Search for Supersymmetry with opposite sign dileptons with the CMS detector

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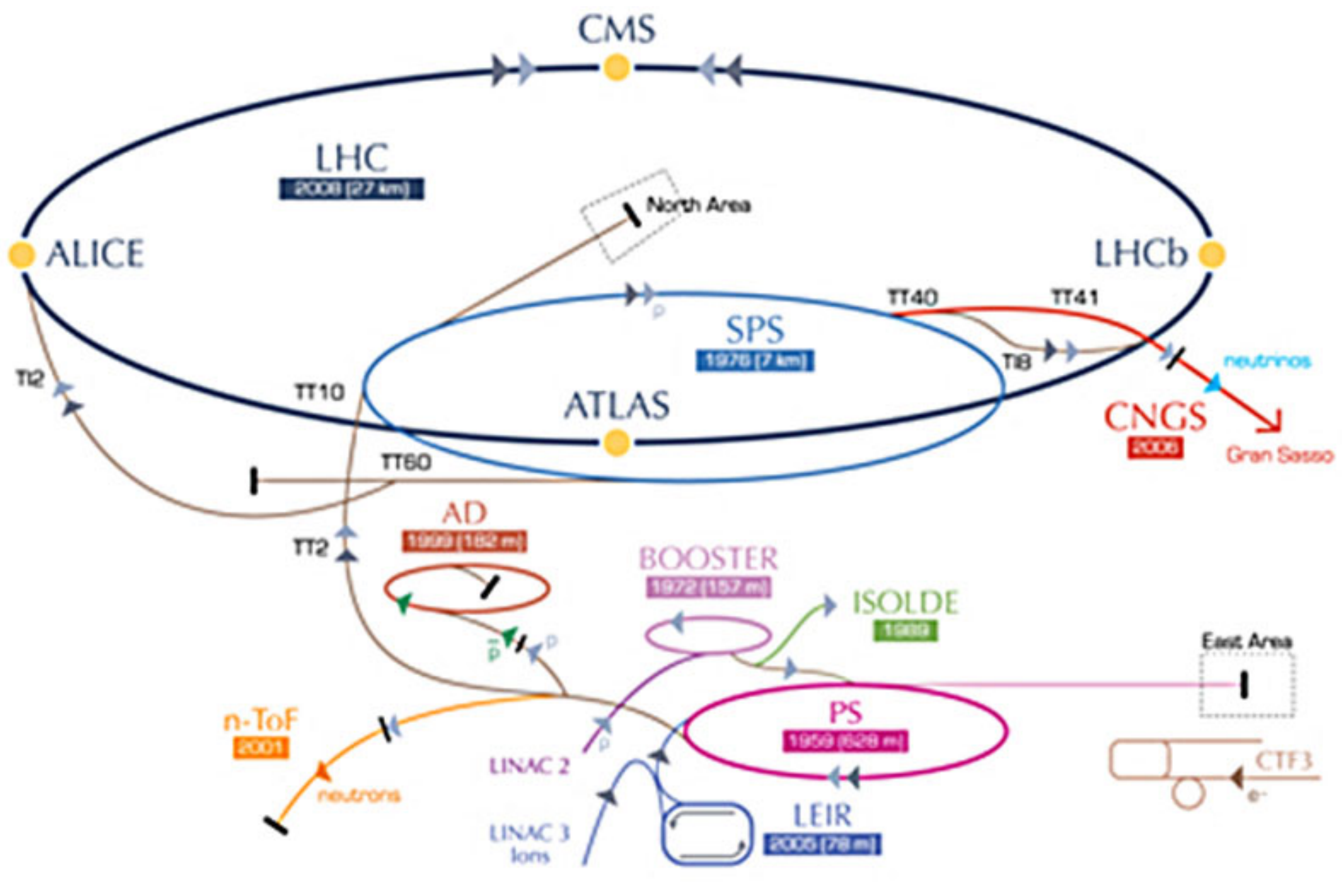
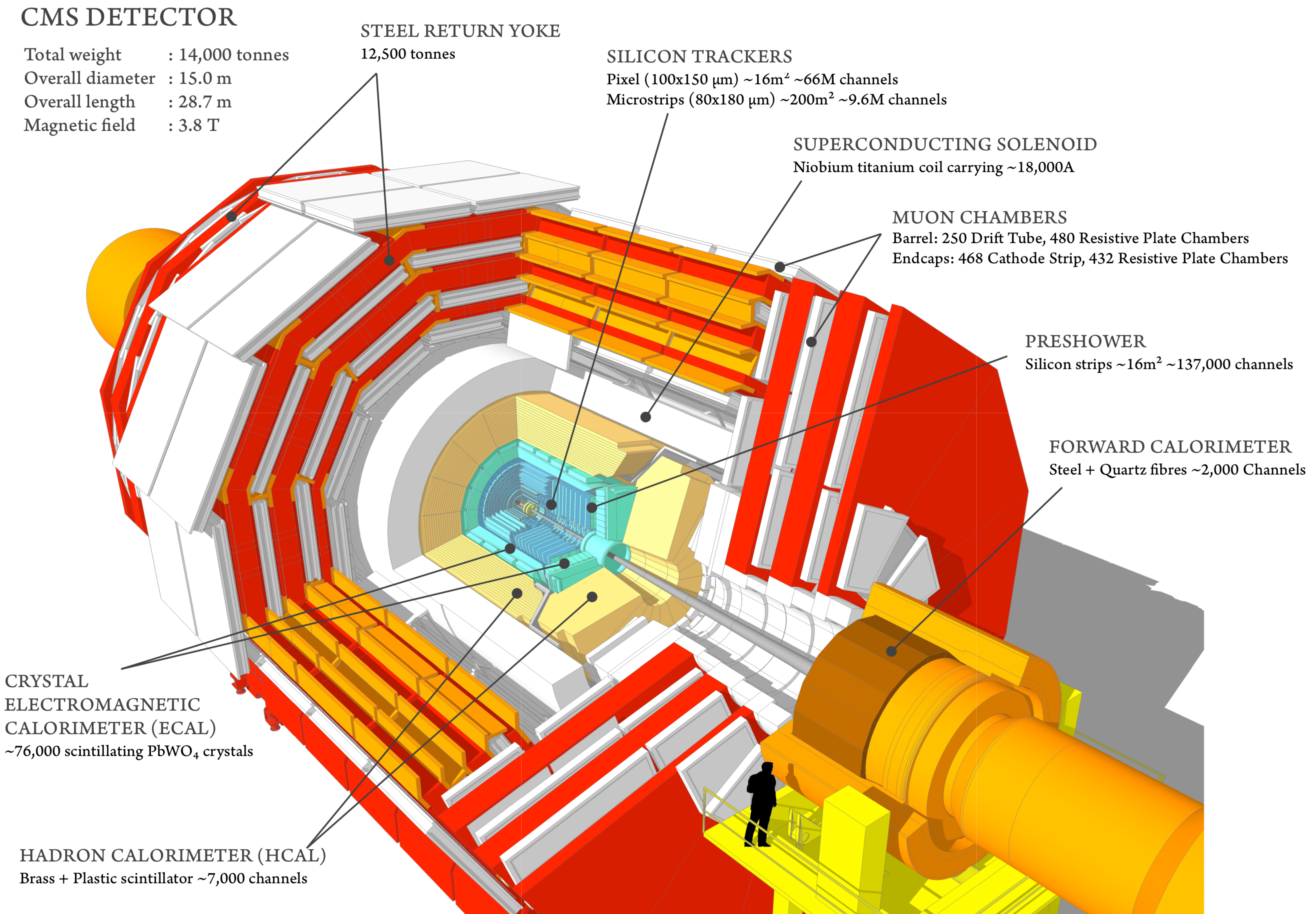
The Large Hadron Collider and CMS



CERN Accelerator Complex and the LHC



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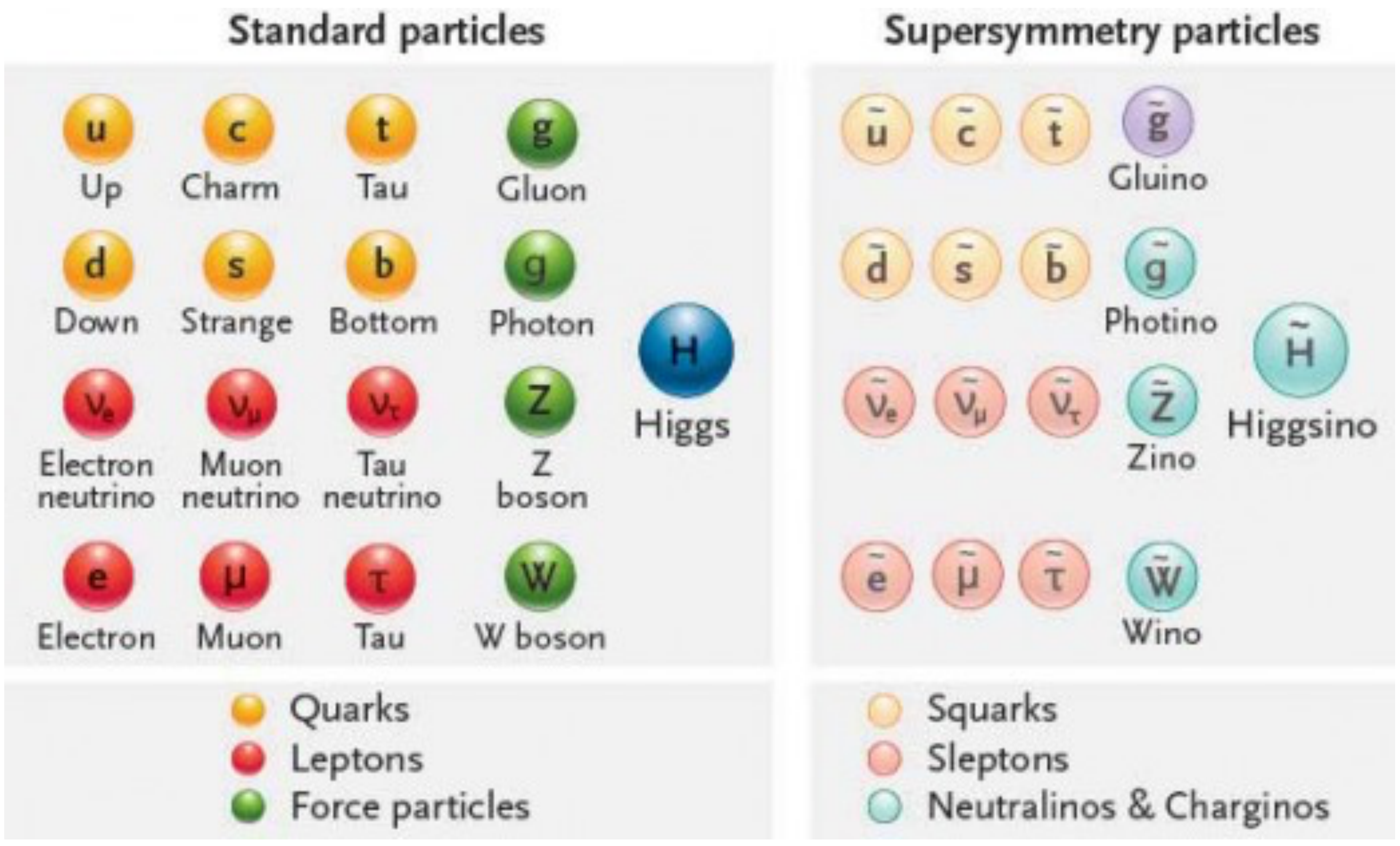
Supersymmetry

New fundamental, broken, symmetry

- provides super partners to standard model (SM) particles
- assigns a new fermion (boson) to every SM boson (fermion)

Theoretically attractive, since it:

- stabilizes the mass hierarchy problem
- facilitates GUT
- provides dark matter candidate



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}**

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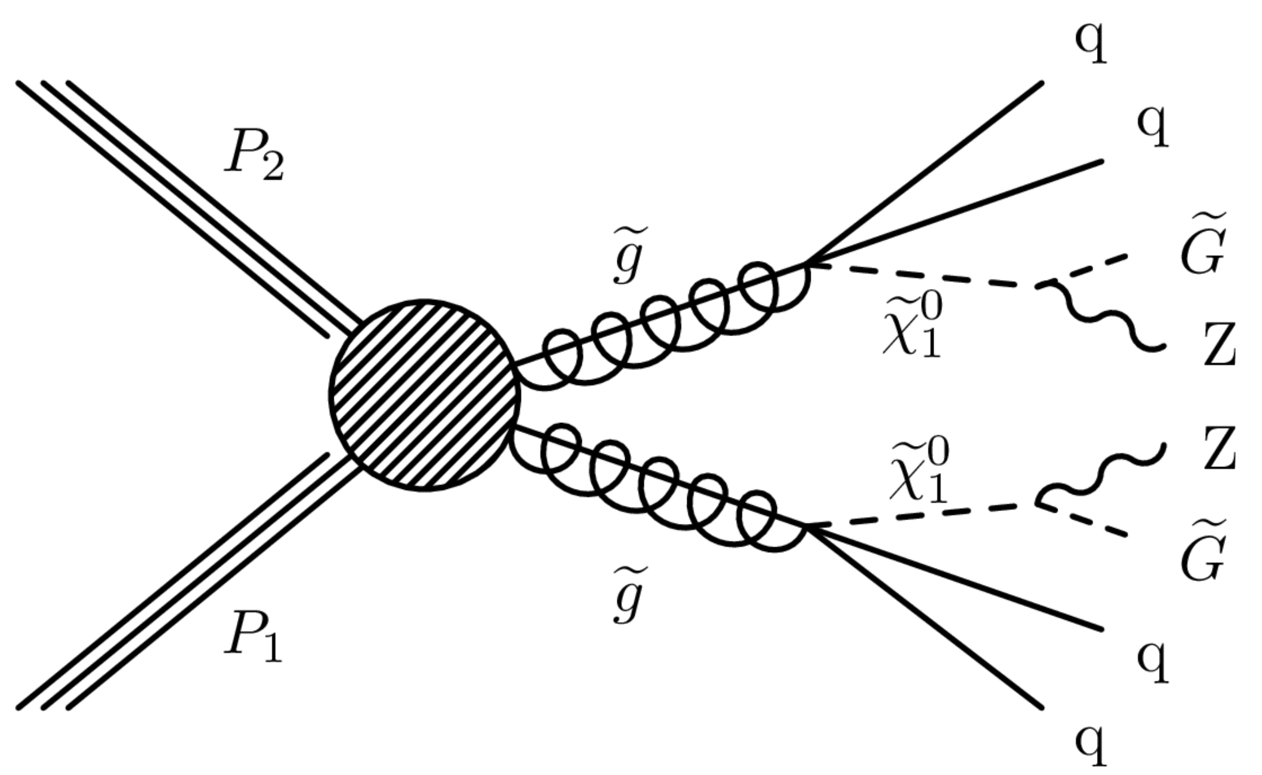
Our search targets two opposite sign same flavour leptons, jets and high missing transverse momentum, E_T^{miss}



GMSB (gluino induced):

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

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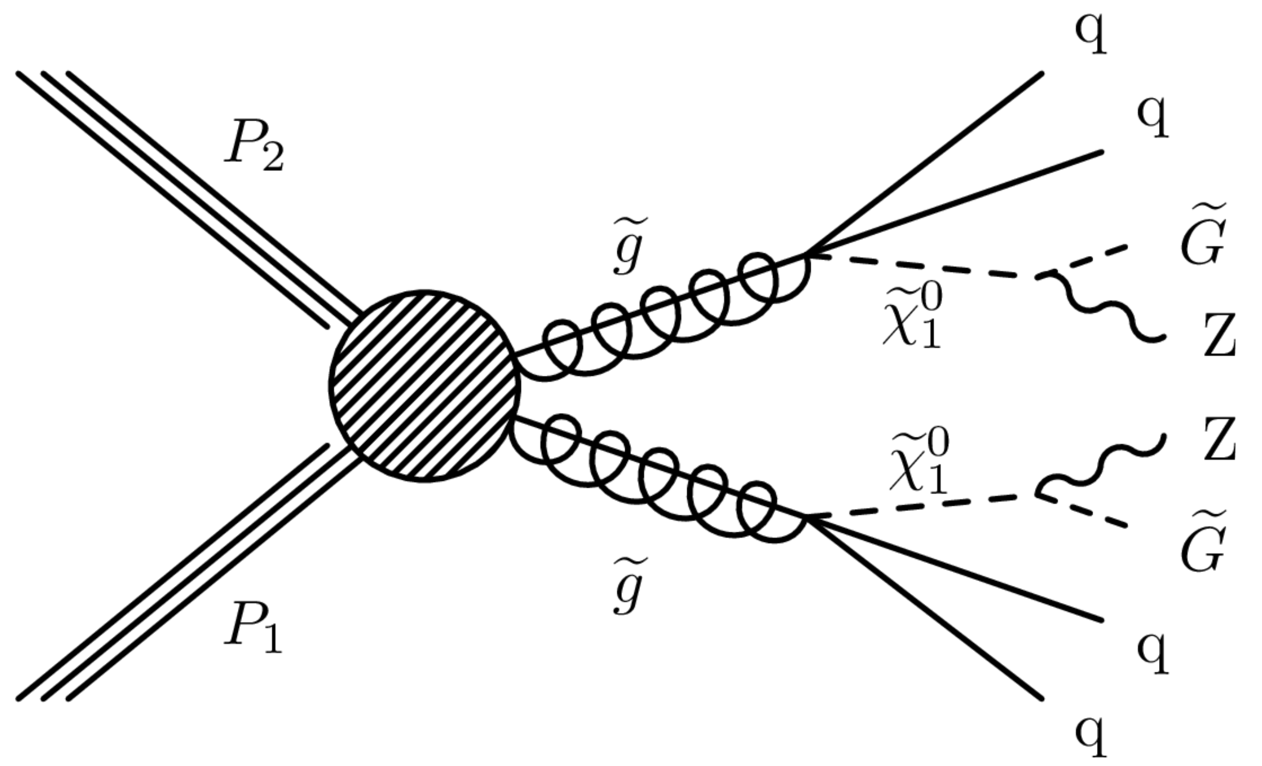

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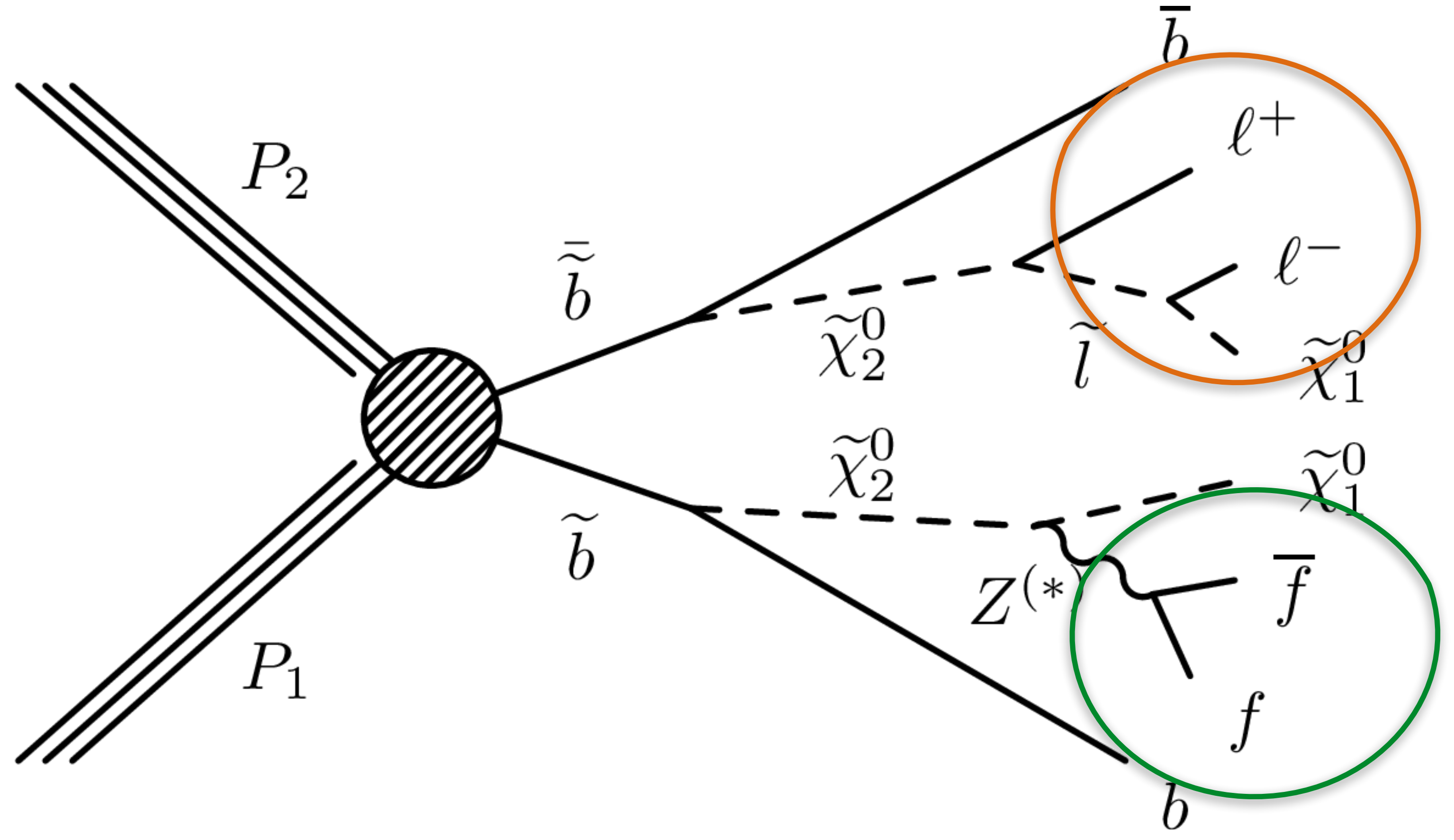

Slepton (sbottom induced):

