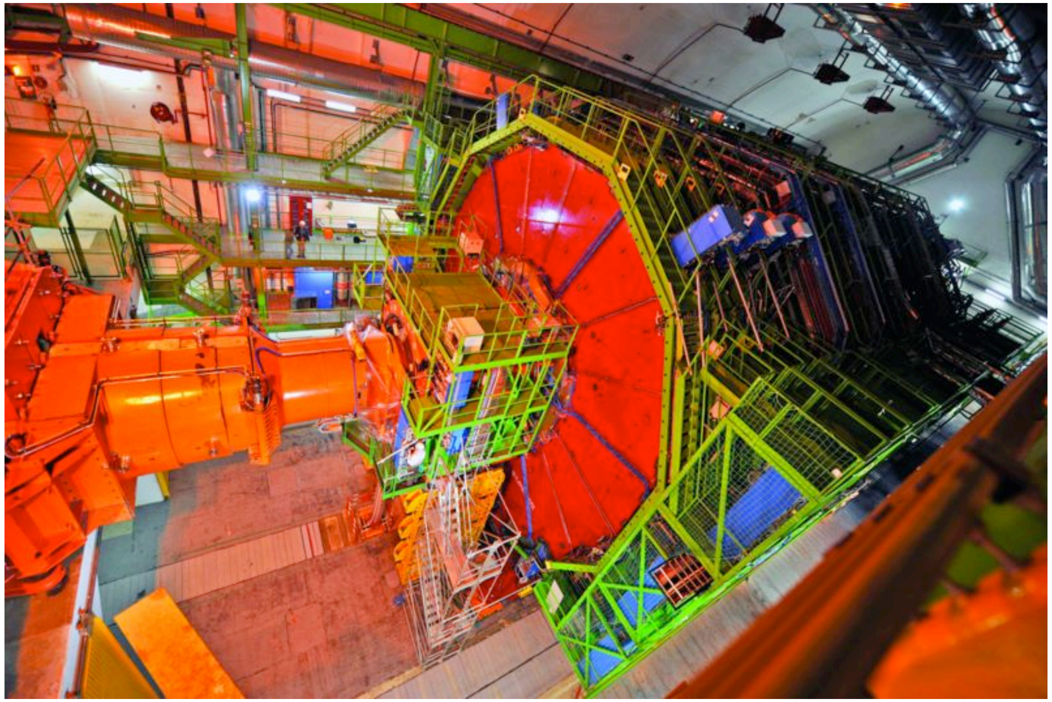

SUSY searches in CMS

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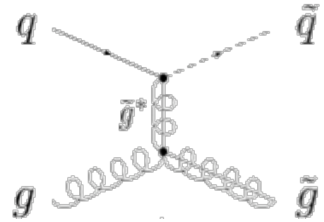
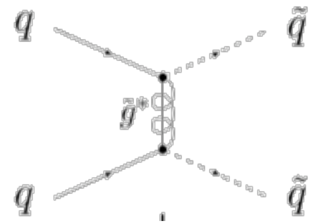
Particle Physics and Cosmology, Blois, France

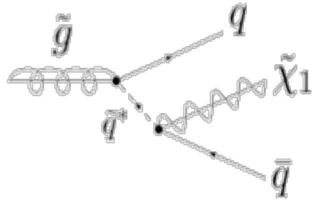
1 June 2011

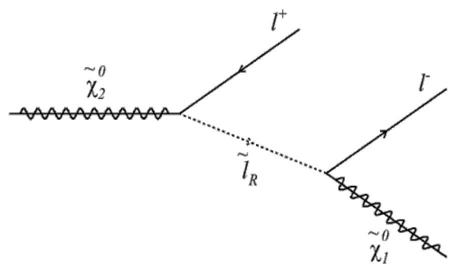
Early SUSY signatures

- The theoretical framework of supersymmetry allows for a large amount of diverse phenomenological features:
  - various mass spectra with distinct decay channels
  - different cross sections and branching ratios
- For early SUSY searches at CMS the focus lies on signatures that have **two features in common**:
  - **high-p_T jets**
    - due to strong production of SUSY particles
    - strong production has high cross sections, hence suitable for small luminosities
  - a **large excess of missing energy**
    - decay chains contain (or even end with) massive weakly-interacting sparticles (e.g. LSP in mSUGRA)
    - natural dark matter candidate



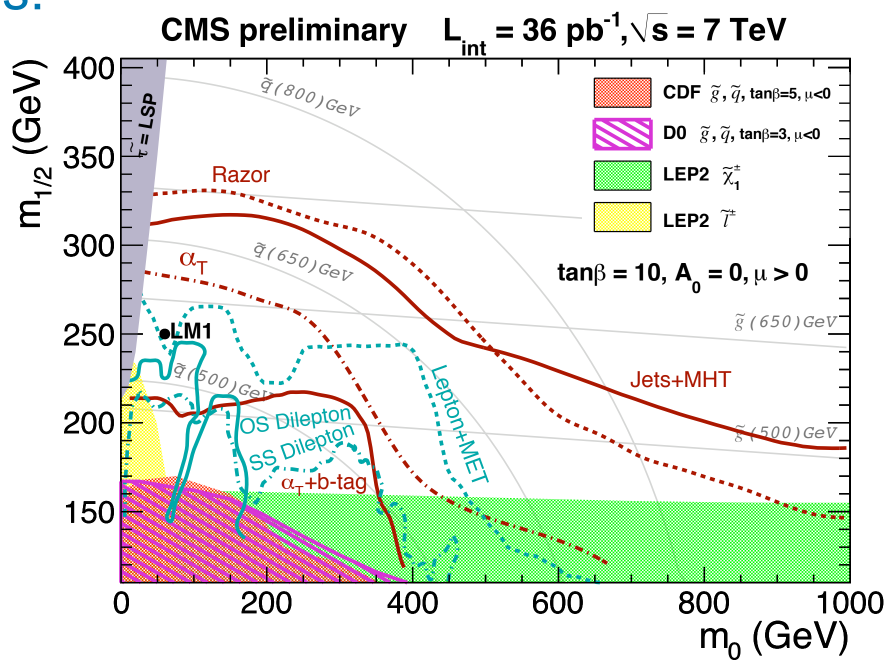






CMS strategy for SUSY searches

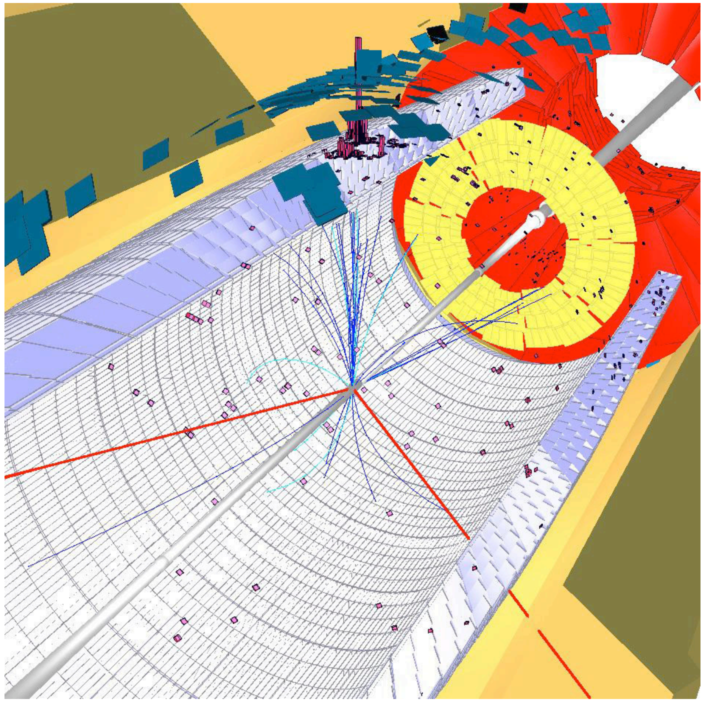
- Search for **inclusive signatures** of the kind **MET + jets + X**
  - overlaps of signatures as small as possible
- So far, results **using the data recorded in 2010** (L_{int} ~ 36 pb^{-1}), have been made public for these signatures:
  - MET + jets
  - MET + jets + b-tag
  - MET + jets + multi-leptons
  - MET + jets + same-sign di-leptons
  - MET + jets + opposite-sign di-leptons
  - MET + jets + single lepton
  - MET + jets + single lepton + photon
  - MET + jets + di-photons
  - MET + jets + Z



- Recent efforts to interpret results in a generalized, less model-dependent manner by means of **phenomenologically simplified models**

