Topical SUSY Results from CMS

"What Next @ LHC?"
TIFR, Bombay, India
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Sunil Somalwar
Rutgers, the State University of New Jersey
USA

Outline

➔Organizers: “Make the talk (graduate) student friendly”

- “Why SUSY?” by analogy (theorists can ignore this)
- SUSY search considerations
- CMS SUSY searches survey (strong production)

- Intermission: SM background determination with multilepton search as an example (experimentalists: ignore)

- Electroweak (and “ElectroHiggs”) searches

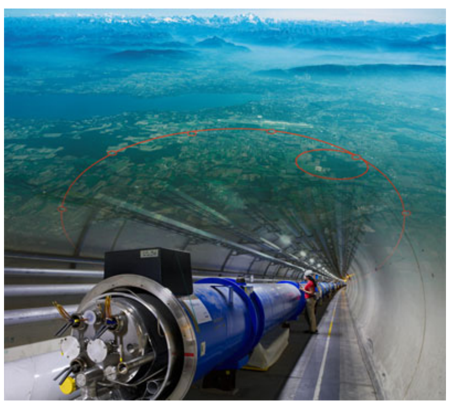
- Apologies to ATLAS colleagues: This talk was (approved and) written as a CMS talk and the holidays made it difficult to include ATLAS results and clear the talk with ATLAS.

Searching for SUSY

Latest results from CMS:

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

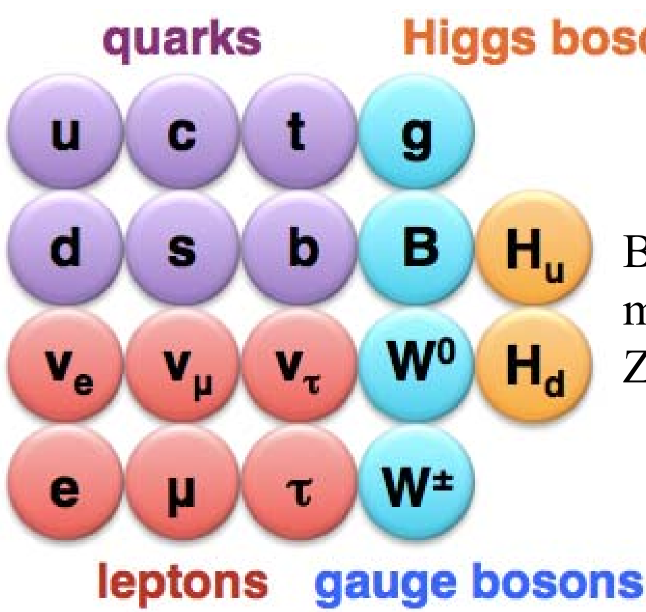
(or search for "cms susy results")



Conventional “SUSY 101”

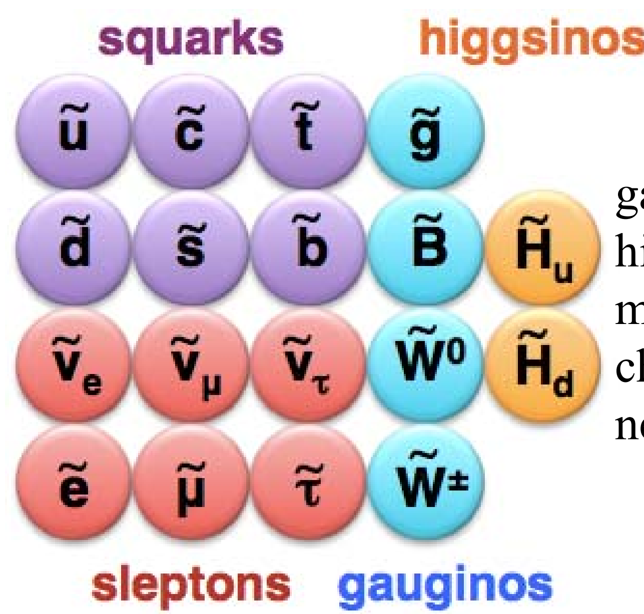
New spin-based symmetry relating fermions and bosons

SM Particles



B & W^0 mix to give Z & γ

SUSY Particles



gauginos & higgsinos mix to give charginos & neutralinos

If R-Parity is conserved, provides Dark Matter Candidate (Lightest Supersymmetric Particle or LSP)

- R-parity = $(-1)^{3(B-L)+2s}$ → R = +1 (-1) for SM (SUSY) particles

Supersymmetry Motivation by Analogy

Doubling the spectrum (particle → sparticle) is a big price.

→Worked once before: Assembling the electron (Murayama, TASI Lectures)

Electron $q=1.6\times10^{-19}$ Coul , radius $< 10^{-19}$m

[200GeV ~ 10^{-18}m ➔ $r_e < 10^{-18}$m (from g_e), LEP 2006: 10 TeV contact interaction ➔ $r_e < 10^{-20}$m]

$E_{assembly} \sim +q^2/r_e \sim$ 10,000 MeV but $m_e \sim$ 0.5 MeV

➔Large *negative* correction

m_e = 0.5 MeV = -9999.5 MeV + 10,000 MeV

FIX: Double the particle spectrum! positron i.e., new physics at ~$2m_e$ ~1MeV~200fm

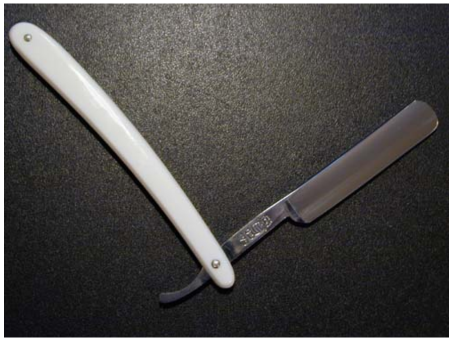
Weisskopf (1939): $E_{assembly} \sim +q^2/r_e$ cancelled by $E_{vacuum\ pair} \sim -q^2/r$ (e^+ from vacuum)

$$(m_e c^2)_{obs} = (m_e c^2)_{bare}\left[1 + \frac{3\alpha}{4\pi}\log\frac{\hbar}{m_e c r_e}\right]$$

Occam’s Razor: Particle Physics Version

We like doubling the particle spectrum.

Single Blade (electron)

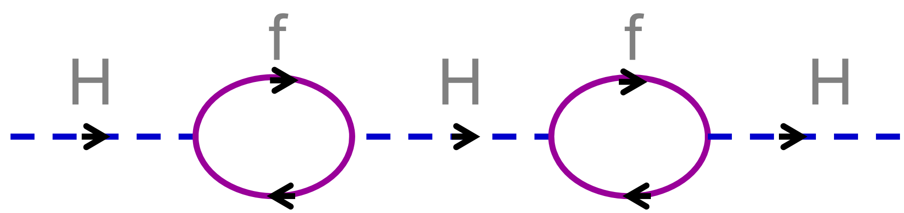


Twin Blade
(electron & positron)

Multiple Blades
(electron, positron, selectron?...)

SUSY: Why?

Today: Higgs has the same "hierarchy problem".



Radiative loops: $M_H \sim 10^{15}$ GeV, but Higgs at 100 GeV (EW scale)

Delicate cancellations at high energy

OR

SUSY at TeV scale

- hierarchy problem solution → stop loops cancel the top loops

But SUSY is badly broken. m(selectron) >> 0.5MeV

SUSY-Breaking Defines Phenomenology

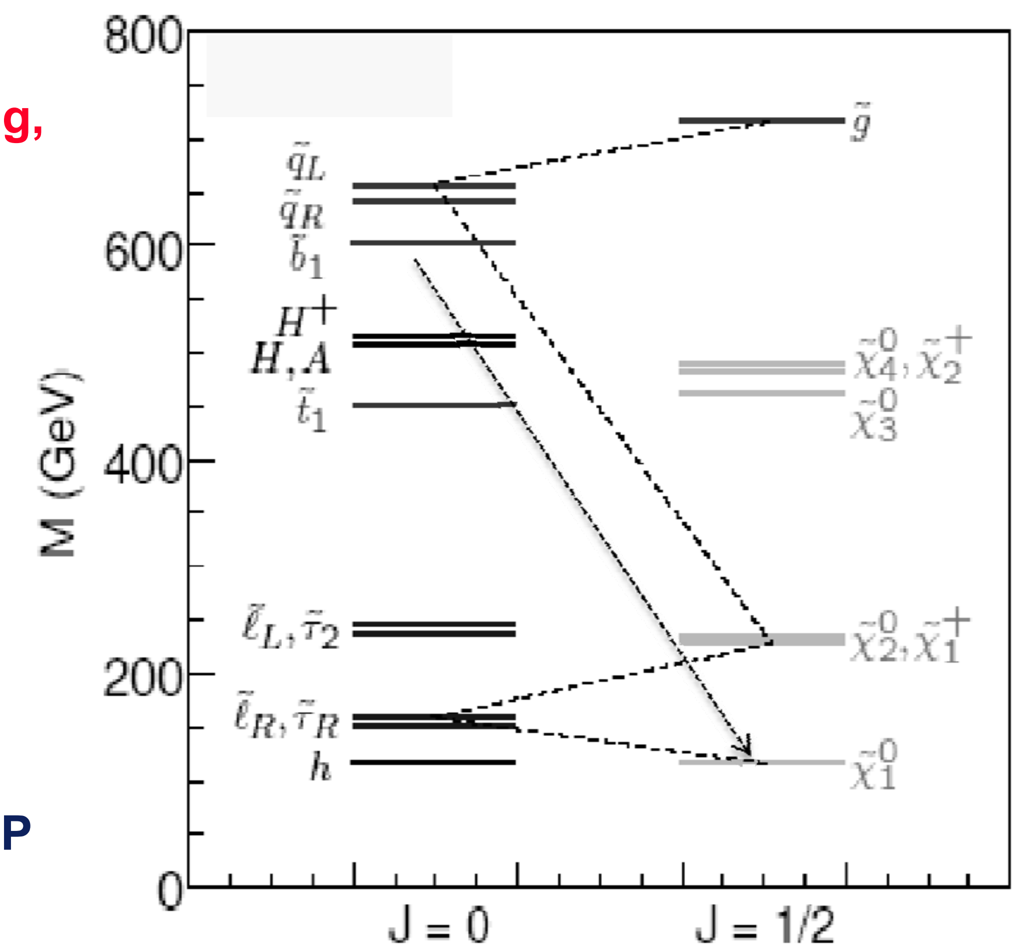
- Signatures depend on SUSY breaking, mass hierarchy and mixing

Many but not all models:
RGE running →

- Strongly interacting particles heavy
- Weakly interacting (middle)

e.g. with R-parity, Stable Lightest Supersymmetric Particle (LSP)

→ Missing E_T (MET) signature (from LSP and neutrinos)

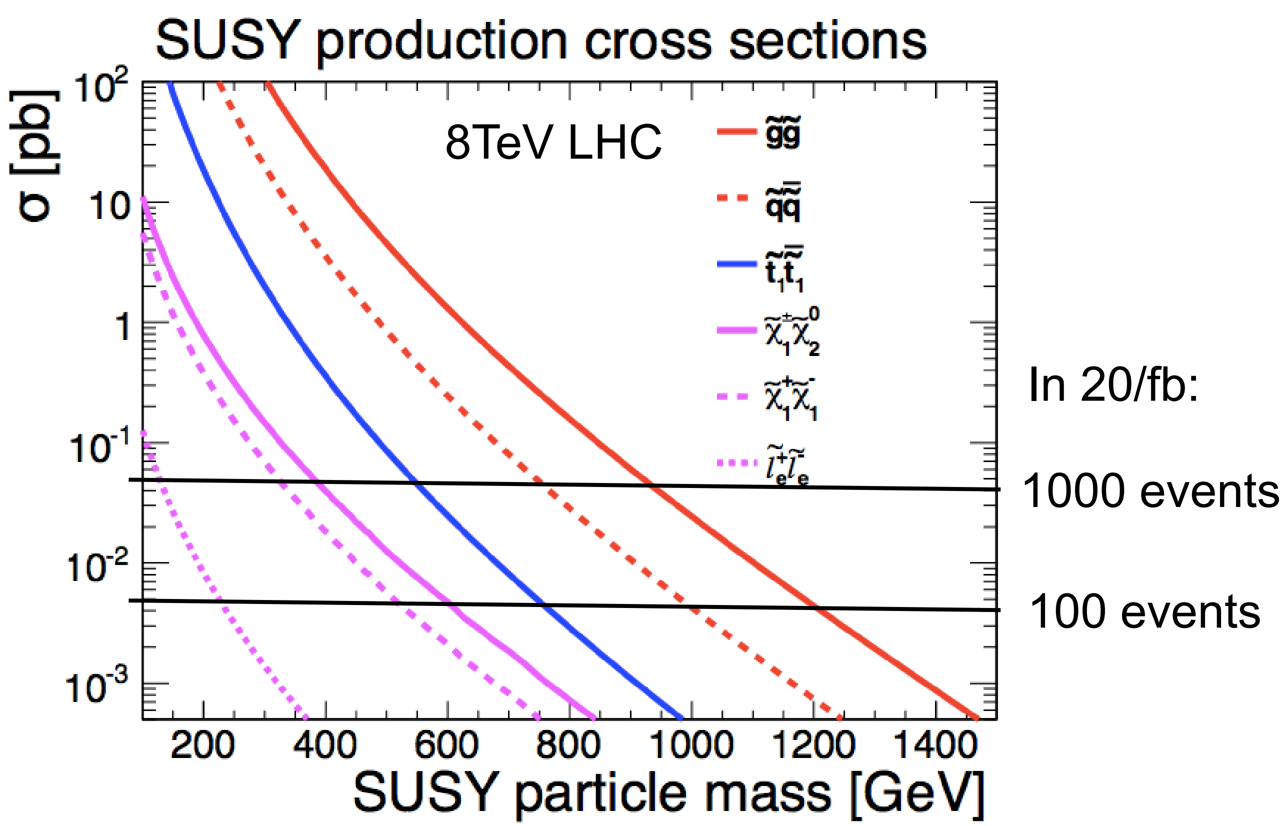


SUSY Search Criteria

- Prompt vs non-prompt (lifetime=?)
- R-Parity conserved? RPV? (nonprompt?)
- Production: Strong or Weak?
- Strong:
  - 3rd Generation (stop/sbottom)? (Naturalness)
  - Squarks/gluinos?
- Electroweak:
  - sleptons
  - gauginos, (electroHiggs?)

→ Map onto: leptons (taus), photons, Jets/HT, MET, ST

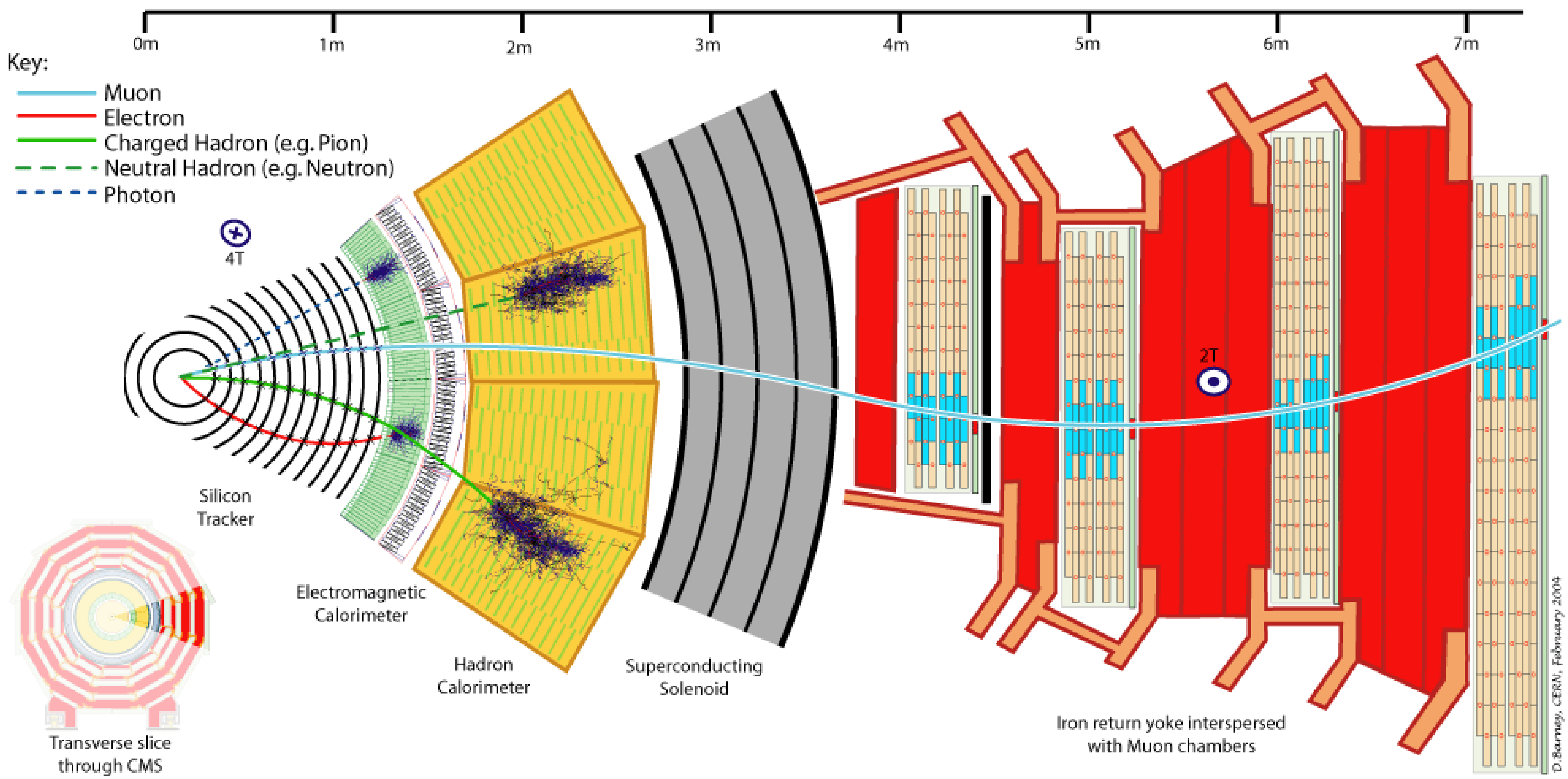
SUSY Particle Production at the LHC



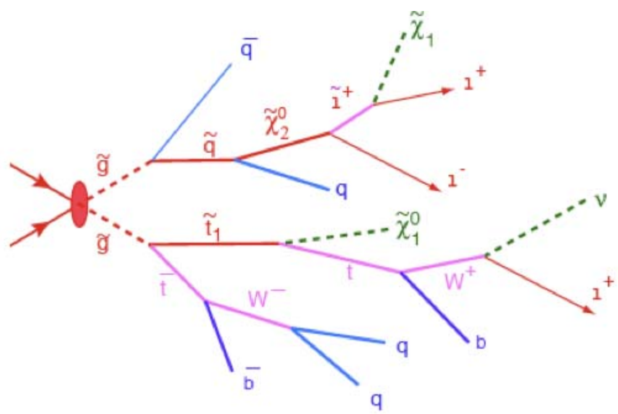
[arXiv:1206.2892]

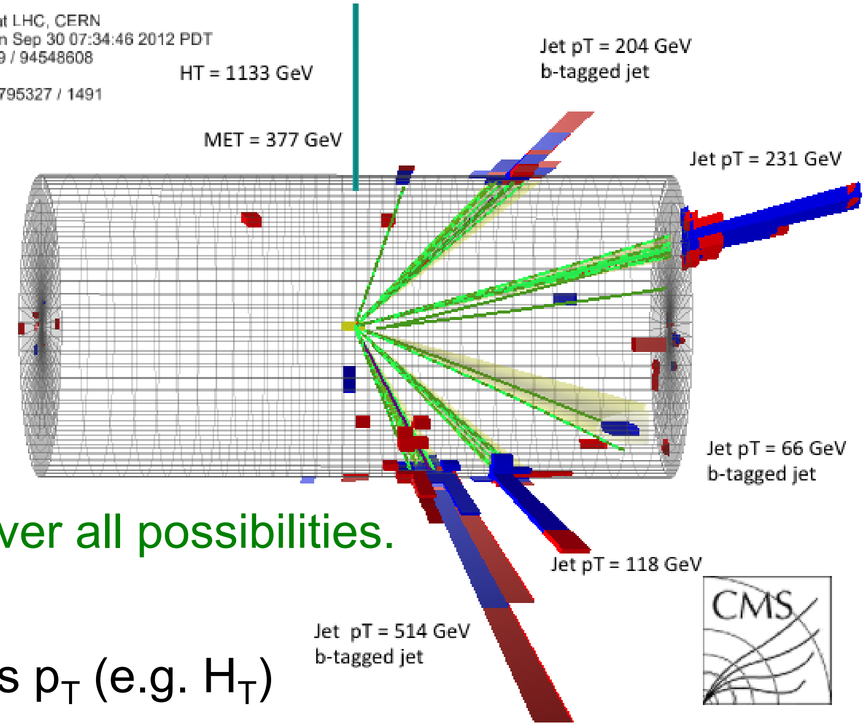
- Gluinos, 1st & 2nd generation squarks
  - High cross sections
  - *Thermal Detection ☺*
- 3rd generation squarks (stops, sbottoms)
  - Moderate cross sections
- Charginos, neutralinos, sleptons
  - Small cross sections, but less SM background.

CMS = Compact MUON solenoid



SUSY Signatures





CMS-PAS-SUS-12-024

Topology oriented signature strategy. Cover all possibilities.

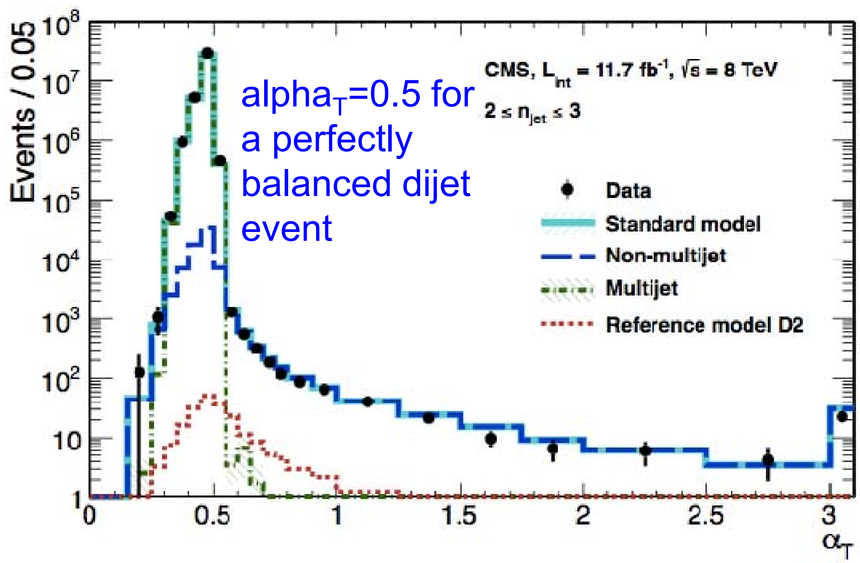
- Jets
  - Number of jets, Number of b-jets, jets p_T (e.g. H_T)
- Leptons:
  - electrons, muons, taus
  - same sign, opposite sign
- MET (Missing Transverse Energy)
- Photons

Kinematic Search Variables

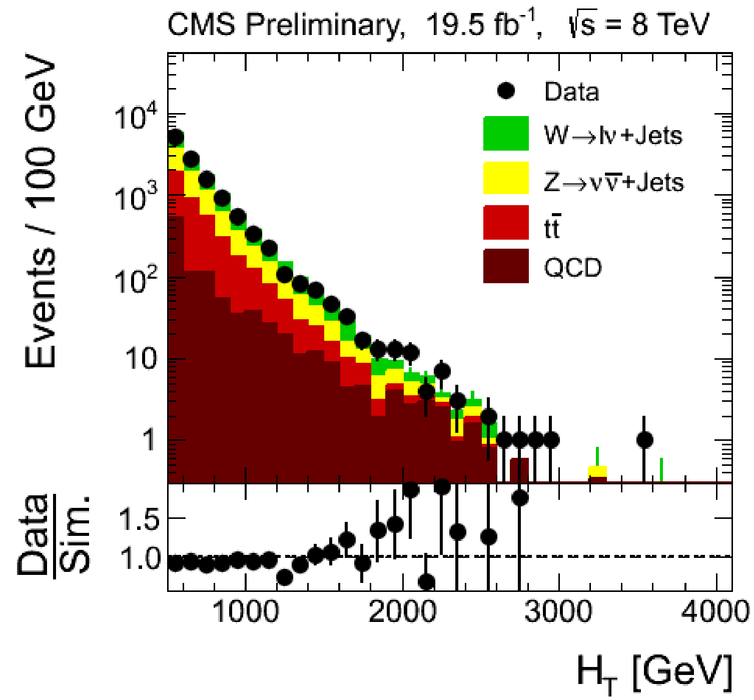
- A variety of discriminating quantities used in SUSY searches
  - Total visible energy (e.g. H_T, M_{eff}), assume 2 LSPs in decay (e.g. MET, M_T, M_{T2}), exploit 2-body nature of decays (alpha$_T$, Razor), particle multiplicities (e.g. N_{jets}, $N_{b\text{-}jets}$), etc…

$$H_T = \sum_{i=1}^{N_{jet}} |\vec{p}_T|$$

$$\alpha_T = E_T^{j2} / M_T = E_T^{j2} / \sqrt{H_T^2 - \not{H}_T^2}$$



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



CMS-PAS-SUS-13-012

Next

➔SUSY searches: strong production

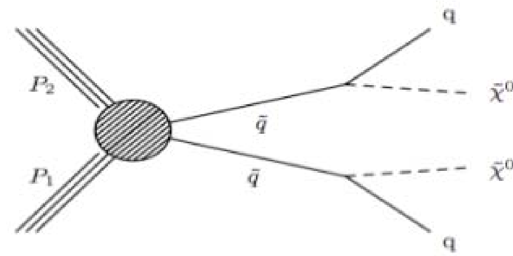
- Jet/Met Squark/gluinos

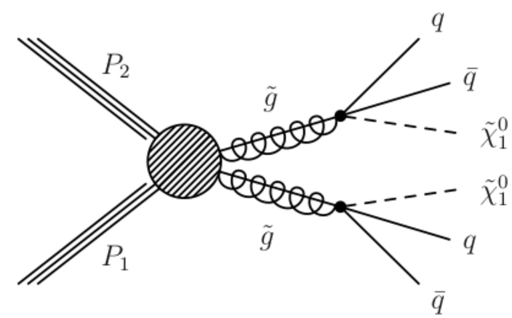
- Naturalness / Third generation
  - Direct stop

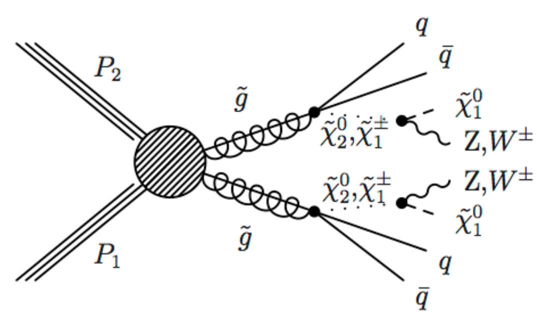
Inclusive Searches for Squarks and Gluinos

- Comprehensive program of inclusive searches for squarks and gluinos
- Signature: jets + MET + “X”
  - e.g. “X” can be with or without leptons
  - e.g. bin in number of jets, b-jets
  - Exploit discriminating kinematic variables
    - Each experiment has their “favorites”.

    For example:
      - CMS: MET, H_T, $alpha_T$, M_{T2}, Razor
      - ATLAS: M_{eff}, MET, MET significance







Jets+H_T+MET Search

$$H_T = \sum_{j=jets} \left|\vec{p}_T^{\,j}\right|$$

$$\not{H}_T = \left|\vec{\not{H}}_T\right| = \left|-\sum_{j=jets} \vec{p}_T^{\,j}\right|$$

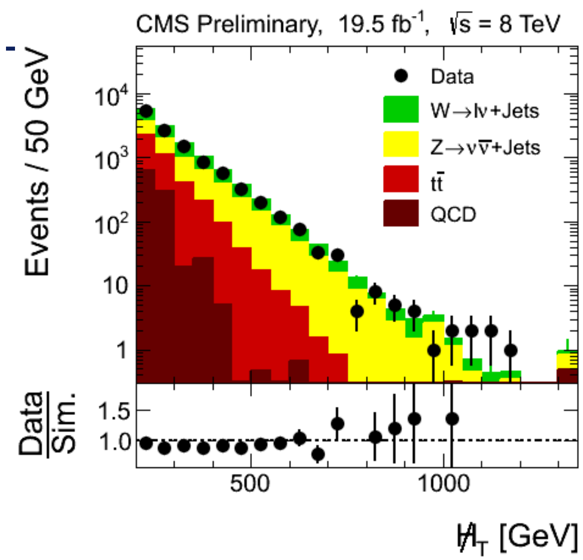
Selection:

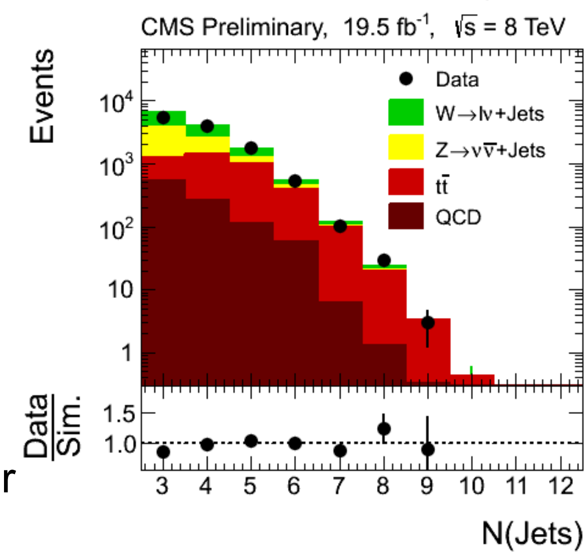
- $N_{jet} \geq 3$ ($p_T > 50$ GeV)
- $H_T > 500$ GeV
- Missing $H_T > 200$ GeV
- Veto event if MH_T vector is ≈ aligned with any of 3 leading jets
- Veto of isolated leptons (e/μ) with $p_T > 10$ GeV

Analysis performed in 36 exclusive bins in (N_{jet}, H_T and MH_T)

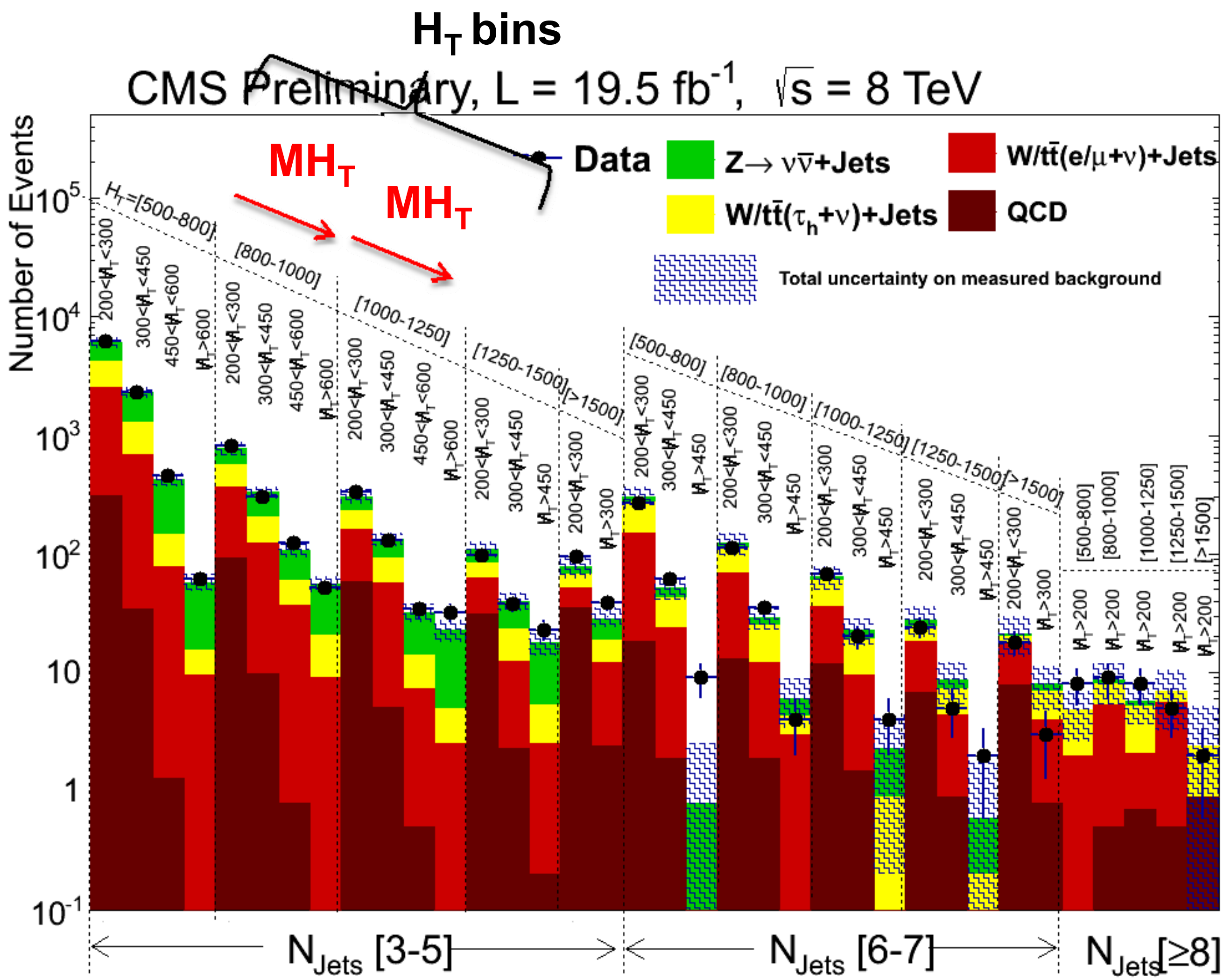
Backgrounds: largely data-driven

- ttbar with W→$l\,\nu$, W→$l\ \nu$ + jets
- ttbar with W→τ (→h) ν , W→τ (→h) ν + jets
  - Control sample: Single- lepton + jets + MH_T
- Z→$\nu\nu$ + jets
  - Control samples: γ + jets, Z($\mu\mu$)+jets
- QCD multijet events
  - re-balance events such that they have no MET, then smear them with jet-response functions



