Search for supersymmetry in multijet events with missing transverse momentum in proton-proton collisions at 13 TeV

Kevin Pedro (FNAL)

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arXiv:1704.07781

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- Limits

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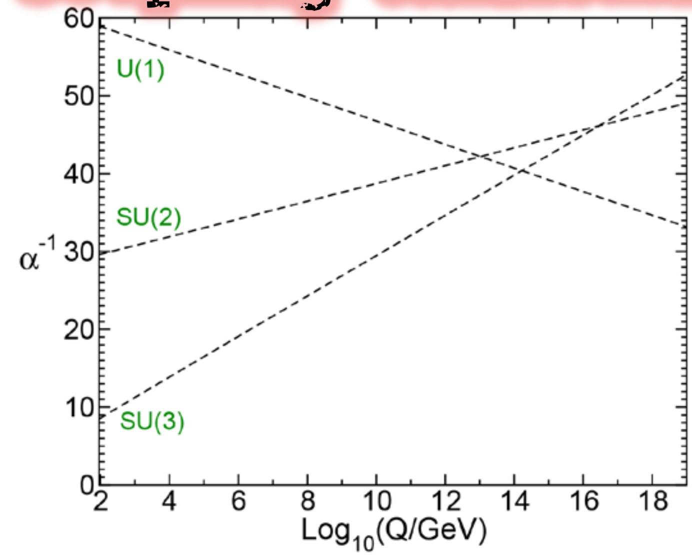
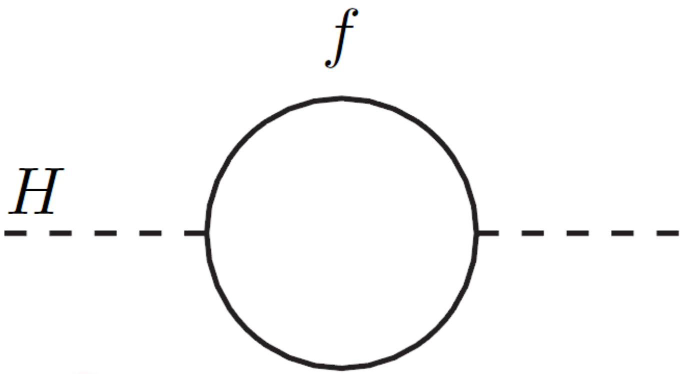
Beyond The Standard Model

Gauge Coupling Unification



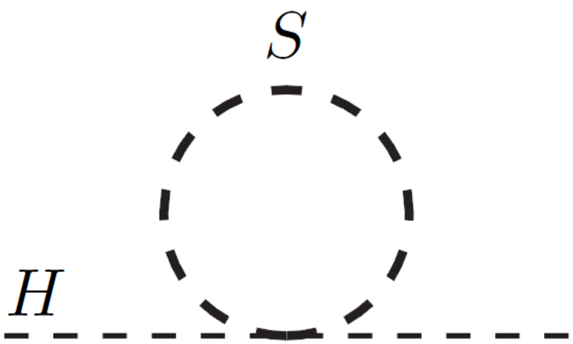


Hierarchy Problem

$$\Delta_f m_{\mathrm{H}}^2 = -\frac{|y_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \cdots$$

NASA, arXiv:astro-ph/0608407

SUSY Solves It All…

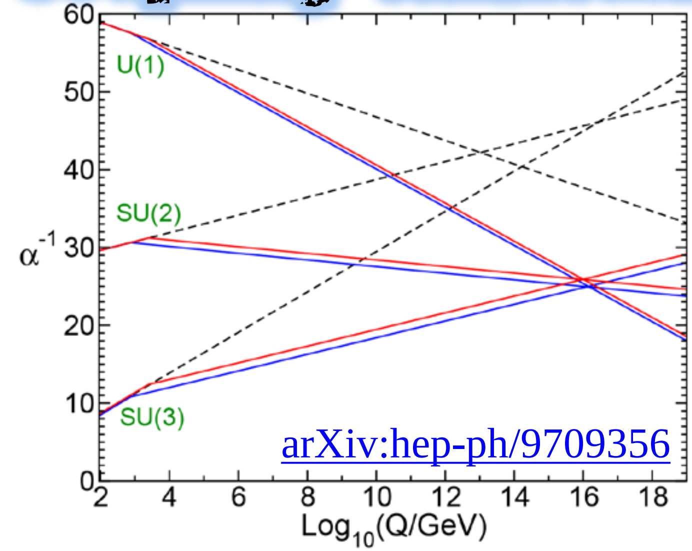


Hierarchy Problem

$$\Delta_S m_H^2 = \frac{y_S}{16\pi^2}\Lambda_{UV}^2 + \cdots$$

✓ Scalar partner(s) for every fermion
→ natural cancellation of Higgs mass divergences

Gauge Coupling Unification



Dark Matter

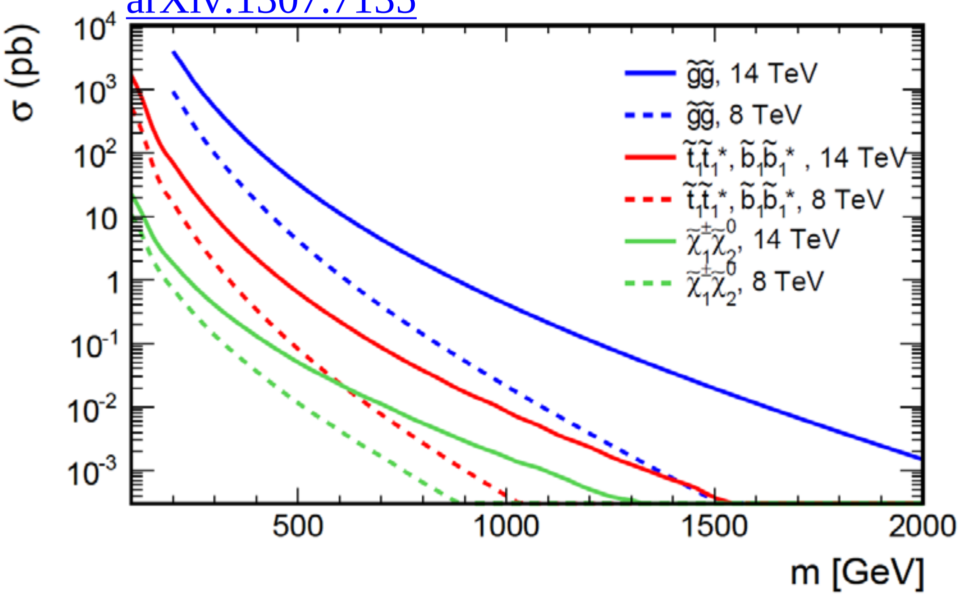
✓ Conserved symmetry between SM and SUSY particles implies lightest supersymmetric particle (LSP)

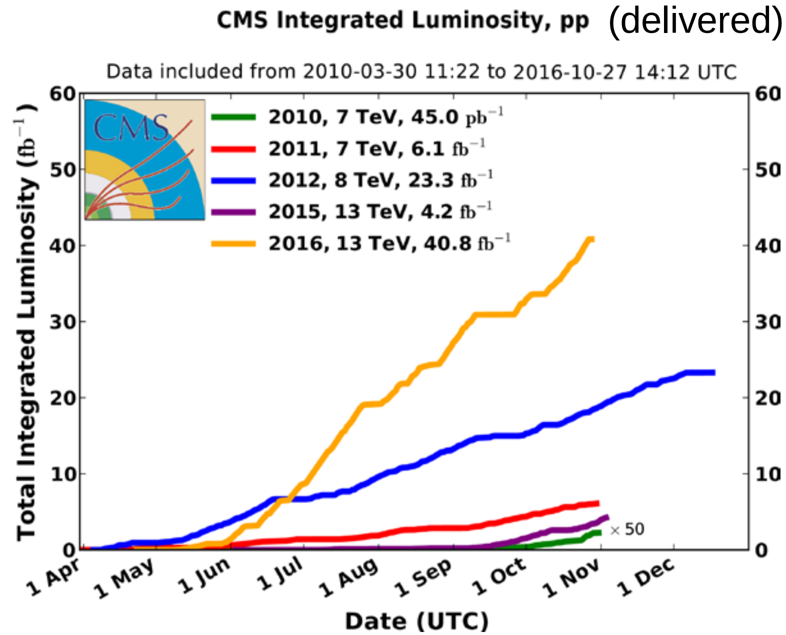
→ dark matter candidate: stable, weakly interacting, massive

… if we can find it!

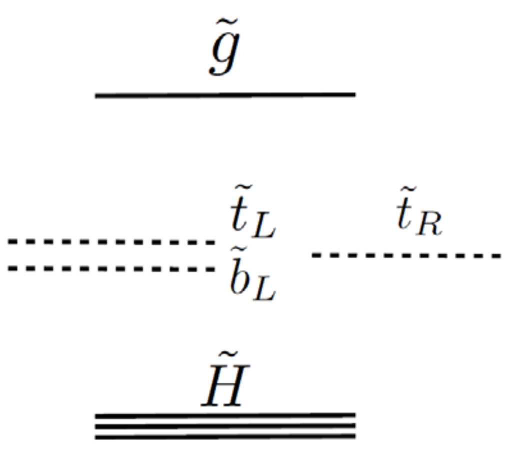
Search at 13 TeV

arXiv:1307.7135





- Gluino pair production expected to have highest cross section at LHC (squarks also strongly produced)
- Record-breaking LHC performance in 2016: ~36 fb^{-1} of 13 TeV data recorded by CMS and ATLAS
- Naturalness is one motivation to expect light† gluinos, stops, sbottoms, and higgsinos



natural SUSY

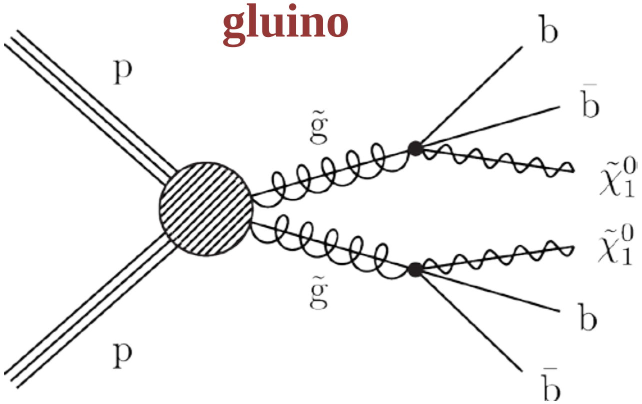
arXiv:1110.6926

†(electroweak scale)

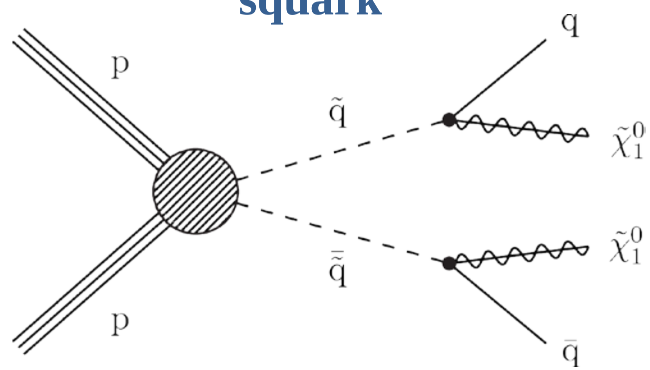
Simplified Model Spectrum

- Minimal supersymmetric model (MSSM) has *120* parameters
- *Simplified models*: only a few parameters, e.g. $m_{\tilde{g}}$, m_{LSP}
- Most SUSY particles given high masses → don't participate in interactions
- Isolate *important kinematics and topologies*
- LSP is taken to be the lightest neutralino $\tilde{\chi}_1^0$

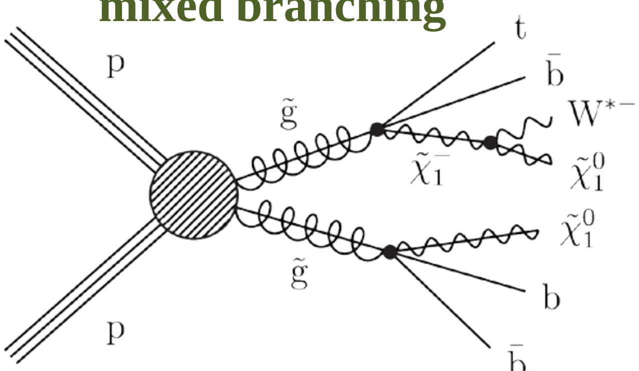
gluino



squark

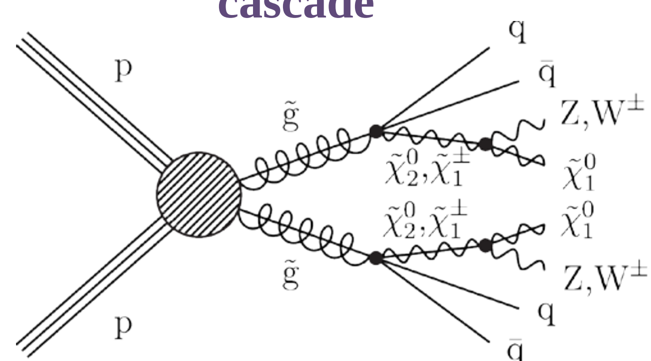


mixed branching



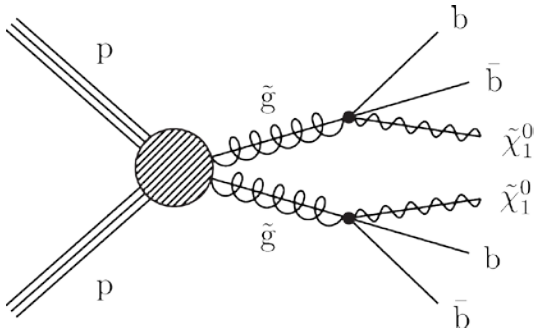
$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 5$ GeV

cascade



$m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} = ½(m_{\tilde{\chi}_1^0} + m_{\tilde{g}})$

Multijets + Missing Energy Analysis



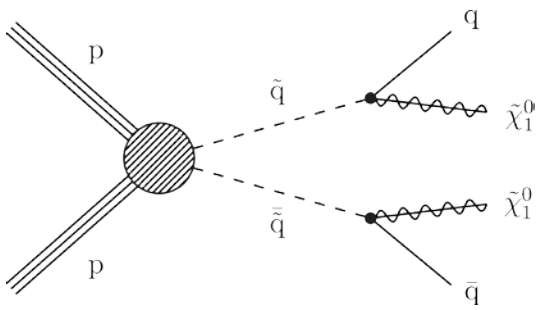
- Goal: cover many SUSY models and parameters

➢ Conduct a *general* and *inclusive* analysis

- Target hadronic final states (largest branching fractions)
- Prototypical signals: $\tilde{g}/\tilde{q} \rightarrow \mathrm{SM} + \tilde{\chi}_1^0$ (pair production)
- Design a search to exploit fundamental event properties:

multiplicity, flavor, visible energy, invisible energy

- Previous CMS results (13 TeV):
  - o CMS PAS SUS-16-014 (2016, ICHEP, 12.9 fb^{-1})
  - o *Phys. Lett. B* 758 (2016) 152 (2015, 2.3 fb^{-1})



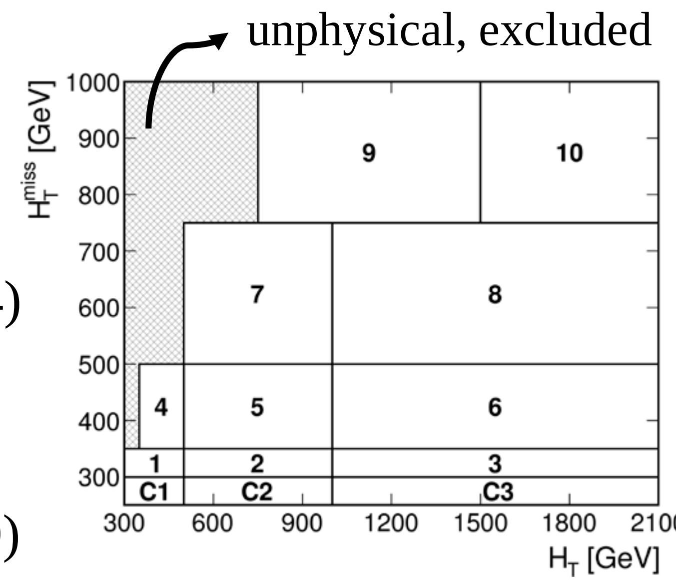
Strategy

Define four important variables:

- $\mathbf{N_{jet}}$ = # of jets
- $\mathbf{N_{b\text{-}jet}}$ = # of b-tagged jets
- $\mathbf{H_T} = \sum p_T^{jet}$

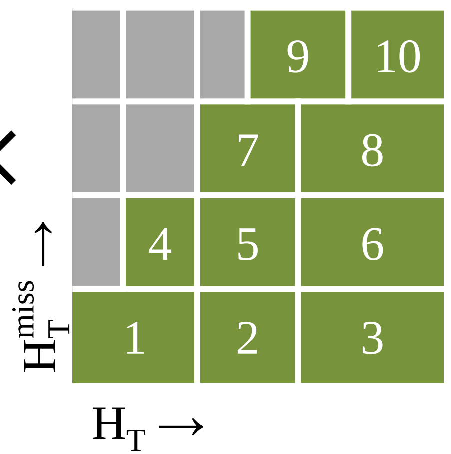
} (p_T > 30 GeV, $|\eta|$ < 2.4)

- $\mathbf{H_T^{miss}} = \left|-\sum \vec{p}_T^{\,jet}\right|$ (p_T > 30 GeV, $|\eta|$ < 5.0)



Bin the search region in these four variables:

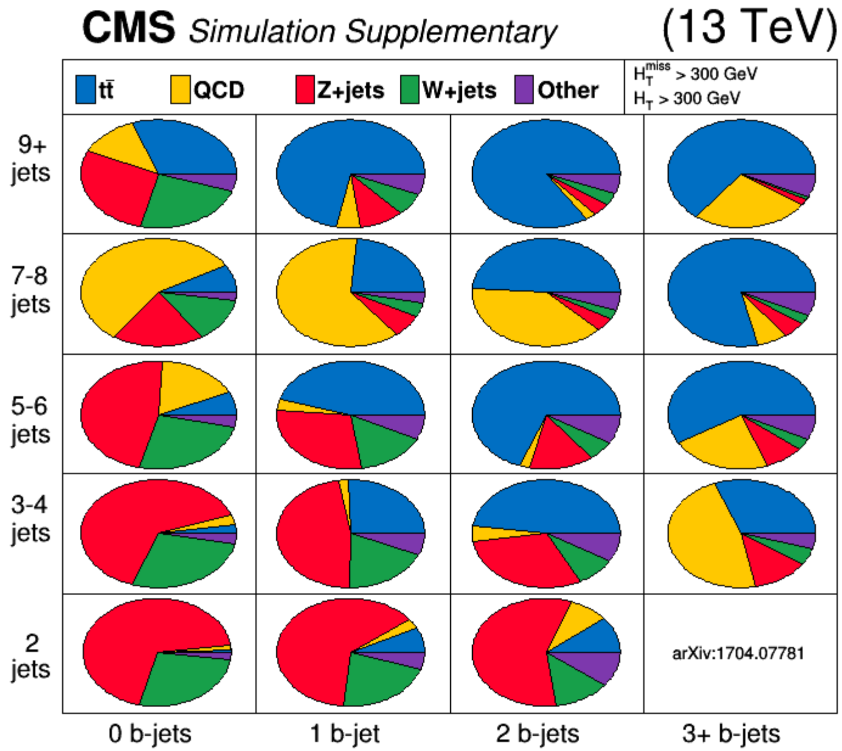
N_{jet}: 2 | 3–4 | 5–6 | 7–8 | 9+ × $N_{b\text{-}jet}$: 0 | 1 | 2 | 3+ ×



= 174 analysis bins

(no $N_{b\text{-}jet}$=3+ for N_{jet}=2, exclude H_T–H_T^{miss} bins 1 and 4 for $N_{jet}\geq$7)

Backgrounds



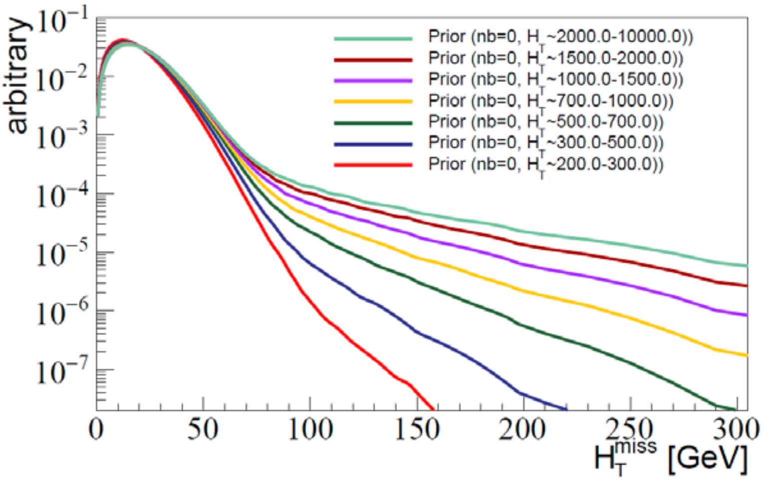
Irreducible:

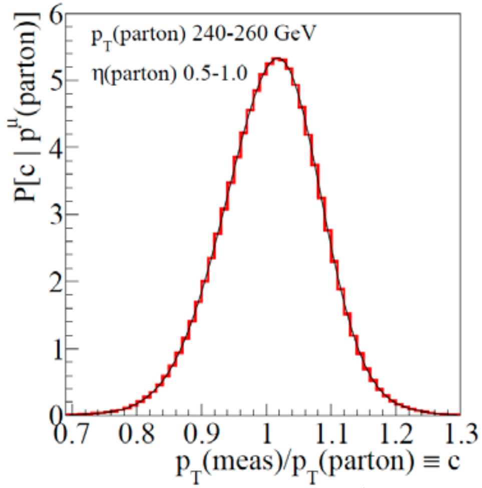
- **$Z \rightarrow \nu\bar{\nu}$ (+ jets)**
  - Real missing energy from neutrinos
  - Most prevalent at low multiplicity

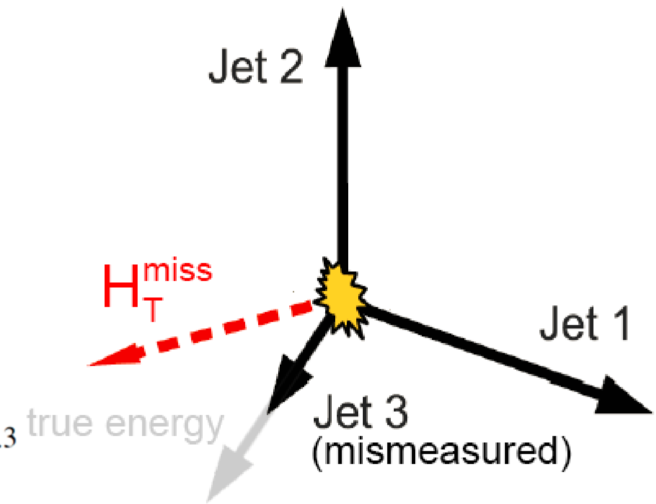
Reducible:

- **QCD multijets**
  - Mismeasured jet energy → "fake" H_T^{miss}
  - Reduce w/ $\Delta\varphi(H_T^{miss}, j_{1,2,3,4})$ requirements
- **$t\bar{t}$, W+jets** (also **single top**)
  - ν from W creates H_T^{miss}
  - **Lepton (e/μ)**: reduce w/ lepton, lepton track vetoes
  - **Hadronic Tau**: reduce w/ pion track veto
  - 50% of overall SM background, 90% of background with high multiplicity
- **Instrumental background**
  - Reduce w/ event cleaning (Jet ID, E_T^{miss} filters)

QCD Background Estimation







New method for 2016 result!

