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ETH zürich

Search for Supersymmetry in Events with two or more Leptons in pp Collisions at 13 TeV at CMS

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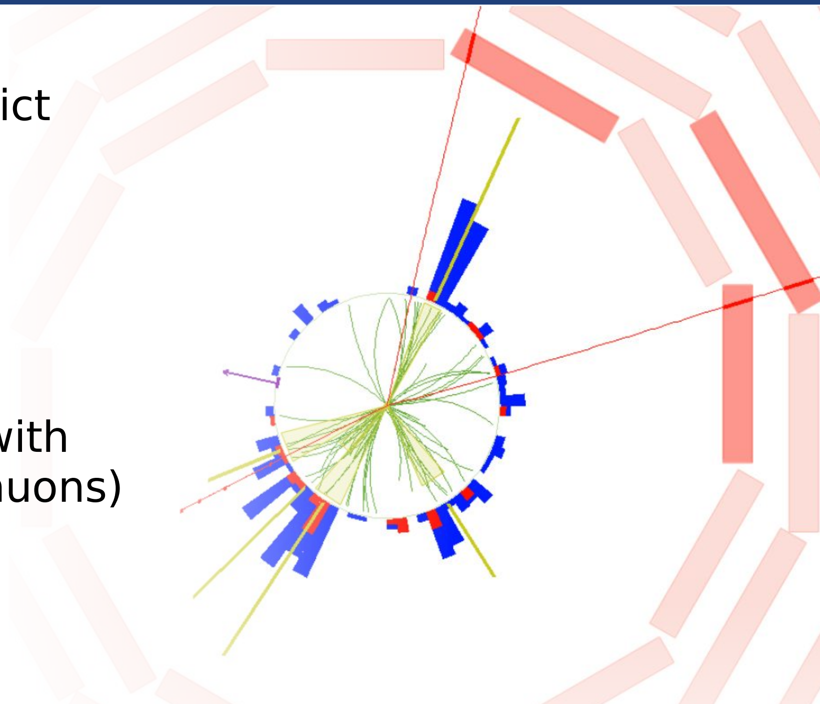
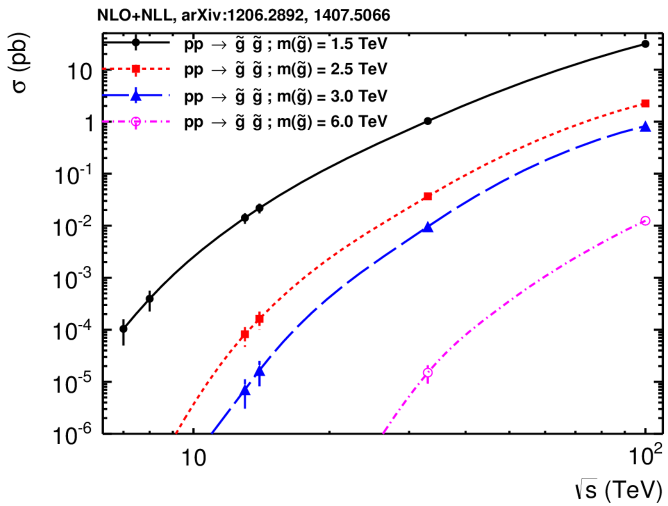
CMS

Leptonic SUSY searches at 13 TeV



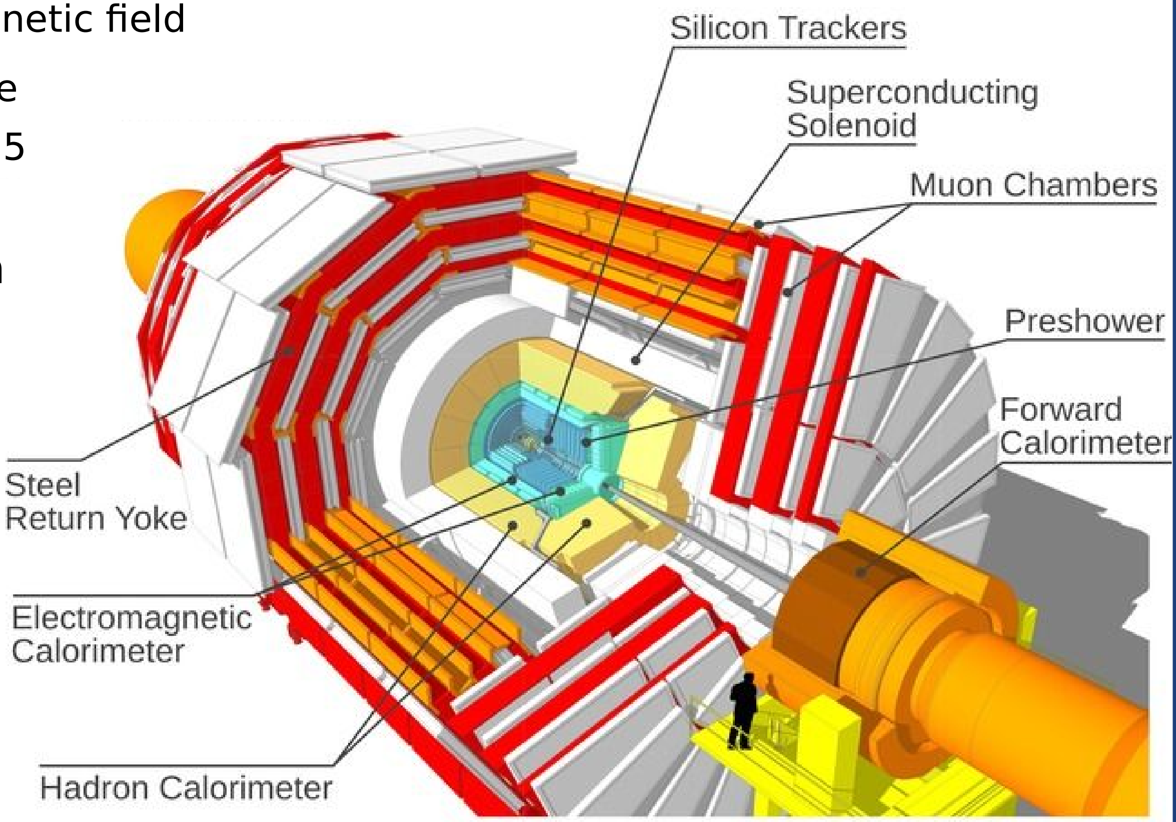
- Several beyond the SM scenarios predict leptons in final state, including SUSY
- Leptons provide clean signature and allow for robust event reconstruction
- Three CMS SUSY searches for events with **two or more leptons** (electrons or muons)



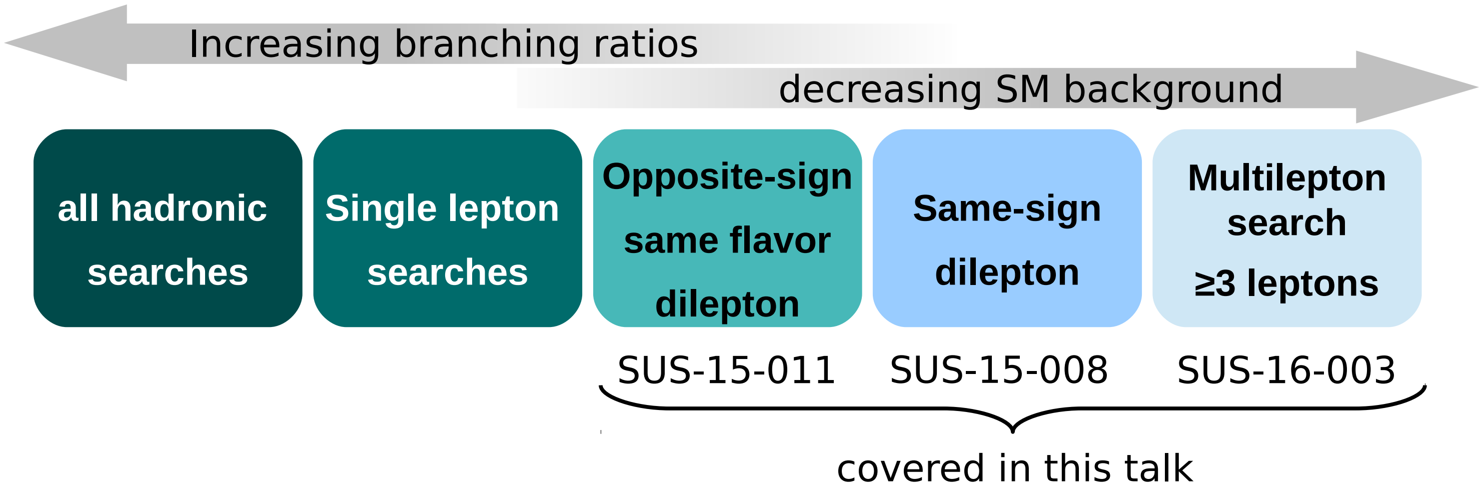
- Early searches with **2.3 fb^{-1}** of pp collisions collected in 2015: focus on models with **strong** squark and gluino production and R-parity conservation
  - Increased cross-sections at **new energy frontier** of 13 TeV
  - Require **jets** and **missing transverse energy** E_T^{miss} in final state

The CMS detector

- Nearly hermetic multi-purpose particle detector consisting of
  - Silicon pixel and strip tracker for vertex and track reconstruction, $|\eta| < 2.4$
  - Scintillating crystal electro-magnetic calorimeter (lead tungsten)
  - Hadronic sampling calorimeter (brass/scintillator), $|\eta| < 5.0$
  - Solenoid for 3.8 T magnetic field
  - Muon detectors outside of the solenoid $|\eta| < 2.5$
- 2-stage trigger system
  - Level-1 trigger: information from calorimeters and muon systems
  - High level trigger rate 1 kHz



SUSY searches at CMS

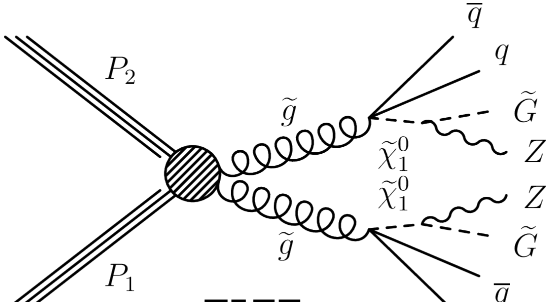


- All three analyses employ dilepton triggers and have similar kinematic acceptances for the leptons and require ≥ 2 jets and E_T^{miss} in final state
  - E_T^{miss}: negative vectorial sum of momenta of all reconstructed particles
  - Hadronic activity $H_\mathrm{T} = \sum_{jets} p_\mathrm{T}$, $m_{\ell\ell}$ refers to dilepton invariant mass
- Main goals:
  - Opposite-sign analysis: scrutinize two different 2.6 - 3.0σ excesses in 8 TeV data from CMS and ATLAS
  - Same-sign and multilepton analysis: improve sensitivity for various models in uncharted territory

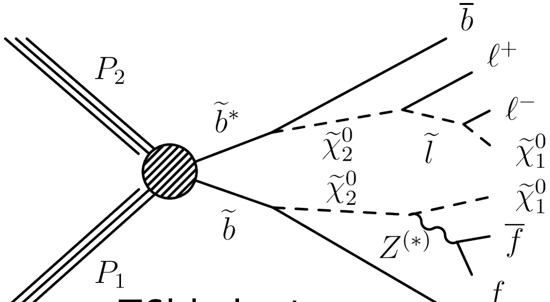
Opposite-sign same-flavor dilepton search

Opposite-sign same flavor dilepton

- Two sub-searches targeting different models
  - both selecting two loosely isolated opposite-sign, same-flavor (ossf) leptons with p_T > 20 GeV
- On-Z search (dilepton $m_{\ell\ell}$ compatible with Z mass):
  - targets T5ZZ GBSM model → scrutinize 3.0σ excess quoted by ATLAS in 8 TeV
  - New: signal regions with higher granularity in N_{jets} and E_T^{miss}, plus ATLAS-like region
- Edge search (inclusive in dilepton $m_{\ell\ell}$):
  - search for edge in dilepton $m_{\ell\ell}$ spectrum, sensitive to T6bbslepton model → scrutinize 2.6σ excess found by CMS in 8 TeV
  - Signal regions (SR) kept as in 8 TeV, plus exclusive SR in b-jet multiplicity (N_{bjet})
  - Additional SR filling gaps in $m_{\ell\ell}$ spectrum of 8 TeV search



T5ZZ

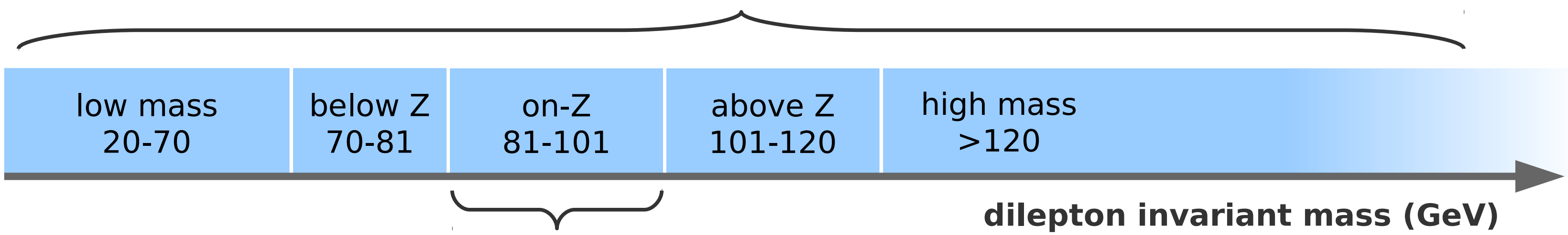


T6bbslepton

Search strategy

Opposite-sign same flavor dilepton

- Cut and count analysis in various search regions
  - **Edge search (off-Z):** binning in forward and central detector region, dilepton $m_{\ell\ell}$, and b-jet multiplicity
    → 20 exclusive SR and 10 inclusive ones for comparison with 8 TeV



  - **On-z search:** binning in number jets (N_{jet})
    - SRA: N_{jet} = 2-3 and H_T > 400 GeV
    - SRB N_{jet} > 3

    further binning in b-jet multiplicity and E_T^{miss}
    → 16 exclusive signal regions
    - ATLAS-like SR: $H_T + p_T^{l_1} + p_T^{l_2} > 600$ GeV | $E_T^{miss} > 225$ GeV $\Delta\phi_{E_T^{miss}, j_1, j_2} > 0.4$
- Signal regions require 2 or more jets and E_T^{miss} > 100 GeV, inclusive in N_{bjet}
- Control regions for data driven background estimation
  - Drell-Yan enriched: ≥2 jets, E_T^{miss} < 50 GeV
  - ttbar enriched: 2 jets, 100 < E_T^{miss} < 150 GeV