- 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**

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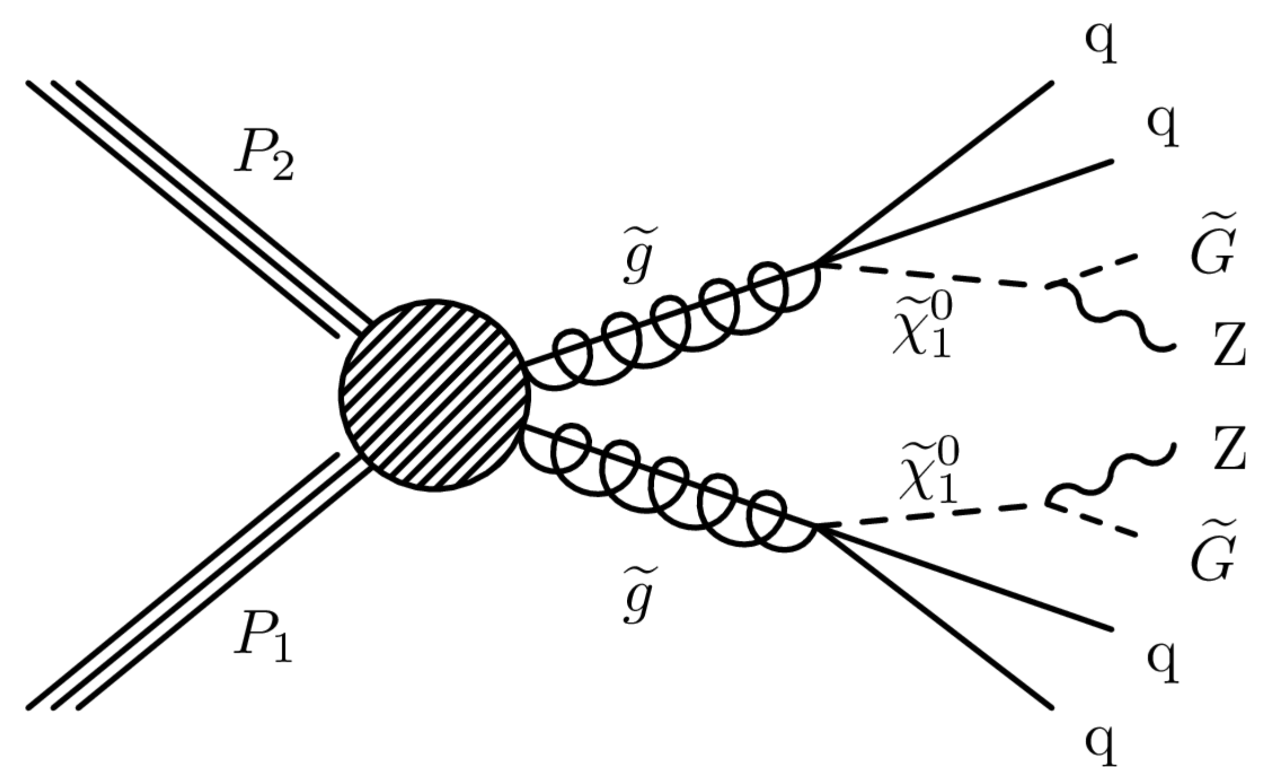

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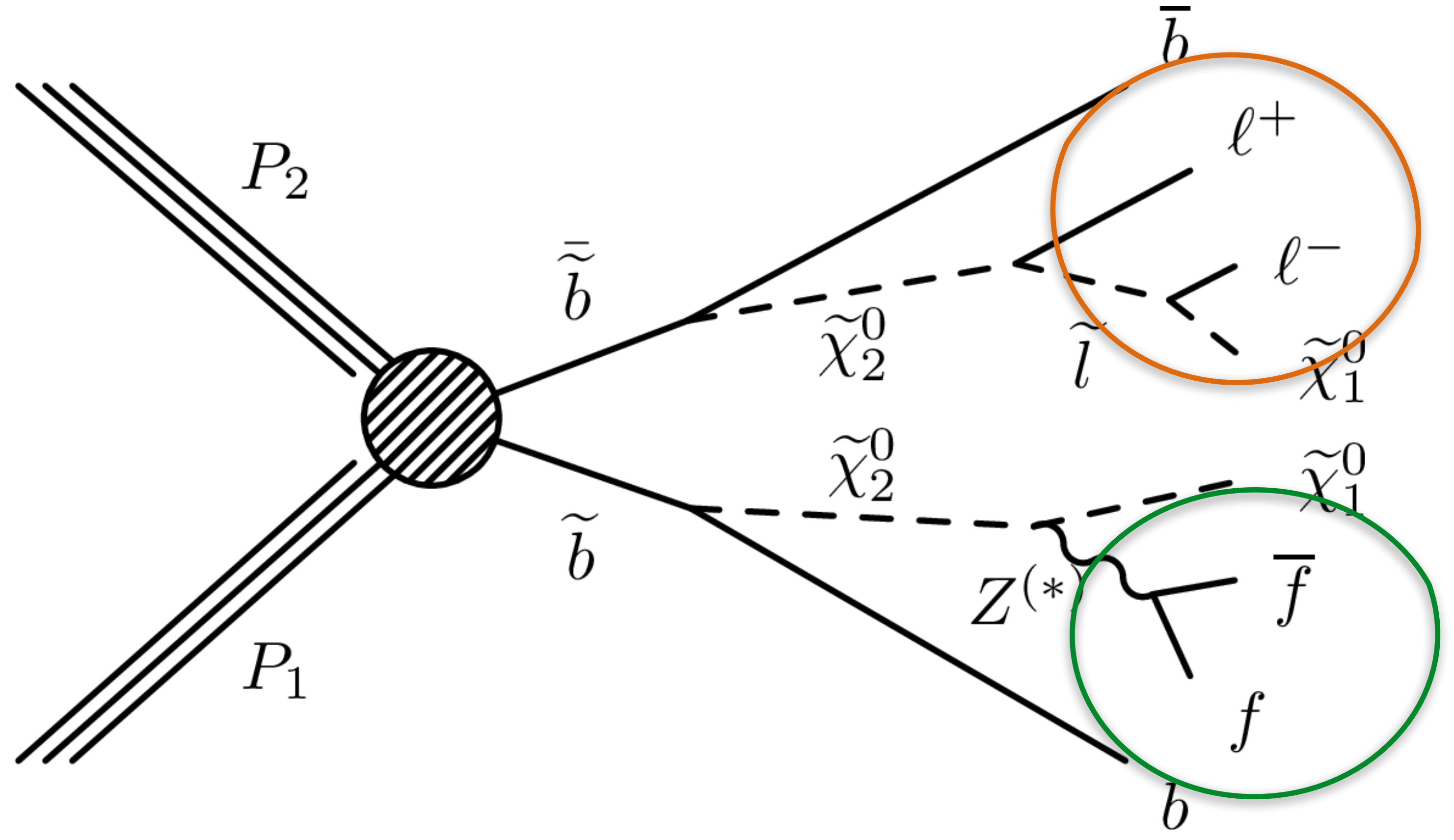

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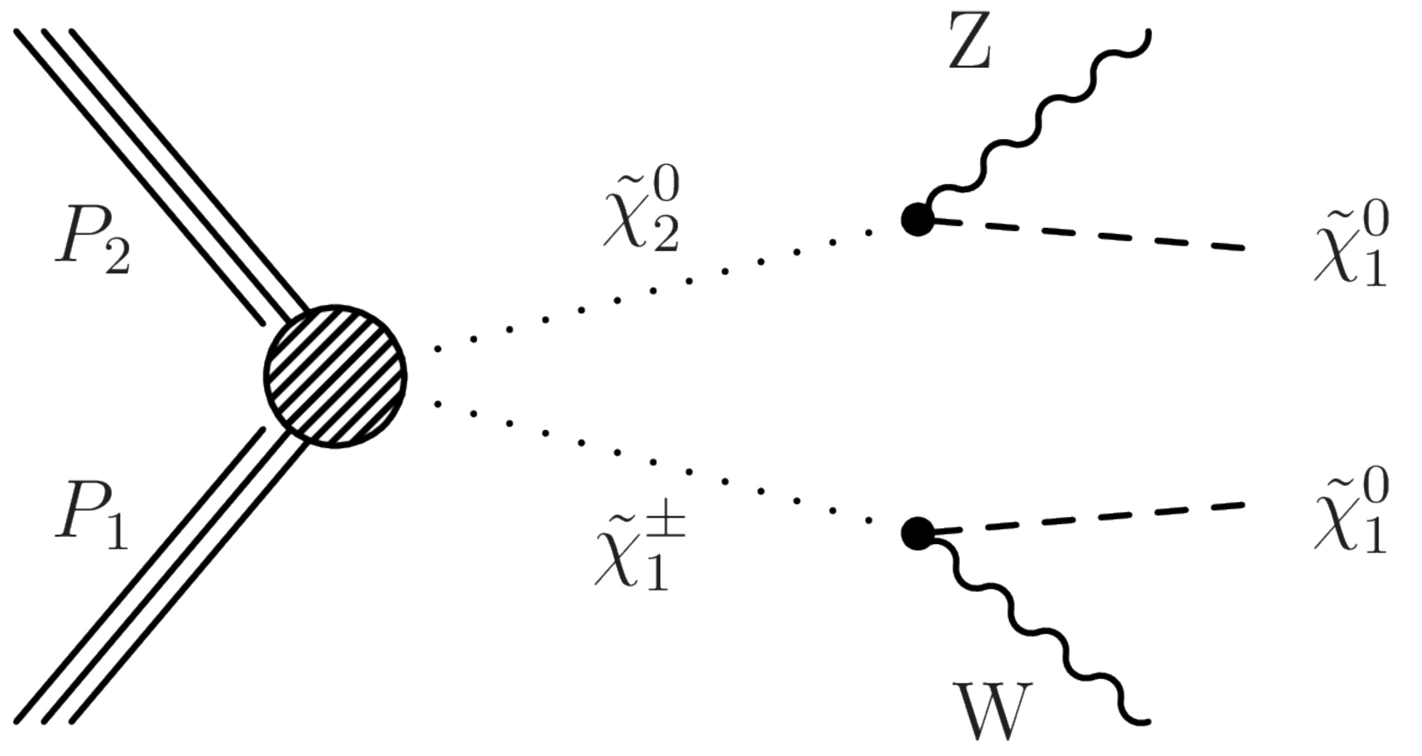

EWK (Chargino/Neutralino induced):

- some **jets**
- large E_T^{miss}
- 2 or 3 leptons where one pair is originating from a Z boson

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SUSY with opposite sign dileptons

We use LHC Run II data recorded in 2016 corresponding to an integrated luminosity of **12.9 /fb**

Baseline selection of 2 OSSF leptons (p_T 25/20 GeV) , E_T^{miss} >150 GeV, at least two jets

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Inclusive m_{ll}:

- model backgrounds and signal with shapes
- fit signal and background

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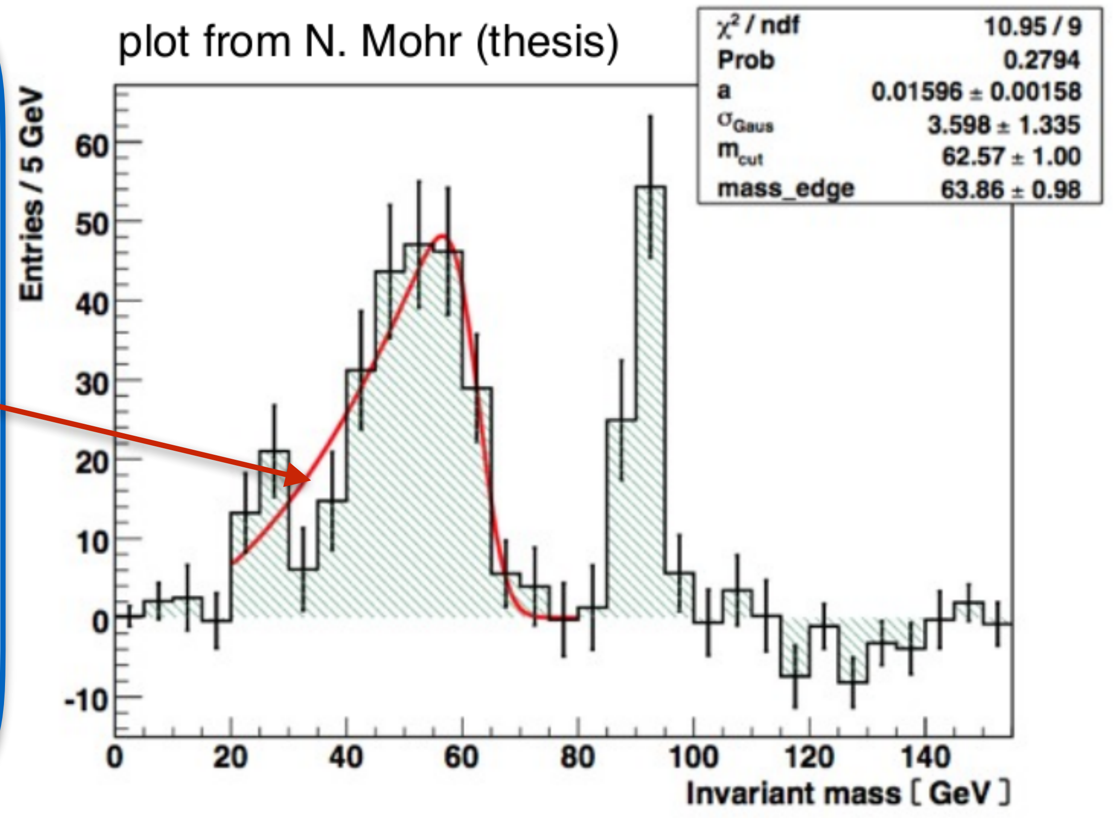
- fit signal and background

Edge/Off-Z:

- search for a kinematic edge in the m_{ll} spectrum
- main background ttbar
- Signal regions:
  - low and high m_{ll}
  - ttbar and non ttbar-like
  - CMS Run I excess signal region kept for verification:
    - E_T^{miss} : 100 GeV if > 3 jets (central leptons)
    - E_T^{miss} : 150 GeV if > 2 jets (central leptons)

plot from N. Mohr (thesis)



All possible mass endpoints calculated in CMS IN 2006/012, L.Pape, e.g. for a 3-body: $M_{ll}^{max} = M_X - M_0$

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SUSY with opposite sign dileptons

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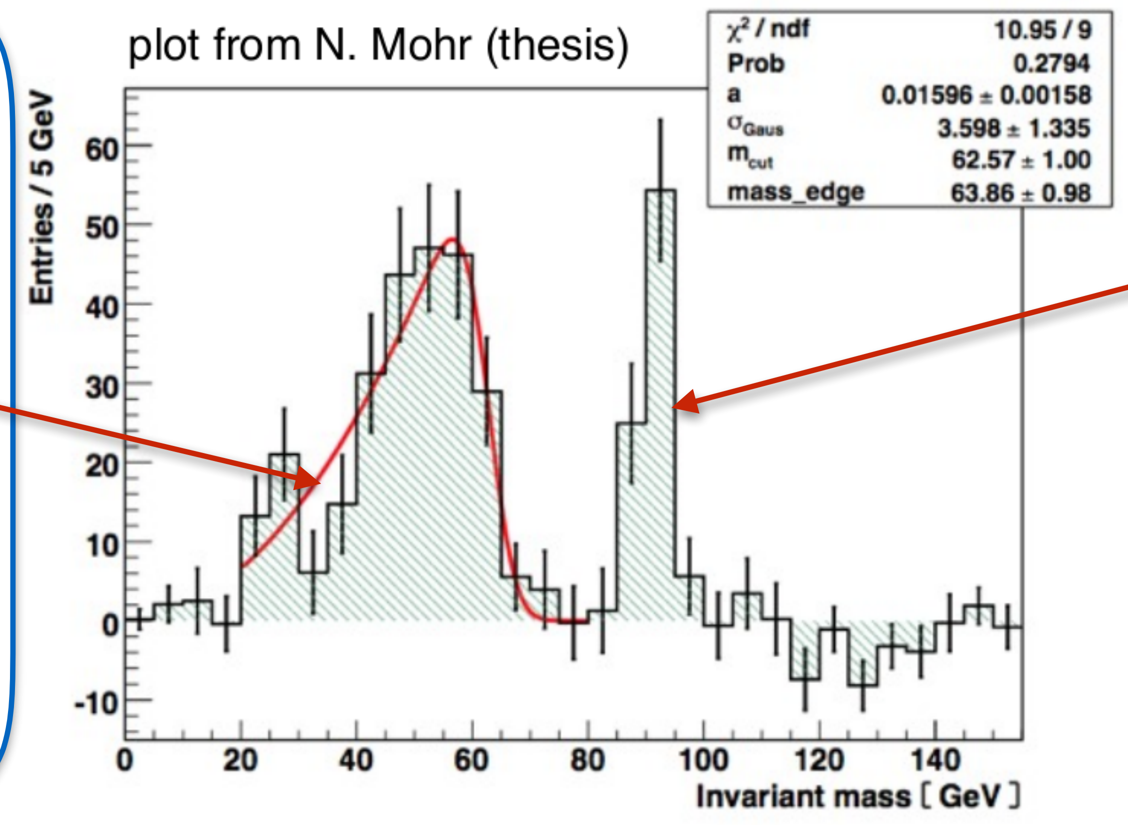

All possible mass endpoints calculated in CMS IN 2006/012, L.Pape, e.g. for a 3-body: $M_{ll}^{max} = M_X - M_0$

On-Z:

- search for an excess in the E_T^{miss} tails in the Z mass window
- main background ttbar + DY
- m_{ll} in 81 - 101 GeV
- General search signal regions:
  - 2-3 jets and H_T > 400 GeV
  - > 4 jets
  - ATLAS Run I excess signal region kept for verification:
    - or (H_T+p_{T1} + p_{T2}) > 600 GeV and E_T^{miss} > 225 GeV
- EWK search signal regions:
  - M_{T2} > 80 GeV and $\Delta\phi$(jet$_1$, E_T^{miss}) > 1
  - > 1 jet
  - E_T^{miss} : 150 - 225 GeV or 225 - 300 GeV or > 300 GeV

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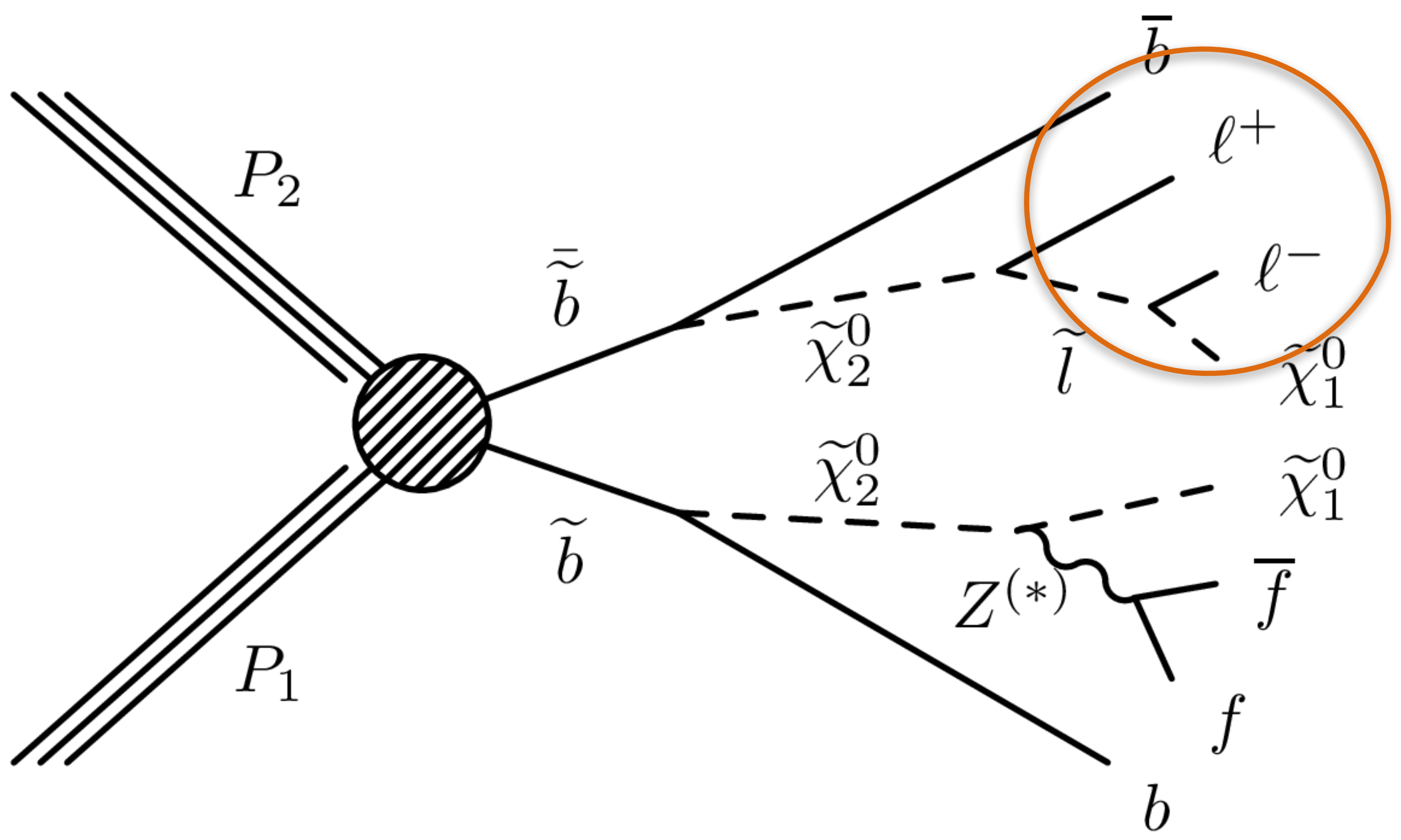
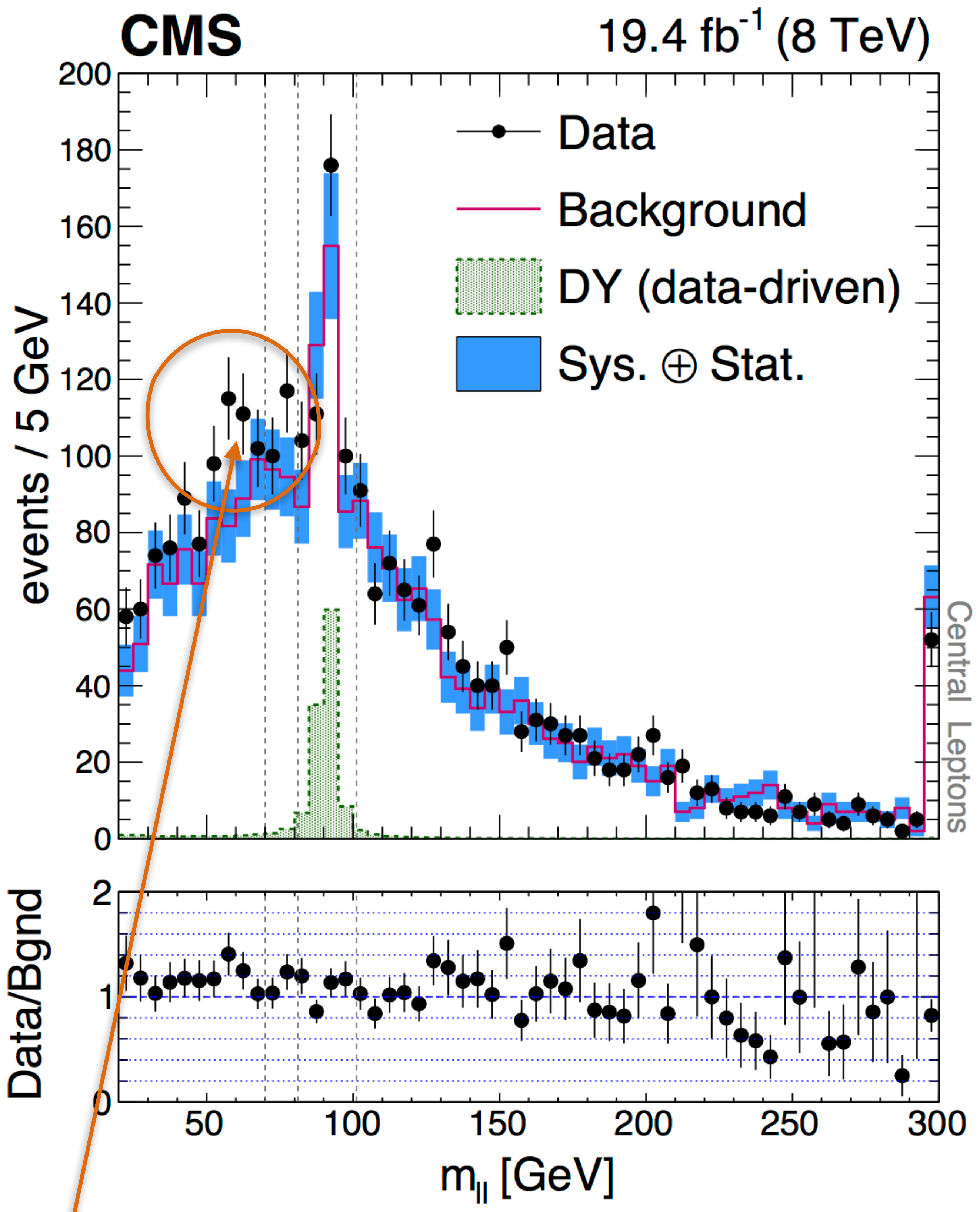
History of the analysis: Edge/Off-Z

