ETH Institute for Particle Physics

Searches for SUSY with the CMS experiment

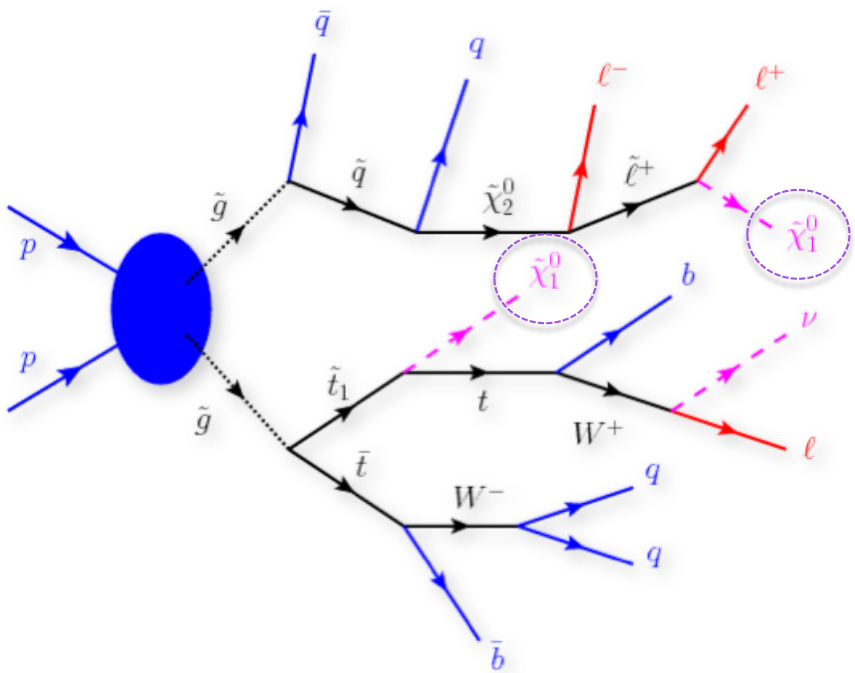
Mario Masciovecchio
(ETH Zürich)

On behalf of the CMS Collaboration

26.08.2015

ICNFP 2015, Kolymbari (Crete), 22-30.08.2015

SUSY (typical) topology



HOW TO LOOK for SUSY:

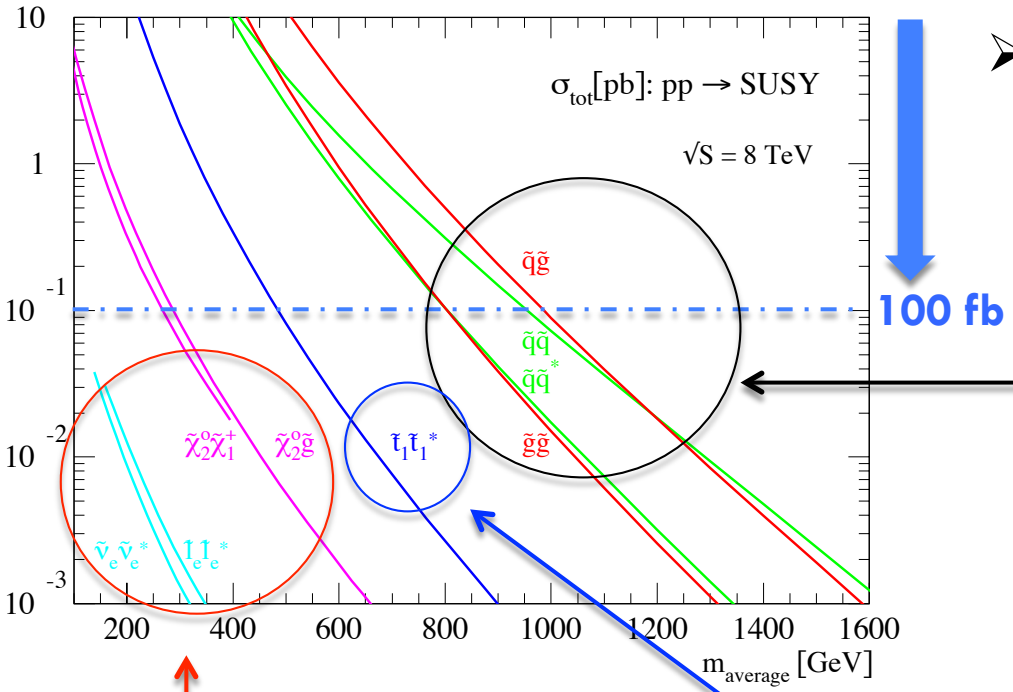
- If R-parity is conserved:
- ✓ S-particles come in pairs
- ✓ **LSP** is undetected → **ME_T**

➢ Look for events with:

- ✓ Large **ME_T**
- ✓ Large **hadronic activity**
- ✓ Low energy **leptons**

SUSY Production at LHC Run I

- SUSY production cross-section at 8 TeV



100 fb

- At 8 TeV, Standard Model probed with success down to cross-sections of 100 fb

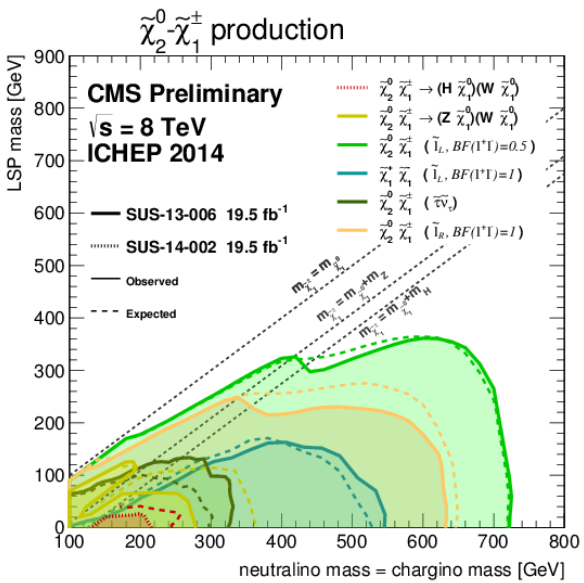
Gluinos & s-quarks:
- Largest cross-section
- Probe up to ~1 TeV

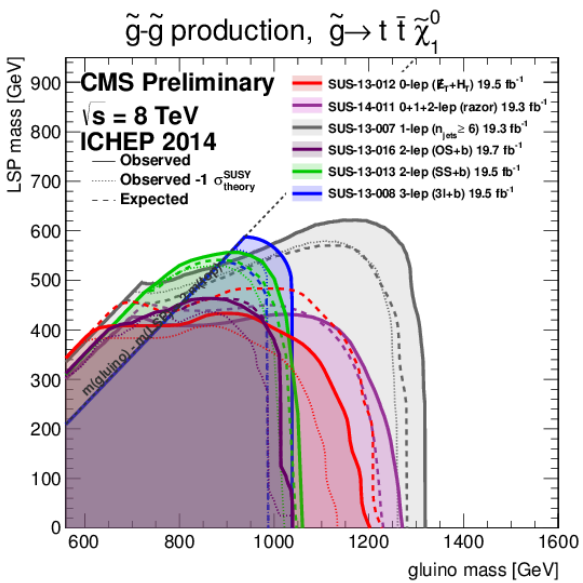
Charginos, neutralinos, s-leptons:
- Smaller cross-section
- Probe up to ~100-200 GeV

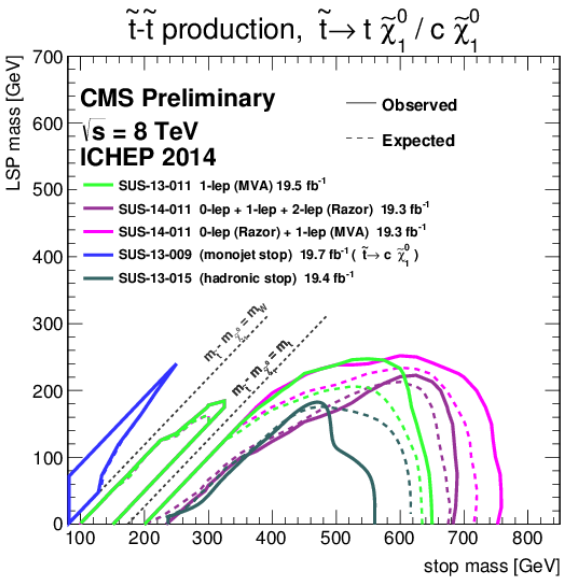
3rd generation s-quarks:
- Intermediate cross-section
- Probe up to ~500 GeV

SUSY Searches at 8 TeV

- CMS SUSY searches reached a great sensitivity at 8 TeV:
  - ❖ **EWK** SUSY excluded up to ~**700 GeV** (95% CL)
  - ❖ **Gluino** excluded up to ~**1.3 TeV** (95% CL)
  - ❖ **Stop** excluded up to ~**750 GeV** (95% CL)

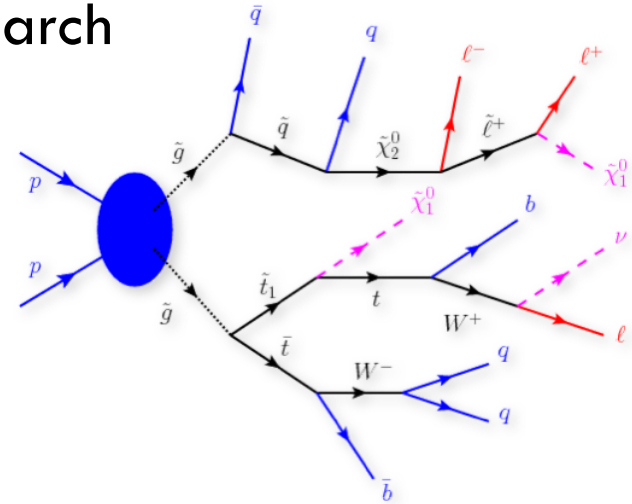






Today On Run I Analyses

- Will only highlight the latest public results from CMS analyses performed on Run I data, with target to various SUSY signatures:
  - ❖ An inclusive SUSY search: the M_{T2} search
  - ❖ 3rd generation s-quark search
  - ❖ Search for compressed SUSY
  - ❖ First search for VBF SUSY