Background estimation

Opposite-sign same flavor dilepton

- Flavor symmetric background, produce $(e^{\pm}\mu^{\mp})$ as often as $(\mu^{+}\mu^{-},\ \mathrm{e}^{+}\mathrm{e}^{-})$
  - dominant: ttbar with genuine E_T^{miss}
    minor contributions: $\mathrm{WW}, \mathrm{Z}/\gamma^{*}(\rightarrow \tau\tau), \mathrm{tW}$
  - estimated with opposite flavor control sample, corrections for different selection efficiencies

- Flavor correlated lepton production
  - mostly Drell-Yan with instrumental E_T^{miss}
    (minor contributions: ZZ, WZ, ttZ)
  - Assumption: instrumental E_T^{miss} from limited detector resolution for hadronic recoil against Z → measure E_T^{miss} shape with $\gamma + \mathrm{jets}$ control sample (E_T^{miss} template technique)

Background estimation and results

- Flavor symmetric background, produce $(e^{\pm}\mu^{\mp})$ as often as $(\mu^{+}\mu^{-},\ e^{+}e^{-})$
  - dominant: ttbar with genuine E_T^{miss}
    minor contributions: $WW, Z/\gamma^{*}(\rightarrow \tau\tau), tW$
  - estimated with opposite flavor control sample, corrections for different selection efficiencies

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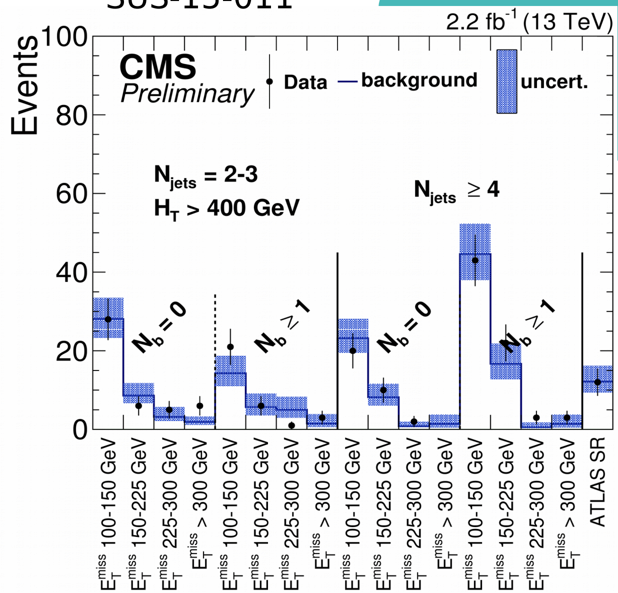

- Flavor correlated lepton production
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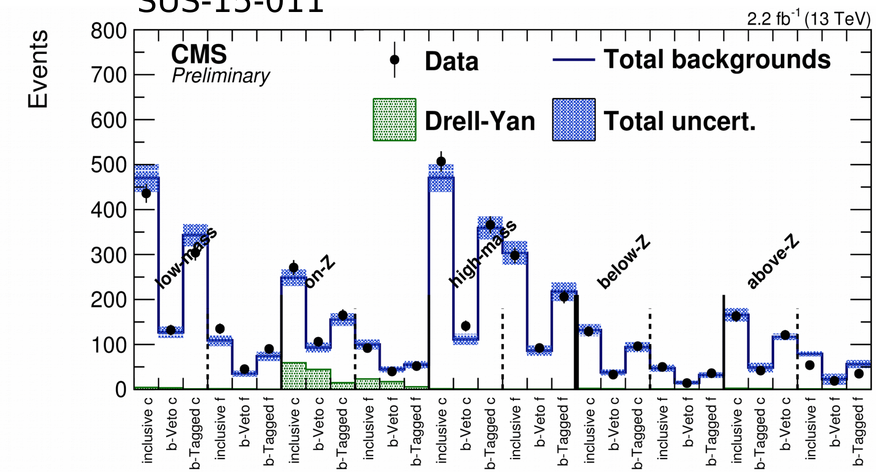
SUS-15-011



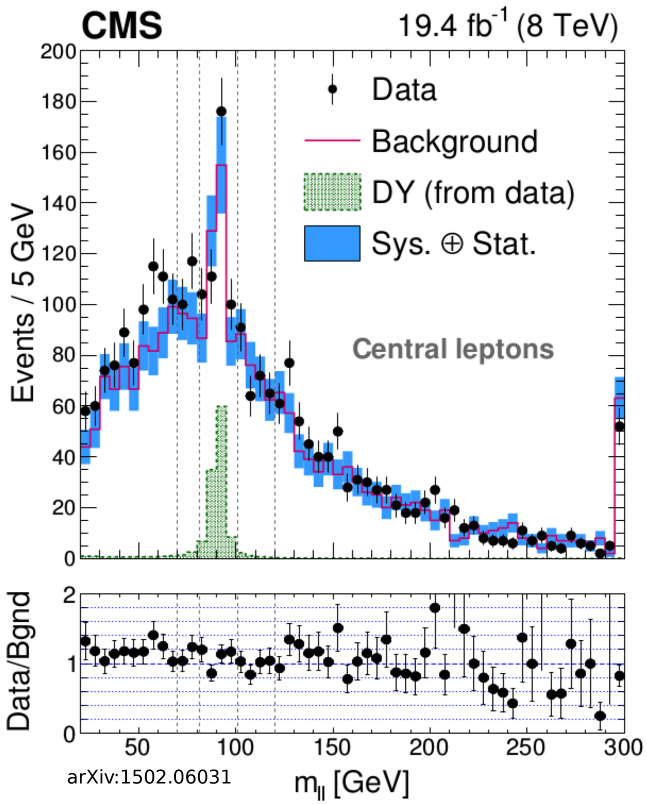
- No significant deviation between data and predictions

Edge search – invariant mass spectrum

Opposite-sign same flavor dilepton

- 13 TeV data does not confirm the 2.6σ excess found by CMS in 8 TeV
- Good agreement in $m_{\ell\ell}$ shape for both inclusive b-jet region and >0 b-jet regions and as well for both forward and central detector regions regions

CMS 8 TeV



arXiv:1502.06031

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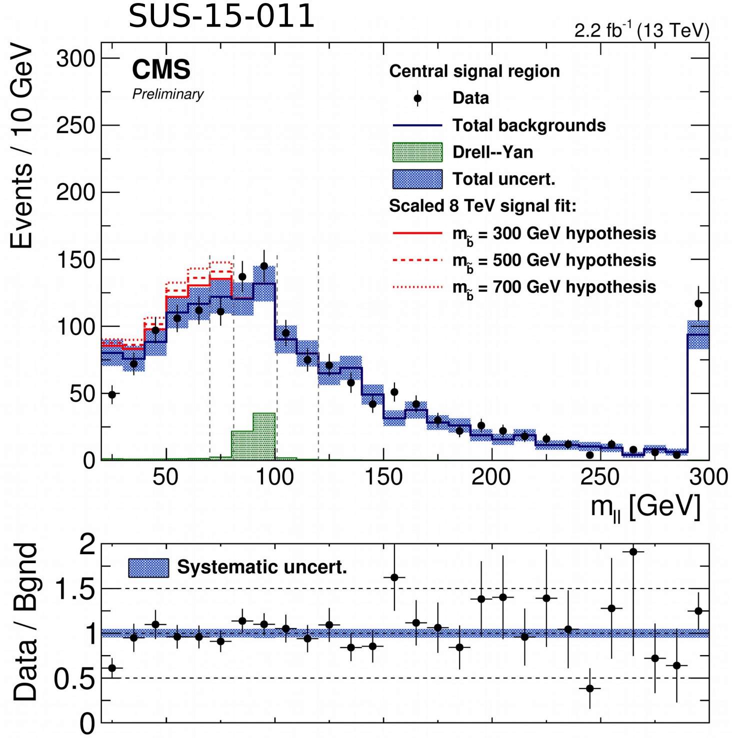


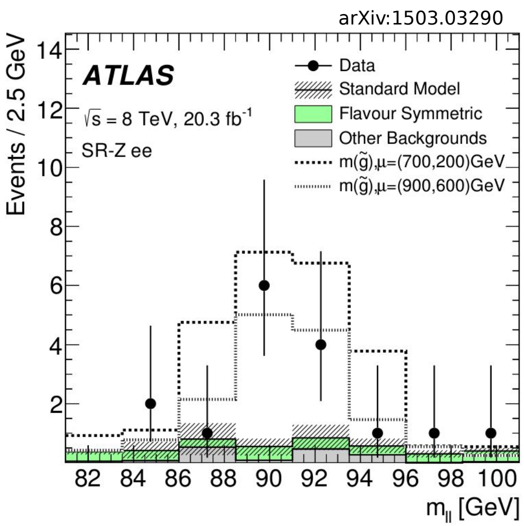
CMS 13 TeV

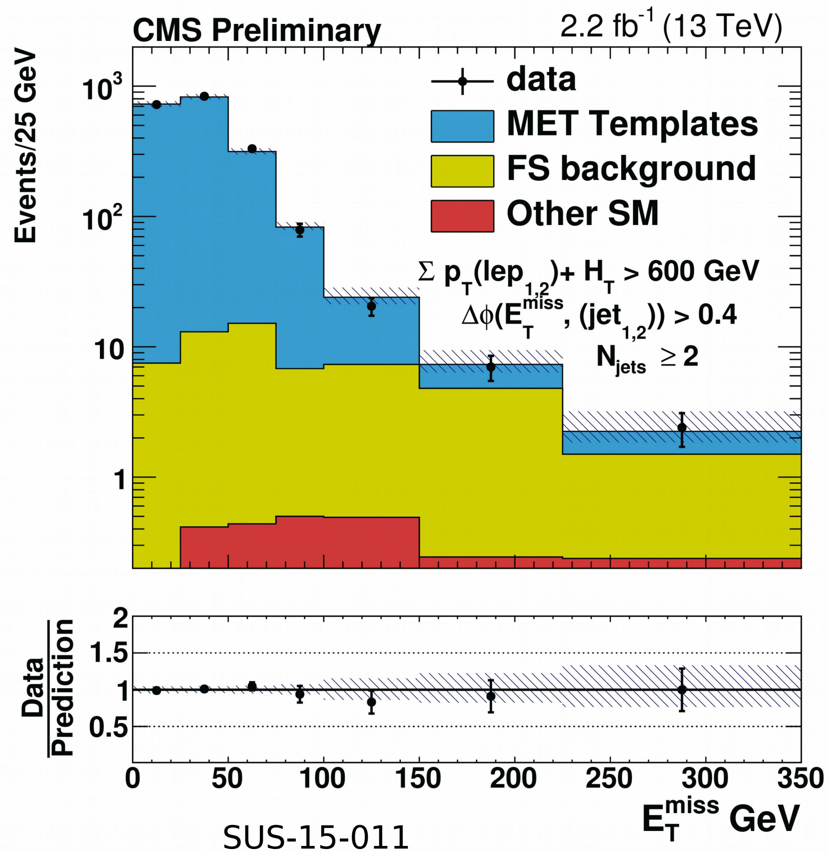
On-Z search: ATLAS-like signal region

Opposite-sign same flavor dilepton

- CMS data disfavors signal hypothesis in ATLAS-like signal region
- Very good agreement between background prediction and data found

ATLAS 8 TeV





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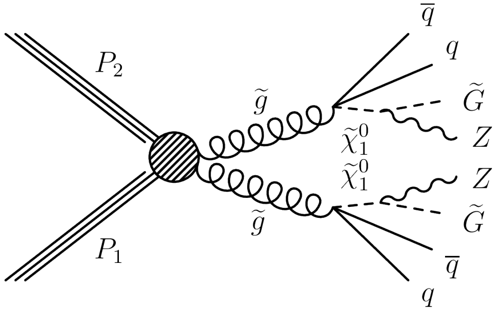
CMS 13 TeV

- ATLAS reports another 2.2σ excess in a similar region with 13 TeV data

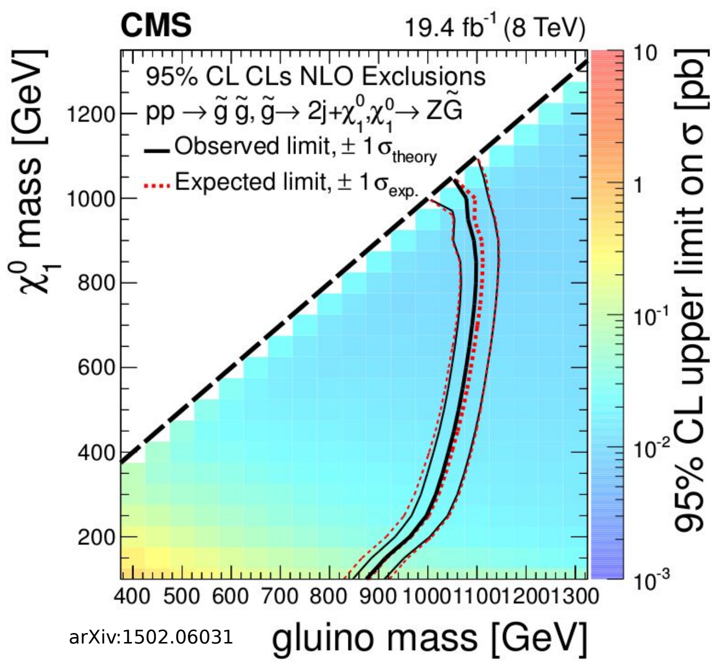
Interpretation

- Absence of excess → set limits on T5ZZ model for massless gravitino
- Asymptotic limits with the LHC-type CL_s method
- on-Z signal regions (most sensitive: SRB)

