SUSY searches in all-hadronic final states with the CMS detector

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on behalf of the CMS Collaboration

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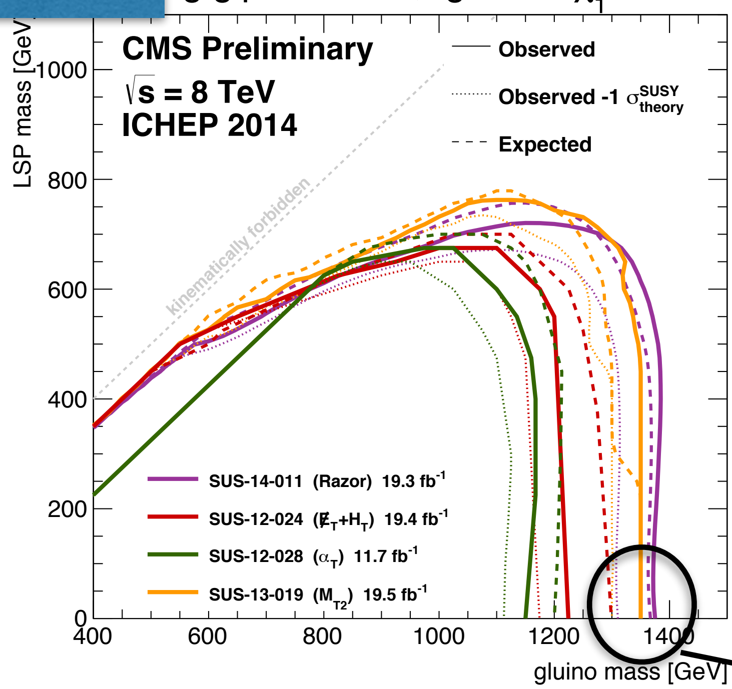
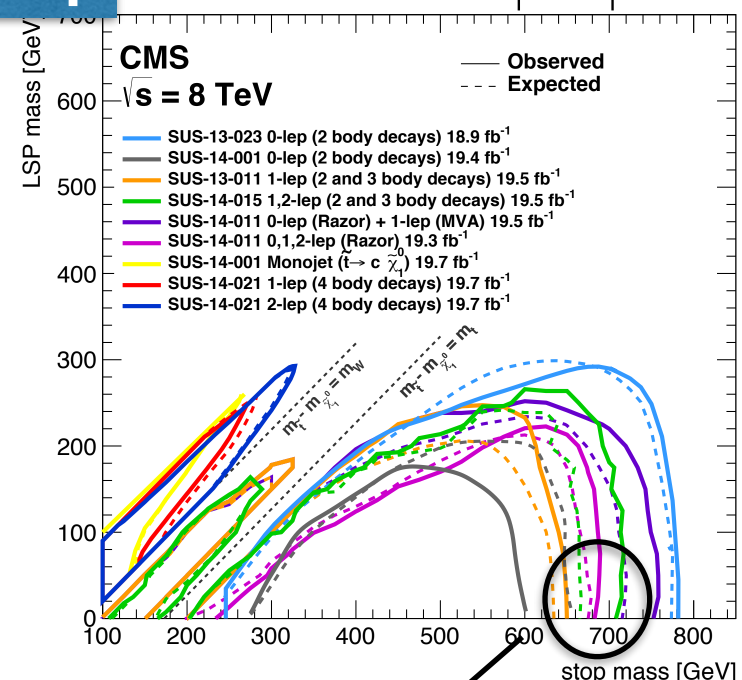
Run1 summary

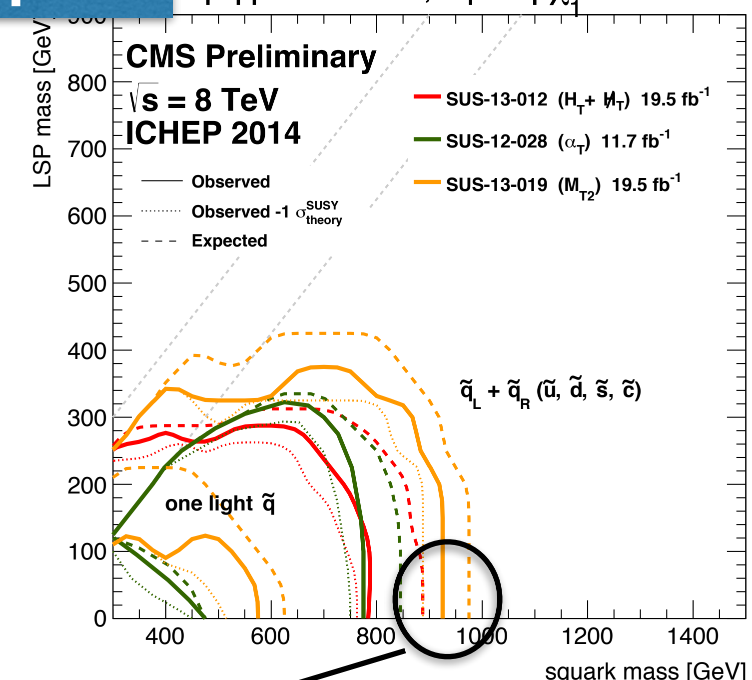
Gluino g̃-g̃ production, $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$

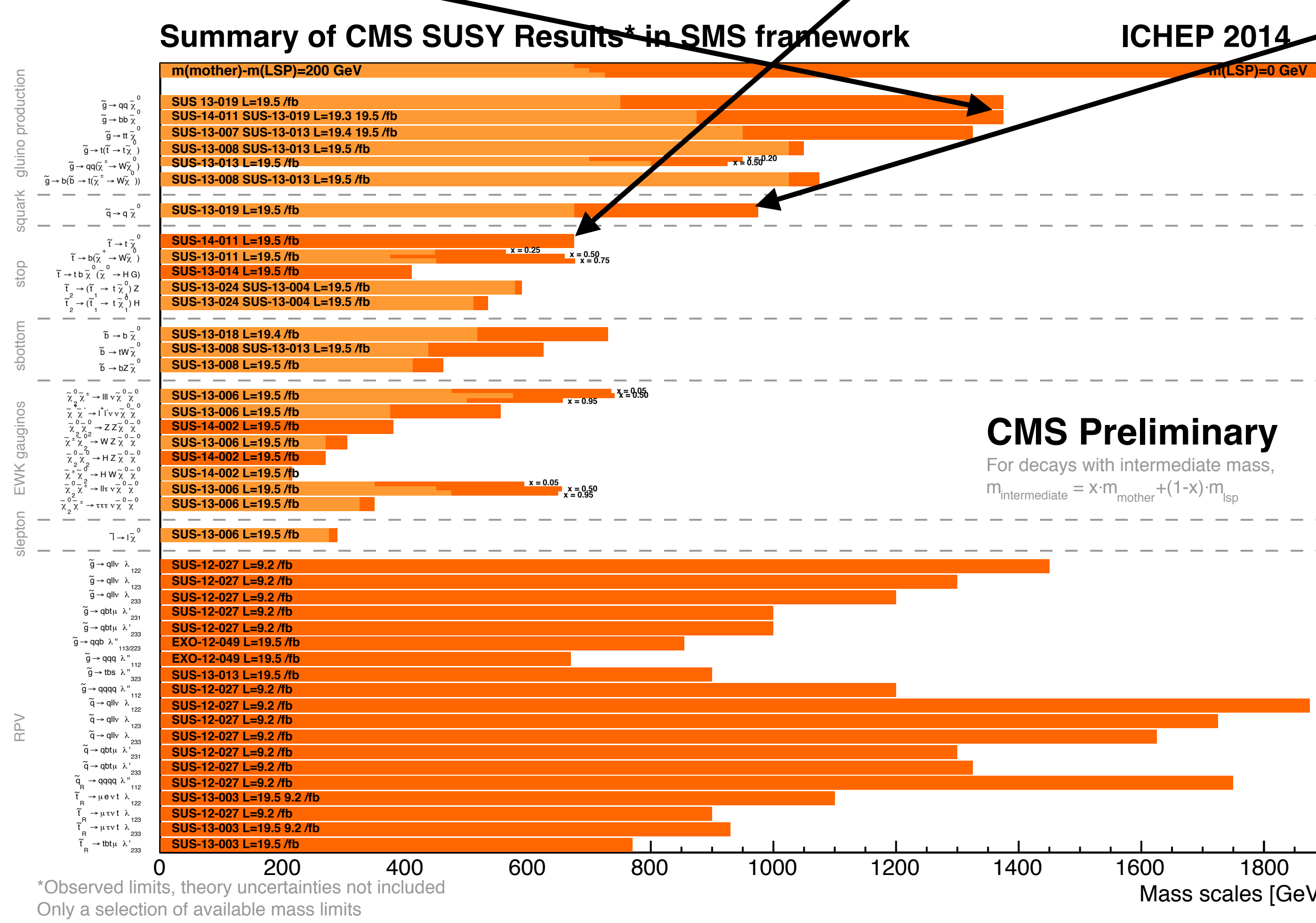


Stop t̃-t̃ production, $\tilde{t} \to t\,\tilde{\chi}_1^0 / c\,\tilde{\chi}_1^0$



Squark q̃-q̃ production, $\tilde{q} \to q\,\tilde{\chi}_1^0$

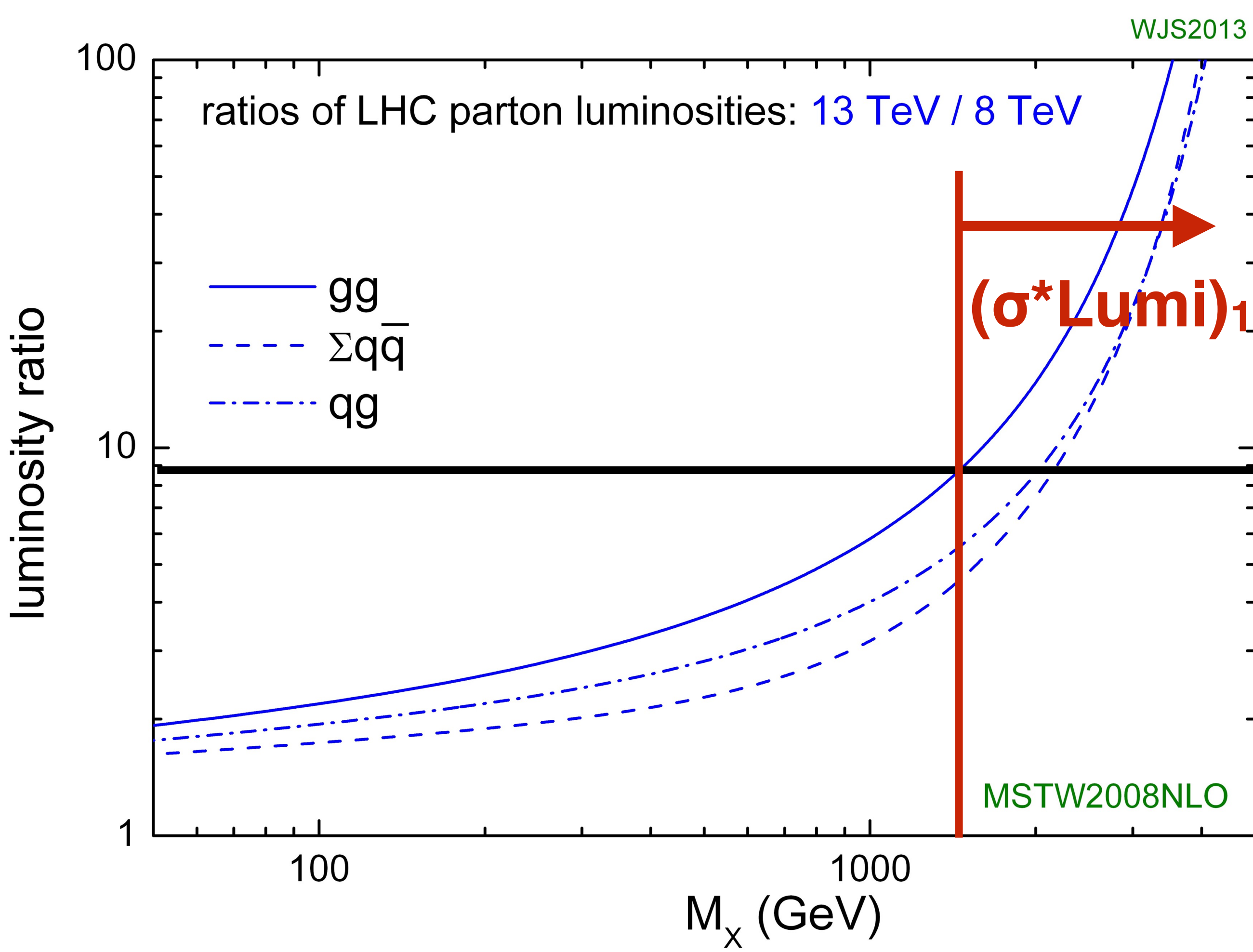




~20 fb^{-1} of p-p collisions
no sign of SUSY…

Run 2

- Higher LHC beam energy gives a boost for the production of high mass particles
    - great opportunity for SUSY searches
- With the 2015 dataset (CMS) ⇒ expect larger production of SUSY particles with $\mathbf{m_{Susy}} \gtrsim$ **700 GeV** with respect to Run 1