Bayesian Rebalance & Smear approach:

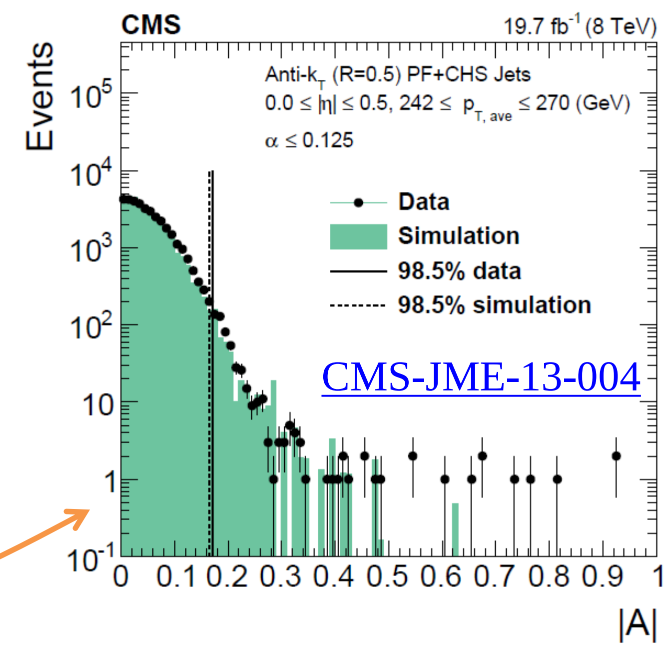
1. Rebalance:

$$\mathrm{P}(\vec{J}_{\mathrm{part}}|\vec{J}_{\mathrm{meas}}) \sim \pi(\vec{J}_{\mathrm{part}}) \cdot \mathrm{P}(\vec{J}_{\mathrm{meas}}|\vec{J}_{\mathrm{part}})$$

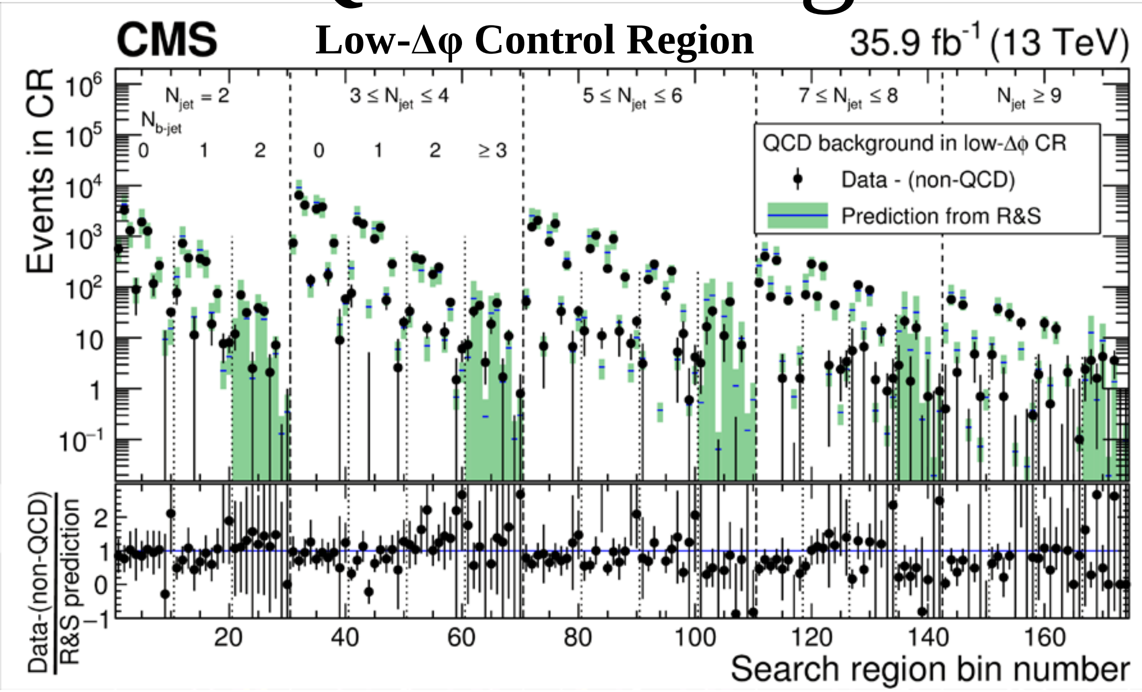
2. Smear:

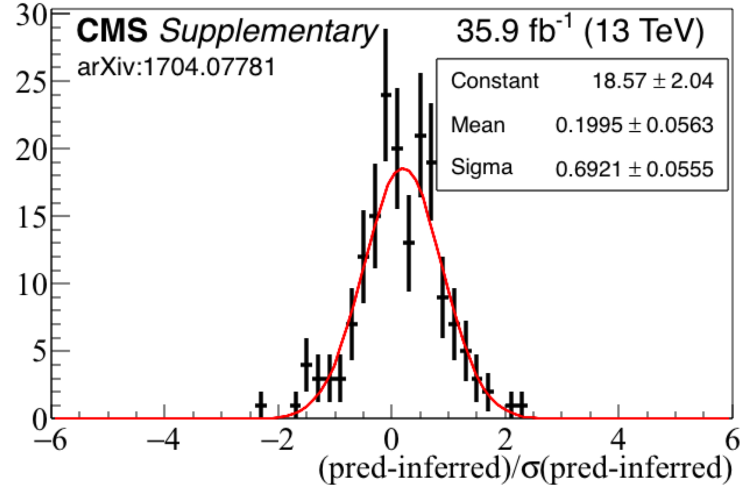
Jet response templates corrected for resolution in data using dijet asymmetry measurements

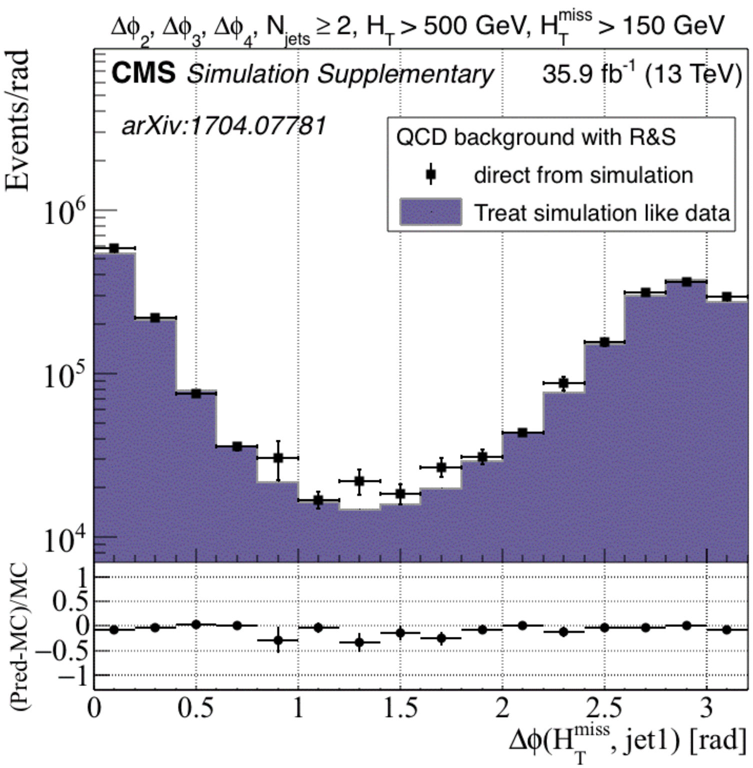
$$\mathcal{A} = \frac{p_{\mathrm{T,\,1st\,jet}} - p_{\mathrm{T,\,2nd\,jet}}}{p_{\mathrm{T,\,1st\,jet}} + p_{\mathrm{T,\,2nd\,jet}}}$$



QCD Background Validation





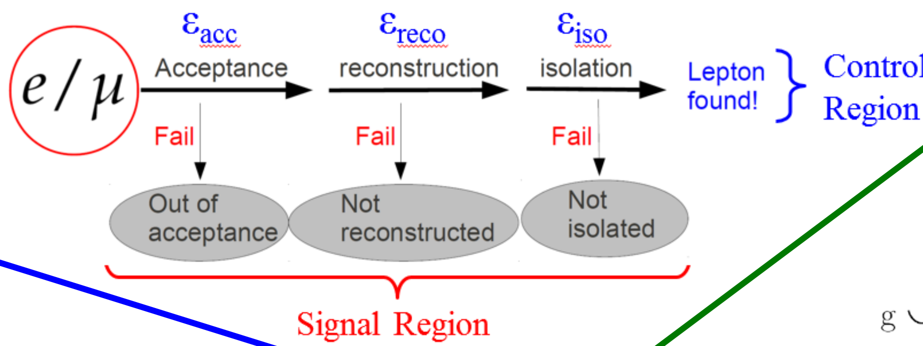


- Models complex distributions like $\Delta\varphi(H_T^{miss}, j)$
- Compare to data in low-Δφ control region†: good agreement (pull plot in upper right)
- Crosscheck in signal region w/ Δφ extrapolation method (used for earlier results)

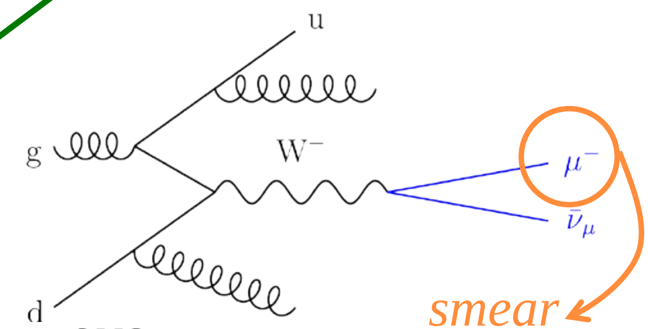
†QCD-enriched

Other Background Estimations

Lost Lepton

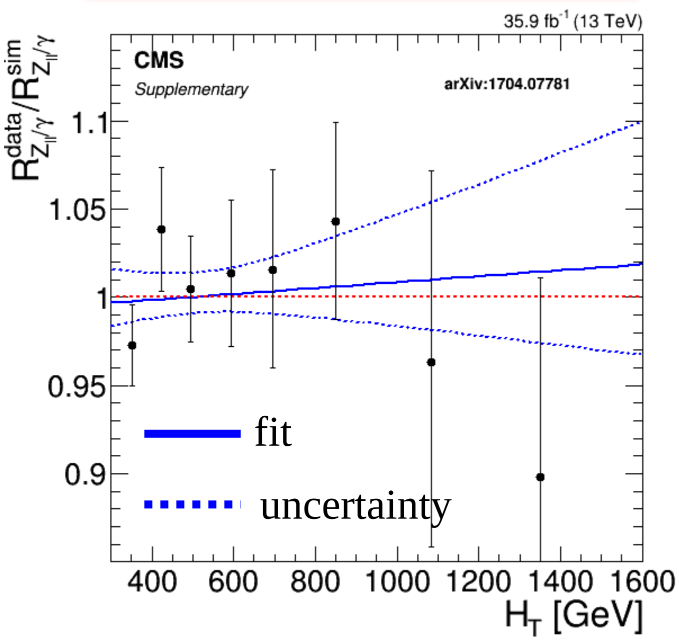


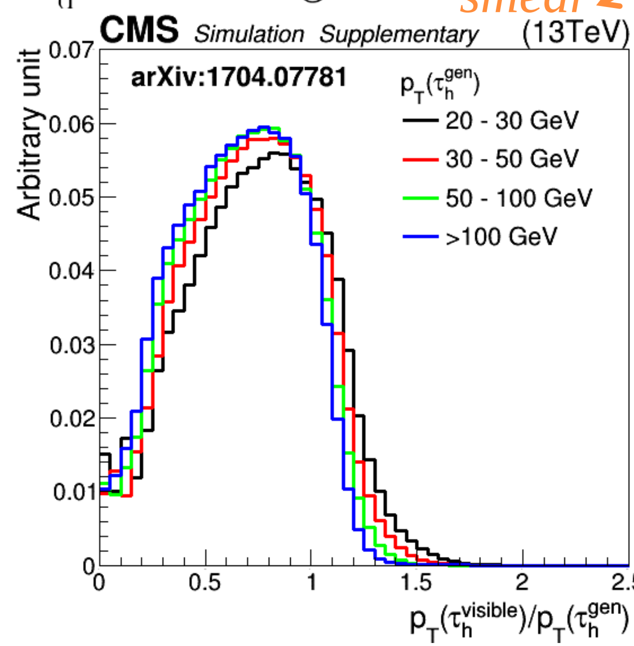
Hadronic Tau



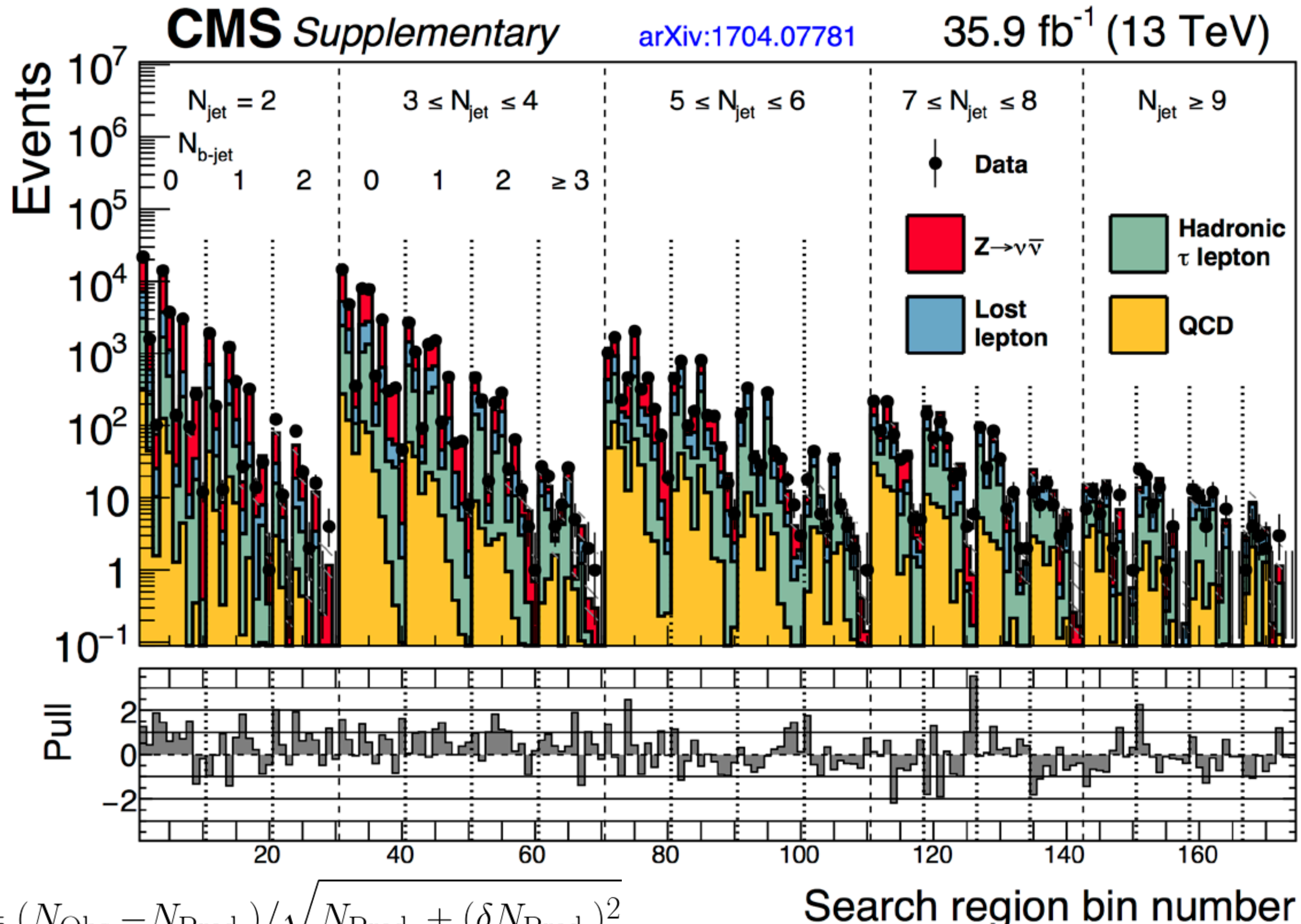
$Z \rightarrow \nu\bar{\nu}$

$\sigma(\gamma\text{+jets})/\sigma(Z\rightarrow\nu\nu) \approx 5$





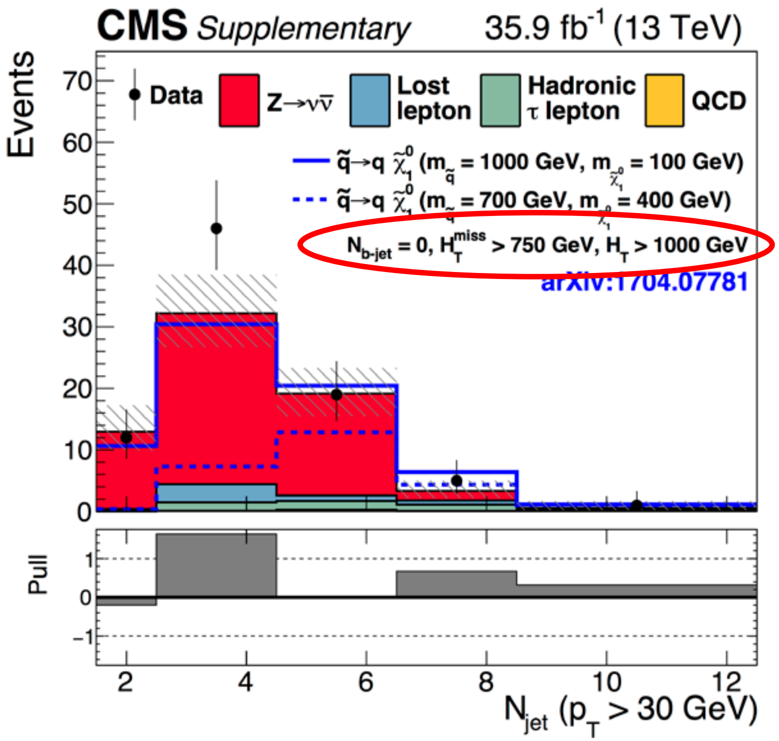
Prediction vs. Observation

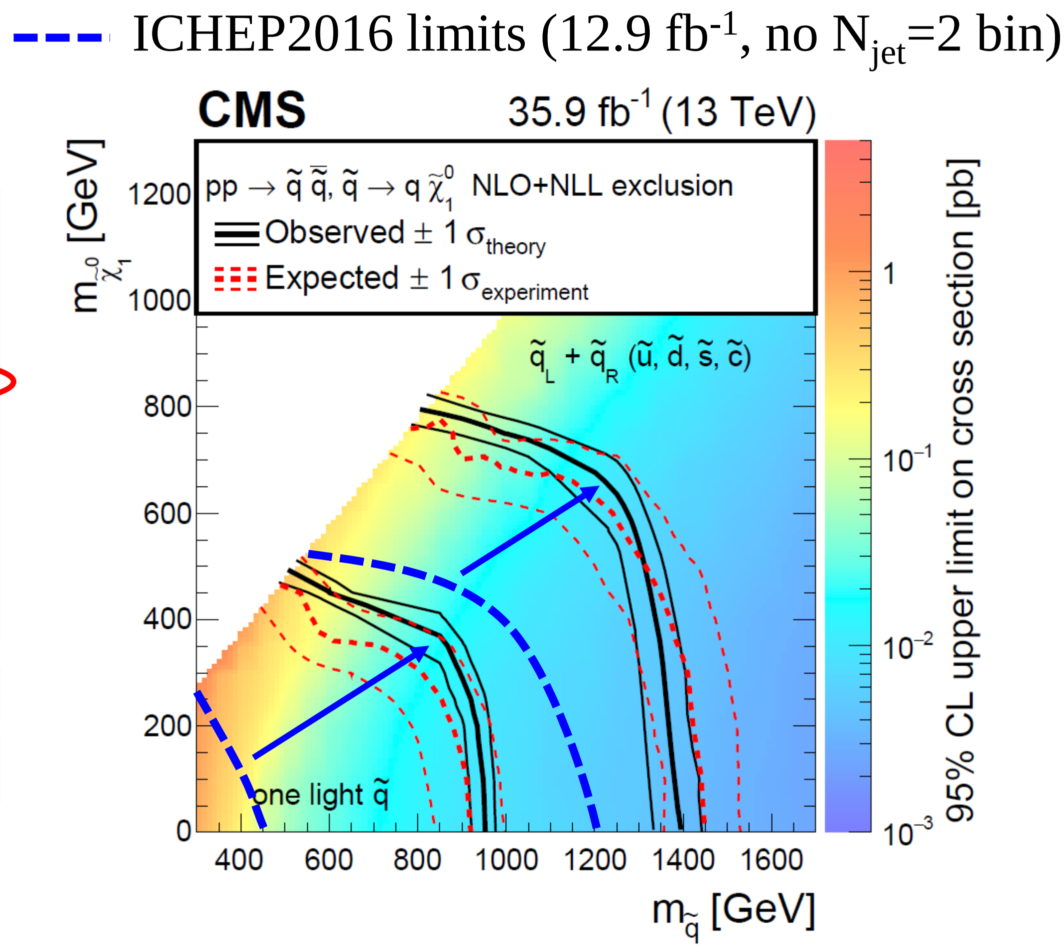


$\text{pull} = (N_{\text{Obs.}} - N_{\text{Pred.}})/\sqrt{N_{\text{Pred.}} + (\delta N_{\text{Pred.}})^2}$