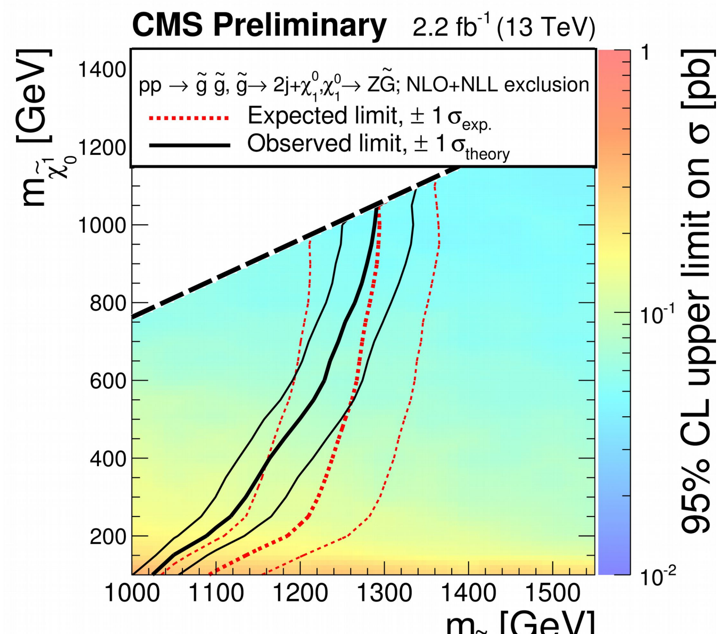


Opposite-sign same flavor dilepton

CMS 8 TeV



arXiv:1502.06031



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CMS 13 TeV

- Limits improved by up to 200 GeV for heavy gluinos

Same-sign dilepton and multi-leptons

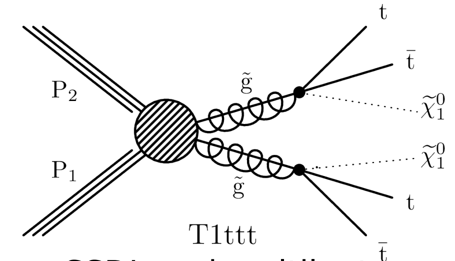
- Searches for two leptons of the same change (SSDL) and three or more leptons (multilepton)
- Similar search strategies and data driven estimation techniques for main backgrounds

- Main differences:
  - Background abundance: multi-lepton has very low SM background but also lower signal branching fraction for leptonic final state → smaller signal region granularity than SSDL analysis
  - Background composition: different dominant backgrounds depending on SR
  - SSDL vetos events were dilepton invariant mass is within 15 GeV of m_Z, multi-lepton has dedicated on-Z signal regions
    → some simplified models are only targeted by one of the two searches

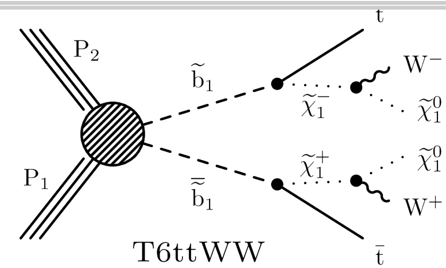
Same-sign dilepton search

Multilepton search

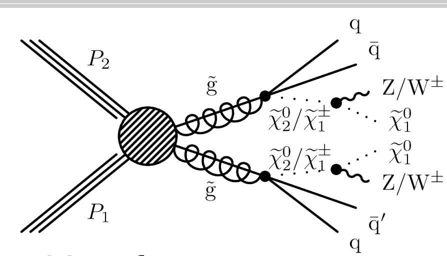
≥3 leptons



SSDL and multilepton



SSDL and multilepton


SSDL for T5qqqqWW

multilepton for T5qqqqWZ

Search strategies

- Two inclusive analyses → search for SUSY in tails of kinematic distributions
- Both employ a dedicated isolation technique developed for improved lepton selection efficiency in boosted topologies (“multi-isolation”)
- Individual signal region optimization for best signal/background separation

Same-sign dilepton search

SSDL

- s/b enhancement by distinguishing lepton p_T high $p_T > 25$ GeV (H) and low $10 < p_T < 25$ GeV (L)
  - 3 SRs depending on p_T of the 2 leptons (HH, HL, and LL)
- Further binning in H_T, E_T^{miss}, N_{jet}, N_{bjet}, and M_T^{min} * → **66 exclusive SR**
- Reject events with $m_{\ell\ell}$ between 76 and 106 GeV and < 12 GeV

$^* M_T^{min} = \min\left[M_T(\ell_1, E_T^{miss}), M_T(\ell_2, E_T^{miss})\right]$

Multilepton search

≥3 leptons

Multilepton

- Pre-selection:
  - ≥3 well identified and isolated leptons
  - $m_{\ell\ell} > 12$ GeV
  - ≥ 2 jets
  - $E_T^{miss} > 50$ GeV
- Divide signal events in on- and off-Z according to dilepton $m_{\ell\ell}$
- Binning in number of b-jets, E_T^{miss} and H_T
  → **2 times 15 exclusive SRs**

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Non-prompt lepton background

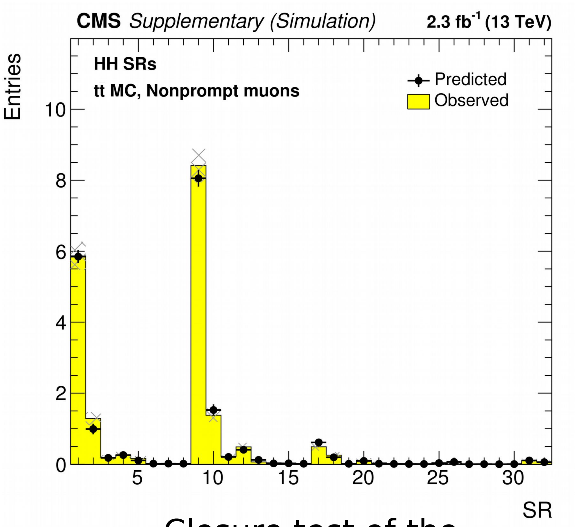
- Prompt leptons: from W, Z, or slepton decays
- Isolation cuts reject non-prompt leptons
  - e.g. heavy flavor decays, misidentified hadrons, photon conversions or muons from light mesons
  - Reducible background from residual non-prompt contribution
- Dominant background in signal regions in the HL part of SSDL and off-Z for multileptons
- Fully data-driven estimation
  - Measure probability for non-prompt lepton which passes loose selection to also pass tight selection ("fake-rate") in QCD enriched control region
  - Reweight yield in control region with fake-rate dependent factor. Control region identical to SR, except that at least one lepton fails tight selection

Same-sign dilepton search

Multilepton search

≥3 leptons

SUS-15-008



Closure test of the tight-to-loose method in ttbar MC for SSDL HH region

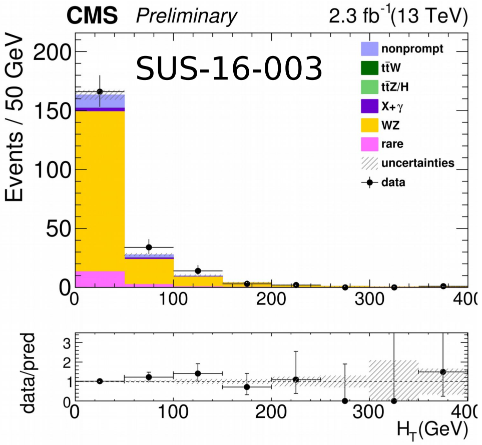
Other backgrounds

Same-sign dilepton search

Multilepton search

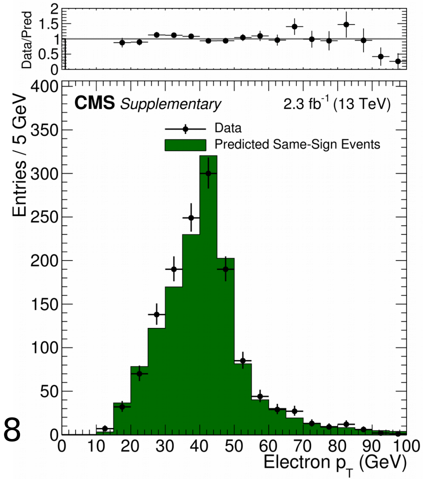
≥3 leptons

- WZ diboson production:
  - important in regions without b-tags and in multilepton on-Z regions
  - Semi data-driven: normalize yields in control region
- Rare standard model processes (e.g. ttW, ttZ..)
  - Dominant background in tail regions
  - Estimated from simulation with appropriate experimental and theoretical uncertainties



- Charge-flip background:
  - Small background in same-sign analysis arising from charge mis-measurements
  - Measure probability in $Z \rightarrow e^+e^-$ events: 10^{-5} – 10^{-3} → reweight yield of opposite-sign lepton pair events
  - Found to be negligible for muons

Same-sign dilepton search



SUS-15-008

Results

Same-sign dilepton search

- Good agreement between prediction and data found in all 66 signal regions of the same-sign dilepton search
- Largest deviations: local significance of 2.2σ in HL SR8 and 1.8σ in HH SR10
  - Both SRs: N_{bjet}=1, M_T<120 GeV, N_{jets}=[2;4], E_T^{miss}=[50;200], H_T=[300;1125]

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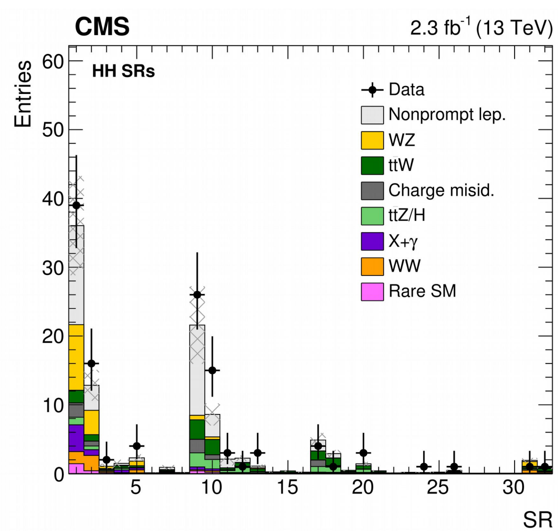

Signal regions in the HH p_T region

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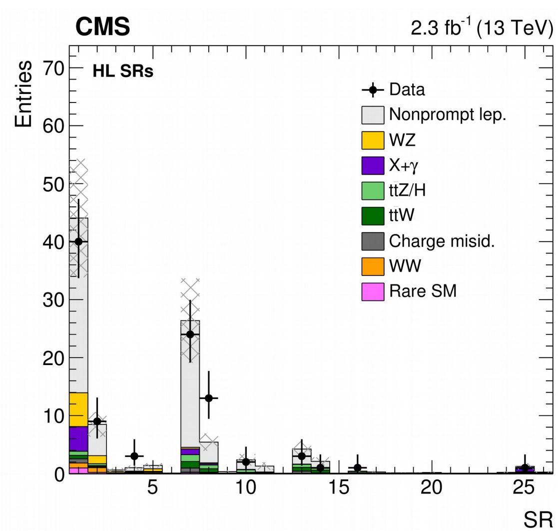

Signal regions in the HL p_T region

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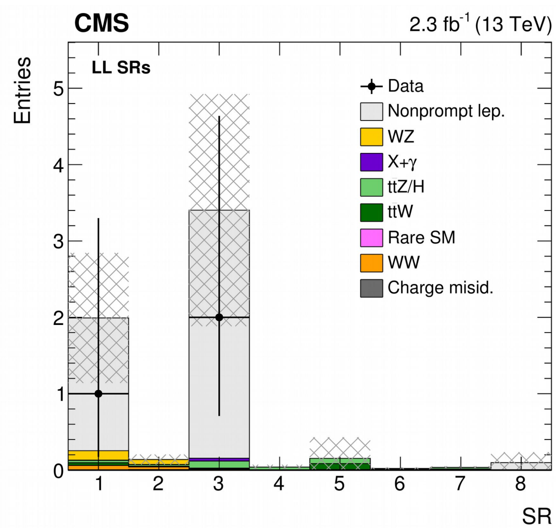
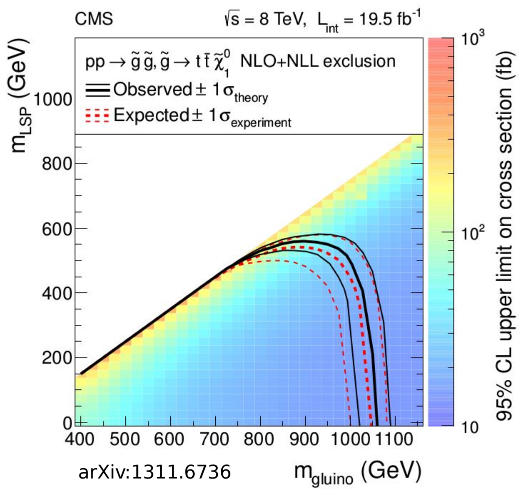


Signal regions in the LL p_T region

- For detailed signal region definition see back-up

Interpretations

CMS 8 TeV



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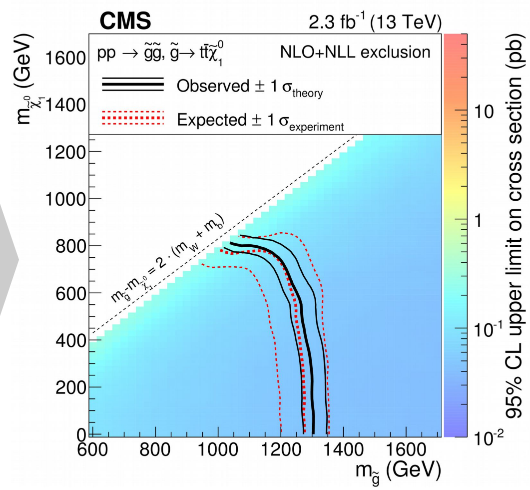
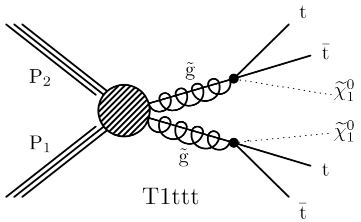
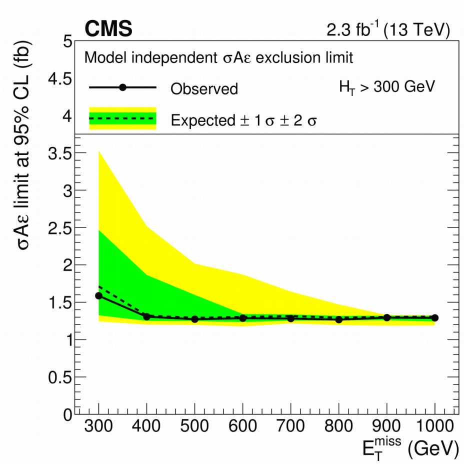


