Searches for strong production of SUSY in final states with two or more leptons at CMS

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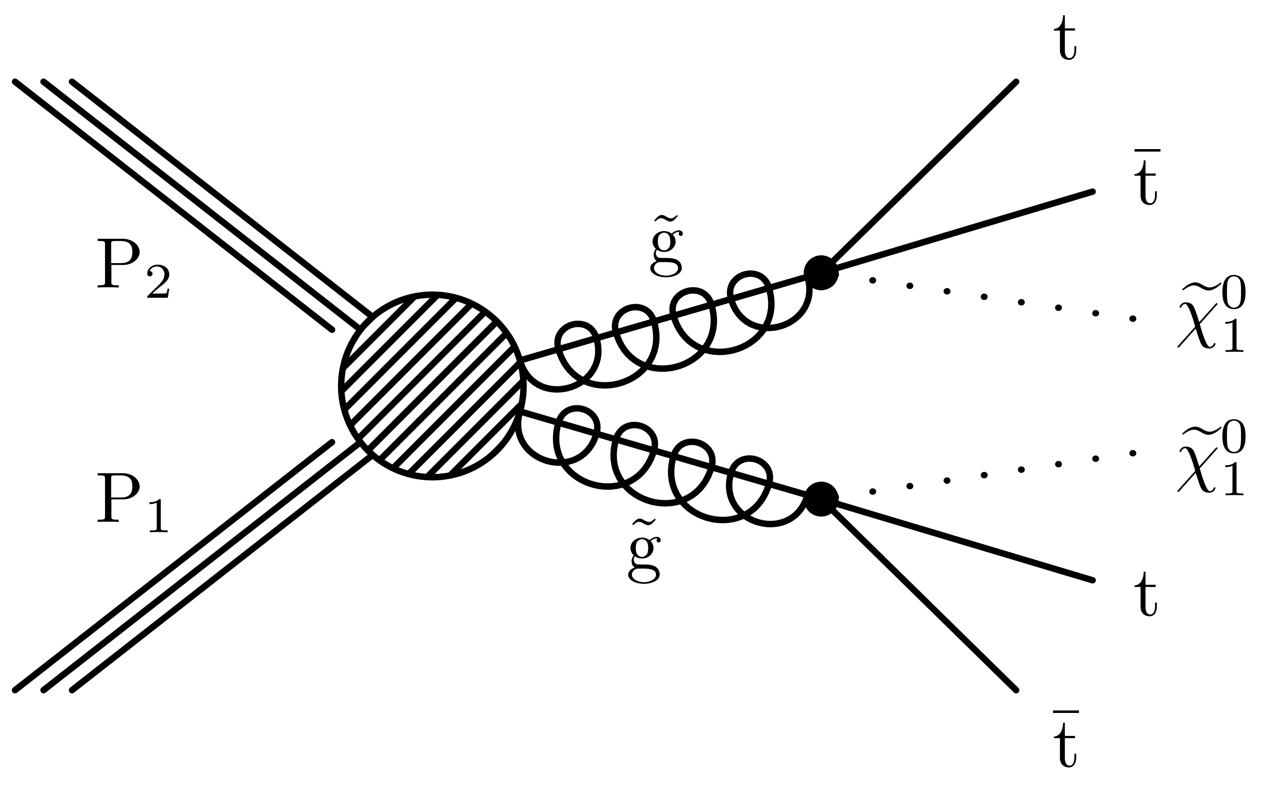
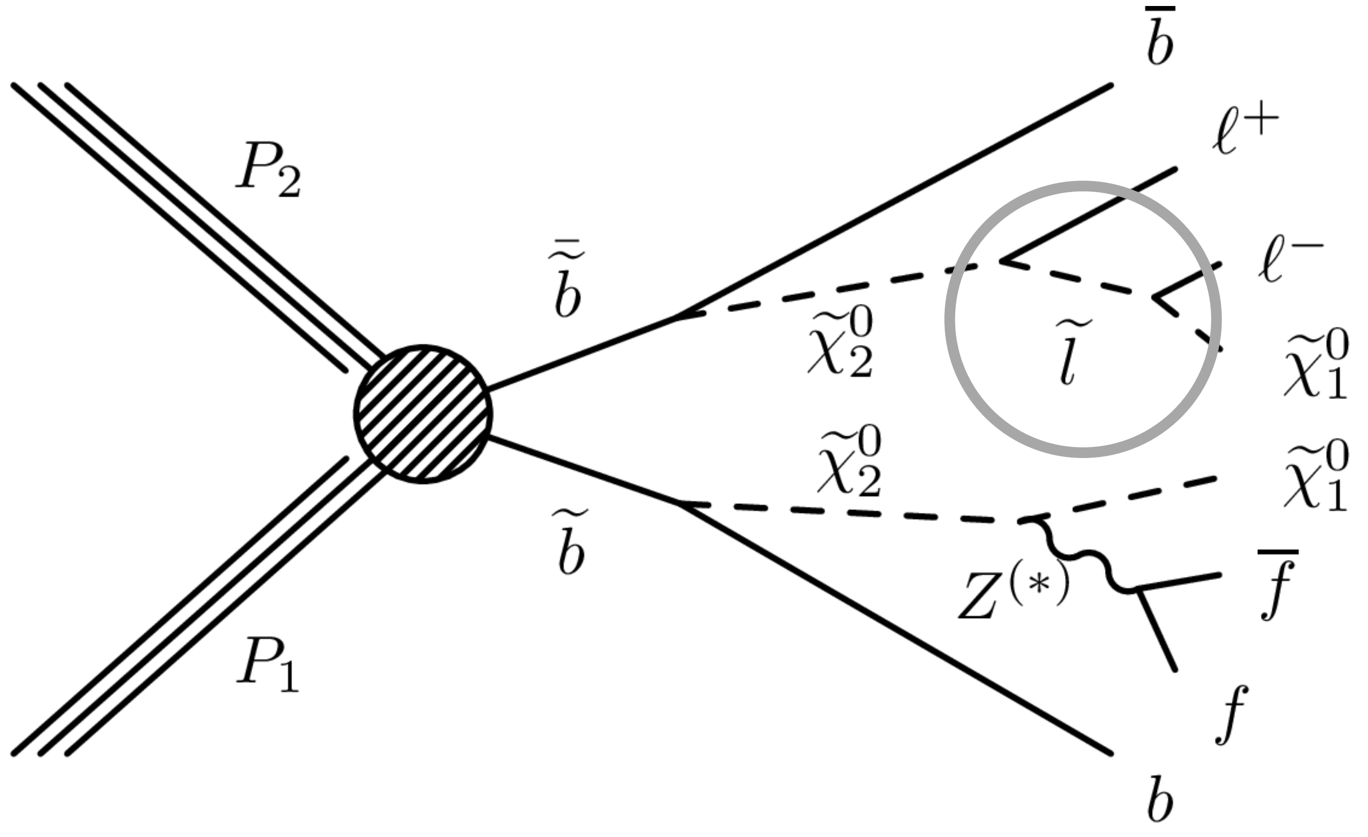
SUSY17 Mumbai

Searching for strong SUSY in leptonic final states

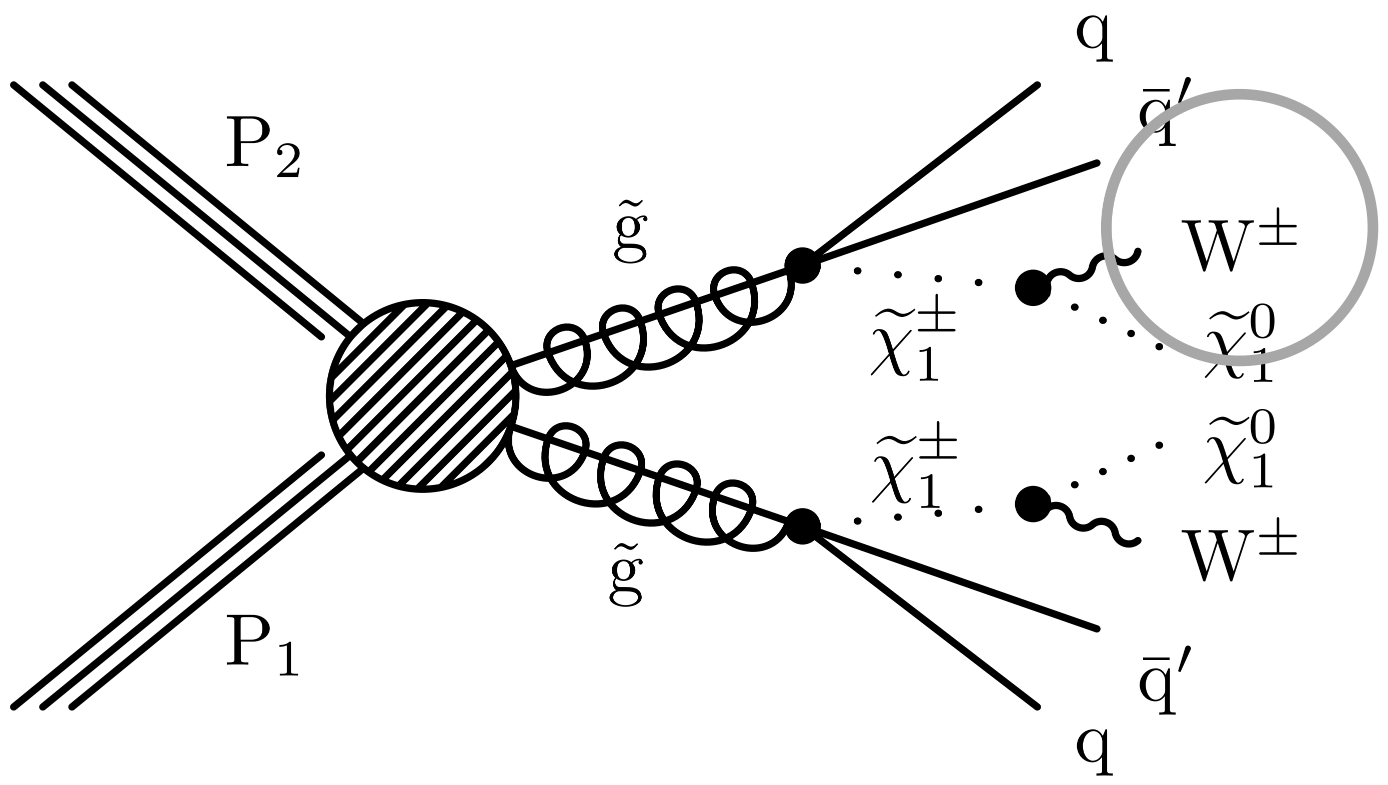
Leptons appear naturally in decay chains of **strongly produced SUSY**



In decays of top quarks from (virtual) top squark decays.



In decays involving sleptons



In decays from W/Z/H bosons from chargino/neutralino decays

Leptonic final states of interest:

- Light stops in "natural" SUSY models + flavor conservation → top quarks → leptons
- Charged leptons are measured with large efficiency and precision in CMS
- Main background processes well understood and can often be estimated from data

Covered searches for strong SUSY in leptonic final states

Dilepton searches (OS, LS):

- CMS-SUS-16-034: Search for new phenomena in final states with **two opposite-sign, same-flavor** leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s}$= 13 TeV
  - arXiv:1709.08908
- CMS-SUS-16-035: Search for physics beyond the standard model in events with **two leptons of same sign**, missing transverse momentum, and jets in proton-proton collisions at $\sqrt{s}$= 13 TeV.
  - arXiv:1704.07323

Multilepton search:

- CMS-SUS-16-041: Search for new physics in events with **multileptons** and jets in 35.9 fb^{-1} of proton-proton collision data at $\sqrt{s}$= 13 TeV
  - arXiv:1710.09154

- The electroweak SUSY searches with CMS covered by Laurent Thomas (Thursday)
- The direct slepton and stau production searches with CMS covered by Illia Babounikau (Thursday)

Searches for SUSY with opposite sign dileptons:

Search for new phenomena in final states with two opposite-sign, same-flavor leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s}$= 13 TeV

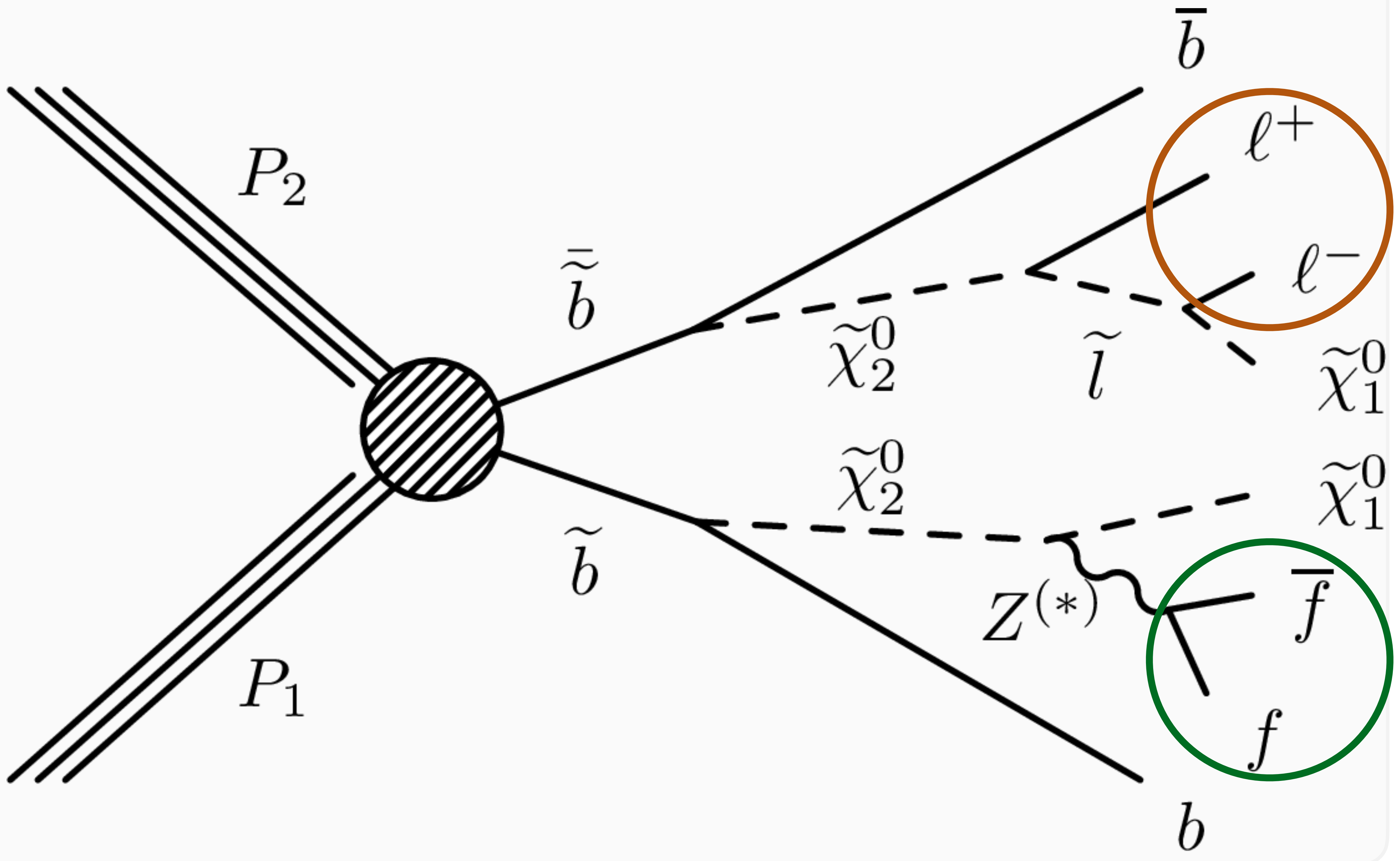
CMS-SUS-16-034

arXiv:1709.08908

SUSY with opposite sign dileptons

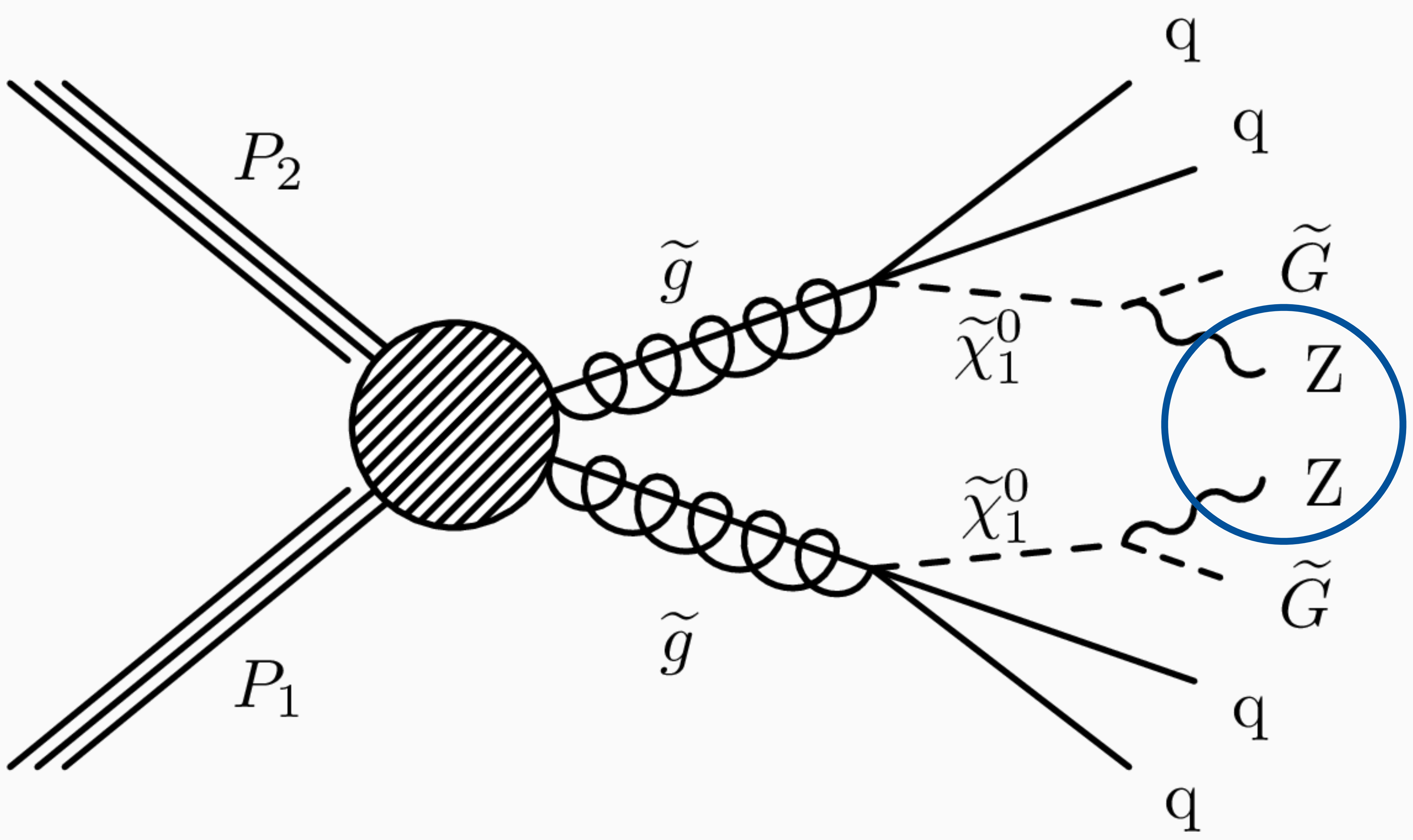
Sbottom induced:

- cascade decay resulting in kinematic edge in invariant mass ("Edge")
- or off-shell Z boson



Gluino induced:

- probes gauge mediated supersymmetry breaking (GMSB)
- resonant Z production ("On-Z")



Search strategy: OSSF

Baseline selection

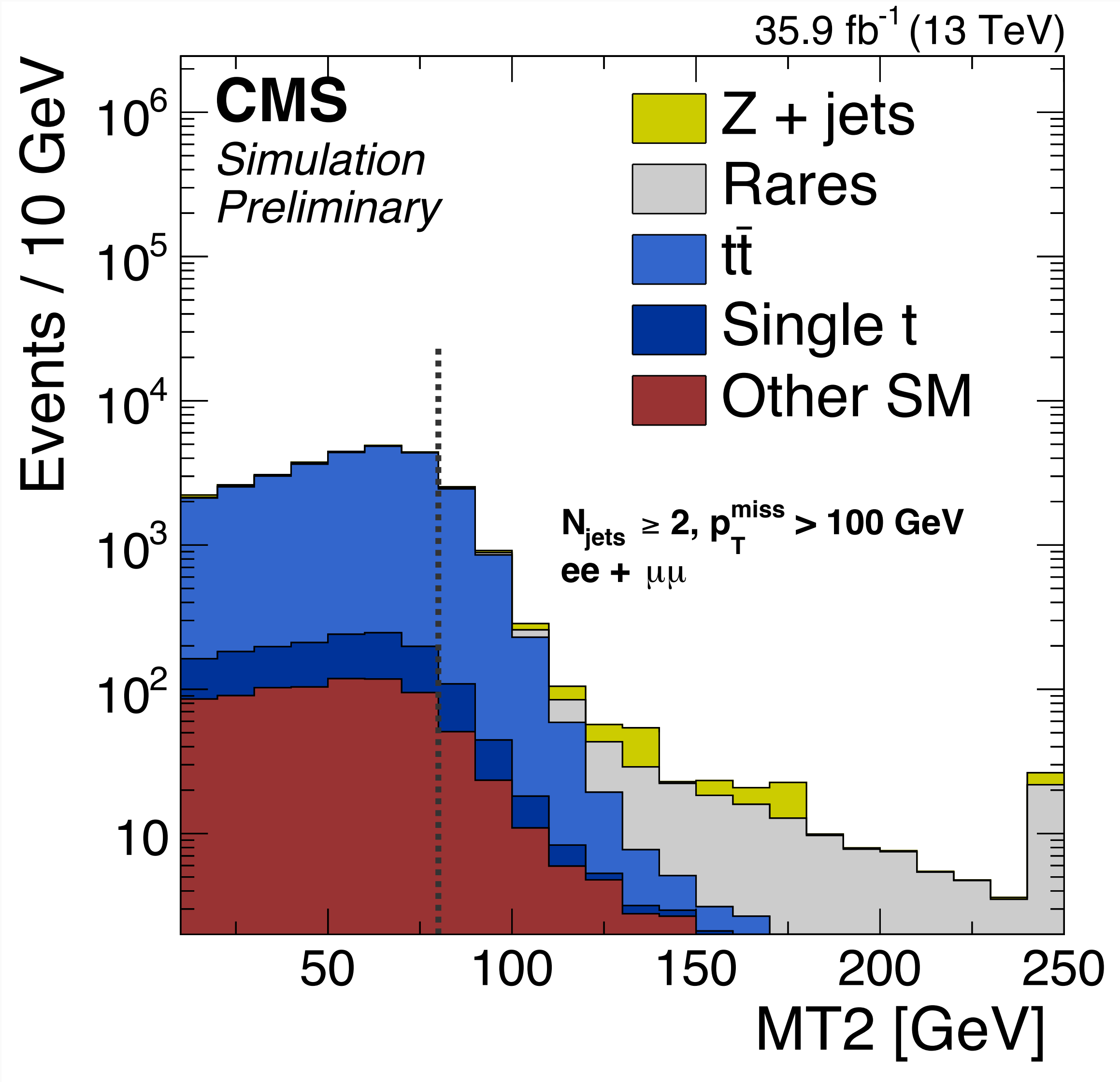
- 2 opposite sign leptons, $p_T^{miss} > 100$ GeV, ≥ 2 jets
- $M_{T2} \geq 80$ GeV

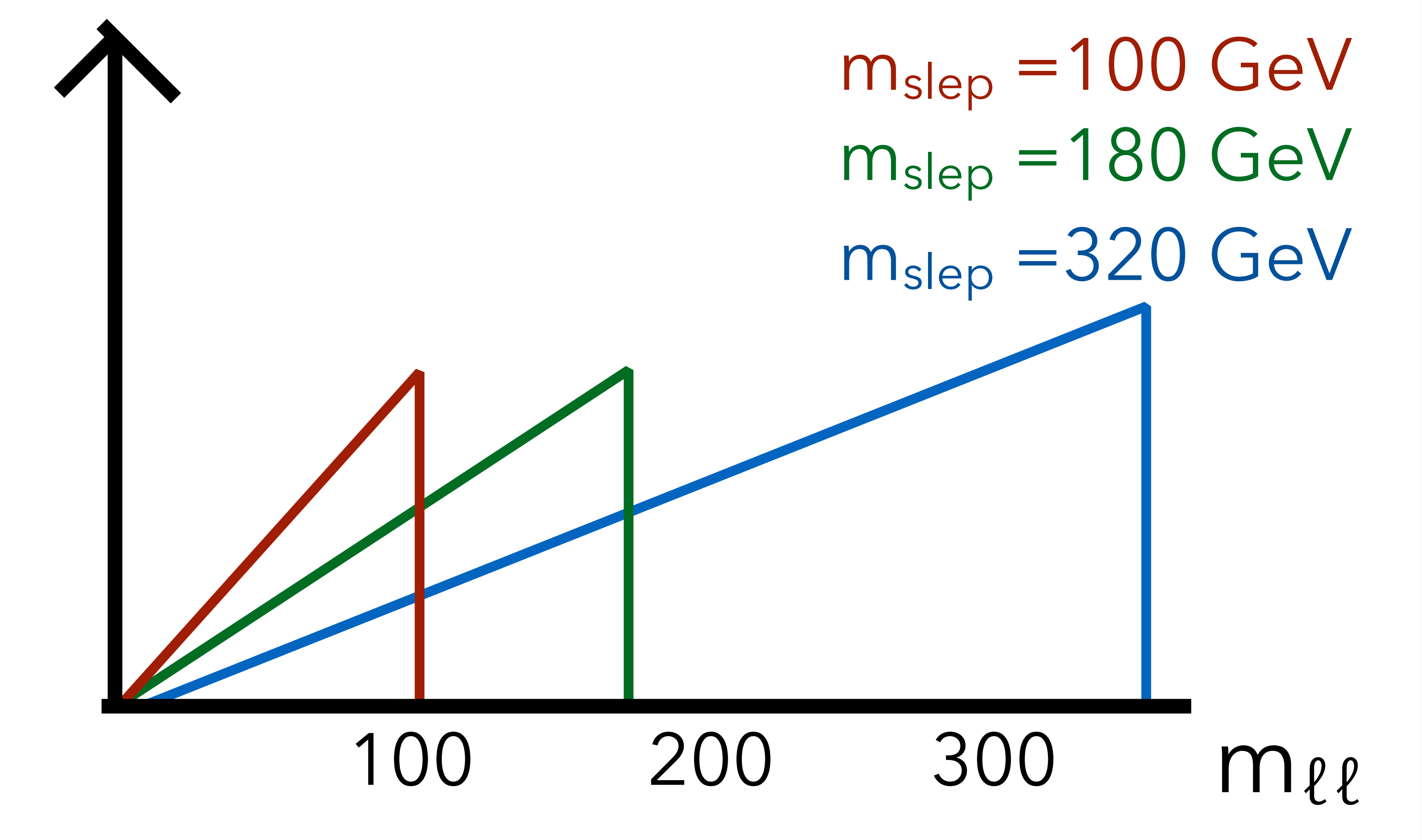
Resonant contribution on the Z peak ("On-Z"):

- binning in b-jet and jet multiplicity, H_T and p_T^{miss}

Edge like feature in $m_{\ell\ell}$ outside the Z window ("Edge"):

- kinematic fit for edge shaped feature in full mass range
- counting experiment binned in $m_{\ell\ell}$ and a **multivariate discriminant to classify events as tt̄ or non-tt̄ like**
  - tt̄ likelihood

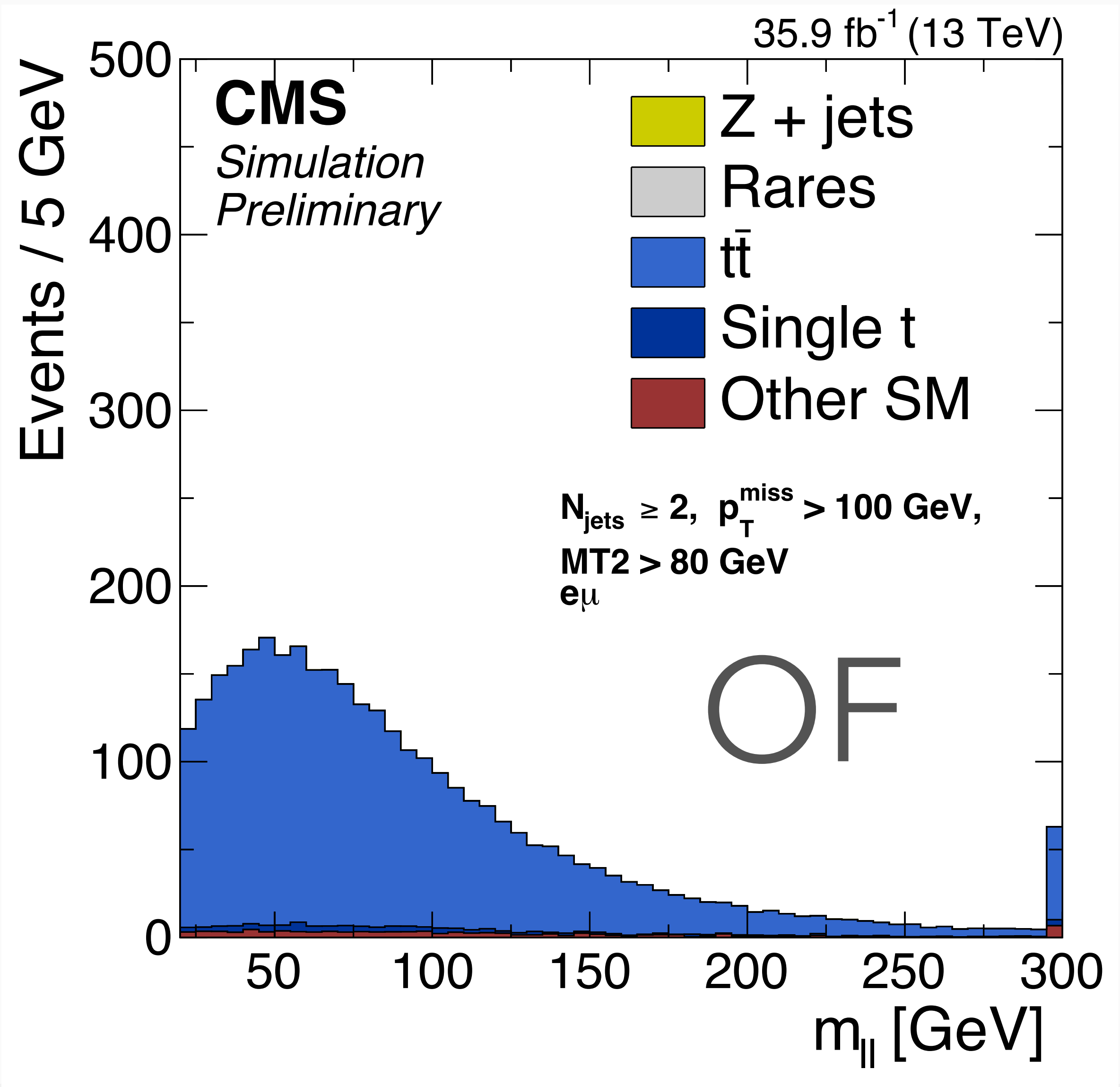


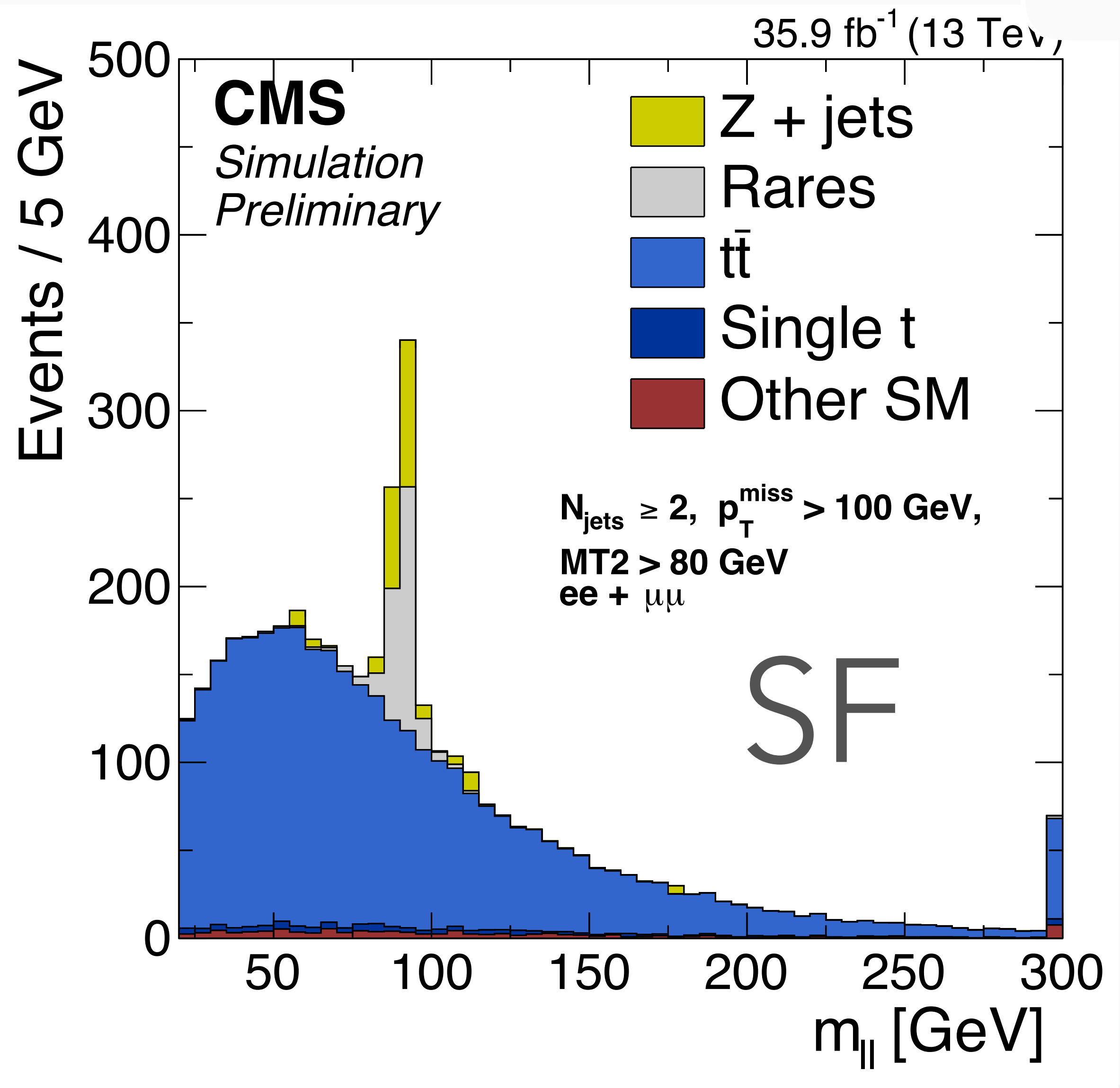


Search strategy: OSSF

Flavor symmetric (data driven) ($t\bar{t}$):

- main background in **Edge** search
- relies on the lepton universality of W decays
  - **#same flavor** ≃**#opposite flavor** lepton pairs
- ee and μμ signal estimated from eμ control sample





Z+jets (data driven):