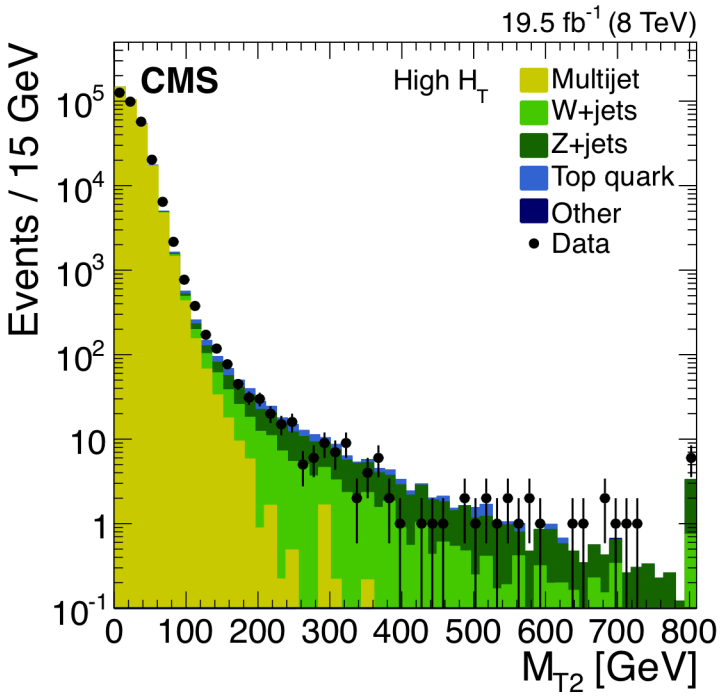
- For ALL CMS SUSY public results:
  - ❖ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

The M_{T2} Search (SUS-13-019)

CMS PAS SUS-13-019, JHEP 05 (2015) 078, arxiv:1502.04358

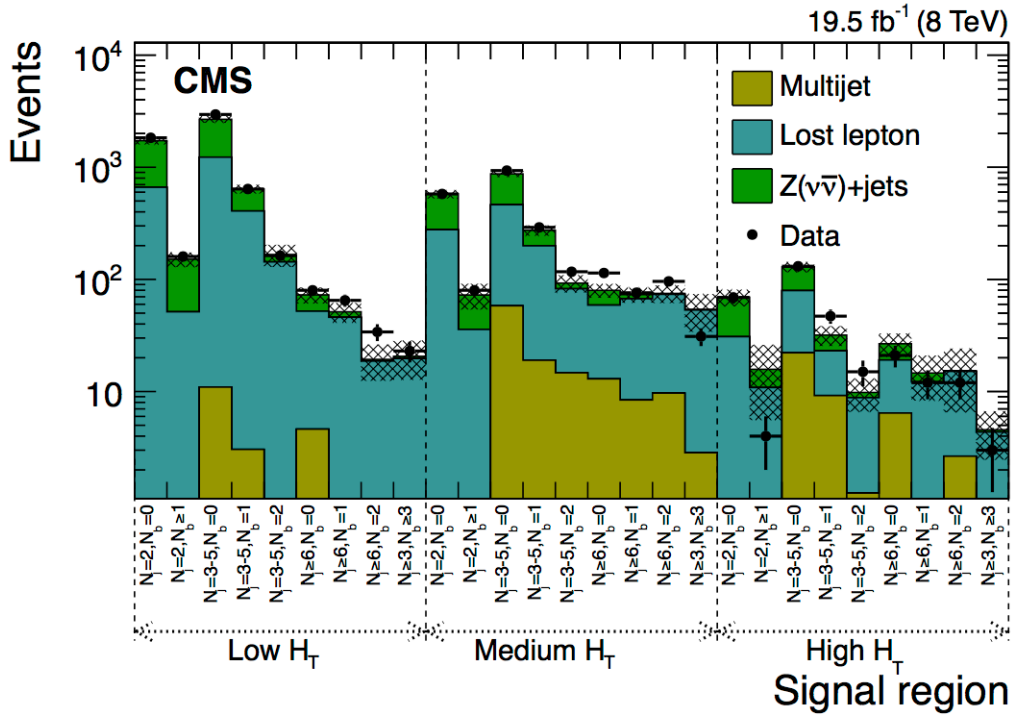
- An all hadronic analysis:
  - Veto leptons
  - At least two central jets
  - Large ME_T
  - Event categorization:
    - Jet/b-jet multiplicity
    - H_T ($= \sum_{jets} p_T$)
    - M_{T2}
  - Data-driven background prediction:
    - Z(νν)+jets → Irreducible BG
    - Top & W(lν)+jets → Lost Lepton
    - QCD multi-jet → Fake ME_T

- Use **M_{T2} as discovery variable**
  - SUSY = broad excess in M_{T2} tails



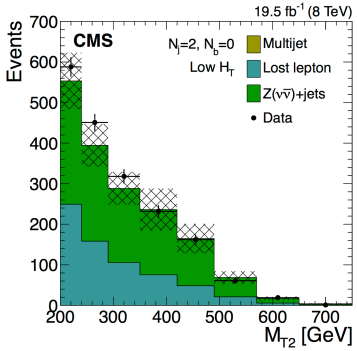
The M_{T2} Search – Results

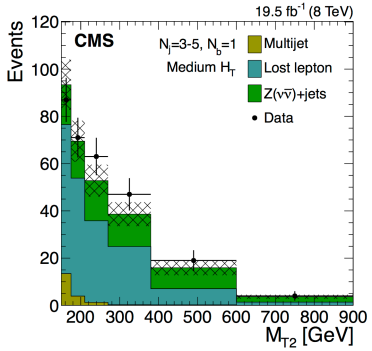
CMS PAS SUS-13-019, JHEP 05 (2015) 078, arxiv:1502.04358

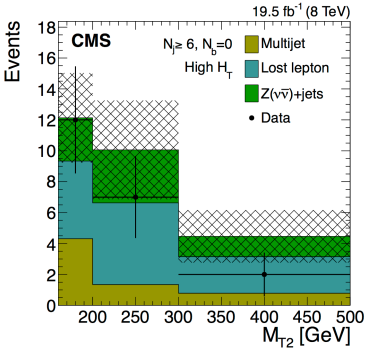


- Observation is consistent with SM background, in all the search regions

➢ Interpretation in terms of exclusion limits on SUSY production cross-section



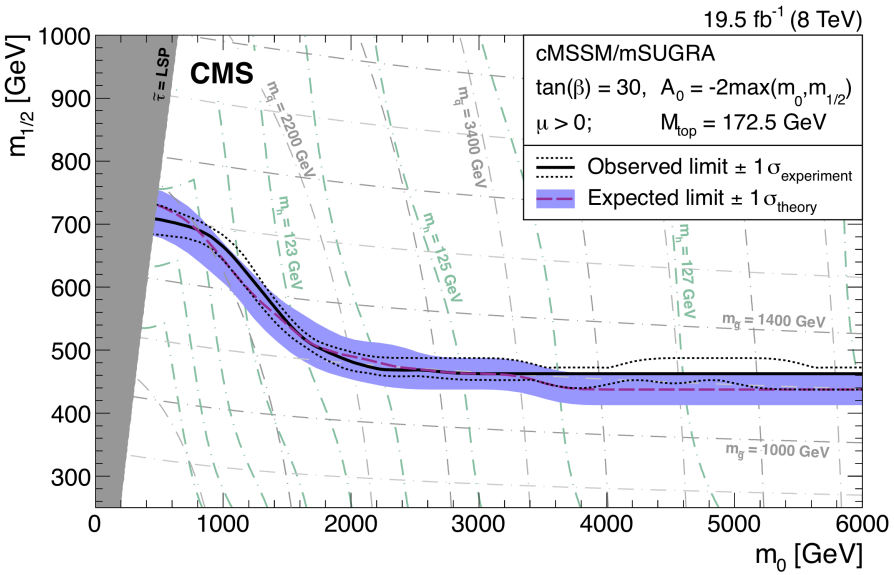


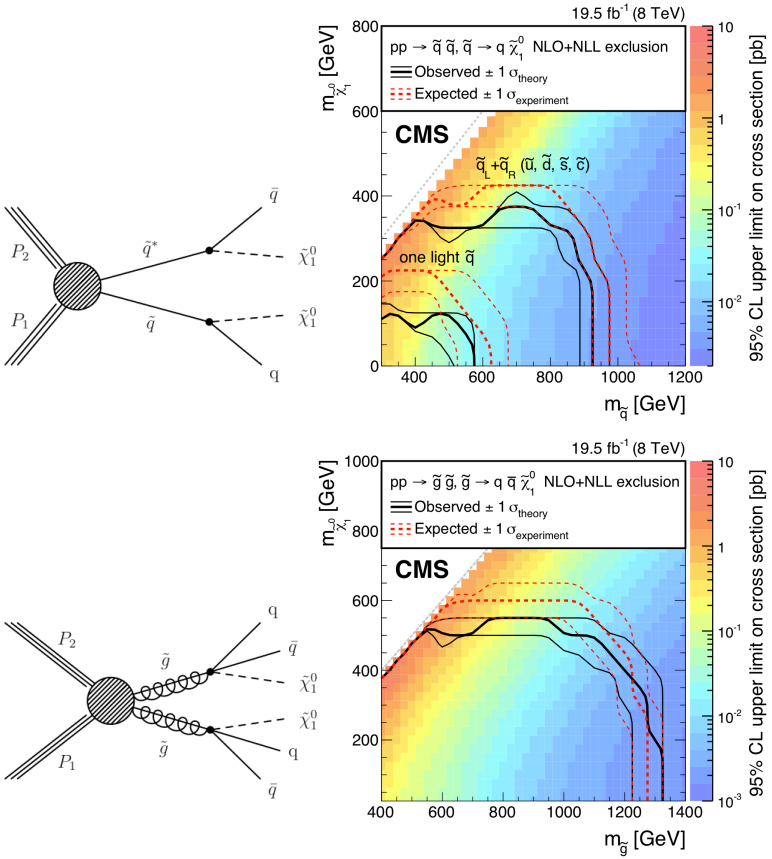


The M_{T2} Search – Interpretation

CMS PAS SUS-13-019, JHEP 05 (2015) 078, arxiv:1502.04358

- Interpretation of results in terms of exclusion limits (95% CL)
  - For a **full SUSY model:**
    - cMSSM/mSUGRA
  - For **simplified SUSY models:**
    - Only two examples here





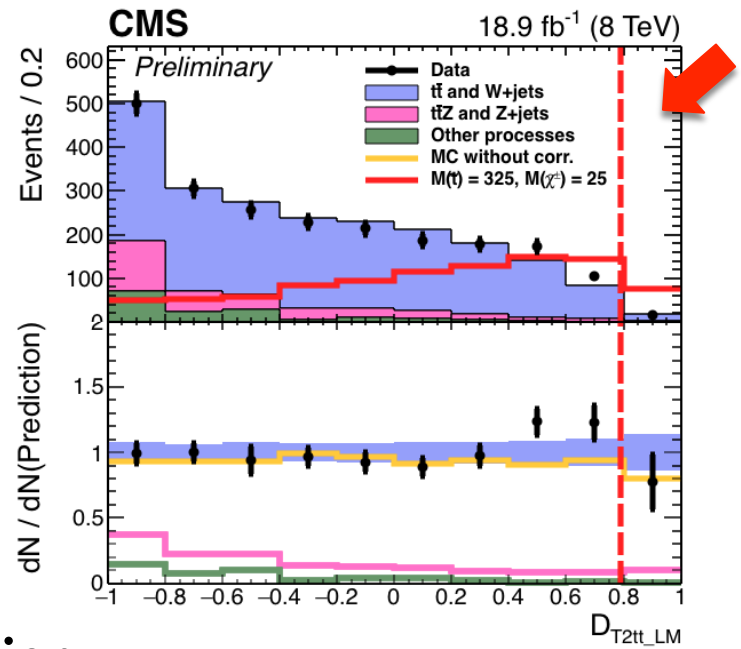
Hadronic Stop Search (SUS-13-023)