Reminder:

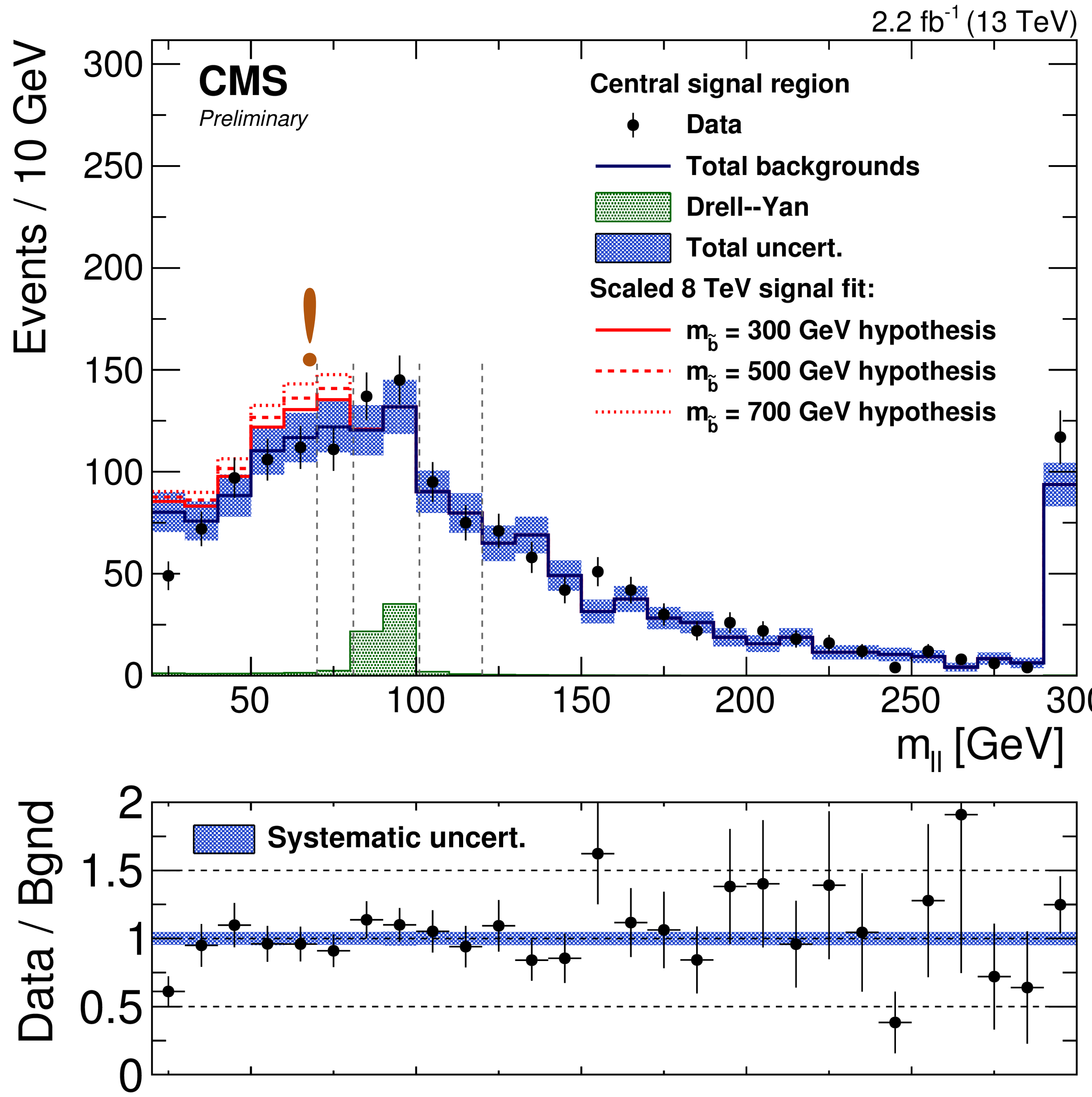
The Edge/Off-Z part of the analysis predicts a kinematic edge in the invariant mass of the two leptons



CMS excess in Run I:



No excess in the first Run II data…



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

This could not be verified with the first 2.3 /fb of Run II data.

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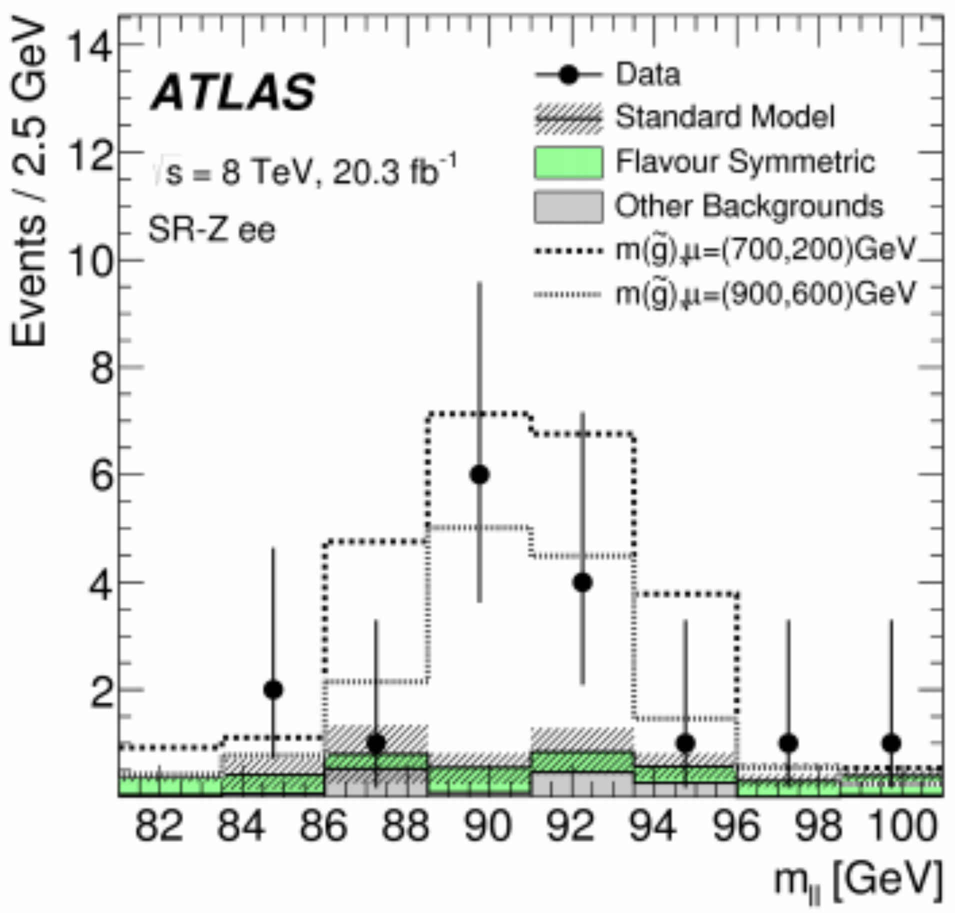
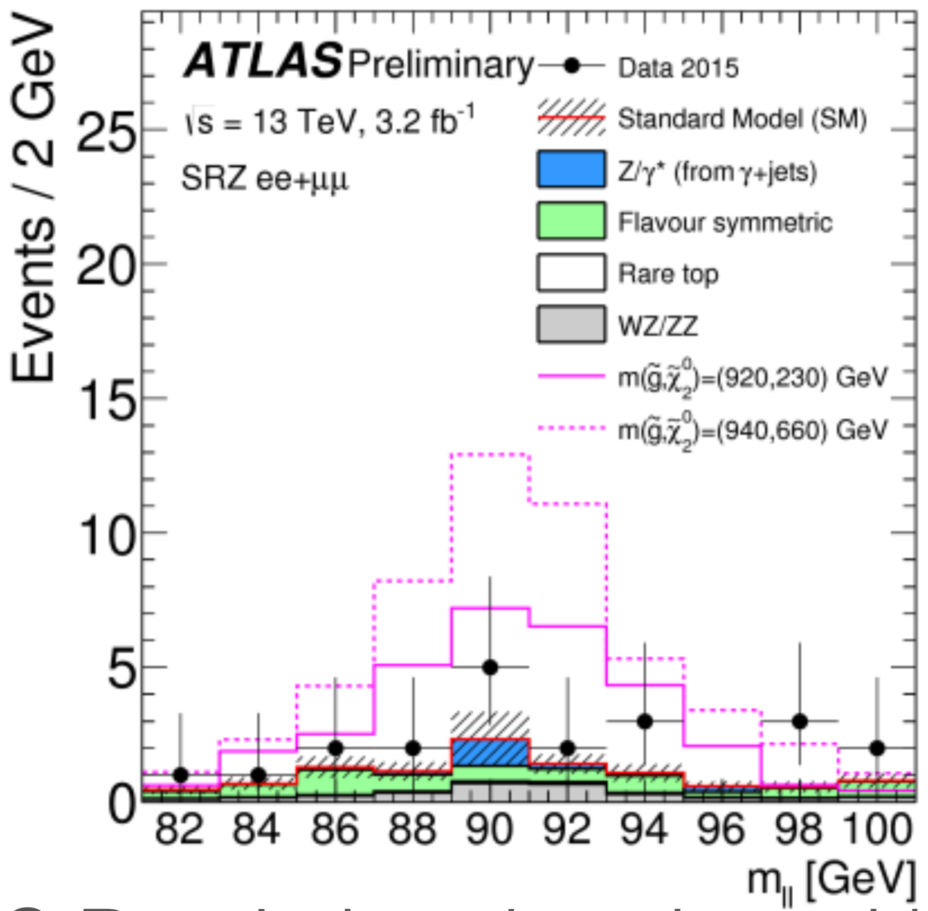
History of the analysis: On-Z

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

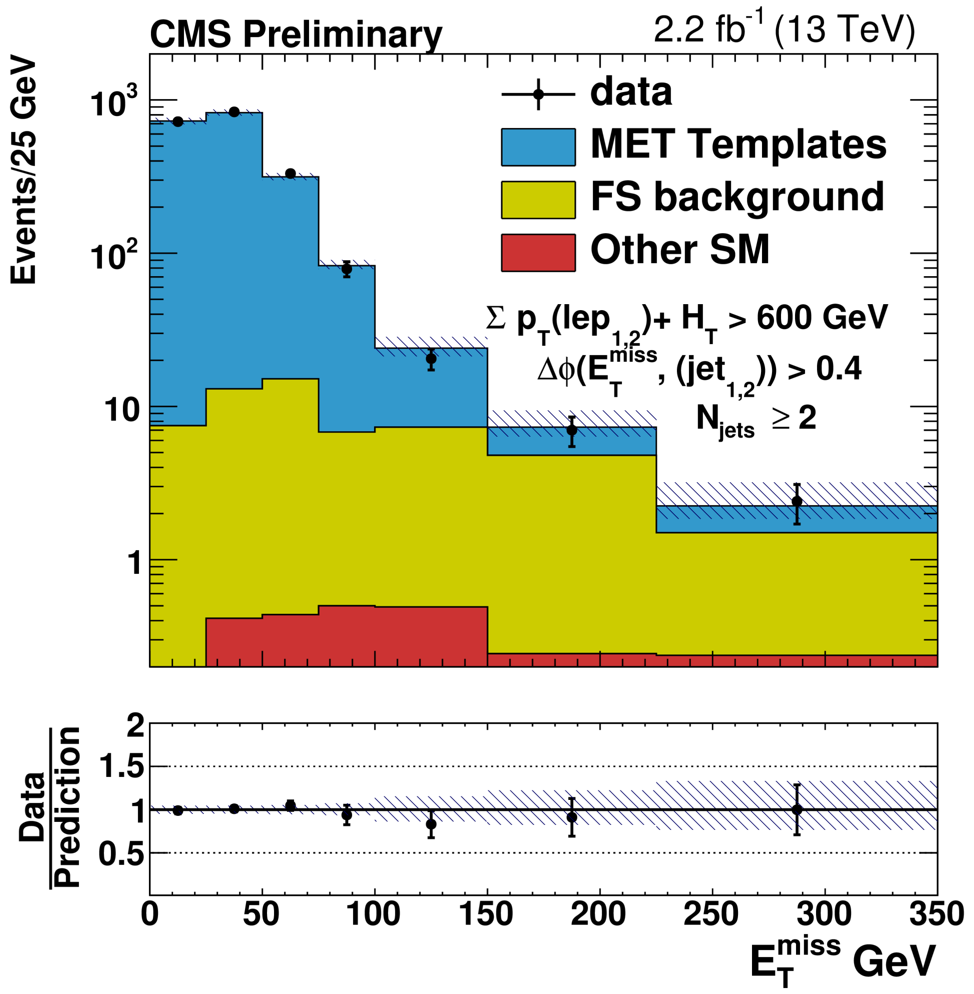
Reminder:

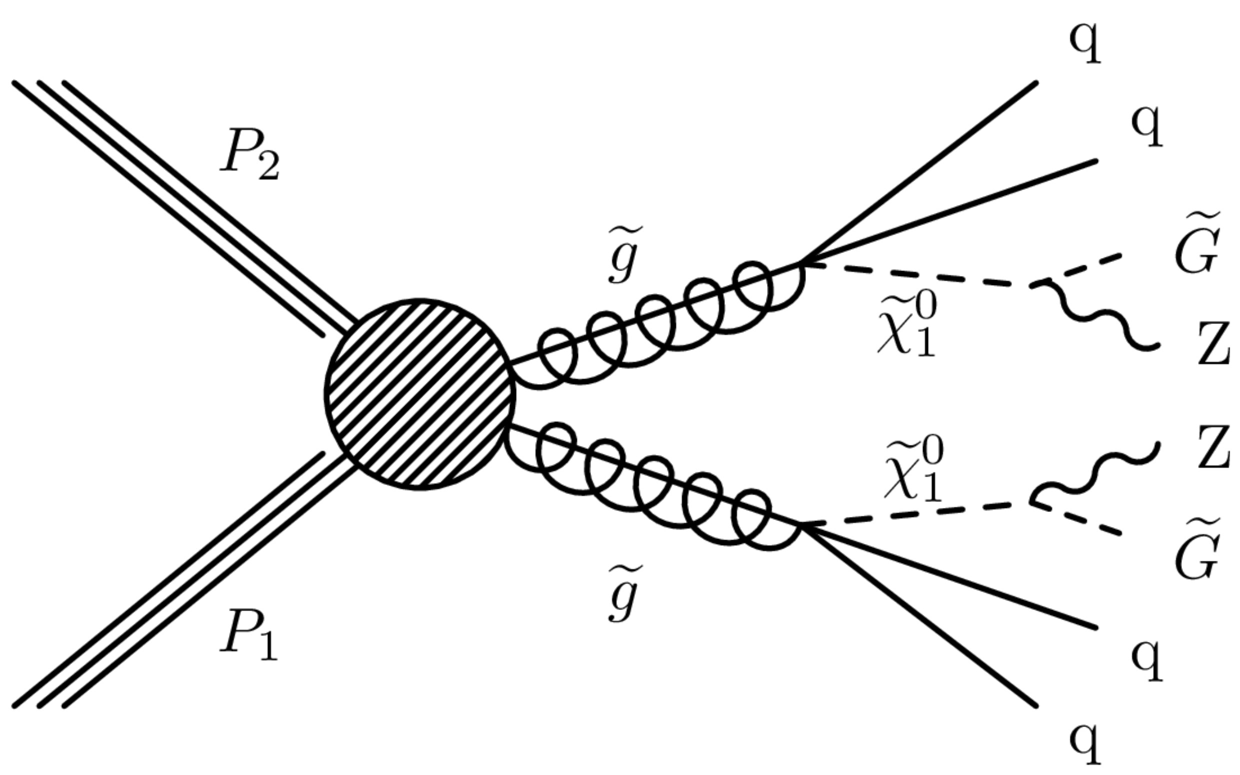
The On-Z part of the analysis targets an excess in the Z mass window in E_T^{miss} tails





CMS has tried to confirm this excess with the first 2.3 /fb data of Run II in the ATLAS Run I signal region with no luck…





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Background prediction

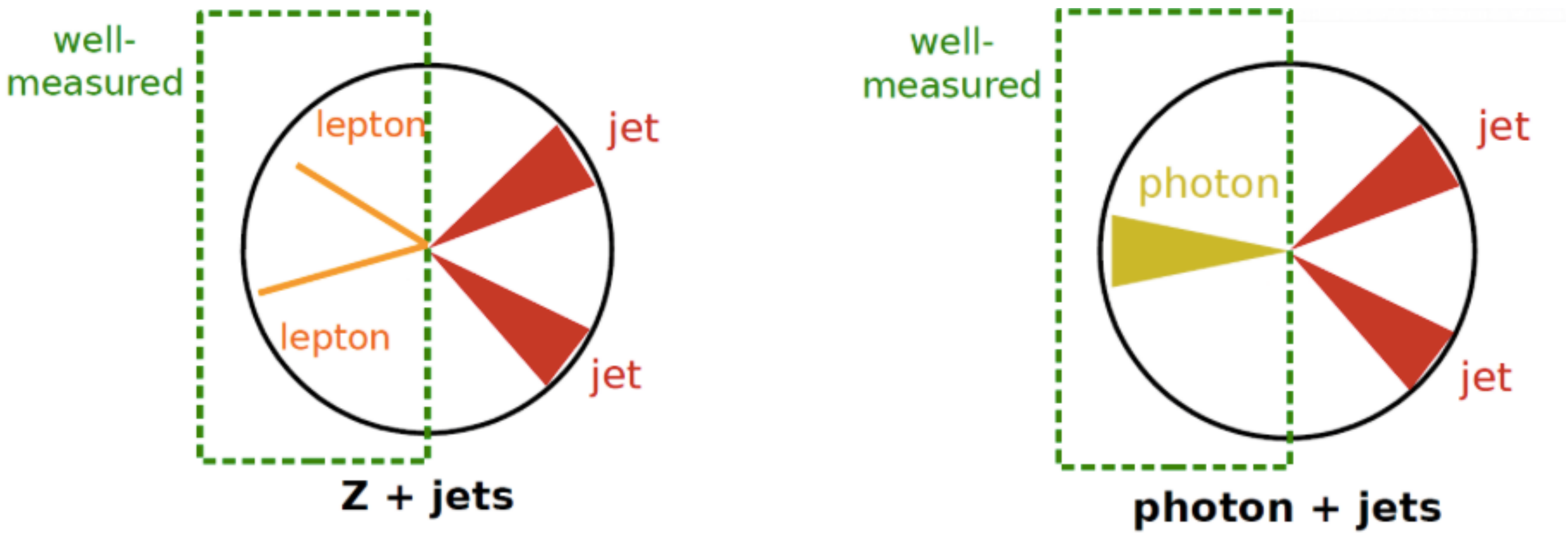
On-Z:

- ~50% Drell-Yan, predicted using E_T^{miss} templates
- ~50% flavour symmetric backgrounds (e.g. ttbar)

Edge/Off-Z:

- ~98% flavour symmetric backgrounds (e.g. ttbar)

E_T^{miss} template method:



Flavour symmetric backgrounds (e.g. ttbar):

- relies on the fact that the W decay has no preferred flavour direction
- estimated from OF control sample
  - correct for different trigger, object and reconstruction efficiencies

DY background:

- E_T^{miss} in Z →ll is events mainly from jet mismeasurements
- Use the fact that the E_T^{miss} in γ+jets events is the same as in Z →ll events

Rare processes:

- processes with real E_T^{miss} from neutrinos are taken directly from MC (WZ, ZZ, ttZ)

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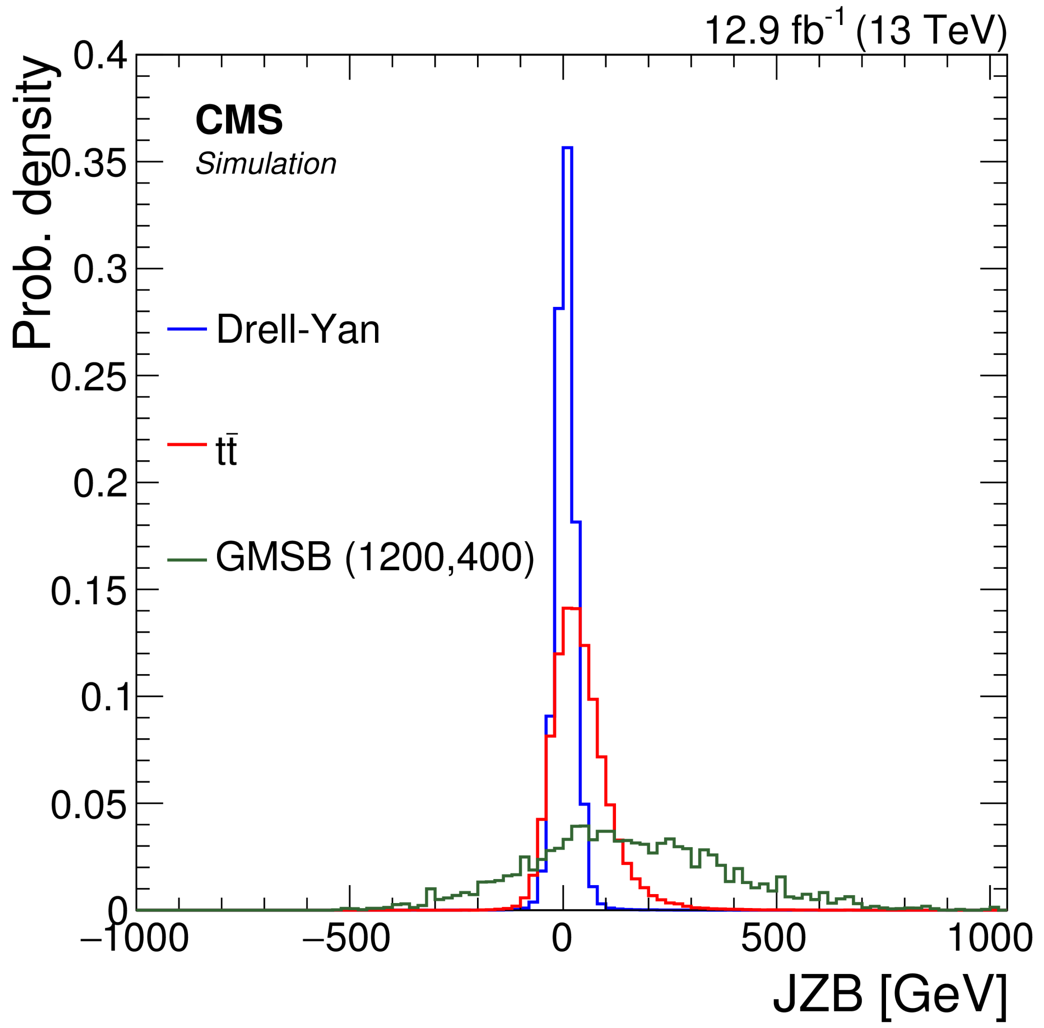
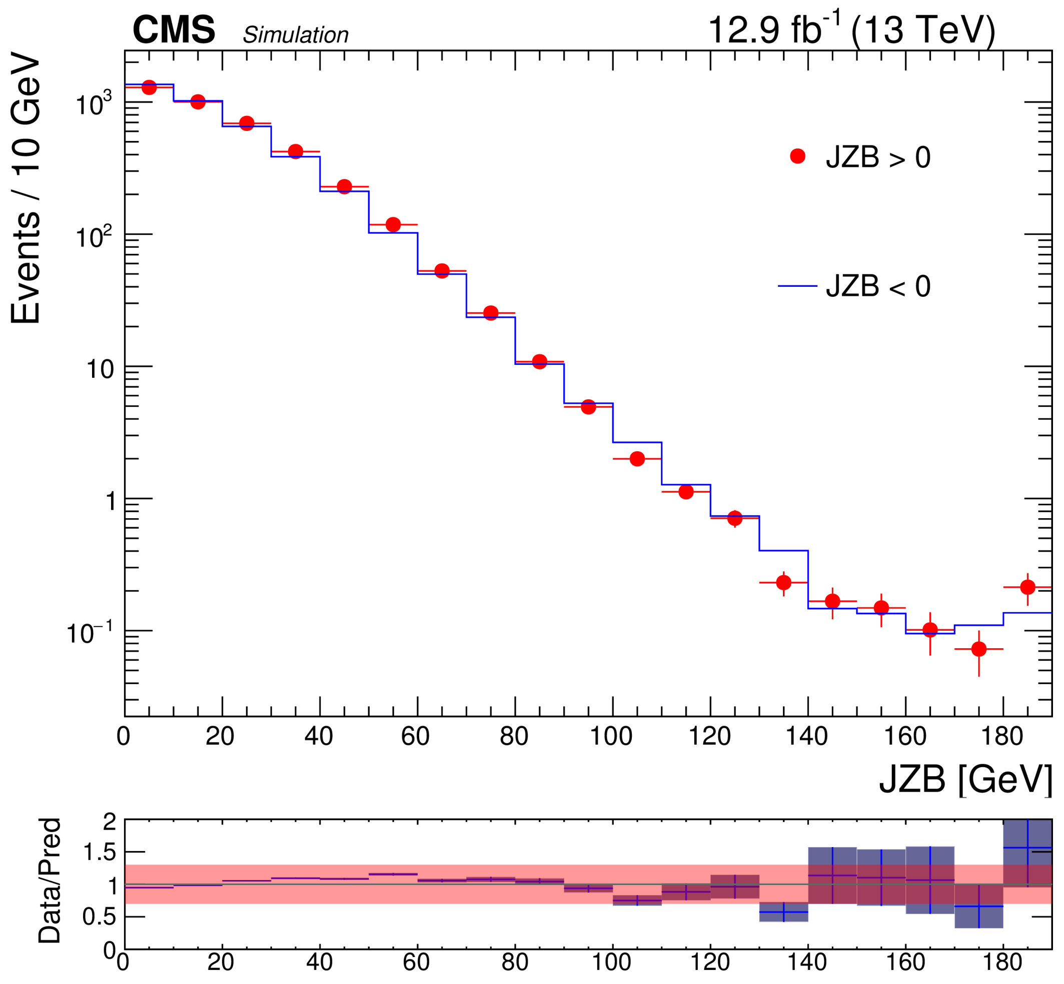
New developments: On-Z

Jet-Z Balance (JZB):

- Complementary DY prediction method
- Used to cross check in the ATLAS signal region
- Defined as the difference between the p_T of the recoil and the Z candidate
- Use negative part to predict positive part





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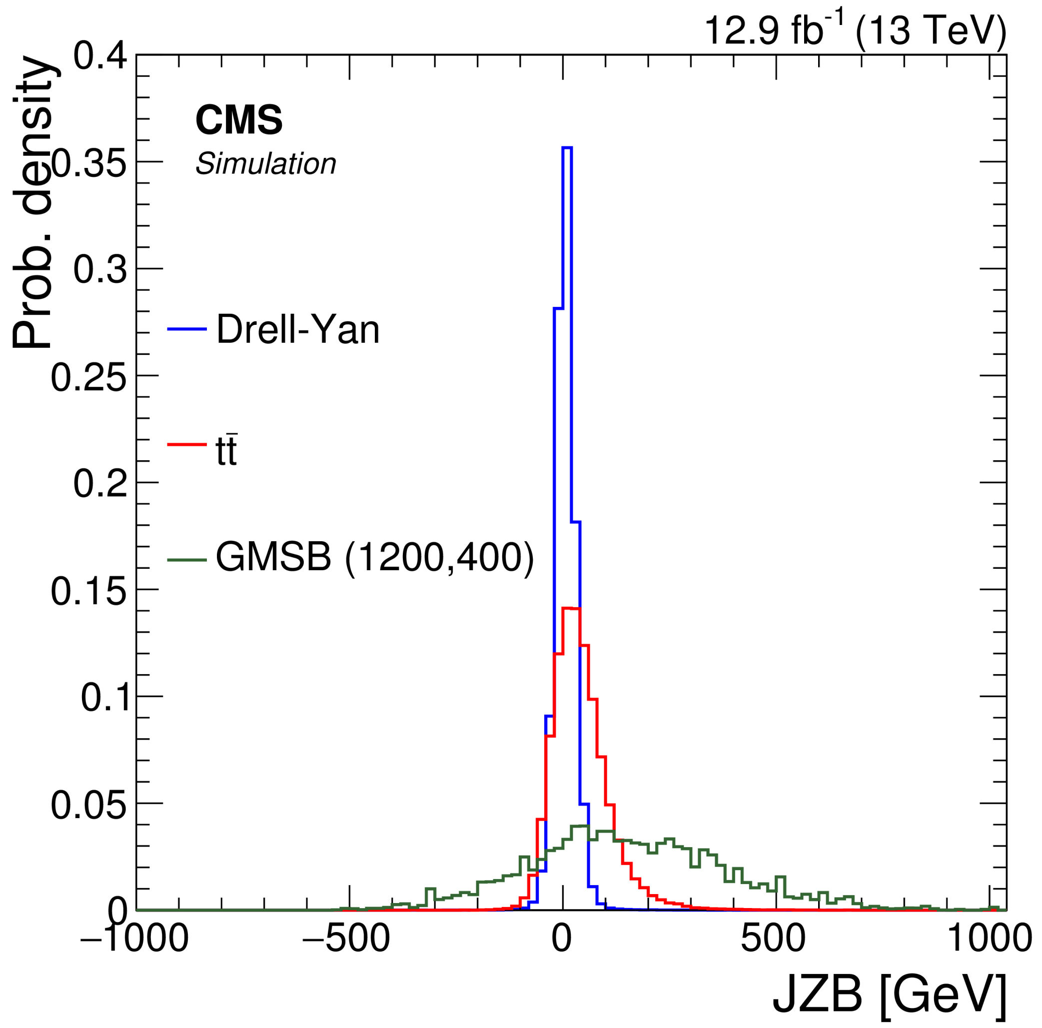
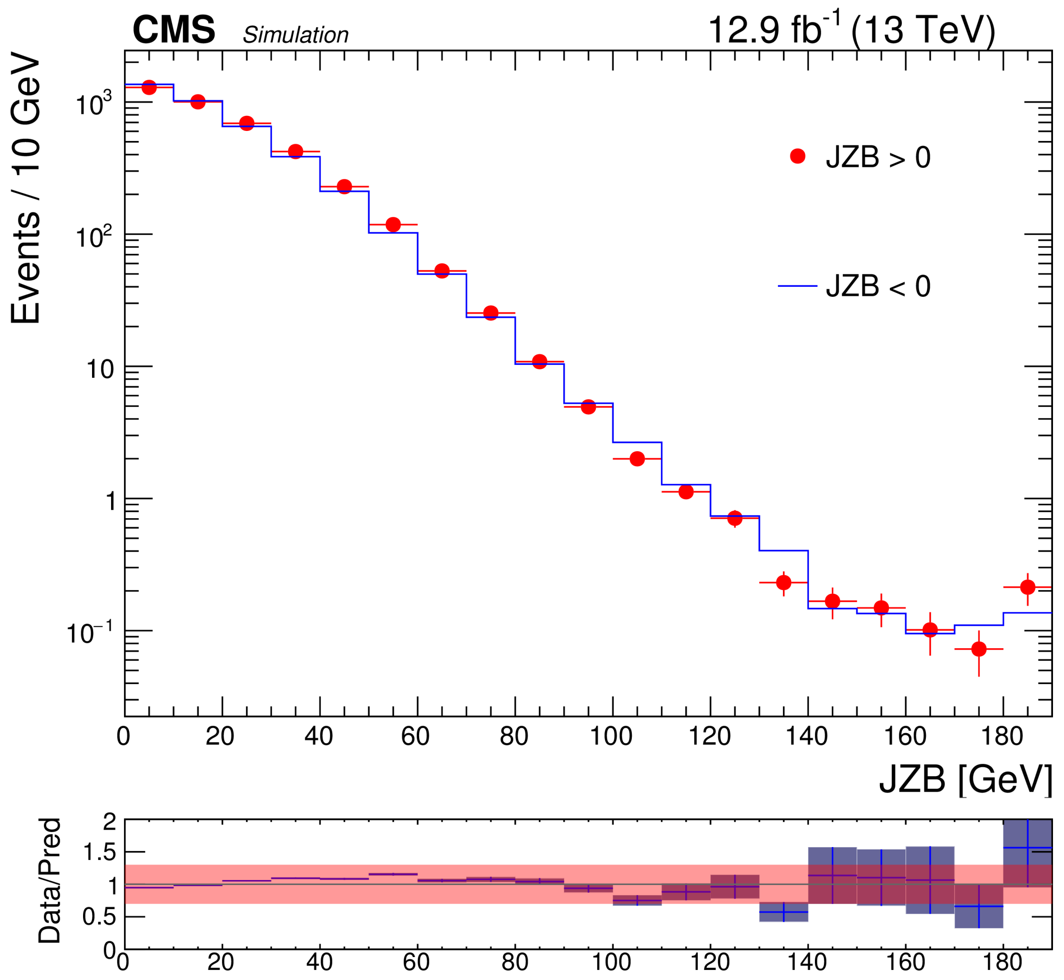
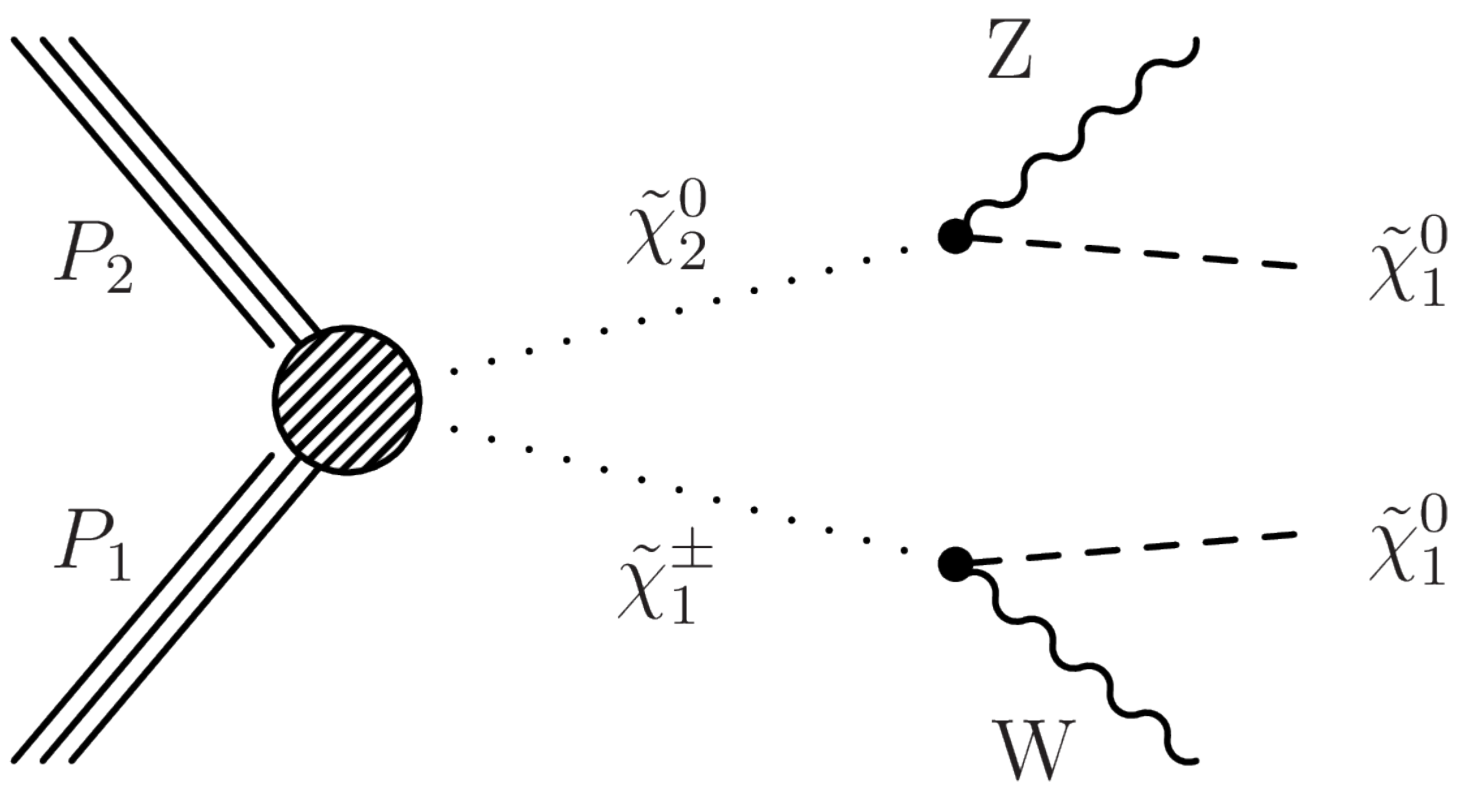




EWK targeted search:

- The On-Z search can be extended to target electroweakly produced SUSY
- Same background prediction models hold, but with additional cuts:
  - $\Delta\phi(\text{jet}_1, E_T^{miss}) > 1$ to reduce Z+jets
  - $M_{T2} > 80$ GeV to reduce ttbar



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New developments: Edge/Off-Z

Background rejection:

In the edge/off-Z 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:

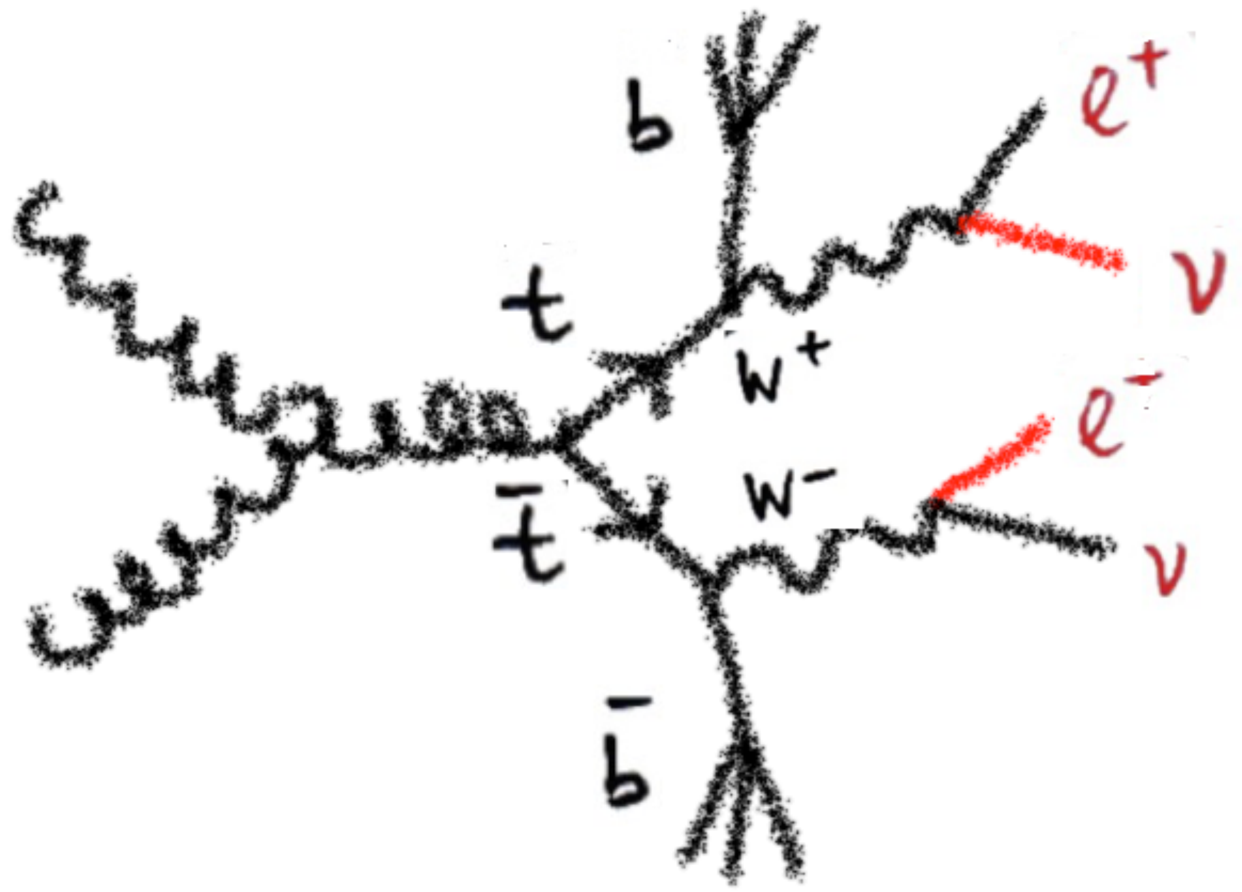
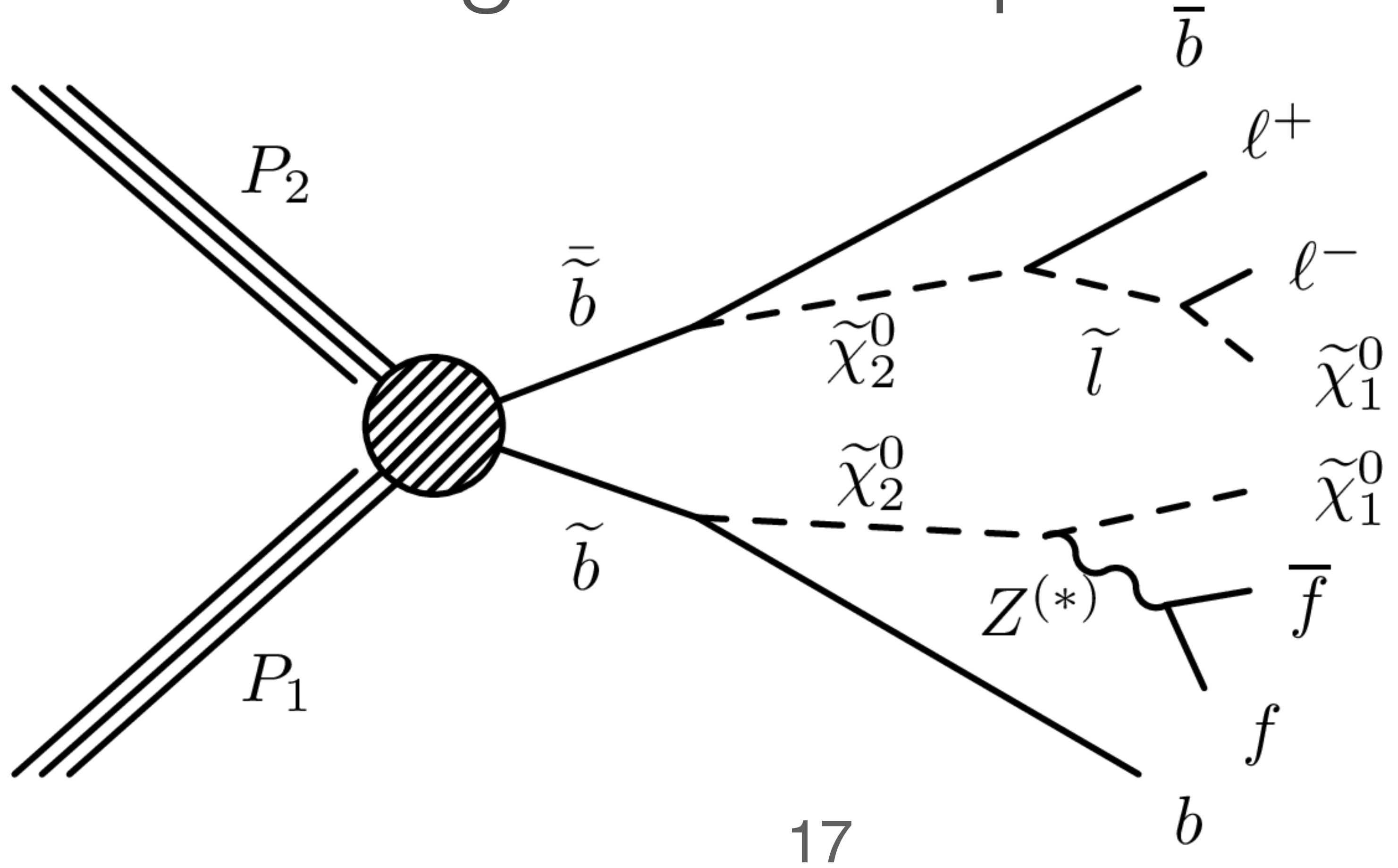


Diagram of a signal SUSY process:



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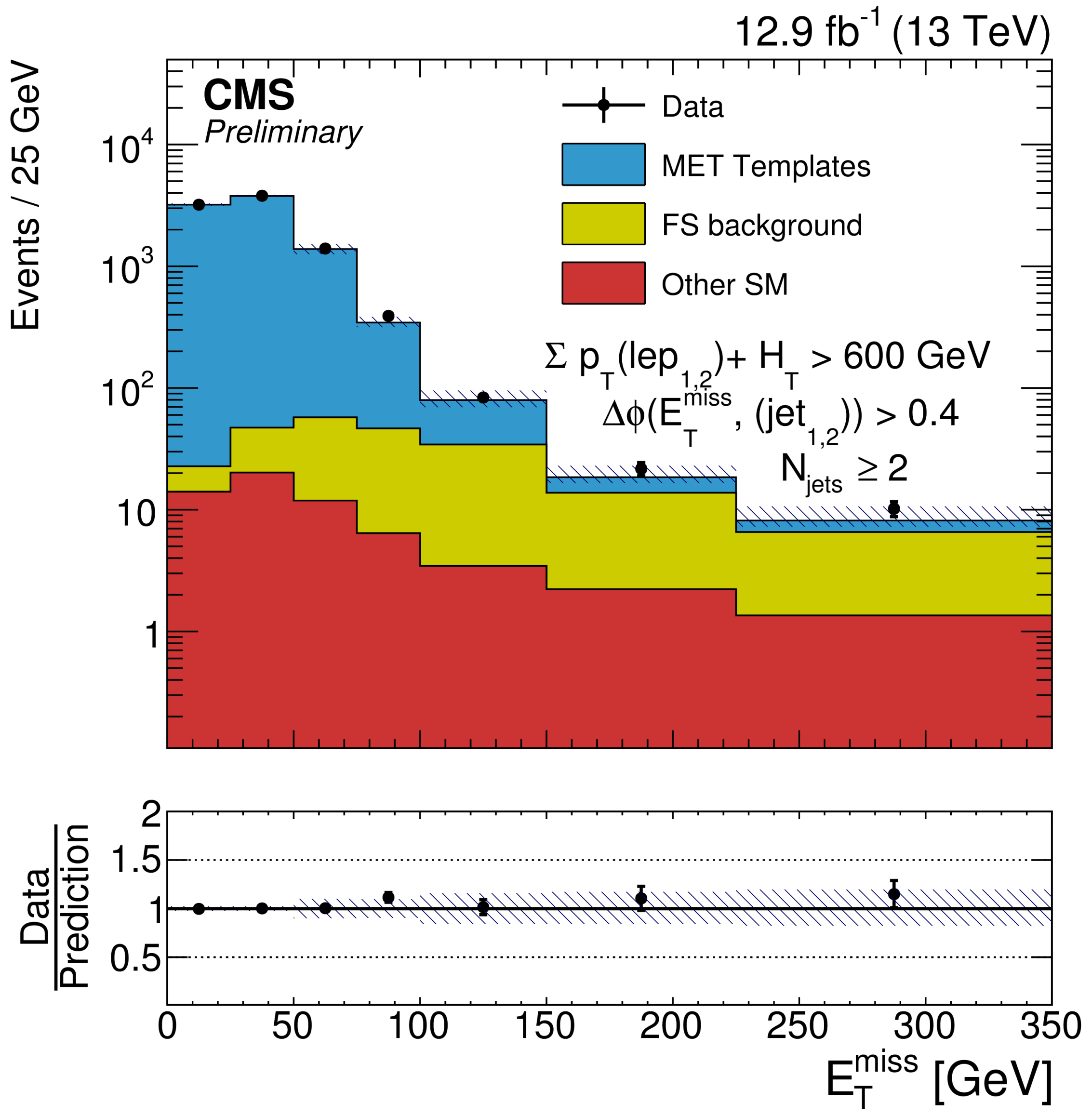
Results: On-Z ATLAS region

ATLAS reported an excess of 3.0 sigma in Run I and 2.2 sigma in Run II

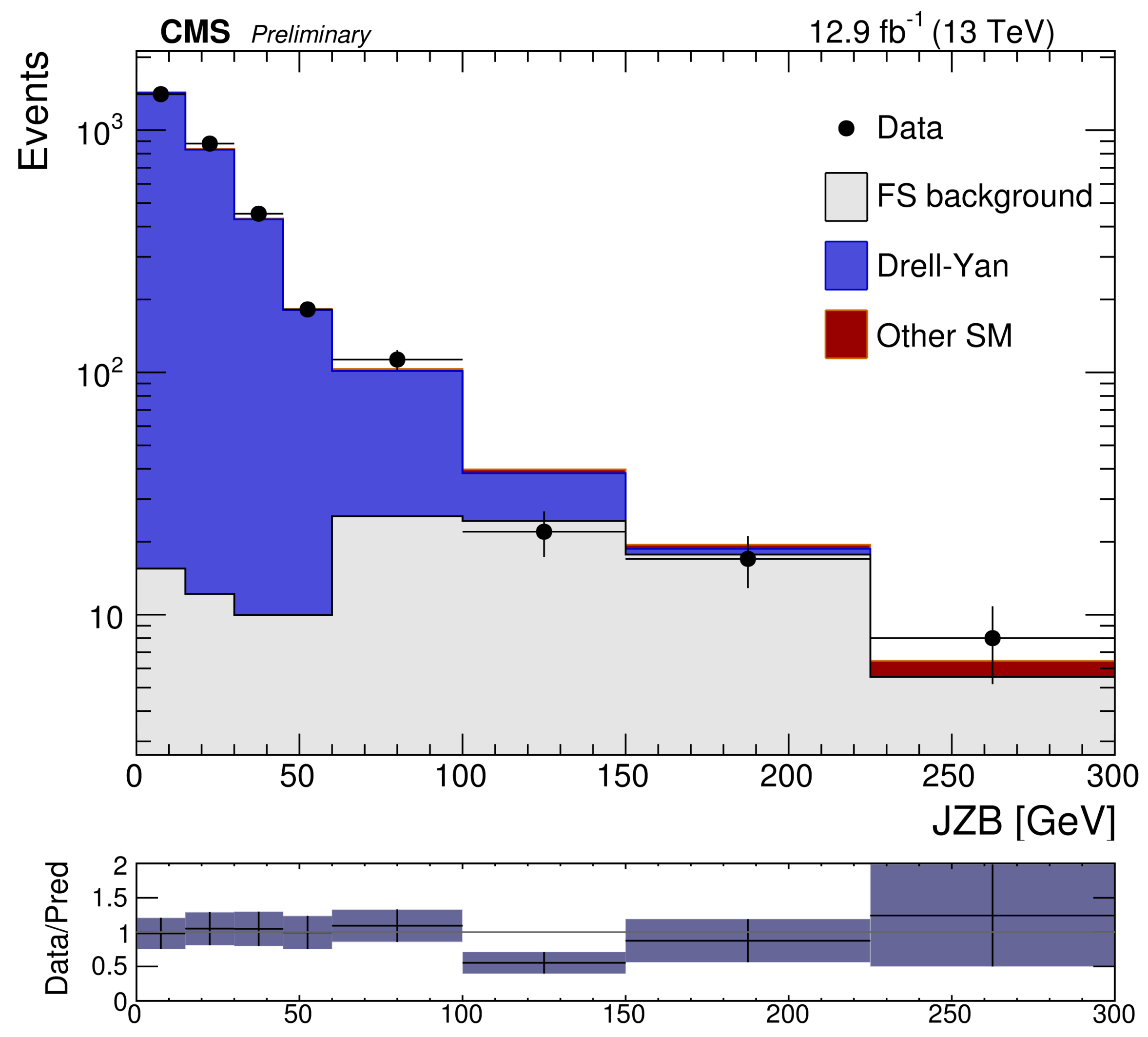
- Two background prediction methods are used to attempt to verify this excess

- The E_T^{miss} templates show good agreement between predicted and observed: 44 ± 8 vs. 51
- The JZB also show good agreement between predicted and observed: 6.1 ± 4 vs. 8

E_T^{miss} template method:



Jet-Z Balance:



Thus the excess reported by ATLAS is not confirmed by CMS

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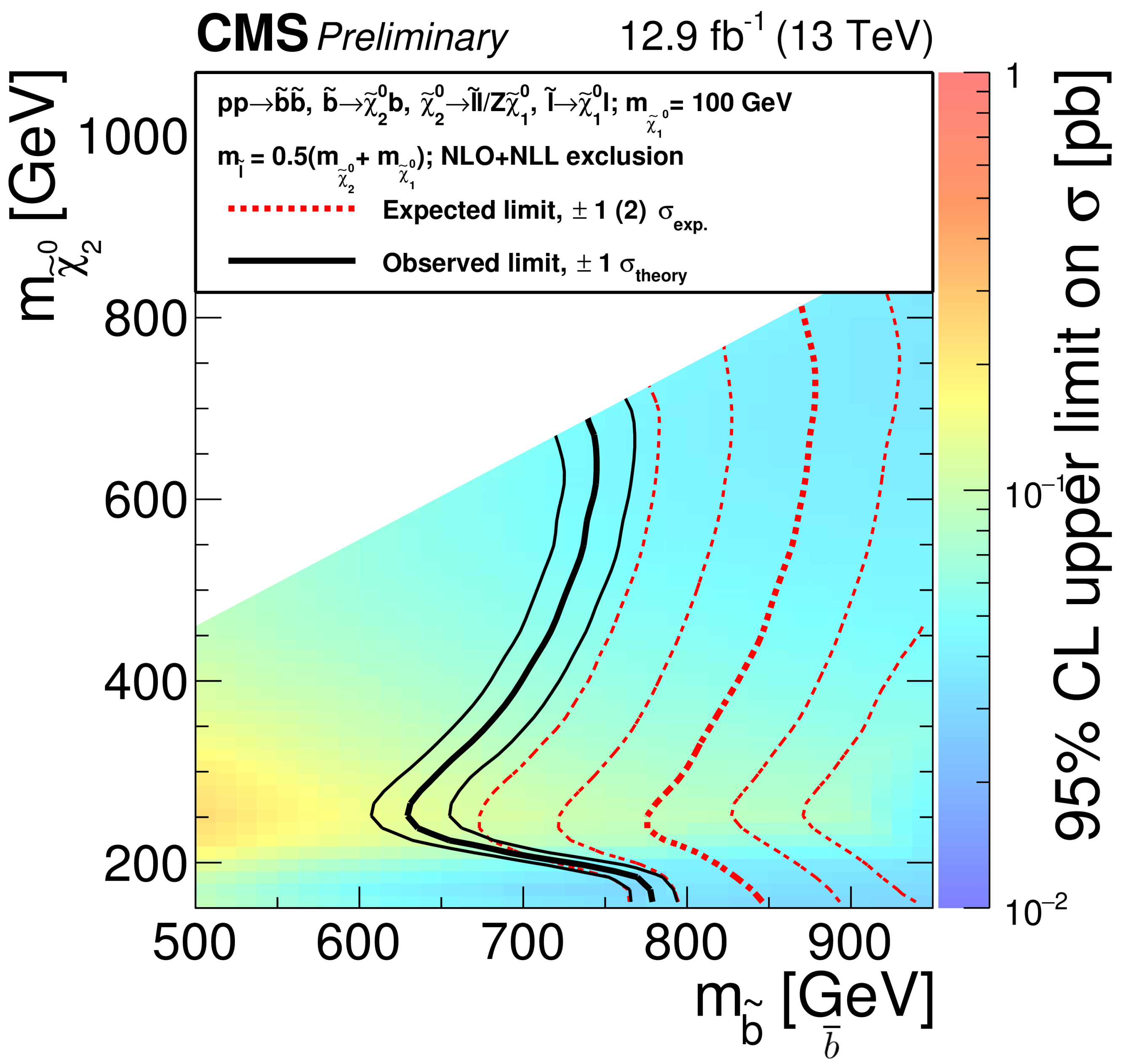
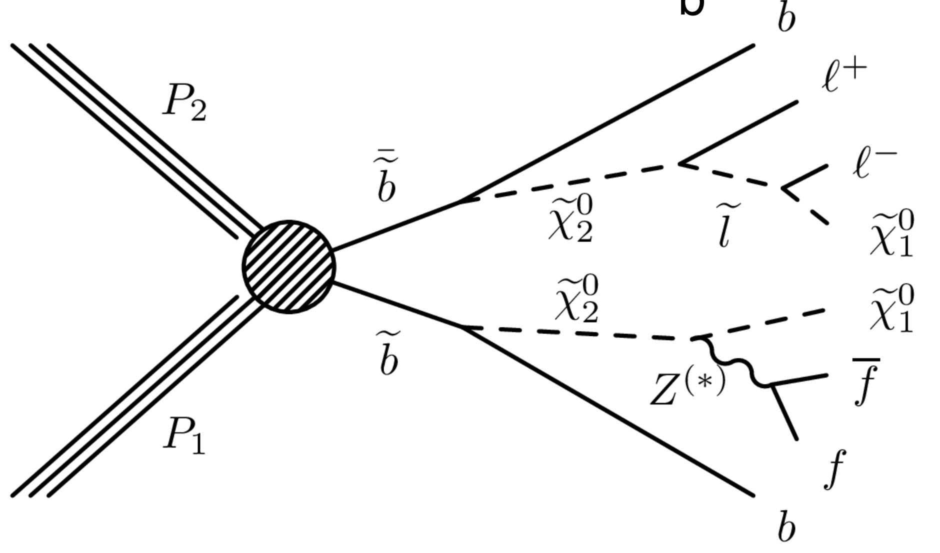
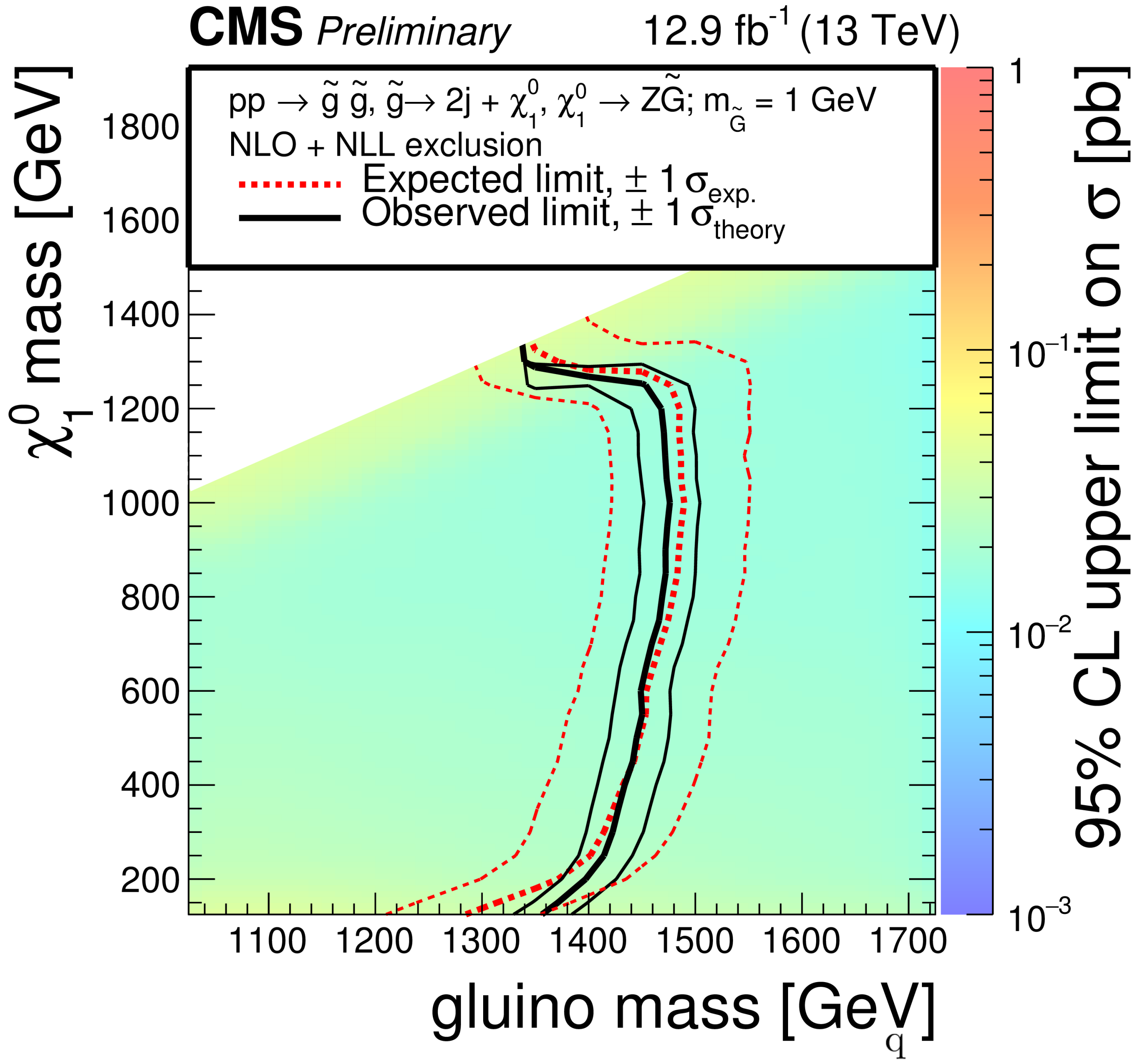
Interpretation

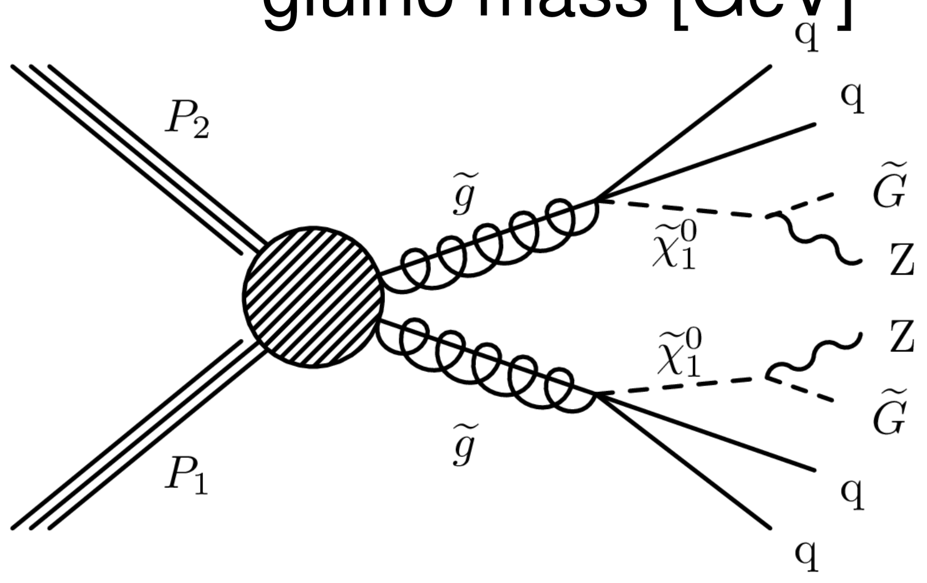
Off-Z/edge search: direct sbottom production



