Search for Supersymmetry with opposite sign dileptons with the CMS detector

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PhD Seminar, ETH Zürich

24/11-2016

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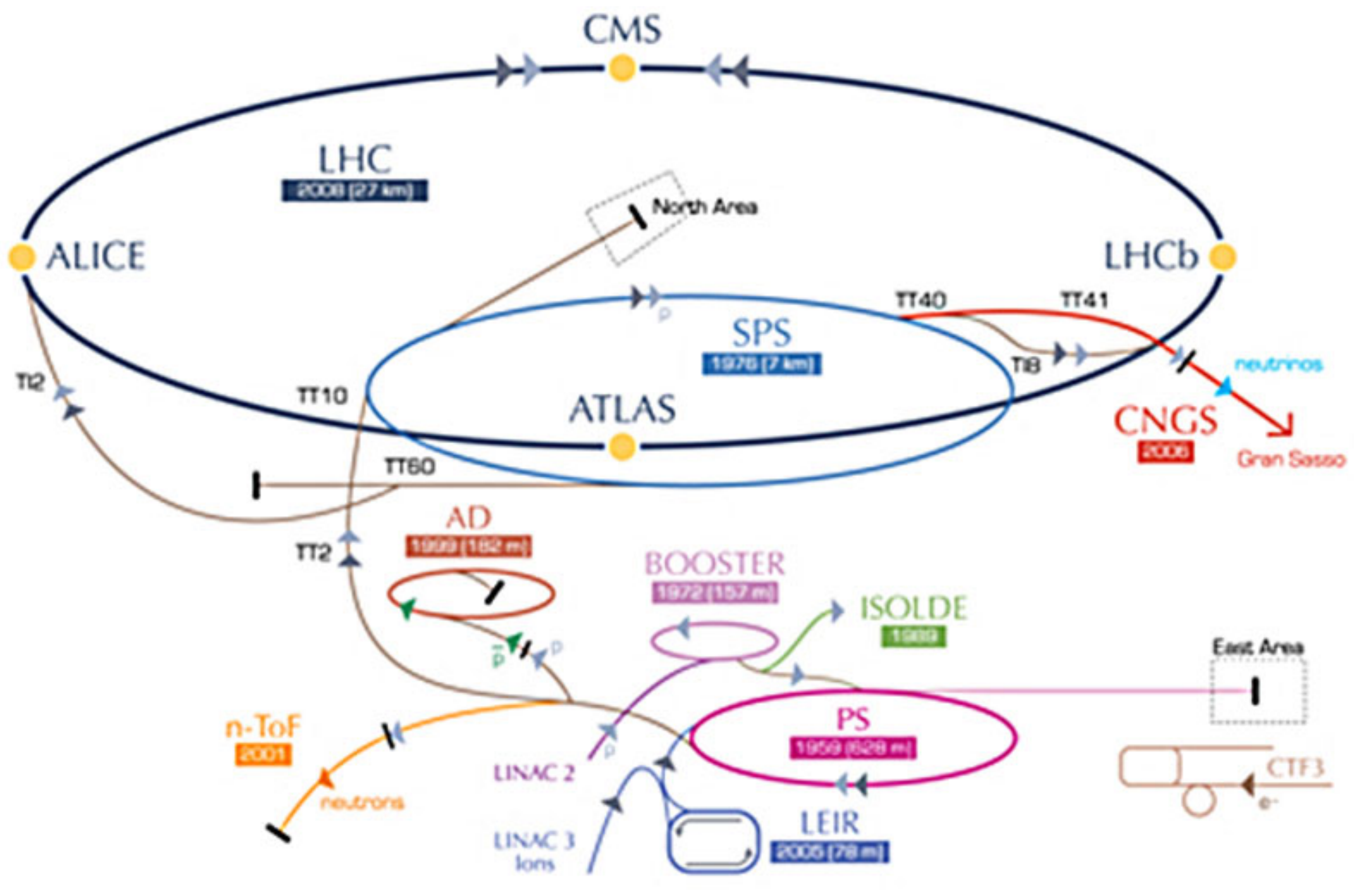
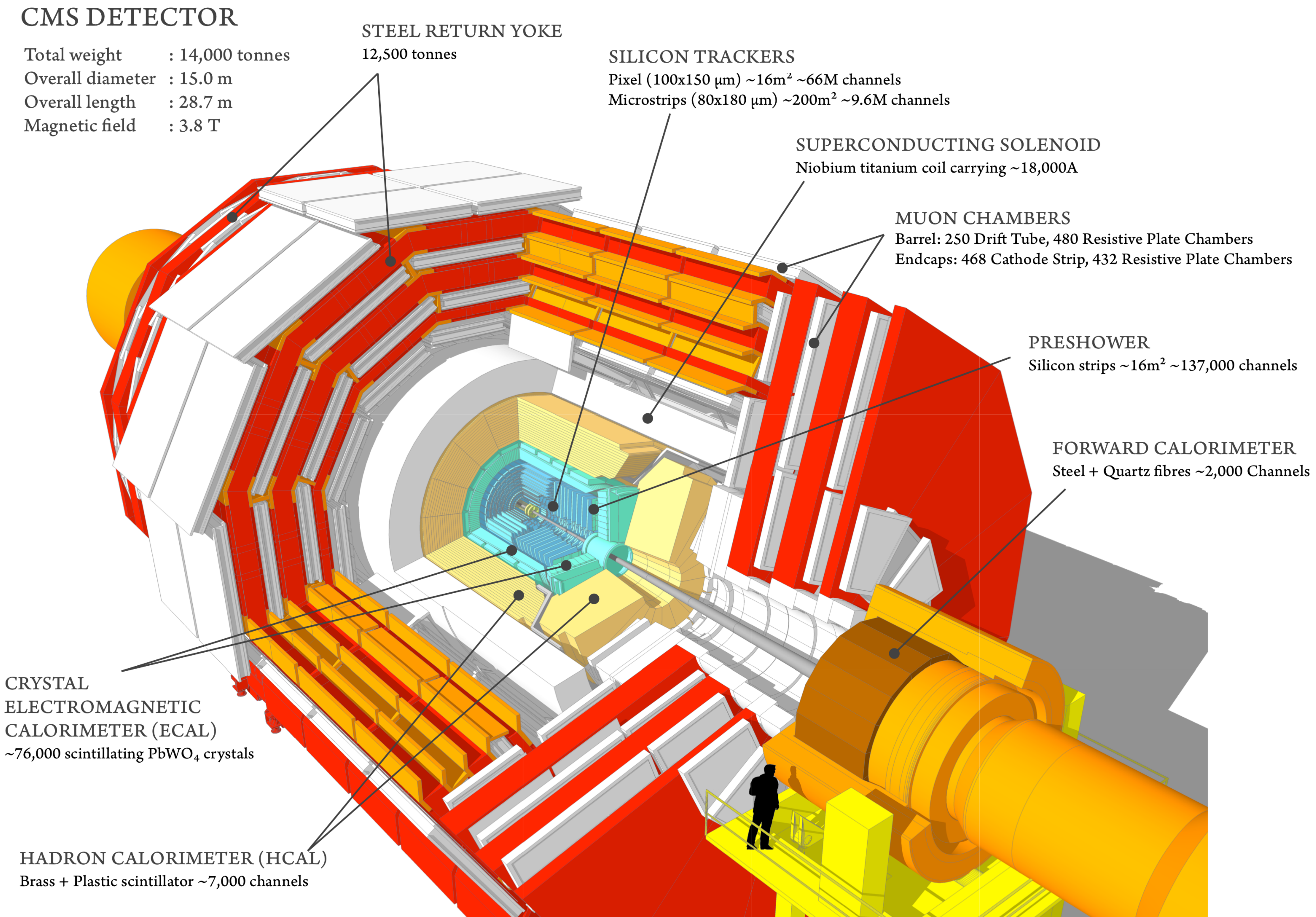
The Large Hadron Collider and CMS



CERN Accelerator Complex and the LHC



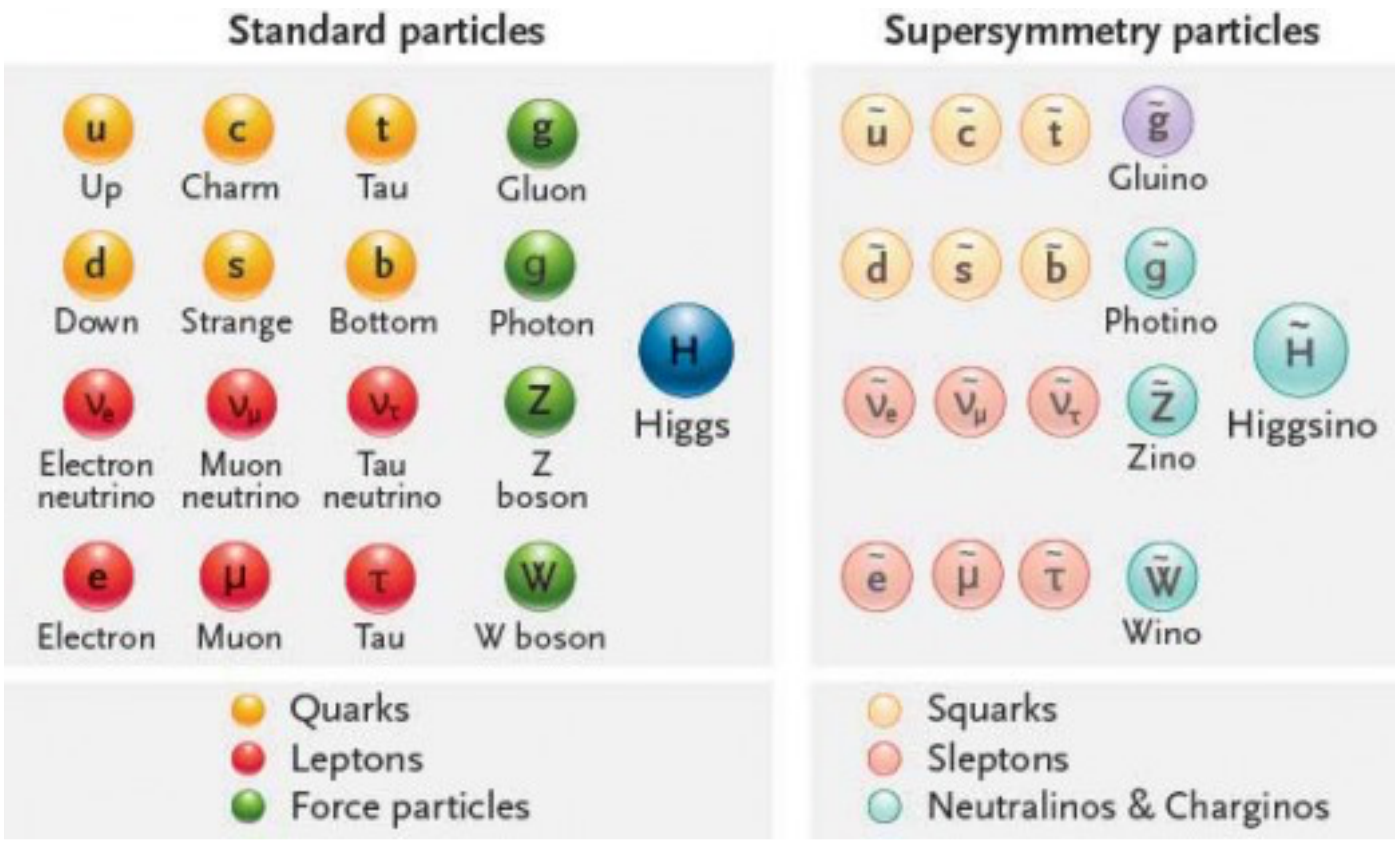
Supersymmetry

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 grand unification theory
- provides a good 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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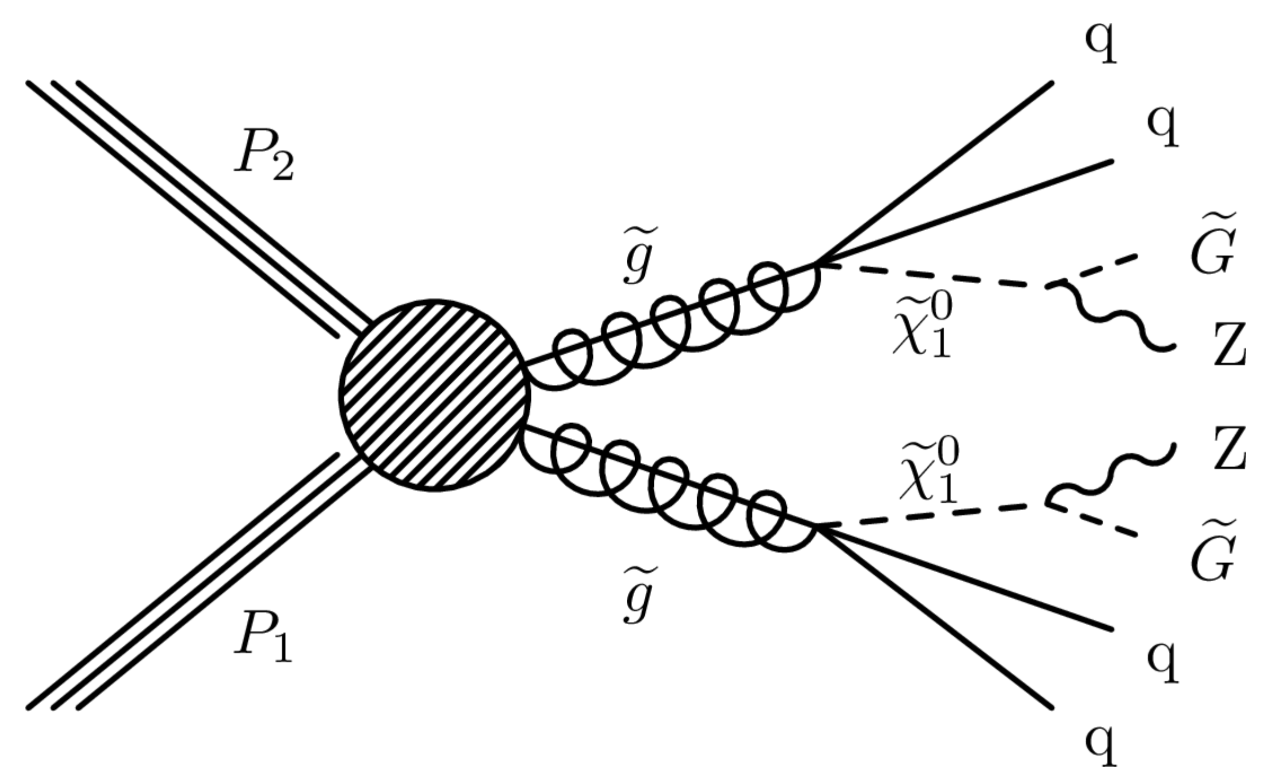

GMSB (gluino induced):

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

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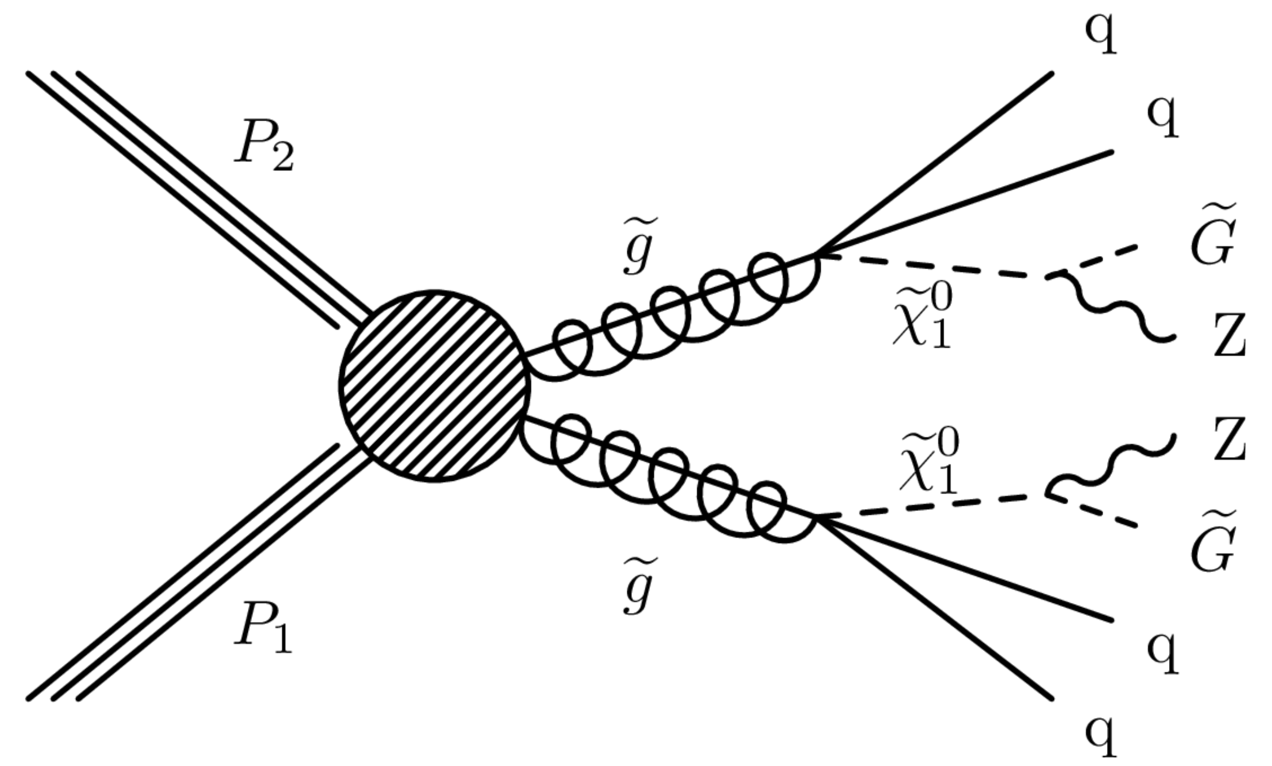

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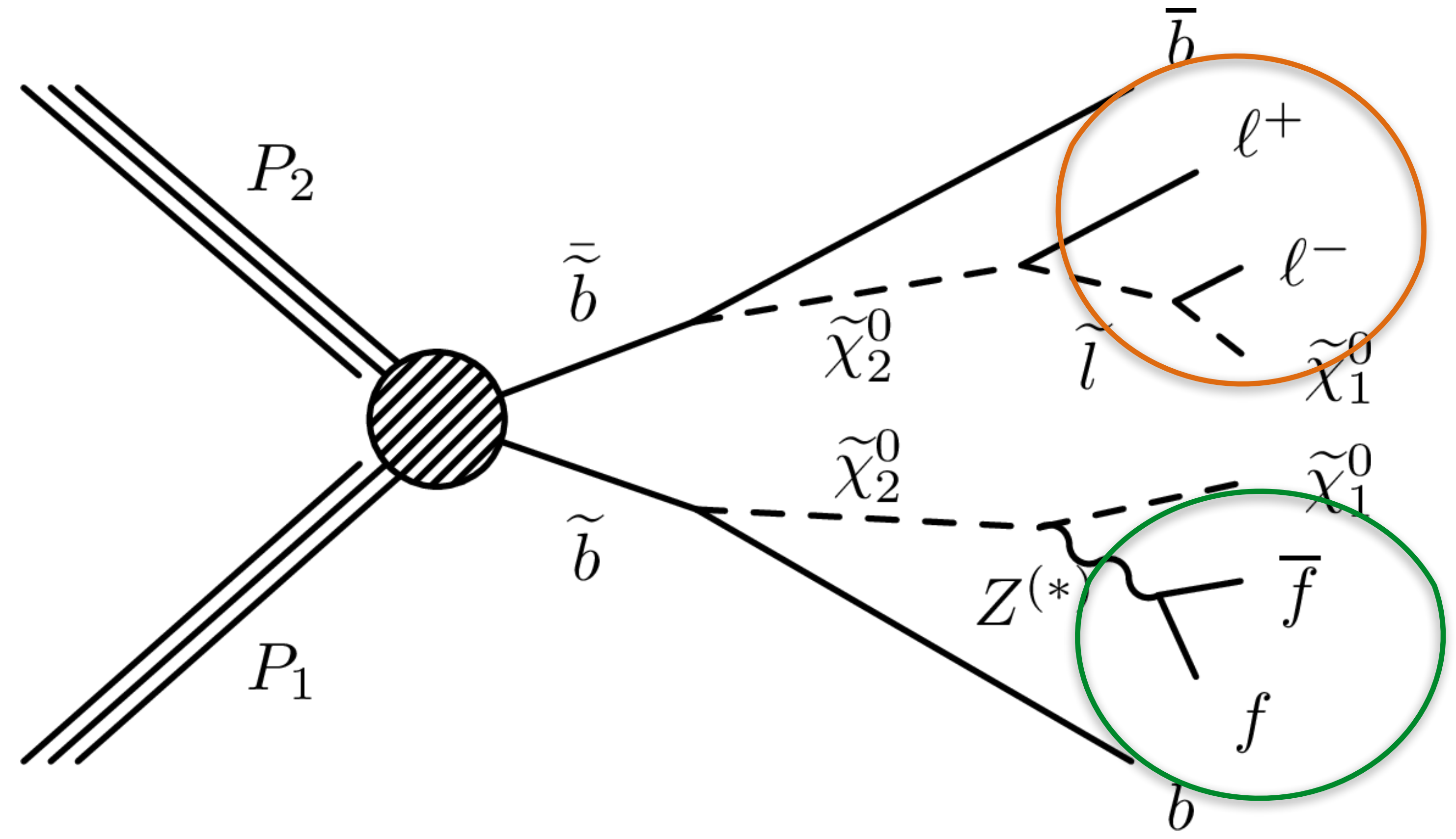

Slepton (sbottom induced):

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- 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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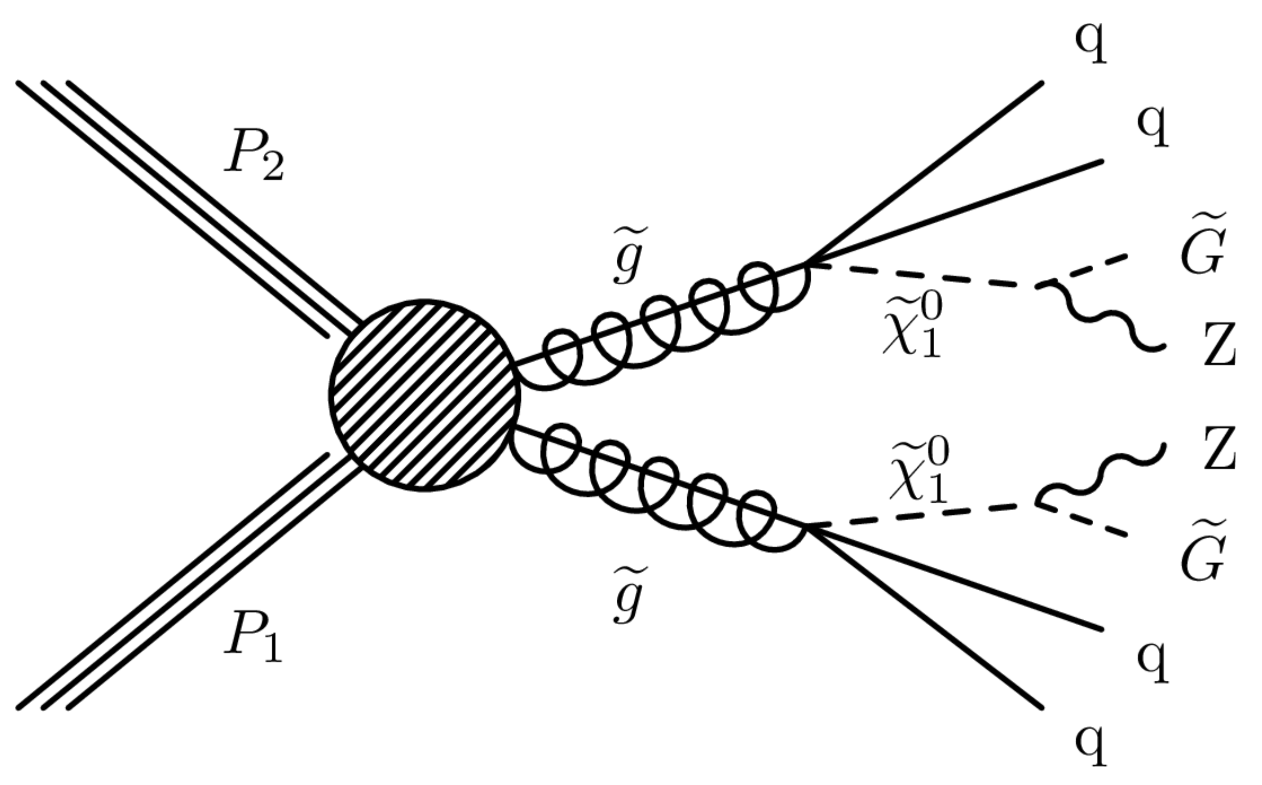

