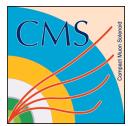




HEP 2015 - Conference on Recent  
Developments in High Energy Physics and  
Cosmology 15-18 April 2015, Athens, Greece

# Search for SUSY in pp collisions at 8 TeV in events with soft opposite-sign leptons and high missing transverse energy



Antonis Agapitos [Univ. of Athens]

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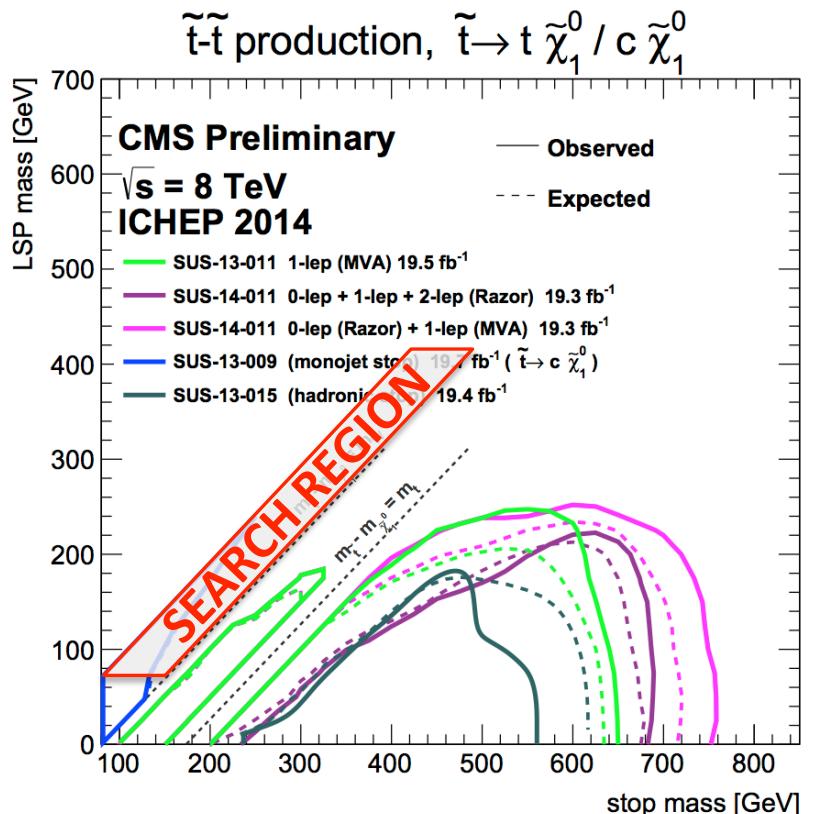
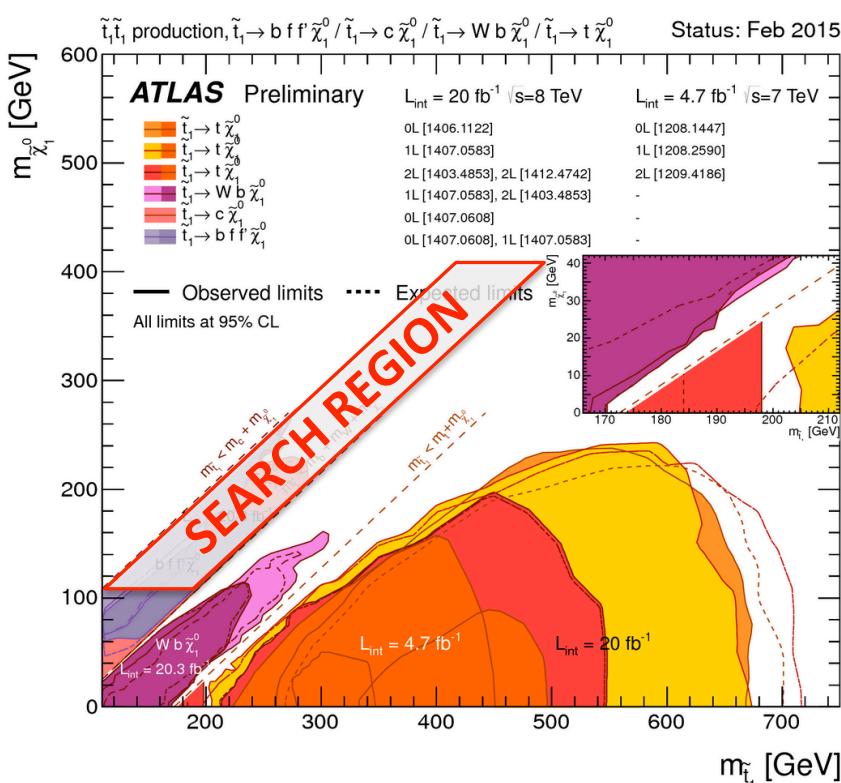
Paris Sphicas [CERN & Univ. of Athens]

Markus Stoye [CERN]

- ① Search Motivation.
- ② Event Selection.
- ③ Data-driven Prediction Methods.
- ④ Validation test of the Prediction Methods.
- ⑤ Systematic Uncertainties.
- ⑥ Results and Interpretation.
- ⑦ Conclusions.

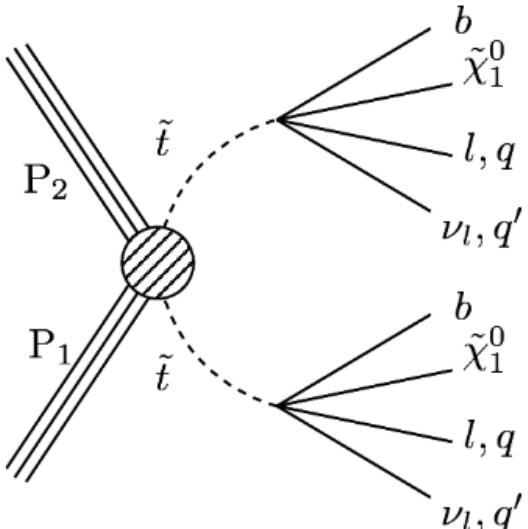
# ① Search Motivation.

- Most of the “stop-LSP” phase space has been explored with no evidence of SUSY.
  - Natural SUSY is still “alive” in compressed spectra.  
(Naturalness preserved by low mass of the lightest 3<sup>rd</sup> generation squark.)



- Focus on “stop-pair” production:  $\tilde{t} \rightarrow t \tilde{\chi}_1^0$
  - In compressed scenario:  $\Delta M(\tilde{t}, \tilde{\chi}_1^0) < 80 \text{ GeV} = M_W$

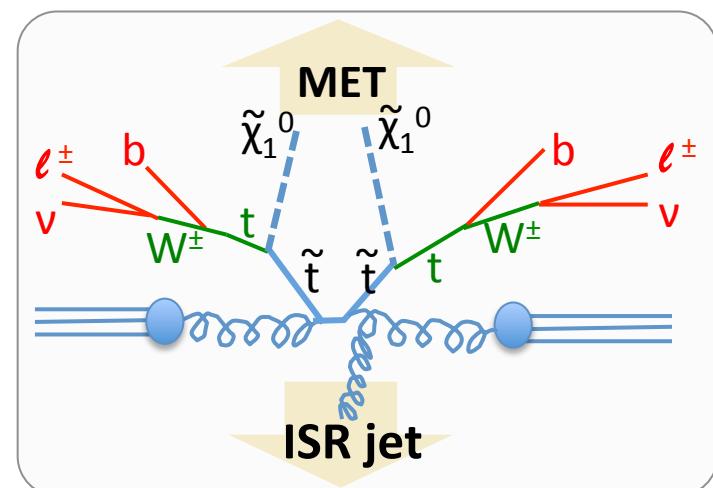
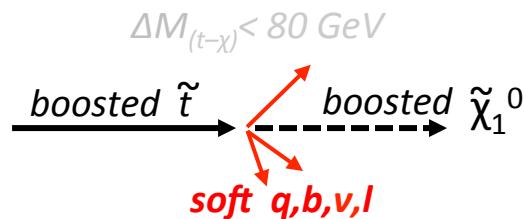
- ◆ Compressed scenario:  $\Delta M(\tilde{t}, \tilde{\chi}_1^0) < 80 \text{ GeV}$  leads to a 4-body decay (off-shell W,t):



$$2\tilde{t} \rightarrow 2t\tilde{\chi}_1^0 \rightarrow 2bW\tilde{\chi}_1^0$$

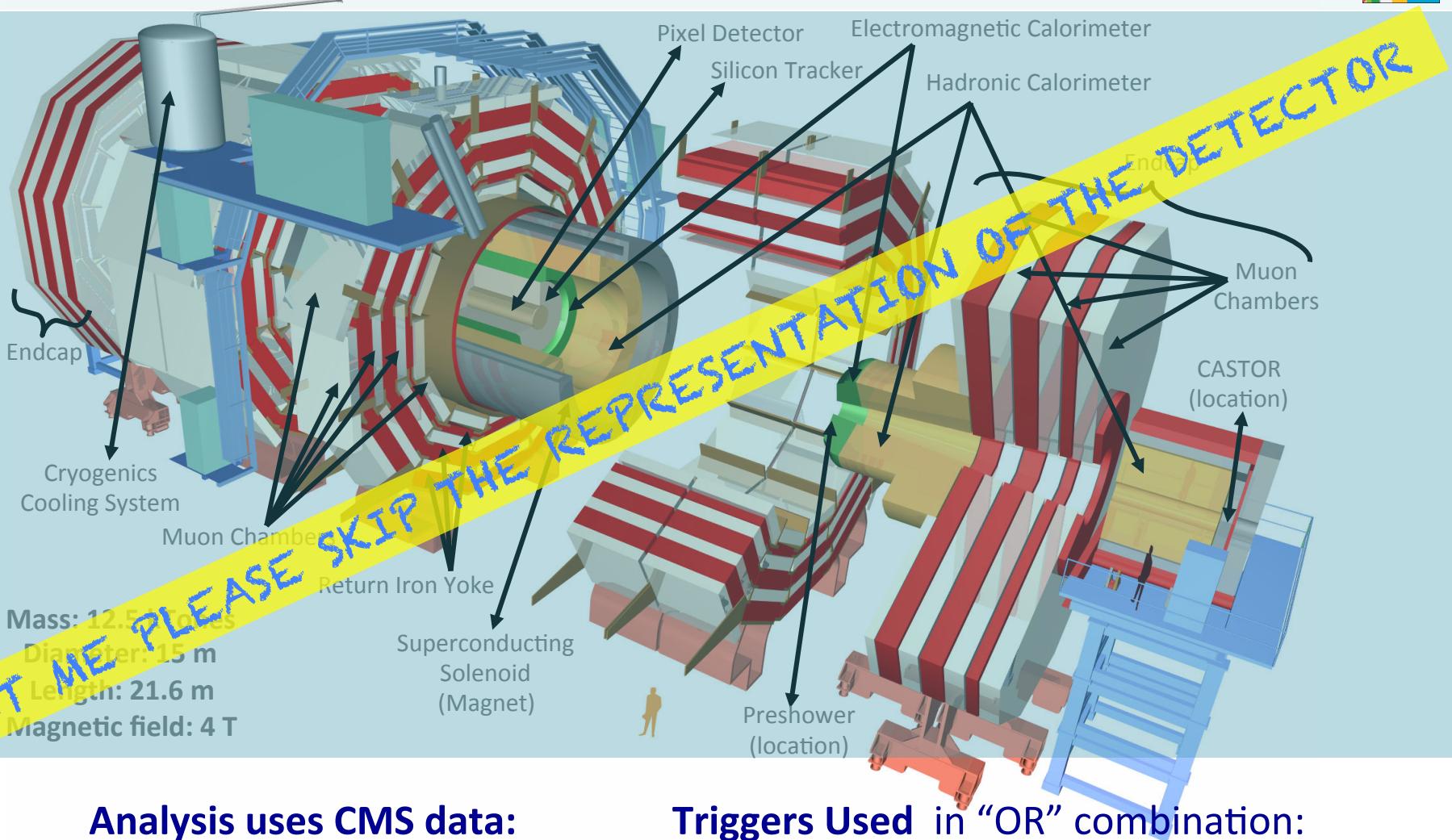
- ◆ 3 decay channels for the 2W:
- [0-Lep.] BR  $\sim 55\%$  full-hadronic:  
Huge irreducible bkd:  $Z \rightarrow vv$ ,  $W \rightarrow v\ell_{\text{miss}}$
- [1-Lep.] BR  $\sim 38\%$  semi-leptonic:  
Bypasses  $Z \rightarrow vv$ , but then  $W \rightarrow v\ell$  & smaller BR.
- [2-Lep.] BR  $\sim 7\%$  di-leptonic:  
Even smaller BR. We work on this...

- ◆ Compressed spectrum leads to **soft final objects**.
- ◆ The way to trigger such events is ISR jet(s).  
**ISR boosts** "back-to-back" the stop-pair:



## ② Events Selection.

# The Compact Muon Solenoid detector



## Analysis uses CMS data:

- collected in 2012
- p-p collisions at 8 TeV
- $L = 19.7 \text{ fb}^{-1}$

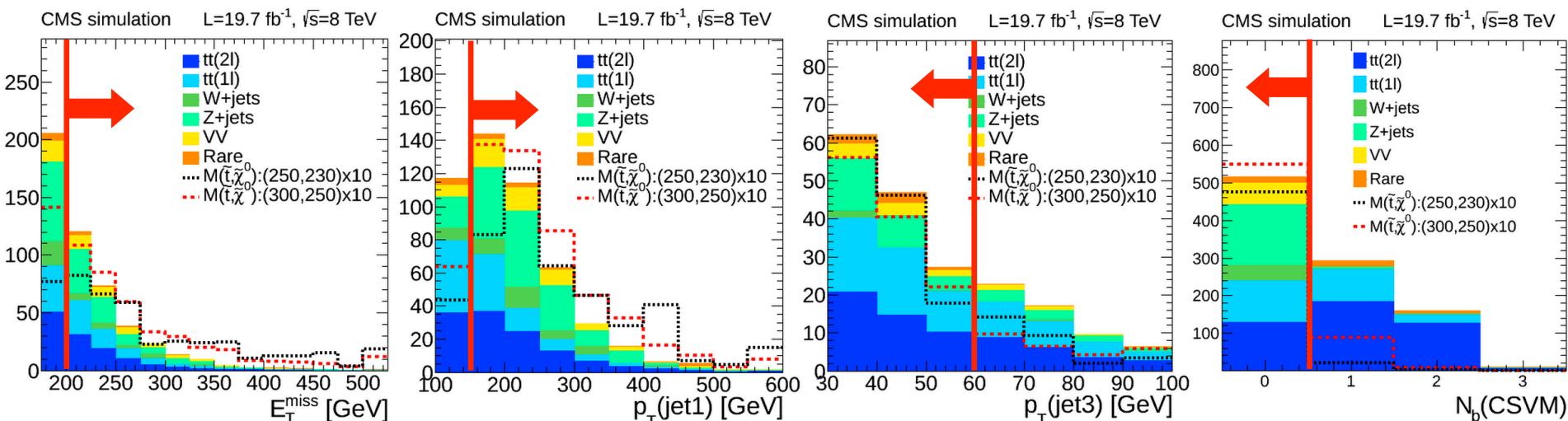
## Triggers Used in “OR” combination:

- MET120\_HBHENoiseCleaned
  - MonoCentralPFJet80\_PFMETNoMu95\_NHEF0p95
  - MonoCentralPFJet80\_PFMETnoMu105\_NHEF0p95
- eff >98% for MET>200 GeV

# Signal Region (SR) Cuts (1/2)

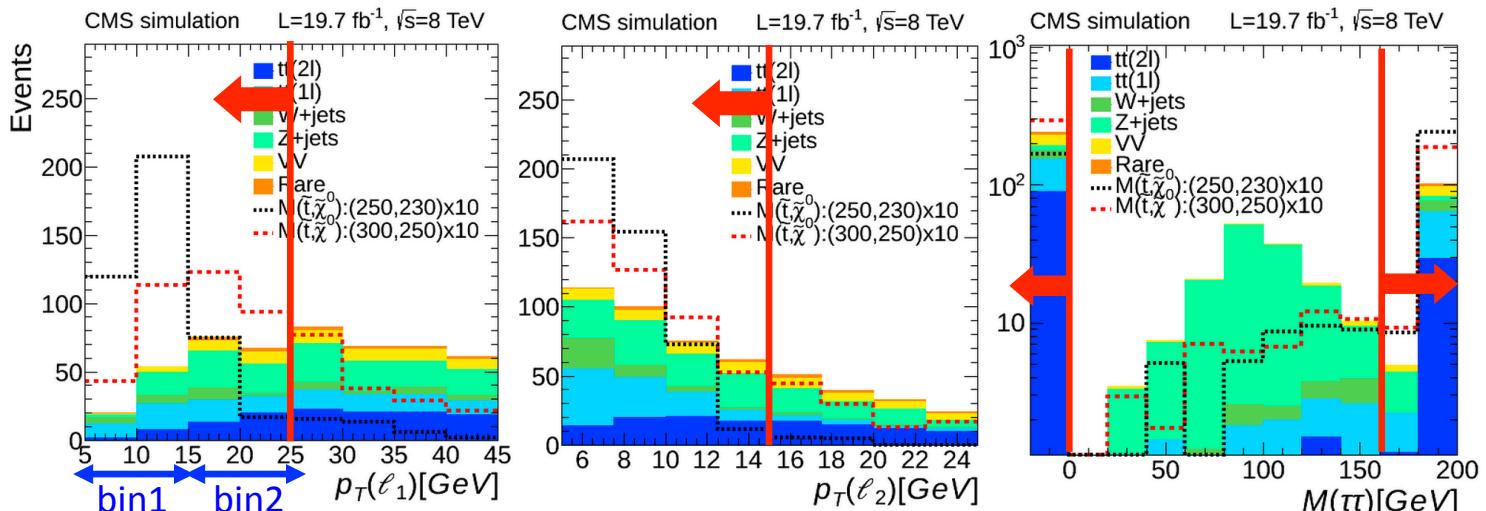
## ◆ Hadronic Sector Cuts:

- MET > 200 GeV driven by the trigger turn-on,
- $P_T(\text{jet1}) > 150 \text{ GeV}$  driven by the trigger turn-on,
- $P_T(\text{jet3}) < 60 \text{ GeV} \rightarrow \text{mono-jet \& di-jet events},$
- $N_b = 0$  (b-tagged jet multiplicity at CSV-M) signal b-jets:  $P_T < 30 \text{ GeV},$



- Signal (stop-LSP points) is scaled by x10 to be visible.
- MET and  $P_T(\text{jet1})$  is flatter for signal.
- Plots stands for a looser than SR-selection: “preselection” (more in backup).

