Searches for SUSY in hadronic final states at CMS

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On behalf of the CMS Collaboration

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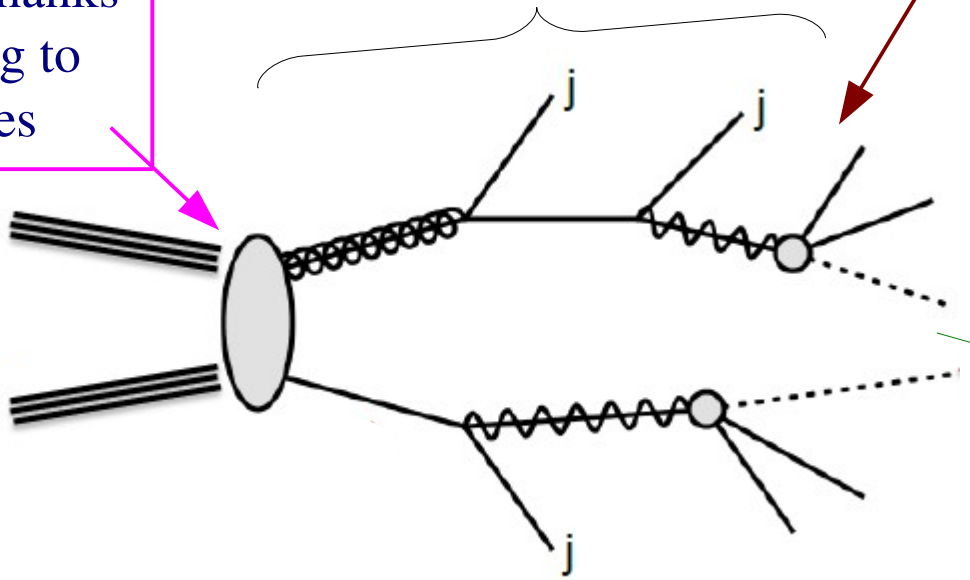
Introduction - Phenomenology

High production cross-sections of gluon/quark super-partners (gluino/squark) thanks to strong coupling to incoming pp states

Cascade decays involving jets, leptons and photons

Fully hadronic final state has the higher cross-section



Under the assumptions of a parity conservation (e.g. R-parity), a lightest stable particle (LSP) is present in the theory

All Sparticles eventually decay into the LSP. These escape the detector without interacting

⇨ **Missing transverse momentum**

⇨ **Good dark matter candidate**

⇨ **Key Signature: multi-jets + missing transverse momentum + X**

Analyses going to be presented

Results from Hadronic and Photon(s) + missing transverse momentum analyses using the **full 2011 dataset at 7 TeV**

- *Search for Supersymmetry in hadronic final states using M_{T2} with the CMS detector at 7 TeV*
  - PAS-SUS-12-002, 4.73/fb.
- *Search for new physics in the **multijets + missing transverse energy** final state*
  - PAS-SUS-12-011, 4.98/fb.
- *Search for supersymmetry with the **razor** variables at $\sqrt{s}$ = 7 TeV*
  - PAS-SUS-12-005, 4.4/fb.
- *Search for supersymmetry in events with **photons** and missing energy*
  - PAS-SUS-12-001, 4.7/fb.

CMS SUSY public results can be found at this link

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

M_{T2} Analysis Strategy

- The analysis is based on **M_{T2}**, which is a generalization of the transverse mass for decay chains with two unobserved particles, as typical in SUSY events.

$$M_{T2} = \min_{p_T^{c1}+p_T^{c2}=\not{p}_T} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right] \Longrightarrow \cong \mathrm{ME_T}, \text{ for SUSY events}$$

Multijet events divided into 2 massless pseudo-jets using a hemisphere algorithm (Lund-distance based)

- **M_{T2} is a QCD killer** ($M_{T2} \approx 0$ for back-to-back events with no genuine ME_T) and provides a very good discriminating power between SM and SUSY-like events in combination with H_T (scalar sum of all p_T^{jets} in the event) cut.

- Two analyses based on the same background estimation techniques and are aiming to cover complementary SUSY topologies

M_{T2}

- 2 H_T bins and 5 M_{T2} bins
- >= 3 central jets (40 GeV), $\Delta\phi_{min}$ (ME_T,jet)> 0.3
- W → jets and Z → υυ are main backgrounds
- Optimized for signal w/ large ME_T (low m_0)

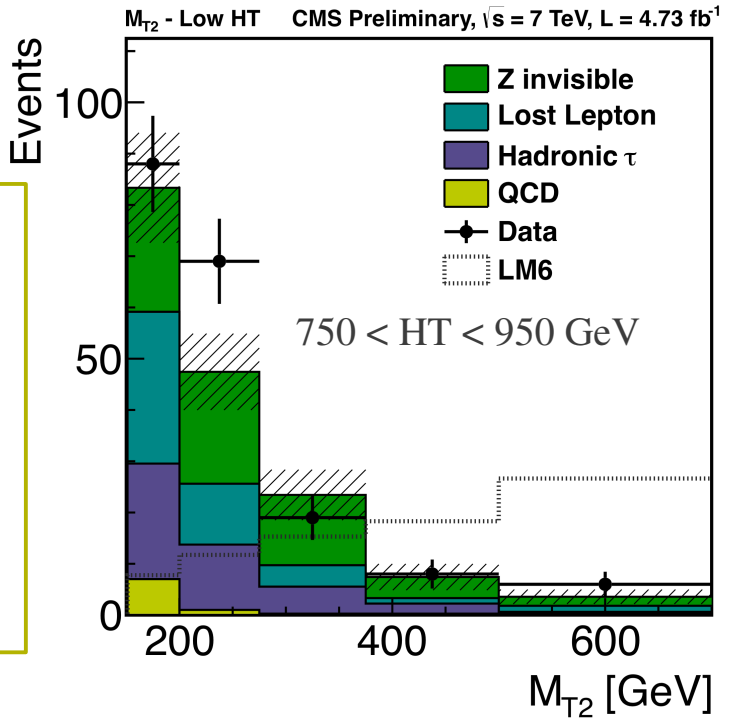
M_{T2}-b (>= 1 b-tagged jet)

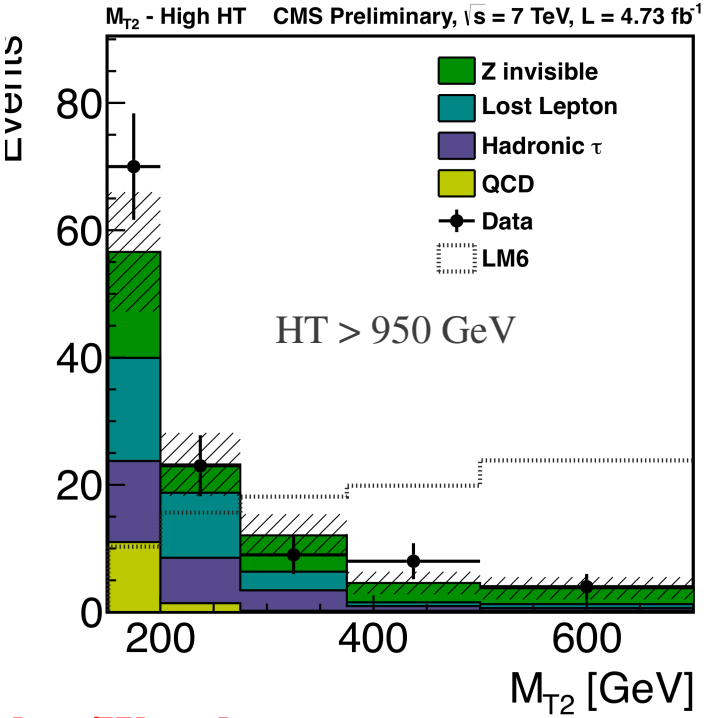
- 2 H_T bins and 4 M_{T2} bins (lower thresholds)
- >= 4 central jets, $\Delta\phi_{min}$ (ME_T,jet)> 0.3
- ttbar is the main background
- Optimized for light gluino decaying to 3rd generation squarks (high m_0)

M_{T2} Background Estimation

QCD

Predict signal region (high M_{T2}, $\Delta\phi_{min} > 0.3$) from QCD enhanced region (high M_{T2}, $\Delta\phi_{min} < 0.2$) using an exponential form with parameters from a fit in the region $50 < M_{T2} < 80$ GeV





$Z \rightarrow \nu\nu$

Prediction is taken as the weighted average of $Z \rightarrow \nu\nu$ from $W \rightarrow \mu\nu$ and from γ + jets estimations, which exploit similarities in the V+jets processes

$$N_{Z\nu\nu} = N_{W\mu\nu} \cdot \frac{1}{\epsilon_{acc}\epsilon_{reco/iso}} \cdot R^{MC}$$

ttbar/W $\rightarrow$ lν

Largely reduced by lepton veto. Remaining is from *e* or *mu* out of acceptance or not identified, and hadronic τ-decays

Estimated from electron and muon samples (**"hadronic" τ from MC**)

$$N_{e,\mu}^{lost\ lepton} = (N_{e,\mu}^{reco} - N_{e,\mu}^{bg})\frac{1-\varepsilon_{e,\mu}}{\varepsilon_{e,\mu}}$$

M_{T2}-b Background Estimation

QCD

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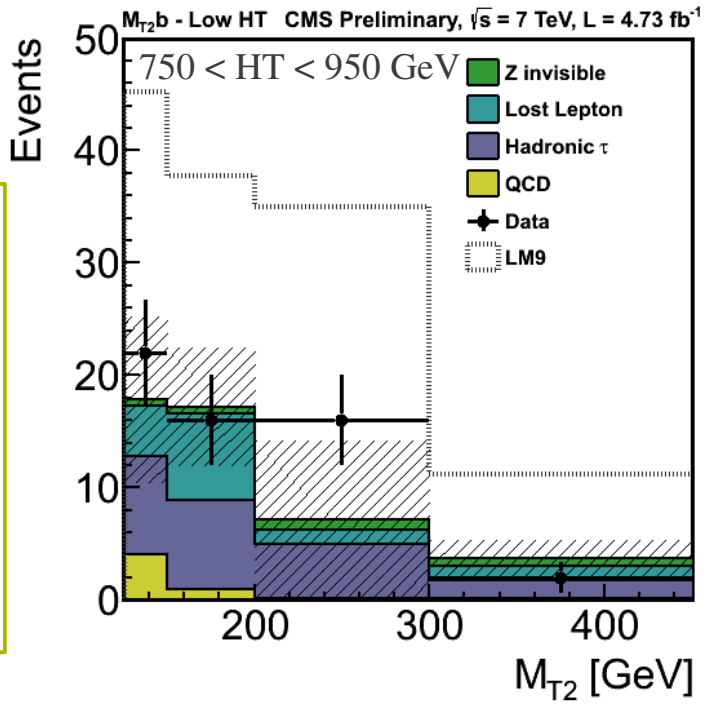

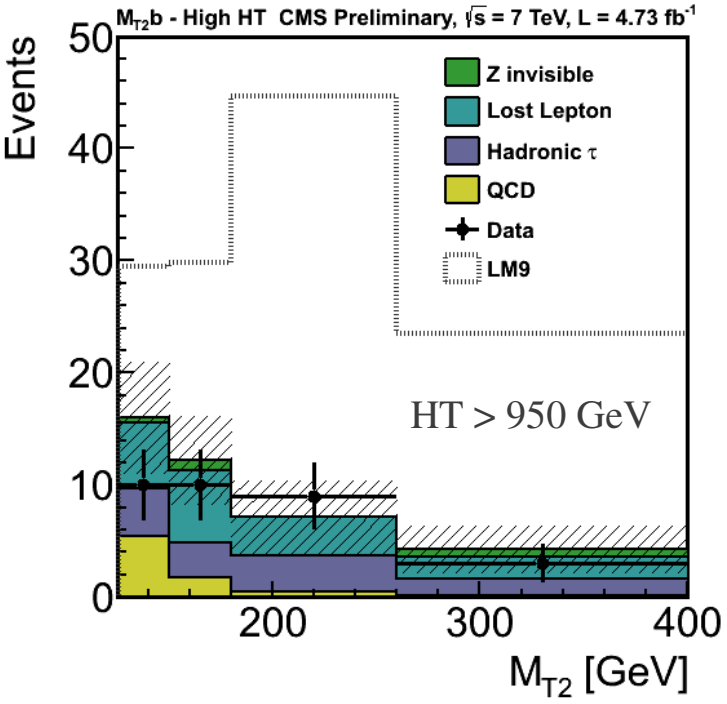

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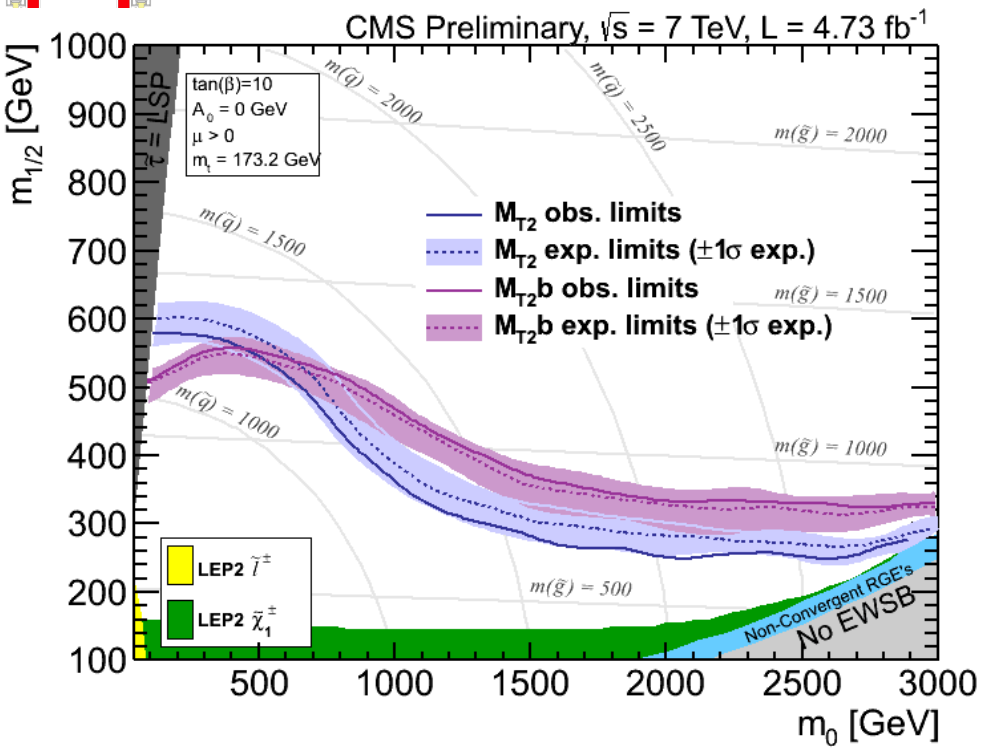
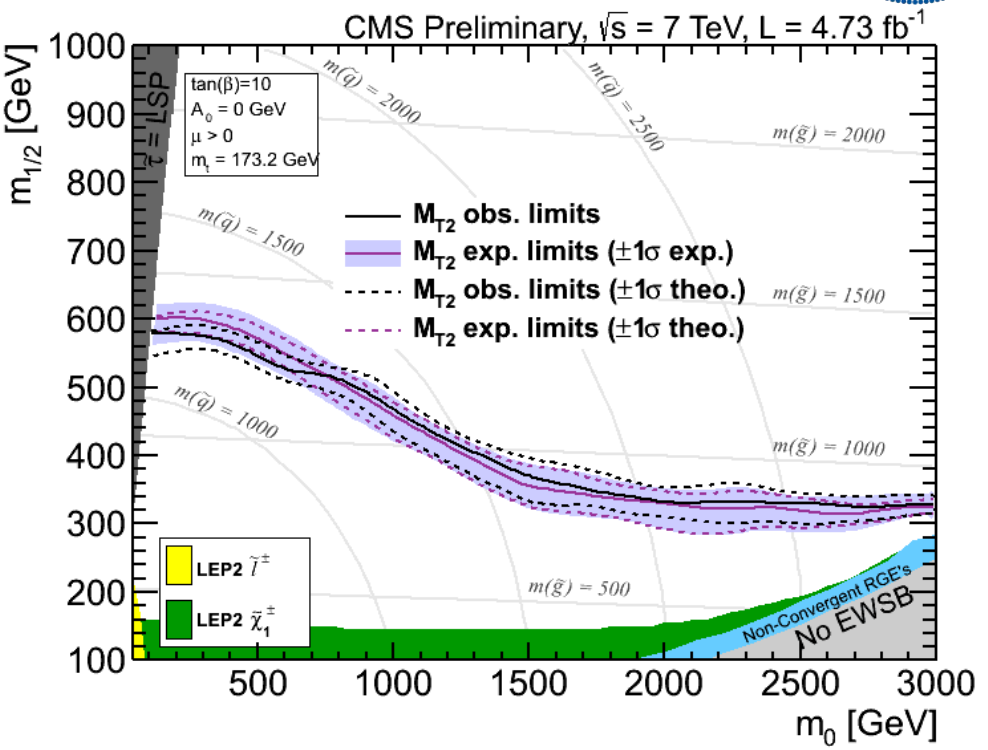
mSUGRA/CMSSM Limits



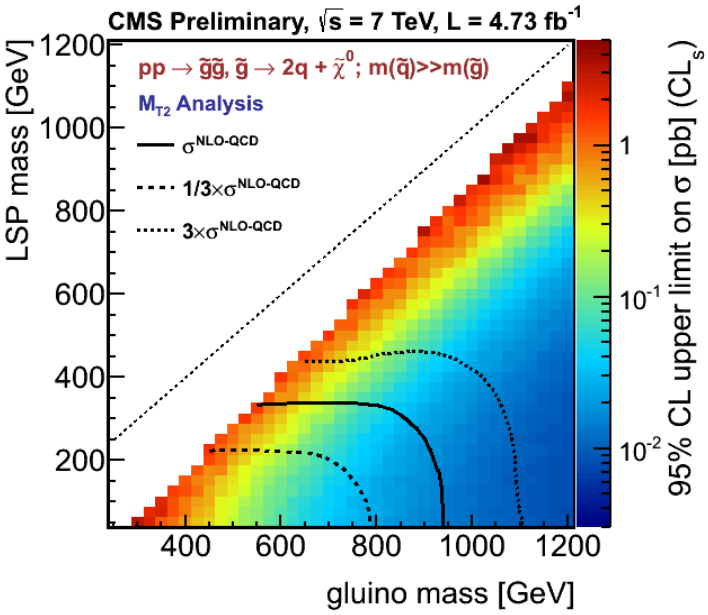


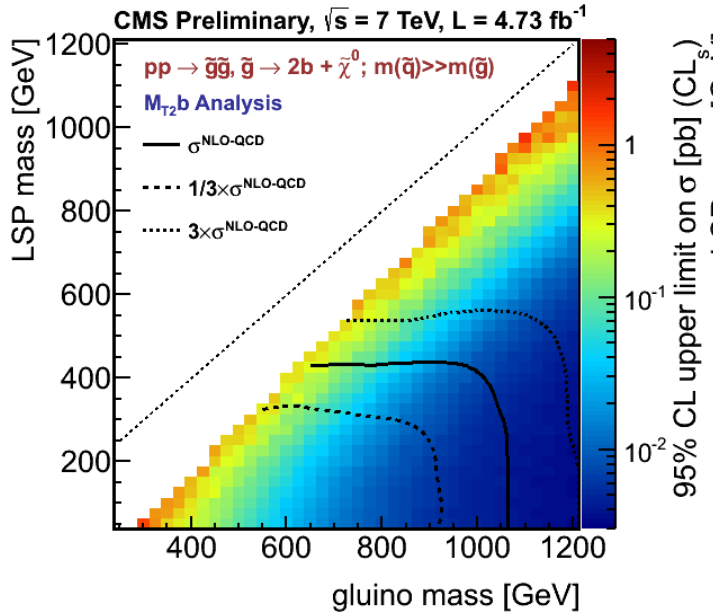
- **No significant excess observed in data**, we proceed by setting upper limits using CLs
- M_{T2}- and M_{T2}-b analyses are not orthogonal, they are not statistically combined, **the best limit is used for the final result**

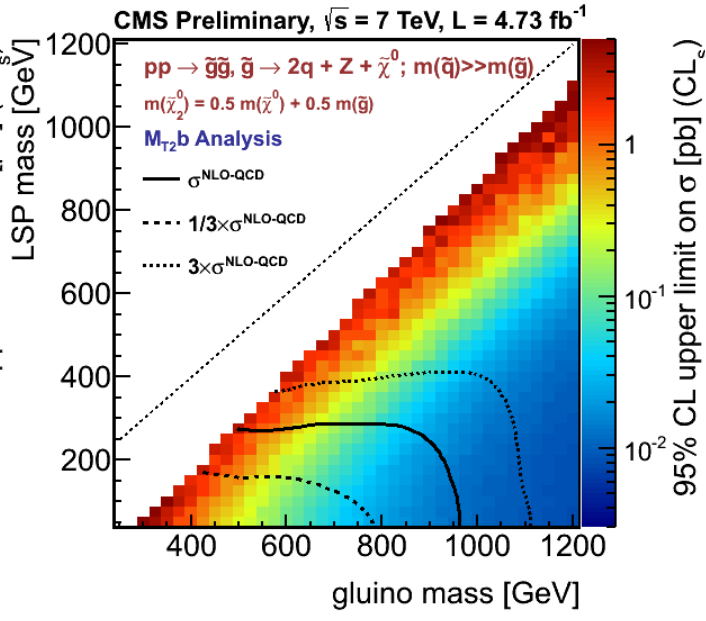
Effects taken into account bin by bin, point by point:

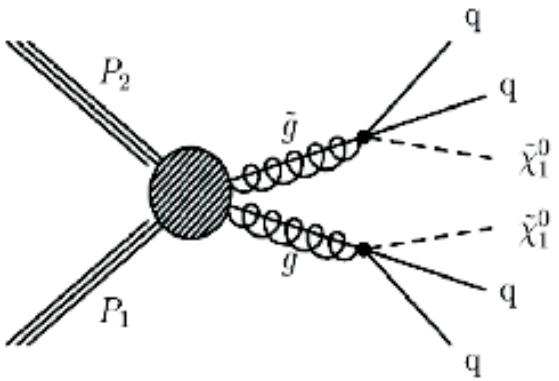
- Signal contamination in leptonic control sample
- Theory uncertainties on PDF and factorization and renormalization scale
- Jet energy scale uncertainty introduced as a nuisance parameter on signal model.
- B-tagging uncertainties introduced as a nuisance parameter on signal model.
- Luminosity uncertainty

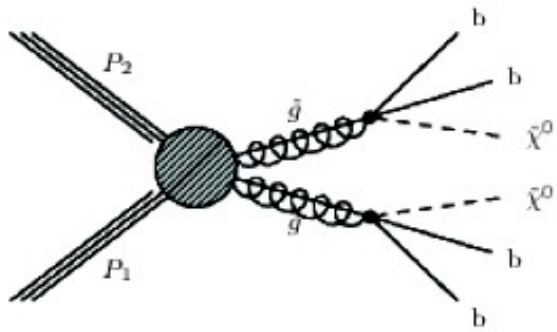
Limits from M_{T2} On Simplified Models

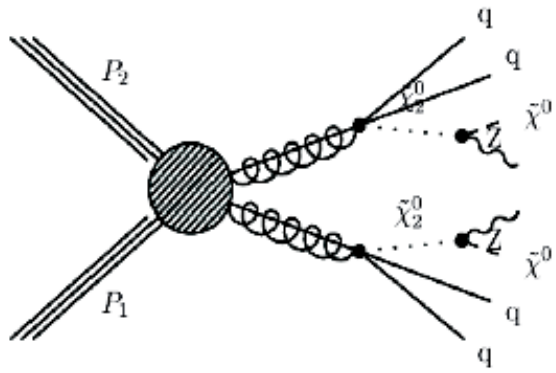












Multi-jets + MH_T Analysis

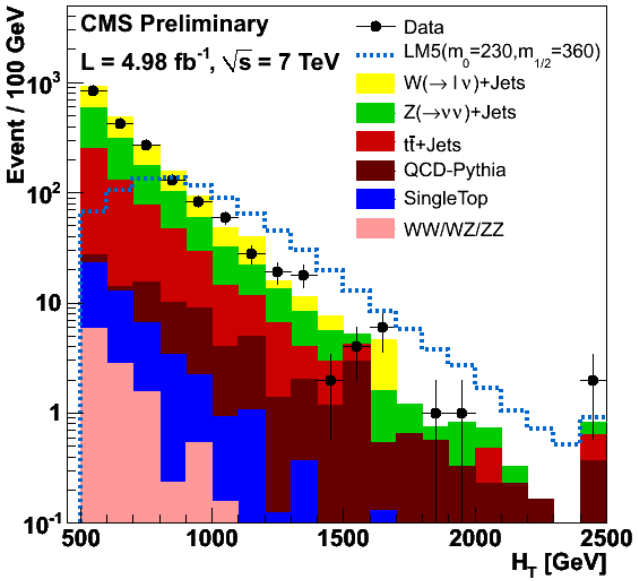
Inclusive analysis in the jets + missing transverse momentum final state, aimed to ***fully characterise*** the event's kinematic in the search regions

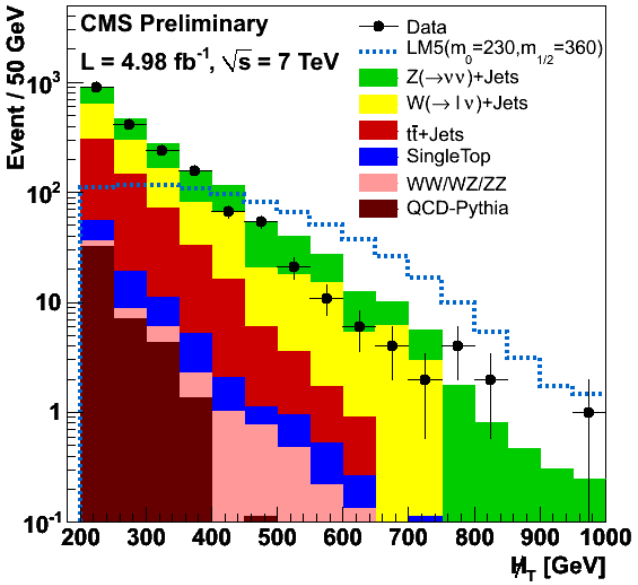
Based on: $H_T = \sum_i^{jets} \left| \vec{p}_T, i \right|$ ⟺ visible-energy scale $\not{H}_T = \left| -\sum_i^{jets} \vec{p}_T, i \right|$ ⟺ Undetected particle energy scale

Requirements:

- At least 3 jets with $p_T > 50$ GeV and $|\eta| < 2.5$, with isolated-lepton veto
- $\Delta\phi(MH_T, jet_i) > .5, .5, .3$, $j = 1^{st}, 2^{nd}, 3^{rd}$ most energetic jets
- $H_T > 500$ GeV and $MH_T > 200$ GeV, then **14 exclusive H_T,MH_T bins**

MHT→ HT ↓	200-350	350-500	500-600	>600
500-800	bin 1	bin 2	bin 3	bin 4
800-1000	bin 5	bin 6	bin 7	bin 8
1000-1200	bin 9	bin 10	bin 11	
1200-1400	bin 12	bin 13		
>1400	bin 14			





Jets+MH_T Background Estimation

QCD: Rebalance and Smearing

- **Rebalance** : Particle level pT is restored from detector level inclusive multijet data using a kinematic fit subject to constraint MHT + soft particle = 0 (using jet resolution functions derived from MC but corrected to match data)
- **Smear** : events are then smeared using the measured jet resolution functions including non-Gaussian tails
- Obtain a data driven estimation of full kinematics of QCD multijet events
  - predict HT, MHT, angles between jets and MHT

ttbar/W → lν, lost lepton

- Similarly as in M_{T2} analysis, it is estimated from electron and muon samples, correcting back for lepton isolation and id efficiencies