- Good agreement between observation and SM background predictions
- Proceed to set limits on SUSY simplified models

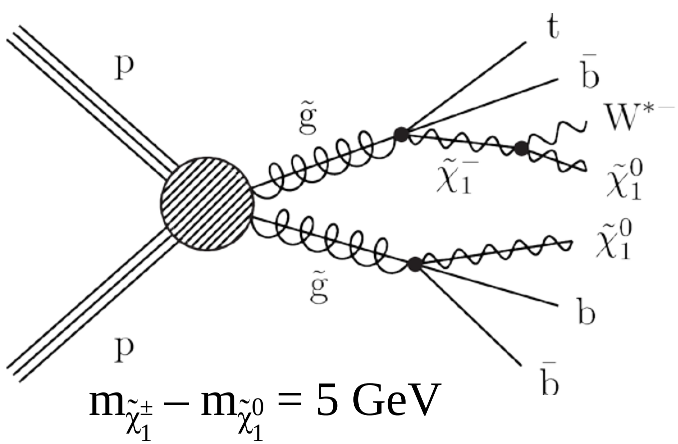
Squark Limits

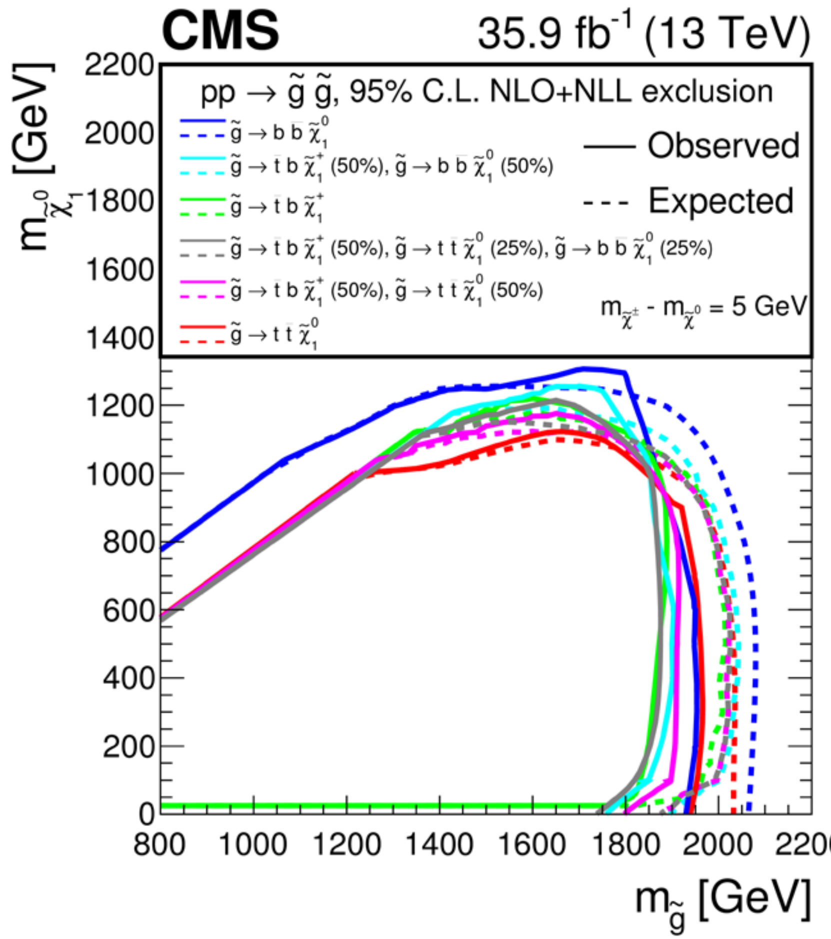




- N_{jet}=2 category significantly improves sensitivity vs. previous results
- "One light q̃" limits now competitive with third-generation squark limits

Gluino Limits





- Mix and match gluino decays:
  $\tilde{g} \to t\,b\,\tilde{\chi}_1^\pm$, $\tilde{g} \to b\,\bar{b}\,\tilde{\chi}_1^0$, $\tilde{g} \to t\,\bar{t}\,\tilde{\chi}_1^0$
- Depicted above:
  one gluino decaying as $\tilde{g} \to t\,b\,\tilde{\chi}_1^\pm$
  one gluino decaying as $\tilde{g} \to b\,\bar{b}\,\tilde{\chi}_1^0$
- High sensitivity to generic "natural" case:
  gluinos, Higgsinos accessible with third-generation decays
- Exclude gluinos w/ masses up to 1850–1880 GeV

Conclusions

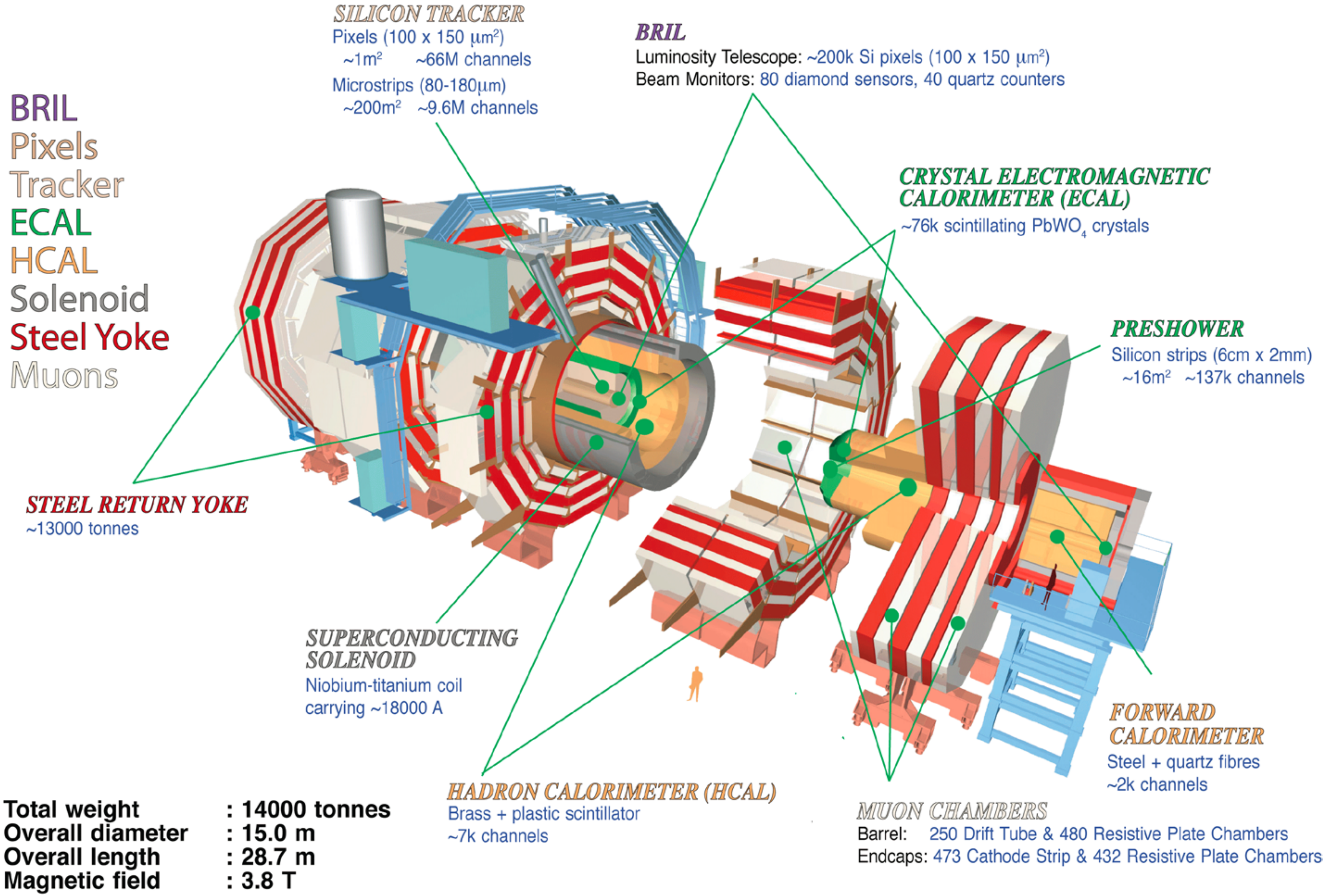
- Hadronic multijet + H_T^{miss} analysis has broad and competitive performance
- Covers large areas of SMS phase space:
  - o different decay flavors and branching fractions
  - o mass splittings between SUSY particles
- Gluino mass limits range from 1800–1960 GeV (for low $m_{\tilde{\chi}_1^0}$)
- Squark mass limits range from 960–1390 GeV (for low $m_{\tilde{\chi}_1^0}$)

❖ First SUSY analysis submitted w/ full 13 TeV dataset: arXiv:1704.07781 (accepted by *Phys. Rev. D*)
  - o Supplementary material available at SUS-16-033 (including efficiency maps & covariance matrices for reinterpretations)

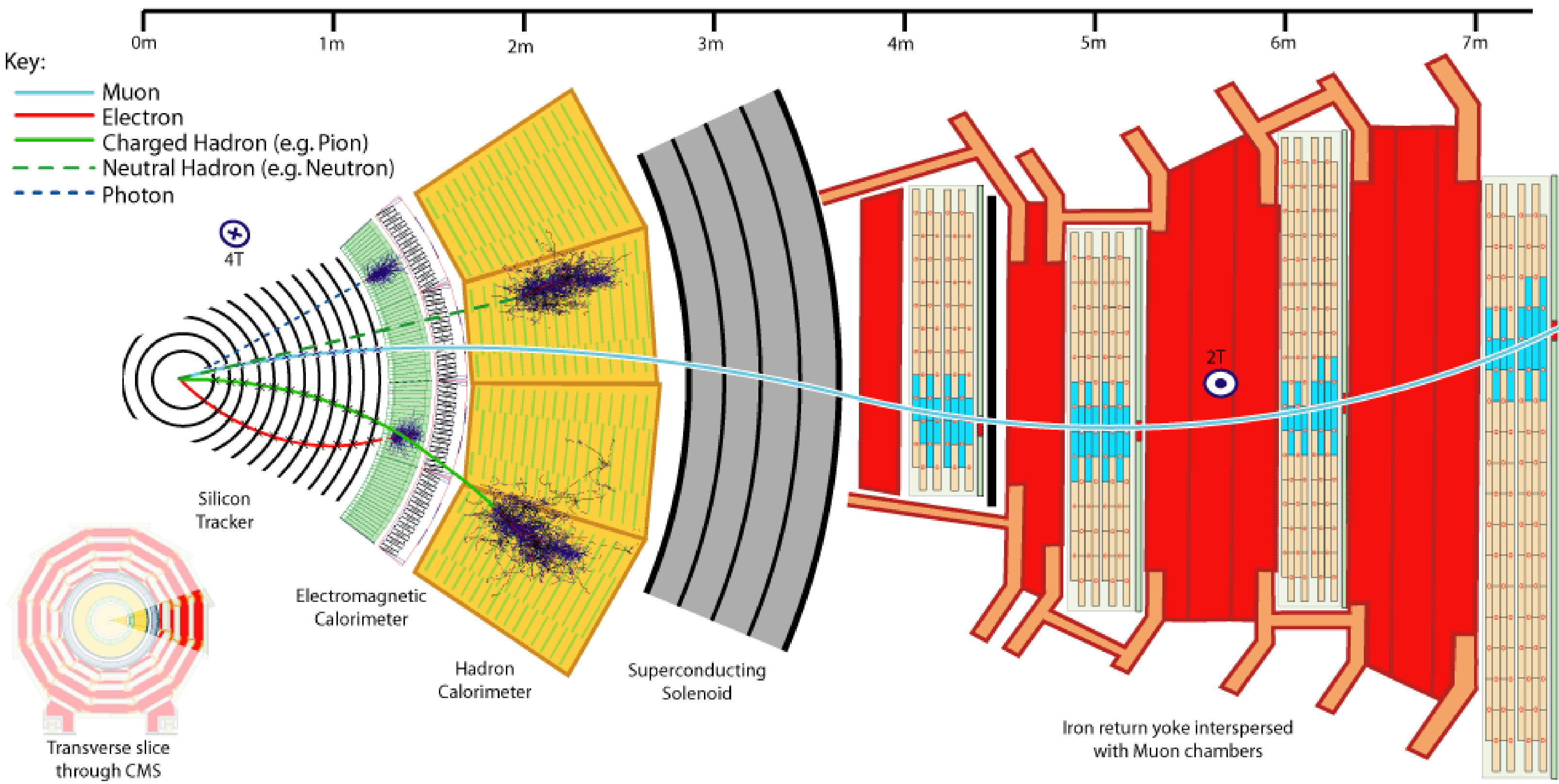
- Ongoing and future work:
  - o Reinterpretations (e.g. pMSSM, arXiv:1707.05783 from David Shih et al.)
  - o “Spinoff” analyses targeting different signatures/models
  - o Updated analysis with full Run2 dataset at 13 TeV (expect ~100 fb^{-1})

Backup

The CMS Detector



CMS Reconstruction

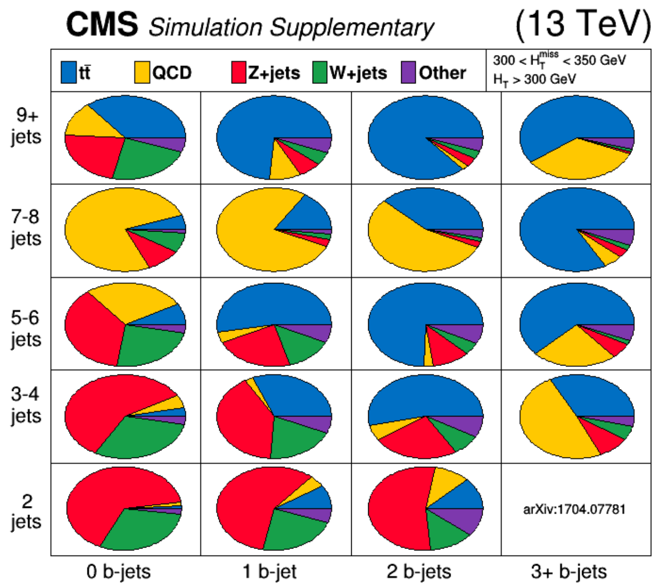


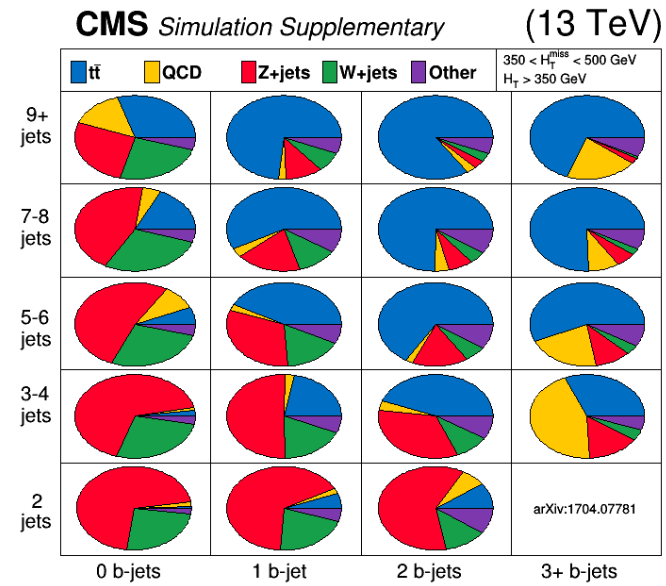
Tracker hits → charged tracks
ECAL hits → clusters
HCAL hits → clusters
Muon hits → muon tracks

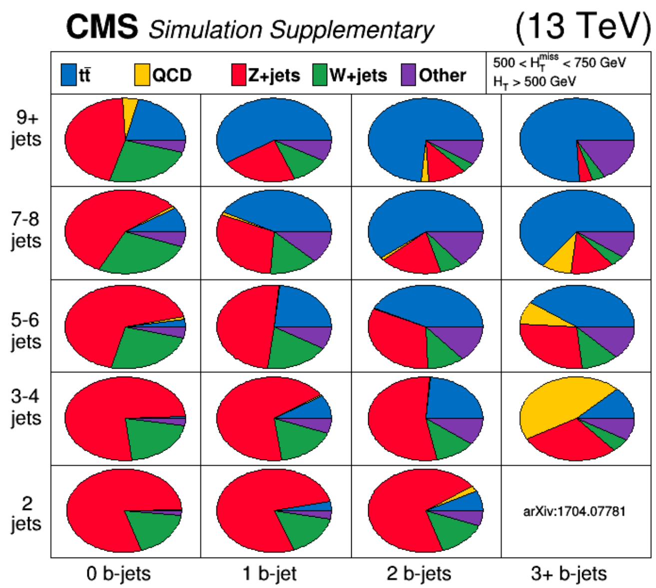
} linking →

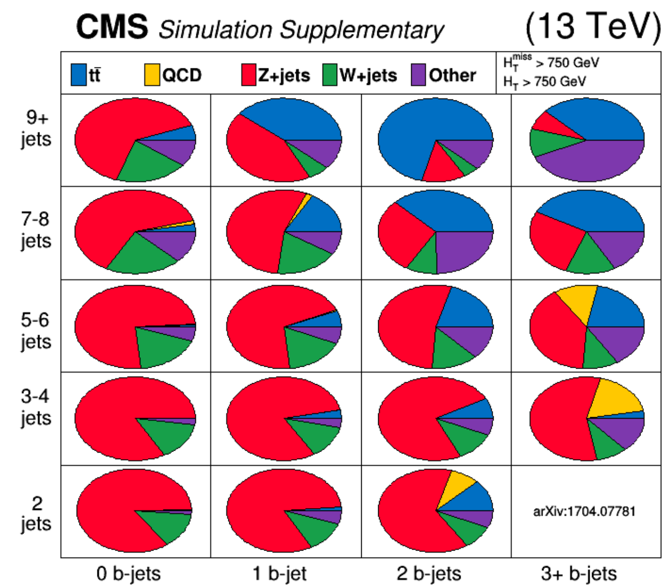
Candidates (particle flow):
electrons, muons, photons,
charged hadrons, neutral hadrons