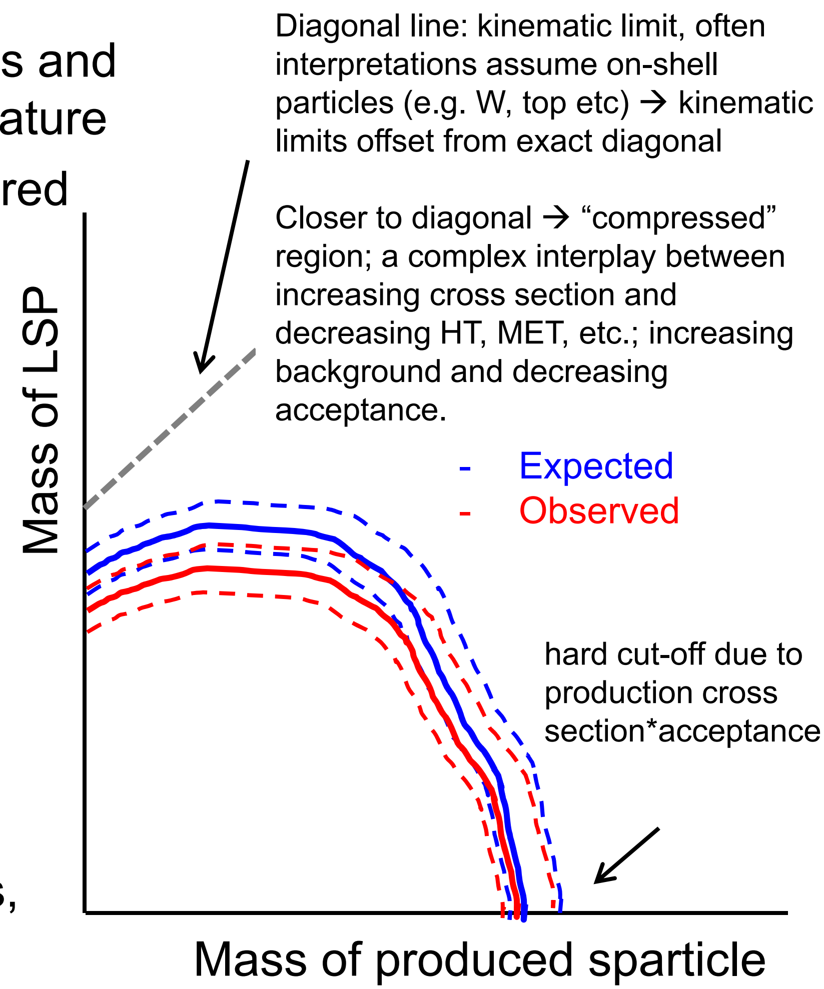


Jets+H_T+MET Search

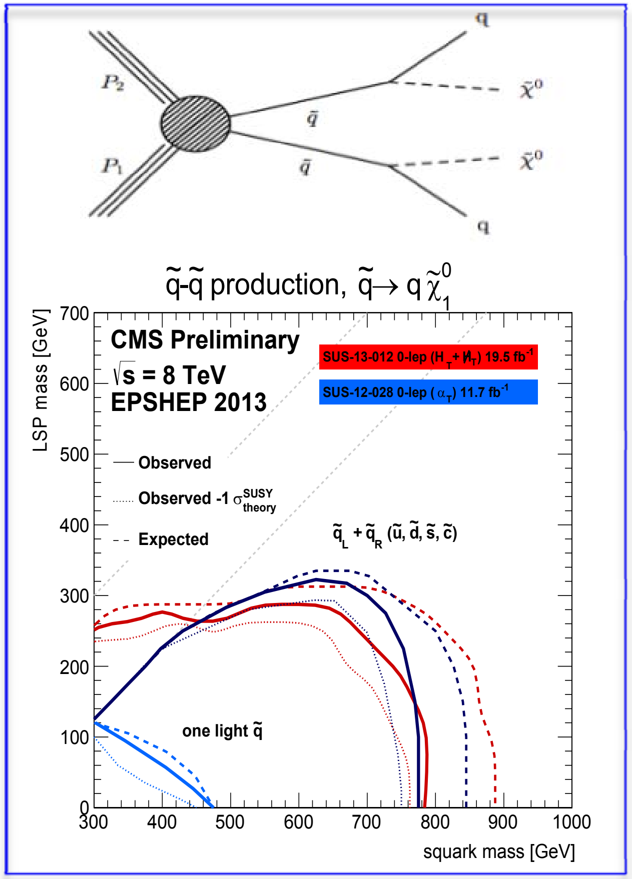


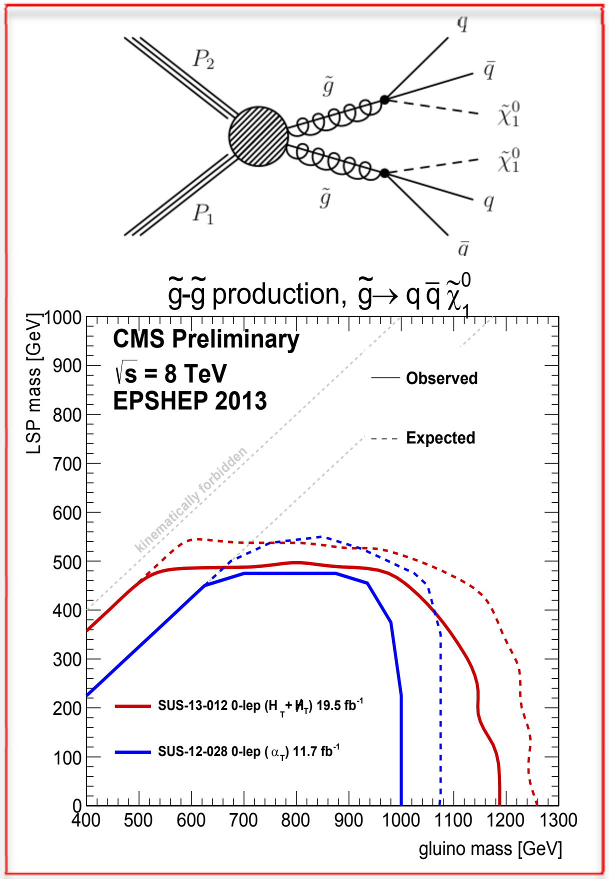
Interpretations: Simplified Models

- Simplified Model Spectra (SMS)
  - Use limited set of new hypothetical particles and decays to produce a given topological signature
  - Assume 100% BR for decay chain considered
- 95% CL upper limits shown
  - Presented in M_{LSP} vs M_{SUSY}
    - M_{SUSY} is mass of the produced sparticle considered
  - Expected, with experimental uncertainty
  - Observed, with theory uncertainty
  - Cross section limits (shown as color map)
- "Typical" systematics
  - Backgrounds: analysis dependent
  - Signal: trigger efficiency, lepton efficiencies, jet energy scale, pileup, ISR, …



Interpretations: Direct and Gluino Mediated Squark Production





- "Best" direct squark (1st & 2nd generation) limits ~800 GeV

  → assuming eight-fold mass degeneracy

  →limits also shown for one light flavor accessible squark

- "Best" gluino mediated limits ~ 1.2TeV

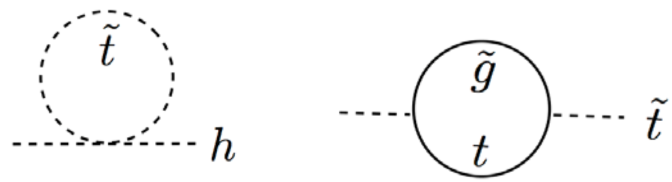
  → assuming 1st and 2nd generation decays for gluinos

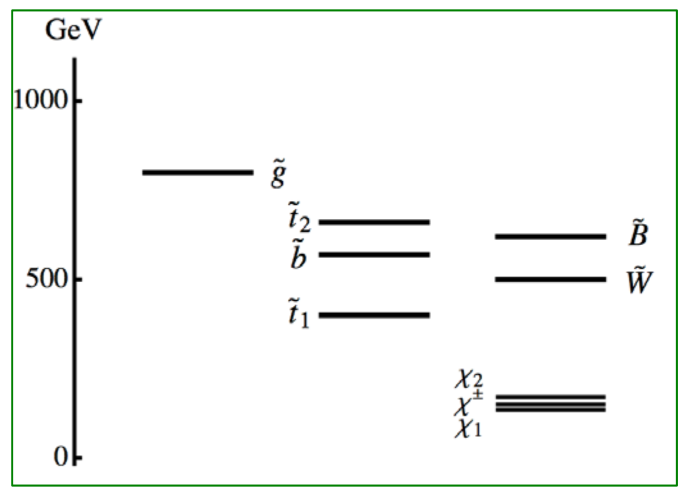
Jets+HT+MET: CMS-PAS-SUS-13-012

alpha$_T$: EPJC 73 (2013) 2568. CMS-PAS-SUS-12-028

“Natural” SUSY Scenarios

- Hierarchy problem:
  - Higgs mass at the weak scale despite the presence of divergent corrections from top quark loops
  - Large cancelations are unnatural
- Solution:
  - SUSY could make this natural
  - top squark adds canceling terms
  - gluino mass should not be too large also so its contributions to the top squark are controlled.
- Leads to “natural” SUSY spectrum:
  - 3rd generation squarks part of “nuclear family”, while the other generations can be heavy and decoupled
  - Some charginos and neutralinos (the higgsinos) at ~ the weak scale.

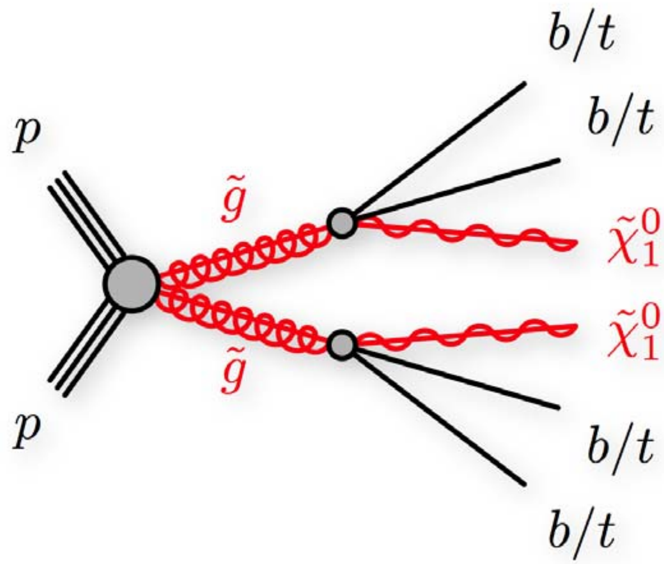




R.Barbieri & D.Pappadopulo JHEP 0910:061,2009

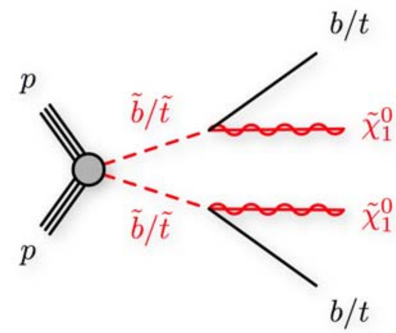
Searches for stops and sbottoms

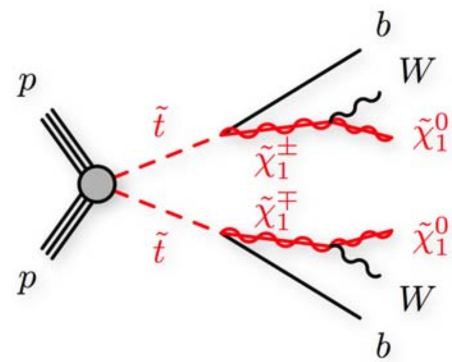
- Gluino mediated searches



Large cross sections.
Spectacular final states.
Many jets and b-jets.

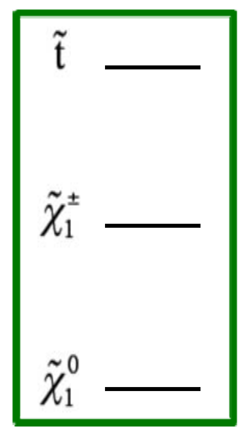
- Direct searches



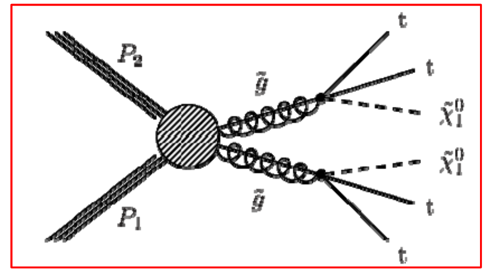


Smaller cross sections.
Many decay modes.
Compressed spectra can make these searches very difficult → close to indistinguishable from top background.

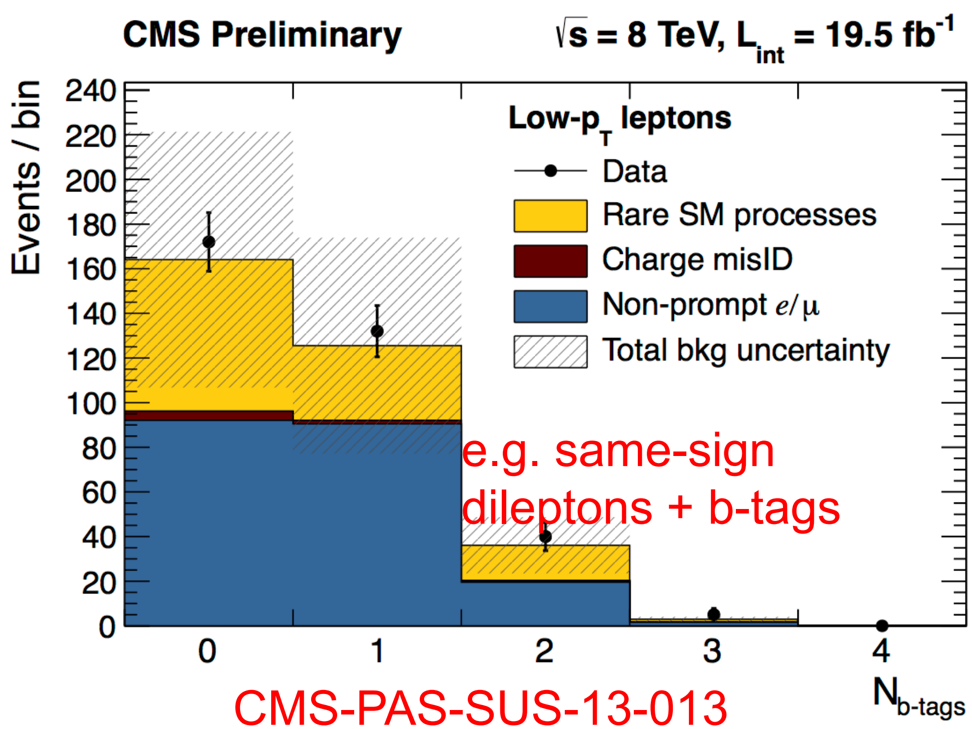
In the decays involving charginos, the stop-chargino-LSP mass hierarchy is important



Gluino Mediated stop Searches



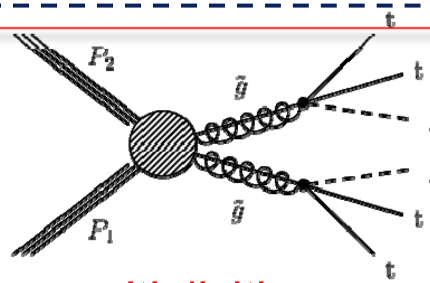
Multi-top final state → searches use 0, 1, 2 leptons + jets + b-jets + MET



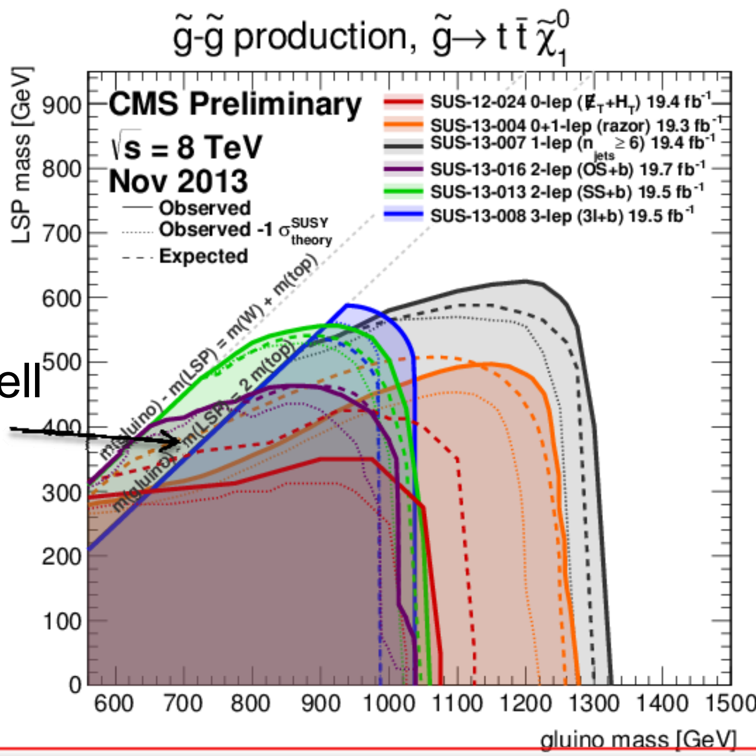
e.g. same-sign dileptons + b-tags

CMS-PAS-SUS-13-013

Interpretations: Gluino Mediated stop and sbottom Searches

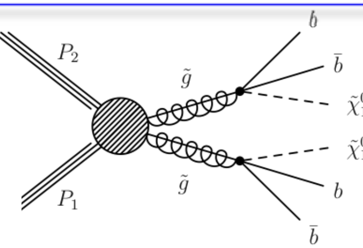


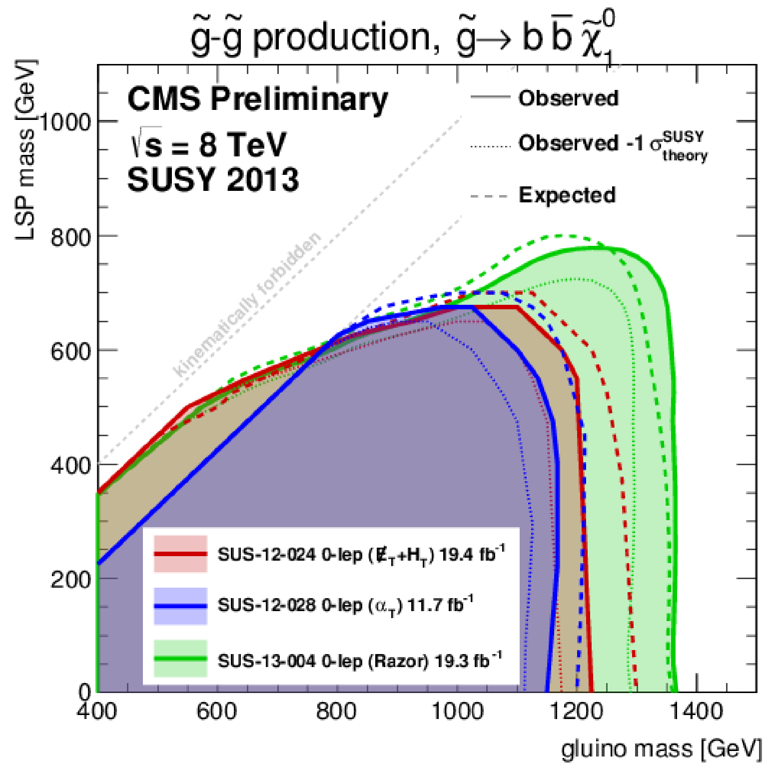
All lepton multiplicities are relevant



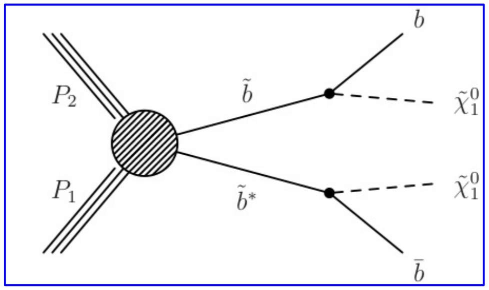
off-shell top

"Best" limits ~1.2-1.4 TeV



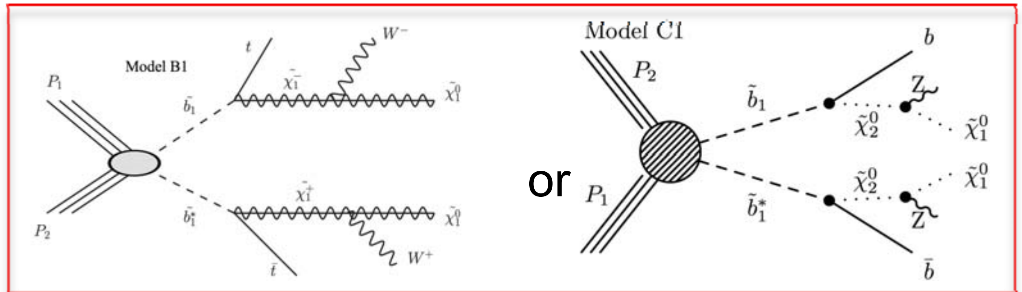


Interpretations: Direct sbottom Searches

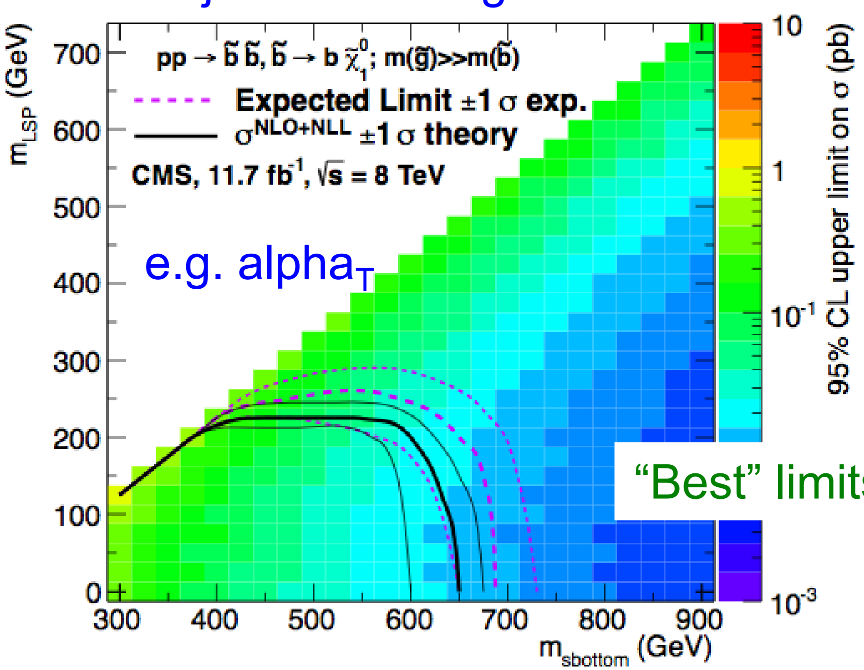


2 b-jets + MET signature

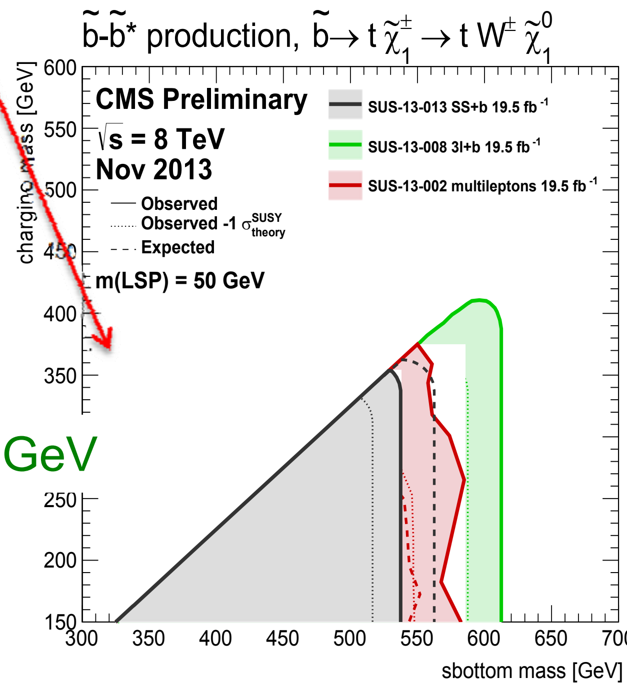
or



leptons + jets + b-jets + MET



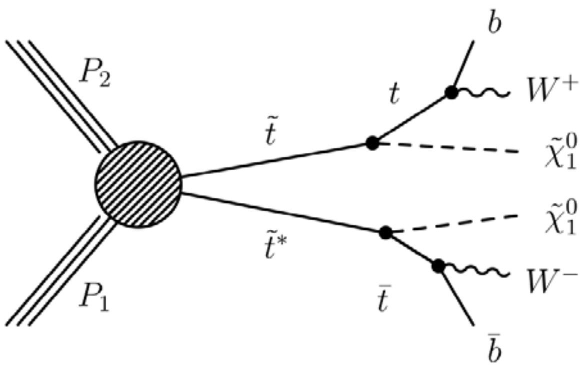
"Best" limits ~650 GeV

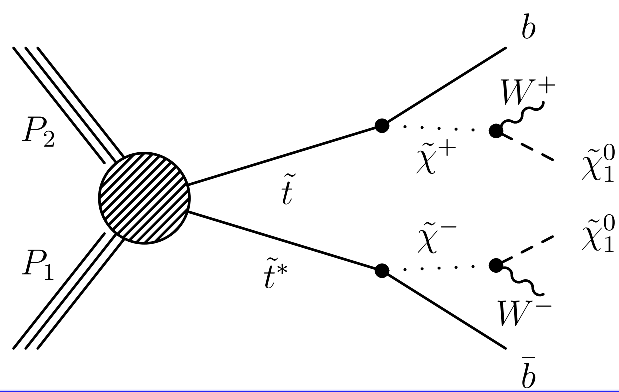


CMS-PAS-SUS-12-028

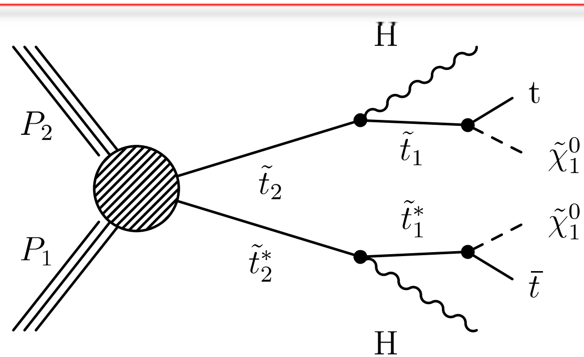
Direct stop Searches

- Challenging analyses. Dominant backgrounds from top pair production and V+jets.
- Make use of shapes of kinematic variables (e.g. M_T, razor) and MVA's (e.g. BDT)
- Searches target 2-body/3-body decays & on/off-shell top regions





Signal looks like "ttbar + MET" from the invisible LSPs



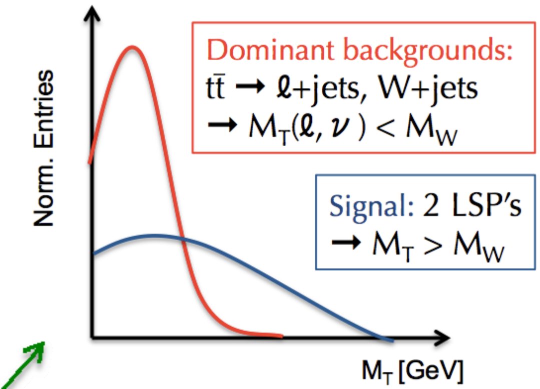
Recent

Again, signal looks like ttbar + X.
Target mass splitting (stop1-LSP) at M_{top}.

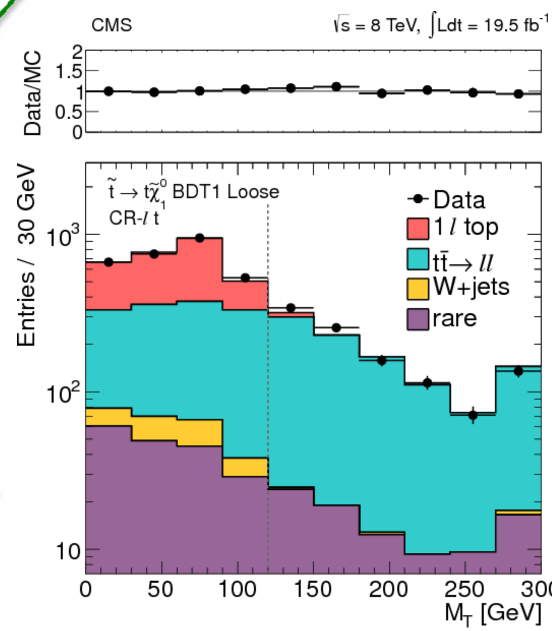
CMS PAS-SUS-13-011
Submitted to EPJC

Direct stop Search -Single lepton channel

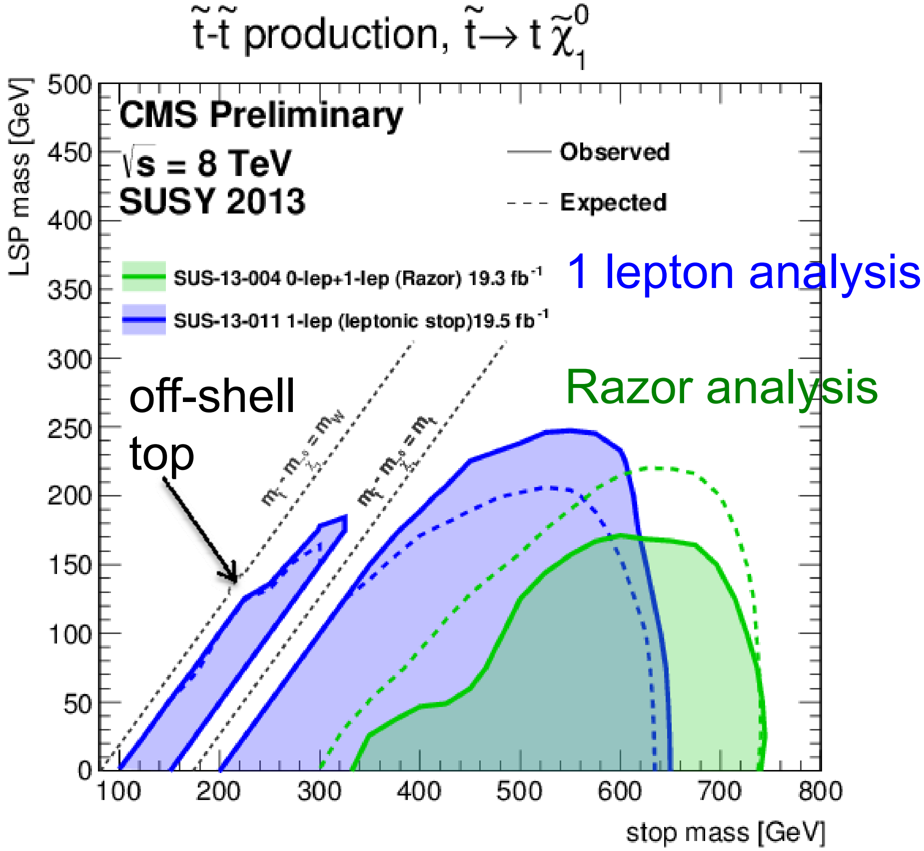
- **Selection**
  - 1 high p_T isolated e or μ
  - ≥ 4 jets with ≥ 1 b-jet
  - Veto events with a second lepton
  - Moderate MET
- **Main Backgrounds**
  - tt→ ll dominant in M_T tail
  - Single lepton backgrounds: tt→l+jets & single top (1l top), W+jets
  - Rare processes: mainly tt+W/Z/γ, tW
- **Analysis Strategy I:**
  - Search in M_T tail M_T(l,MET) >> M_W
  - Backgrounds from simulation, normalized using background-dominated data and validate predictions in **data control samples**



Example: ttbar validation



Interpretations: stop Results: $\tilde{t}_1 \rightarrow W\, b\, \tilde{\chi}_1^0 \,/\, \tilde{t}_1 \rightarrow t\, \tilde{\chi}_1^0$



- Results sensitive to top squarks with masses in range 100-700 GeV
- Sensitive to the $\Delta M < M_{top}$ and $M_{stop} < M_{top}$ regions
- Results have some dependence on polarization of top quark and BF
- Skipping : $\tilde{t}_1 \rightarrow b\, \tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \rightarrow W^{(*)}\, \tilde{\chi}_1^0$

Next

➔Anatomy of a Search

A quick look at the experimental techniques using the CMS inclusive multilepton search as an example

- Getting the Drell-Yan tails right
- Tau's are mostly fakes
- MET resolution – the bad and the ugly
- How many LHC physicists does it take to say uncle Dalitz

But first: Is Double Parton Scattering an issue for (SUSY) searches?

$\sigma(pp \rightarrow AB)_{DPS} \sim 100^*(\sigma_{pp\rightarrow A})^*(\sigma_{pp\rightarrow B})$/barn @7TeV

σ(ttbar) ~160pb, σ(W) ~30nb

$\sigma(tt+W)_{DPS}$ ~ 0.5fb BUT σ(ttW) ~ 150fb.