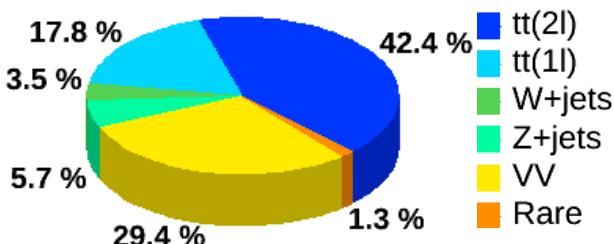
- ◆ Leptonic sector cuts:
  - $N_{\text{lep}}=2$  ,  $N_{\mu}>=1$  ,  $Q(\ell_1)*Q(\ell_2)<0$ : opposite-sign “ $\mu\mu$ ”, “e $\mu$ ” channels,
  - $P_T(\ell_1)$ : [5(7), 25] GeV & binning to cover different  $\Delta M$ ,
  - $P_T(\ell_2)$ : [5(7), 15] GeV,
  - $|n|<1.5$  &  $I_{\text{REL}}<0.5$  &  $I_{\text{ABS}}<5$  GeV : central & isolated  $\ell_1, \ell_2$ ,
  - $d_{xy}$  &  $d_z < 0.01$  cm : small Impact parameters.



- ◆ Composite variables cuts:
  - $M(\ell\ell) > 5 \text{ GeV}$  :  $\gamma^*$ ,  $j/\psi$  “killer”
  - $\text{MET}/H_T > 2/3$  : QCD “killer”
  - $M(\tau\tau)$  cut: [0, 160] GeV:  $Z \rightarrow \tau\tau$  “killer”  
[assuming  $\ell, \tau$  in same direction:  $\Delta R(\tau\ell)=0$ ]
- ◆ SR yields: **8 events**(simulation)
- ◆ background composition:
  -

### ③ Data-driven prediction Methods.

# Prediction methods: the main strategy



◆ We have 4 main background categories:

① tt(2l)

② tt(1l)&W+jets: Non-Prompt lepton events

③ DY+jets

:  $Z \rightarrow \tau\tau \rightarrow \ell\ell vvvv$

④ VV

: di-boson WW,WZ,ZZ (mainly WW~80%)

“Rare”

: single-t, ttW, ttZ, ttH, VVV,  $W^\pm W^\pm$ .

◆ Develop 4 different semi-data-driven prediction methods, one for each category.

◆ Define a **Control Region (CR)** for each of these categories.

- Control regions are carefully checked to be **kinematically similar with SR**.
- Each CR is **enriched** in its corresponded events & signal free.

◆ Same main prediction recipe used:

$$\text{PRED}_{\text{SR}} = (\text{DATA}_{\text{CR}} - \text{PRED-or-MC}_{\text{CR}}) [\text{MC}_{\text{SR}}/\text{MC}_{\text{CR}}]$$

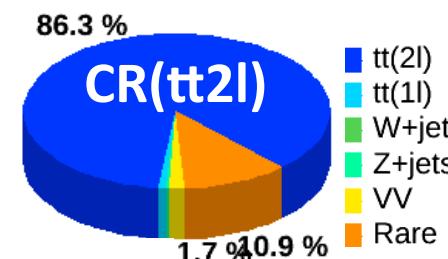
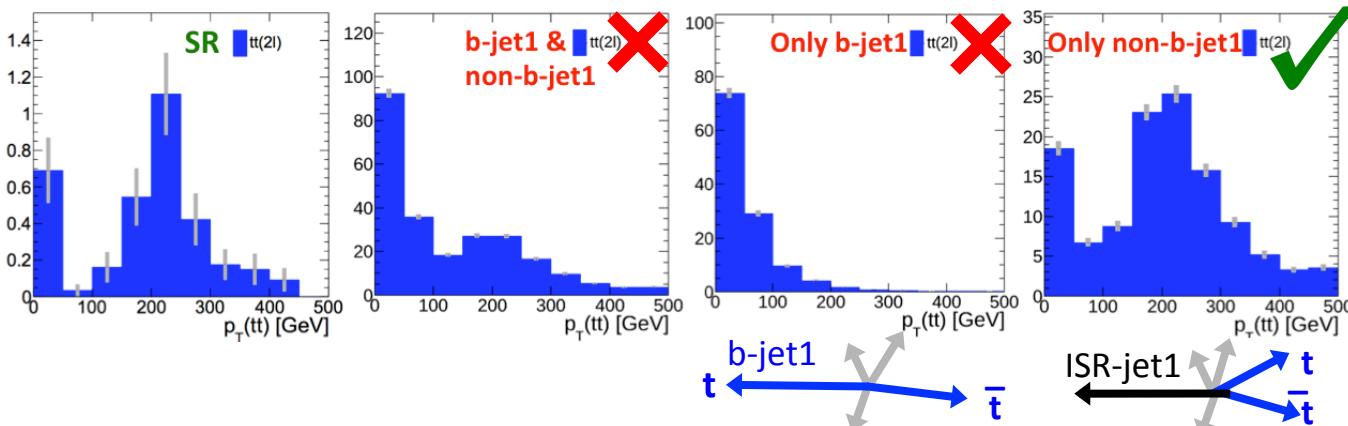
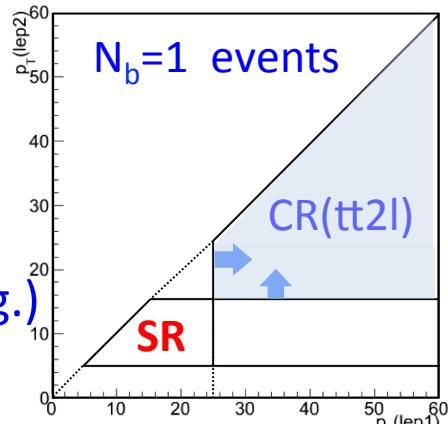
- Measure data in each CR,
- subtract the rest background (predicted or MC),
- use MC-ratio to transfer prediction yields in SR (use the MC yields for “Rare” ~1%)

◆ Test predictions with validation region.



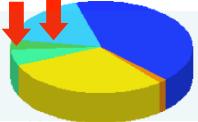
# tt(2l) Prediction

- ◆ Change the leptons to:  $P_T(\ell_1) > 25 \text{ GeV}$ ,  $P_T(\ell_2) > 15 \text{ GeV}$ .
- ◆ Enhance purity of tt(2l)-bgd (remove VV) requiring:  $N_b=1$ .
- ◆ Retain scale of leptonic activity (W-boson) & gain statistics x4.  
(Relax MET>125 GeV, replace: MET  $\rightarrow$  MET+ $P_T(\ell_1)=L_T$ , SingMu trig.)
- ◆ Require “non b-tag-jet1” to maintain the SR  $P_T(t\bar{t})$  kinematics.



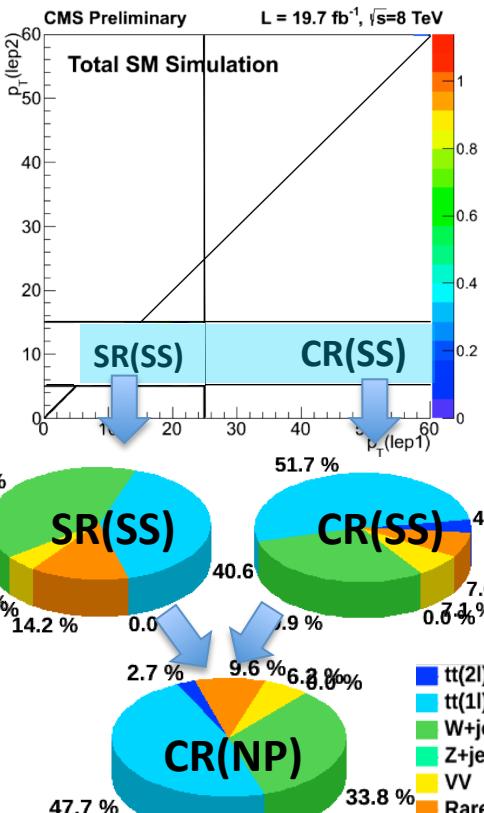
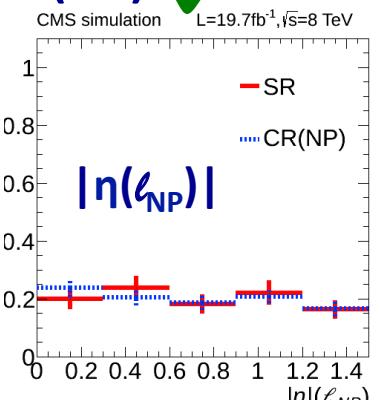
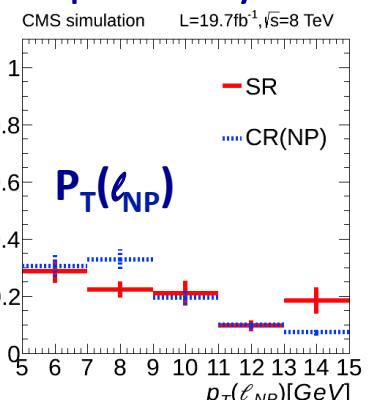
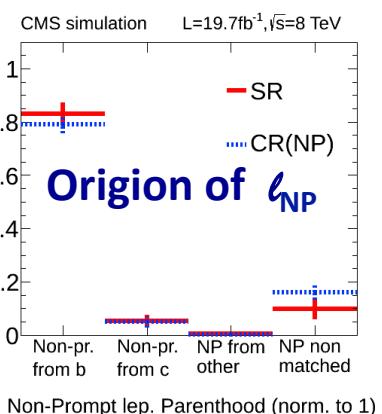
- ◆ Prediction in SR is finally obtained by:
  - measuring data in CR(tt2l),
  - subtract non-tt(2l) MC-events,
  - multiply with the MC-ratio.

$$PRED_{SR}^{t\bar{t}(2\ell)} = \left( DATA_{CR(tt2l)} - MC_{CR(tt2l)}^{non-tt(2\ell)} \right) \left( \frac{MC_{SR}}{MC_{CR(tt2l)}^{tt(2\ell)}} \right)$$



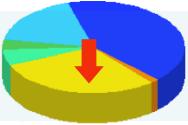
# Non-Prompt Prediction

- ◆ Same as in SR but **Same-Sign** events: **SR(SS)**
- ◆ Extend to events with:  $P_T(\ell_1) > 25$  GeV: **CR(SS)**.
  - $\ell_2$  is mainly the non-prompt ( $\ell_{NP}$ ) which remains the same.
  - CR(SS) events: MET>125 GeV , MET $\rightarrow$ L<sub>T</sub>, SingleMu trigger.
- ◆ Combine: **SR(SS) + CR(SS) to: CR(NP)**
  - Check kinematical compatibility: **SR vs CR(NP)**:



- ◆ Predictions by:

$$PRED_{SR}^{t\bar{t}(1\ell)\&W+jets} = \left( DATA_{CR(NP)} - MC_{CR(NP)}^{non-[t\bar{t}(1\ell)\&W+jets]} \right) \left( \frac{MC_{SR}^{t\bar{t}(1\ell)\&W+jets}}{MC_{CR(NP)}^{t\bar{t}(1\ell)\&W+jets}} \right)$$

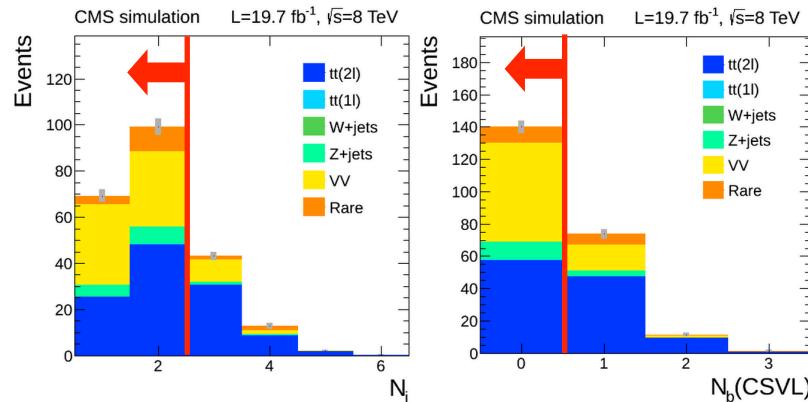


# VV Prediction

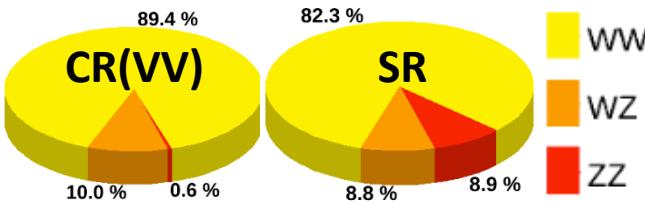
- ◆ Change to high lepton  $P_T$ s and  $L_T$  configuration:  
( $MET > 125$  GeV,  $L_T > 225$  GeV,  $L_T/H_T > 2/3$ , SingleMu trigger)

- ◆ Enhance the purity of VV-bkd (remove mainly tt2l) requiring:

- $N_{\text{jets}} \leq 2$ ,
- $N_{\text{btag}}(\text{CSV}L) = 0$ ,
- $M(\ell\ell) > 50$  GeV,
- $|\Delta\phi(\ell_1, \text{jet1})| > 1$

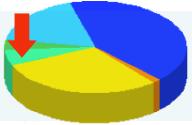


- ◆ Derived sample has:
- ~50% VV purity:
- Similar % abundances of VV sub-processes:



- ◆ Usual prediction formula...  
...but now subtract predictions:

$$PRED_{SR}^{VV} = \left( DATA_{CR(VV)} - PRED_{CR(VV)}^{\bar{t}\bar{t}, Z, W} - MC_{CR(VV)}^{\text{Rare}} \right) \left( \frac{MC_{SR}^{VV}}{MC_{CR(VV)}^{VV}} \right)$$

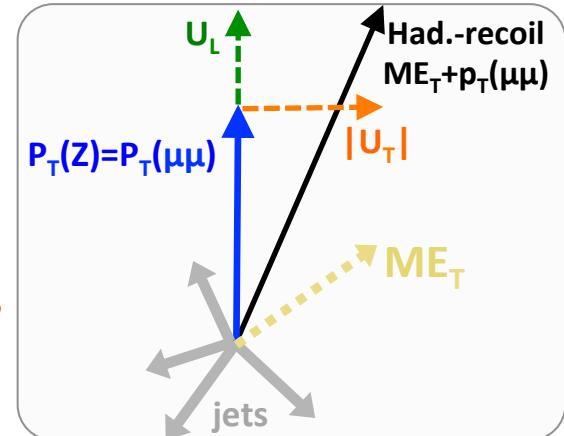


# Prediction of DY+jets

*Define 2 different CR for 2 different corrections*

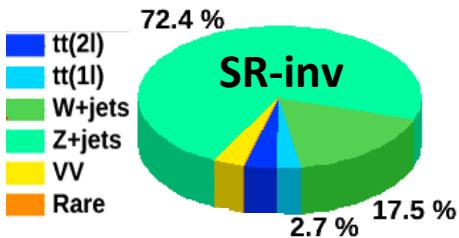
◆ [1] CR(Z) use to correct the hadronic-recoil:

- Select  $Z \rightarrow \mu\mu$  events, (high statistics,  $\sim 100\%$  purity).
- Replace MET  $\rightarrow |\vec{p}_T(\mu_1) + \vec{p}_T(\mu_2)| = P_T(Z) > 200$  GeV
- Measure [data/MC] ratios in “3D-bins of:  $P_T(Z)$ ,  $U_L$ ,  $|U_T|$ .
- Apply an event-per-event correction for each SR event multiplying with its corresponding ratio:



◆ [2] SR-inv. Used to correct potential miss-modeling of  $\tau$ -decay ( $Z \rightarrow \tau\tau \rightarrow \ell\ell v_\tau v_\tau v_\ell v_\ell$ )

- Exactly the same cuts as SR but with **inverted  $M(\tau\tau):[0,160]$  GeV cut.**
- 70% pure sample with similar kinematics.
- Usual prediction method but subtracting predictions:



$$PRED_{SR}^{Z+jets} = \left( DATA_{SR-inv} - PRED_{SR-inv}^{non-Z+jets} \right) \left( \frac{MC_{SR}^{Z+jets}}{MC_{SR-inv}^{Z+jets}} \right)_{recoil-corr}$$

# Predictions in SR

- ◆ The predicted yields in SR finally are:

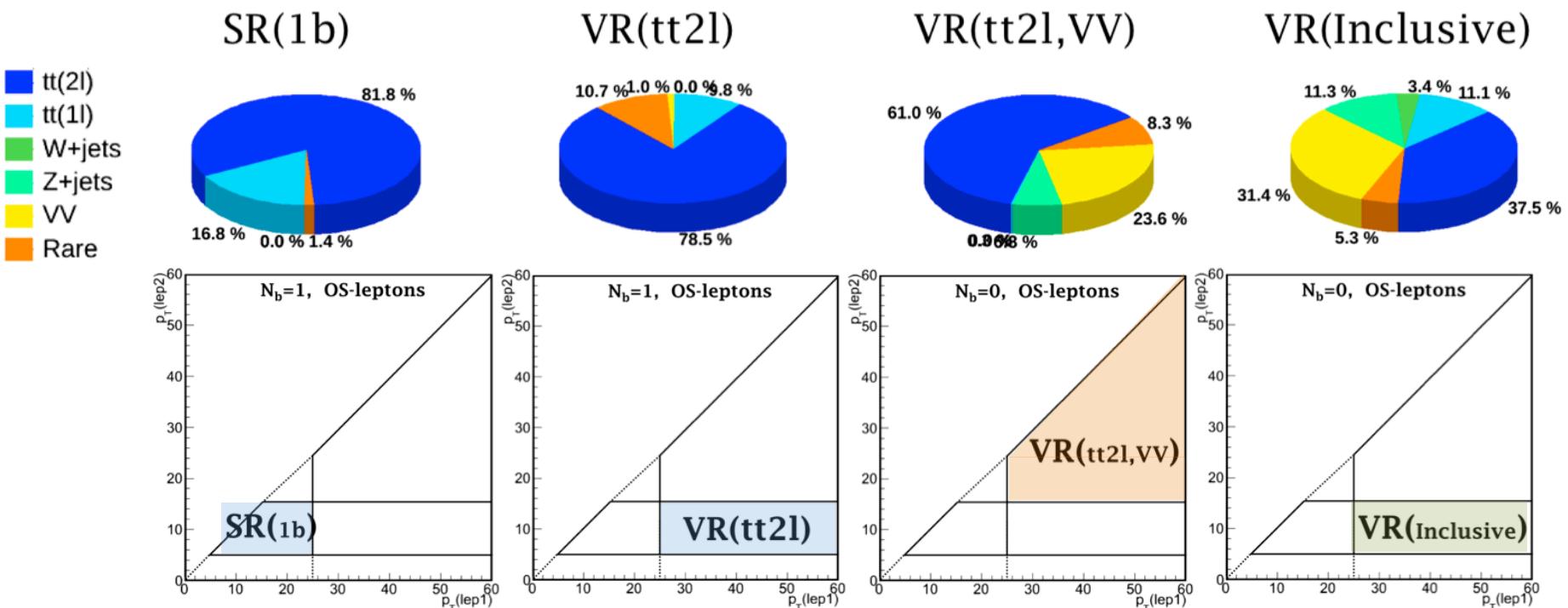
Background	$p_T(\ell_1)$ : 5–15 GeV	$p_T(\ell_1)$ : 15–25 GeV	Inclusive
$t\bar{t}(2\ell)$	$0.75 \pm 0.19$	$2.08 \pm 0.37$	$2.84 \pm 0.42$
$t\bar{t}(1\ell), W+\text{jets}$	$0.60 \pm 0.33$	$1.32 \pm 0.69$	$1.92 \pm 0.76$
$Z/\gamma^*+\text{jets}$	$<0.30$	$0.48 \pm 0.45$	$0.48 \pm 0.45$
VV	$0.74 \pm 0.27$	$1.61 \pm 0.48$	$2.35 \pm 0.55$
Rare backgrounds	$0.03 \pm 0.01$	$0.08 \pm 0.04$	$0.11 \pm 0.04$
Total SM	$2.12 \pm 0.47$	$5.6 \pm 1.0$	$7.7 \pm 1.1$
$\tilde{t}\tilde{t}$ signal (250,230)	$10.0 \pm 1.5$	$3.41 \pm 0.90$	$13.5 \pm 1.8$
$\tilde{t}\tilde{t}$ signal (300,250)	$3.98 \pm 0.61$	$3.83 \pm 0.58$	$7.80 \pm 0.84$

- ◆ Low  $P_T$  bin most sensitive,  
with ~equal background contribution by:  $t\bar{t}(2\ell)$ , NP, VV.

