

Searching for SUSY with CMS

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This talk is intended as a lecture that gives an overview of why and how we do SUSY searches at CMS along with a few examples of current searches. A more thorough description of the current searches will be given in 5 other talks.

Outline:

- **Supersymmetry and LHC:** definition, motivation, production, models and final states
- **Elements of a SUSY search:** signal characterization, trigger, objects, background estimation, statistical analysis, systematics
- **SUSY searches at CMS:** a few inclusive searches and summary of current interpretation

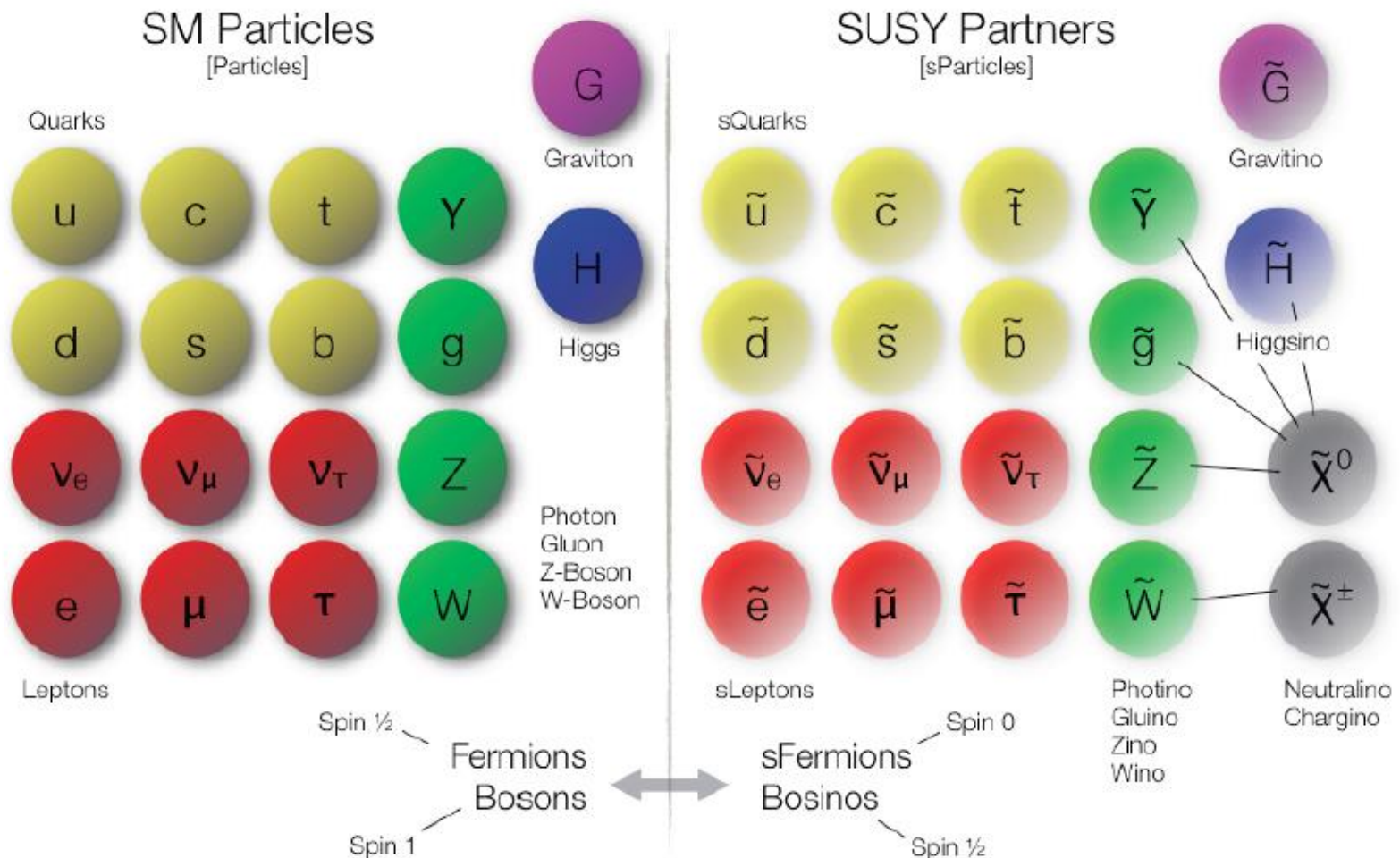


SUSY and the LHC



What is SuperSYmetry?

Supersymmetry (SUSY) is a **symmetry** between **fermions and bosons**, between **matter and force**. It predicts the existence of **new particles**. For every SM particle, there is a **superpartner** with $\frac{1}{2}$ spin difference.

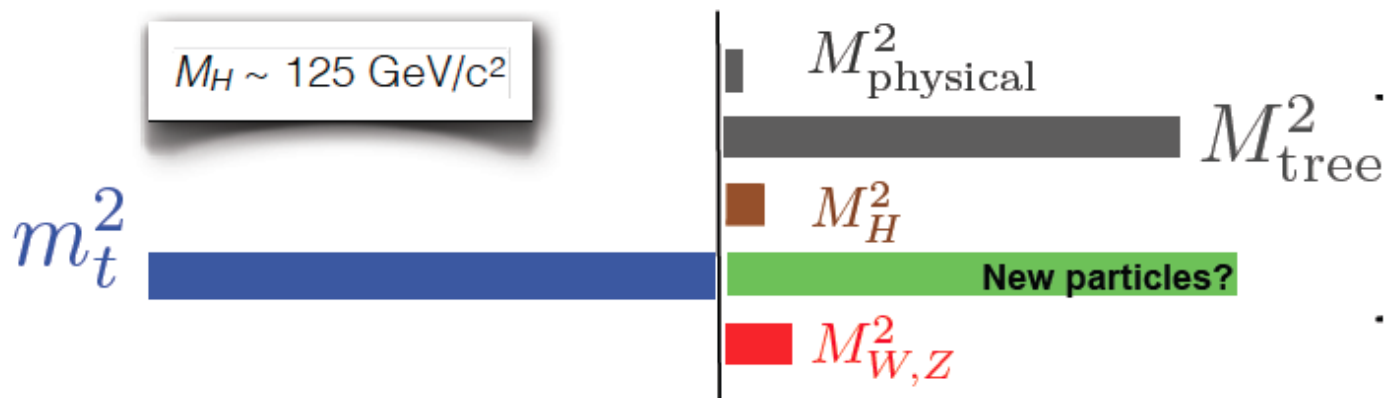




Why supersymmetry? - I

- Standard Model is an **effective theory**. We would like to understand physics in a more **generic framework** which completes the missing pieces.
- SM does not incorporate gravity.
- Fine tuning** in the **corrections to the Higgs mass** can be resolved by **adding new particles with opposite spin**. SUSY contributions to Higgs mass cancel SM contributions.

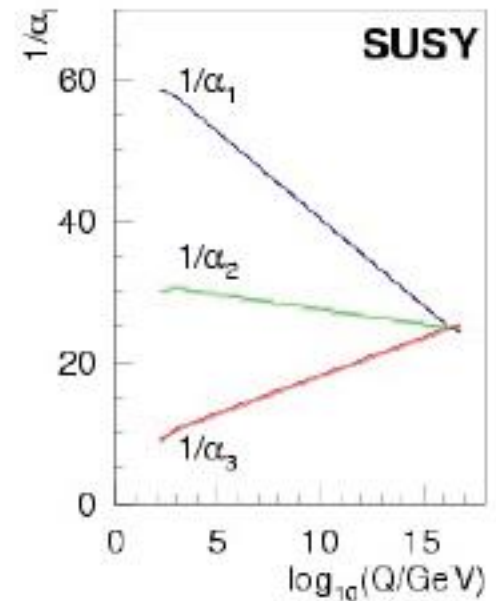
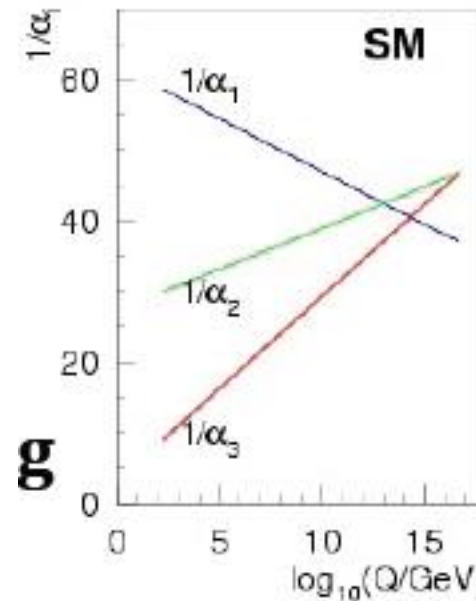
$$M_H^2 = M_{\text{tree}}^2 + \left(\text{Higgs self-energy loop} \right) + \left(\text{top quark loop} \right) + \left(\text{W/Z boson loop} \right) + \left(\text{BSM} \right)$$





Why supersymmetry? - II

- SUSY unifies gauge couplings at the GUT scale, because contributions from new particles modify running of the gauge couplings.



- SUSY offers a dark matter candidate. Lightest supersymmetric particle (LSP) can be heavy, neutral and stable.



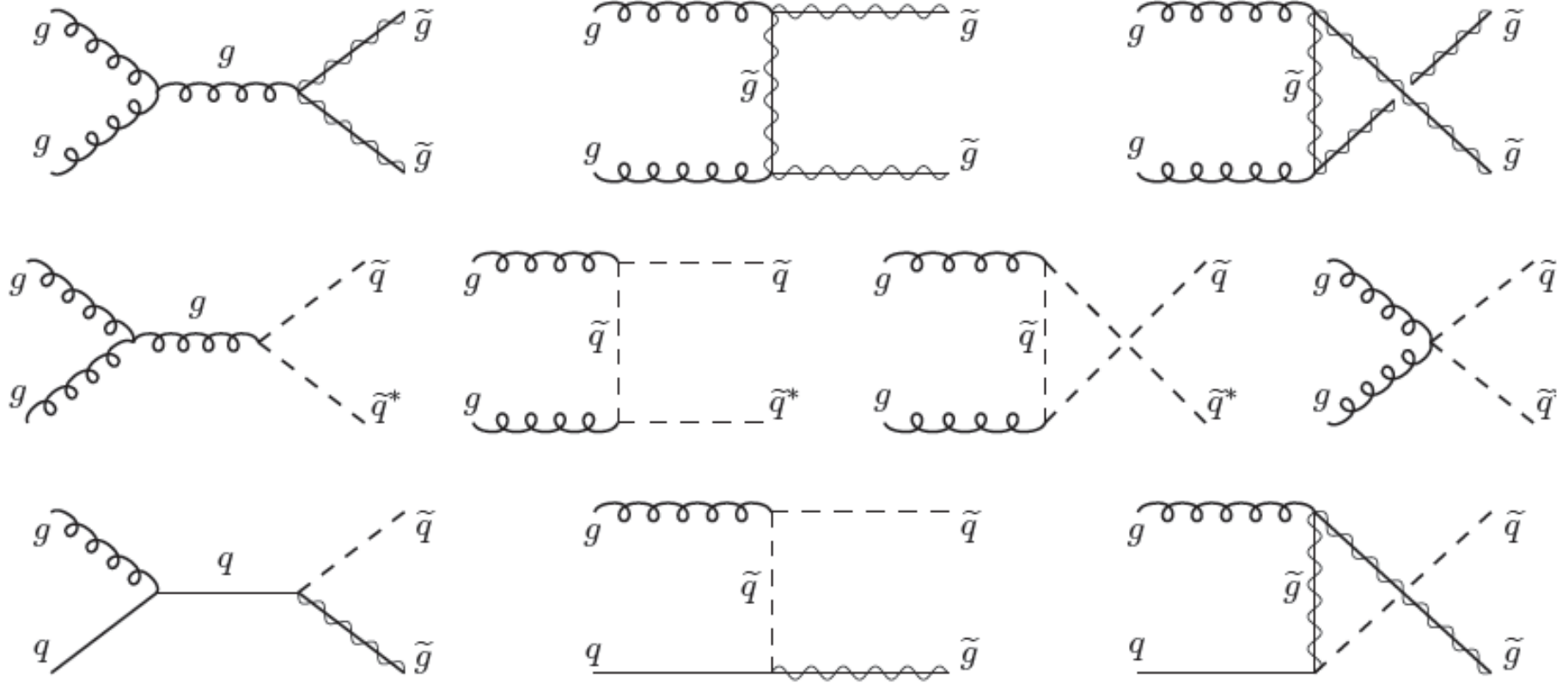


Sparticle production @ LHC - I

Gluino and **squark** production via **gluon-gluon** and **quark-gluon** processes.

Gluon-gluon processes are **dominant** at LHC energies.

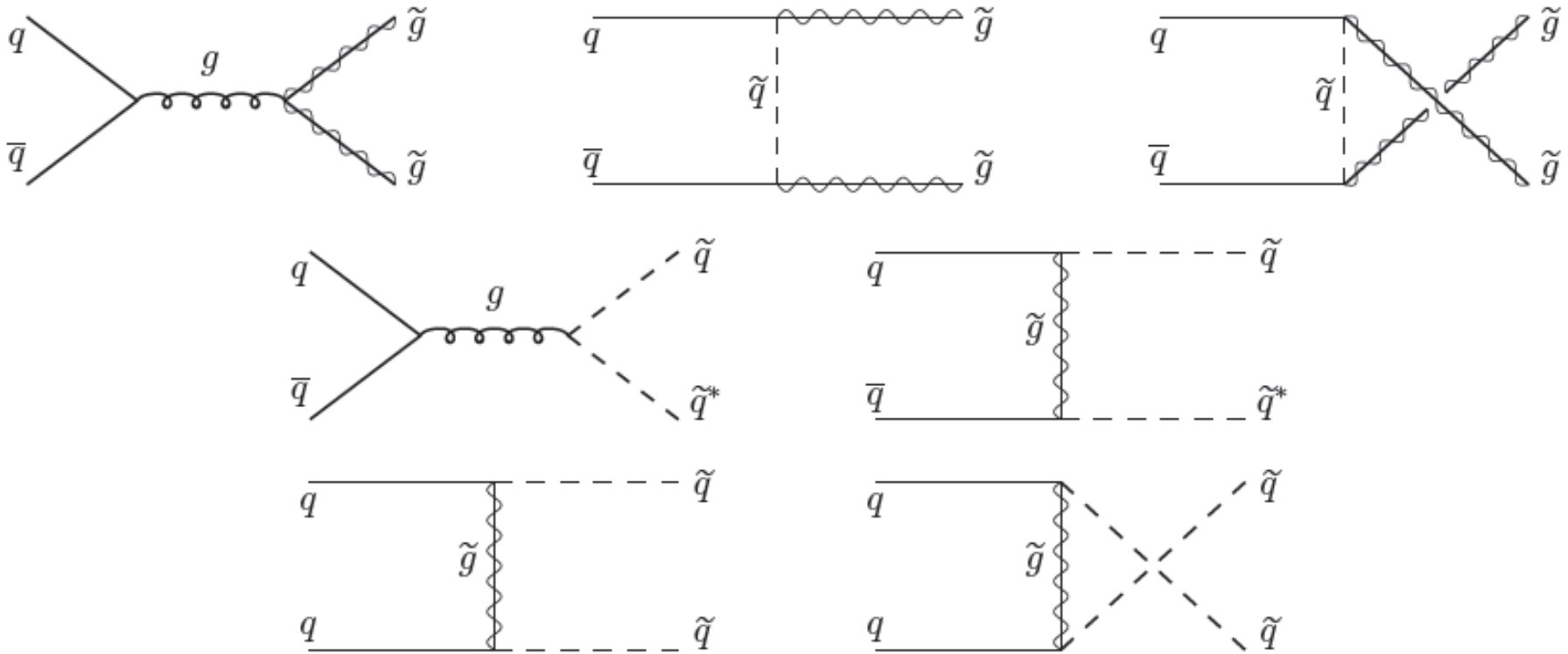
Squark and **gluino** production is dominant for light **gluinos/squarks** (<TeV).





Sparticle production @ LHC - II

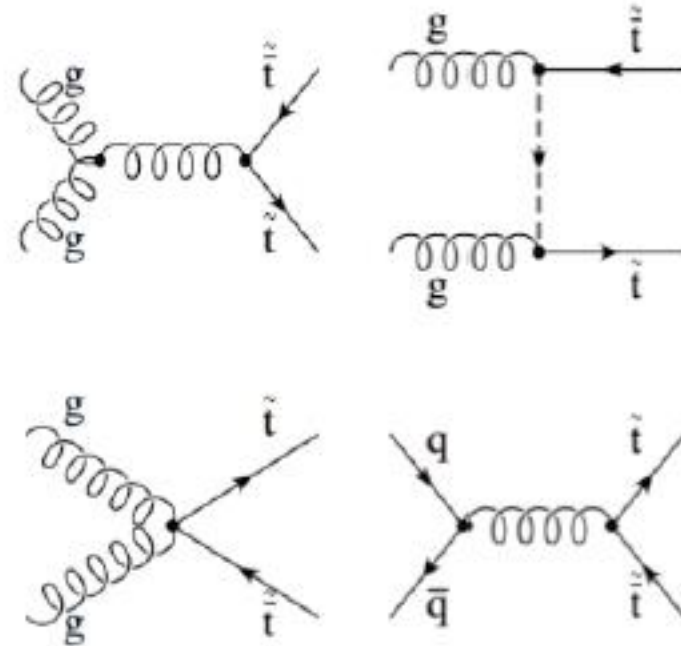
Gluino and squark production via quark-antiquark annihilation and quark-quark scattering at the LHC.



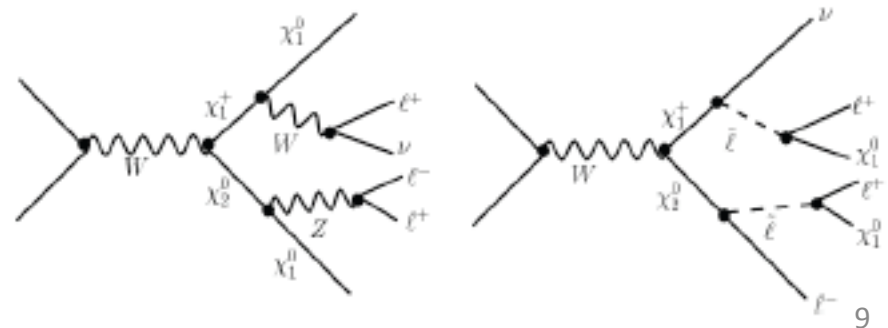


Sparticle production @ LHC - III

Stop-stop production at the LHC.
 Stop1-stop1 or stop2-stop2
 production dominate over stop1-
 stop2 processes since gluon-
 gluon processes are dominant.



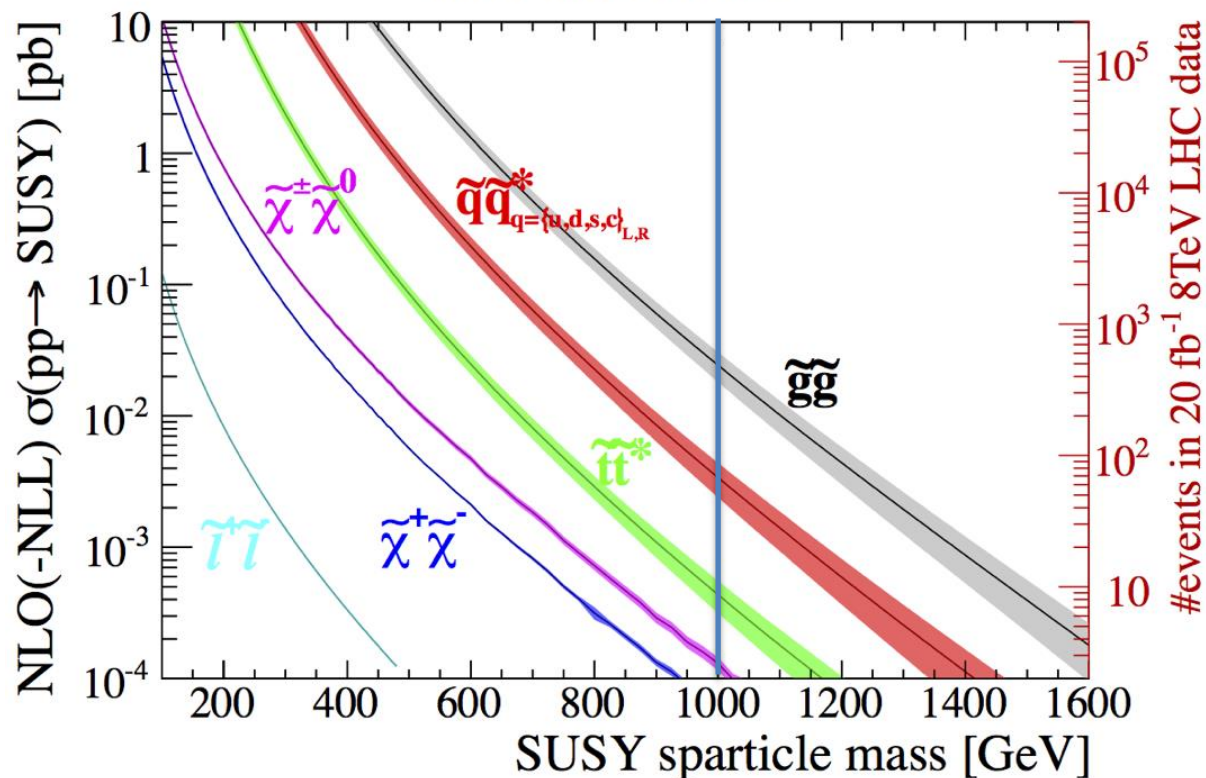
Example chargino-neutralino
 production at LHC from quarks.





