SEARCHES FOR SUPERSYMMETRY WITH THE CMS EXPERIMENT

On behalf of the CMS Collaboration

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

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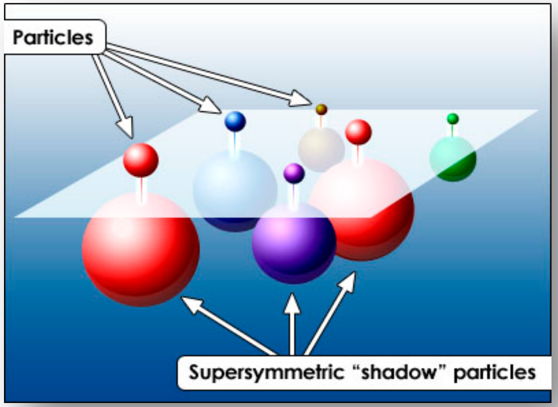
DESY

Ankara YEF Günleri 27-30 Aralik 2011,
Ankara University, Ankara, Turkey.

HELMHOLTZ
ASSOCIATION

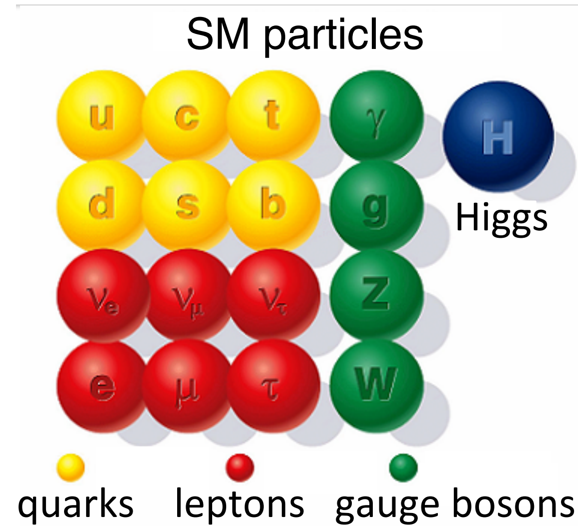
OUTLINE

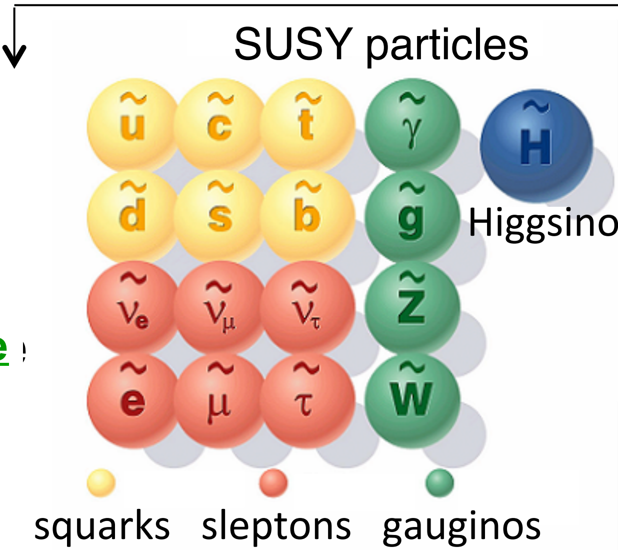
- Supersymmetry (SUSY) – Symmetry of the Nature?
- SUSY Production at Colliders
  - The Strategy
  - The Large Hadron Collider (LHC) Experiment
  - The Compact Muon Solenoid (CMS) Detector
- SUSY Analyses in the CMS Collaboration
  - Hadronic SUSY Searches
  - Leptonic SUSY Searches
- Interpretation of the Physics Results
- Summary



SUPERSYMMETRY

- Standard Model (SM) describes known particles/ forces. Extremely successful at low energy, but several problems:
  - Hierarchy problem
  - Gauge coupling and non-unification
  - Dark matter (DM): preferred explanation WIMP mass O(100 GeV) -> <u>no SM candidate</u>
- SUSY: popular extension to SM, introduces "super-partners" to each SM particle
  - Solves many problems intrinsic to SM
  - Lightest SUSY particle (LSP): stable, weakly-interacting particle EWSB scale~100 GeV -> **<u>natural DM candidate</u>**
  - Implies DM may be produced at **LHC**.





SUSY PRODUCTION AT COLLIDERS

- Many SUSY models postulate conserved quantum number:

"R-Parity"

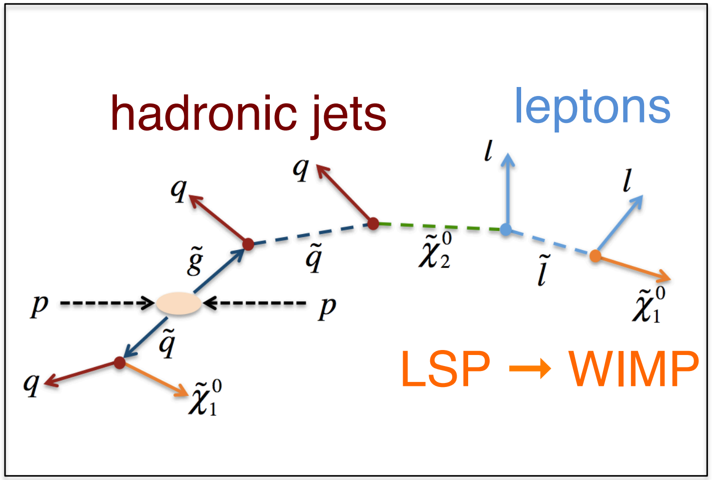
$R = (-1)^{2S - L + 3B}$
where S = spin, L = lepton #, B = baryon #

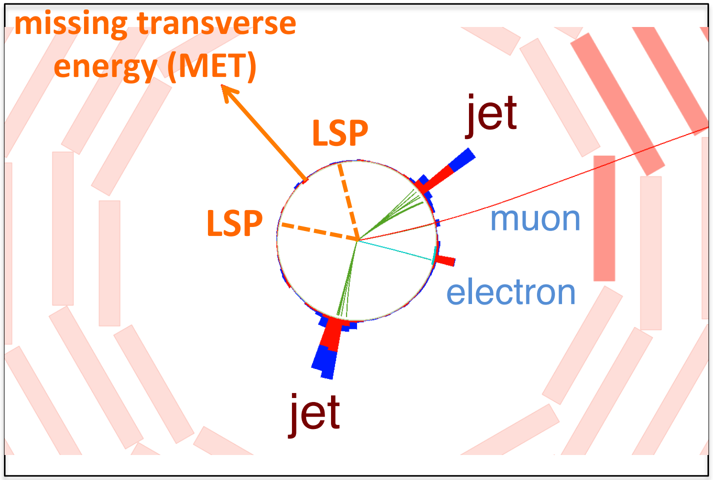
+1 for SM particles
- 1 for SUSY particles

  - SUSY particles produced in pairs (usually strongly produced squarks/gluinos)
  - LSP is stable

- Squarks/gluinos decay via cascade, producing jets, (leptons), LSP's spectacular events with several **high p_T jets + (leptons) + E^T_{miss}!**

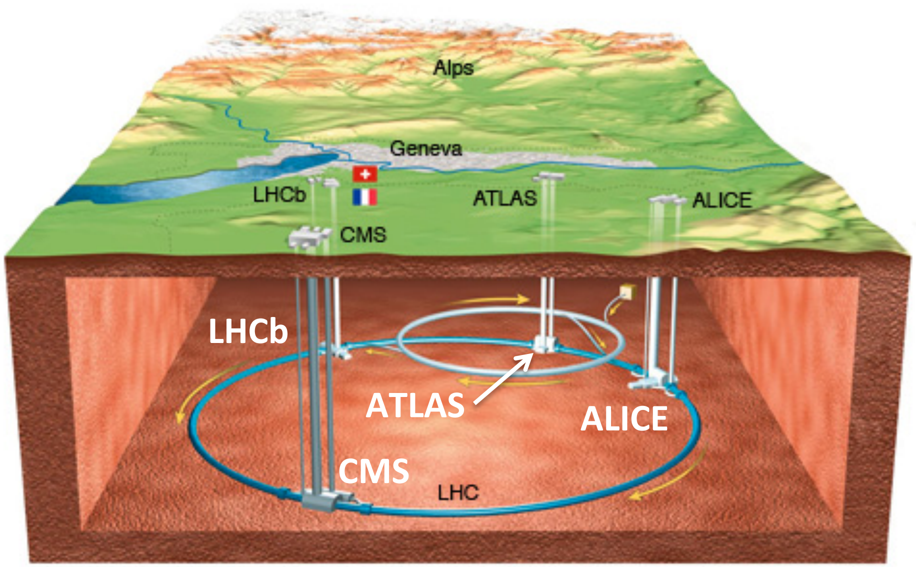
- **Strategy: search for excess of events w/ large E^T_{miss}, HT (sum of jet p_T's)!**

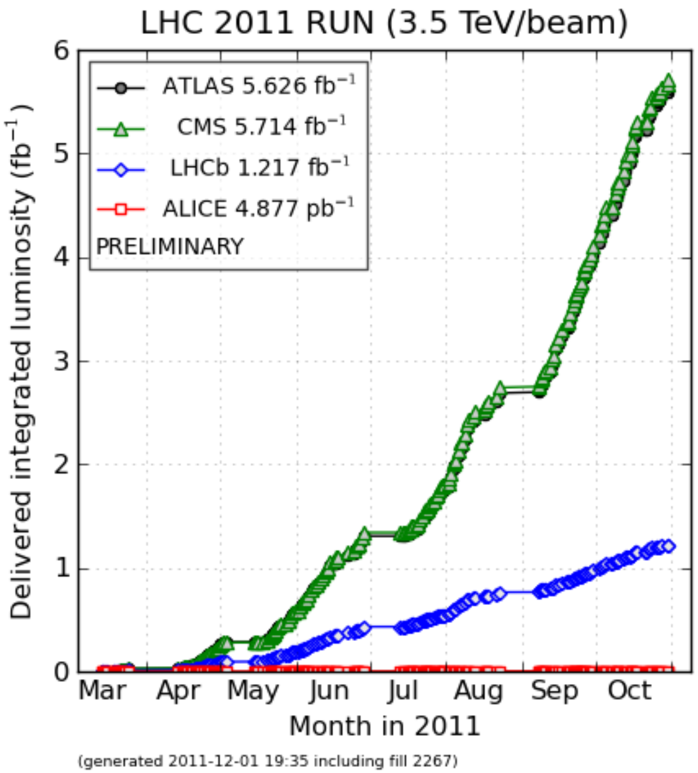




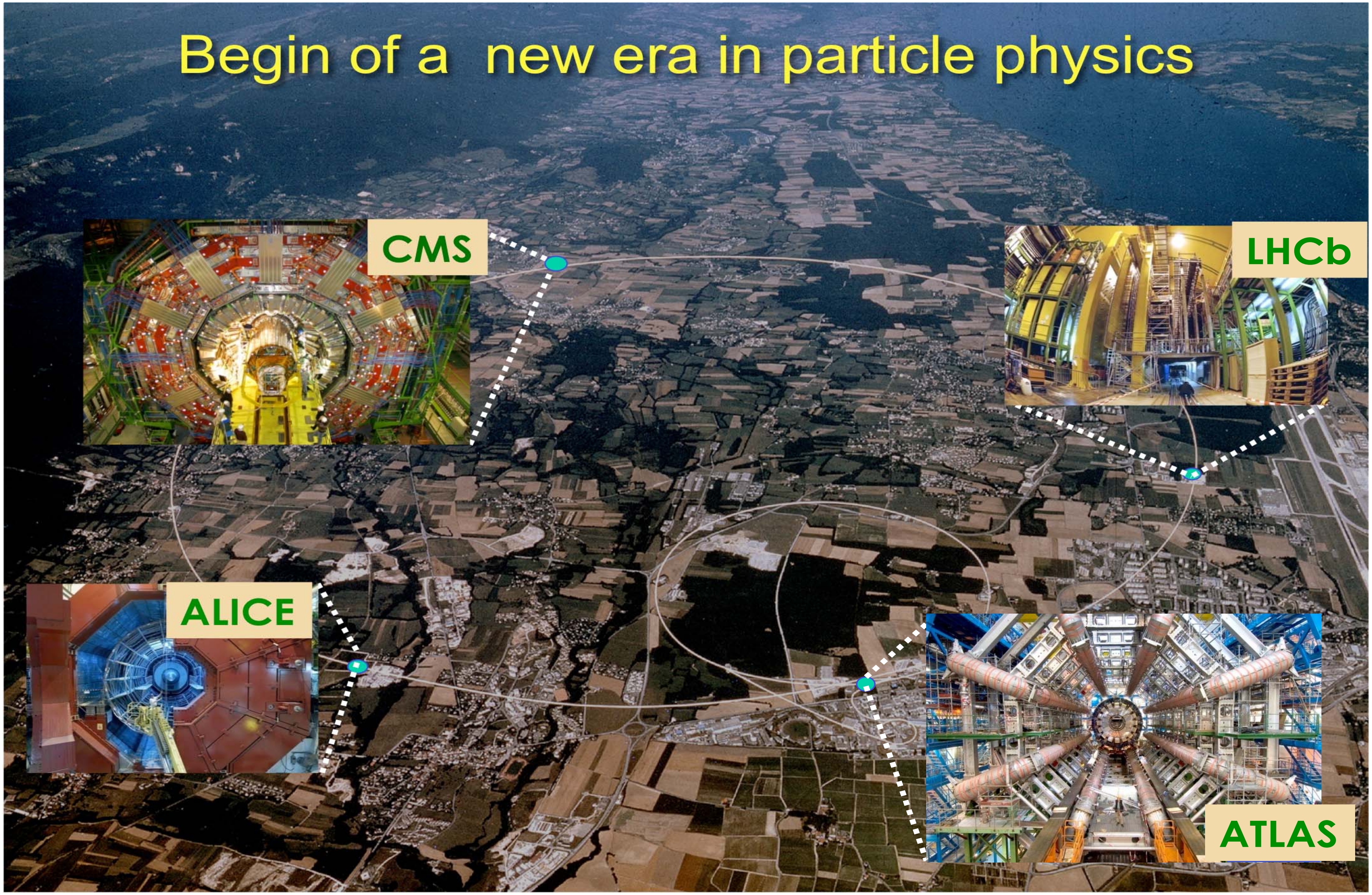
THE LARGE HADRON COLLIDER

- 27km circumference ring on French-Swiss border
- Provides proton-proton collider at 7 TeV center-of-mass-energy
- Data collected by four experiments : **CMS, ATLAS, LHCb, ALICE**

