SUSY searches at the CMS

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On the physics in LHC Run2
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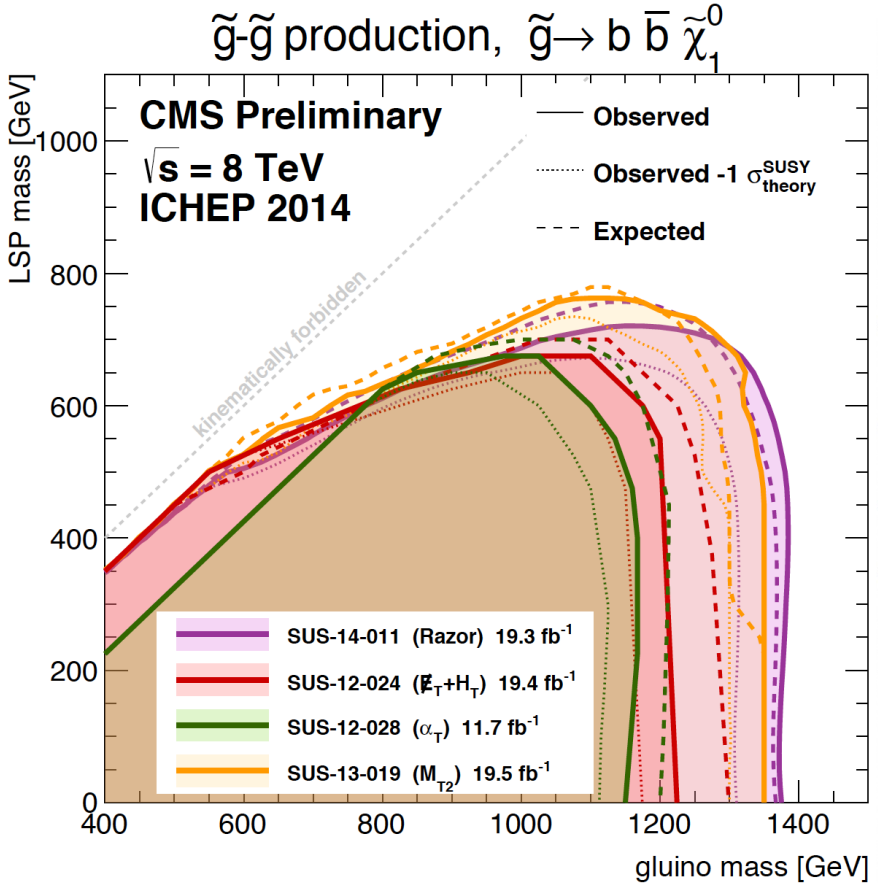
Hunting for SUSY

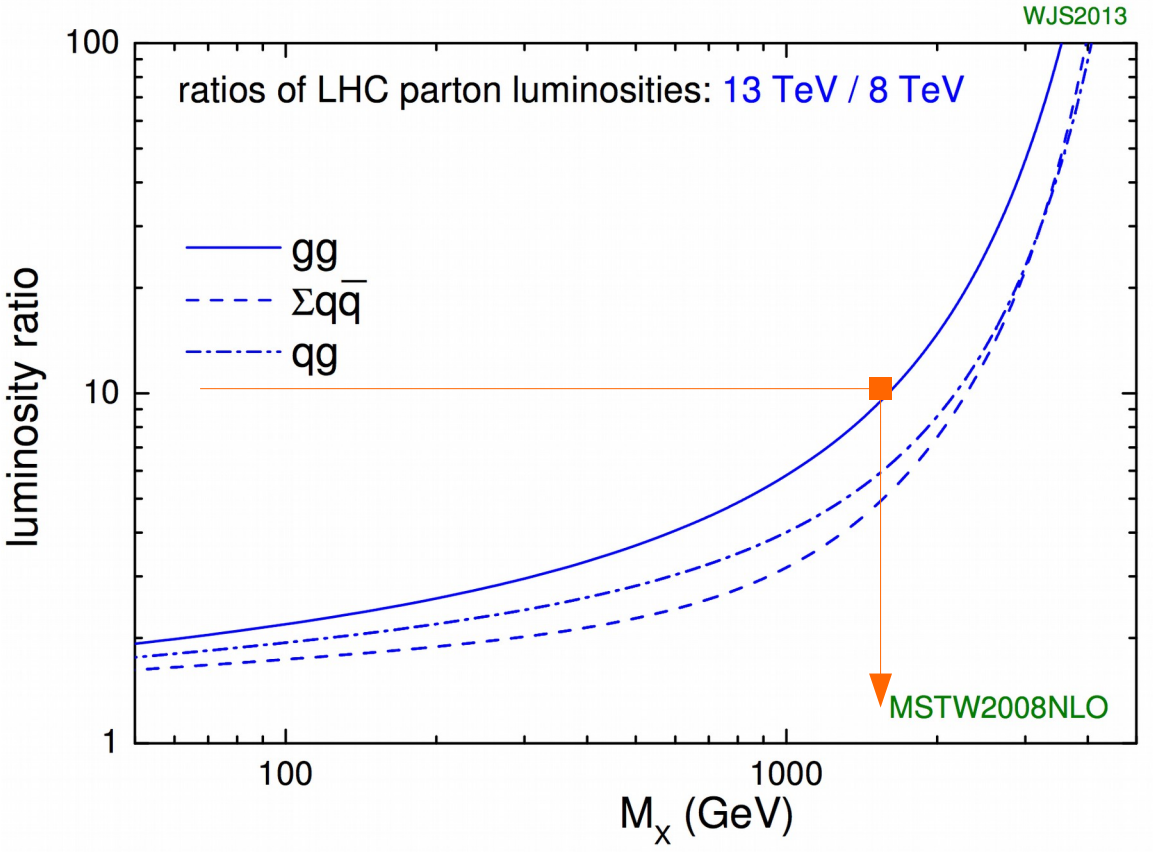
OUTLINE:

- **Various supersymmetric scenarios** can explain
  - low value of the Higgs boson mass and
  - provide a dark matter candidate
- **Review of first SUSY searches in the LHC run 2**
  - **CMS data collected in 2015 – 2.2/fb at 13 TeV**
  - **inclusive analyses**, focused on the **pair production** of **gluinos**, for which σ increases the most from 8 TeV (Run 1) to 13 TeV (Run 2)
    - in all-hadronic channel, based on complementary approaches using the kinematic variables **MHT**, **MT2**, the **razor** variables, and **alphaT**
    - additionally searched with **one** or **two leptons**
- **Simplified Model Spectra interpretation**

Motivation → Early searches

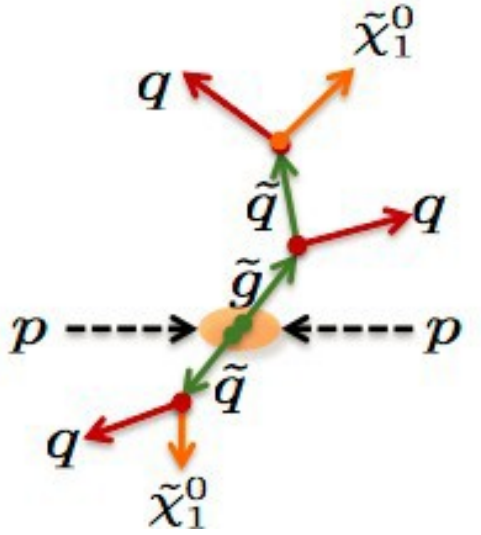
- Large increase in signal cross sections from 8 →13 TeV at Run 1 gluino mass limits
- Strong (gluino) SUSY decaying to hadrons
  → largest cross sections, branching fractions → early sensitivity





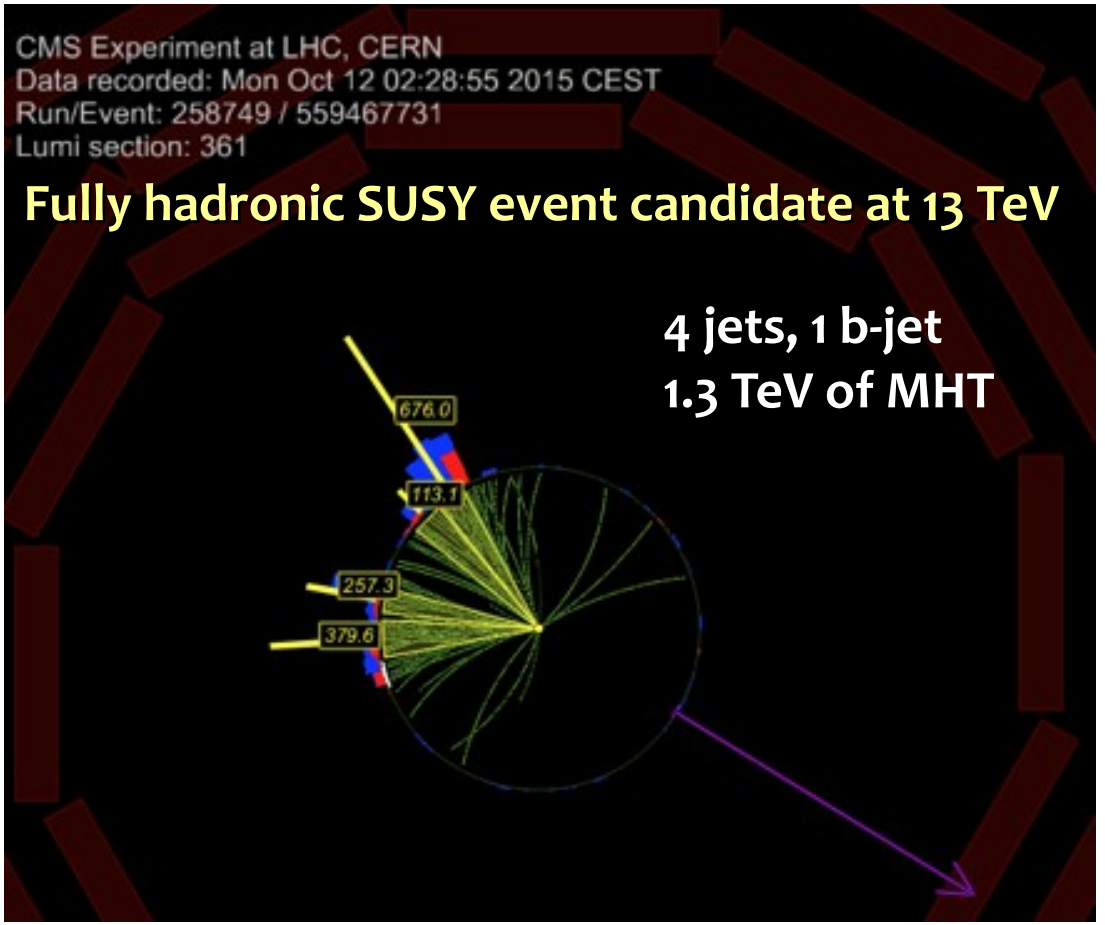
RUN 1 at 8 TeV: Limits on gluino mass up to ~1.4 TeV

Early CMS searches



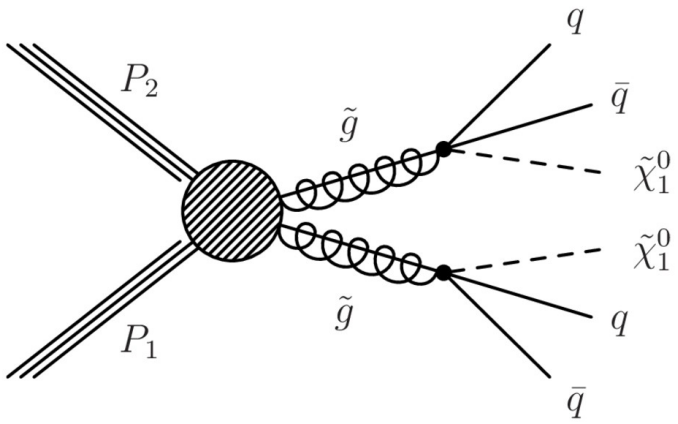
Final states and approaches at 13 TeV:

- **Fully hadronic – 0 leptons** In this presentation
  - MH_T, H_T (SUS-15-002)
  - MT2 (SUS-15-003)
  - Razor (SUS-15-004)
  - alpha $_T$ (SUS-15-005)
- **1 lepton**
  - Sum of jet masses M_J (SUS-15-007)
  - Razor (SUS-15-004)
- **Same-sign dilepton (SUS-15-008)**
  - Rare SM signature
- **Oposite-sign dilepton (SUS-15-011)**
  - Excess in Run 1 ←

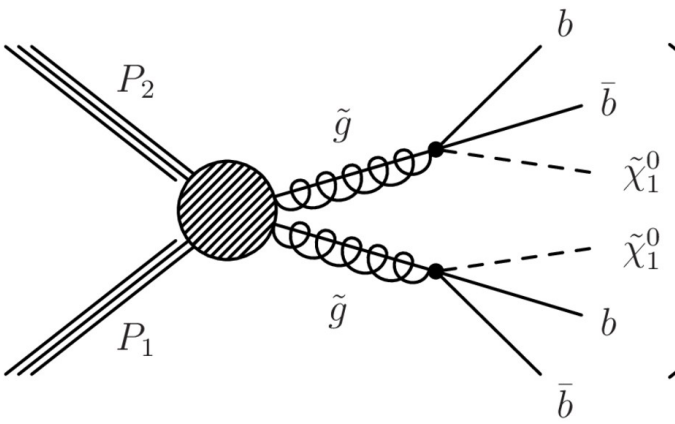


Simplified Model Spectra (SMS)

