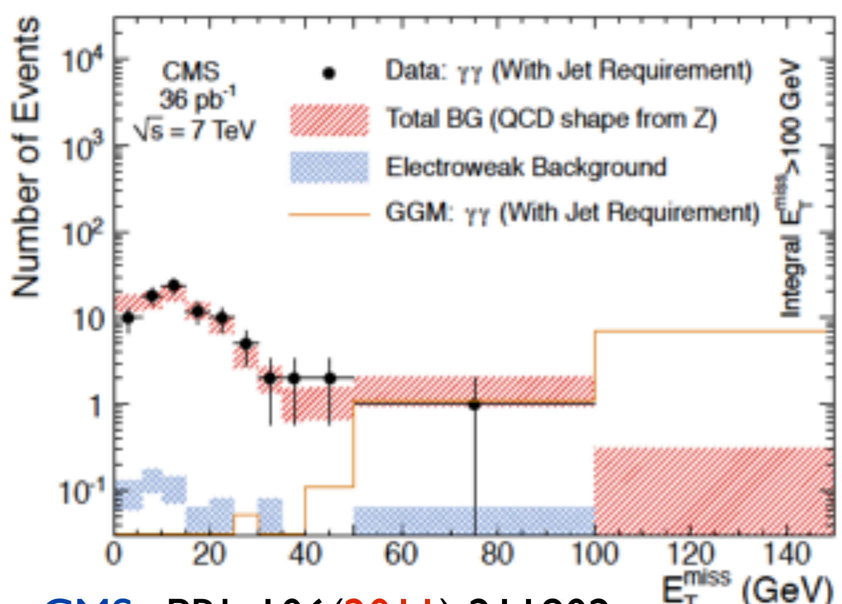
D0: PRL 78(1997) 2070-2074



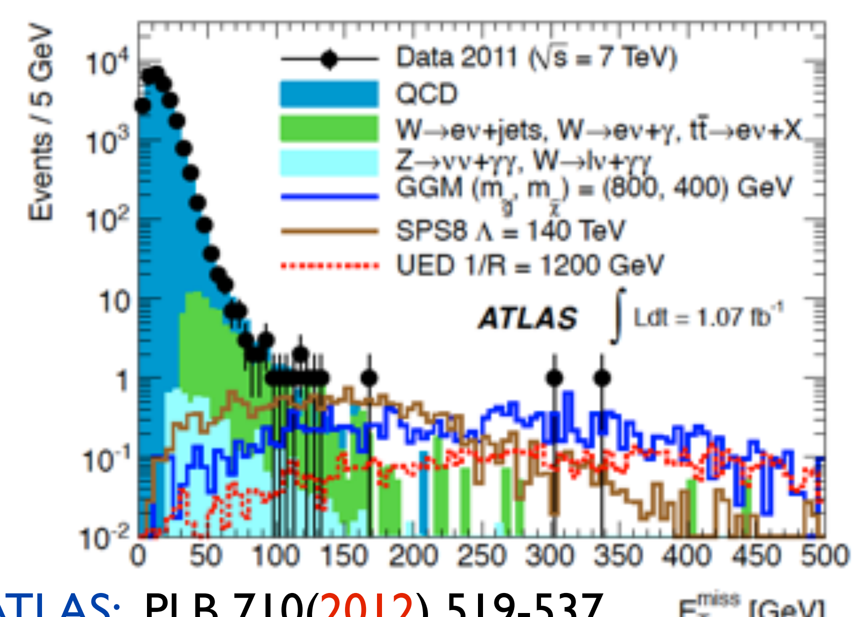
D0: PRL 94(2005) 040801



CDF: PRL 104(2010) 011801



CMS: PRL 106(2011) 211802

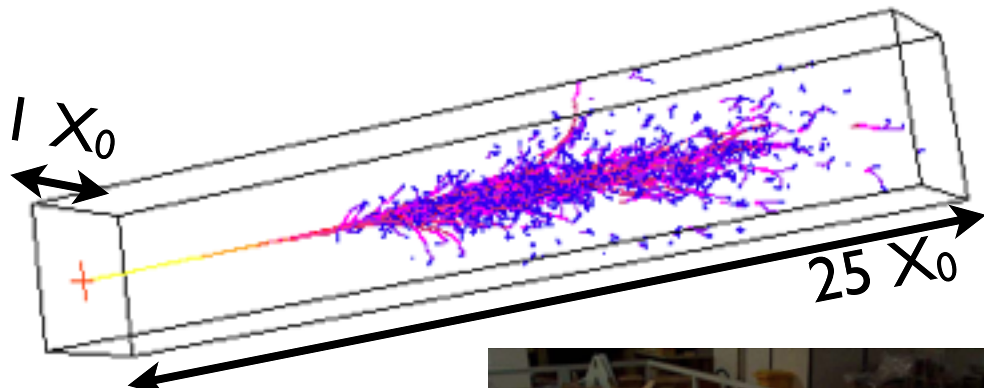


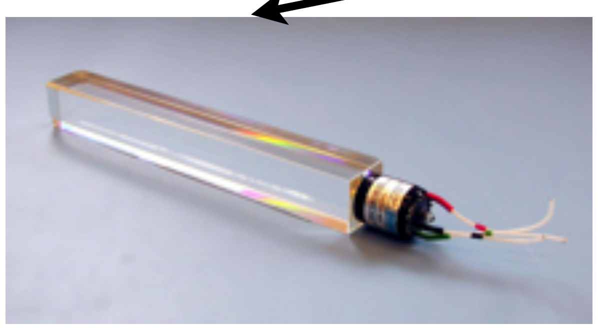
ATLAS: PLB 710(2012) 519-537

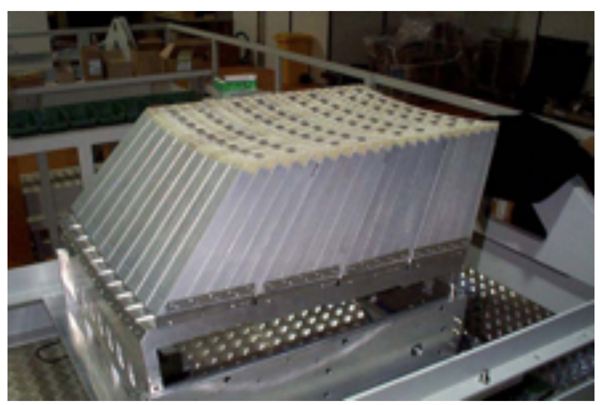
Now we look at CMS after 5 /fb (or more)

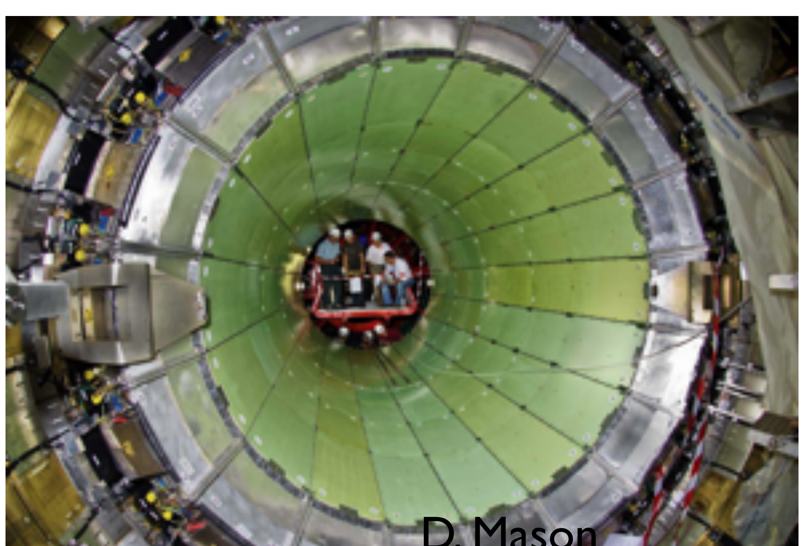
Why look for SUSY with Photons at CMS?

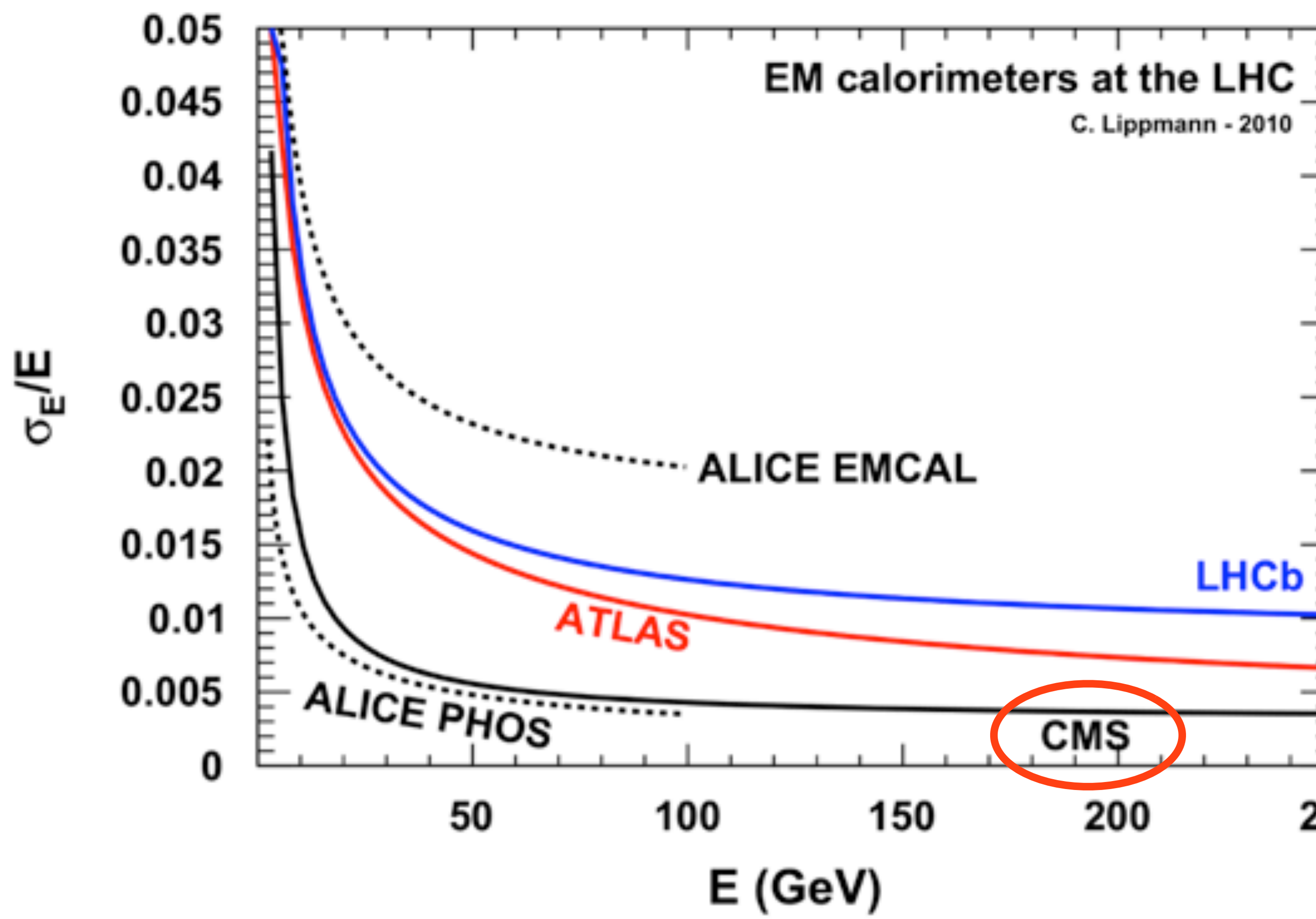
- Photons provide a very clean signature, which are reconstructed in CMS with very high purity.
- CMS has a spectacular EM calorimeter, with high granularity and very good energy resolution (designed with the narrow Higgs width in mind).











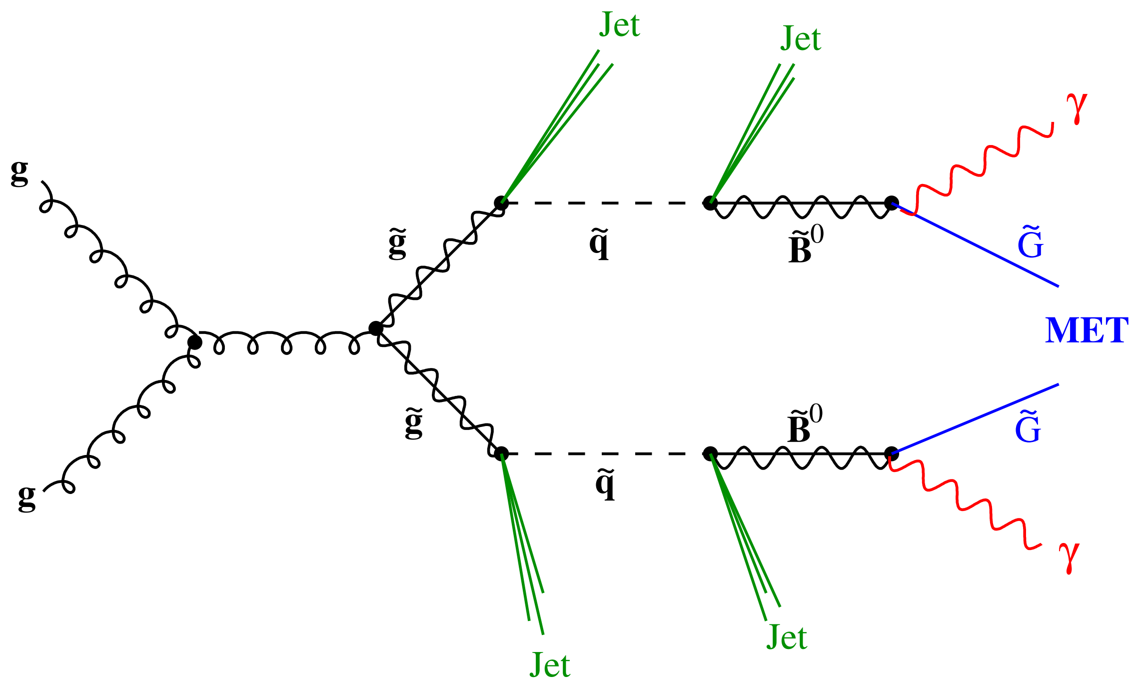
Searches We'll Talk about Today:

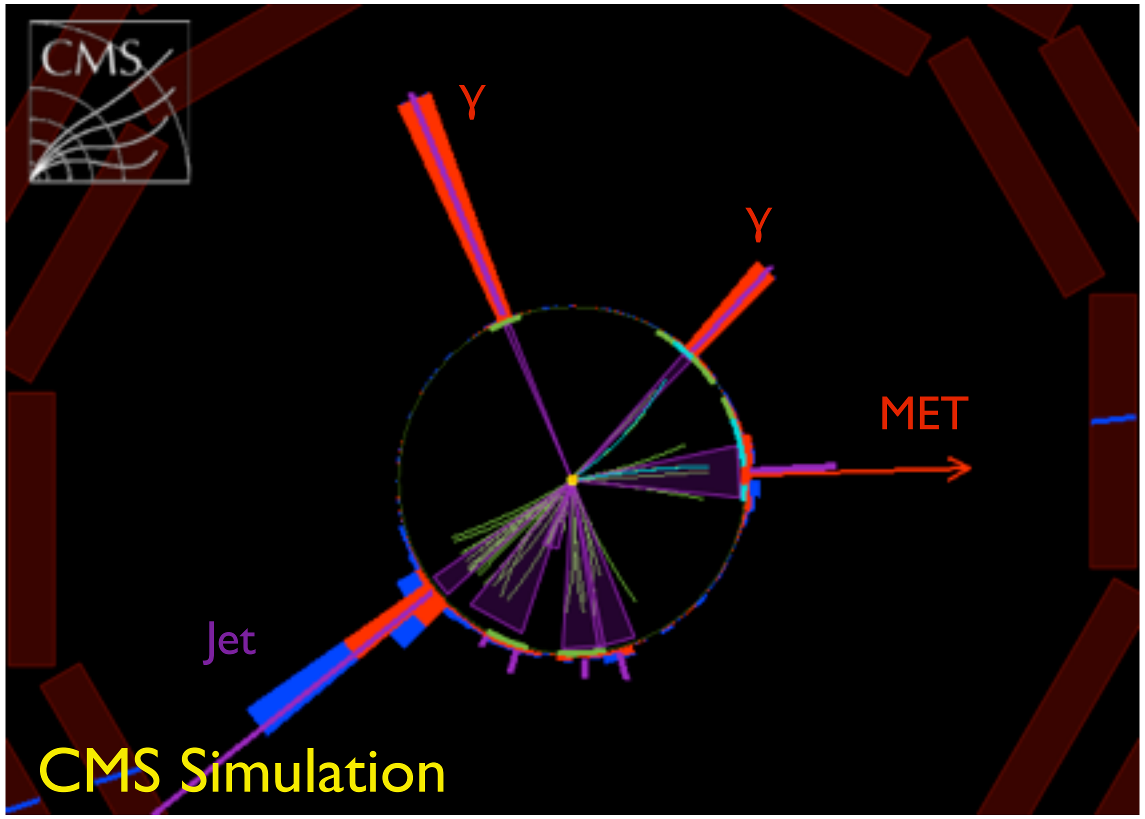
- Diphotons + Jet + MET
- Single Photons + Jets + MET

} https://cdsweb.cern.ch/record/1436111

- Jet-Gamma Balance Search
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS12013
- Stealth SUSY https://cdsweb.cern.ch/record/1460389
- Monophoton Dark Matter Search Phys. Rev. Lett. 108 (2012) 261803
- Some Discussion of the Future and Various Levels of Prognostication...

Diphoton + Jets + ME_T

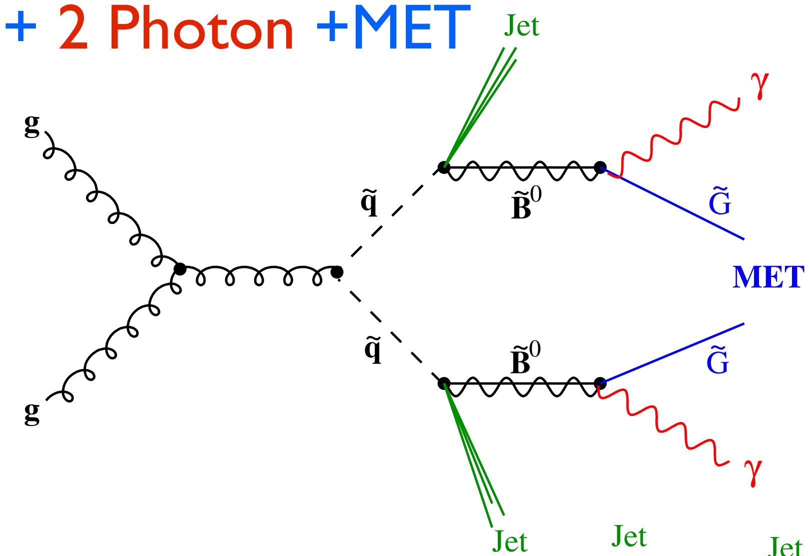




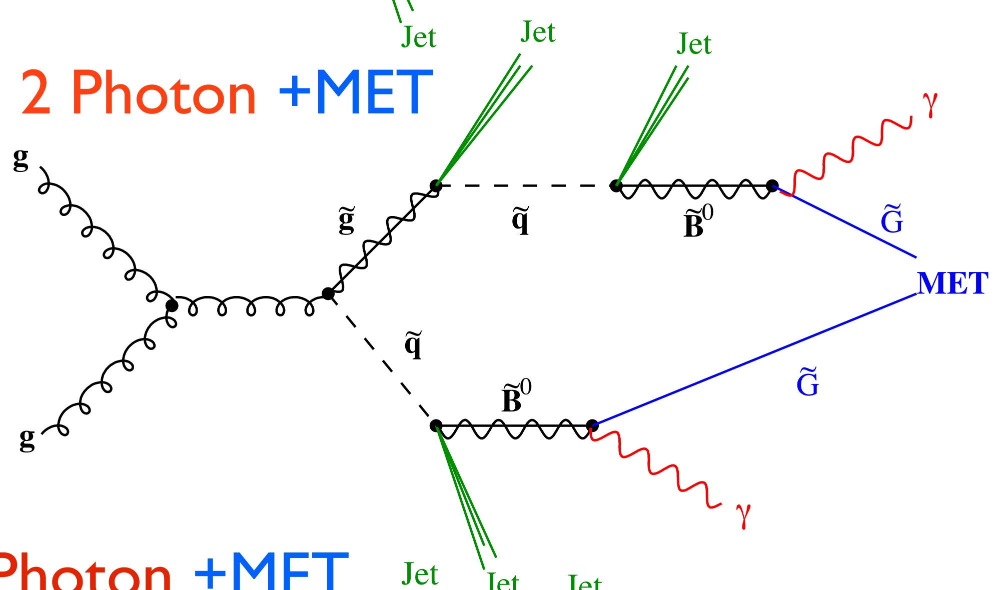
- At the LHC strong production is expected to dominate.
  - This results in decay chains providing jets, ending in the NLSP and LSP.
  - R parity conservation ⇒ 2 binos ⇒ two photons + missing E_T from gravitinos
  - Jetty signal, but number of jets can vary, depending on initial production of gluinos or squarks, and their relative masses.
- Diphoton + ME_T SM backgrounds are small

Can have a varity of jets...