CMS 13 TeV

Same-sign dilepton search



- Same-sign analysis pushes limit for gluino mass in T1tttt model about ≈200 GeV beyond 8 TeV result
- Model independent exclusion limits for production of same-sign dilepton pair set as function of E_T^{miss} and H_T
  → $\sigma \cdot A \cdot \varepsilon < 1.7$ fb in H_T and E_T^{miss} tails



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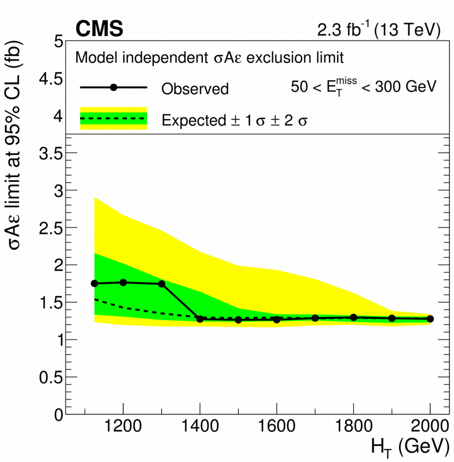

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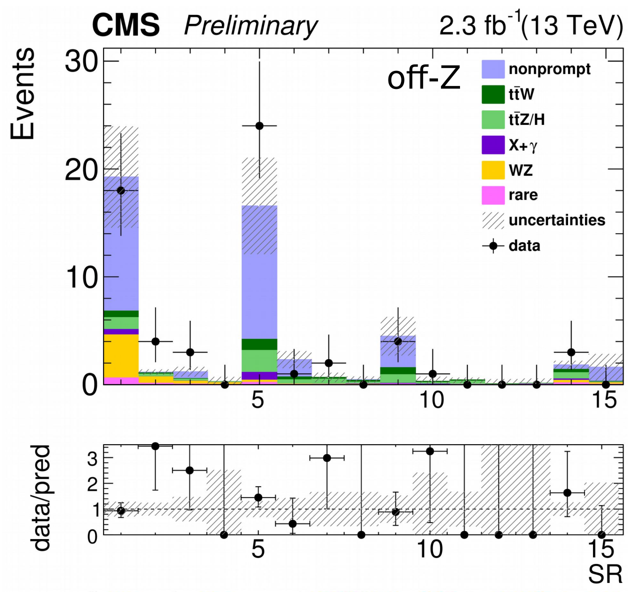
Results

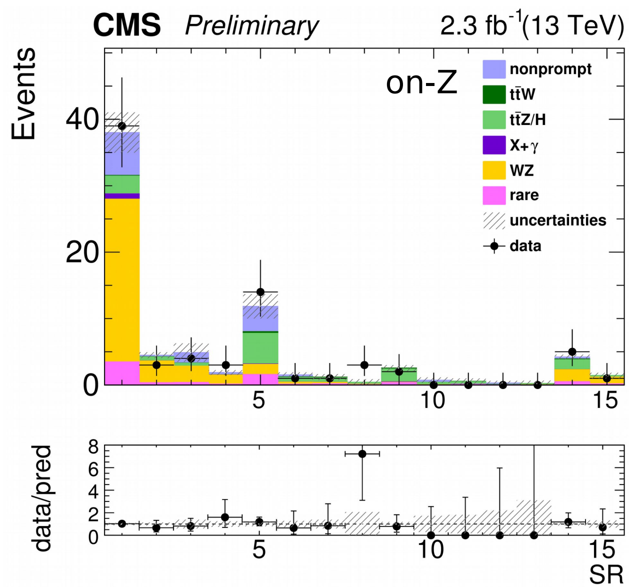
- Also multilepton analysis observes no significant deviation from the expected SM background yields
- Right plots: inclusive baseline yields

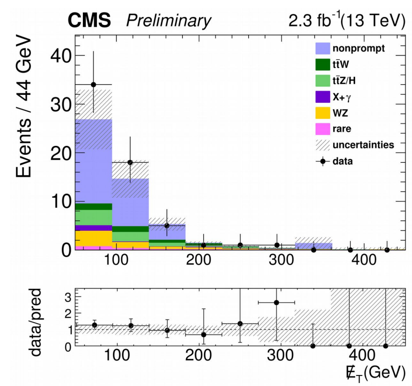
Multilepton search

≥3 leptons

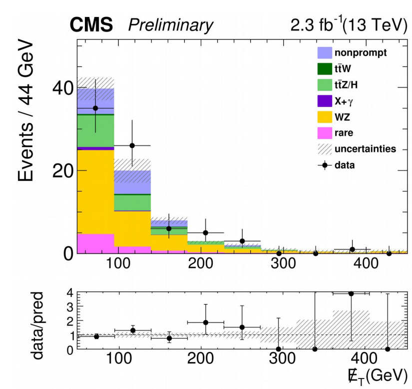
all Fig. SUS-16-003







off-Z all SR



on-Z all SR

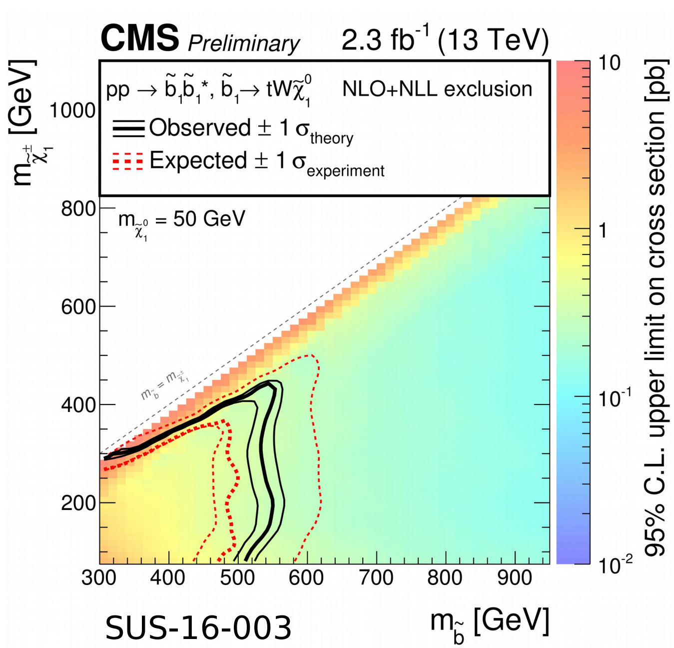
N_{jets}	$N_{b\,jets}$	E_T^{miss} (GeV)	60 GeV $\leq H_T <$ 400 GeV	400 GeV $\leq H_T <$ 600 GeV	$H_T \geq$ 600 GeV
≥ 2	0	50 – 150	SR1	SR3	SR14
		150 – 300	SR2	SR4	
	1	50 – 150	SR5	SR7	
		150 – 300	SR6	SR8	
	2	50 – 150	SR9	SR11	
		150 – 300	SR10	SR12	
	≥ 3	50 – 300	SR13		
	inclusive	≥ 300	SR15		

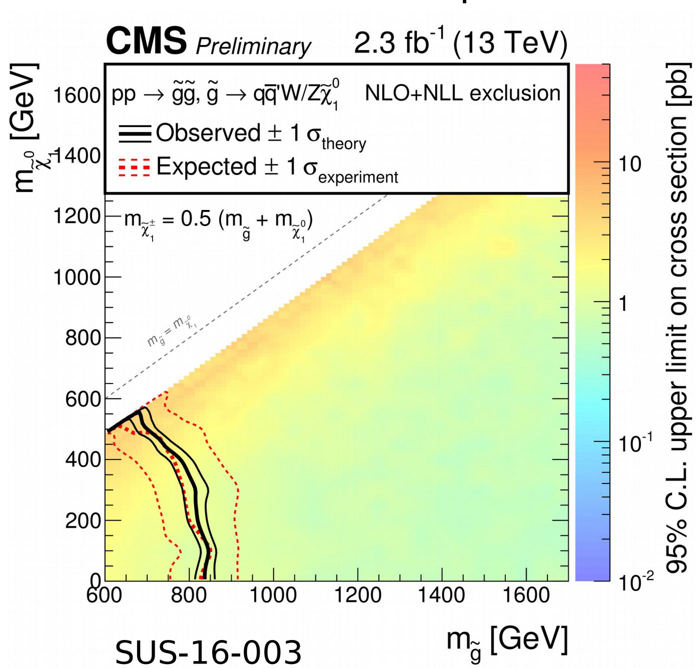
Interpretation

Multilepton search

≥3 leptons

- T1tttt: limit on gluino mass improved by ≈100 GeV w.r.t. 8 TeV
- Set limits on sbottom and chargino mass in T6ttWW model (off-Z regions sensitive)
  - exclude $m_{sbottom}$ < 475 GeV for $m_{chargino}$ = 200 GeV
  - 8 TeV result (19.5 fb^{-1}) not yet reached with 2.3 fb^{-1} at 13 TeV
- On-Z regions sensitive on T5qqqqWZ model
  - Exclude gluino masses up to 825 GeV, and neutralino masses up to 550 GeV





Summary

- **Three searches for SUSY** exploring final states with **two or more leptons** have been performed at CMS with 2.3 fb^{-1} of pp collision data at 13 TeV
- Several advancements **improved** the **sensitivity** of the searches w.r.t. run 1, e.g. signal region optimization and improved lepton reconstruction and isolation techniques
- **No significant excess** of data over the expected SM background has been found
  - New results of the opposite-sign same-flavor search **disfavor the signal hypothesis** in two different search regions where CMS and ATLAS reported excesses of 2.6 and 3.0σ in 8 TeV data
  - The same-sign dilepton and the multilepton searches **pushed exclusion limits** on sparticle masses in various simplified models beyond the 8 TeV limits and added additional interpretations, including model independent limits on SS dilepton pair production
- We have to look behind the next corner!

Opposite-sign same flavor dilepton

Same-sign dilepton search

Multilepton search

≥3 leptons

References

Opposite-sign same flavor dilepton

Search for SUSY in same-sign dilepton events at 13 TeV, CMS PAS SUS-15-008

Same-sign dilepton search

Search for SUSY in same-sign dilepton events at 13 TeV, CMS PAS SUS-15-008
submitted to EPJC, arXiv:1605.03171

Multilepton search

≥3 leptons

Search for SUSY in multilepton events at 13 TeV, CMS PAS SUS-16-003

All public CMS SUSY results here → link

Back-up

OSSF – measurement of $R_{SF/OF}$

- **Method 1)** measure $R_{SF/OF}$ in CR which is enriched in flavor symmetric background
  - $N_{jet} = 2$, $100 < E_t^{miss} < 150$ GeV, $m_{ll} < 70$ GeV, $m_{ll} > 110$ GeV
  - Measure yields N_{OF} and N_{SF} → $R_{SF/OF} = N_{SF}/N_{OF}$
  - Validate extrapolation to signal region with ttbar MC
- **Method 2)** determine $R_{SF/OF}$ from factorized efficiencies
  - Ratio of lepton ID and reco efficiencies $r_{\mu/e} = \sqrt{N_{\mu^+\mu^-}/N_{e^+e^-}}$ from DY control region ($N_{jet}>1$, $E_T^{miss}<50$ GeV, $60 < m_{ll} < 120$ GeV)
  - Ratio of trigger efficiencies: $R_T = \sqrt{\epsilon^T_{\mu^+\mu^-}\epsilon^T_{e^+e^-}}/\epsilon^T_{e^\pm\mu^\mp}$ → $R_{SF/OF} = \frac{1}{2}(r_{\mu/e} + r^{-1}_{\mu/e}) \cdot R_T$

	Central		Forward	
	Data	MC	Data	MC
$\frac{1}{2}(r_{\mu/e} + r^{-1}_{\mu/e})$	1.008 ± 0.013	1.008 ± 0.012	1.022 ± 0.042	1.026 ± 0.046
R_T	1.003 ± 0.072	1.027 ± 0.067	1.061 ± 0.090	1.029 ± 0.071
	$R_{SF/OF}$			
from factorization	1.011 ± 0.074	1.035 ± 0.068	1.084 ± 0.103	1.057 ± 0.087
direct measurement	1.055 ± 0.061	1.050 ± 0.013	1.107 ± 0.134	1.079 ± 0.021
weighted average	**1.037 ± 0.047**	**1.049 ± 0.013**	**1.097 ± 0.068**	**1.079 ± 0.020**

OSSF – E_T^{miss} template technique

- Determine **shape** of E_T^{miss} spectrum of DY background from $\gamma + \text{jets}$ control sample
- Reweight to match Z and photon p_T in simulation for each SR
- **Normalize** obtained E_T^{miss} distribution in Z+jets CR (E_T^{miss} < 50 GeV)
- Uncertainty: statistical power of $\gamma + \text{jets}$ events in SR (10-50%) including statistical uncertainty on normalization (4-10%)

Signal region	SRA; b-veto	SRA; $\geq$ 1 b-tag	SRB; b-veto	SRB; $\geq$ 1 b-tag	ATLAS Signal Region
Uncertainty	4 %	10 %	3 %	6 %	3 %

- MC closure: use $\gamma + \text{jets}$ to predict Z+jets and take discrepancy as uncertainty for respective SR

E_T^{miss} [GeV]	0 - 50	50 - 100	100 - 150	150 - 225	225 - 300	$\geq$ 300
SRA, b-veto	1 %	4 %	4 %	5 %	15 %	35 %
SRA, with b-tags	1 %	3 %	5 %	10 %	30 %	40 %
SRB, b-veto	1 %	2 %	4 %	10 %	20 %	25 %
SRB, with b-tags	2 %	3 %	10 %	10 %	50 %	50 %
ATLAS Signal Region	2 %	2 %	10 %	10 %	10 %	–

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OSSF – result tables (onZ search)

Table 4: Results for the on-Z search, binned in all the variables.