## ④ Validation test of the Prediction Methods

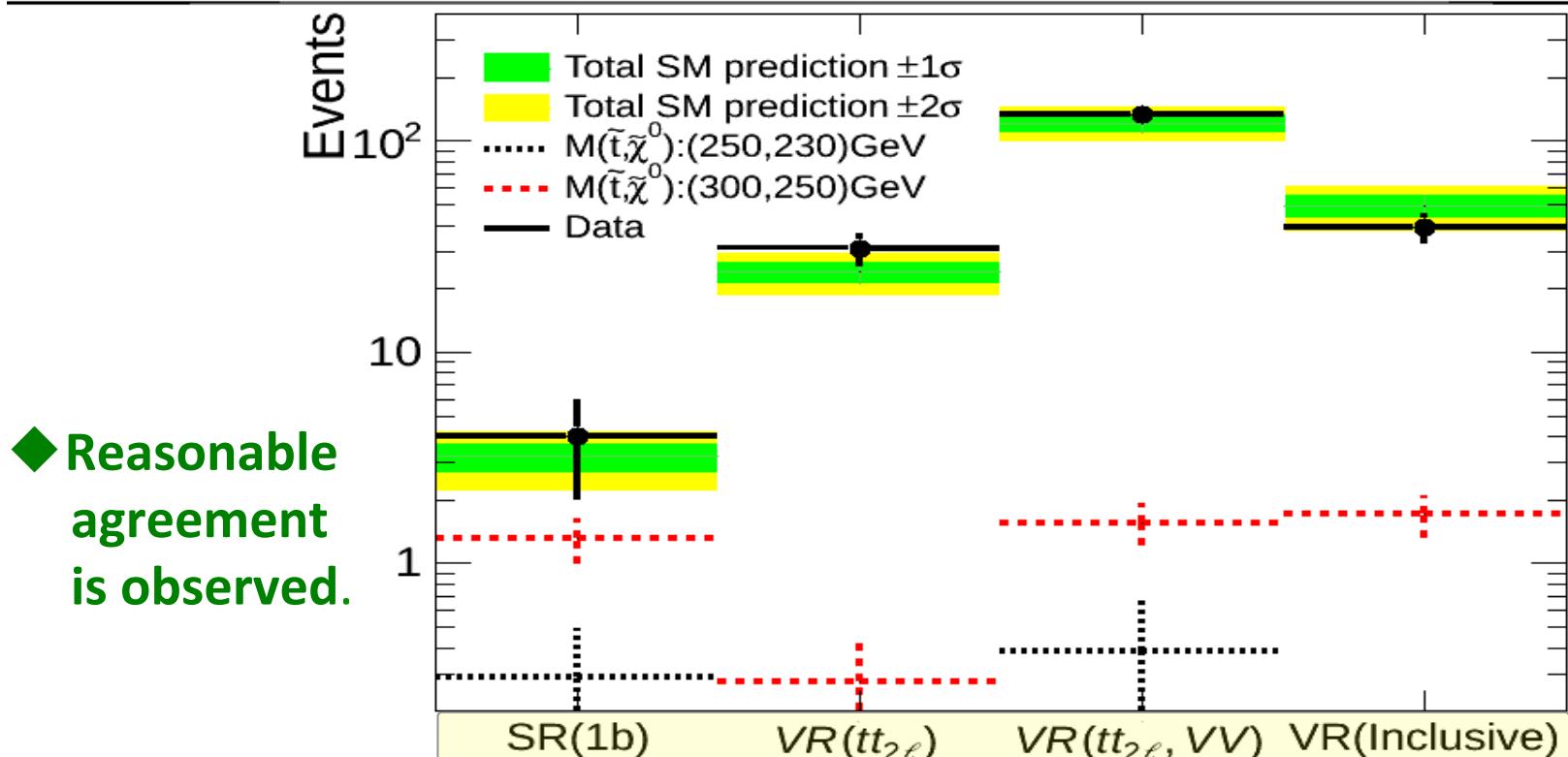
# Validation Regions Definition

- ◆ Regions not used for measurements (as CR) are used to test/validate our methods.
- ◆ We define 4 validation Regions “VR” named:
  - **SR(1b)** : same as SR selection except:  $N_b = 1$ .
  - **VR(tt2l)** : same as SR hadronic cuts,  $N_b = 1$ ,  $p_T(\text{lep1}) > 25\text{GeV}$ ,  $L_T$ -configuration,
  - **VR(tt2l,VV)** : same as CR(VV), requiring inversion of at least one VV-enriched-cut,
  - **VR(Inclusive)** : same as SR hadronic cuts,  $p_T(\text{lep1}) > 25\text{GeV}$ ,  $L_T$  configuration.



# VR: Predictions and Data

Yields/Sample	SR(1b)	VR( $t\bar{t}2l$ )	VR( $t\bar{t}2l, VV$ )	VR(Inclusive)
$t\bar{t}(2\ell)$	$2.48 \pm 0.38$	$17.9 \pm 2.2$	$71 \pm 8$	$15.8 \pm 2.0$
$t\bar{t}(1\ell), W + \text{jets}$	$0.68 \pm 0.32$	$3.0 \pm 1.3$	$0.47 \pm 0.28$	$8.2 \pm 3.6$
DY+jets	0	0	$6.8 \pm 1.9$	$7.1 \pm 2.5$
VV	0	$0.27 \pm 0.14$	$32 \pm 7$	$15.5 \pm 3.6$
Rare	$0.05 \pm 0.03$	$2.9 \pm 1.1$	$11.5 \pm 2.2$	$2.7 \pm 1.1$
Total predicted bkgd	$3.2 \pm 0.5$	$24.0 \pm 2.8$	$122 \pm 11$	$49 \pm 6$
Data	4	31	134	39
$\sigma_{\text{stat}}$	0.4	1.2	0.7	-1.1



## ⑤ Systematic Uncertainties

# Systematic uncertainties

◆ MC Statistics dominates uncertainties

Table lists systematic uncertainties pre source.  
(The % change over the total predicted yields is shown)

Systematic effect	$p_T(\ell_1): 5\text{--}15 \text{ GeV}$	$p_T(\ell_1): 15\text{--}25 \text{ GeV}$
Statistical uncertainty	21.9	18.3
Jet energy scale	1.0	2.8
b tagging	1.5	1.4
Electron efficiency	1.3	1.1
Muon efficiency	6.0	4.5
$t\bar{t}$ background	5.1	5.4
NP background	10.1	5.6
$Z/\gamma^*$ background	0.0	2.3
VV background	8.0	2.6
Rare backgrounds	3.7	3.3
Total uncertainty	26.9	21.1

*Applied to all  
Background processes*

*Accounting quadratically  
many different sources per  
individual background*

◆  $t\bar{t}(2l)$  background

- W-polarization ( $\pm 10\%$ )
- $t\bar{t}$  Spin Correlation ( $\pm 20\%$ )
- top  $P_T$  modeling (reweight)

◆ NP background:

- W+jets/ $t\bar{t}(1l)$  ratio
- c in Parton Shower
- b-originated  $\ell_{NP}$  ( $\pm 50\%$ )
- SR/CR(NP):  
 $P_T(\ell_{NP}), |\eta|(\ell_{NP}), \text{ratio}(\pm 100\%)$
- CR(NP) VV ( $\pm 50\%$ )

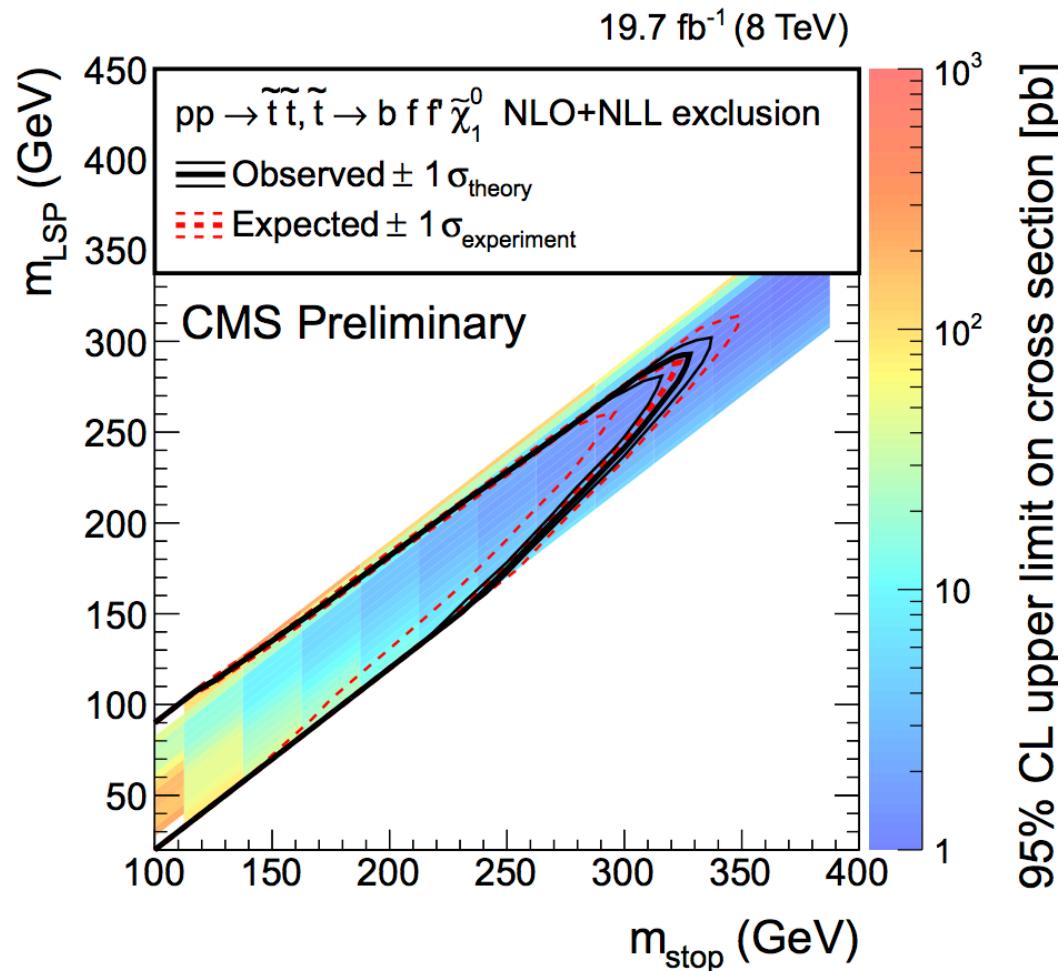
◆ VV background

- V-polarization ( $\pm 10\%$ )
- Boson Asym. Ratio( $\pm 50\%$ )
- $p_T(V^+)/[p_T(V^+) + p_T(V^-)]$
- $V-\gamma^*$  ( $\pm 100\%$ )

## ⑥ Results and Interpretation

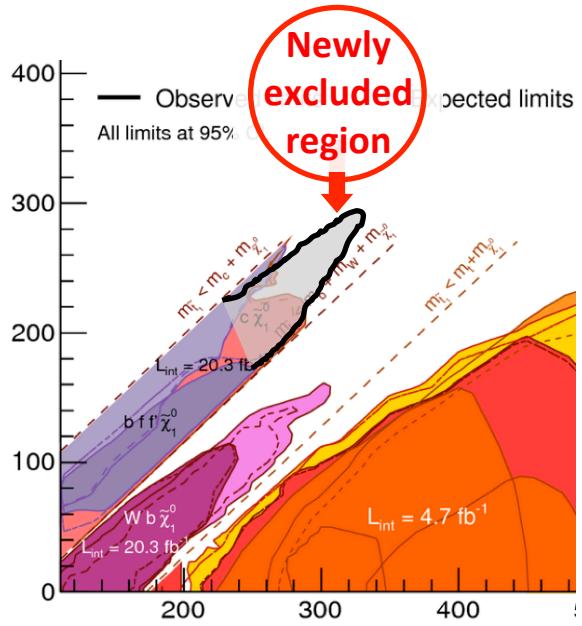
# Results and Exclusion limit in $[\tilde{t}, \tilde{\chi}_1^0]$

	$p_T(\ell_1): 5\text{--}15\text{ GeV}$	$p_T(\ell_1): 15\text{--}25\text{ GeV}$	Inclusive
Total SM	<b>2.12 <math>\pm 0.47</math></b>	<b>5.6 <math>\pm 1.0</math></b>	$7.7 \pm 1.1$
$\tilde{t}\tilde{t}$ signal (250,230)	$10.0 \pm 1.5$	$3.41 \pm 0.90$	$13.5 \pm 1.8$
$\tilde{t}\tilde{t}$ signal (300,250)	$3.98 \pm 0.61$	$3.83 \pm 0.58$	$7.80 \pm 0.84$
DATA	<b>2</b>	<b>4</b>	6
$\sigma_{\text{stat}}$	-0.1	-0.6	-0.6

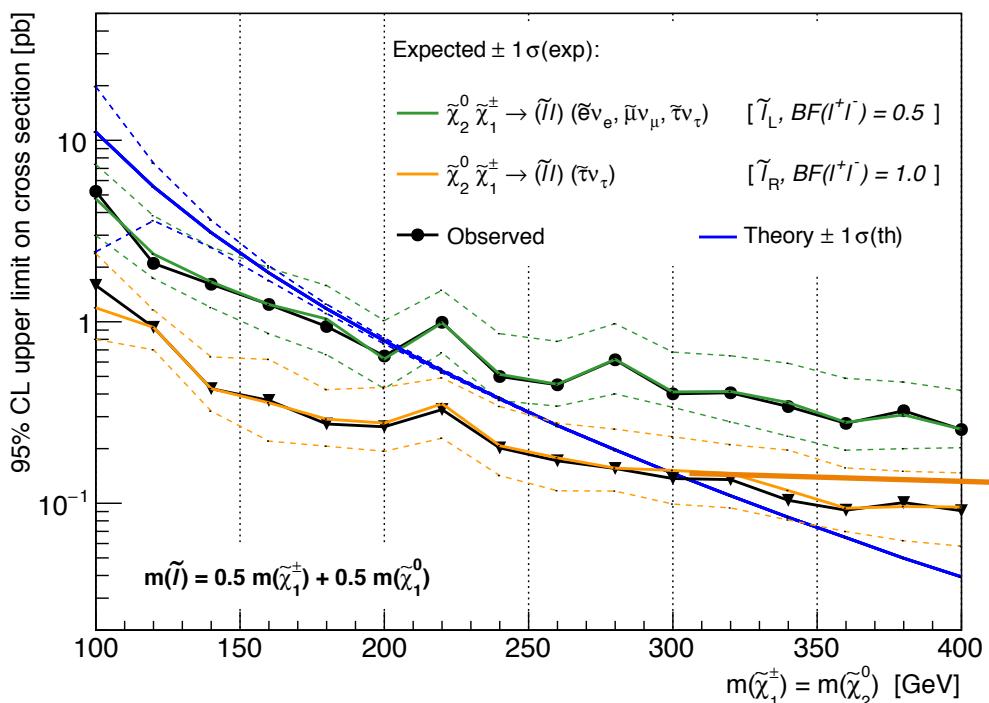
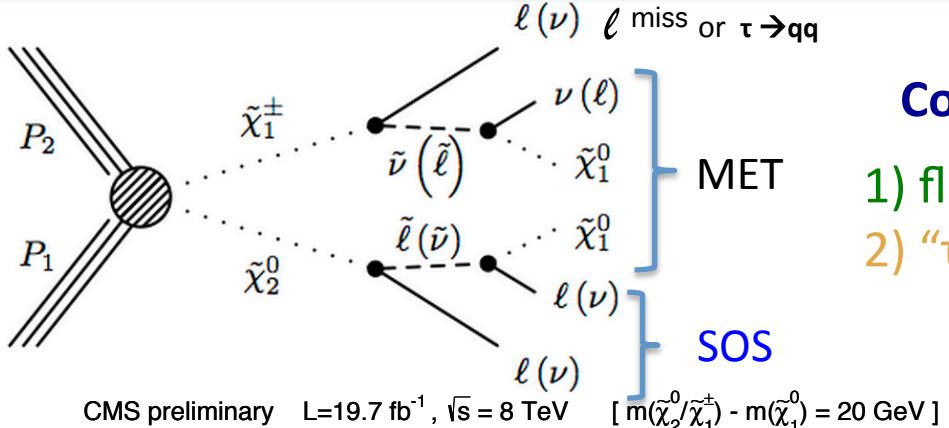


- ◆ No excess observed in either bin.
- ◆ Data-predictions in agreement.
- ◆ Exclusion Limits are imposed.
- ◆ Limit covers unexplored region.

95% CL upper limit on cross section [pb]



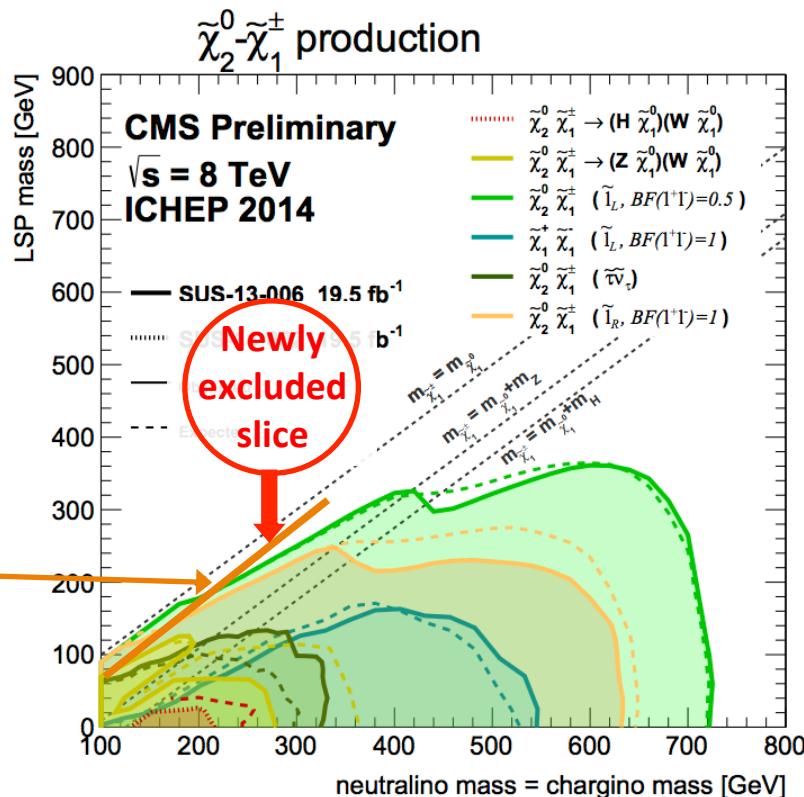
# Alternative interpretations: EWKino $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$



- ◆ SOS lepton allow searches in compressed EWKinos.
- ◆ Exclusion up to 300 GeV in “ $\tau$ ”-enriched scenario.

