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Beyond the Standard Model: Results with the 7 TeV LHC Collision Data

19 - 23 September 2011

Searches for Supersymmetry in the CMS Experiment

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Search for Supersymmetry in CMS experiement

Beyond the Standard Model: Results with the 7 TeV LHC Collision Data

19 Sept - 23 Sep 2011, ICTP, Trieste, Italy

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University of California, San Diego

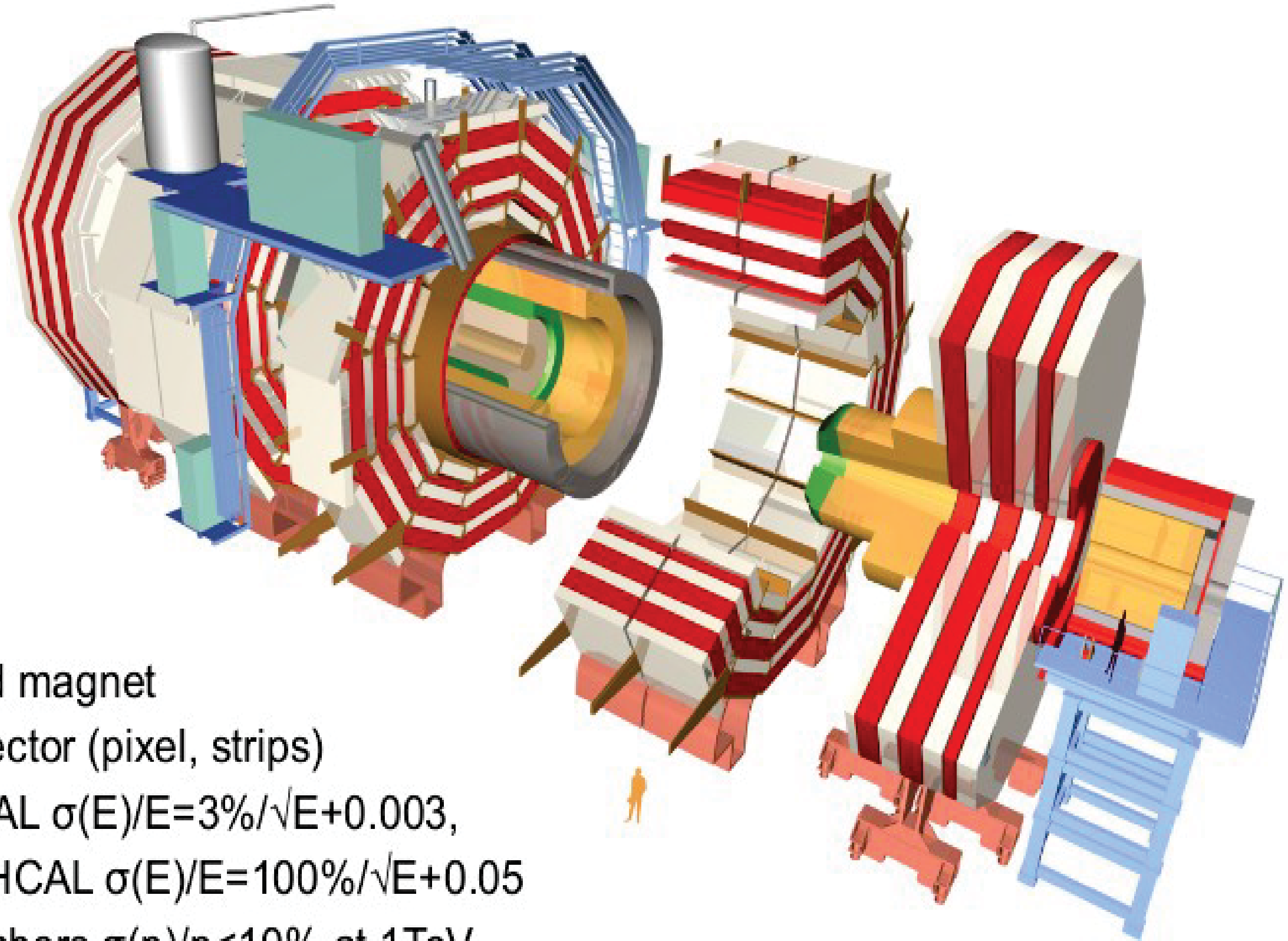
On behalf of the CMS collaboration

Outline

- CMS Performance
  - Why you should believe our searches
- CMS Search Strategy
  - Searches in fully hadronic modes in SUSY
  - Searches in leptonic modes in SUSY
  - Searches involving photons + MET in the final state
- Implication of these results on TeV scale physics
- Summary and Outlook

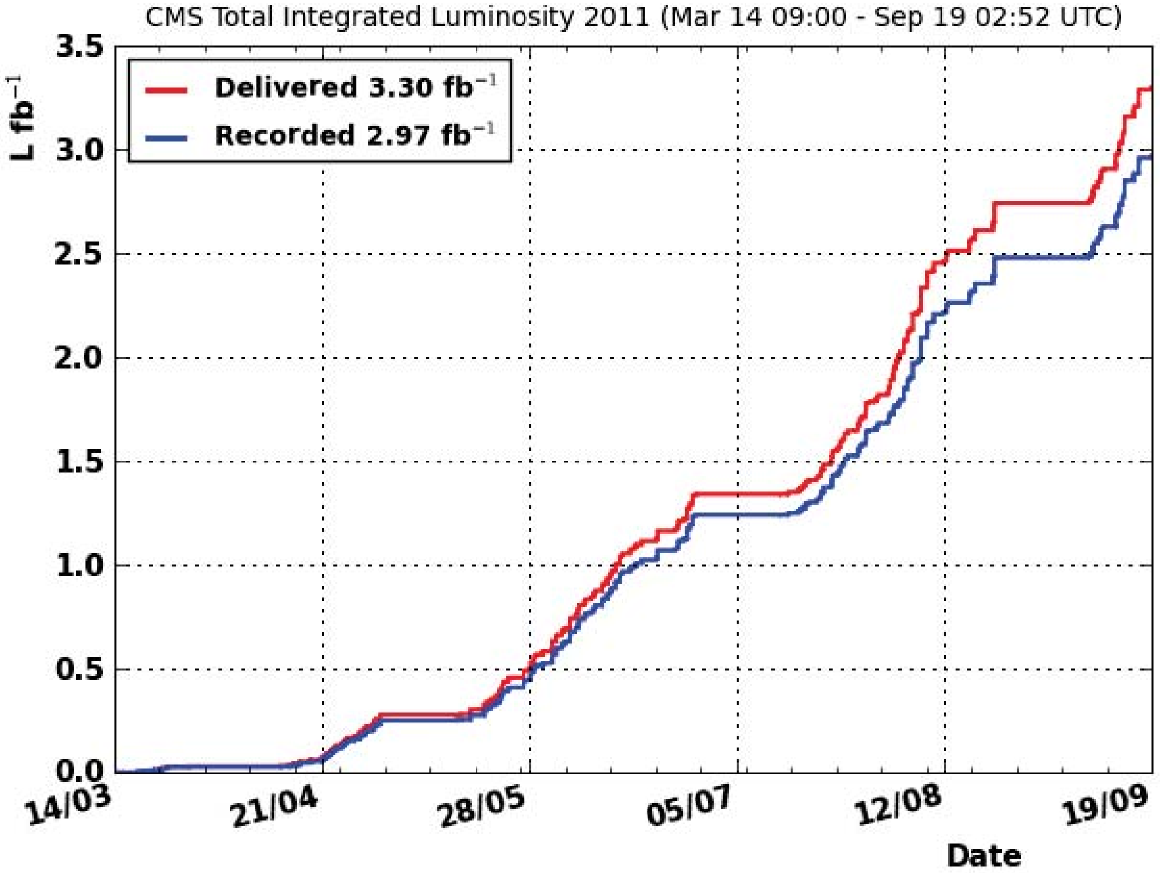
CMS Detector

JINST3:S08004 (2008)



