Chasing SUSY with Dileptons

Frank Würthwein
UCSD

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L. Bauerdick, K. Burkett, I. Fisk, Y. Gao, O. Gutsche, B. Hooberman, S. Jindariani, J. Linacre, V. Martinez Outschoorn

Fermilab National Accelerator Laboratory, Batavia, USA

C. Campagnari, A. George, F. Golf, D. Kovalskyi, V. Krutelyov

University of California, Santa Barbara, Santa Barbara, USA

G. Cerati, M. D'Alfonso, D. Evans, R. Kelley, I. MacNeill, S. Padhi, Y. Tu, F. Würthwein, V. Welke, A. Yagil, J. Yoo

University of California, San Diego, San Diego, USA

The analyses presented today were done by a group of CMS physicists from UCSB, UCSD, and FNAL.

Context

- This work is part of a larger body of work including:
  - Search for H to WW to lv lv
  - Search for H to ZZ to ll vv
  - WW cross section in lv lv
  - 4th generation top search in lvb lvb
  - Top asymmetries and polarizations in dileptons
  - Chasing SUSY with Dileptons

Chasing SUSY with Dileptons

ee, μμ, eμ

Opposite sign
- Outside Z peak
- Inside Z peak

Same sign
- Inclusive
- with ≥2 btags

Different final states require different data driven bkg estimates.
We define multiple signal regions in MET and HT in all cases.

In all cases, we provide interpretations as well as “outreach”

HT = sum of pT of all jets above threshold

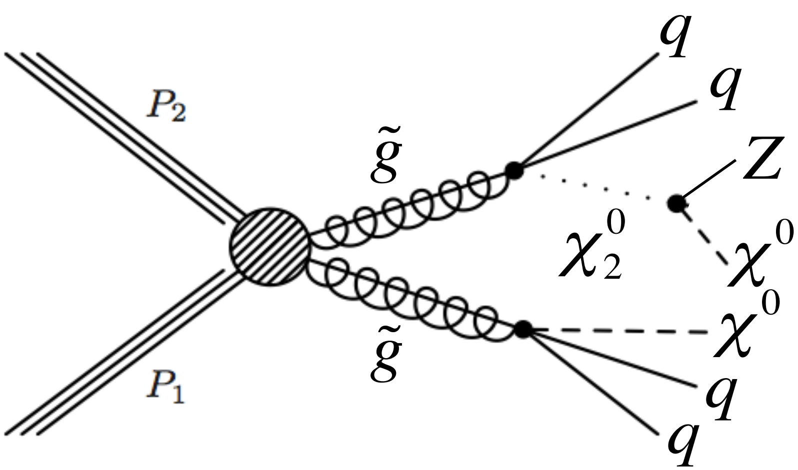
Leptons: e, μ

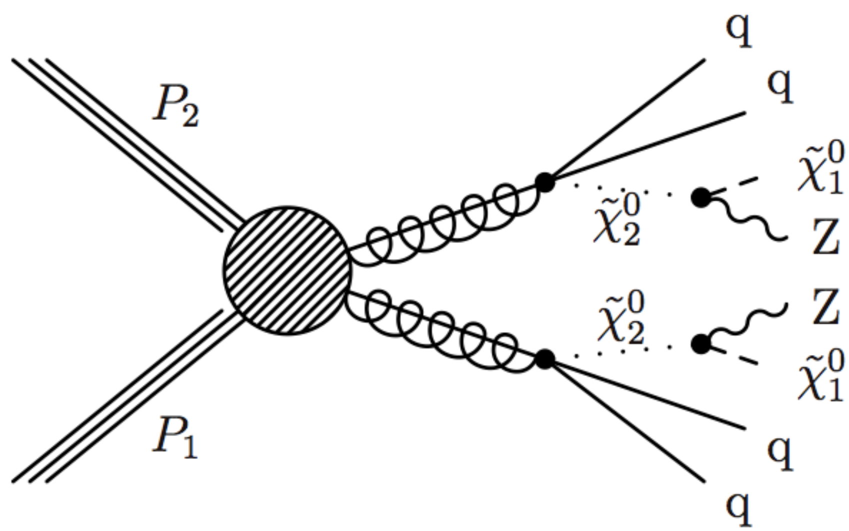
- All leptons are required to be isolated.
- Isolation is defined as sum pT in a cone of 0.3 around the lepton divided by the pT of the lepton.
- Leptons are within $|\eta| < 2.5$
- Muon and electron Id differ slightly among the analyses depending on whether the dominant bkg is due to lepton fakes or not.
- Lepton Id as well as Isolation has evolved over the last couple years in response to running conditions.

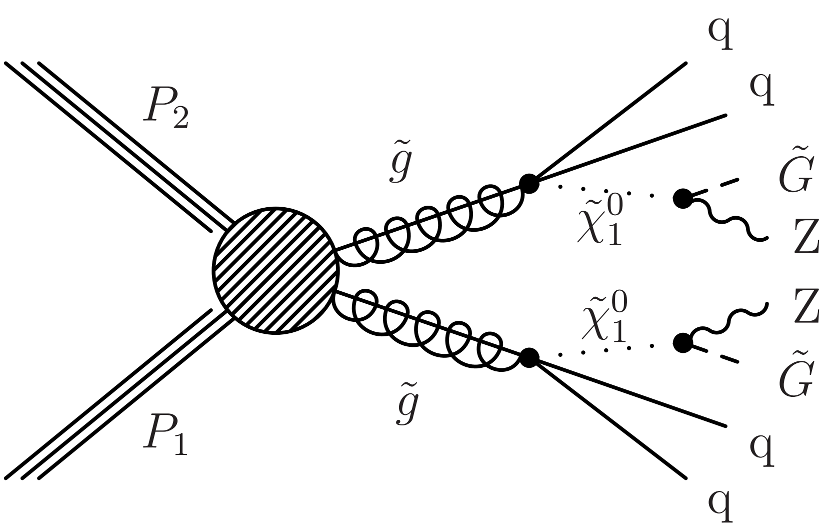
Inside the Z peak

- Two analyses:
  - Inclusive analysis using 5/fb of 7TeV data
    - PLB 716 (2012) 260
  - Exclusive analysis using 5/fb of 7TeV data
    - arXiv:1209.6620

Inclusive Z & MET & Jets





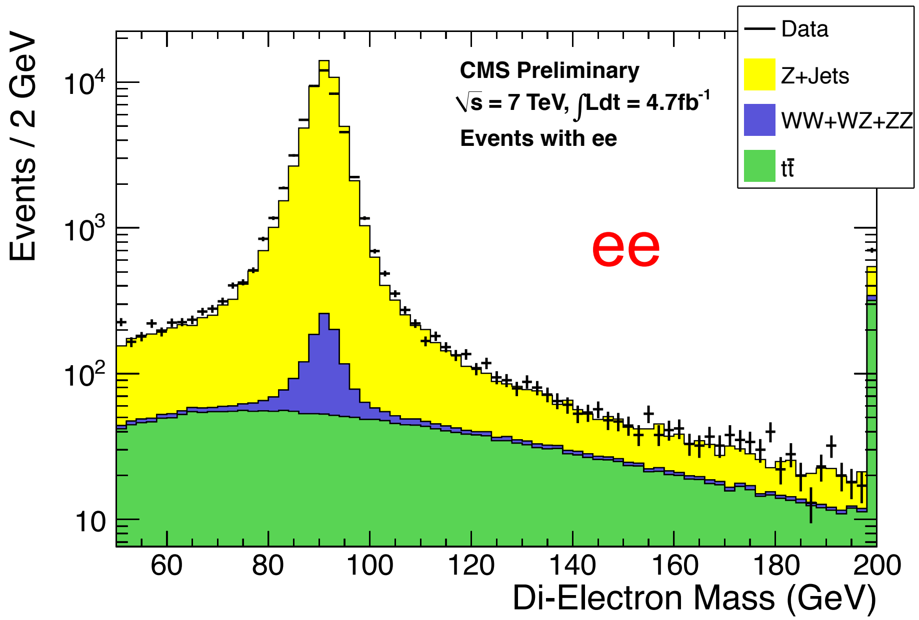


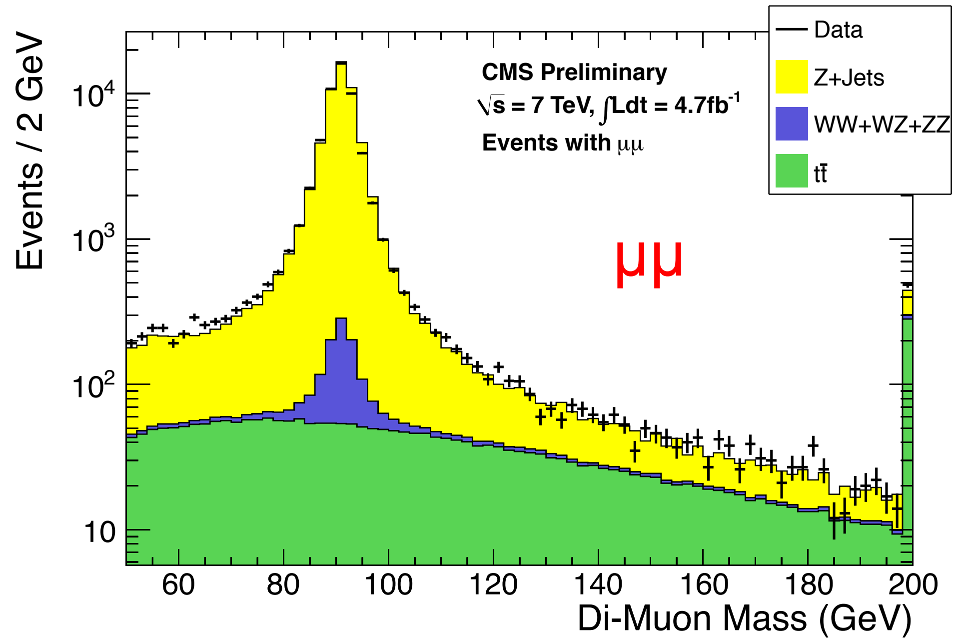
One or two Z's in the final state,
plus MET from LSP,
plus jets.

Inclusive Analysis Strategy

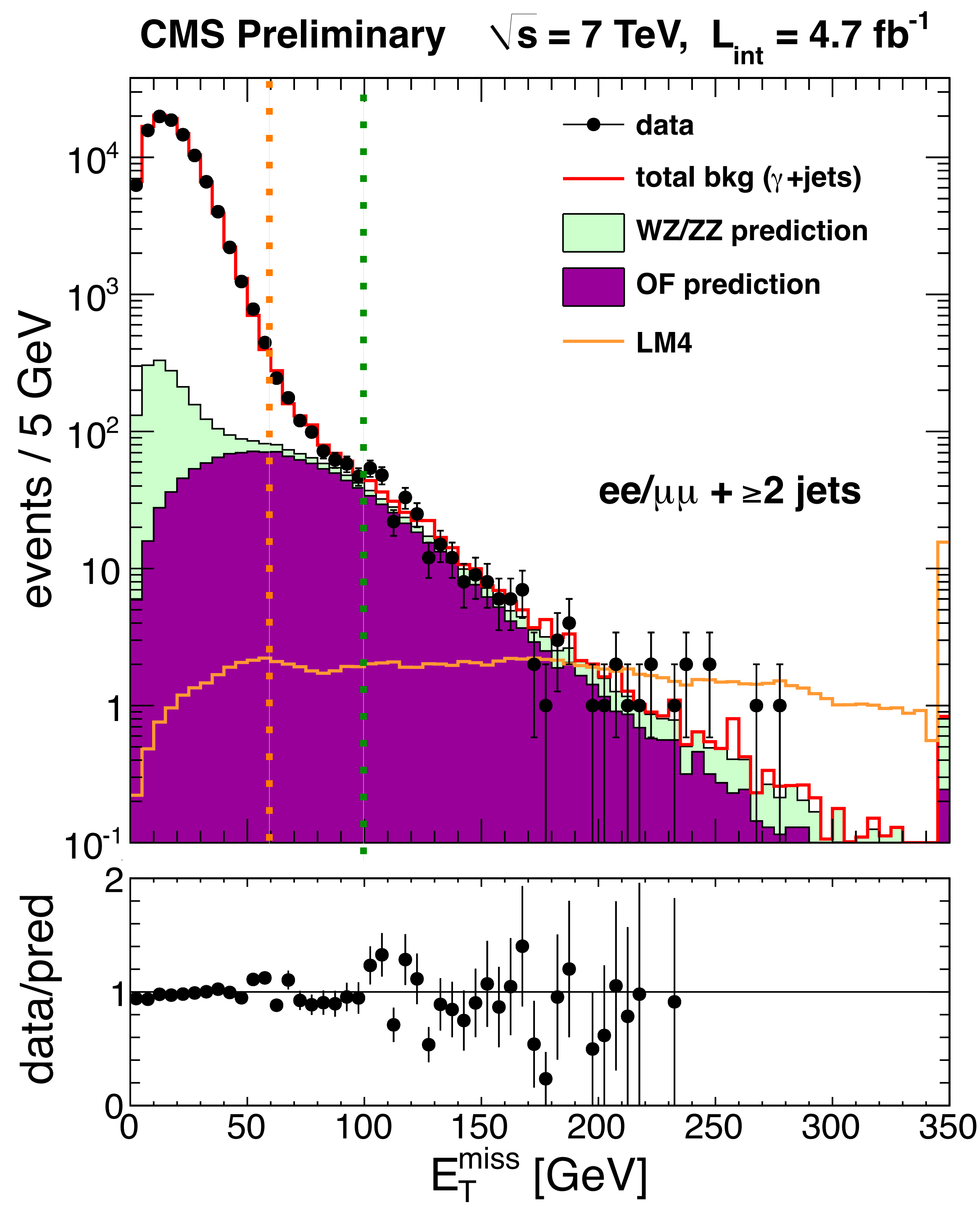
- Dilepton trigger with pT > 17GeV, 8GeV
- Select pT>20GeV ee and μμ in Z peak
  - Require ≥ 2 jets of pT > 30GeV, |η| < 3
- Select eμ control sample to estimate non-Z bkg from data
- Select photon & jets control sample to estimate MET tails from data

Dilepton Invariant Mass





- Measure e,μ Id & Iso & trigger efficiencies in data using tag & probe.
- Z peak = within +-10GeV of the Z mass

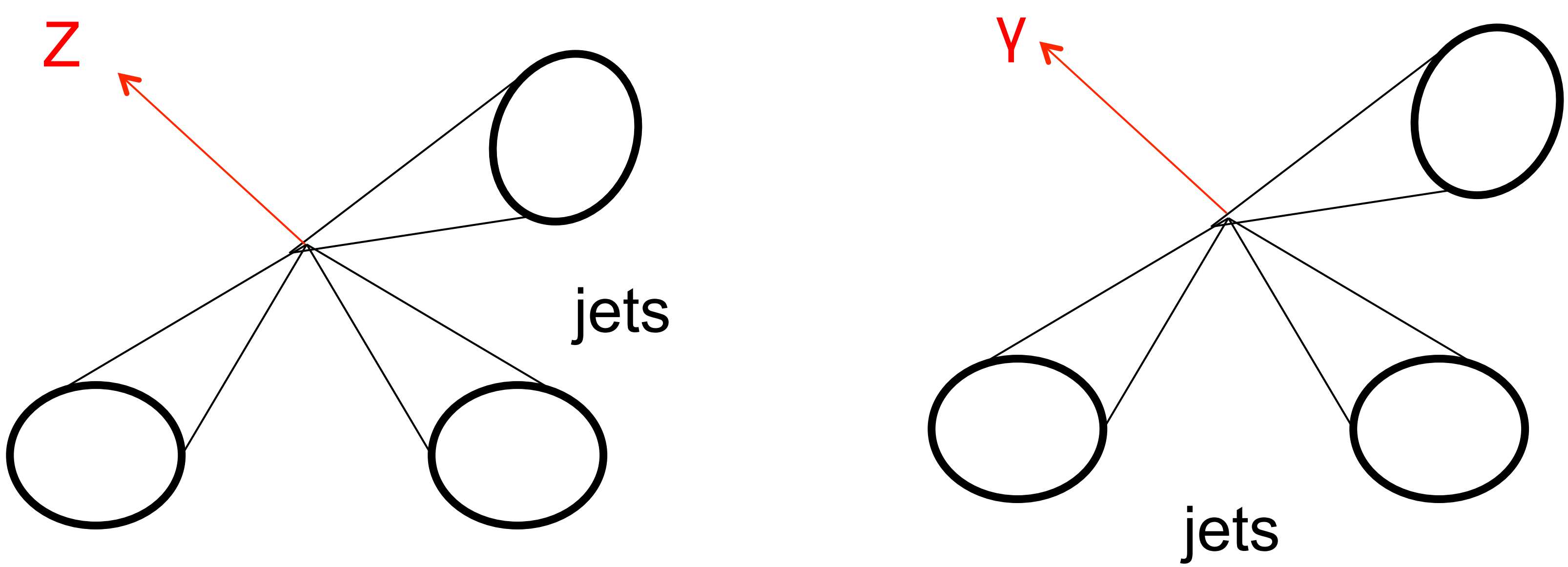


MET

- MET ~ 60GeV
  - Z&jets dominates
- MET ~ 100GeV
  - Top dominates

- Excellent agreement between observed and predicted.