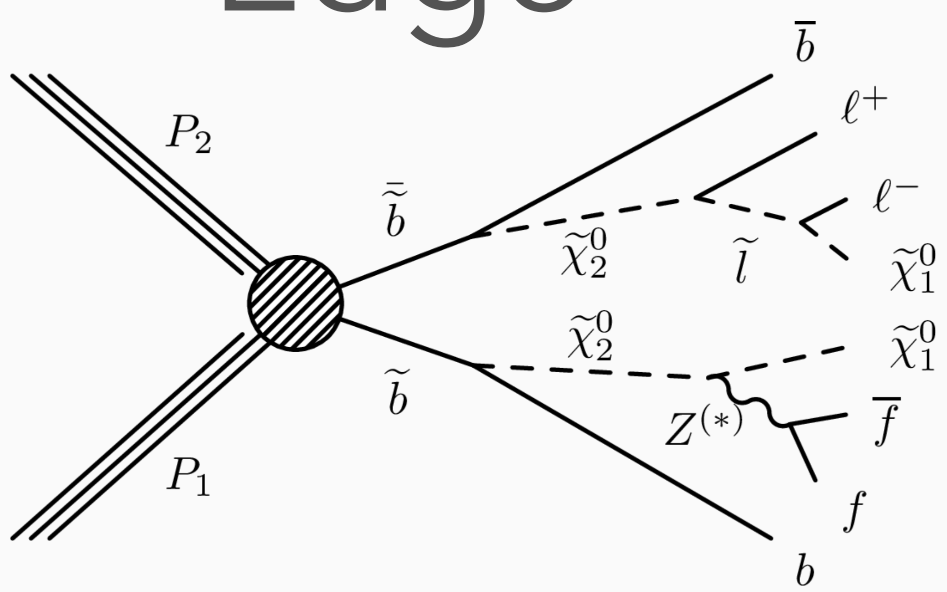
- main background in **On-Z** search
- p_T^{miss} in $Z \rightarrow \ell\ell$ is mainly from jet mismeasurements
- predict p_T^{miss} in Z+jets with p_T^{miss} in γ+jets

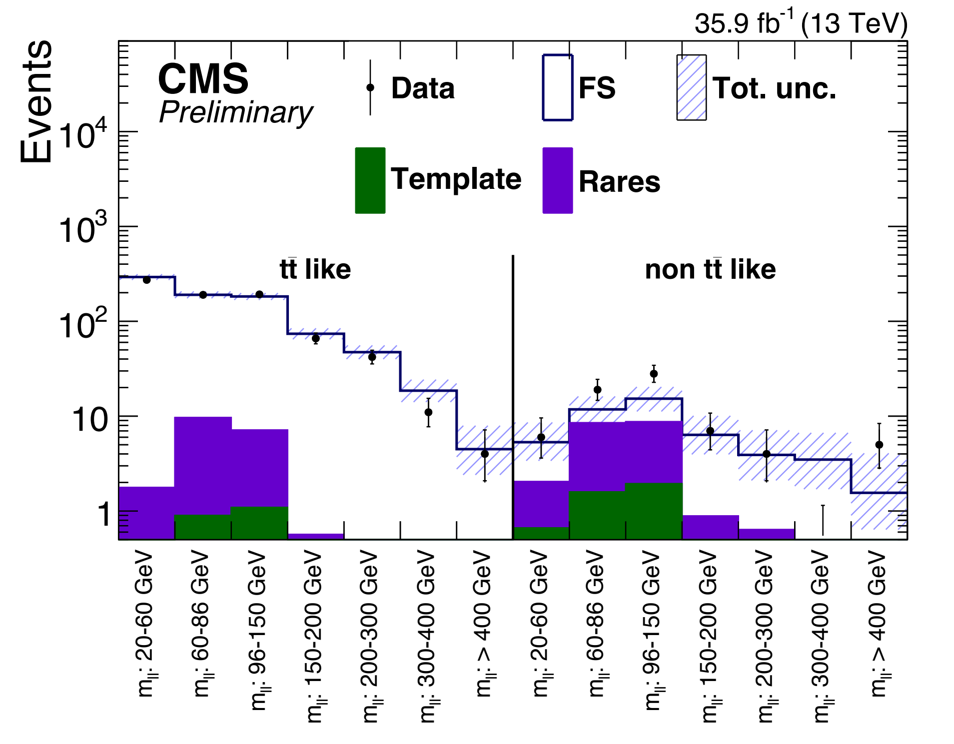
Remaining backgrounds (MC):

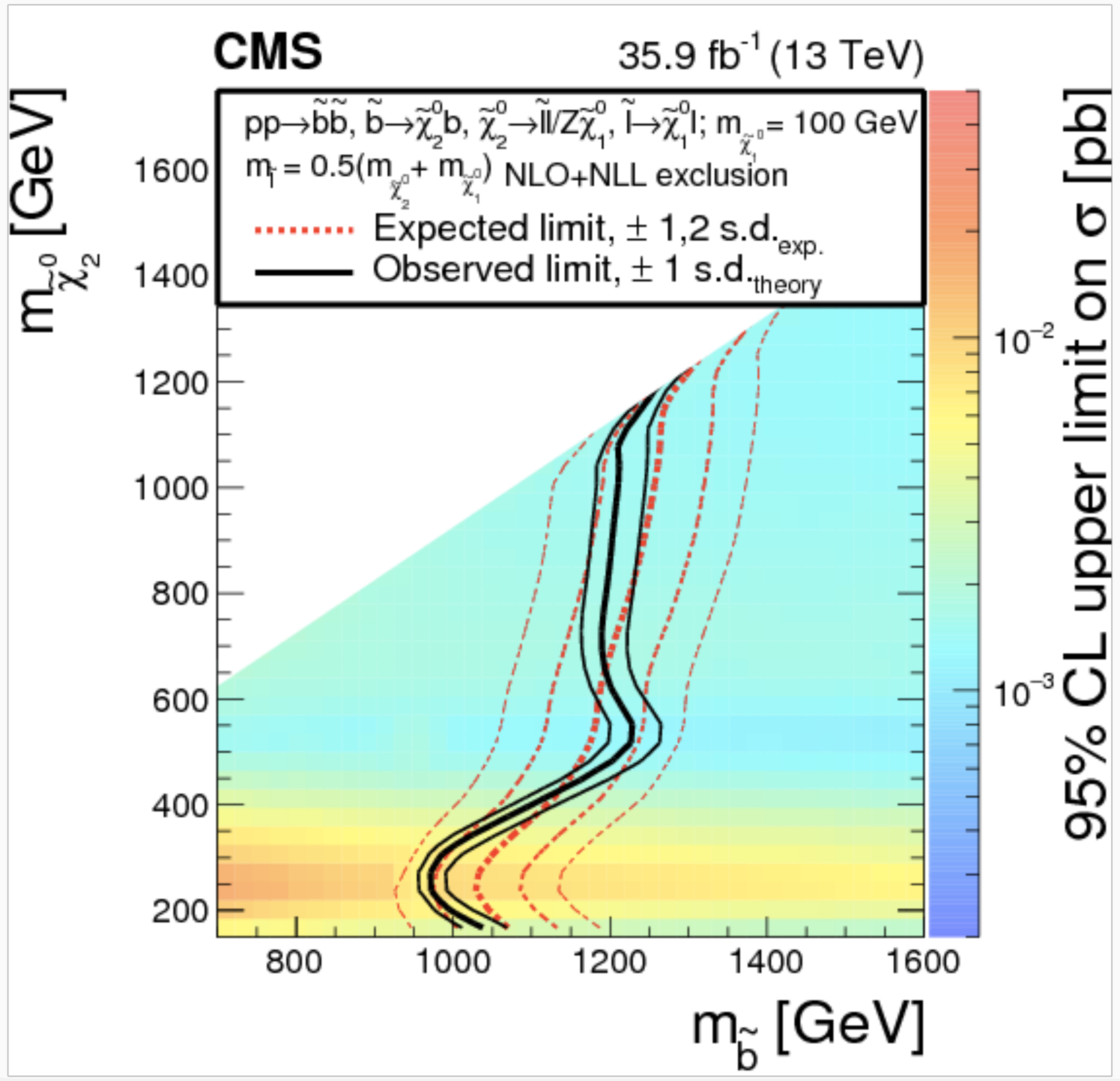
- such as $WZ \rightarrow 3\ell$, $ZZ \rightarrow 4\ell$, $t\bar{t}Z$
- normalization checked in 3ℓ and 4ℓ control regions
  - translation factor of 1.31±0.29 for $t\bar{t}Z$

Results and interpretation: OSSF

Edge

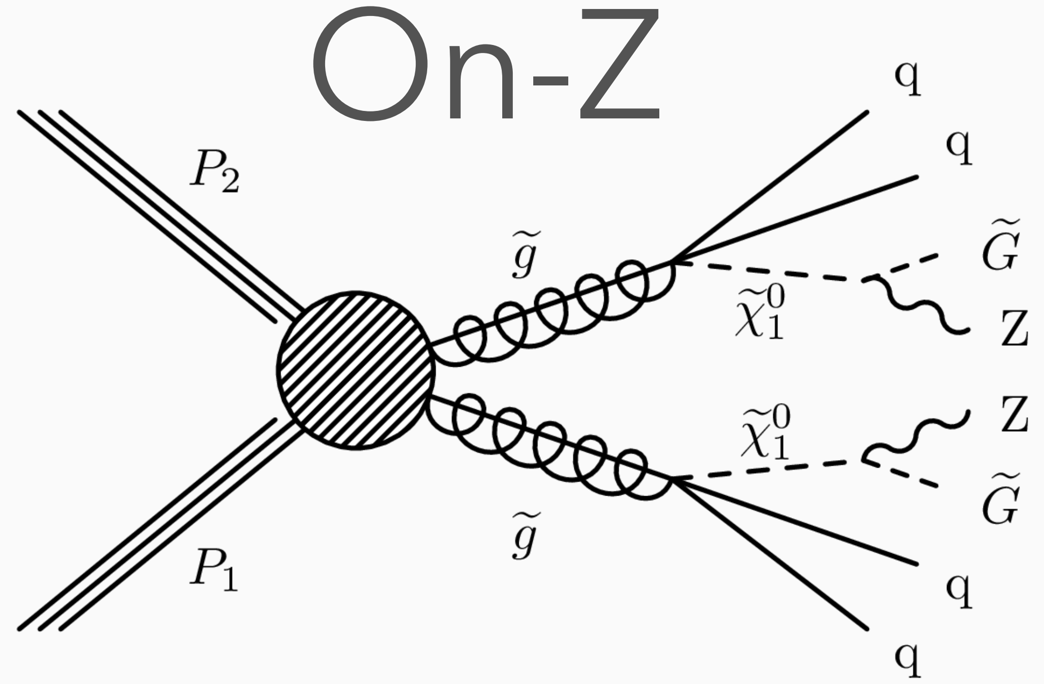


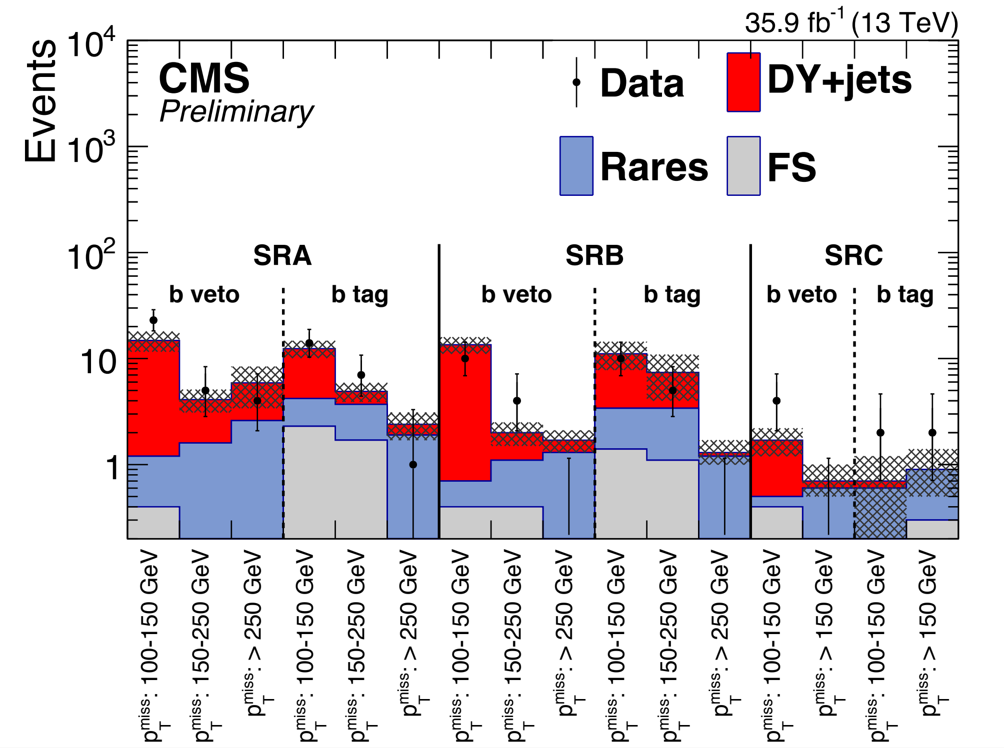


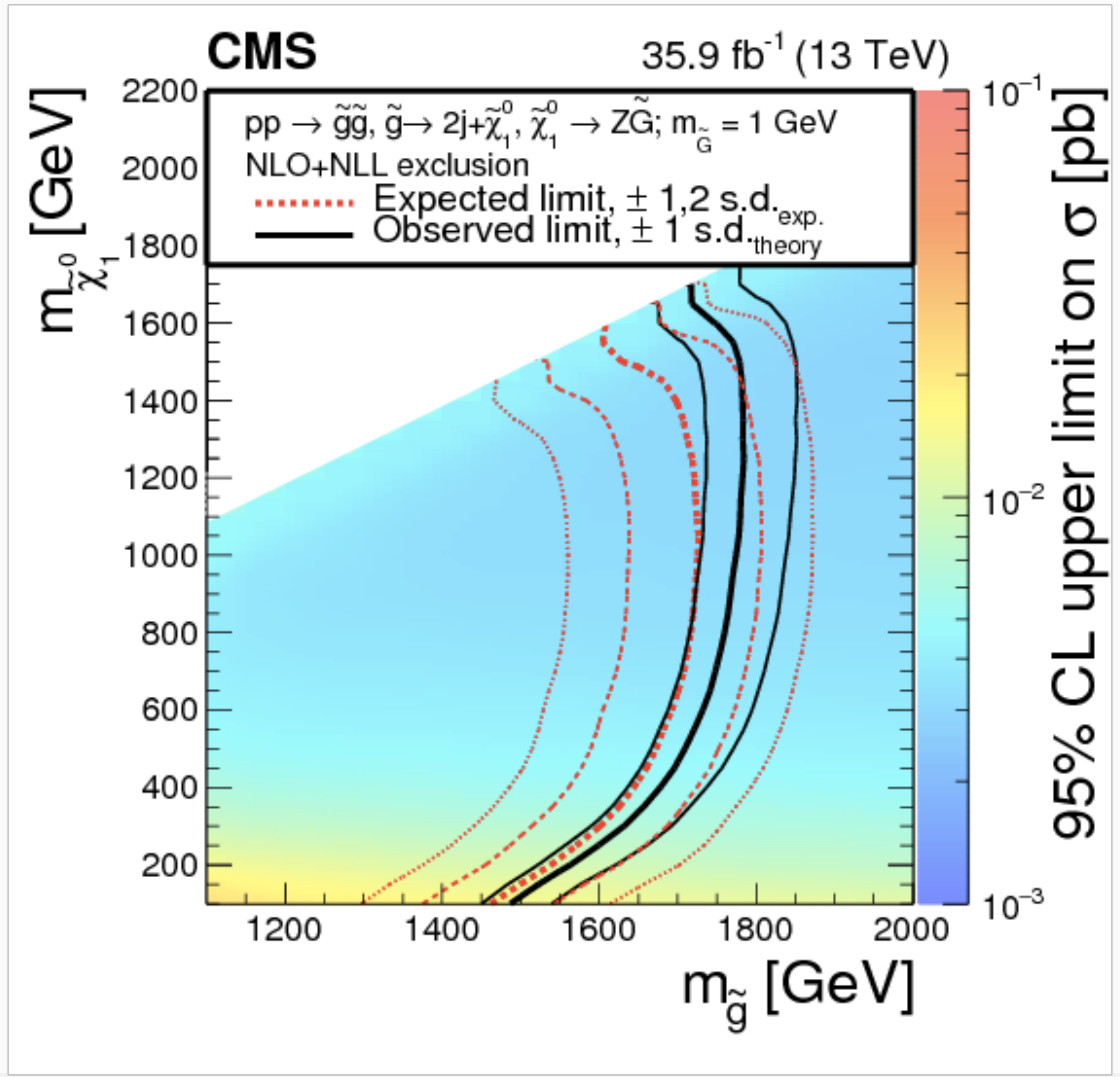


Sbottom exclusion from ~500 GeV (Run I) to **980 -1200 GeV**

On-Z



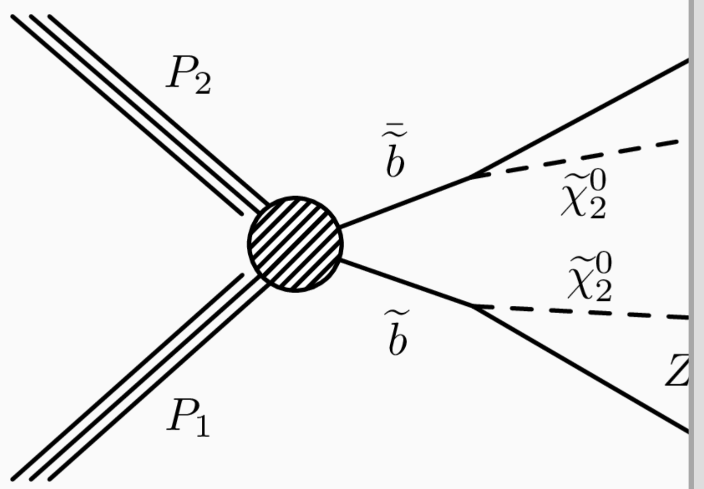


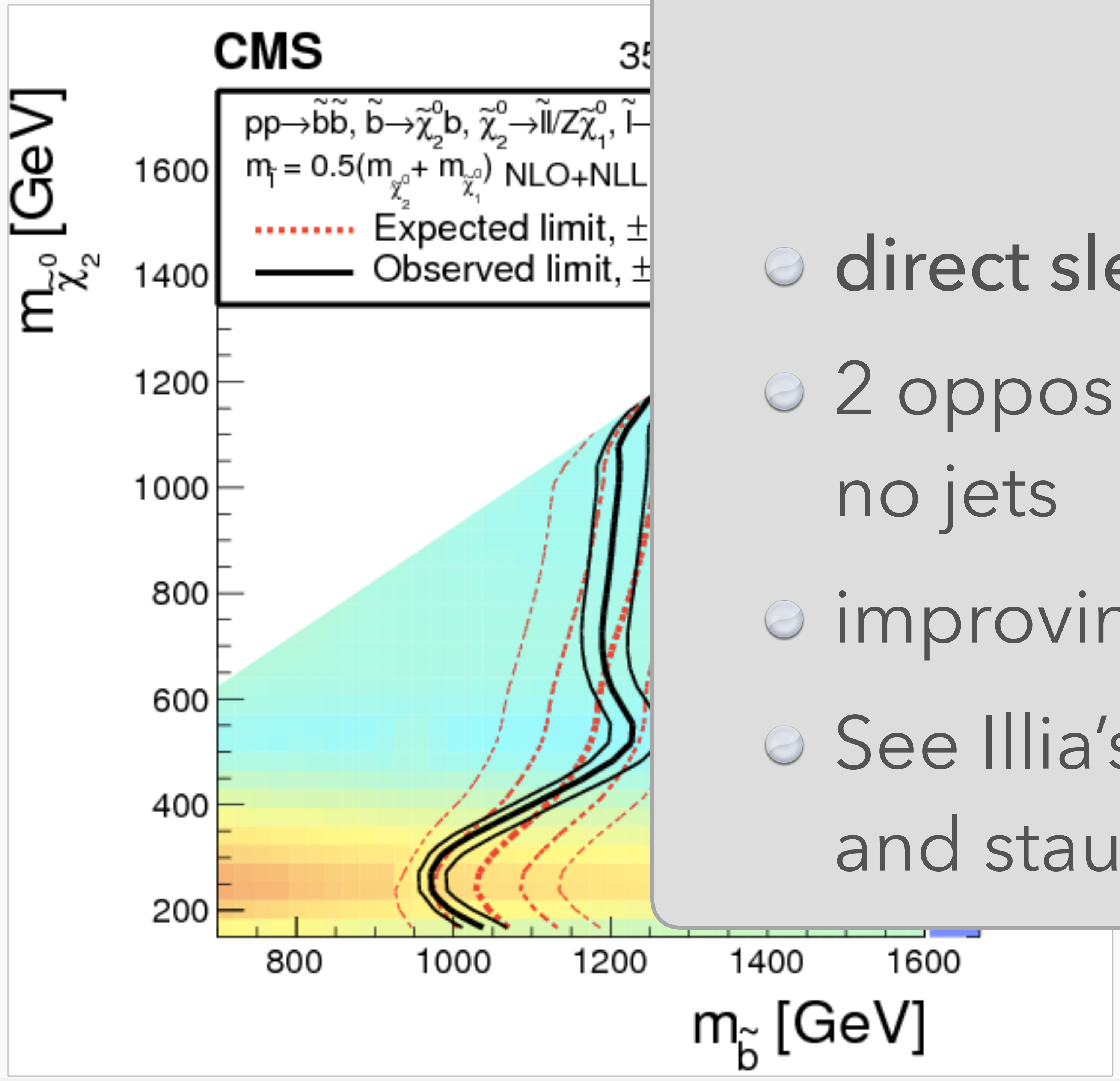


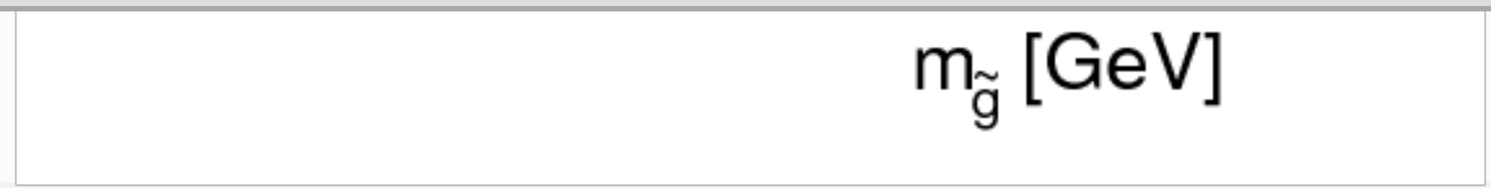
Gluino exclusion from 900–1100 GeV (Run I) to **1500-1770 GeV**, depending on the mass of the Neutralino

Results and interpretation: OSSF

Edge

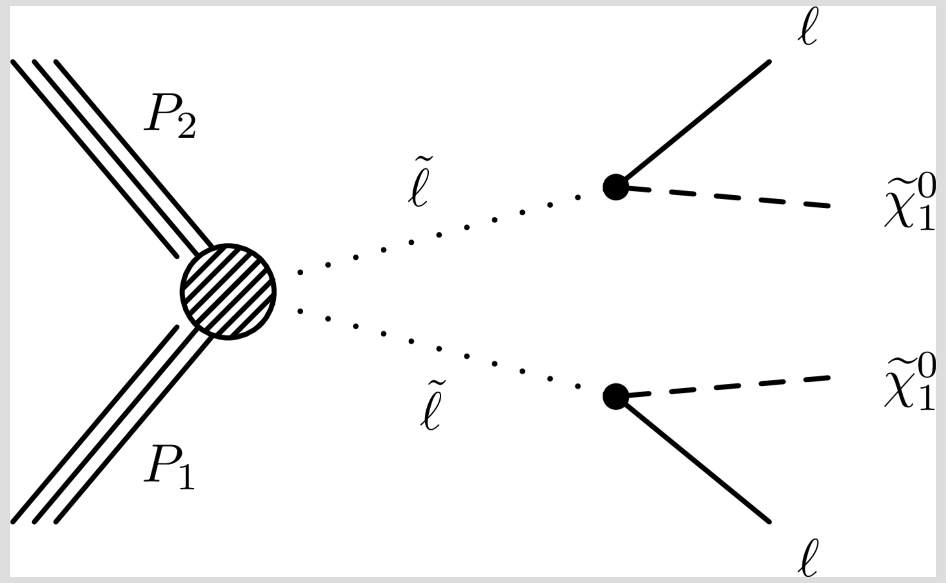




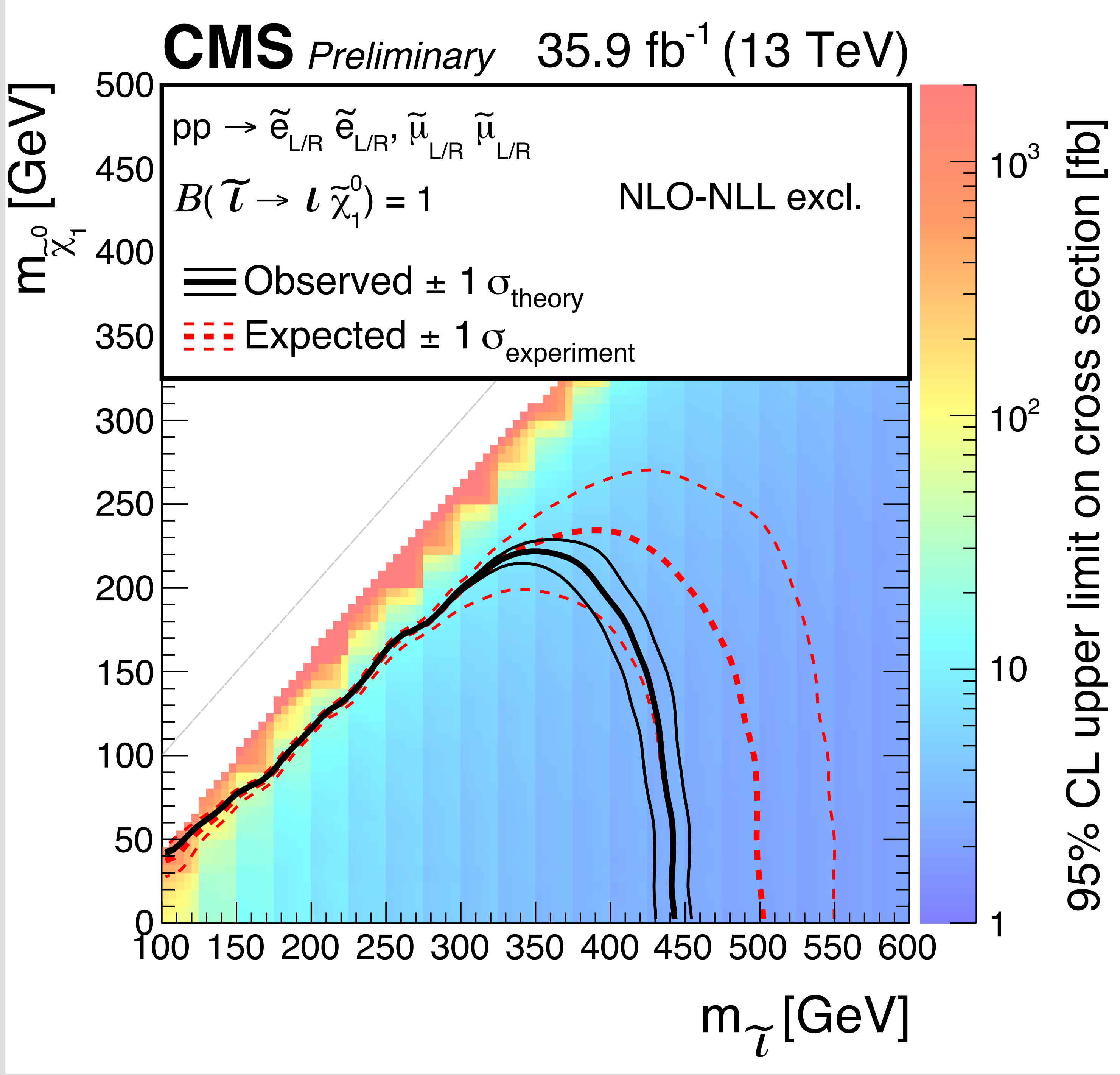


These results publicly available for Moriond17'

- however a new result in the same final state released for SUSY17'



  - **direct slepton production**
  - 2 opposite sign same flavor leptons and no jets
  - improving Run I results by 200 GeV
  - See Illia's talk on Wednesday on slepton and stau production



Searches for SUSY with same sign dileptons:

Search for physics beyond the standard model in events with two leptons of same sign, missing transverse momentum, and jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV.

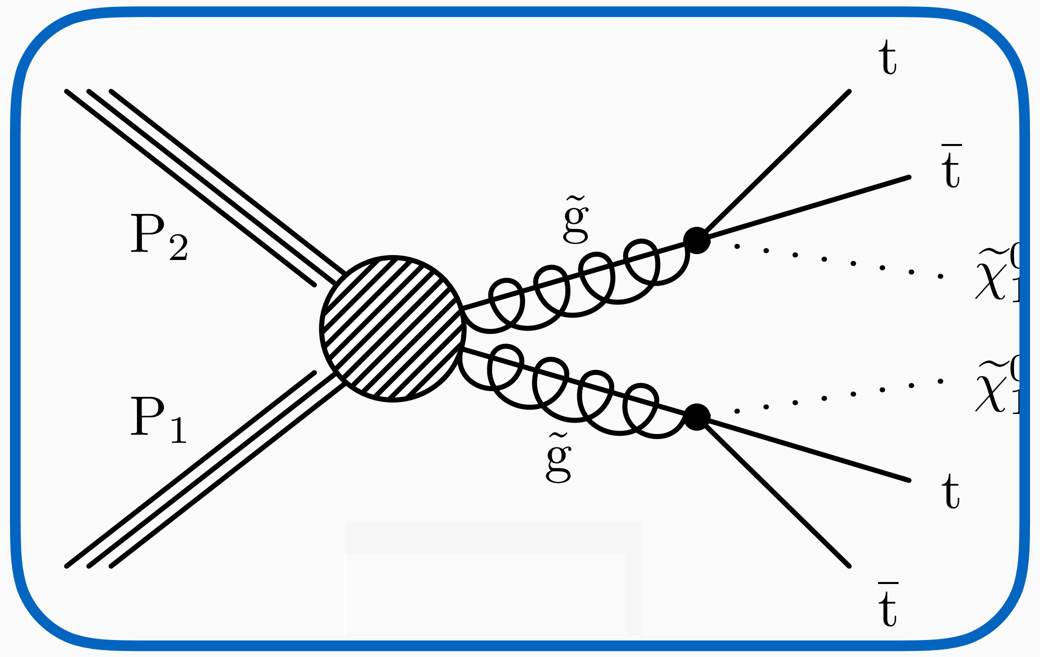
CMS-SUS-16-035

arXiv:1704.07323

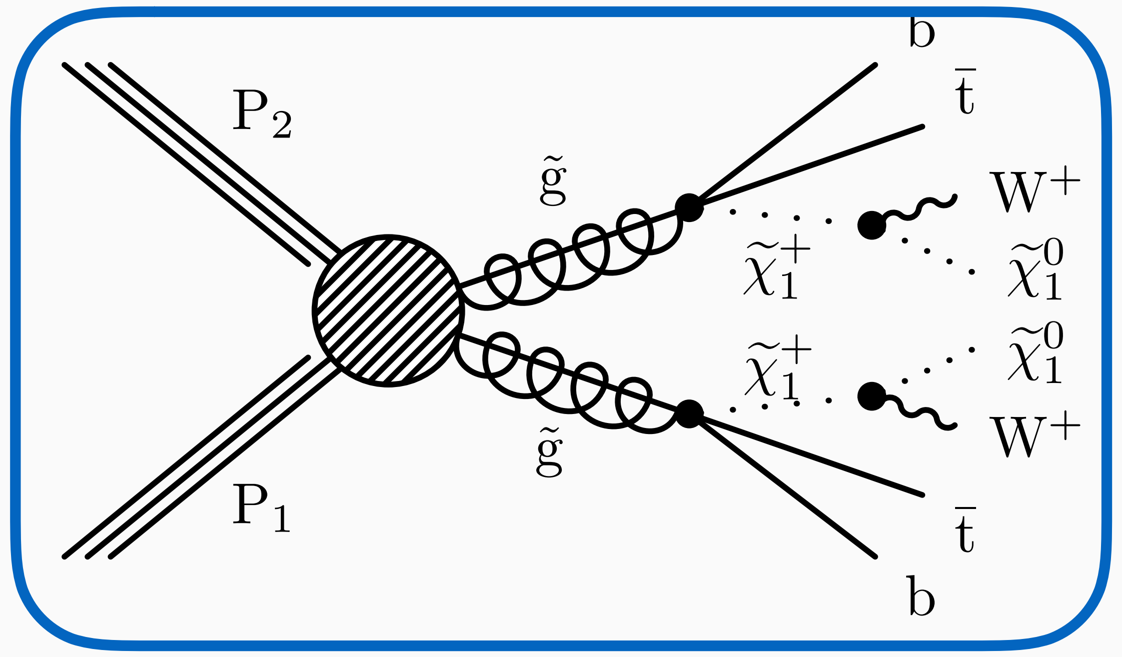
SUSY with same sign dileptons

SM processes with same sign final states are rare

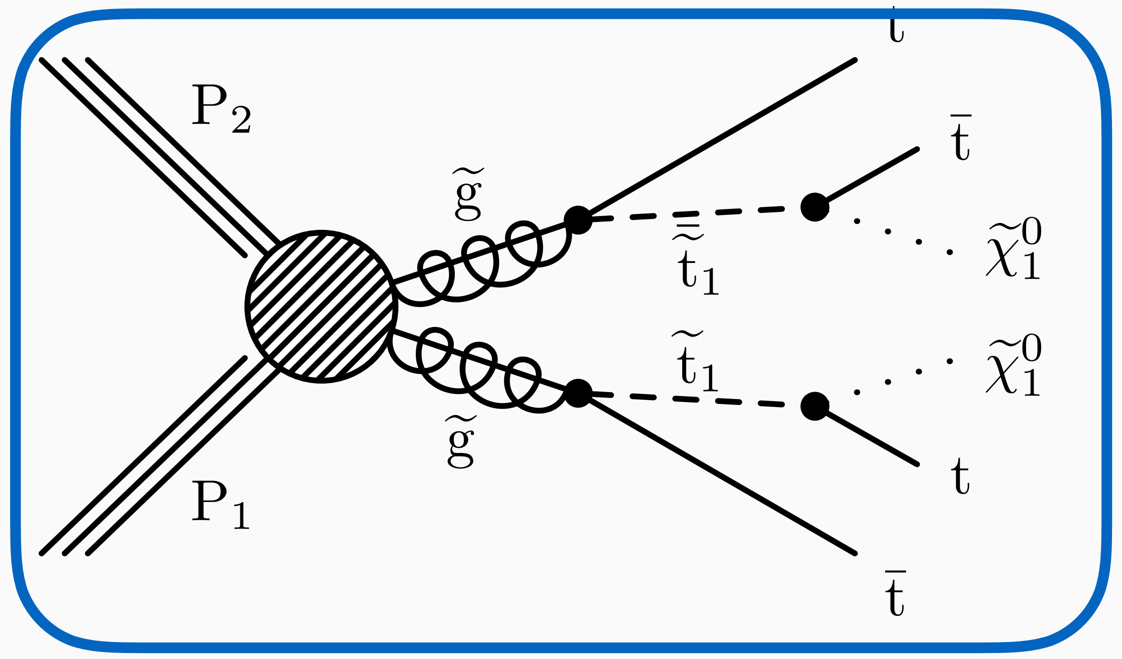
- however, can appear in a wide variety of strong produced SUSY scenarios