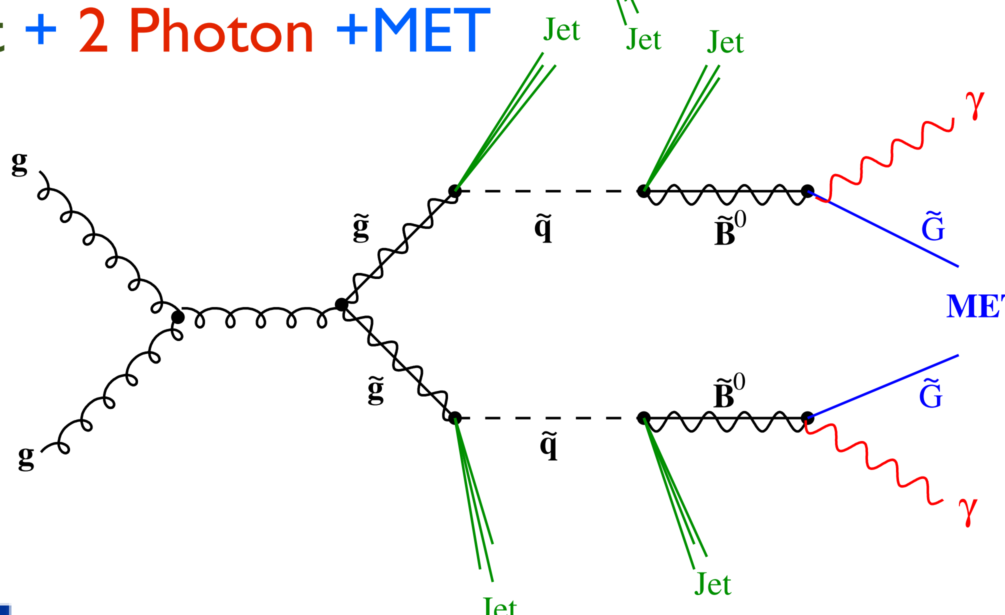
2 Jet + 2 Photon +MET



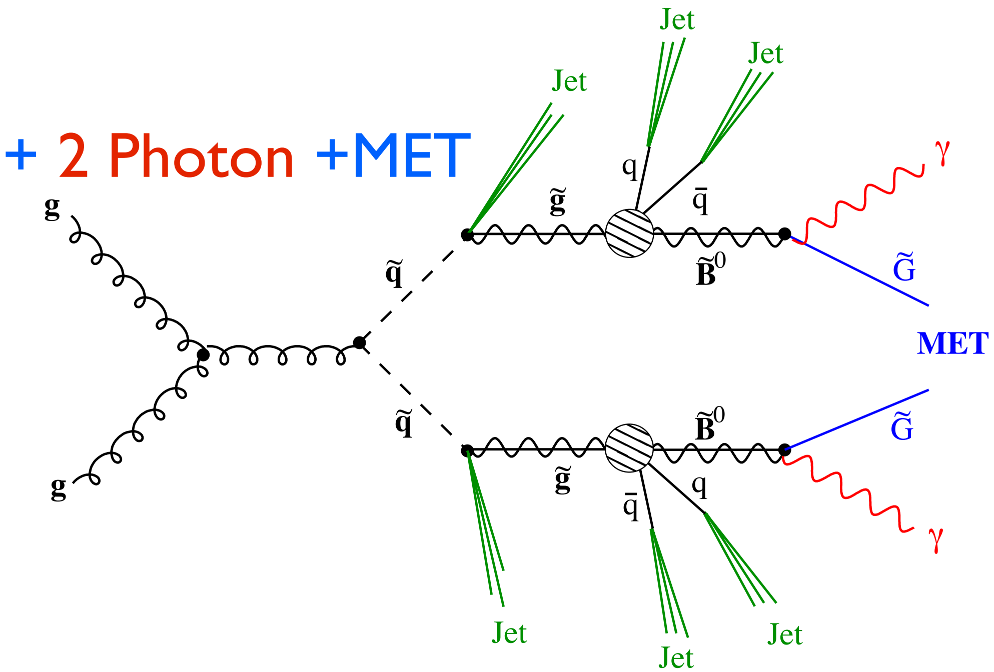
3 Jet + 2 Photon +MET

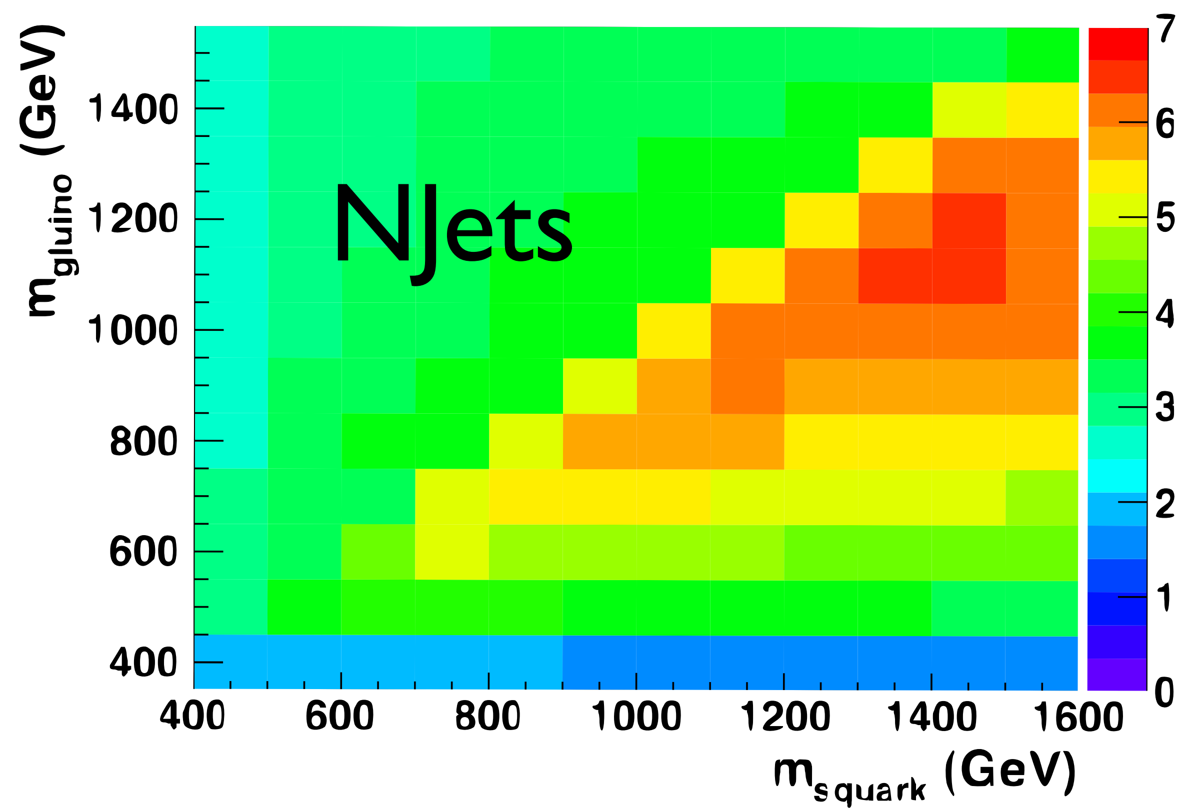


4 Jet + 2 Photon +MET



6 Jet + 2 Photon +MET





Backgrounds

- Dominant backgrounds estimated from the data, minor irreducible backgrounds from MC:

Larger

  - “Non Intrinsic ME_T” backgrounds -- ME_T acquired through mis-reconstruction & resolution effects.
    - i.e. QCD, where highly EM rich jets become “fake” photons.
    - Measure from data in orthogonal samples selected to as closely as possible mimic the hadronic environment of the candidate sample
  - “Intrinsic ME_T” backgrounds -- those with actual ME_T which enter into the sample via electron mis-id as a photon, etc.
    - i.e. EWK backgrounds like Wgamma, W+jet where $W\rightarrow e\nu$
    - Measure from data, use measured $e\rightarrow\gamma$ fake rate to normalize.

Smaller

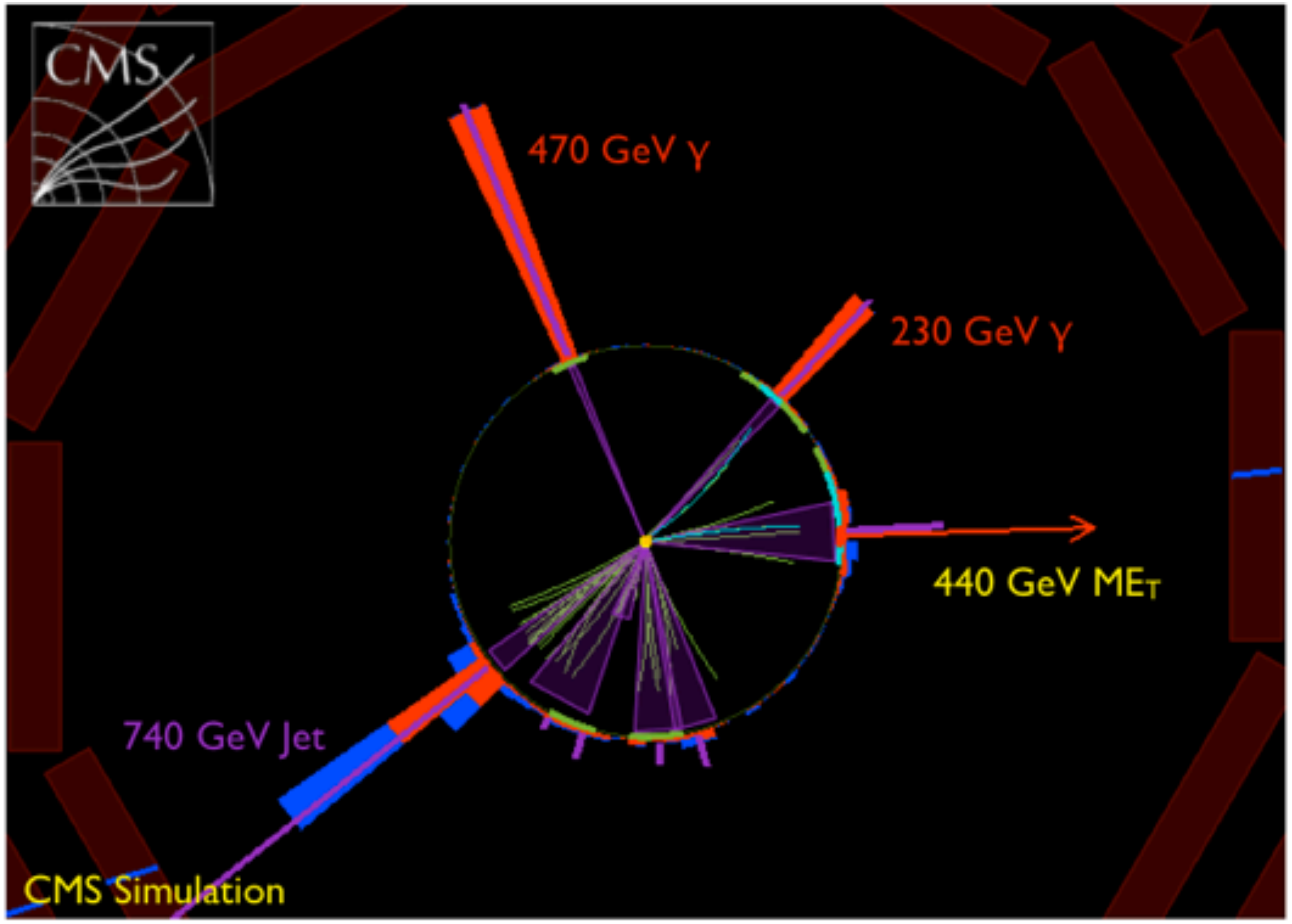
  - A third class, smaller than the other two, enters into the single photon search. ISR/FSR can produce real photons and have real MET, this must be determined from MC
- Finally with candidates and backgrounds in hand, look for evidence of an excess at high ME_T

Event Types

- We begin with requiring one or more EM objects, which are used in either the candidate selection or for background estimates.
  - We use shower shape and the energy sum in a hollow cone around the EM object to differentiate between candidate photons and “fake” photons.
    - Candidate photons are required to have a narrow shower shape, with energy within a hollow cone (ΔR=0.3) summed between the tracker, Ecal and Hcal less than 6 GeV (called the “isolation sum”). ($\Delta R^2 = \Delta\eta^2 + \Delta\varphi^2$)
      - Isolation sums are compensated for pile-up based on the measured transverse energy density of each event.
    - “Fake” photons invert the shower shape or isolation sum requirement
      - In both cases only up to a point however -- the trigger imposes limit on the shower shape, and we limit the isolation sum to 20 GeV. We do not want our fake photons to be grossly different from our candidates.
    - Both photons and “fake” photons require a veto on hits in the pixel tracker.
      - An electron is defined as a photon with pixel tracker hits required

Diphoton Event Selection

- At least two candidate photons
- Leading photon p_T>40 GeV
- Trailing photon p_T>25 GeV
- both photons in barrel ($|\eta|<1.4$)
- At least 1 Jet, p_T>30 GeV, $|\eta|<2.4$



A simulated m_{gluino}=1200 GeV, m_{squark}=1250 GeV, m_{bino}=225 GeV signal event

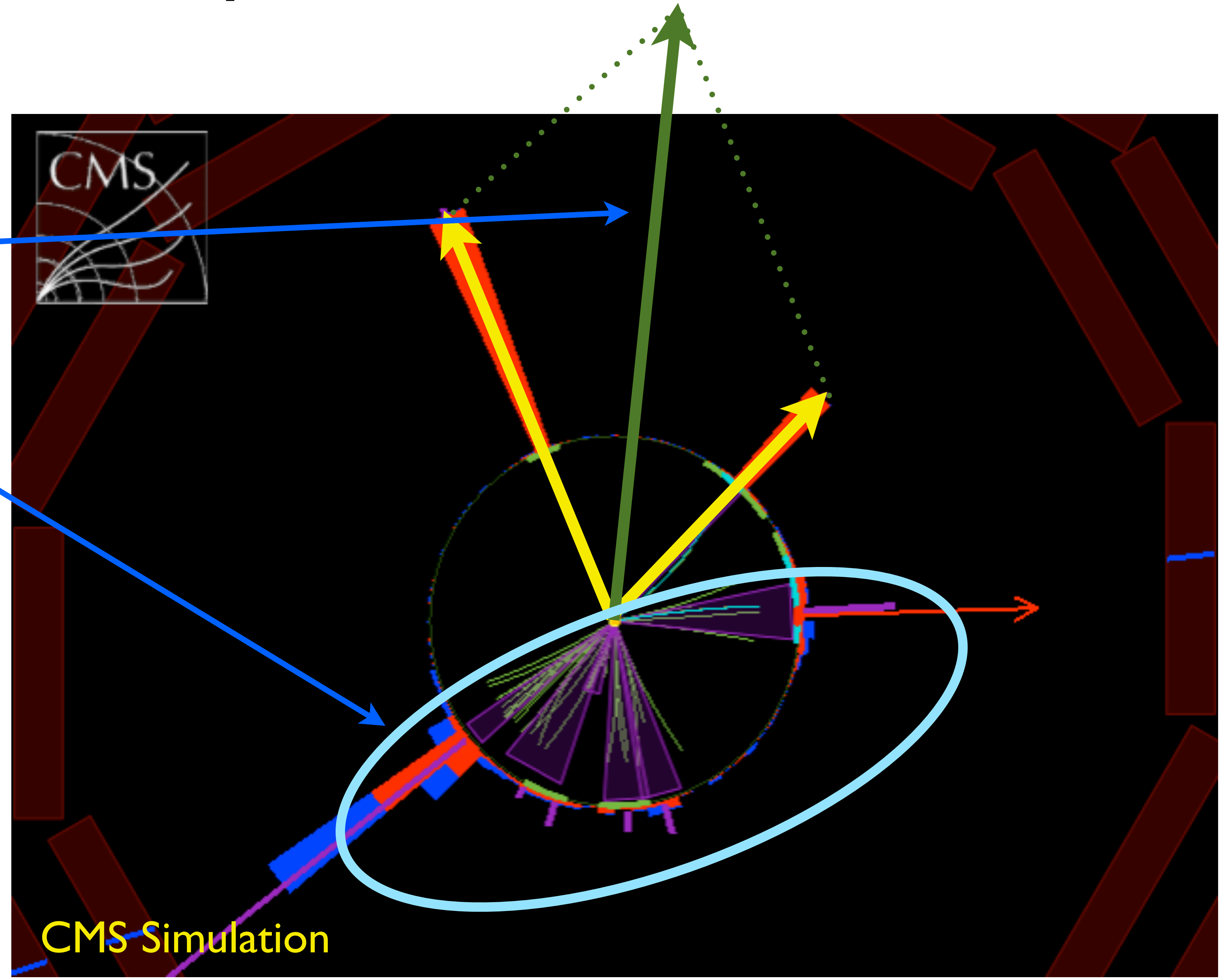
Diphoton Non Intrinsic ME_T Background

- Resolution effects and instrumental mis-measurement can create ME_T in the hadronic environment
  - Dominant background -- thanks to plentiful EM enriched QCD dijets
- Our goal is to find an orthogonal sample which mimics the hadronic environment of our candidate sample.
- We measure the ME_T shape due to this background from a sample of di-"fake" photons.
  - We also use the ME_T shape from $Z \rightarrow ee$ events for a systematic estimate.
- These orthogonal samples can have slightly different kinematics compared to our candidate diphoton sample.
- We correct for this effect by re-weighting the di-"fake" events by the ratio of the distributions of the vector sums of the two EM objects (diphoton or di-"fake").
  - Corresponds to recoil of the hadronic system
- queue the cartoon:

Di-EM p_T cartoon

The pT of the diphoton system

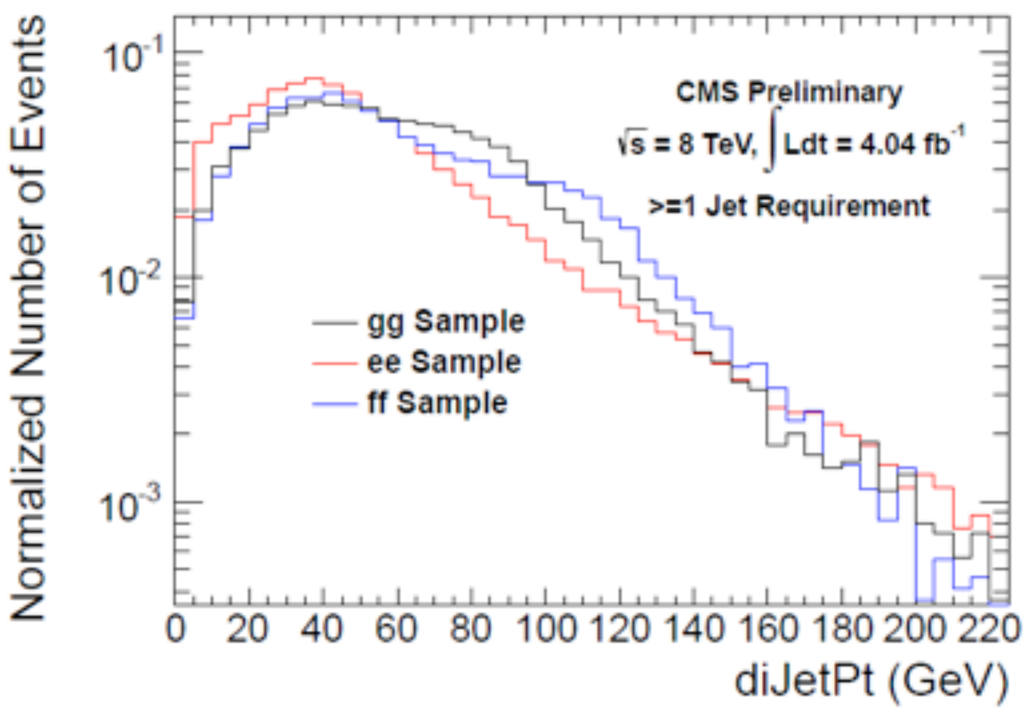
acts as a proxy for
the hadronic system

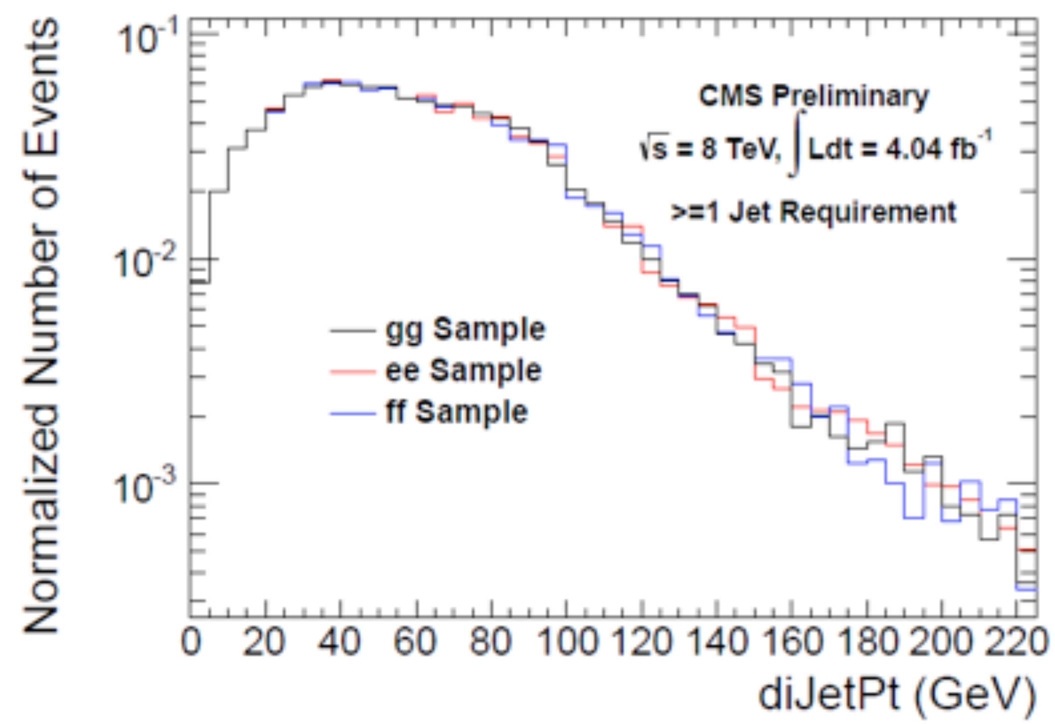


- Reweighting factors from the di-fake sample shape to diphoton sample shape are very small -- low single digit %

- We then normalize the reweighted di-"fake" sample to the diphoton candidate sample in the region where diphoton ME_T < 20 GeV.