Hadronic tau decays from top/W → τυ

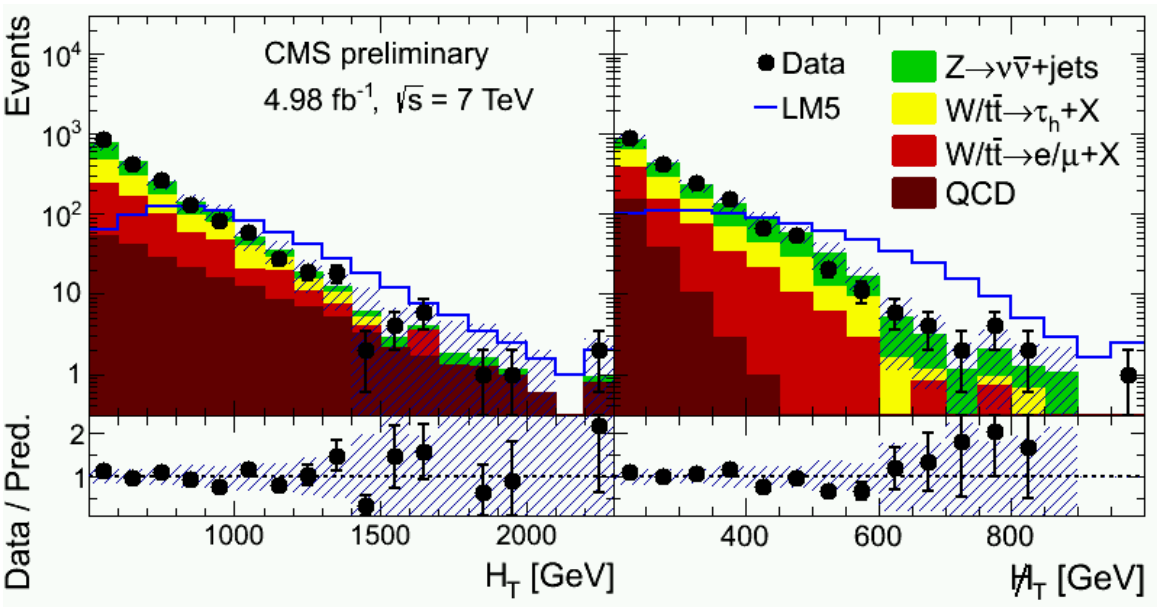
- Estimated from data using a muon control sample and a τ detector-response template used to smear the muon momentum

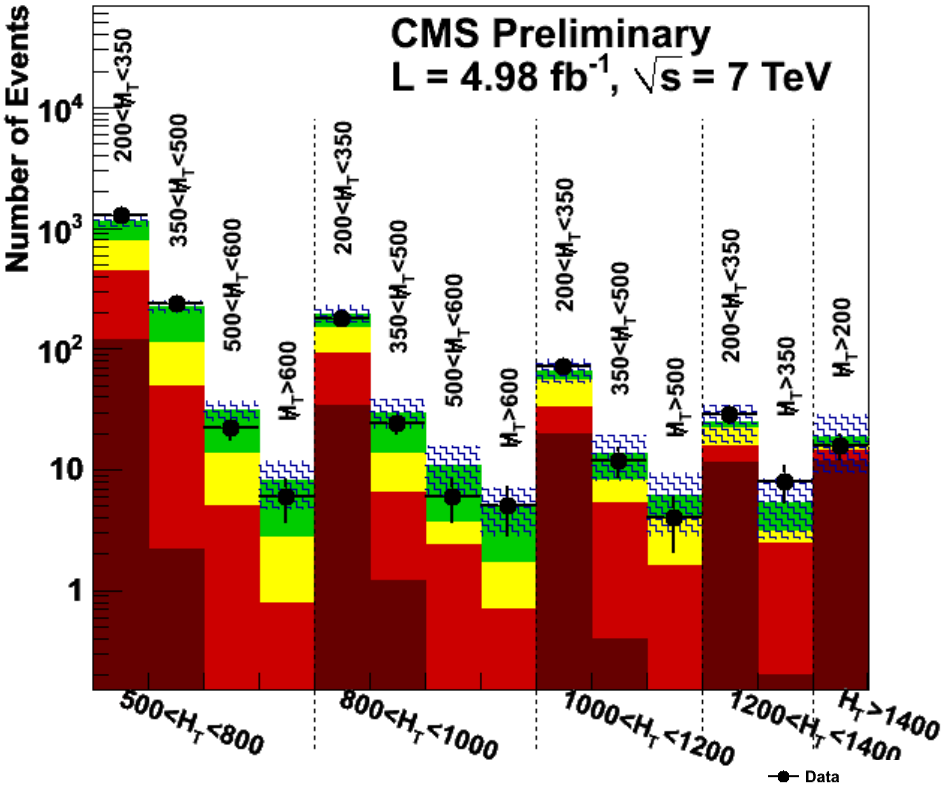
Z → υυ

- Estimated using γ+jets sample (validated w/ prediction from Z → μμ) exploiting the commonalities of the processes with production of γ and Z

$$N^{\text{data}}_{Z\to\nu\bar{\nu}+\text{jet}} = \left(\frac{Z\to\nu\bar{\nu}+\text{jet}}{\gamma+\text{jet}}\right)_{\text{mc}} \times \epsilon^{direct}_{\text{mc}} \times \text{SF}_{\text{data/mc}} \times \epsilon^{prompt}_{\text{data}} \times N^{\text{data}}_{\gamma+\text{jet}}$$

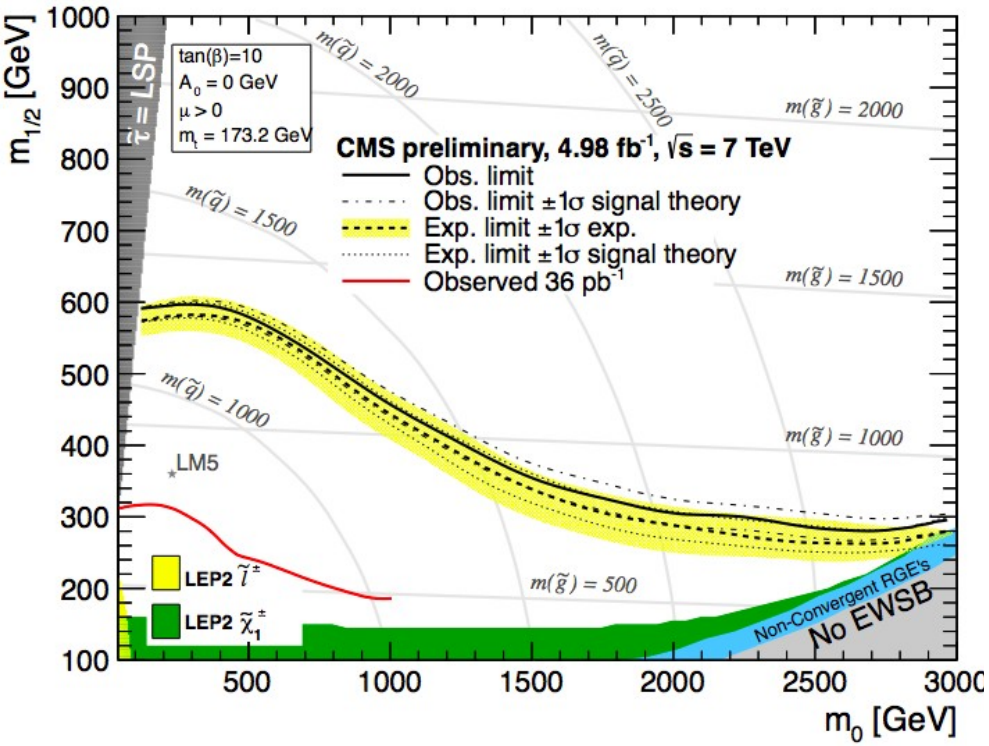
Jets+MH_T Background Prediction

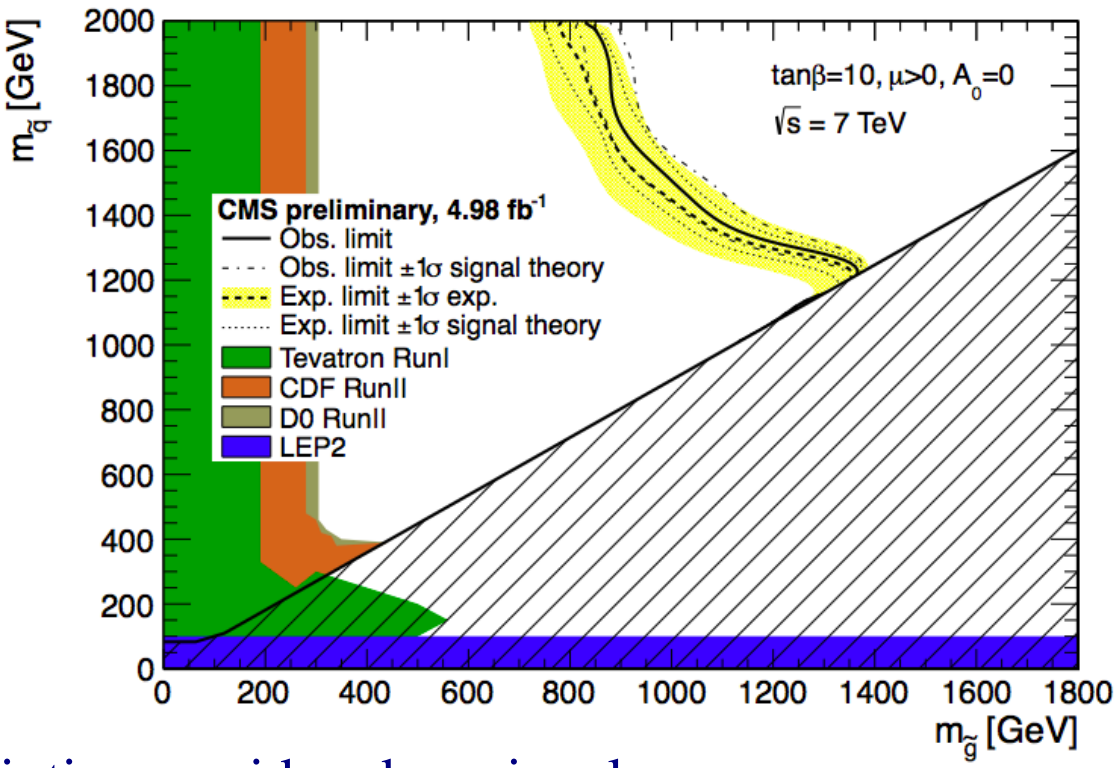




- Quite **good agreement** (*unfortunately*...) between observed and Standard Model expected number of events
- **Set limits** on mSUGRA/CMSSM and in Simplified Models

mSUGRA/CMSSM Limits

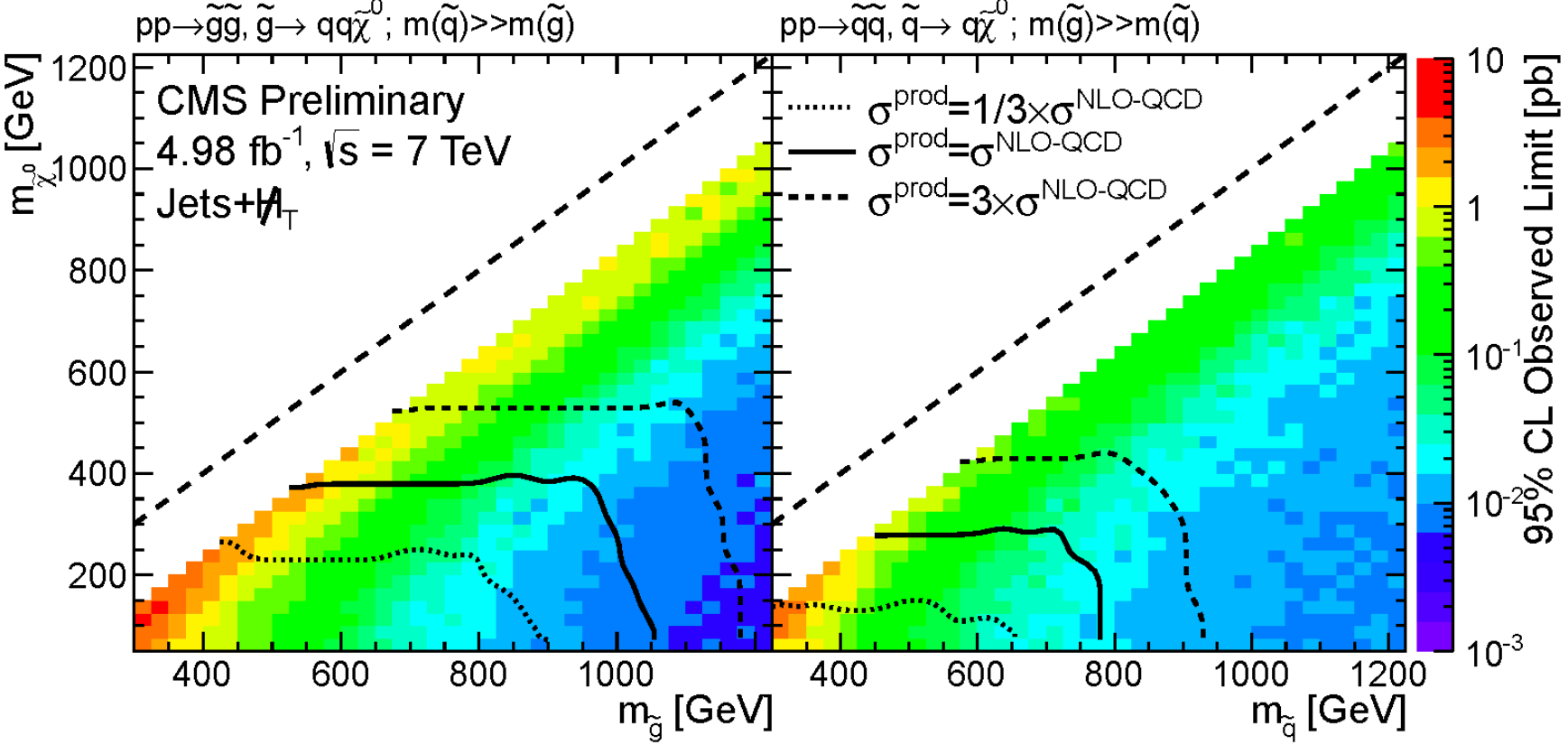


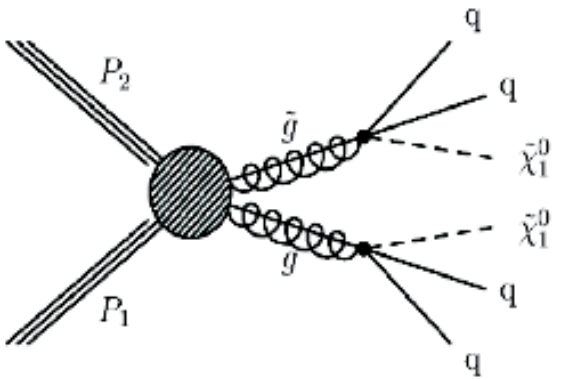


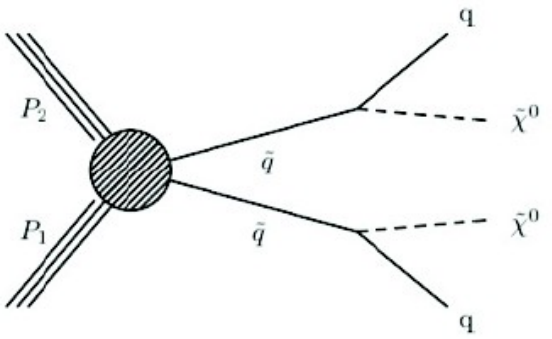
Systematic uncertainties considered on signal

- parameter space dependent
  - Jet Energy Scale (**~8%**)
  - Jet Energy Resolution (**~2%**)
  - Theoretical uncertainties due to PDF (**~6%**)
  - Signal contamination (**3-20%**)
- Flat
  - Luminosity (**2.2%**)
  - Trigger inefficiency (**2%**)
  - Event cleaning (**3%**)

Limits from Jets+MH_T On Simplified Models

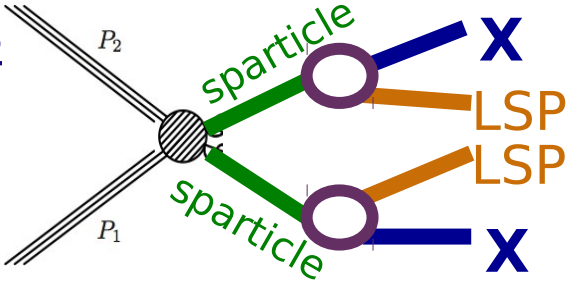






Razor Analysis

- The selection groups all final state objects (jets, leptons) into **two mega-jets**
- Calculate the **Razor variables R/M$_R$** designed for this topology



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

Peaks at ~ $M_\Delta = \dfrac{M_S^2 - M_{\mathrm{LSP}}^2}{M_S}$

In simple case:
S = squark
X = jet

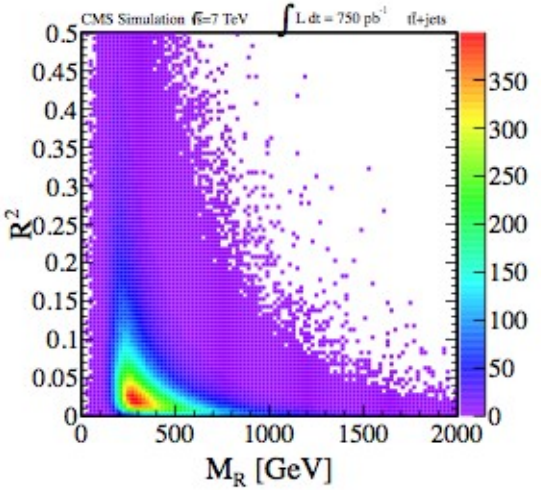
$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

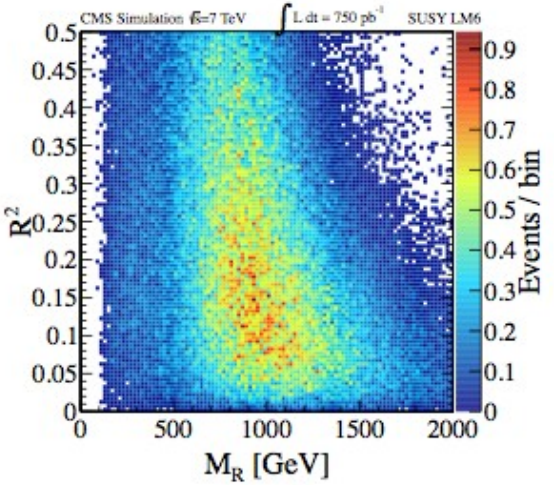
Edge at ~ M_Δ

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

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

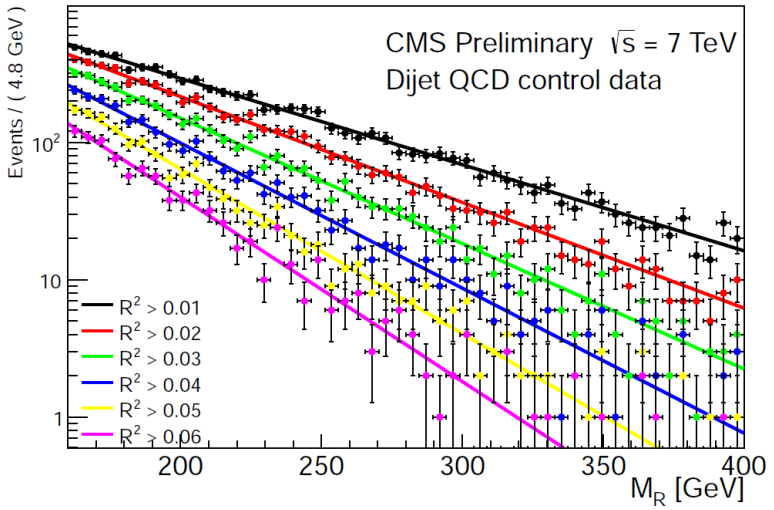
$t\bar{t}$ +jets

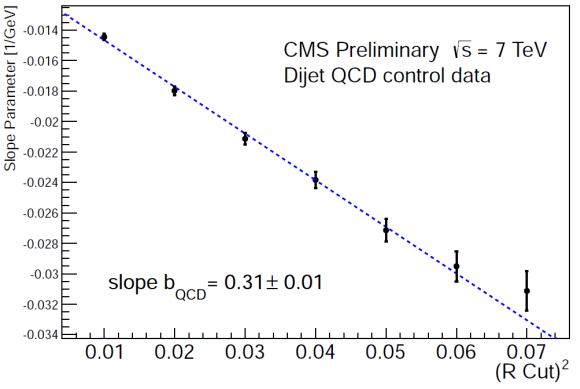




Example of SUSY

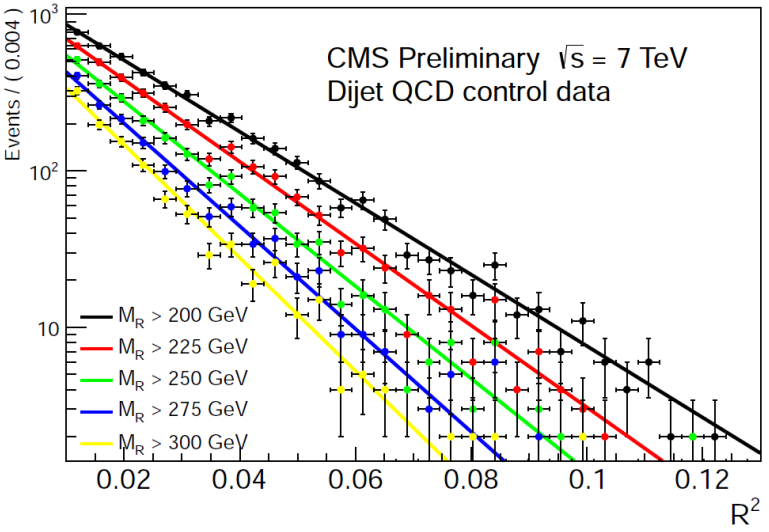
Razor Variables

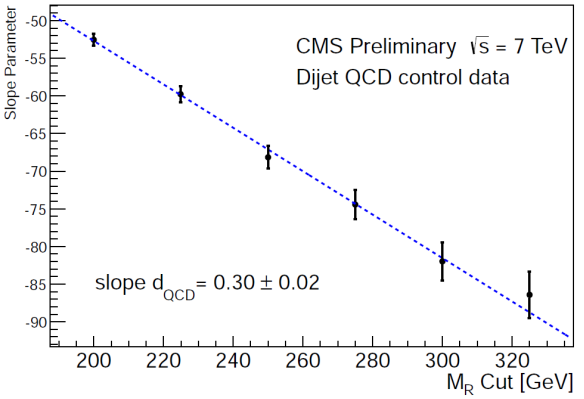




$$f(M_R) \propto e^{-SM_R}$$

$$S = a + b(R\ \text{cut})^2$$





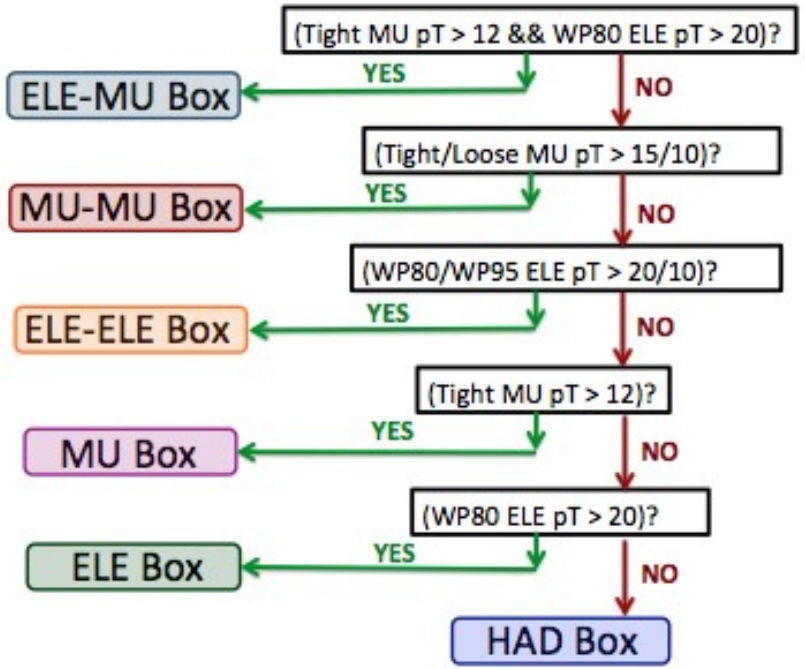
$$f(R^2) \propto e^{-SR^2}$$

$$S = c + d(M_R\ \text{cut})$$

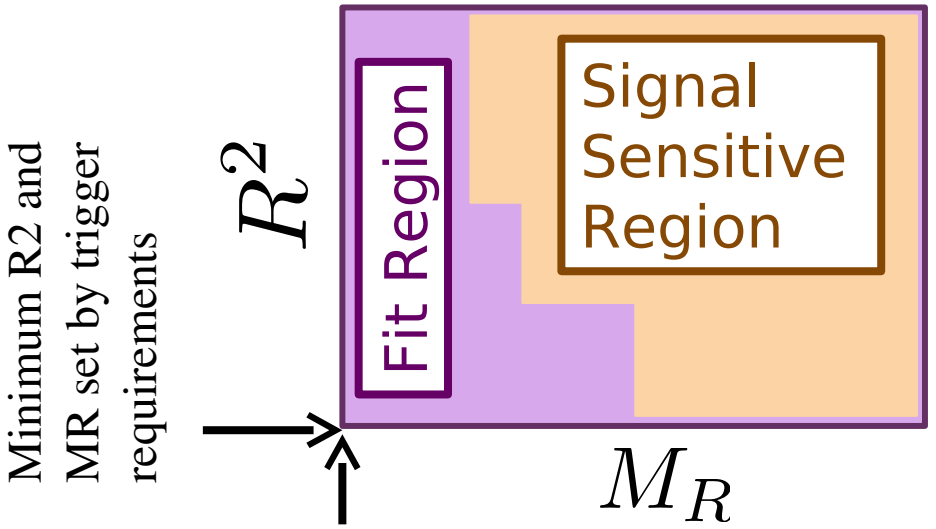
Same functional phenomenology describes each SM background, EWK modelled by double exponential for each variable

$$f(R^2, M_R) \propto \left[k(M_R - M_R^0)(R^2 - R_0^2) - 1\right] e^{-k(M_R - M_R^0)(R^2 - R_0^2)}$$

Razor Background Estimation



Final state BOX classification based on lepton ID

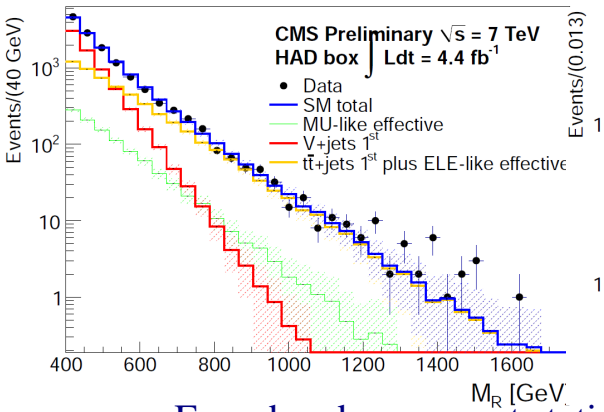


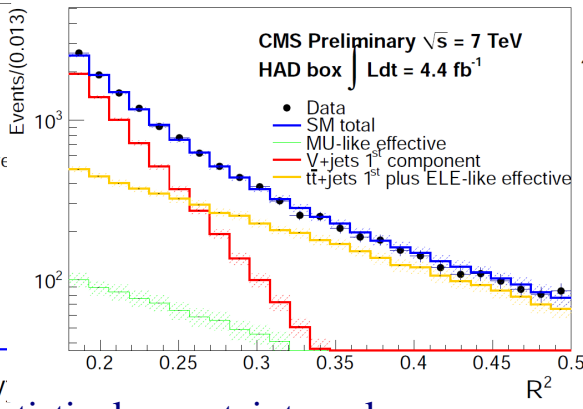
Extended and unbinned maximum likelihood fit performed in 2D R^2-M_R plane independently in each BOX

$$\mathcal{L}_b = \frac{e^{-(\sum_{j\in SM} N_j)}}{N!} \prod_{i=1}^{N} \left(\sum_{j\in SM} N_j P_j(M_{R,i}, R_i^2) \right)$$

