SUSY searches @ CMS

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on behalf of the CMS Collaboration

Les Rencontres de Physique de la Vallée d'Aoste

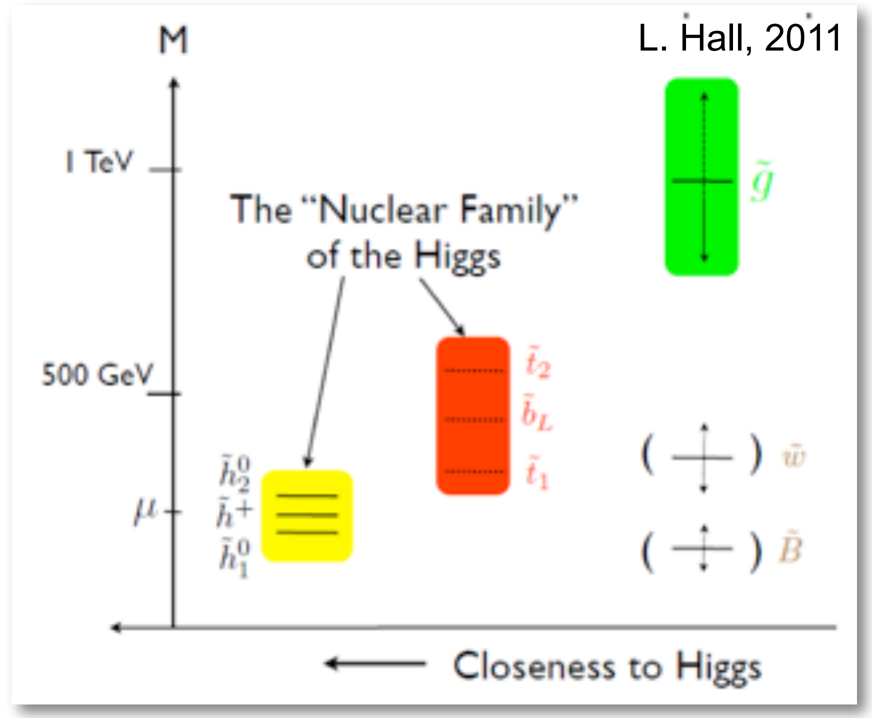
La Thuile, 11th March 2016

Imperial College London

CMS Compact Muon Solenoid

The briefest of introductions...

SUSY imposes a new fundamental symmetry b/w fermions and bosons



Solutions to some limitations of Standard Model

- Hierarchy problem → TeV-scale superpartners
- Dark Matter → neutralino LSP is a possible candidate
- Grand unification → modified running of gauge couplings

High expectations for a spectacular discover at LHC start-up, alas...

But! SUSY can be realised in many ways → rich phenomenology

R-parity conserving:	pair-production, stable LSP → jets + leptons + MET
"Natural":	minimal sparticle content at TeV-scale → b-jets + MET
Compressed:	"invisible" decays → rely on associated jet production
Stealth:	e.g. $m_{stop} \approx m_{top}$, light LSP → SM-like, no extra MET
R-parity violating :	non-stable LSP → high jet/lepton multiplicities, low MET
Split SUSY:	long-lived, R-hadrons → displaced vertices + jets + MET

The scope of this talk

Several analyses frozen and released as preliminary results in Dec. 2015

All are considered "early inclusive searches", based on 2015 data set @ 13 TeV

This talk contains new interpretations relevant to the "natural" parameter space

New results very soon: different final states, targeted searches, ...

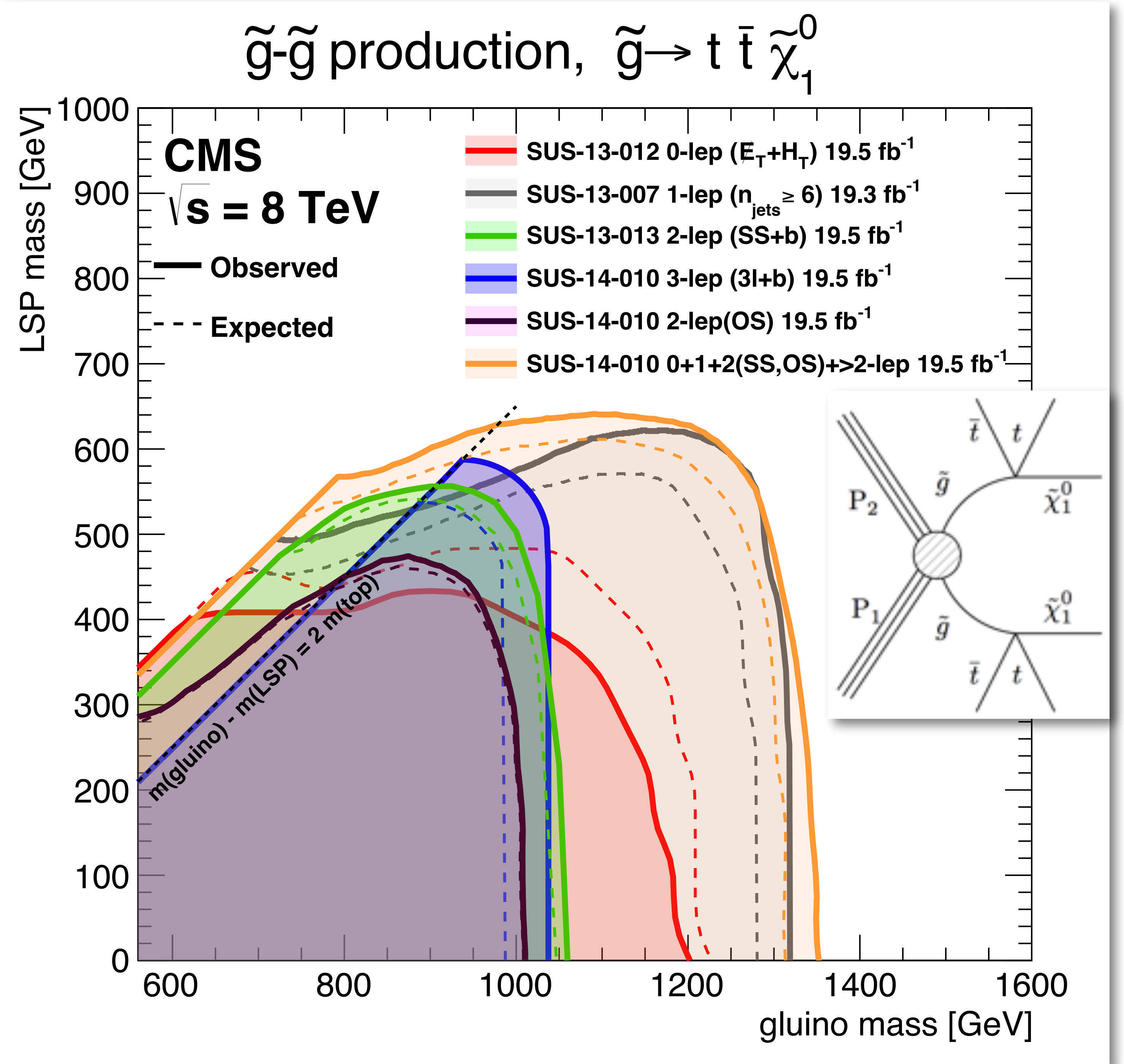
0 Lepton	**1 Lepton**	**≥2 Leptons**
Jets + MHT SUS-15-002	Jet Mass SUS-15-007	Same sign SUS-15-008
MT2 SUS-15-003		Edge/Z SUS-15-011
Razor SUS-15-004	Razor SUS-15-004	
α_T SUS-15-005		

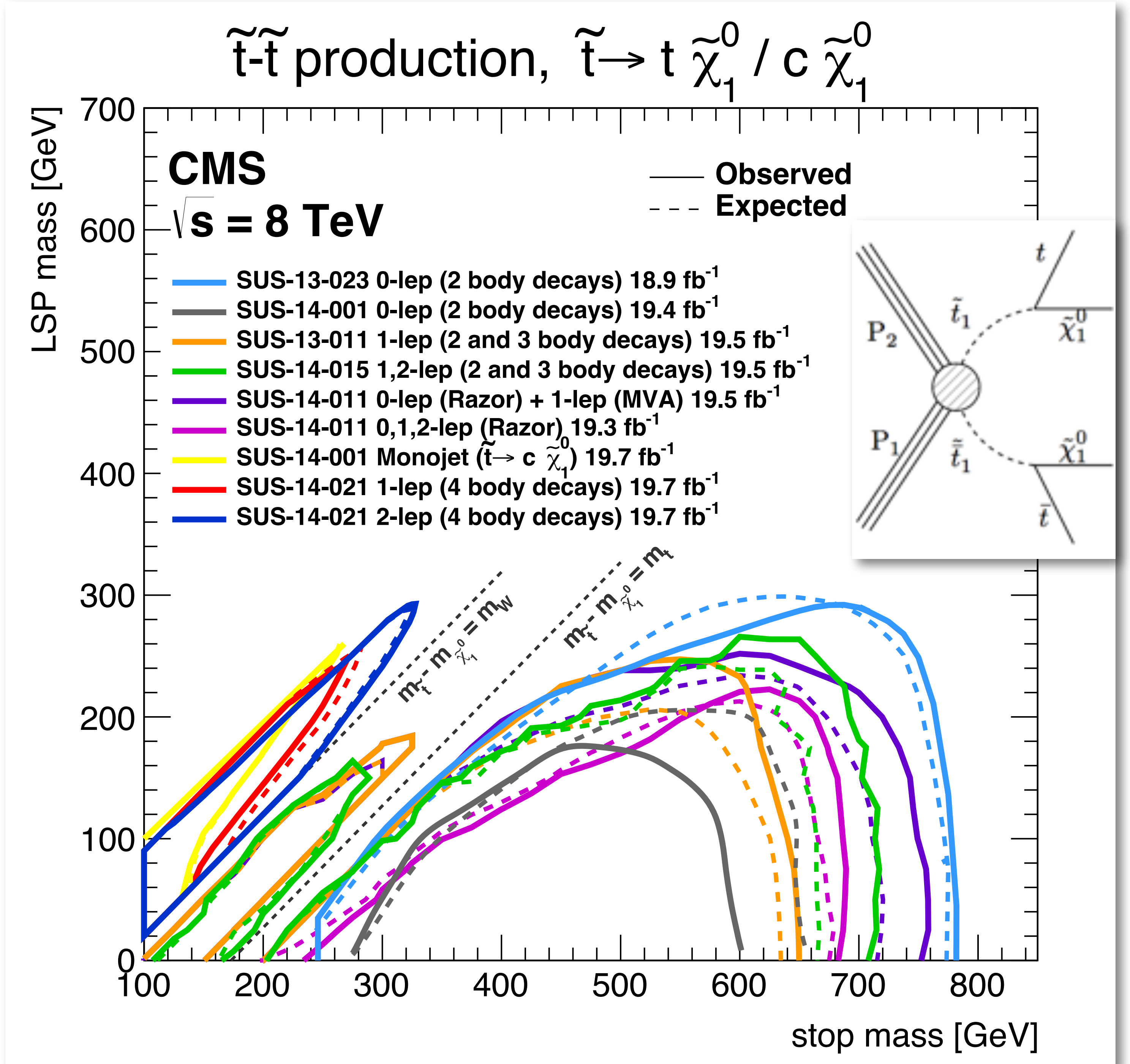
Run 1 legacy

Comprehensive range of results and interpretations available (link)

TeV-scale limits for gluino-mediated stop production (for m_{LSP} < 600 GeV)

Incomplete coverage of natural (m_{stop},m_{LSP}) parameter space

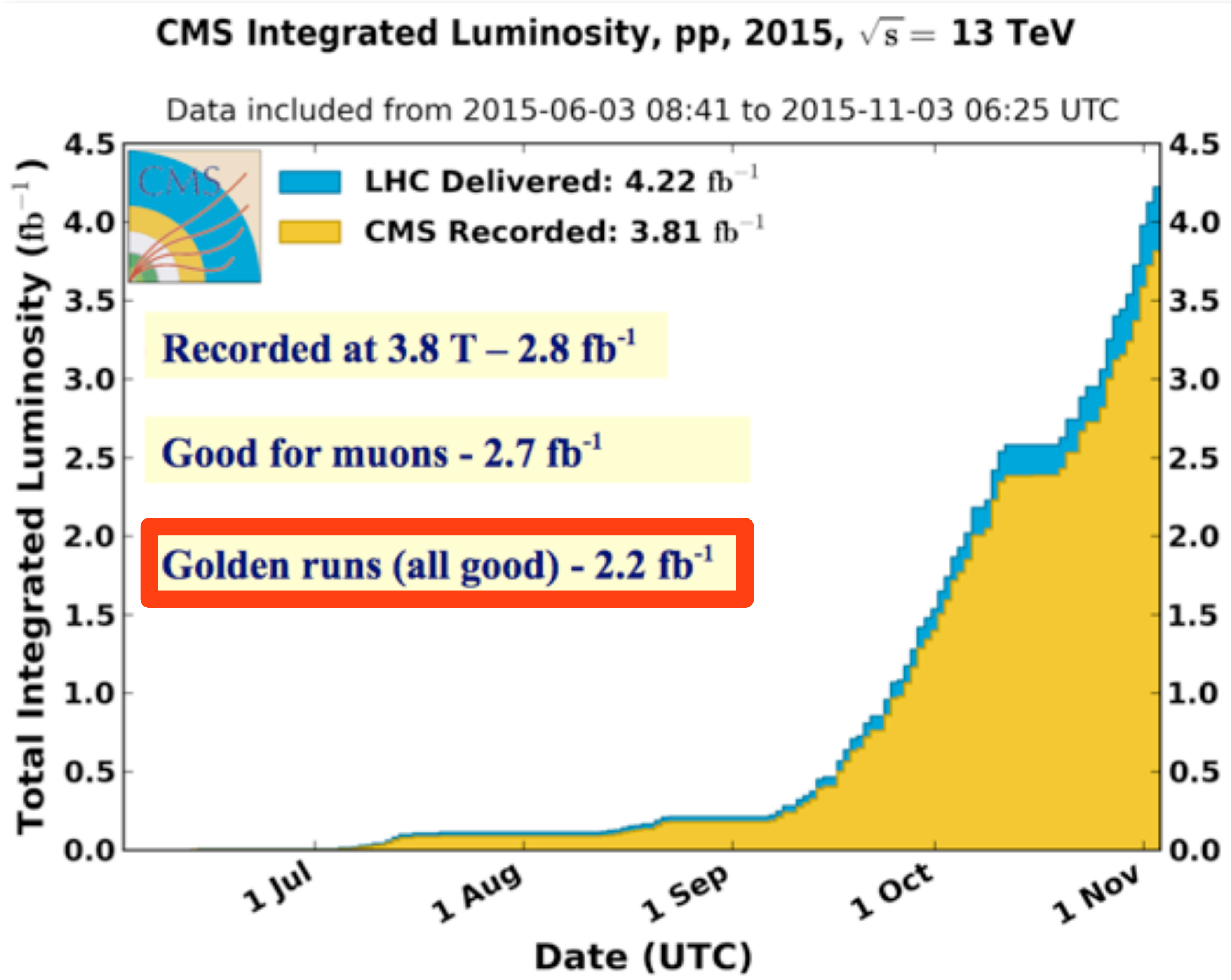


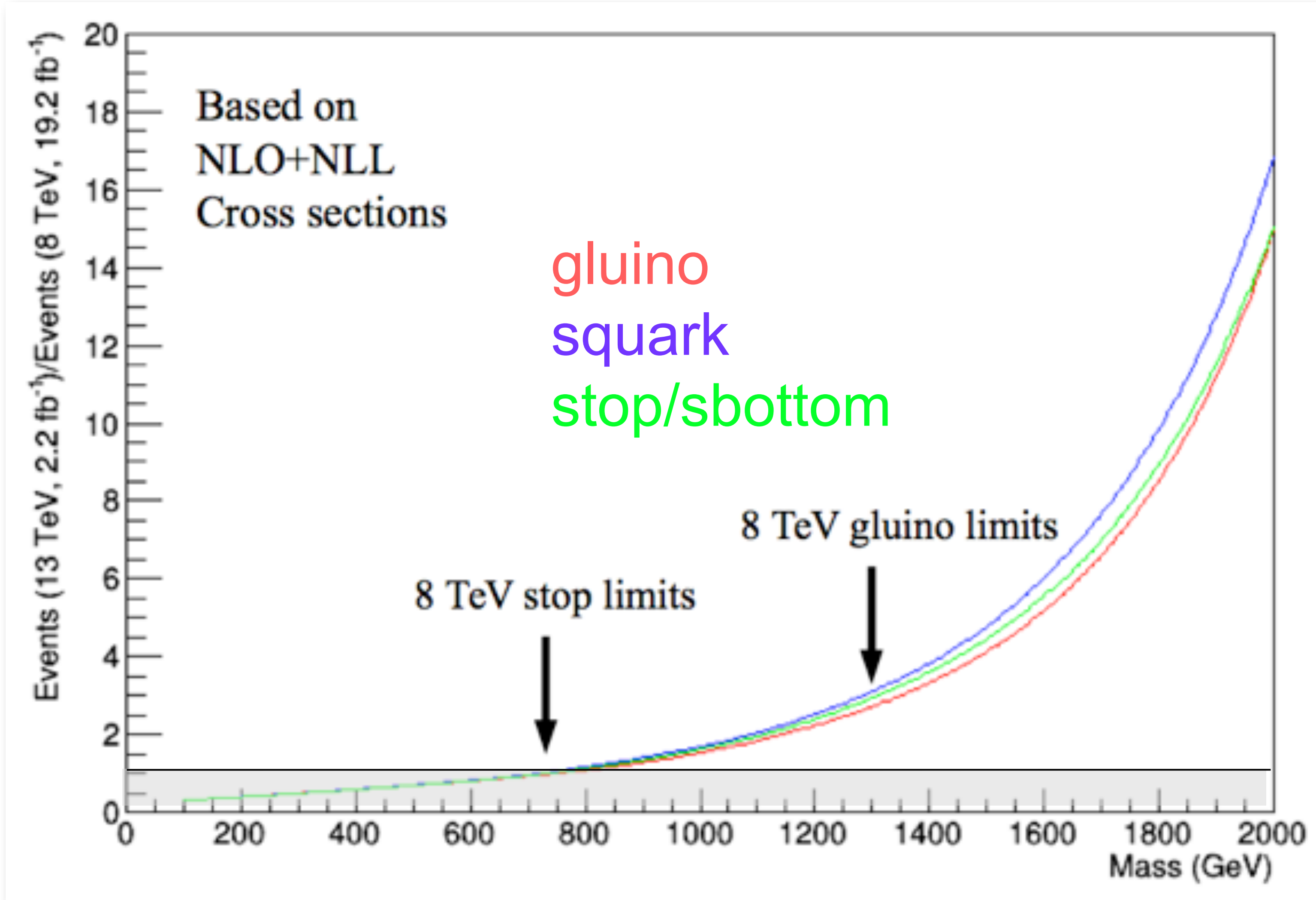


Data set collected in 2015 @ 13 TeV

Data samples collected in 2015 correspond to L_{int} = ~2.2 fb^{-1}

Sufficient luminosity to extend reach for gluinos and squarks

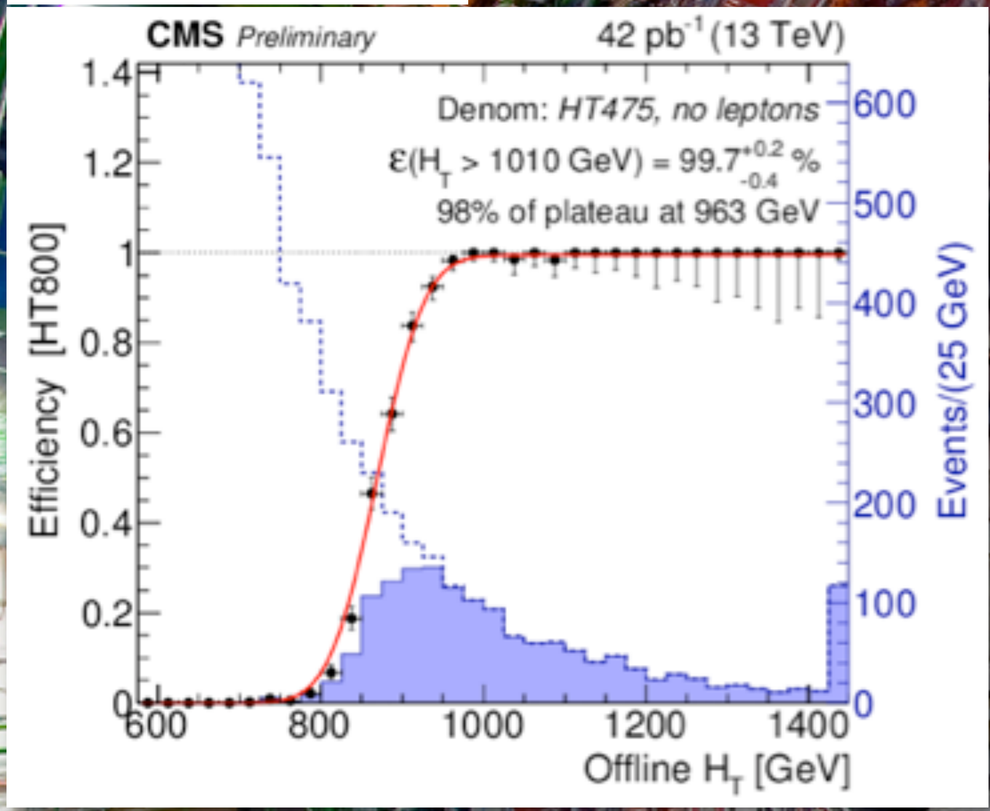




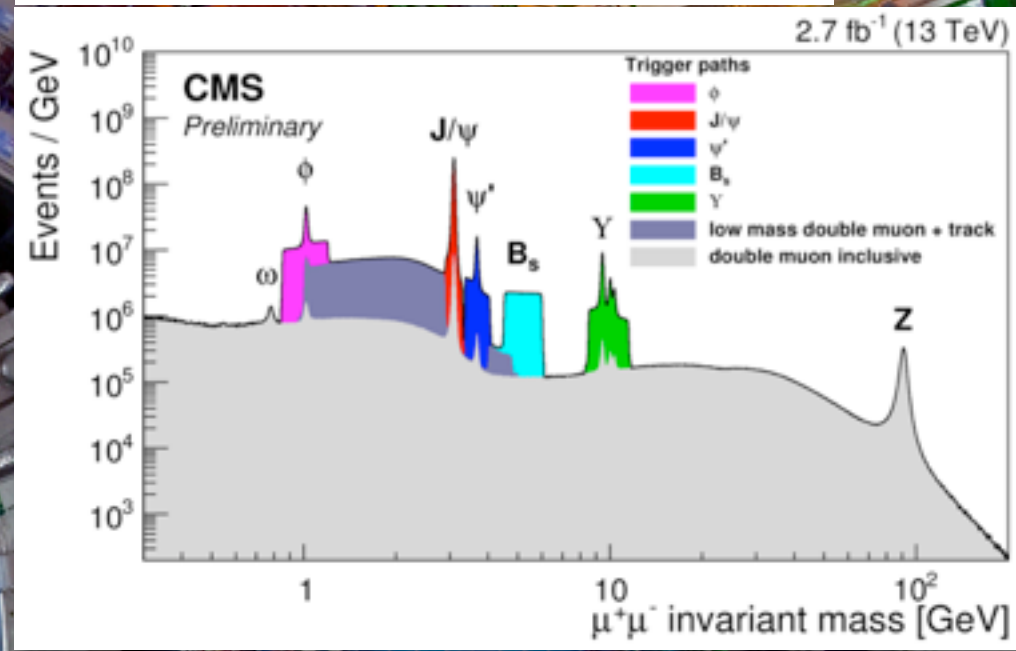
The CMS detector

Searches rely on high-quality physics objects (e.g, MET, b-jets) and high $A \times \varepsilon$

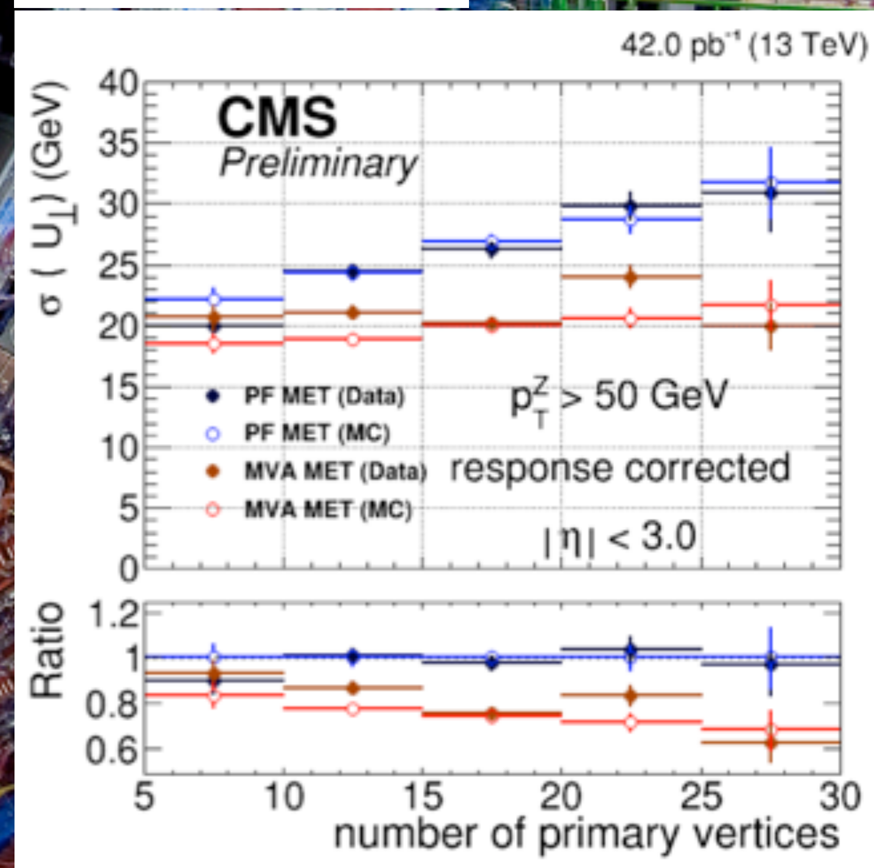
Efficient triggers



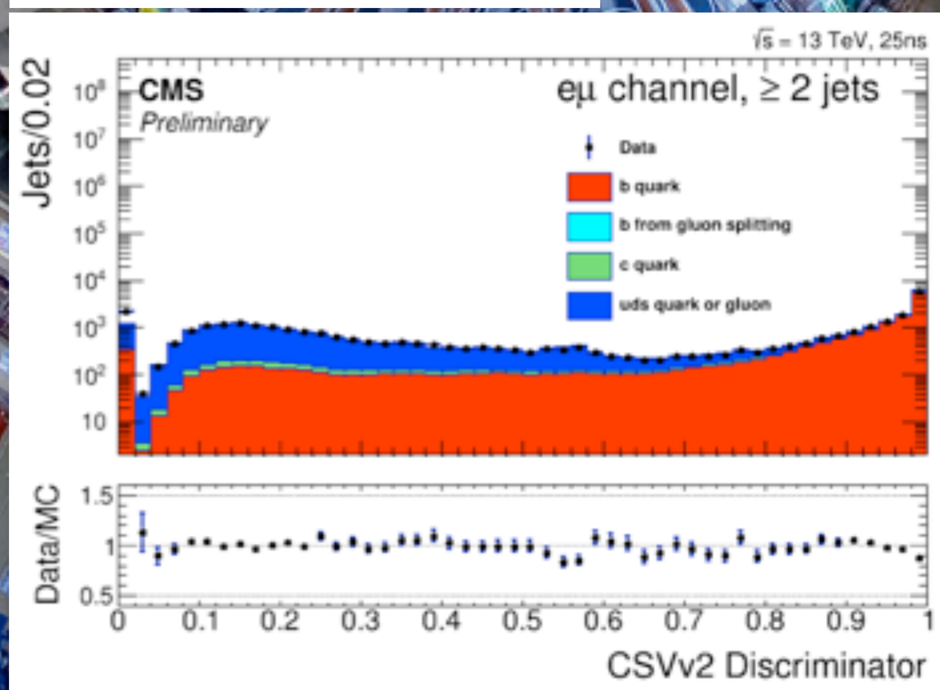
Excellent muon reconstruction



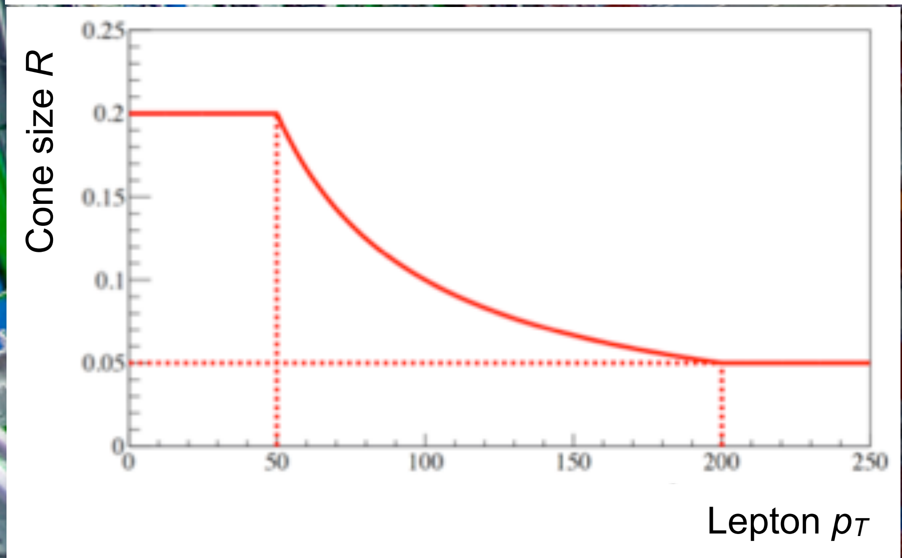
MET performace



Identification of b-jets



Improved efficiency for identifying isolated leptons from boosted tops



Analysis strategy

Exclusively binned signal regions (SR): categorise events by N_{jet}, $N_{b\text{-}jet}$, H_T, MET, ...