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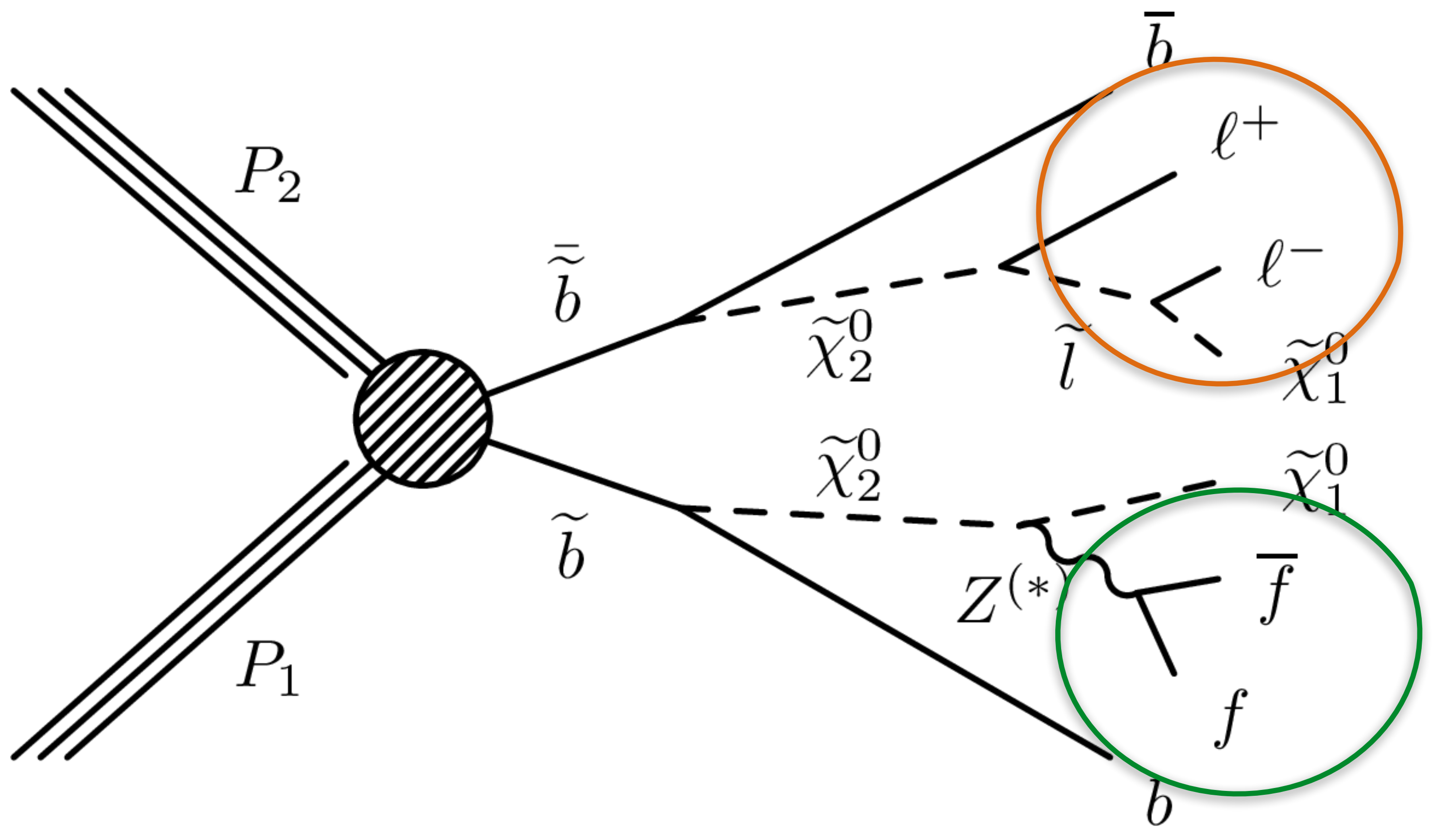

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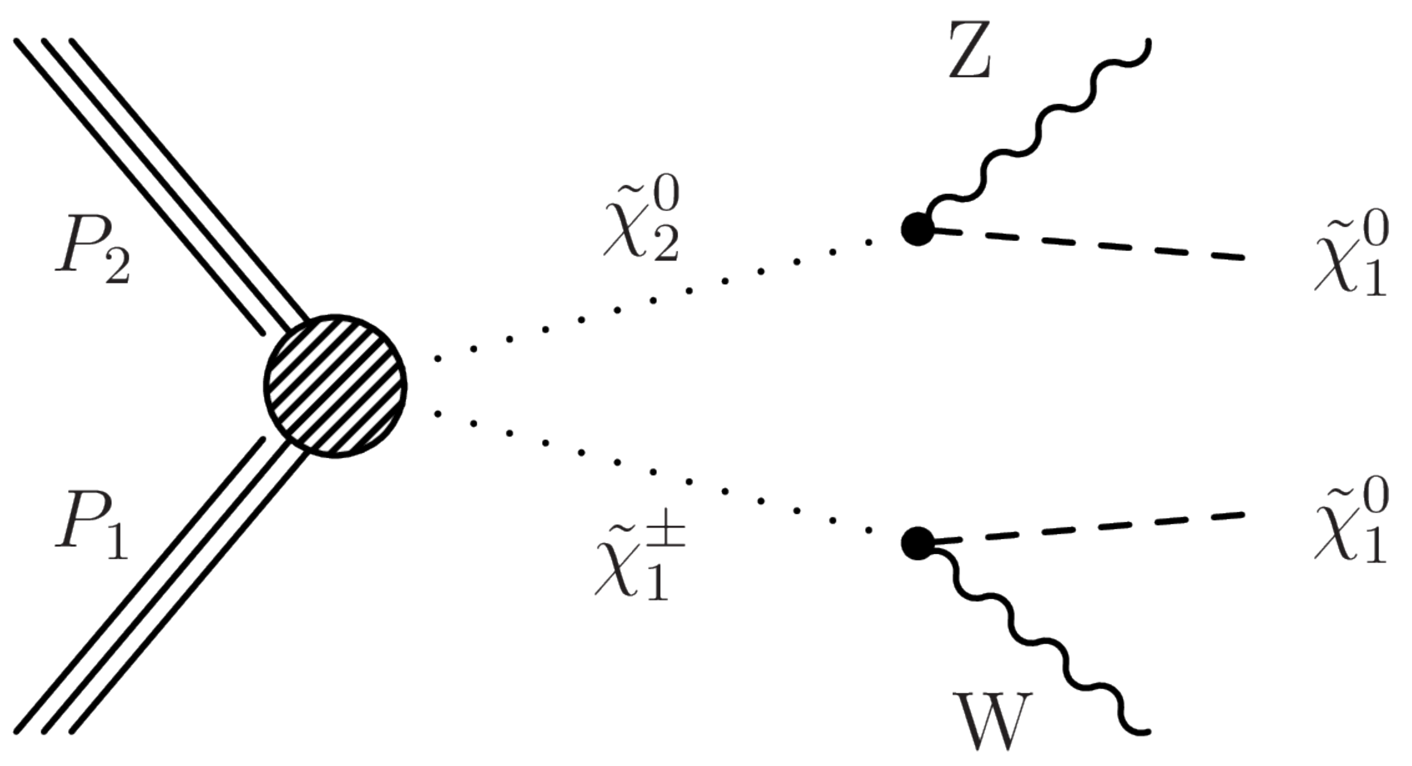

EWK (Chargino/Neutralino induced):

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

SUSY with opposite sign dileptons

This analysis is done using LHC Run II data recorded in 2016 corresponding to an integrated luminosity of 12.9 fb^{-1}

Results were presented for ICHEP in August 2016, new developments for the analysis are made to target a publication by March 2017.

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

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- fit signal and background

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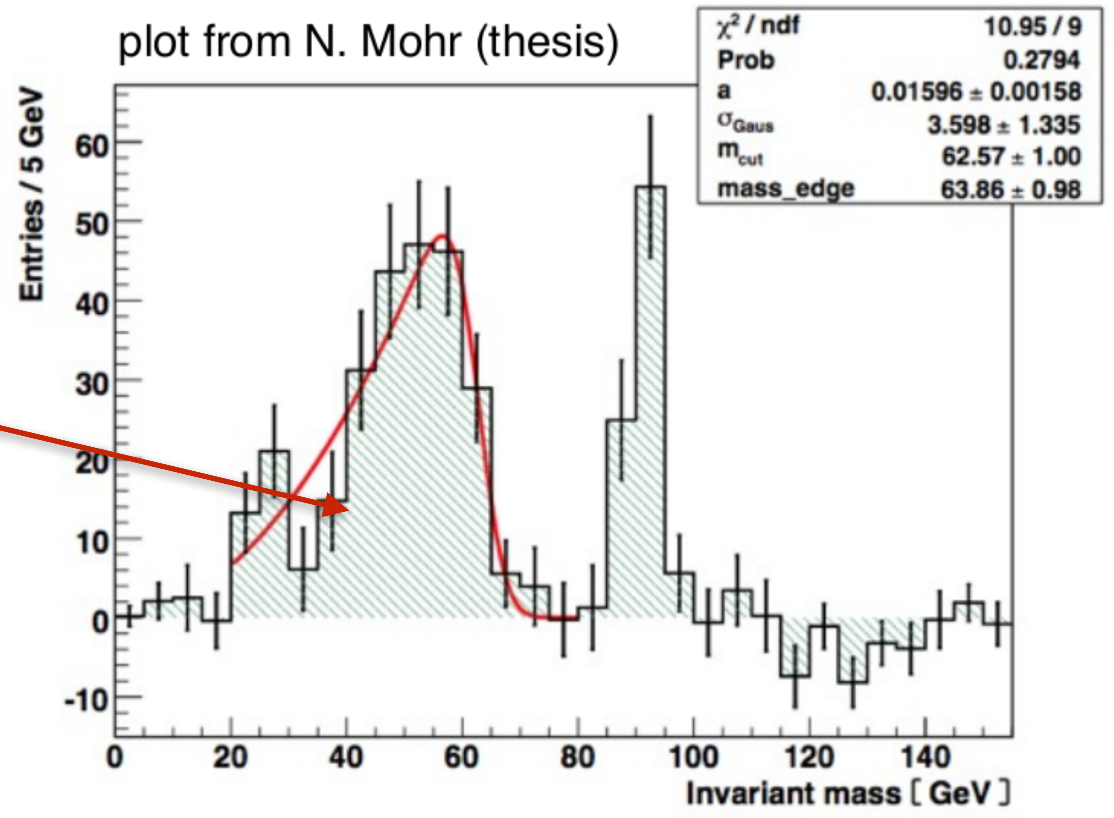
Edge/Off-Z:

- 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

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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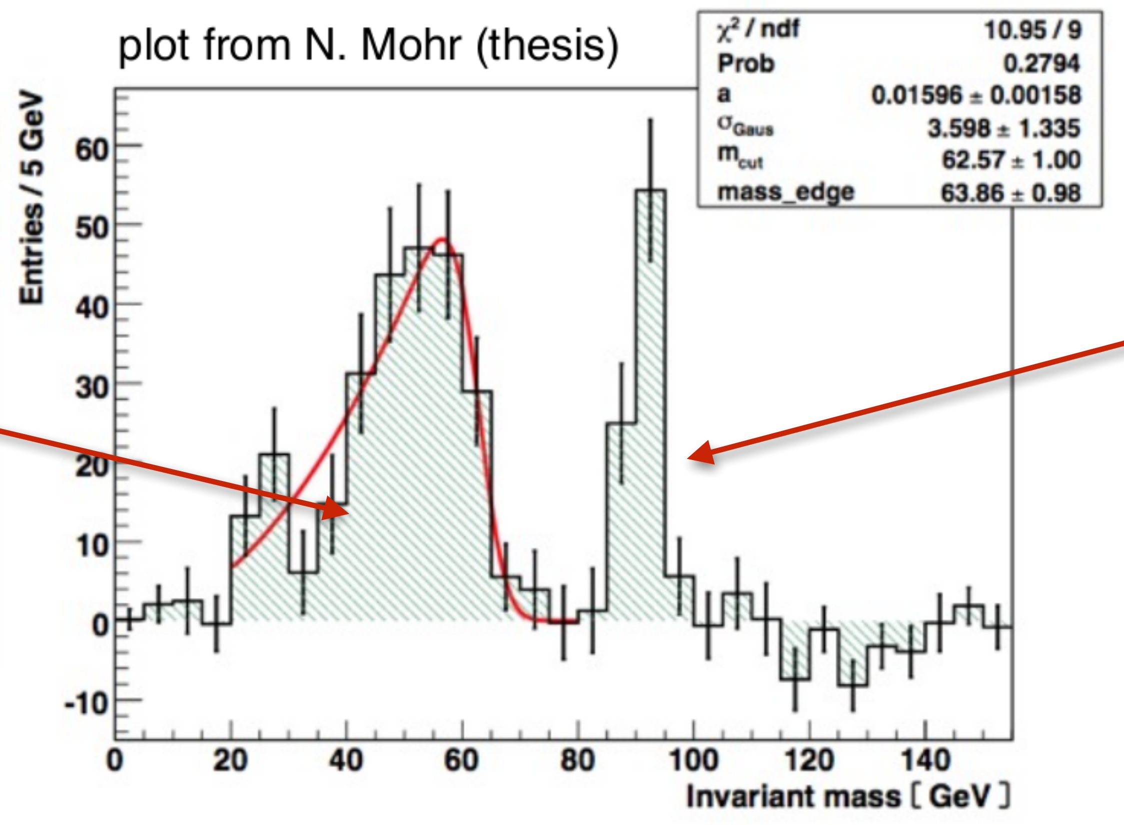

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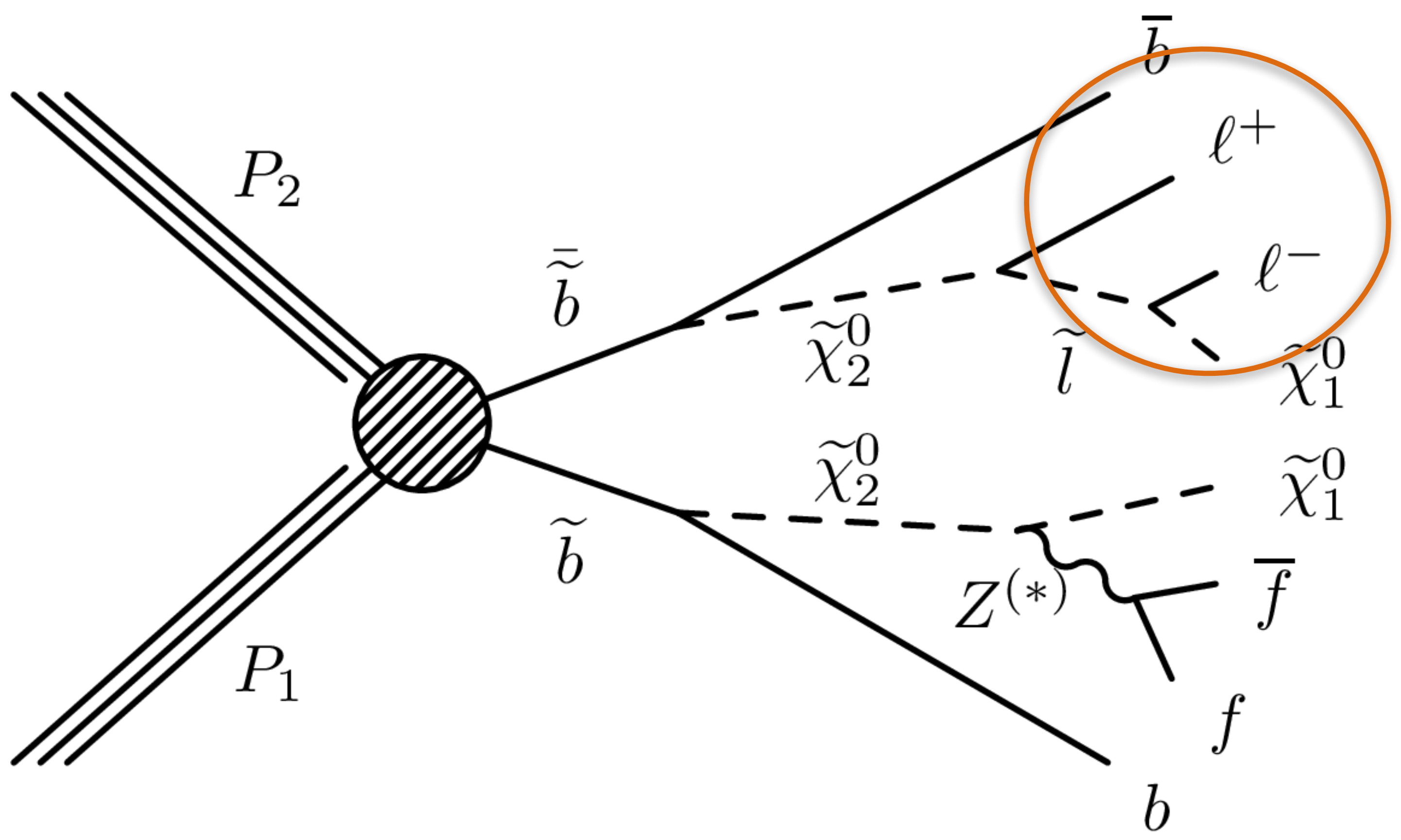
On-Z:

- 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

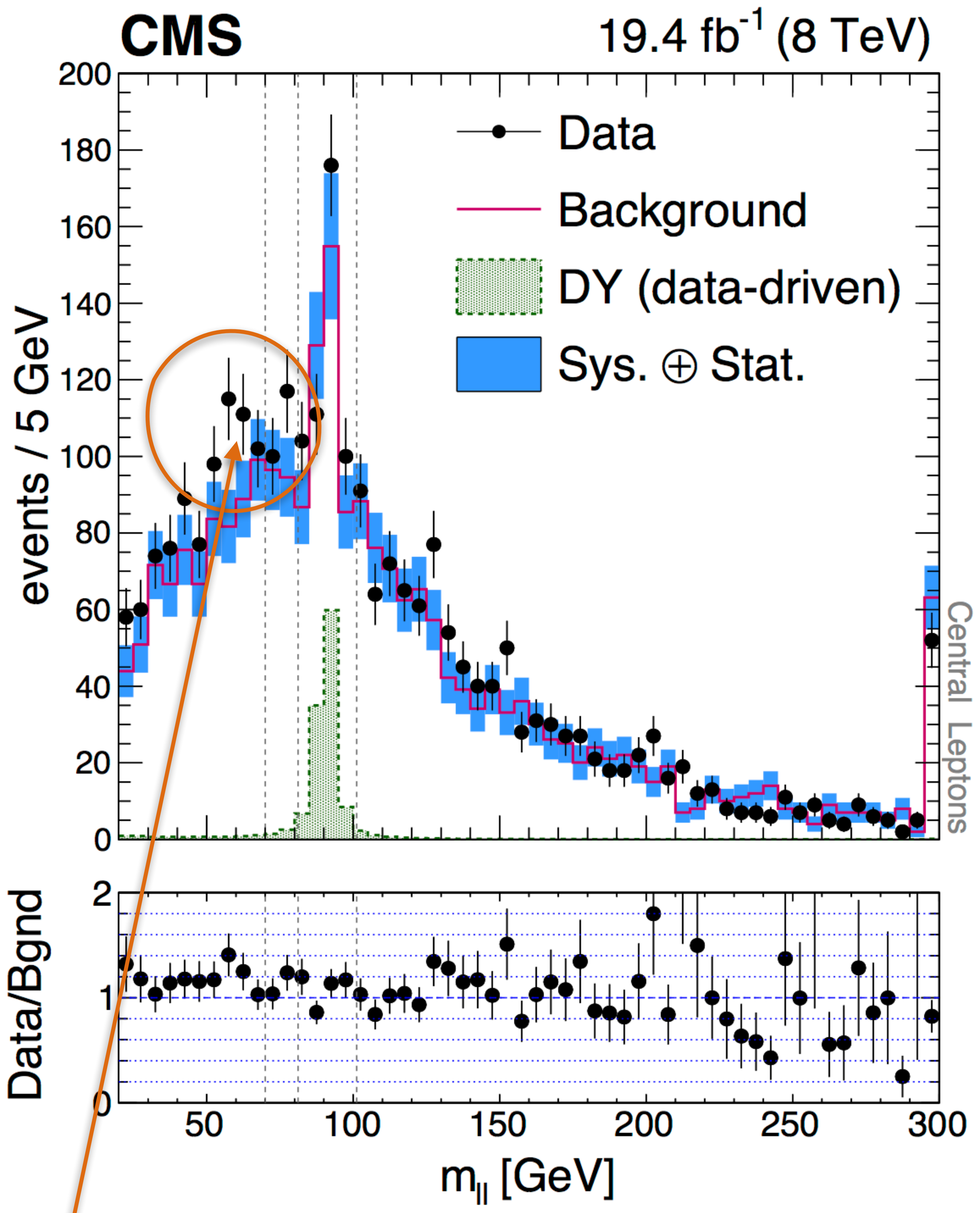
History of the analysis: Edge/Off-Z

Reminder:

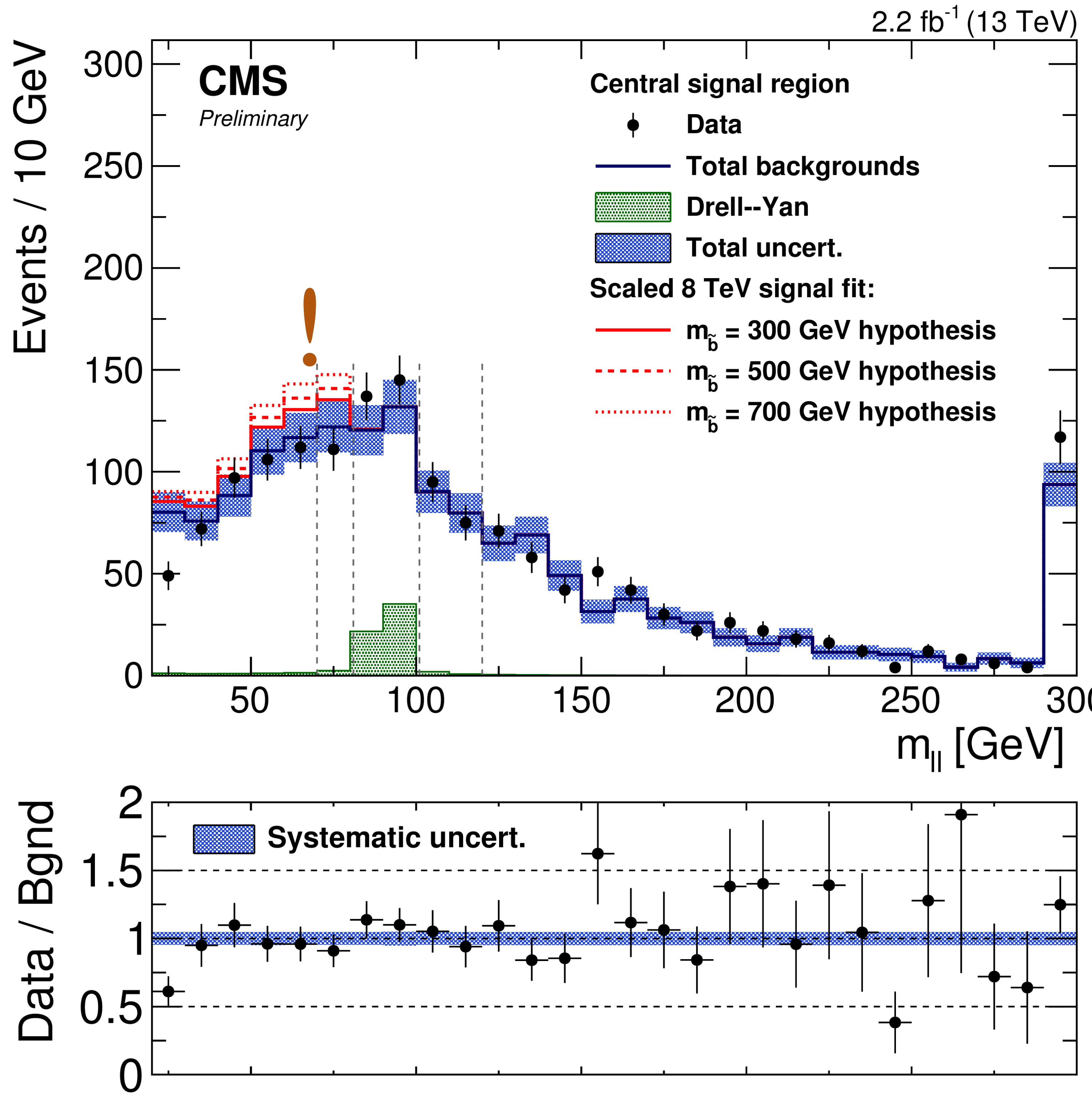
The Edge/Off-Z part of the analysis predicts a kinematic edge in the invariant mass of the two leptons



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

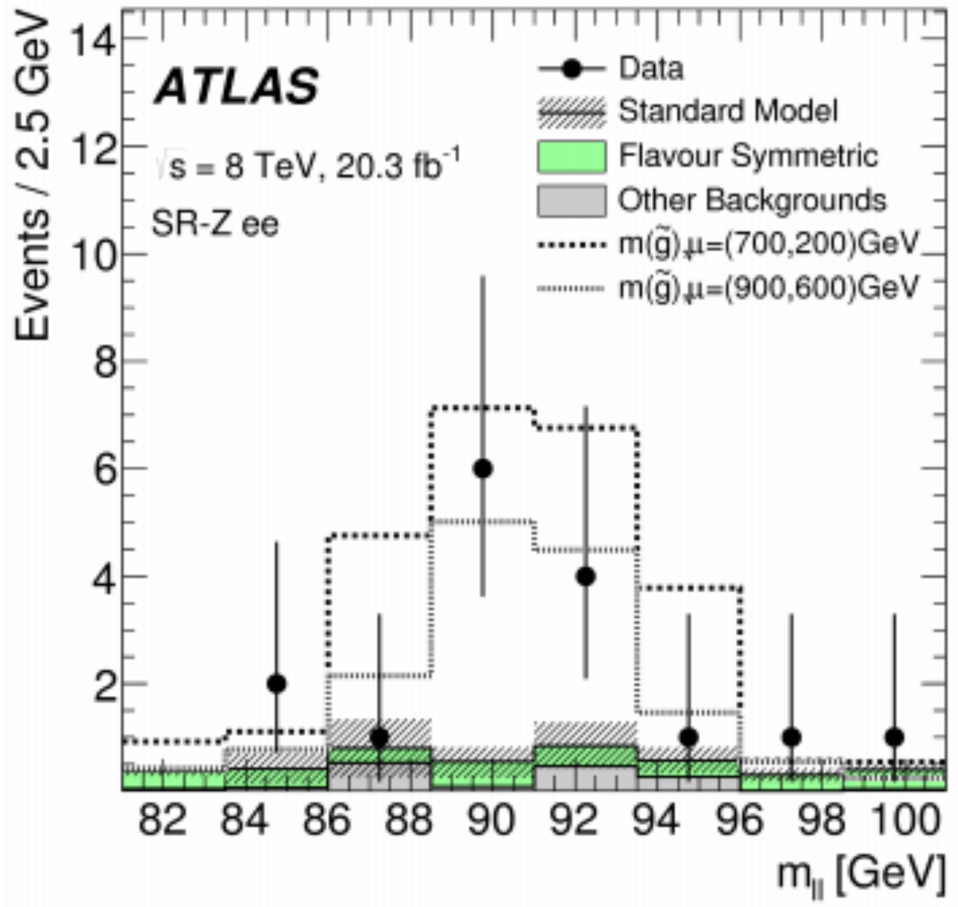
This could not be verified with the first Run II data collected in 2015

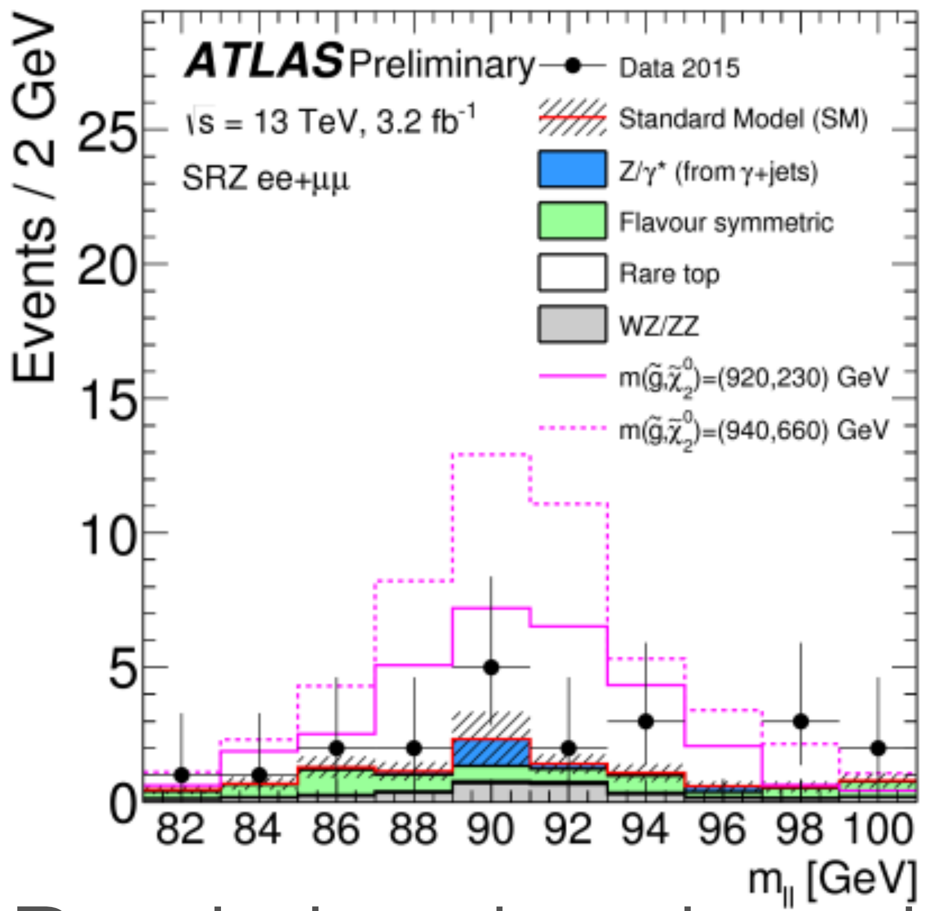
History of the analysis: On-Z

In the LHC Run I ATLAS reported an excess of 3.0 sigma, and in the first Run II data collected in 2015, an excess of 2.2 sigma

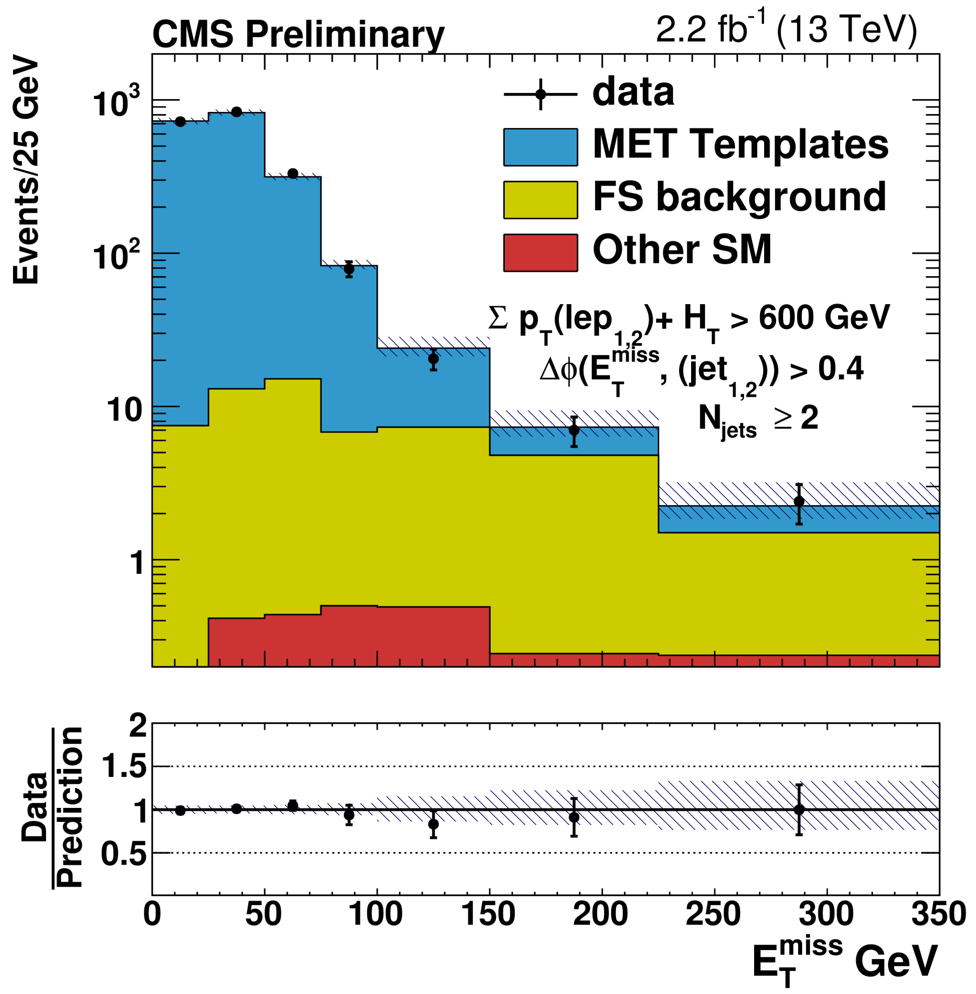
Reminder:

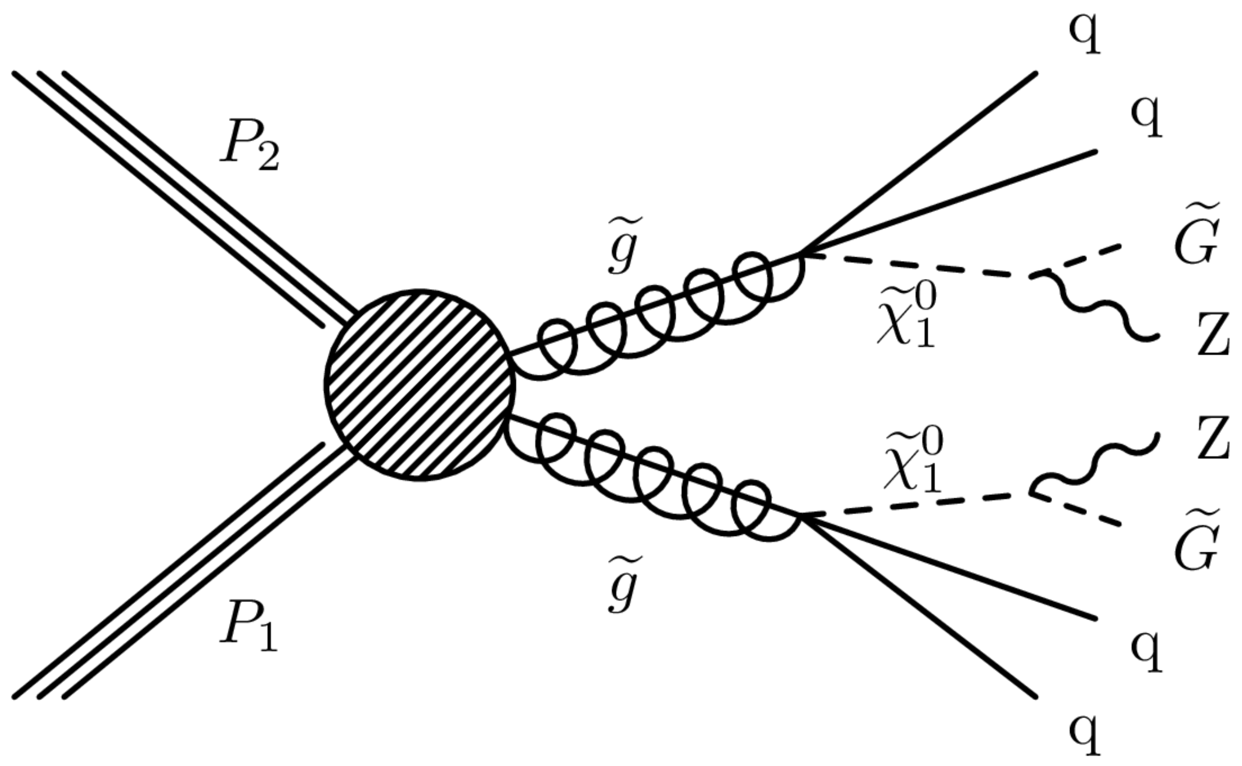
The On-Z part of the analysis targets an excess in the Z mass window in E_T^{miss} tails





CMS tried to confirm this excess with the first data of Run II in the ATLAS Run I signal region without luck…



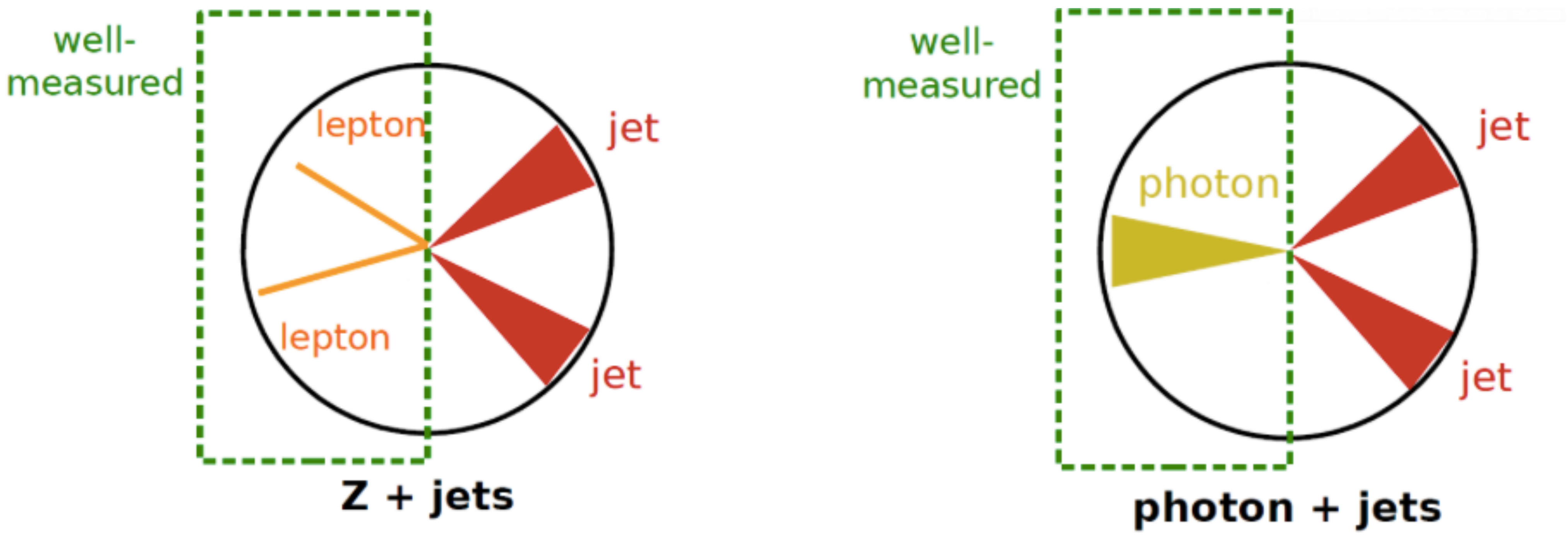


Background prediction

On-Z:
- ~50% Z+jets, 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 flavour symmetry of the W decay (#SF ~#OF events)
- SF signal estimated from OF control sample
  - correct for different trigger, object and reconstruction efficiencies

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

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

Run II 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:

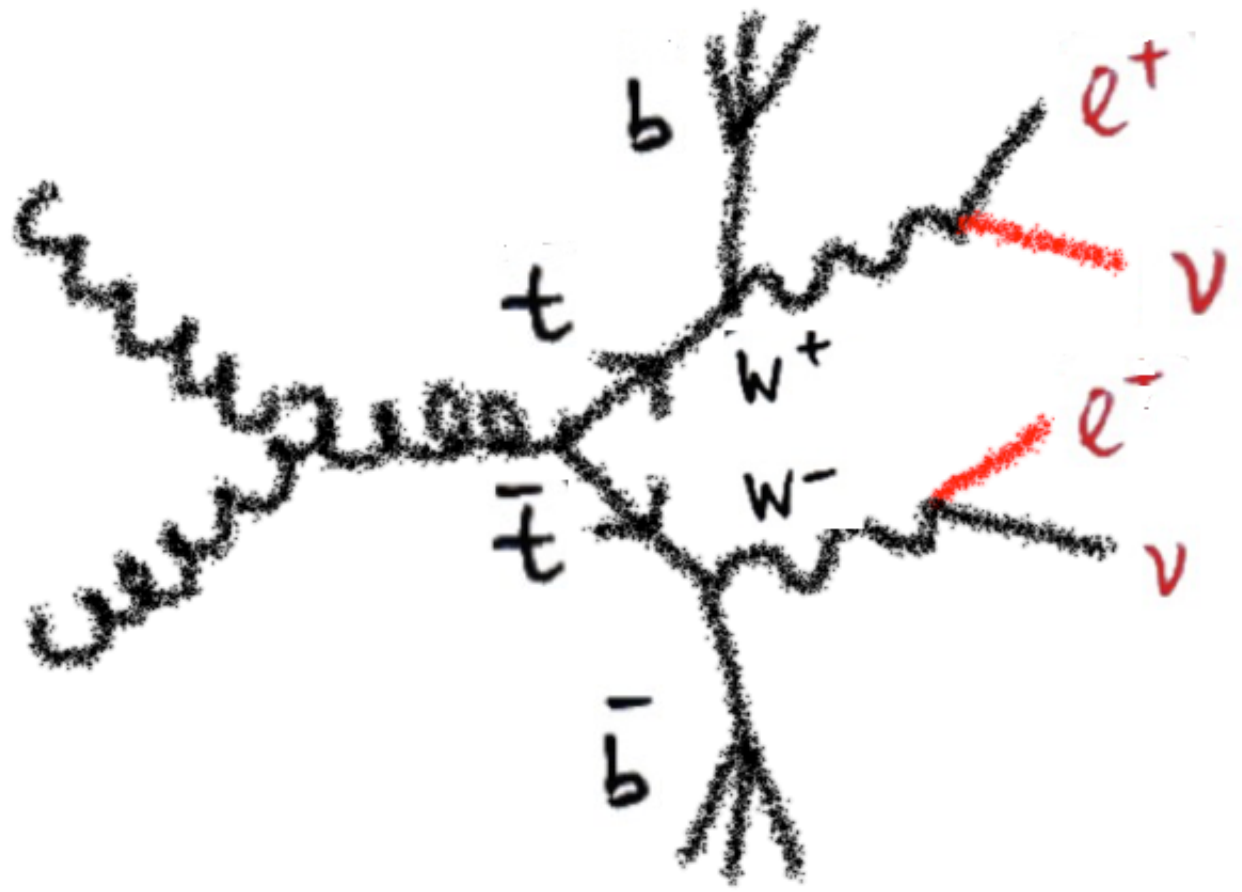
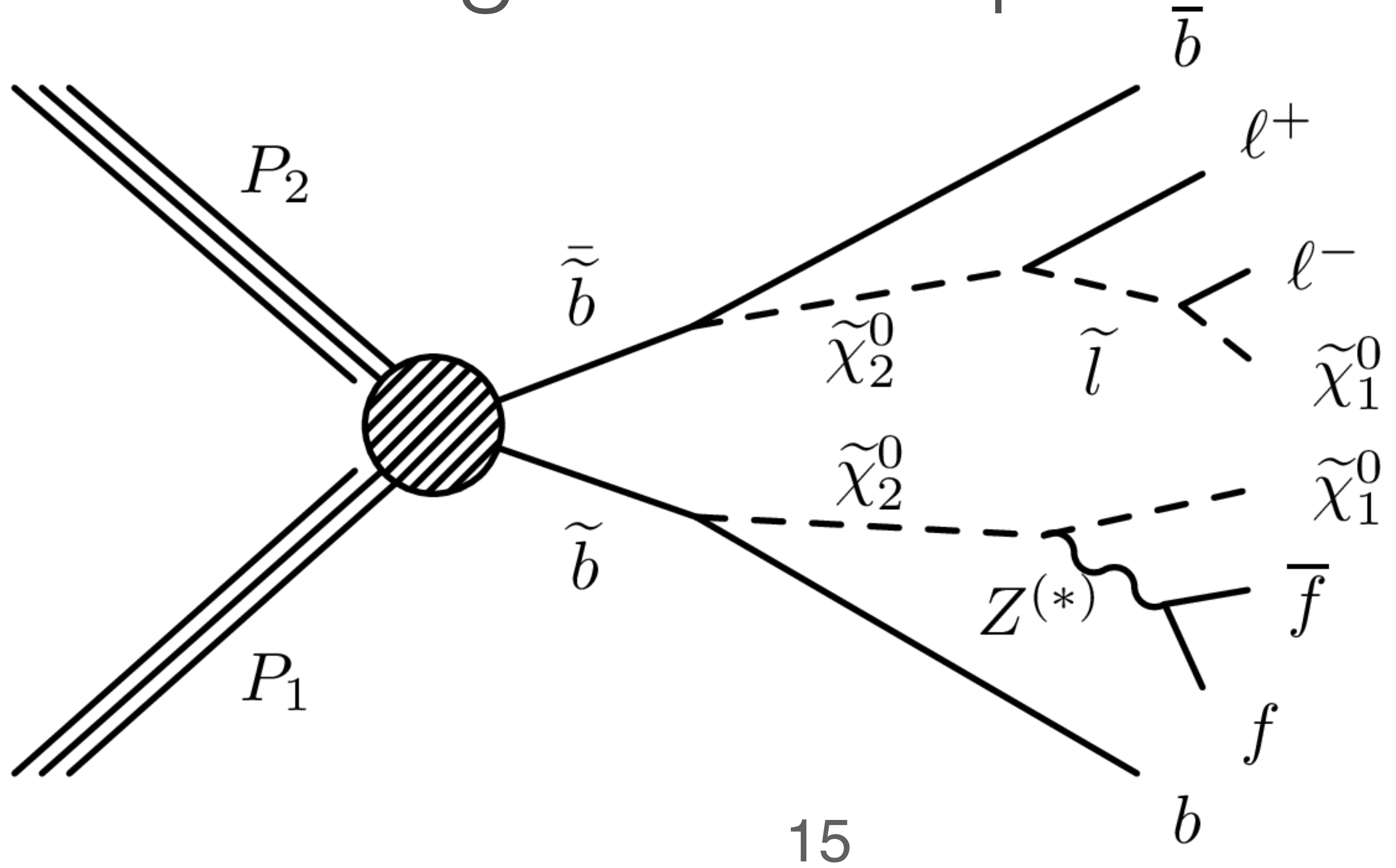


