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Search for Supersymmetry using opposite sign dileptons with the CMS detector

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ETH Zürich

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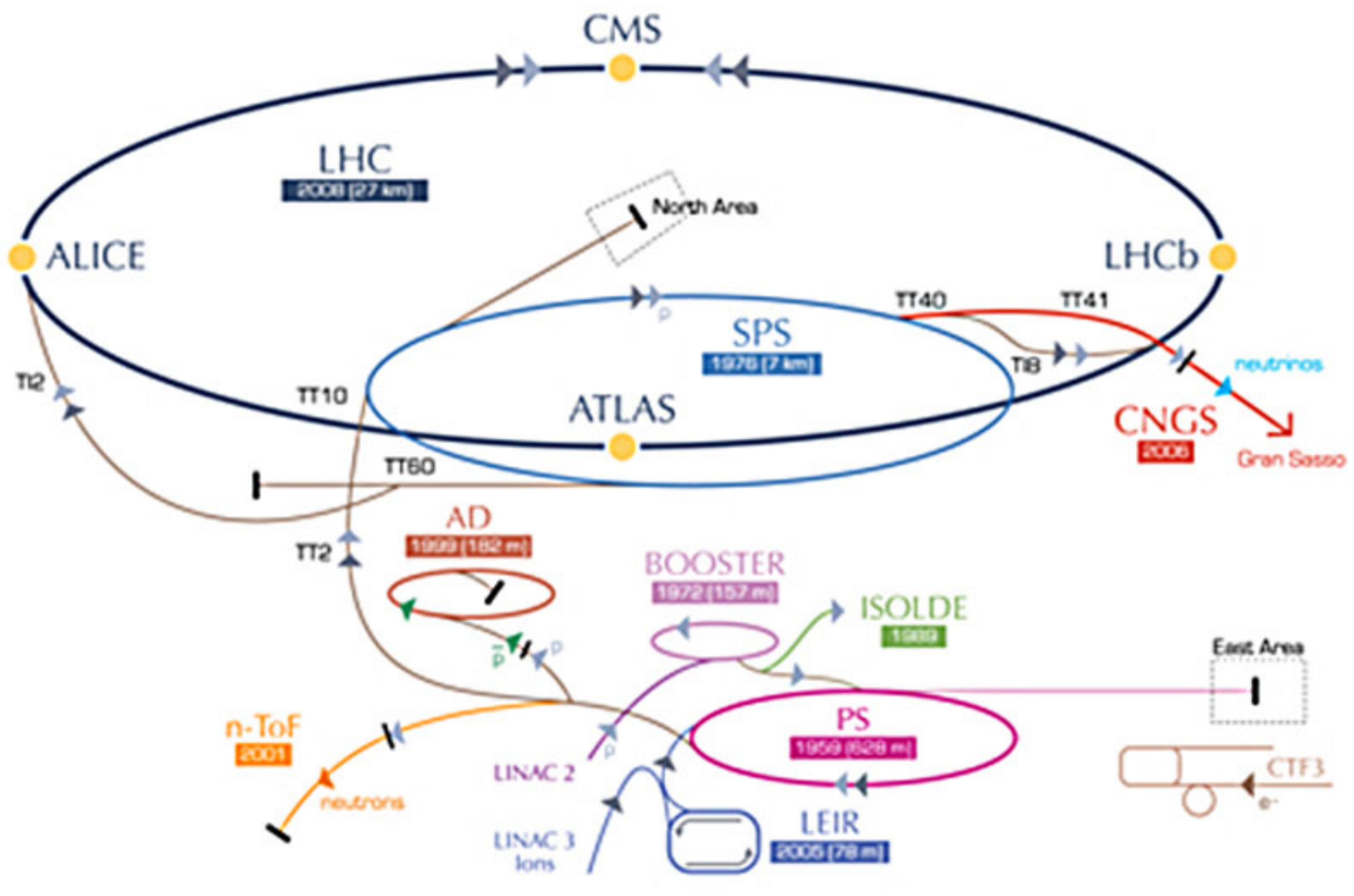
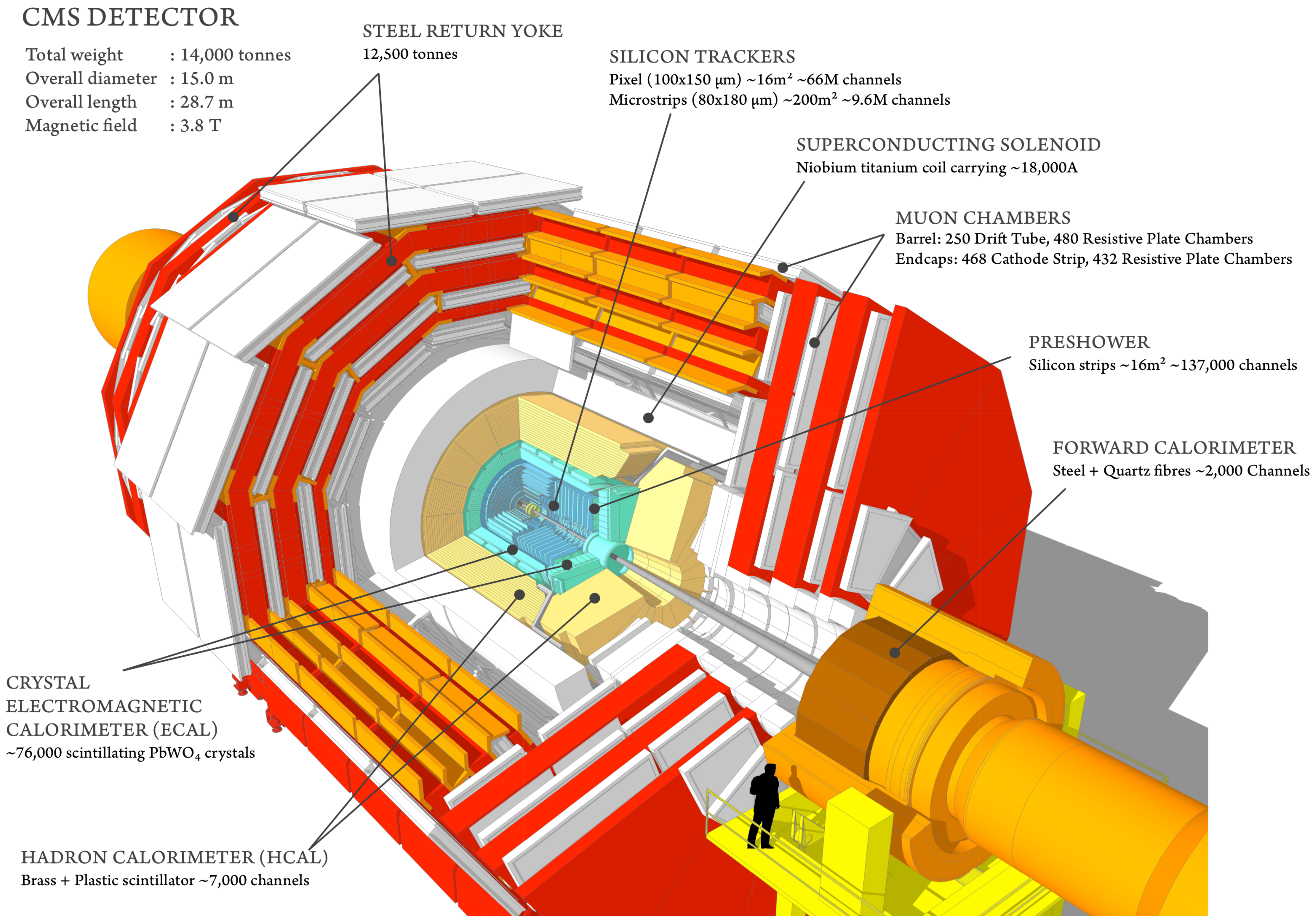
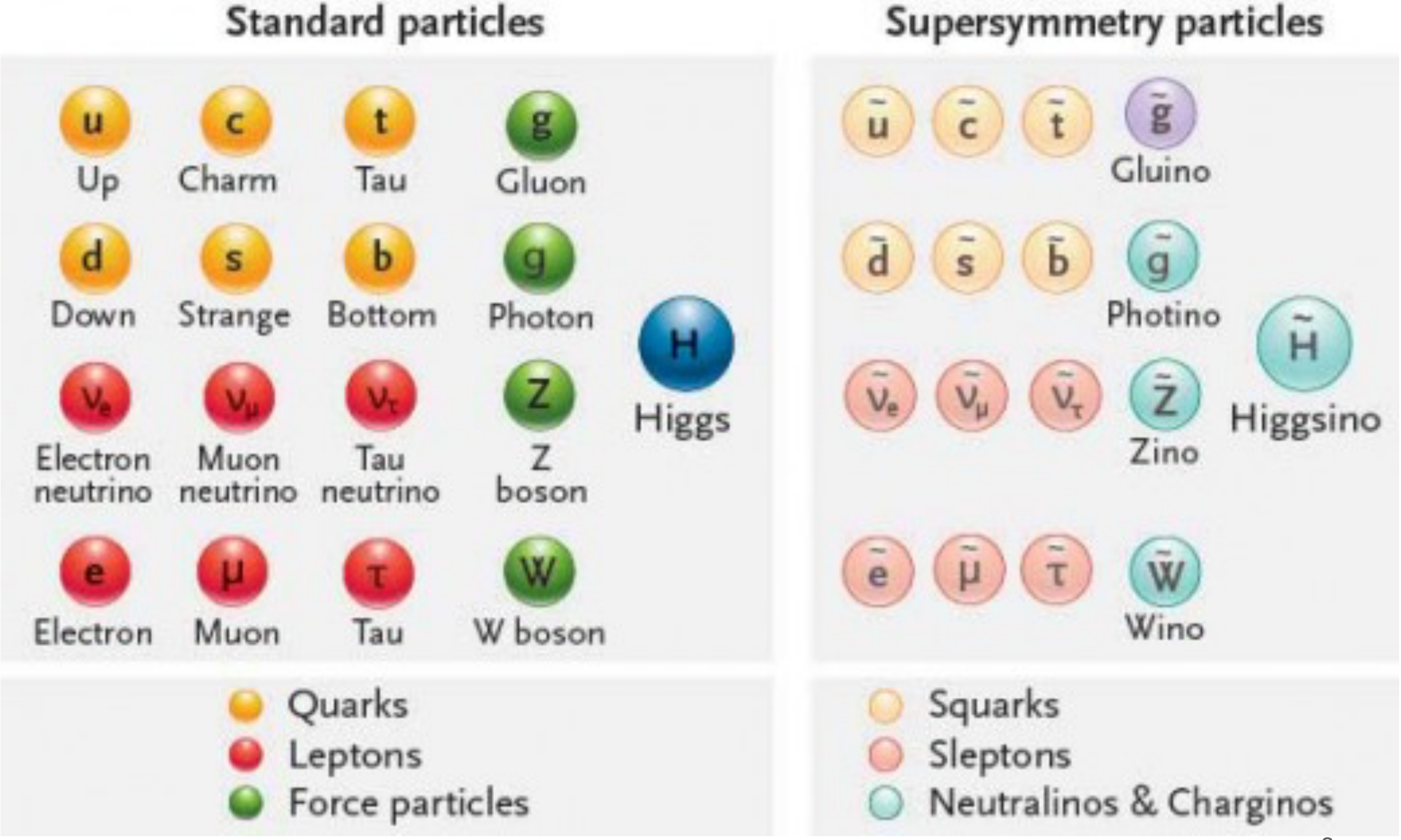
The Large Hadron Collider and CMS



CERN Accelerator Complex and the LHC



Supersymmetry

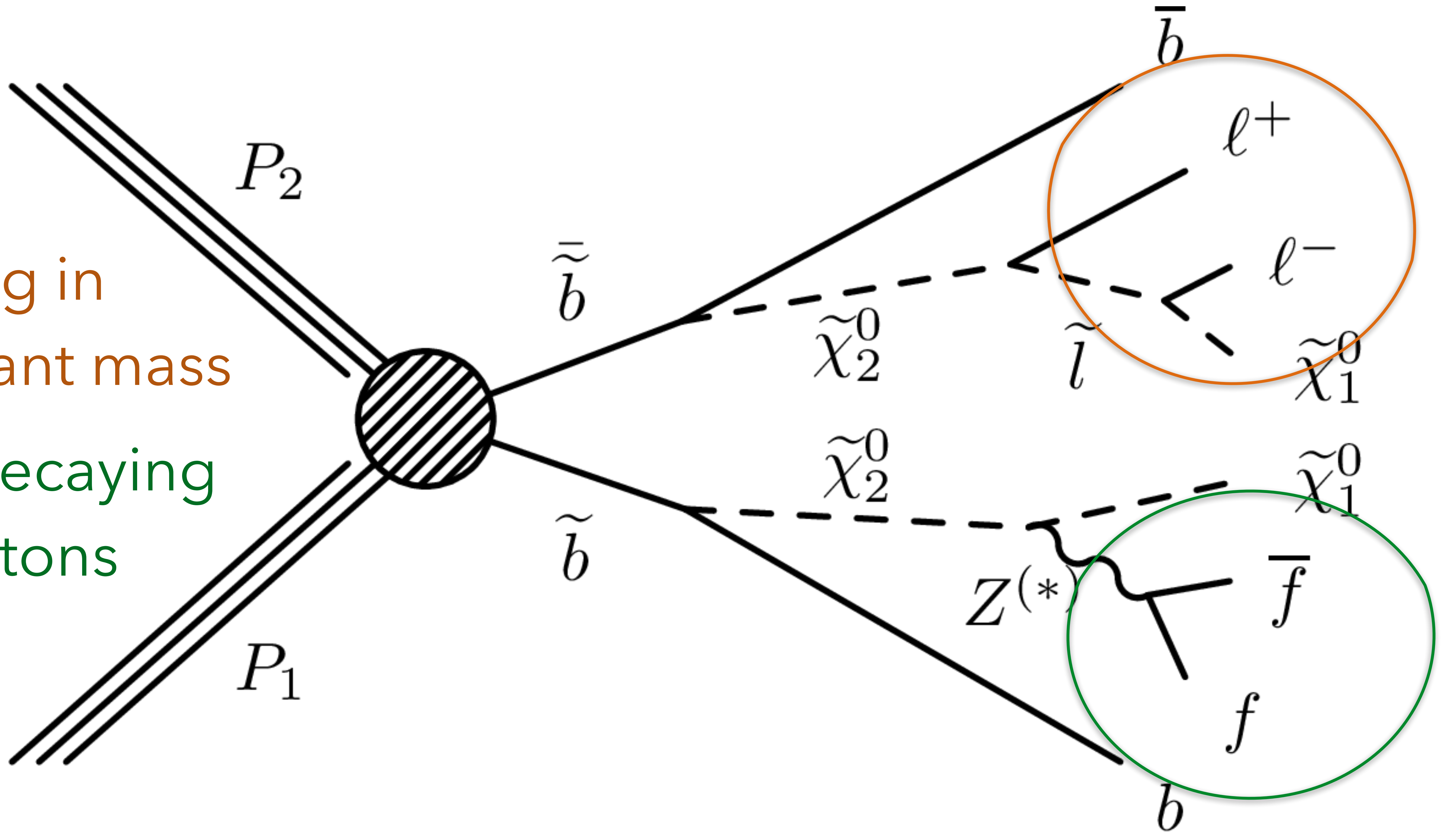


SUSY with opposite sign dileptons

Strong or electroweak SUSY can produce final states with opposite sign leptons

Sbottom induced:

- a cascade decay resulting in kinematic edge in invariant mass
- or an off-shell Z boson decaying to two opposite sign leptons



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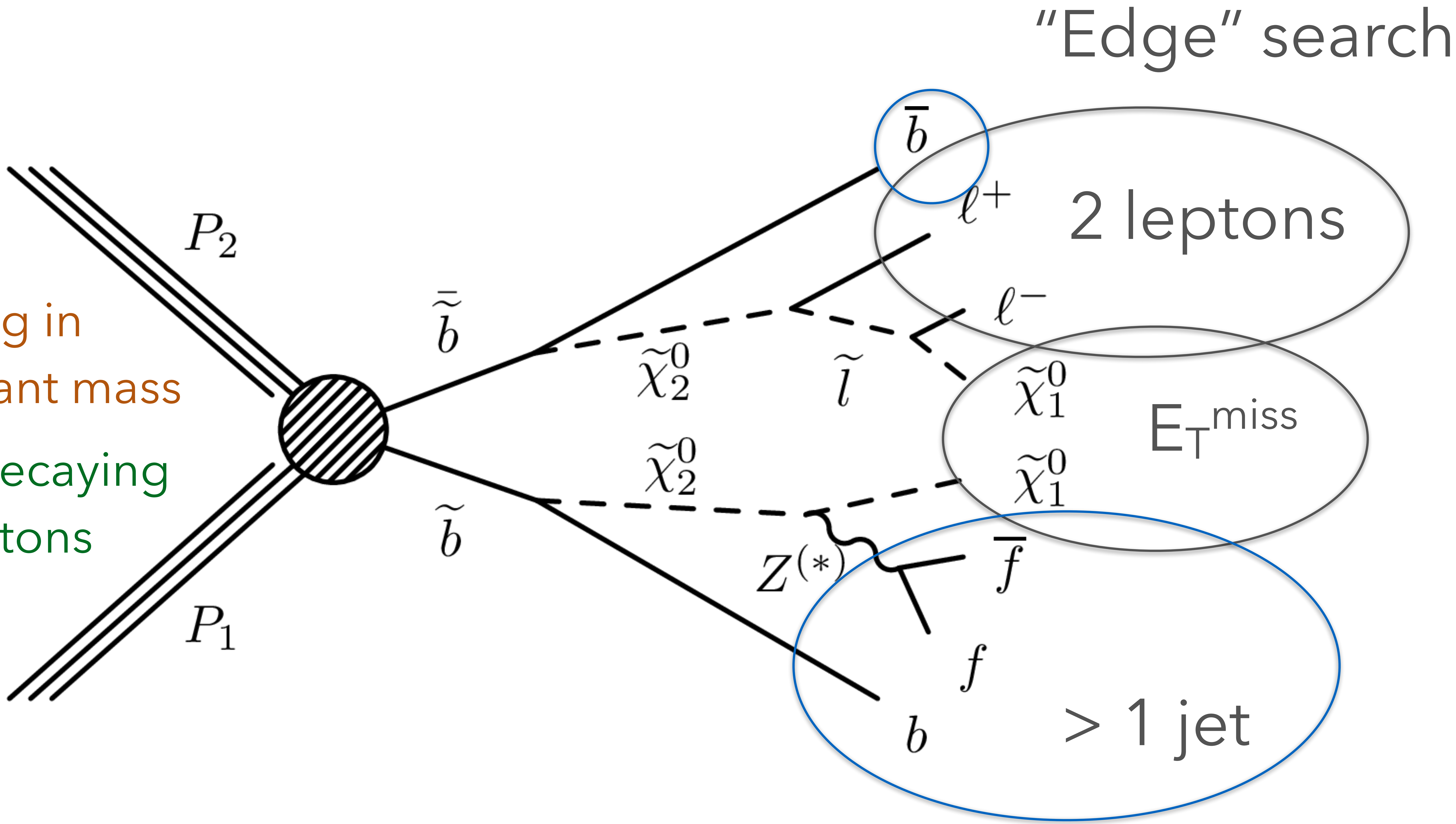
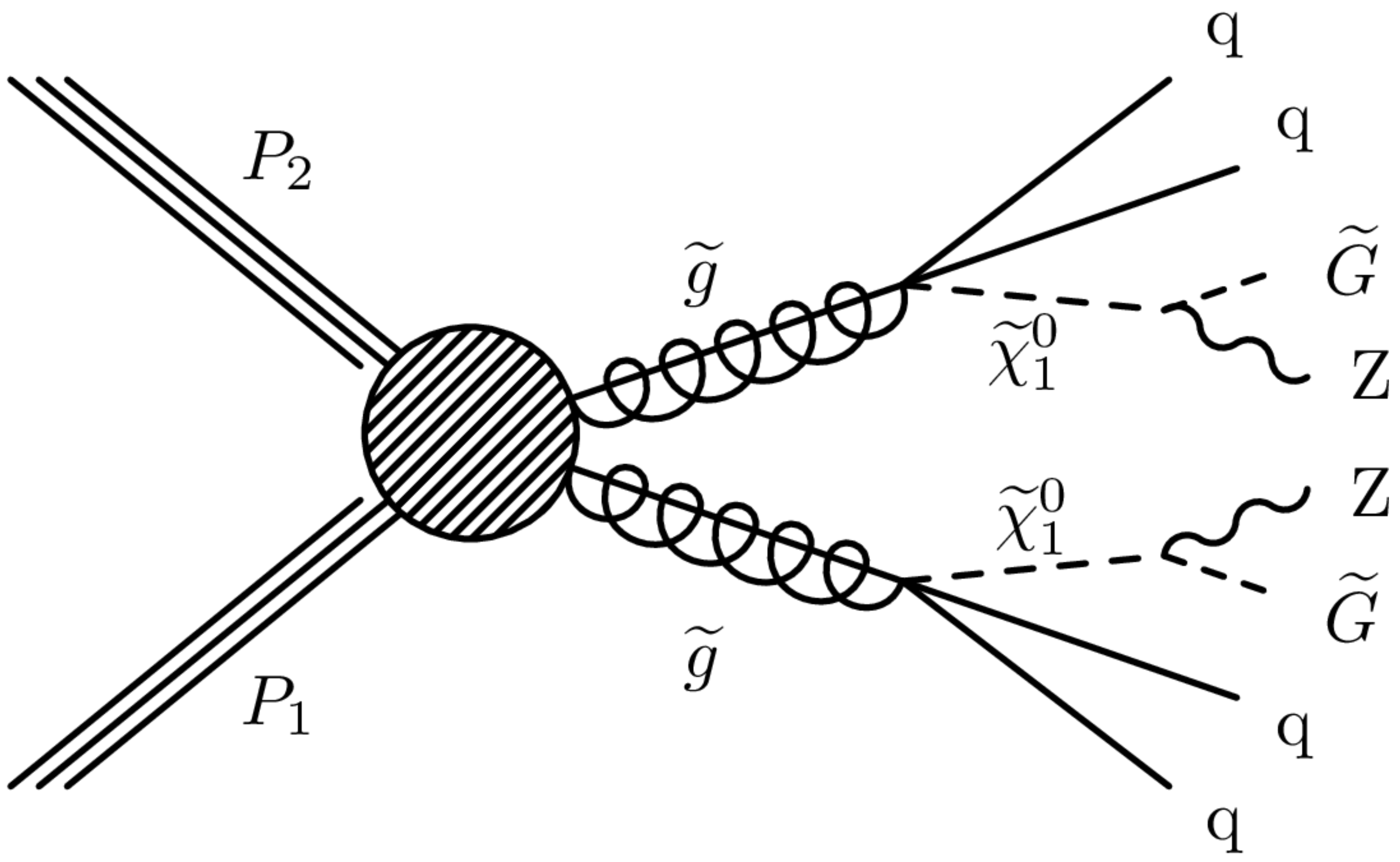


SUSY with opposite sign dileptons

Strong or electroweak SUSY can produce final states with opposite sign leptons

Gluino induced:

- Resonant Z production



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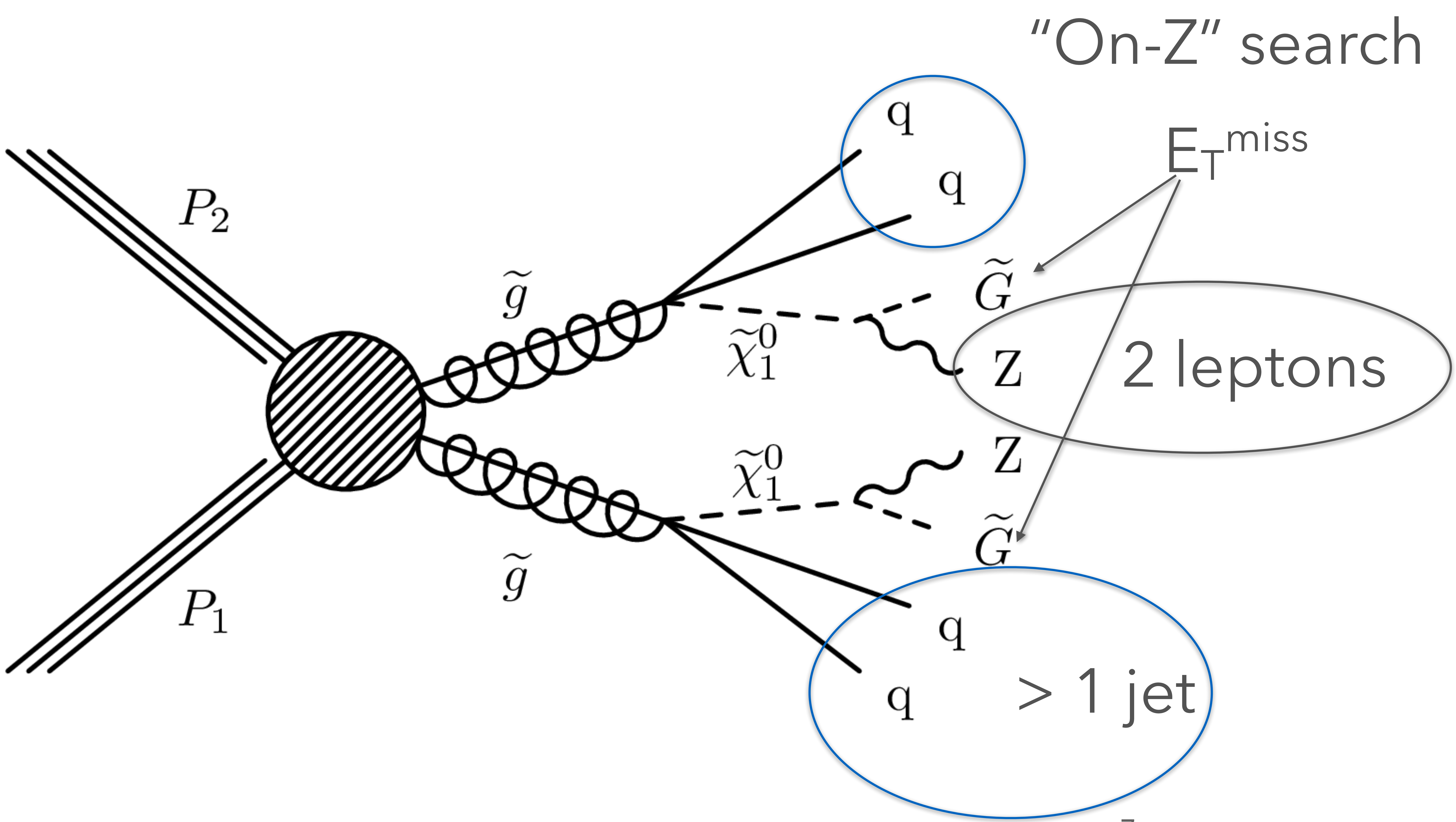
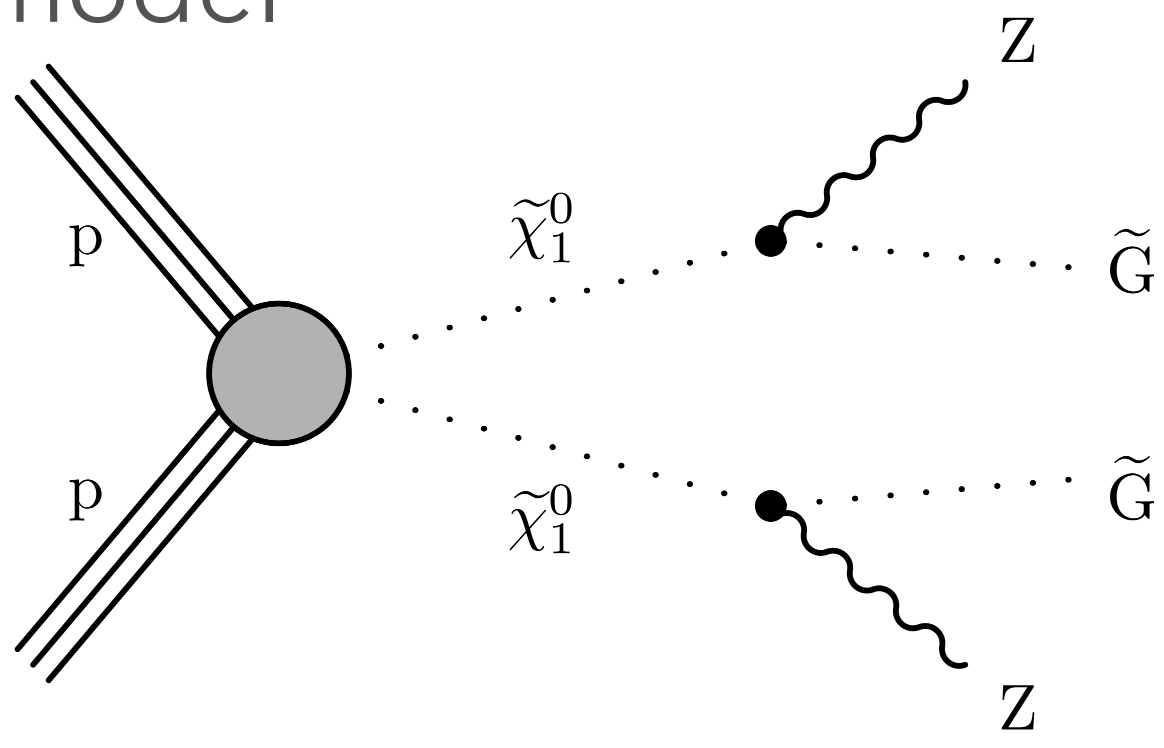
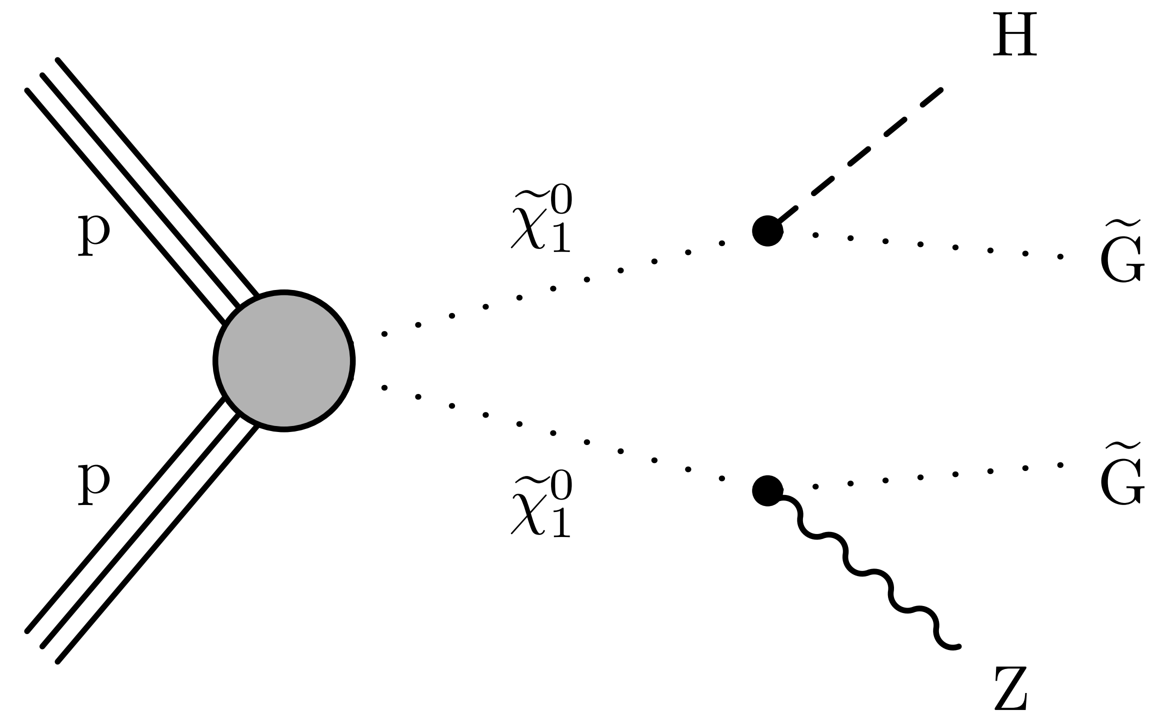