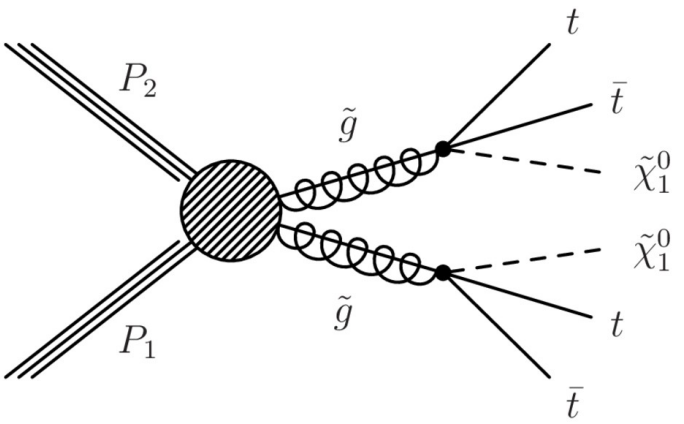
- **SUSY STRONG production,** gluino decays to:



T1qqqq
(low Njets, low Nb-jets)



T1bbbb
(low Njets, high Nb-jets)



T1tttt
(high Njets, high Nb-jets)

- **Jets + MET** (missing energy)
  - Jets from squark – anti-quark pair
    - Many can be a b-quark
  - MET from the LSP neutralino

Multijet and MET channel

[SUS-15-002]

- Inclusive fully-hadronic analysis targeting strong production of gluino pairs → jets + MET

- Search binned in simple variables: **MHT, HT, Njets,** and **Nb-jets**
- SM backgrounds estimated with data-driven methods
- Analysis is sensitive to a wide range of strong SUSY models; interpreted in **T1qqqq, T1bbbb, T1tttt**

- **HT**: Scalar sum of the transverse energy of jets $H_{\mathrm{T}} = \sum_{i=1}^{N_{\mathrm{jet}}} E_{\mathrm{T}}$
- **MHT**: Magnitude of the vector sum of the transverse momenta of jets

$$\not{H}_{\mathrm{T}} = |\sum_{i=1}^{N_{\mathrm{jet}}} \vec{p}_{\mathrm{T}}|$$

Baseline selection in MHT/HT

[SUS-15-002]

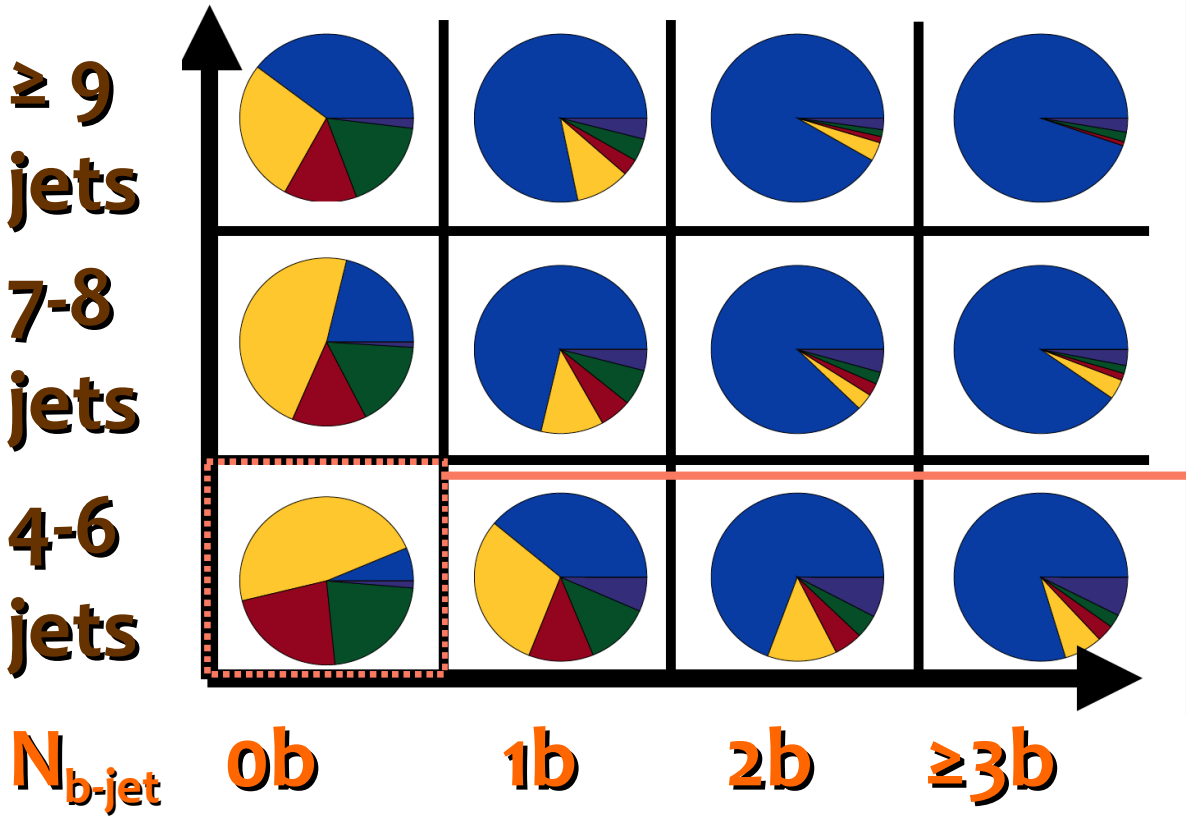
Cut	Motivation	Impact
MHT > 200, HT > 500	Get to trigger plateau	Trigger ~95% efficient here
4+ jets (30+ GeV, CHS)	Target high-multiplicity SUSY models Save compressed signal with low-pt cut	p_T > 30 GeV cut saves up to 50% more signal w.r.t. cut at 50 GeV
$\Delta\phi$(jets 1-4, MHT) > (0.5, 0.5, 0.3, 0.3)	Suppress QCD by targeting under-measured jets	Rejects > 90% of QCD Favorable signal eff / real-MET BG eff
e/μ veto (pt > 10 GeV, veto/medium ID, mini iso)	Suppress top/W $\rightarrow \ell\nu$	> 95% efficient for hadronic signal
Leptonic track veto (p_T > 5 GeV, m_T < 100 GeV, track iso)	Reject more top/W $\rightarrow \ell\nu$ events with lower-pt leptons, leptons failing mini iso	Rejects 30% of lost e/μ events, ~90% of which have 5-10 GeV leptons
Hadronic track veto (p_T > 10 GeV, m_T < 100 GeV, track iso)	Suppress top/W $\rightarrow \tau\nu \rightarrow$ had+MET	Rejects 30% of hadronic tau BG

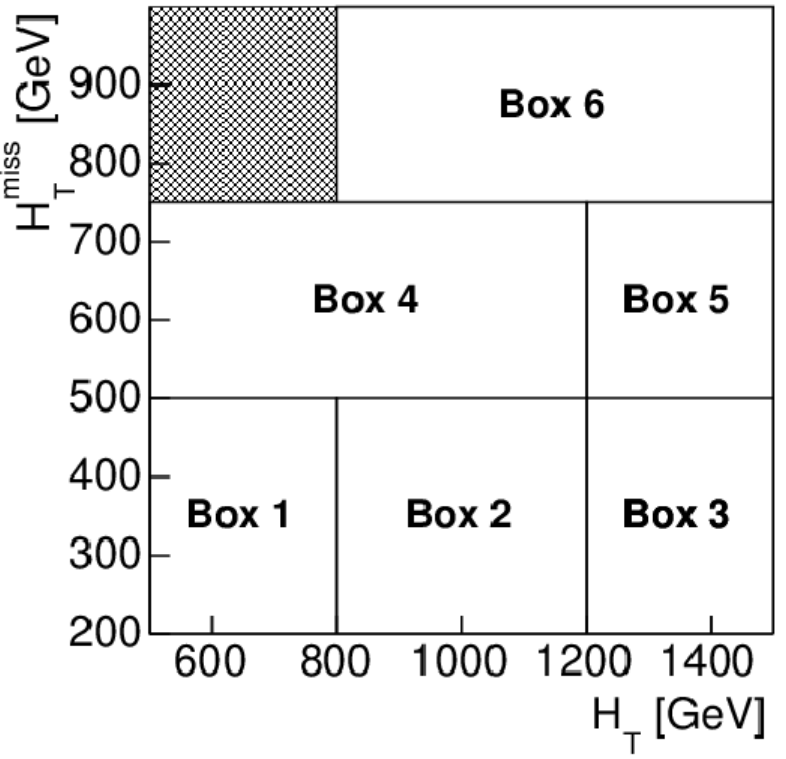
Search in bins

[SUS-15-002]

- Search bins chosen to cover wide range of topologies and help characterize a potential excess

- 3 (Njets) x 4 (Nb-jets) x 6 (HT/MHT) = 72 bins total



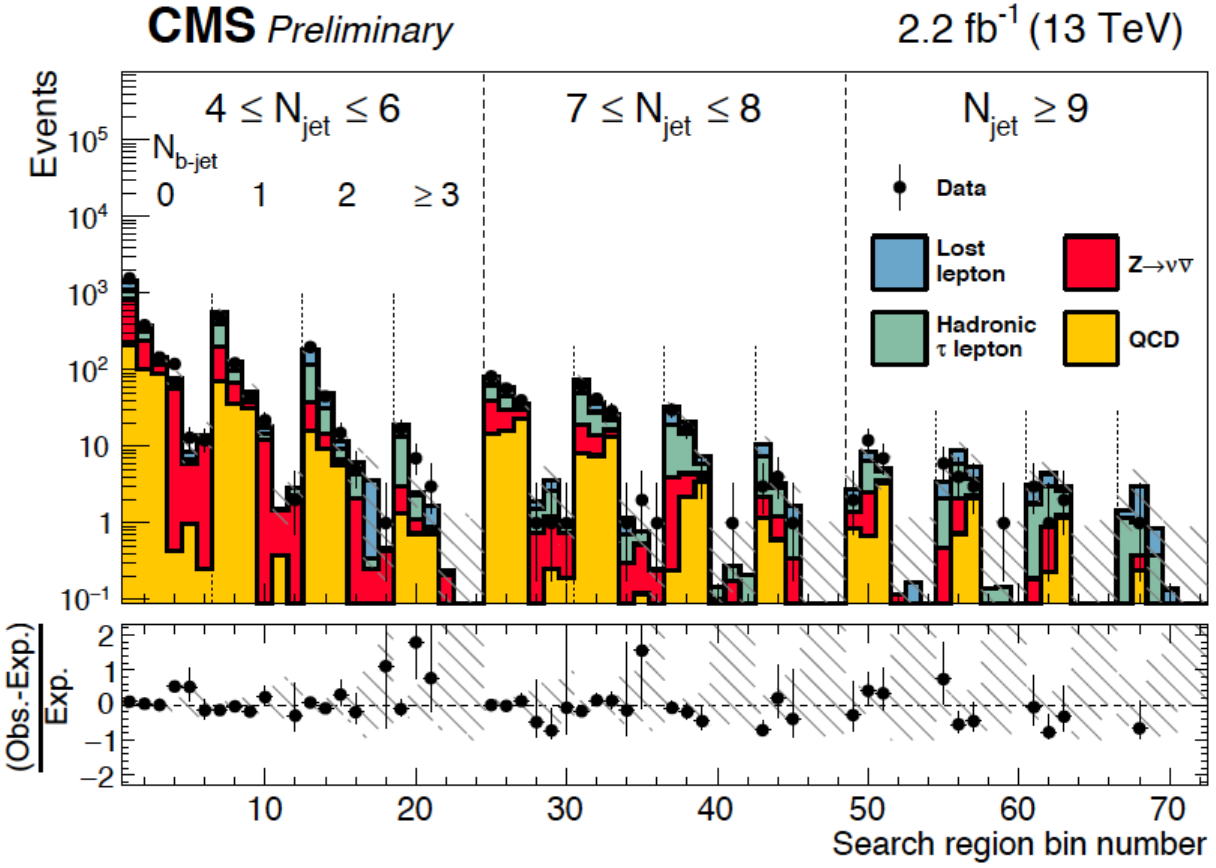


tt̄ W+jets QCD Single Top Z+jets Other

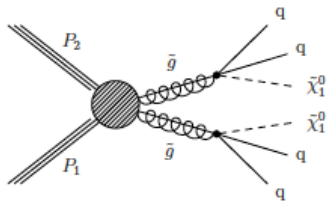
Background predictions

[SUS-15-002]

- SM bkg determined using data-driven techniques:
- Top and W+jets: estimated from single-lepton control samples
- $Z \rightarrow \nu\nu$ (invisible): from γ + jets and $Z \rightarrow \mu\mu$



Observed numbers of events in DATA and corresponding SM background predictions → good agreement