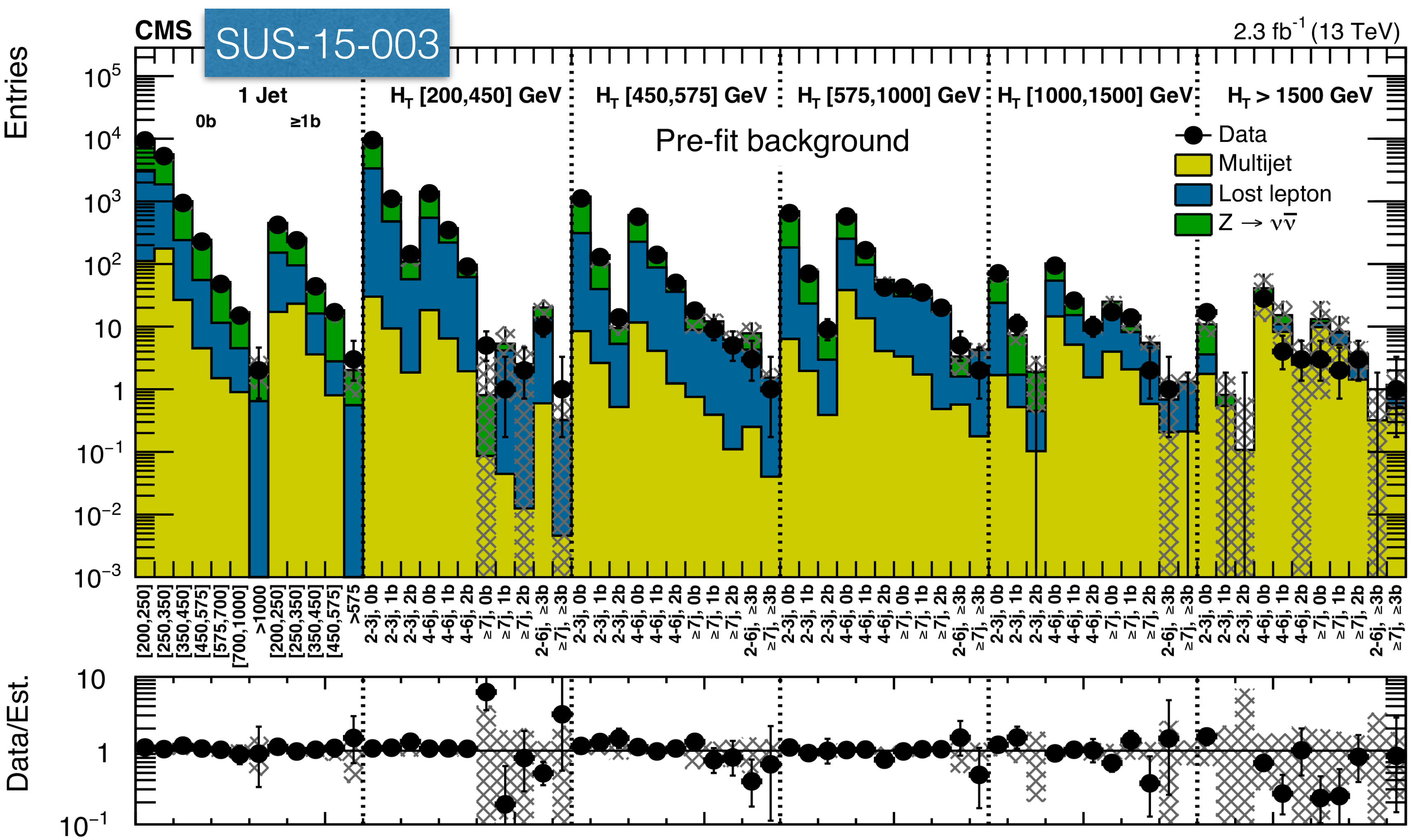
$(\sigma^*\text{Lumi})_{13TeV} > (\sigma^*\text{Lumi})_{8TeV}$

$\text{Lumi}_{8TeV}/\text{Lumi}_{13TeV} \sim 9$

$m_{Susy} \sim 700$ GeV

Inclusive searches

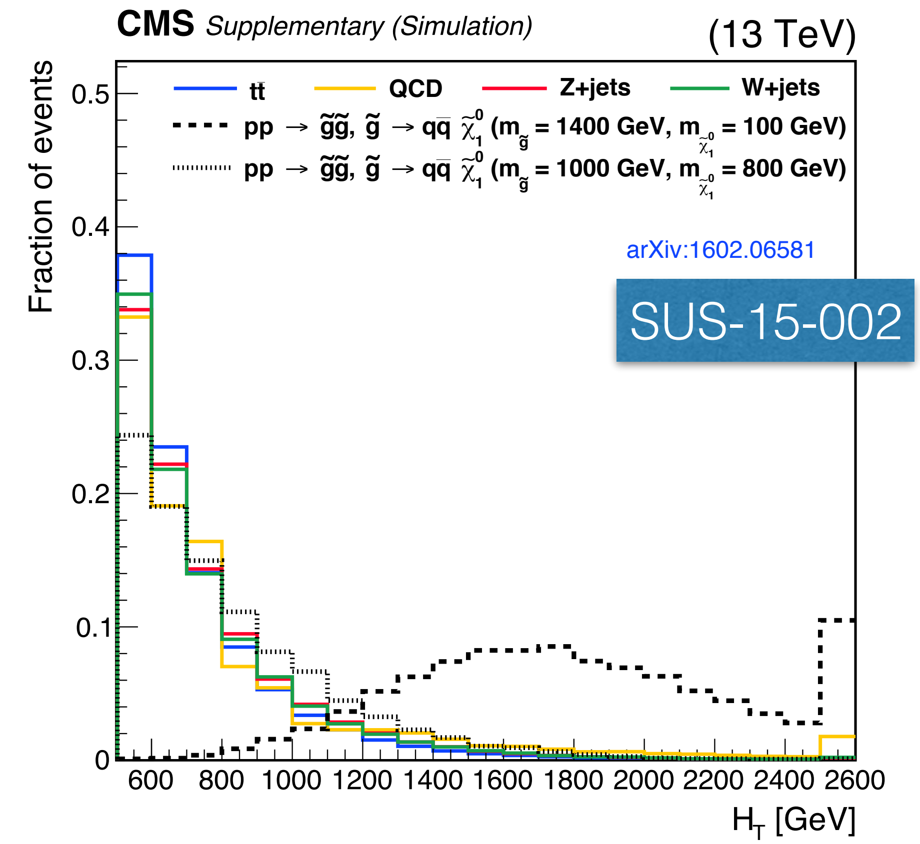
- "Inclusive" vs. "dedicated" searches
  - Looser selection ⇒ larger phase space
  - Finer event categorisation: sensitivity to wide variety of signal topologies
- Inclusive searches typically explore all-hadronic final states
  - Razor analysis combines all-hadronic + 1-lepton
- The main result is a **test of the SM predictions**

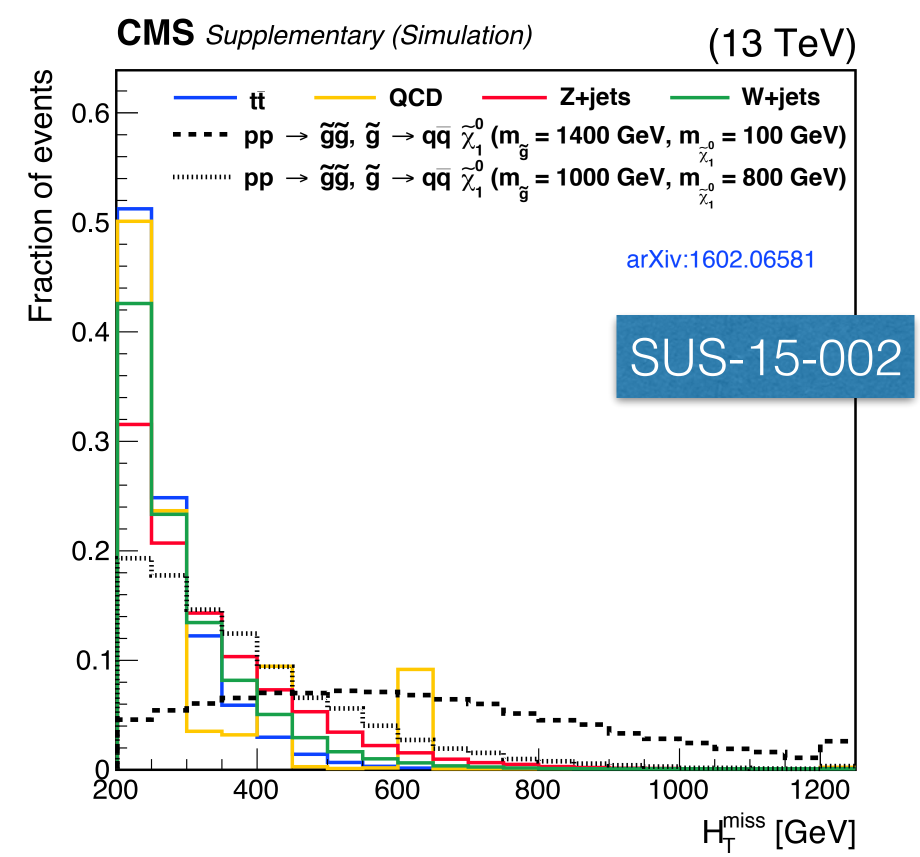


- **SUS-15-003 (M_{T2})**
  - arXiv:1603.04053
- **SUS-15-005 (α_T)**
  - PAS
- **SUS-15-002 (H_T^{miss})**
  - arXiv:1602.06581
- **SUS-15-004 (Razor)**
  - PAS

Search variables: n_{jet}, n_b, H_T, MHT

- Several variables are used to discriminate against the background
  - **n_{jet}**: gluino models have large jet multiplicity (smaller for squark models)
  - **n_b**: b-tag multiplicity improves the sensitivity to heavy flavour decays
  - $H_T = \sum_{jet} p_{T,jet}$ decay products from heavy particles cause large hadronic activity (decrease with mass splitting)
  - $H_T^{miss} = |\sum_{jet} \vec{p}_{T,jet}|$ proxy for missing transverse momentum, captures the presence of LSPs