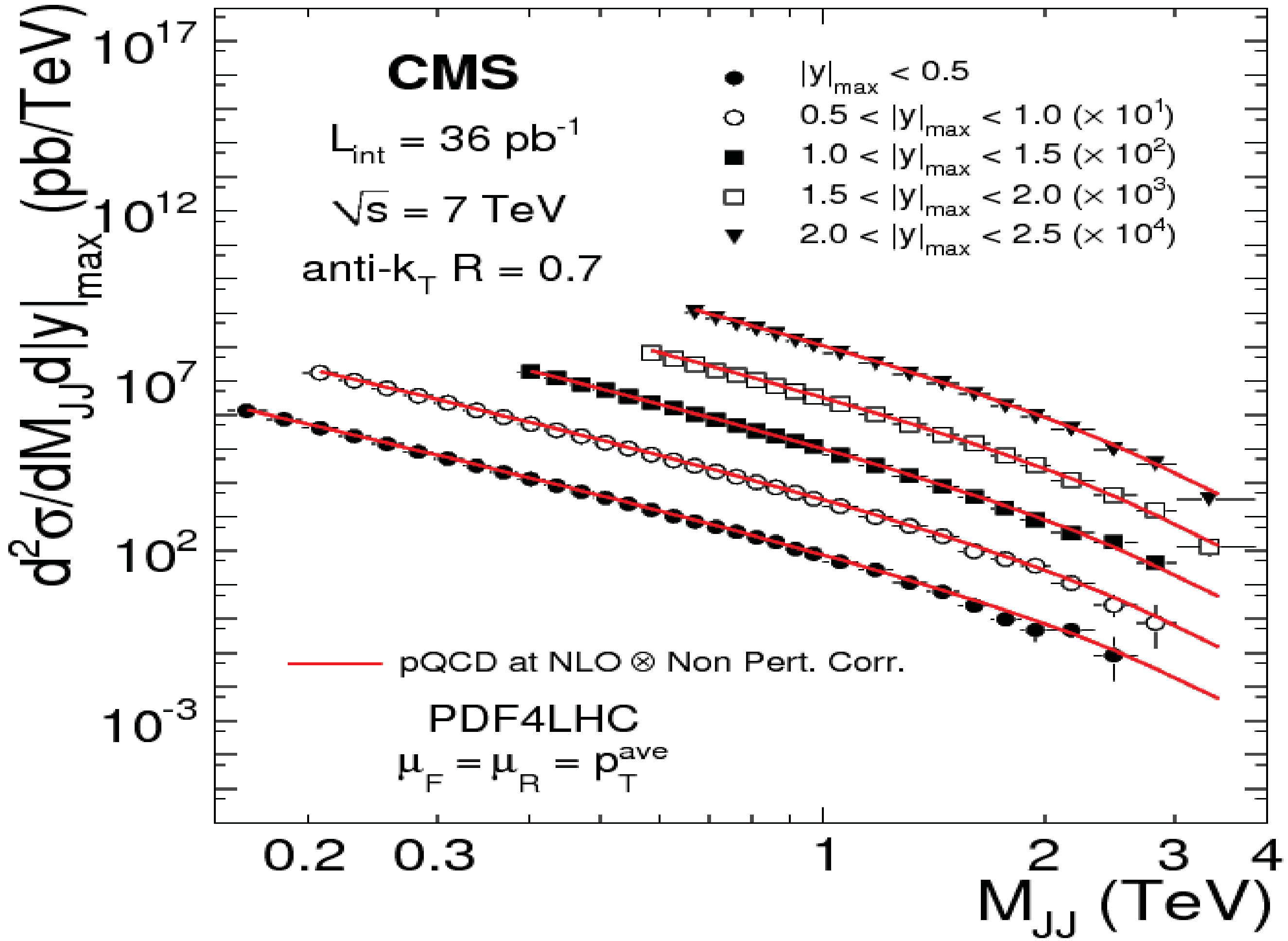
- 4T solenoid magnet
- Silicon detector (pixel, strips)
- Crystal ECAL $\sigma(E)/E=3\%/\sqrt{E}+0.003$,
- Brass/sci. HCAL $\sigma(E)/E=100\%/\sqrt{E}+0.05$
- Muon chambers $\sigma(p)/p<10\%$ at 1TeV

Luminosity profile - 2011



- LHC delivered ~ 3.3 fb^{-1}
- CMS recorded ~ 2.97 fb^{-1} [90%]
- Coped with 5 orders of magnitude increase in instantaneous luminosity

