New Physics with Leptons - Experiment

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Prospects in Theoretical Physics

IAS, July, 2013

Lecture Plan

- Search considerations - Multilepton example.
- It is all about Standard Model. ("fake" rates)

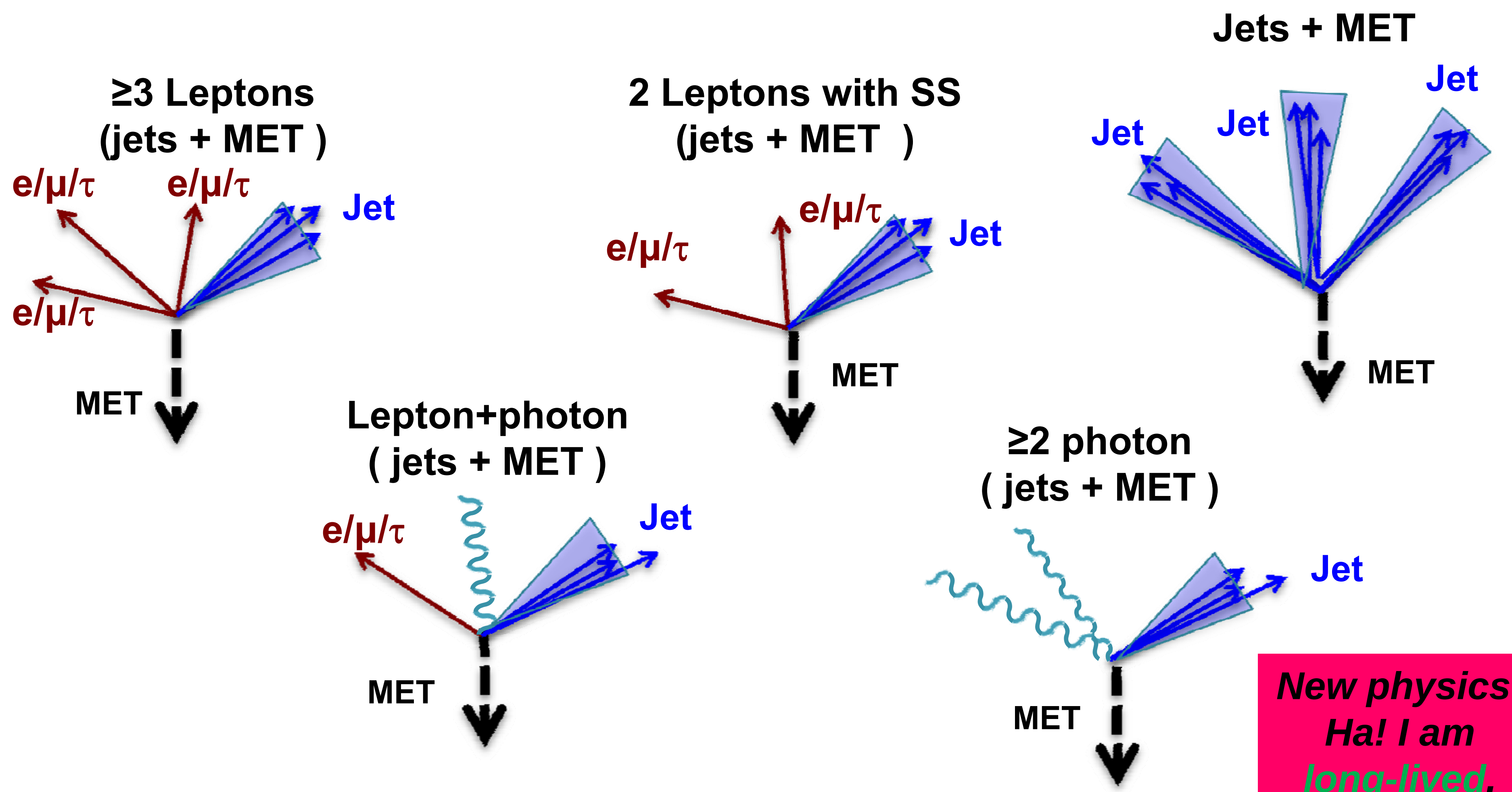
<<<<< Gedanken coffee break: dealing with experimentalists.

- Results. (Beyond SM possible only after SM.)

  - No offense to the mono or dilepton folks, but this is going to be a polylepton talk because that is what I do.
  - In collaboration with Scott Thomas.
  - CMS-centric .
  - ATLAS - Profs. Lipeles (Wed) Heinemann (Thu/Fri) – jet/MET, bkgnds.

Conventional Search Axes

(MET or jets/HT etc not guaranteed!)



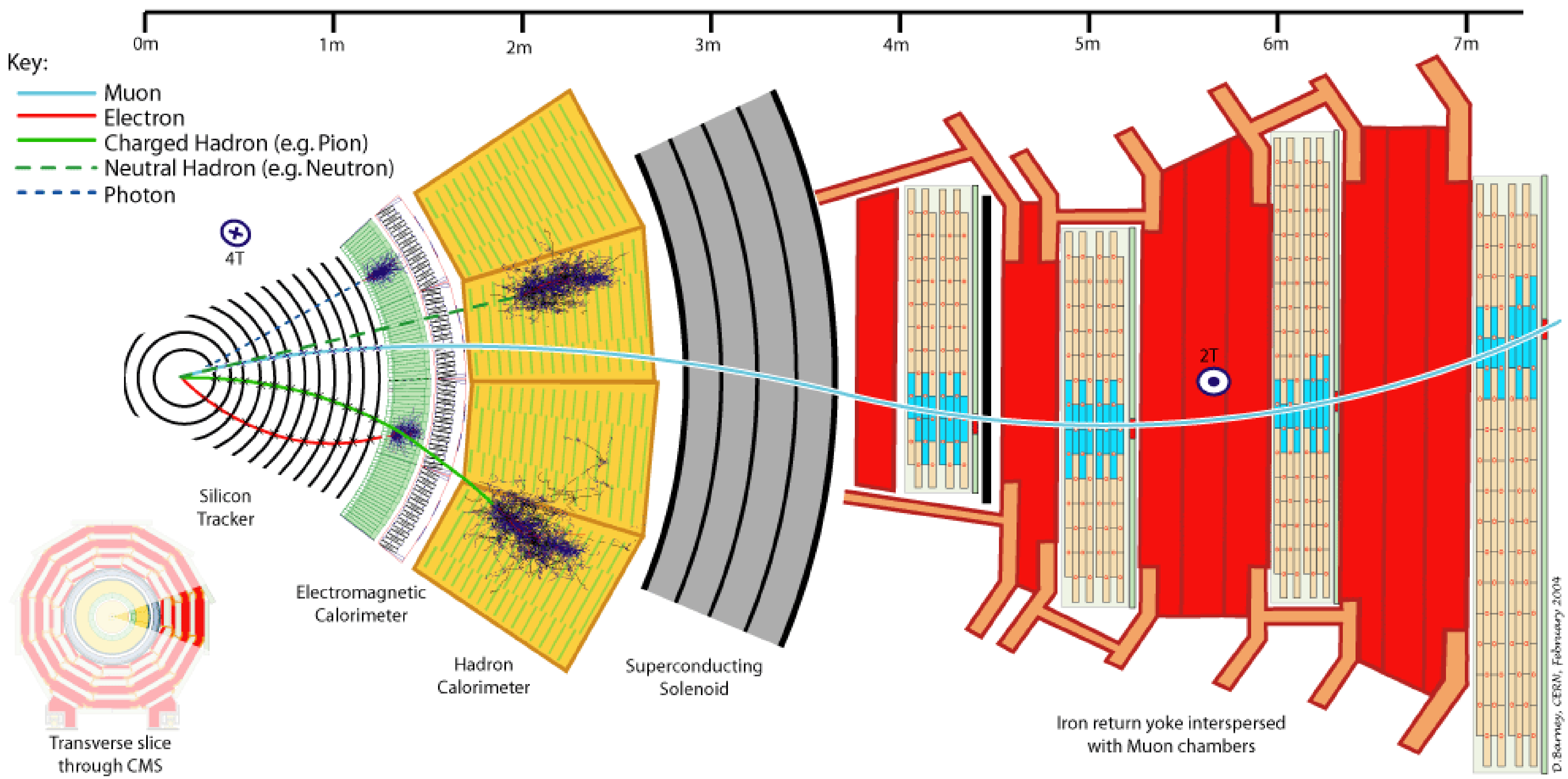
New physics: Ha! I am long-lived.

The odds are pretty bad: SM cross sections

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+? (lemonade) or 2 leptons + ?? (Vodka) or 1 lepton + ??? (H_2SO_4)

From CMS results, internal CMS twiki etc

CMS = Compact MUON solenoid



Trilepton Search Tools

- Muons, electrons
- Tau's
- Lepton kinematics (dilepton invariant mass, eg)
- Missing ET
- Jets:
  - Number of jets (about 30 GeV, say)

    OR
  - HT = Sum of Jet Pt's
  - B tagged jets

Trilepton hierarchy (e/mu)

- $\Sigma q=\pm 3$: $\mu^-\mu^-\mu^-$ then $\mu^+\mu^+\mu^+$
  (e.g. 8TeV $\sigma(W^+Z)/\sigma(W^-Z) \sim 1.81\pm0.12\pm0.03$)
  $\mu\mu\mu$, $\mu\mu e$, μee and eee
- $\Sigma q=\pm 1$:
  - $\mu^+\mu^+e^-$, $e^+e^+\mu^-$ ($\ell^+\ell^+\ell'$) & c.c. (No OSSF, SSSF, DY0)
    (Really no Drell Yan in μ^+e^-?)
  - $\mu^+\mu^-\mu^{+-}$, $\mu^+\mu^-e^{+-}$, $e^+e^-\mu^{+-}$ ($\ell^+\ell^-\ell'$) (OSSF, DY1)
    - $m_{\ell^+\ell^-} > 90$ GeV, $m_{\ell^+\ell^-} < 75$ GeV, $75 < m_{\ell^+\ell^-} < 90$ GeV

"Theory" and "experiment" now diverge → τ

τ

$J = \frac{1}{2}$

PDG

Mass $m = 1776.82 \pm 0.16$ MeV

$(m_{\tau^+} - m_{\tau^-})/m_{\text{average}} < 2.8 \times 10^{-4}$, CL = 90%

Mean life $\tau = (290.6 \pm 1.0) \times 10^{-15}$ s

$c\tau = 87.11\ \mu$m

τ^- DECAY MODES		Fraction (Γ_i/Γ)	Confid
Modes with one charged particle			
particle$^- \geq 0$ neutrals $\geq 0K^0 \nu_\tau$ ("1-prong")		(85.35 ± 0.07) %	
particle$^- \geq 0$ neutrals $\geq 0K_L^0 \nu_\tau$		(84.71 ± 0.08) %	
$\mu^- \overline{\nu}_\mu \nu_\tau$	[g]	(17.41 ± 0.04) %	
$\mu^- \overline{\nu}_\mu \nu_\tau \gamma$	[e]	$(3.6 \pm 0.4) \times 10^{-3}$	
$e^- \overline{\nu}_e \nu_\tau$	[g]	(17.83 ± 0.04) %	
$e^- \overline{\nu}_e \nu_\tau \gamma$	[e]	(1.75 ± 0.18) %	
$h^- \geq 0K_L^0\ \nu_\tau$		(12.06 ± 0.06) %	
$h^- \nu_\tau$		(11.53 ± 0.06) %	
$\pi^- \nu_\tau$	[g]	(10.83 ± 0.06) %	
$K^- \nu_\tau$	[g]	$(7.00 \pm 0.10) \times 10^{-3}$	
$h^- \geq 1$ neutrals ν_τ		(37.10 ± 0.10) %	
$h^- \geq 1\pi^0 \nu_\tau$ (ex.K^0)		(36.58 ± 0.10) %	
$h^- \pi^0 \nu_\tau$		(25.95 ± 0.09) %	
$\pi^- \pi^0 \nu_\tau$	[g]	(25.52 ± 0.09) %	
$\pi^- \pi^0$ non-$\rho(770) \nu_\tau$		$(3.0 \pm 3.2) \times 10^{-3}$	
$K^- \pi^0 \nu_\tau$	[g]	$(4.29 \pm 0.15) \times 10^{-3}$	

Modes with three charged particles		
$h^- h^- h^+ \geq 0$ neutrals $\geq 0K_L^0 \nu_\tau$		(15.20 ± 0.08) %
$h^- h^- h^+ \geq 0$ neutrals ν_τ (ex. $K_S^0 \to \pi^+\pi^-$) ("3-prong")		(14.57 ± 0.07) %
$h^- h^- h^+ \nu_\tau$		(9.80 ± 0.07) %
$h^- h^- h^+ \nu_\tau$ (ex.K^0)		(9.46 ± 0.06) %
$h^- h^- h^+ \nu_\tau$ (ex.K^0,ω)		(9.42 ± 0.06) %
$\pi^- \pi^+ \pi^- \nu_\tau$		(9.31 ± 0.06) %
$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0)		(9.02 ± 0.06) %
$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0), non-axial vector		< 2.4 %
$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0,ω)	[g]	(8.99 ± 0.06) %
$h^- h^- h^+ \geq 1$ neutrals ν_τ		(5.39 ± 0.07) %
$h^- h^- h^+ \geq 1\pi^0 \nu_\tau$ (ex. K^0)		(5.09 ± 0.06) %
$h^- h^- h^+ \pi^0 \nu_\tau$		(4.76 ± 0.06) %
$h^- h^- h^+ \pi^0 \nu_\tau$ (ex.K^0)		(4.57 ± 0.06) %
$h^- h^- h^+ \pi^0 \nu_\tau$ (ex. K^0, ω)		(2.79 ± 0.08) %
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		(4.62 ± 0.06) %
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0)		(4.48 ± 0.06) %
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0,ω)	[g]	(2.70 ± 0.08) %

τ summary (PDG)

- 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

- For possible future use:
- $\tau_{\gamma c\tau}$ =1.7mm @35GeV

τ's in CMS

• Hadronic BR($\tau \rightarrow$ 1+3 prong) ~2/3

• 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.

Trilepton hierarchy (e/mu/τ)

- τ_h is the "experimental" tau. It denotes the reconstructed decay when the parent "theory" tau decays *hadronically.*
- Leptonic decays of the theory tau show up in the search channels as e/mu's. They generally have much better signal/background than channels with τ_h.
- $\mu^+\mu^+e^-$, $e^+e^+\mu^-$ ($\ell^+\ell^+\ell'$) & c.c. (No OSSF, DY0)
- $\mu^+\mu^-\mu^{+-}$, $\mu^+\mu^-e^{+-}$, $e^+e^-\mu^{+-}$ ($\ell^+\ell^-\ell'$) (OSSF,DY1)
  - $m_{\ell^+\ell^-} > 90$ GeV, $m_{\ell^+\ell^-} < 75$ GeV, $75 < m_{\ell^+\ell^-} < 90$ GeV
- $\ell^+\ell'^+\tau_h$ (SSOF + tau)
- $\ell^+\ell^+\tau_h$ (SSSF + tau)
- $\ell^+\ell'^-\tau_h$ (OSOF + tau)
- $\ell^+\ell^-\tau_h$ (and mass subdivisions) (OSSF + tau)
- $\ell\,\tau_h\tau_h$ (needs single lepton trigger, too much background)

- Now make subsamples in bins of MET/HT, b-tags etc etc
- Similarly, 4-lepton categories.

Tau examples

a) 1000 $\ell^+\ell^- \tau$ (theory) signal events with ***normal*** pt's, MET etc.

- 330 show up as $\ell\ell\ell$ (trileptons with e's and mu's)
  - 165 survive detector acceptance (80%^3 = 50%) and have ok S/B
- 660 undergo hadronic tau decay
  - 165 $\ell^+\ell^- \tau_h$ survive acceptance (80%^2 * 40% = 25%) but have lousy S/B

→ Marginal increase in acceptance

b) 1000 $\ell^+\ell^- \tau$ (theory) signal events with ***high*** pt's, MET etc.

- 165 reconstructed $\ell\ell\ell$'s have ***excellent*** S/B
- Equal number of $\ell^+\ell^- \tau_h$ events also have good S/B

→ Acceptance almost doubles

c) $\tau\ \tau\ \tau$ signal → Throw everything you got at it and pray that it has good MET etc.

Next - It is all about the Standard Model.

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.

→ Data-driven backgrounds ("fake" rates)

  →Large data samples available

MC for "irreducible" backgrounds (eg WZ)

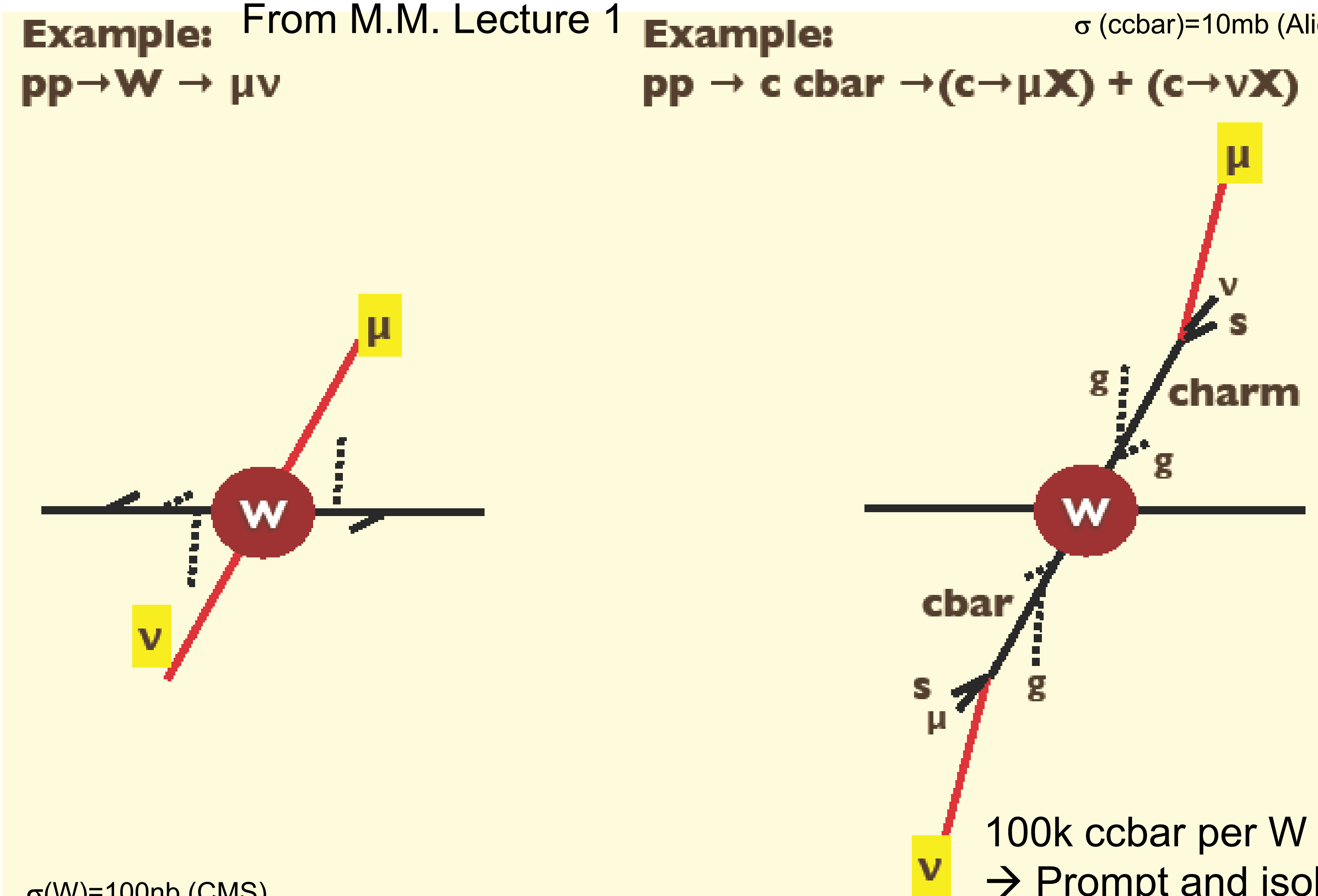
→Smaller cross sections means tails peter out

→Validate in control regions as much as possible

Before Background Issues: Prompt and Isolated

From M.M. Lecture 1

σ (ccbar)=10mb (Alice random doc)



σ(W)=100nb (CMS)

100k ccbar per W
→ Prompt and isolated tails

Simulated Background: ttbar

ttbar validation: Single lepton control Region.