CMS PAS SUS-13-023

- An all hadronic analysis:
  - Veto leptons
  - At least two central jets
  - Large ME_T

  - Dedicated top reconstruction
    - CORRAL
    - Efficient for diverse boost
    - Variable jet size clustering

- **MVA** to define search region
  - ✓ Separate training for each signal

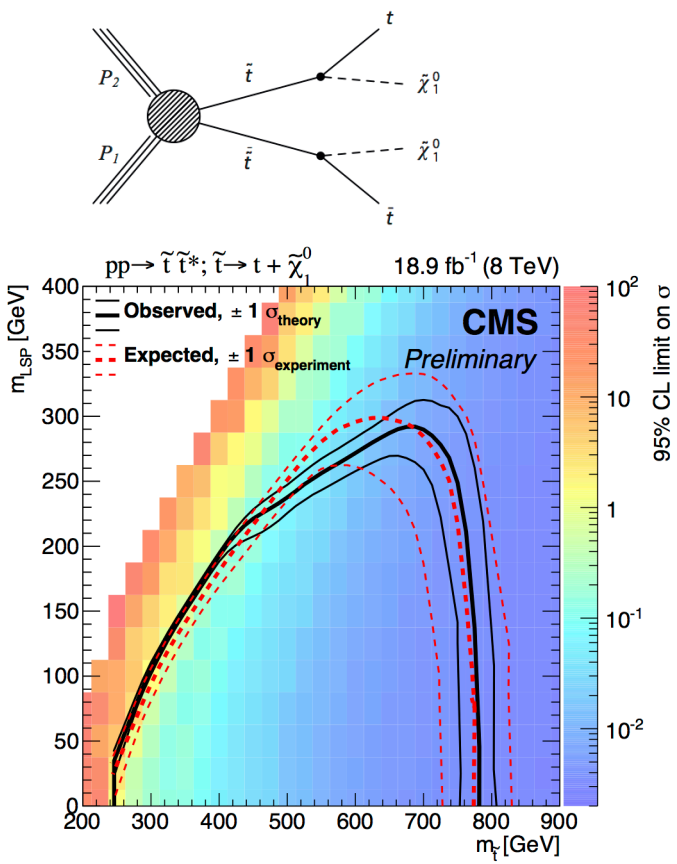


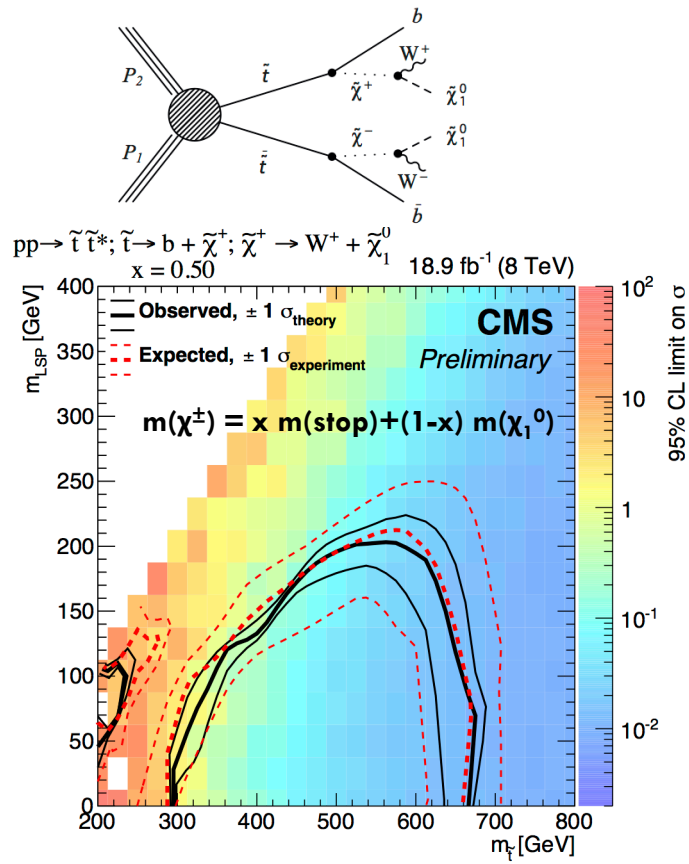
- Data-driven/MC background prediction:
  - ttZ(νν)+jets → Irreducible BG
  - tt, W(lν), Z(νν)+jets → Electroweak BG
  - QCD multi-jet → Fake ME_T

Hadronic Stop Search – Results

CMS PAS SUS-13-023

- Data found in agreement with SM background prediction
- ➢ Exclusion limits in **simplified SUSY models with stop**





Search for Compressed SUSY (SUS-14-021)

CMS PAS SUS-14-021

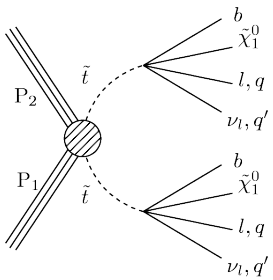
- Target: **stop pair production**
  - ❖ **m(stop) - m(LSP) < m(W)**
  - ❖ Four body decay

➢ One high p_T jet (from ISR)

➢ Large ME_T

➢ At least one μ

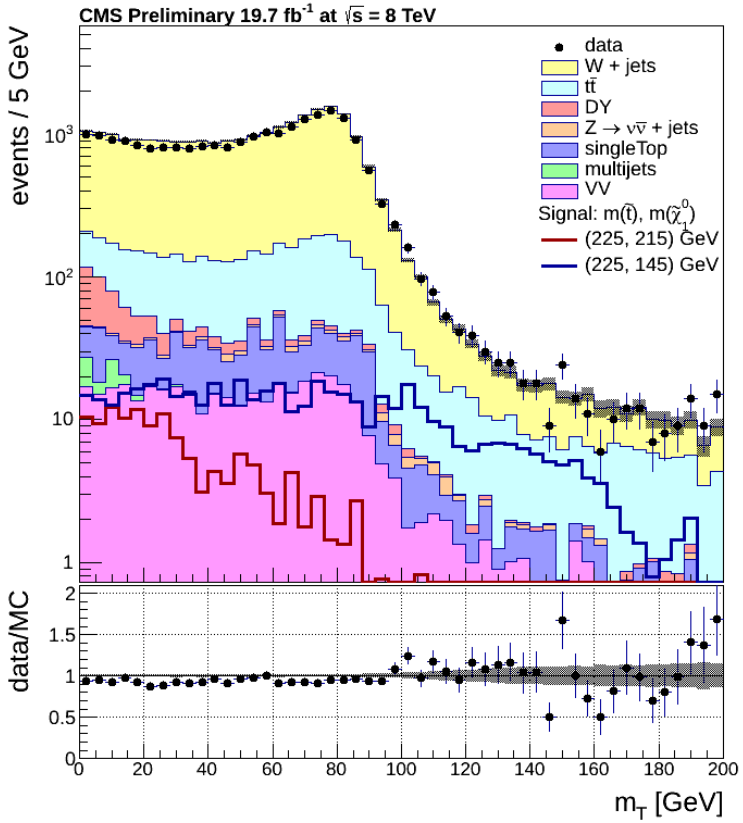
➢ Additional e/μ



➢ Search channels:
  - ❖ Single μ channel
  - ❖ Di-lepton channel

➢ Data-driven background prediction

➢ Use M_T as **discovery variable**
  - ✓ From leading μ + ME_T

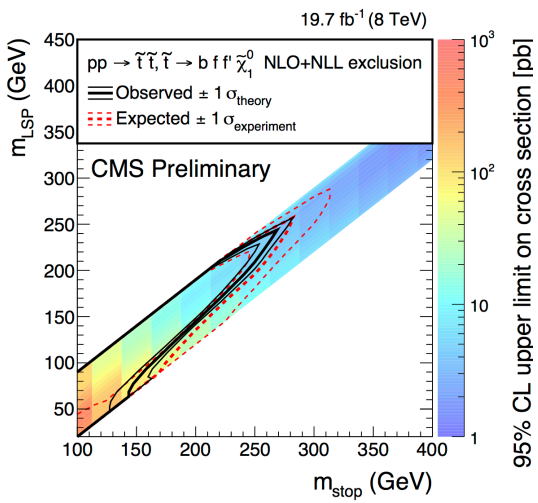


Search for Compressed SUSY – Results

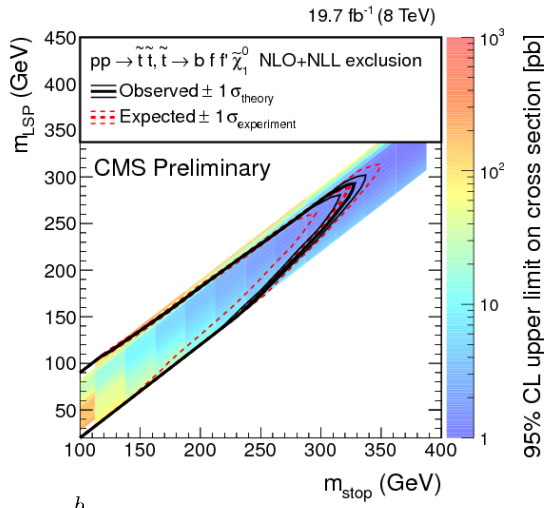
CMS PAS SUS-14-021

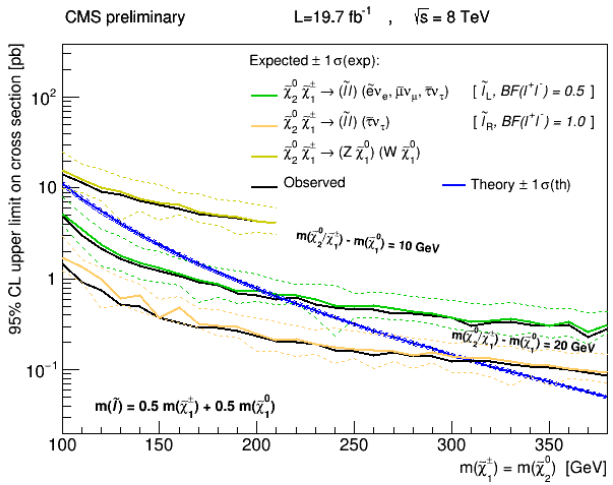
- Data found in agreement with SM background prediction
- ➢ Exclusion limits in **simplified SUSY models**