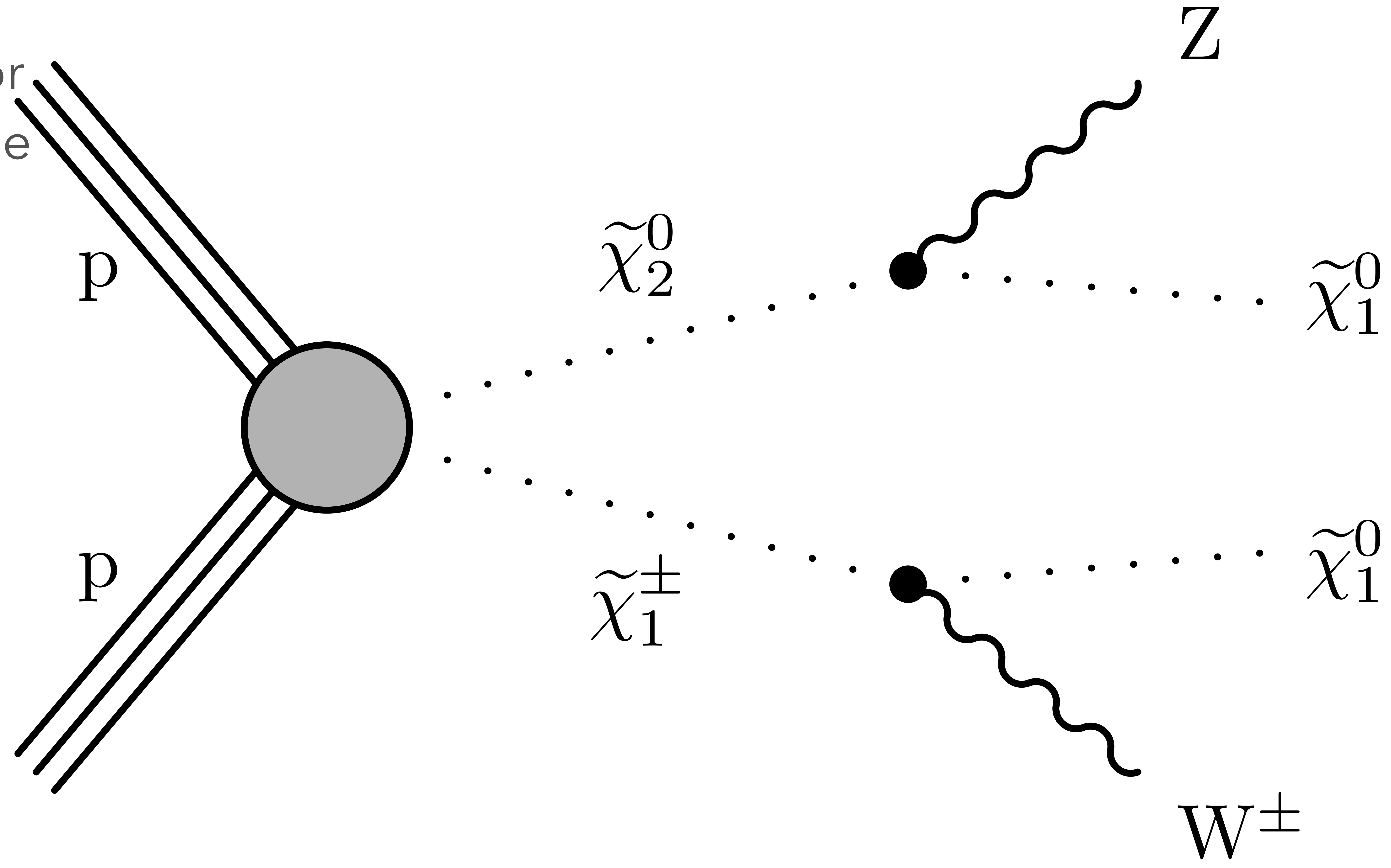
SUSY with opposite sign dileptons

Strong or **electroweak** SUSY can produce final states with opposite sign leptons

- Resonant Z production
- In association with a Z/W or H boson, depending on the model







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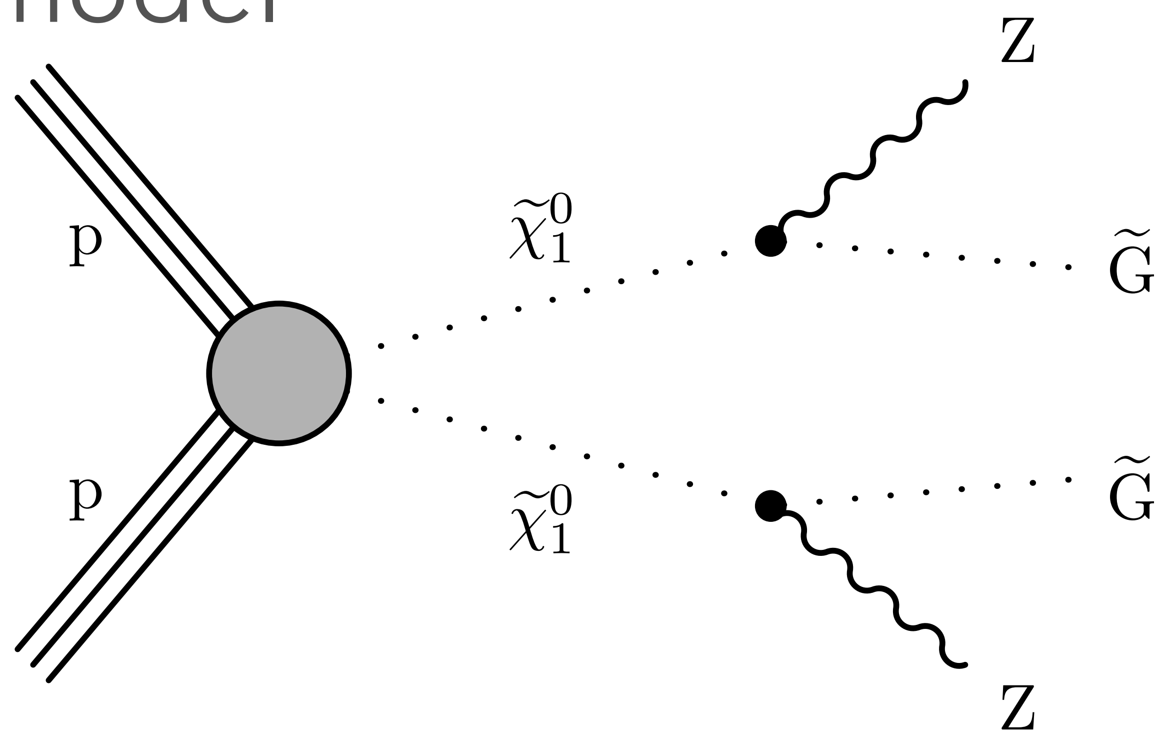
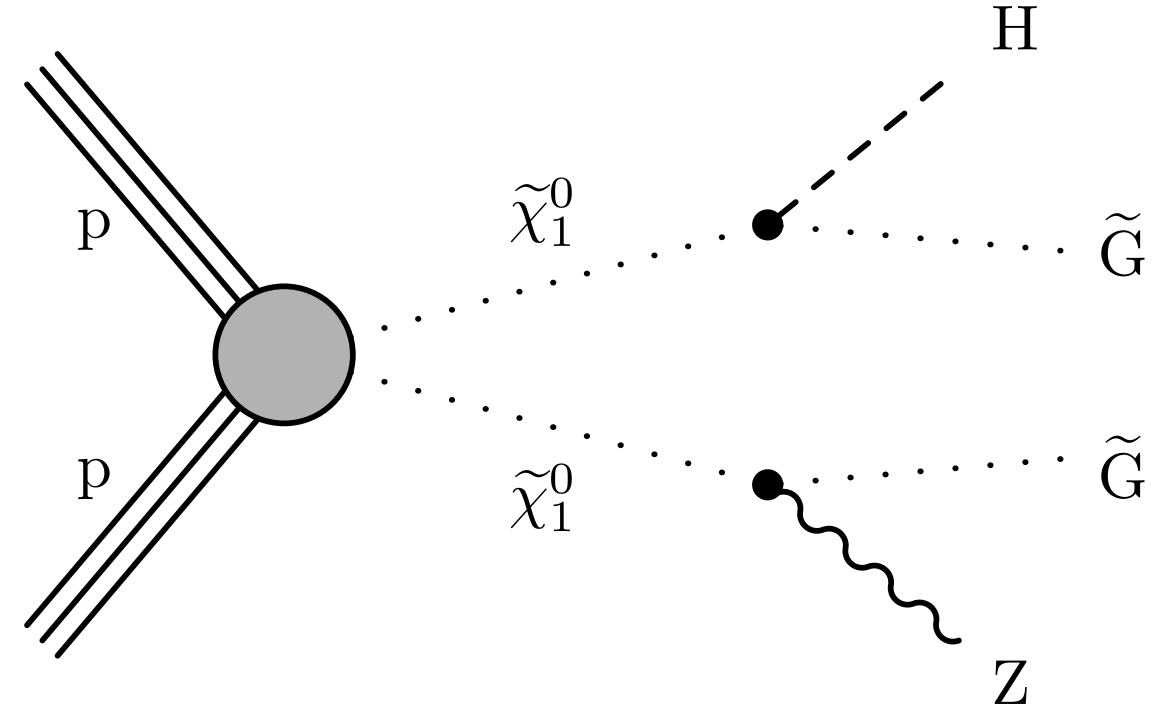
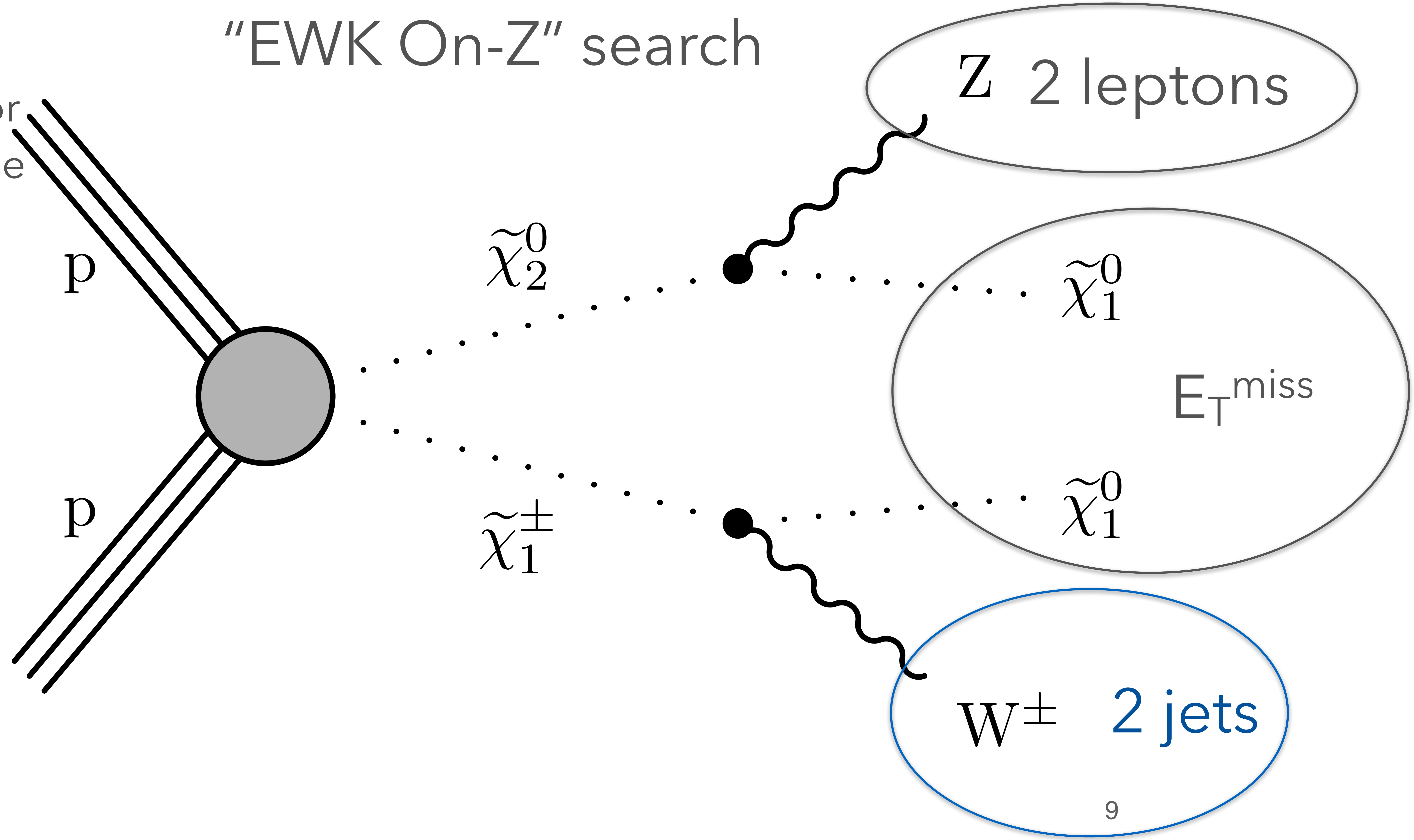
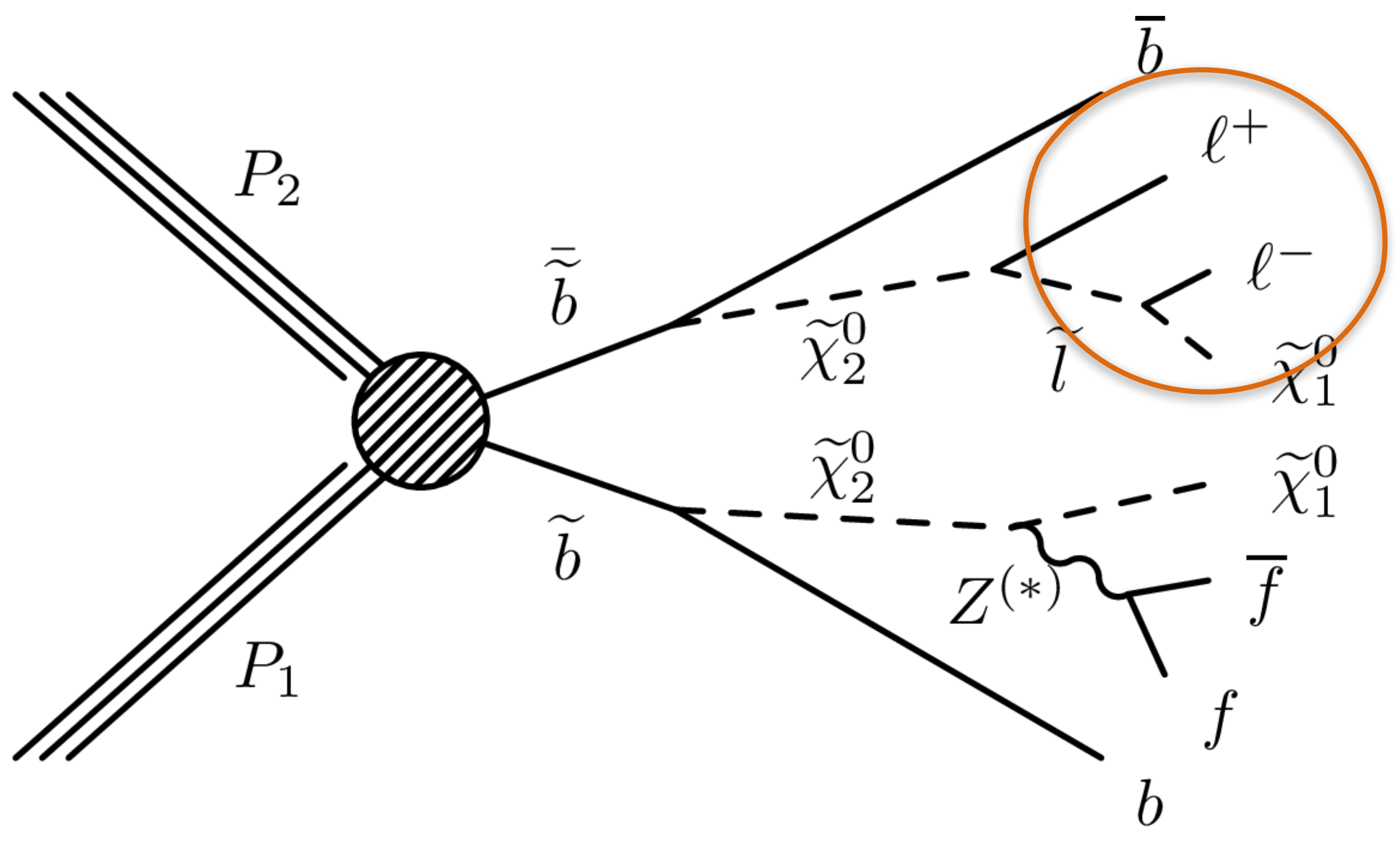




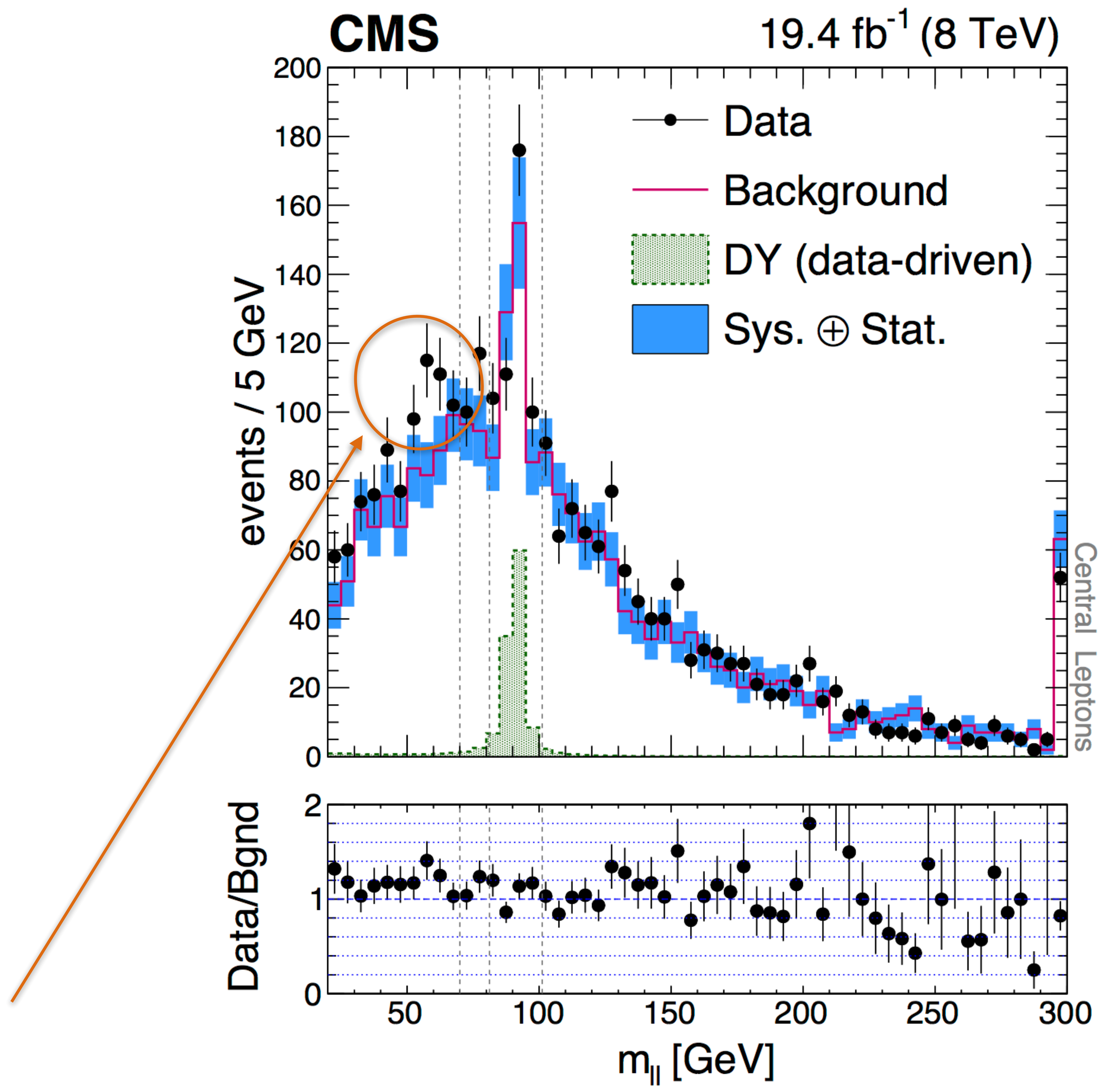
"EWK On-Z" search



History of the analysis: Edge

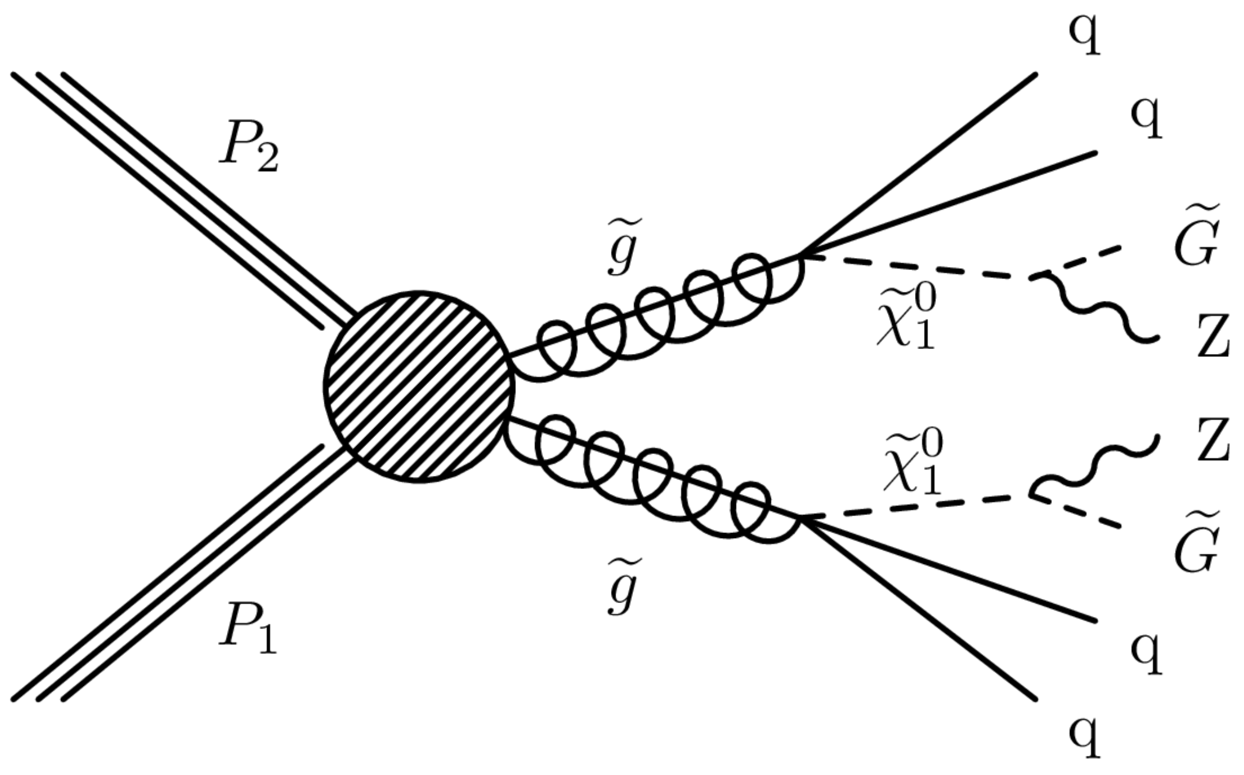


CMS excess in Run I:

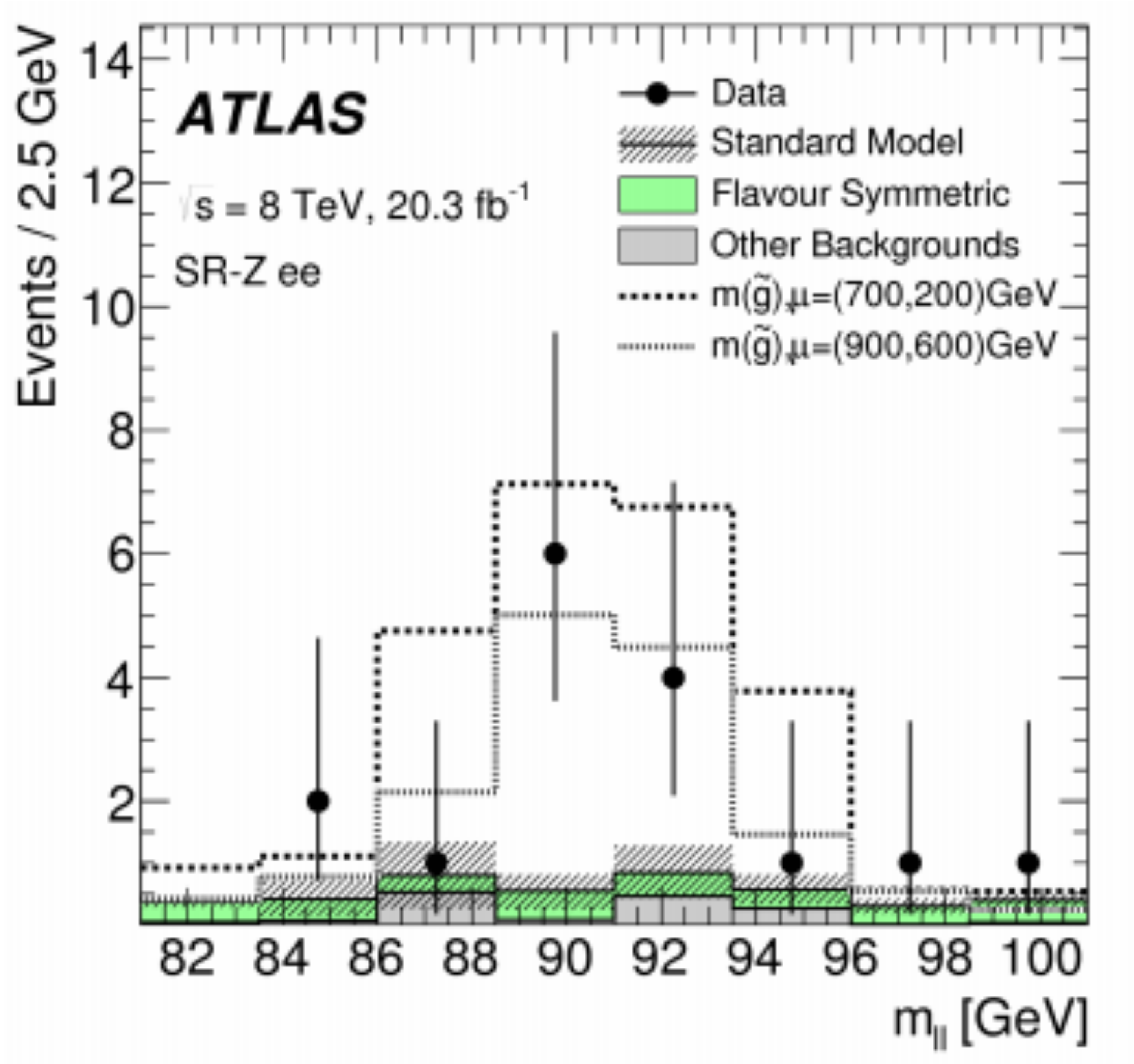


In the LHC Run I CMS reported an excess of 2.6 σ at an invariant mass of 78 GeV

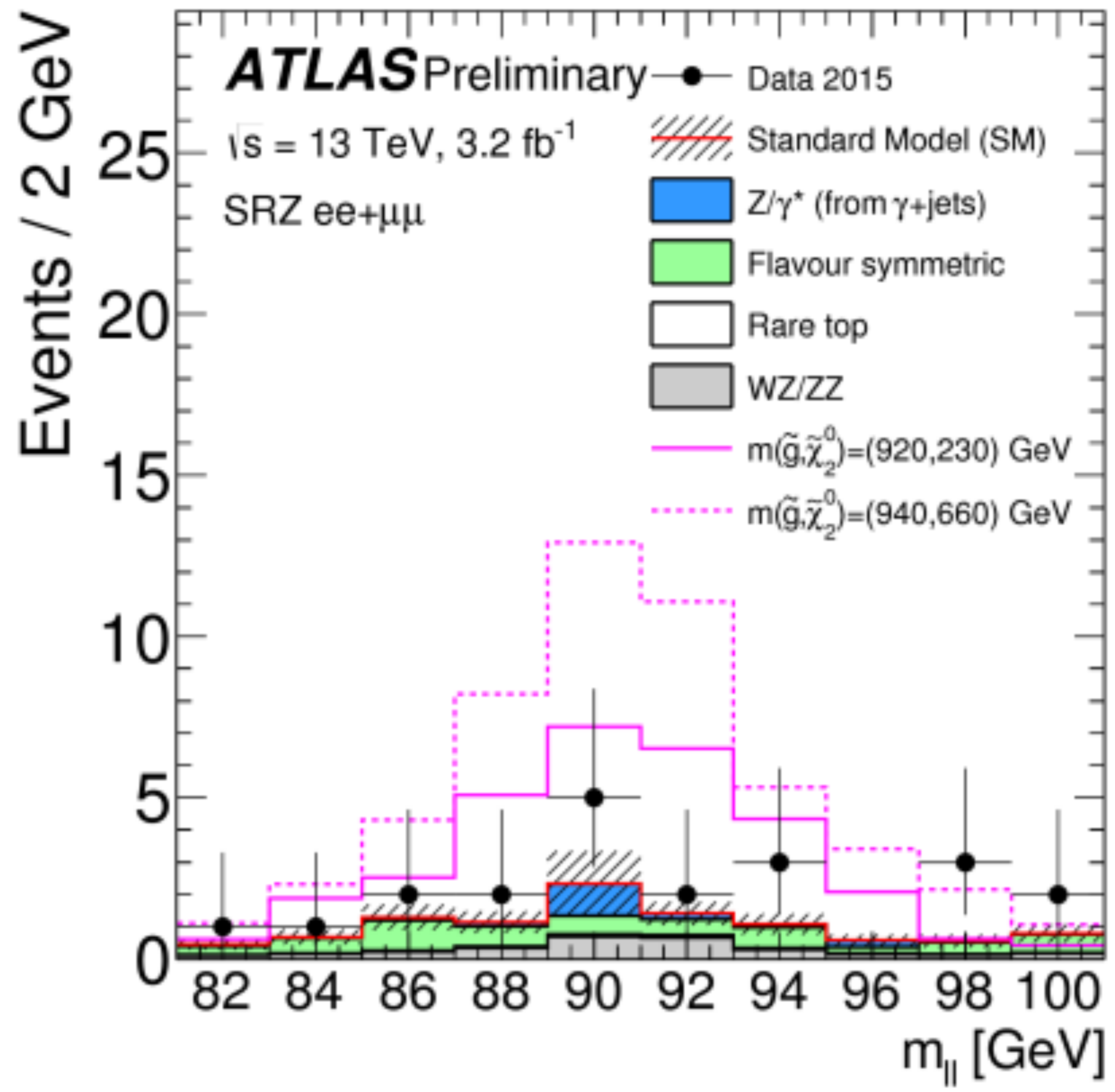
History of the analysis: On-Z



ATLAS excess in Run I:

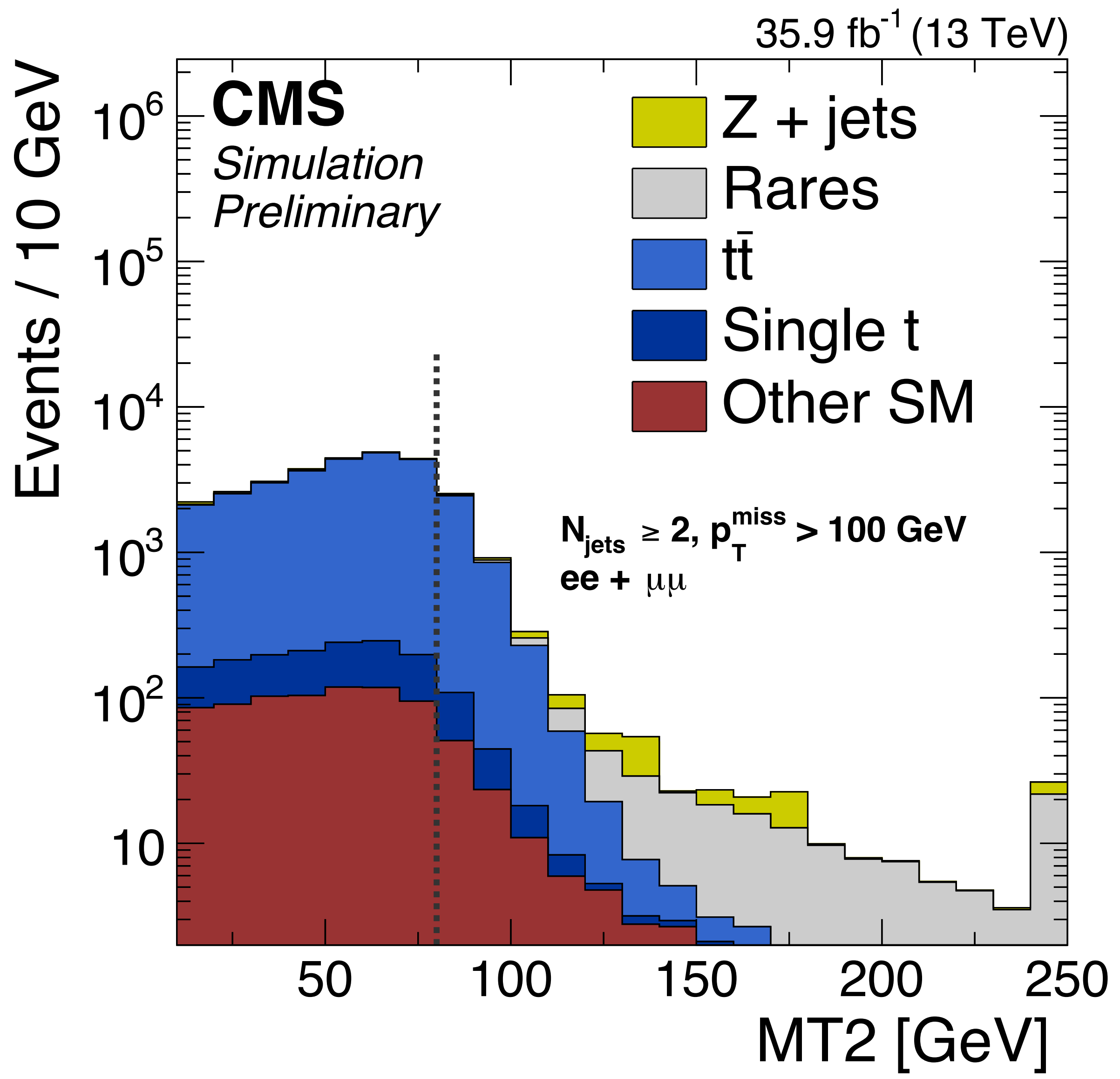


ATLAS excess in start of Run II:



In the LHC Run I ATLAS reported an excess of 3.0 sigma, and in the beginning of Run II an excess of 2.2 σ

Search strategy



- 2 opposite sign, same flavour leptons
- > 1 jet
- $m_{T2} > 80$ GeV
- $E_T^{miss} > 100$ GeV
- third lepton veto

Edge:

- search for a kinematic edge in the m_{ll} spectrum
- main background ttbar
- ttbar and non ttbar-like discriminator
- bins in m_{ll}
- detailed signal region definitions in backup

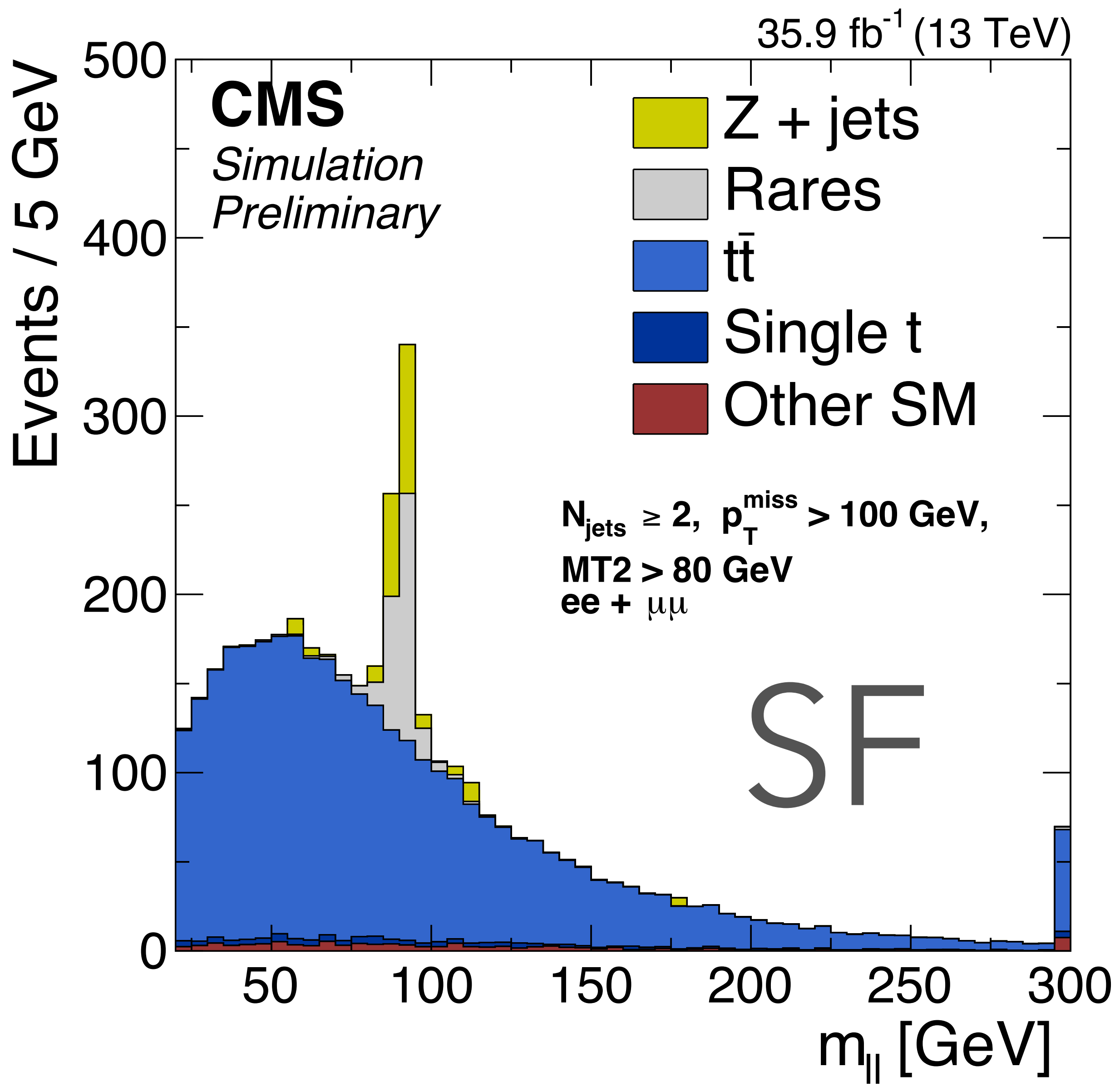
On-Z:

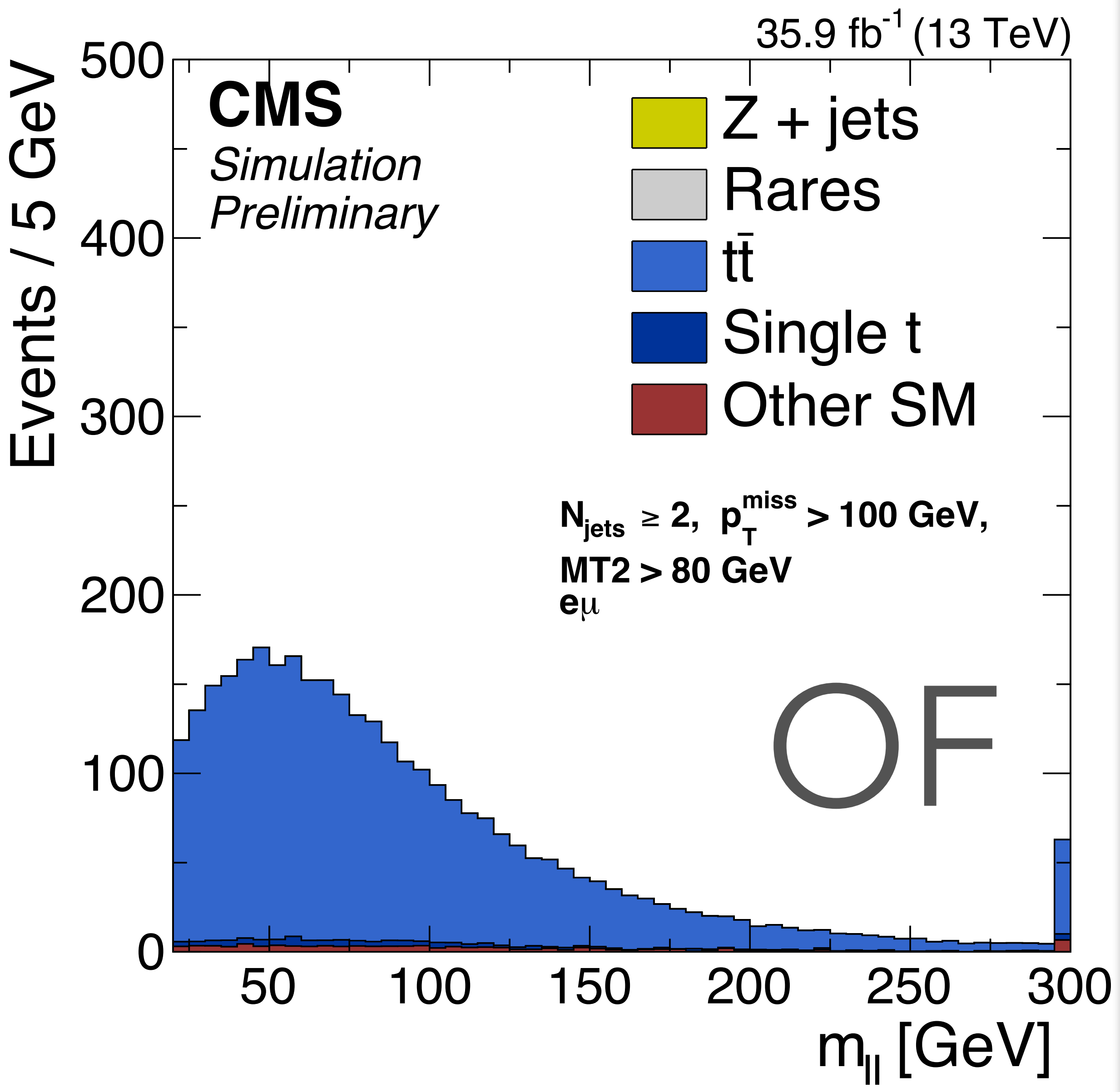
- search for an excess in the E_T^{miss} tails and a resonant decay compatible with a Z boson
- main background ttbar + Z+jets
- signal regions in number of b-jets and jets, bins in E_T^{miss}
- different signal regions for strong and EWK searches

Background prediction

Flavour symmetric (purely data driven):

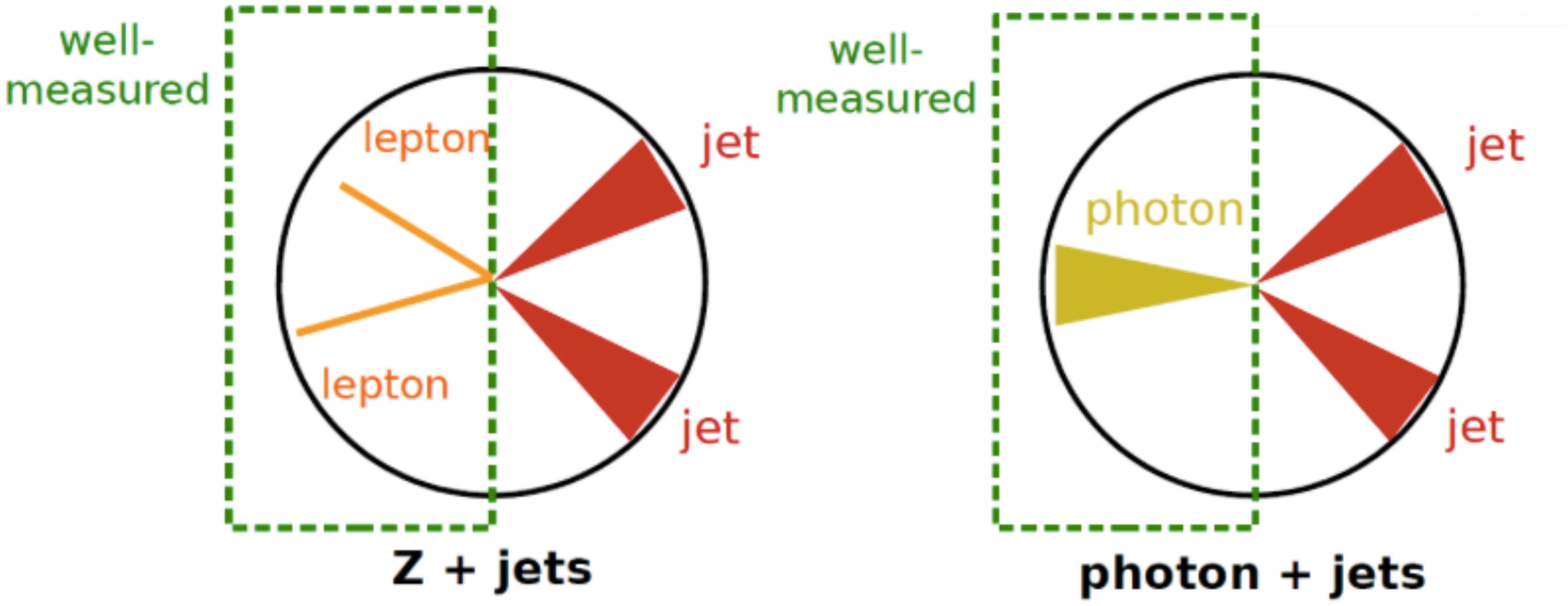
- relies on the flavour symmetry of the W decay
  - #same flavor ~#opposite flavour lepton pairs
- SF signal estimated from OF control sample
  - correct for different trigger, object and reconstruction efficiencies





Z+jets (purely datadriven):

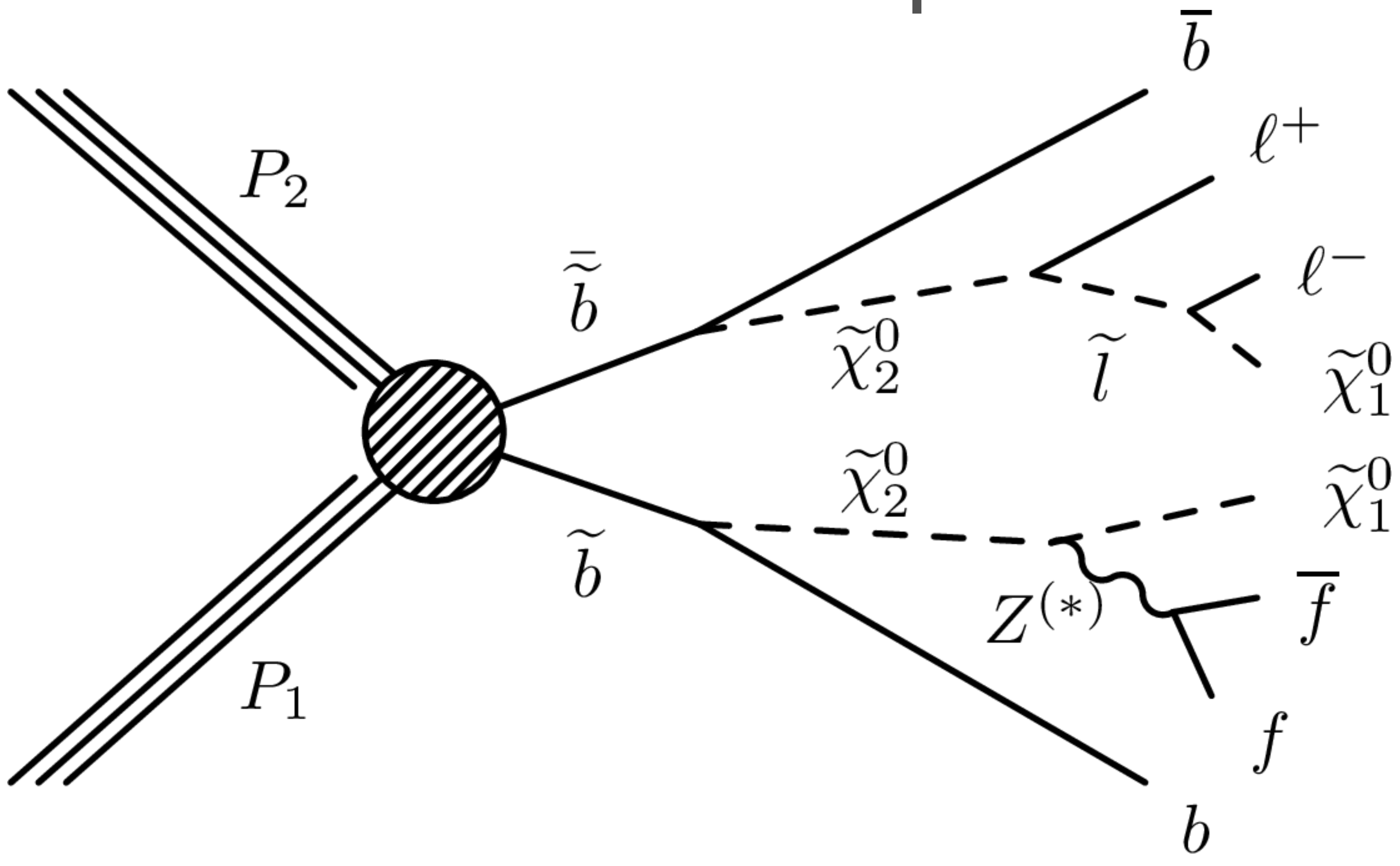
- E_T^{miss} in Z →ll is mainly from jet mismeasurements
- Predict E_T^{miss} using the fact that:
  - E_T^{miss} in γ+jets ~ Z+jets