Diagram of a signal SUSY process:



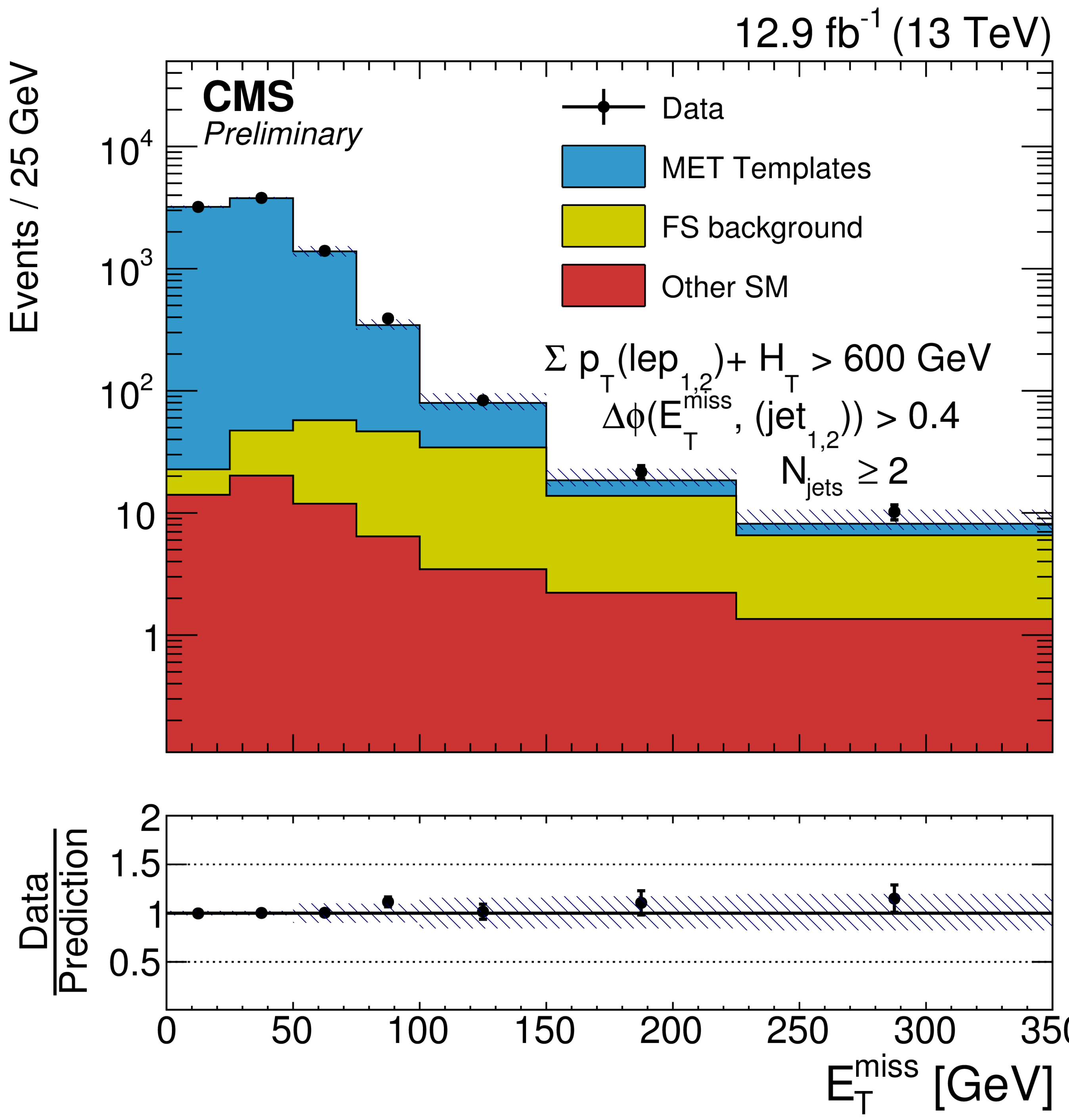
Results: On-Z ATLAS region

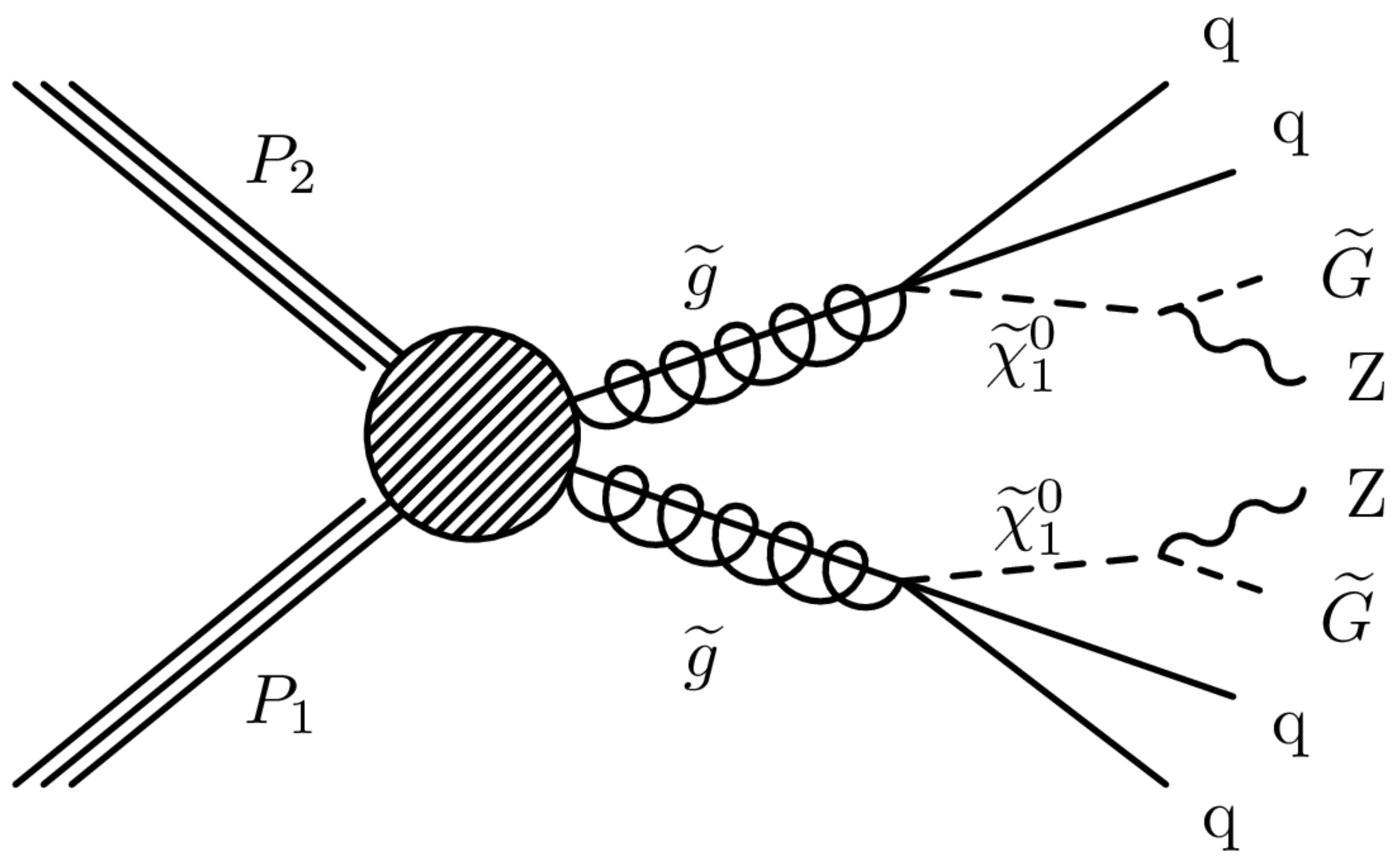
ATLAS reported an excess of 3.0 sigma in Run I and 2.2 sigma in Run II (2015)

- 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

ATLAS has also recently published a paper with 2016 data where they report no excess





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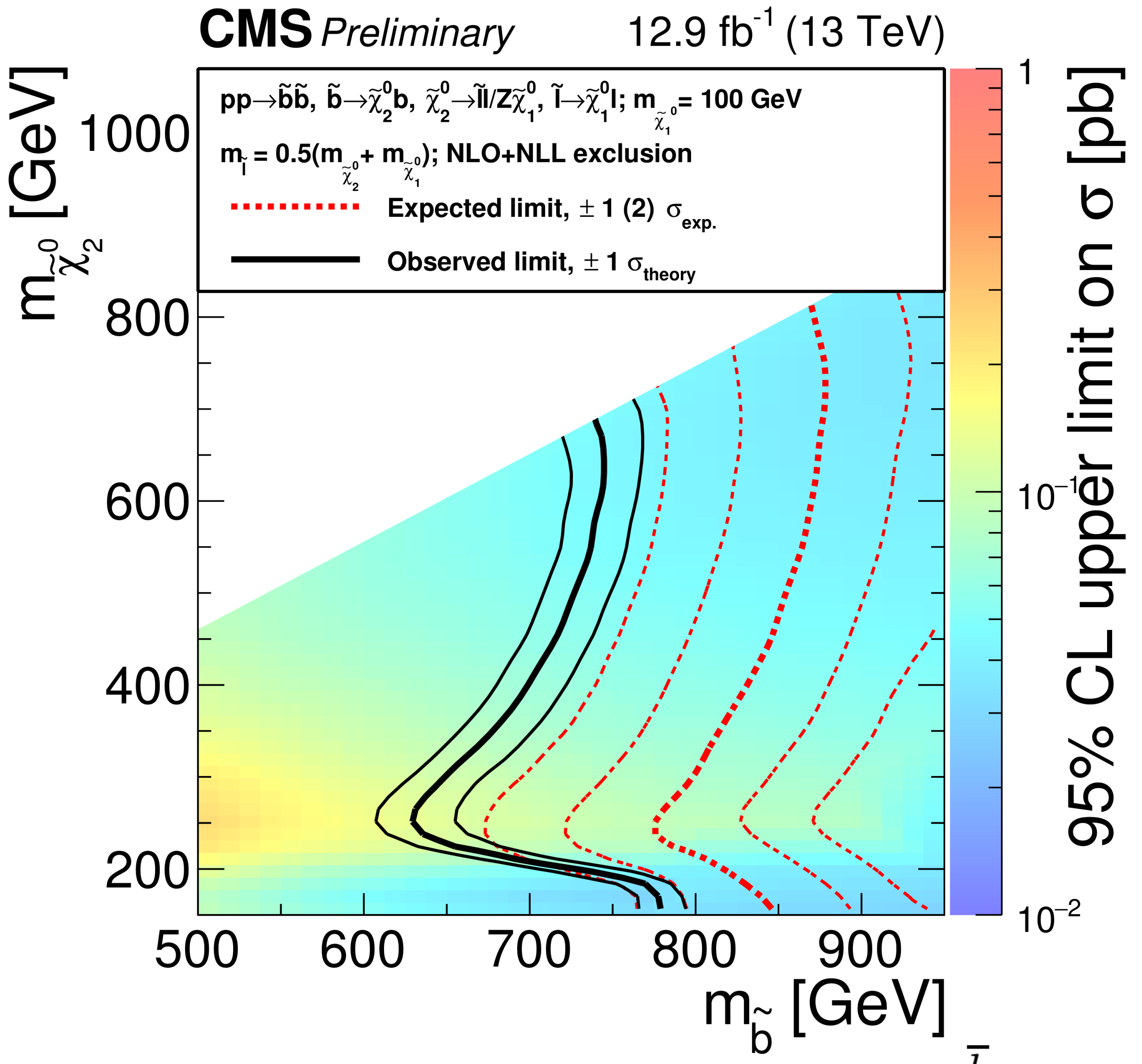
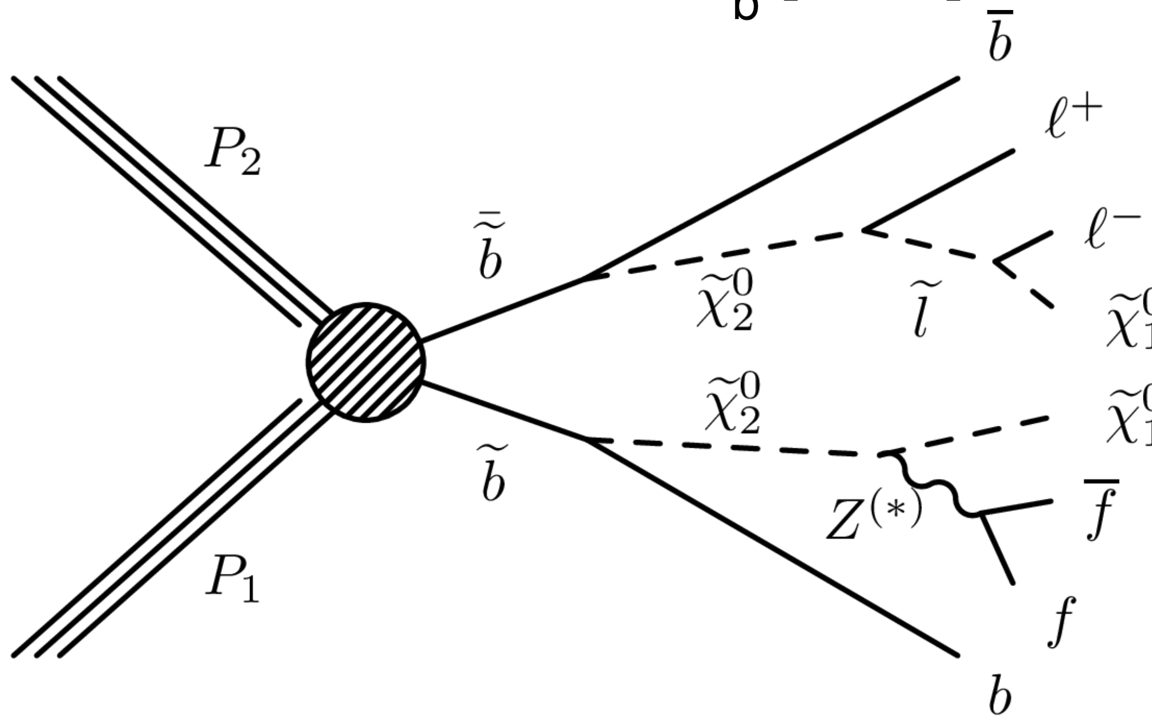
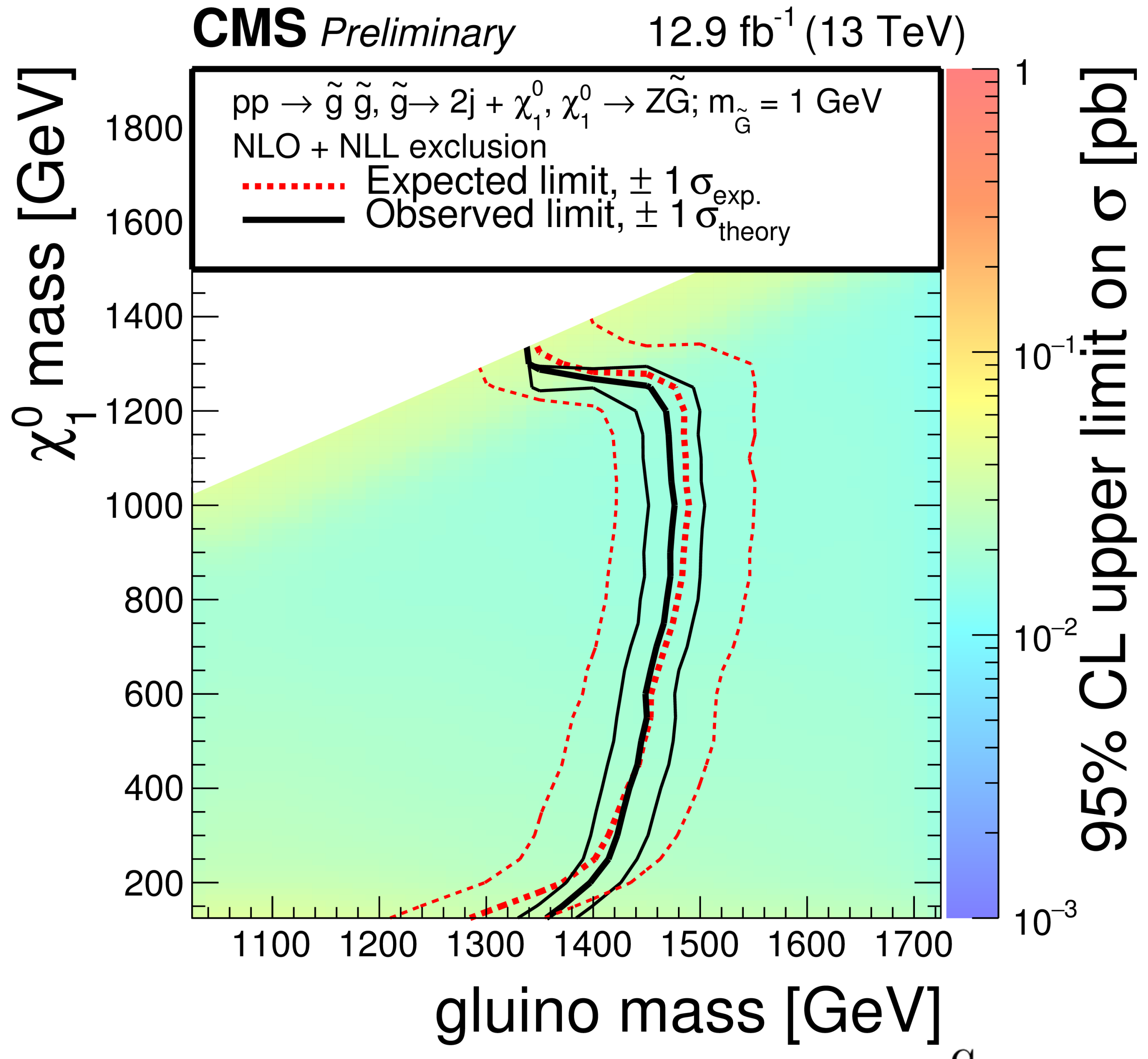
Interpretation

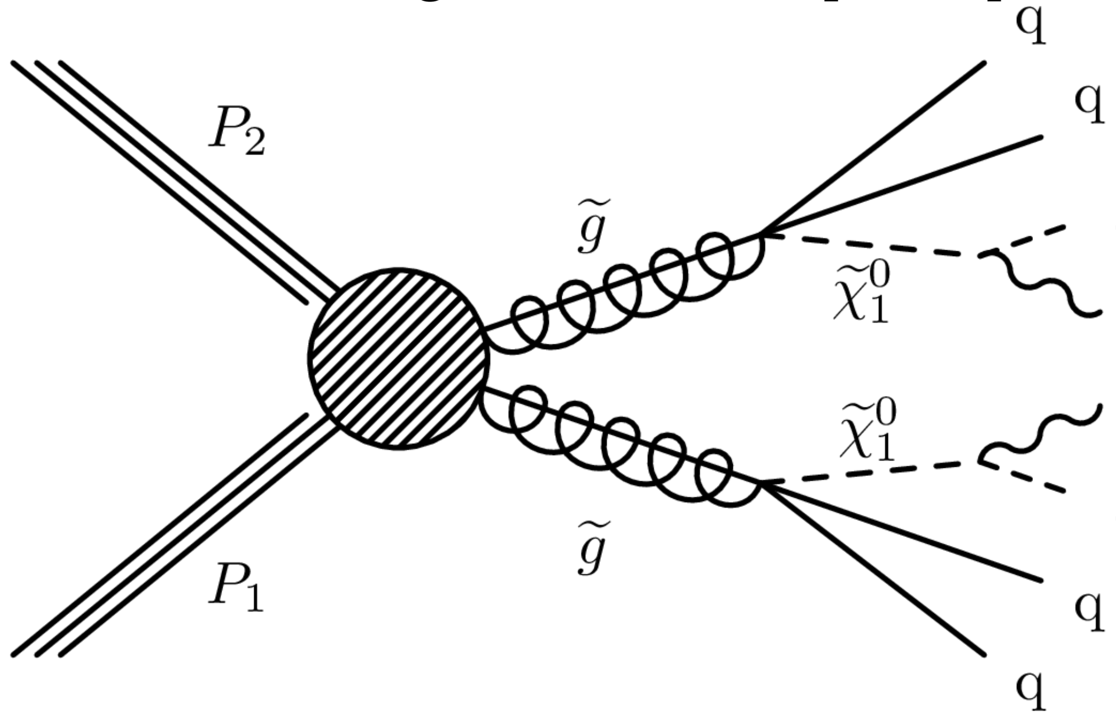
Off-Z/Edge search: direct sbottom production



