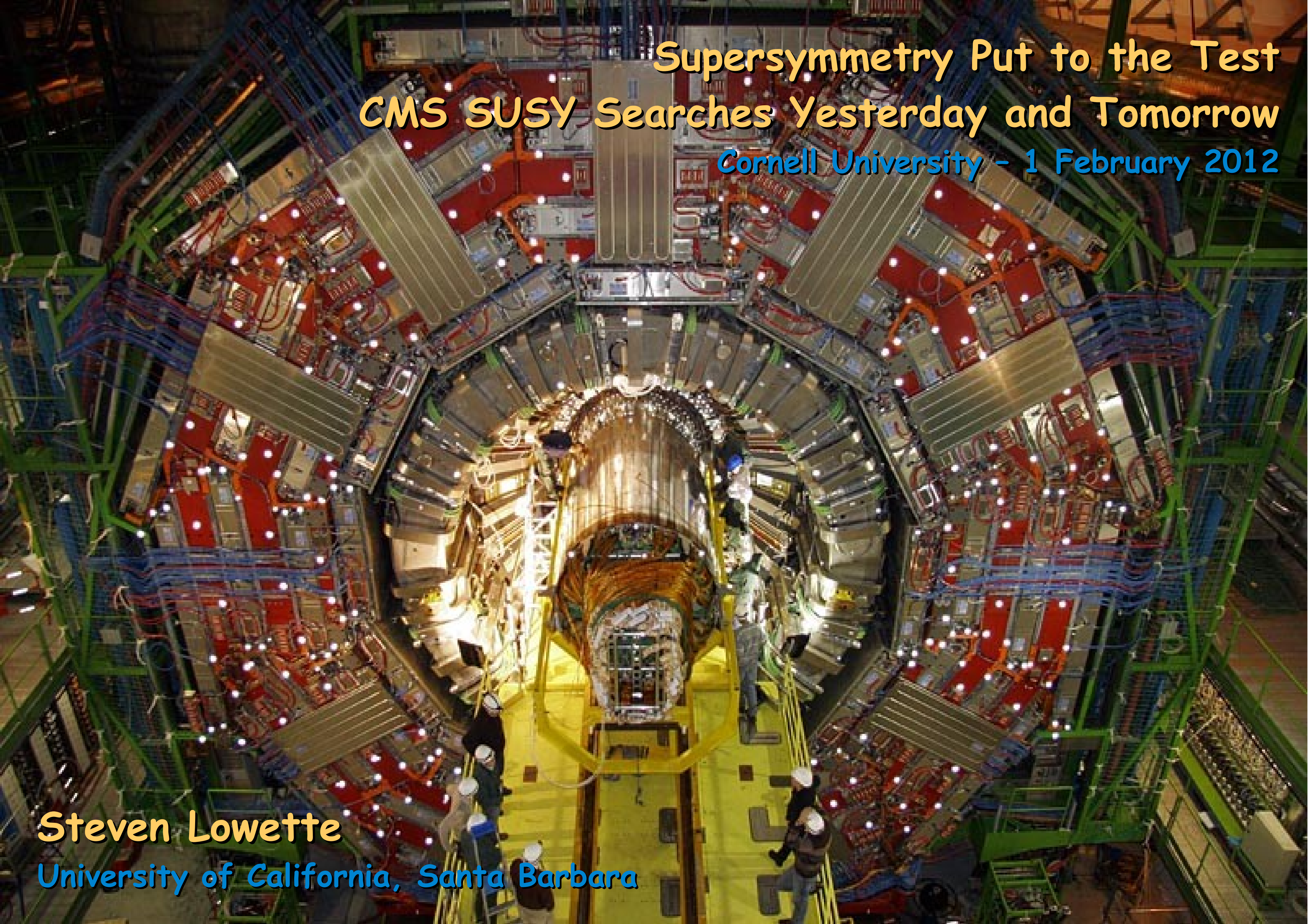
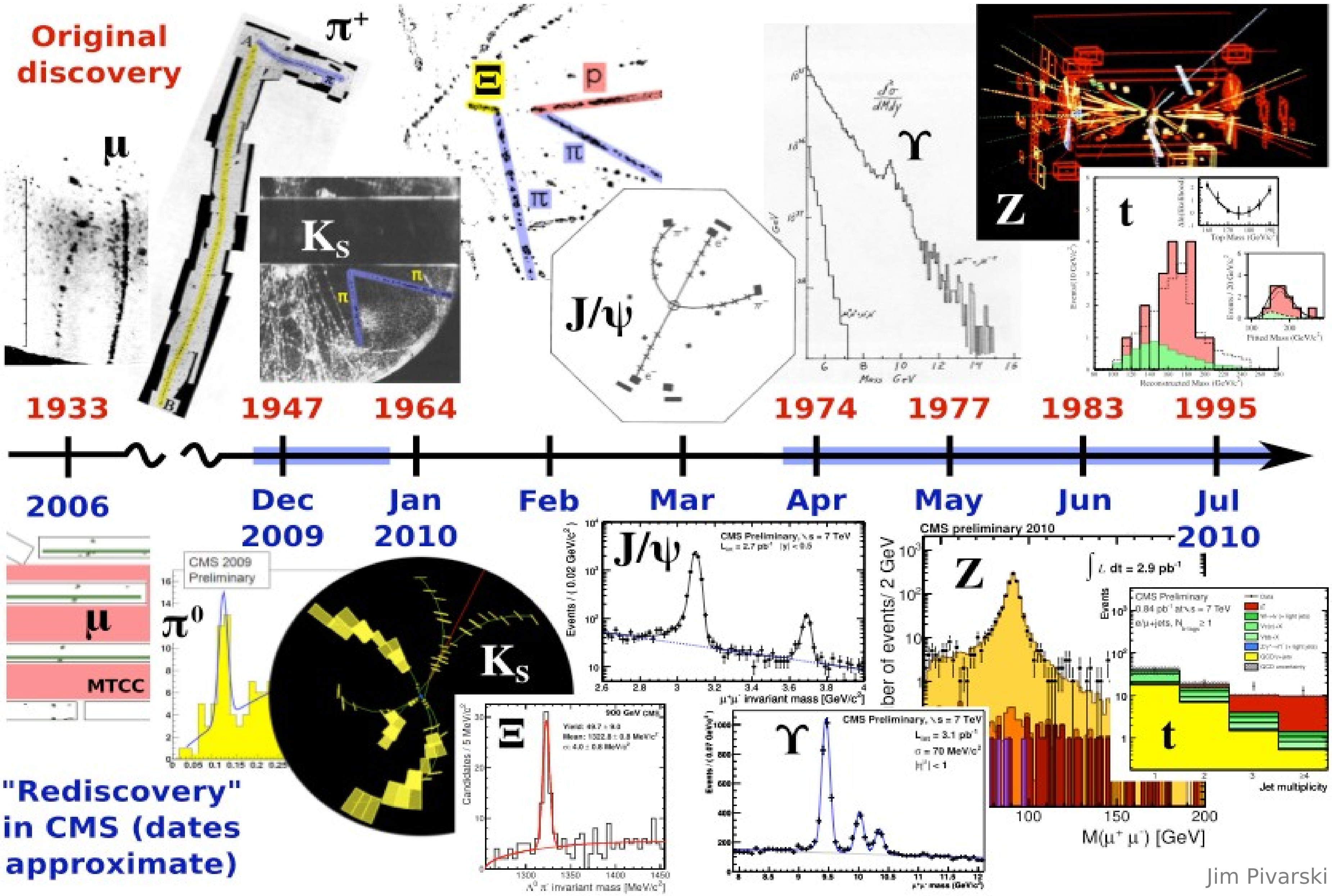


Supersymmetry Put to the Test
CMS SUSY Searches Yesterday and Tomorrow

Cornell University – 1 February 2012

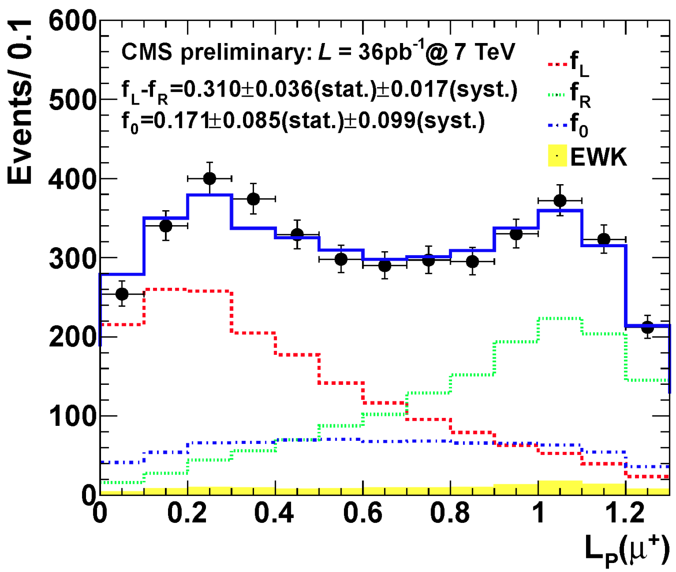
Steven Lowette
University of California, Santa Barbara

