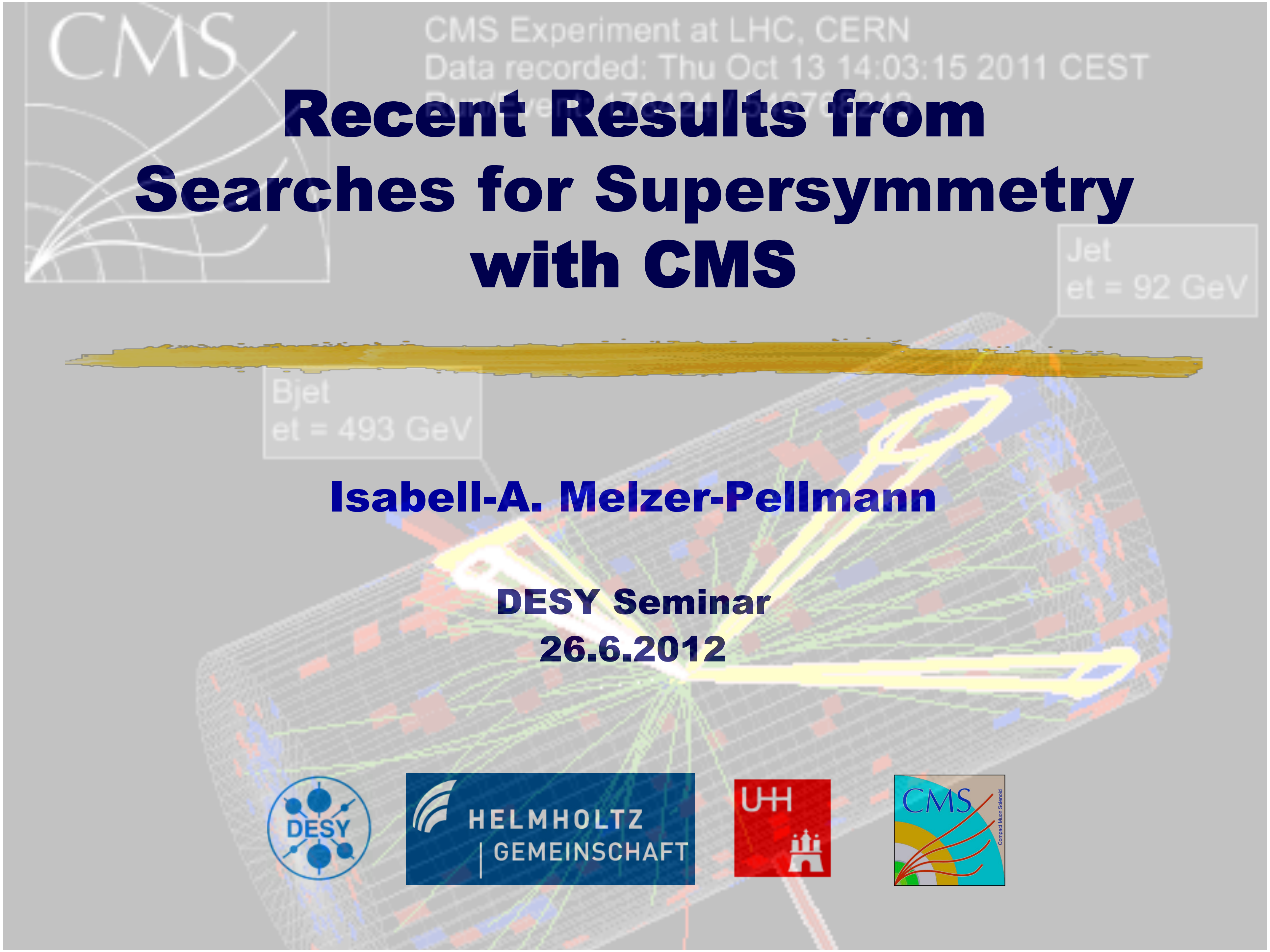
Recent Results from Searches for Supersymmetry with CMS

Isabell-A. Melzer-Pellmann

DESY Seminar
26.6.2012



Outline

- **Introduction**
  - The CMS Experiment
  - Hadronic searches
  - Leptonic searches
  - Searches for 3rd generation squarks
  - Searches with photons
  - Conclusion/Outlook

The Standard Model and remaining open Questions

- **The Standard Model is highly successful since 30 years**
- **But some open questions remain, e.g.**
  - Neutrino masses and mixing
  - Baryogenesis (matter anti-matter asymmetry)
  - Cold dark matter
  - Dark energy

  } **from data**

  - Quadratic divergences in scalar sector ⇒ fine-tuning
  - Origin of generations
  - Unification with gravity

  } **from theory**

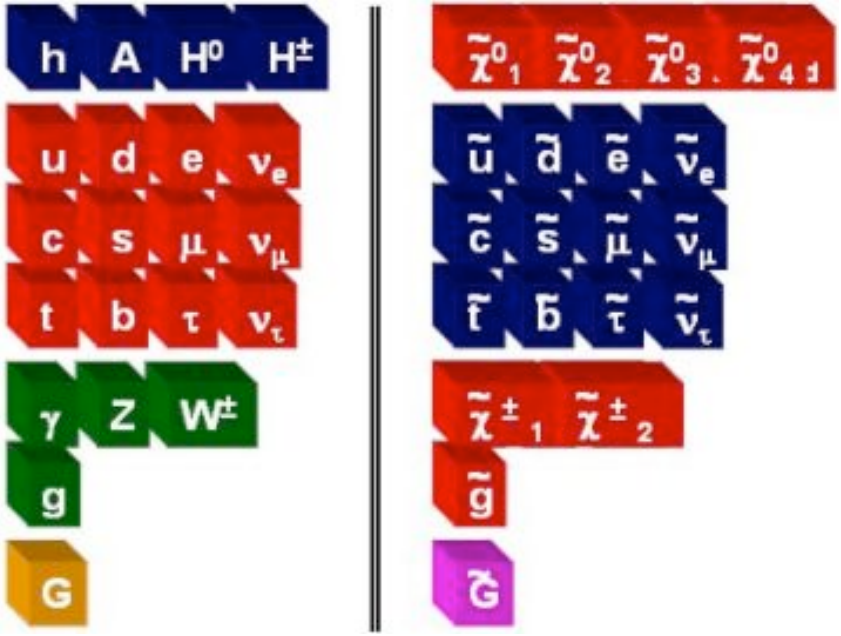
☛ Supersymmetry

- Symmetry between fermions and bosons:

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle \;;\quad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

SUperSYmmetry (SUSY)

- Assign a supersymmetric partner particle to every Standard Model particle



- Spin of SUSY particle reduced by ½ compared to the SM partner
- If SUSY would be an exact theory
  → each partner particle would have the same mass
- **BUT:** No SUSY particles found at same mass
  → Symmetry must be broken

From MSSM to cMSSM

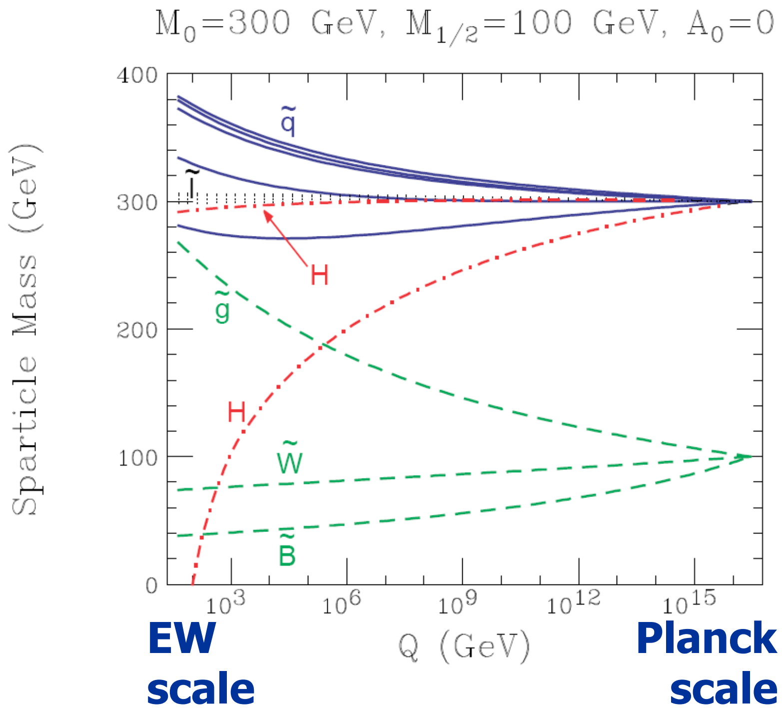
Minimal **S**uper**S**ymmetric **M**odel (**MSSM**): no particular SUSY breaking mechanism assumed

Most general case: 105 new parameters!

- Difficult to predict due to the large number of free parameters
- Try to reduce number of parameters, e.g. by putting universal boundary conditions at GUT scale (running masses equal to running coupling constants)

→ **c**onstrained **MSSM** (**cMSSM**)

- 4 parameters, 1 sign
  - m_0: common scalar mass
  - $m_{1/2}$: common gaugino/higgsino mass
  - tan β: ratio of Higgs vacuum expectation values
  - A_0: common trilinear coupling
  - sign μ: sign of μ SUSY conserving Higgsino mass parameter

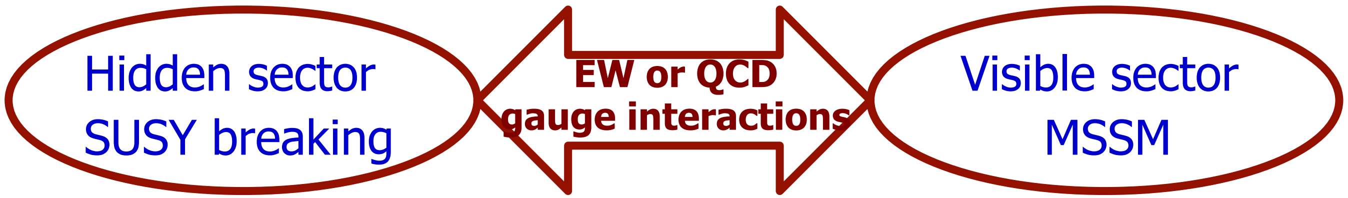


SUSY Breaking Scenarios

- SUSY is supposed to break in a hidden sector
- A priori not clear who is the messenger, famous are:

  - Gravity – cMSSM or mSUGRA

  - Gauge Mediated Symmetry Breaking (GMSB)



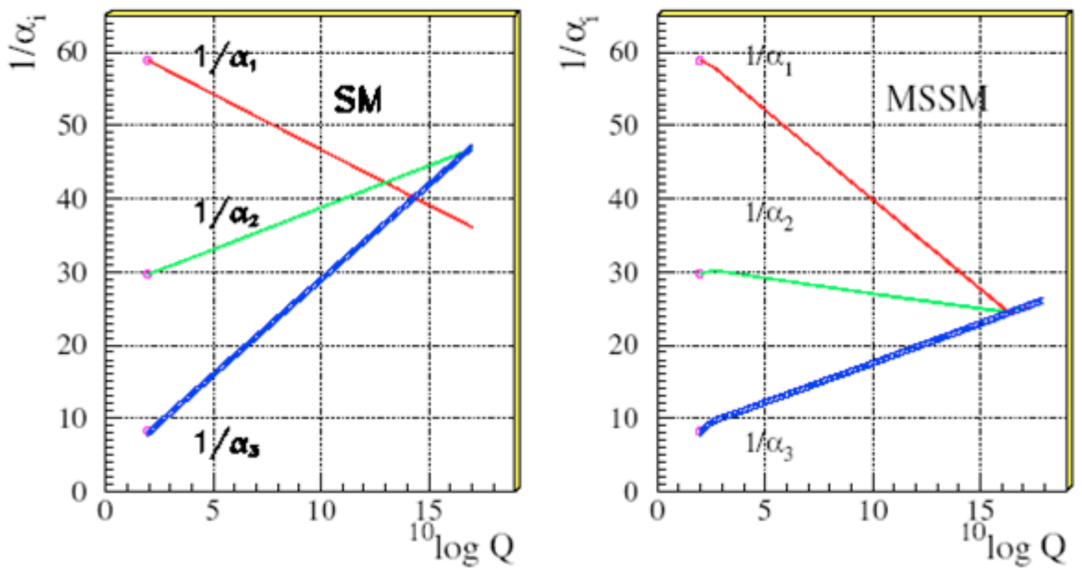
  - …

SUSY: Unification of forces

Running coupling constants can meet in one point for SUSY:

- Energy dependence of coupling constants → RGE
- Coefficients in the RGE depend on the particles in loops
- More particles due to SUSY – coefficients of the RGE change
- With SUSY particles in TeV range

→ all coupling constants reach the same value at $2 \cdot 10^{16}$ GeV

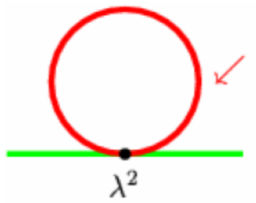


U. Amaldi, W. de Boer, H. Fürstenau, PL B260(1991)

The Hierarchy Problem

Large additive radiative corrections from loop diagrams

$$\mu^2 = \mu^2_{\text{bare}} + \frac{\lambda}{8\pi^2}\Lambda^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 + \cdots$$

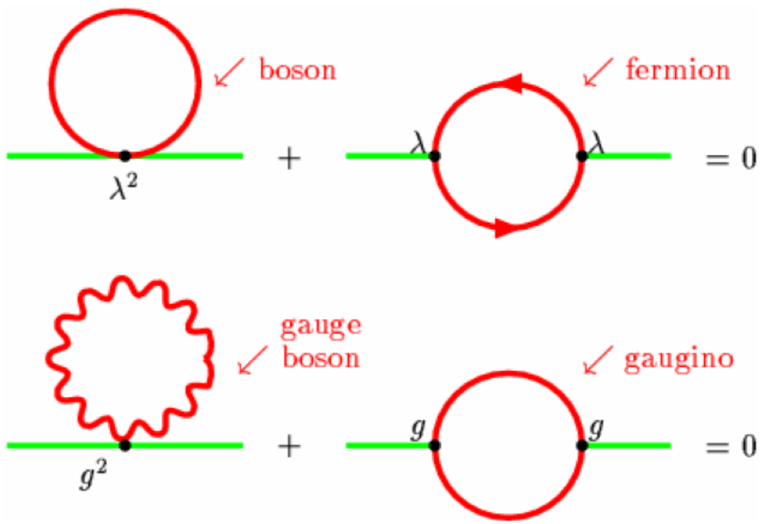


- Higgs mass ultraviolet divergent
  → need momentum cutoff Λ:
- if SM is valid up to the Planck scale, ($\Lambda \sim 10^{19}$ GeV)
  → cancellation μ and the radiative corrections in the first 36 decimal places is required
  →"gauge hierarchy problem"

The Hierarchy Problem

Large additive radiative corrections from loop diagrams

$$\mu^2 = \mu^2_{\text{bare}} + \frac{\lambda}{8\pi^2}\Lambda^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 + \cdots$$

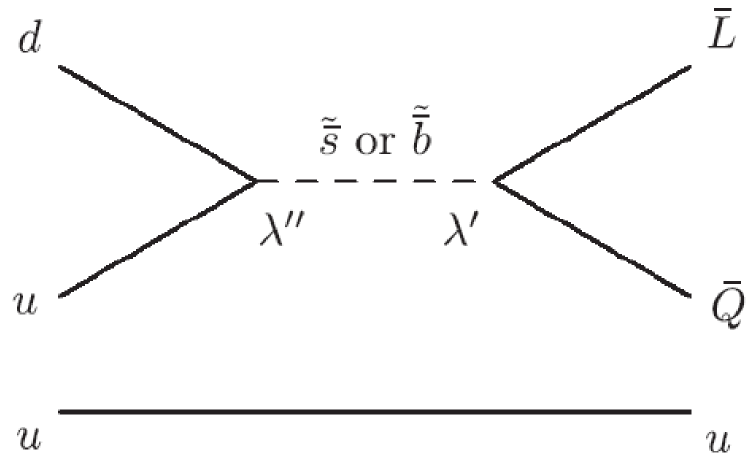


Higgs mass ultraviolet divergent
→ need momentum cutoff Λ:
if SM is valid up to the Planck scale, ($\Lambda \sim 10^{19}$ GeV)
→ cancellation μ and the radiative corrections in the first 36 decimal places is required
→"gauge hierarchy problem"

- SUSY offers canceling diagrams (different spin, different sign)
- Best if SUSY masses O(TeV)

R-Parity

- **BUT:** SUSY particles could add couplings leading to proton decay:



- Solution: Define R-Parity, which has to be conserved (in most SUSY models)

  $R_P=(-1)^{3B+2S+L}$
- $R_P=1$ for SM particles, $R_P=-1$ for SUSY particles

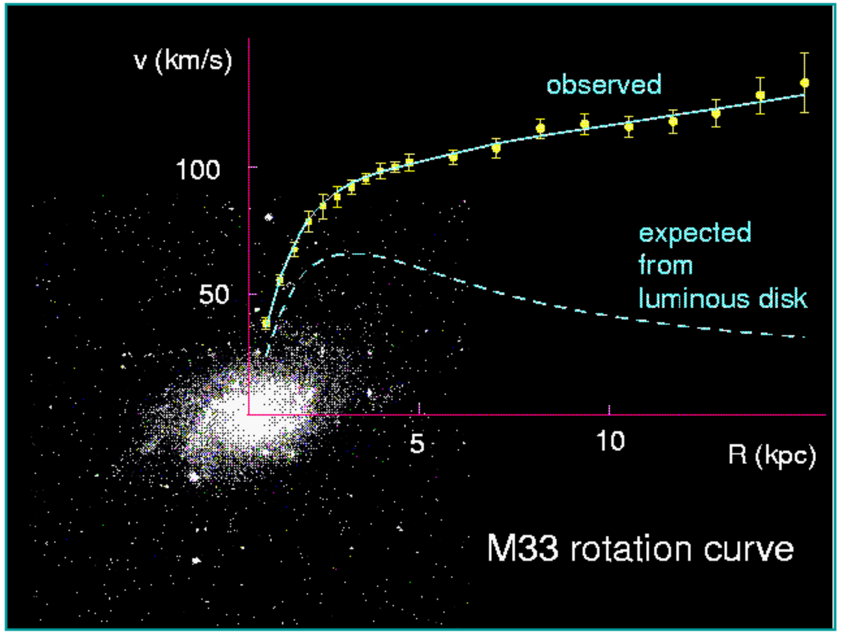
→ SUSY particles get produced in pairs, and the lightest SUSY particle (LSP) cannot decay to SM particles

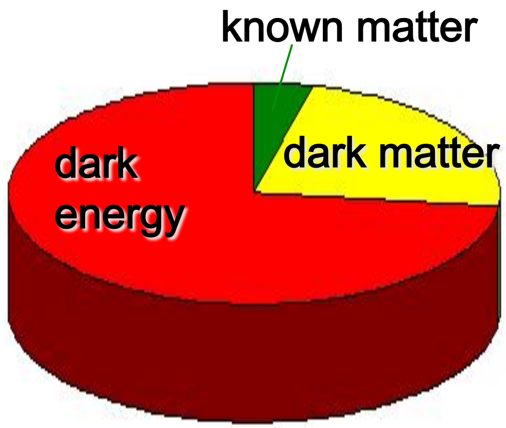
Dark Matter

- Rotation curves of spiral galaxies are quite flat, while luminous (visible) matter predicts a falling curve

→ **Dark matter**

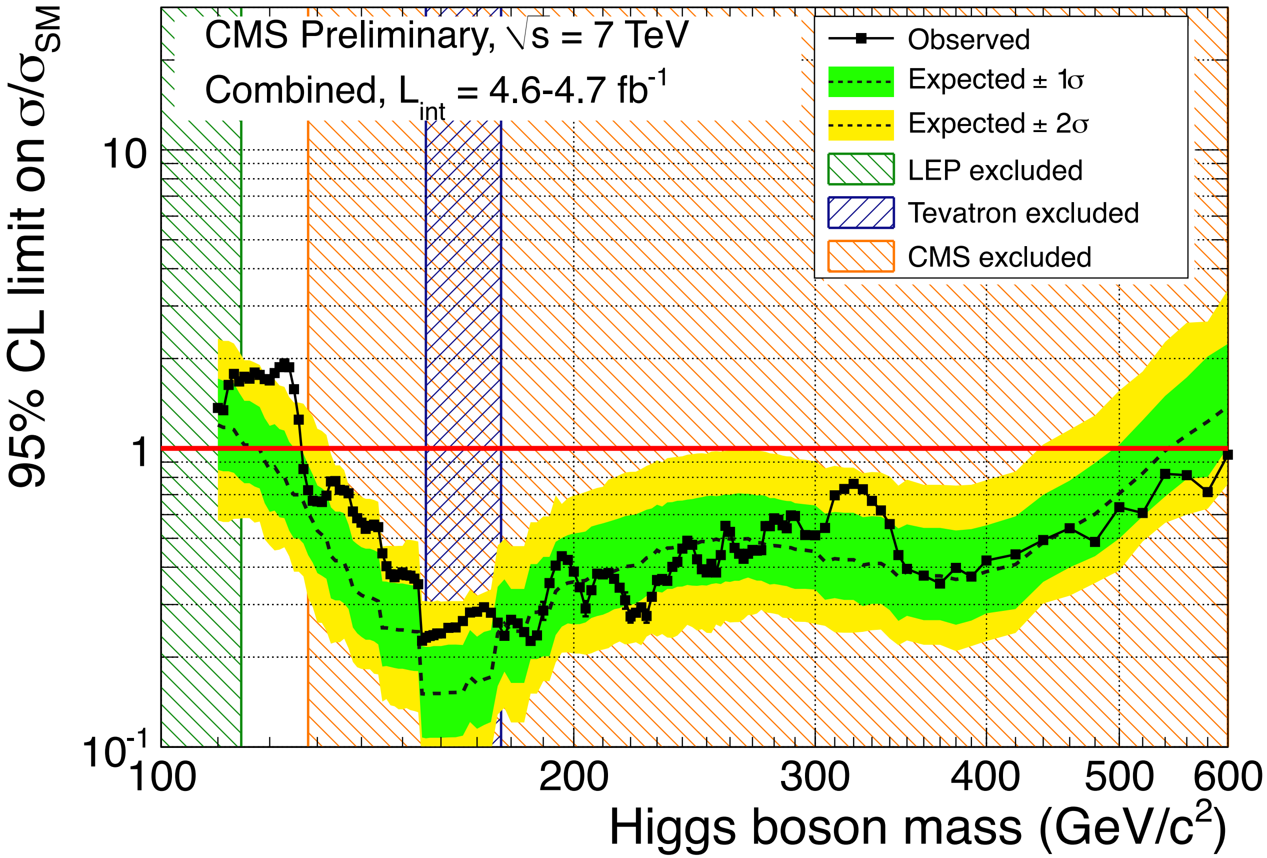
- SUSY offers "natural" dark matter candidate: the lightest stable neutral supersymmetric particle (**LSP**)





SUSY and Higgs

- Higgs searches ongoing – up to now good news for SUSY
- Higgs with M_H > 135 GeV would have ruled out the MSSM



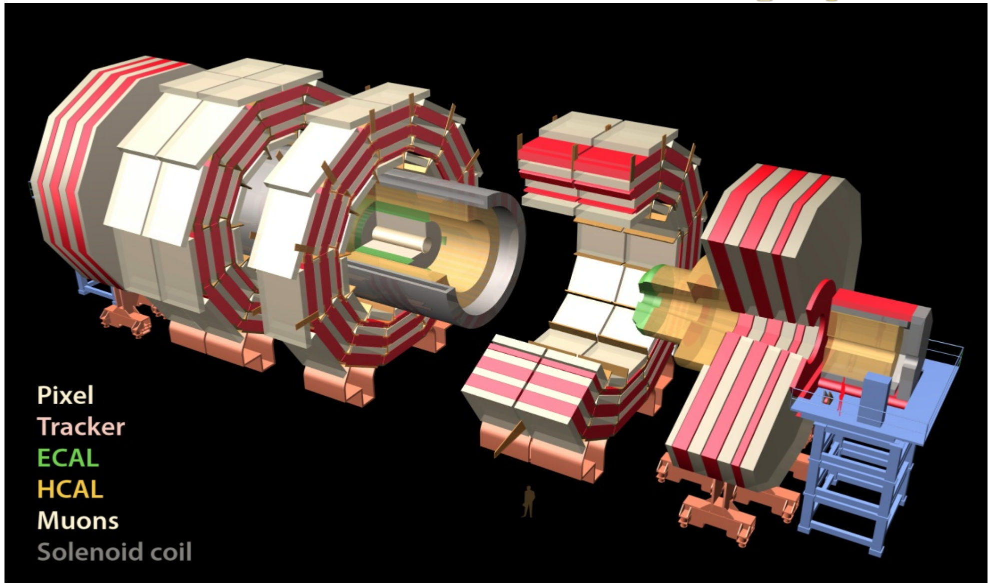
Quoting Nima Arkani-Hamed:

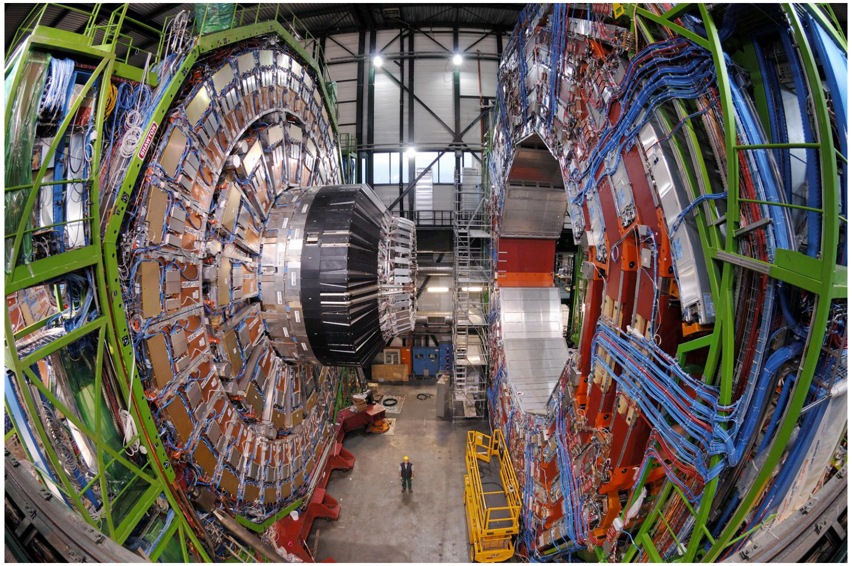
"As many people have remarked, $m_H \sim 125$ seems almost maliciously designed to prolong the agony of BSM theorists ...."