Sparticle production cross sections @ LHC

LPCC SUSY σ WG



<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections>

arXiv:1206.2892

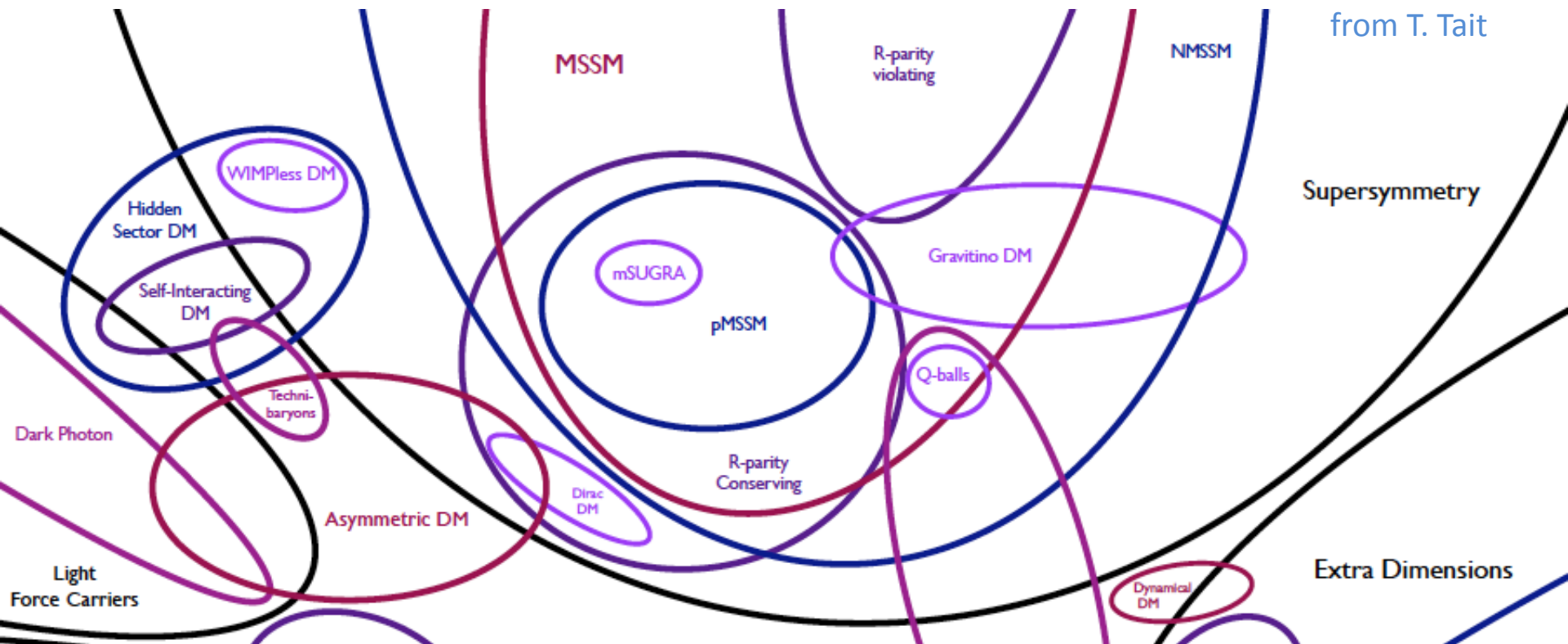
- Gluinos, 1st and 2nd generation squarks (when they are degenerate) – high cross sections.
- 3rd generation squarks (stops, sbottoms) – moderate cross sections.
- Charginos, neutralinos, sleptons – small cross sections, but feasible.



Which supersymmetry?

Supersymmetry is a **wide framework** with **diverse realizations** → **diverse final states at the LHC**.

In its most generic form, it is defined by **>100 free parameters**.



Sparticles are heavier than particles. SUSY is a **broken symmetry**.
We **don't know the nature of SUSY breaking** yet – but there are many models.
SUSY breaking models define SUSY phenomenology.



Which supersymmetry?

Split SUSY

(long-living gluinos+
compressed ewikinos)

...

???



Natural SUSY

(squarks, sbottom, higgsinos)

RPV models

(no MET)

...

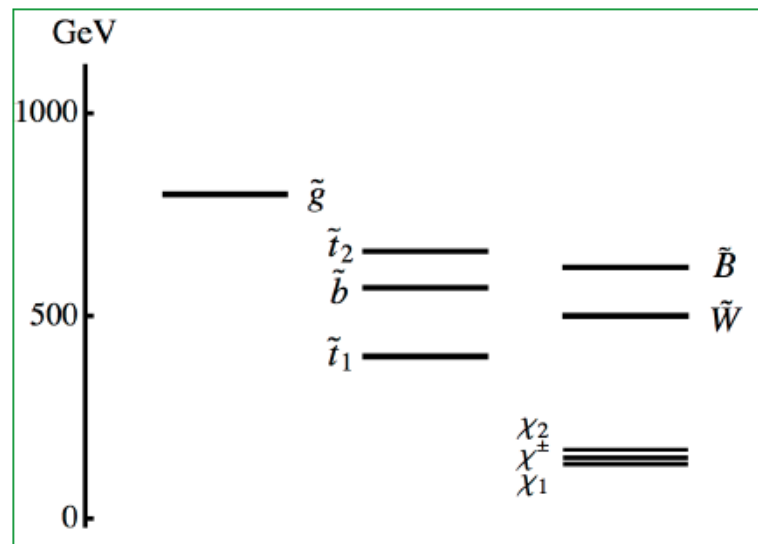
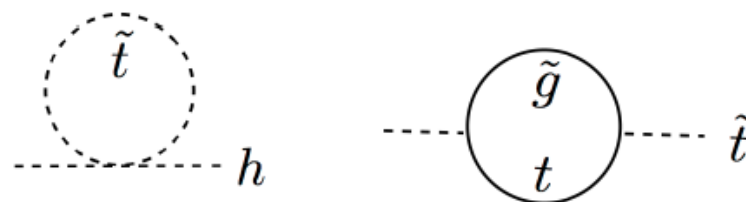
SUSY proposes **diverse realizations**. We need to **search every direction**.
But it is nice to have some **well-motivated principles** to guide our searches.



Natural SUSY?

Hierarchy problem: Higgs mass is 125GeV despite the divergent corrections from the top loop. The divergencies can be cancelled by introducing SUSY particles – but this imposes requirements to the SUSY mass spectrum.

- Leading contribution to the Higgs mass comes from **Higgsinos** $\rightarrow \leq$ few hundred GeV
- **Stops** contribute to Higgs mass via 1-loop corrections $\rightarrow \leq$ few hundred GeV
- **Sbottom left** is tied to stop left $\rightarrow \leq$ few hundred GeV.
- **Gluinos** contribute to Higgs mass via 2-loop corrections $\rightarrow \leq$ few TeV
- Rest of the spectrum can be **decoupled / heavy**.



R.Barbieri & D.Pappadopulo JHEP 0910:061,2009



A generic framework: pMSSM



Given that we are not convinced by a theoretical motivation, we can consider a more generic framework.

- **p(henomenological)MSSM** is a **19-dimensional** parameterization of MSSM at the **SUSY scale**.
- pMSSM is defined by
 - 3 gaugino mass parameters
 - 10 sfermion mass parameters
 - 3 trilinear couplings
 - ratio of Higgs VEVs $\tan\beta$, Higgsino mass parameter μ and pseudoscalar Higgs mass m_A
 - plus a set of minimal assumptions.
- It is a **full model** with **no assumptions** on the nature of SUSY breaking mechanism and **no correlations** between the sparticle masses. It allows to make **generic statements** on sparticle masses.



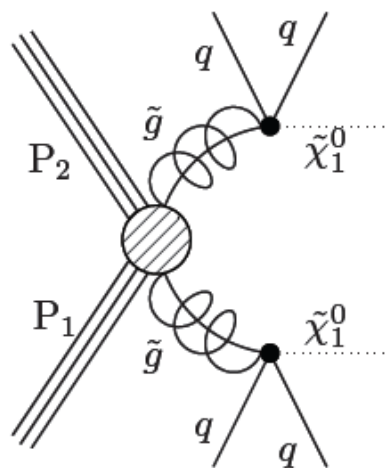
Simplified models

Or maybe we would like to simply have a way of modeling SUSY-like final states one-by-one in terms of an effective framework?

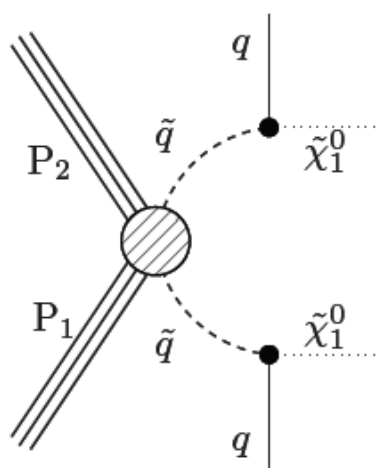
- A **simplified model** is defined by a **set of hypothetical particles** and a **sequence of their production and decays**.
- For each simplified model, values for the **product of the experimental acceptance and efficiency ($A \times \epsilon$)** are calculated to **translate a number of signal events into a signal cross section**.
- From this information, a **95% confidence level upper limit** on the **product of the cross section and branching fraction** is derived as a **function of the particle mass**.
- Only the production process of **two particles** is considered.
- Each particle **decays directly or via a cascade** to particles **X + a neutral, undetected particle** (i.e., the **LSP**.)



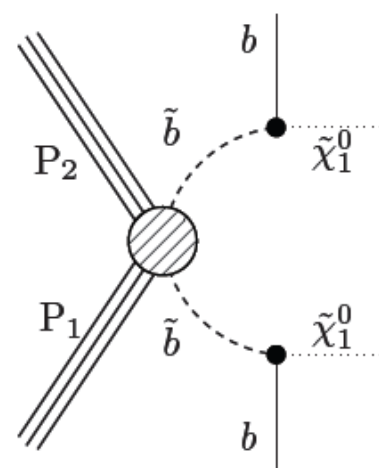
Simplified models



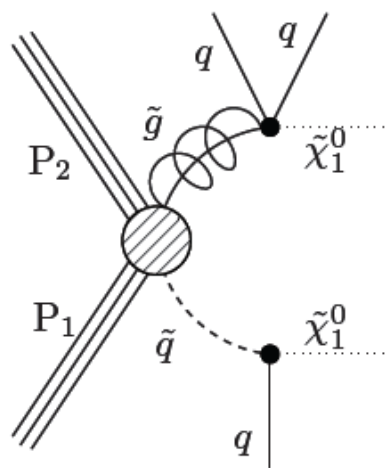
(a) T1



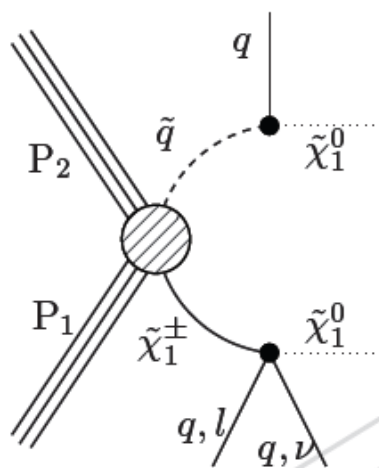
(b) T2



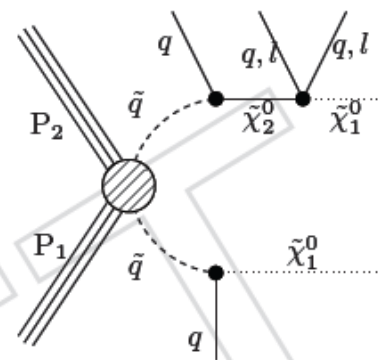
(c) T2bb



(d) TGQ



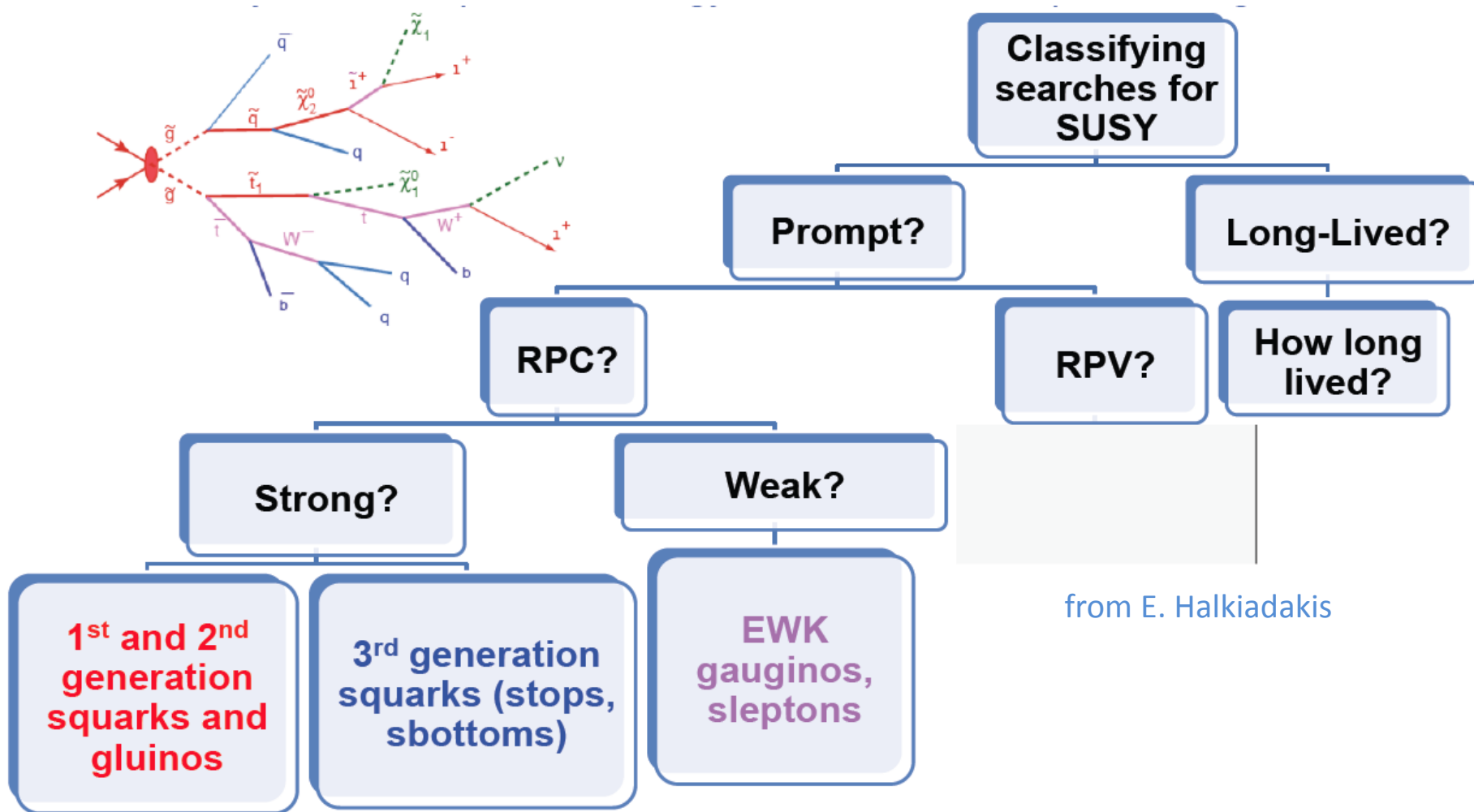
(e) TNS



(f) T4N



What are we searching for?



from E. Halkiadakis

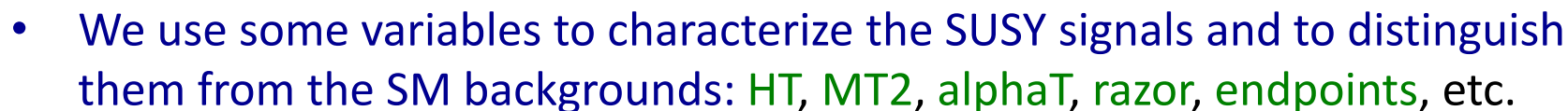


Elements of a SUSY search



Elements of SUSY (new physics) search

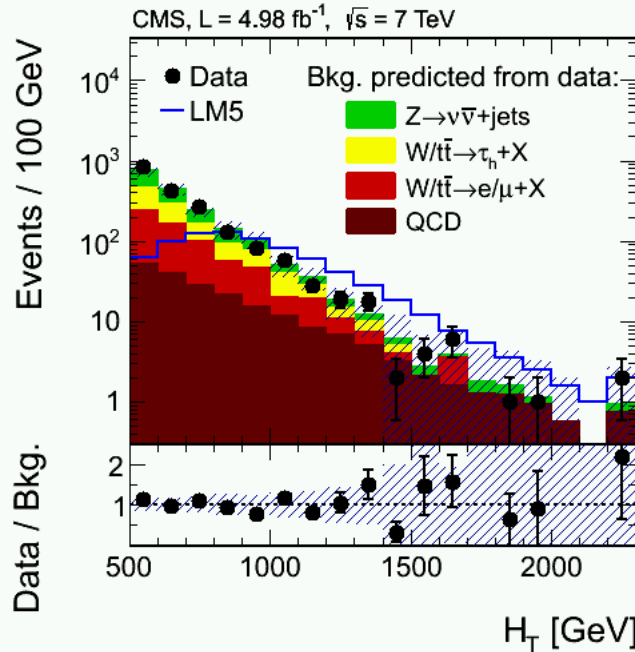
- Signal characterization and search strategy
- Designing the triggers
- Object reconstruction and identification
- Signal characterization and event selection
- Background estimation
- Statistical analysis
- Systematic uncertainties
- Results
- Interpretation



- SUSY can appear in diverse final states, but we can still classify and investigate some characteristic SUSY topologies.
- Some classical topologies with missing ET:
 - Dijets
 - Multijets
 - 1 lepton + jets
 - 2 leptons (same sign/opposite sign) + jets
 - Multileptons + jets
 - photons + jets
 - 3rd generation (tau/b/top) versions of the above

Characterizing the signal – kinematic variables

Global variables: HT and MHT



CMS-SUS-12-011
PRL 109, 171803 (2012)

Hadronic transverse energy is the scalar sum of the momenta of all jets in the event.

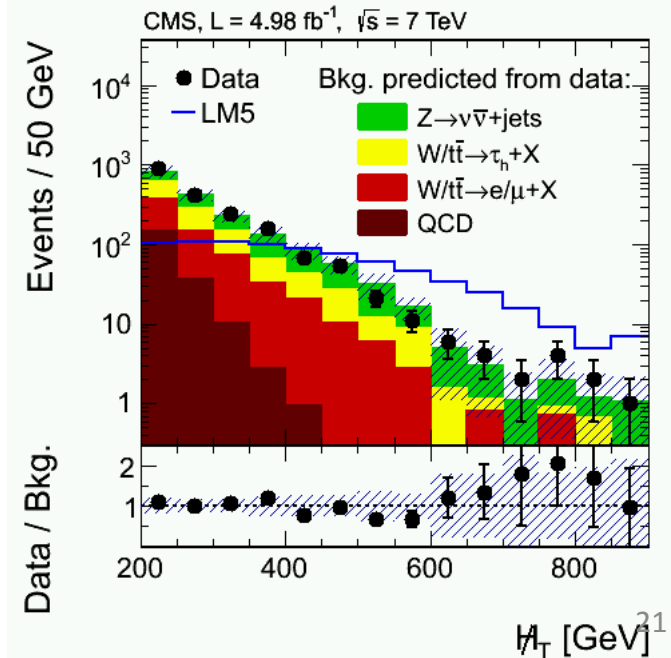
$$H_T = \sum_i^{n \text{ jets}} p_T^{\text{jet}_i}$$

Conventional SUSY events are supposed to have high hadronic transverse activity and high H_T .