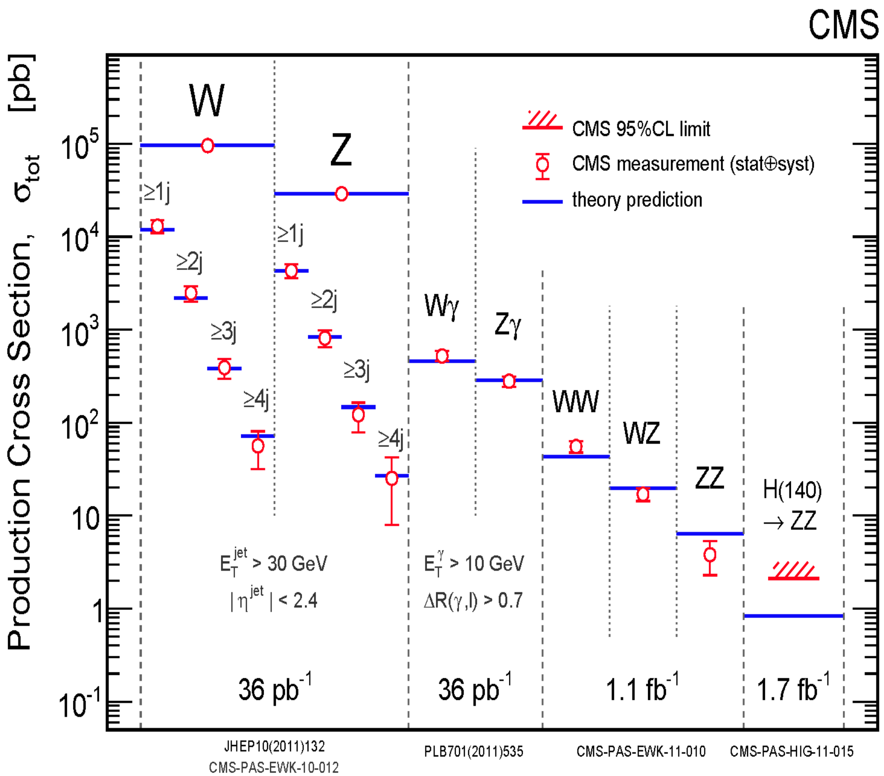
2010: Rediscovery of the Standard Model



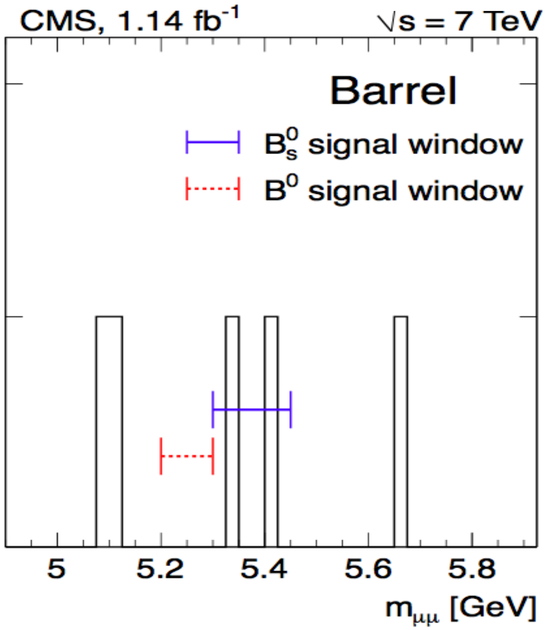
- CMS delivered excellent results in very short time
  - years of preparations paid off
  - very prompt commissioning with collisions
  - SM validation deep into new phase space
  - all measurements coincided with SM prediction

PRL 107 021802 (2011)



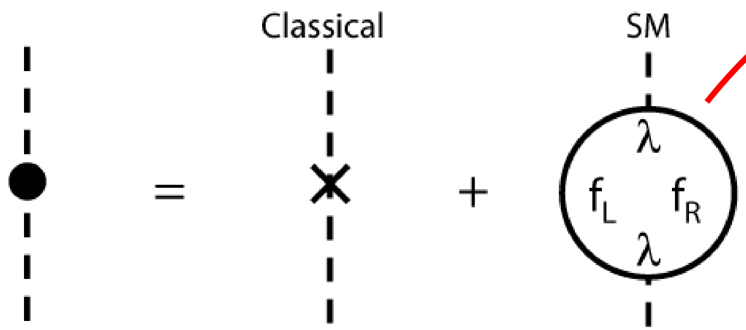


PRL 107, 191802 (2011)



- in addition many searches were done, all validating many corners of the SM

- the SM has shortcomings though
  - notorious one: the hierarchy problem



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

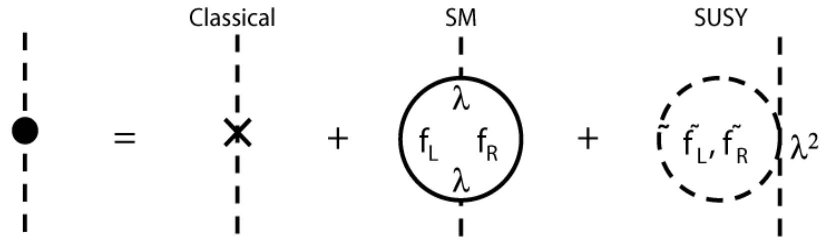
problematic

  - need extreme fine-tuning to keep standard model valid all the way up to the Planck scale
    - phrased differently: why is gravity so much weaker than the other forces?

Moving Beyond The Standard Model

- over the years many solutions to the hierarchy problem have been proposed
  - supersymmetry, extra dimensions, little Higgs models, technicolor, ...

- supersymmetry (SUSY)
  - solution to the hierarchy problem: SUSY partners cancel the quadratic dependence on the cut-off scale
  - whole spectrum of new particles to be discovered



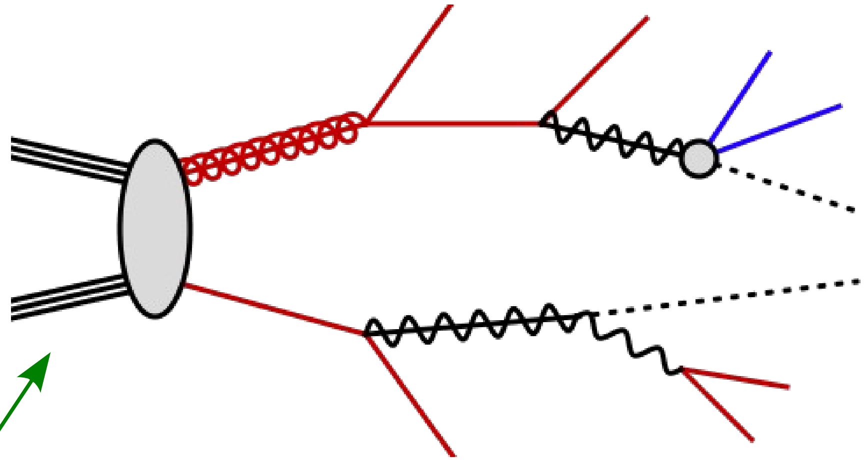
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots \quad \textbf{cancels}$$

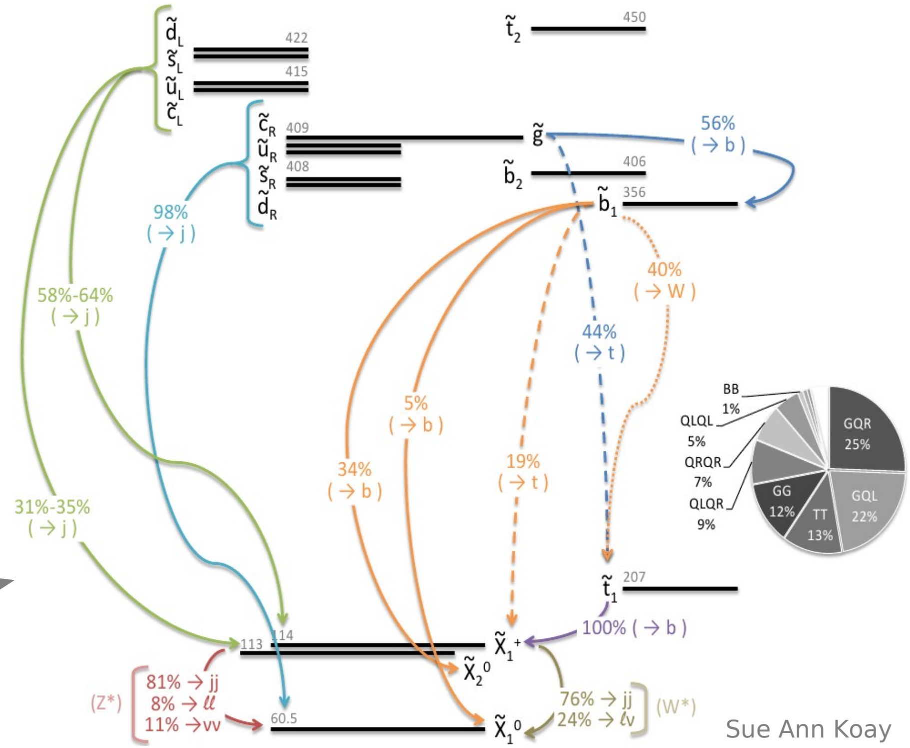
$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde f}^2 - m_f^2)\ln(\Lambda/m_{\tilde f}), \quad \textbf{small}$$

  - to avoid rapid proton decay an extra symmetry is commonly imposed: R parity
  - implies that SUSY particles are always produced in pairs
  - hence, the lightest supersymmetric particle (LSP) is stable!
    - eg. the neutralino
  - SUSY harbors an excellent dark-matter candidate

Searching for SUSY at the LHC

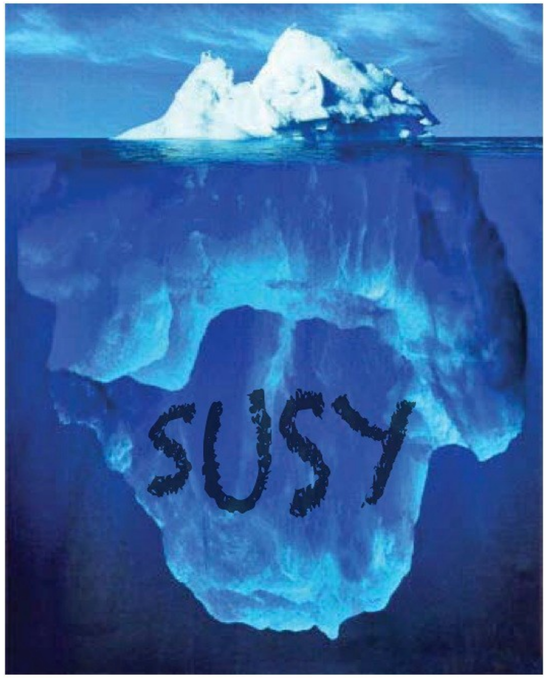
- with the early LHC data the first target was to search for SUSY produced with a high cross section
  - rare processes not yet accessible
  - and backgrounds sometimes huge
- strong production dominates
  - squarks and gluinos carry QCD color charge
  - and LHC collides colored quarks and gluons
- squarks and gluinos decay directly or through lighter SUSY particles into jets, leptons, and LSPs
  - always with jets, due to colored production
- the decay chains are very diverse, and determined by the SUSY particle spectrum
  - we don't know the spectrum
  - this is just one example: "LM0"