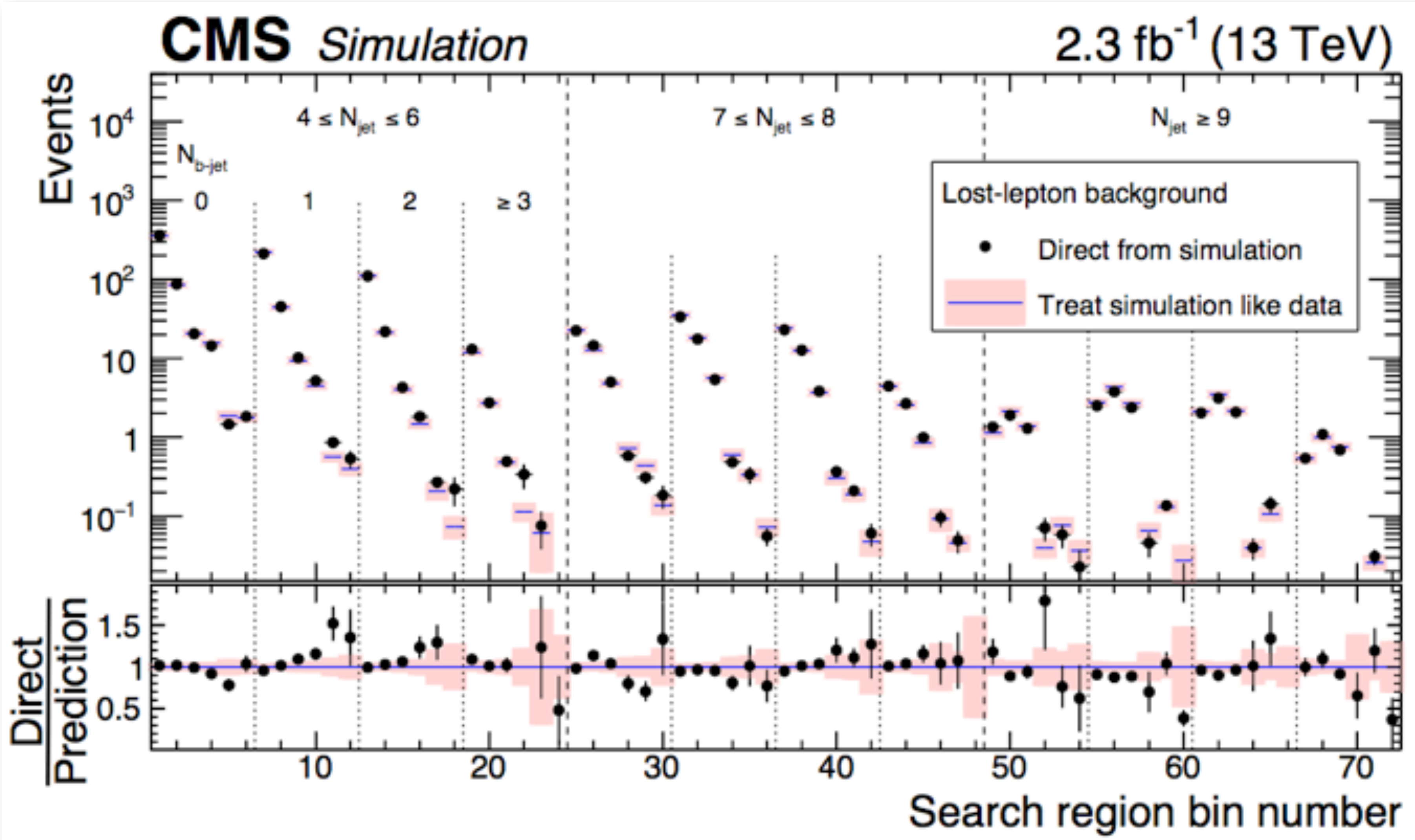
Data control regions (CR): “SR-like”, SM-enriched, multiple (redundancy)

SM background estimates: derive transfer factors from simulation to extrapolate

Uncertainties: statistical, non-closure of methods, experimental uncertainties, ...

Data validation regions (VR): “checks in SR phase space”, “data-driven systematics”

arXiv:1602.06581 [hep-ex]

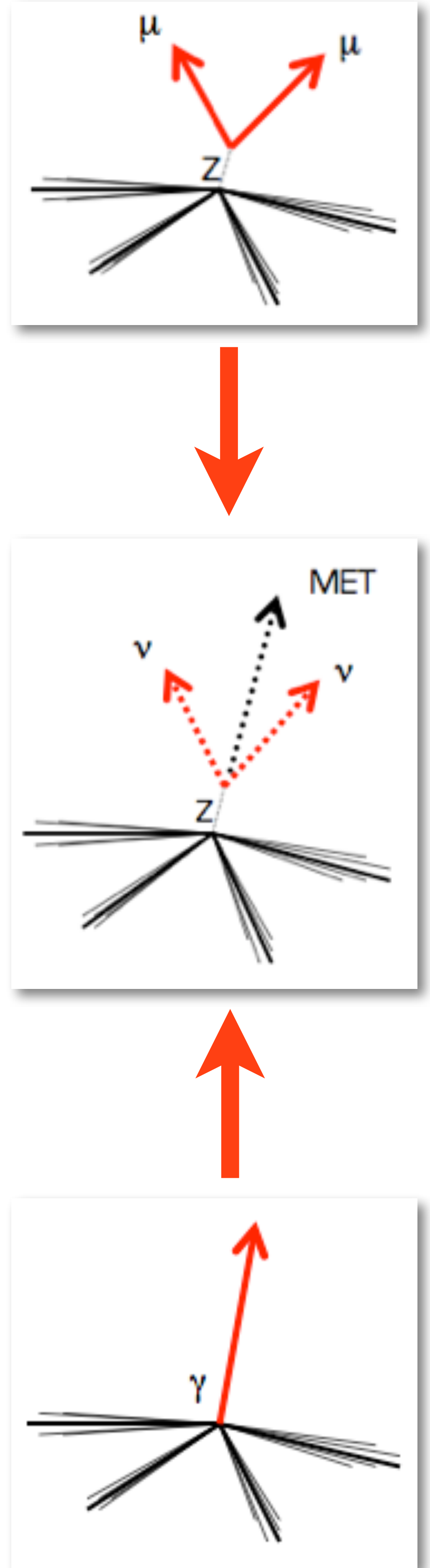


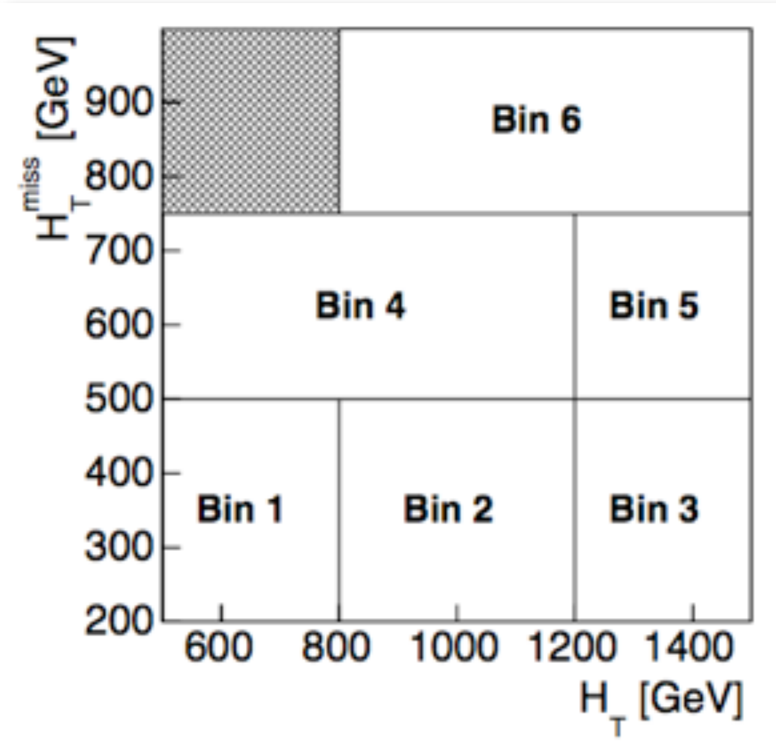
Friday, 11 March 16

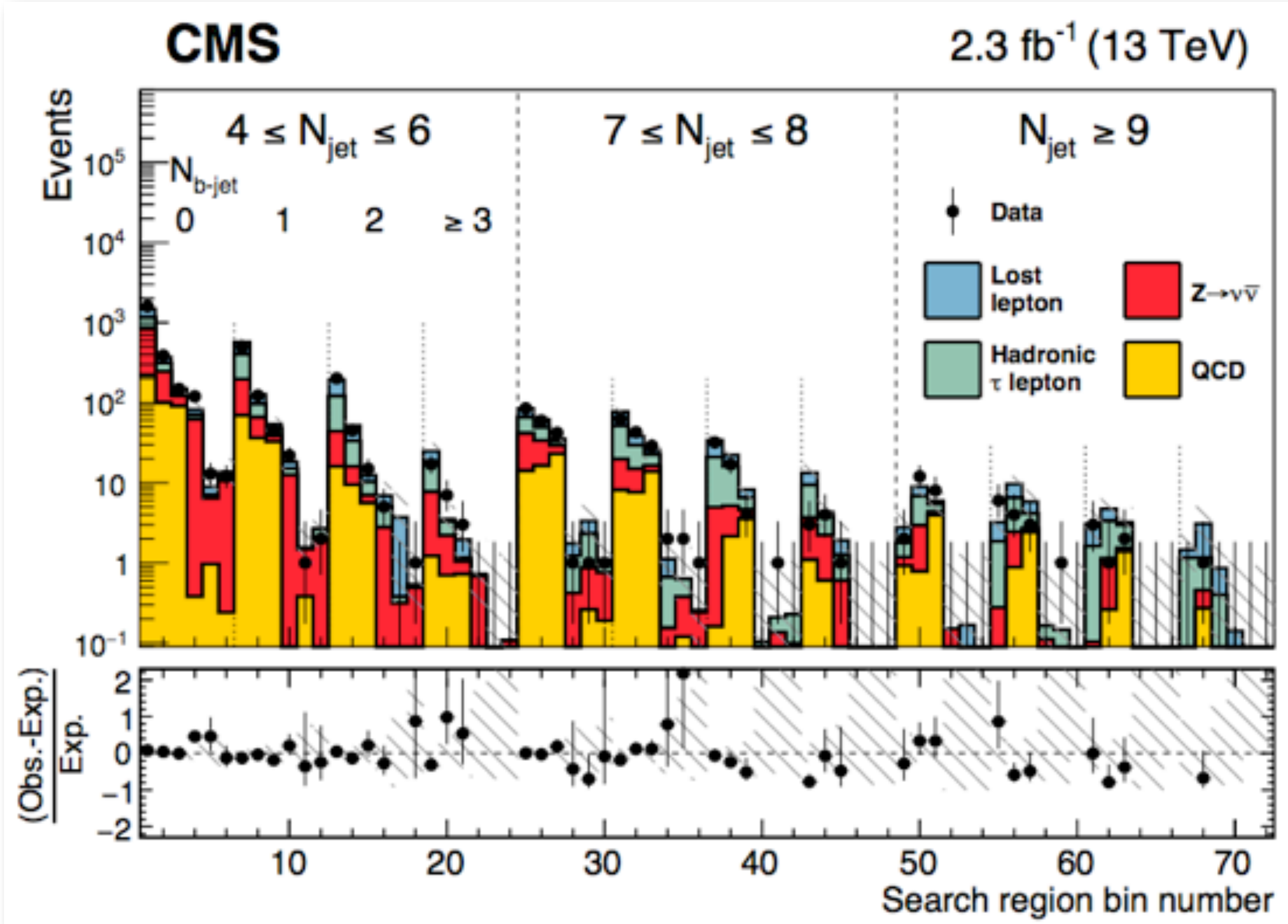
Search in 0L final state with the MHT variable

arXiv:1602.06581 [hep-ex]

- Sensitive to strongly produced SUSY and 3rd generation
- Binned signal region: N_{jet} (≥4), $N_{b\text{-}jet}$, H_T (>500 GeV), H_T^{miss} (>200 GeV)
- SM backgrounds: QCD, Z($\nu\nu$)+jets, tt and W+jets ("lost leptons")
- Multiple data control regions: (di-)lepton+jets, photon+jets
- QCD multijet: extrapolate in Δφ, validated in low MHT data sideband
- Largely statistically-limited in the tails (systematics-limited elsewhere)







Search in 0L final state with M_{T2} variable

CMS-PAS-SUS-15-003
CMS-PAS-SUS-16-004

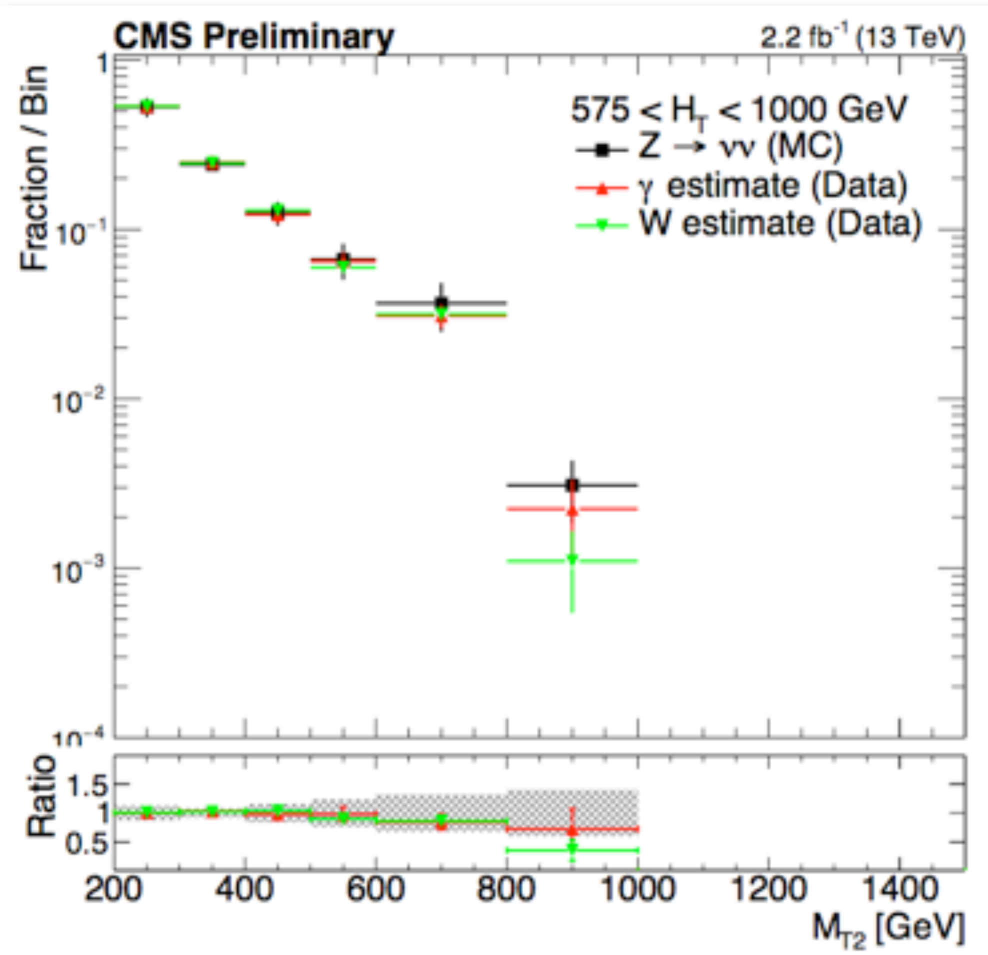
Sensitivity to strongly produced SUSY, including compressed scenarios

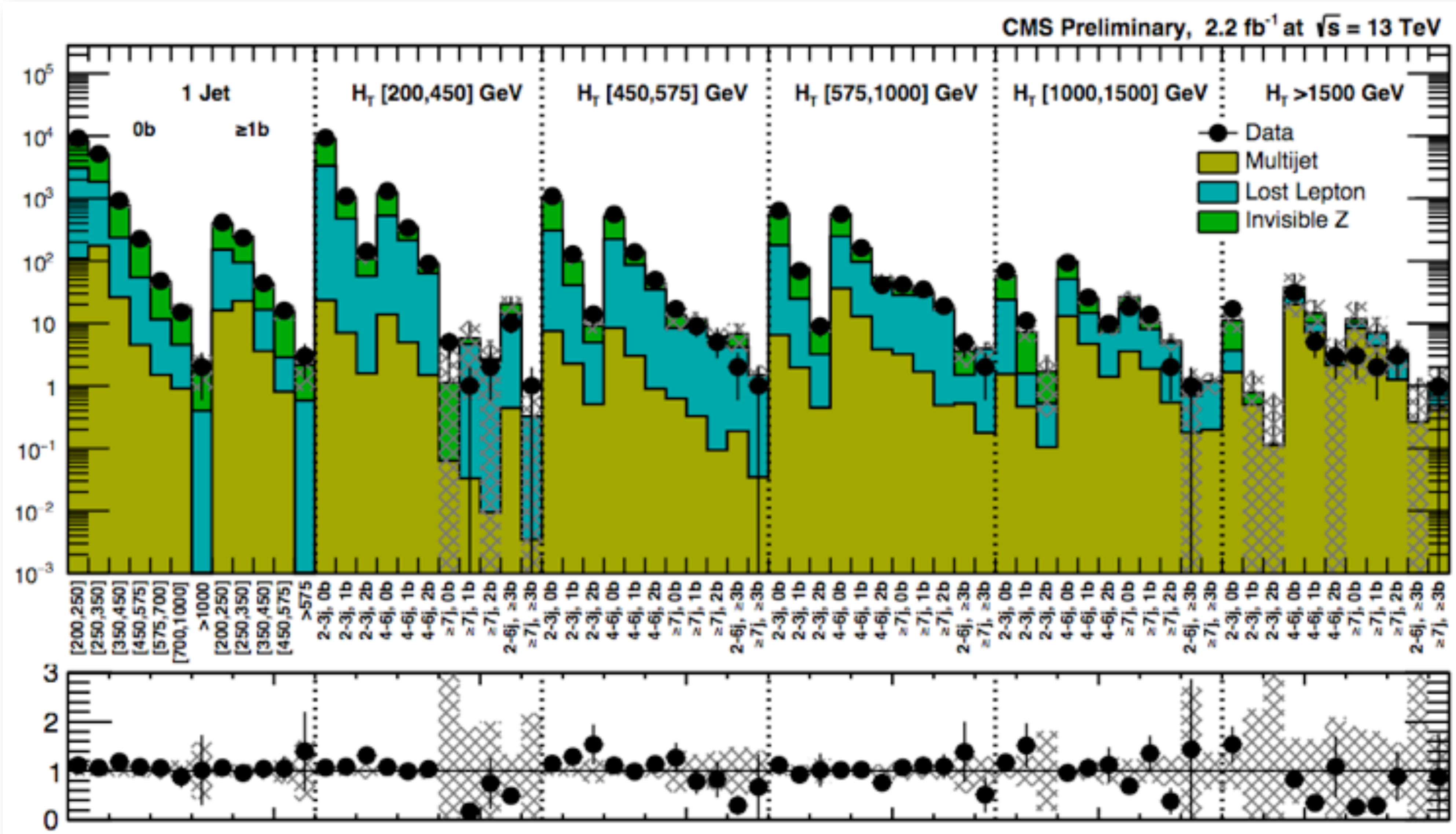
Low thresholds, high acceptance,: H_T > 200 GeV, $N_{jet} \geq 1$ (i.e. monojet topology)

Signal region binned in N_{jet}, $N_{b\text{-}jet}$, H_T and stransverse mass, MT2

MT2 shape taken from simulation, extensive use of data validation regions

$$M_{T2}(m_{\tilde{\chi}}) = \min_{\vec{p}_T^{\,\tilde{\chi}(1)} + \vec{p}_T^{\,\tilde{\chi}(2)} = \vec{p}_T^{\,\text{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$





Search in 0L final state with the α_T variable

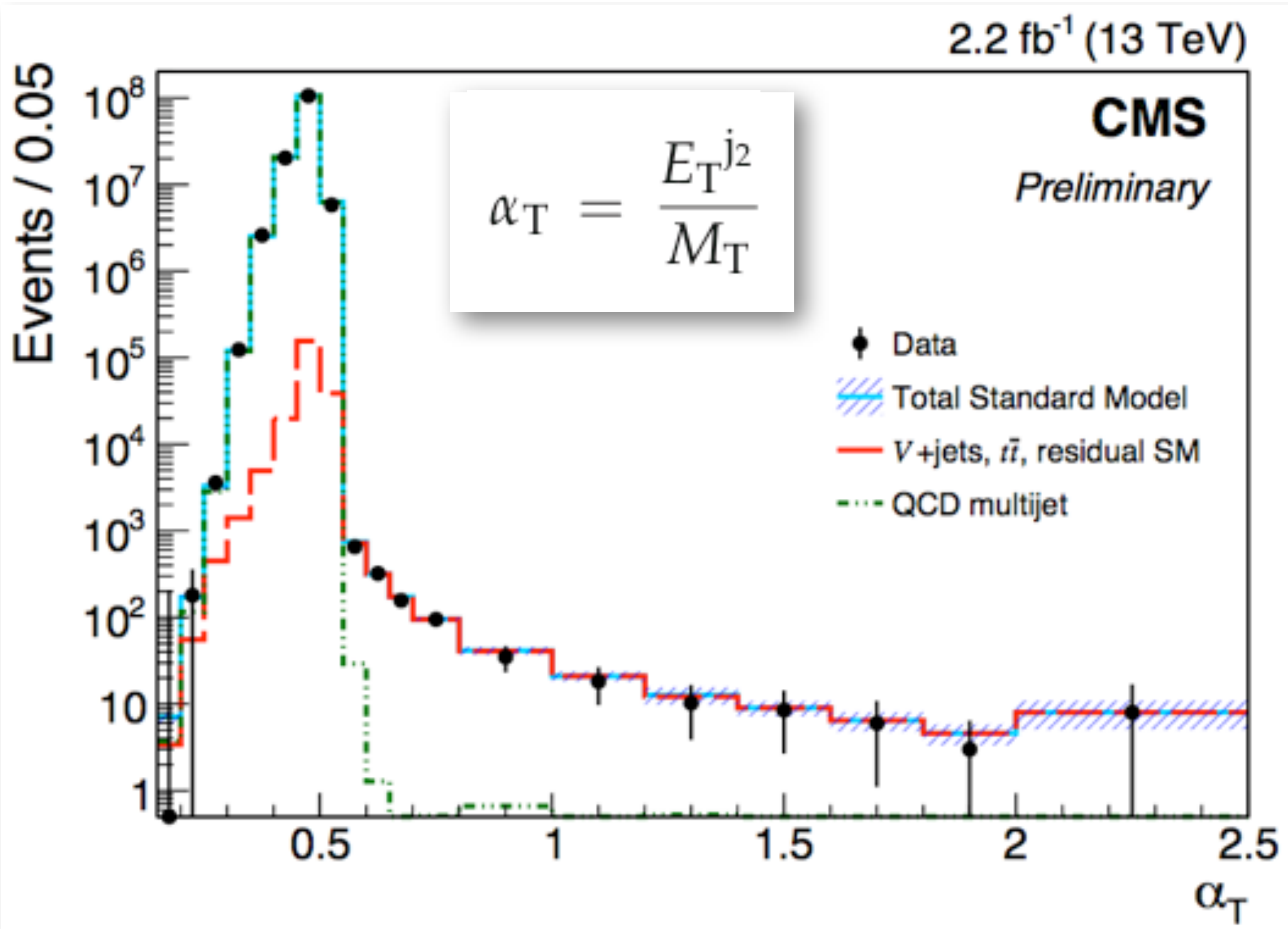
CMS-PAS-SUS-15-005
CMS-PAS-SUS-16-004

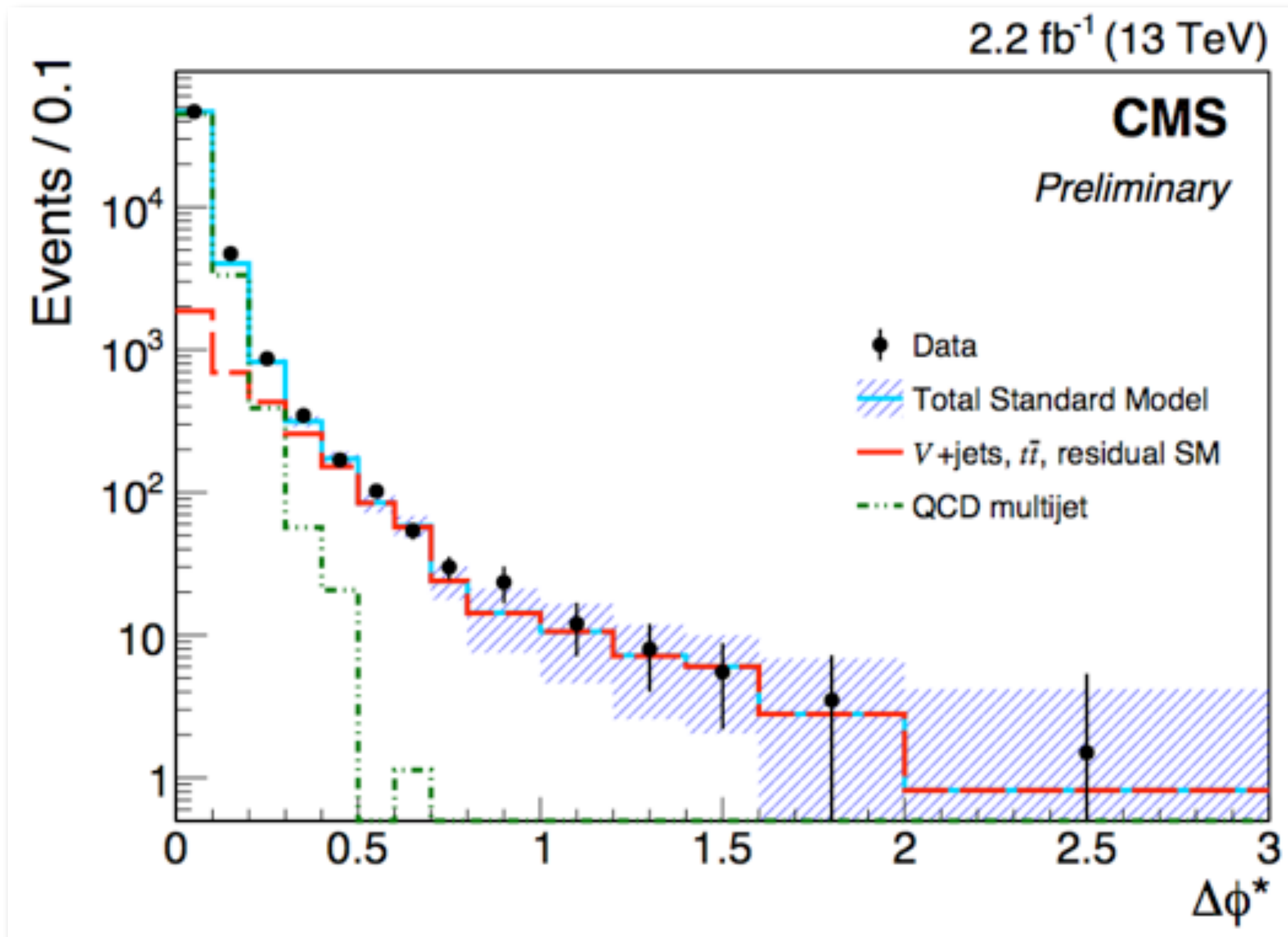
Sensitivity broad range of SUSY models, including compressed scenarios

Emphasis on suppression of QCD multijet to %-level (w.r.t. tt, V+jets) for all SR bins

- α_T: multijet events containing jet energy mismeasurements
- "biased" $\Delta\phi$: over/under-measurements + semi-leptonic heavy flavour decays
- H_T^{miss}/MET: ensures soft jets below threshold do not contribute significantly to H_T^{miss}
- Instrumental: control variables to check for localised instrumental effects in (η,ϕ)

Heavy reliance on data control and validation regions: checks, derive systematics