A before - after picture

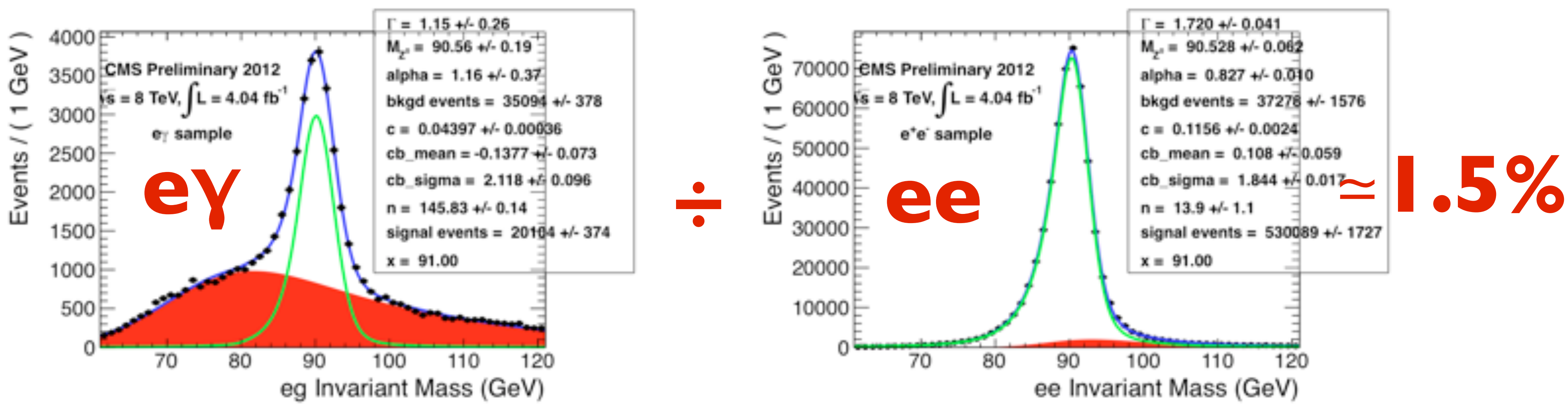




- The recoil to the jet activity after reweighting agrees very well...

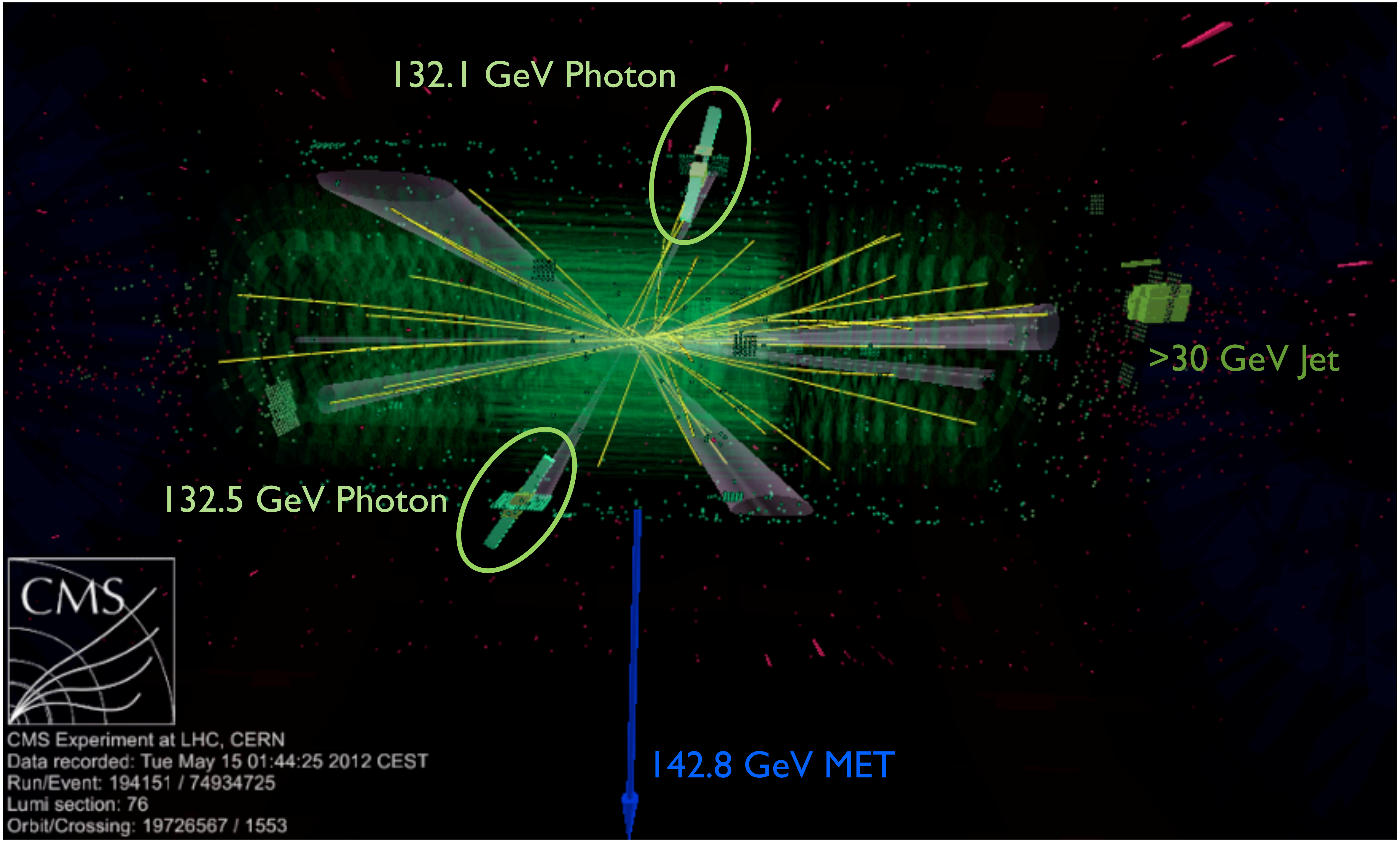
Diphoton Intrinsic ME_T Background

- This subdominant background comes from EW processes where an electron is mistaken for a photon. (at low ME_T around 1%, but at high ME_T closer to 10% of the Non-Intrinsic MET bkg.)
- We measure this from our data as well, measuring the $e \rightarrow \gamma$ fake rate, then applying that to the ME_T background measured from a sample of electron-photon events.
- We measure the rate that an electron is mis-reconstructed as a photon from fits in invariant mass at the Z peak in di-electron events and electron-photon events.



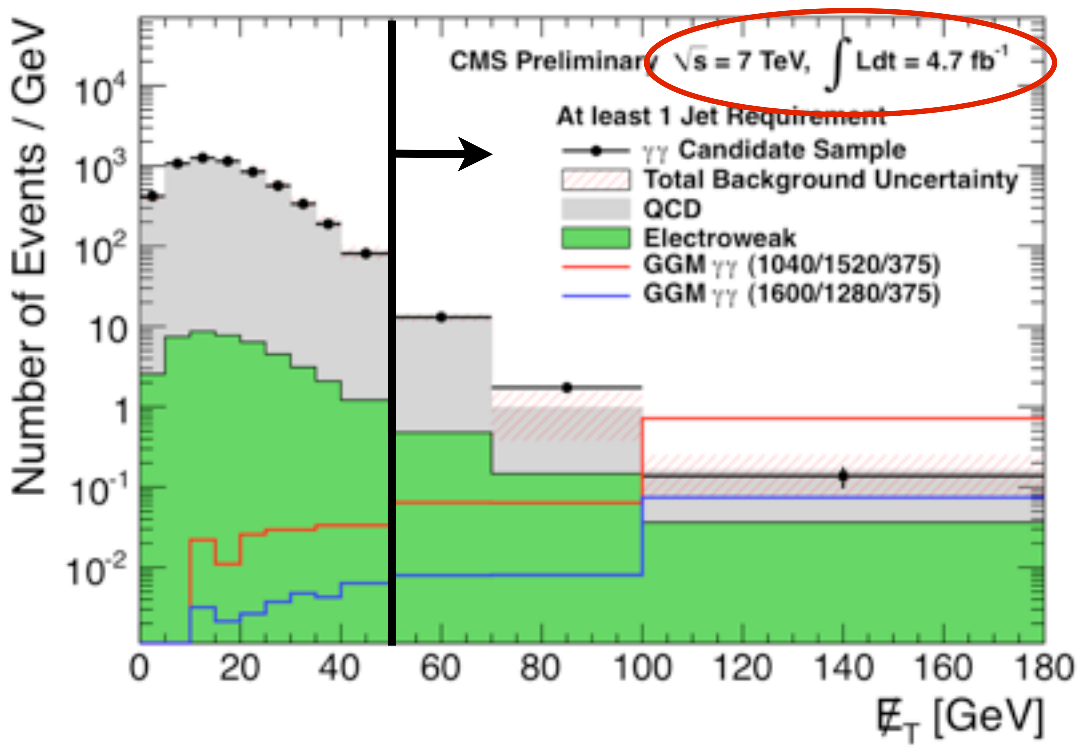
  - Different shape assumptions tried, difference becomes a systematic.
- This measured $e\gamma$ fake rate is used to normalize the ME_T shape obtained from the full electron-photon sample to the diphoton candidate ME_T distribution.

Event Display of a Candidate!

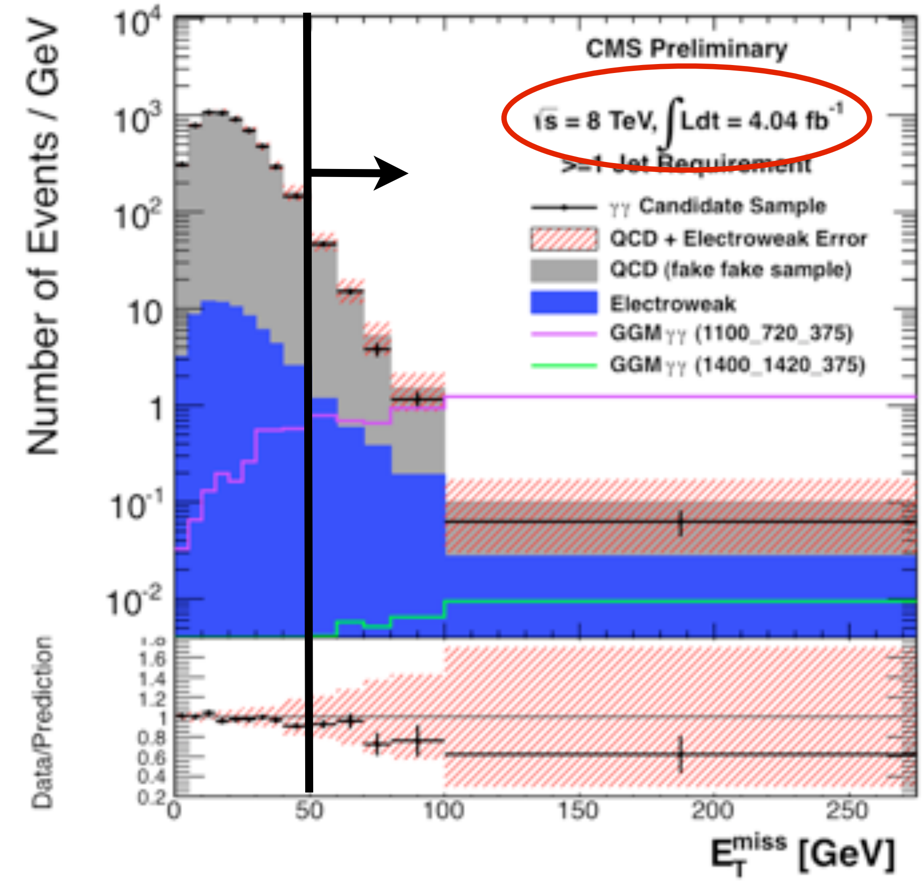


Rolling this all together...

2011 7 TeV



2012 8 TeV

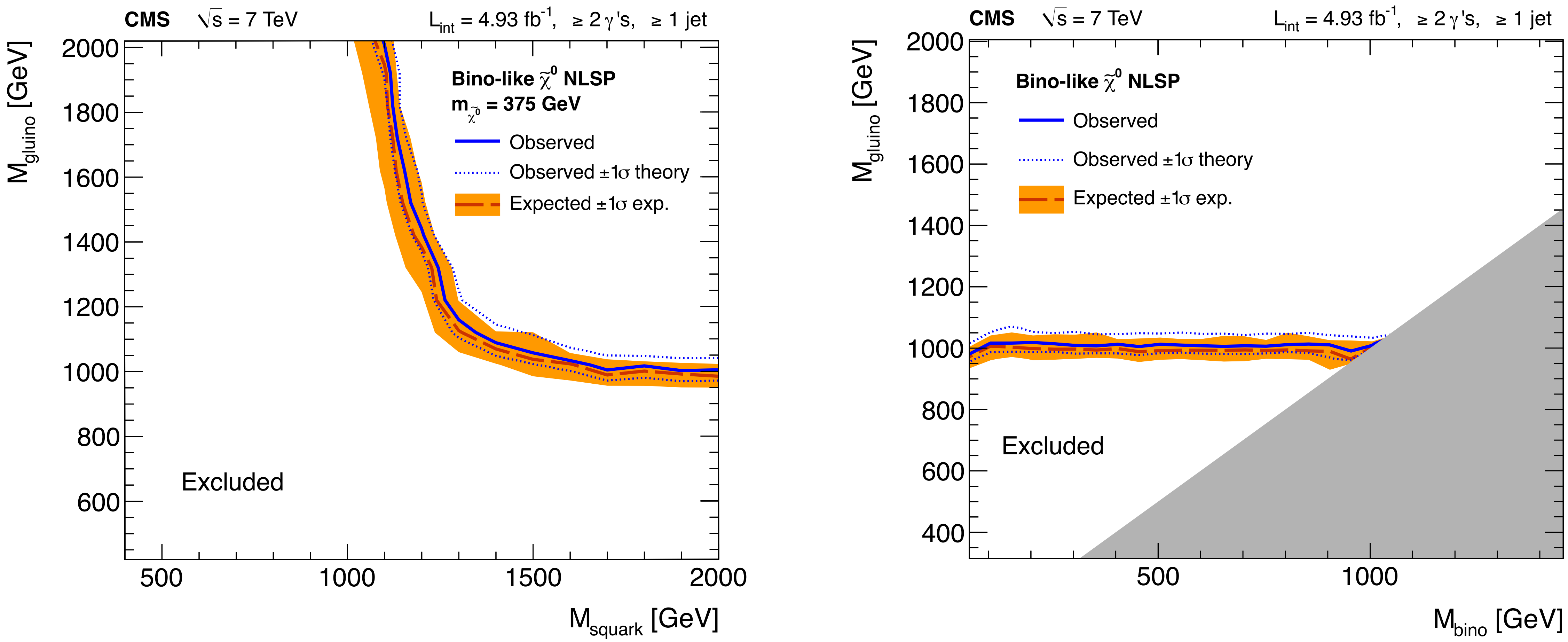


- These are the missing transverse energy spectra from the 2011 data (left) and now 8 TeV 2012 data (right). Signal regions indicated by black lines.
  - Both have examples of SUSY signals superimposed -- the signal would manifest as an excess at high MET.
- We see excellent agreement between observations and the data driven background estimates -- so we proceed to set limits on the theory:

GGM Interpretation

- In both the single and diphoton searches our candidates are in very good agreement with our background estimates -- we observe no excess.
- We then provide CLs limits in the context of GGM SUSY by performing counting experiments (individually within the diphoton and single photon analyses) in 6 bins at high ME_T.
  - 2-D scans performed across pairs of model parameters (gaugino and squark masses) Using models from *Y. Kats et al* http://arxiv.org/abs/1110.6444
    - For each pair we generate thousands of MC events to calculate our acceptance
    - 1st & 2nd generation squark vs gluino mass (with neutralino mass at 375 GeV)
    - gluino vs neutralino (bino) mass (squarks decoupled at 2500 GeV)
  - Squarks assumed ~degenerate
  - All other masses decoupled (3500 GeV)
  - Prospino cross sections and PDF uncertainties according to PDF4LHC

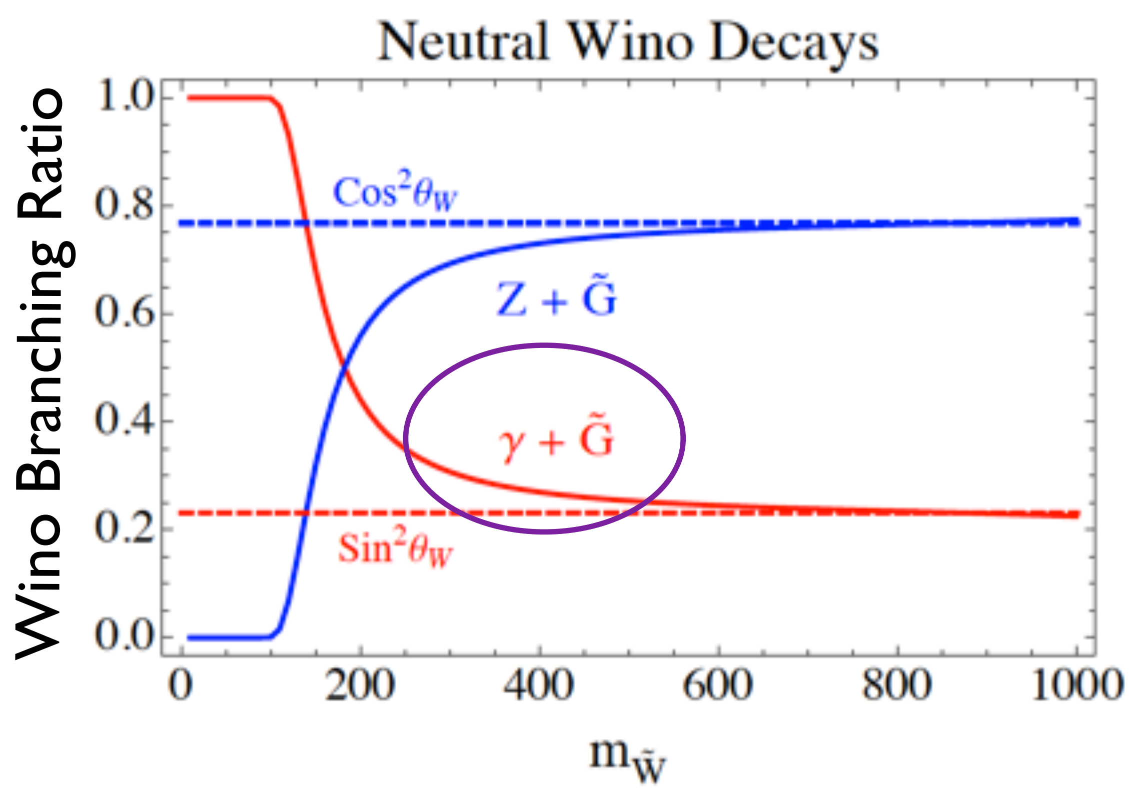
Squark-gluino and gluino-bino planes



- A statement we can make here:
    - Within GMSB with a bino-like NLSP gluinos < ~1.0 TeV and squarks < ~1.1 TeV are incompatible with our observations
- Oh my. Is SUSY dead then?
- Well -- what if neutralinos aren't so bino-like? What if strong production doesn't dominate?