Background functionally extrapolate to signal region, then toy MC generated accordingly with Likelihood function

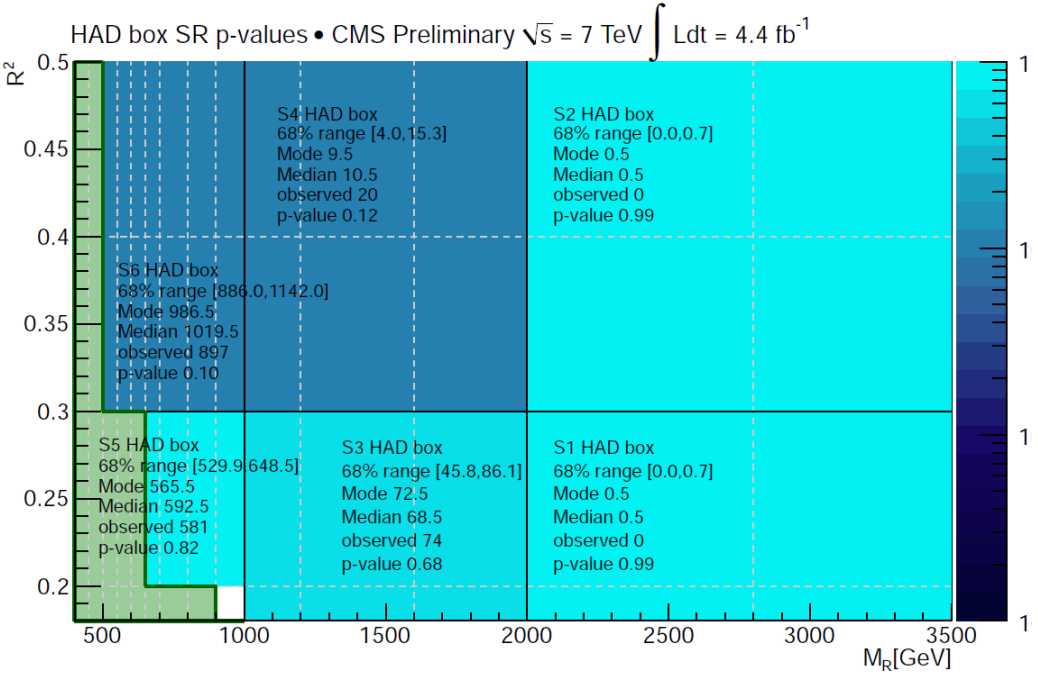
Based on functional form shown in previous page

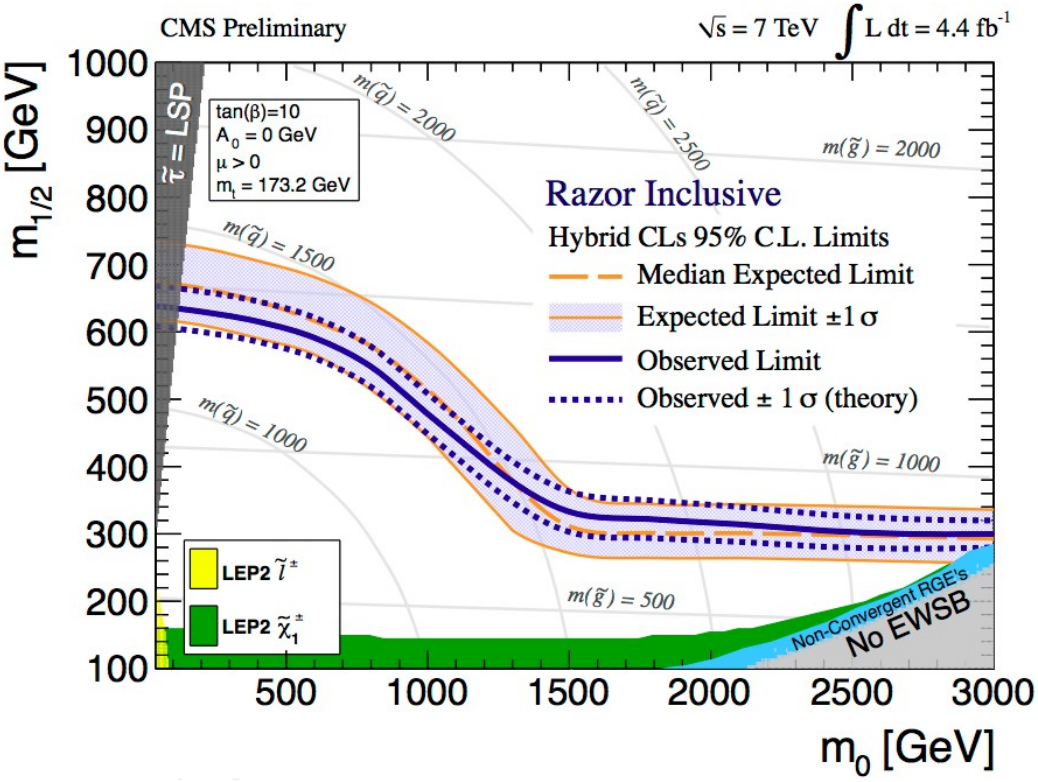




Error bands represent statistical uncertainty only

Razor CMSSM Limits

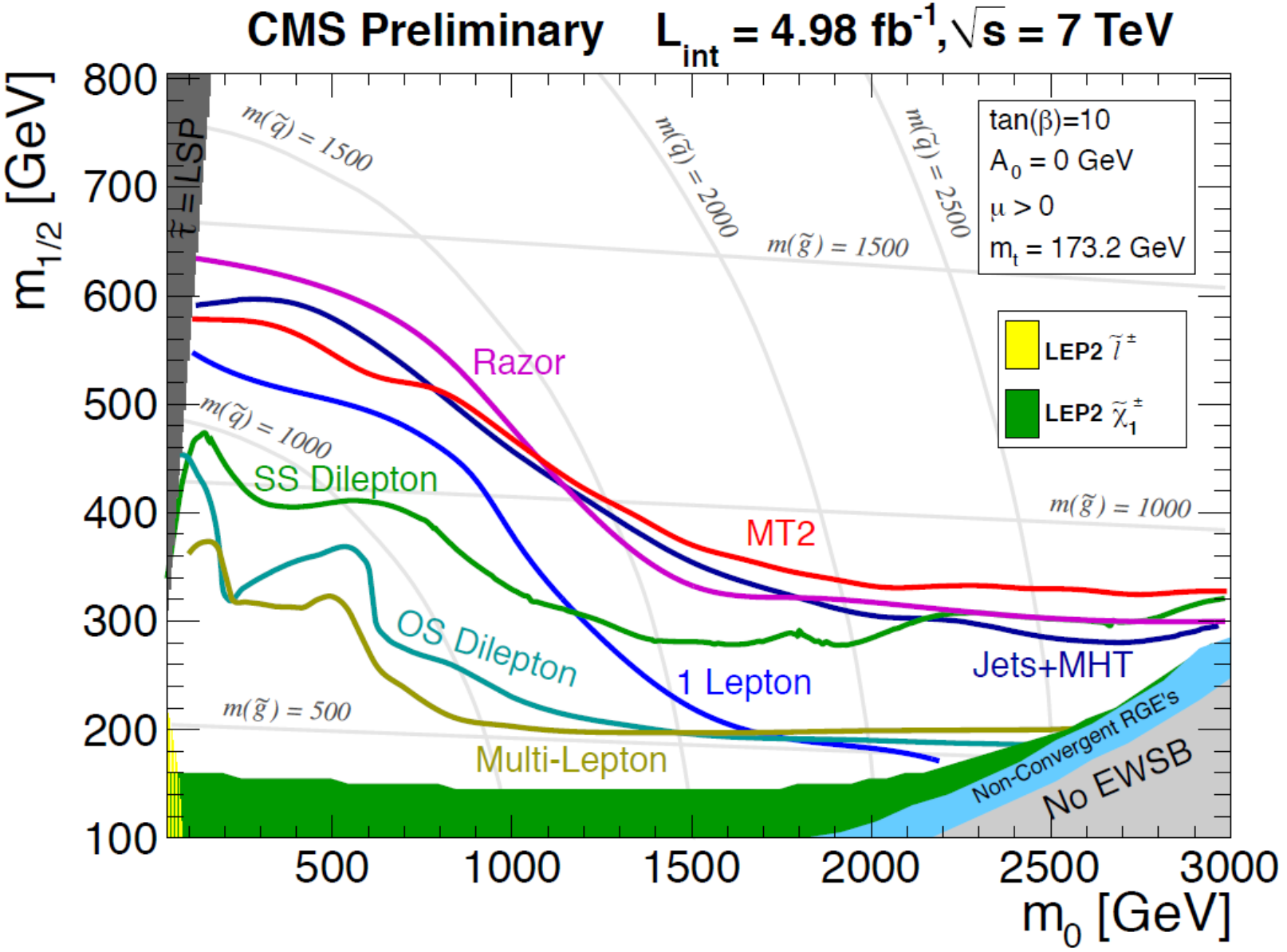




Model-*independent* representation of the results showing data-prediction / observation compatibility

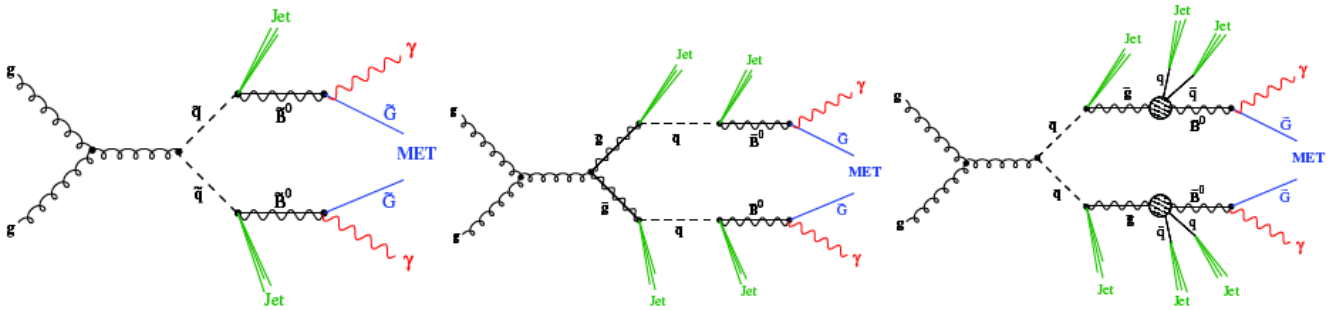
Model-*dependent* interpretation, in CMSSM

CMSSM Summary Fully Hadronic Final States

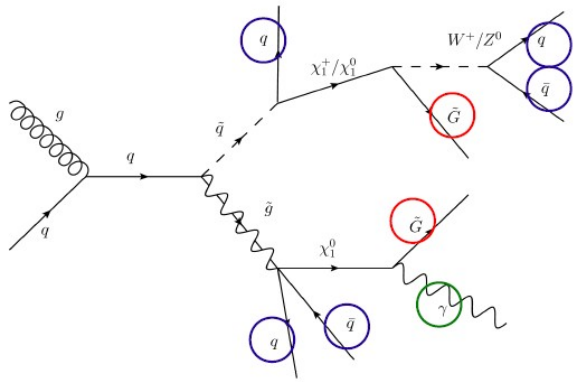


Photon(s) + Jets + ME_T Analysis

- Analysis motivated *General Gauge Mediation* (GGM) models, where gravitino (G) is the LSP, which get produced from other SUSY particle with **emission of a photon**. *NLSP is the neutralino*.
- 2 different scenarios investigated for the neutralino:



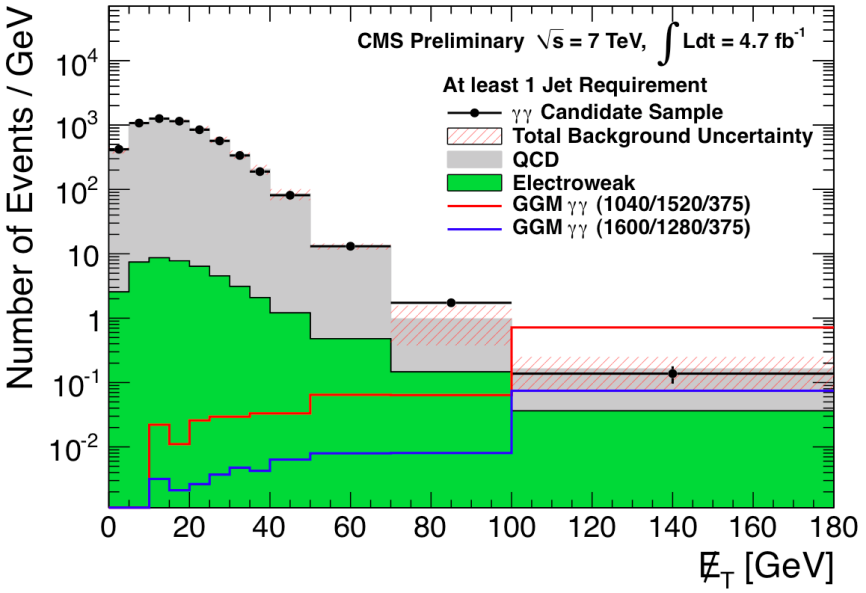
(1) **Bino-like neutralino**: χ_1^0 (dominant decay in γ+G) → di-γ analysis



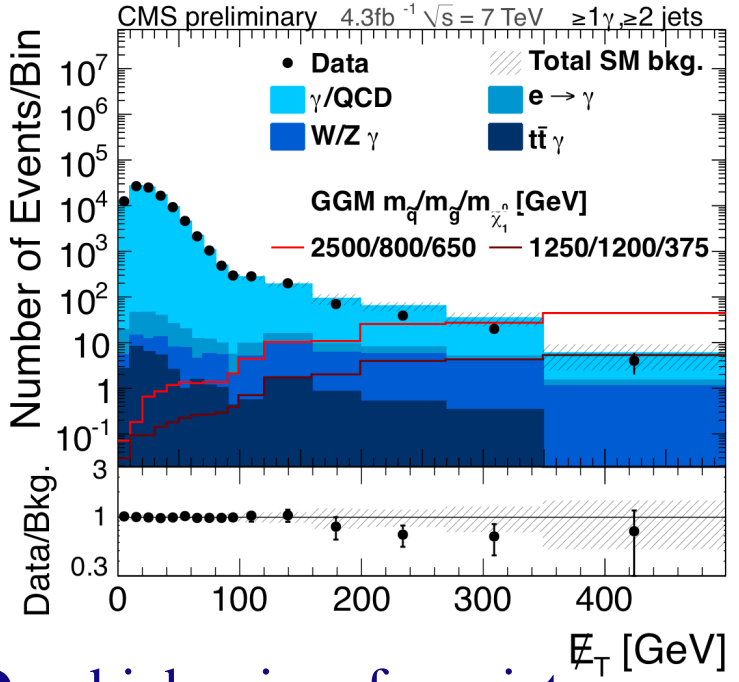
(2) **Wino-like neutralino/chargino**: $\chi_1^{\pm}$ (decay mostly in W+G) → single photon analysis

Photon(s) + Jets + ME_T Prediction

di-photon analysis



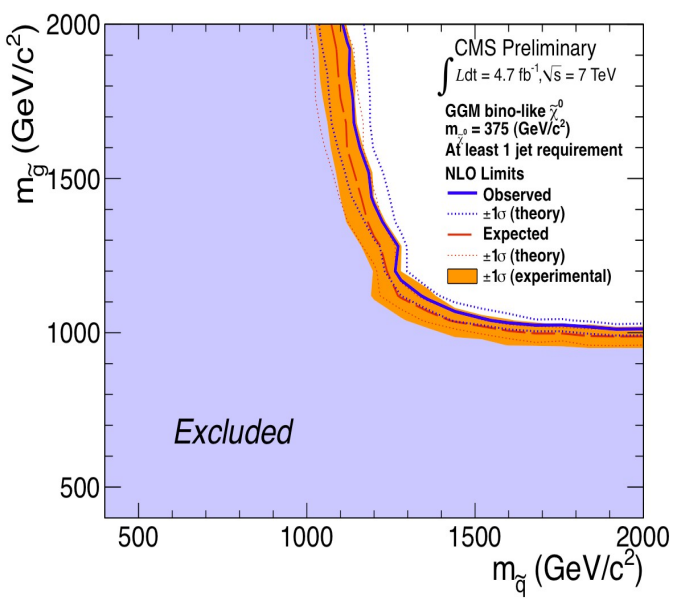
single photon analysis



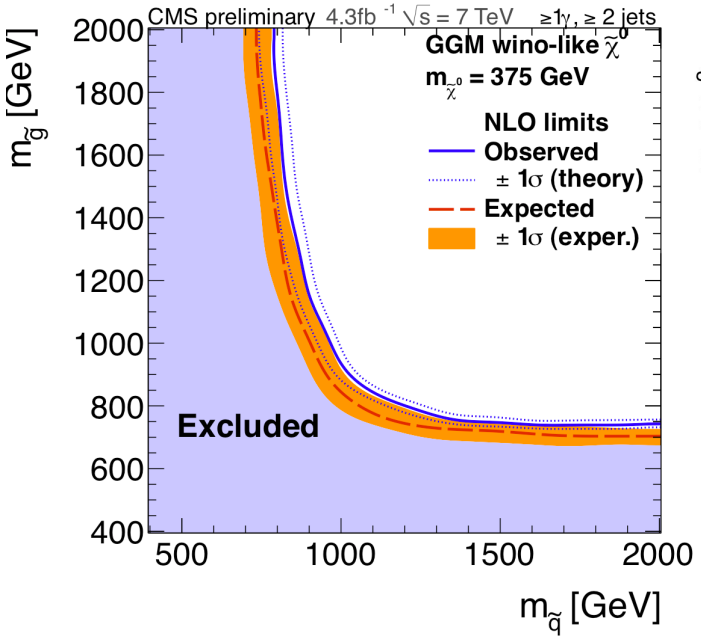
- **The dominant background is QCD**, which arises from jet energy resolution and tails. Selections: ≥ 2 jets + photon and 1 jet + ≥2 photons.
- QCD background estimated from non-isolated photon(s) sample and normalized/reweighted in a control region aside the search region
- Real MET background (from EWK) estimated in *ee*, *eγ*, *e* control samples and reweighting for e → γ probability (masured in data)

Photons Analysis GGM Limits

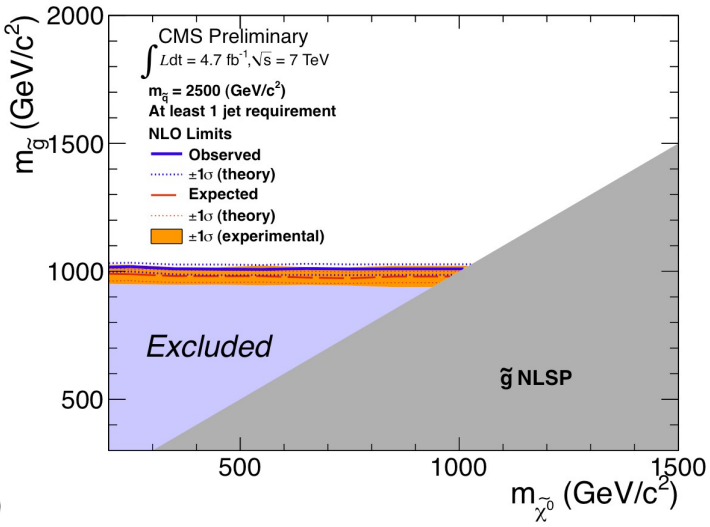
di-γ analysis, Bino-like χ^0



γ analysis, Wino-like χ^0



di-γ analysis, Bino-like χ^0



- Best exclusion limits in Bino-like neutralino scenario from di-photon analysis, while single photon provides better exclusion in Wino-like neutralino scenario (see also backup)
- Upper limit on signal production cross-section of order of 0.01 pb for bino-like χ^0 scenario and 0.1 pb for wino-like χ^0.

Experimental uncertainties on signal:

- Background prediction: **14 – 60%**
- PDF on the acceptance: **1 – 15%**
- Data / MC scale : **4%**, Luminosity, **4.5%**

Uncertainties on the signal cross section:

- Renormalization and factorization: **10-25%**
- PDF on the cross-section **5 – 70%**

Summary

- Results from searches for Super-Symmetry in **fully hadronic (ME_T+jets) and photon(s) + ME_T + jets final states** have been presented
  - Based on full 2011 data-set at 7 TeV collected by the **CMS experiment**
- **No-evidence of deviation from Standard Model predictions** has been observed in any of the analyses nor channels

We proceed to ***set limits @ 95% C.L.***

- in the reference cMSSM/mSUGRA m_0-$m_{1/2}$ plane (for parameters $A_0 = 0$, $tan\beta = 10$, $sign(\mu) > 0$)
- on *SUSY-like* processes in a variety of Simplified Models

The exclusion power of the presented analyses (when applied to the same models) is comparable among each other and **represent the current best CMS exclusion limits in these channels on the 7 TeV data.**

Backup Slides

MT2 Analysis

A search for supersymmetry or similar new physics was carried out using a sqrt(s) = 7 TeV pp collisions data sample corresponding to 4.73/fb of integrated luminosity collected by the CMS experiment at the LHC. Fully hadronic final states were selected based on the stransverse mass variable MT2. Two complementary analyses were performed. The first targets the region of parameter space with medium to high squark and gluino masses, in which the signal can be separated from the Standard Model backgrounds by a strong cut on MT2. A second analysis has been optimized to look for events with a light gluino but heavy squarks. In this case, the MT2 cut was relaxed, but a higher jet multiplicity and at least one b-tagged jet were required. The dominant backgrounds in both analyses are different and they were estimated using data-driven methods. As no excess of events over the expected background was observed, exclusion limits were derived on the parameter space of the constrained minimal supersymmetric extension of the Standard Model (mSUGRA/CMSSM), as well as on a variety of Simplified Model Spectra.

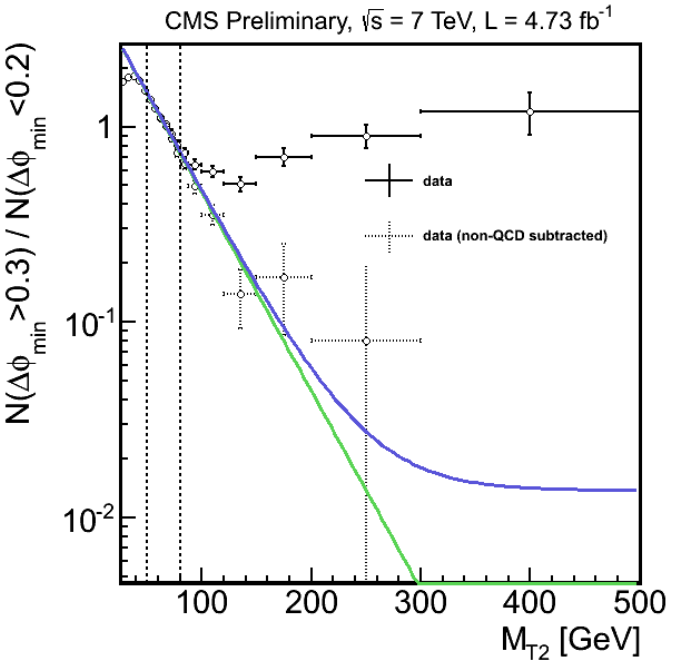
MT2 Cuts

- At least one good primary vertex
- At least 3 jets with $p_T > 40$ GeV, $|\eta| < 2.4$ ($\geq$ 4 jets for MT2b analysis)
- $H_T > 750$ GeV (driven by the trigger)
- M_{T2} specific
  - $\not{E}_T > 30$ GeV to define a MET direction
  - $|\vec{\not{E}}_T - \vec{\not{H}}_T| < 70$ GeV to control upstream transverse momentum
- Event cleaning:
  - Veto events with jets failing PF-JID and with $p_T > 50$ GeV, $|\eta| < 2.4$
  - Standard noise filters
- Lepton veto: in order to reduce EWK and top backgrounds
- QCD removal: $\Delta\phi_{min}(\textit{all jets}, \not{E}_T) < 0.3$ (only 4 leading jets used for MT2b)
- At least one *b*-jet identified by the SSVHPT b-tagger (for the MT2b analysis)

MT2 QCD Background

- QCD factorization method:
- Predict signal region (high M_{T2}, $\Delta\phi_{min} > 0.3$) from QCD enhanced region (high M_{T2}, $\Delta\phi_{min} < 0.2$)
- Exponential functional form motivated from simulation

$$r(M_{T2}) = \frac{N(\Delta\phi_{min} > 0.3)}{N(\Delta\phi_{min} < 0.2)} = e^{a - b \cdot M_{T2}} + c$$

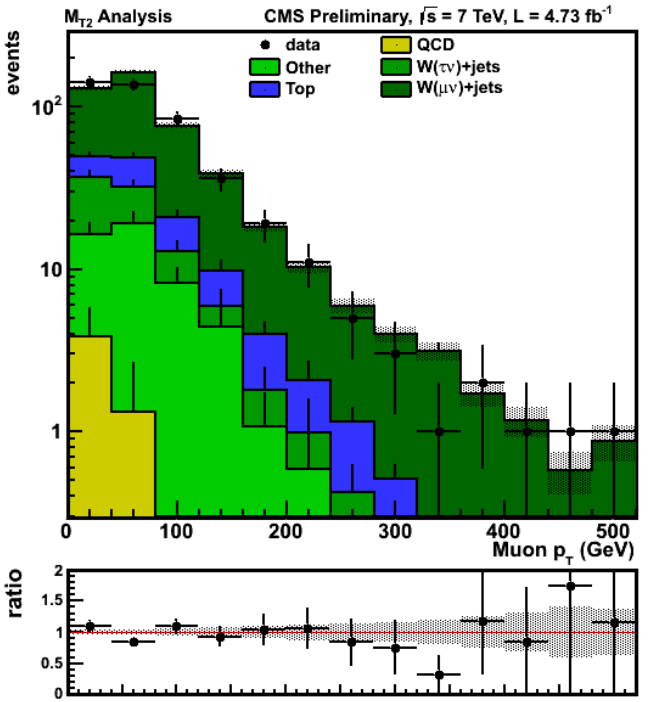


- Fit region $50 < M_{T2} < 80$ GeV chosen to have minimal contamination from non-QCD data
- EWK background is subtracted from data, and a fit is performed to extract *a* and *b*
- Constant term *c* taken conservatively as the value of the fitted exponential at $M_{T2} = 250$ GeV
- Stability of method against fit variation is extensively checked in MC and data

The solid points correspond to raw data after all selection cuts, while the dashed points correspond to data after subtracting electroweak and $t\bar{t}$ backgrounds. An exponential fit (green curve) is performed in the region 50 < MT2 < 80 GeV where the non-QCD contribution is minimal. The constant term of the final functional model (blue curve) is taken as the value of the exponential at MT2 = 250 GeV.