Search in 1L final state with the MJ variable

CMS-PAS-SUS-15-007
CMS-PAS-SUS-16-004

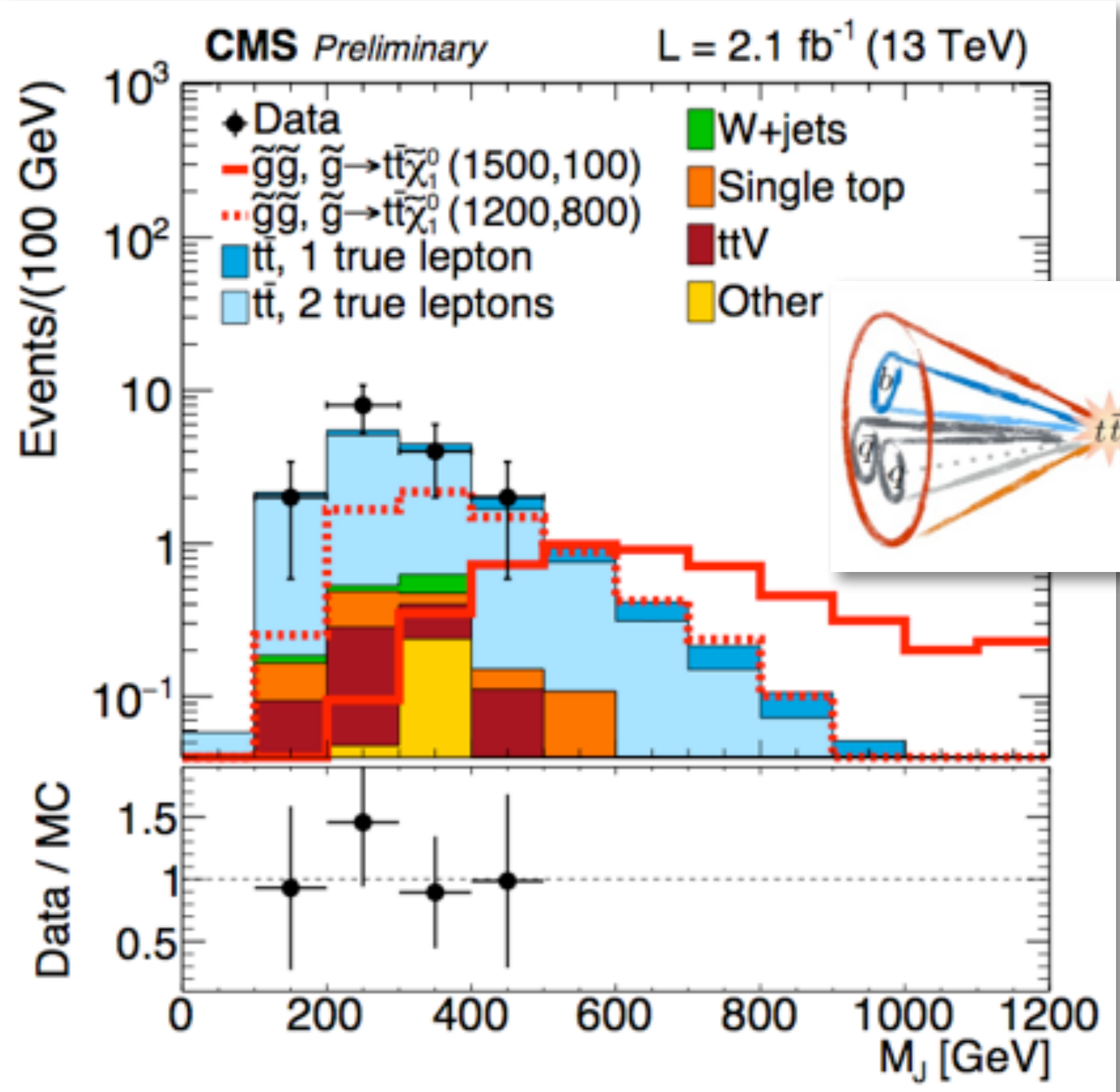
Targets gluino-mediated stop production

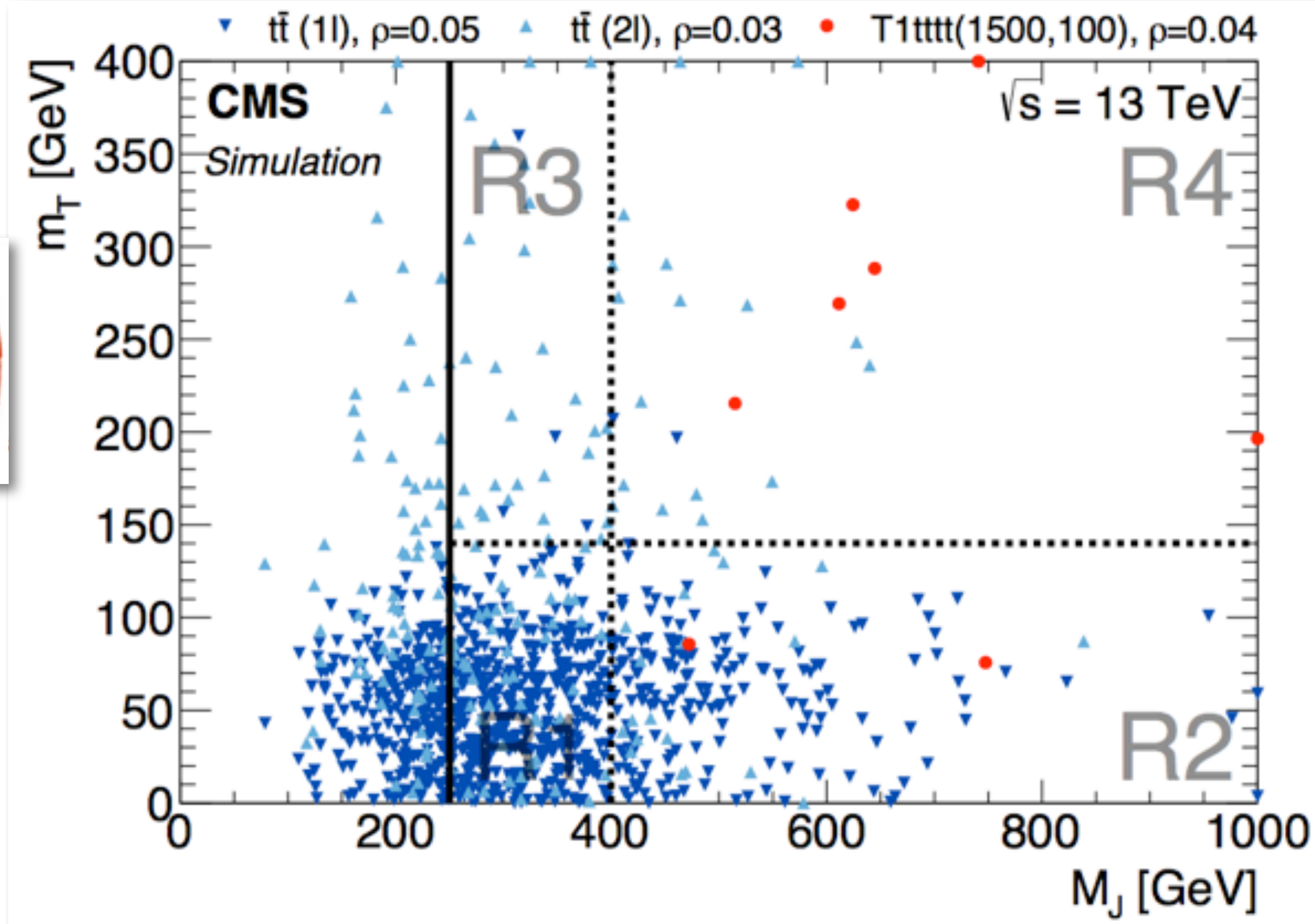
MJ: sum of masses of large-cone jets (R=1.2), inputs are calibrated AK4 jets

Large MJ from decays of boosted heavy objects (e.g. tops from gluino decay)

MJ and MT are weakly correlated, use ABCD method; SR binned in N_{jet}, $N_{b\text{-}jet}$, MET

SM bkgd: di-leptonic tt, checks and systematics from 2L data validation region

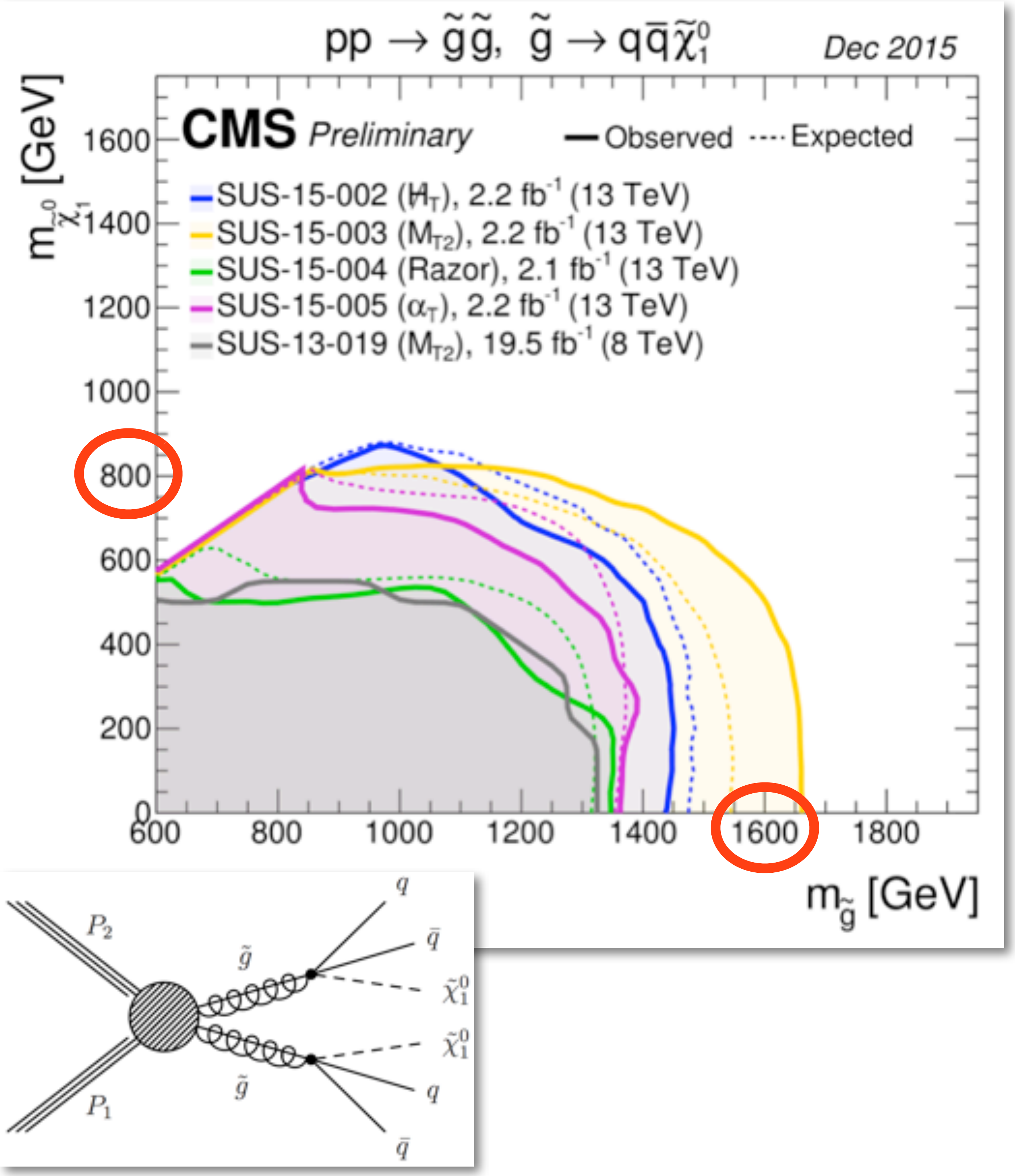


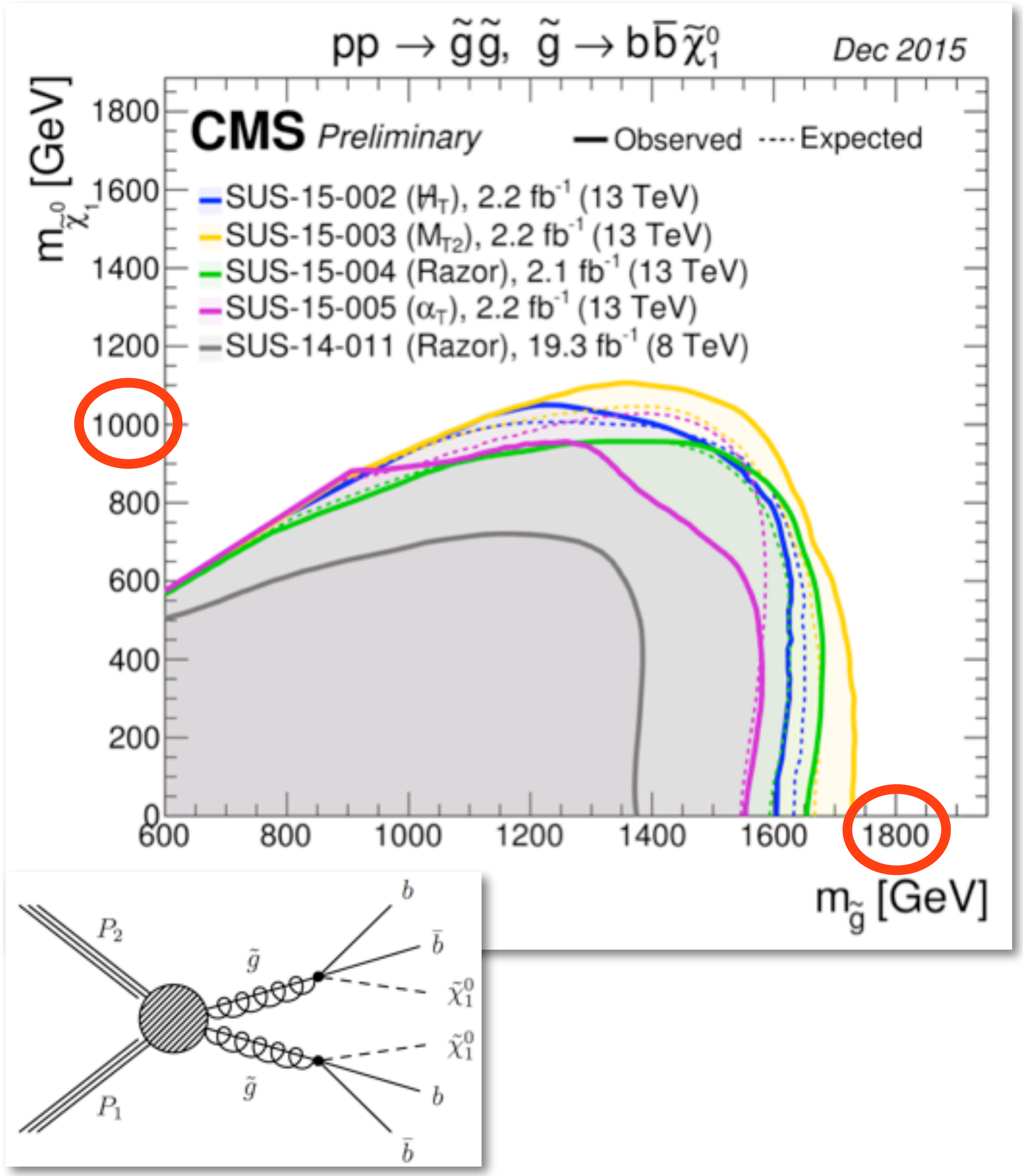


Gluino-mediated (off-shell) squark production

Data compatible with SM expectations for all relevant search regions → limits

Improved reach of up to ~350 GeV in m_{gluino} **and** m_{LSP} w.r.t. 8 TeV

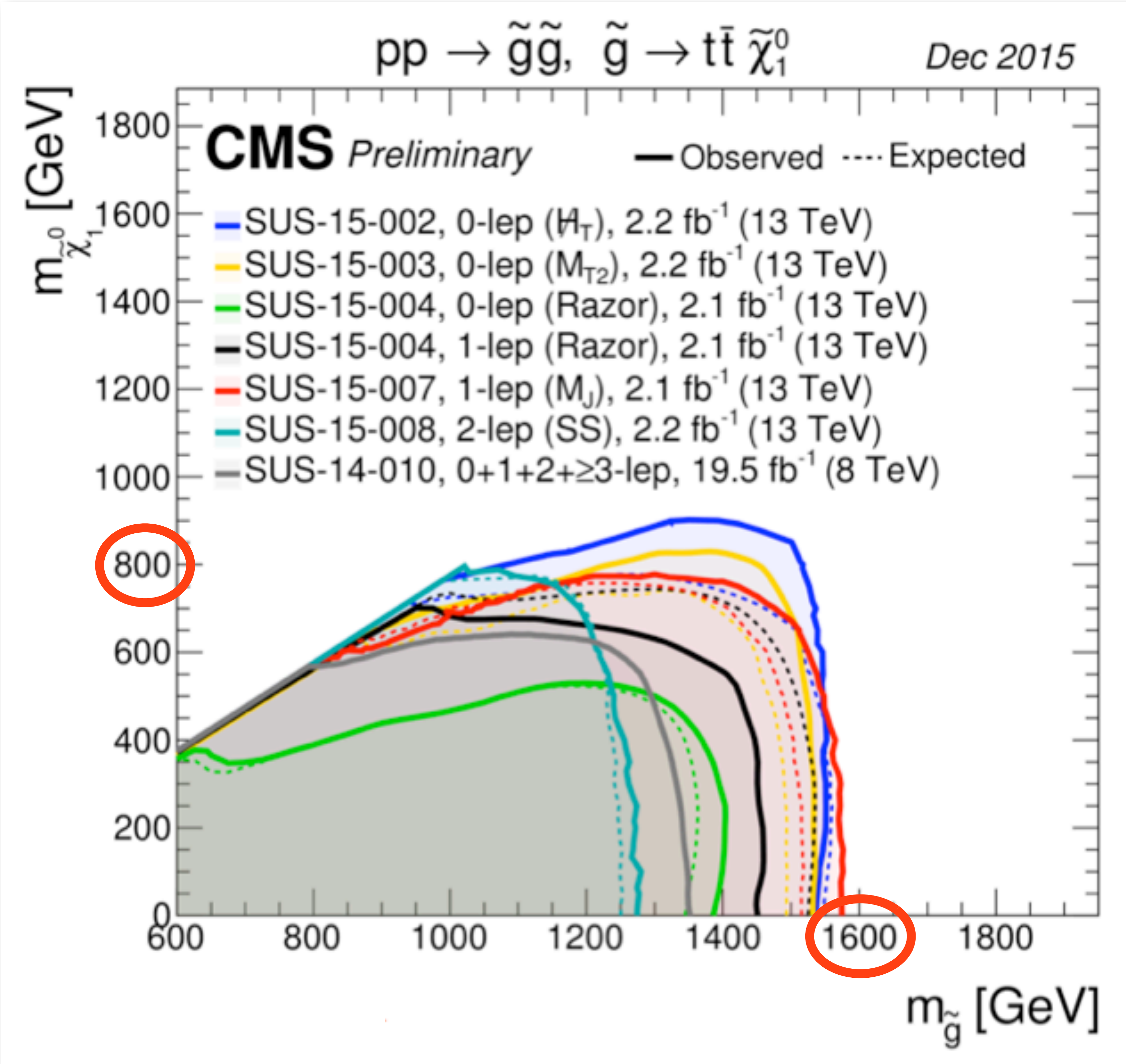




Gluino-mediated (off-shell) stop production

Data compatible with SM expectations for all relevant search regions → more limits

Extended reach of ~250 GeV in m_{gluino} **and** m_{LSP} w.r.t. 8 TeV

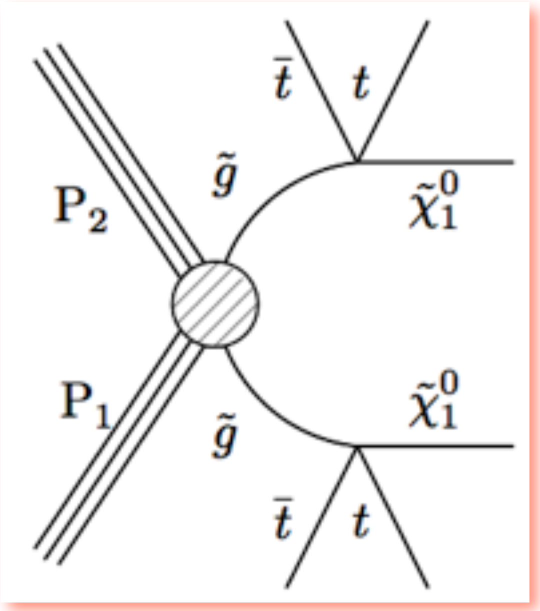


Gluino-mediated (on-shell) stop production

CMS-PAS-SUS-15-007
CMS-PAS-SUS-16-004

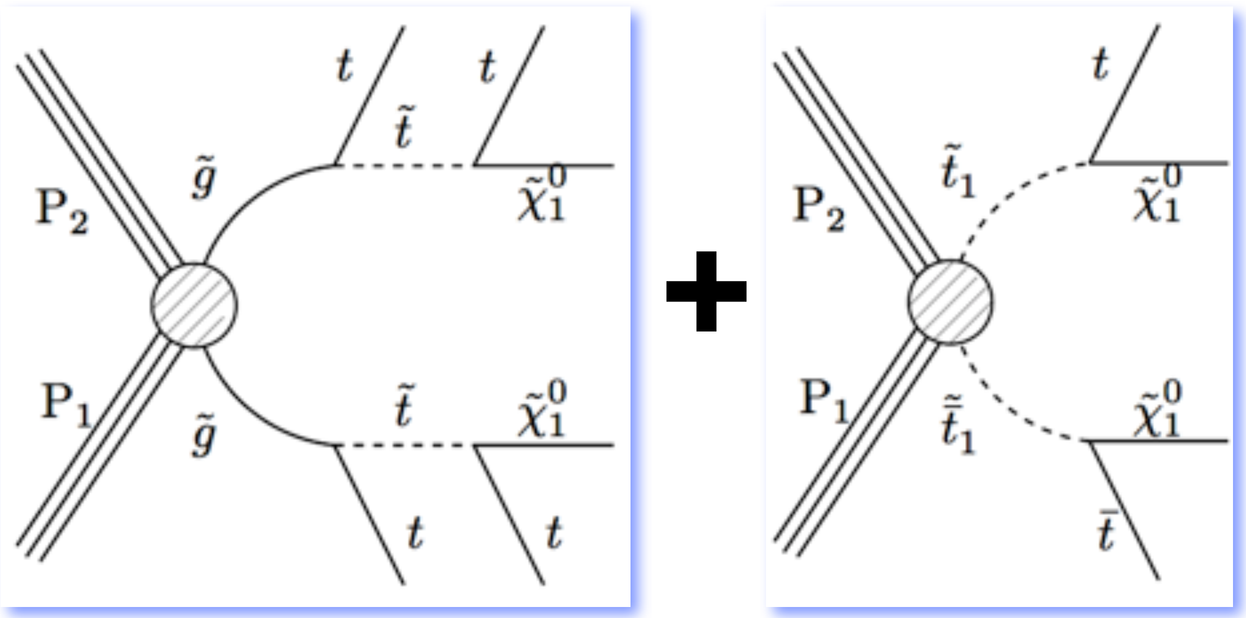
1L final state → competitive reach due to presence of four W bosons

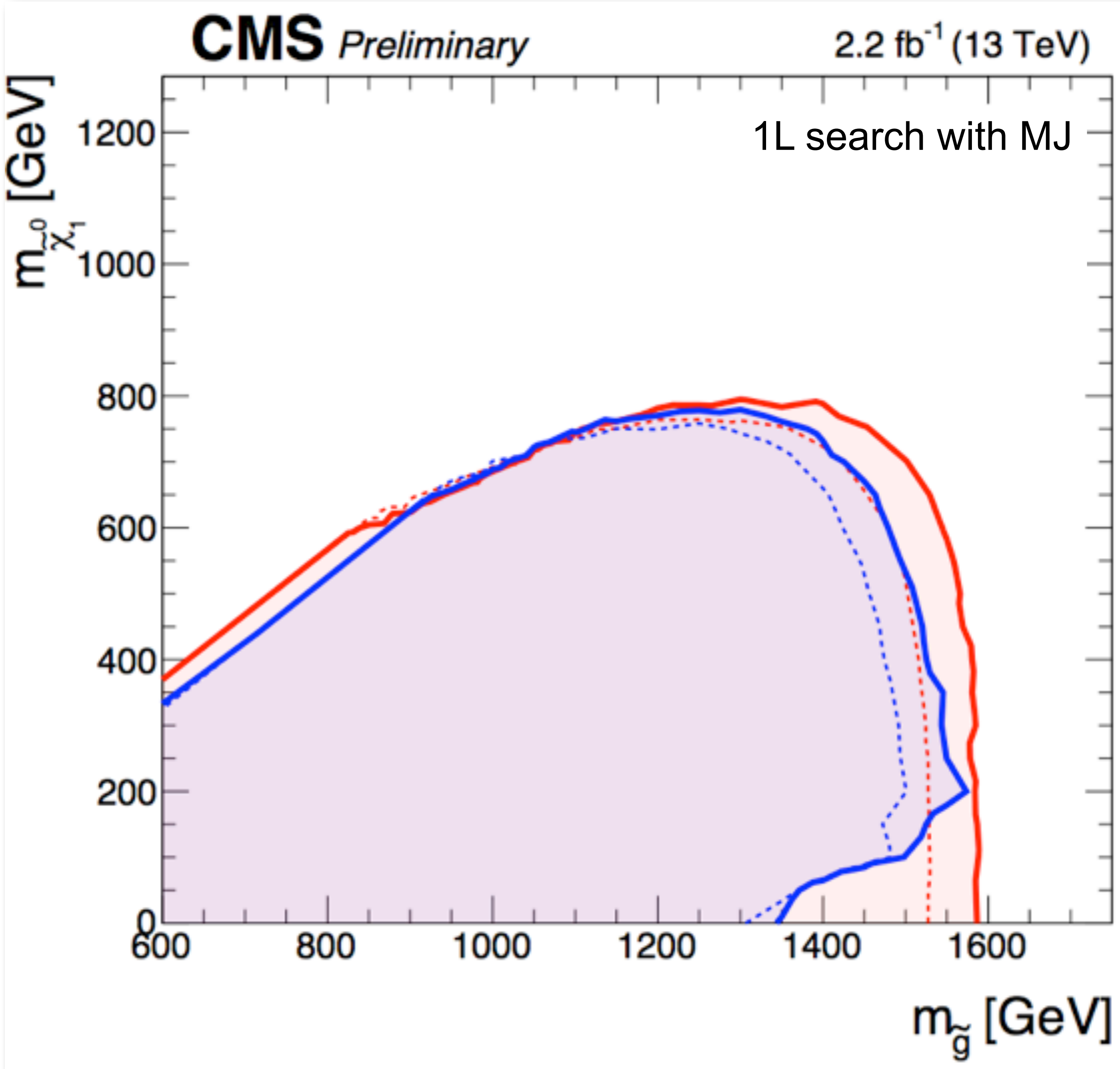
Similar reach in m_{gluino} for decays via off-shell and on-shell stops



Gluino-mediated off-shell stop production

Direct and gluino-mediated on-shell stop production with m_{gluino} - m_{stop} = 175 GeV





Direct pair-production of squarks

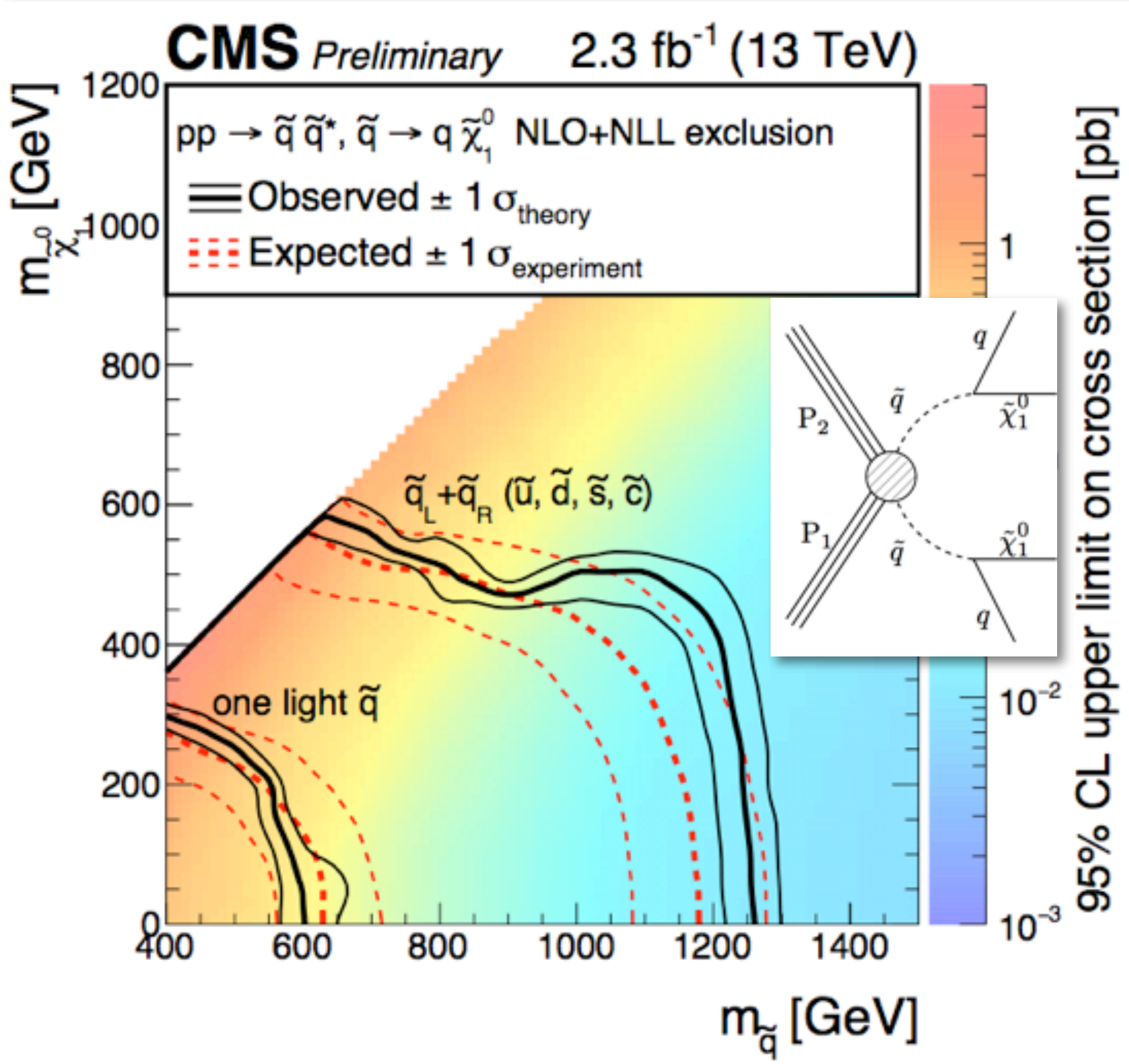
CMS-PAS-SUS-15-003
CMS-PAS-SUS-16-004

Mass-degenerate squarks: ~300 GeV increase in m_{squark} **and** m_{LSP} (w.r.t. 8 TeV)