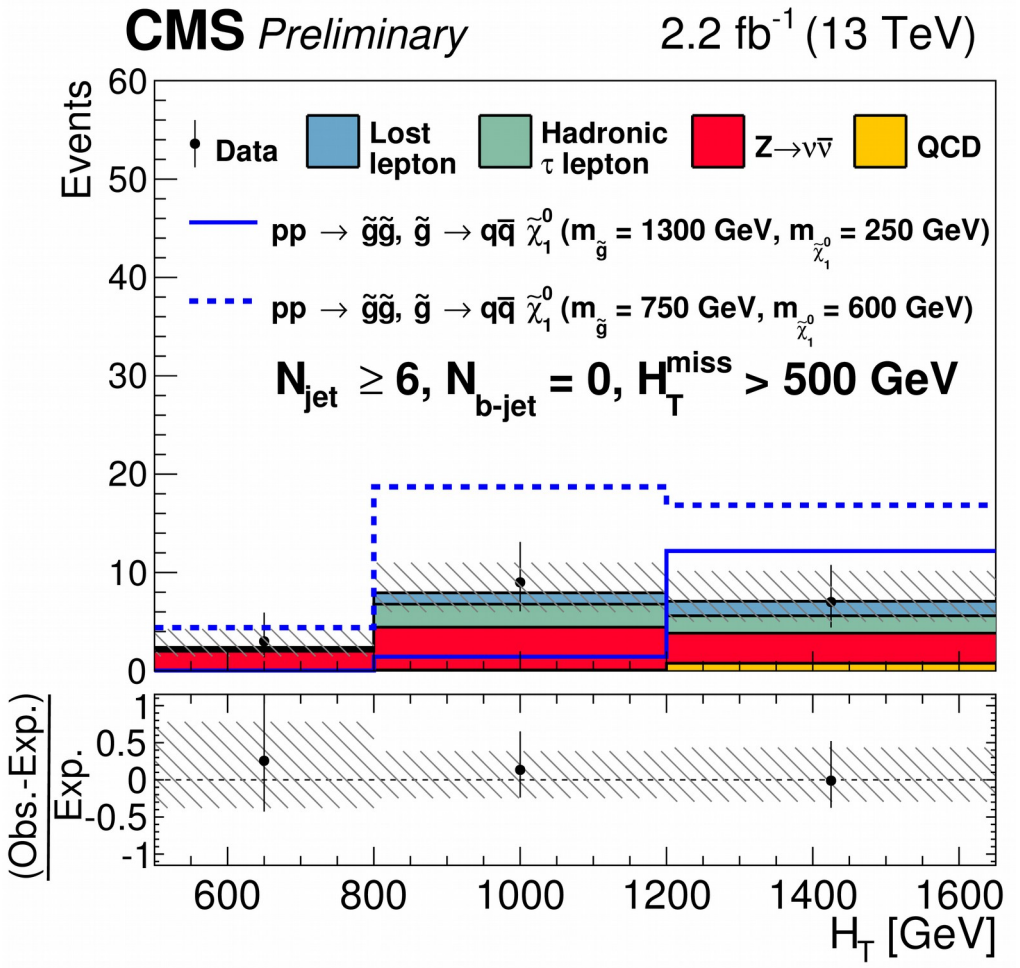


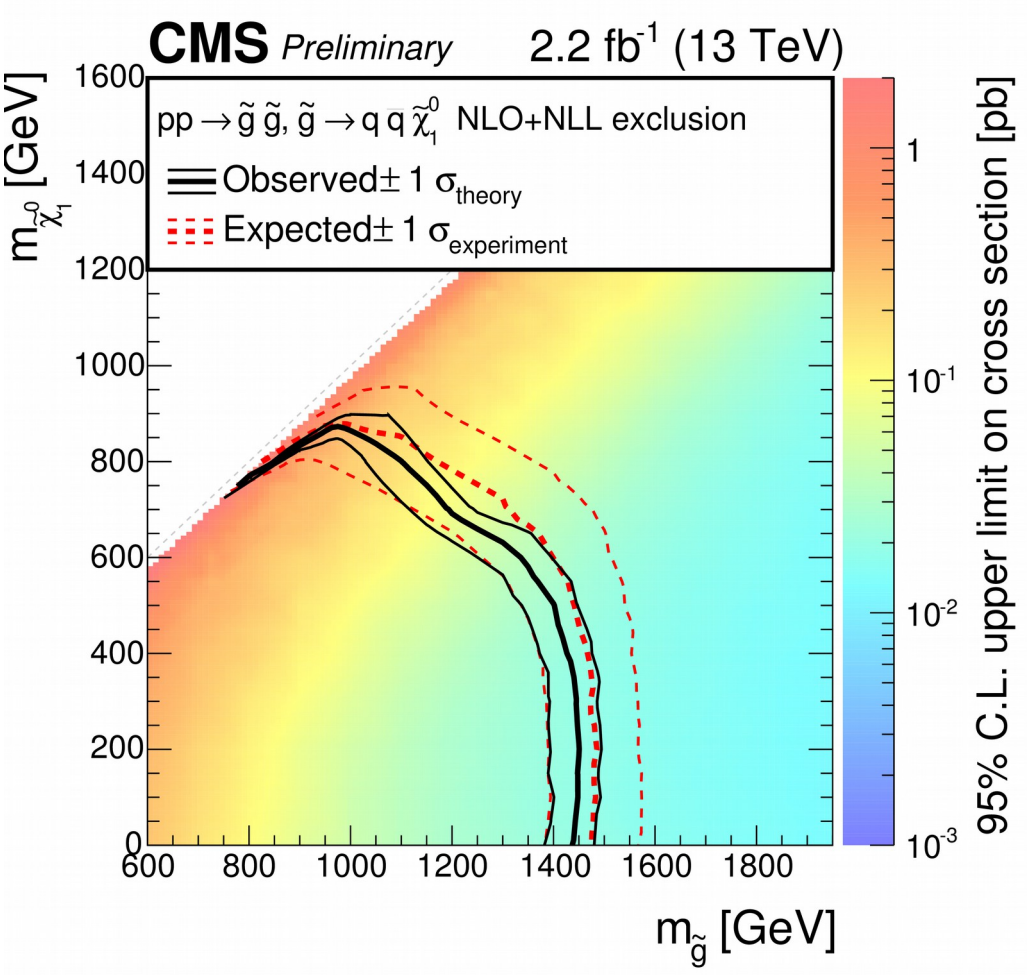
Results T1qqqq

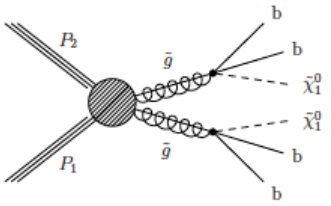
[SUS-15-002]

- Good expected/observed agreement
- Exclude up to $m_{\tilde{g}} \approx 1.45$ TeV for low m_{LSP}

$N_{b\text{-jet}} = 0$ channel







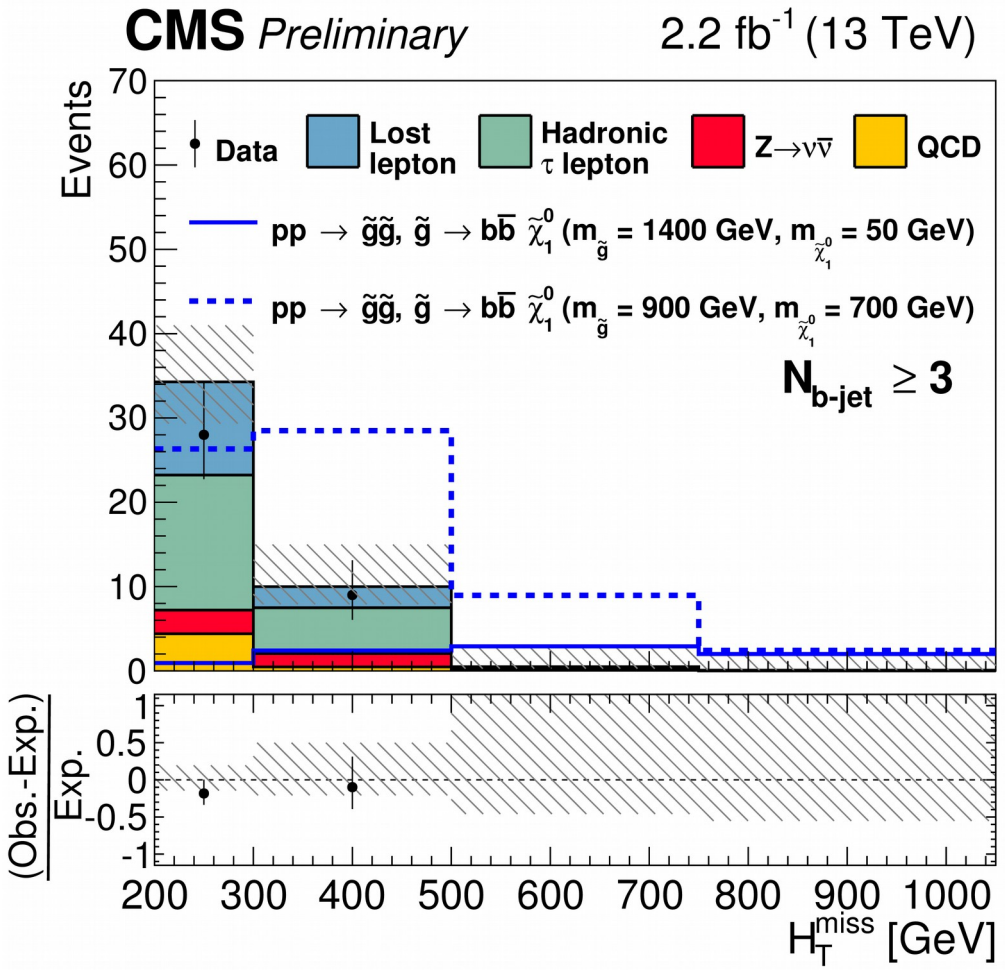
Results T1bbbb

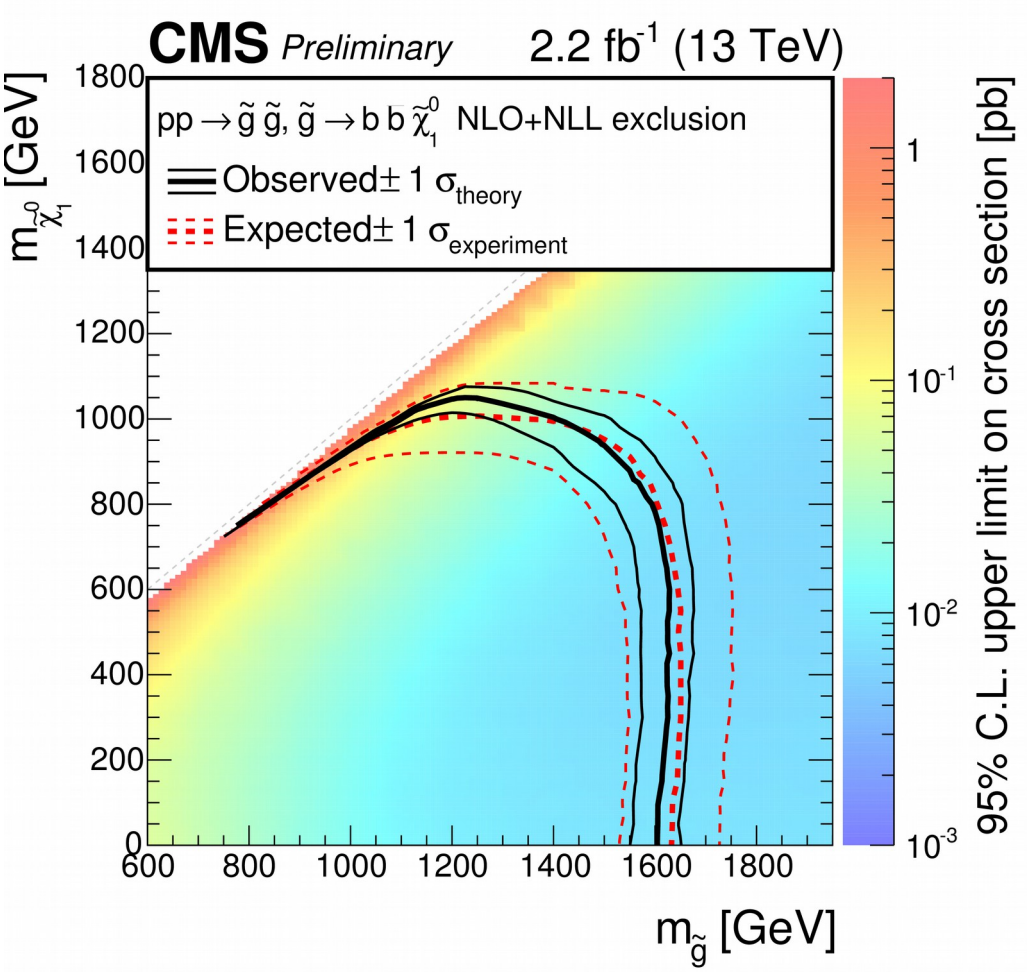
[SUS-15-002]

- Exclude up to $m_{\tilde{g}} \approx 1.65$ TeV for low m_{LSP}

→ **Strongest exclusion** in T1bbbb channel

$N_{b\text{-jet}} \geq 3$ **channel**





RAZOR variables

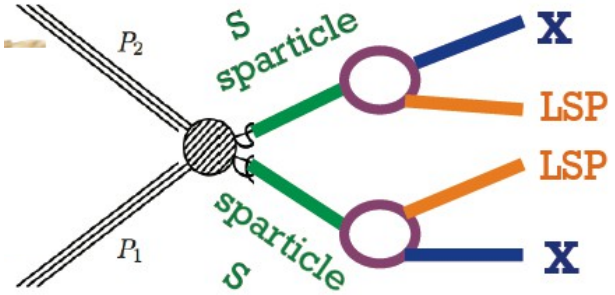
[SUS-15-004]

- **Razor variables R (~MET) and M_R (has a peak)**

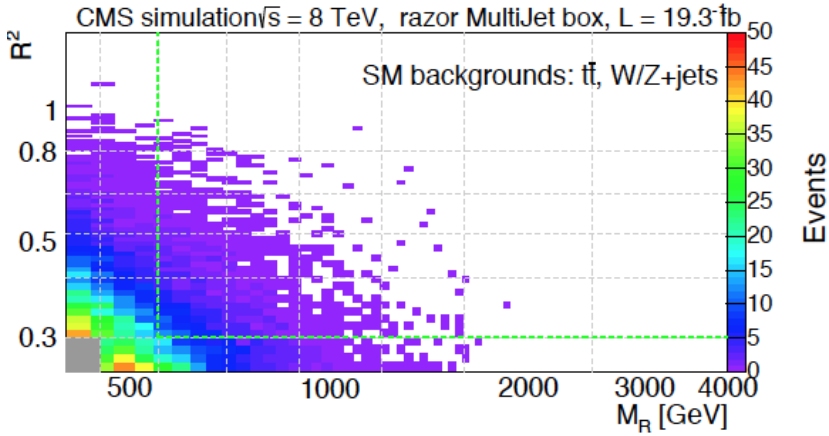
  SUSY signal well separated from the SM background