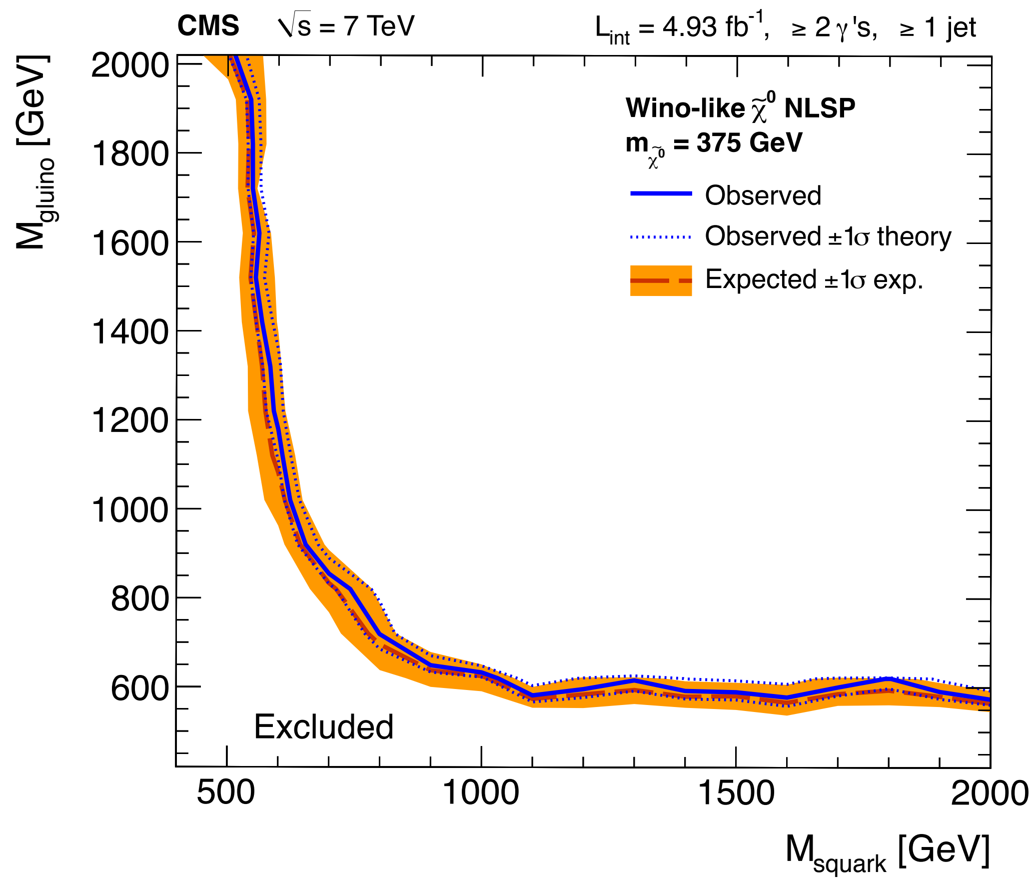
The not so low berries...

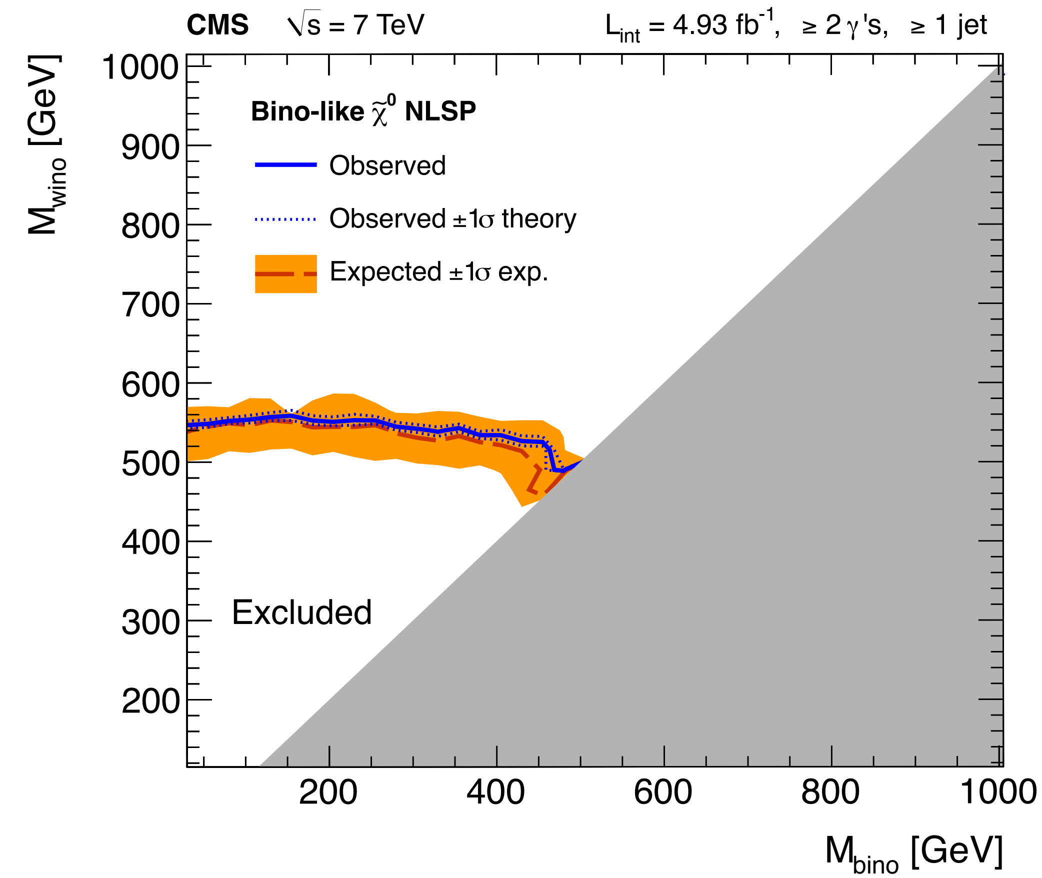
- Although not dominant, wino-like neutralino NLSP's have a fair shot at decaying to photons as well:



- So here we're taking a ~x4 hit in branching ratio, but still have sensitivity if neutralinos were wino-like:

More interpretation!

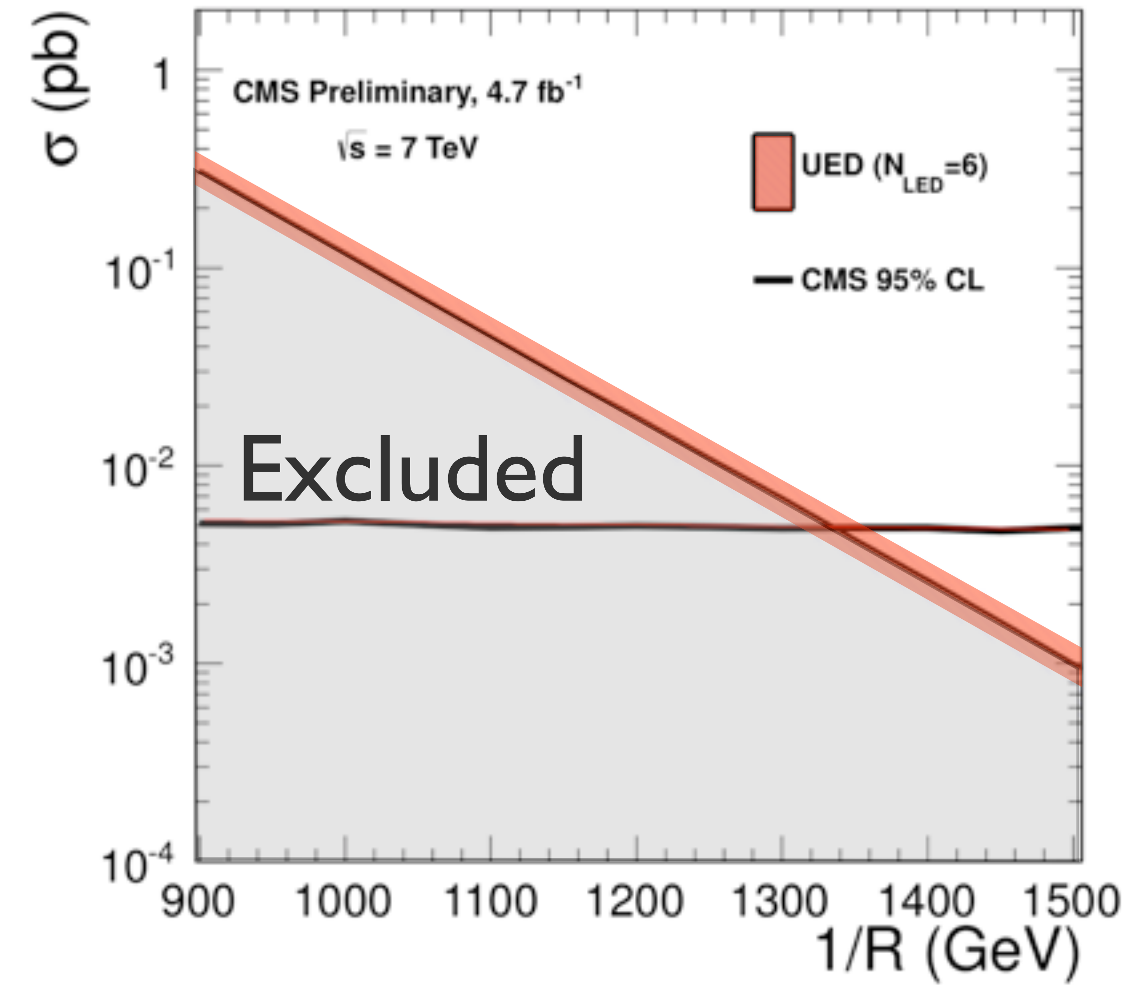




- On the left we see our squark-gluino plane, now assuming a completely wino-like neutralino. We exclude less, because we're less likely to get photons in the final state.
    - But wait -- aren't you hurting yourself by needing two photons?
    - YES! -- we'll deal with that in a few slides
- On the right we assume BOTH squarks and gluinos have high masses, then look in wino vs squark mass -- Limits on EW production!

Universal Extra Dimensions Interpretation

- One can construct similar event topologies as GGM SUSY through Universal Extra Dimensions
  - Kaluza-Klein excited states ("towers") could be produced, at LHC predominantly through strong interactions
  - These excitations decay, producing particles and jets, not entirely unlike a SUSY cascade, leading down to the lightest Kaluza-Klein particle, in this case a photon.
  - The UED space is embedded a space with N Large Extra Dimensions (LEDs) where only a graviton may propagate.
  - The KK photon then decays gravitationally to a photon + graviton, which then results in ME_T.

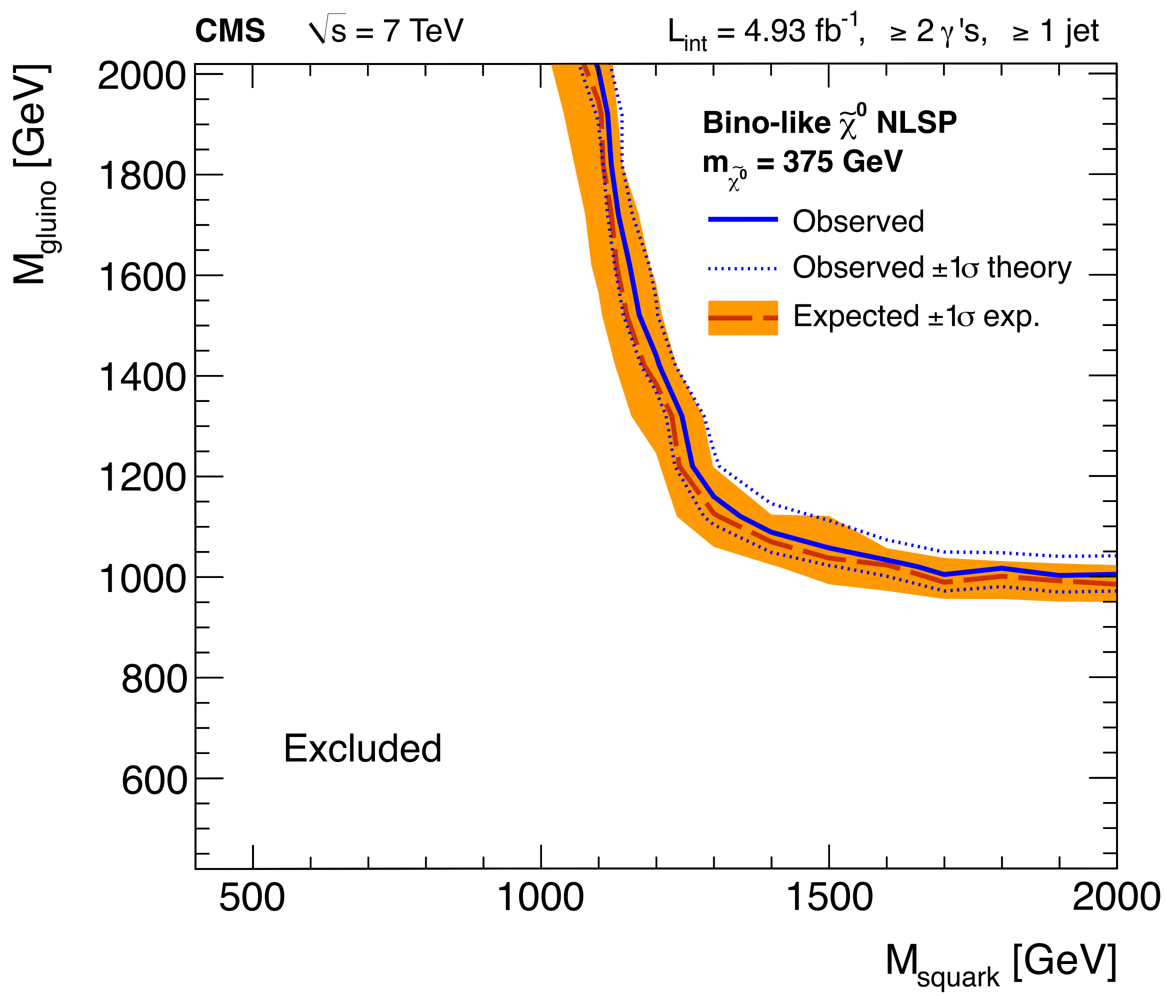


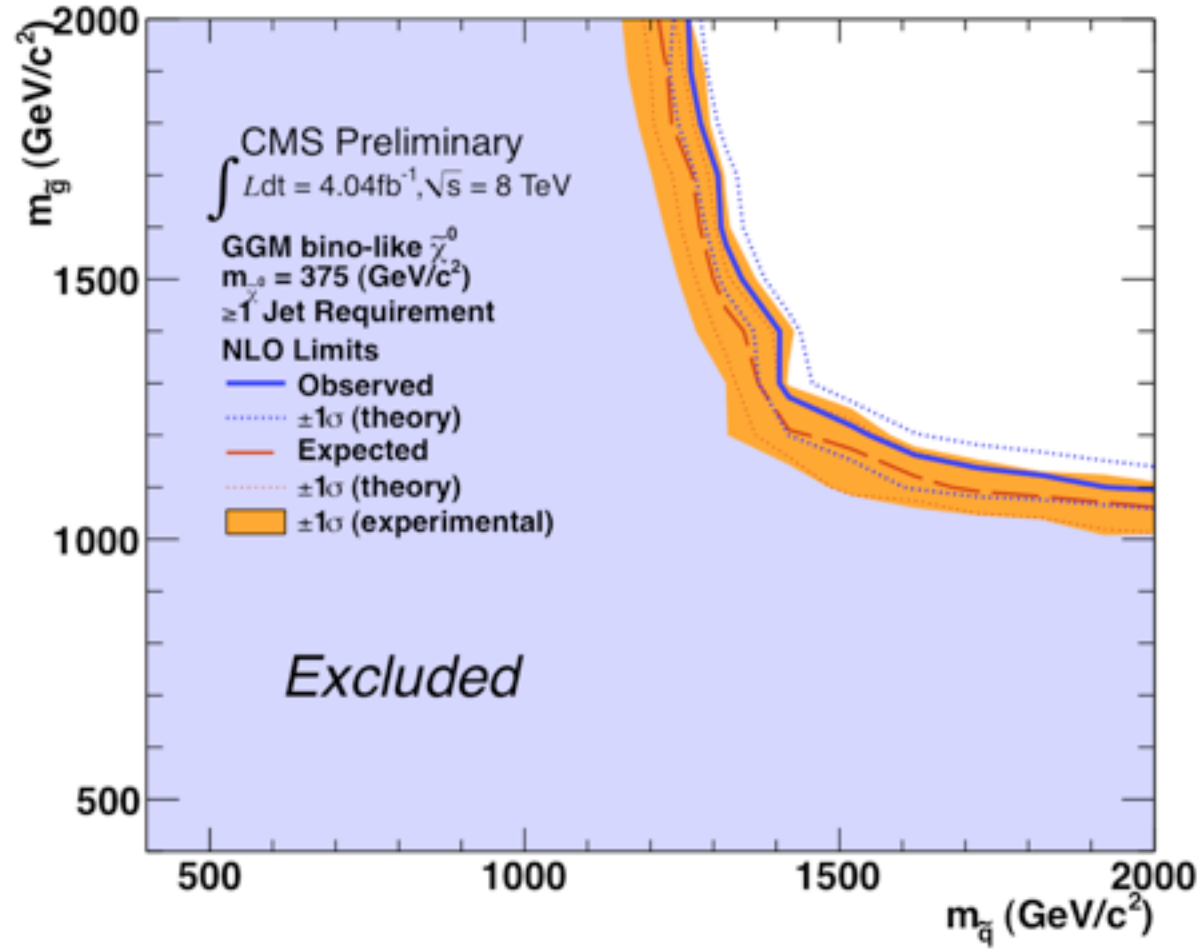
UED cross section upper limit for 6 Large Extra Dimensions. R is the radius of compactification, the UV cutoff, Λ, is ΛR=20, M_D, (N+1) dimensional Planck scale = 5 TeV, #KK excitation quark flavors = 5

1/R < 1335 GeV excluded

What do we see at 8 TeV?