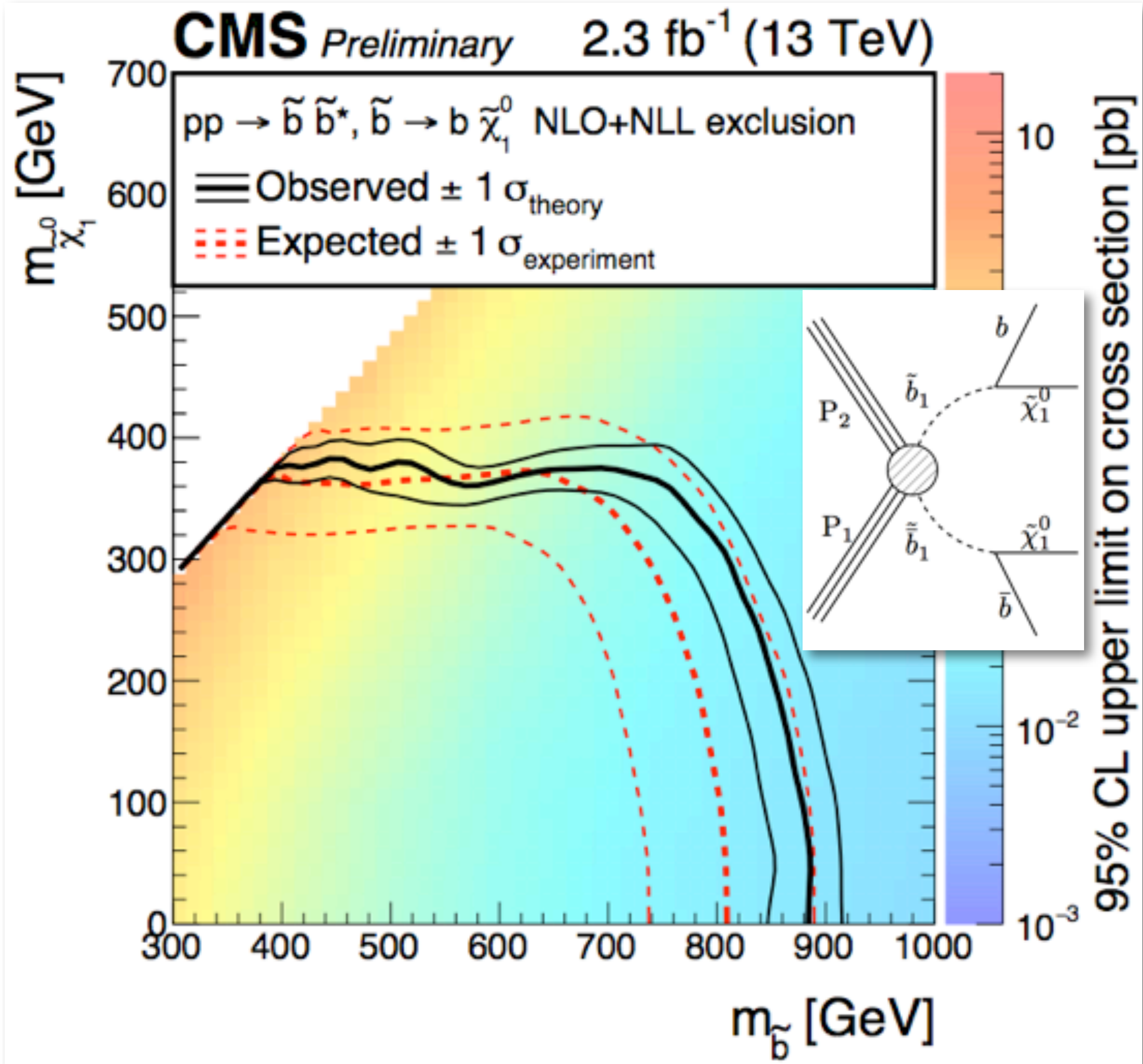
Single light squark: comparable limits, difficult region

Sbottom: ~200 GeV increase (obs.) in $m_{sbottom}$, ~100 GeV gain in m_{LSP}

0L search with MT2



0L search with MT2



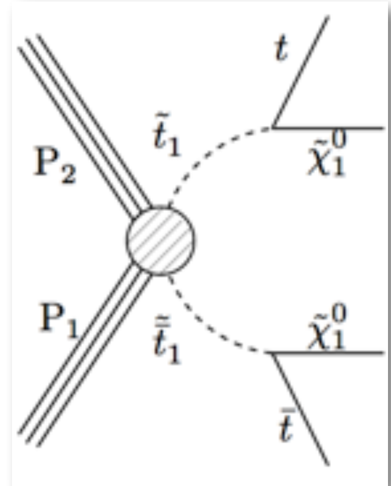
Direct pair-production of stops

CMS-PAS-SUS-16-004

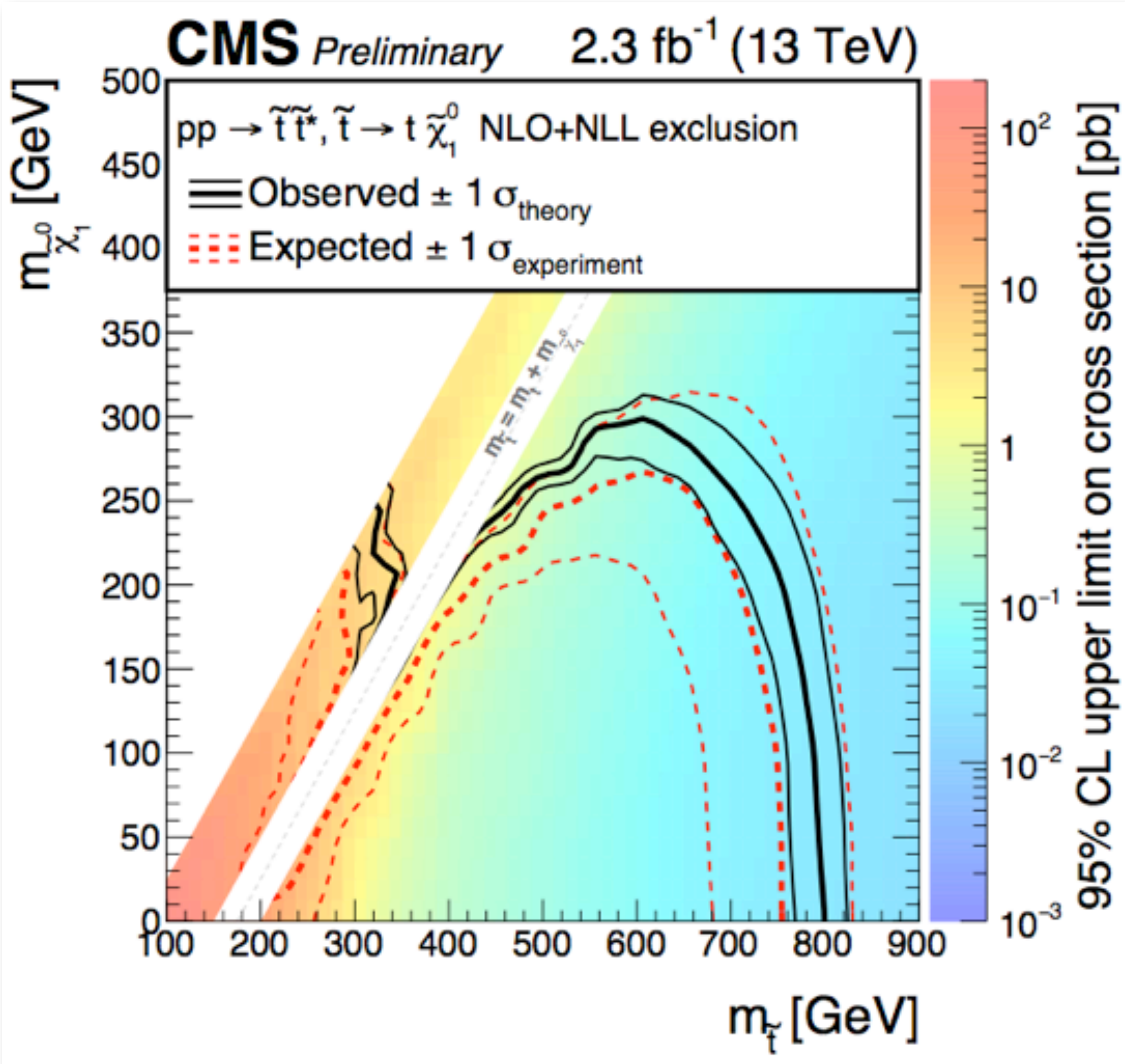
2-body decay: slightly stronger limits, up to m_{LSP} ~300 GeV (w.r.t. 8 TeV)

3-body decay: ~50 GeV increase, up to m_{LSP} ~250 GeV

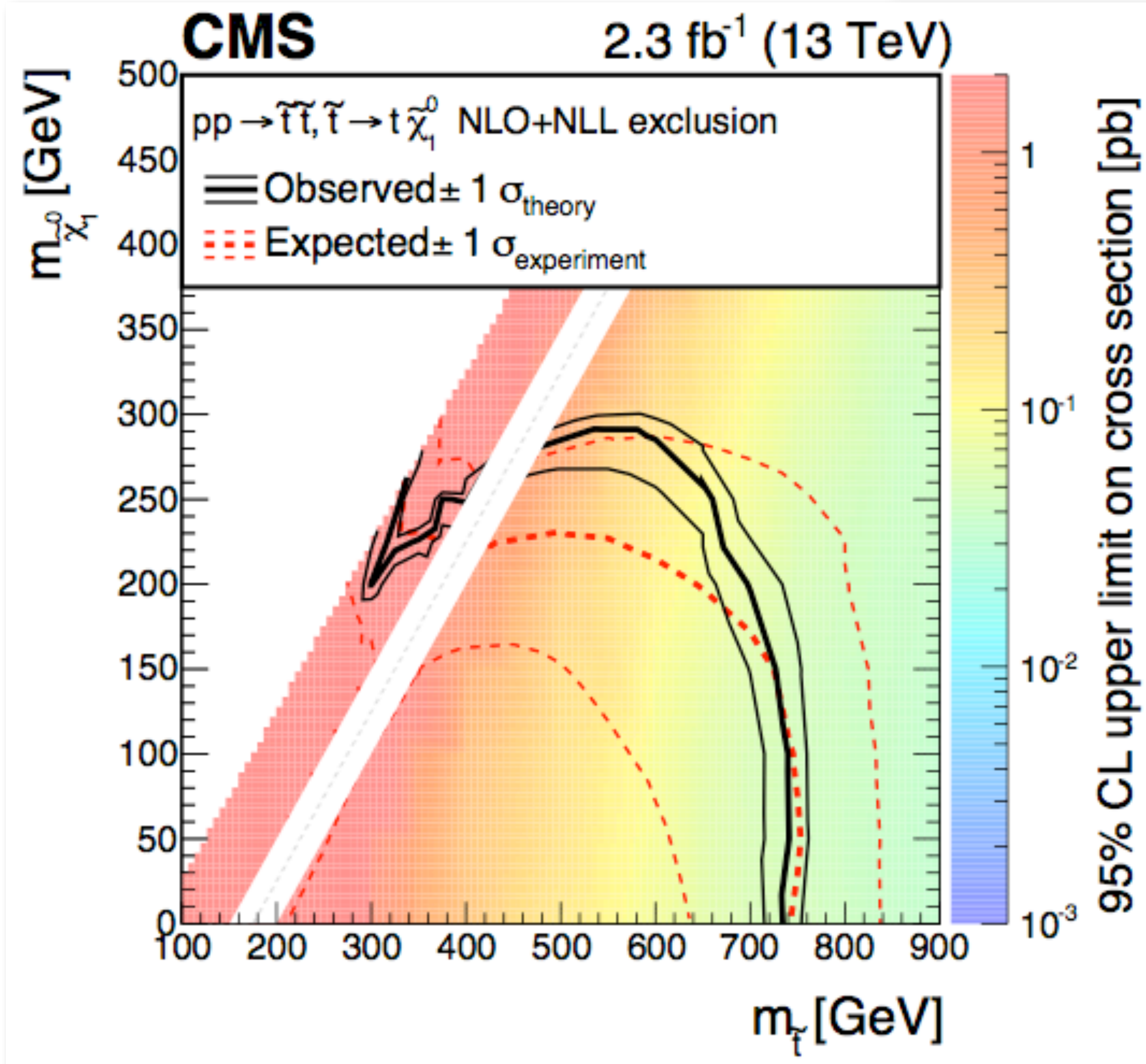
"Top corridor" ($\Delta m \approx m_{top}$) to be studied in more detail, results soon



0L search with MT2



0L search with MHT



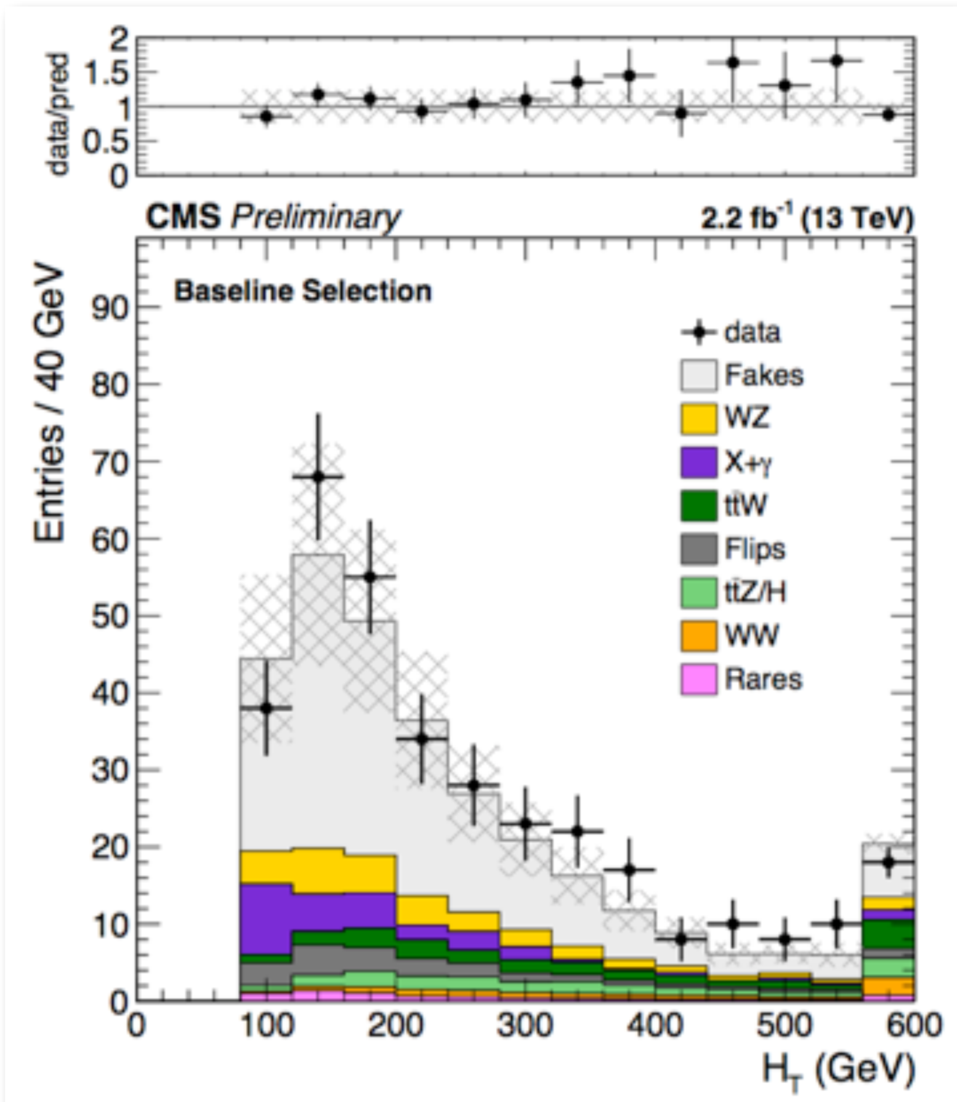
Same-sign di-lepton final state

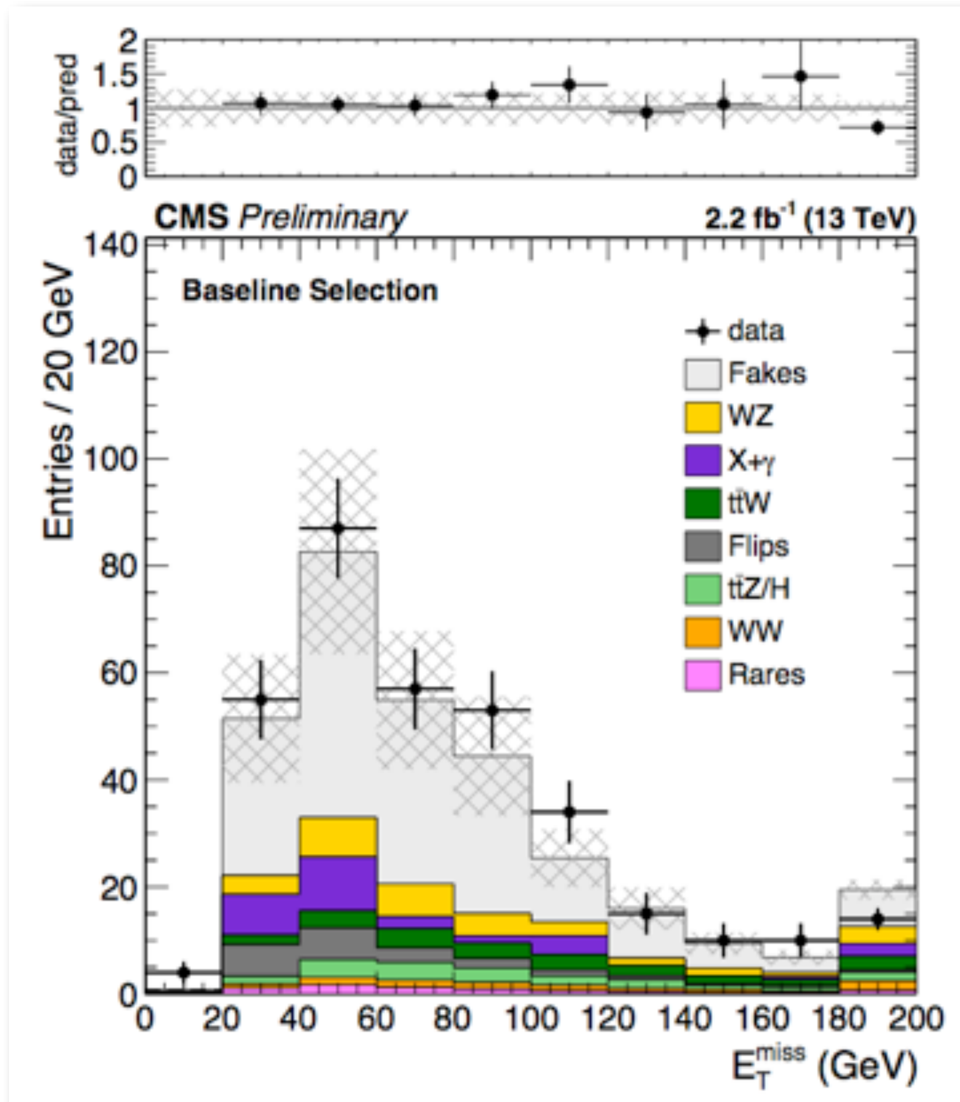
Sensitivity to range of SUSY scenarios with very low SM backgrounds

Clean final state, low thresholds on HT and E_T^{miss}

- Fake / non-prompt leptons (jet mis-ID, HF decay, γ conversion): use multijet-enriched CR
- WZ (normalisation from CR), ttW (from simulation)
- Charge flipping for electrons: use $Z/\gamma^* \to e^+e^-$ CR

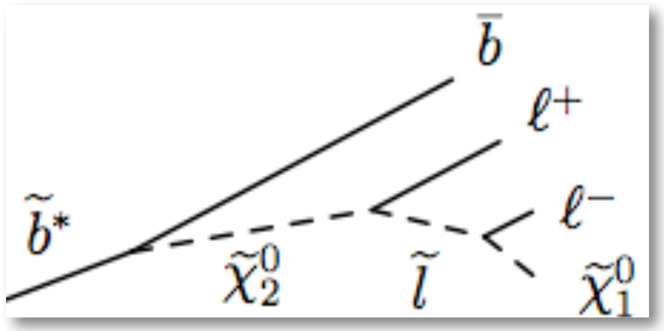
Binned signal region: HT, MET, M_T^{min}, $N_{b\text{-}jet}$, lepton pT (15-25, >25 GeV)

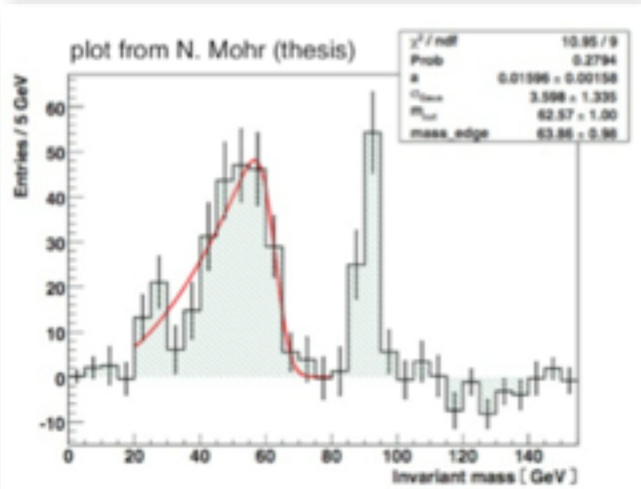


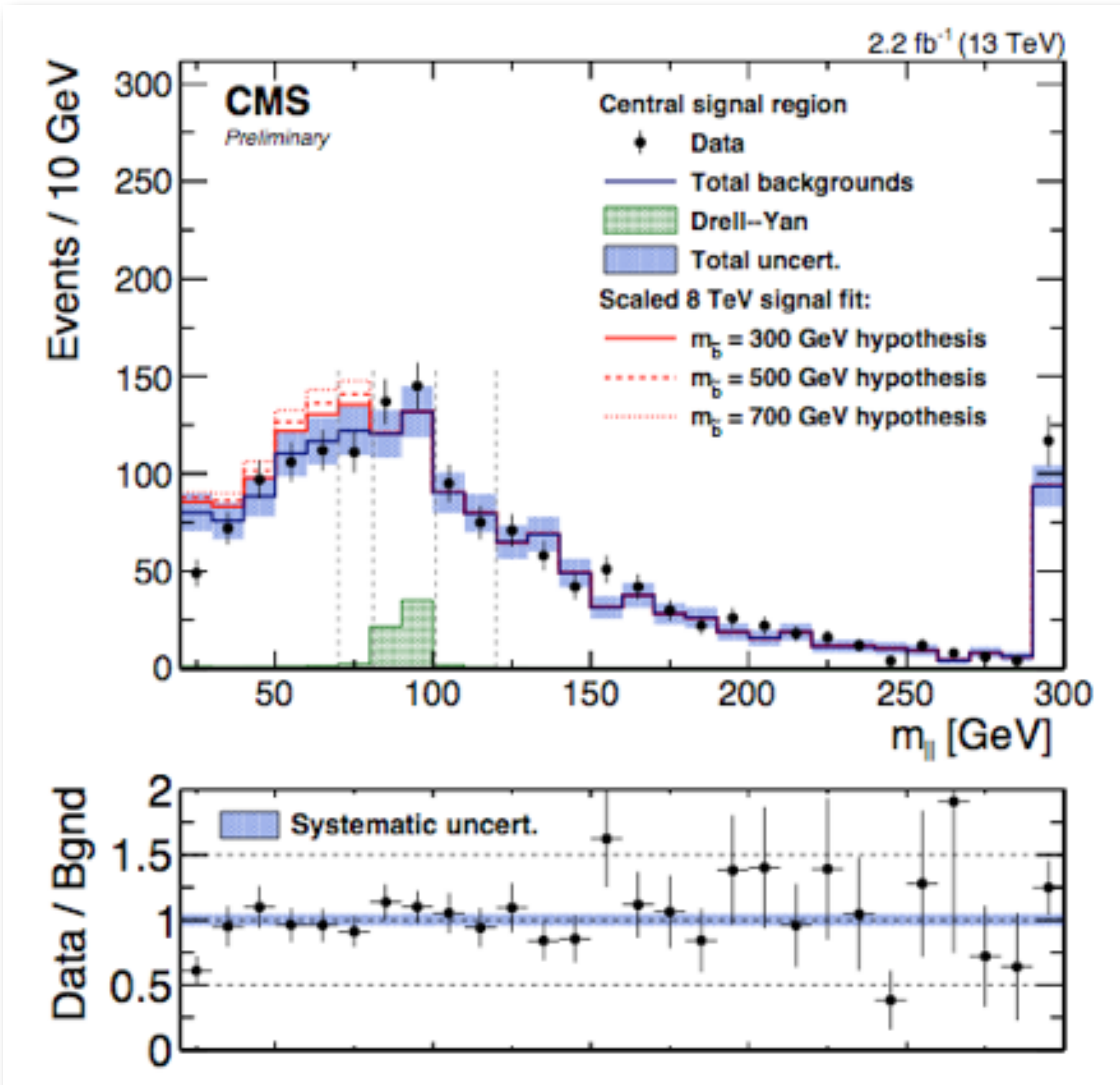


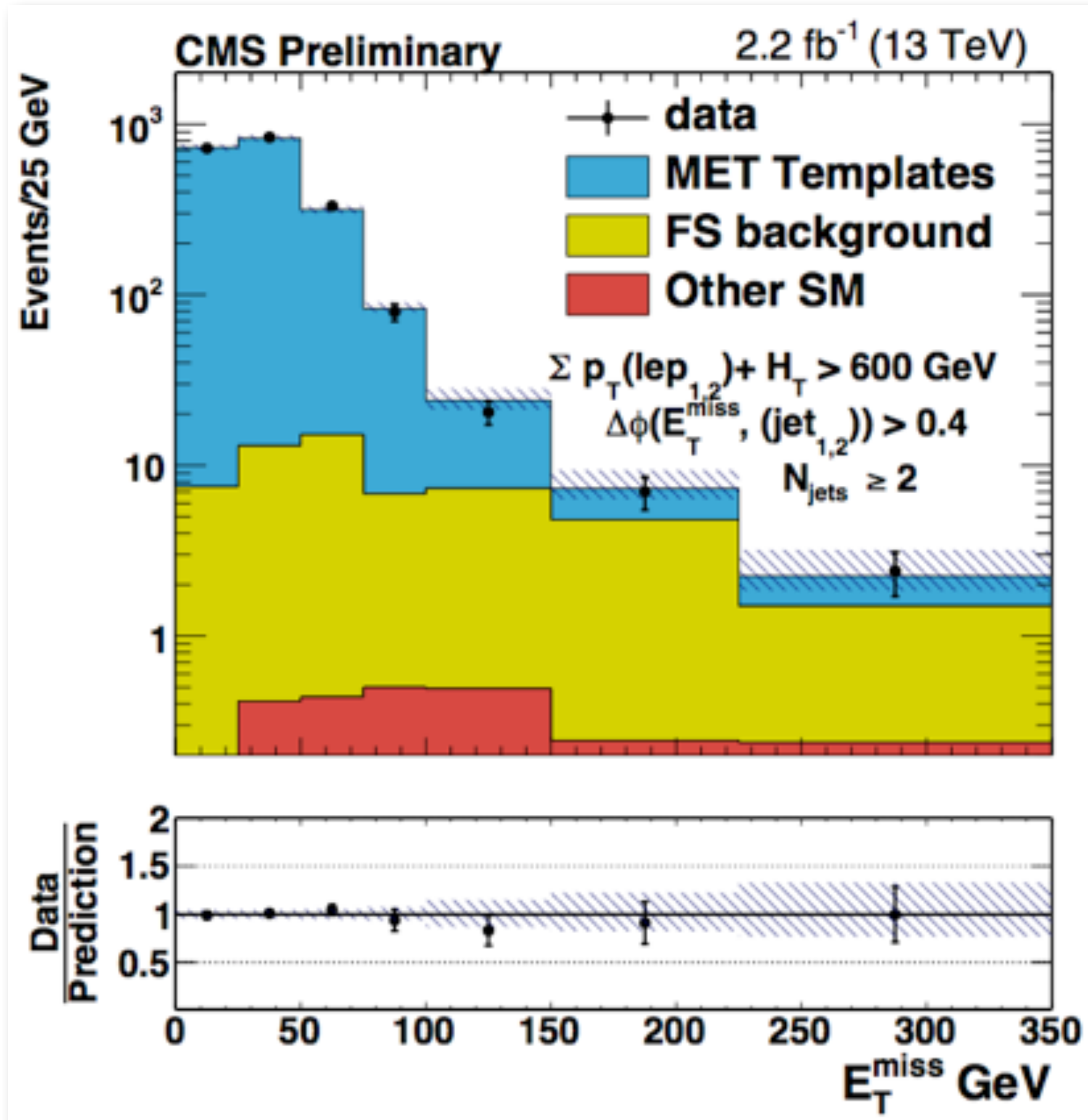
"Edge/Z": opposite-sign di-lepton final state