→ Relief! Move on…

(Also, DPS kinematics softer)

CMS Inclusive Multilepton Search

CMS SUS-13-002

- Three or more e/μ/τ, at least two (e/μ)
- Bin in lepton number, flavor (e/μ or $\tau_{hadronic}$), b-jets, opposite-sign same-flavor pairs, MET, HT and dilepton pair mass (on-above-below Z).
- SM backgrounds using data-driven methods for Z+jets, τ and internal γ conversions, validated MC for ttbar, WZ and rare SM such as ttV.
- Many SUSY interpretations including natural Higgsino, GMSB, SMS and also top → charm+higgs, 2HDM etc

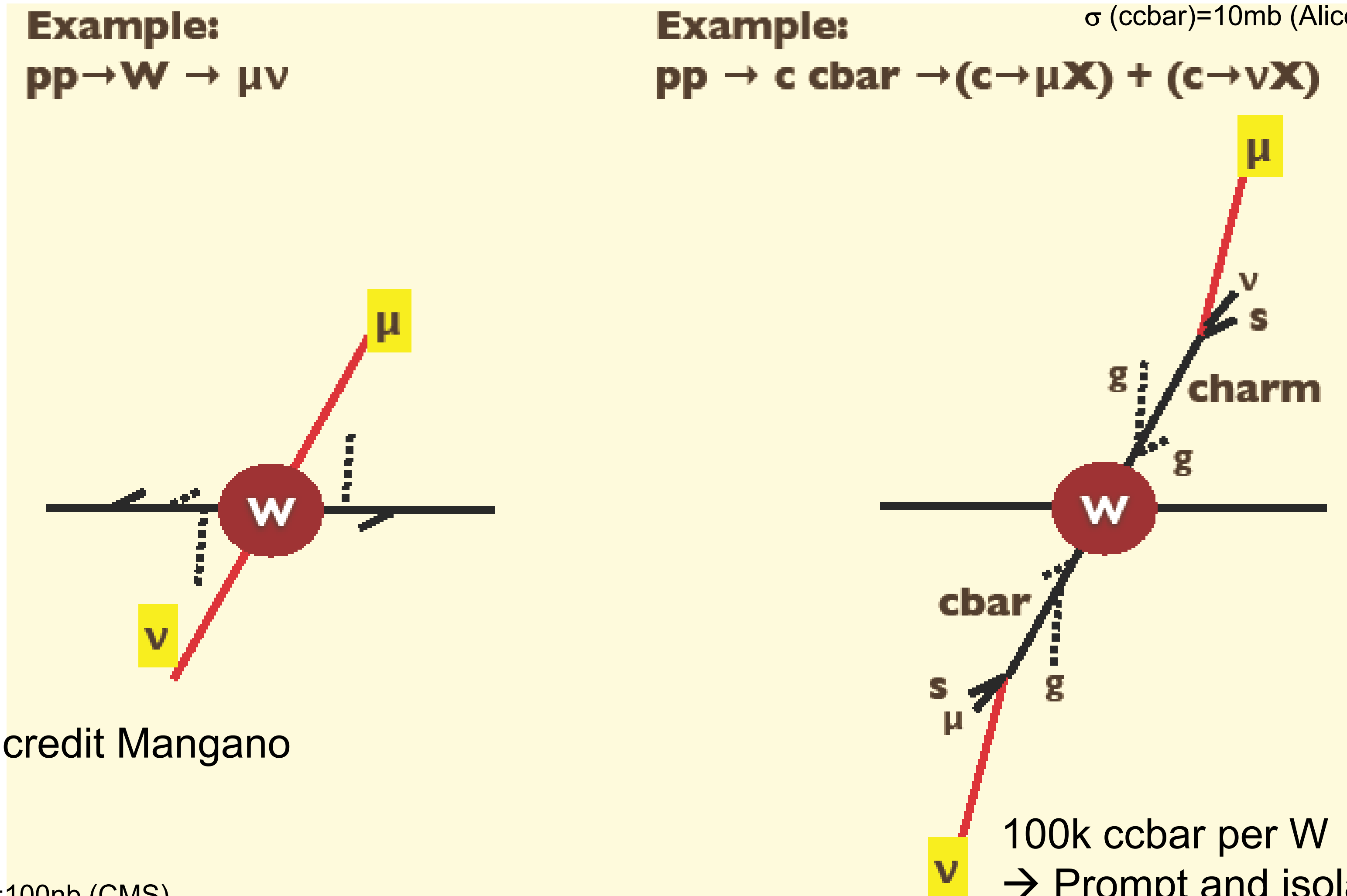
SM Bkgnd Example with Leptonic BR's (The odds are pretty bad!)

Process pp → X	**σ*B (8 TeV)**	**Events ($20\ fb^{-1}$)**	**"Objects"**
W (→ **ℓ=e**,μ,τ)	38 nb	750M	one lepton + MET
Z/γ* (→ $\ell^+\ell^-$) ($m_{\ell\ell}$>20GeV)	6 nb (~60% pole)	110M	Two leptons
ttbar (→bWbW, W → $\ell\nu$)	24 pb	500K	Two leptons + MET
WZ(→ $\ell\nu\ell^+\ell^-$)	1 pb	20K	Three leptons + MET
New physics	10 fb (say)	200	3 leptons+? or 2 leptons + ?? or 1 lepton + ???

From CMS results, internal CMS twiki etc

Before Background Issues: Prompt and Isolated

σ (ccbar)=10mb (Alice random doc)



Slide credit Mangano

100k ccbar per W
→ Prompt and isolated tails

σ(W)=100nb (CMS)

SM Backgrounds: MC vs "Data-Driven"

Why not just Monte Carlo all the backgrounds?

→ Recall 110M Z/g* dileptons vs 2000 signal events

→ Devil is in da tails (more on MET resolution later).

→ Data-driven backgrounds ("fake" rates)

  →Large data samples available

MC for "irreducible" backgrounds (eg WZ)

→Smaller cross sections means tails peter out

→Validate/Reinforce in control regions as much as possible (e.g. ttbar dilepton easy → trilepton with care)

Data-driven trilepton background: Z/γ^*

- $\sigma(Z/\gamma^* \rightarrow \ell^+\ell^-)$ ($m_{\ell\ell}$>20GeV) = 6nb!
  → High degree of rejection/understanding needed.

- Dileptons from Z + "fake" lepton. The fake is mostly a real lepton from semileptonic decays posing to be prompt and isolated.

- Fake rate methods have to take into account the environment, in particular, the b-quark content in the decay products.

- Also should have good statistical power

- Avoid signal contamination issues etc

Data-driven Z/γ*: The “CFO” Method

• Want: The rate of getting a third (“fake”) isolated e/mu in the dilepton sample.

$B^{\mp/0} \to D^{0/\mp}\mu^{+}\nu \qquad D^{+/0} \to \mu^{+}\nu K^{\mp}$ Heavy flavor content important!

• (For a subsample of interest that has certain MET, HT, b-tags etc.)

→ Count the number of isolated tracks in the sample, multiply by measured ratio fμ (how many isolated muons per isolated track?)

• To measure the ratio fμ, factorize:

$$f_{\mu} = \frac{N_{\mu}}{N_{T}} \times \frac{\epsilon_{\mu}^{iso}}{\epsilon_{T}^{iso}}$$

•1st factor is easy: production ratio of muons to tracks in the subsample (non-isolated, so plenty).

•2nd factor (isolation efficiency ratio): Measure in the full dilepton sample, but….

Data-driven Z/γ^*: CFO Method (CMS)

- Rate of a third isolated muon = fμ * Rate of isolated tracks
- To measure fμ :

$$f_\mu = \frac{N_\mu}{N_T} \times \frac{\epsilon_\mu^{Iso}}{\epsilon_T^{Iso}}$$

- 1st factor: ratio of non-isolated muons to tracks in the trilepton subsample of given kinematics.

- 2nd factor (isolation efficiency ratio): Measured in the full dilepton set, but as a function of heavy flavor (HF) content (B,D mesons).

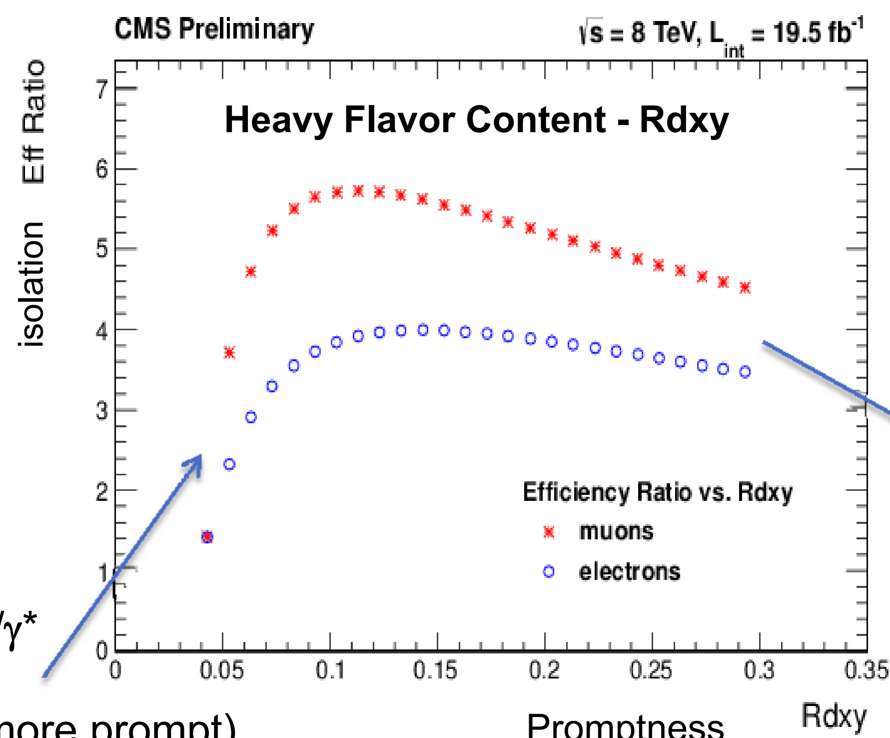
- This is because the HF content of the subsample varies with MET/HT etc. This impacts the isolation efficiency.

Quantifying the heavy-flavor content

Back to the “prompt” in “prompt and isolated”
B’s and D’s have nonzero lifetimes. π^{+-}’s don’t.

Rdxy = (#Tracks w impact parameter >200 microns) ÷ (…. < 200 microns)

$$\epsilon_{\rm ratio}(R_{dxy}) = \frac{\dfrac{(1+\frac{R_{dxy}-R^b_{dxy}}{R^a_{dxy}-R_{dxy}}\frac{1+R^a_{dxy}}{1+R^b_{dxy}})*(\epsilon_\ell^{\rm Iso,a}\epsilon_\ell^{\rm Iso,b}+\epsilon_\ell^{\rm Iso,a})+(\epsilon_\ell^{\rm Iso,b}-\epsilon_\ell^{\rm Iso,a})}{(1+\frac{R_{dxy}-R^b_{dxy}}{R^a_{dxy}-R_{dxy}}\frac{1+R^a_{dxy}}{1+R^b_{dxy}})*(1+\epsilon_\ell^{\rm Iso,b})+(\epsilon_\ell^{\rm Iso,b}-\epsilon_\ell^{\rm Iso,a})}}{\dfrac{(1+\frac{R_{dxy}-R^b_{dxy}}{R^a_{dxy}-R_{dxy}}\frac{1+R^a_{dxy}}{1+R^b_{dxy}})*(\epsilon_T^{\rm Iso,a}\epsilon_T^{\rm Iso,b}+\epsilon_T^{\rm Iso,a})+(\epsilon_T^{\rm Iso,b}-\epsilon_T^{\rm Iso,a})}{(1+\frac{R_{dxy}-R^b_{dxy}}{R^a_{dxy}-R_{dxy}}\frac{1+R^a_{dxy}}{1+R^b_{dxy}})*(1+\epsilon_T^{\rm Iso,b})+(\epsilon_T^{\rm Iso,b}-\epsilon_T^{\rm Iso,a})}}$$



Z/γ*

(more prompt)

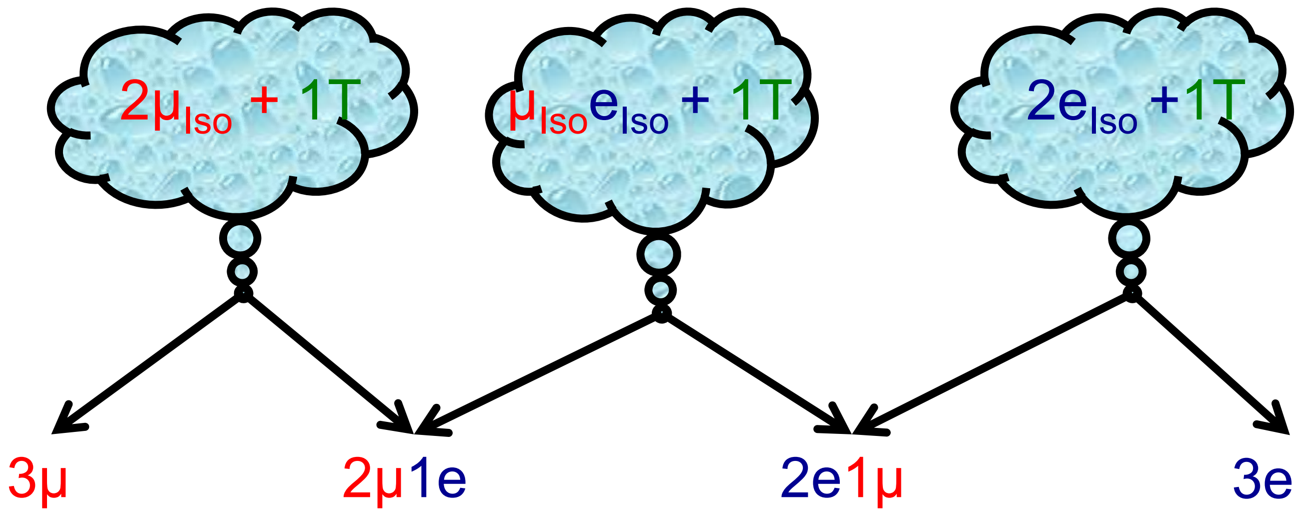
Promptness

Dilepton sample enriched with ttbar (less prompt)

Look up the isolation efficiency ratio for subsample of interest

Put it together: Trilepton Data-Driven "Fake" Prompt Lepton Prediction

- Multiply the number of isolated tracks in the dilepton subsample by f_μ and f_e separately



Done with e/mu's. Tau?

τ's in CMS

- Leptonic - BR($\tau \rightarrow$ e/mu) ~1/3 ->Comes automatically
- Hadronic ~2/3
  - ~1/3 “Single prong” - Isolated track with or w/o π^0
  - ~1/3 “Three prong” - (also) like a pencil jet

• Use “particle flow” reconstruction of jets etc (HPS algorithm) to reconstruct hadronic tau’s with ~40% efficiency (pt > 20 GeV)

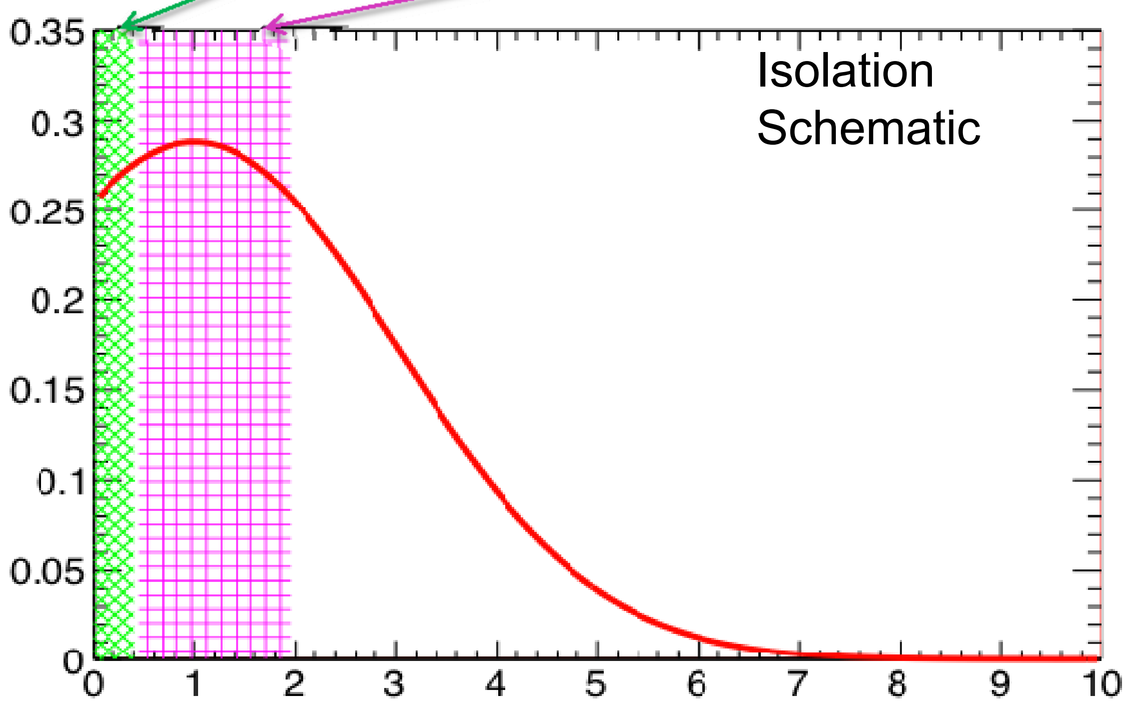
• But ~1% of jets (which are ubiquitous) still show up as fake tau’s. This is a hard business.

• Still useful for tau-dominated new physics and also when S/B is high (e.g. high MET, ST etc)

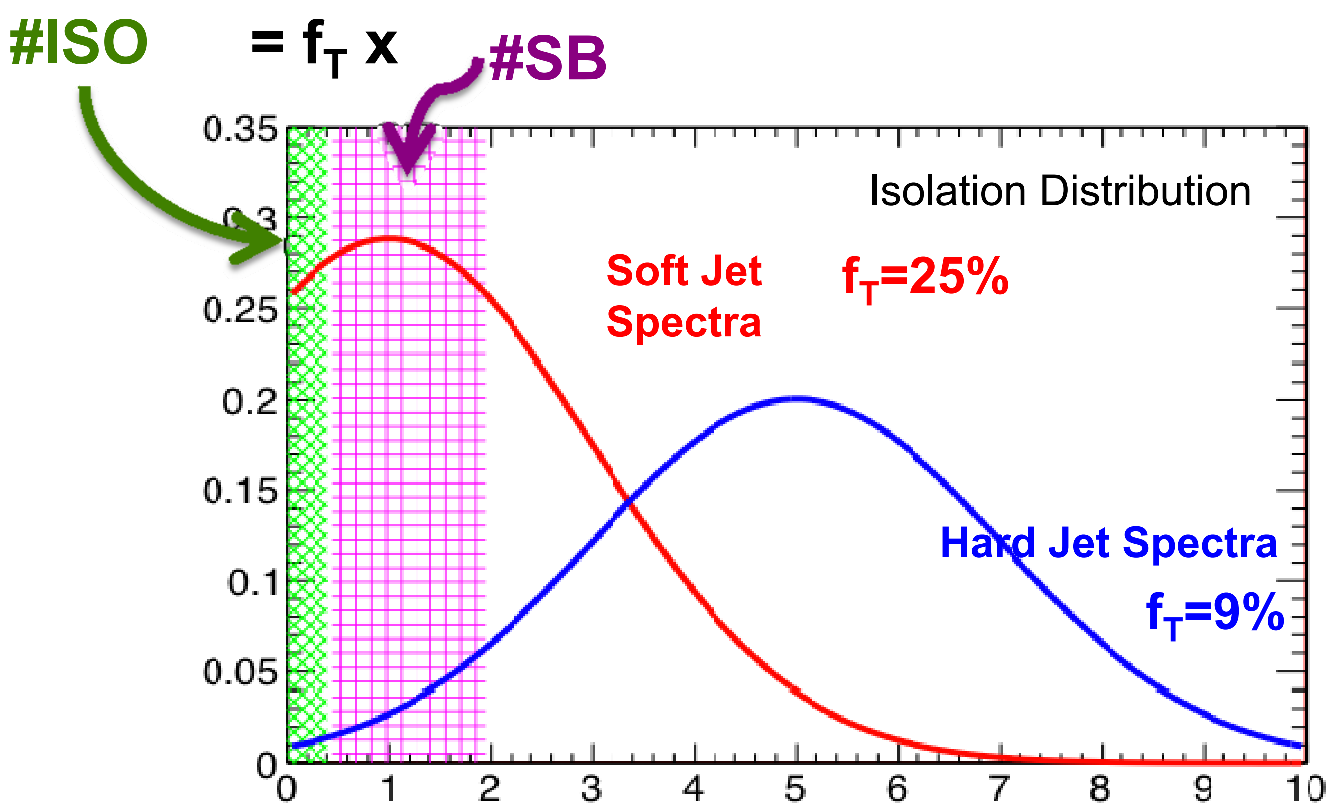
Isolated Tau fake rates

- Tau's are pencil jets being faked by fatter jets

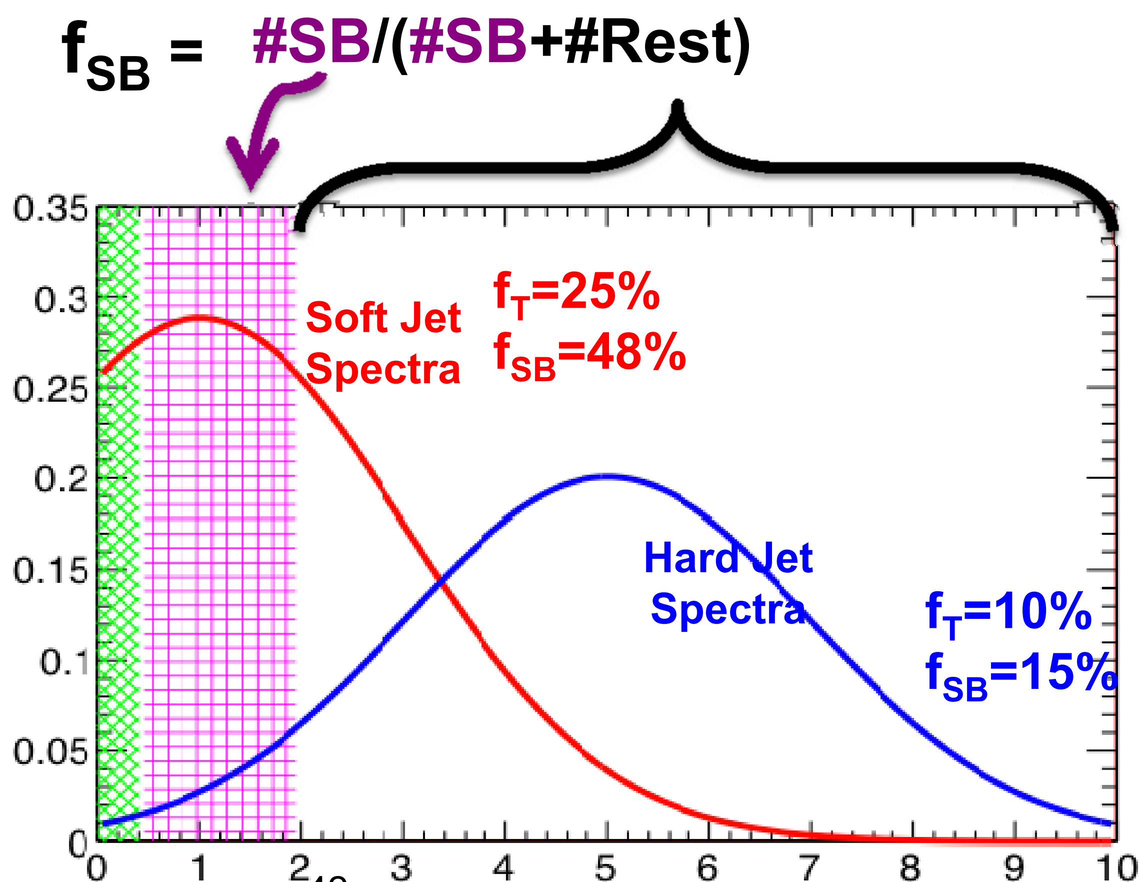
→ Extrapolate into isolated signal region from isolation sideband



But tau isolation environment changes!

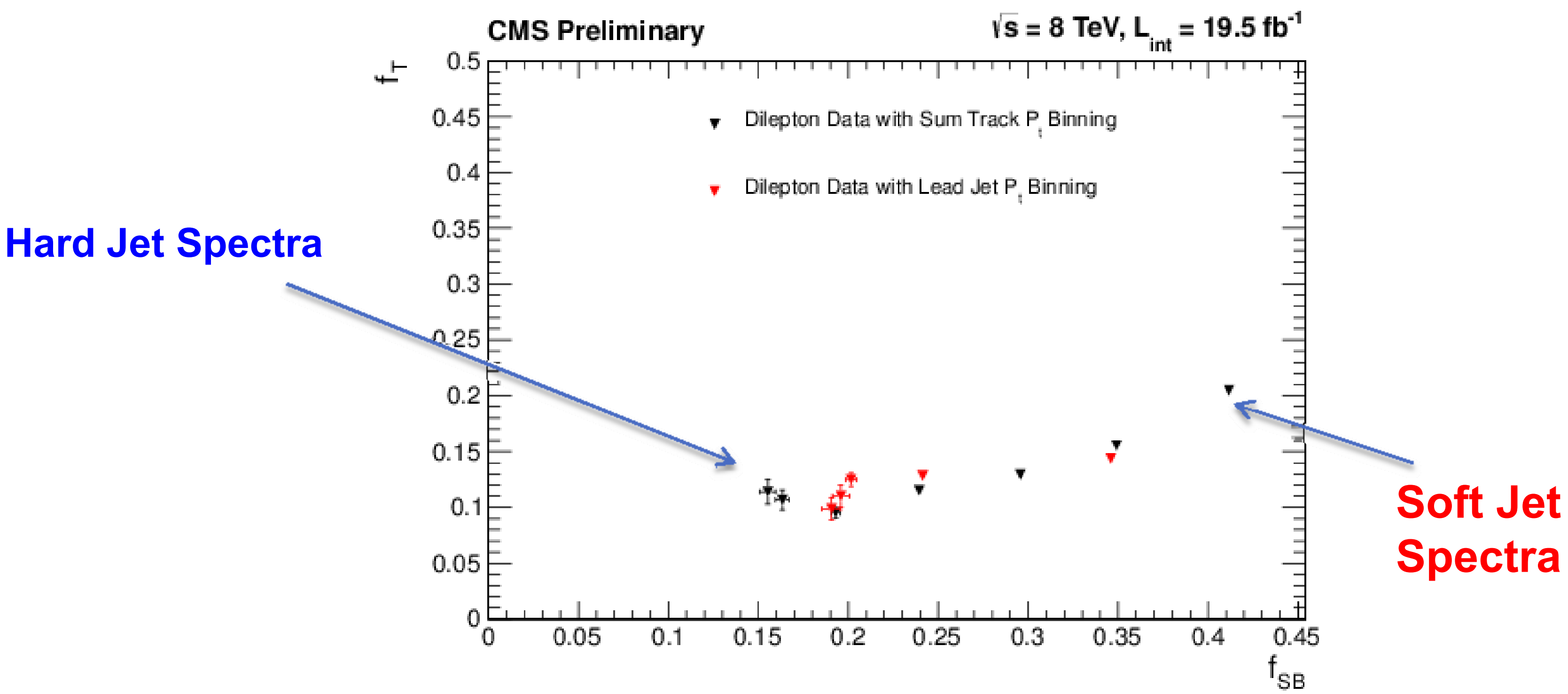


Use the full tau isolation distribution



Tau: f_T vs f_{SB}
(Data)

- Use low MET control data and plot f_T vs f_{SB}
- In signal region use f_{SB} to predict f_T



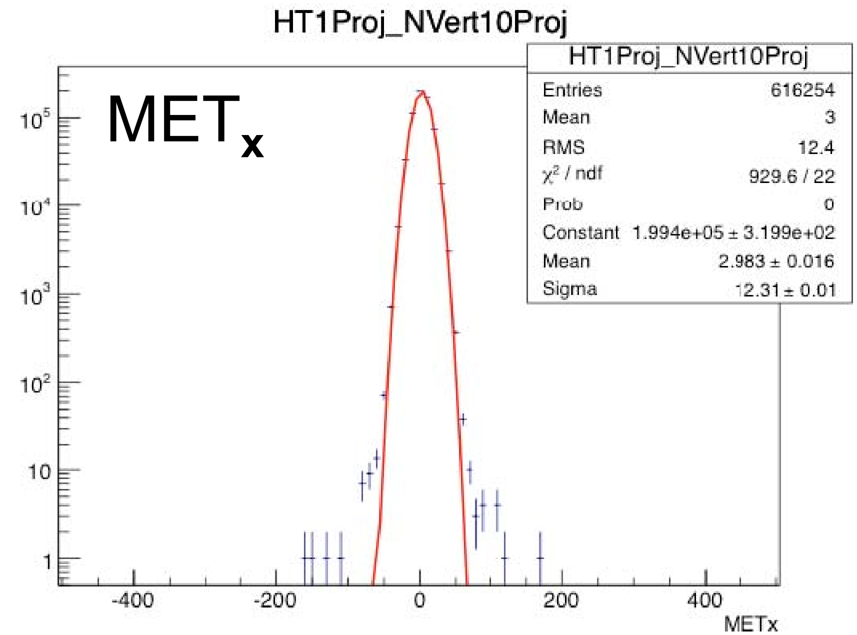
MET/pileup issues
(Very relevant for “What next?”)

Subtitle:

Boring things that excite experimentalists.

MET is critical in search for new physics

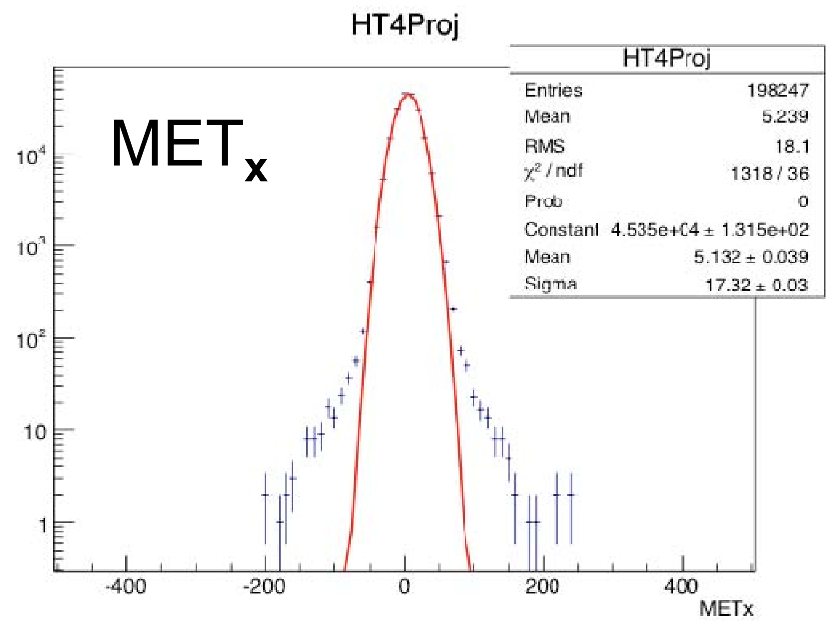
- Must understand/improve its resolution because of possible new physics on the tails
- We match the MET resolutions in simulated SM backgrounds to data.
- & learn interesting things about underlying issues such as pileup and jets.



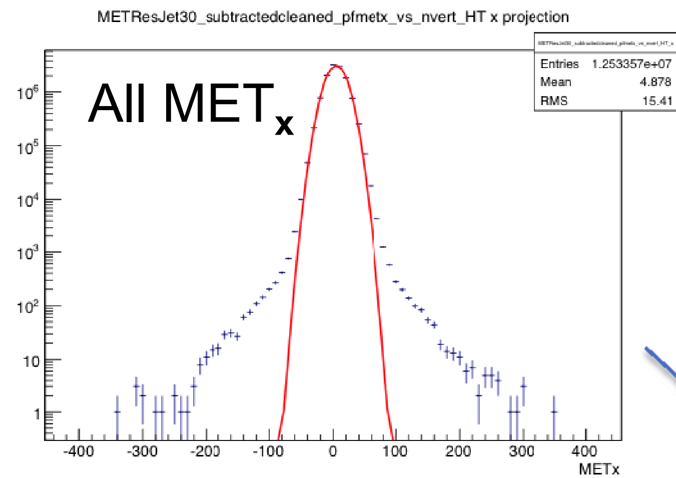
- Start with an impressive DATA plot →
  Gaussian to ***four orders of magnitude***

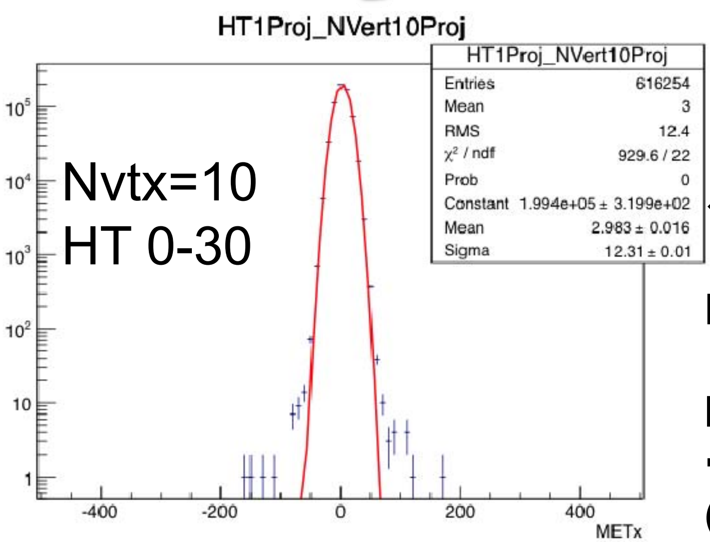
MET/pileup issues

- Same METx under different conditions →
  - Only two orders of magnitude.
  - RMS also went from 12 to 18 GeV
  - What changed?
- Last plot:
  - Nvertex = 10, i.e. low pileup conditions
  - HT 0-30 GeV, i.e. fewer and low pt jets.
    (jet misreconstruction screws up MET)
- This plot:
  - All nvertex (=average 2012 pileup conditions)
  - HT ~100 GeV
- Let us separate the impact of pileup and jet misreconstruction



MET/pileup issues (nvtx 30 → 150!!)