- With data now rapidly coming in at 8 TeV, this summer we've already taken a peek at what the factor of 2 this buys us in the cross section:





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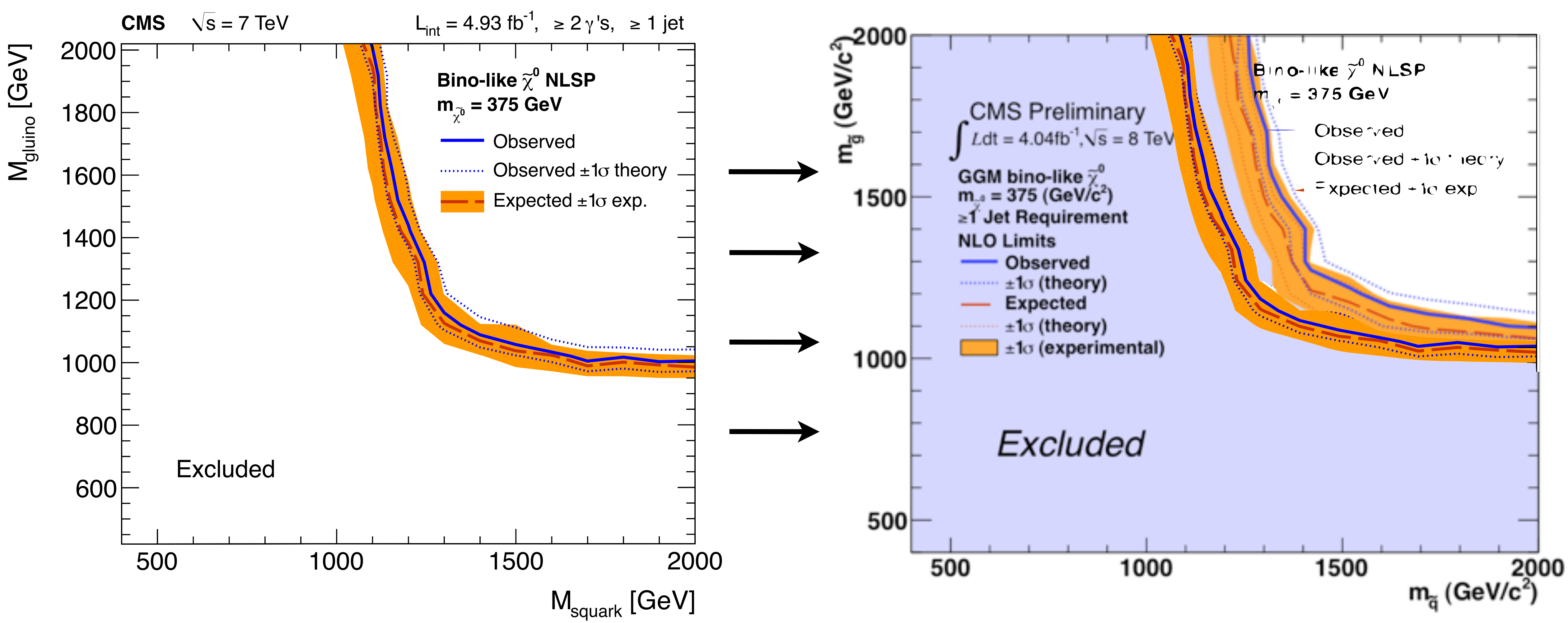
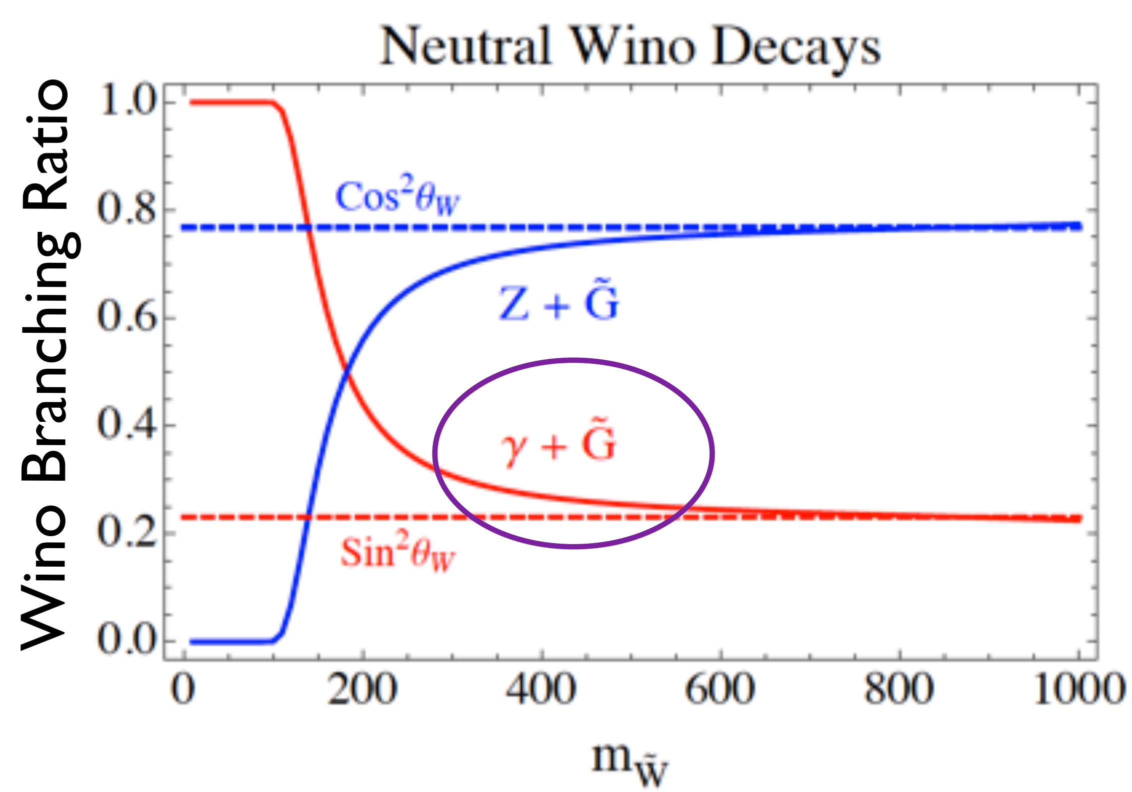


- Even at slightly less luminosity, exclusions move 100-150 GeV higher

- As of today we've recorded almost 14/fb! Stay tuned!

Back to our wino-like case...

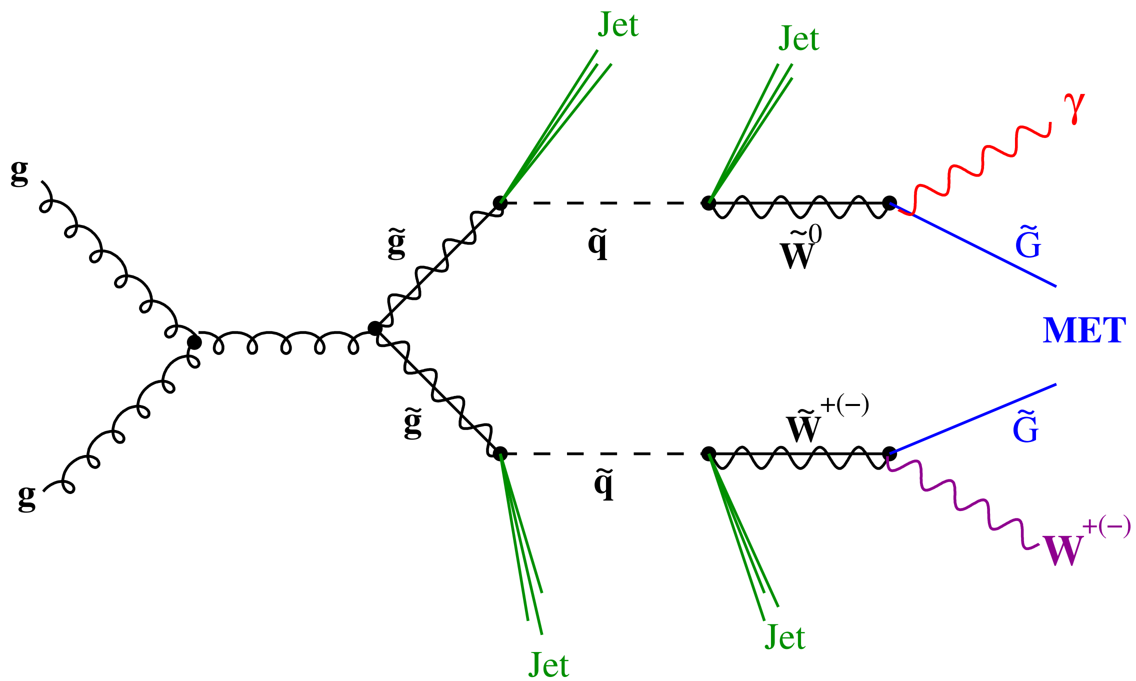
- As we saw a couple slides ago, we are less sensitive to models less likely to produce photons:

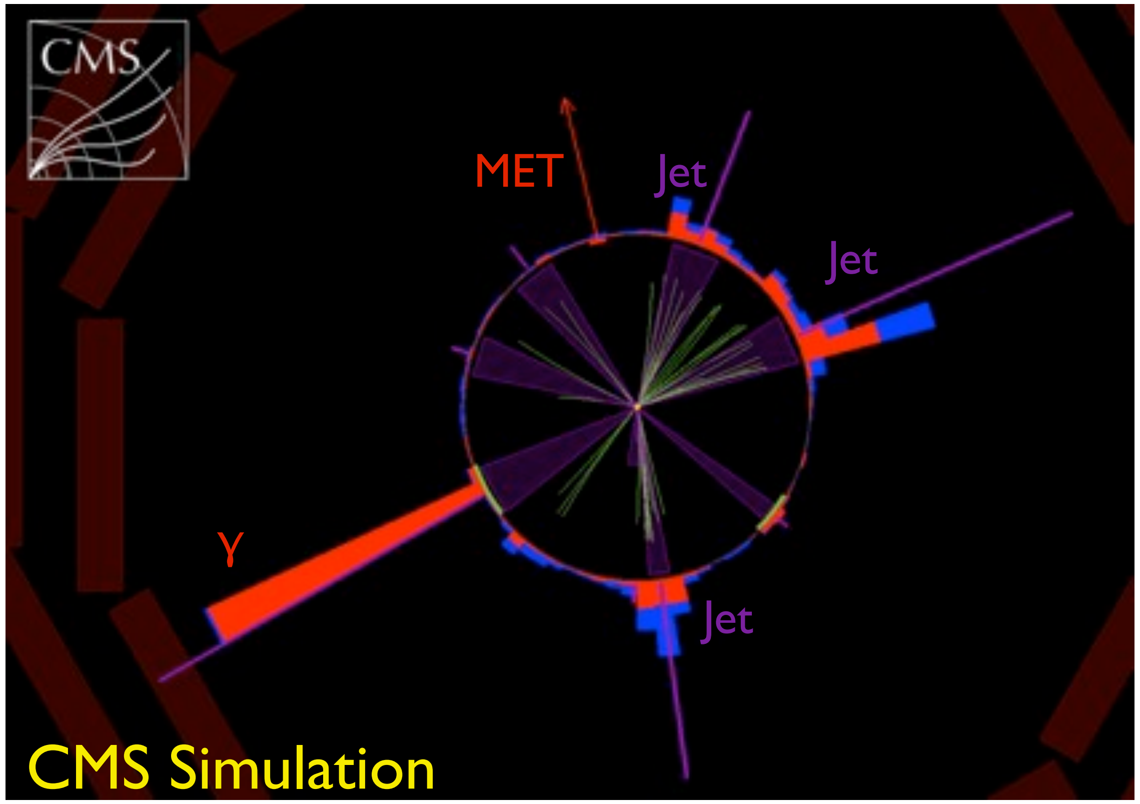


- So instead of assuming BOTH NLSP's produce a photon, lets take 2 runs at it -- assume AT LEAST ONE NLSP produces a photon.

- Instead we search for at least one photon, some jets and ME_T

Photon + Jets + ME_T

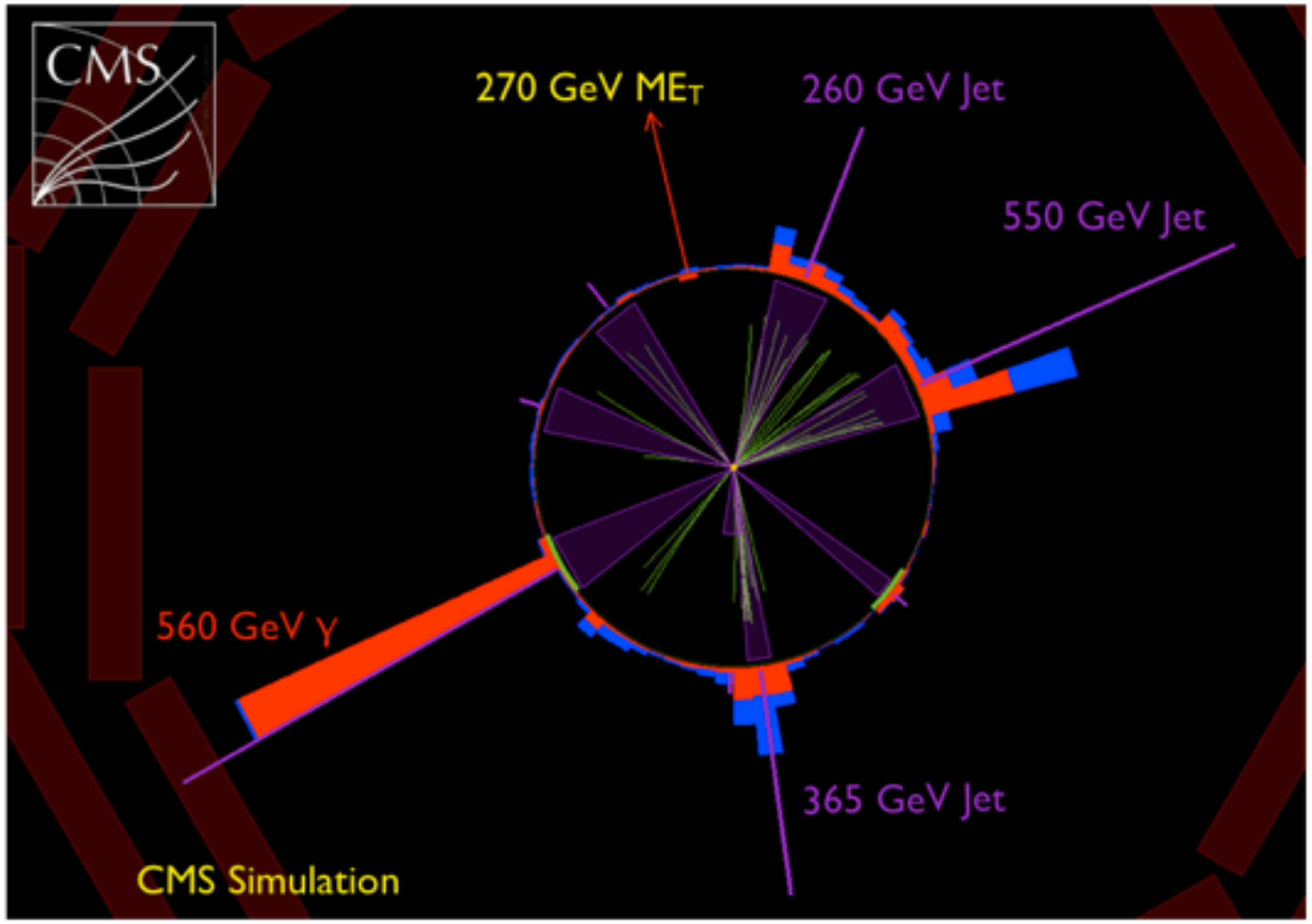




- Here we're targetting a wino-like neutralino/chargino co-NLSP.
  - Branching ratio favors EW bosons over photons -- search for at least one photon with several jets. (though this is inclusive I will be calling this the "single photon" search)
  - SM backgrounds are larger, must suppress by increasing energy thresholds and requiring more jets.
- CMS first to extend SUSY photon based searches to winos!

Event Selection

- At least one candidate photon
- photon p_T > 80 GeV, in barrel
- H_T > 450 GeV*
- NJets ≥ 2, $|\eta|<2.4$



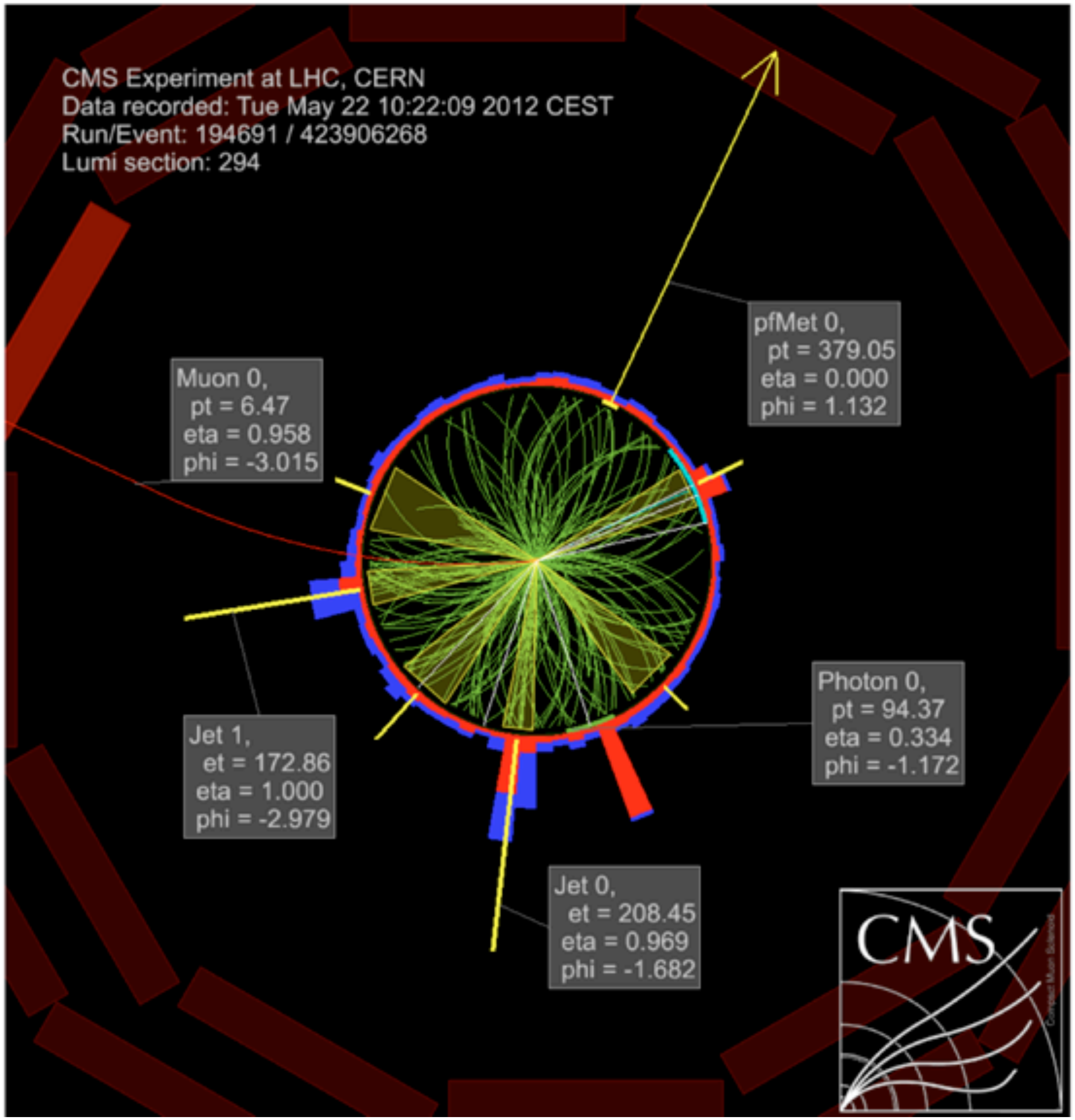
A simulated m_{gluino}=1200 GeV, m_{squark}=1250 GeV, m_{bino}=225 GeV signal event

* H_T is the scalar sum of transverse energies of the photon, and the jets with p_T>30 GeV, $|\eta|<2.6$ that have $\Delta R>0.3$ from the photon or an isolated lepton

“Single” Photon Background Estimates

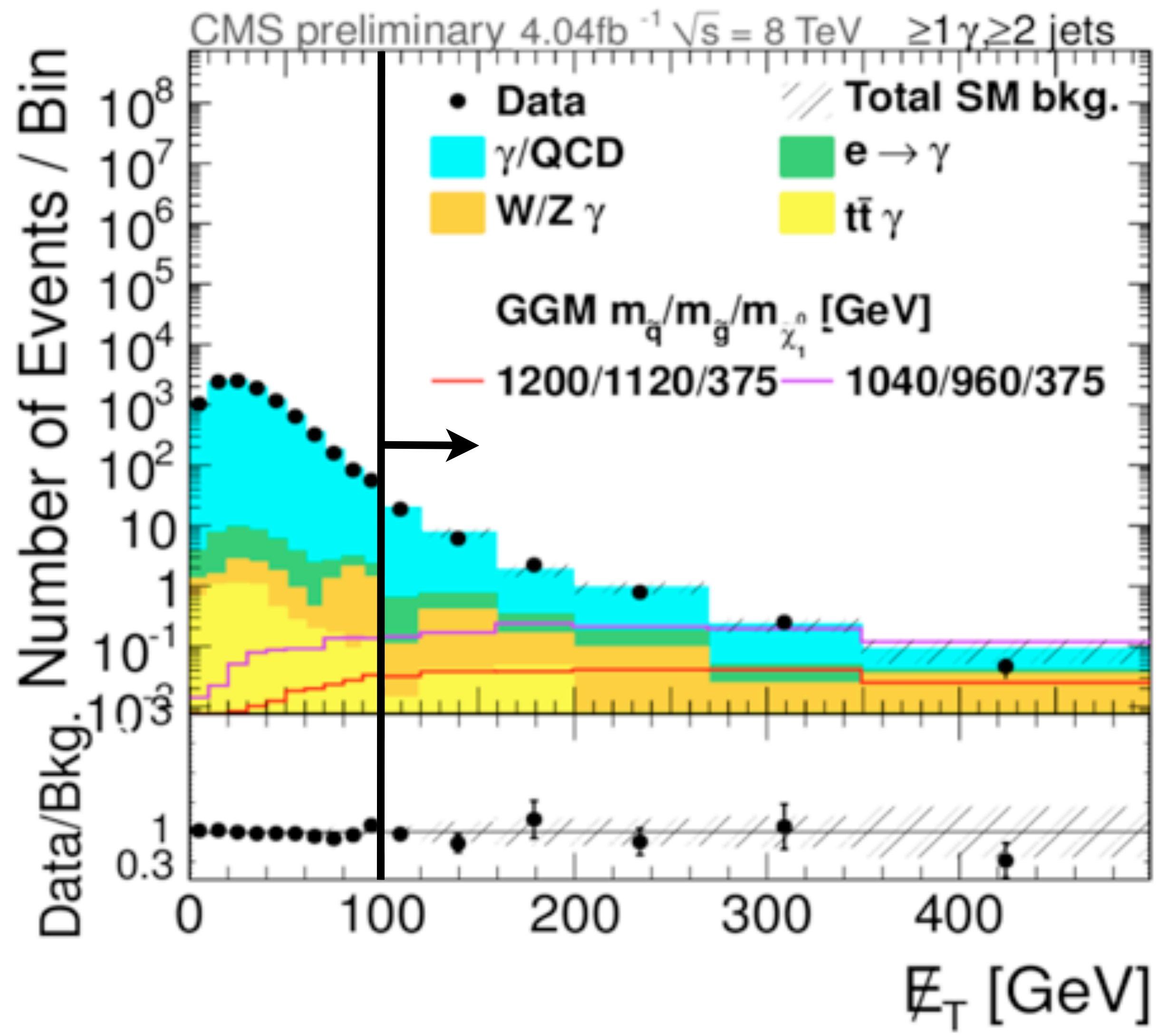
- Dominant background from multijets where jet “fakes” a photon, and QCD photon + jets. Non-intrinsic MET
- Analogous to the diphoton analysis, use the “fake” photon + jet sample
  - Reweight by photon p_T, using ratio in shapes between candidates and fakes in ME_T<100 GeV region. (Here shape and scaling magnitude are the same step)
    - Individual shape ratios for jet multiplicities =2 jets and ≥ 3 jets
- Intrinsic ME_T also analogous to diphoton -- electron-jet sample scaled by fake rate.
  - For photon p_T>80 GeV fake rate is determined to be 0.6 ± 0.25%
- Irreducible background due to ISR/FSR estimated from W+Jets and ttbar MC
  - Very small, and take 50% systematic