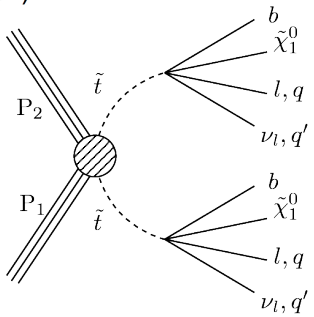
Single μ channel

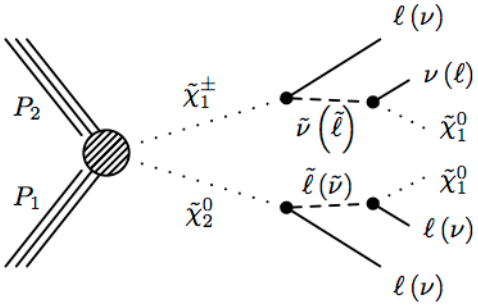


Di-lepton channel









Search for VBF SUSY with s-τ (SUS-14-005)

CMS PAS SUS-14-005

- Target: **VBF SUSY** with **s-τ**

➢ At least two isolated leptons
  - ❖ $\mu\mu$, $e\mu$, $\mu\tau_h$, $\tau_h\tau_h$
  - ❖ Same/Opposite Sign

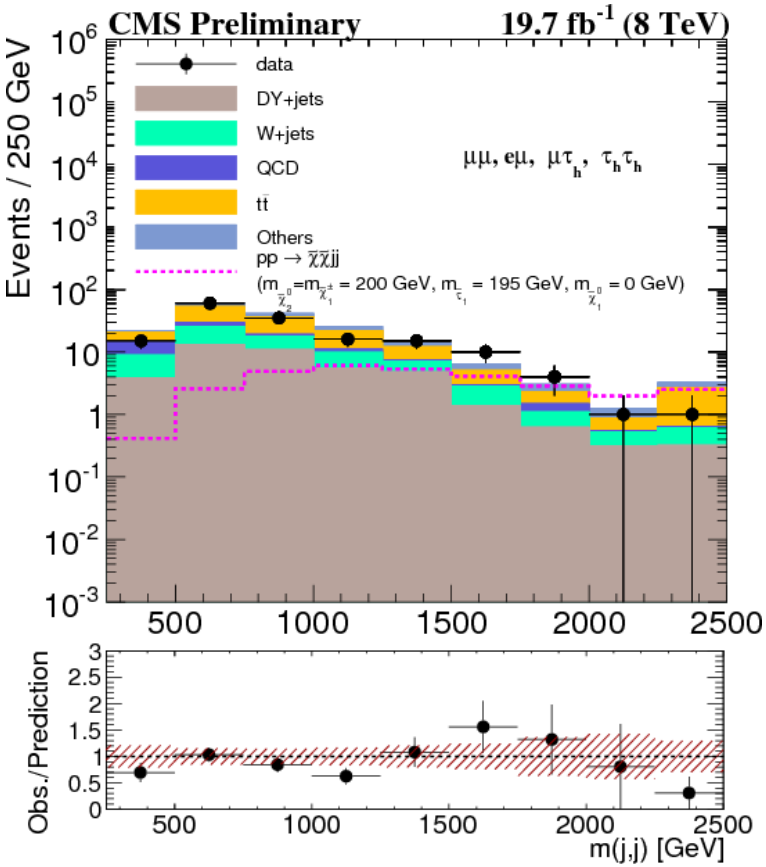
➢ At least two jets
  - ❖ VBF-like
  - ❖ $\Delta\eta > 4.2$ & $\eta_1 \times \eta_2 < 0$
  - ❖ Large M_{jj}

➢ Large ME_T

➢ Data-driven background prediction

➢ Use M_{jj} as **discovery variable**

➢ VBF SUSY = broad excess

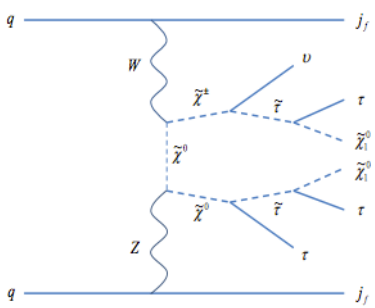


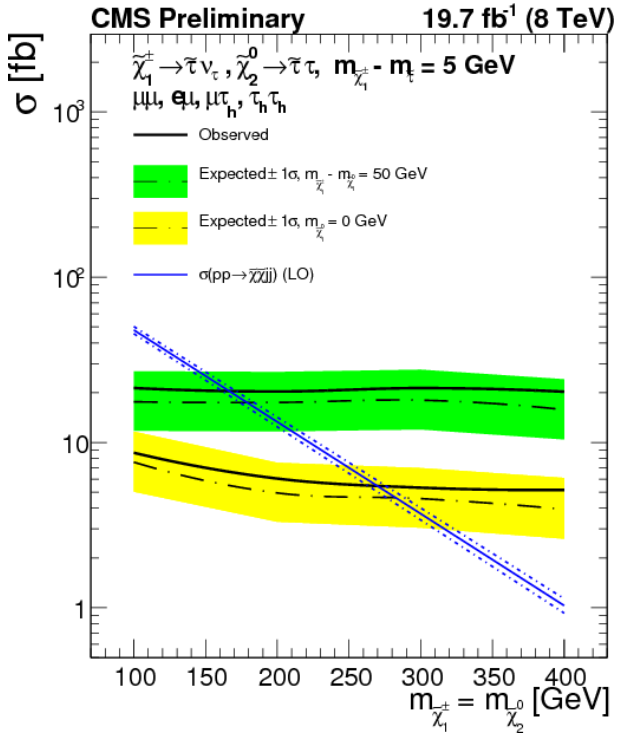
Search for VBF SUSY with s-τ – Results

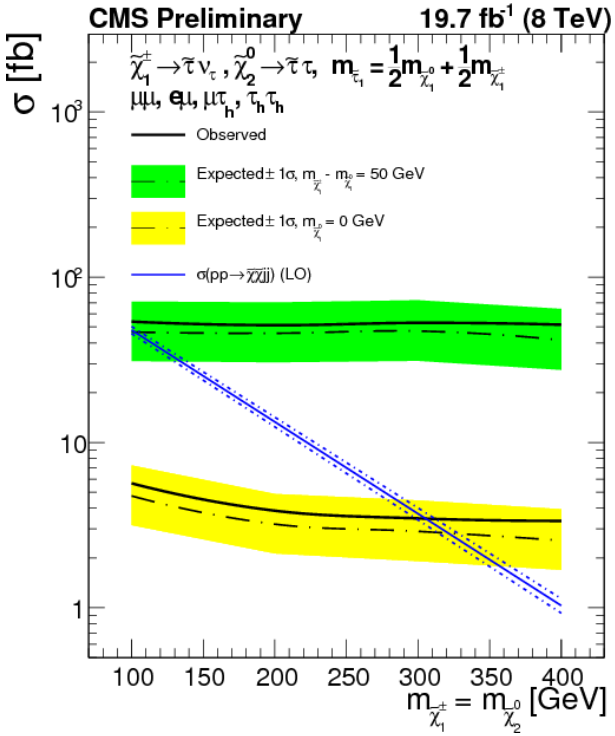
CMS PAS SUS-14-005

- Data found in agreement with SM background prediction
- ➢ Exclusion limits in **simplified SUSY models with** s-τ

VBF SUSY:

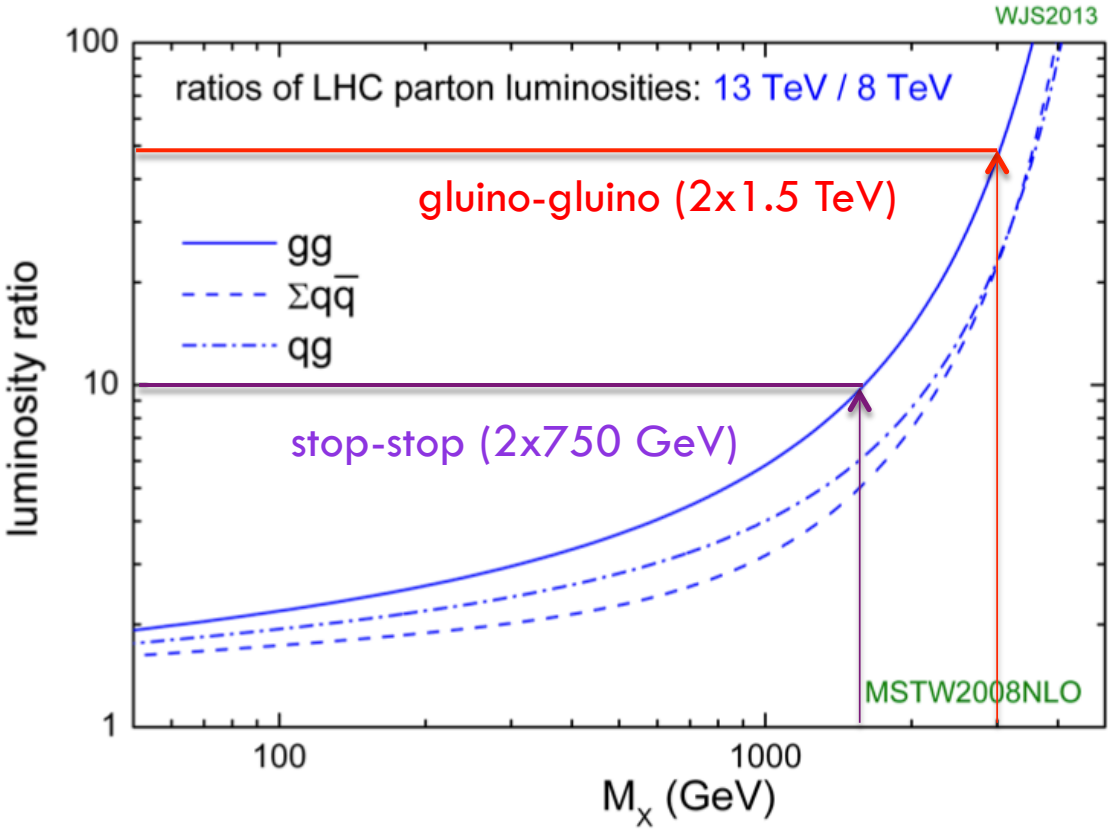






SUSY Searches at 13 TeV

- SUSY cross-section increase is much larger than center-of-mass energy ratio!
  - x50 for **1.5 TeV gluino-gluino**
  - x10 for **750 GeV stop-stop**



2015: a very important year

- By the end of 2015, expect to collect $\gtrsim$ 3 fb^{-1} at 13 TeV
- About **same** amount of **SM events** as in **whole Run I** dataset
  - ❖ Most of background estimates are data-driven
  - ❖ About **same statistical uncertainty** on SM background
- **SUSY** signal has much larger cross-section (**x 10-50**)

➢ Will push our sensitivity to the borders of **natural SUSY**

- ❖ **Gluino mass $\lesssim$ 1.5 TeV**
- ❖ **Stop mass $\lesssim$ 700 GeV**
- ❖ *Papucci, Ruderman, Weiler, arxiv:110.6926*