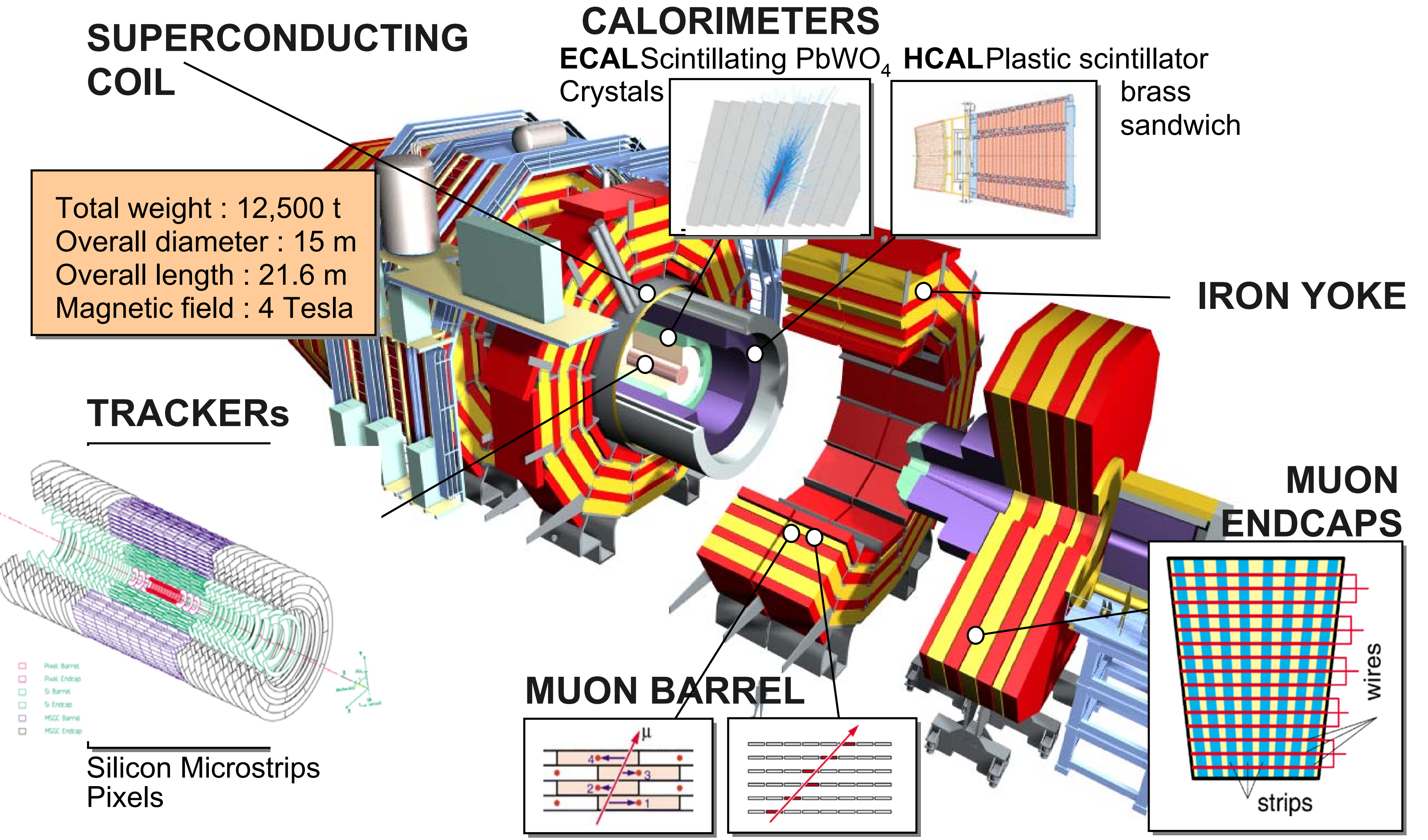




THE LARGE HADRON COLLIDER: Detectors



THE CMS EXPERIMENT: Design

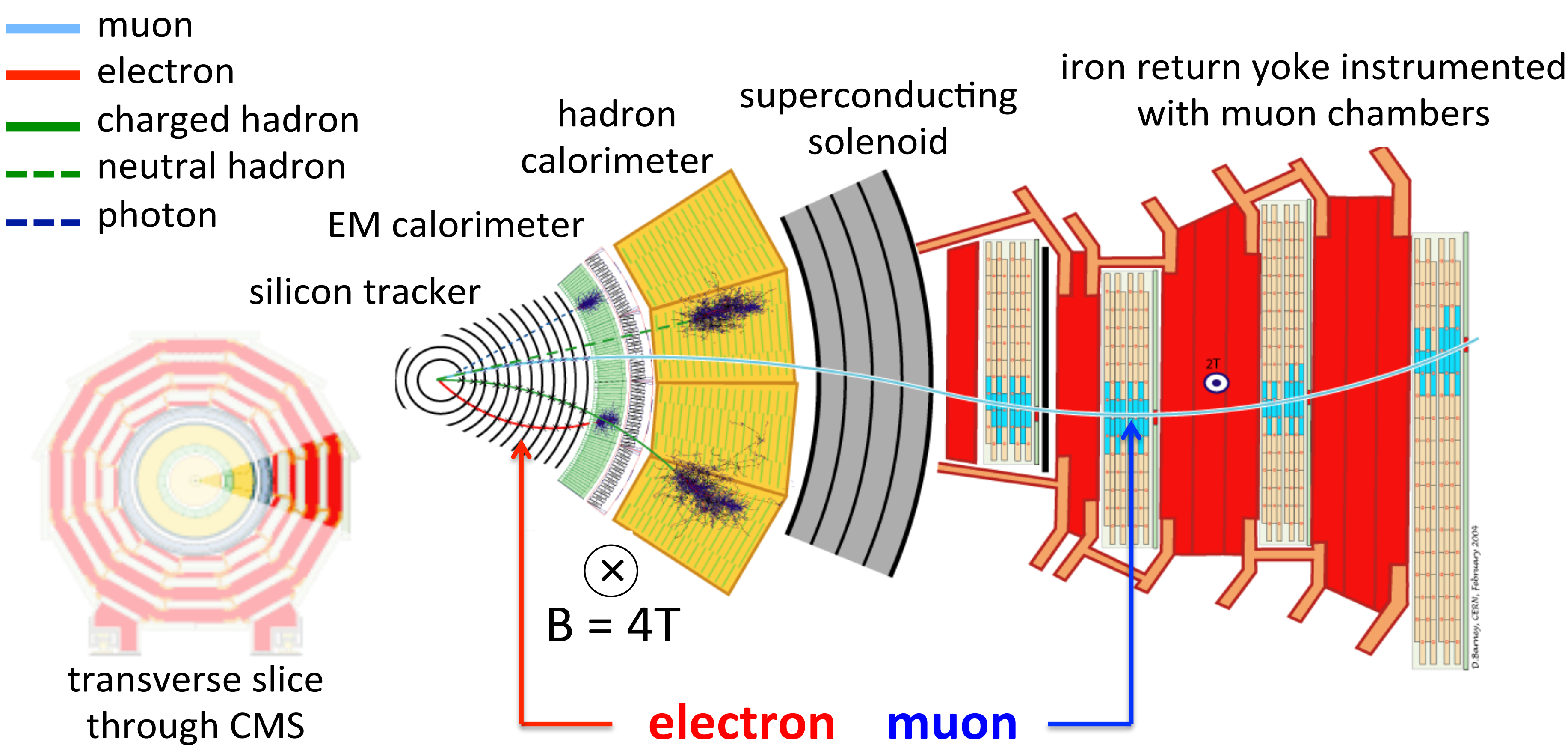


Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

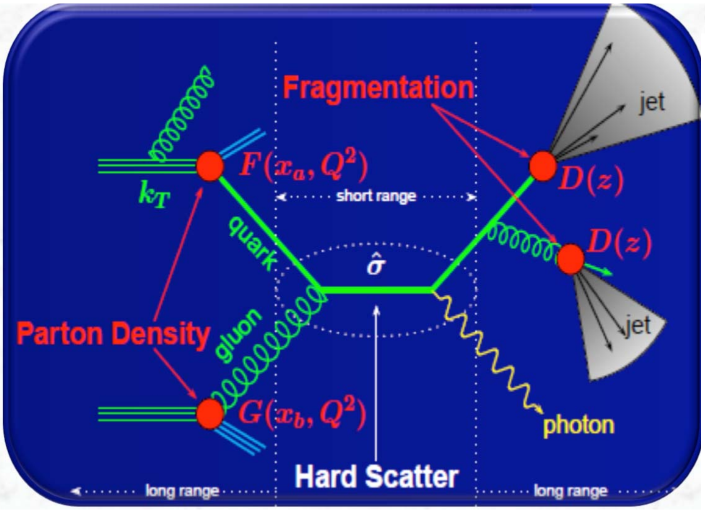
Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

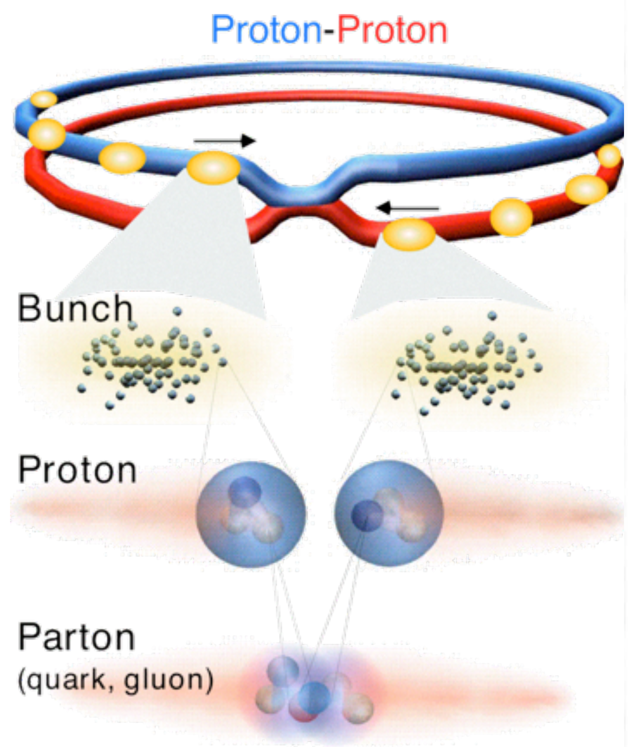
THE CMS EXPERIMENT AND LEPTON-ID

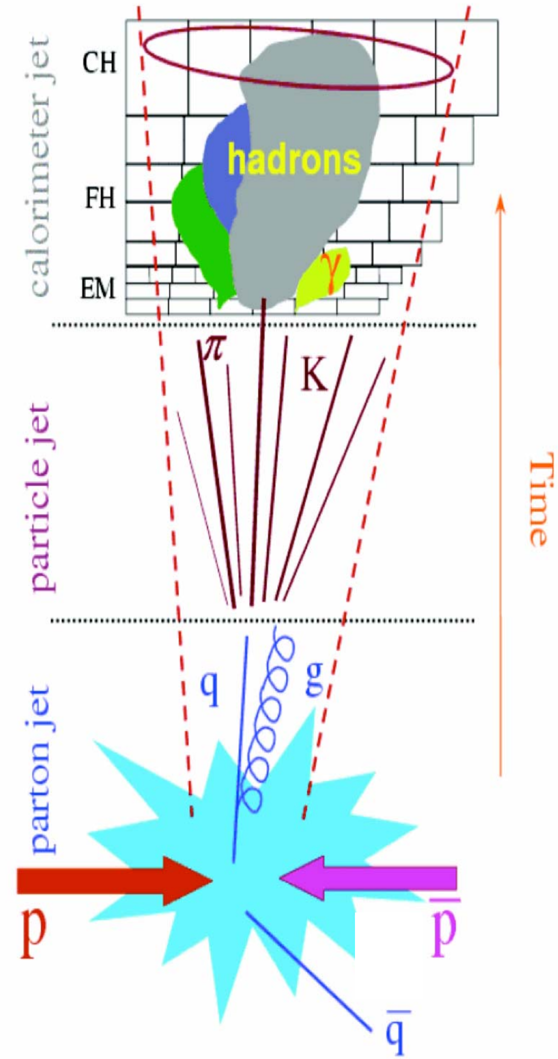


- Most particles are hadrons → electrons/muons very rare
- Electrons: electromagnetic shower in EM calorimeter → deposit full energy
- Muons: minimum ionizing → penetrate deeply into muon system

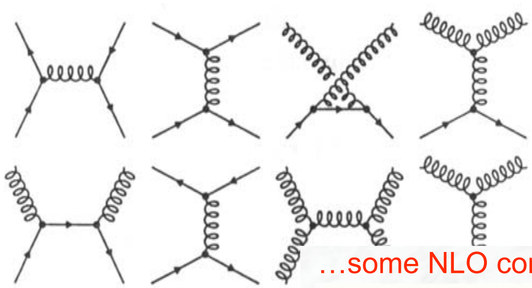
PHYSICS AT THE LHC



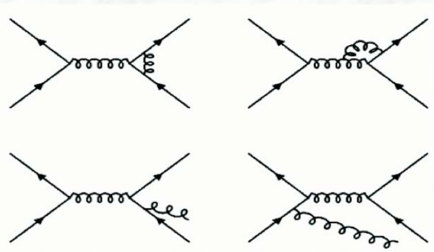


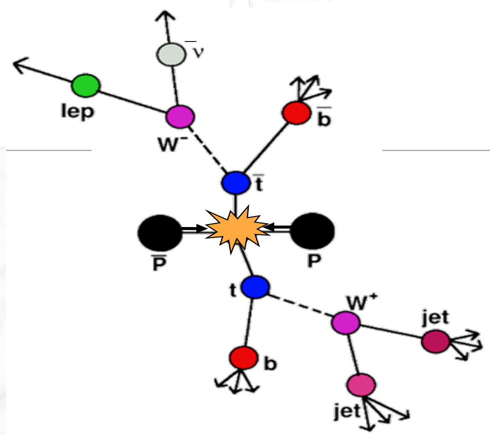


Leading order



…some NLO contributions

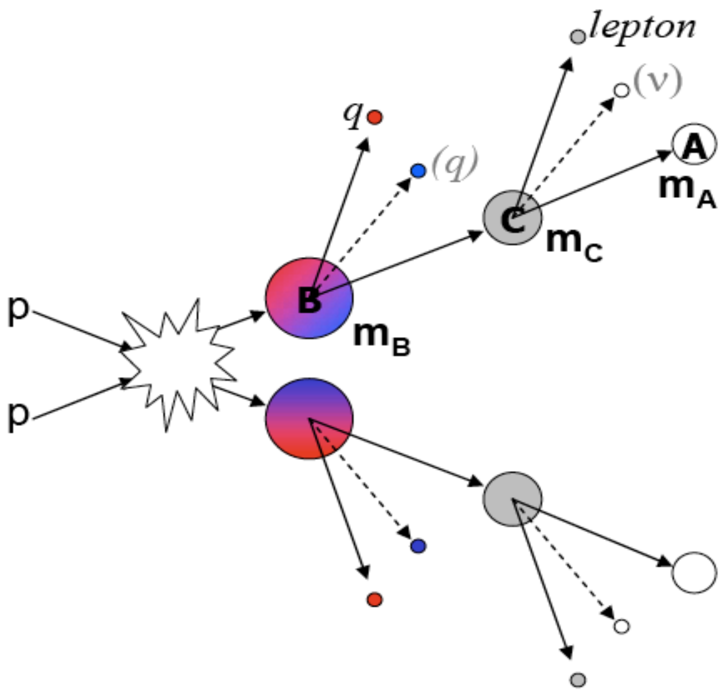




SUSY ANALYSES IN THE CMS COLLABORATION

- In the SUSY processes:
  - m_B drives the xsections
  - Δm_{bc} drives the hadronic scale
  - Δm_{ca} drives the leptonic p_T
  - A drives E^T_{miss}
- The experimental techniques:
  - Topology based searches,

  not optimized for any particular SUSY model
  - E^T_{miss} considered the basis for all the searches
  - Try to cover as much phase space as possible
    - Keep the p_T`s as low as possible?



- Estimate backgrounds from data (data-driven bkg estimate) ➞ minimize reliance on MC
  - Especially important for bkg's with detector (mis)reconstruction effects!

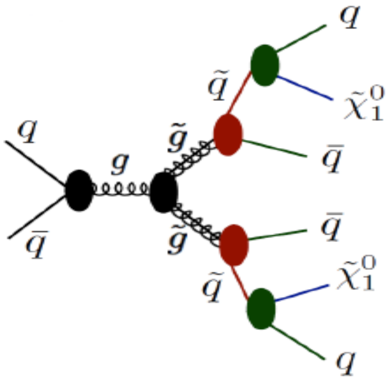
SUSY Searches in the CMS Collaboration

Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

HADRONIC SUSY SEARCHES

Jet+E^T_{miss} analyses:

- **Jets+E^T_{miss} inclusive:** inclusive search – relies on precise determination of all SM backgrounds with robust data-driven techniques
- **Razor:** uses kinematic variables to characterise SUSY pair- production
- **The kinematic variable α_T:** Reduces QCD background substantially
  - Consider R-Parity conserving SUSY
  - Strongly interacting *sparticles* dominate
  - Cascade decay of squarks/ gluinos stable LSP $(\tilde{\chi}_1^0)$
  - Leads to signature of **E^T_{miss}** and **Jets**



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  - ❑ Cascade decay of squarks/ gluinos stable LSP $(\tilde{\chi}^0_1)$
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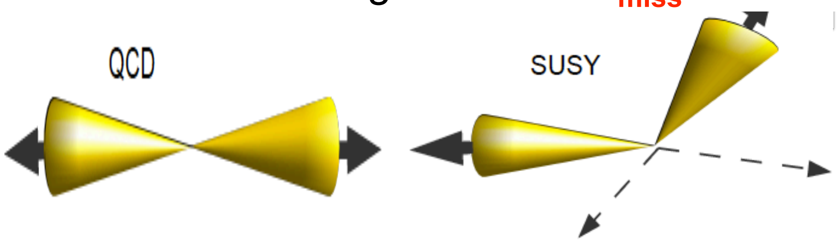
SUSY-PAS-11-003

SUSY Low Mass (LM) Benchmark Points

m0: unified scalar mass
m1/2: unified gaugino mass
A0: trilinear soft couplings
tanβ: $\langle H^0_2\rangle / \langle H^0_1\rangle$, sign μ parameter

LM4: 210, 285, 0, 10, + / 1.879pb (K_{NLO}=1.35)
LM6: 85, 400, 0, 10, + / 0.3104pb (K_{NLO}=1.3)

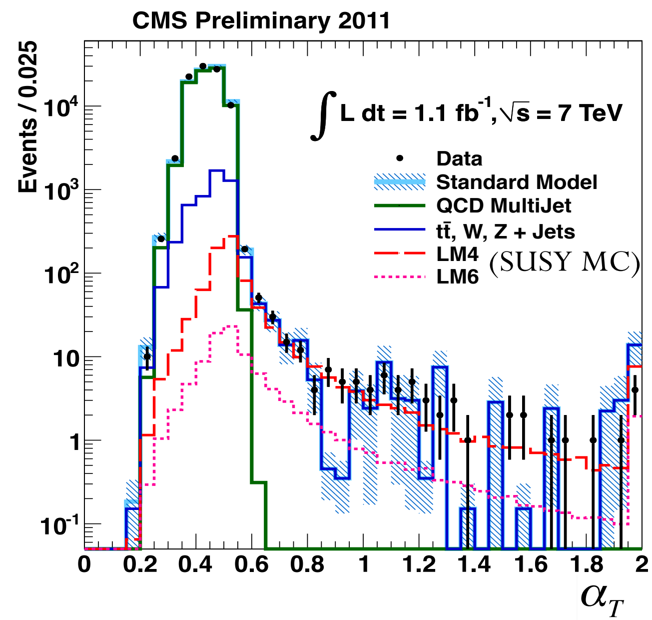


Effective QCD reduction by using kinematic variable:

$$\alpha_T = \sqrt{\frac{p_{T,j_2}/p_{T,j_1}}{2(1-\cos\Delta\phi)}}$$

QCD : $\cos\Delta\Phi \approx -1$, $\alpha_T \leq 0.5$

Processes with genuine Missing Transverse Energy: $\alpha_T > 0.5$



Jets+E^T_{miss} analysis with the kinematic variable α_T : Background estimation

SUSY-PAS-11-003

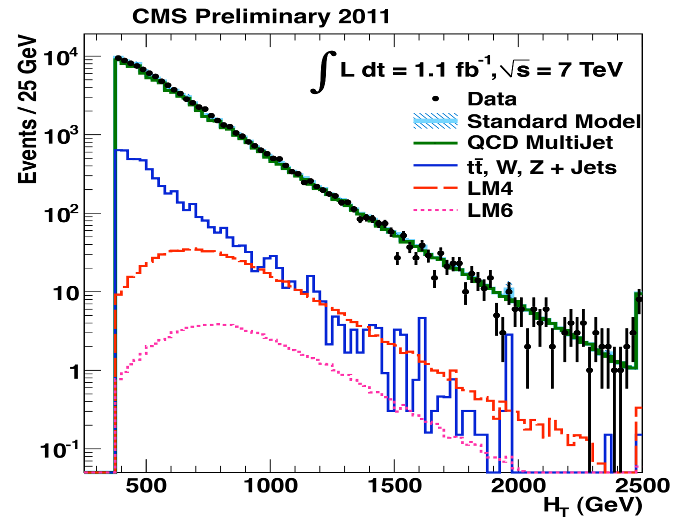
✓ The comparisons between data and MC simulation for the H_T variable and the number of reconstructed jets per event, **before the requirement on α_T.**

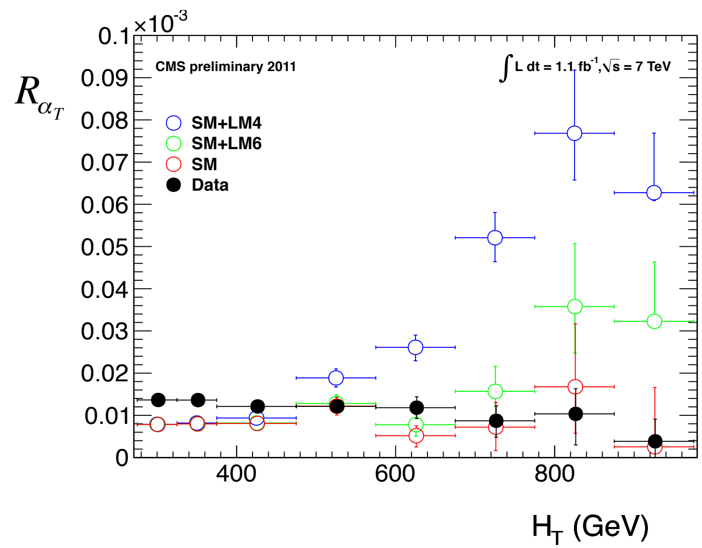
✓ The ratio **$R\alpha_T$** exhibits **no dependence on HT** if **0.55** is chosen such that the numerator of the ratio in all H_T bins is dominated by tt, W +jets and Z → νν+jets events

$$R_{\alpha_T} = \frac{\alpha_T > 0.55}{\alpha_T < 0.55}$$

- Electroweak backgrounds: real E^T_{miss} – flat $R_{\alpha T}$
- QCD – there is no significant contribution from events from QCD
- Data – ratio consistent with SM background predictions