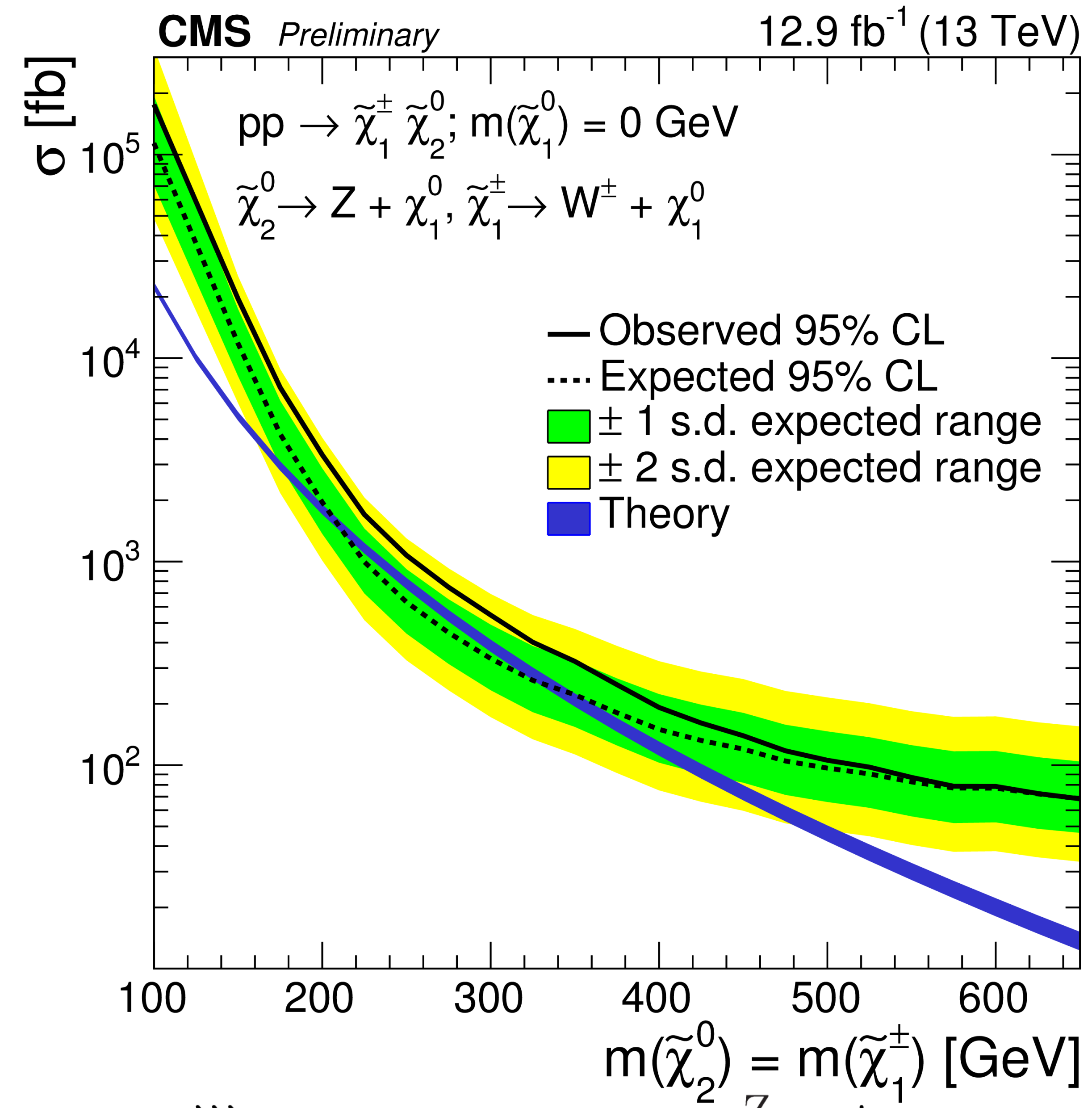


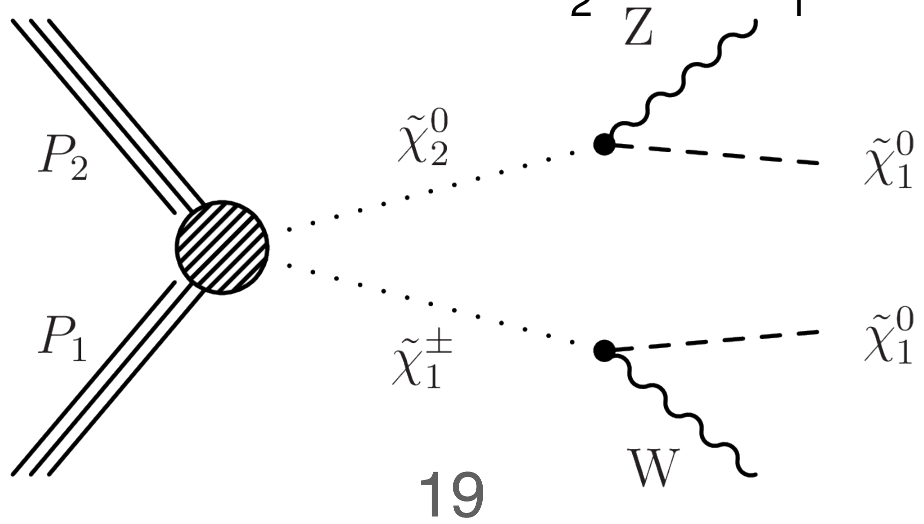
On-Z general search: GMSB gluino production





On-Z EWK search: Chargino-Neutralino





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Summary

A search for Supersymmetry using opposite sign dileptons was motivated and presented

- Data used was recorded with the CMS detector at 13 TeV in 2016, corresponding to an integrated luminosity of 12.9 /fb, published in CMS PAS SUS-16-021 for ICHEP
- New developments have been implemented for the Run II data taking to improve the analysis and facilitate potential discoveries
- Run I excesses reported by ATLAS and CMS has been attempted to verify
  - without luck, the observed events agree well with the SM expectation
  - limits has been set on the masses of the sparticles produced in the three targeted SUSY models
- With the excellent performance of the LHC in 2016 we are looking forward to more data

Backup

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Objects and triggers

$12.9\ fb^{-1}$ of 2016 data

'standard' muons and electrons

- special in this analysis: veto crack region |eta| from 1.4 - 1.6
- medium Muon ID, miniIso < 0.2
- electron MVA ID, miniIso < 0.1
- $p_{T1} > 25$, $p_{T2} > 20$ GeV, select the hardest pair

corrected jets and type-1 ME_T with V6 JECs

- jet-$p_T > 35$ GeV
- b-jet-$p_T > 25$ GeV for b-jet veto

plethora of di-lepton triggers, isolated and non-isolated

- trigger efficiency measured in JetHT

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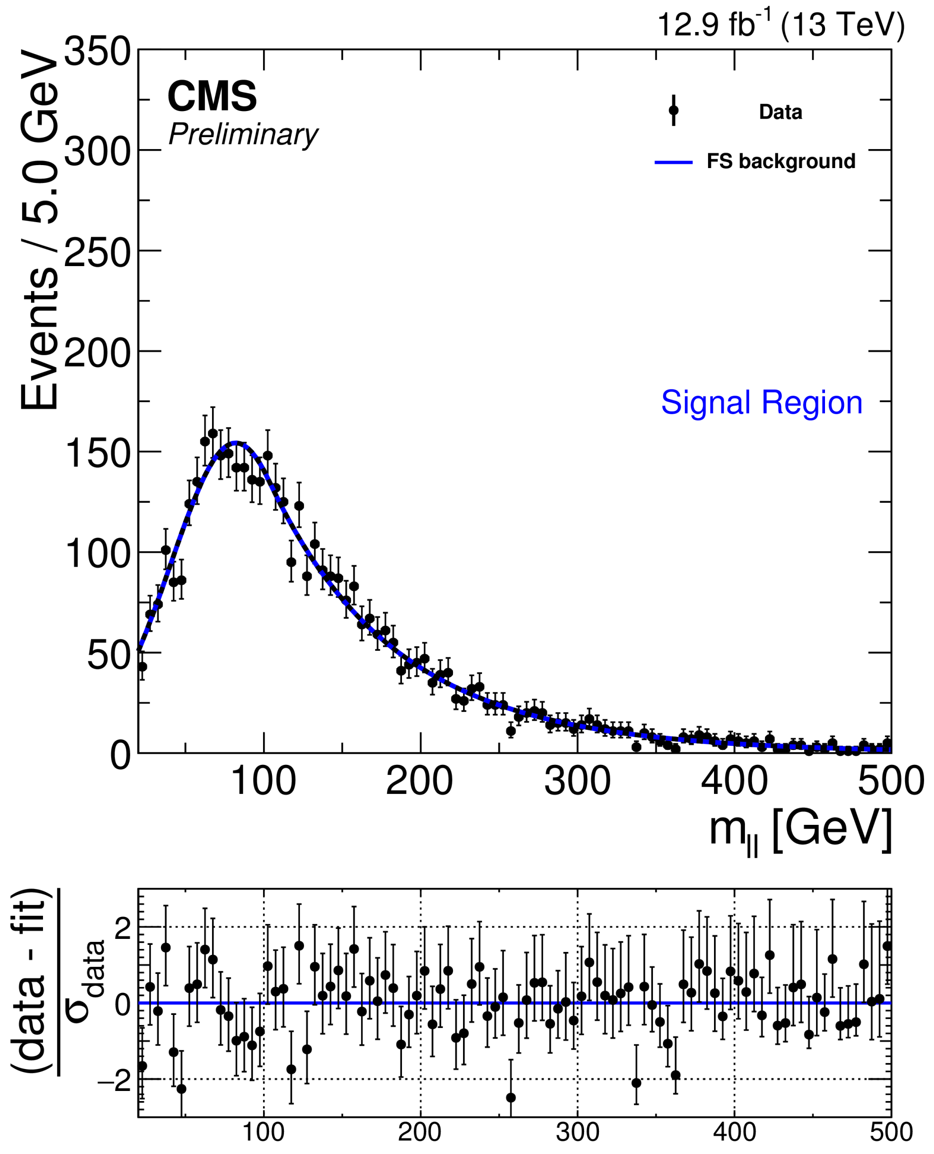
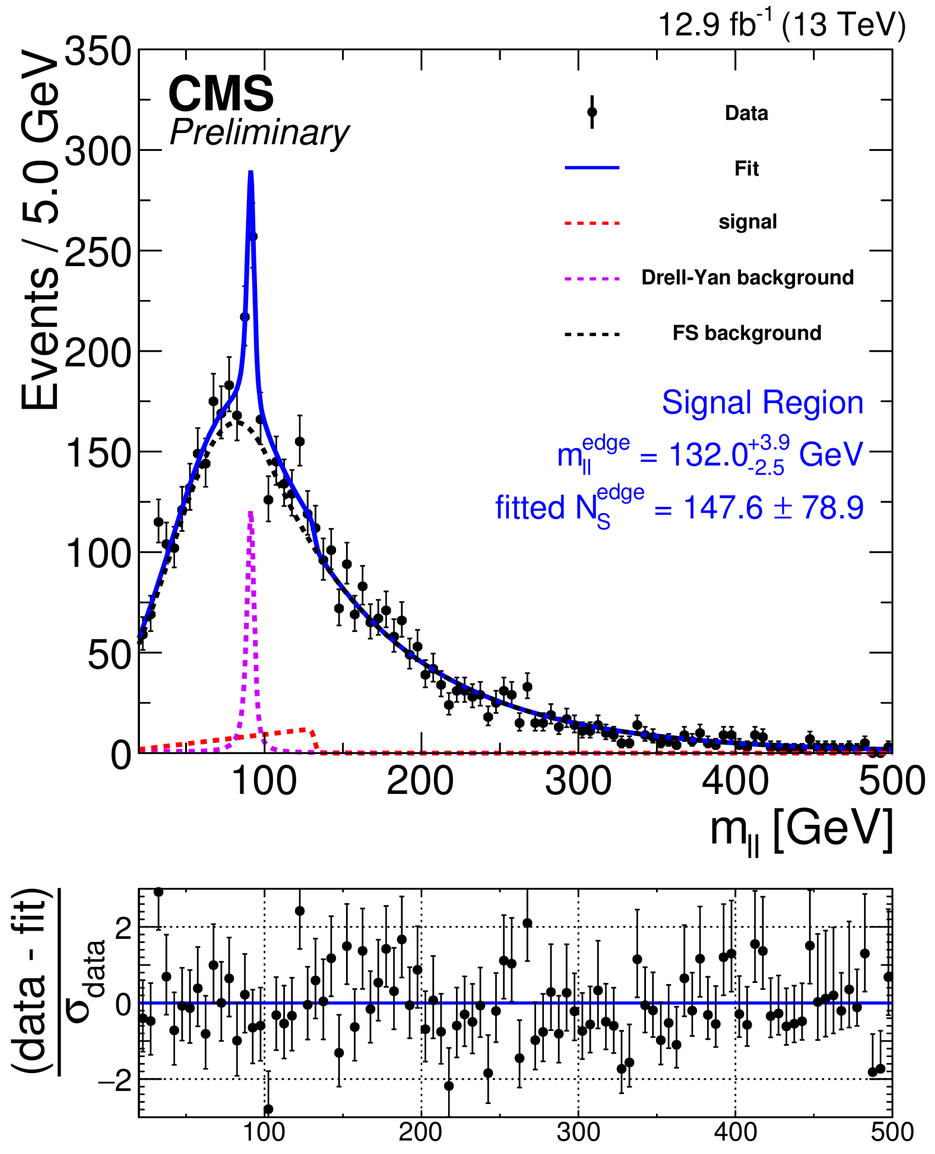
Results: Edge/Off-Z

Perform a fit on the baseline selection on the invariant mass spectrum

- simultaneous fit OF+SF for ttbar
- best fit at 132 GeV (148 ± 80 events)

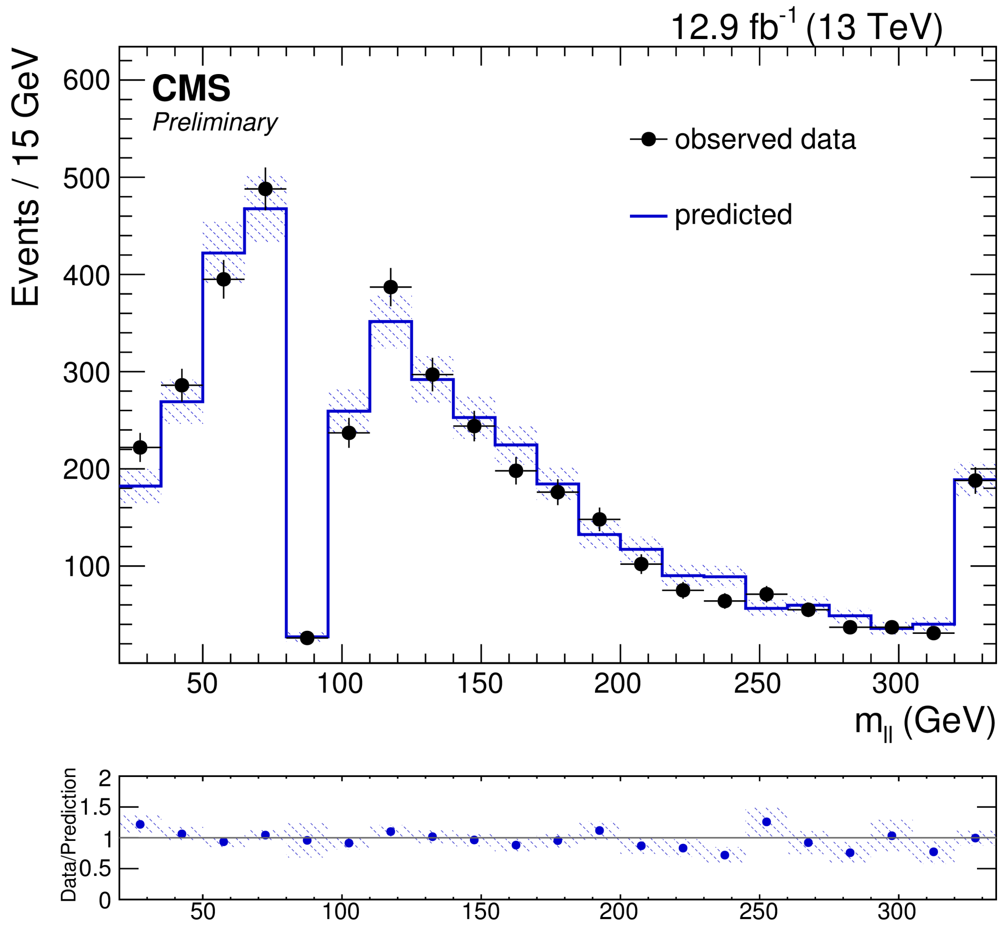


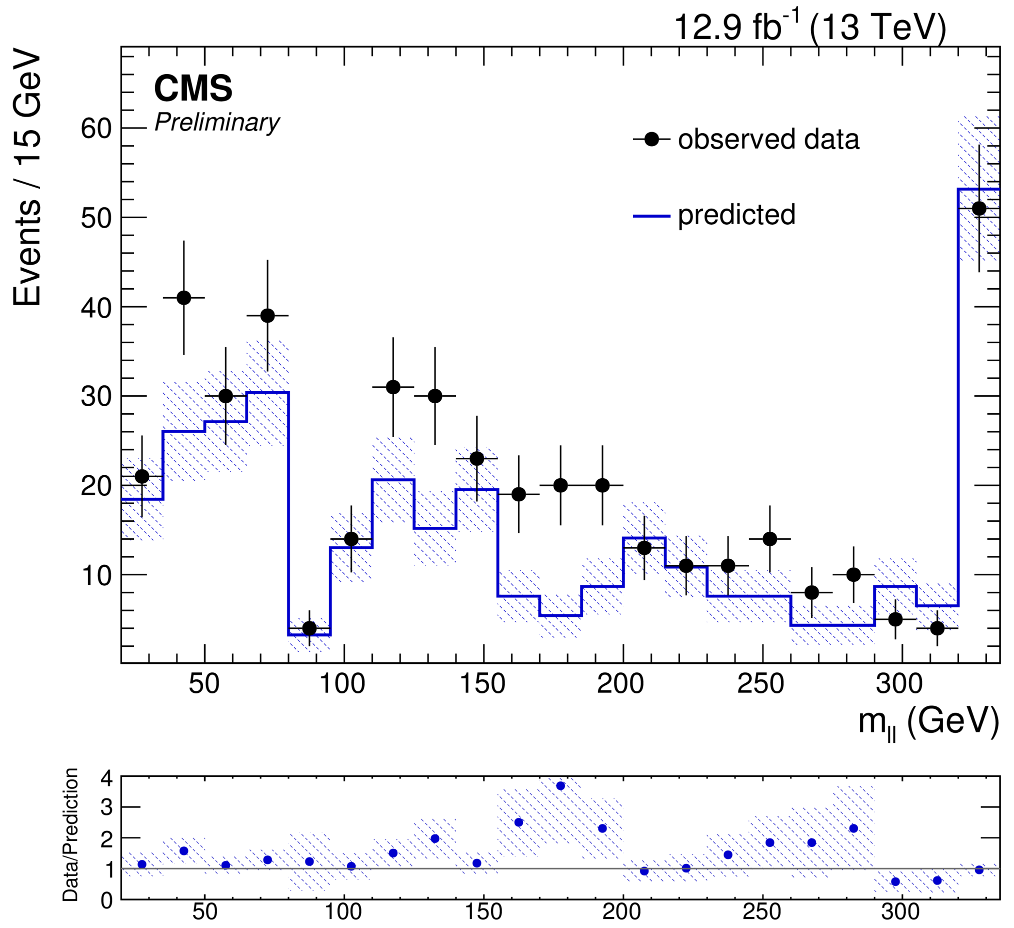


The Off-Z counting shows disagreement

- in one signal region
- 3.1 sigma local

		ttbar-like	non-ttbar-like
mll < 81 GeV	pred. FS	1374.4 ± 48.1	105.8 ± 10.9
	pred. DY	13.5 ± 4.6	7.3 ± 2.5
	pred. total	1387.9 ± 48.3	113.1 ± 11.2
	obs	1417	135
mll > 101 GeV	pred. FS	2435.8 ± 72.2	208.3 ± 15.7
	pred. DY	7.6 ± 2.6	4.1 ± 1.4
	pred. total	2443.4 ± 72.3	212.4 ± 15.7
	obs	2347	285