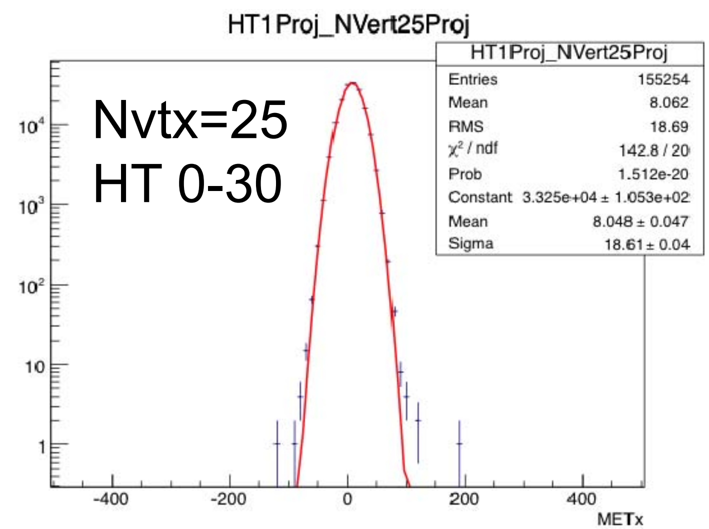




←Thinner, less pileup

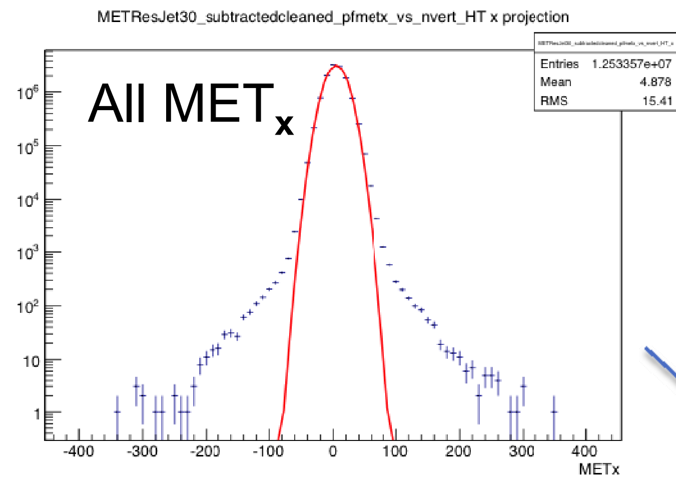
Fatter, more pileup →

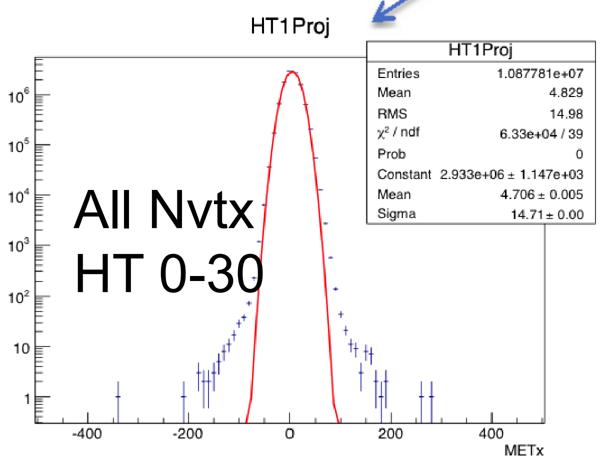
But same tails
→Pileup is stochastic
(Gaussian)



Same behavior in other HT bins

MET/pileup issues

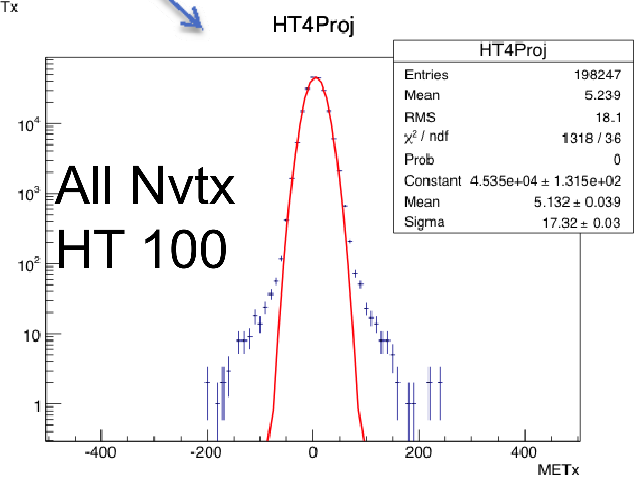




←Fewer tails, less HT

More tails, higher HT →

➔Jet misreconstruction has non-Gaussian systematic effects



Same behavior in Nvtx bins

New physics impact: Fat gaussians (pileup) impact not too bad, but keep the long tails at bay

Last data-driven background : Asymmetric Photon Conversions

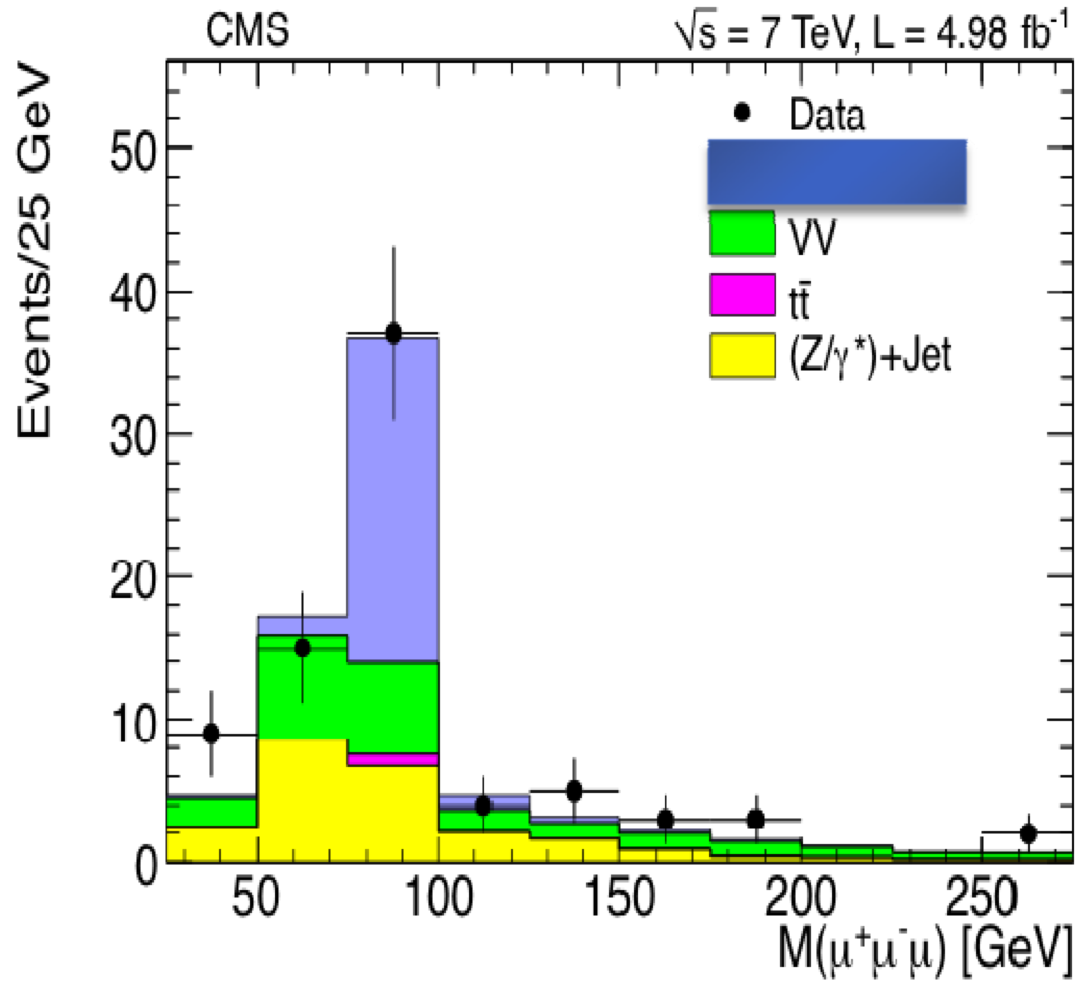
- How many physicists does it take to forget about Dalitz decays in 20 years? Answer: ~6000

- "The only (non)surprise from LHC so far?"

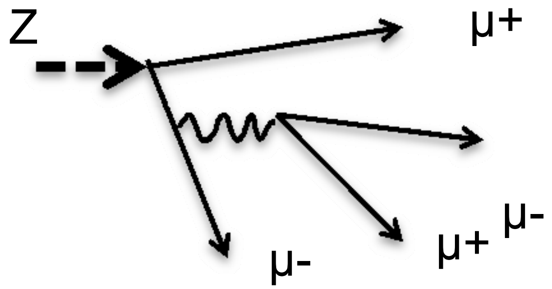
From 2011 archives….

Note: Muons!

Note again: 3 muons!!



Z→3μ - Asymmetric Internal (Dalitz) Photon Conversions



Z→(3)4μ

Feynman level (γ*) (NOT γ)

gives e+e- and μ+μ-

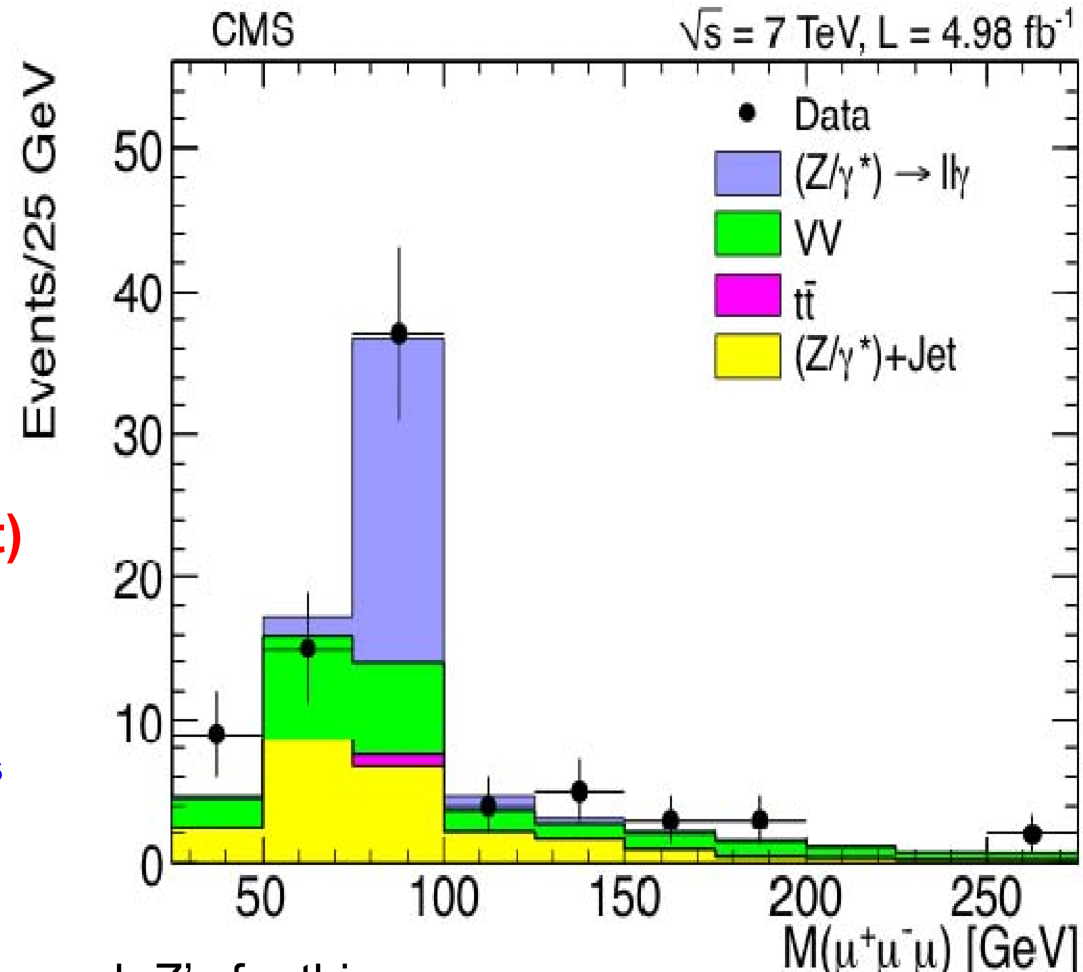
Observe 3μ Z peak (4th μ soft)

BUT

Also W→2μ (Higgs!)

Wg* was not in Higgs WW searches

arXiv:1110.1368 R. C. Gray et. al.



LEP-I did not produce enough Z's for this

Asymmetric Conversion Fake Rate

- Go to low MET-HT control region

  (no new physics)

- Measure the (catchall) ratio of three-leptons on Z-pole to dileptons+photon in the same mass window.

 ~ 0.35%

• --

Done with SM backgrounds…

Multilepton Results: 3 leptons

CMS-SUS-13-002

number of opposite-sign same flavor (OSSF) dilepton pair

presence of τ-had

OSSF pair invariant mass is in Z mass window?

presence of b tagged jets

HT

MET (HT>200 below)

Selection 3 Lepton Results			E_T^{miss}	$N(\tau_h)=0$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=0$, $N_{b-jets}\geq1$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}\geq1$ obs	exp
OSSF0	$H_T > 200$	NA	(100,∞)	5	3.7 ± 1.6	35	33 ± 14	1	5.5 ± 2.2	47	61 ± 30
OSSF0	$H_T > 200$	NA	(50,100)	3	3.5 ± 1.4	34	36 ± 16	8	7.7 ± 2.7	82	91 ± 46
OSSF0	$H_T > 200$	NA	(0,50)	4	2.1 ± 0.8	25	25 ± 9.7	1	3.6 ± 1.5	52	59 ± 29
OSSF1	$H_T > 200$	above-Z	(100,∞)	5	3.6 ± 1.2	2	10 ± 4.8	3	4.7 ± 1.6	19	22 ± 11
OSSF1	$H_T > 200$	below-Z	(100,∞)	7	9.7 ± 3.3	18	14 ± 6.4	8	9.1 ± 3.4	21	23 ± 11
OSSF1	$H_T > 200$	on-Z	(100,∞)	39	61 ± 23	17	15 ± 4.9	9	14 ± 4.4	10	12 ± 5.8
OSSF1	$H_T > 200$	above-Z	(50,100)	4	5 ± 1.6	14	11 ± 5.2	6	6.8 ± 2.4	32	30 ± 15
OSSF1	$H_T > 200$	below-Z	(50,100)	10	11 ± 3.8	24	19 ± 6.4	10	9.9 ± 3.7	25	32 ± 16
OSSF1	$H_T > 200$	on-Z	(50,100)	78	80 ± 32	70	50 ± 11	22	22 ± 6.3	36	24 ± 9.8
OSSF1	$H_T > 200$	above-Z	(0,50)	3	7.3 ± 2	41	33 ± 8.7	4	5.3 ± 1.5	15	23 ± 11
OSSF1	$H_T > 200$	below-Z	(0,50)	26	25 ± 6.8	110	86 ± 23	5	10 ± 2.5	24	26 ± 11
OSSF1	$H_T > 200$	on-Z	(0,50)	*135	127 ± 41	542	543 ± 159	31	32 ± 6.5	86	75 ± 19

Multilepton Results for Three Leptons

CMS SUS-13-002

Selection 3 Lepton Results		E_T^{miss}	$N(\tau_h)=0$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=0$, $N_{b-jets}\geq1$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}\geq1$ obs	exp
OSSF0 $H_T < 200$	NA	(100,∞)	7	11 ± 4.9	101	111 ± 54	13	10 ± 5.3	87	119 ± 61
OSSF0 $H_T < 200$	NA	(50,100)	35	38 ± 15	406	402 ± 152	29	26 ± 13	269	298 ± 151
OSSF0 $H_T < 200$	NA	(0,50)	53	51 ± 11	910	1035 ± 255	29	23 ± 10	237	240 ± 113
OSSF1 $H_T < 200$	above-Z	(100,∞)	18	13 ± 3.5	25	38 ± 18	10	6.5 ± 2.9	24	35 ± 18
OSSF1 $H_T < 200$	below-Z	(100,∞)	21	24 ± 9	41	50 ± 25	14	20 ± 10	42	54 ± 28
OSSF1 $H_T < 200$	on-Z	(100,∞)l	150	152 ± 26	39	48 ± 13	15	14 ± 4.8	19	23 ± 11
OSSF1 $H_T < 200$	above-Z	(50,100)	50	46 ± 9.7	169	139 ± 48	20	18 ± 8	85	93 ± 47
OSSF1 $H_T < 200$	below-Z	(50,100)	142	125 ± 27	353	355 ± 92	48	48 ± 23	140	133 ± 68
OSSF1 $H_T < 200$	on-Z	(50,100)	*773	777 ± 116	1276	1154 ± 306	56	47 ± 13	81	75 ± 32
OSSF1 $H_T < 200$	above-Z	(0,50)	178	196 ± 35	1676	1882 ± 540	17	18 ± 6.7	115	94 ± 42
OSSF1 $H_T < 200$	below-Z	(0,50)	510	547 ± 87	9939	8980 ± 2660	34	42 ± 11	226	228 ± 63
OSSF1 $H_T < 200$	on-Z	(0,50)	*3869	4105 ± 666	*50188	50162 ± 14984	*148	156 ± 24	906	925 ± 263

HT < 200

Multilepton Results for Four Leptons

CMS-SUS-13-002

HT < 200

Selection 4 Lepton Results		E_T^{miss}	N(τ_h)=0, N_{b-jets}=0 obs	exp	N(τ_h)=1, N_{b-jets}=0 obs	exp	N(τ_h)=0, $N_{b-jets}\geq1$ obs	exp	N(τ_h)=1, $N_{b-jets}\geq1$ obs	exp
OSSF0 $H_T < 200$	NA	(100,∞)	0	0.11 ± 0.08	0	0.17 ± 0.1	0	0.03 ± 0.04	0	0.04 ± 0.04
OSSF0 $H_T < 200$	NA	(50,100)	0	0.01 ± 0.03	2	0.7 ± 0.33	0	0 ± 0.02	0	0.28 ± 0.16
OSSF0 $H_T < 200$	NA	(0,50)	0	0.01 ± 0.02	1	0.7 ± 0.3	0	0.001 ± 0.02	0	0.13 ± 0.08
OSSF1 $H_T < 200$	off-Z	(100,∞)	0	0.06 ± 0.04	3	0.6 ± 0.24	0	0.02 ± 0.04	0	0.32 ± 0.2
OSSF1 $H_T < 200$	on-Z	(100,∞)	1	0.5 ± 0.18	2	2.5 ± 0.5	1	0.38 ± 0.2	0	0.21 ± 0.1
OSSF1 $H_T < 200$	off-Z	(50,100)	0	0.18 ± 0.06	4	2.1 ± 0.5	0	0.16 ± 0.08	1	0.45 ± 0.24
OSSF1 $H_T < 200$	on-Z	(50,100)	2	1.2 ± 0.34	9	9.6 ± 1.6	2	0.42 ± 0.23	0	0.5 ± 0.16
OSSF1 $H_T < 200$	off-Z	(0,50)	2	0.46 ± 0.18	15	7.5 ± 2	0	0.09 ± 0.06	0	0.7 ± 0.31
OSSF1 $H_T < 200$	on-Z	(0,50)	4	3 ± 0.8	41	40 ± 10	1	0.31 ± 0.15	2	1.5 ± 0.47
OSSF2 $H_T < 200$	off-Z	(100,∞)	0	0.04 ± 0.03	-	-	0	0.05 ± 0.04	-	-
OSSF2 $H_T < 200$	on-Z	(100,∞)	0	0.34 ± 0.15	-	-	0	0.46 ± 0.25	-	-
OSSF2 $H_T < 200$	off-Z	(50,100)	2	0.18 ± 0.13	-	-	0	0.02 ± 0.03	-	-
OSSF2 $H_T < 200$	on-Z	(50,100)	4	3.9 ± 2.5	-	-	0	0.5 ± 0.21	-	-
OSSF2 $H_T < 200$	off-Z	(0,50)	7	8.9 ± 2.4	-	-	1	0.23 ± 0.09	-	-
OSSF2 $H_T < 200$	on-Z	(0,50)	*156	159 ± 34	-	-	4	2.9 ± 0.8	-	-

Multilepton Results for Four Leptons

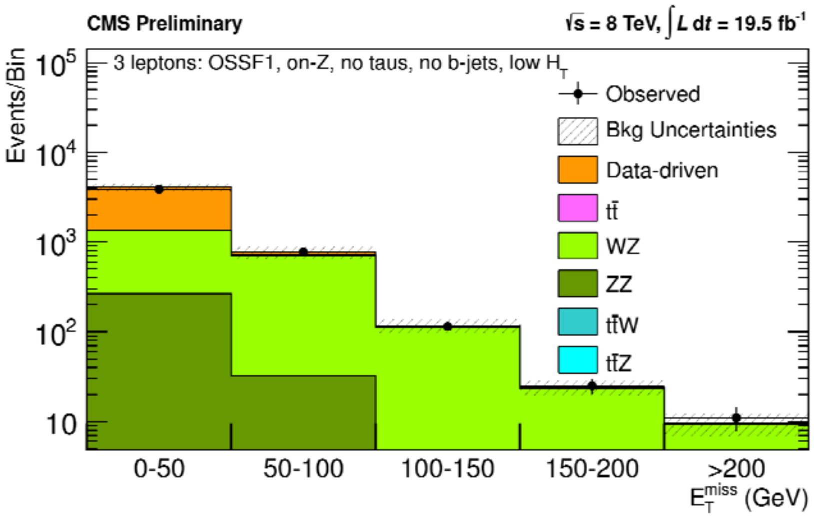
CMS-SUS-13-002

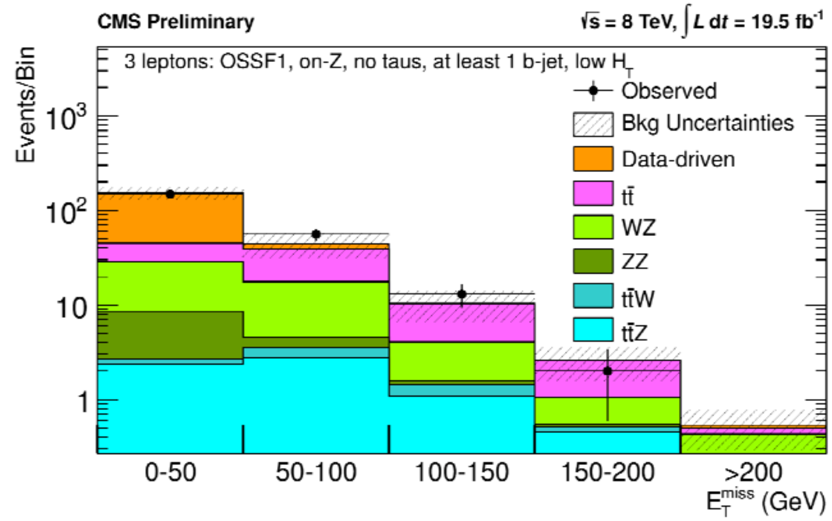
HT > 200

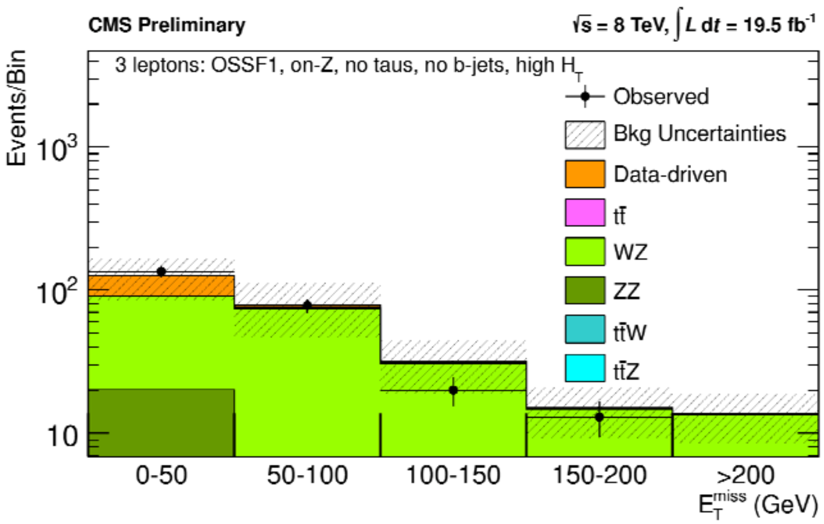
Selection 4 Lepton Results		E_T^{miss}	N(τ_h)=0, N_{b-jets}=0 obs	exp	N(τ_h)=1, N_{b-jets}=0 obs	exp	N(τ_h)=0, $N_{b-jets}\geq$1 obs	exp	N(τ_h)=1, $N_{b-jets}\geq$1 obs	exp
OSSF0 $H_T > 200$	NA	(100,∞)	0	0.01 ± 0.03	0	0.01 ± 0.06	0	0.02 ± 0.04	0	0.11 ± 0.08
OSSF0 $H_T > 200$	NA	(50,100)	0	0 ± 0.02	0	0.01 ± 0.06	0	0 ± 0.03	0	0.12 ± 0.07
OSSF0 $H_T > 200$	NA	(0,50)	0	1e-05 $\pm$ 0.02	0	0.07 ± 0.1	0	0 ± 0.02	0	0.02 ± 0.02
OSSF1 $H_T > 200$	off-Z	(100,∞)	0	0.005 ± 0.02	1	0.25 ± 0.11	0	0.13 ± 0.08	0	0.12 ± 0.12
OSSF1 $H_T > 200$	on-Z	(100,∞)	1	0.1 ± 0.06	0	0.5 ± 0.27	0	0.42 ± 0.22	0	0.42 ± 0.19
OSSF1 $H_T > 200$	off-Z	(50,100)	0	0.07 ± 0.06	1	0.29 ± 0.13	0	0.04 ± 0.04	0	0.23 ± 0.13
OSSF1 $H_T > 200$	on-Z	(50,100)	0	0.23 ± 0.11	1	0.7 ± 0.31	0	0.23 ± 0.13	1	0.34 ± 0.16
OSSF1 $H_T > 200$	off-Z	(0,50)	0	0.02 ± 0.03	0	0.27 ± 0.12	0	0.03 ± 0.04	0	0.31 ± 0.15
OSSF1 $H_T > 200$	on-Z	(0,50)	0	0.2 ± 0.08	0	1.3 ± 0.47	0	0.06 ± 0.04	1	0.49 ± 0.19
OSSF2 $H_T > 200$	off-Z	(100,∞)	0	0.01 ± 0.02	-	-	0	0.01 ± 0.06	-	-
OSSF2 $H_T > 200$	on-Z	(100,∞)	1	0.15 ± 0.16	-	-	0	0.34 ± 0.18	-	-
OSSF2 $H_T > 200$	off-Z	(50,100)	0	0.03 ± 0.02	-	-	0	0.13 ± 0.09	-	-
OSSF2 $H_T > 200$	on-Z	(50,100)	0	0.8 ± 0.4	-	-	0	0.36 ± 0.19	-	-
OSSF2 $H_T > 200$	off-Z	(0,50)	1	0.27 ± 0.13	-	-	0	0.08 ± 0.05	-	-
OSSF2 $H_T > 200$	on-Z	(0,50)	5	7.4 ± 3.5	-	-	2	0.8 ± 0.4	-	-

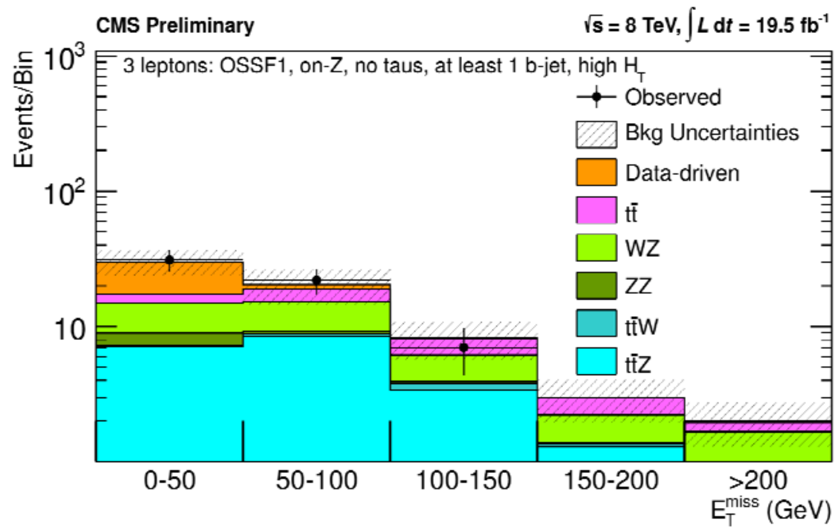
Results with Background Breakdown

CMS-SUS-13-002

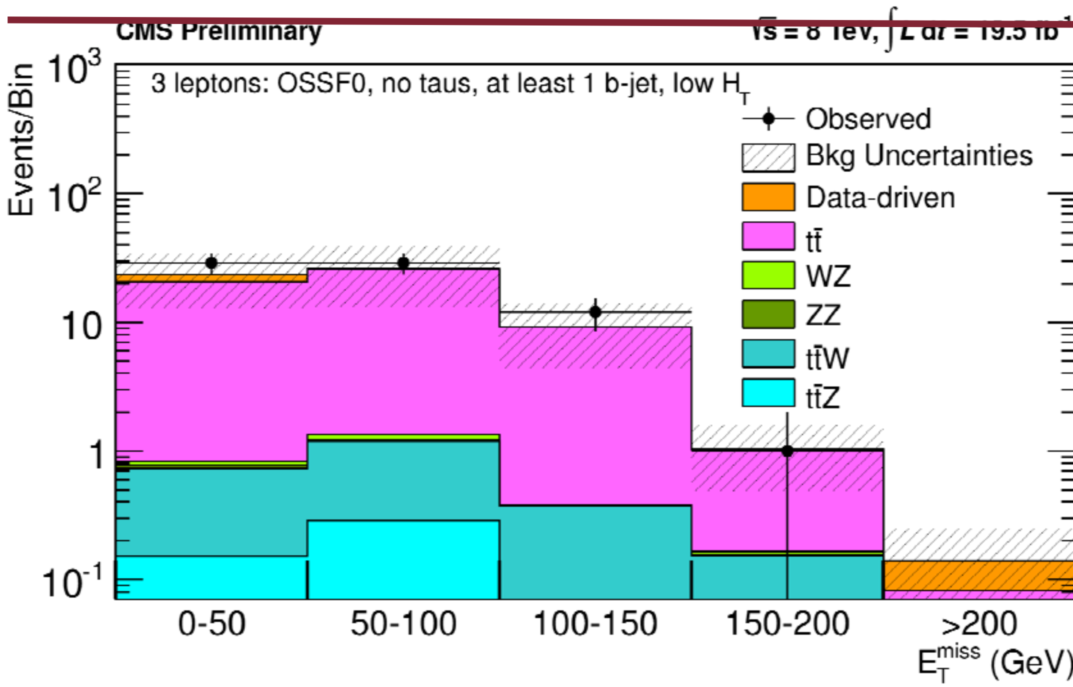








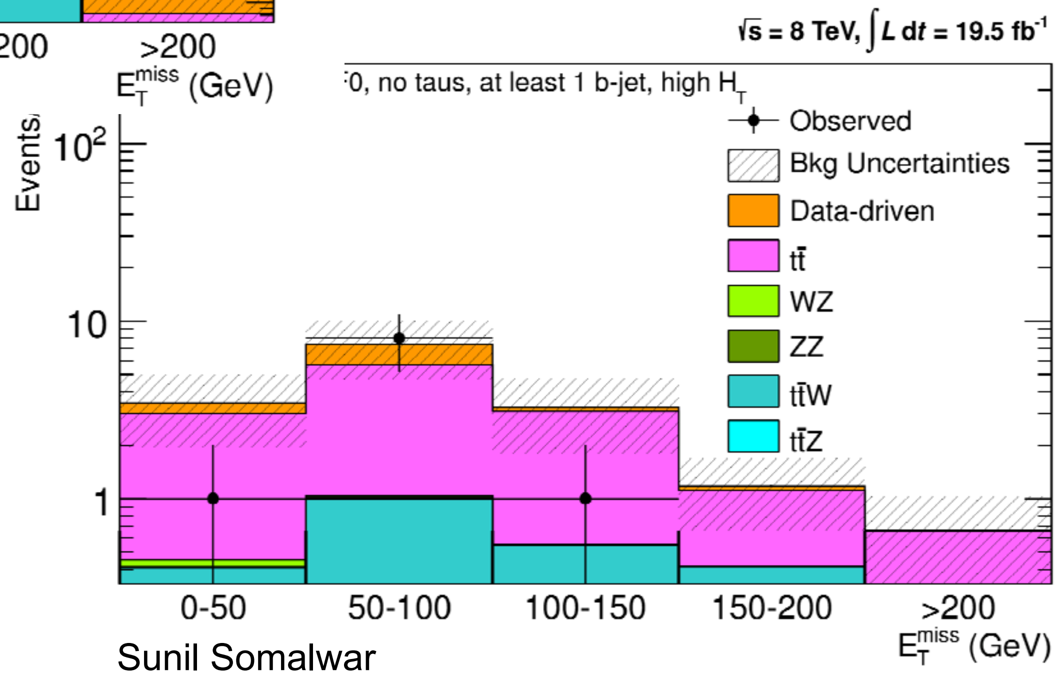
More Background Breakdown examples (b-tag)



HT<200

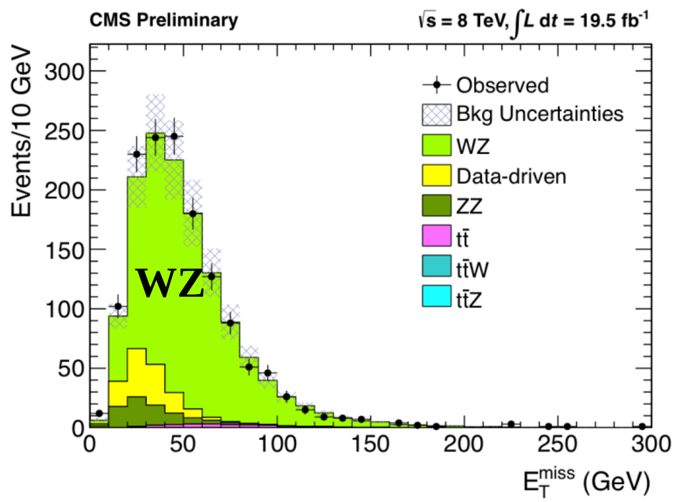
CMS SUS-13-002

HT>200

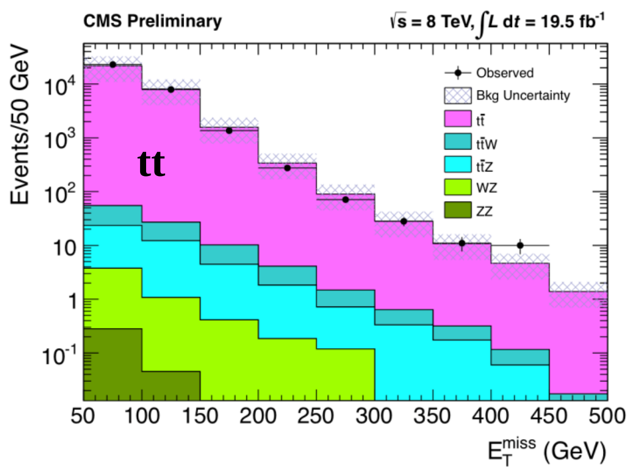


Kinematic distributions

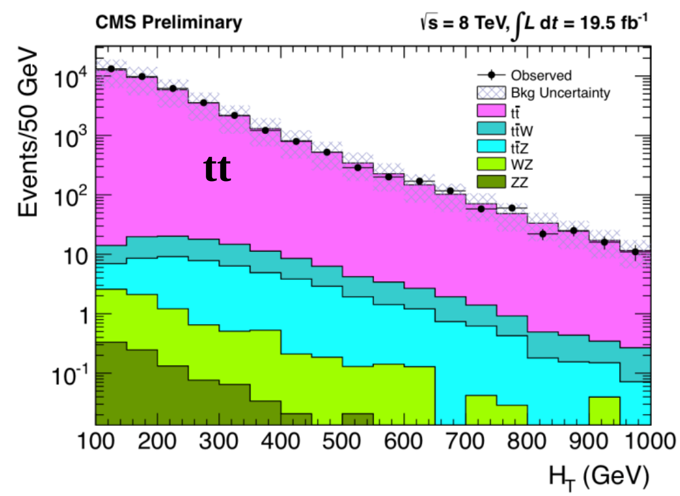
CMS-SUS-13-002



WZ control region
MET distribution



tt(bar) control region
MET and HT distributions



Interpretations: GMSB scenarios

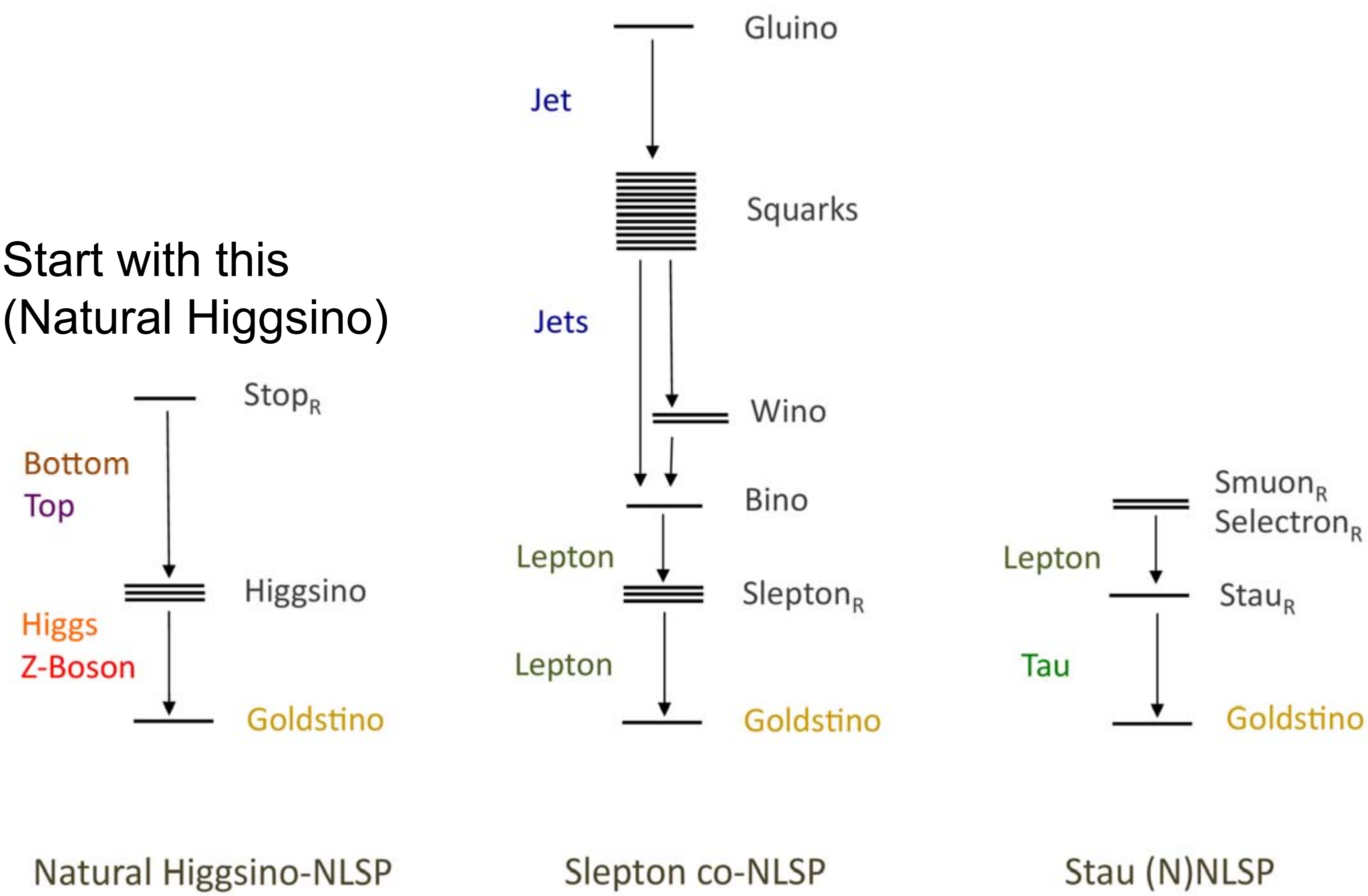
GMSB = Gauge Mediated Supersymmetry Breaking

CMS-SUS-13-002

Mass spectra in 3 models

Gravitino is the lightest SUSY particle (LSP).