- **Selection:**

  Group all final state objects (jets, leptons) into **two mega-jets**

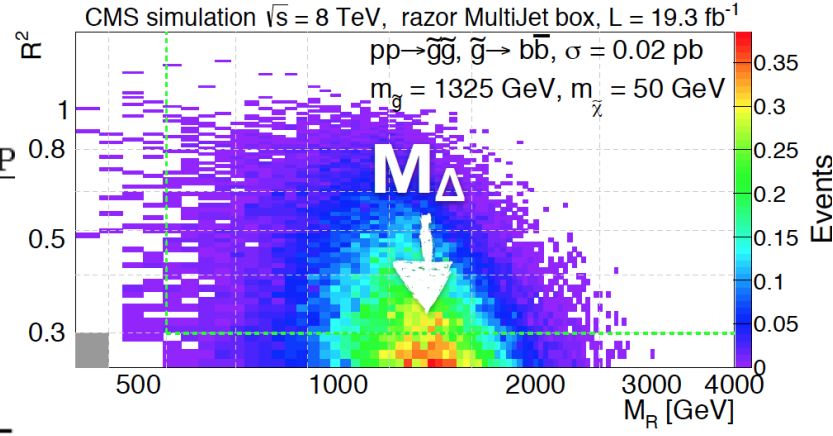


In simple case:
S = squark
X = jet



$$M_R = \sqrt{(|\vec{p}_{j_1}| + |\vec{p}_{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

Peaks at $M_R = M_\Delta = \frac{M_S^2 - M_{\mathrm{LSP}}^2}{M_S}$



$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

Edge at M_Δ

$$R = \frac{M_T^R}{M_R}$$

Ratio of two estimators of SUSY scale – describes transverse shape of event

RAZOR Regions

[SUS-15-004]

- 3 analysis CATEGORIES - boxes:

1st : Multijet 2nd : MU 3rd : ELE

- At least 4 jets with pT > 40 GeV and |η|<3

Multijet
M_R > 500 GeV
R^2 > 0.25
>=4 Jets

Muon Multijet
Electron Multijet
M_R > 400 GeV and R^2 > 0.15
>=4 Jets
>=4 Jets

- Tight muon/electron with pT > 20/ 25 GeV

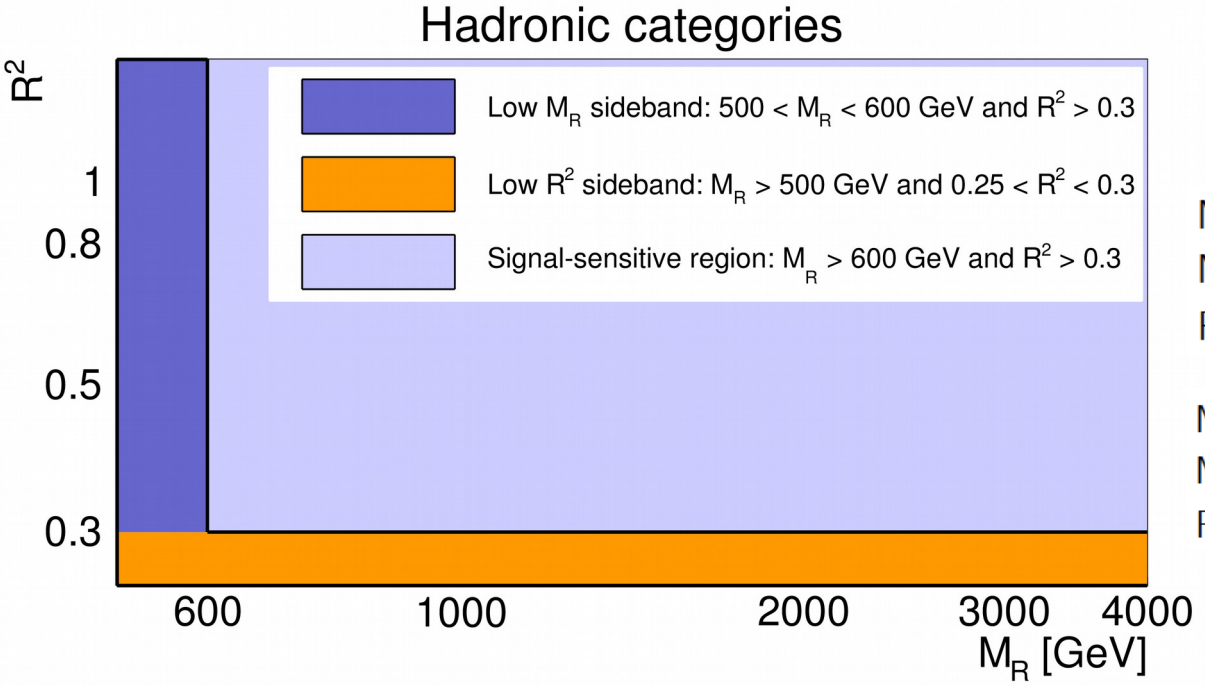
0, 1, 2, ≥3 b-tags
0, 1, 2, ≥3 b-tags
0, 1, 2, ≥3 b-tags

Background Estimation

[SUS-15-004]

- SM background shape is modelled by a parametric 2D function in M_R & R^2
- The **fit is performed using only the data in the sideband,** and the functional form is extrapolated to the full M_R & R^2 plane
- 2D fits of distributions separately for events with 0, 1, 2,≥3 b-tags

→ **12 fits** (3 boxes x Nbjets) for 2D bins



2D bins

MultiJet

$M_R \in$ [500, 600, 700, 900, 1200, 1600, 2500, 4000]

$R^2 \in$ [0.25, 0.30, 0.41, 0.52, 0.64, 1.5]

MuMultiJet and EleMultiJet

$M_R \in$ [400, 500, 600, 700, 900, 1200, 1600, 2500, 4000]

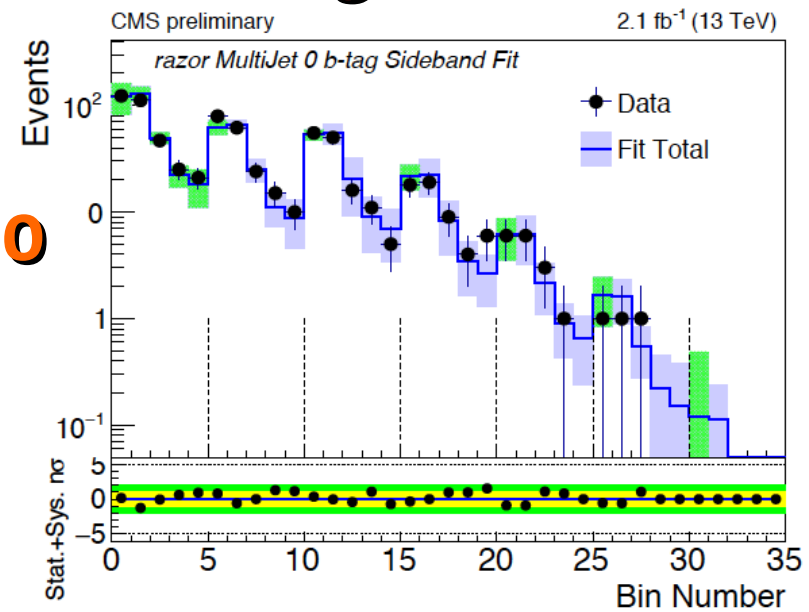
$R^2 \in$ [0.15, 0.20, 0.25, 0.30, 0.41, 0.52, 0.64, 1.5]

Muiltijet BOX

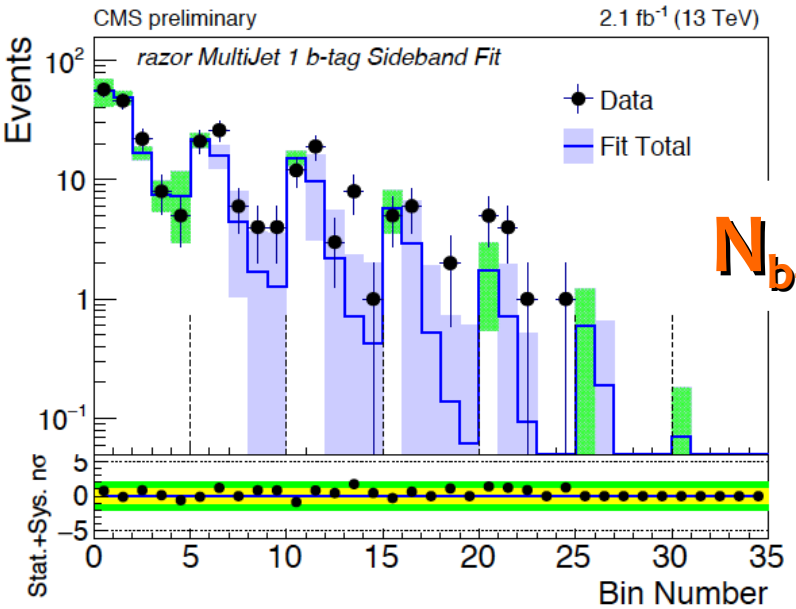
[SUS-15-004]