- Search in m(ℓℓ) for enhanced Z peak or kinematic edge, or enhanced MET tail
- Minor analysis updates w.r.t. 8 TeV (added $N_{b\text{-jet}}$ bins, finer N_{jet} and MET binning)
- SM bkgds: "fake" MET from DY+jets (templates from γ+jets), MET from tt (eμ CR)
- CMS "edge" signal hypothesis @ 8 TeV (2.6σ): disfavoured @ 13 TeV
- New "ATLAS-like" SR: no excess observed (ATLAS: 3σ @ 8 TeV, 2.2σ @ 13 TeV)







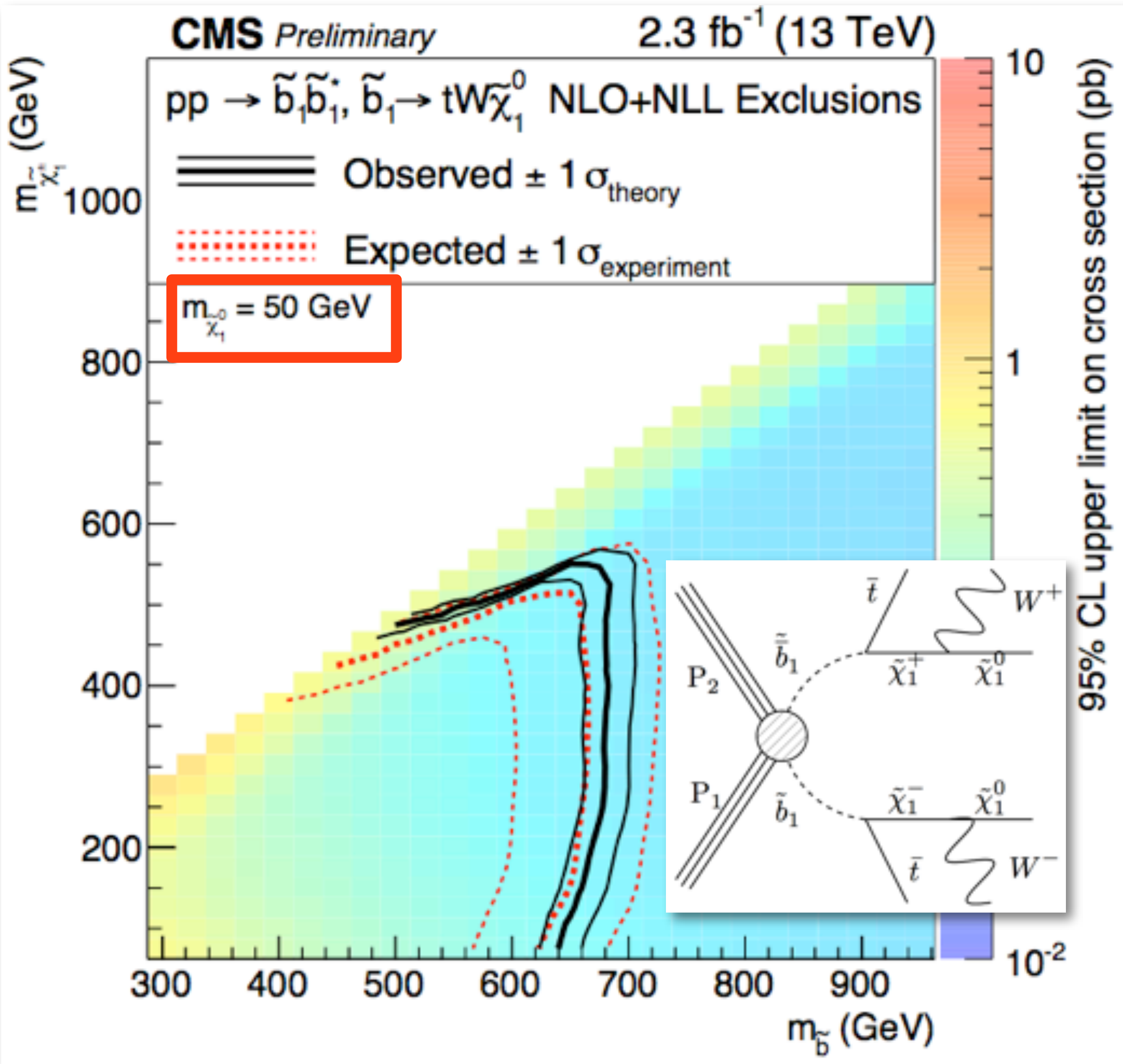


Sbottom pair-production + decays via $\chi^{\pm}$ / χ^{0}

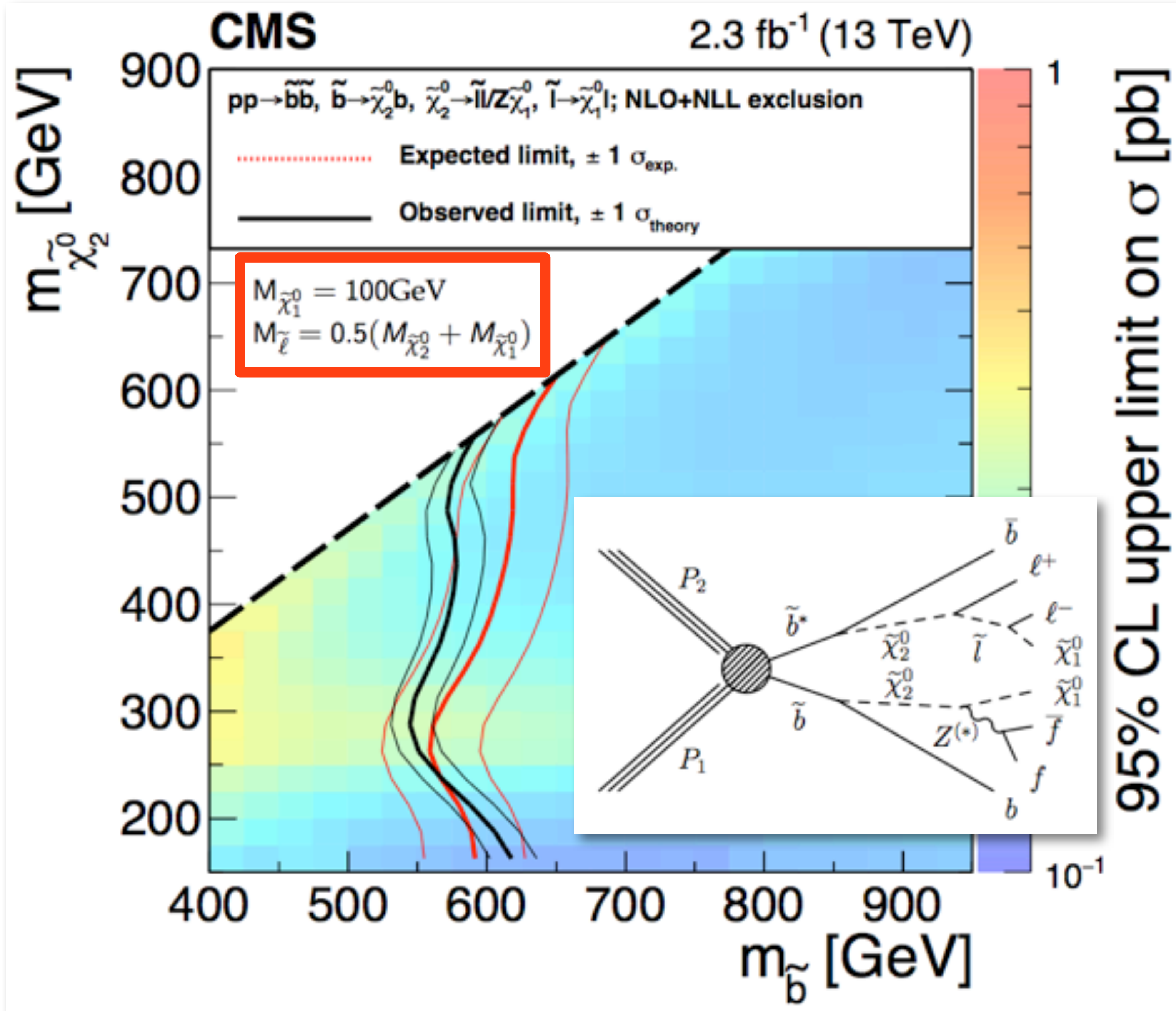
$\tilde{b} \rightarrow t\,\chi^{\pm}$, then $\chi^{\pm} \rightarrow W^{(*)}\,\chi_1^{0}$ (100% BR)

$\tilde{b} \rightarrow b\,\chi_2^{0}$, then $\chi_2^{0} \rightarrow Z^{(*)}\,\chi_1^{0}$ (50% BR) or $\chi_2^{0} \rightarrow \ell\tilde{\ell} \rightarrow \ell\ell\chi_1^{0}$ (12.5%, $e^{\pm}$,$\mu^{\pm}$)

Same-sign di-lepton search



"Edge/Z" search



Concluding remarks

Several preliminary results based on 2.2 fb^{-1} @ 13 TeV

- Limits extended significantly for (m_{gluino},m_{LSP}), moderately for (m_{squark},m_{LSP})
- No excess @ 13 TeV in “Edge/Z” dilepton search, in both off-Z or on-Z regions

Is the Natural parameter space under duress?...

Many new analyses will arrive very soon:

- e.g. $\Delta\varphi$ (1L), multi-leptons, dedicated stop searches in 0L and 1L channels, ...
- https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html

Next challenges: compressed SUSY, EWino sector, RPV, long-lived, ...

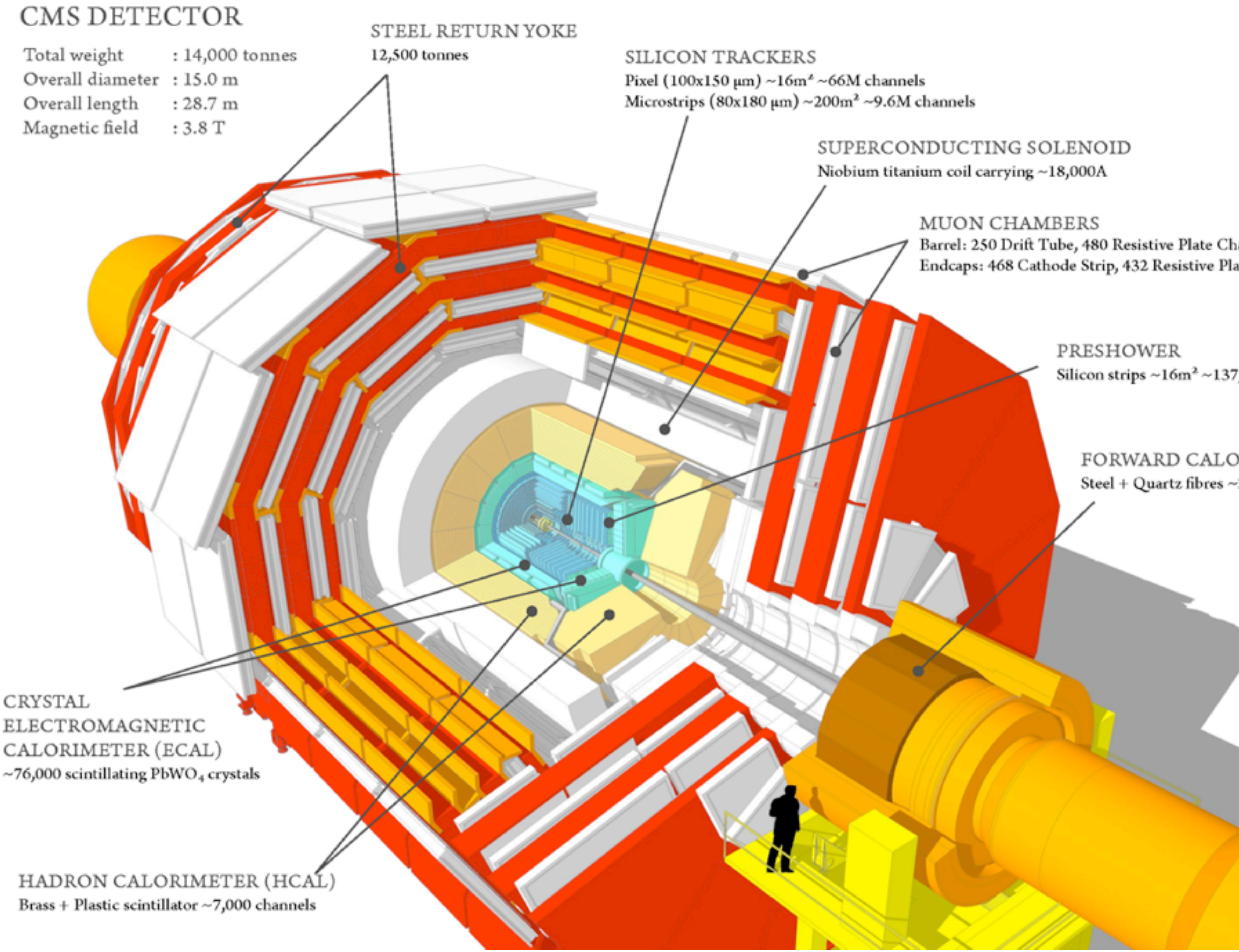
Expect significantly larger data set in 2016 (20-30 fb^{-1})

- Challenge will be to maintain $A \times \varepsilon$, relevant for the more difficult regions

Thank you for your attention!

Additional material

The CMS detector



Search strategy, interpretations

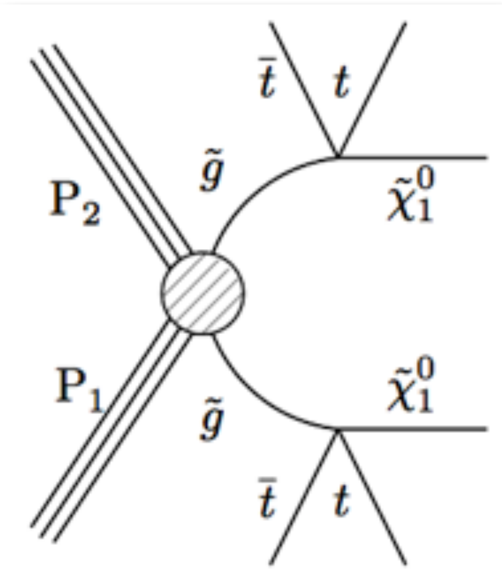
Early "inclusive" topology-orientated searches, covering different final states

Targeted searches and combinations on longer timescales

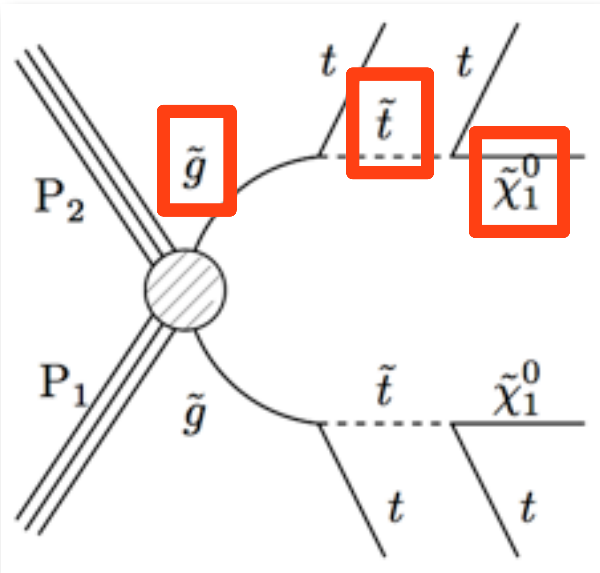
Interpretations with Simplified Models, e.g:

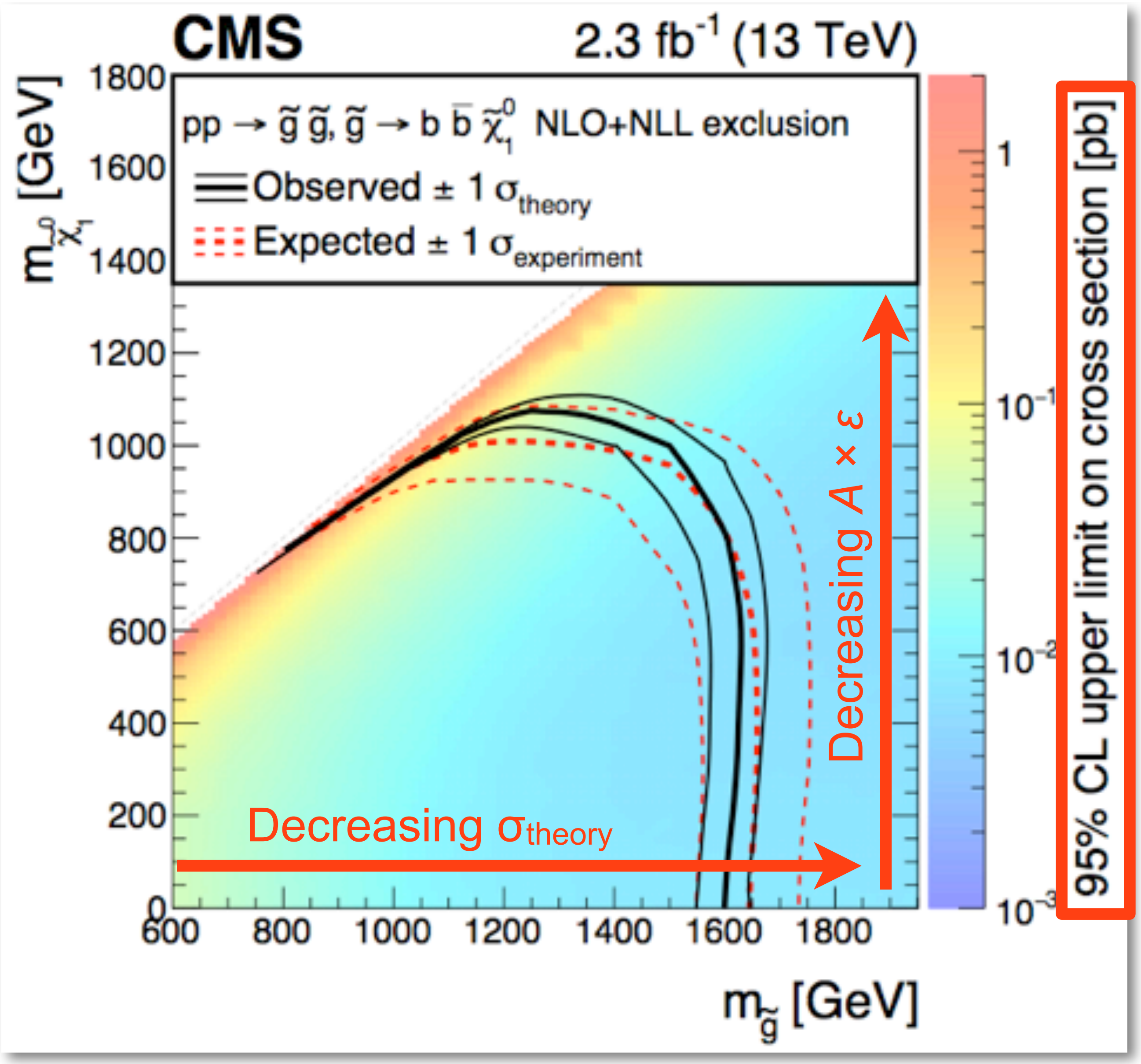
- Assume unique sparticle production & decay mode
- All other sparticle masses decoupled
- Scan masses of parent sparticle and LSP
- Can insert 3rd sparticle and BR assumptions

Gluino-mediated off-shell stop production

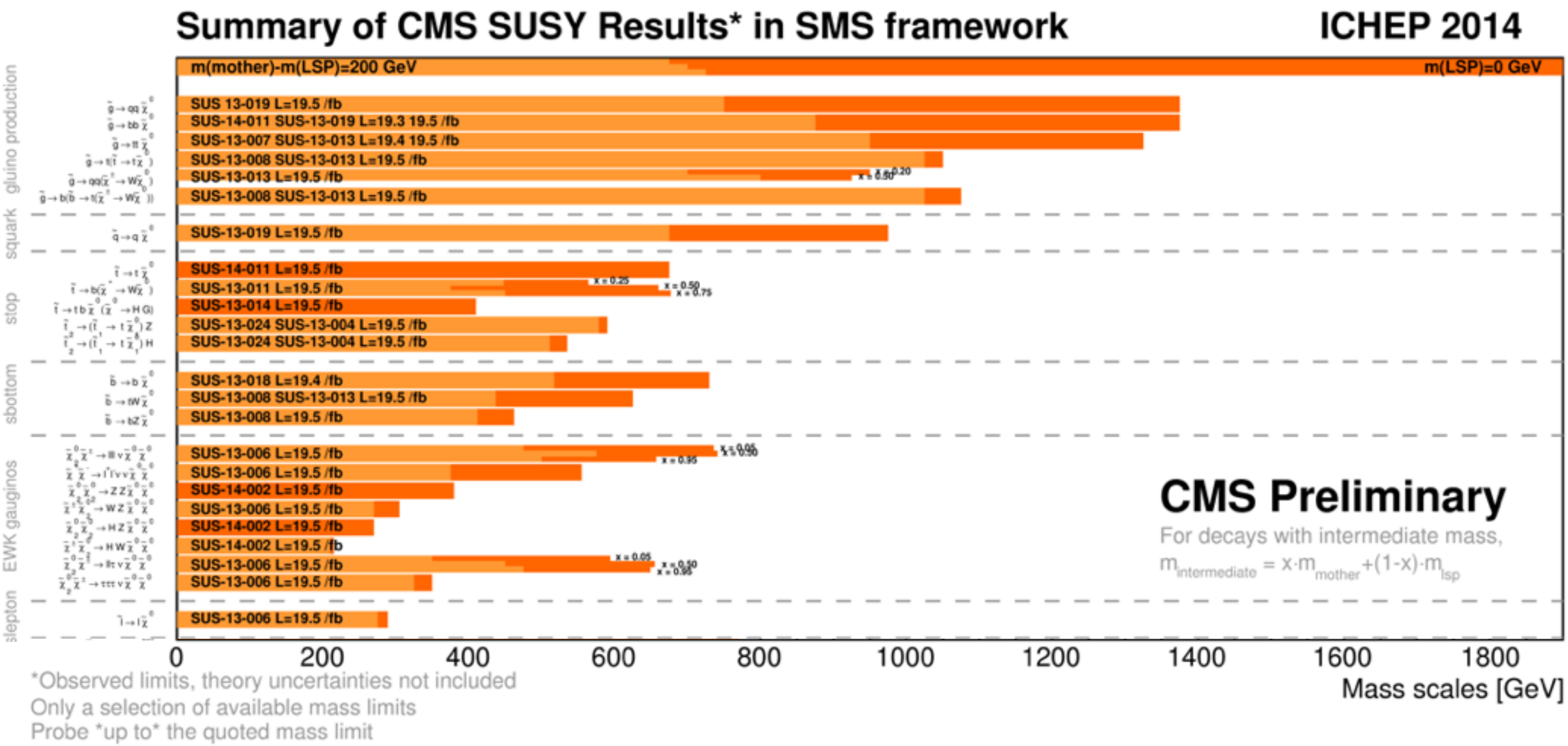


Gluino-mediated on-shell stop production





Run 1 legacy



Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
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SUS-13-011 L=19.5 /fb
SUS-13-014 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-018 L=19.4 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
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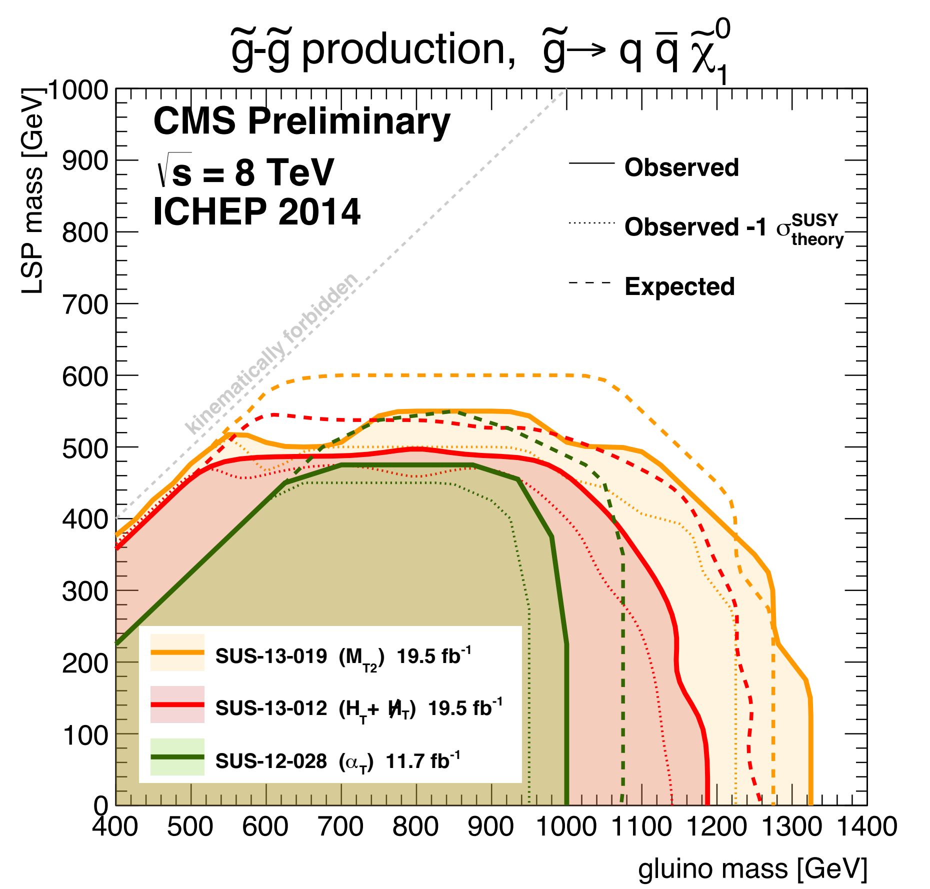
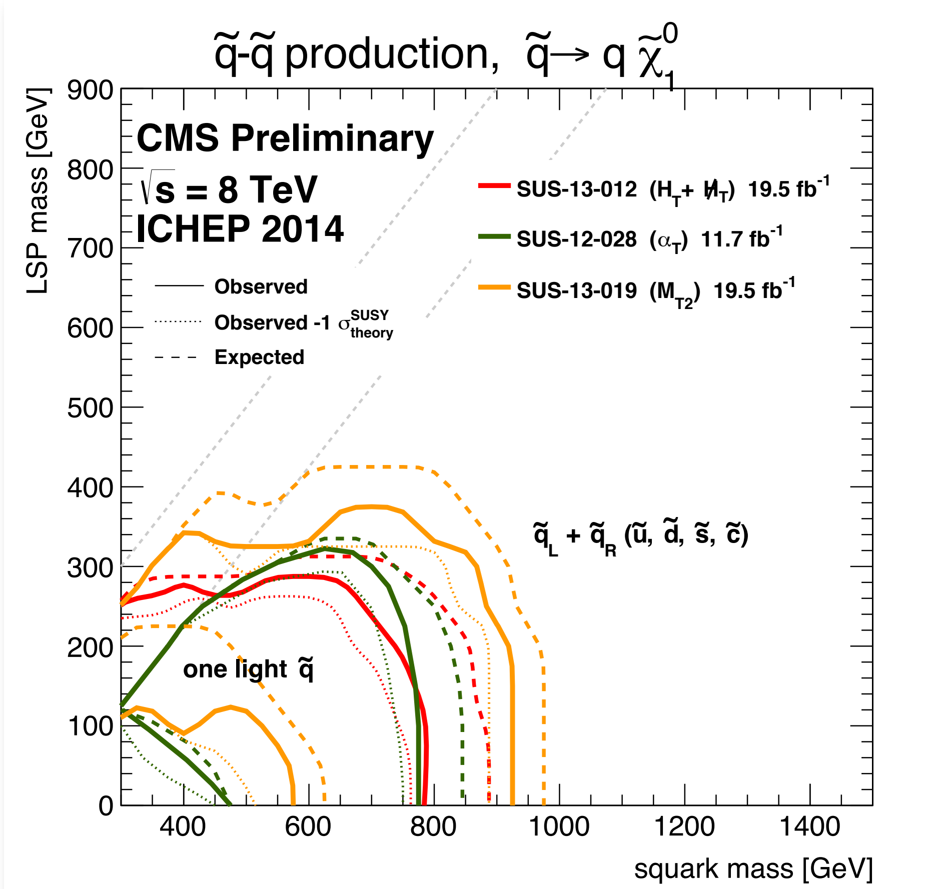
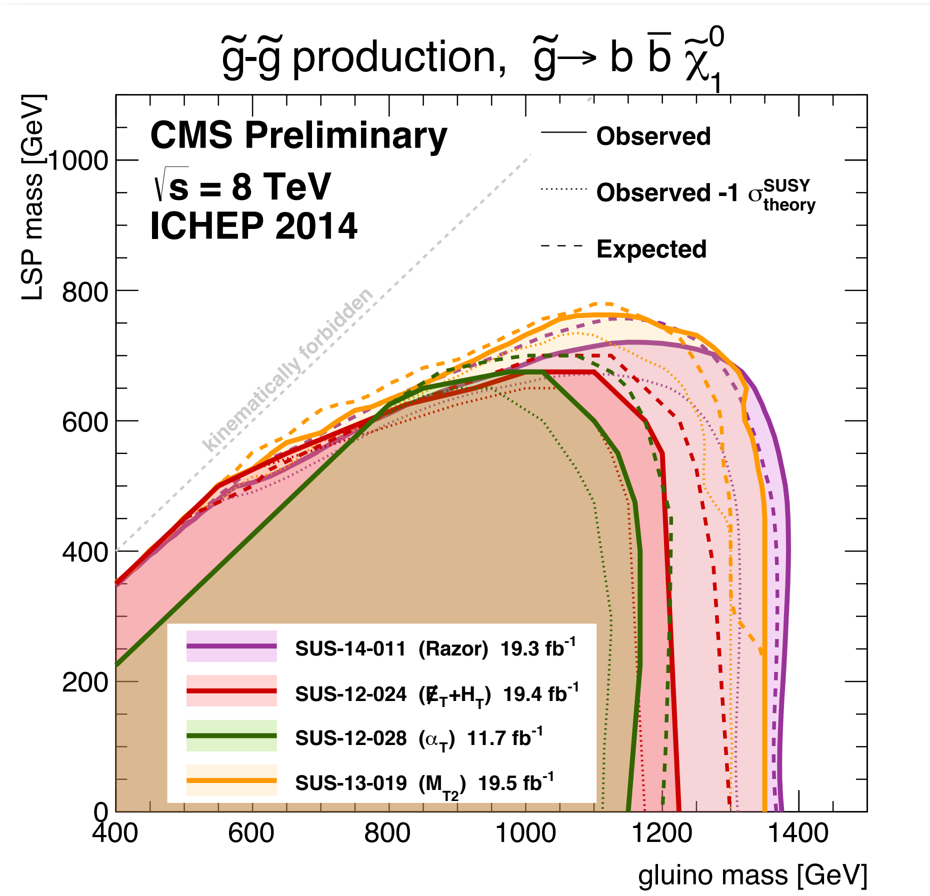
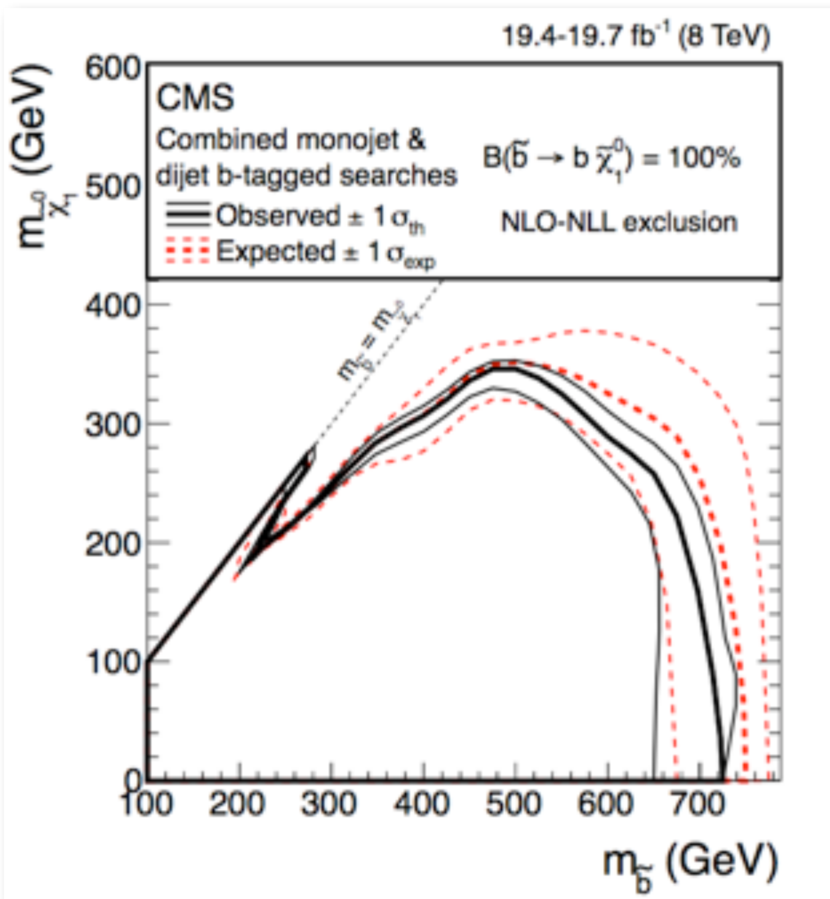
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
x = 0.25
x = 0.50
x = 0.75
x = 0.95
x = 0.05
CMS Preliminary
For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} + (1-x) \cdot m_{lsp}$
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