(a) T1tttt



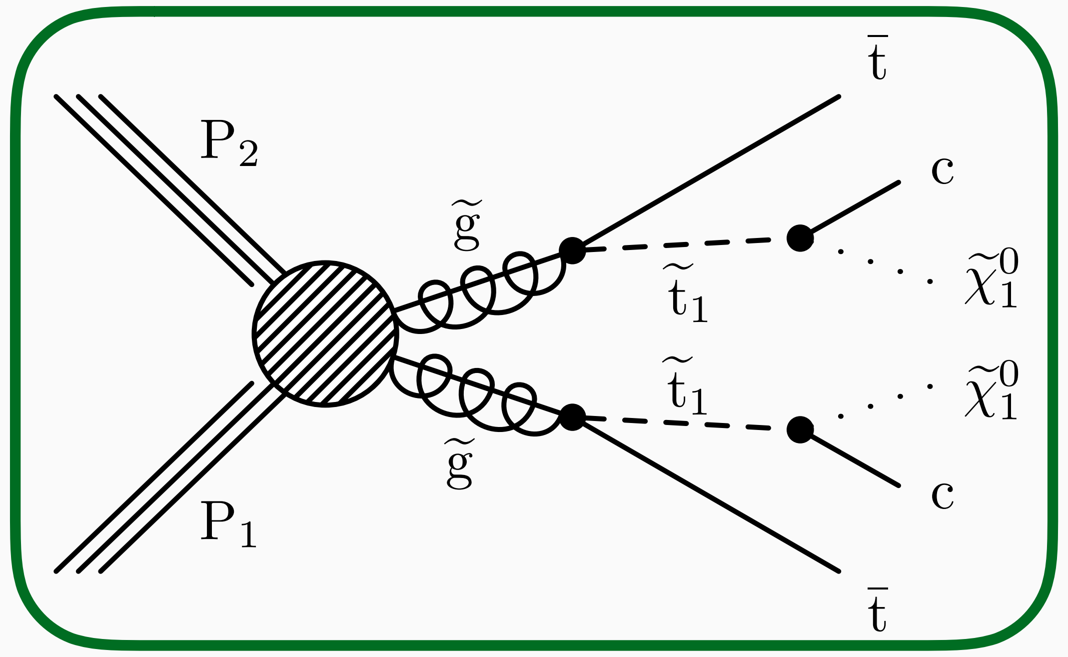
(b) T5ttbbWW



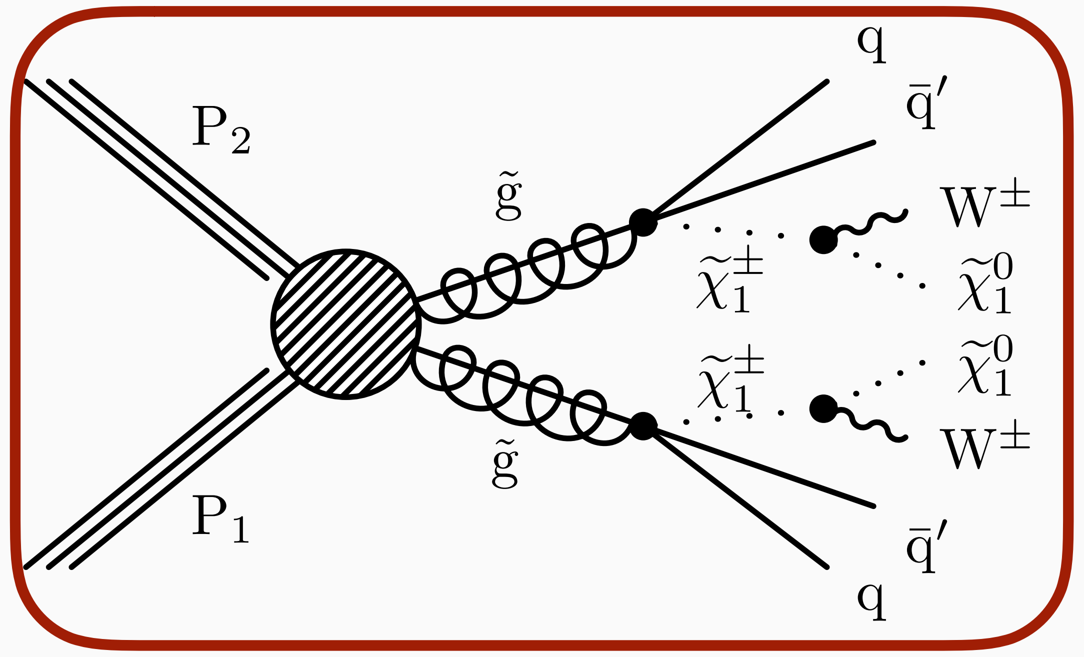
(c) T5tttt

Final states with 4 W bosons:

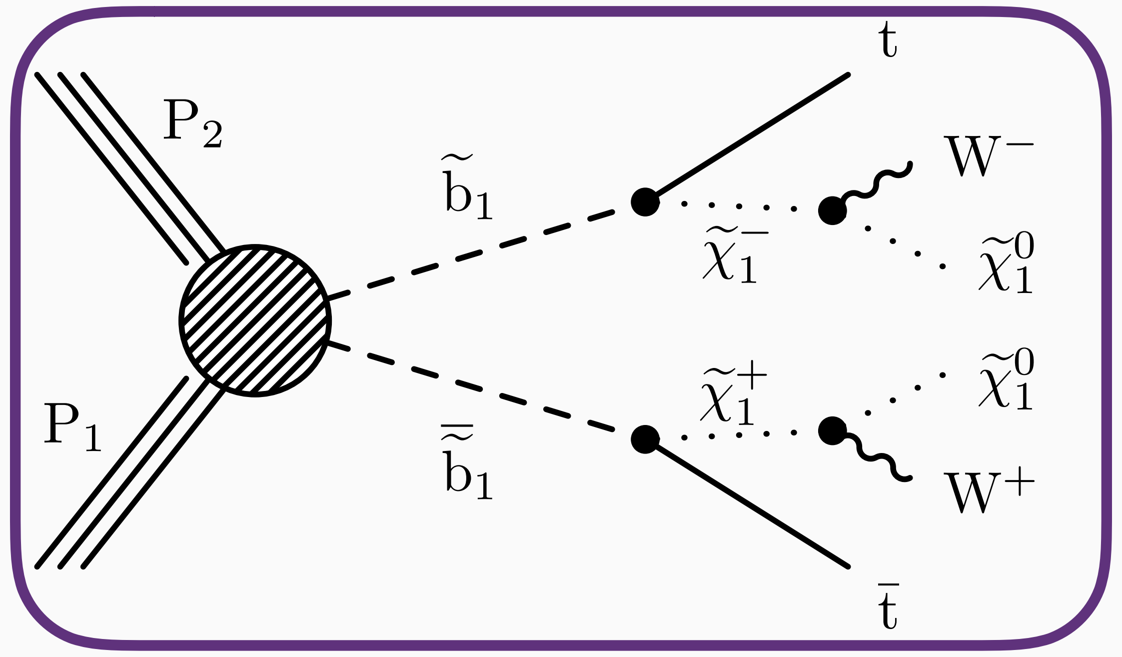
- 4 b-jets
- 2 b-jets and 2 light flavor jets
- 4 light flavor jets
- 2 b-jets



(d) T5ttcc



(e) T5qqqqWW

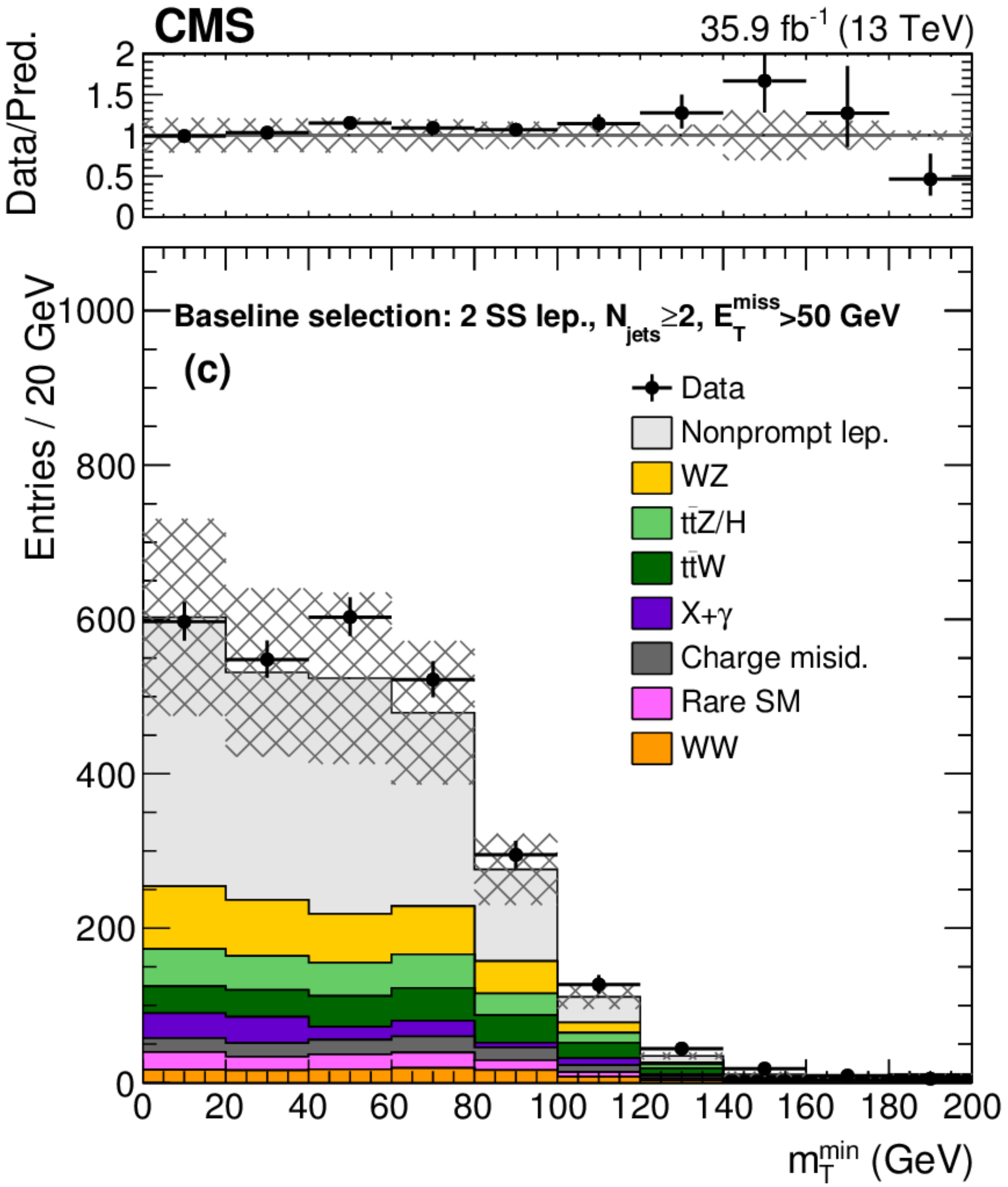


(f) T6ttWW

Search strategy: same sign dileptons

Baseline selection

- Two equally charged leptons, ≥2 jets, p_T^{miss} > 50 GeV
- Signal regions binned in **p_T^{miss} ,H_T, number of (b-) jets** and
  - **high and low p_T lepton regions (HH/HL/LL)**
- Selection on **$\ell^+\ell^+$ vs. $\ell^-\ell^-$**
  - the SM in pp collisions is asymmetric in charge
- Selection on min(M_T^{ℓ}):
  - for $t\bar{t} \rightarrow 1\ell$ have **M_T^{ℓ} < M_W.**
  - reduces non-prompt background



Background prediction: same sign dileptons

Non-prompt leptons (data driven):

- **Tight-to-loose** ratio estimated from control region

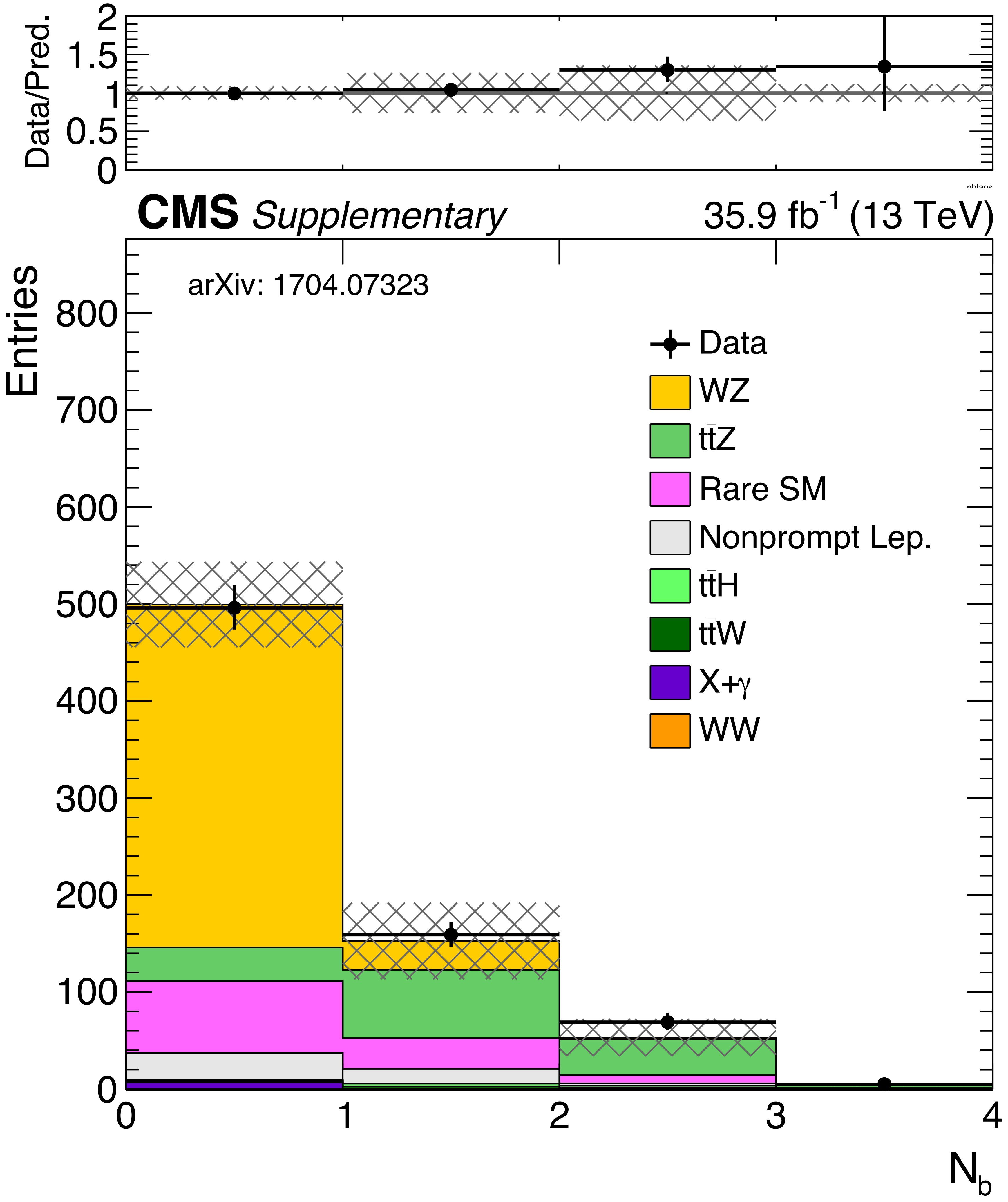
Charge-misidentification of electrons (data driven):

- estimated using a $\mathbf{e^{\pm}e^{\mp}}$ control sample

Rare SM processes with prompt SS pairs (MC):

- **WZ→3ℓ** and **tt̄Z** validated in 3ℓ control region
  - translation factor of 1.26±0.09 for tt̄Z
- template fit to the distribution of the **number of b jets**
- **tt̄W** and **WW**

Rare and X+γ: (MC)



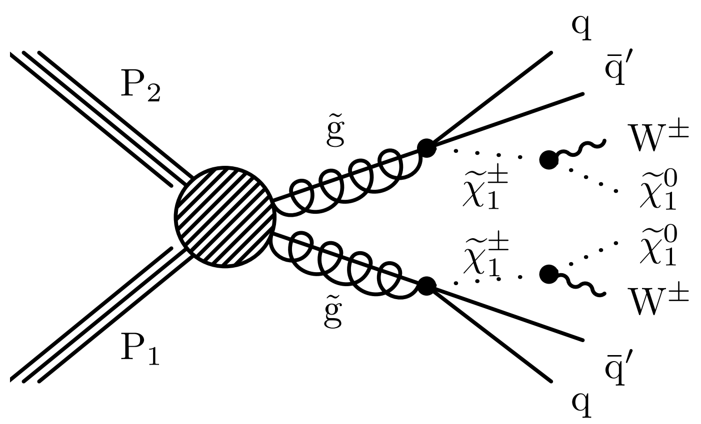
Results and interpretation: same sign dileptons

Interpretation in a variety of SUSY models (all in backup)

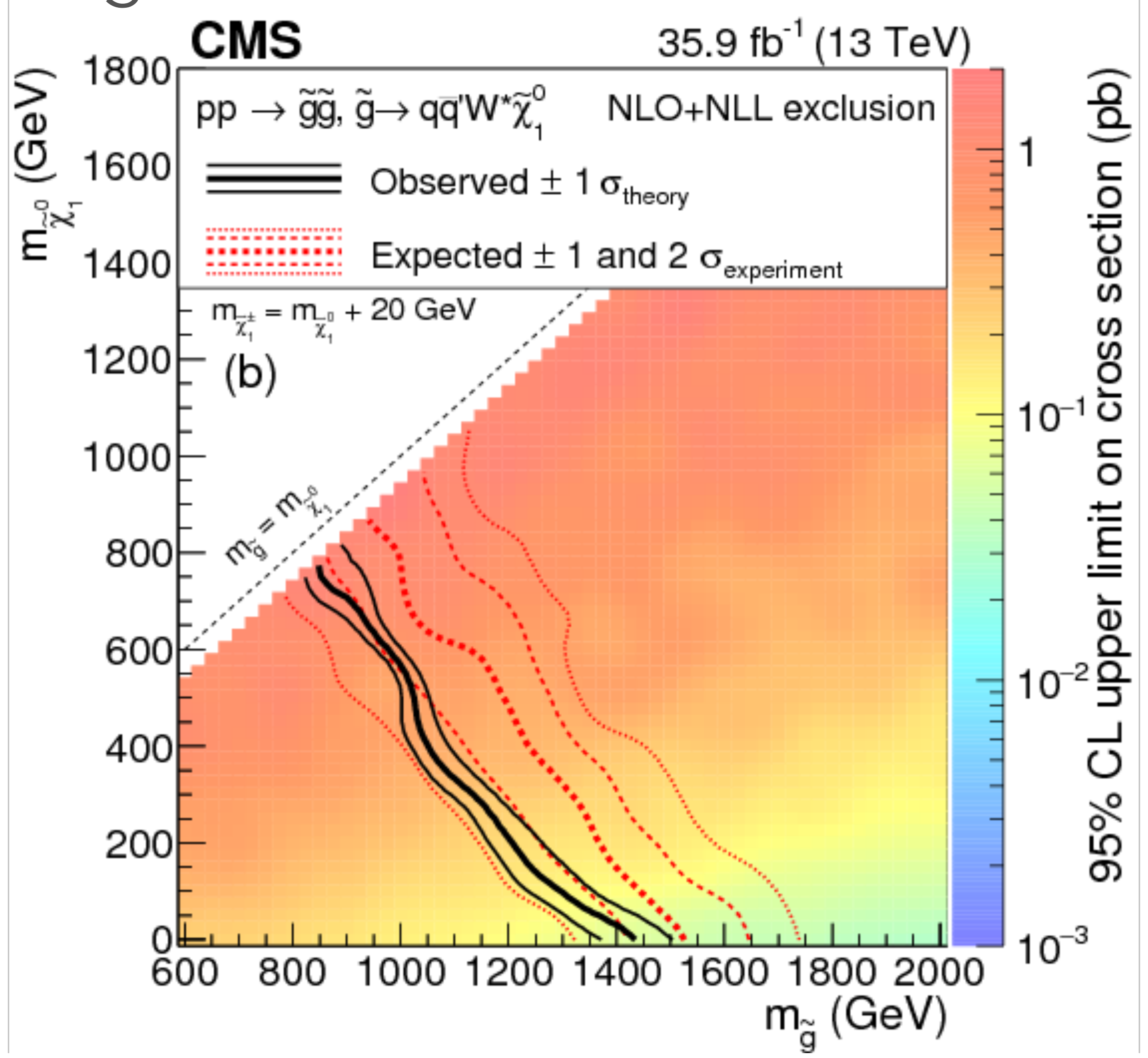
- Run I limits on gluino and bottom squark masses are improved by 200-300 GeV

T5qqqqWW

$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 20$ GeV

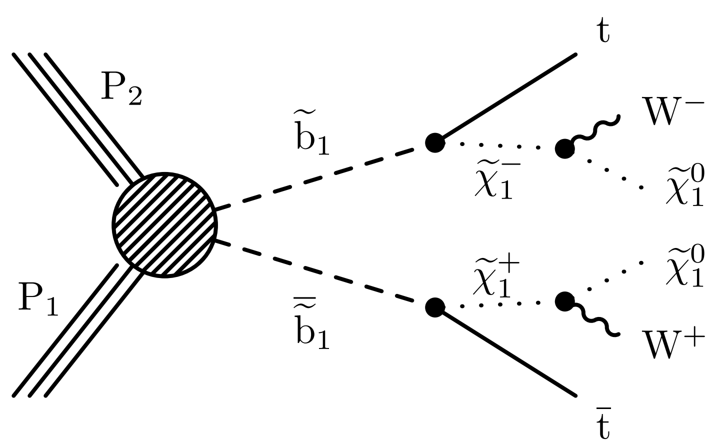


Targets off-shell Ws

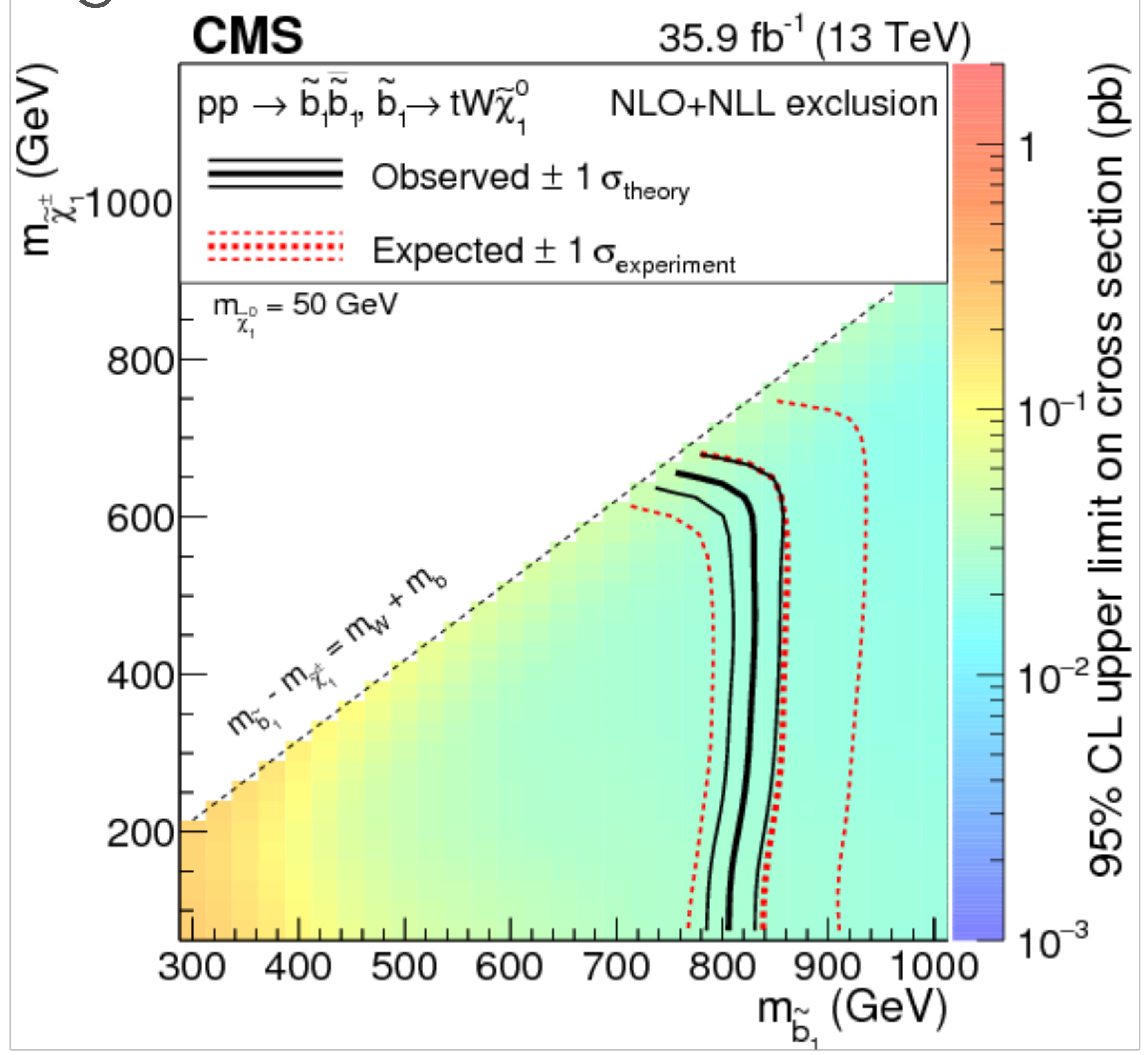


T6ttWW

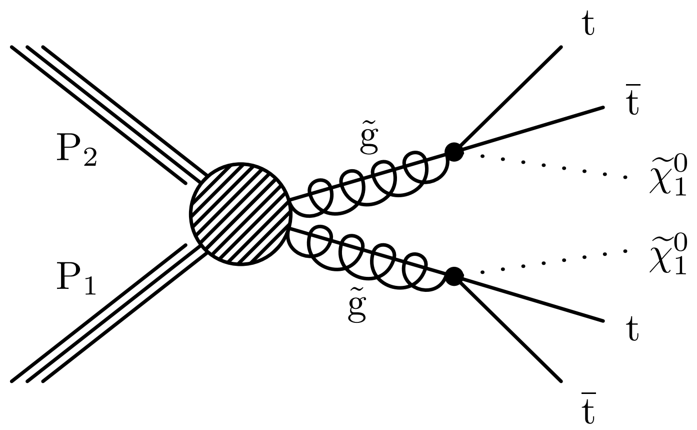
$m_{\tilde{\chi}_1^0} = 50$ GeV



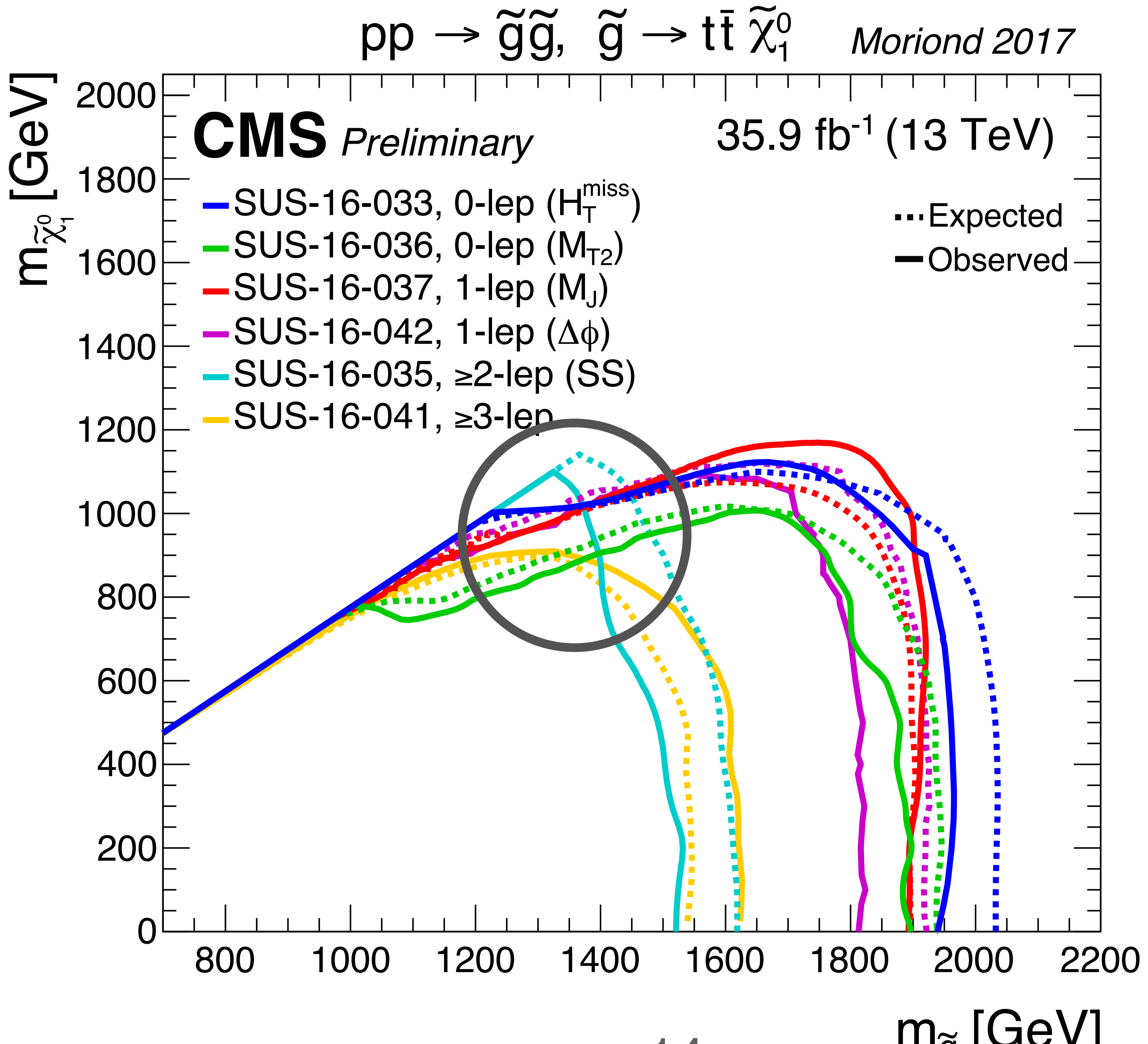
Targets off-shell Ws



T1tttt



Best in compressed scenarios



Searches for SUSY with multileptons:

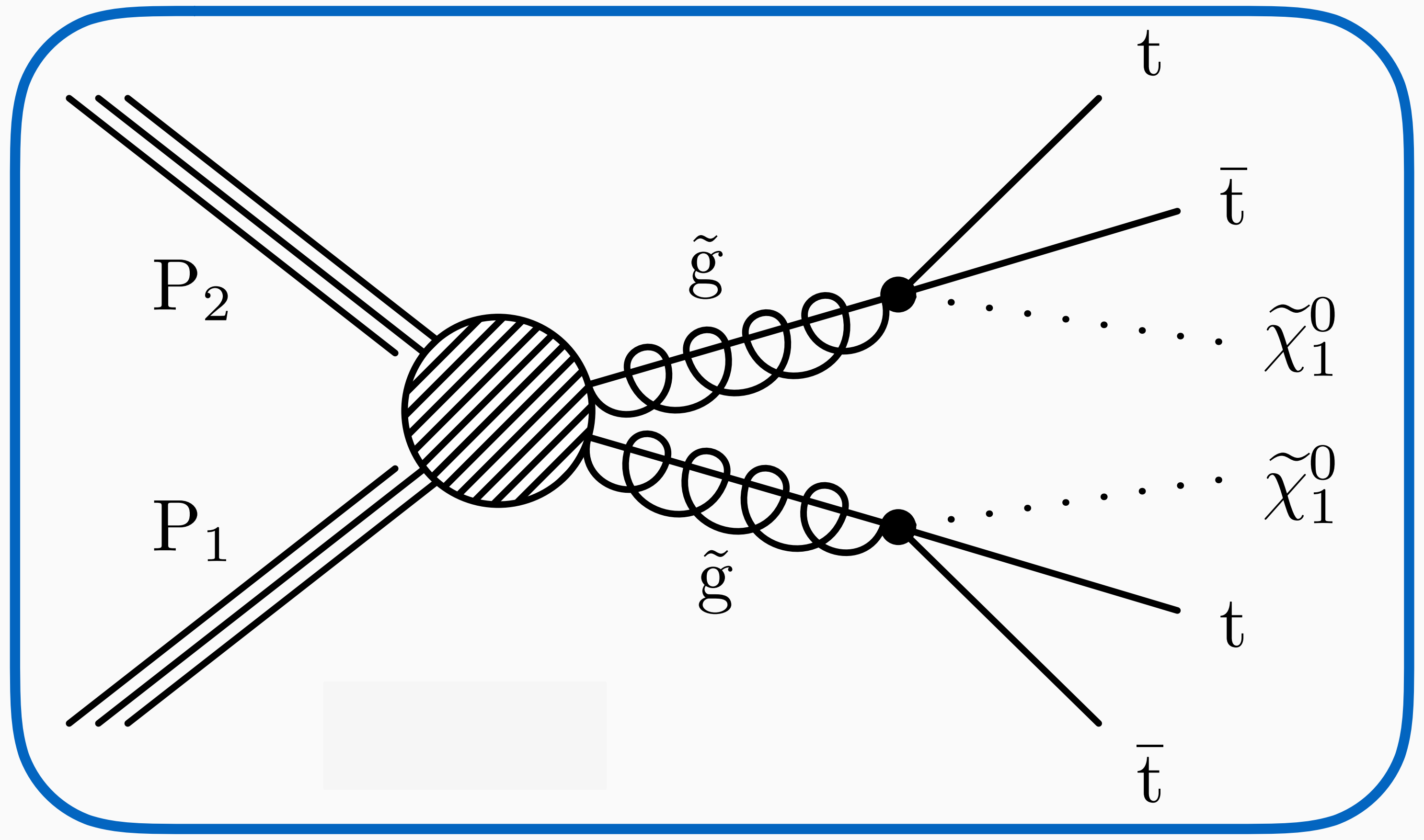
Search for new physics in events with multileptons and jets in 35.9 fb^{-1} of proton-proton collision data at $\sqrt{s}$= 13 TeV