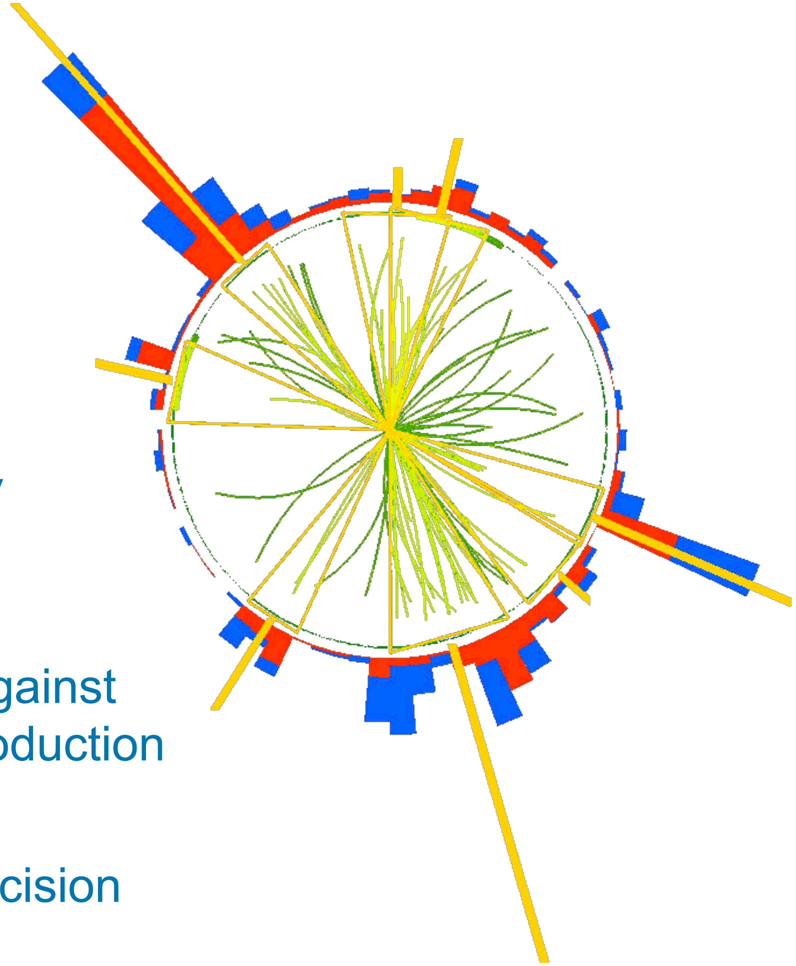
Backgrounds for SUSY searches at the LHC

- SUSY cross sections are expected to be **orders of magnitude smaller** than typical QCD cross sections:
  - backgrounds from QCD processes have to be understood and controlled
- Modeling and controlling the high-energy tails of QCD processes is very difficult:
  - QCD cross sections are not predicted with high enough precision
  - key topological and kinematic distributions such as the number of jets and their p_T spectra are difficult to predict
- Determination of backgrounds using **data-driven methods**:
  - use dedicated control samples
  - use multiple methods for cross-checks whenever possible



Hadronic signatures

- Highest potential for early discoveries due to large cross-sections for strong processes at the LHC
- Search signature
  - events with high-p_T jets
  - large missing transverse enery
  - veto on isolated, high-p_T leptons
- Three complementary approaches:
  - α_T **method** (with & without b-tagging):
    - reduces QCD background drastically by exploiting kinematical constraints
  - **razor method**:
    - tests kinematic consistency of events against the hypothesis of heavy particle pair-production
  - **inclusive method**:
    - estimates all backgrounds with high precision without applying kinematical constraints



The razor method

CMS PAS SUS-10-009

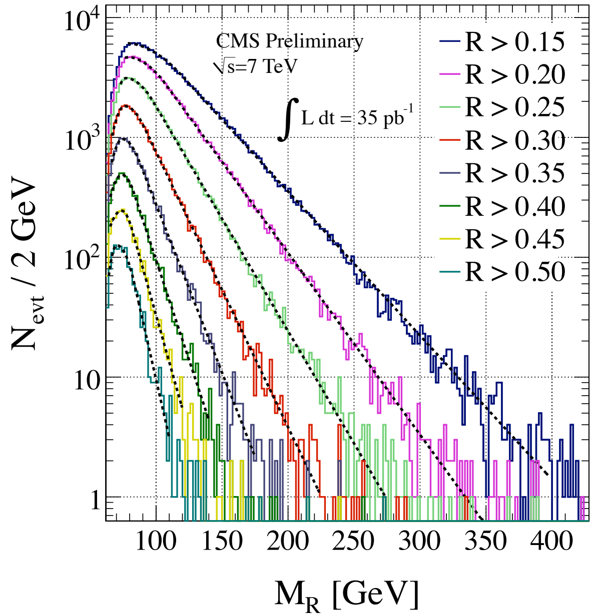
- Divide events in hemispheres and combine all jets in each hemisphere into a "mega-jet"
  - hemisphere algorithm selects jet combinations minimizing the invariant masses
  - resulting kinematics correspond to pair production of two heavy squarks (with $\tilde{q} \rightarrow \text{jet} + \tilde{\chi}_0$)
- Characterize resulting system kinematically:
  - **transverse variable** M_T^R (similar to m_T):

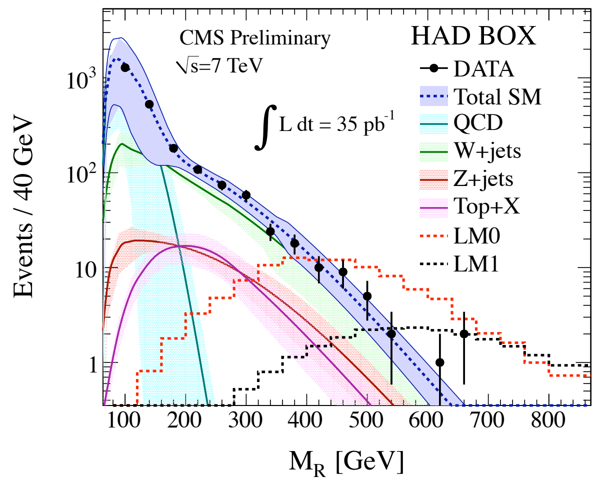
$$M_T^R = \sqrt{\frac{\left|E_T^{miss}\right|\left(p_T^{j1} + p_T^{j2}\right) - \vec{E}_T^{miss} \cdot \left(\vec{p}_T^{j1} + \vec{p}_T^{j2}\right)}{2}}$$

  - **event-by-event estimator** M_R:

$$M_R = 2\sqrt{\frac{\left(E^{j1}p_z^{j2} - E^{j2}p_z^{j1}\right)^2}{\left(p_z^{j1} - p_z^{j2}\right)^2 - \left(E^{j1} - E^{j2}\right)^2}}$$

  - background suppressing **razor variable** $R \equiv M_T^R / M_R$





The razor method

- SUSY decay-chains arise from pair production of heavy sparticles and end with an LSP:
  - M_R peaks around $M_\Delta \equiv (M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2)^2 / M_{\tilde{q}}$
  - signal region: $M_R \geq 500$ GeV and $R \geq 0.5$
- QCD background estimation:
  - only relevant scale for backgrounds is $\sqrt{s}$
    - distribution of M_R is falling exponentially
  - **slopes** of background distribution shapes can be parameterized as a function of R^2
- W/Z+jets and t+X background estimation:
  - similar to QCD estimate, but use control samples including leptons into the hemisphere algorithm
  - relative and absolute **normalizations** of back-ground distributions shapes
    - cross-section measurements
    - data-driven corrections from simulation

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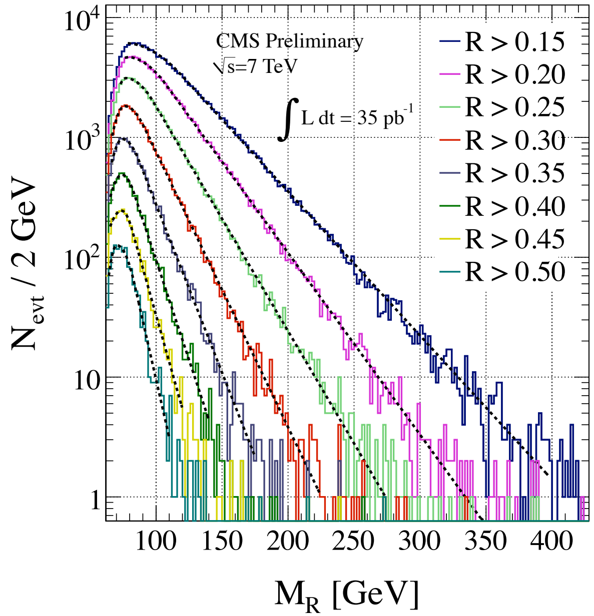
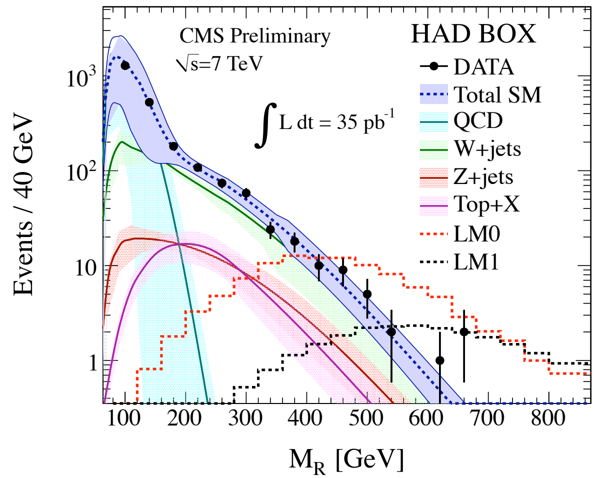
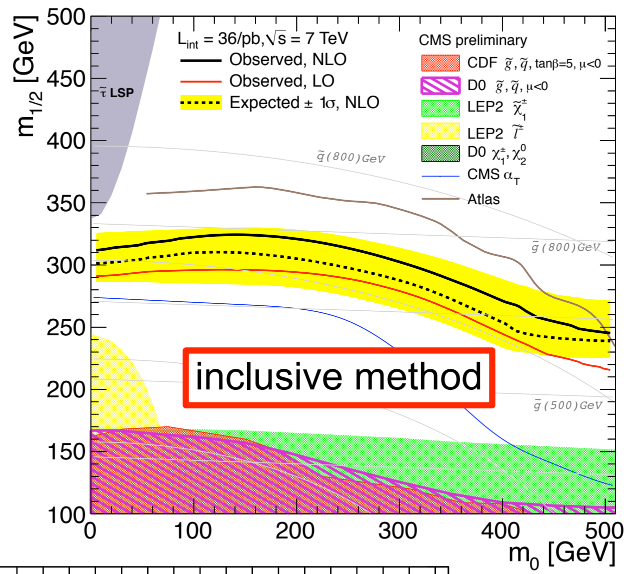
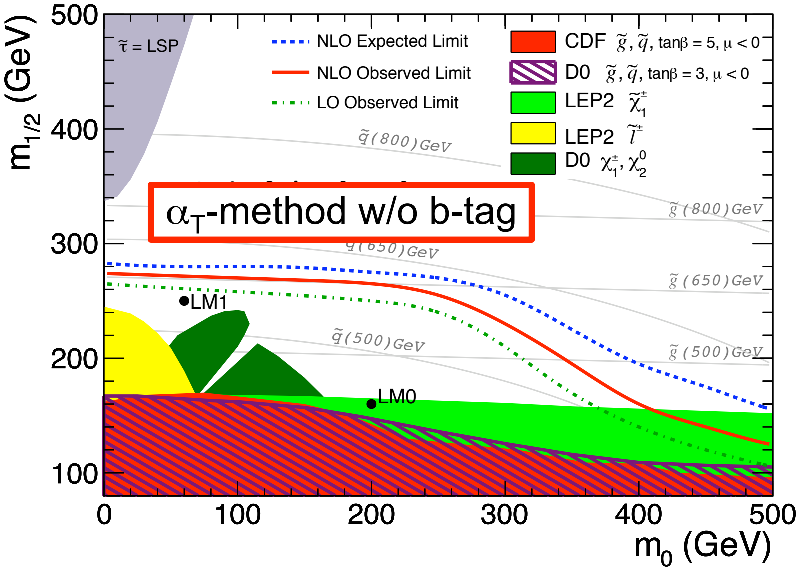