Searching for SUSY at the LHC

- searching in this new energy regime, we need to keep our eyes wide open
  - commonality is missing energy (MET) from the dark matter particle
  - inclusive selections at first: use all the signal you can
- generic signatures rather than specific models
  - search for MET + X
  - X = jets, single lepton, opposite-sign dileptons sams-sign dileptons, multileptons, photons, b's, taus
  - and combinations of those
- think discovery!
  - need to convince that you know your data
    - new detector, new phase space
  - to claim an excess, you need to prove you control your backgrounds
    - CMS has very successful simulation tools, but we're probing unexplored territory
    - estimate backgrounds as much as possible from the data itself
  - need to show robustness of the results
    - many analyses and methods to cross check each other



Searching for SUSY at the LHC

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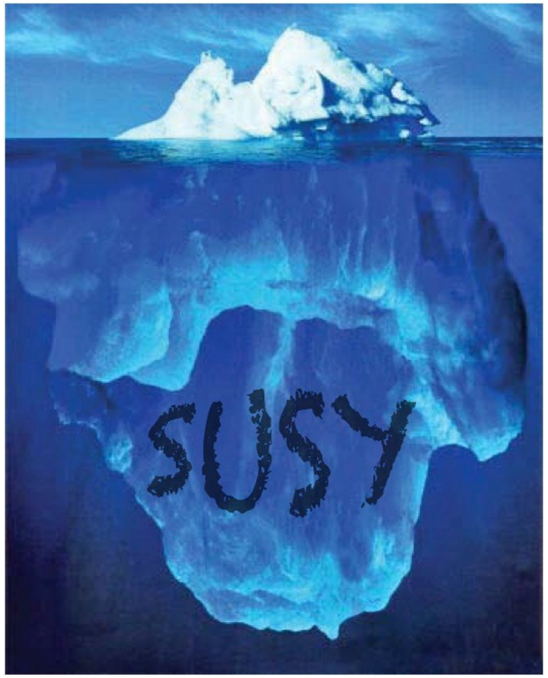
  - commonality is missing energy (MET) from the dark matter particle
  - inclusive selections at first: use all the signal you can
- generic signatures rather than specific models
  - search for MET + jets + no leptons
  - X = jets,
    sams-sigı
  - and comb

→ **most sensitivity early on**



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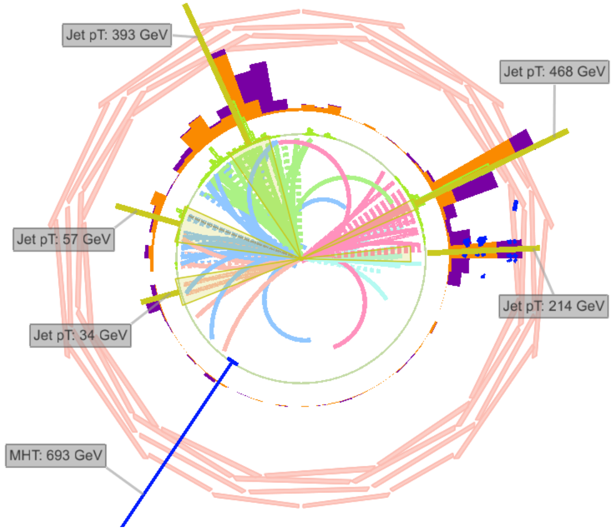
New Physics Search with MET + Jets

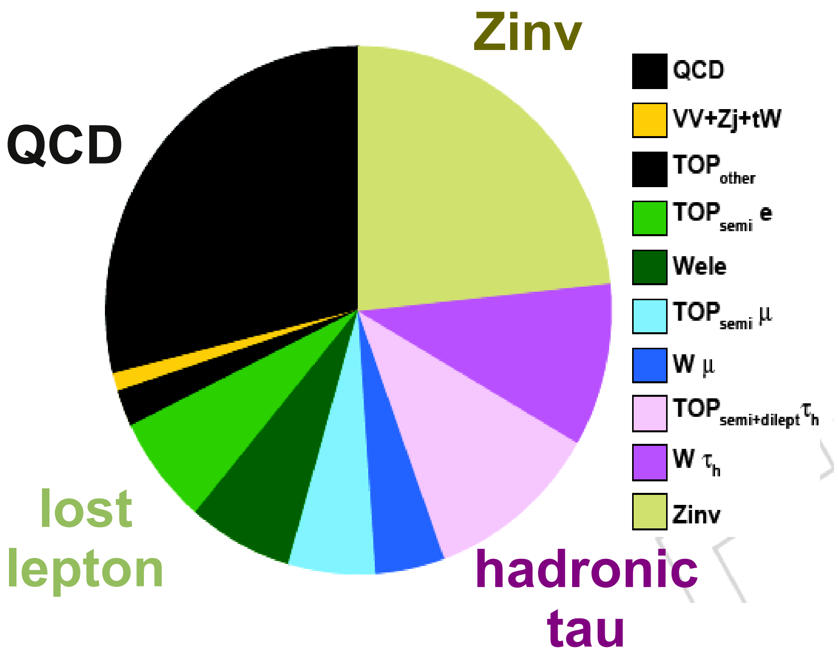
JHEP 08 (2011) 155 - arXiv:1106.4503

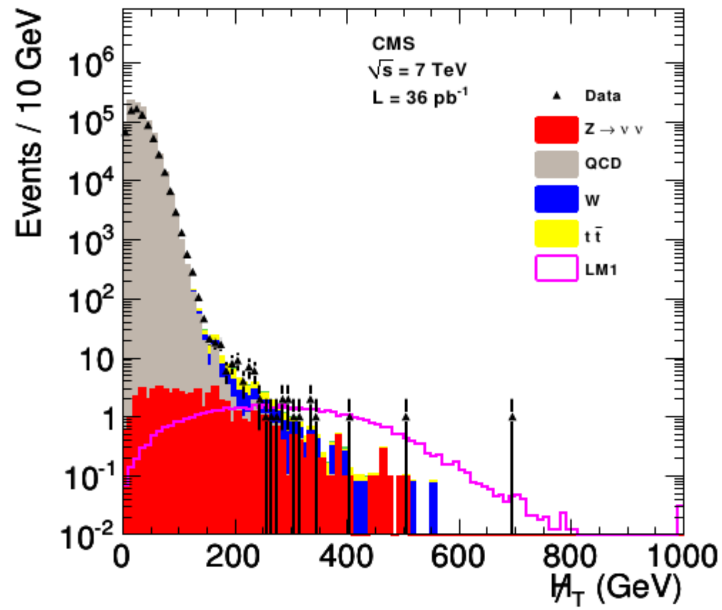


- search observables: invisible and visible energy
  - MHT → MET from jets
  - HT → scalar sum of jet transverse momenta
- aim for generic inclusive selection
  - MHT > 150 GeV, HT > 300 GeV
  - 3 central jets → central "massive" production
  - these jets not aligned with the MHT → suppress QCD multijet background
  - isolated electron and muon veto → reduce W and top with real MHT
- 2 search regions
  - high HT : HT > 500 GeV → sensitive to decays with mostly visible energy
  - high MHT : MHT > 250 GeV → yields high background rejection
- peculiarity: in this search we predict the full kinematics of all background events
  - makes the analysis extra ready for discovery
  - flexibility to change selections to focus the search
  - excellent starting point for the characterization of just-discovered new physics

Backgrounds to the MET + Jets Search

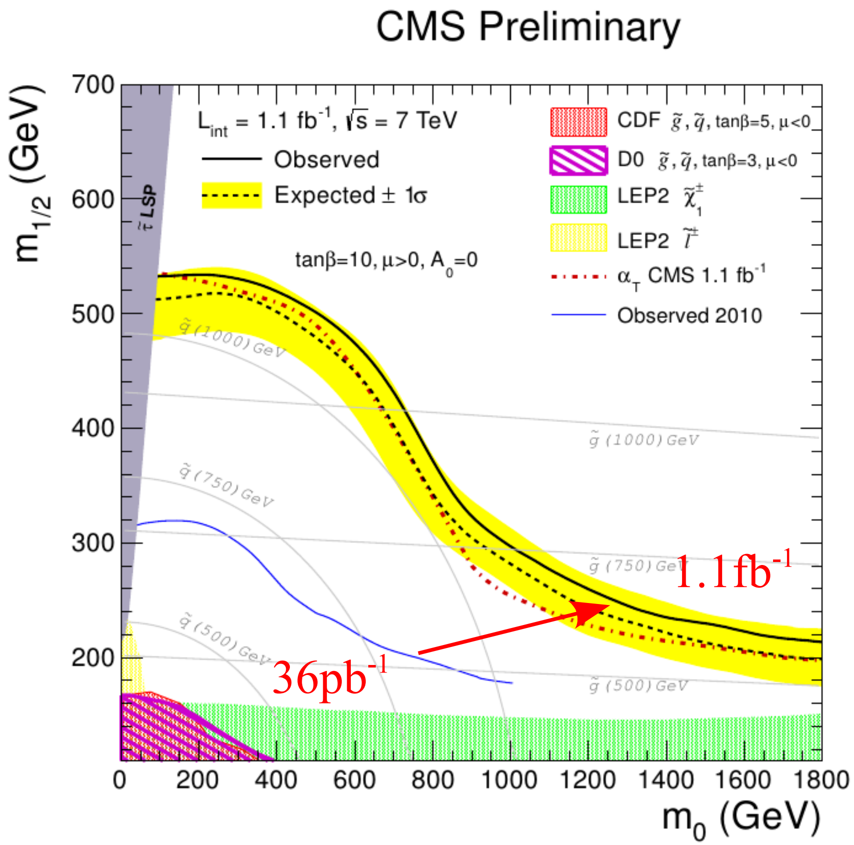
- QCD multijet background
  - multijet events with large jet mis-measurement, or with neutrino from b-quark
  - predicted with novel method, using jet resolutions to smear "rebalanced" seed events
- W boson and top quark background
  - leptonic decays with real missing energy
  - W → electron or muon, where the lepton is 'lost' (eg. overlapping a jet)
  - W → tau, where the tau decays hadronically and looks like a jet
  - predict from 1 muon events by substituting the muon with MET or a tau-jet
- Z → neutrino background (invisible Z)
  - looks just like signal: irreducible
  - most precise prediction from photon+jets
    - using well-controlled theory correction