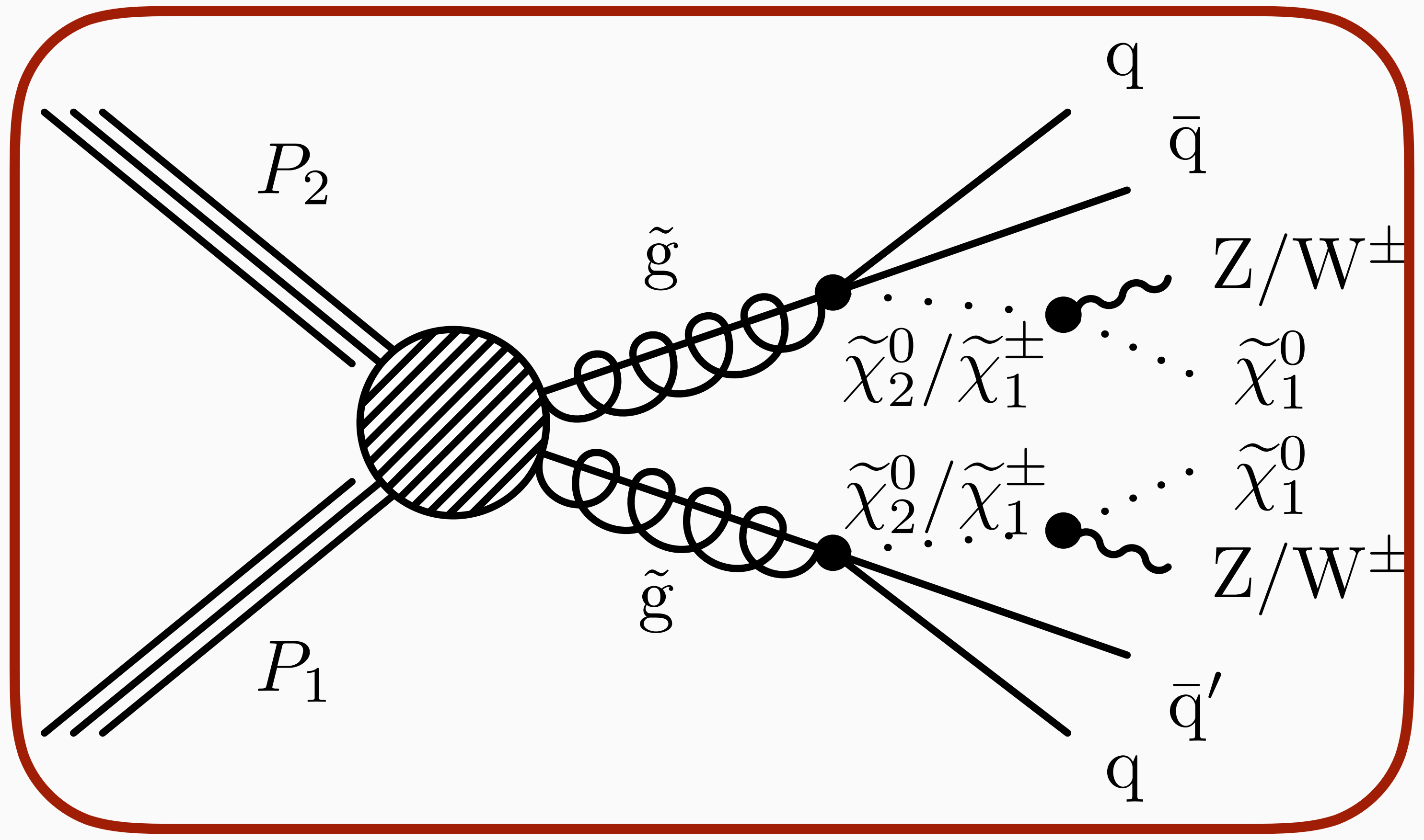
CMS-SUS-16-041

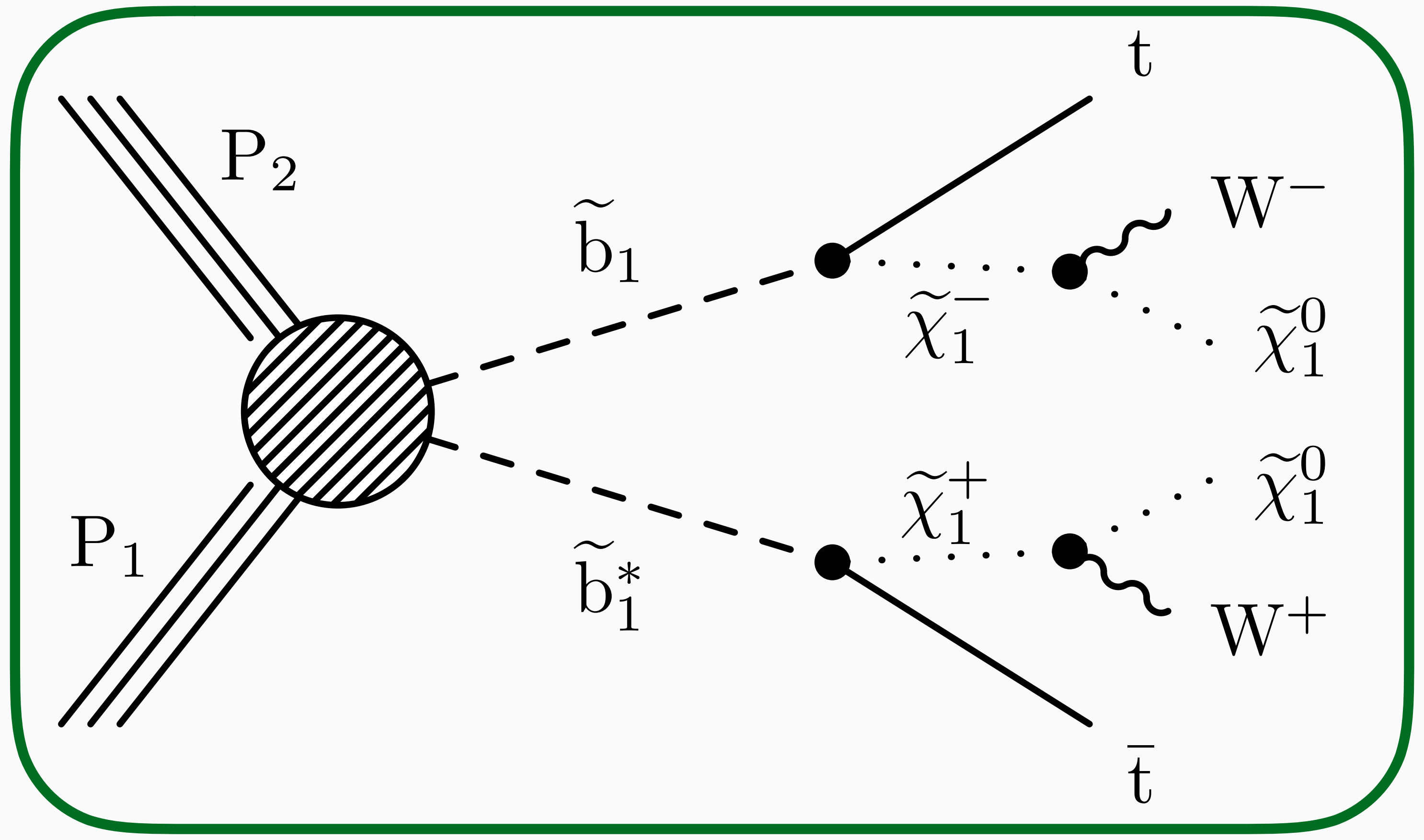
arXiv:1710.09154

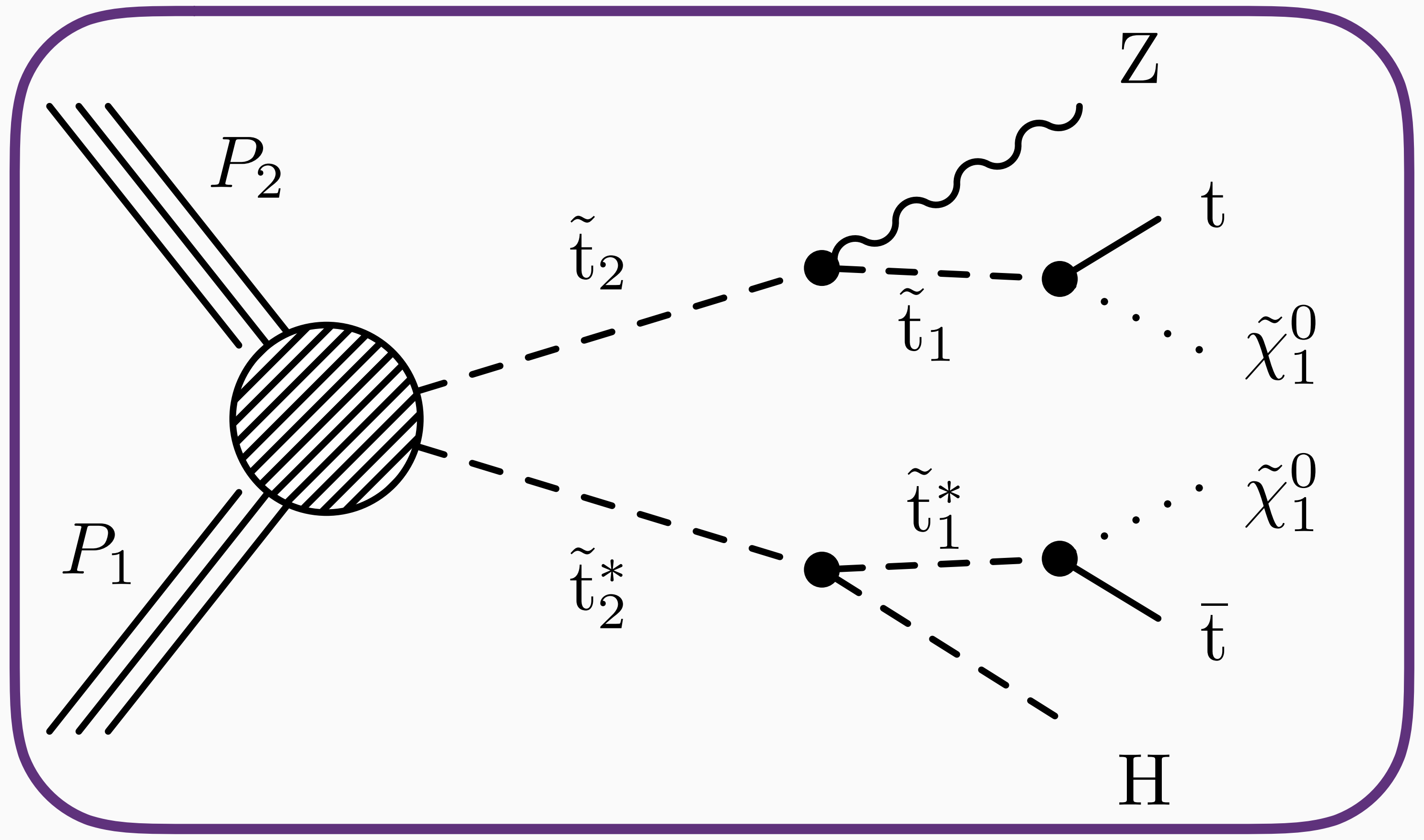
SUSY with multileptons

≥3ℓ processes are rare in the SM, but can be natural to SUSY production









Strong production of SUSY resulting in final states with

- 4 b-jets and ≥3ℓ from 4 W bosons
- 2 b-jets ≥3ℓ from 4 W bosons
- 4 light flavor jets and ≥3ℓ from Z/W bosons
- 2 b-jets and ≥3ℓ from Z/H bosons

Search strategy: multileptons

Selection:

- $\geq 3\ell$, $m_{\ell\ell} > 12$ GeV for OSSF, ≥2 jets, $p_T^{miss} > 50$ GeV
- On-Z regions:
  - OSSF pair with $|m_{\ell\ell} - m_Z| < 15$ GeV
- Off-Z regions:
  - OSSF pair with $|m_{\ell\ell} - m_Z| \geq 15$ GeV

Signal regions:

- Binning in (b-) jet multiplicity, H_T, p_T^{miss}, $m_{\ell\ell}$ and m_T
- 46 signal regions

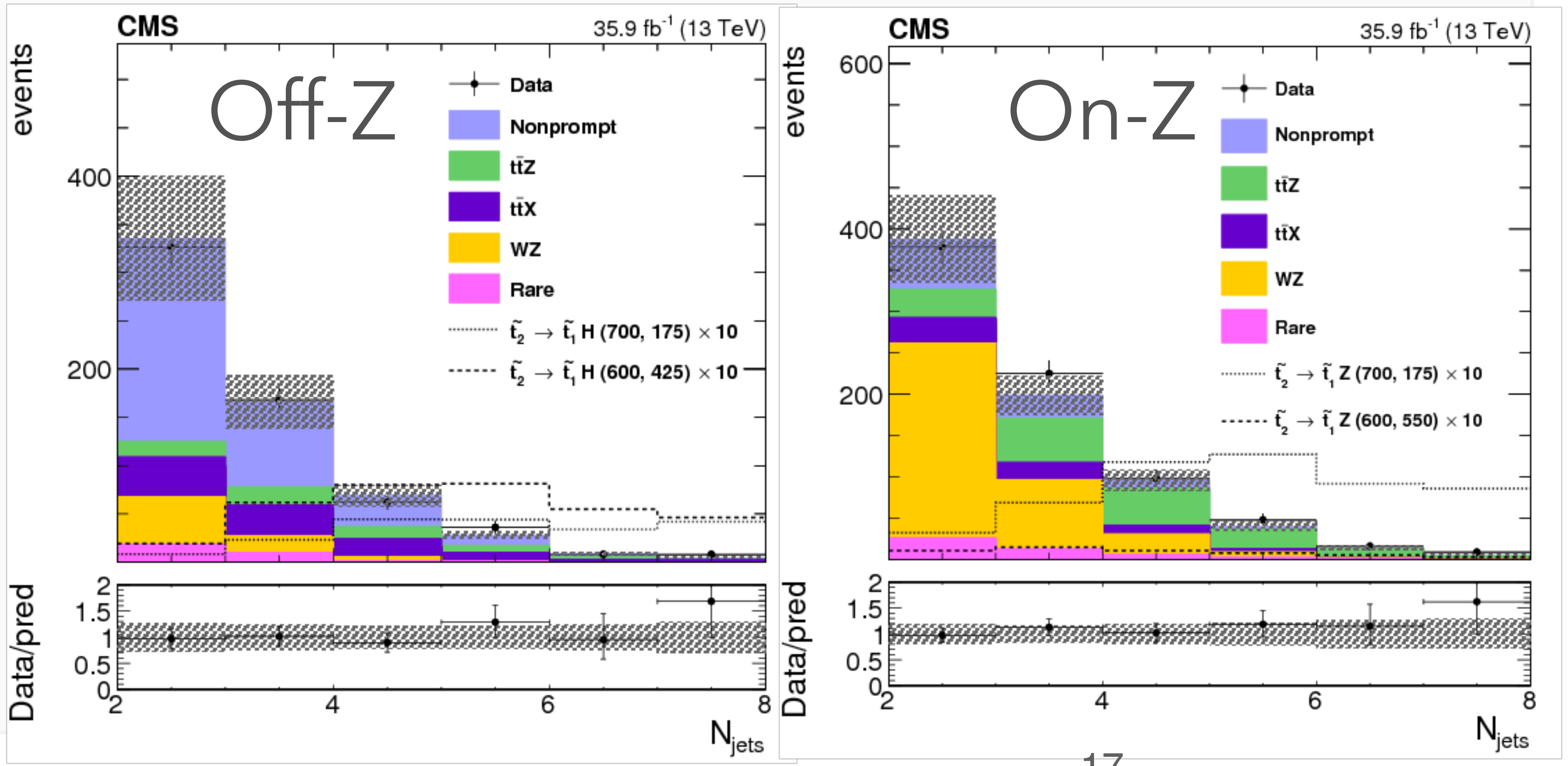
Non-prompt leptons (data driven):

- same estimation method as same sign analysis

Diboson production and rare SM processes (MC):

- same estimation method as same sign analysis
  - translation factor of 1.14±0.28 for $t\bar{t}Z$

Other rare backgrounds: ZZ, $t\bar{t}W$, VVV, X+γ (MC)

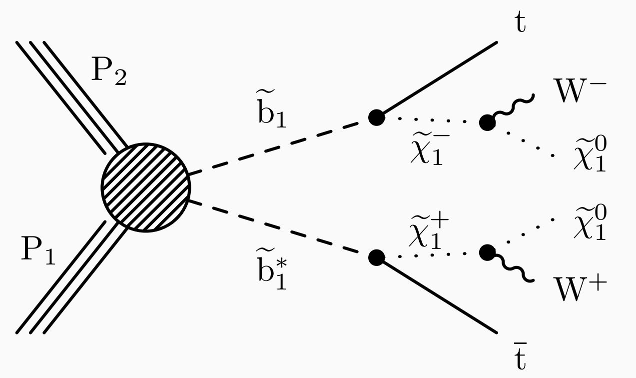


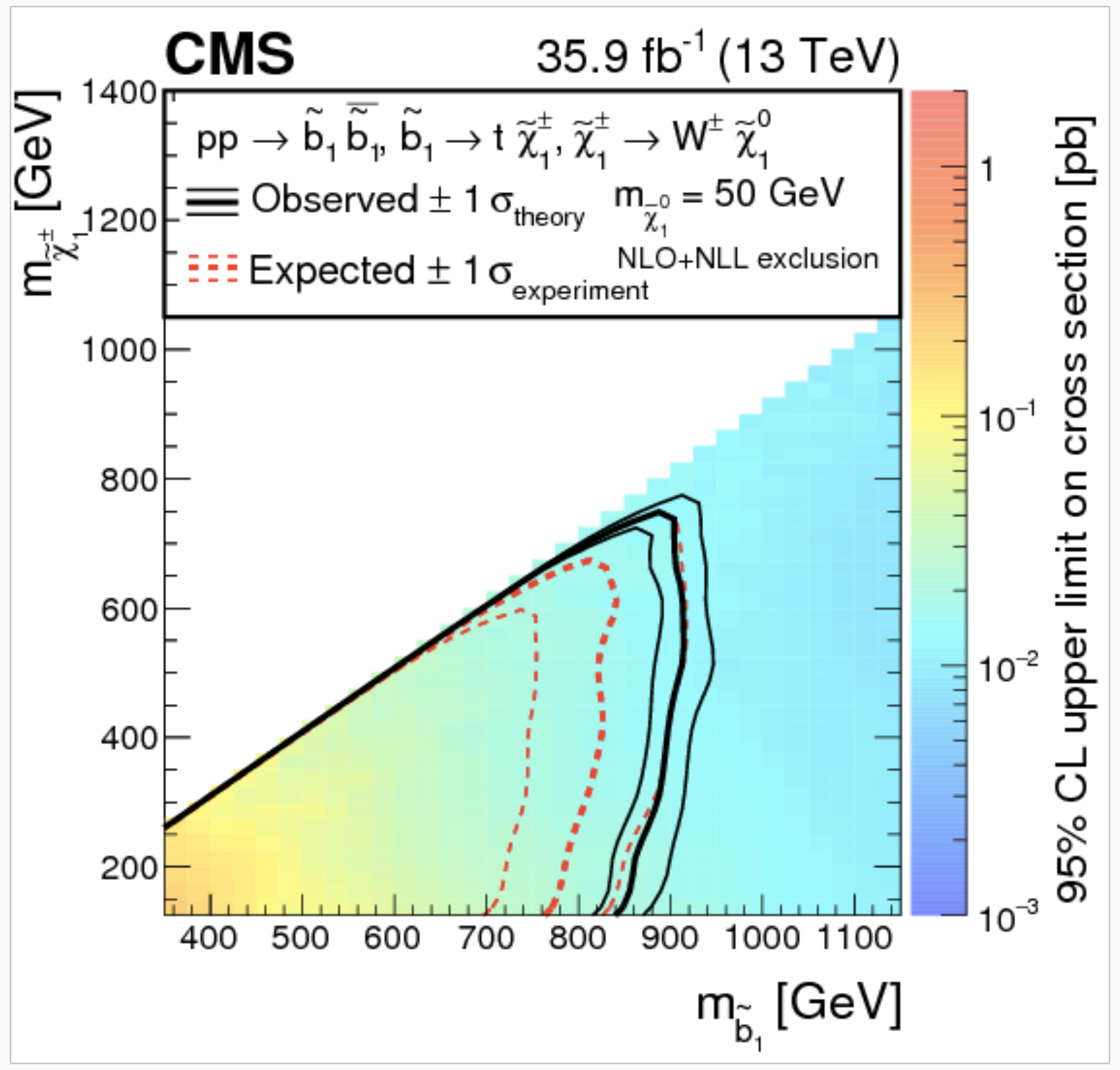
Results and interpretation: multileptons

Interpretation in a variety of SUSY models (all in backup)

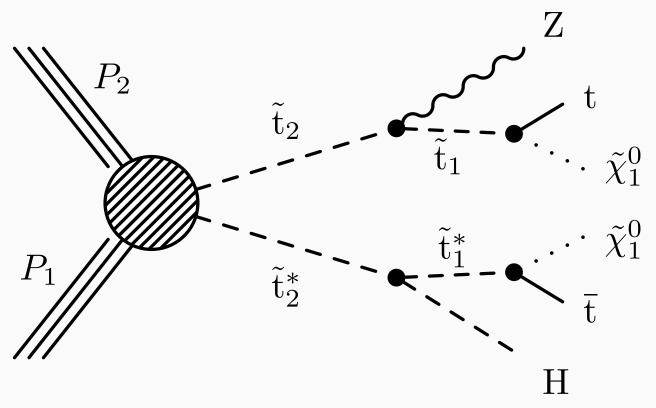
- Interpretation on many of the same signals as for the same-sign search

T6ttWW

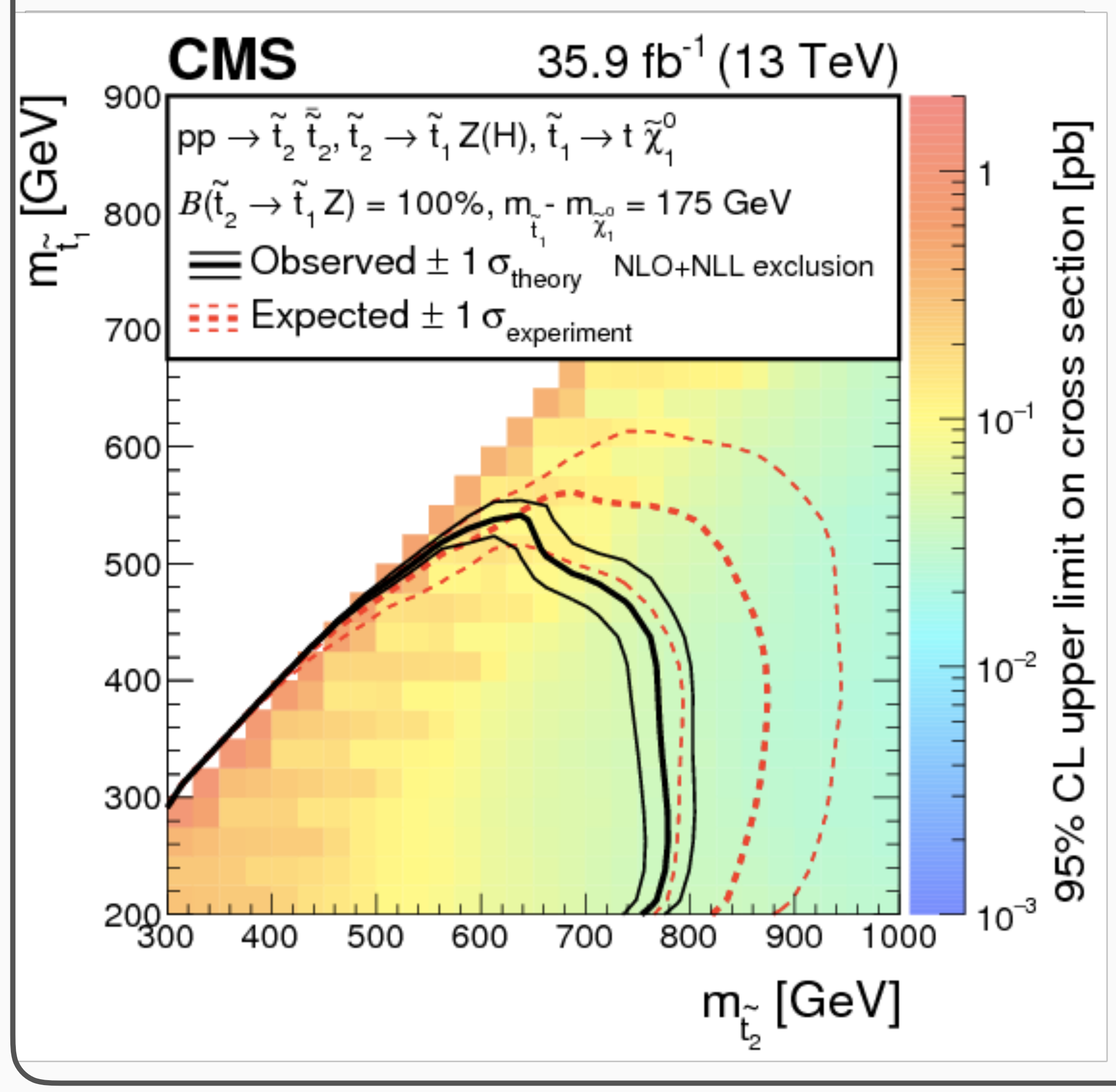


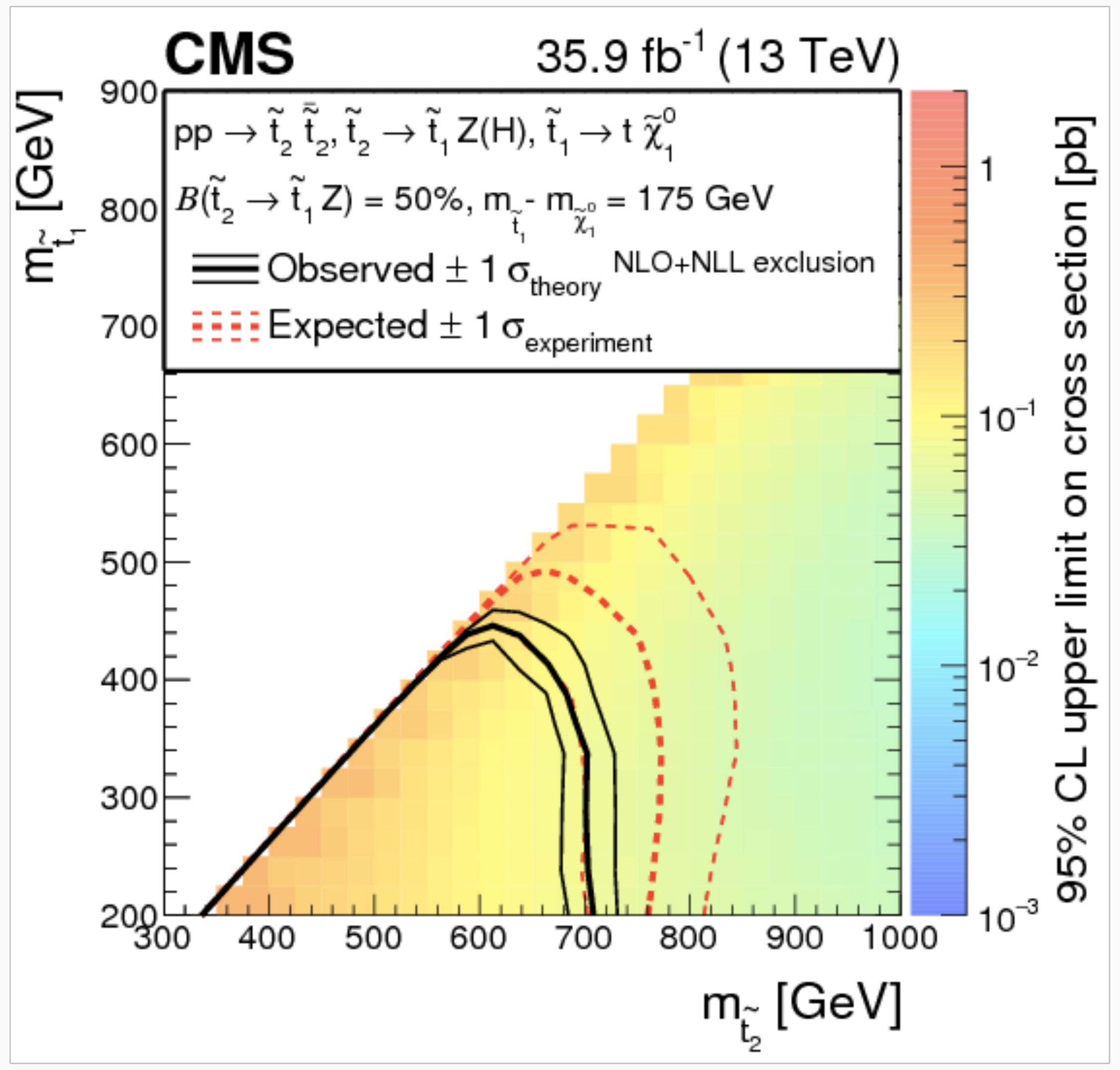


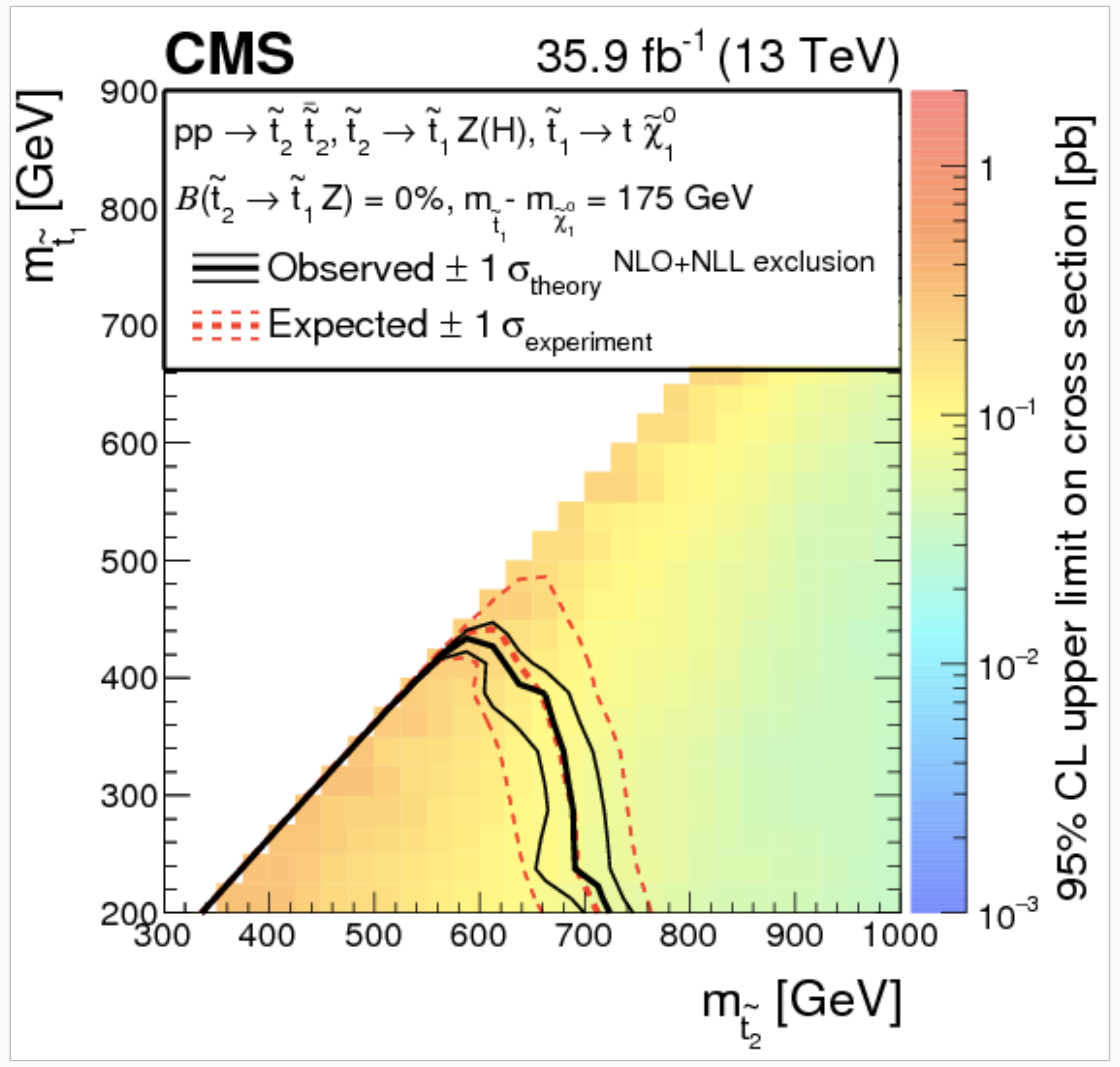
T6ttHZ



- Different branching fractions tested
  - 0%, 50%, 100% Z (H)







Summary

Searches for Strong Supersymmetry in leptonic final states has been presented

- Opposite sign leptons (CMS-SUS-16-034)
- Same sign leptons (CMS-SUS-16-035)
- Multileptons (CMS-SUS-16-041)
- All using data collected by the CMS detector at $\sqrt{s}$= 13 TeV in 2016

All searches reporting a large translation factor for $t\bar{t}Z$

- 1.31 for opposite sign, 1.26 for same-sign and 1.14 for multileptons
- interesting observation

No significant excess reported

- limits set on a variety of SUSY models, greatly exceeding the Run I exclusion and 2015 Run II exclusion
- aggregated signal regions provided to facilitate reinterpretation: http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/

Backup

Isolation variables to reduce non prompt backgrounds

Relative Isolation I_{rel}:

- defined as the ratio of the amount of energy measured in a cone around the lepton to the p_T of the lepton, p_T^l, with a p_T dependent radius
- $\Delta R \leq 10$ GeV/(min(max(p_T^l, 50 GeV), 200 GeV))

p_T^{ratio}:

- defined as the ratio of the lepton p_T and that of the jet geometrically closest to the lepton: p
- p_T^{ratio}: p_T^l / p_T^{jet}
- provides a way to identify low-p_T leptons from b-jets which has a larger opening angle

p_T^{rel}:

- defined as the magnitude of the component of the lepton momentum perpendicular to the axis of the closest jet
- this variable allows the recovery of leptons from accidental overlap with jets in Lorentz-boosted topologies

$I_{rel} < I_1$ AND ($p_T^{ratio} > I_2$ OR $p_T^{rel} > I_3$)

- where I_1, I_2 and I_3 are flavor dependent values

Tight-to-loose ratio

Tight-to-loose ratio

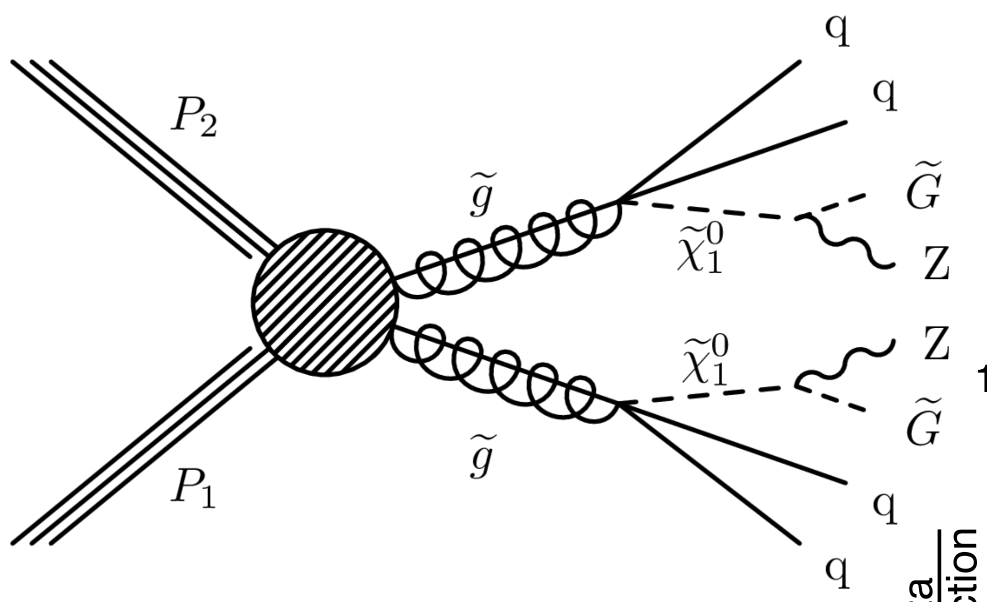
- used to predict background from non-prompt leptons same sign and multilepton analyses
- Yield is estimated in application region that is similar to signal region but contains at least one lepton that fails the tight identification and isolation requirements but satisfies the loose requirements
- The events in this region are weighted by f/(1-f) where the tight-to-loose ratio f is the probability that a loosely identified lepton also satisfies the full set of requirements
- f measured as a function of lepton p_T and eta in a control sample of multijet events that is enriched in non-prompt leptons