arXiv:1104.1693



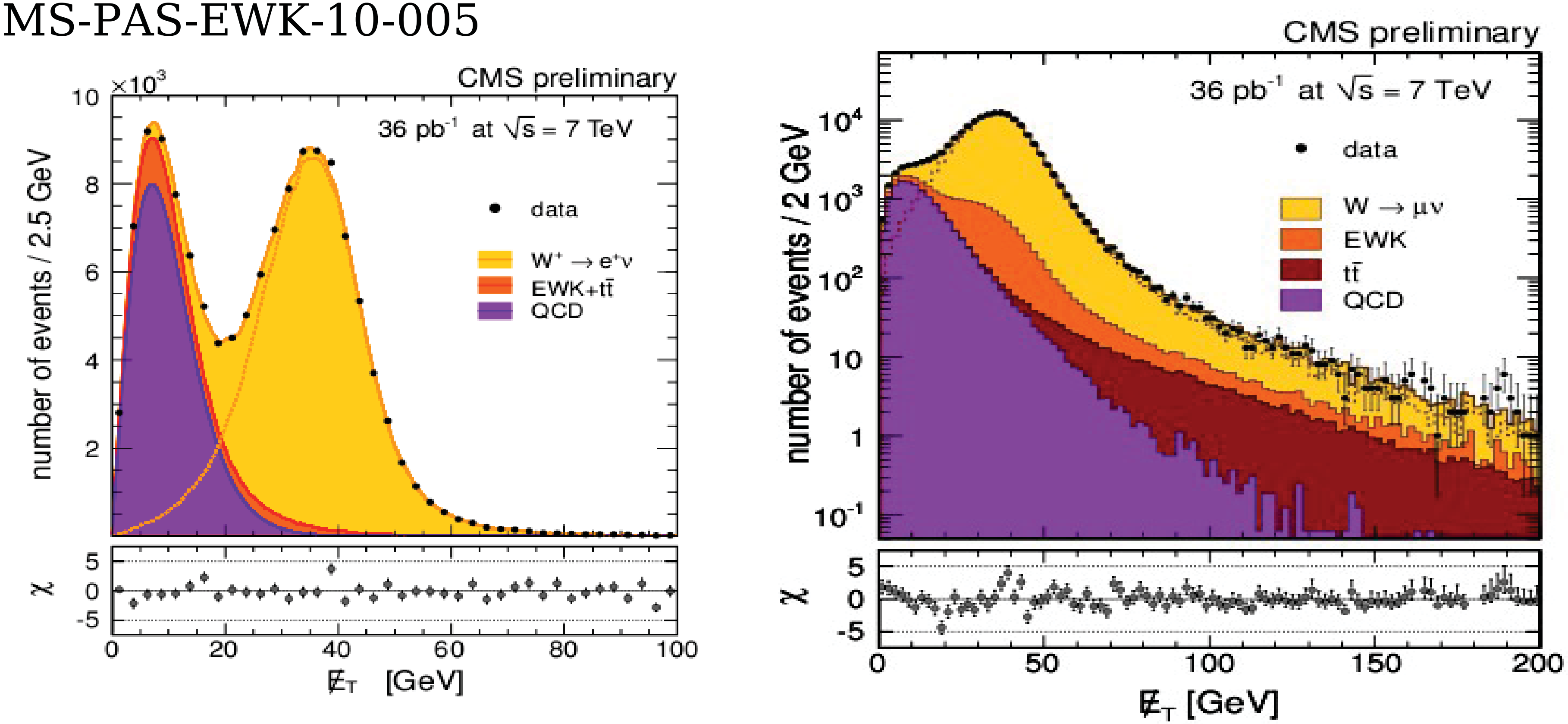
P_T (Particle Flow diJet) > 60, 30 GeV

Mjj = √ (x_1 . x_2 . s) ; √s is the centre-of-mass energy of the colliding beams

Probed: $8 \cdot 10^{-4} \leq x_1 \cdot x_2 \leq 0.25$

Jets are in good shape

CMS-PAS-EWK-10-005

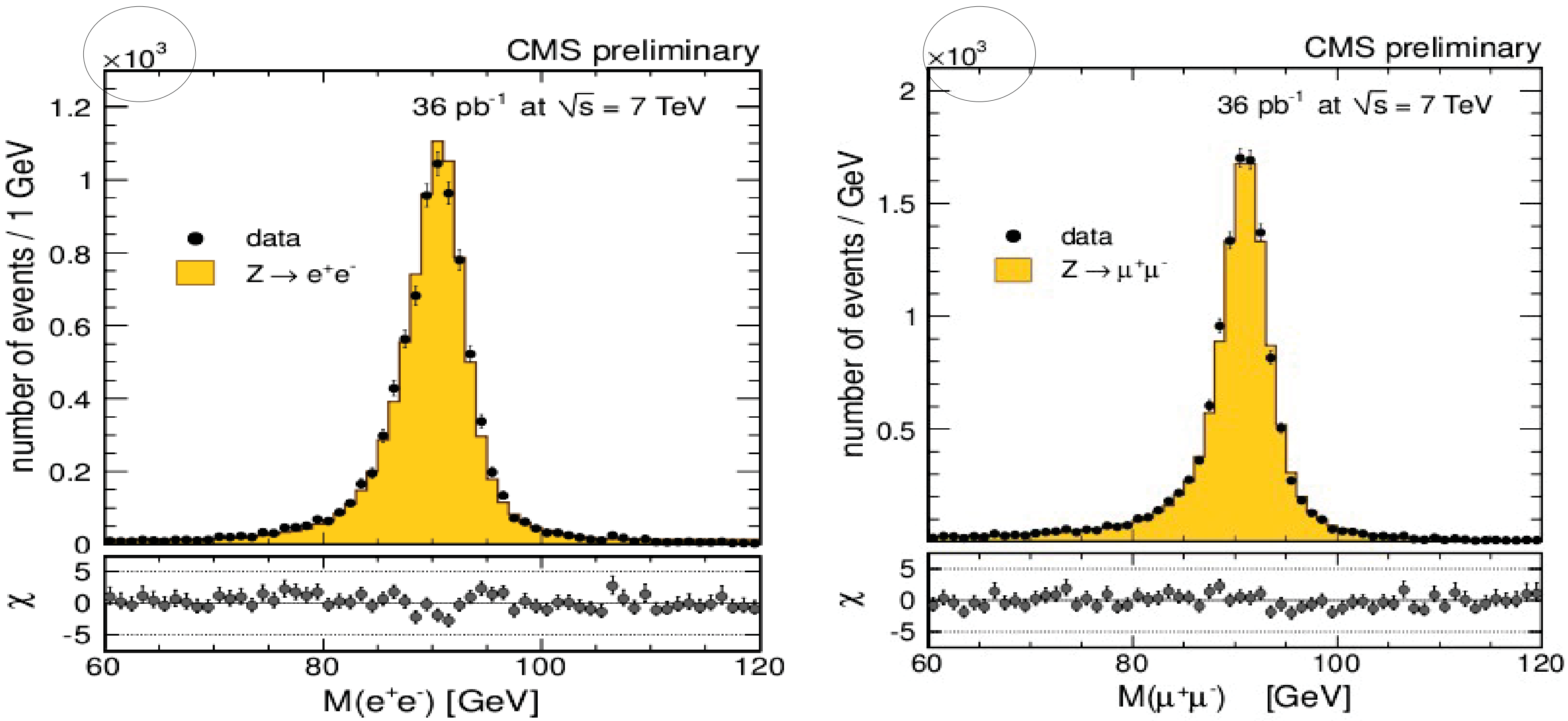


CMS uses 3 different MET reconstructions:

- Calorimeter only (Calo MET)
- Calo &tracking (tcMET)
- particle flow (pfMET)

We use pfMET as MET for most of this talk

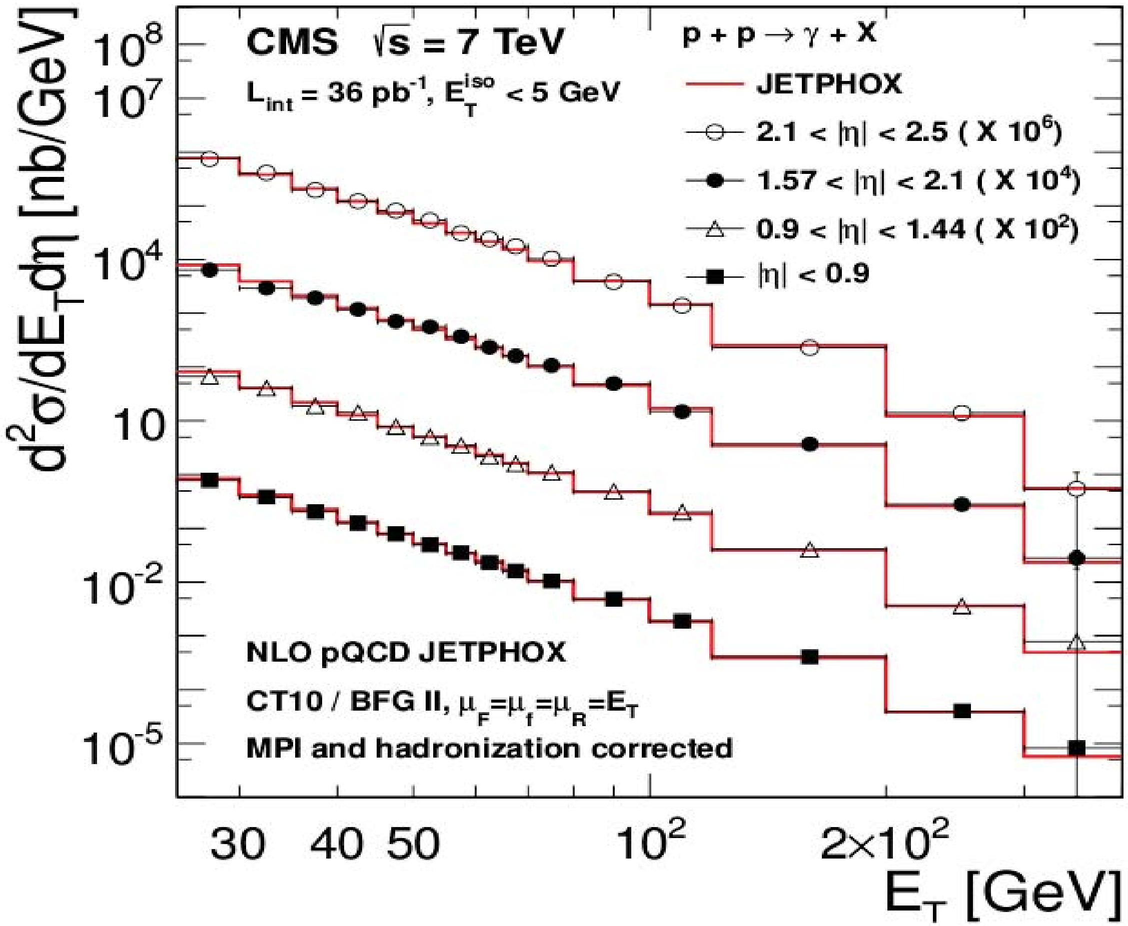
CMS-PAS-EWK-10-005



- High purity reconstruction of W (earlier slide) and Z bosons.
- Lepton and MET reconstruction performing well