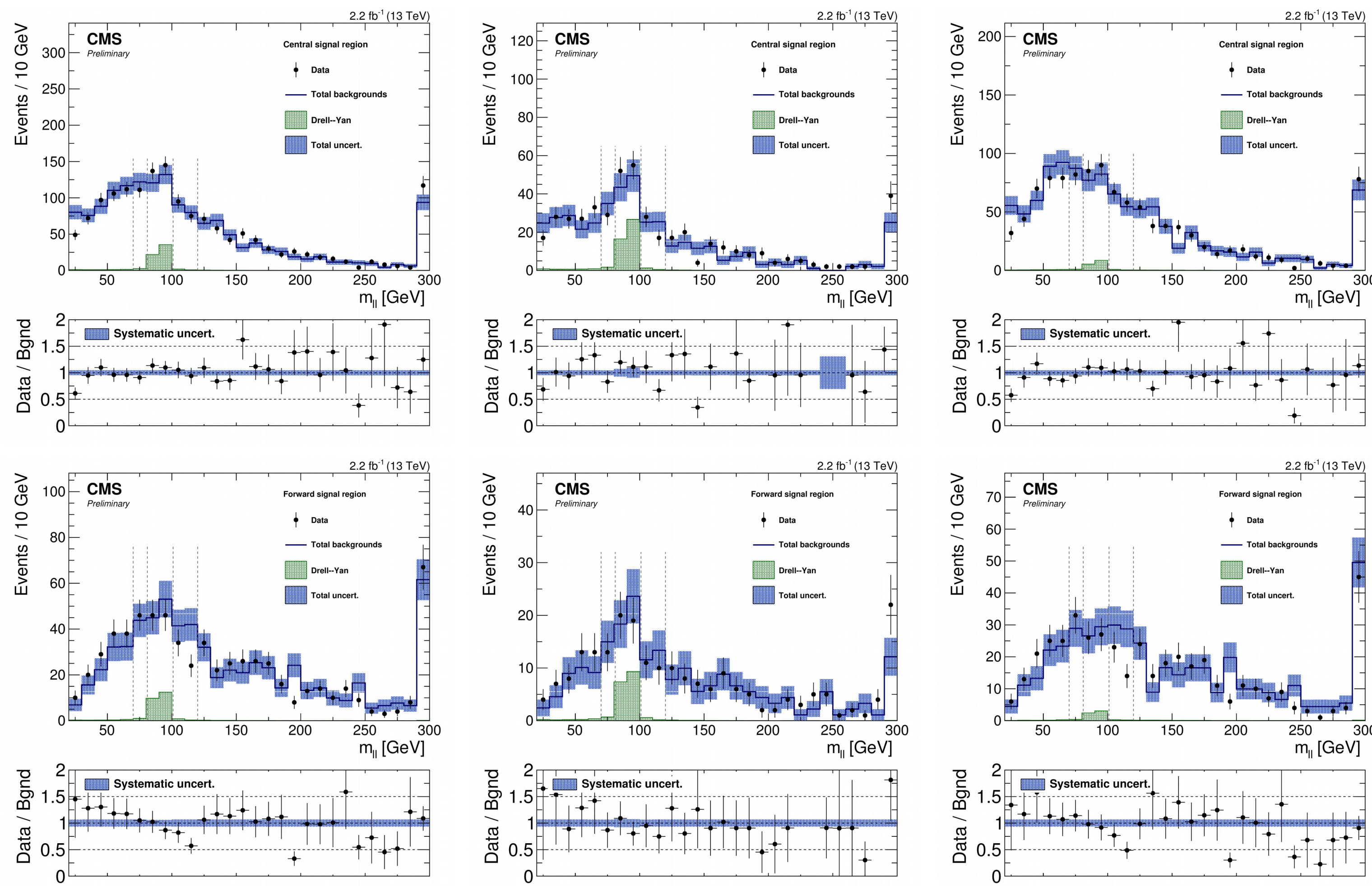
N_{jets}/H_T	N_{b-jets}	E_T^{miss}	predicted	observed
SRA 2- 3 jets *and* $H_T > 400$	== 0	100-150	$28.2\,^{+5.4}_{-4.8}$	**28**
		150-225	$8.7\,^{+3.2}_{-1.9}$	**6**
		225-300	$3.3\,^{+2.5}_{-1.0}$	**5**
		> 300	$1.9\,^{+1.4}_{-0.7}$	**6**
	≥ 1	100-150	$14.2\,^{+4.4}_{-3.3}$	**21**
		150-225	$5.8\,^{+3.4}_{-2.1}$	**6**
		225-300	$5.0\,^{+3.3}_{-2.0}$	**1**
		> 300	$1.6\,^{+2.4}_{-0.9}$	**3**
SRB ≥ 4 jets	== 0	100-150	$23.1\,^{+4.9}_{-3.7}$	**20**
		150-225	$8.2\,^{+3.4}_{-2.1}$	**10**
		225-300	$0.8\,^{+1.2}_{-0.2}$	**2**
		> 300	$1.5\,^{+2.4}_{-0.9}$	**0**
	≥ 1	100-150	$44.6\,^{+7.7}_{-6.6}$	**43**
		150-225	$16.7\,^{+5.1}_{-3.9}$	**22**
		225-300	$0.6\,^{+1.2}_{-0.3}$	**3**
		> 300	$1.4\,^{+2.4}_{-0.9}$	**3**
ATLAS - SR:				
$H_T + p_T^{l_1} + p_T^{l_2} > 600$ GeV	$E_T^{miss} > 225$ GeV	$\Delta\phi_{E_T^{miss}, j_1, j_2} > 0.4$	$12.0\,^{+4.0}_{-2.8}$	**12**

OSSF – result tables (edge search)

	$m_{\ell\ell}$ range [GeV]	$N_{\text{b-jets}} \geq 0$ pred. total (DY)	$N_{\text{b-jets}} \geq 0$ obs.	$N_{\text{b-jets}} = 0$ pred. total (DY)	$N_{\text{b-jets}} = 0$ obs.	$N_{\text{b-jets}} \geq 1$ pred. total (DY)	$N_{\text{b-jets}} \geq 1$ obs.
central	20 - 70	470.9 ± 29.9 (4.6 ± 1.3)	**437**	126.7 ± 12.3 (3.4 ± 1.0)	**132**	344.2 ± 23.9 (1.2 ± 0.3)	**305**
	70 - 81	132.2 ± 12.6 (2.6 ± 0.7)	**129**	38.2 ± 6.2 (2.0 ± 0.6)	**33**	93.9 ± 10.4 (0.7 ± 0.2)	**96**
	81 - 101	247.9 ± 17.8 (59.3 ± 7.8)	**271**	93.1 ± 10.5 (44.4 ± 7.6)	**106**	154.8 ± 13.4 (14.9 ± 2.1)	**165**
	101 - 120	164.7 ± 14.5 (2.0 ± 0.6)	**163**	48.1 ± 7.0 (1.5 ± 0.5)	**42**	116.6 ± 11.8 (0.5 ± 0.1)	**121**
	> 120	467.8 ± 29.9 (1.5 ± 0.4)	**507**	109.9 ± 11.4 (1.1 ± 0.3)	**141**	357.9 ± 24.6 (0.4 ± 0.1)	**366**
forward	20 - 70	107.6 ± 11.9 (1.5 ± 0.4)	**135**	34.7 ± 6.0 (1.1 ± 0.3)	**45**	72.9 ± 9.4 (0.4 ± 0.1)	**90**
	70 - 81	46.6 ± 7.1 (1.2 ± 0.3)	**50**	15.0 ± 3.7 (0.9 ± 0.3)	**14**	31.7 ± 5.7 (0.3 ± 0.1)	**36**
	81 - 101	98.9 ± 10.1 (23.1 ± 3.0)	**92**	44.4 ± 5.9 (17.3 ± 2.7)	**40**	54.5 ± 7.5 (5.8 ± 1.2)	**52**
	101 - 120	76.7 ± 9.6 (0.9 ± 0.3)	**54**	22.3 ± 4.7 (0.7 ± 0.2)	**19**	54.3 ± 7.8 (0.2 ± 0.1)	**35**
	> 120	299.4 ± 25.0 (0.7 ± 0.2)	**298**	84.9 ± 10.3 (0.5 ± 0.2)	**92**	214.5 ± 19.4 (0.2 ± 0.1)	**206**

OSSF – invariant mass spectrum by regions

	N_{bjets} inclusive	$N_{bjets} = 0$	$N_{bjets} > 0$
central			
forward			

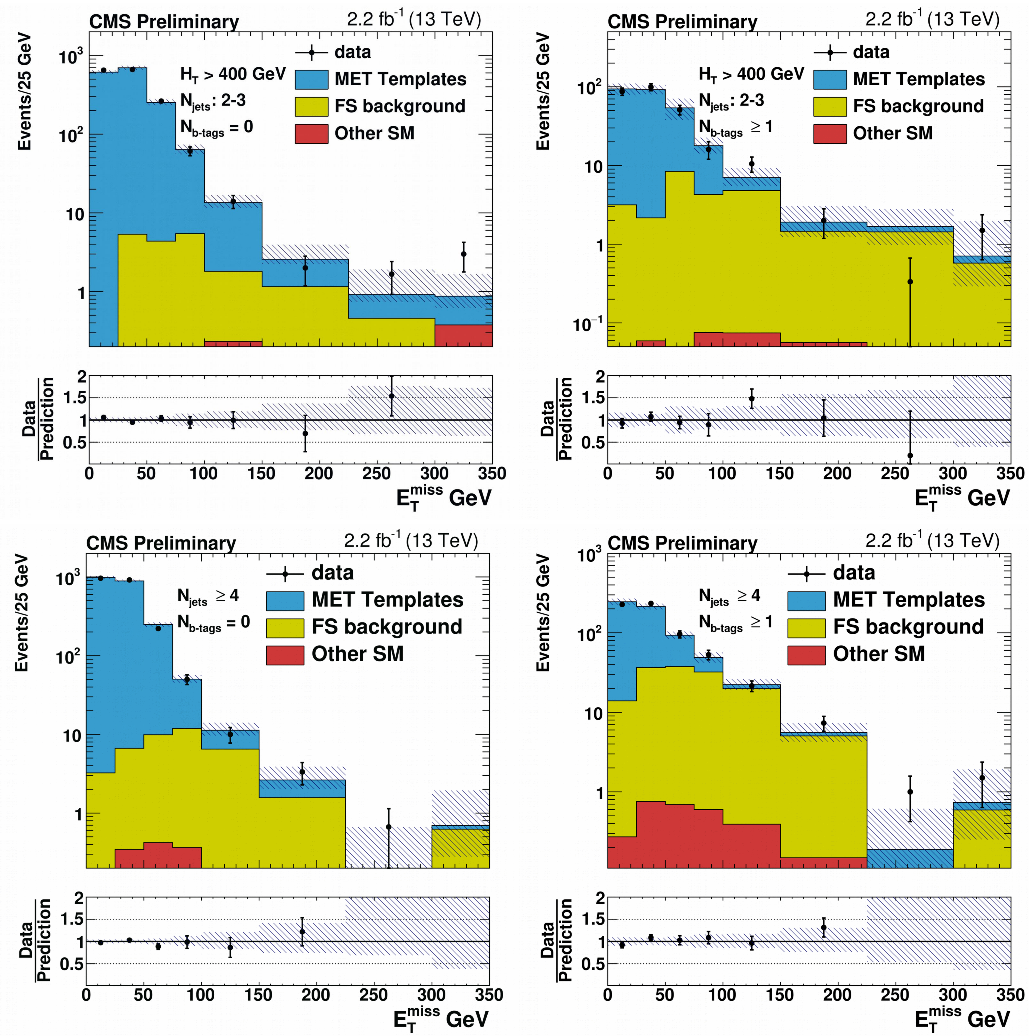


OSSF – on-Z signal regions

$N_{bjets} = 0$ | $N_{bjets} > 0$

SRA

SRB



OSSF – Systematic uncertainties

Source of uncertainty	Uncertainty [%]
Luminosity	4.6%
PDF	$\sim$ 10%
Pileup	$\sim$ 5%
b-tag modeling	2- 5%
Lepton Reconstruction and Isolation	3%
Trigger modeling	5%
Jet energy scale	2-5%
ISR modeling	1%
Statistical uncertainty	5-20%
Total uncertainty	$\sim$13-24%

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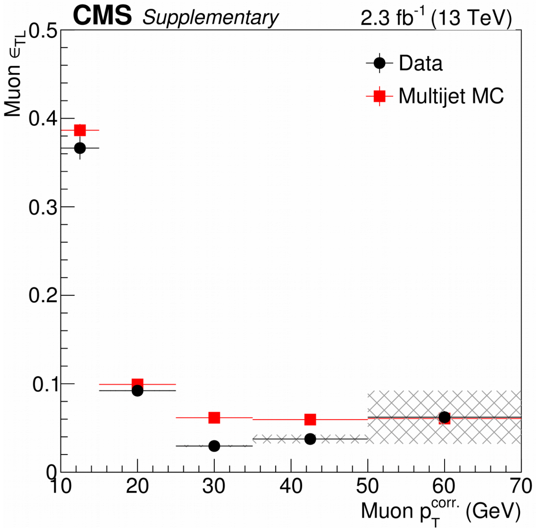
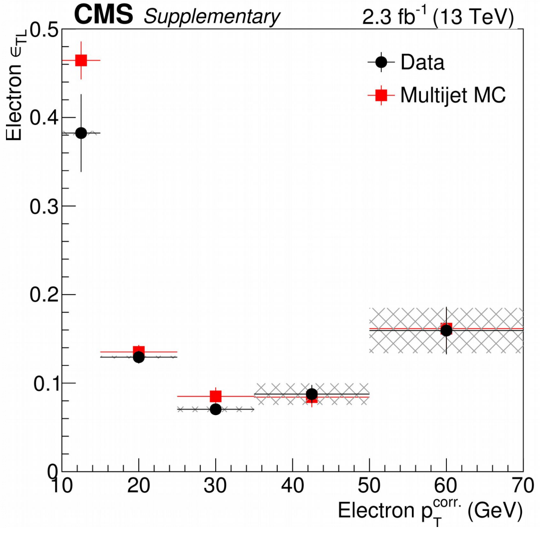
SSDL – tight-to-loose method