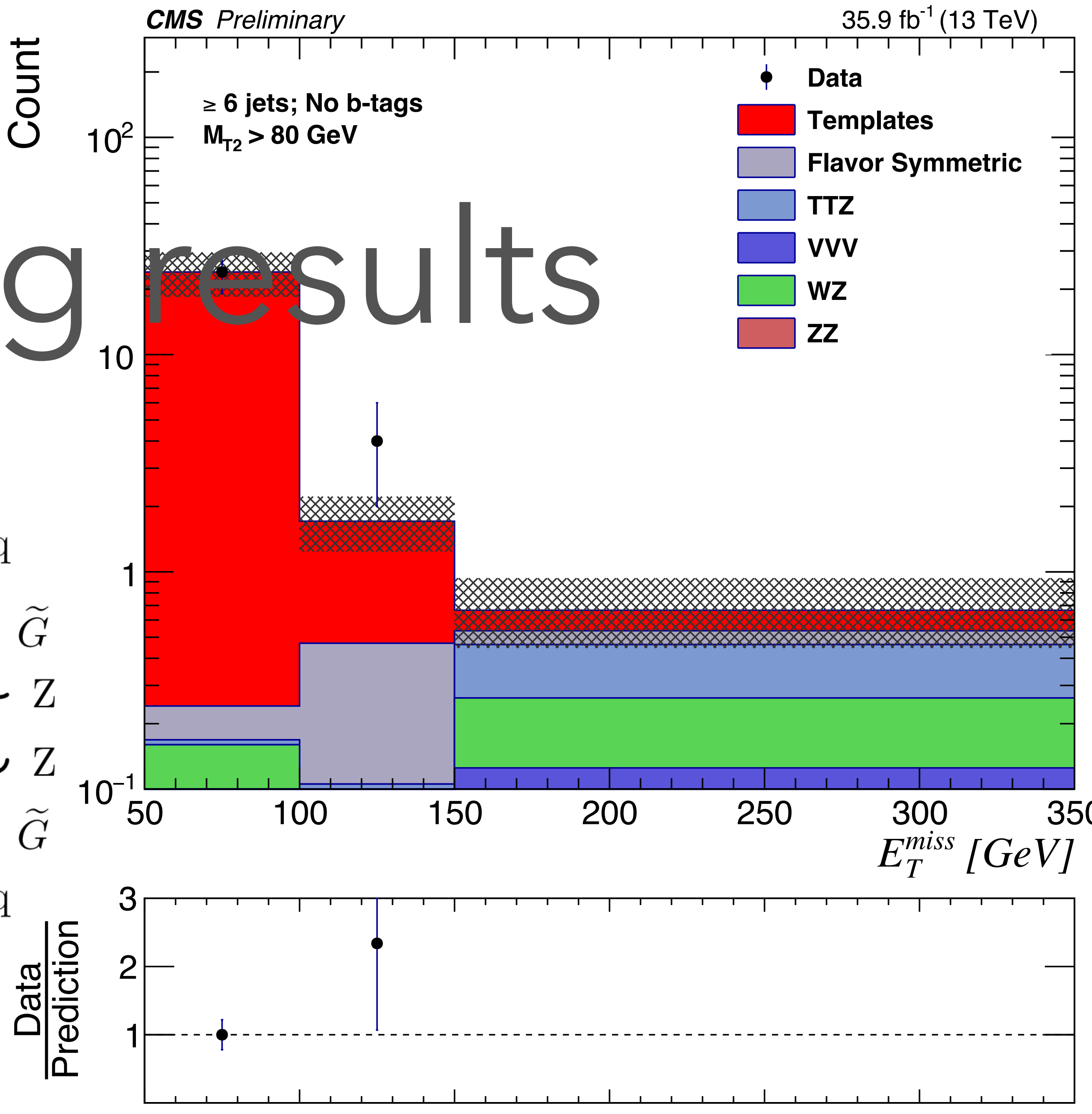
Opposite sign dileptons backup

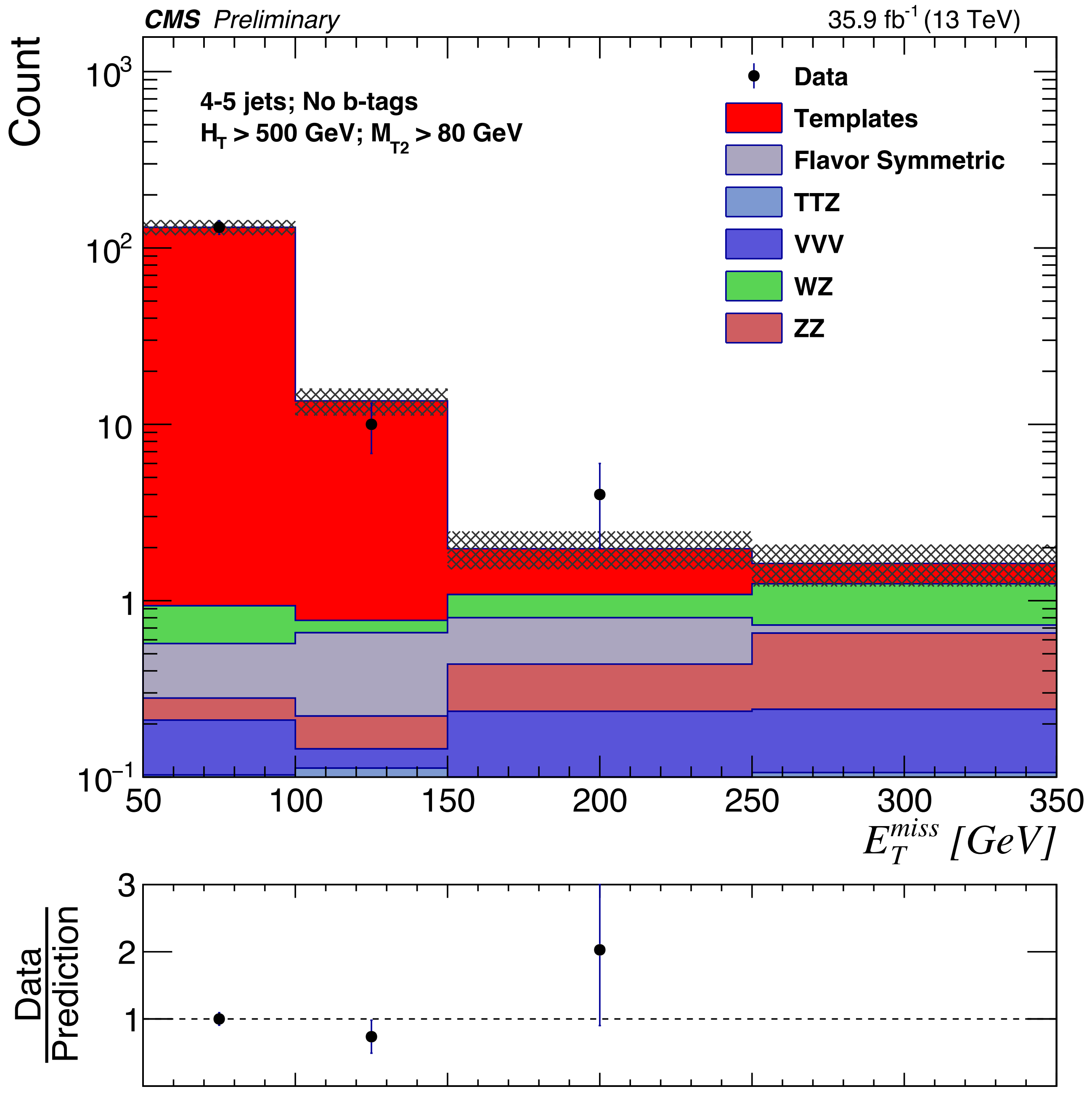
Summary of signal regions

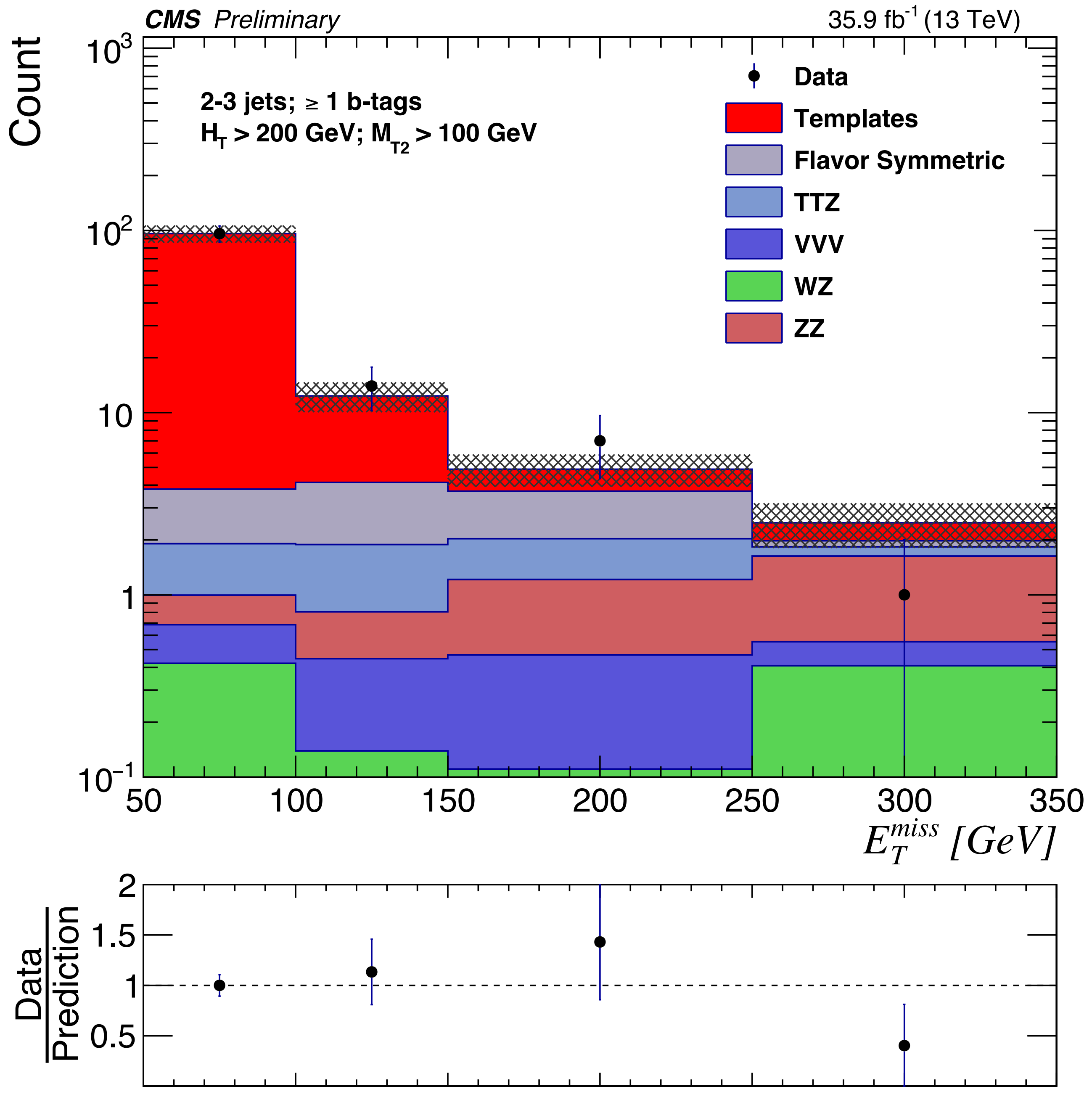
Strong-production on-Z ($86 < m_{\ell\ell} < 96$ GeV) signal regions					
Region	N_{jets}	$N_{\text{b-jets}}$	H_T [GeV]	$M_{T2}(\ell\ell)$ [GeV]	p_T^{miss} binning [GeV]
SRA b veto	2–3	$= 0$	> 500	> 80	100–150, 150–250, > 250
SRB b veto	4–5	$= 0$	> 500	> 80	100–150, 150–250, > 250
SRC b veto	≥ 6	$= 0$	-	> 80	100–150, > 150
SRA b tag	2–3	≥ 1	> 200	> 100	100–150, 150–250, > 250
SRB b tag	4–5	≥ 1	> 200	> 100	100–150, 150–250, > 250
SRC b tag	≥ 6	≥ 1	-	> 100	100–150, > 150
Electroweak-production on-Z ($86 < m_{\ell\ell} < 96$ GeV) signal regions					
Region	N_{jets}	$N_{\text{b-jets}}$	Dijet mass [GeV]	M_{T2} [GeV]	p_T^{miss} binning [GeV]
VZ	≥ 2	$= 0$	$m_{jj} < 110$	$M_{T2}(\ell\ell) > 80$	100–150, 150–250, 250–350, > 350
HZ	≥ 2	$= 2$	$m_{bb} < 150$	$M_{T2}(\ell b \ell b) > 200$	100–150, 150–250, > 250
Edge signal regions					
Region	N_{jets}	p_T^{miss} [GeV]	$M_{T2}(\ell\ell)$ [GeV]	$t\bar{t}$ likelihood	$m_{\ell\ell}$ binning [GeV]
Edge fit	≥ 2	> 150	> 80	-	> 20
$t\bar{t}$-like	≥ 2	> 150	> 80	< 21	20–60, 60–86, 96–150, 150–200, 200–300, 300–400, > 400
not-$t\bar{t}$-like	≥ 2	> 150	> 80	> 21	same as $t\bar{t}$-like

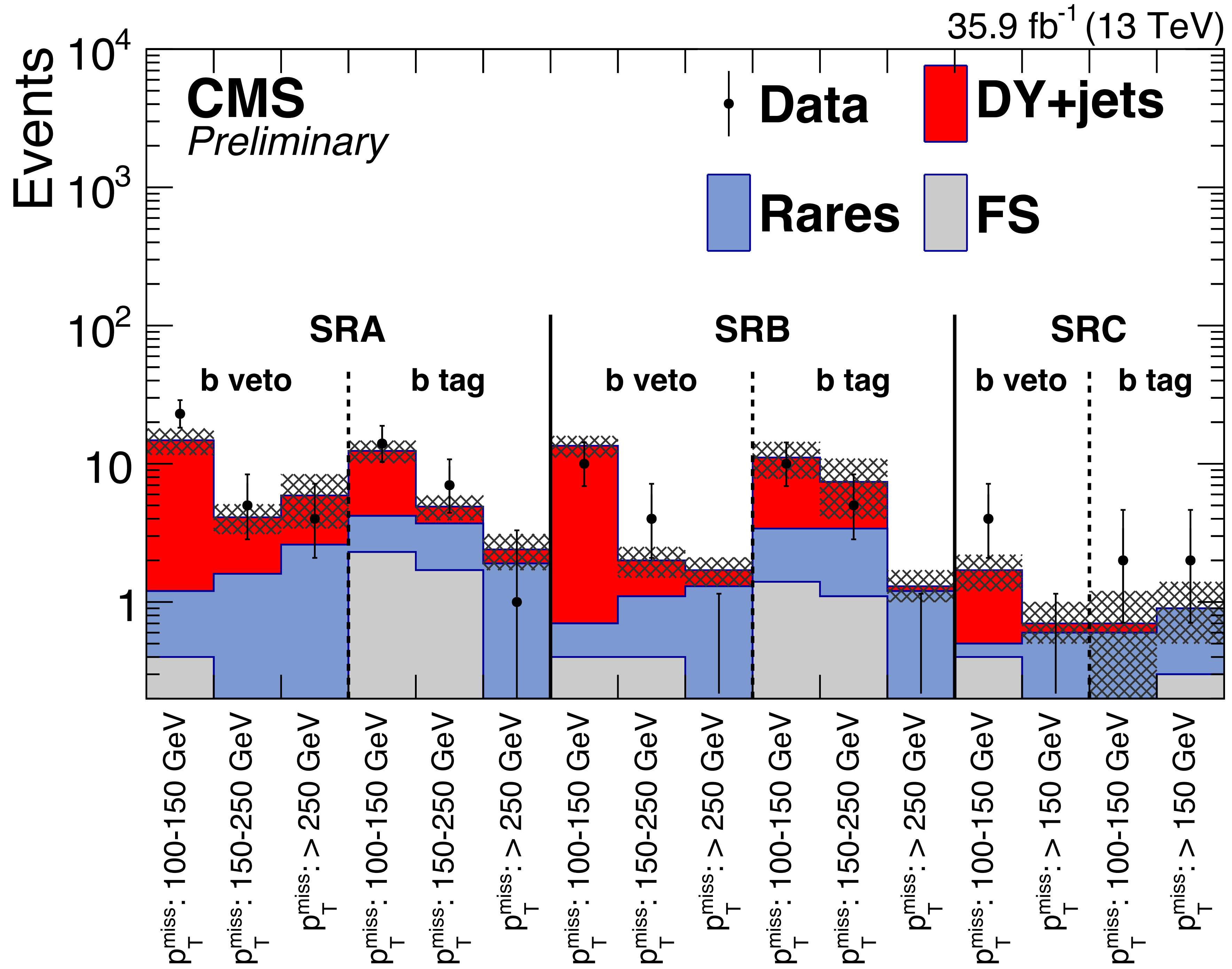
On-Z strong results

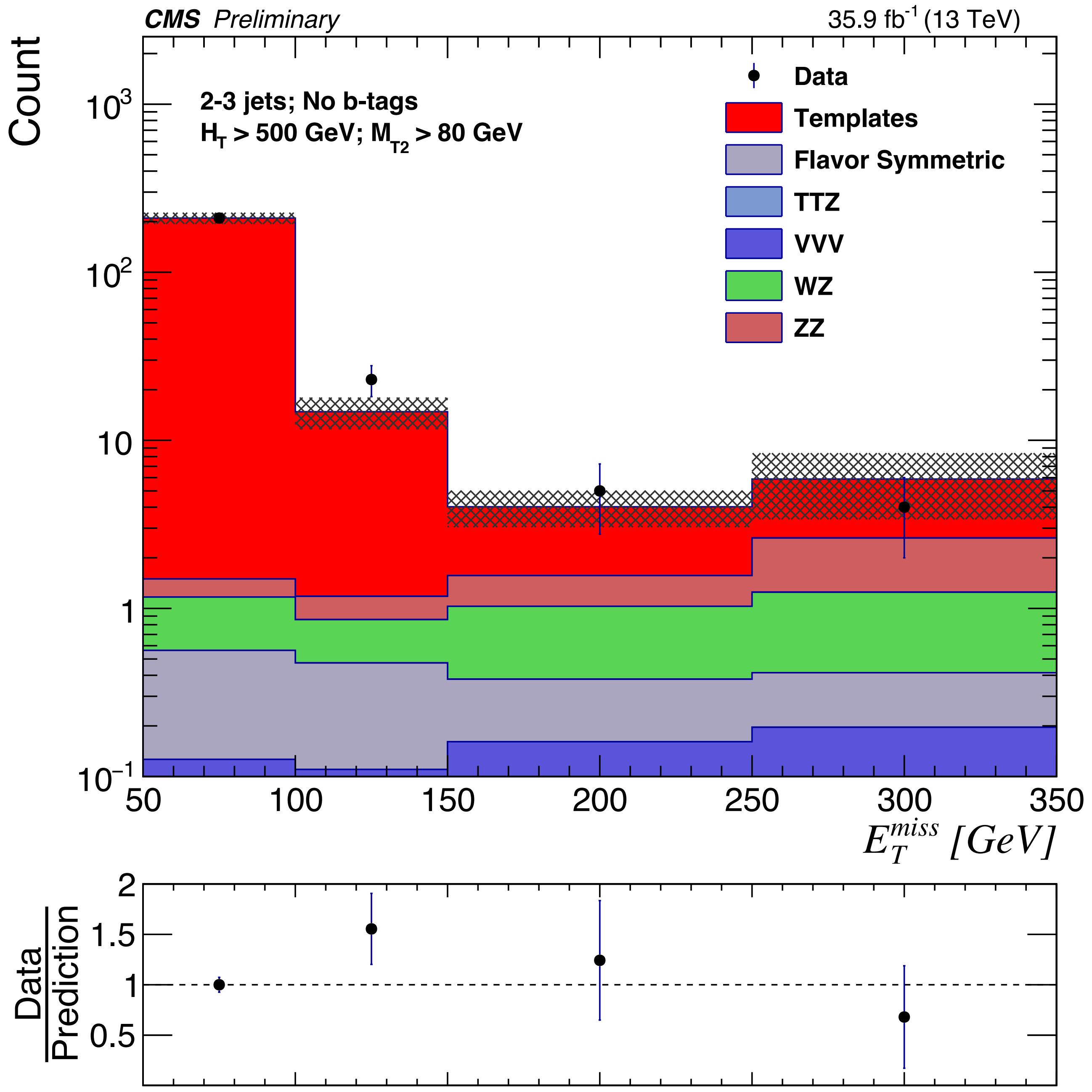


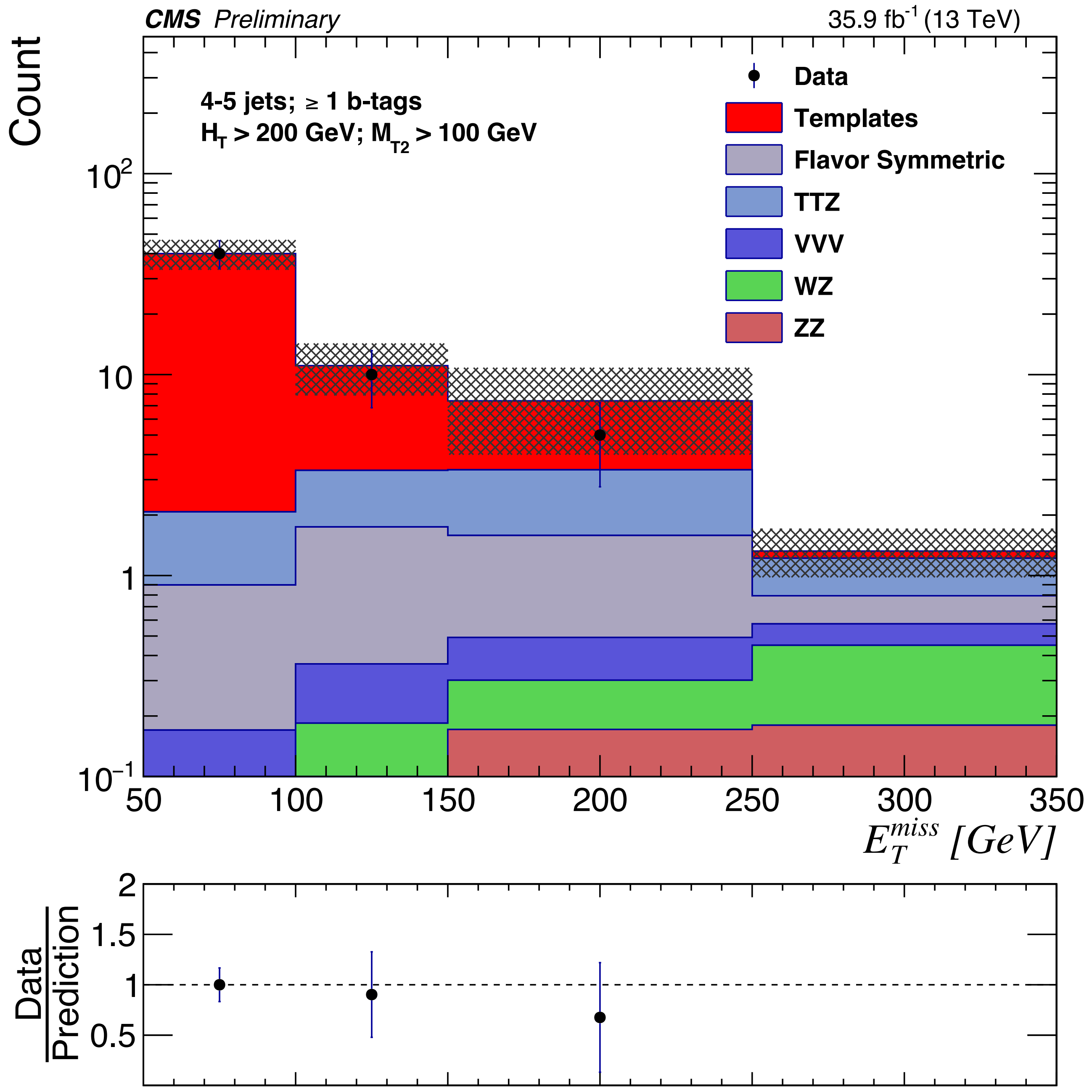












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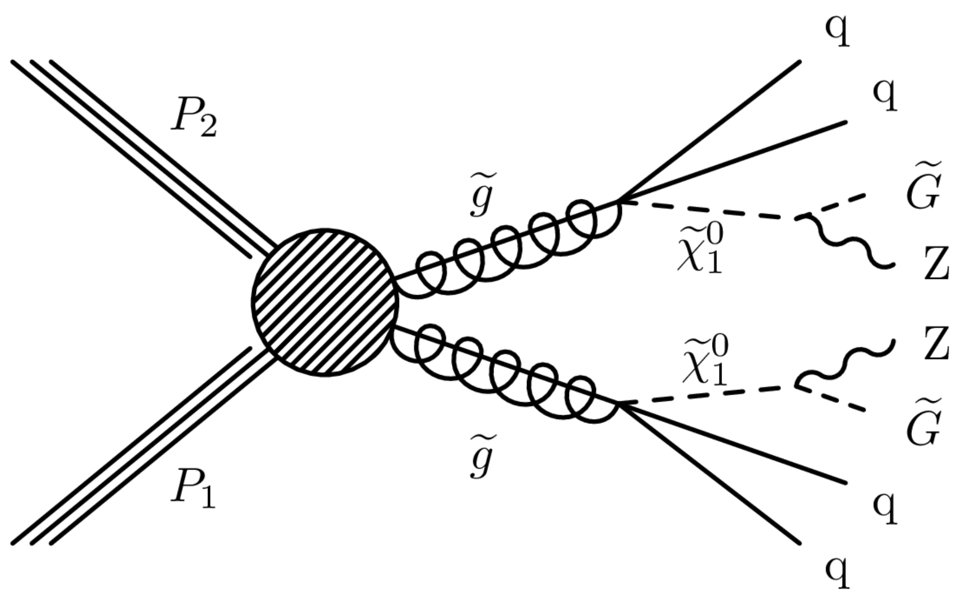
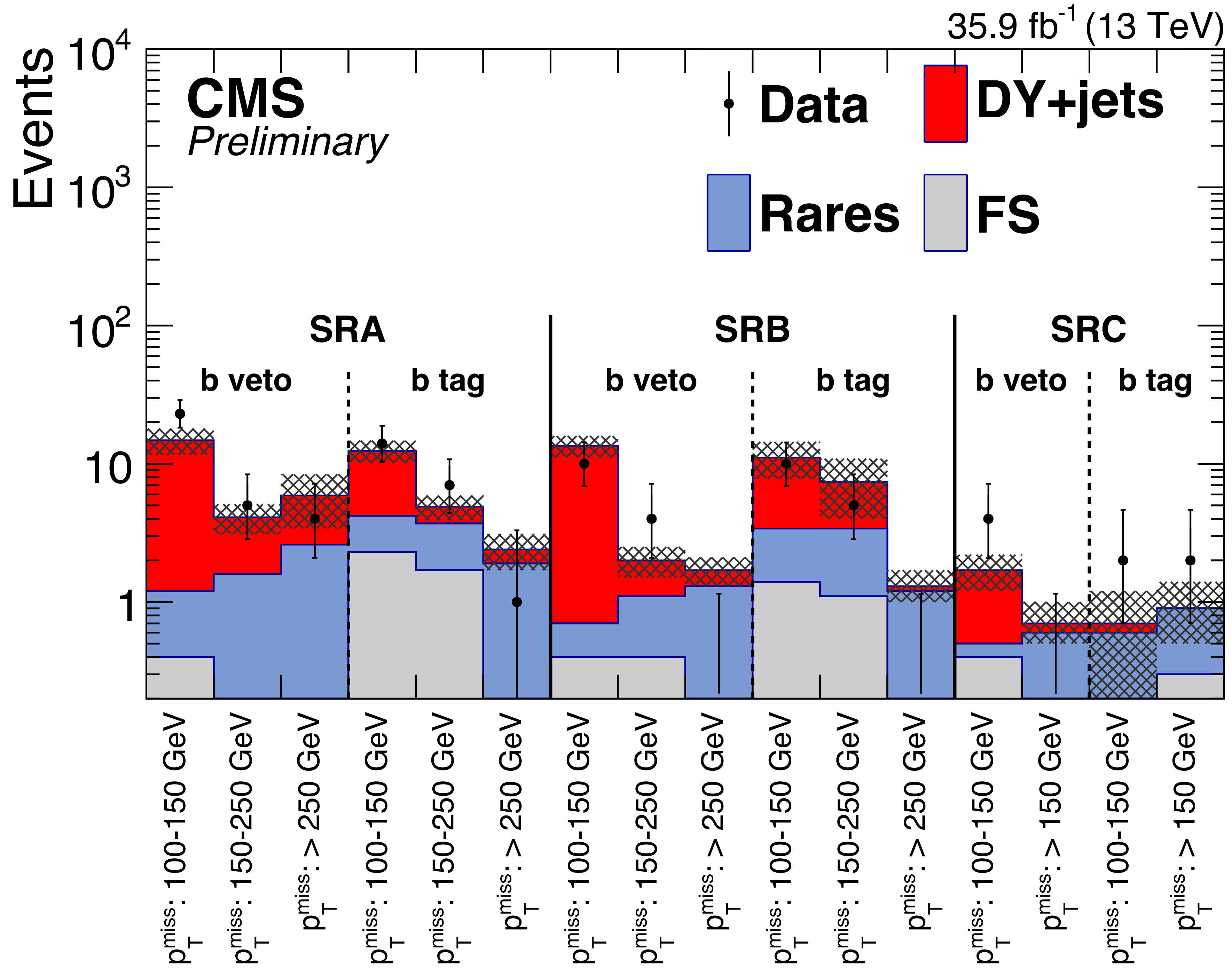
On-Z strong results





SRA, b veto	p_T^{miss} [GeV]	100–150	150–250	> 250
	DY+jets	13.6±3.1	2.5±0.9	3.3±2.4
	FS	$0.4^{+0.3}_{-0.2}$	$0.2^{+0.2}_{-0.1}$	$0.2^{+0.2}_{-0.1}$
	Z+ν	0.8±0.3	1.4±0.4	2.4±0.8
	Total background	14.8±3.2	4.0±1.0	5.9±2.5
	Data	23	5	4
SRA, b tag	p_T^{miss} [GeV]	100–150	150–250	> 250
	DY+jets	8.2±2.1	1.2±0.5	0.5±0.3
	FS	2.3±0.8	$1.7^{+0.7}_{-0.6}$	$0.1^{+0.2}_{-0.1}$
	Z+ν	1.9±0.4	2.0±0.5	1.8±0.6
	Total background	12.4±2.3	4.9±1.0	2.5±0.7
	Data	14	7	1
SRB, b veto	p_T^{miss} [GeV]	100–150	150–250	> 250
	DY+jets	12.8±2.3	0.9±0.3	0.4±0.2
	FS	$0.4^{+0.3}_{-0.2}$	$0.4^{+0.3}_{-0.2}$	$0.1^{+0.2}_{-0.1}$
	Z+ν	0.3±0.1	0.7±0.2	1.2±0.4
	Total background	13.6±2.4	2.0±0.5	1.6±0.4
	Data	10	4	0
SRB, b tag	p_T^{miss} [GeV]	100–150	150–250	> 250
	DY+jets	7.7±3.2	4.0±3.4	0.1±0.1
	FS	$1.4^{+0.6}_{-0.5}$	$1.1^{+0.5}_{-0.4}$	$0.2^{+0.2}_{-0.1}$
	Z+ν	2.0±0.5	2.3±0.6	1.0±0.3
	Total background	11.1±3.3	$7.4^{+3.5}_{-3.4}$	$1.3^{+0.4}_{-0.3}$
	Data	10	5	0
SRC, b veto	p_T^{miss} [GeV]	100–150	> 150	
	DY+jets	1.2±0.4	0.1±0.1	
	FS	$0.4^{+0.3}_{-0.2}$	$0.1^{+0.2}_{-0.1}$	
	Z+ν	0.1±0.1	0.5±0.2	
	Total background	1.7±0.5	$0.7^{+0.3}_{-0.2}$	
	Data	4	0	
SRC, b tag	p_T^{miss} [GeV]	100–150	> 150	
	DY+jets	0.1±0.4	0.0±0.3	
	FS	$0.0^{+0.1}_{-0.0}$	0.3±0.2	
	Z+ν	0.6±0.2	0.6±0.2	
	Total background	0.8±0.5	$0.9^{+0.5}_{-0.4}$	
	Data	2	2	

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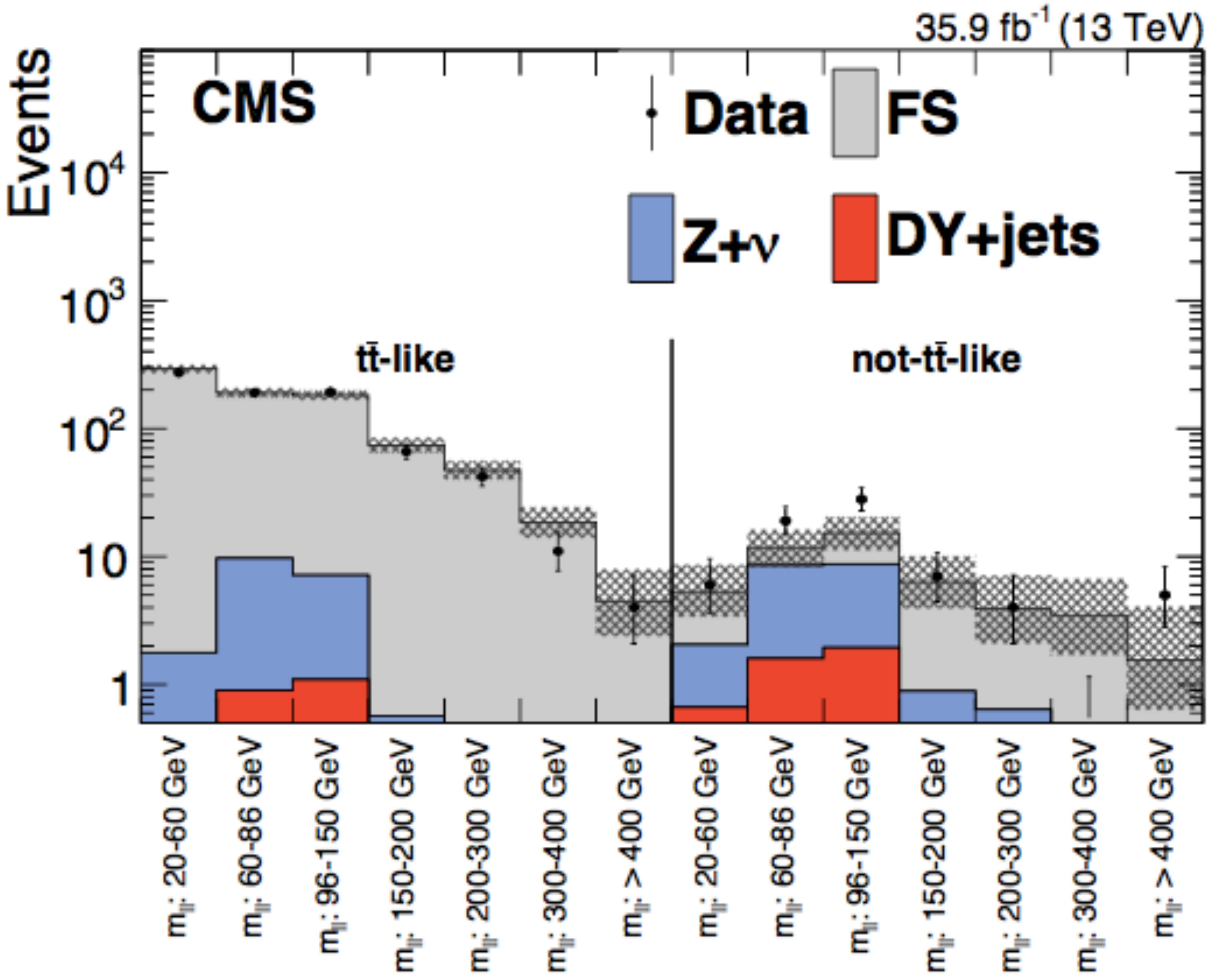
Edge results

- first MET bin used for normalization
- over prediction in high MET bins in EWK WZ region
- causing better observed limits than expe



$m_{\ell\ell}$ range [GeV]	FS	DY+jets	Z+ν	Total background	Data
tt̄-like					
20–60	291^{+21}_{-20}	0.4±0.3	1.4±0.5	293^{+21}_{-20}	273
60–86	181^{+16}_{-15}	0.9±0.7	8.8±3.4	190^{+16}_{-15}	190
96–150	176^{+15}_{-14}	1.1±0.9	6.0±2.4	182^{+16}_{-15}	192
150–200	73^{+10}_{-9}	0.1±0.1	0.4±0.2	74^{+10}_{-9}	66
200–300	$46.9^{+8.4}_{-7.3}$	< 0.1	0.3±0.1	$47.3^{+8.4}_{-7.3}$	42
300–400	$18.5^{+5.7}_{-4.5}$	< 0.1	< 0.1	$18.6^{+5.7}_{-4.5}$	11
> 400	$4.3^{+3.4}_{-2.1}$	< 0.1	< 0.1	$4.5^{+3.4}_{-2.1}$	4
Not-tt̄-like					
20–60	$3.3^{+3.2}_{-1.8}$	0.7±0.5	1.4±0.5	$5.3^{+3.3}_{-1.9}$	6
60–86	$3.3^{+3.2}_{-1.8}$	1.6±1.3	6.9±2.7	$11.8^{+4.4}_{-3.5}$	19
96–150	$6.6^{+3.9}_{-2.6}$	1.9±1.5	6.8±2.7	$15.3^{+5.0}_{-4.1}$	28
150–200	$5.5^{+3.7}_{-2.4}$	0.2±0.3	0.7±0.3	$6.4^{+3.7}_{-2.4}$	7
200–300	$3.3^{+3.2}_{-1.8}$	0.2±0.2	0.5±0.2	$3.9^{+3.2}_{-1.8}$	4
300–400	$3.3^{+3.2}_{-1.8}$	< 0.1	0.2±0.1	$3.5^{+3.2}_{-1.8}$	0
> 400	$1.1^{+2.5}_{-0.9}$	< 0.1	0.4±0.2	$1.6^{+2.5}_{-0.9}$	5
Aggregate SRs (not-tt̄-like)					
20–86	$6.5^{+3.9}_{-2.6}$	2.3±1.5	8.3±3.2	$17.1^{+5.3}_{-4.4}$	25
> 96	$19.6^{+5.8}_{-4.6}$	2.4±1.6	8.5±3.4	$30.6^{+7.0}_{-6.0}$	44

Opposite sign dileptons: 3L control region for ttZ

3 lepton control region for ttZ

- derived in data and used to scale the simulation
- == 2 b tagged jets, p_T^{miss} > 30 GeV, 3 leptons, two of which must form an OSSF pair with m_{ll} close to Z mass
- SF of 1.31+-0.09 for ttZ

ttbar discriminant

Background rejection:

In the edge/ counting search, ttbar is ~the only background.