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Search variables: α_T

Di-jet

$$\alpha_T = \frac{E_T^{j2}}{M_T}$$ ← sub-leading jet

Multi-jet

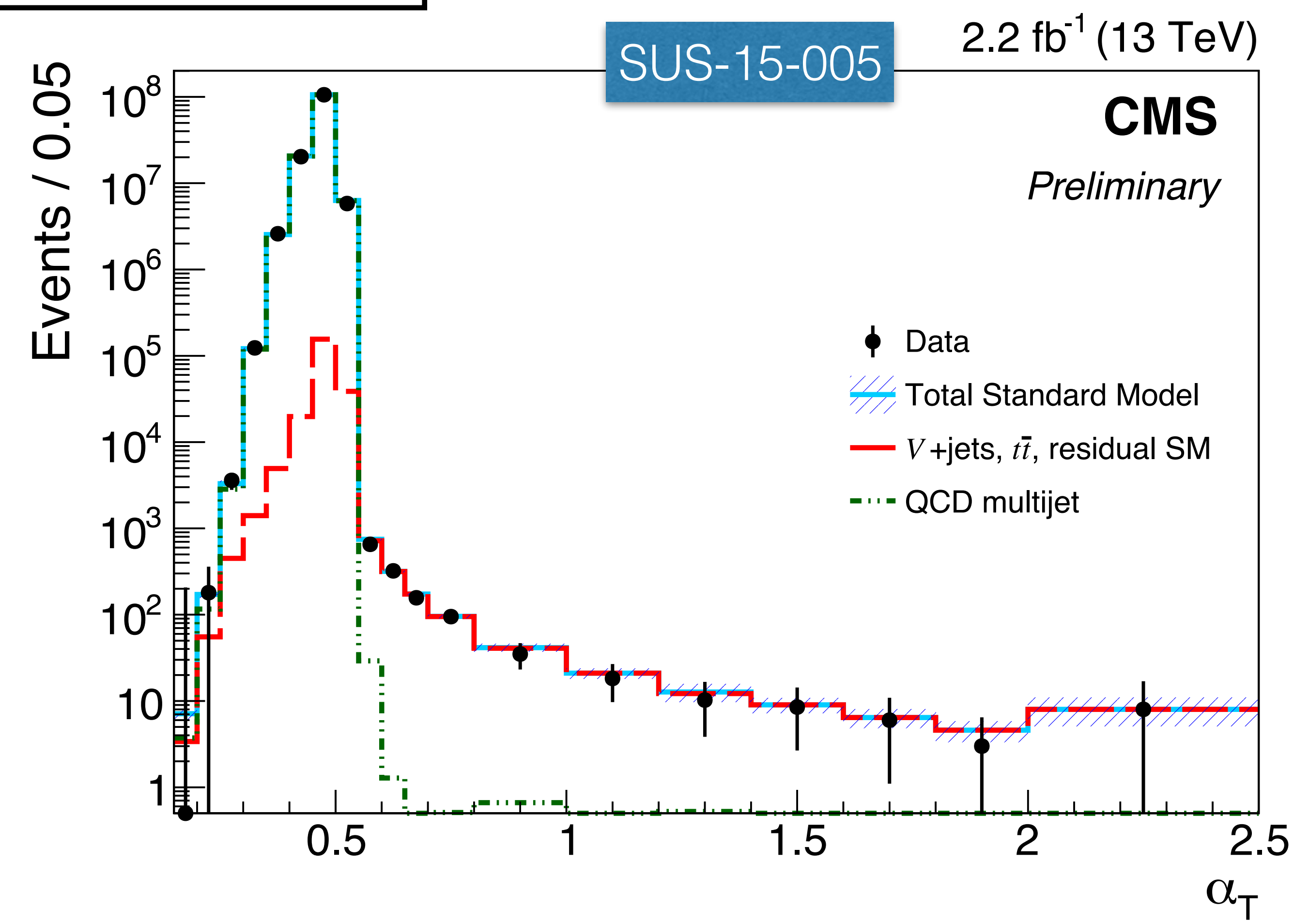
$$\alpha_T = \frac{1}{2} \times \frac{H_T - \Delta H_T}{\sqrt{{H_T}^2 - {\not{H}_T}^2}}$$

← collapse event into 2 pseudo-jet which minimise: $\Delta H_T = E_T^{j1} - E_T^{j2}$

$$\alpha_T \approx \sqrt{\frac{p_T^{j2}}{2p_T^{j1}} \frac{1}{(1 - \cos\Delta\phi_{1,2})}}$$

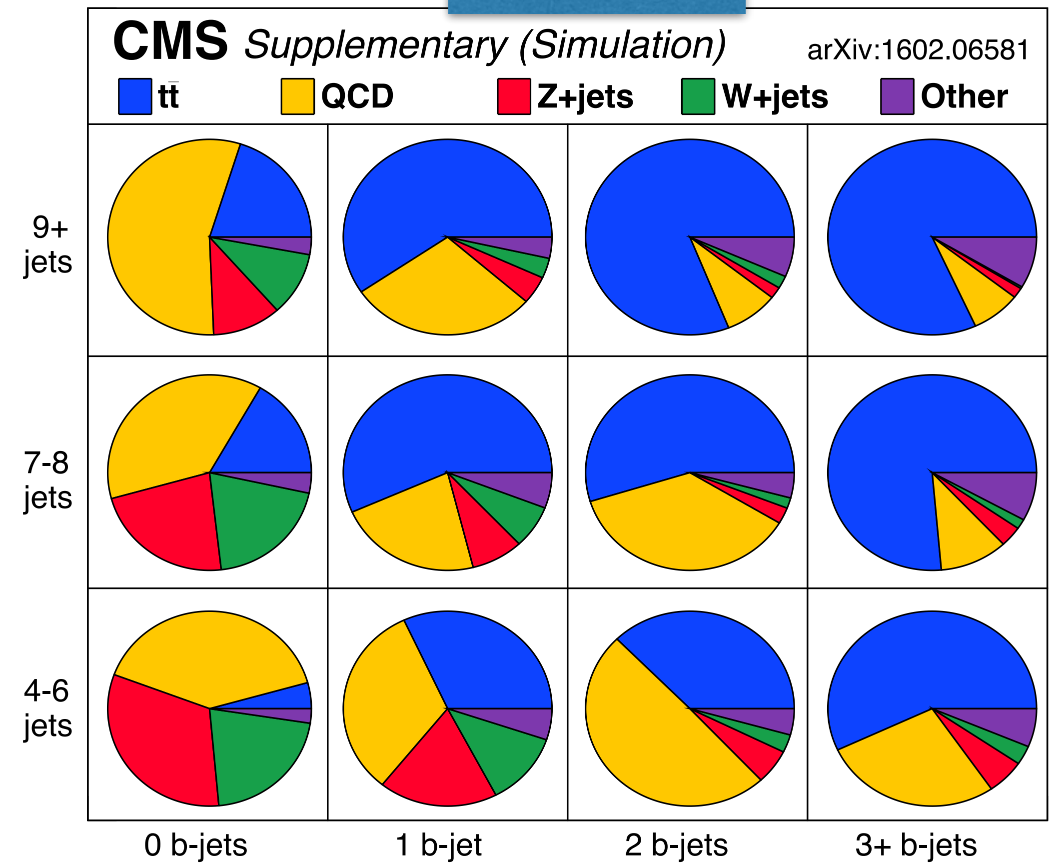
Effective in rejecting multi-jet background:

- back-to-back events ⇒ $\alpha_T = 0.5$
- "unbalanced" events ⇒ $\alpha_T < 0.5$
- genuine MET events ⇒ $\alpha_T > 0.5$



Backgrounds

SUS-15-002 (13 TeV)



- All analysis require significant <u>jet activity and missing transverse momentum (MET)</u>
- All-hadronic analyses <u>veto leptons and photons</u>
- After this selection, the remaining backgrounds are
  - **Multi-jet**: mainly from severe mis-measurements of the jet energy (“fake MET”)
  - **Z→νν**: most SUSY-like background
  - **“lost-lepton”**: W,tt + jets leptonic events where the lepton is not reconstructed
  - Rare backgrounds: single top,Di-boson,tt+Z,tt+W
- **Data-driven techniques** are used and little reliance on simulation is left

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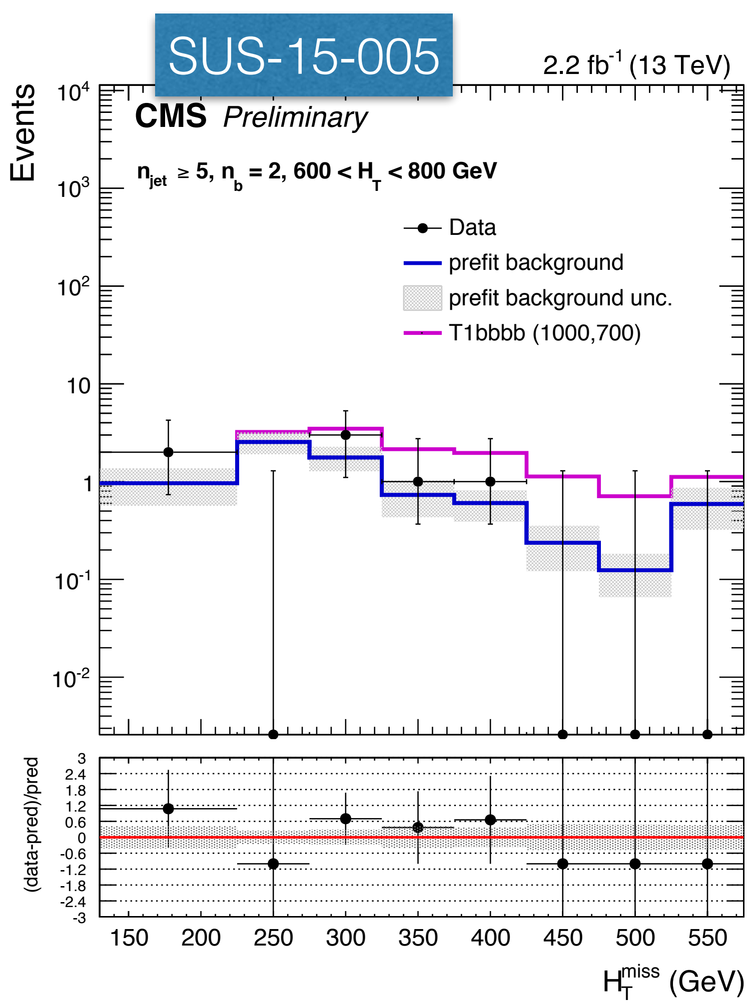
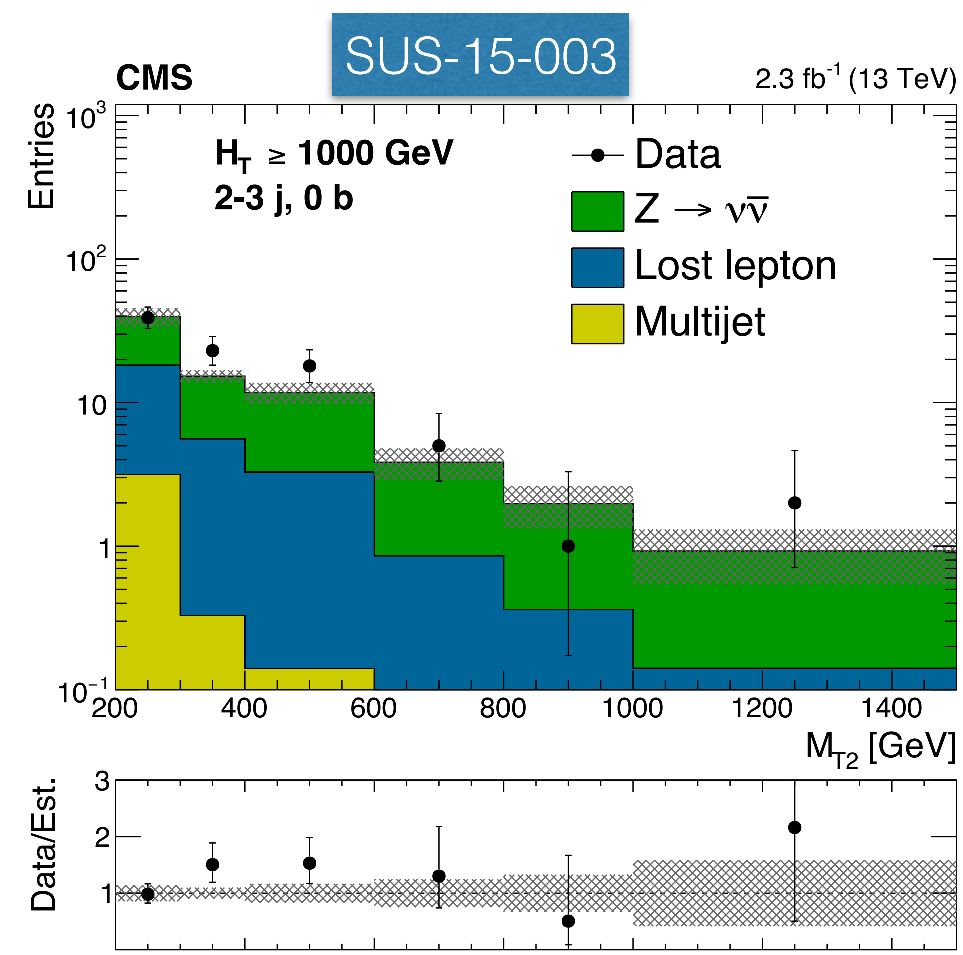
Results