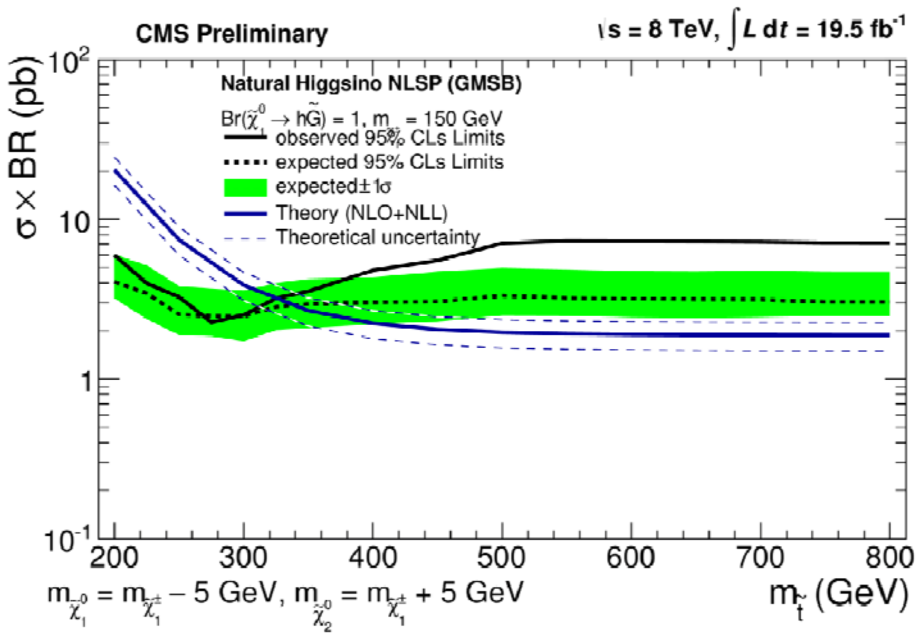
Start with this (Natural Higgsino)

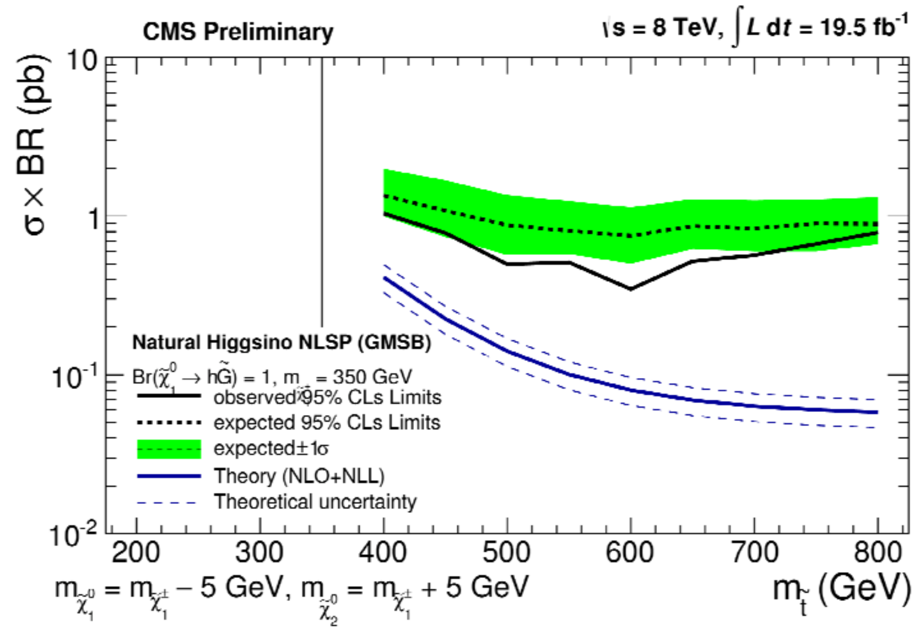


Interpretations: Natural Higgsino NLSP

Gauge Mediated Supersymmetry Breaking (GMSB) model
Strong and weak production

CMS-SUS-13-002



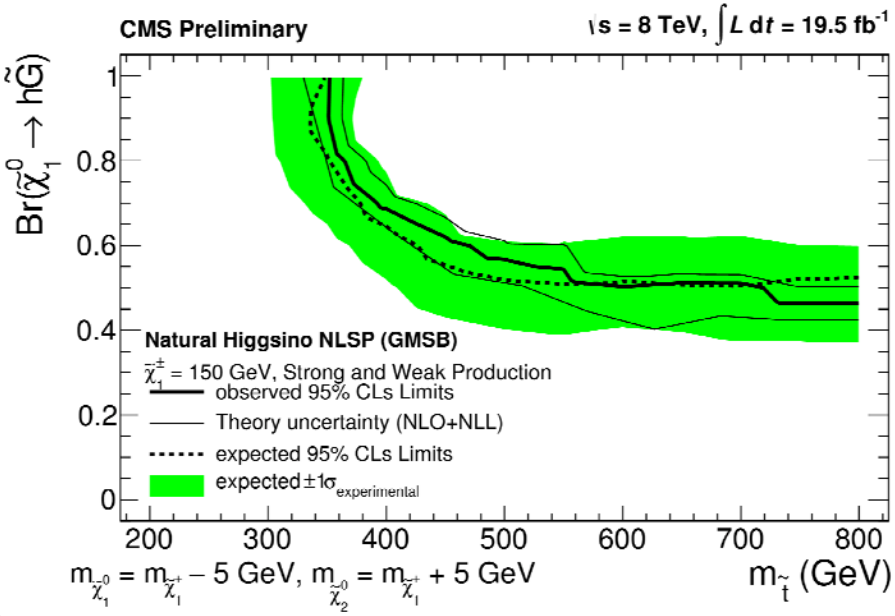


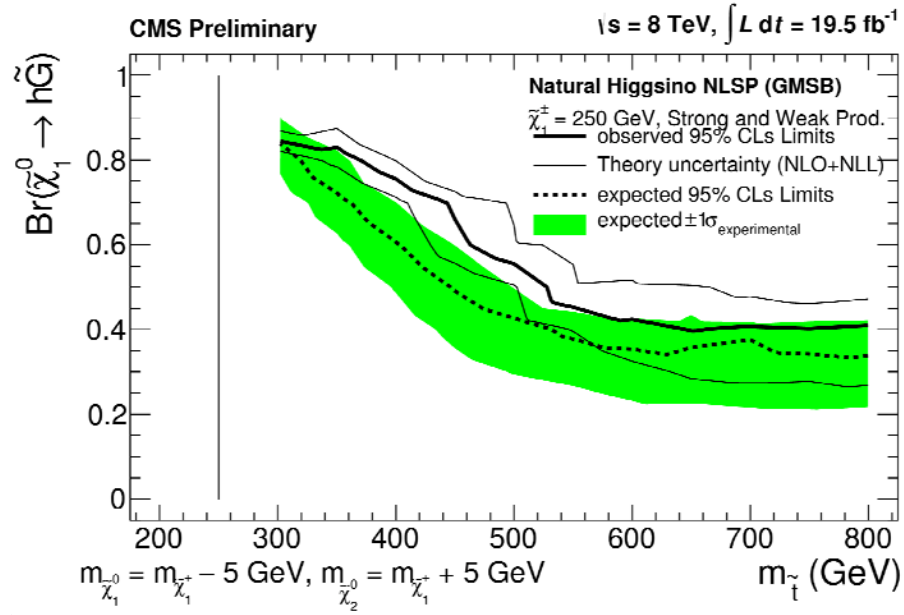
All Higgs (no Z), different chargino masses

Natural Higgsino NLSP scenario

Gauge Mediated Supersymmetry Breaking (GMSB) model

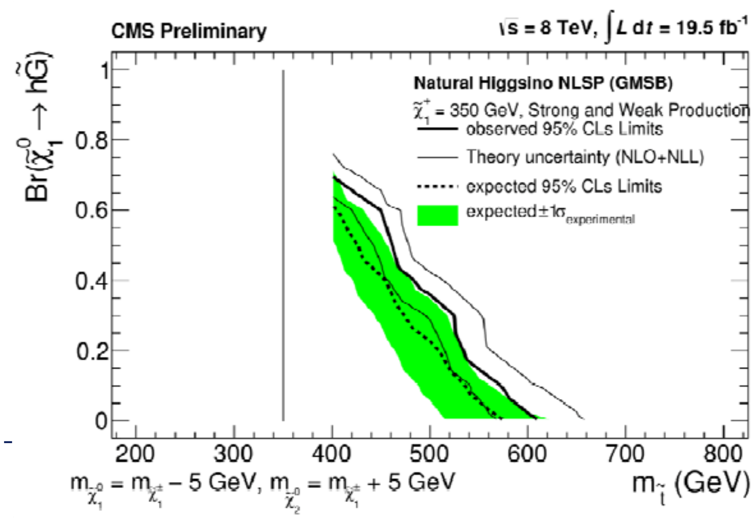
CMS-SUS-13-002





All Higgs (no Z),
different chargino masses

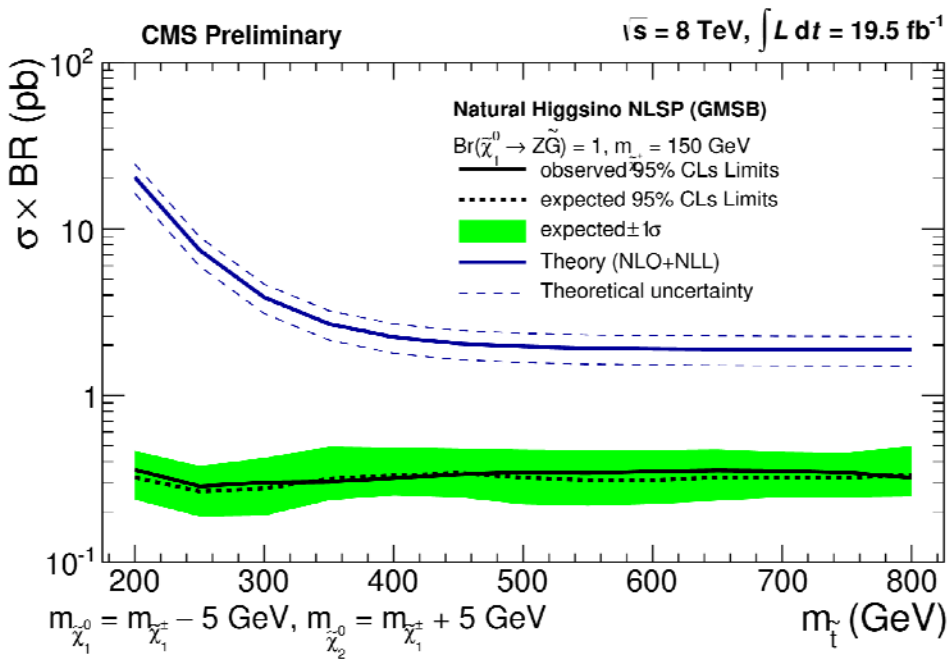
Strong vs weak production

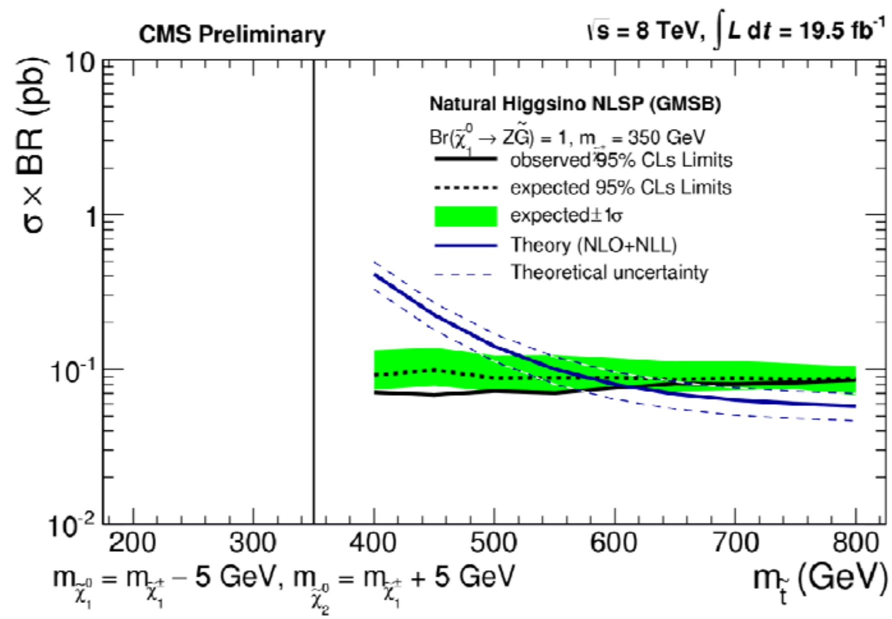


Natural Higgsino NLSP scenario

Gauge Mediated Supersymmetry Breaking (GMSB) model

CMS-SUS-13-002



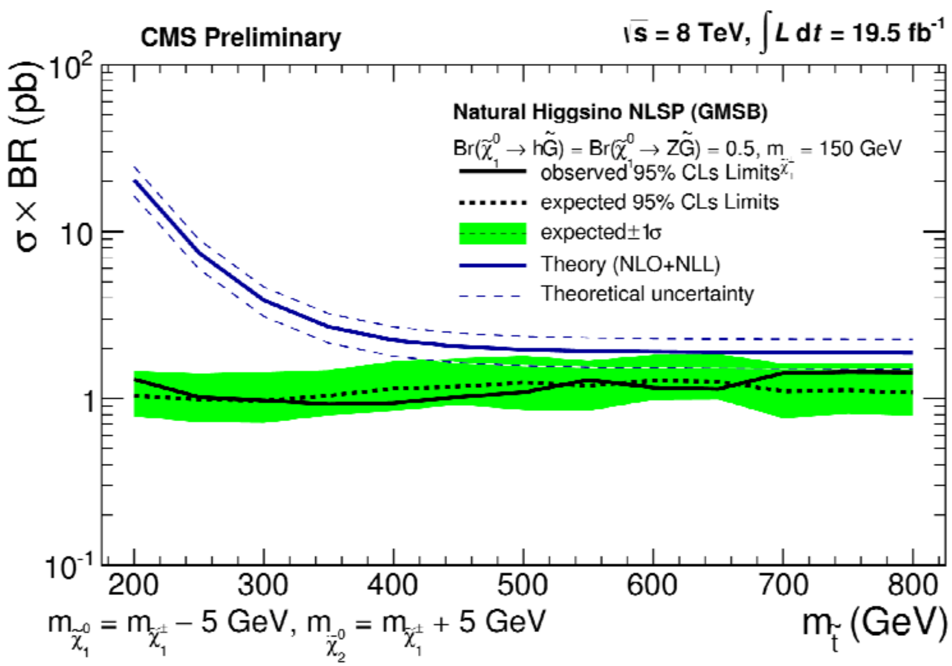


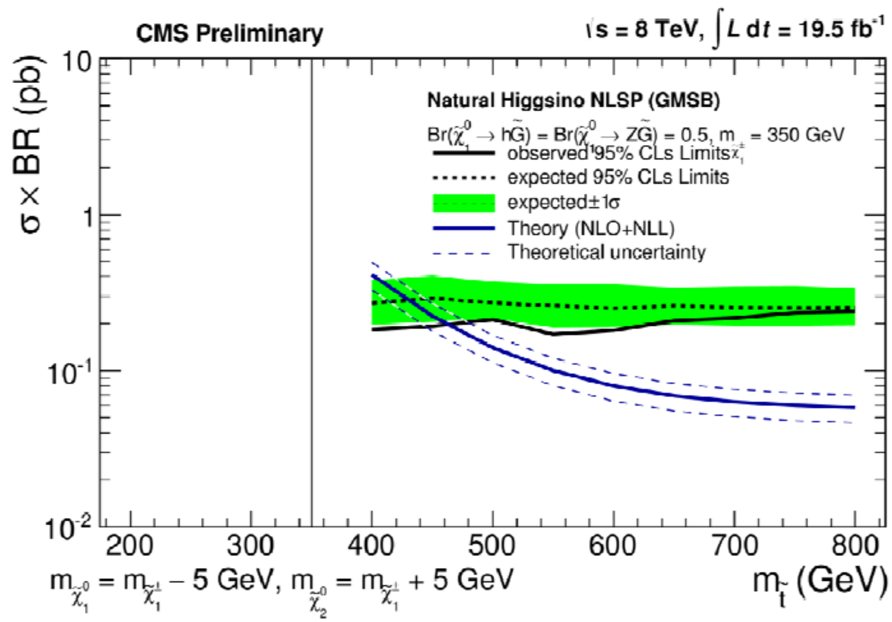
Now all Z (no Higgs), different chargino masses
Better exclusion

Natural Higgsino NLSP scenario

Gauge Mediated Supersymmetry Breaking (GMSB) model

CMS-SUS-13-002

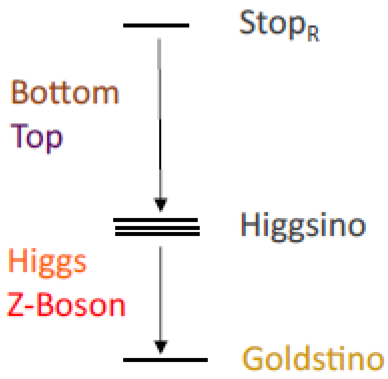


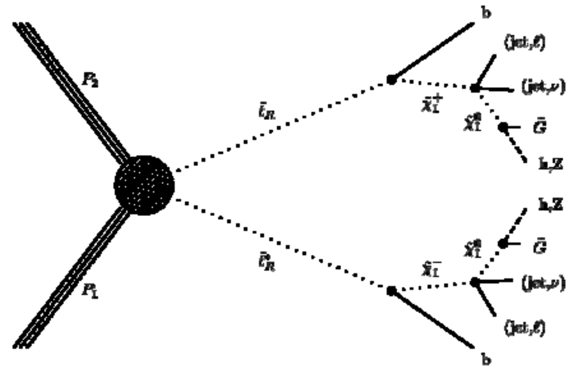


One side to Higgs, other to Z (unphysical), different chargino masses

Natural Higgsino NLSP (GMSB, strong vs weak)

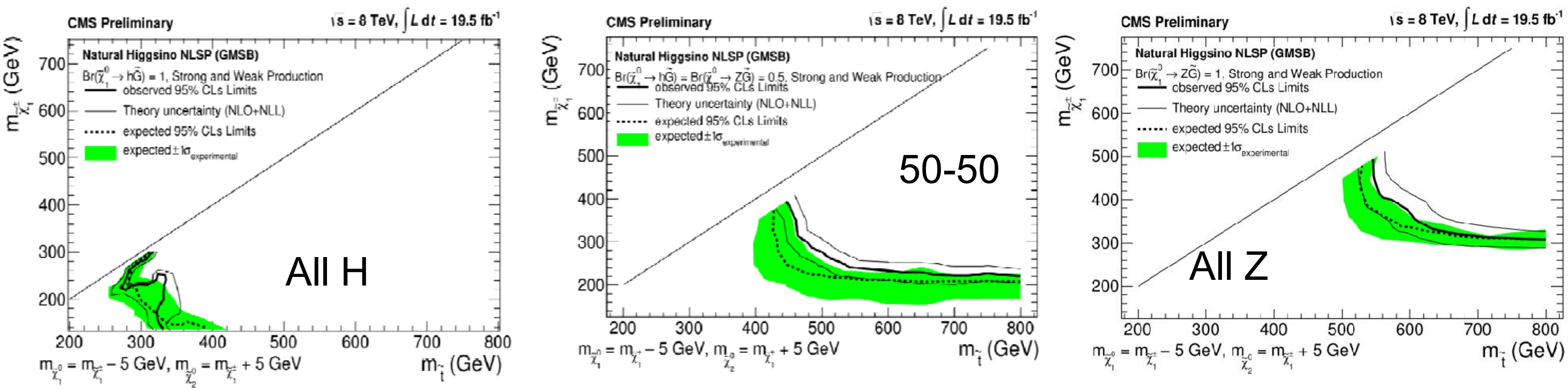
CMS-SUS-13-002





Top squark production with decays to neutral di-boson pair

Finally: Put H and Z BR's together properly



GMSB scenarios

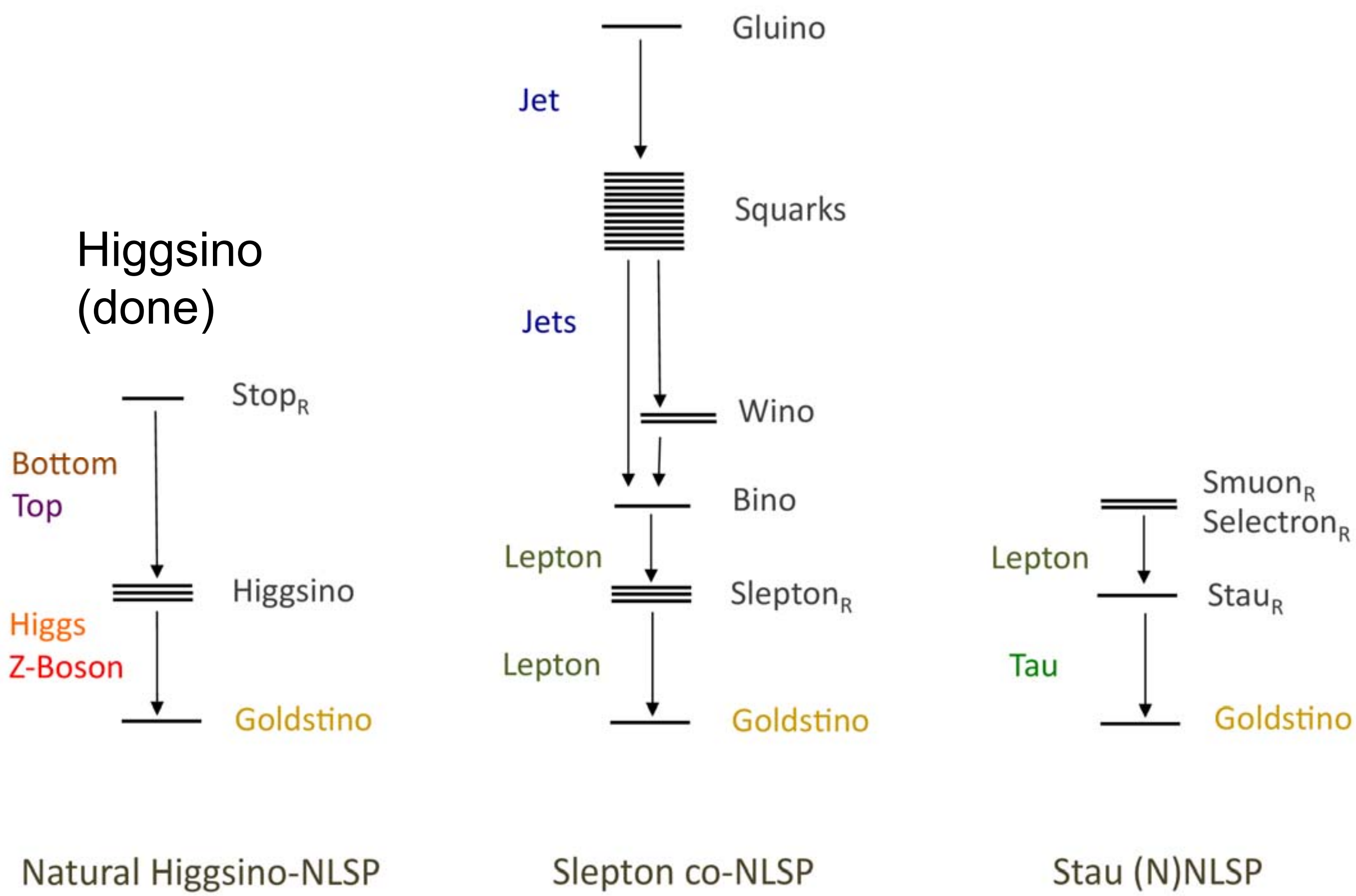
CMS-SUS-13-002

GMSB = Gauge Mediated Supersymmetry Breaking

Gravitino is the lightest SUSY particle (LSP).

Mass spectra in 3 models

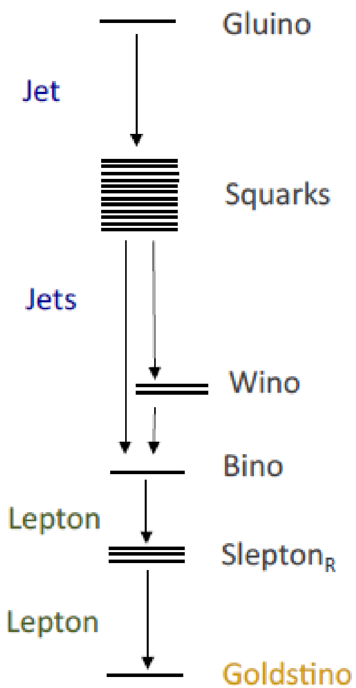
Higgsino (done)

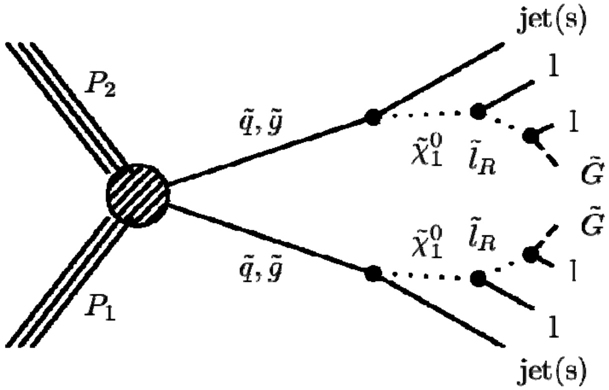


Slepton co-NLSP scenario

Gauge Mediated Supersymmetry Breaking (GMSB) model

CMS-SUS-13-002

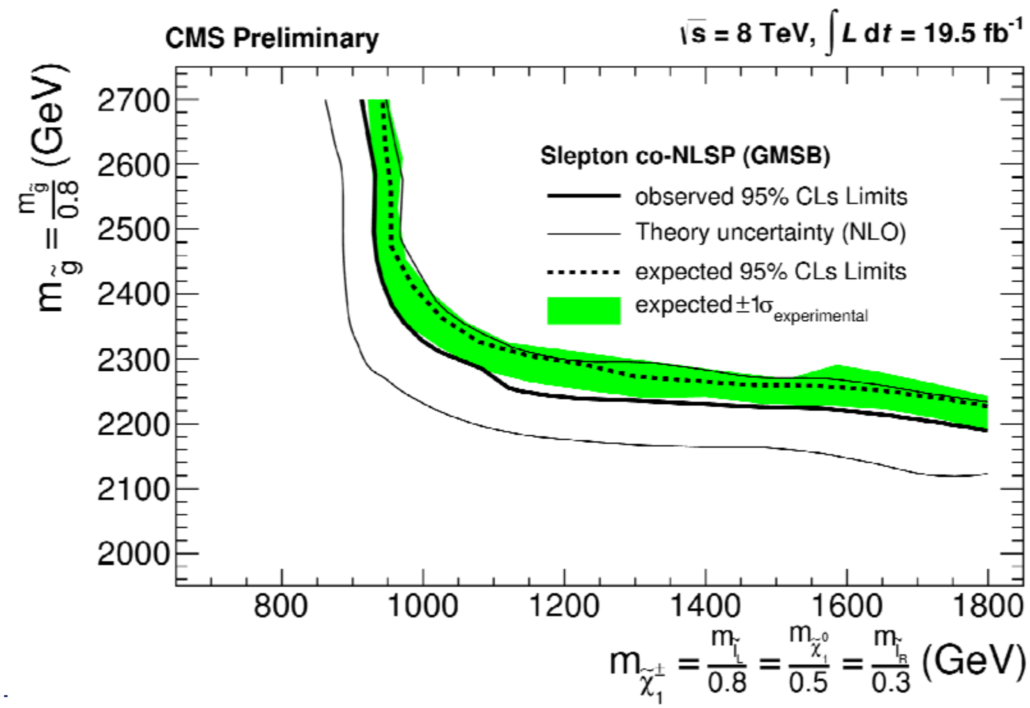




Model includes strong & weak production of squarks, gluinos, sleptons, gauginos

Signal populates high MET and 3 and 4 leptons channels.

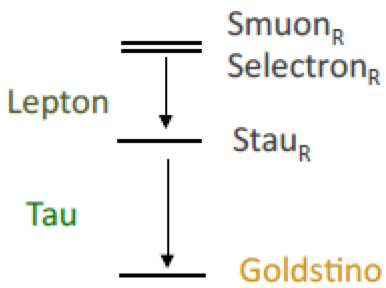
Exclusion limits in the lightest chargino-gluino mass plane

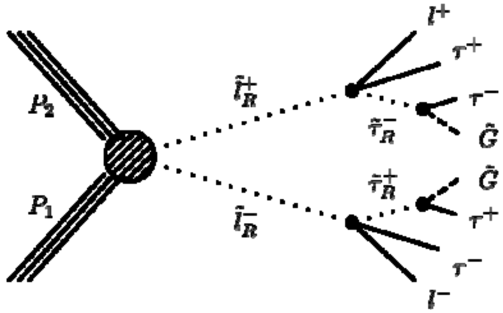


Stau (N)NLSP scenario

Gauge Mediated Supersymmetry Breaking (GMSB) model

CMS-SUS-13-002

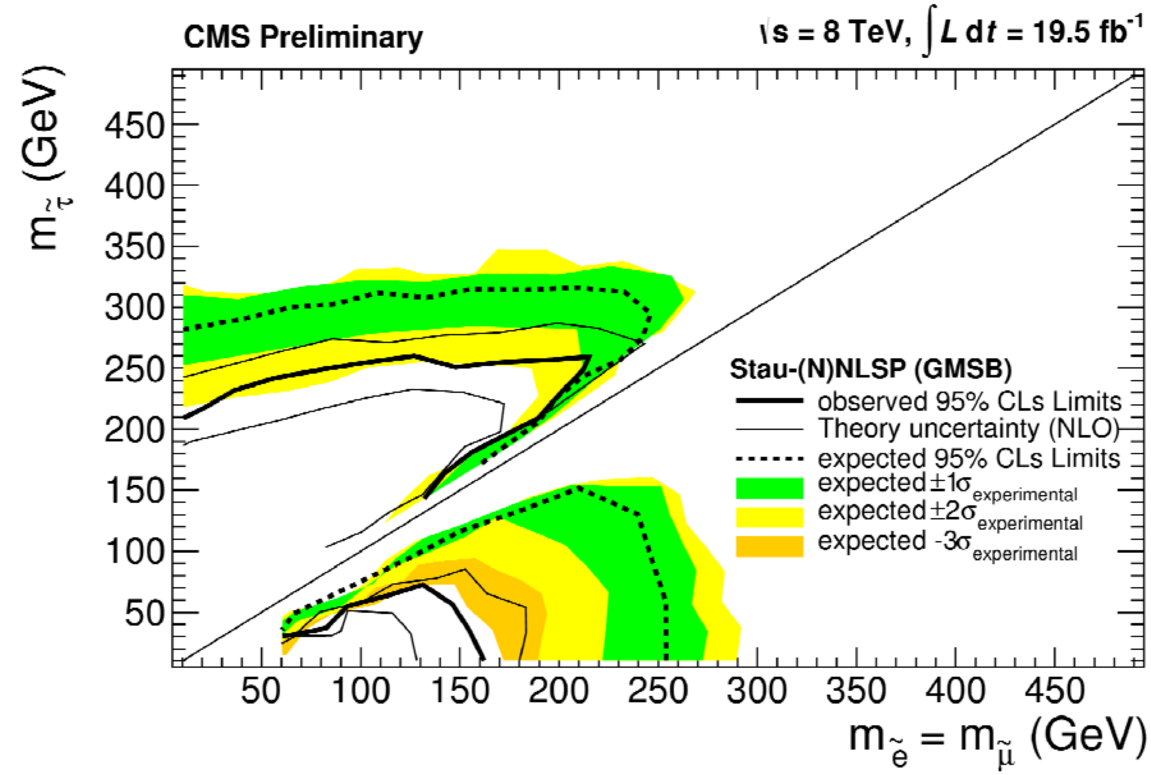




Electroweak production of right-handed sleptons

Signal populates high MET and τ channels.