Considering  $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$  and final states:

- 1) flavor-democratic:  $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \ell^\pm \nu 2\tilde{\chi}_2^0$
- 2) “ $\tau$ ”-enriched:  $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tau^\pm \nu 2\tilde{\chi}_2^0$

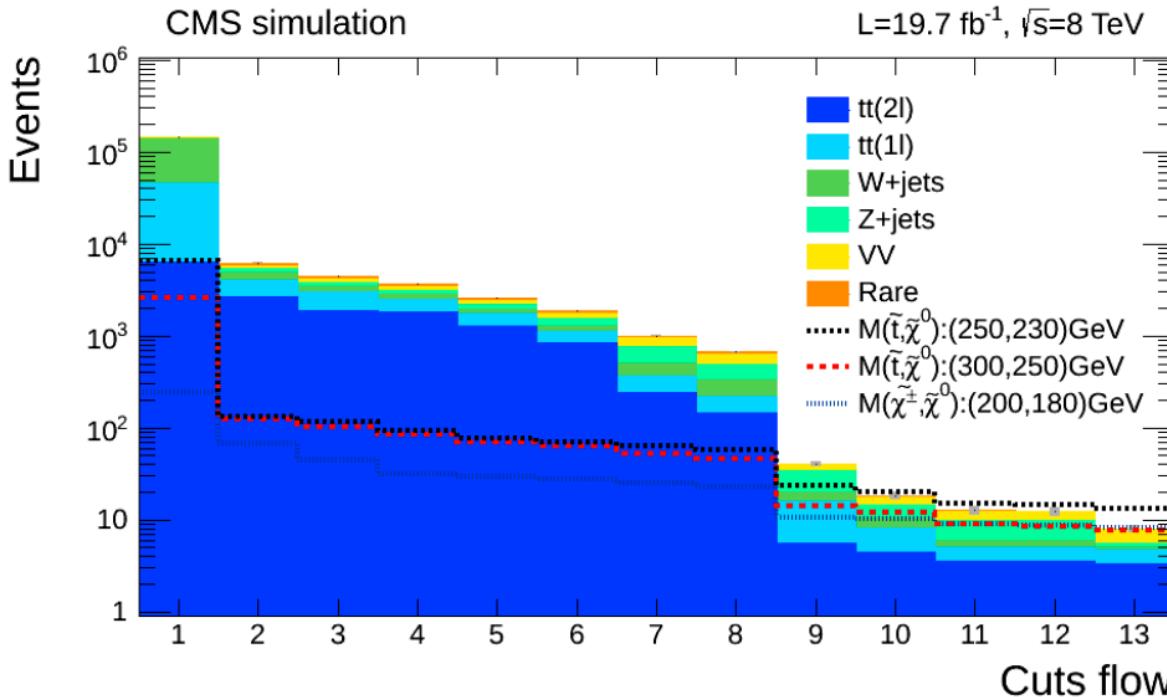


## ⑦ Conclusions

- ◆ A search for SUSY in compressed spectra has been performed in events with:
  - 2 Soft OS-leptons [ $\mu\mu$ ] or [ $e\mu$ ],
  - high MET,
  - 1 or 2 high- $P_T$  (ISR) jet(s) which allows the triggering.
- ◆ Data-driven prediction methods have been performed in background estimate.
- ◆ Data are in agreement with predicted SM processes.
- ◆ Results are interpreted in:
  - a model of  $\tilde{t}\tilde{t}$ -pair production, with a mass difference:  $\Delta M(\tilde{t}, \tilde{\chi}_1^0) < 80$  GeV and assuming 100% BR for 4-body decays of the stop.  
Cross section limits are set in the stop-LSP mass plane excluding unexplored areas.  
• two models of:  $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$  production with  $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 20$  GeV.
    - 1) a flavor-democratic:  $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \ell^\pm \nu 2\tilde{\chi}_2^0$  (BR: 50%)
    - 2) a “ $\tau$ ”-enriched:  $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tau^\pm \nu 2\tilde{\chi}_2^0$  - These limits slightly improved existing results in the flavor-democratic and exceed them by  $\sim 200$  GeV in the “ $\tau$ ”-enriched one.

# Backup Material

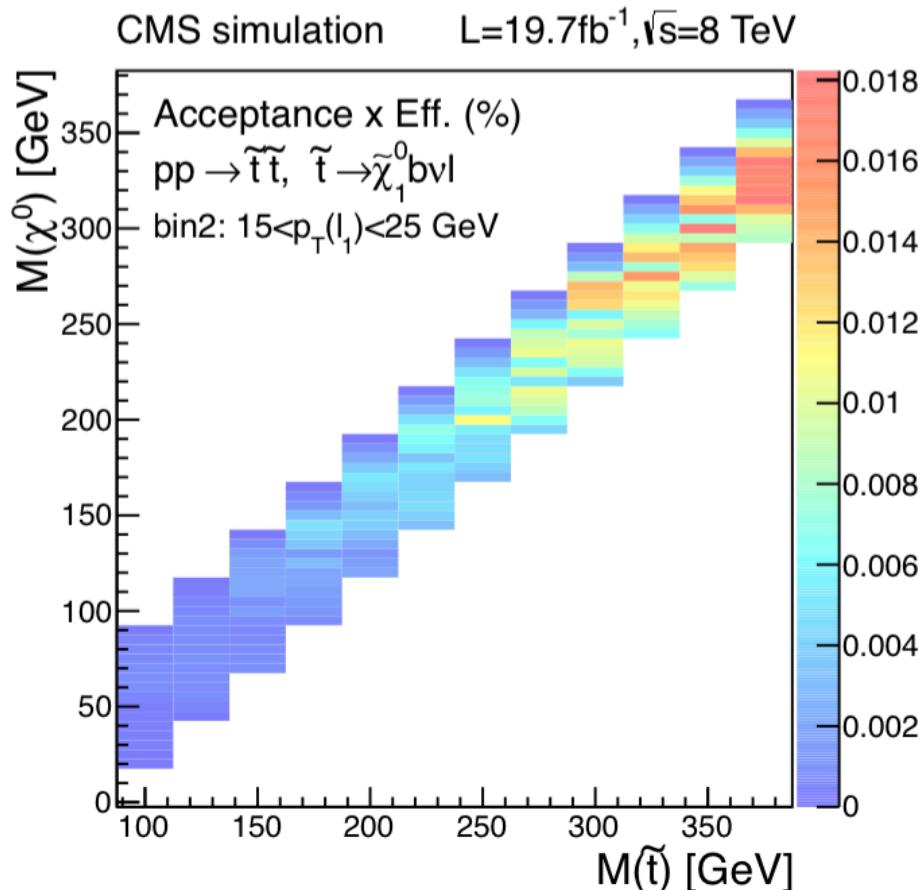
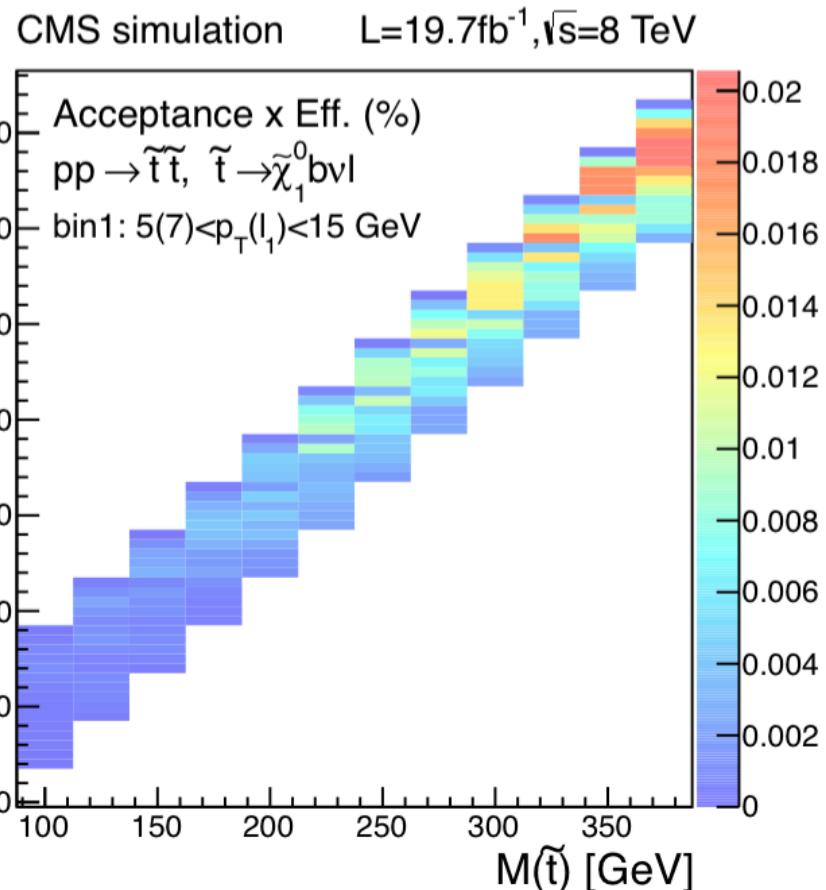
# The Cut flow towards to SR

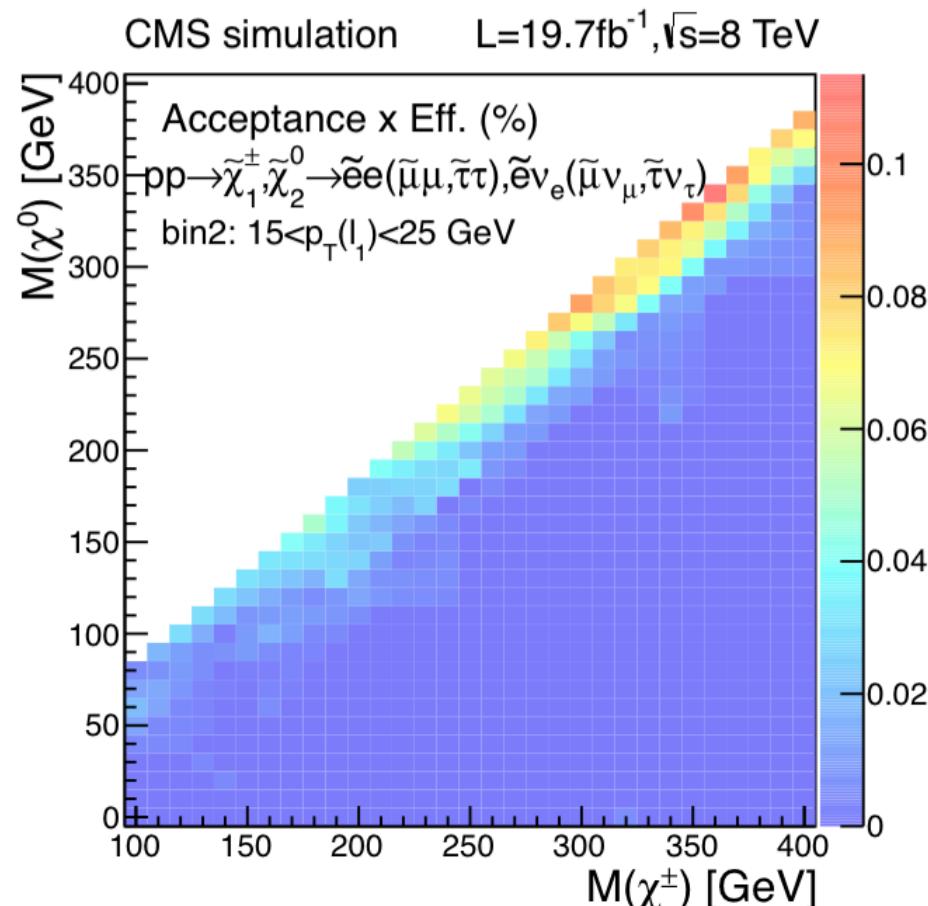
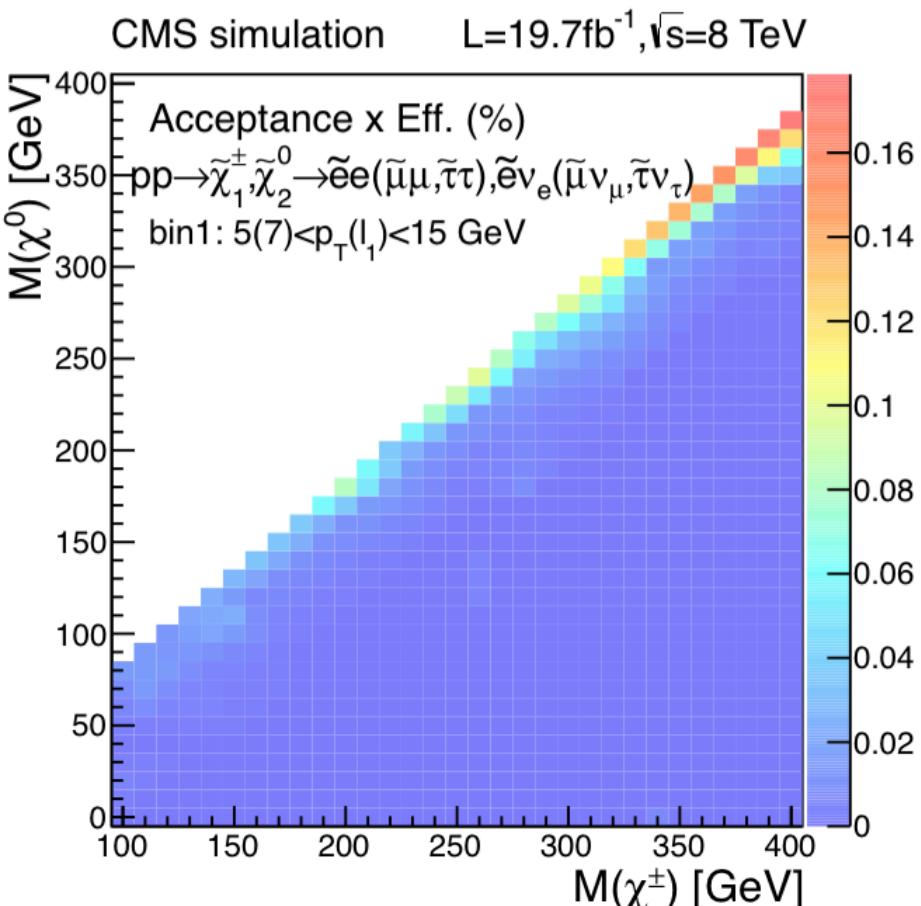