Predicting MET tails from data

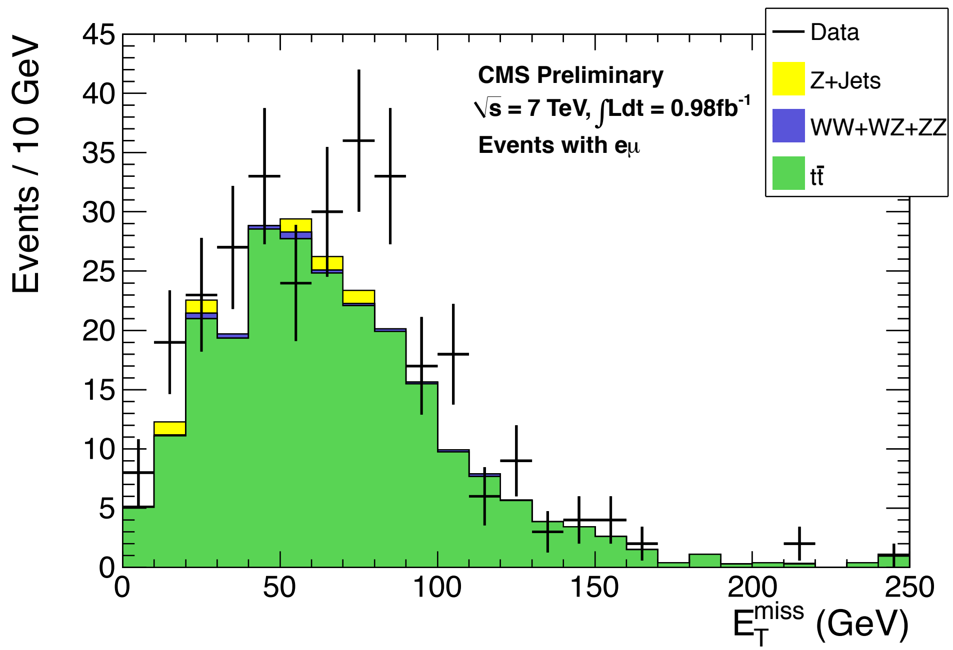


Assumptions:
MET is dominated by mismeasurement of hadronic recoil.
Hadronic recoil can be parametrized in Njet and HT,
MET as function of Njet,HT can be measured in γ & jets in data.

MET templates

- Measure MET in γ & jets events in data
  - In bins of HT, Njet
  - For each bin, normalize MET template to 1.
- For each Z & jets event
  - Pick MET template based on HT,Njet of the event
  - Sum MET templates over all events with Njet ≥ 2

MET in eμ control sample



- For each MET bin, predict non-Z bkg from eμ sample, after correcting for differences in e,μ efficiencies.

Results

	$E_T^{miss} > 30$ GeV	$E_T^{miss} > 60$ GeV	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 200$ GeV	$E_T^{miss} > 300$ GeV
Z bkg	15070 ± 4825	484 ± 156	36 ± 12	2.4 ± 0.9	0.4 ± 0.3
OF bkg	1116 ± 101	680 ± 62	227 ± 21	11.4 ± 3.2	1.6 ± 0.6
VZ bkg	252 ± 126	79 ± 39	32 ± 16	5.0 ± 2.5	1.1 ± 0.7
total bkg	**16438 ± 4828**	**1243 ± 173**	**295 ± 29**	**18.8 ± 4.2**	**3.1 ± 1.0**
data	**16483 (8243,8240)**	**1169 (615,554)**	**290 (142,148)**	**14 (8,6)**	**0**
upper limit	6389	239	57	8.3	2.9
LM4	113 ± 9.1	102 ± 8.5	88 ± 7.9	50 ± 7.4	22 ± 6.0
LM8	49 ± 4.1	43 ± 3.7	35 ± 3.2	19 ± 2.9	9 ± 2.2

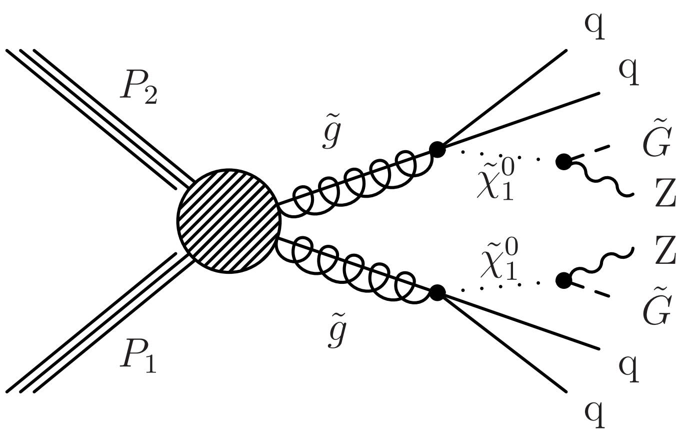
Agreement: 0.3% 6% 2%

Observed and predicted agree exceptionally well.
No sign of new physics anywhere.

Interpretation

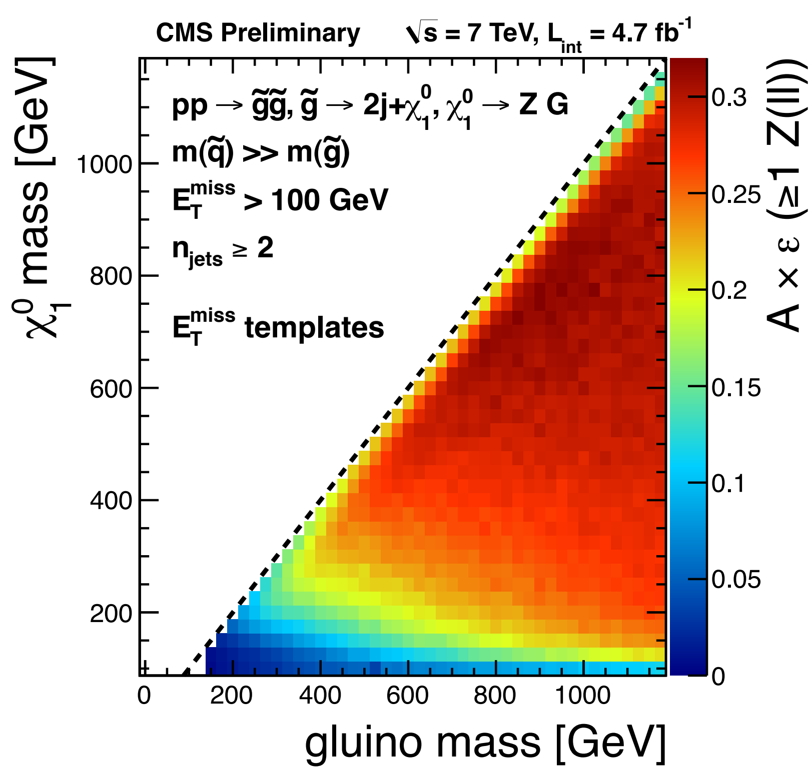
- Throughout our analyses, we provide two ways to interpret the results:
  - Pick example models
  - "Outreach" for theorists
    - Provide enough information in the paper such that a theorist can crudely estimate the exclusion of a model's parameter space due to our results.
    - Theorist only needs a hard scatter generator for the model. We provide approximate efficiencies at the "parton" level, as well as turn-on curves for MET,HT.

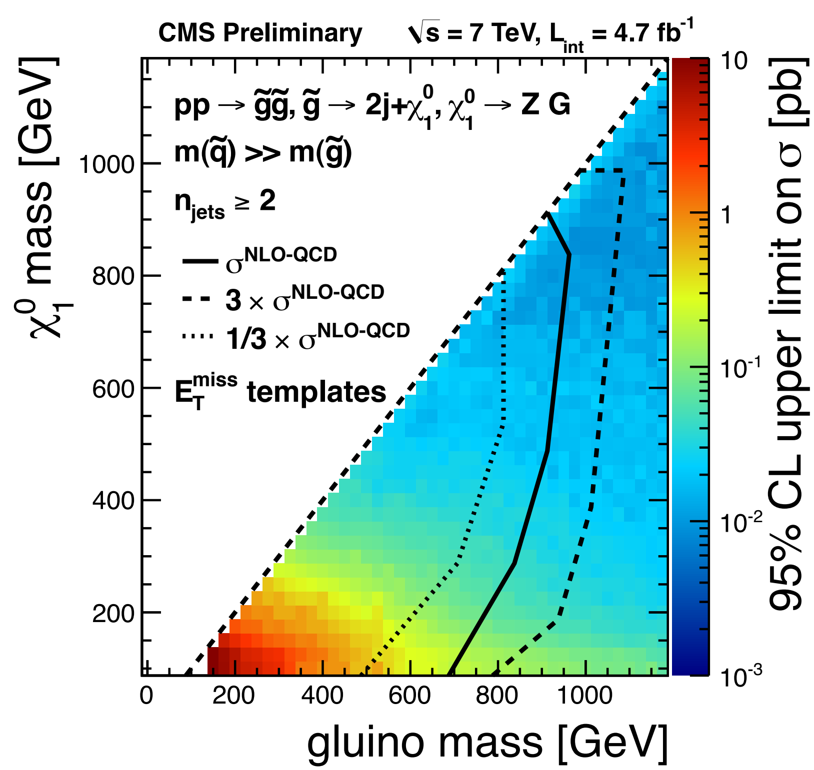
Example GMSB



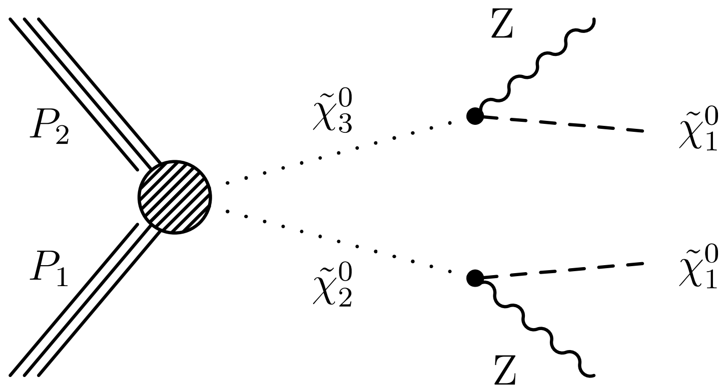
Assume each event has 2 Z's

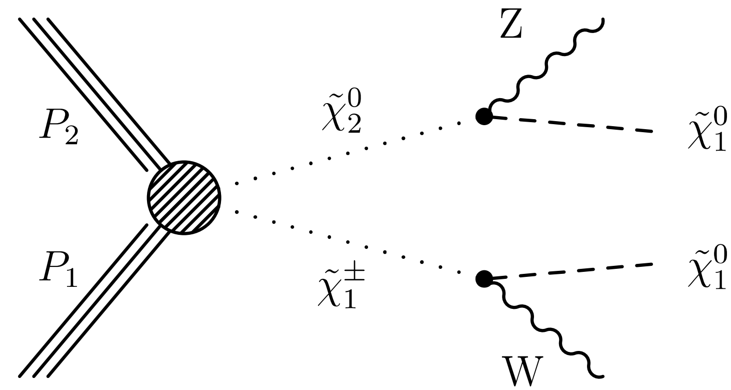
Exclusion in the χ^0 – gluino mass plane