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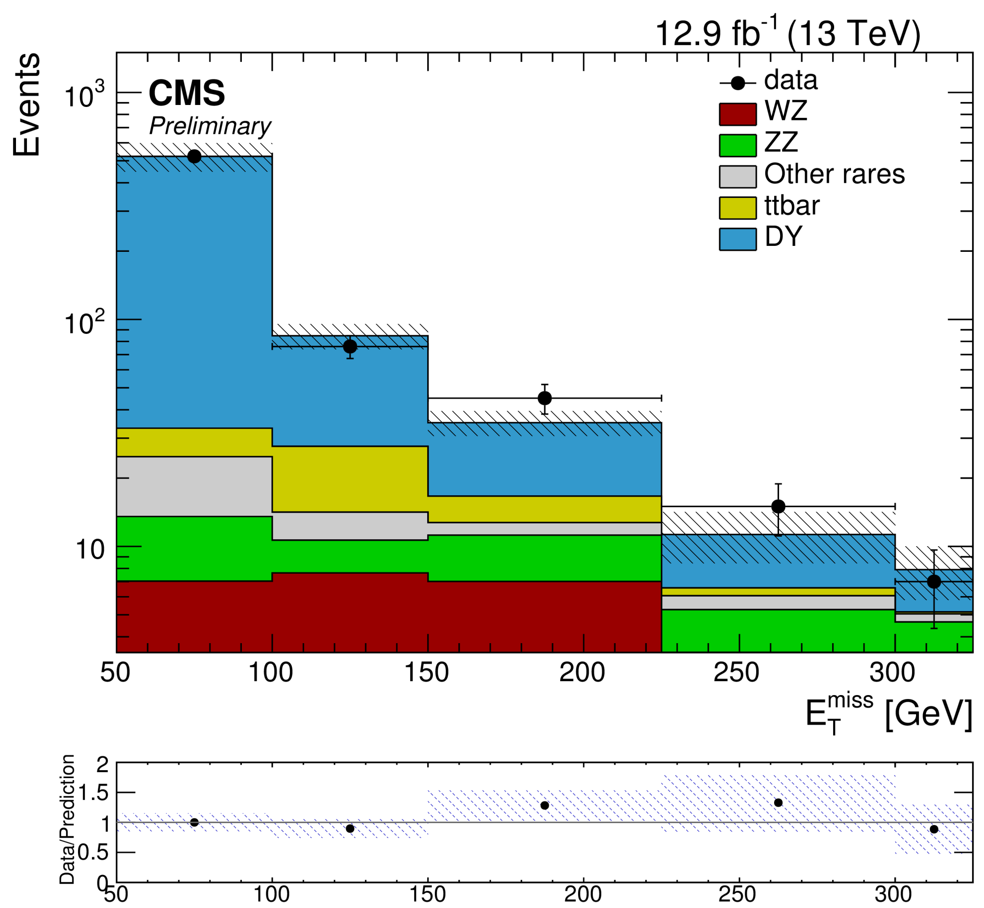
Results: On-Z

The On-Z results show good agreement in all signal regions

The EWK targeted search show good agreement between predicted and observed events

N_{jets} / H_T	$N_{b\text{-}jets}$	E_T^{miss} (GeV)	Predicted	Observed
		100-150	$169.6\,^{+16.1}_{-15.7}$	**177**
SRA	0	150-225	$43.6\,^{+7.1}_{-6.3}$	**45**
		225-300	$24.3\,^{+12.7}_{-12.4}$	**11**
2–3 jets		> 300	$15.0\,^{+4.8}_{-3.8}$	**23**
		100-150	$77.2\,^{+9.2}_{-8.1}$	**87**
and $H_T > 400$ GeV	≥ 1	150-225	$40.0\,^{+7.4}_{-6.2}$	**34**
		225-300	$12.0\,^{+4.6}_{-3.4}$	**22**
		> 300	$11.5\,^{+4.5}_{-3.3}$	**11**
		100-150	$126.3\,^{+12.5}_{-11.8}$	**122**
SRB	0	150-225	$39.5\,^{+7.0}_{-5.9}$	**45**
		225-300	$11.7\,^{+4.4}_{-3.1}$	**11**
		> 300	$5.7\,^{+3.3}_{-2.1}$	**7**
		100-150	$240.8\,^{+18.9}_{-16.1}$	**238**
≥ 4 jets	≥ 1	150-225	$81.2\,^{+10.7}_{-9.6}$	**99**
		225-300	$24.1\,^{+6.1}_{-5.0}$	**24**
		> 300	$7.2\,^{+3.9}_{-2.6}$	**7**
ATLAS - SR:				
$H_T + p_T^{\ell_1} + p_T^{\ell_2} > 600$ GeV	$E_T^{miss} > 225$ GeV	$\Delta\phi_{E_T^{miss}, j_1, j_2} > 0.4$	$44.1\,^{+8.4}_{-7.5}$	**51**

MET region	150 – 225 GeV	225 – 300 GeV	≥ 300 GeV
Other rare	1.53 ± 0.79	0.80 ± 0.45	0.40 ± 0.23
WZ	7.01 ± 2.16	2.67 ± 0.85	2.61 ± 0.84
ZZ	4.20 ± 1.98	2.60 ± 1.36	2.03 ± 1.08
DY prediction	18.28 ± 2.91	4.69 ± 2.32	2.73 ± 1.56
$t\bar{t}$	3.91 ± 1.36	0.50 ± 0.27	0.10 ± 0.11
Total bkg	34.9 ± 4.4	11.3 ± 2.9	7.9 ± 2.1
Observed	45	15	7



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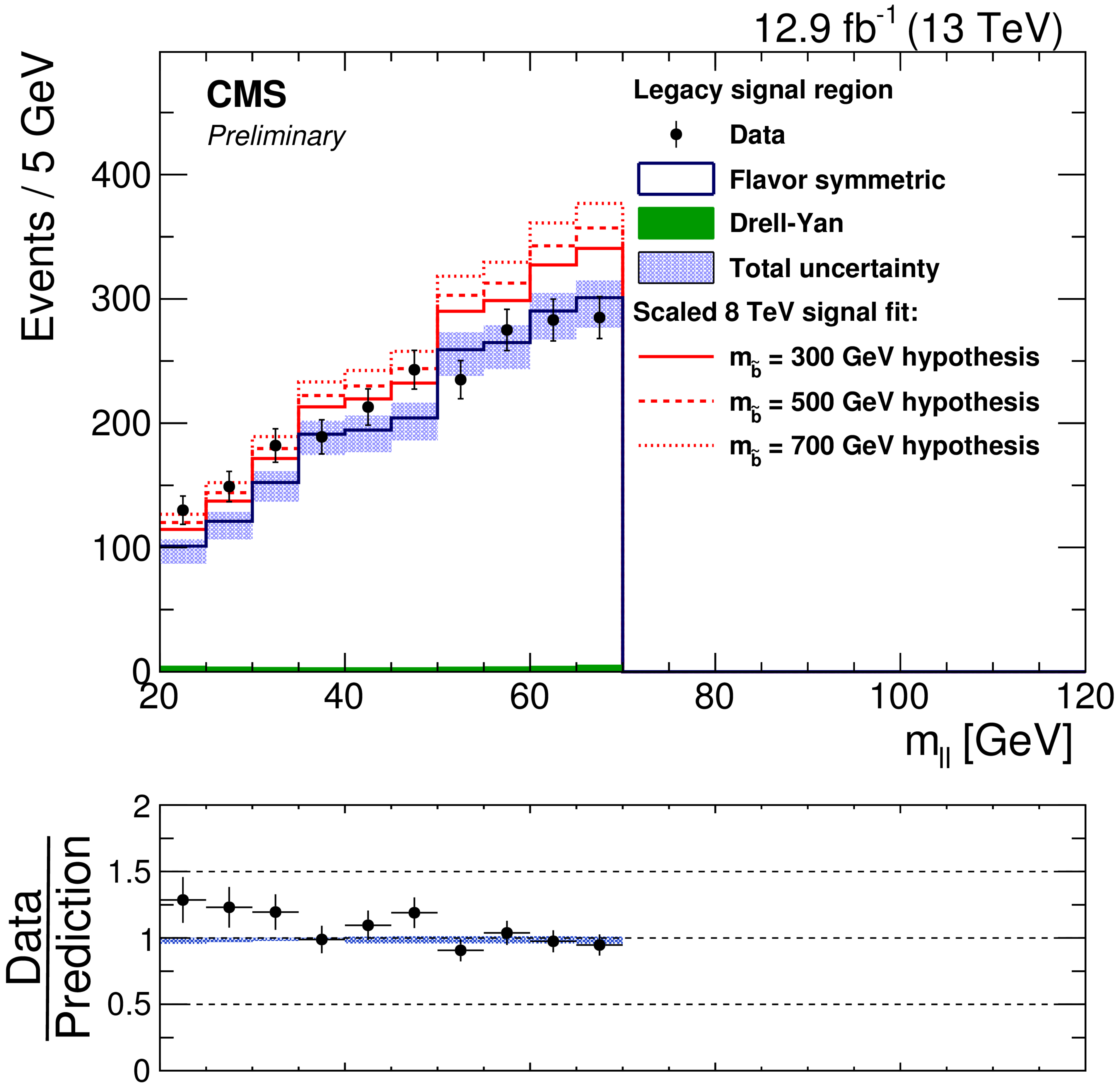
Results: Run I CMS legacy region

CMS Run I excess signal region kept for verificatior

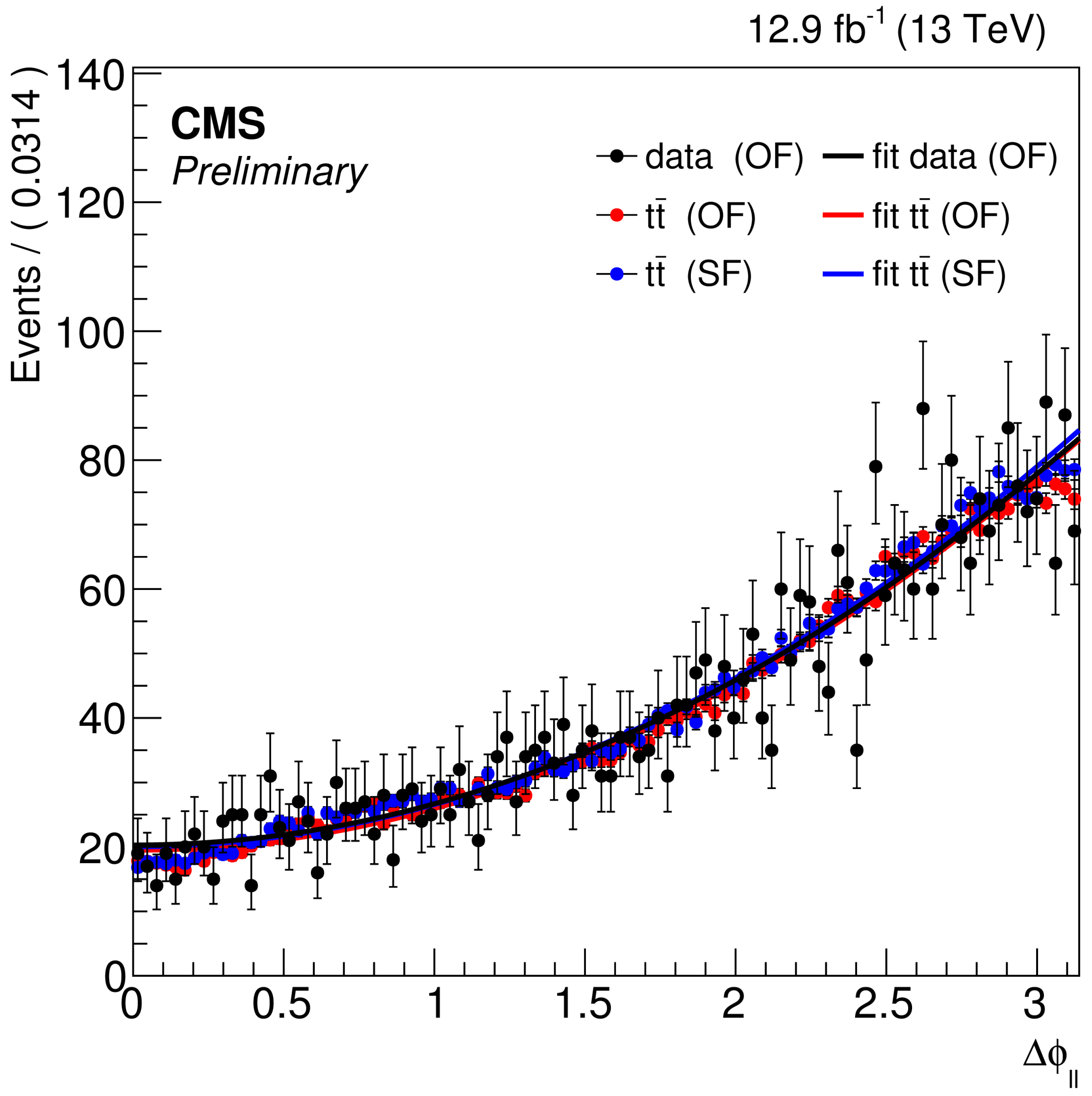
- E_T^{miss} : 100 GeV if > 3 jets (central leptons)
- E_T^{miss} : 150 GeV if > 2 jets (central leptons)

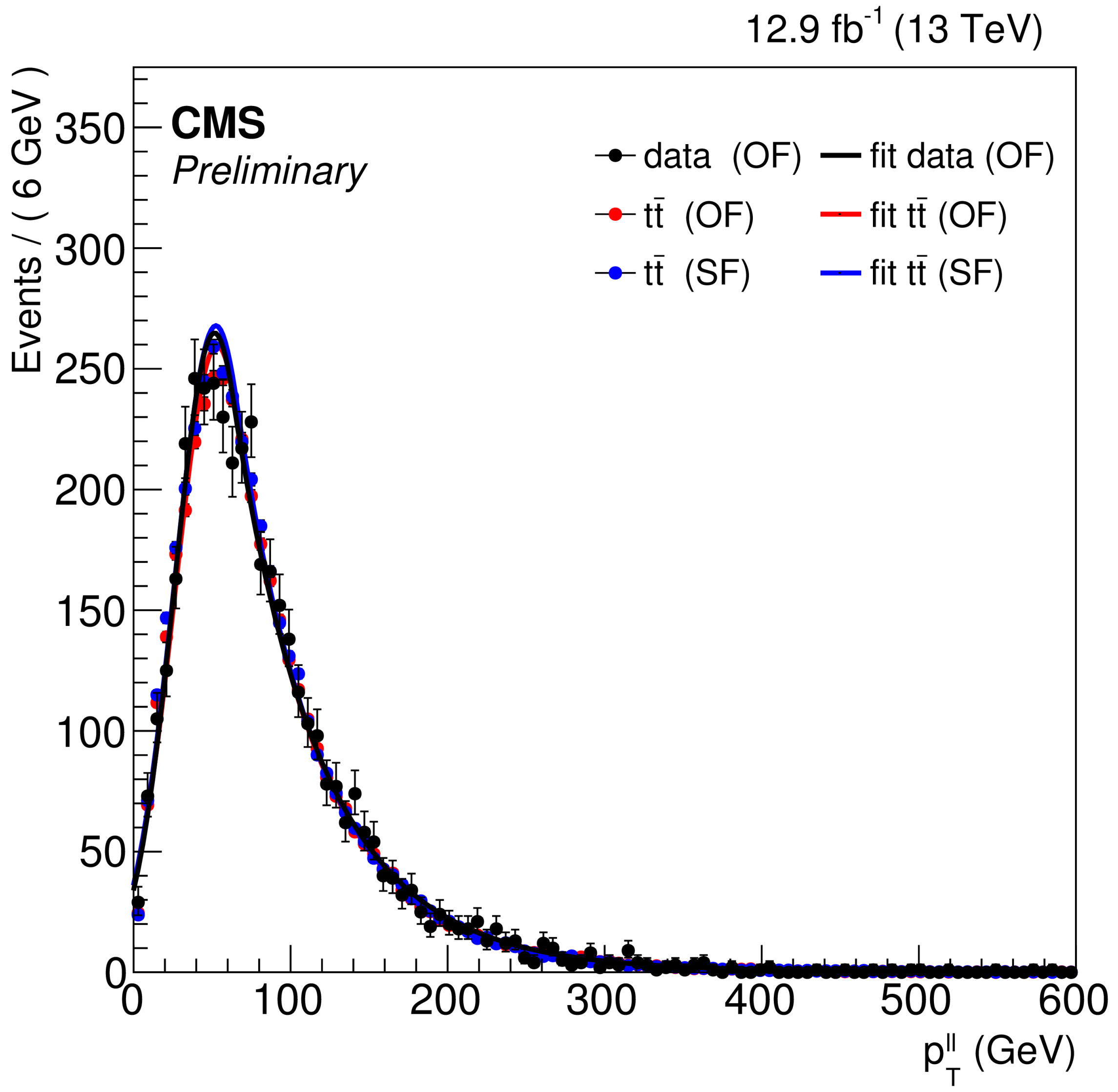
- Results in numbers:
  - observed: 2170
  - predicted: 2053 +- 68 (1.4 sigma local significance)