No significant deviations found in data

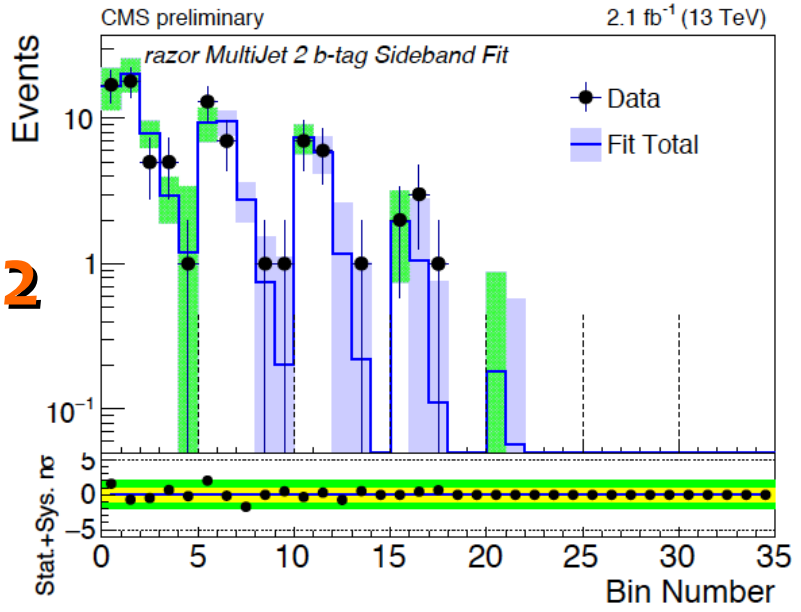
$N_{b\text{-jet}} = 0$



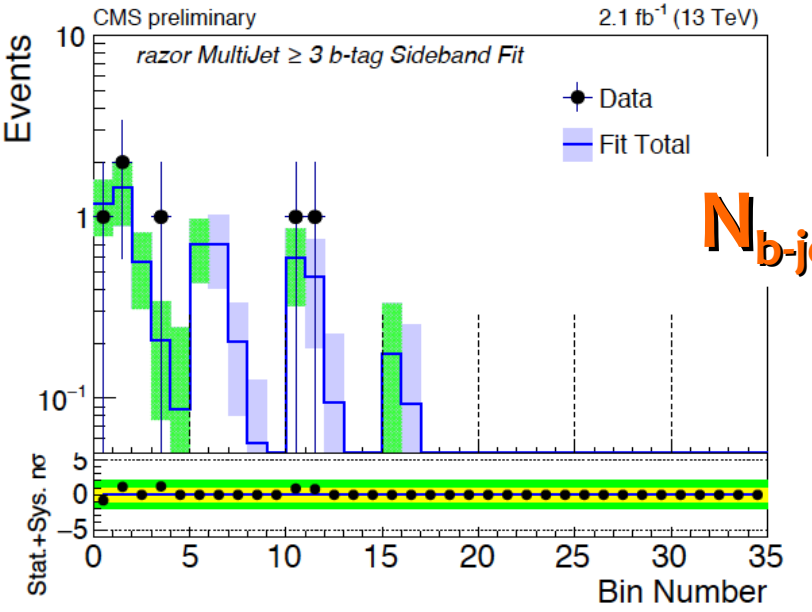
$N_{b\text{-jet}} = 1$



$N_{b\text{-jet}} = 2$



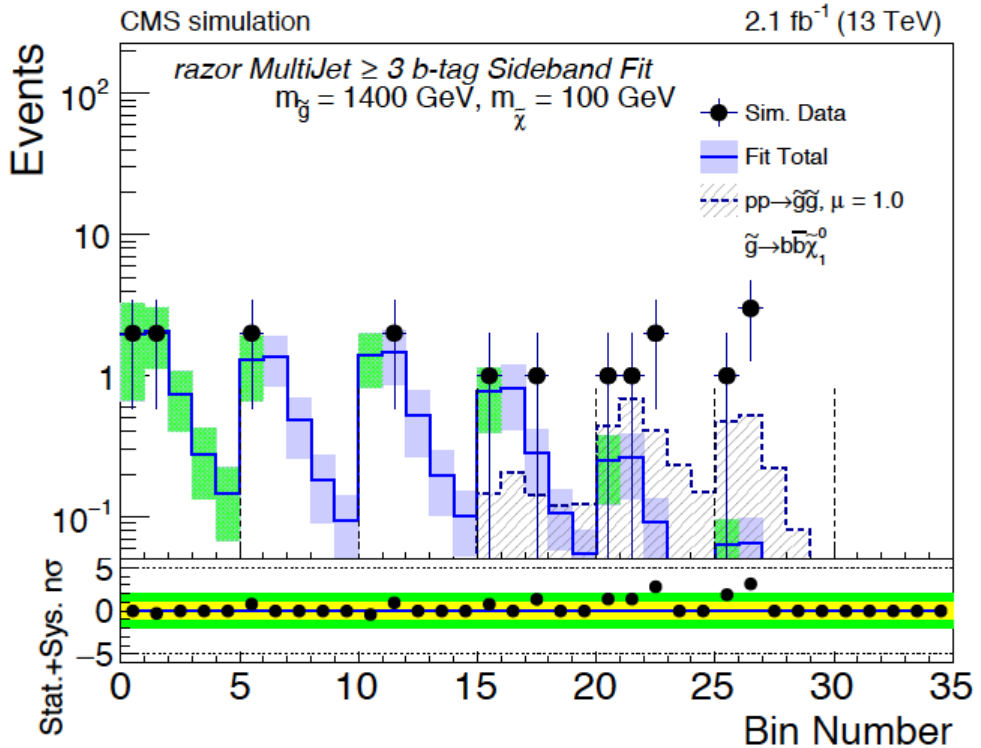
$N_{b\text{-jet}} \geq 3$

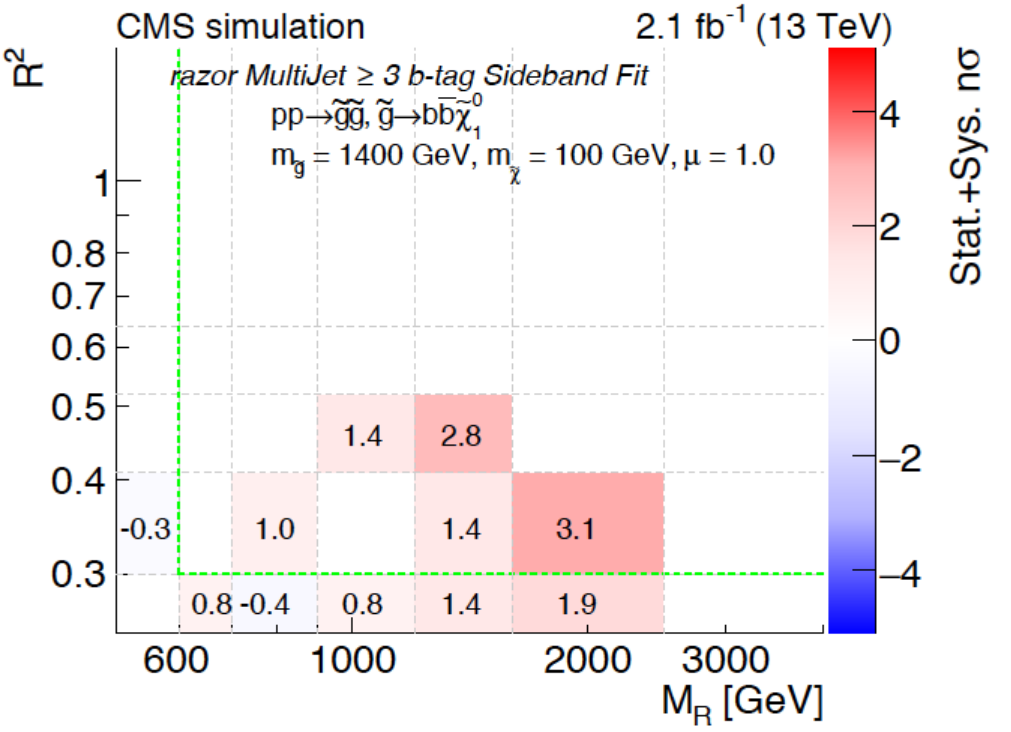


Signal Injection (toy study)

[SUS-15-004]

- What happens when a signal is present?
- Events corresponding to a T1bbbb signal are injected and a background-only sideband fit is performed
- In signal sensitive region, we would observed fluctuation (nσ) above background

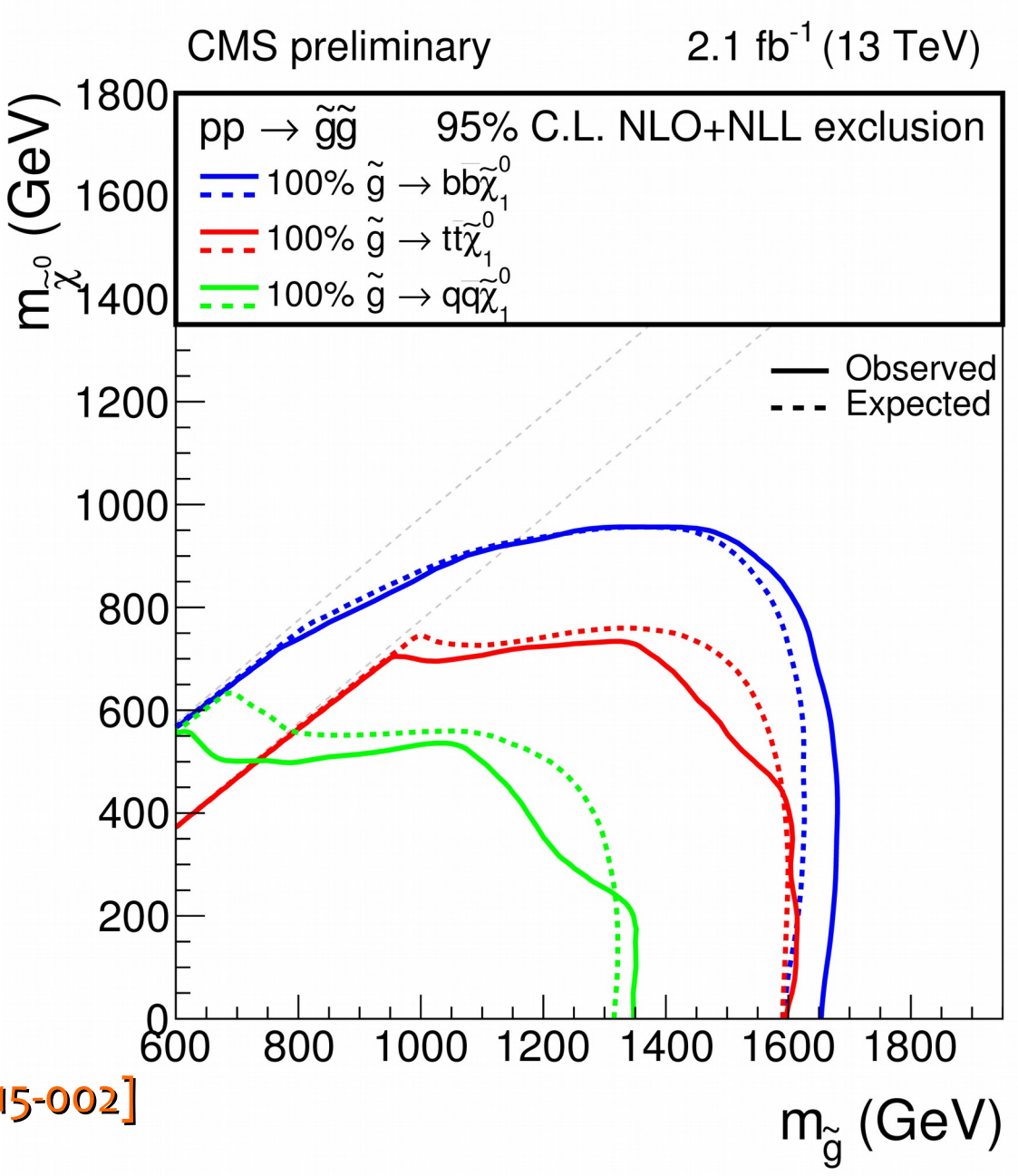




LIMITS

[SUS-15-004]

- For a massless LSP, gluino is excluded below masses
- T1bbbb: $m_{\tilde{g}} < 1.65$ TeV
- T1tttt: $m_{\tilde{g}} < 1.60$ TeV (0L+1L combined)
- T1qqq: $m_{\tilde{g}} < 1.35$ TeV
- Results complementary to the MHT/HT search [SUS-15-002]



SUSY with alphaT

[SUS-15-005]

- **AlphaT:** For events with 2 (pseudo-) jets:

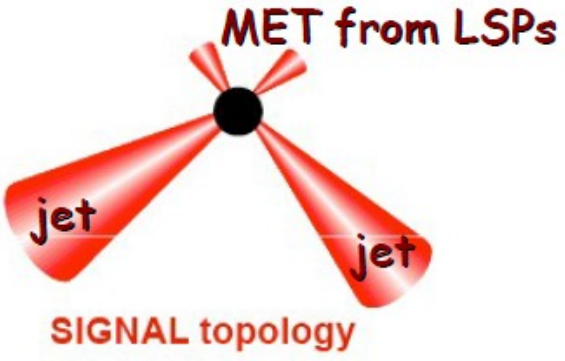
$$\alpha_T = E_T^{j2} / M_T = E_T^{j2} / \sqrt{H_T^2 - \not{H}_T^2}$$

less energetic jet — transverse mass of di-jet system

- **discriminator** between events with **misreconstructed and genuine MET**

α_T = 0.5

For a perfectly measured dijet event with $ET^{j1} = ET^{j2}$ jets are back-to-back in φ in the limit of large jet momenta compared to their masses



α_T is smaller than 0.5

in the case of an imbalance in the measured ETs of back-to-back jets

α_T is greater than 0.5

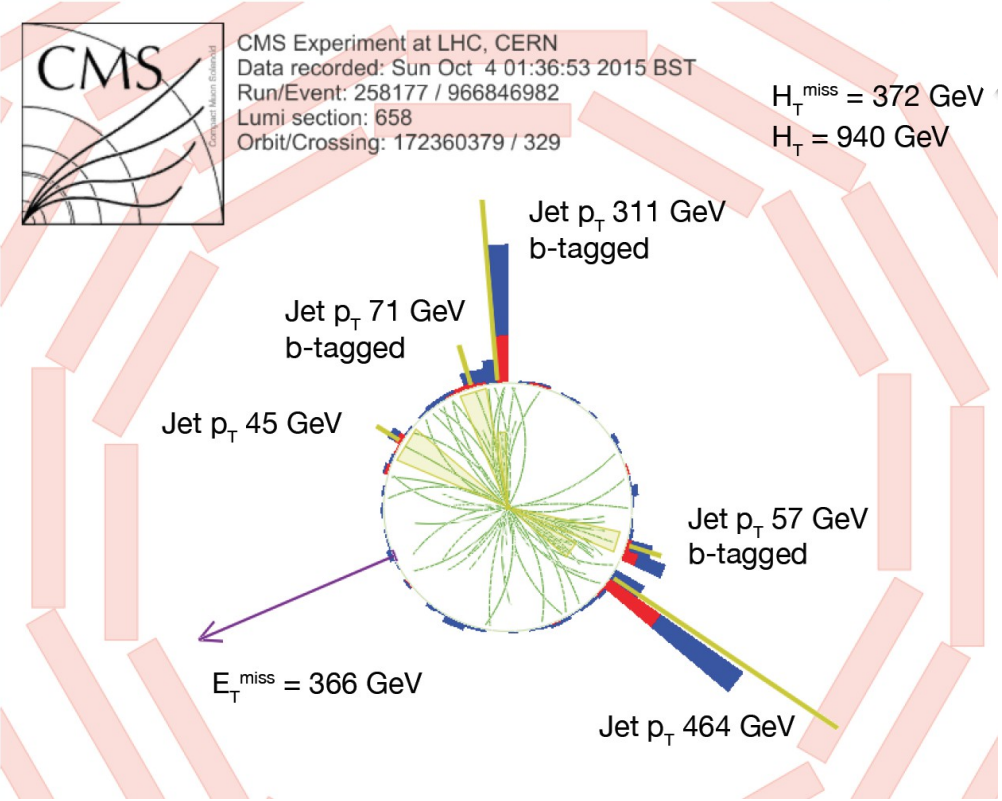
when the two jets are not back-to-back and balancing genuine MET

AlphaT analysis strategy

[SUS-15-005]

- **Inclusive search**
  - jets+MET signatures
  - all jet/b-tag multiplicities
  - low trigger thresholds
- **Robust analysis**
  - Suppress QCD multi-jet to a negligible level
  - Rely heavily on multiple control samples for background estimation and systematics

- **Sensitivity**
- Discriminating variables: n_{jet}, n_b, H_T, MHT
- Give sensitivity to a wide variety
- of models, decays and topologies



Baseline selection

[SUS-15-005]

Selection:

- njet ≥ 1
  - pT,j1 > 100 GeV, |ηj1| < 2.5
  - pT,j2 > 40 GeV, |ηj2| < 3
- HT > 200 GeV
- MHT > 130 GeV
- Forward jet veto
  pT,j > 40 GeV, |ηj| > 3
- Isolated track veto
  pT,t > 10 GeV, |ηt| < 2.5

Categorization

Based on 2nd jet

- Monojet
  pT,j2<40 GeV
- Asymmetric
  40<pT,j2<100 GeV
- Symmetric
  pT,j2>100 GeV

Binning:

- 191 (njet,nb,HT) bins x MHT bins (6-14)
  →Total of ~850 bins

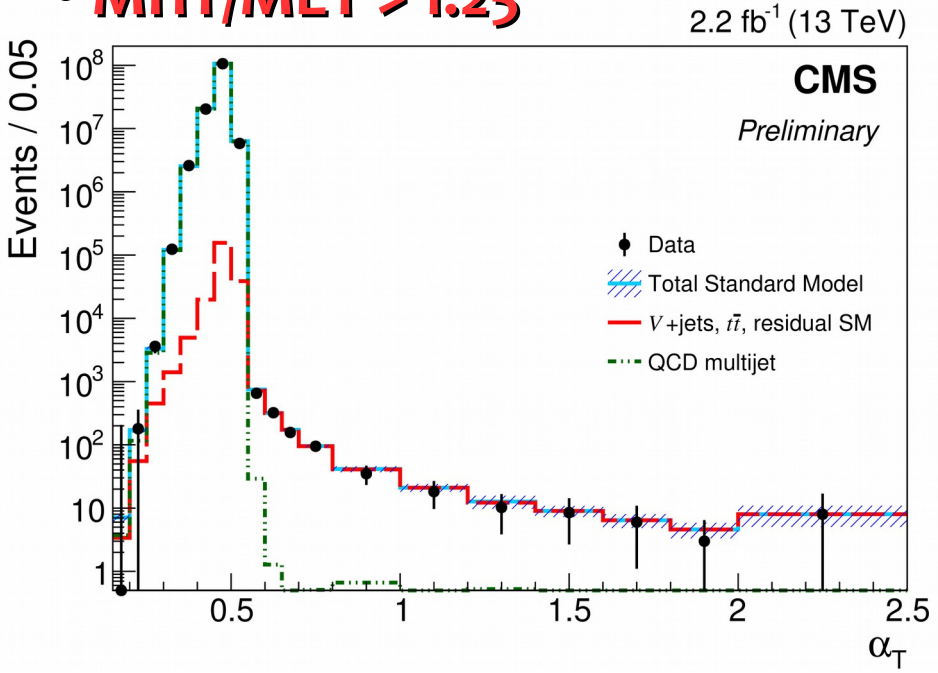
Background suppression

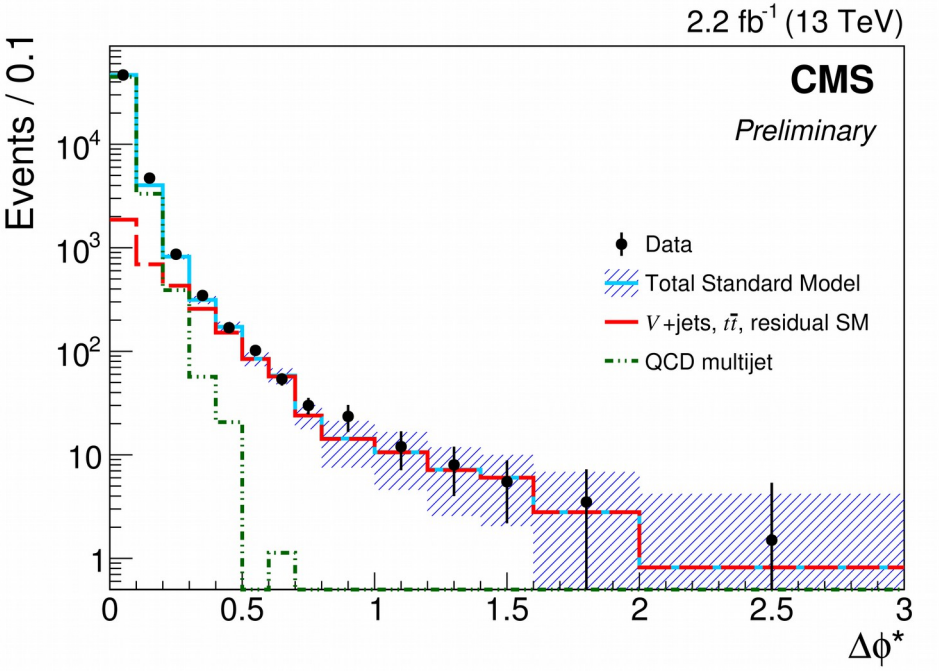
[SUS-15-005]

QCD multi-jet is a key background for hadronic searches

- Reduction of this background to a negligible level achieved with very tight cuts on:
- αT > 0.65 to 0.52,
- Δϕ* > 0.5 ,
- MHT/MET > 1.25

Δϕ* – Minimum Δϕ between jet and the MHT vector computed without that jet, peak in low values for mis-reco jets and jets w/ υs





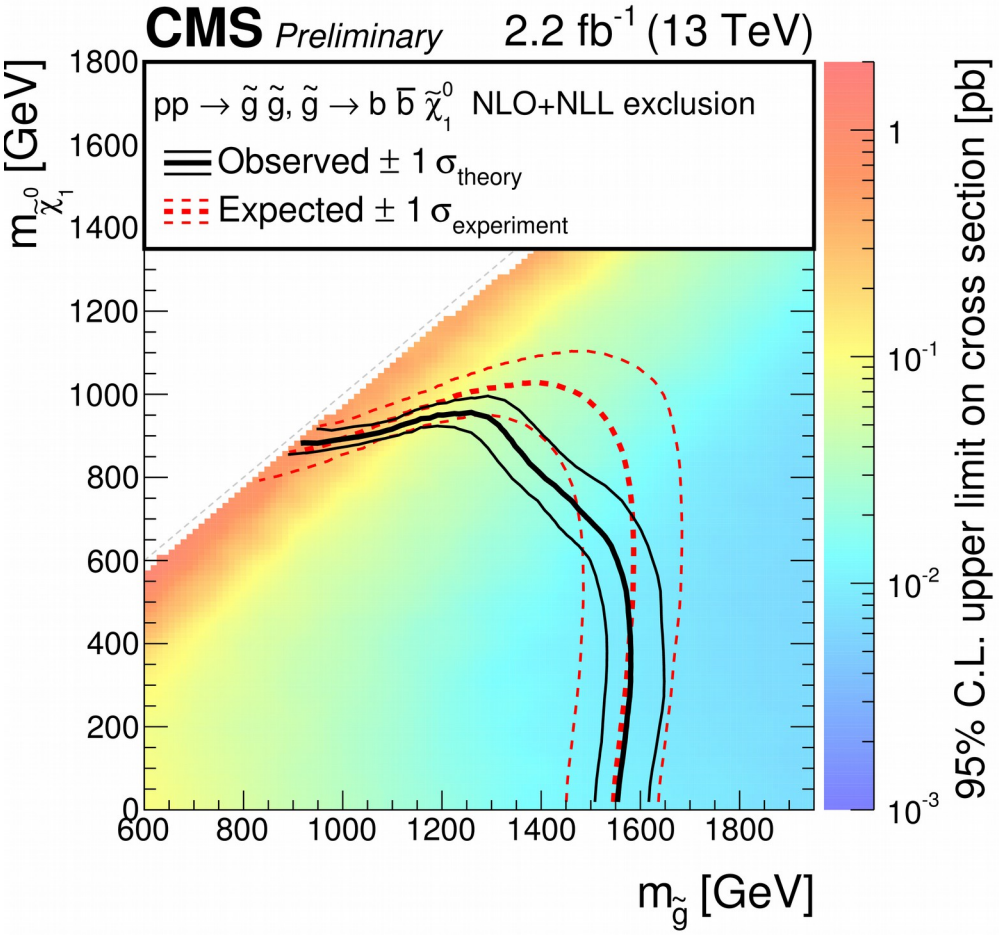
Remaining backgrounds stem mainly from: tt +jets, W + jets, Z→inv

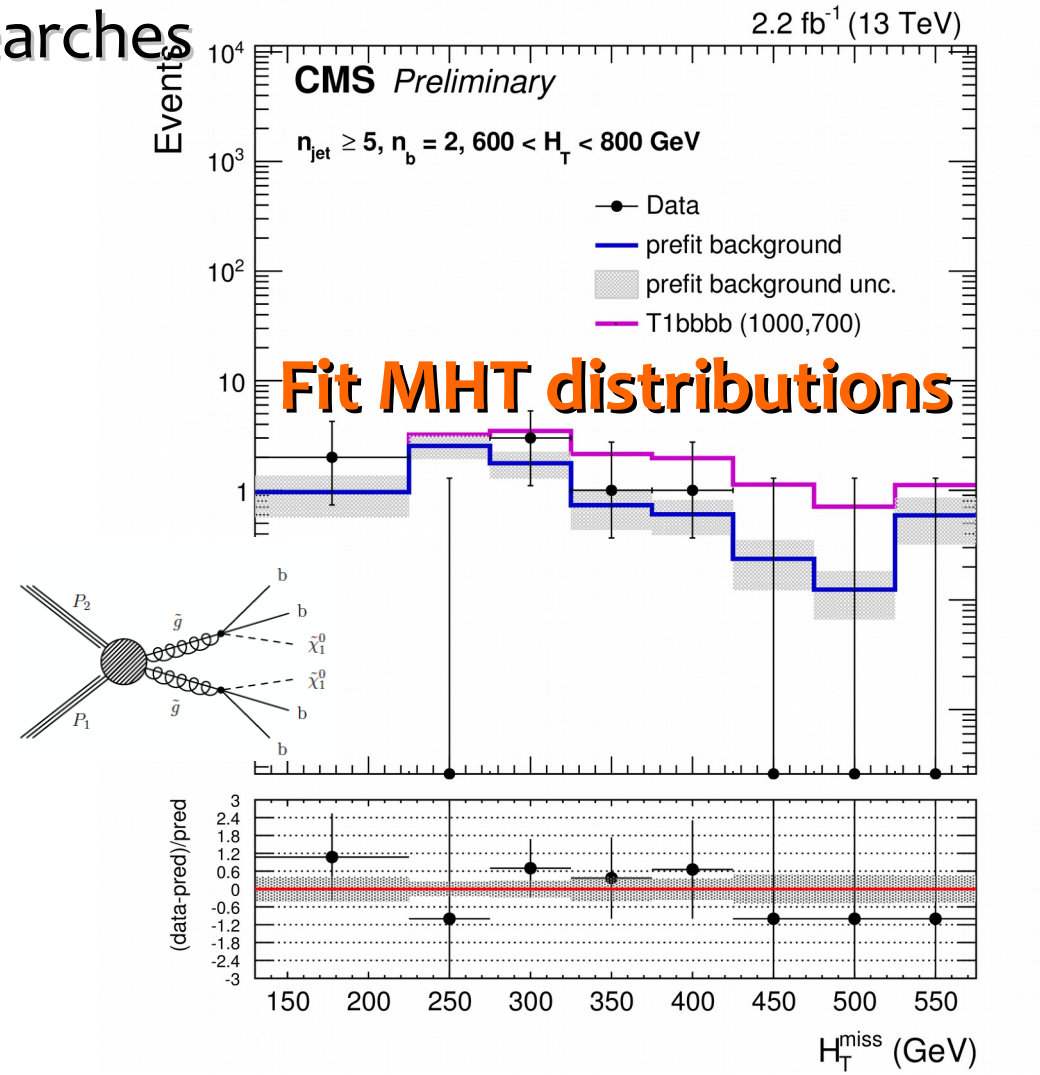
Predicted in the signal region from observed counts in control regions

AlphaT results and T1bbbb limit

[SUS-15-005]

- Expected/observed exclusion are in reasonable agreement
- At low LSP mass, **$m_{\tilde{g}} \simeq 1.6$ TeV** is excluded
  → similar result to previous searches



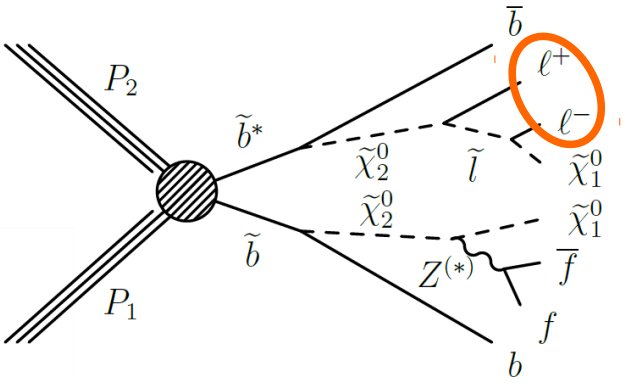


Opposite-sign dileptons at 8 TeV

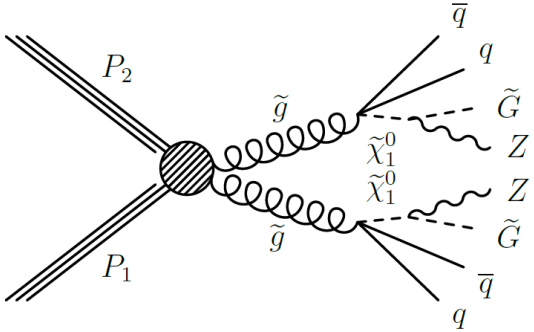
[SUS-15-011]