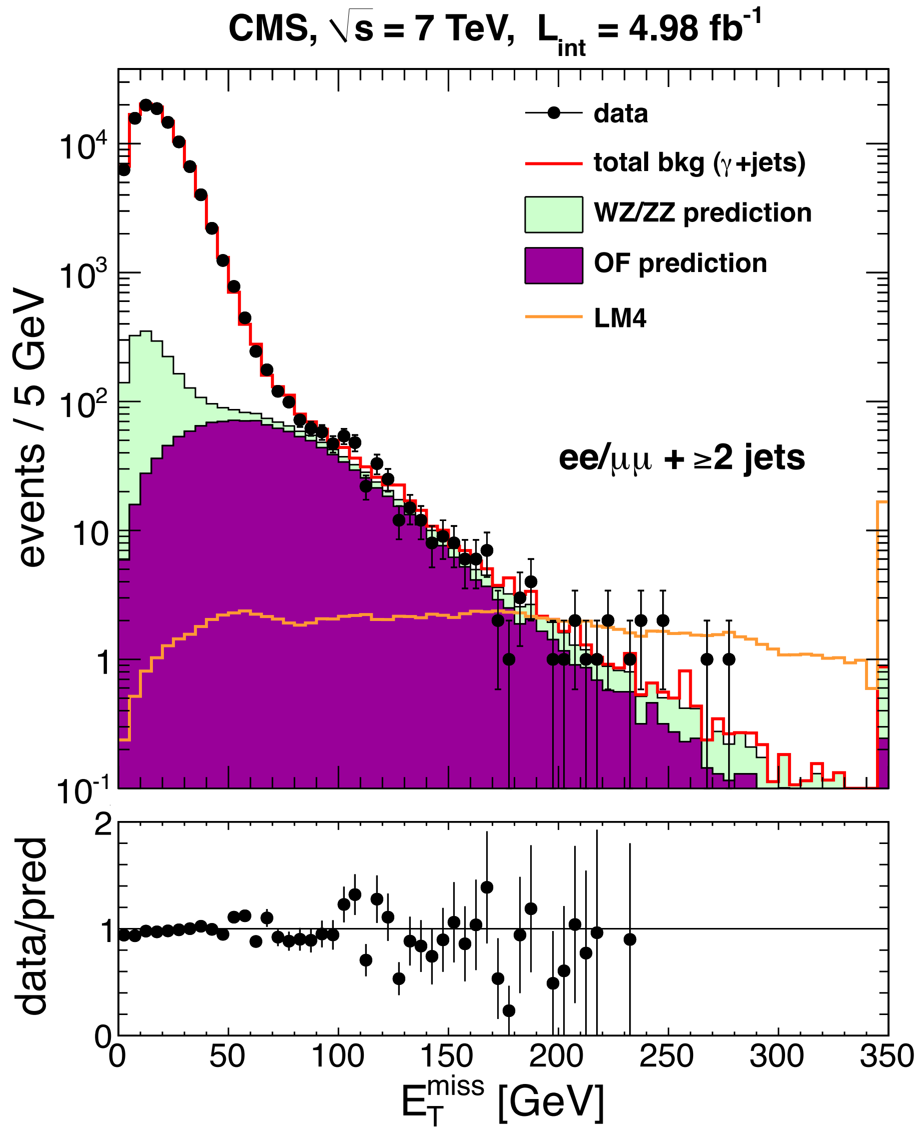
Exclusive Analysis

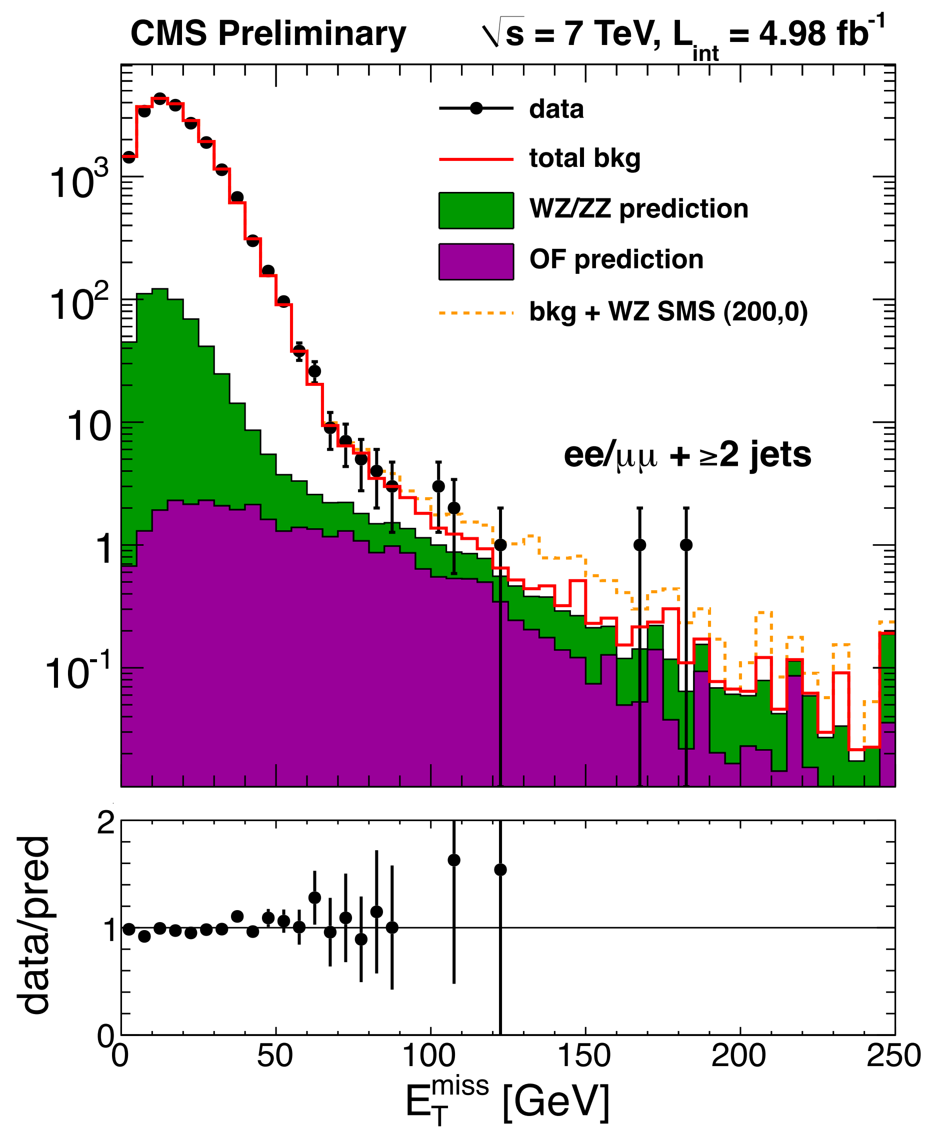




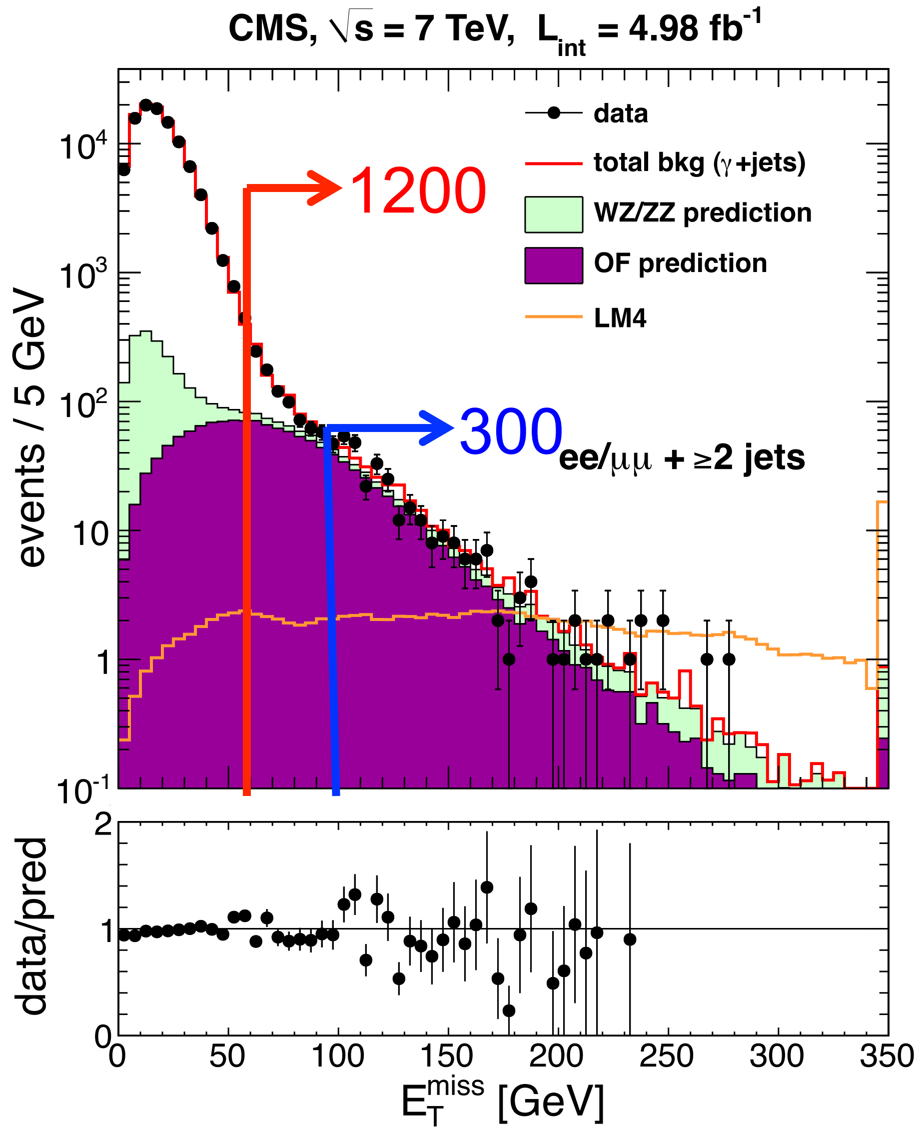
- Search for EWK SUSY particles justifies additional cuts:
  - B-veto to suppress top bkg
  - Dijet invariant mass cut (70-110GeV) to suppress both Z+jets and top bkg
  - Third lepton veto to suppress WZ/ZZ

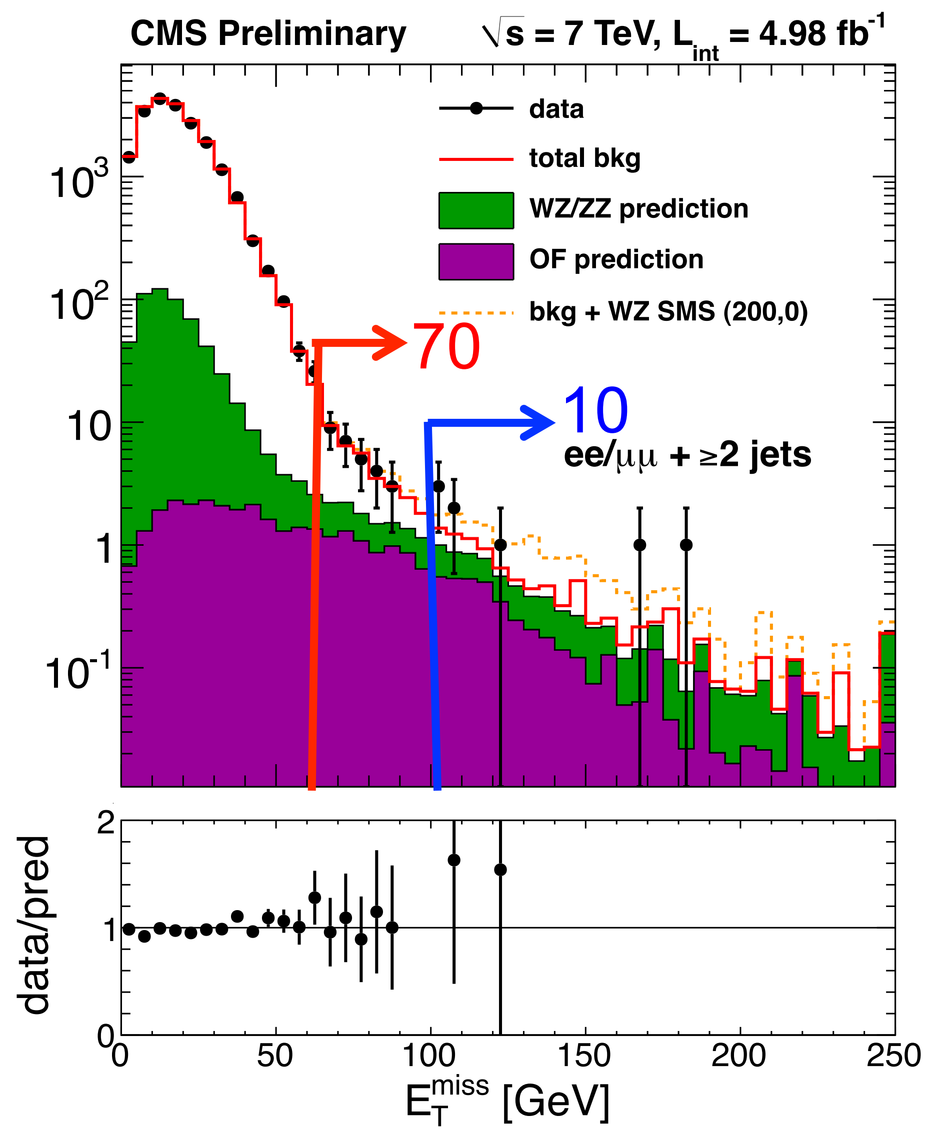
Inclusive vs Exclusive





Inclusive vs Exclusive





Exclusive Yields

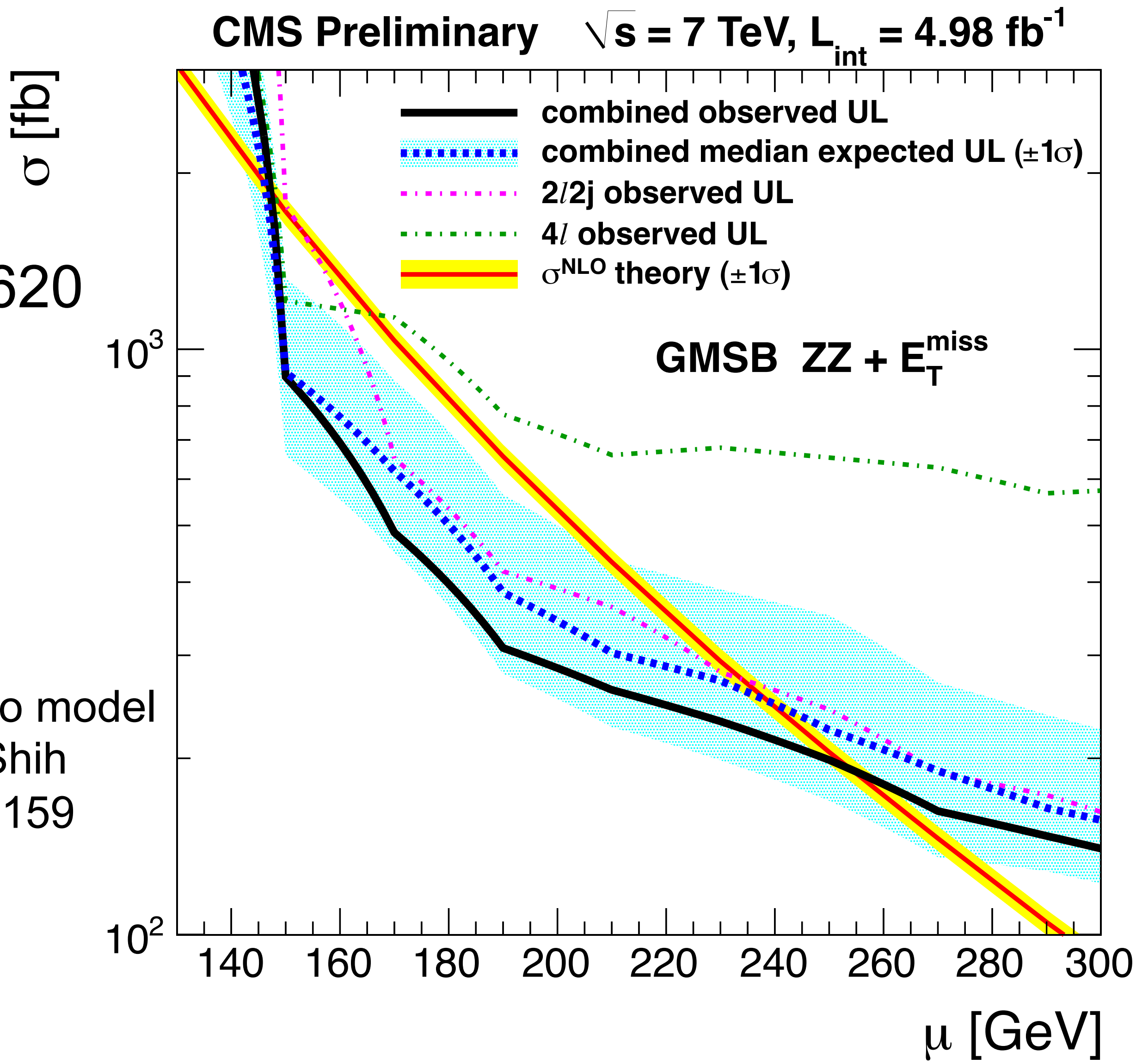
Source	$30 < E_T^{miss} < 60$ GeV	$60 < E_T^{miss} < 80$ GeV	$80 < E_T^{miss} < 100$ GeV
Z + jets background	2298 ± 737	32.9 ± 11.1	5.2 ± 1.8
OF background	11 ± 2	6.6 ± 1.6	4.6 ± 1.2
WZ/ZZ background	50 ± 25	3.9 ± 2.0	2.2 ± 1.1
Total background	2359 ± 737	43.4 ± 11.4	12.0 ± 2.4
Data	2416	47	7

Source	$100 < E_T^{miss} < 150$ GeV	$150 < E_T^{miss} < 200$ GeV	$E_T^{miss} > 200$ GeV
Z + jets background	1.7 ± 0.6	0.4 ± 0.2	0.2 ± 0.09
OF background	4.6 ± 1.2	0.8 ± 0.3	0.06 ± 0.07
WZ/ZZ background	2.5 ± 1.3	0.7 ± 0.4	0.4 ± 0.2
Total background	8.8 ± 1.8	1.9 ± 0.5	0.7 ± 0.3
Data	6	2	0

Once again, no sign of new physics!

Exclusive Interpretation

arXiv:1209.6620



Z-enriched Higgsino model
Ruderman & Shih
JHEP08(2012)159

Opposite sign Outside Z peak

arXiv:1206.3949

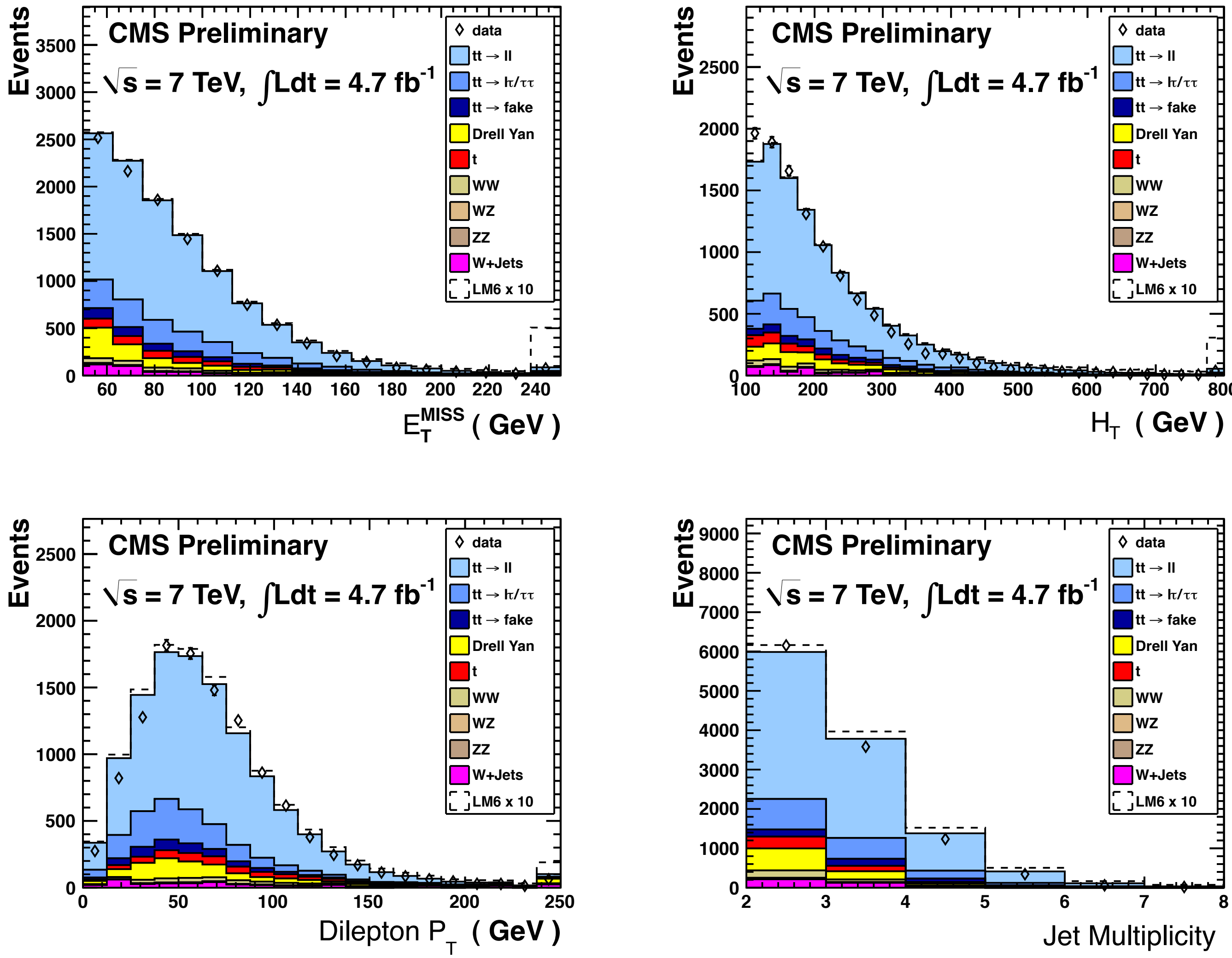
Baseline Selection

- ee, eμ, μμ with pT > 20GeV/10GeV
- ≥ 2 jets of pT > 30GeV and HT > 100GeV
- MET > 50GeV
- Z veto for ee, μμ, dilepton mass > 12GeV