Missing hadronic transverse momentum is the negative vectorial sum of momenta of all jets in the event:

$$\cancel{H}_T = H_T^{\text{miss}} = - \sum_i^{n \text{ jets}} \vec{p}_T^{\text{jet}_i}$$

Conventional SUSY events have energetic missing particles, and hence high H_T^{miss} .





Characterizing the signal – kinematic variables

Transverse mass

Sometimes, we'd like to get information on the heavy particles produced. When all decay products are visible, we can reconstruct its **invariant mass**.

BUT, sometimes some decay products are invisible, and we **don't have access to full 4-momenta** of the final state particles.

For example, in $W \rightarrow l\nu$ decays, **invisible neutrinos escape the detector**. If there is only one ν in the event, we can **approximate ν transverse momentum p_T^ν by the MET**. We define the **transverse mass** for W as:

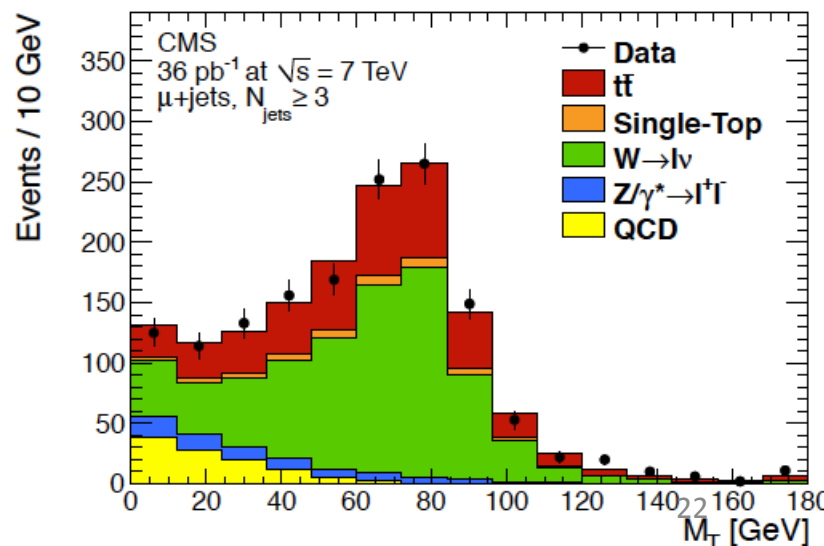
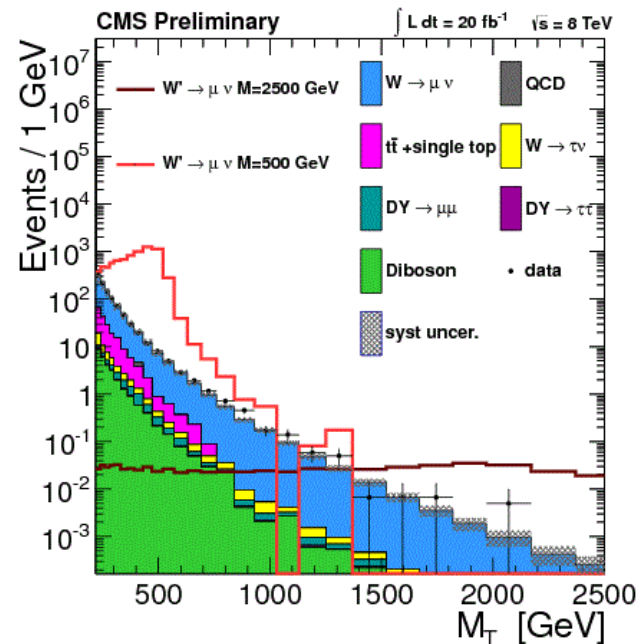
$$m_{T,W}^2 = m_\ell^2 + m_\nu^2 + 2(p_T^\ell p_T^\nu - \vec{p}_T^\ell \vec{p}_T^\nu)$$

$$(m_\ell, m_\nu \sim 0 \rightarrow) \simeq 2p_T^\ell p_T^\nu (1 - \cos \Delta\phi(\ell, \nu))$$

where $m_{T,W}^{\max}$ gives m_W because $m_{T,W} < m_W$.

Top plot: $W M_T$ used in new physics searches. M_T distribution for hypothetical W' particles where $W' \rightarrow e\nu$.

Bottom plot: $W M_T$ is used extensively in top searches and searches for new physics with top-like particles as a discriminating variable in the event selection (Right: from $t\bar{t}$ cross section measurement in leptons+jets channel).





Characterizing the signal – kinematic variables

“s”transverse mass

BUT...what if we have **more than one invisible particles** in the final state? Take the typical case

$$pp \rightarrow \tilde{q}_1 \tilde{q}_2 \rightarrow j_1 \tilde{\chi}_1 j_2 \tilde{\chi}_2$$

where $\tilde{\chi}$ s are invisible. Two invisible particles make up the MET. The **stransverse mass**

$$m_{T2}(m_{\tilde{\chi}}) = \min_{\vec{p}_T^{\tilde{\chi}_1} + \vec{p}_T^{\tilde{\chi}_2} = \vec{p}_T^{miss}} \left[\max \left(m_T(\vec{p}_T^{j_1}, \vec{p}_T^{\tilde{\chi}_1}), m_T(\vec{p}_T^{j_2}, \vec{p}_T^{\tilde{\chi}_2}) \right) \right] \leq m_{\tilde{q}}^2$$

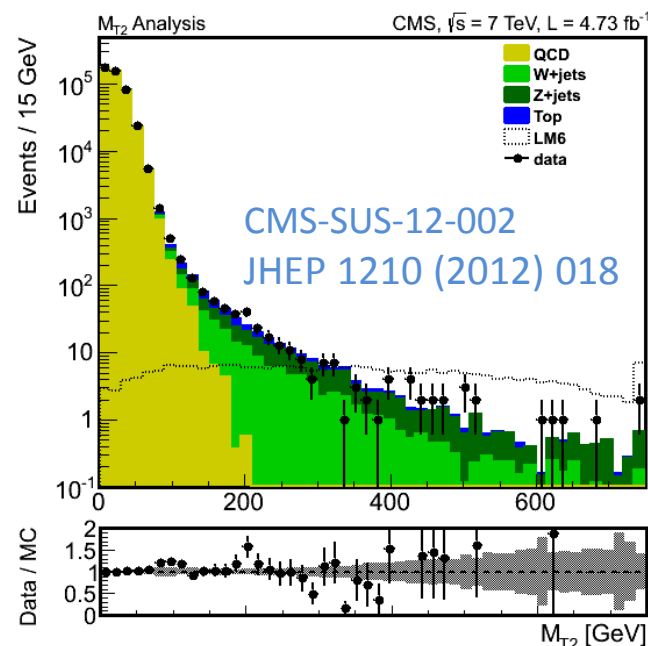
suggests a way to **decompose the MET** into these particles.

more on E. Eskandari's talk

The **minimization** is over **all possible partitions** of the measured MET.

However, for **massive $\tilde{\chi}$** , we **need the $\tilde{\chi}$ mass** for calculating m_{T2} . It is shown that for different input $m_{\tilde{\chi}}$ values, **endpoint of the corresponding m_{T2} distributions** makes a **kink** at the correct $m_{\tilde{\chi}}$ value.

MT2 is used as a selection variable in SUSY searches in ATLAS and CMS





Characterizing the signal – kinematic variables

alphaT

Can we distinguish events with genuine MET from events with misreconstructed MET?

We quantify the **unbalance** caused by the nature of MET in dijet events with the **alphaT** variable

$$\alpha_T = E_T^{j_2} / M_T$$

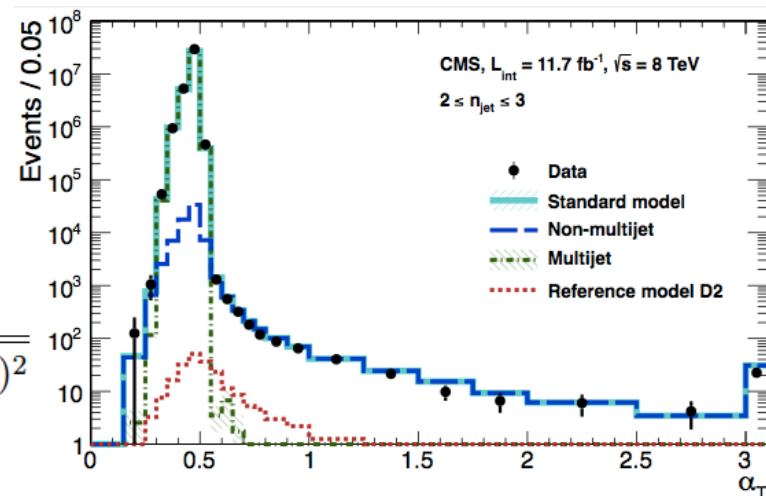
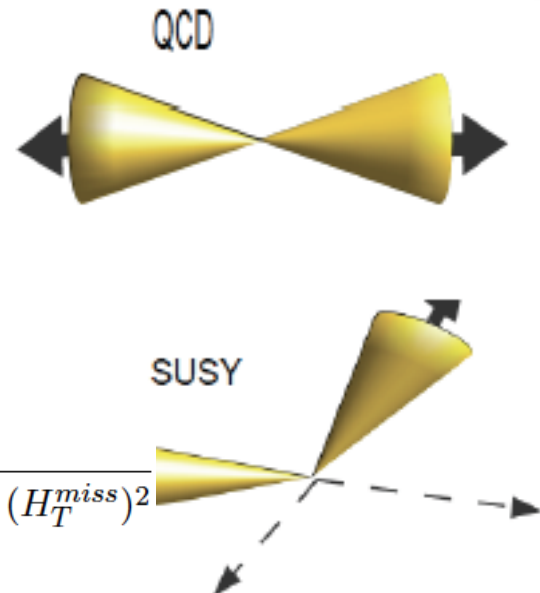
$$M_T = \sqrt{\left(\sum_{i=1}^n E_T^{j_i}\right)^2 - \left(\sum_{i=1}^n p_x^{j_i}\right)^2 - \left(\sum_{i=1}^n p_y^{j_i}\right)^2 - \left(\sum_{i=1}^n p_z^{j_i}\right)^2} = \sqrt{H_T^2 - (H_T^{miss})^2}$$

If $n_{\text{jets}} > 2$, we reconstruct two **pseudojets** by combining all jets in the event.

alphaT can also be generalized as

$$\alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{M_T} = \frac{1}{2} \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - (H_T^{miss})^2}} = \frac{1}{2} \frac{1 - \Delta H_T / H_T}{\sqrt{1 - (H_T^{miss} / H_T)^2}}$$

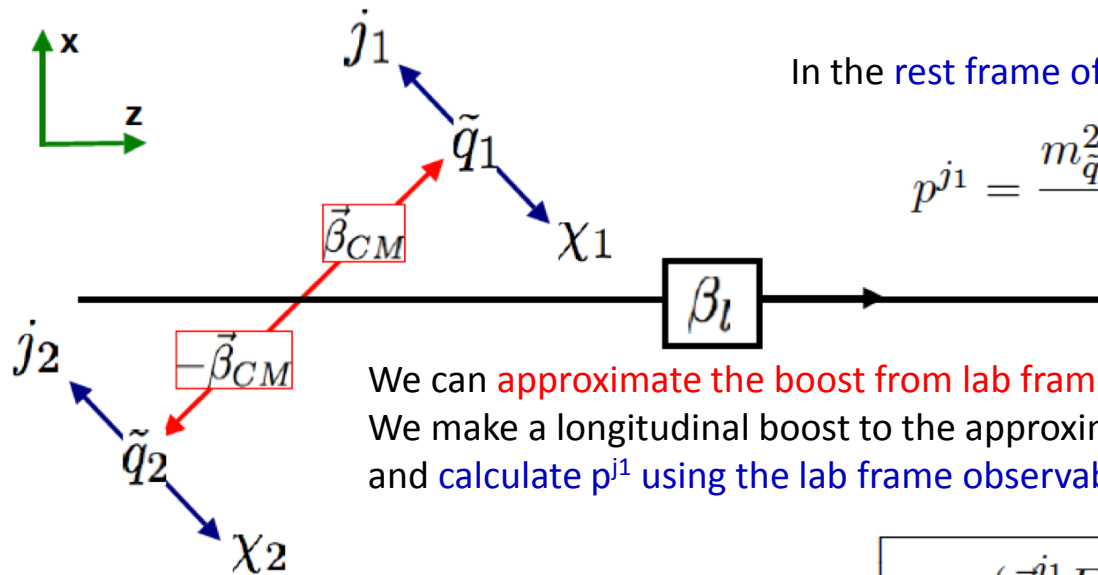
$$\Delta H_T = p_T^{j_1} - p_T^{j_2}$$



Characterizing the signal – kinematic variables

Mighty razor variables - I

C. Rogan, arXiv:1006.2727



In the rest frame of \tilde{q} , we have

$$p^{j1} = \frac{m_{\tilde{q}}^2 - m_{\tilde{\chi}}^2}{m_{\tilde{q}}^2} = \frac{m_{\Delta}}{2}$$

We can approximate the boost from lab frame to q rest frame to be a longitudinal boost. We make a longitudinal boost to the approximate q rest frame (we call it “the R frame”) and calculate p^{j1} using the lab frame observables as:

$$M_R = 2p^{j1(R \text{ frame})} = \sqrt{\frac{(\vec{p}_z^{j1} E^{j2} - \vec{p}_z^{j2} E^{j1})^2}{(\vec{p}_z^{j1} - \vec{p}_z^{j2})^2 - (E^{j1} - E^{j2})^2}} = m_{\Delta}$$

And there is a second (MT2-like) way to approximate the m_{Δ} distribution using the transverse components of the lab frame objects, whose kinematic endpoint gives m_{Δ} :

$$M_T^R = \sqrt{\frac{E_T^{miss}}{2}(p_T^{j1} + p_T^{j2}) - \frac{1}{2}\vec{E}_T^{miss} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})} < m_{\Delta}$$

Then, the ratio

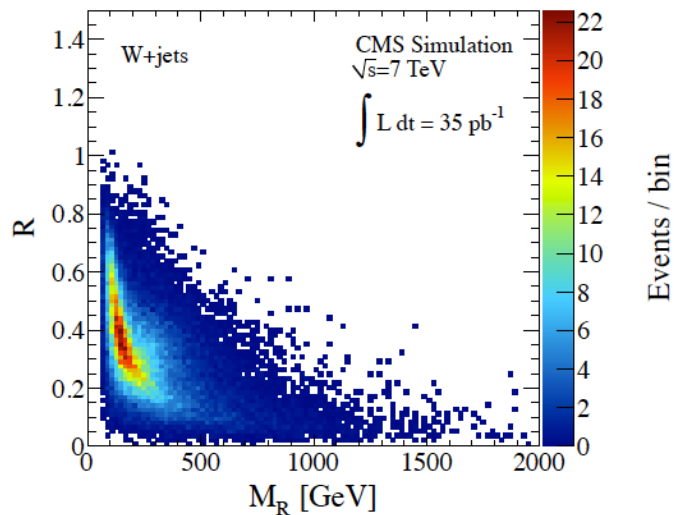
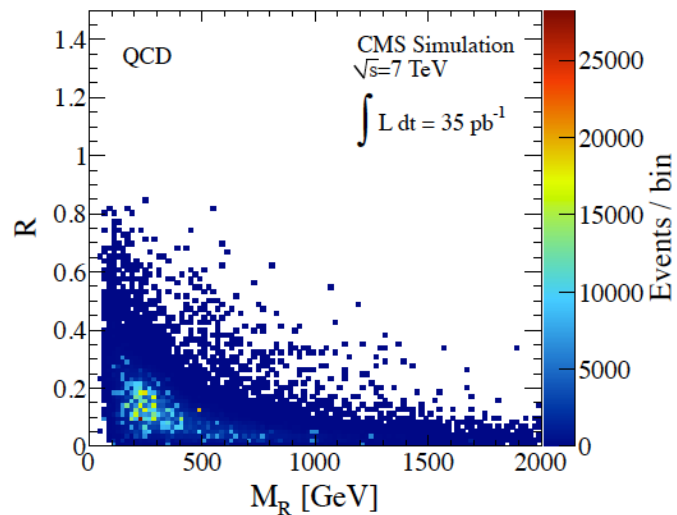
$$R \equiv M_T^R / M_R$$

is a dimensionless quantity that combines two different ways of measuring the same thing.

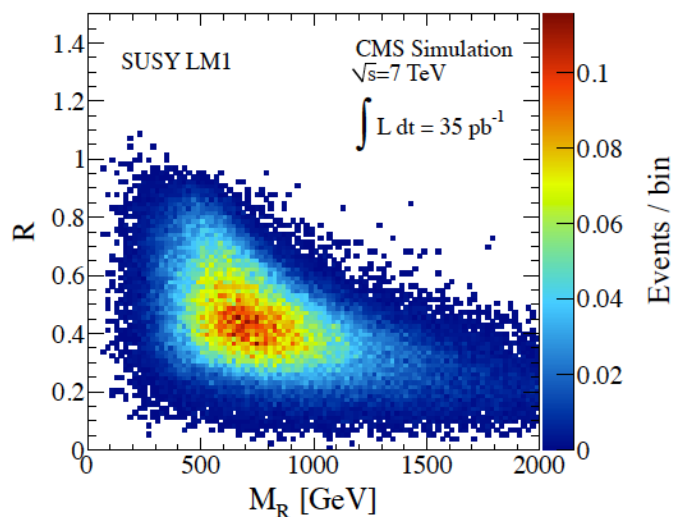
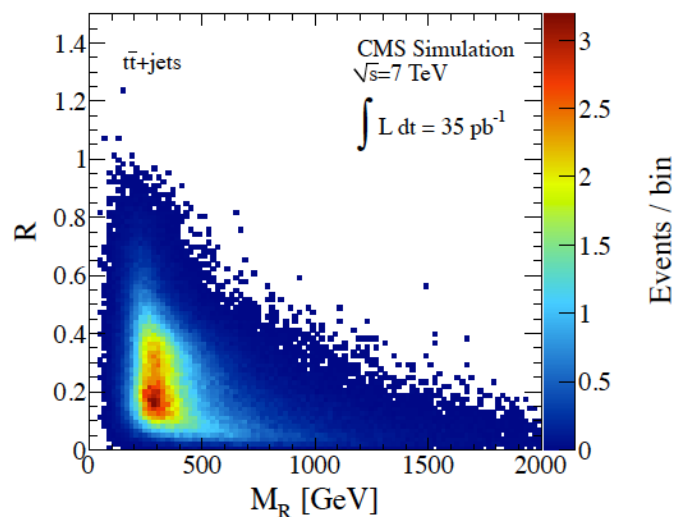


Characterizing the signal – kinematic variables

Mighty razor variables - II



Most kinematic discriminators give an excess in the tails (e.g. MET), but razor variables define a “bump”, hence they provide very good signal-BG discrimination.



more on S. Paktinat's talk

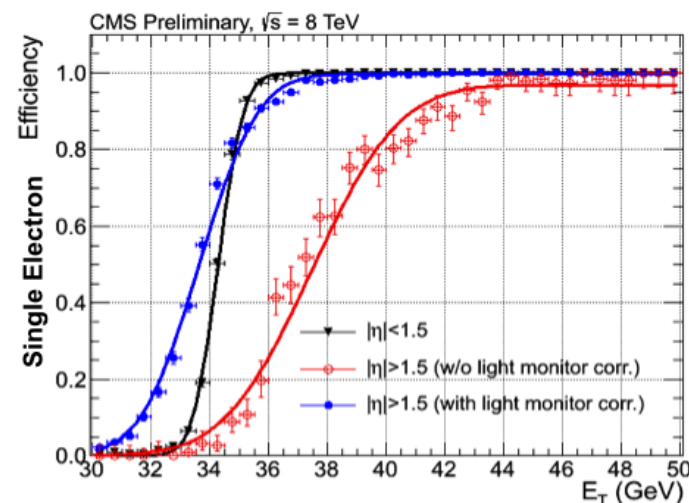
CMS and ATLAS use razor extensively for new physics searches.