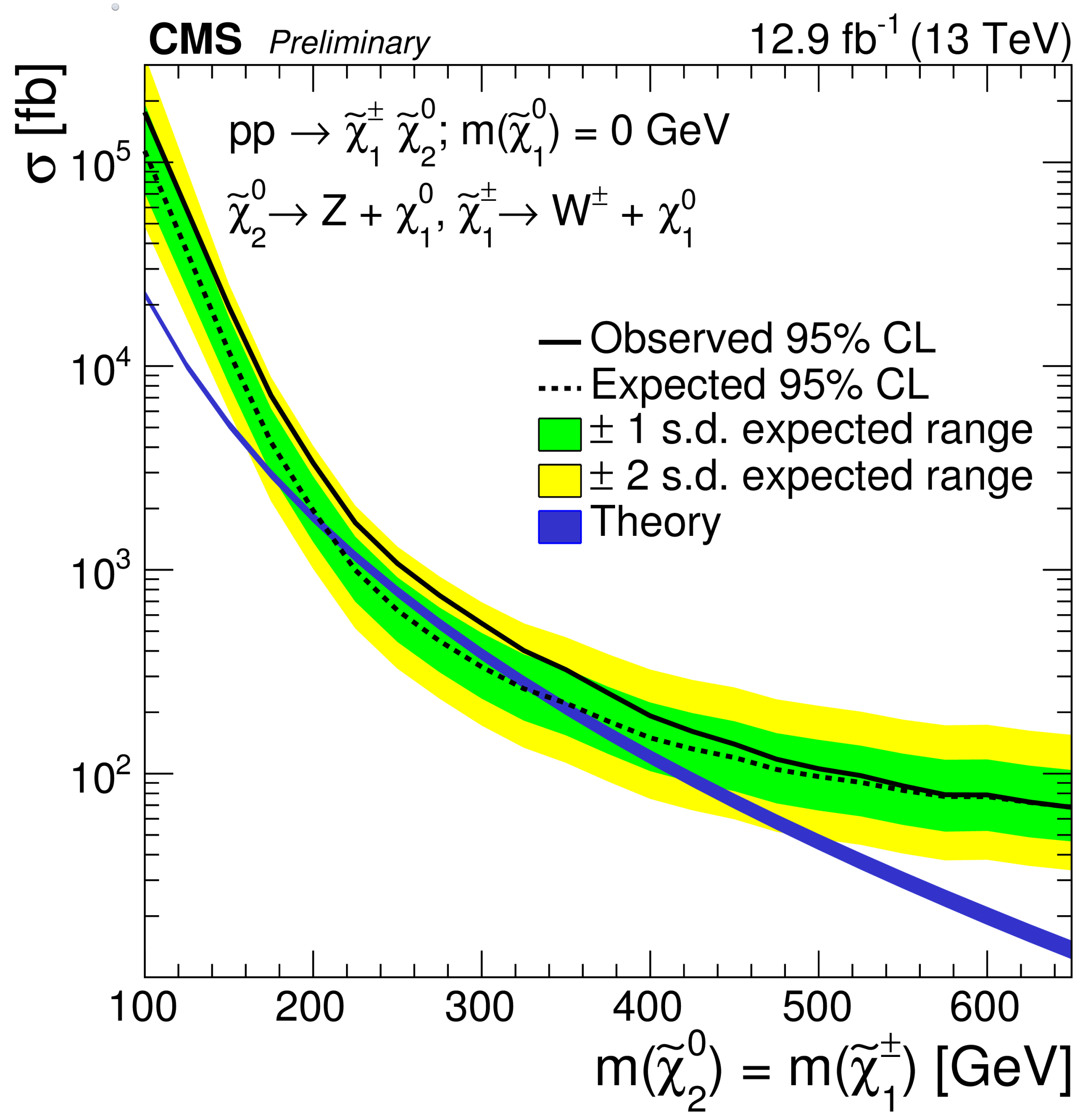


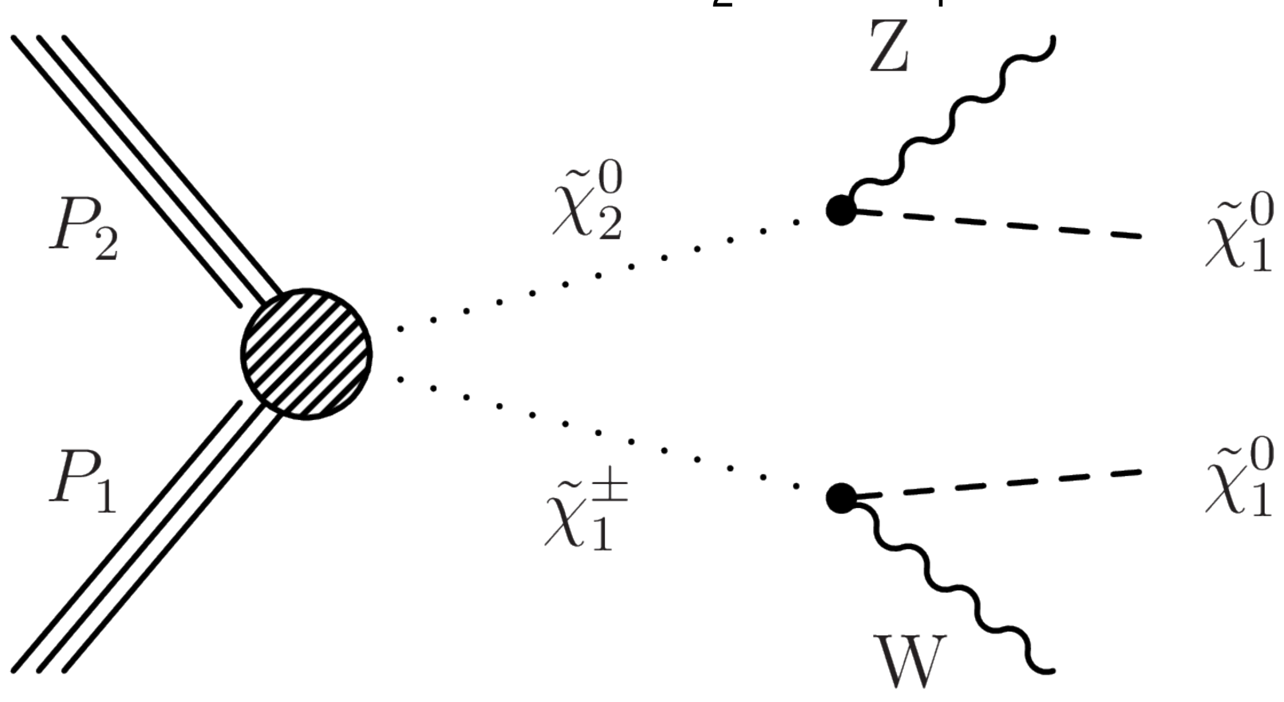
On-Z general search: GMSB gluino production





On-Z EWK search: Chargino-Neutralino





Outlook: Analysis adaptation for full 2016 data

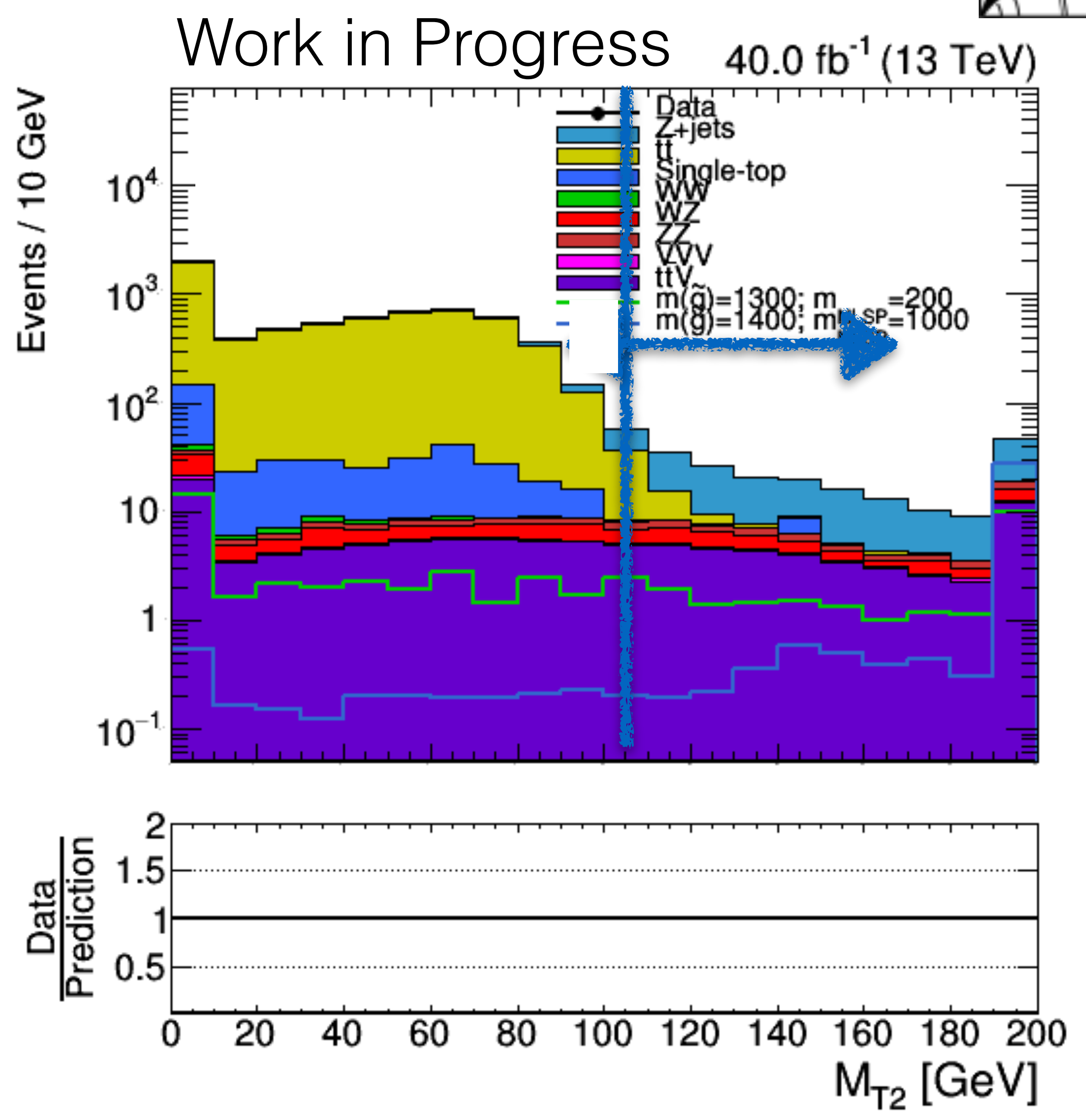
- The results presented above were obtained using 12.9 fb^{-1} of data
- Now the analysis needs to be adapted to account for the full statistics obtained in the 2016 (~35 fb^{-1})
  - include new baseline cuts to reduce backgrounds
  - reoptimize signal regions to maintain or improve sensitivity
  - include low cross section signal models

New baseline selections

M_{T2}:

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

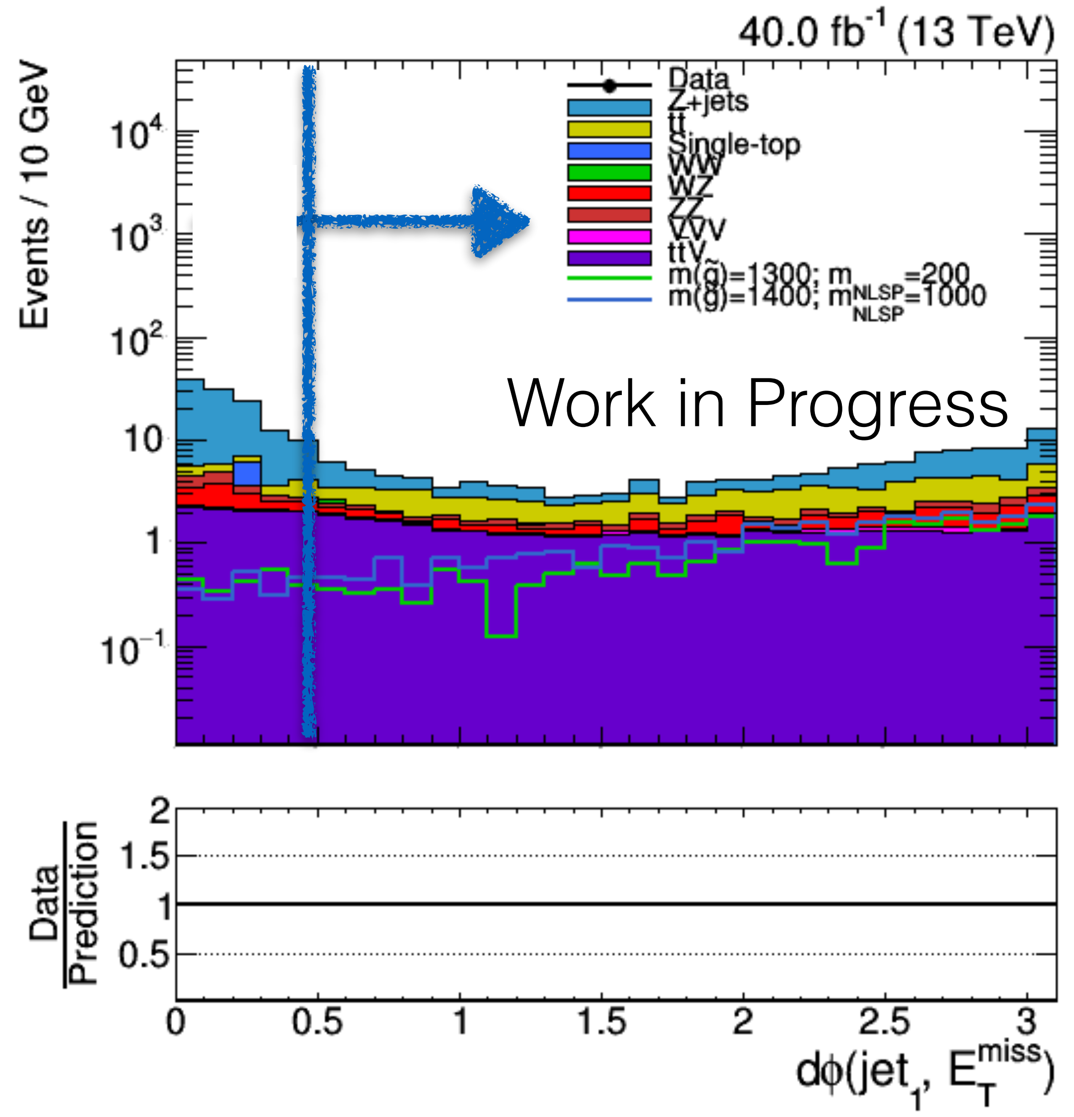
- gives $M_{T2} < E_T^{miss}$ for SUSY events and $M_{T2} \rightarrow 0$ for multijet-like events
- Very efficient to reduce e.g. ttbar background
- M_{T2} > 80 GeV proposed as a new baseline cut

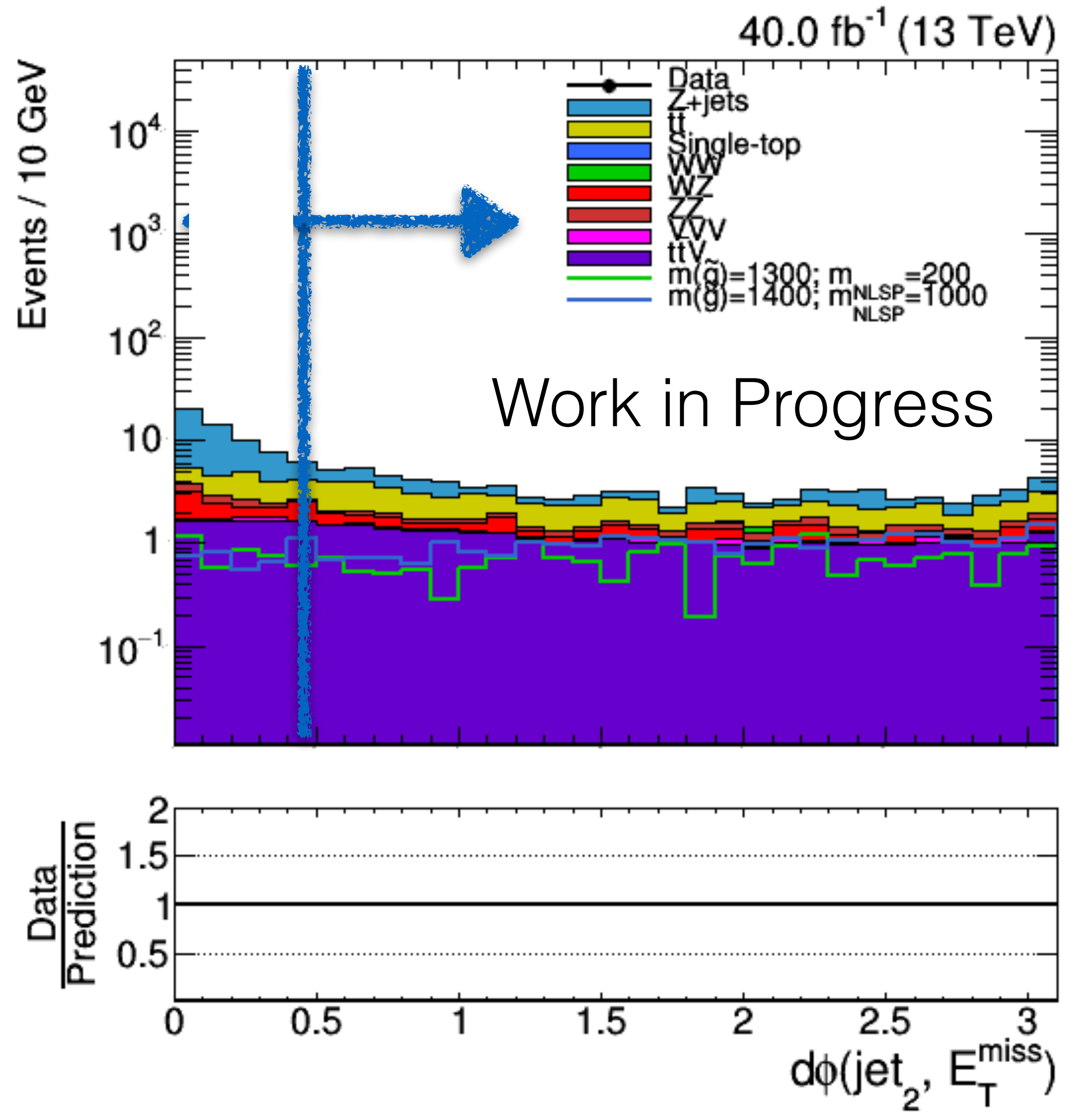


$\Delta\phi(jet_{1,2}, E_T^{miss})$:

A cut on the angle between the jets and the E_T^{miss} reduces backgrounds from mismeasured jets, e.g. Drell-Yan

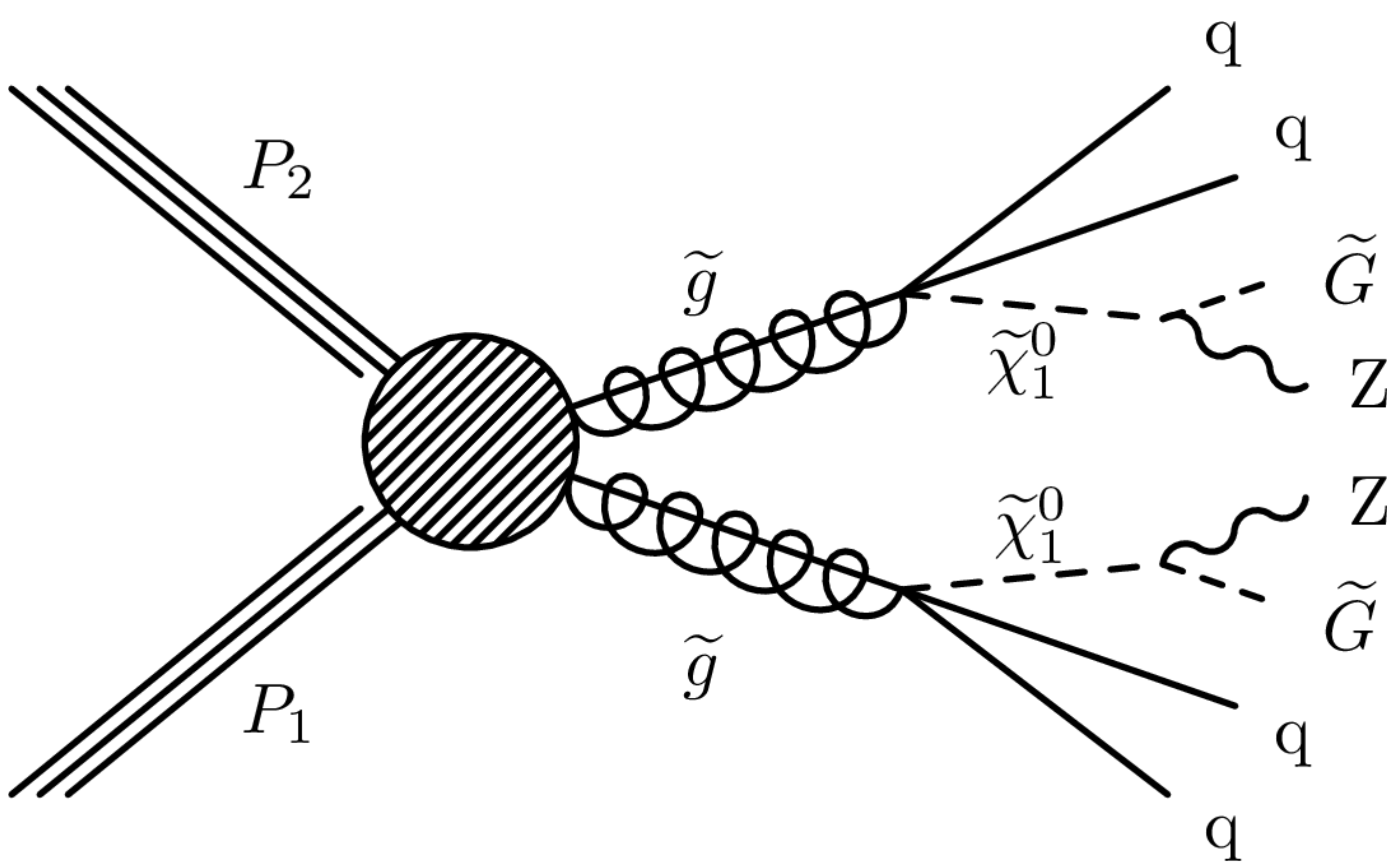
- $\Delta\phi(jet_{1,2}, E_T^{miss})$ > 0.4 proposed as a new baseline cut





On-Z new signal regions

- $|M_{ll} - M_Z| < 5$ GeV (NEW) to reduce FS backgrounds
- M_{T2} (NEW) to suppress ttbar
- 3rd lepton veto (NEW) to suppress WZ and ttZ
  - Veto leptons that pass either veto lepton from multilepton analysis OR isotrack from MT2 analysis
- Lowest signal region starts at $E_T^{miss} > 100$ GeV
- Binning in H_T, njets and btags (NEW)



OLD binning

N_{jets}	2-3 jets	> 4 jets
H_T	>400 GeV	No Cut
ATLAS SR	$(H_T + p_{T1} + p_{T2}) > 600$ GeV and $E_T^{miss} > 225$ GeV	