- Measure **tight-to-loose ratio** in non-prompt enriched control region
  - == 1 lepton passing loose selection
  - 1 recoiling jet with p_T > 40 GeV, $\Delta R(jet, lep) > 1.0$
  - E_T^{miss} < 20 GeV, M_T < 20 GeV
- Ensure trigger selection is looser than loose selection
- **Subtract prompt contamination** by measuring MC yield in EKW control region (E_T^{miss} > 20 GeV, 70 < M_T < 120 GeV)

muons

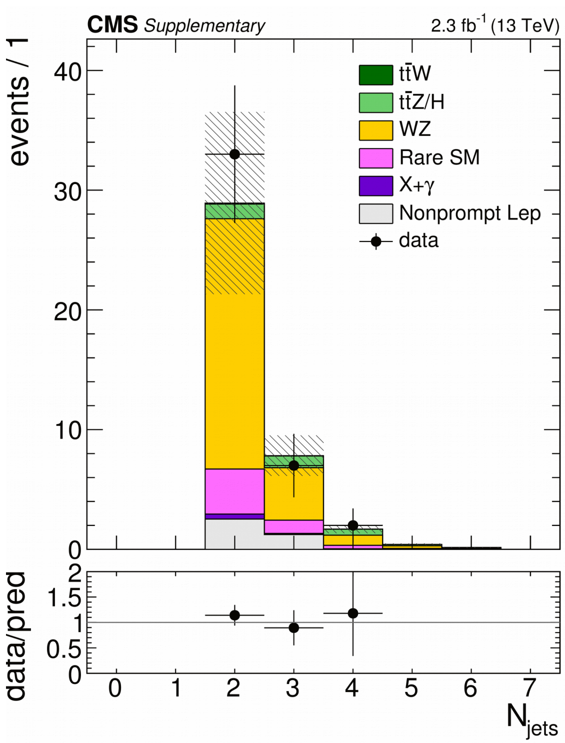


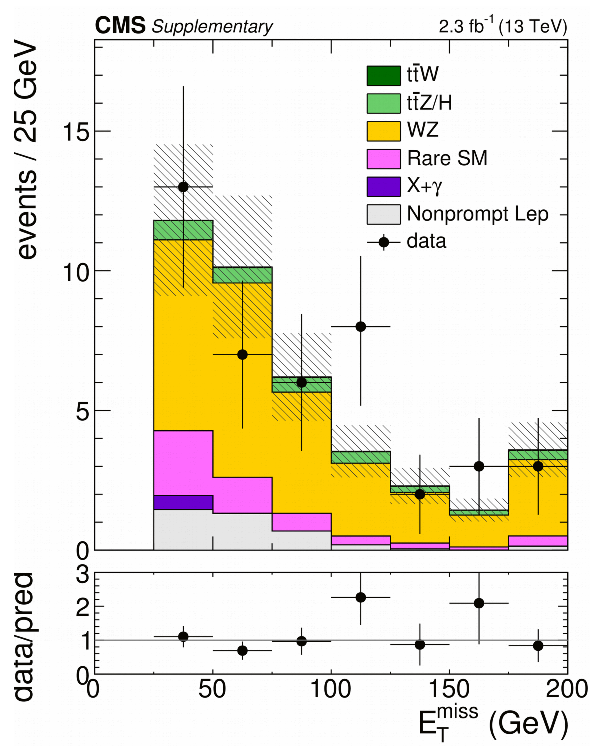


electrons

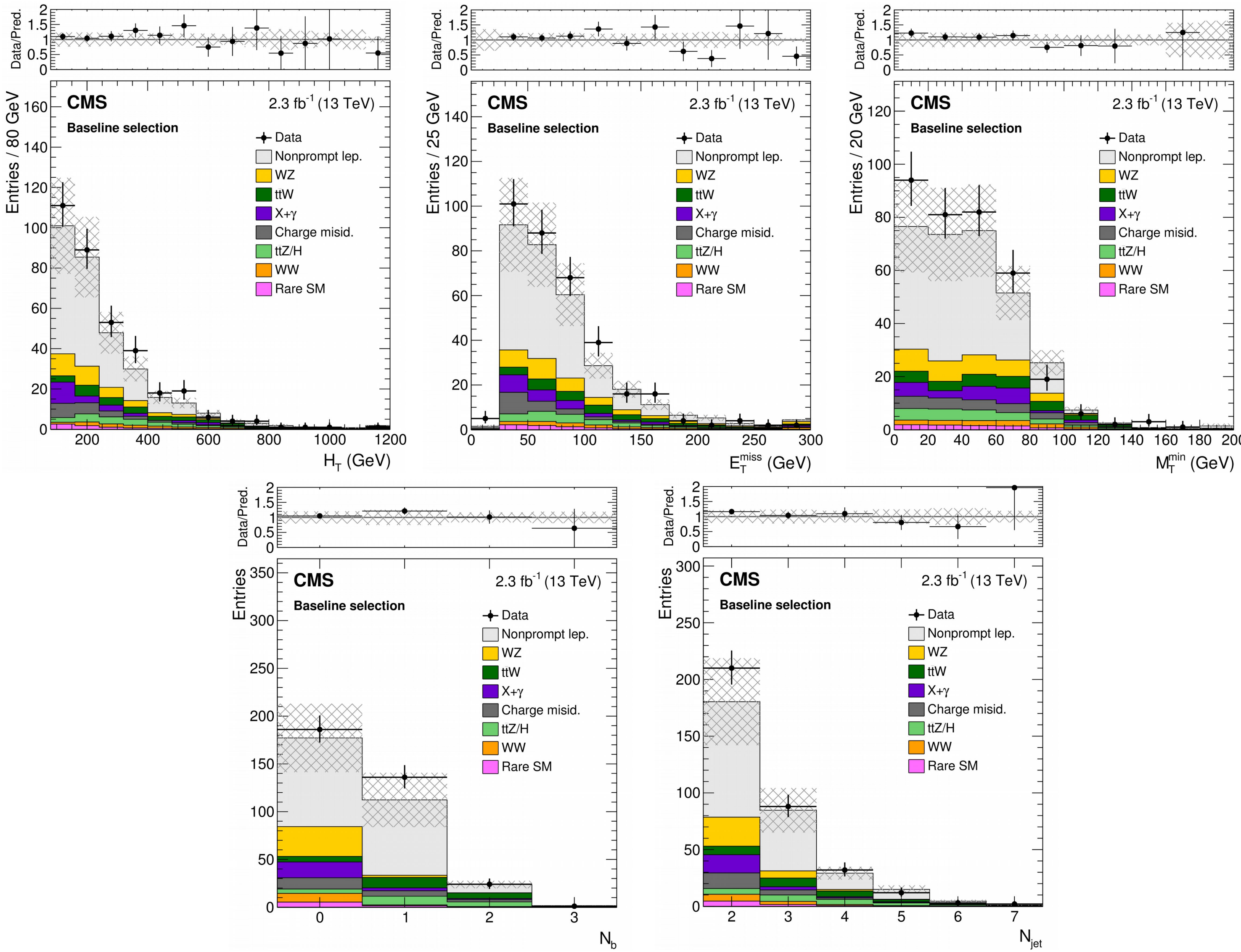
SSDL – WZ control region

- WZ control region (70% purity)
  - Lepton p_T > 25/20/10 GeV for p_T ordered leptons, 3rd lepton forms ossf pair with other lepton such that invariant mass is within 15 GeV around m_Z
  - H_T > 80 GeV, $2 \leq N_{jet} \leq 4$, $N_{bjet} = 0$, E_T^{miss} > 30 GeV
- Measured scale factor 1.22 ± 0.35 → compatible with 1





SSDL – baseline region



SSDL – signal regions

2 SS high p_T leptons (HH)

N_b	M_T^{min} (GeV)	E_T^{miss} (GeV)	N_{jet}	$H_T < 300$ GeV	$H_T \in [300, 1125]$ GeV	$H_T > 1125$ GeV
0	< 120	$50 - 200$	2-4	SR1	SR2	SR32
			≥ 5	SR3	SR4	
		$> 200^{(*)}$	2-4		SR5	
			≥ 5		SR6	
	> 120	$50 - 200$	2-4		SR7	
			≥ 5		SR8	
		$> 200^{(*)}$	2-4			
			≥ 5			
1	< 120	$50 - 200$	2-4	SR9	SR10	
			≥ 5	SR11	SR12	
		$> 200^{(*)}$	2-4		SR13	
			≥ 5		SR14	
	> 120	$50 - 200$	2-4		SR15	
			≥ 5		SR16	
		$> 200^{(*)}$	2-4			
			≥ 5			
2	< 120	$50 - 200$	2-4	SR17	SR18	
			≥ 5	SR19	SR20	
		$> 200^{(*)}$	2-4		SR21	
			≥ 5		SR22	
	> 120	$50 - 200$	2-4		SR23	
			≥ 5		SR24	
		$> 200^{(*)}$	2-4			
			≥ 5			
≥ 3	< 120	$50 - 200$	≥ 2	SR25	SR26	
		$> 200^{(*)}$	≥ 2	SR27	SR28	
	> 120	$> 50^{(*)}$	≥ 2	SR29	SR30	
Inclusive	Inclusive	> 300	≥ 2	——	SR31	

1 high p_T and 1 low p_T lepton (HL)

N_b	M_T^{min} (GeV)	E_T^{miss} (GeV)	N_{jet}	$H_T < 300$ GeV	$H_T \in [300, 1125]$ GeV	$H_T > 1125$ GeV
0	< 120	$50 - 200$	2-4	SR1	SR2	SR26
			≥ 5	SR3	SR4	
		$> 200^{(*)}$	2-4		SR5	
			≥ 5		SR6	
1	< 120	$50 - 200$	2-4	SR7	SR8	
			≥ 5	SR9	SR10	
		$> 200^{(*)}$	2-4		SR11	
			≥ 5		SR12	
2	< 120	$50 - 200$	2-4	SR13	SR14	
			≥ 5	SR15	SR16	
		$> 200^{(*)}$	2-4		SR17	
			≥ 5		SR18	
≥ 3	< 120	$50 - 200$	≥ 2	SR19	SR20	
		$> 200^{(*)}$	≥ 2	SR21	SR22	
Inclusive	> 120	$> 50^{(*)}$	≥ 2	SR23	SR24	
Inclusive	Inclusive	> 300	≥ 2	——	SR25	

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	

2 SS low p_T leptons (LL)

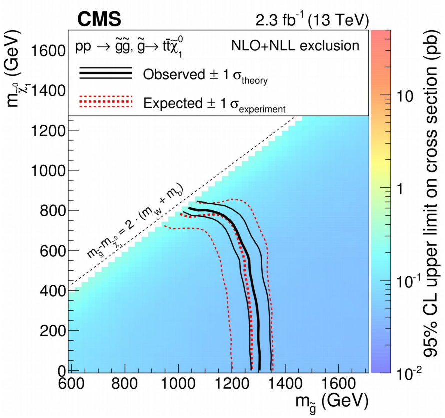
SSDL – results

Region	HH event yields		HL event yields		LL event yields	
	Expected SM	Observed	Expected SM	Observed	Expected SM	Observed
SR1	36.0 ± 7.0	39	44.1 ± 10.9	40	1.99 ± 0.94	1
SR2	12.8 ± 2.1	16	8.5 ± 2.1	9	0.14 ± 0.07	0
SR3	1.05 ± 0.36	2	0.61 ± 0.36	0	3.4 ± 1.5	2
SR4	1.49 ± 0.52	0	1.01 ± 0.38	3	0.04 ± 0.03	0
SR5	2.29 ± 0.49	4	1.40 ± 0.37	0	0.15 ± 0.28	0
SR6	0.11 ± 0.04	0	0.08 ± 0.04	0	0.02 ± 0.01	0
SR7	0.91 ± 0.31	0	26.4 ± 7.6	24	0.03 ± 0.01	0
SR8	0.16 ± 0.06	0	5.4 ± 1.5	13	0.10 ± 0.10	0
SR9	21.6 ± 5.2	26	0.34 ± 0.20	0		
SR10	8.6 ± 1.4	15	2.37 ± 0.99	2		
SR11	2.10 ± 0.92	3	1.29 ± 0.65	0		
SR12	2.24 ± 0.40	1	0.05 ± 0.04	0		
SR13	1.09 ± 0.21	3	4.2 ± 1.3	3		
SR14	0.25 ± 0.11	0	2.11 ± 0.69	1		
SR15	0.37 ± 0.12	0	0.06 ± 0.03	0		
SR16	0.19 ± 0.08	0	0.42 ± 0.09	1		
SR17	4.9 ± 1.0	4	0.29 ± 0.15	0		
SR18	2.90 ± 0.47	1	0.10 ± 0.08	0		
SR19	0.47 ± 0.09	0	0.11 ± 0.06	0		
SR20	1.43 ± 0.25	3	0.18 ± 0.17	0		
SR21	0.40 ± 0.10	0	0.001 ± 0.001	0		
SR22	0.08 ± 0.04	0	0.04 ± 0.04	0		
SR23	0.17 ± 0.06	0	0.03 ± 0.03	0		
SR24	0.14 ± 0.04	1	0.21 ± 0.17	0		
SR25	0.21 ± 0.06	0	1.25 ± 0.53	1		
SR26	0.46 ± 0.12	1	0.25 ± 0.12	0		
SR27	0.005 ± 0.016	0				
SR28	0.03 ± 0.02	0				
SR29	0.02 ± 0.01	0				
SR30	0.02 ± 0.01	0				
SR31	1.91 ± 0.32	1				
SR32	0.85 ± 0.18	1				

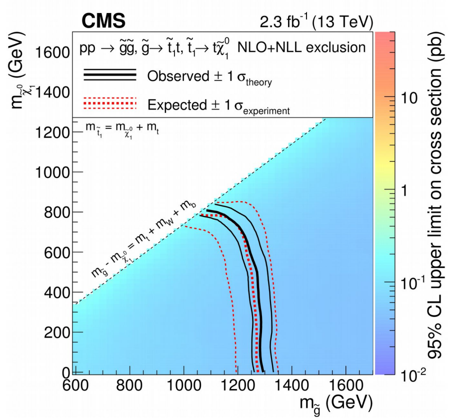
SSDL - Systematic uncertainties

Source	Typical uncertainty (%)
Lepton selection	2
Trigger efficiency	4
Jet energy scale	2–10
b tagging	5
Pileup	1–5
Integrated luminosity	2.7
Scale variations ($t\bar{t}Z$ and $t\bar{t}W$)	11–13
Parton distribution functions ($t\bar{t}W$ and $t\bar{t}Z$)	4
$W^{\pm}W^{\pm}$ normalization	30
Other backgrounds	50
Monte Carlo statistical precision	1–30
Nonprompt leptons	30–36
Charge misidentification	26
WZ normalization	30