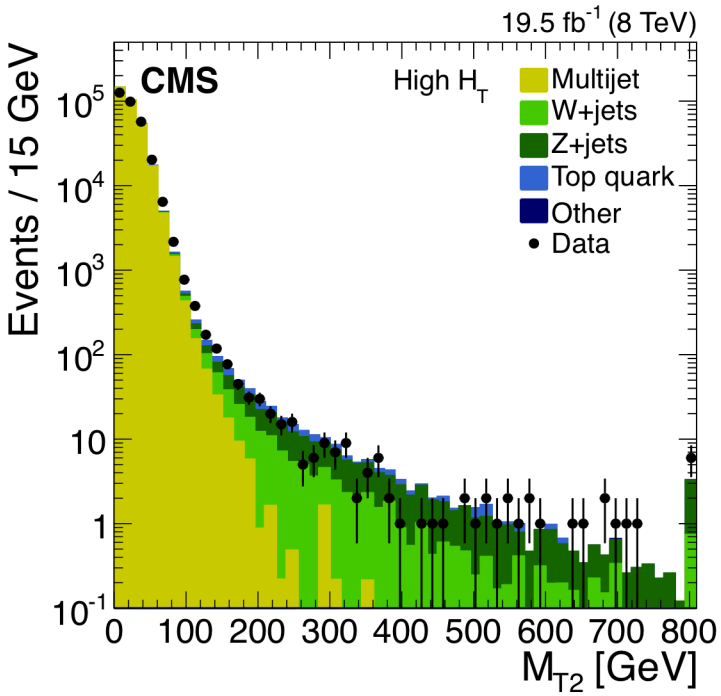
First Look at Data at 13 TeV (SUS-15-001)

- Using all available luminosity collected at 13 TeV (**42 pb^{-1}**)
- Still too few data in order to reach same sensitivity as in Run I
- Early data have been used to validate **SUSY key observables**
  - ❖ To validate **data-driven** background estimation techniques
- Will use **M_{T2} inclusive search** as a reference in the next slides
  - ❖ For (my) convenience, since already presented today
- **Validation has been performed by all SUSY Early Analyses**

The M_{T2} Search

CMS PAS SUS-13-019, JHEP 05 (2015) 078, arxiv:1502.04358

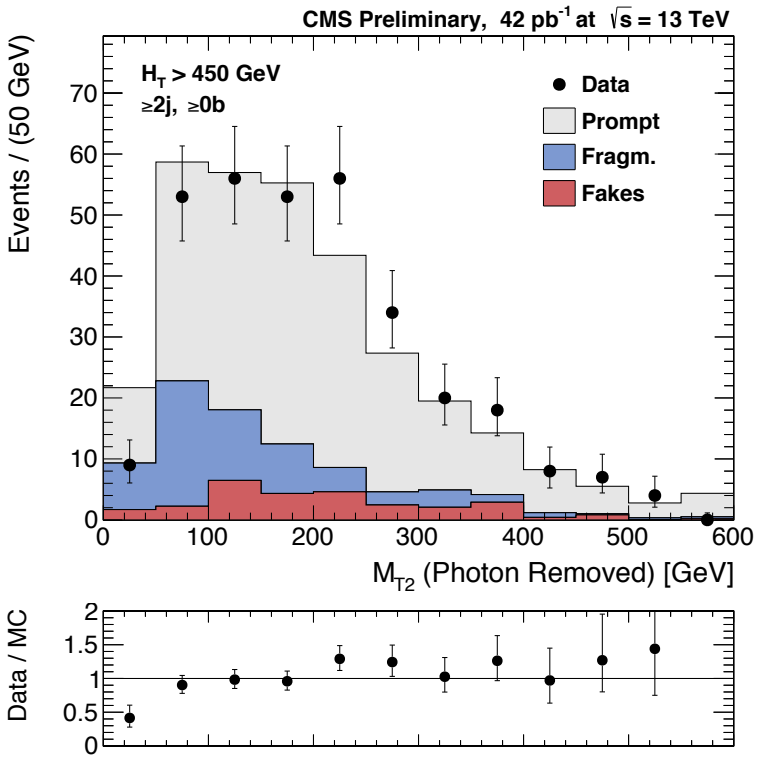
- An all hadronic analysis:
  - Veto leptons
  - At least two central jets
  - Large ME_T
  - Event categorization:
    - Jet/b-jet multiplicity
    - H_T (= $\sum_{jets} p_T$)
    - M_{T2}
- Use **M_{T2} as discovery variable**
  - SUSY = broad excess in M_{T2} tails

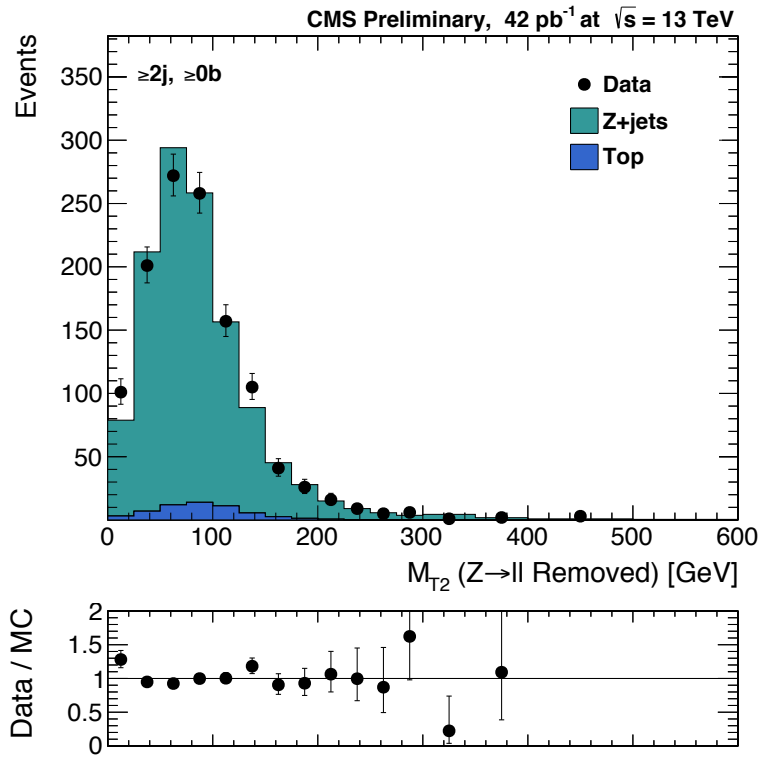


- Data-driven background prediction:
  - Z(νν)+jets → Irreducible BG
  - Top & W(lν)+jets → Lost Lepton
  - QCD multi-jet → Fake ME_T

The M_{T2} Search at 13 TeV: Z/γ

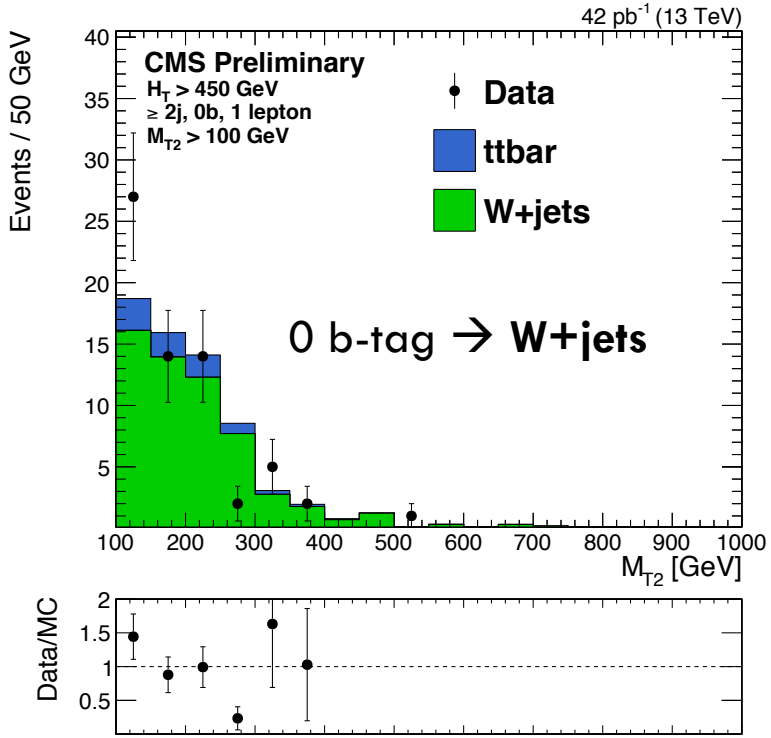
- Z(νν)+jets events, with genuine ME_T → Irreducible background
- ➢ **Estimated from a control sample of γ+jets events**
- ➢ Reweight by expected ratio R(Z/γ) in MC
- ➢ **Ratio is validated on data in Z(ll)+jets control region**

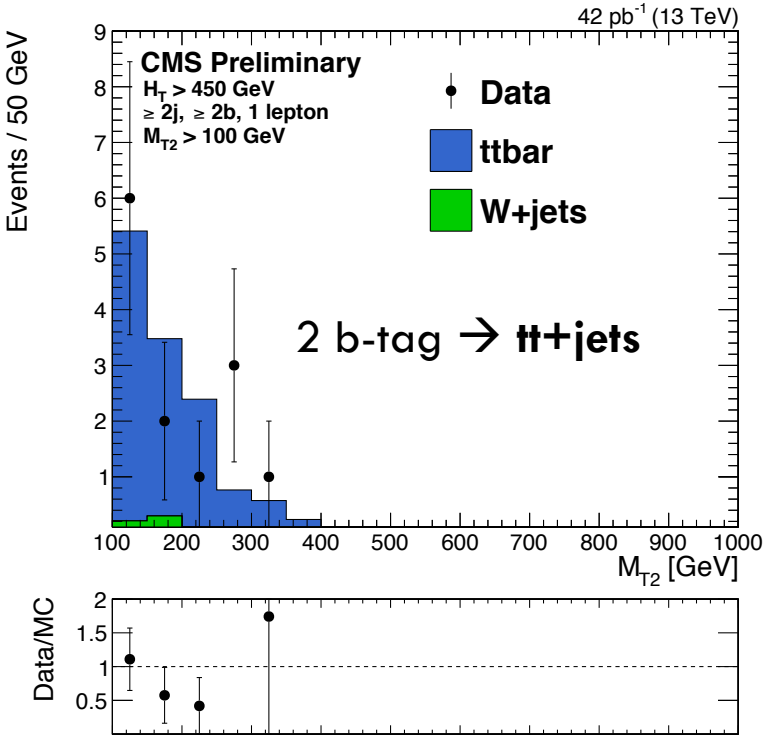




The M_{T2} Search at 13 TeV: lost lepton

- Top and W(lν)+jets events, with genuine ME_T from ν
  - ➢ Largely rejected by lepton veto
  - ➢ Entering search regions if lepton is 'lost'
  - ➢ Estimate from a control sample of one-lepton events





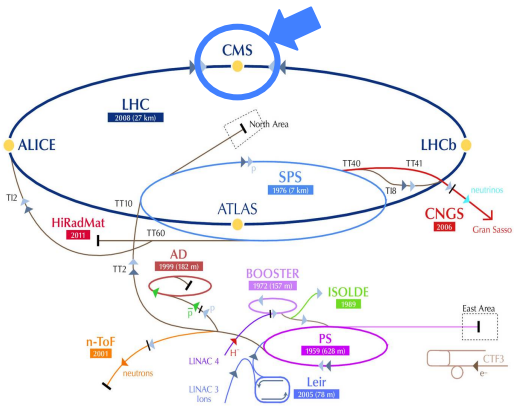
Summary

- A selection of SUSY searches performed at 8 TeV using data collected by the CMS experiment has been presented
- Validation of SUSY key observables at 13 TeV has been presented, using M_{T2} search as reference analysis
  - ❖ Data and MC are found in good agreement
- Run II could be the key to disclose SUSY at the LHC…
- … Let's cross our fingers!