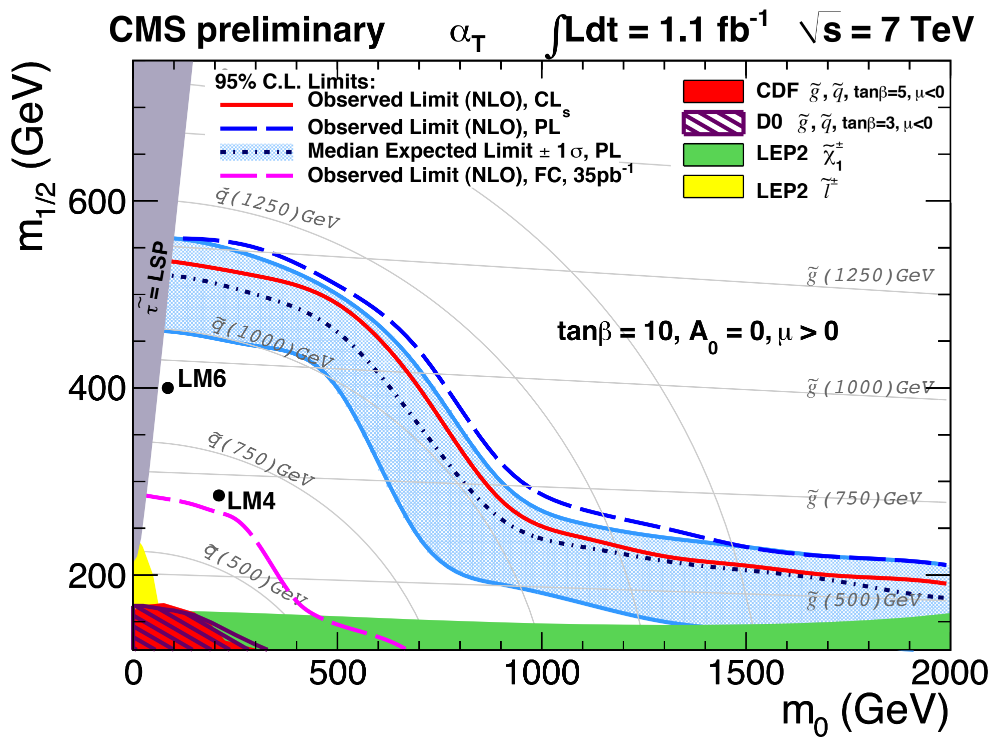
Use data-driven techniques to estimate W, top, from W -> *lv*, Z background from Gamma +Jets





Jets+E^T_{miss} analysis with the kinematic variable α_T : Interpretation of Physics Results 2011

SUSY-PAS-11-003



H_T Bin (GeV)	275–325	325–375	375–475	475–575
W + $t\bar{t}$ background	363.7	152.2	88.9	28.8
$Z \to \nu\bar{\nu}$ background	251.4	103.1	86.4	26.6
QCD background	172.4	55.1	26.9	5.0
Total Background	787.4	310.4	202.1	60.4
Data	782	321	196	62

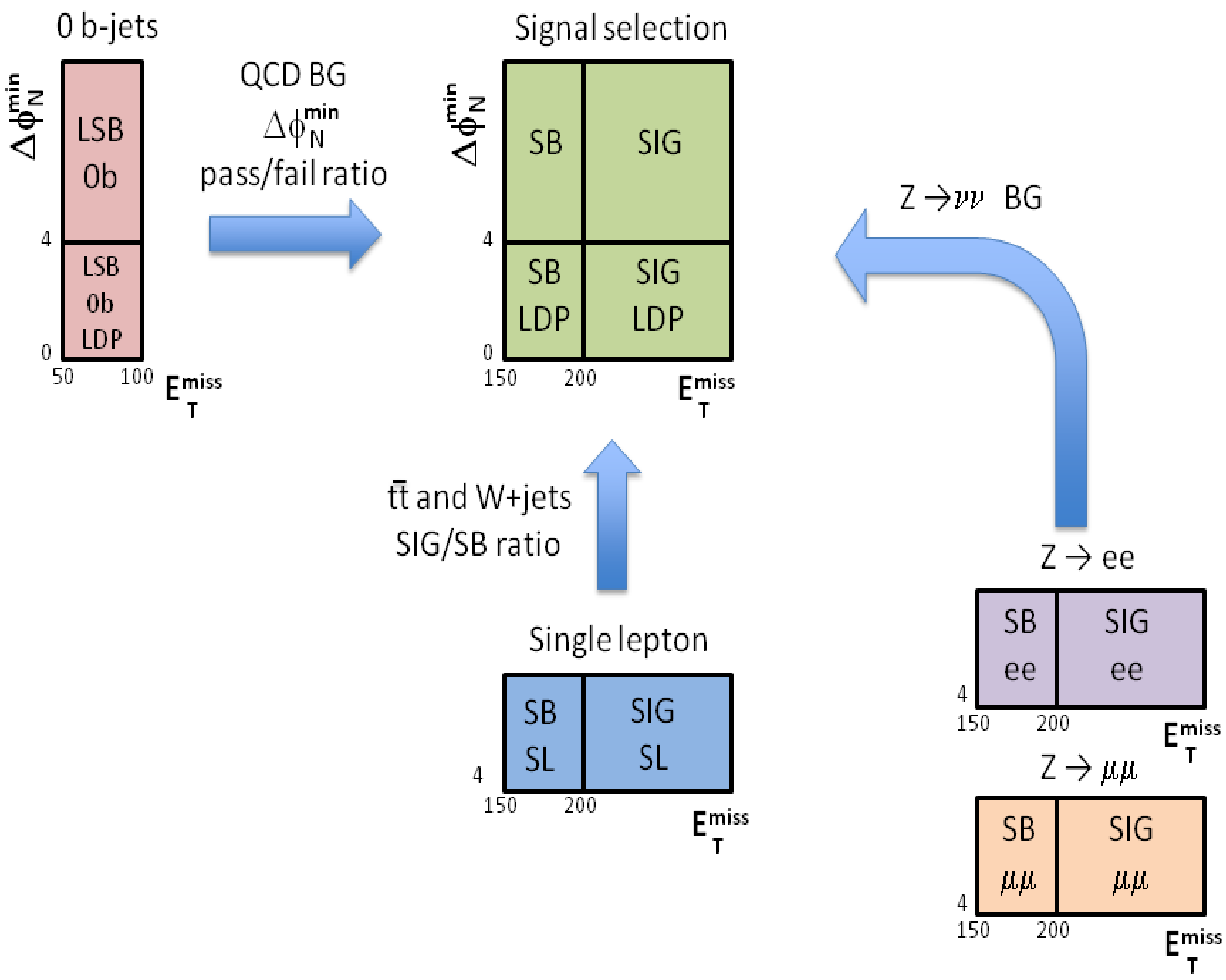
H_T Bin (GeV)	575–675	675–775	775–875	875–∞
W + $t\bar{t}$ background	10.6	3.1	0.6	0.6
$Z \to \nu\bar{\nu}$ background	8.7	4.3	2.5	2.2
QCD background	1.0	0.2	0.1	0.0
Total Background	20.3	7.7	3.2	2.9
Data	21	6	3	1

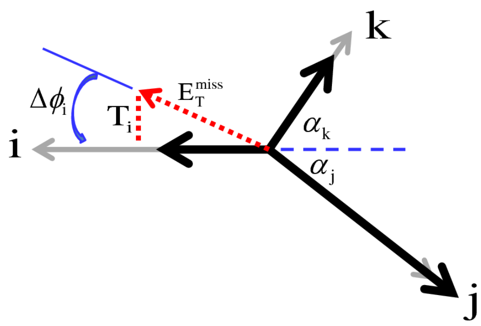
No evidence, unfortunately, for SUSY in the hadronic channel yet, Up to 1.1fb-1 has been analyzed.

Jets+E^T_{miss} analysis with b-quark Jets

SUSY-PAS-11-006

Schematic diagram indicating the various event samples used for background evaluvation





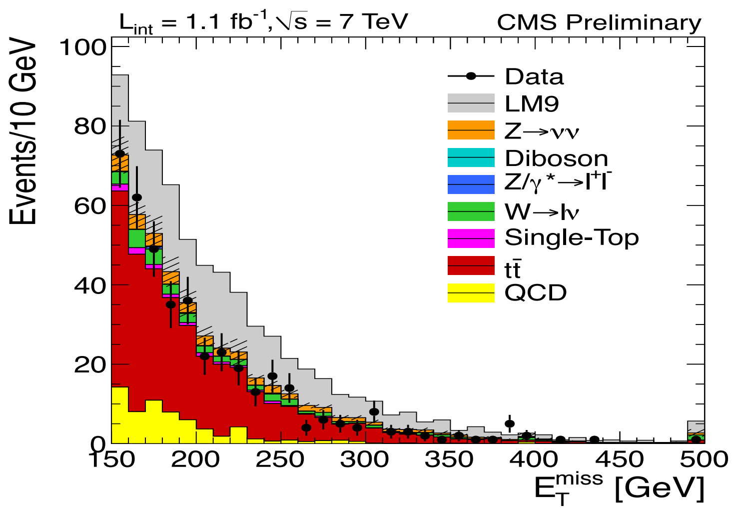
SIG: Signal Regions

SB: Side Band

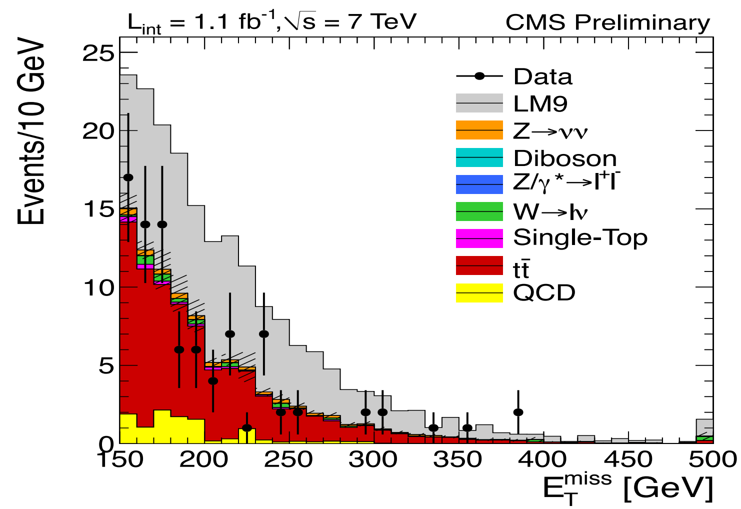
LSB: Low Side Band

LDP: Low Delta Phi

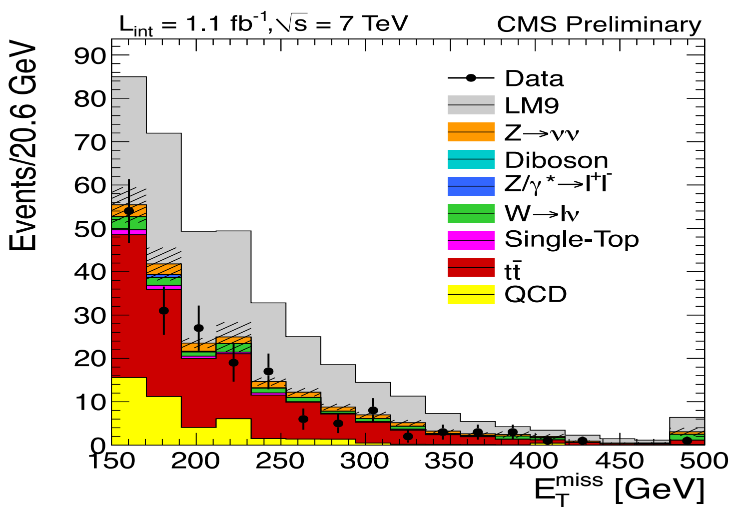
Jets+E^T_{miss} analysis with b-quark Jets



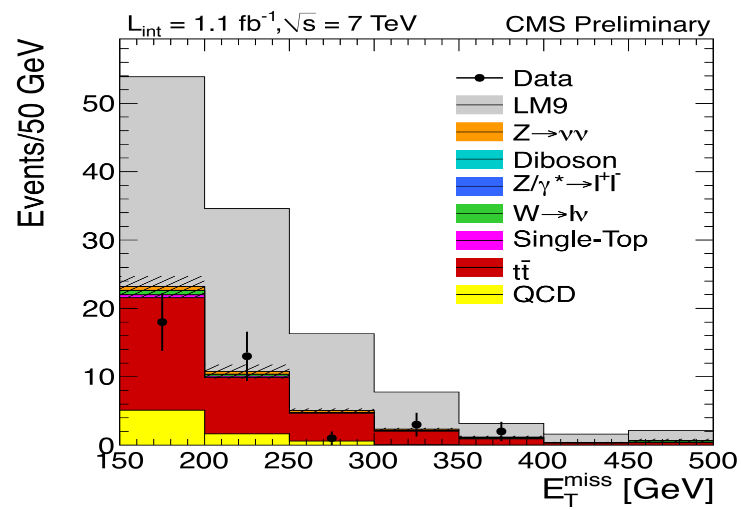
(a)



(b)



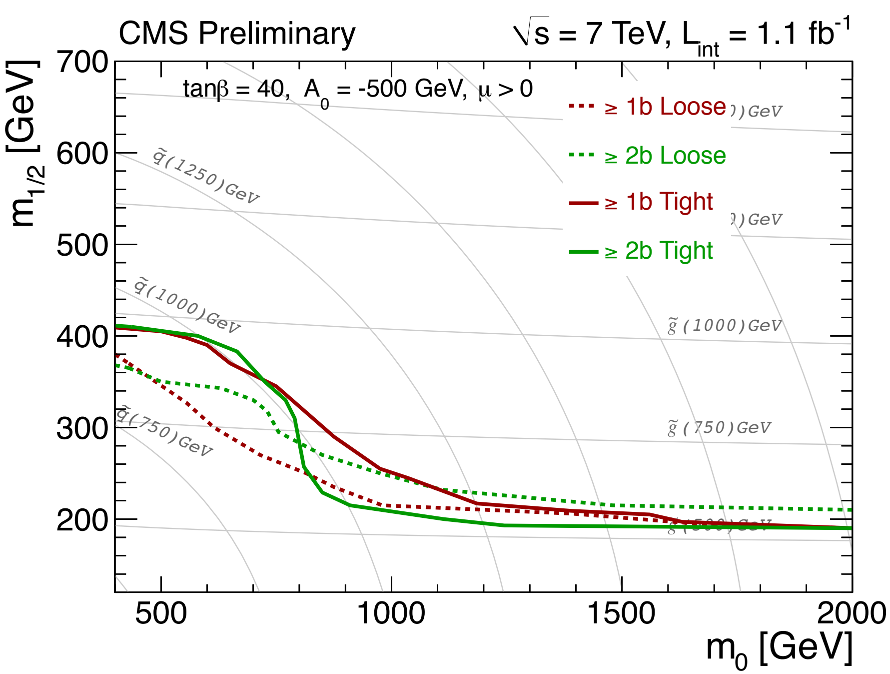
(c)

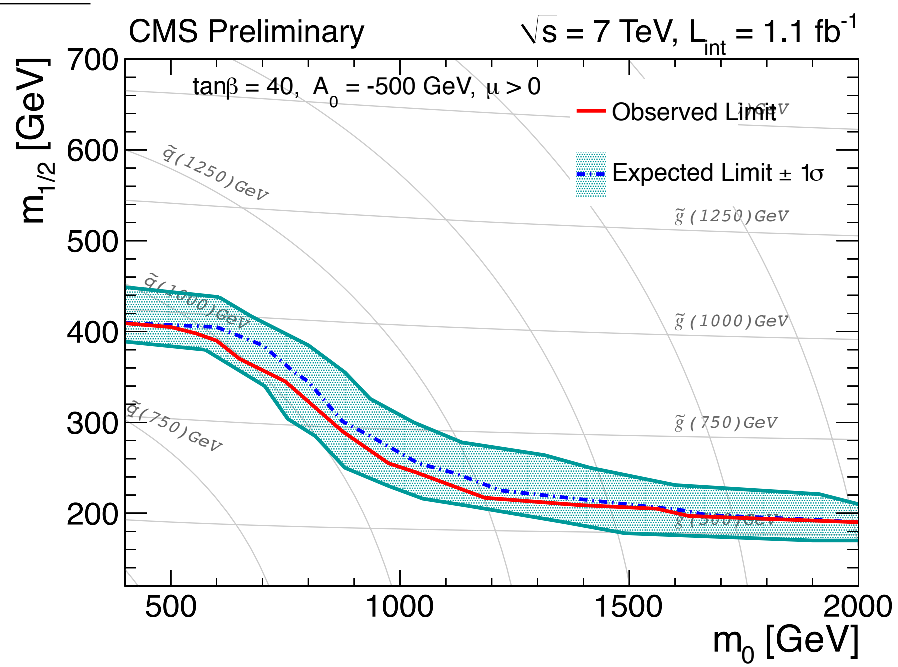


(d)

Jets+E^T_{miss} analysis with b-quark Jets: Summary

	Loose search region		Tight search region	
	≥ 1 b	≥ 2 b	≥ 1 b	≥ 2 b
QCD	$9.7^{+10.1}_{-8.4}$	$0.0^{+3.7}_{-0.0}$	$0.2^{+0.8}_{-0.2}$	$0.1^{+0.6}_{-0.1}$
top and W+jets	115 ± 15	24.5 ± 5.5	$13.9^{+4.6}_{-4.3}$	$5.0^{+2.4}_{-1.9}$
$Z \to \nu\overline{\nu}$	29^{+14}_{-11}	$5.2^{+4.6}_{-2.9}$	$5.3^{+3.6}_{-2.7}$	$0.6^{+0.9}_{-0.6}$
Total SM (LH)	152.8	29.7	19.5	5.7
Data	155	30	20	5
LM9 95% CL upper limit	91	21	20	7.3
LM9 MC	145	58	27	9.3