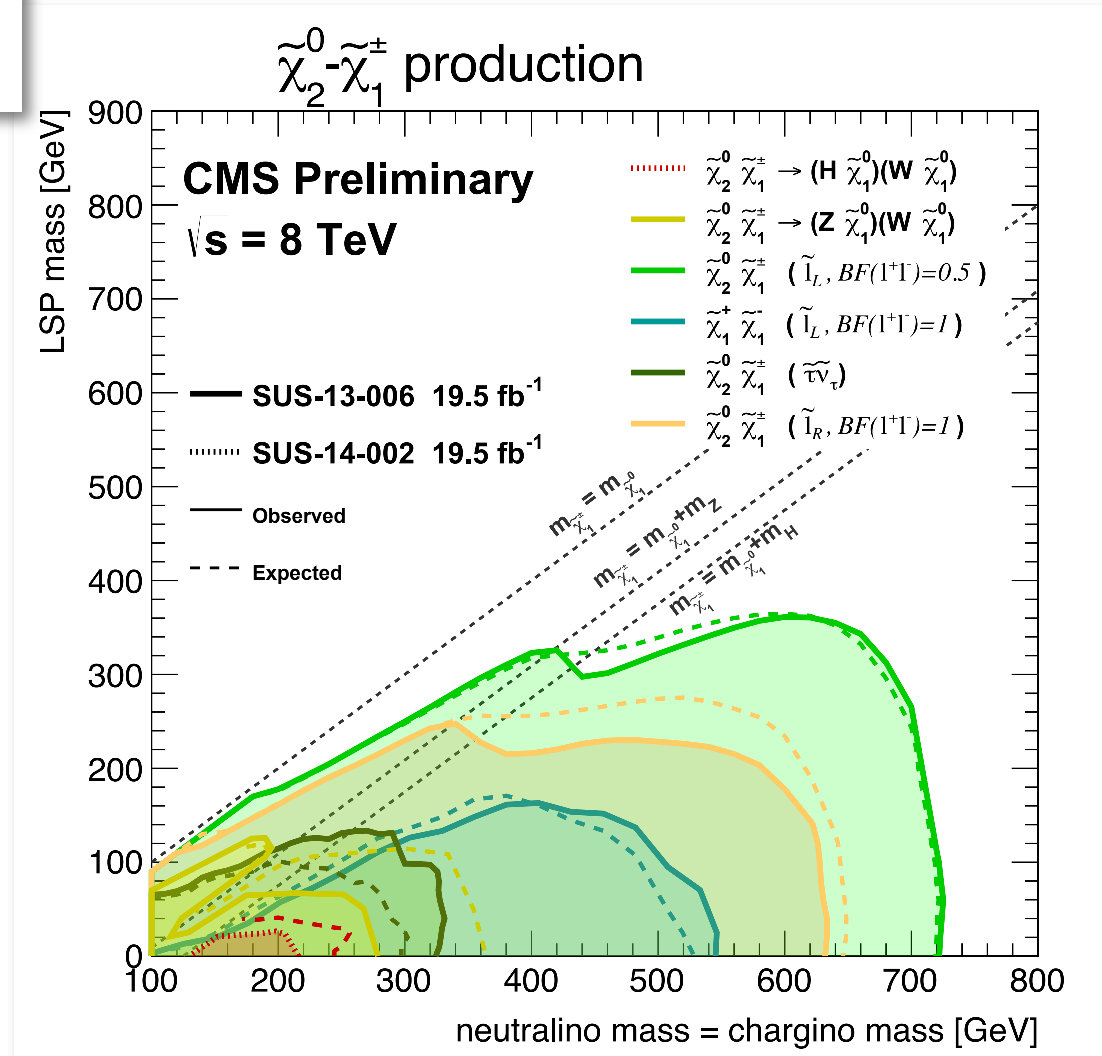
Run 1 legacy


g̃-g̃ production, g̃→ q q̄ $\tilde{\chi}_1^0$
CMS Preliminary
√s = 8 TeV
ICHEP 2014
Observed
Observed -1 σ_{theory}^{SUSY}
Expected
kinematically forbidden
SUS-13-019 (M_{T2}) 19.5 fb^{-1}
SUS-13-012 (H_T+ $\not{H}_T$) 19.5 fb^{-1}
SUS-12-028 (α_T) 11.7 fb^{-1}
LSP mass [GeV]
gluino mass [GeV]


q̃-q̃ production, q̃→ q $\tilde{\chi}_1^0$
CMS Preliminary
√s = 8 TeV
ICHEP 2014
SUS-13-012 (H_T+ $\not{H}_T$) 19.5 fb^{-1}
SUS-12-028 (α_T) 11.7 fb^{-1}
SUS-13-019 (M_{T2}) 19.5 fb^{-1}
Observed
Observed -1 σ_{theory}^{SUSY}
Expected
$\tilde{q}_L + \tilde{q}_R$ (ũ, d̃, s̃, c̃)
one light q̃
LSP mass [GeV]
squark mass [GeV]


g̃-g̃ production, g̃→ b b̄ $\tilde{\chi}_1^0$
CMS Preliminary
√s = 8 TeV
ICHEP 2014
Observed
Observed -1 σ_{theory}^{SUSY}
Expected
kinematically forbidden
SUS-14-011 (Razor) 19.3 fb^{-1}
SUS-12-024 ($\not{E}_T$+H_T) 19.4 fb^{-1}
SUS-12-028 (α_T) 11.7 fb^{-1}
SUS-13-019 (M_{T2}) 19.5 fb^{-1}
LSP mass [GeV]
gluino mass [GeV]


19.4-19.7 fb^{-1} (8 TeV)
CMS
Combined monojet &
dijet b-tagged searches
Observed ± 1 σ_{th}
Expected ± 1 σ_{exp}
B($\tilde{b} \to b \tilde{\chi}_1^0$) = 100%
NLO-NLL exclusion
$m_{\tilde{b}} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ (GeV)
$m_{\tilde{b}}$ (GeV)

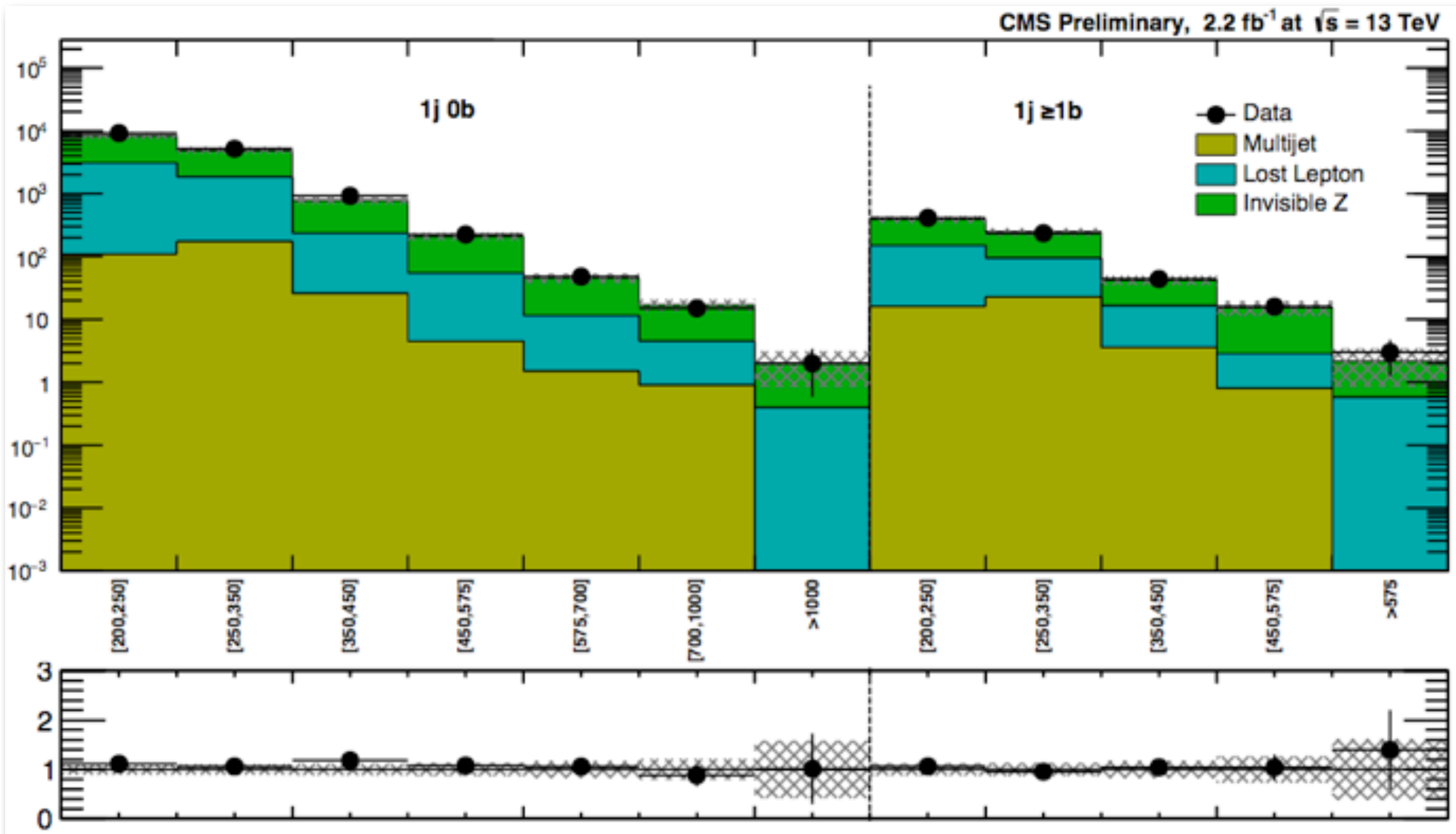

$\tilde{\chi}_2^0$-$\tilde{\chi}_1^\pm$ production
CMS Preliminary
√s = 8 TeV
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to (H \tilde{\chi}_1^0)(W \tilde{\chi}_1^0)$
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to (Z \tilde{\chi}_1^0)(W \tilde{\chi}_1^0)$
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ ($\tilde{l}_L$, BF(l^+l^-)=0.5)
$\tilde{\chi}_1^+ \tilde{\chi}_1^-$ ($\tilde{l}_L$, BF(l^+l^-)=1)
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ ($\tilde{\tau}\nu_\tau$)
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ ($\tilde{l}_R$, BF(l^+l^-)=1)
SUS-13-006 19.5 fb^{-1}
SUS-14-002 19.5 fb^{-1}
Observed
Expected
LSP mass [GeV]
neutralino mass = chargino mass [GeV]

Extensions to monojet-like topologies

CMS-PAS-SUS-15-003
CMS-PAS-SUS-15-005

- MT2 search has added monojet category: binned in jet p_T and $N_{b\text{-jet}}$
- α_T search categorises events according to p_T of 2nd most energetic jet in event
- Extension of signal region phase space w.r.t. 8 TeV
- Targets compressed SUSY models (small Δm), EWKino sector, DM (simplified) models
- Will be fully exploited with large data set collected in 2016

Jet category	p_T^{jet2} [GeV]
"Symmetric"	> 100
"Asymmetric"	40−100
Monojet	< 40



Search in 1L final state with the Δφ variable

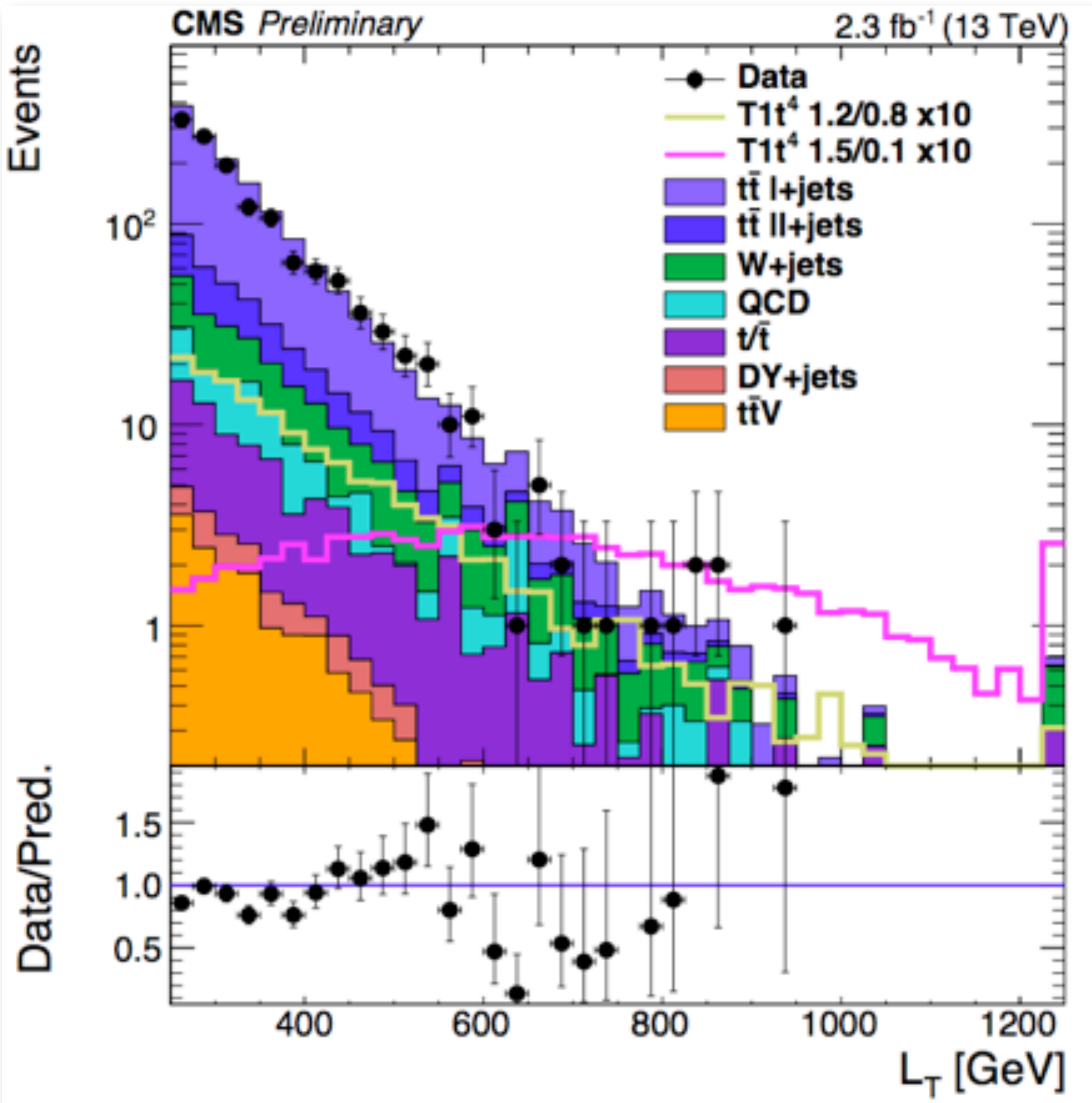
CMS-PAS-SUS-15-006

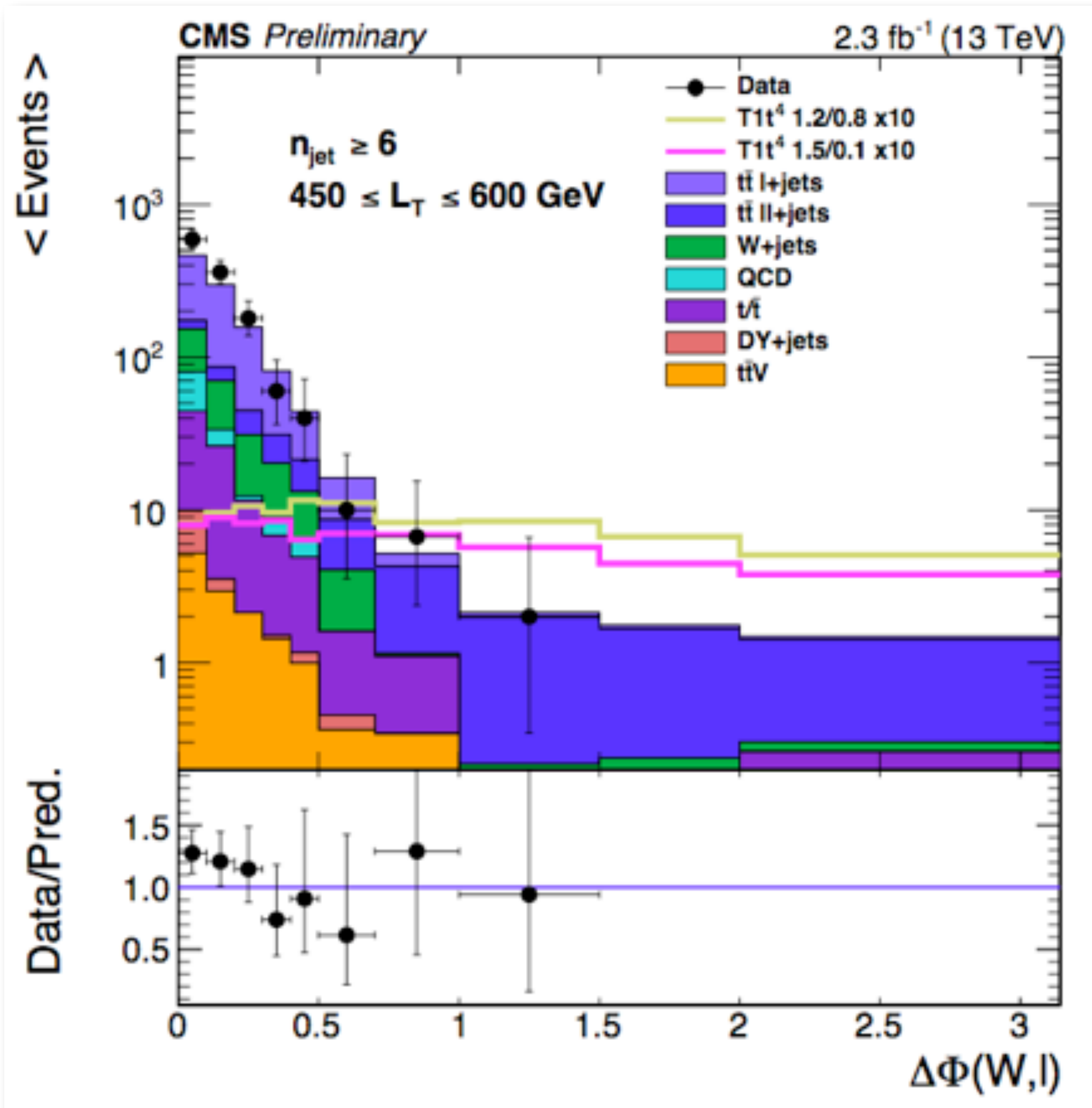
Targets gluino-mediated stop and/or chargino production

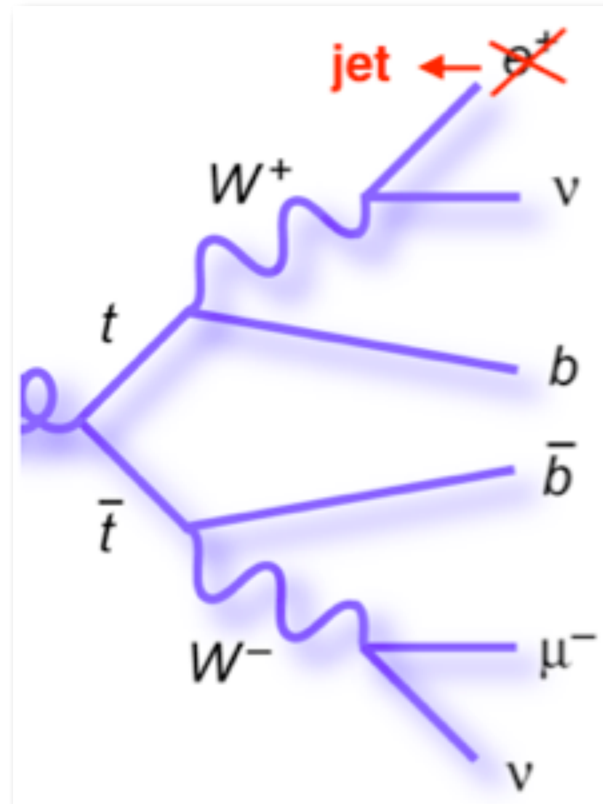
Primary discriminating variable: $\Delta\varphi(\ell, p_T^W)$, binned SR using L_T, H_T, N_{jet}, $N_{b\text{-}jet}$

Δφ and Njet are weakly correlated, corrections from simulation, use ABCD method

SM background is mainly dileptonic tt, systematics from 2L data validation region







0L and 1L final states with the Razor variables

CMS-PAS-SUS-15-004
CMS-PAS-SUS-16-004

Shape analysis: 2D analytical function to model kinematic variables M_R and R^2

- Variables related to the mass and transverse energy flow of pair-produced particles

Model extensively validated in simulation (+ data-driven cross check, coming soon)

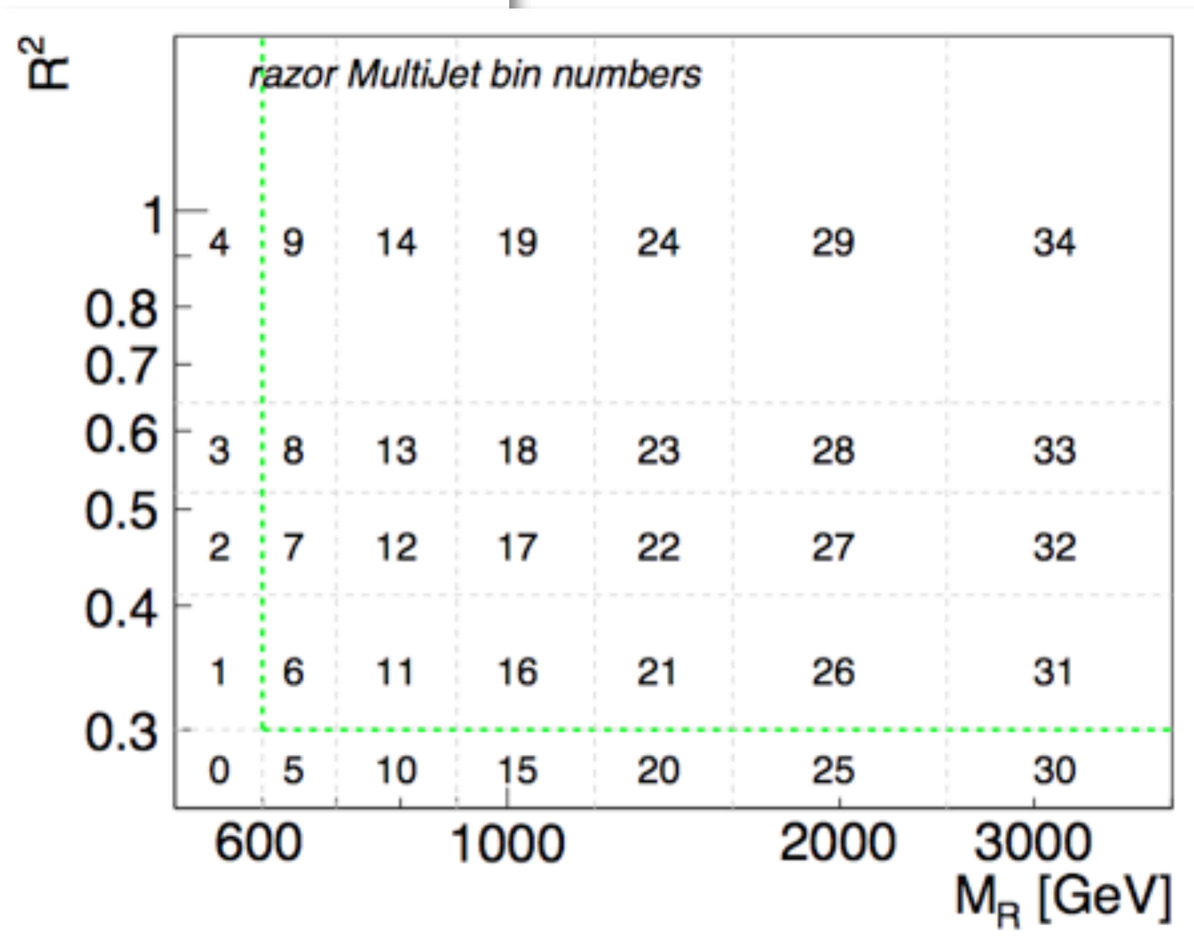
Easy combination of final states: 0L + MultiJet ($N_{jet} \geq 4$), 1μ/1e + MultiJet (+ $N_{b\text{-}jet}$)