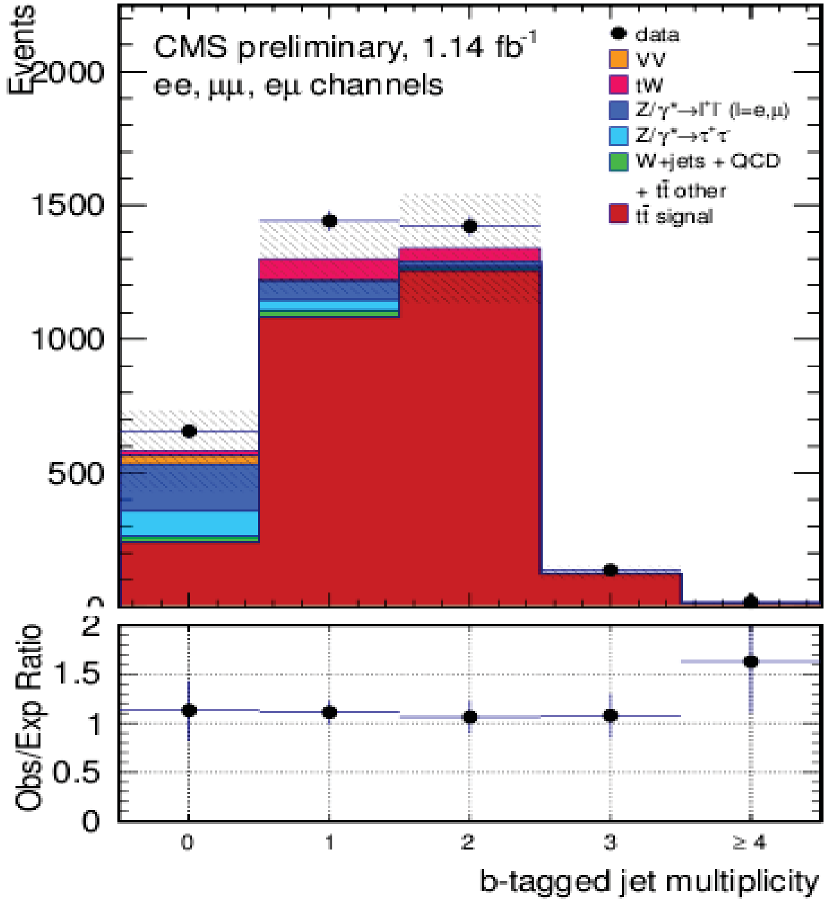
Photons

arXiv:1108.2044

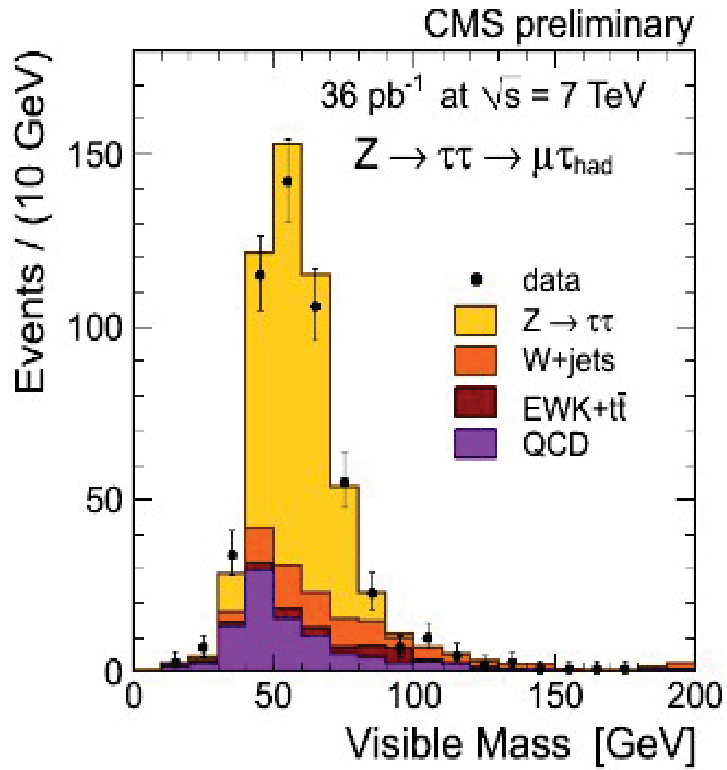


- Differential cross section for isolated prompt photons ($25 < E_T$ (GeV) < 400)
- Excellent agreement with the theory
- Probed: $0.007 < x_T < 0.114$,, where $x_T = 2E_T/\sqrt{s}$

CMS-TOP-11-005



CMS-EWK-10-013



- Top-quark pair-production and Z→ $\tau^+\tau^-$
- b-tagging and τ-tagging performing well

CMS Search Strategy

CMS has chosen to require data driven techniques for all the major backgrounds in their searches for new physics

Disclaimer: In this talk, recent results from CMS using ~1 fb^{-1} of 2011 data are summarized

CMS SUSY Search strategy

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
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

SUSY has many properties:

- Provides dark matter candidates, solves the hierarchy problem, better unification of couplings etc.
- We do not know where it is, so we look generically everywhere.

Inclusive searches are defined (explore MET +X signatures):

- Categorized by the number of leptons in final state
- Generic missing energy signatures
- Many include jet requirements to be sensitive to strong production

Results of the studies not covered in this talk (including b-jets), can be found at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Searches in fully hadronic modes in SUSY:

Focus on multiple complementary but overlapping analysis strategies

- Inclusive search using hadronic jets and MET (CMS SUS-11-004)

  (Inclusive, least model-dependent)

- Measurements based on α_T (CMS SUS-11-003)

  (Effective suppression of QCD-multijet production)

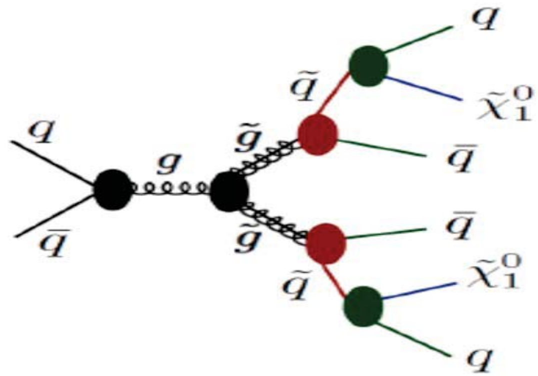
- Stransverse momentum (MT2) based study (CMS SUS-11-005)

  (Partition of the MET components)

- Inclusive search for squarks and gluinos (CMS SUS-10-009)

  (Variables related to SUSY mass-scale using hemisphere algorithm)

Inclusive search for multijets with large MET signature.

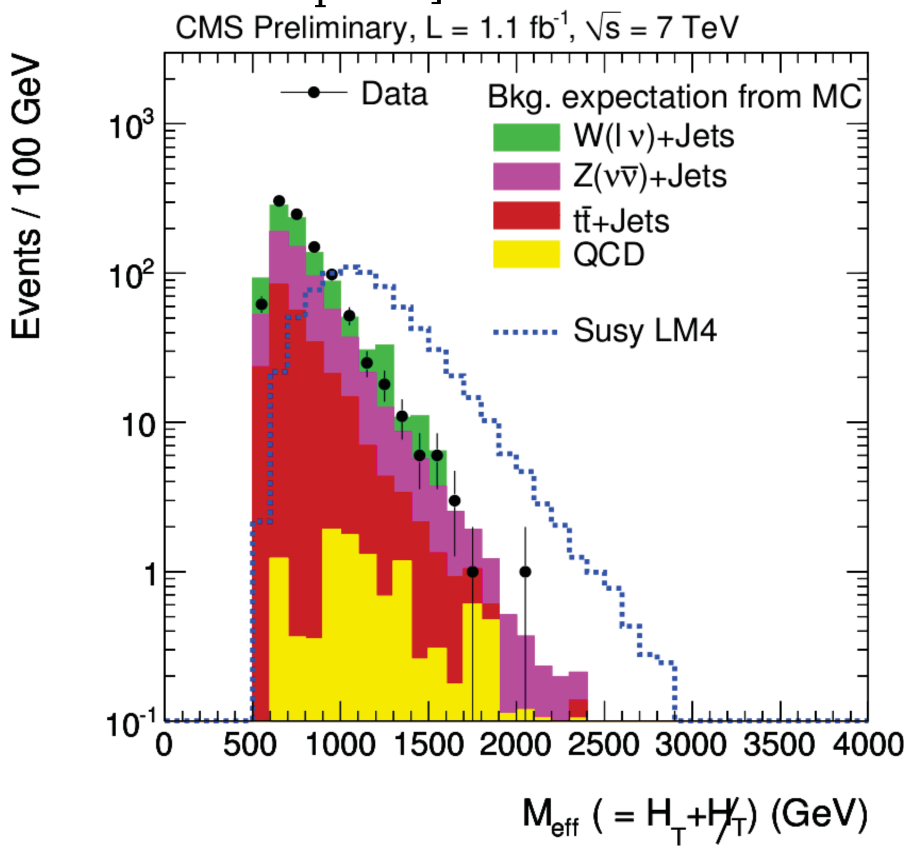


<u>Baseline Selection:</u>

- At least 3 jets with $p_T > 50$ GeV, $|\eta| < 2.5$
- $|\Delta\varphi(J_n, H_t^{miss})| > 0.5$, n=1,2 ; $|\Delta\varphi(J_n, H_T^{miss})| > 0.3$