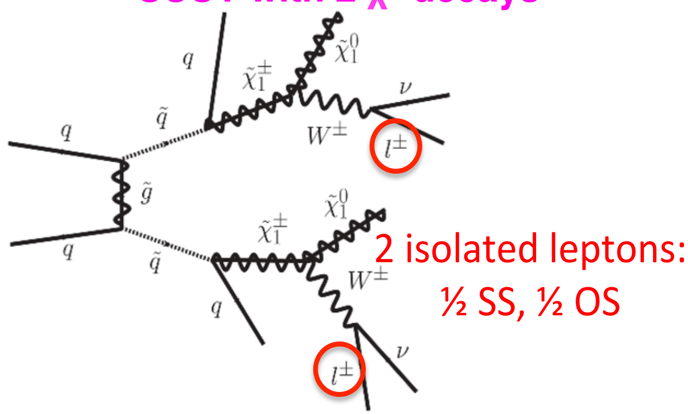
LEPTONIC SUSY SEARCHES

SUSY-PAS-11-010

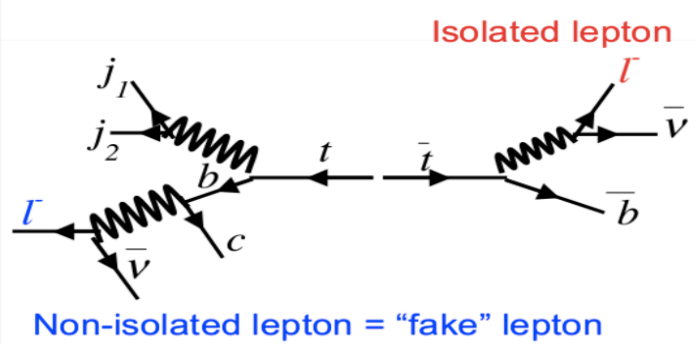
Jets+Lepton(s) +E^T_{miss} analysis: Same-Sign Di-Lepton Search (2011, L = 0.98 fb^{-1})

- Same-Sign pairs extremely rare in SM, but appear naturally in many Beyond the Standard Model (BSM) scenarios.
  - **SUSY**, Universal Extra Dimensions, SS top pair production, Heavy Majorana neutrinos.
- Dominant SM backgrounds:
  - **ttbar with "fake" leptons (b/c <-> e/μ)** → **fake ratio / isolation extrapolation**
  - **Charge mis-reconstruction** → **use Z`s for charge**
  - (both of the above:) **From Data**
  - **Rare SM processes: qq →q'q'$W^{+/-}W^{+/-}$, ttW** → **estimate from MC**

example signal:
SUSY with 2 $\chi^{\pm}$ decays



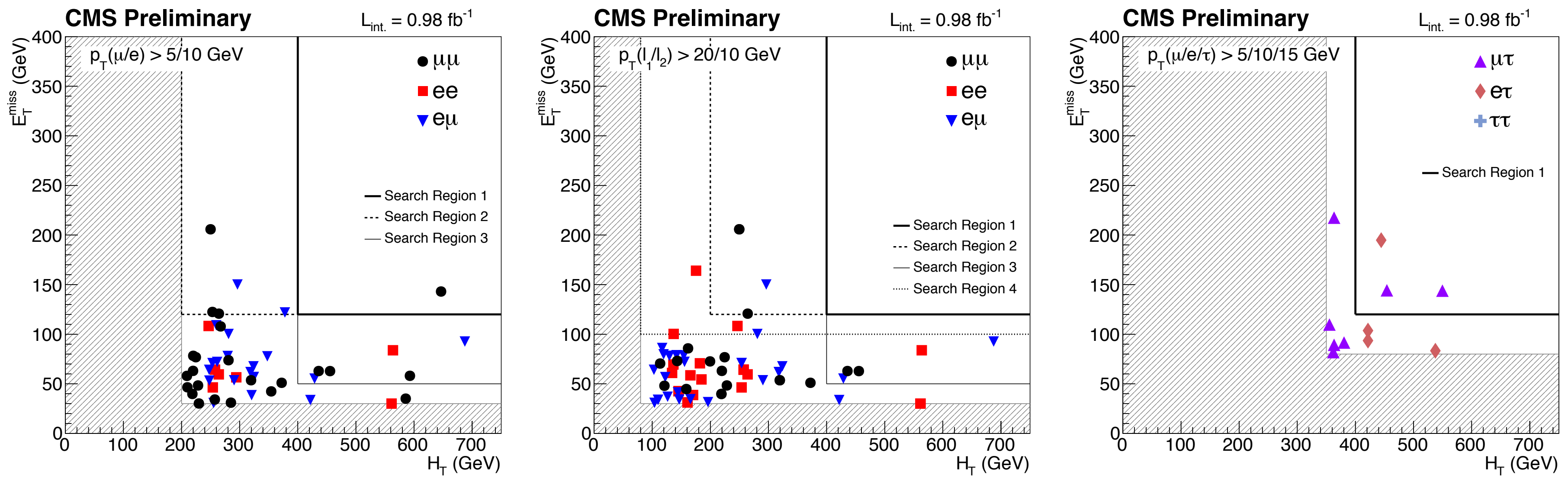
dominant background:
tt with fake lepton



Same-Sign Di-Lepton Search: Search Regions

SUSY-PAS-11-010

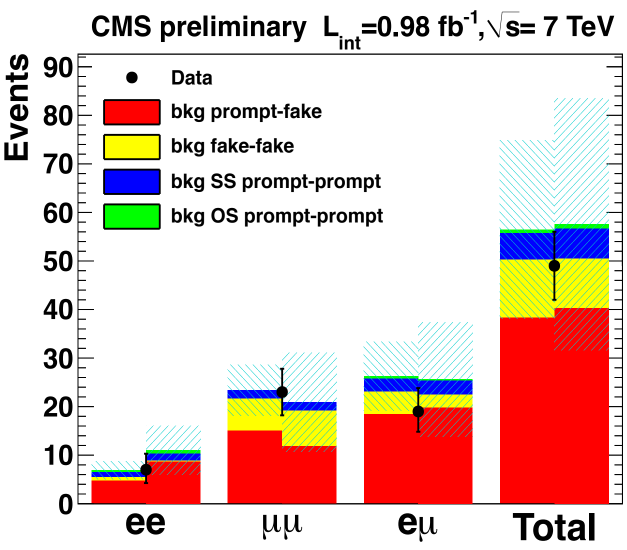
- Search for new physics in three complementary samples
  - **High-p_T leptons:** search for **high lepton p_T**
  - **Inclusive leptons:** extend search to **low lepton p_T** → compensate trigger rate by increasing **H_T** cut
  - **Tau – hadrons:** improve sensitivity to 3rd generation
- Define pre-selection regions in E^T_{miss} - H_T plane (veto shaded regions)
  - Validate data-driven background estimates with ~10-100 events
- Define search regions by adding E^T_{miss}, H_T requirements ->Data Driven techniques



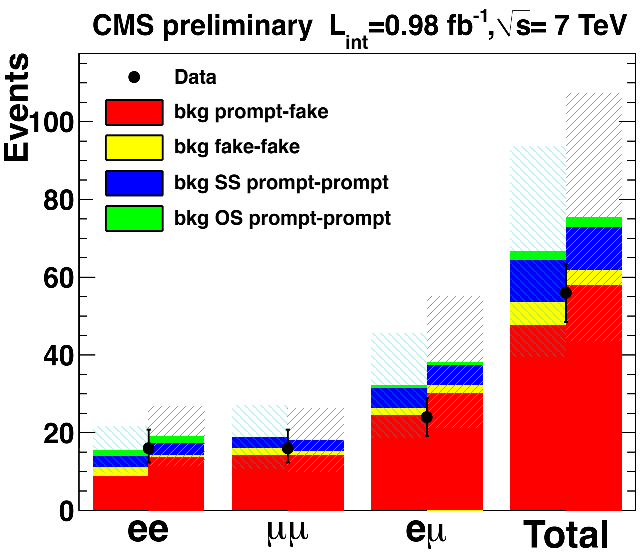
Same-Sign Di-Lepton Search: Results for 2011

SUSY-PAS-11-010

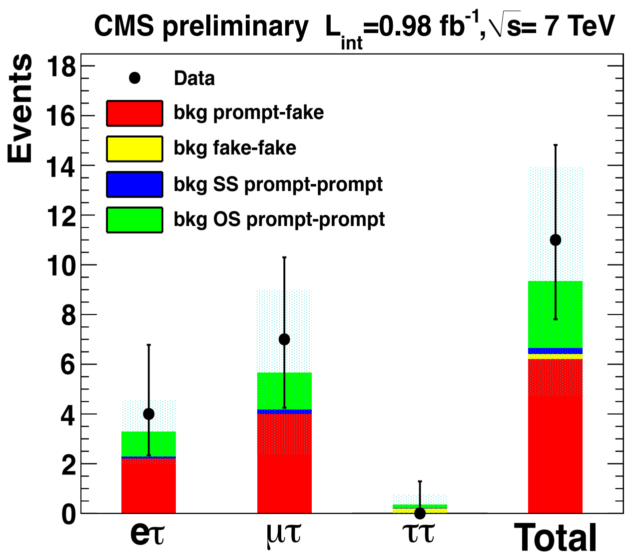
- Search regions: good agreement between observed yields and predicted background.



Inclusive selections



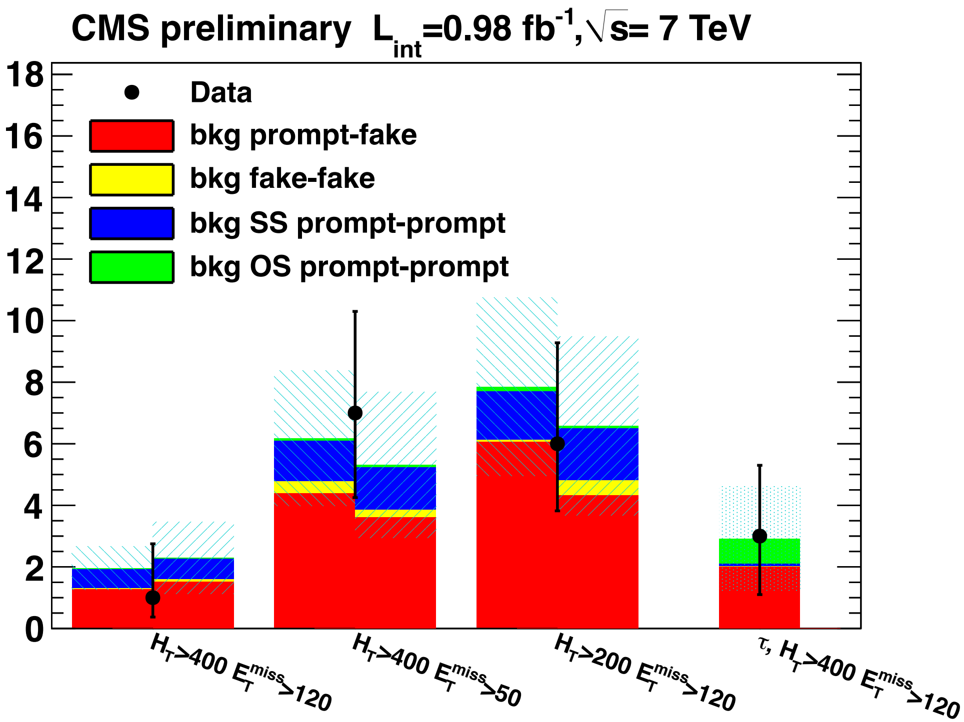
High-p_T selections



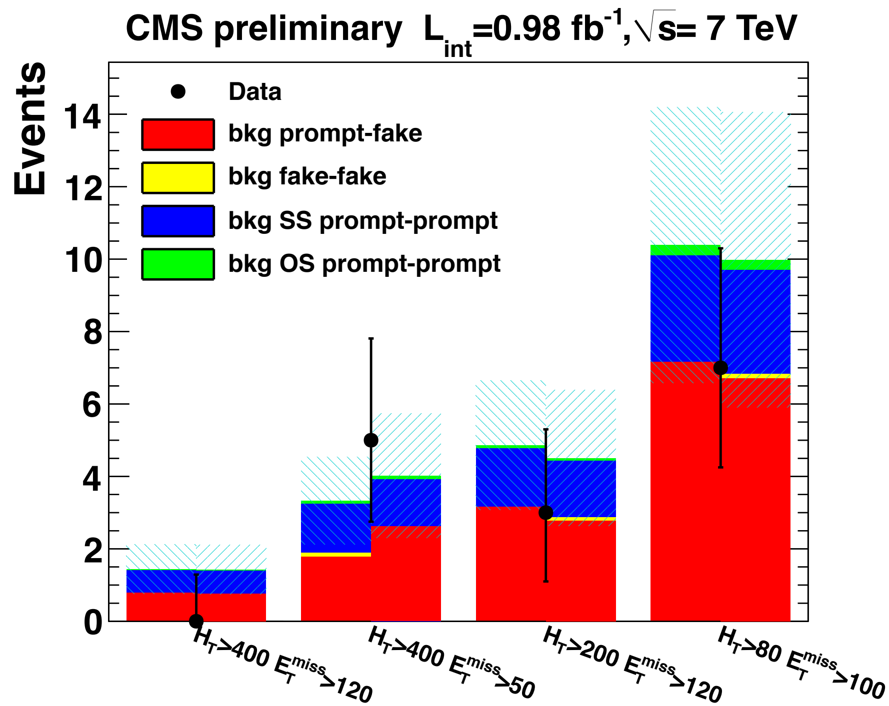
τ-dilepton selections

Same-Sign Di-Lepton Search: Results for 2011

SUSY-PAS-11-010



Inclusive & тau-dilepton selections



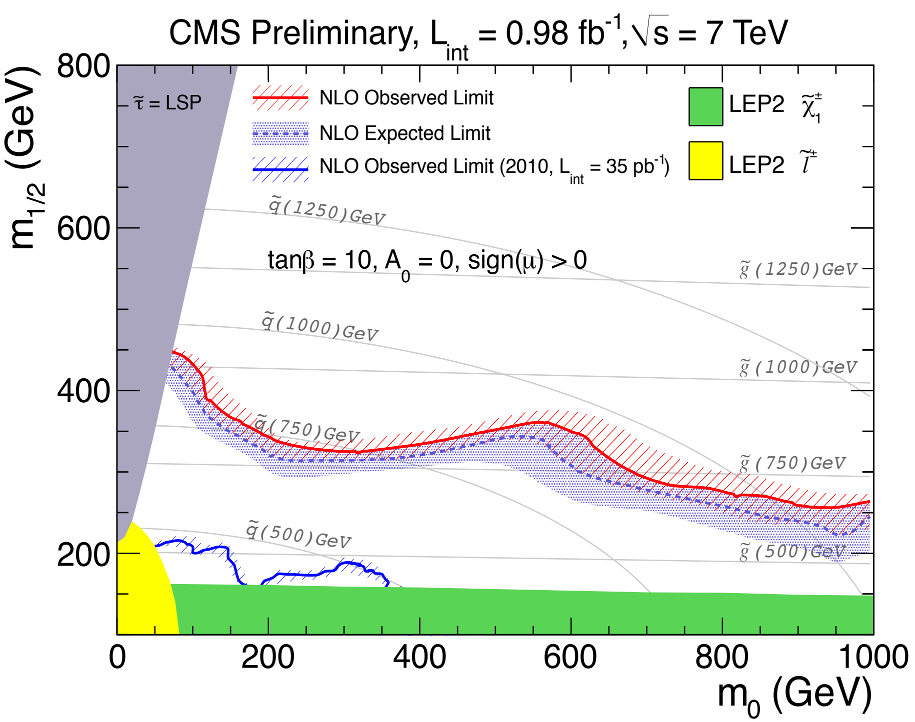
High-p_T selections

Predictions for events with one and two fakes, contributions from simulated backgrounds, and those from events with a lepton charge misreconstruction are shown separately.

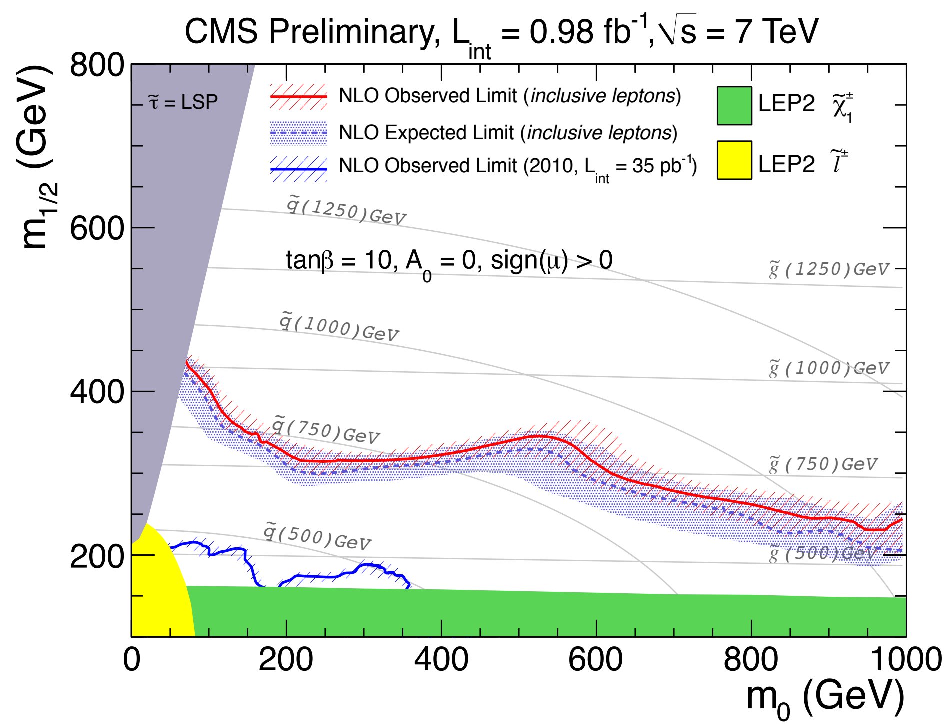
SS - Di-Lepton Search: Interpretation of Results 2011

SUSY-PAS-11-010

Exclusion region in the CMSSM corresponding to the observed upper limit events



High-p_T selections



Inclusive di-lepton selections

LEPTONIC SUSY SEARCHES

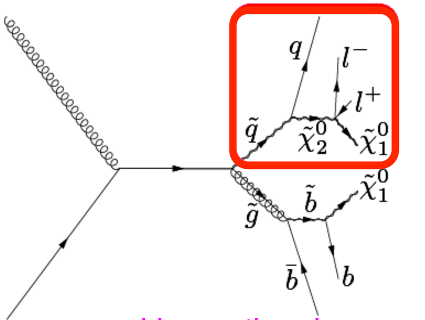
SUSY-PAS-11-011

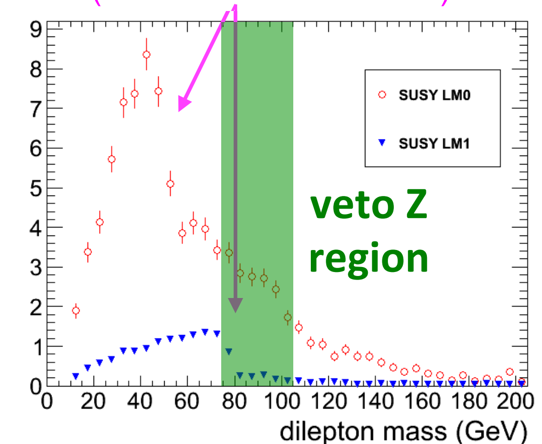
Jets+Lepton(s) +E^T_{miss} analysis: Opposite-Sign Di-Lepton Search (2011, L = 0.98 fb^{-1})