Excesses in Run 1

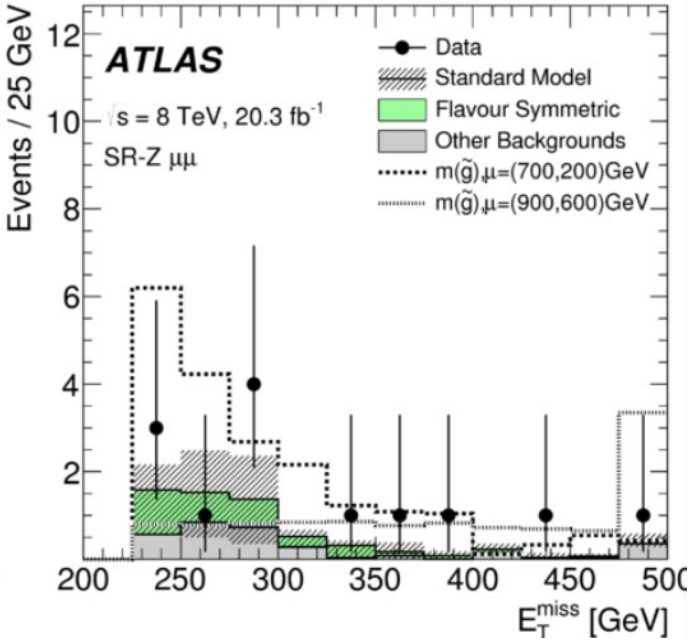
e.g. **T6bbslep**

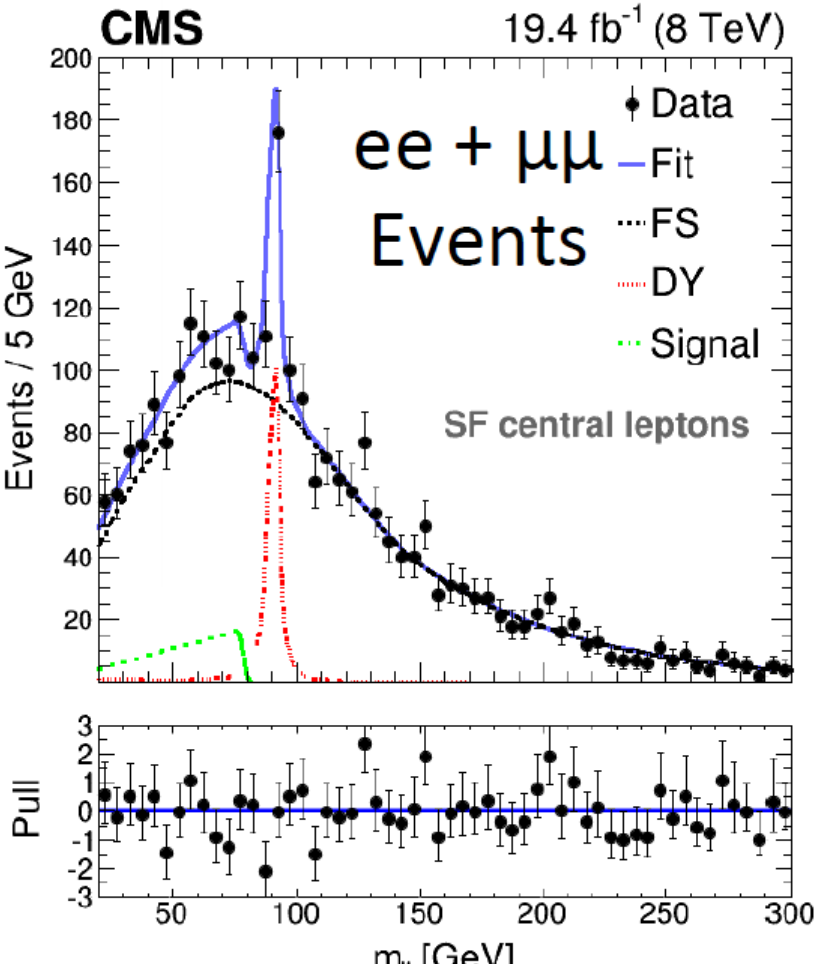


- **Edge:** CMS saw **2.6σ excess** in low Mll, no excess in ATLAS
- **On-Z:** ATLAS saw **3.0σ excess** in high HT region, no excess in CMS



e.g. **T5ZZgmsb**



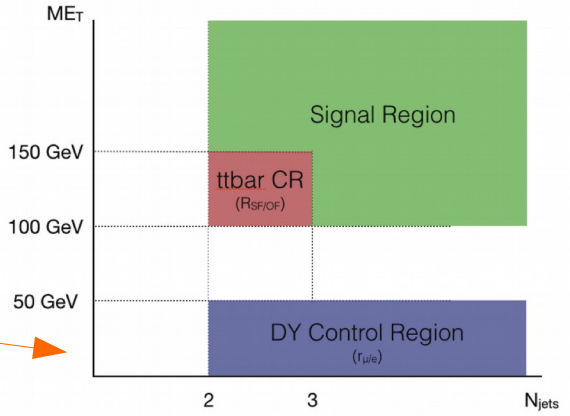


Opposite-sign dileptons at 13 TeV

[SUS-15-011]

- Search with **2 OSSF** same-flavor leptons (ee, μμ) **+ jets + MET**
- 2 search strategies: **on and off(edge) the Z-peak**
  - Tight selection for *leptons* pT > 20 GeV, |η|<2.4, Mll > 20 GeV
  - Loose selection for *jets* pT > 35 GeV, |η|<2.4

- Data driven prediction for 2 main backgrounds: DY and FS(eμ data), for others – MC
- Perform **cut and count analysis in regions** binned in **Njets, Nb-tags, HT, and MET**
  - **On-Z**: 17 bins with **new one like ATLAS for high HT**
  - **Edge**: 30 bins with 5 bins on Mll

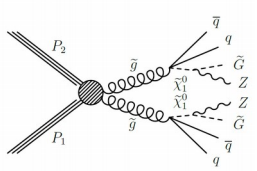


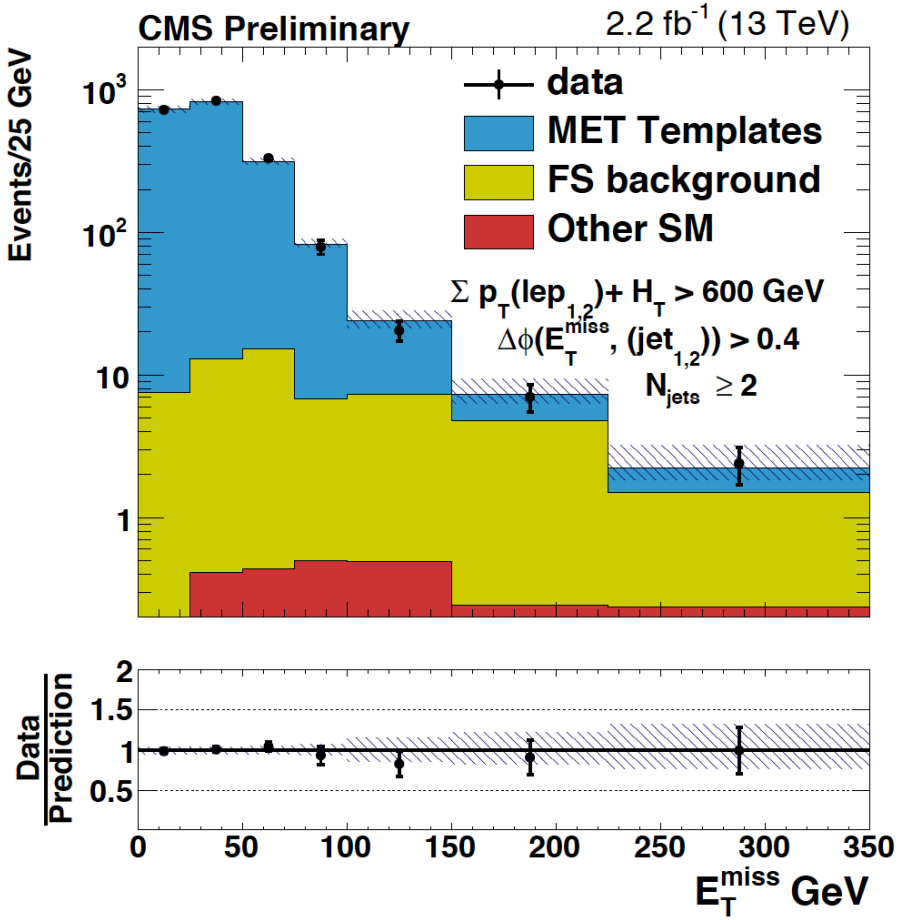
On-Z OS dileptons – Results

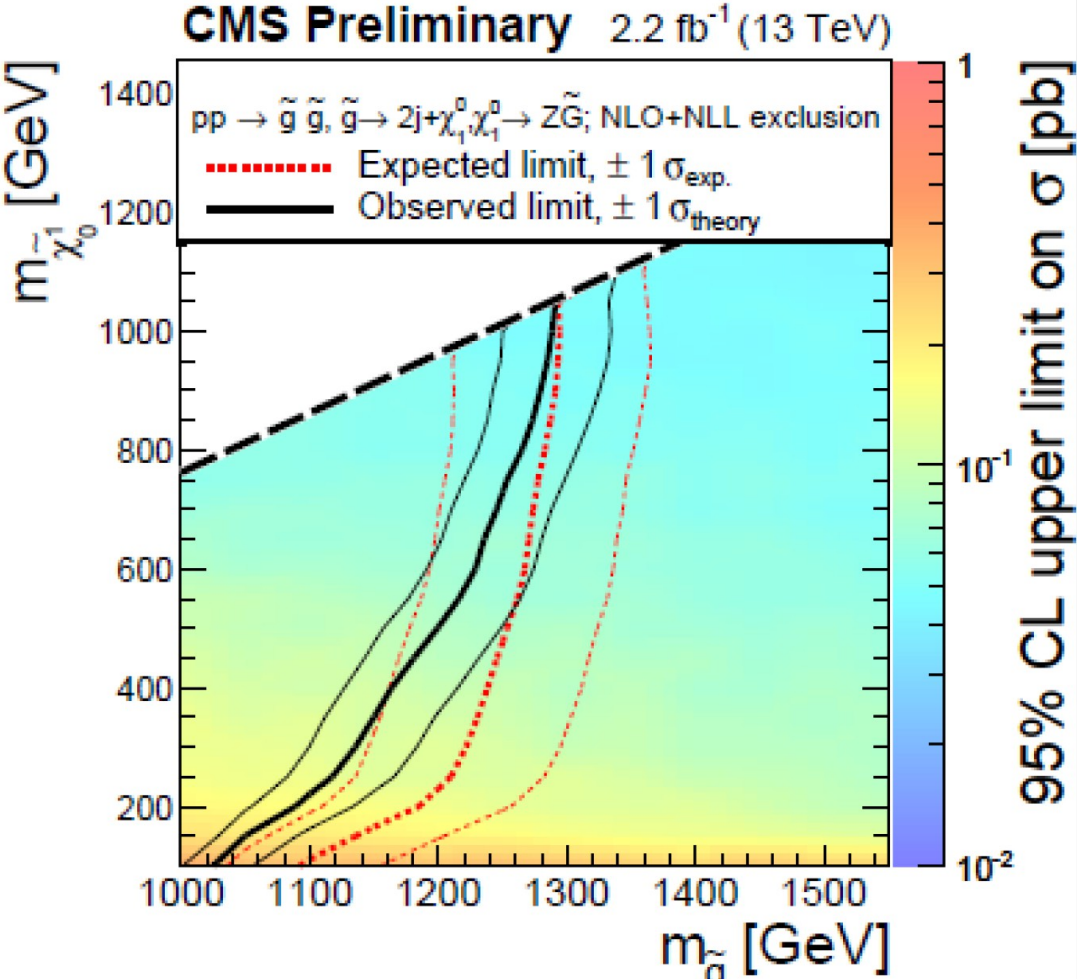
[SUS-15-011]