Top likelihood classification:

- Use four characteristic ttbar variables:
  - dR between the leptons, di-lepton p_T, E_T^{miss}, sum of the two m_{lb}'s
  - Extract these events in data by selecting opposite flavour leptons (~100% ttbar)
- The NLL variable is defined as -2log(Likelihood)
  - where the likelihood is the product of the probabilities from the four ttbar pdf's

This NLL allows us to bin in ttbar efficiency

- ttbar like (95% efficiency) and non-ttbar like (5% efficiency)

Diagram of a fully leptonic ttbar process:

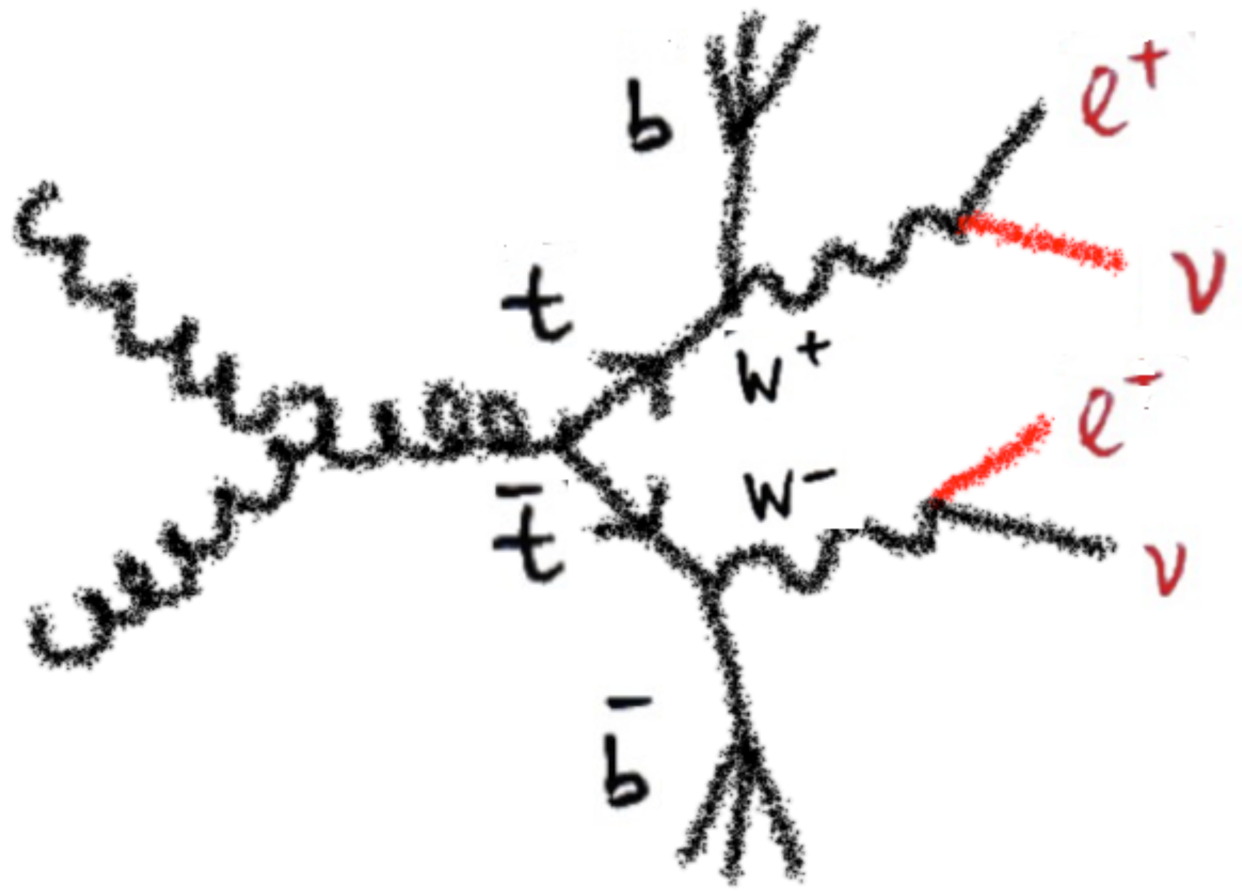
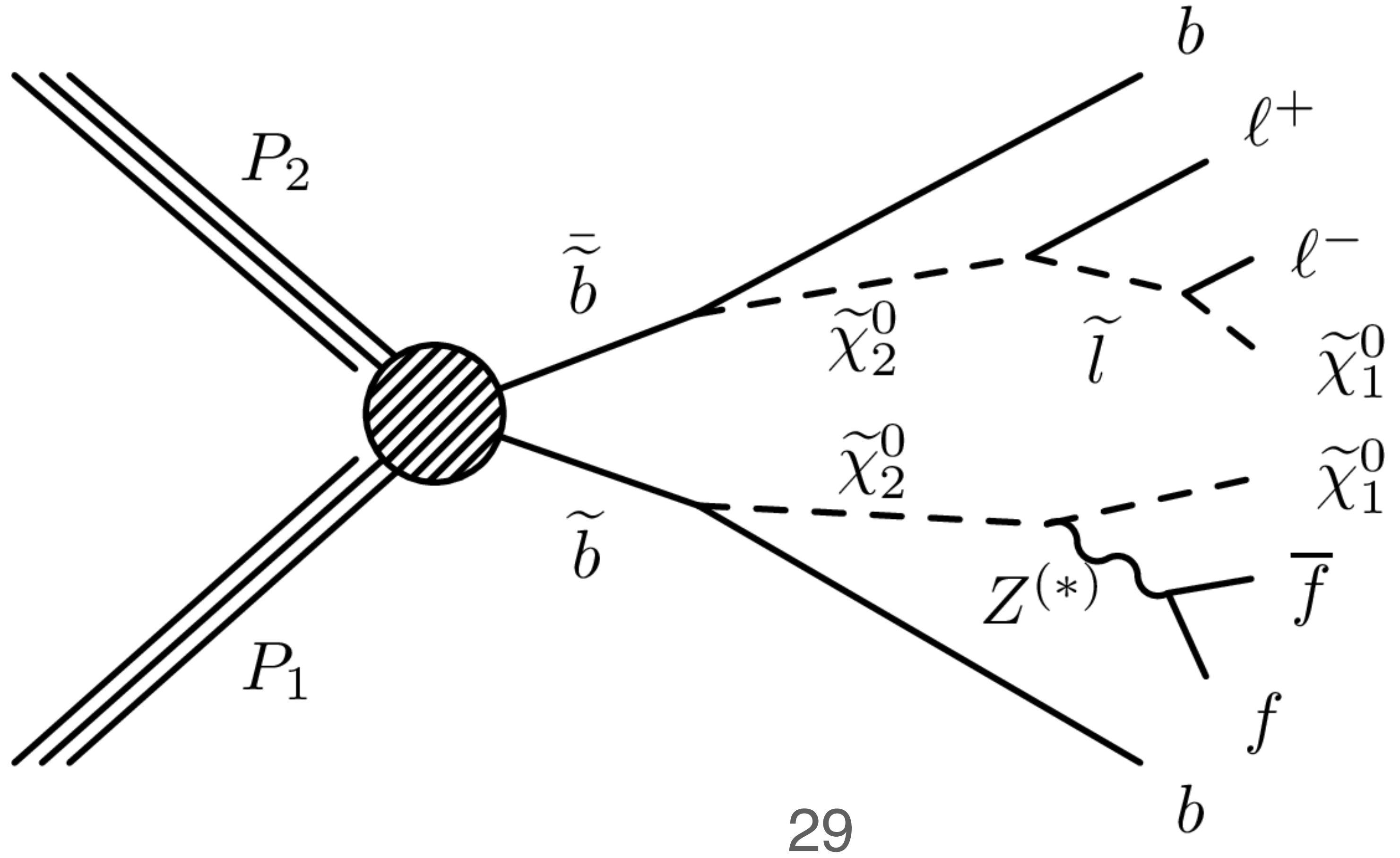
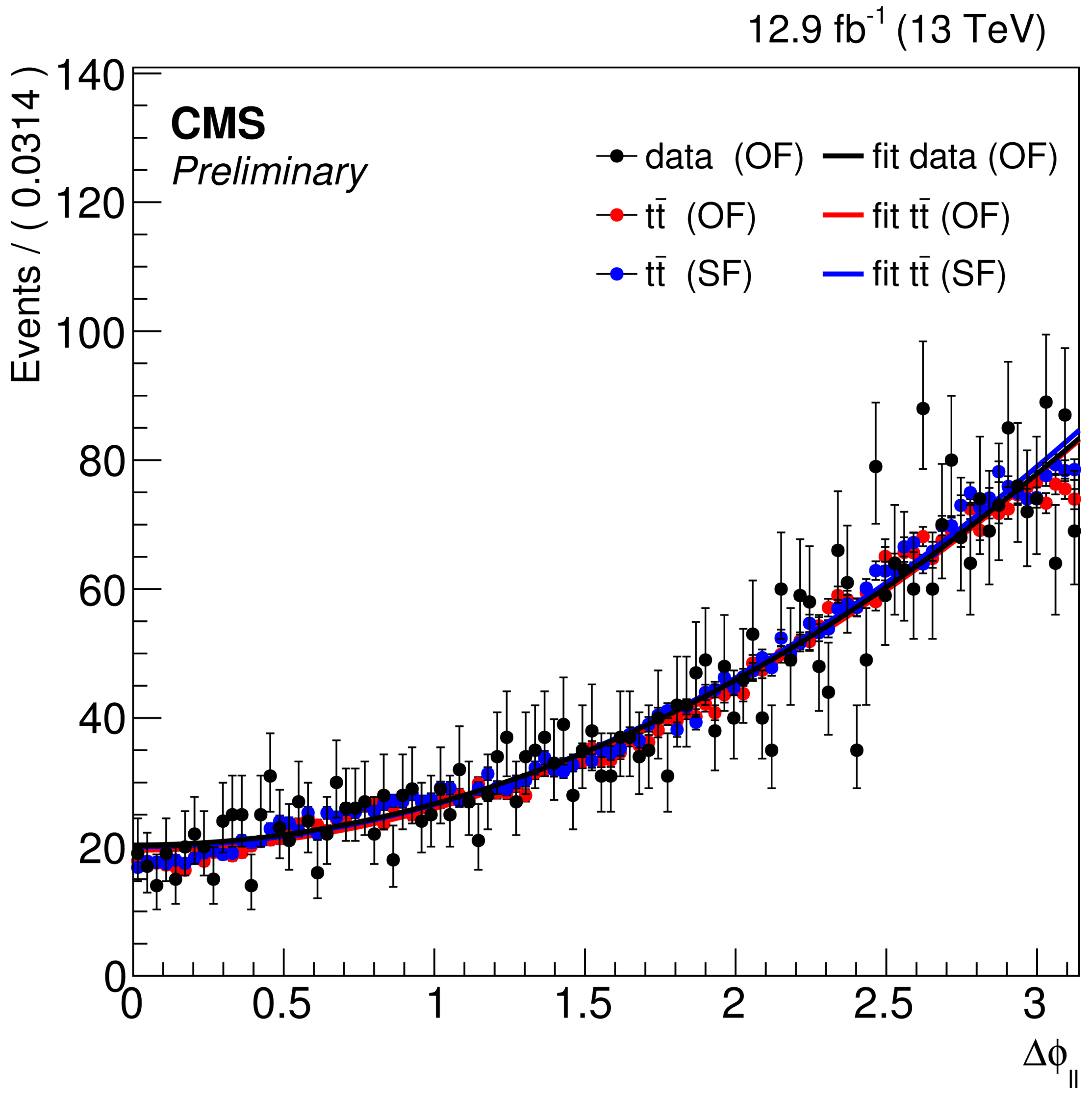


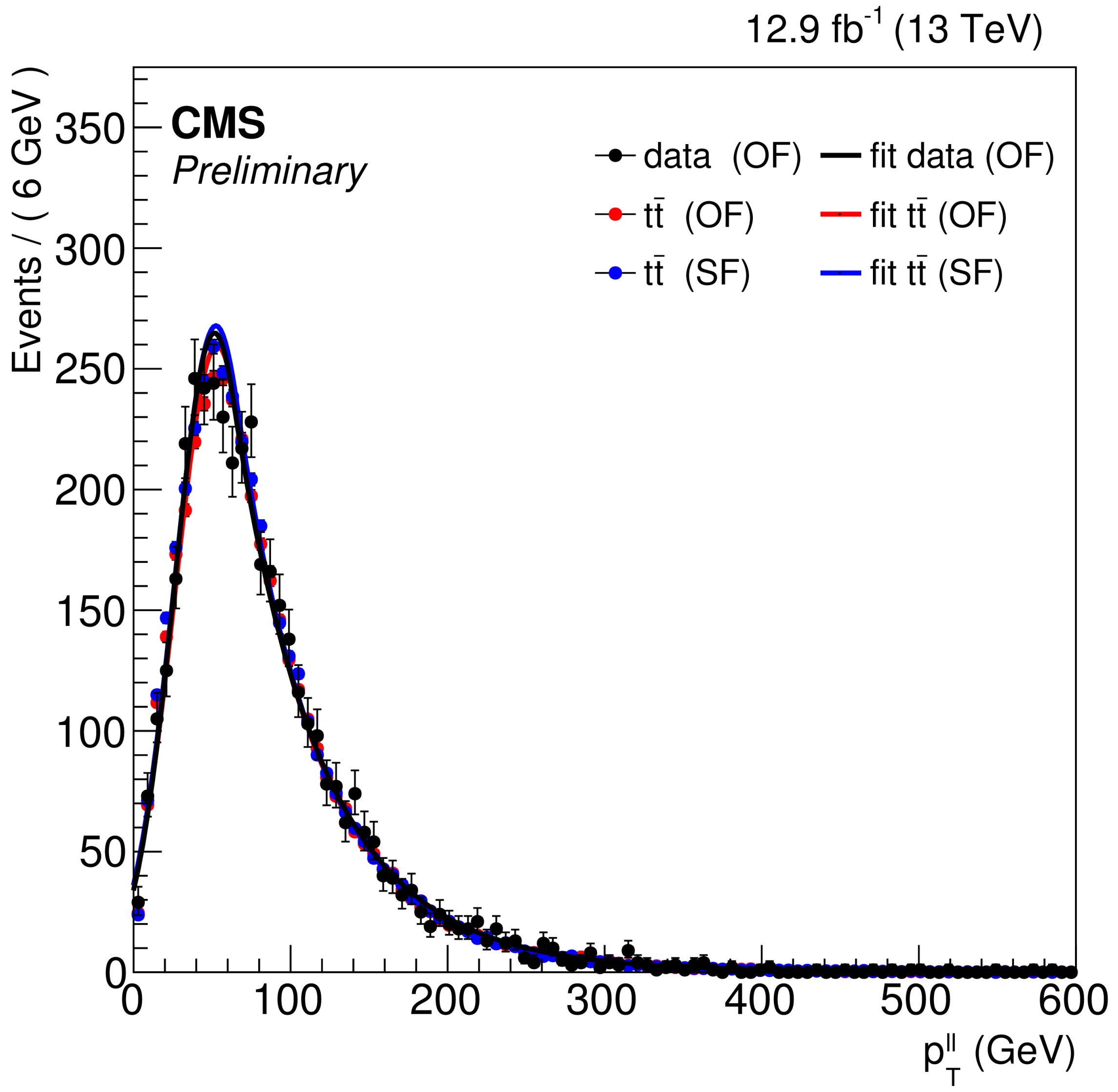
Diagram of a signal SUSY process:

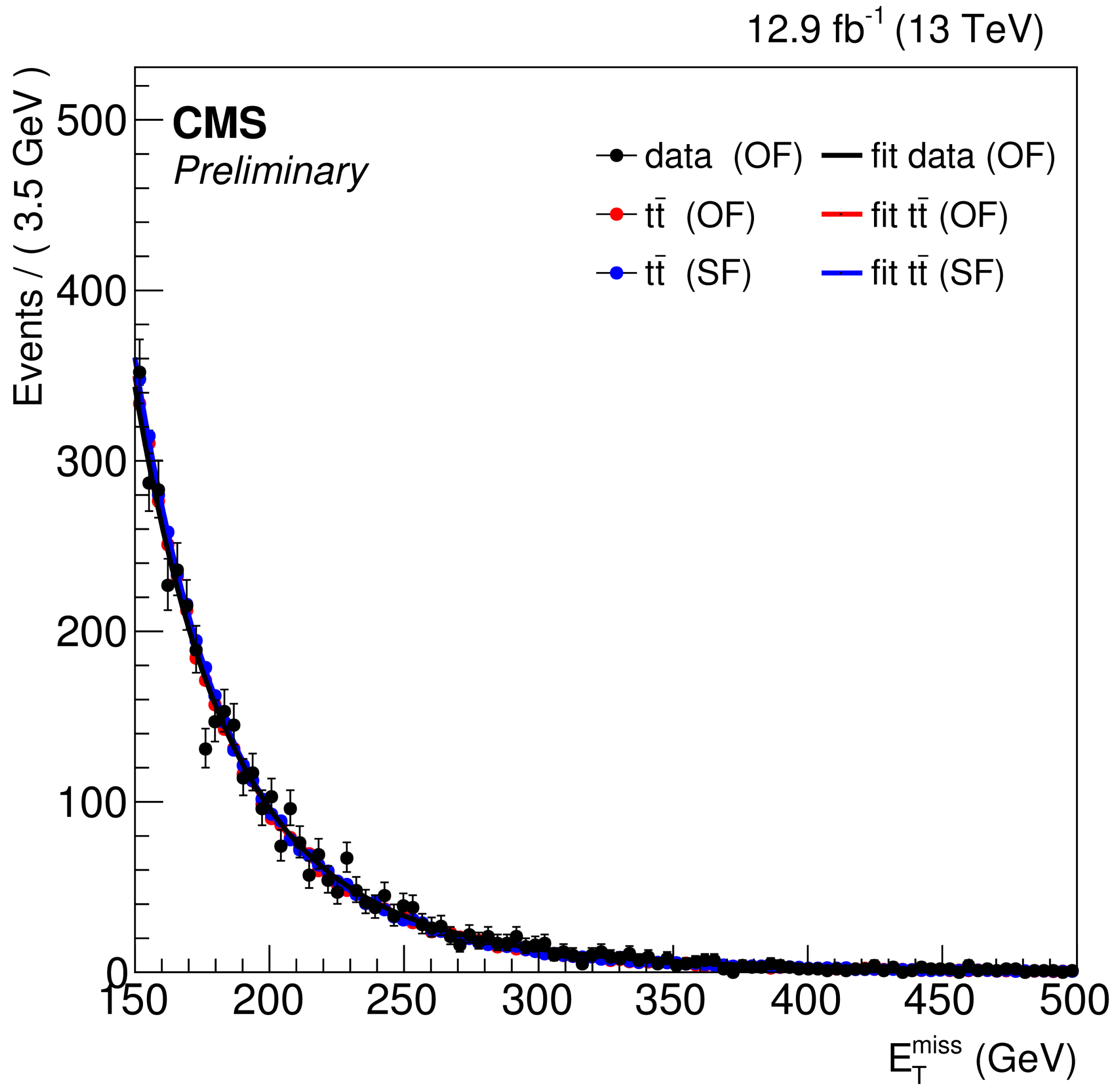


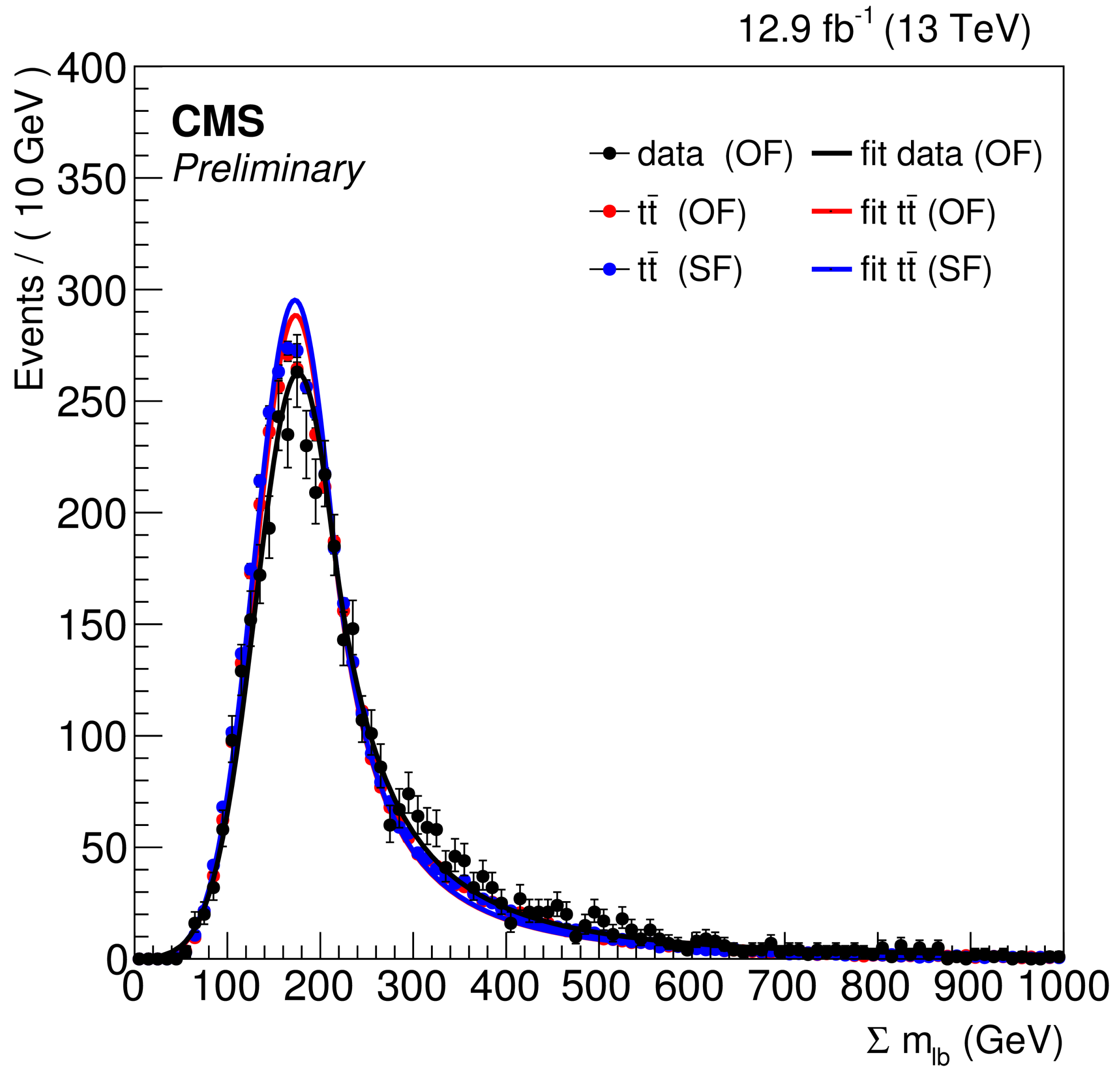
ttbar discriminant

- The four characteristic ttbar variables used as input in the NLL variable:
  - dR between the leptons, di-lepton p_T, E_T^{miss}, sum of the two m_{lb}'s









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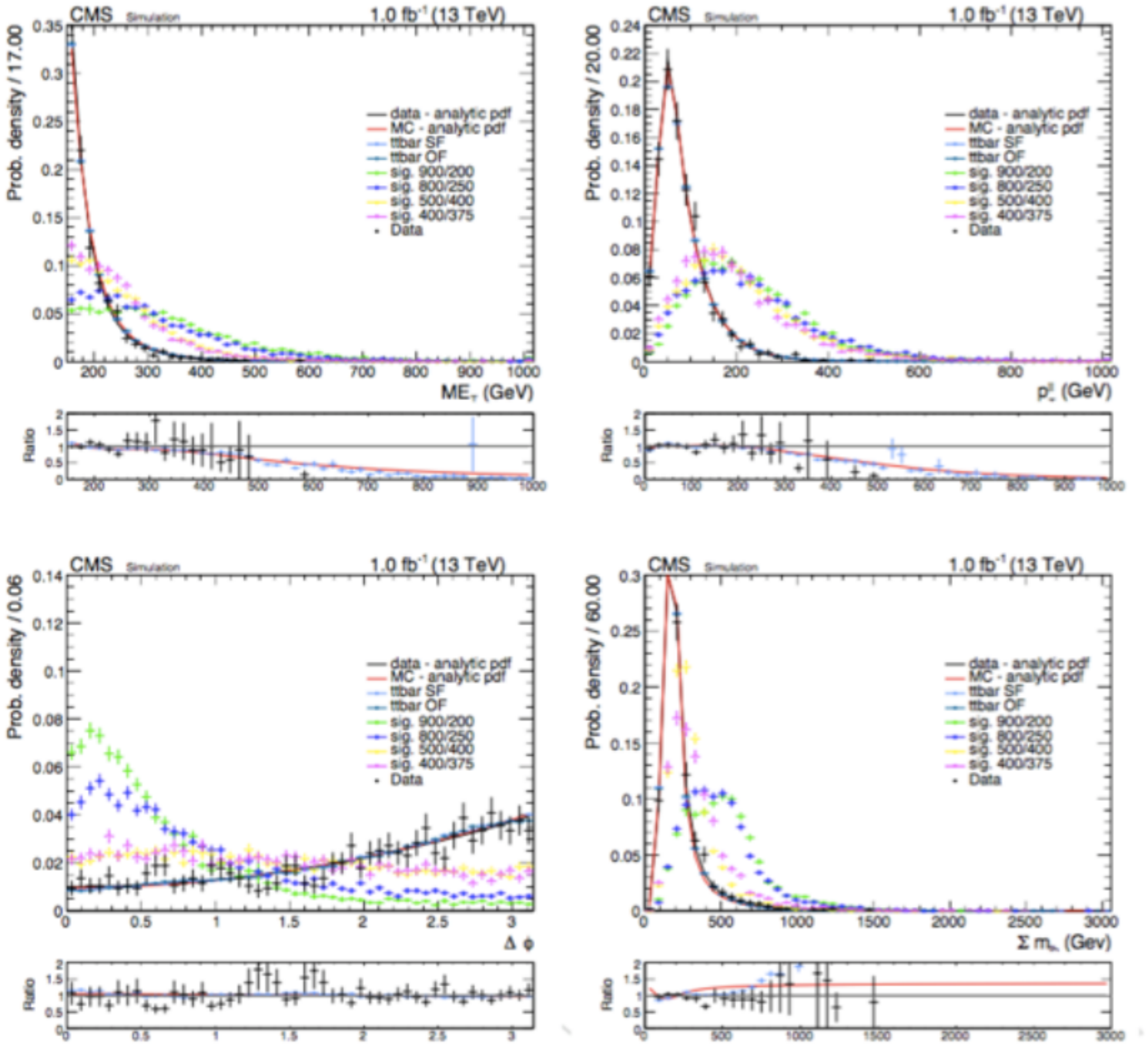
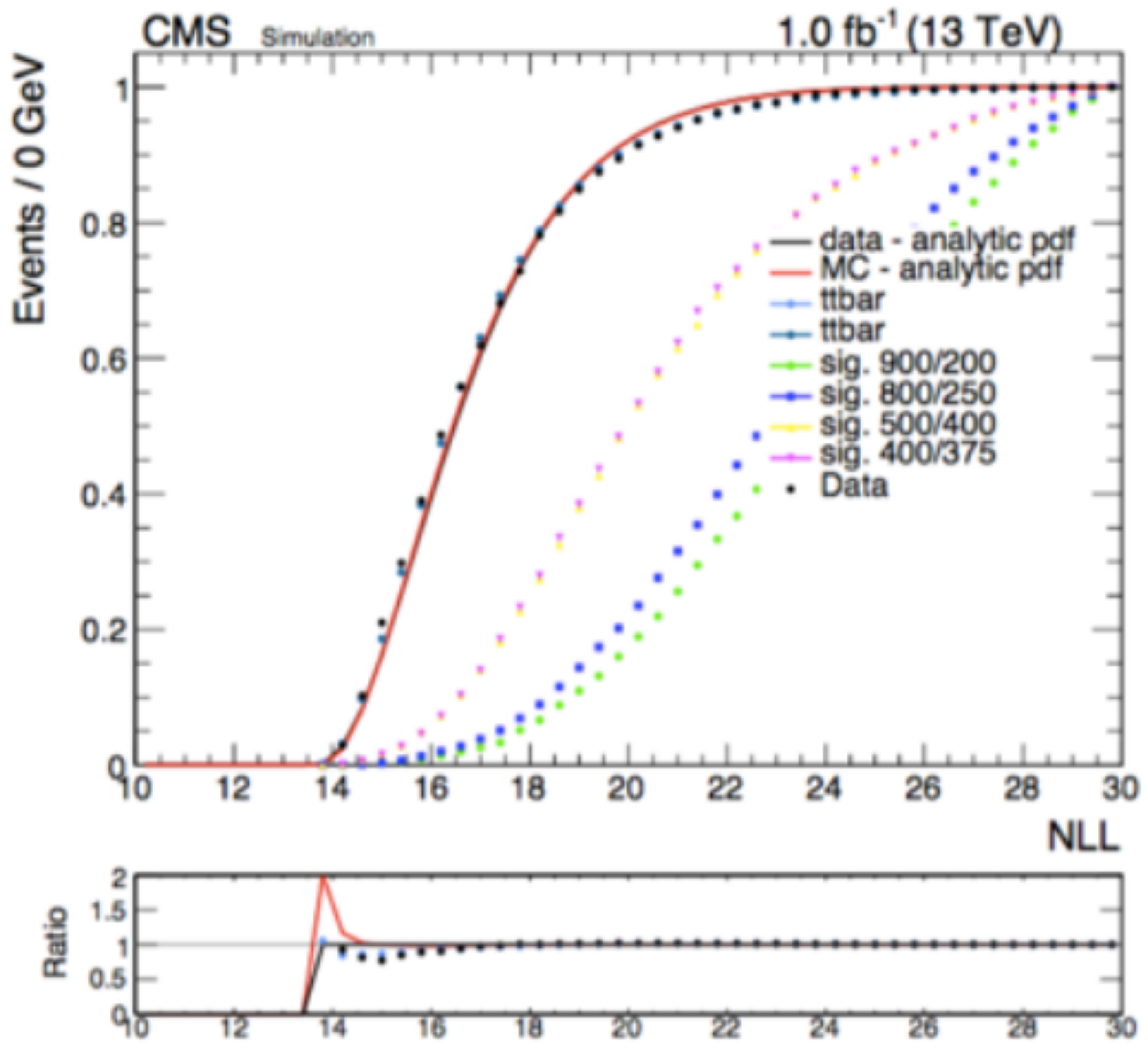
ttbar discriminant