Exclusion limits in the degenerate smuon- and selectron-stau mass plane



Next slide
more on discrepancy

Origin & significance of discrepancy

CMS-SUS-13-002

Most significant contributing channel:

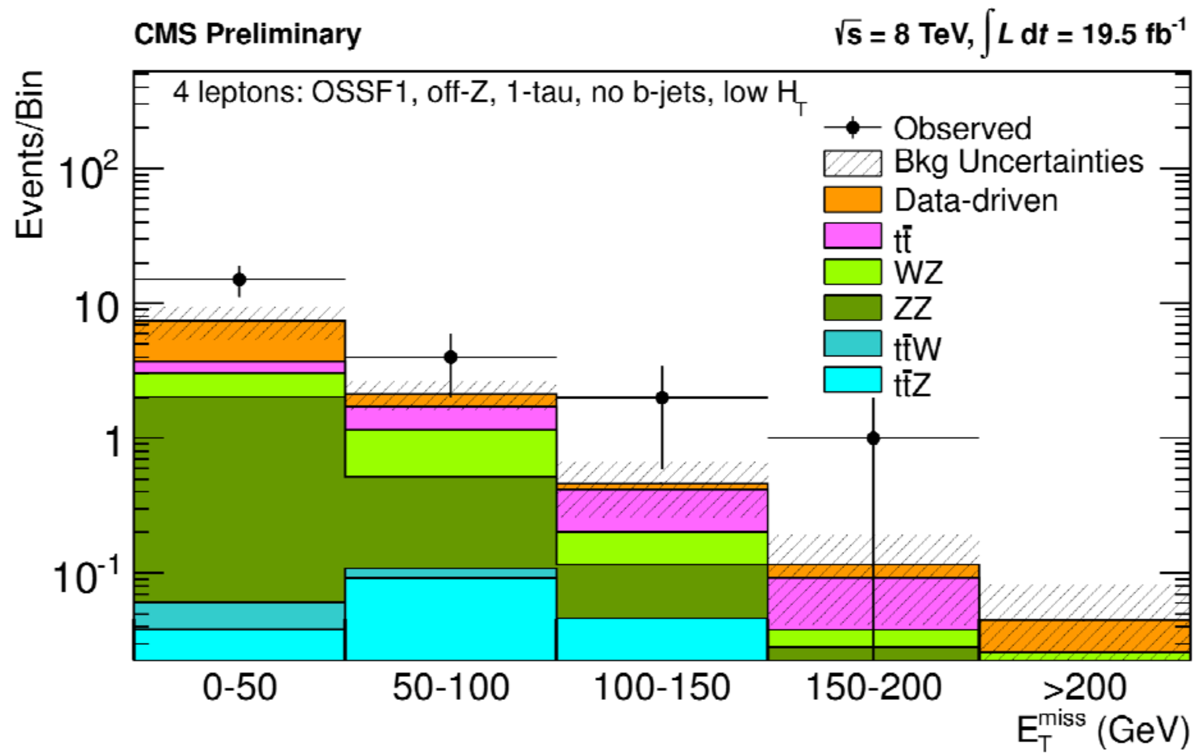
4 leptons, OSSF1, off-Z,

including 1 τ,

no b-tags, HT< 200 GeV

Observe = 22 events

Expected = 10 ± 2.4



LEE: 64 different categories of met-binned multi-lepton events.

BUT: One of the first things for 2015

Discrepancy studies

CMS-SUS-13-002

Categorie:

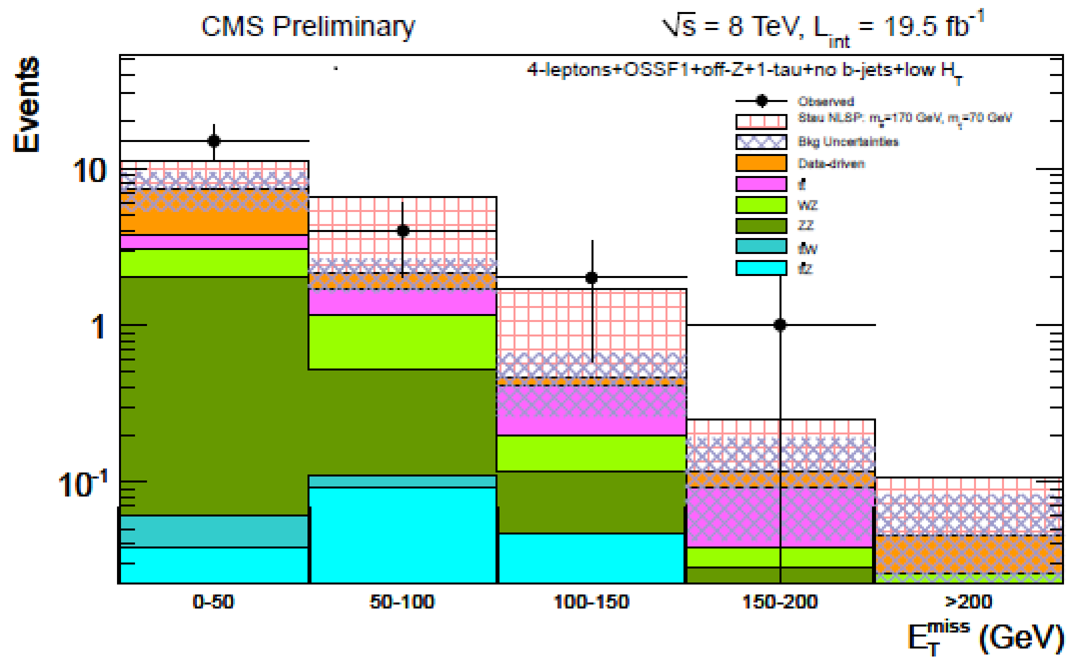
4 leptons, including 1 τ,

OSSF1, off-Z,

no b-tags, HT< 200 GeV

Observe = 22 events

Expected = 10 ± 2.4 events



Same plot, with stau NLSP signal filling the SM void.

Multilepton Physics - I

- A partial and biased list:
  - Open search
    - Detailed observations vs expectations for multilepton final states
  - RPC SUSY
    - GMSB-derived slepton-coNLSP, stau-NLSP
    - Electroweak with Higgs (MET+WZ,ZZ,Wh,Zh,hh final states)
    - natural Higgsino with strong production.
  - RPV SUSY
    - A host of RPV λ couplings
    - With and w/o MET,HT
    - Third generation (stop/tau) enriched
  - Simplified Models
    - T1tttt
    - T2WWWW
- Continued……..

Multilepton Physics - II

- A partial and biased list, continued:
  - Higgs Doublet Models (with diphotons)
    - H → hh
    - A → Zh
  - t → c+higgs (with diphotons)
  - Fourth Generation
    - b' → tW,bZ,bh
  - SM: ttW, ttZ
  - Exotic
    - Flavored Dark Matter (tau-heavy)
    - See-Saw (total charge binning)

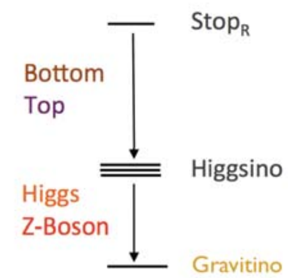
Natural GMSB Higgsino with Diphotons(+b-jets)

If SUSY is broken by Gauge Mediation

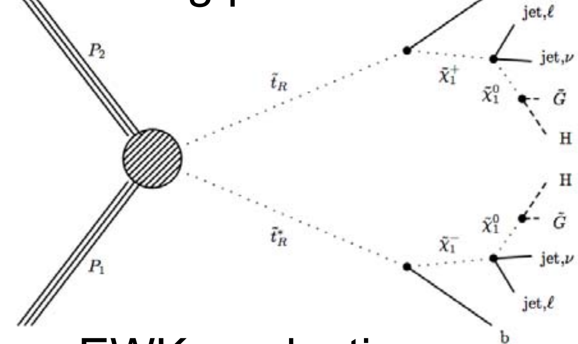
→ Gravitino is LSP

Decay chain depends on nature of NLSP

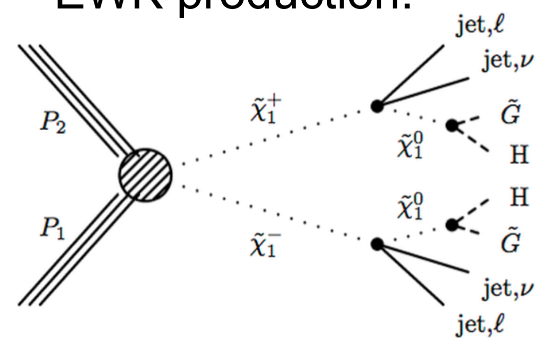
→ Large higgsino component



Strong production:



EWK production:



Signature:

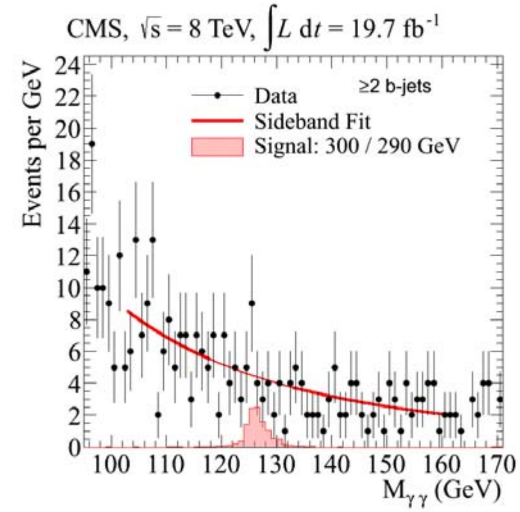
- ≥2 photons (p_T > 40, 25 GeV)
- ≥2 *b*-tags (p_T > 30 GeV)

Backgrounds:

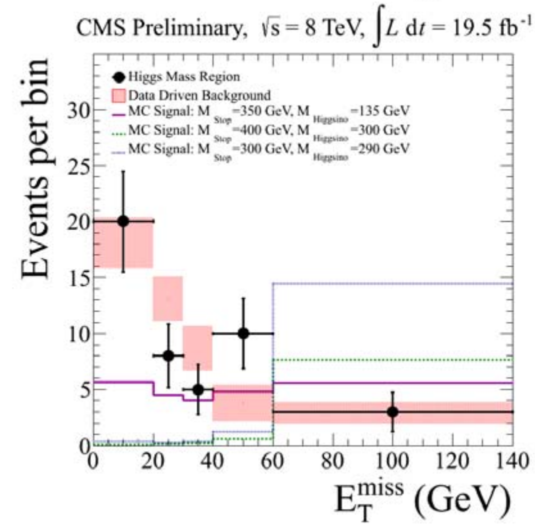
- QCD: γγbbbar+ γbbbar +jet (with γ-fakes from jets)
- Small bkg from electrons (faking a photon)

Natural SUSY GMSB (diphotons)

- **Strategy:**
  - Require 1 Higgs to decay to γγ
  - Higgs →γγ allows us to use Higgs mass sidebands for data-driven background estimate
  - Take MET shape from sidebands
- **3 search regions ($M_{\gamma\gamma}$ 118-133 GeV):**
  - bb pair in the Higgs mass window of 95 to 155 GeV
  - Not consistent with Higgs mass
  - ≥ 3 btags
- **Combine 3 signal regions**



$M_{\gamma\gamma}$

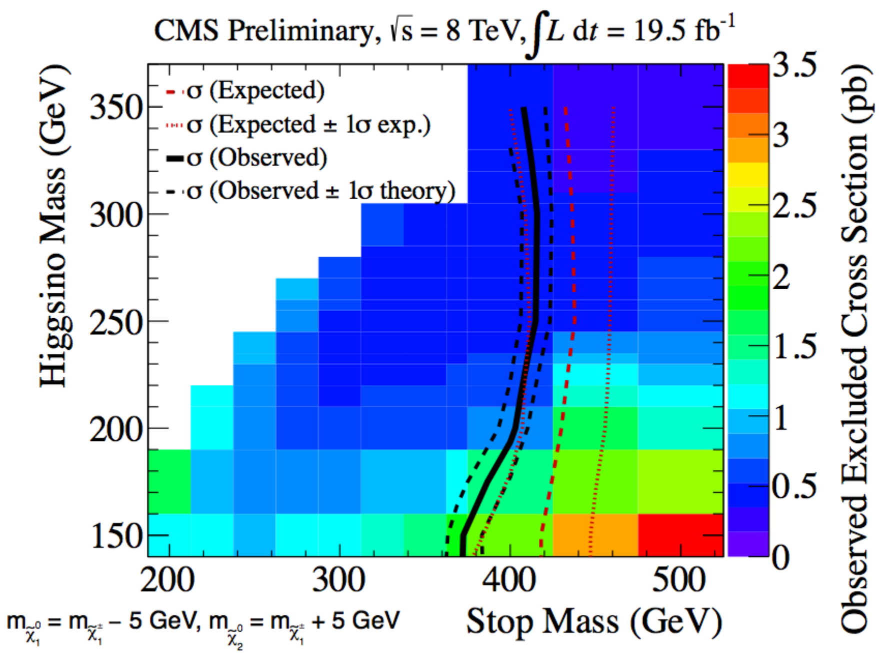


MET

CMS PAS-SUS-13-014

Natural SUSY with GMSB (with diphotons)

	2 b-jets on h mass		2 b-jets off h mass		3+ b-jet		Total	
E_T^{miss} (GeV)	Data	Bkg	Data	Bkg	Data	Bkg	Data	Bkg
0-20	3	5.0 ± 1.3	15	11.0 ± 1.8	2	1.77 ± 0.73	20	18.1 ± 2.3
20-30	2	3.4 ± 1.3	4	7.9 ± 1.7	1	1.8 ± 1.1	7	13.1 ± 2.0
30-40	0	1.39 ± 0.71	5	6.3 ± 1.3	1	0.73 ± 0.84	6	8.7 ± 2.0
40-60	1	0.58 ± 0.68	7	2.2 ± 1.7	2	0.73 ± 0.84	10	3.8 ± 1.6
60+	1	0.19 ± 0.28	2	1.35 ± 0.73	0	1.3 ± 1.0	3	2.8 ± 1.0



- Exclude stop mass below ~ 360 to 410 GeV, depending on the higgsino mass.

Next

➔Pure Electroweak production, with or without higgs in the final state (the distinction is becoming pointless)

Electroweak Production

- Squarks and gluinos getting heavier in simple scenarios
- What if weak production beats strong production?

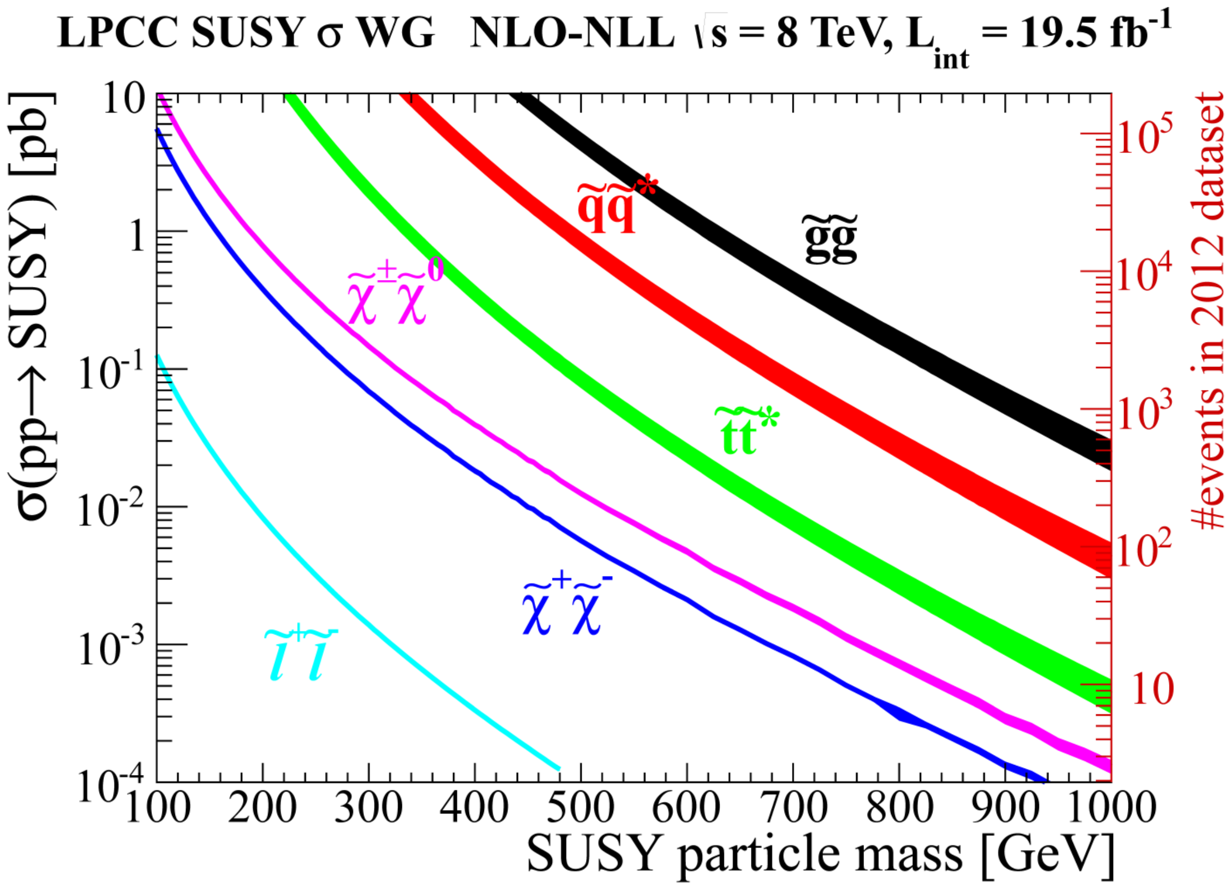
→Electroweak production to the rescue?

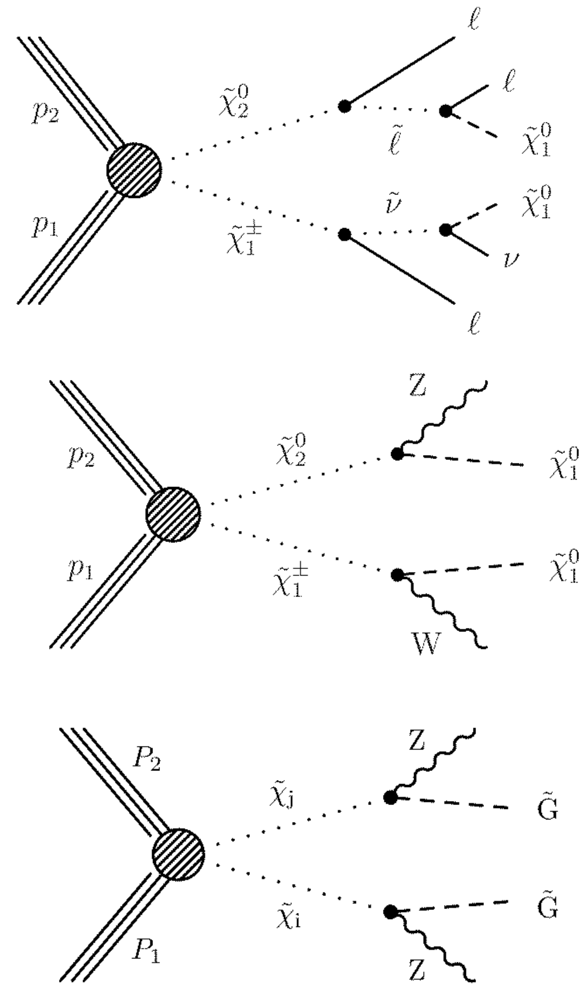
- Less copious, so lesser reach in mass
- *Less* hadronic activity

  cf: classic trilepton SUSYsignature from Tevatron Run II. mSUGRA limits were mostly due to EWK production.

  (CDF: We got grief for cutting on jets → LHC: bin, don't cut.)

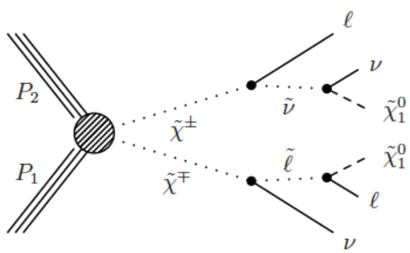
The Leftward March

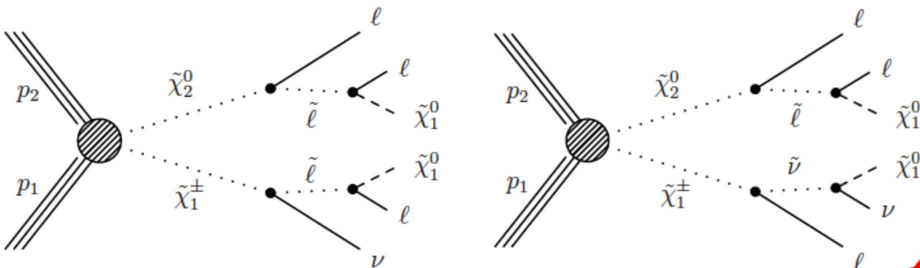




Searches for Production of EWKinos

decay via sleptons



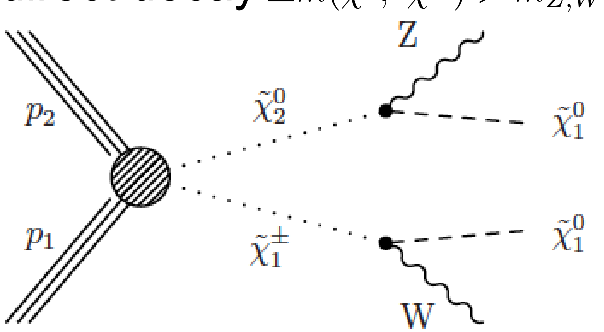


- Extensive set of searches for chargino and neutralino production
- Final states and search strategy depends on assumption of sleptons masses: e.g. all light, only stau light, all heavy
- Signatures:

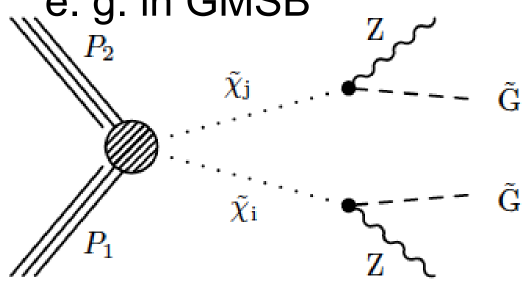
  2 (opposite and same sign),

  3, 4 leptons + MET

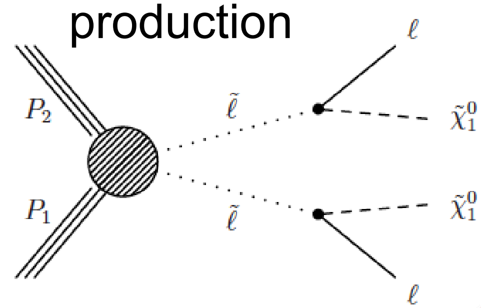
direct decay $\Delta m(\tilde{\chi}^0,\ \tilde{\chi}^{\pm}) > m_{Z,W}$



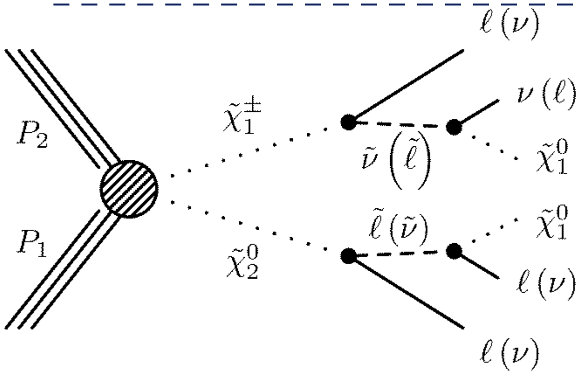
ZZ enriched models: e. g. in GMSB



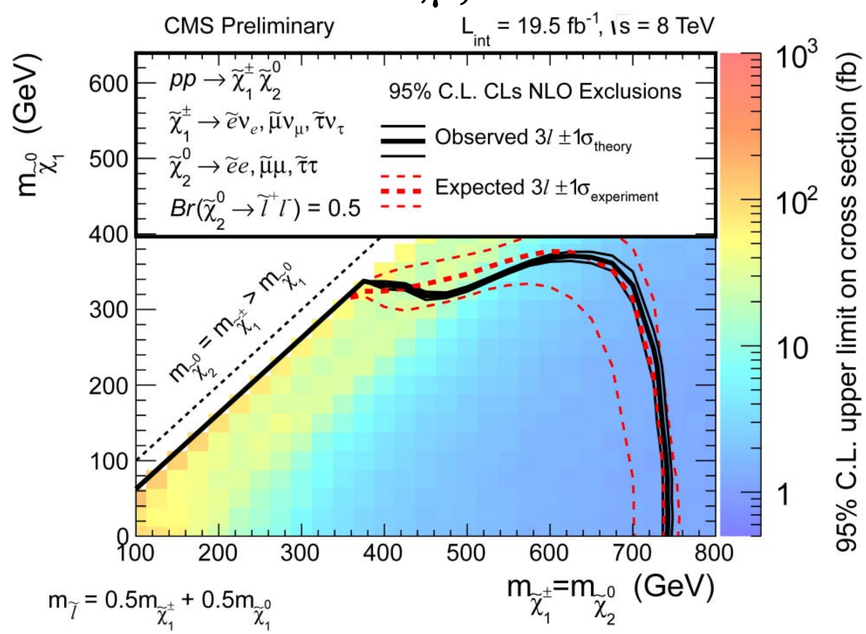
Direct slepton production

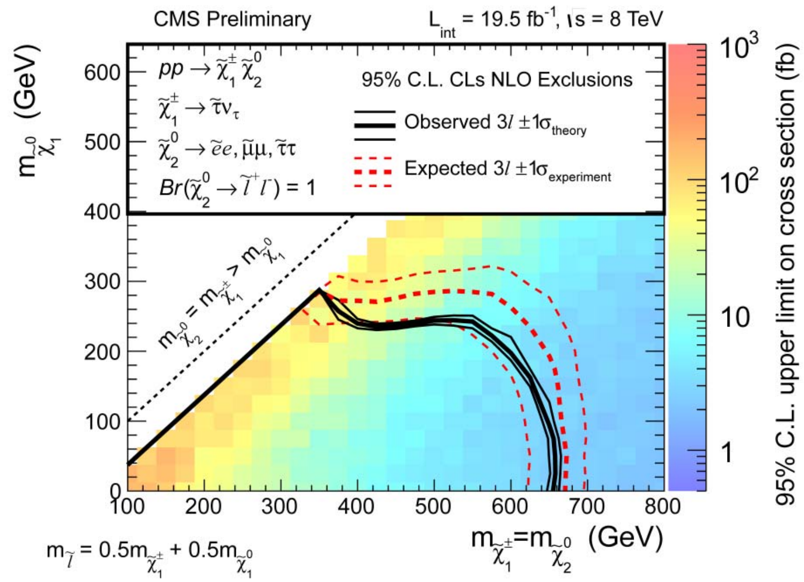


EWKino results

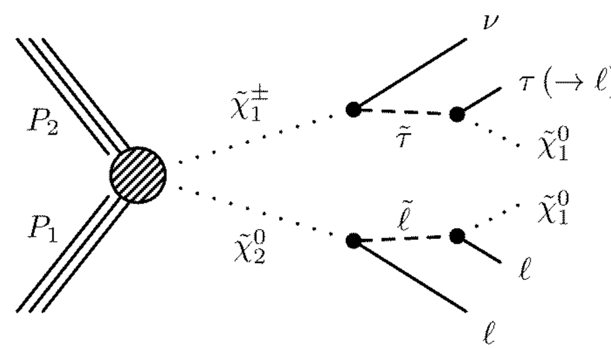


Democratic e,μ,τ

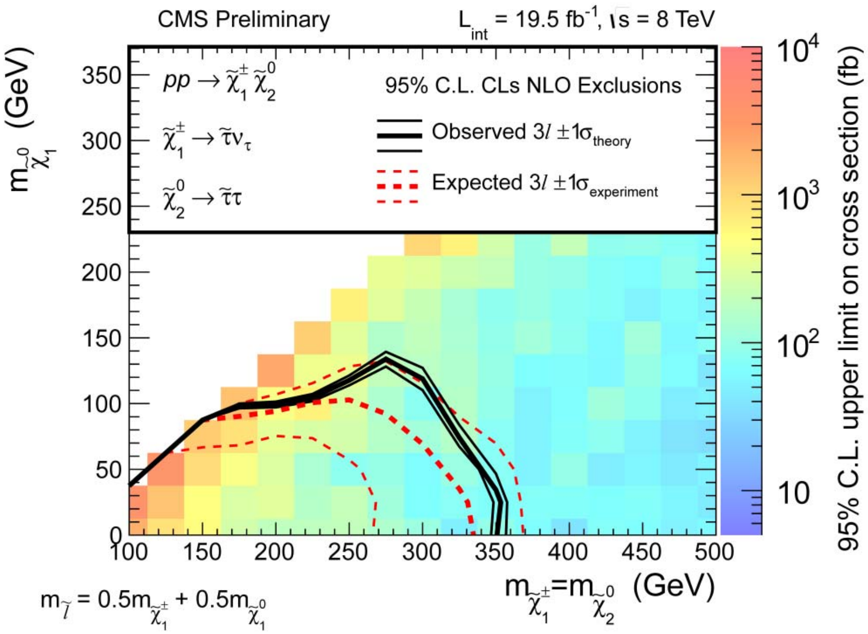




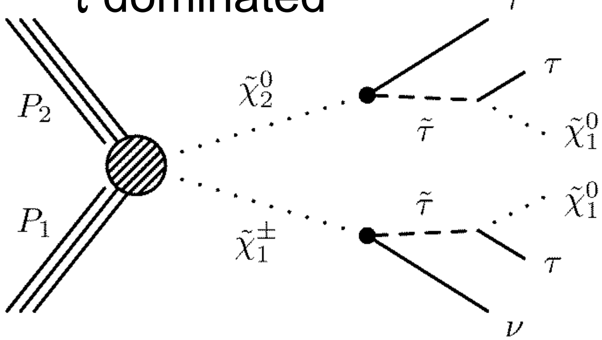
τ enriched

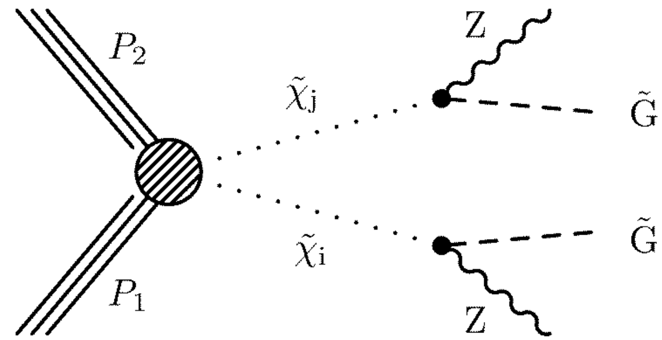


EWKino results (contd)

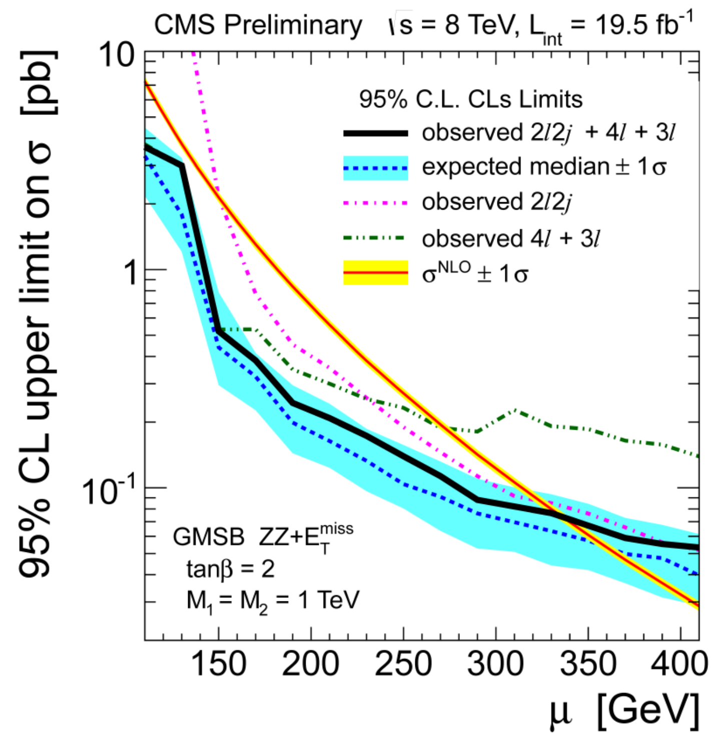


τ dominated

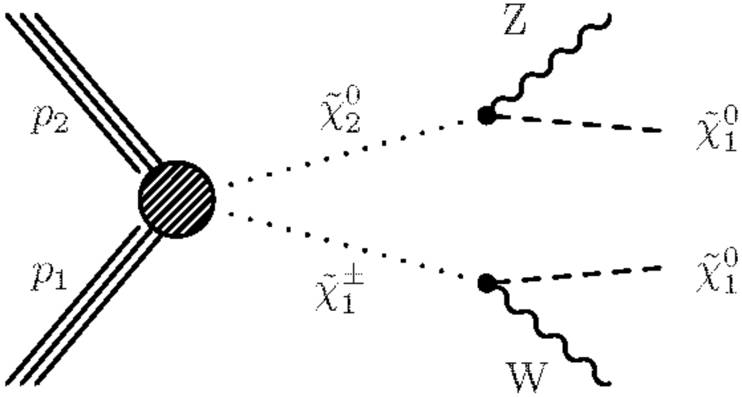




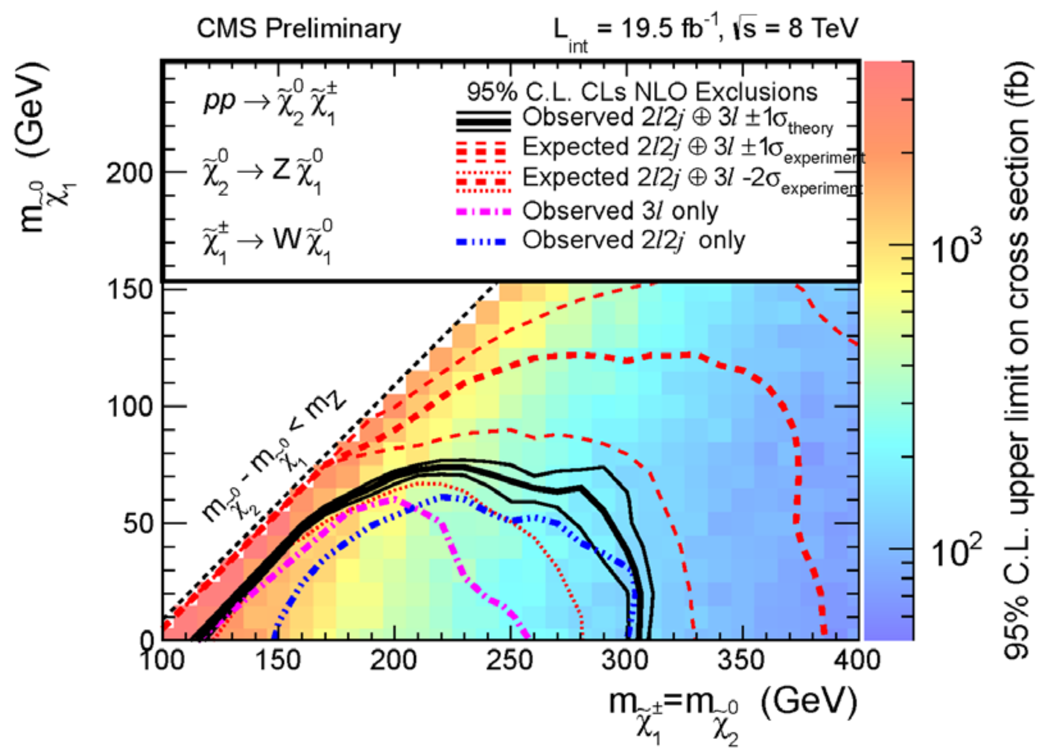
GMSB SUSY ZZ - includes Z(ll)+Z(jj)



EWKino results (contd)

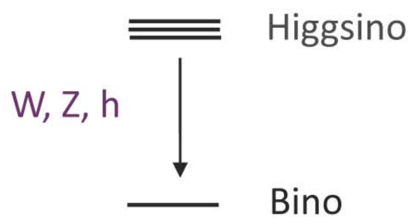


Sleptons heavy/decoupled
WZ+ MET signature
trileptons on Z & Z(ll)+Z(jj)



EWKino with Higgs (contd)

Higgsino-Bino:



"Draining the swamp"
(Scott Thomas)

Higgs – multibinned approach essential !!