Backgrounds in H_T, H_T^{miss} bins

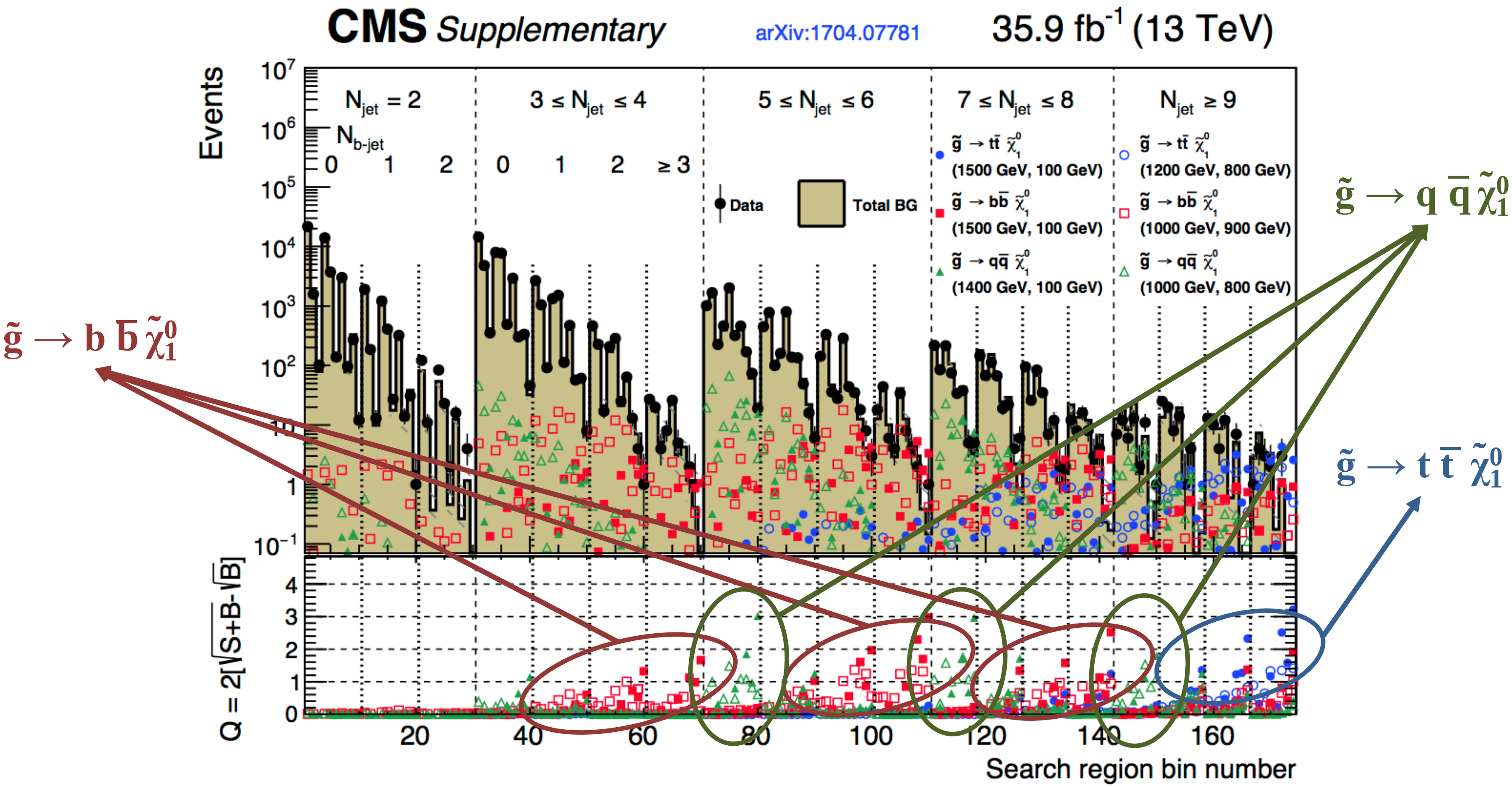




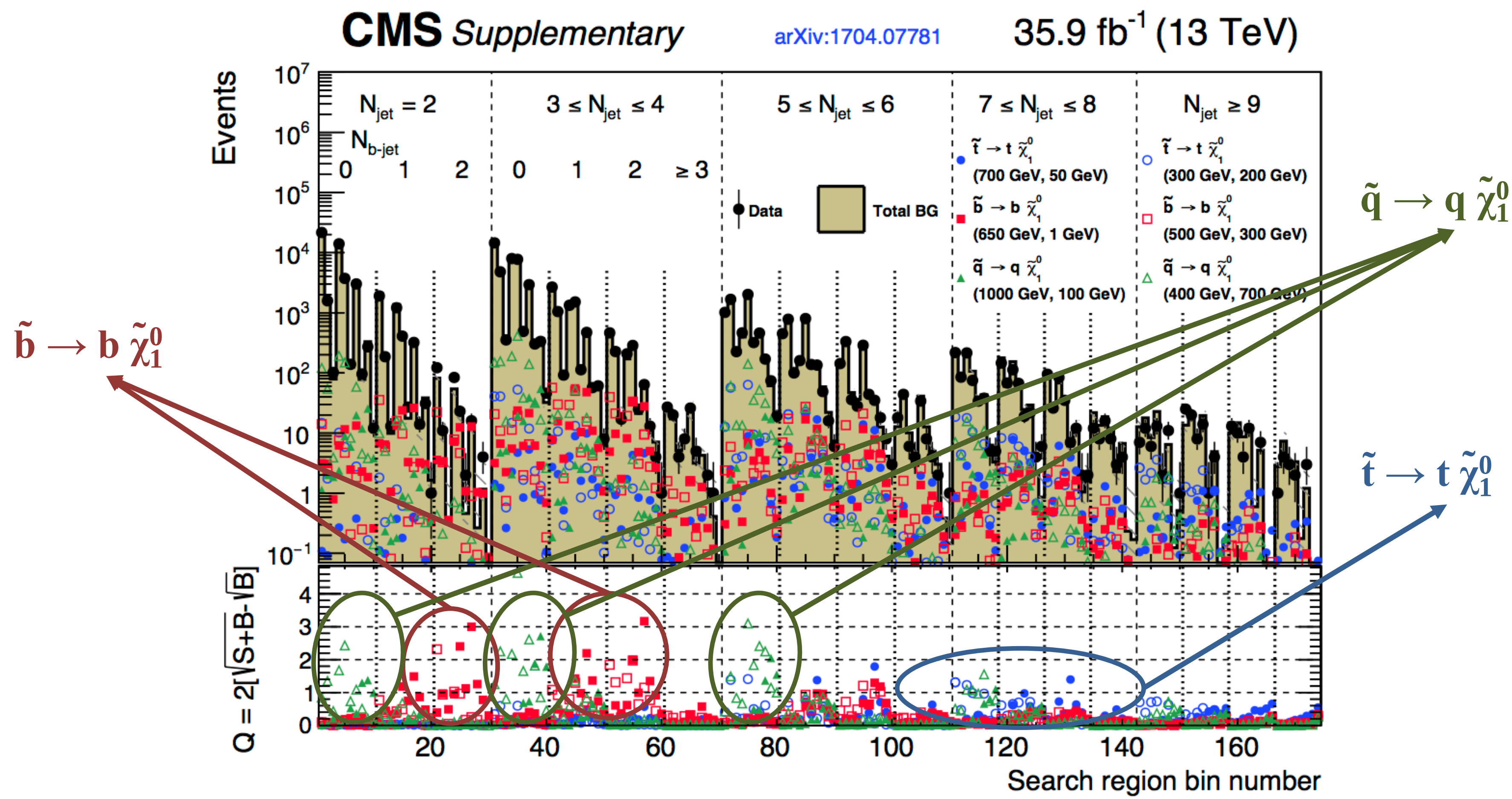




Sensitivity (gluinos)

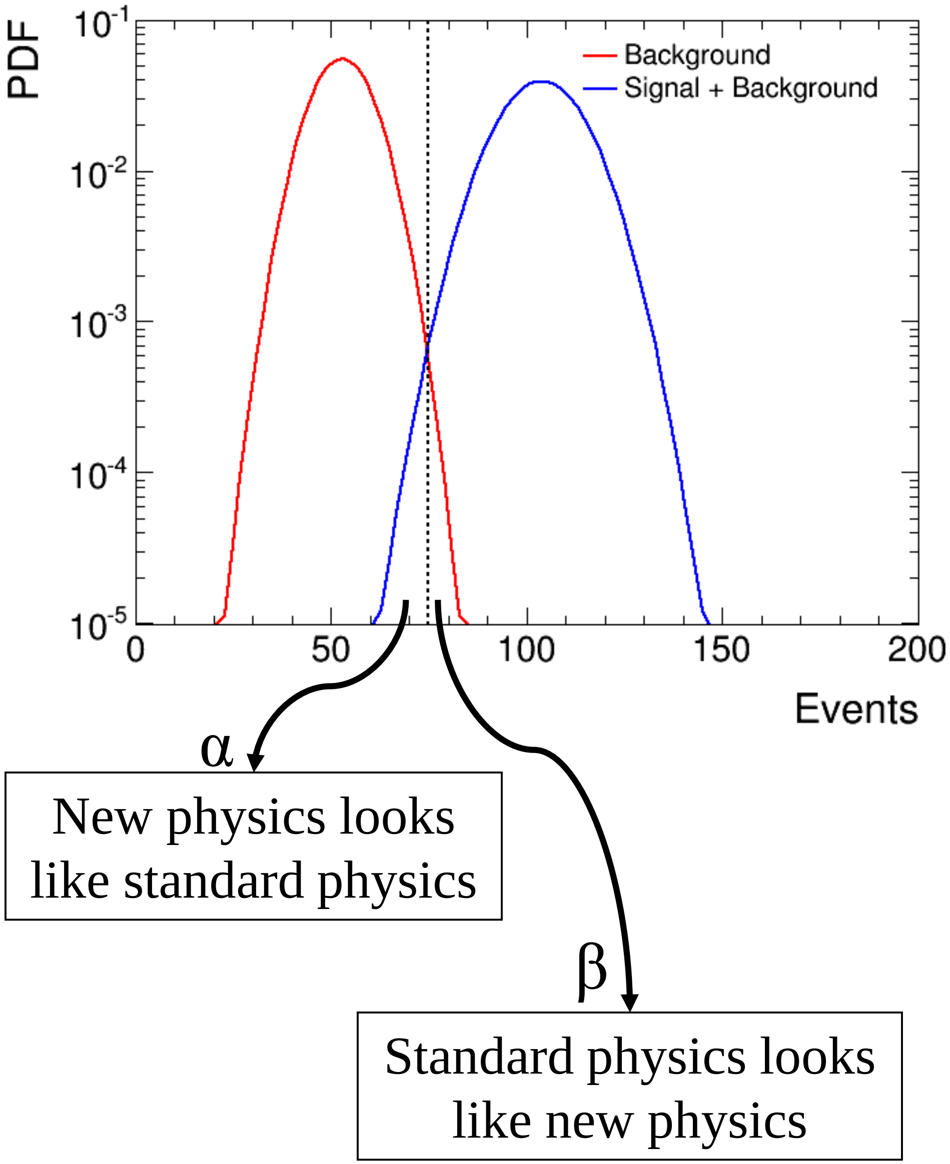


Sensitivity (squarks)



- Sensitivity comes from lower N_{jet} and $N_{b\text{-}jet}$ bins

$Q = 2[\sqrt{(S+B)} - \sqrt{(B)}]$



- Common area = probability that "new physics" can be described by "standard physics"

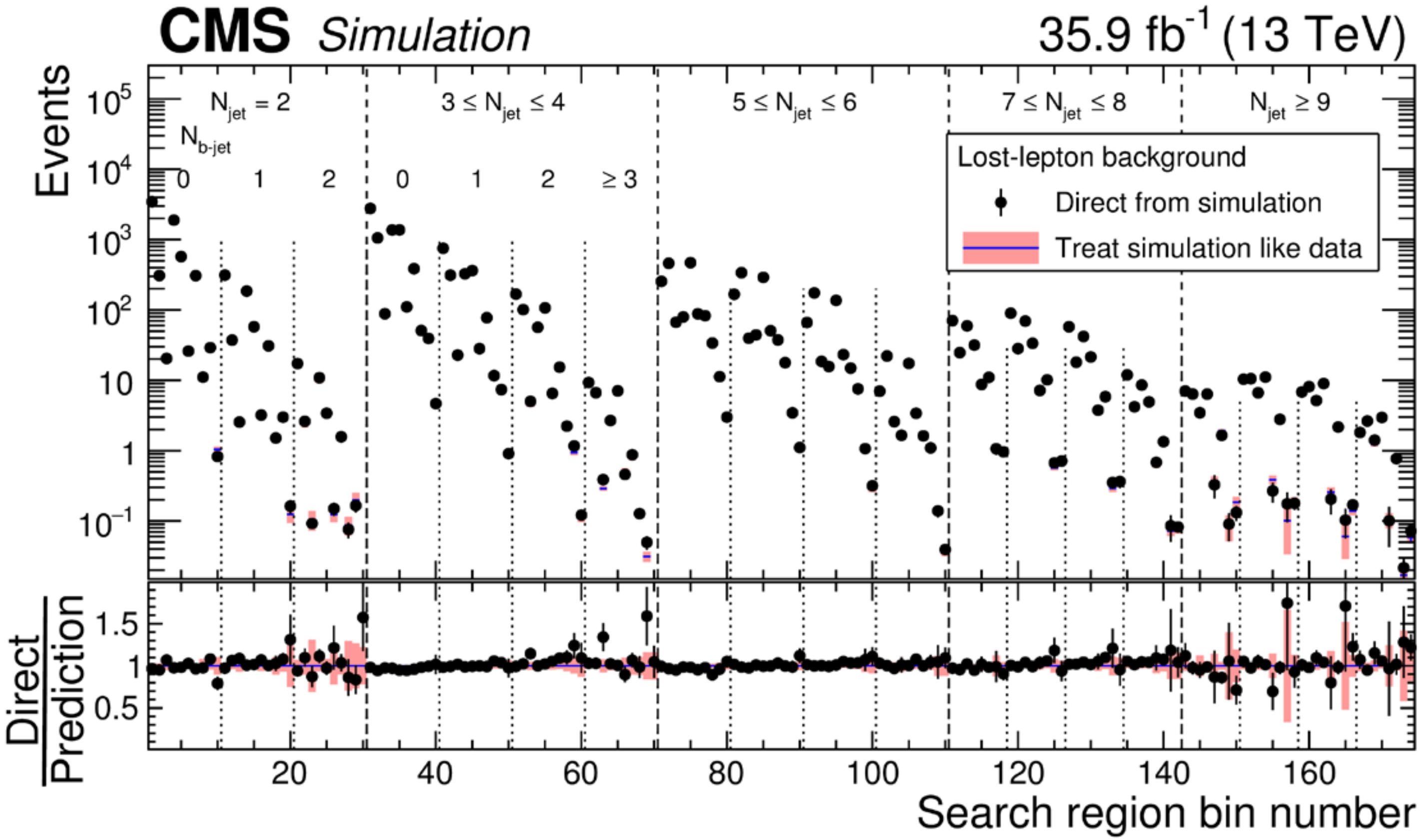
$$\kappa = \alpha + \beta = 1 - \mathrm{erf}\left(\frac{\sigma_2 - \sigma_1}{\sqrt{2}}\right)$$

$$Q = \sigma_2 - \sigma_1 = \sqrt{S+B} - \sqrt{B}$$

- (factor 2 included by convention)

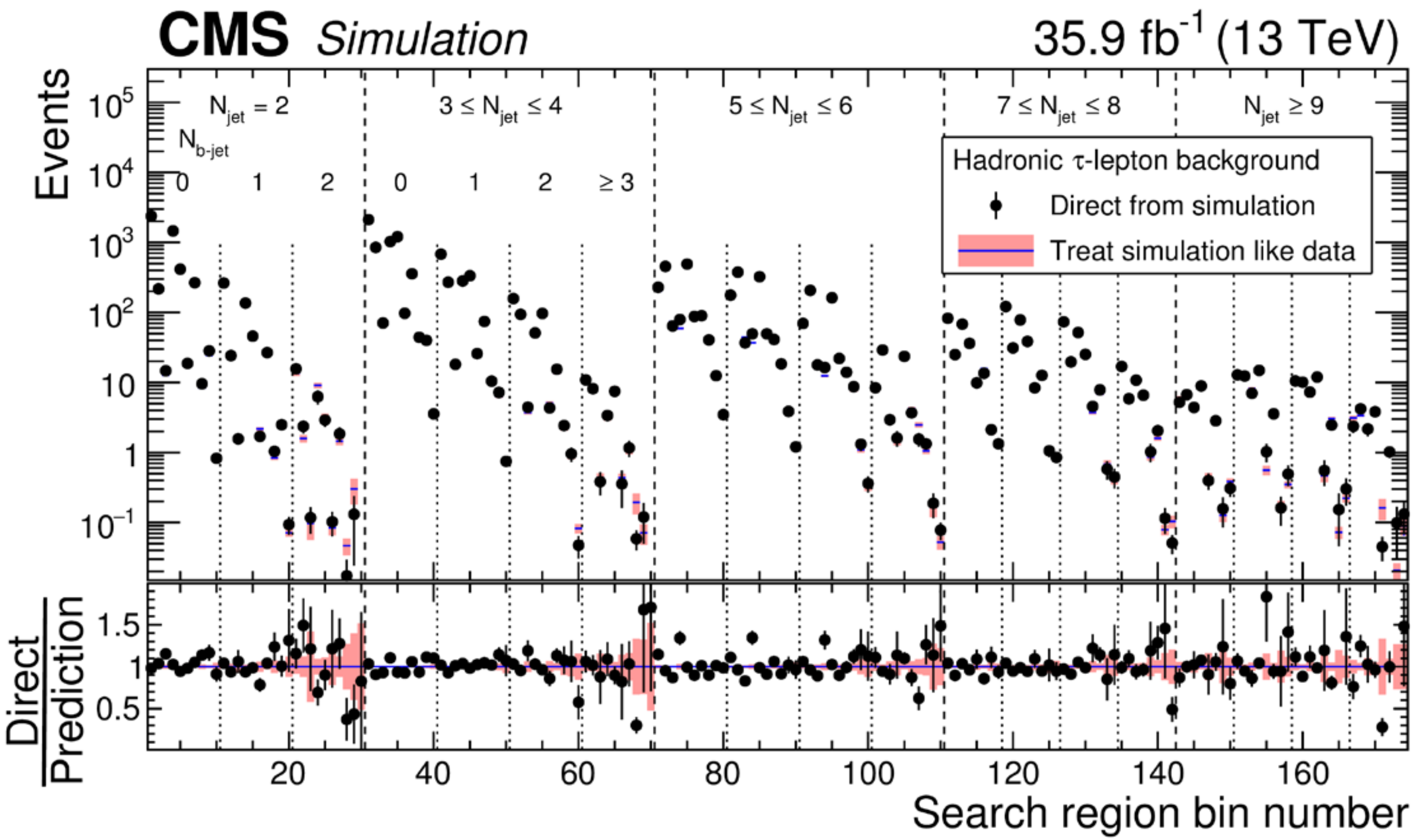
- Full derivation: arXiv:physics/9811025

Lost Lepton Closure Test



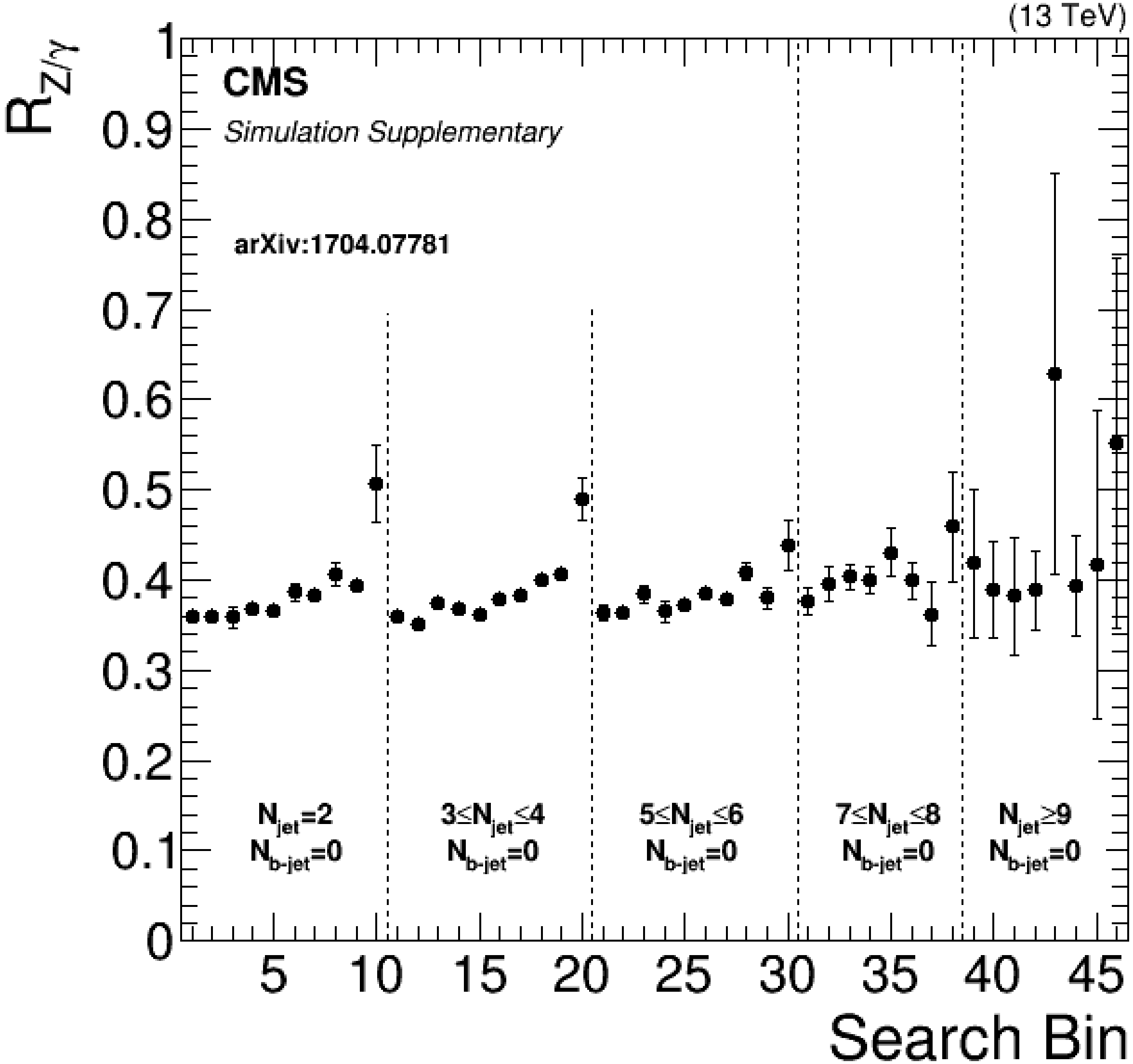
- Test parametrization of efficiencies in simulation
- "Zero Lepton" signal region vs. extrapolation from Single Lepton control region (only **$t\bar{t}$**, **W+jets**, **single top** samples)
- Largest systematic uncertainty: statistical uncertainty of control region