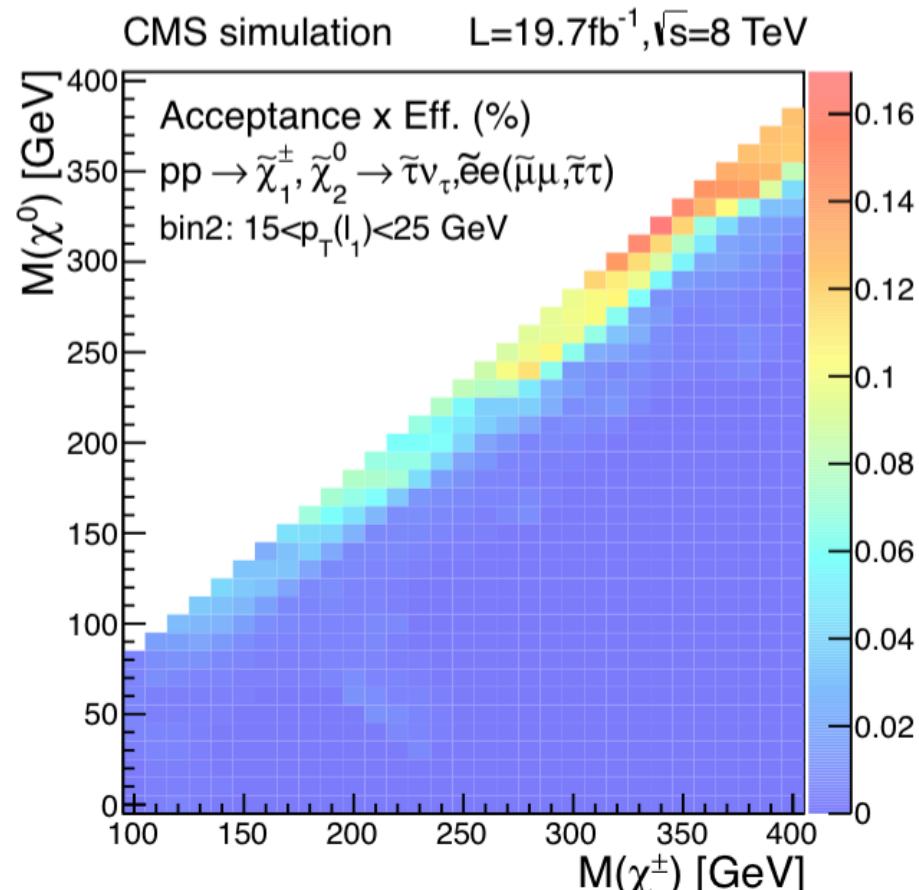
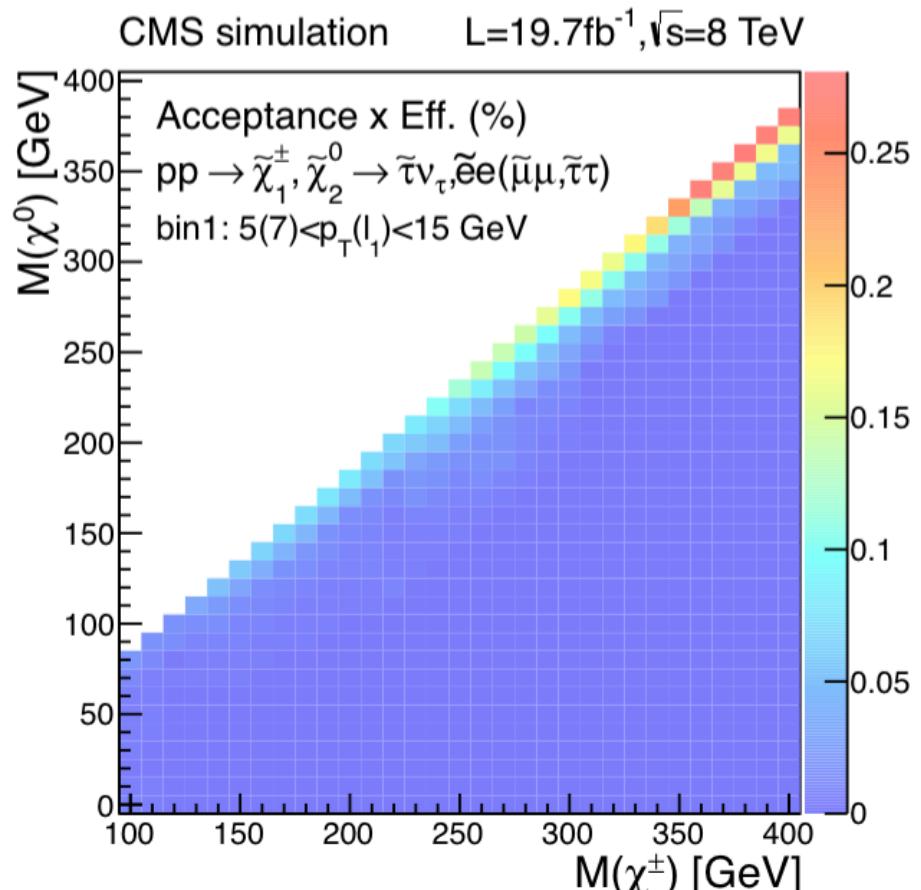
Selection cuts	$t\bar{t}(2\ell)$	$t\bar{t}(1\ell)$	$W+jets$	$Z+jets$	$VV$	Rare	Total SM background	$M(\tilde{t}), M(\tilde{\chi}_1^0): (250,230)$	$M(\tilde{t}), M(\tilde{\chi}_1^0): (300,250)$
$\cancel{E}_T > 200\text{GeV}$	$6384 \pm 17$	$39289 \pm 55$	$94093 \pm 216$	$3848 \pm 36$	$1074 \pm 9$	$2844 \pm 35$	$147533 \pm 229$	$6640 \pm 39$	$2563 \pm 15$
$N_\ell = 2$	$2649 \pm 11$	$1468 \pm 11$	$742 \pm 19$	$498 \pm 14$	$460 \pm 6$	$430 \pm 13$	$6247 \pm 32$	$132 \pm 6$	$125.9 \pm 3.4$
$N_\mu \geq 2$	$1904 \pm 9$	$1122 \pm 9$	$477 \pm 15$	$335 \pm 11$	$325 \pm 5$	$308 \pm 11$	$4472 \pm 26$	$117 \pm 6$	$102.8 \pm 3.1$
$Q(\ell_1)Q(\ell_2) = -1$	$1852 \pm 9$	$681 \pm 7$	$281 \pm 12$	$327 \pm 11$	$310 \pm 5$	$261 \pm 11$	$3712 \pm 23$	$92.5 \pm 4.9$	$83.5 \pm 2.8$
$p_{T,jet1} > 150\text{GeV},  \eta  < 2.4$	$1301 \pm 8$	$468 \pm 6$	$149 \pm 9$	$290 \pm 11$	$224 \pm 4$	$178 \pm 9$	$2610 \pm 19$	$76.2 \pm 4.4$	$69.7 \pm 2.5$
$p_{T,jet3} < 60\text{GeV}$	$842 \pm 6$	$292 \pm 5$	$147 \pm 8$	$265 \pm 10$	$206.1 \pm 3.9$	$135 \pm 8$	$1887 \pm 18$	$69.2 \pm 4.2$	$63.1 \pm 2.3$
$N_b = 0$	$245.0 \pm 3.4$	$124.7 \pm 3.1$	$141 \pm 9$	$249 \pm 10$	$190.1 \pm 3.7$	$53 \pm 5$	$1003 \pm 15$	$64.3 \pm 4.1$	$53.2 \pm 2.2$
$\cancel{E}_T / H_T > 2/3$	$147.1 \pm 2.6$	$74.5 \pm 2.4$	$115 \pm 8$	$162 \pm 8$	$137.5 \pm 3.1$	$30.0 \pm 3.8$	$667 \pm 13$	$57.5 \pm 3.6$	$46.3 \pm 2.0$
$p_{T,\ell_{1(2)}}: [5, 25(15)]\text{GeV},  \eta  < 1.5$	$5.6 \pm 0.5$	$10.5 \pm 0.9$	$3.8 \pm 1.4$	$15.0 \pm 2.2$	$5.4 \pm 0.7$	$0.62 \pm 0.45$	$41.0 \pm 3.0$	$23.2 \pm 2.3$	$14.3 \pm 1.1$
$ d_z ,  d_{xy} _{\ell_{1,2}} < 0.01\text{cm}$	$4.45 \pm 0.45$	$3.9 \pm 0.6$	$2.4 \pm 1.1$	$4.1 \pm 1.2$	$3.11 \pm 0.45$	$0.56 \pm 0.44$	$18.5 \pm 1.9$	$20.3 \pm 2.2$	$12.1 \pm 1.1$
$I_{Rel}(\ell) < 0.5, \& I_{Abs}(\ell) < 5\text{GeV}$	$3.53 \pm 0.40$	$1.52 \pm 0.35$	$1.0 \pm 0.7$	$3.8 \pm 1.1$	$2.77 \pm 0.43$	$0.11 \pm 0.04$	$12.7 \pm 1.5$	$15.3 \pm 1.9$	$9.0 \pm 0.9$
$M_{\ell\ell} > 5\text{GeV}$	$3.53 \pm 0.40$	$1.52 \pm 0.35$	$1.0 \pm 0.7$	$3.8 \pm 1.1$	$2.47 \pm 0.40$	$0.11 \pm 0.04$	$12.4 \pm 1.5$	$14.6 \pm 1.8$	$8.4 \pm 0.9$
$M_{\tau\tau}\text{cut}: [0, 160]\text{GeV}$	$3.38 \pm 0.39$	$1.42 \pm 0.33$	$0.28 \pm 0.28$	$0.45 \pm 0.33$	$2.34 \pm 0.39$	$0.11 \pm 0.04$	$8.0 \pm 0.8$	$13.5 \pm 1.8$	$7.8 \pm 0.8$

# Systematics Explicitly:

Systematic Uncertainty Source / Bins	$p_T(\ell_1) : [5, 15] \text{ GeV}$	$p_T(\ell_1) : [15, 25] \text{ GeV}$	Inclusive
Total Default SM Predicted events	2.12	5.57	7.69
Statistical uncertainty:	21.9%	18.3%	14.6%
JES:	1.0 %	2.8 %	2.1 %
SF btag b quark:	0.9 %	0.9 %	0.7 %
SF btag light quark:	1.3 %	1.1 %	1.1 %
electron efficiency:	1.3 %	1.1 %	1.1 %
Muon efficiency:	6.0 %	4.5 %	4.9 %
$t\bar{t}(2\ell)$ spin corr:	4.1 %	3.5 %	3.6 %
$t\bar{t}(2\ell)$ W polarization:	2.5 %	2.6 %	2.6 %
$t\bar{t} p_T$ reweighted $t\bar{t}(1\ell, 2\ell, W, Z, H)$ :	1.7 %	3.3 %	2.9 %
Non-Prompt W+jets/ $t\bar{t}(1\ell)$ ratio:	6.1 %	2.7 %	3.6 %
Non-Prompt c in PS :	0.4 %	0.4 %	0.2 %
Non-Prompt b-originated NP:	4.9 %	3.5 %	3.9 %
Non-Prompt SR/CR(NP) $p_T(\ell_{NP})$ ratio:	2.3 %	1.7 %	1.9 %
Non-Prompt SR/CR(NP) $\eta(\ell_{NP})$ ratio:	1.6 %	1.9 %	1.8 %
Non-Prompt CR(NP) VV:	5.7%	2.4%	3.3%
VV W&Z polarization:	2.5%	1.9 %	1.4 %
VV ( $p_T^{V+} / [p_T^{V+} + p_T^{V-}]$ ) :	2.5%	1.7 %	0.7 %
VV private:	7.2%	0.7 %	2.5%
W,Z polarization $\pm 10\%$ :	0.6 %	0.8%	0.4%
DY $E_T$ resolution:	0.0 %	2.3 %	1.7 %
Rare reweight:	3.7%	3.3 %	3.4 %
Rare $t\bar{t}$ spin correlation:	0.1%	0.0 %	0.0 %
Rare W & Z polarization:	0.1%	0.2 %	0.2 %
Total systematic uncertainty:	15.7%	10.7 %	11.3 %
Total uncertainty:	26.9%	21.1 %	18.3 %





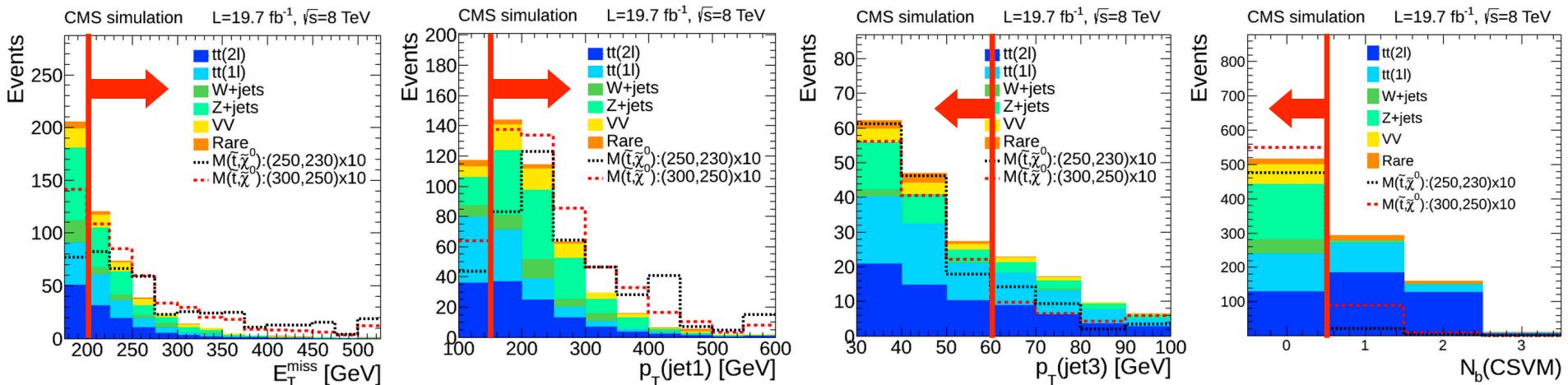


# Signal Region Cuts 1/3

- ◆ Cuts driven by the trigger turn-on:
  - MET > 200 GeV
  - $P_T(\text{jet1}) > 150 \text{ GeV}$  (& jet1 quality requirements)
- ◆ Additional hadronic Sector Cuts:
  - $N_b = 0$  (b-tagged jet multiplicity at CSV-M)
  - $P_T(\text{jet3}) < 60 \text{ GeV}$
- Signal is scaled by x10 to be visible.
- MET and  $P_T(\text{jet1})$  is flatter for signal.
- Signal b-jets typically below threshold of 30 GeV.
- The  $P_T(\text{jet3}) < 60 \text{ GeV}$  vetoes events with more than 2 “hard jets”: mono/di-jet events.

In order to develop the "SR" selection, a looser "Pre-selection" is applied to explore the background characteristics. These plots are for preselection.

$N_\ell$	= 2
$N_\mu$	$\geq 1$ (soft $\mu$ ID)
$Q(\ell_1)Q(\ell_2)$	= -1
$p_T(\ell_1)$	[5(7),45] GeV
$p_T(\ell_2)$	[5(7),25] GeV
$ \eta (\ell_{1,2})$	< 2.1
$d_z(\ell_{1,2}) \& d_{xy}(\ell_{1,2})$	< 0.1 cm
$p_T(\text{jet1})$	> 100 GeV
$p_T(\text{jet3})$	< 100 GeV
$ \eta (\text{jet1})$	< 2.4
$N_b(CSV M)$	= 0
$\cancel{E}_T$	> 175 GeV

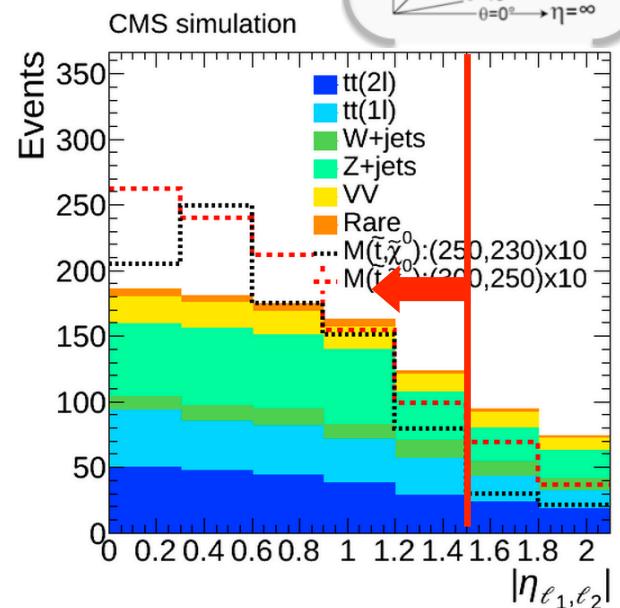
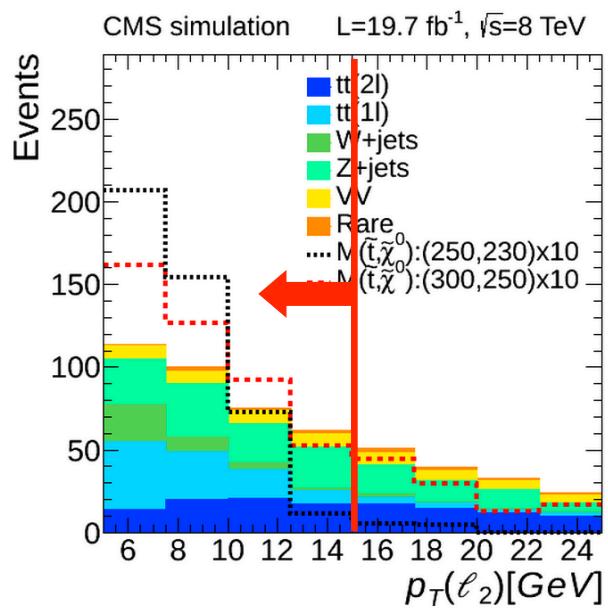
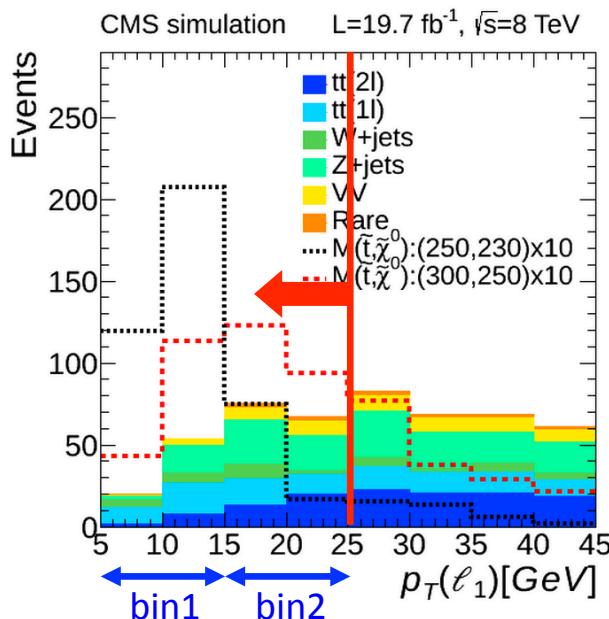


# Signal Region Cuts 2/3

## ◆ Leptonic Sector Cuts:

- $N_{\text{lep}} = 2$
- $N_{\mu} \geq 1$
- $Q(\ell_1) * Q(\ell_2) < 0$
- $P_T(\ell_1): [5(7), 25] \text{ GeV}$
- $P_T(\ell_2): [5(7), 15] \text{ GeV}$
- $|\eta| < 1.5$
- IP:  $d_{XY} \& d_z < 0.01 \text{ cm}$
- $\text{Iso}_{\text{REL}} < 0.5$
- $\text{Iso}_{\text{ABS}} < 5 \text{ GeV}$

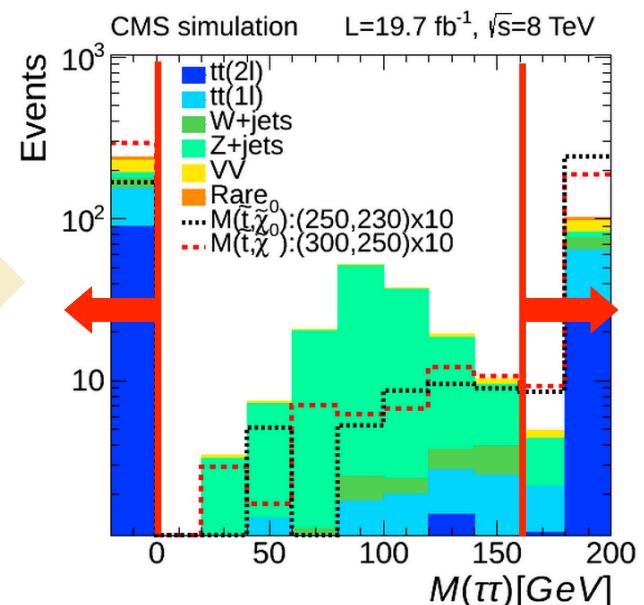
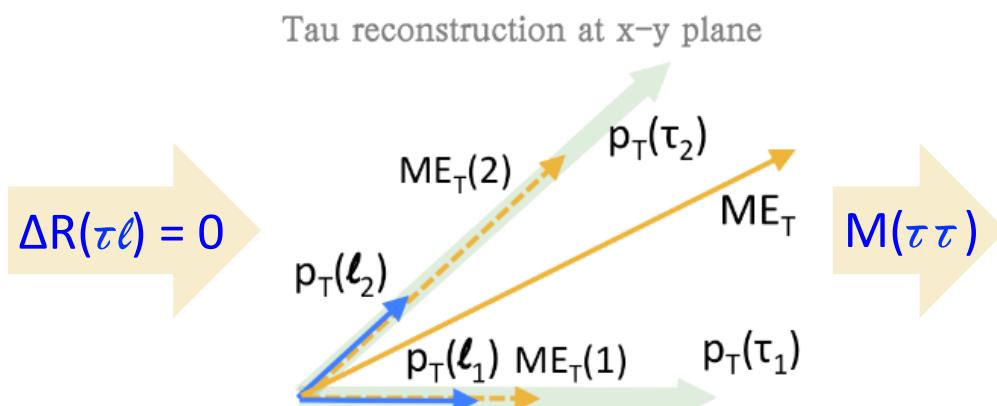
$$\eta \equiv -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$$



- Smaller mass-splitting lead to softer  $P_T(\text{lep1})$ .
- Binning over  $P_T(\text{lep1})$  to cover different  $\Delta M$ : **bin1: [5,15]GeV , bin2: [15,25]GeV**

# Signal Region Cuts 3/3

- ◆  $\gamma^*, j/\psi$  “killer” cut:
  - $M(\ell\ell) > 5 \text{ GeV}$
- ◆ QCD “killer” cut:
  - $\text{MET}/\text{HT} > 2/3$
- ◆  $Z \rightarrow \tau\tau$  “Killer” cut:
  - $M(\tau\tau)$  cut the:  $[0,160] \text{ GeV}$  (Z-peak).