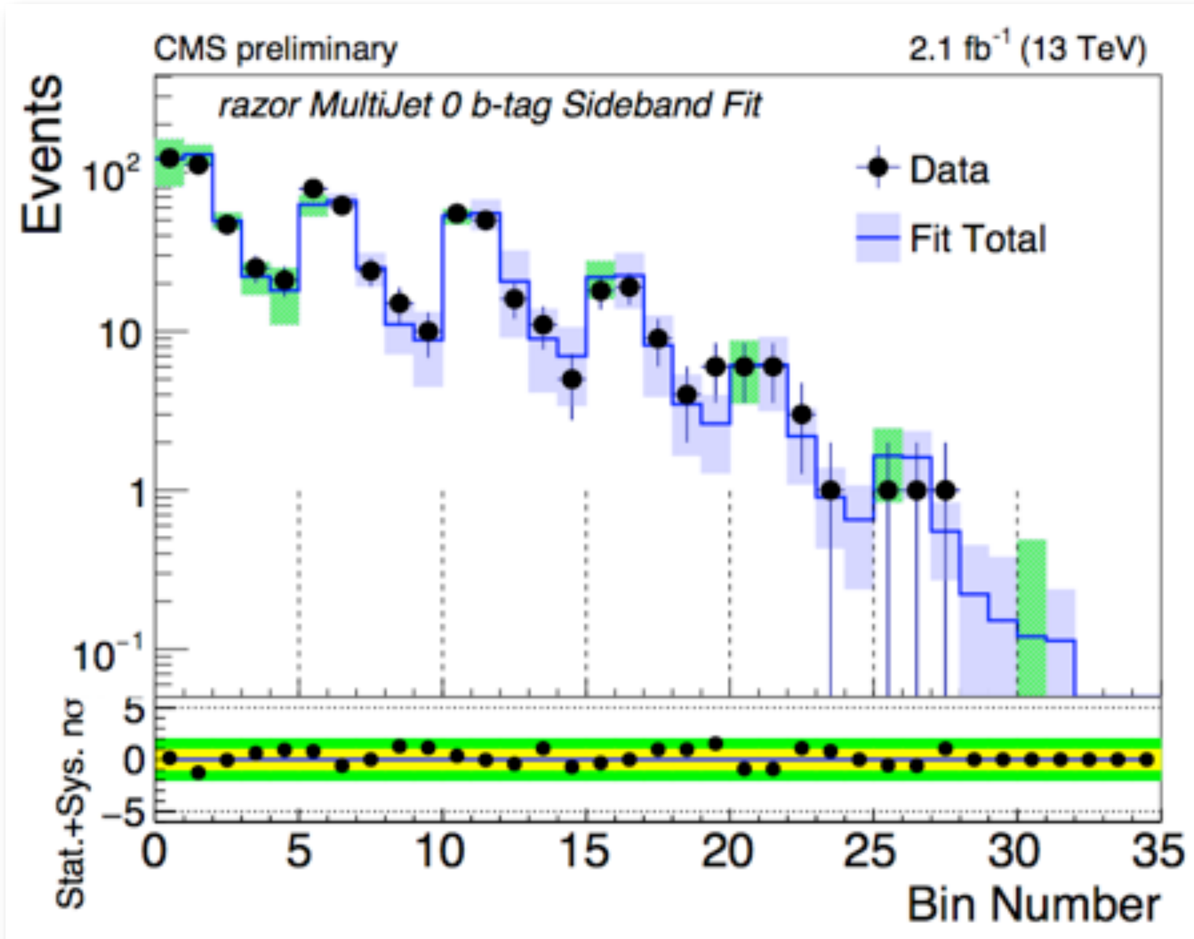
$$M_R \equiv \sqrt{(P_{j_1}+P_{j_2})^2 - (p_z^{j_1}+p_z^{j_2})^2}$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1}+p_T^{j2}) - \vec{p}_T^{miss}\cdot(\vec{p}_T^{j1}+\vec{p}_T^{j2})}{2}}$$

$$R^2 \equiv \left(\frac{M_T^R}{M_R}\right)^2$$

$$f_{SM}(M_R, R^2) = \left[b(M_R - M_R^0)^{1/n}(R^2 - R_0^2)^{1/n} - 1\right] e^{-bn(M_R - M_R^0)^{1/n}(R^2 - R_0^2)^{1/n}}$$



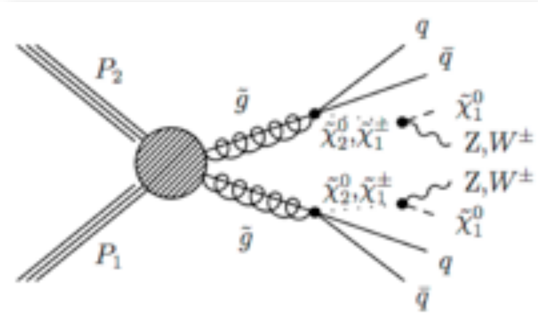


Search in 0L final state with the MHT variable

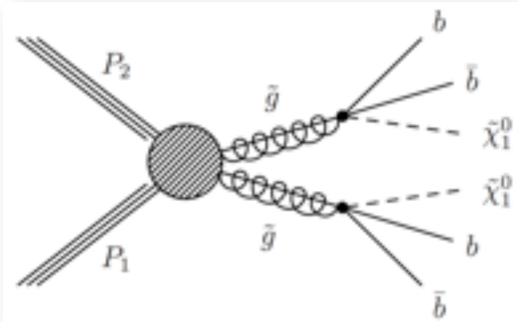
arXiv:1602.06581 [hep-ex]

Gain w.r.t. Run 1 legacy

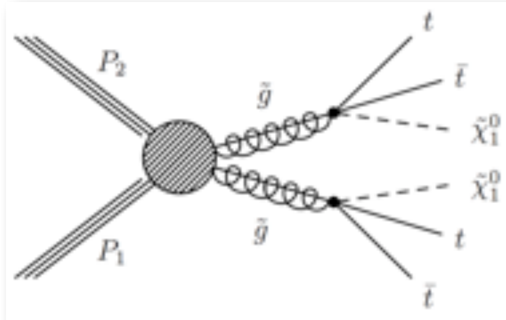
Model	Best limit on $\mathbf{m_{gluino}}$ [GeV]	Best limit on $\mathbf{m_{LSP}}$ [GeV]
T1qqqq	~100	~200
T1bbbb	~200	~300
T1tttt	~300	~250



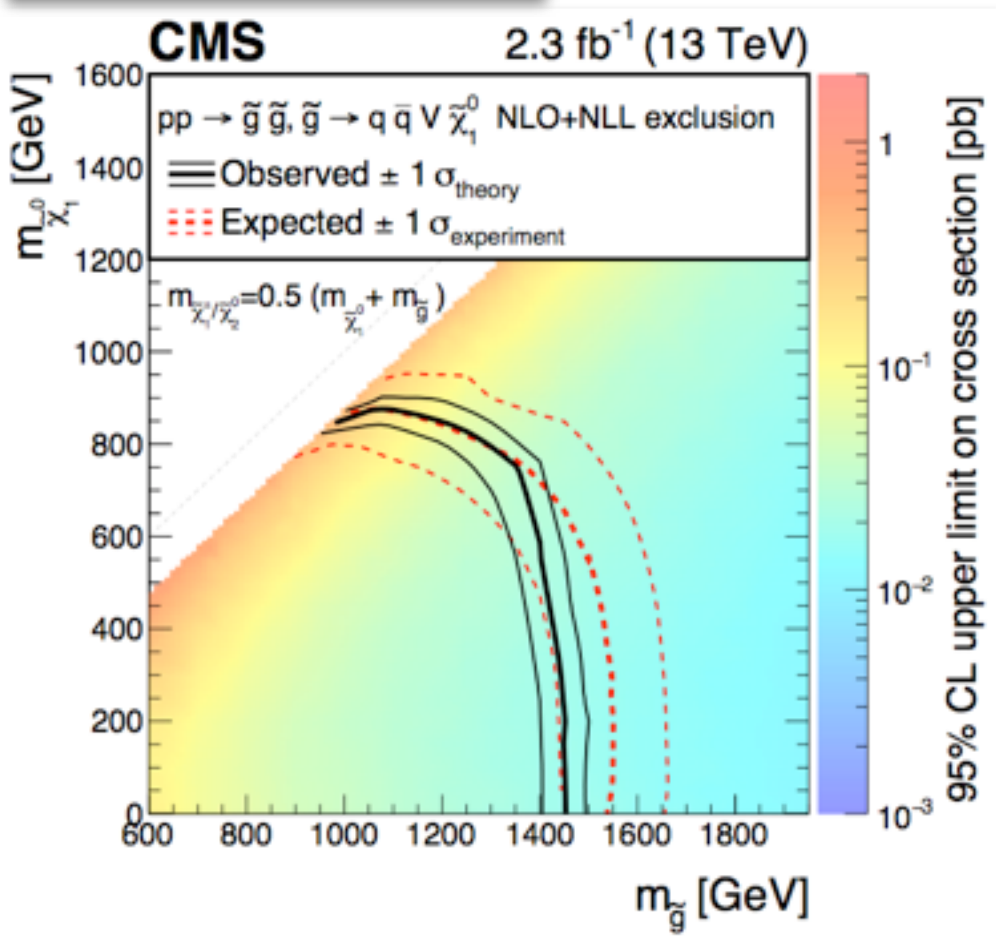
T1qqqqVV

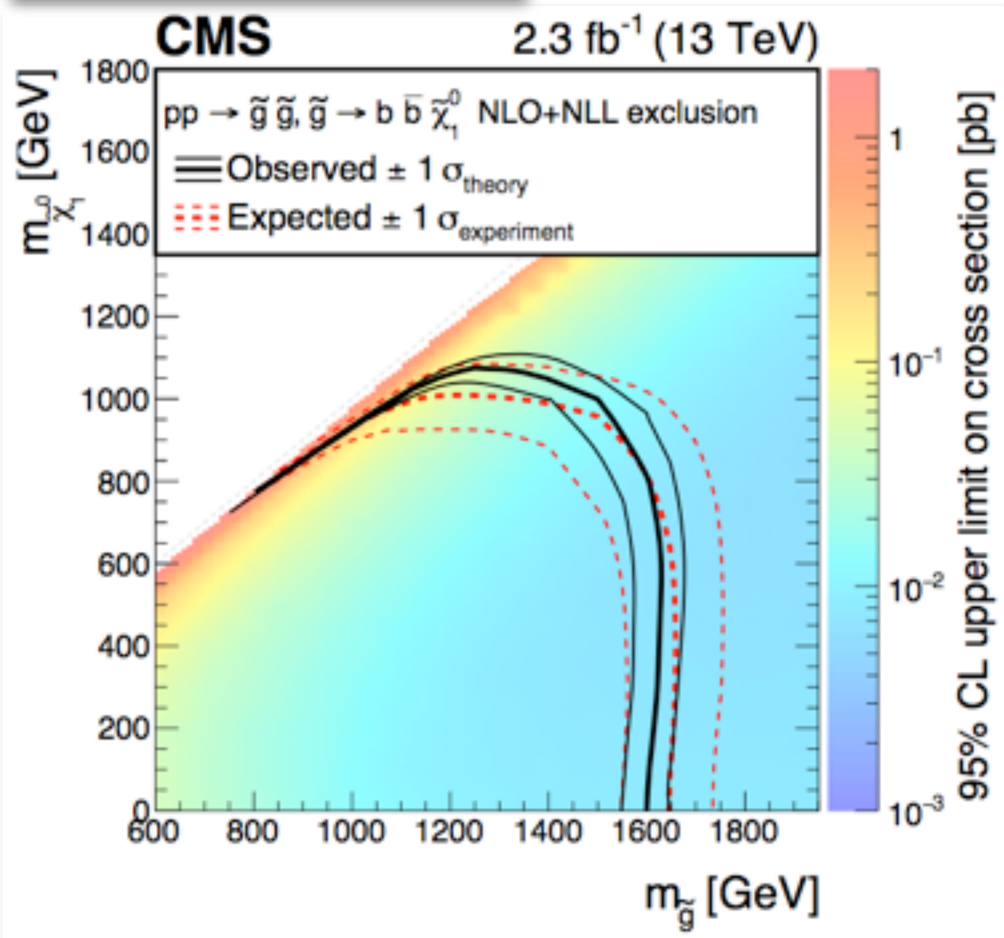


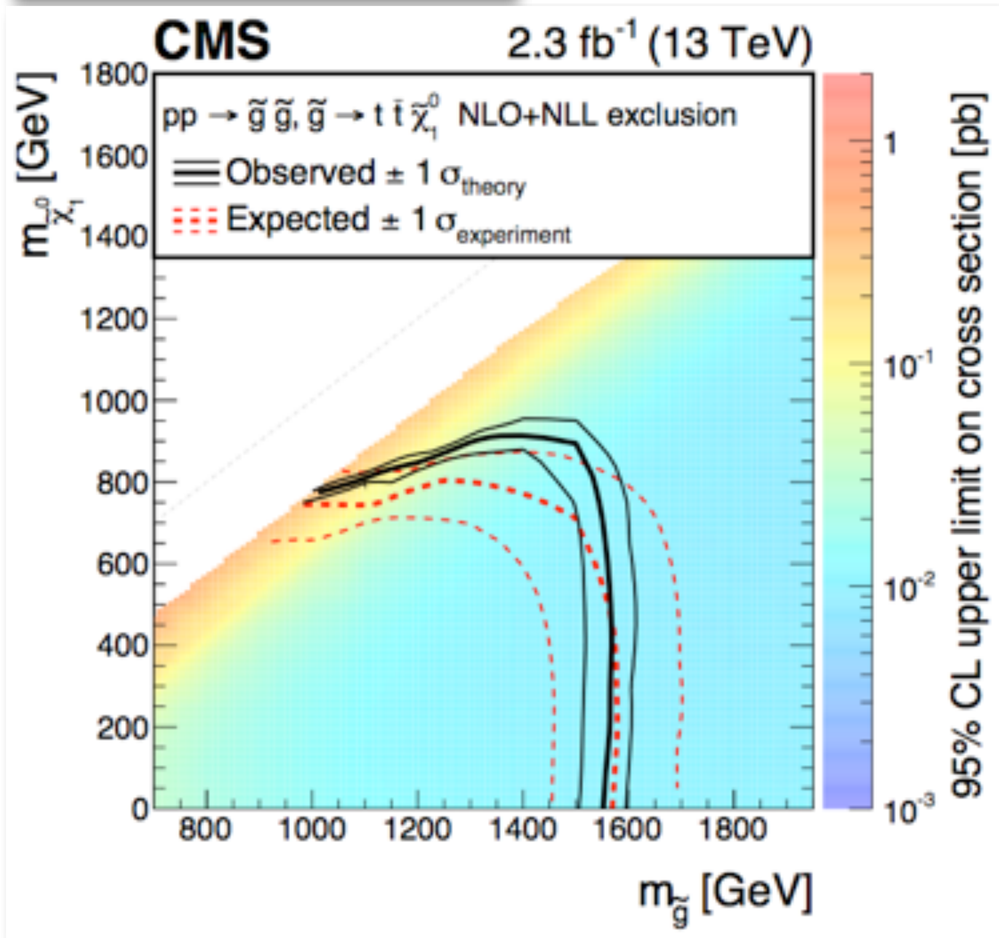
T1bbbb



T1tttt



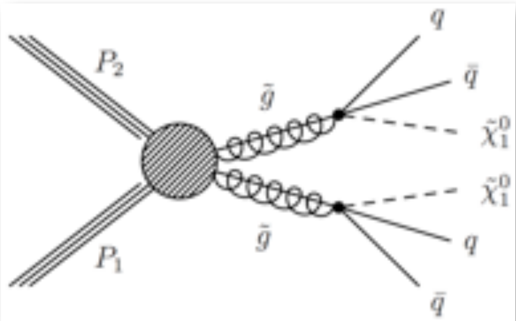




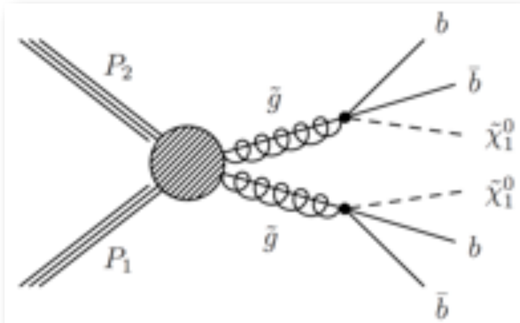
Search in 0L final state with the MT2 variable

Gain w.r.t. Run 1 legacy

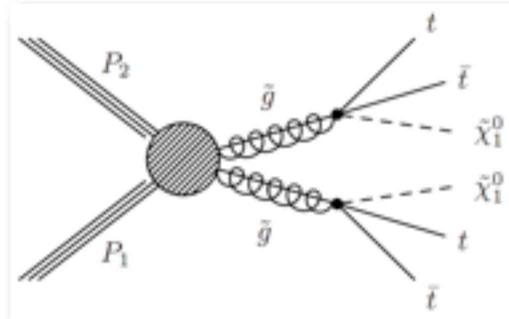
Model	Best limit on $\mathbf{m_{gluino}}$ [GeV]	Best limit on $\mathbf{m_{LSP}}$ [GeV]
T1qqqq	~350	~250
T1bbbb	~300	~300
T1tttt	~200	~150



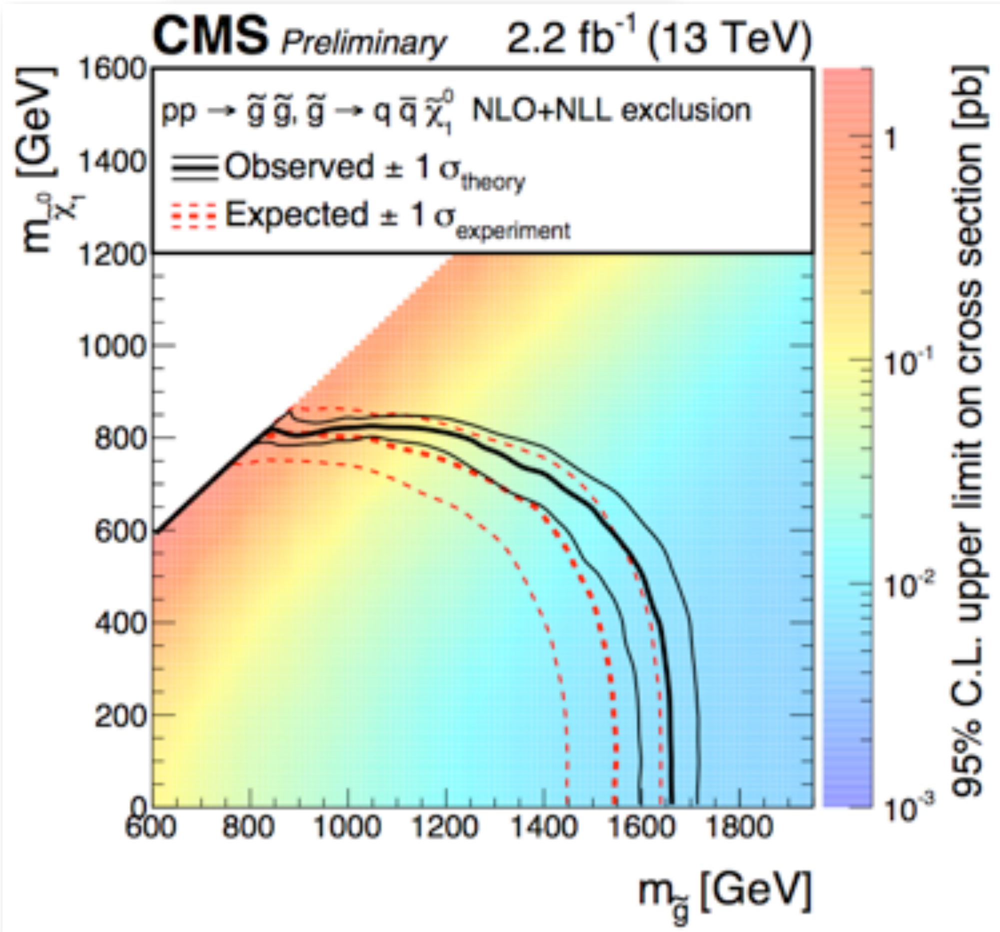
T1qqqq

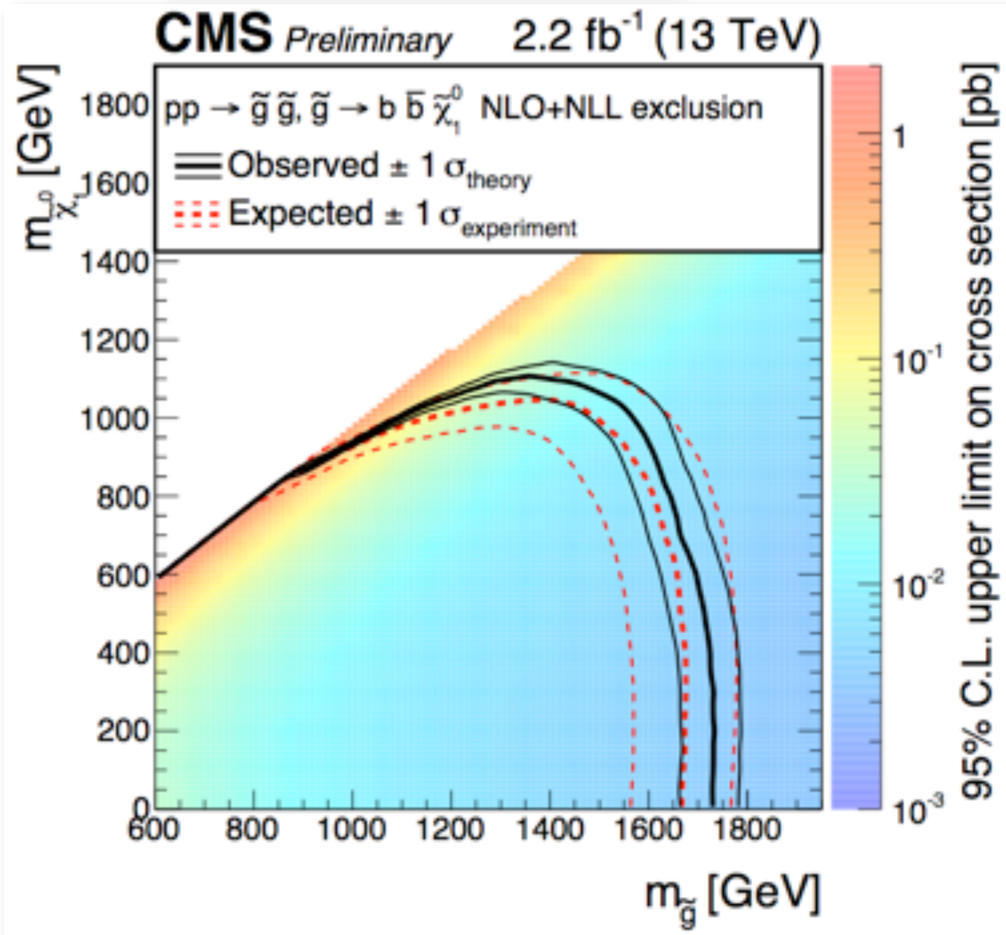


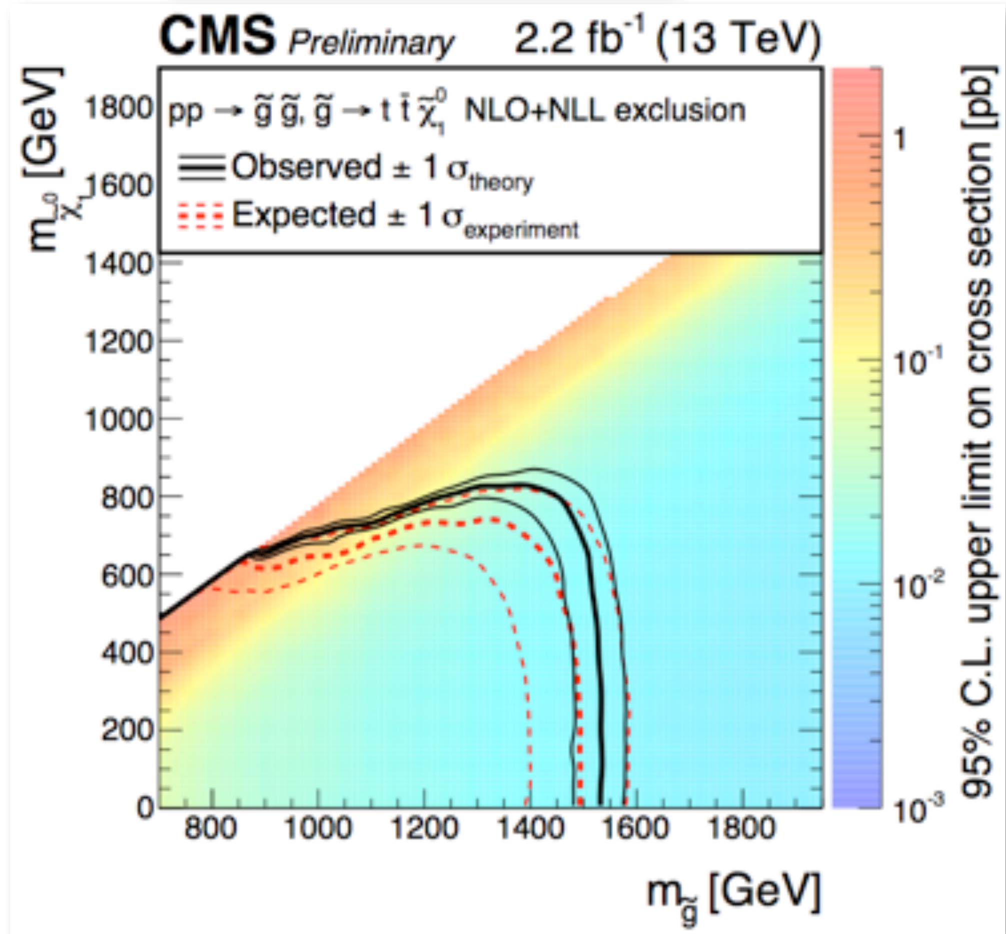
T1bbbb



T1tttt







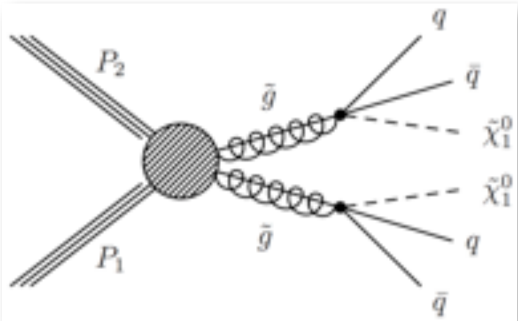
Search in 0L final state with the α_T variable

Weaker-than-expected T1tttt limit

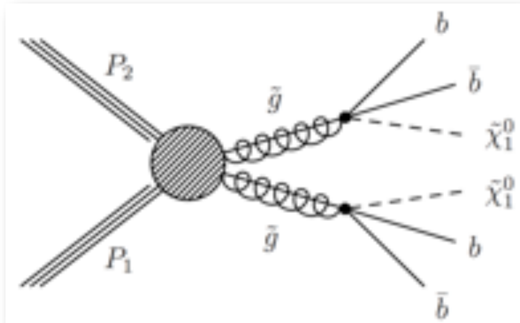
- Mild excess in two adjacent bins at high HT, N_{jet}, $N_{b\text{-}jet}$
- Good physics events, consistent with statistical fluctuation
- Region excluded by other searches at 8 TeV and 13 TeV

Gain w.r.t. Run 1 legacy

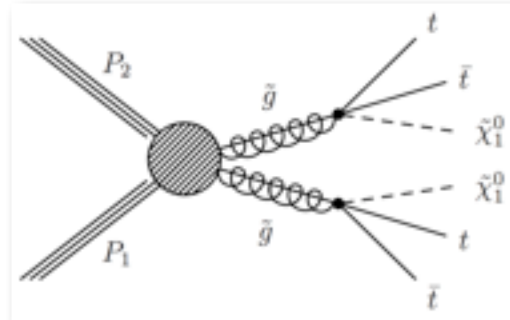
Model	Best limit on m_{gluino} [GeV]	Best limit on m_{LSP} [GeV]
T1qqqq	~100	~250
T1bbbb	~200	~200
T1tttt	~0	~0