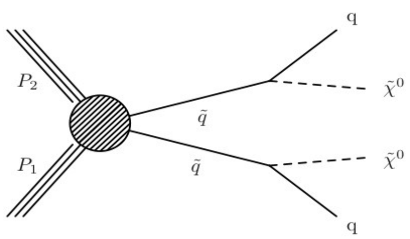
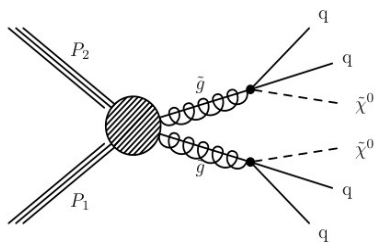
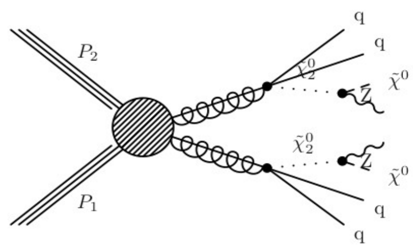
Results of the MET + Jets Search

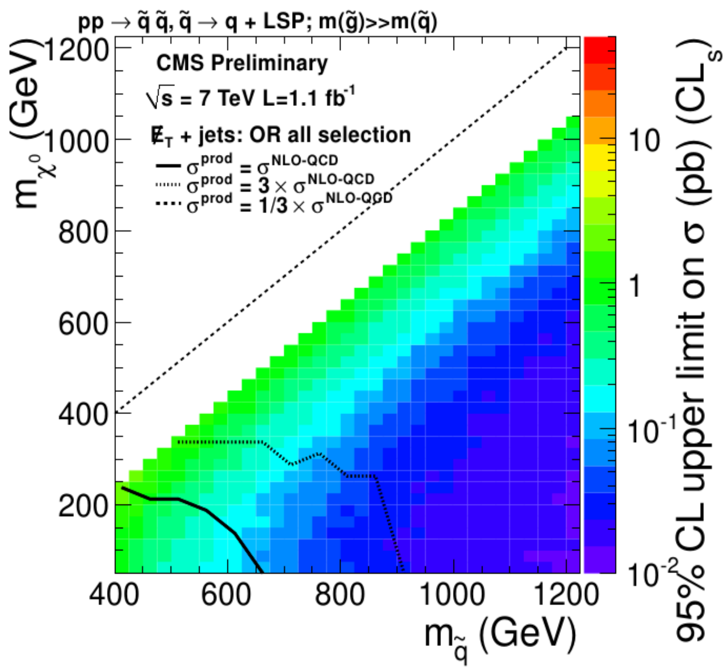
- no excess observed, unfortunately...
  - excellent match between background predictions and the observed data
- strong limits on new physics as a result
  - in the CMSSM this analysis reached among the strongest limits, in particular in parameter space with residual QCD background
- in the summer of 2011 the search was re-loaded with 30 times more data (PAS-SUS-11-004)
- new challenges and improvements
  - high luminosity requires stringent online selectivity
    - at the forefront of Particle-Flow and PU-subtraction trigger improvements
    - indispensable to preserve hadronic physics reach in 2012
  - evolving to a shape analysis in HT-MHT

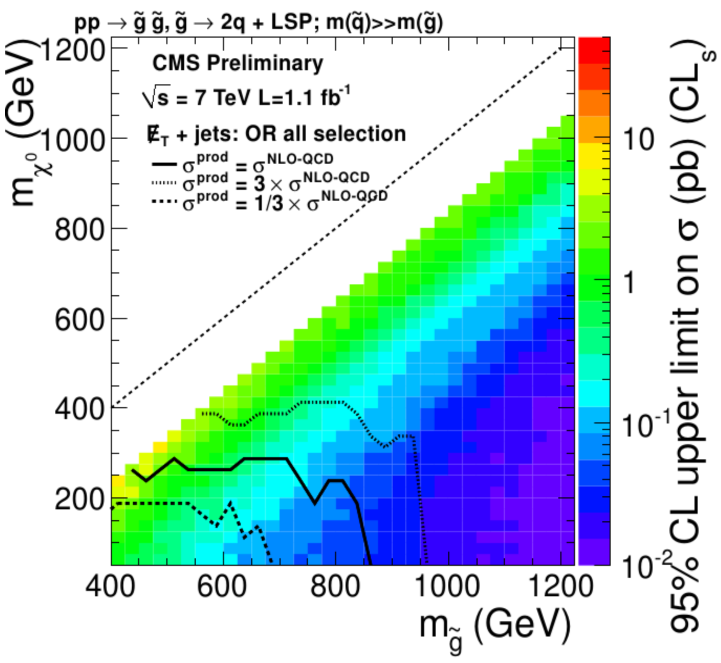


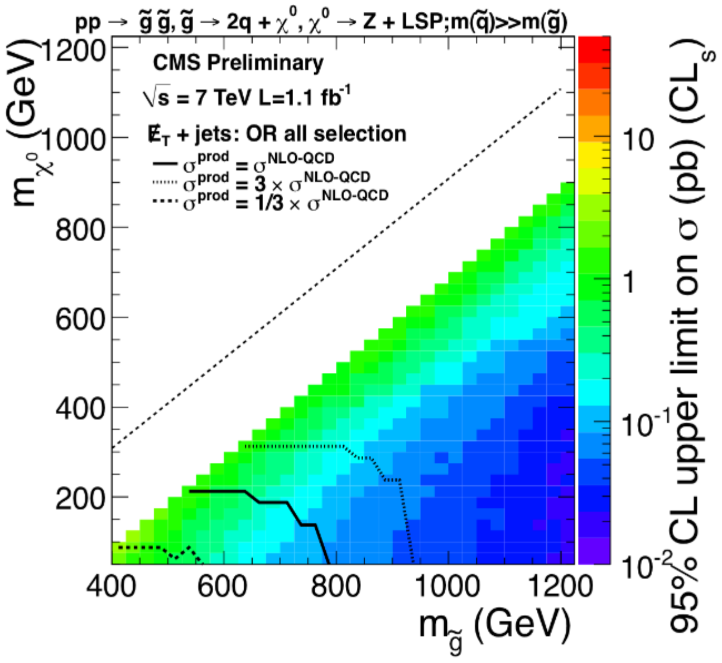
Results of the MET + Jets Search

- the search was also interpreted in so-called simplified models with only generic heavy colored particles and a dark matter candidate particle
  - results presented as cross section upper limit
  - allows theorists to more easily interpret our results in other models
  - allows us experimentalists to learn about the analysis' behavior in corners of phase space

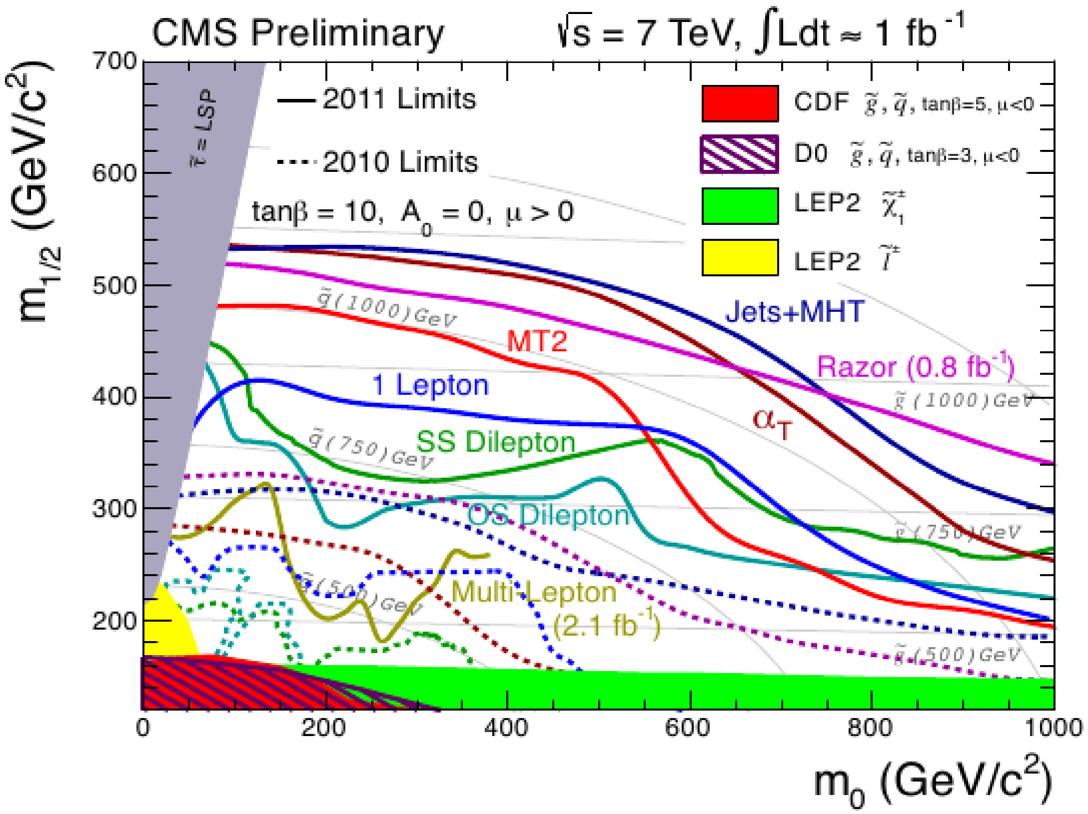






Summer Status of CMS SUSY Searches

- multitude of generic searches in final states with missing energy
- no sign of new physics yet
- overall status for the CMSSM in summer 2011:



- all analyses currently being updated using the full 2011 dataset

Evolution of SUSY Searches

- to further improve the analyses which search on the kinematic tails, we need:
  - an increase of the collider's energy
  - or a big jump in amount of collected data
- but the speed at which we collect new data at the LHC is not exponential anymore
  - projections foresee 15/fb for 2012, maybe a bit more
  - these tail-searches eventually become long-term projects

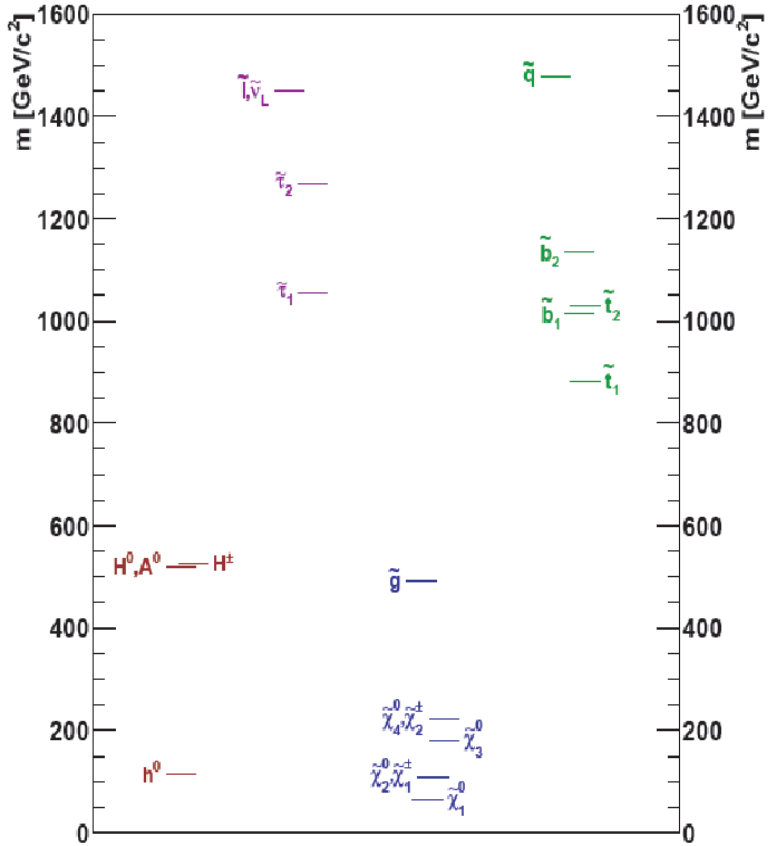
- one way forward is to expand our field of view
- optimize searches towards uncovered areas in phase space
  - compressed spectra
    - tough to trigger on, but innovative ideas are being worked on
    - ISR dependence requires solid modeling in signal
  - long decay chains
    - high jet multiplicity, with important QCD background component
    - ATLAS has already a generic multijet search (see backup)
- add more "dimensions" to the existing searches
  - eg. adding b-quarks or taus

Inclusive 3rd Generation Searches

- 3rd generation is special
  - expected light, stabilizing the Higgs
  - mixing because of large top Yukawa
  - couples strongest to Higgs/Higgsino
- final states with b's and MET arise from direct stop/sbottom production, or from gluino decays

- a hadronic search with b-jets with 2010 data
  - JHEP 07 (2011) 113 – arXiv:1106.3272
- also in 2011 searches have been inclusive so far
  - use b-enriched models (eg. "LM9" in CMSSM) as a guideline
- two all-hadronic analyses available with 1.1 fb^{-1}
  - MT2+b (PAS-SUS-11-005)
  - MET+b (PAS-SUS-11-006)

"LM9" benchmark mass spectrum

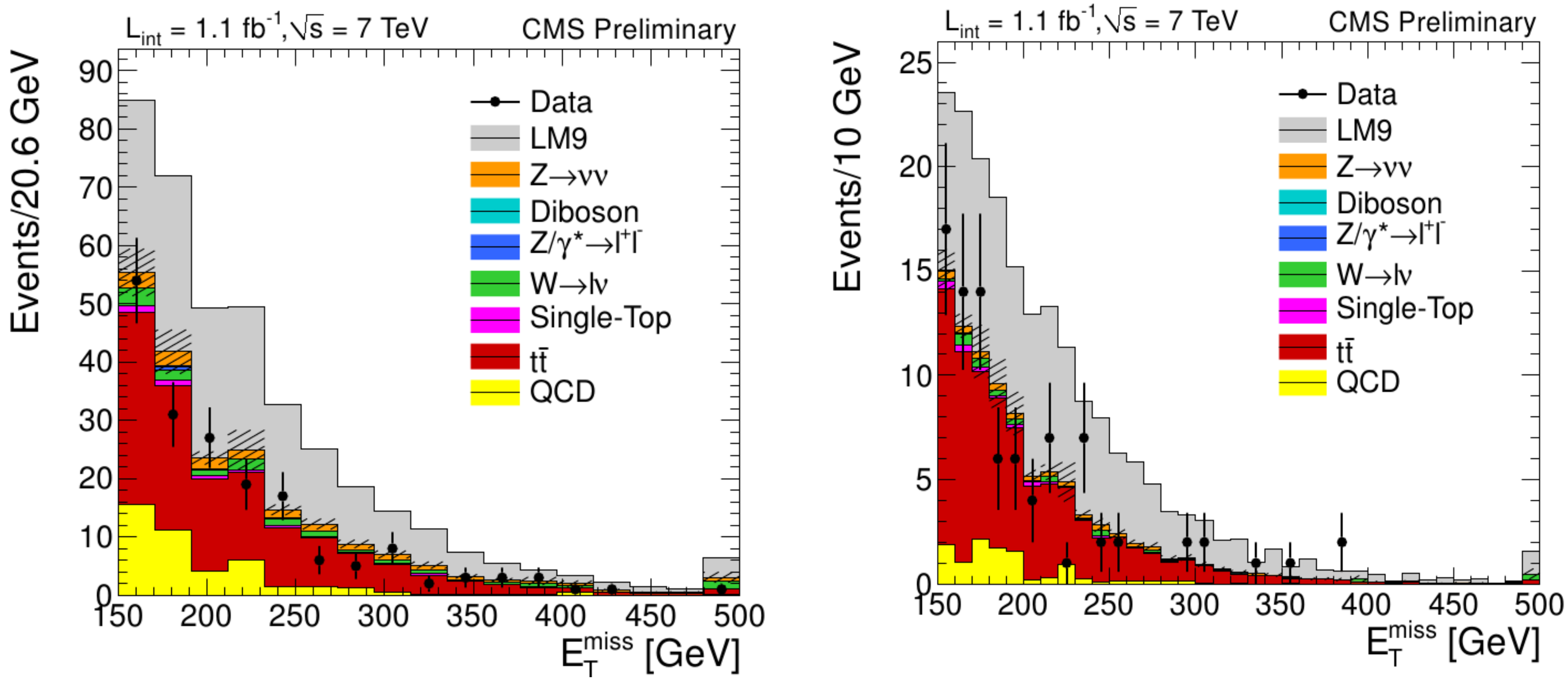


- single-lepton and same-sign dilepton search with b's also in the works
- also signatures with taus actively being searched for

MET + b: Selection

- MET used as search variable
- search both with loose and tight HT and MET
- search both with >=1 and >=2 b-tags
- further selections are similar to the previous all-hadronic search
  - at least 3 jets pT>50GeV
  - MET not aligned to jets
    - uses novel resolution-normalized Δφ(jet,MET) variable
  - lepton veto