Candidate "Single" Photon Event



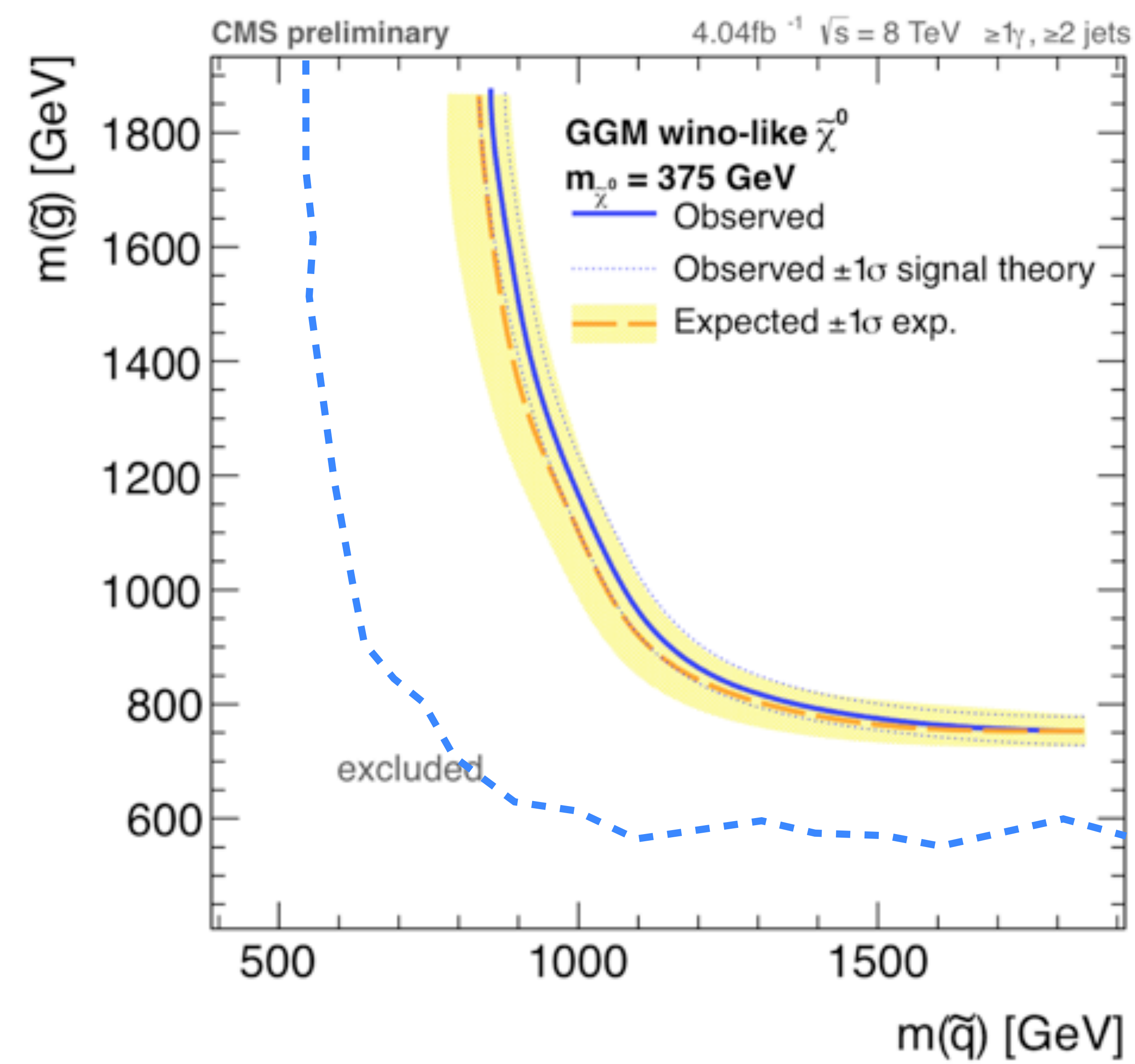
"Single" Photon Results

- The MET distribution from 8 TeV is shown on the right
  - Dominant QCD in blue, and EWK from e→γ (green) are measured from the data.
  - W/Z and ttbar from MC estimates
- Black line shows signal region
- Very good agreement between candidates (black points) and background estimates
- With this we set 95% CL limits on the theory



Wino-like neutralino results

- In yellow at the right is the resulting exclusion contour from the single photon search from 4/fb at 8 TeV.
- Shown in dotted blue are the results from the diphoton search.
- Between the two analyses we can now say that we exclude squarks to about 900 GeV, and gluinos to ~800 GeV irrespective of neutralino being wino or bino-like.
- Both of these results however are relatively simple "cut & count" searches based on MET.
- We can push on the event kinematics further to try to improve sensitivity.

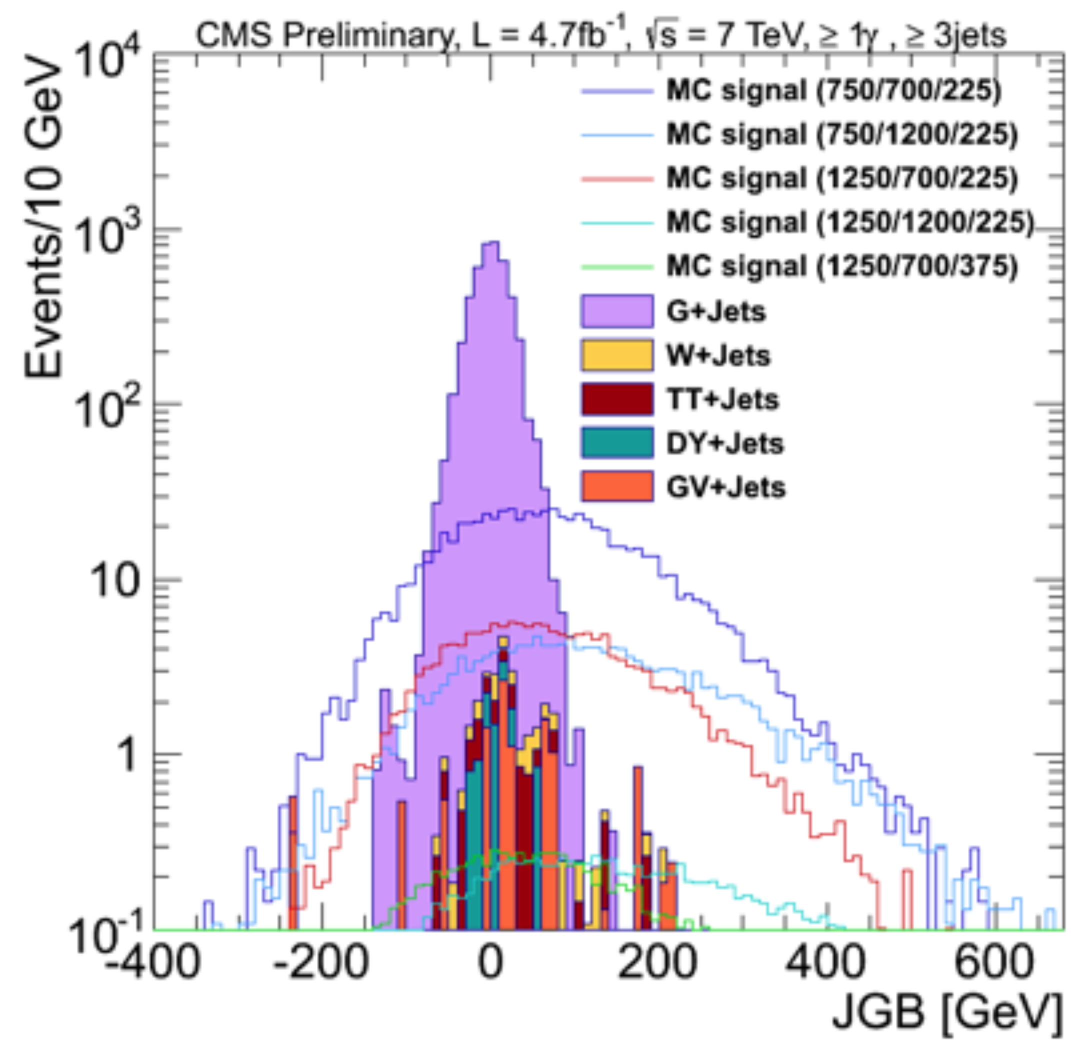


Jet-Gamma Balance Search

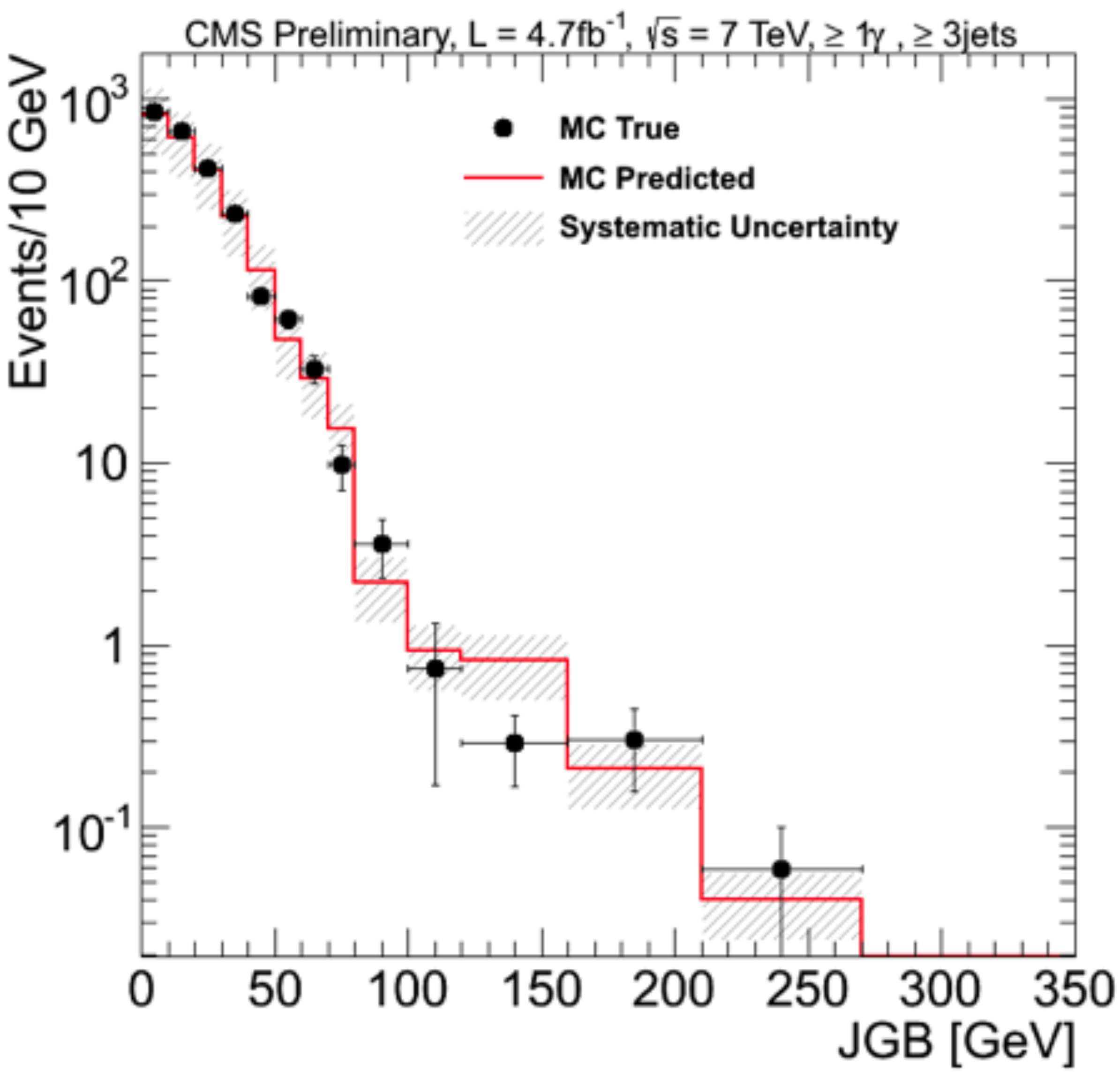
- Uses the "JGB" variable to reduce background:

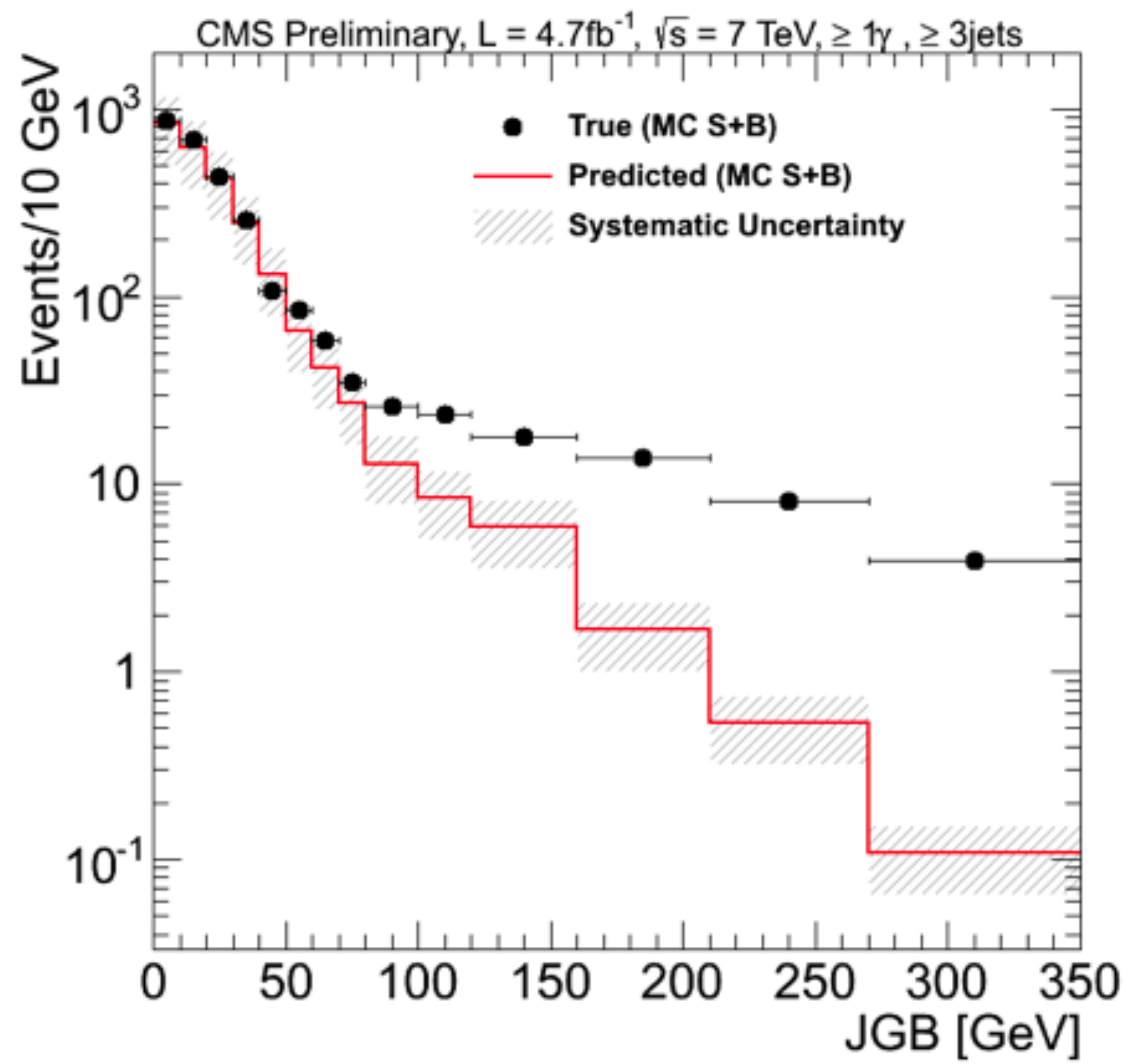
$$\mathrm{JGB} = |\sum_{\mathrm{jets}} \overrightarrow{P_{\mathrm{T}}}| - P_{\mathrm{T}}^{\mathrm{photon}}$$

- Can think of it as "MET with sign"
- MC simulation of backgrounds (solid) with SUSY signal (hollow histograms) shown at right.
- SUSY signals will tend to have an asymmetric JGB distribution, with an excess on the positive side.
- QCD will have a symmetric distribution.
  - Use negative side of distribution to predict the QCD background -- measured from data
- Less significant EWK backgrounds with MET will reach into the positive side of the distribution. These backgrounds estimated from MC simulation



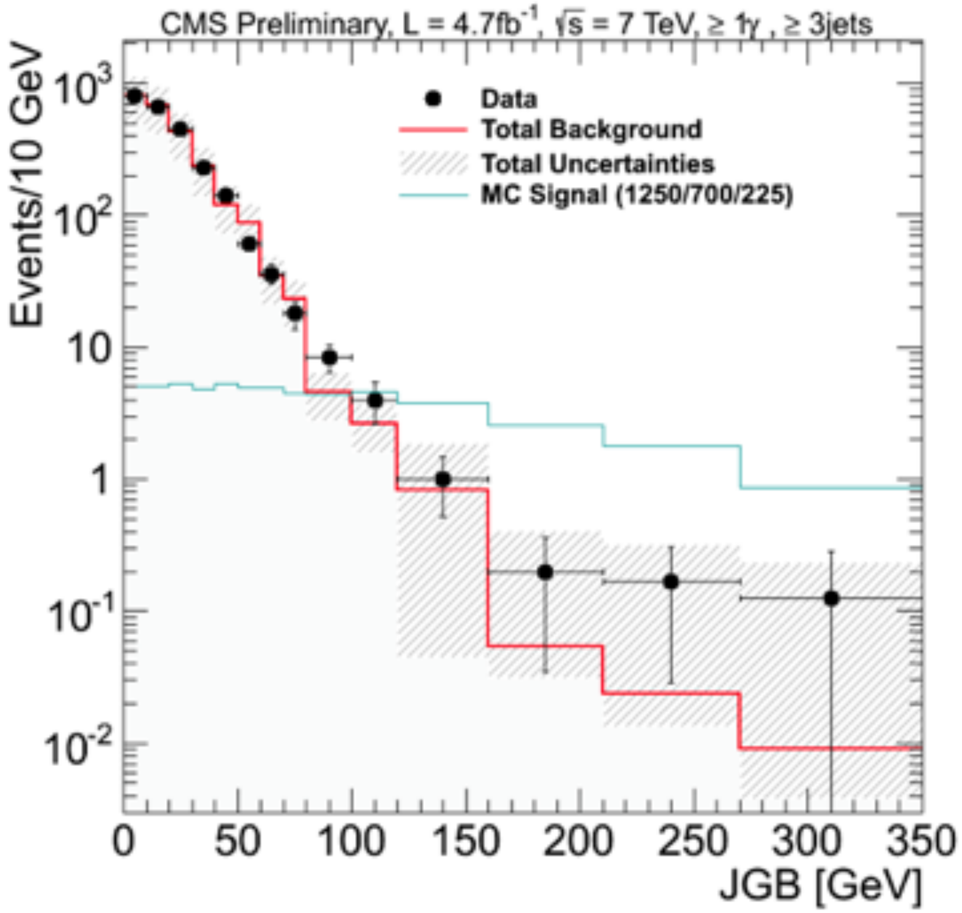
MC Closure tests

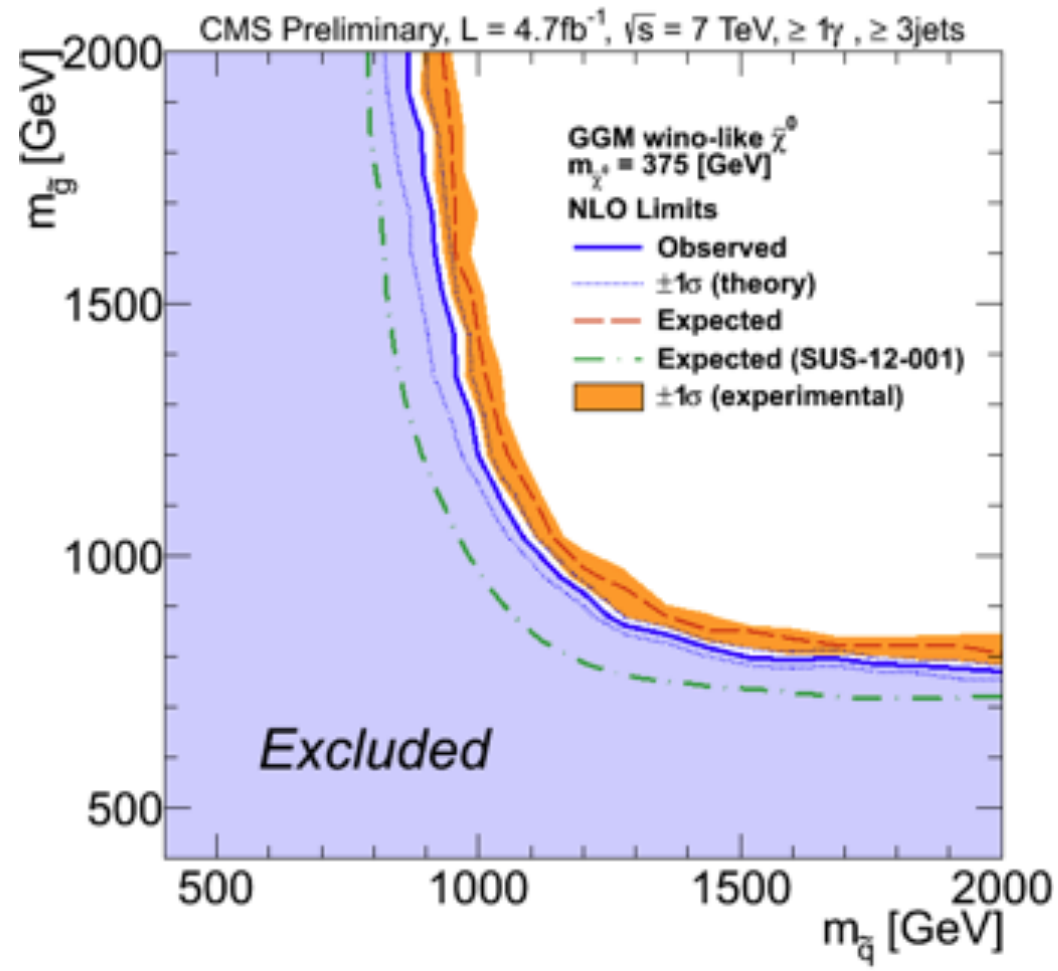




- JGB distributions both without a signal injected (left) and with a signal.
  - Some signal contamination, but signal clearly stands out from the background estimate.