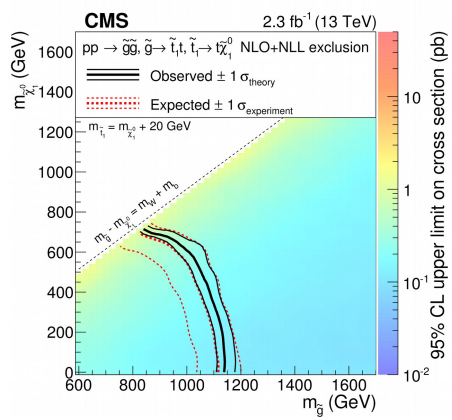
SSDL – Interpretations



T1tttt



T5tttt



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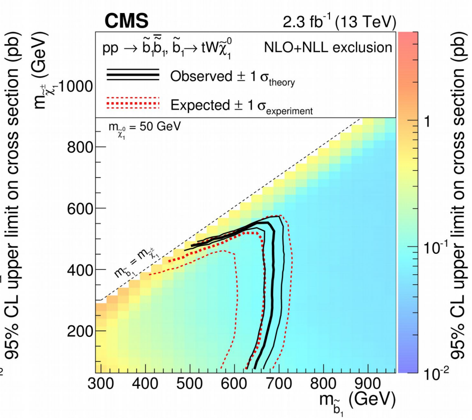
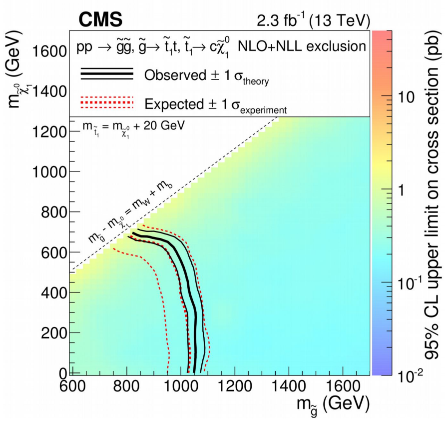
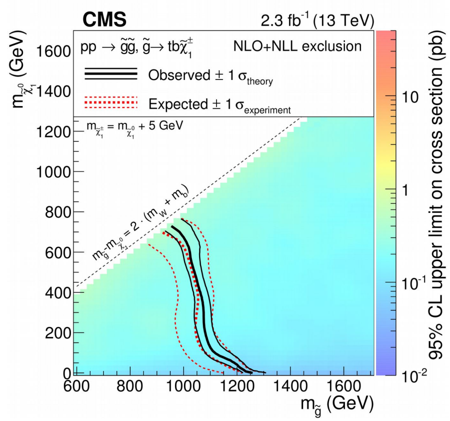


T6ttWW



T5ttcc



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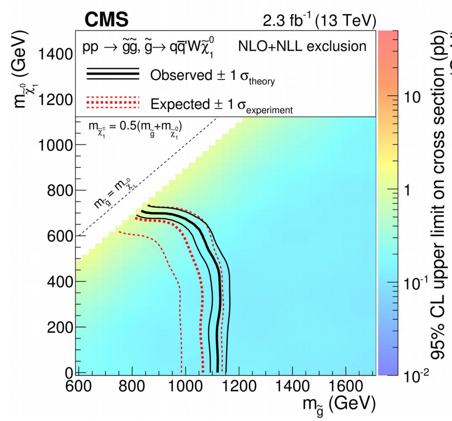
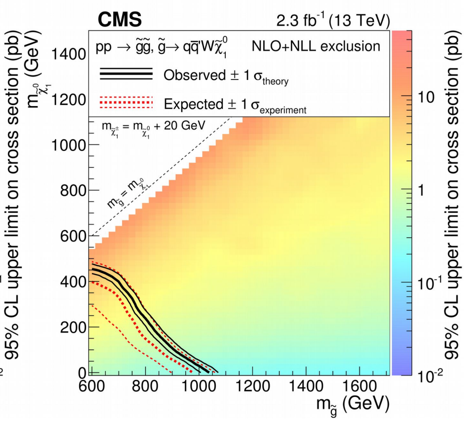


T5qqqqWW



T5qqqqWW

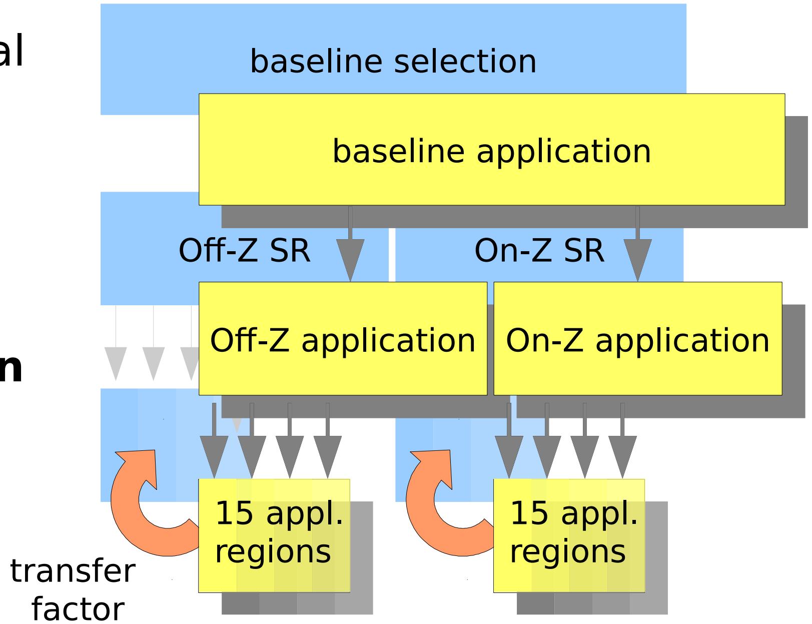
Multileptons: non-prompt lepton background estimation

- Define application region for each signal region
  → at **least one** lepton passing the **loose** but failing the tight selection

- Events in application region need to satisfy **same cuts and categorization** as for signal regions

- Weight each event in the application region with a **transfer factor**
  - 1 fakeable lepton: $f/(1-f)$
  - 2 fakeable leptons: $-f_i f_j/((1-f_i)(1-f_j))$
  - 3 fakeable leptons: product of all $f/(1-f)$

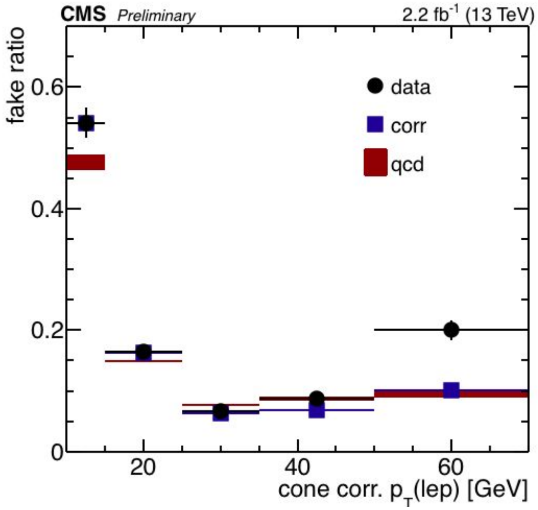
- Application region dominated by events with 1 loose lepton and 2 tight leptons

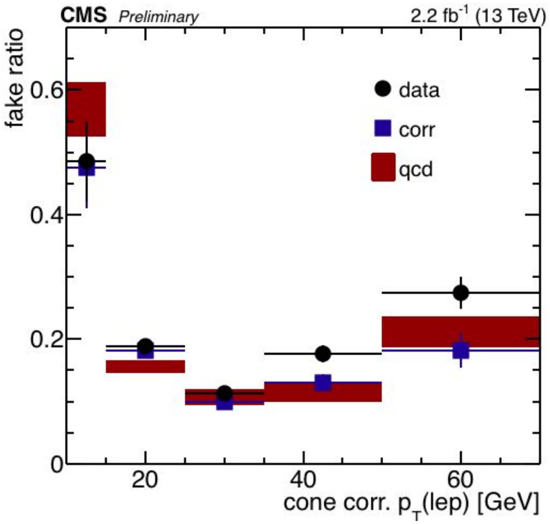


Multileptons: non-prompt lepton background estimation

- Measure **tight-to-loose ratio** in fake enriched control region
  - == 1 lepton passing loose selection
  - 1 recoiling jet with p_T > 40 GeV, $\Delta R(jet, lep) > 1.0$
  - E_T^{miss} < 20 GeV, M_T < 20 GeV
- Ensure trigger selection is looser than loose selection
- **Subtract prompt contamination** by measuring
  MC yield in EKW control region (E_T^{miss} > 20 GeV, 70 < M_T < 120 GeV)

muons

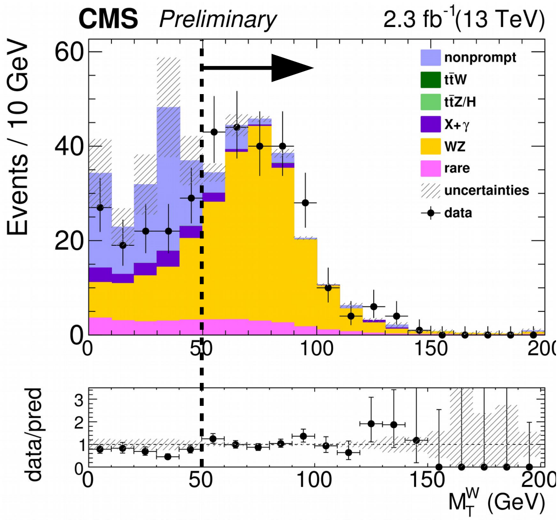


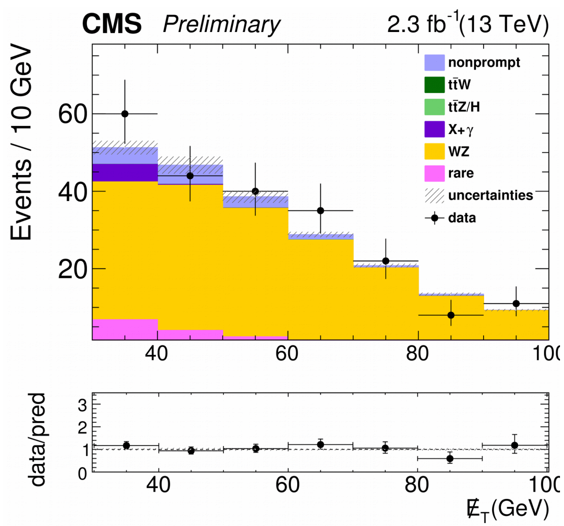


electrons

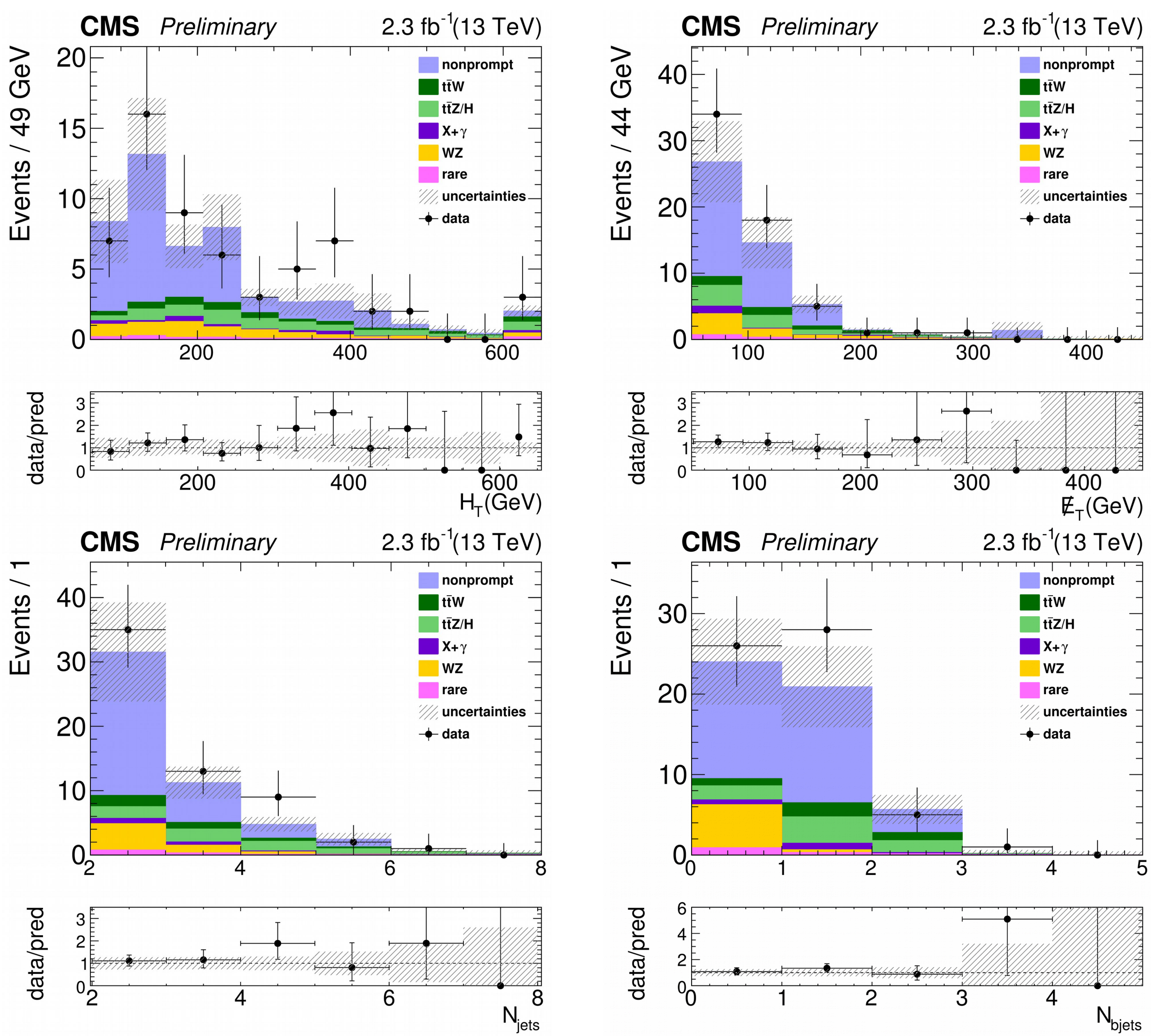
Multileptons - WZ control region

- Measure scale factor in WZ enriched control region with **84% purity**
  - 3 tight leptons, nominal ID, ISO, and p_T
  - $N_{jets} < 2$ Orthogonality to SR
  - $N_{b\text{-}jets} = 0$
  - $30 \leq E_T^{miss} \leq 100$ GeV Prevent signal contamination
  - At least on On-Z ossf pair
  - $M_T^{3rd\ lep} > 50$ GeV Suppress DY
- Scale factor measured with 2.3 fb^{-1}: **1.08 ± 0.15** → compatible with 1
- From uncertainty: assign **15% flat uncertainty** for WZ normalization
- b-tag SF and JES uncertainty considered
- Theoretical **uncertainty for extrapolation** to higher b-jet multiplicities are added. Conservative estimate from Z → 2 lepton study: 10% (20%) for SR below (above) H_T = 400 GeV, 30% SR13