- Results are presented as <u>compatibility with the SM</u> predictions over the whole signal region
- *No significant discrepancy is seen* and upper limits are set on the cross section of SUSY particle production, for different decays (next slide)
- Limits are extracted from a maximum-likelihood fit across all the signal region bins
  - CL_S criterium and Asymptotic formulae are used

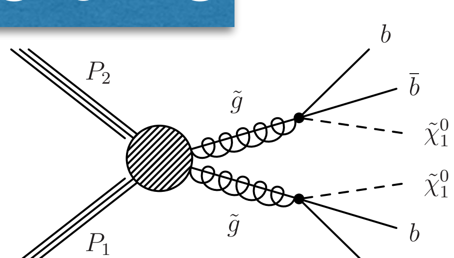




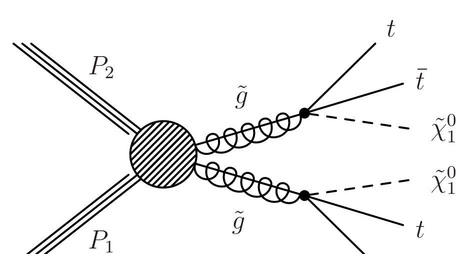
Simplified models

- Pair-production of SUSY particles (m_{Susy})
- One/two decay chains ending with LSP (m_{LSP})
  - in general, assume 100% BR to the specific decay
  - cross section (NLO+NLL) depends only on m_{Susy} (other particles are decoupled)
- Scan in (m_{Susy},m_{LSP})
  - if intermediate states ($\chi^{\pm}$) are injected, mass splitting with LSP is fixed

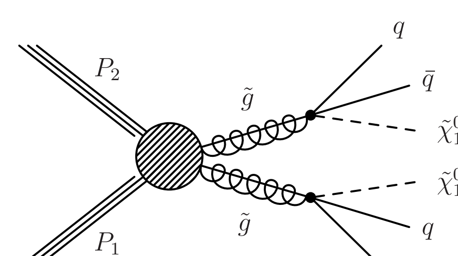
Gluino



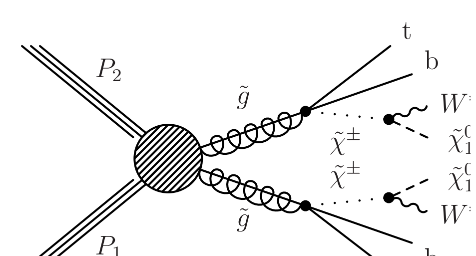
T1bbbb



T1tttt



T1qqqq



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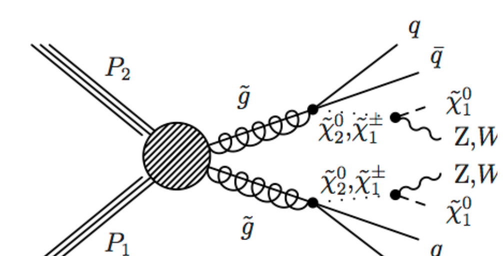
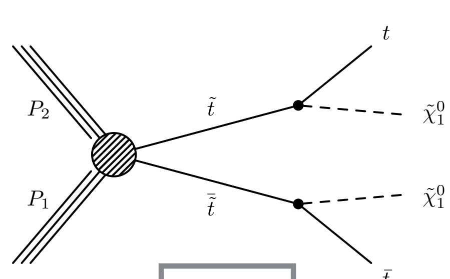
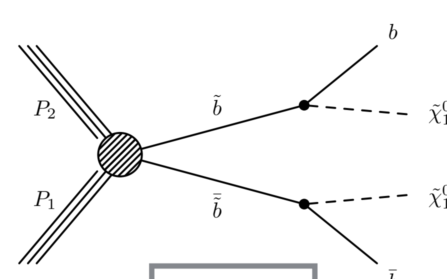