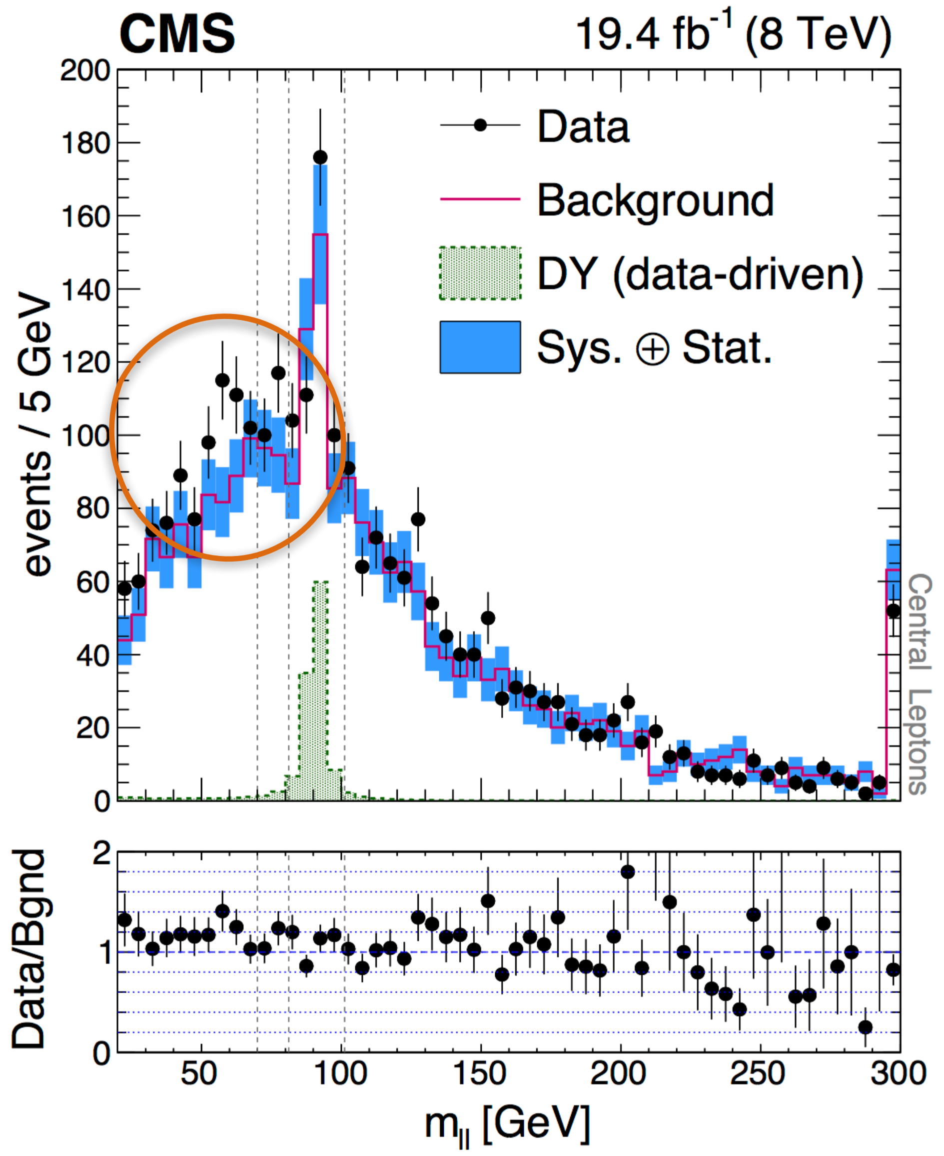


Remaining backgrounds

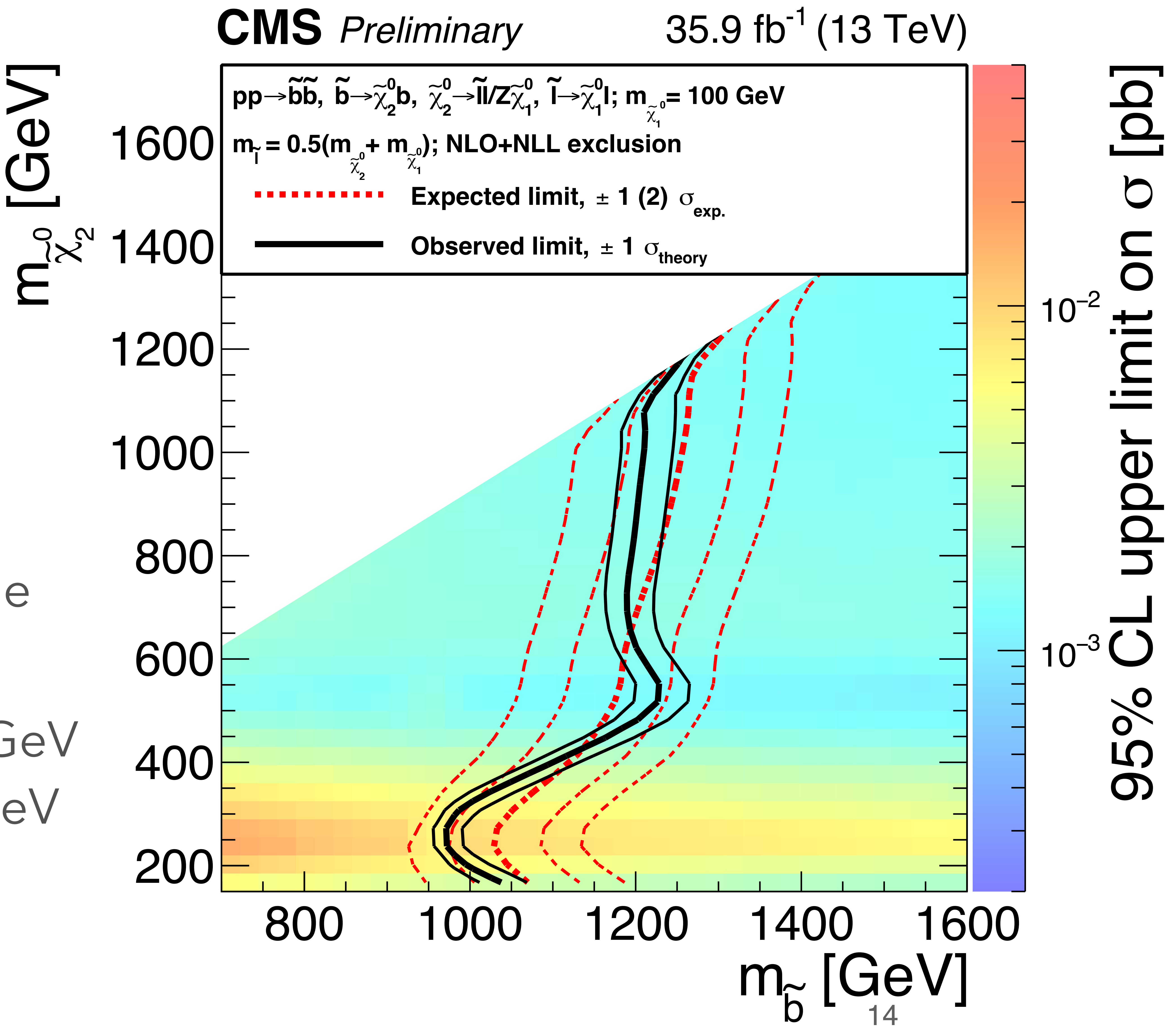
- such as WZ→3l, ZZ→4l, ttZ
- from Monte Carlo

Results and interpretation: Edge search

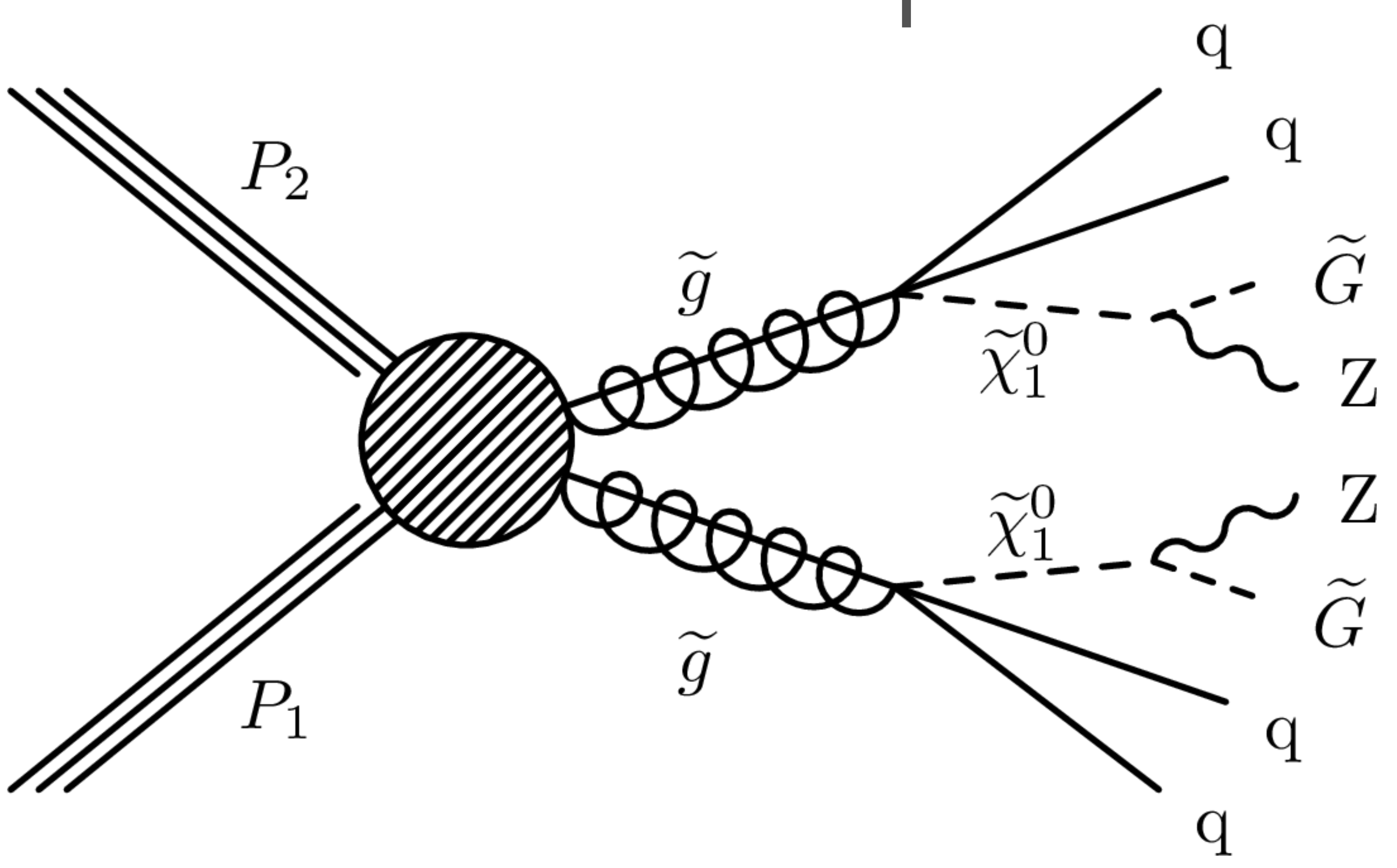


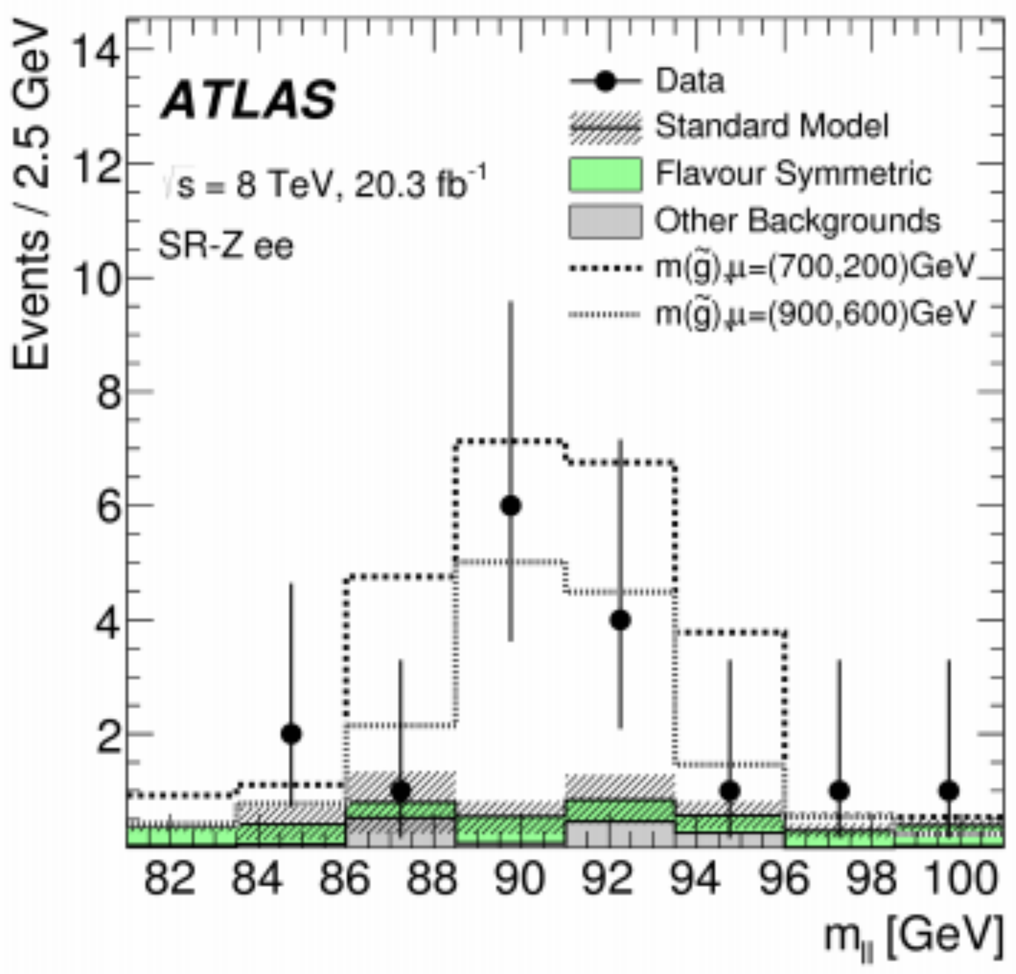


- CMS Run I excess gone
- sbottom particle exclusion from ~500 GeV (Run I) to 980 -1200 GeV

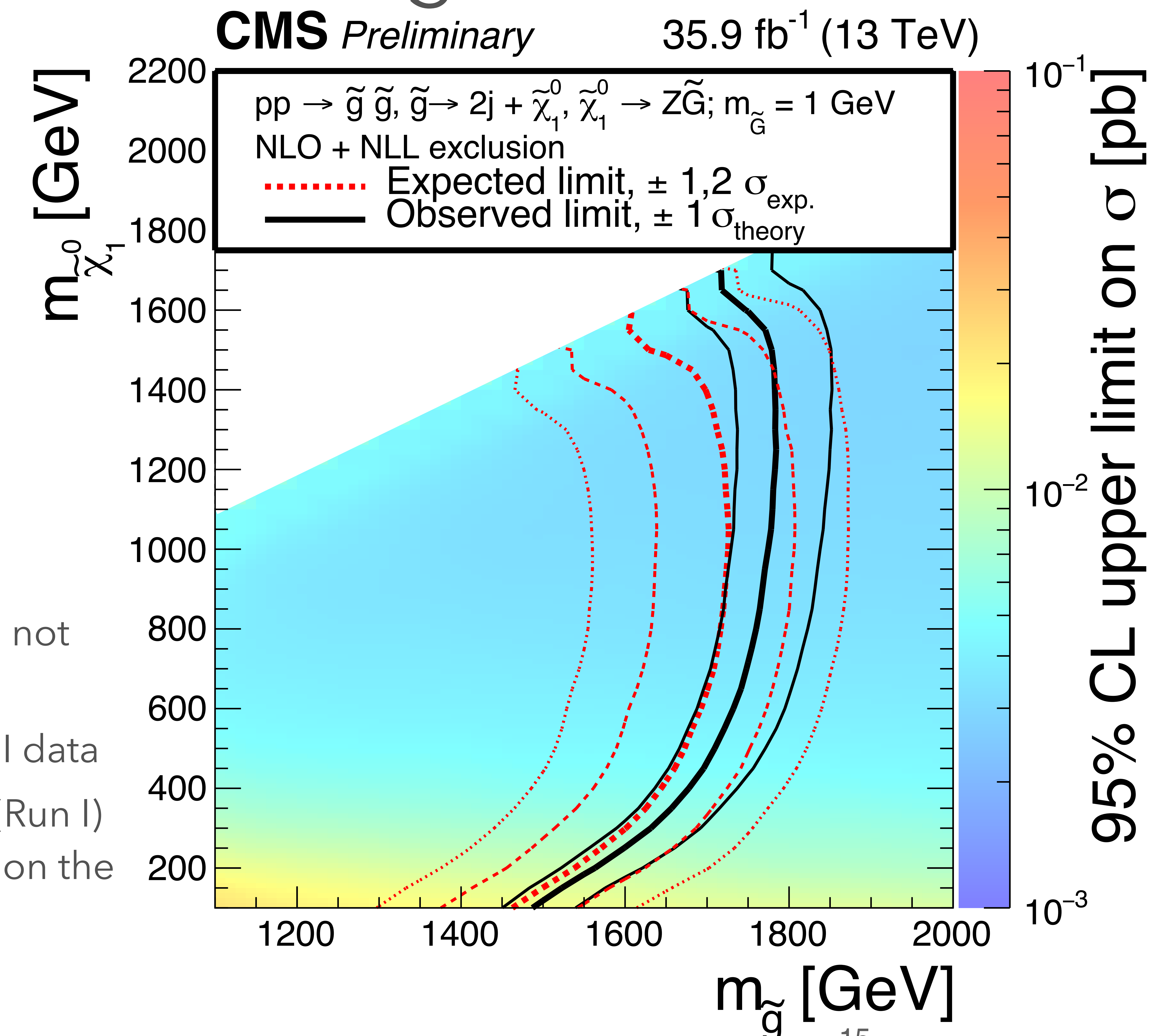


Results and interpretation: On-Z strong search

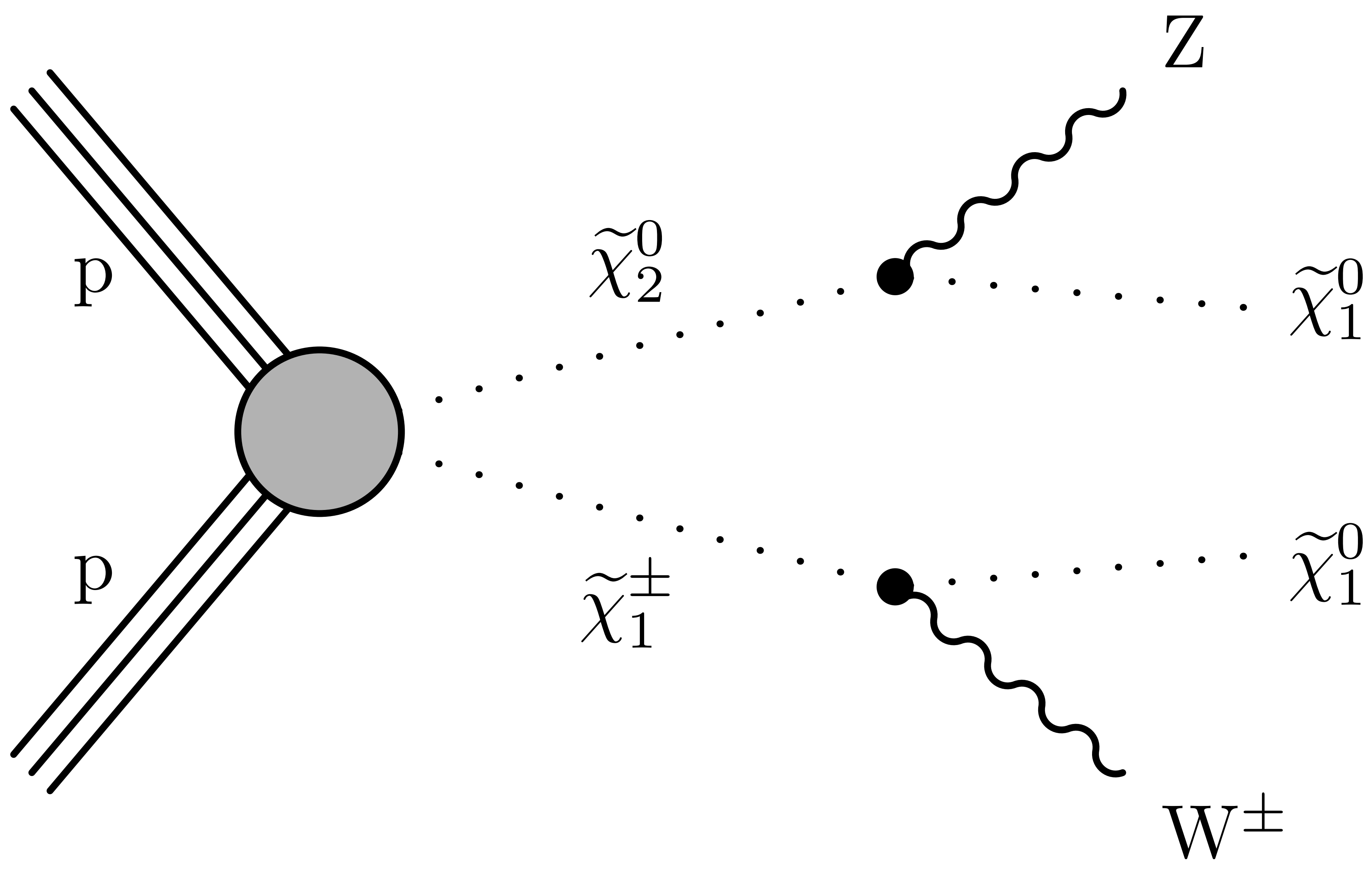


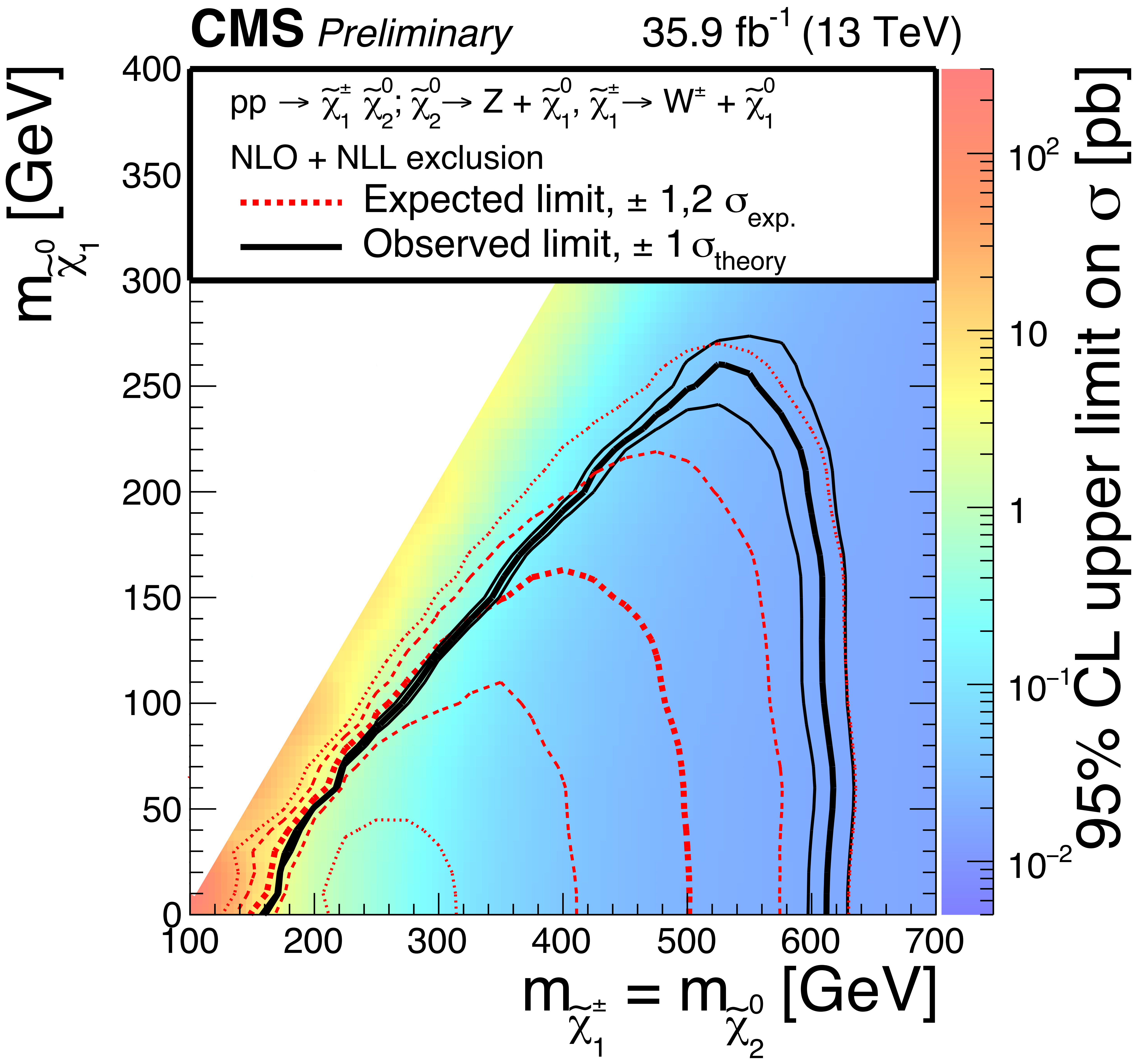


- ATLAS Run I/early Run II excess not confirmed
- ATLAS excess gone in full Run II data
- Exclusion from 900–1100 GeV (Run I) to 1500-1770 GeV, depending on the mass of the $\tilde{\chi}_1^0$



Results and interpretation: On-Z electroweak search





- Electroweakly produced SUSY
- Charginos excluded up to 610 GeV

Summary

- A search for Beyond Standard Model Physics has been presented (CMS-SUS-16-034)
  - SUSY resulting in final states with two leptons of opposite charge and same flavor
- One of the most sensitive leptonic analyses using mainly data driven methods
- Run I excesses in ATLAS and CMS gone
  - exclusions are set on various SUSY particles
- Ready to analyze 2017 LHC data and also discover/exclude direct slepton production!

Backup

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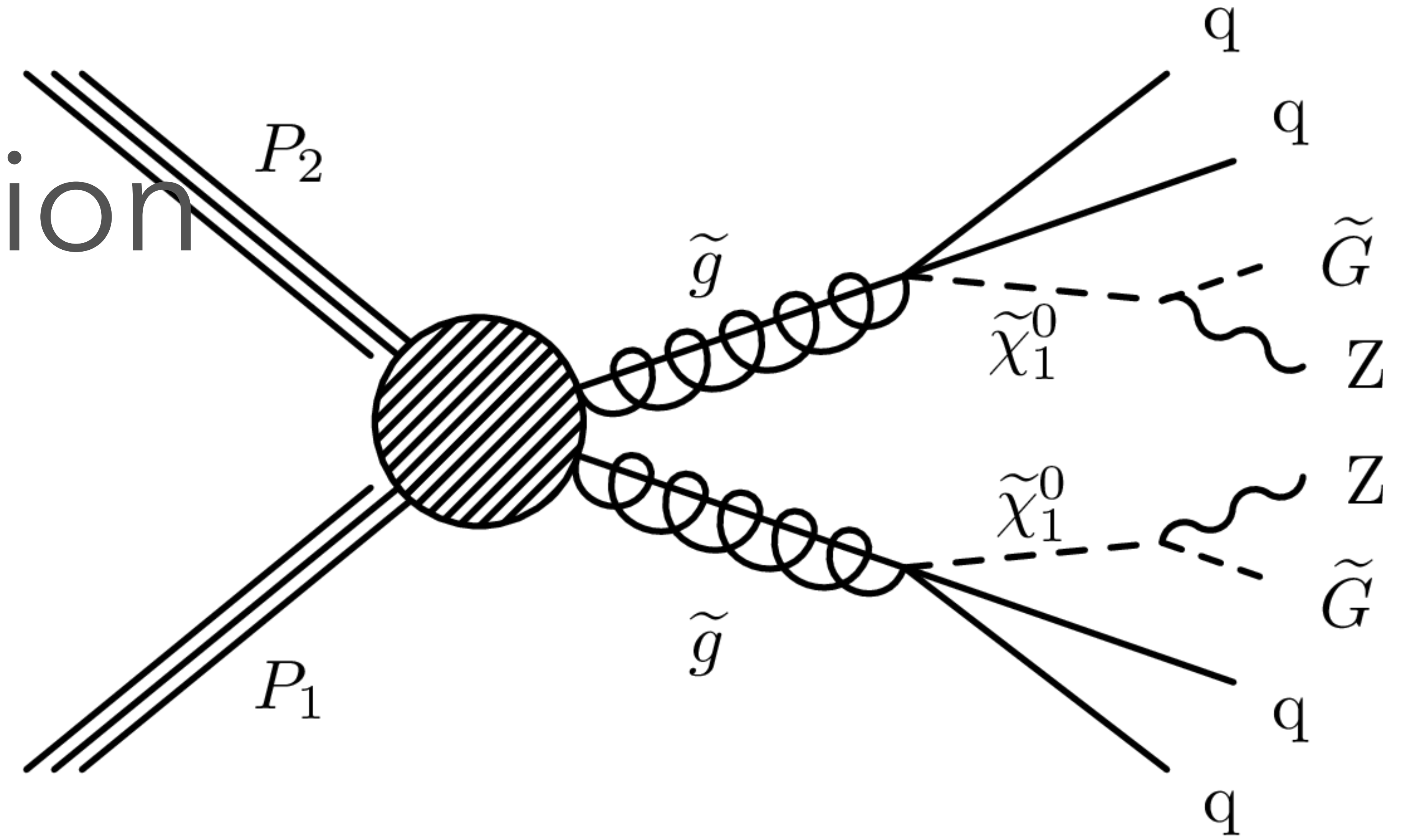
On-Z strong detailed signal region



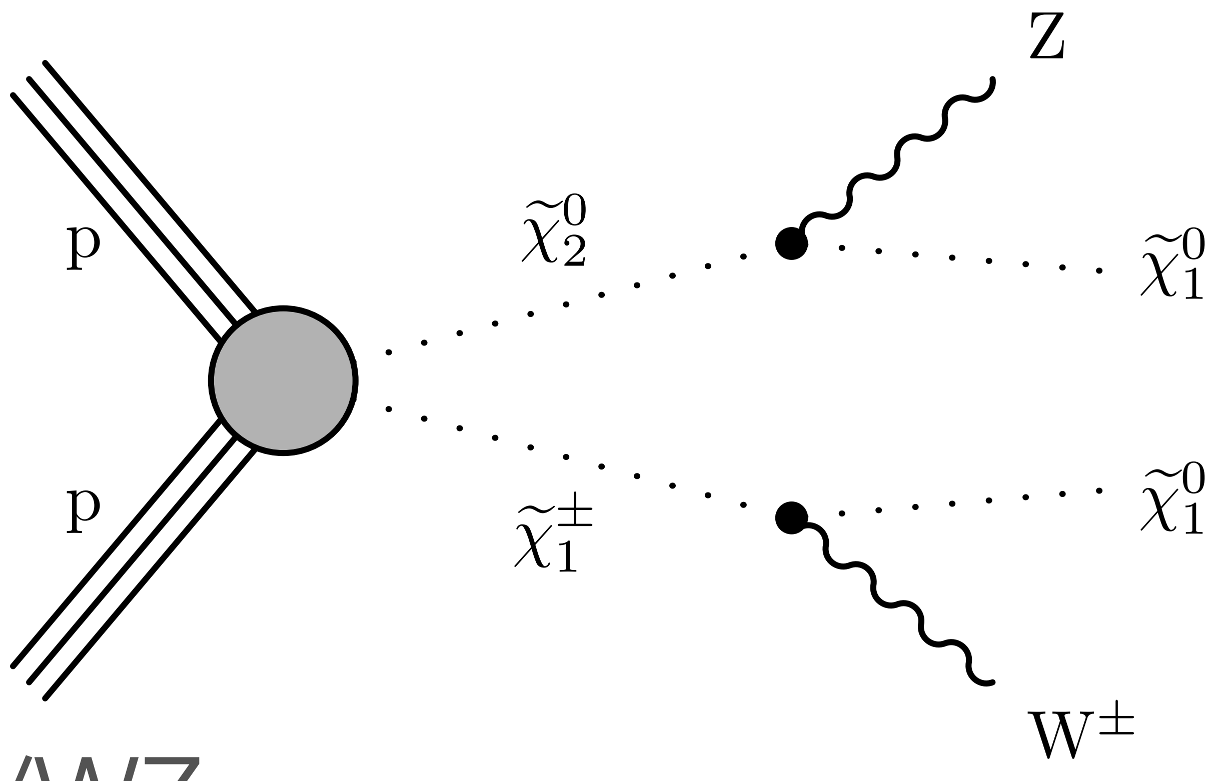
- $|M_{ll} - M_Z| < 5$ GeV to reduce FS backgrounds
- M_{T2} to suppress ttbar
- 3rd lepton veto to suppress WZ and ttZ
- Lowest signal region starts at $E_T^{miss} > 100$ GeV
- Binning in H_T, njets and btag