tight, 1 b tag



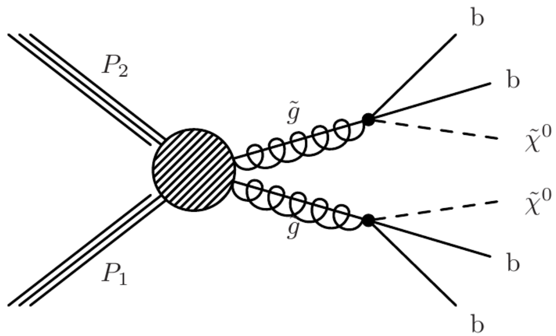
loose, 2 b tags

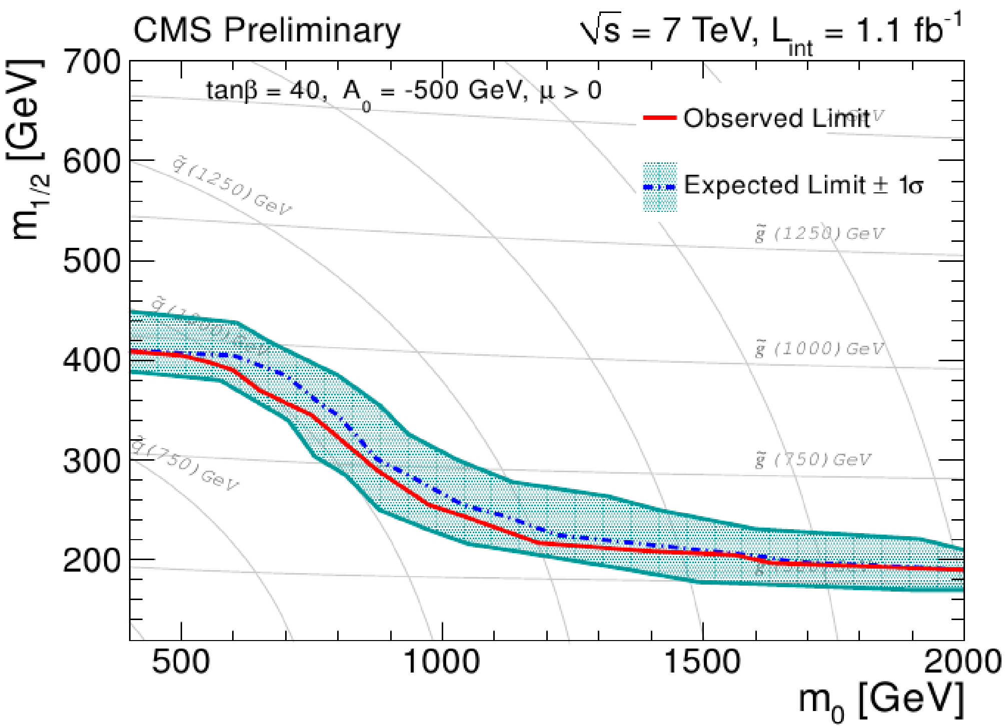
MET + b Backgrounds and Results

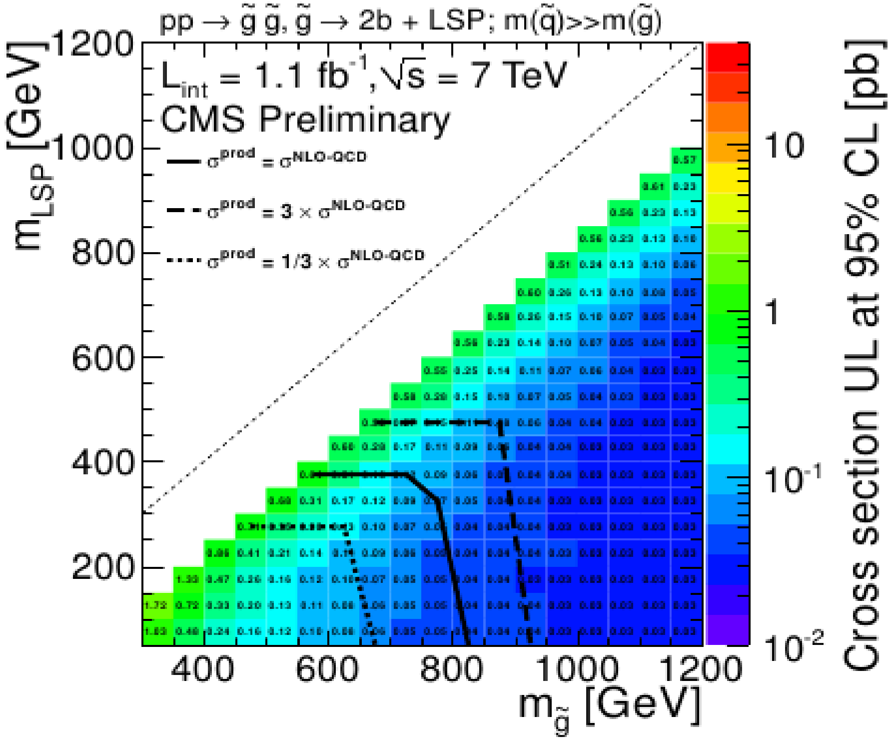
- top (and W) background dominant
  - use MET shape in 1-lepton control sample as template for 0-lepton case
  - cross check like in MET+jets search (hadronic taus) and with W polarization (lost leptons)
- Z→neutrinos background: irreducible
  - use Z→l+l- control sample
  - treating leptons as MET
  - extrapolation into the search region
- QCD background negligible
  - estimated exploiting absence of correlation between novel resolution-normalized $\Delta\phi$(jet,MET) variable and MET
- challenge with high-pT b-tagging
  - up to recently very large uncertainty at high jet pT
  - but new measurements are underway, using the large datasamples collected
  - based on samples with high b-jet purity from top decays
    - top quark as a calibration tool
- background predictions in all search regions agree with data

MET + b Results

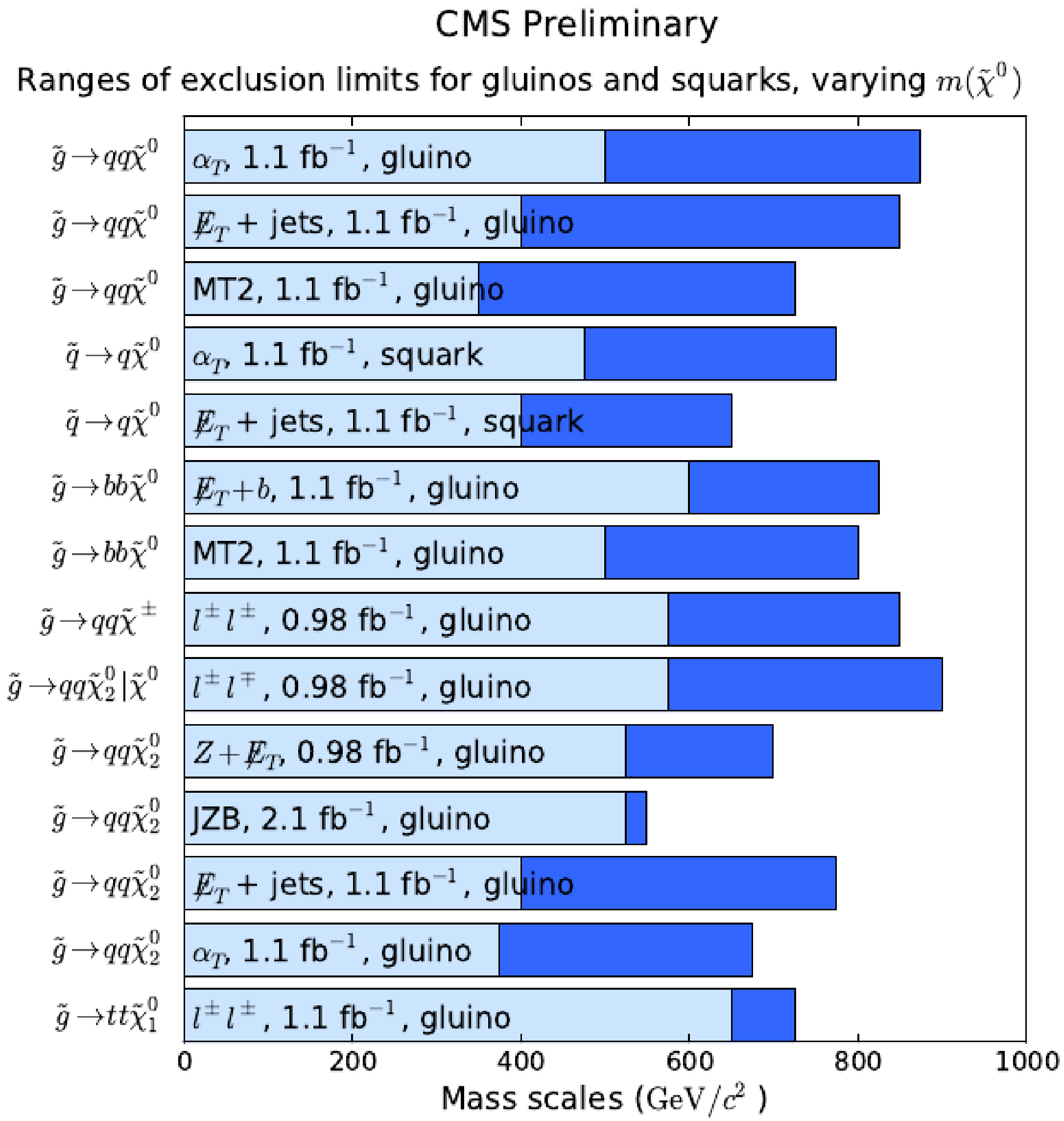
- interpretation in CMSSM (at tanβ=40)
- also interpreted in simplified model
  - in this case we used $pp \rightarrow gg \rightarrow bbbb\chi^0\chi^0$
  - put cross section upper limits for this production mode







Gluino and Squark Search Summary



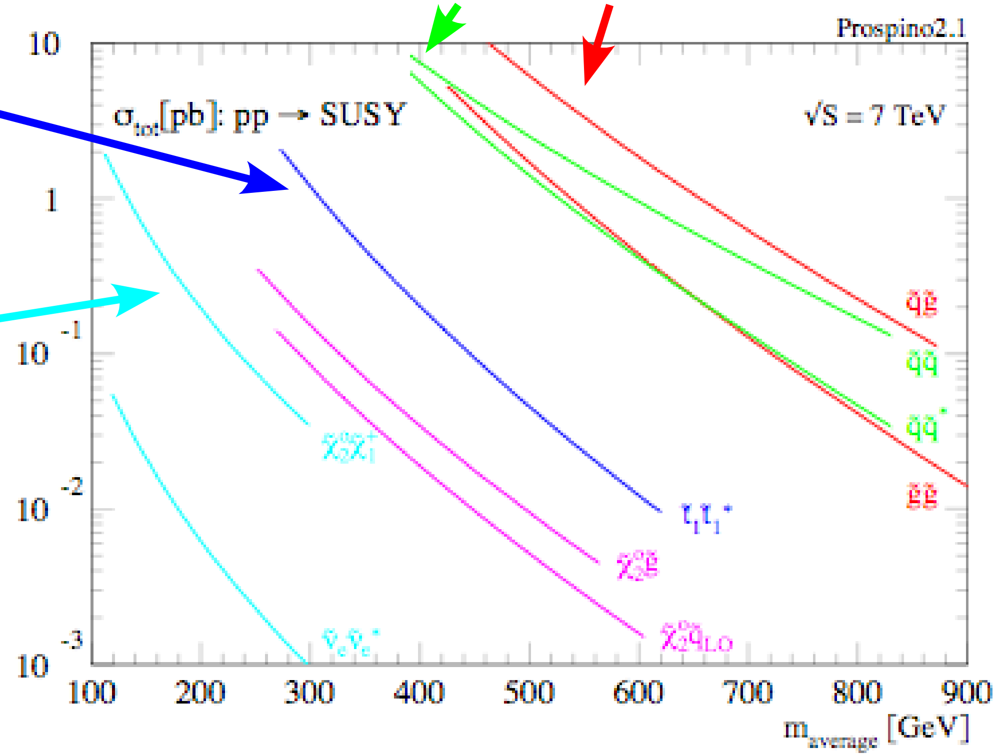
For limits on $m(\tilde{g}), m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{prod} = \sigma^{NLO-QCD}$.
$m(\tilde{\chi}^\pm), m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$.
$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g}) - 200$ GeV/c^2 (light blue).