- Signature: Opposite-Sign (OS) leptons + ≥2 jets + E^t_{miss}
  - Dominant background: tt → di-lepton
- Perform pre-selection to reject non-tt backgrounds
  - ≥2 isolated leptons: (e or μ) p_T > (20,10) GeV
  - Reject same-flavor pairs consistent with Z-mass
  - ≥2jets (pT >30GeV, |η|<3.0), H_T >100GeV, E^T_{miss} > 50 GeV
- Pre-selection region results
  - Background is > 90% tt (from MC)
  - Reasonable Data/MC agreement in yields, kinematic distributions

Neutralino decays

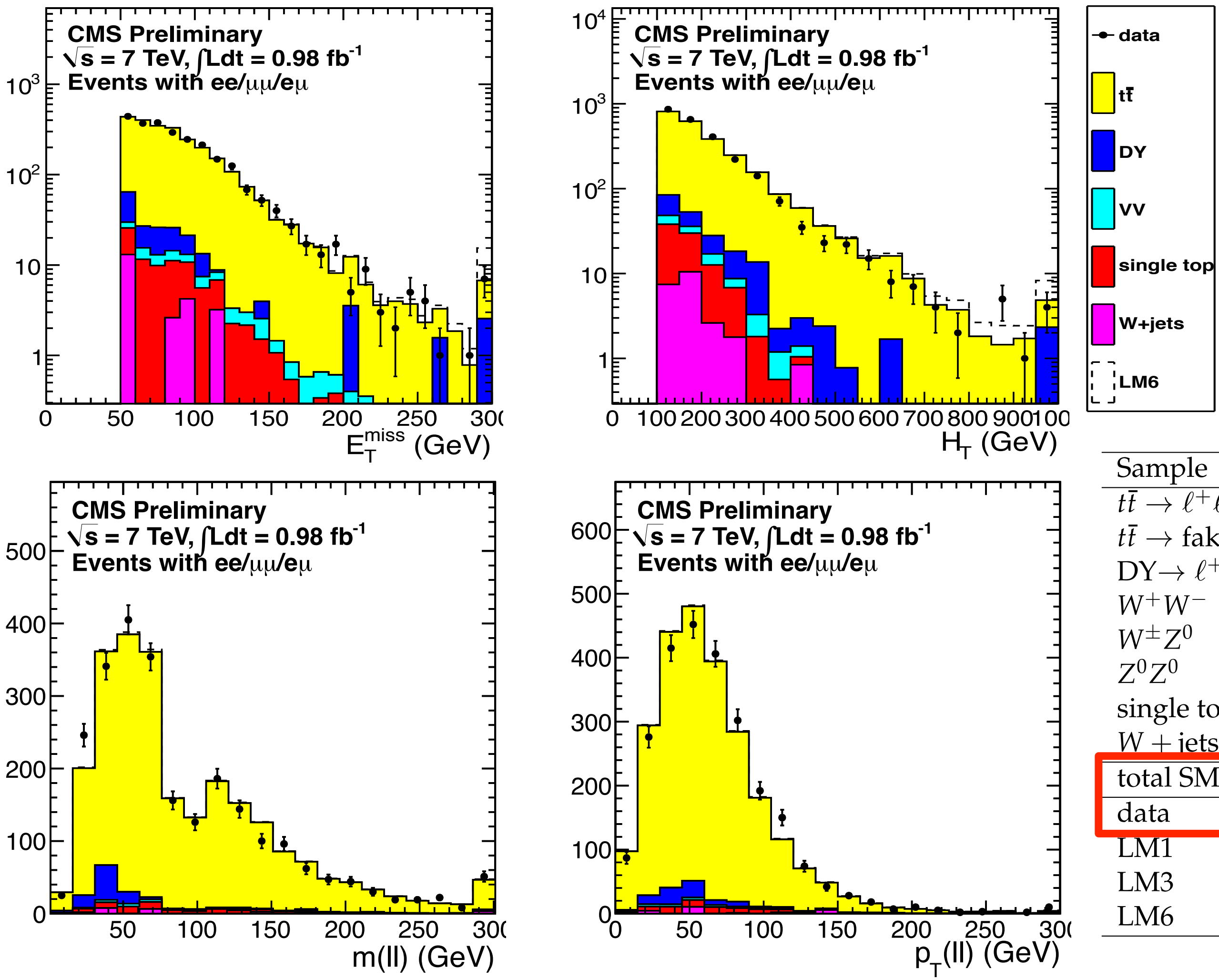
$$\chi_2^0 \rightarrow \chi_1^0 \ell^+ \ell^-$$





Opposite-Sign Di-Lepton Search: Results for 2011

SUSY-PAS-11-011



- ❑ Pre-selection region results
  - ❑ Background is > 90% tt (from MC)
  - ❑ Reasonable Data/MC agreement in yields, kinematic distributions

Sample	σ [pb]	total
$t\bar{t} \to \ell^+\ell^-$	17	1973.8 ± 19.0
$t\bar{t} \to$ fake	141	39.0 ± 2.7
DY$\to \ell^+\ell^-$	16677	82.8 ± 10.6
W^+W^-	43	17.7 ± 0.9
$W^\pm Z^0$	18	3.8 ± 0.2
Z^0Z^0	5.9	1.2 ± 0.1
single top	102	59.9 ± 1.3
$W+$jets	96648	20.5 ± 7.1
total SM MC		2198.5 ± 23.1
data		2481
LM1	6.7	167.5 ± 2.6
LM3	5.3	88.6 ± 1.7
LM6	0.5	15.3 ± 0.2

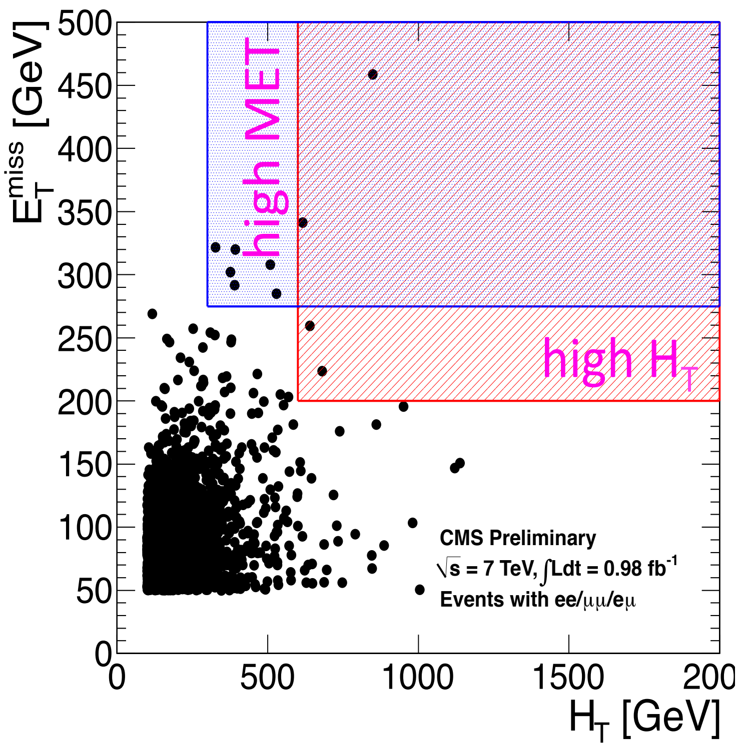
Opposite-Sign Di-Lepton Search: Search Regions

SUSY-PAS-11-011

	high E_T^{miss} signal region	high H_T signal region
observed yield	8	4
MC prediction	7.3 ± 2.2	7.1 ± 2.2
ABCD′ prediction	4.0 ± 1.0 (stat) ± 0.8 (syst)	4.5 ± 1.6 (stat) ± 0.9 (syst)
$p_T(\ell\ell)$ prediction	14.3 ± 6.3 (stat) ± 5.3 (syst)	10.1 ± 4.2 (stat) ± 3.5 (syst)
N_{bkg}	4.2 ± 1.3	5.1 ± 1.7
non-SM yield UL	10	5.3
LM1	49 ± 11	38 ± 12
LM3	18 ± 5.0	19 ± 6.2
LM6	8.1 ± 1.0	7.4 ± 1.2

$E^t_{miss} > 275$ GeV
$H_T > 300$ GeV

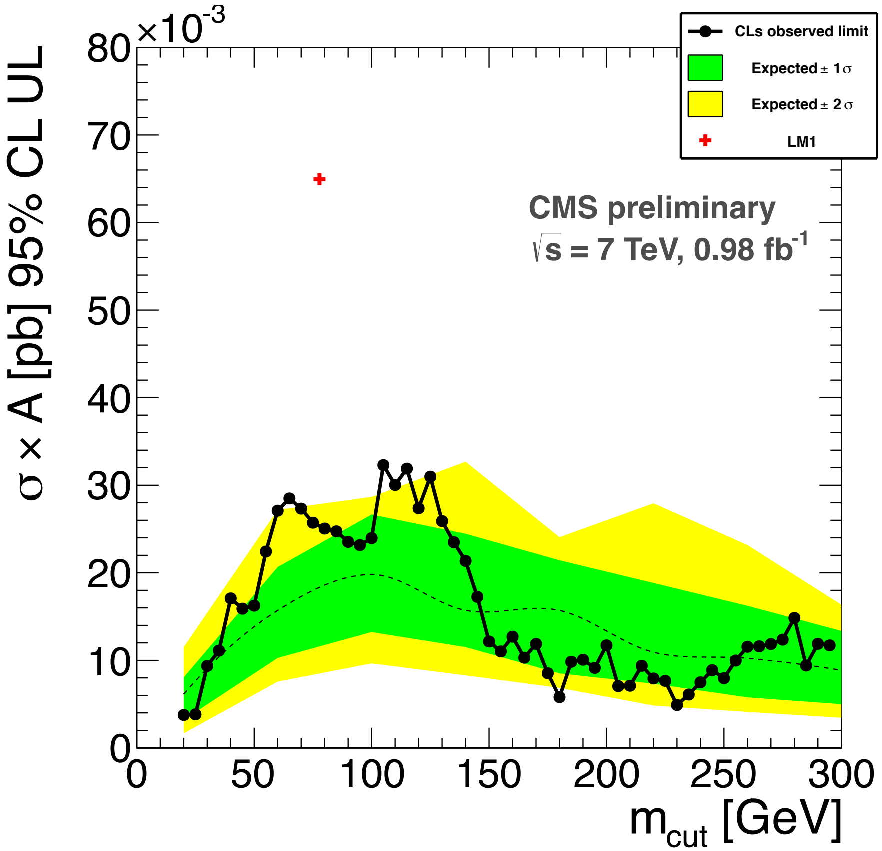
$E^t_{miss} > 200$ GeV
$H_T > 600$ GeV

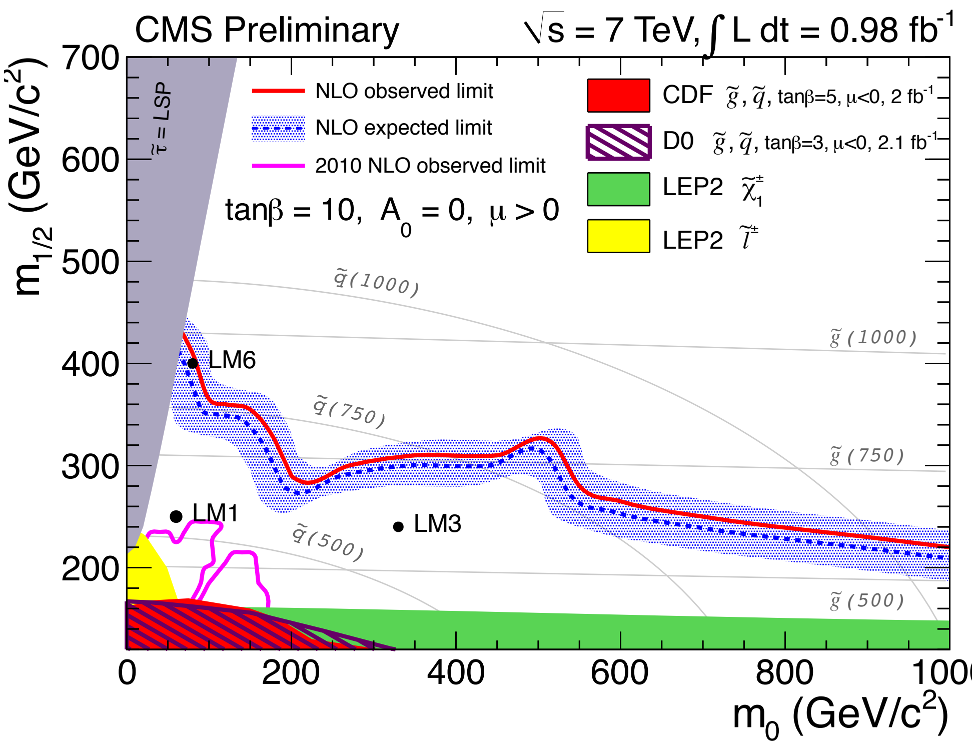


- Estimate background in signal regions with two data-driven techniques:
  - Factorization (ABCD) method using 2 weakly correlated variables: $y = E^T_{miss}/\sqrt{(H_T)}$
  - p_T(ll): use p_T(ll) to model $p_T(\nu\nu) \sim E^T_{miss}$
  - N_{bckg} : error-weighted average of 2 predictions
- Observed yields consistent with MC, data-driven background estimates → **no evidence for SUSY**
- **Extract 95% CL upper limits on non-SUSY yields**

OS - Di-Lepton Search: Interpretation of Results 2011

SUSY-PAS-11-011





Invariant mass spectrum assuming tri-angular shaped signal

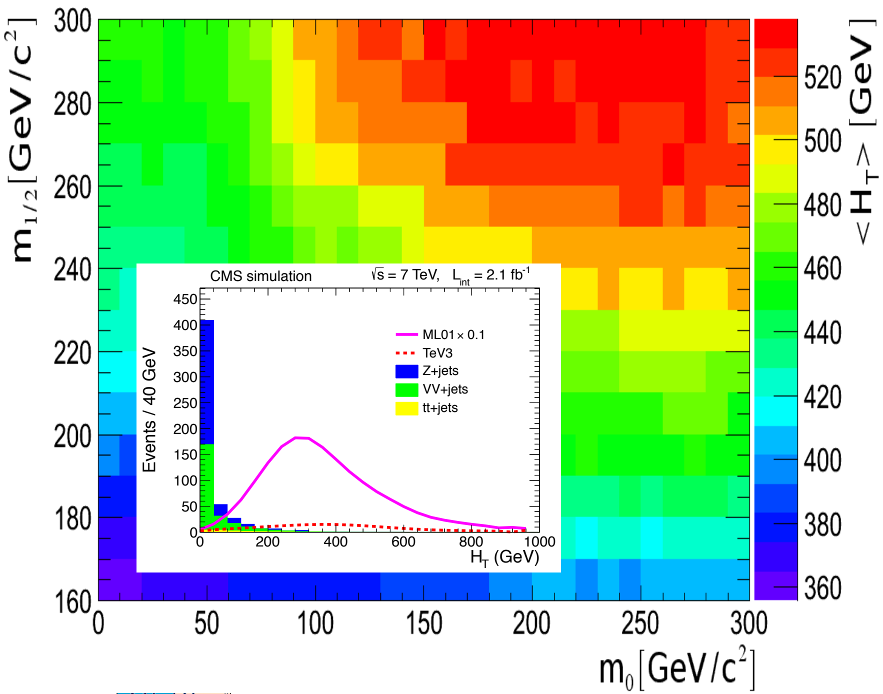
SUSY-PAS-11-013

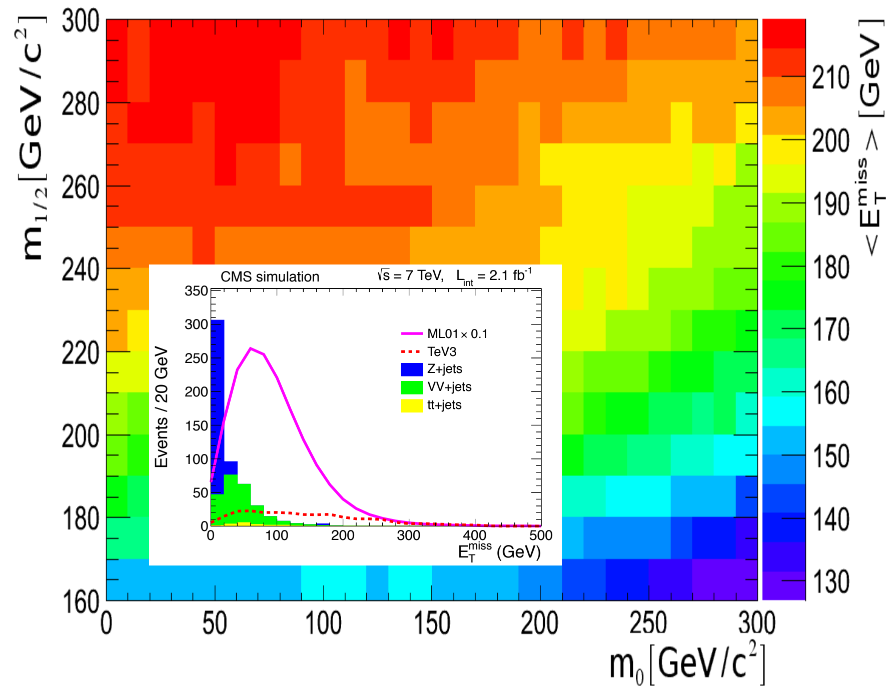
Jets+Lepton(s): Multi-Lepton Search (2011, L = 2.1 fb^{-1})

Candidate events in this search must have at least three leptons, of which at least one must be an electron or a muon.