MT2 $Z \to$ inv Background from W (I)

- Predict $Z \to \nu\bar{\nu}$ from $W \to \mu\nu$ after "removing" the muon and recomputing all relevant quantities
- $W \to \mu\nu$ enriched sample obtained by using all selection cuts and:
  - One μ with $p_T > 10$ GeV
  - B-tag veto, using SSVHEM, to suppres $t\bar{t}$
  - $m_T(W) < 100$ GeV to reduce signal contamination

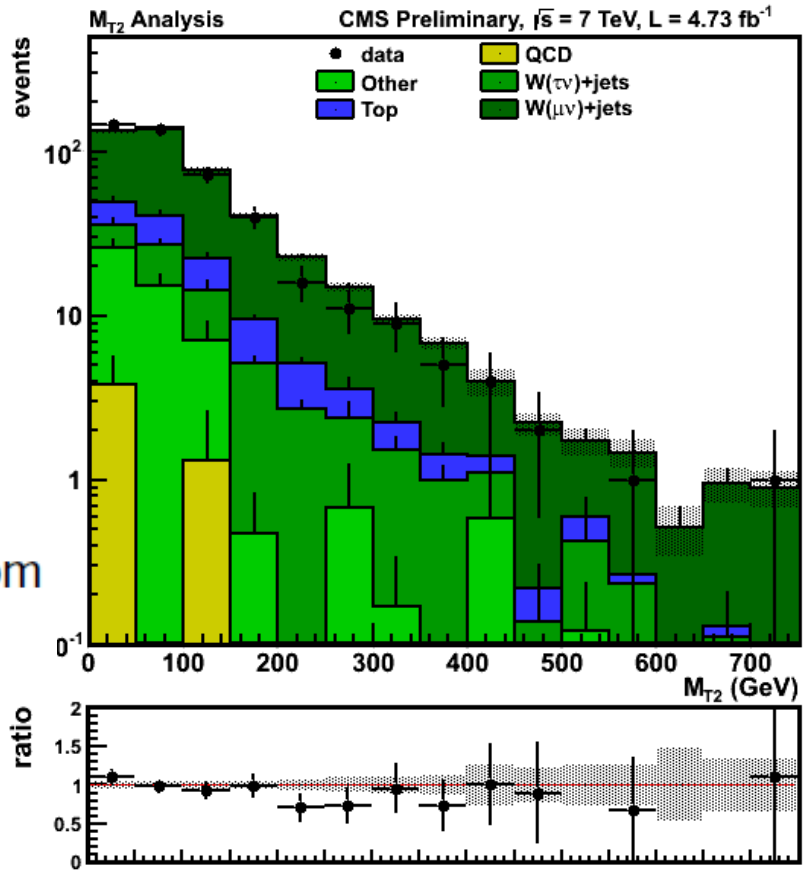


$Z \to \nu\bar{\nu}$ estimated as: $N_{Z\nu\nu} = N_{W\mu\nu} \cdot \frac{1}{\epsilon_{acc}\epsilon_{reco/iso}} \cdot R^{MC}$

- ϵ_{acc} muon acceptance from MC
- $\epsilon_{reco/iso}$ muon efficiencies obtained from Tag&Probe in data, parameterized in p_T, η and $\Delta R(\mu, \text{closestjet})$
- R^{MC} corrects for: kinematic differences, cross-sections, M_T and b-tag veto efficiencies
- Backgrounds contributions are subtracted using MC, except $t\bar{t}$:
  - estimated using a $t\bar{t}$ enriched region in data by requesting 1 SSVHPT b-tag

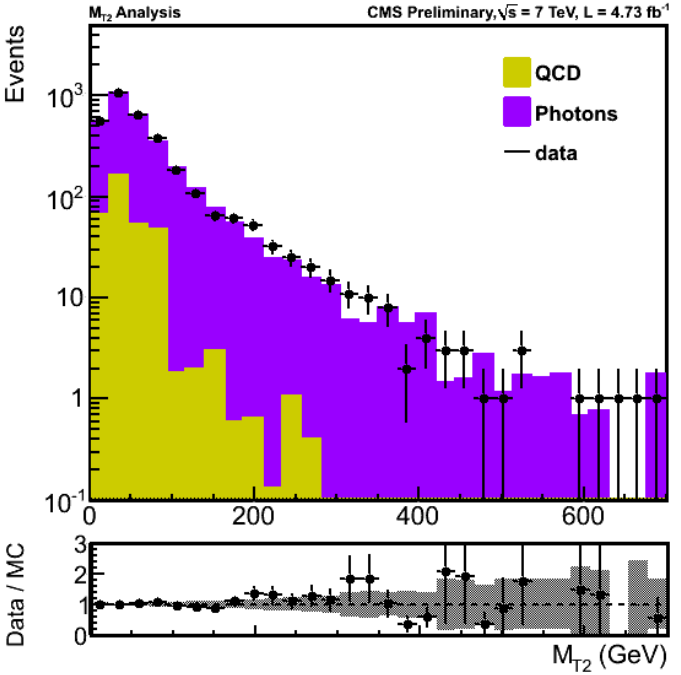
MT2 Z → inv Background from W (II)

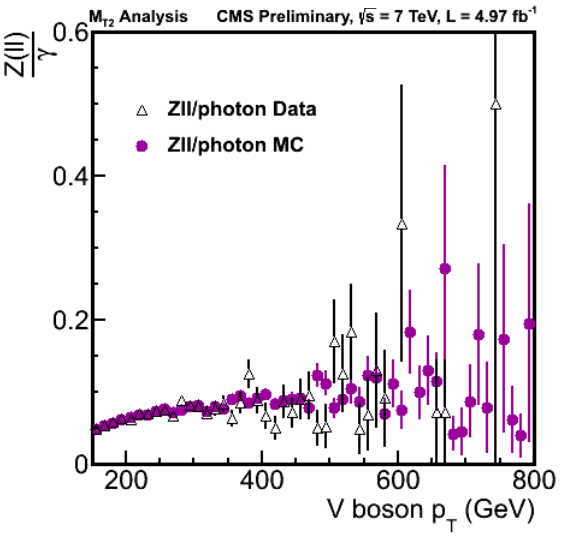
- Systematic uncertainties
  - uncertainties on b-tag scale factors
  - 100% uncertainties on MC subtracted backgrounds
  - Tag&Probe efficiency uncertainties
  - R^{MC}: pdf, MC statistics, and b-tag scale factors
  - Total uncertainties on final prediction ranges from 25% to ~100%



MT2 $Z \to$ inv Background from γ

- Select γ+jets events passing all selection cuts
  - $\not\!\!E_T < 100$ GeV to minimize signal contamination
  - $Z \to \nu\bar{\nu}$ mimicked by adding the recoed γ to $\not\!\!E_T$
- $Z \to \nu\bar{\nu}$ estimated as: $R^{MC}(\frac{Z\nu\nu}{\gamma}) \cdot \text{Purity} \cdot N_\gamma^{data}$
- Perform extended ML fit in shower shape $\sigma_{i\eta i\eta}$ to extract prompt photon and background yields
- R^{MC} accounts for residual kinematic differences, photon acceptance and reco efficiency
- Further x-checks are carried out to test the modeling of the V-boson p_T spectra as well as R^{MC}
  - Comparing JetPhox NLO to MadGraph: good agreement found
  - comparing Z/γ ratio in data and MC using photon and $Z \to \ell\ell$ data
- Systematic uncertainties
  - MC statistics for R^{MC}
  - additional 20% on R^{MC} for $M_{T2} < 275$ GeV, 30% for $M_{T2} > 275$ GeV
    - reflecting the precision to which we could validate the p_T spectra and Z/γ ratio
  - 5% (bin dependent) purity uncertainty
  - Total uncertainties on final prediction ranges from 25% to 65%



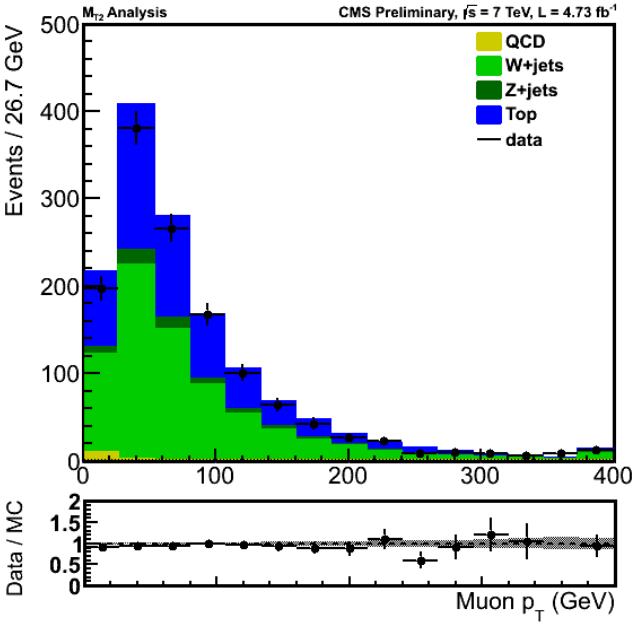


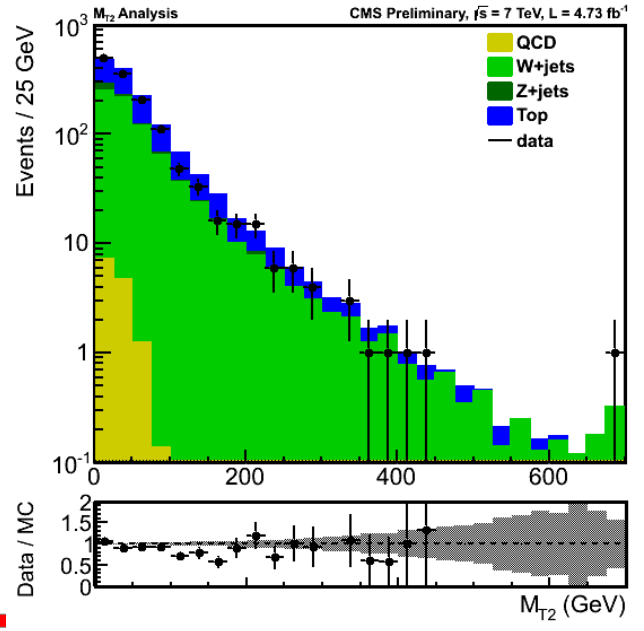
MT2 Lost Lepton Background

- EWK and top background laregely reduced by lepton veto. Remaining is:
  - electron or muon out of acceptance
  - electron or muon not isolated or not identified
  - hadronic τ-decays
- Lost lepton contribution from W+jets and $t\bar{t}$ is estimated from electron and muon samples

$$N_{e,\mu}^{lost\ lepton} = (N_{e,\mu}^{reco} - N_{e,\mu}^{bg}) \frac{1 - \varepsilon_{e,\mu}}{\varepsilon_{e,\mu}}$$

  - $\varepsilon_{e,\mu}$ accounts for acceptance and reco efficiency as well as difference in phase space
- $\Delta\phi_{min}(jets, \not{E}_T)$ cut dropped to increase statistics (was designed to fight QCD)
- $m_T < 100$ GeV required to reduce signal contamination in the lepton sample
  - Signal contamination can still be sizable and we thus taken it into account in the statistical interpretation





Systematic uncertainties

- 100% on MC subtracted backgrounds
- MC statistics
- additional 5% on $\varepsilon_{e,\mu}$ motivated from T&P data-MC differences
- Total uncertainty on final estimate ranges from 30% to 100%

MT2/MT2b-bYelds

MT2

M_{T2} bin	$Z \to \nu\nu$ MC	$Z \to \nu\nu$ data pred.	Lost lepton MC	Lost lepton data pred.	$\tau \to had$ Estimate	QCD MC	QCD data pred.	Total bkg. MC	Total bkg. data pred.	Data
$750 \leq H_T \leq 950$										
[150,200)	27.9	24.2 ± 4.9	36.0	29.6 ± 7.1	22.5 ± 5.4	3.1	7.0 ± 3.5	89.5	83.3 ± 10.7	88
[200,275)	20.3	21.8 ± 4.8	17.2	11.9 ± 3.9	12.7 ± 4.2	0.0	1.0 ± 0.5	50.2	47.4 ± 7.5	69
[275,375)	11.6	13.7 ± 3.8	7.1	4.2 ± 1.9	5.4 ± 2.5	0.0	0.14 ± 0.07	24.1	23.4 ± 4.9	19
[375,500)	6.1	4.1 ± 1.6	2.2	1.1 ± 0.9	2.2 ± 1.8	0.0	0.08 ± 0.05	10.4	7.4 ± 2.6	8
$\geq$500	3.5	1.8 ± 0.9	1.1	1.2 ± 1.0	0.6 ± 0.5	0.0	0.00 ± 0.00	5.3	3.6 ± 1.4	6
$H_T \geq 950$										
[150,200)	12.9	16.7 ± 3.6	18.7	16.2 ± 5.3	12.7 ± 4.1	9.8	11.0 ± 5.5	54.2	56.6 ± 9.4	70
[200,275)	10.5	4.5 ± 2.0	11.7	10.2 ± 3.7	7.1 ± 2.6	0.47	1.4 ± 0.7	29.8	23.2 ± 5.0	23
[275,375)	6.4	5.7 ± 2.2	5.0	2.9 ± 1.7	3.3 ± 1.9	0.04	0.13 ± 0.07	14.7	12.1 ± 3.3	9
[375,500)	2.5	3.0 ± 1.4	1.1	0.6 ± 0.6	0.9 ± 0.9	0.0	0.06 ± 0.04	4.6	4.6 ± 1.8	8
$\geq$500	2.2	2.5 ± 1.5	0.6	0.6 ± 0.6	0.6 ± 0.6	0.0	0.06 ± 0.04	3.4	3.8 ± 1.7	4

MT2b

M_{T2} bin	$Z \to \nu\nu$ MC	$Z \to \nu\nu$ data pred.	Lost lepton MC	Lost lepton data pred.	$\tau \to had$ Estimate	QCD MC	QCD data pred.	Total bkg. MC	Total bkg. data pred.	Data
$750 \leq H_T \leq 950$										
[125,150)	1.0	0.5 ± 0.4	12.8	4.5 ± 3.2	8.7 ± 6.3	5.16	4.1 ± 2.1	28.3	17.8 ± 7.3	22
[150,200)	2.0	0.7 ± 0.3	11.3	7.6 ± 3.6	8.0 ± 3.8	0.16	0.90 ± 0.51	22.1	17.2 ± 5.2	16
[200,300)	1.3	1.0 ± 0.5	6.1	1.3 ± 1.7	4.9 ± 6.7	0.0	0.04 ± 0.03	12.6	7.2 ± 6.9	16
$\geq$ 300	0.5	0.6 ± 0.3	1.3	1.3 ± 0.9	1.8 ± 1.3	0.0	0.00 ± 0.00	3.7	3.7 ± 1.6	2
$H_T \geq 950$										
[125,150)	0.6	0.4 ± 0.3	6.2	5.9 ± 3.3	4.3 ± 2.4	1.25	5.4 ± 2.8	12.7	16.0 ± 4.9	10
[150,180)	0.4	0.9 ± 0.4	4.6	6.4 ± 3.3	3.2 ± 1.7	0.57	1.7 ± 0.9	9.0	12.2 ± 3.9	10
[180,260)	0.6	0.1 ± 0.1	4.2	3.4 ± 2.3	3.3 ± 2.3	0.67	0.45 ± 0.25	9.1	7.2 ± 3.2	9
$\geq$ 260	0.6	0.7 ± 0.4	2.2	2.0 ± 1.6	1.6 ± 1.3	0.04	0.05 ± 0.04	4.6	4.3 ± 2.0	3

MT2 Statistical Interpretation

- No significant excess observed in data, we proceed by setting upper limits
- MT2- and MT2b-analyses are not orthogonal, they are not statistically combined, rather the best limit is used for the final result
- The Higgs "CombinedLimit" tool is used for limit setting
- Statistical approach following most common CMS recomendations
- Likelihood constructed from Poisson probabilities for each bin in M_{T2} and H_T

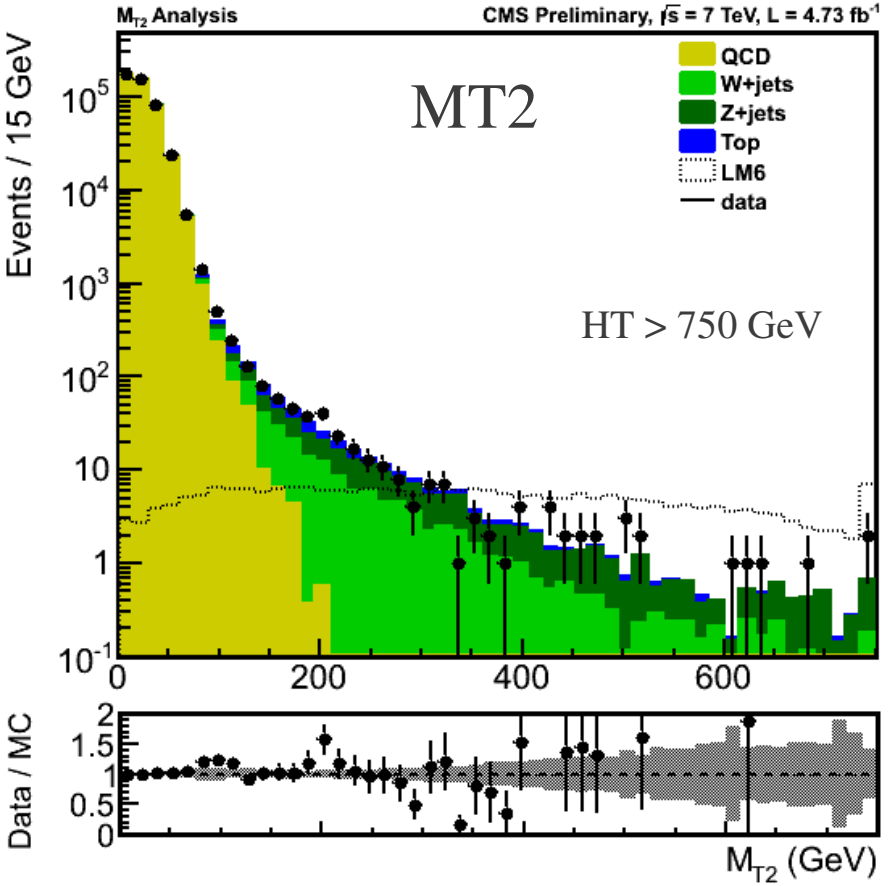
$$\mathcal{L} = \prod_{i=1}^{N_{\text{bins}}} \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!}, \quad \lambda_i = \mu \cdot s_i + \sum_{j=1}^{N_{\text{bkg}}} b_{ij}$$

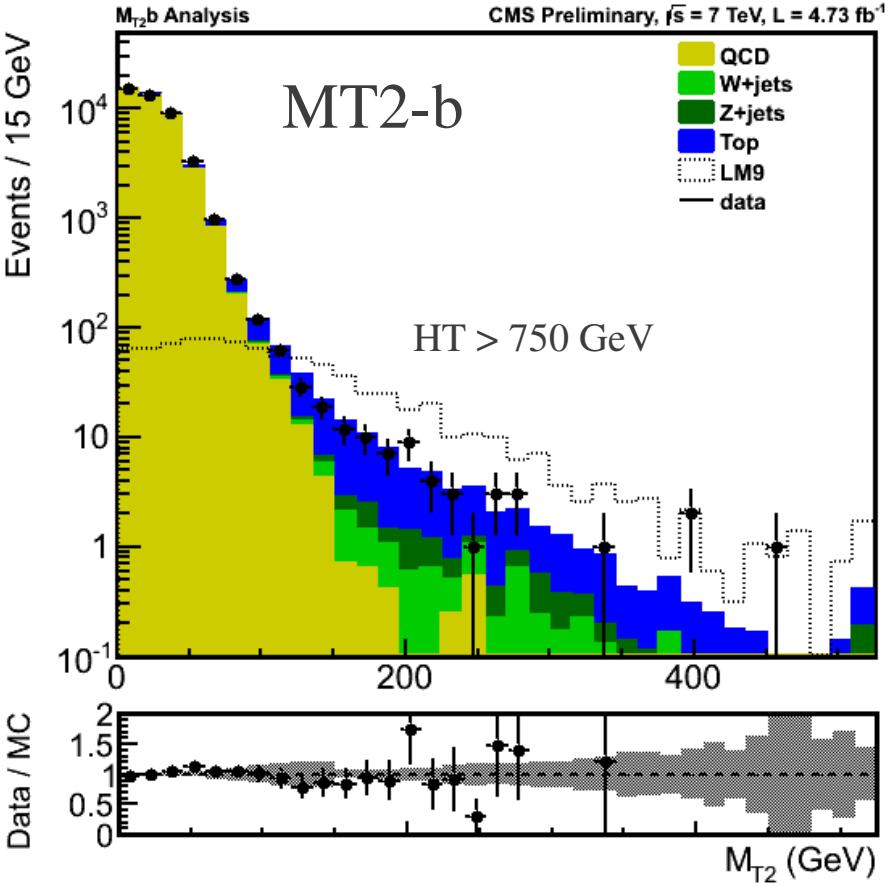
- Test statistic q_μ constructed as the profile likelihood ratio: $q_\mu = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}$
- Toys tossed using frequentist approach
- We test the background-only and the signal+background hypotheses using a modified frequentist CLs approach

$$CL_{s+b} = P(q_\mu \geq q_\mu^{obs}|H_1), \; CL_b = P(q_\mu \geq q_\mu^{obs}|H_0)$$

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

MT2 data/MC comparison



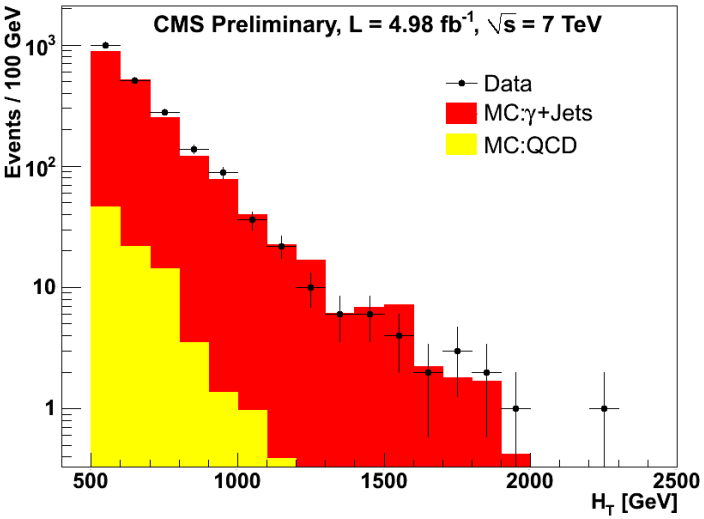


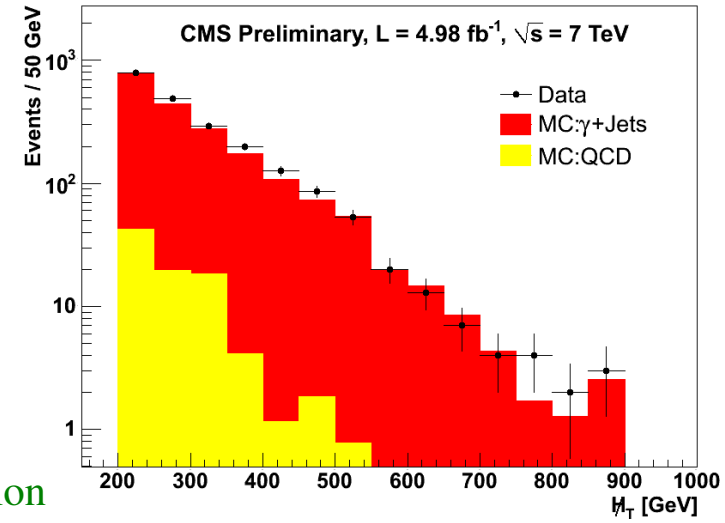
Jets+MHT Analysis

A search for physics beyond the standard model is performed in events with at least three jets and large missing transverse momentum produced in 7 TeV proton-proton collisions. The data were collected with the CMS detector at the Large Hadron Collider, and correspond to an integrated luminosity of 4.98 fb−1. No significant excess of events is observed above the expected backgrounds, which are determined from the data. The results are presented in the context of the constrained minimal supersymmetric extension of the standard model, and more generically for simplified models with new massive particles decaying to one or two jets and a stable weakly interacting particle.

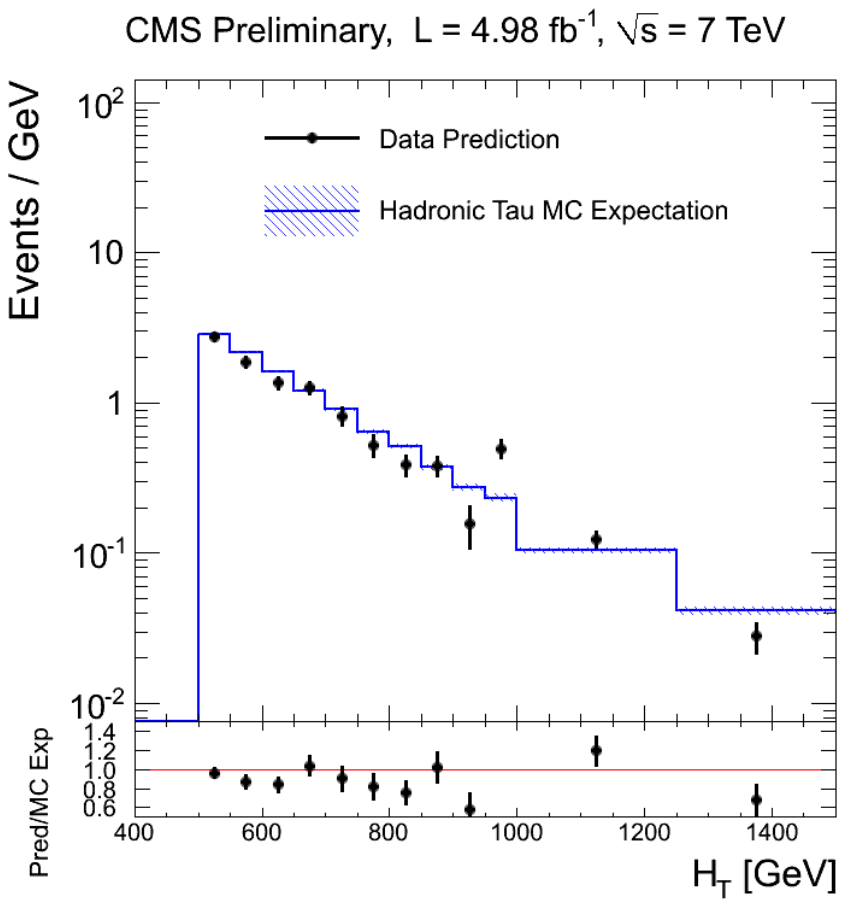
Jets+MHT Z → inv Background

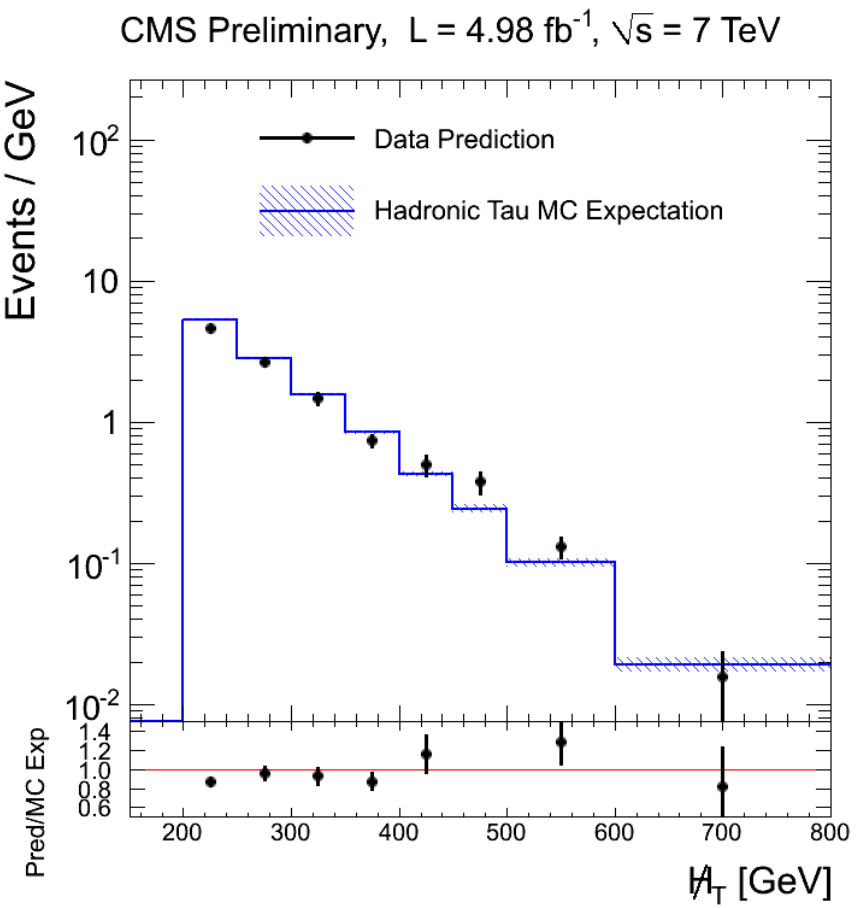
- Start with a γ+jets control sample : pT(γ)>100 GeV combined isolation<5.0, pileup subtraction applied.
- Subtract the contribution from secondary photons
  - Purity is 98-99% as measured from data using isolation template technique
- Subtract photons radiated from final state partons.
  - JETPHOX : (5±5)% contribution
- Correct for photon reconstruction & isolation efficiencies measured from data
- Scale with Z(ν ν)+Jets/γ + Jets production ratio taken from theory.
- Systematic uncertainties
  - theory uncertainty on ratio (21-42%)
  - detector acceptance (5%)
  - trigger (1-2%)
  - mis-tag rate (~1%)
  - photon purity (~2%)
  - Data/MC efficiency s.f.
  - fragmentation contribution (5%)