I_{rel} = (Σ (Calo Energy+Track pt)/lepton pt

(in a 0.3 $\eta-\phi$ cone)

Require an isolated muon Pt>30GeV,3jets,b-jet.

→ Look at other muons (from ttbar jets) that have large impact parameter (>200 microns in xy).

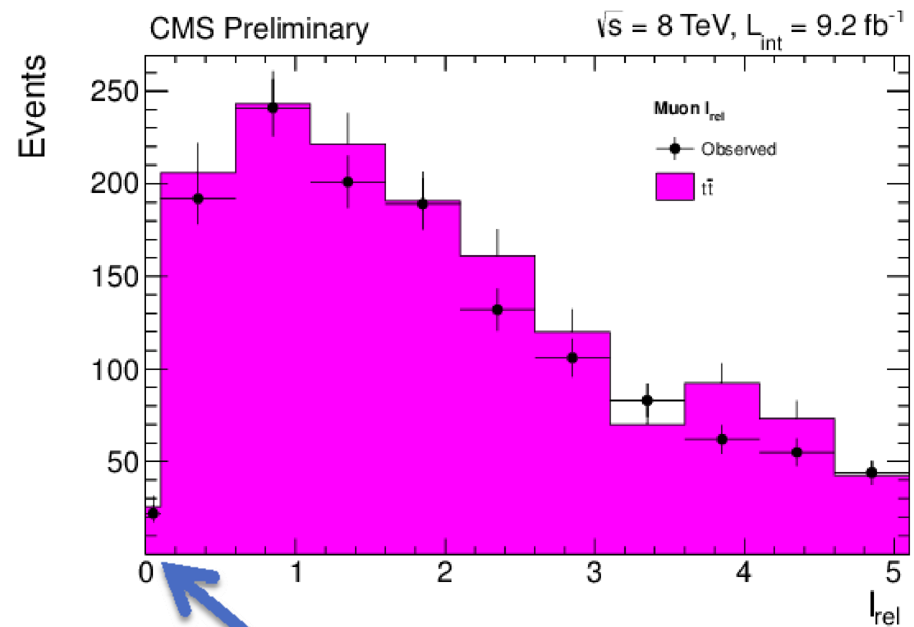
PDG - $B^0_{c\tau}$ = 450microns

→ $\gamma c\tau$ for a 50 GeV B^0 = 4500 microns

CMS vertex resolution ~ 25 microns

Isolation tail of muons already on the “prompt” tail

NOTE: Tail in this case goes to the left!



Isolated = I_{rel}<0.15

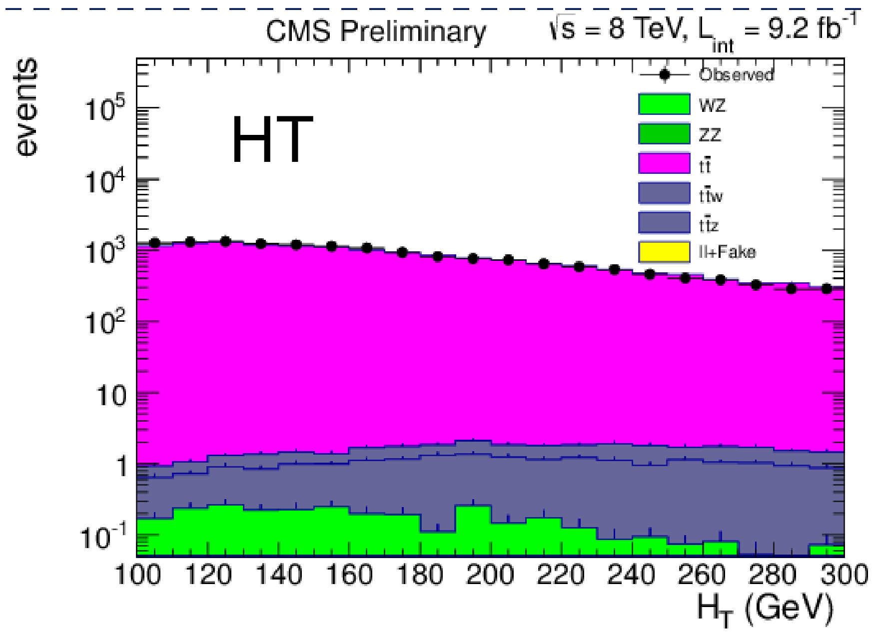
Simulated Irreducible Background: ttbar

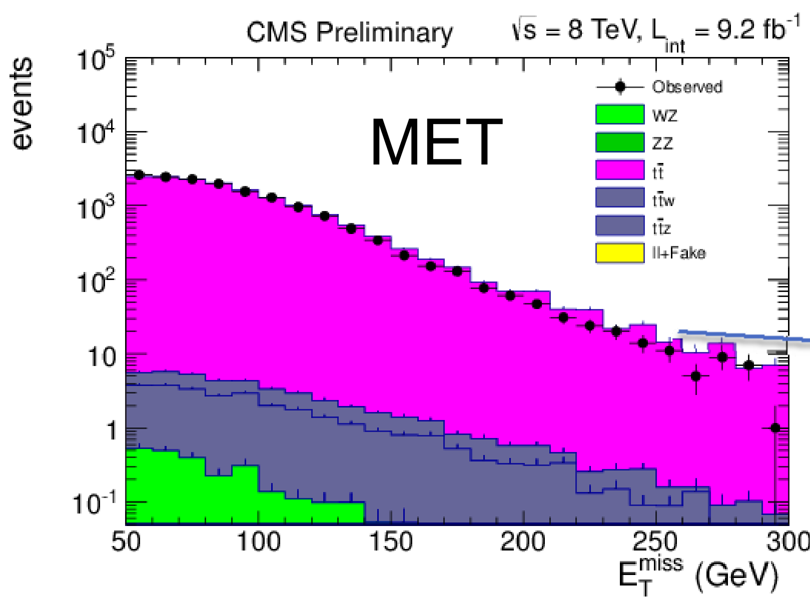
ttbar MC validation: Dilepton control Region.

Opposite sign electron-muon pairs

(different flavor – No Drell Yan)

HT = Σ (jet pt for jets with pt>30 GeV)





NOTE SIGNS OF TROUBLE.

More on matching MET later

Simulated Irreducible Background: WZ

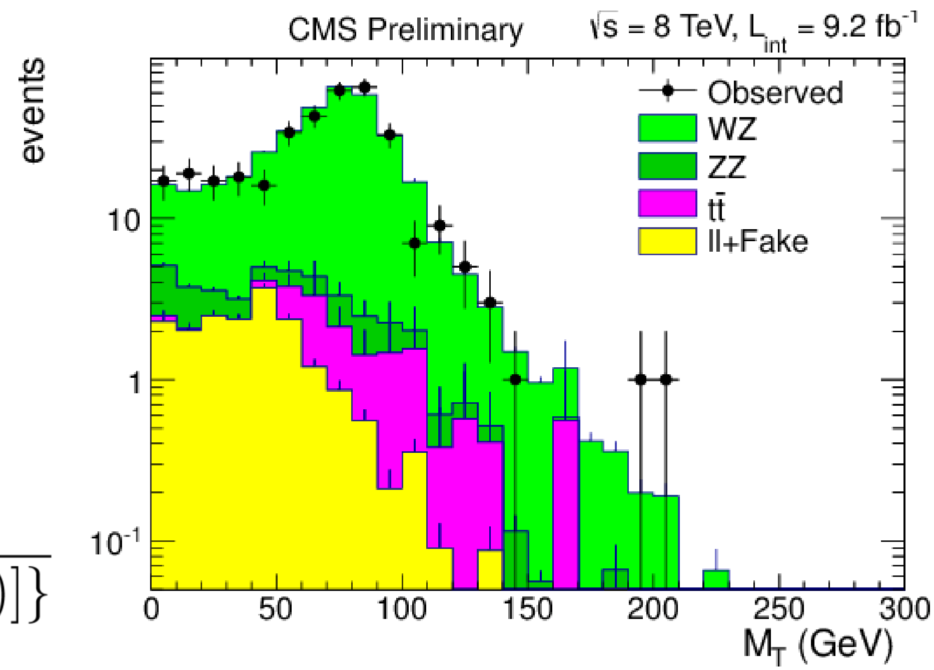
WZ MC validation in a trilepton control region

- OSSF pair in the Z window
  75GeV < m_{ll} < 90GeV
- 50 GeV < MET < 100 GeV
- HT < 200

m_T – Lepton-MET transverse mass

$$m_T = \sqrt{2\, p_T(l)\, p_T(\nu)\, \{1 - \cos[\phi(l) - \phi(\nu)]\}}$$

m_T

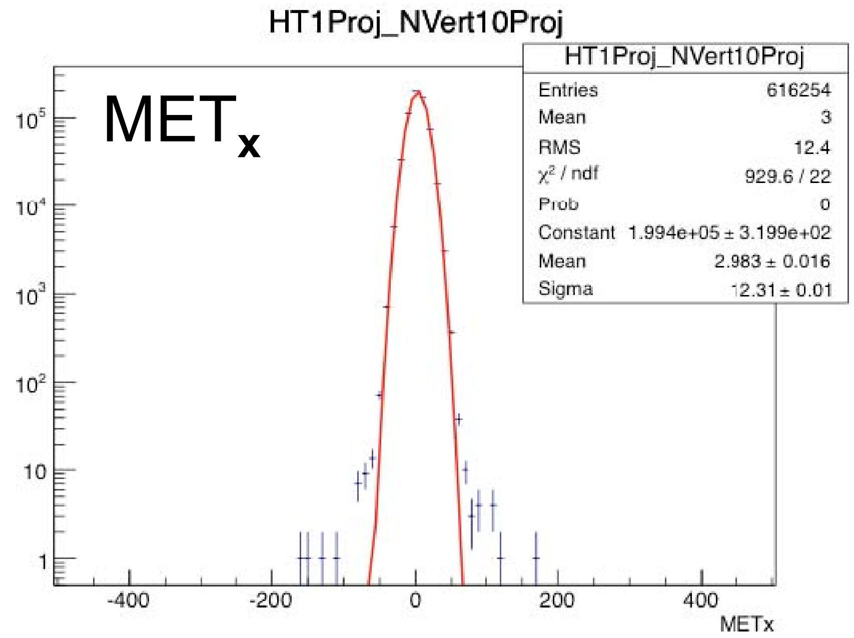


MET (neutrino proxy) and mT are highly correlated

MET/pileup issues

Subtitle:

Boring things that excite experimentalists.



MET is critical in search for new physics

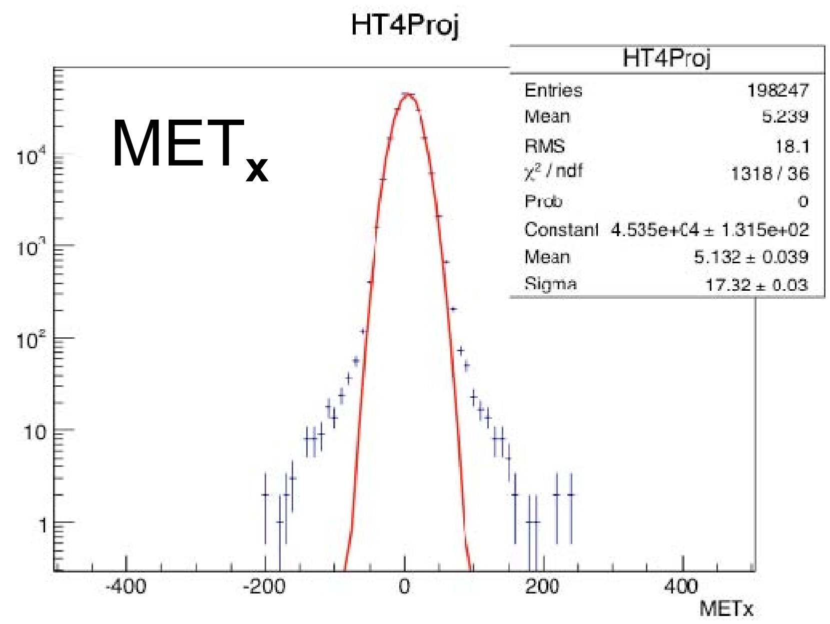
- Must understand/improve its resolution because of possible new physics on the tails
- We match the MET resolutions in simulated SM backgrounds to data.
- & learn interesting things about underlying issues such as pileup and jets.

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

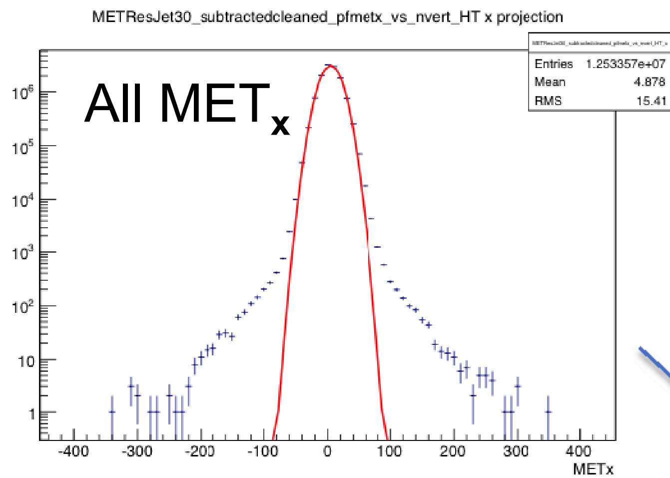
Sanjay Arora

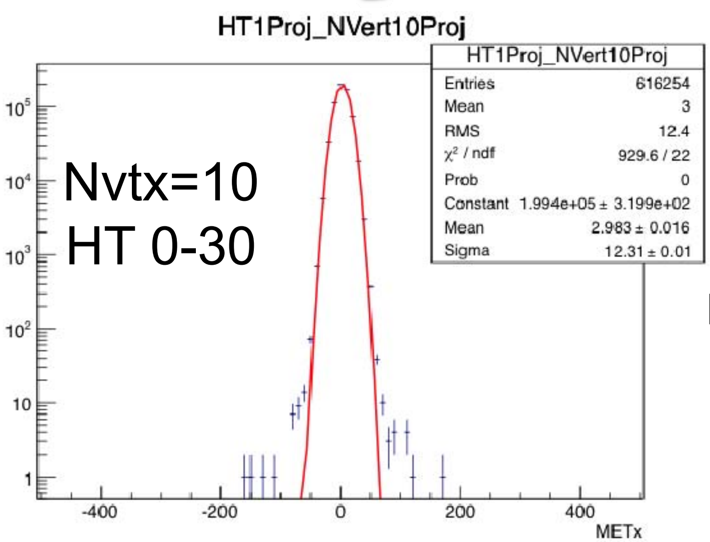
MET/pileup issues

- 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





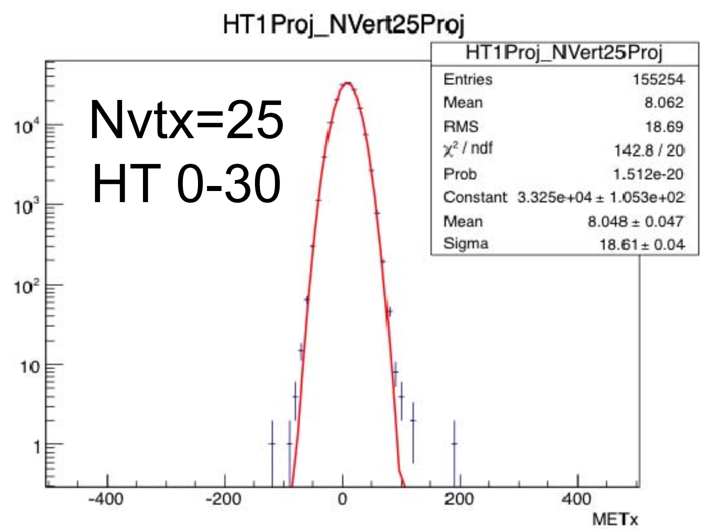
←Thinner, less pileup

Fatter, more pileup →

But same tails

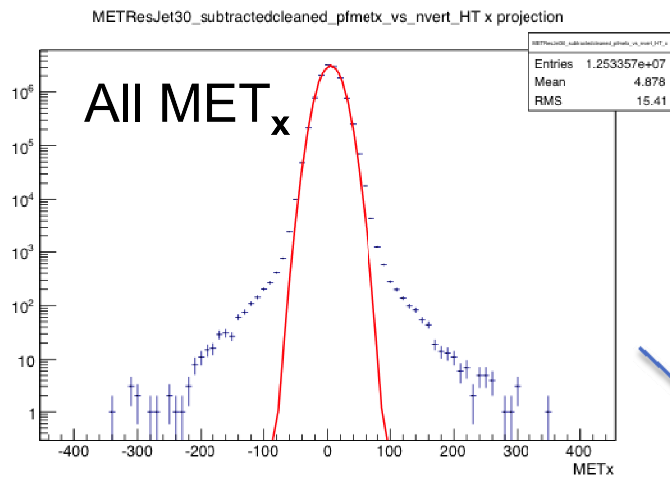
➔Pileup is stochastic

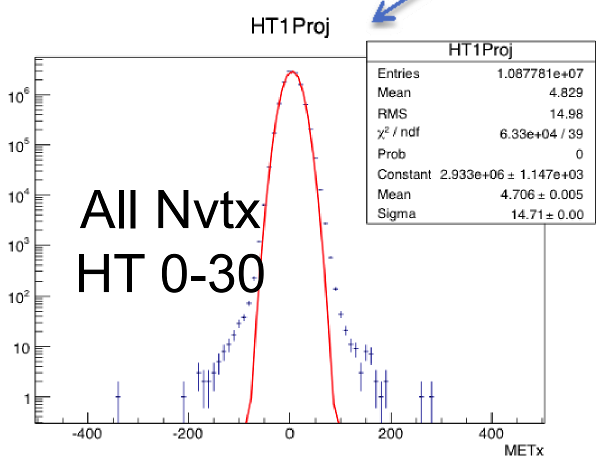
(Gaussian)



Same behavior in other HT bins

MET/pileup issues

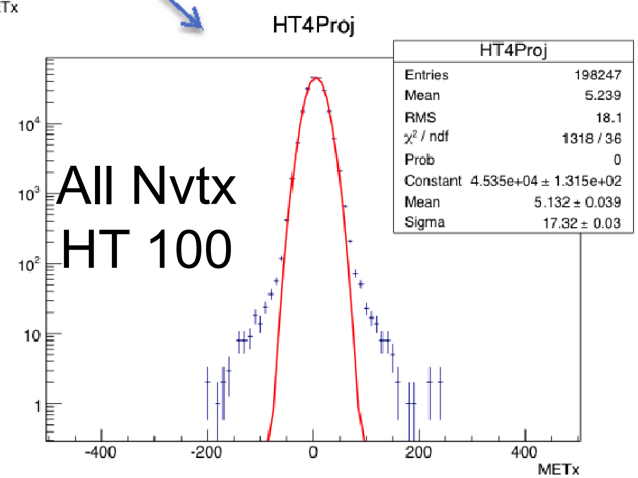




←Fewer tails, less HT

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

Now to more challenging backgrounds…

Data-driven backgrounds: 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*: CFO Method (CMS)

• Want: The probability of a third ("fake") isolated and e/mu in the dilepton sample. (tau's later.)