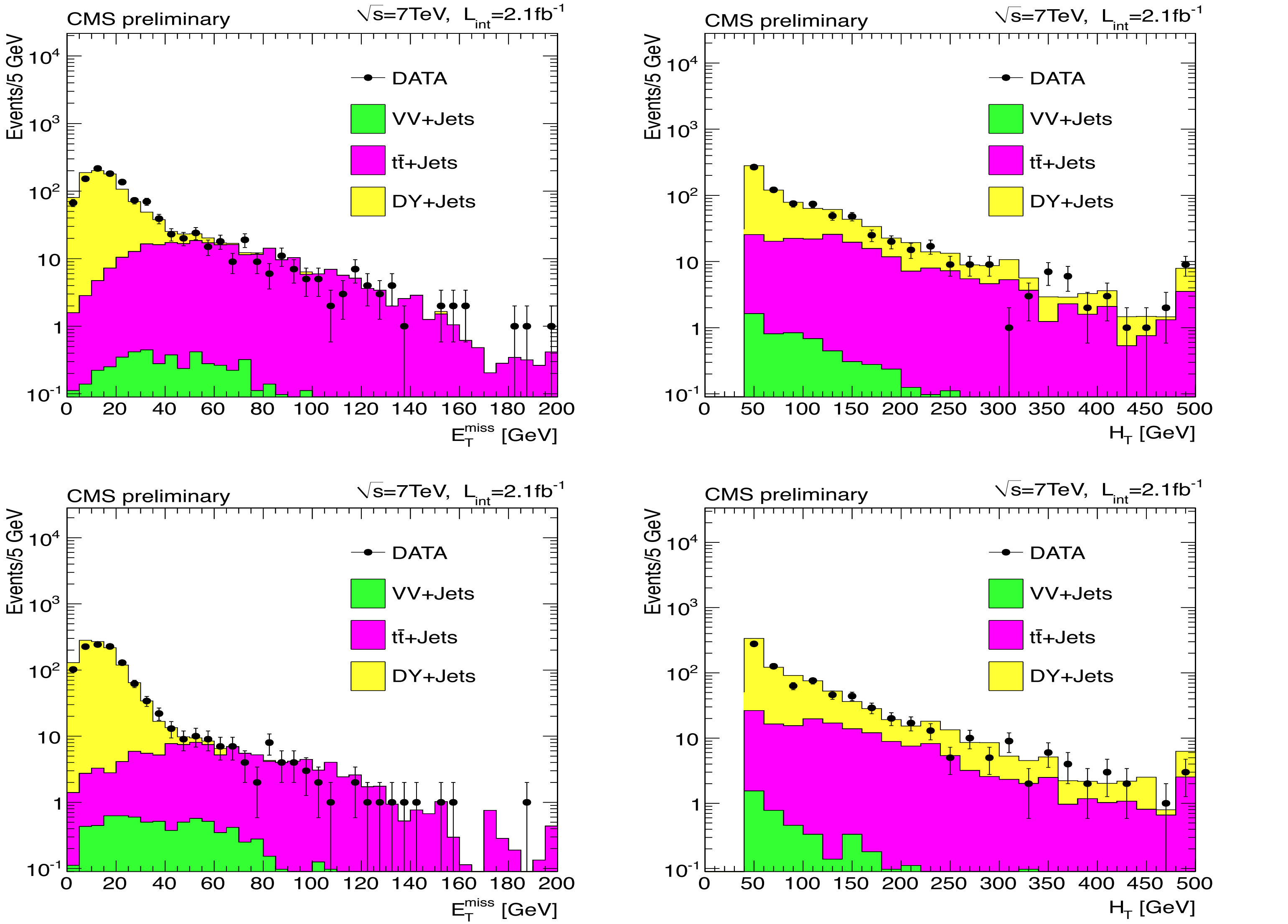
- for single lepton triggers: a leading muon (electron) with pT > 20(70) GeV;
- for same-flavor dilepton triggers: a leading muon (electron) with pT > 15(20) GeV and a next to leading muon(electron) with pT > 10(10)GeV;
- for different-flavor dilepton triggers: a leading muon (electron) with pT > 20 GeV

  and a leading electron (muon) with pT > 10 GeV.

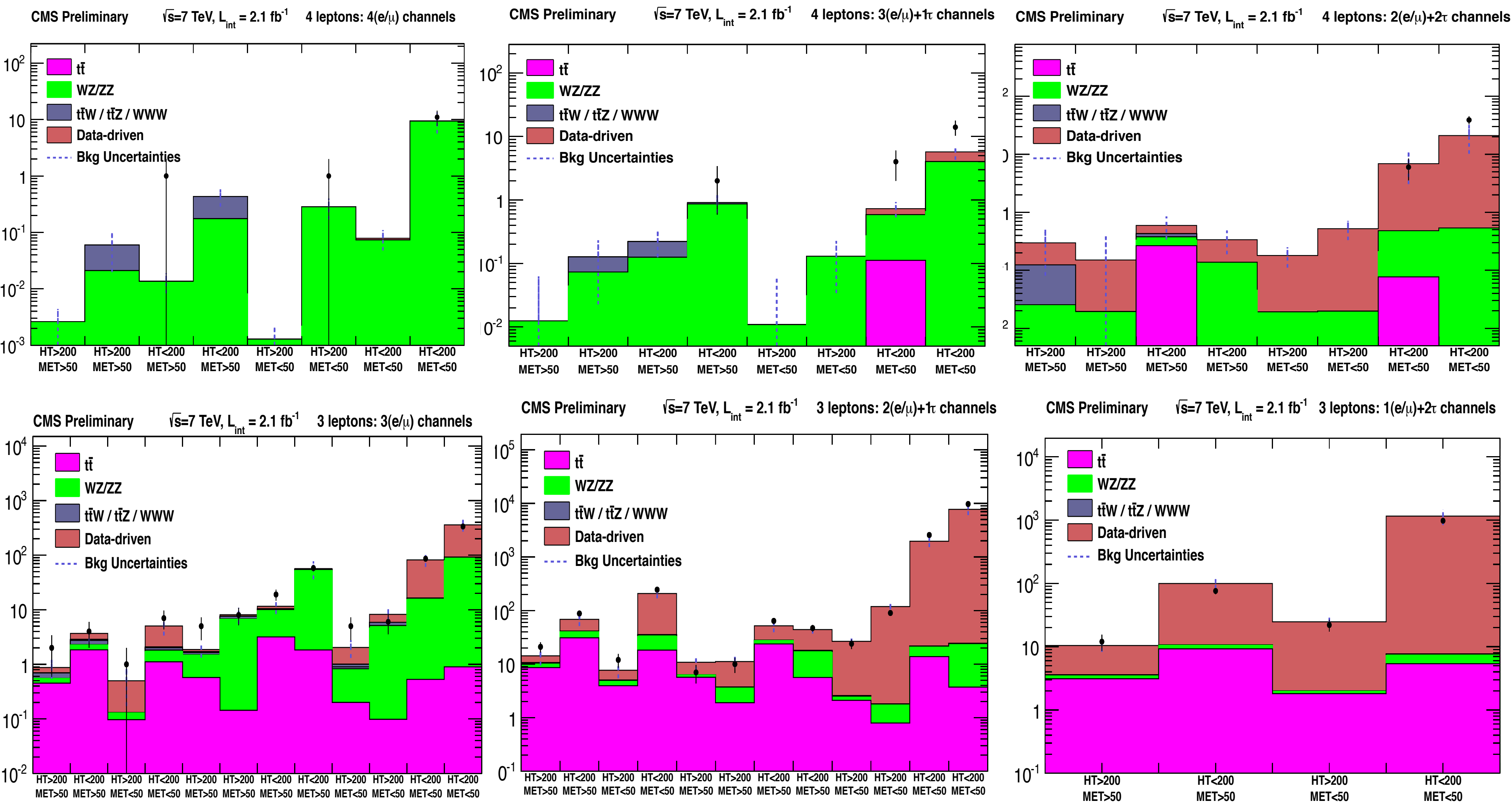




Multi-Lepton Search: Control Plots

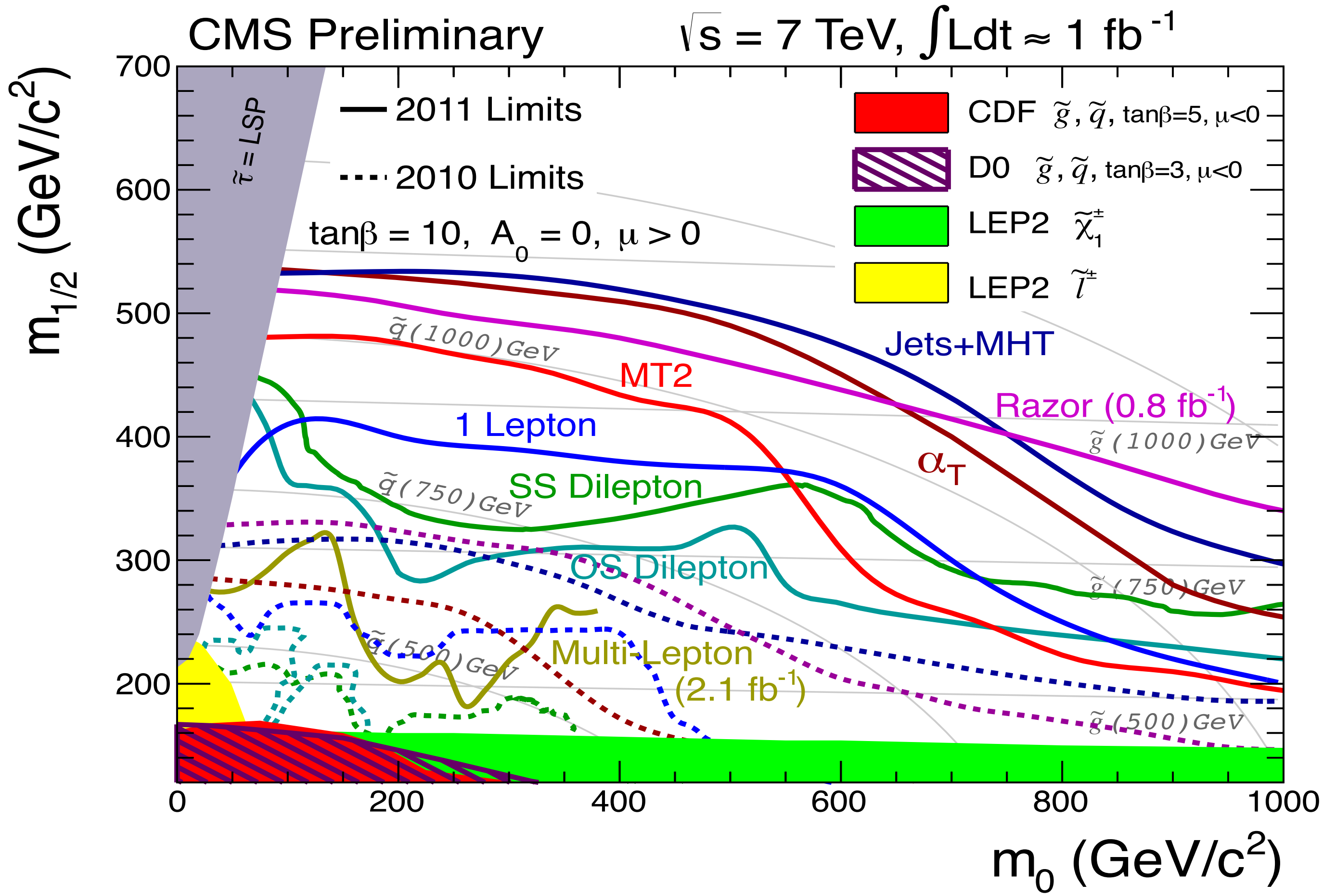


Multi-Lepton Search: Results



SUSY-PAS-11-016

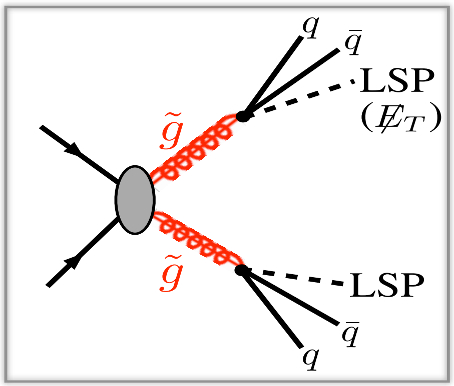
Observed exclusion limits from several 2011 CMS SUSY searches plotted in the CMSSM (m_0, $m_{1/2}$) plane



SUSY Phase Space

BSM Problems for the LHC Era

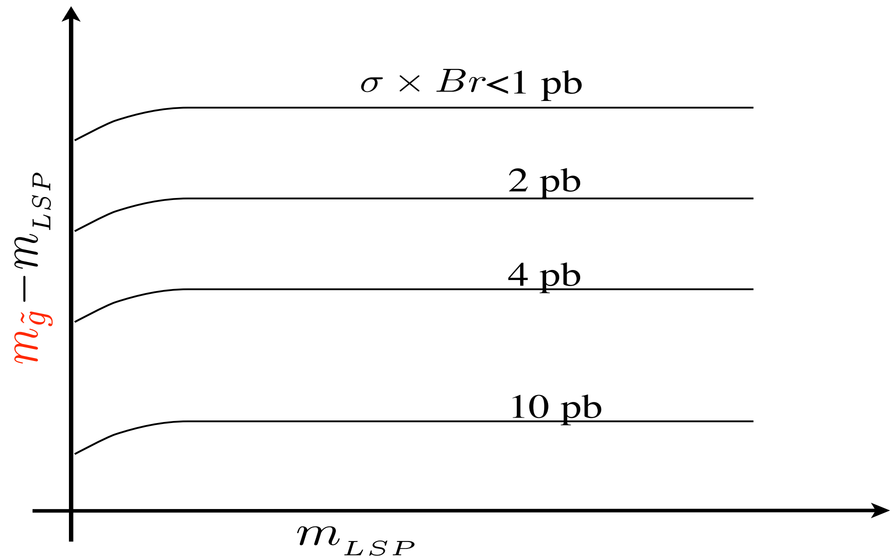
- Search in all the Right Places
- Present search results so that useful limits can be extracted
- If new physics is seen, characterize it as much as possible, describe **observed properties** of New Physics with minimal reliance on **untested assumptions.**



Parameters:

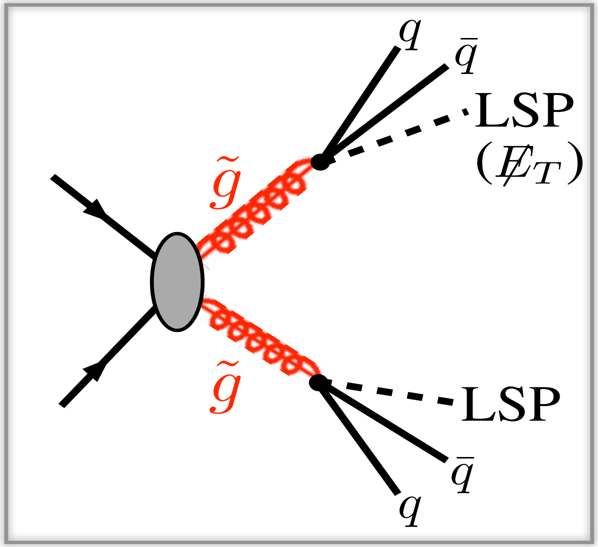
- 2 masses
  $m_{\tilde{g}}$
  m_{LSP}
- $\sigma \times Br$

Limit on (Cross-section)x(Branching ratio) as function of mass parameters

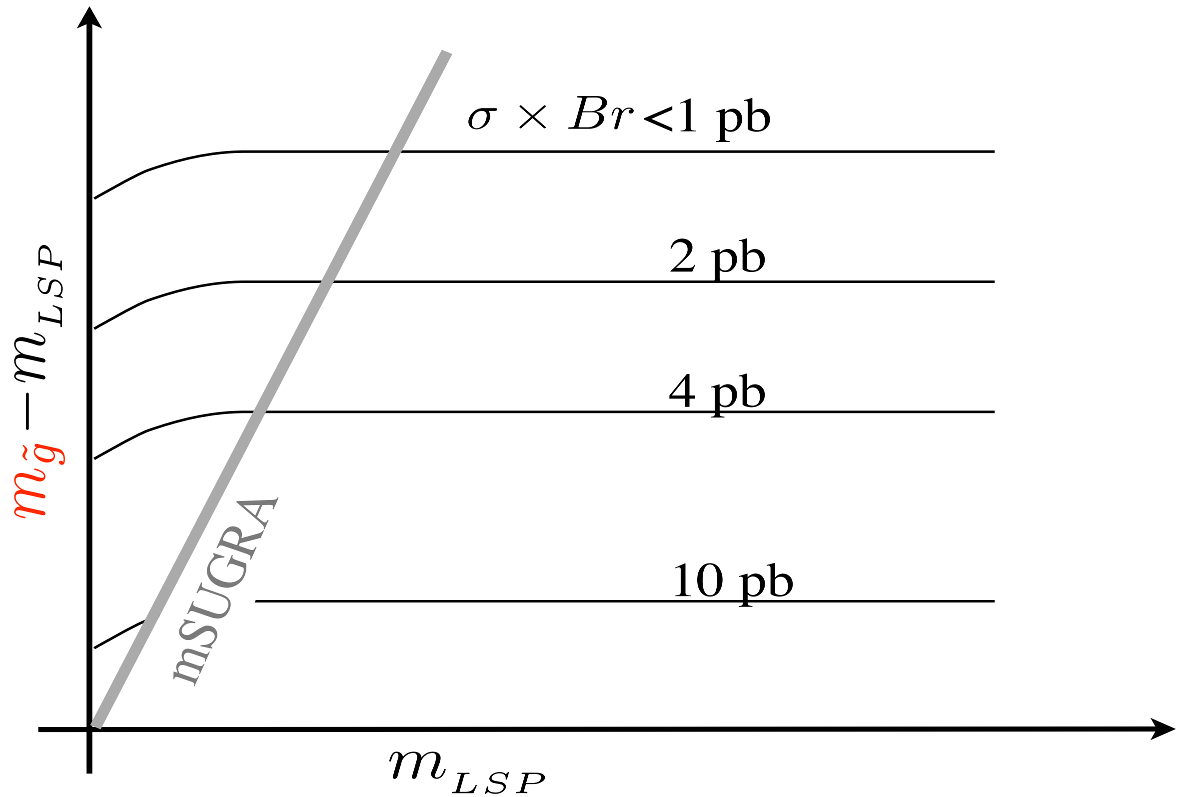


Efficiency for multi-jet+MET search cuts decreases for small mass difference ⇒ weaker cross-section limits
Approximately independent of m_{LSP}, except at low masses.