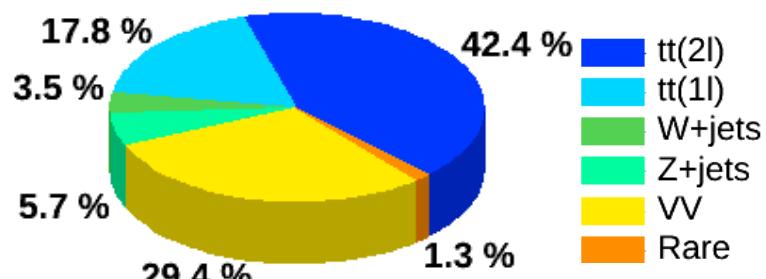
- Assuming  $\tau$  direction same direction of soft lepton and its parent  $\tau$  i.e.:  $\Delta R(\tau\ell) = 0$ .
- Getting the two  $\tau$  amplitudes by  $P_T(\tau\tau) = P_T(Z) = \text{hadronic recoil}$ .
- **Build  $M(\tau\tau)$  mass** and make the **cut of  $M(\tau\tau):[0,160] \text{ GeV}$** .

Our SR selections is summarized as:

Variable:	SR selection cut:
$N_\ell$	= 2
$N_\mu$	$\geq 1$ (& soft Muon ID)
$Q(\ell_1)Q(\ell_2)$	-1
$p_T(\ell_1)$	[5(7), 25] GeV
$p_T(\ell_2)$	[5, 15] GeV
$ \eta (\ell_{1,2})$	< 1.5
$d_z(\ell_{1,2}) \& d_{xy}(\ell_{1,2})$	< 0.01 cm
$Iso_{rel}(\ell_{1,2}) \& Iso_{Abs}(\ell_{1,2})$	< 0.5, < 5 GeV
$p_T(jet1)$	> 150 GeV
$p_T(jet3)$	< 60 GeV
$ \eta (jet1)$	< 2.4
$N_b (>30 \text{ GeV, CSVM})$	= 0
$\cancel{E}_T$	> 200 GeV
$\cancel{E}_T/H_T$	> 2/3
$M_{\ell\ell}$	> 5 GeV
$M_{\tau\tau}$	cut:[0, 160] GeV

After all cuts in “SR” we have (simulation):

- bin1:  $5 < P_T(\ell_1) < 15$  GeV : ~2 events.
- bin2:  $15 < P_T(\ell_1) < 25$  GeV : ~6 events.



◆ We have 4 main background categories:

① tt(2l)

② tt(1l) & W+jets: Non-Prompt lepton events

③ DY+jets ( $Z \rightarrow \tau\tau \rightarrow \ell\ell vvvv$ )

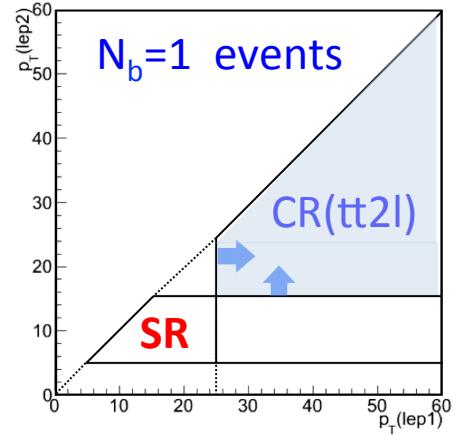
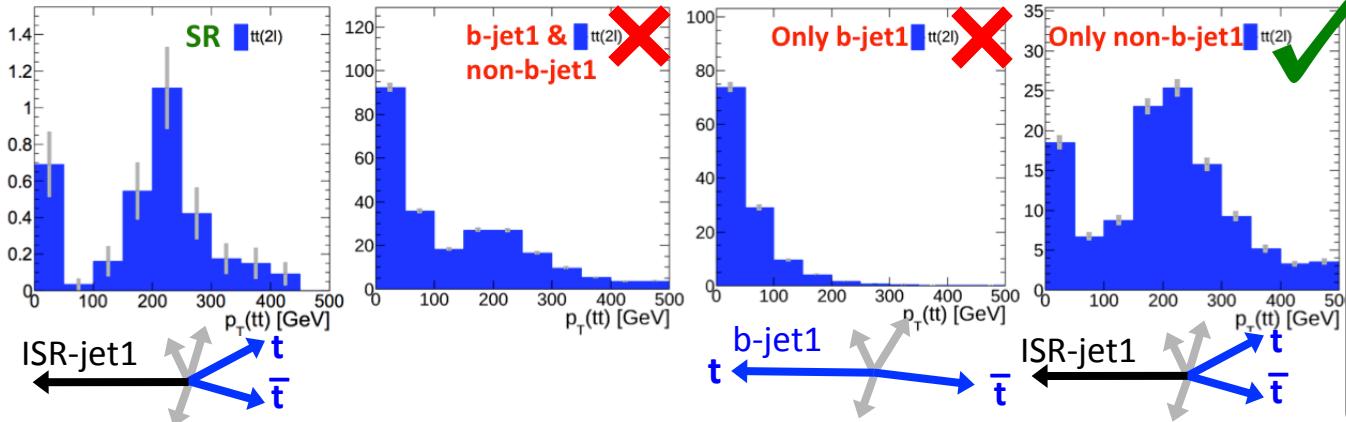
④ VV di-boson: WW,WZ,ZZ (mainly WW ~80%)

As “Rare” events we consider all the:

single-t, ttW, ttZ, ttH, WWW, WWZ, WZZ, ZZZ,  $W^\pm W^\pm$ .

# Control region CR(tt2l)

- ◆ Hadronic-sector cuts the same.
- ◆ Change the leptons to:  $P_T(\ell_1) > 25 \text{ GeV}$ ,  $P_T(\ell_2) > 15 \text{ GeV}$ .
- ◆ Enhance purity of tt(2l)-bgd (remove VV) requiring:  $N_b = 1$ .
- ◆ Retain scale of leptonic activity (W-boson) & gain statistics x4:
  - Relax cut: MET > 125 GeV.
  - Replace: MET  $\rightarrow L_T = \text{MET} + P_T(\ell_1) > 225 \text{ GeV}$ .
  - Replace: MET/H<sub>T</sub>  $\rightarrow L_T/H_T > 2/3$ .
- ◆ Use "SingleMu trigger" to "capture" lower MET events.
- ◆ Require "non b-tag-jet1" to maintain the SR  $P_T(\text{tt})$  kinematics.  
Only the "non-b-leading" sub-sample has similar  $P_T(\text{tt})$  with SR:

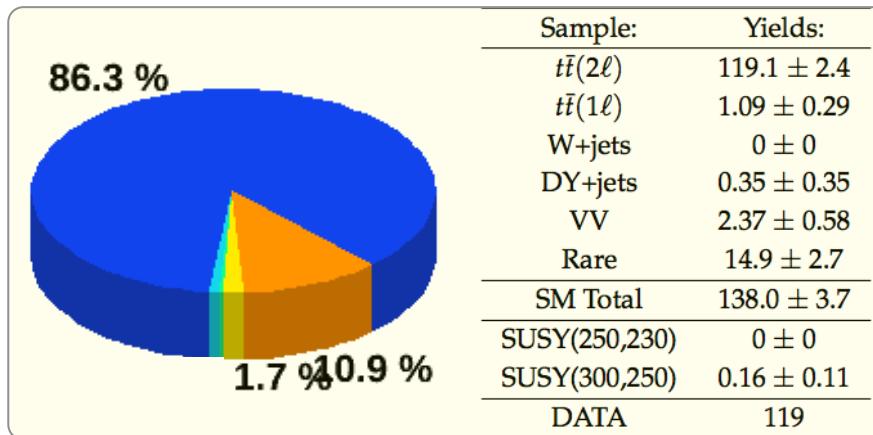


**CR(tt2l) definition:**  
(Only changes with respect to SR are listed)

$Q(\ell_1)Q(\ell_2)$	
$N_\mu$	
1st lepton flavor & ID	$\mu$ tight ID
$p_T(\ell_1)$	> 25 GeV
$p_T(\ell_2)$	> 15 GeV
$ \eta (\ell_{1,2})$	< 0.12[0.5]
$d_z(\ell_{1,2}) \& d_{xy}(\ell_{1,2})$	none [< 5 GeV]
$\text{Rel.Iso}(\ell_{1,2})$	
$\text{Ab.Iso}(\ell_{1,2})$	
$N_j$	
$N_b$ (CSVM)	= 1 & jet1: non b
$N_b$ (CSVL)	
$ \Delta\phi(\ell_1, \text{jet1}) $	
$\cancel{E}_T$	> 125 GeV
$\cancel{E}_T + p_T(\ell_1) \equiv L_T$	> 225 GeV
$ \vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) $	
$\cancel{E}_T/H_T$	
$L_T/H_T$	
$ \vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) /H_T$	
$M_{\ell\ell}$	
$M_{\tau\tau}$	
Triggers used	Single_Mu_*

# tt(2l) prediction formula

- Applying all cuts we have the following yields in CR(tt2l):



- ~ 90% purity,
  - ~ x40 higher statistics with respect to SR.
- ◆ The Prediction in SR is finally obtained by:  
- measuring data events in CR,  
- subtract the non-tt(2l) MC-events,  
- multiply with the MC-ratio of events in signal over control region:

$$PRED_{SR}^{t\bar{t}(2\ell)} = \left( DATA_{CR(t\bar{t}2l)} - MC_{CR(t\bar{t}2l)}^{non-t\bar{t}(2\ell)} \right) \left( \frac{MC_{SR}^{t\bar{t}(2l)}}{MC_{CR(t\bar{t}2l)}^{t\bar{t}(2\ell)}} \right)$$

# Non-Prompt Control Region(s)

◆ Full selection the same as in SR but **Same-Sign** events: **SR(SS)**

◆ Extend to events with:  $P_T(\ell_1) > 25$  GeV: **CR(SS)**.

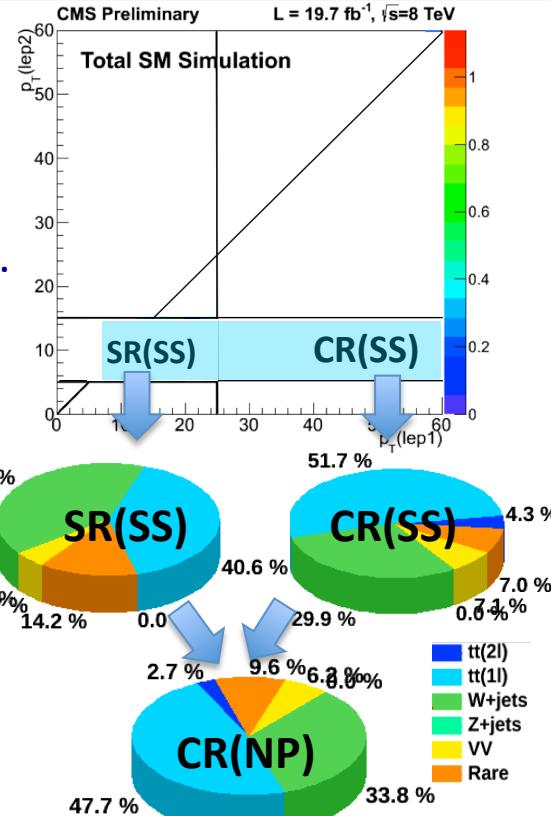
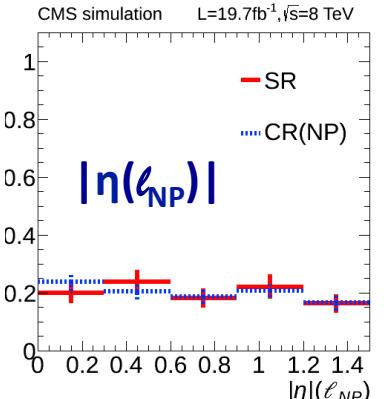
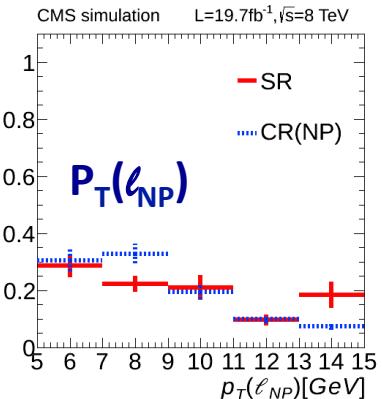
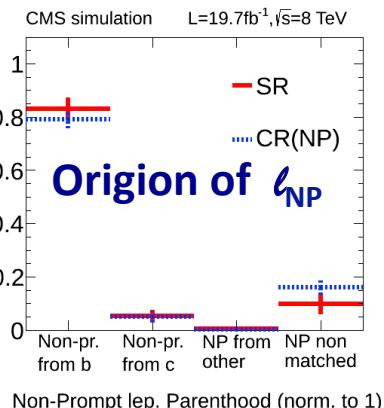
- $\ell_2$  is mostly the non-prompt one ( $\ell_{NP}$ ) which remains the same.

For the CR(SS) events:

- Relax cut: MET > 125 GeV.
- Replace: MET  $\rightarrow L_T = \text{MET} + P_T(\ell_1) > 225$  GeV.
- Replace: MET/H<sub>T</sub>  $\rightarrow L_T/H_T > 2/3$ .
- Use SingleMu trigger to trigger lower MET.

◆ Combine: **SR(SS) + CR(SS)** to: **CR(NP)**

- Test kinematical compatibility between SR and CR(NP): ✓



**CR(NP) definition:**

(Only changes with respect to SR are listed)

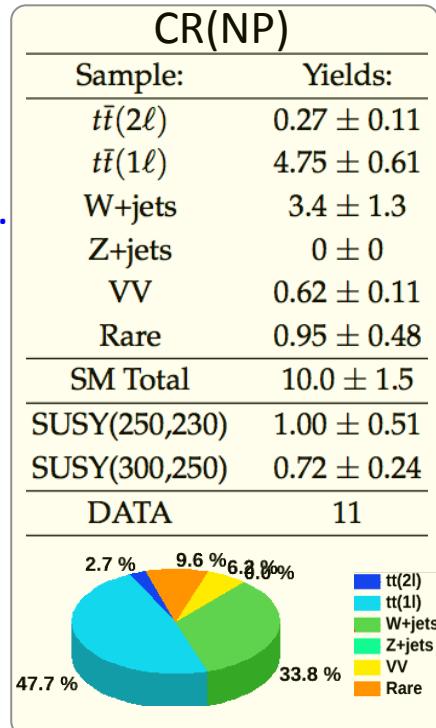
Control Regions:	CR(NP)	
Sub Regions	SR(SS)	CR2(SS)
$Q(\ell_1)Q(\ell_2)$	+1	+1
$N_\mu$		
1st lepton flavor & ID		$\mu$ tight ID $> 25$ GeV
$p_T(\ell_1)$		
$p_T(\ell_2)$		
$ \eta (\ell_{1,2})$		
$d_z(\ell_{1,2}) \& d_{xy}(\ell_{1,2})$		
$Rel.\text{Iso}(\ell_{1,2})$		
$\cancel{E}_T$		$> 125$ GeV
$\cancel{E}_T + p_T(\ell_1) \equiv L_T$		$> 225$ GeV
$ \vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) $		
$\cancel{E}_T/H_T$		none
$L_T/H_T$		$> 2/3$
$ \vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) /H_T$		
$M_{\ell\ell}$		
$M_{\tau\tau}$		
Triggers used	Single Muon*	

## ◆ The CR(NP) has:

- ~80% purity.
- ~x7 higher stat.(with respect to SR).
- Similar  $\ell_{NP}$  parenthesis.
- Similar  $\ell_{NP}$  kinematics.

## ◆ Predictions by:

- measure data in CR(NP),
- subtract rest background,
- scale with MC ratio: [SR/CR(NP)],



$$PRED_{SR}^{t\bar{t}(1\ell)\&W+jets} = \left( DATA_{CR(NP)} - MC_{CR(NP)}^{non-[t\bar{t}(1\ell)\&W+jets]} \right) \left( \frac{MC_{SR}^{t\bar{t}(1\ell)\&W+jets}}{MC_{CR(NP)}^{t\bar{t}(1\ell)\&W+jets}} \right)$$

# CR(VV): Cuts, Yields Prediction

## CR(VV) definition:

(Only changes with respect to SR are listed)

Control Regions:	CR(VV)
Sub Regions	
$Q(\ell_1)Q(\ell_2)$	
$N_\mu$	
1st lepton flavor & ID	$\mu$ tight ID
$p_T(\ell_1)$	$> 25 \text{ GeV}$
$p_T(\ell_2)$	
$ \eta (\ell_{1,2})$	
$d_z(\ell_{1,2}) \& d_{xy}(\ell_{1,2})$	
$\text{Rel.Iso}(\ell_{1,2})$	$< 0.12[0.5]$
$\text{Ab.Iso}(\ell_{1,2})$	none [ $< 5 \text{ GeV}$ ]
$N_j$	$\leq 2$
$N_b$ (CSVM)	
$N_b$ (CSVL)	$= 0$
$ \Delta\phi(\ell_1, \text{jet1}) $	$> 1$
$\cancel{E}_T$	$> 125 \text{ GeV}$
$\cancel{E}_T + p_T(\ell_1) \equiv L_T$	$> 225 \text{ GeV}$
$ \vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) $	
$\cancel{E}_T/H_T$	none
$L_T/H_T$	$> 2/3$
$ \vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) /H_T$	
$M_{\ell\ell}$	$> 50 \text{ GeV}$
$M_{\tau\tau}$	
Triggers used	Single Mu.*

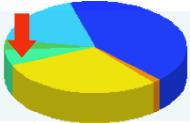
Appling all the CR(VV) the yielded bkgd is:

CR(VV)	
Sample:	Yields:
$t\bar{t}(2\ell)$	$30.3 \pm 1.2$
$t\bar{t}(1\ell)$	$0.30 \pm 0.14$
W+jets	$0 \pm 0$
DY+jets	$4.9 \pm 1.3$
VV	$45.9 \pm 1.8$
Rare	$6.4 \pm 1.7$
SM Total	$87.8 \pm 3.0$
SUSY(250,230)	$0 \pm 0$
SUSY(300,250)	$0.50 \pm 0.20$
DATA	81

The Prediction Formula is outlined:

- Measure data in CR(VV)
- Subtract rest predicted background
- Scale with MC ratio SR/CR(NP)

$$PRED_{SR}^{VV} = \left( DATA_{CR(VV)} - PRED_{CR(VV)}^{t\bar{t}, Z, W} - MC_{CR(VV)}^{Rare} \right) \left( \frac{MC_{SR}^{VV}}{MC_{CR(VV)}^{VV}} \right)$$

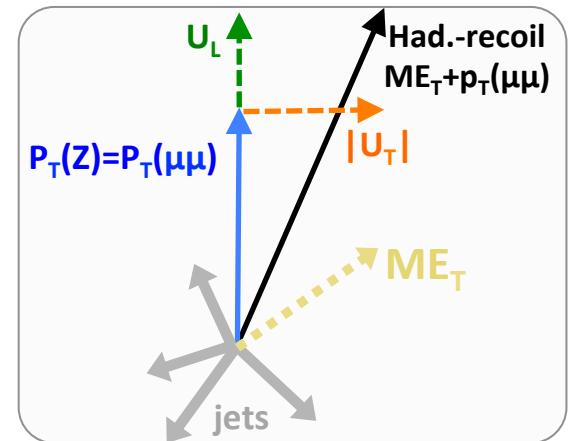


# Prediction of DY+jets

*Define 2 different CR for 2 different corrections*

◆ [1] CR(Z) use to correct the hadronic-recoil:

- Same hadronic cuts.
- Select  $Z \rightarrow \mu\mu$  events, high statistics,  $\sim 100\%$  purity.
- Replace MET with:  $|p_T(\mu_1) + p_T(\mu_2)| = P_T(Z)$
- Measure [data/MC] ratios in “3D-bins of:  $P_T(Z)$ ,  $U_L$ ,  $|U_T|$ .
- Apply an event-per-event correction for each SR event multiplying with its corresponding ratio:



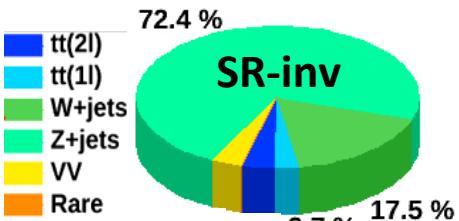
$$(MC_{SR}^{Z+jets})_{recoil-corr} = MC_{SR}^{Z+jets} \left( \frac{DATA_{CR(Z)}}{MC_{CR(Z)}} \right)_{P_T(Z), U_L, |U_T|}$$

◆ [2] SR-inv. Used to correct potential miss-modeling of  $\tau$ -decay:

$Z \rightarrow \tau\tau \rightarrow \ell\ell v_\tau v_\tau v_l v_l$  to soft leptons.