Trigger

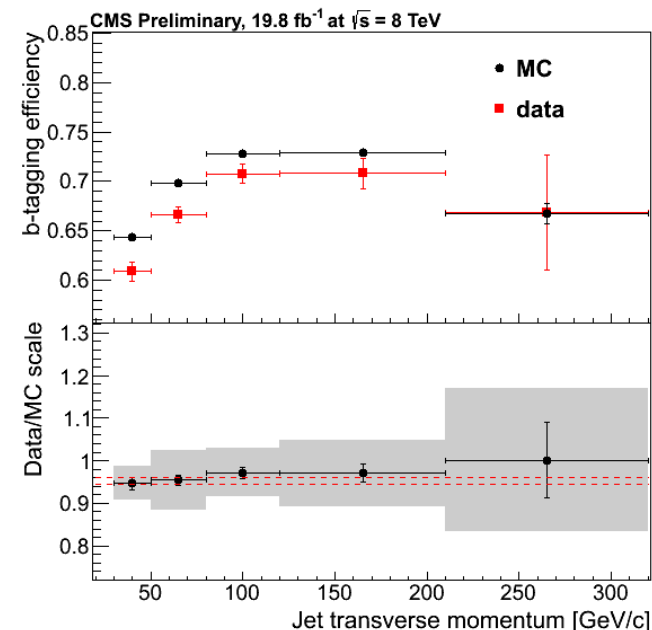
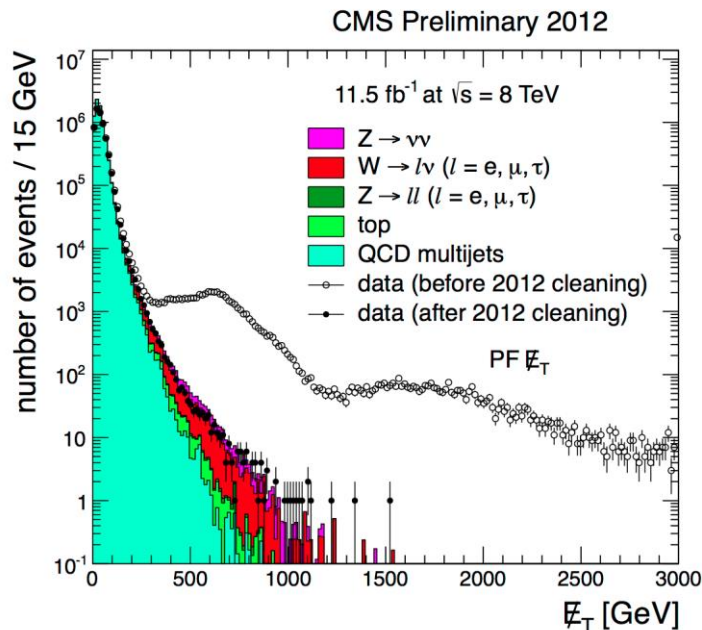
- Triggers are fast online filters that select the most interesting events during data taking, and store them for the offline analysis – if not stored, events are lost forever!
- Trigger is a rough sketch of the offline analysis: we select events with final states representative of the physics we're looking for.
 - Trigger on object kinematics and multiplicities
 - Trigger on kinematic variables: HT, HTmiss, alphaT, razor
- Two important trigger tasks for new physics searches:
 - Design the triggers that would cover the target signals.
 - Triggers are not fully efficient with respect to the offline cuts. Estimate the trigger efficiency given by:

$$\epsilon_{\text{trigger}} = \frac{\text{number of events that pass the trigger}}{\text{number of total events}}$$



Objects

- Information from subdetectors is combined to reconstruct objects (jets, electrons, muons, taus, photons, missing transverse energy, b-tagged jets, boosted objects (Ws and tops)).
 - CMS uses **particle flow (PF)** which combines information from all subdetectors to **reconstruct particles**.
- Objects are then required to pass some **identification and isolation criteria**. We must find the **optimum criteria** that reflect our final state best.





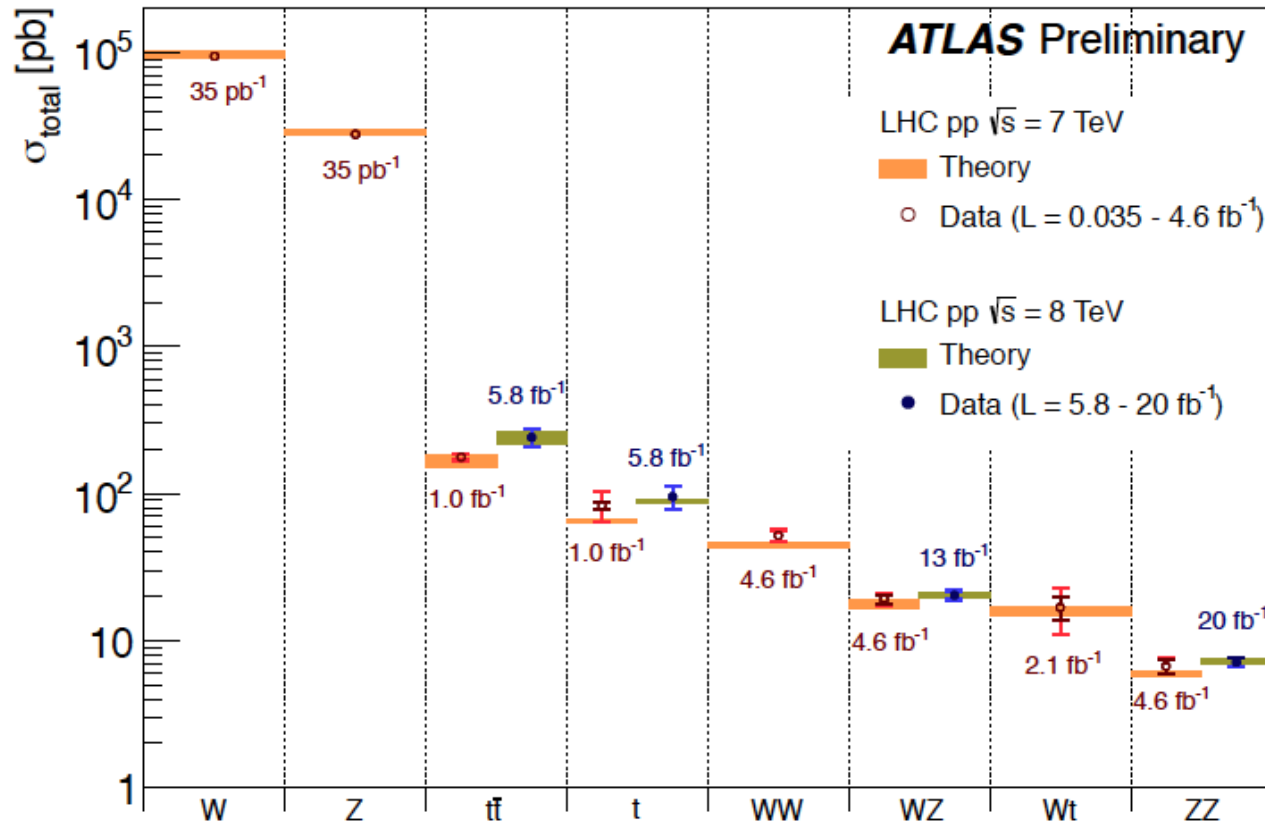
Event selection: principles

- Characterize the signal. Find final state topologies and kinematic variables that discriminate the signal from the backgrounds. Multijets? Opposite-sign dileptons? b-rich? Discriminating kinematic properties?
- Look for statistically significant signal regions. There should be sufficient number of events, and sufficient number of predicted signal events over the expected background.
- Make sure that there is a way to estimate the expected background in the signal region.
- Make sure that the offline selection corresponds to a region where the trigger efficiency is well-modeled.
- Make sure that the selection variables are reconstructed and identified in well-defined regions of the detector (not feasible to design a search with forward electrons).
- Numerous multivariate methods exist for selection optimization: rectangular cuts, fisher discrimination, likelihoods, neural networks, decision trees, support vector machines, ...

BAAACKGROOOOUNDSSS!!!



SM backgrounds in SUSY searches



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots>

Inclusive SM cross sections are measured with precision and over many orders of magnitude.

Precise measurements of kinematical distributions are crucial for SUSY searches.

Greatest background sources are QCD (not shown), W s, Z s and $t\bar{t}$.



Background estimation

We need to estimate the amount (and shape) of the **irreducible backgrounds** that remain in the signal region after the event selection.

A crucial part of the analysis – numerous methods available and are being devised.



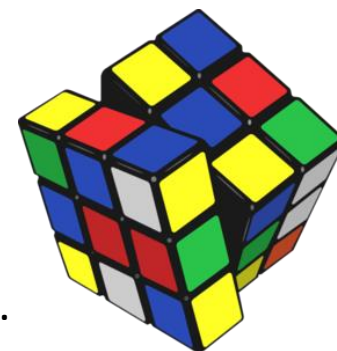
Use **predictions from Monte Carlo simulations!**

- Contains all our knowledge on the theory and on our detector.
- It is a long, but persistent way from roughness to precision.

Devise **data-driven estimation methods:**

A common principle: Use **control regions**

- Find a region in the cut phase space which is **background enriched and signal depleted** (the control region).
- Obtain the information on BG and **extrapolate** it to the signal region.



Data and MC work together:

- Data is used for **tuning** MC parameters
- For well-described kinematic variables, **MC shapes** are used in BG estimation.

Example signal and control sample definition

Final state: $\geq 3j$, $\geq 1b$, MET - I

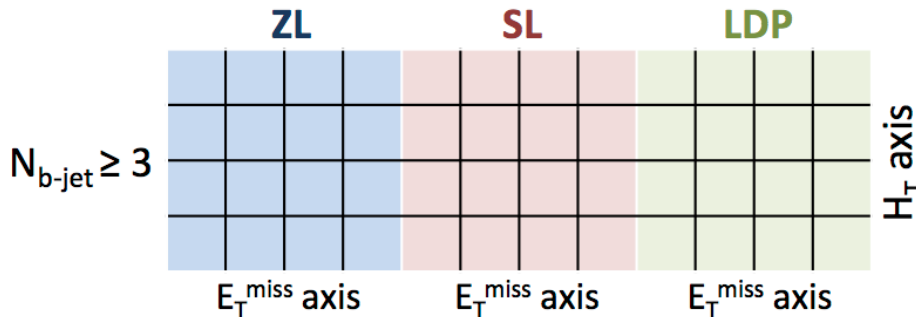
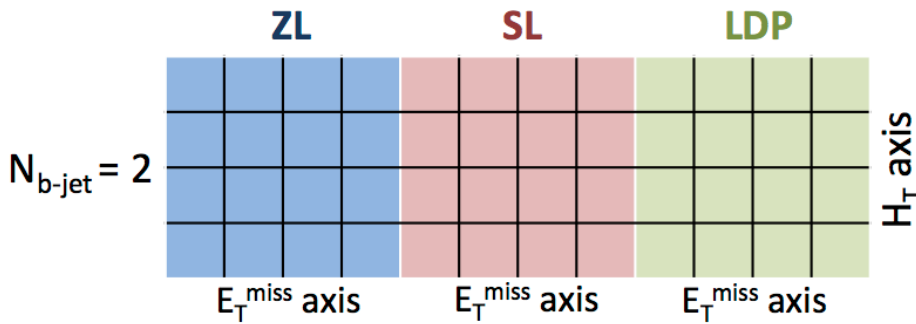
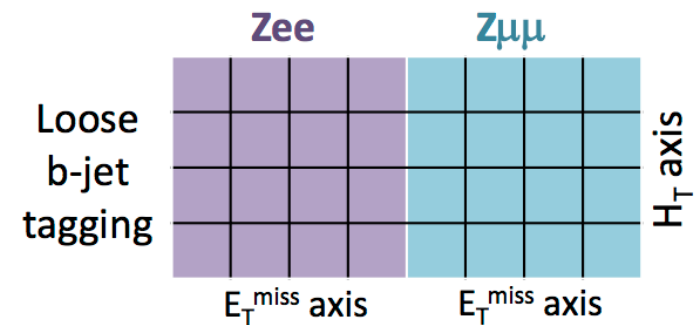
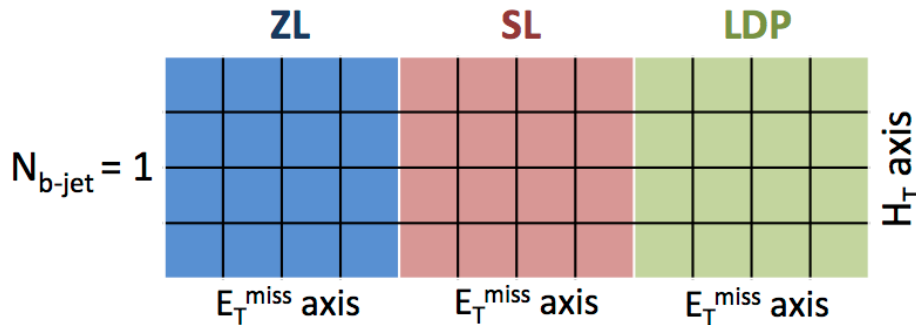
ZL = Zero Lepton;
signal sample

SL = Single Lepton;
top & W+jets control
sample

LDP = low $\Delta\phi_{\min}^{\hat{e}}$;
QCD control
sample

Zee = $Z \rightarrow e^+e^-$;
Z to $\nu\bar{\nu}$ control
sample

Z $\mu\mu$ = $Z \rightarrow \mu^+\mu^-$;
Z to $\nu\bar{\nu}$ control
sample



Bin	H_T (GeV)	E_T^{miss} (GeV)
1	400 – 500 (HT1)	125 – 150 (MET1)
2	500 – 800 (HT2)	150 – 250 (MET2)
3	800 – 1000 (HT3)	250 – 350 (MET3)
4	> 1000 (HT4)	> 350 (MET4)



Example signal and control sample definition

Final state: $\geq 3j$, $\geq 1b$, MET - II

Build an expression that links expected background yield for each background in each bin with the observed yield in the control sample for the relevant background for each bin.

Expected BG in bin ijk of signal sample

scale factor common to all bins

$$\mu_{ZL;i,j,k}^{ttWj} = S_{i,j,k}^{ttWj} \cdot R_{ZL/SL}^{ttWj} \cdot \mu_{SL;i,j,k}^{ttWj}$$

Observed yield in the control sample

bin-by-bin MC-based scale factor which accounts for the shape difference between signal and control samples.

There are many more methods. A few more are in the backup slides.



Statistical modeling and likelihood analysis

- The **statistical model** of an analysis provides the **complete mathematical description** of that analysis.
- It relates the **observed quantities** \mathbf{x} to the **parameters** θ through the **probability density** $p(\mathbf{x} | \theta)$.
- The **likelihood** $L(\theta) = p(X_0 | \theta)$ is the probability density $p(\mathbf{x} | \theta)$ **evaluated at the observed values** X_0 of the observables \mathbf{x} .
- A likelihood is the starting point of any serious interpretation.



Example model – multibin Poisson

We count events. The probability of counting/observing N events for an expected average $n = s$ (:signal) + b (:background) is given by a **Poisson distribution**:

$$Pois(N|s + b) = \frac{(s + b)^N e^{-(s+b)}}{N!}$$

Generally, s and b are given in terms of some **parameters**:

$$Pois(N|\sigma, \epsilon, \mathcal{L}, \beta_j) = \frac{(s(\sigma, \epsilon, \mathcal{L}) + b(\beta_j))^N e^{-(s(\sigma, \epsilon, \mathcal{L}) + b(\beta_j))}}{N!}$$

σ : cross section, \mathcal{L} : luminosity, ϵ : efficiency and β_j : some BG shape parameters. When we have I disjoint bins, we can take the product of the Poisson for each bin:

$$p\left(\sum_i N_i | \sigma, \epsilon_i, \mathcal{L}, \beta_j\right) = \prod_i \frac{(s_i(\sigma, \epsilon_i, \mathcal{L}) + b_i(\beta_j))^{N_i} e^{-(s_i(\sigma, \epsilon_i, \mathcal{L}) + b_i(\beta_j))}}{N_i!}$$

We insert the observed counts N_i to get the likelihood, and estimate the parameters from the likelihood using dedicated statistical methods.



Results and interpretation

- An **experimental result** is the **empirical outcome of the experiment**, such as an **event count**, or the measurement of some **physical quantity**, such as mass, cross section, spin, charge asymmetry, kinematic edges, etc.
- Given an experimental result, we can find its effect on a theoretical model.
- **Interpretation** is the act of **comparing the experimental results to theoretical model predictions**. Beware - it is NOT the experimental result!
- We use likelihoods that incorporate signal predictions to evaluate the impact of the searches on the candidate models.

Systematic uncertainties

Systematic uncertainties are those that cause a shift in the mean of a measurement from the true value.

Systematics are calculated for background estimates, derived measurements (mass, cross section, endpoint, etc.) and for MC predictions of signals (which are used for interpretation).

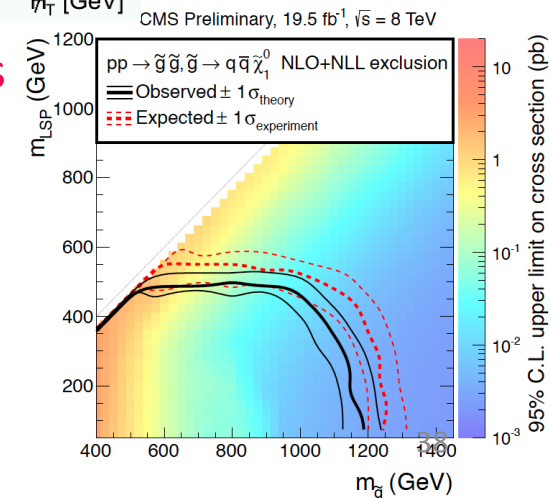
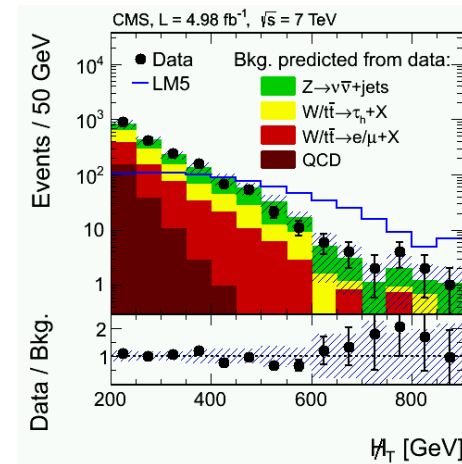
Typical sources of systematics are:

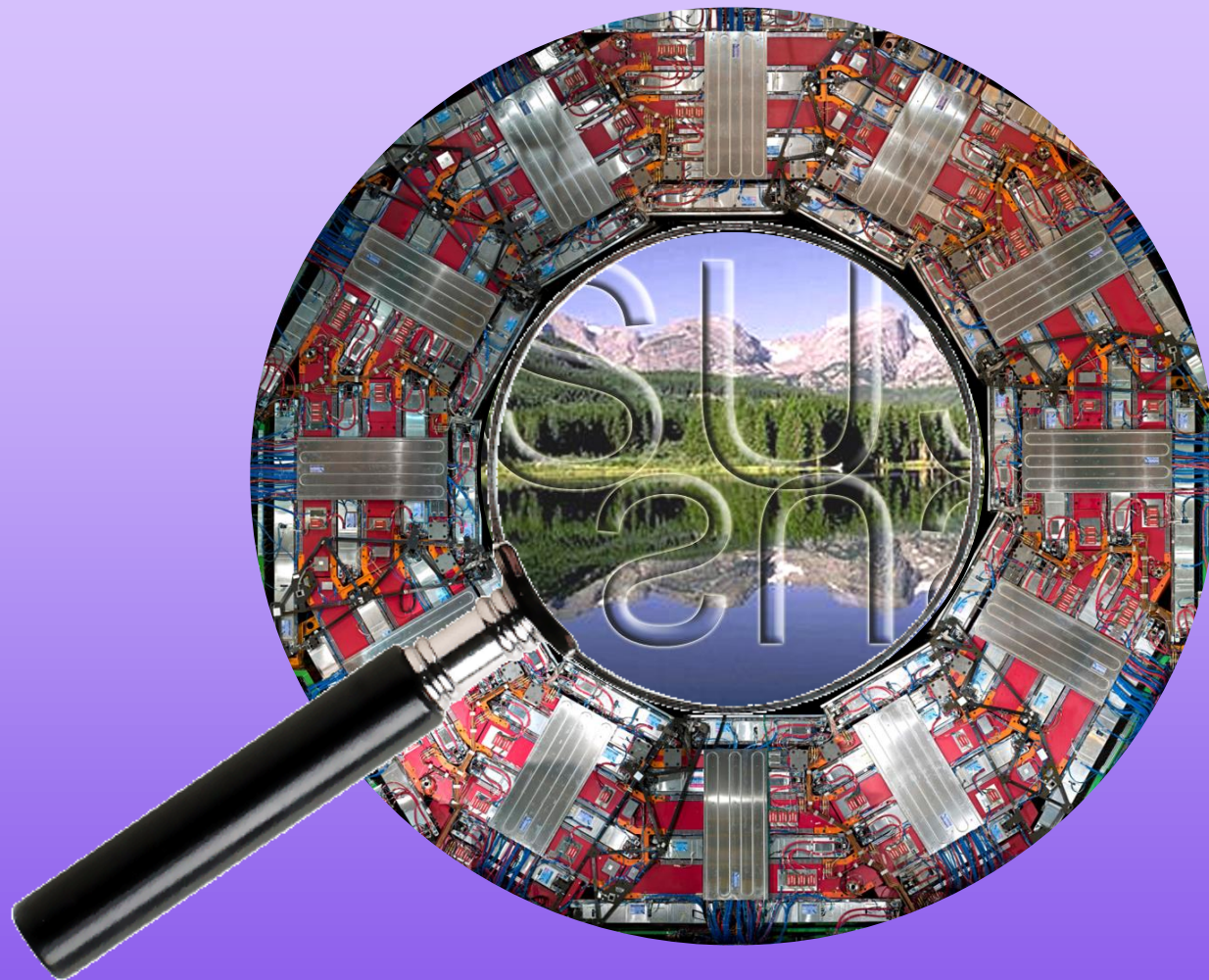
Experimental:

- Luminosity calculation
- Trigger efficiencies
- Jet energy scale, jet energy resolution
- Lepton, photon, b-tag, W-tag, top-tag, etc. efficiencies

Theoretical:

- Cross section and branching ratio calculations
- Parton distribution functions
- ISR/FSR, renormalization scale/factorization scale





SUSY searches at CMS

in other words “how we couldn’t yet find SUSY yet”



What is going on in CMS SUSY now?