Sample	σ [pb]	ee	$\mu\mu$	$e\mu$	total
$t\bar{t} \to \ell^+\ell^-$	7	1465.8 ± 66.1	1872.4 ± 84.4	4262.2 ± 192.0	7600.4 ± 342.2
$t\bar{t} \to \ell^\pm\tau^\mp/\tau^+\tau^-$	9	302.8 ± 13.8	397.5 ± 18.0	888.6 ± 40.1	1588.9 ± 71.7
$t\bar{t} \to$ fake	141	50.2 ± 2.4	15.0 ± 0.8	90.0 ± 4.2	155.2 ± 7.1
DY$\to \ell\ell$	16677	192.6 ± 13.6	236.6 ± 15.6	311.8 ± 19.1	740.9 ± 39.0
W^+W^-	43	55.0 ± 2.7	66.2 ± 3.2	150.7 ± 7.0	272.0 ± 12.5
$W^\pm Z^0$	18	13.4 ± 0.7	15.0 ± 0.7	24.6 ± 1.2	53.0 ± 2.4
Z^0Z^0	5.9	2.6 ± 0.1	3.3 ± 0.2	3.3 ± 0.2	9.1 ± 0.5
single top	102	94.6 ± 4.9	119.6 ± 6.0	278.1 ± 13.1	492.3 ± 22.8
$W+$jets	96648	47.3 ± 10.7	9.8 ± 4.7	59.4 ± 11.7	116.6 ± 17.0
MC		**2224.3 ± 101.4**	**2735.4 ± 123.9**	**6068.8 ± 273.8**	**11028.5 ± 497.1**
data		**2333**	**2873**	**6184**	**11390**

Excellent Agreement between Data and MC

Baseline Selection

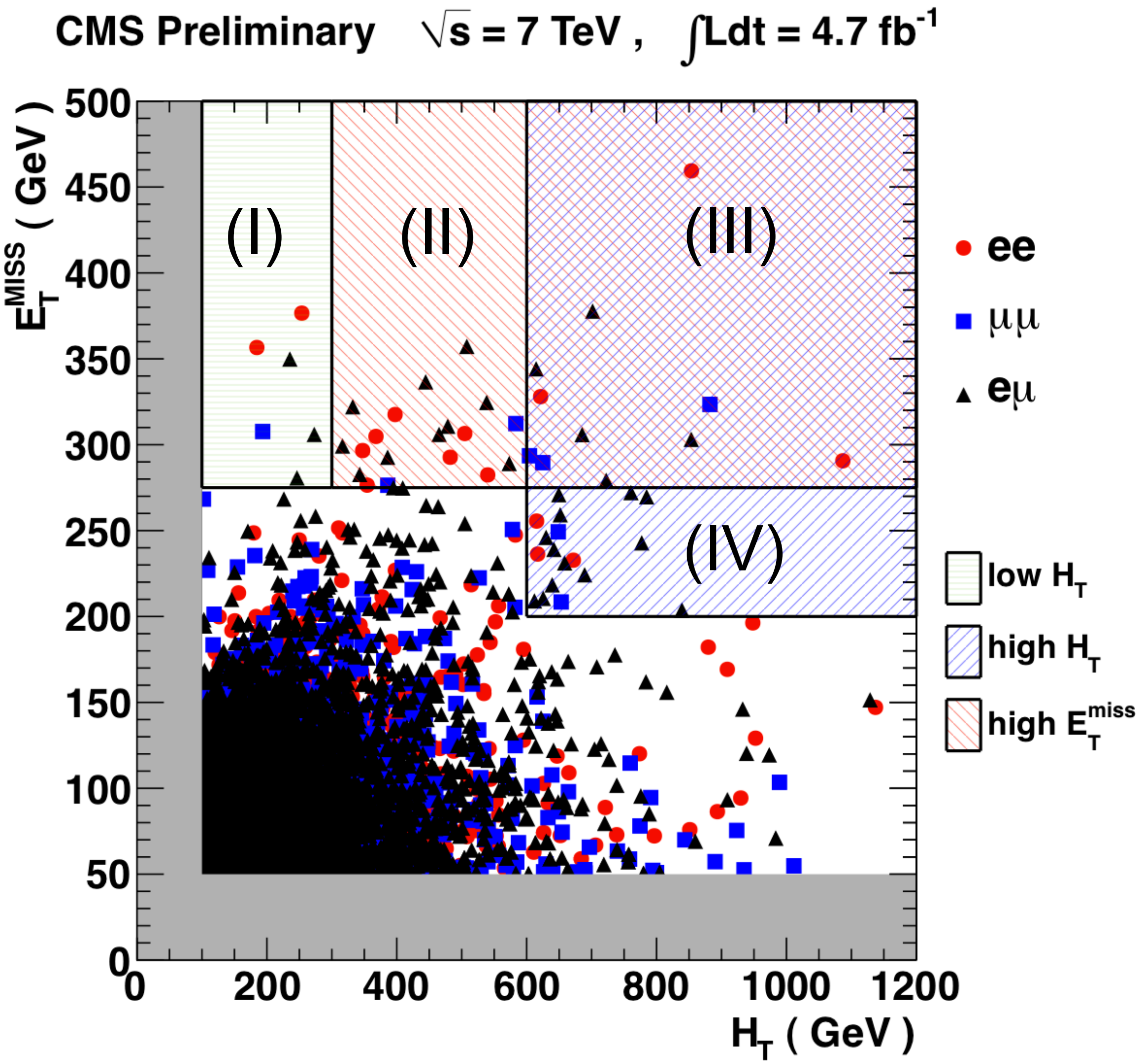


Excellent Agreement between Data and MC

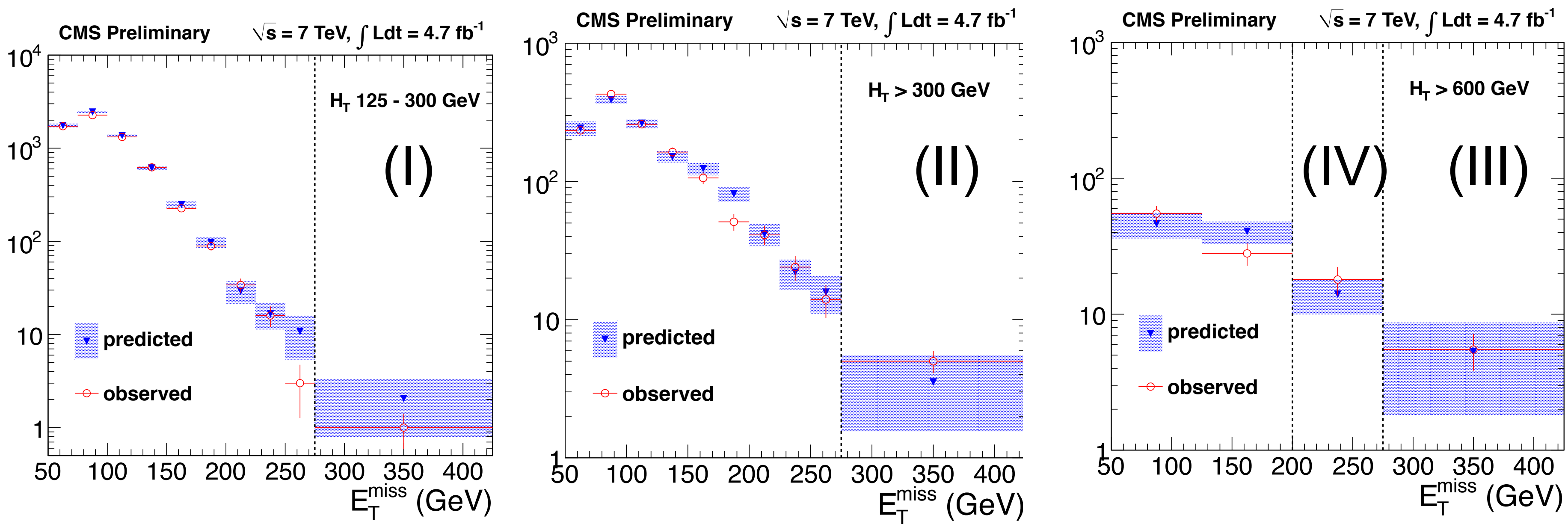
Predict MET tails using dilepton pT

- Predominant bkg due to top.
  - MET is real, i.e. the sum pT of the two neutrinos.
  - On average, dilepton pT is a good estimate of di-neutrino pT

Four Signal Regions



MET tails from dilepton pT



Agreement between observed and predicted for all HT regions.

No sign of new physics.

Results

	high E_T^{miss}	high H_T	tight	low H_T
SF yield	15	11	6	3
OF yield	15	18	5	3
total yield	**30**	**29**	**11**	**6**
$\mathbf{p_T(\ell\ell)}$ **prediction**	$\mathbf{21 \pm 8.9 \pm 8.0}$	$\mathbf{22 \pm 7.5 \pm 6.9}$	$\mathbf{11 \pm 5.8 \pm 3.8}$	$\mathbf{12 \pm 4.9 \pm 5.7}$
MC prediction	30 ± 1.2	31 ± 0.9	12 ± 0.6	4.2 ± 0.3
non-SM yield UL	26	23	11	6.5
LM1	221 ± 5.1	170 ± 4.5	106 ± 3.5	6.2 ± 0.9
LM3	79 ± 2.4	83 ± 2.5	44 ± 1.8	2.3 ± 0.4
LM6	35 ± 0.6	33 ± 0.5	26 ± 0.5	0.6 ± 0.1
	(II)+(III)	(III)+(IV)	(III)	(I)

Observed agrees well with both MC and data driven predictions.
No sign of new physics.

To reach few evts bkg requires HT > 600GeV & MET > 275GeV

Conclusions for Opposite sign dilepton production

- At high MET and/or high HT top production dominates.
- MC predicts the overall kinematic properties of top quite well, both in the bulk and in the tails.
- At low MET Z production dominates
- The MET distribution in events with a Z is predicted quite well from events with a photon.
- No new physics anywhere.

Same-sign Dileptons
Two Analyses

Generic Same-sign:

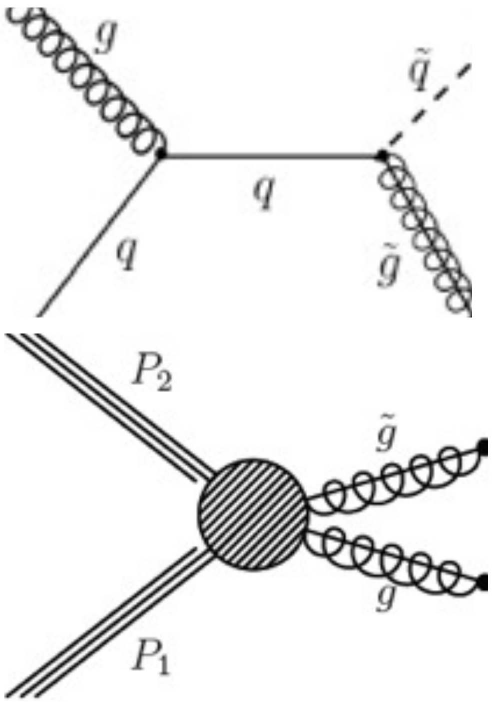
Phys. Rev. Lett. 109, 071803 (2012)

Same-sign w. >= 2 b-tags:

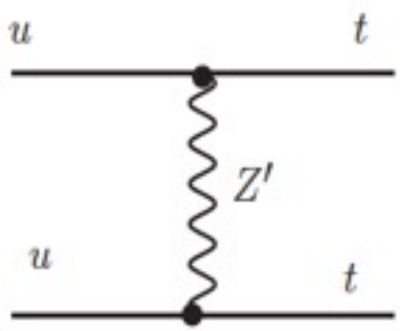
JHEP08 (2012) 110

Motivation

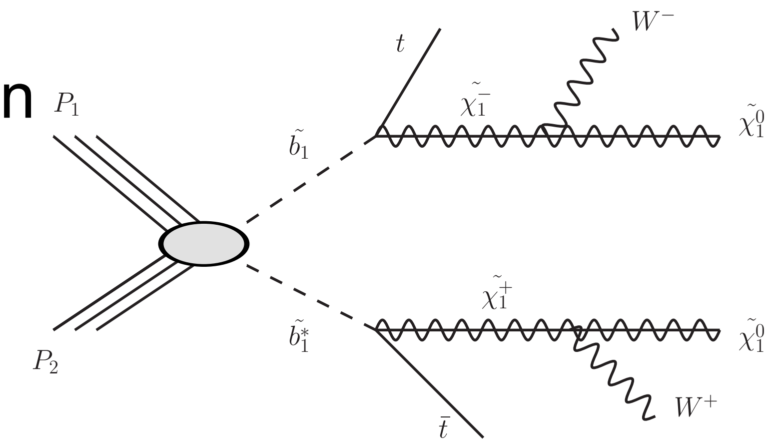
Production of
Majorana Particles



T-channel same-sign
top production



Any final state with 3 or more W's.
E.g. sbottom pair production.



Sbottom -> top W LSP

Same-sign dileptons are rare in SM,
but quite common beyond the SM.

Same-sign Dileptons Common bkg characteristics

Three types of bkg:

"fake leptons"

Electron charge mismeasurement

Irreducible bkg from genuine same-sign

Two Types of Triggers

- Dilepton trigger 20/10 GeV
- Dilepton & HT trigger
  - Muons at 5GeV
  - Electrons at 10GeV
  - HT > 200GeV

Pursuing both strategies to cover maximal phase space in searches.