Jets+MHT Hadronic Tau Background

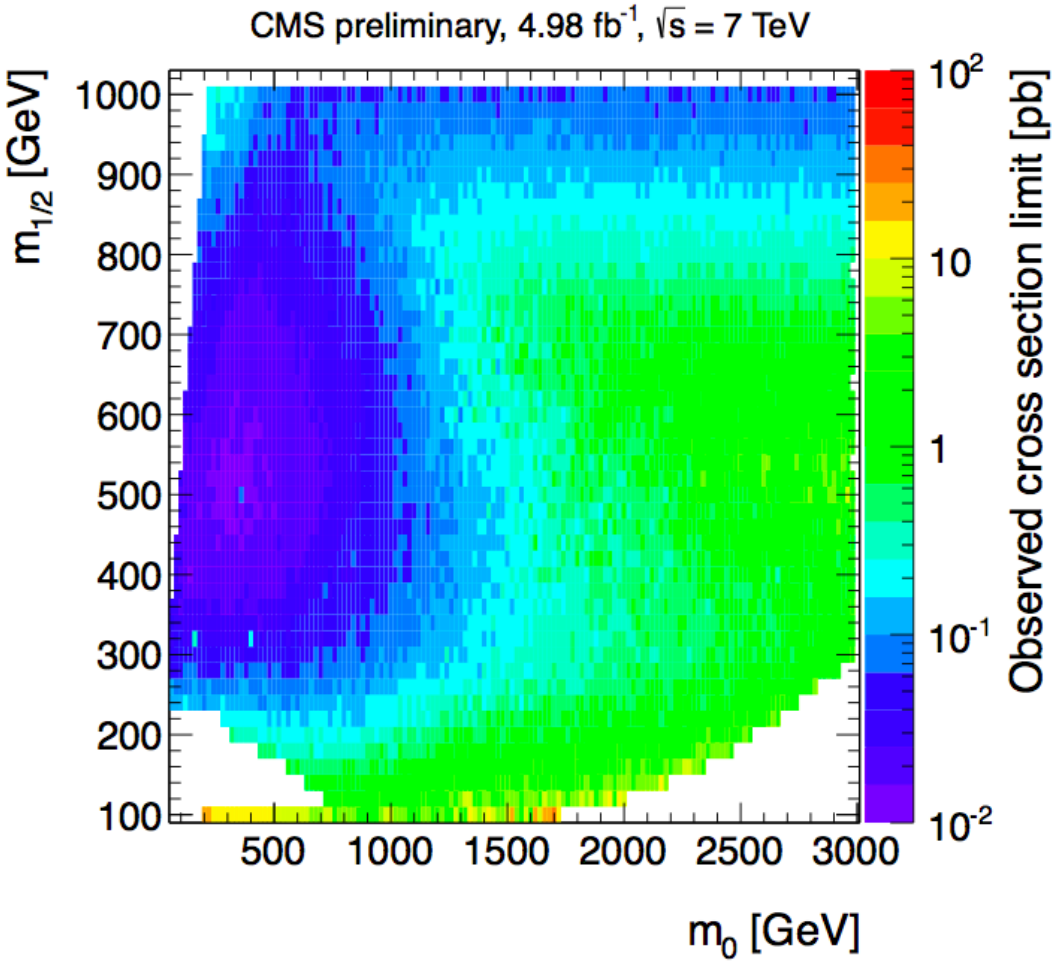




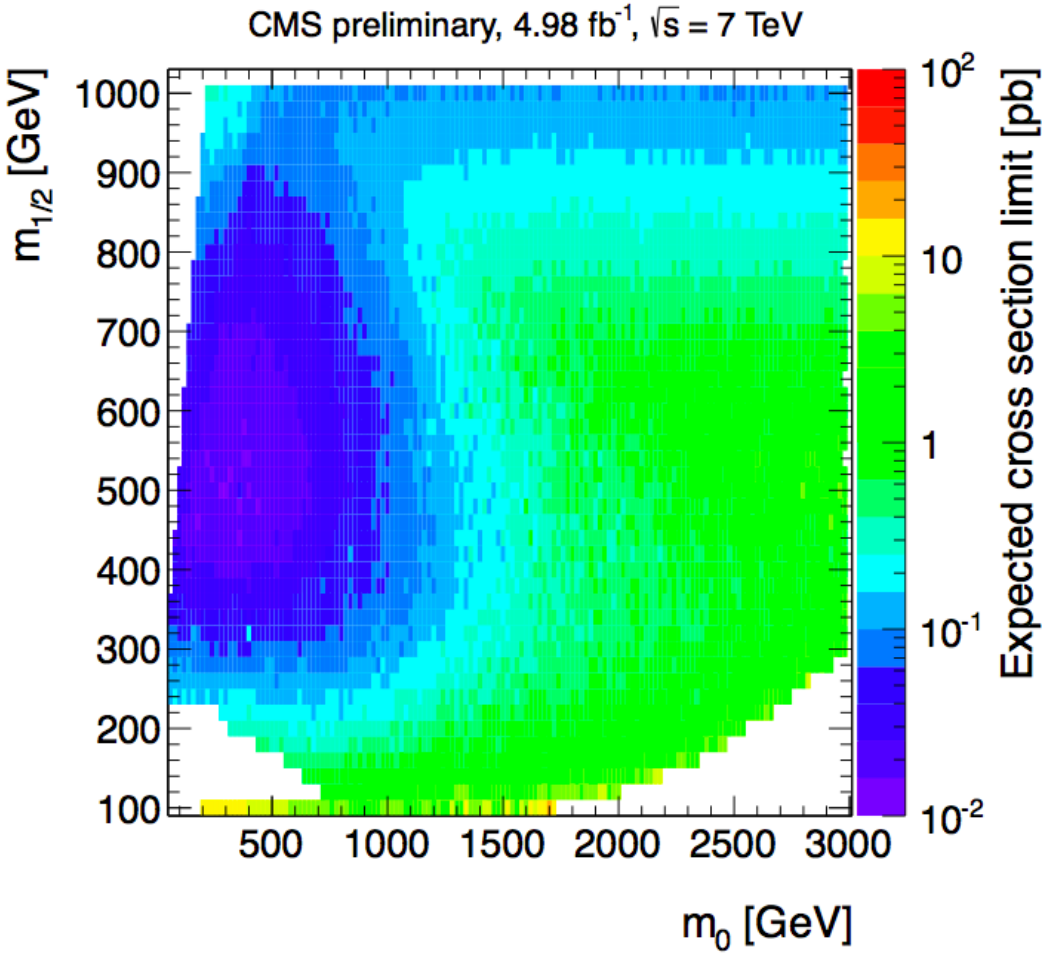
Jets+MHT Analysis Yields

Selection		$Z \to \nu\bar{\nu}$		$t\bar{t}/W$		$t\bar{t}/W$		QCD		Total		Data
H_T (GeV)	$\not{H}_T$ (GeV)	from γ+jets		$\to e, \mu$+X		$\to \tau_{had}$+X		multijets		background		
500–800	200–350	359.2	± 82.2	326.5	± 47.0	348.5	± 40.1	118.6	± 76.9	1152.8	± 128.4	1269
500–800	350–500	112.3	± 27.4	47.8	± 9.2	62.5	± 8.7	2.2	± 2.2	224.8	± 30.3	236
500–800	500–600	17.6	± 5.6	5.0	± 2.2	8.7	± 2.5	0.0	± 0.1	31.3	± 6.5	22
500–800	>600	5.5	± 3.1	0.8	± 0.8	2.0	± 1.8	0.0	± 0.0	8.3	± 3.6	6
800–1000	200–350	48.4	± 19.1	57.7	± 15.3	56.3	± 8.3	34.6	± 24.0	197.0	± 35.3	177
800–1000	350–500	16.0	± 7.3	5.4	± 2.3	7.2	± 2.0	1.2	± 1.3	29.8	± 8.0	24
800–1000	500–600	7.1	± 4.5	2.4	± 1.5	1.3	± 0.6	0.0	± 0.2	10.8	± 4.8	6
800–1000	>600	3.3	± 2.0	0.7	± 0.7	1.0	± 0.3	0.0	± 0.1	5.0	± 2.2	5
1000–1200	200–350	10.9	± 5.5	13.7	± 3.8	21.9	± 4.6	19.7	± 13.3	66.2	± 15.5	71
1000–1200	350–500	5.5	± 3.5	5.0	± 4.4	2.9	± 1.3	0.4	± 0.7	13.8	± 5.8	12
1000–1200	>500	2.2	± 2.9	1.6	± 1.2	2.3	± 1.0	0.0	± 0.2	6.1	± 3.3	4
1200–1400	200–350	3.1	± 2.0	4.2	± 2.1	6.2	± 1.8	11.7	± 8.3	25.2	± 9.0	29
1200–1400	>350	2.3	± 2.3	2.3	± 1.4	0.6	± 0.8	0.2	± 0.6	5.4	± 2.9	8
>1400	>200	3.2	± 2.4	2.7	± 1.6	1.1	± 0.5	12.0	± 9.1	19.0	± 9.6	16

Jets+MHT Cross Section Limits on CMSSM

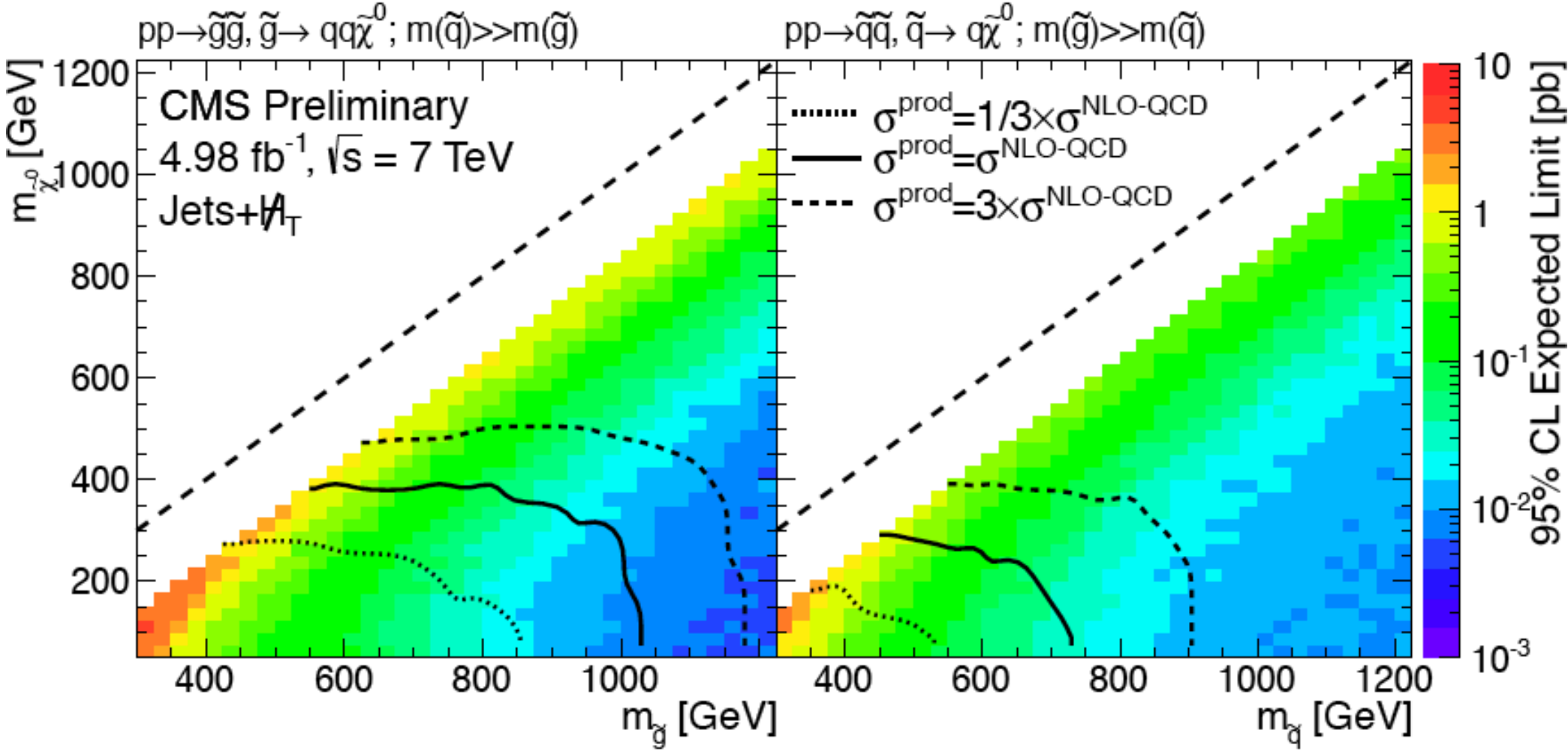


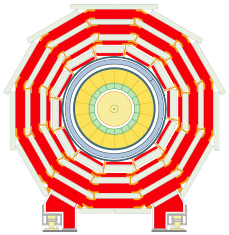
observed



expected

Jets+MHT Expected Limits on SMS



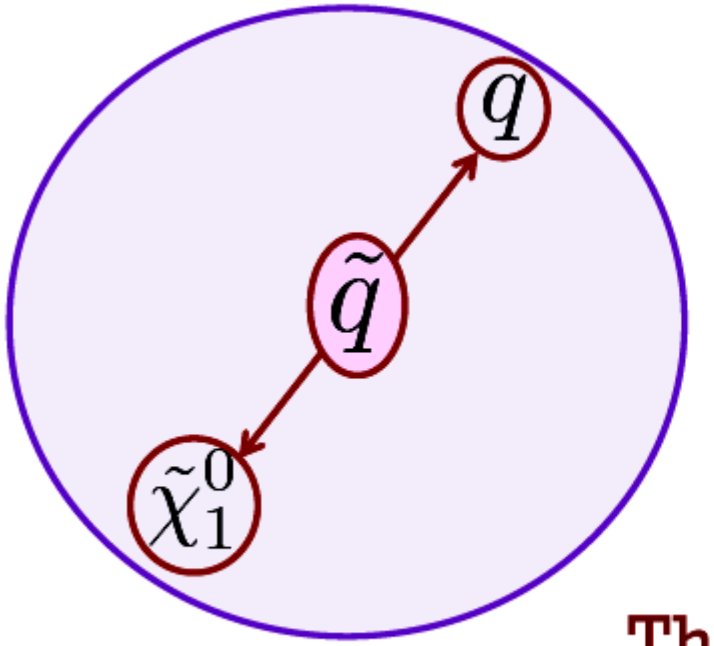


Razor

A search is performed for heavy particle pairs produced in $\sqrt{s}$ = 7 TeV proton-proton collisions with 4.4 fb^{-1} of data collected by the CMS experiment in 2011 at the CERN Large Hadron Collider. The search is sensitive to generic supersymmetry models provided superpartner particles are kinematically accessible, with minimal assumptions on properties of the lightest superpartner particle. The kinematic consistency of the selected events is tested against the hypothesis of heavy particle pair production using the dimensionless razor variable R, related to the missing transverse energy MET. The new physics signal is characterized by a broad peak in the distribution of MR, an event-by-event indicator of the heavy particle mass scale. This approach is complementary to MET based searches. After background modelling based on data and background rejection based on R and MR no significant excess of events is found beyond the Standard Model expectations. The results are interpreted in the context of the Constrained Minimal Supersymmetric Standard Model.

Razor, SUSY Kinematics

squark rest frame



$\tilde{q}\tilde{q} \to (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0)$

Each squark undergoes a two-body decay, meaning that, in the squark's rest frame, the quark and LSP will each have the same characteristic momentum:

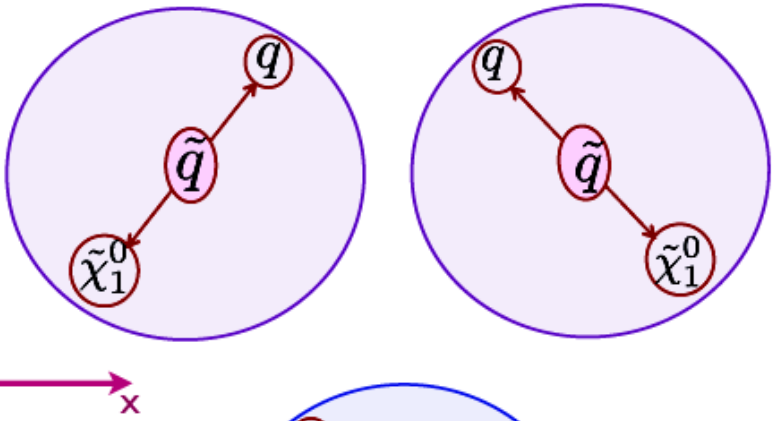
$$|\vec{P}_{jet}| = M_\Delta/2 = \frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2}{2M_{\tilde{q}}}$$

This is the 'scale' of new physics processes we want to be sensitive to

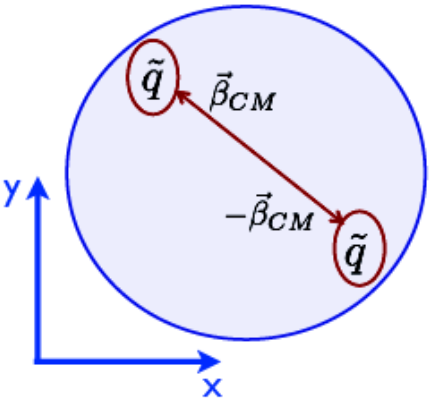
Razor Reference Frame (I)

- Two squarks decaying to quark and LSP. In their rest frames, they are two copies of the same monochromatic decay. In this frame p(q) measures M_Δ

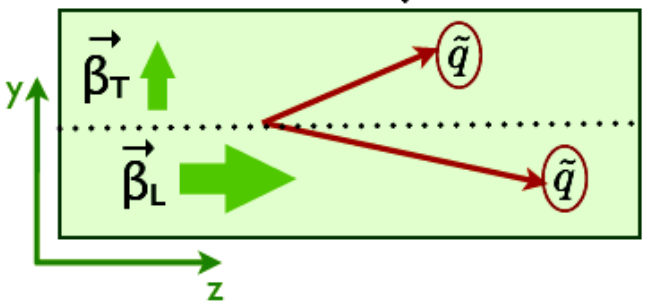
$$M_\Delta/2 = \frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2}{2M_{\tilde{q}}}$$



- In the rest frame of the two incoming partons, the two squarks recoil one against each other.



- In the lab frame, the two squarks are boosted longitudinally. The LSPs escape detection and the quarks are detected as two jets



If we could see the LSPs, we could boost back by β_L, β_T, and β_{CM}
In this frame, we would then get
$|p_{j1}| = |p_{j2}|$
Too many missing degrees of freedom to do just this

Razor Reference Frame (II)

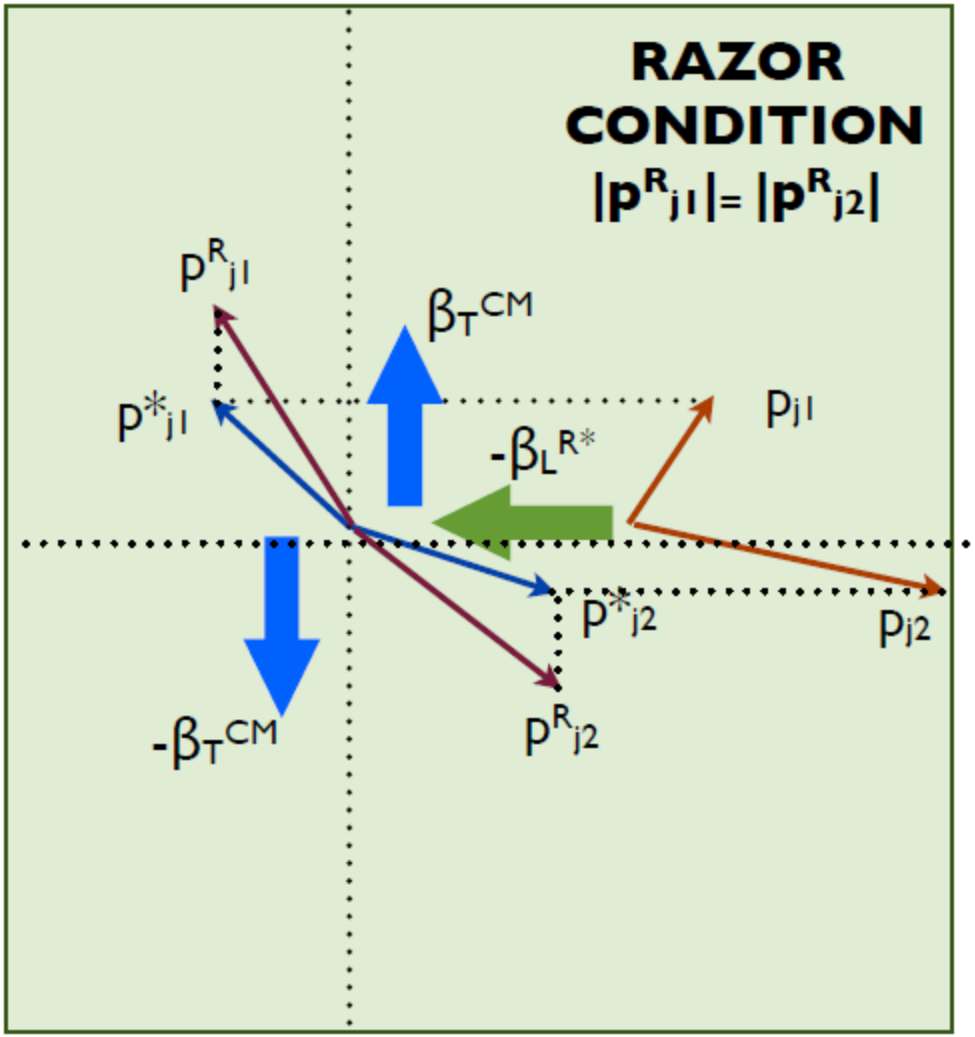
- In reality, the best we can do is to compensate the missing degrees of freedom with assumptions on the boost direction

- The parton boost is forced to be longitudinal
- The squark boost in the CM frame is assumed to be transverse

- We can then determine the two by requiring that the two jets have the same momentum after the transformation

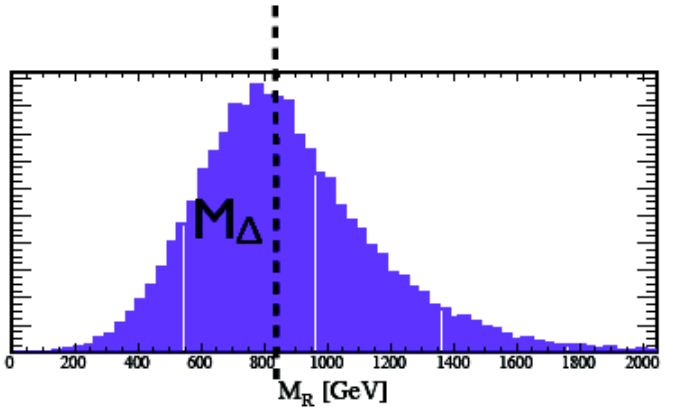
- The transformed momentum defines the M_R variable

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

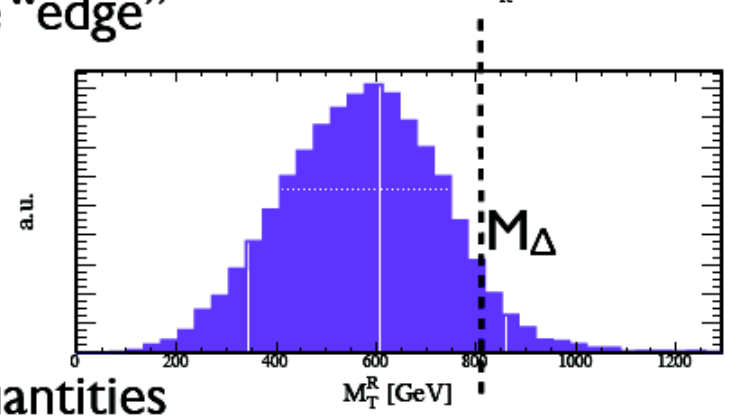


Razor Variables

- M_R is boost invariant, even if defined from 3D momenta
- No information on the MET is used
- The peak of the M_R distribution provides an estimate of M_Δ



- M_Δ could be also estimated as the "edge" of M_T^R



- M_T^R is defined using transverse quantities and it is MET-related
- The Razor (aka R) is defined as the ratio of the two variables

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

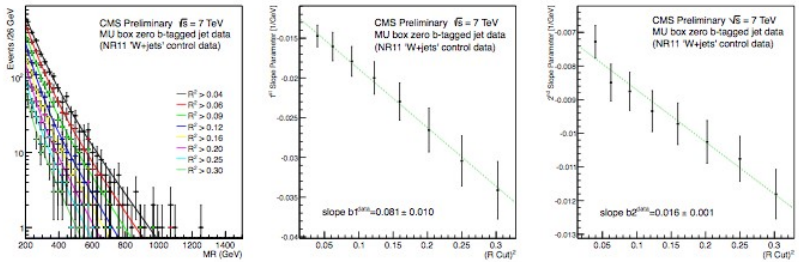
Razor ID Shapes

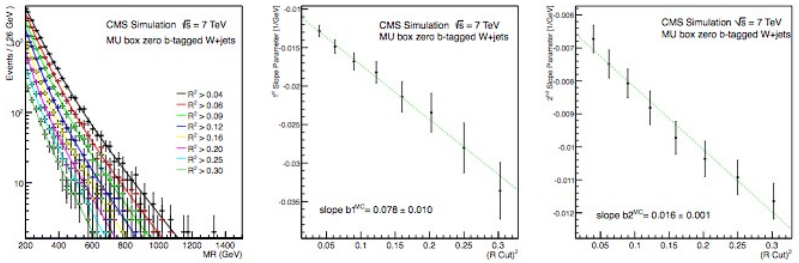
The M_R shape after a R^2 cut is exponential

$$f(M_R) \sim \exp^{-k_{M_R} M_R}$$

The exponent constant depends on the R^2 lower cut

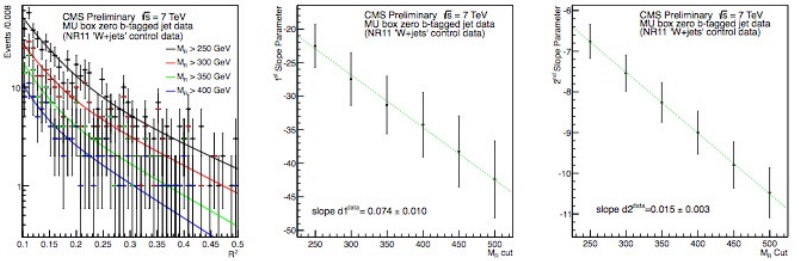
$$k_{M_R} = a_{M_R} + b_{M_R} R^2_{cut}$$