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

• Not a global rate, but the rate for a subsample of interest that has certain MET, HT, b-tags etc.

• People extrapolate semi-isolated leptons ("tight-loose" method), but the subsamples can be small.

• Combined Fakable Object (CFO)(Richard Gray, CMS) Method – use the (non-isolated) tracks and leptons in the subsamples and apply the isolation probability measured separately.

• Count the number of isolated tracks in the sample, multiply by the known ratio fμ of production rate of isolated muons and isolated tracks.

• How to measure the ratio fμ of isolated leptons and isolated tracks? 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 sample, but….

Data-driven Z/γ^*: CFO Method (CMS)

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

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

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

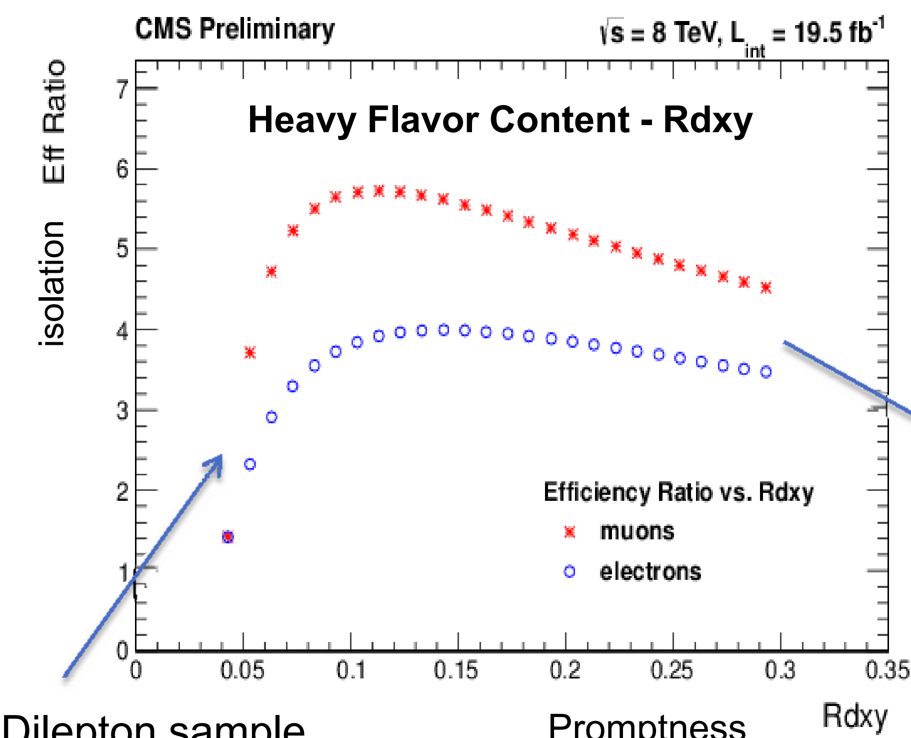
- 2nd factor (isolation efficiency ratio): Measured in the full dilepton set, but as a function of heavy flavor (HF) content (B,D mesons).

- 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)



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

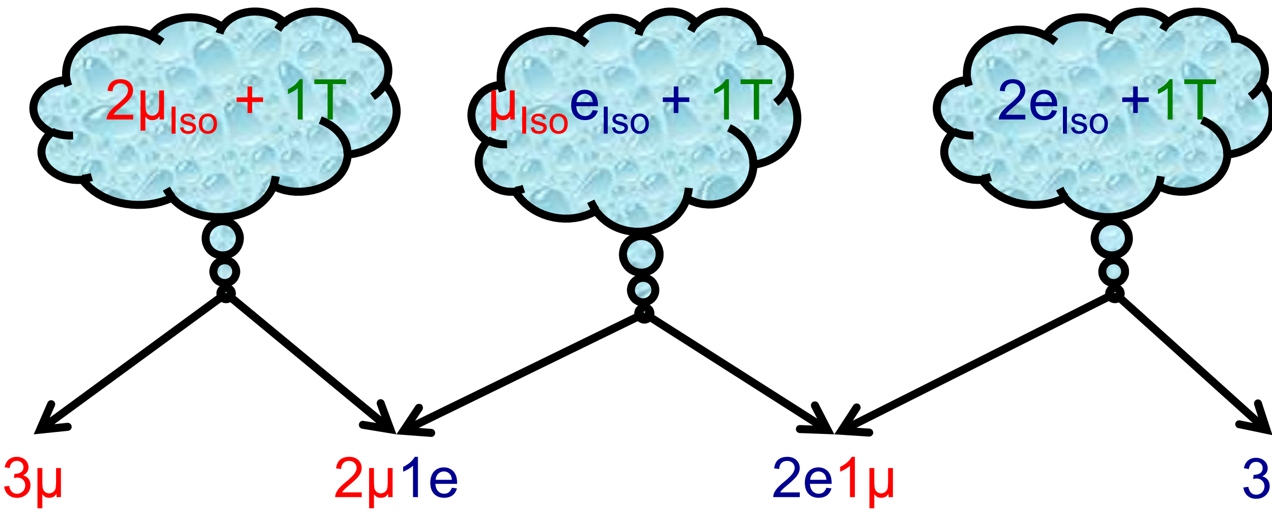
Look up the isolation efficiency ratio for subsample of interest

Dilepton sample enriched with ttbar (less prompt)

Dilepton sample enriched with Z/γ* (more prompt)

Summary: Predicting SM Background due to "Fake" Prompt Lepton

- Multiply the number of isolated tracks in the dilepton subsample by f_{μ} and f_{e} separately

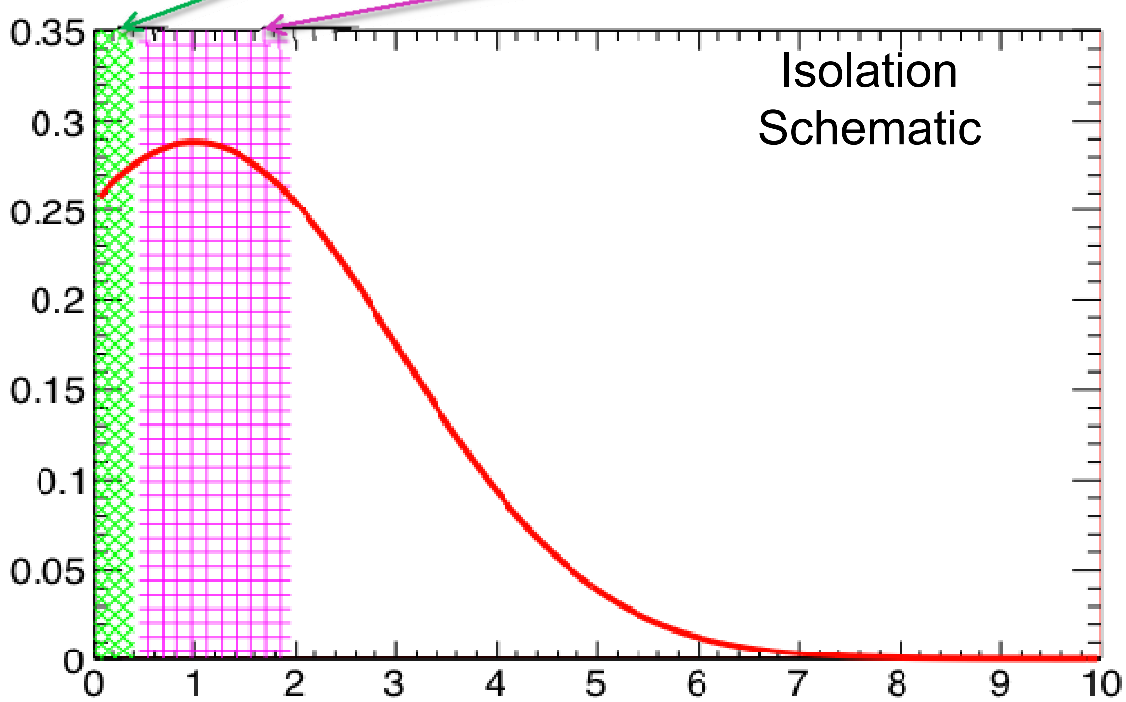


Done with e/mu's. Tau?

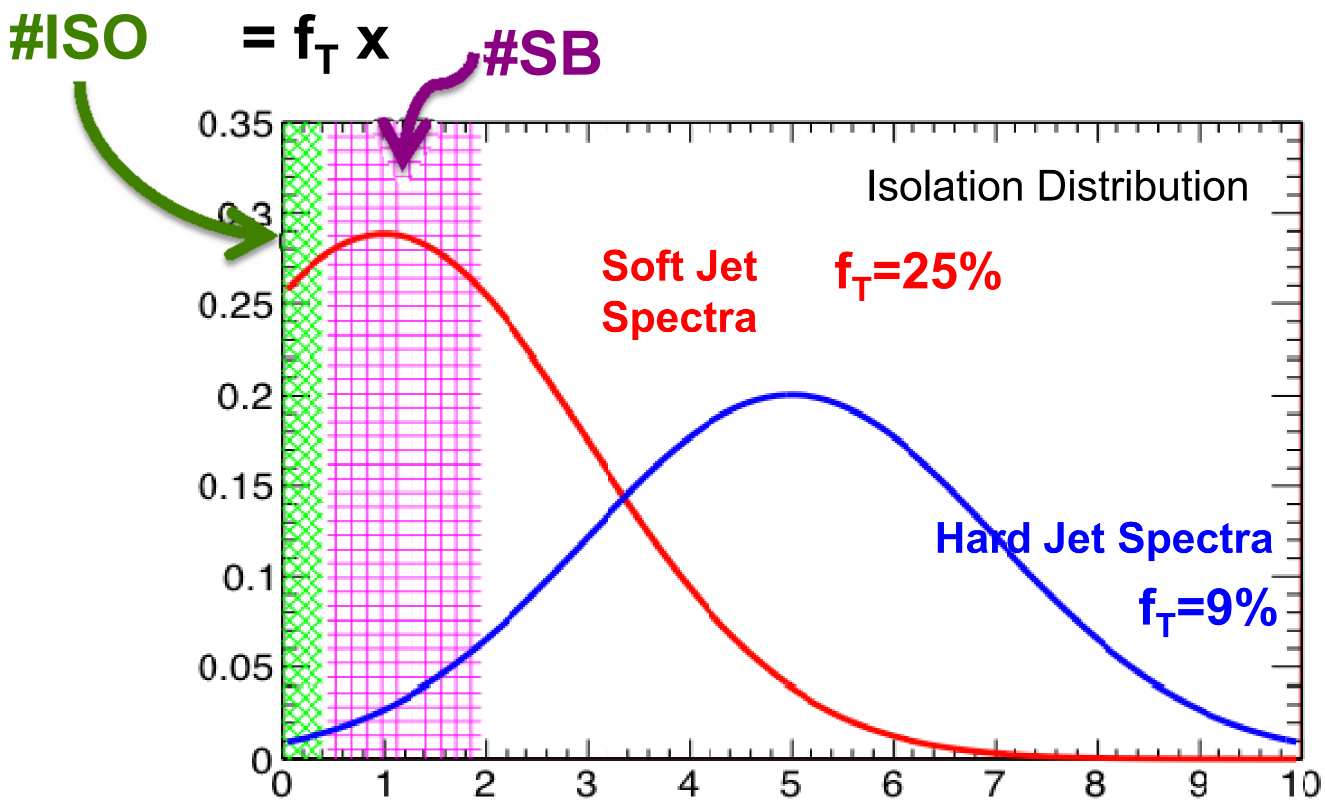
Isolated Tau fake rates

- Unfortunately, plenty of jets fake tau's, so statistics is not a problem.
- Tau's are pencil jets being faked by fatter jets
- Subsample environment still is (in terms of isolation)
- Promptness not an issue - culprits are generic jets, tau's are not prompt

→ Extrapolate into isolated signal region from isolation sideband

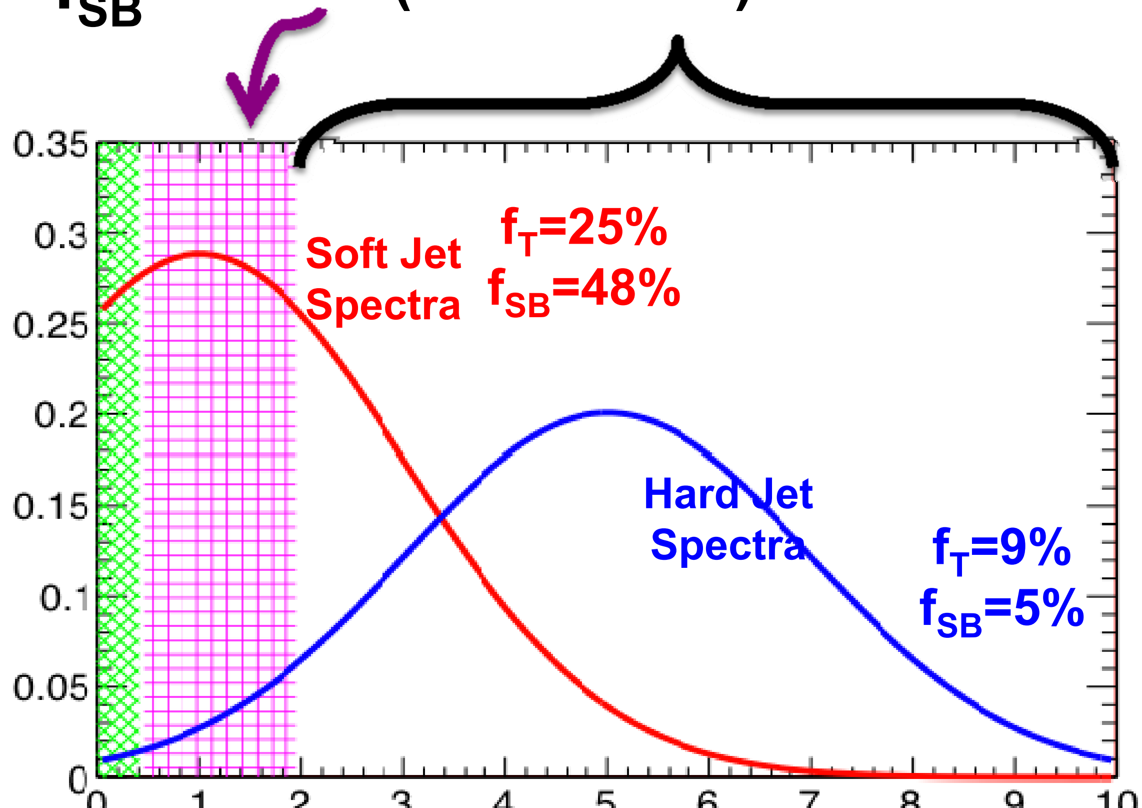


But tau isolation environment changes!