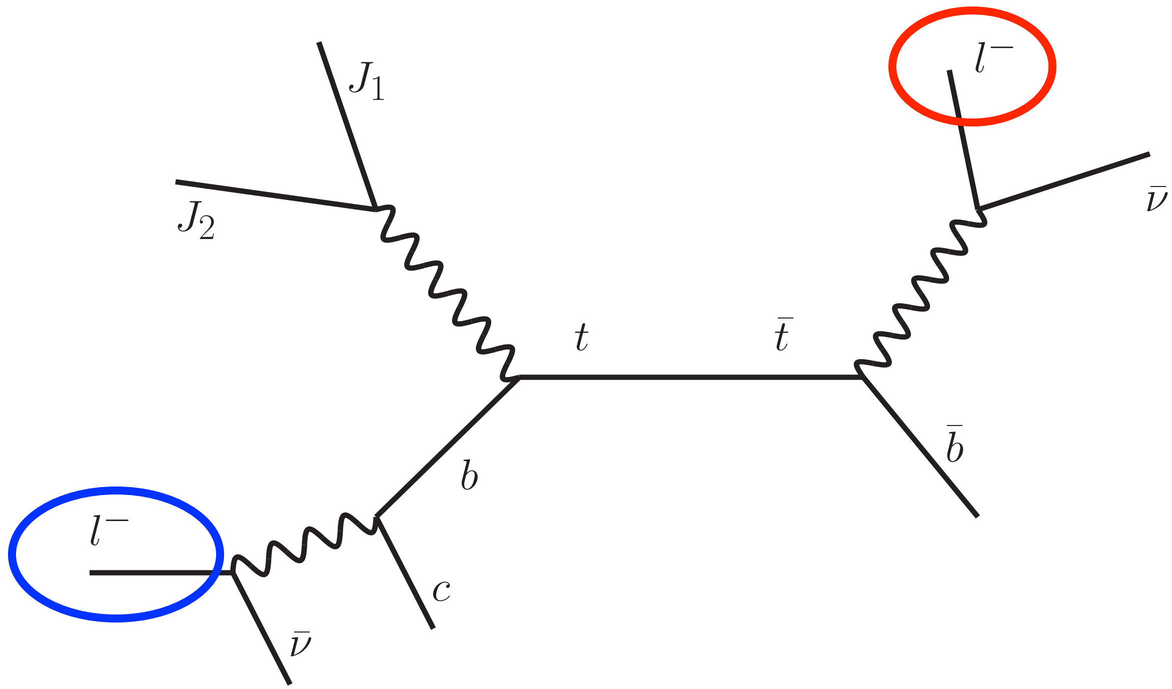
Two Search Strategies

- As inclusive as possible
  - Low pT leptons & high HT & MET
  - 20/10 pT leptons & moderate HT & MET
- As clean as possible
  - Focus on leptons from W only => 20/20 pT
  - Tighter isolation requirement
  - At least two btags

Inclusive same sign dileptons

5/fb at 7TeV
Phys. Rev. Lett. 109, 071803 (2012)

Dominant bkg



Estimate this bkg from data with “fake rate method”

Fake Rate Method

- Same technique as used at CDF for the last ~ 20 years.
  - lepton fake estimates in all our CDF and CMS analyses are done this way
- Define a "Loose" and a "Tight" lepton selection
- Define a "Fake Rate":

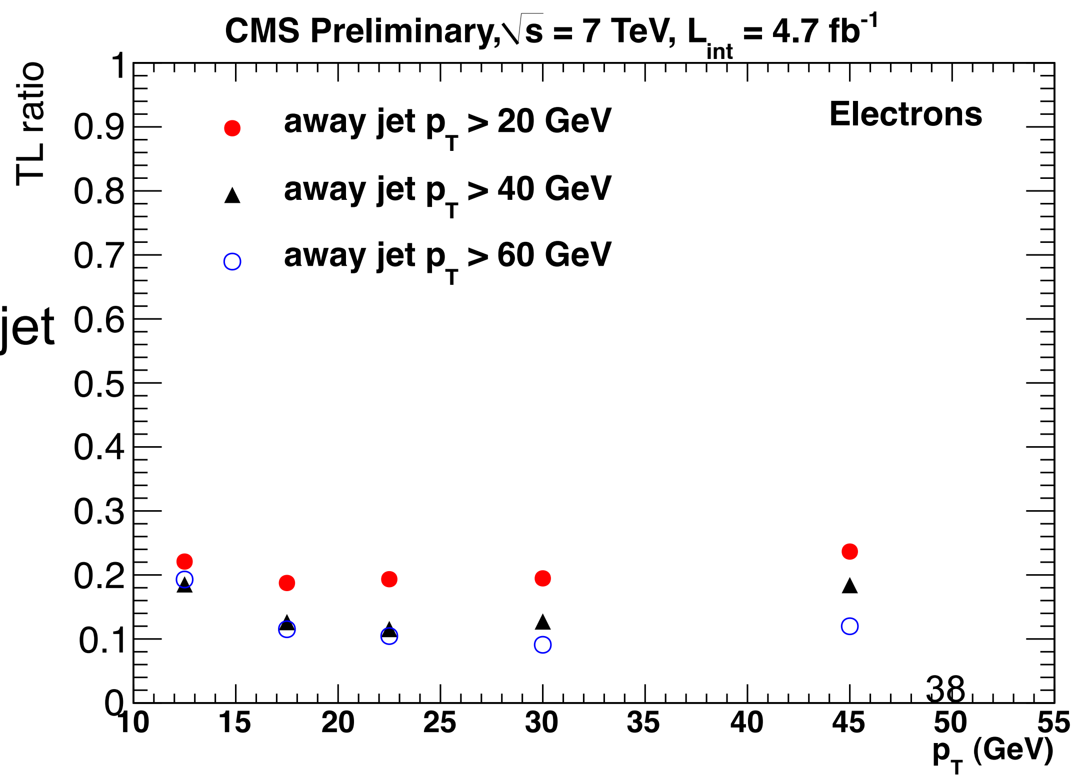
  FR = (# of evts passing tight) / (# of evts passing loose) = f(pT,η)
- Measure f(pT,η) in unbiased single lepton trigger sample.
  - Use a pre-scaled trigger for that is ~100% efficient for "Loose" in order to guarantee that f(pT,η) is not biased by trigger.
- Apply f(pT,η) to sample with:
  - Two-loose to estimate "double fakes"
  - one-tight-one-loose leptons to estimate "single-fakes + 2x double-fakes"
  - Total fake estimate = "one-tight-one-loose" - "two-loose" estimates
- Statistical error = sample stats in appropriate signal region for:
  - one-tight-one-loose
  - Two-loose
- Systematic error = 50% due to systematics in determining f(pT,η).

Dominant Systematics

- Assumption: $f(pT,\eta)$ is independent of the parton pT that created the loose lepton.

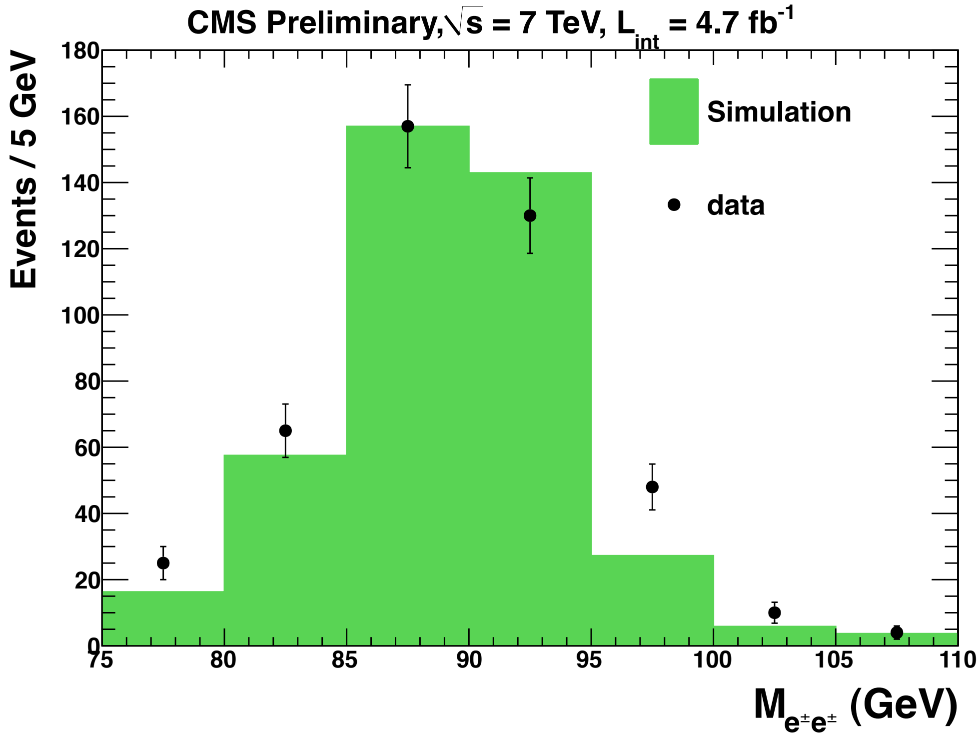
Test the assumption by varying pT of away-jet in "loose" lepton sample.

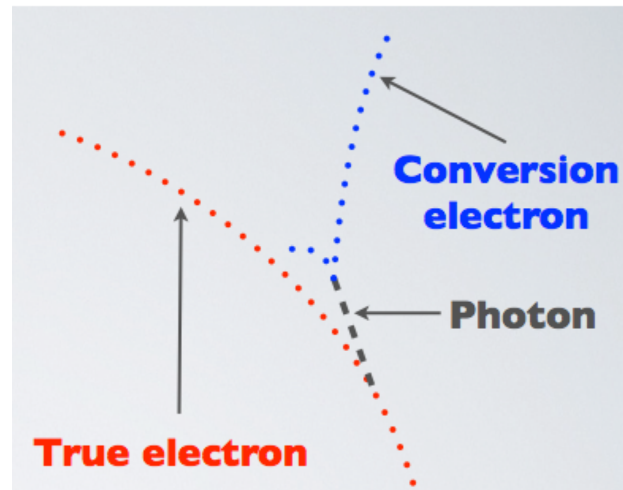
"Dijet" characteristics produces correlation in pT between away-jet and parton that produces "loose" lepton.



Electron Charge mismeasurement

Electron momentum is measured (mostly) by ECAL.
Electron charge is measured (mostly) by tracker.
=> Charge mismeasurement leaves p unchanged.





Hard brems followed by conversion can lead to Charge mismeasurement

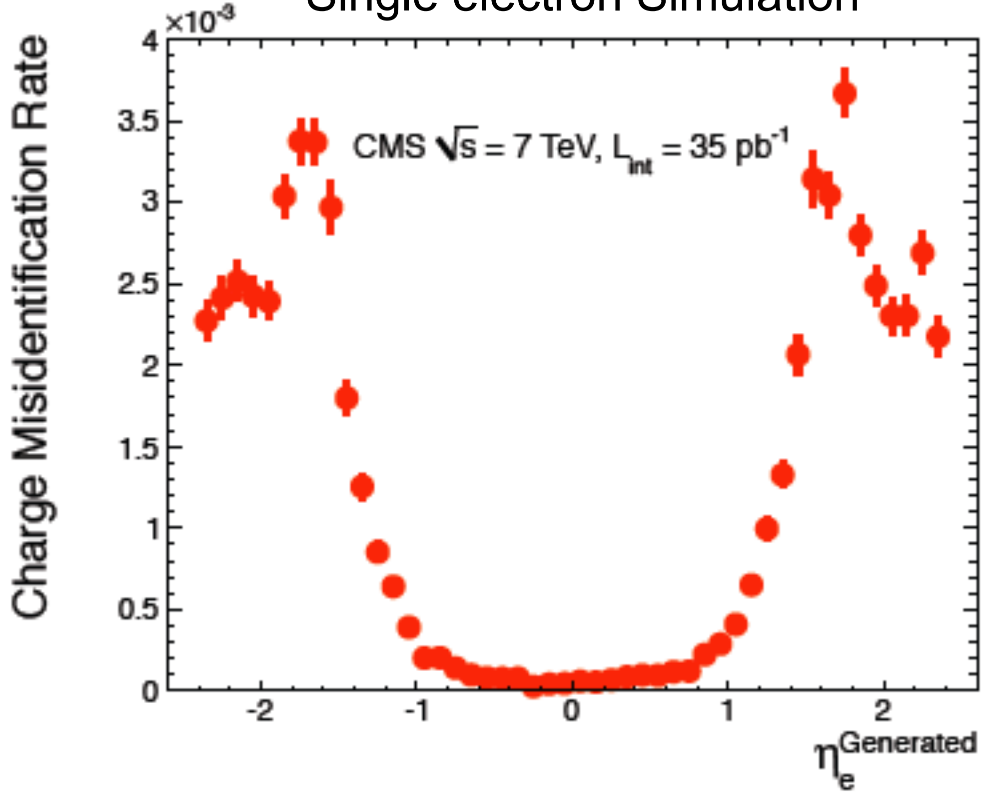
Same sign Z to ee in data and MC.

(selected after vetoing Ws using MET and M_T)

Electron Charge mismeasurement

Rate of charge misId ranges from ~ 10^{-4} in central detector, to few 10^{-3} at $|\eta|$ ~ 1.5

Single electron Simulation



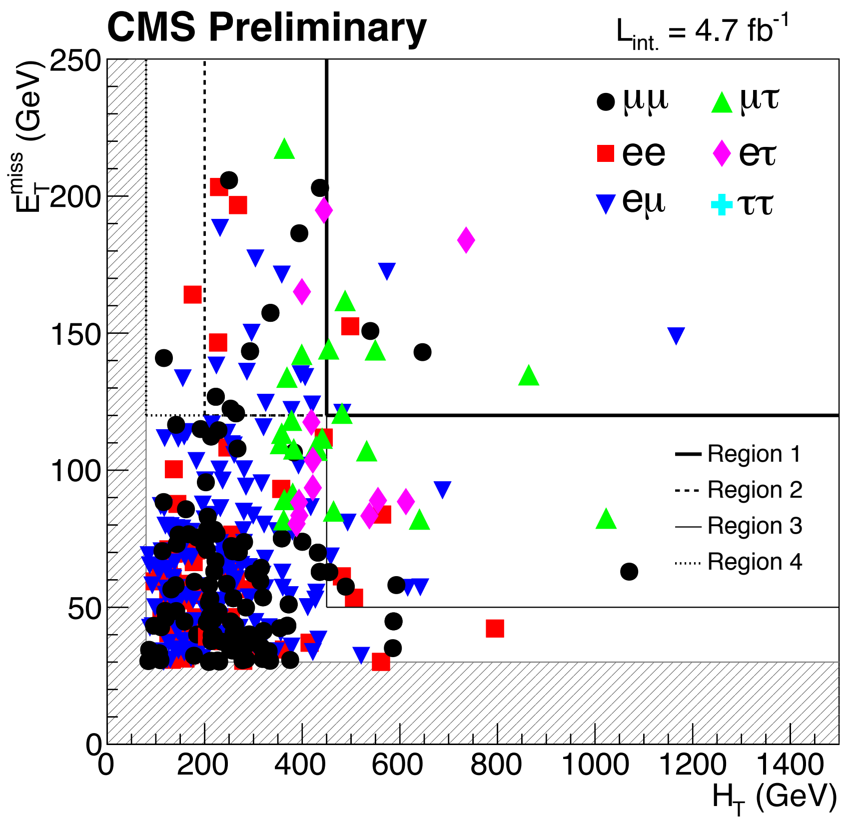
Estimate bkg using OS in signal region in data times charge misId rate as a function of pT and η from MC

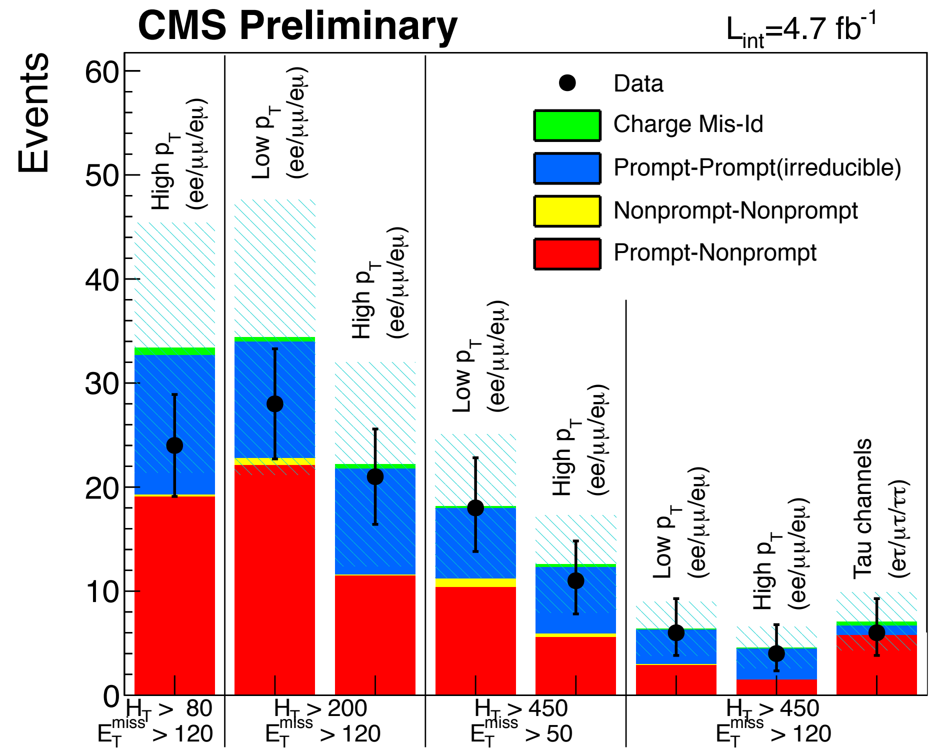
Irreducible bkg

- Top pairs with additional W or Z
- Single parton same sign WW production
- WZ/ZZ production
- And to a lesser extend:
  - Double parton WW
  - Tri-boson production

These bkg are estimated from MC with 50% systematic error.

Results for Inclusive Search





In most signal regions bkg from fakes dominate.