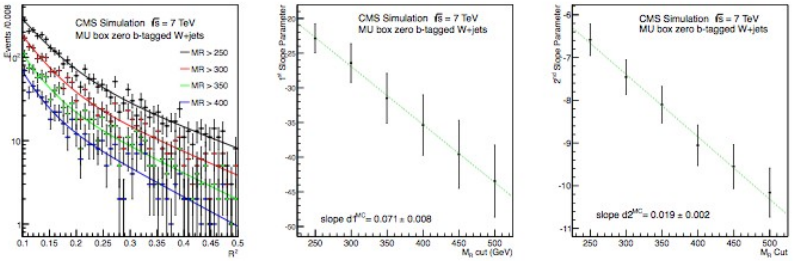




$$f(M_R) \sim (1 - f_2) \exp^{-k^1_{M_R} M_R} + f_2 \exp^{-k^2_{M_R} M_R}$$

$$k^i_{M_R} = a^i_{M_R} + b^i_{M_R} R^2_{cut}$$





The R^2 shape after a M_R cut is exponential

$$f(R^2) \sim \exp^{-k_{R^2} R^2}$$

The exponent constant depends on the M_R lower cut

$$k_{R^2} = a_{R^2} + b_{R^2} M_{Rcut}$$

The two linear slopes are the same

$$b_{M_R} = b_{R^2}$$

Razor ML Fit

$$\mathcal{L} = \frac{e^{-(\sum_{SM} N_{SM})}}{N!} \prod_{i=1}^{N} \left(\sum_{SM} N_{SM} P_{SM}(M_R, R^2) \right)$$

The background PDFs are given by

$$P_{SM}(M_R, R^2) = (1 - f_2^{SM}) \times F_{SM}^{1st}(R^2, M_R) + f_2^{SM} \times F_{SM}^{2nd}(R^2, M_R)$$

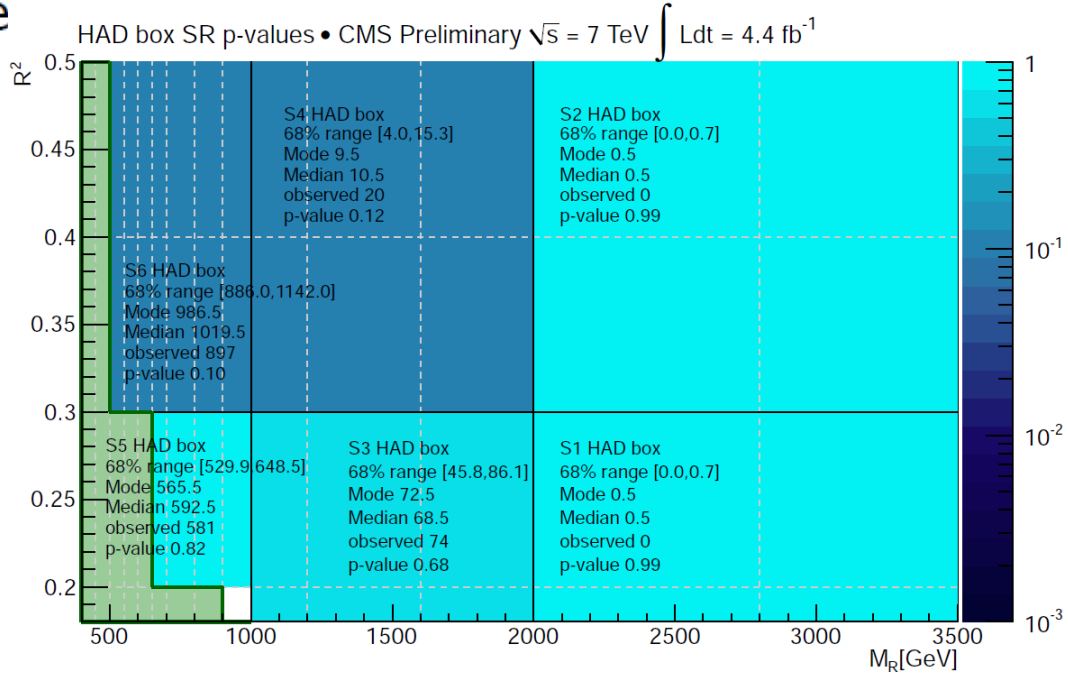
with

$$F(M_R, R^2) = \left[b(M_R - M_R^0)(R^2 - R_0^2) - 1 \right] e^{-b(M_R - M_R^0)(R^2 - R_0^2)}$$

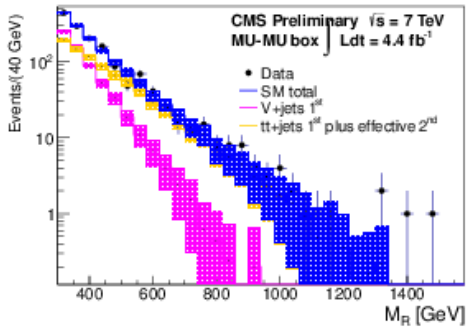
To guide the fit, the likelihood is multiplied by Gaussian penalty terms which force the shape parameters around our a-priori knowledge (May10 ReReco ~250 pb^{-1} b-tagged and b-vetoed samples)
This helps the fit to converge and have limited impact on the fit at minimum (errors dominated by the fit, not the a-priori knowledge)

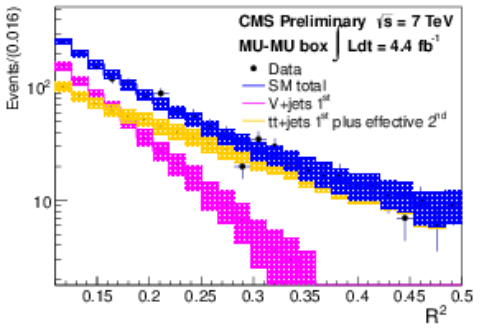
Razor Background Prediction Strategy

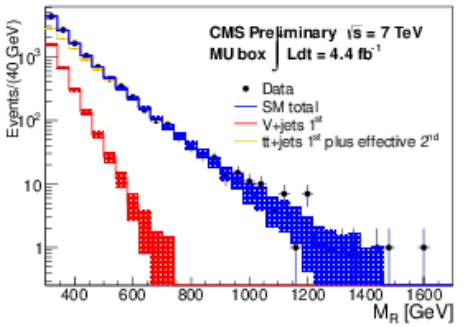
- We fit a sample in its fit region. The fit is such that the likelihood refers to the full region already (i.e. it already extrapolate beyond the fit region)
- We generate a set of toy MCs. In each toy MC the background shape changes (generated according to the fit output and errors, including correlation)
- We obtain a distribution for the expected yield in a given signal-sensitive region, to be compared to observation
- We evaluate agreement through a two-sides p-value
- We use the same approach (adding signal in CLs calculation) to set a limit

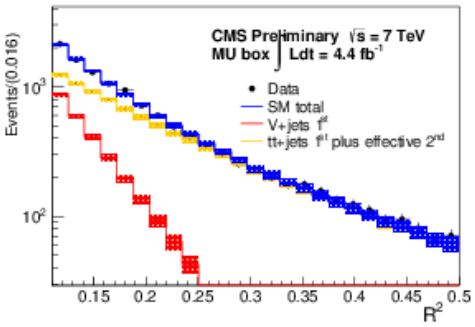


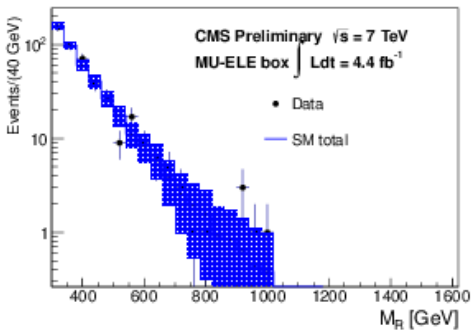
Background in Razor Boxes

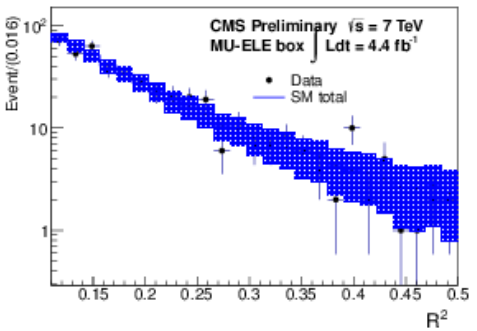


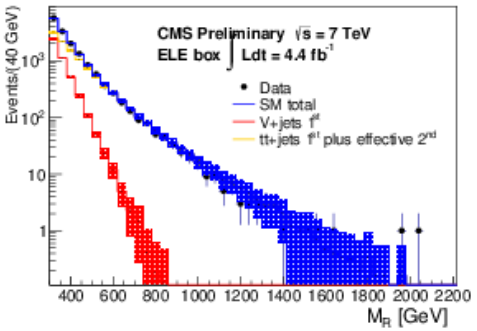


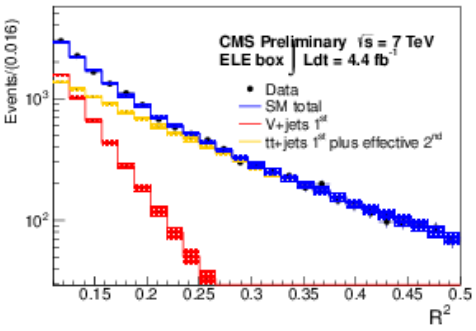


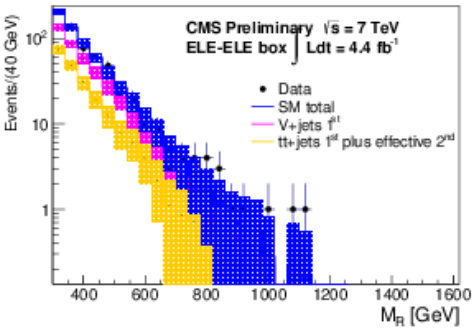


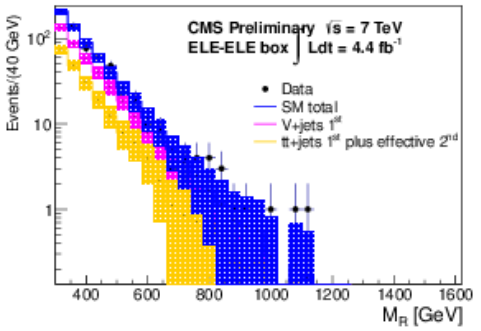


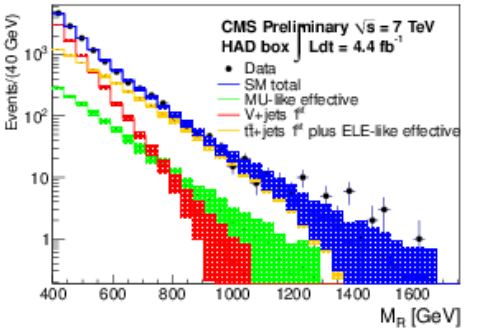


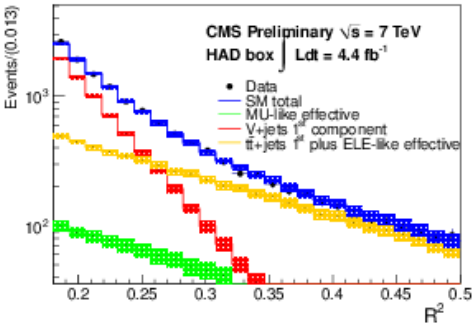












Error bands represent statistical uncertainty only

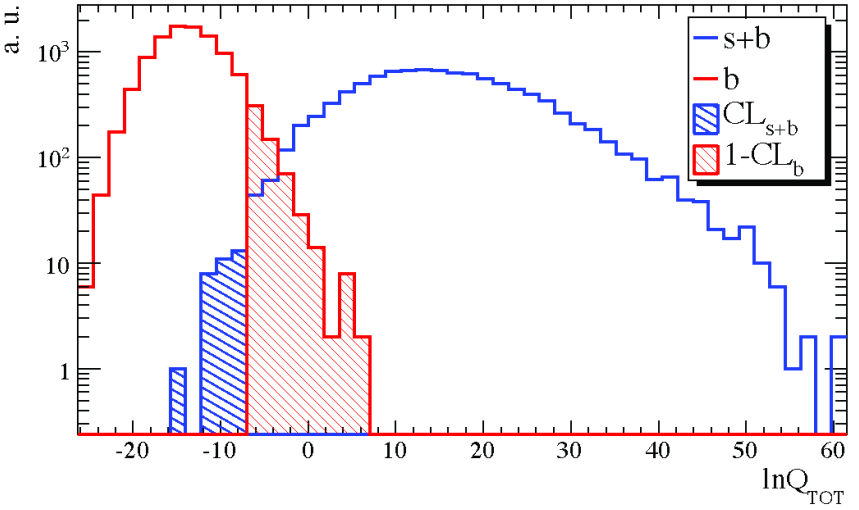
Razor Limit Computation (I)

Restrict to signal region
Generate B-only and S+B toys to evaluate the likelihood ratio

Compute hybrid CLs to put limit

BKG-shape PDF included sampling the toy bkg shape from fit covariance matrix

Signal shapes included sampling the signal toy distributions bin-by-bin according to log-normal functions

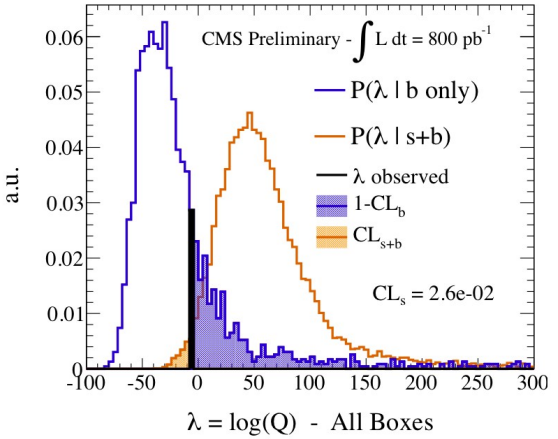


yield systematics	
$\mathcal{L}$[34]	4.5%
cross section	point-by-point
trigger efficiency R^2-M_R	2%
trigger efficiency lepton	3% (lepton, dilepton boxes)
shape systematics	
PDF	point-by-point (up to 30%)
JES	point-by-point (up to 1%)
lepton-id (tag-and-probe)	1% (per lepton)

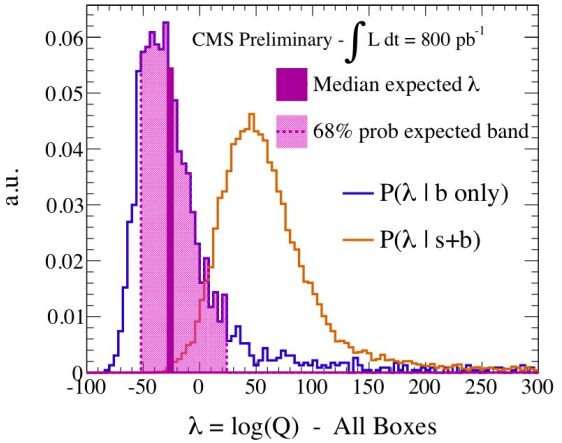
Razor Limit Computation (II)

example hypothesis test

m_0=240, $m_{1/2}$=500, $\tan\beta$ =10, A_0=0, $\mu > 0$



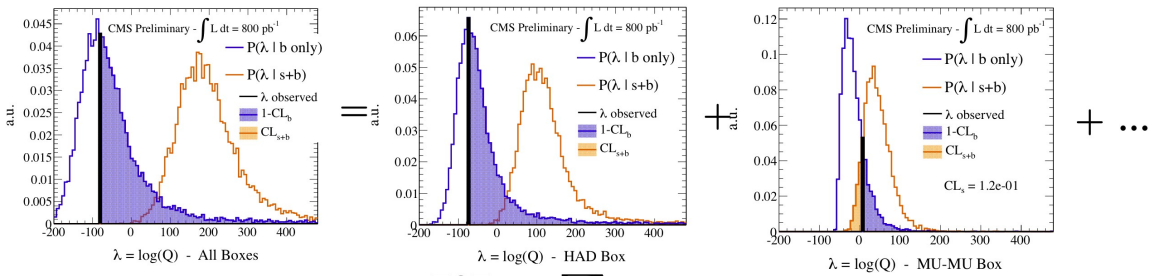
observed



expected $\pm 1\sigma$

$$\lambda = \log Q = \log(\mathcal{L}_{s+b}/\mathcal{L}_b)$$

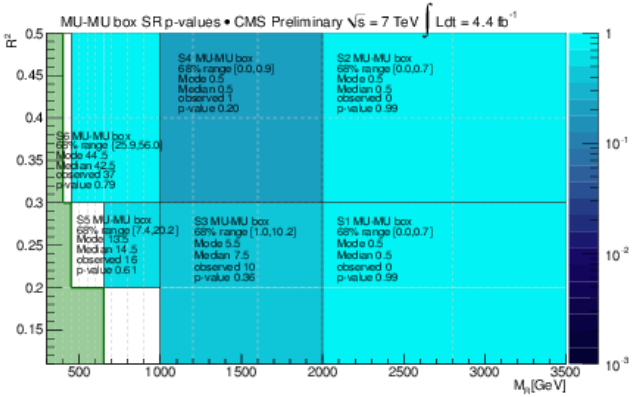
Boxes are combined by adding the test-statistic (log-likelihood ratio)

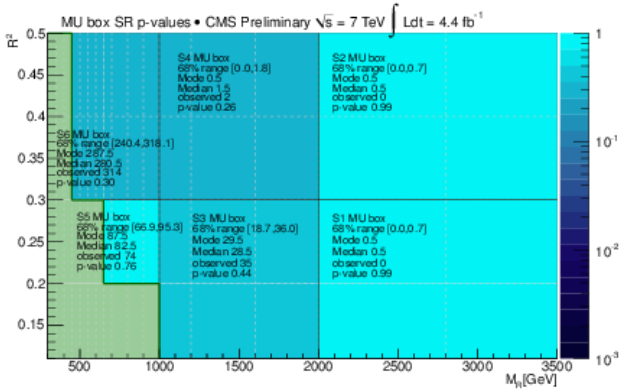


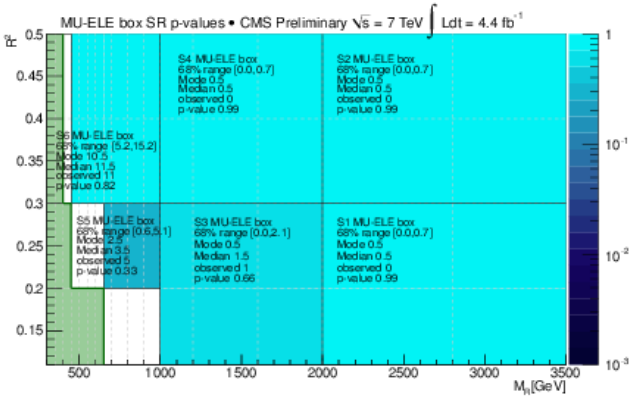
$$\lambda^{\mathrm{TOT}} = \sum_{i \in \mathrm{boxes}} \lambda^i$$

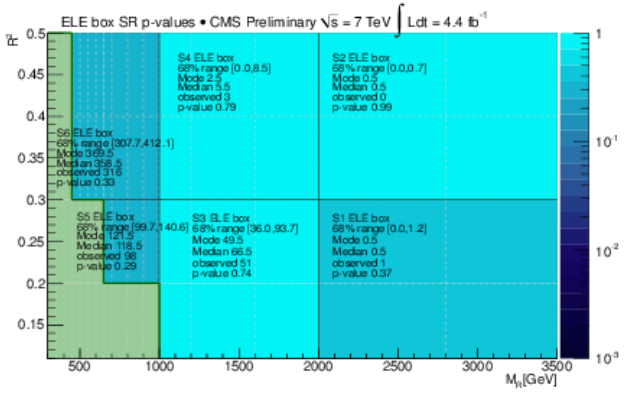
$$\mathcal{L}^{\mathrm{TOT}} = \prod_{i \in \mathrm{boxes}} \mathcal{L}^i \qquad \lambda^i = \log Q^i = \log(\mathcal{L}^i_{s+b}/\mathcal{L}^i_b)$$

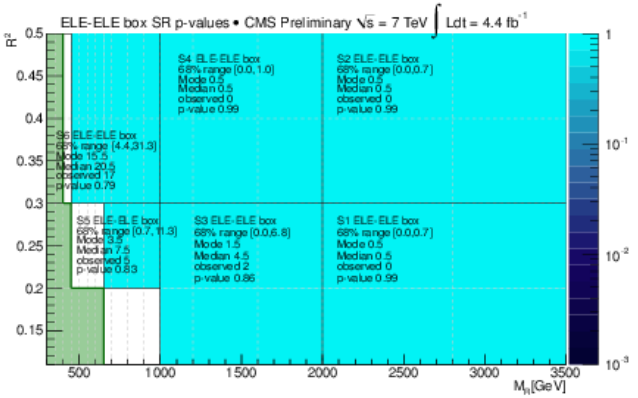
Razor Model Independent Inerpretation

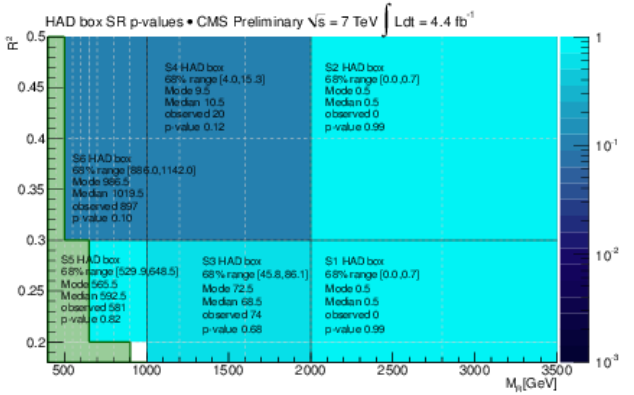




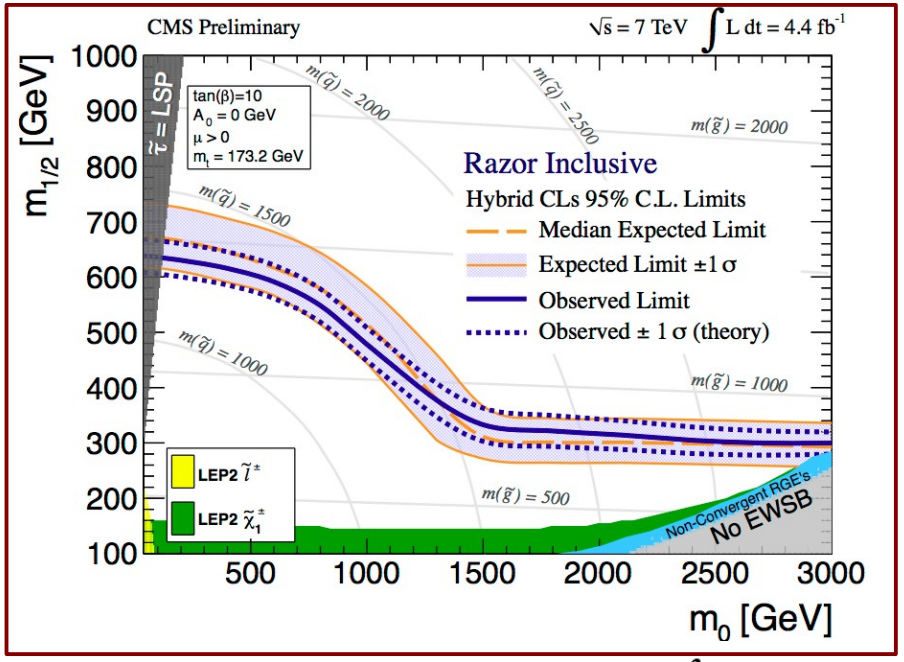


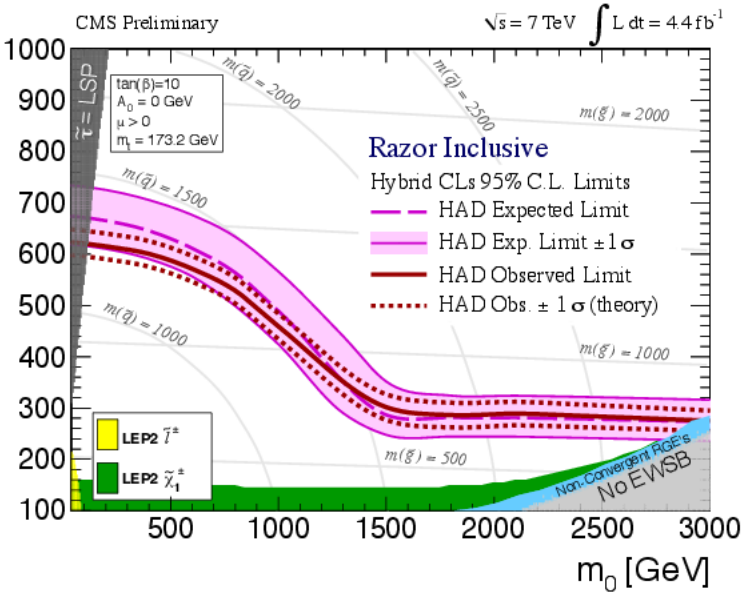


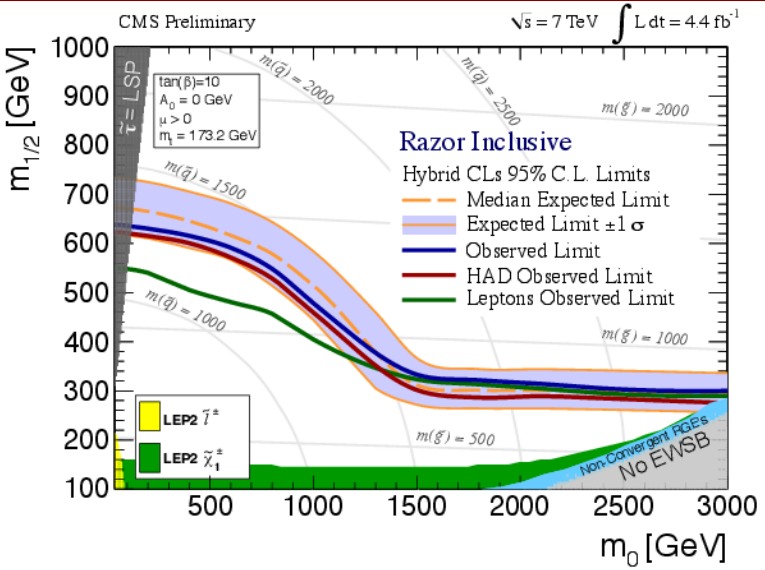


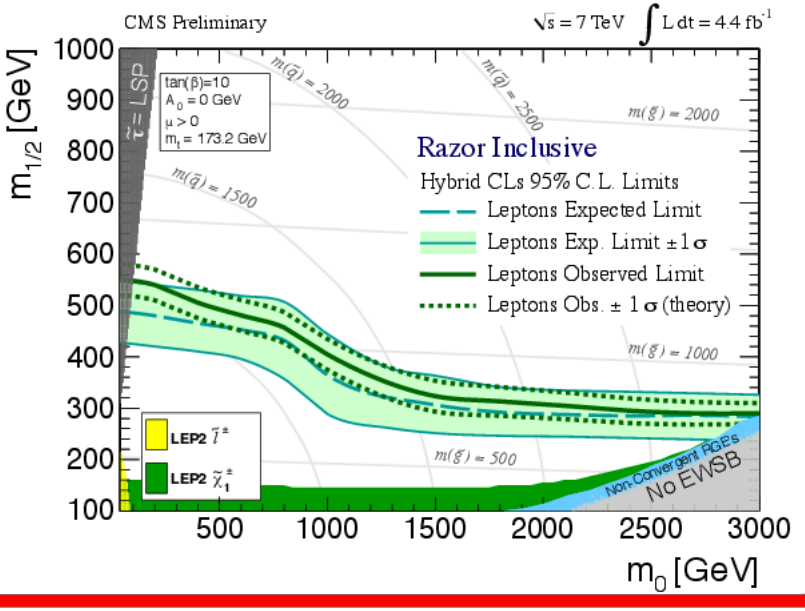


Razor Model Dependent Interpretation



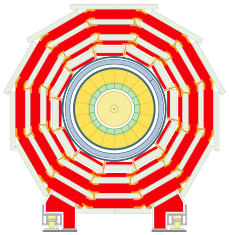






Photon(s) + Jets + MET Analysis

We have performed a search for supersymmetry in a gauge-mediation scenario with the gravitino as the lightest supersymmetric particle. The data sample corresponds to an integrated luminosity of 4.7 fb^-1 of pp collisions at sqrt(s) = 7 TeV, recorded by the CMS experiment at the LHC.We compare the missing transverse energy distribution in events containing either at least two photons plus at least one hadronic jet or at least one photon plus at least two hadronic jets to the spectra expected from standard model processes. No excess of events at high missing transverse energy is observed and upper limits on the signal production cross sections of order 0.01 pb (0.1 pb) at the 95% confidence level for the bino-like (wino-like) scenarios are determined for a range of squark, gluino, and neutralino masses.