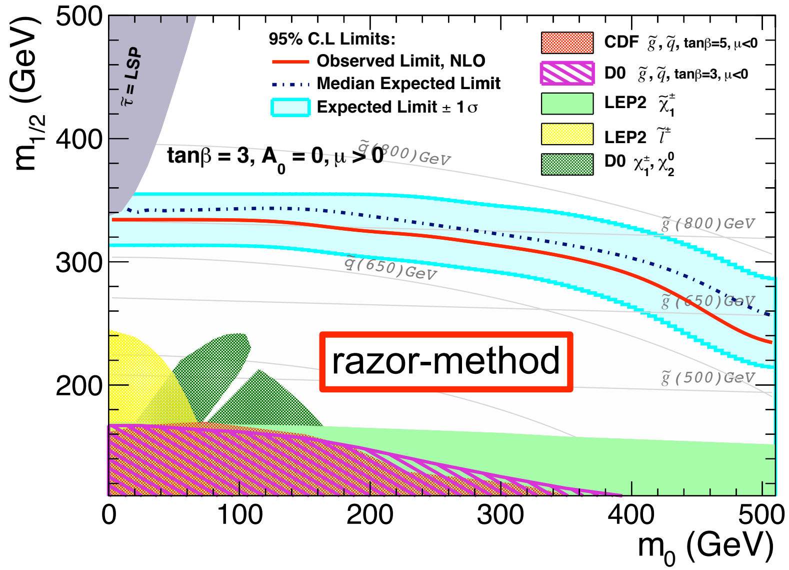


Results for hadronic signatures

- Results show great improvement with respect to previous studies
- Results from all hadronic analyses give a coherent picture
- Example:
  - mSUGRA exclusions with $\tan\beta = 3$, $\mu > 0$, $A_0 = 0$

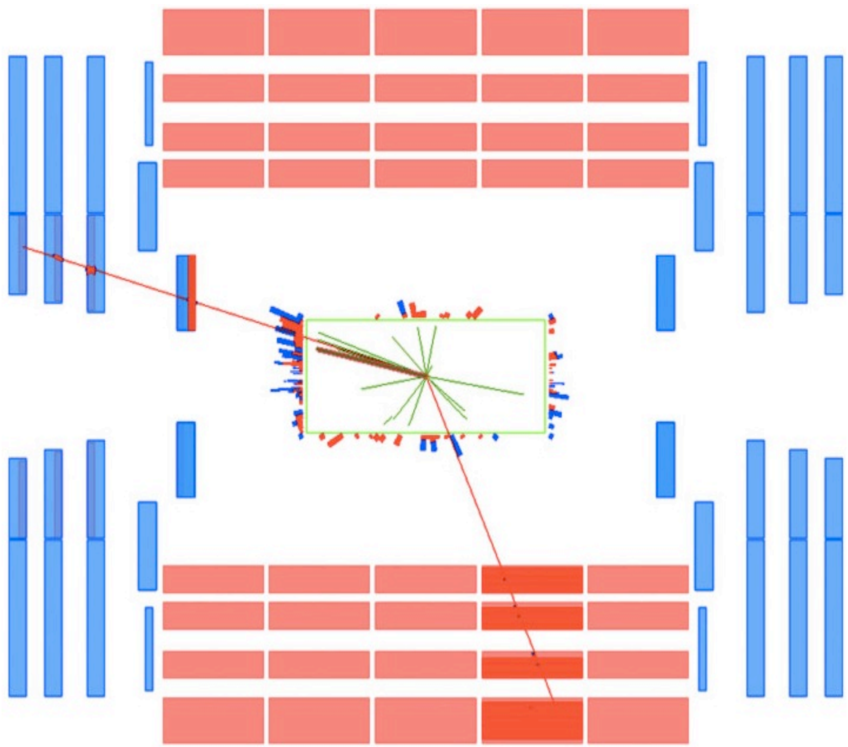






Leptonic signatures

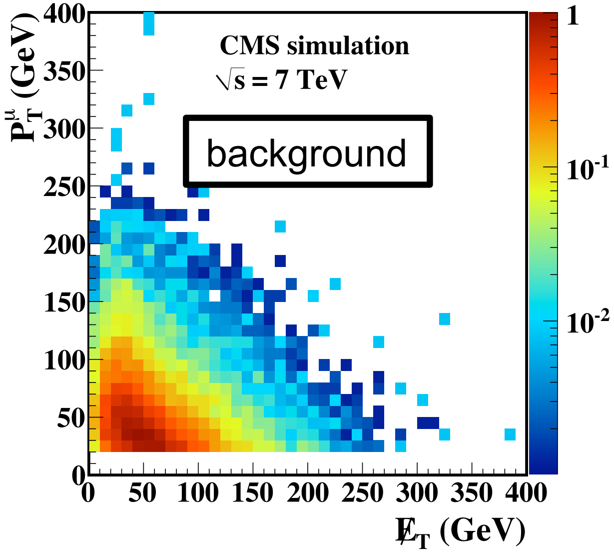
- Isolated high-p_T lepton:
  - in conjunction with large amounts of missing transverse energy an **indication of a weak decay of a heavy object**
  - reduced QCD background
- Search signature:
  - events with hight-p_T jets
  - large missing transverse energy
  - well isolated, high-p_T leptons
- Four complementary approaches:
  - **multi-lepton** analysis
  - **opposite-sign di-lepton** analysis
  - **same-sign di-lepton** analysis
  - **single lepton** analysis
- Small topological overlap between leptonic searches allows for clear phenomenological interpretations

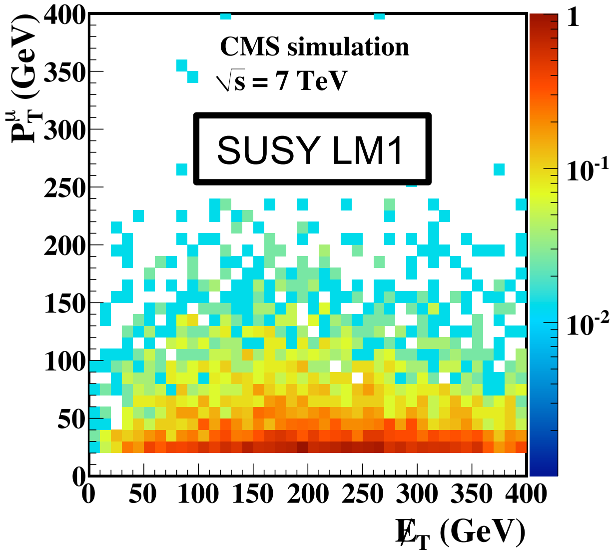


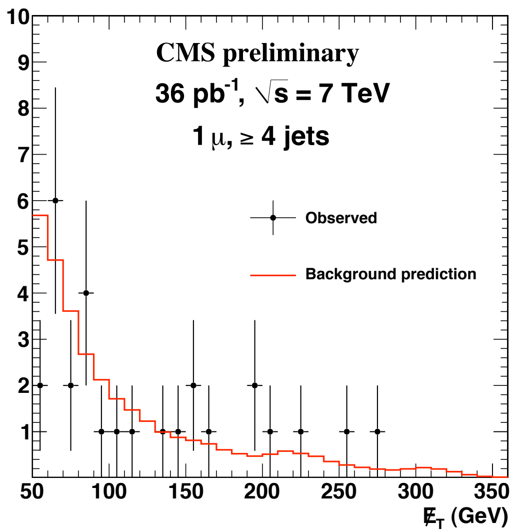
The single lepton analysis

- Search for excesses in region with $H_T > 500$ GeV and $\not\!\!E_T > 250$ GeV
- Background estimation:
  - **lepton-spectrum method**:
    - p_T distributions of lepton and neutrinos from W-two body decays are closely related
    - determine spectrum of $\not\!\!E_T$ from lepton p_T spectrum from $t\bar{t}$- and W-backgrounds
    - robust against signal contamination from typical SUSY topologies
  - cross-checked with **ABCD-method** (matrix method):
    - uses (almost) uncorrelated observables H_T and $y \equiv \not\!\!E_T/\sqrt{H_T}$