Use the full tau isolation distribution

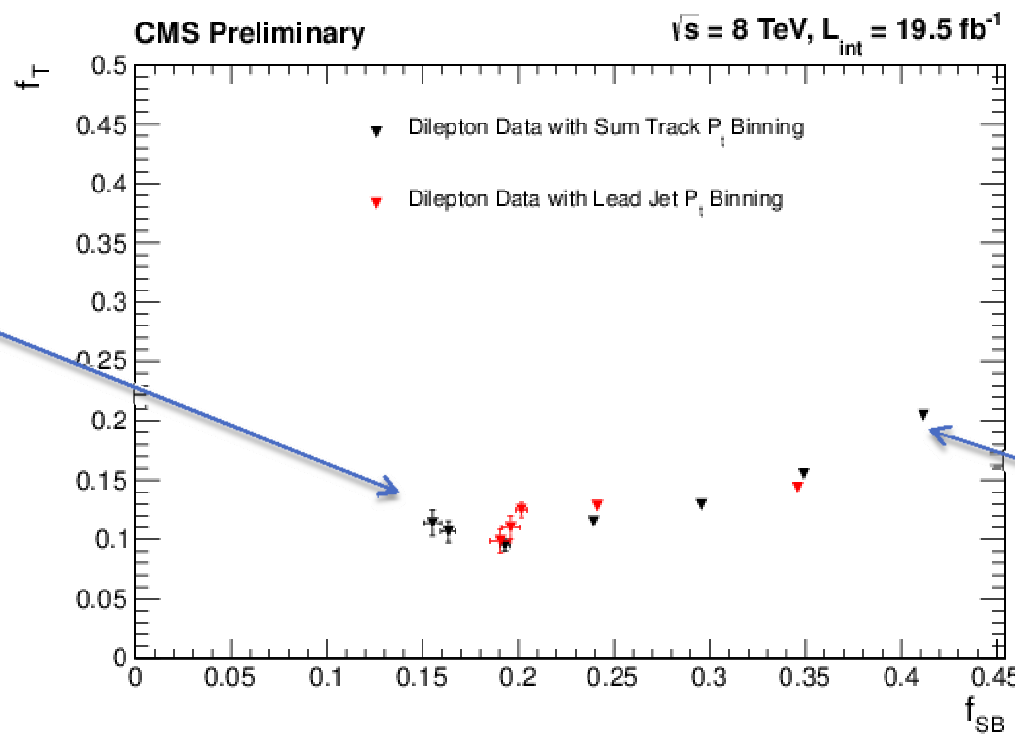
$f_{SB} = \#SB/(\#SB+\#Rest)$



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

Hard Jet Spectra



Soft Jet Spectra

Richard Gray

Last data-driven background : Asymmetric Photon Conversions

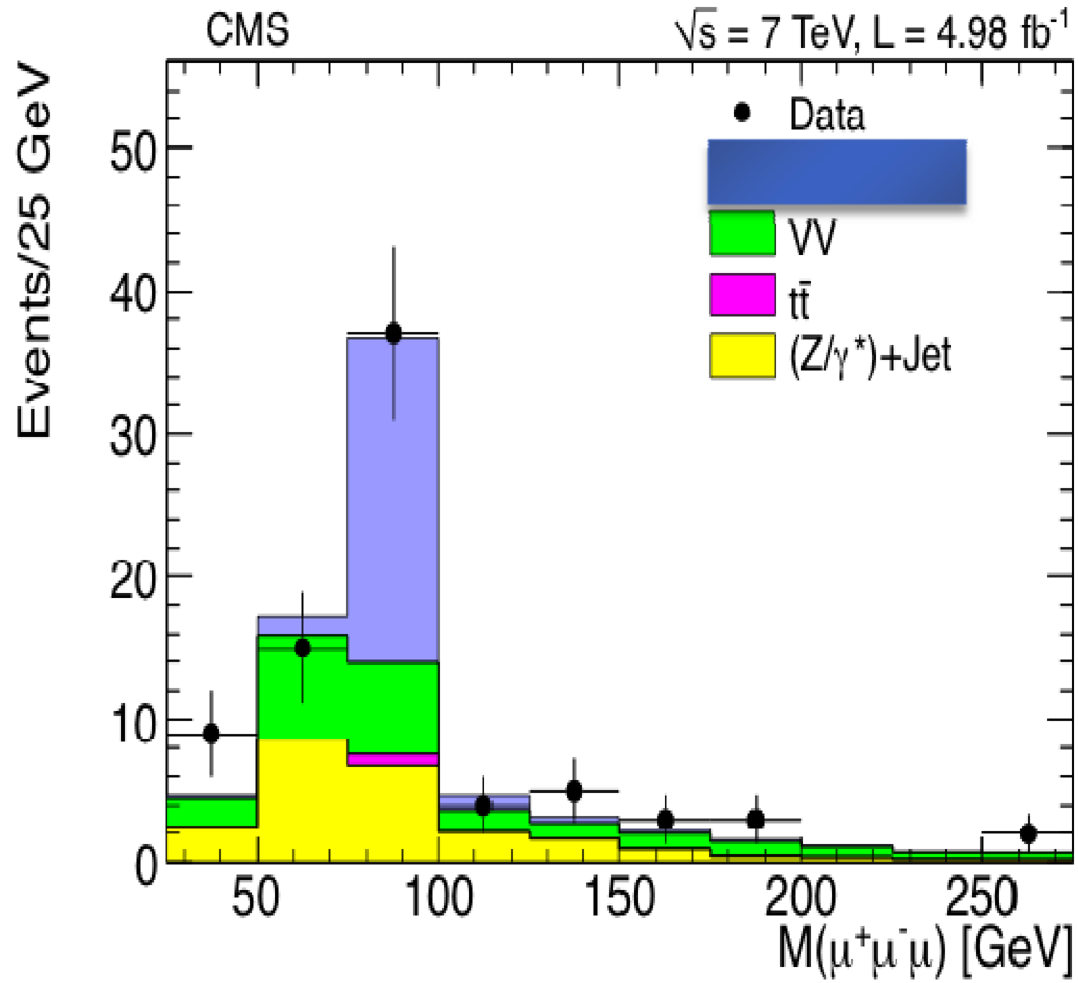
- How many physicists does it take to forget about Dalitz decays in 20 years? Answer: 6000

- "The only surprise from LHC so far" 

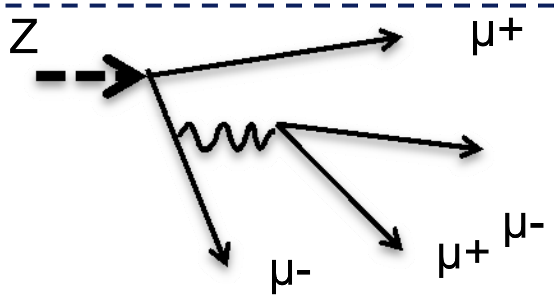
From 2011 archives….

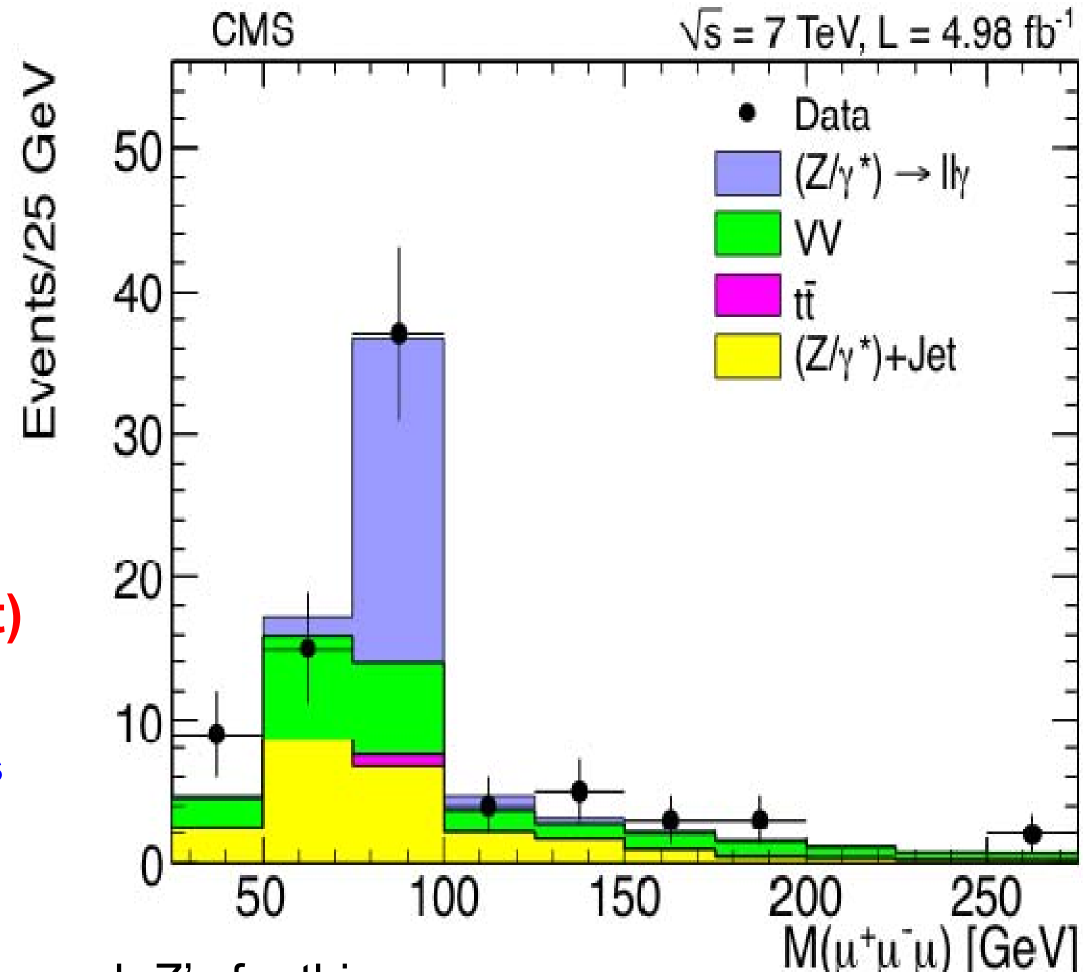
Note: Muons!

Note again: 3 muons!!



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





Observation of Z→(3)4μ

Feynman level (γ*) gives

e+e- and μ+μ-

Analogous to π^0 → e+e-γ

Observe 3μ Z peak (4^{th} μ soft)

Also W→2μ (Higgs!)

Wg* was not in Higgs WW searches

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

Important for Higgs ~125 GeV

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

~ 0.35%

- Done with SM backgrounds…

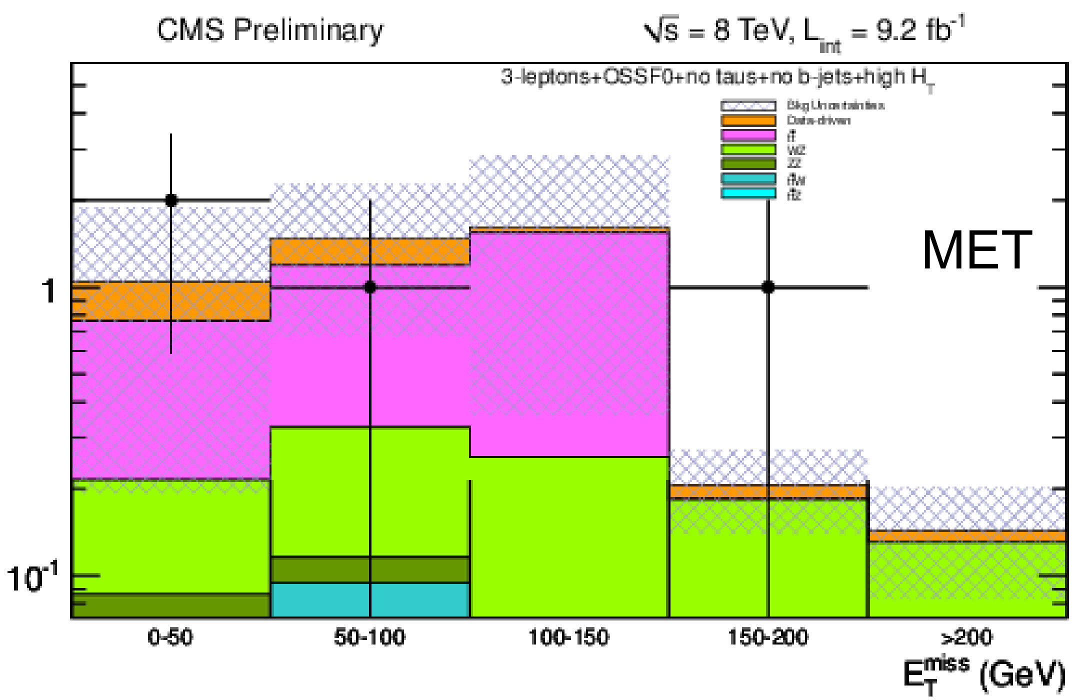
Intermission

- Six S's of LHC experimental particle physicists
  (S does not stand for Smart in this case)

  - Style
  - Statistics
  - Stage
  - pSeudotheorists
  - Citation
  - Superanalyses (Patrick M knows this one…)

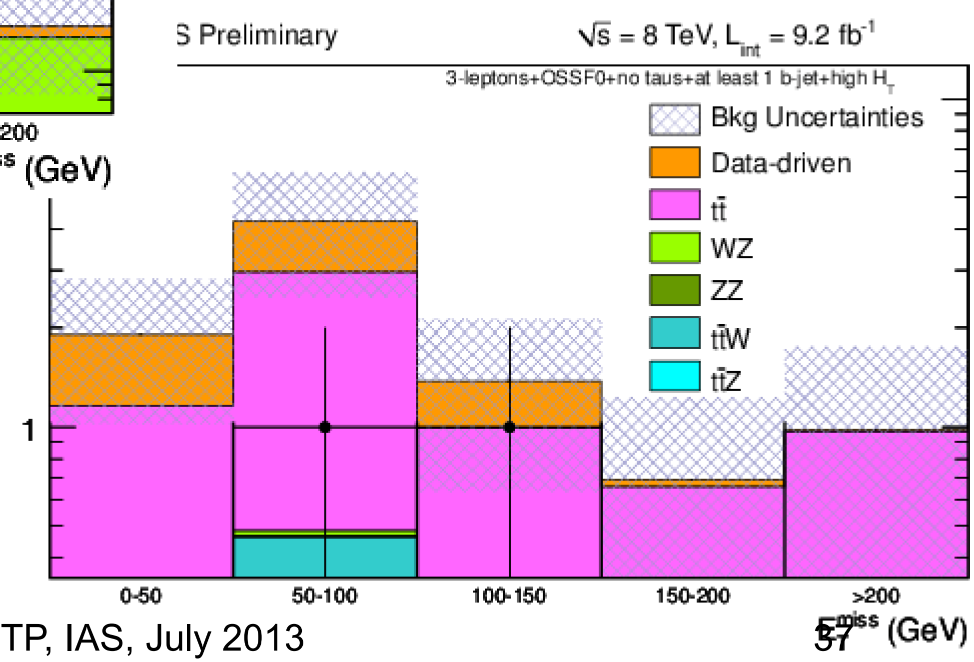
→ Now to results and new physics opened up by your hard slog through the experimental details…..

Sample Multilepton Results

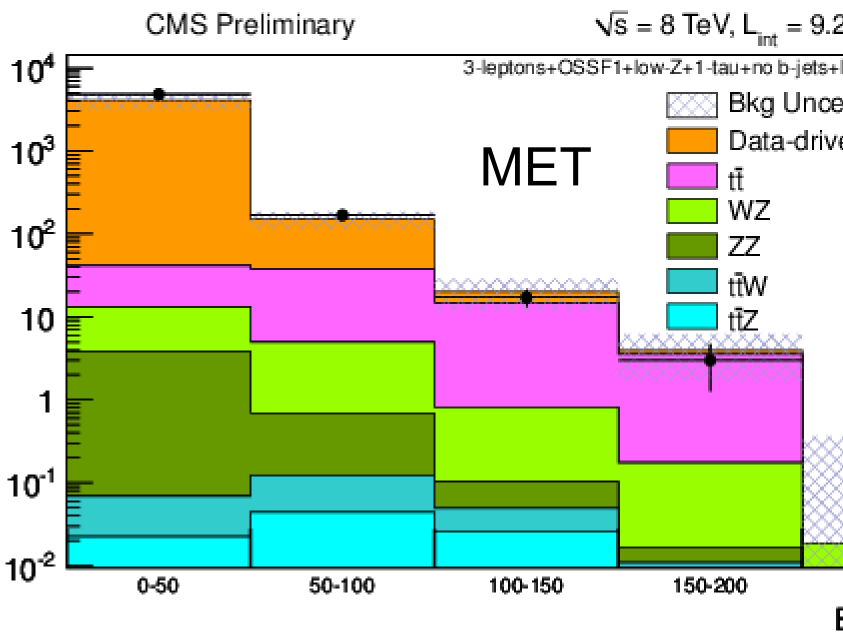


3-leptons, OSSF0, Tau0,HT > 200GeV
No b-jets

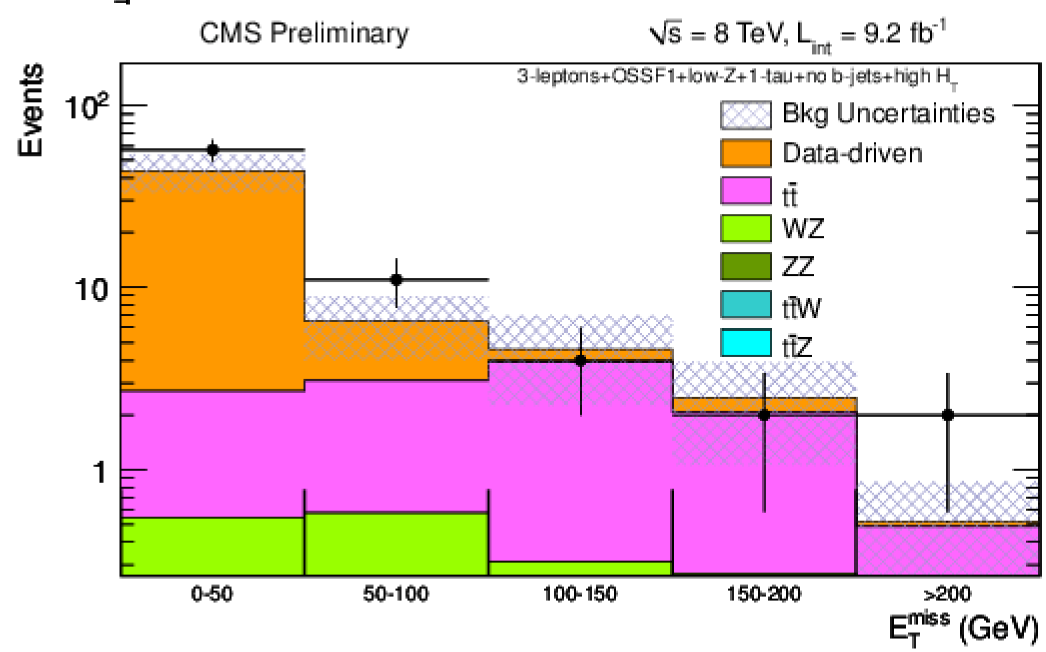
Same except
At least 1 b-jet



Sample Multilepton Results (tau channels)



Same except HT>200



3-leptons, OSSF1, below Z, 1Tau, No b-jets, HT < 200GeV

Zillion more channels…

Multilepton Result Tables

Selection		MET	N(τ)=0, NbJet=0 obs	N(τ)=0, NbJet=0 expect	N(τ)=1, NbJet=0 obs	N(τ)=1, NbJet=0 expect	N(τ)=0, NbJet$\geq$1 obs	N(τ)=0, NbJet$\geq$1 expect	N(τ)=1, NbJet$\geq$1 obs	N(τ)=1, NbJet$\geq$1 expect
4 Lepton Results $H_T > 200$										
OSSF0	NA	$(100, \infty)$	0	0.007 ± 0.01	0	0.001 ± 0.01	0	0 ± 0.01	0	0 ± 0.009
OSSF0	NA	$(50, 100)$	0	0 ± 0.01	0	0.007 ± 0.01	0	0.01 ± 0.02	0	0.008 ± 0.01
OSSF0	NA	$(0, 50)$	0	1e-05 ± 0.009	0	0.01 ± 0.01	0	0 ± 0.009	0	0 ± 0.009
OSSF1	off-Z	$(100, \infty)$	0	0.0005 ± 0.009	1	0.09 ± 0.03	0	0.06 ± 0.04	0	0.05 ± 0.03
OSSF1	on-Z	$(100, \infty)$	0	0.03 ± 0.02	0	0.27 ± 0.07	0	0.19 ± 0.11	0	0.17 ± 0.09
OSSF1	off-Z	$(50, 100)$	0	0.03 ± 0.03	1	0.13 ± 0.07	0	0.02 ± 0.02	0	0.07 ± 0.04
OSSF1	on-Z	$(50, 100)$	0	0.08 ± 0.04	1	0.29 ± 0.08	0	0.1 ± 0.06	1	0.12 ± 0.08
OSSF1	off-Z	$(0, 50)$	0	0.007 ± 0.01	0	0.12 ± 0.06	0	0.001 ± 0.01	0	0.04 ± 0.03
OSSF1	on-Z	$(0, 50)$	0	0.1 ± 0.04	0	0.5 ± 0.12	0	0.02 ± 0.02	0	0.23 ± 0.11
OSSF2	off-Z	$(100, \infty)$	0	0.004 ± 0.01	0	0 ± 0	0	0.008 ± 0.01	0	0 ± 0
OSSF2	on-Z	$(100, \infty)$	0	0.05 ± 0.05	0	0 ± 0	0	0.13 ± 0.08	0	0 ± 0
OSSF2	off-Z	$(50, 100)$	0	0.01 ± 0.01	0	0 ± 0	0	0.01 ± 0.02	0	0 ± 0
OSSF2	on-Z	$(50, 100)$	0	0.39 ± 0.1	0	0 ± 0	0	0.16 ± 0.07	0	0 ± 0
OSSF2	off-Z	$(0, 50)$	0	0.11 ± 0.03	0	0 ± 0	0	0.05 ± 0.03	0	0 ± 0
OSSF2	on-Z	$(0, 50)$	2	3.3 ± 0.7	0	0 ± 0	1	0.37 ± 0.09	0	0 ± 0

Table 1: Results for 4 leptons wiht $H_T > 200$ GeV. $*$ denotes channels used as controls.