Hadronic Tau Closure Test

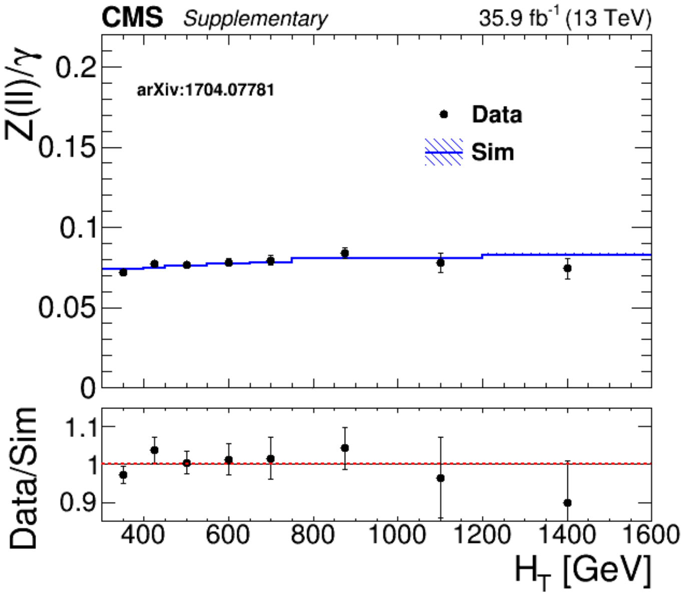


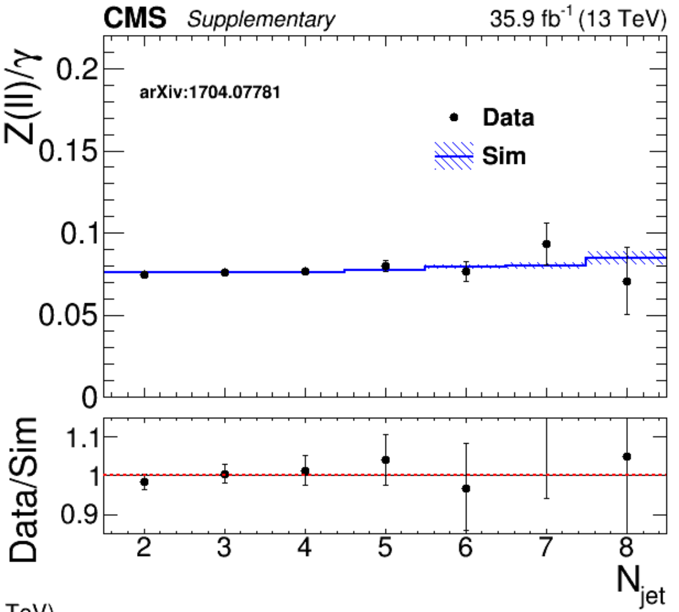
- Test accuracy of p_T template smearing in simulation
- Account for misidentification of τ_h jets as b jets
- "Zero Lepton" signal region vs. extrapolation from Single Muon control region (only **$t\bar{t}$**, **W+jets**, **single top** samples)
- Largest systematic uncertainty: statistical uncertainty of control region

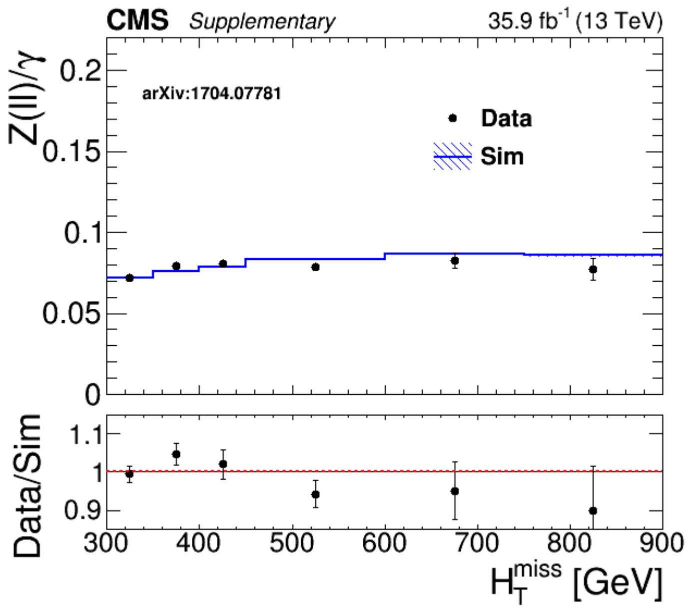
$(Z \rightarrow \nu\nu)/\gamma$ Ratio



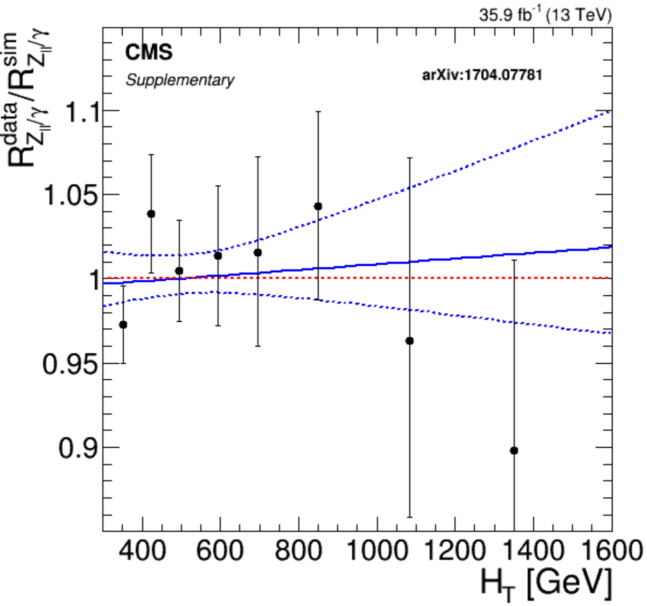
$(Z \rightarrow \ell\ell)/\gamma$ Ratios

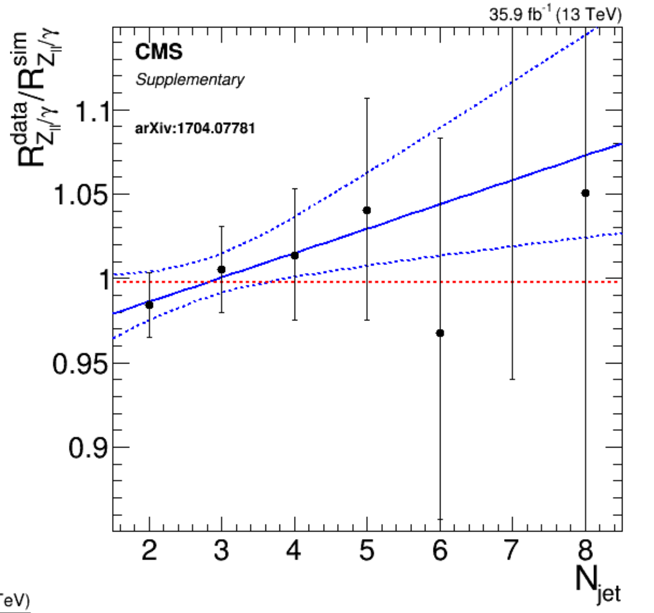


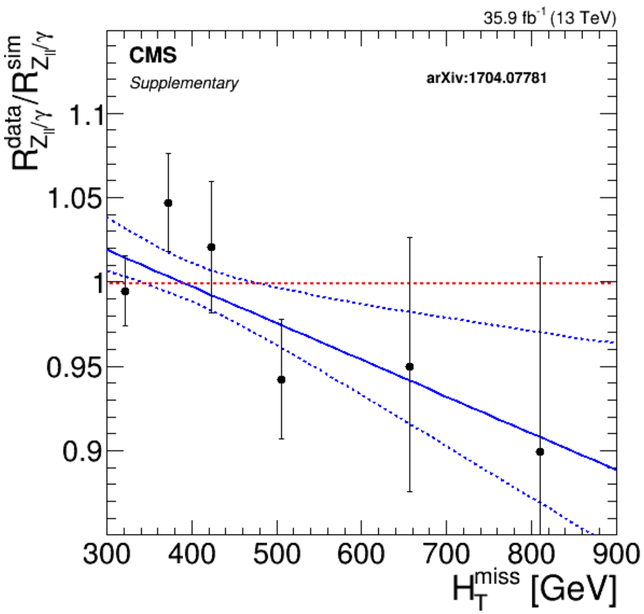




$(Z \to \ell\ell)/\gamma$ Double Ratios (Data/MC)







$Z \to \nu\nu$ Background, $N_{\text{b-jet}} > 0$

γ+jets Control Region

- ✓ σ(γ+jets)/σ(Z→νν) ≈ 5
- × Different couplings (EM vs. weak)
- × Different masses (0 vs. ≠0)
- → Smaller statistical uncertainty but larger systematic uncertainties

Z→ℓℓ Control Regions

- × $\mathcal{B}$(Z→ℓℓ)/$\mathcal{B}$(Z→νν) ≈ 1/3
- ✓ Same couplings (weak)
- ✓ Same masses (≠0)
- → Larger statistical uncertainty but smaller systematic uncertainties

$$\left(N^{\text{pred}}_{Z\to\nu\bar{\nu}}\right)_{j,b,k} = \left(N^{\text{pred}}_{Z\to\nu\bar{\nu}}\right)_{j,0,k} \mathcal{F}_{j,b}$$

From γ+jets method

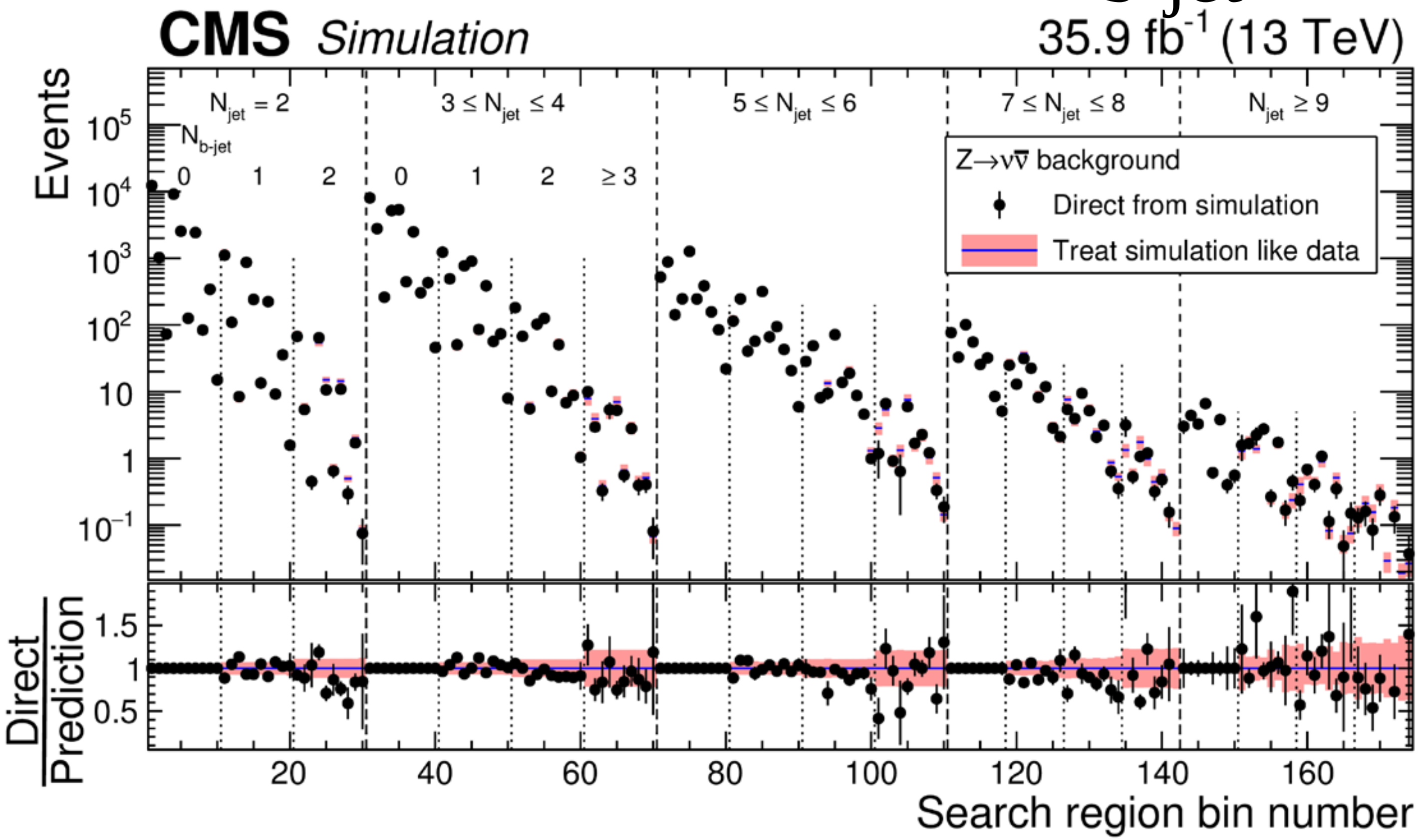
$$\mathcal{F}_{j,b} = \left(N^{\text{data}}_{Z\to\ell^+\ell^-}\beta^{\text{data}}_{\ell\ell}\right)_{j,b} / \left(N^{\text{data}}_{Z\to\ell^+\ell^-}\beta^{\text{data}}_{\ell\ell}\right)_{j,0}; \quad j = 0,1,2,3$$

$$\mathcal{F}_{4,b} = \mathcal{F}_{3,b}\left(\mathcal{F}^{\text{sim}}_{4,b} / \mathcal{F}^{\text{sim}}_{3,b}\right)$$

N_{jet} extrapolation factor calculated from data
β: correction for $N_{\text{b-jet}}$-dependent purity

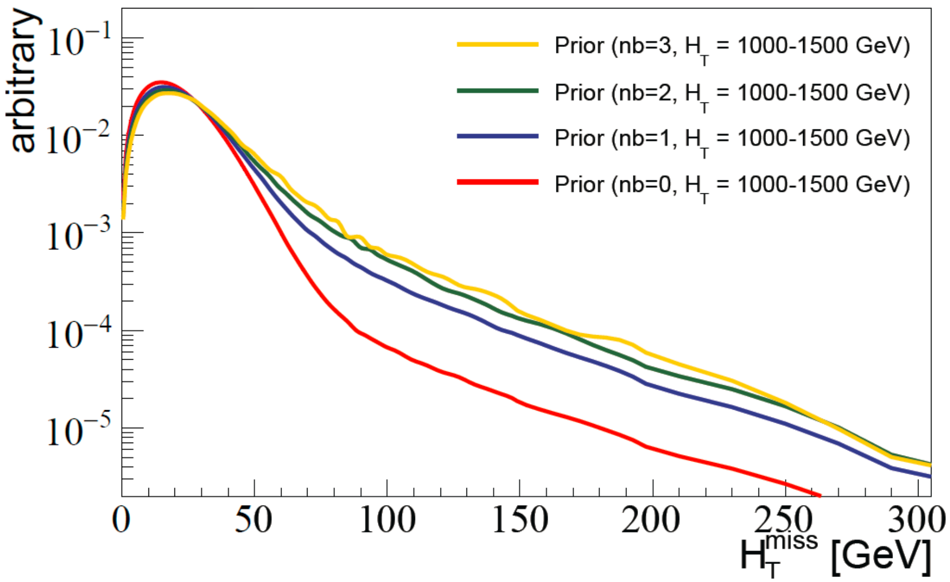
$N_{\text{b-jet}}$ extrapolation factor based on MC for highest N_{jet} bin (limited # events in data)

$Z \rightarrow \nu\nu$ Closure Test ($N_{b\text{-}jet} > 0$)



- Test accuracy of $N_{b\text{-}jet}$ extrapolation from $Z \rightarrow \ell\ell$ control regions
- $N_{b\text{-}jet} = 0$ bins are exact by construction of $R_{Z\rightarrow\nu\nu/\gamma}$ from simulation
- Systematic uncertainty dominated by limited number of events in CRs

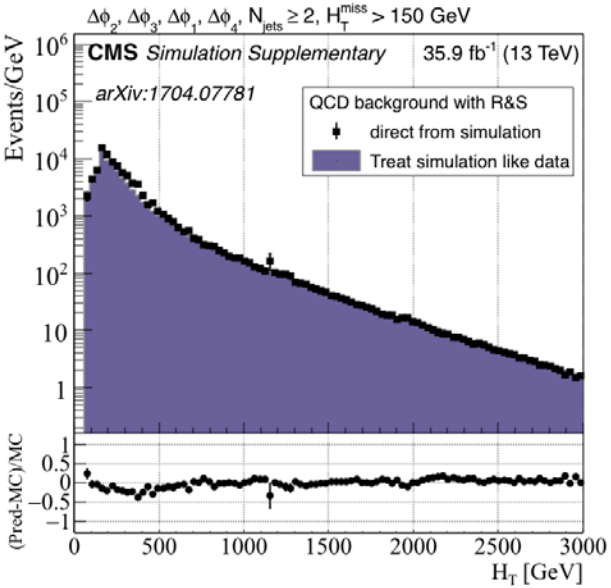
QCD R+S Further Details

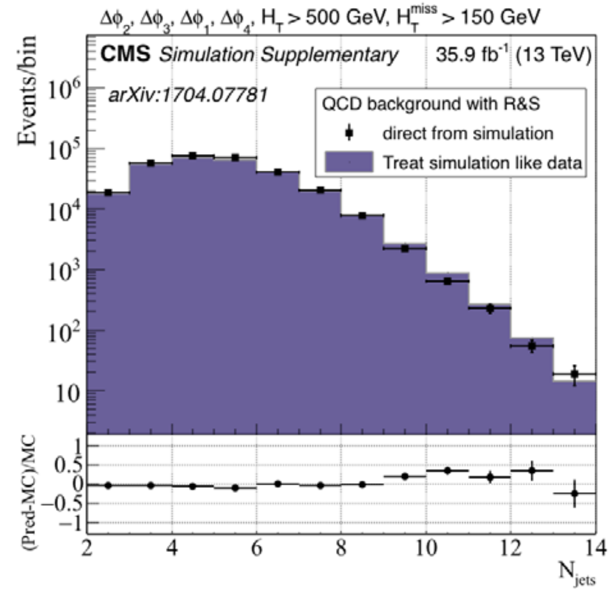


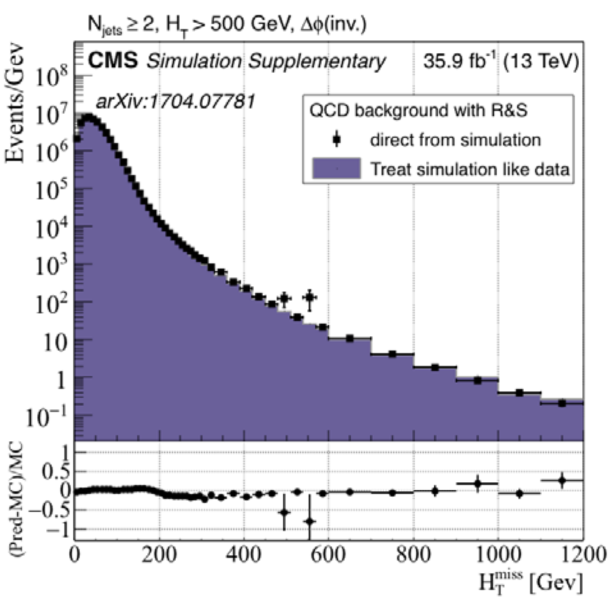
- Use jets w/ p_T < 15 GeV and $|\eta|$ < 5.0
- H_T^{miss} prior binning in H_T accounts for jets failing selection
- H_T^{miss} prior distribution also binned in $N_{b\text{-jet}}$ (see above), accounts for neutrinos in heavy flavor decays
- Prior $\pi(\vec{J}_{part})$ also includes distribution of $\Delta\varphi(H_T^{miss}, j_1)$ if $N_{b\text{-jet}} = 0$, $\Delta\varphi(H_T^{miss}$, leading b-jet) if $N_{b\text{-jet}} > 0$