CMS PAS SUS-10-006

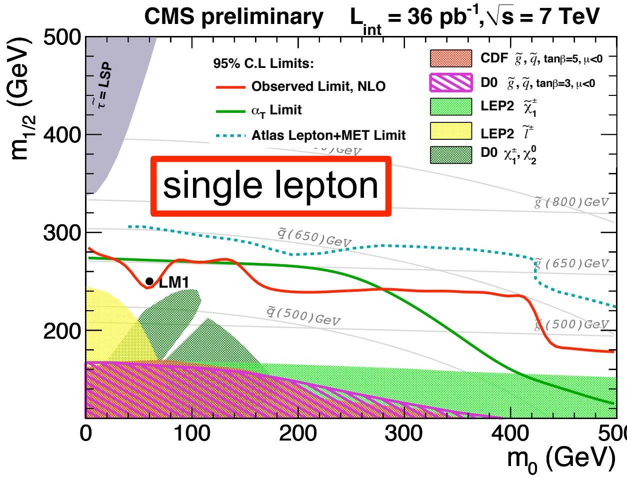


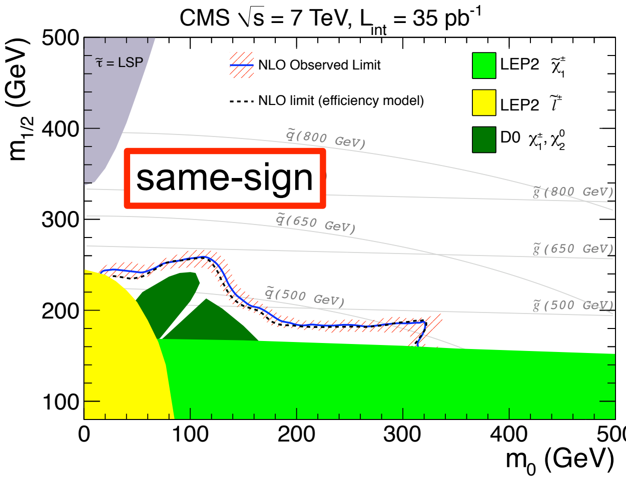


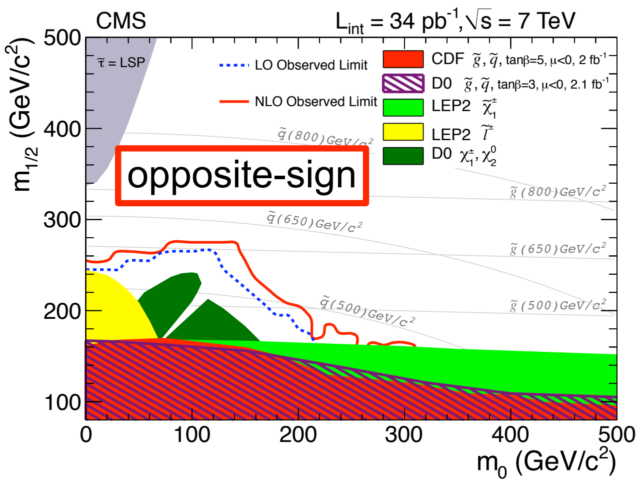


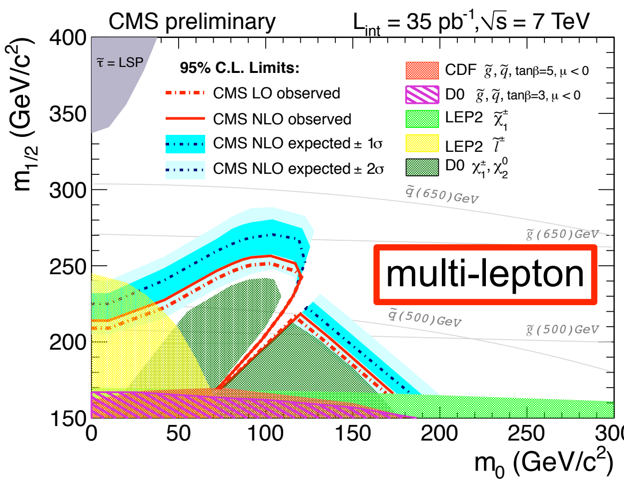
Results for leptonic signatures

- Results show improvements with respect to previous studies
  - even though much smaller cross-section than for fully hadronic processes
- Consistent with hadronic analyses
- Example:
  - mSUGRA exclusions with $\tan\beta = 3$, $\mu > 0$ and $A_0 = 0$



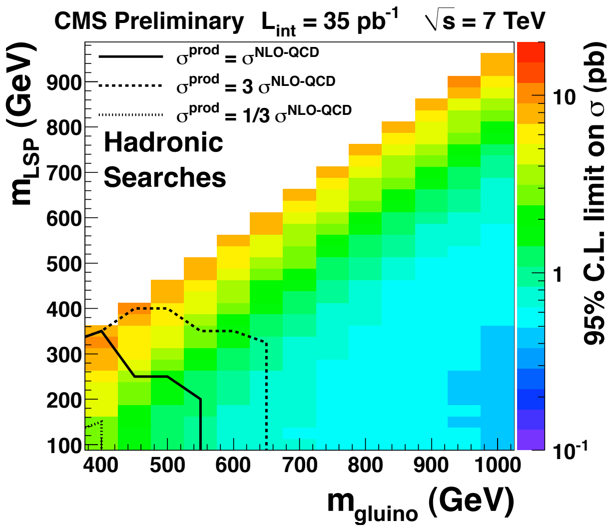


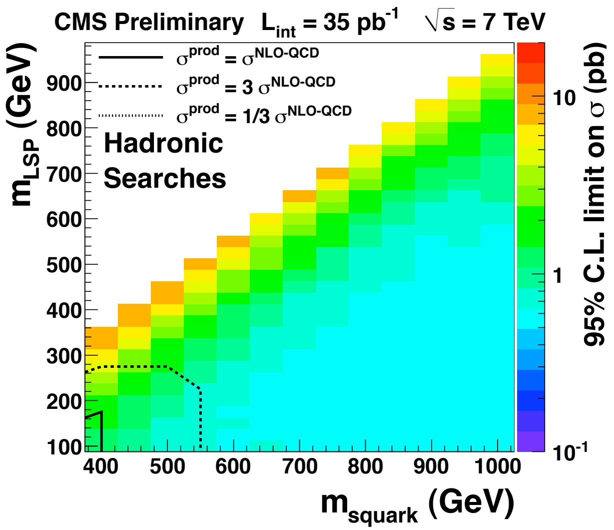




Simplified models

- Simplified models allow for more generalized interpretations
  - reduced SUSY-like particle content
  - masses are generic, not model dependant
  - assume constant cross sections, branching ratios are described by phase space
  - broadens reach of kinematically accessible regions of parameter space
  - describe features of data in a way that is useful for further model-building
- Results can be used by theorists outside of the LHC collaborations
  - good interface between experimentalists and theorists

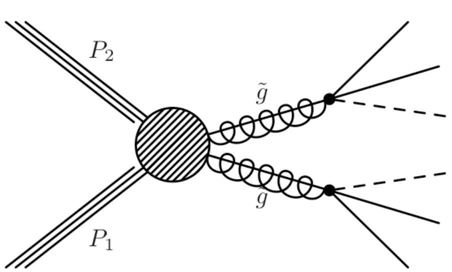


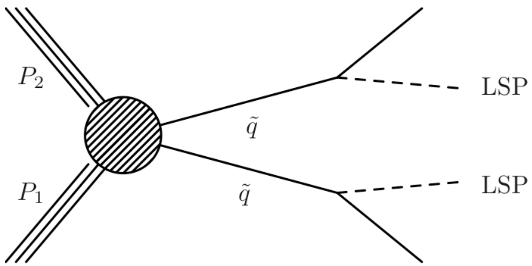


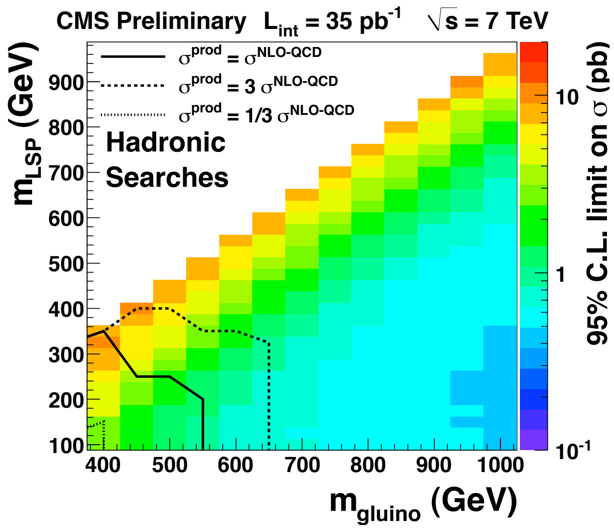
Simplified models

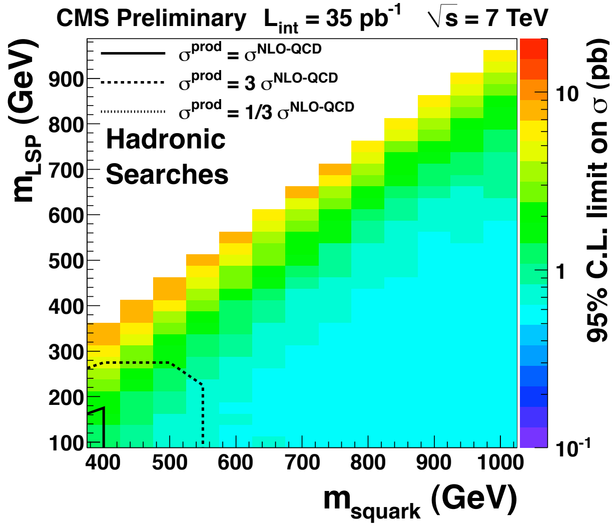
- Extended interpretation of all hadronic analysis
  - two simplified models based on proposals from the **LHC New Physics Working Group**
    - group of theorists addressing questions regarding characterization of BSM at the LHC
    - initiated by a workshop at a joint CMS, ATLAS and theory meeting in June 2010
  - Considered signatures:
    - pair-produced gluinos, gluinos decay to 2 light quarks and an LSP
    - pair-produced squarks, squark decay to 1 jet and an LSP
  - Generated with Pythia and CMS fast simulation