- another way forward with SUSY searches is to optimize for other than squark/gluino production modes
  - → this does not necessarily introduce more model dependence
- with the large data samples available, rarer SUSY processes become accessible
  - → leads to softer signatures
  - → needs new, dedicated, exclusive strategies

- direct stop or sbottom production
  - → look for b-quarks
  - → try top reconstruction

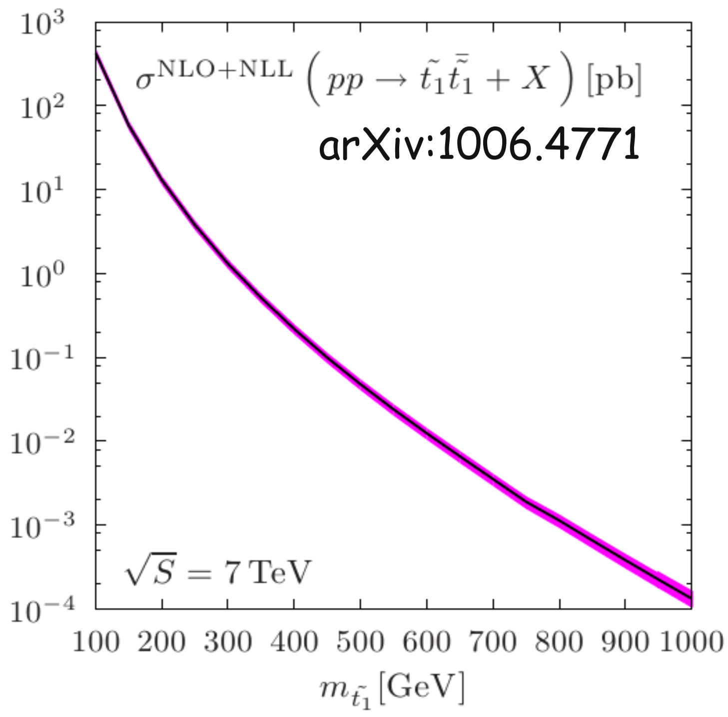
- direct neutralino/chargino production
  - → (multi)lepton signatures
  - → possibly very clean, without hadronic activity (jet veto)
  - → several analyses exist already CMS is ready to tackle this

squark/gluino production

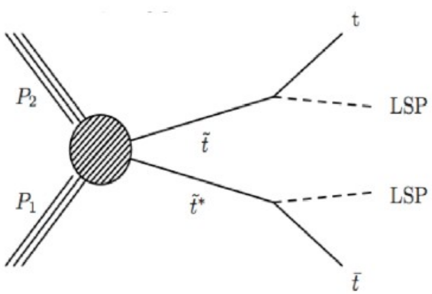


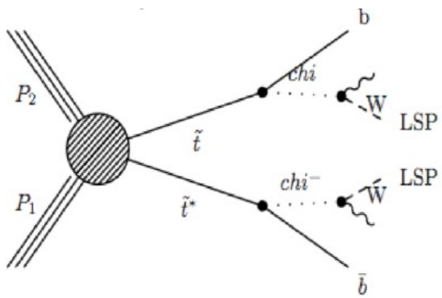
Direct Stop Search

- direct stop production
  - with ~5fb^{-1} of data on tape we're in the game
  - m(stop) = 200 / 400 / 600 GeV
  - # stop pairs: ~60000 / ~1000 / ~60



- stop decay
  - depends on mass splittings with other particles
  - 2 decay modes as starting points
    - the final state is actually the same: WWbb+MET
    - difference in presence of top





  - intermediate particles can also be off-shell: 3-body and 4-body decays
  - if not much is kinematically allowed, then loop-induced decay: stop → c χ^0
    - these decays can be very hard to dig out of the background...

Direct Stop Search: Challenges

- the lighter the stop, the more the events look like ttbar
  - and if it's light, there is not much MET to play with
  - in the extreme of a stop nearly degenerate with top, and a light LSP, the only thing observable is a deviation from the top cross section
  - highly-efficient trigger not straightforward
    - especially hadronic, but also single-lepton

- the heavier the stop, the less selection inefficiency one can afford
  - every inefficiency needs to be well-thought through
  - just a question of cross section
  - eg. top reconstruction comes with substantial inefficiency
    - and not useful in decays without on-shell tops

- in general, the stop search is systematically limited
  - S/N is typically well below 1
  - need excellent control of the backgrounds
    - systematics can hurt in case background is large: significance ~ $S/\mathrm{sqrt}(S+B+\Delta B^2)$

- signal contamination could be an issue
  - depending on the background estimation methods

Single-Lepton Stop Search

- typical stop selection
  - trigger: lepton+jets
    - not very efficient actually
  - 1 isolated lepton
  - 4 or more jets
  - 1 or more b-tagged jets
- but how to suppress top? use the MET vector!
  - require high |MET| eg. MET > 100 GeV
  - require high MT, above the W peak eg. MT > 150 GeV
- signal becomes accessible on MT tail

- ttbar → dilepton is the main background
- two components, both reducible
  - hadronically decaying tau
  - 1 lepton lost

- key issue for this analysis: suppress the remaining background, while keeping the systematics small

All-Hadronic Stop Search

- typical stop selection
  - at least 6 jets
  - at least 1 b-tagged jet
  - MET > 250 GeV
  - MET and leading jets not aligned
  - lepton veto

- all-hadronic search is potentially more sensitive
  - larger branching ratio than single lepton
  - no MT cut (though must go to higher MET)

- but harder in terms of backgrounds
- similar to the inclusive MET + jets search
  - top is dominant, also here
  - but QCD is non-negligible at MET ~ 150 GeV
    - and is very sensitive to pileup
  - also Z → neutrinos plays a subdominant role
  - ttZ, Z → neutrinos is at the few percent level
- but high jet multiplicity and presence of b-jet pose problems

All-Hadronic Stop Search

- main backgrounds are from single-lepton ttbar
  - also here hadronic tau and lost lepton
- effort to further reduce these backgrounds
  - innovative directional isolation
  - indirect tau veto (using MT)
- also here systematics limited
  - goal of 10% (or less)
  - developed for taus MC-in-data embedding of hadronically decaying tau

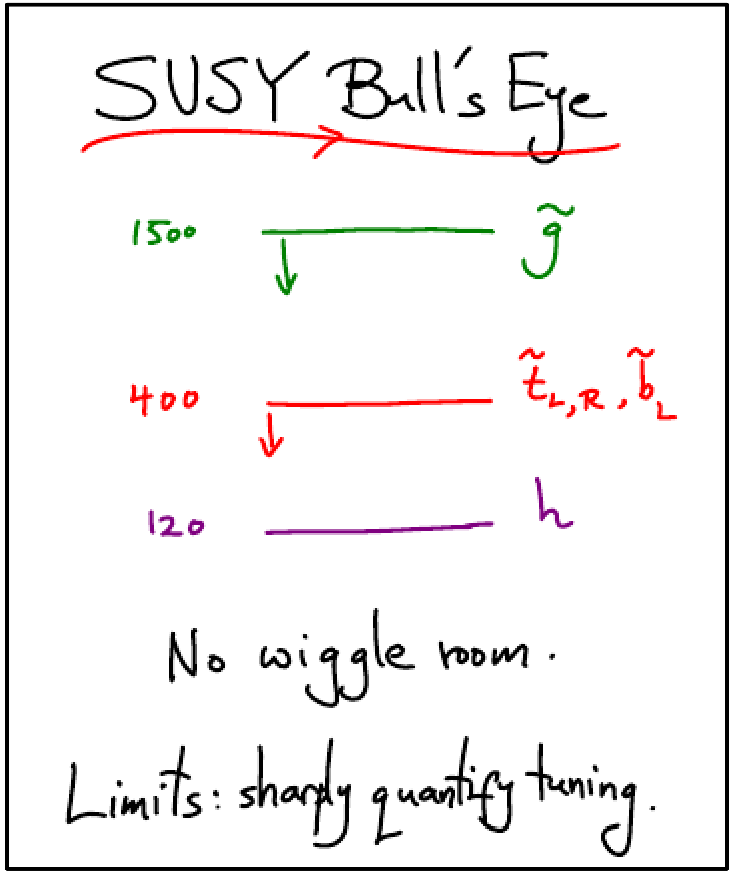
- analysis in full swing, full updates expected soon

The Fate of SUSY?

- so far we were just pushing the limits up
- now we plan to expand into different production and uncovered phase space
- but the question many people ask: isn't SUSY ruled out already?

- rephrasing it: has SUSY already lost its power of solving the hierarchy problem?
  - → the higher the SUSY scale gets pushed, the larger the corrections to the Higgs mass
  - → until a new hierarchy problem arises
  - → can minimal SUSY still be a natural theory?