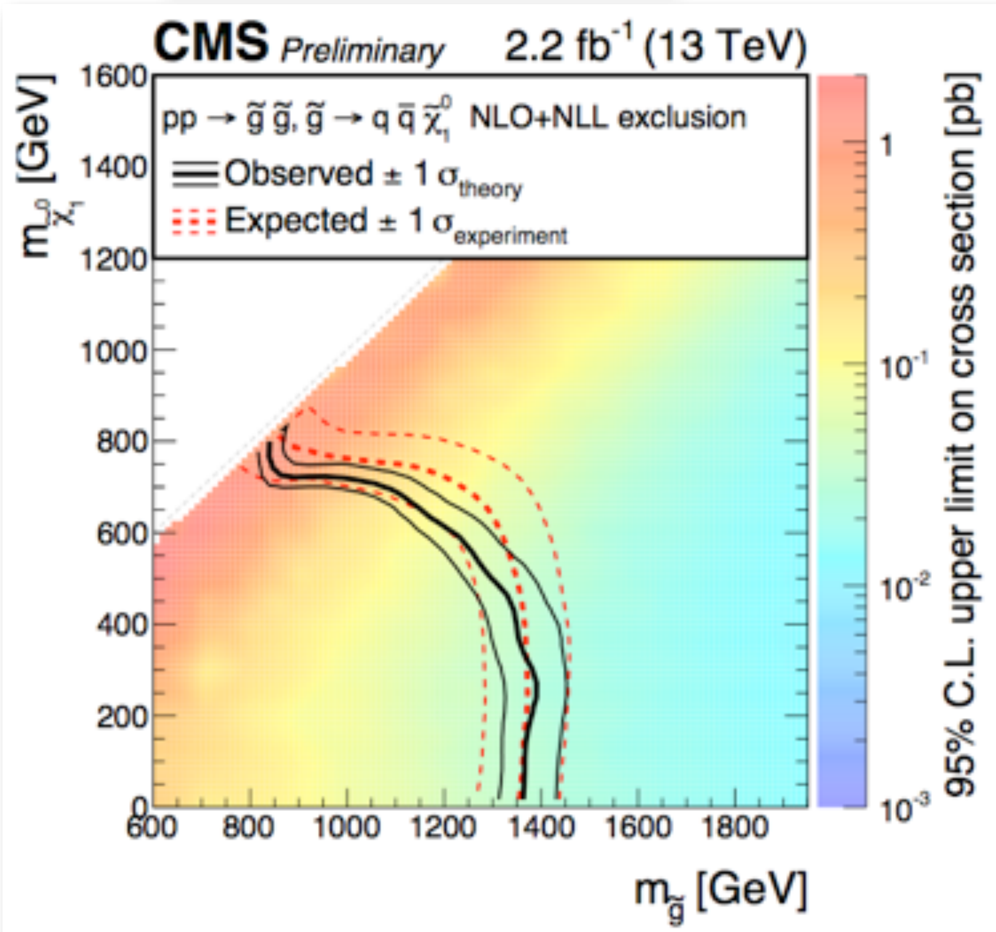
T1qqqq

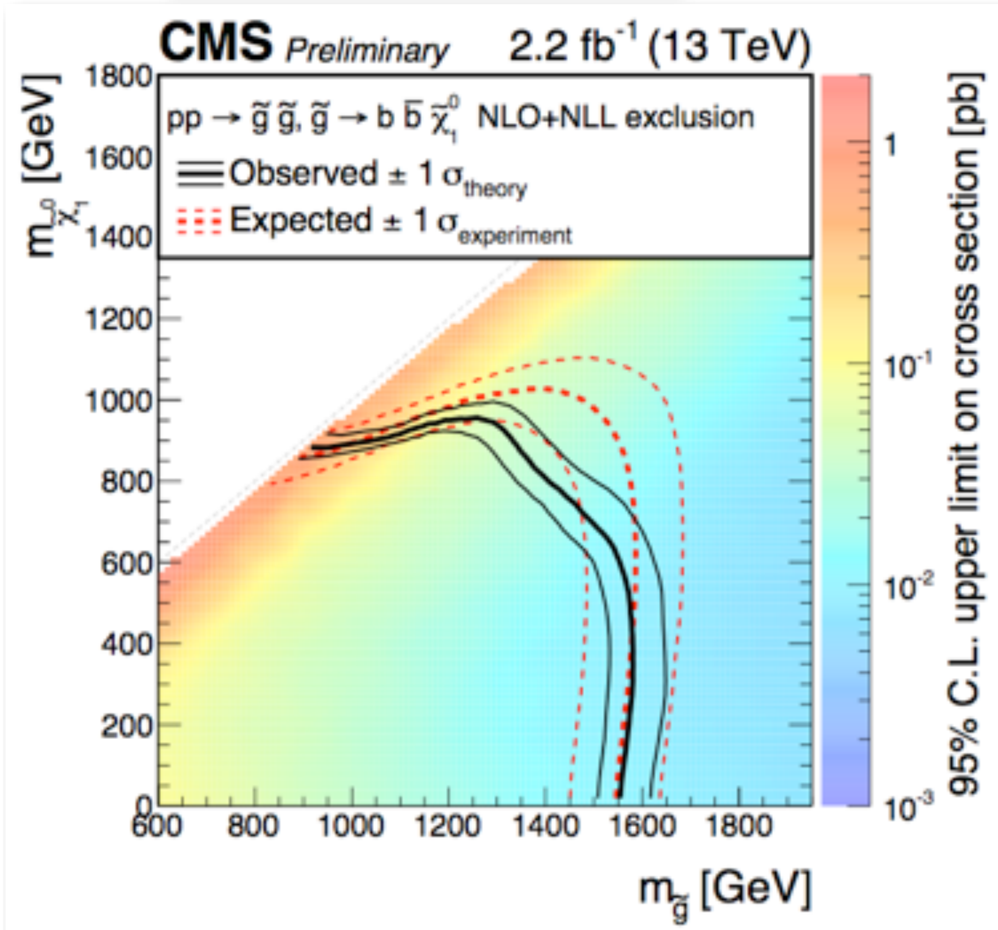


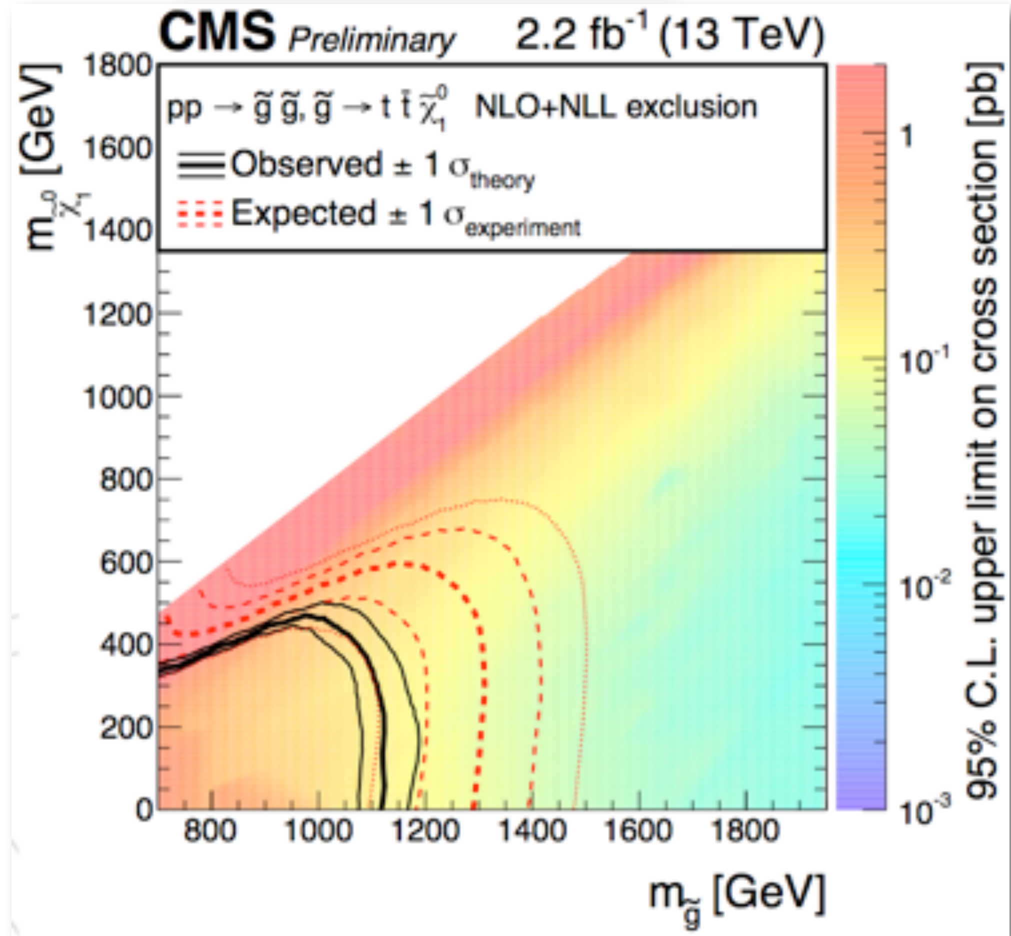
T1bbbb



T1tttt

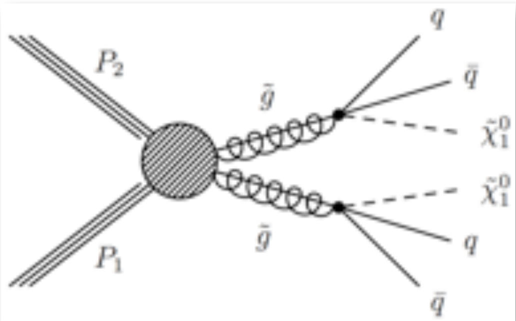




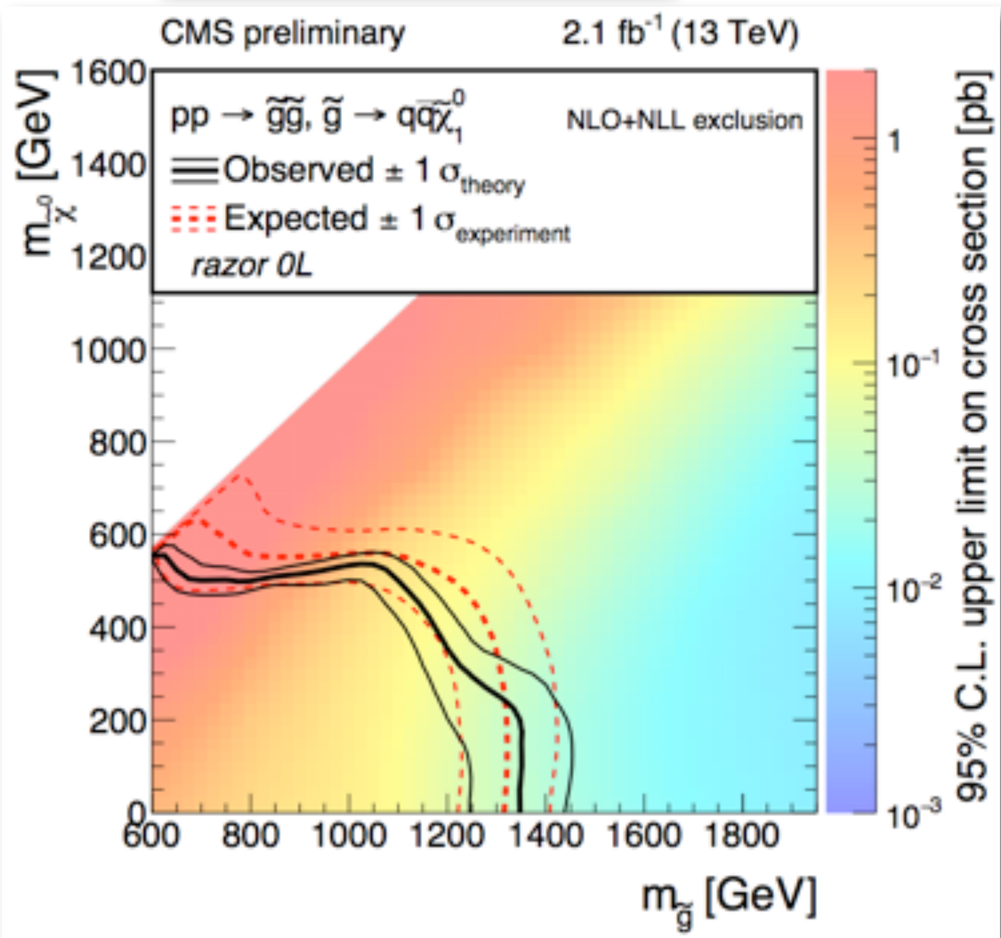


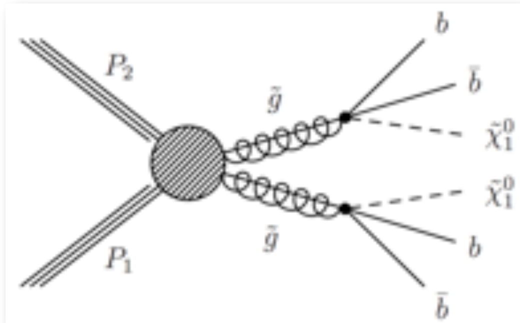
Search in 0L final state with the Razor variables

Model	Best limit on $\mathbf{m_{gluino}}$ [TeV]	Best limit on $\mathbf{m_{LSP}}$ [TeV]
T1qqqq	~1.3	~0.5
T1bbbb	~1.6	~0.9
T1tttt	~1.6	~0.7

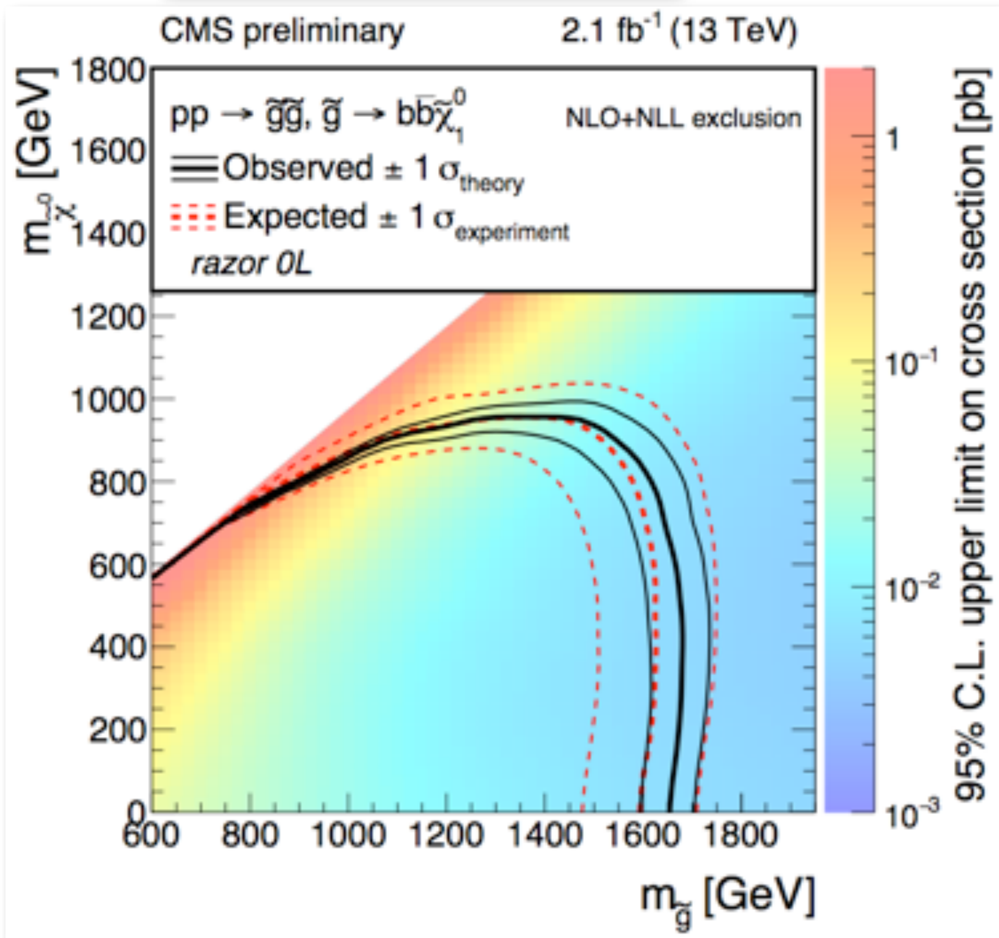


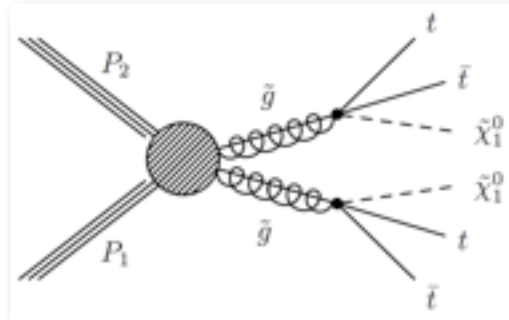
T1qqqq



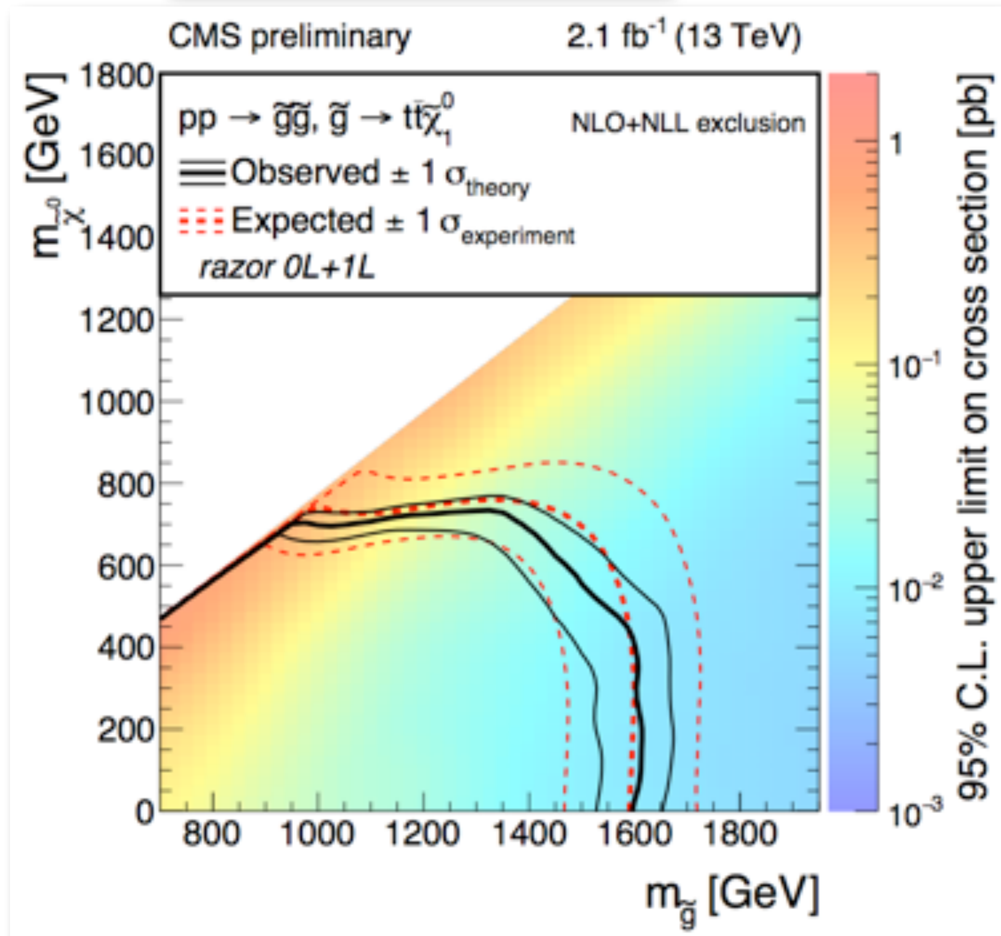


T1bbbb

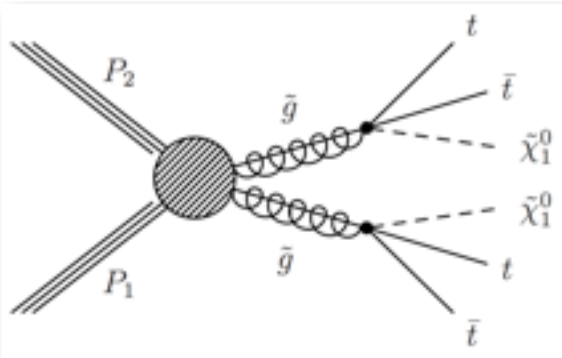




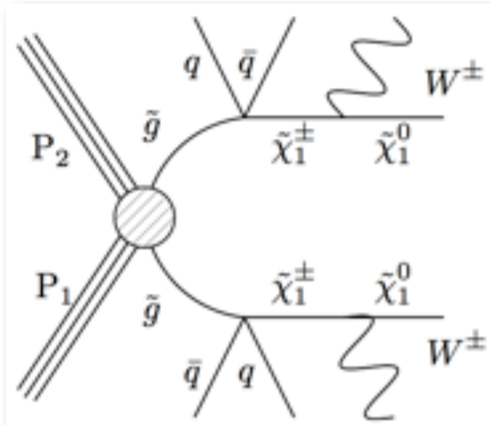
T1tttt



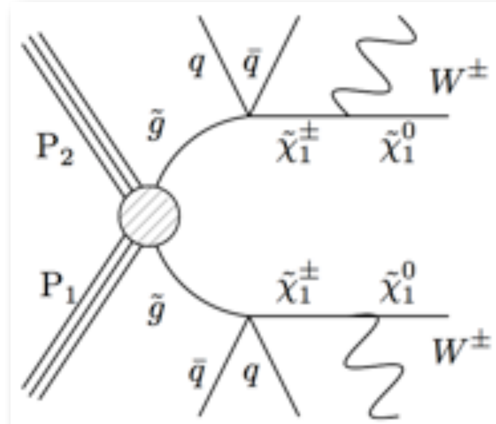
Same-sign di-lepton final state



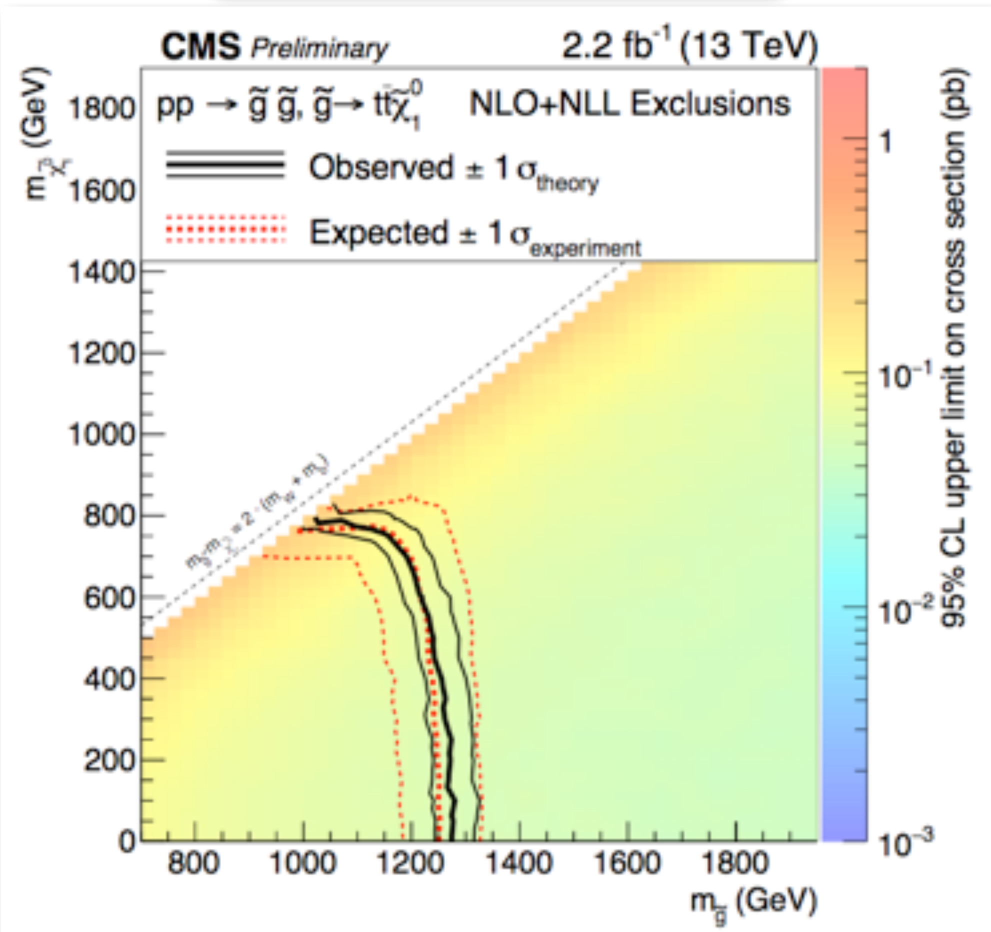
T1tttt

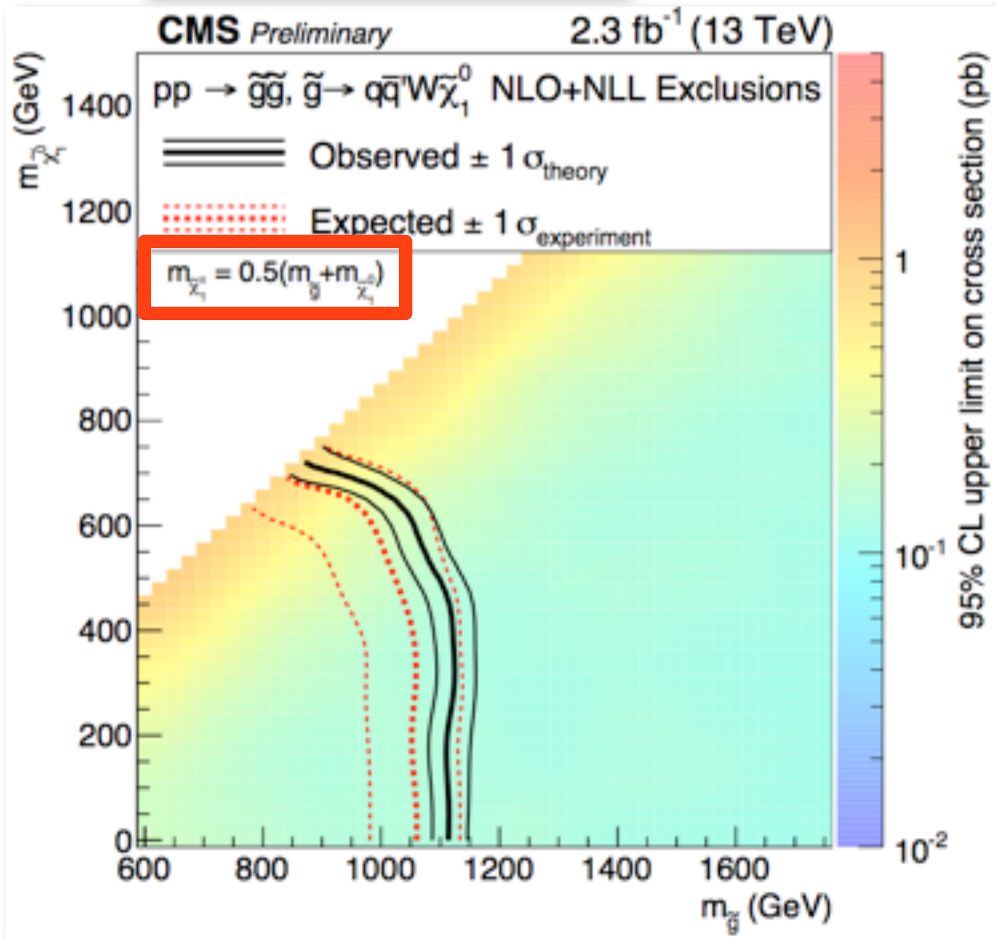


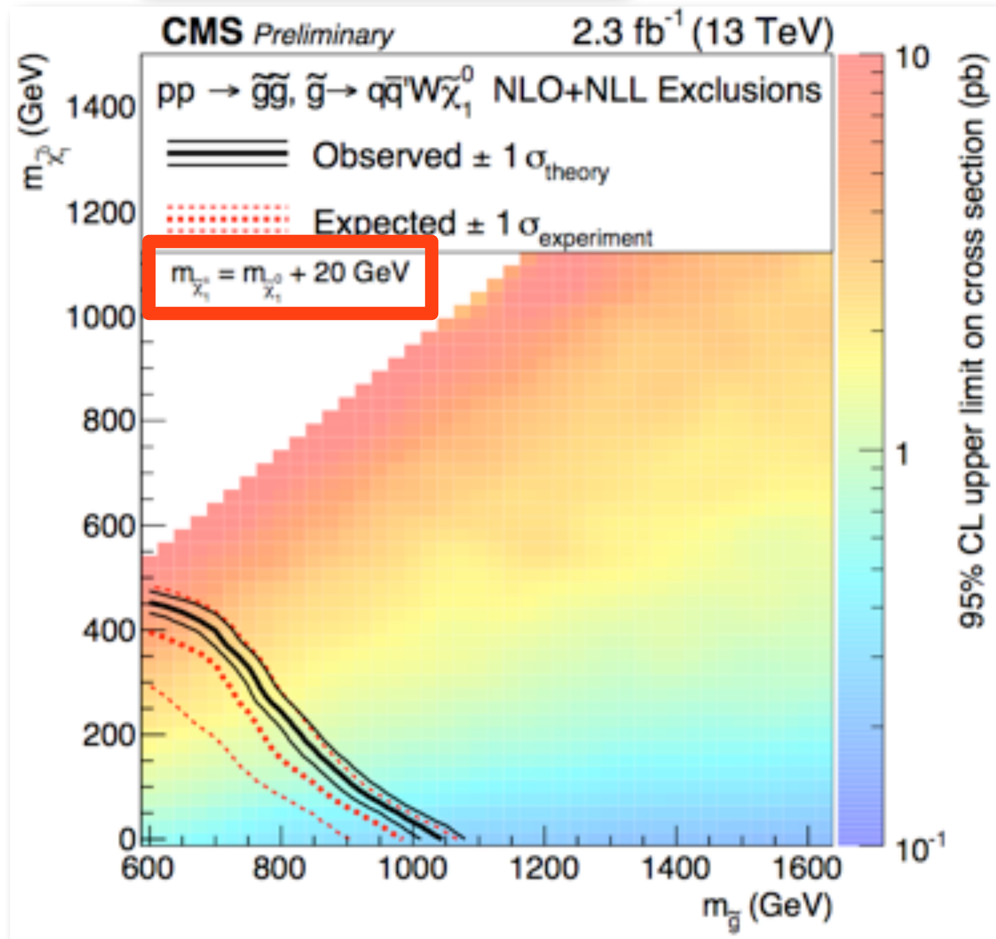
T1qqqqVV



T1qqqqVV







Edge/Z search

GMSB model (χ_1^0 NLSP → Z^0G)

T5ZZ