T5qqqqVV

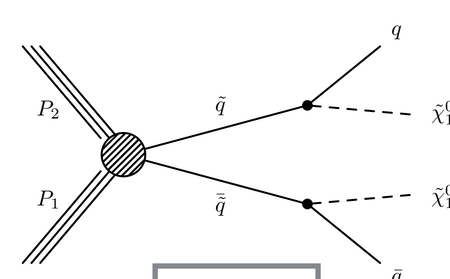
Squark



T2tt

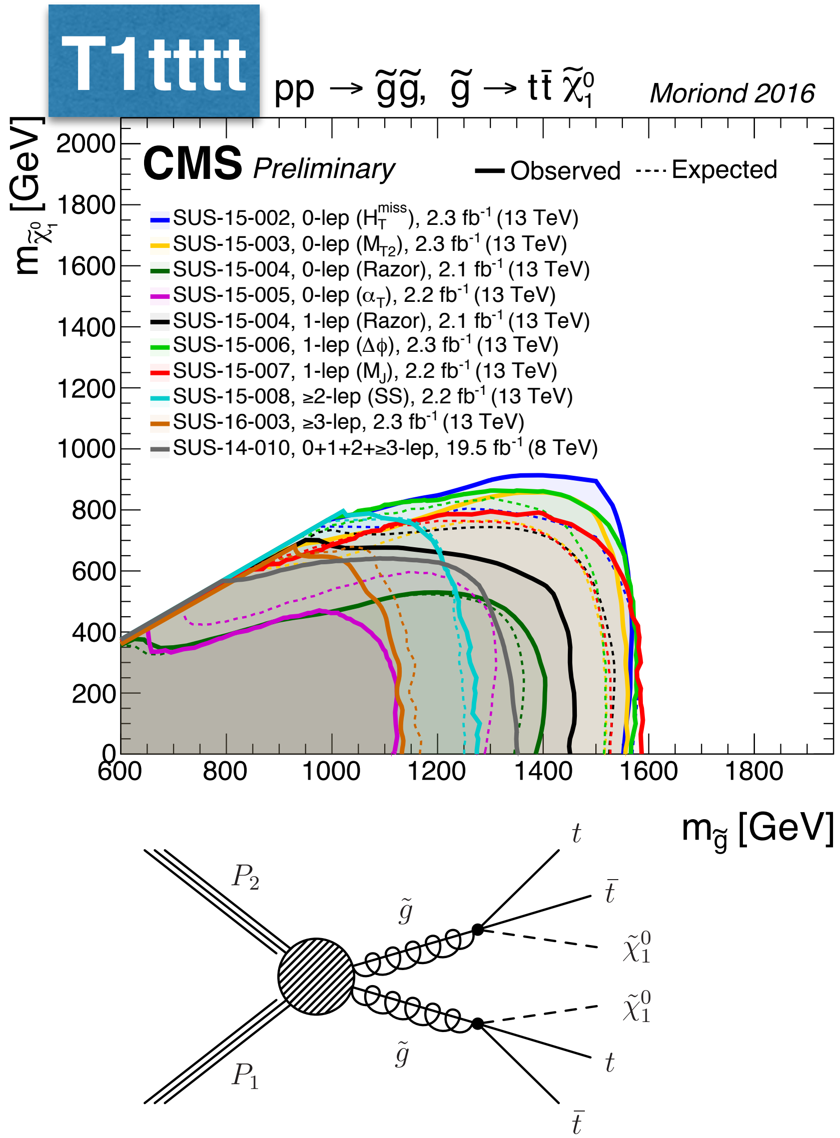


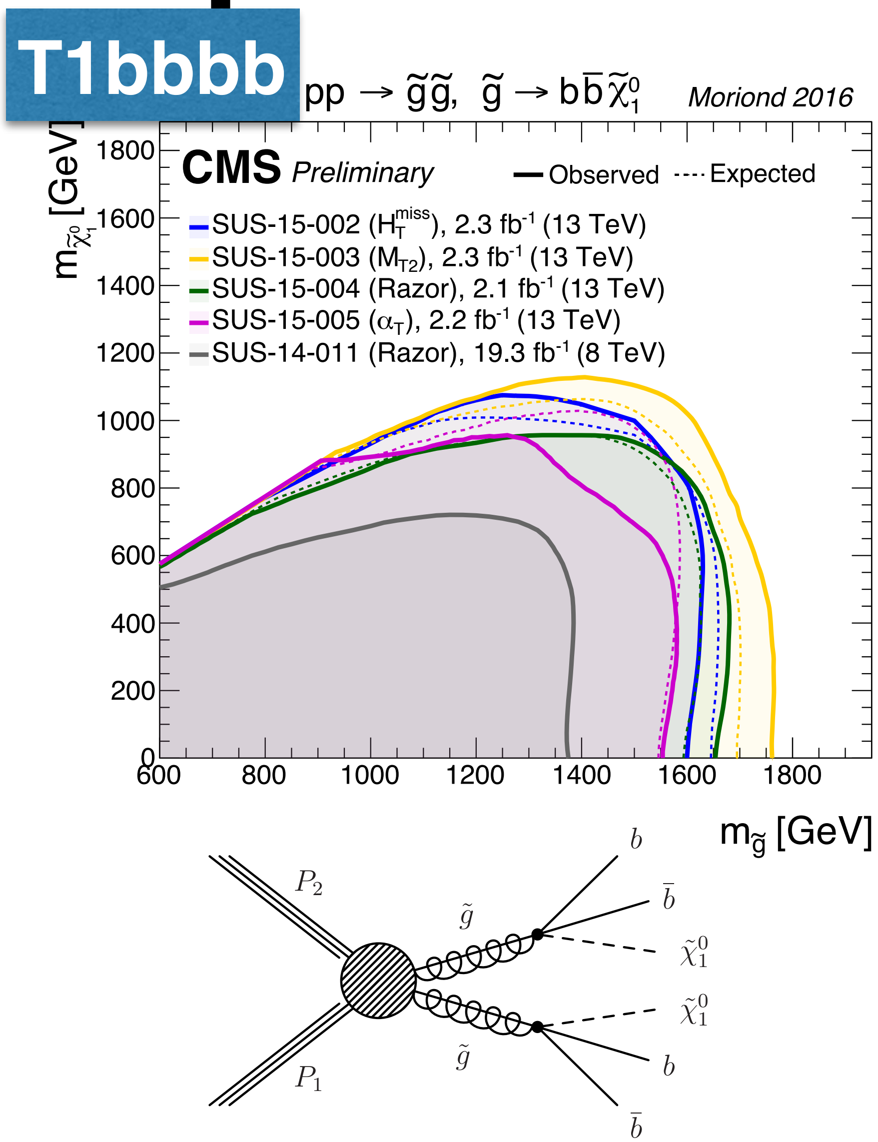
T2bb

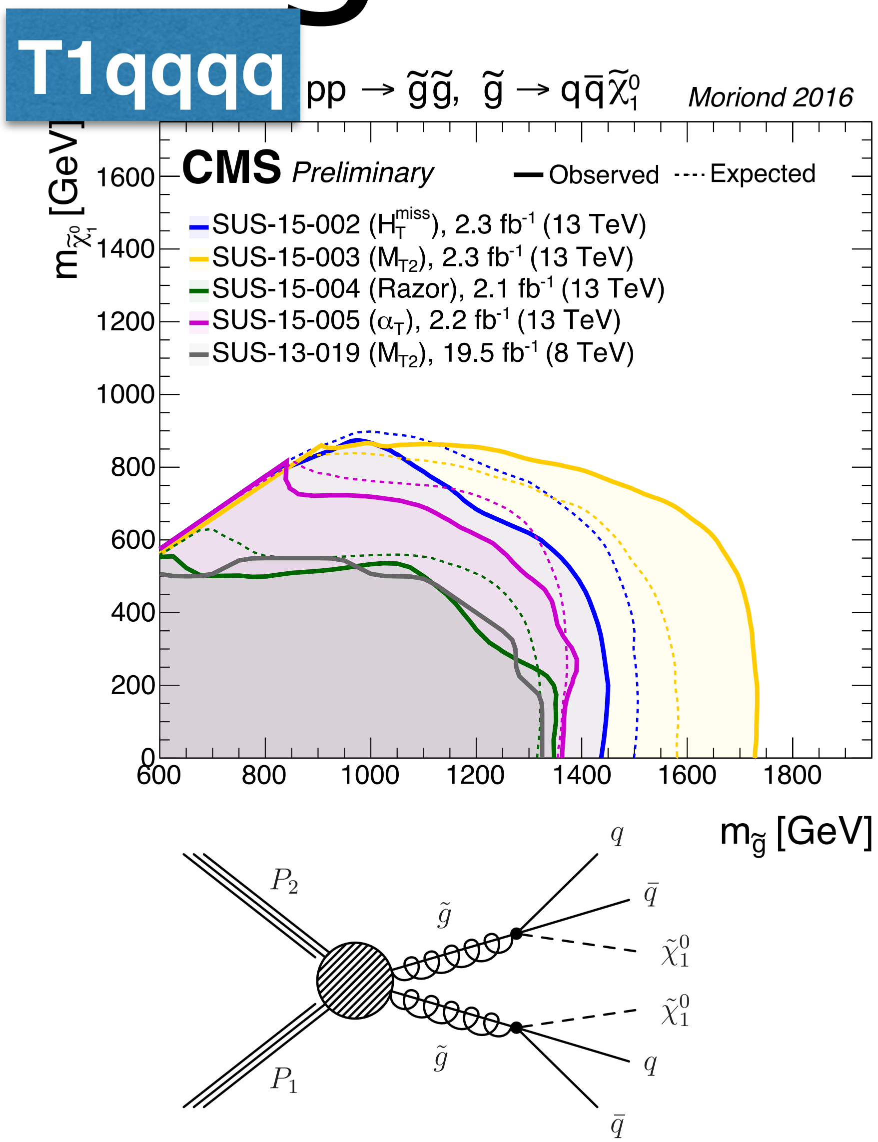


T2qq

Interpretation: gluino

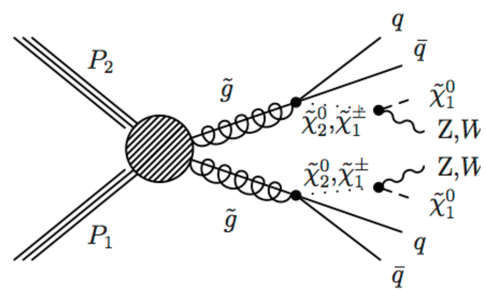


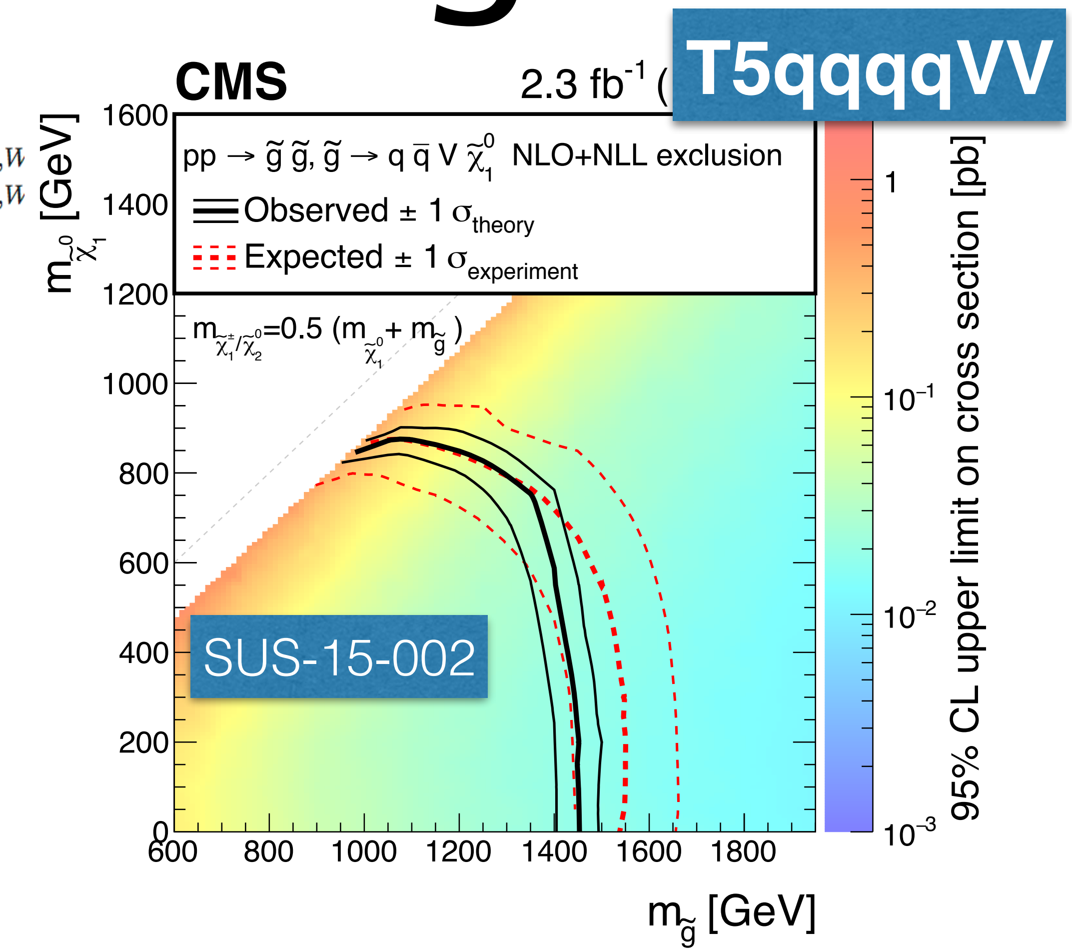




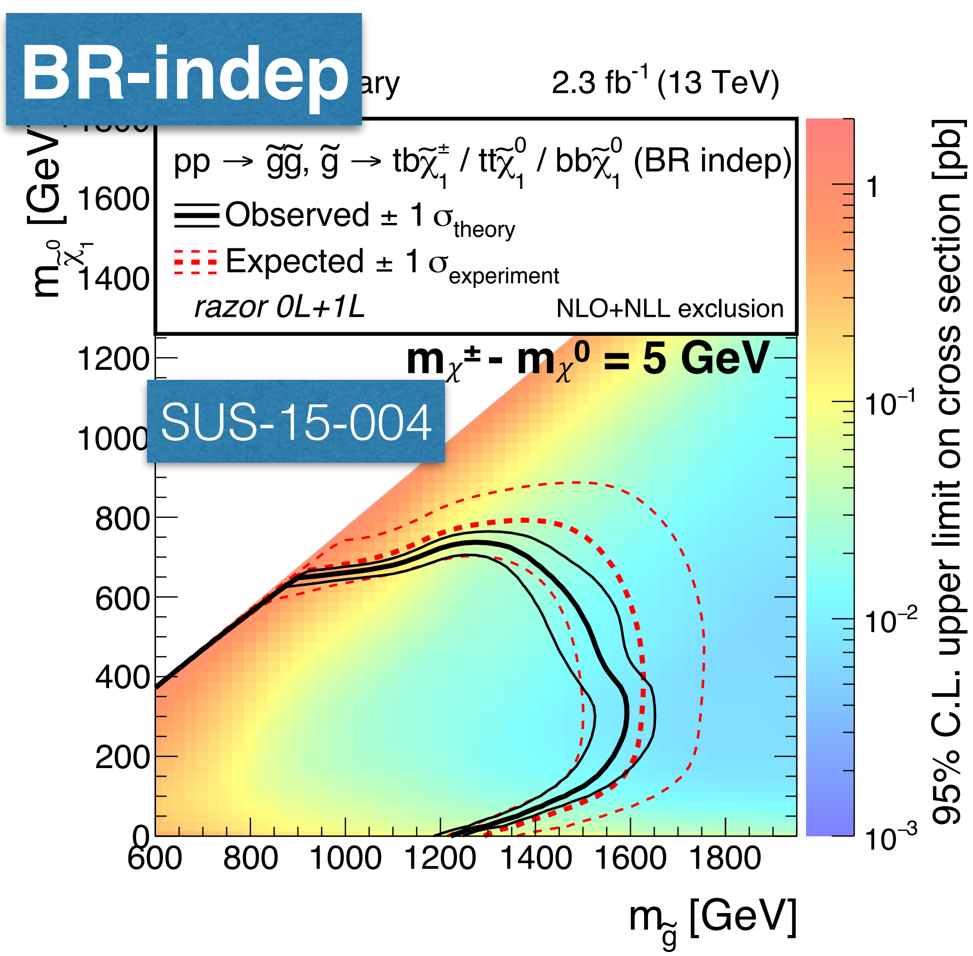
- **Gluino masses < 1.55-1.75 TeV are excluded,** at small LSP mass (depending on the final state)
- **LSP masses up to 900-1150 GeV are excluded**
- 8 TeV results (grey) are exceeded

Interpretation: gluino

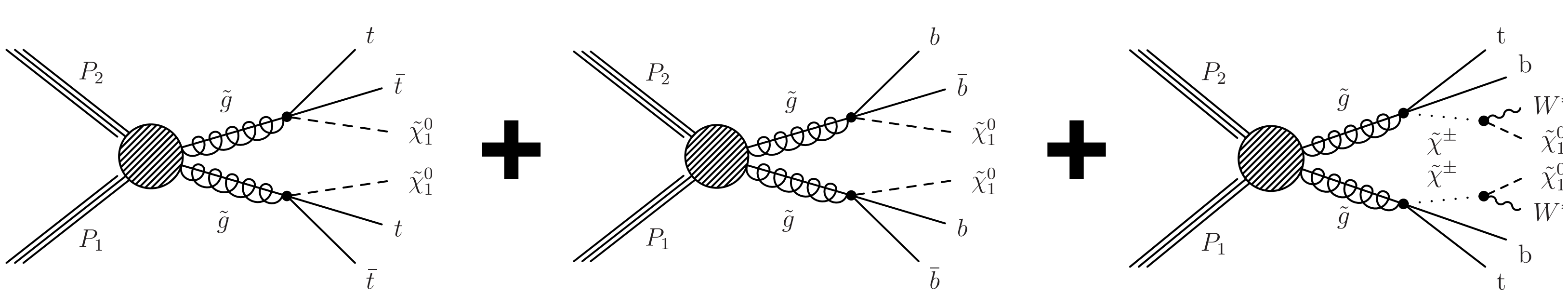




- **T5qqqqVV** = T1qqqq + intermediate state (chargino or NLSP)
- $m_{interm} = 0.5 \times (m_{LSP}+m_{Gluino})$



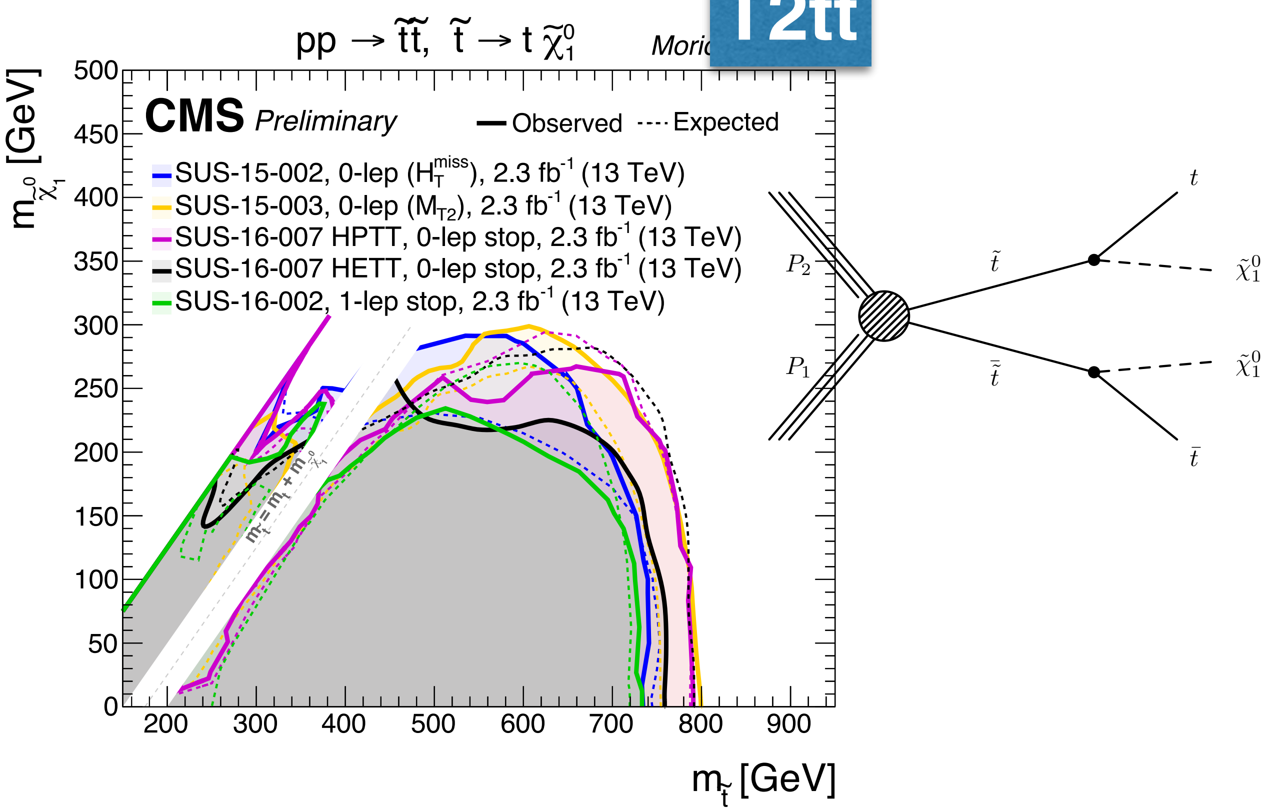
- **BR-independent gluino limit** is set in the (m_{Gluino}, m_{LSP}) considering all combinations of
  - BR(gluino→tt+LSP)
  - BR(gluino→bb+LSP)
  - BR(gluino→tb+chargino)