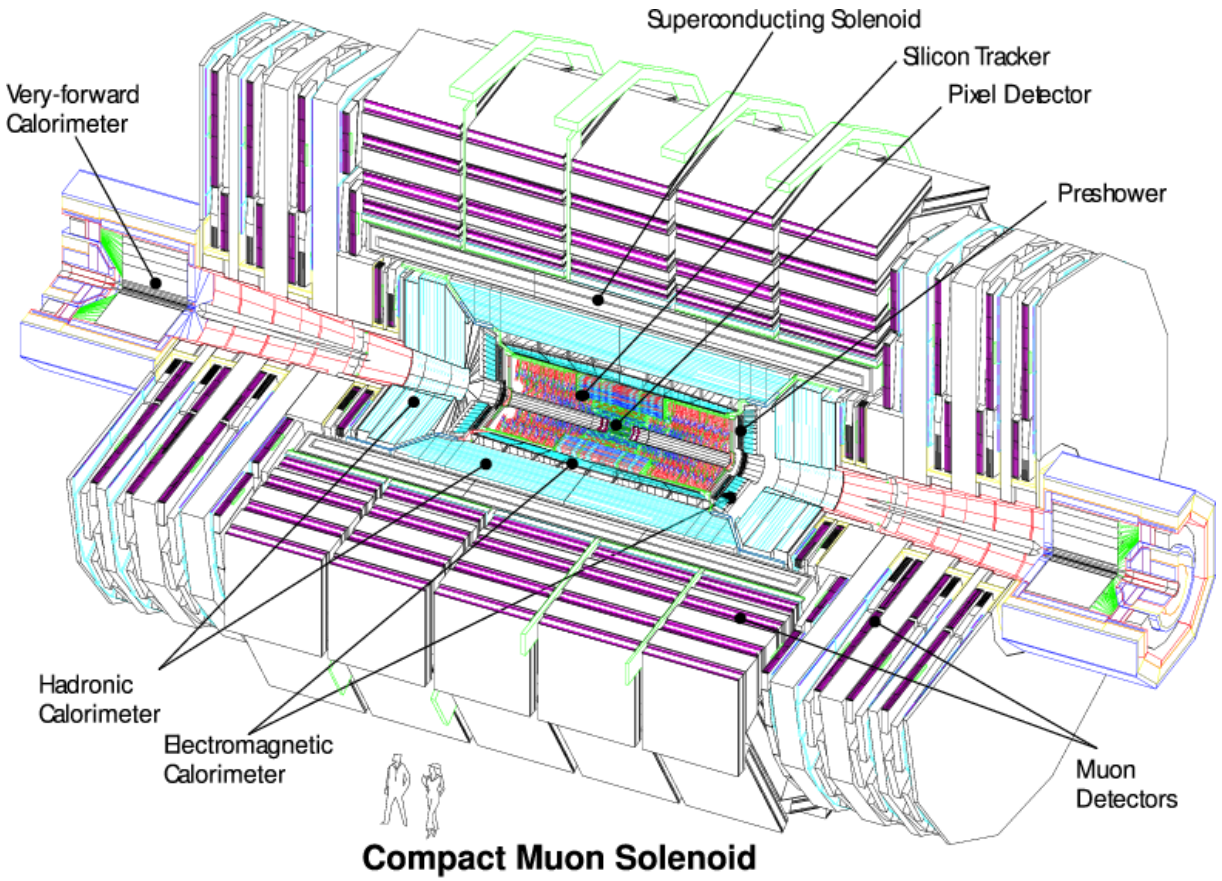
<u>The end.</u>

Backup

The CMS Experiment at the LHC



CERN Accelerator Complex

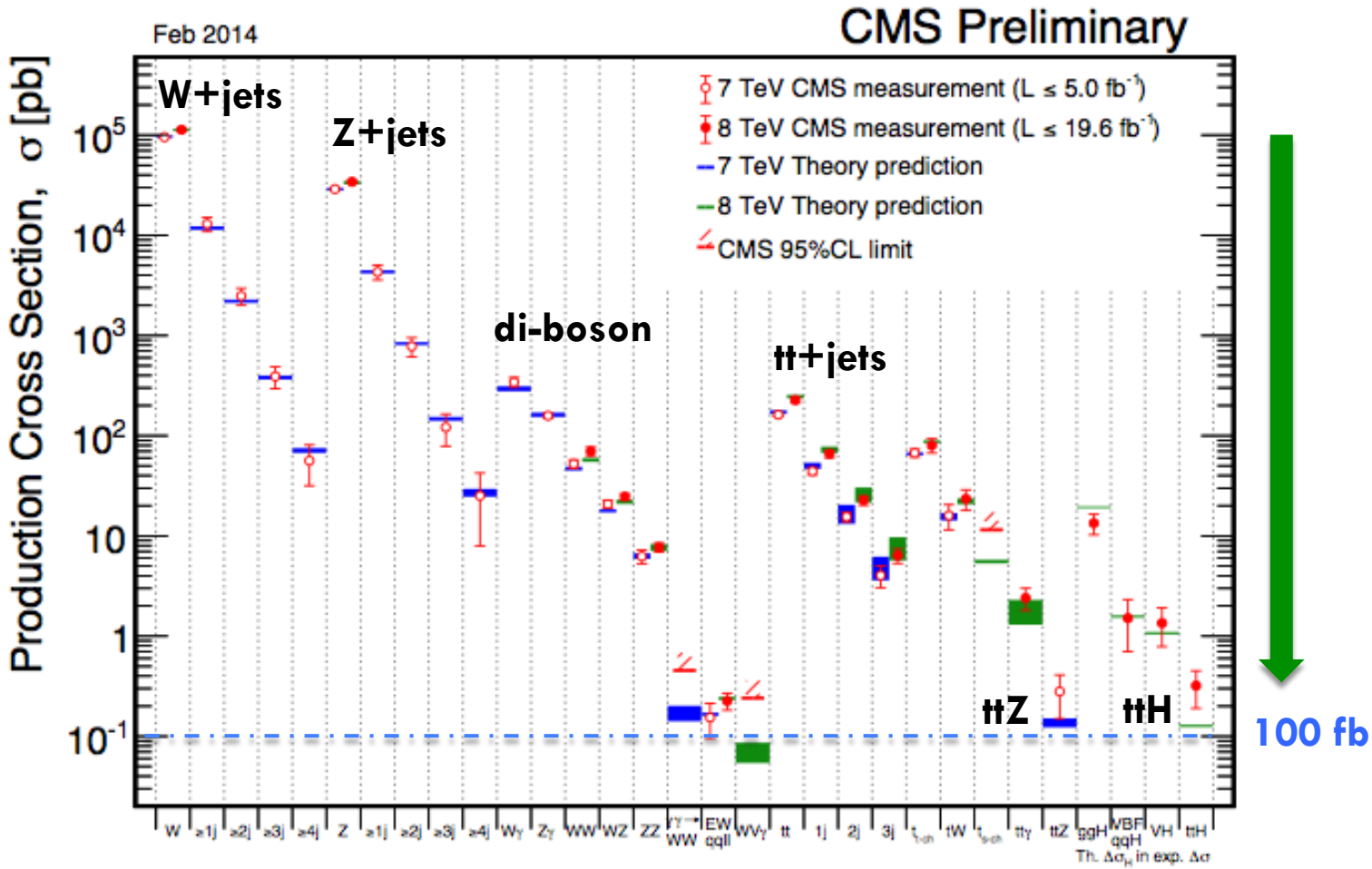


Overview

- Introduction
  - Why SUSY?
  - How to look for SUSY
- SUSY Searches at 8 TeV
  - Highlights from searches with Run I data
  - Selection of latest results
- SUSY Searches at 13 TeV
  - First look at Run II data
  - What's next?

The Standard Model at LHC Run I

- Undeniable success of Standard Model

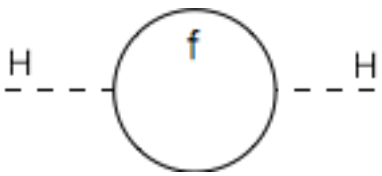


Why SUSY?

- The **fine-tuning** problem:
  - $(m_H)^2 = (m_{H,0})^2 + (\Delta m_H)^2$

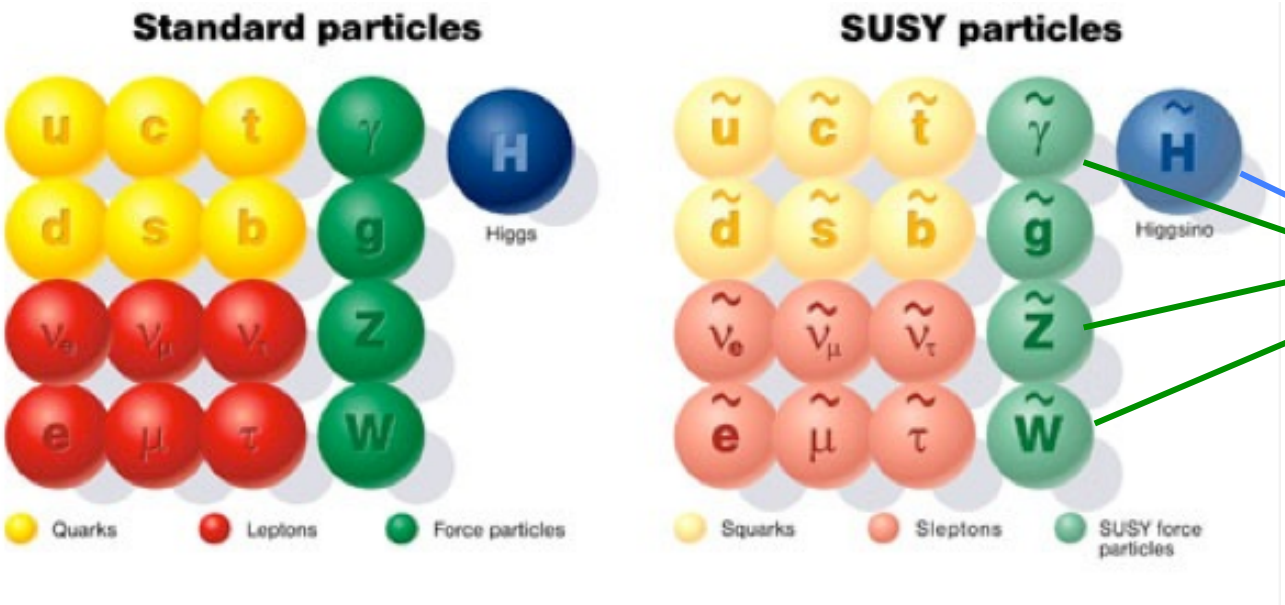
    $(m_H)^2 \rightarrow$ 125 GeV

    $(\Delta m_H)^2 \propto \sum_f -g_f \Lambda_{UV}$ → $\Lambda_{UV} \leq \Lambda_{Planck}$