Production Mode		Di-boson Channel
Chargino-Chargino	->	WW
Chargino-Neutralino	->	WZ, Wh
Neutralino-Neutralino	->	ZZ, Zh, hh

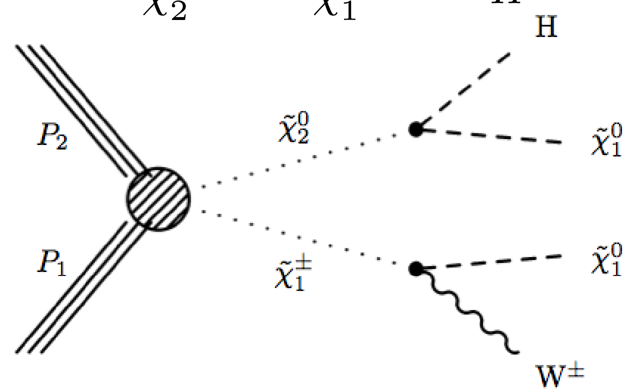
Dominates if Open

$\text{Neutralino}_{\text{Higgsino}} \rightarrow \text{Neutralino}_{\text{Bino}} + h$ — 0^{th} order in mixing

$\text{Neutralino}_{\text{Higgsino}} \rightarrow \text{Neutralino}_{\text{Bino}} + Z$ — 1^{st} order in mixing

Now with Higgs in the final state (WH + MET)

Novel approaches: **"Higgs tagging" in SUSY searches** $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > m_H$



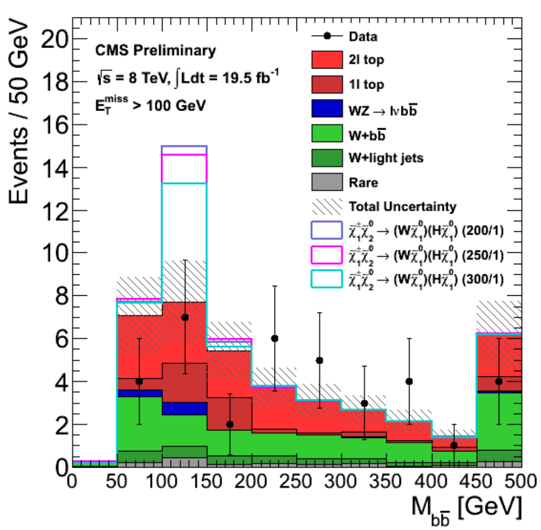
H decay modes considered:

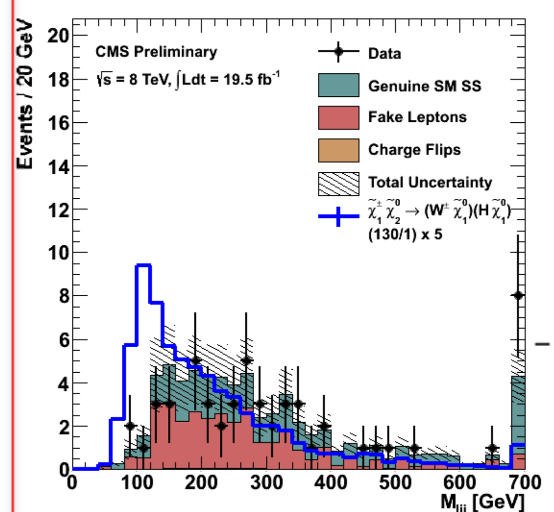
- $H \rightarrow b\bar{b}$: 1ℓ + 2 b-tags
- $H \rightarrow W(\rightarrow l\nu)W(\rightarrow q\bar{q})$: 2ℓ (SS)
- $H \rightarrow W^+W^-/\tau^+\tau^-/ZZ$: 3ℓ

Combination of 1ℓ + 2 b-tags, 2ℓ (SS) and 3ℓ

1ℓ + 2 b-tags

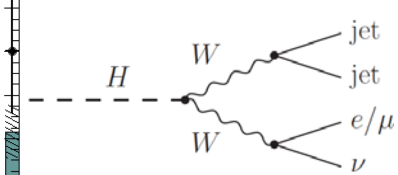
Uses M_{bb}





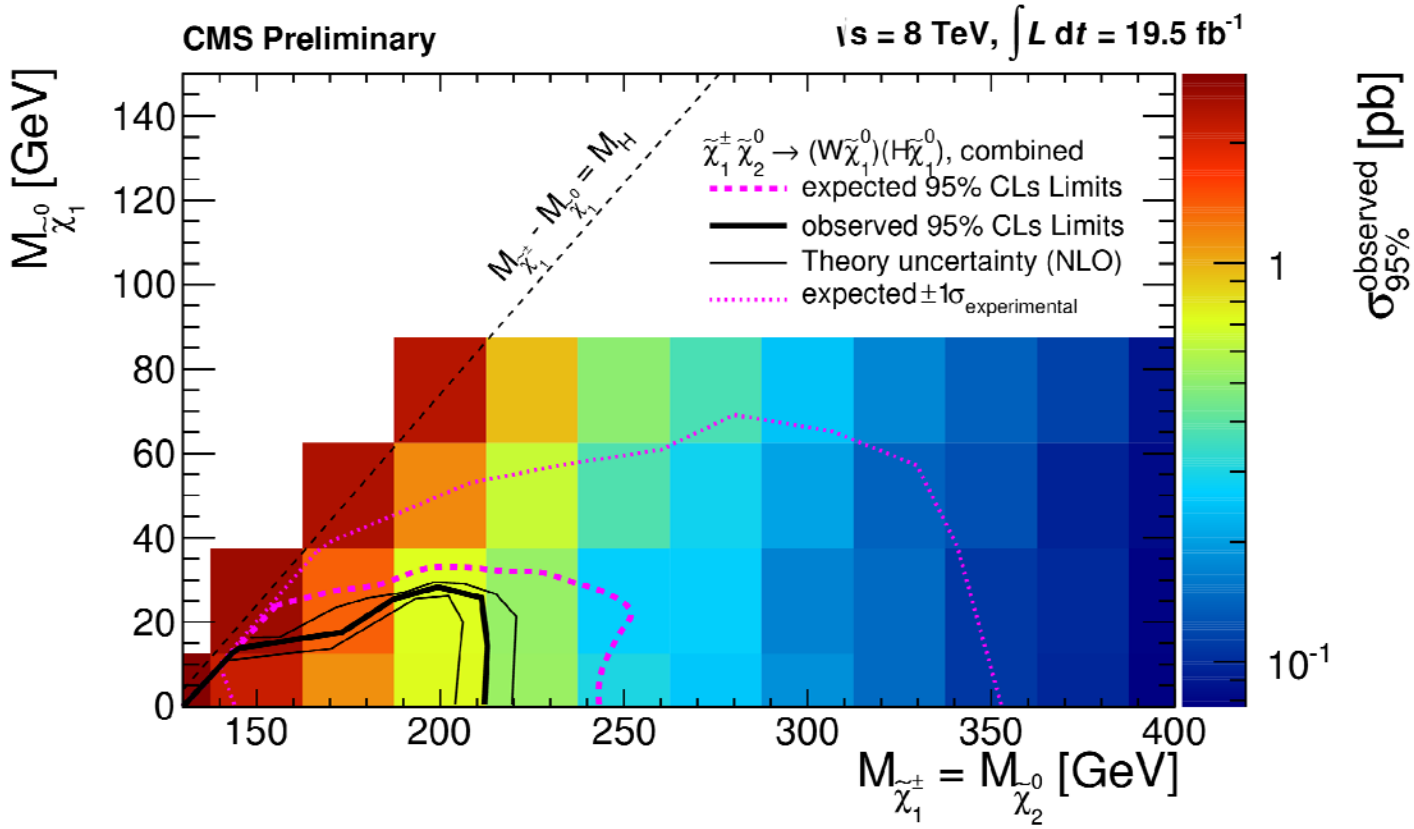
2ℓ (SS)

Uses M_{ljj}



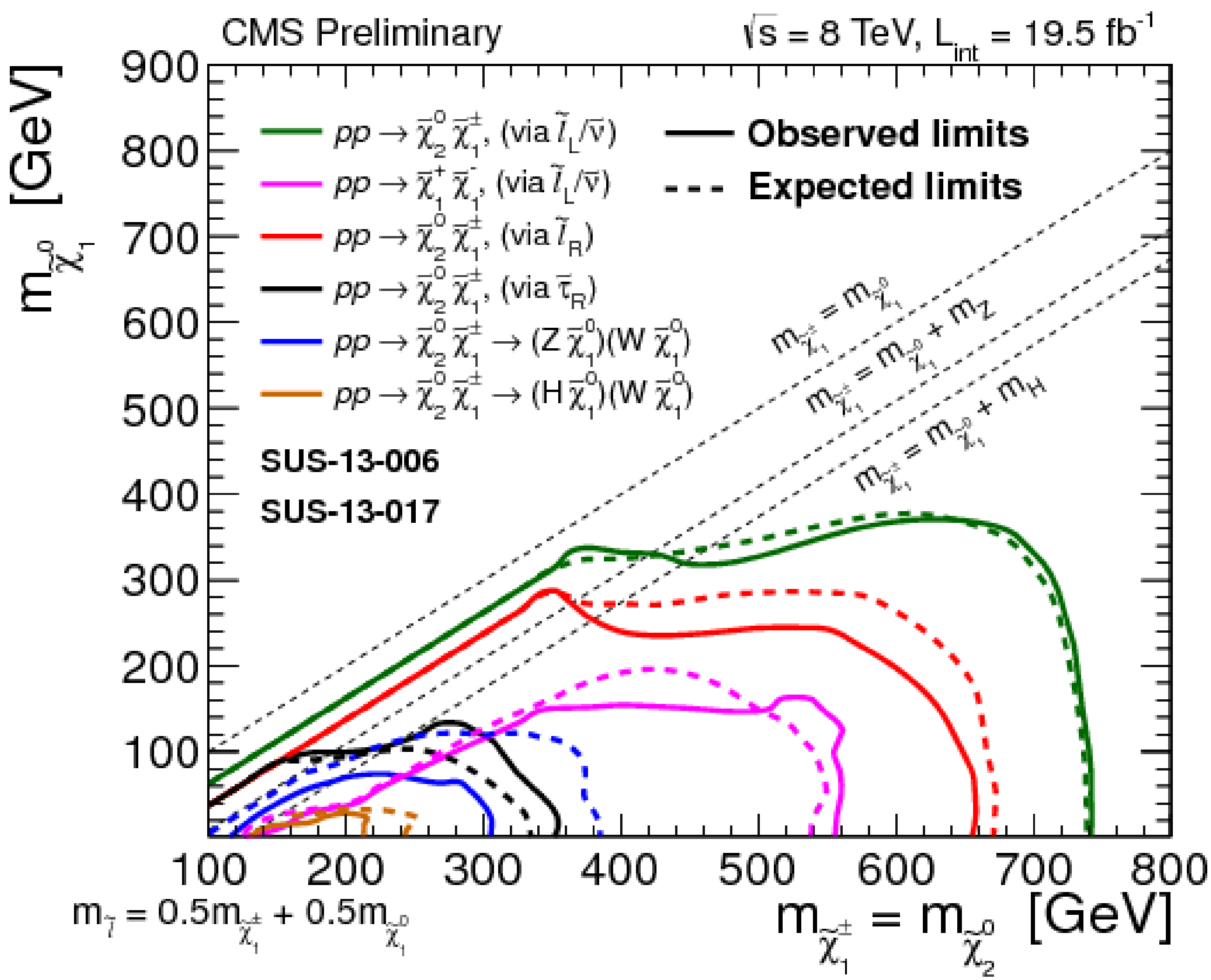
EWKinos with Higgs in the final state

Probing neutralino/chargino masses up to ~ 204 GeV



CMS-PAS-SUS-13-006
CMS-PAS-SUS-13-017

Update Summary of EWKino Searches



Before concluding: Topics in extra slides

- RPV
  - Leptonic and Hadronic (couplings) with multilepton final states, natural (3rd generation) stop-RPV
  - Hadronic with paired three jet resonances

- Direct stop with higgs

LHC vs SUSY Models

LHC

This was a sugra free talk

Slide Credit: Stephen Martin

SUSY Possibilities: Ways to go

Nascent SUSY

SUSY is very amorous. There isn't a signature that it does not like….

SUSY Search Conclusions and What Next?

- **Masses heavy in simple schemes, but many foxholes left. The hunt continues. (but wrap up 2012 null interpretations.)**

- More off-the-beaten-path ideas coming into focus.
- 2014 should bring plenty of fresh insights as well. Also need to prepare improved environment-sensitive data-driven and hybrid bkgnd techniques. Isolation, pileup will be even more important.
- A new energy regime in 2015. Back to the fox chase (rat race?)
- If a search team discovers an excess, it will NOT be the physics model they were looking for → open (inclusive) searches important.
- Recall CP violation (1964). Search such as t→ch important!

→Rumors of SUSY's demise are greatly exaggerated.

Credits

- WNL organizers / TIFR/ India-CMS !!
- LHC staff.
- CMS collaborators, conveners and management.

Another Escape Valve: R-Parity Violation

- Squarks and gluinos getting heavier in simple scenarios

  BUT

- R-Parity Violation can pull the rug from under searches requiring MET because the Lightest Supersymmetric Particle (LSP) decays.

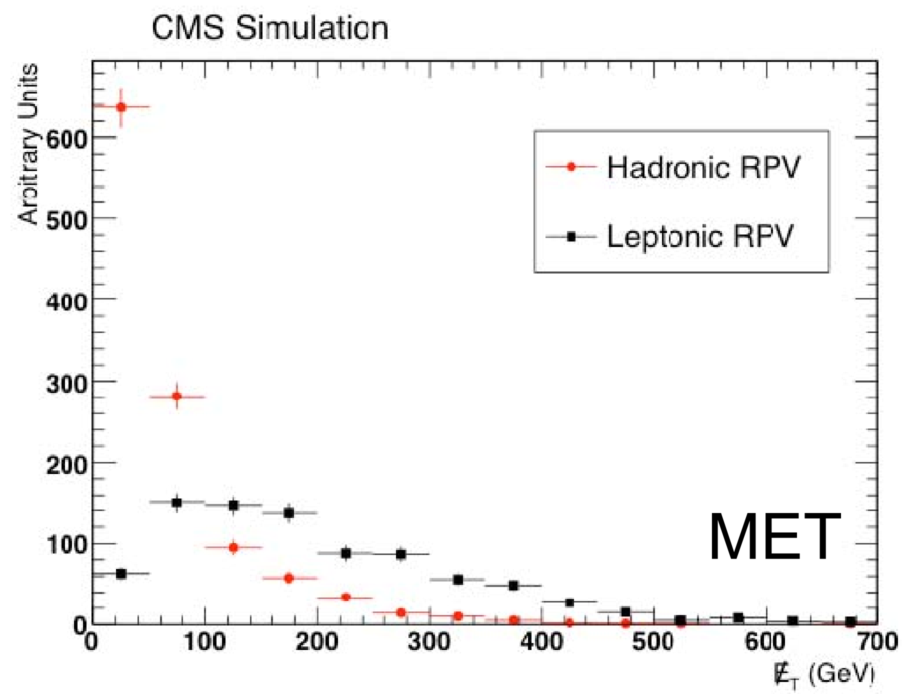
Also, possibly finite lifetimes depending on RPV couplings.

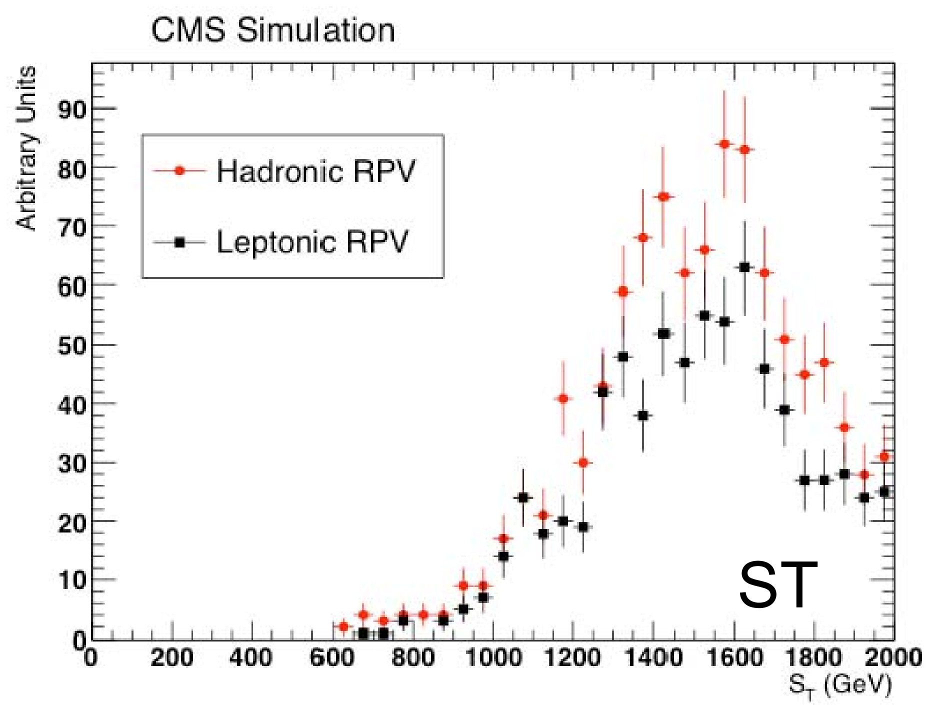
RPV can be tricky

- A CMS multilepton study.
- Two RPV signals:
  no MET in hadronic RPV

- Examine ST instead
  (ST = sum of jet+lepton
  pt's and MET)
  (Also, "effective mass")

- ST recovers the low-MET
  signal





Topologies by Scott Thomas

RPV Searches

- Program of searches for RPV: leptonic, LQD and hadronic RPV
- No dark matter candidate, but could still address naturalness
- Low MET final states; resonances

$$W \propto \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c U_k^c D_k^c + \mu_i H_u L_i$$

Leptonic RPV

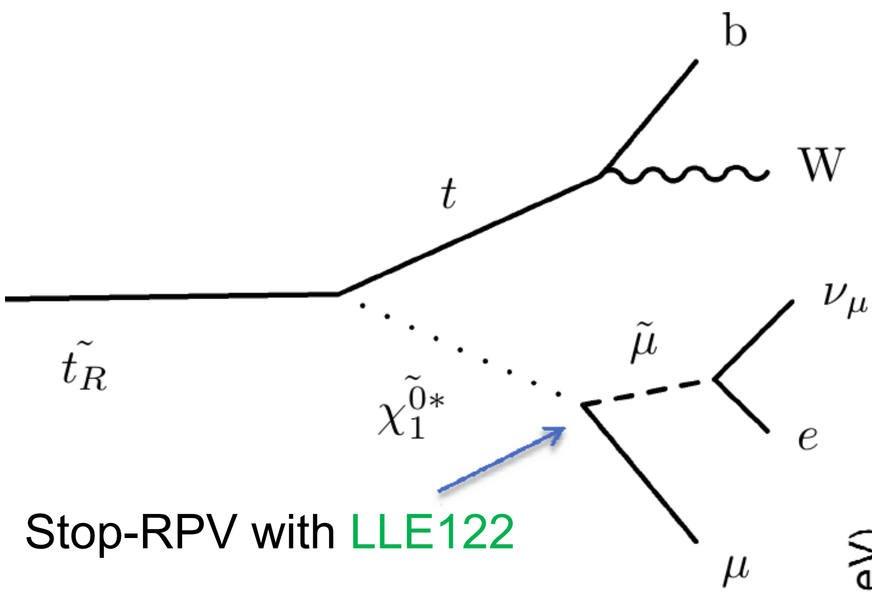
LQD ("semi-leptonic") RPV

Hadronic RPV

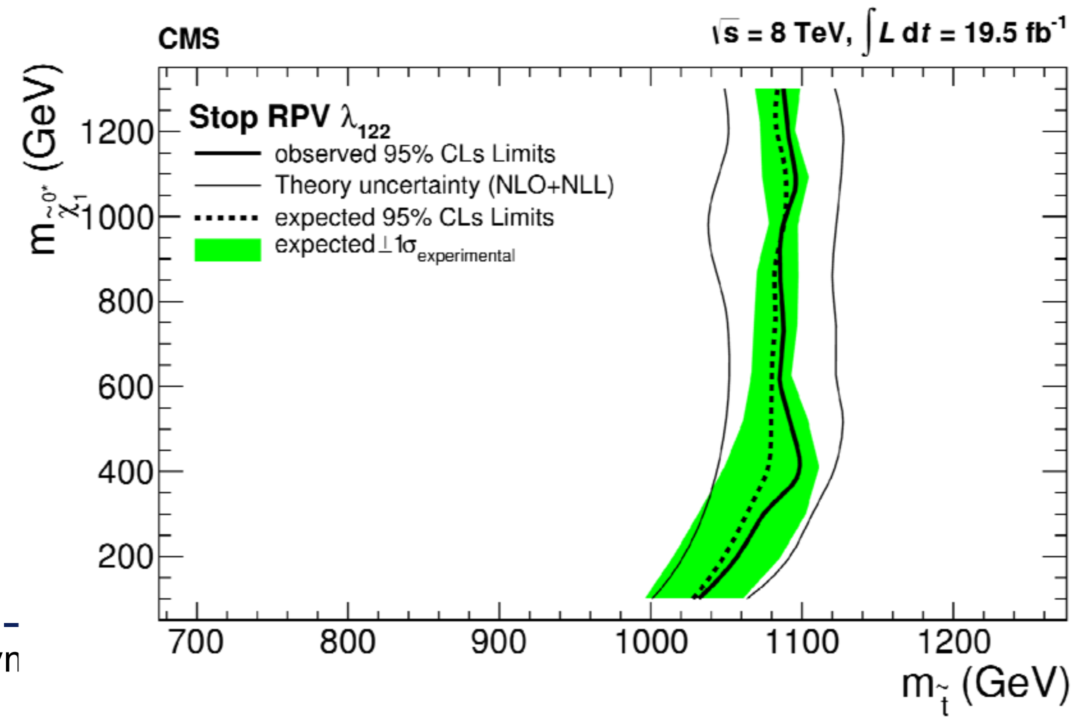
3rd generation RPV (*natural* stop)

to PRL - arXiv:1306.6643
Thanks: Jared Evans,
Yevgeny Katz

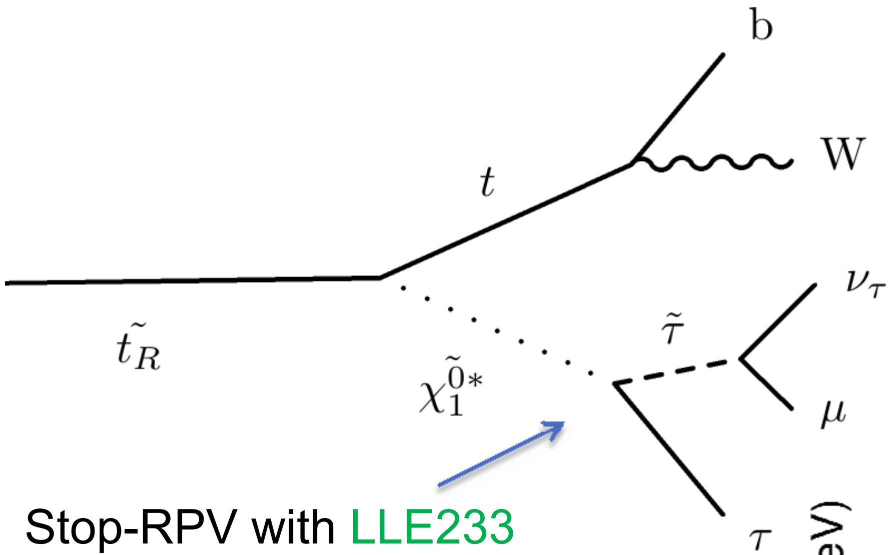
Note the mass reach.



Stop-RPV with LLE122

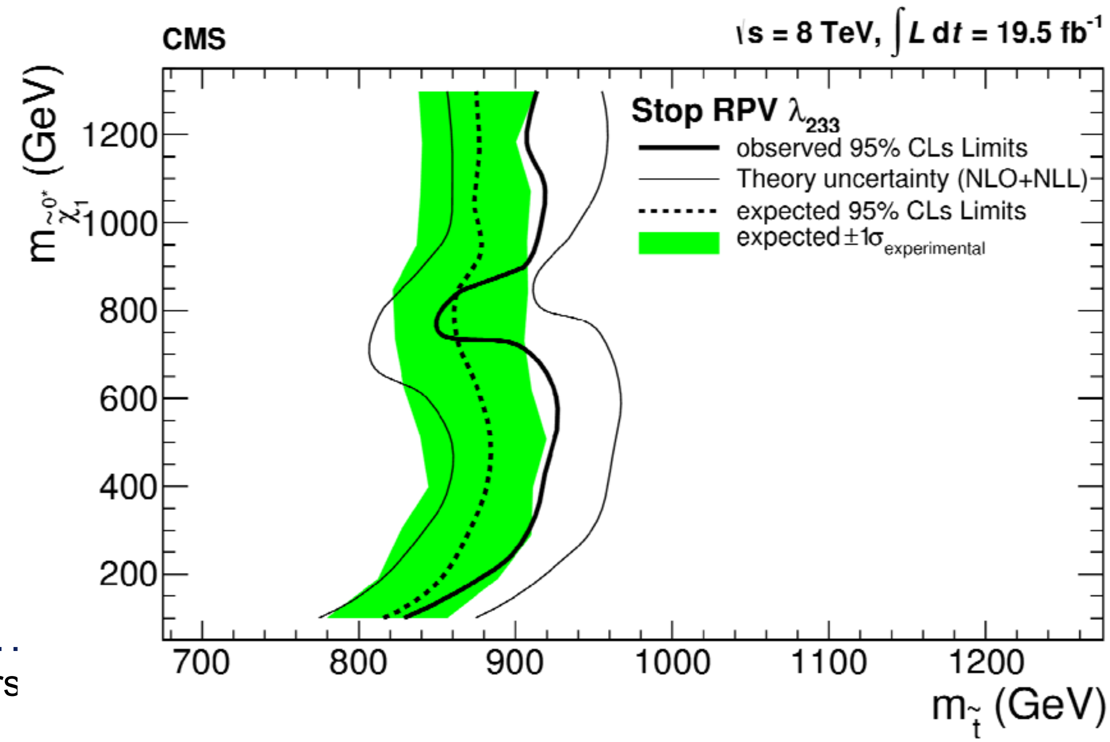


3^{rd} generation RPV (*natural* stop)



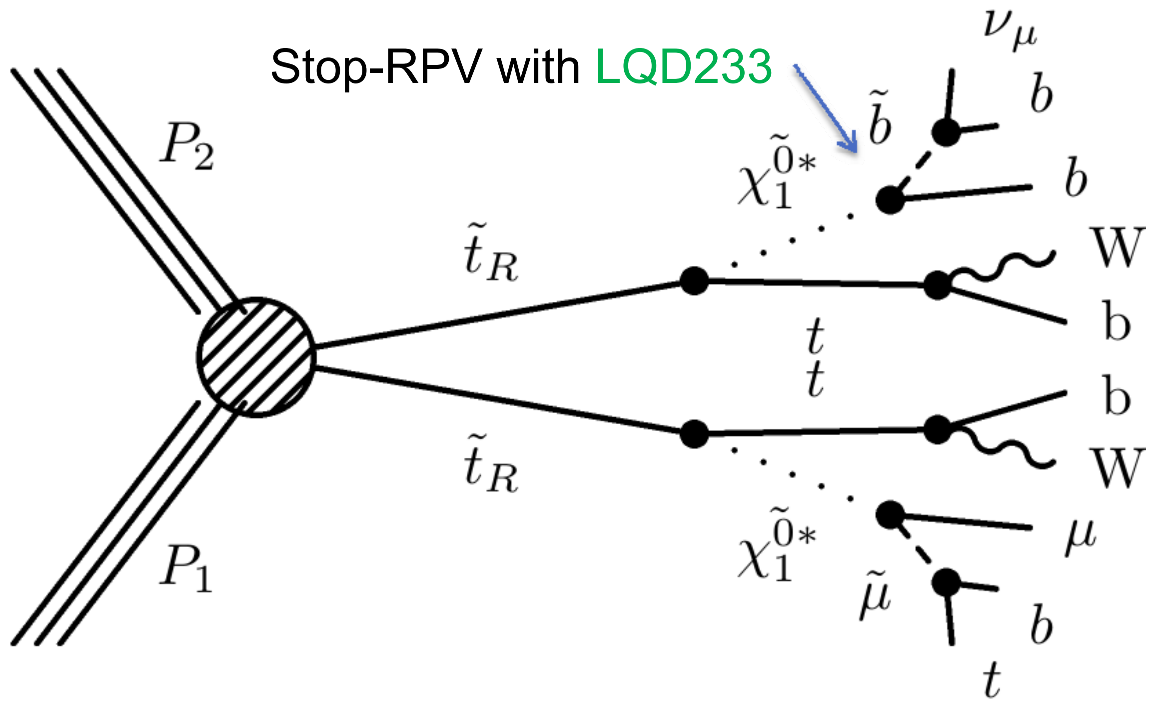
Stop-RPV with LLE233

Note sensitivity loss (tau)
Offshell top in the middle

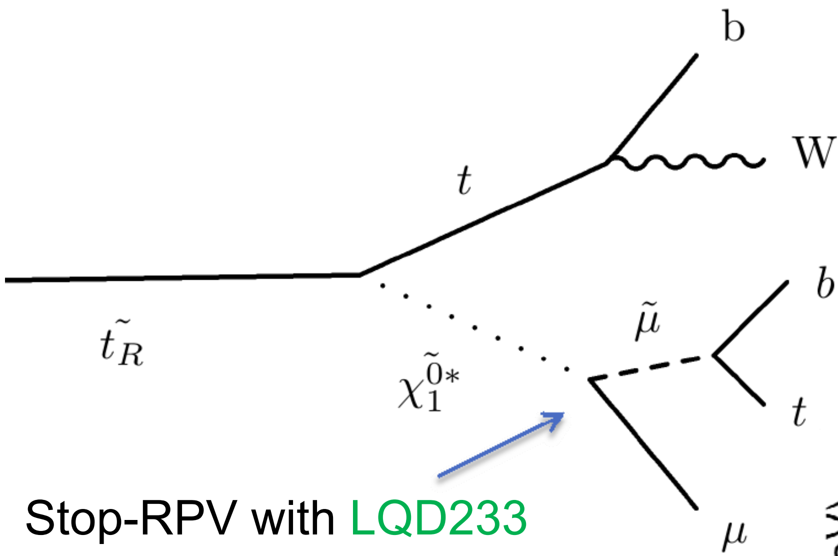


Stop RPV (contd)

Pause and ask a very important experimental question:
Are the exclusion curves too straightforward to get into PRL?
Yes!
→Add wiggles, loops and other complications.