Selection		MET	N(τ)=0, NbJet=0 obs	N(τ)=0, NbJet=0 expect	N(τ)=1, NbJet=0 obs	N(τ)=1, NbJet=0 expect	N(τ)=0, NbJet$\geq$1 obs	N(τ)=0, NbJet$\geq$1 expect	N(τ)=1, NbJet$\geq$1 obs	N(τ)=1, NbJet$\geq$1 expect
3 Lepton Results $H_T > 200$										
OSSF0	NA	$(100, \infty)$	1	1.9 ± 1.2	15	7.7 ± 3.6	1	2.9 ± 1.5	27	21 ± 11
OSSF0	NA	$(50, 100)$	1	1.4 ± 0.8	13	17 ± 7.4	1	4.2 ± 1.7	41	37 ± 19
OSSF0	NA	$(0, 50)$	2	1 ± 0.8	13	10 ± 3.4	0	1.9 ± 0.8	32	21 ± 11
OSSF1	above-Z	$(100, \infty)$	2	2.2 ± 0.9	2	4 ± 2.4	3	2.8 ± 1.3	11	6.8 ± 3.7
OSSF1	below-Z	$(100, \infty)$	2	3.5 ± 0.8	8	7.6 ± 3.4	3	3.4 ± 1.6	12	8.3 ± 4.3
OSSF1	on-Z	$(100, \infty)$	17	30 ± 5.3	4	7.9 ± 2.2	5	6.3 ± 1.9	8	5.4 ± 2.8
OSSF1	above-Z	$(50, 100)$	1	1.9 ± 0.49	10	3.7 ± 2.3	4	3.1 ± 1.2	17	12 ± 6.6
OSSF1	below-Z	$(50, 100)$	4	4.5 ± 0.9	11	6.4 ± 2.4	3	5 ± 2.1	9	9.4 ± 5.3
OSSF1	on-Z	$(50, 100)$	39	38 ± 6.2	34	26 ± 5.4	10	9.6 ± 2.7	12	9.5 ± 3.9
OSSF1	above-Z	$(0, 50)$	3	3.2 ± 0.42	19	18 ± 4.5	0	2.7 ± 0.8	6	9.9 ± 4.6
OSSF1	below-Z	$(0, 50)$	9	11 ± 1.2	57	43 ± 10	2	4.7 ± 1.4	11	13 ± 5.3
OSSF1	on-Z	$(0, 50)$	58	63 ± 8.7	256	271 ± 66	12	14 ± 2.6	39	34 ± 7.9

Table 3: Results for 3 leptons wiht $H_T > 200$ GeV. $*$ denotes channels used as controls.

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……..

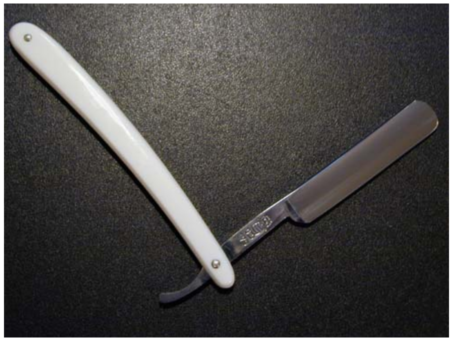
Multilepton Physics - II

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

Supersymmetry: Particle Physics Version of Occam's Razor

We like doubling the particle spectrum.

Single Blade (electron)



Twin Blade
(electron & positron)

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

LHC vs SUSY Models

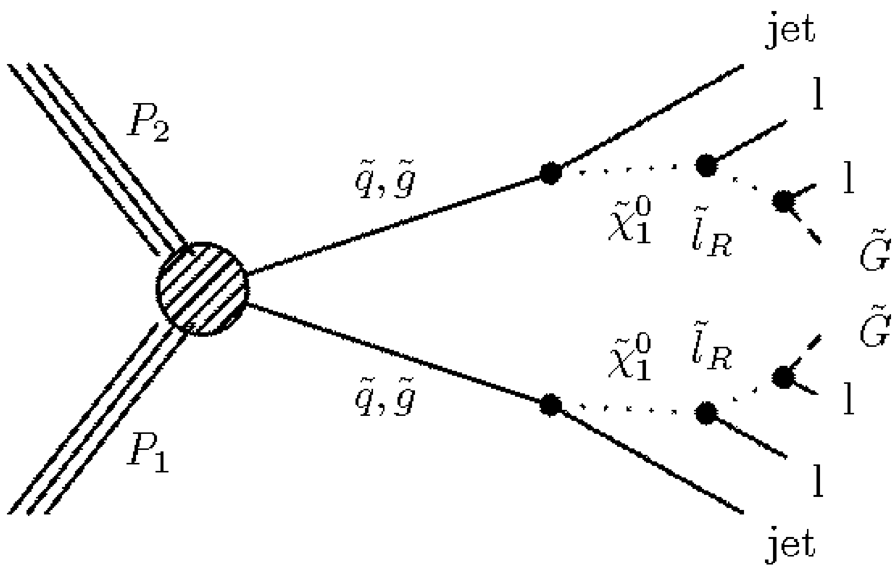
LHC

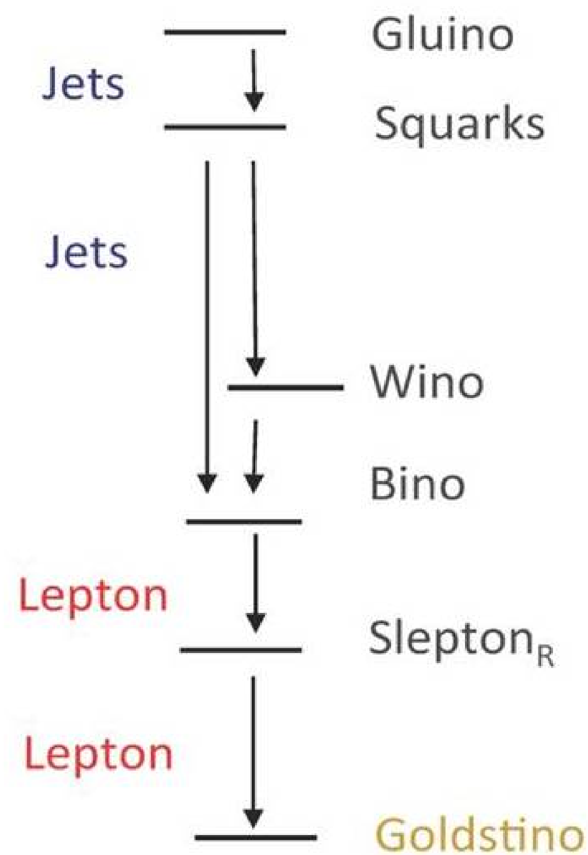
This is a sugra free talk

Slide Credit: Stephen Martin

SUSY with R-Parity: Strong production

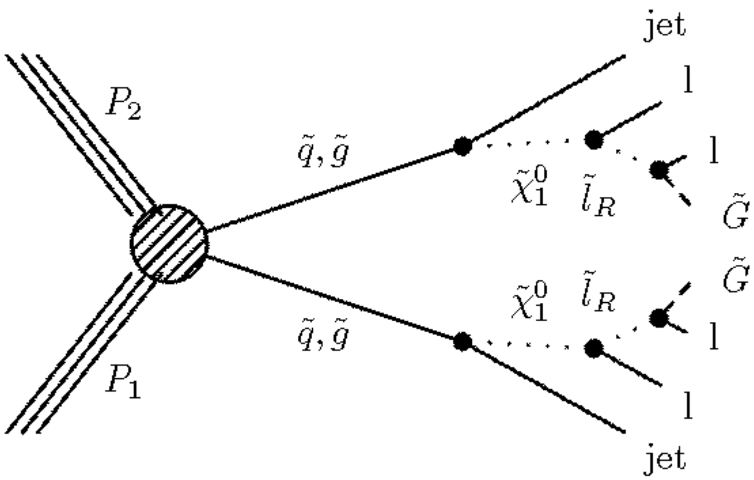
- GMSB slepton-CoNLSP, since 2010 (35 ipb) when everybody was feeling the beampipe for hadronic SUSY.

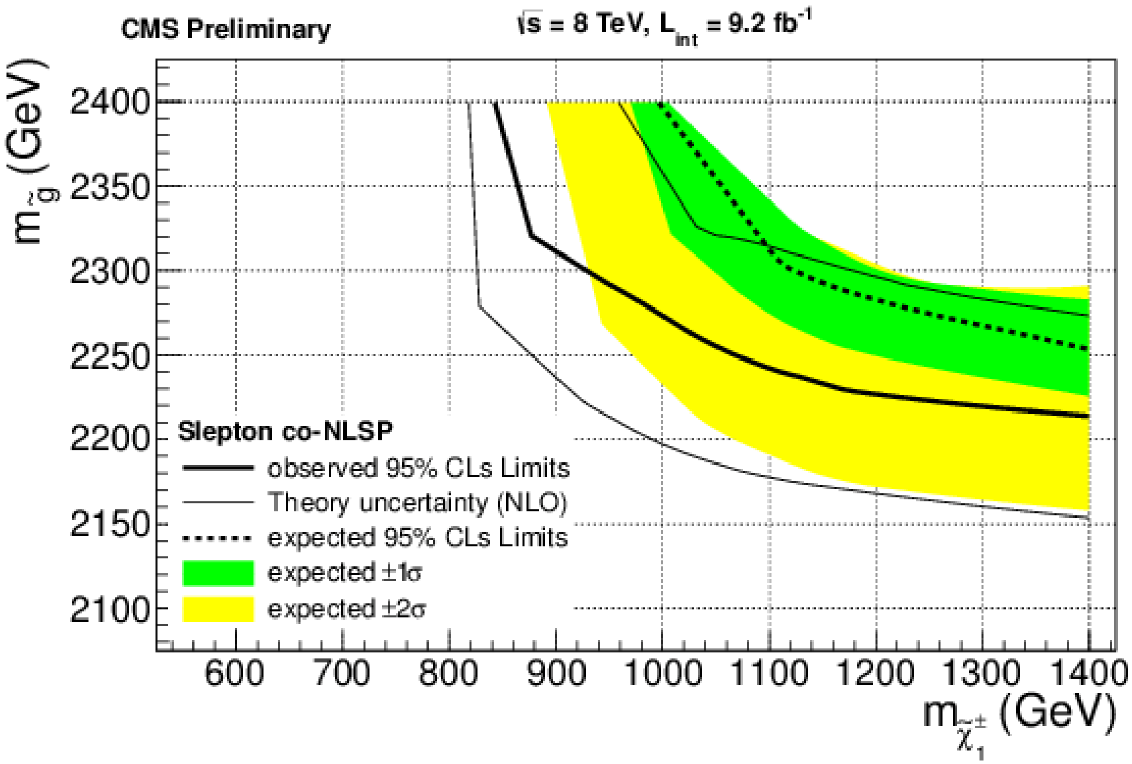




Strong production.
No compressed spectrum, etc
Prompt decay to Goldstino
(Scott Thomas)

Slepton co-NLSP (contd)





- Note the strong bounds thanks to strong production, plenty of leptons, jets, MET…

Keep an eye on stau-NLSP to be released at SUSY'13 (sleptons →staus…)

Electroweak Production

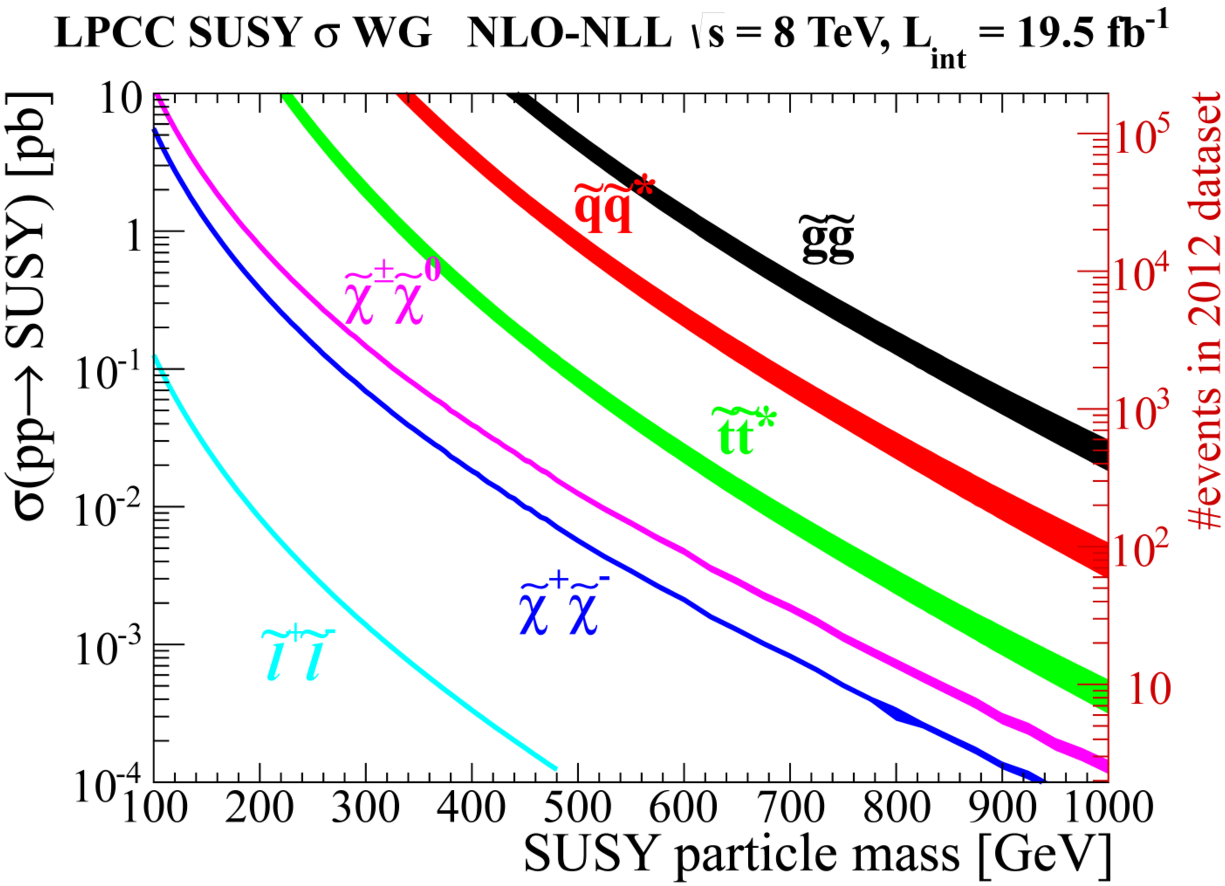
- Squarks and gluinos getting heavier in simple scenarios
- What if weak production beats strong production?

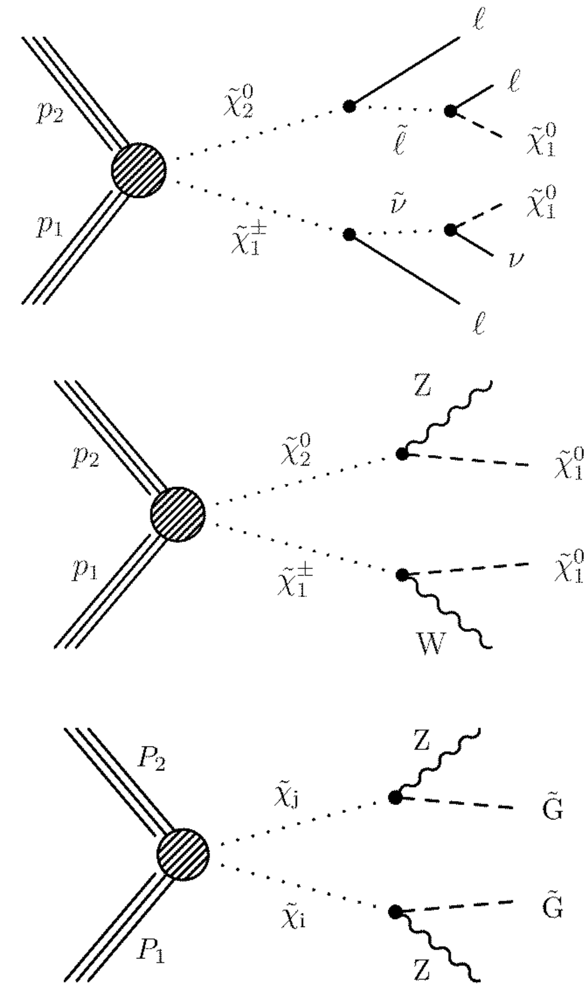
→Electroweak production to the rescue?

- Less copious, so lesser reach in mass
- *Less* hadronic activity (a long ways from the LHC beampipe getting hot from SUSY production circa 2010)

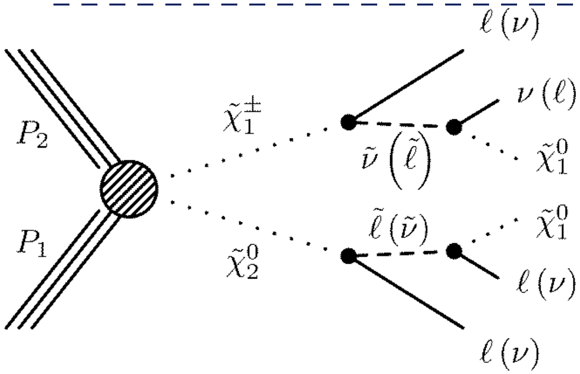
cf: classic trilepton SUSYsignature from Tevatron Run II.
mSUGRA limits were mostly due to EWK production.
(CDF:We got grief for cutting on jets → LHC: bin, don't cut.)