  [Veto events in which H_T^{miss} is aligned with jets in the transverse plane]
- $H_T > 350$ GeV, $H_T^{miss} > 200$ GeV

  [H_T^{miss} = negative vectorial sum of the jet p_T]
- Veto isolated leptons with $p_T > 10$ GeV

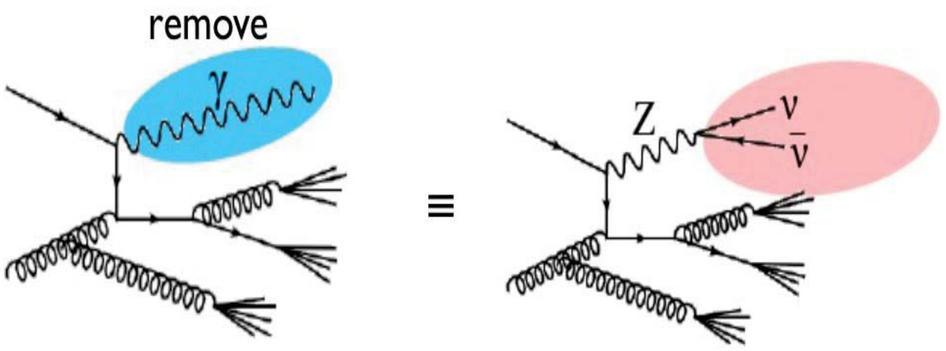


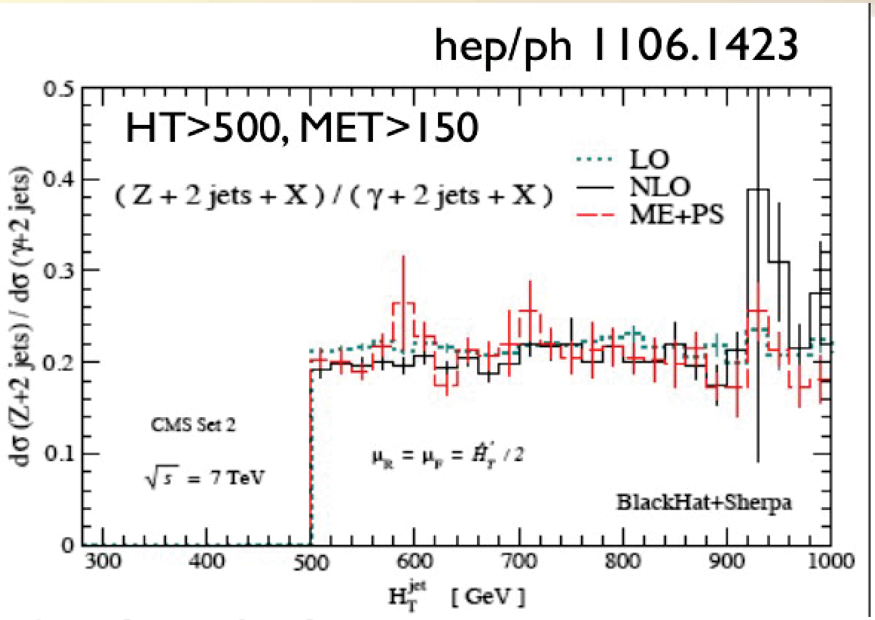
<u>Major backgrounds</u>

- $Z \rightarrow \nu\nu$ + Jets
- W + Jets (where either e/μ is lost or $W \rightarrow \tau\nu$)
- ttbar + Jets (same as above)
- QCD

Use data driven estimate ⇒ See next

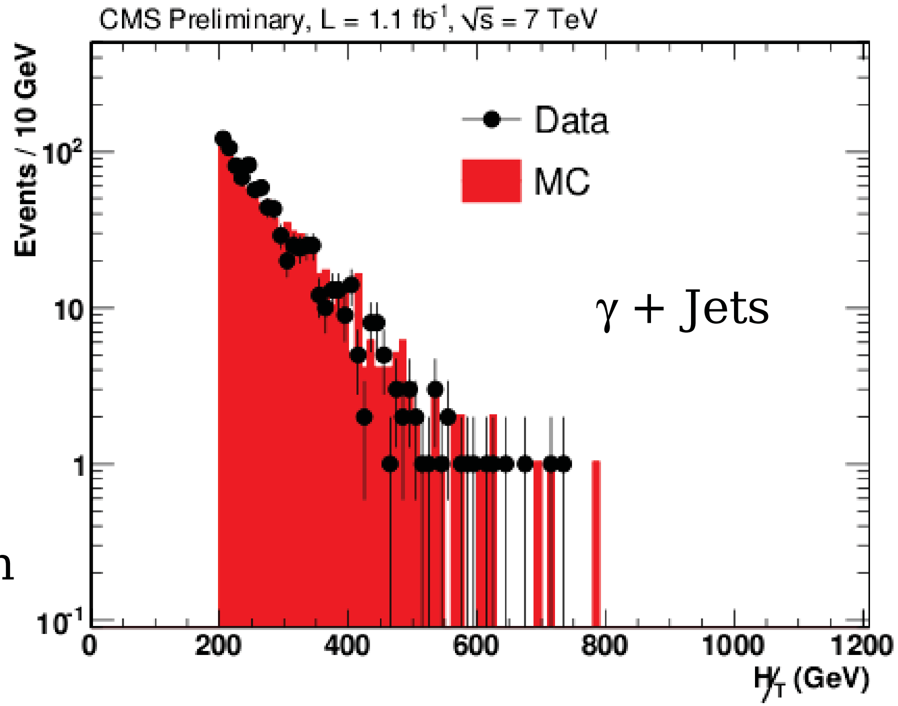
Background estimation for $Z \to \nu\nu$ + Jets





Using γ + Jets events:

- remove the identified photon
- recompute the MET
- correct for photon efficiency and ν BRs

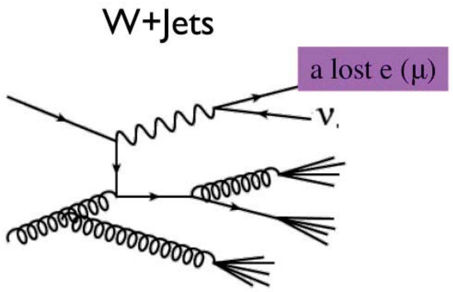


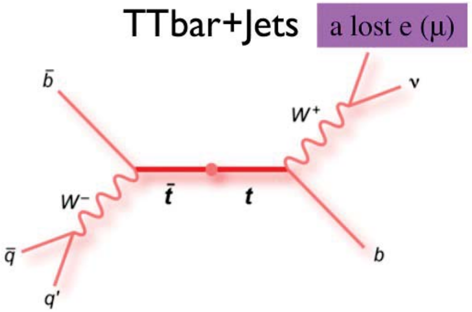
Use Z (→ ll)+ Jets for cross check:

- remove the leptons
- low stat in the signal region
- results agree well in the baseline region

Inclusive search using hadronic jets and MET

W + Jets and ttbar background estimation





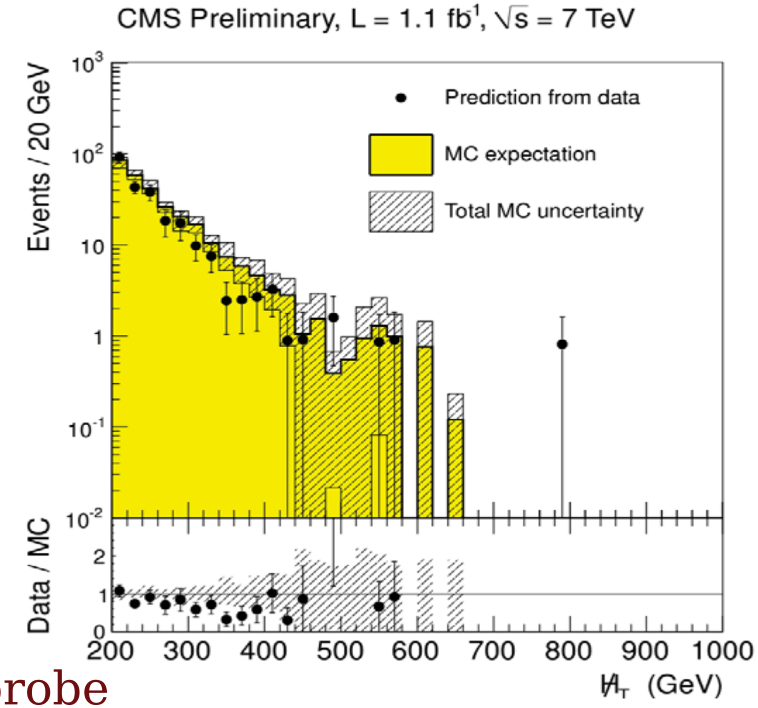
1. W/Top ($\rightarrow$ lost lepton + ν) + jets