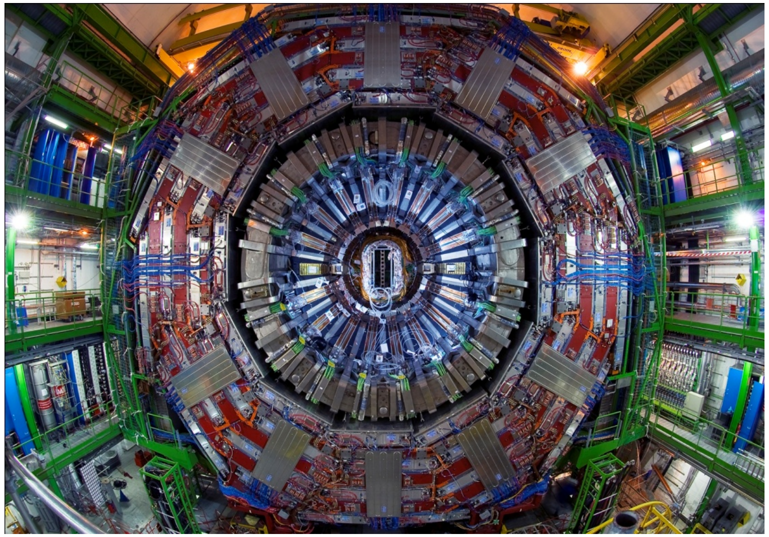
Where we are

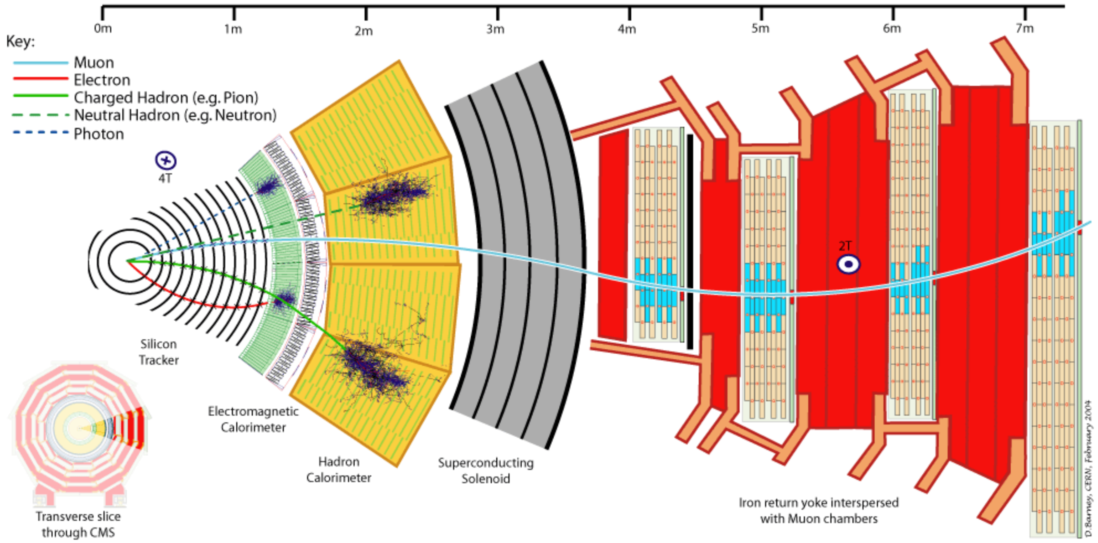
- Introduction
- **The CMS Experiment**
- Hadronic searches
- Leptonic searches
- Searches for 3rd generation squarks
- Searches with photons
- Conclusion/Outlook

Compact Muon Solenoid (CMS)





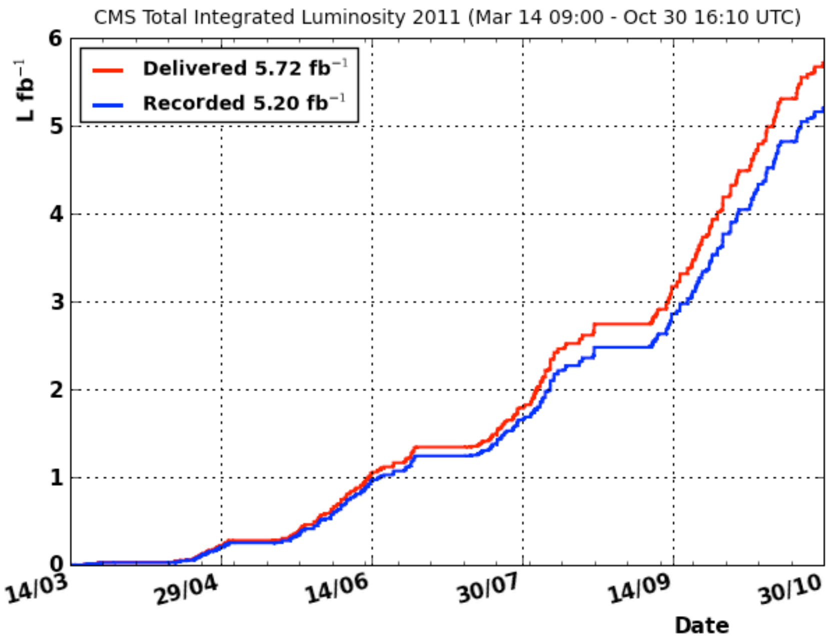




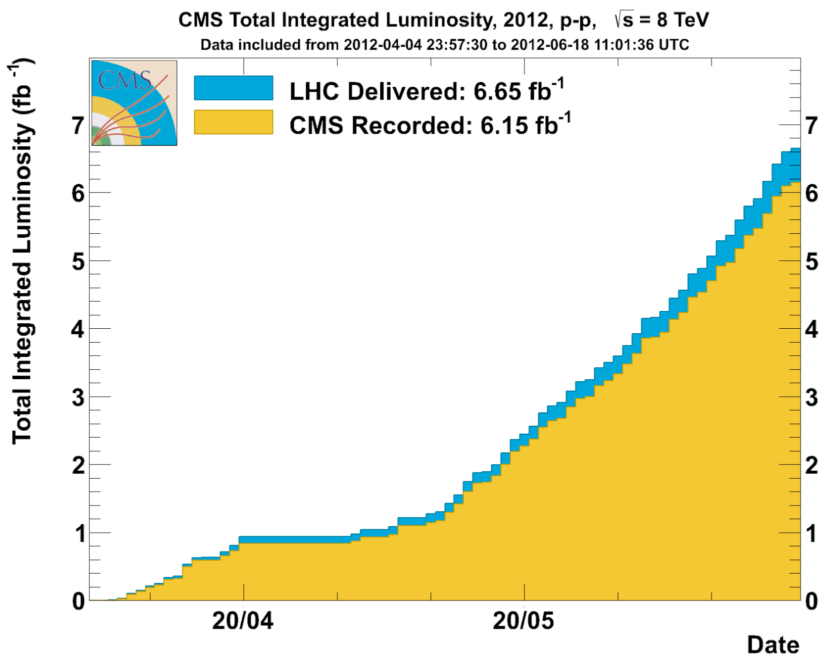
Luminosity accumulated 2011

- Very successful running in 2011
- ~5.7 fb^{-1} delivered, ~5 fb^{-1} certified good data
- Same amount already recorded in 2012 → new results for ICHEP

2011

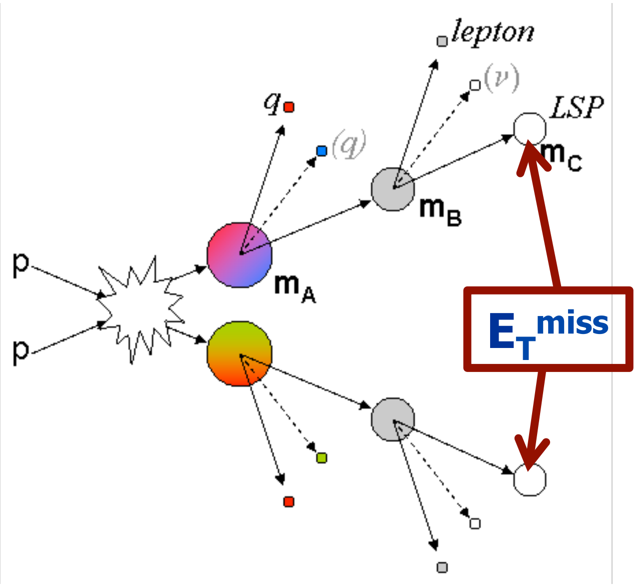


2012



Search Strategy

- **Topology based searches, not optimized for any particular SUSY model**
- Most searches probe tails of $\mathbf{E_T^{miss}}$ distribution
- Try to cover as much phase space as possible (e.g. as low lepton p_T as possible)
- Estimate backgrounds from data (data-driven bkg estimate) to minimize reliance on MC (e.g. for detector (mis)reconstruction effects)
- Exclude area in common benchmark scenarios, e.g. cMSSM and simplified models



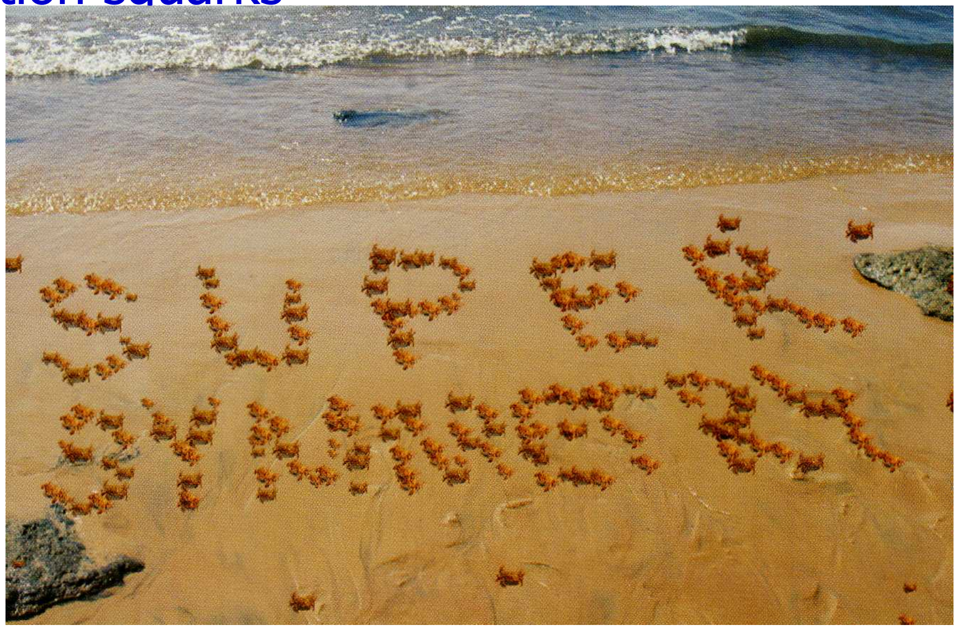
0 leptons	1 lepton	OSDL	SSDL	≥3 lep.	1 or 2 γ	1 γ+ 1 lep.
Jets + E_T^{miss} (+special variables)	Single lepton+ jets+E_T^{miss}	Opposite sign di-leptons+ jets+E_T^{miss}	Same-sign di-leptons + jets +E_T^{miss}	Multi-leptons	(Di-) photon +jets +E_T^{miss}	Photon +lepton +E_T^{miss}

- Add b-tag requirement in order to be more sensitive to light 3rd generation squarks

Where we are...

- Introduction
- The CMS Experiment
- **Hadronic searches**
  - ⇨ Inclusive hadronic analysis ⇦
- Leptonic searches
- Searches for 3rd generation squarks
- Searches with photons
- Conclusion/Outlook

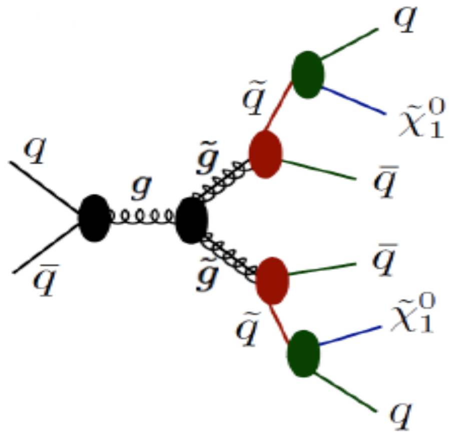
Contribution by UHH



Inclusive All-Hadronic Search: Introduction

Signature:
Many jets and large missing transverse energy

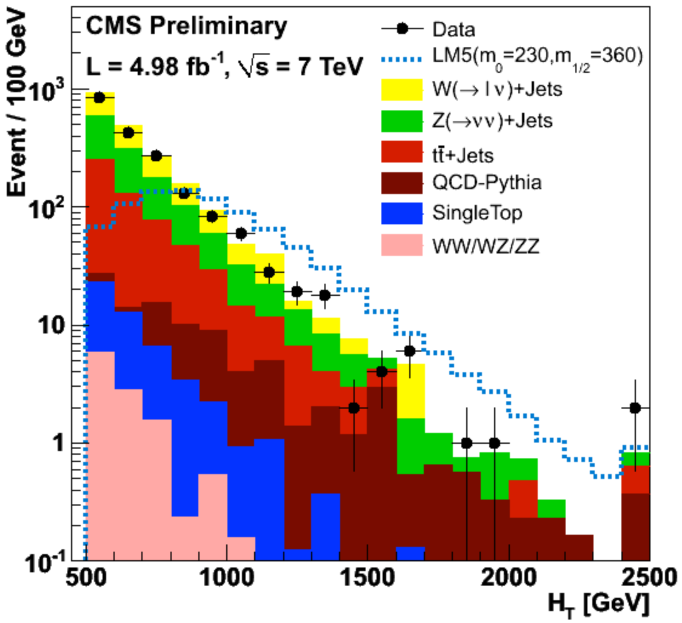
- Least model-dependent analysis
- Large backgrounds:
  - Z+jets with Z→ $\nu\nu$ (irreducible)
  - W+jets and ttbar with W → $l\nu$ and lost lepton or τ → hadrons + ν
  - QCD multijet events with large missing transverse momentum due to:
    - Leptonic decays of heavy flavor hadrons inside jets
    - Jet energy mismeasurement
    - Instrumental noise
    - Non-functioning detector components

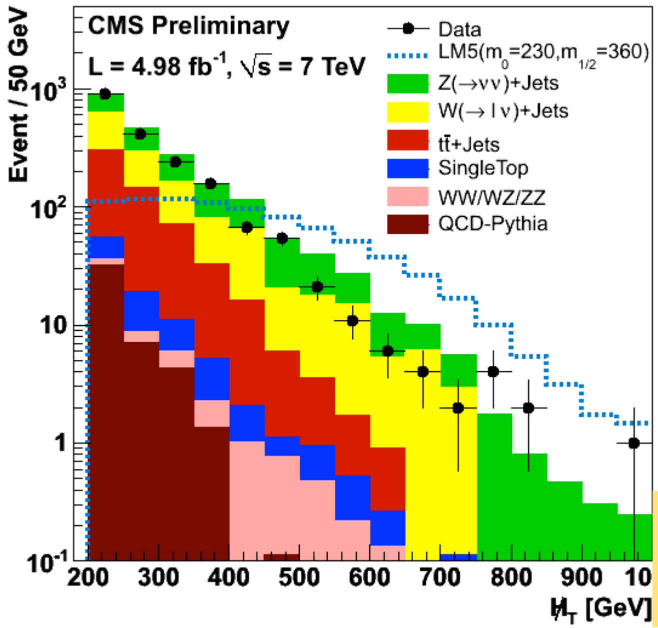


Phys. Lett. B698:196-218 (2011)
CMS PAS SUS-11-004

Inclusive All-Hadronic Search: Event Selection

- **Baseline selection**
  - At least 3 jets with $p_T^{jet} > 50$ GeV and $|\eta| < 2.5$
  - $H_T > 350$ GeV
  - $H_T^{miss} > 200$ GeV
  - $|\Delta\Phi(\vec{J}_{1,2}, \vec{H}_T^{miss})| > 0.5$ and $|\Delta\Phi(\vec{J}_3, \vec{H}_T^{miss})| > 0.3$ to veto events where H_T^{miss} is aligned in transverse plane with one of the 3 leading jets
  - Veto on isolated muons and electrons





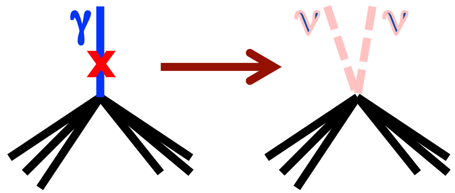
$H_T = \Sigma|\vec{p}_T^{jet}|$

$\vec{H}_T^{miss} = -\Sigma\,\vec{p}_T^{jet}$

CMS PAS SUS-11-004
CMS PAS SUS-12-011

Inclusive All-Hadronic Search: Background Estimation for Z → νν

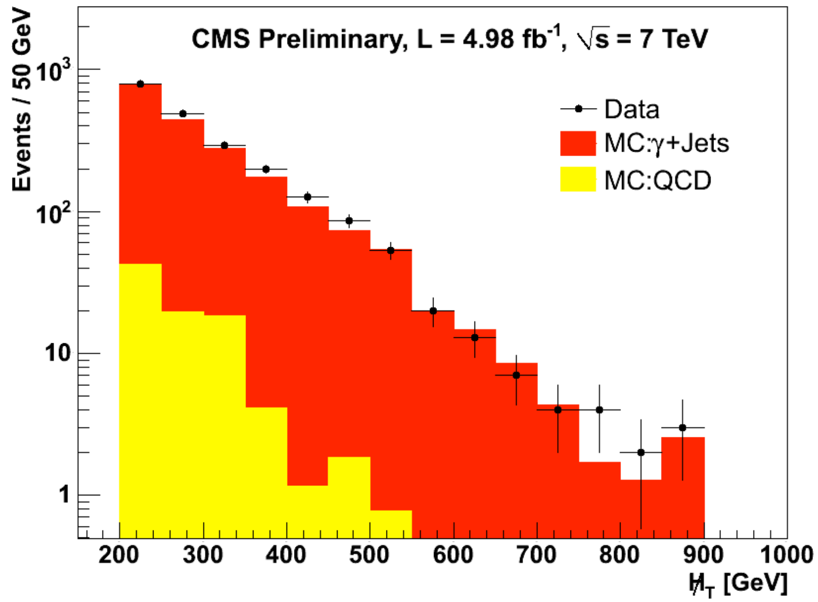
- **Background estimation with γ+jets :**
- Strategy:
  - Declare photon invisible to emulate neutrinos
  - Then re-calculate H_T^{miss} for this event
  - Correct for the photon reconstruction efficiency and neutrino branching ratio



SUSY signals could bias the prediction

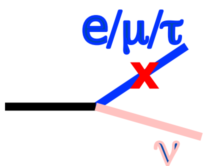
→ Crosscheck with Z→μμ +jets:

→ Drawback: Low statistics in signal region, but comparable result in baseline selection



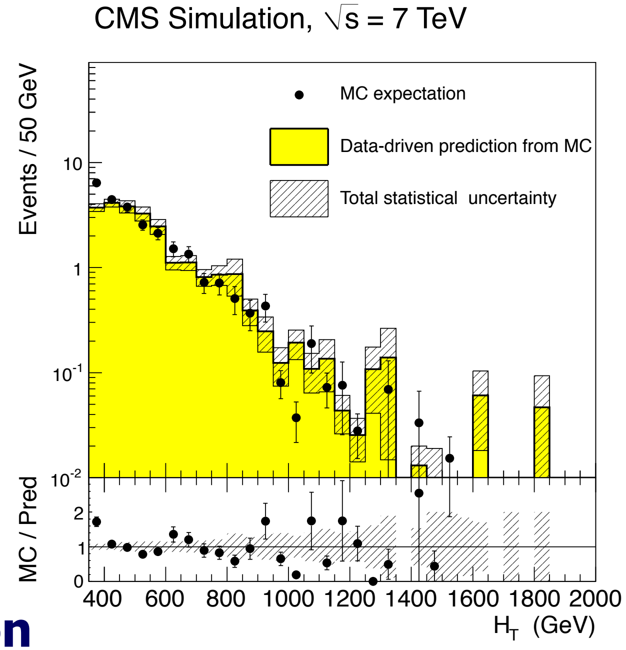
CMS PAS SUS-11-004
CMS PAS SUS-12-011

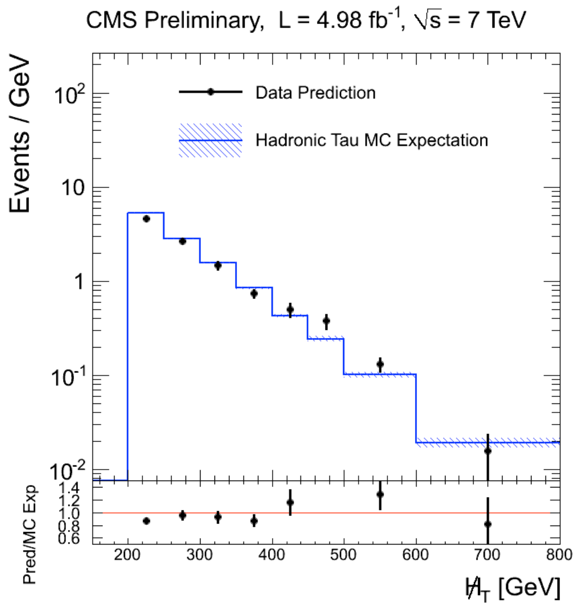
Inclusive All-Hadronic Search: W and Top Background Estimation



Lost Lepton Background Estimation

- Muon control sample with $M_T < 100$ GeV with $M_T=\sqrt{(2p_T^{\mu} E_T^{miss} (1-\cos\phi))}$ used to model:
  - Non-isolated (but identified) leptons
  - Non-identified leptons (ratio id/non-id taken from Monte Carlo)





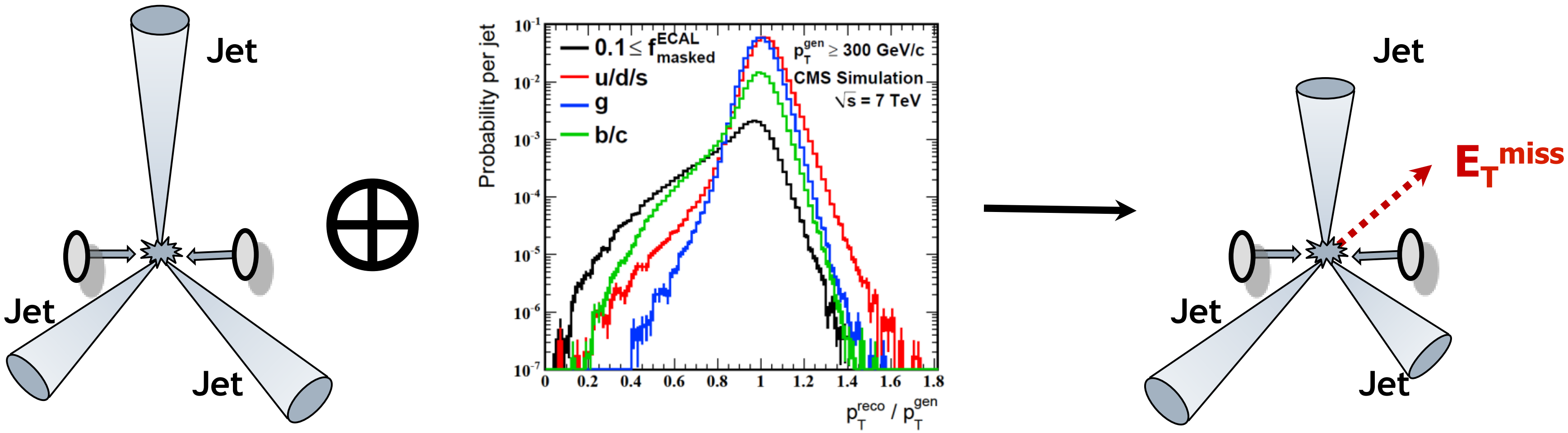
τ Background Estimation

- Determined with a muon control sample
- Substitute μ with τ jet using response template to model the fraction of visible momentum
- Recalculate all quantities like H_T

CMS PAS SUS-11-004
CMS PAS SUS-12-011

Inclusive All-Hadronic Search: QCD Background Estimation

- Most difficult background, derived here by 'Rebalance & Smear' method:
  - Rebalance all jets to overall p_T balance (=kind of 'generator level jet', robust against seed jet mismeasurements and non-QCD processes)
  - Smear p_T of each seed jet by a factor derived from jet resolution distribution (from simulation, and corrected for data/MC differences)
- Smearing of the jets results in artificially created E_T^{miss} used to estimate the real E_T^{miss} distribution