Yield Table

Region	Mode or p_T threshold			Total	UL 95% CL
	$p_{\mathrm{T}}^{\ell 1,\ell 2} > 20, 10$ GeV				
	ee	$\mu\mu$	$e\mu$		
1	6.7 ± 2.7	8.3 ± 3.1	18.3 ± 6.9	33.2 ± 12.0	
	5	7	12	24	14.0
2	4.2 ± 1.7	5.9 ± 2.3	11.9 ± 4.5	22.1 ± 9.8	
	4	6	11	21	16.3
3	3.7 ± 1.5	3.0 ± 1.2	5.8 ± 2.3	12.5 ± 4.7	
	4	2	5	11	9.9
4	1.1 ± 0.8	1.1 ± 0.6	2.5 ± 1.1	4.6 ± 2.0	
	1	0	3	4	6.1
	$p_{\mathrm{T}}^{e,\mu} > 10, 5$ GeV				
	ee	$\mu\mu$	$e\mu$		
2	4.3 ± 1.7	13.9 ± 6.0	16.1 ± 6.2	34.3 ± 13.2	
	4	10	14	28	17.4
3	3.3 ± 1.5	6.3 ± 2.8	8.6 ± 3.5	18.2 ± 6.9	
	4	6	8	18	14.3
4	1.0 ± 0.8	2.3 ± 1.2	3.1 ± 1.4	6.4 ± 2.6	
	1	2	3	6	7.4
	$p_{\mathrm{T}}^{\tau,e,\mu} > 15, 10, 5$ GeV				
	$e\tau$	$\mu\tau$	$\tau\tau$		
4	2.6 ± 1.0	4.4 ± 2.2	0.0 ± 0.1	7.1 ± 2.8	
	1	5	0	6	7.1

HT>80GeV, MET>120GeV

HT>200GeV, MET>120GeV

HT>450GeV, MET>50GeV

HT>450GeV, MET>120GeV

Same-sign with ≥ 2 btags

Motivated by signals with multiple top's and W's

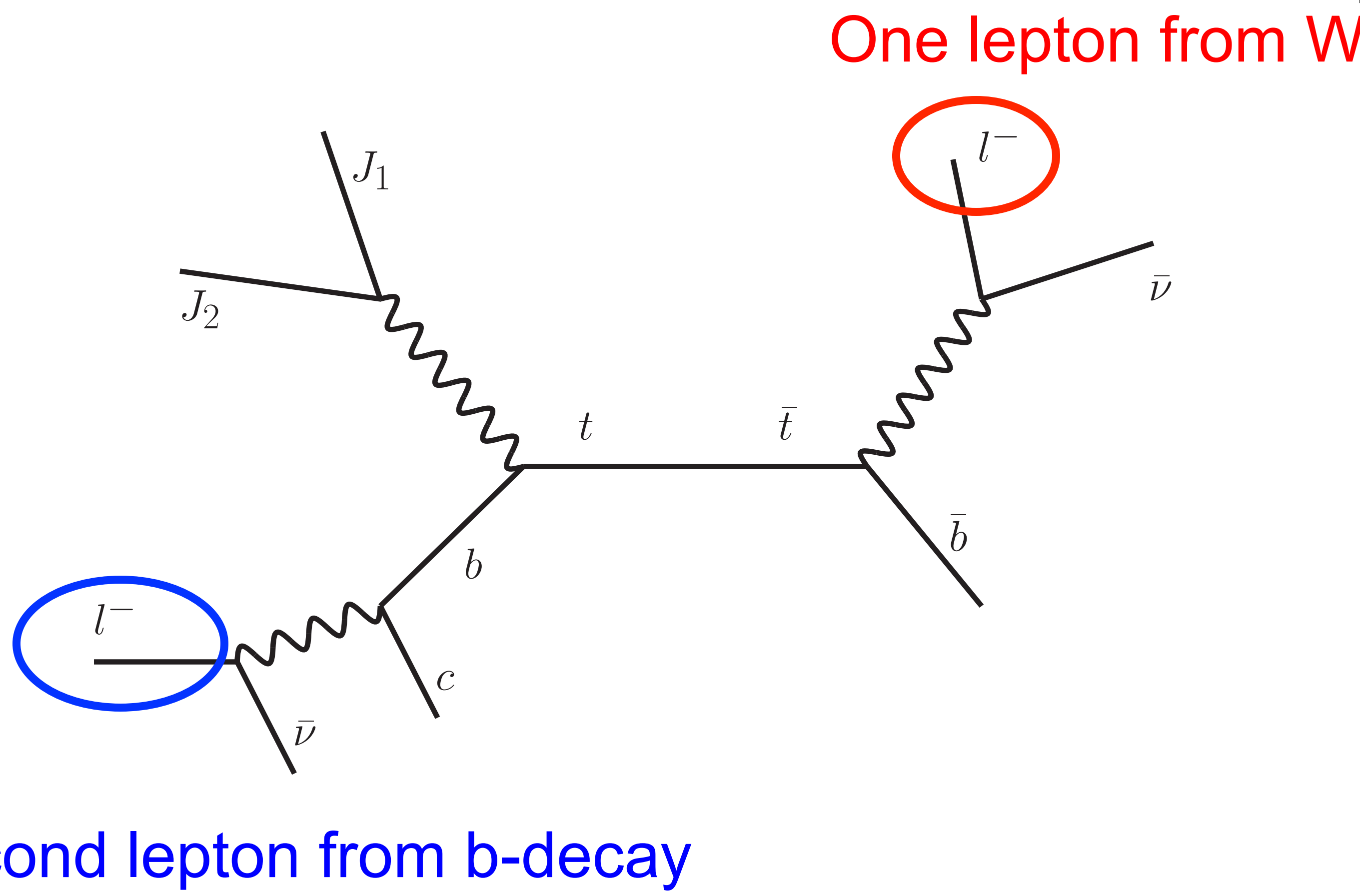
Focus on leptons from W only => 20/20 pT

Tighter isolation requirement

At least two btags

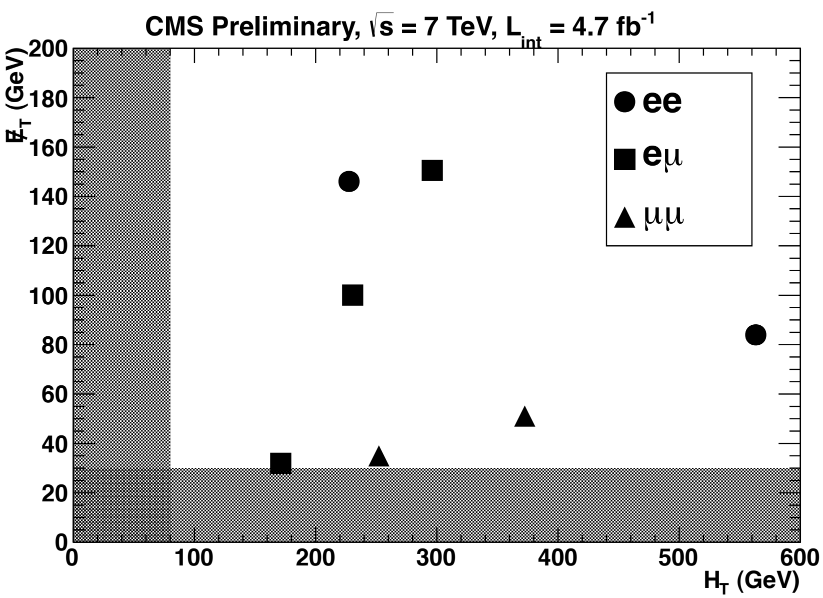
5/fb at 7TeV: JHEP08 (2012) 110
4/fb at 8TeV: CMS-PAS-SUS-12-017 (ICHEP 2012)

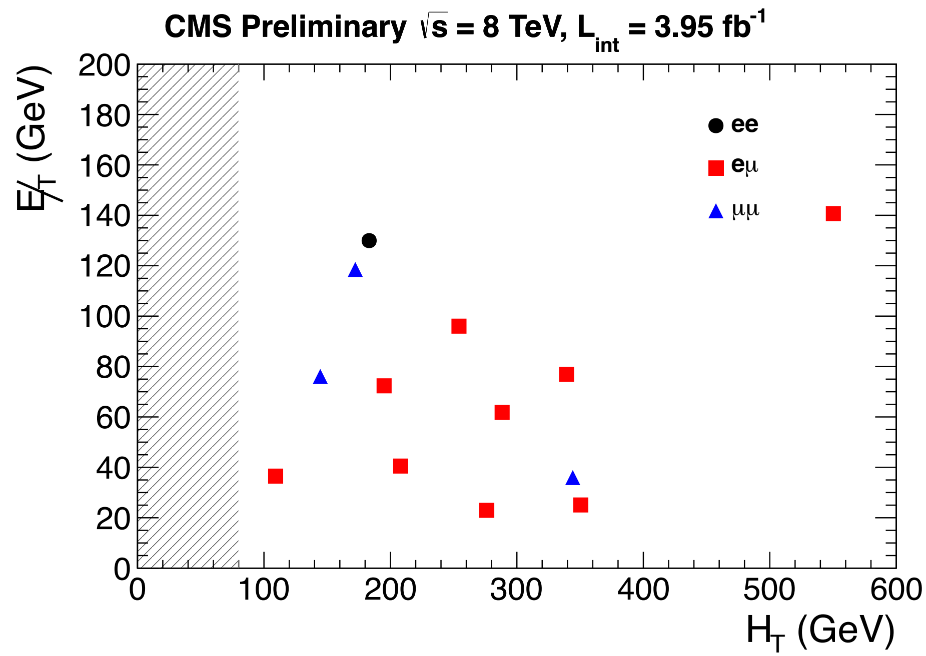
Reminder



This bkg is reduced by x150 because a b-quark can not simultaneously provide a btag and an isolated lepton!

Yield





7 events for HT > 80GeV & MET > 30GeV
a x35 (x2) decrease in bkg (signal)
compared to inclusive pT> 20/10GeV

Repeated same analysis with first 4/fb of 8TeV data

Comparison with/without b-tags

pT > 20/20GeV & MET > 30GeV & HT > 80GeV

Origin of bkg	Without b-tags	≥ 2 b-tags
Fakes from b	31%	5%
Other fakes	20%	25%
Charge misId	10%	26%
irreducible	39%	44%

- Composition changes, also within categories
  - Other fakes: W+jets bkg eliminated
  - Charge misId: only top pairs survive
  - Irreducible: only ttW and ttZ survive

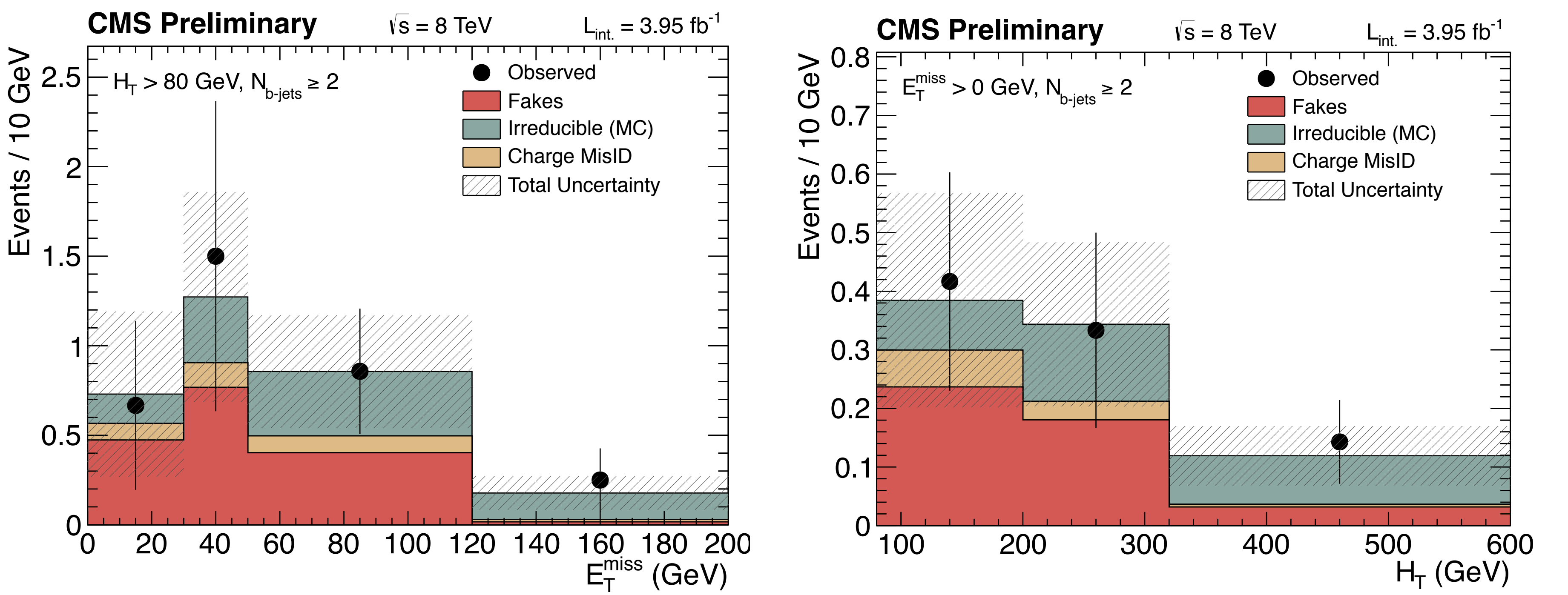
Signal regions ICHEP 2012 Result

	SR0	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8
No. of jets	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 3	≥ 2
No. of btags	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 3	≥ 2
Lepton charges	$++/--$	$++/--$	$++$	$++/--$	$++/--$	$++/--$	$++/--$	$++/--$	$++/--$
E_T^{miss}	> 0 GeV	> 30 GeV	> 30 GeV	> 120 GeV	> 50 GeV	> 50 GeV	> 120 GeV	> 50 GeV	> 0 GeV
H_T	> 80 GeV	> 80 GeV	> 80 GeV	> 200 GeV	> 200 GeV	> 320 GeV	> 320 GeV	> 200 GeV	> 320 GeV
Charge-flip BG	1.32 ± 0.28	1.04 ± 0.22	0.52 ± 0.11	0.05 ± 0.01	0.35 ± 0.08	0.11 ± 0.03	0.02 ± 0.01	0.01 ± 0.01	0.18 ± 0.05
Fake BG	5.89 ± 3.78	4.46 ± 2.68	1.86 ± 1.12	0.33 ± 0.36	2.46 ± 2.16	0.77 ± 0.82	0.20 ± 0.33	0.08 ± 0.52	1.36 ± 1.12
Rare SM BG	4.92 ± 2.57	4.44 ± 2.32	2.95 ± 1.59	1.01 ± 0.62	2.95 ± 1.56	1.77 ± 1.03	0.71 ± 0.51	0.24 ± 0.40	2.24 ± 1.27
Total BG	12.13 ± 4.58	9.94 ± 3.55	5.33 ± 1.95	1.39 ± 0.72	5.76 ± 2.67	2.64 ± 1.32	0.93 ± 0.61	0.33 ± 0.66	3.78 ± 1.69
Event yield	13	11	0	1	4	2	1	1	4
N_{UL} (13% unc.)	11.6	10.6	2.7	3.7	5.5	4.5	3.8	4.2	6.4
N_{UL} (20% unc.)	12.0	11.0	2.8	3.8	5.6	4.7	3.9	4.3	6.6
N_{UL} (30% unc.)	12.9	11.9	2.8	4.0	6.0	4.9	4.2	4.6	6.9

Excellent agreement between observed and predicted.
No sign of new physics.

("Amusing fluctuation" in - - vs ++)

MET & HT Projections



Using the "fake rate method" we can predict the kinematic distributions of the bkg.

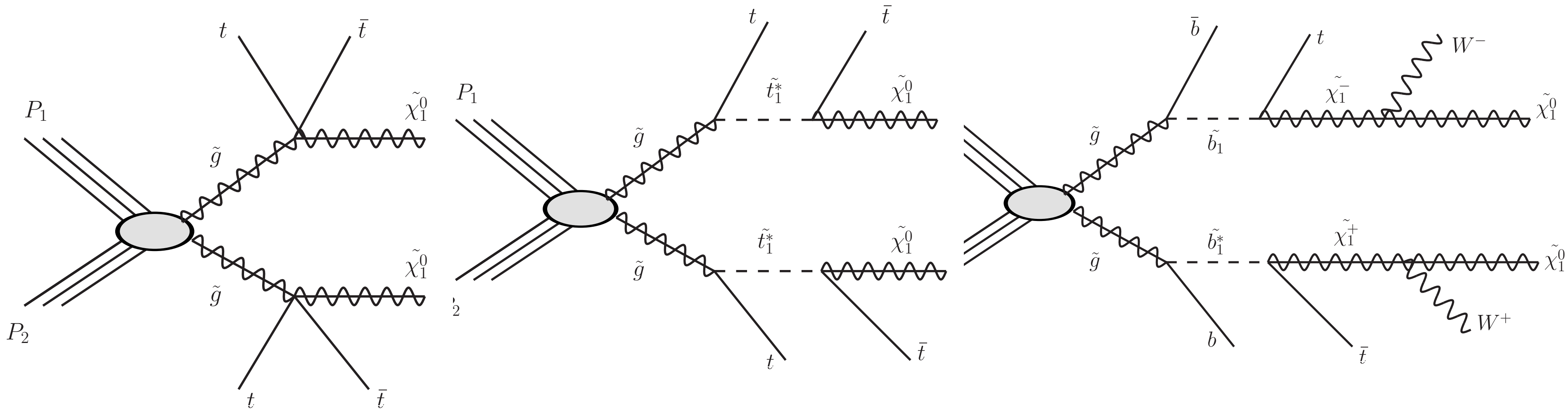
Totals as well as distributions are as expected from bkg.