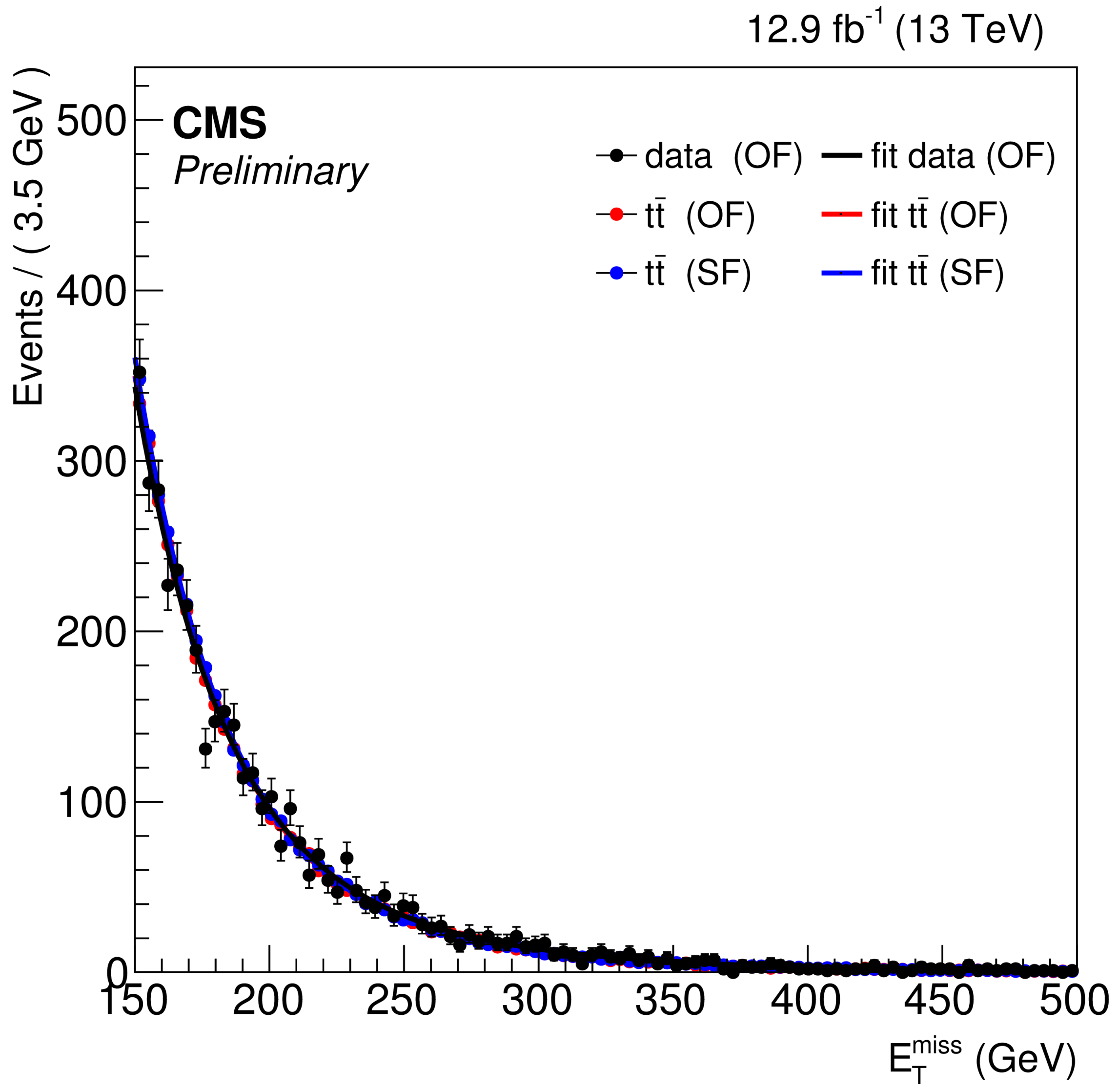


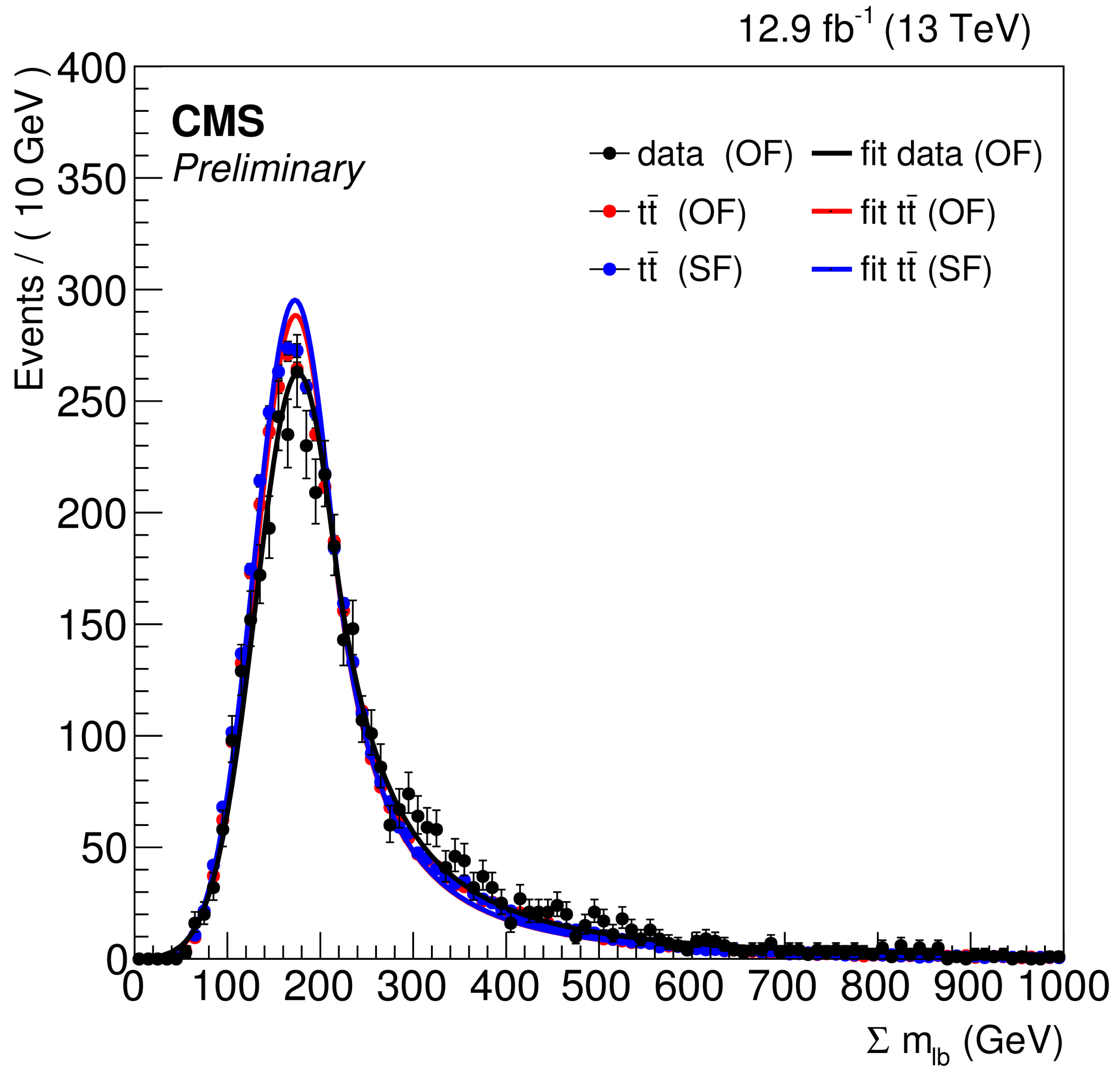
Top likelihood classification

- The four characteriztic 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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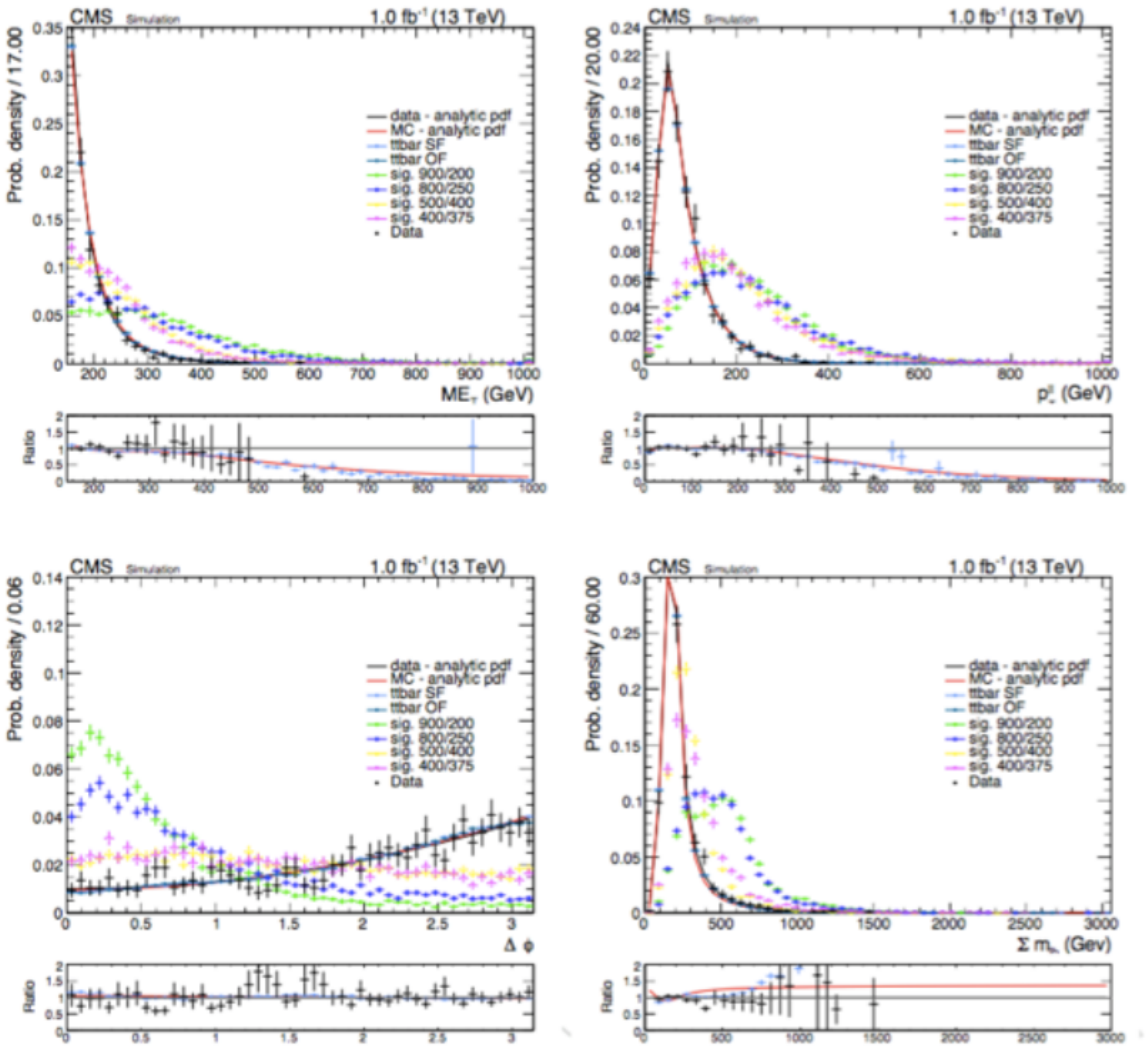
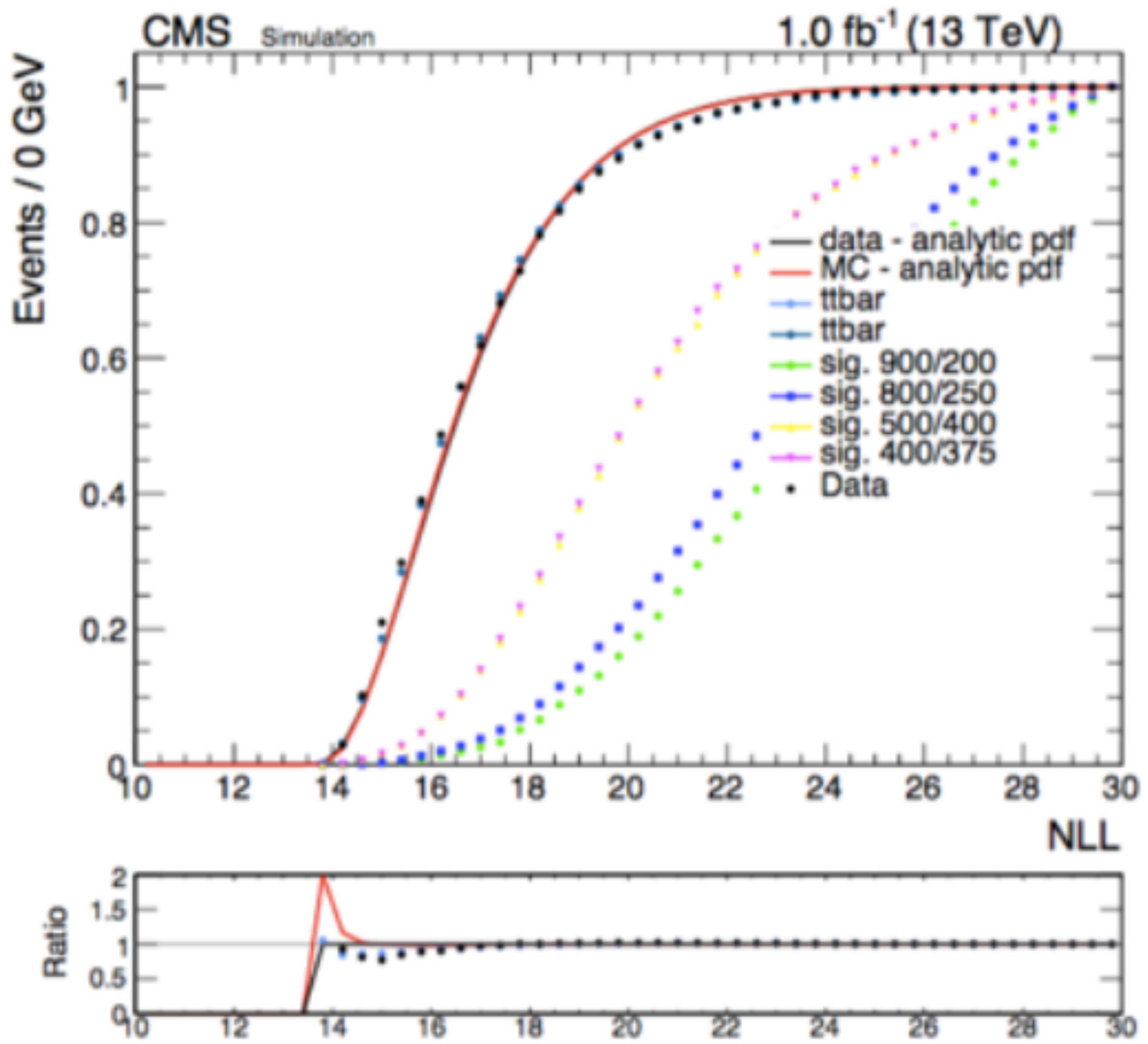
Top likelihood classification





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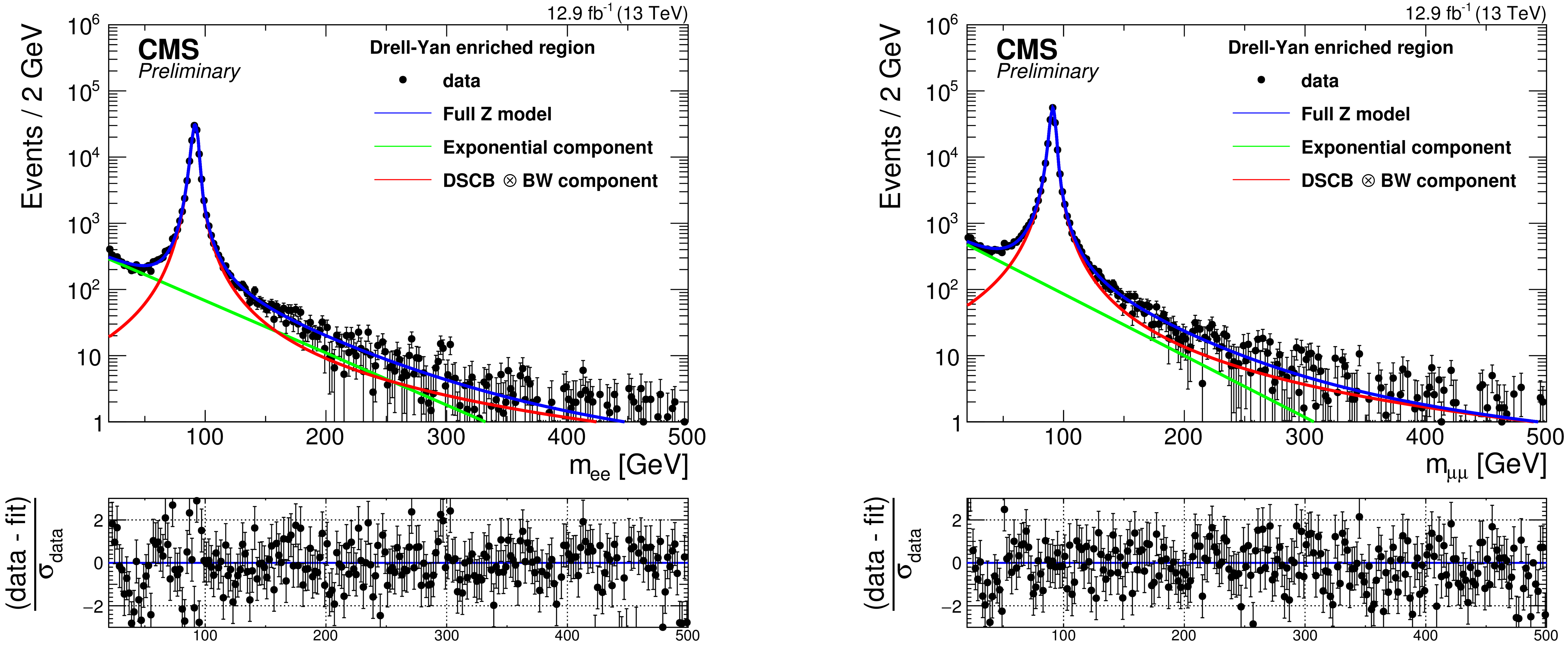
Fits

Fitted shape for backgrounds containing a Z boson for dielectron and dimuon events. The fitted shape consists of an exponential (green) and a Breit-wigner convolved with a double-sided Crystal-Ball (red), whose sum (blue) describes the backgrounds containing a Z boson

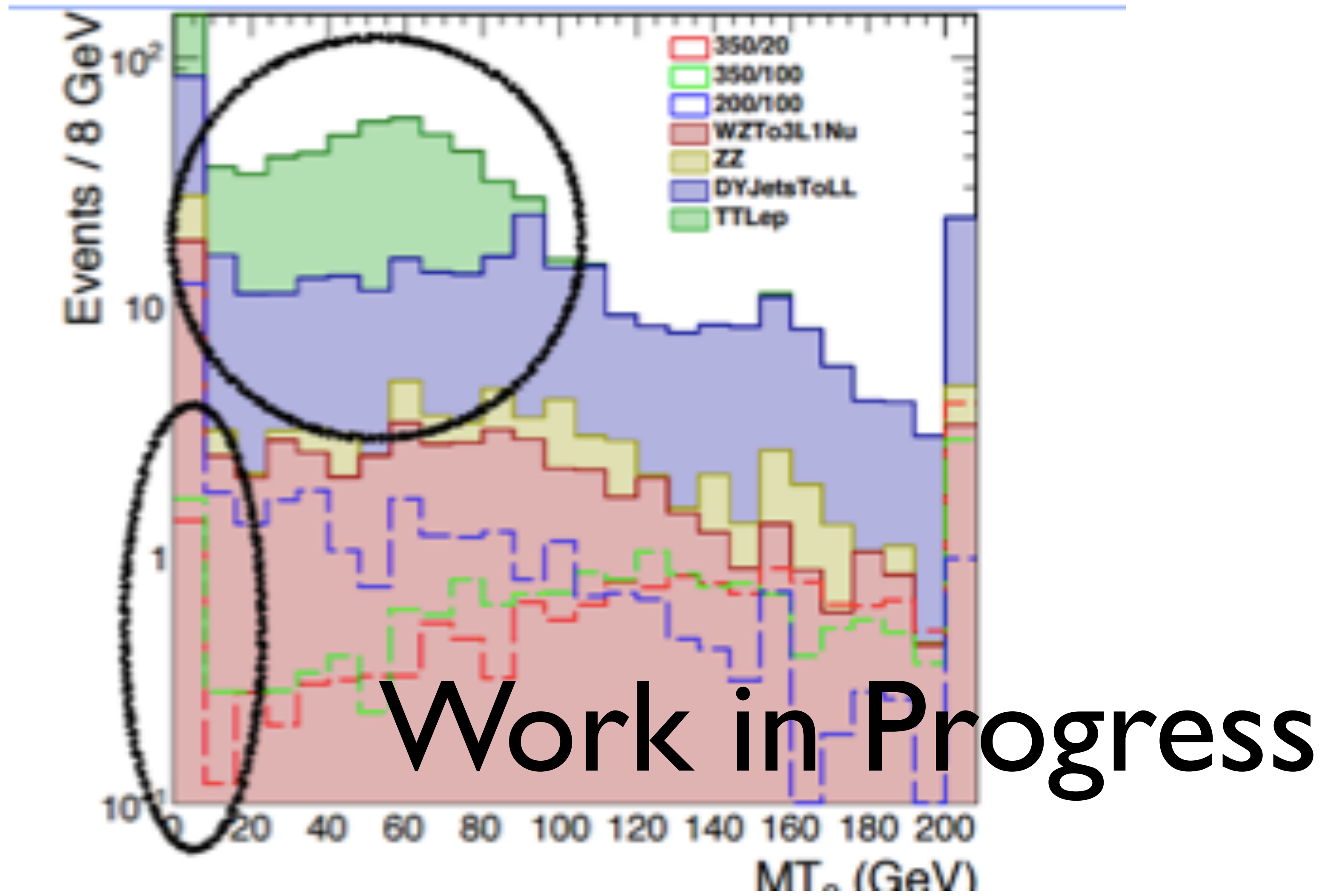


M_{T2}

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 ($\sim M_T$)
- Very efficient to reduce ttbar and other backgrounds



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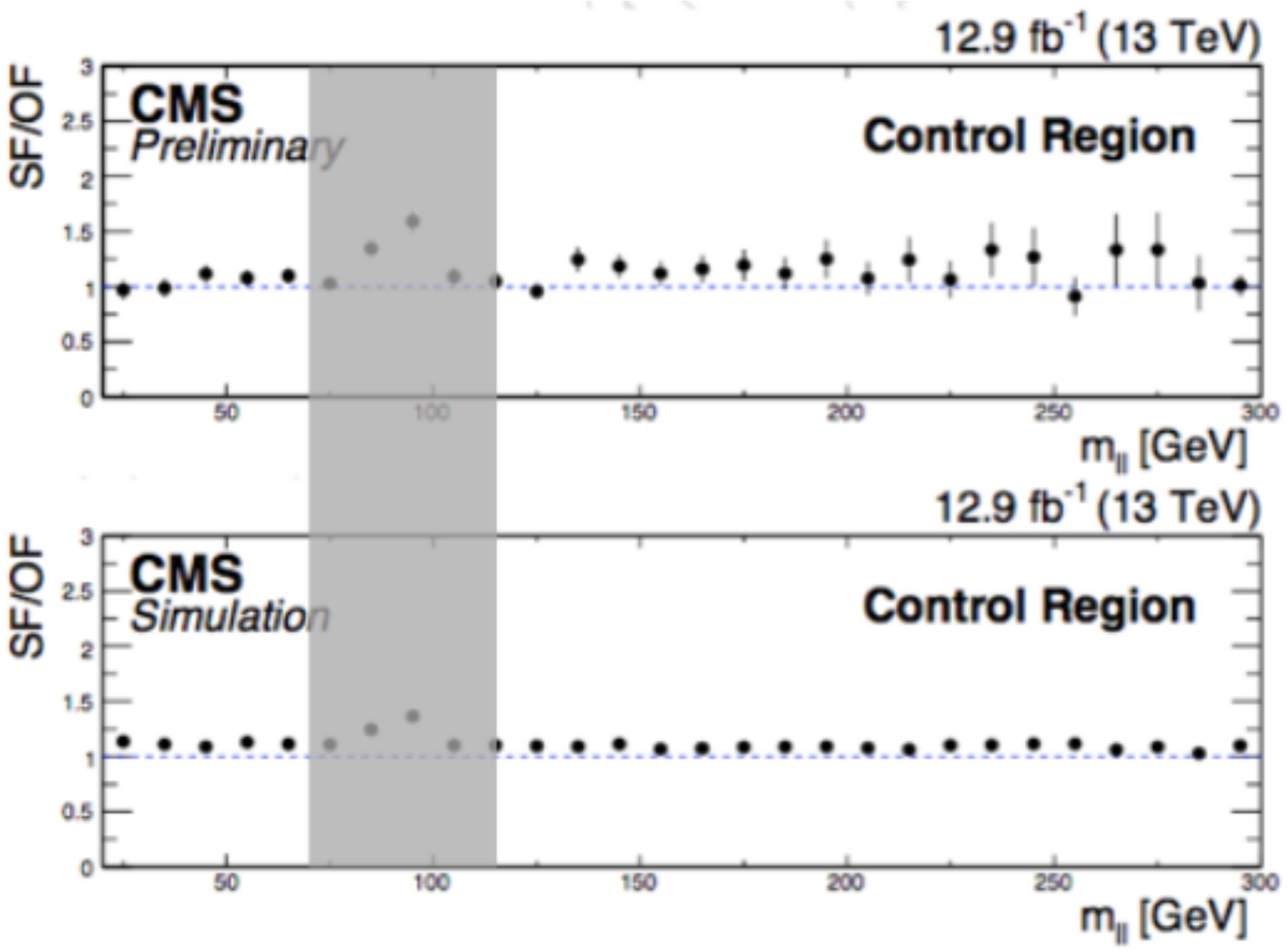
$R_{SF/OF}$

direct measurement

ME_T 50-100, == 2 jets

	N_{SF}	N_{OF}	$R_{SF/OF} \pm \sigma_{stat}$
Data	4901	4495	1.090±0.023
MC	5120.3	4649.4	1.101±0.003
	N_{ee}	N_{OF}	$R_{ee/OF} \pm \sigma_{stat}$
Data	1822	4495	0.405±0.011
MC	1930.2	4649.4	0.415±0.001
	$N_{\mu\mu}$	N_{OF}	$R_{\mu\mu/OF} \pm \sigma_{stat}$
Data	3079	4495	0.685±0.016
MC	3190.2	4649.4	0.686±0.003



factorized method: $R_{SFOF} = 0.5*(r_{\mu e} + r_{\mu e}^{-1})*R_T$

$R_T = sqrt(ee_T*\mu\mu_T)/e\mu_T$

$r\mu e = sqrt(ee/\mu\mu)$

	$R_{SF/OF}$ Data	$R_{SF/OF}$ MC
from factorization method	1.096±0.076	1.083±0.073
from direct measurement	1.090±0.024	1.101±0.003
weighted avarage	1.091±0.023	1.101±0.003

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Systematic uncertainties for the signal

Source of uncertainty	Uncertainty (%)
Luminosity	6.2
Pileup	0-3
b tag modeling	0-5
Lepton reconstruction and isolation	7
Fast simulation scale factors	4-5
Fast simulation MET uncertainty	1-10
Trigger modeling	5
Jet energy scale	1-5
ISR modeling	0-10
Statistical uncertainty	1-9
Total uncertainty	12-16