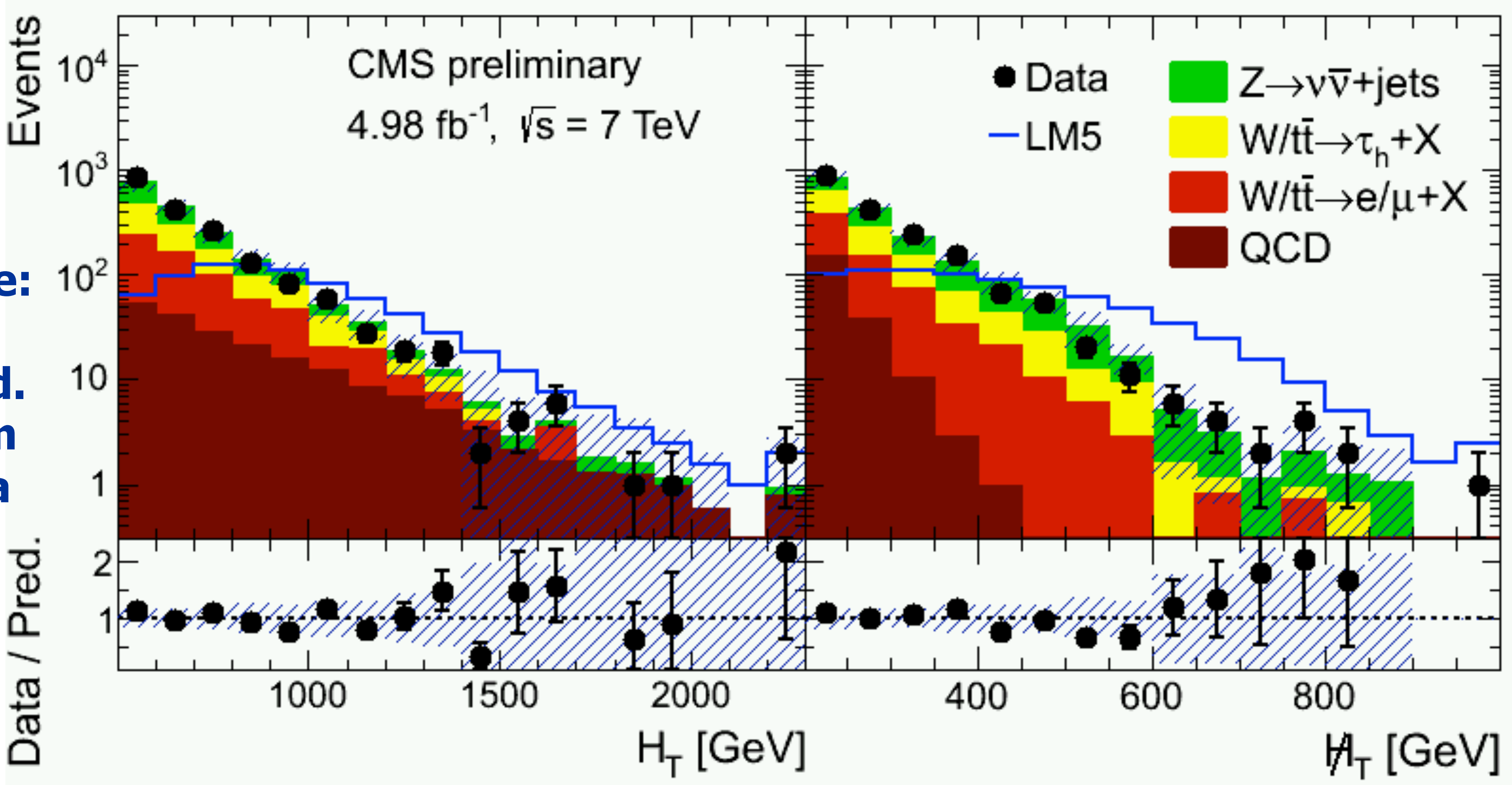


CMS PAS SUS-11-004
CMS PAS SUS-12-011

Inclusive All-Hadronic Search: Results

- Result split into 14 search regions

Here: Bkg pred. from data



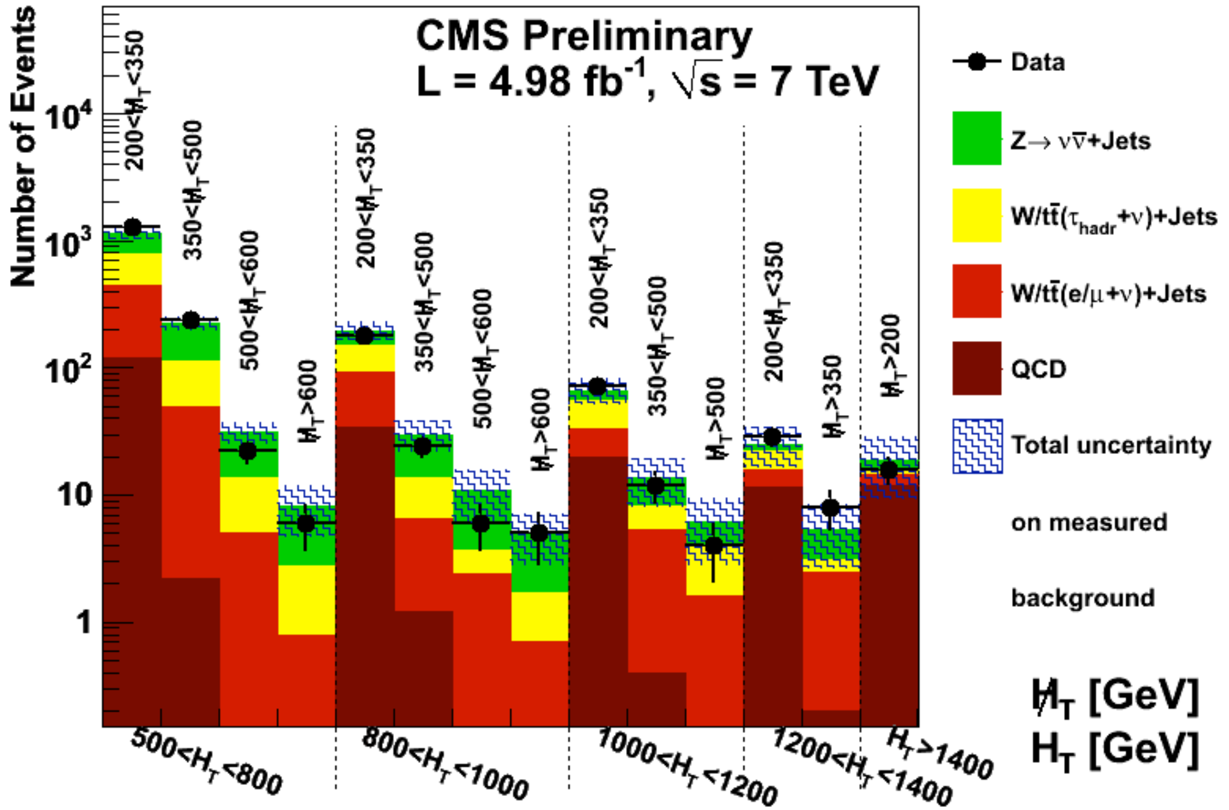
No excess observed!

CMS PAS SUS-11-004
CMS PAS SUS-12-011

Inclusive All-Hadronic Search: Results

- Result split into 14 search regions

Here: Bkg pred. from data

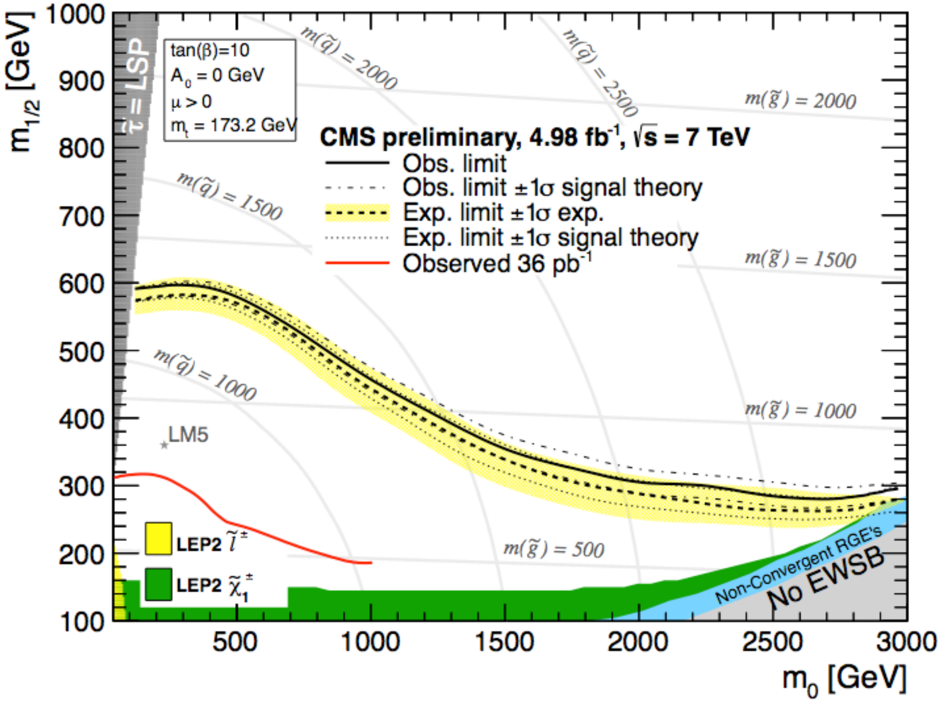


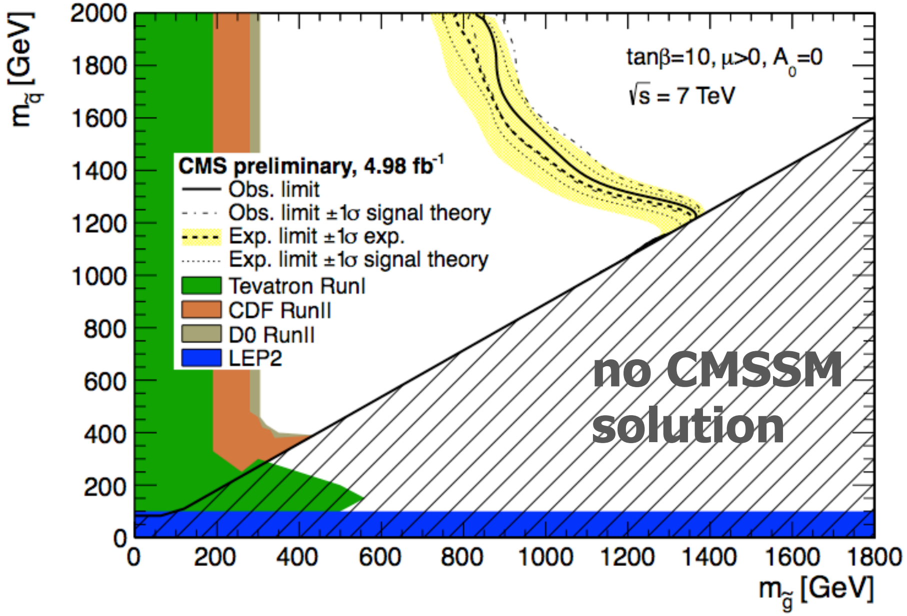
No excess observed – how to interpret?

CMS PAS SUS-11-004
CMS PAS SUS-12-011

Inclusive All-Hadronic Search: Exclusion Plot

- Observed and expected 95% CL exclusion limit in the cMSSM using the signal cross sections calculated at NLO
- Contours are the combination of the different selections, such that the shown contours are the envelope with respect to best sensitivity



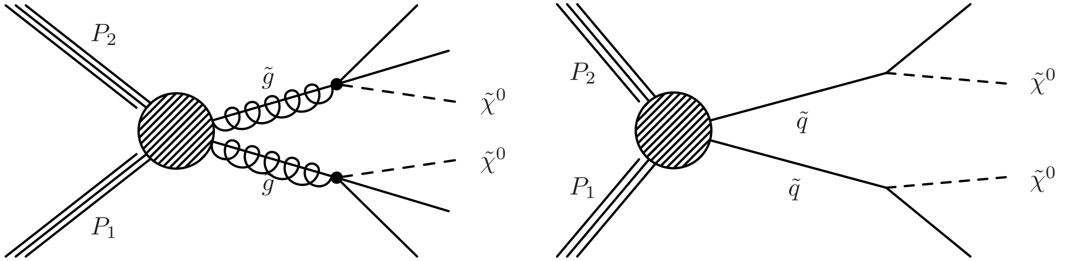


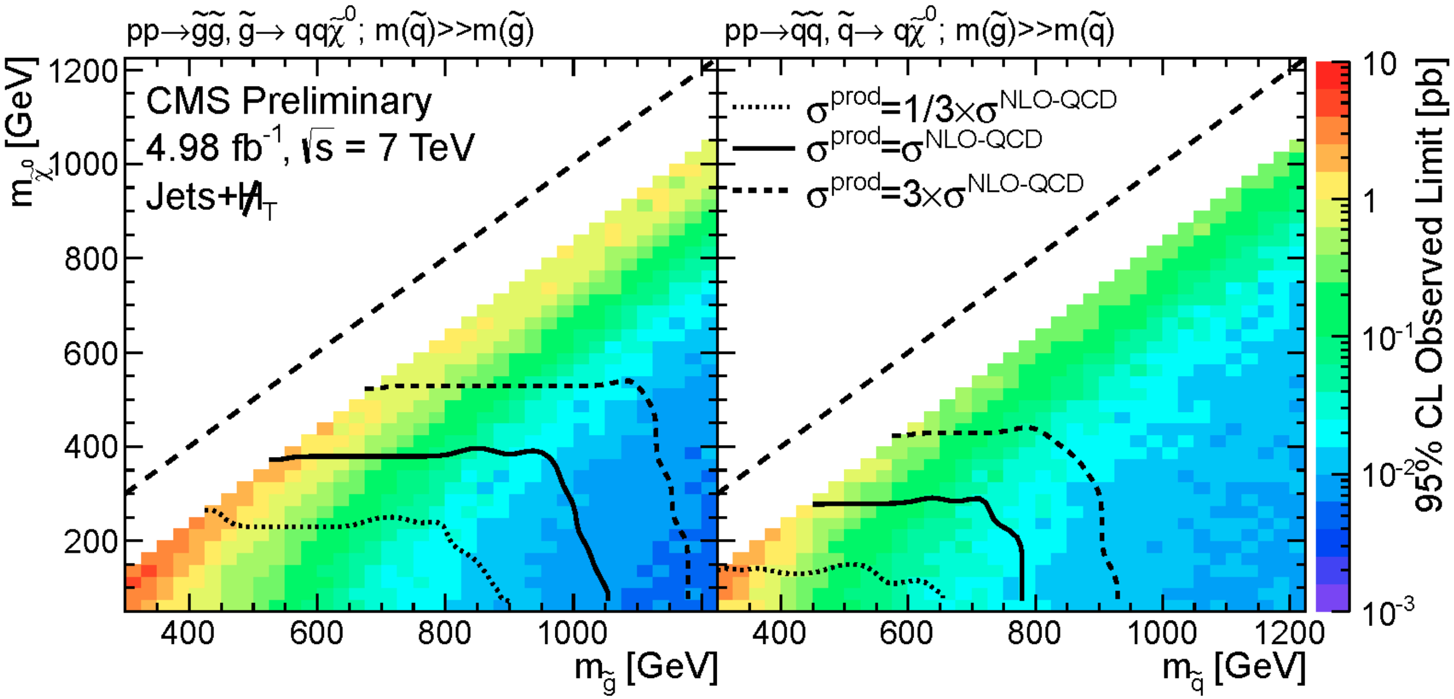
CMS PAS SUS-11-004
CMS PAS SUS-12-011

Hadronic Analysis: Interpretation

- Simplified models (on-shell effective theory): intermediate step between a complete theory and experimental signature

CMS PAS SUS-11-004
CMS PAS SUS-12-011





Where we are…

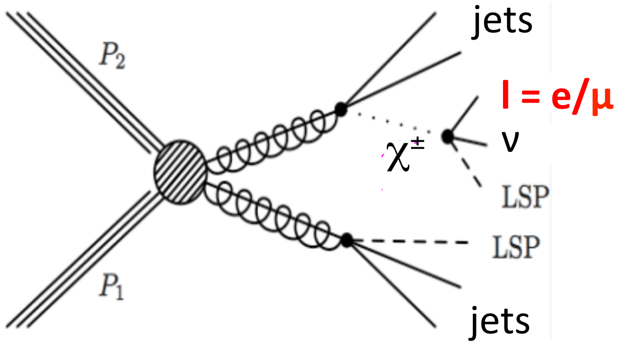
- Introduction
- The CMS Experiment
- Hadronic searches
- **Leptonic searches**
  - Searches including one lepton
  - Searches with opposite-sign leptons in the Z region
- Searches for 3rd generation squarks
- Searches with photons
- Conclusion/Outlook

Contribution by DESY/UHH

Searches including one Lepton: Introduction

Signature:
Exactly one lepton, several jets and large missing transverse energy

- QCD background reduced by 1 lepton requirement



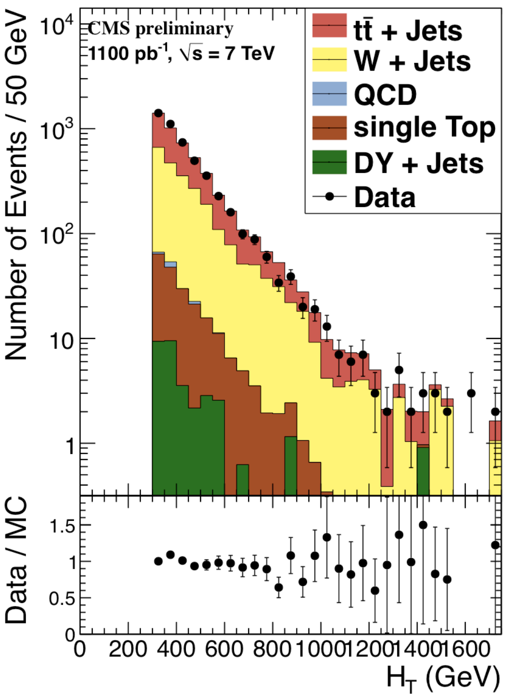
- Two complementary methods to determine the remaining background:
  - *Lepton spectrum method*
    - Prediction of E_T^{miss} spectrum with the observed lepton spectrum
  - *Lepton projection method*
    - Sensitive to the helicity angle of the lepton in the W rest frame

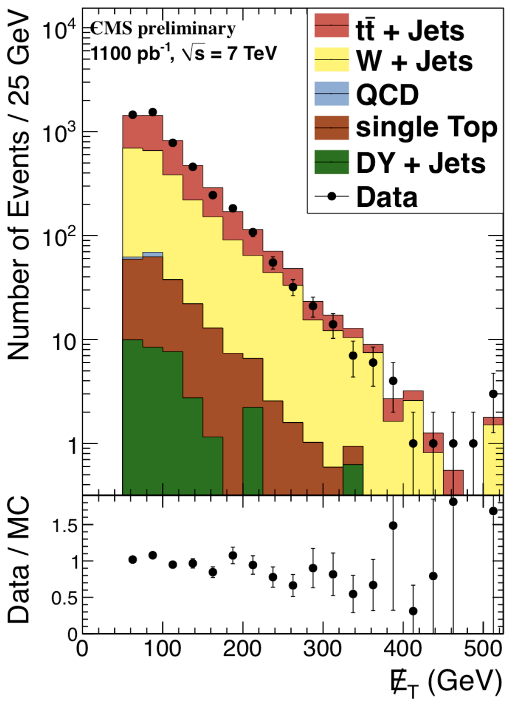
$$\mathrm{L_P} = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

CMS PAS SUS-11-015
CMS PAS SUS-12-010

Searches including one Lepton: Event selection

- **Baseline selection**
  - At least 3 (4) jets with p_T > 40 GeV and $|\eta| < 2.4$
  - Exactly 1 isolated muon or electron with
    - $p_T^{\mu} > 20$ GeV and $|\eta| < 2.1$
    - $p_T^{e} > 20$ GeV and $|\eta| < 2.4$, excluding $1.44 < |\eta| < 1.57$
    - Relative isolation: $I = \Sigma(E_{T(Cal.)}+P_{T(Tracker)})/p_T^{lep} < 0.1\ (\mu)$, $I < 0.3$ (e)

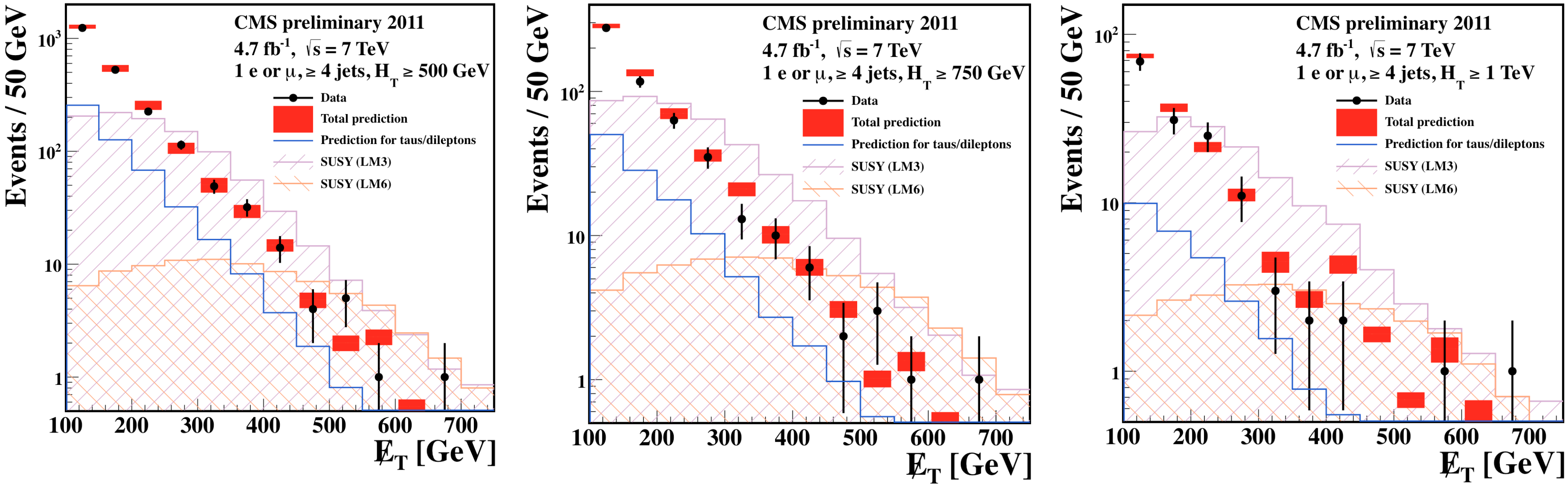




CMS PAS SUS-11-015

Searches including one Lepton: BG with Lepton Spectrum Method

- Idea: in W decays the charged lepton and neutrino p_T spectrum are related
  - Take muon p_T spectrum
  - Correct for acceptance, efficiency and polarization effects
  - E_T^{miss} resolution worse than e/mu → smear muon p_T

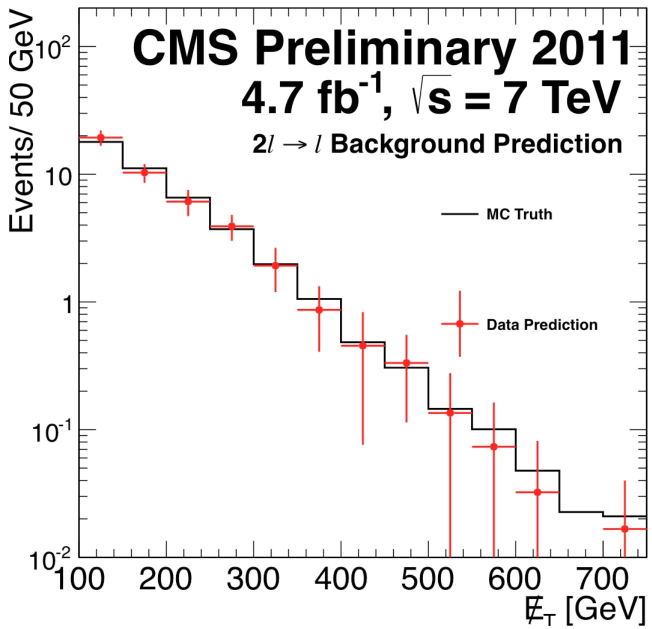


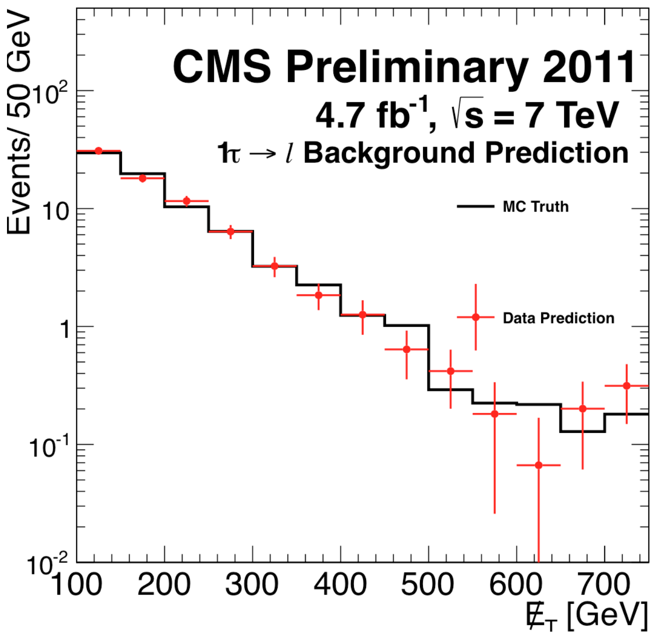
No excess observed!