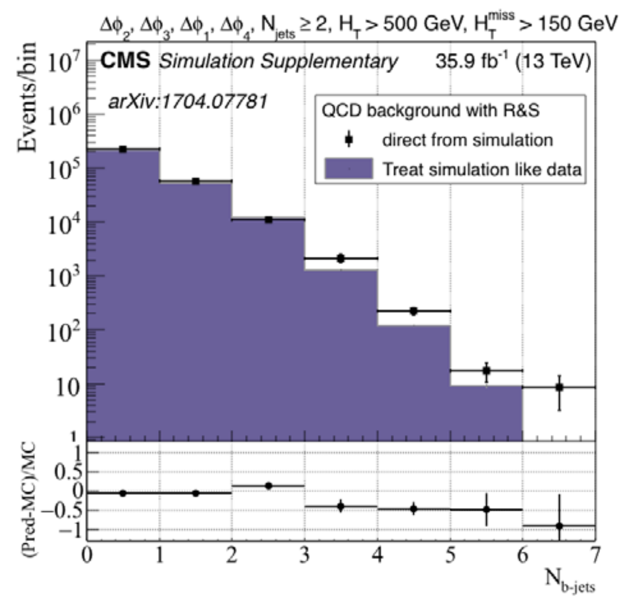
→ Consider magnitude *and* direction of H_T^{miss}

QCD R+S Closure Plots (1)

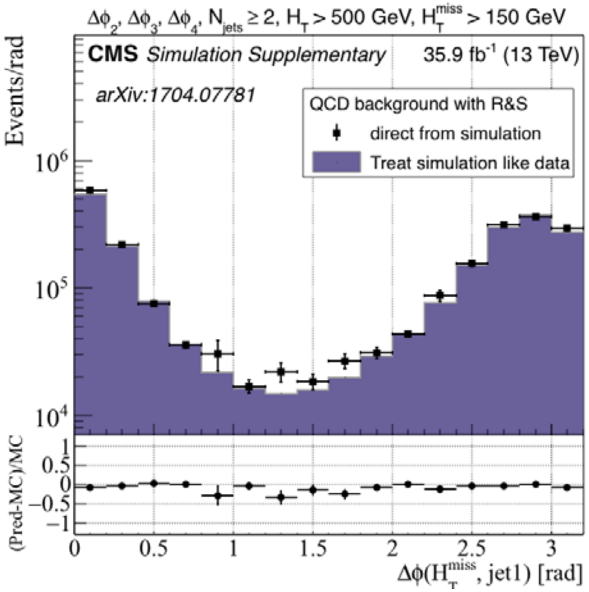


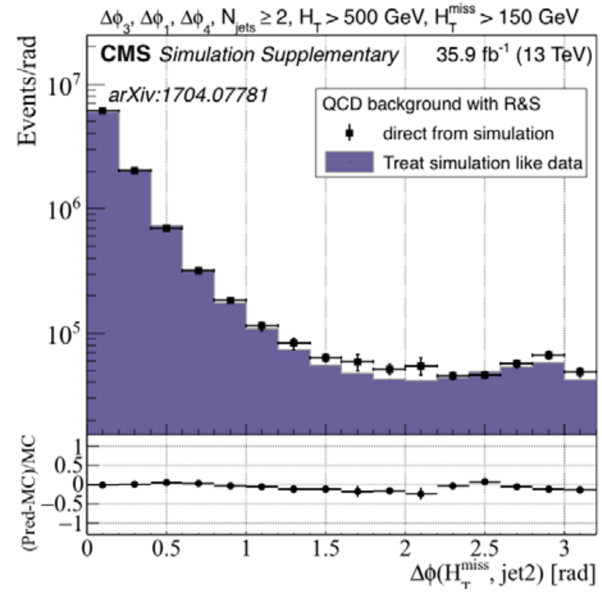


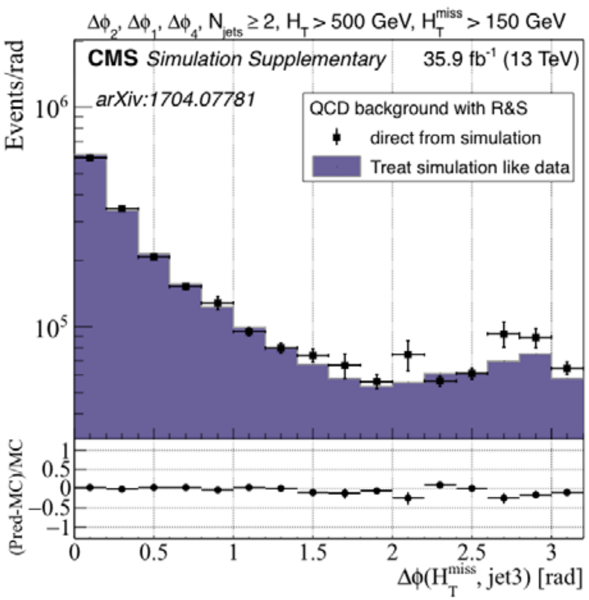


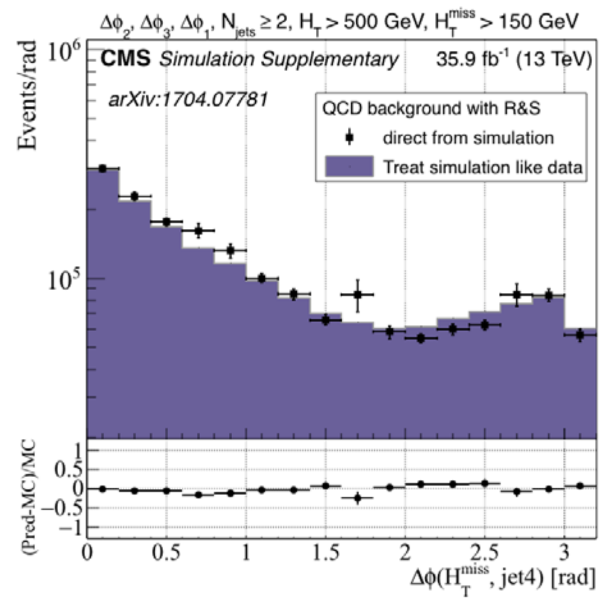


QCD R+S Closure Plots (2)

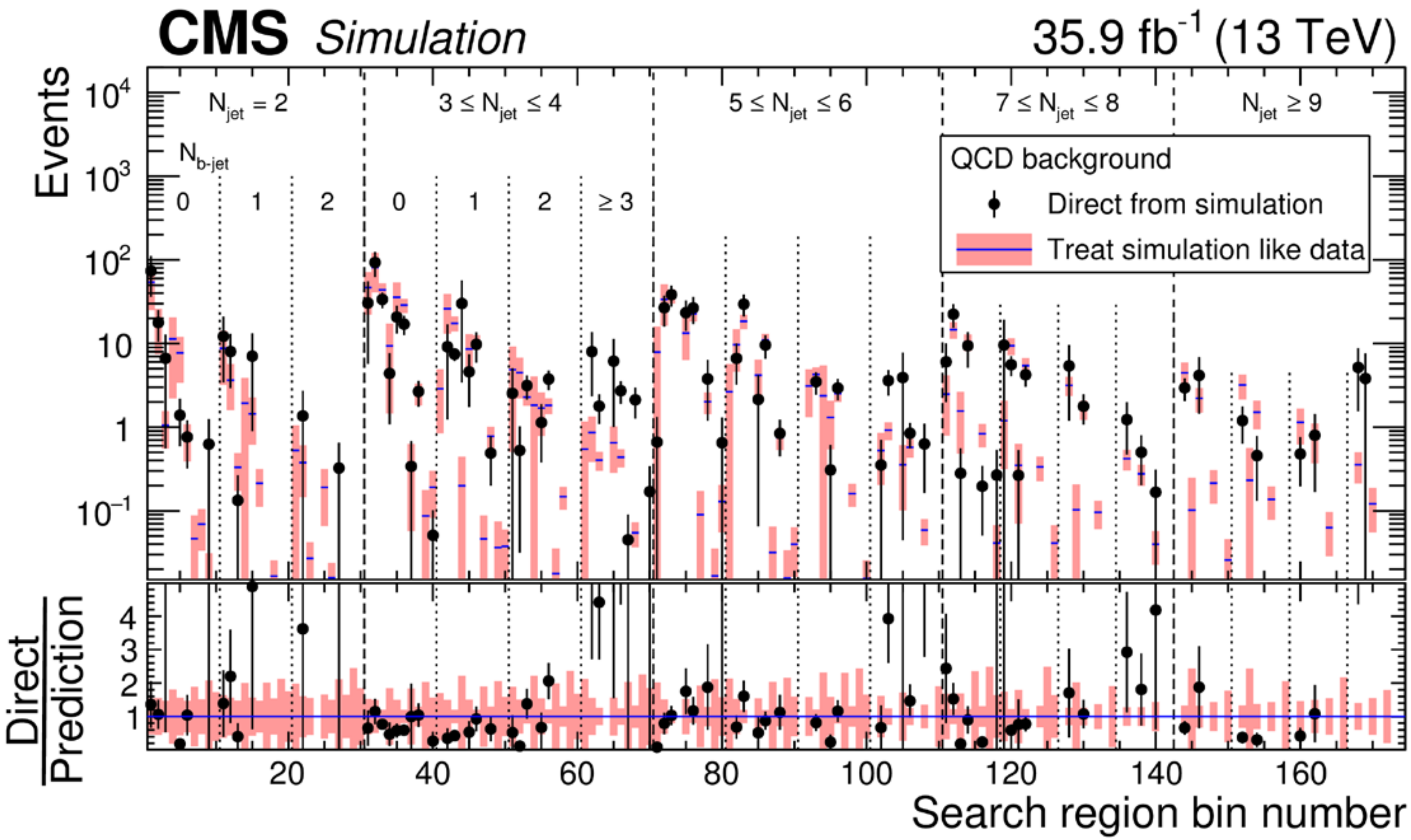






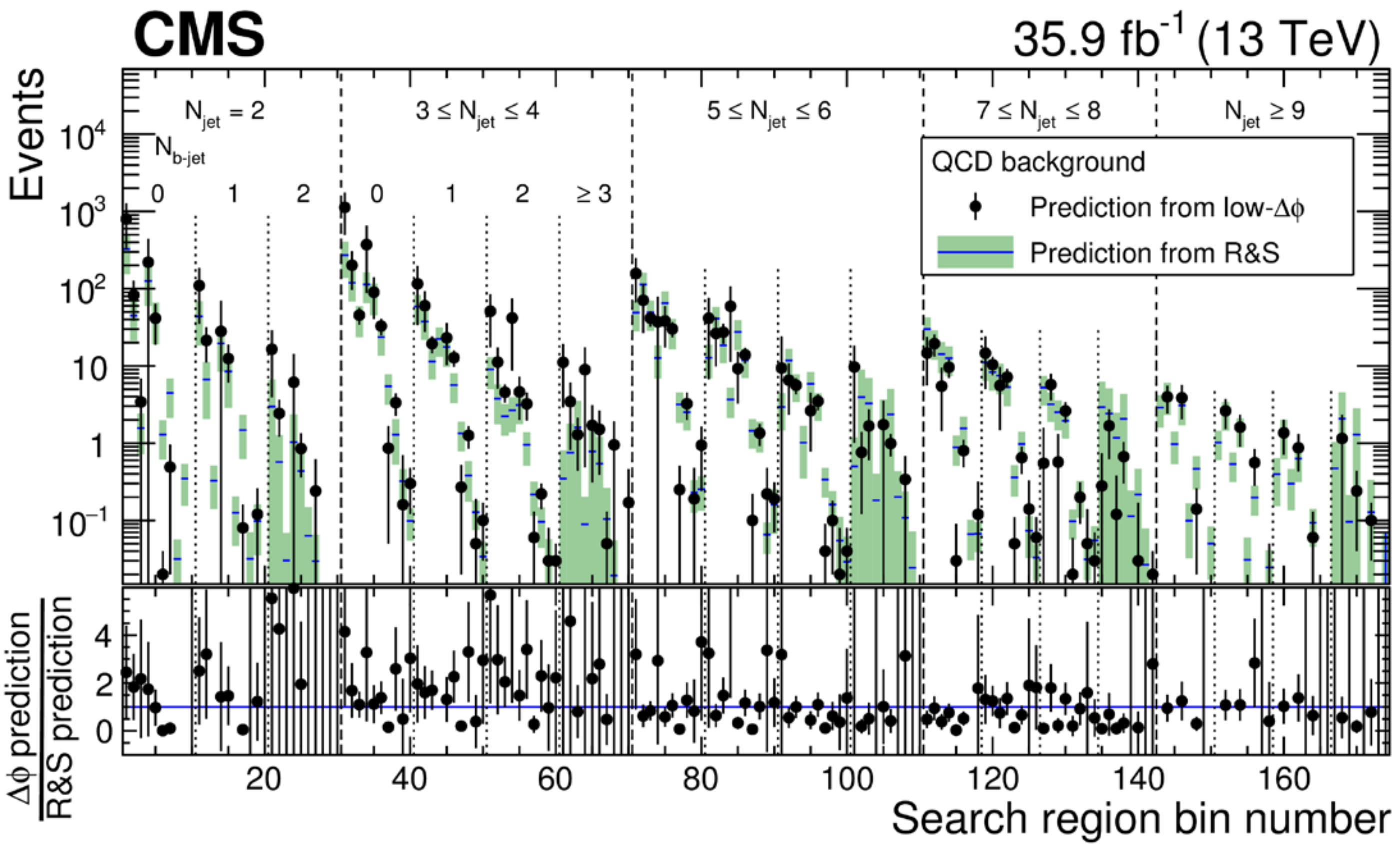


QCD Closure Test (Δφ extrapolation)



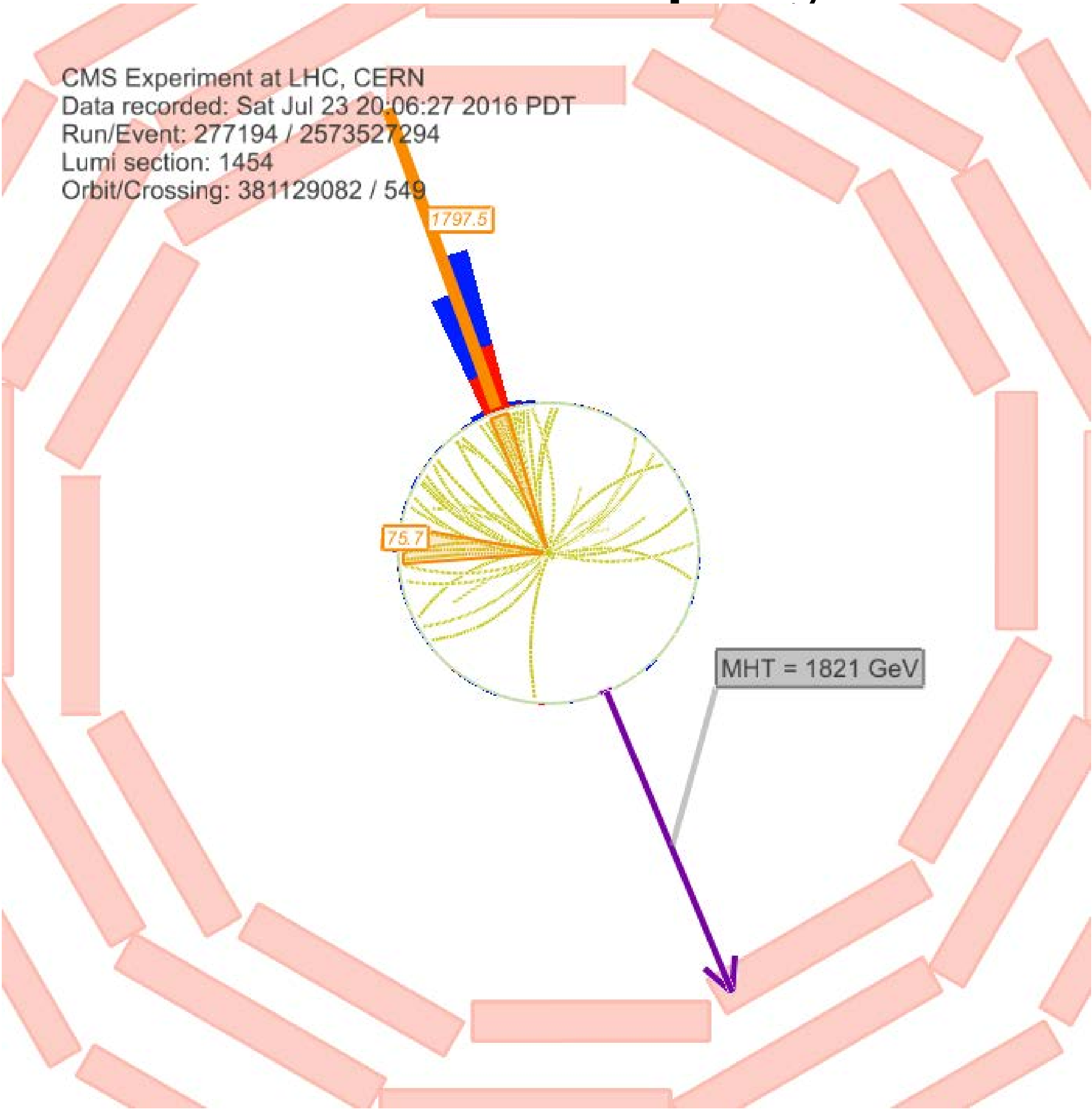
- Test parametrization of high/low Δφ ratio: $R^{\mathrm{QCD}}_{i,j,k} = K^{\mathrm{data}}_{ij}\, S^{\mathrm{sim}}_{ik}$
- K^{data} from low-H_T^{miss} sideband; i, j, k = H_T, N_{jet}, H_T^{miss} indices
- Systematic uncertainties from statistical uncertainty in QCD MC & estimations of magnitude of jet mismeasurements

QCD Crosscheck (R+S vs. Δφ)

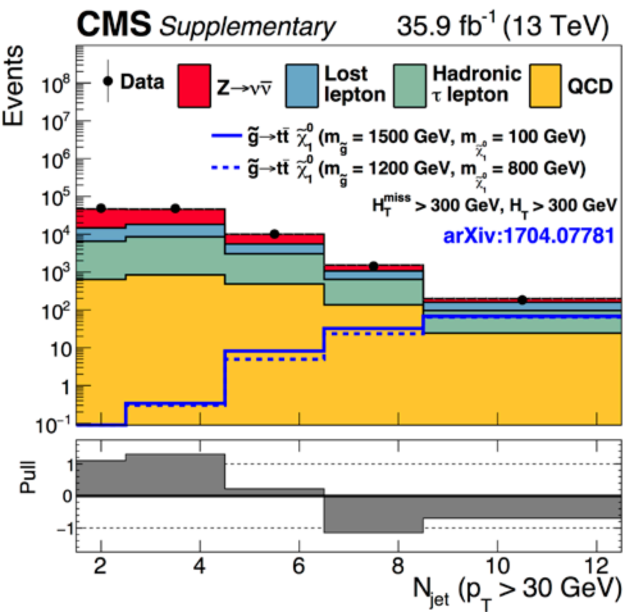


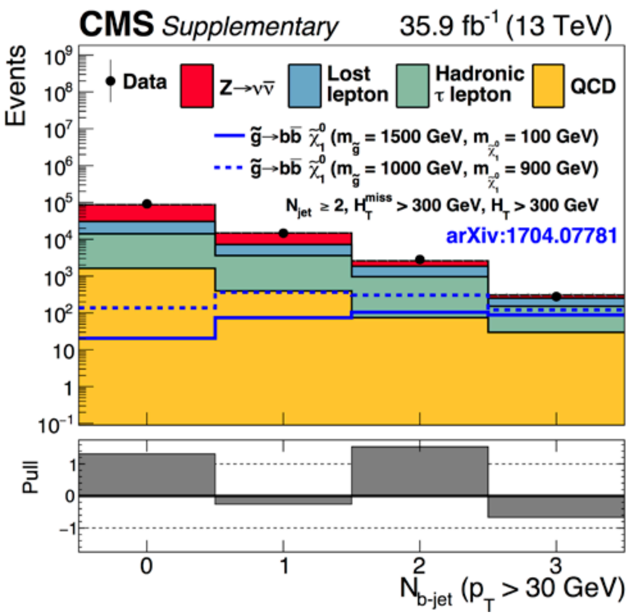
- Good agreement between two methods (within uncertainties)