JGB results

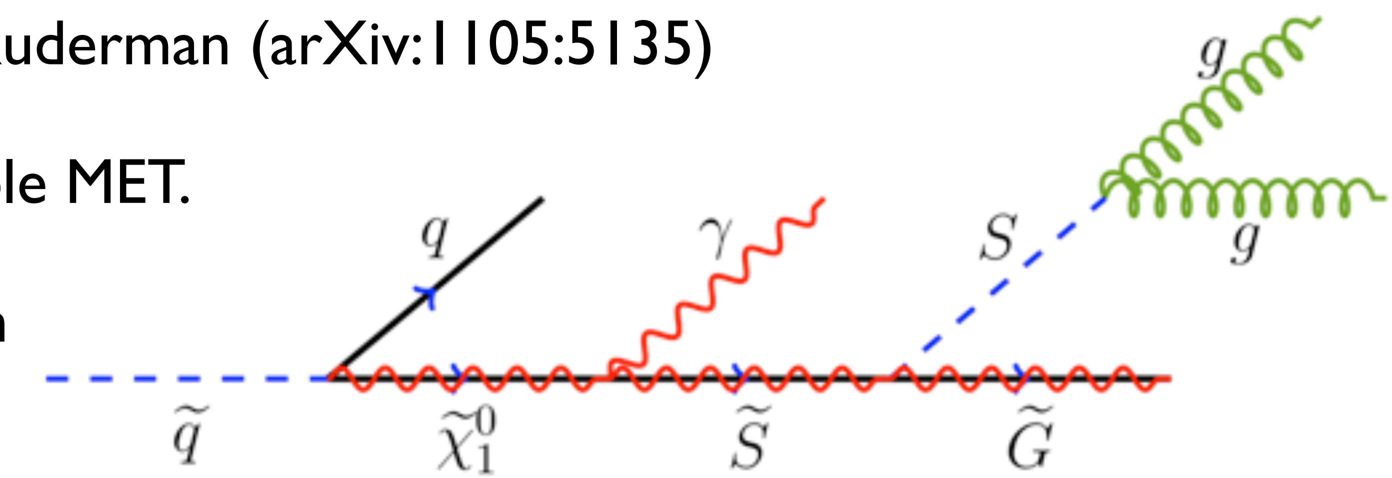




- Preliminary results from the 7 TeV data are shown above
- The candidate JGB spectrum (black points) matches well with the background estimate
- Technique allows further extension of the excluded region in the wino-like case. (7 TeV MET based analysis contour compared as the green dotted line)

"Stealth" SUSY

- The 3 analyses we have seen so far have excluded a fair amount of phase space.
- But in all of them we are relying on a significant amount of MET.
- What if SUSY is there, but has a spectrum without large enough mass splittings to allow for large MET -- these analyses would not be sensitive.
- Enter "Stealth" SUSY: Fan, Reece, Ruderman (arXiv:1105:5135)
  - Soft LSP gives small if not invisible MET.
  - Singlet state couples to a hidden sector



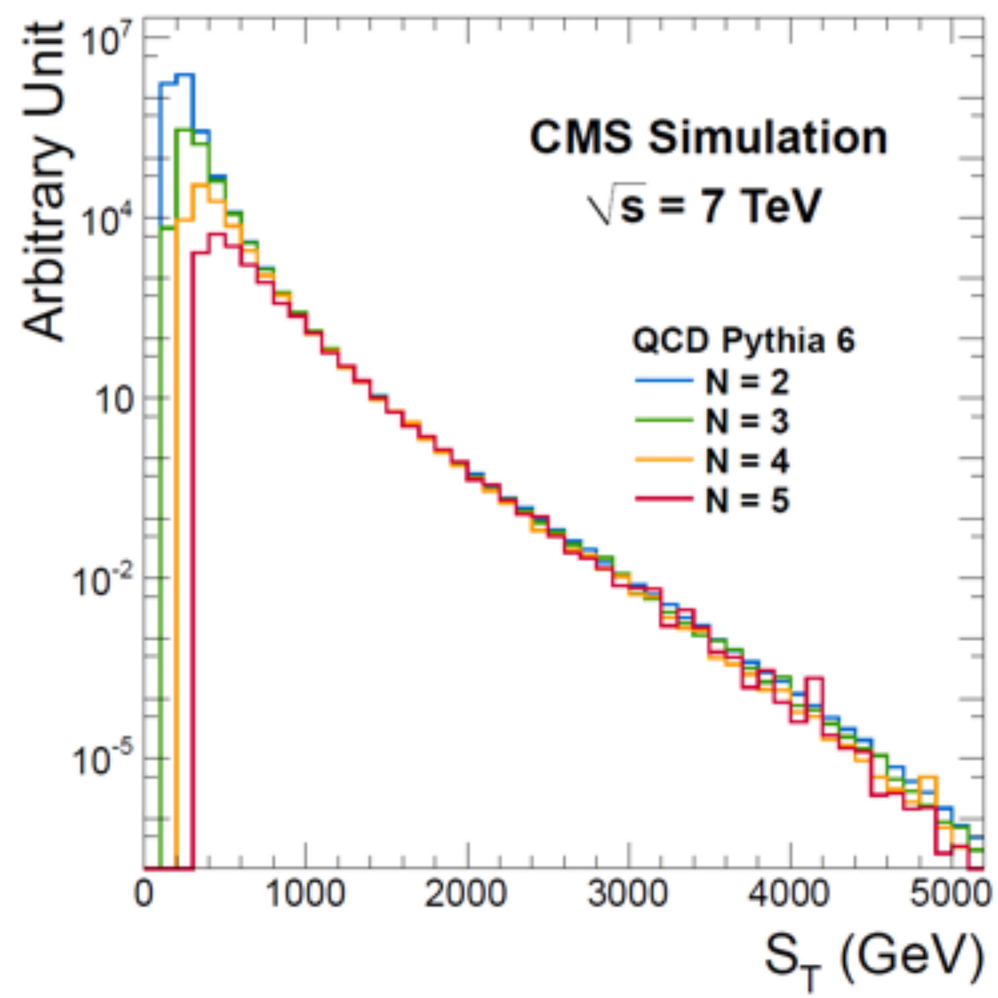
  - R parity still conserved -- pair of photons in the final state, jets from strong production and singlet decay.

S_T Scaling and Stealth SUSY

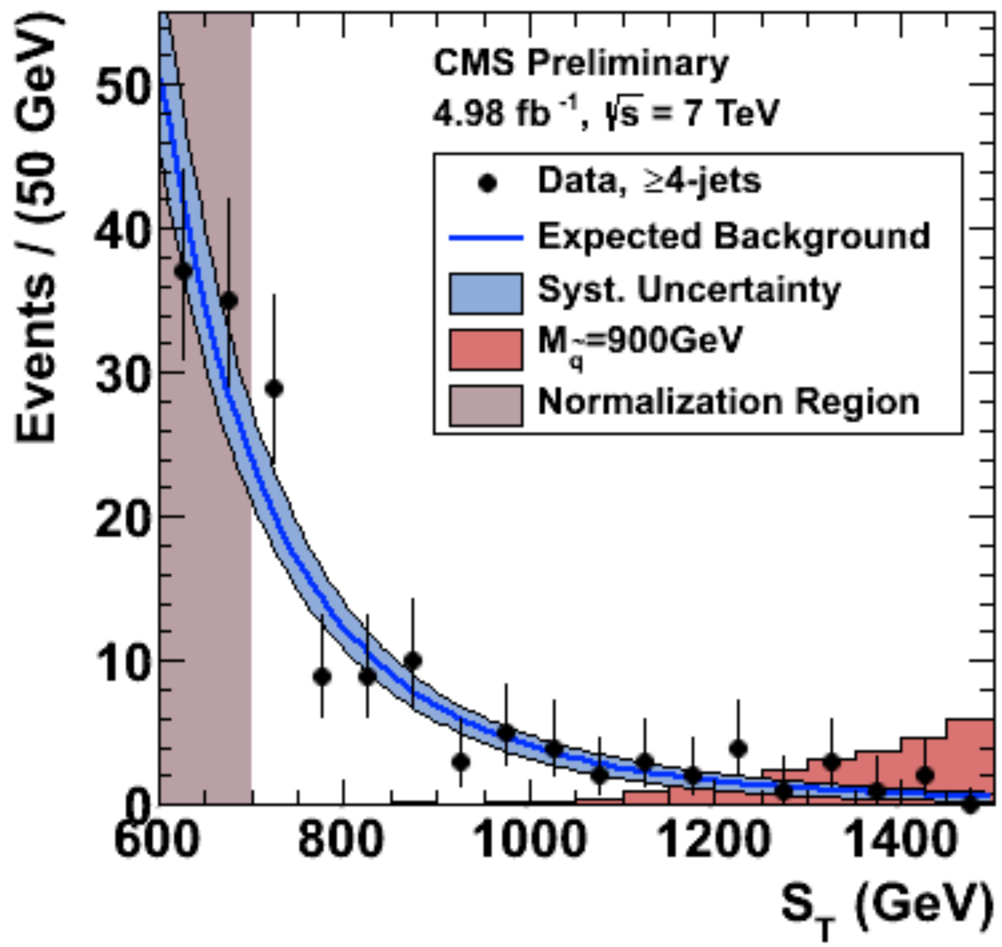
- Use scaling properties of S_T variable in QCD to estimate background (also used in CMS black hole search (JHEP04(2012)061)

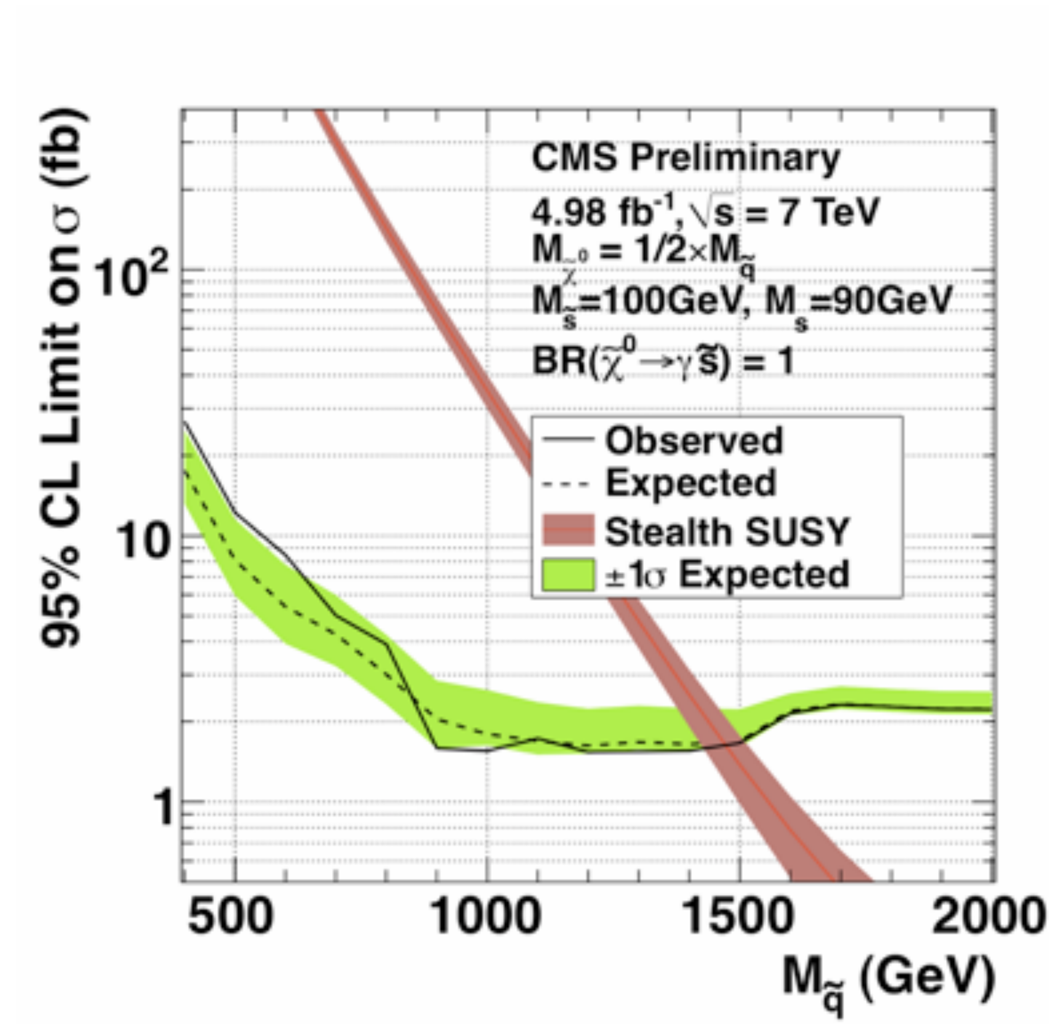
$$S_{\mathrm{T}} = E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{\mathrm{photons}} P_{\mathrm{T}} + \sum_{\mathrm{jets}} P_{\mathrm{T}}$$

- The scaling of this variable is independent of object multiplicity
- Allows us to use lower multiplicity data to estimate background for higher multiplicity data, where signal is expected to be.
- Define search region in diphoton events with at least 4 jets and S_T>700 GeV
- Obtain background from 2-3 jet data, S_T > 600 GeV
- Normalize bkg estimate to 600 > S_T > 700 GeV in search region.



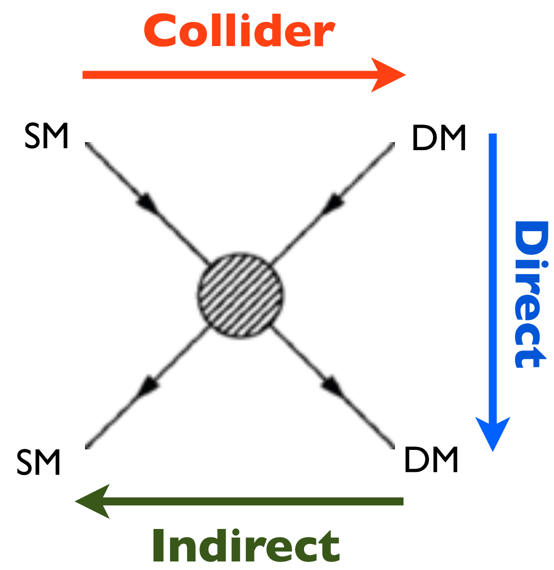
Stealth SUSY Results





- Search region and background estimate (blue) shown at left -- black points are from candidate sample. Pink appearing at higher S_T is superposed signal MC.
- 95% CL exclusion contour in squark mass shown at right
  - Squarks < 1430 GeV excluded in this search.

Dark Matter and Large E.D. searches

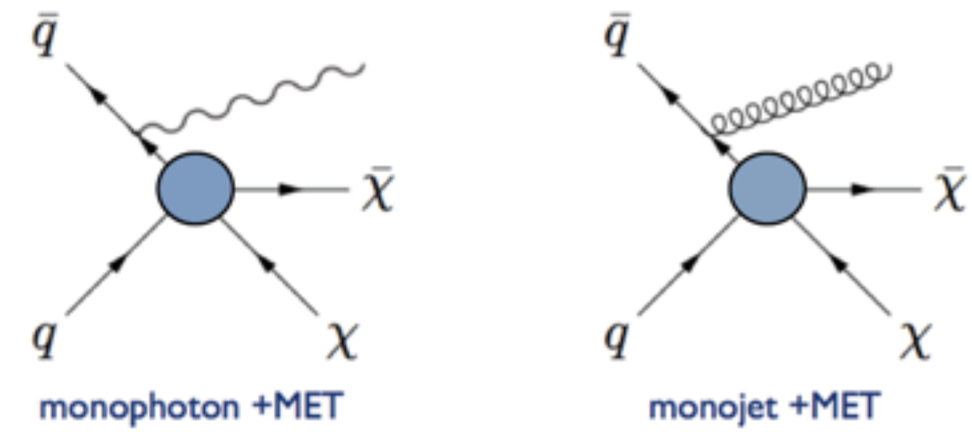


A generic DM interaction with SM particles

- Collider searches for production of dark matter (DM) adds a 3rd front to Direct (i.e. DM → nucleus) and Indirect (i.e. detecting DM annihilation products) DM search techniques

- Dark matter, if a particle, necessarily would be a weakly interacting thing, and potentially massive. A SUSY LSP could be a nice candidate.

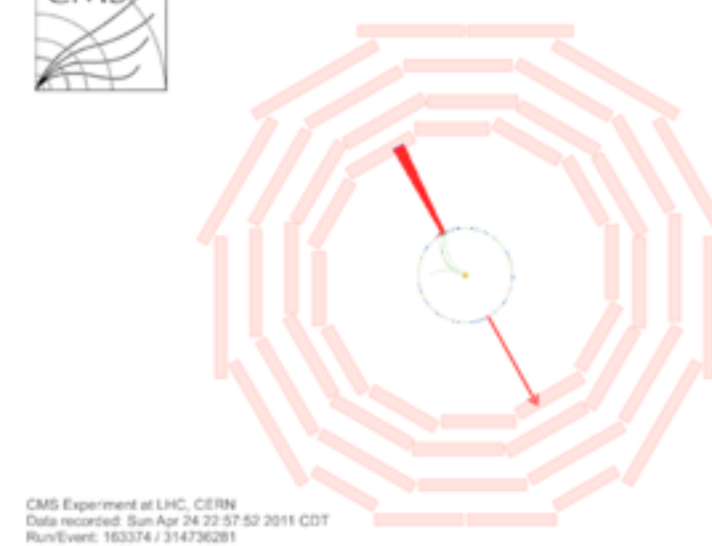
- Can potentially detect direct production of DM candidates through ISR/FSR radiation.



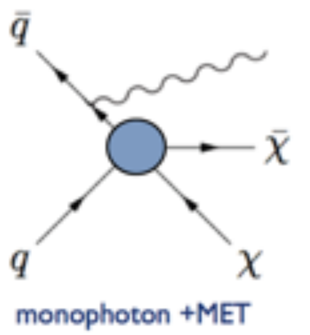
- Do this through mono-object (photon and jet) searches.