Photon Analysis Signals

- Fix Bino-like neutralino mass at 375 GeV
  - Squark and gluino masses run from 400 to 2000 with 80 GeV binning
- Fix Wino-like neutralino mass at 375 GeV
  - Squark and gluino masses run from 400 to 2000 with 80 GeV binning
- Fix squark mass at 2500 GeV
  - gluino mass from 400 to 2000 with 80 GeV binning
  - Neutralino mass from 150 to 1050 with 100 GeV binning

Photon Analysis Selection

- Diphoton analysis selection
  - Et(1) > 40 GeV & Et(2) > 25 GeV satisfying photon ID
  - DR(1,2) > 0.6 for two photons
  - Dphi(1,2) > 0.05
  - Reconfirm trigger requirement (IsoVL)
- Single photon analysis selection
  - Et > 80 GeV satisfying photon ID
  - Reconfirm trigger requirement (CaloHT>450)
  - Njets >= 2/3

Di-Photon Background Estimation (I)

- Real MET Background (called EW)
  - Wγ (W->eν) where an electron fakes a γ
  - Use data-driven method
  - Measure e->γ fake rate using Z->ee
  - Apply fake rate to electron from eγ selection
- No real MET Background (called QCD)
  - QCD: γγ, γj,jj where jets fake photons
  - Use data-driven method
  - Select control samples where no real MET is expected
  - Take MET shape from the control samples and normalize the shape to candidate shape (MET < 20 GeV)
- Fake-Fake (ff) Control Samples
  - Fakes are defined as photons but inverting isolation and sigmaIetaIeta cut
  - Events with R9Id triggers are included to increase statistics
- Electron-Electron (ee) Control Samples
  - Select Z->ee samples with invariant mass between 81-101 GeV and subtracting sideband contributions

Di-Photon Background Estimation (II)

- Electroweak Background
  - Real MET
  - Main contribution from Wγ (W->eν) where electron fakes photon
  - Take MET distribution from eγ sample
  - Apply fake rate with the formula below

$$N^{obs}_{\gamma\gamma} = f_{e\to\gamma} N^{true}_{W\gamma}$$

$$N^{obs}_{e\gamma} = (1-f_{e\to\gamma}) N^{true}_{W\gamma}$$

$$N^{obs}_{\gamma\gamma} = \frac{f_{e\to\gamma}}{(1-f_{e\to\gamma})} N^{obs}_{e\gamma}$$

- QCD background
  - Fake MET
  - Mostly QCD
  - Two control samples
    - Select Z->ee sample by subtracting sideband to eliminate possible contributions from ttbar (called ee)
    - Select non-isolated photons (called ff)
  - Take MET shape
    - JetPt reweighting is applied to the samples to simulate the hadronic recoils
    - Normalize the shape to γγ sample where MET < 20 GeV

Single Photon Background Estimation

Main background γ/ QCD:

- Multi-jet: jet → γ , γ-jet

MET (not intrinsic):

- Dominated by hadronic activity: jet res, non-gaussian tails due to e.g dead cells
- Same effects for multi-jet & photon-jet

Define fake γ selection to get data-driven c. s.:

- Disjunct to tight photon selection, but still photon-like
- The control-sample is re-weighted according to the photon-object pT:
  - Binned weights determined in control region MET<100 GeV
  - Jet-Multiplicity dependance: individual corrections for =2 jets & ≥3 jets, assign 10% systematic unc.
  - Stat. bin uncertainties propagated as systematics
  - Syst. unc. on extrapolation from low to high MET

EWK already minor background

- electron → γ

Intrinsic MET from neutrinos:

- W, ttbar

Disjunct control sample:

- Iso electron, reweighted according to e → γ fakerate

Fake-rate:

- measured pT-dependent on the Z-peak
- For photon pT>80 GeV: 0.006 ± 0.0025

ISR/FSR minor background:

- Initial- or final-state radiation of γ

From MC simulation

- Assign 100% systematic uncertainty on the cross-section

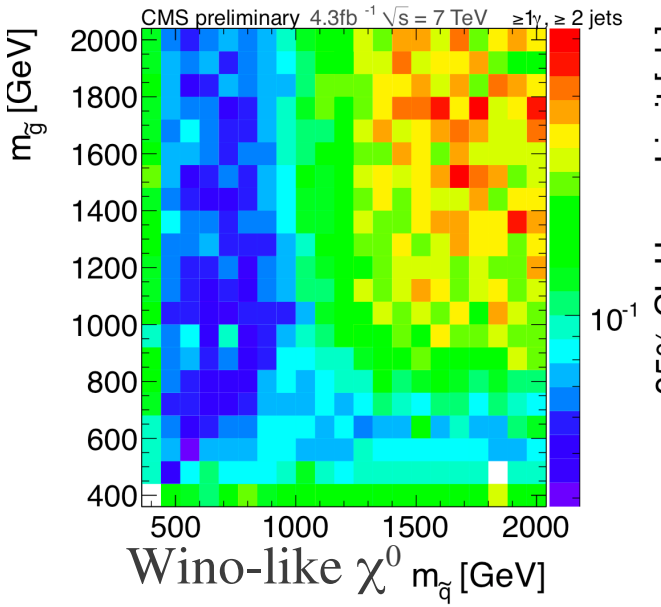
Photon(s) Analysis Yields

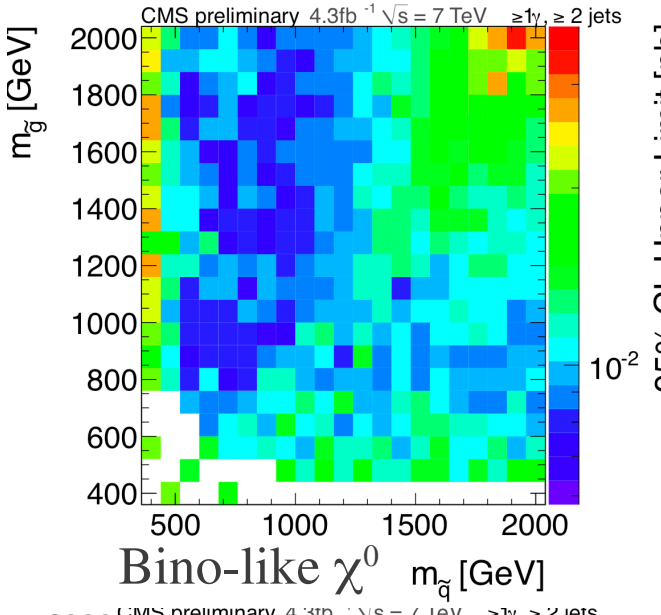
NLSP type	$\gamma + 2\,\text{jets} + E_T^{miss}$	$\gamma\gamma + \text{jet} + E_T^{miss}$
Bino	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma + Z + \tilde{G}\tilde{G}$	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma\gamma + \tilde{G}\tilde{G}$
Wino	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma + Z + \tilde{G}\tilde{G}$ $\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^\pm \to \text{jets} + \gamma + W^\pm + \tilde{G}\tilde{G}$	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma\gamma + \tilde{G}\tilde{G}$

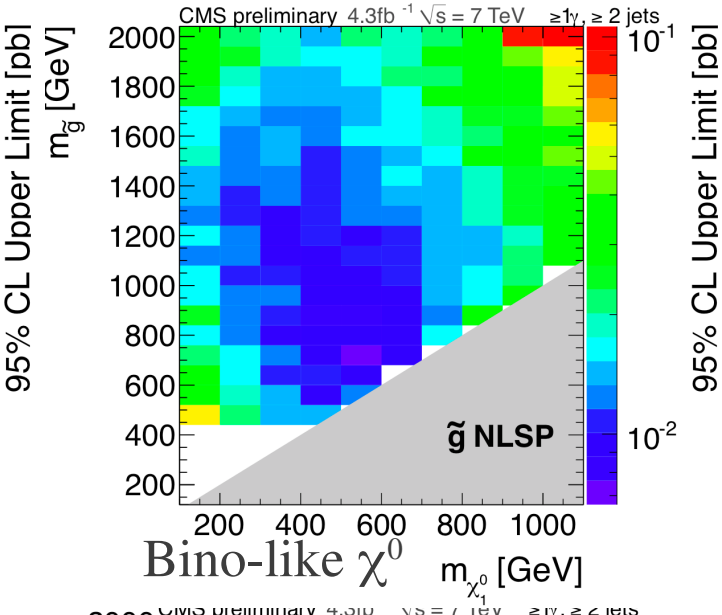
Type di-photon analysis	Events	scal. error	norm. error
$\gamma\gamma$ candidates	11		
ff QCD background	10.1 ± 4.2	± 0.3	± 0.03
ee QCD background	14.7 ± 3.1	± 0.1	± 0.03
EWK background	2.9 ± 1.0	± 0.0	± 0.9
Total background (ff)	13.0 ± 4.3		

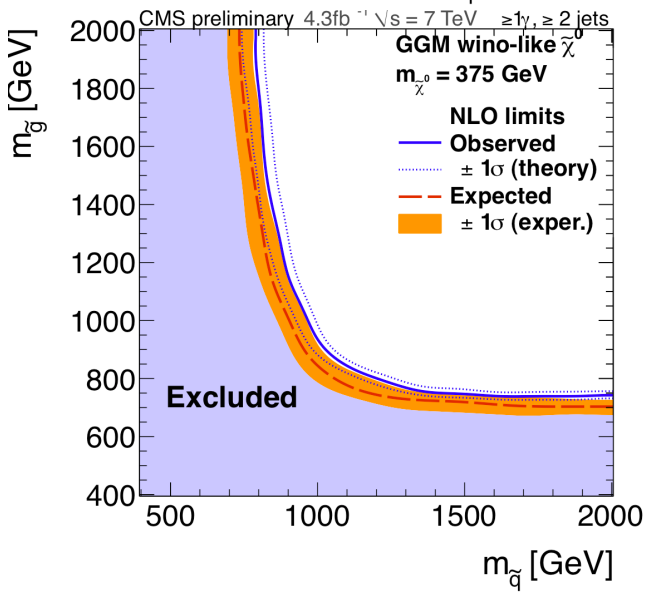
Single photon analysis $\geq 1\gamma, \geq 2$ jets	$E_T^{miss} \geq 100$ GeV	(stat.)	(syst.)	$E_T^{miss} \geq 200$ GeV	(stat.)	(syst.)	$E_T^{miss} \geq 350$ GeV	(stat.)	(syst.)
QCD (from data)	607.7	± 46.7	± 54.0	90.7	± 16.4	± 9.9	6.8	± 4.1	± 0.8
$e \to \gamma$ (from data)	17.2	± 0.3	± 7.2	3.5	± 0.2	± 1.5	0.4	± 0.01	± 0.2
FSR/ISR(W, Z)	27.6	± 3.2	± 27.6	10.4	± 2.0	± 10.4	1.6	± 0.8	± 1.6
FSR/ISR($t\bar{t}$)	3.8	± 0.9	± 3.8	0.8	± 0.4	± 0.8	< 0.01	< 0.01	< 0.01
total SM estimate	656.4	± 46.9	± 92.7	105.5	± 16.5	± 22.6	8.7	± 4.2	± 2.5
Data	615			63			4		

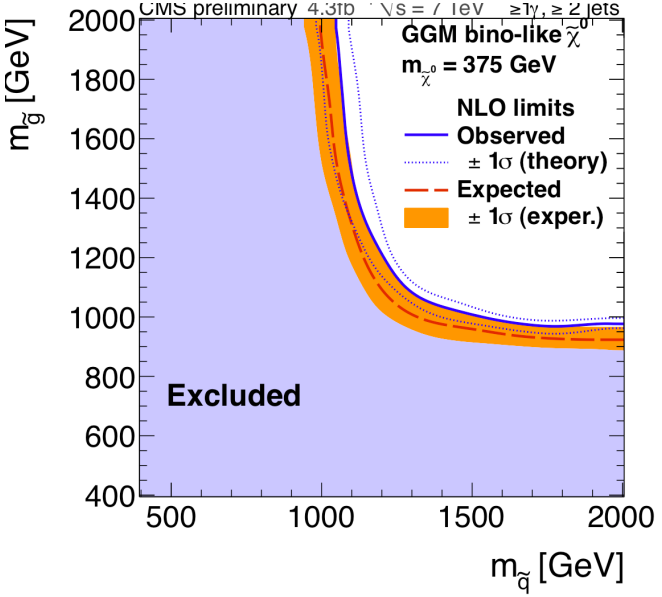
Single Photon GGM Limits

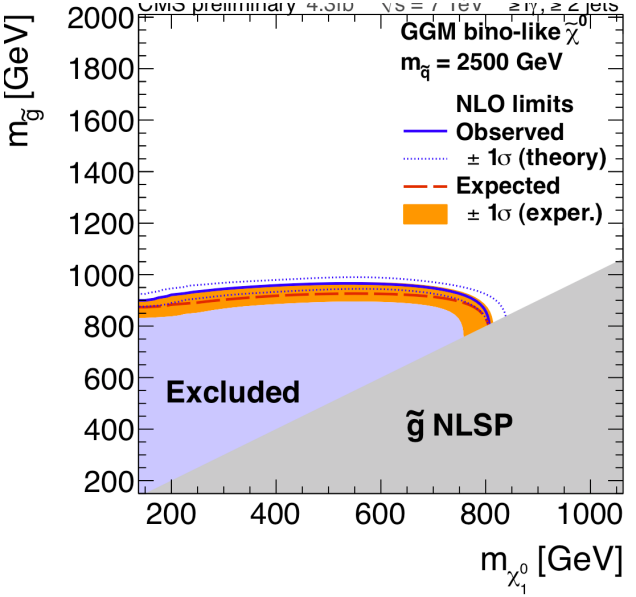




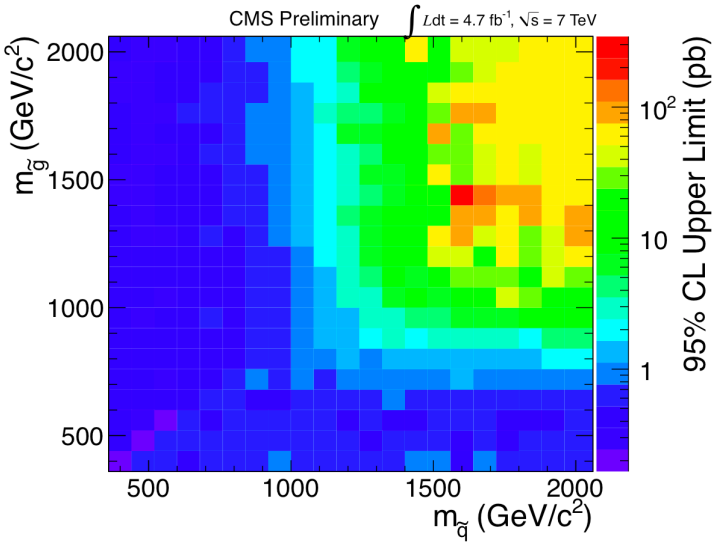




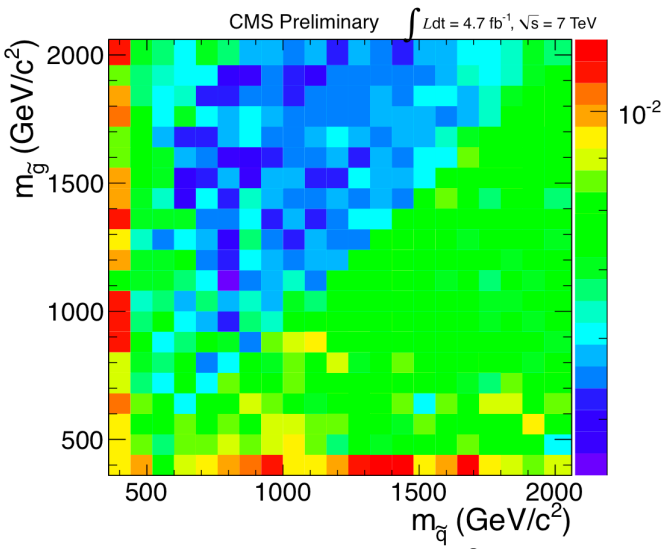




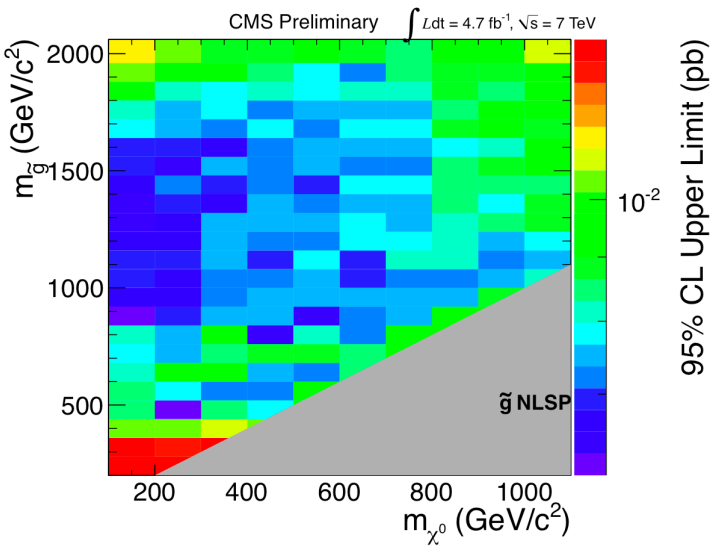
Di-Photon GGM Limits



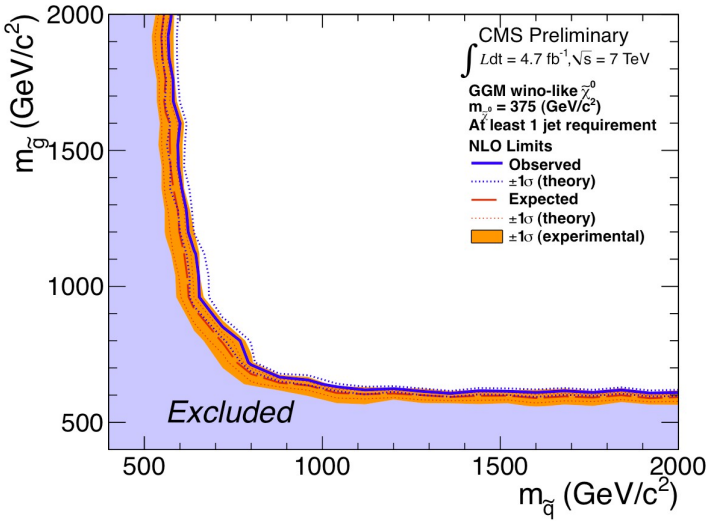
Wino-like χ^0

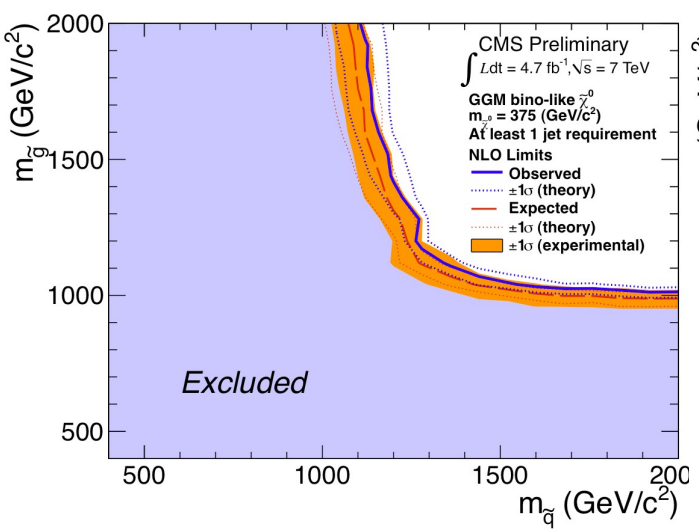


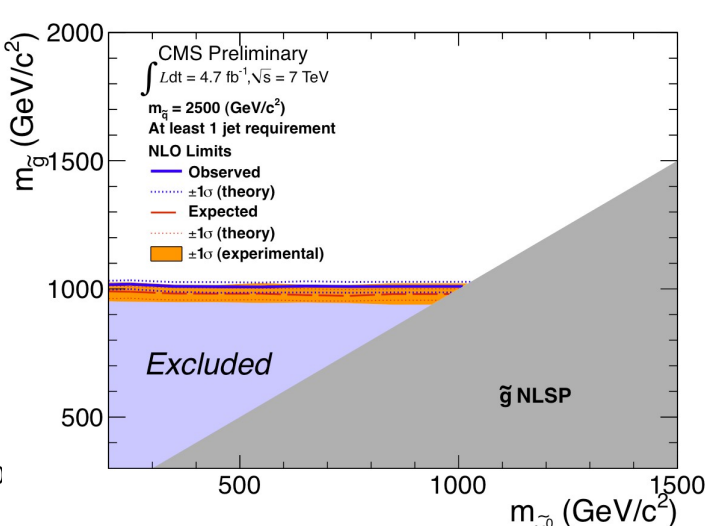
Bino-like χ^0



Bino-like χ^0

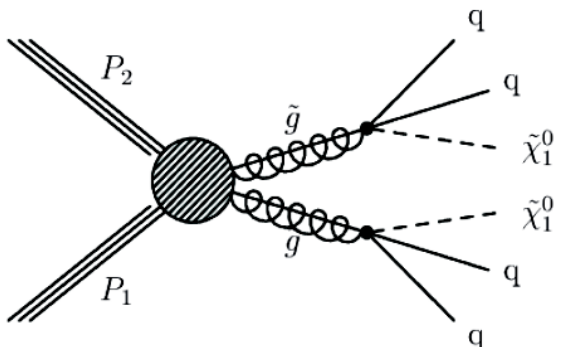






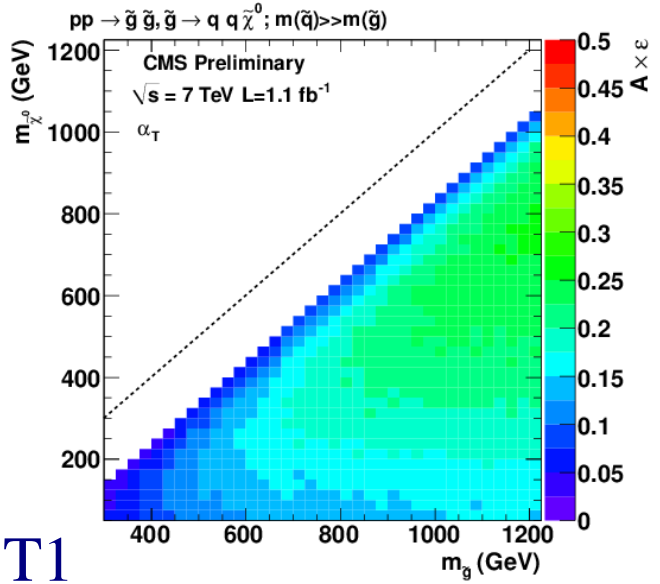
Simplified Models

In a simplified model a very reduced set of hypothetical particles is introduced; the phenomenological masses and the decay ratios are free parameters of the model. Such models allow us to describe and compare results of CMS analyses in a fashion independent from full/constrained models.