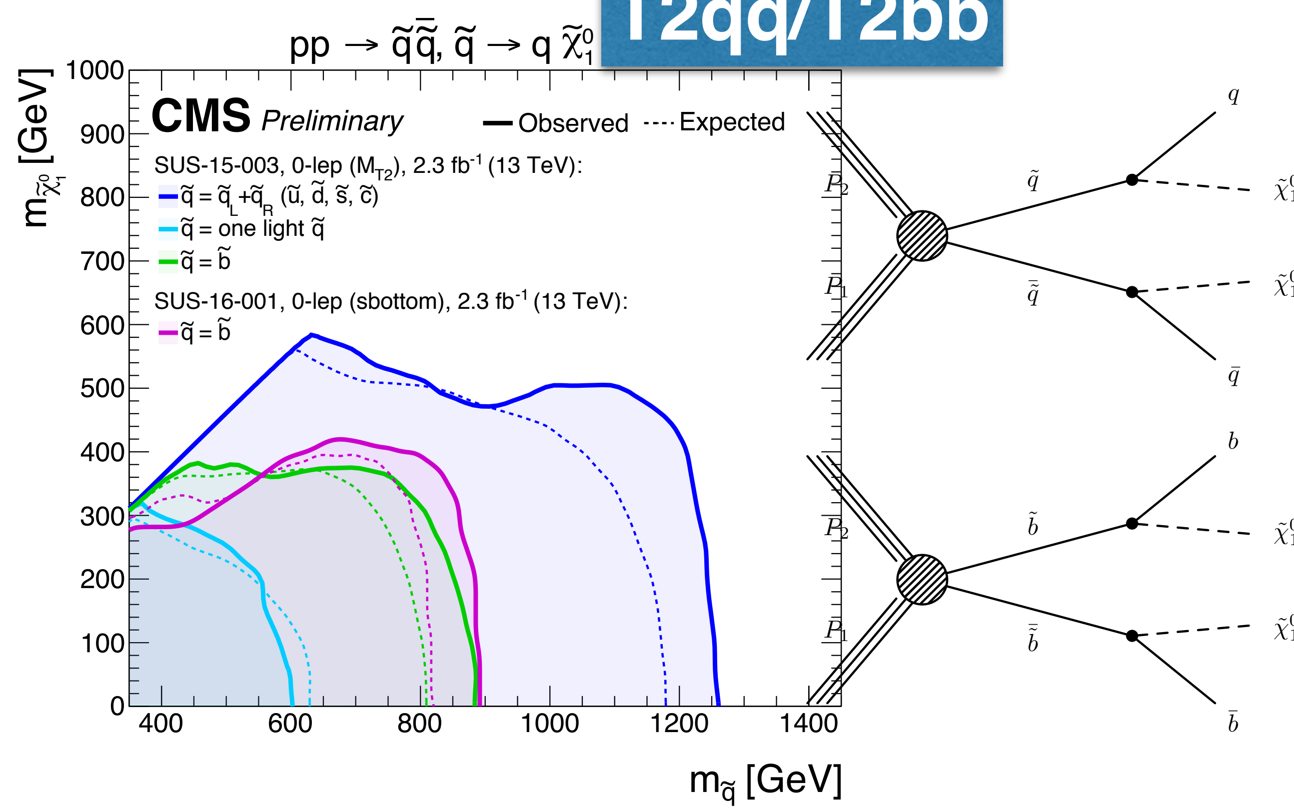
Interpretation: stop/sbottom/squark

- In CMS, dedicated searches for stop/sbottom exist (see talk by A. Garcia-Bellido)
- "Top corridor" ($\Delta m \simeq m_{top}$) excluded to allow more detailed studies (results to come soon)
  - $m_{Stop} < m_{top} + m_{LSP}$ (3-body decay): $\mathbf{m_{Stop} > 370}$ **GeV**
  - $m_{Stop} > m_{top} + m_{LSP}$ (2-body decay): $\mathbf{m_{Stop} > 800}$ **GeV** (small m_{LSP})
- For light squark 1-fold and 8-fold squark degeneracy
  - $\mathbf{m_{Squark} > 600}$ **GeV** and $\mathbf{m_{Squark} > 1250}$ **GeV** (small m_{LSP})
  - $\mathbf{m_{Sbottom} > 900}$ **GeV** (small m_{LSP})

T2tt



T2qq/T2bb



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Summary

- The **Run2** of the LHC is a unique opportunity to look for the production of new particles
- The results of the **inclusive all-hadronic SUSY searches in CMS** have been presented
- No significant deviation from the SM prediction is observed
- Limits are set on the production cross section of gluinos, stops and squarks using the Simplified Model framework
  - exclude **gluinos** with mass up to 1.75 TeV
  - exclude **stops** with mass up to 800 GeV
  - exclude **squarks/sbottoms** with mass up to 1250/900 GeV
- New interesting results results coming soon: stay tuned!

Additional material

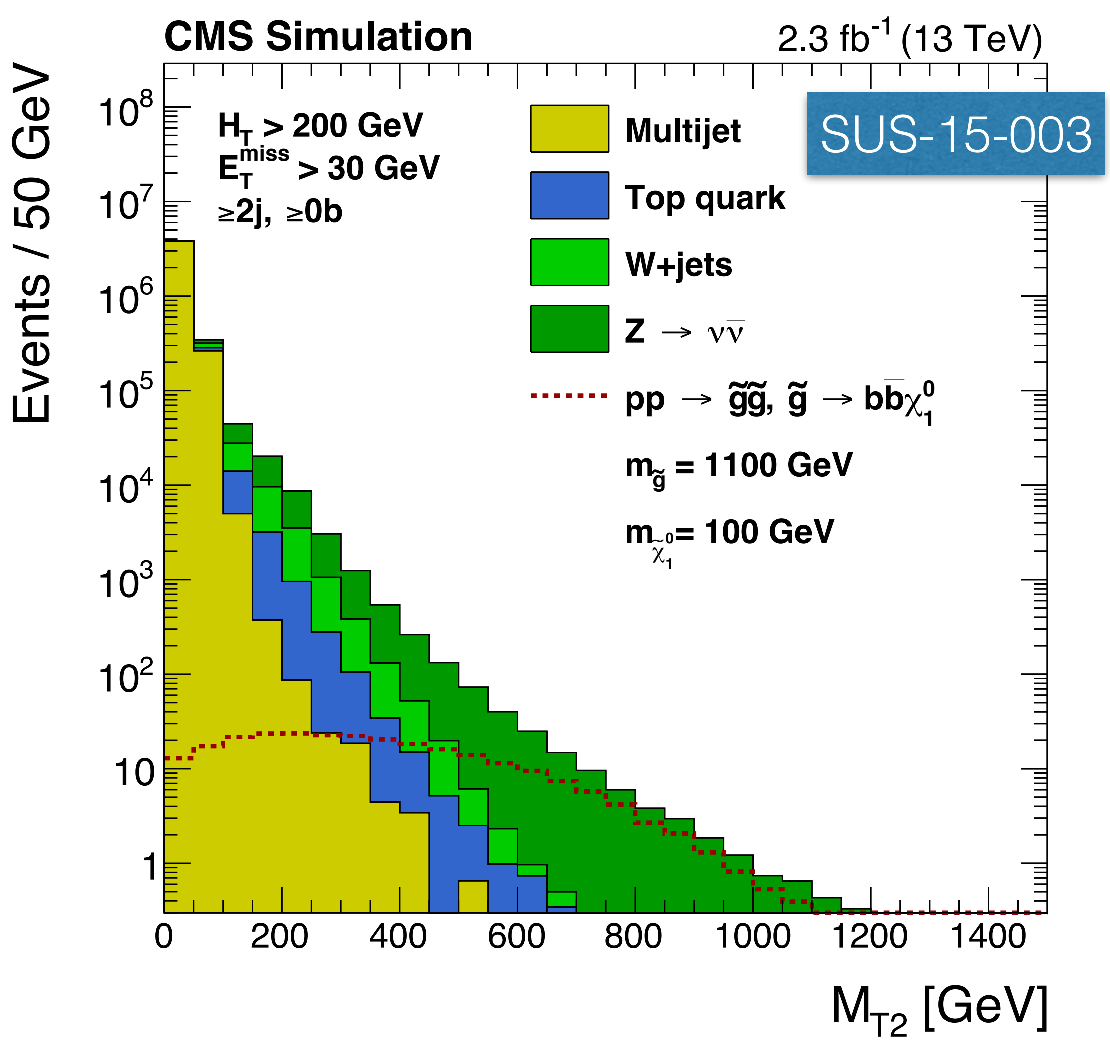
Search variables: MT2

Jets are clustered into 2 *visible system* ("hemisphere" algorithm, min. Lund distance)

$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}X(1)} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}X(2)} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left[\max\left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)} \right) \right]$$

$$(M_{\mathrm{T}}^{(i)})^2 = (m^{\mathrm{vis}(i)})^2 + m_{\tilde{\chi}}^2 + 2\left(E_{\mathrm{T}}^{\mathrm{vis}(i)} E_{\mathrm{T}}^{\tilde{\chi}(i)} - \vec{p}_{\mathrm{T}}^{\,\mathrm{vis}(i)} \cdot \vec{p}_{\mathrm{T}}^{\,\tilde{\chi}(i)} \right)$$

$$M_{\mathrm{T2}} \approx \sqrt{2 p_T^{j1} p_T^{j2} (1 + \cos\Delta\phi_{1,2})}$$



- Introduced to measure the mass of pair-produced particles decaying to the same undetected particle
- Intrinsically protects against mis-measurement of jets ("fake MET")