- Exactly the same cuts as SR but with inverted  $M(\tau\tau):[0,160]$  GeV cut.

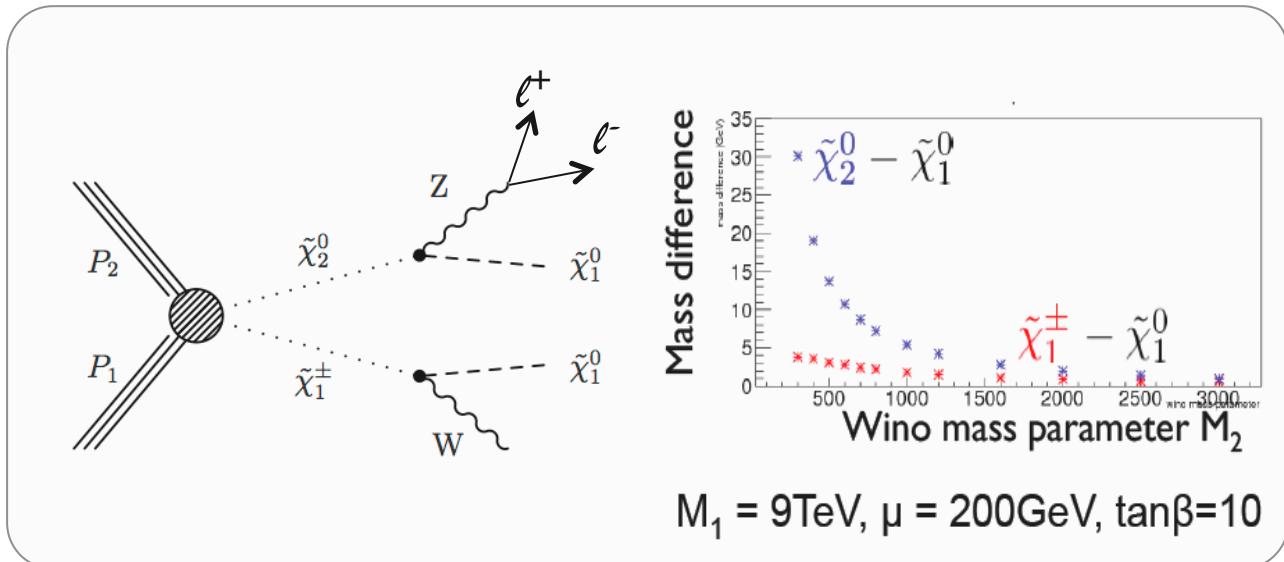
- 70% pure sample,
- usual method but subtracting predictions:



SR-inv. Yields	
Sample:	Yields:
$t\bar{t}(2\ell)$	$0.15 \pm 0.08$
$t\bar{t}(1\ell)$	$0.11 \pm 0.11$
W+jets	$0.67 \pm 0.67$
DY+jets	$2.80 \pm 0.91$
VV	$0.13 \pm 0.09$
Rare	$0 \pm 0$
SM Total	$3.9 \pm 1.1$
SUSY(250,230)	$1.12 \pm 0.48$
SUSY(300,250)	$0.57 \pm 0.22$
DATA	5

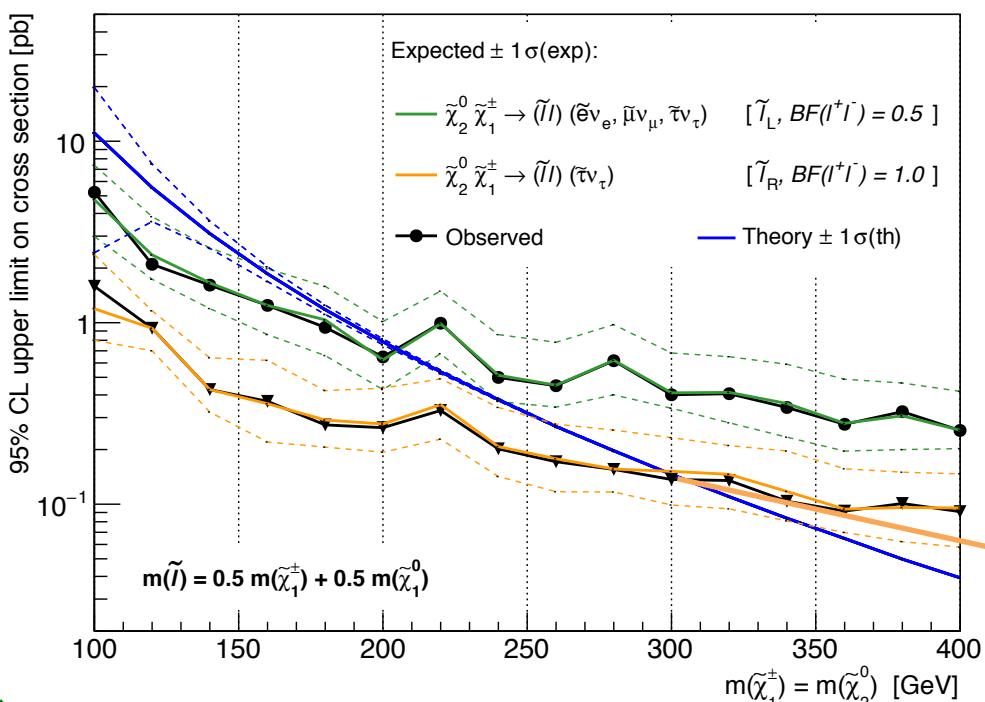
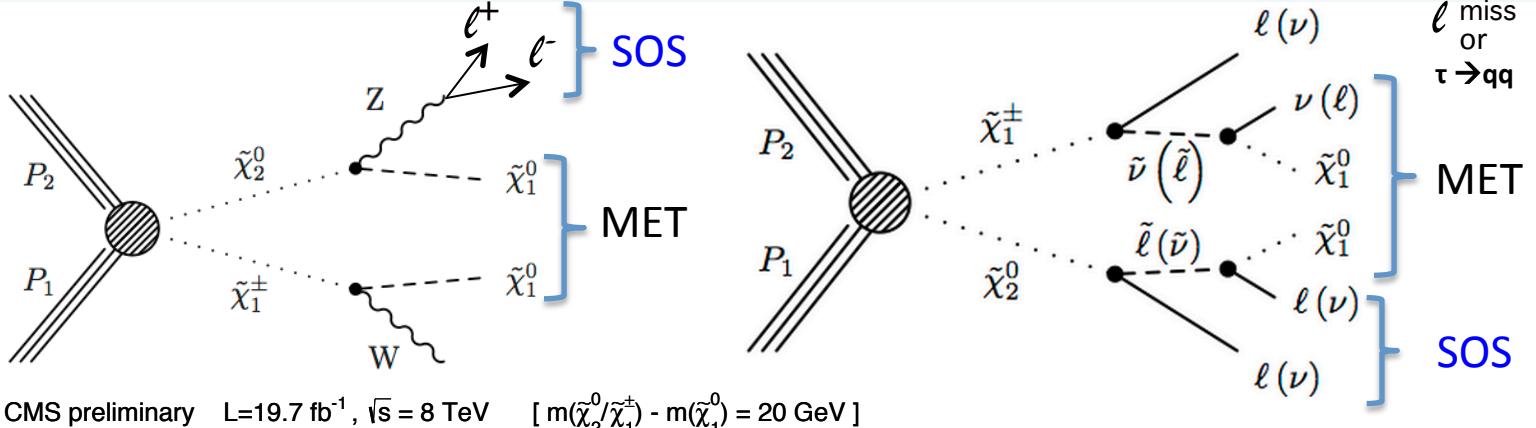
$$PRED_{SR}^{Z+jets} = (DATA_{SR-inv} - PRED_{SR-inv}^{non-Z+jets}) \left( \frac{MC_{SR}^{Z+jets}}{MC_{SR-inv}^{Z+jets}} \right)_{recoil-corr}$$

# Compressed EWKinos



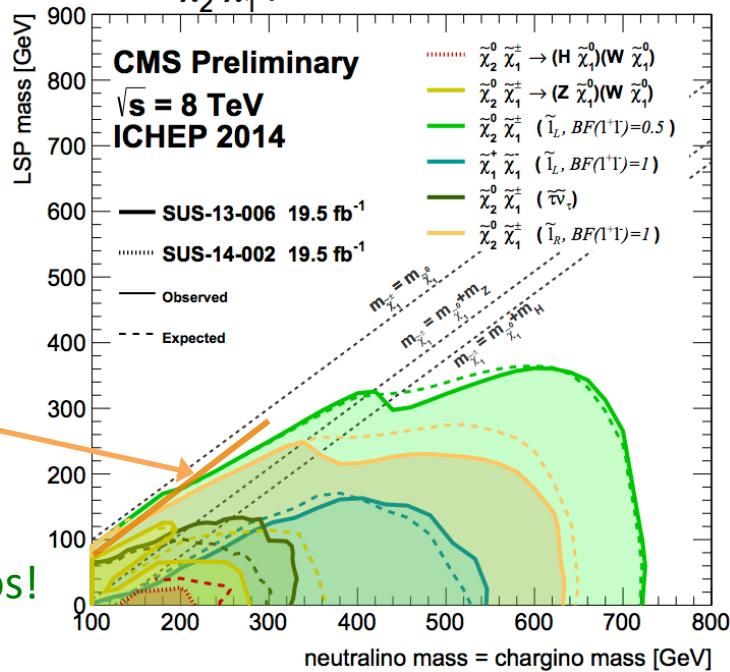
- $\mu \sim 200 \text{ GeV}$  (natural)  $\ll M_1$  (bino),  $M_2$  (wino): Then: LSP,  $\tilde{\chi}_2^0$ ,  $\tilde{\chi}_1^\pm$  higgsinos masses compressed.
- For Ewkinos mass degeneracy is not an accidental feature, but a consequence of the mixing.
- Soft dilepton + ISR can probe this topology!

# Alternative interpretations: EWKino $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ production



- ◆ Soft OS lepton allow searches for compressed EWKinos!
- ◆ Exclusion up to 300 GeV in “ $\tau$ ”-enriched scenario.

1) flavor-democratic:  $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow l^+ l^- l^\pm \nu 2\tilde{\chi}_2^0$   
 2) “ $\tau$ ”-enriched:  $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow l^+ l^- \tau^\pm \nu 2\tilde{\chi}_2^0$   
 $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$  production

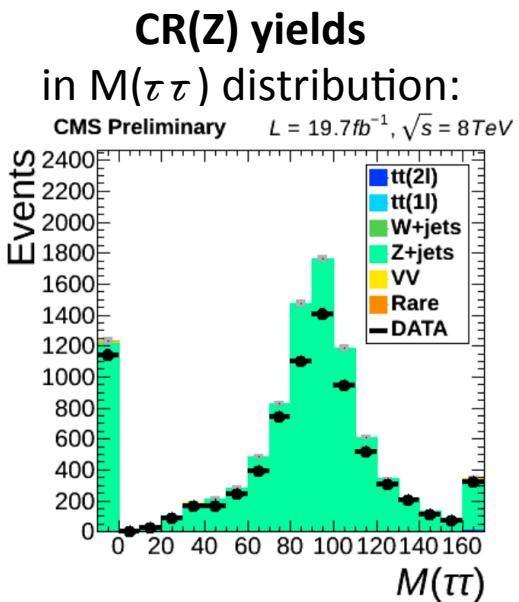


# Control regions for DY+jets

We define 2 different Control regions:

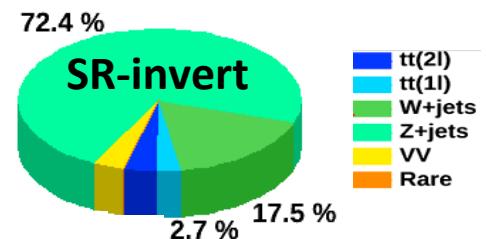
- **CR(Z):** Used for hadronic recoil corr.
  - same hadronic cuts,
  - select  $Z \rightarrow \mu\mu$  events,
  - Replace MET with  $|p_T(\mu_1) + p_T(\mu_2)|$

- **SR-invert:** Used to correct a potential missmodeling of the tau decay:  
 $Z \rightarrow \tau\tau \rightarrow \ell\ell\nu_\tau\nu_\tau\nu_\ell\nu_\ell$  to soft leptons.
  - same cuts as SR,
  - but with **inverted  $M(\tau\tau)$ : [0,160] GeV cut.**



Control Regions: Sub Regions	CR(Z)	
	CR(Z)	SR-inv
$Q(\ell_1)Q(\ell_2)$		
$N_\mu$	= 2	
1st lepton flavor & II		
$p_T(\ell_1)$	$\mu$ tight ID $> 125 \text{ GeV}$	
$p_T(\ell_2)$	$> 10 \text{ GeV}$ , $\mu$ tight ID $< 2.1$	
$ \eta (\ell_{1,2})$	$< 0.02$ & $< 0.5 \text{ cm}$	
$d_z(\ell_{1,2}) \& d_{xy}(\ell_{1,2})$	$< 0.12$	
$Rel.Iso(\ell_{1,2})$	none	
$Ab.Iso(\ell_{1,2})$	none	
$E_T$		
$E_T + p_T(\ell_1) \equiv L_T$	$> 200 \text{ GeV}$	
$ \vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) $	none	
$E_T/H_T$		
$L_T/H_T$		
$ \vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) /H_T$	$> 2/3$	
$M_{\ell\ell}$	$> 10 \text{ GeV}$	
$M_{\tau\tau}$	none	(0,160) GeV
Triggers used	Single_Mu_*	

(Only changes with respect to SR are listed)

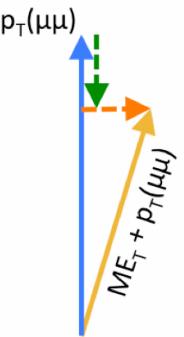


## SR-invert Yields

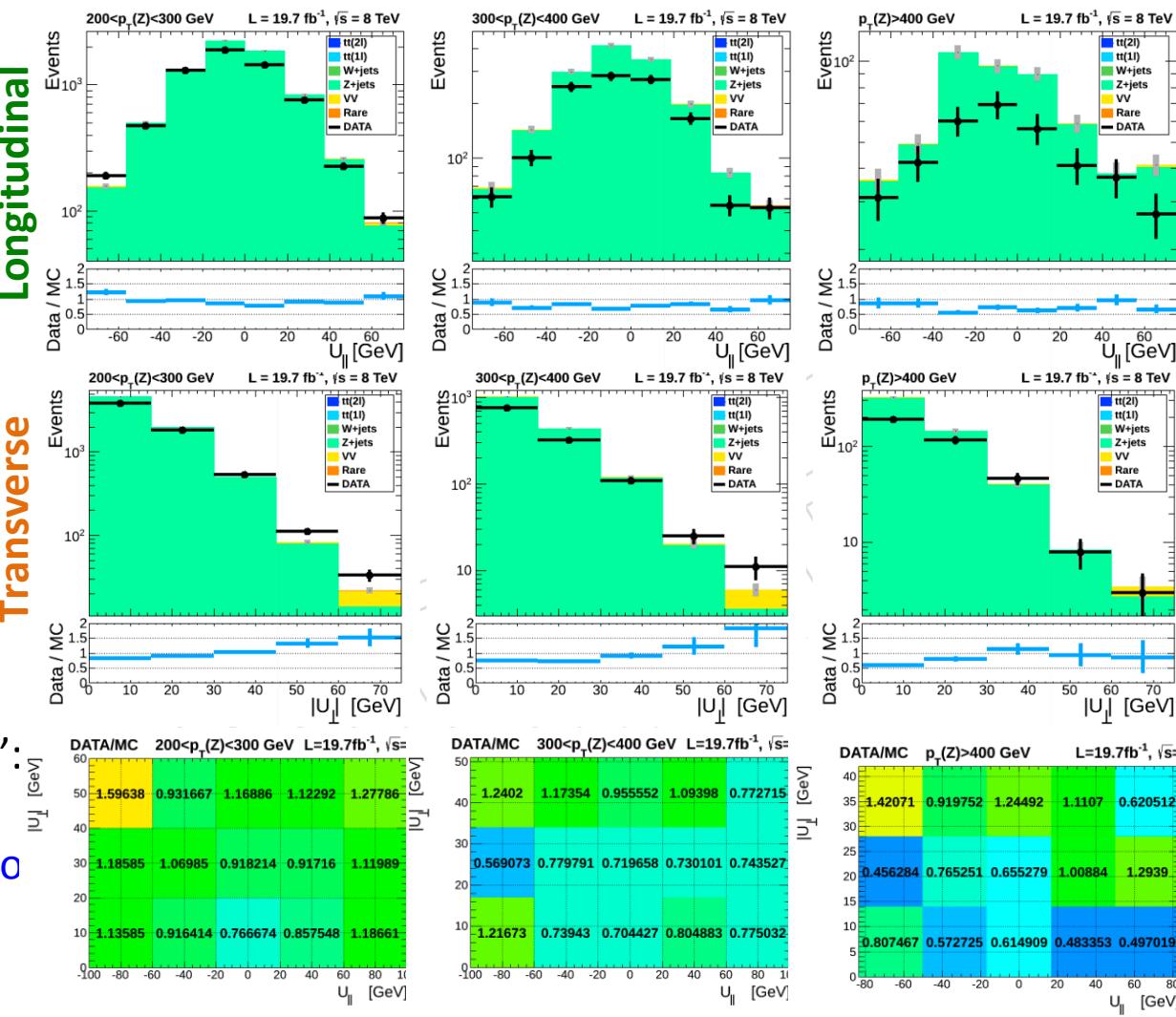
Sample:	Yields:
$t\bar{t}(2\ell)$	$0.15 \pm 0.08$
$t\bar{t}(1\ell)$	$0.11 \pm 0.11$
W+jets	$0.67 \pm 0.67$
DY+jets	$2.80 \pm 0.91$
VV	$0.13 \pm 0.09$
Rare	$0 \pm 0$
SM Total	$3.9 \pm 1.1$
SUSY(250,230)	$1.12 \pm 0.48$
SUSY(300,250)	$0.57 \pm 0.22$
DATA	5