CMS PAS SUS-11-001









Conclusions and outlook

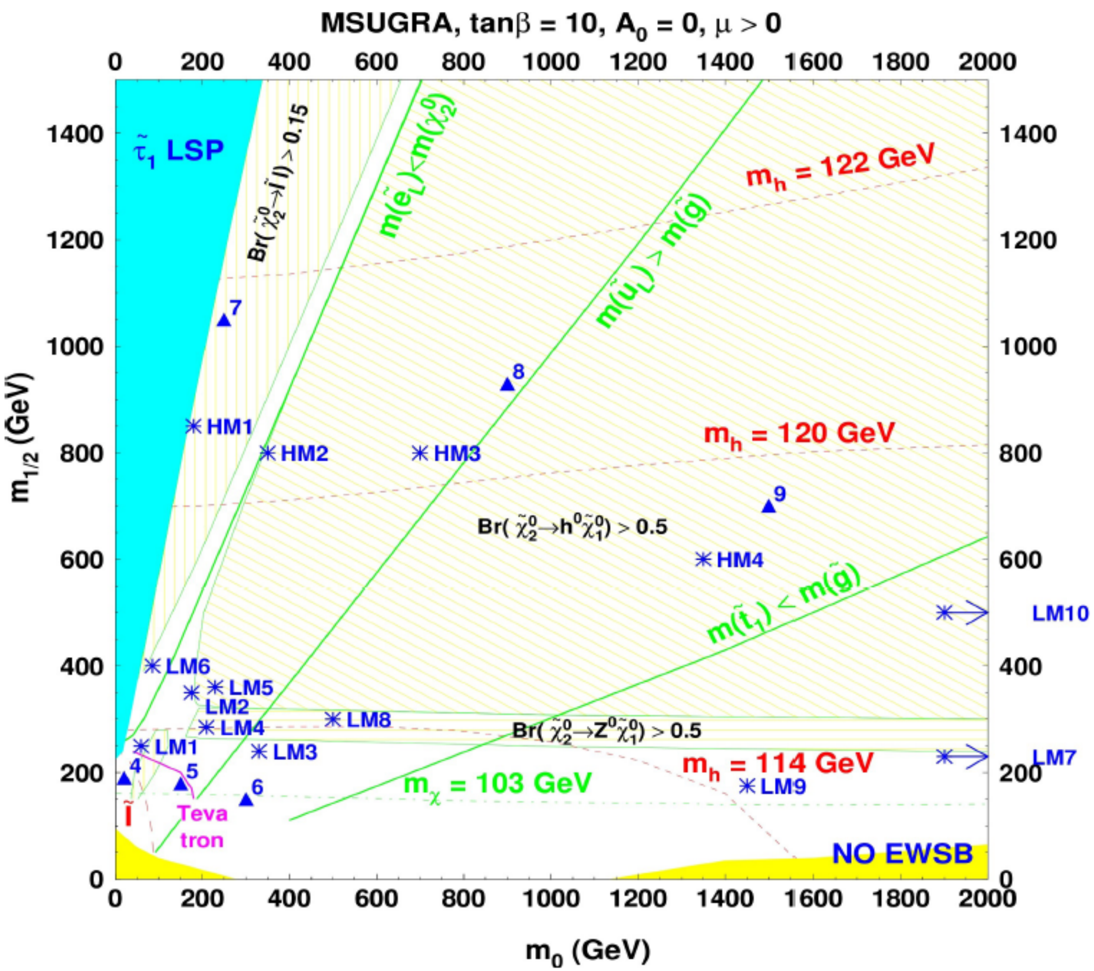
- The CMS effort to discover supersymmetry covers a broad range of signatures
- All analyses have pushed the previously known exclusion limits further using the LHC data recorded in 2010
- Characterization of new results through simplified models allows for generalized, model-independent BSM searches inspired by SUSY
- The CMS analysis effort is not focused on optimized exclusions, but rather on identifying possible new signals
- With the excellent performance of the LHC in mind, we hope for new physics to be just around the corner …

- Martin, S., *"A Supersymmetry Primer"*, arXiv:hep-ph/9709356v5
- *"The CMS Experiment at the CERN LHC"*, JINST **3**, S08004
- *"Search for Supersymmetry in pp Collisions at √s = 7 TeV in Events with Two Photons and Missing Transverse Energy"*, CMS Physics Analysis Summary: **SUS-10-002**
- *"Search for Supersymmetry in pp Collisions at 7 TeV in Events with Jets and Missing Transverse Energy"*, CMS Physics Analysis Summary: **SUS-10-003**
- *"Search for new physics with same-sign isolated dilepton events with jets and missing transverse energy at the LHC"*, CMS Physics Analysis Summary: **SUS-10-004**
- *"Search for new physics at CMS with jets and missing momentum"*, CMS Physics Analysis Summary: **SUS-10-005**
- *"Search for Physics Beyond the Standard Model in Opposite-sign Dilepton Events in pp Collisions at √s = 7 TeV"*, CMS Physics Analysis Summary: **SUS-10-007**
- *"Inclusive search for squarks and gluinos at √s = 7 TeV"*, CMS Physics Analysis Summary: **SUS-10-009**
- *"Search for Supersymmetry in Final States with b Jets and Missing Energy at the LHC"*, CMS Physics Analysis Summary: **SUS-10-011**
- *"Further interpretation of the search for supersymmetry based on α_T"*, CMS Physics Analysis Summary: **SUS-11-001**
- LHC New Physics Working Group Collaboration, "*Simplified Models for LHC New Physics Searches*", to be published (June, 2010), http://www.lhcnewphysics.org.

Backup Slides

Low mass benchmark scenarios

- All **benchmark points** are mSUGRA scenarios
- Parameterized by only five different parameters ($m_{1/2}$, m_0, $\tan\beta$, A_0, sign μ)
- Pros:
  - beyond the exclusion reaches of SPS, LEP, Tevatron, etc.
  - cover a large variety of distinct signatures
  - very well understood
- Cons:
  - restrictive ($m_{gluino} \sim 6\ m_{LSP}$)



The α_T method

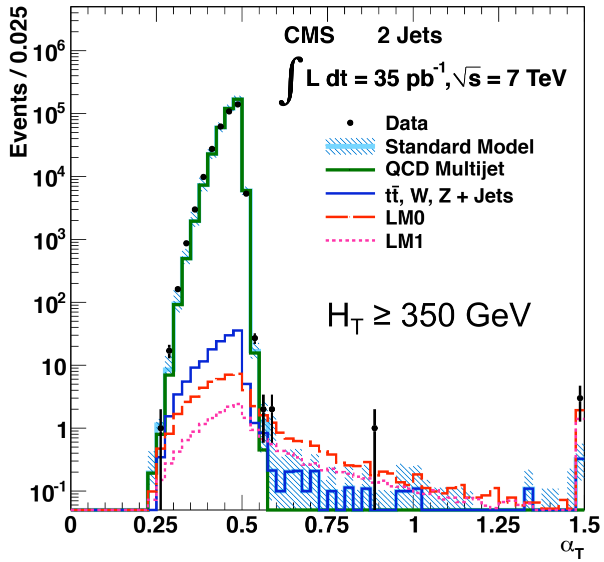
- Using the kinematic variables H_T and α_T to suppress SM backgrounds:
  - characterize the overall p_T-balance of the event

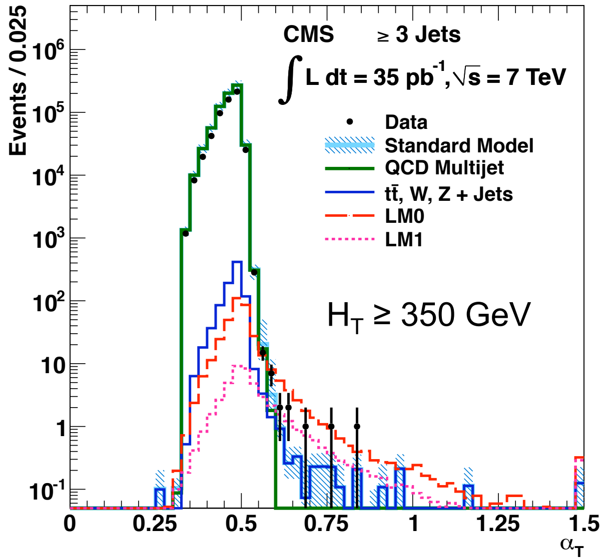
$$H_T = \sum_{\text{jets}\, j} p_{T,j} \qquad \Delta H_T = \min_{\text{jets}} \left(p_{T,\text{pseudojet}1} - p_{T,\text{pseudojet}2} \right)$$

$$MHT = \left| \sum_{\text{jets}\, j} -\vec{p}_{T,j} \right| \qquad \alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - (MHT)^2}}$$