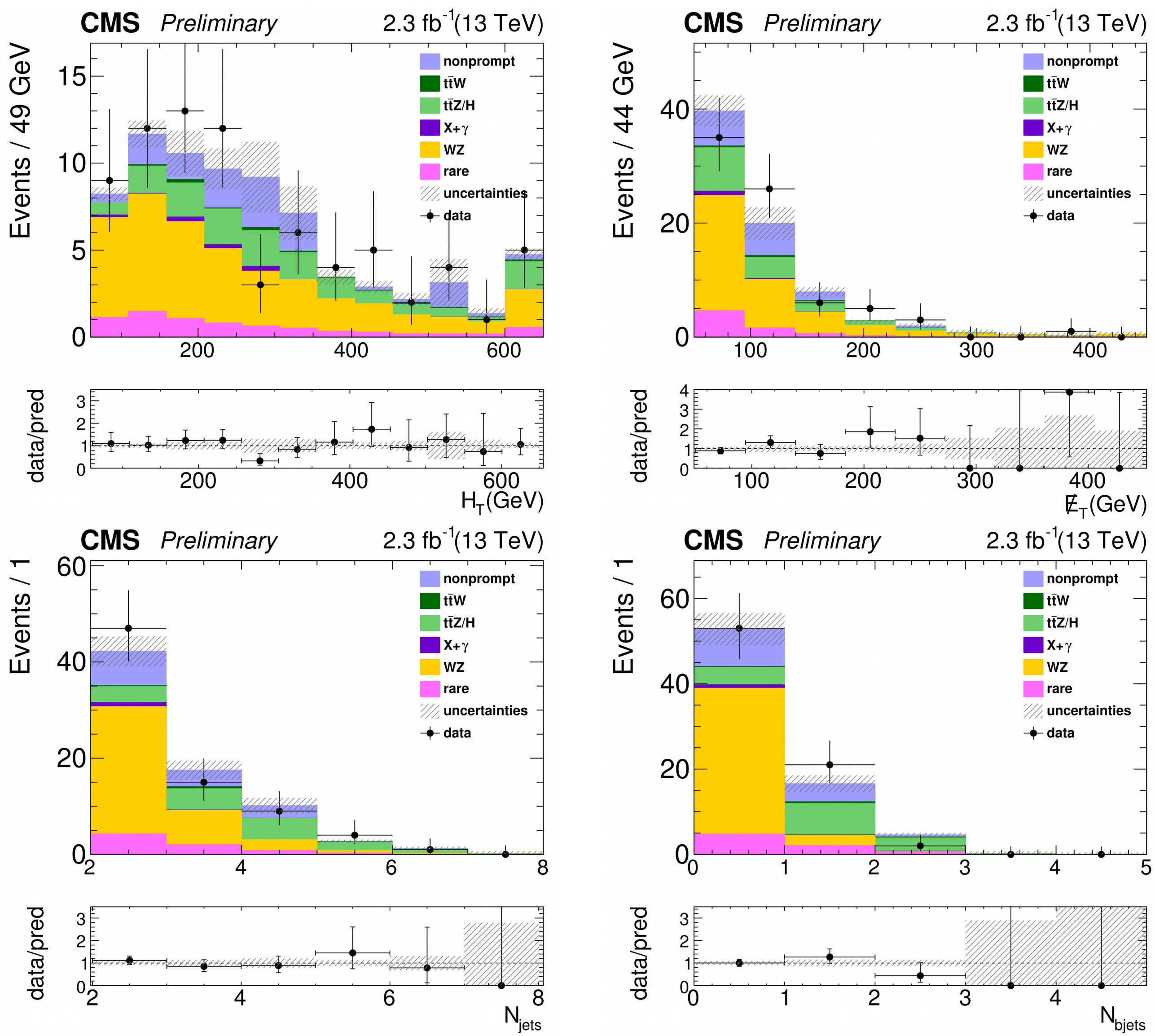




Multileptons – SR inclusive distributions (off-Z regions)



Multileptons – SR inclusive distributions (on-Z regions)



Multileptons – yields (off-Z regions)

- Expected and observed yields in 2.3 fb^{-1} for the off-Z signal regions
- Yields for two different T1tttt mass points are given for comparison

b-tags	H_T (GeV)	E_T^{miss} (GeV)	Expected	Observed	T1tttt ($m_{\tilde{g}}$=1000 GeV, $m_{\tilde{\chi}_1^0}$=600 GeV)	T1tttt ($m_{\tilde{g}}$=1150 GeV, $m_{\tilde{\chi}_1^0}$=100 GeV)	SR
0 b-tags	60-400	50-150	$19.26^{+4.81}_{-4.80}$	18	0.23 ± 0.06	0.00 ± 0.00	SR1
		150-300	$1.16^{+0.31}_{-0.20}$	4	0.14 ± 0.04	0.04 ± 0.01	SR2
	400-600	50-150	$1.20^{+0.47}_{-0.40}$	3	0.05 ± 0.02	0.00 ± 0.00	SR3
		150-300	$0.29^{+0.44}_{-0.09}$	0	0.06 ± 0.02	0.04 ± 0.01	SR4
1 b-tags	60-400	50-150	16.57 ± 4.52	24	0.92 ± 0.20	0.03 ± 0.01	SR5
		150-300	$2.32^{+0.80}_{-0.76}$	1	0.65 ± 0.14	0.07 ± 0.02	SR6
	400-600	50-150	$0.67^{+0.45}_{-0.09}$	2	0.25 ± 0.06	0.04 ± 0.01	SR7
		150-300	$0.48^{+0.29}_{-0.07}$	0	0.33 ± 0.08	0.09 ± 0.02	SR8
2 b-tags	60-400	50-150	$4.49^{+1.81}_{-1.79}$	4	1.12 ± 0.24	0.04 ± 0.01	SR9
		150-300	$0.31^{+0.44}_{-0.09}$	1	0.86 ± 0.18	0.08 ± 0.02	SR10
	400-600	50-150	$0.40^{+0.27}_{-0.26}$	0	0.42 ± 0.10	0.05 ± 0.02	SR11
		150-300	$0.08^{+0.43}_{-0.08}$	0	0.58 ± 0.13	0.13 ± 0.03	SR12
60-600	≥ 3 b-tags	50-300	$0.13^{+0.43}_{-0.09}$	0	2.26 ± 0.47	0.21 ± 0.05	SR13
> 600	inclusive	50-300	$1.84^{+0.44}_{-0.37}$	3	1.49 ± 0.31	1.47 ± 0.30	SR14
inclusive	inclusive	≥ 300	$1.62^{+1.22}_{-1.19}$	0	1.95 ± 0.40	3.04 ± 0.61	SR15

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Multileptons – yields (on-Z regions)

- Expected and observed yields in 2.3 fb^{-1} for the on-Z signal regions
- Yields for two different T5qqqqWZ mass points are given for comparison

b-tags	H_T (GeV)	E_T^{miss} (GeV)	Expected	Observed	T5qqqqWZ ($m_{\tilde{g}}$=1000 GeV, $m_{\tilde{\chi}^{\pm}}$=600 GeV)	T5qqqqWZ ($m_{\tilde{g}}$=1150 GeV, $m_{\tilde{\chi}^{\pm}}$=100 GeV)	SR
0 b-tags	60-400	50-150	38.01 ± 5.92	39	0.00 ± 0.00	6.85 ± 0.81	SR1
		150-300	$4.48^{+0.84}_{-0.75}$	3	0.82 ± 0.36	4.08 ± 0.62	SR2
	400-600	50-150	$4.88^{+1.49}_{-1.47}$	4	0.38 ± 0.19	0.86 ± 0.29	SR3
		150-300	$1.88^{+0.47}_{-0.39}$	3	0.21 ± 0.13	1.29 ± 0.36	SR4
1 b-tags	60-400	50-150	$11.84^{+2.28}_{-2.26}$	14	-	0.55 ± 0.21	SR5
		150-300	$1.53^{+0.42}_{-0.34}$	1	0.16 ± 0.16	0.49 ± 0.19	SR6
	400-600	50-150	$1.18^{+0.49}_{-0.23}$	1	0.02 ± 0.02	-	SR7
		150-300	$0.42^{+0.44}_{-0.10}$	3	0.16 ± 0.16	0.29 ± 0.15	SR8
2 b-tags	60-400	50-150	$2.55^{+0.67}_{-0.51}$	2	-	0.18 ± 0.13	SR9
		150-300	$0.72^{+0.76}_{-0.28}$	0	-	0.00 ± 0.00	SR10
	400-600	50-150	$0.55^{+0.45}_{-0.13}$	0	0.00 ± 0.00	-	SR11
		150-300	$0.31^{+0.51}_{-0.17}$	0	-	-	SR12
60-600	≥ 3 b-tags	50-300	$0.21^{+0.44}_{-0.13}$	0	-	-	SR13
> 600	inclusive	50-300	$4.22^{+0.68}_{-0.63}$	5	3.48 ± 0.65	1.01 ± 0.29	SR14
inclusive	inclusive	≥ 300	$1.41^{+0.50}_{-0.25}$	1	4.85 ± 0.81	2.37 ± 0.44	SR15

Multileptons – Systematic uncertainties

- Experimental and theoretical uncertainties

source	magnitude	effect on yield	induces SR migration
luminosity	4.6%	4.6% *	–
jet ES	2 – 8%	1 – 20% *	✓
b-tag efficiency	5 – 10%	1 – 20% *	–
pileup	5%	3% *	–
lepton efficiencies	2%	2% *	–
HLT efficiencies	3%	3% *	–
HLT lepton effic.	3 – 10%	3 – 10% FastSim signals	–
HLT FastSim	5%	5% FastSim signals	–
FO CR stat.	1 – 100%	1 – 100% (fake bkg. only)	–
FR extrapolation	30%	30% (fake bkg. only)	–
EWK subtraction in FR	100% (ewk. SF)	1 – 5% (fake bkg. only)	–
WZ CR stat. and norm.	15%	15 % (WZ only)	–
MonteCarlo stat.	1 – 100%	1 – 100% *	–
QCD scales	$\times 0.5 / \times 2$	$11-13\%(\sigma)/3-18\%(\mathcal{A})$ ($t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$)	–
PDFs	–	2–3% ($t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$)	–
other bkgs.	50%	50% (rare processes, tribosons, etc.)	–

* $t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$, rare processes and signals only

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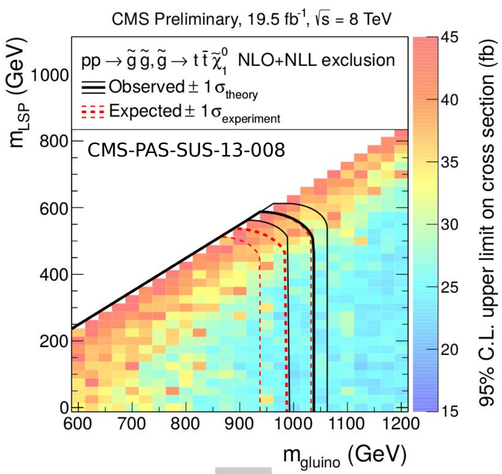
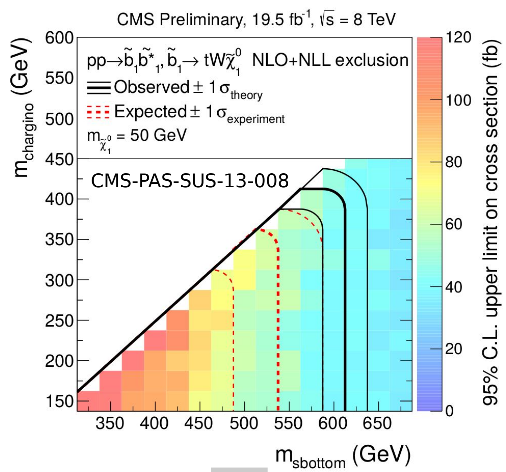
Multileptons – interpretations

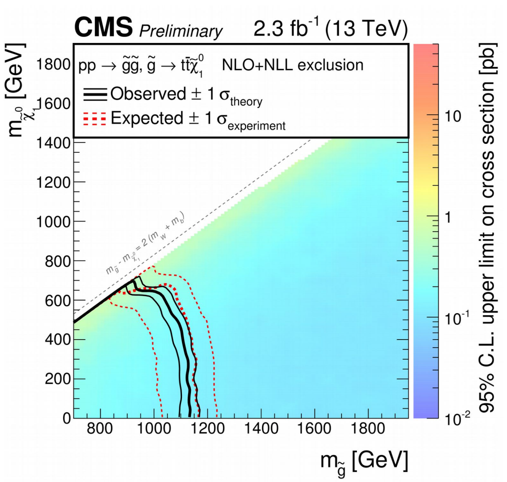
CMS 8 TeV





No 8 TeV multilepton interpretation

CMS 13 TeV



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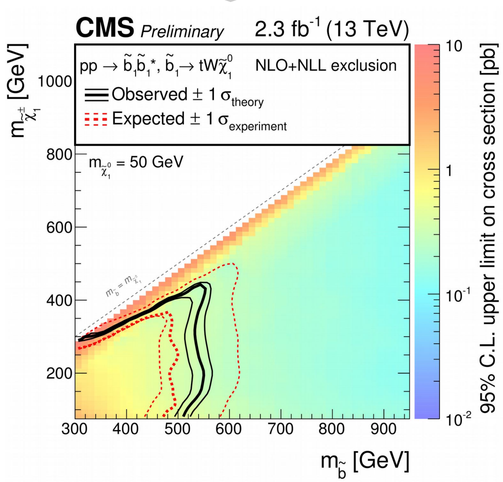

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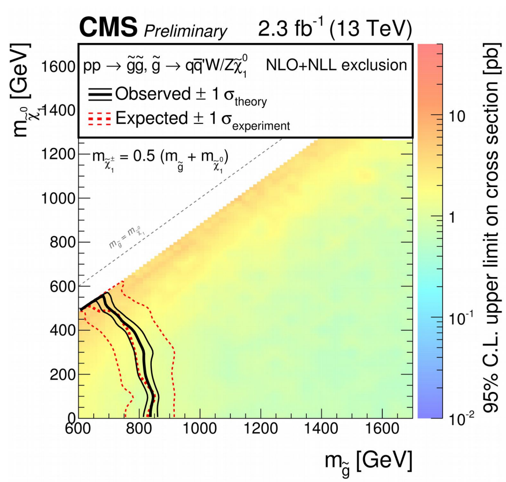

T5qqqqWZ