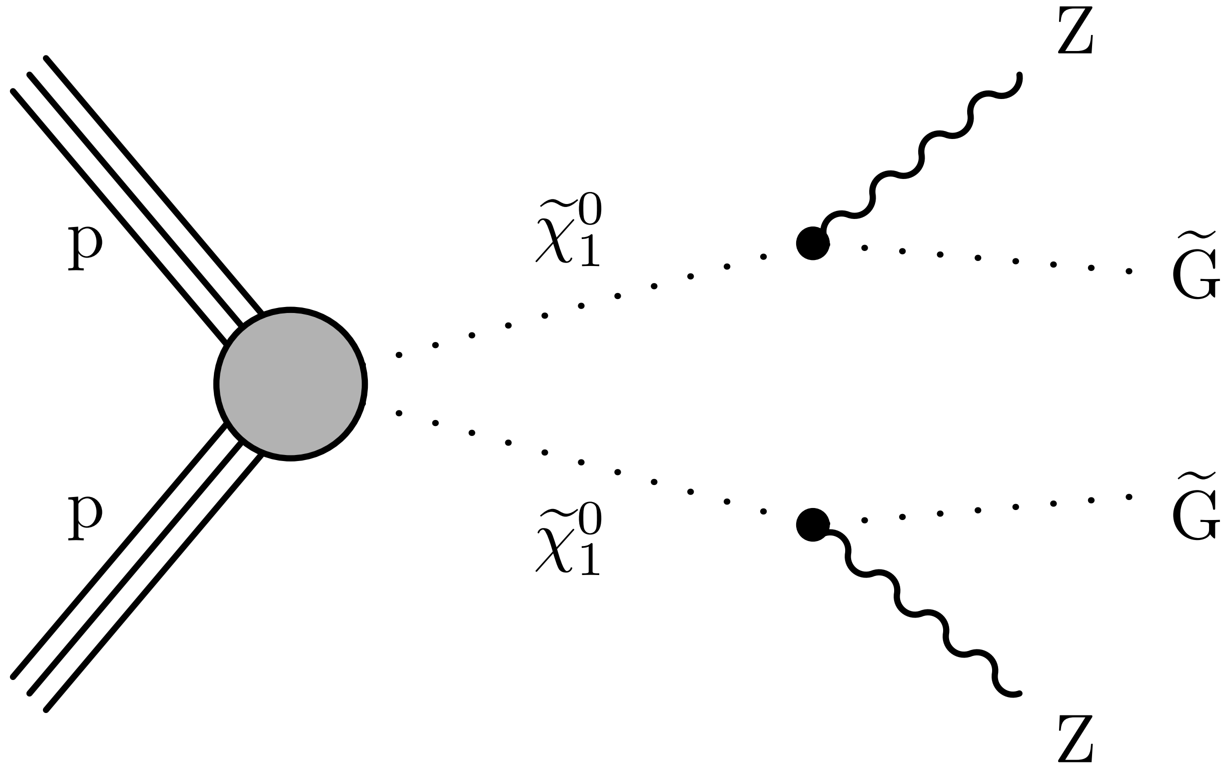
B-veto			
N_{jets}	2-3	4-5	≥ 6
H_T	> 500 GeV		No Cut
MT2	> 80 GeV		

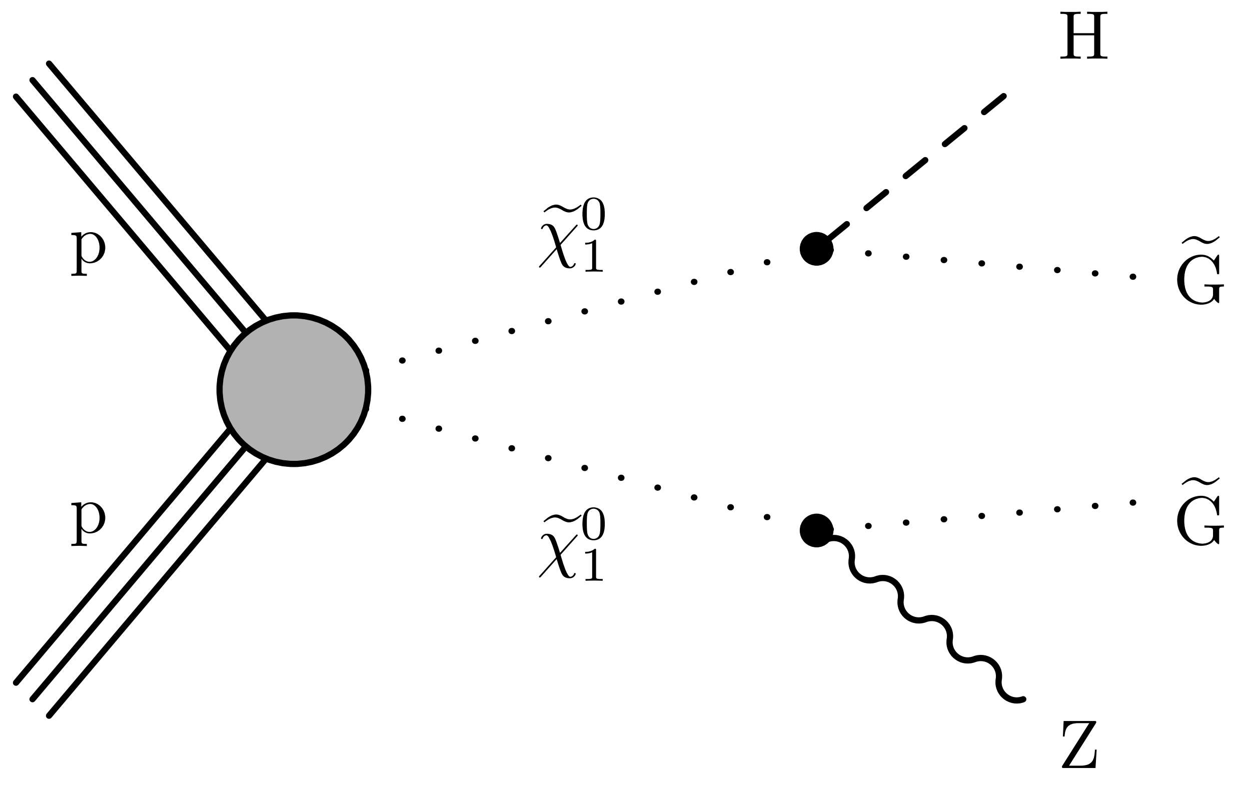
With bs			
N_{jets}	2-3	4-5	≥ 6
H_T	> 200 GeV		No Cut
MT2	> 100 GeV		

On-Z EWK detailed signal region

- $|M_{ll} - M_Z| < 5$ GeV to reduce FS backgrounds
- 3rd lepton veto to suppress WZ and ttZ







ZZ/WZ:

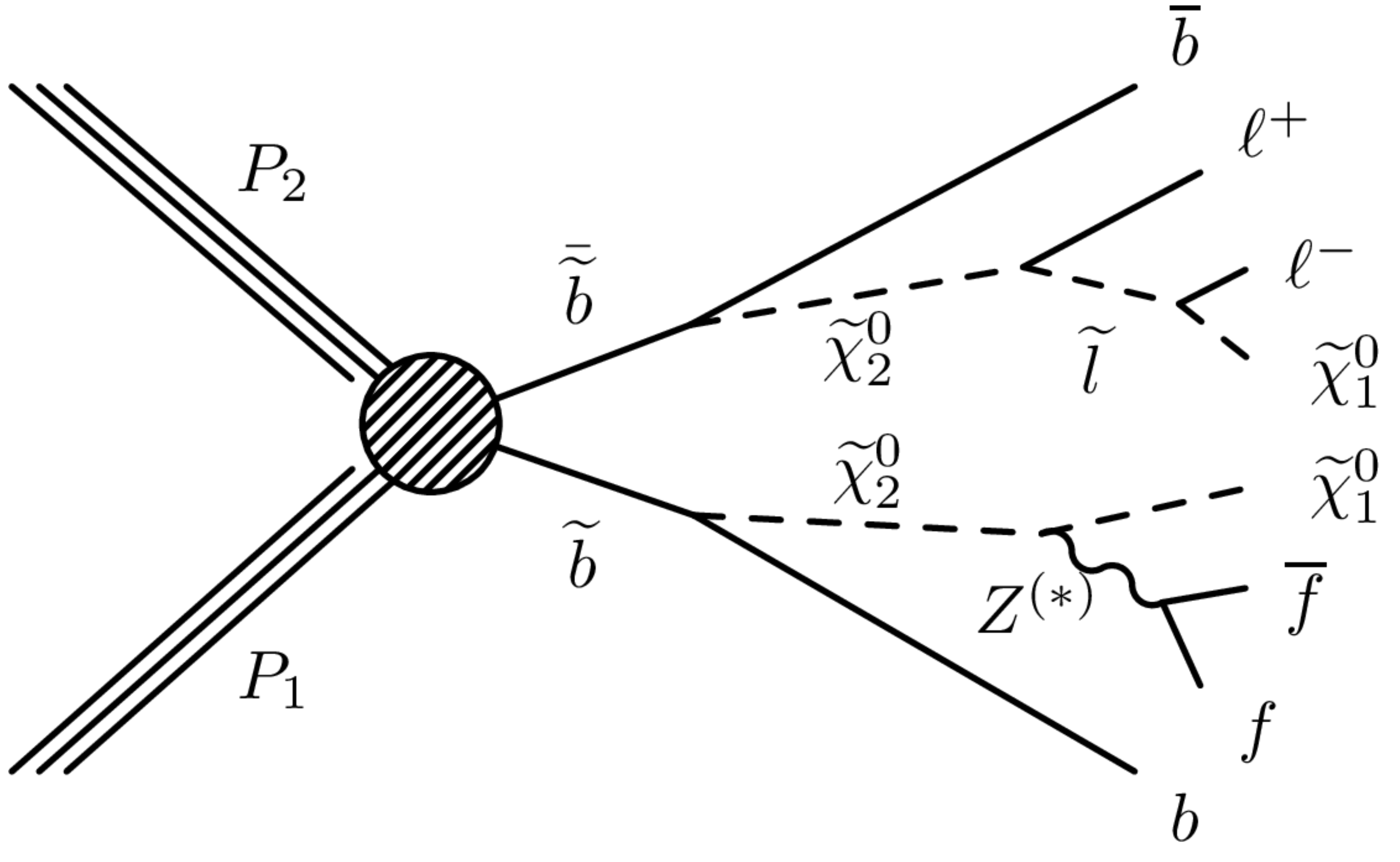
- 0 b-tagged jets,
- $M_{T2} > 80$ GeV, and
- $M_{jj} < 110$ GeV,
- where M_{jj} is the invariant mass of the two jets closest in φ.

H(bb)Z(ll)

- ==2 b-tagged jets
- $M_{T2}(bb) > 200$ GeV, and
- $M_{bb} < 150$ GeV,
  - where M_{bb} is the invariant mass of the two b-tagged jets.

Edge detailed signal region

- With the full dataset new binning needs to be introduced to keep the sensitivity
- $E_T^{miss} > 150$ GeV
- New cut on $M_{T2} > 80$ GeV and binning in m_{ll}
- Signal Regions with 7 mass bins [20-60, 60-86, 96-150, 150-200, 200-300, 300-400, 400+] and ttbar and non-ttbar like classification as signal regions

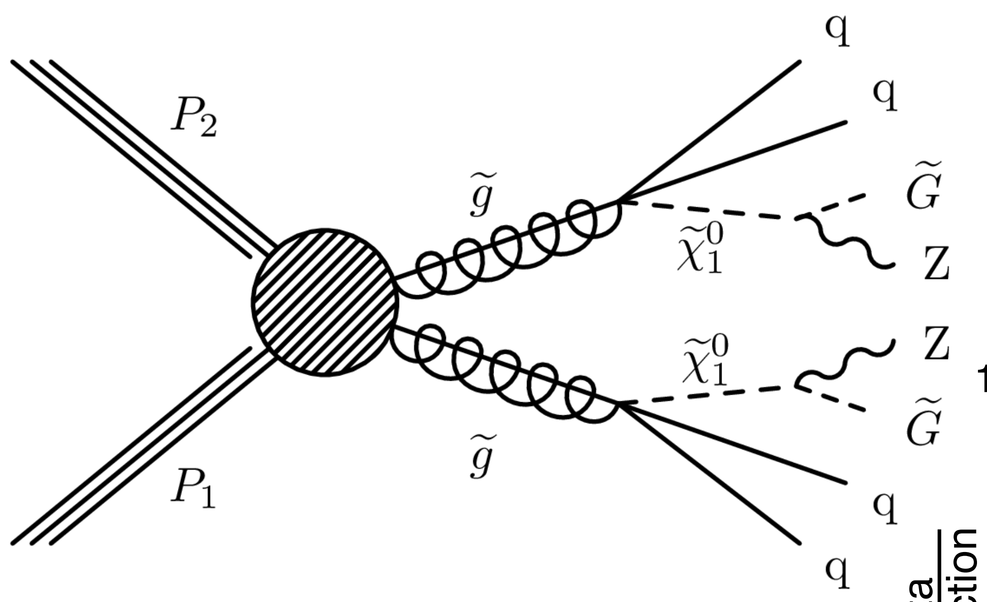


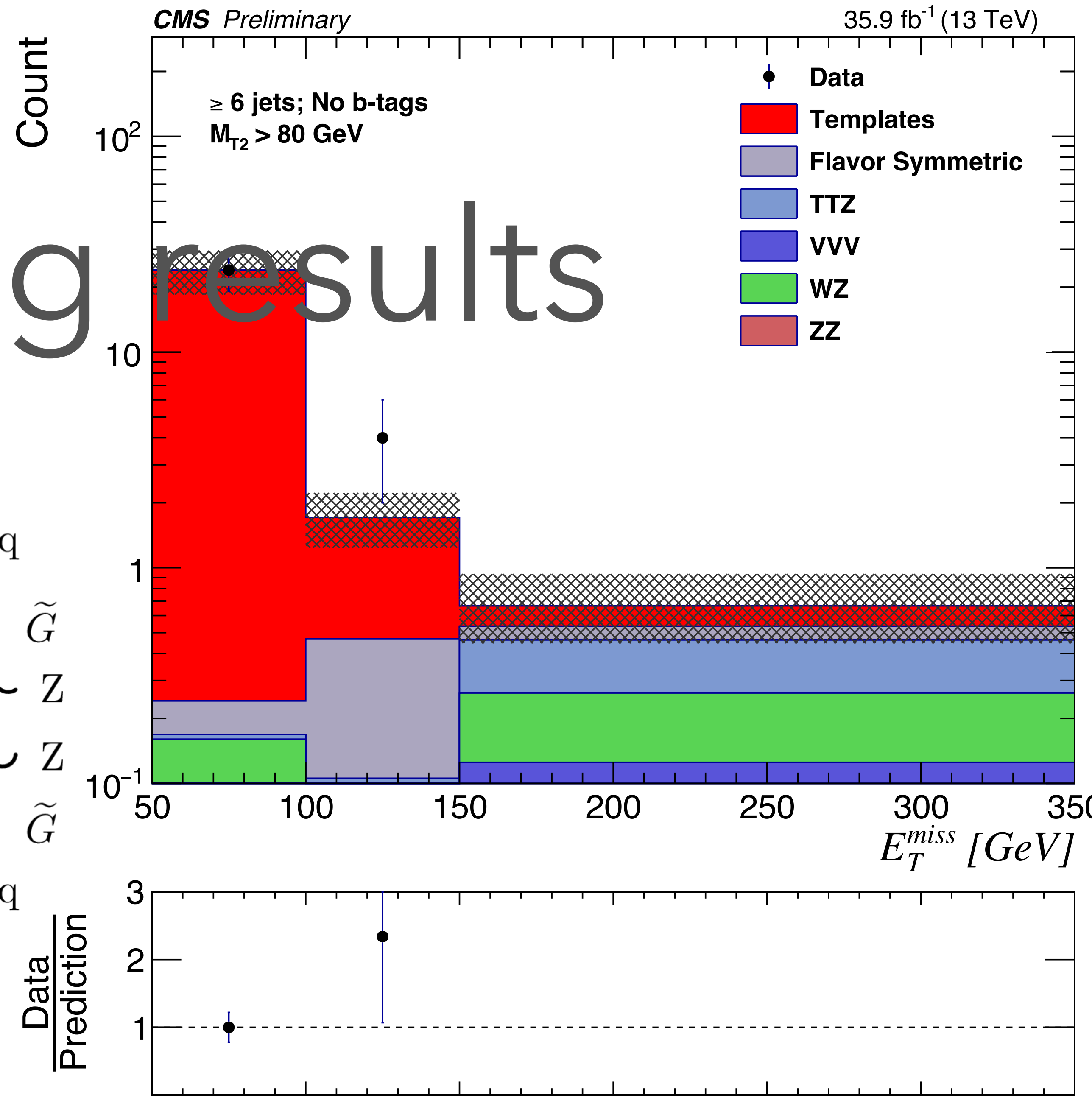
m_{ll} [GeV]	20-60	60-86	96-150	150-200	200-300	300-400	400+
ttbar							
non-ttbar							

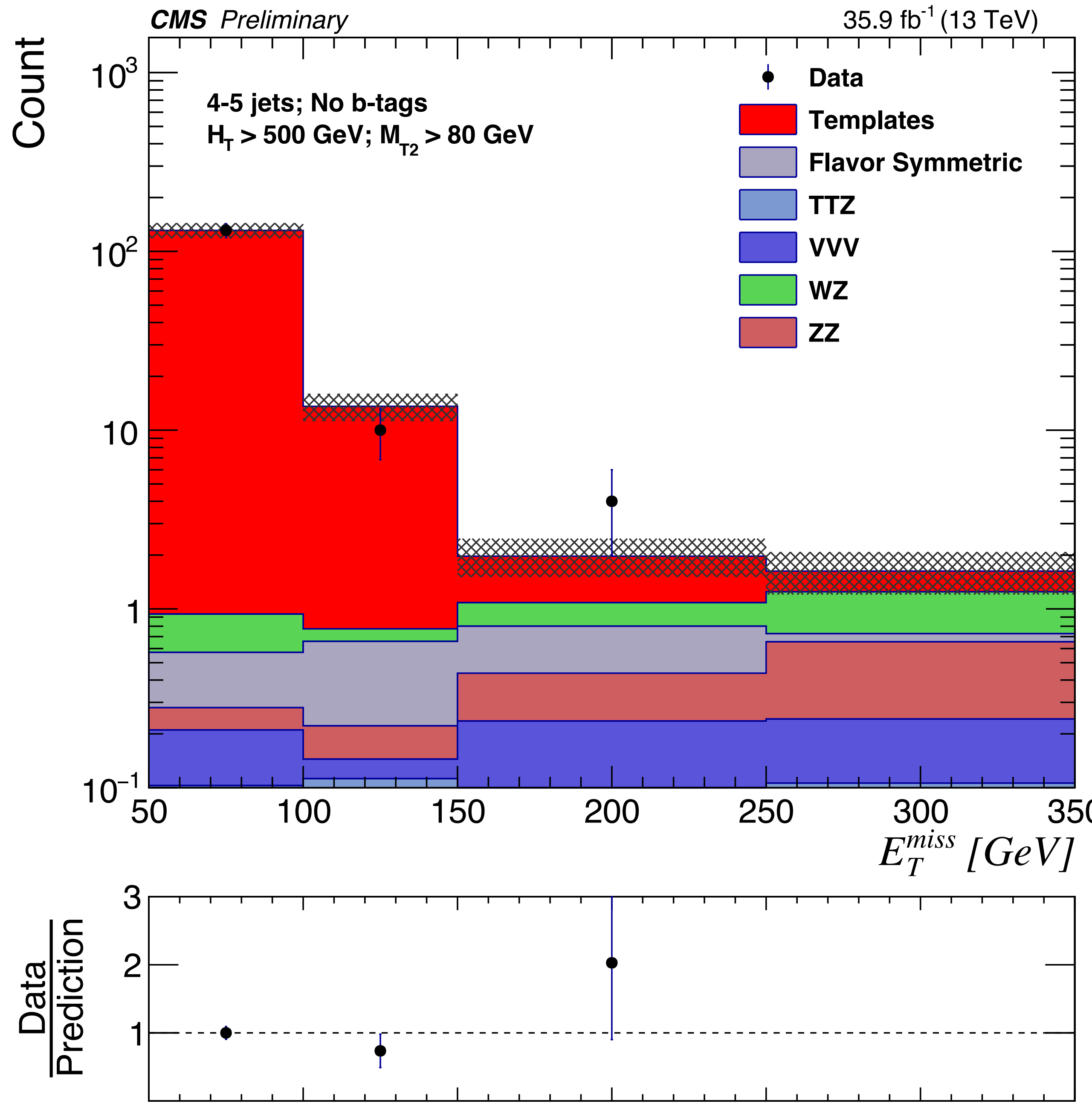
Summary of signal regions

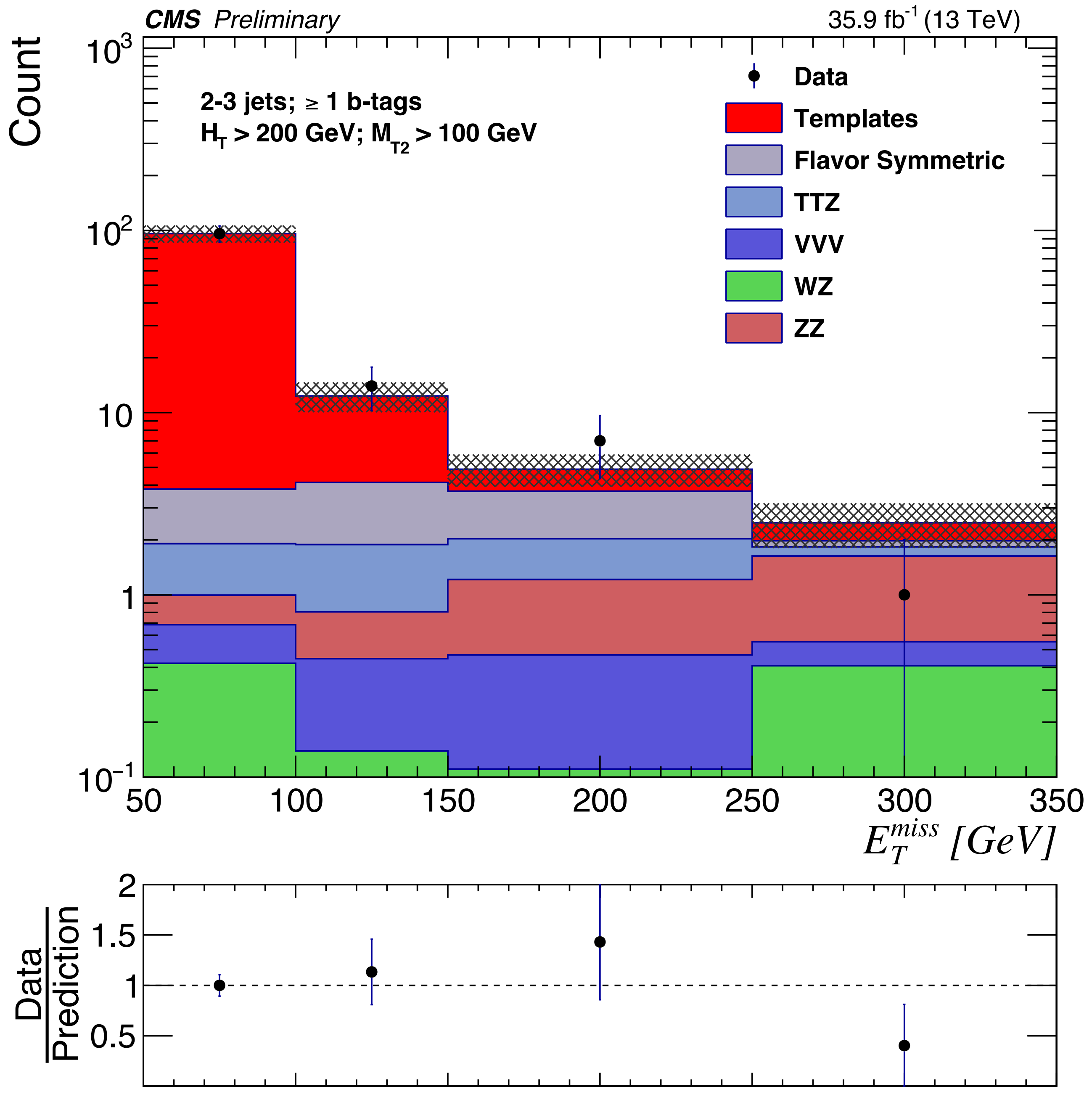
Strong-production on-Z ($86 < m_{\ell\ell} < 96$ GeV) signal regions					
Region	N_{jets}	$N_{\text{b-jets}}$	H_T [GeV]	$M_{T2}(\ell\ell)$ [GeV]	p_T^{miss} binning [GeV]
SRA b veto	2–3	$= 0$	> 500	> 80	100–150, 150–250, > 250
SRB b veto	4–5	$= 0$	> 500	> 80	100–150, 150–250, > 250
SRC b veto	≥ 6	$= 0$	-	> 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