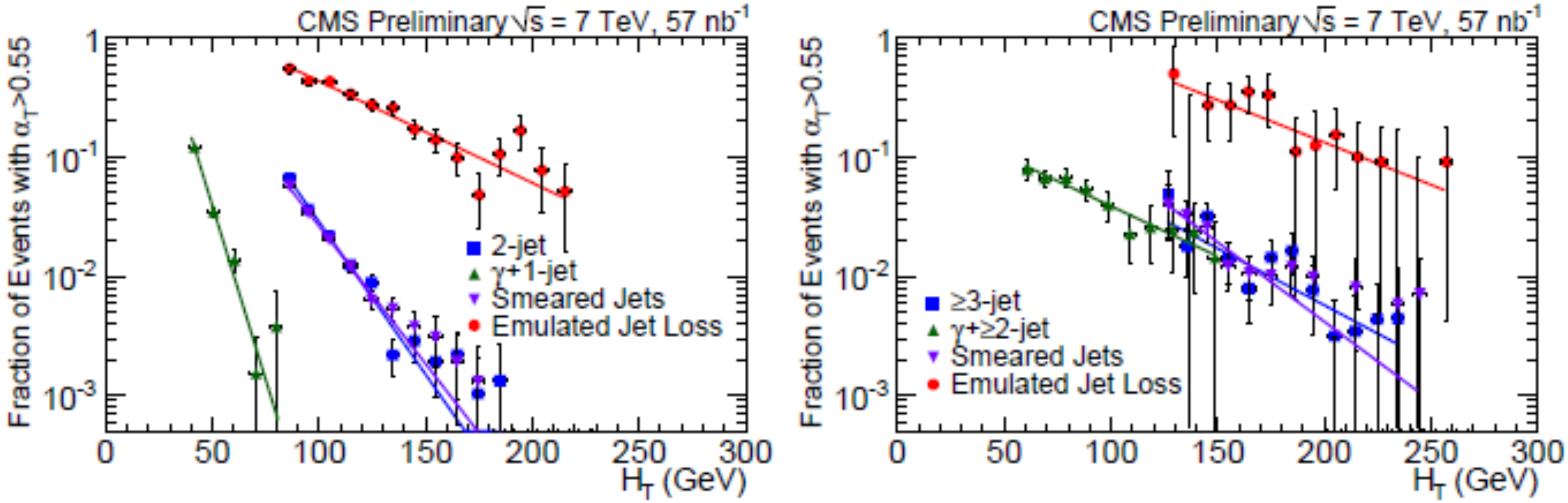
  - motivated by di-jet analyses, generalized for multi-jet events
- Properties extensively validated on data:
  - SM backgrounds mostly confined to α_T<0.55
  - suppression improves with increasing H_T
  - ratio of background events failing an α_T-cut decreases exponentially
  - allows for background estimates in higher H_T-bins

CMS PAS SUS-10-003



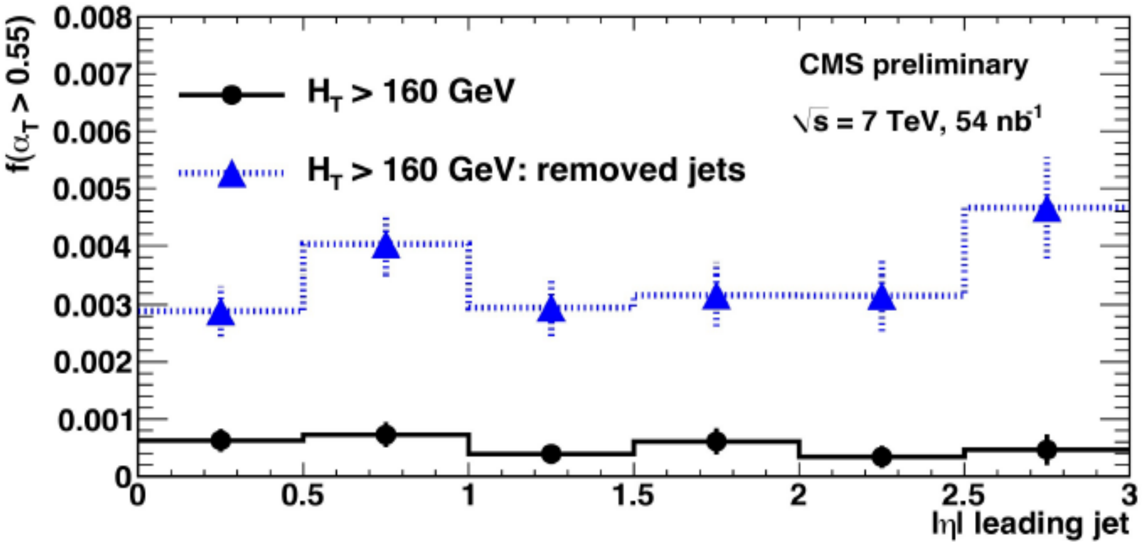


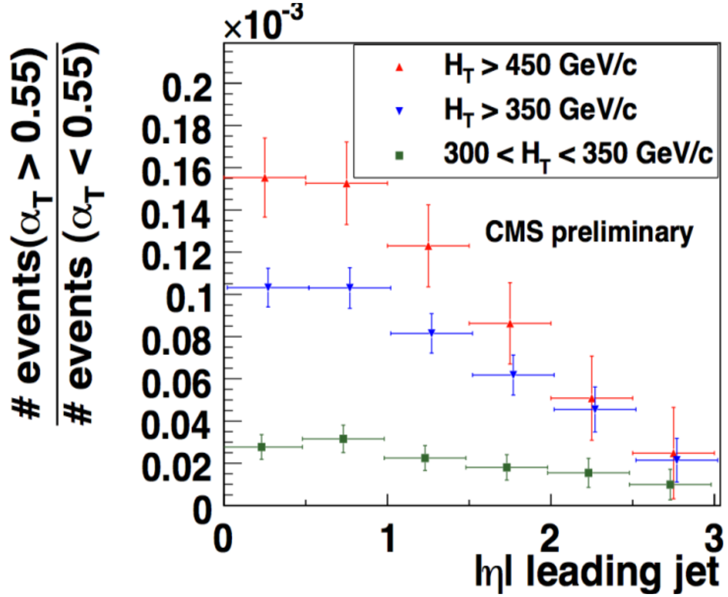
Validating α_T on data



- Jet-triggered QCD events (blue) decrease exponentially with increasing H_T
  - behavior can be used to calculate a limit for higher H_T-bins
- Artificially degraded data shows a consistent exponential trend
  - emulation of jet-loss with a 5-10 times increased removal probability (red)
  - photon-triggered events, dominated by misidentified jets (green)
  - the momentum of 10% of all jets is smeared using a one-sided Gaussian with σ=0.5$\cdot p_T$ (violet)

Validating α_T on data



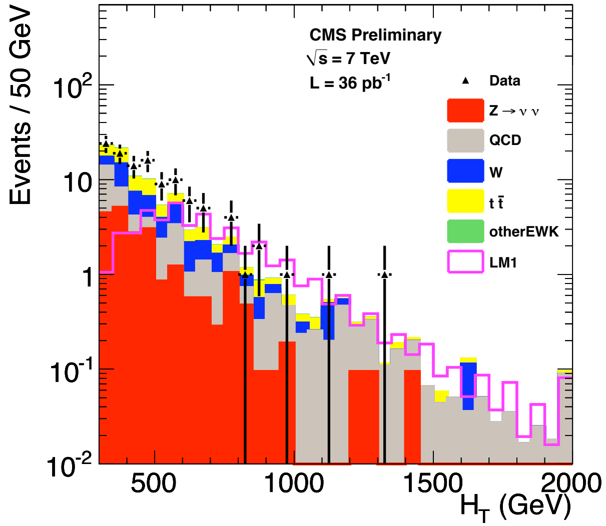


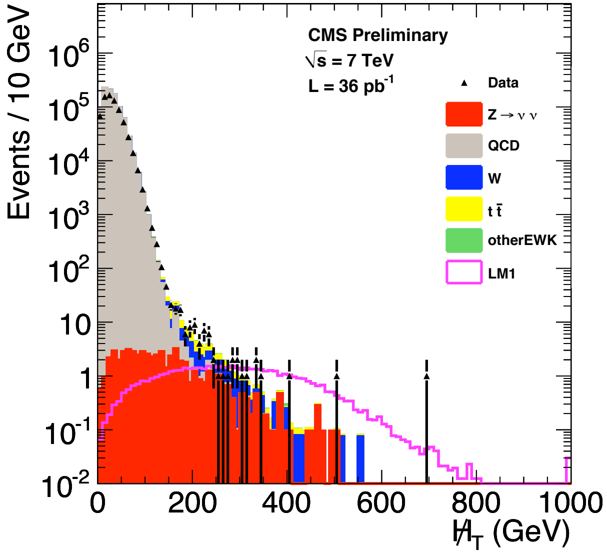
- Distribution of leading jets w.r.t. η is uniform for QCD events failing α_T<0.55
  - robustness: even when introducing artificial MET by randomly removing jets the uniformity remains
- SUSY events are produced more centrally
  - aim: use η-sidebands of leading jets to estimate background