CMS PAS SUS-11-015
CMS PAS SUS-12-010

Searches including one Lepton: BG with Lepton Spectrum Method

- Remaining background:
  - Di-leptons (with lost or ignored lepton)
  - → estimated from ratio of the combined yield of dilepton events (ee, eμ, and μμ) in data to the one in simulated event samples
  - τ
  - → estimated by replacing a lepton in a reconstructed dilepton event with a hadronic τ jet response function





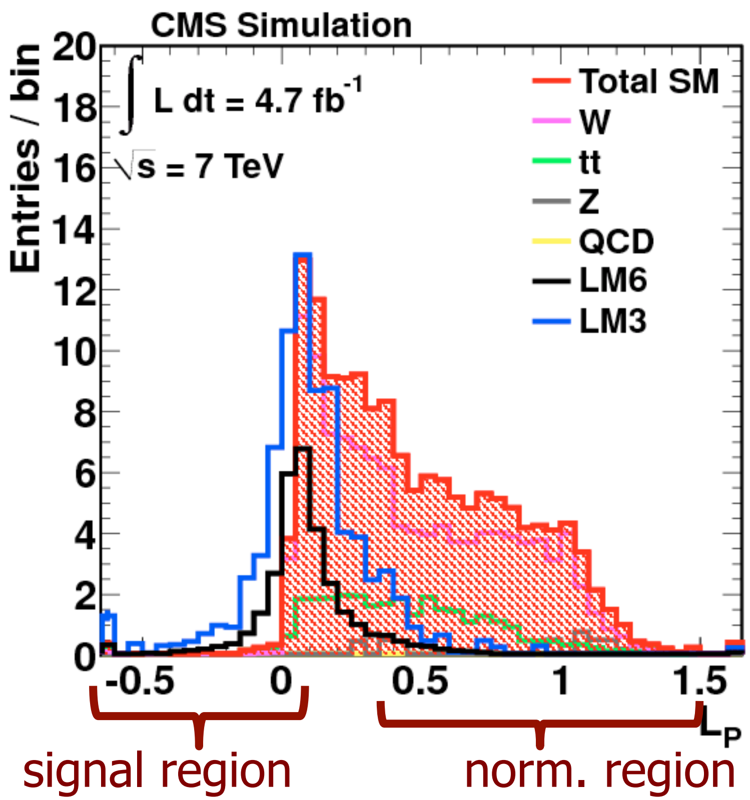
CMS PAS SUS-11-015
CMS PAS SUS-12-010

Searches including one Lepton: BG with Lepton Projection Method

- SM background in signal region predicted by

$$N_{\text{pred}}(L_P < 0.15) = R\, N_{\text{data}}(L_P > 0.30)$$

with $R = \dfrac{N_{\text{MC}}(L_P < 0.15)}{N_{\text{MC}}(L_P > 0.30)}$

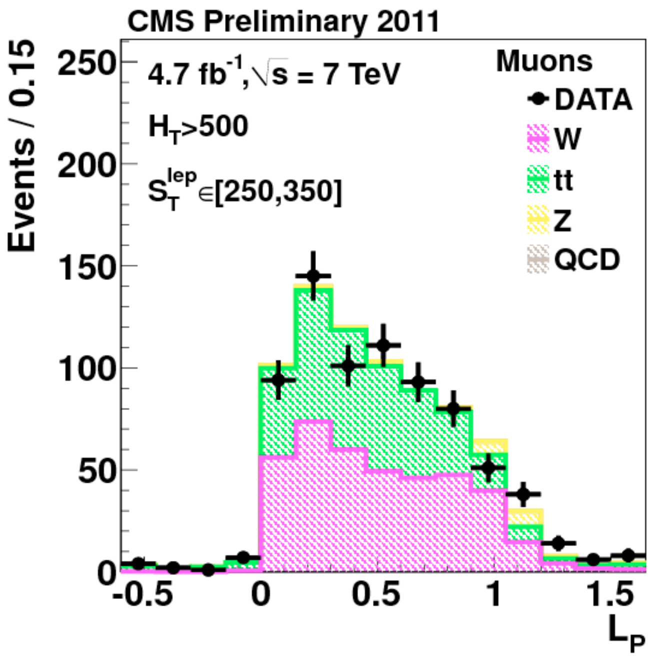


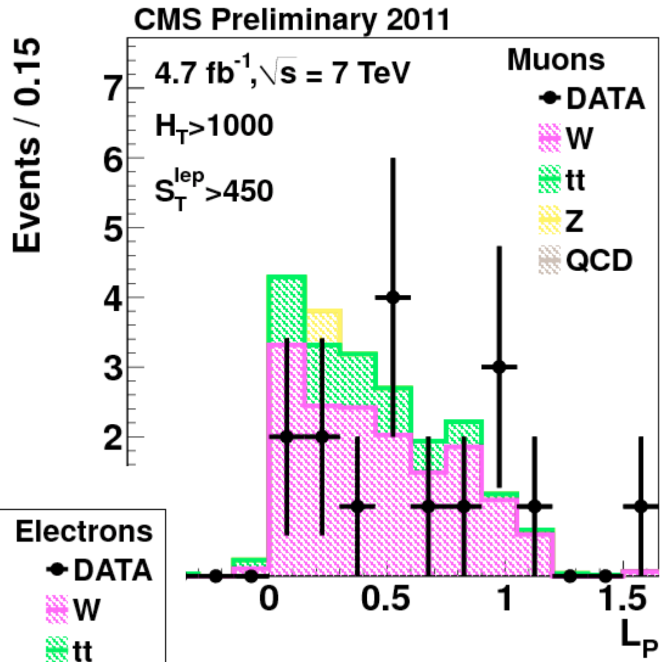
In addition: data-driven estimation of QCD background due to fake electrons

- Analysis is performed in several bins of H_T and the leptonic mass scale: $S_T^{lep} = |\vec{p}_T^{\,lep}| + |\vec{E}_T^{miss}|$

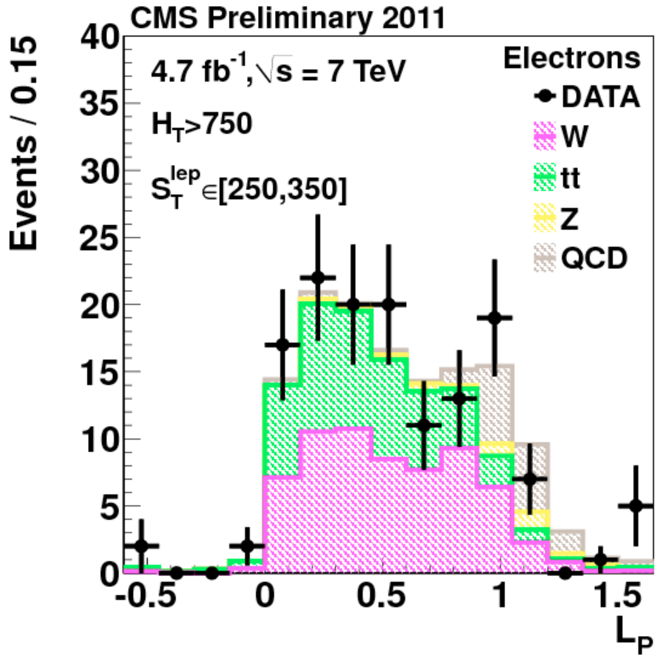
CMS PAS SUS-11-015
CMS PAS SUS-12-010

Searches including one Lepton: Results from the LP method





No excess observed!

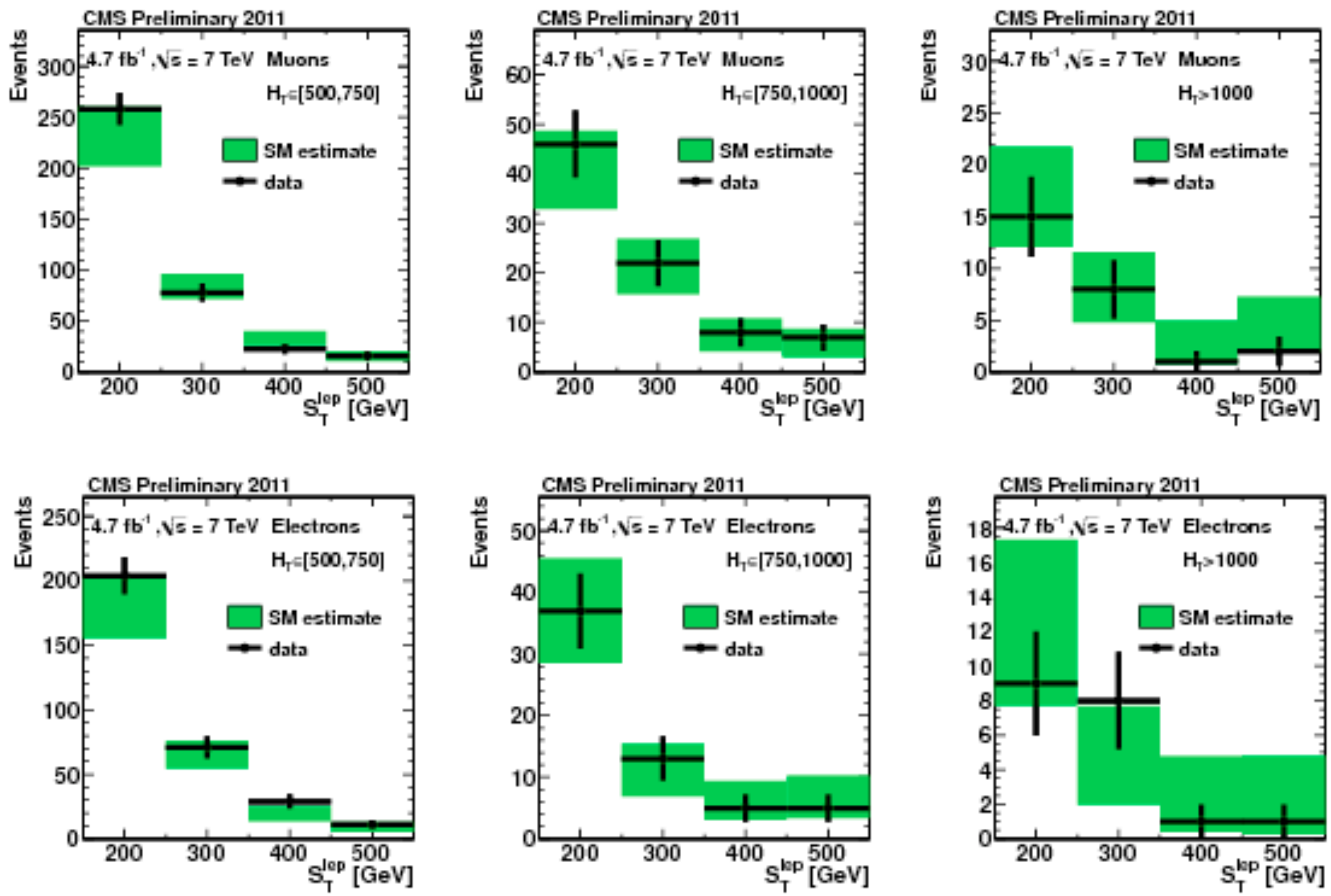


MS PAS SUS-11-015
MS PAS SUS-12-010

Searches including one Lepton: Results from the LP method (2)

H_T=[500,750] H_T=[750,1000] H_T>1000 GeV

No excess observed!

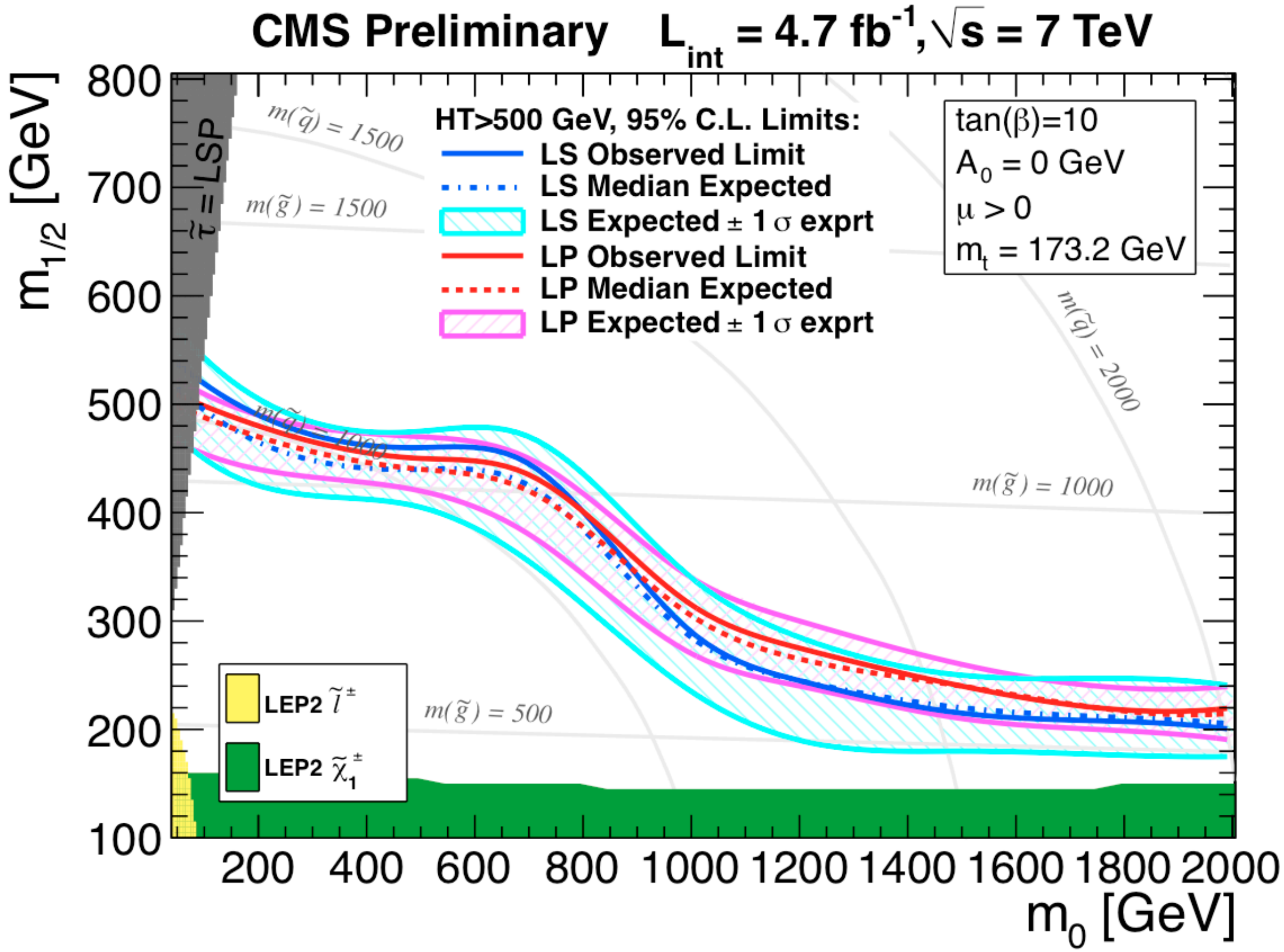


Muons

Electrons

SUS-11-015
SUS-12-010

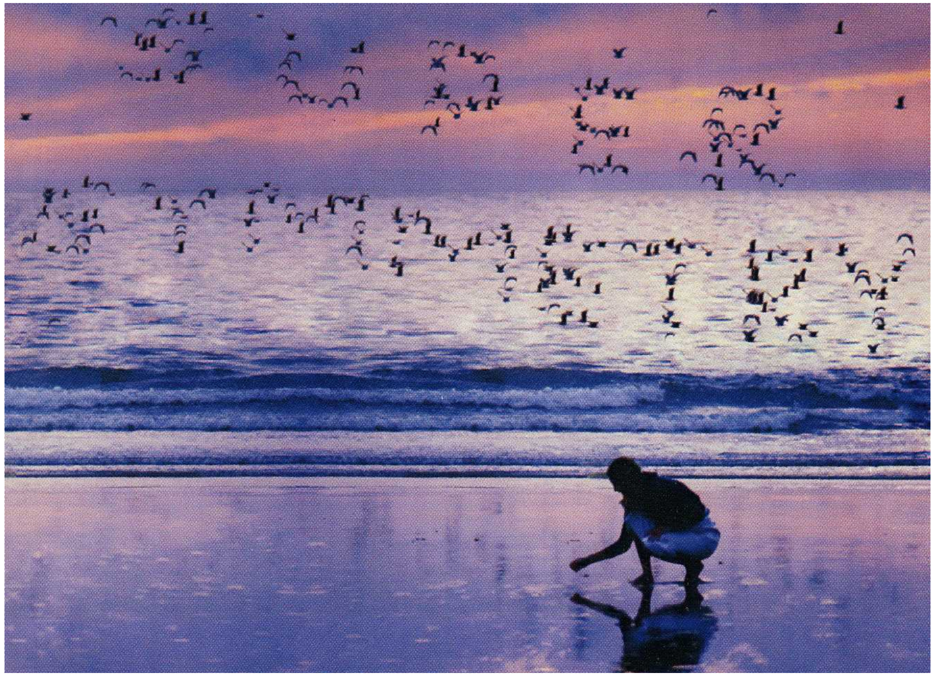
Searches including one Lepton: Exclusion Limits for cMSSM



CMS PAS SUS-11-015
CMS PAS SUS-12-010

Where we are…

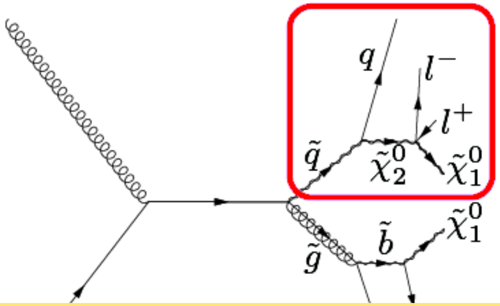
- Introduction
- The CMS Experiment
- Hadronic searches
- **Leptonic searches**
  → Searches including one lepton
  ⇨ Searches with opposite-sign leptons in the Z region ⇦
- Searches for 3rd generation squarks
- Searches with photons
- Conclusion/Outlook

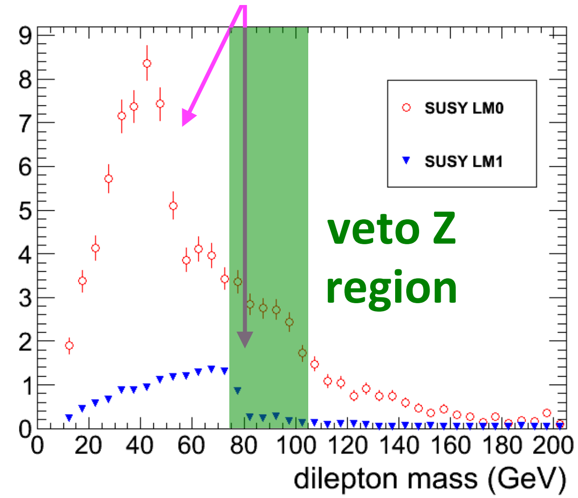


Opposite Sign Di-Leptons: Introduction

Opposite-sign di-leptons can have two sources:

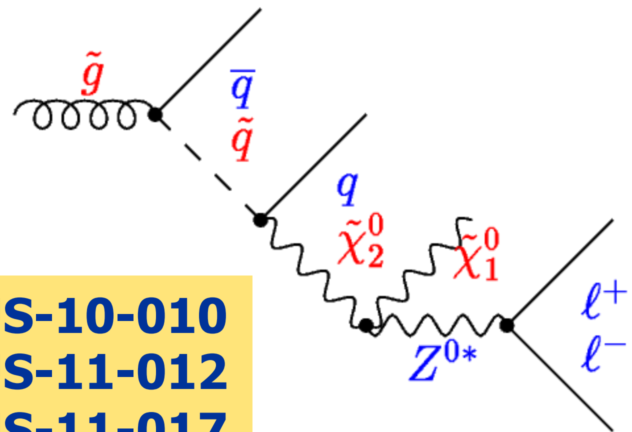
- Neutralino decays

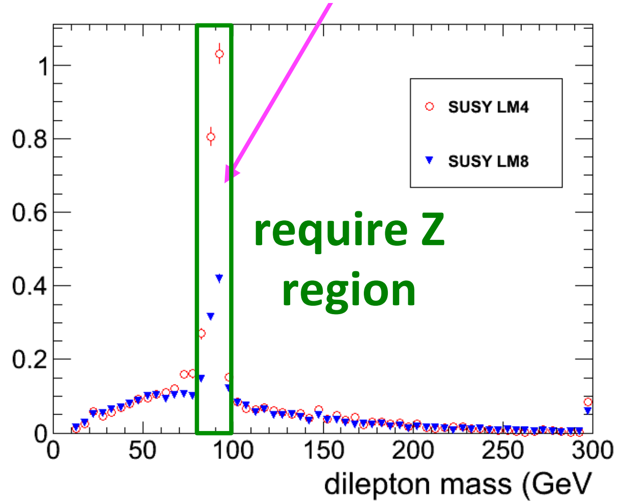




Phys. Rev. Lett. 106, 211802 (2011)
CMS PAS SUS-11-011

- Z production

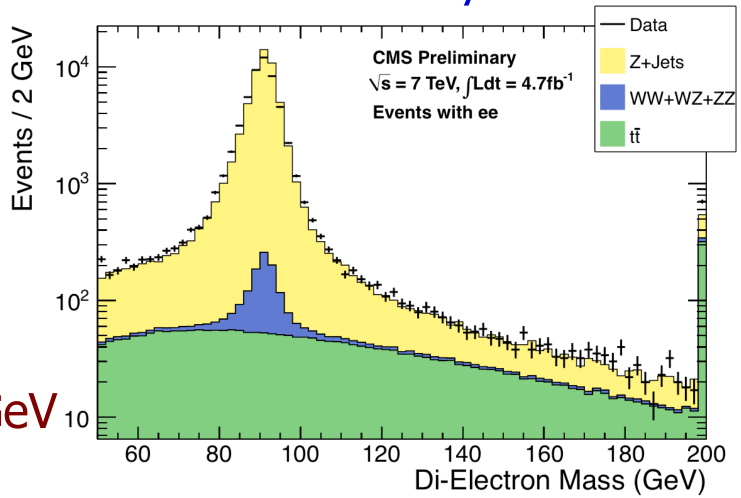




CMS PAS SUS-10-010
CMS PAS SUS-11-012
CMS PAS SUS-11-017

Opposite Sign Di-Leptons: Event Selection on Z-region

- New physics expected to connect to EW sector, e.g. $\chi_2^0 \rightarrow Z\,\chi_1^0$
- **Baseline selection**
  - $p_T^{lep1,lep2} > 20$ GeV, $|\eta| < 2.4$ (μ) and $|\eta| < 2.5$ (e)
  - Relative isolation : $I = \Sigma(E_{T(Cal.)}+P_{T(Tracker)})/p_T^{lep} < 0.15$ for leptons
  - At least 2(3) jets with $P_T > 30$ GeV, $|\eta| < 3$ and $\Delta R=0.4$ away from leptons
  - $|m_{lep,lep} - m_Z| < 10(20)$ GeV



- **Two search strategies**
  - ***E_T^{miss} measurement:***
    - $E_T^{miss} > 30 / 60 / 100 / 200 / 300$ GeV
  - ***Jet-Z balance method:***
    - At least 3 jets with $P_T > 30$ GeV, $|\eta| < 3$ and $\Delta R=0.4$ away from leptons
    - $JZB = |\Sigma \vec{p}_T^{jets}| - |\vec{p}_T^{Z}| > 50 / 100 / 150 / 200 / 250$ GeV

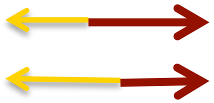
CMS PAS SUS-11-021

Opposite Sign Di-Leptons: Background Determination (Z-region)

- **Jet-Z balance method:**

  $JZB = |\Sigma \vec{p}_T^{\,jets}| - |\vec{p}_T^{\,Z}|$

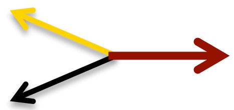
  SM Z + jet

  JZB > 0

  JZB < 0

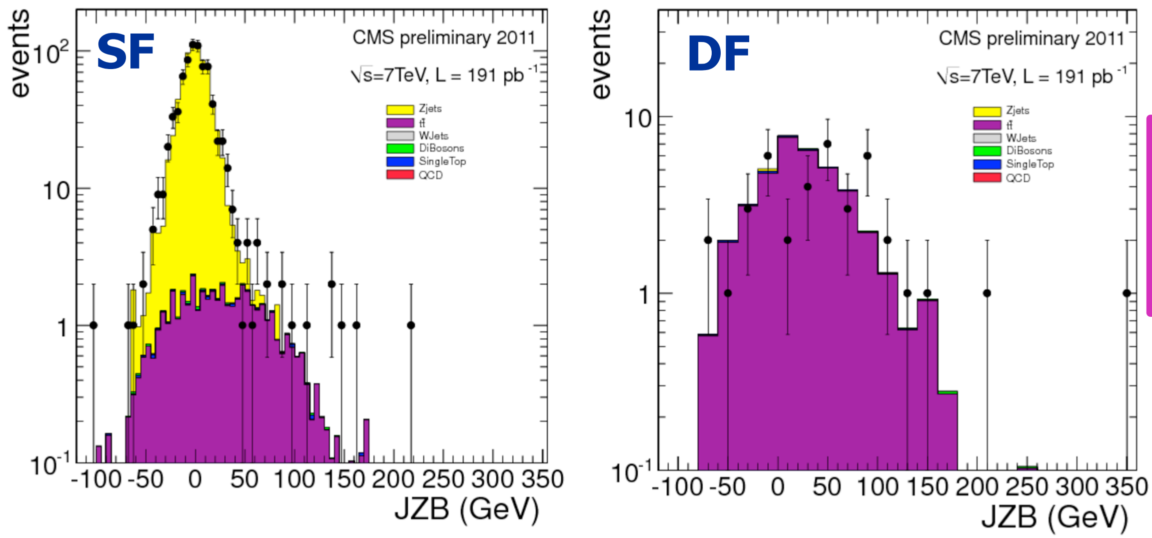
  Signal Z + jet + E_T^{miss}

  JZB > 0

- Total SM background in JZB > 0 estimated in two control regions:

SM Z+jets from same flavor



ttbar from different flavor

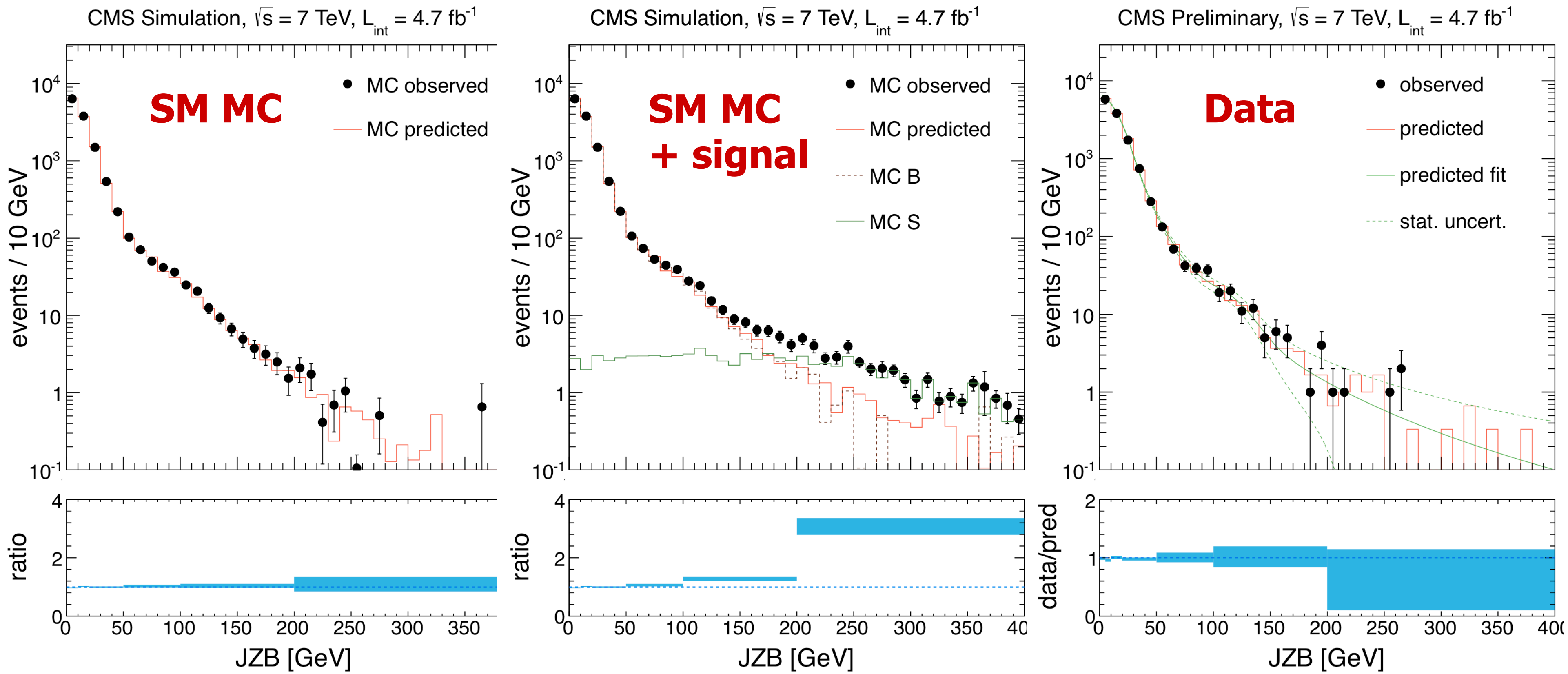
$$JZB_{bkg}^{pred} = \left| JZB_{SF}^{neg} - JZB_{DF}^{neg} \right| + JZB_{DF}^{pos}$$

CMS PAS SUS-11-012
CMS PAS SUS-11-017

Opposite Sign Di-Leptons: Results (Z-region)

CMS PAS SUS-11-021

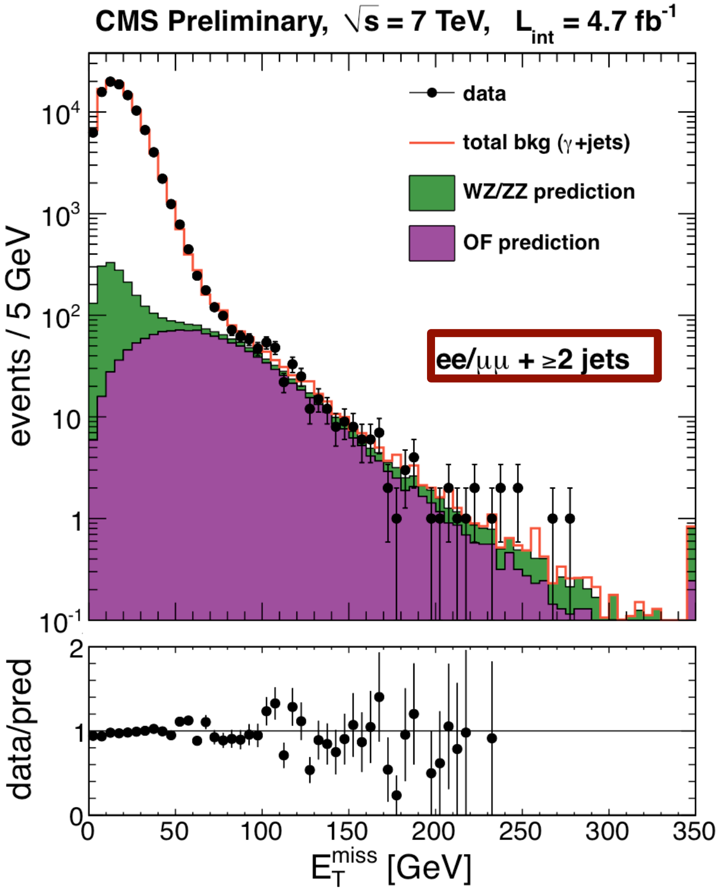
- **JZB**

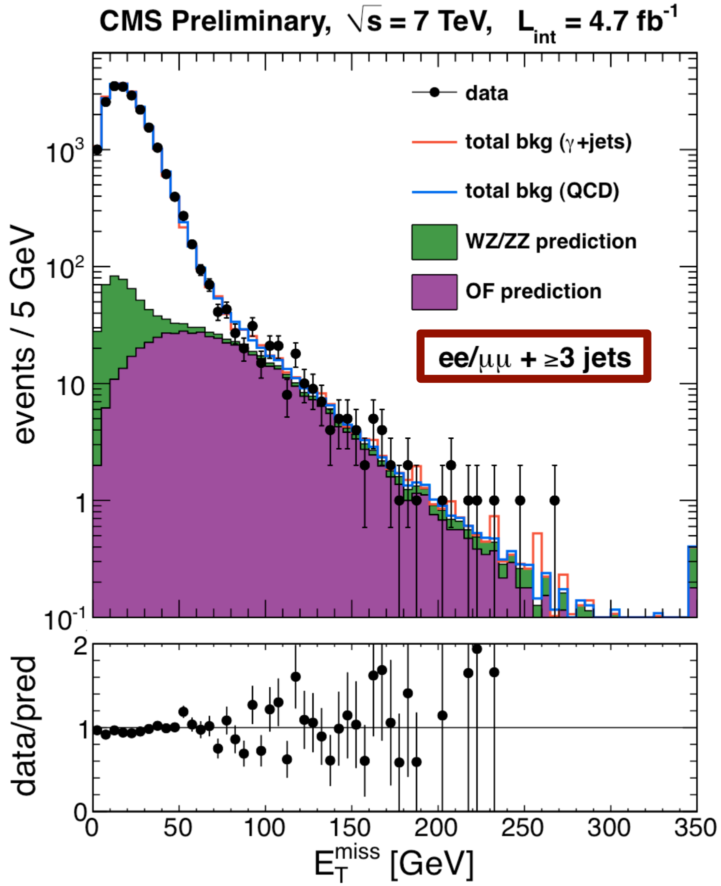


Opposite Sign Di-Leptons: Results (Z-region)

CMS PAS SUS-11-021

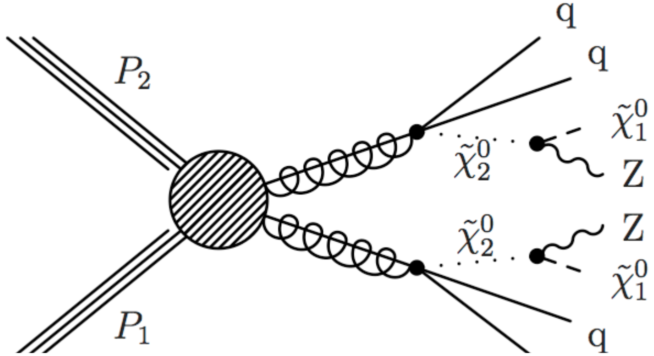
- **E_T^{miss} measurement:**

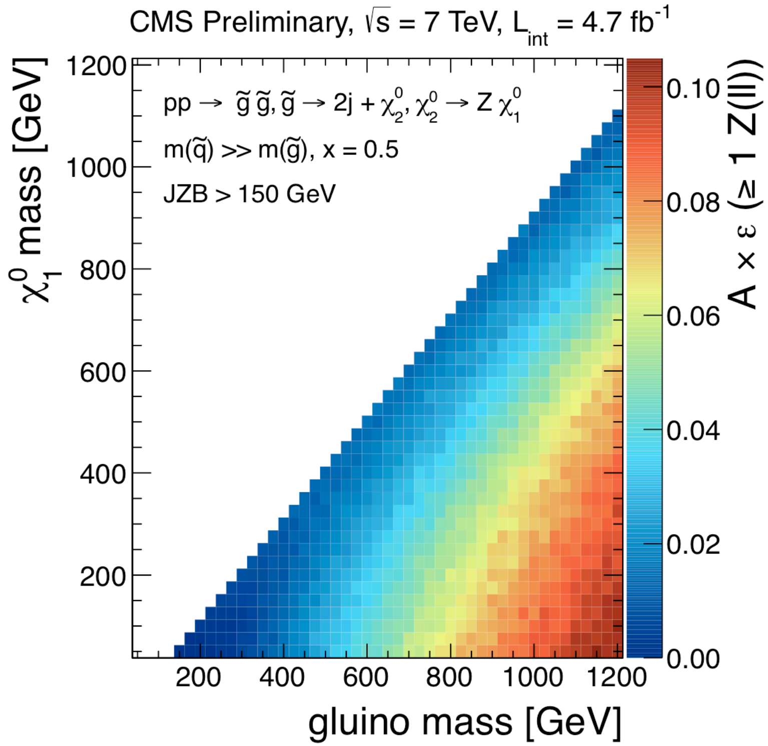


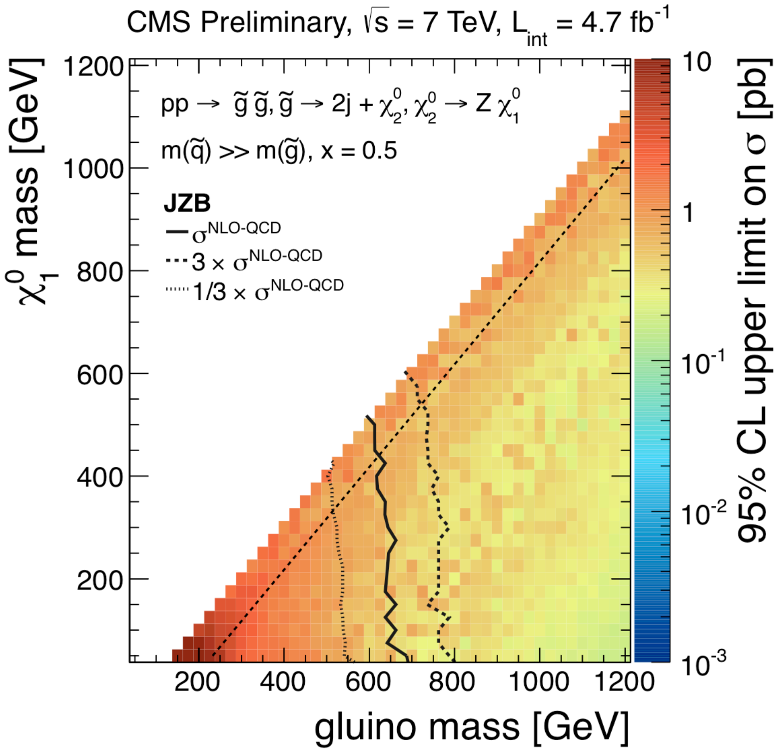


Opposite Sign Di-Leptons: Interpretation (Z-region, JZB)

- Simplified Model

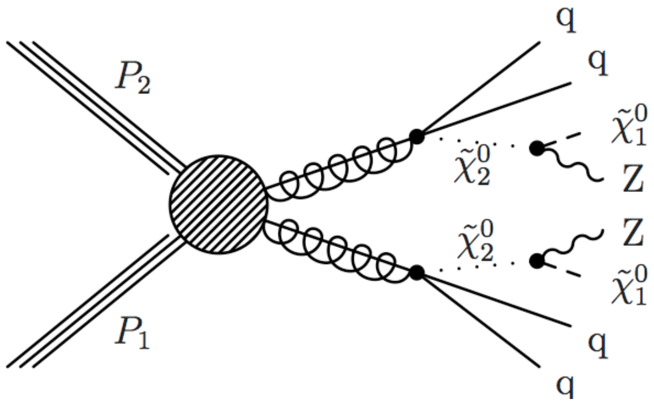


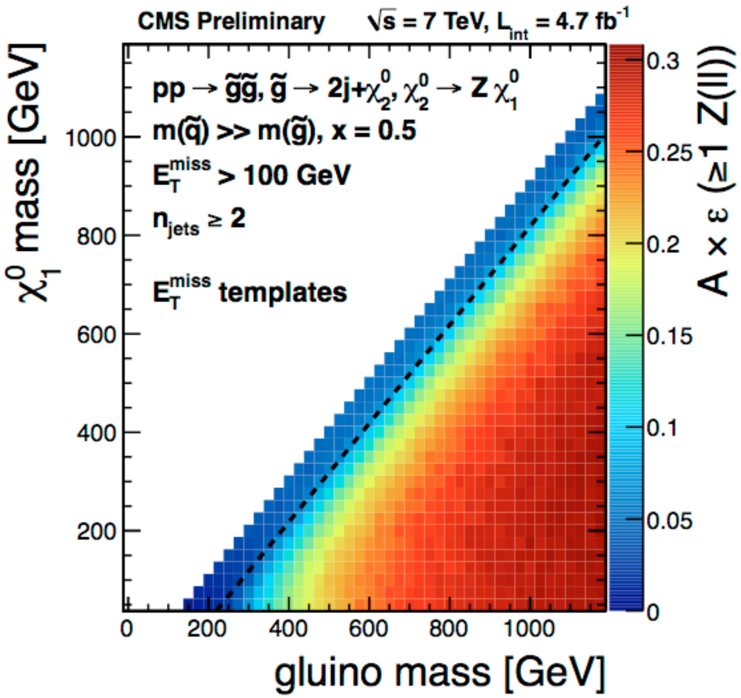


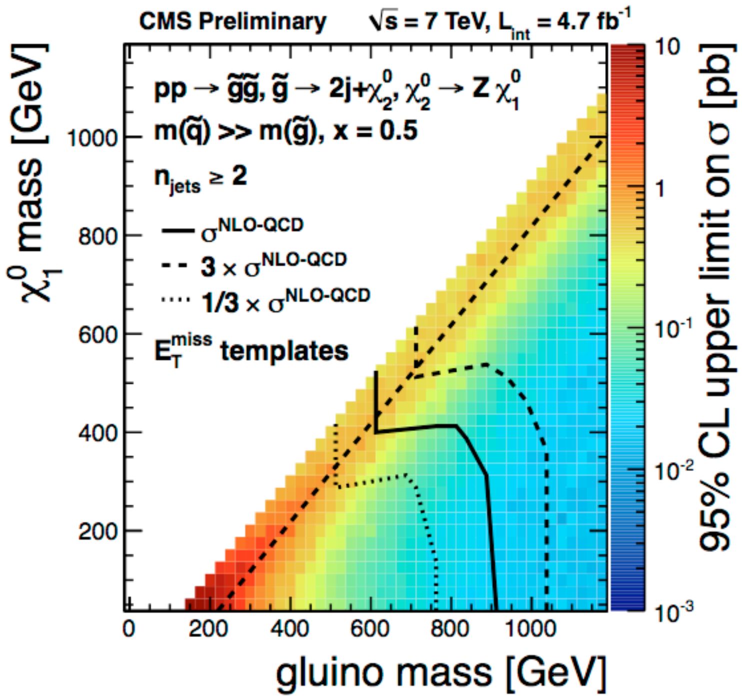


Opposite Sign Di-Leptons: Interpretation (Z-region, E_T^{miss})

- Simplified Model







Where we are...

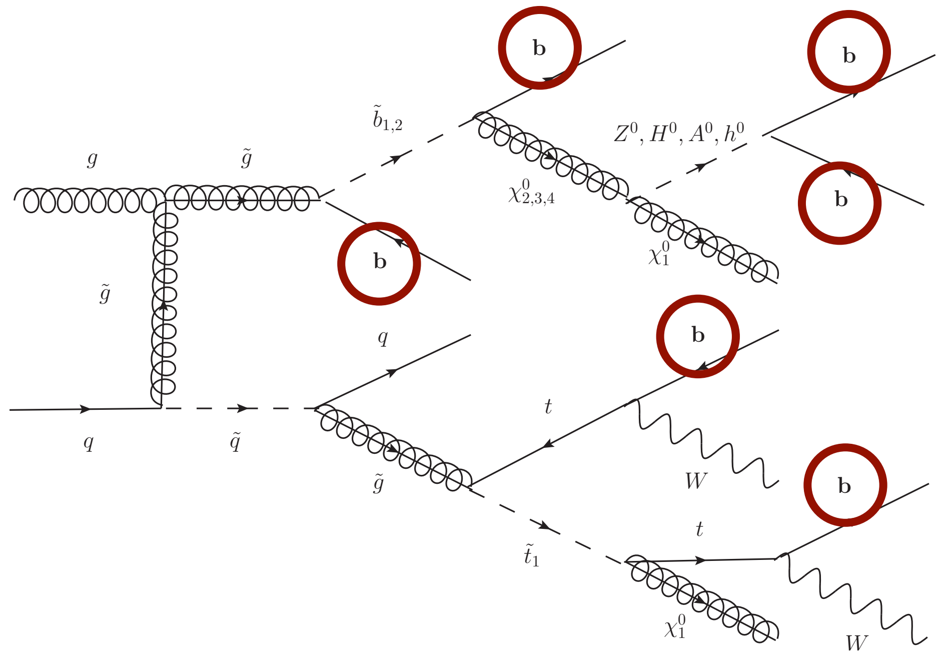
- Introduction
- The CMS Experiment
- Hadronic searches
- Leptonic searches
- **Searches for 3rd generation squarks**
  - ⇒ Search with one lepton, b-jets and E_T^{miss} ⇐
- Searches with photons
- Conclusion/Outlook

Contribution by DESY/UHH

Search with one lepton, b-jets and E_T^{miss}: Motivation

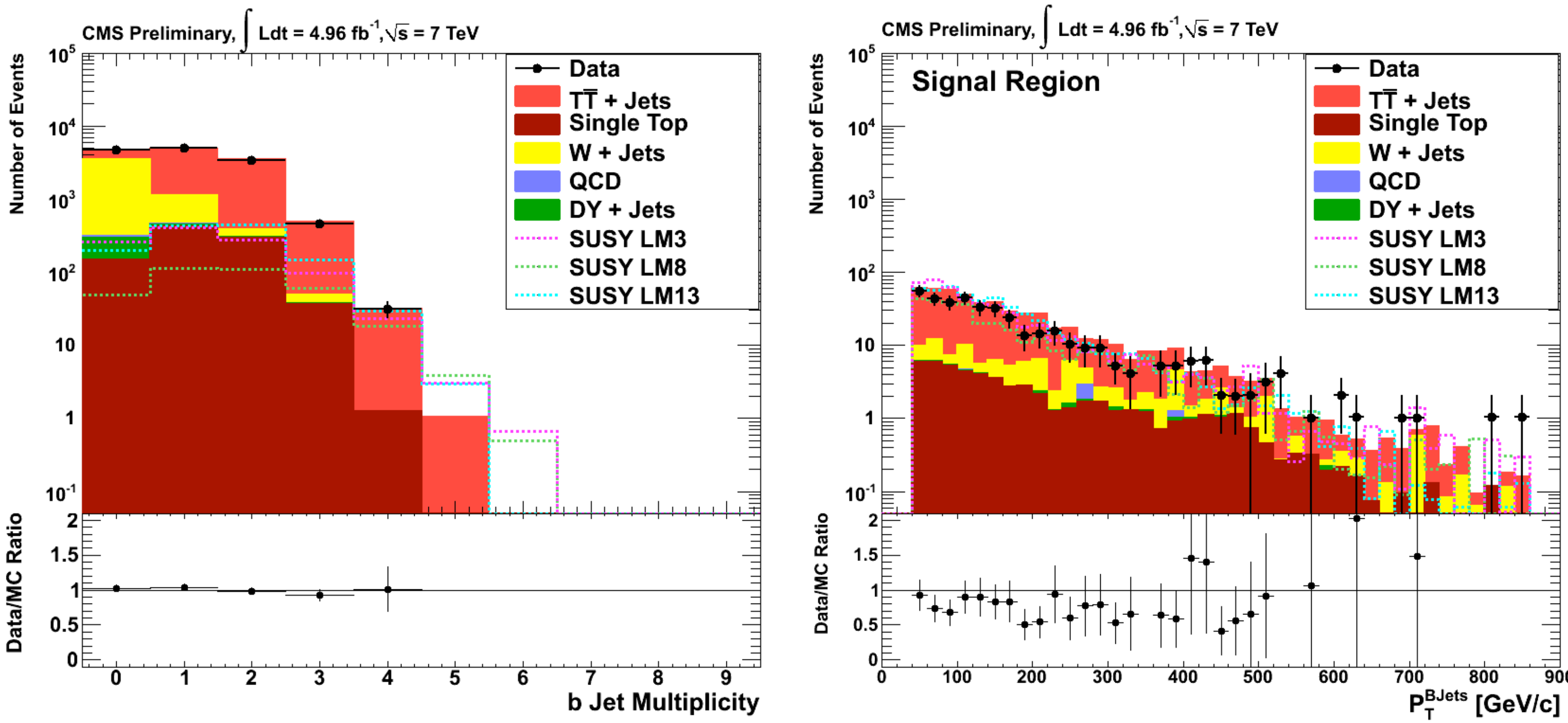
- One 3rd generation squark is typically significantly lighter than 1st or 2nd generation squarks
- In scenarios with "light" gluinos, the gluino predominantly decays into 3rd generation squark pairs
- Decays of 3rd generation squarks into light quarks are strongly flavor suppressed
- The gluino decay is expected to result in at least two b-jets and MET (assuming R-Parity conservation)

→ Expect excess of events with a large b-jet multiplicity and E_T^{miss}



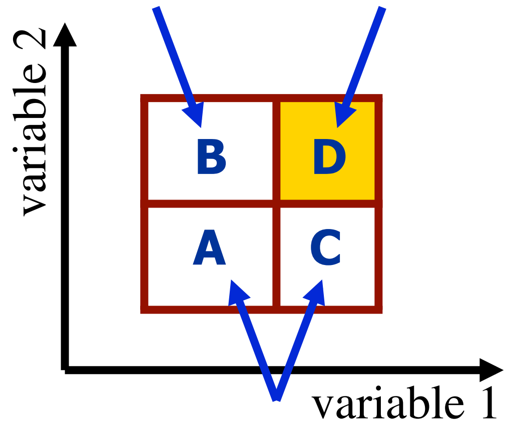
Search with one lepton, b-jets and E_T^{miss}: Event Selection

- Event selection similar to single lepton analysis described before
- In addition: requirement of 1, 2, 3 or more b-tags (determined with a track counting high efficiency method)

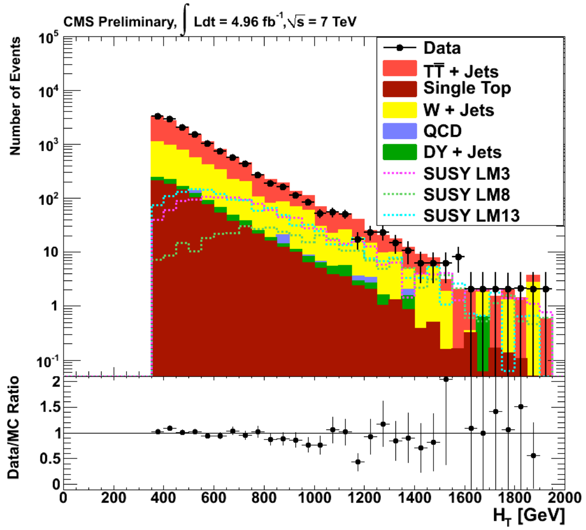


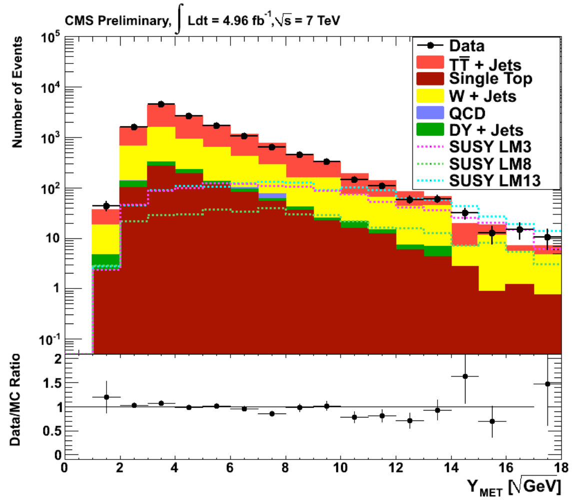
Search with one lepton, b-jets and E_T^{miss}: Factorization Method