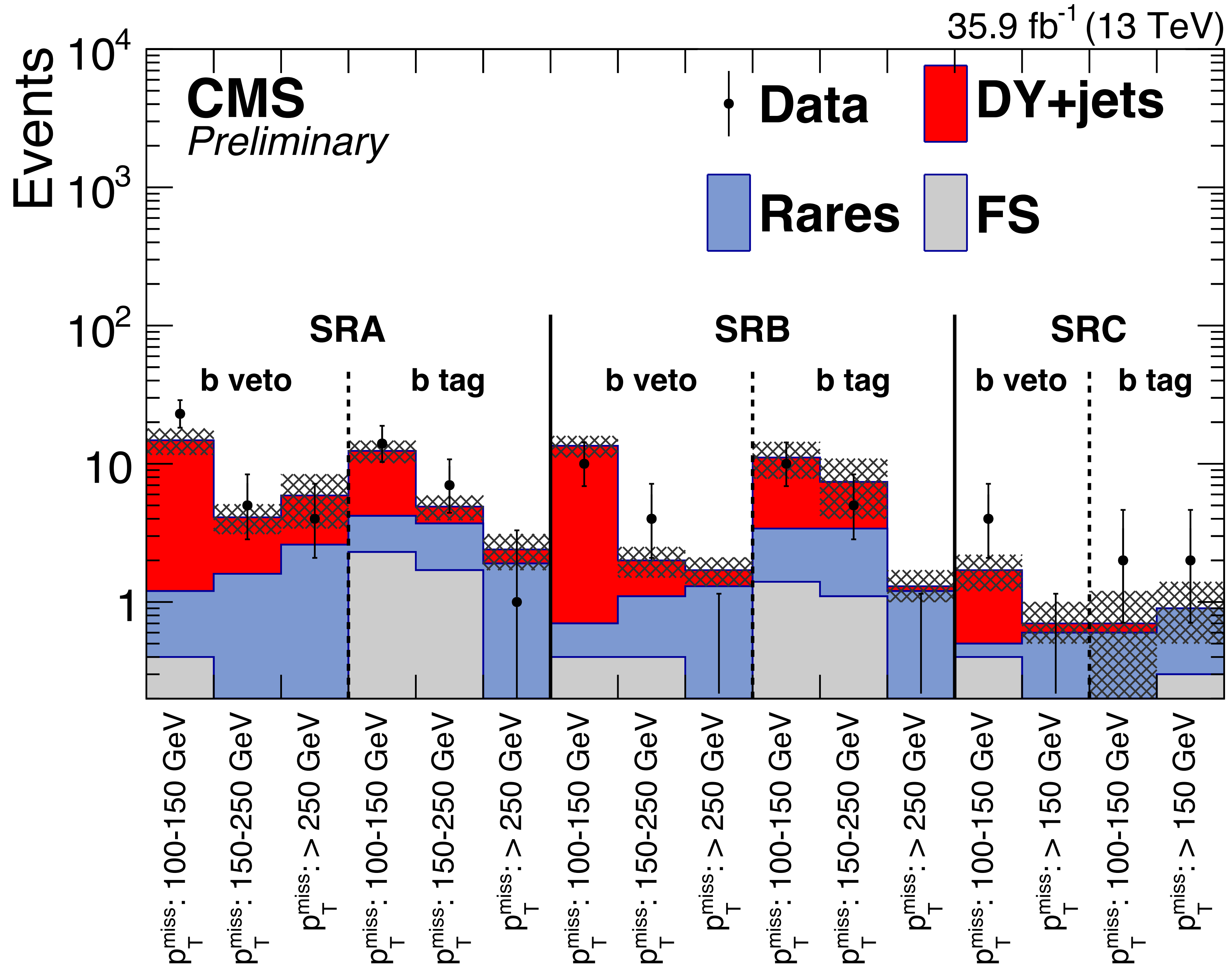
On-Z strong results

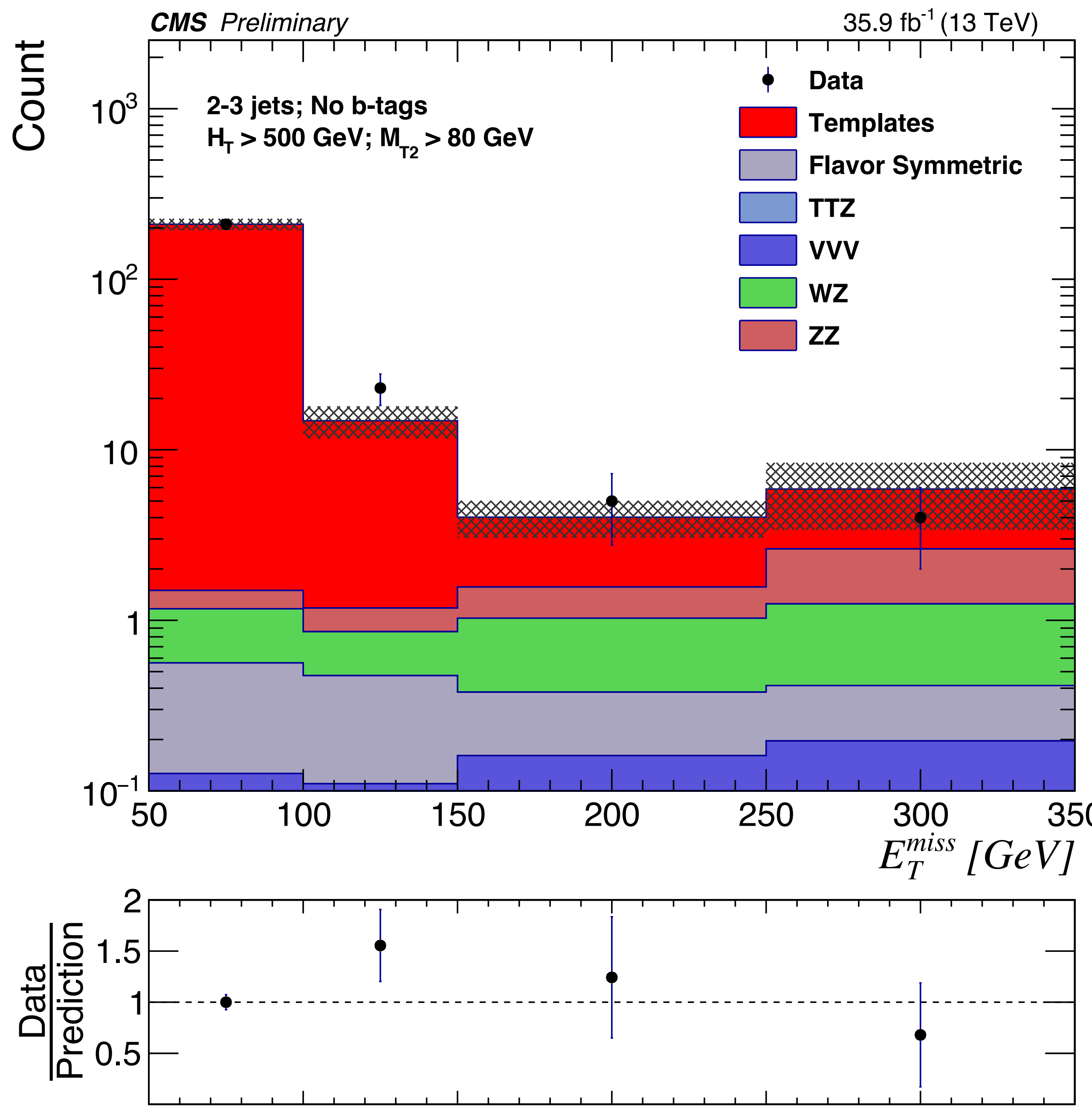


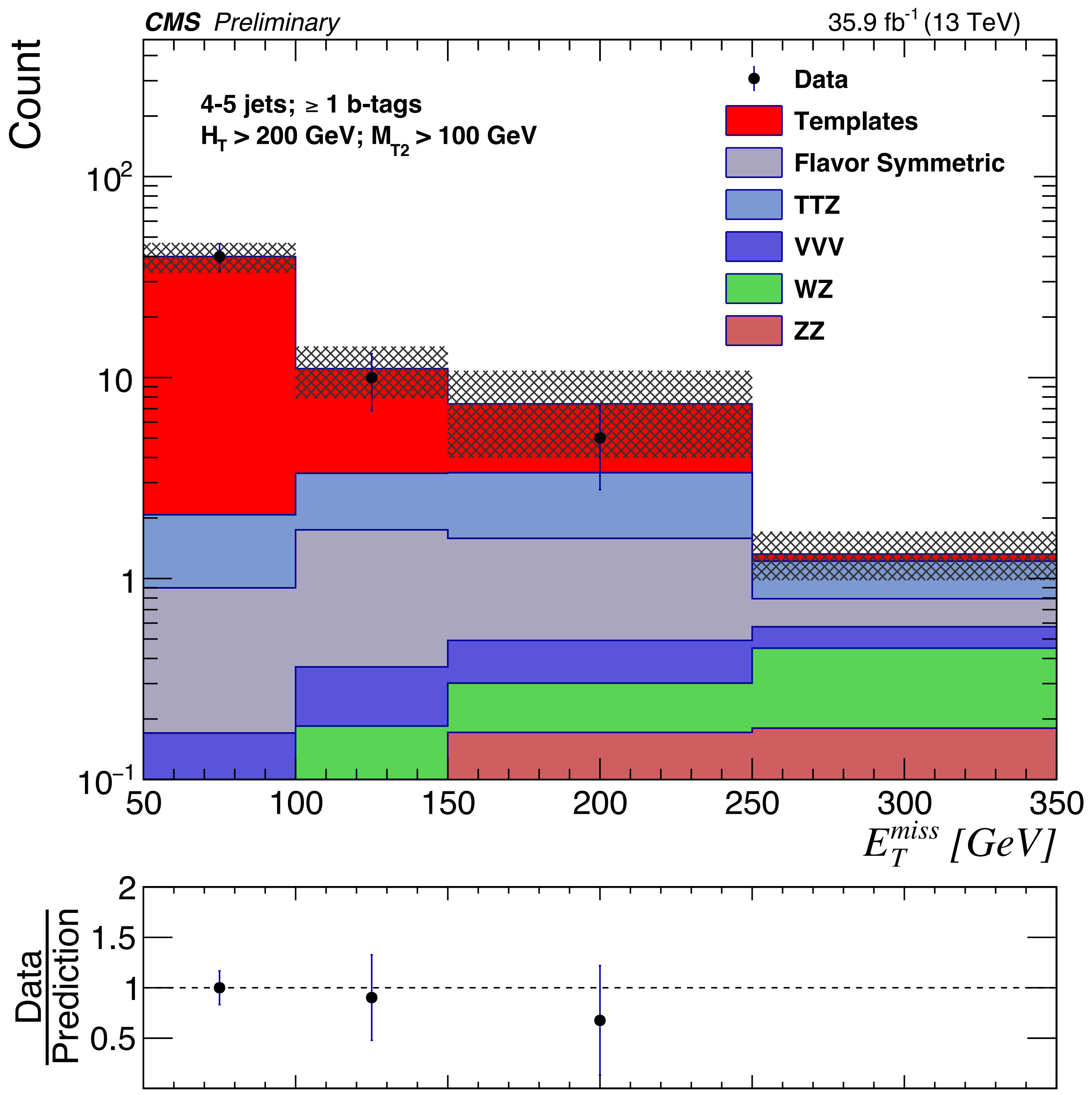




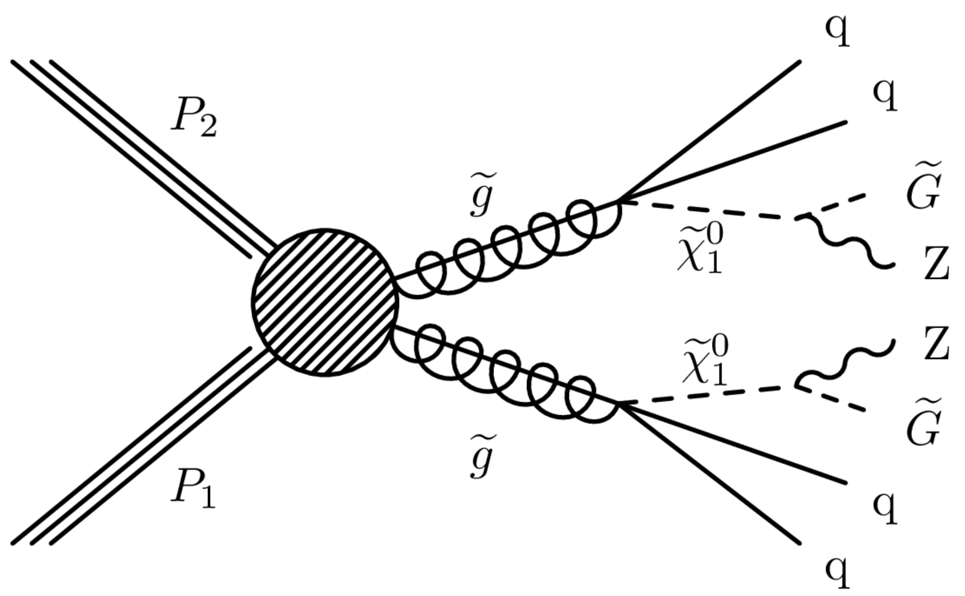


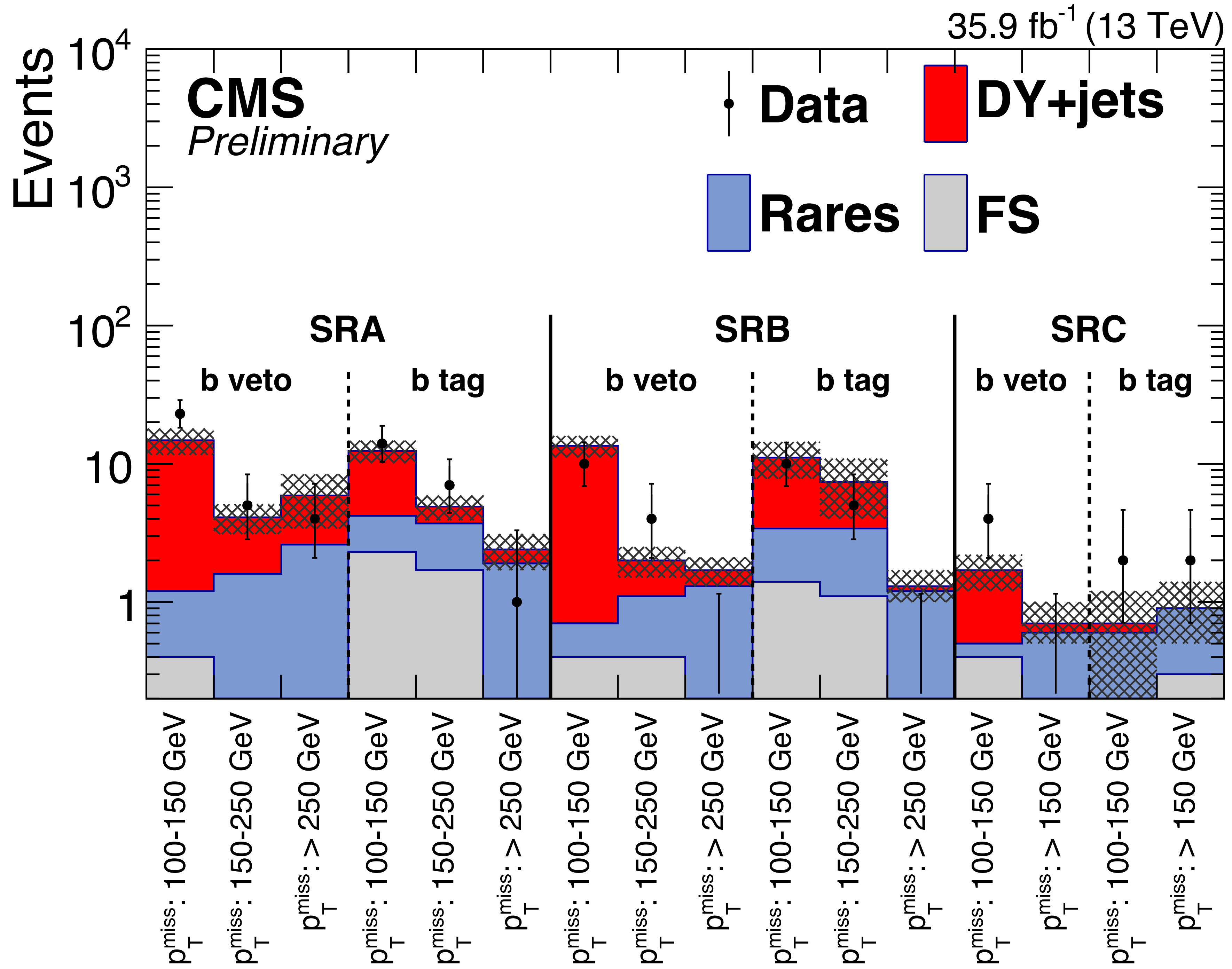






On-Z strong results





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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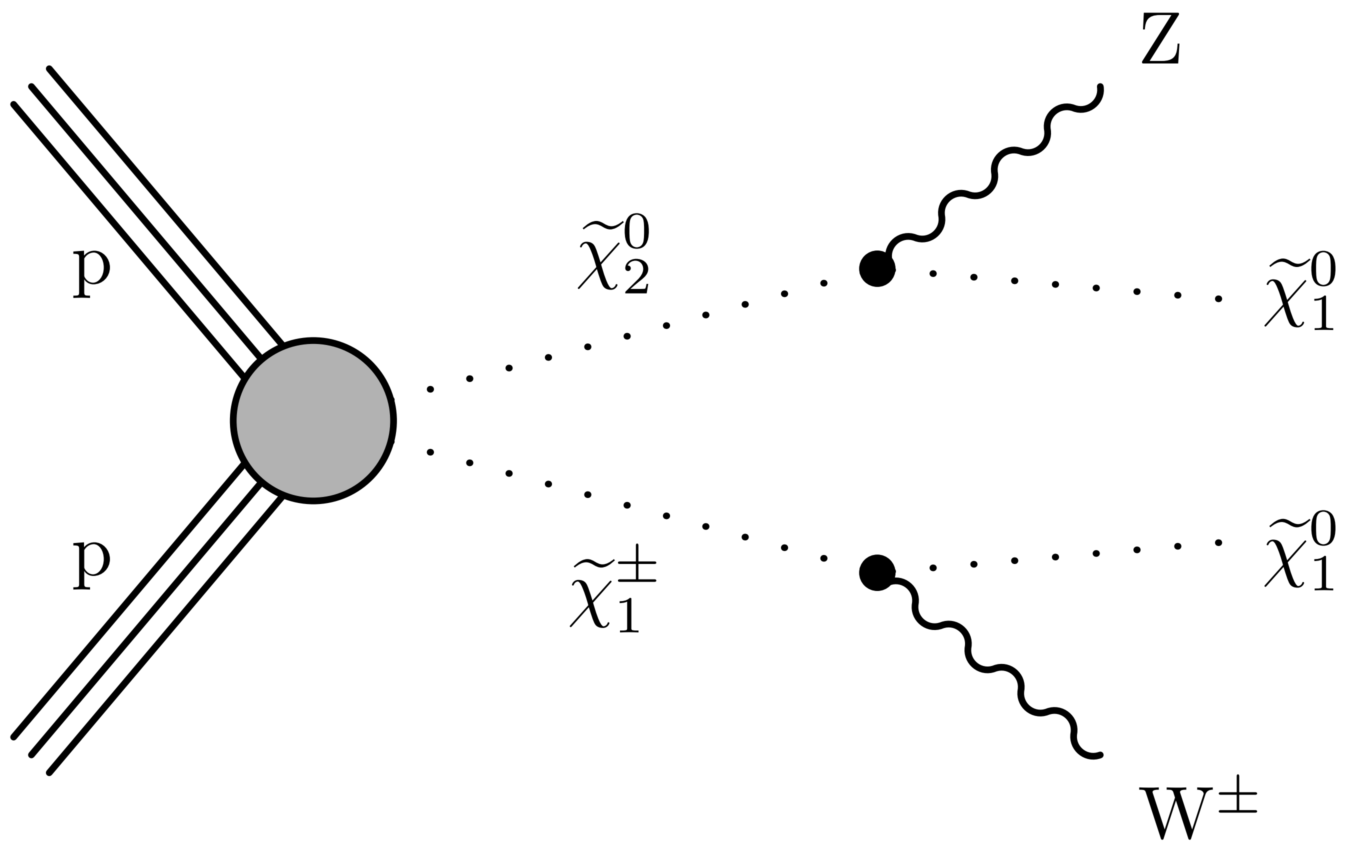
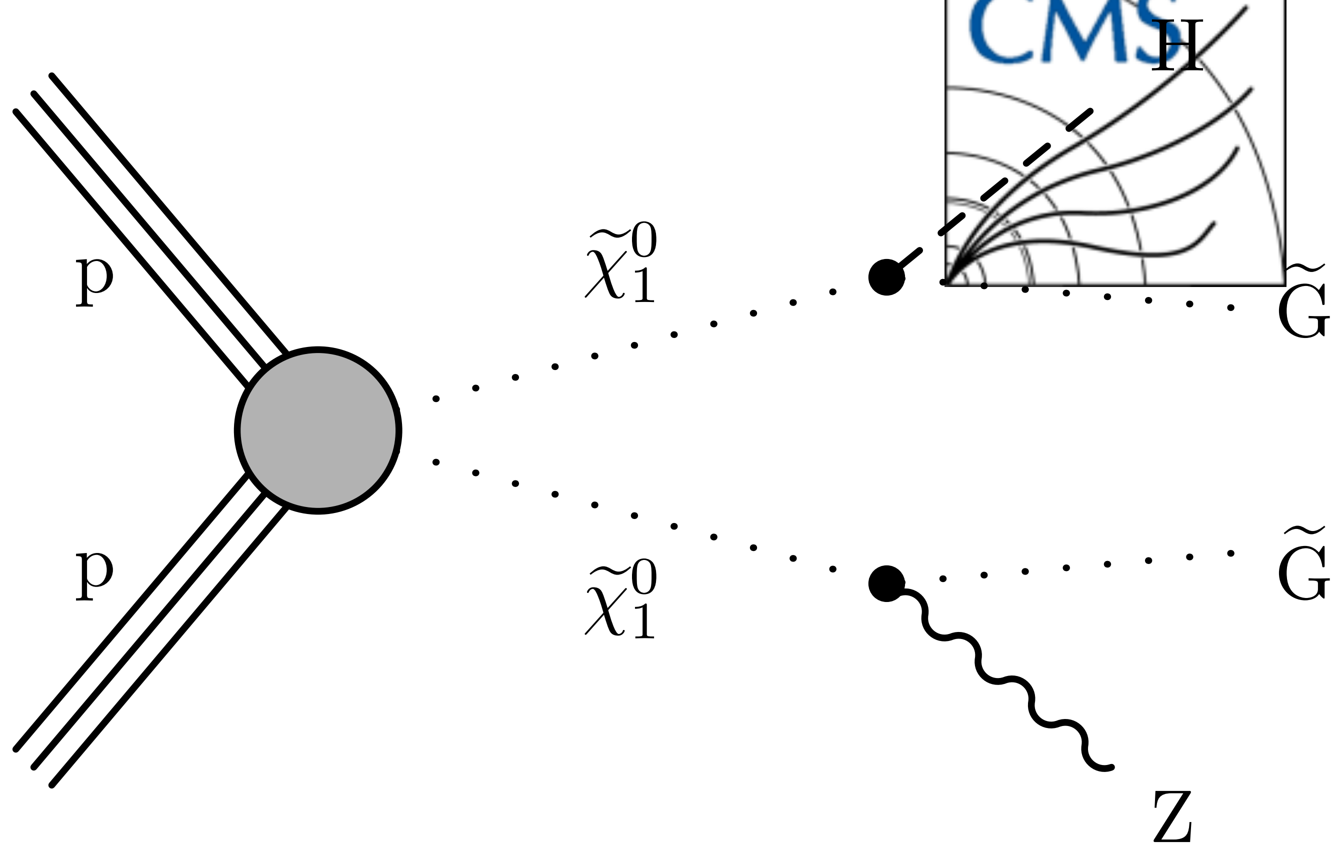
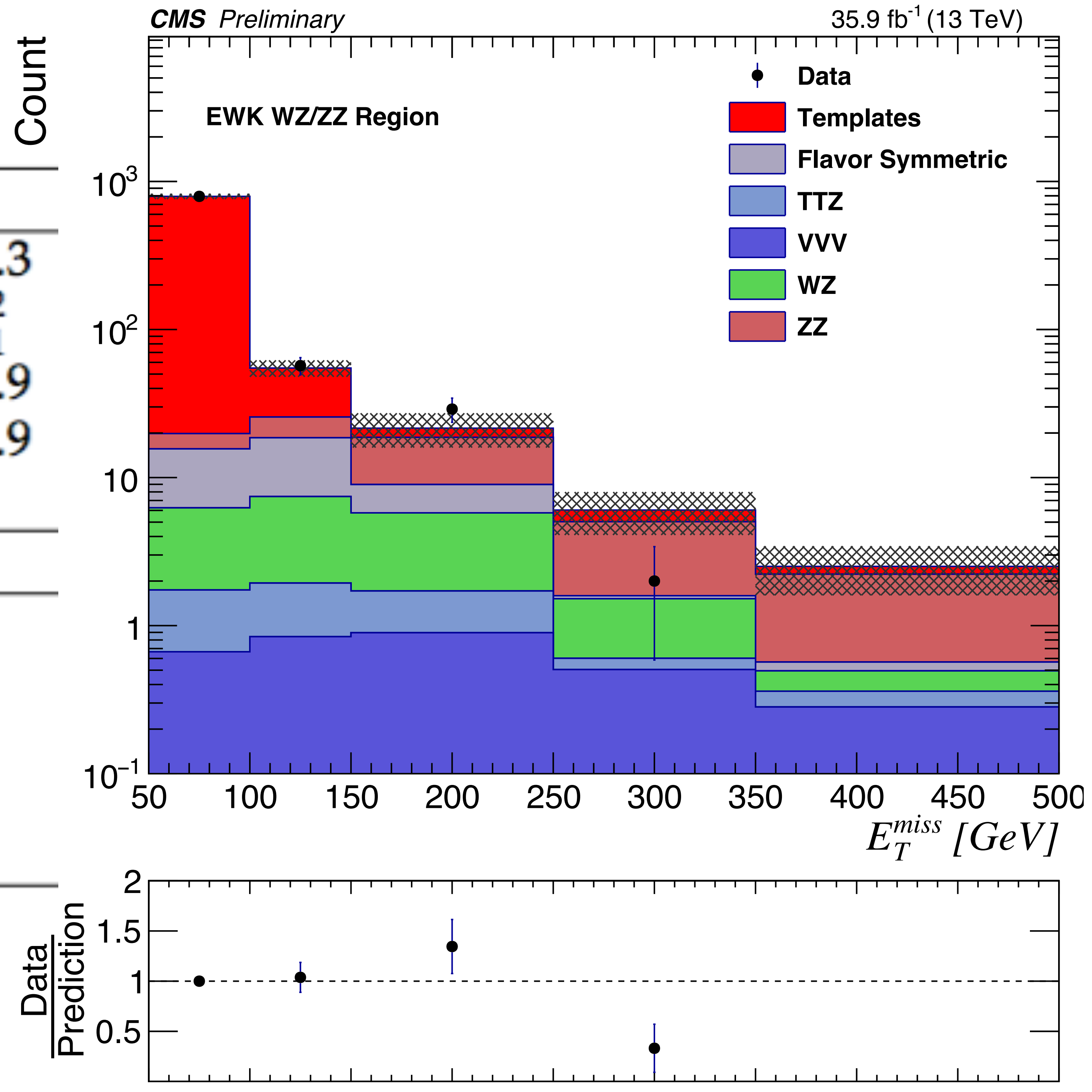
On-Z EWK results

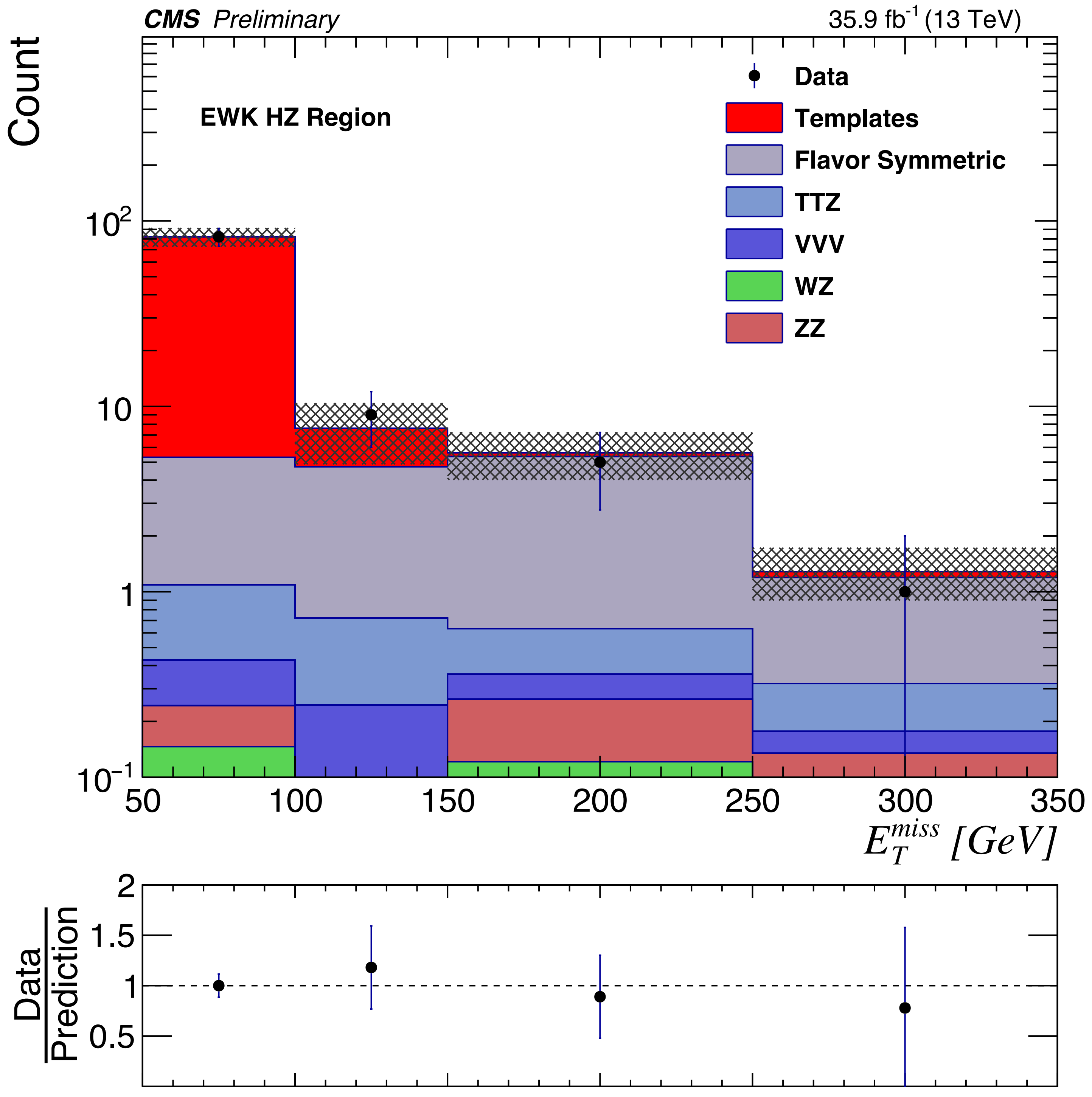
- first EMT bin used for normalization
- over prediction in high MET bins in EWK ZZ/WZ region
- causing better observed limits than expected