The inclusive method

- search for deviations from expected SM distributions in H_T and $\not{H}_T$
- event selection aims to be as inclusive as possible
  - avoid topological restrictions due to kinematical constraints
- all sources of backgrounds are measured from data, including the complete QCD background
  - invisible $Z \to \nu\nu$:
    - directly from $Z \to l^+l^-$ (small sample)
    - via Z/γ-correspondence at large p_T from γ+jets
  - W and top:
    - estimate events with lost leptons from μ+jets data sample using efficiency information from tag&probe
    - mimic effect from hadronic τ's using by replacing μ's with τ-jet templates in μ+jets data samples

CMS PAS SUS-10-005

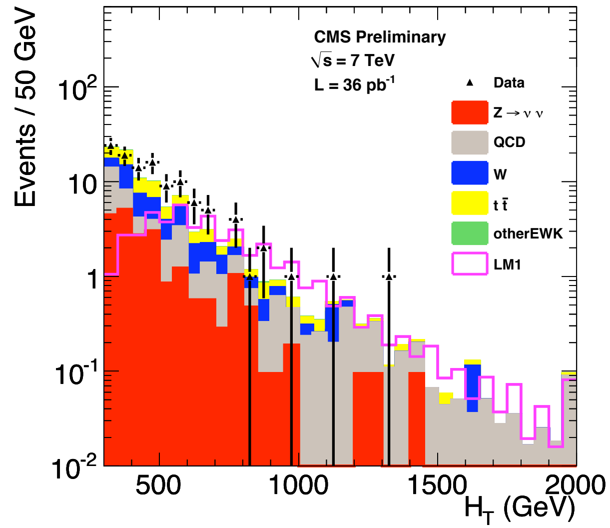


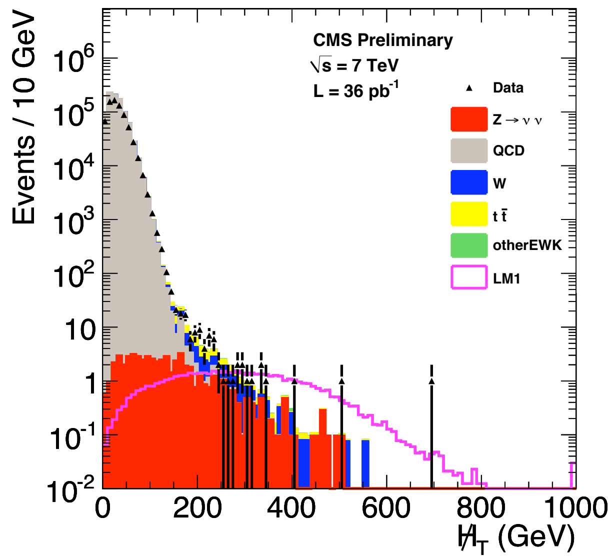


The inclusive method

CMS PAS SUS-10-005

- QCD background estimation:
  - **“Rebalance and Smear” method**
    - predicts full kinematics in multi-jet events
    - unaffected by events with true missing momentum
    - produce so-called seed events in **“Rebalance” step**:
      - adjust jet momenta such that $\not{H}_T \approx 0$
    - use seed events in **“Smear” step**:
      - scale jets with values drawn from jet resolution distribution
      - apply search cut to the resulting events to predict complete jet kinematics and correlations
  - cross-check using **factorization method**
    - uses relation between $\not{H}_T$ and $\Delta\phi_{min}$ (minimum azimuthal angle between $\not{H}_T$ and three leading jets)
    - $\not{H}_T$ and $\Delta\phi_{min}$ are not uncorrelated: functional form of the correlation is estimated at low $\not{H}_T$
    - use relation to estimate background in signal region (high $\not{H}_T$, low $\Delta\phi_{min}$) from sideband (high $\not{H}_T$, low $\Delta\phi_{min}$)

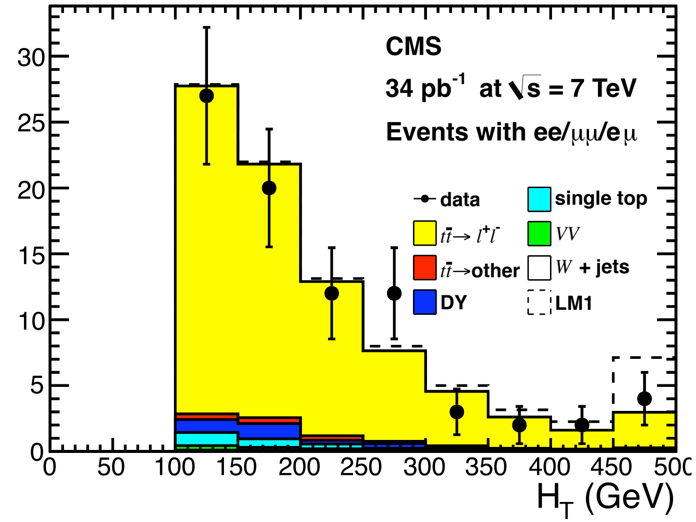


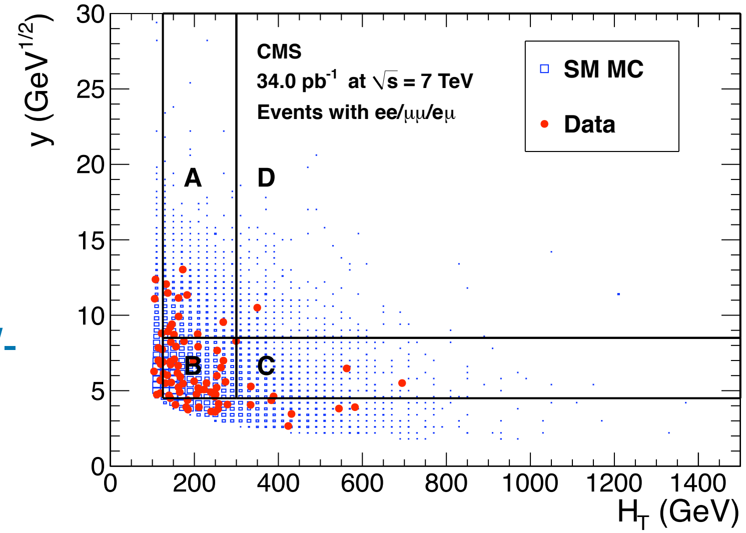


The opposite-sign di-lepton analysis

CMS PAS SUS-10-007

- Search for signals in region with:
  - high hadronic activity: $H_T > 300$ GeV
  - significant amount of missing transverse energy: $y \equiv \not{E}_T/\sqrt{H_T} > 8.5\ \mathrm{GeV}^{1/2}$
- Require isolated opposite-sign lepton pairs
  - Drell-Yan suppression via invariant mass exclusion interval: $M_{ll} < 76$ GeV and $M_{ll} > 106$ GeV
- Background estimation:
  - apply **ABCD method**
    - H_T and y are (almost) uncorrelated
    - estimate $N_D = N_A \times N_C / N_b$
  - cross-check using **p_T(ll)-method**
    - p_T distributions of lepton and neutrinos from W-two body decays are closely related
    - correct lepton spectrum for differences in pre-selection efficiency and W polarization

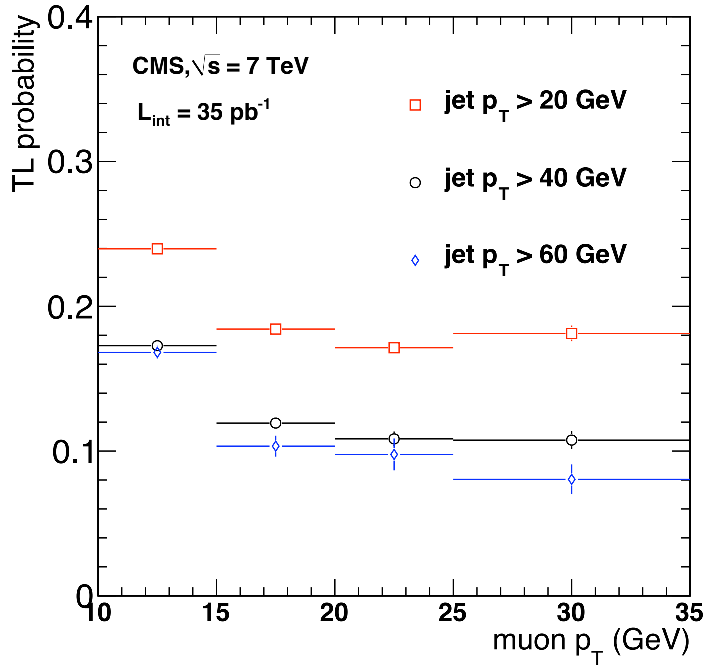




The same-sign di-lepton analysis

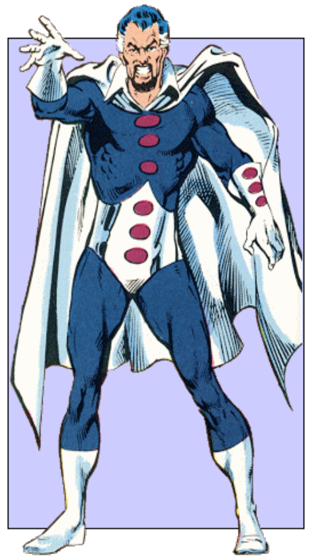
- Search for excesses in regions with $H_T > 200$ GeV and $\not{E}_T > 80$ GeV
- Same-sign isolated lepton pairs from hadron collisions are very rare
- Analysis includes **hadronically decayed τ's**
  - use neural network, trained to identify the hadronic τ-decay modes using the kinematics of the reconstructed charged and neutral pions
- Background estimation with **tight-loose method**:
  - determine probability ε_{TL} for leptons passing a loose isolation selection to also pass the tight analysis selection
  - measure in a QCD multi-jet sample
  - applying ε_{TL} to a sample of di-lepton events, where one of the leptons fails the tight selection but passes the loose one