Most up-to-date public CMS SUSY results are listed here:

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>

- Inclusive / generic searches: target mostly gluinos and 1st/2nd generation squarks
 - in this talk, S. Paktinat's and E. Eskandari's talks
- Naturalness-inspired searches: targeting light stops/sbottoms and light gluinos with 3rd generation decay modes
 - in S.Paktinat's talk
- Search for pair production of electroweak gauginos and sleptons
 - in H. Bakshian's and A. Fahim's talks
- Search for Higgs in SUSY decays
 - in this talk
- Search for multi-leptons and R-parity violating signatures
 - in B. Safarzadeh's talk



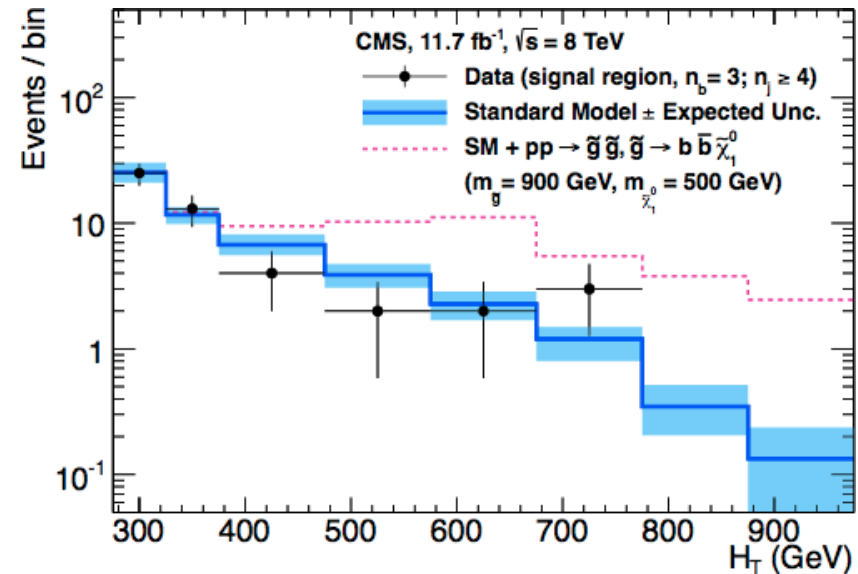
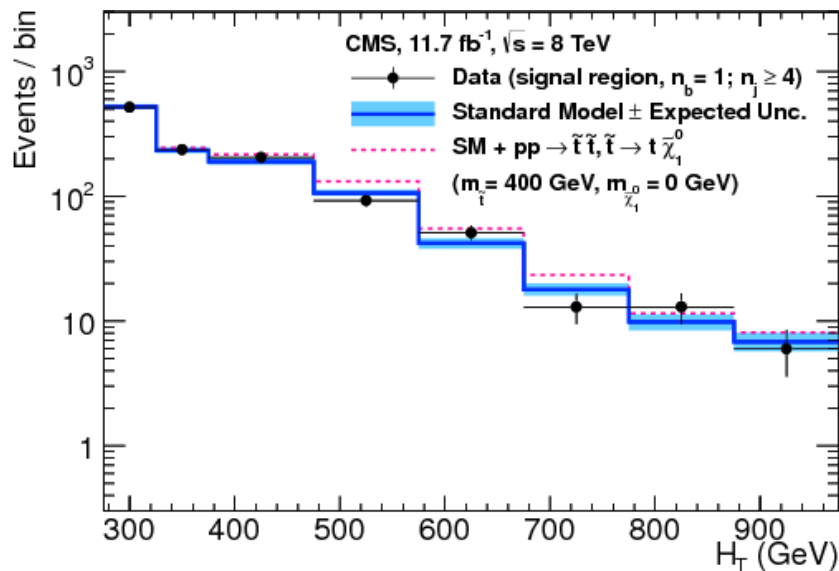
Jets, b-jets, E_T^{miss} with H_T , α_T (8 TeV, 11.7 fb⁻¹) Inclusive search

CMS-SUS-12-028, EPJC 73 (2013) 2568

Signal selection: ≥ 2 jets, jet_{1,2} $p_T > 100$ GeV, no isolated leptons, $\alpha_T > 0.55$

Signal final state: binned in **jet multiplicity** (sensitivity to $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$), **b jet multiplicity** (sensitive to 3rd generation) and **HT** (probe models with large mass splitting range)

Likelihood analysis using a multibin Poisson. **No excess over SM observed.**





Jets, H_T^{miss} (8 TeV, 11.7 fb $^{-1}$) Inclusive search

CMS-SUS-13-012

Signal selection: ≥ 3 jets, $HT > 500$ GeV, $H_T^{\text{miss}} > 200$ GeV, no isolated leptons,
 $\Delta\Phi(\text{jet}_{1,2,3}, H_T^{\text{miss}}) > (0.5, 0.5, 0.3)$

Signal final state:

36 bins in **jet
multiplicity, H_T
and H_T^{miss} .**

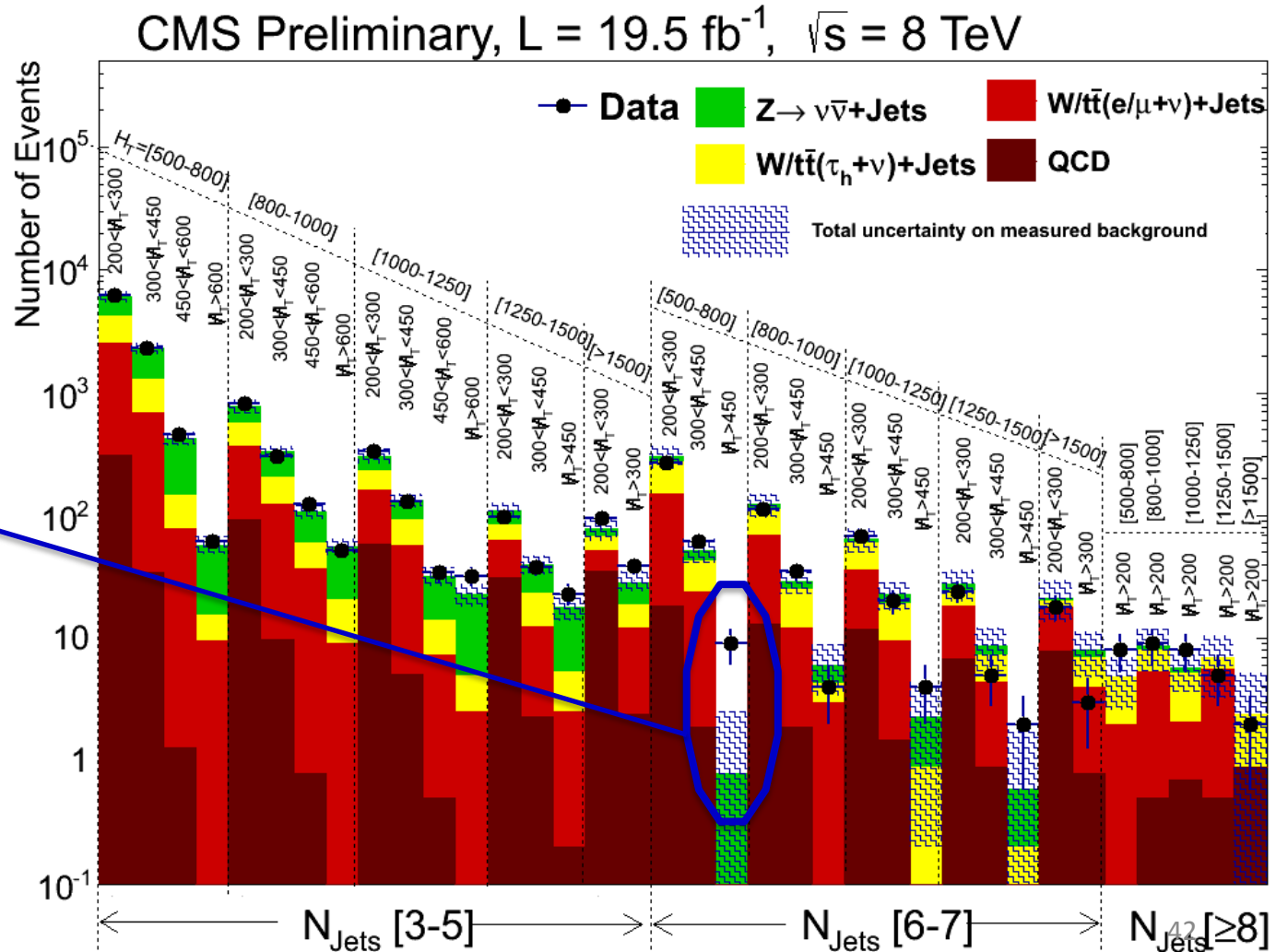
$N = 9$

$b = 0.8 \pm 1.7 (2.7\sigma)$

Could this be
interesting?

The effect reduces
when we include
the impact of
doing the analysis
simultaneously in
36 bins.

More data will tell.





Jets, b-jets, E_T^{miss} with H_T , $\Delta\Phi_{\text{min}}$ (8 TeV, 19.4 fb⁻¹) Inclusive search, 3rd generation

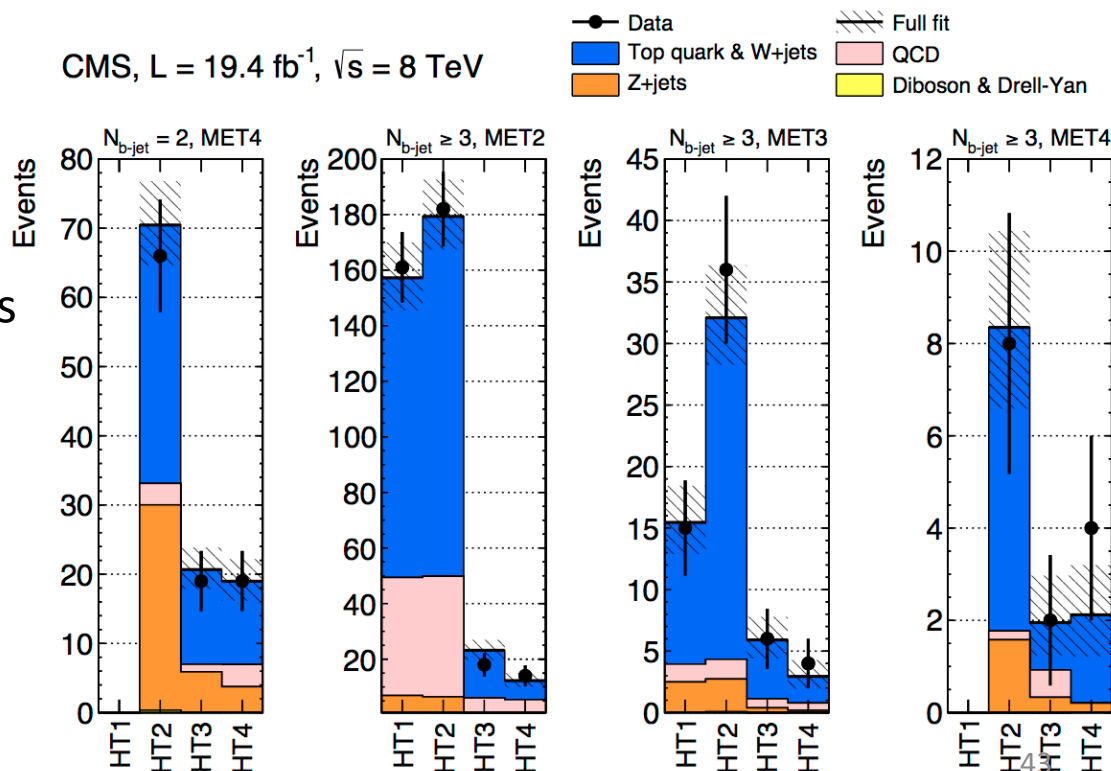
CMS-SUS-12-024, PLB 725 243 (2013)

Signal selection: ≥ 3 jets, jet_{1,2} $p_T > 70$ GeV, ≥ 1 b-tagged jets, no isolated leptons, $H_T > 400$ GeV, MET > 125 GeV, $\Delta\Phi_{\text{min}}(\text{jet}_i, \text{MET}) > 4.0$

Signal final state: binned in **jet multiplicity**, **H_T** and **MET**.

Likelihood analysis using a multibin Poisson. **No excess** over SM observed.

Comparison of data with the SM prediction in the **14 most sensitive bins to new physics**, as found in the likelihood fit with SUSY signal strengths set to 0.
Data consistent with the SM.





Anomalous production of multileptons - I

Inclusive search

CMS-SUS-13-002

Signal selection:

- 3 or 4 leptons (e/μ) with possibly one tau with $p_T > 20$ GeV among them
- 0 or >1 b tagged jet
- $HT < 200$ GeV or > 200 GeV
- 0, 1 or 2 opposite-sign-same-flavor (OSSF) lepton pairs
- If OSSF exist: dilepton invariant mass m_{ll} below/on/above Z mass.
- Reject events with $m_{ll} < 12$ GeV to avoid low mass resonances.
- Reject events with both $|m_{l+l-} - m_Z| > 15$ GeV and $|m_{l+l'} - m_Z| < 15$ GeV to avoid photon conversion from final state radiation.

Signal final states: MET distributions in 64 bins of number of leptons, OSSF pairs, b-tagged jets, taus; dilepton mass wrt Z-mass and H_T .

Backgrounds:

- **$t\bar{t}bar$, WZ** \rightarrow smear MC MET distributions using data
- **non-prompt leptons or taus** \rightarrow find conversion factor from data
- **asymmetric internal photon conversions** \rightarrow find conversion factor from data

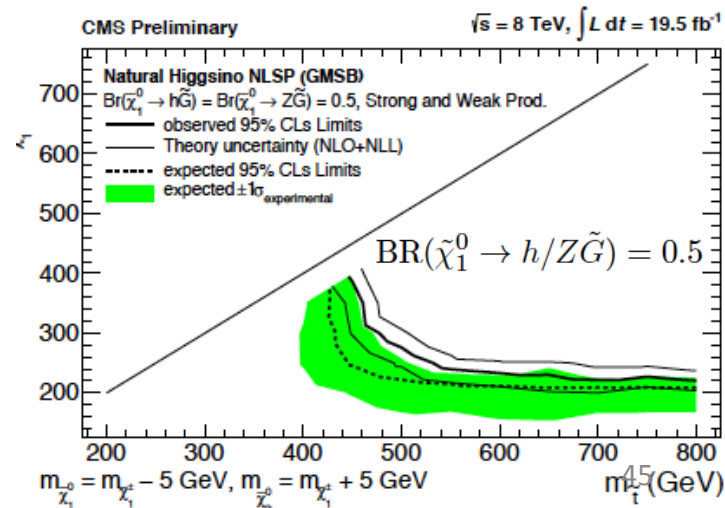
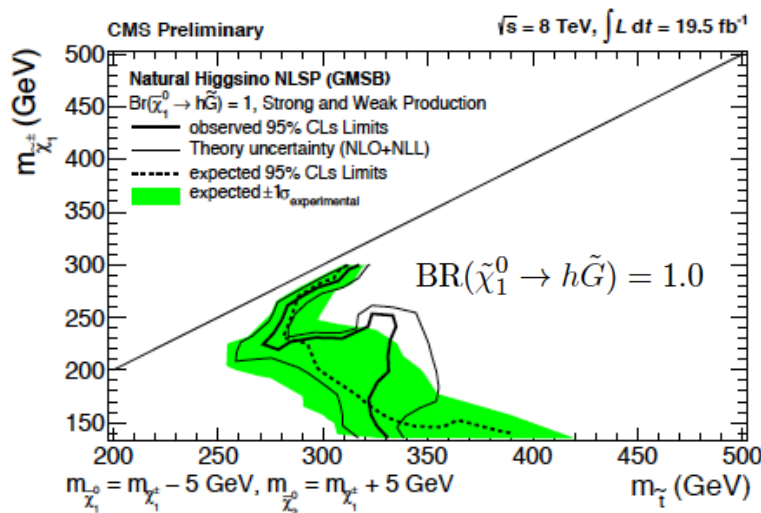
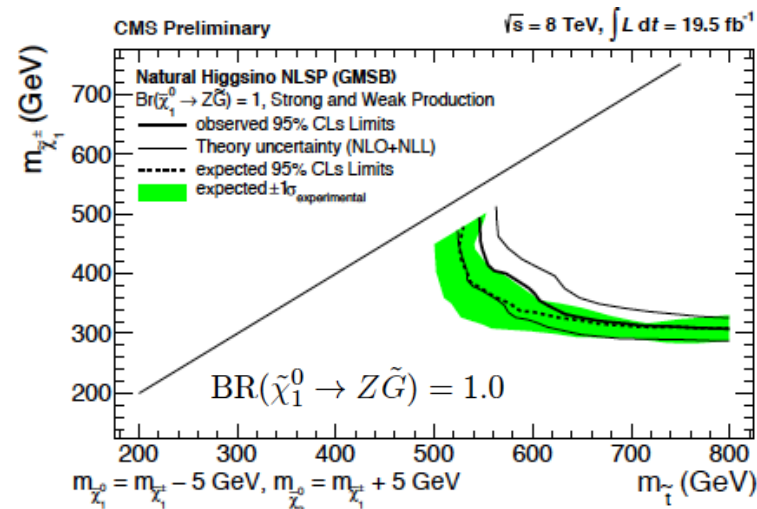
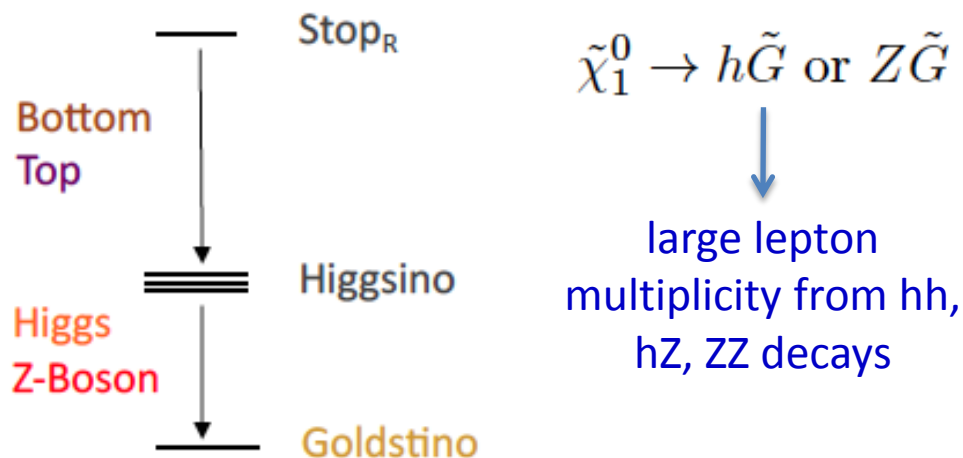


