2010: Rediscovery of the Standard Model

Original discovery

1933 1947 1964


"Rediscovery" in CMS (dates approximate)

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Cornell Seminar - 1 February 2012
The Standard Model Validation at 7 TeV

* 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

* in addition many searches were done, all validating many corners of the SM
the SM has shortcomings though
→ notorious one: the hierarchy problem

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

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?
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.
- 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.

\[
m_h^2 = \left( m_h^2 \right)_0 - \frac{1}{16\pi^2} \lambda^2 \lambda^2 + \frac{1}{16\pi^2} \lambda^2 \lambda^2 + \ldots 
\approx \left( m_h^2 \right)_0 + \frac{1}{16\pi^2} (m_f^2 - m_f^2) \ln(\Lambda / m_f),
\]

cancels
small
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: “LMO”
• 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
    same-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, single lepton, opposite-sign dileptons
  ➔ same-sign dileptons, multileptons, photons, b's, taus
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→ most sensitivity early on

• search observables: invisible and visible energy
  → \text{MHT} → \text{MET from jets}
  → \text{HT} → scalar sum of jet transverse momenta

• aim for generic inclusive selection
  → \text{MHT} > 150 \text{ GeV}, \text{HT} > 300 \text{ GeV}
  → 3 central jets
  → these jets not aligned with the \text{MHT}
  → isolated electron and muon veto
  → central “massive” production
  → suppress QCD multijet background
  → reduce W and top with real \text{MHT}

• 2 search regions
  → high HT: \text{HT} > 500 \text{ GeV}
  → high \text{MHT}: \text{MHT} > 250 \text{ GeV}
  → sensitive to decays with mostly visible energy
  → yields high background rejection

• peculiarity: in this search \textbf{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
  - $W \rightarrow$ electron or muon, where the lepton is 'lost' (e.g. overlapping a jet)
  - $W \rightarrow$ 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 $\rightarrow$ neutrino background (invisible Z)**
  - looks just like signal: irreducible
  - most precise prediction from photon+jets
    - using well-controlled theory correction
• 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
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
• 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
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
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

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)

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
• **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**
• 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

CMS Preliminary

Ranges of exclusion limits for gluinos and squarks, varying \( m(\tilde{\chi}^0) \)

\[
\begin{array}{ll}
g \rightarrow q\bar{q}\tilde{\chi}^0 & \alpha_T, 1.1 \text{ fb}^{-1}, \text{gluino} \\
g \rightarrow q\bar{q}\tilde{\chi}^0 & E_T + \text{jets}, 1.1 \text{ fb}^{-1}, \text{gluino} \\
g \rightarrow q\bar{q}\tilde{\chi}^0 & \text{MT2}, 1.1 \text{ fb}^{-1}, \text{gluino} \\
\bar{q} \rightarrow q\tilde{\chi}^0 & \alpha_T, 1.1 \text{ fb}^{-1}, \text{squark} \\
\bar{q} \rightarrow q\tilde{\chi}^0 & E_T + \text{jets}, 1.1 \text{ fb}^{-1}, \text{squark} \\
g \rightarrow bb\tilde{\chi}^0 & E_T + b, 1.1 \text{ fb}^{-1}, \text{gluino} \\
g \rightarrow bb\tilde{\chi}^0 & \text{MT2}, 1.1 \text{ fb}^{-1}, \text{gluino} \\
g \rightarrow qq\tilde{\chi}^{\pm} & l^\pm l^\mp, 0.98 \text{ fb}^{-1}, \text{gluino} \\
g \rightarrow q\bar{q}\tilde{\chi}^0_2 \tilde{\chi}^0 & l^\pm l^\mp, 0.98 \text{ fb}^{-1}, \text{gluino} \\
\tilde{g} \rightarrow qq\tilde{\chi}^0_2 & Z + E_T, 0.98 \text{ fb}^{-1}, \text{gluino} \\
\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0_2 & \text{JZB}, 2.1 \text{ fb}^{-1}, \text{gluino} \\
\tilde{g} \rightarrow qq\tilde{\chi}^0_2 & E_T + \text{jets}, 1.1 \text{ fb}^{-1}, \text{gluino} \\
\tilde{g} \rightarrow qq\tilde{\chi}^0_2 & \alpha_T, 1.1 \text{ fb}^{-1}, \text{gluino} \\
\tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0_1 & l^\pm l^\mp, 1.1 \text{ fb}^{-1}, \text{gluino} \\
\end{array}
\]

For limits on \( m(\tilde{g}), m(\tilde{q}) > m(\tilde{\chi}) \) (and vice versa), \( \sigma_{\text{prod}} = \sigma_{\text{LO-QCD}} \).

\( m(\tilde{\chi}^\pm), m(\tilde{\chi}^0_2) = m(\tilde{g}) + m(\tilde{q}) \).

\( m(\tilde{\chi}^0_2) \) is varied from 0 GeV/c^2 (dark blue) to \( m(\tilde{g}) - 200 \text{ GeV/c}^2 \) (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
• **direct stop production**
  ➔ with ~5 fb⁻¹ of data on tape *we're in the game*
  ➔ $m(\text{stop}) = 200 / 400 / 600$ 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 $\chi^0$
    - these decays can be very hard to dig out of the background...
• 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/sqrt(S+B+ΔB^2)

• signal contamination could be an issue
  -> depending on the background estimation methods
• 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 $|\text{MET}|$ eg. $\text{MET} > 100 \text{ GeV}$
  ➔ require high MT, above the $W$ peak eg. $\text{MT} > 150 \text{ GeV}$
• signal becomes accessible on MT tail

• $t\bar{t}b\bar{t}$ → 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 $MET \sim 150$ GeV
    - and is very sensitive to pileup
  - also $Z \rightarrow$ neutrinos plays a subdominant role
  - $ttZ, Z \rightarrow$ neutrinos is at the few percent level

- **but high jet multiplicity and presence of b-jet pose problems**
• **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
things seem to look good for a low-mass Higgs...

→ this is the major LHC target for 2012
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\textsuperscript{rd} generation searches ramping up
  ➔ direct chargino/neutralino production
  ➔ direct probing of naturalness
• 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