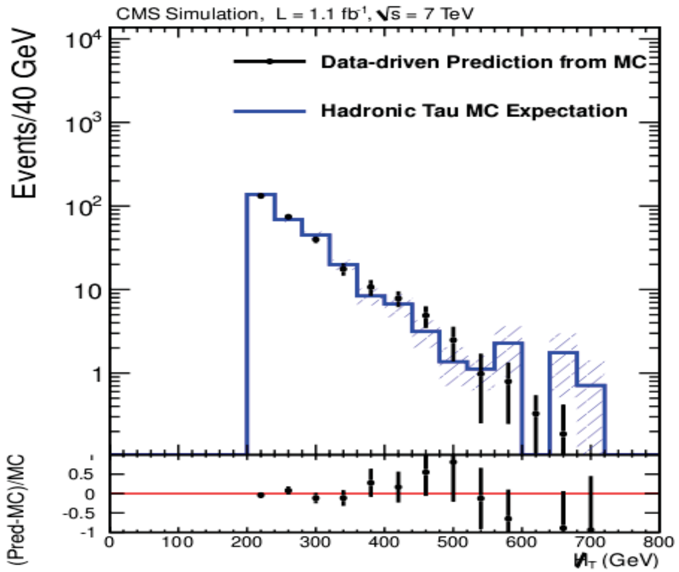
(Lepton is not reconstructed, non isolated or outside acceptance)

- Use well identified muon + Jets sample ($M_T < 100$)
- Measure ID & isolation (in)efficiencies using tag&probe
- Scale the control sample according to (in)efficiencies

2. W/Top ($\rightarrow$ hadronic τ + ν) + jets

- Determine it from muon control sample
- Replace μ with τ using response template to model the fraction of visible momentum
- Recompute all quantities like H_T and MHT





Also correct for muon acceptance, reco eff, and BR ($W\rightarrow\tau\mu$)/BR($W\rightarrow\mu$)*BR ($\tau \rightarrow$ hadrons)

Inclusive search using hadronic jets and MET

QCD background estimation using “Re-balance & Smear”

- Rebalance all jets to overall p_T balance

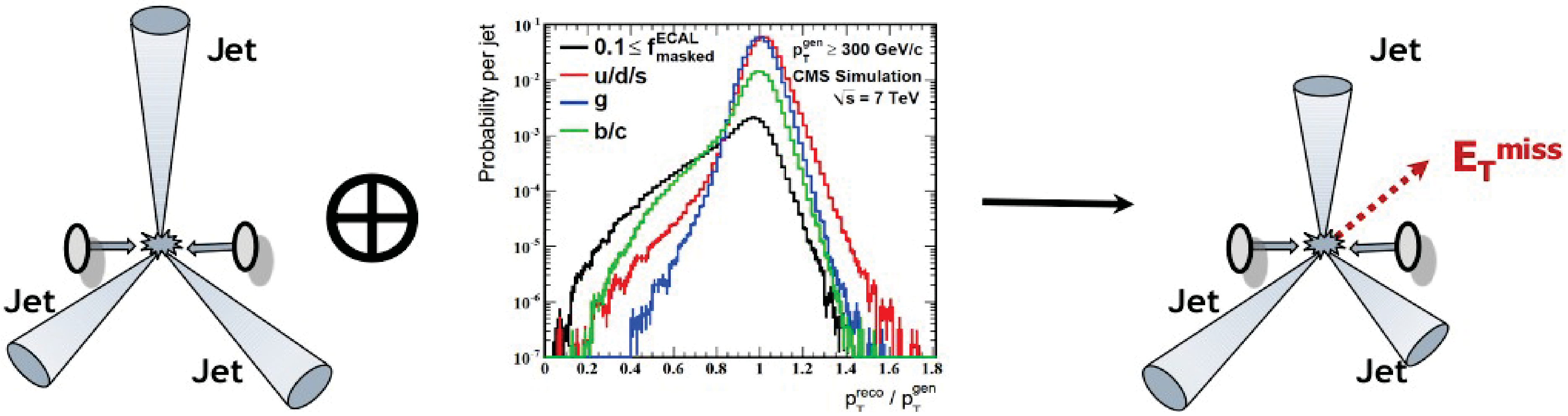
    - robust against seed jet mis-measurement and non QCD processes

- Smear p_T of each seed jet by the jet resolution distribution

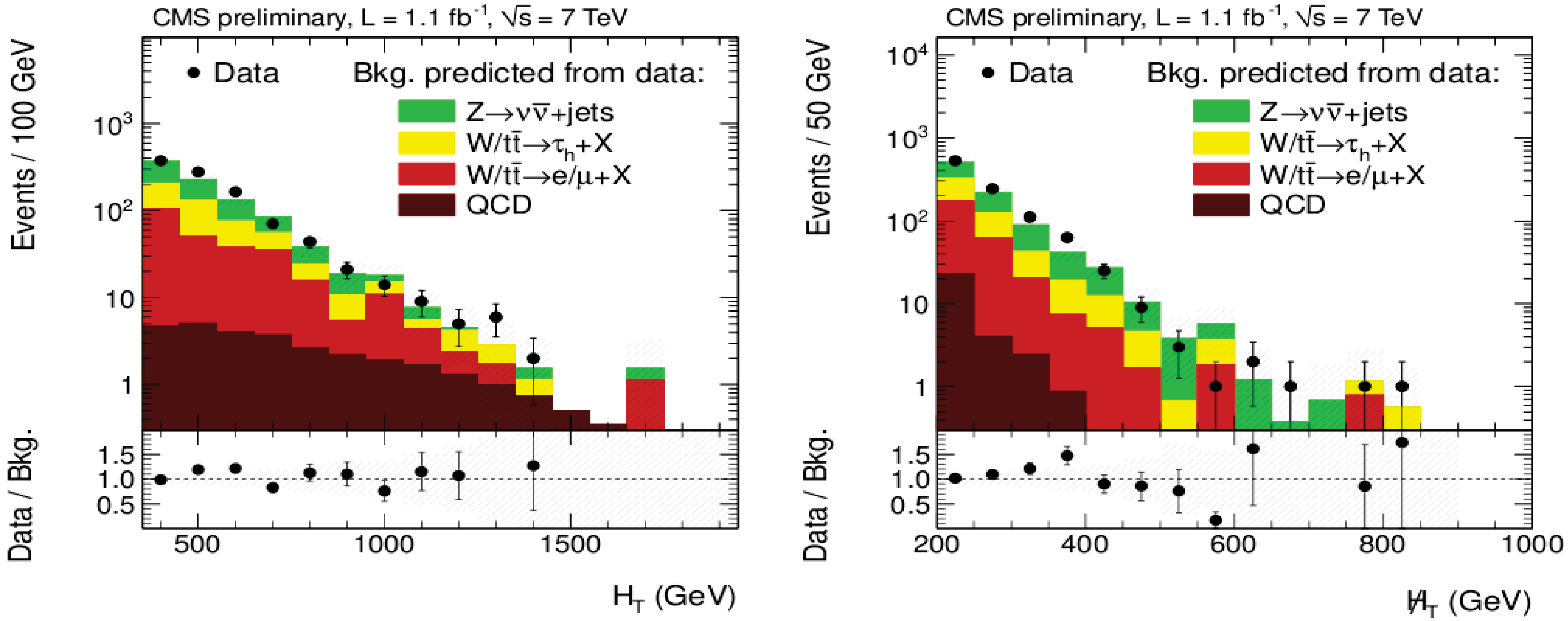
    - from simulation and correct for data/MC differences