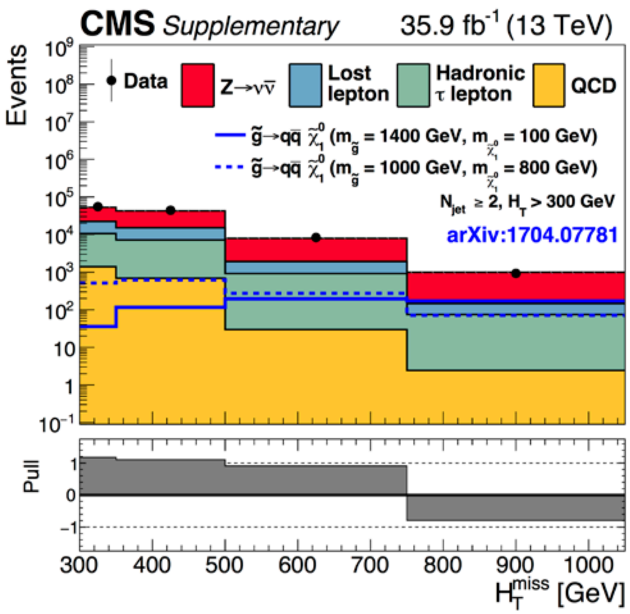
Event Display



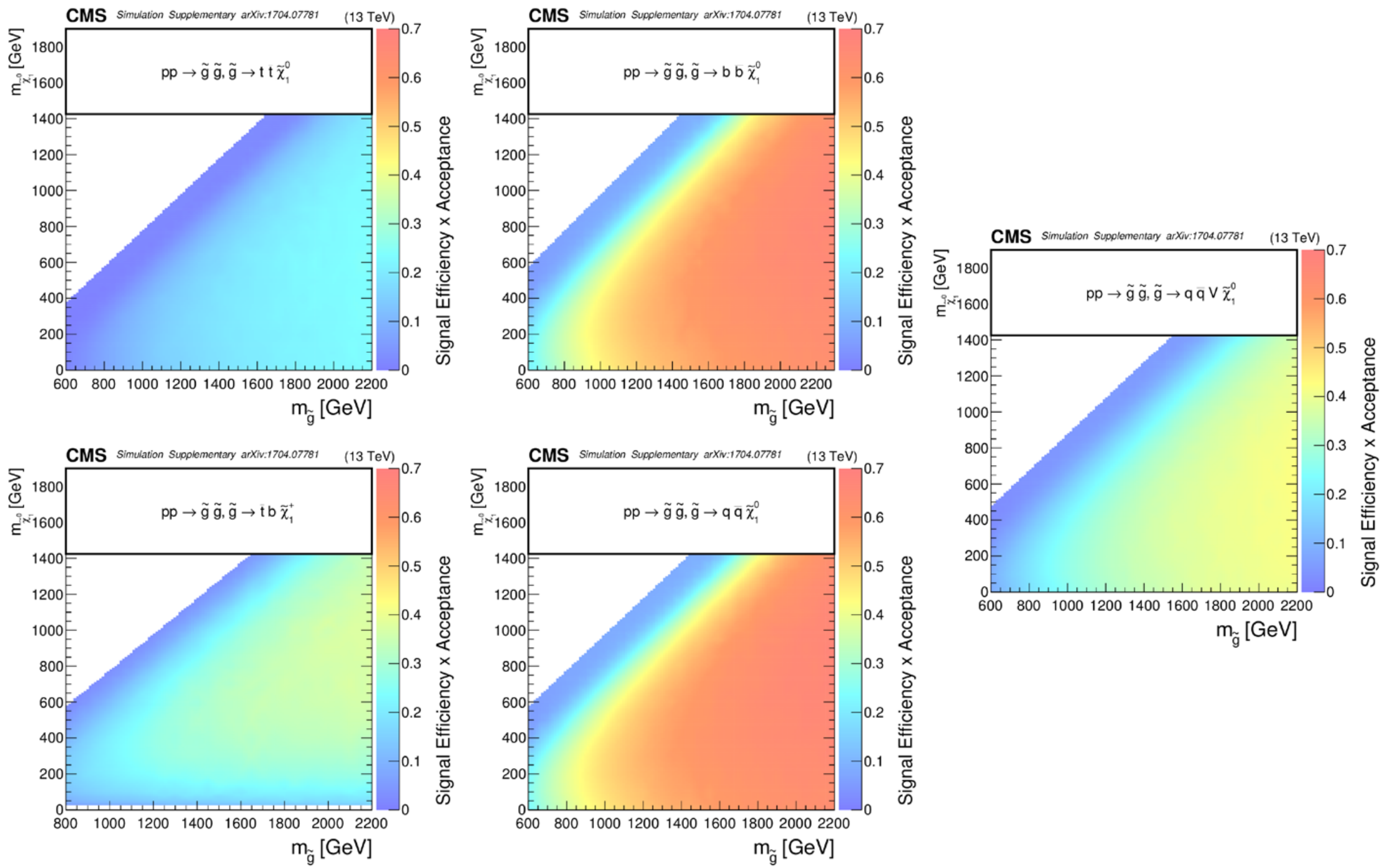
Results: 1D Projections



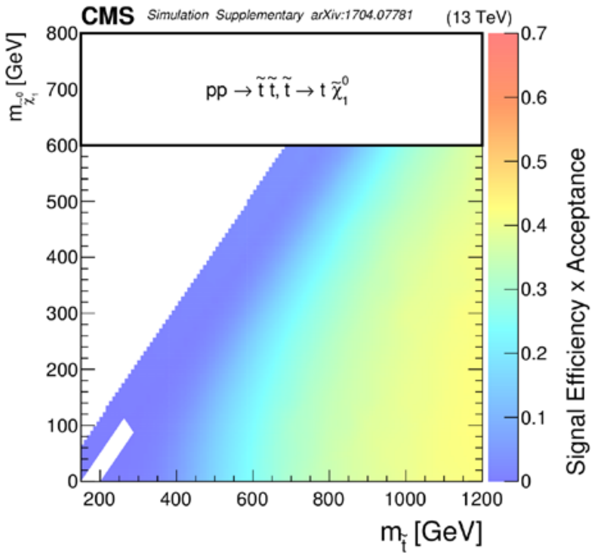


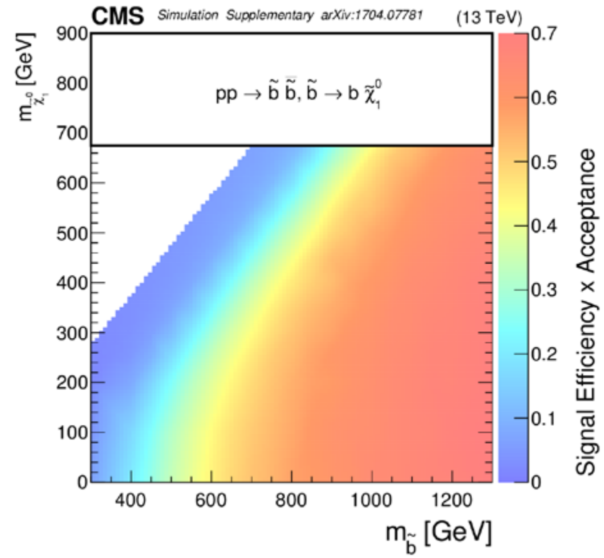


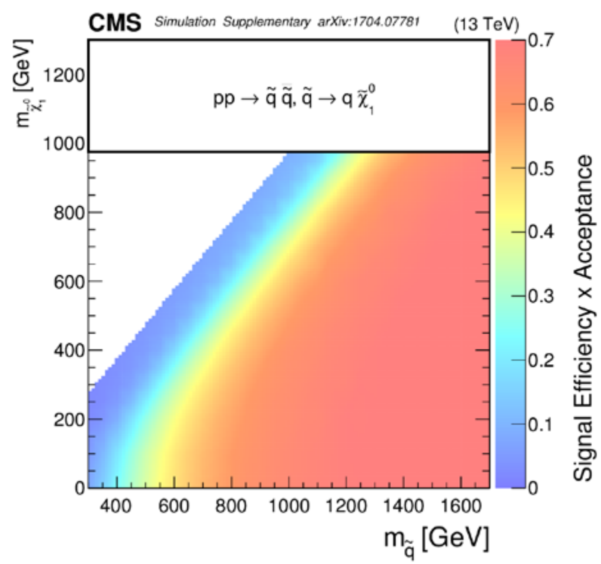
Signal Efficiencies (gluinos)



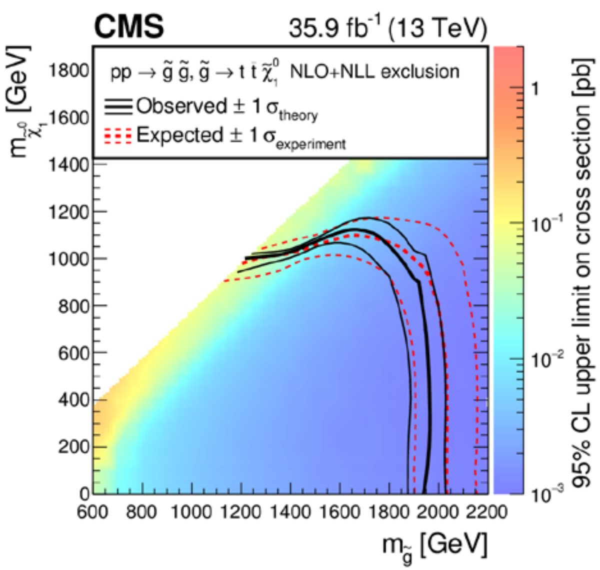
Signal Efficiencies (squarks)

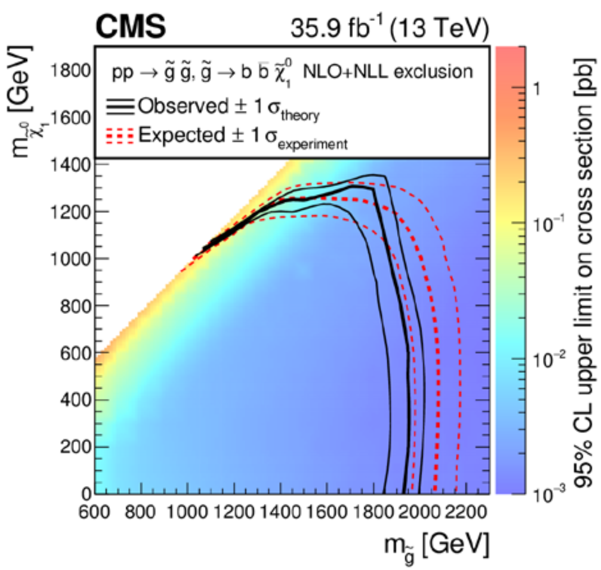


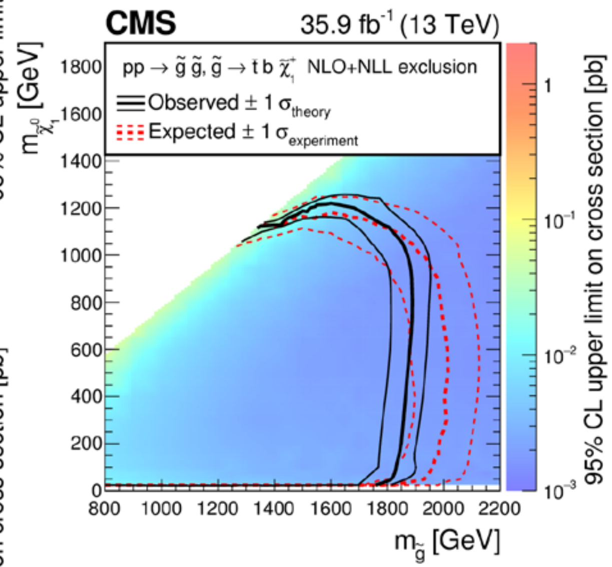


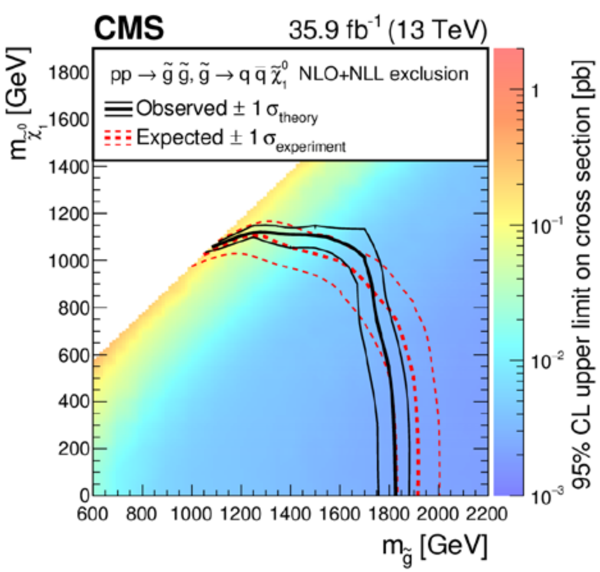


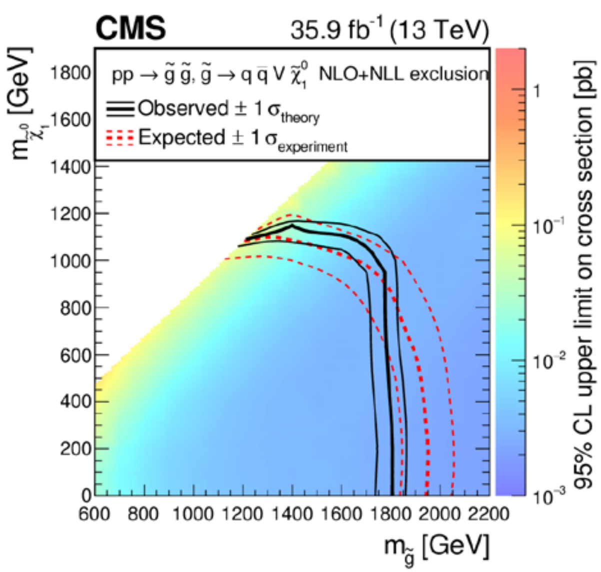
Limits (gluinos)



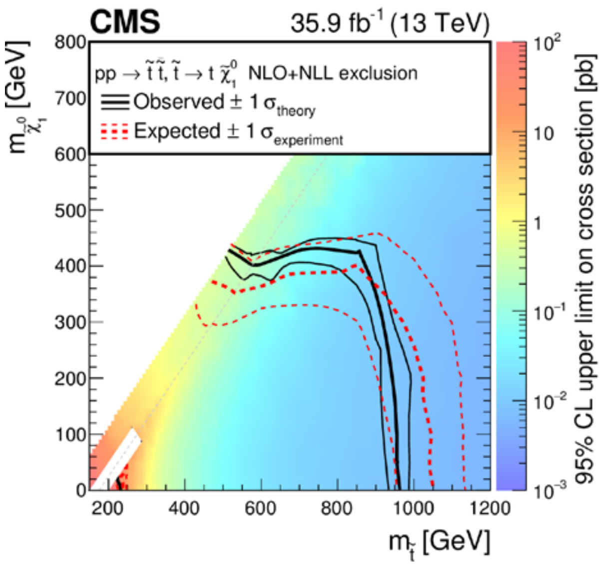


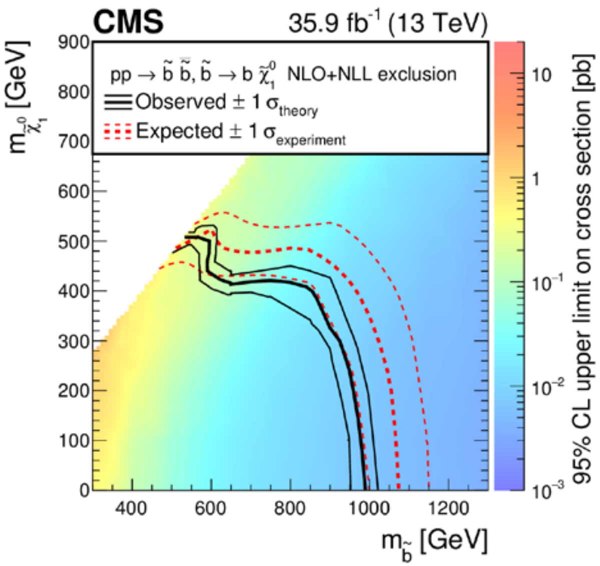


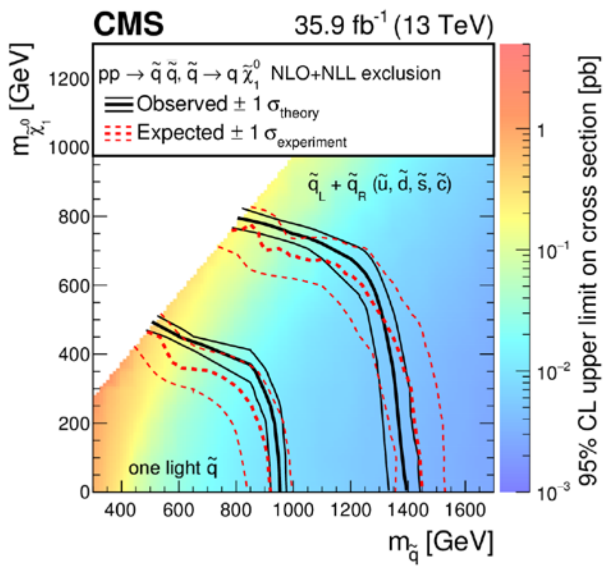




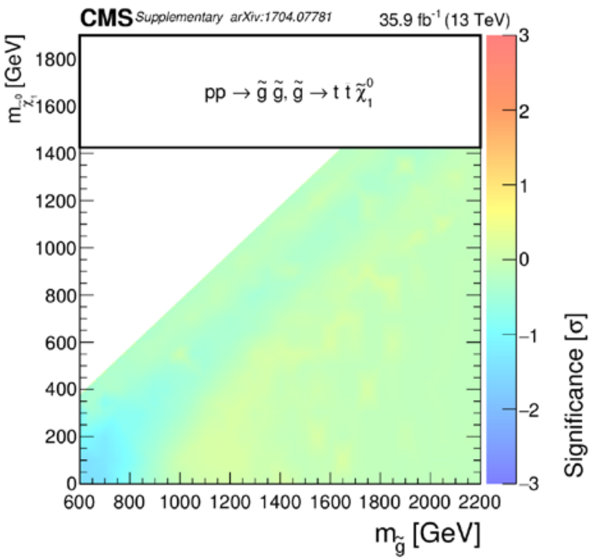
Limits (squarks)

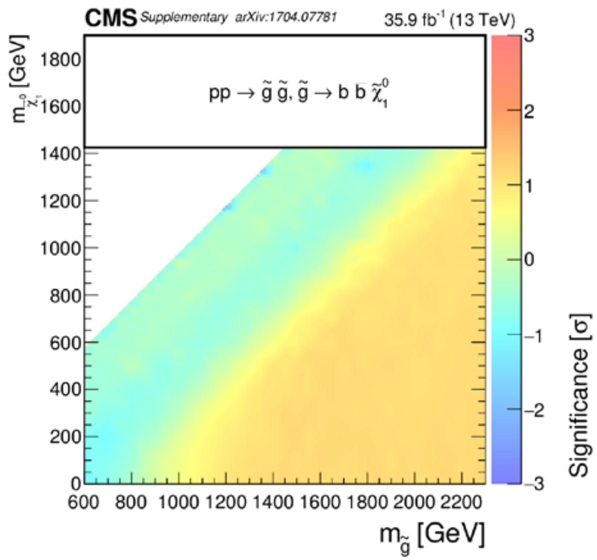


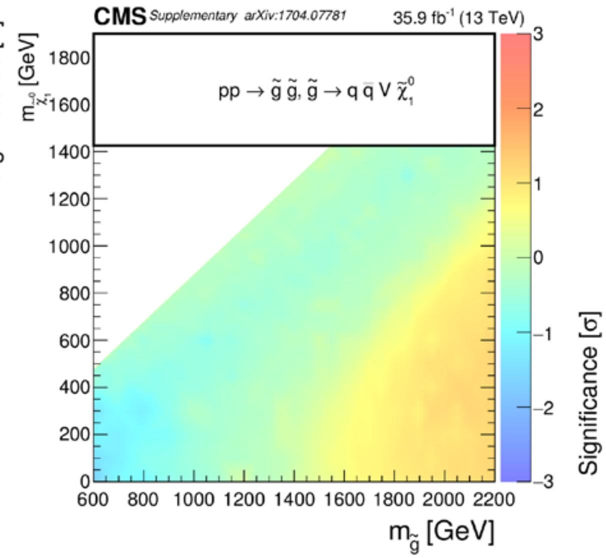


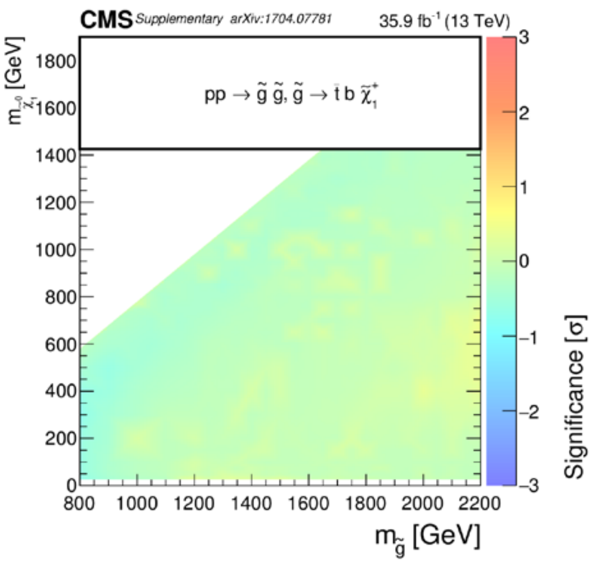


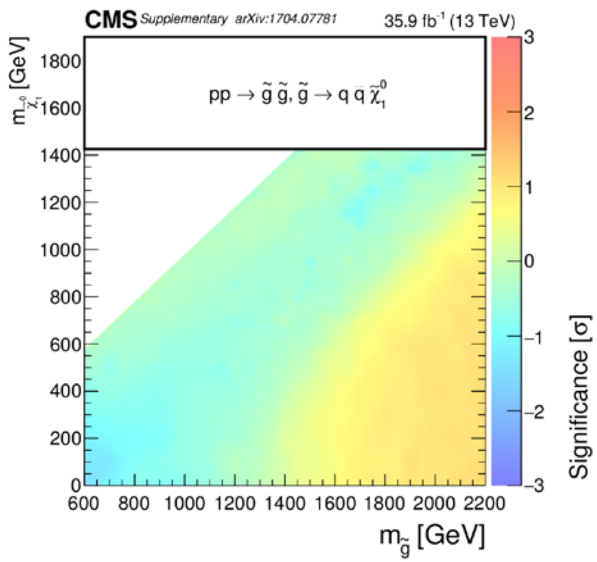
Significances (gluinos)