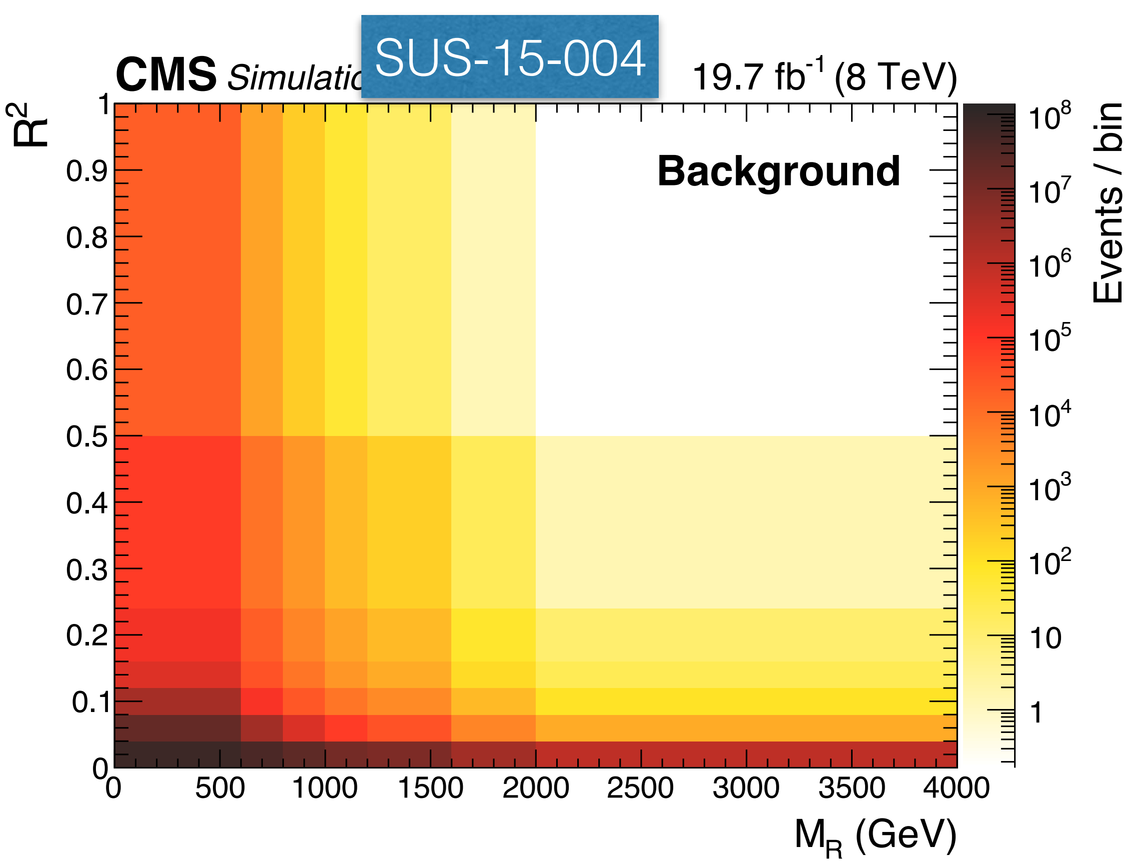
Search variables: Razor

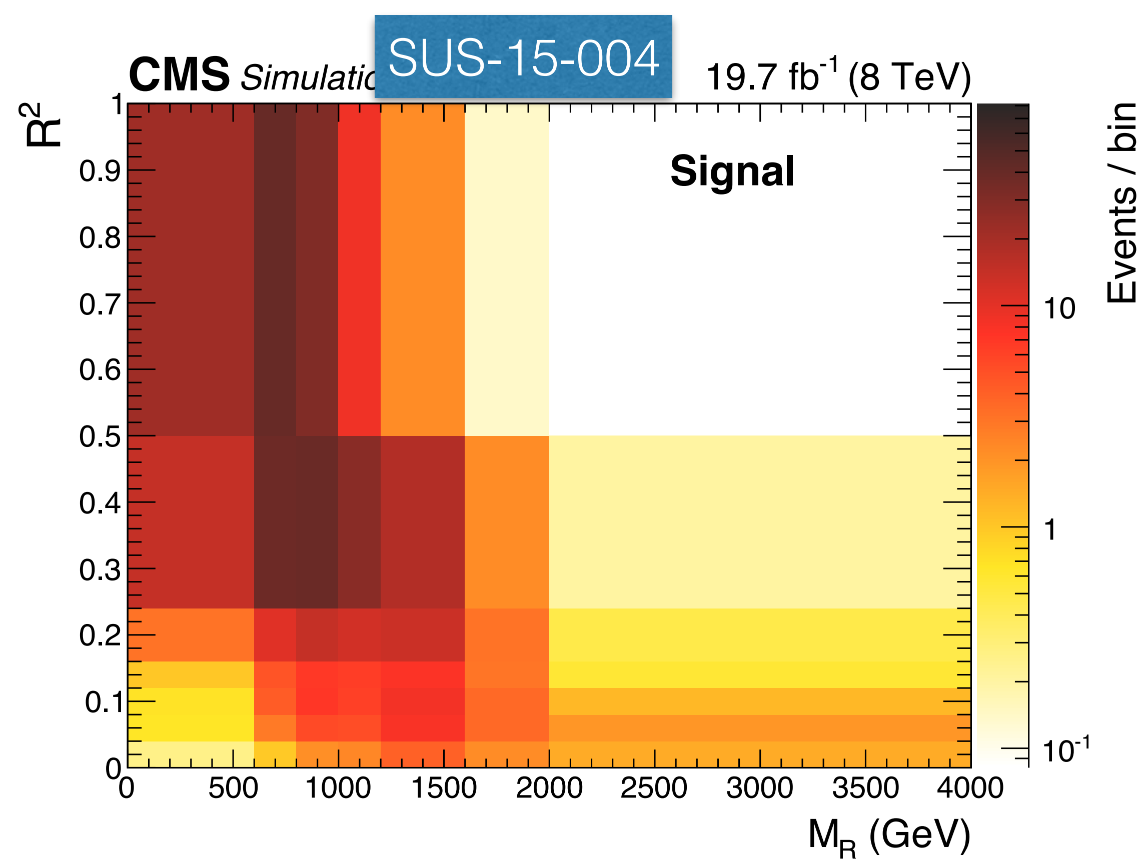
Objects are clustered into 2 *megajets* (min. sum of invariant mass)

$$M_R \equiv \sqrt{(P_{j_1} + P_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2} \qquad R^2 \equiv \left(\frac{M_T^R}{M_R}\right)^2$$

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

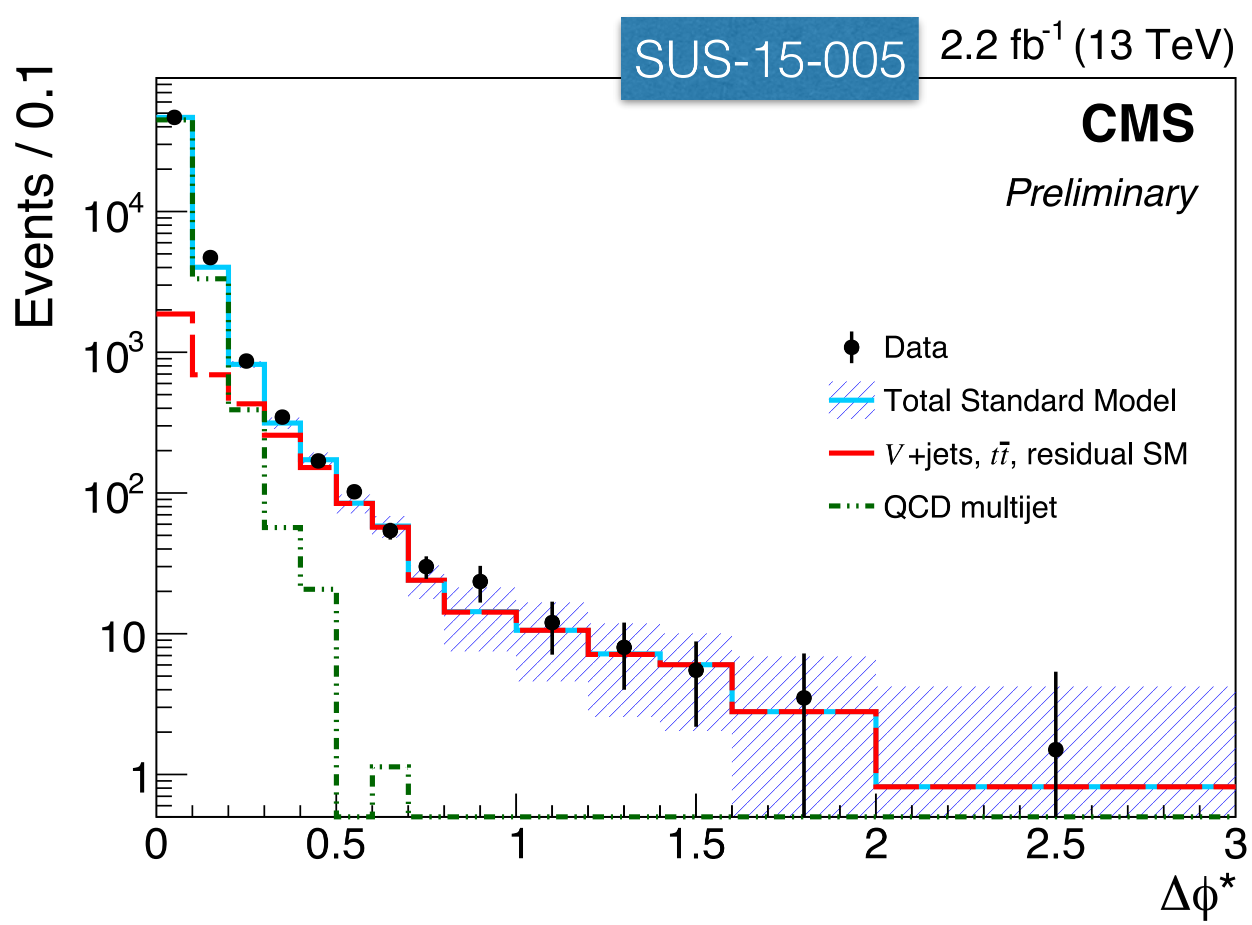
- M_R peaks at ~ $(m_{Squark} - m_{LSP})/m_{Squark}$ for signal
  - exponential fall for background
- R^2 is a proxy for MET





$\Delta\phi^*_{min}$

- Minimum $\Delta\phi$ between jet and the MHT vector computed without that jet ("biased MHT")
  - among ALL jets in the event
- Very robust even against severe under/over mis-measurement
  - as MHT is expected to be aligned with the mis-measured jet
- Mis-reconstructed jets and jets with significant neutrino component peak at low $\Delta\phi^*$



Transfer factors

- Most analyses employ the "transfer factor" (TF) method for background prediction
- Control regions (CR) in data are used to predict backgrounds in the signal region (SR)
  - CR selection and binning closely resembles SR, mainly differing for relaxing photon/lepton veto
  - ɣ+jets, l+jets, ll+jets
- **TF in simulation** is used to translate CR observation in data to background predictions in SR

Example: α_T analysis

$$N_{\mathrm{pred}}^{\mathrm{signal}}(n_{\mathrm{jet}}, n_{\mathrm{b}}, H_{\mathrm{T}}) = \frac{N_{\mathrm{MC}}^{\mathrm{signal}}(n_{\mathrm{jet}}, n_{\mathrm{b}}, H_{\mathrm{T}})}{N_{\mathrm{MC}}^{\mathrm{control}}(n_{\mathrm{jet}}, n_{\mathrm{b}}, H_{\mathrm{T}})} \times N_{\mathrm{obs}}^{\mathrm{control}}(n_{\mathrm{jet}}, n_{\mathrm{b}}, H_{\mathrm{T}})$$

- Appropriate systematic uncertainties are assigned for the simulation modelling and (if needed) CR→SR extrapolations
- Additional binning (MHT) is usually taken from simulation with proper uncertainties

Z→νν: example

Example: M_{T2} analysis

- The γ+jets control region is used, with same baseline selection as the SR

$$N^{SR}_{Z\to\nu\bar{\nu}}\left(H_T, N_j, N_b, M_{T2}\right) = N^{CR}_{\gamma}\left(H_T, N_j, N_b\right)\, P_{\gamma}\left(H_T, N_j, N_b\right)\, f\, R^{Z/\gamma}_{MC}\left(H_T, N_j, N_b\right)\, k_{MC}\left(M_{T2}\right)$$