NEW binning

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

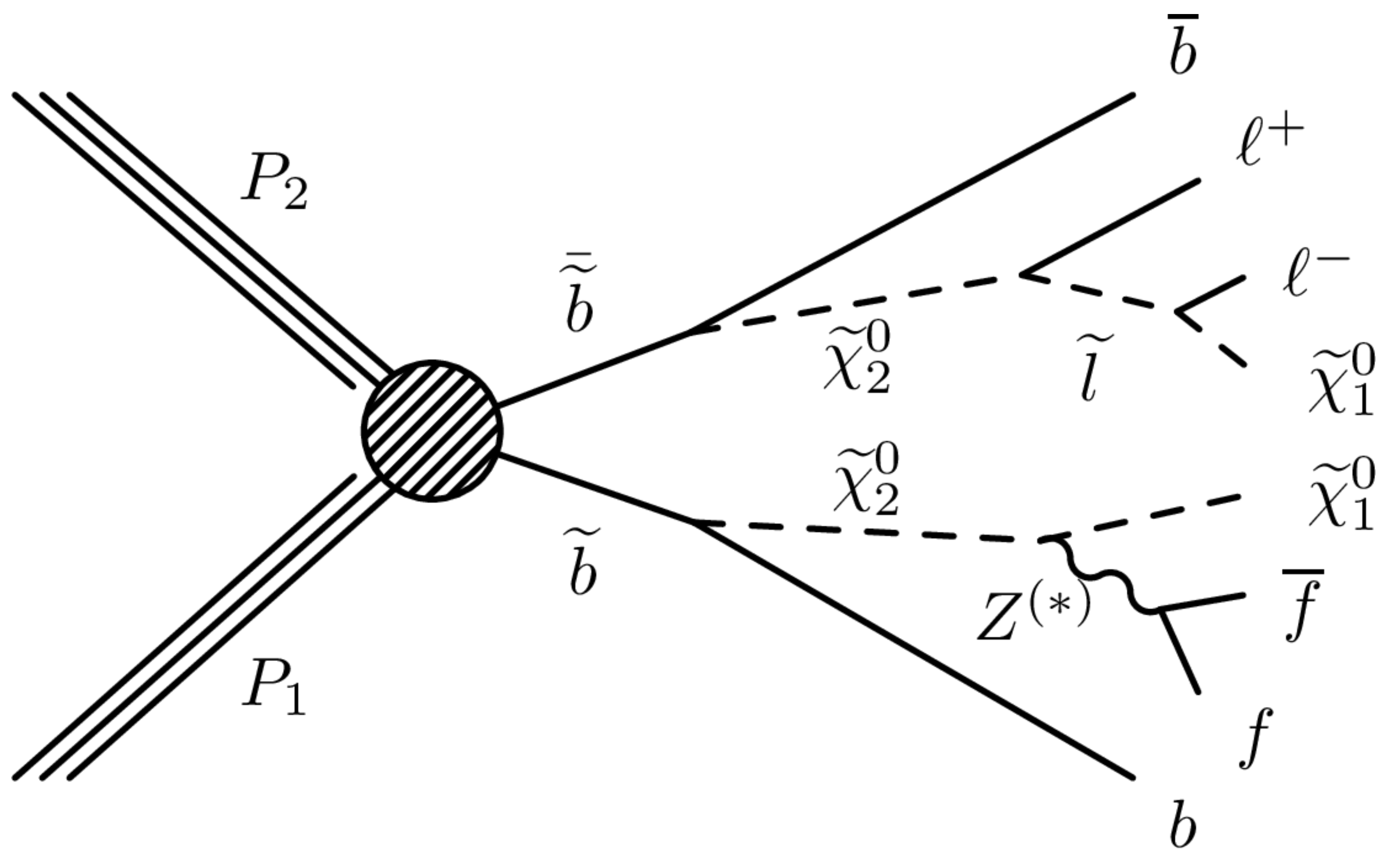
NEW binning

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

Edge new signal regions

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}
- Proposition:
  - 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
- Include the region with the 3 sigma deviation we had at ICHEP



OLD binning

m_{ll} [GeV]	<81	> 101
ttbar		
non-ttbar		

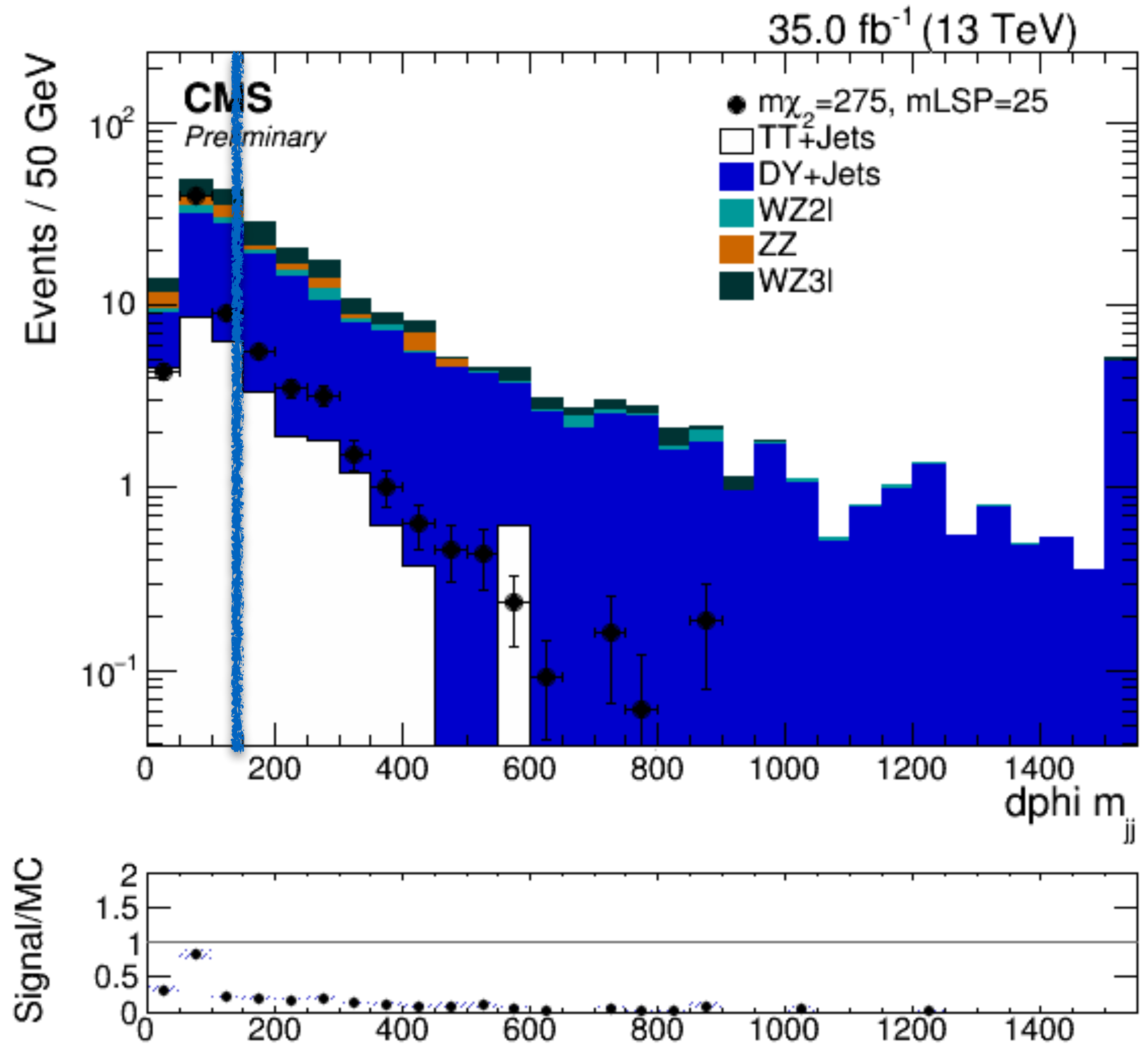
NEW binning + M_{T2} > 80 GeV

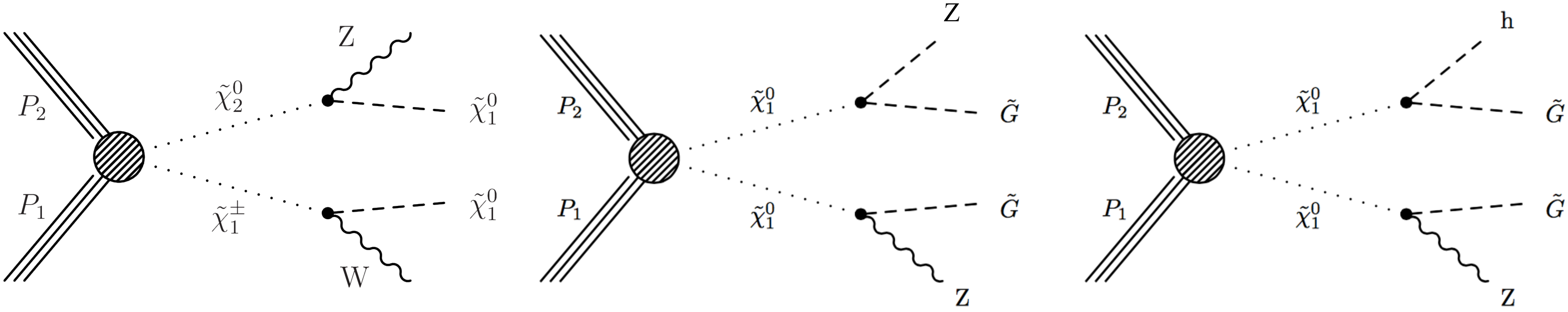
m_{ll} [GeV]	20-60	60-86	96-150	150-200	200-300	300-400	400+
ttbar							
non-ttbar							

EWK SUSY searches

EWK targeted search:

- The On-Z search can be extended to target electroweakly produced SUSY, i.e. LSPs produced in association with WZ, ZZ (NEW) and HZ (NEW)
- The previously optimized cuts ($\Delta\phi(\text{jet}_1, E_T^{miss}) > 1$) to reduce Z+jets for WZ signal a bit too aggressive
  - New cut proposed to reduce Z+jets
  - m_{jj} < 110 GeV (where the mjj is made with the jets closest ϕ).





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Summary

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

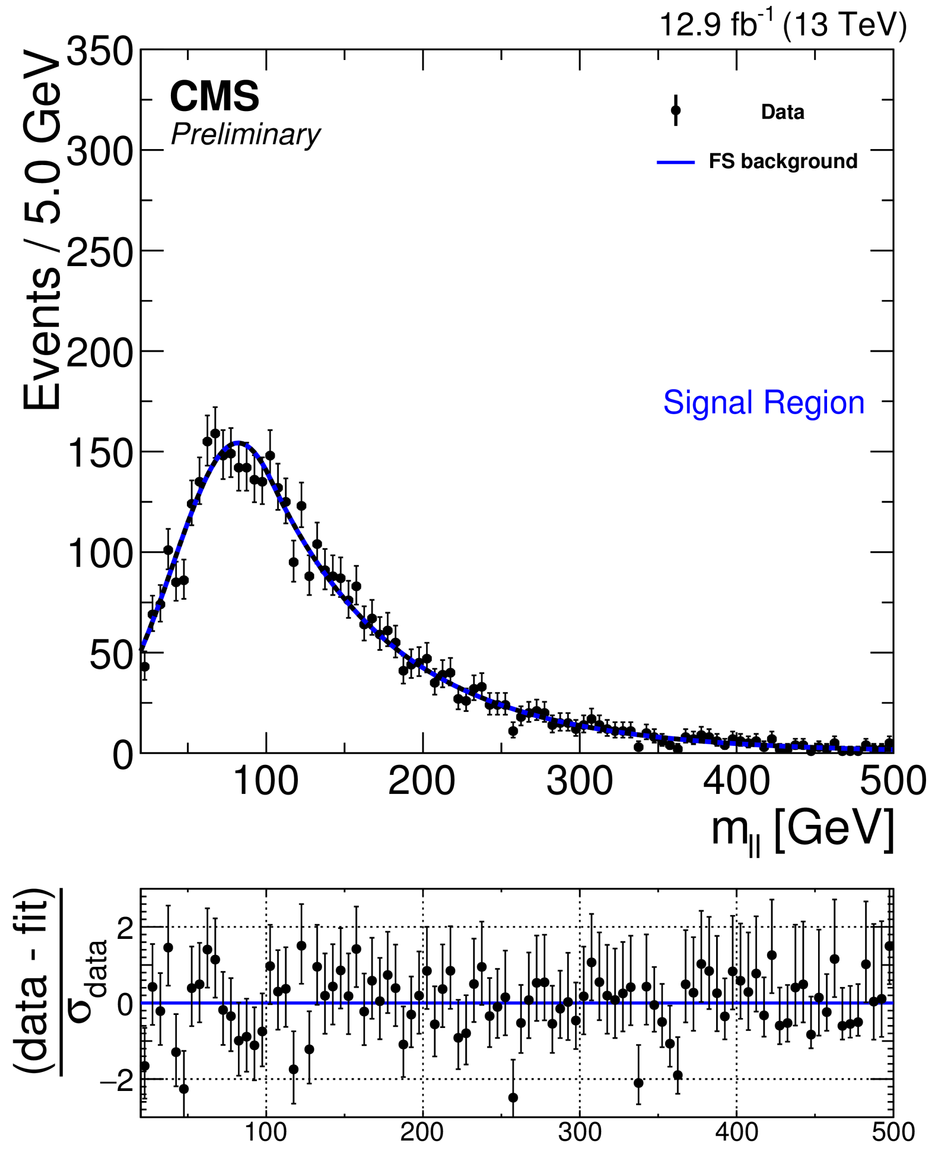
- The results presented were obtained using data recorded with the CMS detector at 13 TeV in the first half of 2016 (12.9 fb^{-1}), published in CMS PAS SUS-16-021 for ICHEP
- New developments have been implemented for the Run II data taking to improve the analysis and facilitate potential discoveries
- Run I excesses reported by ATLAS and CMS has been attempted to verify
  - without luck, the observed events agree well with the standard model expectation
  - limits have been set on the masses of the sparticles produced in the three targeted SUSY models
- New developments of the analysis have been done to account for the full set of data collected in 2016
- A paper is planned to be published with the full RunII dataset by March next year

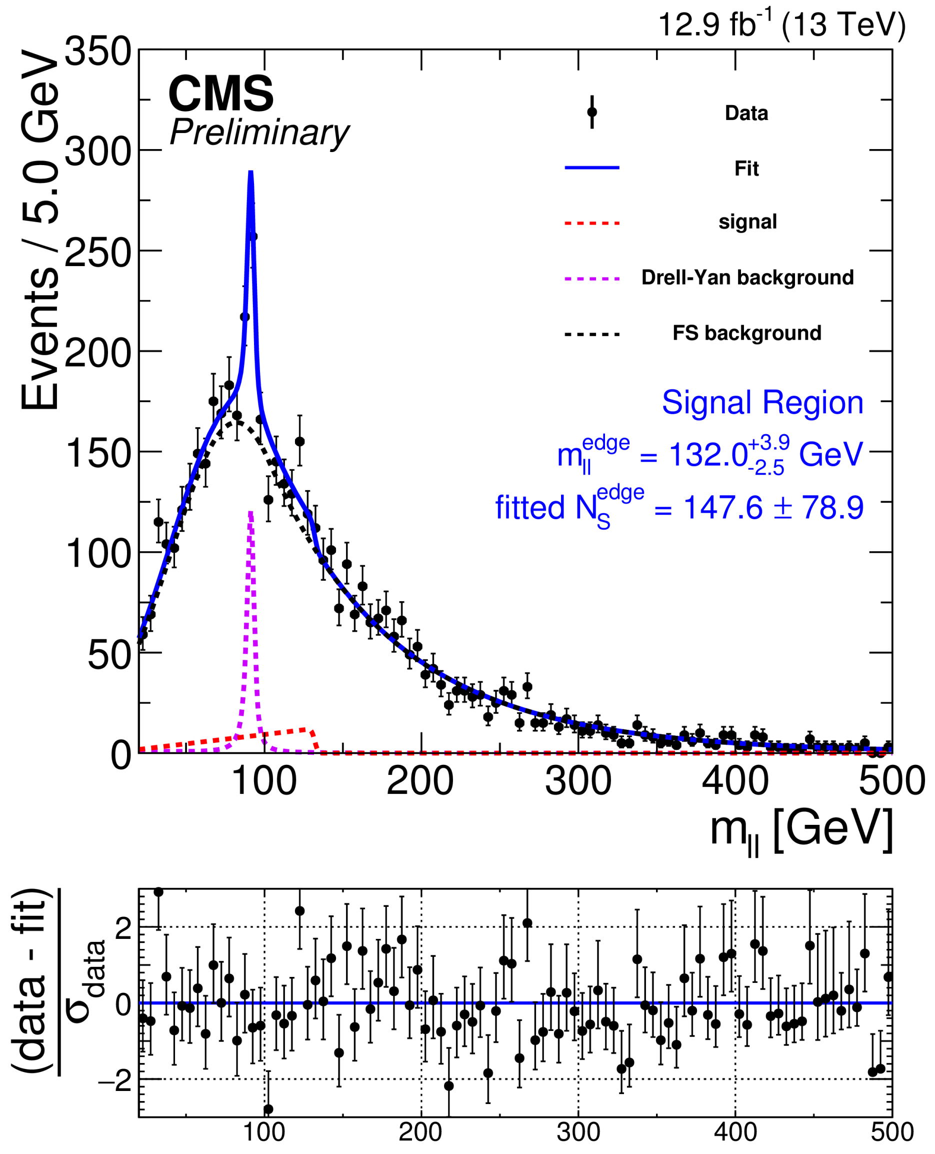
Backup

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)

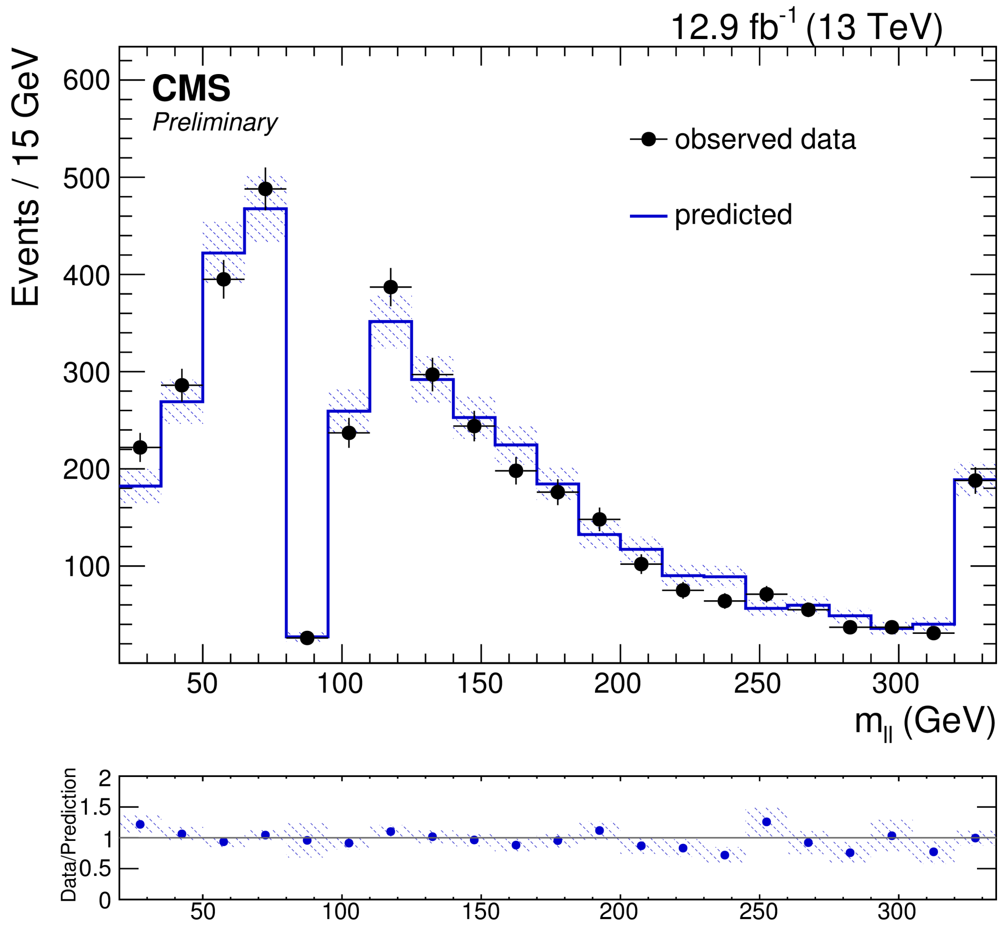


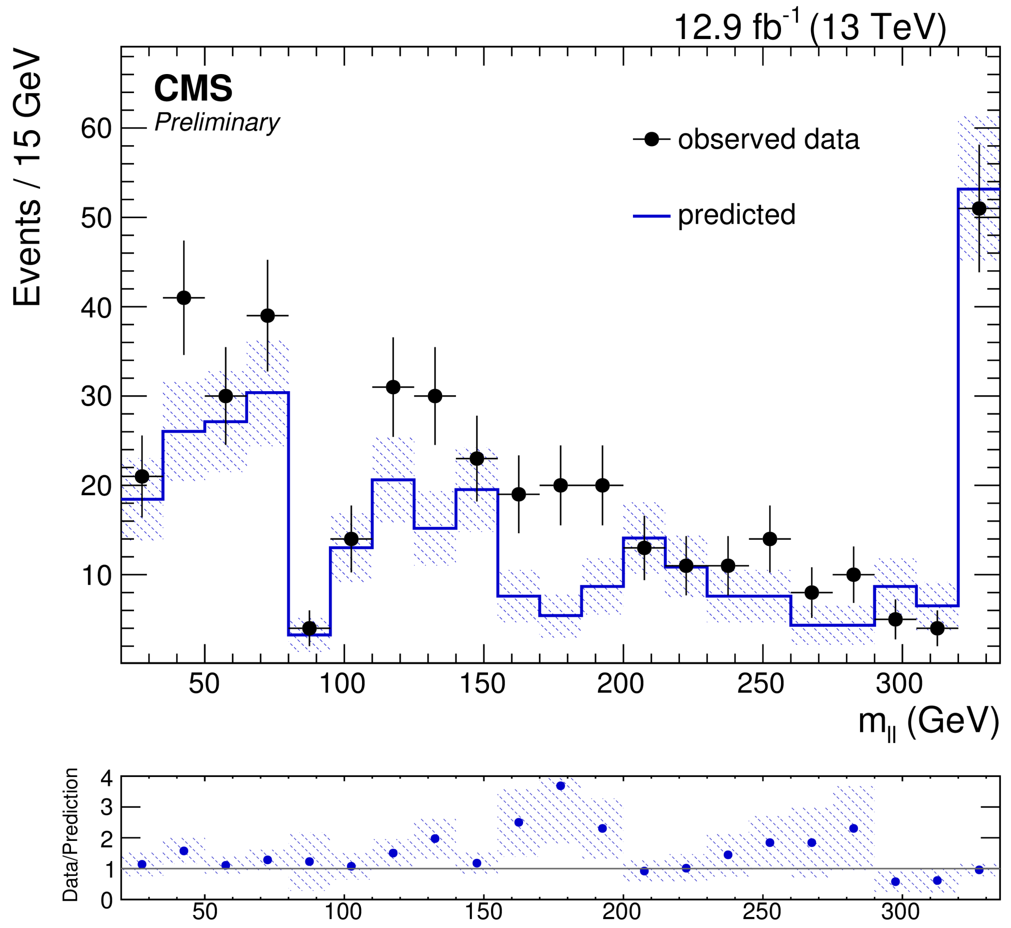


The Off-Z counting shows disagreement

- 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





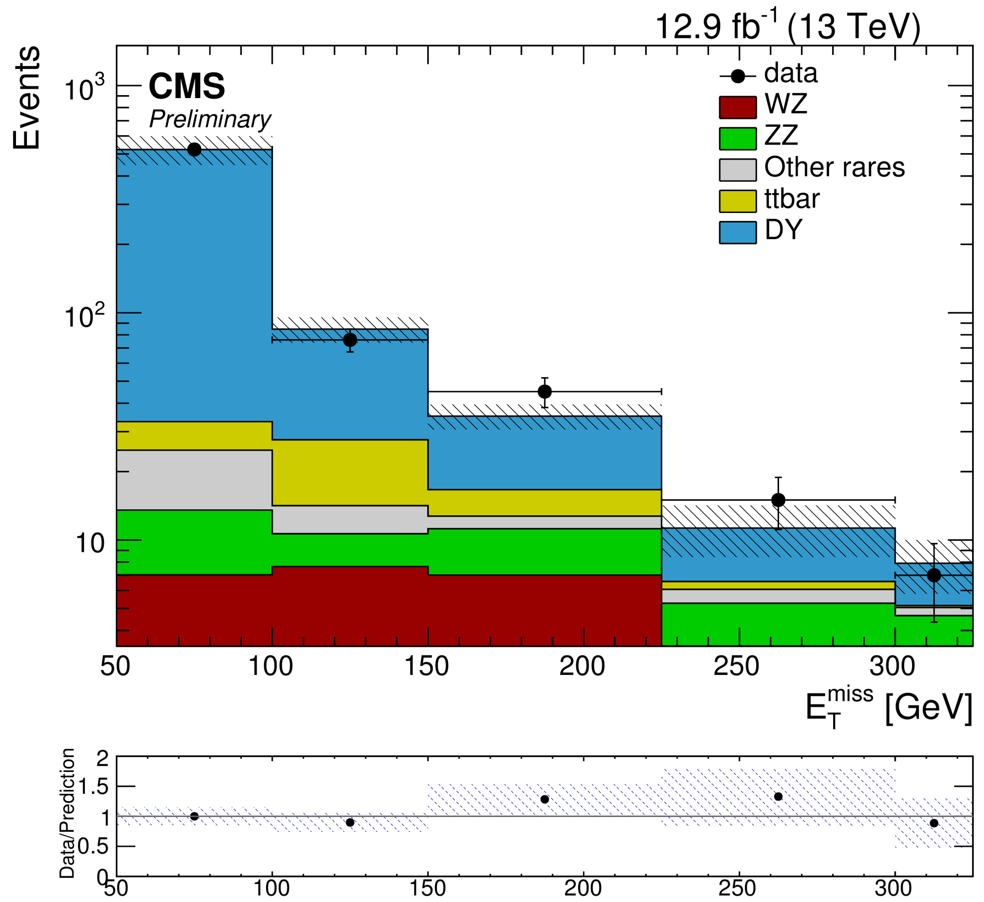
Results: On-Z

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
SRA 2–3 jets and $H_T > 400$ GeV	0	100-150	$169.6\ ^{+16.1}_{-15.7}$	**177**
		150-225	$43.6\ ^{+7.1}_{-6.3}$	**45**
		225-300	$24.3\ ^{+12.7}_{-12.4}$	**11**
		> 300	$15.0\ ^{+4.8}_{-3.8}$	**23**
	≥ 1	100-150	$77.2\ ^{+9.2}_{-8.1}$	**87**
		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**
SRB ≥ 4 jets	0	100-150	$126.3\ ^{+12.5}_{-11.8}$	**122**
		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**
	≥ 1	100-150	$240.8\ ^{+18.9}_{-16.1}$	**238**
		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