Interpretations for same-sign w. b-tags

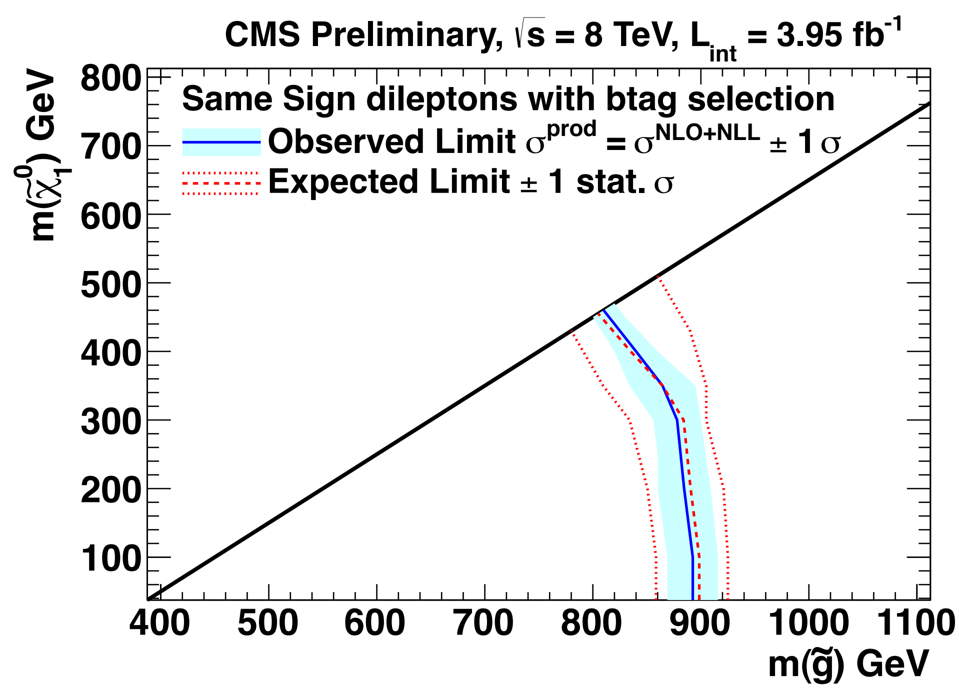
Gluino production

Sbottom production

Gluino Pair production

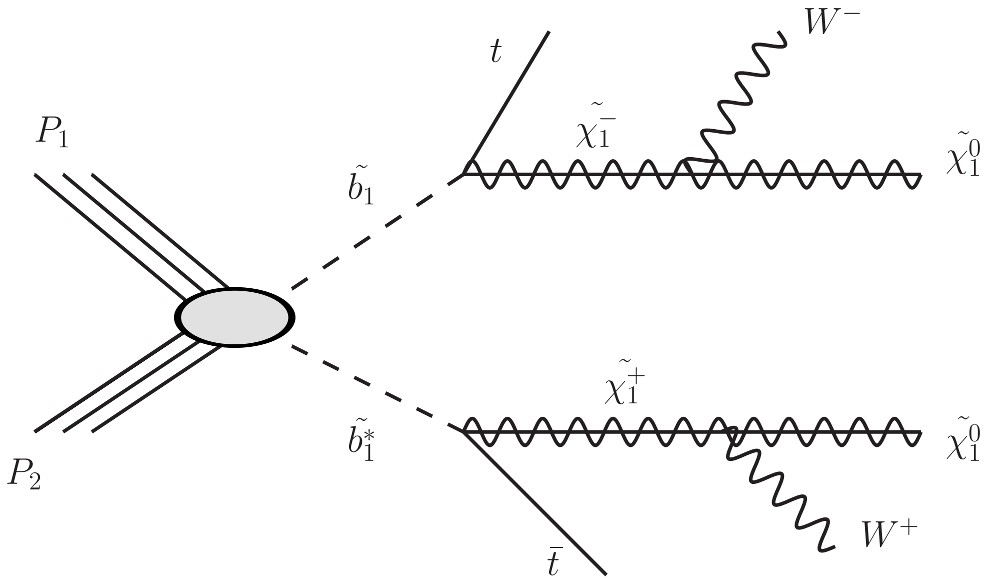


Final states with 4W, and 2-4 b-quarks from gluino pair production, are rulled out up to ~900 GeV gluino mass, irrespective of decay chain details.



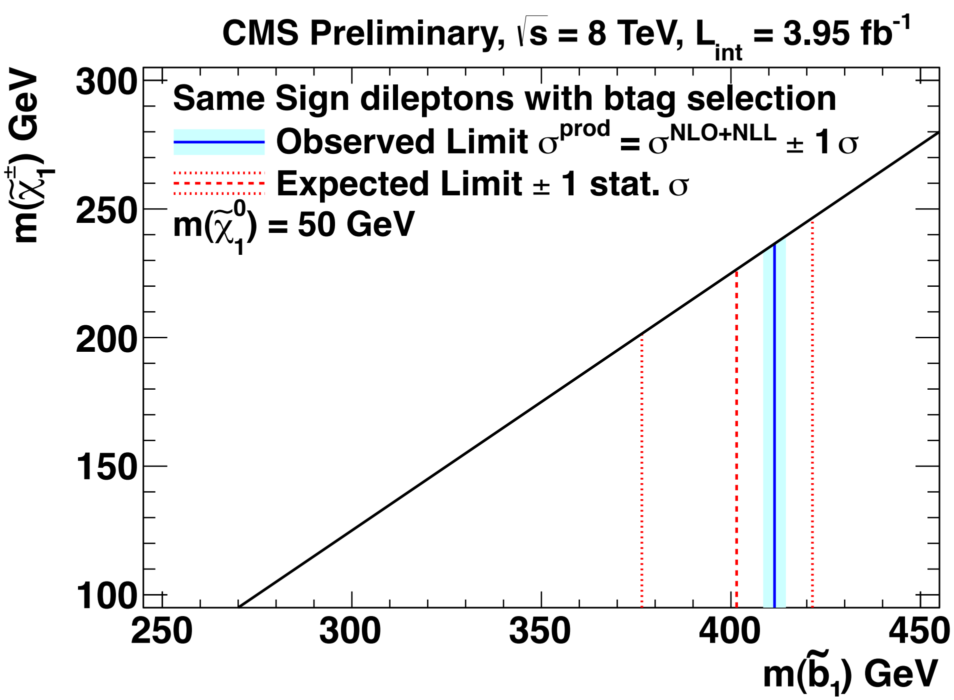
10/25/12

Sbottom pair production



Sbottom to top + W + LSP

Ruled out up to
sbottom masses ~ 410GeV



10/25/12

Conclusions on same-sign search

- No new physics found anywhere.
- Less bkg than in hadronic and single lepton searches when probing the same mass scale.
  – Thus more promising as luminosity increases.
- Significant constraints on physics with >= 4W's and >=2 b-quarks
  – I showed only a small subset of the things that have been proposed that lead to final states with same-sign dileptons and >= 2 b-quarks.

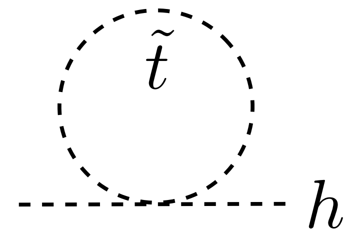
Where do we go from here?

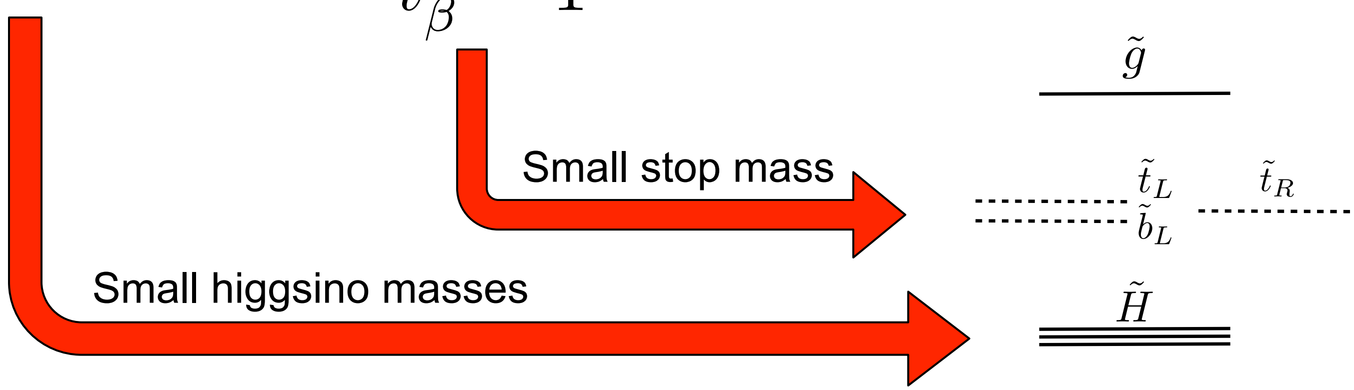
- SUSY was not just “around the corner”.
  - In fact, the energy increase from 2 -> 8TeV got us no new physics of any kind.
- **We are still in the dark about dark matter**
- We found something that looks like the Higgs
  - Can this be used to guide us?

Naturalness for Experimentalists

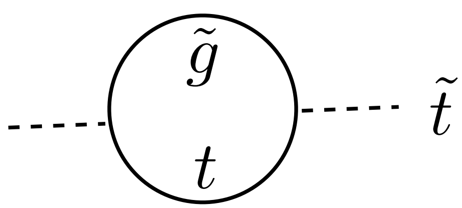
"Large" cancellations are "unnatural"

$$M_Z^2 = -2\mu^2 + 2\,\frac{m_{H_d}^2 - t_\beta^2\, m_{H_u}^2}{t_\beta^2 - 1}\,,$$





natural SUSY



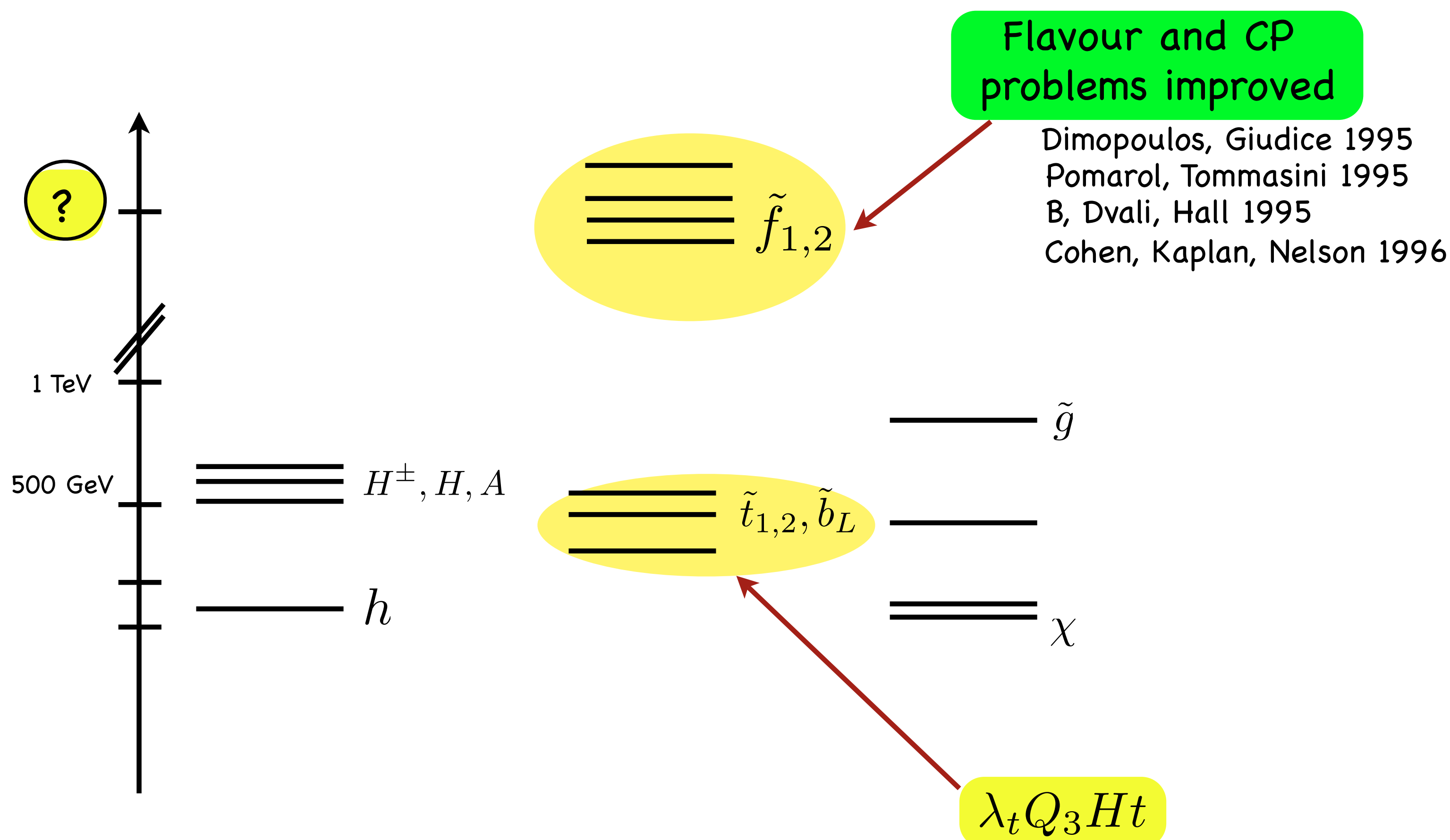
Loop effects then require the gluino also to not be too large in mass.

"Natural" Mass Spectra

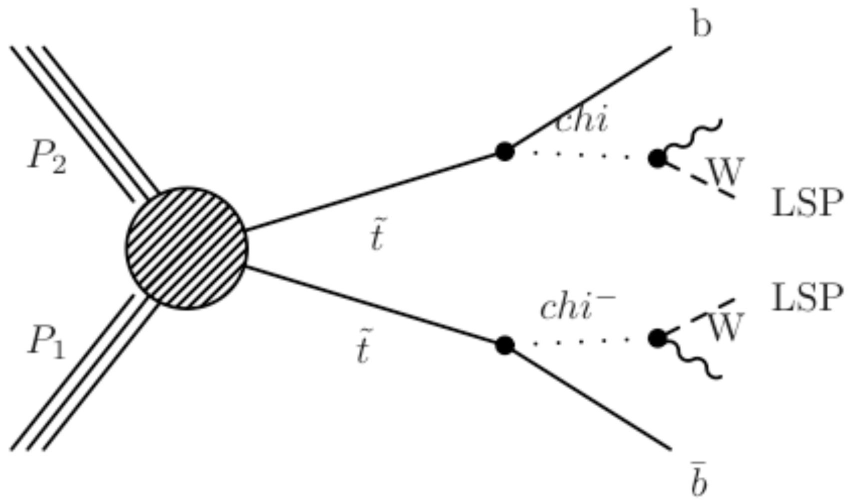
"Beyond mSUGRA"

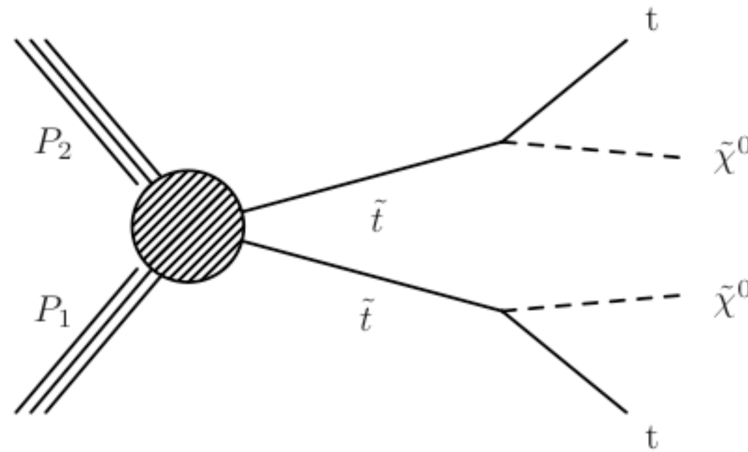
R. Barbieri
HCP2011
Slide 11

(minimal natural spectrum is 15 years old)