CMS PAS SUS-10-004



The di-photon channel

- Aims for **general gauge-mediation scenarios**:
  - decay chains include one or several quarks/gluons plus a neutralino, which in turn decays to a photon and a **gravitino**
  - the gravitino escapes detection, leading to a significant amount of **missing transverse energy**
- Search signature:
  - two or more isolated high-p_T photons ($p_T \geq 30$ GeV)
  - at least one high-p_T jet ($p_T \geq 30$ GeV)
  - large missing transverse energy ($\not{E}_T \geq 30$ GeV)
- QCD Background:
  - direct photons
  - quarks/gluons hadronizing predominantly to π^0s decaying into photons
  - estimated from two control samples:
    - events containing two fake photons
    - events containing 2 electrons with invariant mass 70 - 110 GeV (mostly $Z \rightarrow ee$)

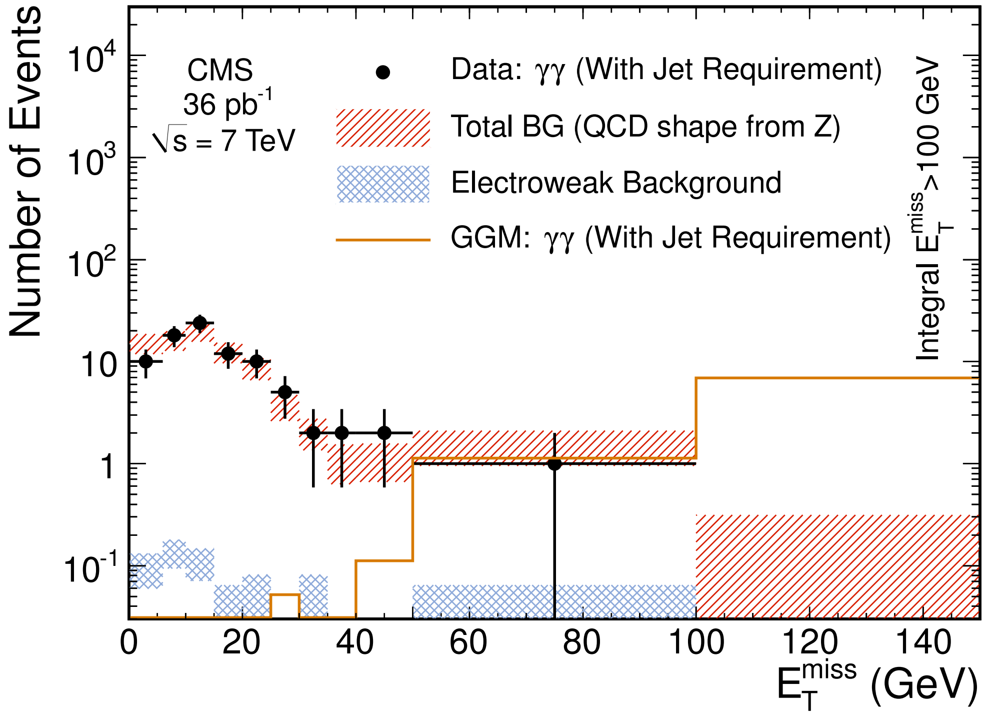


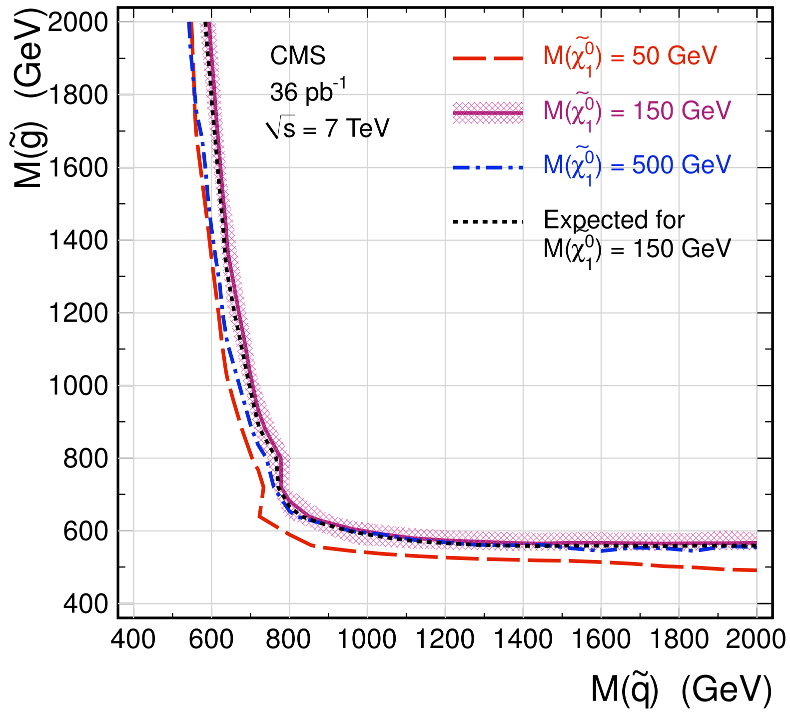
Franklin Hall a.k.a. “Graviton”

CMS PAS SUS-10-002

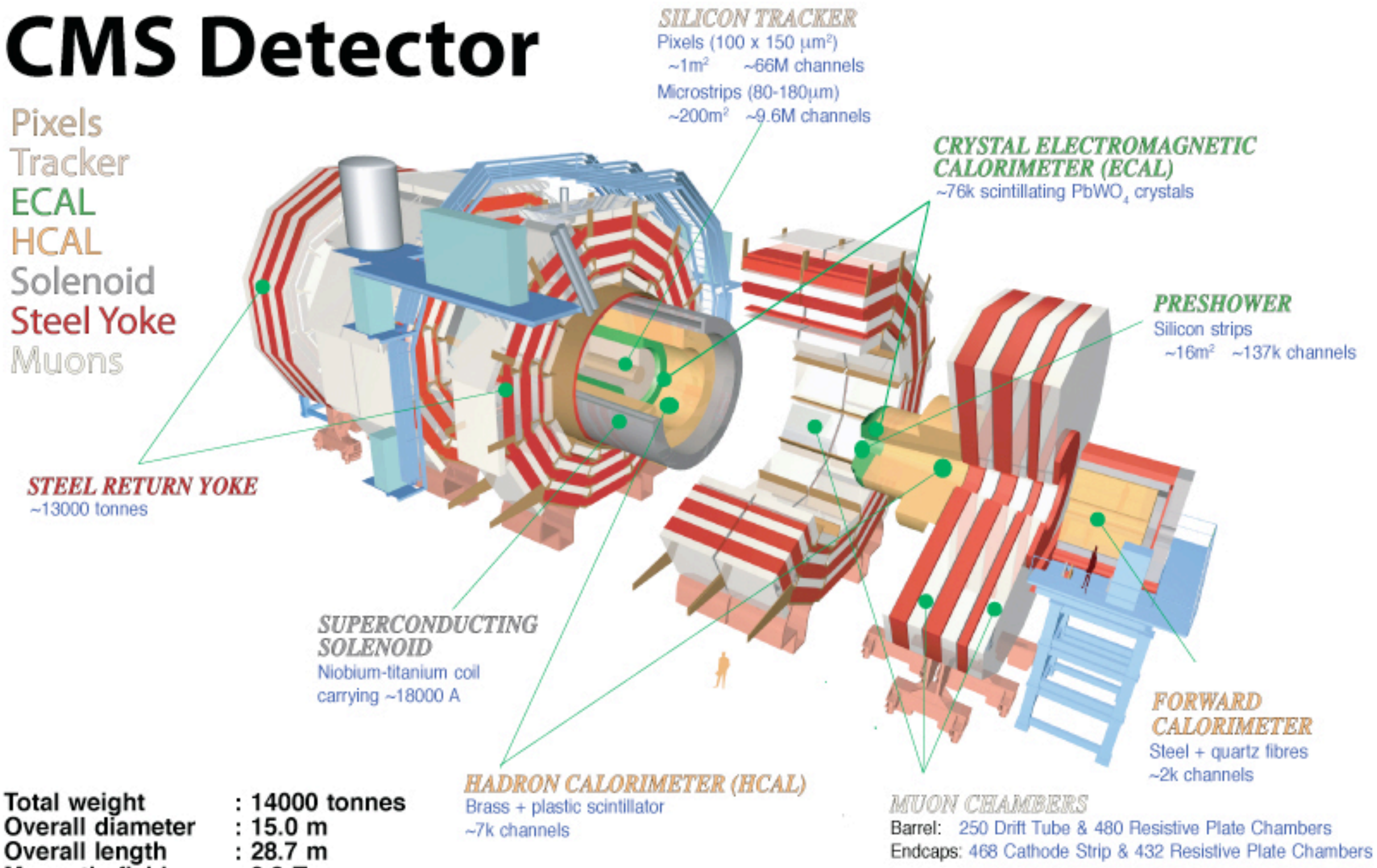
The di-photon channel

- Electroweak background:
  - events with a genuine or fake photon and a W that decays into a neutrino and an electron, with the latter mis-identified as a photon
  - estimated from events containing 1 electron plus 1 photon





CMS Detector



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**