The Leftward March

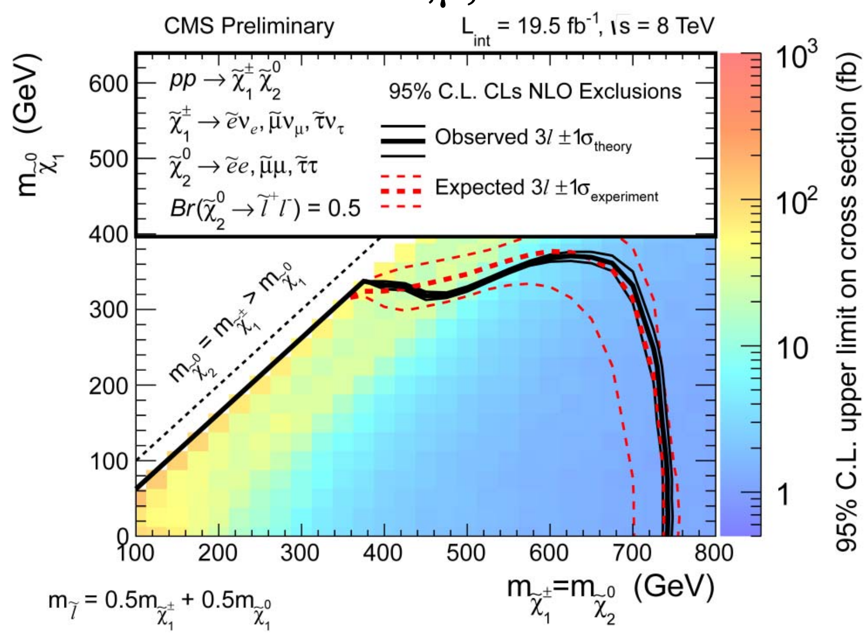


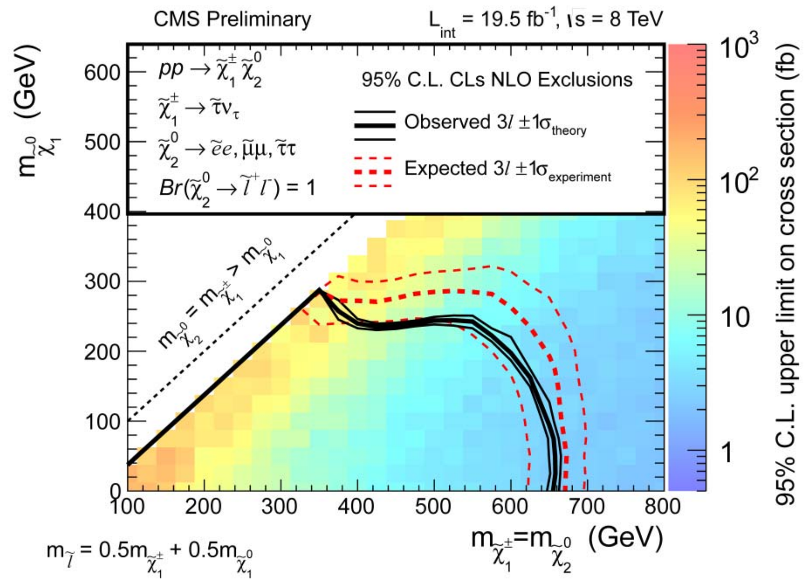


EWKino results (EPS'13)

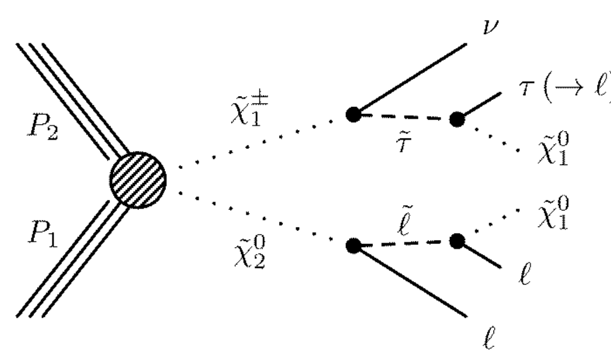


Democratic e,μ,τ

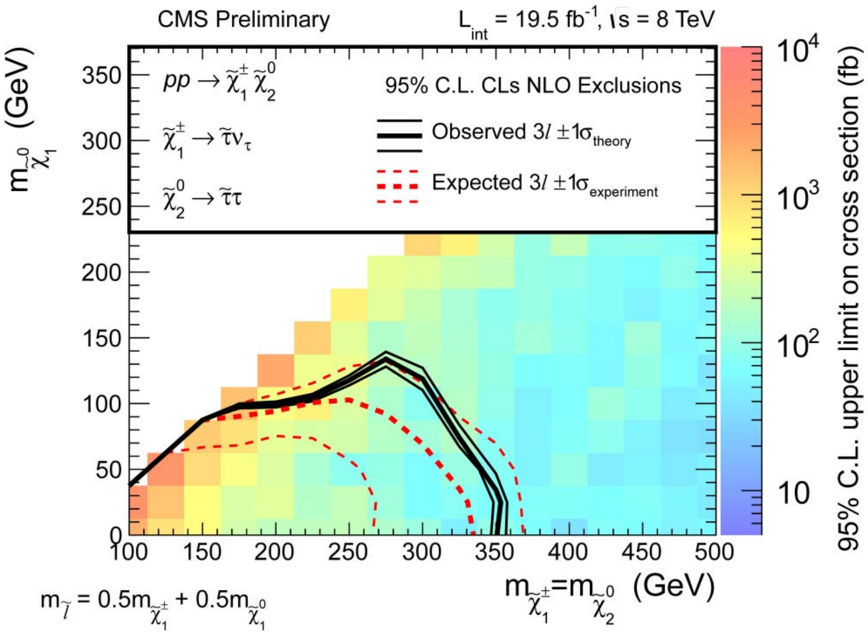




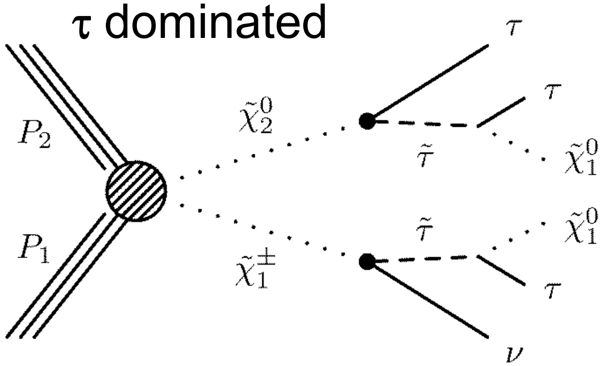
τ enriched

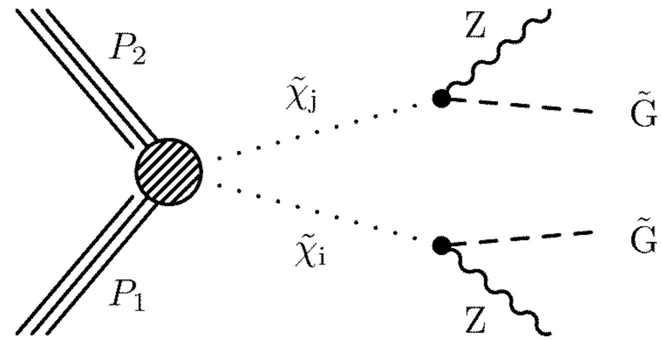


EWKino results (contd)

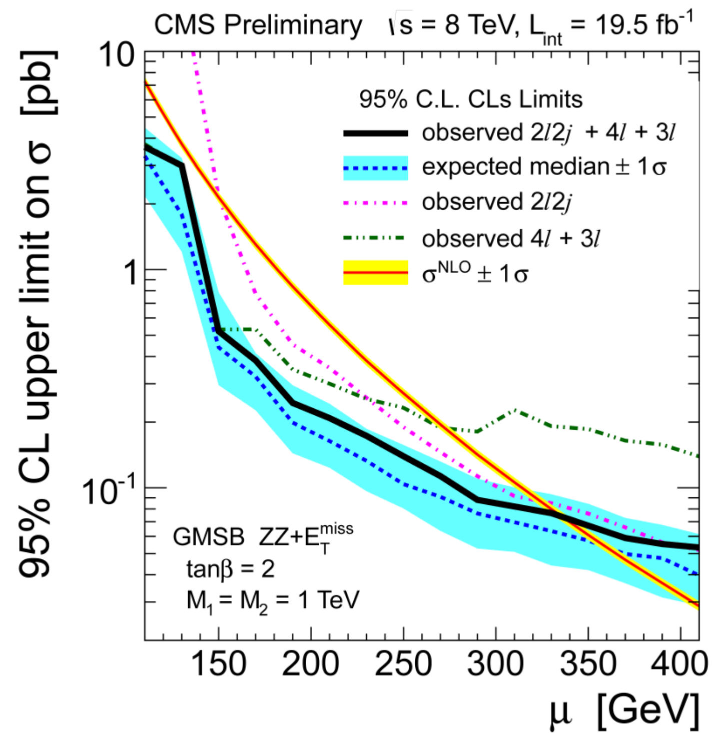


τ dominated

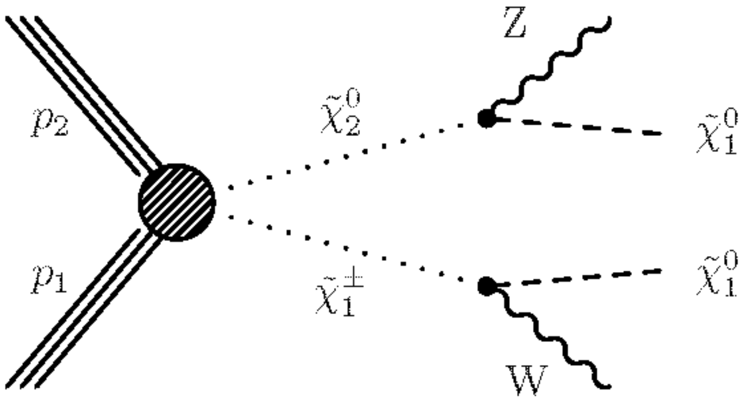




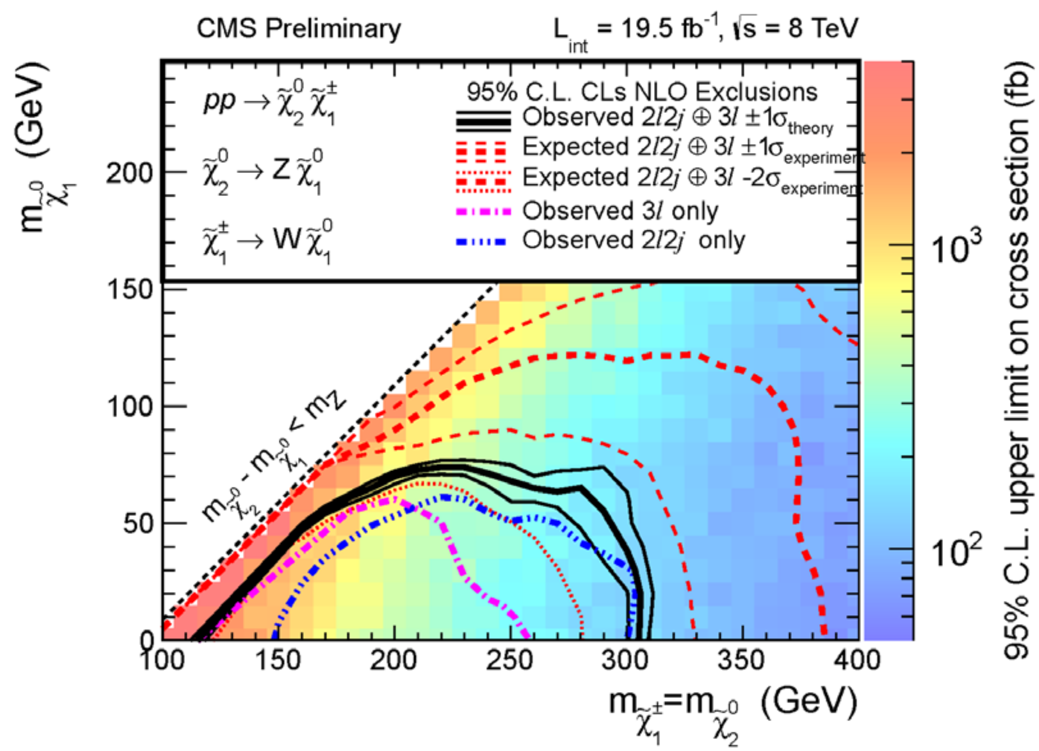
GMSB SUSY ZZ - includes Z(ll)+Z(jj)



EWKino results (contd)

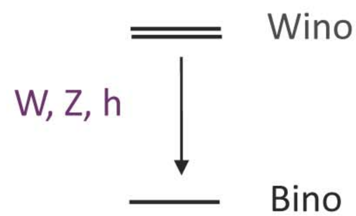


Sleptons heavy/decoupled
WZ+ MET signature
trileptons on Z & Z(ll)+Z(jj)



Higgs from ElectroWeak SUSY

Wino-Bino:



(Scott Thomas)

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

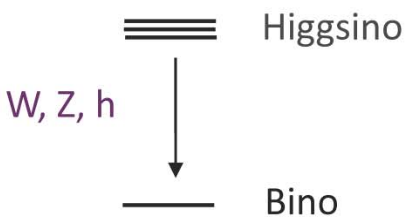
Dominates if Open

$\text{Neutralino}_{\text{Wino}}$ -> $\text{Neutralino}_{\text{Bino}}$ + h 1st order in mixing

$\text{Neutralino}_{\text{Wino}}$ -> $\text{Neutralino}_{\text{Bino}}$ + Z 2nd order in mixing

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

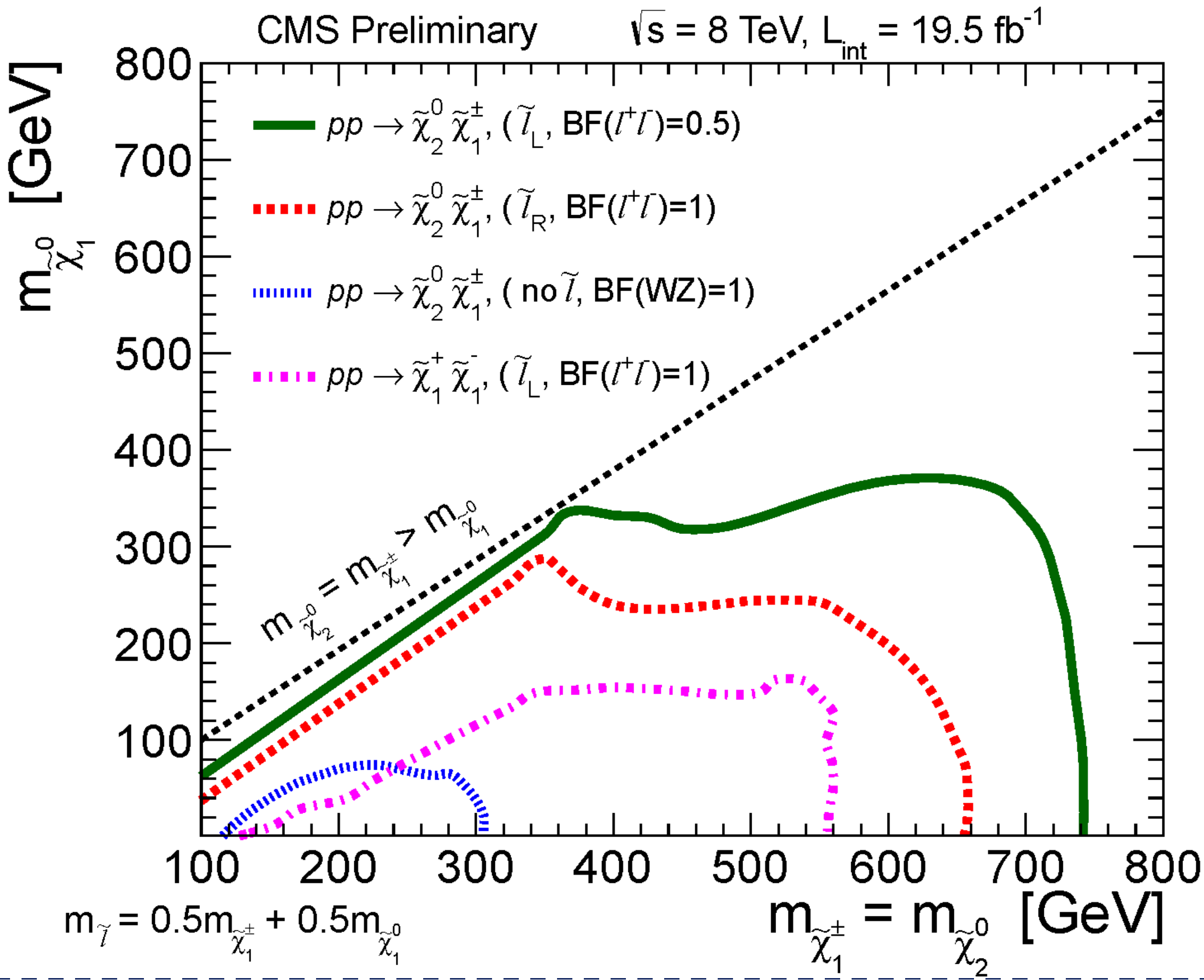
Dominates if Open

SUSY'13

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

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

CMS Electroweak Summary Slide
(discussed by P.M. earlier today)



An 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.