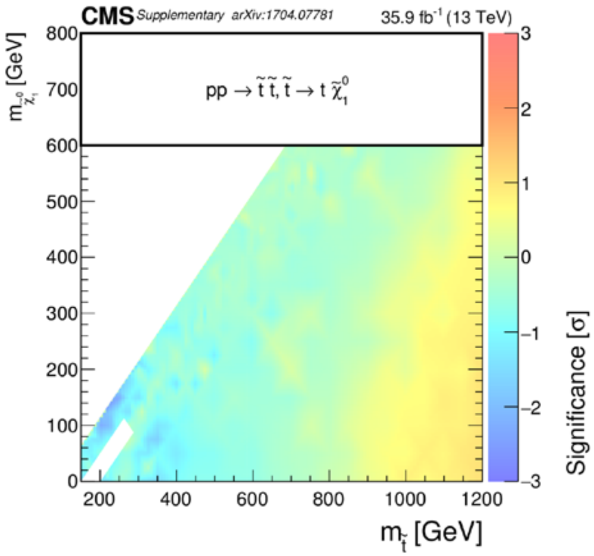


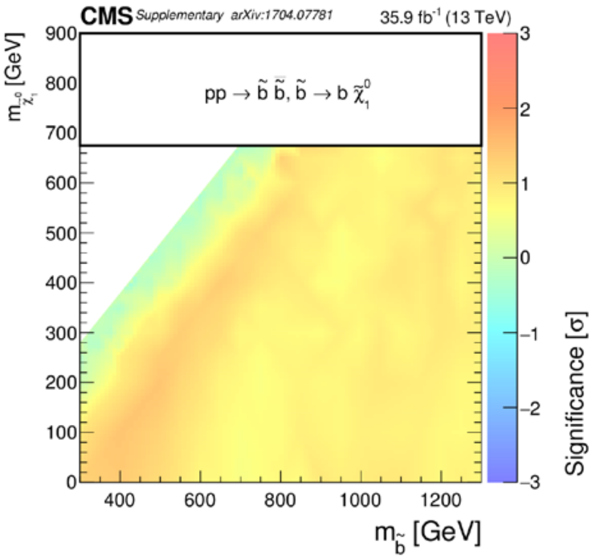


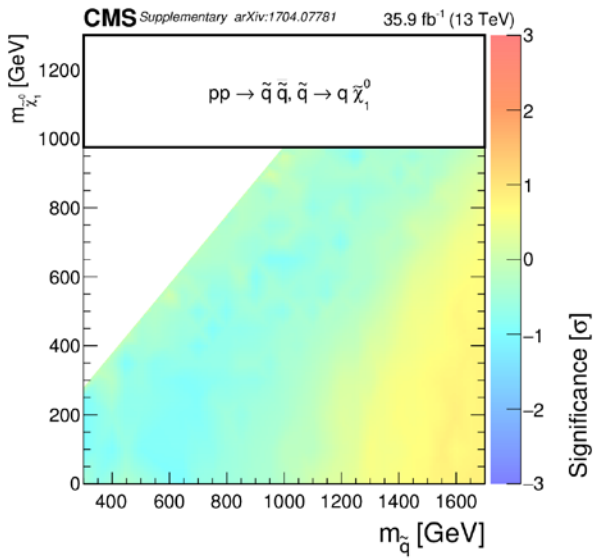




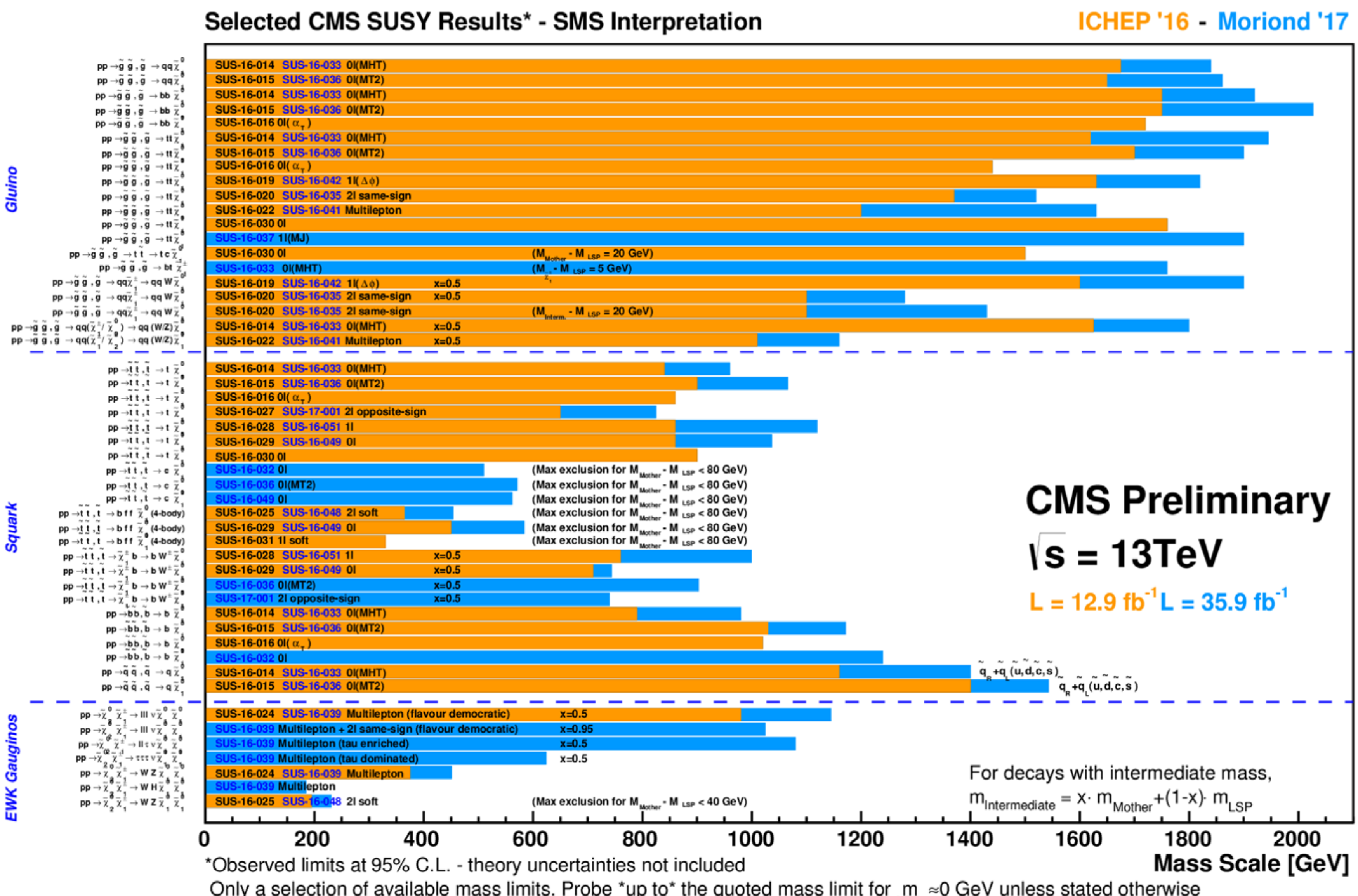
Significances (squarks)





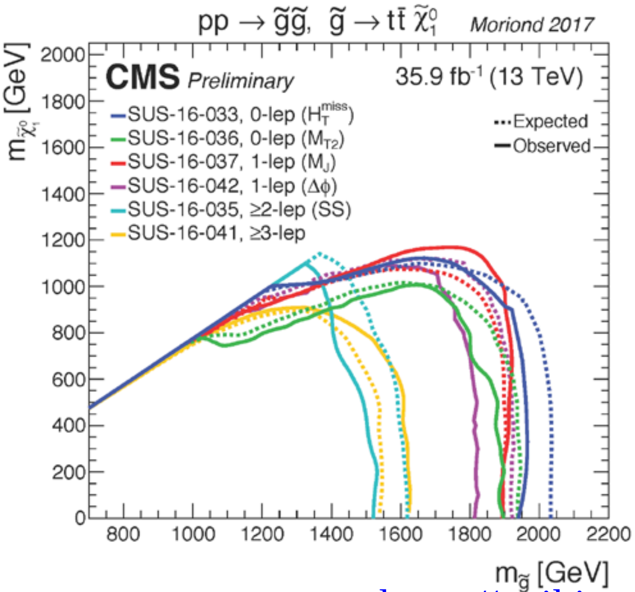


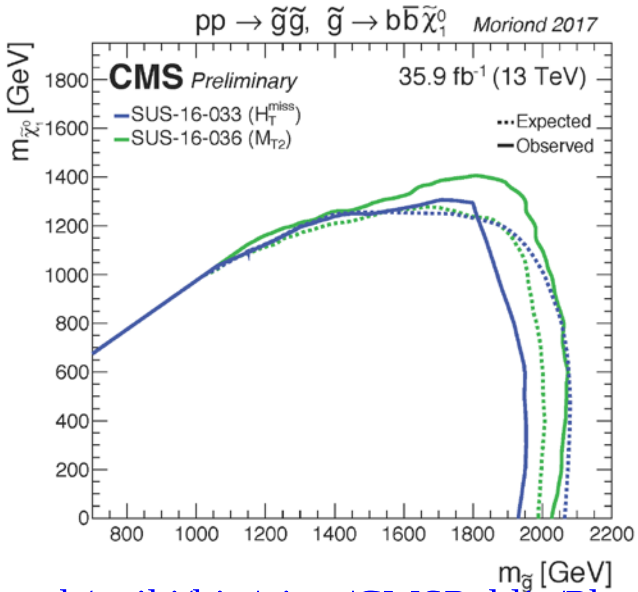
SUSY 13 TeV Summary (CMS)

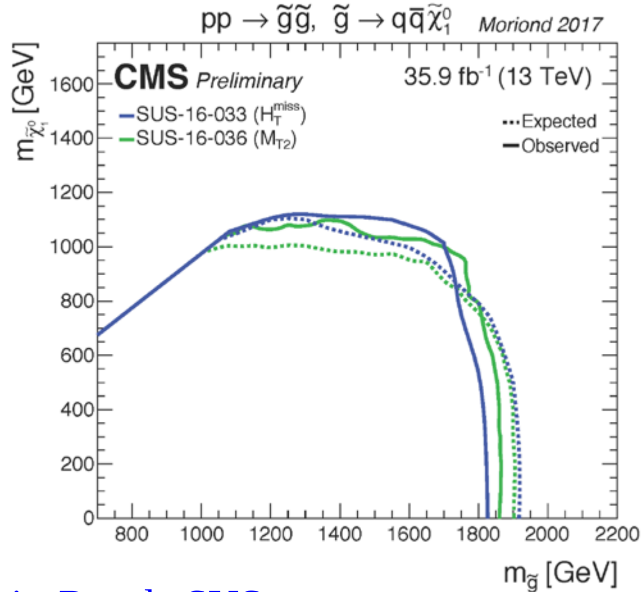


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

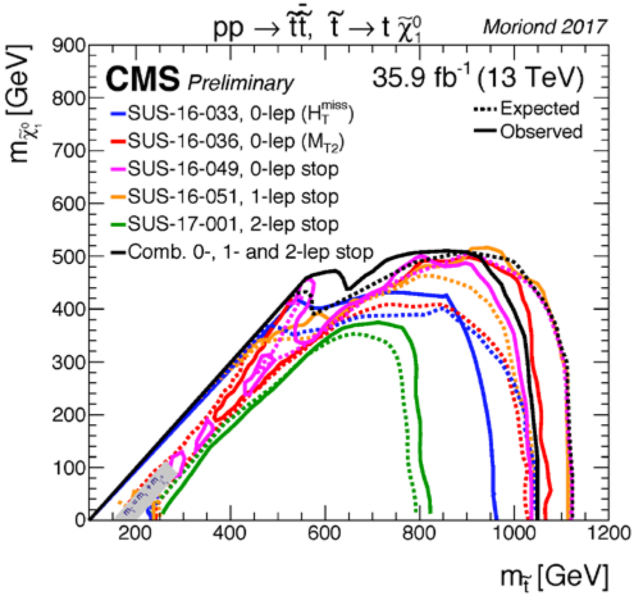
Limit Comparisons (CMS)

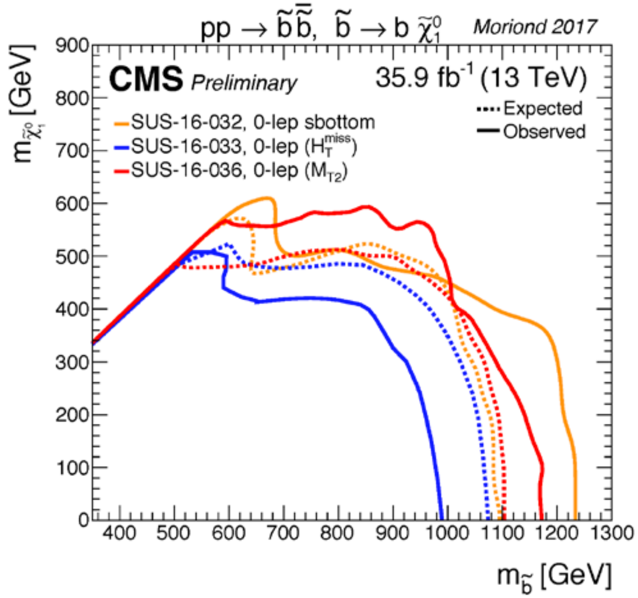


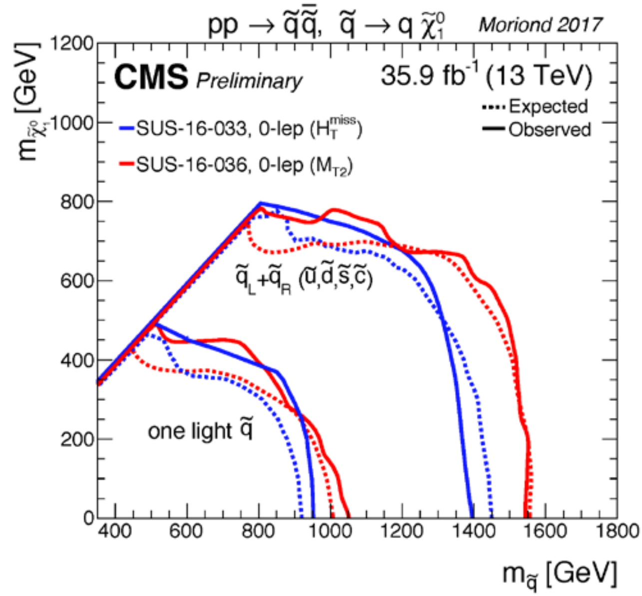




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS





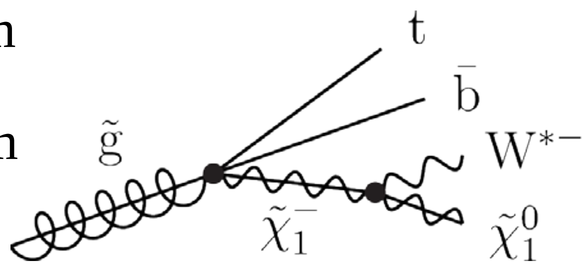


Details: $\tilde{g} \rightarrow t\, b\, \tilde{\chi}_1^{\pm}$ with $m_{\tilde{\chi}_1^0} \rightarrow 0$

- Near-degeneracy between $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$

➢ As $m_{\tilde{\chi}_1^0} \rightarrow 0$, $m_{W*} \approx m_{\tilde{\chi}_1^0}$

- $\tilde{\chi}_1^0$ carries smaller fraction of $\tilde{\chi}_1^{\pm}$ momentum
- W* carries larger fraction of $\tilde{\chi}_1^{\pm}$ momentum
- $\tilde{\chi}_1^{\pm}$ mass is lower → more boosted



$m_{W*} = 5$ GeV

$m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0} = 5$ GeV

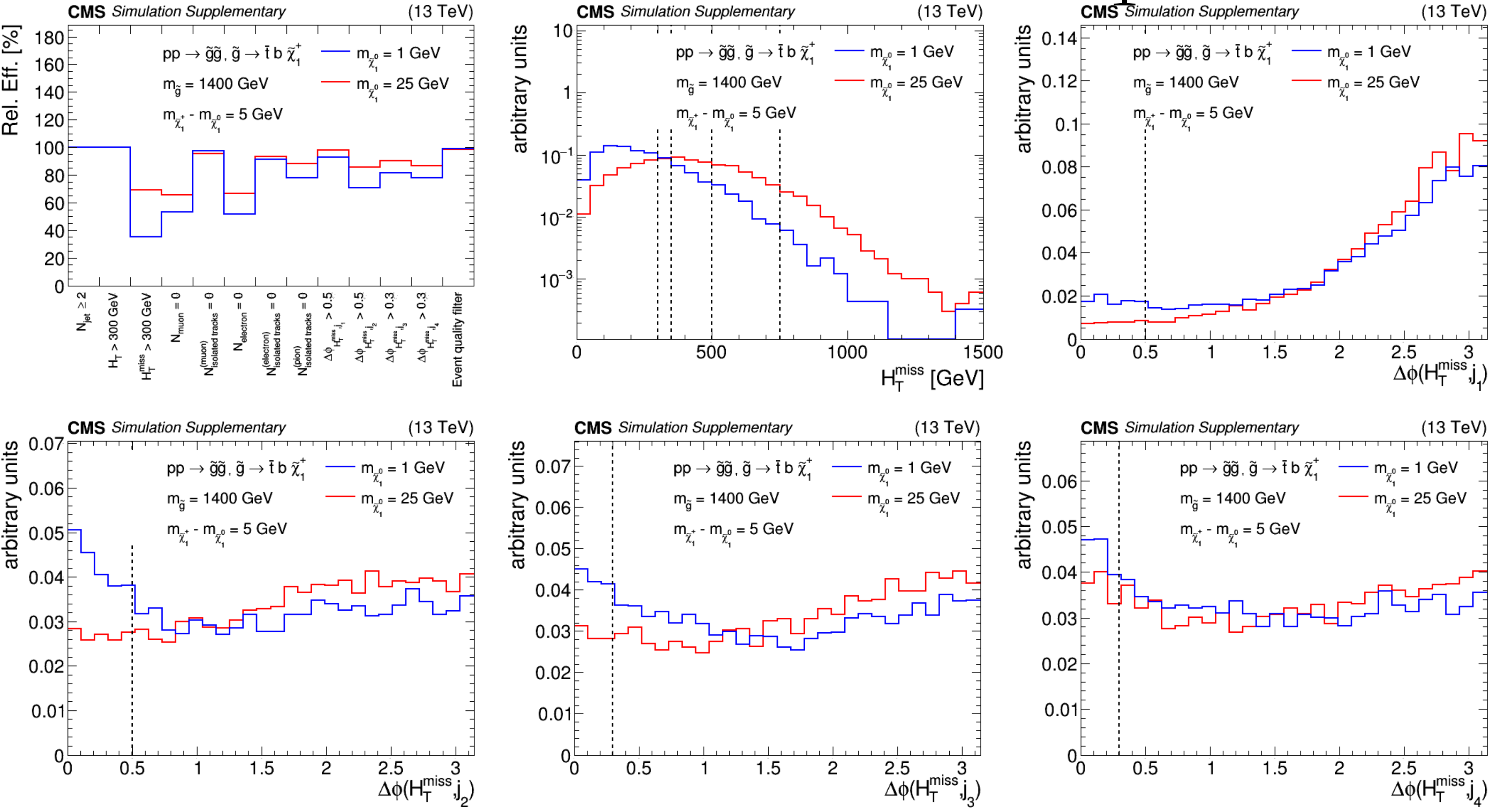
➢ **Softer H_T^{miss} spectrum** → H_T^{miss} cut rejects more signal

➢ W* produces **harder leptons** → lepton veto rejects more signal (pion track veto acts as hadronic τ veto)

➢ W* produces **jets aligned with H_T^{miss}** from $\tilde{\chi}_1^0$ → Δφ cuts reject more signal

❖ When both gluinos decay as $\tilde{g} \rightarrow t\, b\, \tilde{\chi}_1^{\pm}$, signal contamination in control regions becomes comparable to signal yield in signal region

Plots: $\tilde{g} \to t\, b\, \tilde{\chi}_1^{\pm}$ with $m_{\tilde{\chi}_1^0} \to 0$



Dotted lines indicate search region bin boundaries or cut values