- Straightforward method, if two variables are uncorrelated
- Variables used here:
  - H_T and $Y_{MET} := E_T^{miss}/\sqrt{H_T}$ (slightly correlated)



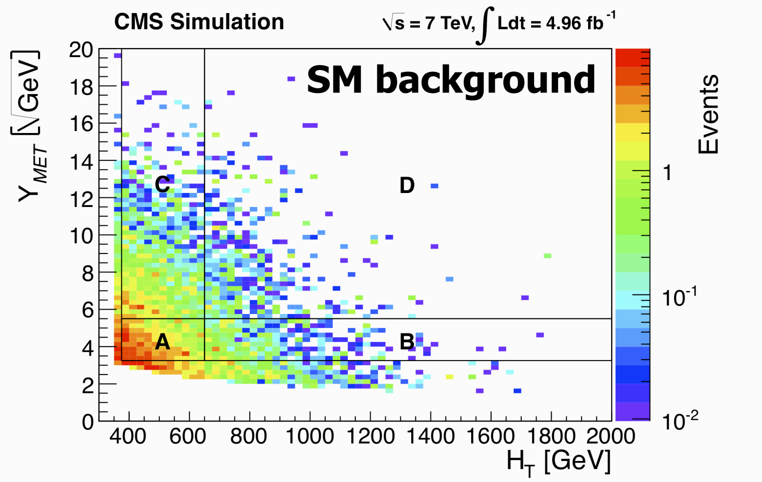
$$\frac{D}{C} = \frac{B}{A}$$

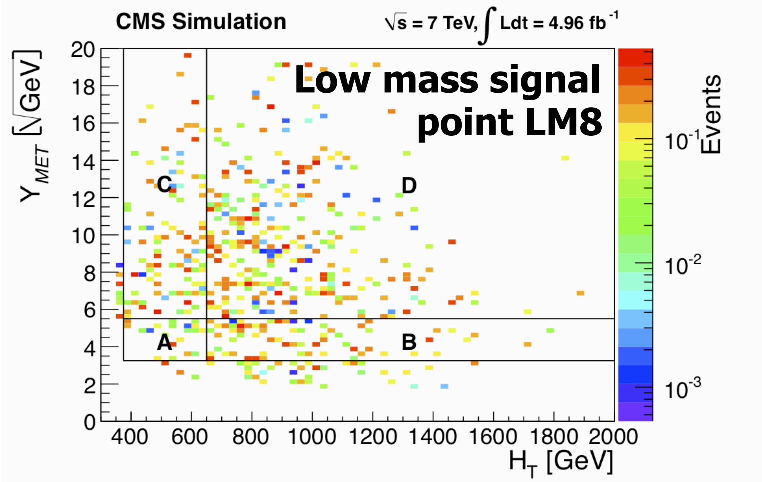




Search with one lepton, b-jets and E_T^{miss}: Factorization Method

- H_T and Y_{MET} are only slightly correlated
- Factorization method can be used to predict SM background





- Predict events in signal region D from control regions A,B,C:

$$\hat{N}_D = \kappa N_B \frac{N_C}{N_A}$$

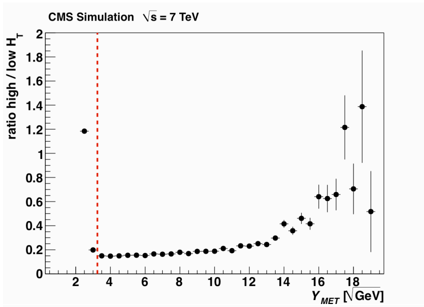
- κ takes into account small correlation between the two variables

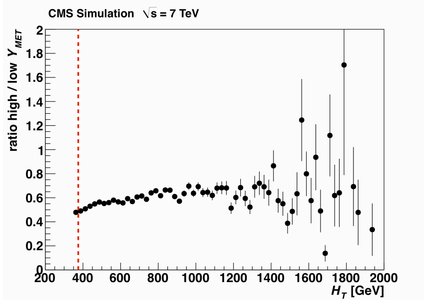
Search with one lepton, b-jets and E_T^{miss}: Factorization Method

- Studying κ

No. of b-tags	$\kappa(t\bar{t})$	κ(SingleTop)	κ(W+jets)	κ(All SM bkgs)
0 b-tags	1.14 ± 0.06	1.36 ± 0.14	1.01 ± 0.17	1.08 ± 0.13
1 b-tag	1.20 ± 0.05	1.29 ± 0.10	1.03 ± 0.20	1.19 ± 0.06
2 b-tags	1.19 ± 0.06	1.34 ± 0.12	1.42 ± 0.58	1.23 ± 0.06
$\geq$ 3 b-tags	1.19 ± 0.08	1.36 ± 0.18	1.23 ± 0.91	1.21 ± 0.07
$\geq$ 1 b-tags	1.19 ± 0.04	1.31 ± 0.07	1.08 ± 0.18	1.20 ± 0.04

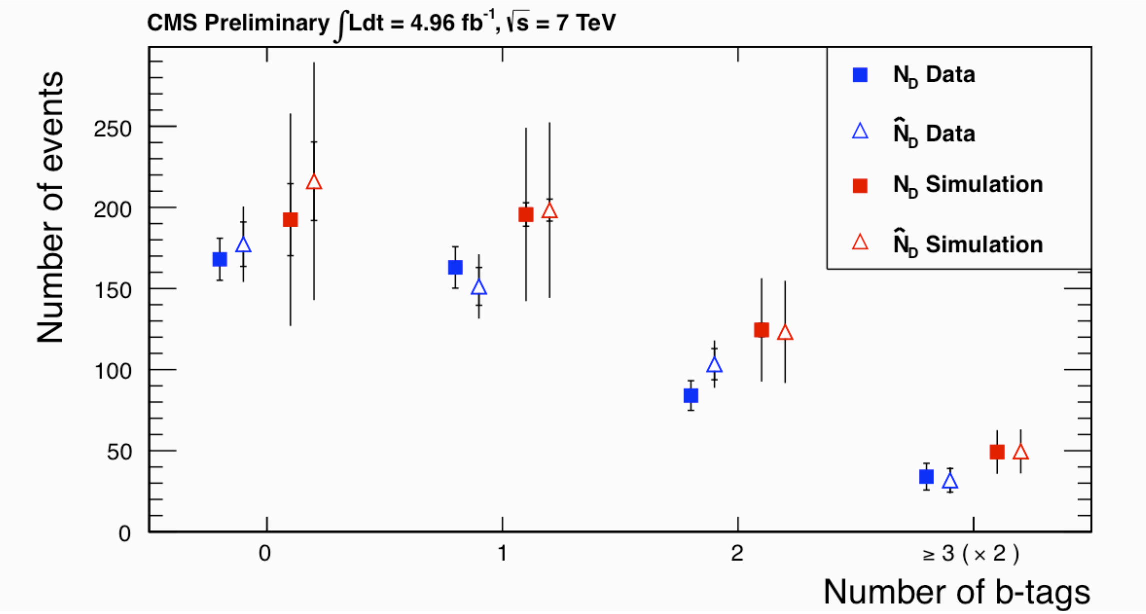
- Ratio of number of events in high/low region in Y_{MET} vs H_T and vice versa shows small correlation
- Nonlinear region above Y_{MET} =13 is nearly unpopulated (less than 0.5% of all events)





Search with one lepton, b-jets and E_T^{miss}: Result

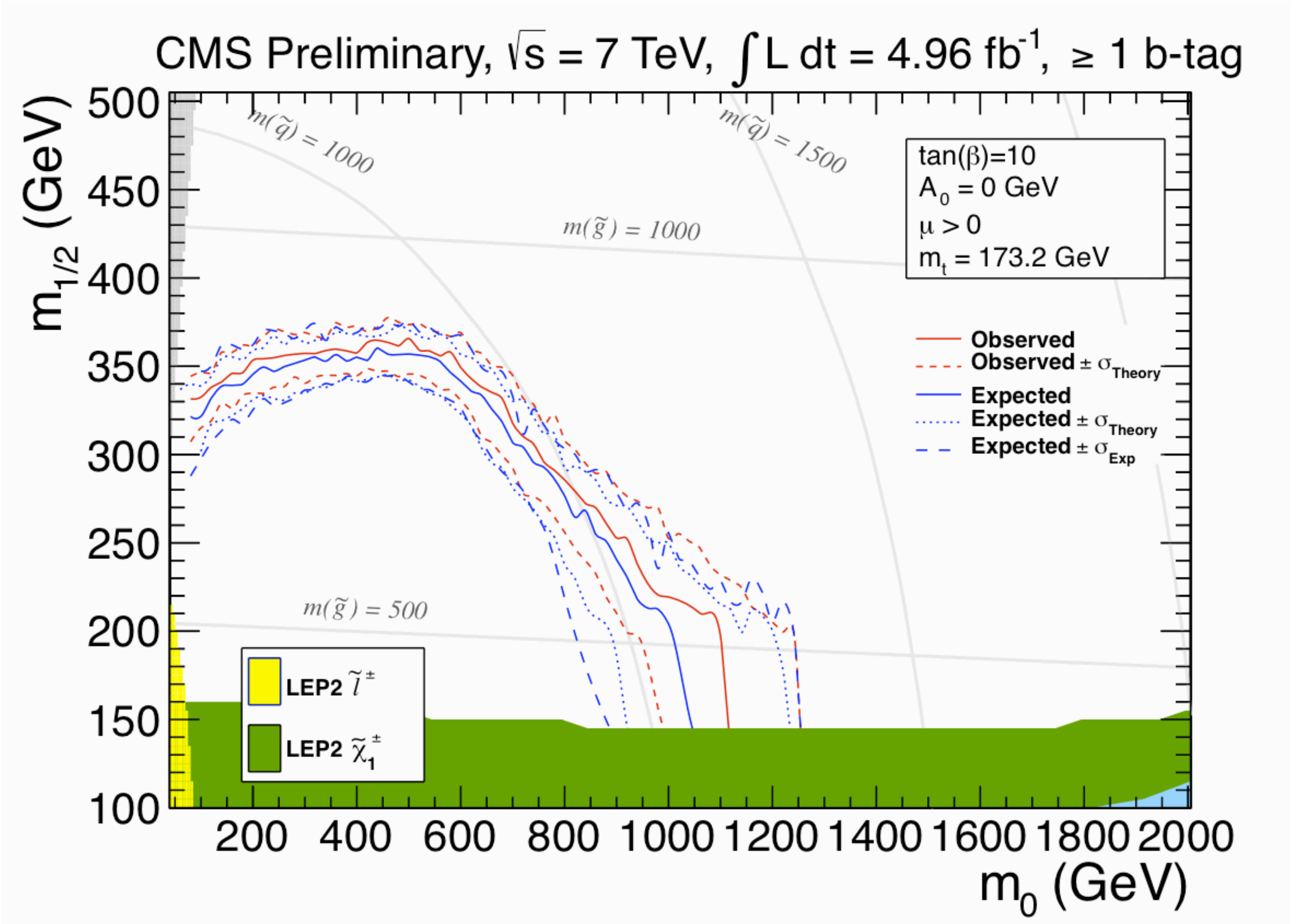
- Result presented in b-tag bins



- Data and data prediction agrees well → no signal
- MC closure → factorization method works
- Small systematic uncertainties in data prediction due to cancellation in ABCD method
- Large systematic uncertainties apply only for data vs MC comparison (scale factors)

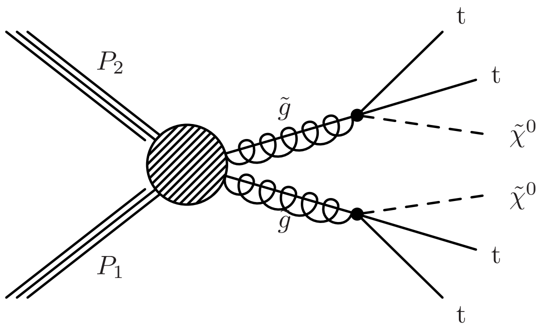
Search with one lepton, b-jets and E_T^{miss}: Interpretation

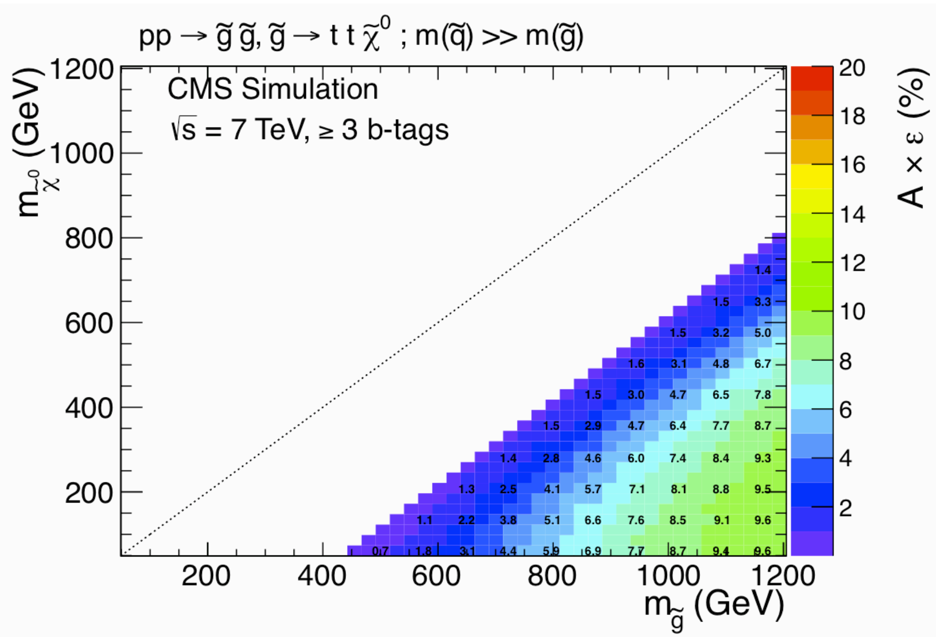
- cMSSM

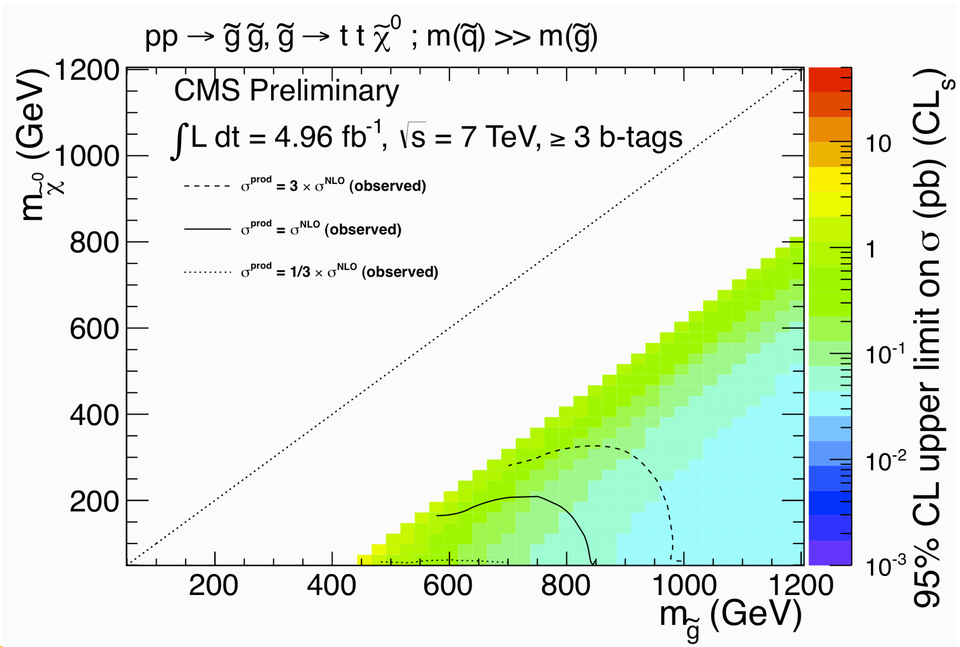


Search with one lepton, b-jets and E_T^{miss}: Interpretation

- Simplified Model







Where we are …

- The CMS Experiment
- Hadronic searches
- Leptonic searches
- Searches for 3rd generation squarks
- **Searches with photons**
  - → Search with di-photon
  - → Search with one photon

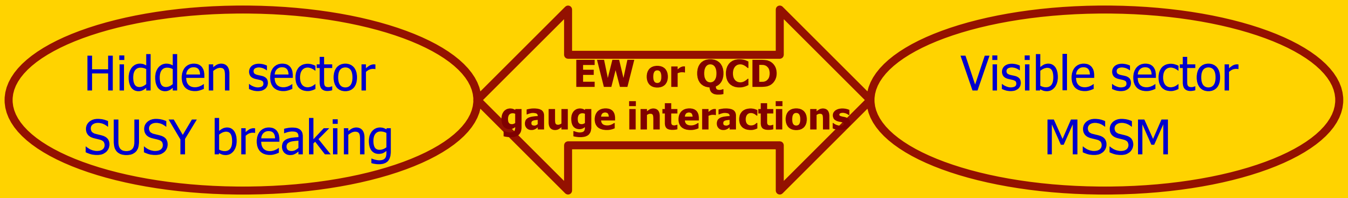
Contribution by UHH

SUSY Breaking Scenarios

- SUSY is supposed to break in a hidden sector
- A priori not clear who is the messenger, famous are:

  - Gravity – mSUGRA or cMSSM

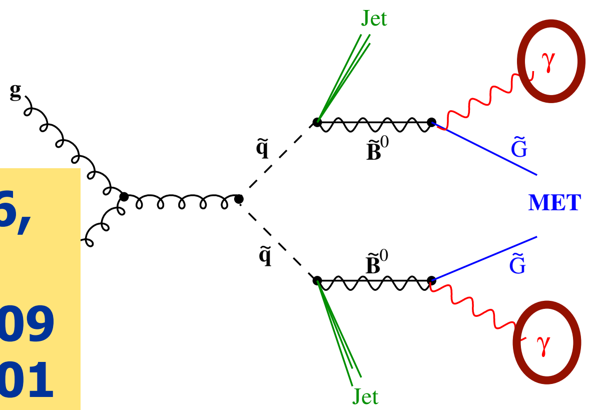
  - Gauge Mediated Symmetry Breaking (GMSB)

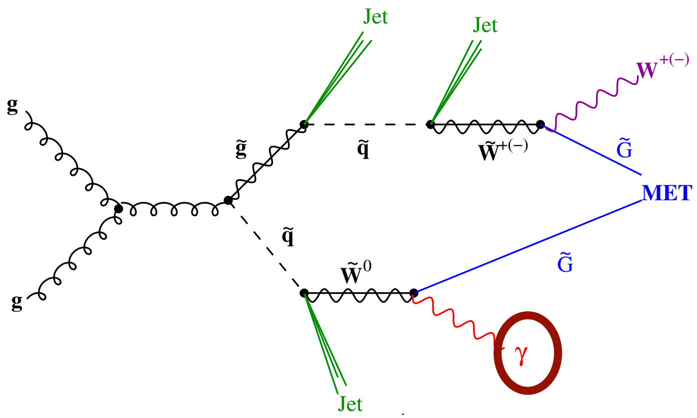


Searches with Photons: Introduction

In General Gauge Mediated SUSY
- Gravitino is LSP
- Neutralino is NLSP
  - Neutralinos: mix of Binos, neutral Winos, and Higgsinos
- Interpretation
  - Via a "Bino-like" neutralino model, with $\chi_0^1 \rightarrow \gamma + G$
    →Conserve R parity ⇒ two neutralinos ⇒ di-photon analysis
  - With simplified model where the Wino is less massive than the Bino, resulting in a neutralino-chargino co-NLSP
    →Photons not as common as in Bino-like case, but still occuring, most frequently at lower neutralino mass ⇒ single photon analysis

Phys. Rev. Lett. 106, 211802 (2011)
CMS PAS SUS-11-009
CMS PAS SUS-12-001





Searches with Photons: Event Selection

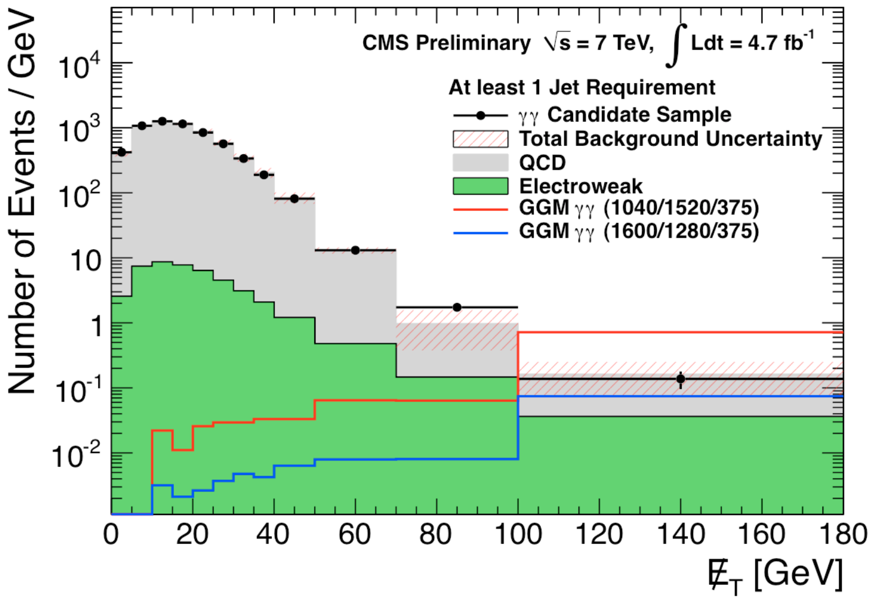
- **Di-photon analysis:**
  - At least 2 photons in barrel with $p_T^{\gamma 1} > 40$ GeV, $p_T^{\gamma 2} > 25$ GeV
  - At least 1 jet with $p_T > 30$ GeV, $|\eta|<2.6$
  - *Signal region:* $E_T^{miss} > 100$ GeV

- **Single photon analysis:**
  - Exactly 1 photon in barrel with $p_T^{\gamma} > 75$ GeV (due to trigger constraint)
  - $H_T > 400$ GeV (also from trigger)
  - At least 3 jets with $p_T > 30$ GeV, $|\eta|<2.6$
  - $E_T^{miss} > 200$ GeV

CMS PAS SUS-12-001

Searches with Di-Photons: Background Determination

- **QCD background (no true E_T^{miss})**
  - Mis-measurement of E_T^{miss} in QCD processes and/or photon mis-identification:
    - Direct di-photon production
    - γ+jets and multijets, with jets mimicking photons
  - Background determined from samples with 2 fake γ or 2 electrons
- **Electroweak background with true E_T^{miss}**
  - Background from events with real or fake photon and W → νe (where e is misidentified as γ)



CMS PAS SUS-12-001

Searches with Di-Photons: Results

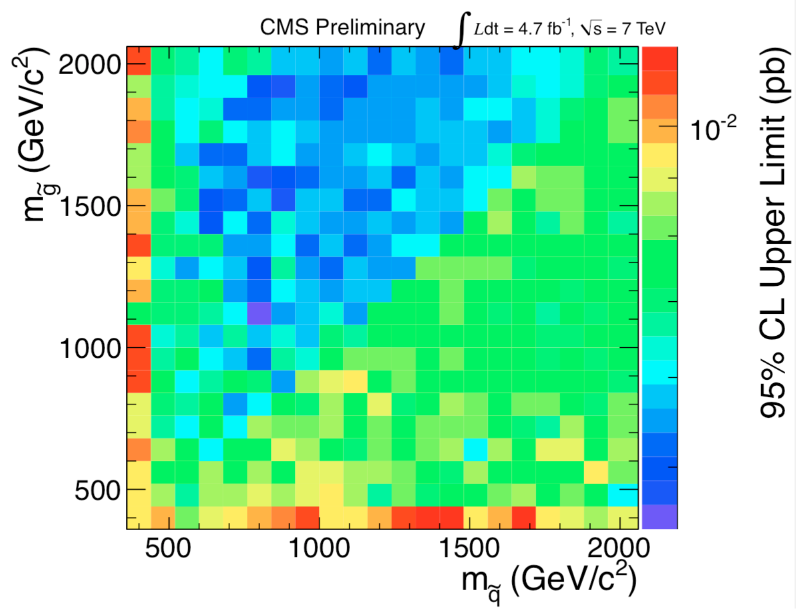
CMS PAS SUS-12-001

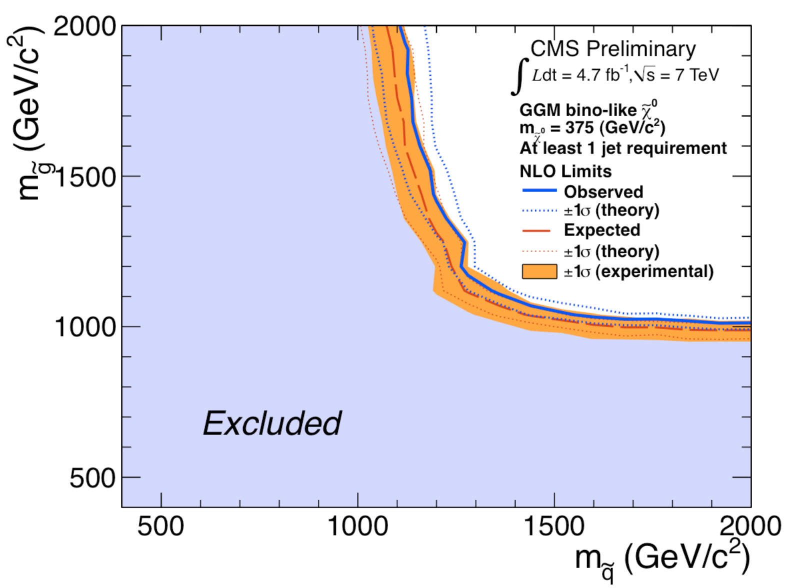
Sample	Events with E_T^{miss} > 100 GeV
Total predicted SM	13.0 ± 4.3 (stat.) ± 4.6 (syst.)
Data	11

No excess observed!