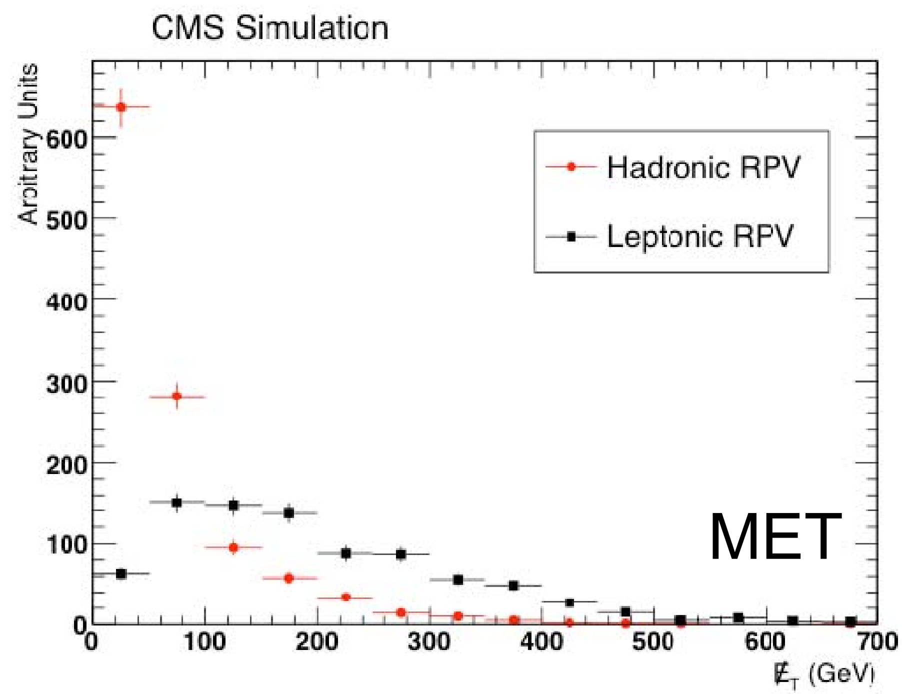
RPV can be tricky

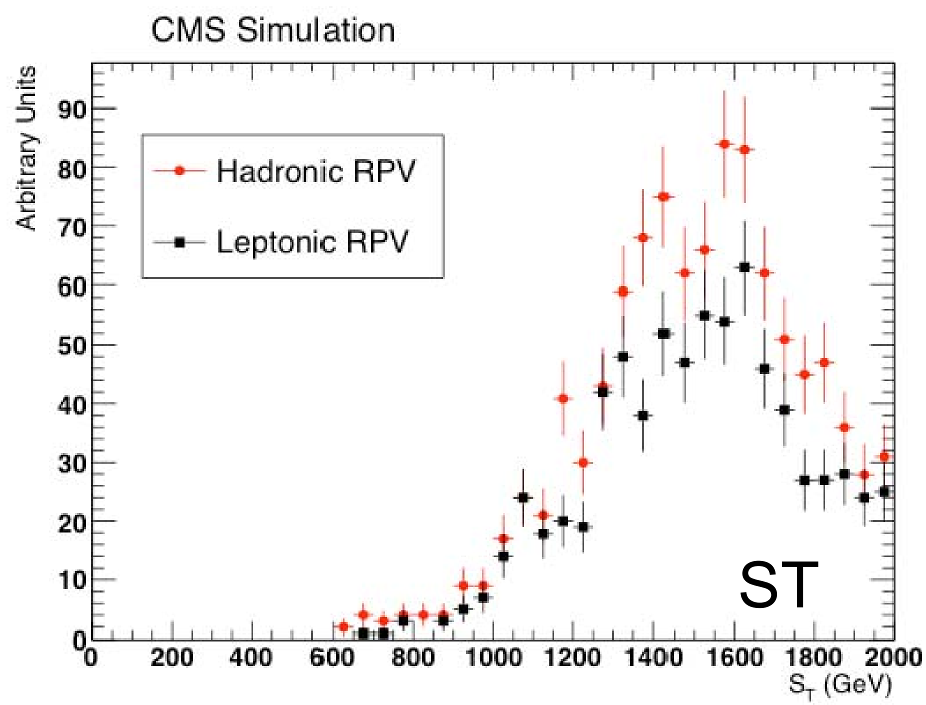
- A CMS multilepton study.
- Two RPV signals:
  no MET in hadronic RPV

- 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

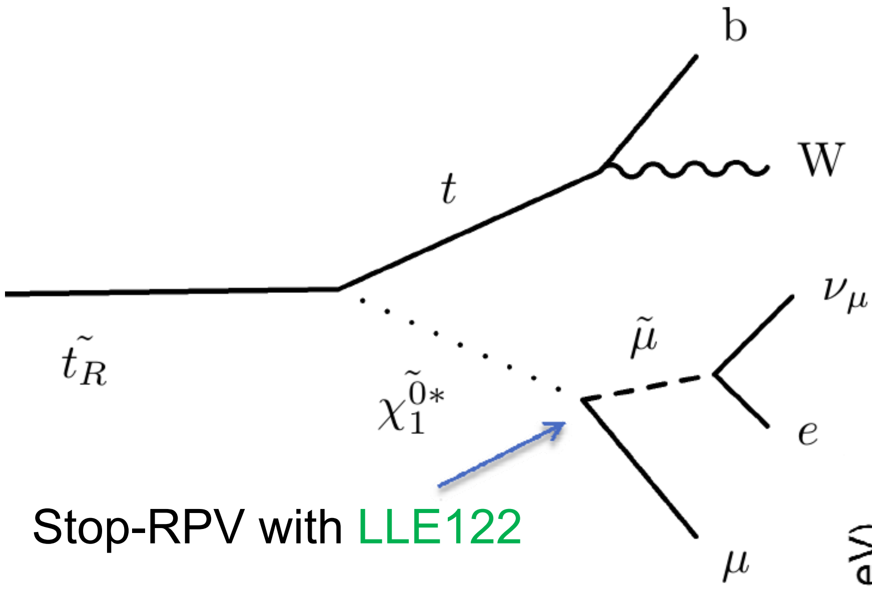




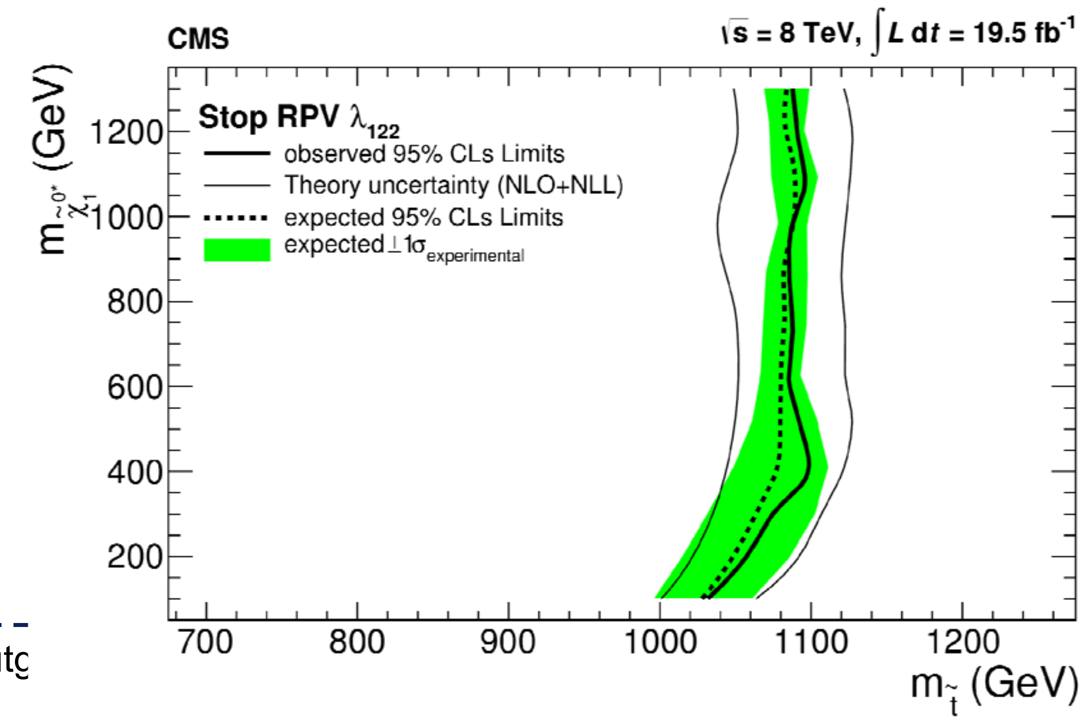
3rd generation RPV (*natural* stop)

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

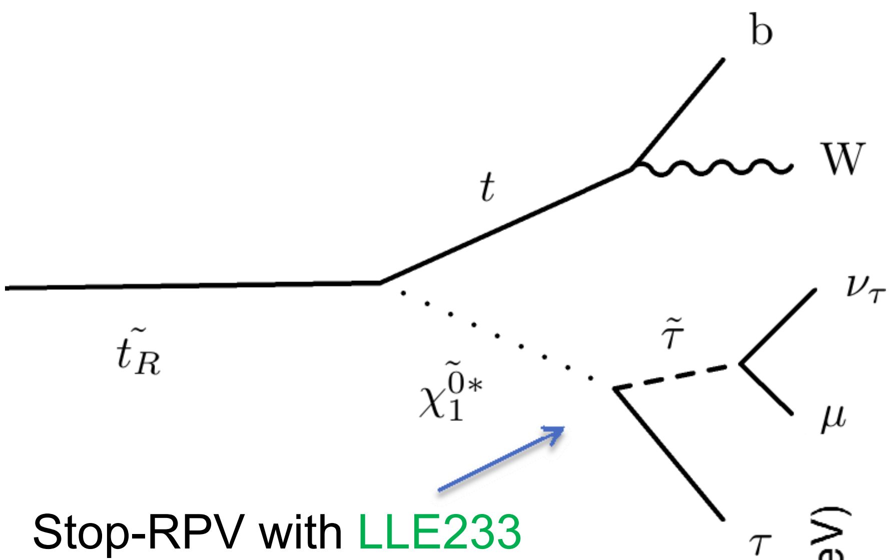
Note the mass reach.



Stop-RPV with LLE122

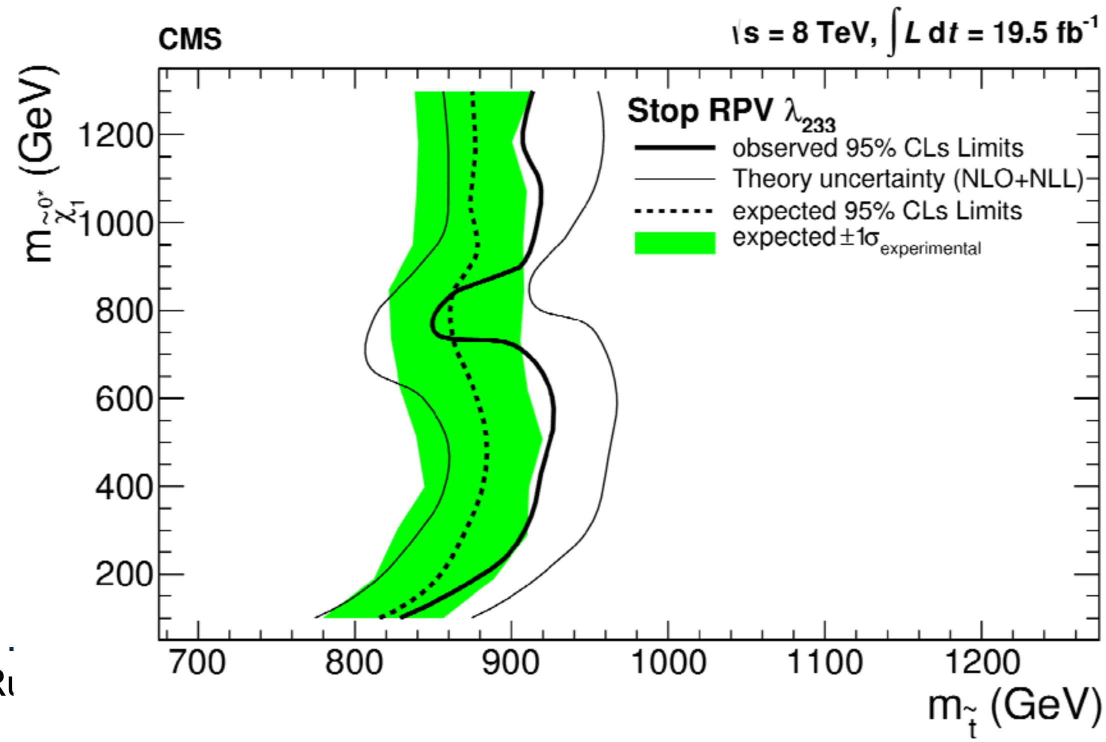


3^{rd} generation RPV (*natural* stop)



Stop-RPV with LLE233

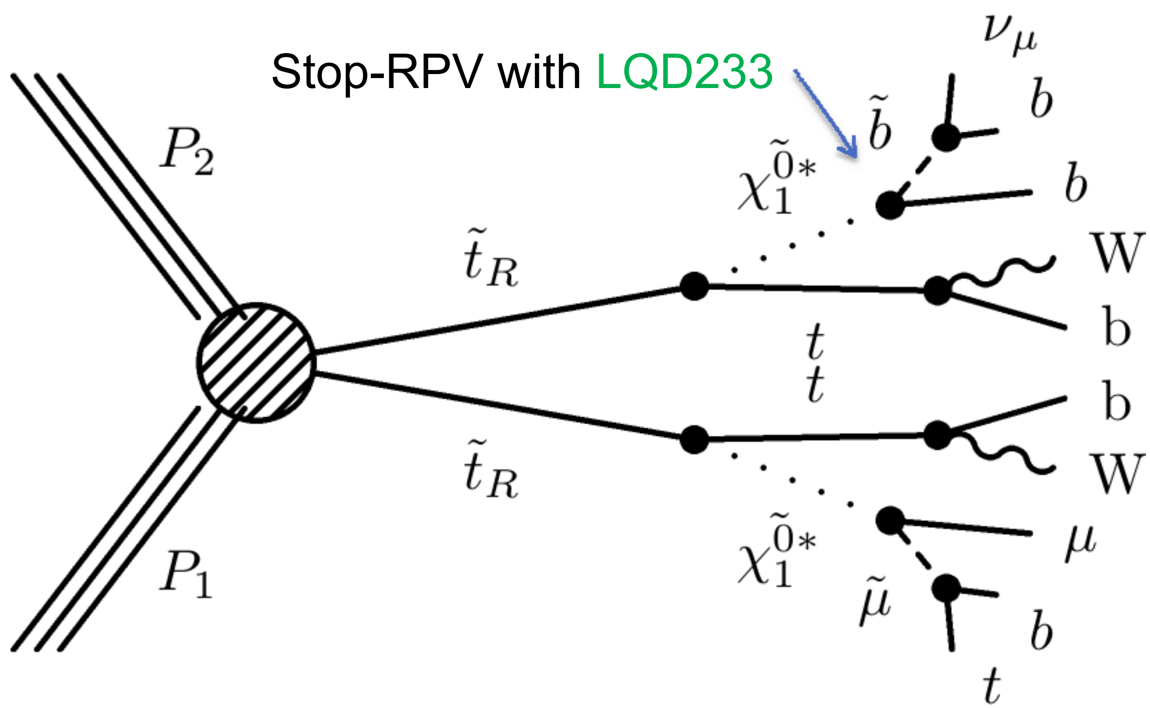
Note sensitivity loss (tau)
Offshell top in the middle



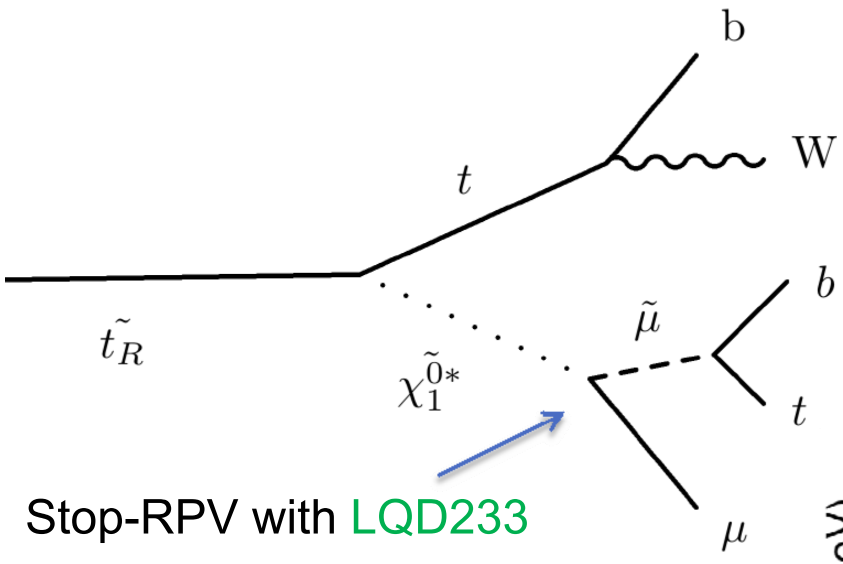
Stop RPV (contd)

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.

Stop-RPV with LQD233

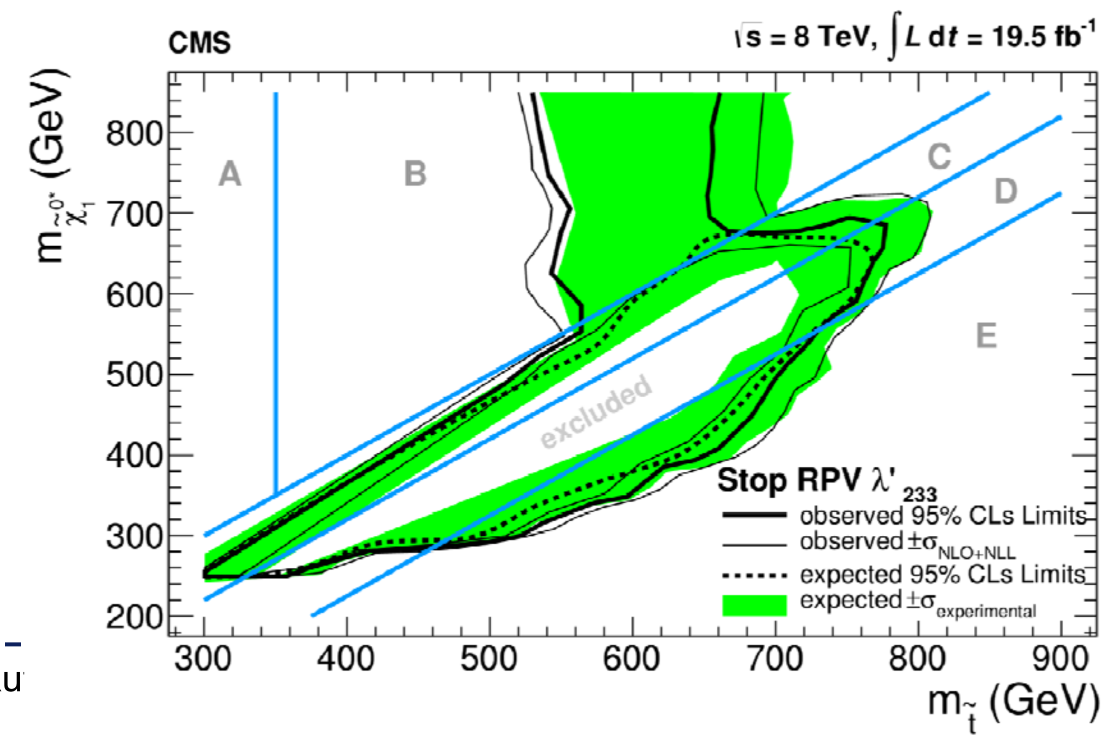


3rd generation RPV (*natural* stop)