Simplified Models (OSETs)



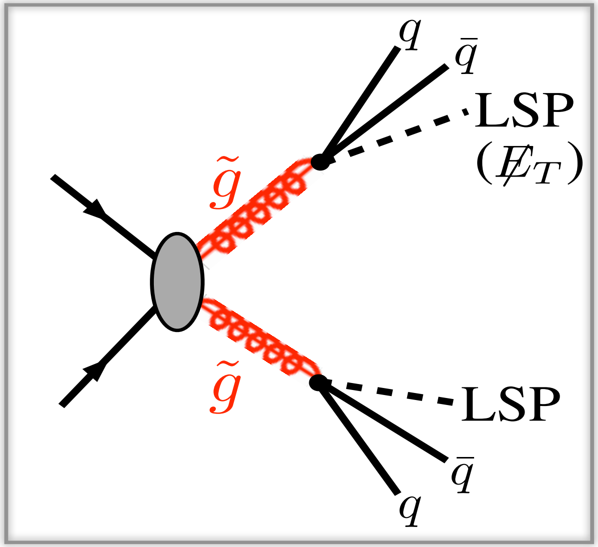
Limit on (Cross-section)x(Branching ratio) as function of mass parameters



Parameters:

- 2 masses
  - $m_{\tilde{g}}$
  - m_{LSP}
- $\sigma \times Br$

In mSUGRA, ratio of gluino and LSP masses is approximately fixed (~7 to 1), so mSUGRA only explores a line on this plane.



Parameters:

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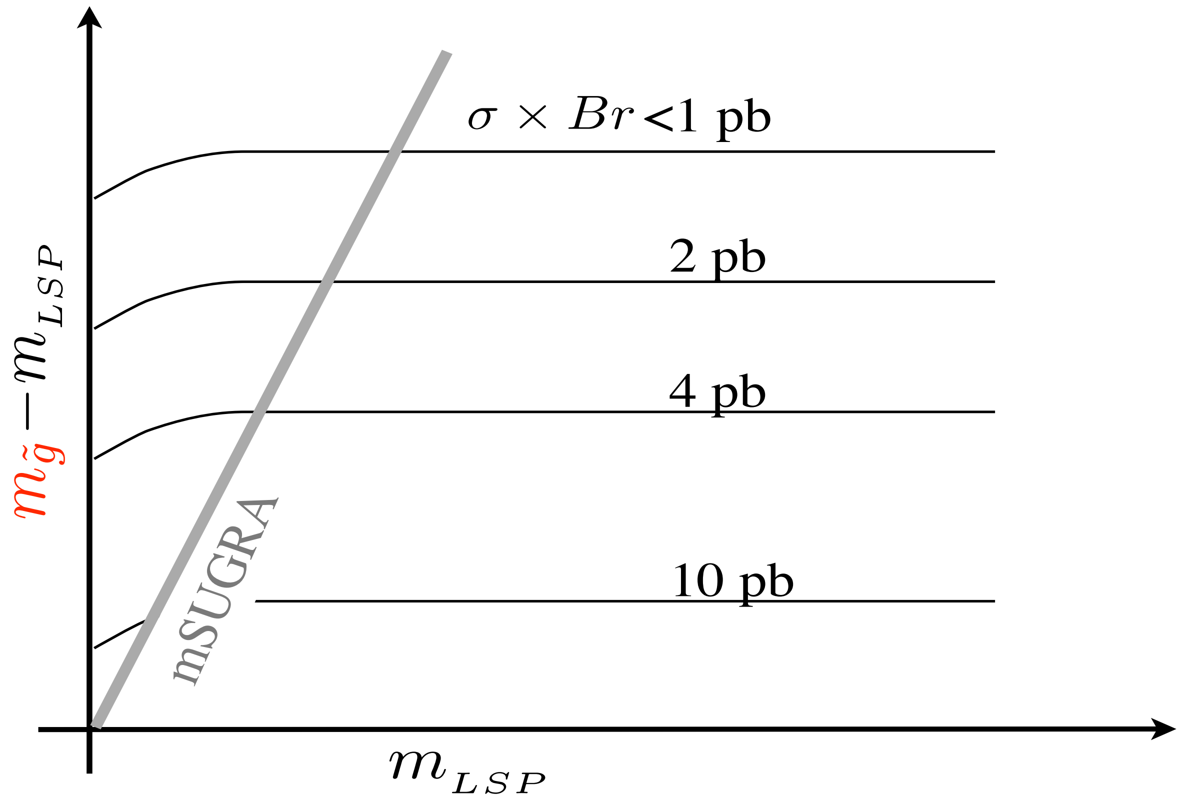

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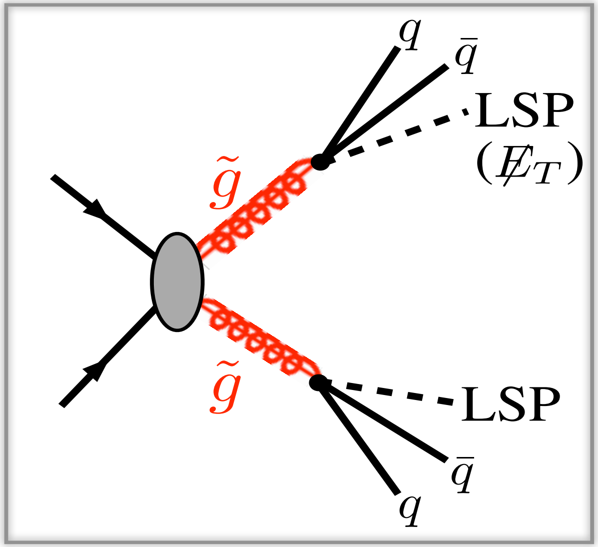
Simplified Models (OSETs)



Parameters:

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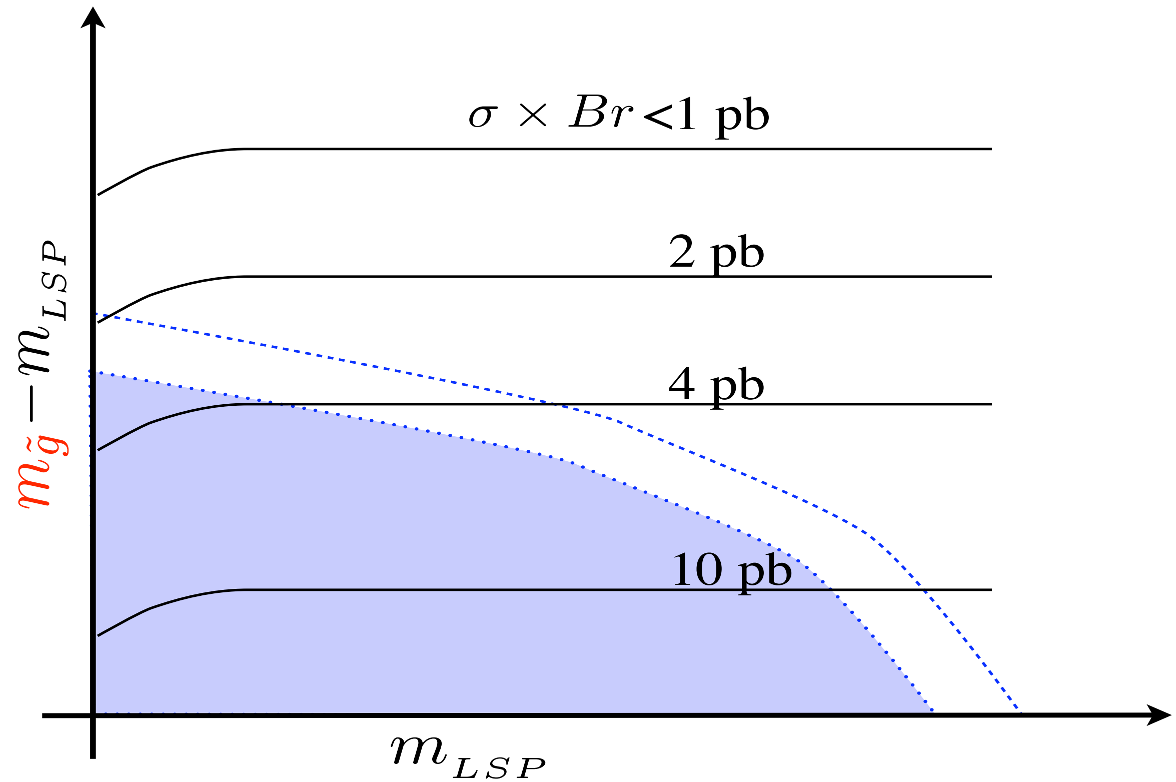
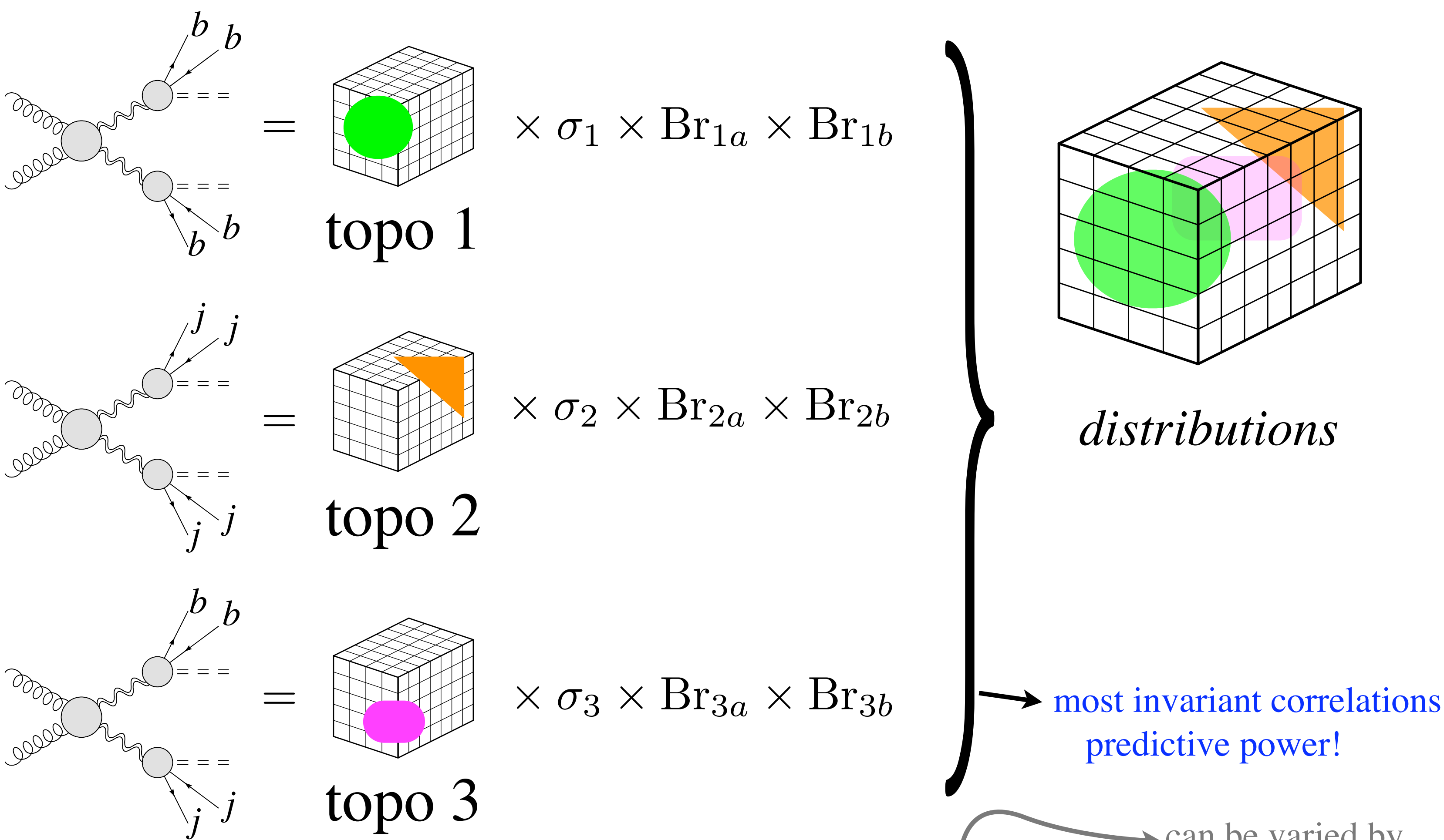
Limit on (Cross-section)x(Branching ratio) as function of mass parameters



Different models (e.g. spins, squark mass) imply different mass–(σ x Br) relations.

Blue curves: exclusions on models, i.e. contours where **expected** cross-section equals maximum allowed cross-section (region below curves provides approximate exclusion).

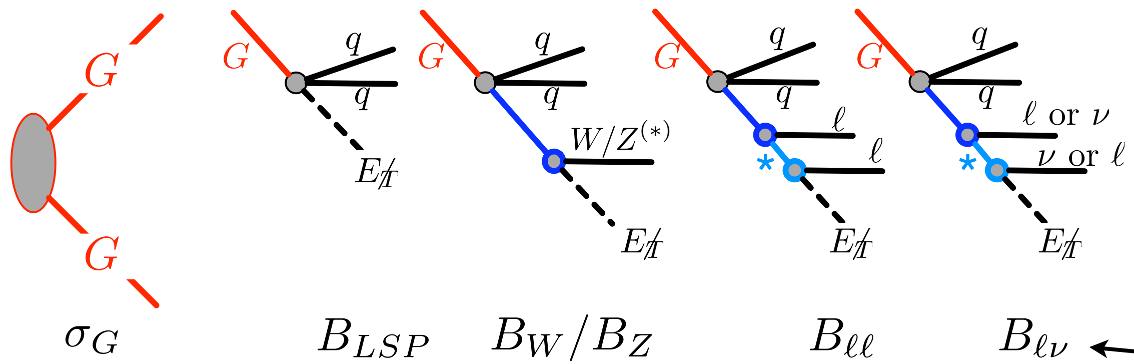
Organizing Process Sets



Parameters are masses, cross-sections, and branching ratios

Examples

From gluon partner:



*on or off-shell

Masses

M_G

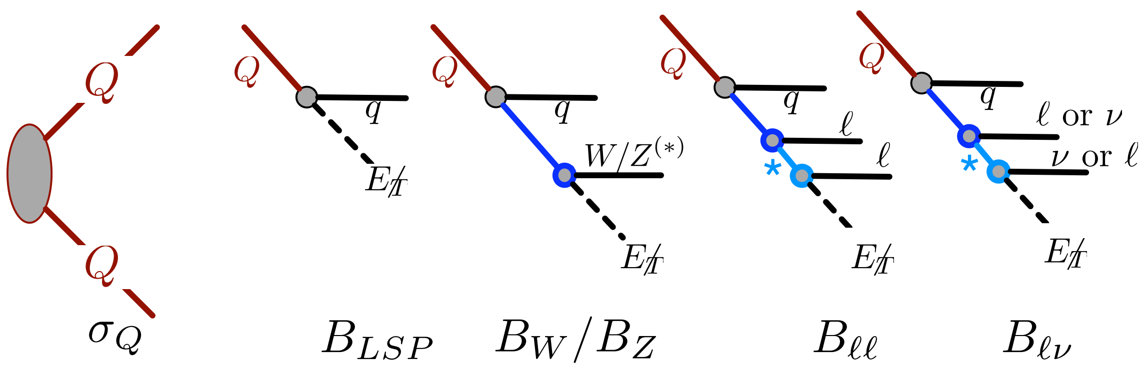
M_I

(M_L)

M_{LSP}

physical parameters **directly** connected to *observables* (*rates, kinematics, efficiencies*).

From quark partner:



Masses

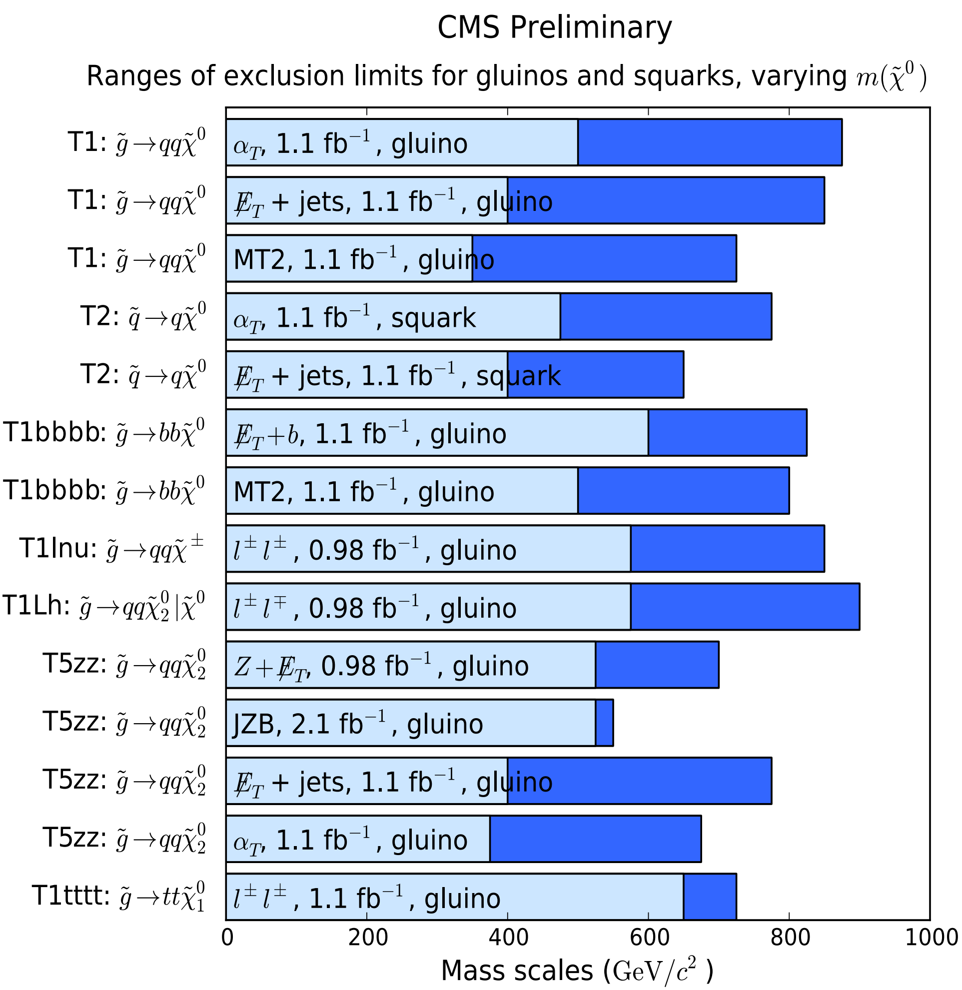
M_Q

M_I

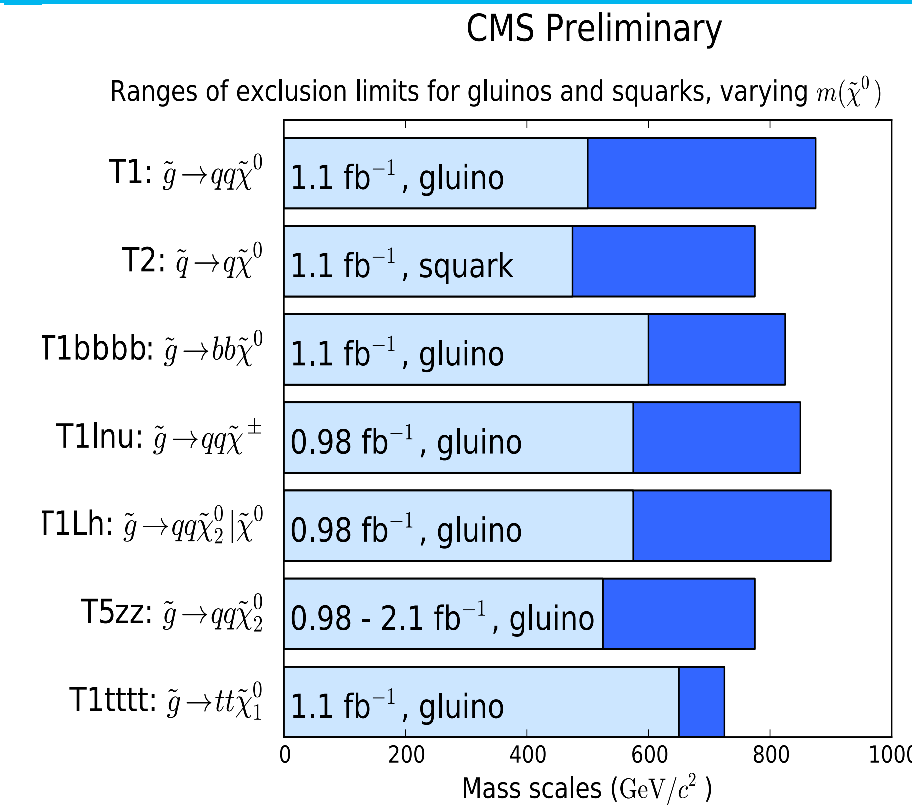
(M_L)

M_{LSP}

Interpretation of the Physics Results for OSETs



For limits on $m(\tilde{g}),m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{\mathrm{prod}} = \sigma^{\mathrm{NLO-QCD}}$.
$m(\tilde{\chi}^\pm),m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g})+m(\tilde{\chi}^0)}{2}$.
$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})-200$ GeV/c^2 (light blue).