T5ZZgmsb

- ATLAS-like search bin: no excess seen





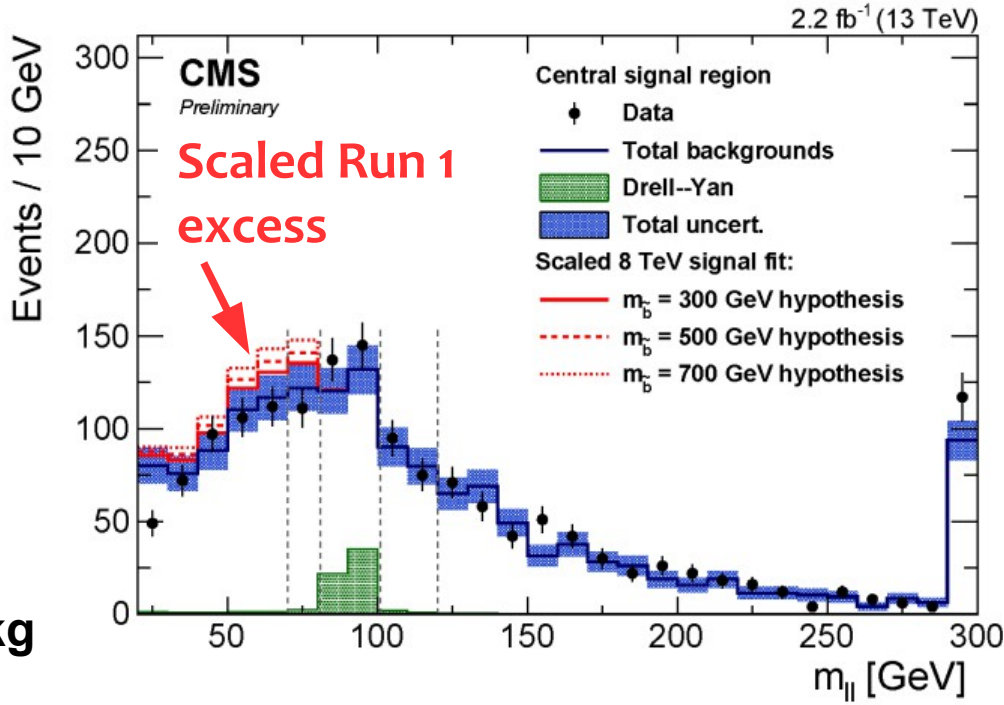


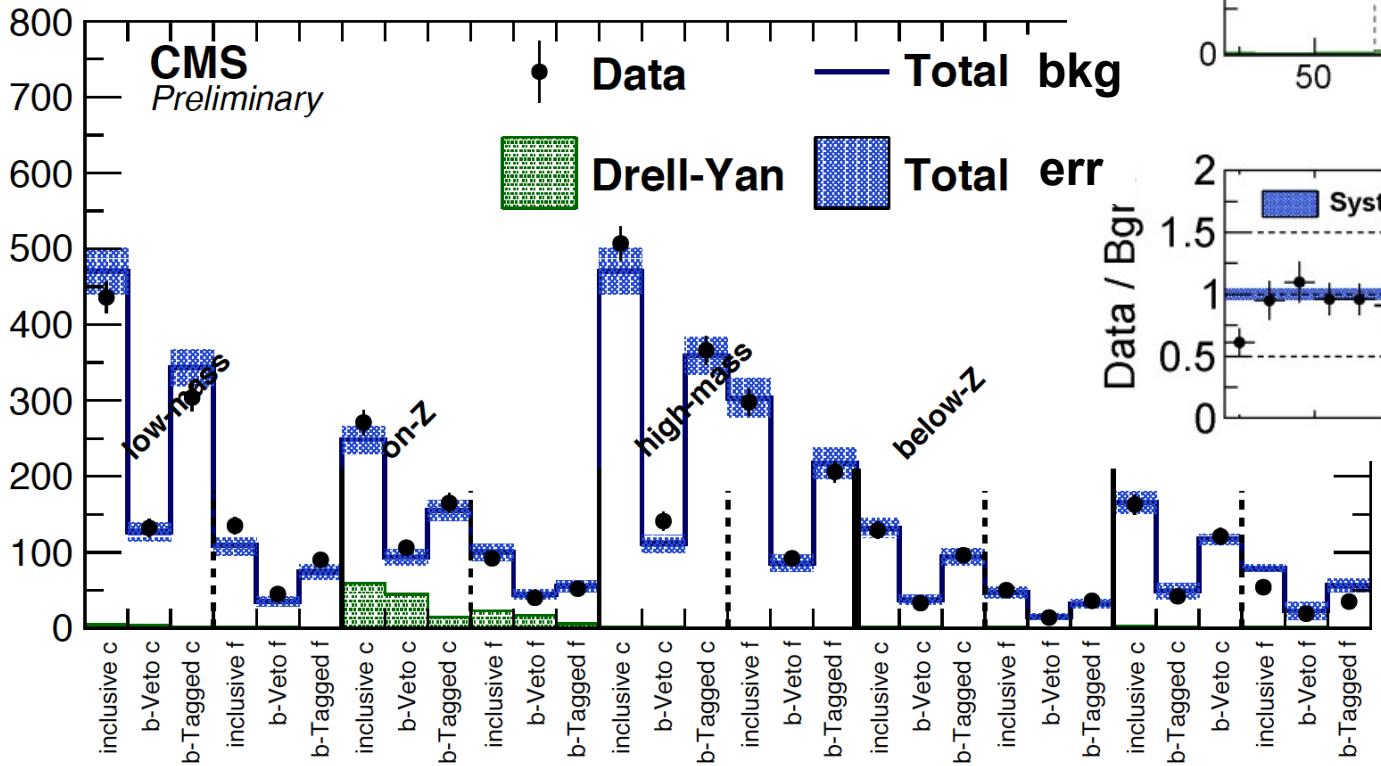
- Observed limit improved by 50-150 GeV in gluino mass wrt 8 TeV result

Edge OS dileptons – Results

[SUS-15-011]

- **Any significant excess** in the kinematic edge in 13 TeV data is observed

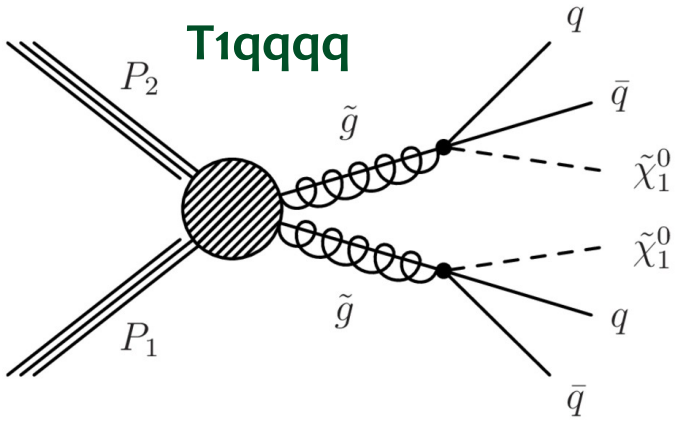




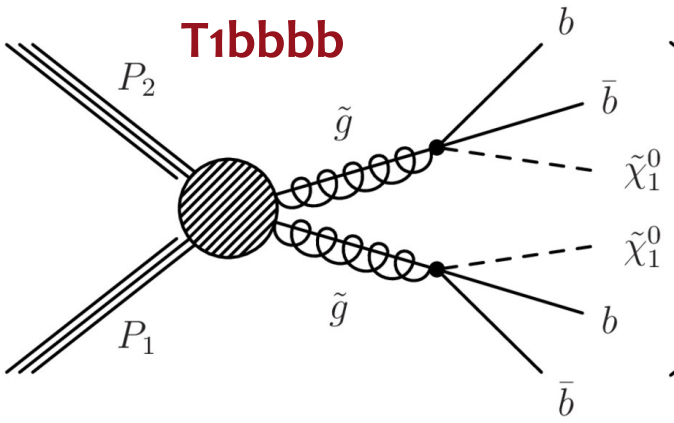
In all signal regions, **data - background agreement**

Early SUSY Searches – Summary

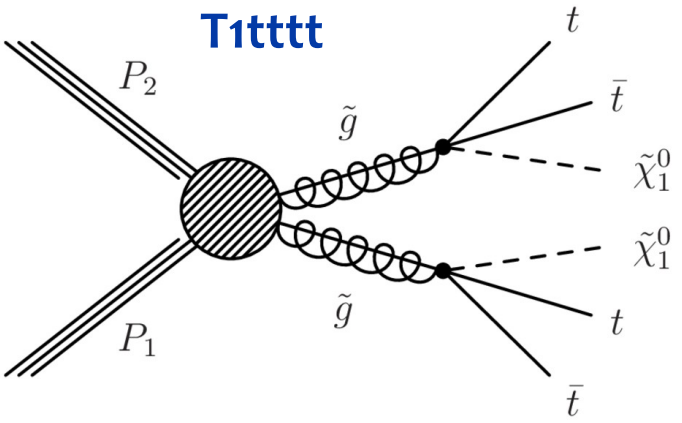
T1qqqq

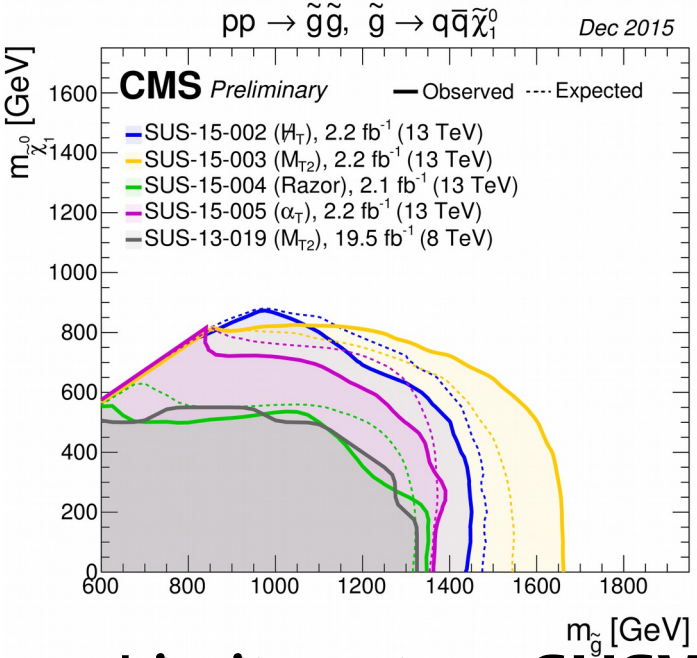


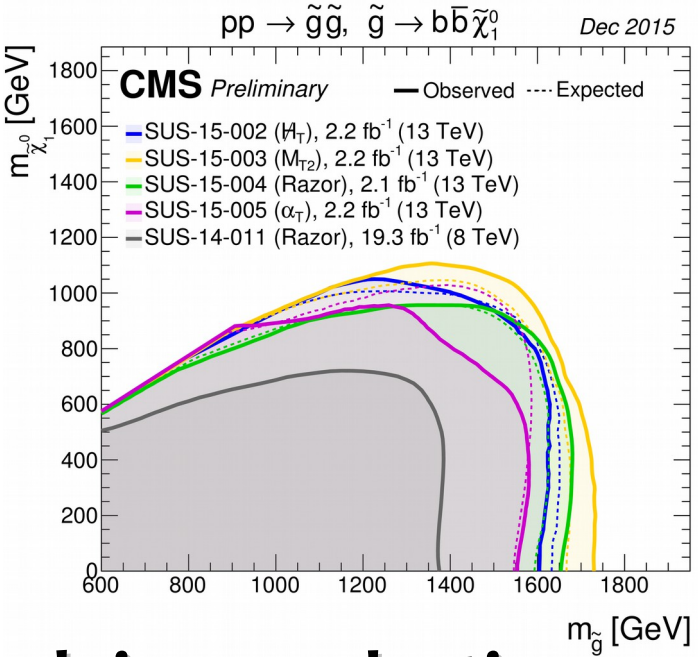
T1bbbb

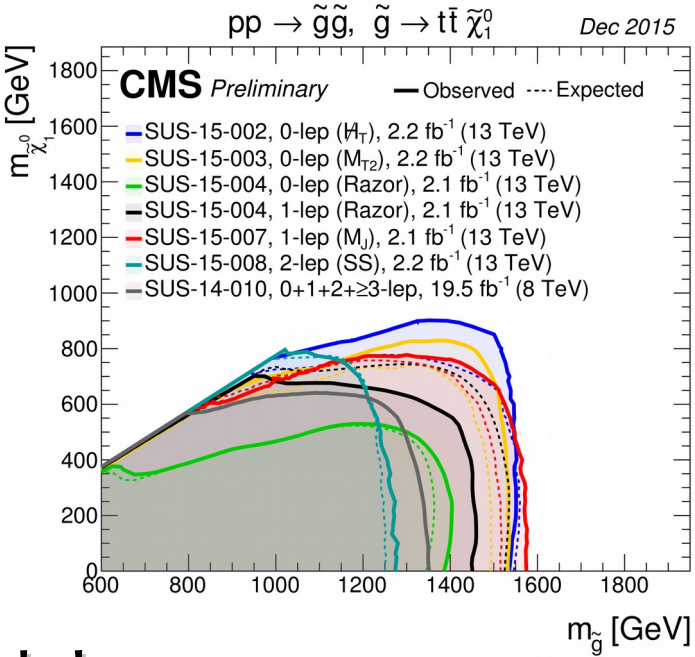


T1tttt









- Limits set on **SUSY gluino production** models,

extending Run 1 sensitivity by ~300 GeV in m_{Gluino} up to 1.7 TeV

Conclusions

- **No evidence** of **SUSY particles found…** yet
- **No significant excess in data** in first look for SUSY
  - Run 1 excess in OS dilep channel cancelled by Run 2
  - but **a ~2.5σ bump in X→ γγ observed**

    (more in Exotica talk on Sat)
- **Run2** data **constrains stronger** (by 300 GeV)
  gluino masses up to 1.7 TeV
  in many SUSY-simplified models
- **2016 pp @ 13 TeV** → hunting for new physics be restarted
  → more results in spring and summer

Work supported by Polish National Science Centre
UMO-2014/14/M/ST2/00428 & UMO-2014/15/B/ST2/03998

Backup

References

- - **CMS-PAS-SUS-15-002** Search for supersymmetry in the multijet and missing transverse momentum channel in pp collisions at 13 TeV
- **CMS-PAS-SUS-15-003** Search for new physics in the all-hadronic final state with the MT2 variable
- - **CMS-PAS-SUS-15-005** Search for new physics in final states with jets and missing transverse momentum in √s= 13 TeV pp collisions with the αT variable
- - **CMS-PAS-SUS-15-004** Inclusive search for supersymmetry using the razor variables at √s= 13 TeV
- **CMS-PAS-SUS-15-007** Search for supersymmetry in pp collisions at √s= 13 TeV in the single-lepton final state using the sum of masses of large radius jets
- **CMS-PAS-SUS-15-008** Search for SUSY in same-sign dilepton events at √s= 13 TeV
- - **CMS-PAS-SUS-15-011** Search for new physics in final states with two opposite-sign same-flavor leptons, jets and EmissT in pp collisions at √s= 13 TeV

Systematics in MHT/HT search

[SUS-15-002]

Item	Relative uncertainty (%)
Integrated luminosity	4.6
Trigger efficiency	1.1
Pileup reweighting	0.5
Parton distribution functions	10
Renormalization and factorization scales	0–3
Initial-state radiation	0-11
Jet energy scale	0.5–4
Isolated-lepton and -track vetoes (T1tttt only)	2

Razor systematics

[SUS-15-004]

Systematic Uncertainty Source	Uncertainty
Lepton Selection Efficiency	2%
Fast Simulation Lepton Selection Efficiency	0 – 10%
Lepton Trigger Efficiency	3%
B-Tagging Efficiency	5 – 15%
Fast Simulation B-Tagging Efficiency	0 – 10%
Jet Energy Scale	5 – 10%
Luminosity	4.6%
Ren./Fac. Scale	3 – 5%
Parton Distribution Functions	10%
Initial State Radiation	2% – 20%
Pileup	< 1%
Monte Carlo Statistics	0 – 10%

AlphaT systematics

[SUS-15-005]

n_{jet}	Uncertainty (%) in background component	
	$t\bar{t}$, W+jets, residual SM	$Z \to \nu\bar{\nu}$ + jets
"Monojet":		
1	9–36	9–36
"Asymmetric":		
2	11–105	9–46
3	12–86	12–78
4	16–52	13–43
$\geq$5	19–47	27–73
"Symmetric":		
2	7–34	11–30
3	9–31	13–44
4	13–36	8–34
$\geq$5	15–22	17–28
Additional contributions:		
α_T ($H_T < 800$ GeV)	10-27	10-27
$\Delta\phi^*_{min}$ ($H_T > 800$ GeV)	22	22
b-quark identification	<5	<5