- **Solution:**
  - For every fermion, add scalar with same mass/coupling
    - Additional diagram that cancels Δm_H
    - Double degrees of freedom of theory

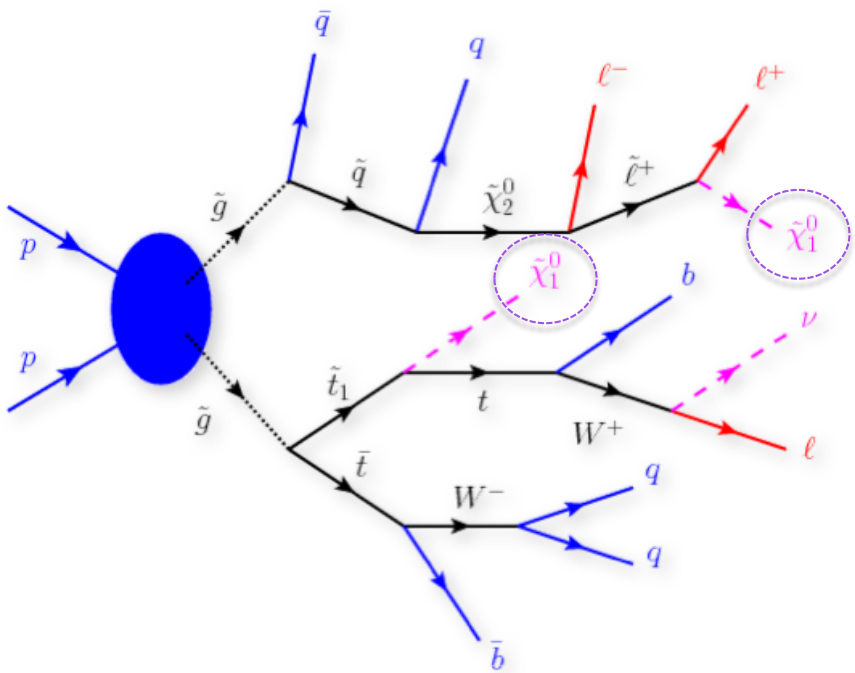
How SUSY would look like?



- Neutralinos: χ^0_i (i = 1, …, 4)
- Charginos: $\chi^\pm_i$ (i = 1, 2)

- New fundamental symmetry
  - ➢ Q |fermion⟩ = |boson⟩ & Q |boson⟩ = |fermion⟩
  - ✓ Stability of mass hierarchy problem
  - ✓ Facilitation of Great Unification Theory
  - ✓ Candidate for Dark Matter

SUSY (typical) topology



HOW TO LOOK for SUSY:

- If R-parity is conserved:
- ✓ S-particles come in pairs
- ✓ **LSP** is undetected → **ME_T**

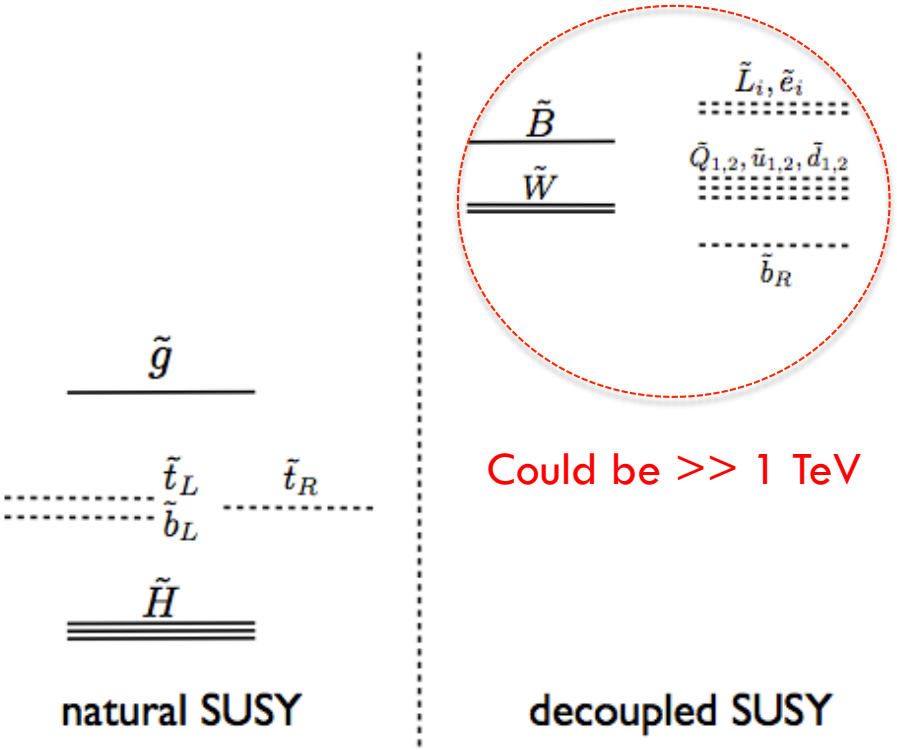
➢ Look for events with:

- ✓ Large **ME_T**
- ✓ Large **hadronic activity**
- ✓ Low energy **leptons**

Natural SUSY

Natural SUSY:

- Higgsino $\lesssim$ 300 GeV
- Stop $\lesssim$ 700 GeV
- Gluino $\lesssim$ 1.5 TeV



Papucci, Ruderman, Weiler, arxiv:110.6926

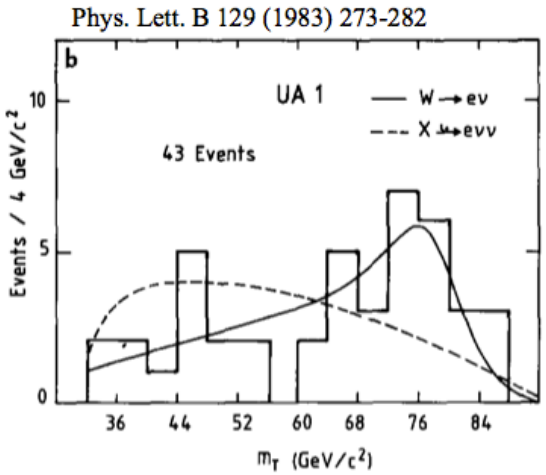
Transverse mass – M_T

- Projection of the mass M on the transverse plan

$$M_T^2=(E_{T,1}+E_{T,2})^2-(\vec{p}_{T,1}+\vec{p}_{T,2})^2$$

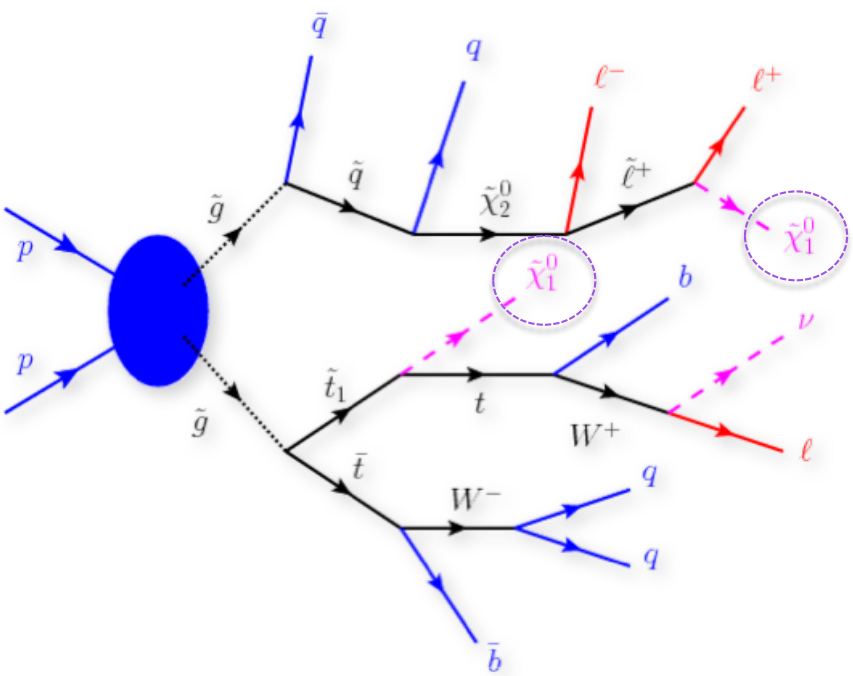
➢ $M_T \leq M$

⇒ **End-point** at parent mass



Discovery of W boson at UA1 (1983)

What is M_{T2}?