- 95% CL upper limits on the cross section in gluino-squark mass space for a $m_{\chi 0}$=375 GeV
- 95% CL exclusion contours in gluino-squark mass space for $m_{\chi 0}$=375 GeV

Wino like neutralinos

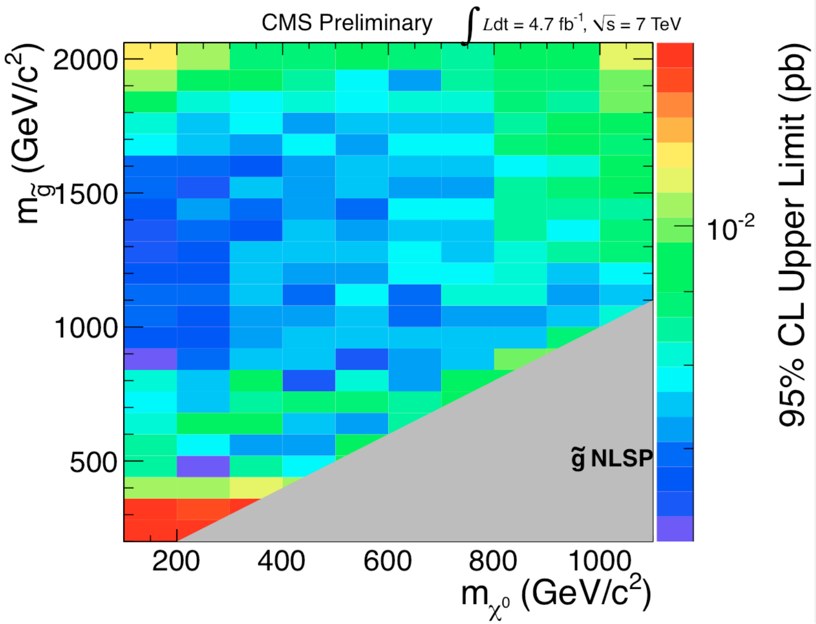


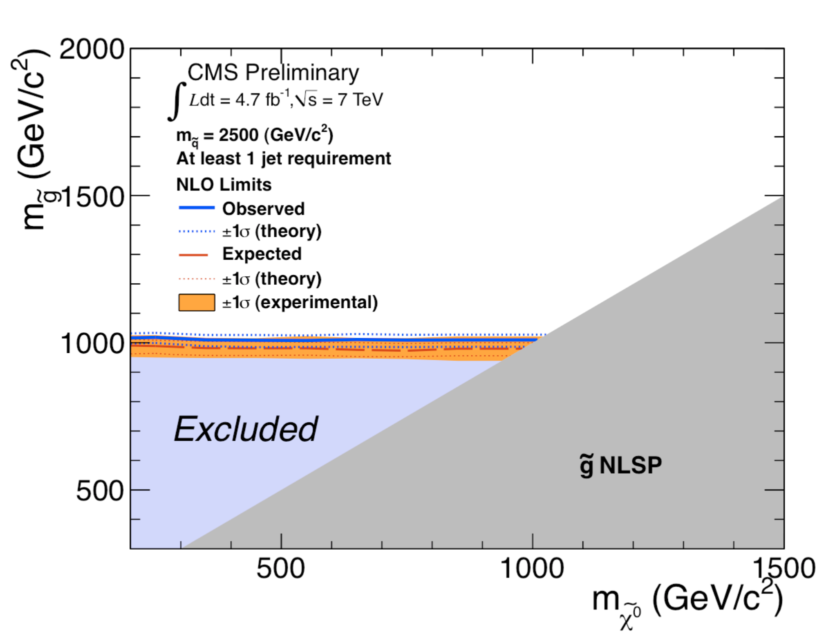


Searches with Di-Photons: Results

- Gluino-bino mass space for **Bino like neutralinos**

- 95% CL upper limits on the cross section in gluino-bino mass space for a m_{squark}=2500 GeV
- 95% CL exclusion contours in gluino-bino mass space for m_{squark}=2500 GeV

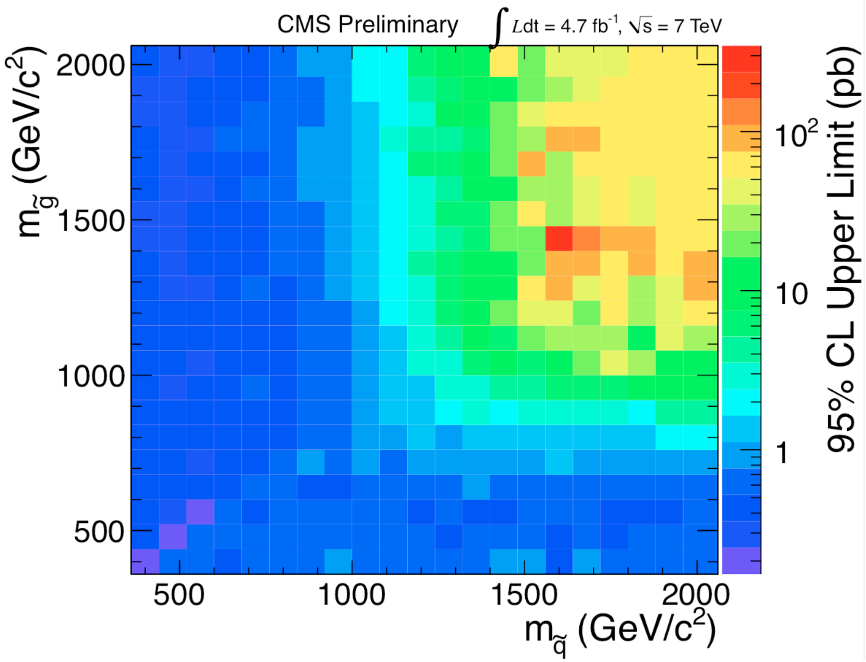


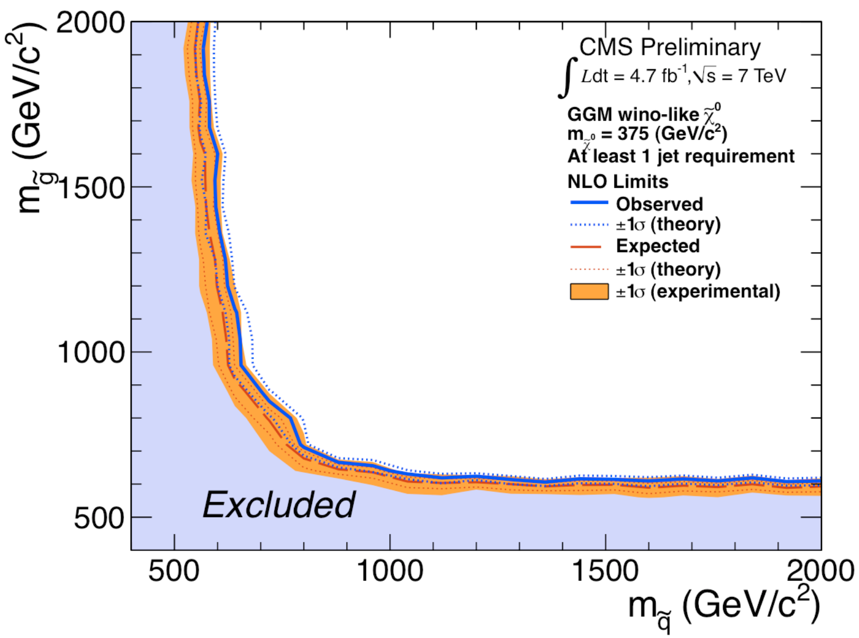


Searches with Di-Photons: Results

- Previous plots were for Bino like neutralinos
- Here: Exclusion plots for **Wino like neutralinos**

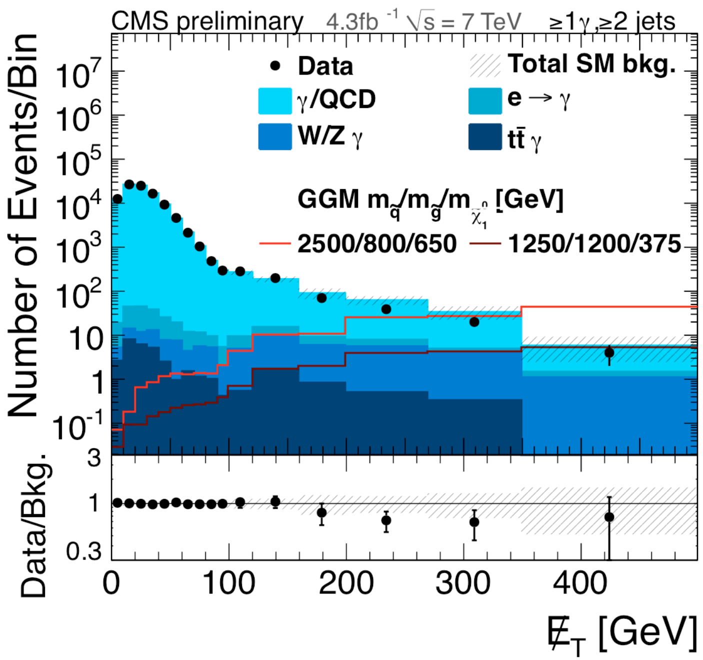
- 95% CL upper limits on the cross section in gluino-squark mass space for a $m_{\chi 0}$=375 GeV
- 95% CL exclusion contours in gluino-squark mass space for $m_{\chi 0}$=375 GeV





Searches with Single Photons: Background Determination

- Background determination similar to di-photon case
- Additional backgrounds: initial state radiation (ISR) and final state radiation (FSR) of photons:
  - ISR and FSR in events with electrons in final state covered by EW background prediction from data
  - Remaining contributions from SM process are very small – taken from Monte Carlo simulation with a systematic uncertainty of 100%.

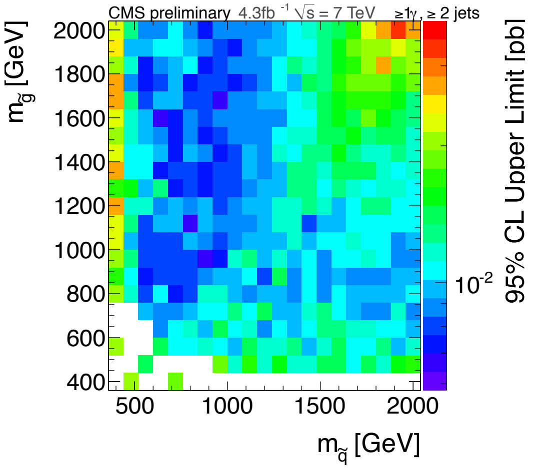


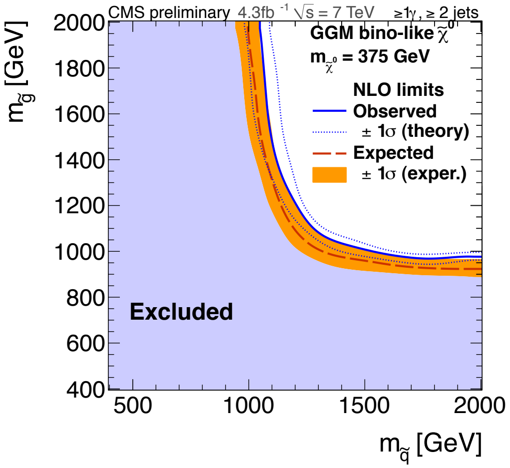
No excess observed!

CMS PAS SUS-12-001

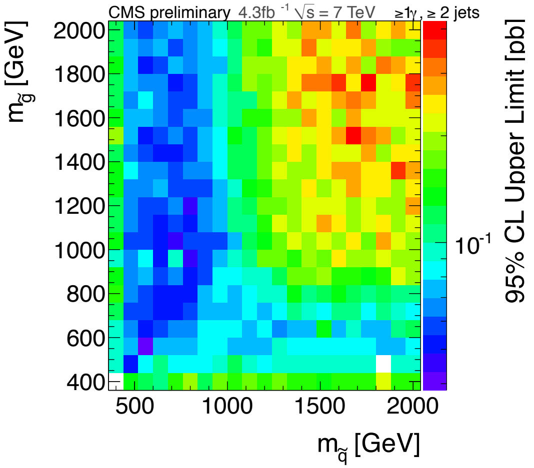
95% CL upper limit in gluino-squark mass space

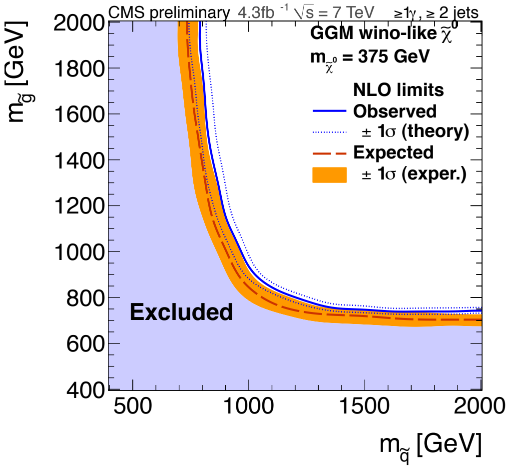
95% CL exclusion contours in gluino-squark mass space





- Bino-like





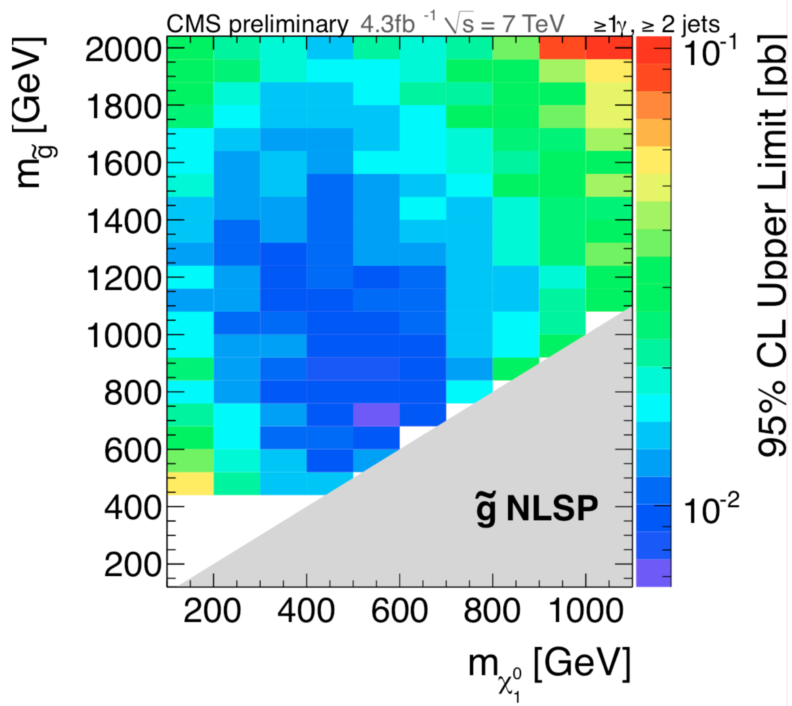
- Wino-like

CMS PAS SUS-12-001

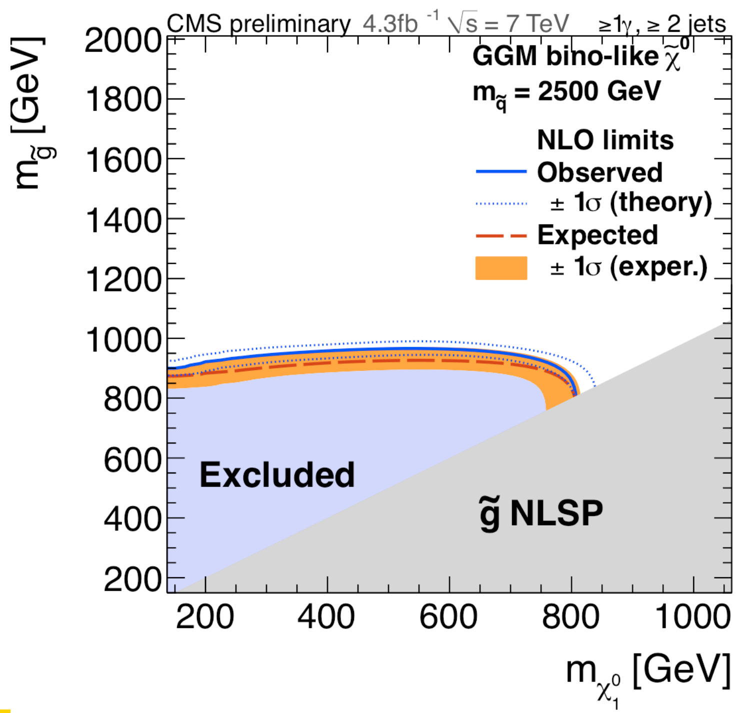
Searches with Single Photons: Results

- Gluino-bino mass space for bino like neutralinos

- 95% CL upper limits on the cross section in gluino-bino mass space for a m_{squark}=2500 GeV



- 95% CL exclusion contours in gluino-bino mass space for m_{squark}=2500 GeV

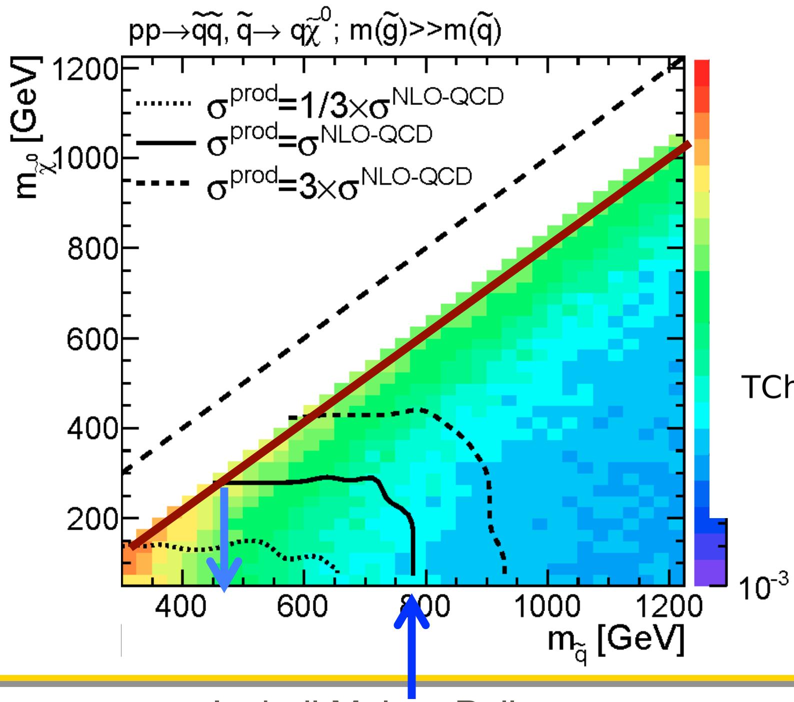


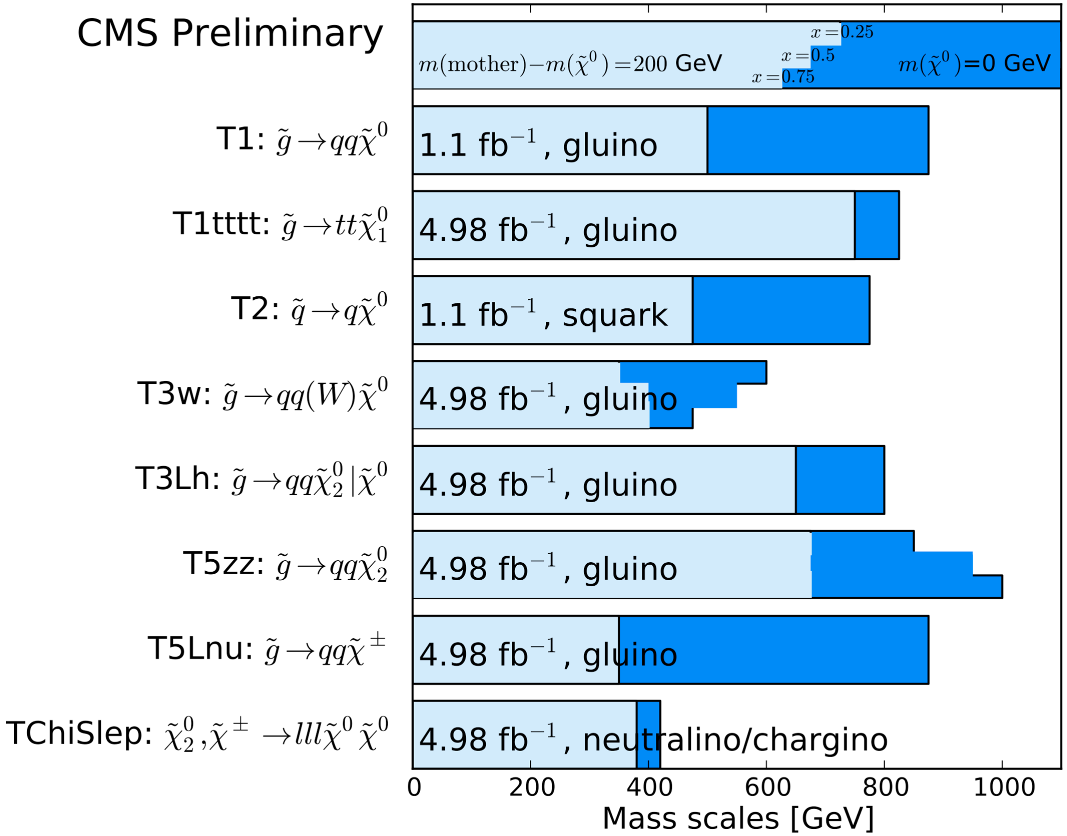
Summary: Interpretation with Simplified Models

- For limits on m(gluino): m(squark)>>m(gluino) and vice verso

$$\sigma^{prod} = \sigma^{NLO\text{-}QCD}$$

$$m(\tilde{\chi}^{\pm}), m(\tilde{\chi}_2^0) = \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$$





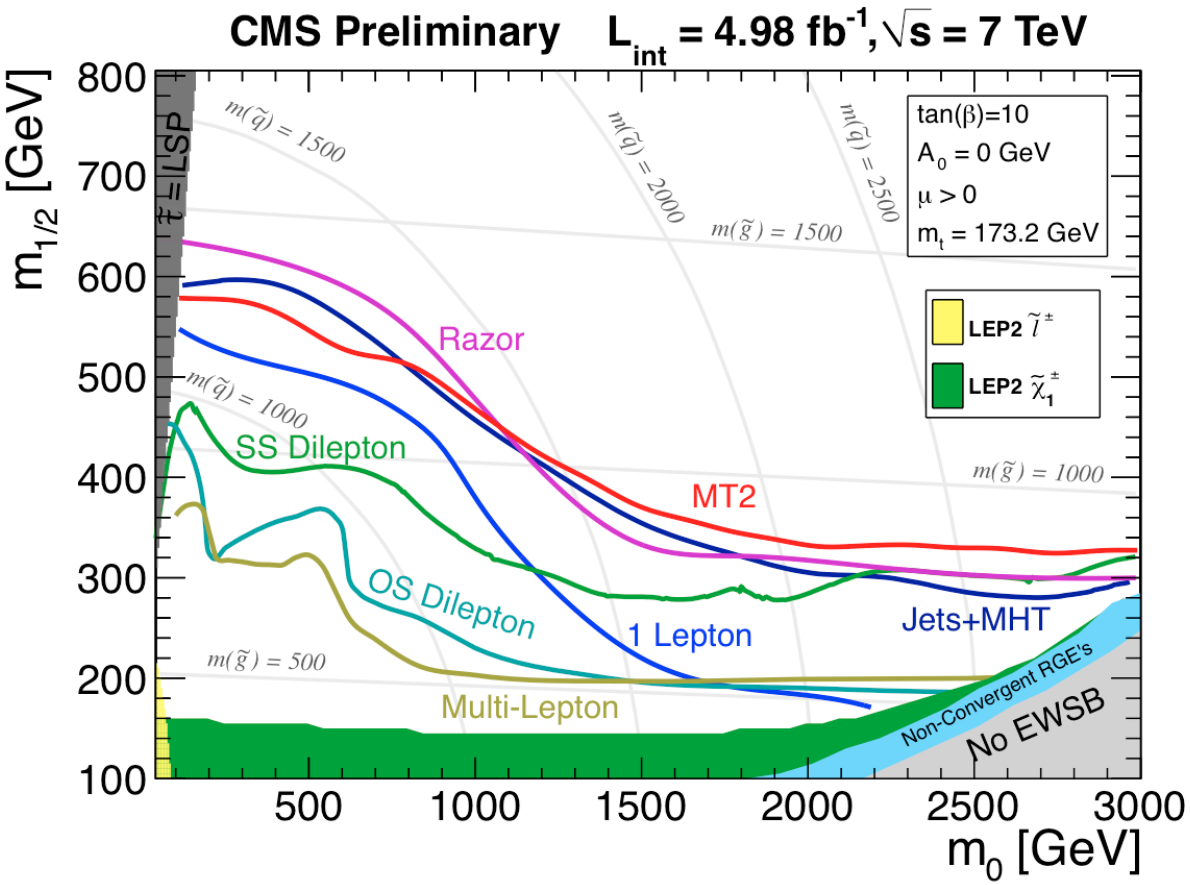
$m(\chi^0)$=m(gluino)-200GeV (light blue)