Anomalous production of multileptons - II

Natural Higgsino LSP scenario

CMS-SUS-13-002

Natural SUSY in GMSB models:

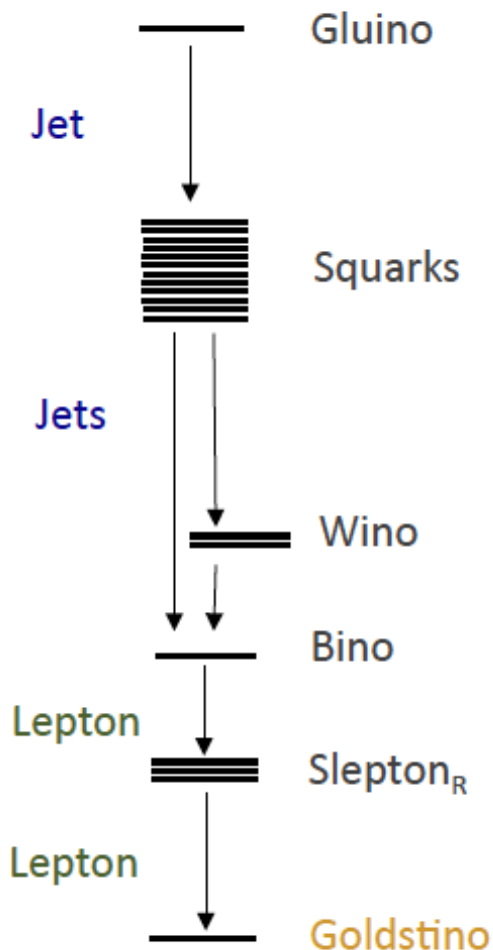




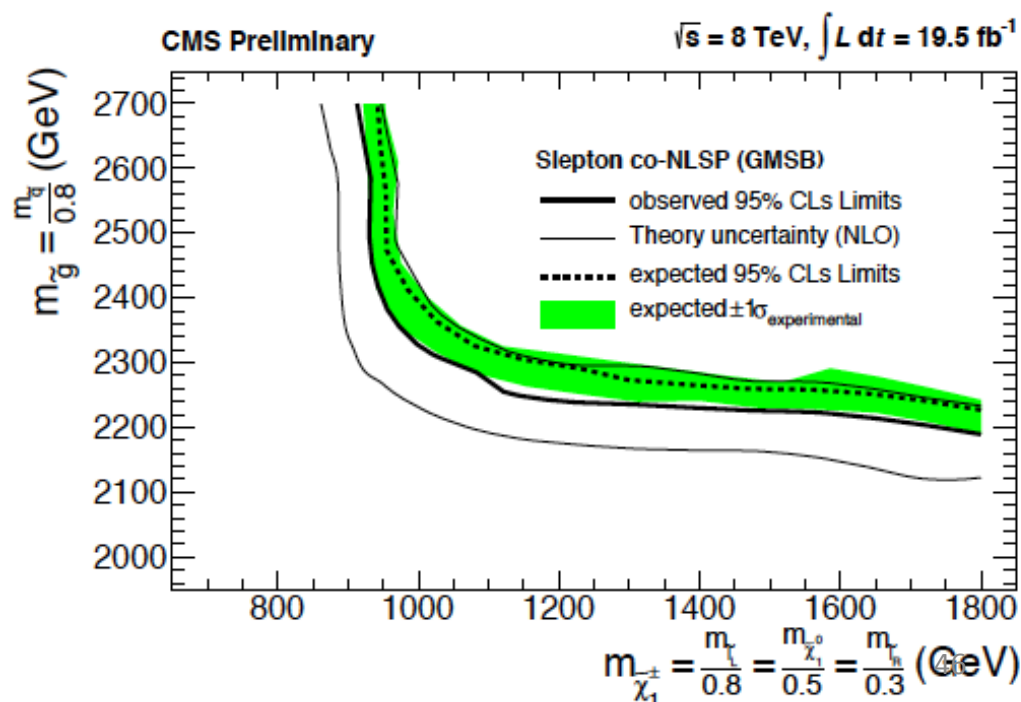
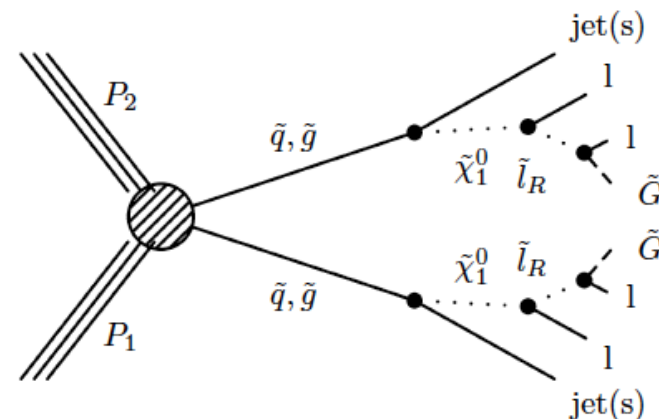
Anomalous production of multileptons - III

Slepton co-LSP

CMS-SUS-13-002



Light sleptons from bino decays lead to multilepton signatures





Anomalous production of multileptons - III

Stau-(N)NLSP scenario

CMS-SUS-13-002

Taus will come from stau decays.

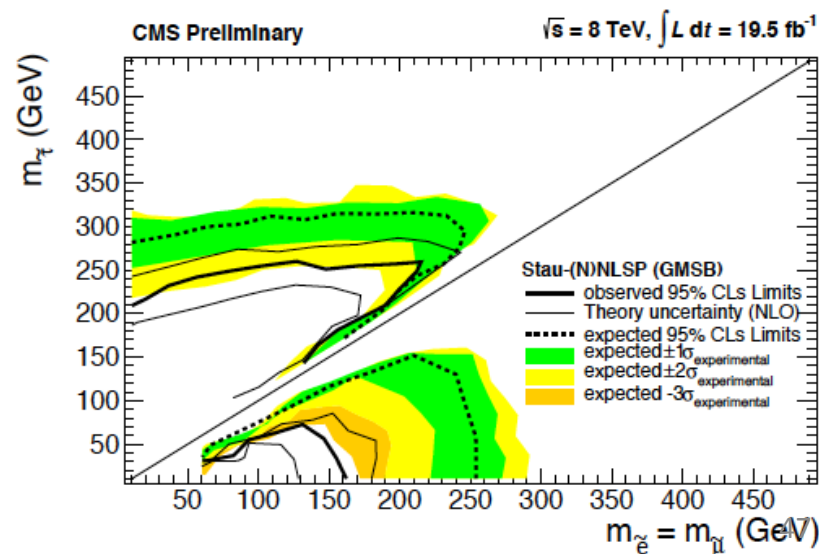
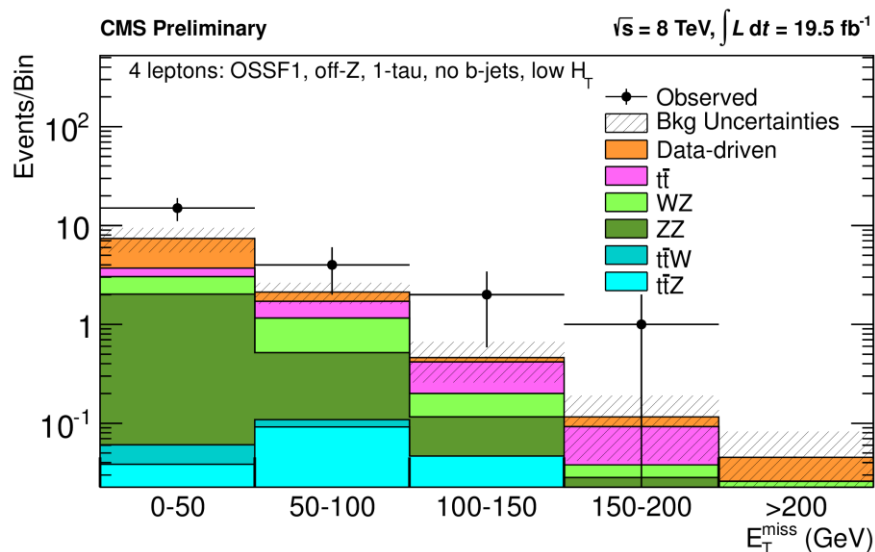
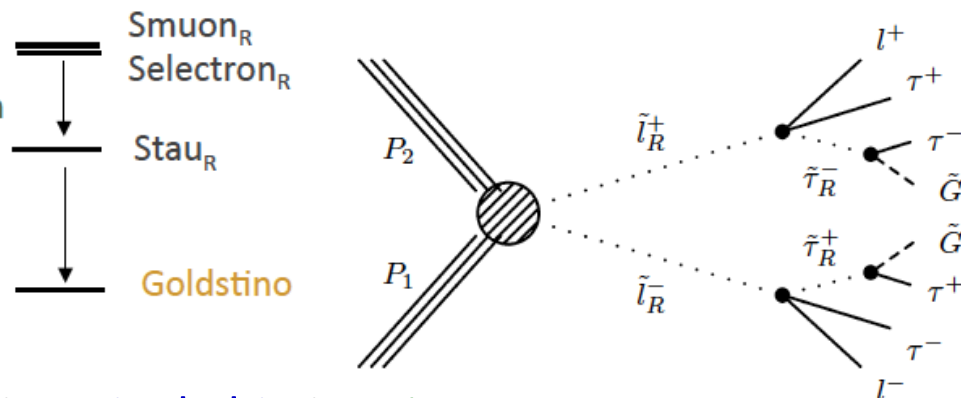
4l (1 τ), 1OSSF (off-Z), no b, low HT Lepton
bin is sensitive to this model.

An excess has been observed:

$N = 22$, $b = 10 \pm 2.4$

Probability of observing such an excess in a single bin is 1%.

Probability of observing such an excess for this analysis looking at 64 bins simultaneously is 50%.

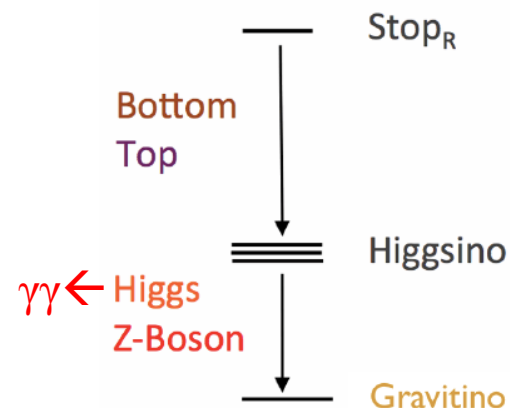




Search for stops and higgsinos in $H \rightarrow \gamma\gamma$ decays

SUSY Higgs search – naturalness-motivated GMSB

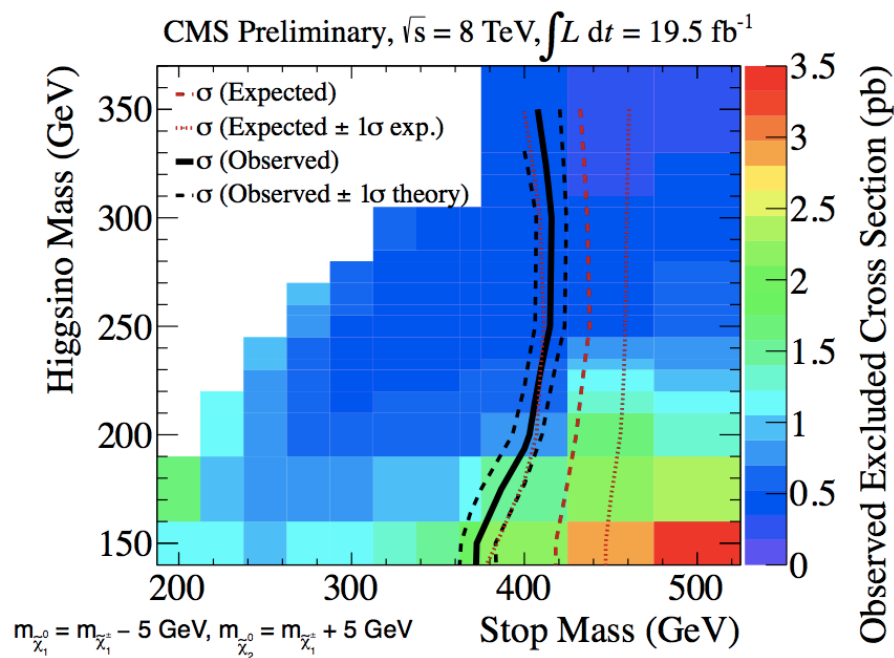
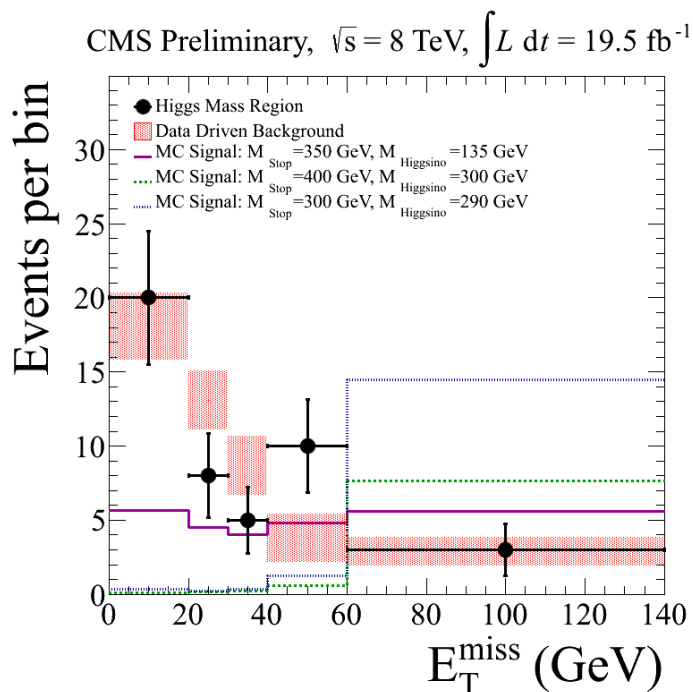
CMS-SUS-13-014



Signal selection: 2 isolated photons ($E_T > 40, 25$ GeV), ≥ 2 b-jets ($p_T > 30$ GeV)

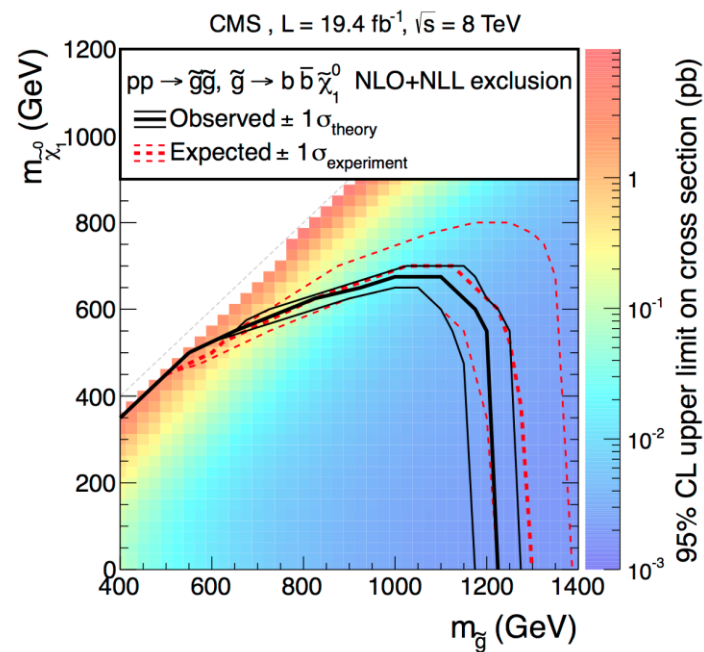
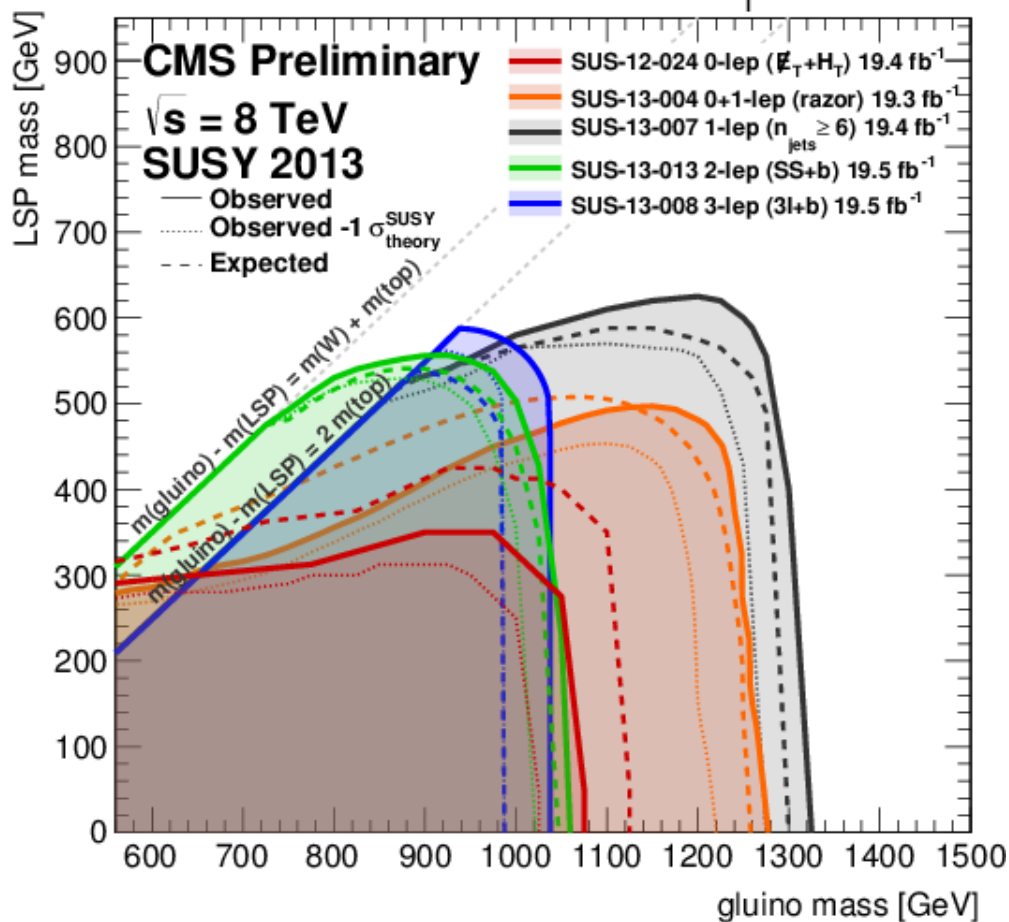
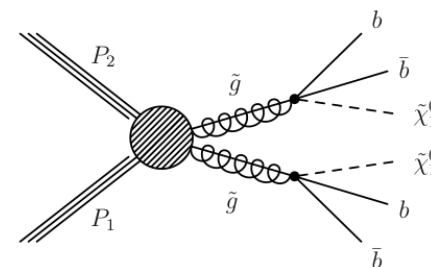
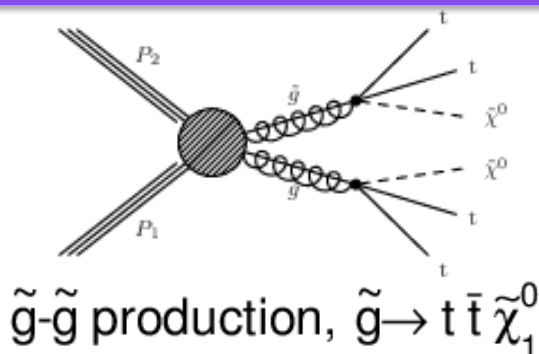
BG estimation: Fit a function to $m_{\gamma\gamma}$ in sidebands and extrapolate the fit to the signal region $120 < m_{\gamma\gamma} < 131$.

Take the MET shape from the sidebands, normalize to the BG fitted in the signal region and compare with data.