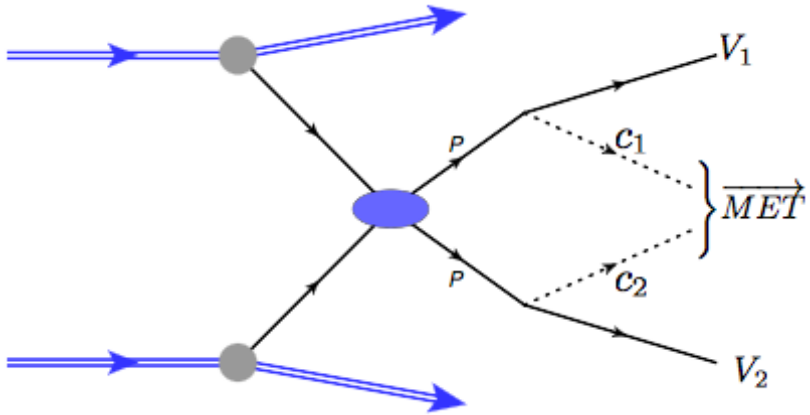
- <u>The **M_{T2}** recipe:</u>

❖ Two decay chains

❖ One LSP in each decay

The M_{T2} Recipe

arXiv: hep-ph/9906349, hep-ph/0907.2713



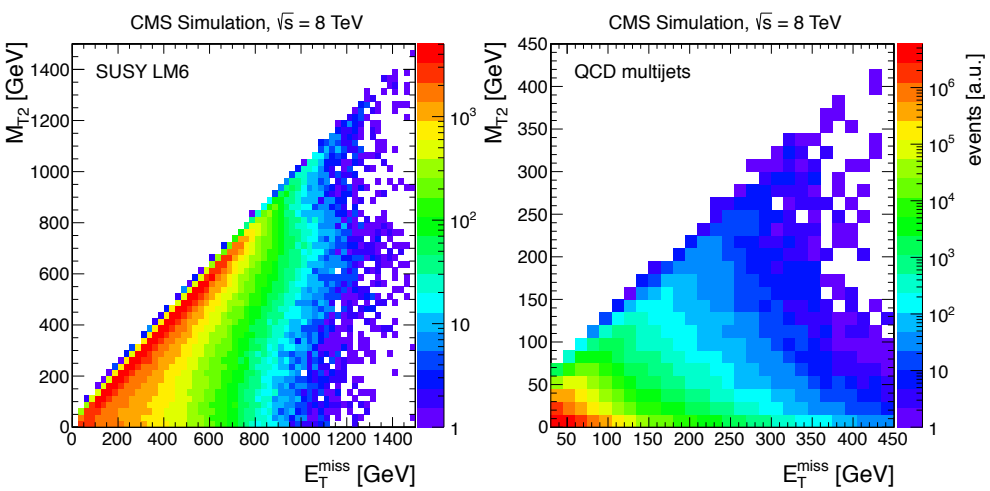
- <u>The **M_{T2}** recipe:</u>

❖ Two decay chains

❖ One LSP in each decay

➢ **Can generalize definition of transverse mass M_T:**

$$M_{T2}(m_c) = \min_{\vec{p}_T^{c(1)}+\vec{p}_T^{c(2)}=\vec{p}_T^{miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$



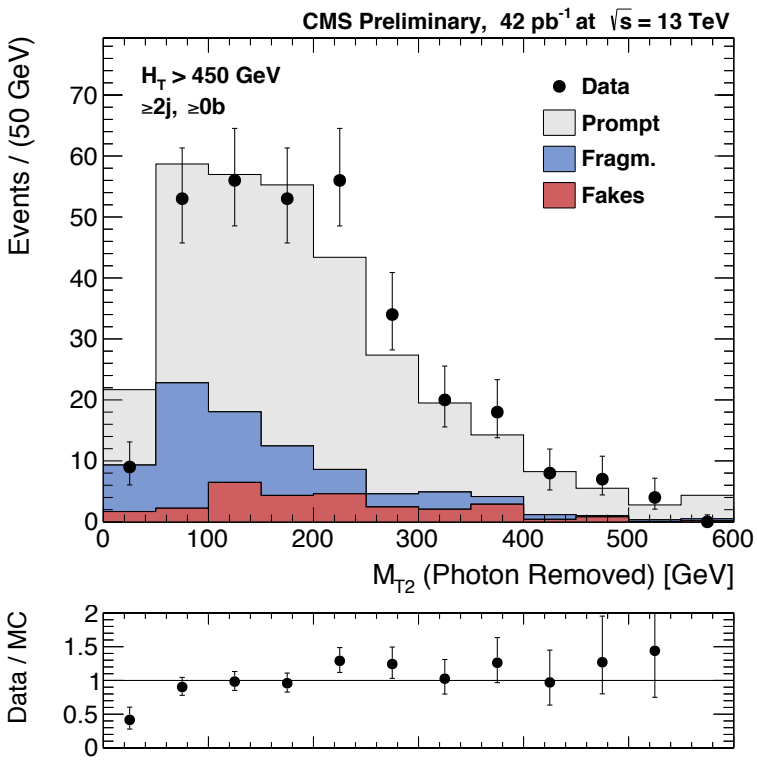
❖ **SUSY**-like: $M_{T2} \lesssim ME_T$

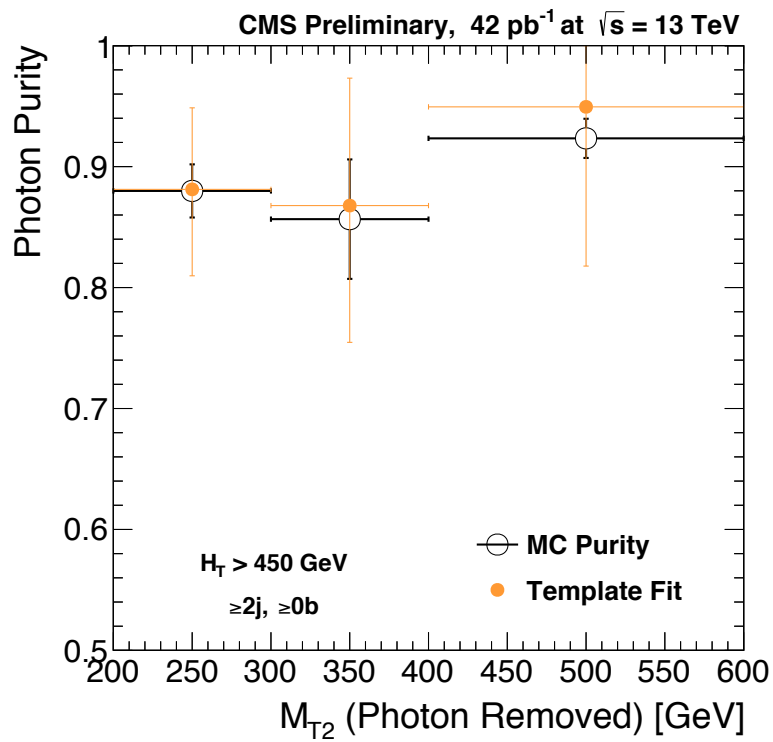
❖ **QCD**-like: $M_{T2} \rightarrow 0$

The M_{T2} Search at 13 TeV: invisible Z

CMS PAS SUS-15-001

- Z(νν)+jets events, with genuine ME_T → Irreducible background
- ➢ Estimated from a control sample of **γ+jets events**
- ➢ Reweight by expected ratio R(Z/γ) in MC

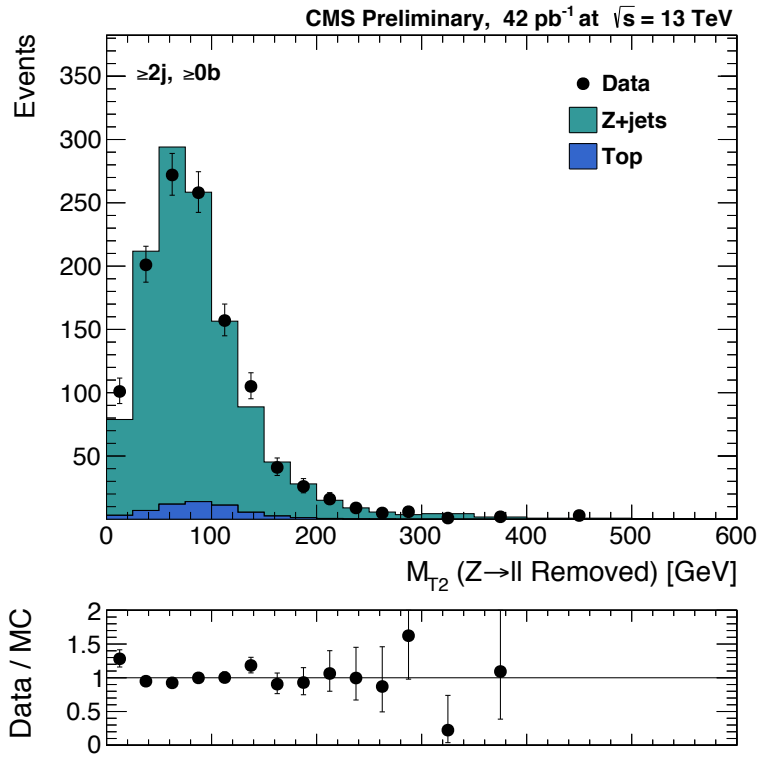


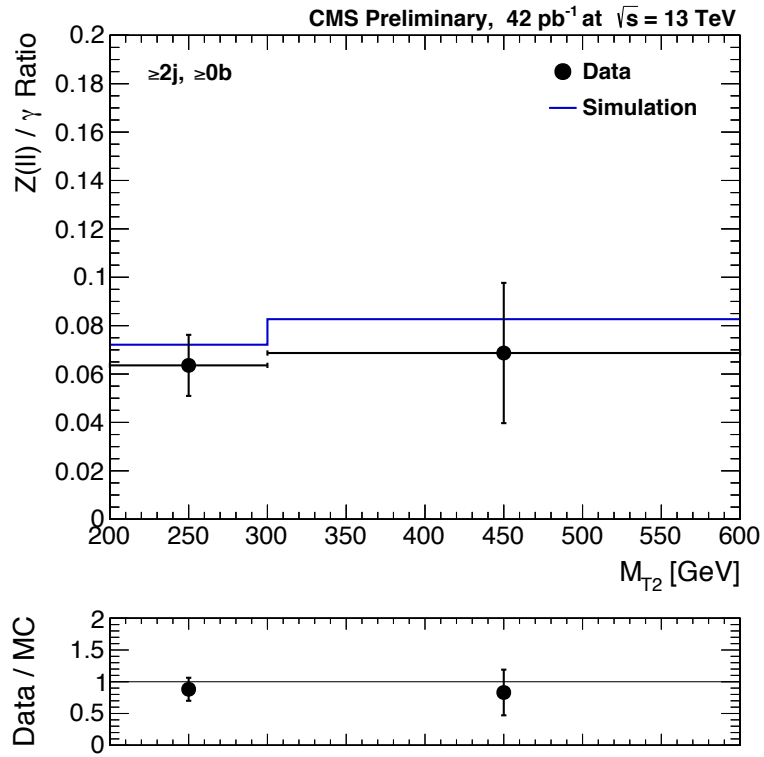


The M_{T2} Search at 13 TeV: Z/γ

CMS PAS SUS-15-001

- Z(νν)+jets events, with genuine ME_T → Irreducible background
- ➢ Estimated from a control sample of γ+jets events
- ➢ Reweight by expected ratio R(Z/γ) in MC
- ➢ **Ratio is validated on data in Z(ll)+jets control region**





CMS Magnet

CMS PAS SUS-15-001

- The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic in providing liquid Helium
- Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system
- Currently the magnet can be operated, but the continuous up-time is till limited by the performance of the cryogenic system, requiring more frequent maintenance than usual
- A comprehensive program to re-establish its nominal performance is underway
- The recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods
- A consolidation and repair program for the cryogenic system is being organized for the next technical stop at the end of the year
- The Collaboration appreciated the priority being given to this issue by CERN's Technology Department, which is responsible for the maintenance and operation of the CMS magnet external cryogenic system