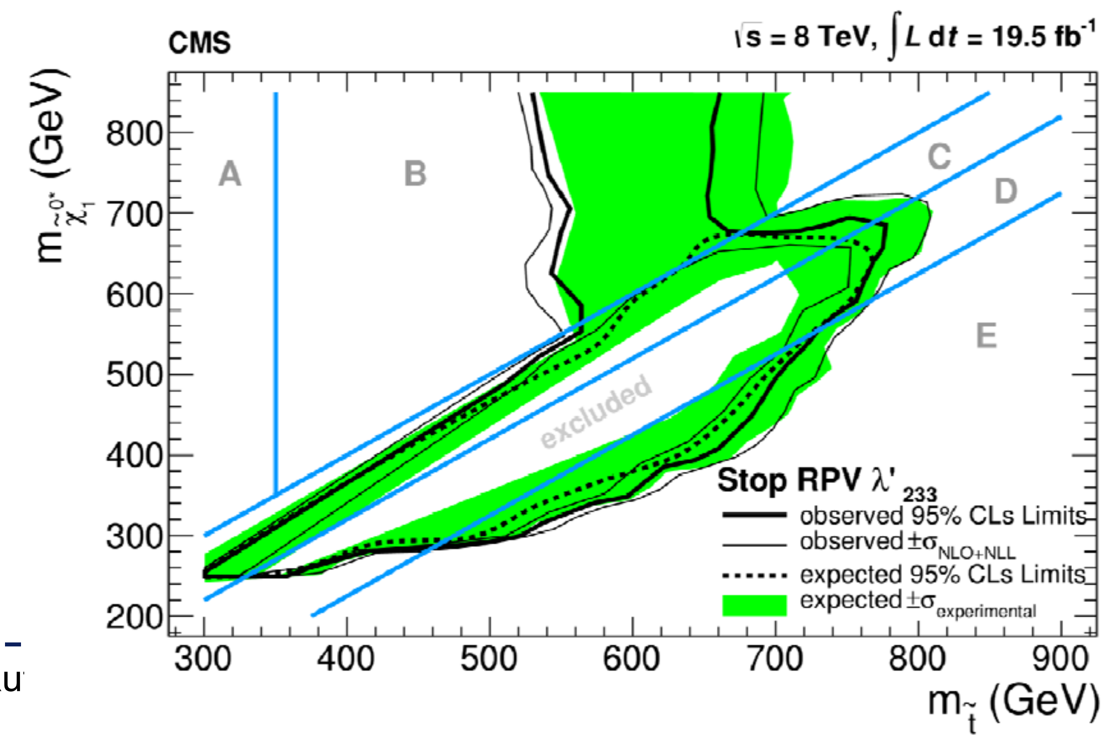
Stop-RPV with LQD233

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	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \to t\tilde{\chi}_1^0$



LHC vs SUSY Models

LHC

Slide Credit: Stephen Martin

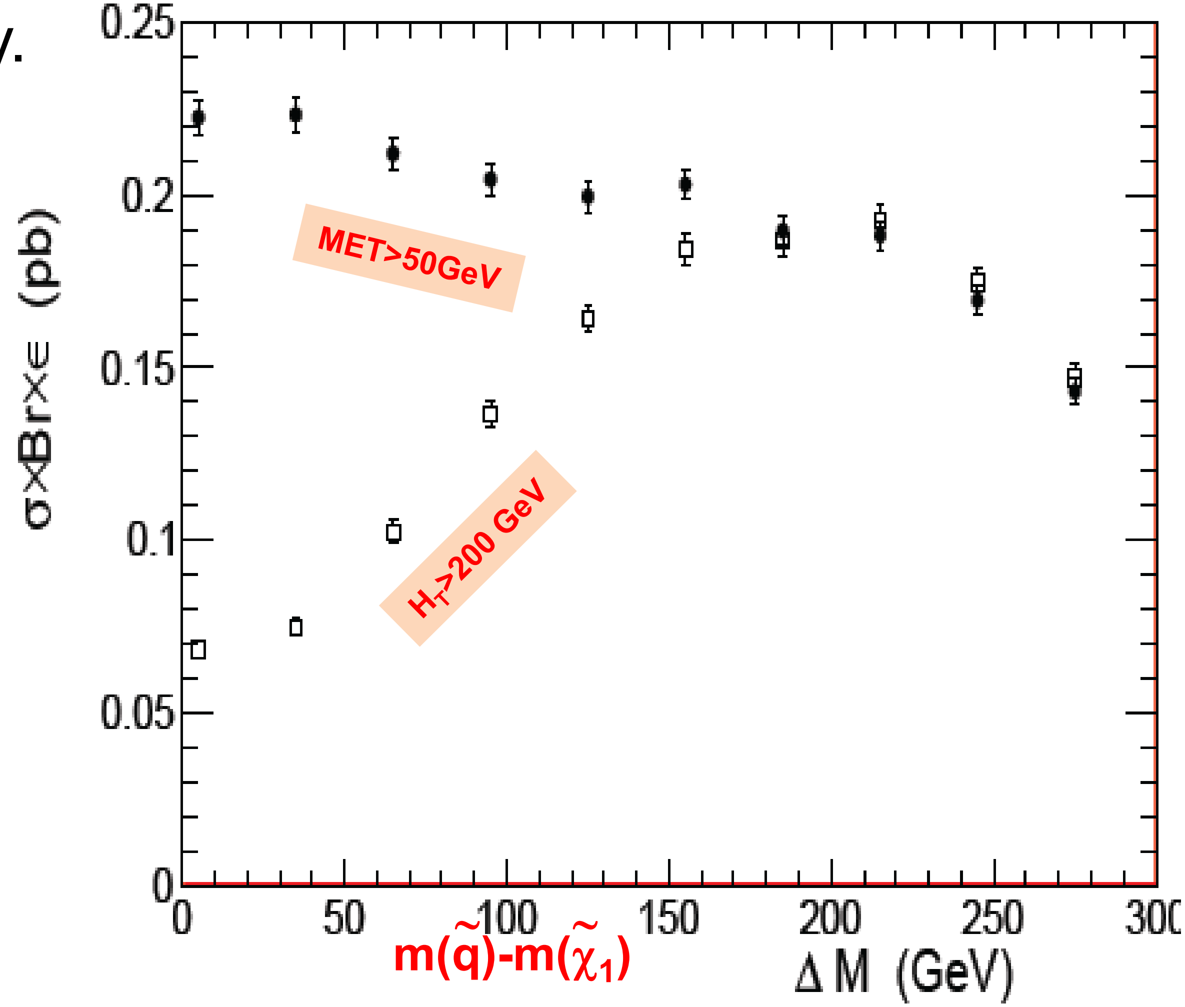
Nontrivial SUSY Scenarios

- A CMS multilepton study.
- ***Strong*** production but minimal jets/HT

•Strong production captured by Lepton Sector

Slepton co-NLSP GMSB topology by Scott Thomas

Also, non-zero lifetimes etc.…



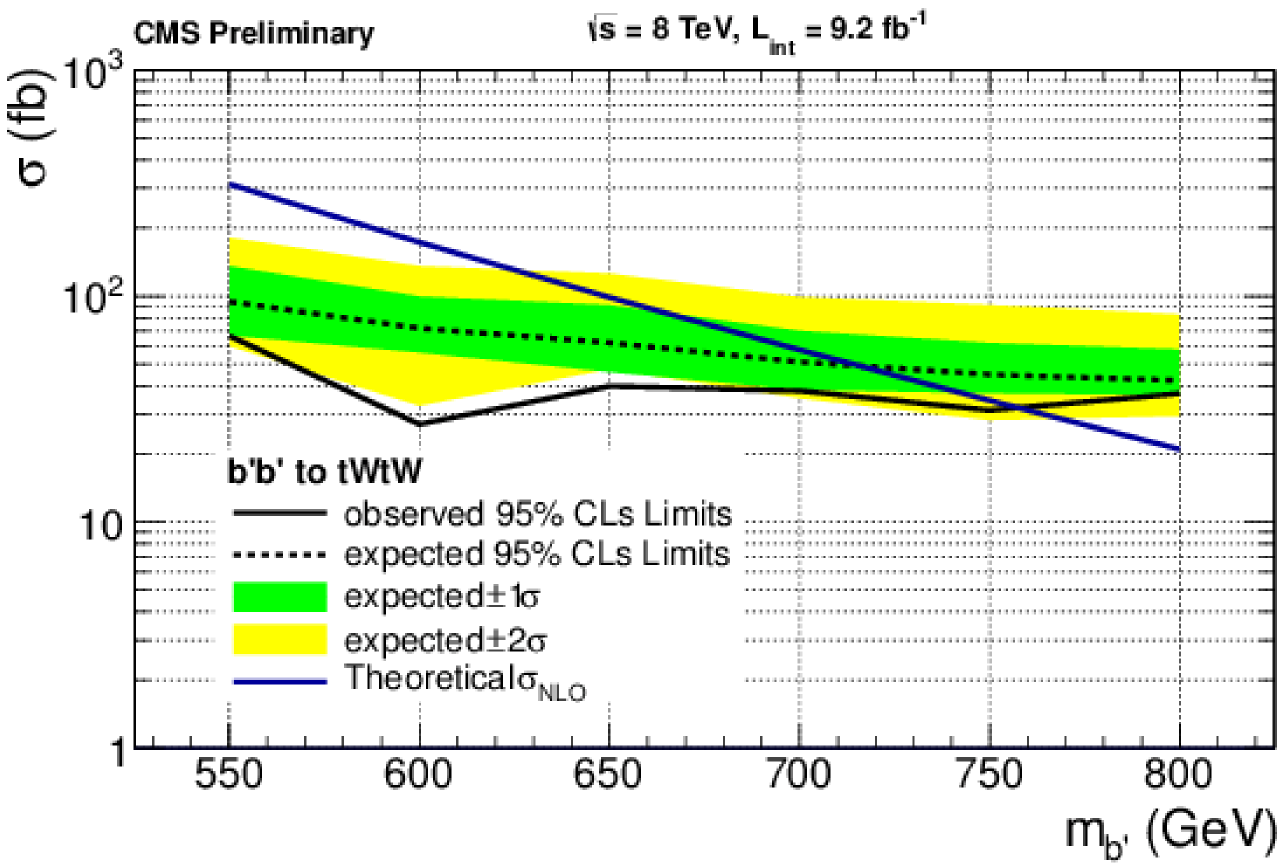
SUSY Possibilities: Ways to go

Nascent SUSY

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

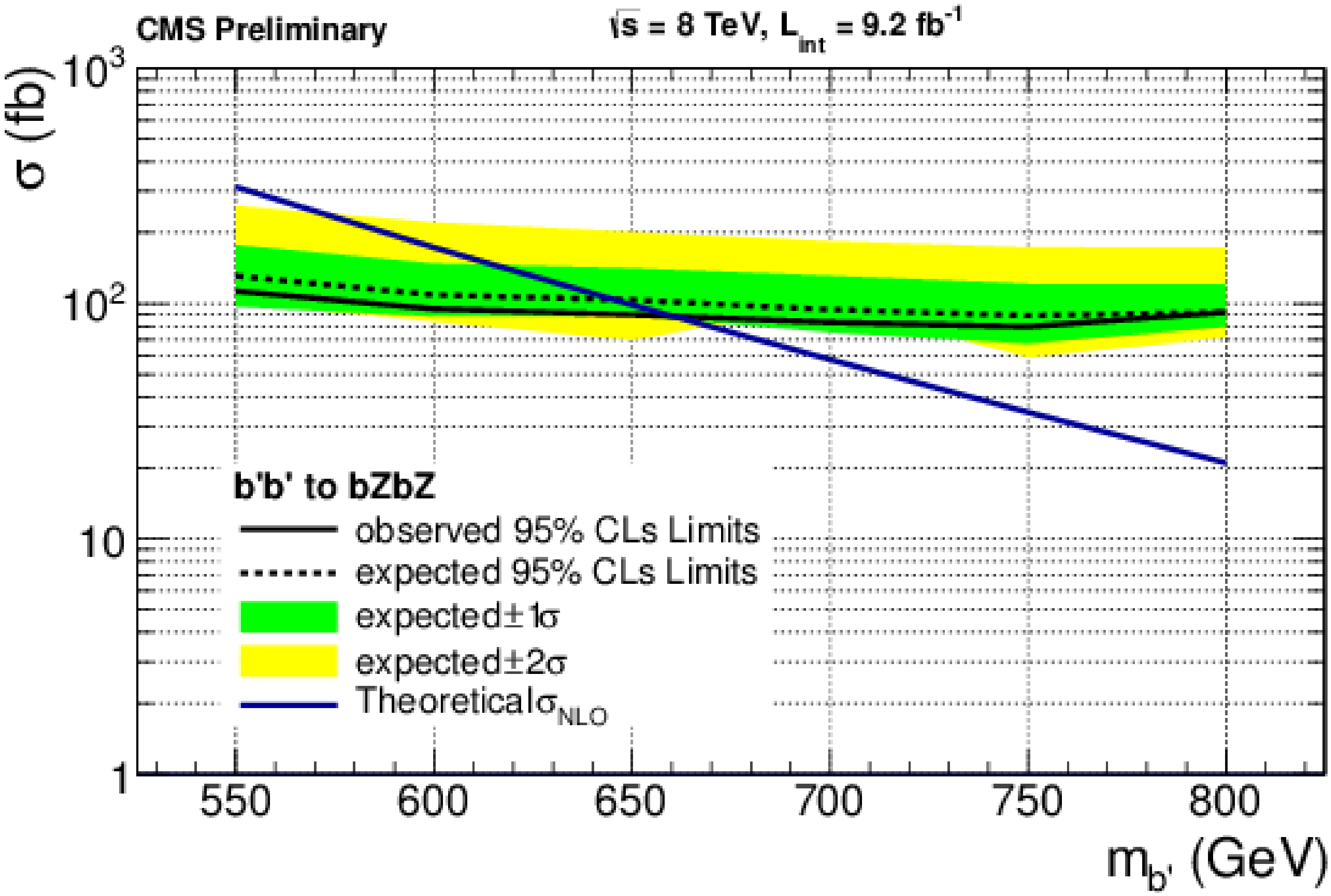
NOT SUSY – b’ (a partner particle)

- Illustrates the versatility of a multibinned approach where “signal” and “control” channels are all treated uniformly. Some signals, e.g. b’ → bZ show up in the “control” channels.

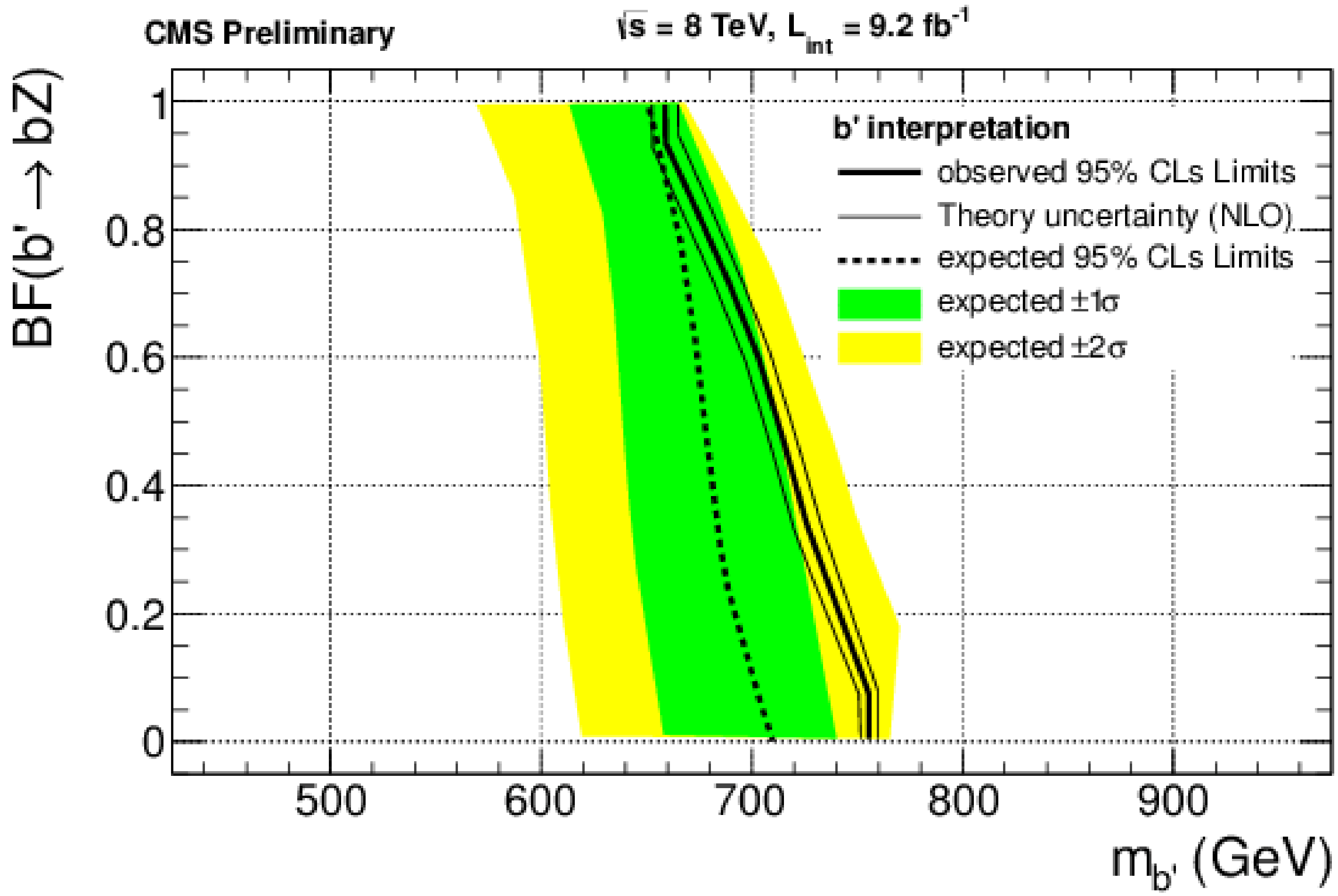


b’b’→tWtW →bWWbWW

b' - contd


CMS Preliminary
√s = 8 TeV, L_int = 9.2 fb-1
σ (fb)
10^3
10^2
10
1
550
600
650
700
750
800
m_b' (GeV)
b'b' to bZbZ
observed 95% CLs Limits
expected 95% CLs Limits
expected±1σ
expected±2σ
Theoretical σ_NLO

b' – tW to bZ transition



Susy'13: Also b' →bh

CMS Multileptons: Example of a Broad Search

Three or more electrons, muons or taus. Up to two tau's reconstructed.

54-channel ST table and 52 channel MET/HT results on and off Z

Signal (low-bkgnd) and control (high bkgnd) channels treated uniformly.

CMS multileptons:

a) Strong production GMSB slepton co-NLSP

b) R-parity Violation

c) Sensitive to accidents of spectrum (strong production captured by lepton sector)

d) Missing MET: e.g. RPV (Hadronic): S_T comes handy

e) Electroweak Production: fitting MET/MT

SURPRISES (detailed background studies)

- CMS pristine di-Z event ~5/pb (2010)
- Very rare four lepton event(s) in 2011, still outstanding.
- Trimuon Z (!!!???) and impact on Higgs

Credits

- PiTP organizers !!
- Richard Gray, Scott Thomas.
- LHC staff.
- CMS collaborators, conveners and management.
- Uncredited photographers and artists who produce images of penguins, foxes, smiley and sweaty emoticons...