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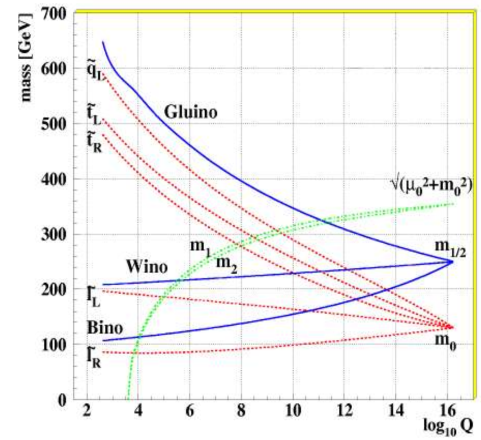
Summary

- L = 1 fb^{-1} of data analyzed (summer) by the CMS Collaboration
  - Unfortunately, no evidence of Supersymmetry
  - Extended previously explored range of model parameters
  - Results are presented in the cMSSM scenario just for reference with previous limits.
- Road-map for SUSY discoveries
  - Many final states, many different analyses, complementarity between analyses, cross-checks
  - Data-Driven estimation methods and multiple techniques for different analyses and for different backgrounds
  - Aim is to set up robust analyses for discoveries and define larger limits
- Prospects for 2011: analyzed L= ~5 fb^{-1} data. Results coming soon!

BACKUP SLIDES

CMSSM



- SUSY related fermion and bosons
- Minimal Field Content:
  - Chiral superfields, Gauge (vector) superfields, Higgs superfields
- Gauge interactions as SM plus SUSY "equivalents"
- Superpotential:

$$W_{MSSM} = U^c Y_u Q H_2 - D^c Y_d Q H_1 - E^c Y_e L H_1 + \mu H_1 H_2$$

- The Soft SUSY breaking Lagrangian

$$\begin{aligned} L_{soft} = & \frac{1}{2}\left(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g}\right) + \text{h.c.} \\ & + m^2_{\tilde{Q}} \tilde{Q}^* \tilde{Q} + m^2_{\tilde{U}^c} \tilde{U}^{c*} \tilde{U}^c + m^2_{\tilde{D}^c} \tilde{D}^{c*} \tilde{D}^c + m^2_{\tilde{L}} \tilde{L}^* \tilde{L} + m^2_{\tilde{E}^c} \tilde{E}^{c*} \tilde{E}^c + \mathrm{l} \\ & + m^2_{H_1} H_1^* H_1 + m_{H_2} H_2^* H_2 + \text{h.c.} \\ & + \tilde{U}^c a_u \tilde{Q} H_2 - \tilde{D}^c a_d \tilde{Q} H_1 - \tilde{E}^c a_e \tilde{Q} H_1 + \text{h.c.} \\ & + b H_1 H_2 + \text{h.c.} \end{aligned}$$

Soft SUSY Breaking parameters can be simplified at the GUT scale: The CMSSM

$$M_3 = M_2 = M_1 = m_{1/2}$$
$$m^2_{\tilde{Q}} = m^2_{\tilde{U}^c} = m^2_{\tilde{D}^c} = m^2_{\tilde{L}} = m^2_{\tilde{E}^c} = m^2_0$$
$$a_u = A_0 Y_u \quad a_d = A_0 Y_d \quad a_e = A_0 Y$$
$$b = B_0 \mu$$

Gravity Mediated SUSY Breaking: Flavour blind interactions communicate SUSY breaking to MSSM e.g. gravity

$$m_0 \quad m_{1/2} \quad A_0 \quad \text{sign}() \quad \tan$$

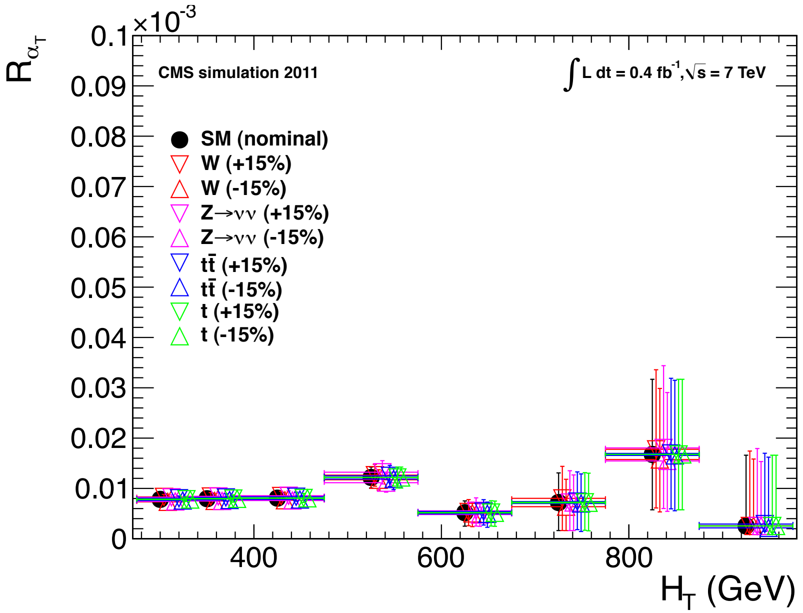
The kinematic variable α_T

Event Selections:

- Events with two or more high-p_T jets, reconstructed using the anti-k_T algorithm ($\Delta R=0.5$)
- Jets are required to have $E_T > 50$ GeV, $|\eta| < 3$
- The pseudo-rapidity of the jet with the highest E_T (leading jet) is required to be within $|\eta| < 2.5$, and the transverse energy of each of the two leading jets must exceed 100 GeV.
- Events in which an isolated lepton (electron or muon) with $p_T > 10$ GeV is identified are rejected to suppress events with genuine missing energy from neutrinos.
- To select a pure multi-jet topology, events are vetoed in which an isolated photon with pT > 25 GeV is found.
- Events are required to satisfy $H_T > 275$ GeV.

$$\alpha_T = \frac{E_T^{\text{jet}_2}}{M_T} = \frac{E_T^{\text{jet}_2}}{\sqrt{\left(\sum_{i=1}^{2} E_T^{\text{jet}_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{\text{jet}_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{\text{jet}_i}\right)^2}}$$

The dependence of $R_{\alpha T}$ on H_T when varying the effective cross-section of the four major EWK background components individually by ±15%.



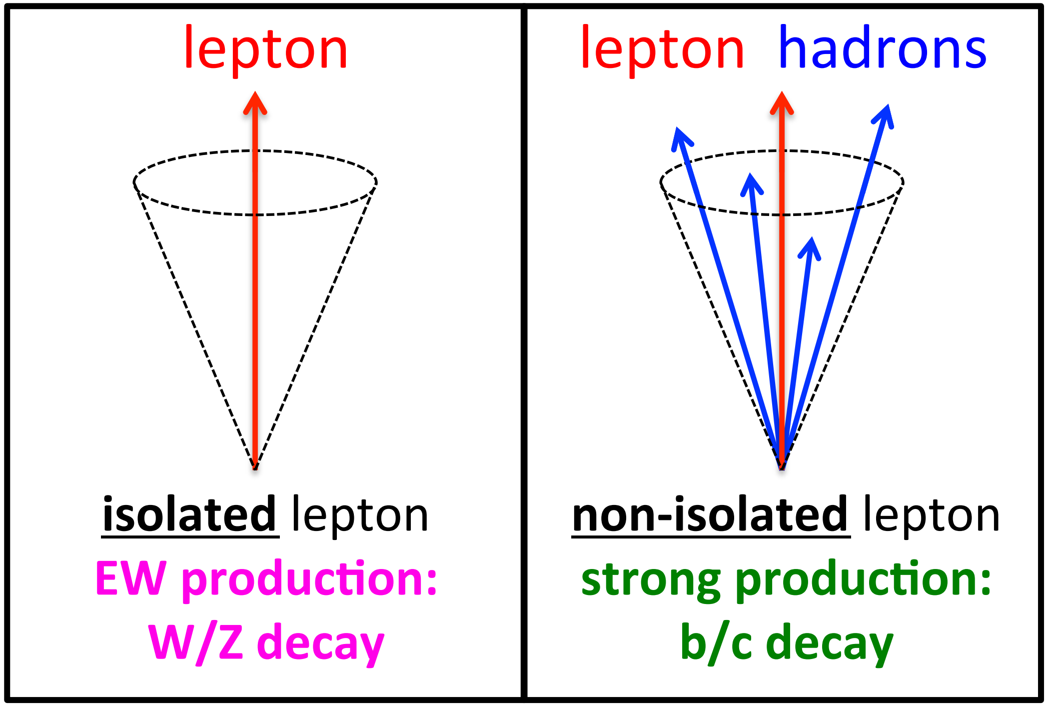
The kinematic variable α_T: Estimation of Background from tt and W + Jets Events using a Muon Control Sample

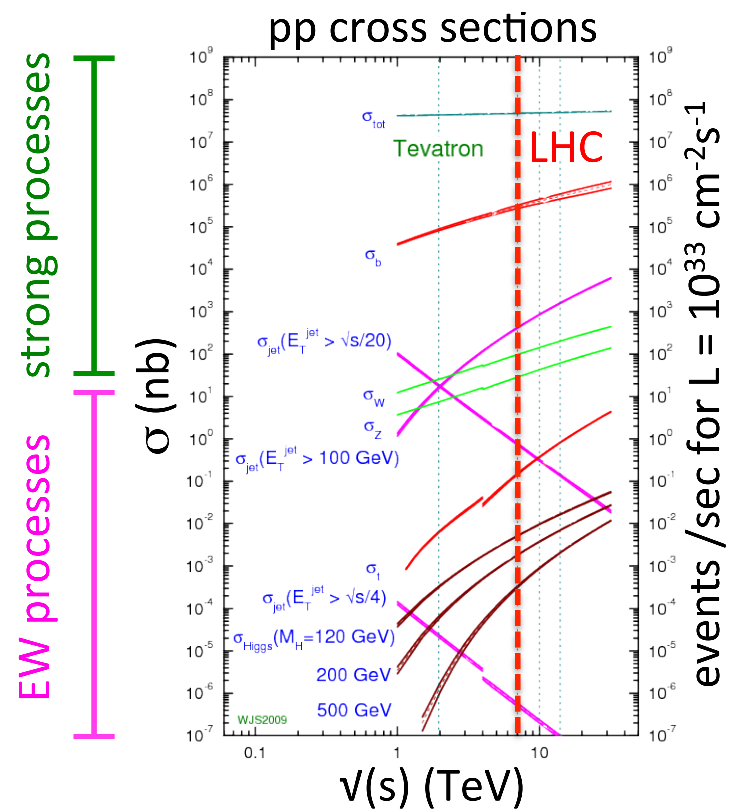
- An estimate of the backgrounds from unidentified leptons and hadronic tau decays originating from high-p_T W bosons is obtained through the use of a muon control sample.
- In this sample, it is explicitly selected W's decaying to a muon and a neutrino in the phase-space of the signal. This is performed in the same HT bins as for the hadronic signal selection.
  - One isolated muon with $p_T > 10$ GeV and $|\eta| < 2.5$.
  - $M_T > 30$ GeV, where M_T is the transverse mass of the W candidate.
  - $\Delta R(\text{jet,muon}) > 0.5$
  - $\not{H}_T / H_T > 0.4$
  - No second isolated muon in the event. This reduces $Z \to \mu\mu$.
- The number of events from W+jet events in the hadronic selection $W^{had/data}$ can be estimated from data the event yield, W^{μ}_{data}, of these type of events. The value of this ratio is extracted from the MC simulation.

$$W^{had}_{data} = W^{\mu}_{data} \times \frac{W^{had}_{MC}}{W^{\mu}_{MC}}.$$

H_T Bin (GeV)	275–325	325–375	375–475	475–575
MC W + $t\bar{t}$	$463.0 \pm 16.0_{stat}$	$171.2 \pm 9.5_{stat}$	$116.3 \pm 8.3_{stat}$	$43.7 \pm 5.1_{stat}$
MC μ+ jets	$407.5 \pm 14.5_{stat}$	$179.1 \pm 9.6_{stat}$	$131.6 \pm 8.8_{stat}$	$48.7 \pm 5.5_{stat}$
MC Ratio	1.14	0.96	0.90	0.90
Data μ+ jets	389	156	113	39
W + $t\bar{t}$ Prediction	$442.0 \pm 22.4_{stat} \pm 132.6_{syst}$	$149.1 \pm 11.9_{stat} \pm 44.7_{syst}$	$101.9 \pm 9.6_{stat} \pm 30.6_{syst}$	$35.2 \pm 5.6_{stat} \pm 10.6_{syst}$
H_T Bin (GeV)	575–675	675–775	775–875	875–∞
MC W + $t\bar{t}$	$17.5 \pm 3.2_{stat}$	$5.1 \pm 1.8_{stat}$	$1.1 \pm 0.7_{stat}$	$1.8 \pm 1.0_{stat}$
MC μ+ jets	$13.3 \pm 2.9_{stat}$	$8.0 \pm 2.3_{stat}$	$3.2 \pm 1.4_{stat}$	$0.9 \pm 0.7_{stat}$
MC Ratio	0.90	0.90	0.90	0.90
Data μ+ jets	17	5	0	0
W + $t\bar{t}$ Prediction	$15.3 \pm 3.7_{stat} \pm 4.6_{syst}$	$4.5 \pm 2.0_{stat} \pm 1.4_{syst}$	$0.0 \pm 1.0_{stat}$	$0.0 \pm 1.0_{stat}$

New Physics with Leptons





$$Iso = \frac{\left[\sum_{Ecal} E_T + \sum_{HCAL} E_T + \sum_{Tracker} p_T\right]_{dR<0.3}}{p_T}$$

SS – Dilepton Search: Triggers

Leptonic datasets:

- *ee* channel:
  HLT_Ele17_CaloIdL_CaloIsoVL_Ele8_CaloIdL_CaloIsoVL_v* OR
  HLT_Ele17_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL_Ele8_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL_v* OR
  HLT_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL_Ele8_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL_v* OR
- $\mu\mu$ channel: HLT_DoubleMu7_v* OR HLT_Mu13_Mu8_v*
- $e\mu$ channel: HLT_Mu17_Ele8_CaloIdL_v* OR HLT_Mu8_Ele17_CaloIdL_v*

Control regions:

- μ: HLT_Mu8_Jet40_v*
- e: HLT_Ele8_CaloIdL_CaloIsoVL_Jet40_v*

SS –Dilepton Search: Fake Ratio Method

$$
\begin{aligned}
N_l &= N_{pp} + N_{fp} + N_{ff} = N_{t2} + N_{t1} + N_{t0} \\
N_{t0} &= (1-p)^2 N_{pp} + (1-p)(1-f) N_{fp} + (1-f)^2 N_{ff} \\
N_{t1} &= 2p(1-p) N_{pp} + [f(1-p) + p(1-f)] N_{fp} + 2f(1-f) N_{ff} \\
N_{t2} &= p^2 N_{pp} + pf N_{fp} + f^2 N_{ff}
\end{aligned}
$$

These equations assume that the prompt and the fake ratios for different leptons are independent of each other. The factors p and $(1-p)$ are weighting (or are averaged over) the distribution of prompt leptons and f and $(1-f)$ are weighing (or are averaged over) the distributions of fake leptons.

$$
N_{pp} = \frac{1}{(p-f)^2} \left[(1-f)^2 N_{t2} - f(1-f) N_{t1} + f^2 N_{t0} \right]
$$

$$
\begin{aligned}
N_{fp} &= \frac{1}{(p-f)^2} \left[-2fp N_{t0} + [f(1-p) + p(1-f)] N_{t1} - 2(1-p)(1-f) N_{t2} \right] \\
N_{ff} &= \frac{1}{(p-f)^2} \left[p^2 N_{t0} - p(1-p) N_{t1} + (1-p)^2 N_{t2} \right]
\end{aligned}
$$

OS – Dilepton Search: Triggers

- HLT_DoubleEle8_CaloIdL_TrkIdVL_HT160_v*
- HLT_DoubleEle8_CaloIdL_TrkIdVL_HT150_v*
- HLT_DoubleMu3_HT160_v*
- HLT_DoubleMu3_HT150_v*
- HLT_Mu3_Ele8_CaloIdL_TrkIdVL_HT160_v*
- HLT_Mu3_Ele8_CaloIdL_TrkIdVL_HT150_v*