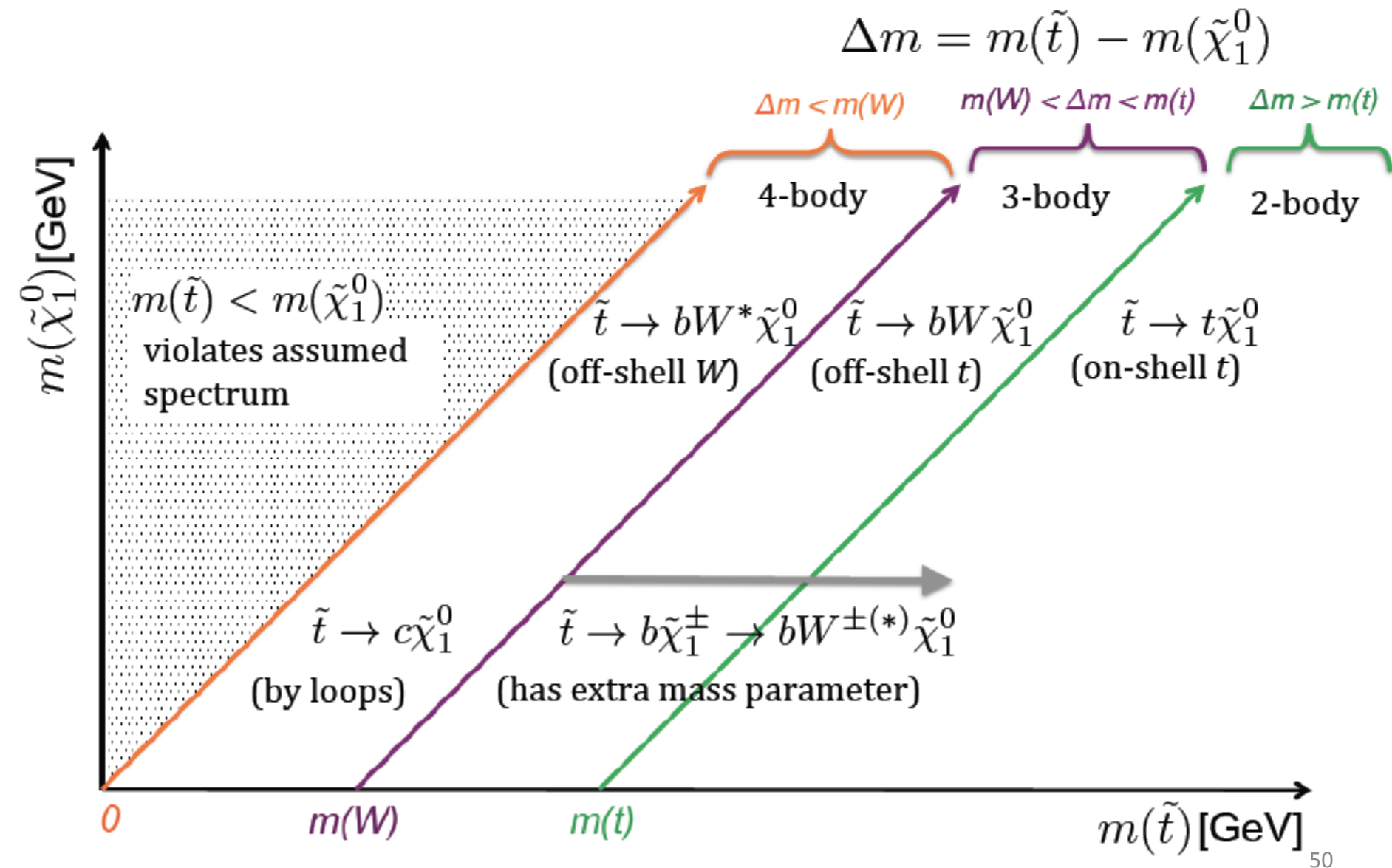


Gluino-neutralino mass reach summary





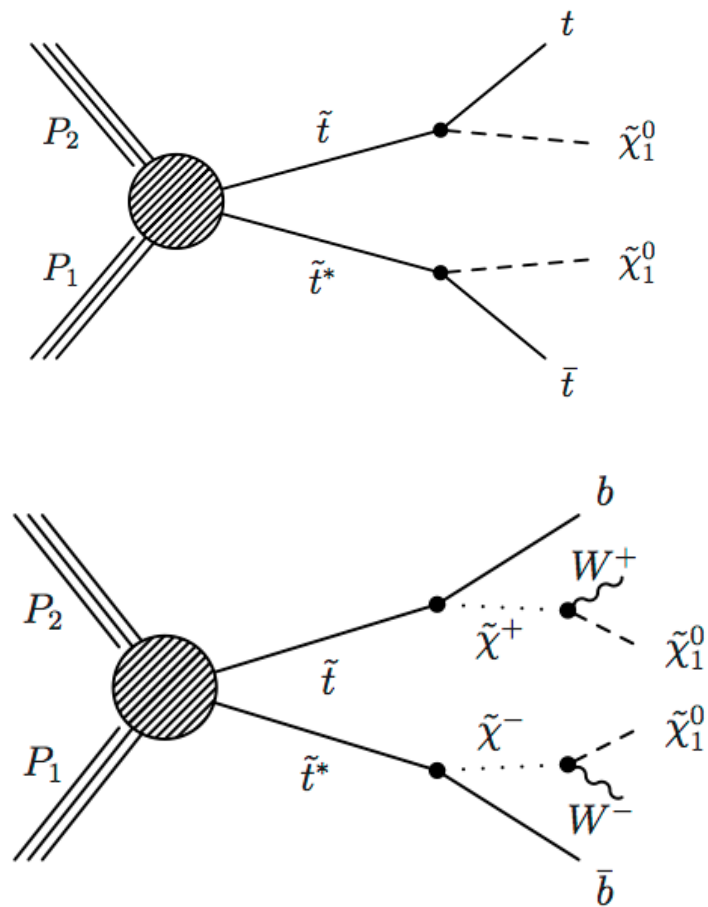
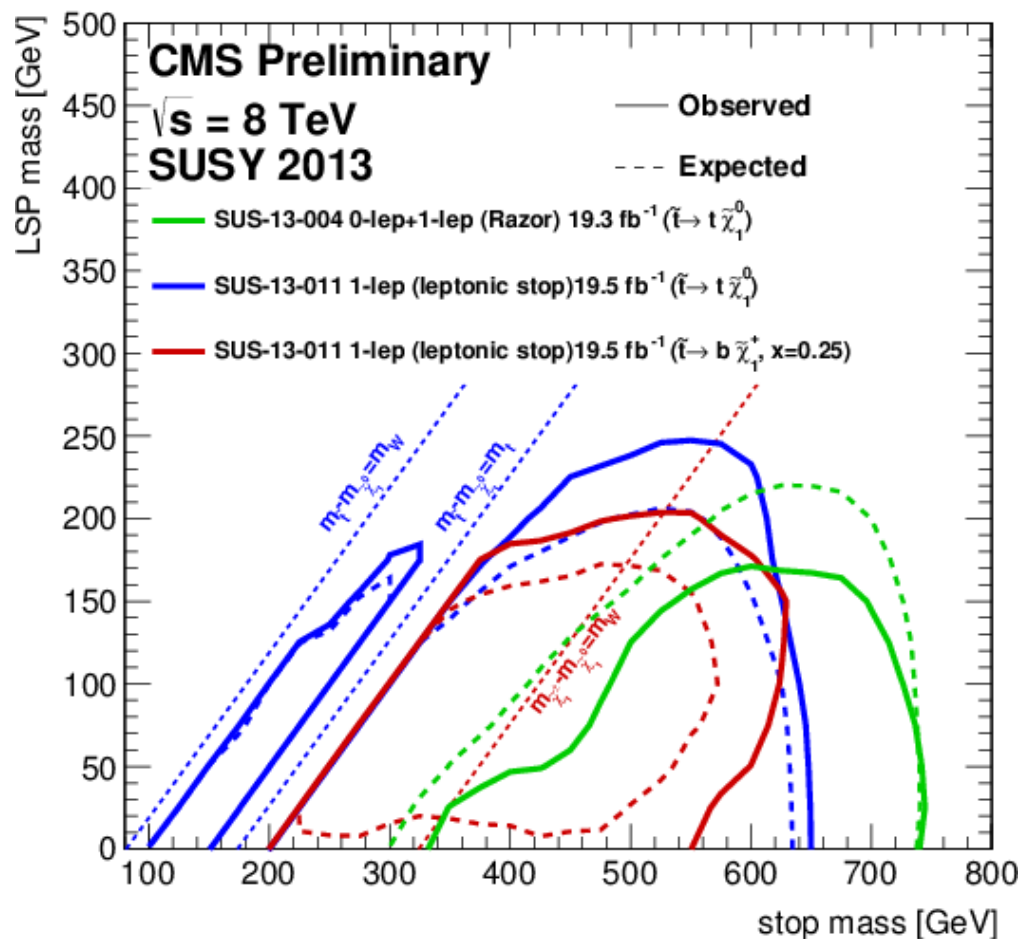
Stop decays and final states





Stop-neutralino mass reach summary

$\tilde{t}\tilde{t}^*$ production



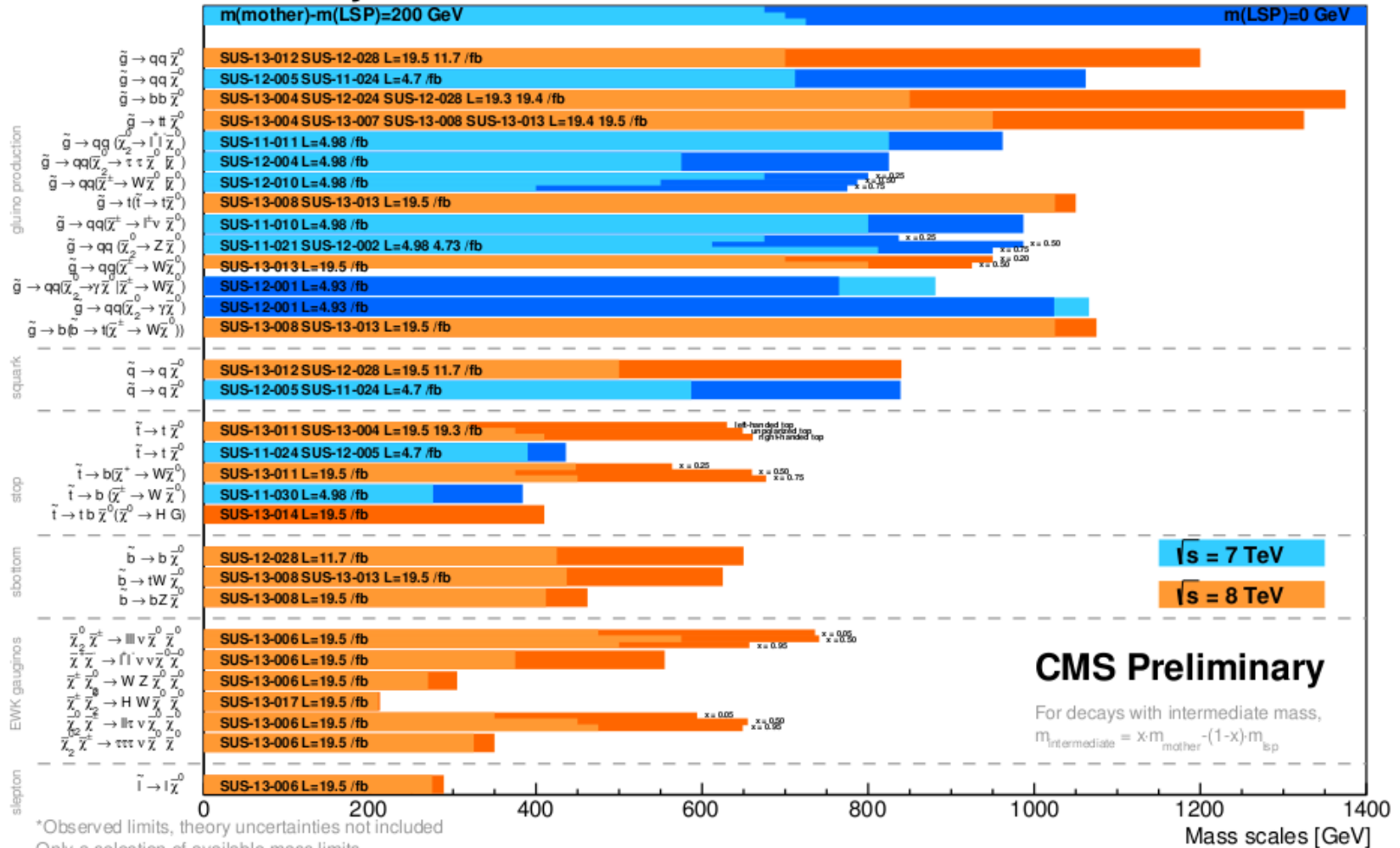




Summary of SMS mass limits

Summary of CMS SUSY Results* in SMS framework

SUSY 2013



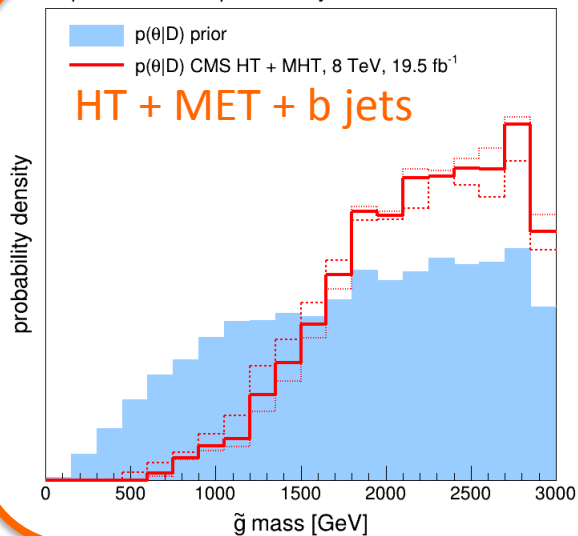
*Observed limits, theory uncertainties not included
 Only a selection of available mass limits
 Probe *up to* the quoted mass limit



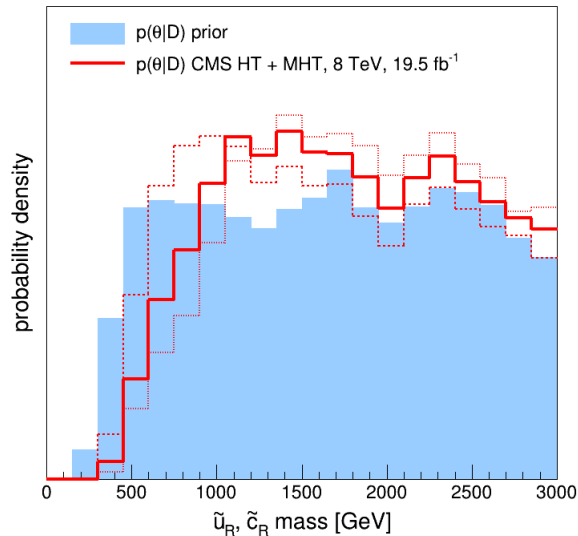
pMSSM interpretation of inclusive searches



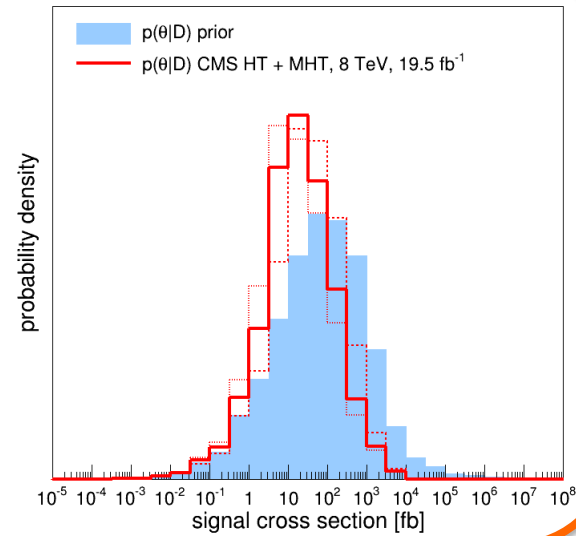
pMSSM, CMS preliminary



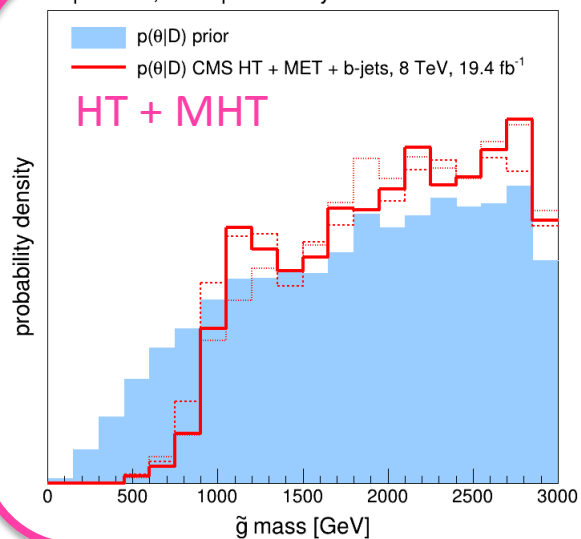
pMSSM, CMS preliminary



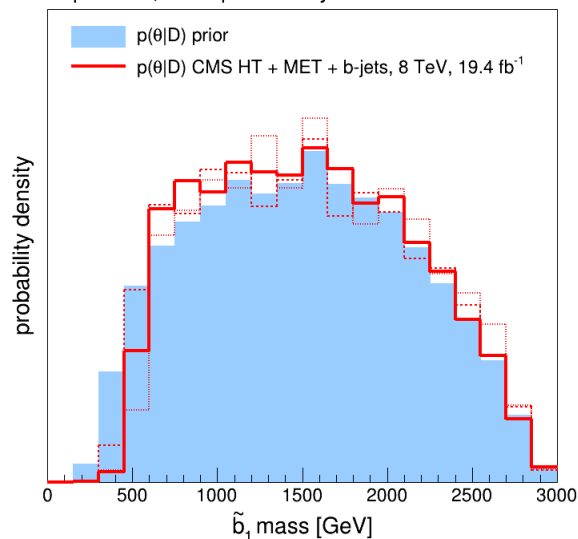
pMSSM, CMS preliminary



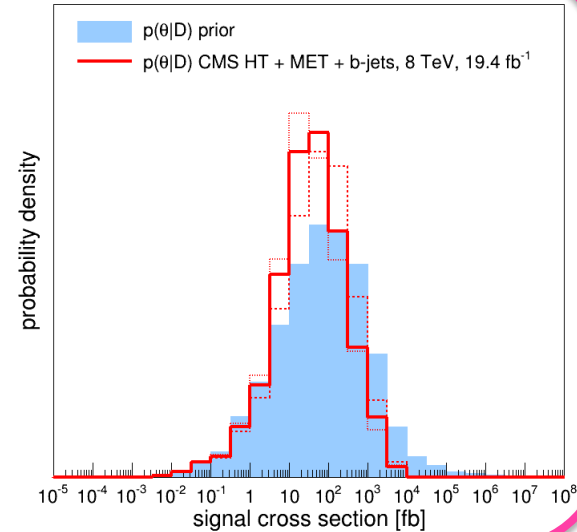
pMSSM, CMS preliminary



pMSSM, CMS preliminary



pMSSM, CMS preliminary



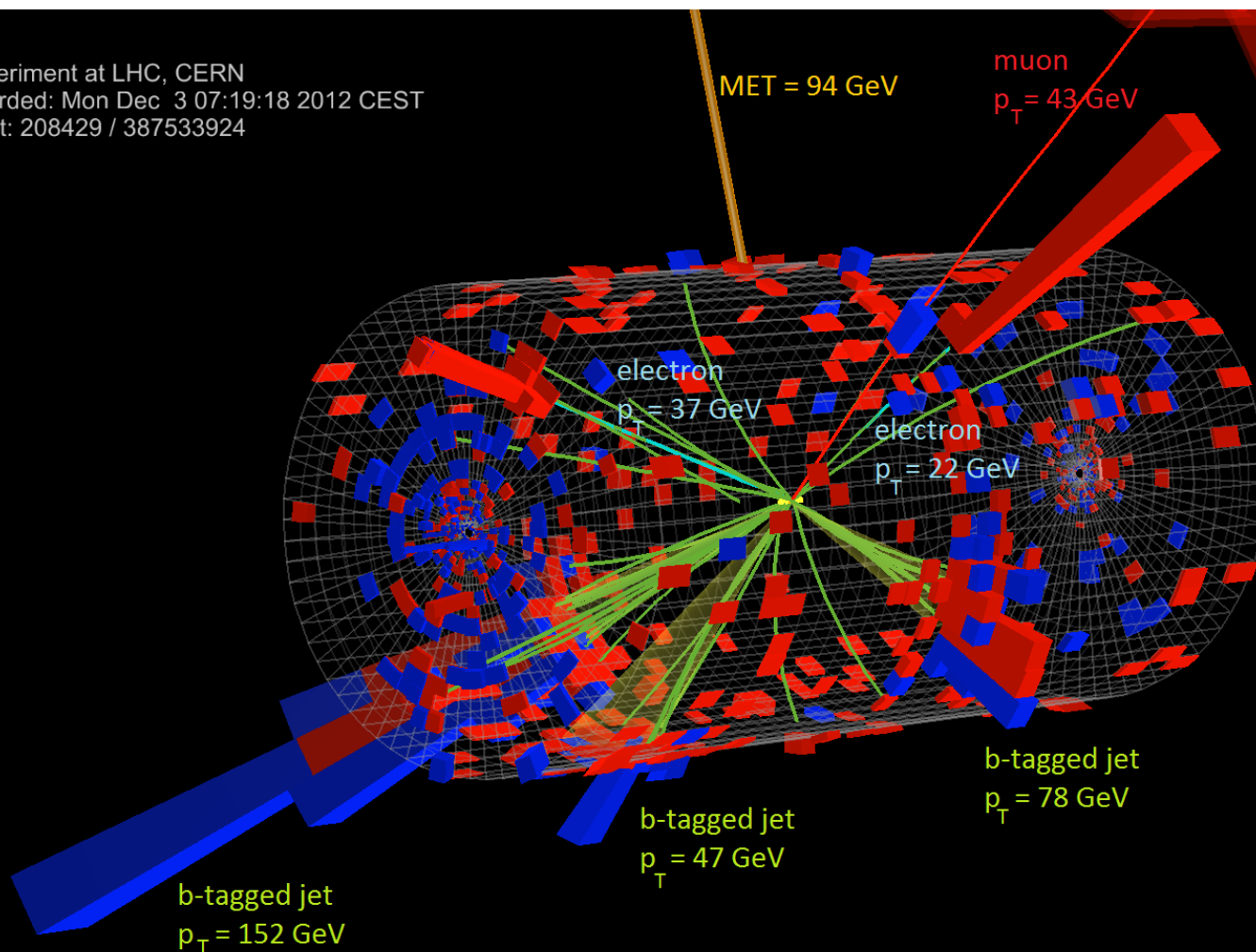


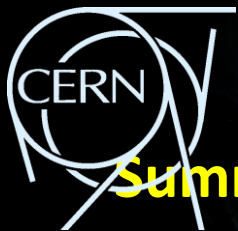
Could this be SUSY?