$m(\chi^0)=0$ (dark blue)

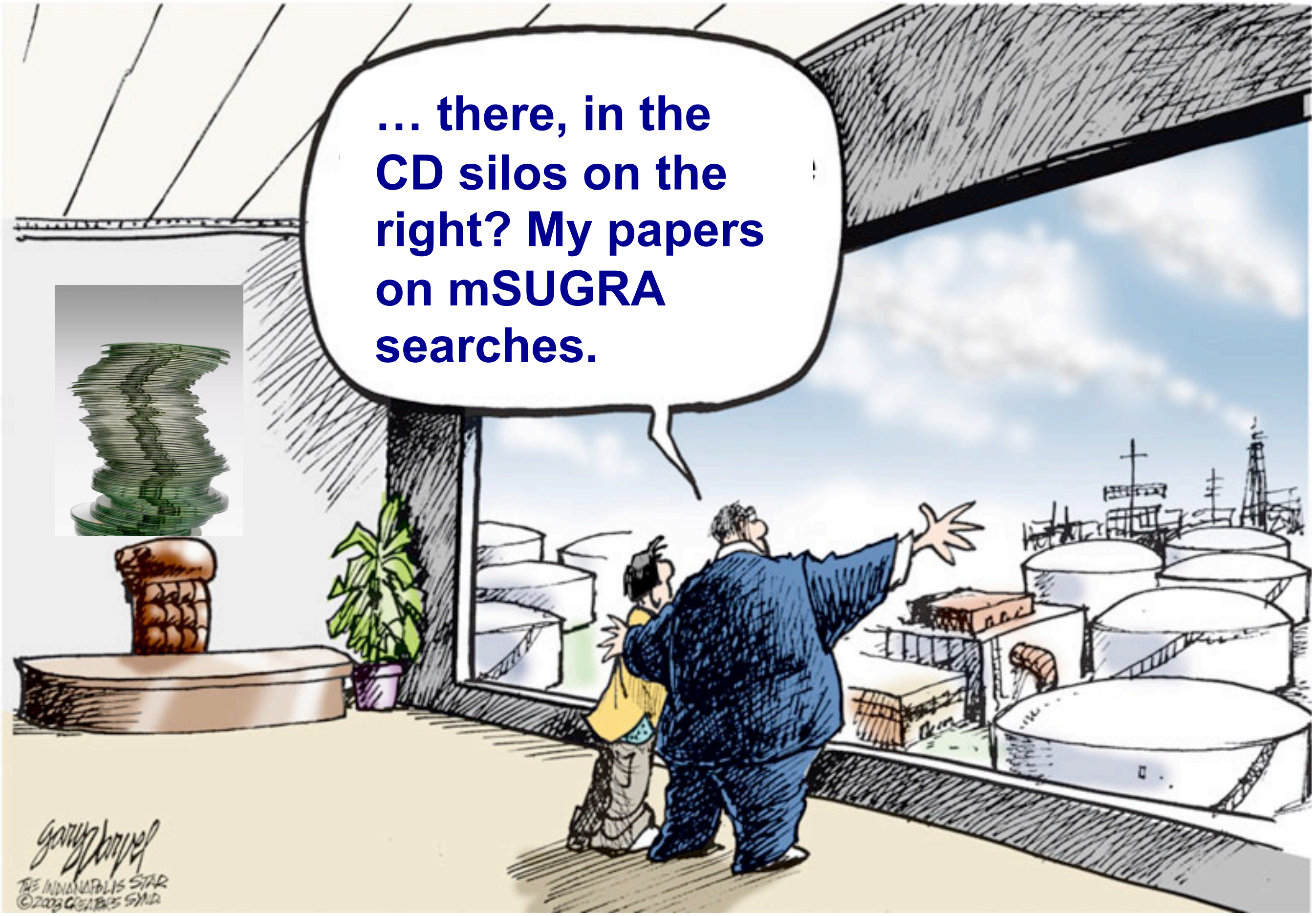
Summary and Outlook

- Results from several analyses with ~5 fb^{-1} have been presented
- None of the analyses have observed any significant deviation from the Standard Model ☹
- Exclusion limits have been set
  - Using the cMSSM
  - In simplified models

8 TeV data taking well going, but SUSY discovery in a single channel unlikely in 2012
→ Need to prepare for combination of searches
→ Start looking for light stops / EW (need higher lumi)



Outlook: SUSY in Modern Times



… mSUGRA not yet excluded, and SUSY space remains huge… let's keep on searching!

Thank you for listening

Backup slides follow…

CMSSM

Simplest ansatz: CMSSM – assume universality at high energy scale

- Universal scalar masses: $m^2 \cong m_0^2$
- Universal gaugino masses: $M_i = m_{1/2}$ ("GUT relation")
- Universality of soft-breaking trilinear terms:

$$\mathcal{L}_{\rm tri} = A_0(H_U Q y_u \bar{u} + H_D Q y_d \bar{d} + H_D L y_l \bar{e})$$

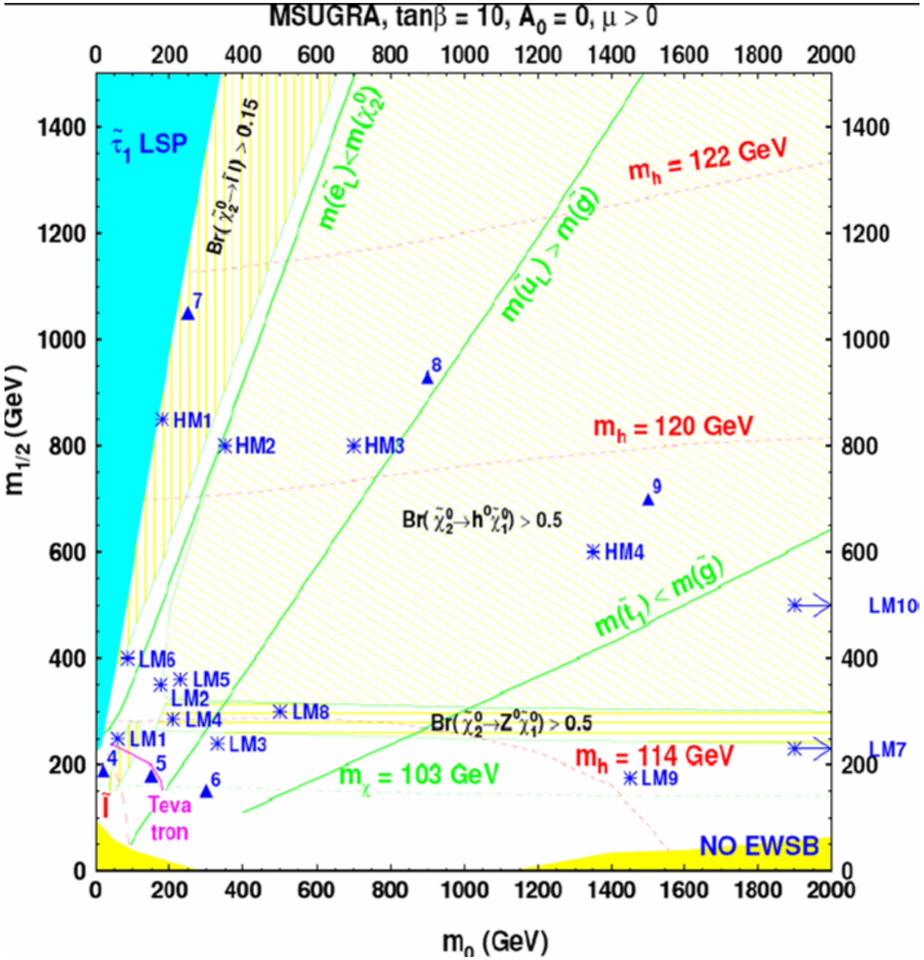
- Results in **five** parameters, if possible phases are ignored:
  $m_0^2, m_{1/2}, A_0, b, \mu$
- Require correct value of M_z,
  → $|\mu|$, b given in terms of $\tan\beta = v_u/v_d$ and sign μ

➔ CMSSM parameters:
$m_0^2, m_{1/2}, A_0, \tan\beta$, sign μ

CMS Benchmark Points

Interesting for our nearer future are the Low Mass (LM points)
The High Mass (HM) points are close to the ultimate LHC reach…

Model	Cross Section (pb)	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0	$\tan\beta$
LM0	110	200	160	-400	10
LM1	16.06	60	250	0	10
LM2	2.42	185	350	0	35
LM3	11.79	330	240	0	20
LM4	6.70	210	285	0	10
LM5	1.94	230	360	0	10
LM6	1.28	85	400	0	10
LM7	2.90	3000	230	0	10
LM8	2.86	500	300	-300	10
LM9	11.58	1450	175	0	50



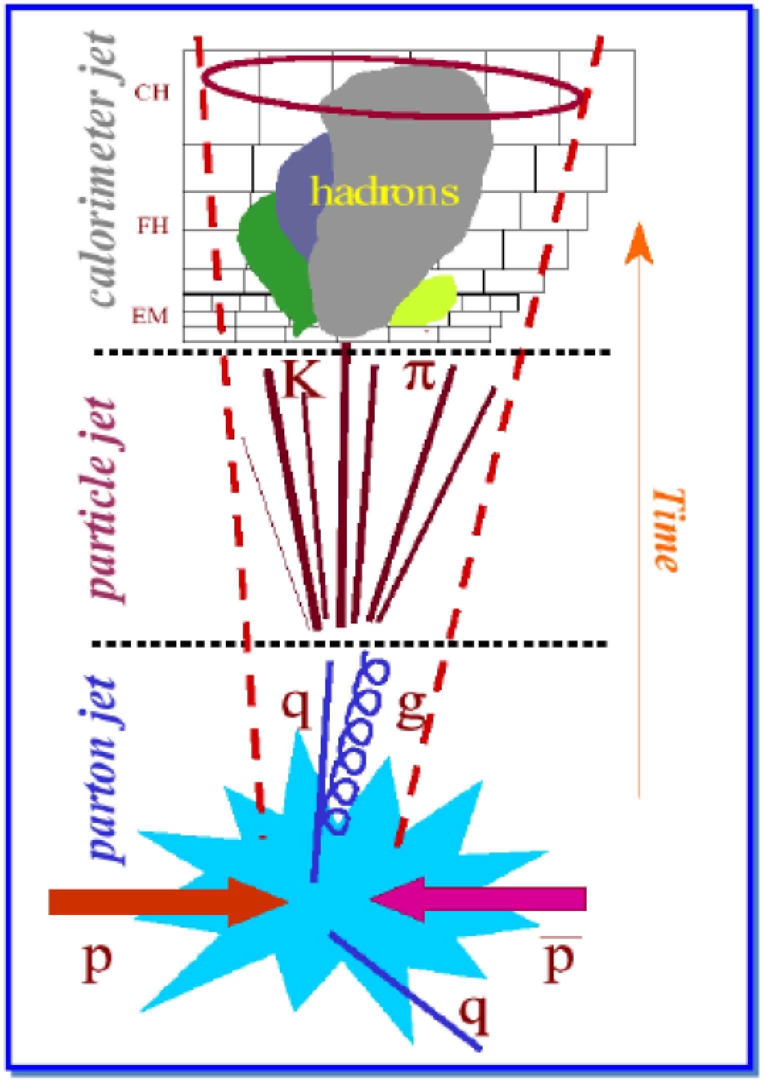
CMS Benchmark Point Characteristics

- **Point LM1 :**
  - Same as post-WMAP benchmark point B' and near DAQ TDR point 4.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant
  - B(X02 -> slep_R lept) = 11.2%, B(X02 -> stau_1 tau) = 46%, B(X+1 -> sneut_L lept) = 36%
- **Point LM2 :**
  - Same as post-WMAP benchmark point I'.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant (sbot1+b is 25%)
  - B(X02 -> stau_1 tau) = 96%, B(X+1 -> stau_1 nu) = 95%
- **Point LM3 :**
  - Same as NUHM point gamma and near DAQ TDR point 6.
  - M(gluino) < M(squark), hence gluino -> squark+quark is forbidden except B(gluino -> sbot1,2 bot) = 85%
  - decays: B(X02 -> lept lept X01) = 3.3%, B(X02 -> tau tau X01) = 2.2%, B(X+1 -> W+ X01) = 100%
- **Point LM4 :**
  - Near NUHM point alpha in on-shell Z0 decay region.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant with B(gluino -> sbot1 bot) = 24%
  - decays: B(X02 -> Z0 X01) = 97%, B(X+1 -> W+ X01) = 100%
- **Point LM5 :**
  - In h0 decay region, same as NUHM point beta.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant with B(gluino -> sbot1 bot) = 19.7% and B(gluino -> stop1 top) = 23.4%
  - decays: B(X02 -> h0 X01) = 85%, B(X02 -> Z0 X01) = 11.5%, B(X+1 -> W+ X01) = 97%

CMS Benchmark Point Characteristics (2)

- **Point LM6 :**
  - Same as post-WMAP benchmark point C'.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant
  - B(X02 -> slepL lept) = 10.8%, B(X02 -> slepR lept) = 1.9%, B(X02 -> stau1 tau) = 14%, B(X+1 -> sneut lept) = 44%
- **Point LM7 :**
  - Very heavy squarks, outside reach, but light gluino.
  - M(gluino) = 678 GeV, hence gluino -> 3-body is dominant
  - B(X02 -> lept lept X01) = 10%, B(X+1 -> lept nu X01) = 33%
  - EW chargino-neutralino production cross-section is about 73% of total.
- **Point LM8 :**
  - Gluino lighter than squarks, except sbot1 and stop1.
  - M(gluino) = 745 GeV, M(stop1) = 548 GeV (A0 = -300), gluino -> stop1+t is dominant
  - B(gluino -> stop1+t) = 81%, B(gluino -> sbot1+b) = 14%, B(squarkL -> q+X02) = 26-27%,
  - B(X02 -> Z0 X01) = 100%, B(X+1 -> W+ X01) = 100%
- **Point LM9 :**
  - Heavy squarks, light gluino. Consistent with EGRET data on diffuse gamma ray spectrum, WMAP results on CDM and MSUGRA (see W. de Boer et al., astro-ph/0408272 v2). Similar to LM7.
  - M(gluino) = 507 GeV, hence gluino -> 3-body is dominant
  - B(X02 -> lept lept X01) = 6.5%, B(X+1 -> lept nu X01) = 22%
- **Point LM10 :**
  - Similar to LM7, but heavier gauginos.
  - Very heavy squarks, outside reach, but lighter gluino.
  - M(gluino) = 1295 GeV, hence gluino -> 3-body is dominant
  - B(gluino> -> t tbar X04) = 11%, B(gluino -> t b X+2) = 27%

Jets


calorimeter jet
CH
FH
EM
hadrons
particle jet
K
π
parton jet
q
g
p
p̄
q
Time

Pseudorapidity

- **Rapidity** of a particle of momentum $p=(E,0,0,p_z)$ is defined to be

  $y = ½ \log ((E+p_z)/(E-p_z))$

  Advantage: the rapidity difference is invariant under the longitudinal boost

- For massless particles, $p_z = E \cos\theta$, (θ : polar angle)

→ $y = ½ \log((1+\cos\theta)/(1-\cos\theta))$
$= \log(\cot(\theta/2))$
$= \eta$: pseudo-rapidity

Example for Prediction from Templates: Artificial E_T^{miss}

Missing transverse energy can have several artificial sources:

- Instrumental effects
- Software
- Collision or non-collision backgrounds
- Some effect you haven't yet thought of…

Predict these effects from data with templates!

→ Fill measured E_T^{miss} of collected QCD events in 2-dim matrix (e.g. with variable1=N_{jet}, variable2=H_T, which is expected to be less polluted by artificial effects)

→ Then measure these variables for your signal candidate event, and extract the E_T^{miss} template for this bin

Sounds straight forward, but attention:

- H_T of QCD events lower than expected for SUSY
  → need extrapolation
- QCD and signal events might be triggered by different (and differently efficient) triggers

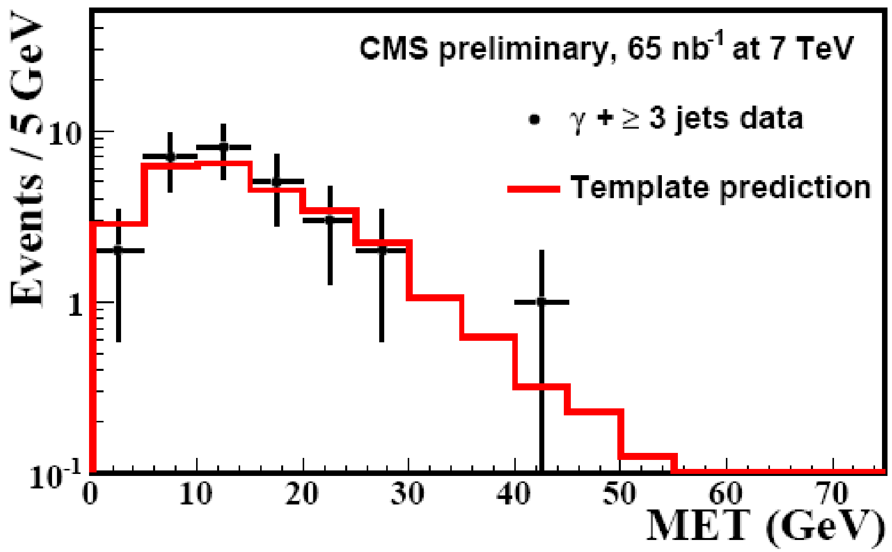
Example for Prediction from Templates: Artificial E_T^{miss}(2)

How can we check that it works with early data?

Predict the E_T^{miss} for γ+jets events using QCD jets:

→ Prediction quite good, given that:

- Photon sample expected to be polluted by neutral pions
- Jet energy scale for jets less well measured than the photon
- Different triggers used for the two data samples



Jet Smearing – Gaussian Part

Idea: Generate the **Gaussian** response function either with well measured dijet or with γ+jet events:

- In case of γ+jet events (photon well measured):
  - Use transverse momentum conservation in γ+jet events to calculate Gaussian response of calorimeters to jets from the distribution of the photon-jet p_T balance (with events containing exactly 1 jet):

$$R_1 = 1 + \frac{p_T^{miss} \cdot p_T^{\gamma}}{\left|p_T^{\gamma}\right|^2}$$

  - Measure this distribution in bins of p_T^{γ}

Jet Smearing – Gaussian Part (2)

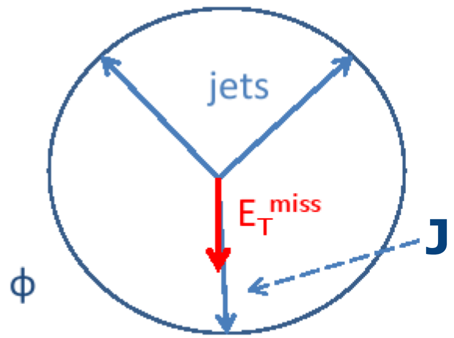
- In case of dijet events:
  - Apply jet smearing with the Gaussian jet response on low E_T^{miss}, well measured, dijet seed events
  - This produces a set of smeared events
  - Compare the E_T^{miss} distribution of the smeared events with the E_T^{miss} distribution of all jet data in the low E_T^{miss} region
  - Vary the Gaussian parametrisation and repeat the above two steps to find the closest match and therefore the optimal Gaussian fit

  - Still need to measure the non-Gaussian part… (see next page)

Jet Smearing – Non-Gaussian Part

- Generate the **non-Gaussian** response function with multi-jet events (preferably Mercedes-like events) where exactly one jet 'J' is parallel to the E_T^{miss}
  - Response of the calorimeter to jet J, if its p_T lies in the non-Gaussian tail, can be obtained from:

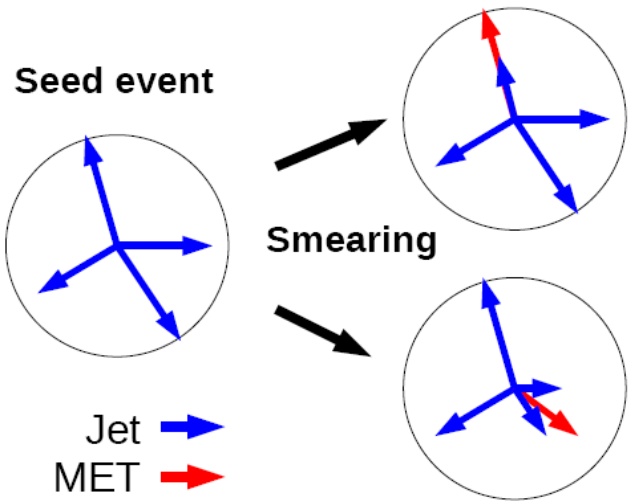
$$R_2 = \frac{p_T^{J} \cdot p_T^{J,true}}{\left| p_T^{J,true} \right|^2} \quad \text{with} \quad p_T^{J,true} \approx p_T^{J} + p_T^{miss}$$



Jet Smearing – Full Jet Response

- Construct full jet response by approximately normalising the Gaussian and the non-Gaussian components
- Derive the normalisation by comparing the measured non-Gaussian response with the tail of the dijet balance distribution
- Use the full response function to 'smear' the four-momenta of jets in events with low E_T^{miss}

→ The smeared jets can now have sufficient E_T^{miss} to enter the SUSY signal region and hence provide an estimation of the multijet background in this region



Jet Smearing

- From SUS-11-04

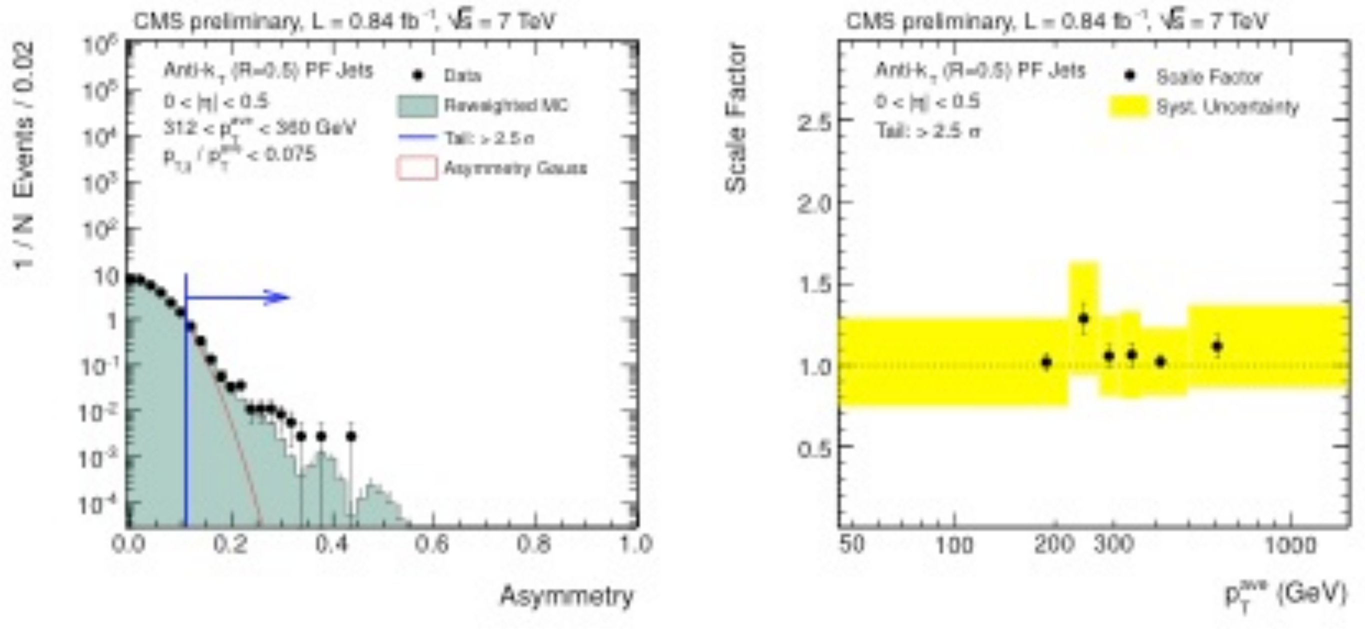


Figure 8: (Left) Example di-jet asymmetry distribution for data (solid circles) compared to the Monte Carlo simulation (filled histogram). The latter has been corrected for the measured core resolution differences. The area beyond asymmetries of 0.1, indicated by the arrow, defines the tail region. For comparison, the hatched area shows number of events expected for a purely Gaussian response. (Right) Ratios of the fractional number of tail events in data and MC simulation in bins of p_T^{ave} for the central η region. They were used as scale factors for the tails of the MC truth response distribution.

SMS

- SMS intermediate mass definition:

$$m_{\tilde{\chi}_2^0} | m_{\tilde{\chi}^\pm} = x \cdot m_{\tilde{g}} + (1 - x) \cdot m_{\tilde{\chi}^0}$$

SUSY in the 80's (and 90's)

"One day, all of these will be SUSY phenomenology papers."