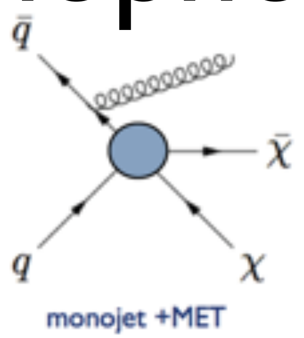
- Monophoton search: http://arxiv.org/abs/1204.0821 -and- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11096

- Monojet search: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012

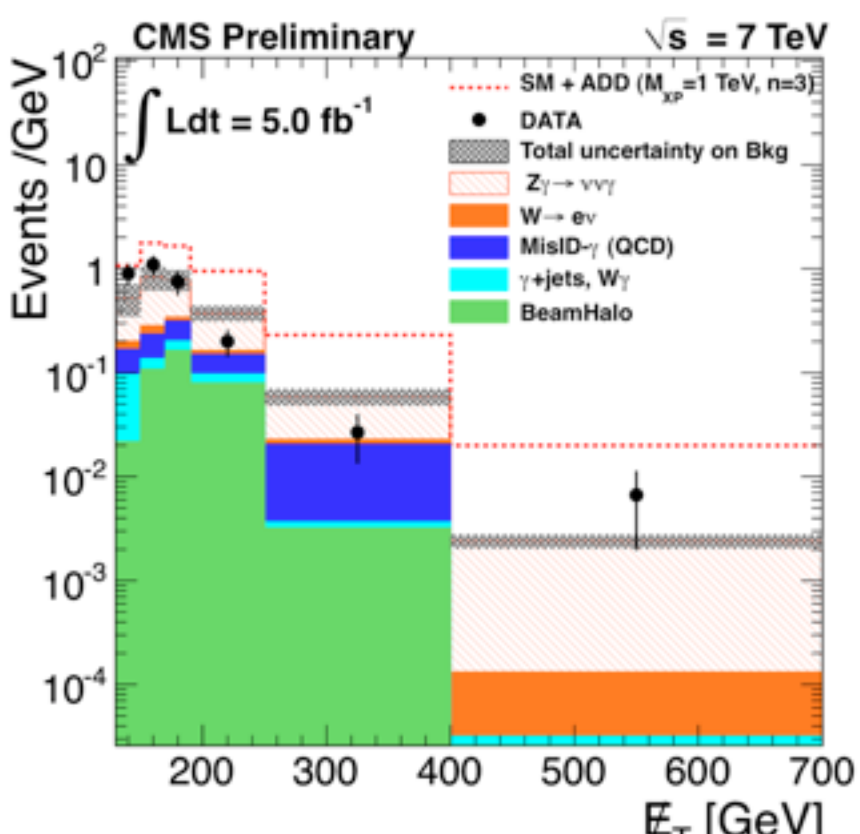


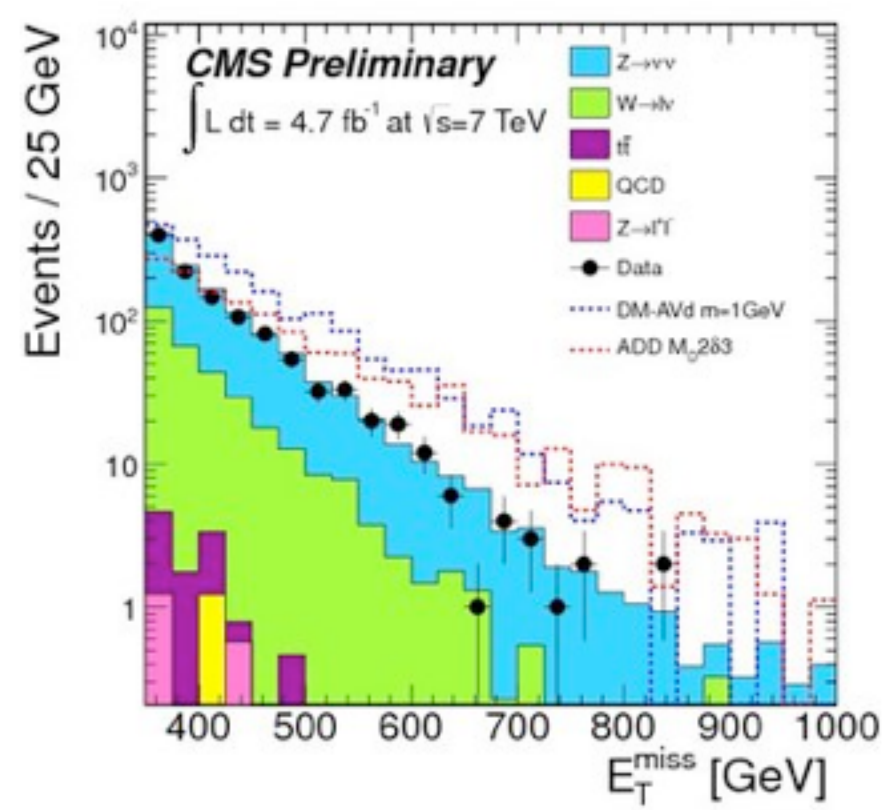
Monophotons and Monojets + missing E_T

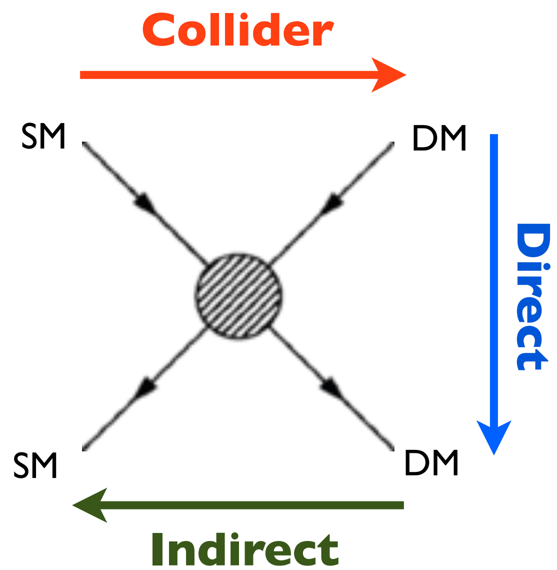




- The dark matter particles would be undetected, and therefore manifest in missing transverse energy.
- Monophoton events are required to have photon E_T > 145 GeV and MET > 130 GeV. Monojets it they must be 110 GeV with MET > 200 GeV.
- Counting experiments are then performed (MET plots below), signal points for ADD extra dimension G+γ and G+jet production, as well as DM signal are included as dotted lines

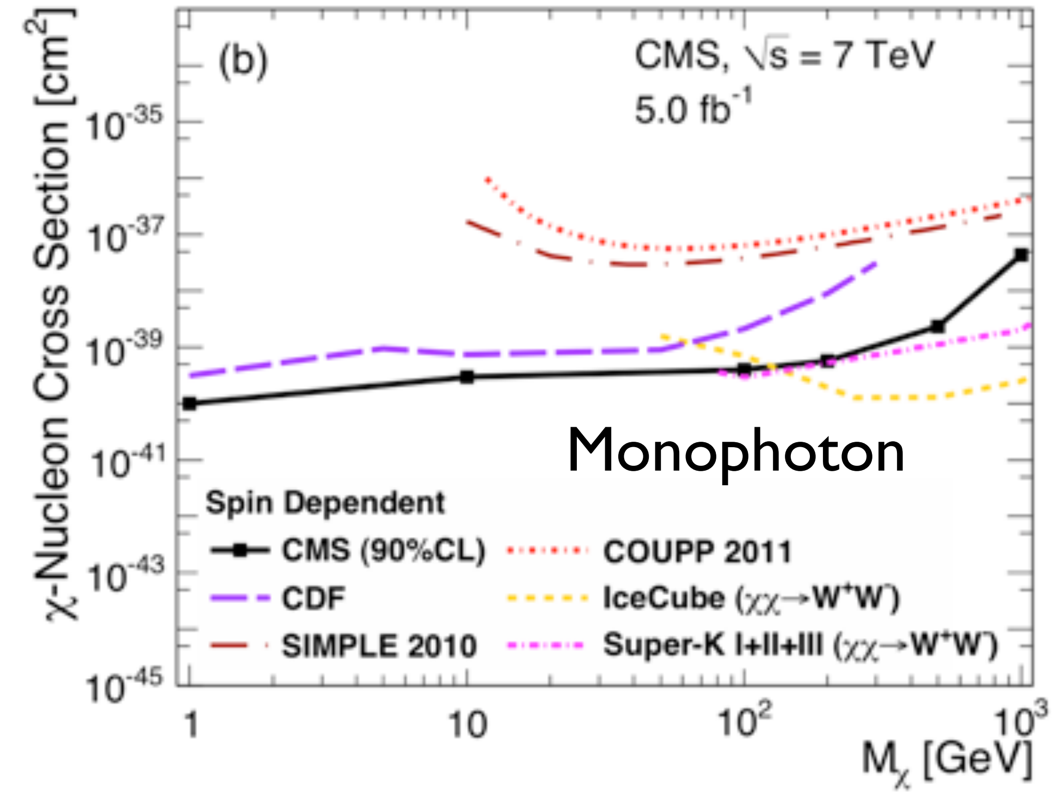


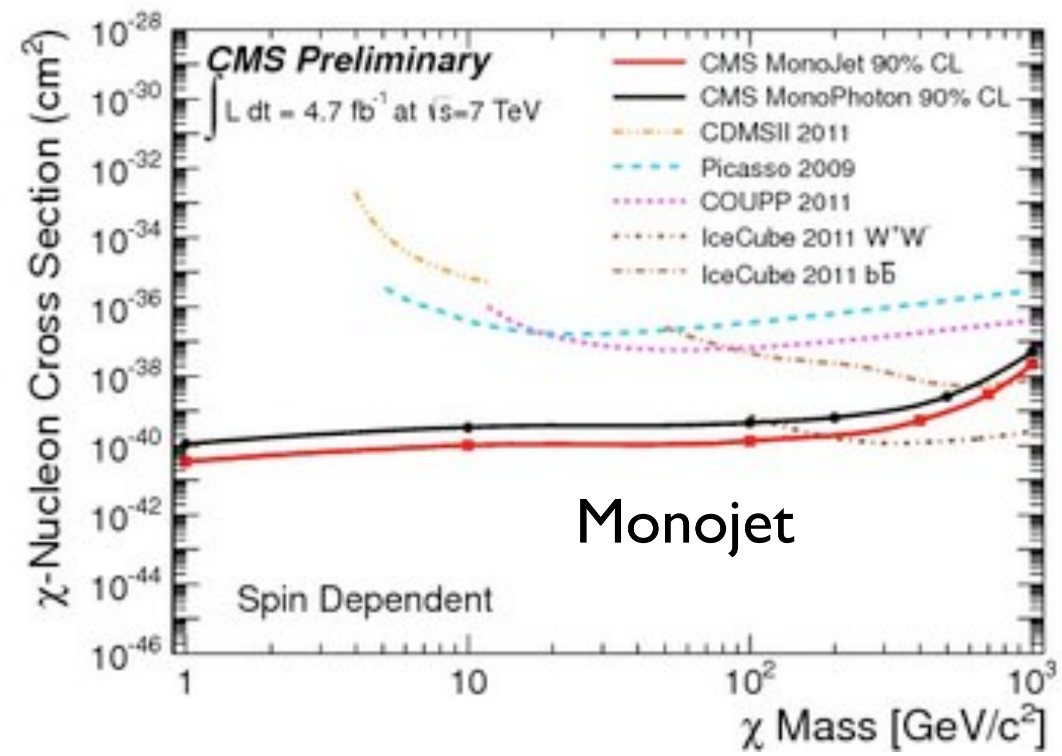




Results compared to other experiments

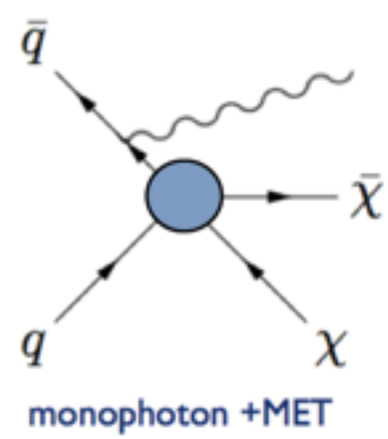
- Data agrees with SM backgrounds
- 95% CL limits for photon (top) and jet (bottom) analyses
- Results are mapped to χ-nucleon cross section vs χ mass to compare to direct and indirect DM search experiments
- CMS is adds additional constraints for low mass DM
    - Constrains spin dependent cross section several orders of magnitude
    - In region hard to reach by direct experiments!

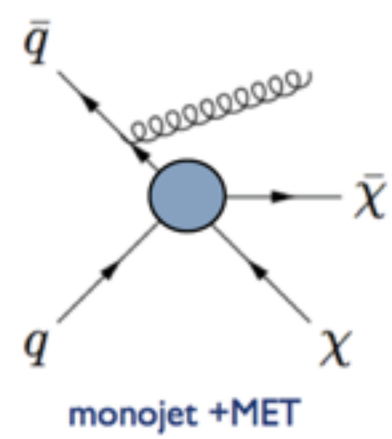




Why did I talk about that?

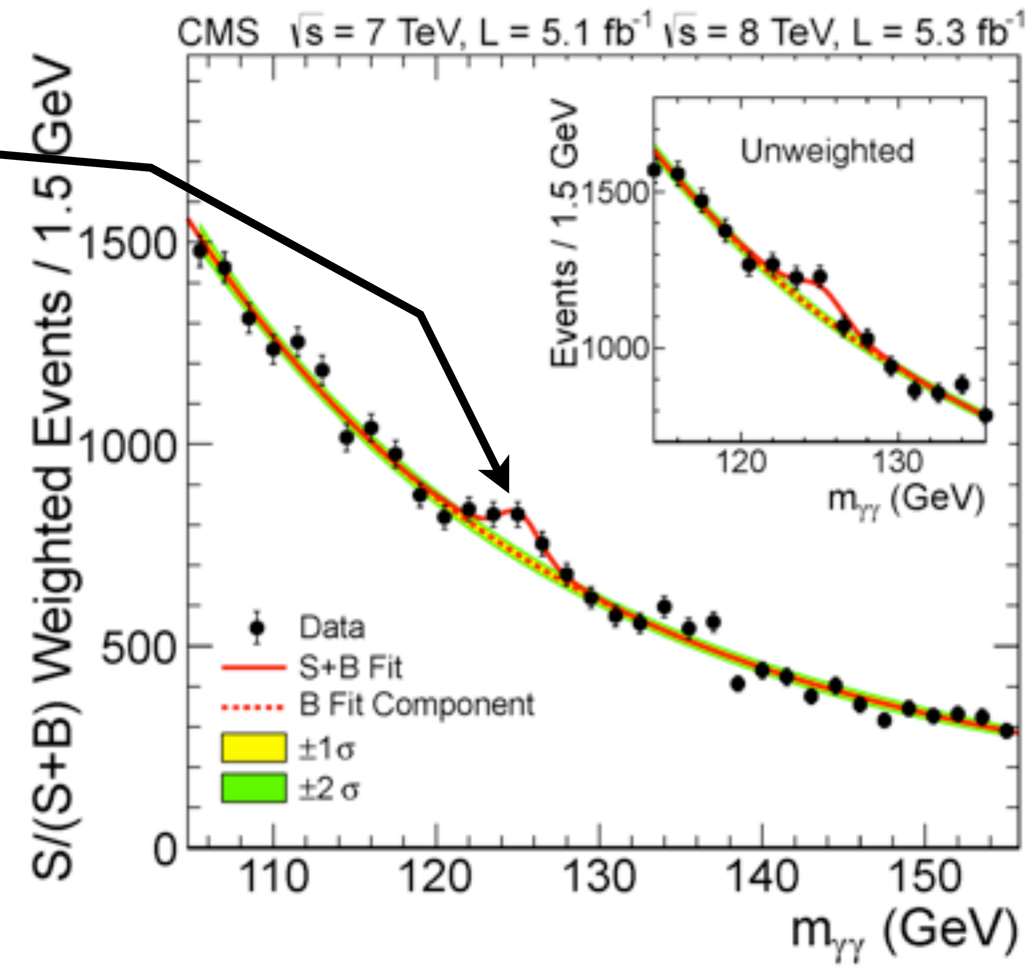
- So admittedly this was not strictly a SUSY search (though a SUSY LSP is considered a good dark matter candidate)
- The main reason I included it is to in some sense complete the transition from obvious high MET searches to searches for the most subtle objects.
- These ISR-based searches for particles that practically don't even interact allow us to look for even the LSP we've all but given up on in the MET based searches.





What Now?

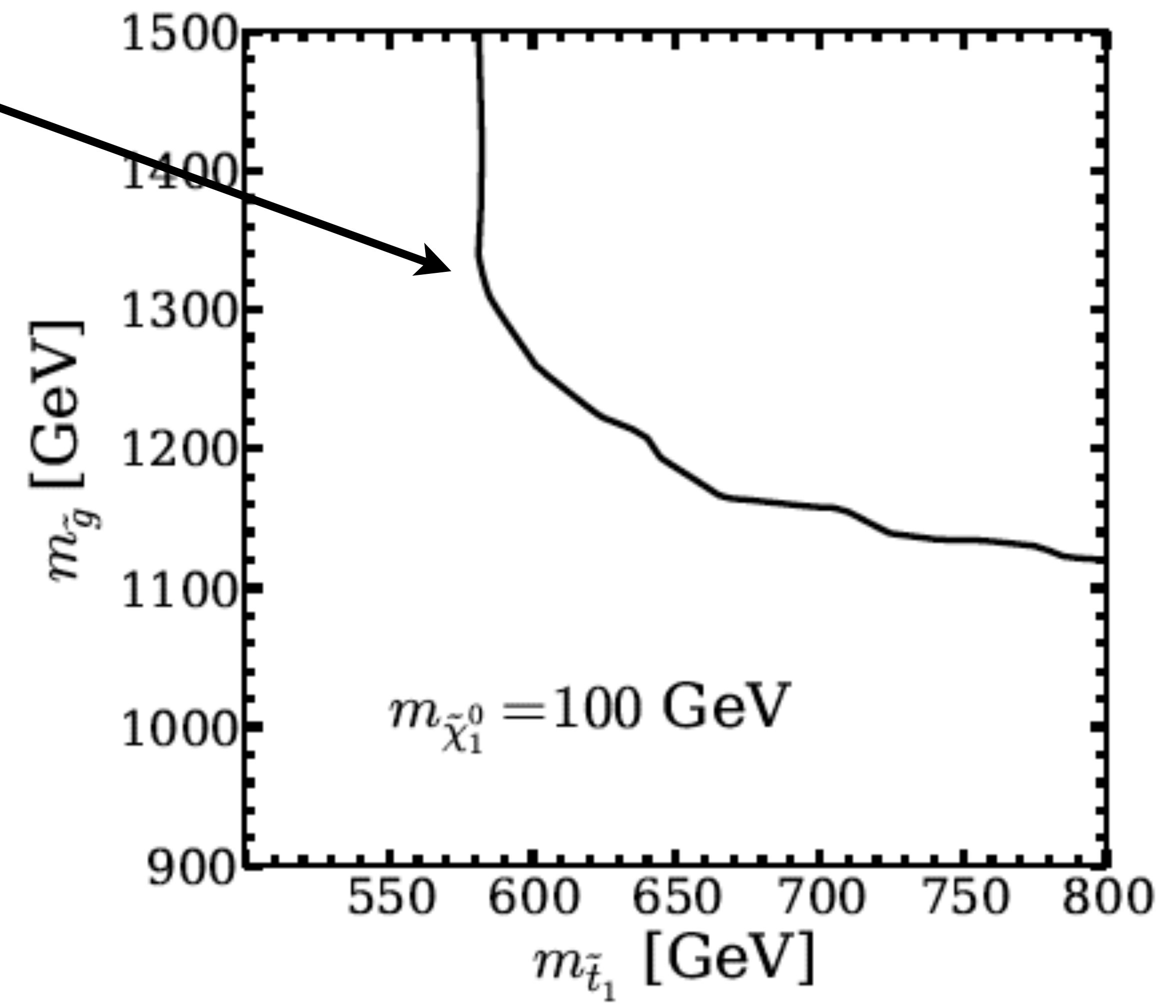
- So after all this we have not yet observed SUSY (except on Google).
- Does it mean we are done? Is the BBC right? Is SUSY "all but dead"?
- But there is some light at the end of the tunnel:
  We've seen this



- If its a Higgs it means we have a heirarchy problem.
  - Which should imply something like SUSY remains to be found...
  - If we invoke naturalness we should see enhanced 3rd generation content in final states -- can use this to refine searches
- This particle also appears to like to decay to photons
  - Meaning photon based searches could provide important insight into the nature of this particle and the new physics its presence implies!

Naturally:

- ~a week ago on arXiv 1208:6062v1:
- Reinterpretation of ATLAS 2011 diphoton result in terms of stop-gluino plane -- “Natural GGM”
- Typically whats been done is the “unnatural” lighter 1&2gen squark with decoupled stops vs gluinos
- We see here even without optimizing the analysis -- i.e. requiring B or added lepton tags there is already considerable sensitivity to Natural SUSY



- Expect this can be pushed further by adding requirements targetted to 3rd generation particles...

SUSY with Photons at CMS

- CMS has a rich program of searches for beyond the standard model physics using photons in the final state.
- We have grown from the simpler "hit you over the head" counting experiments, to more sophisticated hunts for more subtle signatures.
  - In the process we have excluded vast regions of theory-space
- We now enter a new era -- with the "New Boson" we know there must now be something more to find.
  - If its a Higgs, something must keep its vacuum expectation value stable
  - If we live in a "natural" universe these things should soon be within reach of the LHC experiments.
- With this particle's unexpected need to become photons, photon based searches can continue to be a useful tool to search for new physics!

Is SUSY Somewhere In Here?