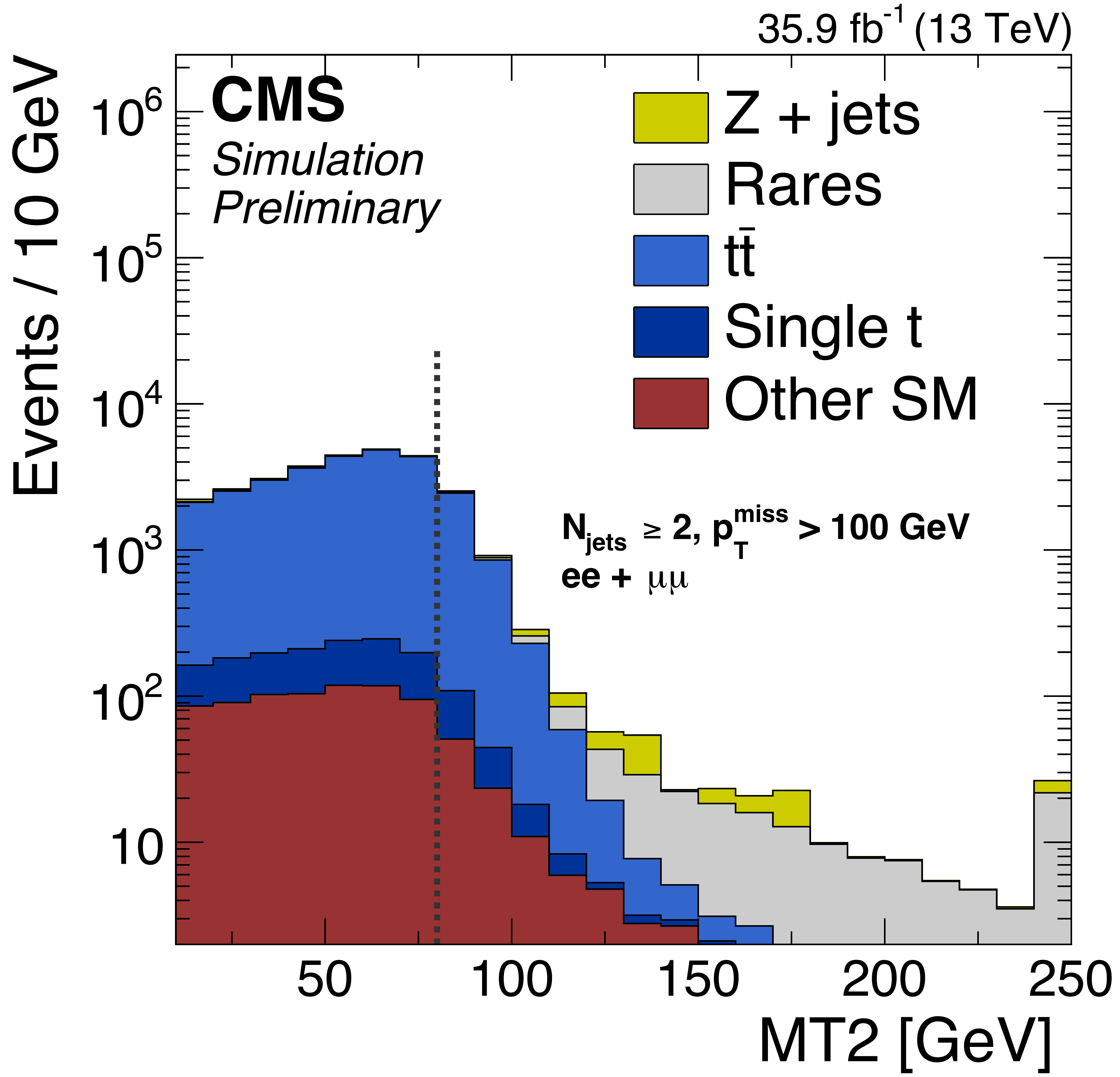


M_{T2}

The M_{T2} is a generalization of the transverse mass for decay chains with two unobserved particles

- Division of events into two massless pseudo jets
- $M_{T2}(m_c) = \min_{\vec{p}_T^{c(1)} + \vec{p}_T^{c(2)} = \vec{p}_T^{miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$
- this gives $M_{T2} < E_T^{miss}$ for SUSY events and $M_{T2} \to 0$ for multijet-like events

- If all masses are known, M_{T2} will have an endpoint at the parent mass (~M_T)
- Very efficient to reduce ttbar and other backgrounds



Systematic uncertainty

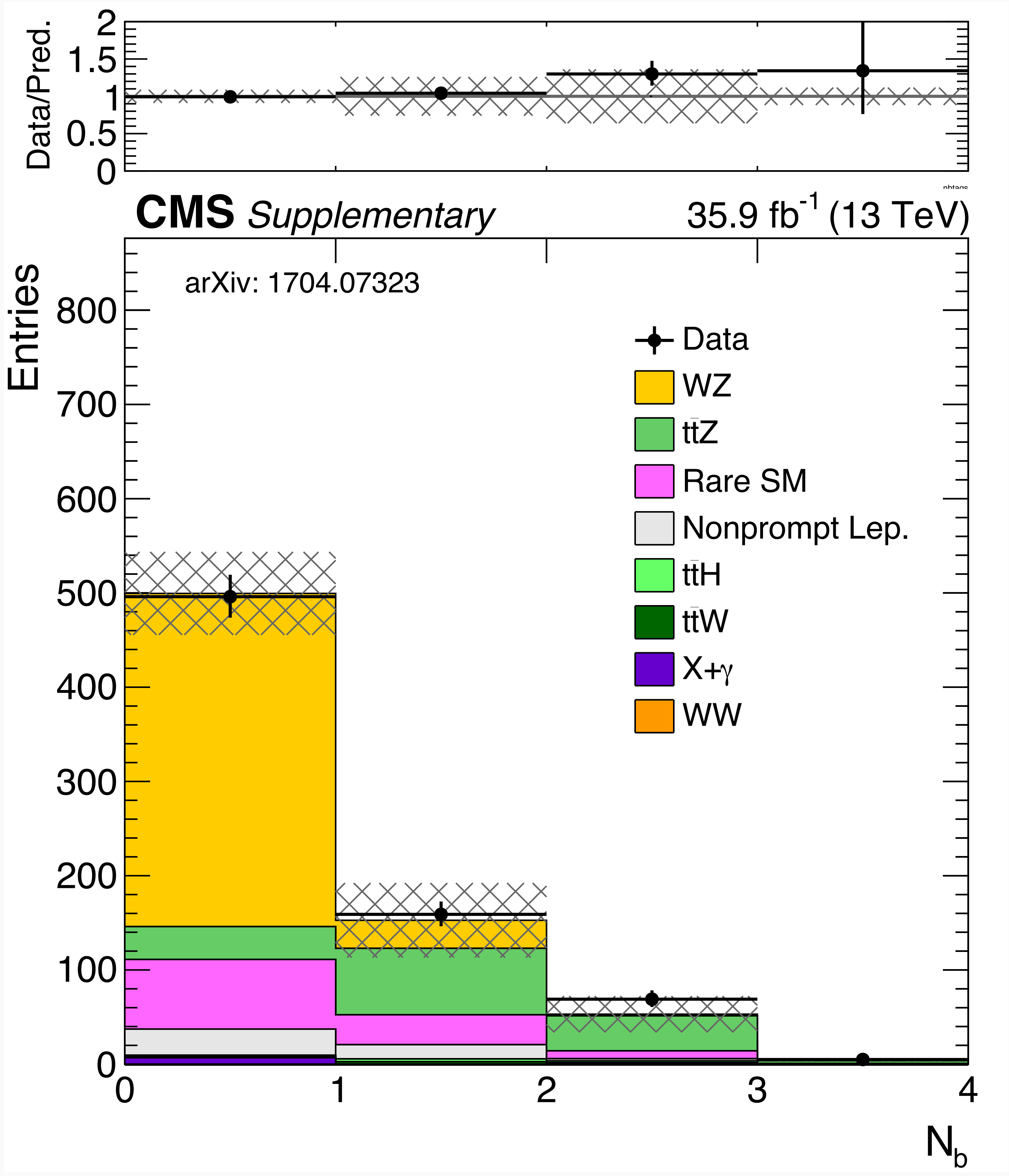
Source of uncertainty	Uncertainty (%)
Integrated luminosity	2.5
Lepton reconstruction and isolation	5
Fast simulation lepton efficiency	4
b tag modeling	0–5
Trigger modeling	3
Jet energy scale	0–5
ISR modeling	0–2.5
Pileup	1–2
Fast simulation p_T^{miss} modeling	0–4
Renorm./fact. scales	1–3
Statistical uncertainty	1–15
Total uncertainty	9–18

Same sign dileptons backup

Same sign dileptons: 3L control region

3 lepton control region

- derived in data and used to scale the simulation
- applicable for SM backgrounds as WZ and ttZ
- $\leq$ 2 jets, p_T^{miss} > 30 GeV, 3 leptons, two of which must form an OSSF pair with m_{ll} close to Z mass
- based on a template fit to the distribution of the number of b jets
- SF of 1.26+-0.09 for WZ and 1.14+-0.30 for ttZ



Same sign dileptons: signal regions

HH

N_b	m_T^{min} (GeV)	E_T^{miss} (GeV)	N_{jets}	$H_T < 300$ GeV	$H_T \in [300, 1125]$ GeV	$H_T \in [1125, 1300]$ GeV	$H_T \in [1300, 1600]$ GeV	$H_T > 1600$ GeV
0	<120	50 – 200	2-4	SR1	SR2	SR46 (++) / SR47 (--)	SR48 (++) / SR49 (--)	SR50 (++) / SR51 (--)
			≥5	SR3	SR4			
		200 – 300	2-4		SR5 (++) / SR6 (--)			
			≥5		SR7			
	>120	50 – 200	2-4		SR8 (++) / SR9 (--)			
			≥5		SR10			
		200 – 300	2-4					
			≥5					
1	<120	50 – 200	2-4	SR11	SR12			
			≥5	SR13 (++) / SR14 (--)	SR15 (++) / SR16 (--)			
		200 – 300	2-4		SR17 (++) / SR18 (--)			
			≥5		SR19			
	>120	50 – 200	2-4		SR20 (++) / SR21 (--)			
			≥5		SR22			
		200 – 300	2-4					
			≥5					
2	<120	50 – 200	2-4	SR23	SR24			
			≥5	SR25 (++) / SR26 (--)	SR27 (++) / SR28 (--)			
		200 – 300	2-4		SR29 (++) / SR30 (--)			
			≥5		SR31			
	>120	50 – 200	2-4		SR32 (++) / SR33 (--)			
			≥5		SR34			
		200 – 300	2-4					
			≥5					
≥3	<120	50 – 200	≥2	SR35 (++) / SR36 (--)	SR37 (++) / SR38 (--)			
		200 – 300			SR39			
	>120	50 – 300	≥2	SR40	SR41			
inclusive	inclusive	300 – 500	≥2	—	SR42 (++) / SR43 (--)			
		>500		—	SR44 (++) / SR45 (--)			

LL

N_b	m_T^{min} (GeV)	H_T (GeV)	$E_T^{miss} \in [50, 200]$ GeV	$E_T^{miss} > 200$ GeV
0	<120	>300	SR1	SR2
1			SR3	SR4
2			SR5	SR6
≥3			SR7	
Inclusive	>120		SR8	

HL

N_b	m_T^{min} (GeV)	E_T^{miss} (GeV)	N_{jets}	$H_T < 300$ GeV	$H_T \in [300, 1125]$ GeV	$H_T \in [1125, 1300]$ GeV	$H_T > 1300$ GeV
0	<120	50 – 200	2-4	SR1	SR2	SR38 (++) / SR39 (--)	SR40 (++) / SR41 (--)
			≥5	SR3	SR4		
		200 – 300	2-4		SR5 (++) / SR6 (--)		
			≥5		SR7		
1	<120	50 – 200	2-4	SR8	SR9		
			≥5	SR10 (++) / SR11 (--)	SR12 (++) / SR13 (--)		
		200 – 300	2-4		SR14 (++) / SR15 (--)		
			≥5		SR16 (++) / SR17 (--)		
2	<120	50 – 200	2-4	SR18	SR19		
			≥5	SR20 (++) / SR21 (--)	SR22 (++) / SR23 (--)		
		200 – 300	2-4		SR24 (++) / SR25 (--)		
			≥5		SR26		
≥3	<120	50 – 200	≥2	SR27 (++) / SR28 (--)	SR29 (++) / SR30 (--)		
		200 – 300			SR31		
inclusive	>120	50 – 300	≥2	SR32	SR33		
inclusive	inclusive	300 – 500	≥2	—	SR34 (++) / SR35 (--)		
		>500		—	SR36 (++) / SR37 (--)		

	HH regions		HL regions		LL regions	
	Expected SM	Observed	Expected SM	Observed	Expected SM	Observed
SR1	468 ± 98	435	419 ± 100	442	12.0 ± 3.9	12
SR2	162 ± 25	166	100 ± 20	101	1.88 ± 0.62	3
SR3	24.4 ± 5.4	30	9.2 ± 2.4	6	15.5 ± 4.7	17
SR4	17.6 ± 3.0	24	15.0 ± 4.5	13	1.42 ± 0.69	4
SR5	17.8 ± 3.9	22	7.3 ± 1.5	14	4.2 ± 1.4	5
SR6	7.8 ± 1.5	6	4.1 ± 1.2	5	0.84 ± 0.48	2
SR7	1.96 ± 0.47	2	1.01 ± 0.28	0	0.95 ± 0.52	0
SR8	4.58 ± 0.81	5	300 ± 82	346	0.09 ± 0.07	0
SR9	3.63 ± 0.75	3	73 ± 17	95		
SR10	2.82 ± 0.56	3	2.30 ± 0.61	1		
SR11	313 ± 87	304	2.24 ± 0.87	1		
SR12	104 ± 20	111	12.8 ± 3.3	12		
SR13	9.5 ± 1.9	13	8.9 ± 2.3	8		
SR14	8.7 ± 2.0	11	4.5 ± 1.3	5		
SR15	14.4 ± 2.9	17	4.7 ± 1.6	4		
SR16	12.7 ± 2.6	10	2.3 ± 1.1	1		
SR17	7.3 ± 1.2	11	0.73 ± 0.29	1		
SR18	3.92 ± 0.79	2	54 ± 12	62		
SR19	3.26 ± 0.74	3	23.7 ± 4.9	24		
SR20	2.6 ± 2.7	4	0.59 ± 0.17	2		
SR21	3.02 ± 0.75	3	0.34 ± 0.20	1		
SR22	2.80 ± 0.57	1	5.2 ± 1.2	9		
SR23	70 ± 12	90	4.9 ± 1.4	6		
SR24	35.7 ± 5.9	40	0.97 ± 0.27	0		
SR25	3.99 ± 0.73	2	1.79 ± 0.74	0		
SR26	2.68 ± 0.80	0	1.01 ± 0.27	1		
SR27	9.7 ± 1.8	9	1.03 ± 0.44	1		
SR28	7.9 ± 2.5	8	1.33 ± 0.61	0		
SR29	2.78 ± 0.58	1	2.89 ± 0.99	3		
SR30	1.86 ± 0.38	1	2.24 ± 0.79	2		
SR31	2.20 ± 0.54	1	0.27 ± 0.30	1		
SR32	1.85 ± 0.39	5	0.79 ± 0.33	1		
SR33	1.20 ± 0.32	0	0.53 ± 0.13	0		
SR34	1.81 ± 0.42	3	6.3 ± 1.3	6		
SR35	1.98 ± 0.61	1	2.92 ± 0.87	3		
SR36	1.43 ± 0.37	2	0.51 ± 0.15	3		
SR37	4.2 ± 1.3	2	0.15 ± 0.07	0		
SR38	3.04 ± 0.68	4	1.07 ± 0.33	3		
SR39	0.63 ± 0.17	1	0.81 ± 0.47	0		
SR40	0.29 ± 0.34	0	1.54 ± 0.50	4		
SR41	0.80 ± 0.22	3	1.23 ± 0.53	1		
SR42	13.4 ± 1.9	19				
SR43	8.0 ± 3.0	8				
SR44	3.33 ± 0.74	3				
SR45	0.94 ± 0.26	1				
SR46	2.92 ± 0.50	3				
SR47	1.78 ± 0.42	3				
SR48	1.95 ± 0.39	5				
SR49	1.23 ± 0.30	3				
SR50	1.46 ± 0.31	0				
SR51	0.74 ± 0.18	0				

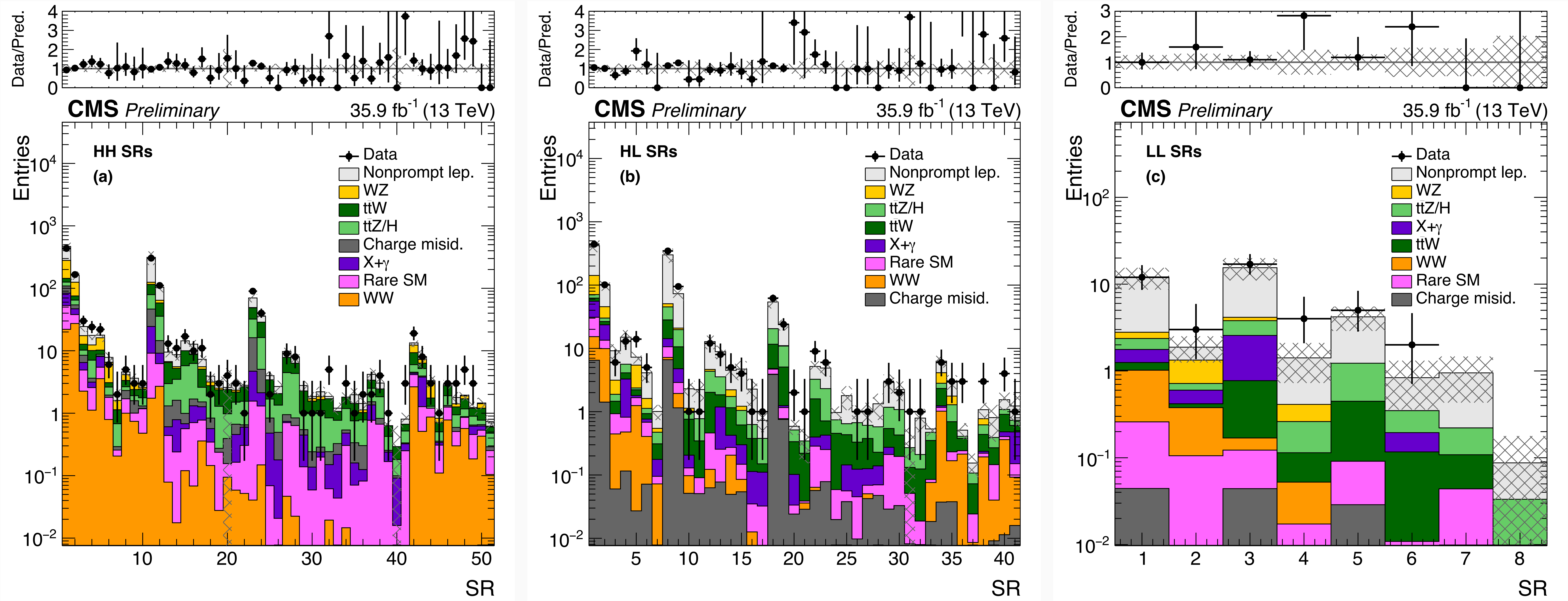
Aggregate inclusive signal regions

SR	Leptons	N_{jets}	N_b	H_T (GeV)	E_T^{miss} (GeV)	m_T^{min} (GeV)	SM expected	Observed	$N^{95\%CL}_{obs,UL}$
InSR1	HH	≥2	0	≥1200	≥50	—	4.00 ± 0.79	10	12.35
InSR2		≥2	≥2	≥1100	≥50	—	3.63 ± 0.71	4	5.64
InSR3		≥2	0	—	≥450	—	3.72 ± 0.83	4	5.62
InSR4		≥2	≥2	—	≥300	—	3.32 ± 0.81	6	8.08
InSR5		≥2	0	—	≥250	≥120	1.68 ± 0.44	2	4.46
InSR6		≥2	≥2	—	≥150	≥120	3.82 ± 0.76	7	9.06
InSR7		≥2	0	≥900	≥200	—	5.6 ± 1.1	10	10.98
InSR8		≥2	≥2	≥900	≥200	—	5.8 ± 1.3	9	9.77
InSR9		≥7	—	—	≥50	—	10.1 ± 2.7	9	7.39
InSR10		≥4	—	—	≥50	≥120	15.2 ± 3.5	22	16.73
InSR11		≥2	≥3	—	≥50	—	13.3 ± 3.4	17	13.63
InSR12		≥2	0	≥700	≥50	—	3.6 ± 2.5	3	4.91
InSR13	LL	≥2	—	—	≥200	—	4.9 ± 2.9	10	11.76
InSR14		≥5	—	—	≥50	—	7.3 ± 5.5	6	6.37
InSR15		≥2	≥3	—	≥50	—	1.06 ± 0.99	0	2.31

Aggregate exclusive signal regions

SR	Leptons	N_{jets}	N_b	E_T^{miss} (GeV)	H_T (GeV)	m_T^{min} (GeV)	SM expected	Observed
ExSR1	HH	≥2	0	50–300	<1125	<120 for H_T > 300	700 ± 130	685
ExSR2		≥2	0	50–300	300–1125	≥120	11.0 ± 2.2	11
ExSR3		≥2	1	50–300	<1125	<120 for H_T > 300	477 ± 120	482
ExSR4		≥2	1	50–300	300–1125	≥120	8.4 ± 3.5	8
ExSR5		≥2	2	50–300	<1125	<120 for H_T > 300	137 ± 25	152
ExSR6		≥2	2	50–300	300–1125	≥120	4.9 ± 1.2	8
ExSR7		≥2	≥3	50–300	<1125	<120 for H_T > 300	11.6 ± 3.1	10
ExSR8		≥2	≥3	50–300	300–1125	≥120	0.8 ± 0.24	3
ExSR9		≥2	—	≥300	≥300	—	25.7 ± 5.4	31
ExSR10		≥2	—	50–300	≥1125	—	10.1 ± 2.2	14
ExSR11	HL	≥2	—	50–300	<1125	<120	1070 ± 250	1167
ExSR12		≥2	—	50–300	<1125	≥120	1.33 ± 0.46	1
ExSR13		≥2	—	≥300	≥300	—	9.9 ± 2.5	12
ExSR14		≥2	—	50–300	≥1125	—	4.7 ± 1.8	8
ExSR15	LL	≥2	—	≥50	≥300	—	37 ± 12	43

Same sign dileptons: results



Same sign dileptons: systematics

Source	Typical uncertainty (%)
Integrated luminosity	2.5
Lepton selection	4 – 10
Trigger efficiency	2 – 7
Pileup	0 – 6
Jet energy scale	1 – 15
b tagging	1 – 15
Simulated sample size	1 – 10
Scale and PDF variations	10 – 20
WZ (normalization)	12
$t\bar{t}Z$ (normalization)	30
Nonprompt leptons	30 – 60
Charge misidentification	20

Same sign dileptons: Interpretations

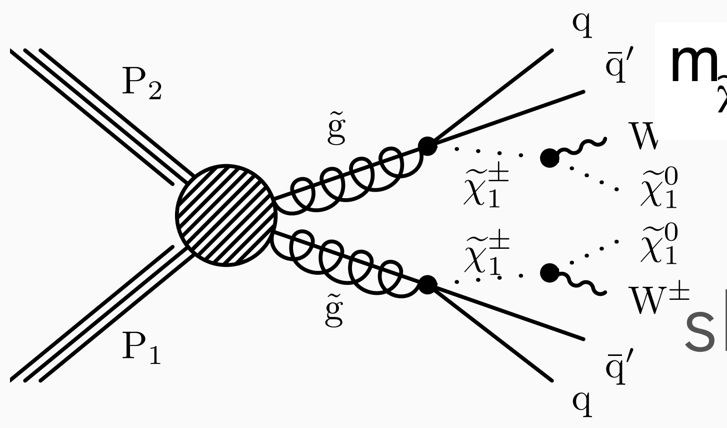
Interpretation in a variety of SUSY models

- **no significant deviation** in any of the SRs
- Run I limits on gluino, LSP and bottom squark masses are improved by 200-300 GeV

T5qqqqWW

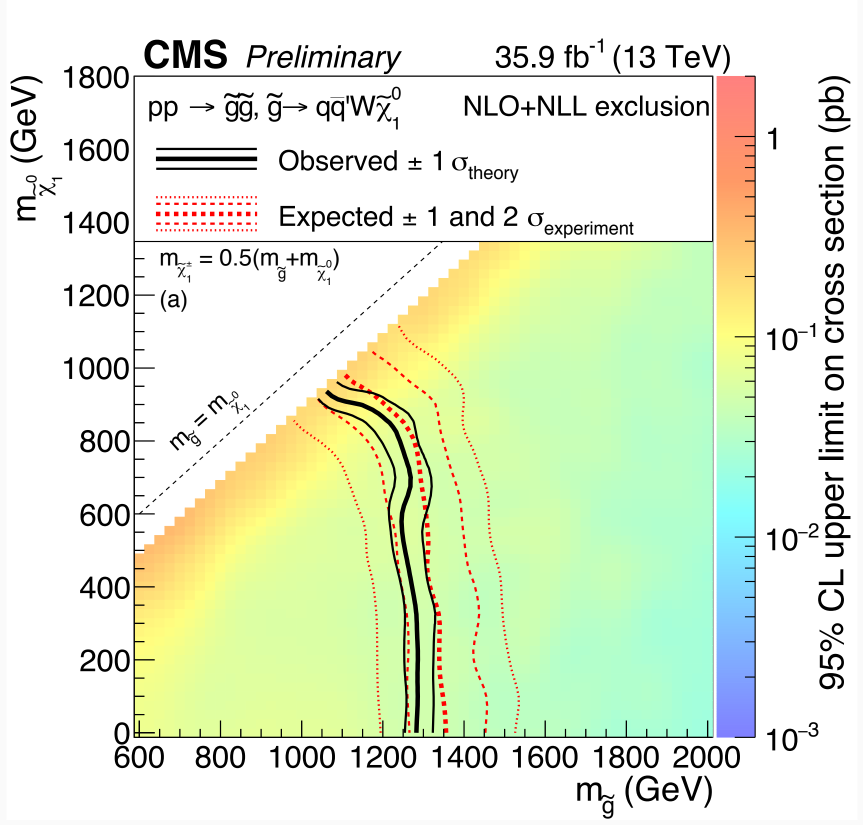
$m_{\tilde{\chi}_1^\pm} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$

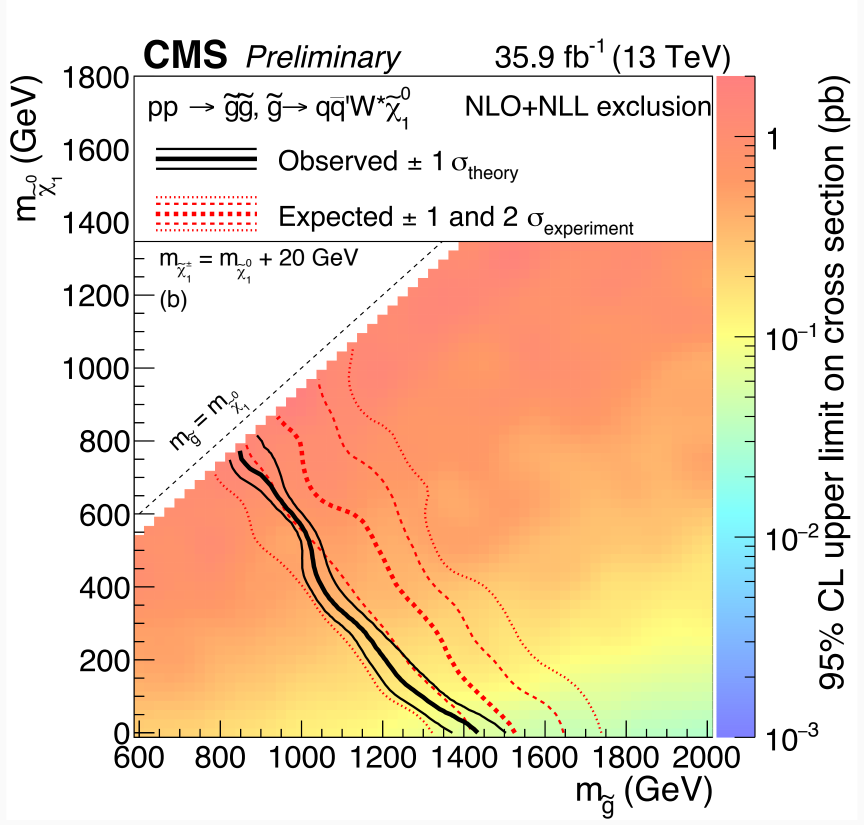
Targets on-shell W bosons



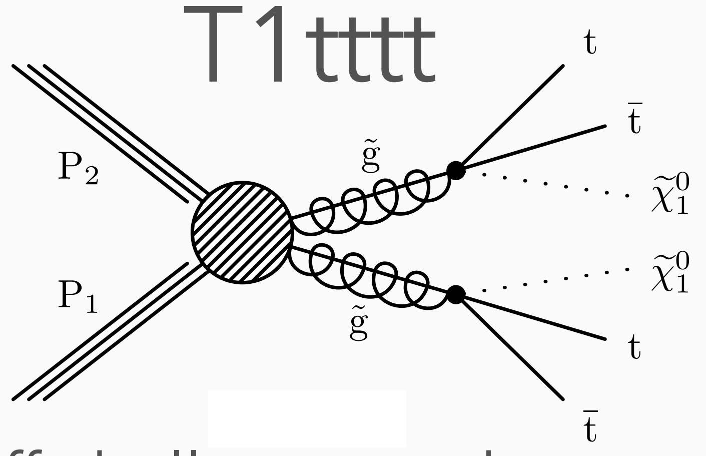
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 20$ GeV