A spectacular 3 leptons + 3-b jets + high missing E_T event at CMS.

CMS-PAS-SUS-13-008

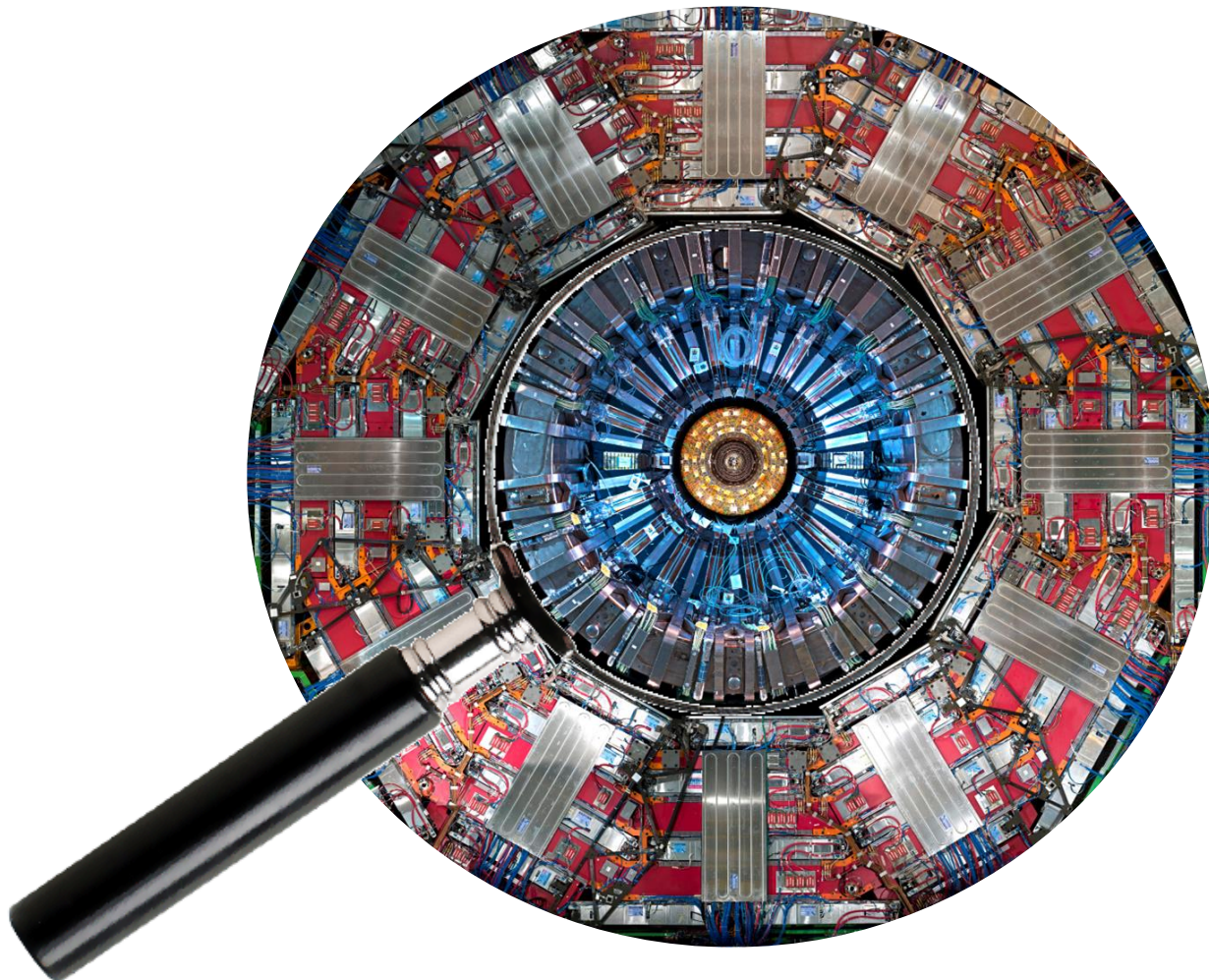
CMS Experiment at LHC, CERN
Data recorded: Mon Dec 3 07:19:18 2012 CEST
Run/Event: 208429 / 387533924





Summary

- CMS has conducted a rich variety of searches with up to 19.5 fb^{-1} of 8 TeV proton proton data – but data is (more or less!) consistent with the SM.
- So we entertain ourselves with disfavoring models and setting limits.
- We've probed gluinos up to 1.3 TeV, squarks up to 800 GeV and stops up to 750 GeV.
- We are focusing more on difficult scenarios with low cross sections, low MET, with compressed spectra (soft objects) and with kinematics resembling the SM.
- We are trying to see Higgs being born from SUSY decays.
- And we are getting ready for the 13-14 TeV run in 2015!



No
SUSY
yet?



**KEEP
CALM
AND
SEARCH
ON**

BACKUP SLIDES





Background estimation methods

Sideband method

Used in searches for resonances, where the BG has a **smooth, well-described shape**, and the signal peaks over the BG.

- Define a signal region, and the signal-free control regions, i.e. the **sideband regions** around the signal.
- Deduce the **shape of the BG from the sidebands** (polynomial, exponential, etc.?)
- **Extrapolate the BG** in sidebands to the signal region.
- Either **count** the extrapolated events under the signal peak – or -- **fit** the data distribution to BG shape + signal shape and extract the parameters of the BG function.

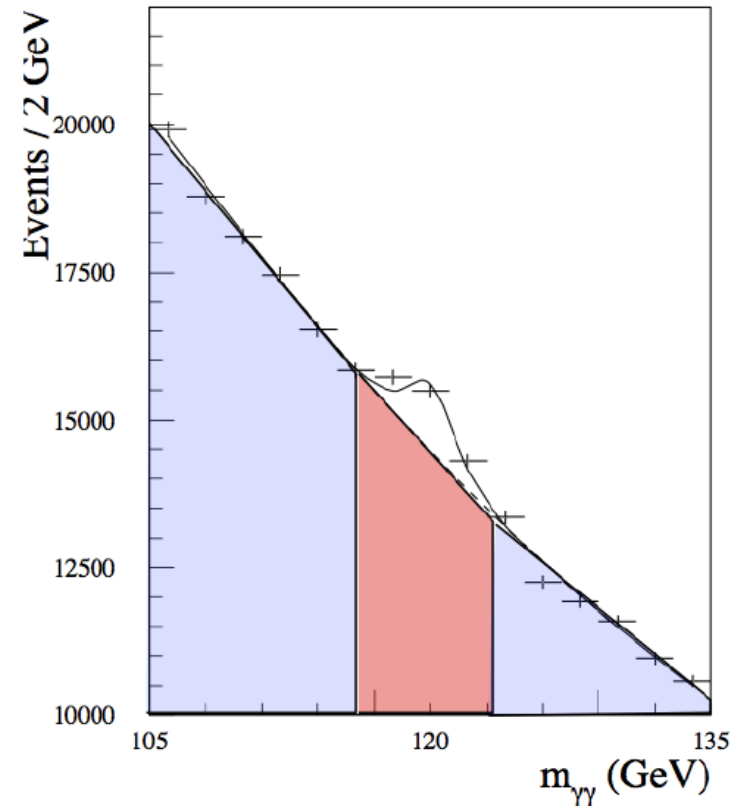


Figure from P. Govoni HCP2011 lectures

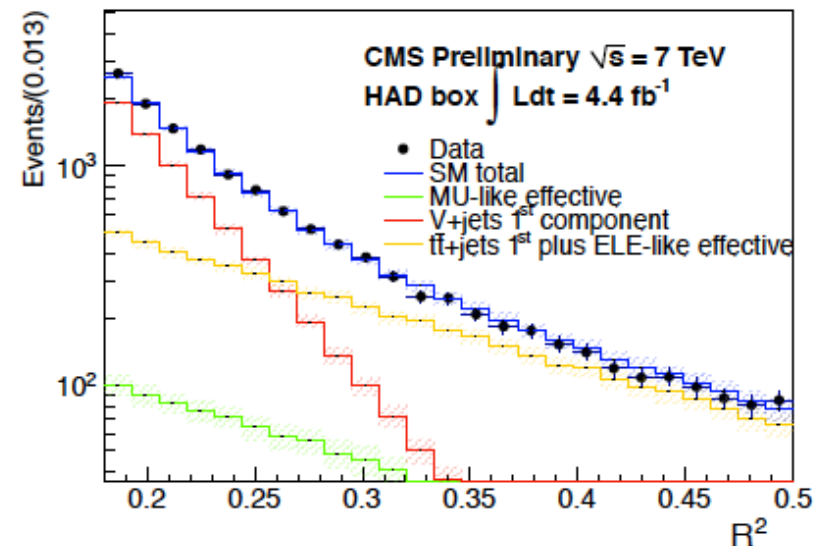
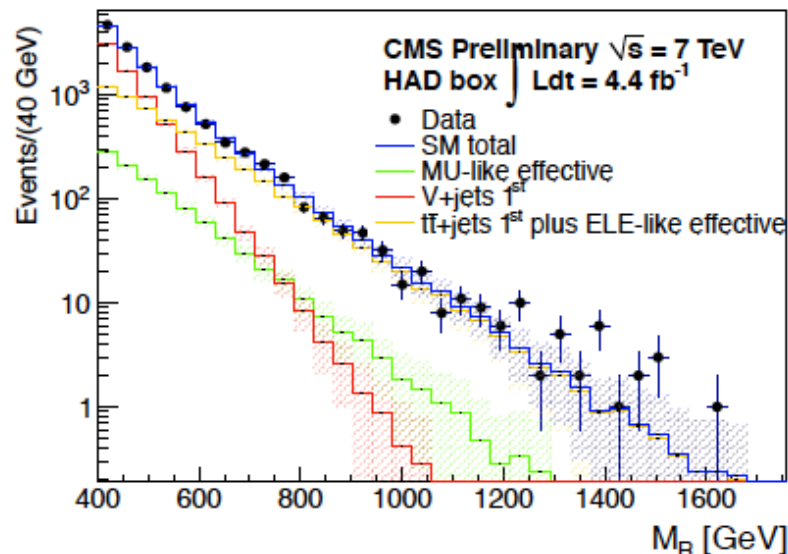


Background estimation methods

Fitting to an analytical function

Sometimes the BG is well-described by an **analytical function**. In these cases

- Find a control region dominated by the BG.
- Find an analytical function that describes the BG well.
- Fit the data to this analytical function in the control region and find the parameters of the analytical function.
- Extrapolate the fit to the signal region.



CMS razor analysis employs a fit to a 2D exponential-like function.



Background estimation methods

The matrix – or ABCD - method

When there exist two variables x and y for which the BG is **uncorrelated**, i.e. factorizable:

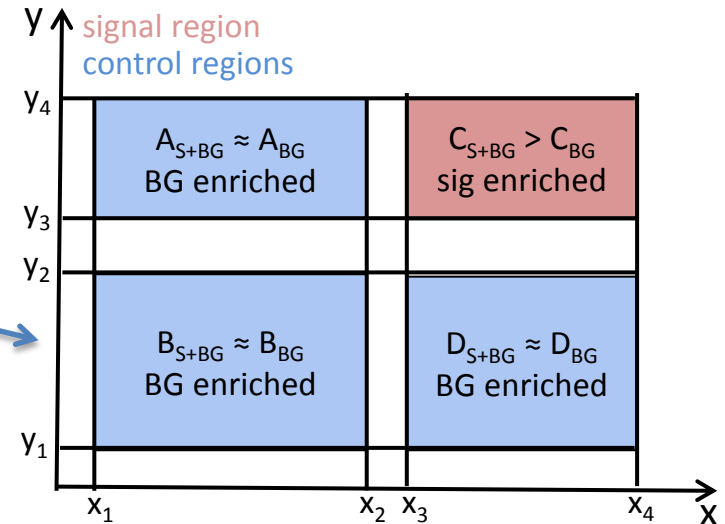
$$f^{BG}(x, y) = f^{BG}(x) \cdot f^{BG}(y)$$

- Apply **all cuts except those on x and y** on data
- Divide the x - y plane into 4-regions:
- When there is no signal, we have

$$\frac{N_A^{BG}}{N_C^{BG}} = \frac{N_B^{BG}}{N_D^{BG}}$$

- In the presence of signal, C will be contaminated by the signal. But we can estimate the number of BG events in C from

$$N_A^{BG} = \frac{N_B^{BG} \cdot N_C^{BG}}{N_D^{BG}}$$



Note: Always beware the **signal contamination in the control regions**.
Add it as a **systematic**.



Background estimation methods

Fake rates method

The ratios of objects found by a tight identification over objects found by a loose identification is widely used as a BG estimation tool.

Suppose we would like to estimate QCD in a signal region that has leptons. Real leptons come from the signal and fake leptons come from QCD (jets faking leptons). We define two event selections with loose and tight lepton ID criteria, which can be decomposed as:

$$N_{loose} = N_{loose}^{real} + N_{loose}^{fake}$$

$$N_{tight} = N_{tight}^{real} + N_{tight}^{fake}$$

$$\epsilon^k \equiv N_{tight}^k / N_{loose}^k \rightarrow \epsilon^{real} N_{loose}^{real} + \epsilon^{fake} N_{loose}^{fake}$$



Background estimation methods

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Get these
counts from
data

$$\begin{aligned} N_{loose} &= N_{loose}^{real} + N_{loose}^{fake} \\ N_{tight} &= N_{tight}^{real} + N_{tight}^{fake} \end{aligned}$$

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N_{loose}

$$= N_{loose}^{real} + N_{loose}^{fake}$$

N_{tight}

$$= N_{tight}^{real} + N_{tight}^{fake}$$

$$\epsilon^k \equiv N_{tight}^k / N_{loose}^k \rightarrow = \epsilon^{real} N_{loose}^{real} + \epsilon^{fake} N_{loose}^{fake}$$

Find the ID efficiency, using e.g. tag
and probe method.

Find this efficiency, i.e. the fake rate
using e.g. a QCD control sample (e.g.
low MET)



Background estimation methods

Fake rates method

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Get these counts from data

$$\begin{aligned} N_{loose} &= N_{loose}^{real} + N_{loose}^{fake} \\ N_{tight} &= N_{tight}^{real} + N_{tight}^{fake} \end{aligned}$$

Solve the two equations simultaneously to get these numbers.

$$\epsilon^k \equiv N_{tight}^k / N_{loose}^k \rightarrow \epsilon^{real} N_{loose}^{real} + \epsilon^{fake} N_{loose}^{fake}$$

Find the ID efficiency, using e.g. tag and probe method.

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Background estimation methods

Fake rates method

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Get these counts from data

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Solve the two equations simultaneously to get these numbers.

$$\epsilon^k \equiv N_{tight}^k / N_{loose}^k \rightarrow \epsilon^{real} N_{loose}^{real} + \epsilon^{fake} N_{loose}^{fake}$$

Find the ID efficiency, using e.g. tag and probe method.

Find this efficiency, i.e. the fake rate using e.g. a QCD control sample (e.g. low MET)

Finally obtain the number of BG events from $\epsilon^{fake} N_{loose}^{fake} = N_{tight}^{fake} = N_{BG}$



Background estimation methods

Replacing particles: $Z \rightarrow \nu\nu$ from $Z \rightarrow \mu\mu$

$Z \rightarrow \nu\nu$ is a troublesome irreducible BG for the **hadronic searches that use high MET**. But we can **use the $Z \rightarrow \mu\mu$ events to estimate the BG contribution from $Z \rightarrow \nu\nu$** , because $Z \rightarrow \nu\nu$ and $Z \rightarrow \mu\mu$ events have **same kinematic characteristics**.

- Select a $\mu^+\mu^-$ sample with $m(\mu^+\mu^-)$ in the Z mass range (we assume this sample is signal-free).
- **Count the muons as MET**, i.e.: add muon momenta to MET and recalculate the MET.
- Apply the MET cut and count the observed events. The $Z \rightarrow \mu\mu$ can be estimated from

$$N_{Z \rightarrow \nu\nu}^{estm} = \frac{N_{\mu\mu}^{obs} - N_{\mu\mu}^{BG}}{A_{\mu\mu}^{GEN} \cdot \epsilon_{\mu}} \cdot R \left(\frac{BR(Z \rightarrow \nu\nu)}{BR(Z \rightarrow \mu\mu)} \right)$$

Diagram illustrating the components of the equation:

- $N_{\mu\mu}^{obs}$: Number of observed $\mu\mu$ events
- $N_{\mu\mu}^{BG}$: non- $Z \rightarrow \mu\mu$ BG in the $\mu\mu$ sample
- $A_{\mu\mu}^{GEN}$: $Z \rightarrow \mu\mu$ selected / total $Z \rightarrow \mu\mu$ in generator level
- ϵ_{μ} : muon reconstruction efficiency
- R : ratio of branching ratios



Background estimation methods

Using flavors – opposite flavor subtraction

Suppose we have a signal and a BG with **dilepton final state** where

- for the signal, flavors of the two leptons are **correlated** (i.e. decays to same flavor (SF), ee or $\mu\mu$ alone, but not to opposite flavor (OF), $e\mu$) - e.g. Z/Z' decays, neutralino decays, etc.
- for the BG, flavors of the two leptons are **uncorrelated** (i.e. decays to ee, $\mu\mu$ and $e\mu$) - e.g. $t\bar{t}$, WW .

The amount of BG in the SF and OF regions can be **related via branching ratios** (for $t\bar{t}$, $N_{SF} = N_{OF}$).

Thus, to estimate the BG in SF region:

- Count the events in the OF region
- Correct the number for branching ratios and lepton ID efficiencies.

	<div>ee S+BG signal region</div>
<div>$\mu\mu$ S+BG signal region</div>	<div>$e\mu$ BG BG region</div>