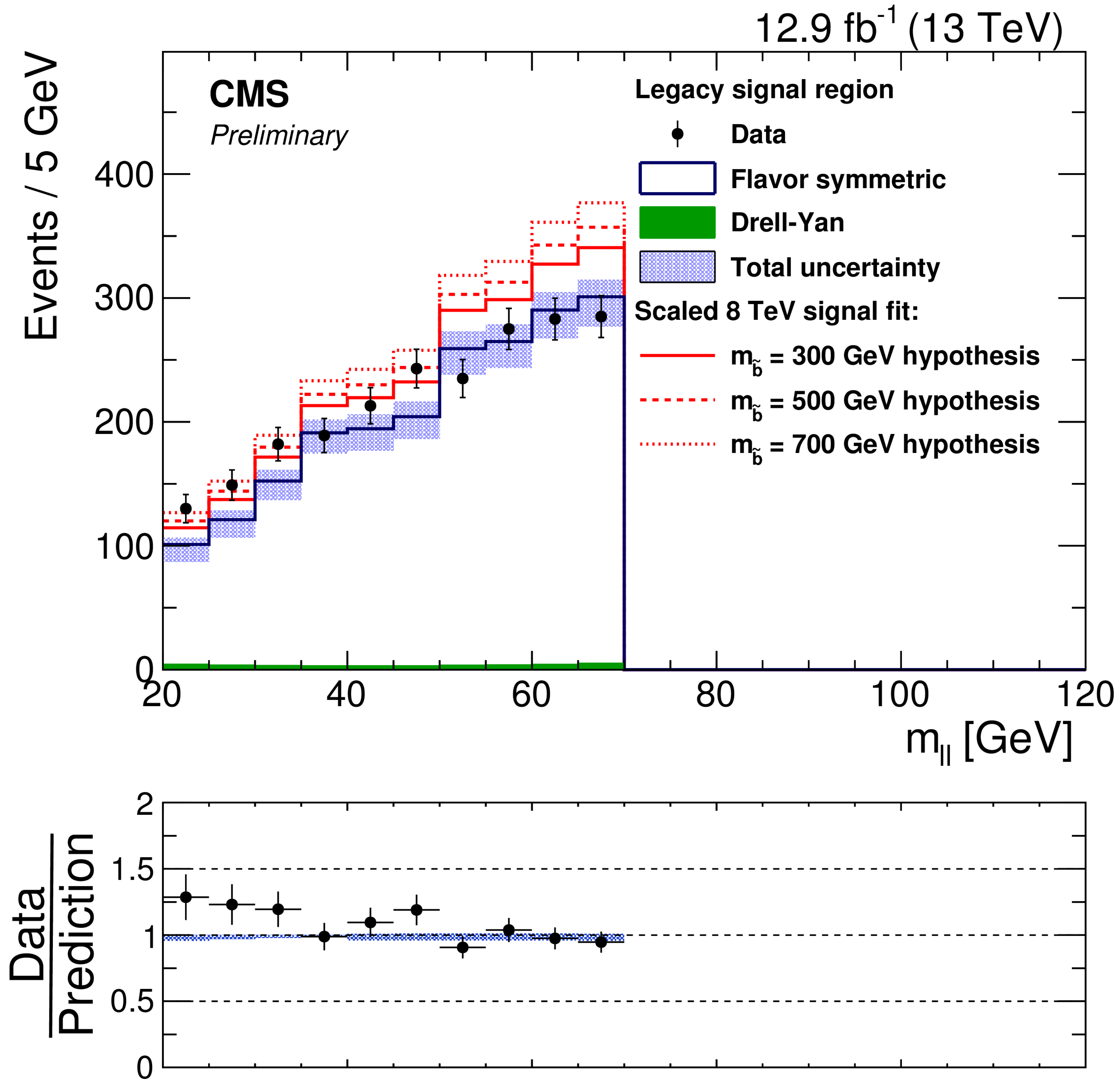


Results: Run I CMS legacy region

CMS Run I excess signal region kept for verification

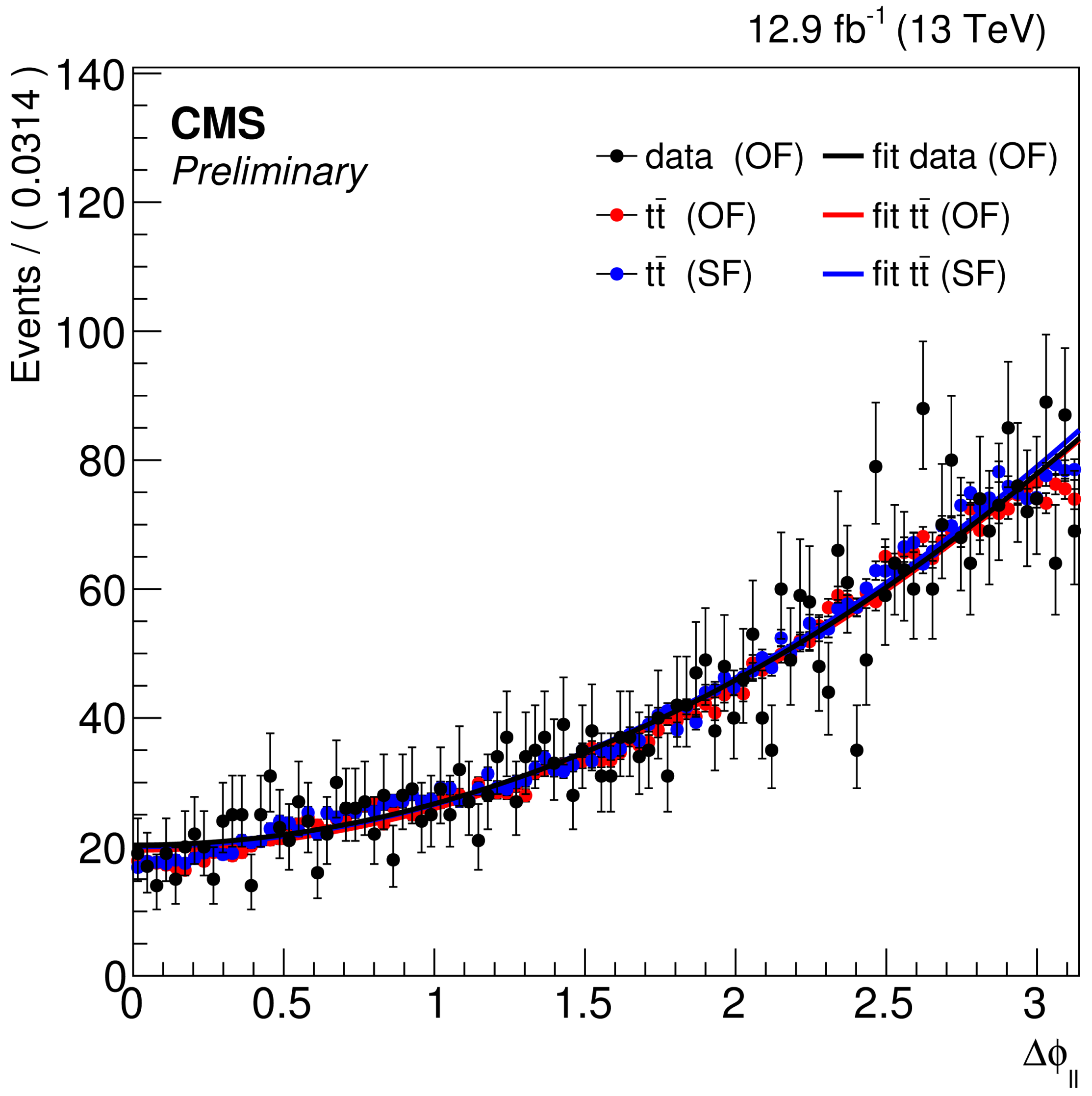
- E_T^{miss} : 100 GeV if > 3 jets (central leptons)
- E_T^{miss} : 150 GeV if > 2 jets (central leptons)

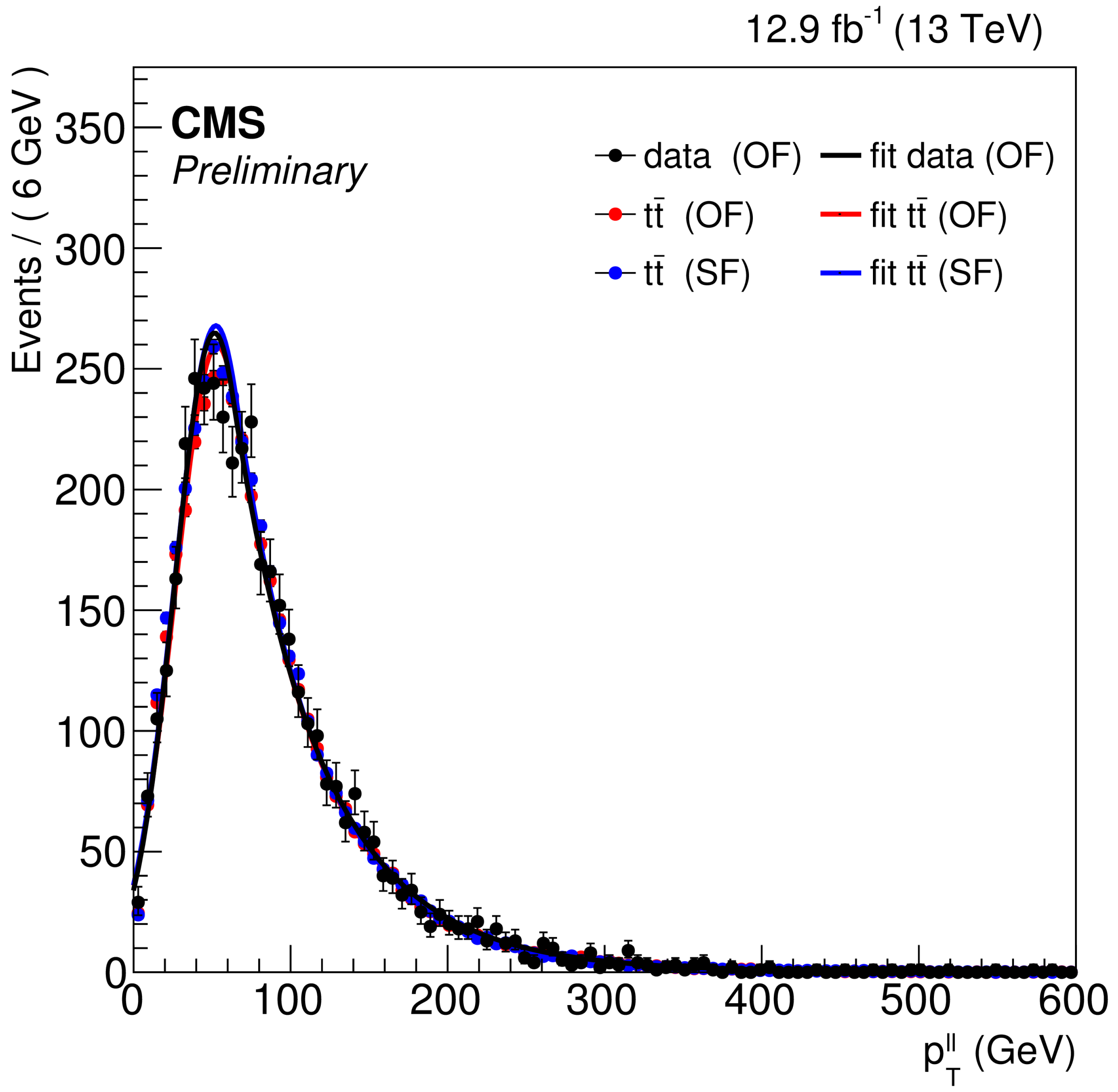
- **Results in numbers**:
  - observed: 2170
  - predicted: 2053 +- 68 (1.4 sigma local significance)