# Control region CR(Z): The $U_L, U_T$ in 3 $p_T(z)$ bins

- Decompose hadronic recoil to  $U_L, U_T$  across  $p_T(\mu\mu)$

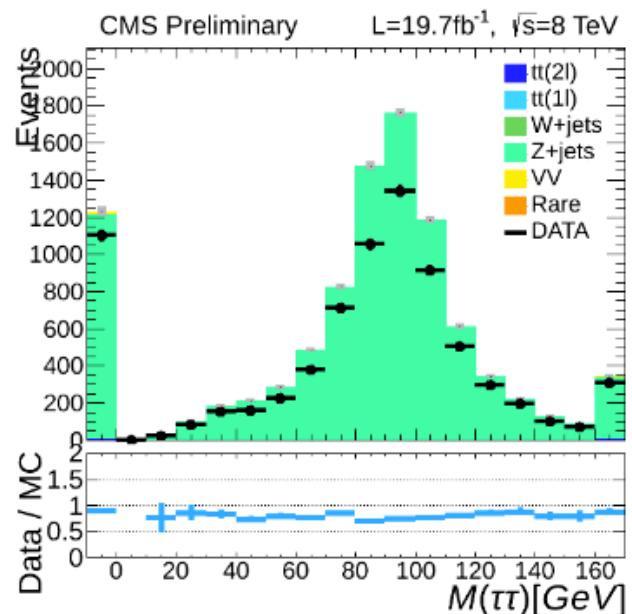
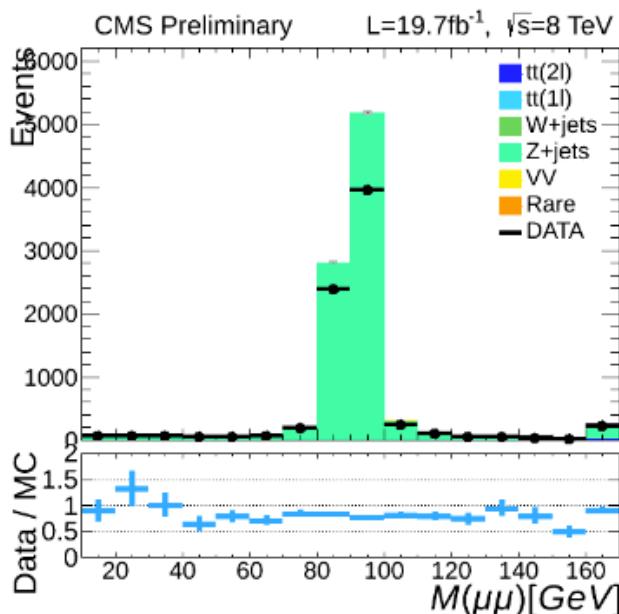
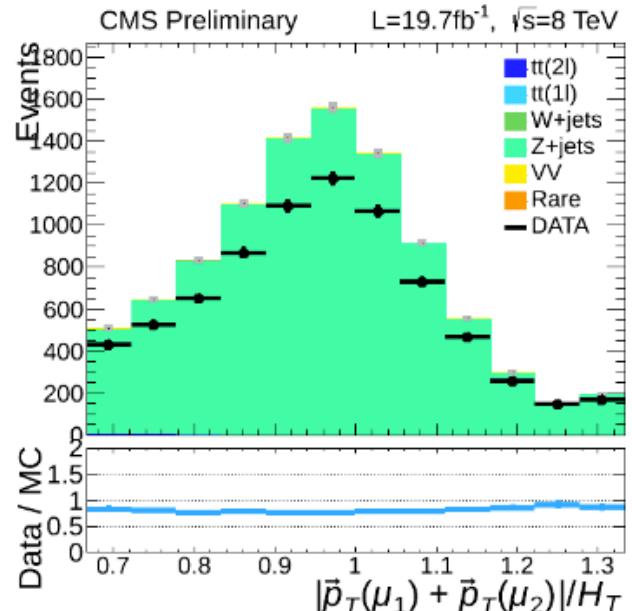
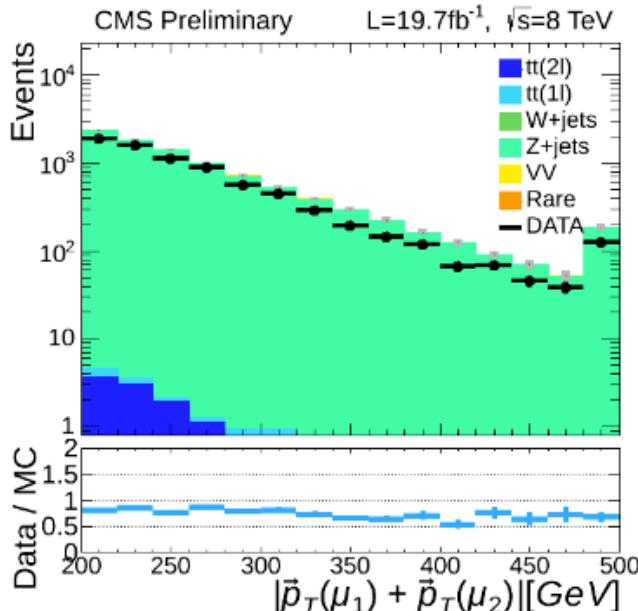


- Form 2-D Data/MC Ratio in 3  $p_T(\mu\mu)$  bins to correct Z+jets hadronic recoil in SR.

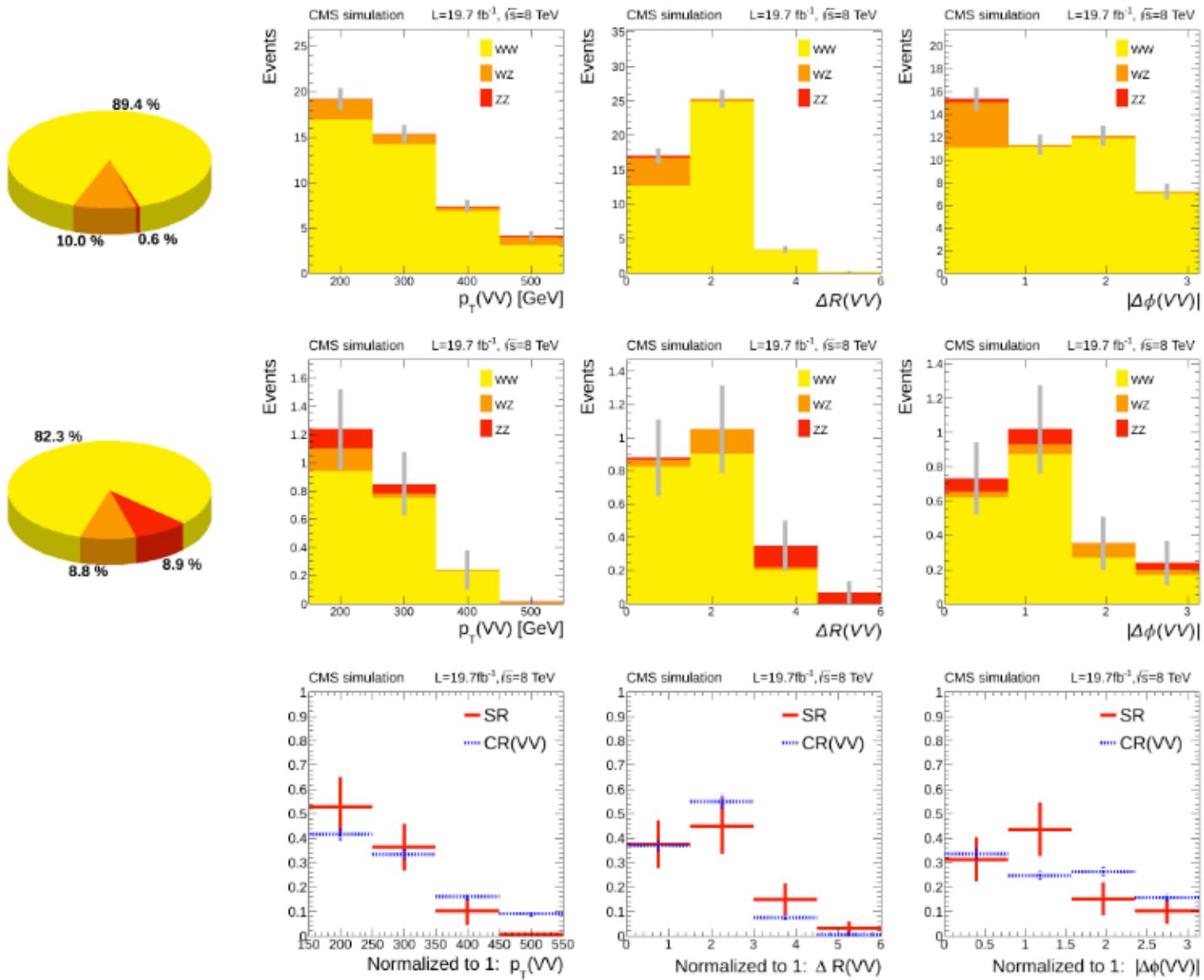


Ratio yields are corrected due to hadronic recoil via the CR(Z) sample

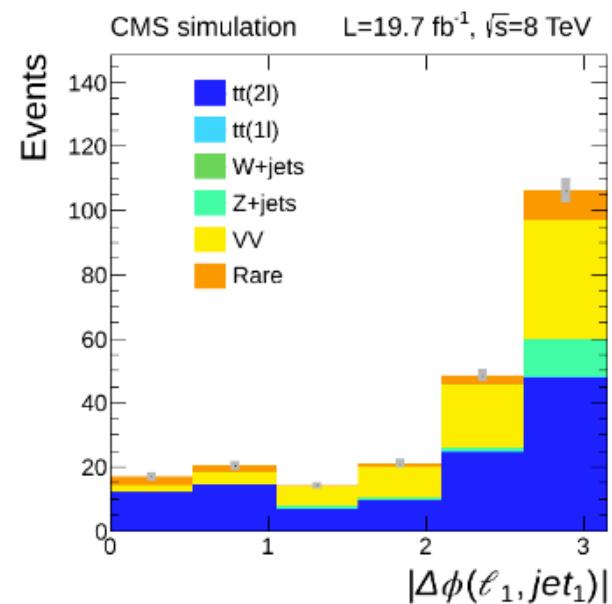
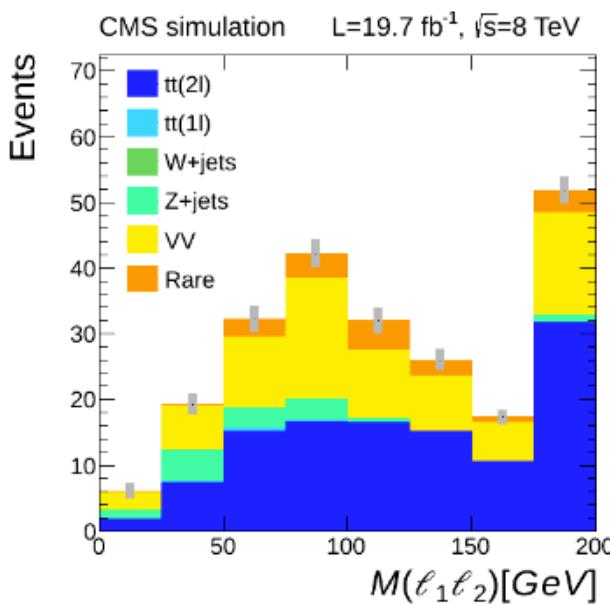
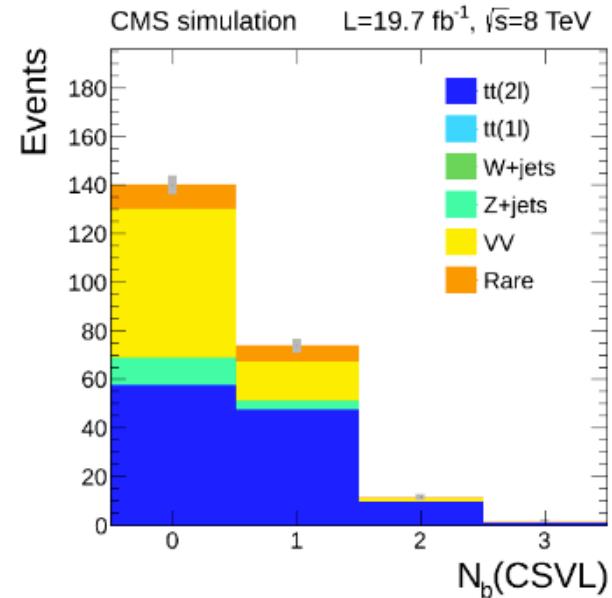
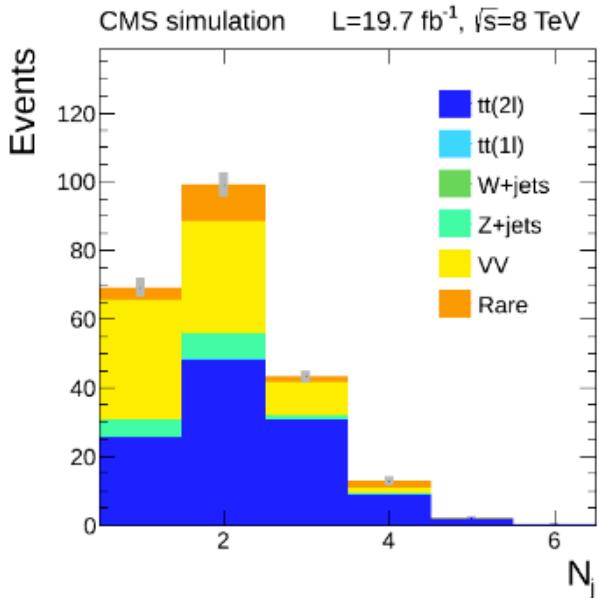
# Control region CR(Z)



# Control region CR(VV)



# Control region CR(VV)



# Control region CR(Z)

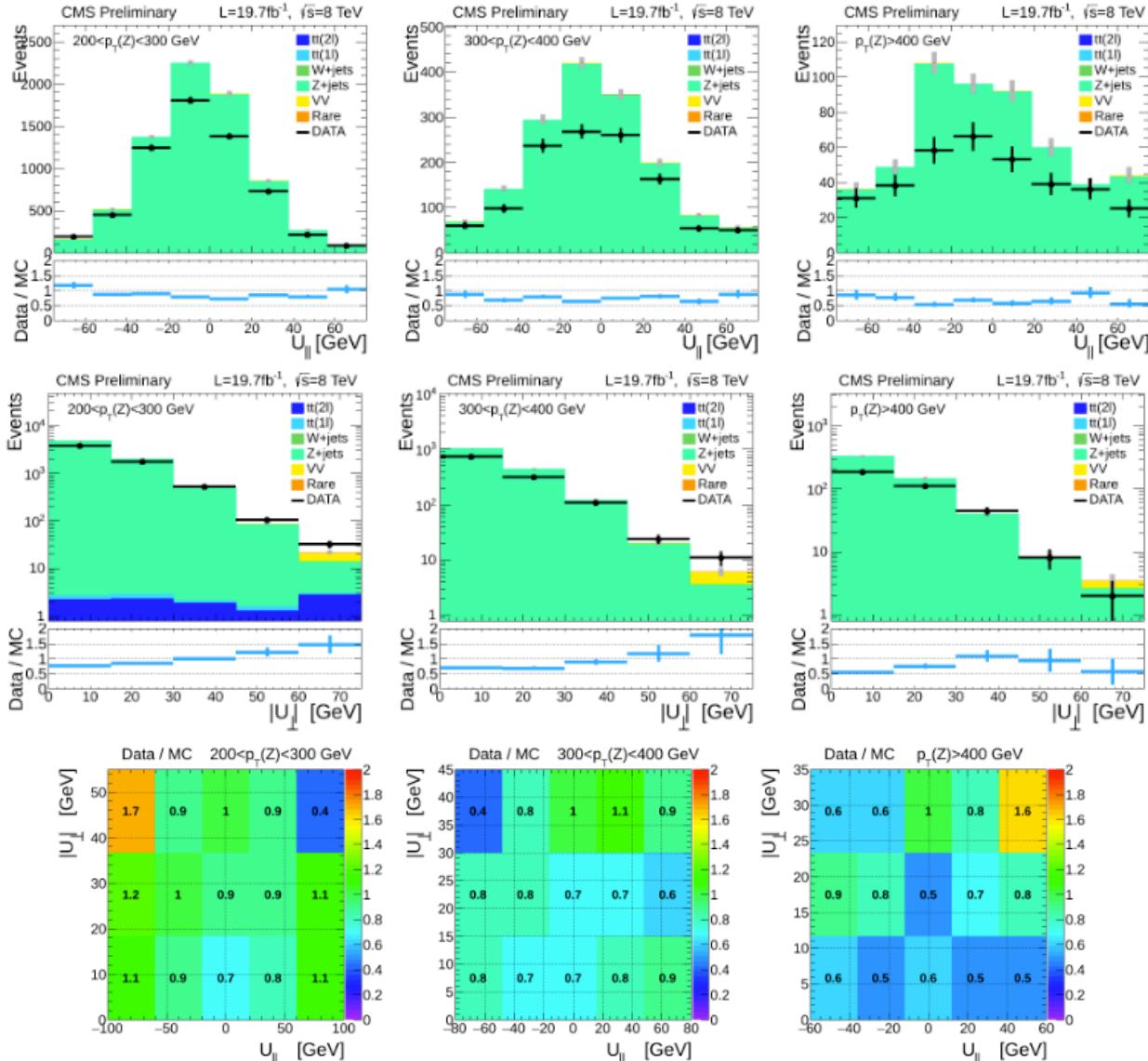


Figure 2.11: The data over MC(reco) ratios of the CR(Z) events, as distributed over the:  $p_T(Z), U_L, |U_T|$  variables. From left to right bins:  $200 < p_T(Z) < 300 \text{ GeV}$ ,  $300 < p_T(Z) < 400 \text{ GeV}$ ,  $p_T(Z) > 400 \text{ GeV}$ . These are the values used for the event-per-event 1<sup>st</sup> – step correction.

## Control region CR(Z)