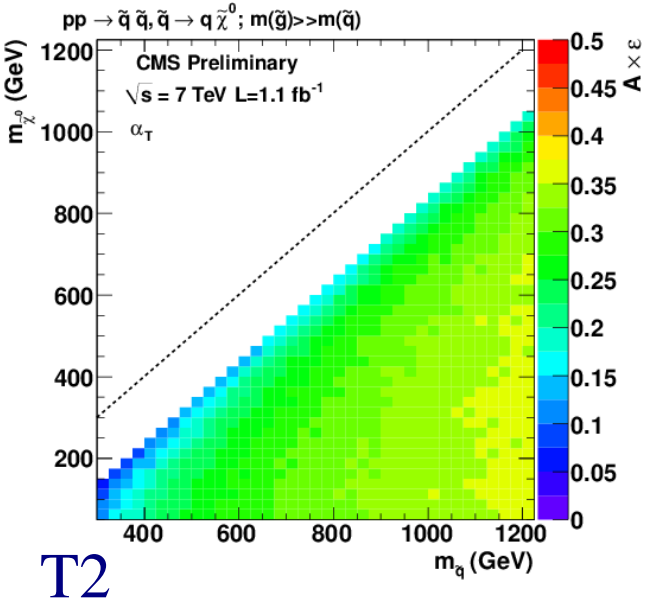


name	prod. mode	decay	visibility
T1	$\tilde{g}\tilde{g}$	$\tilde{g} \to qq\tilde{\chi}^0$	hadronic
T2	$\tilde{q}\tilde{q}$	$\tilde{q} \to q\tilde{\chi}^0$	hadronic
T5zz	$\tilde{g}\tilde{g}$	$\tilde{g} \to qqZ\tilde{\chi}^0$	hadronic di-leptons
T3w	$\tilde{g}\tilde{g}$	$\tilde{g} \to qq\tilde{\chi}^0$ $\tilde{g} \to qq\tilde{\chi}^\pm, \tilde{\chi}^\pm \to W^\pm\tilde{\chi}^0$	single lepton
T5lnu	$\tilde{g}\tilde{g}$	$\tilde{g} \to qq\tilde{\chi}^\pm\ \tilde{\chi}^\pm \to l\nu\tilde{\chi}^0$	di-leptons
T3lh	$\tilde{g}\tilde{g}$	$\tilde{g} \to qq\tilde{\chi}^0$ $\tilde{g} \to qqll\tilde{\chi}^0$	di-leptons
T1bbbb	$\tilde{g}\tilde{g}$	$\tilde{g} \to bb\tilde{\chi}^0$	hadronic
T1tttt	$\tilde{g}\tilde{g}$	$\tilde{g} \to tt\tilde{\chi}^0$	hadronic di-leptons(b)
TChiSlepSlep	$\tilde{\chi}^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_2^0 \to ll, \tilde{l} \to l\tilde{\chi}^0$ $\tilde{\chi}^\pm \to \nu\tilde{l}, \tilde{l} \to l\tilde{\chi}^0$	multi-leptons
TChiwz	$\tilde{\chi}^\pm\tilde{\chi}_2^0$	$\tilde{\chi}^\pm \to W^\pm\tilde{\chi}^0, \tilde{\chi}_2^0 \to Z\tilde{\chi}^0$	multi-leptons
TChizz	$\tilde{\chi}_2^0\tilde{\chi}_3^0$	$\tilde{\chi}_2^0, \tilde{\chi}_3^0 \to Z\tilde{\chi}^0$	multi-leptons

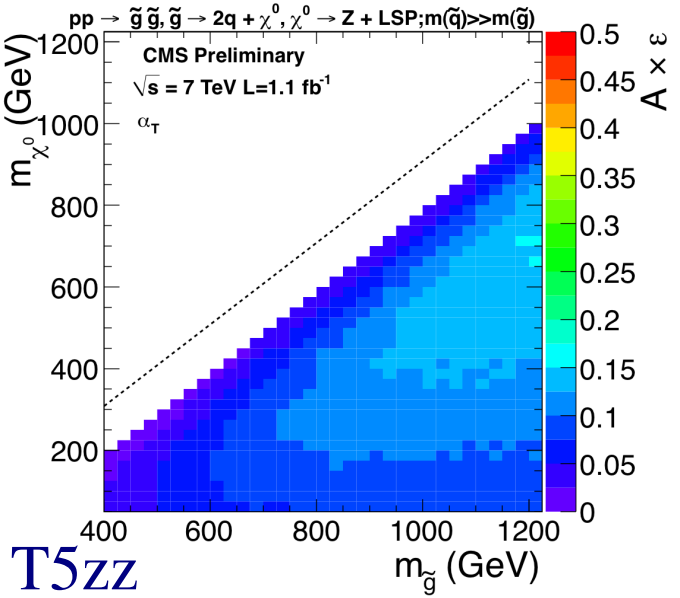
SMS - α_T 1.1 fb^{-1}



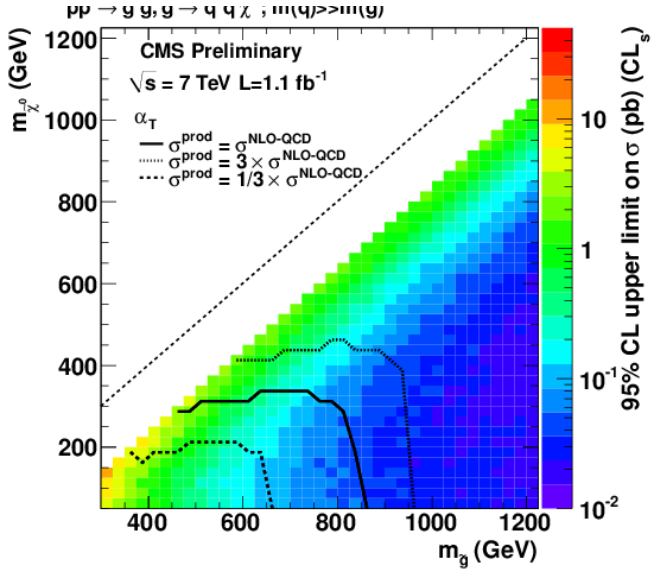
T1

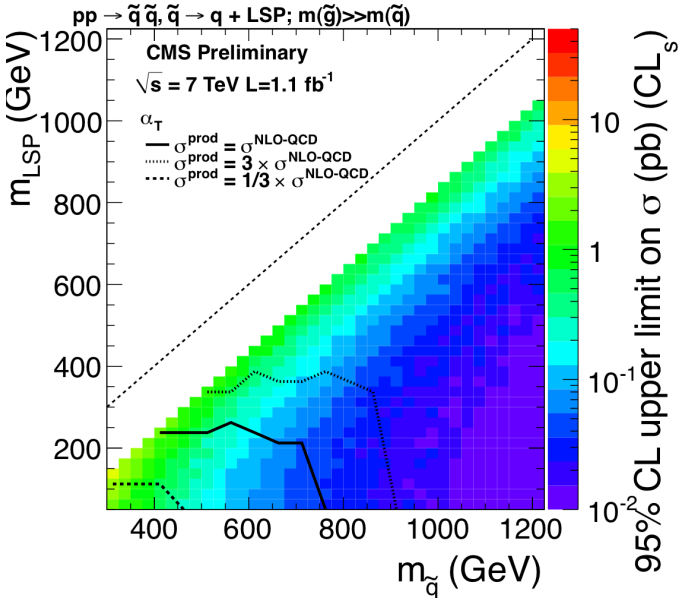


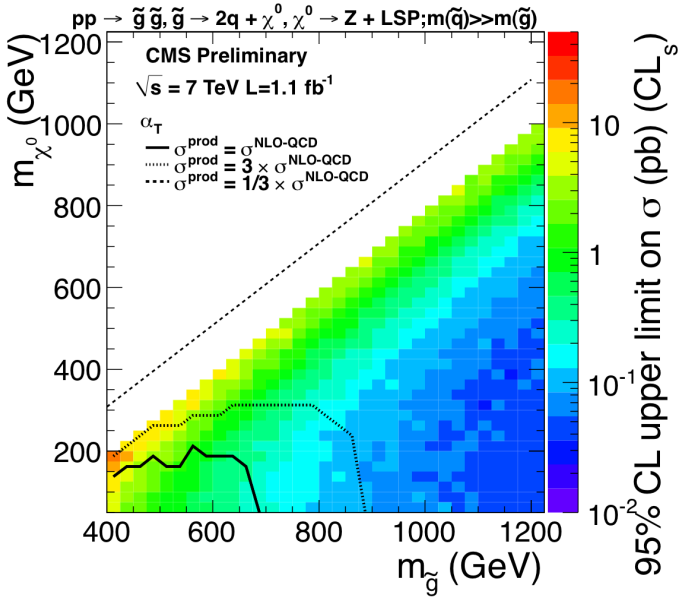
T2



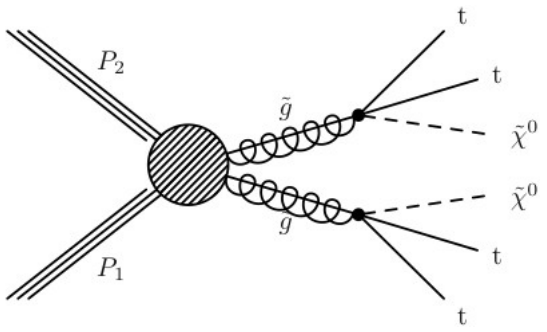
T5zz

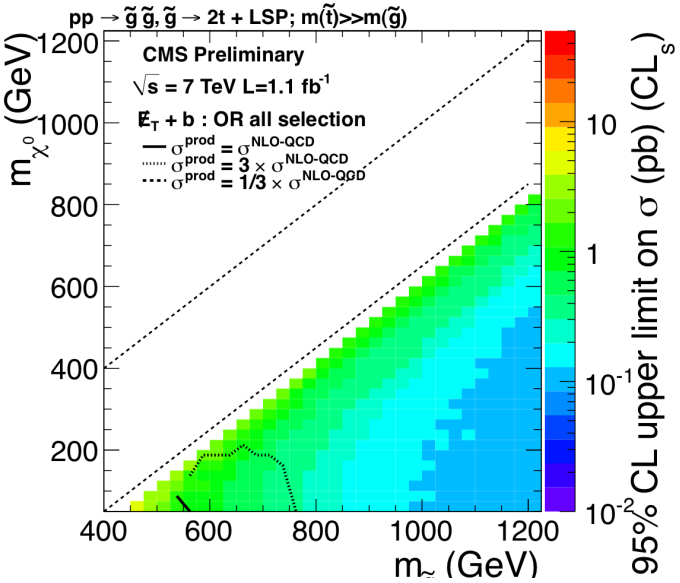


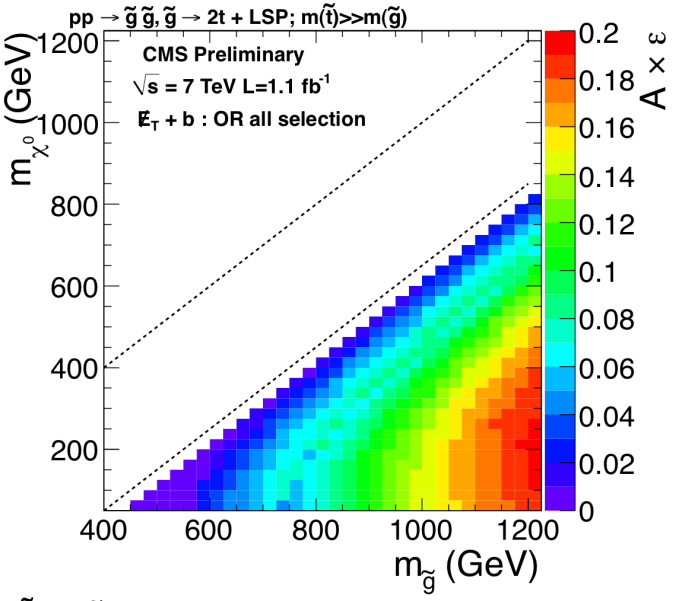


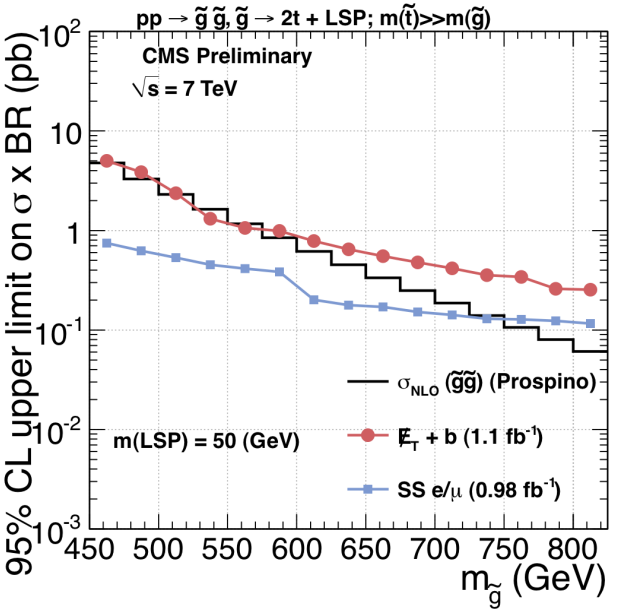


SMS – MET+b 1.1 fb^{-1}



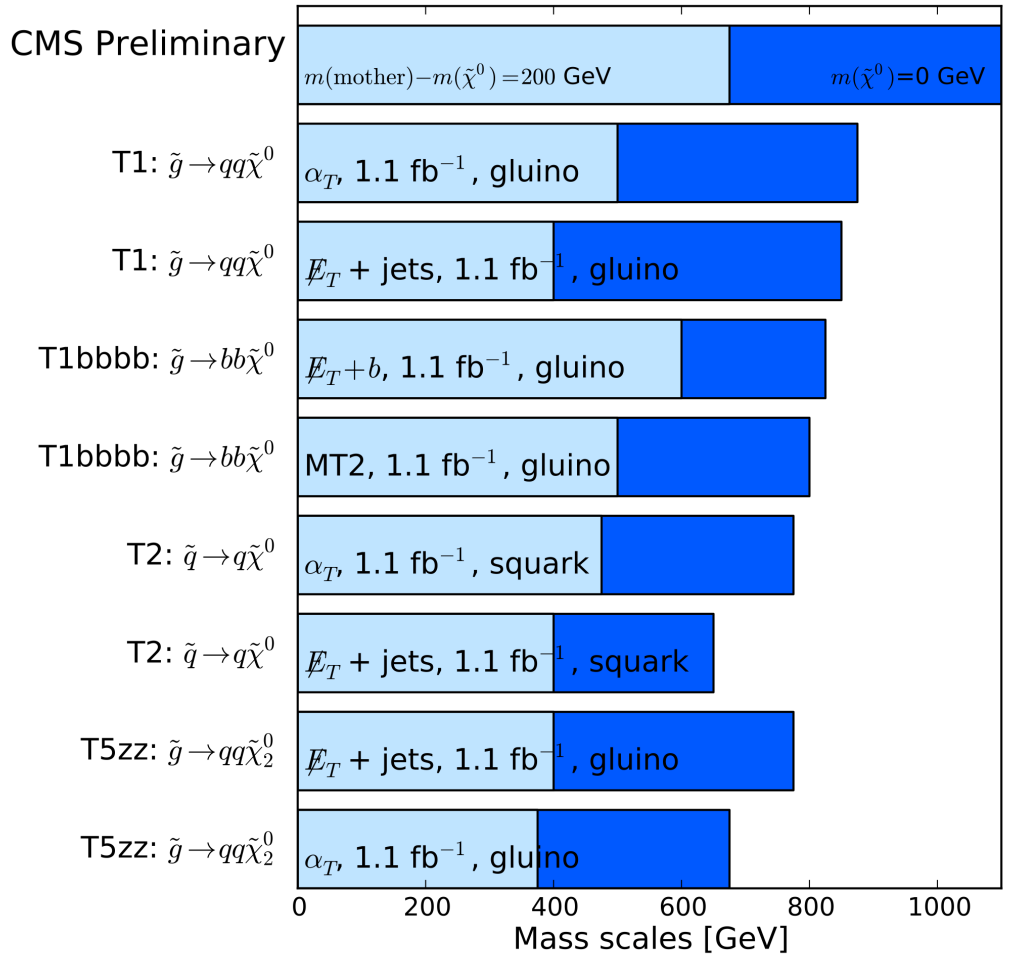




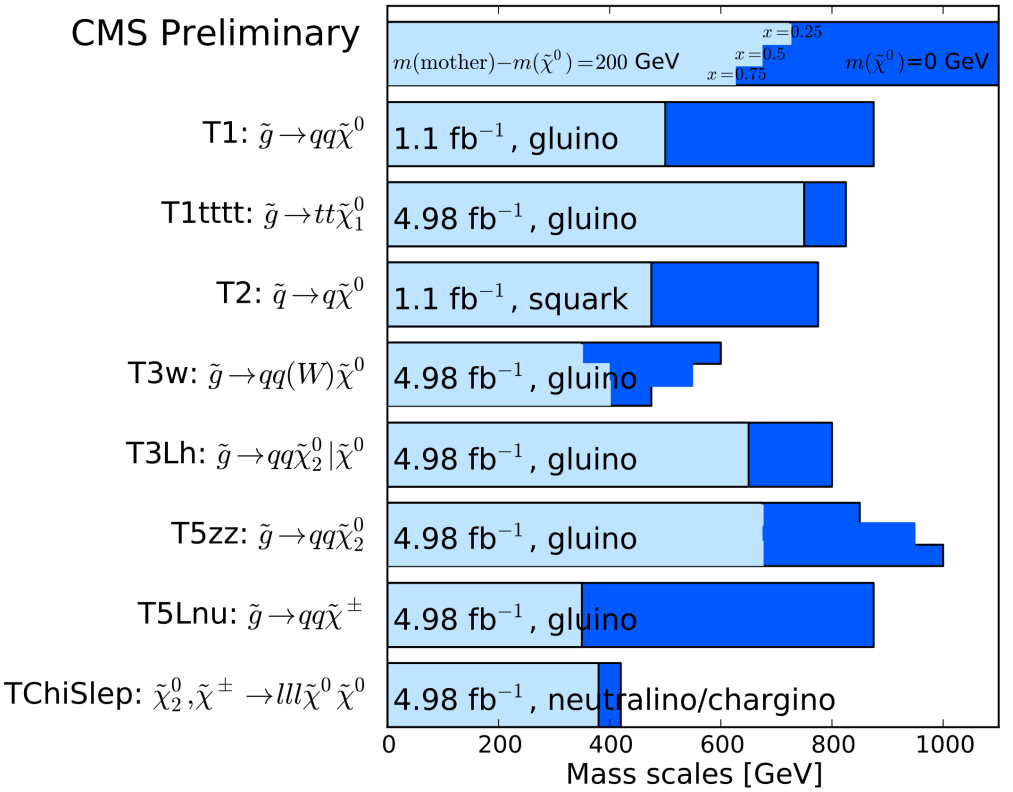


SMS Summary (1.1-4.98 fb^{-1})

Hadronic analysis only (1.1 fb-1 only)

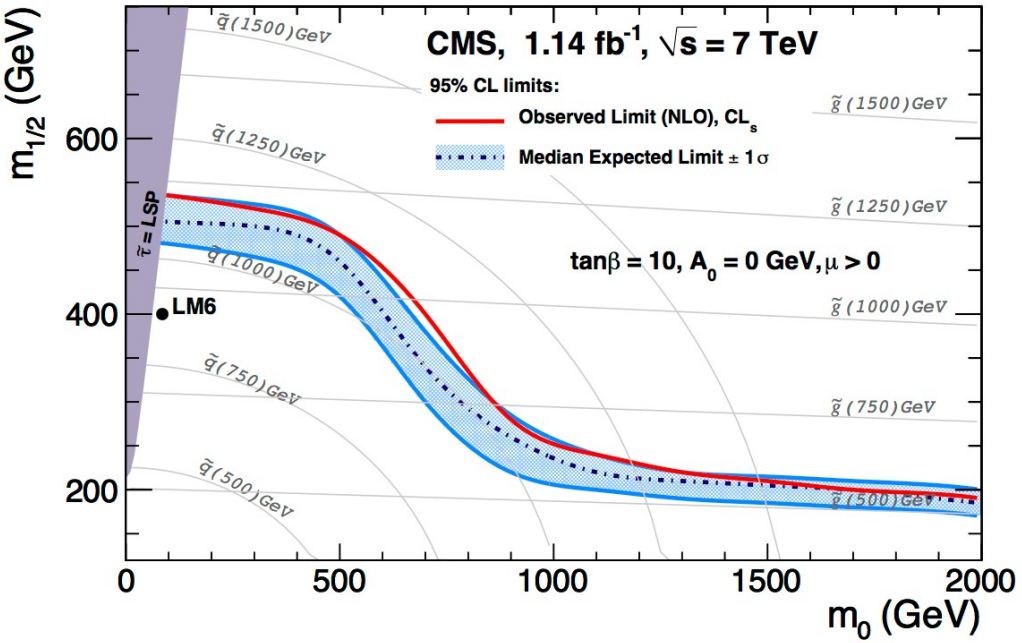


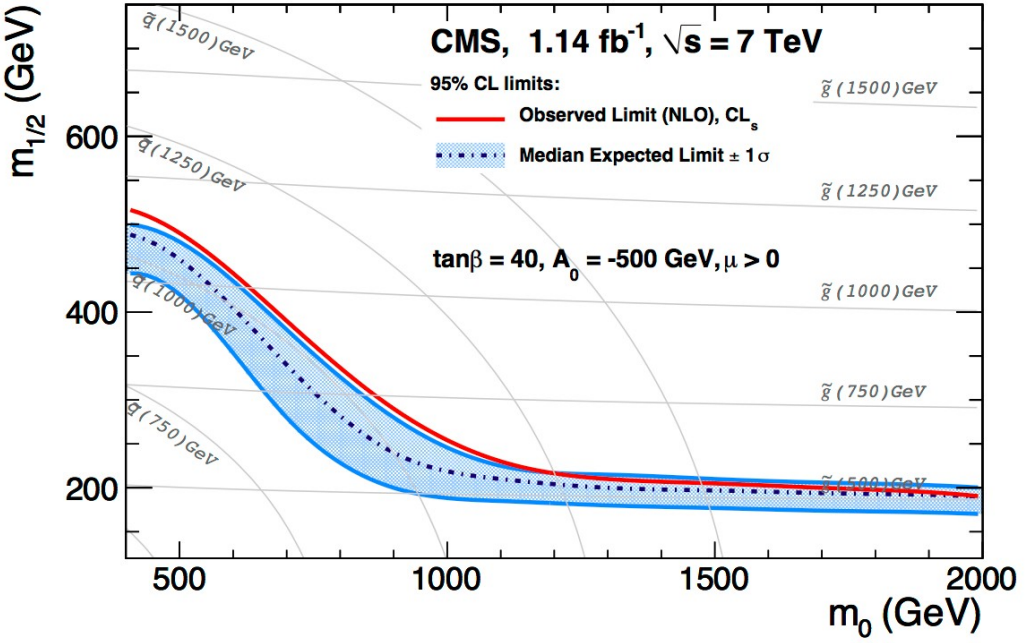
Best of leptonic (up to 4.98 fb-1) and Hadronic (up to 1.1 fb-1) exclusion



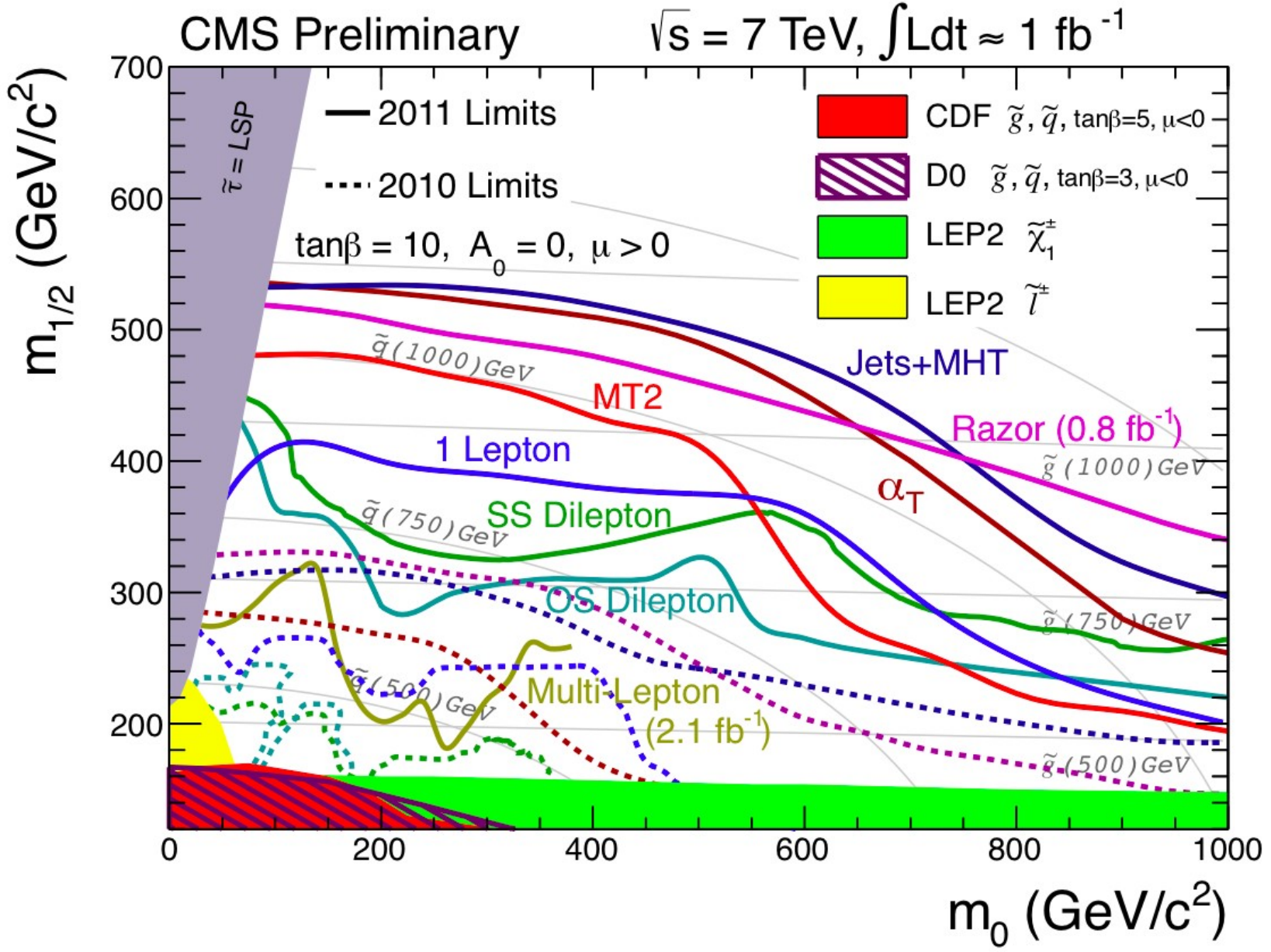
Best exclusion limits for gluino and squark masses, for m(chi0)=0 GeV (dark blue) and m(mother)-m(chi0)=200 GeV (light blue)

CMSSM Limits - α_T 1.1 fb^{-1}

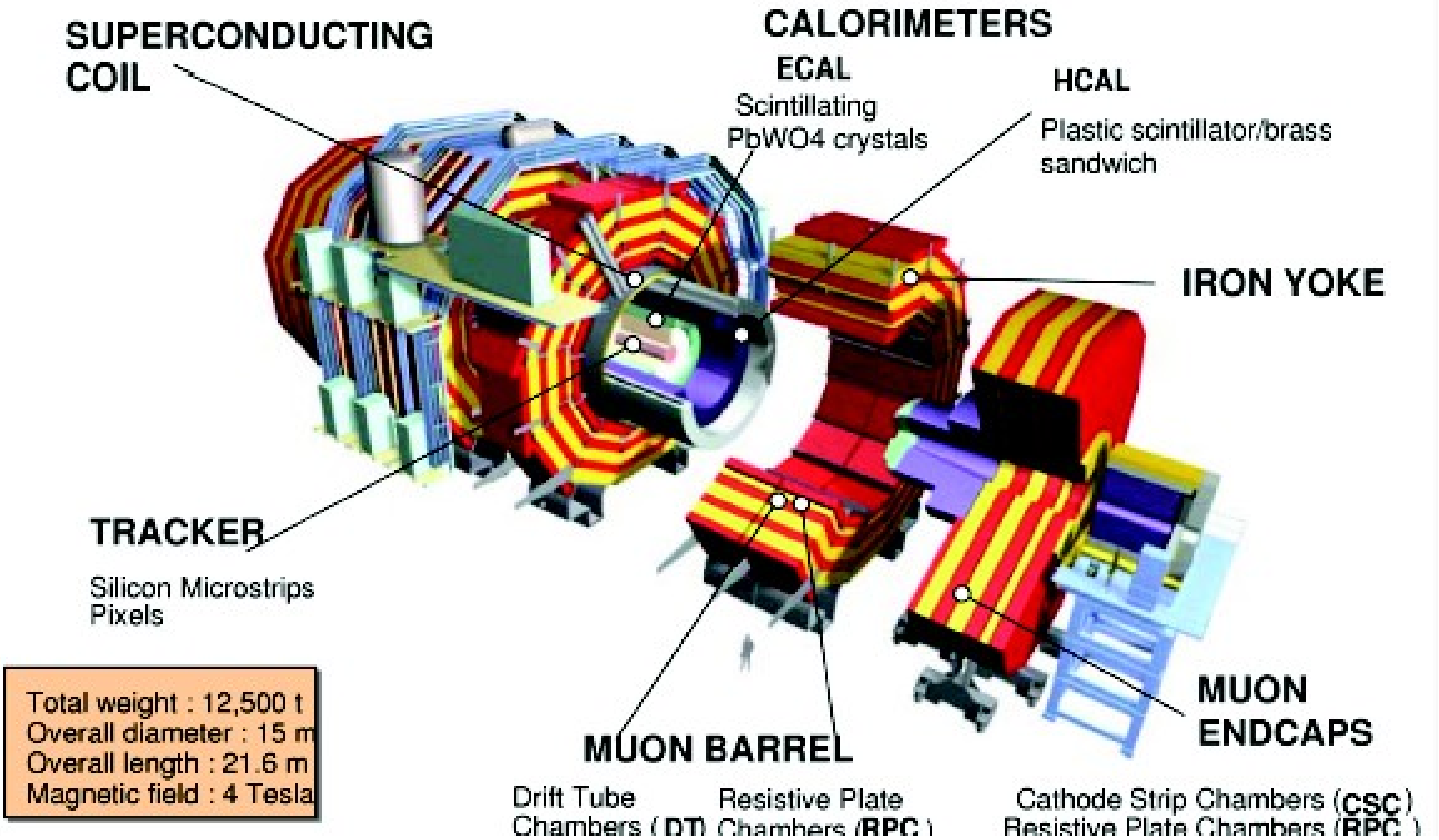




CMSSM Limits 1 fb^{-1} (Summary Plot)



CMS


SUPERCONDUCTING COIL
CALORIMETERS
ECAL
Scintillating PbWO4 crystals
HCAL
Plastic scintillator/brass sandwich
IRON YOKE
TRACKER
Silicon Microstrips
Pixels
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Luminosity Change Statement

- In the process of precision determination of the luminosity collected by CMS in 2011, a slight time-dependent calibration drift was found in the calorimeter used as a luminometer
- To remedy this, we developed an independent luminosity determination using stable and precise pixel tracker
- Preliminary result presented at the LHC Luminosity Days suggests an upward change in the estimated luminosity for 2011 by ~6%, i.e. slightly outside the 1σ-band of our original estimate of the luminosity uncertainty
  - The corresponding change for the low-luminosity part of the run (2011A), which is the basis of our new and published precision measurements, is ~3.5%, well within the quoted systematics
- We are finalizing determination of the new luminosity measurement, with significantly better precision
- The anticipated change has a very minor effect on our preliminary results and no visible change in published limits
- Instability does not affect the 2010 luminosity determination, as it only affects high-luminosity running