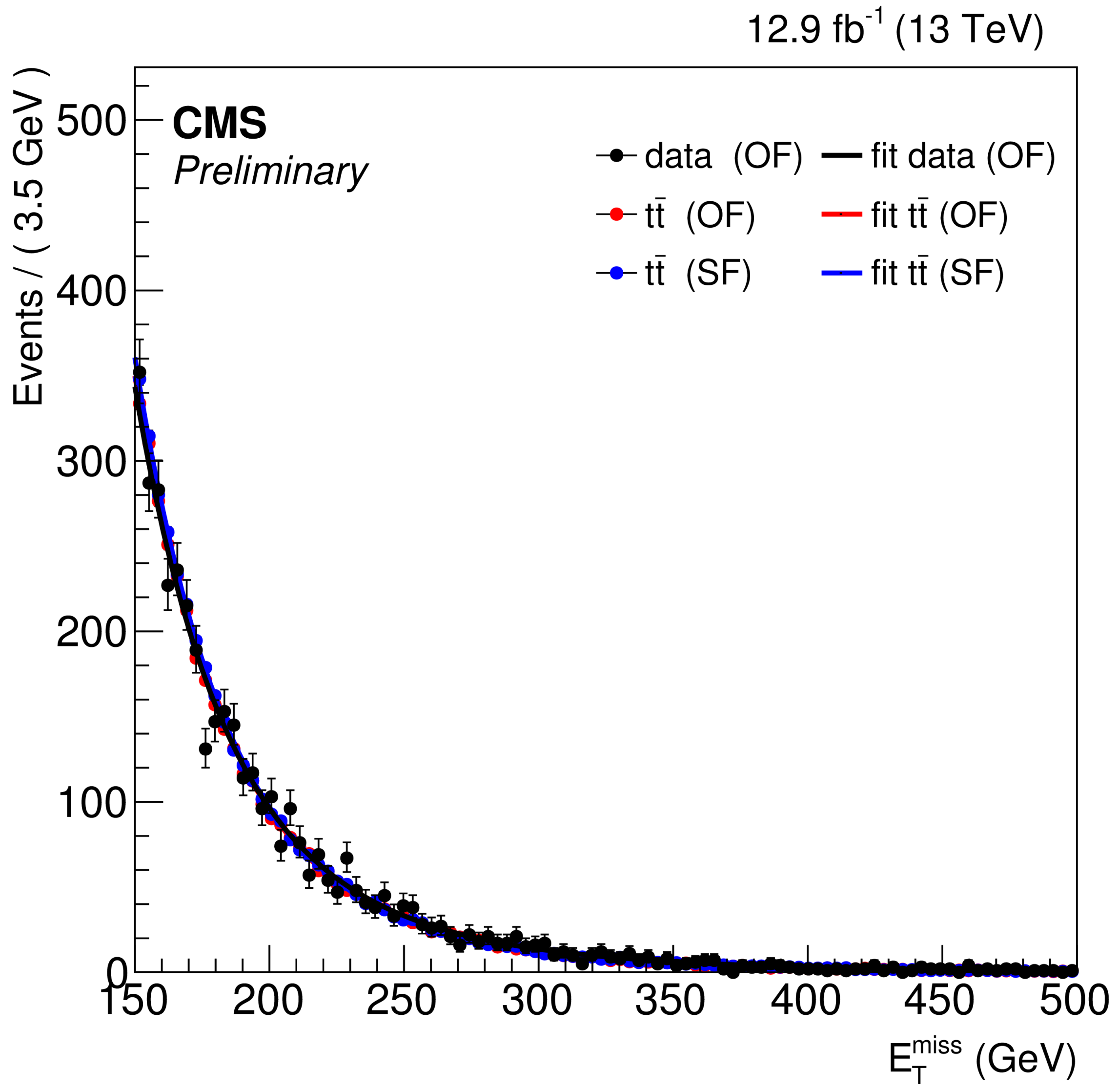


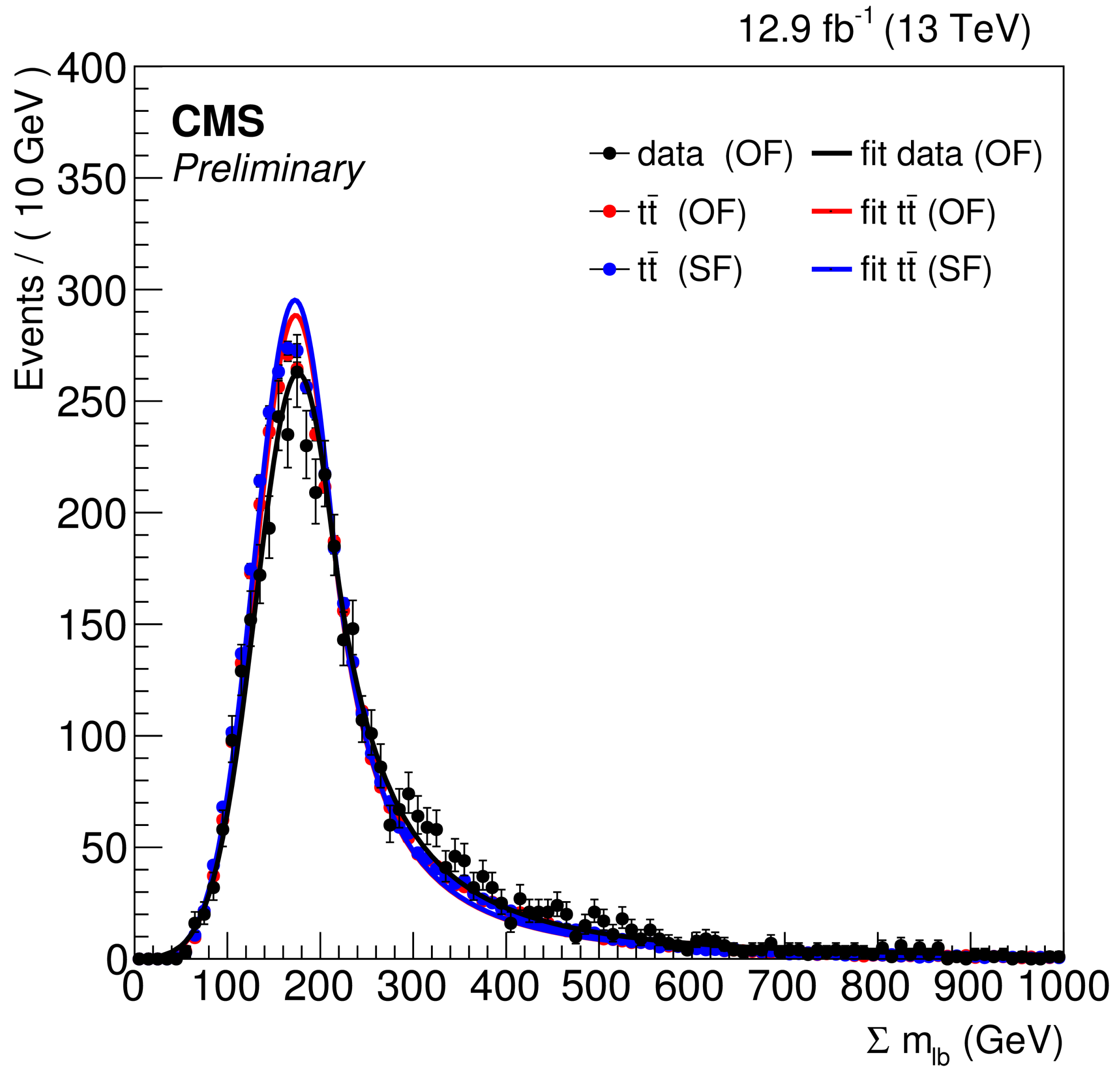
Top likelihood classification

- 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

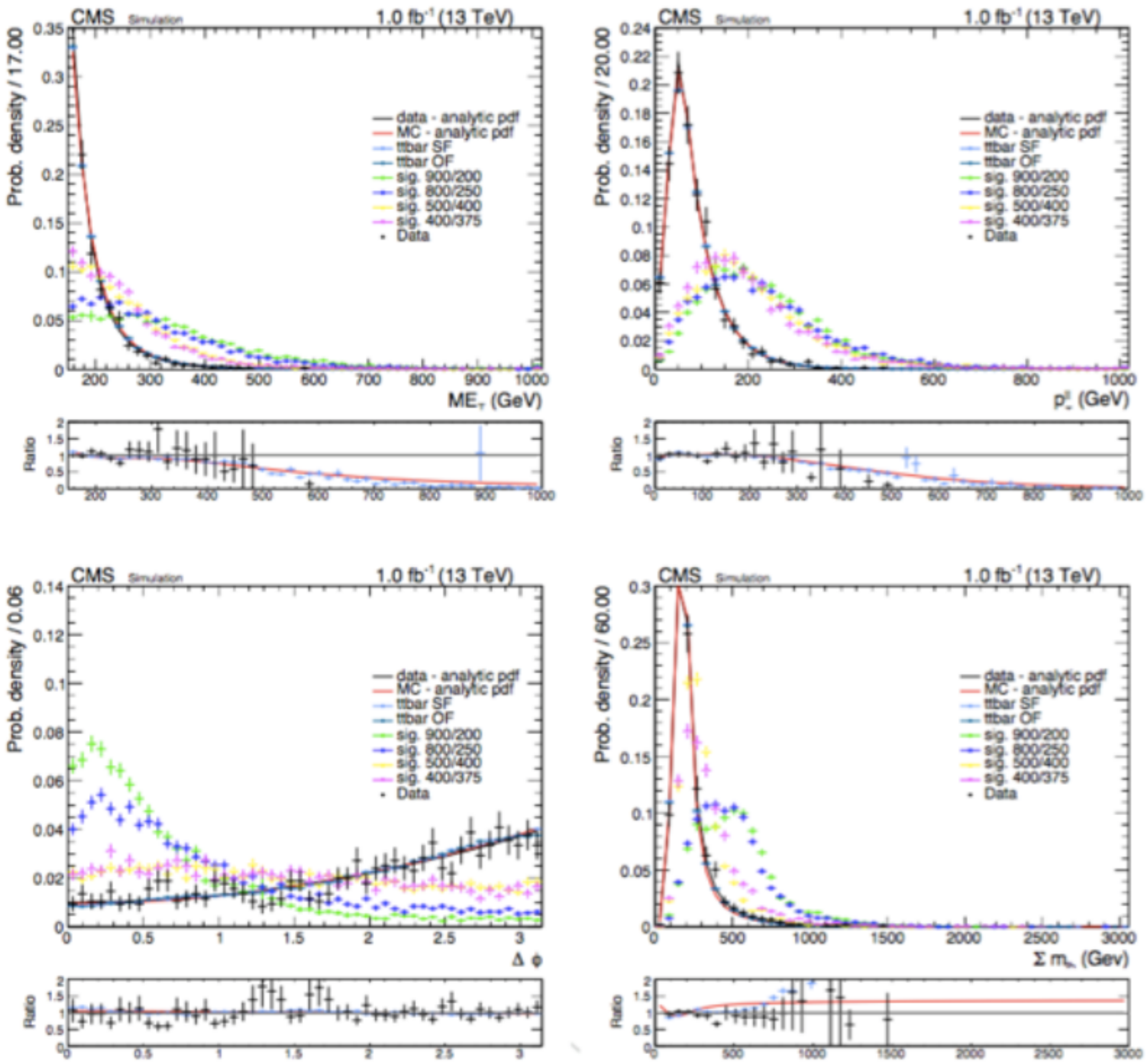


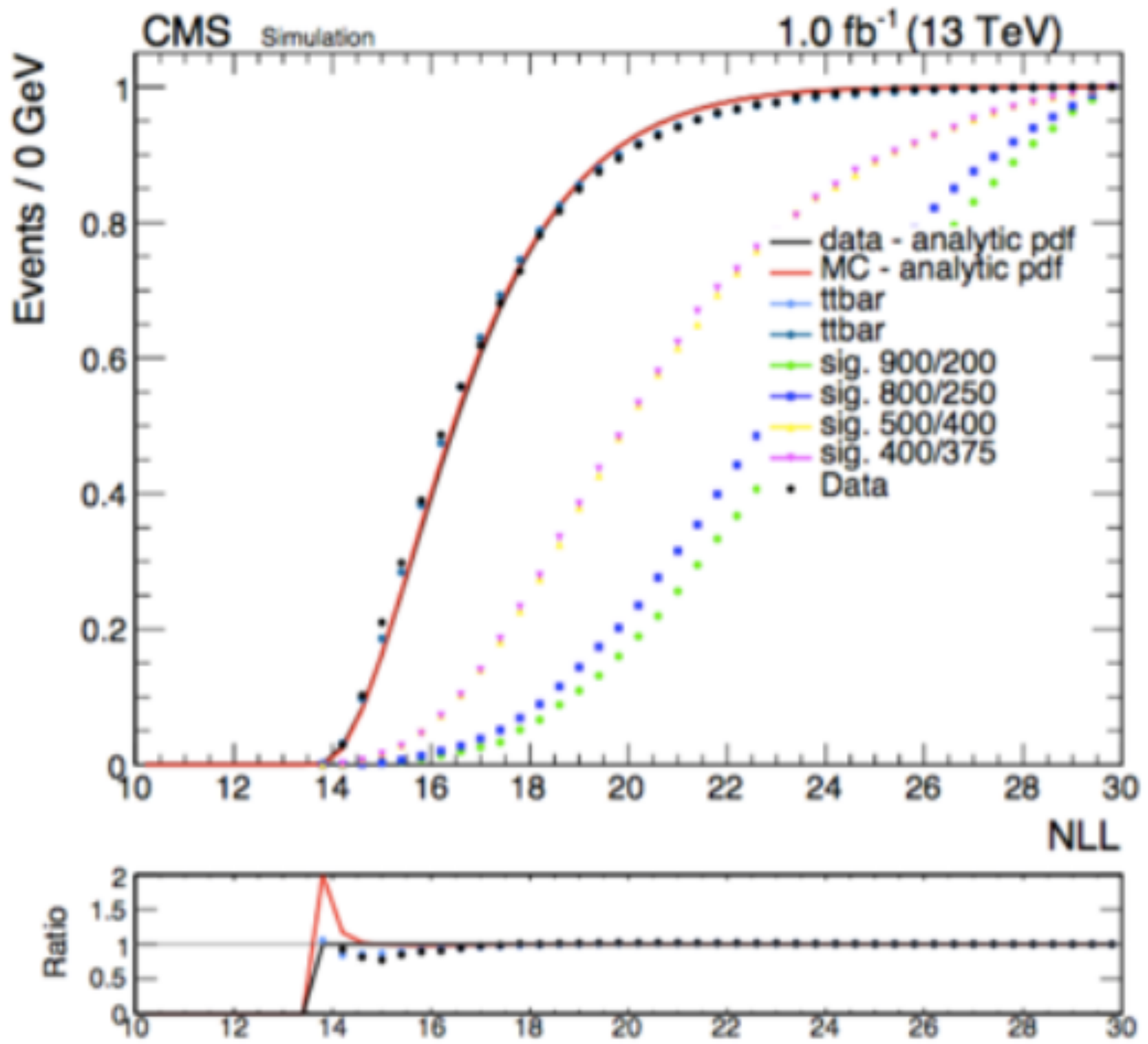






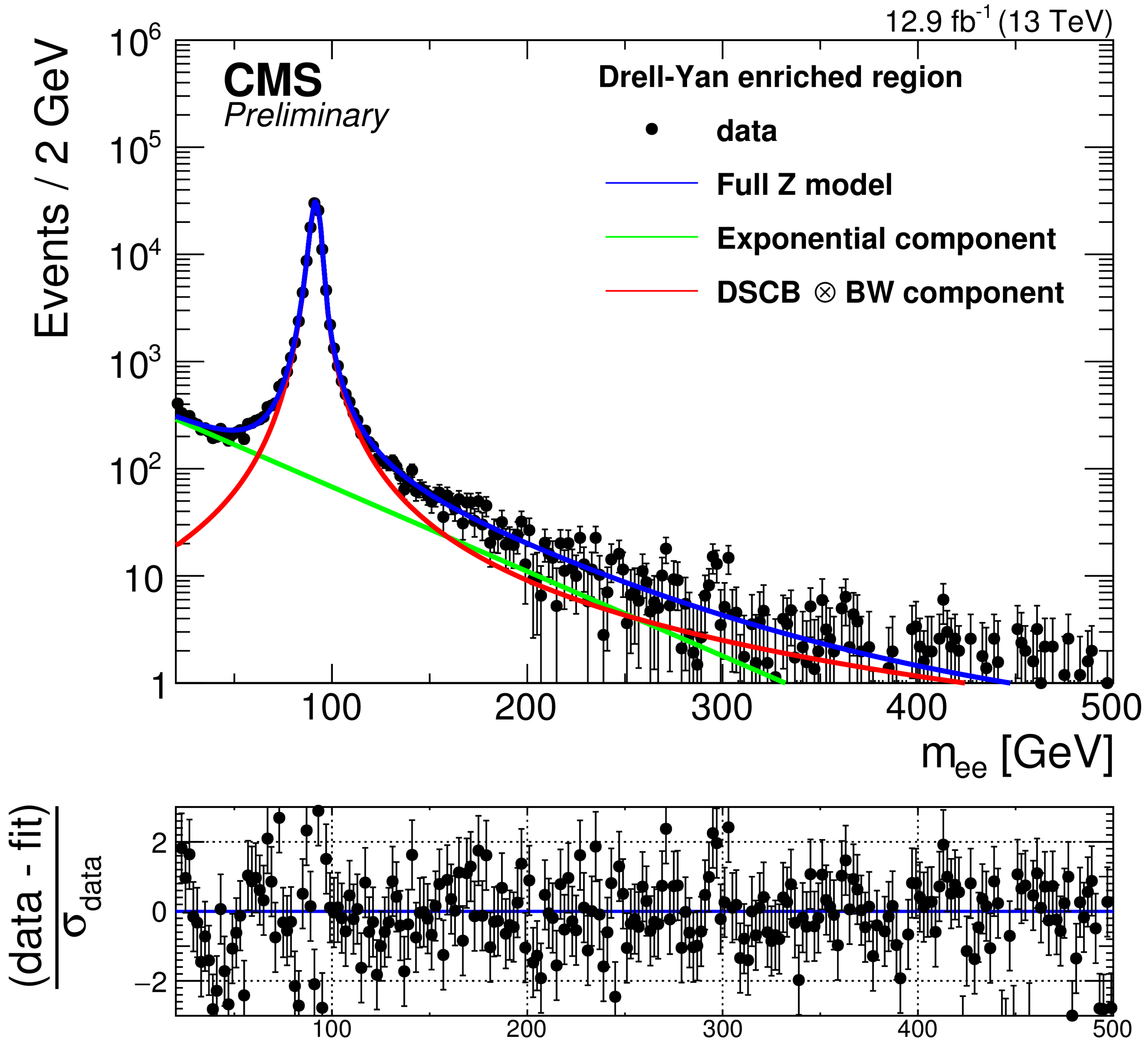
Top likelihood classification

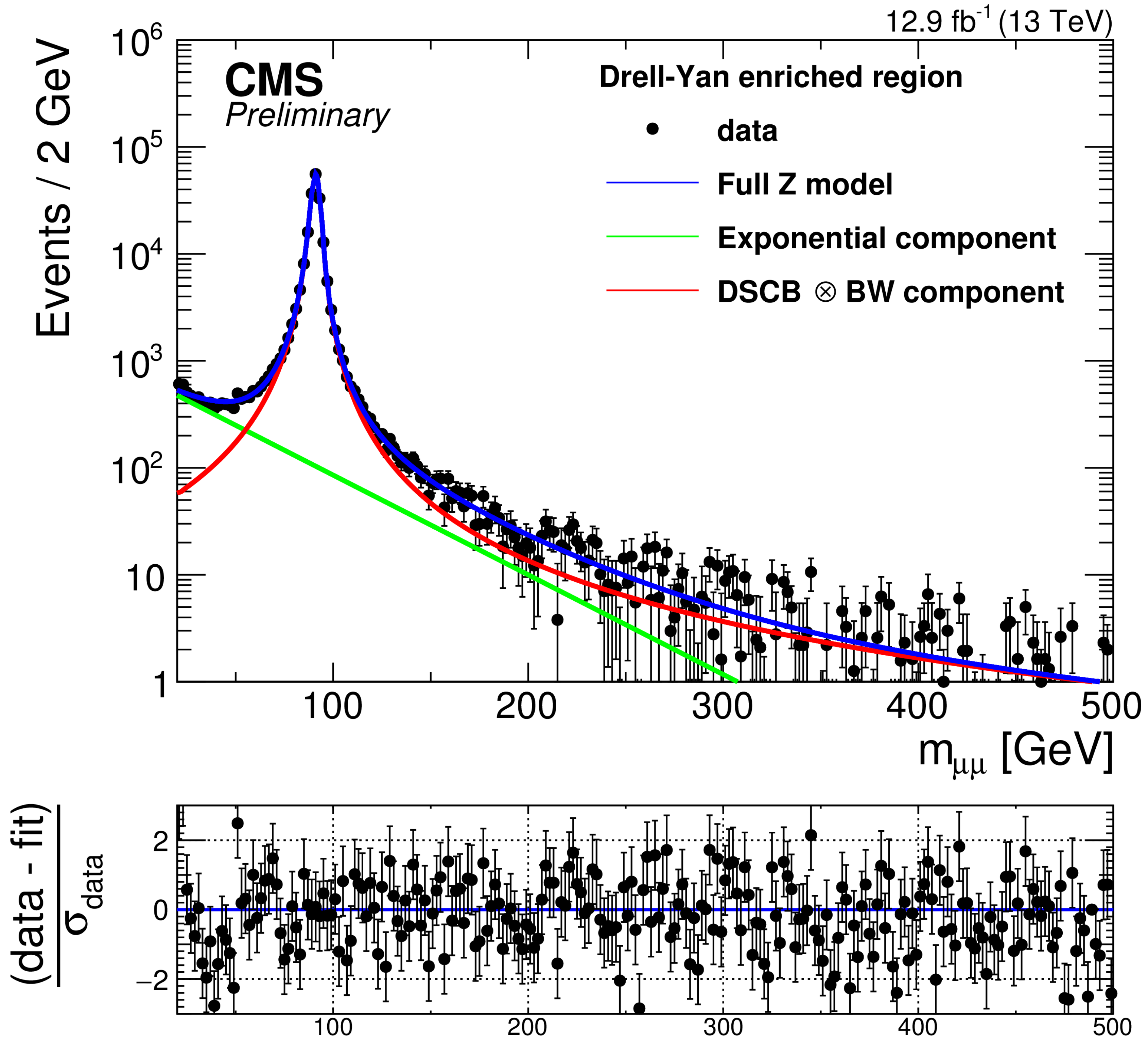




Fits

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



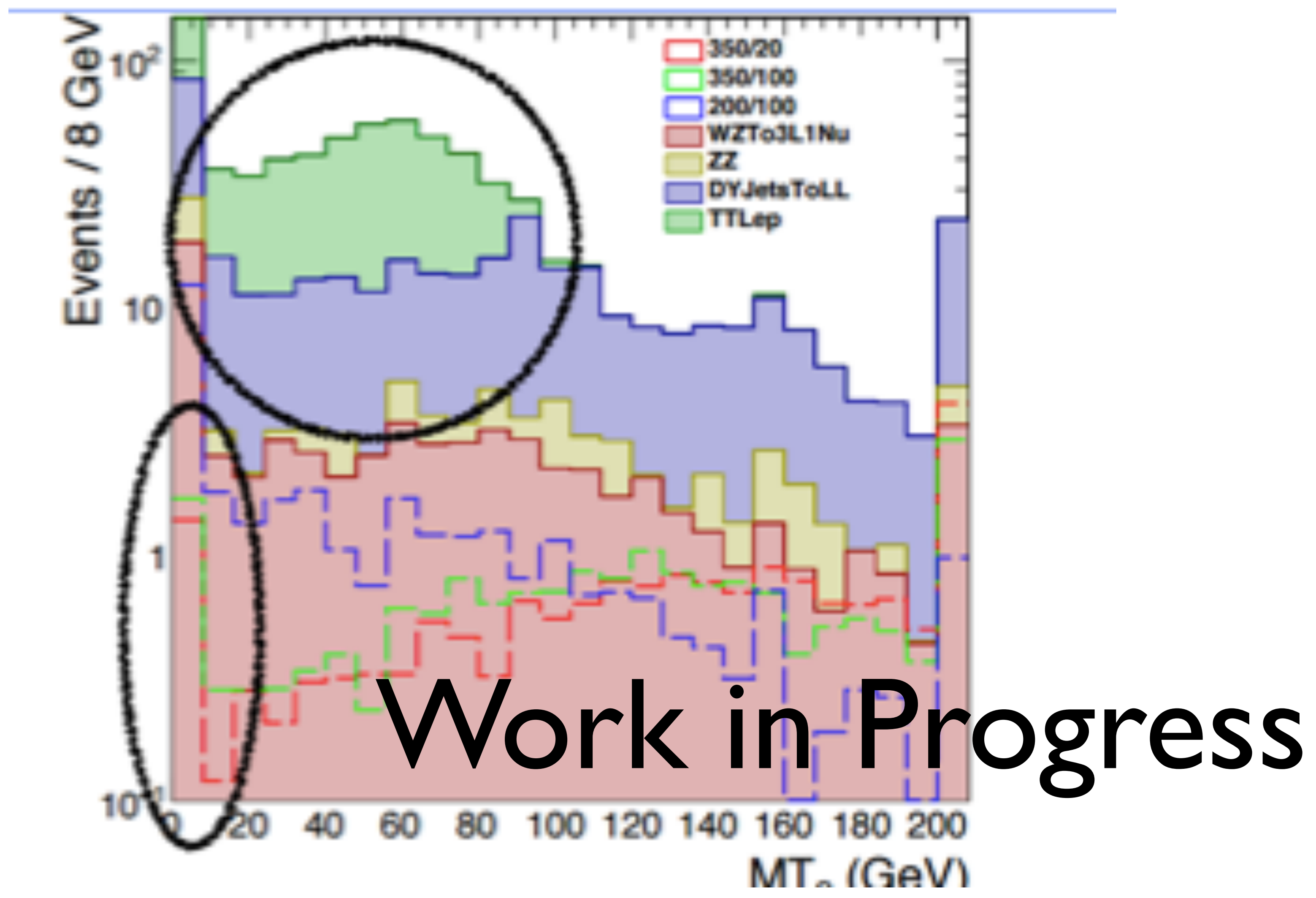


M_{T2}

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

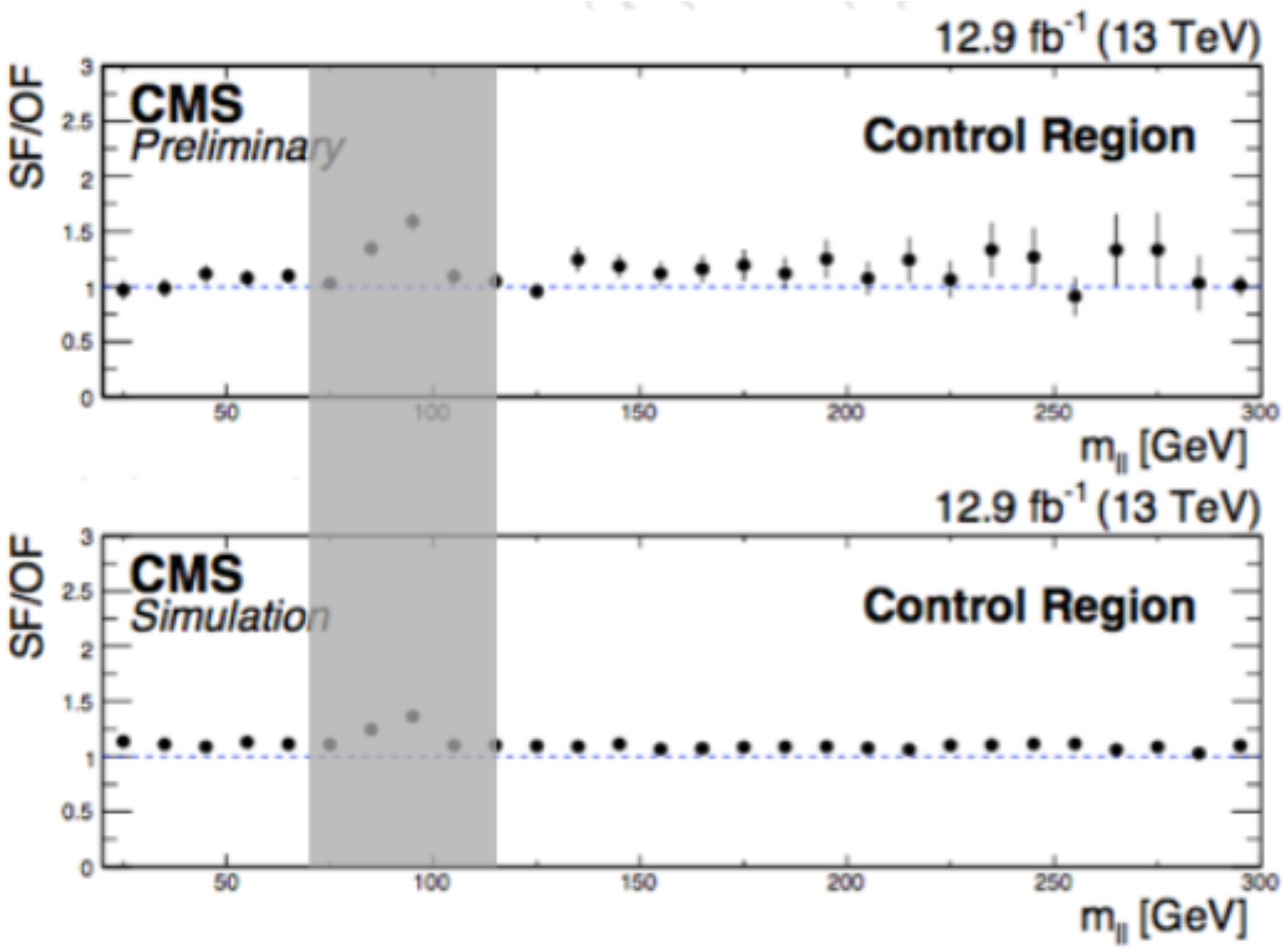


$R_{SF/OF}$

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

SUSY with opposite sign dileptons

This analysis is done using LHC Run II data recorded in 2016 corresponding to an integrated luminosity of **12.9 fb^{-1}**

Results were presented for ICHEP in August 2016, new developments for the analysis are made to target a publication by March 2017.

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

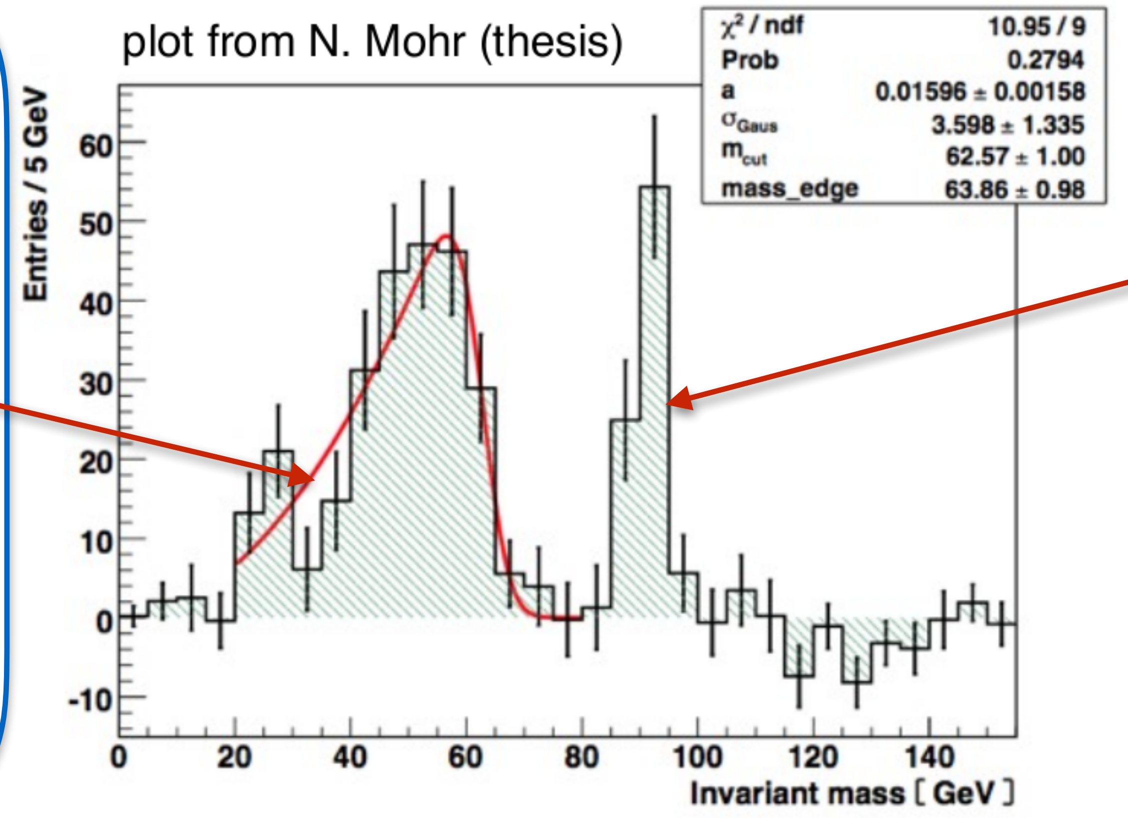
Inclusive m_{ll}:

- model backgrounds and signal with shapes
- 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: $M_{ll}^{max} = M_X - M_0$

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

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

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