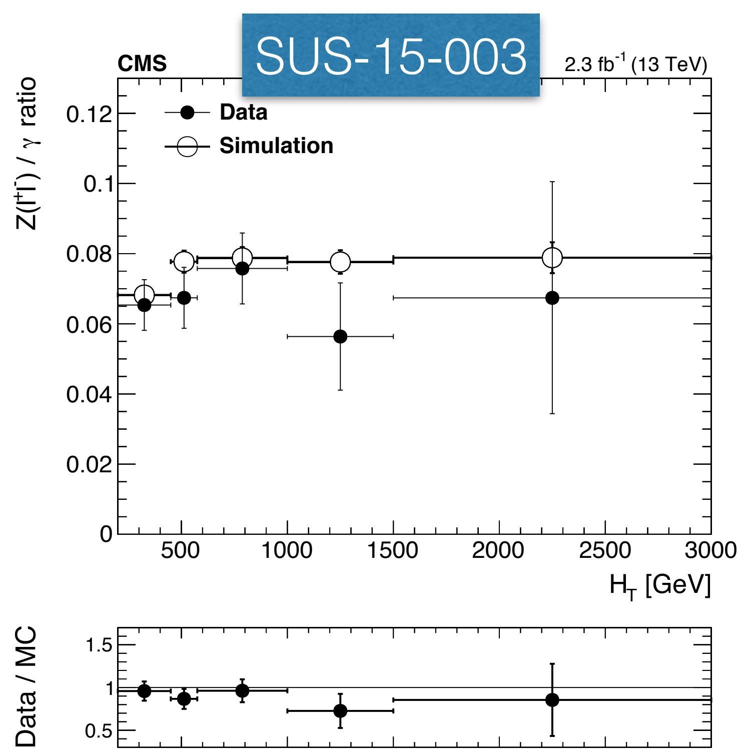
obs. in CR

purity (promp photons)

corr. for ΔR(γ,parton)>0.4 (simulation)

ratio of σ/ε (simluation)

Fraction of events in each M_{T2} bin



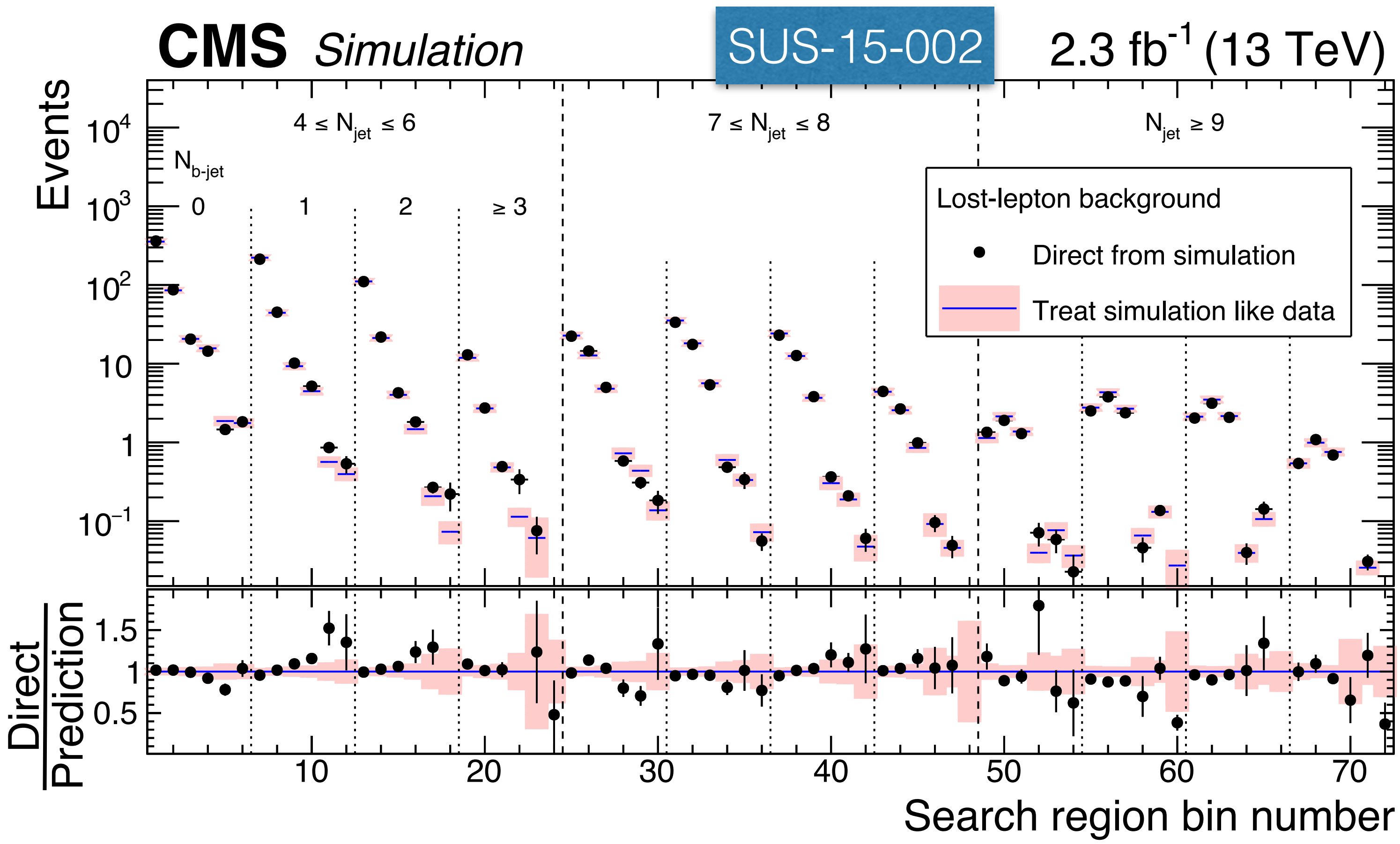
- Modelling of Z/γ ratio is checked in data in Z→μμ events
- Appropriate systematics are derived to cover offset/trends

lost-lepton: example

Example: H_T^{miss} analysis

- Single-muon/electron CR are selected in data by inverting the lepton veto and applying $M_T(l,MET) < 100$ GeV (reduce signal contamination)
- Yields in CR are re-weighted to account for the probability for a lepton to be "lost"
  - lepton acceptance, reconstruction, isolation
  - trigger efficiency
  - non-prompt electrons

SUS-15-002



- Two independent predictions are combined for the final estimates
- Systematic uncertainties cover: data/MC discrepancies, limited CR statistics, PDFs (acceptance), M_T efficiency

Multi-jet: example

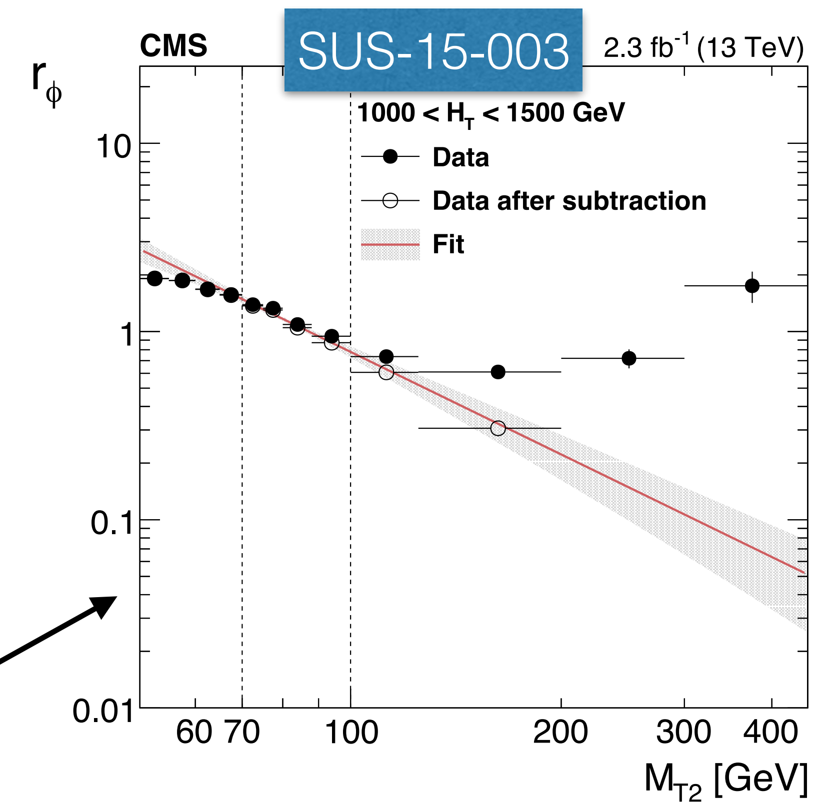
Example: M_{T2} analysis

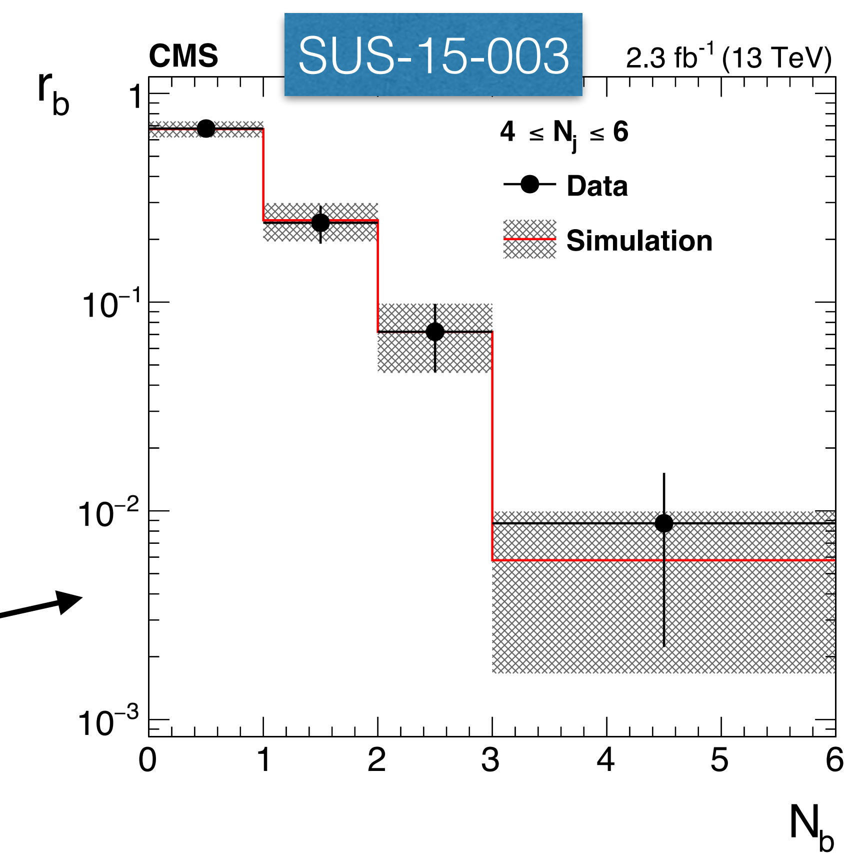
- A sideband in data is defined by inverting the $\Delta\phi_{min}$ cut ($\Delta\phi_{min}<0.3$)
- Ratio of passing/failing the $\Delta\phi_{min}$ derived with a power-law fit in M_{T2} sideband, in each H_T bin separately
- n_{jet}/n_b inclusive predictions are extrapolated to make predictions in each SR bin by measuring f_j and r_b in a (M_{T2},$\Delta\phi_{min}$) sideband in data

$$r_\phi(M_{T2}) = N(\Delta\phi_{min} > 0.3)/N(\Delta\phi_{min} < 0.3)$$

$$N^{SR}_{inc}(M_{T2}) = N^{CR}_{inc}(H_T)\, \boxed{r_\phi(M_{T2})}$$

$$N^{SR}_{j,b}(M_{T2}) = \boxed{N^{SR}_{inc}(M_{T2})}\, f_j(H_T)\, r_b(N_j)$$





Razor sideband fit

- The Razor analysis utilises a complementary approach to estimate the background in the signal region
  - fit to the data assuming a functional form for the the background shape in the (M_R, R^2) plane

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

$$f_{SM}^{3b}(M_R, R^2) = (1 + m_{M_R}(M_R - M_R^{offset})) f_{SM}^{2b}(M_R, R^2) \quad n_b \geq 3$$

  - for n=1 ⇒ exponential shape in both M_R and R^2 dimensions
- Fit is performed in sideband in (M_R, R^2) and cross-checked by using the full signal region
- Results of the fit-based analysis are used as cross-check of the nominal strategy (using TF method)

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Signal systematics

- The following systematics are considered for the signal (common to all CMS analysis)
  - Luminosity: 4.6%
  - Pile-up reweighting: 5% on Min. Bias cross section
  - ISR: 15% (30%) for 400 < p_T(Susy) < 600 GeV (p_T(Susy) > 600 GeV)
  - PDFs, factorisation/renormalisation scale

T1ttbb

- Limits on gluino decaying to top,bottom quarks can be computed with different assumptions on the relative BR

BR(g→tt+LSP) **+** **BR(g→bb+LSP)** **+** **BR(g→tb+chargino)**