VZ	p_T^{miss} [GeV]	100–150	150–250	250–350	> 350
	DY+jets	29.3±4.4	2.9±2.0	1.0±0.7	0.3±0.3
	FS	11.1±3.6	3.2±1.1	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$
	Z+ν	14.5±4.0	15.5±5.1	5.0±1.8	2.2±0.9
	Total background	54.9±7.0	21.6±5.6	6.0±1.9	2.5±0.9
	Data	57	29	2	0
HZ	p_T^{miss} [GeV]	100–150	150–250	> 250	
	DY+jets	2.9±2.4	0.3±0.2	0.1±0.1	
	FS	4.0±1.4	4.7±1.6	0.9±0.4	
	Z+ν	0.7±0.2	0.6±0.2	0.3±0.1	
	Total background	7.6±2.8	5.6±1.6	1.3±0.4	
	Data	9	5	1	



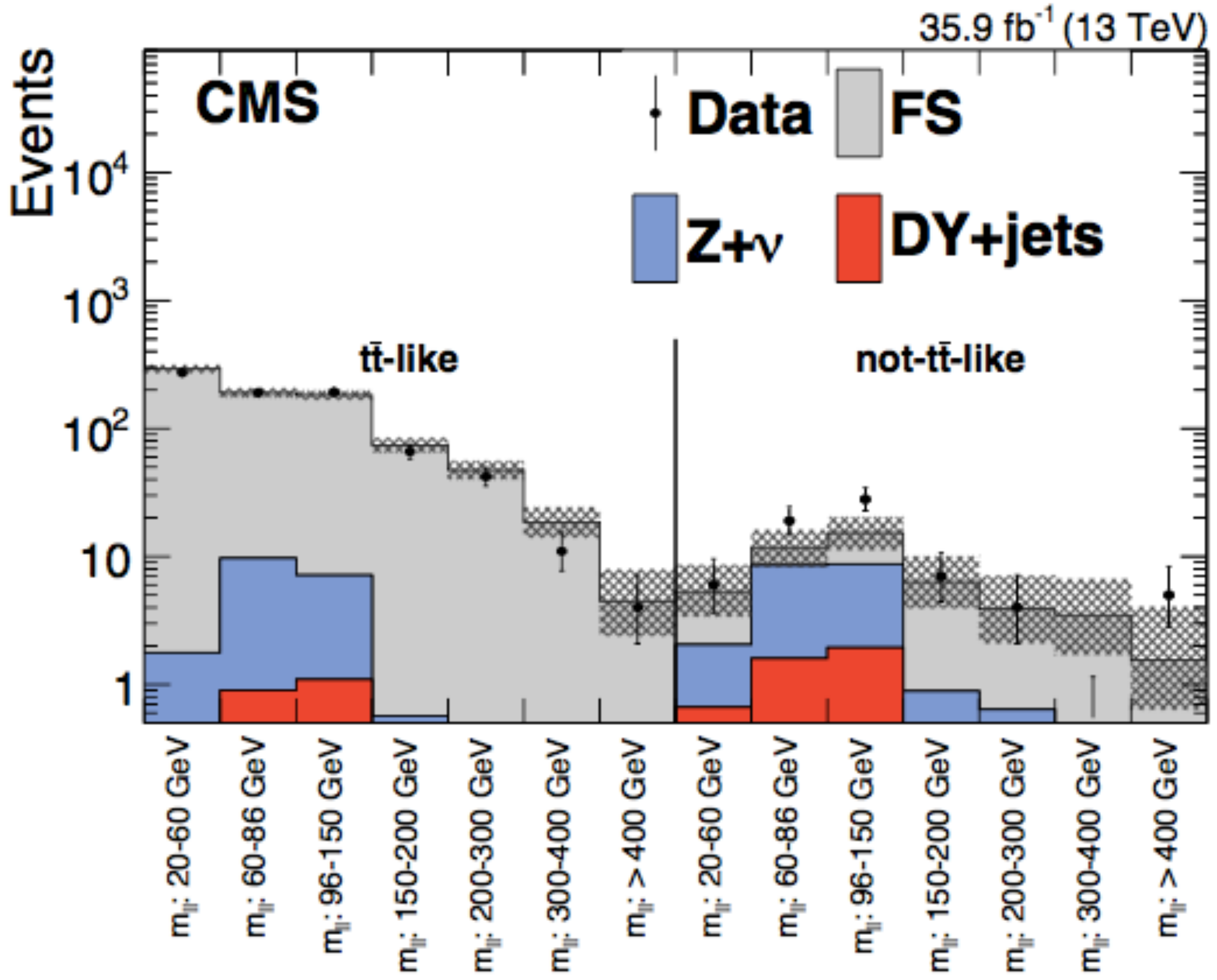






Edge results

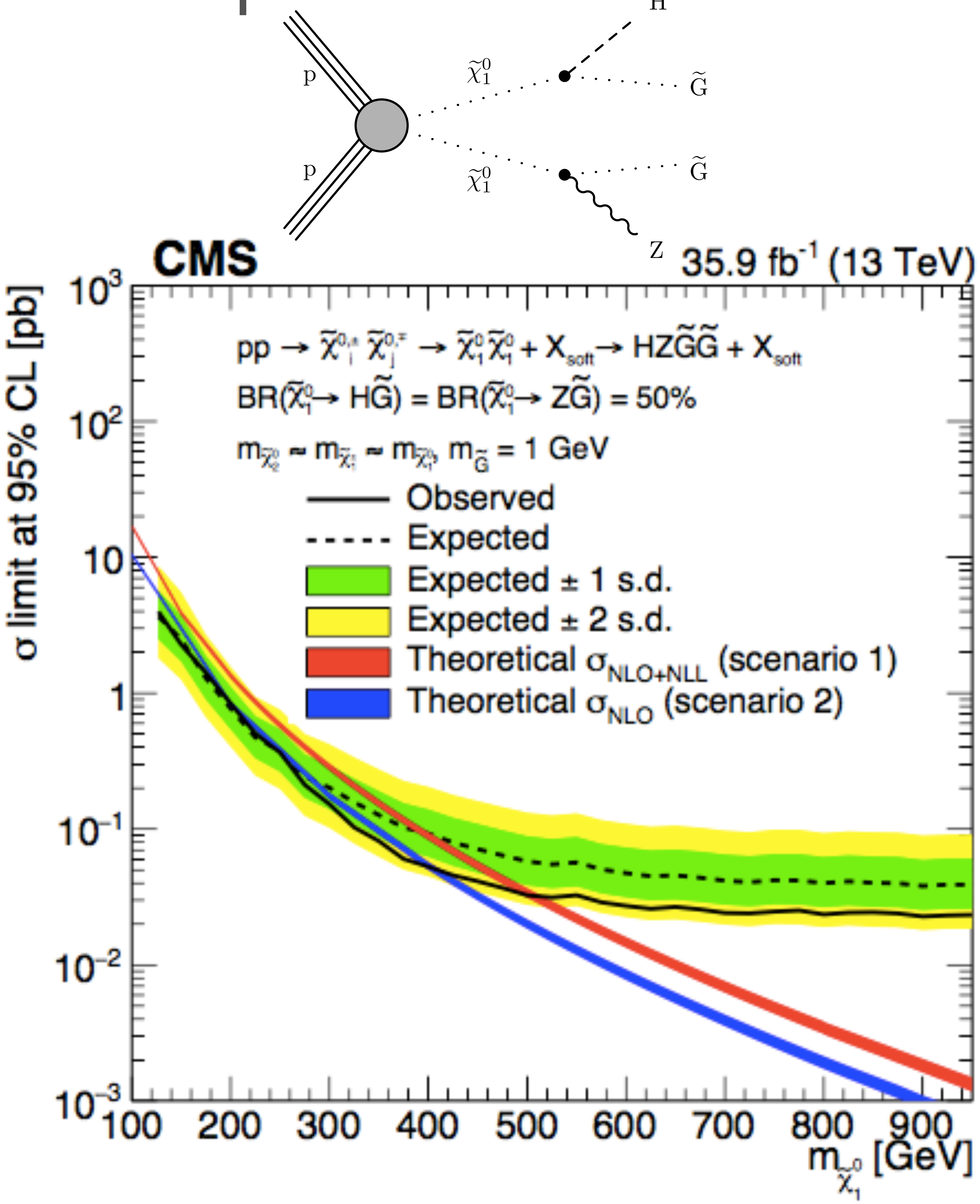
- first EMT bin used for normalization
- over prediction in high MET bins in EWK WZ region
- causing better observed limits than expe

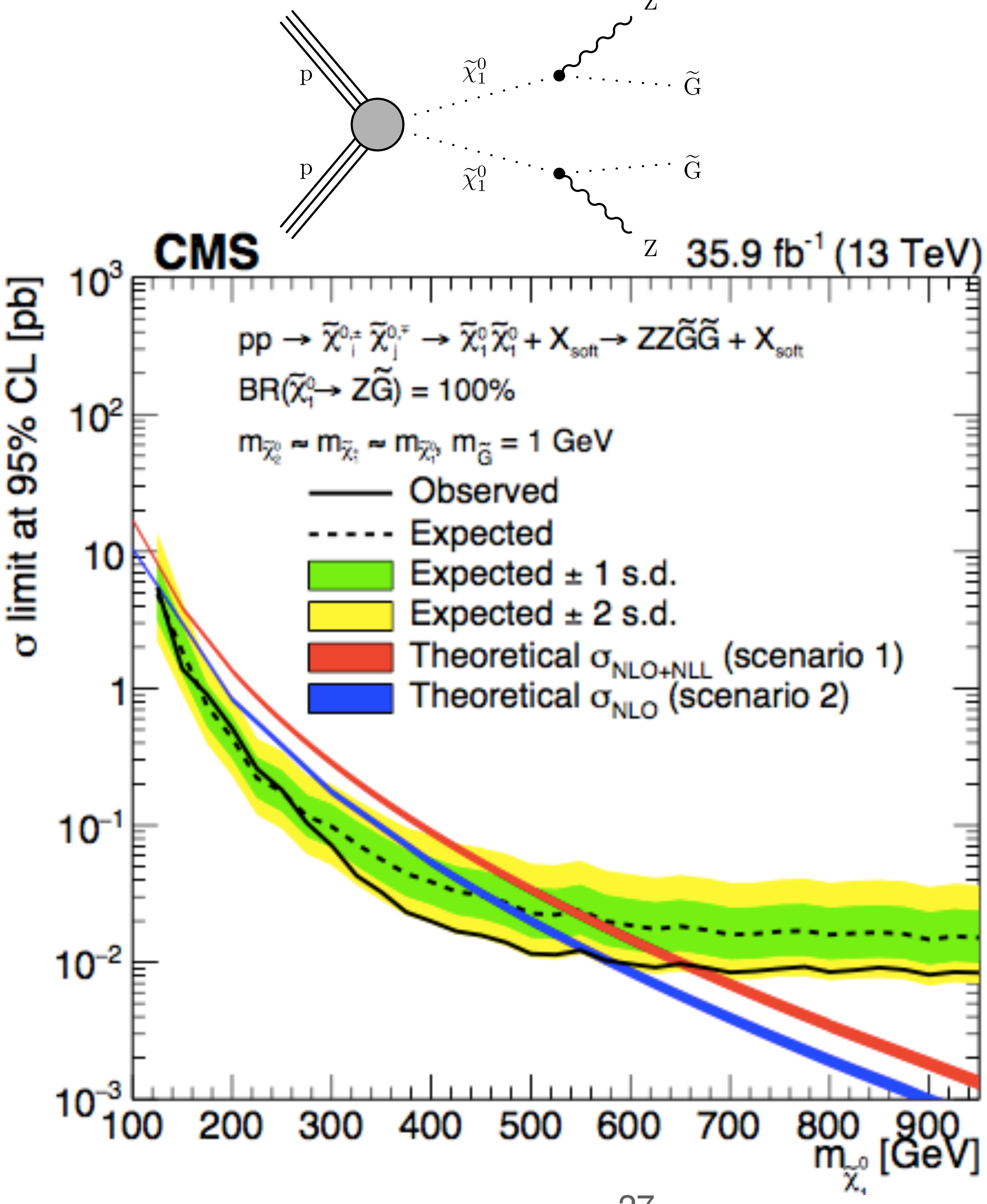


$m_{\ell\ell}$ range [GeV]	FS	DY+jets	Z+ν	Total background	Data
tt̄-like					
20–60	291^{+21}_{-20}	0.4±0.3	1.4±0.5	293^{+21}_{-20}	273
60–86	181^{+16}_{-15}	0.9±0.7	8.8±3.4	190^{+16}_{-15}	190
96–150	176^{+15}_{-14}	1.1±0.9	6.0±2.4	182^{+16}_{-15}	192
150–200	73^{+10}_{-9}	0.1±0.1	0.4±0.2	74^{+10}_{-9}	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

Results and interpretation: On-Z electroweak search

- In electroweak neutralino-neutralino production, neutralino masses up to 500 – 650 GeV are excluded depending on the decay mode assumed





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:

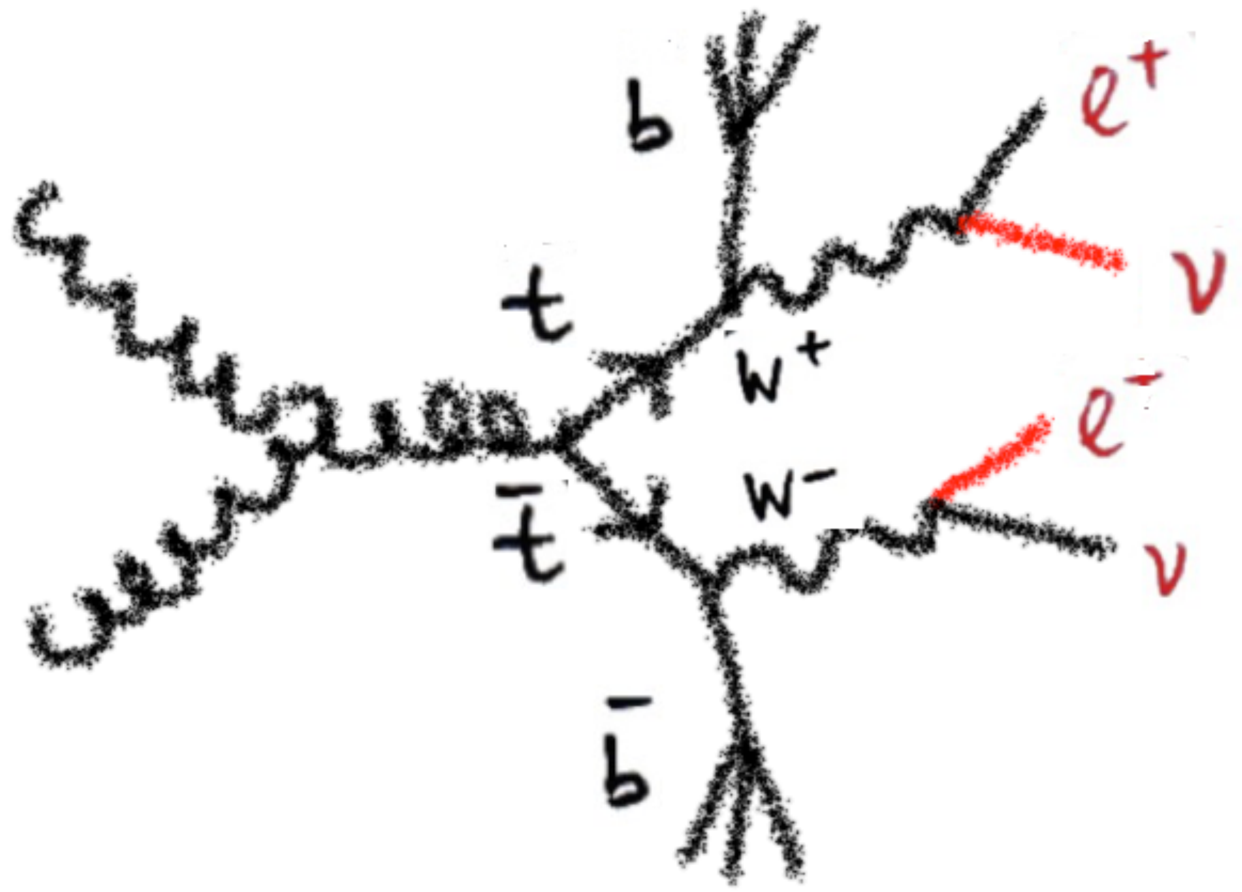
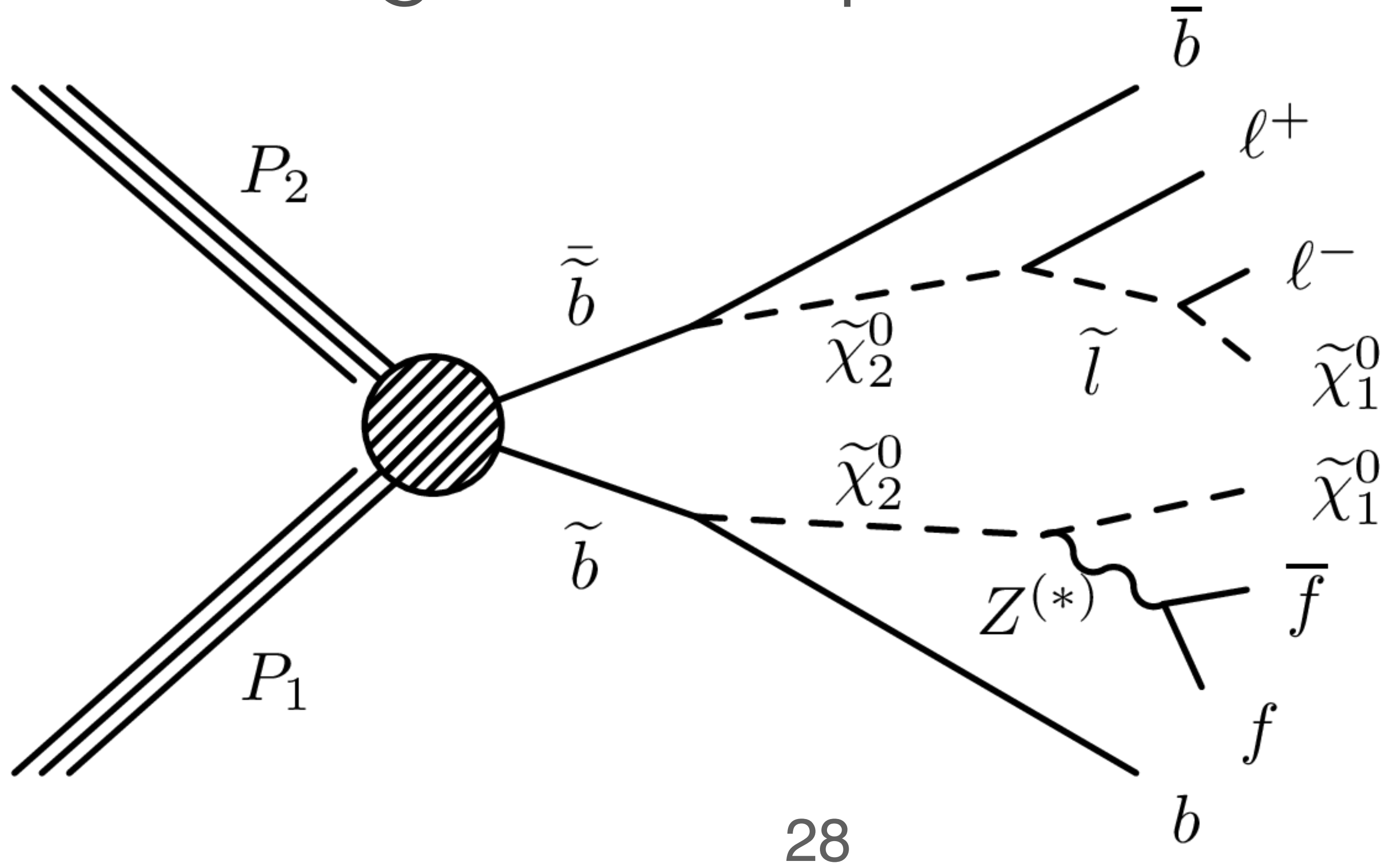
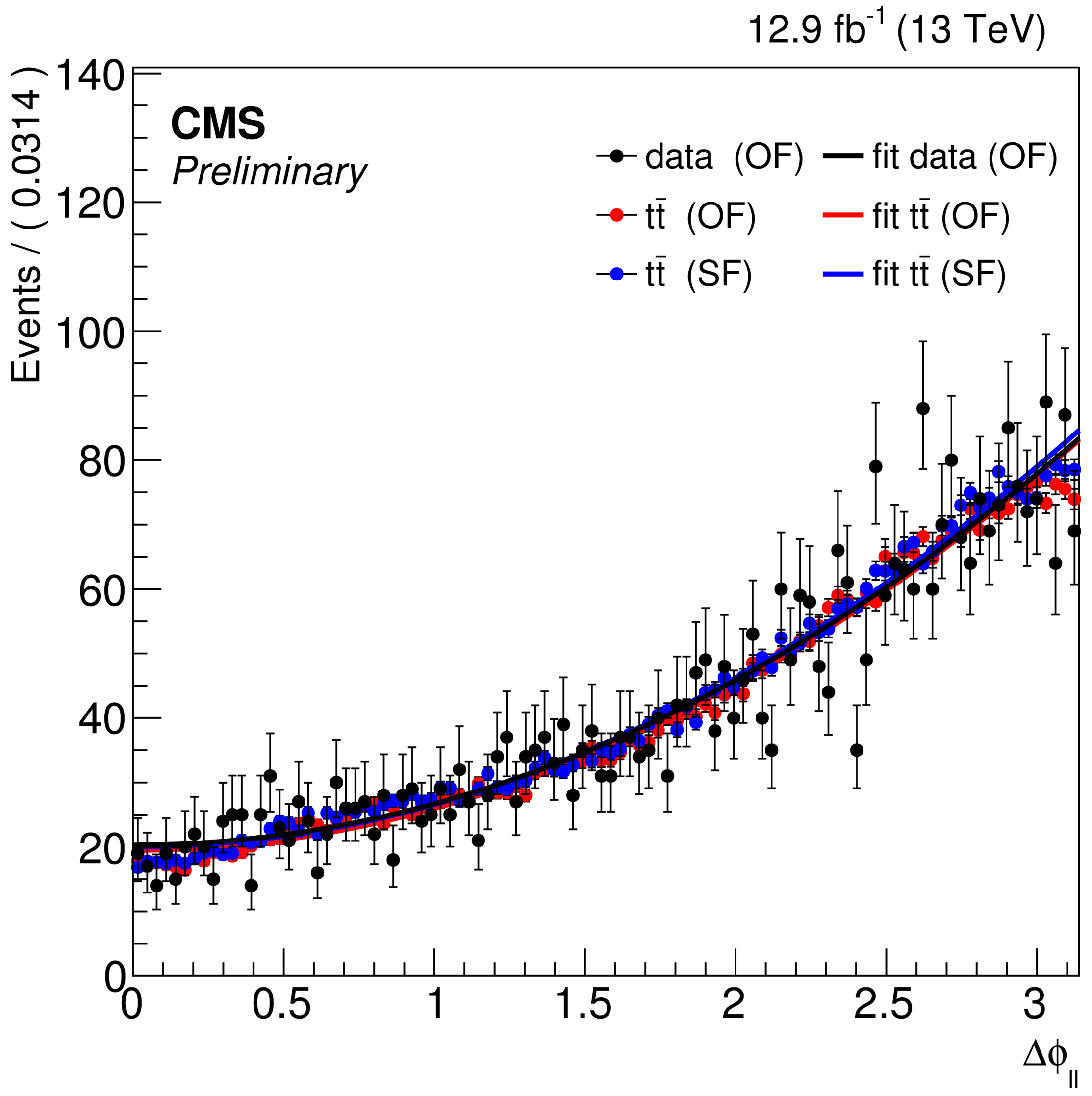


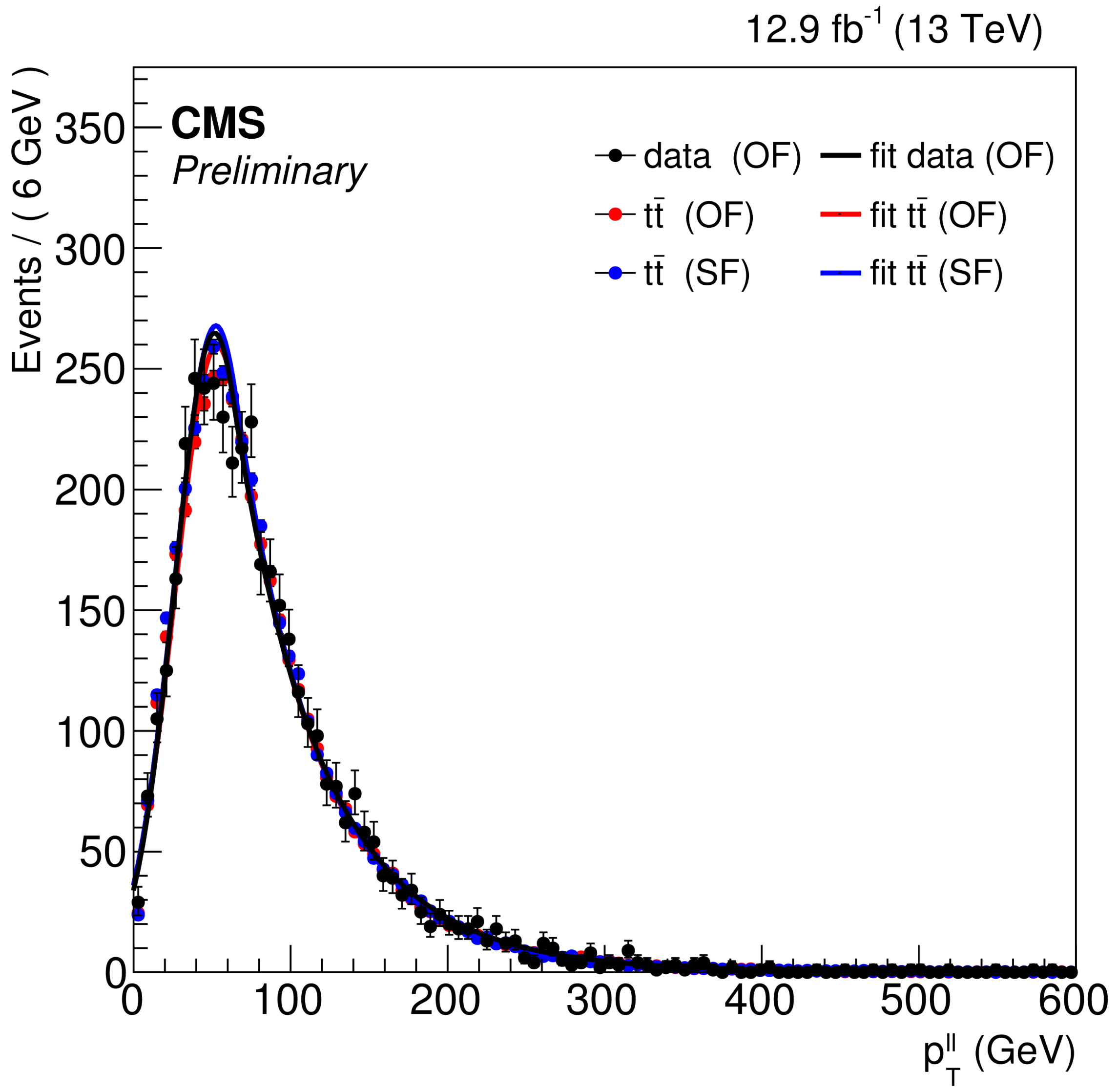
Diagram of a signal SUSY process:

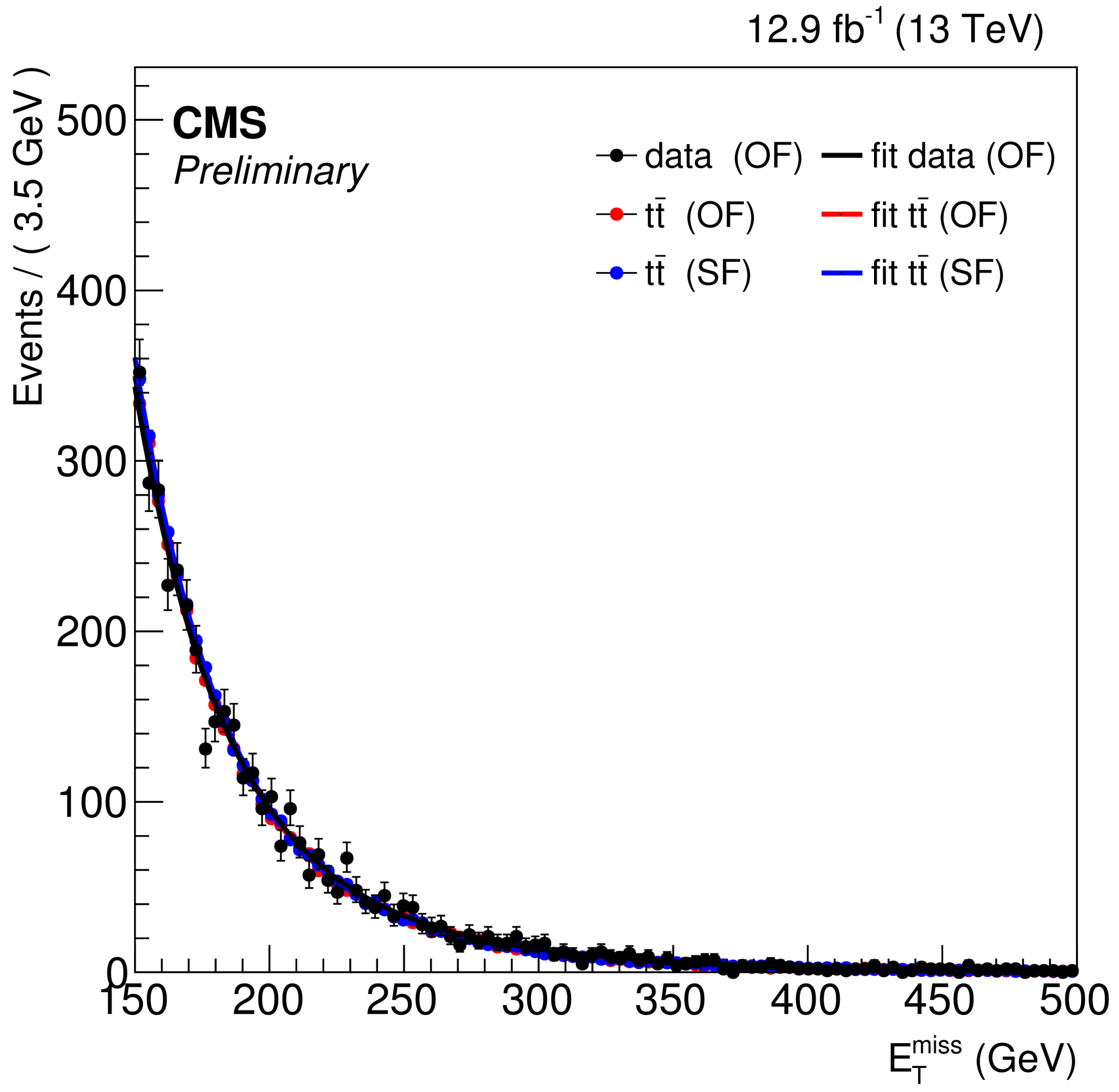


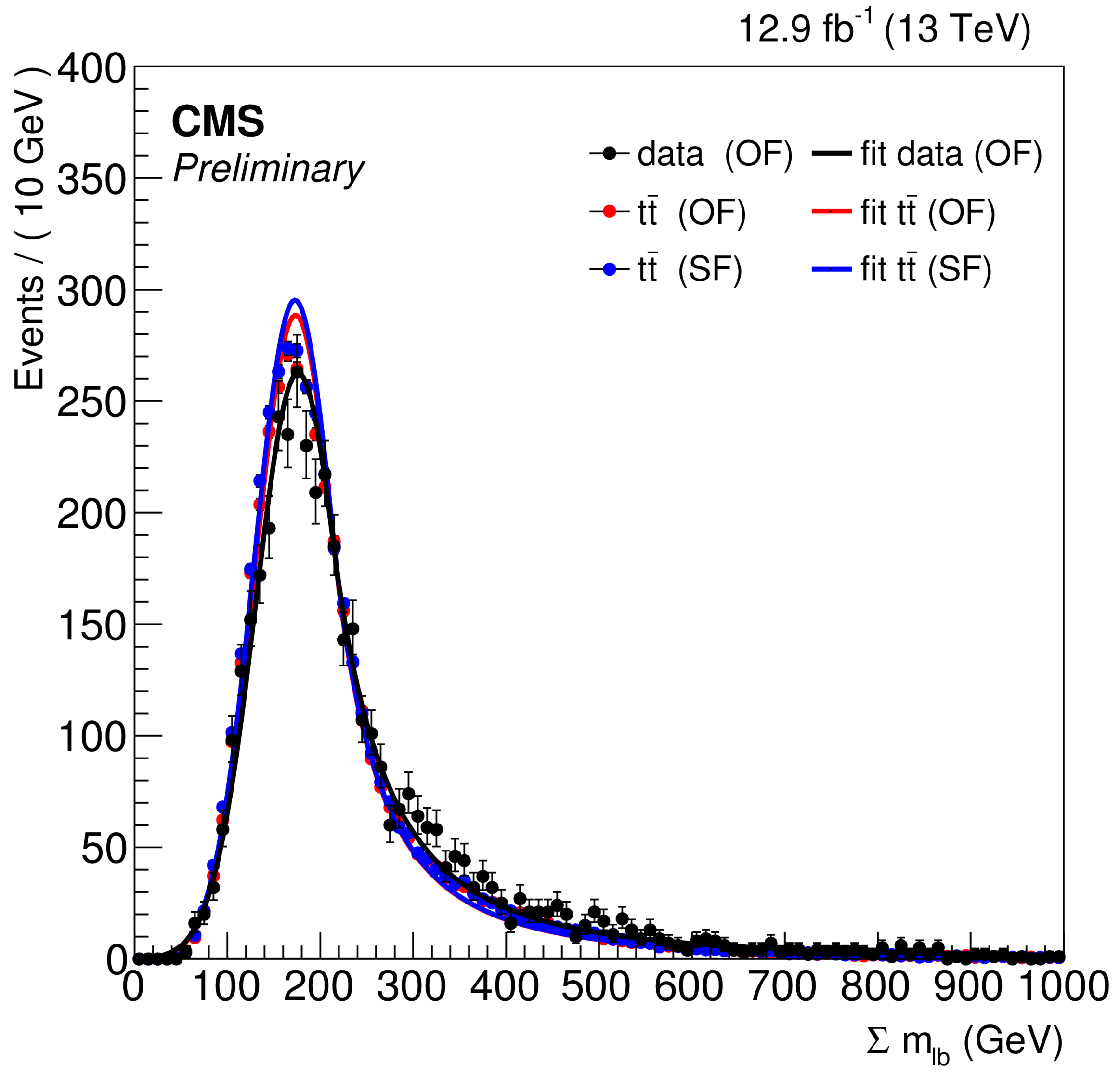
ttbar discriminant

- 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

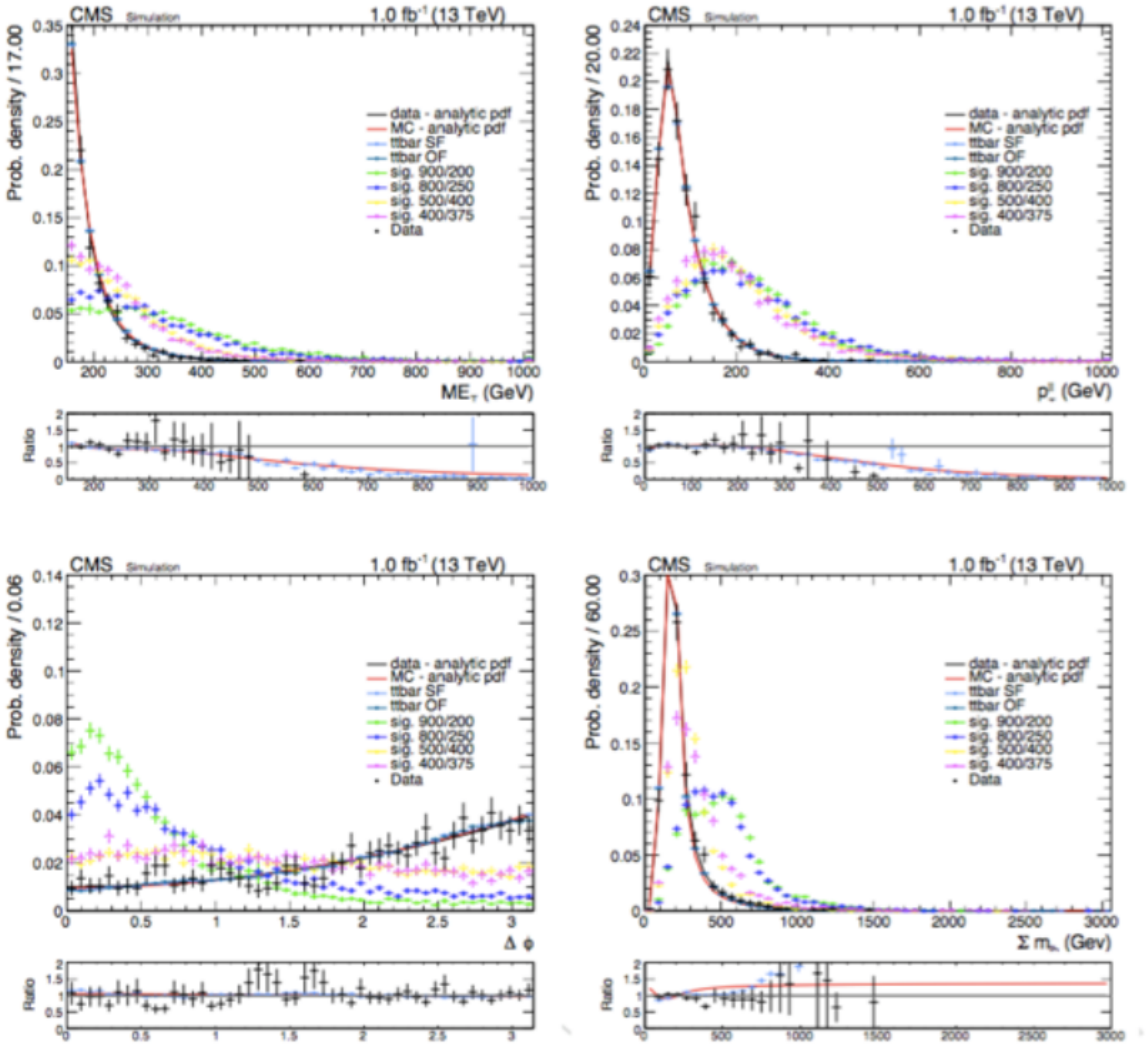


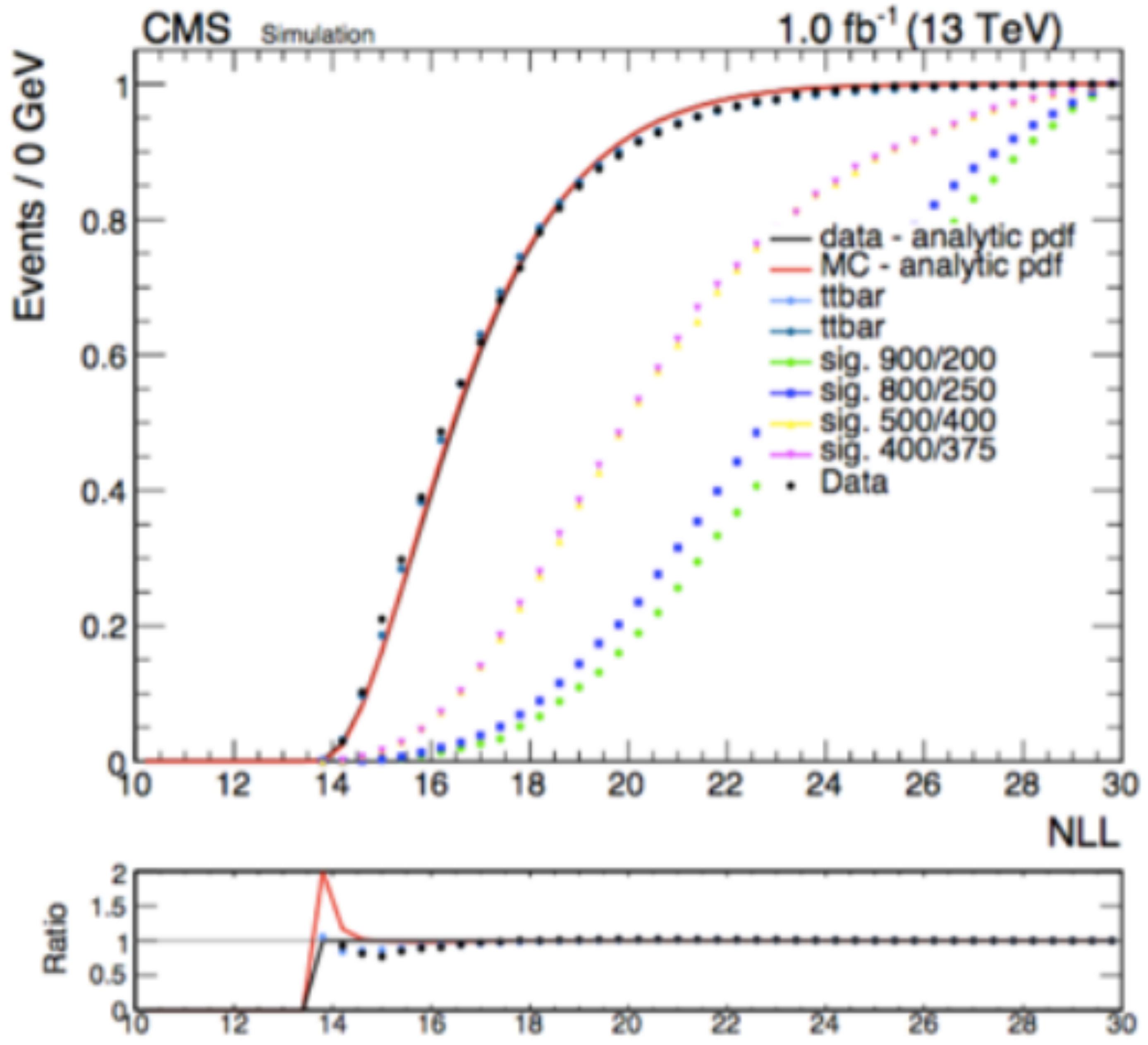






ttbar discriminant



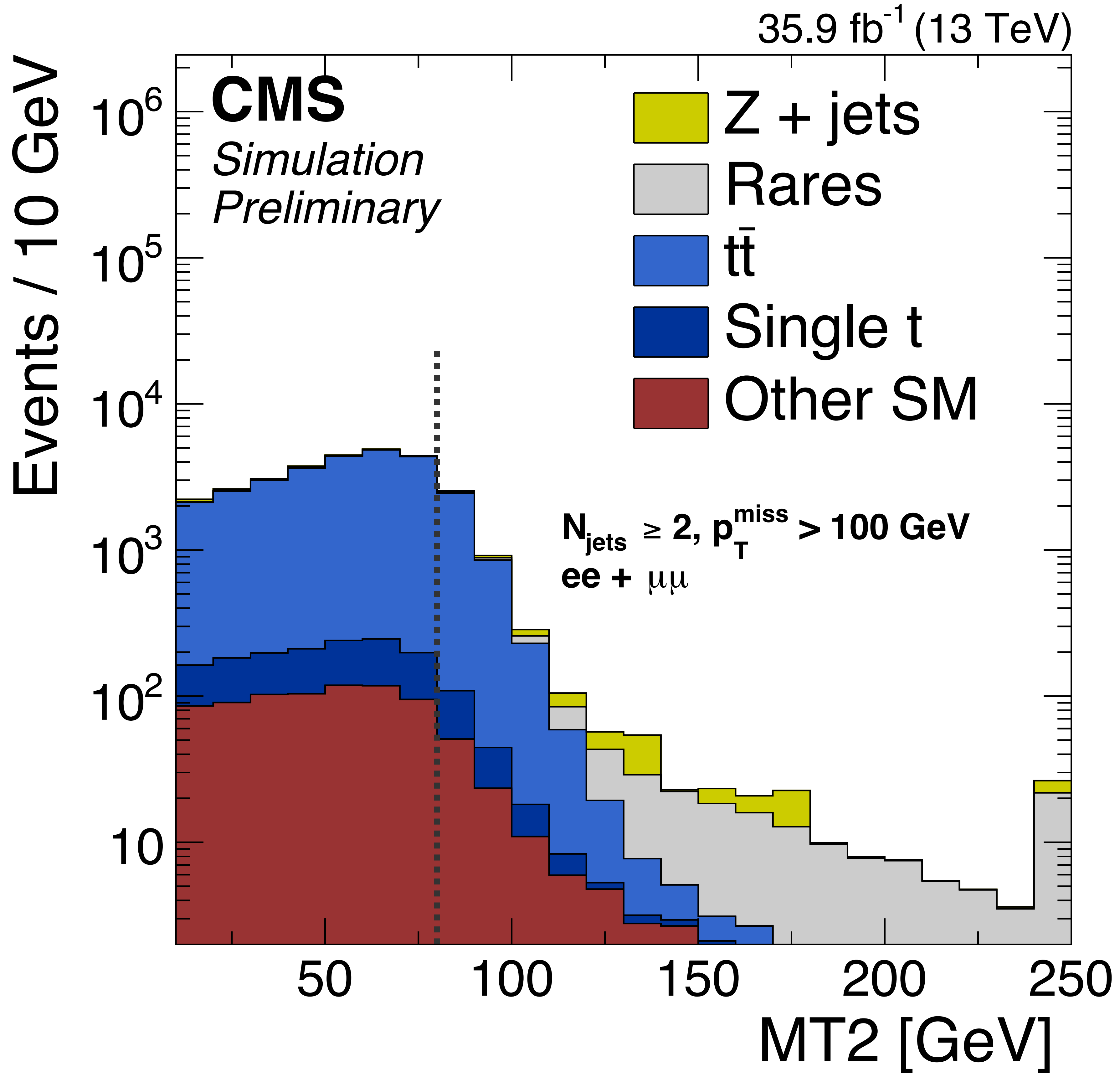


M_{T2}

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 $M_{T2} \rightarrow 0$ for multijet-like events

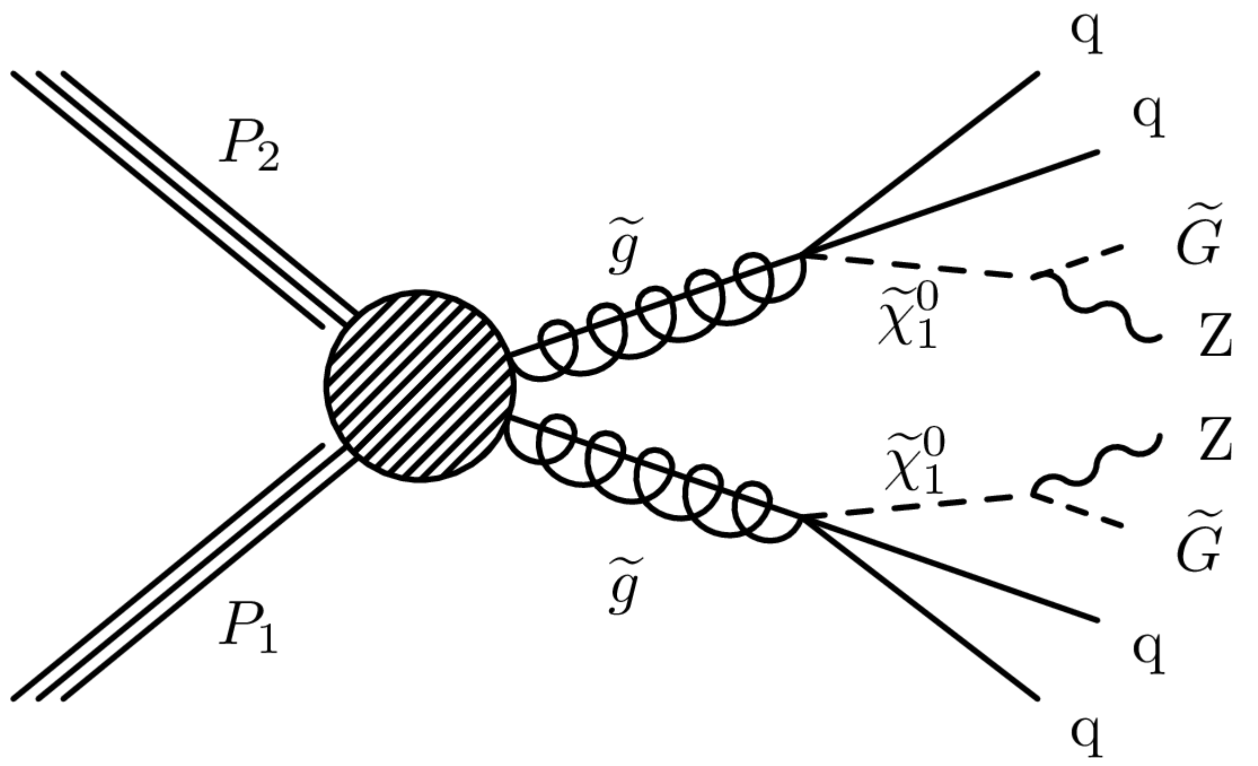
- If all masses are known, M_{T2} will have an endpoint at the parent mass (~M_T)
- Very efficient to reduce ttbar and other backgrounds



SUSY with opposite sign dileptons

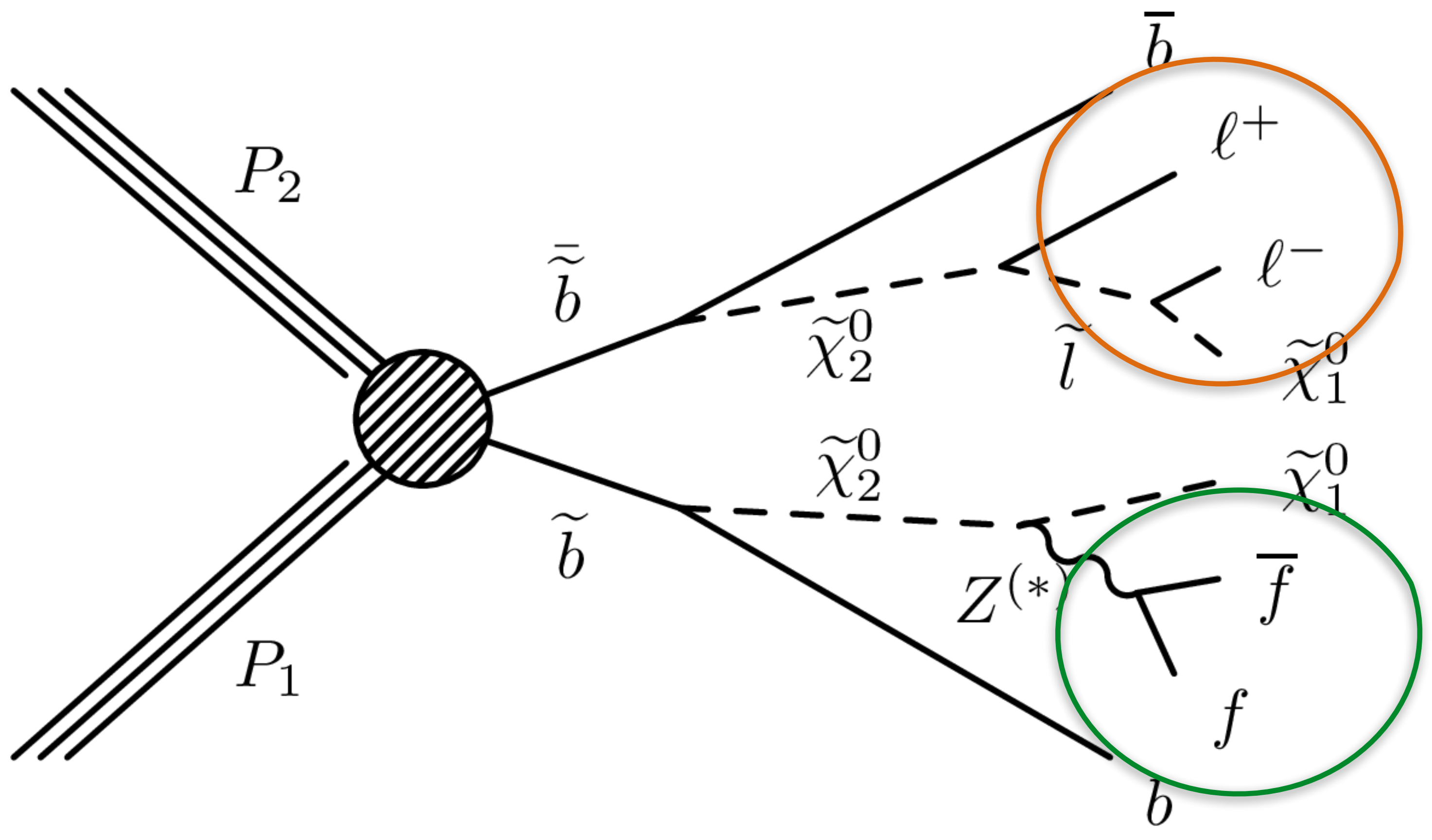
Final states with opposite sign dileptons can occur in both strongly or electroweakly produced SUSY decay chains involving W/Z bosons and/or sleptons

Our search targets two opposite sign same flavour leptons, jets and high missing transverse momentum, E_T^{miss}



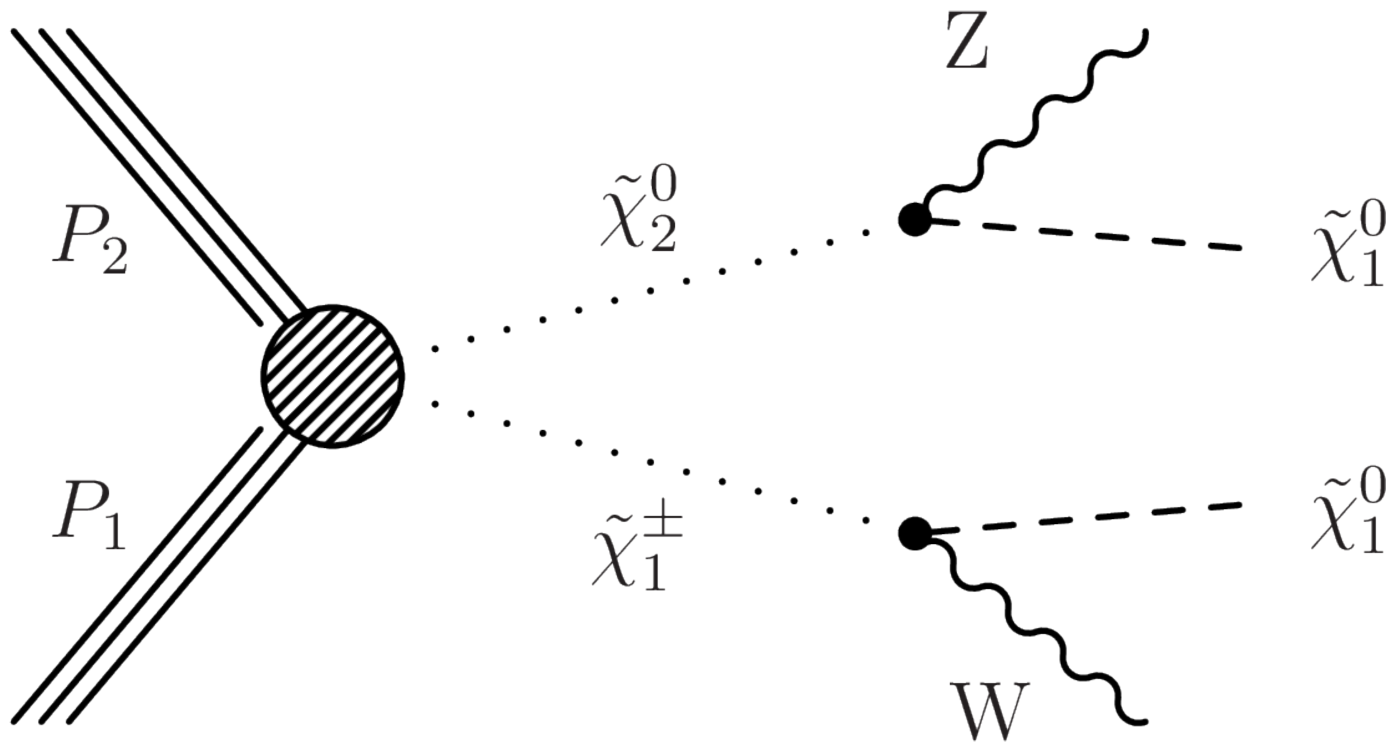
GMSB (gluino induced):

- some jets
- large E_T^{miss}
- two leptons originating from an on-shell Z boson



Slepton (sbottom induced):

- some jets
- large E_T^{miss}
- either a cascade decay of a Neutralino and a slepton resulting in two opposite sign leptons, kinematic edge in m_{ll}
- or an off-shell Z boson giving two opposite sign leptons



EWK (Chargino/Neutralino induced):

- some jets
- large E_T^{miss}
- 2 leptons from the Z boson

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