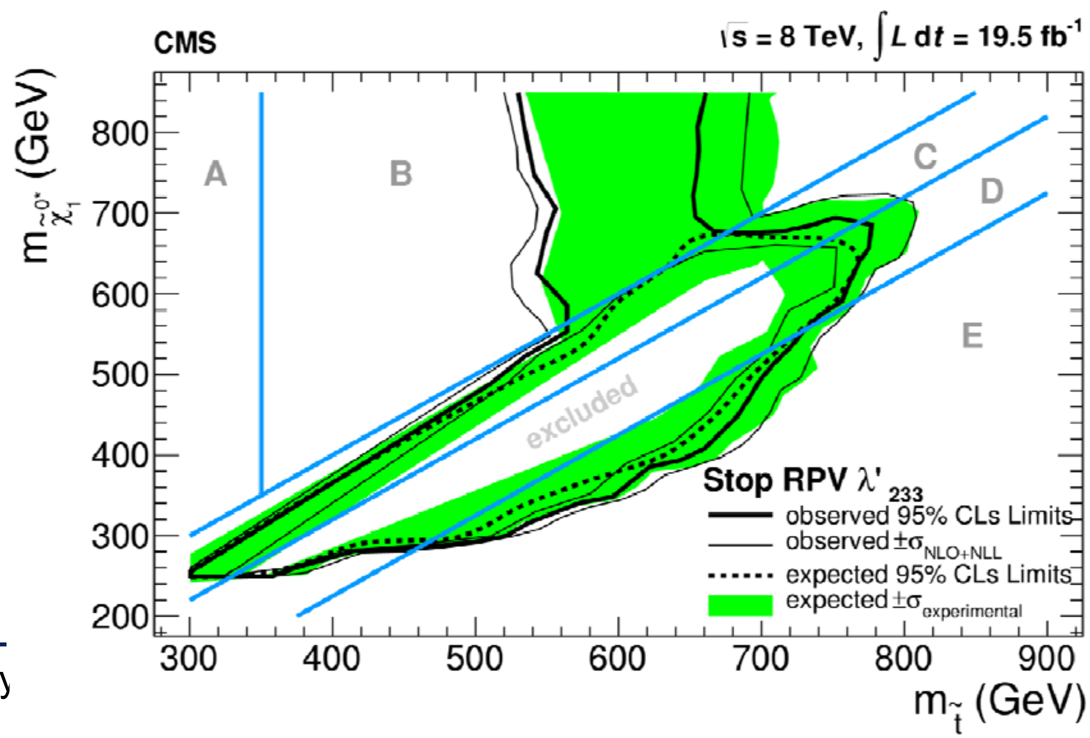


3rd generation RPV (*natural* stop)



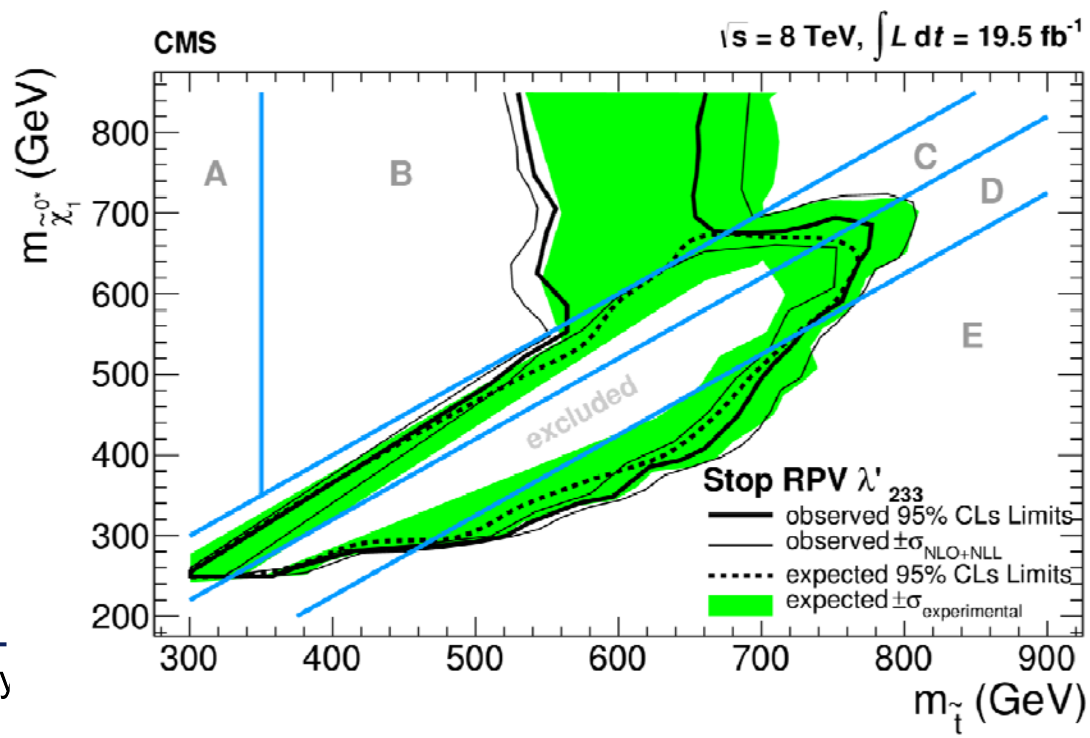
Stop-RPV with LQD233

Voila! But we overshot. Too complicated for a 90 min lecture. (Read the paper). Note the expected-observed difference due to decoupling.



Stop RPV (contd) LQD233

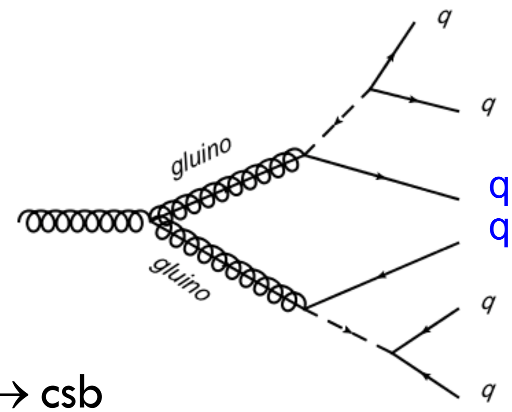
region label	kinematic region	stop decay mode(s)
A	$m_t < m_{\tilde{t}} < 2m_t, m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\nu b\bar{b}$
B	$2m_t < m_{\tilde{t}} < m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\mu t\bar{b} + t\nu b\bar{b}$
C	$m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_W + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to \ell\nu b\tilde{\chi}_1^0 + jjb\tilde{\chi}_1^0$
D	$m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to Wb\tilde{\chi}_1^0$
E	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \to t\tilde{\chi}_1^0$

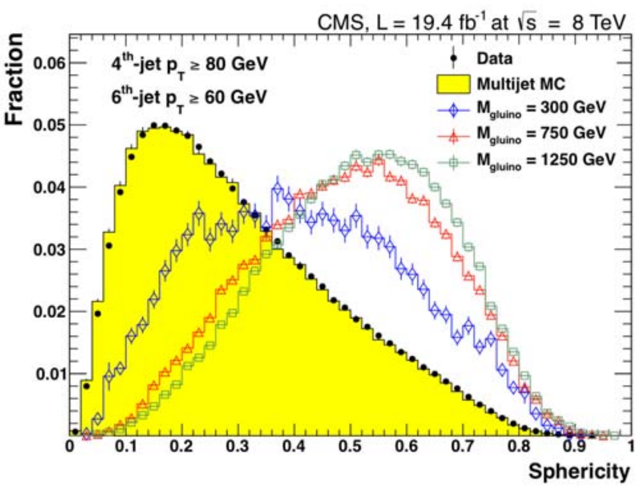


CMS-PAS-EXO-12-049
arXiv:1311.1799

RPV: Search for Three-jet Resonances

- Search for strongly coupled resonances decaying into three jets
- Benchmark model pair produced gluinos with R-parity violating decay
  - Scenario 1: light-flavor decay $\tilde{g} \rightarrow uds$
  - Scenario 2: heavy-flavor decay $\tilde{g} \rightarrow udb$ or $\tilde{g} \rightarrow csb$





- Event Selection:
  - ≥ 6 jets (4th-jet > 80 GeV, 6th-jet > 60 GeV) increases to 110 GeV for higher masses
  - Use of event shape variable sphericity to reduce background for higher masses
  - b-tagging for scenario 2

CMS-PAS-EXO-12-049
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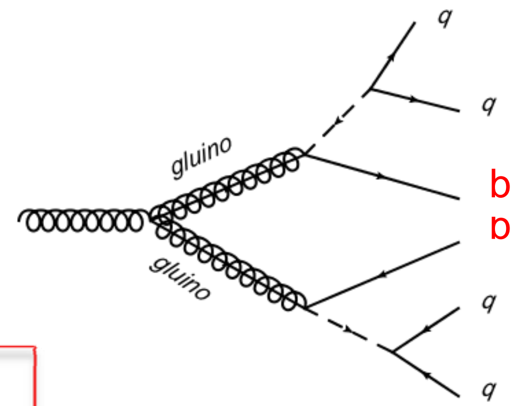
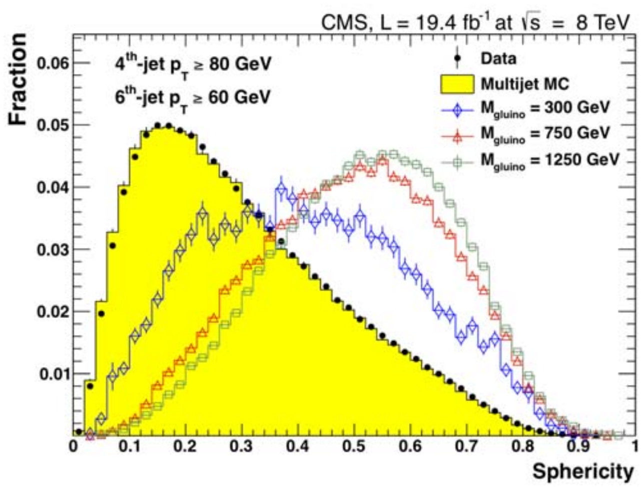
- Benchmark model pair produced gluinos with R-parity violating decay
  - Scenario 1: light-flavor decay $\tilde{g} \rightarrow uds$
  - Scenario 2: heavy-flavor decay $\tilde{g} \rightarrow udb$ or $\tilde{g}$ -





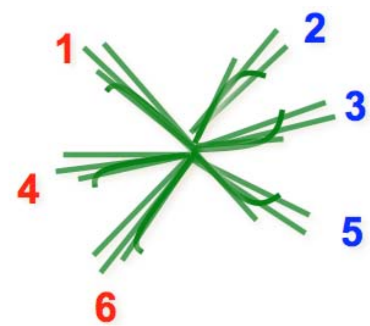
First search with heavy-flavor

- Event Selection:
  - ≥ 6 jets (4th-jet > 80 GeV, 6th-jet > 60 GeV) increases to 110 GeV for higher masses
  - Use of event shape variable sphericity to reduce background for higher masses
  - b-tagging for scenario 2

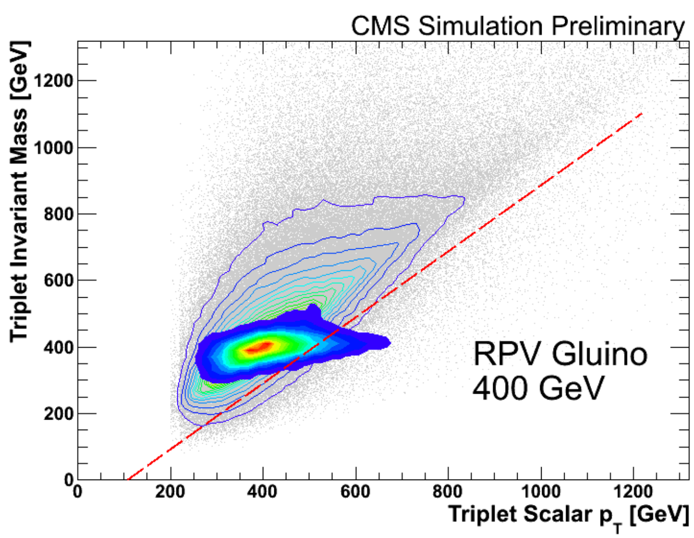
CMS-PAS-EXO-12-049
arXiv:1311.1799

Search for Three-jet Resonances: Jet Ensemble

- Combine the six highest jets into 20 unique triplet combinations
  123, 124, 125, 126, 134, 135, 136, 145,
  146, 156, 234, **235**, 236, 245, 246, 256,
  345, 346, 356, 456 M_{jjj} versus $\sum^{jjj} |p_T^{Jet}|$



- For each triplet plot:



CMS-PAS-EXO-12-049
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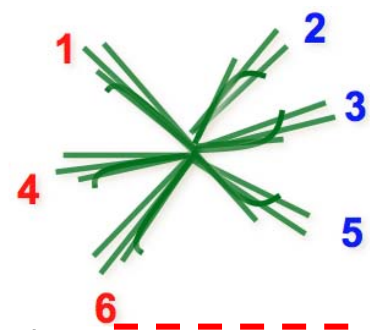
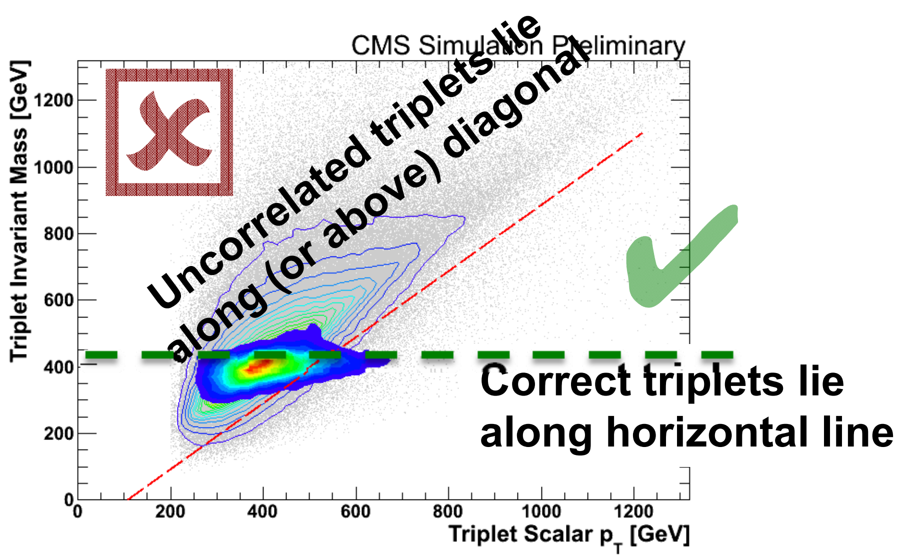


M_{jjj} versus $\sum^{jjj} |p_T^{Jet}|$

- For each triplet plot:

$$M_{jjj} < \sum^{jjj} |p_T^{Jet}| - \Delta \text{ (offset)}$$



CMS-PAS-EXO-12-049
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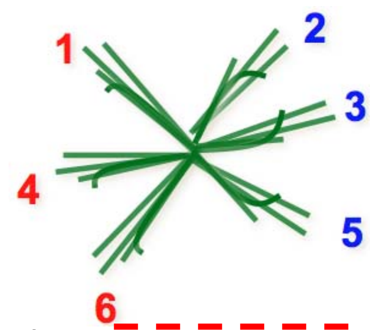

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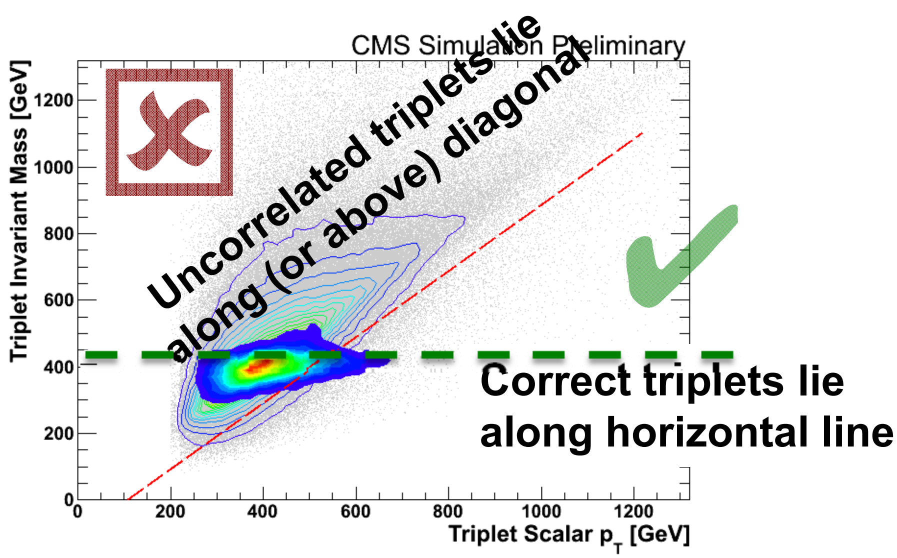
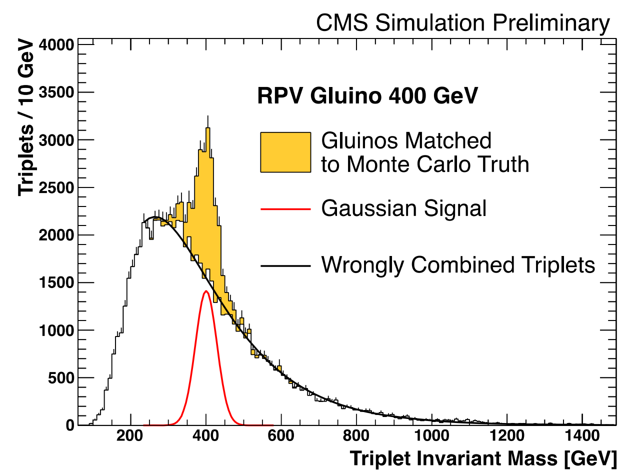




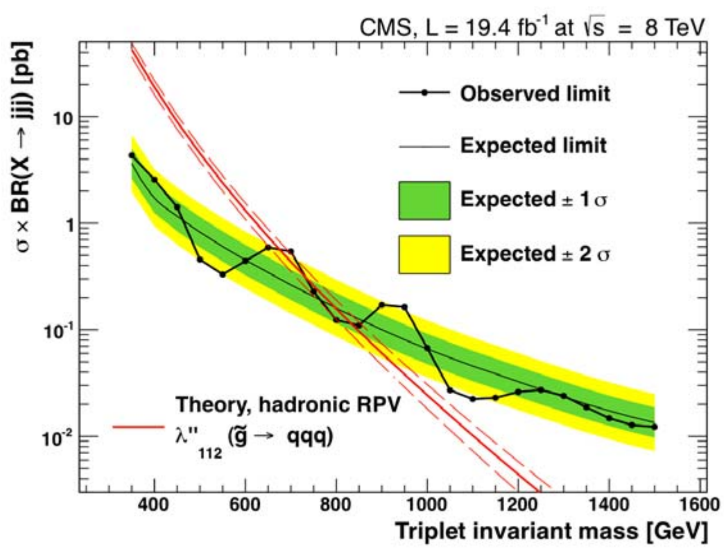
CMS-PAS-EXO-12-049
arXiv:1311.1799

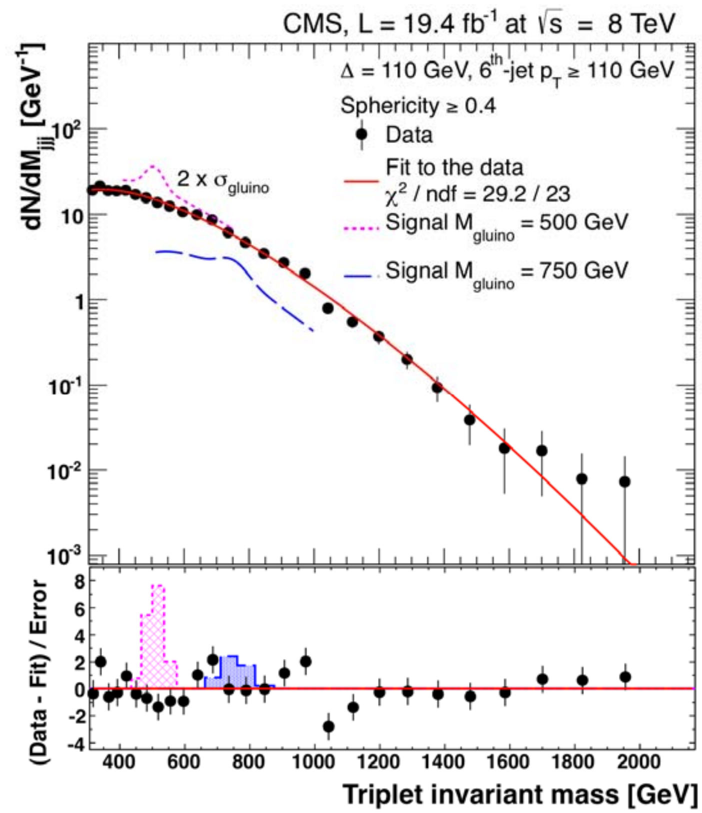
Search for Three-jet Resonances: Results

- Background for light-flavor search comes from parameterized fit
- Good agreement between data and fit
  - Similar function as in dijet search
- Limits are placed at 650 GeV

Scenario 1

Data after Δ= 110 GeV





CMS-PAS-EXO-12-049
arXiv:1311.1799

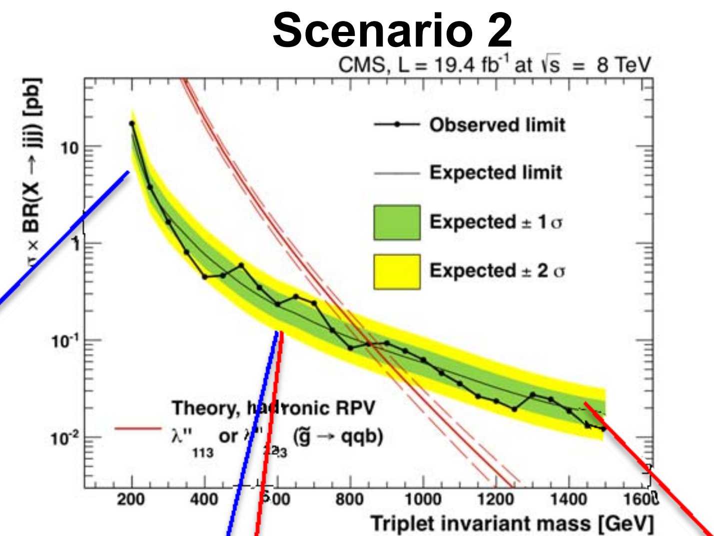
Search for Three-jet Resonances: Results

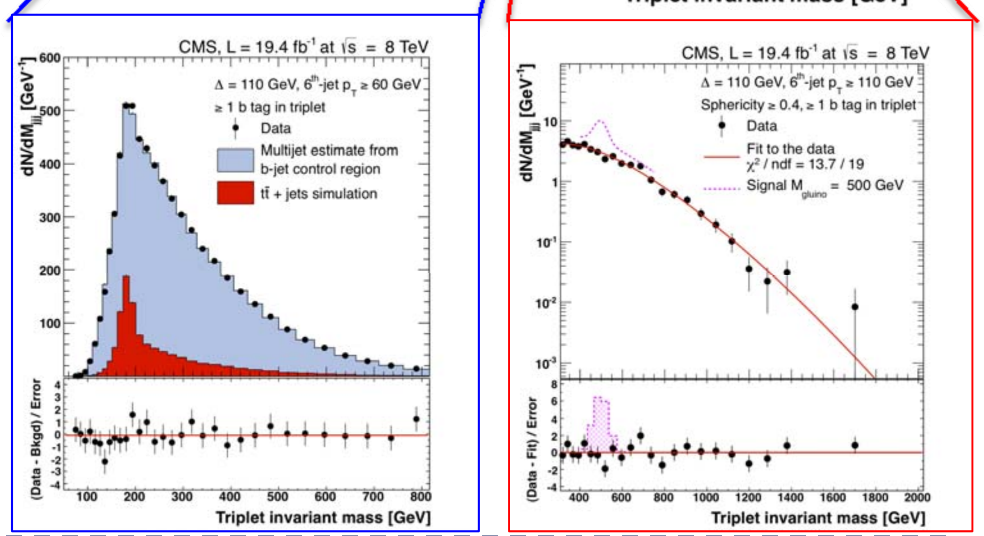
- Require ≥1 b tag in the triplet

- Low mass (200 – 600 GeV)
  - All-hadronic ttbar becomes visible
  - Background estimated from b jet control region in data and ttbar MC

- High mass (> 600 GeV)
  - Background from parameterized fit

- Heavy-Flavor RPV excluded below glunio mass ~835 GeV

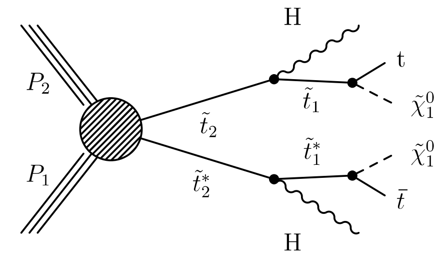




New

CMS PAS-SUS-13-021

Direct Stop Production with Higgs



- stop1 and stop2 are eigenstates of stop L/R
- Assume this mass splitting and H is SM Higgs
- **Search for:**
  - 1 or 2 leptons
  - ≥4jets
  - ≥ 2b-tagged jets
  - With evidence of H→bb decay
  - MET > 50 GeV
    - Supress SM W+jets
- **Strategy:**
  - Single lepton channels require large M_T
  - Dilepton channels select bb pairs consistent with Higgs decay
  - Dominant background from tt pair production
    - Estimated by extrapolating from simulation which is validated using data in the sidebands
    - Rare processes are derived from simulation with 50% uncertainty

N(lep)	Lep. veto	N(b-tags)	Signal region		Sideband region	
			N(jets)	Kinematic requirement	N(jets)	Kinematic requirement
1	track or τ_h	$= 3$b	≥ 5	$M_T > 150$ GeV	$= 5$	$50 \leq M_T \leq 100$ GeV
		≥ 4b	≥ 4	$M_T > 120$ GeV	$= 4$	
2 OS	extra e/μ	$= 3$b	≥ 5	$100 \leq M(b,b) \leq 150$ GeV	$= 5$	$N(b,b) = 0$
		≥ 4b	≥ 4	$N(b,b) = 1$, $100 \leq M(b,b) \leq 150$ GeV or $N(b,b) \geq 2$	$= 4$	or $N(b,b) = 1$, ($M(b,b) \leq 100$ or $M(b,b) \geq 150$ GeV)

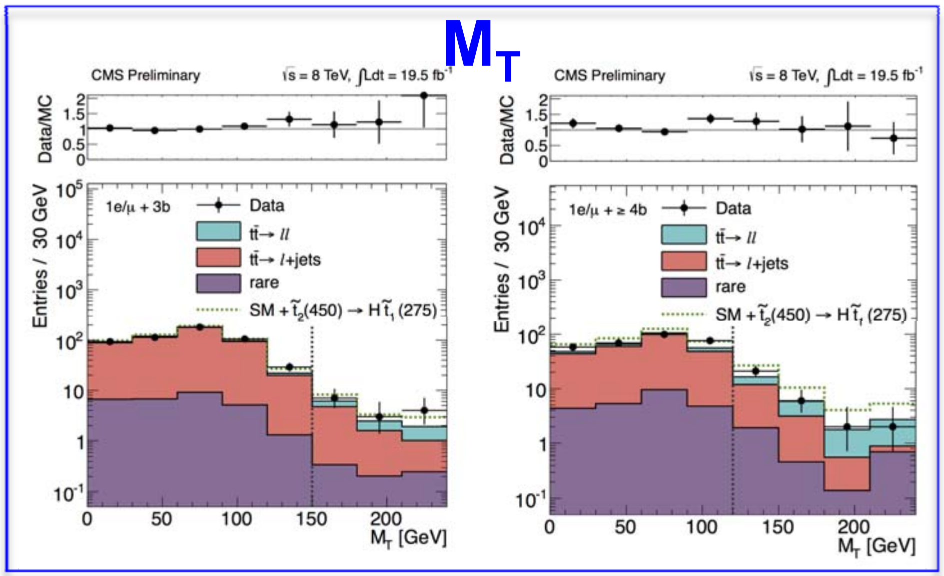
New

CMS PAS-SUS-13-021

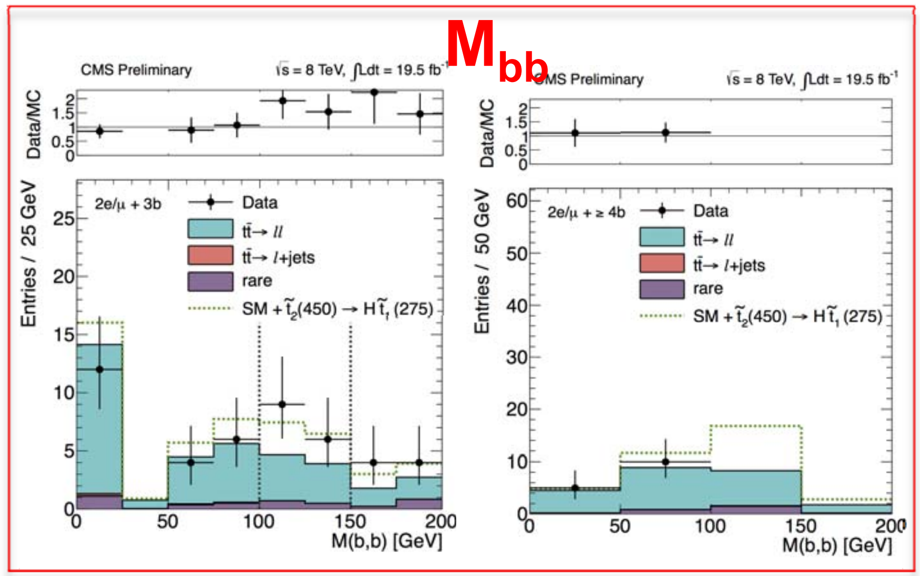
Direct Stop Production with Higgs

Sample	1l + 3b	1l + ≥4b	2l + 3b	2l + ≥4b
$t\bar{t} \to \ell + \text{jets}$	6.1 ± 1.1	13.2 ± 3.2	0.0 ± 0.1	0.1 ± 0.1
$t\bar{t} \to \ell\ell + \text{jets}$	3.2 ± 0.9	10.4 ± 4.3	7.2 ± 2.1	8.8 ± 3.8
Rare	0.8 ± 0.1	3.2 ± 0.8	1.2 ± 0.2	1.7 ± 0.6
Total background prediction	10.0 ± 1.8	26.8 ± 5.6	8.4 ± 2.7	10.6 ± 5.1
Total relative uncertainty [%]	17.5	20.9	31.7	48.2
Data	14	31	15	3

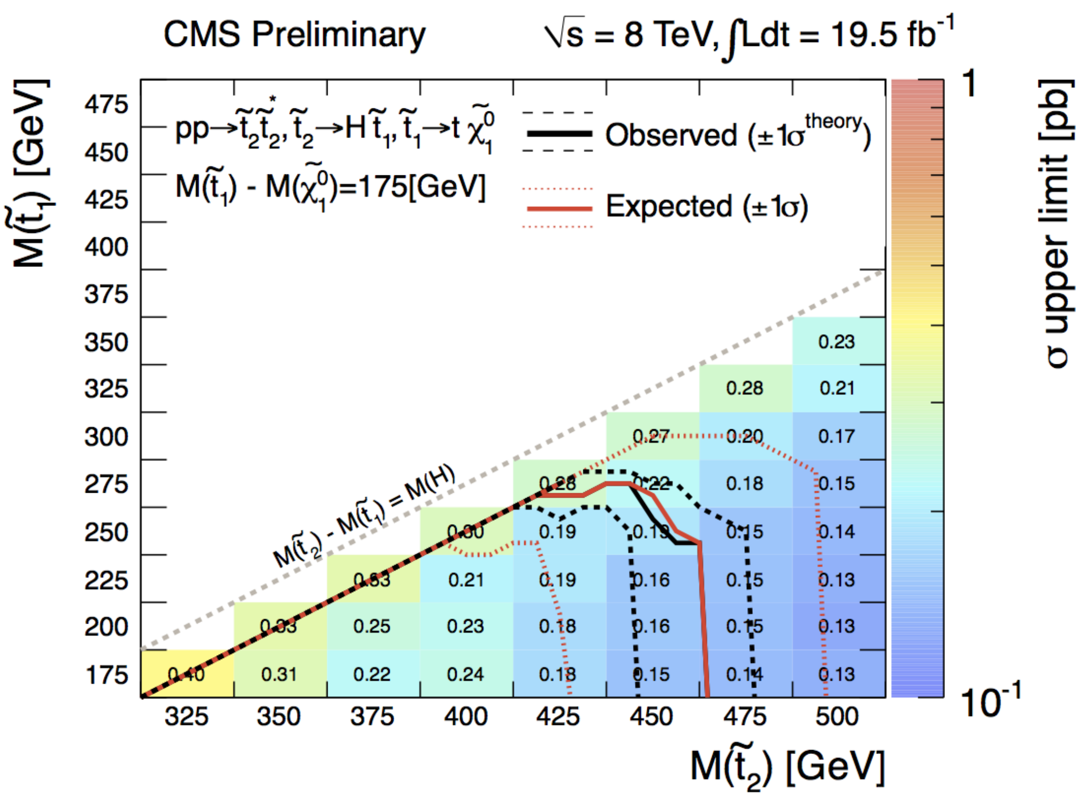
M_T

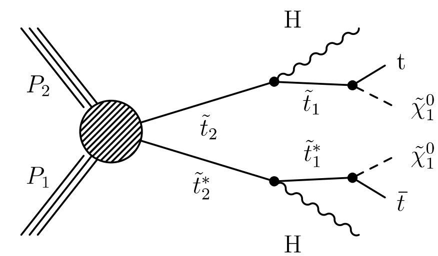


M_{bb}



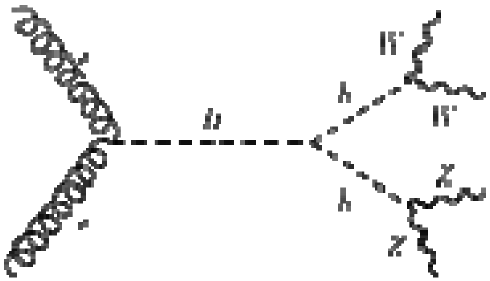
Direct Stop Production with Higgs



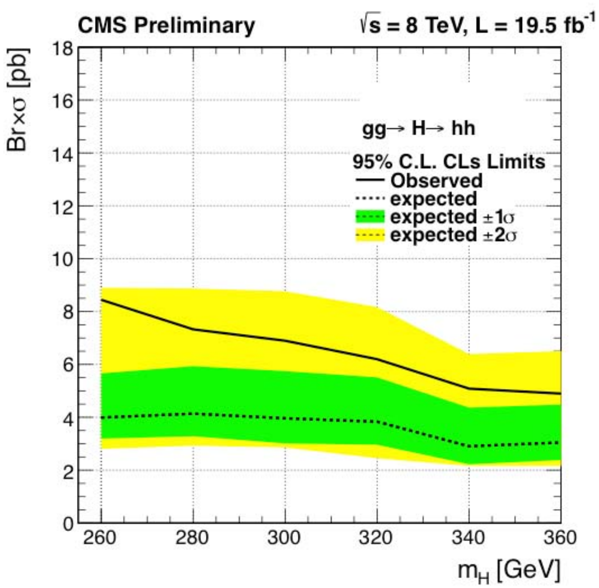


- Excludes masses M_{stop2} < 450 GeV for M_{stop1} < 250 GeV
- Closing the gap!
- First search of it's kind!

Search for Heavy Higgs and A in Extended Higgs Sector



- Search for decays of heavy scalar (H→hh) and pseudo scalar Higgs boson(A→Zh), where 'h' is SM-like higgs.
- Use multileptons and diphoton+leptons search channels (HIG-13-025)



- Model independent limits on σ.BR(gg-H->hh) and σ.BR(gg->A->Zh)
- SM-like h assumed to have SM BR's.
- 2HDM model-specific limits and further details to follow soon.

Nathaniel Craig et. al hep-ph:arXiv:1210.0559 & 1305.2424