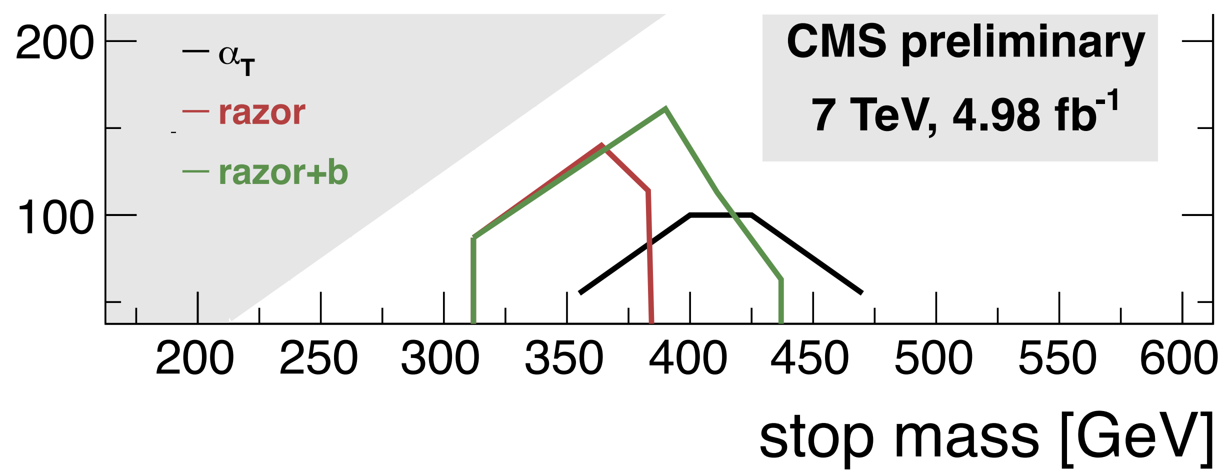
CMS Stop Strategy thus far





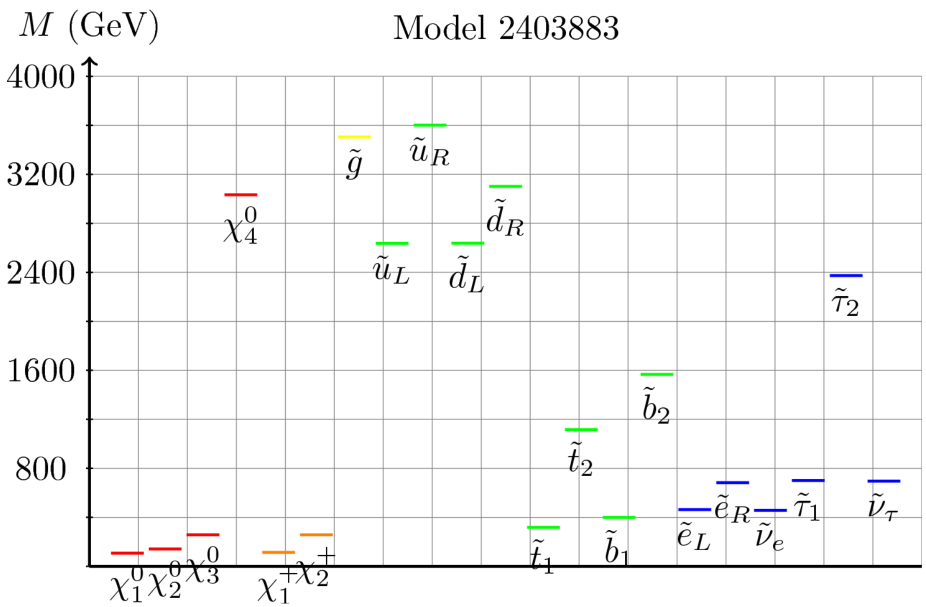
In both cases, we kept the W and top on shell.

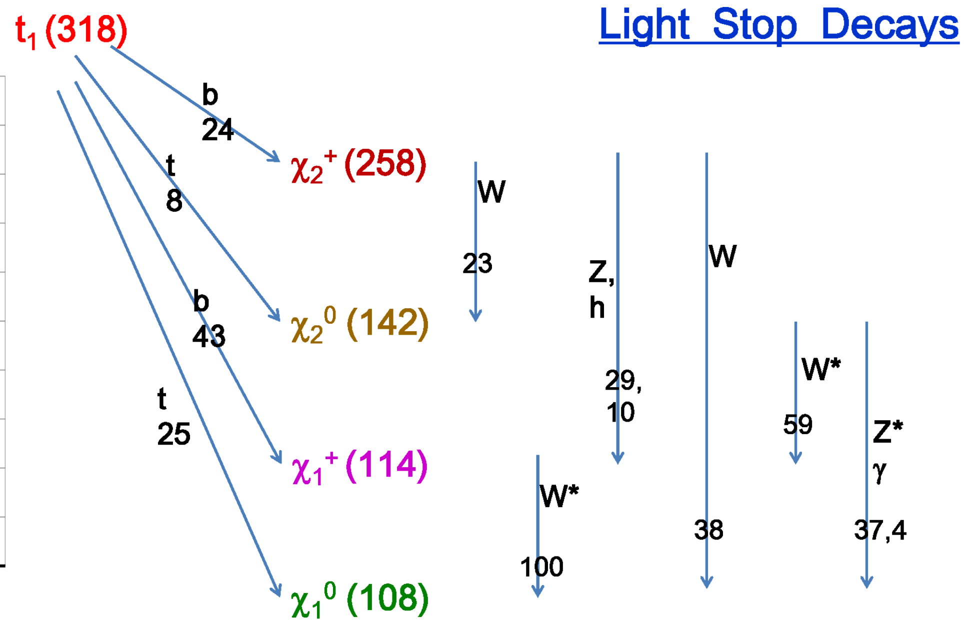
We have not studied compressed spectra.



What's a reasonable spectrum?

arXiv:1206.5800





Five weak and two colored sparticles within reach.
Complex decay chains with small Q-values in decays.
Nevertheless, this is not yet ruled out!

Summary & Conclusion

- So far no new physics was found.
- Next steps:
  - Search for natural SUSY …
  - … especially in compressed spectra …
  - … for weakly interacting sparticles …
  - … as well as colored third generation.

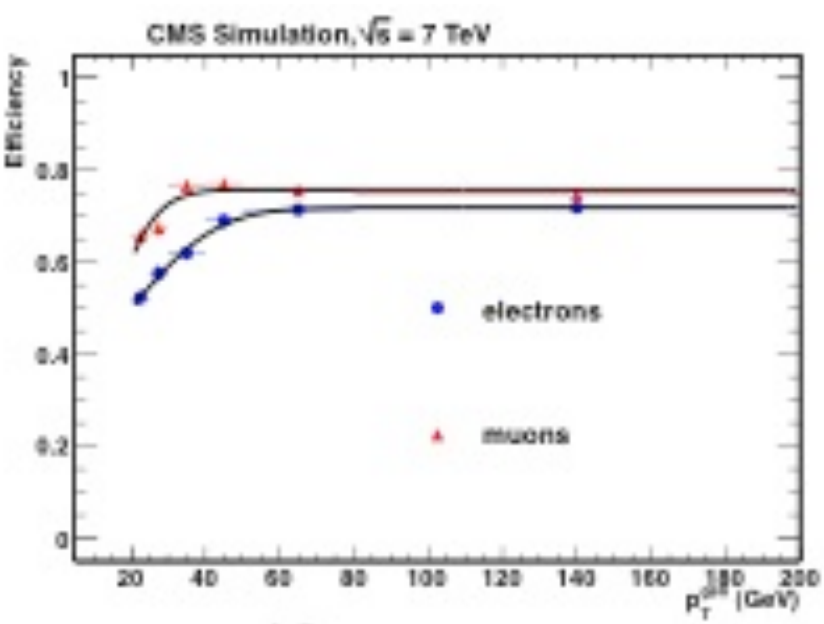
Backup

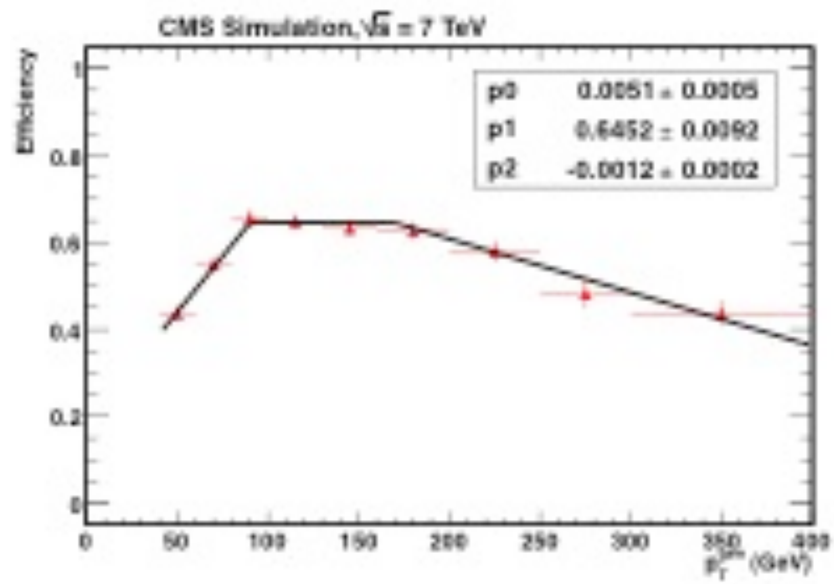
Outreach to theorists

Objective:

Describe our efficiencies and turn-on curves such that theorists can do parameter scans on their favorite theories to constrain new physics.

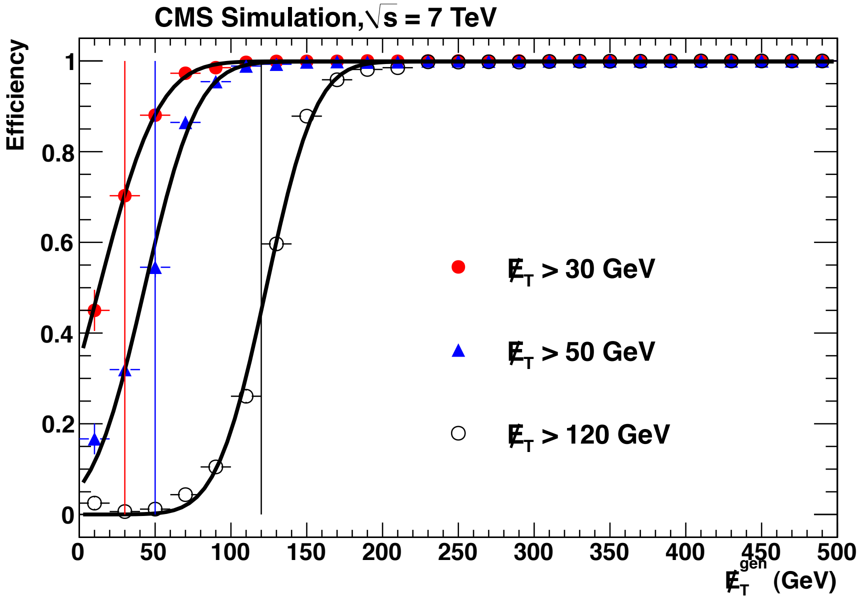
Lepton & b-tagging Efficiencies within acceptance

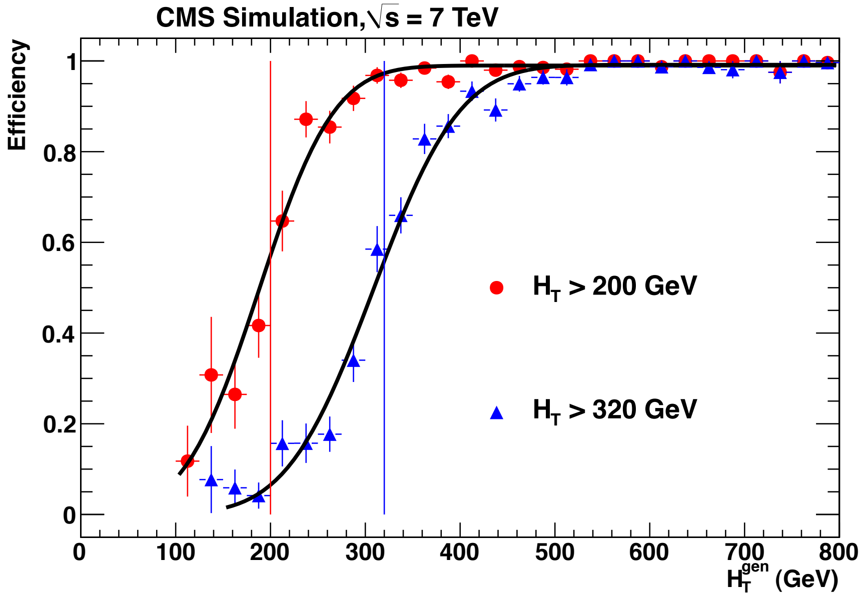




Require a b-quark (lepton) to be within acceptance at gen-level, then apply these efficiencies, to estimate the efficiency for our analysis.

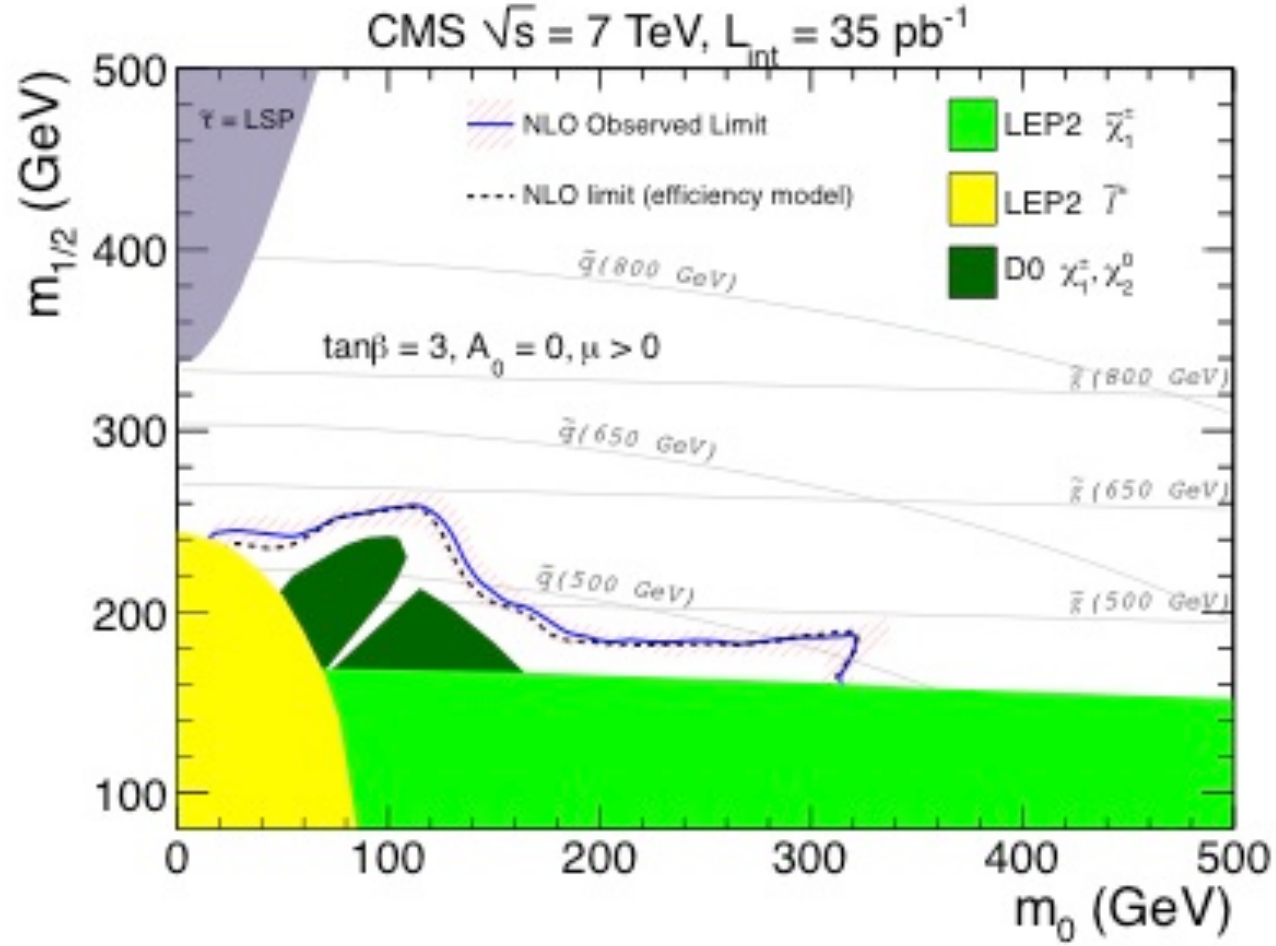
Turn-on curves for HT,MET





Add colored partons (non-interacting particles) within acceptance to construct "HT" ("MET"), and apply turn-on curves to estimate efficiency for our selection.

How well does this work?



We showed in 2010 same-sign paper that this works better, than the theoretical error due to pdf and higher order corrections.

(10-30% or so)

When does it fail ?

- Lepton isolation efficiency depends on the event environment.
- The more hadronic energy in the event, the lower the efficiency.
- However, if the new physics provides leptons only from heavily boosted objects that decay “semi-leptonically” then all bets are off, and a full simulation is needed to estimate the efficiency.

Dijet Invariant mass in EWKino Search