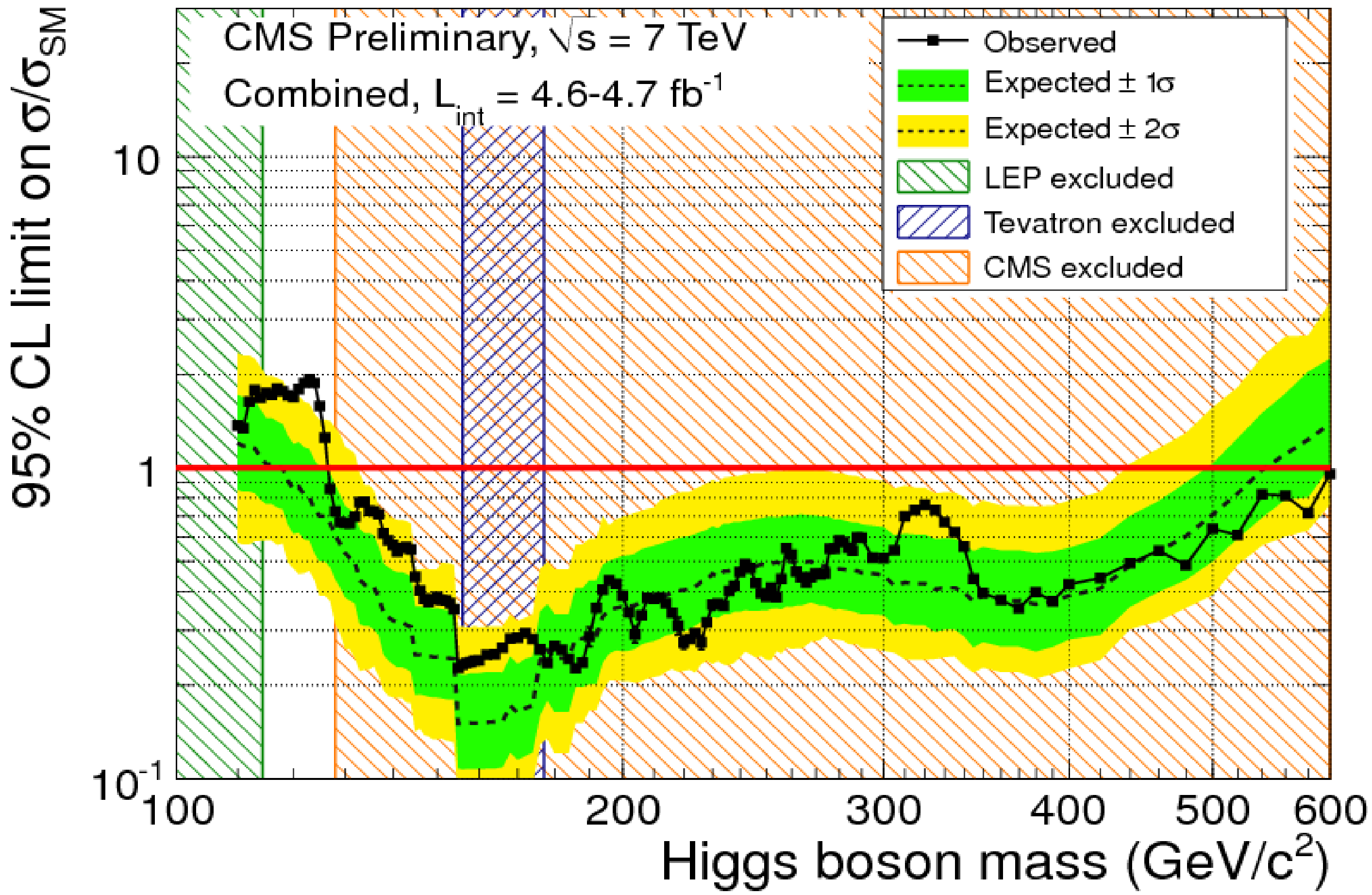
- starting from the naturalness a few very general requirements can be imposed on standard SUSY models to avoid fine-tuning
  - → gluino below ~ 1.5 TeV
  - → stop mass < 400 GeV
  - → Higgs around and about 120 GeV



Arkani-Hamed - LPCC workshop 10/31/2011

Testing Naturalness

- things seem to look good for a low-mass Higgs...
  - this is the major LHC target for 2012



Testing Naturalness

- what about a gluino below ~ 1.5 TeV
  - still perfectly possible
  - current inclusive analyses will keep pushing the limits
  - eventually need high energy and lumi to constrain further
  - there will always be corners of phase space where a lighter gluino can keep hiding

- what about a stop mass < 400 GeV
  - we have currently no direct production constraints from LHC whatsoever
  - we will get a first look soon with the 2011 dataset of 5/fb
  - with the 2012 dataset we should be able to exclude a natural-SUSY stop
    - or start seeing first evidence of it

- unless nature chose a very peculiar compressed-type of spectrum?
- in such a case, we need:
  - more luminosity (and energy)
  - new avenues, like looking for hard ISR jets recoiling against the sparticles
  - new analysis techniques
  - good triggers
  - time

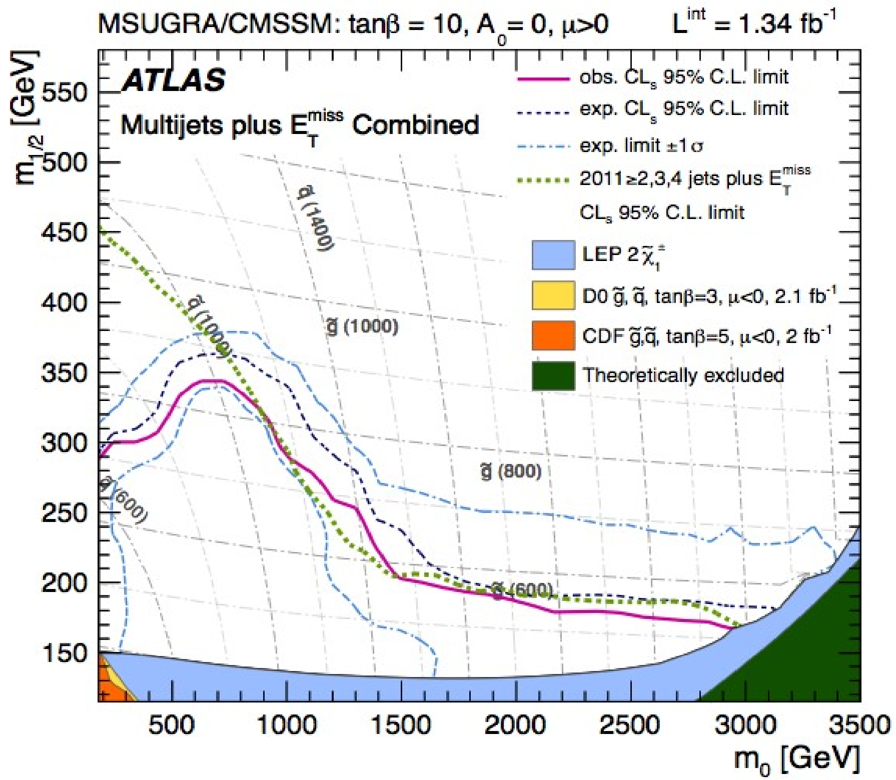
Conclusions

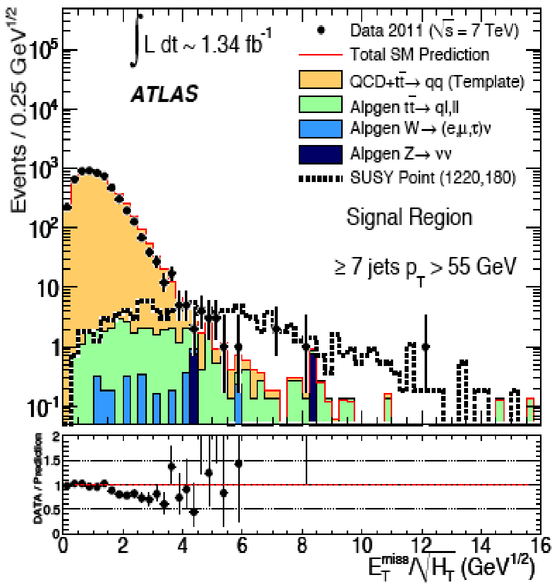
- 2010 was an exciting year for SUSY at the LHC
  - → large phase space opening up from jump in energy
  - → ready for discovery very early on
- 2011 was another great year for SUSY
  - → analyses updated with factor 30 more data, and another time with another factor 4
  - → extensions with b's, taus, new analyses, new methods, etc.
- 2012 to become a superb SUSY millesime?
  - → start targeting compressed spectra and long decay chains
  - → 3^{rd} generation searches ramping up
  - → direct chargino/neutralino production
  - → direct probing of naturalness

Backup

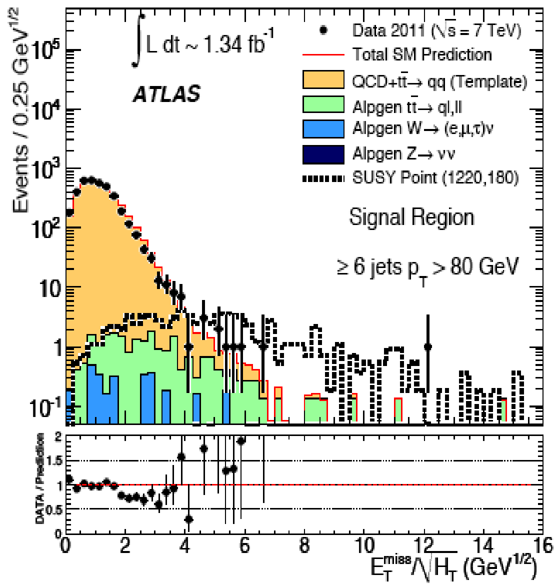
ATLAS Multijet Search

- MET + 6 or 8 jets
- expected to increase the sensitivity to long cascade decays of gluinos, including multi-top final states
- expected limit curves show better or equal sensitivity at higher m0 compared to >= 2 or 4 jet search





(a)



(b)