- Smearing of the jet results in artificially created MET

    - use this as an estimation of the real MET



Inclusive search using hadronic jets and MET

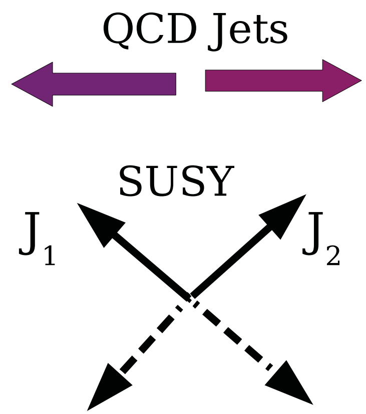


	Baseline (H_T >350 GeV) ($\not{H}_T$ >200 GeV)	Medium (H_T >500 GeV) ($\not{H}_T$ >350 GeV)	High H_T (H_T >800 GeV) ($\not{H}_T$ >200 GeV)	High $\not{H}_T$ (H_T >800 GeV) ($\not{H}_T$ >500 GeV)
$Z \to \nu\bar{\nu}$ from γ+jets	$376 \pm 12 \pm 79$	$42.6 \pm 4.4 \pm 8.9$	$24.9 \pm 3.5 \pm 5.2$	$2.4 \pm 1.1 \pm 0.5$
$t\bar{t}/W \to e, \mu$+X	$244 \pm 20^{+30}_{-31}$	$12.7 \pm 3.3 \pm 1.5$	$22.5 \pm 6.7^{+3.0}_{-3.1}$	$0.8 \pm 0.8 \pm 0.1$
$t\bar{t}/W \to \tau_h$+X	$263 \pm 8 \pm 7$	$17 \pm 2 \pm 0.7$	$18 \pm 2 \pm 0.5$	$0.73 \pm 0.73 \pm 0.04$
QCD	$31 \pm 35^{+17}_{-6}$	$1.3 \pm 1.3^{+0.6}_{-0.4}$	$13.5 \pm 4.1^{+7.3}_{-4.3}$	$0.09 \pm 0.31^{+0.05}_{-0.04}$
Total background	928 ± 103	73.9 ± 11.9	79.4 ± 12.2	4.6 ± 1.5
Observed in data	986	78	70	3

No excess observed in several search regions

Measurements based on α_T

$$\alpha_T = \frac{p_{T,j2}}{M_T} \quad \rightarrow \alpha_T = \sqrt{\frac{p_{T,j2}/p_{T,j1}}{2(1-\cos\Delta\phi)}}$$



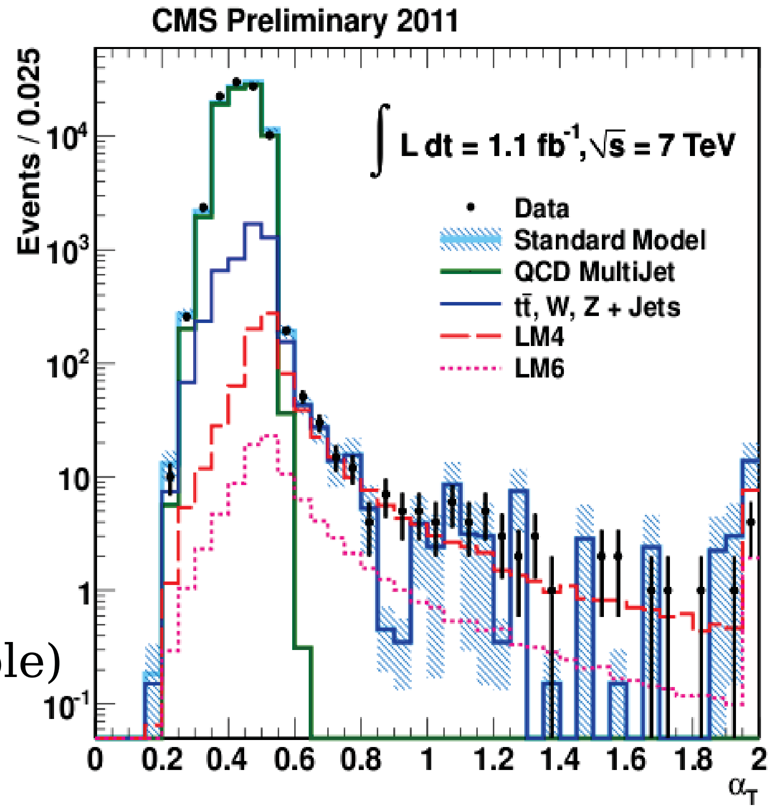
QCD can be heavily suppressed using $\alpha_T > 0.5$

- Recombine jets to pseudo-jets (suppress QCD)
- Njet ≥ 2, $|\eta| < 3.0$, $E_T > 50$ GeV
- $Pt_{Jet1,2} > 100$ GeV, $\alpha_T > 0.55$
- H_T (Scalar sum jet p_T) > 275 GeV
- Veto leptons with $p_T > 10$ GeV (and photons)