Targets off-shell W bosons

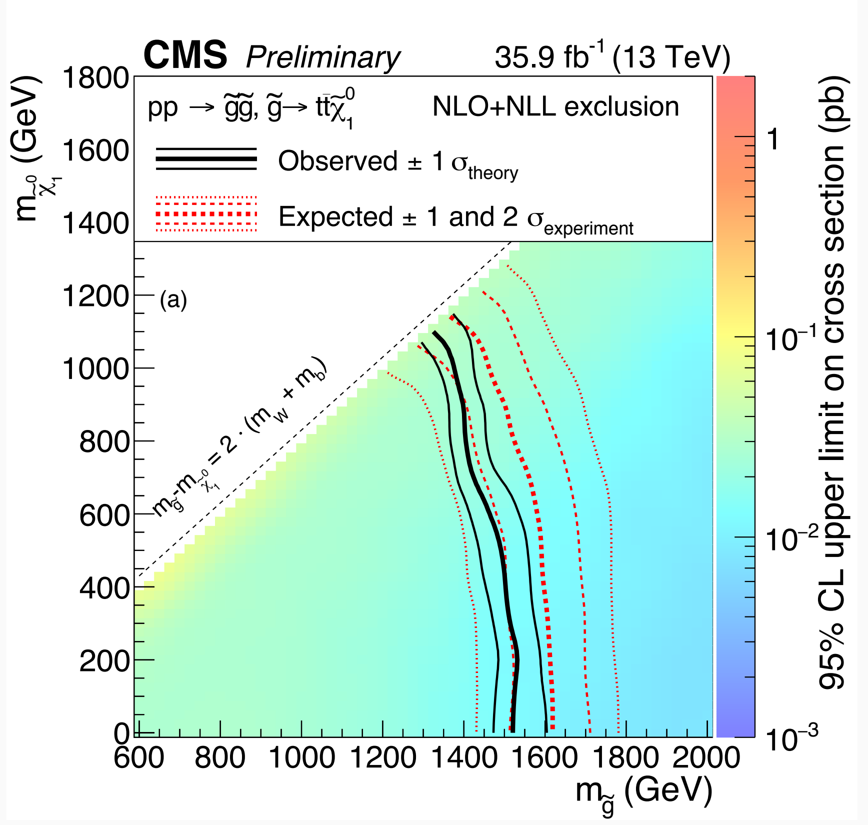




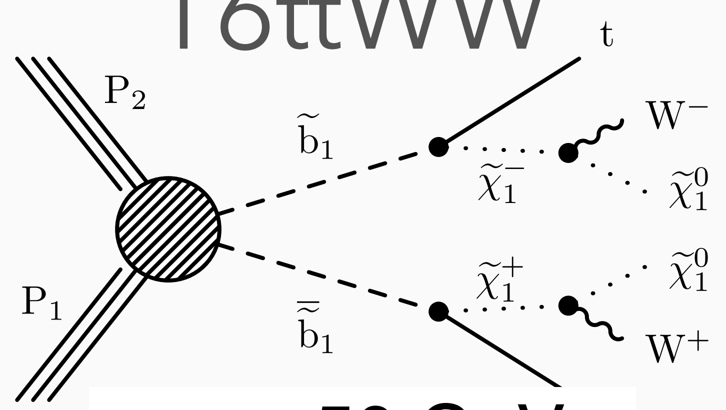
T1tttt



Off-shell stop or sbottom
→three body decay of gluino

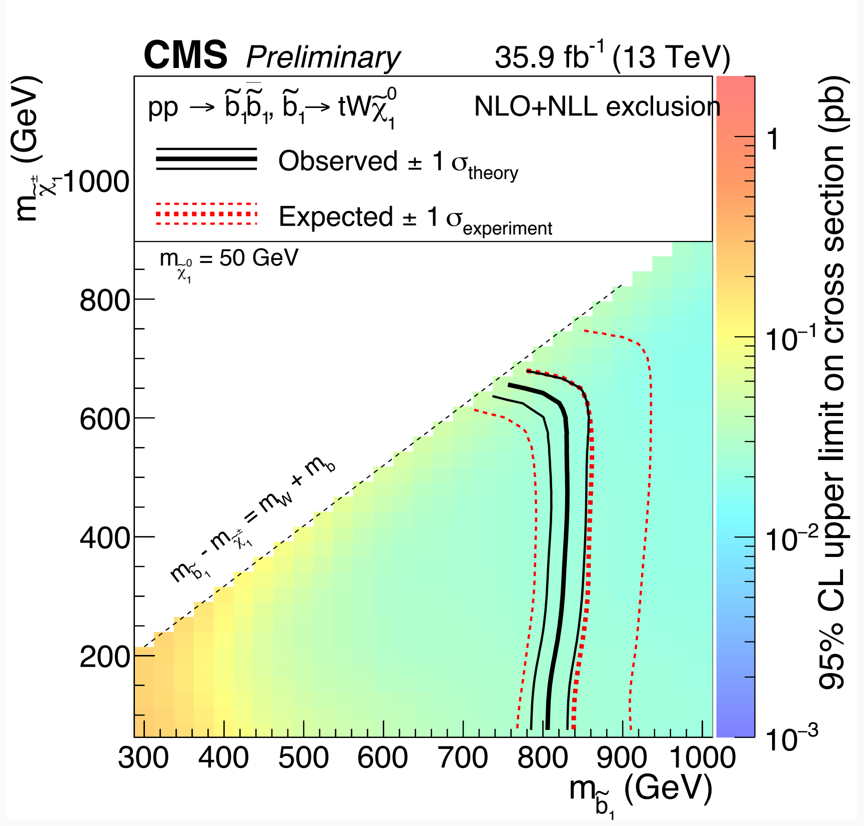


T6ttWW

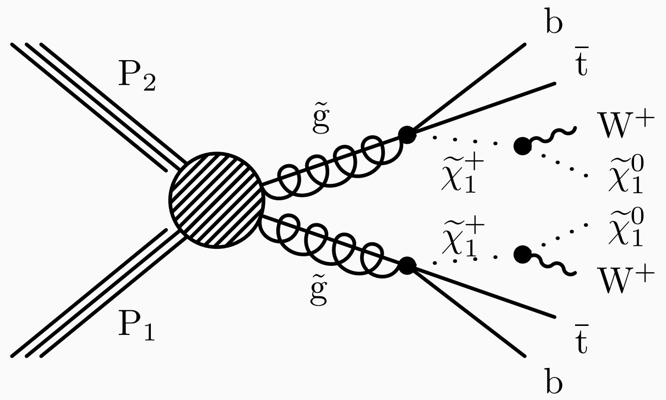


$m_{\tilde{\chi}_1^0} = 50$ GeV

→two Ws produced off-shell

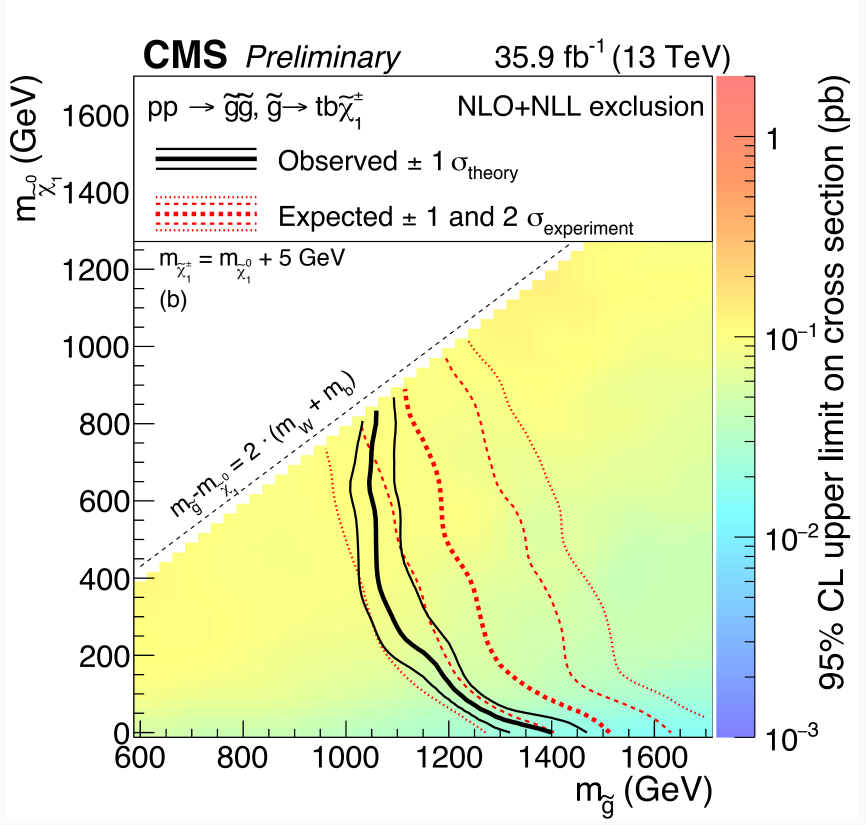


T5ttbbWW



$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 5$ GeV

→off-shell W bosons giving low p_T leptons

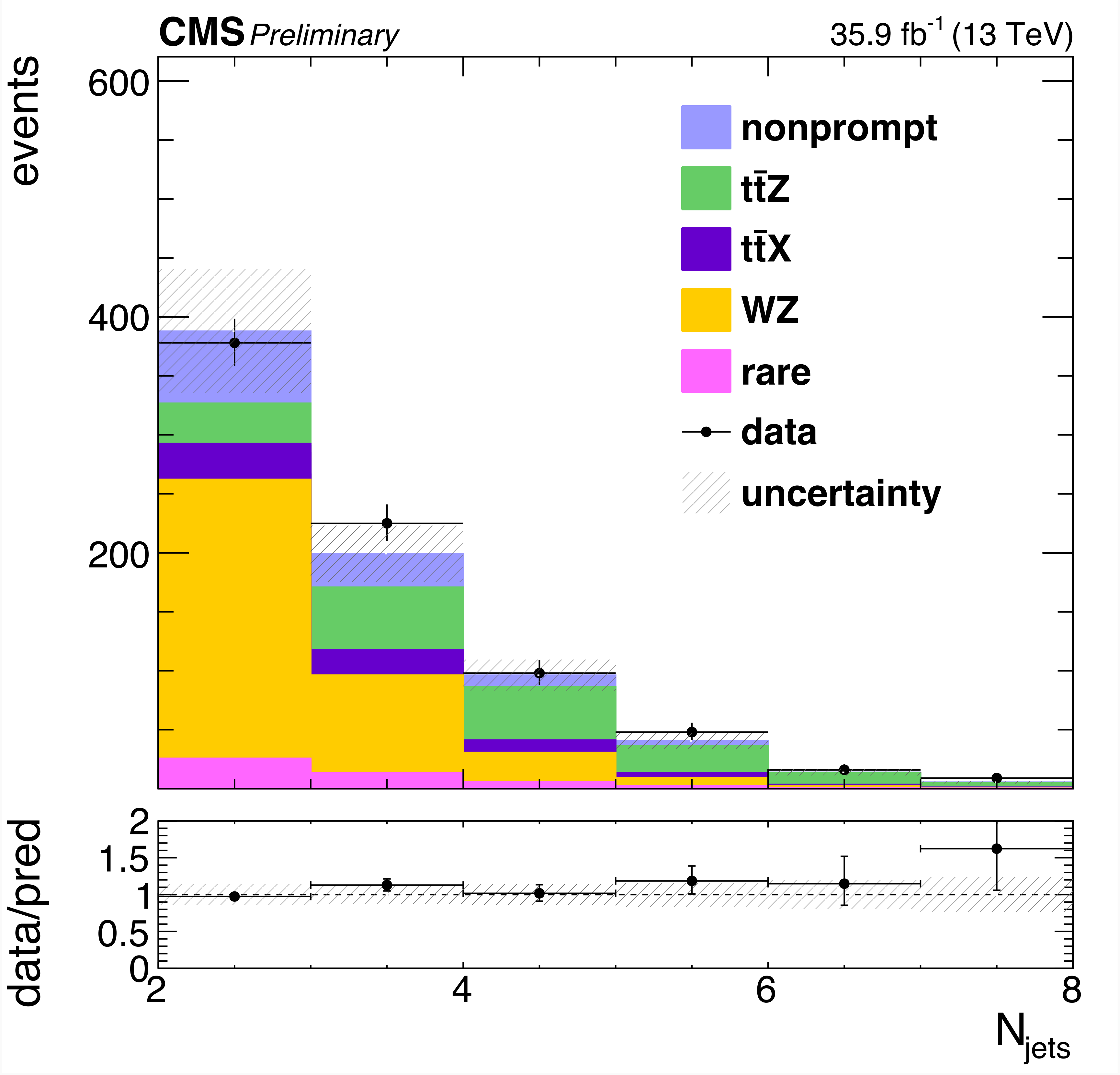


Multileptons backup

Multileptons: 3L control region

3 lepton control region

- derived in data and used to scale the simulation
- applicable for SM backgrounds as WZ and ttZ
- based on a template fit to the distribution of the number of b jets
- WZ region:
  - **≥ 2 jets**, 30 GeV < p_T^{miss} < 100 GeV, **M_T** > 50 GeV, **3 leptons**, two of which must form an OSSF pair with m_{ll} close to Z mass (76-106 GeV)
  - 80% purity of WZ
  - SF of 1.01+-0.07
- ttZ region:
  - **≥ 3 jets**, 30 GeV < p_T^{miss} < 50 GeV, **3 leptons**, two of which must form an OSSF pair with m_{ll} close to Z mass (76-106 GeV)
  - 20% purity overall and 50% purity in > 0 bjet bins
  - SF of 1.14 +-0.28

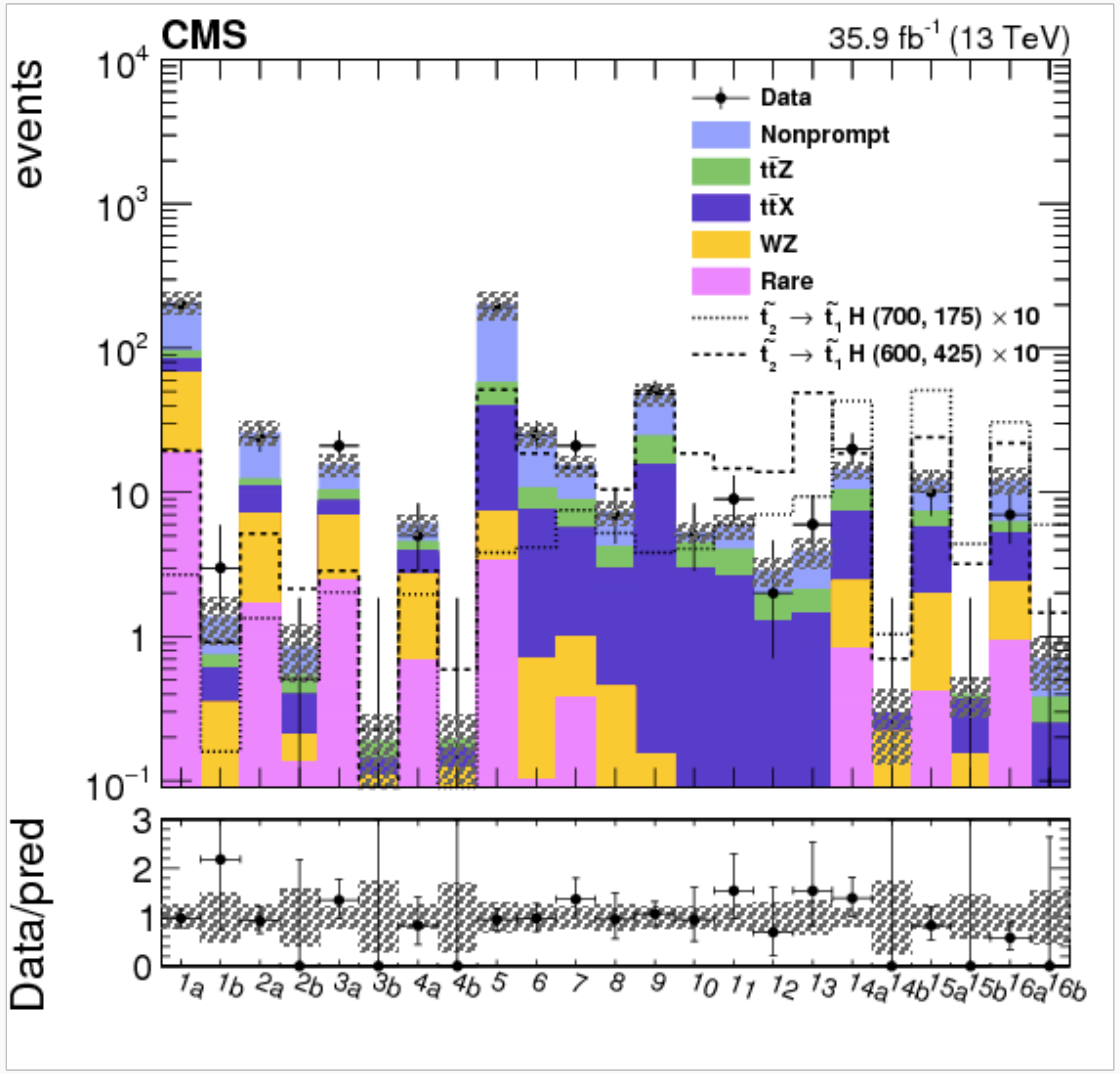


Multileptons: signal regions

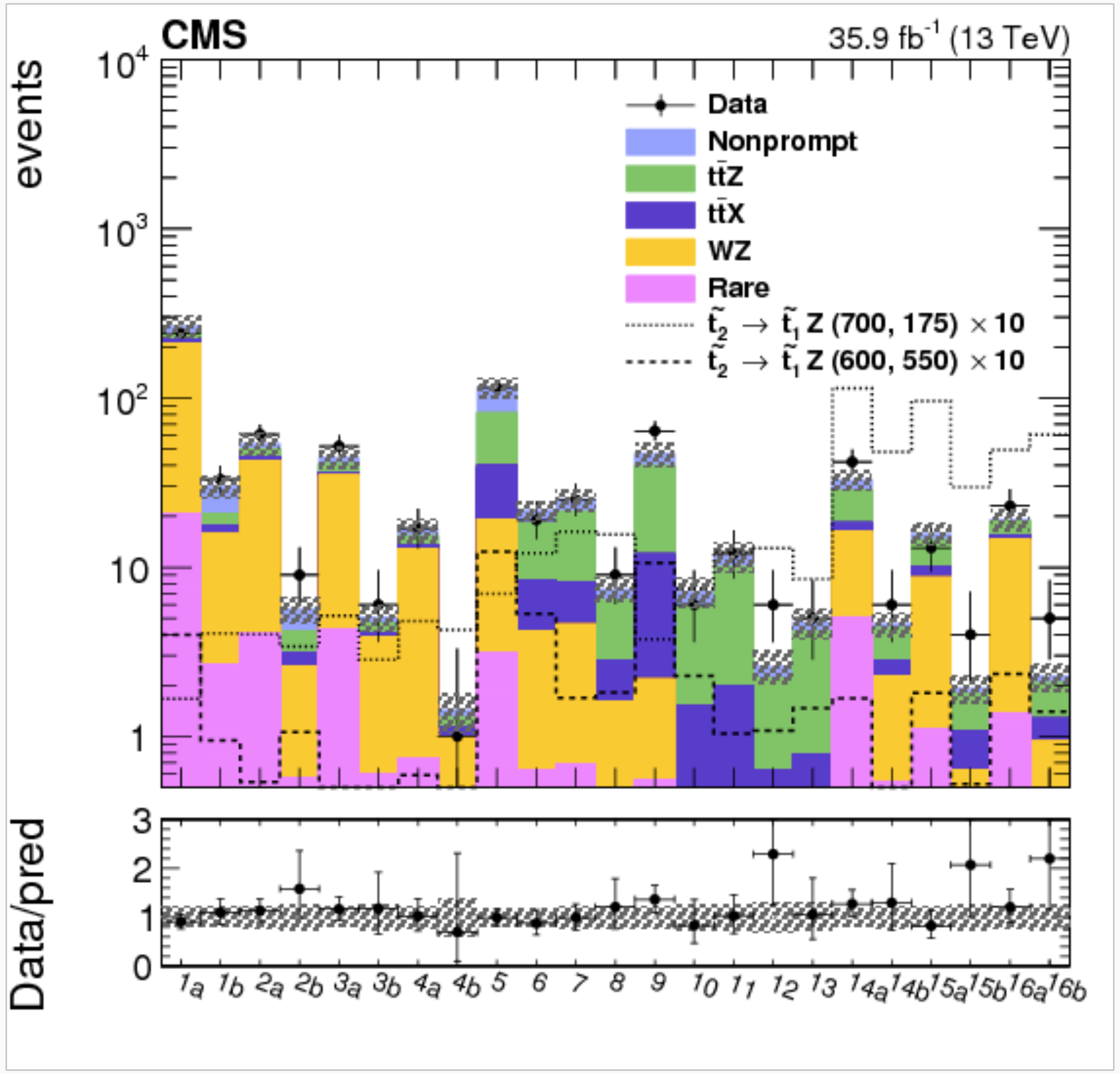
N_{jets}	$N_{\text{b jets}}$	H_{T} [GeV]	$50(70) \leq p_{\text{T}}^{\text{miss}} < 150\,\text{GeV}$	$150 \leq p_{\text{T}}^{\text{miss}} < 300\,\text{GeV}$	$p_{\text{T}}^{\text{miss}} \geq 300\,\text{GeV}$
≥2	0	60 – 400	SR1 †	SR2 †	SR16 †
		400 – 600	SR3 †	SR4 †	
	1	60 – 400	SR5	SR6	
		400 – 600	SR7	SR8	
	2	60 – 400	SR9	SR10	
		400 – 600	SR11	SR12	
	≥3	60 – 600	SR13		
	inclusive	≥600	SR14 †	SR15 †	

Multileptons: results

Off Z



On Z



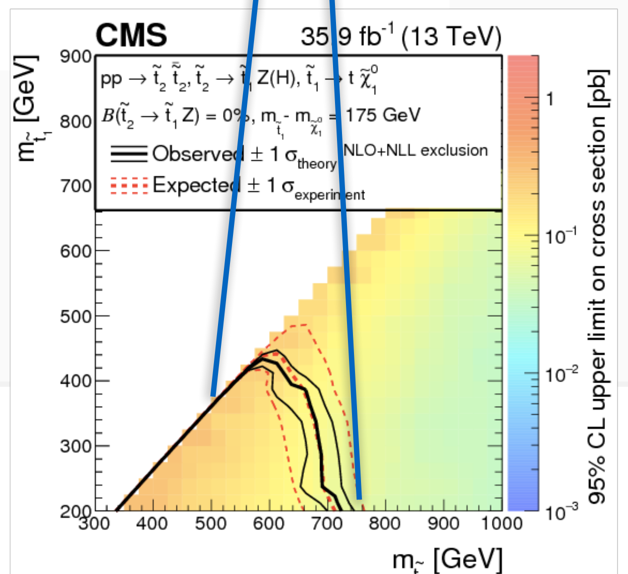
Multileptons: results

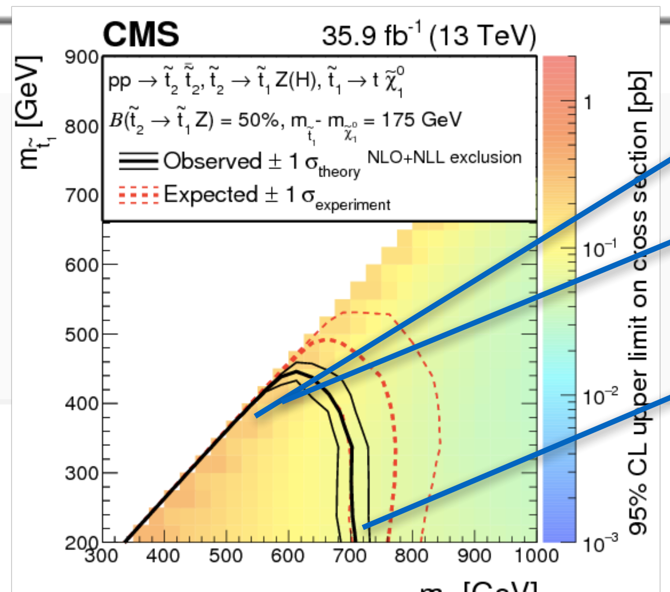
Off Z

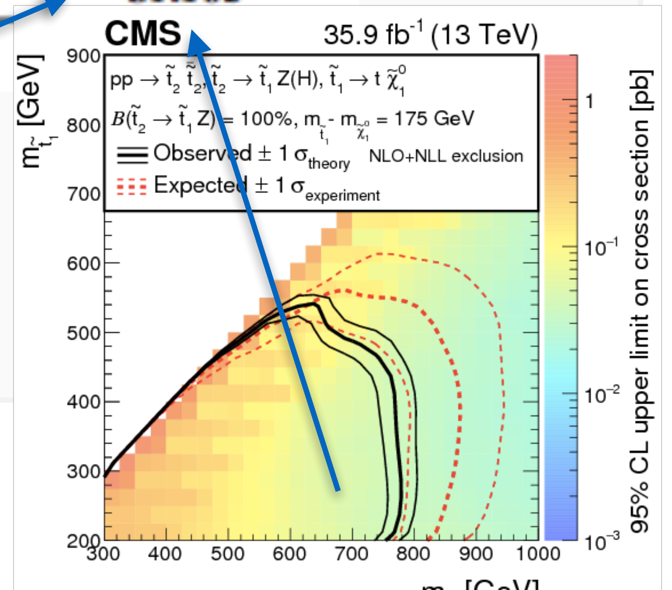
$N_{b\,jets}$	H_T [GeV]	p_T^{miss} [GeV]	M_T [GeV]	Expected [events]	Observed [events]	SR
0	60-400	50-150	<120	$206 \pm 6 \pm 35$	201	SR1a
			≥120	$1.4 \pm 0.5 \pm 0.2$	3	SR1b
		150-300	<120	$25.9 \pm 2.1 \pm 4.3$	24	SR2a
			≥120	$0.84 \pm 0.34 \pm 0.12$	0	SR2b
	400-600	50-150	<120	$15.6 \pm 1.6 \pm 2.1$	21	SR3a
			≥120	$0.19 \pm 0.09 \pm 0.02$	0	SR3b
		150-300	<120	$6.0 \pm 0.8 \pm 0.7$	5	SR4a
			≥120	$0.19 \pm 0.09 \pm 0.04$	0	SR4b
1	60-400	50-150	Inclusive	$202 \pm 6 \pm 44$	191	SR5
		150-300		$25.6 \pm 1.9 \pm 4.6$	25	SR6
	400-600	50-150		$15.4 \pm 1.3 \pm 2.2$	21	SR7
		150-300		$7.3 \pm 1 \pm 1.1$	7	SR8
2	60-400	50-150	Inclusive	$47.7 \pm 2.8 \pm 7.6$	51	SR9
		150-300		$5.3 \pm 0.5 \pm 0.6$	5	SR10
	400-600	50-150		$5.8 \pm 0.7 \pm 0.8$	9	SR11
		150-300		$2.9 \pm 0.5 \pm 0.4$	2	SR12
≥3	60-600	50-300	Inclusive	$3.9 \pm 0.7 \pm 0.6$	6	SR13
Inclusive	≥600	50-150	<120	$14.4 \pm 1.2 \pm 1.6$	20	SR14a
			≥120	$0.28 \pm 0.14 \pm 0.04$	0	SR14b
		150-300	<120	$12.1 \pm 1.4 \pm 1.6$	10	SR15a
			≥120	$0.40 \pm 0.12 \pm 0.05$	0	SR15b
	≥60	≥300	<120	$12.1 \pm 1.5 \pm 1.9$	7	SR16a
			≥120	$0.70 \pm 0.25 \pm 0.11$	0	SR16b

On Z

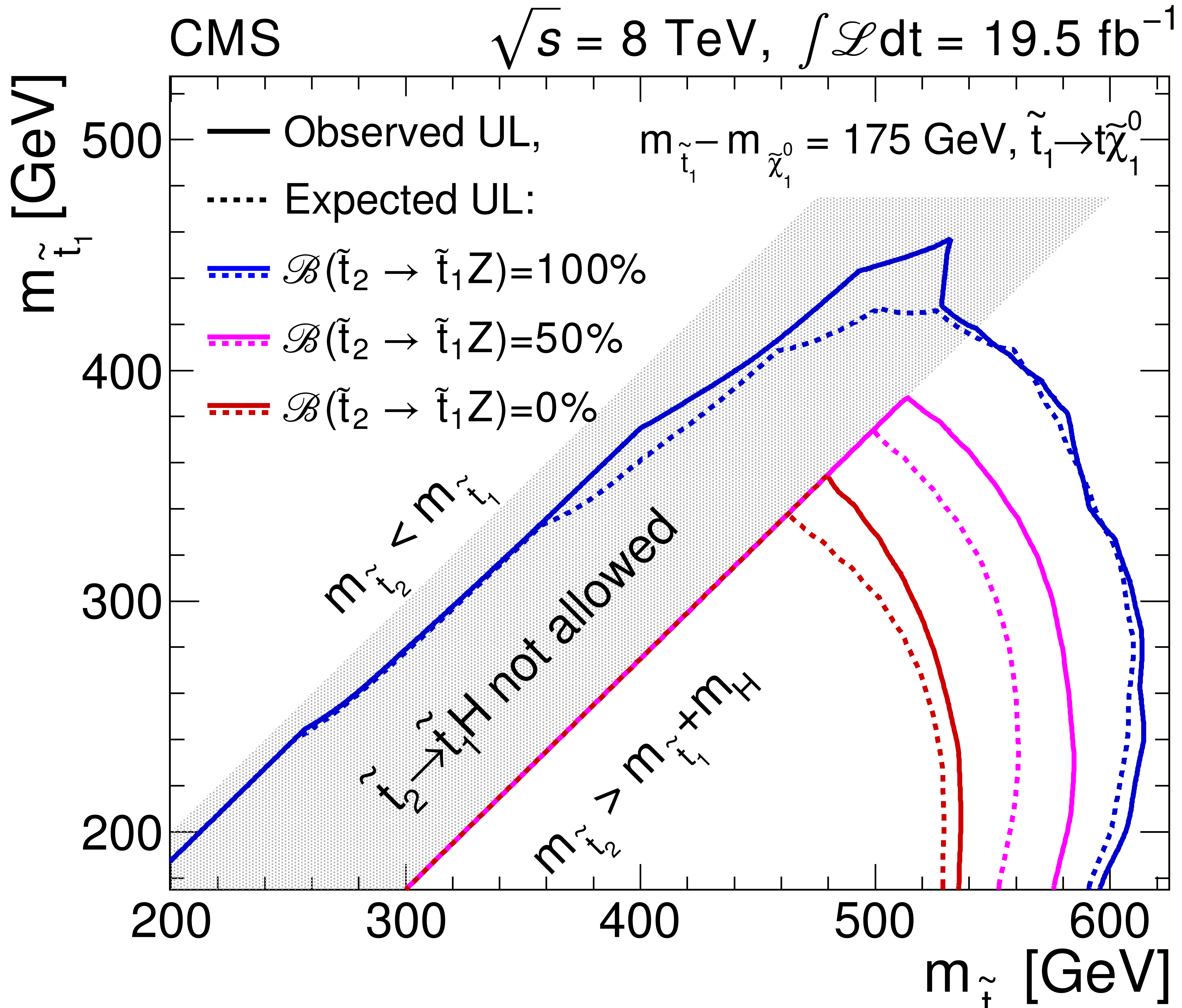
$N_{b\,jets}$	H_T [GeV]	p_T^{miss} [GeV]	M_T [GeV]	Expected [events]	Observed [events]	SR
0	60-400	50-150	<120	$266 \pm 5 \pm 39$	241	SR1a
			≥120	$30 \pm 2 \pm 4$	33	SR1b
		150-300	<120	$53.8 \pm 2.2 \pm 8$	61	SR2a
			≥120	$5.7 \pm 0.8 \pm 0.7$	9	SR2b
	400-600	50-150	<120	$44.6 \pm 1.9 \pm 6.5$	52	SR3a
			≥120	$5.1 \pm 0.6 \pm 0.7$	6	SR3b
		150-300	<120	$16.6 \pm 1.3 \pm 2.5$	17	SR4a
			≥120	$1.43 \pm 0.33 \pm 0.2$	1	SR4b
1	60-400	50-150	Inclusive	$116 \pm 4 \pm 15$	115	SR5
		150-300		$21.7 \pm 1.2 \pm 2.8$	19	SR6
	400-600	50-150		$25.2 \pm 1.2 \pm 3.6$	25	SR7
		150-300		$7.5 \pm 0.8 \pm 1$	9	SR8
2	60-400	50-150	Inclusive	$47 \pm 1.6 \pm 7.4$	64	SR9
		150-300		$7.2 \pm 0.8 \pm 1.2$	6	SR10
	400-600	50-150		$11.7 \pm 1 \pm 2.1$	12	SR11
		150-300		$2.6 \pm 0.4 \pm 0.4$	6	SR12
≥3	60-600	50-300	Inclusive	$4.7 \pm 0.5 \pm 0.9$	5	SR13
Inclusive	≥600	50-150	<120	$33 \pm 2 \pm 4$	42	SR14a
			≥120	$4.6 \pm 0.6 \pm 0.6$	6	SR14b
		150-300	<120	$15.8 \pm 1.2 \pm 2$	13	SR15a
			≥120	$1.9 \pm 0.3 \pm 0.2$	4	SR15b
	≥60	≥300	<120	$19.1 \pm 1.1 \pm 2.8$	23	SR16a
			≥120	$2.28 \pm 0.35 \pm 0.26$	5	SR16b





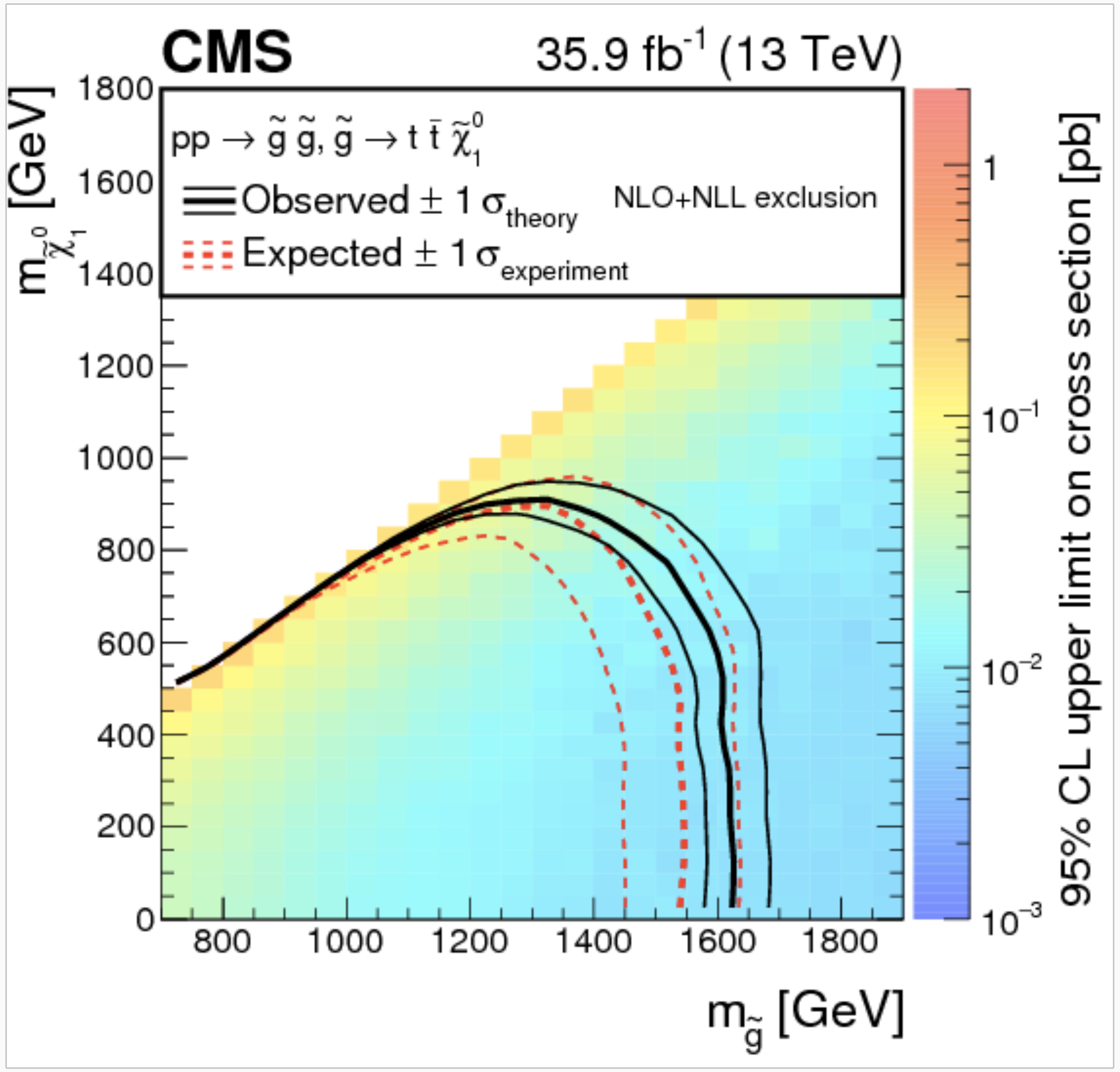


Multileptons: results

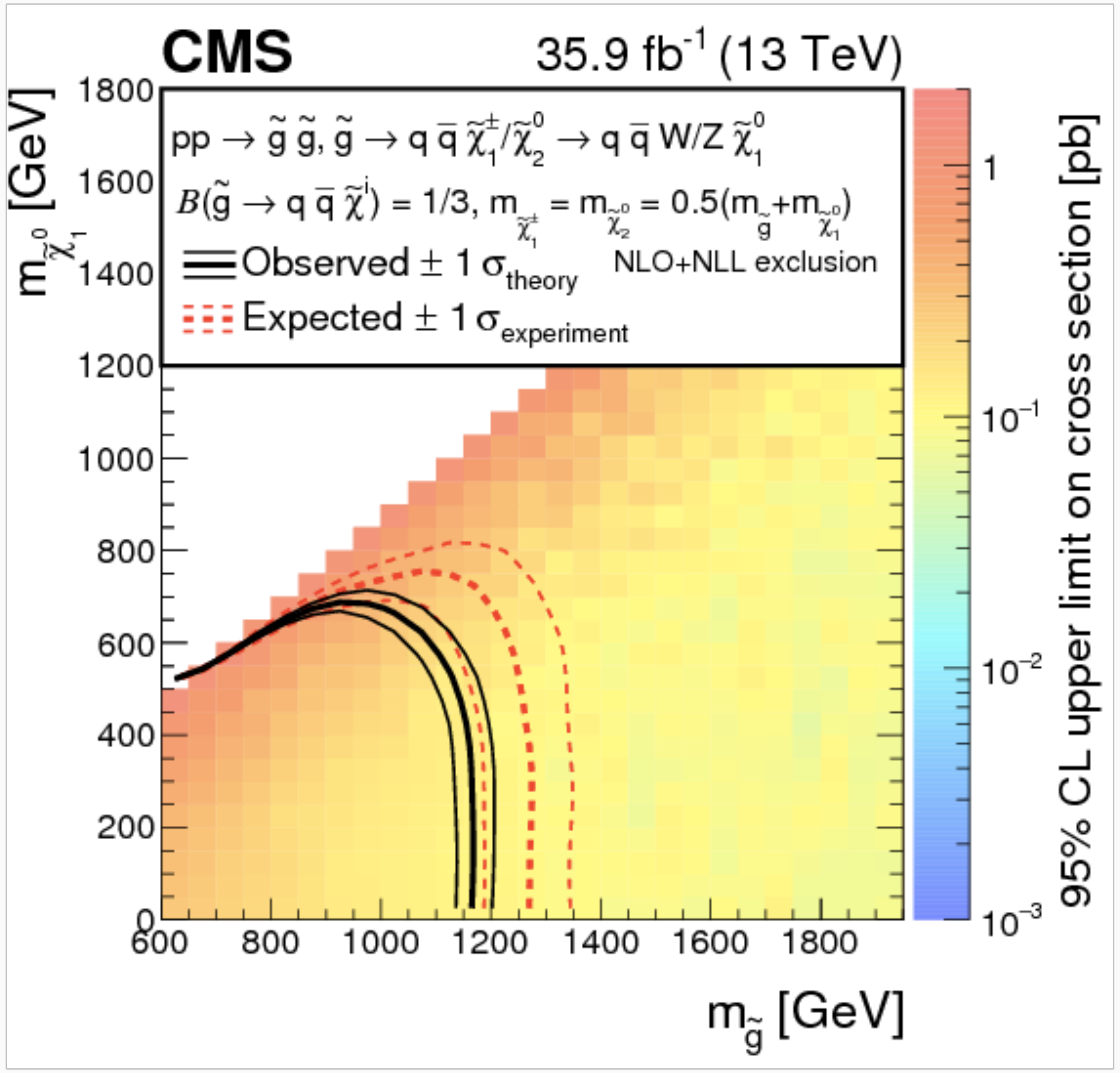


Multileptons: additional interpretation

T1tttt



T5qqqqVV



Multileptons: systematics

Source	Effect on the backgrounds [%]	Effect on signal [%]
Integrated luminosity	2.5	2.5
JES	1–8	1–10
b tag efficiency	1–8	1–10
Pileup	1–5	1–5
Lepton efficiencies	9	15
HLT efficiencies	3	3
Nonprompt application region statistics	10–100	–
Nonprompt extrapolation	30	–
WZ control region normalization	10	–
$t\bar{t}Z$ control region normalization	25	–
Limited size of simulated samples	1–100	10–100
ISR modeling	–	1–10
Modeling of unclustered energy	–	1–20
Ren., fact. scales, cross section ($t\bar{t}W$, $t\bar{t}H$)	11–13	–
Ren., fact. scales, acceptance ($t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, signal)	3–18	3–18
PDFs ($t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$)	2–3	–
Other rare backgrounds	50	–