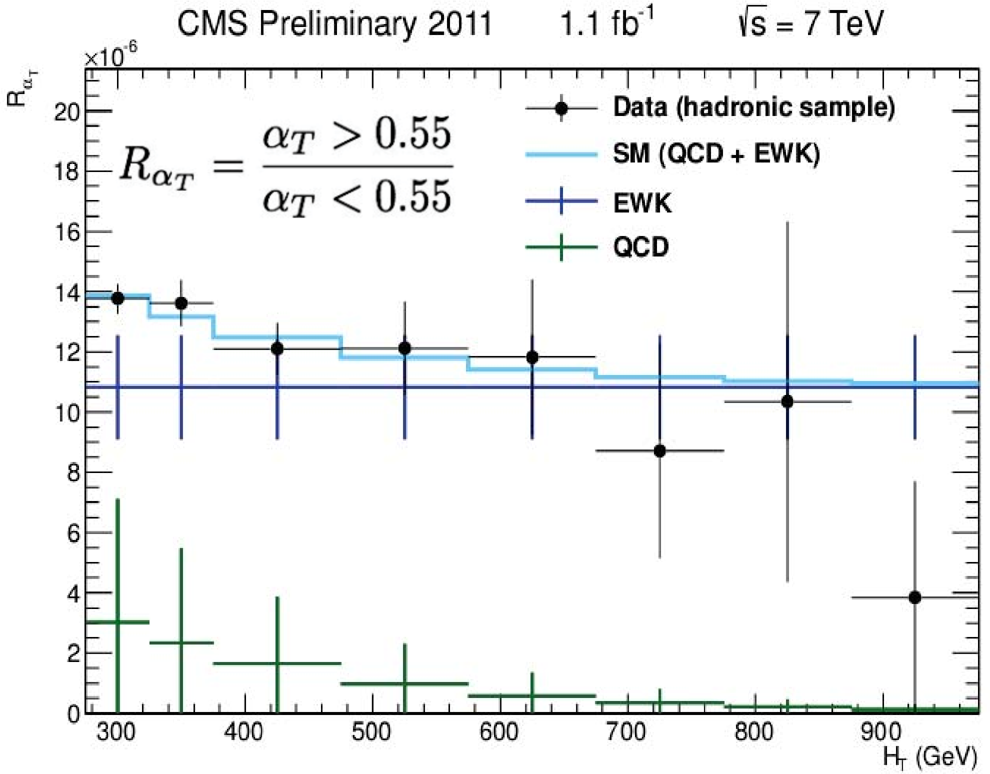
<u>Major backgrounds:</u>

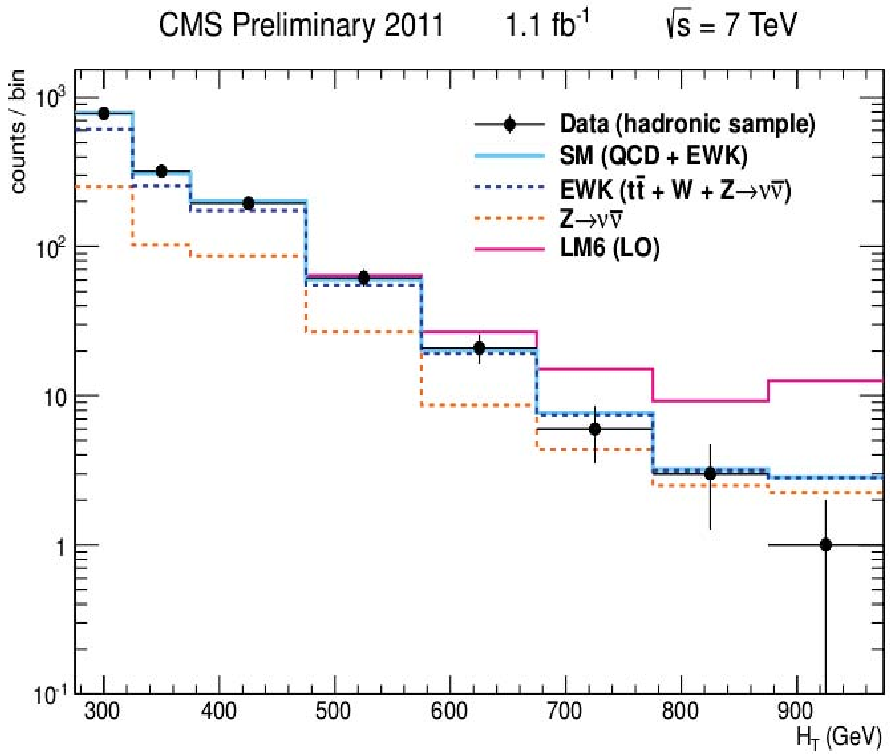
- $Z \rightarrow \nu\nu$ + Jets (Estimation using gamma + Jets)
- W + Jets (Estimate using muon control sample)
- ttbar + Jets (Estimate using muon control sample)

All bkg estimation uses data driven approach



Expected and observed event yields





QCD modeled by exponential distribution

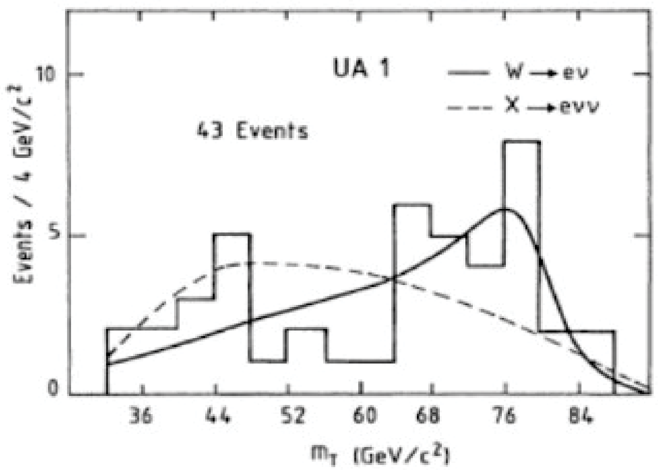
- MET due to jet resolution improves with high H_T, thus $R_{\alpha T}$ drops.

EWK has real MET $\rightarrow$ constant $R_{\alpha T}$

No excess observed in data for various exclusive H_T bins as separate channels

Stransverse momentum (M_{T2}) based study

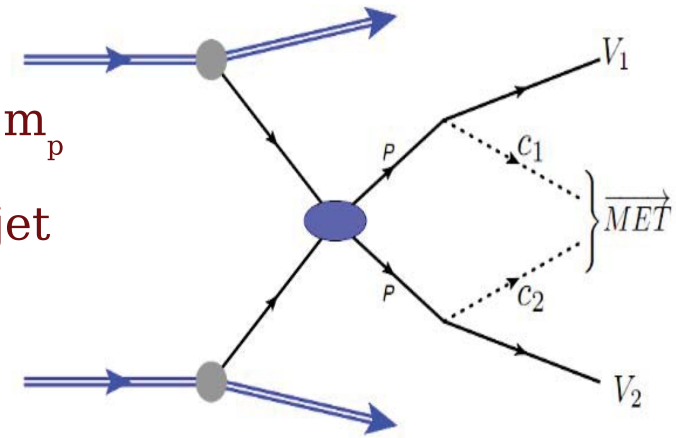
Note the discovery of W boson in UA1



In case of W decay, the mass is given by the transverse projection M_T

M_T has an endpoint at the true-W mass.

- The "stransverse mass" M_{T2} has been proposed as an extension of M_T, where there is one unobserved particle for each chain (hep-ph/9906349)



- If m_c is known, M_{T2} endpoint would correspond to m_p
- In case of multijet events, divide into two pseudo-jet topology using a hemisphere algorithm.
- Minimize over all possible partitions with

Total MET = MET_1 + MET_2 such that:

Stransverse mass = $m_c \geq M_{T2}$

$$M_{T2}(m_c) = \min_{p_T^{c(1)} + p_T^{c(2)} = p_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)} \right) \right]$$

M_{T2} is used as a discovery variable (hep-ph/0907.2713)

Stransverse momentum (M_{T2}) based study

Baseline selection:

At least 3 jets with $p_{T1,2}$ > 100 GeV, $|\eta| < 2.5$

MET > 30 GeV, |MHT – MET| < 70 GeV

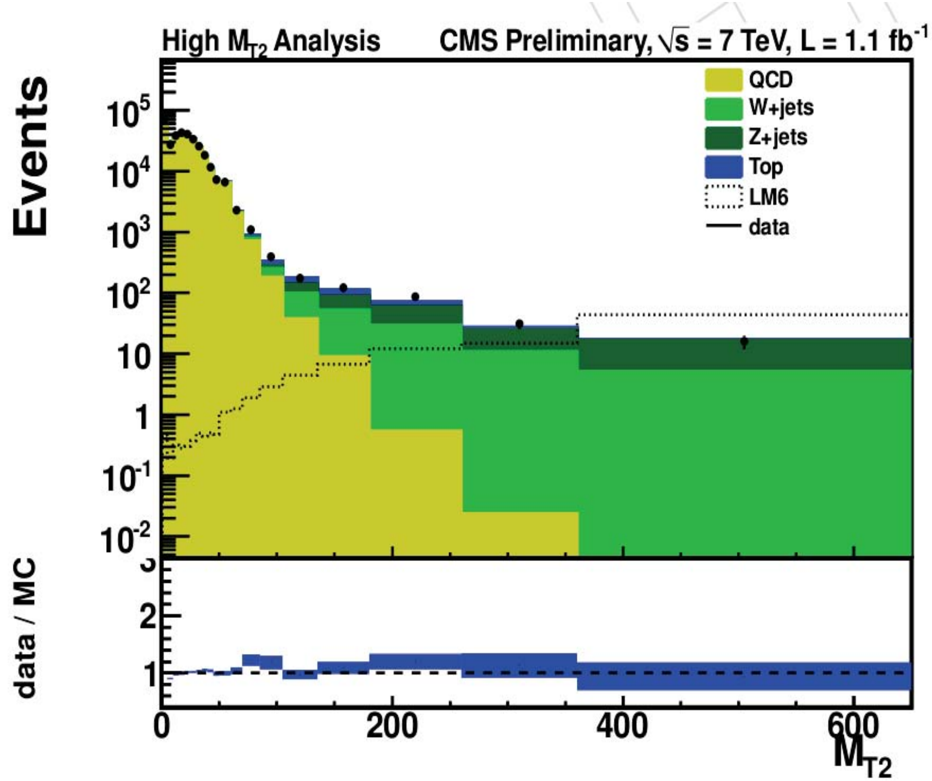
$|\Delta\varphi(\text{Jet, MET})| > 0.3$

Veto isolated electrons and muons

Search regions:

High M_{T2} Analysis:

$H_T > 600$ GeV, $M_{T2} > 300$



Low M_{T2} Analysis :

$H_T > 650$, $M_{T2} > 150$ GeV

Njets ≥ 4 and ≥ 1 b-tagged jet

Major backgrounds:

$Z \to \nu\nu$ + Jets

(Estimate using $W \to l\nu$ events)

W + Jets and ttbar:

(Similar method as previous studies)

QCD – Estimate using matrix method

Stransverse momentum (M_{T2}) based study

Analysis	Predicted BG	Data	σ x BR (pb)	
			observed limit	expected limit
High M_{T2}	12.6 ± 1.3 ± 3.5	12	0.010	0.011
Low M_{T2}	10.6 ± 1.9 ± 4.8	19	0.020	0.014

Expectation agrees with the prediction.

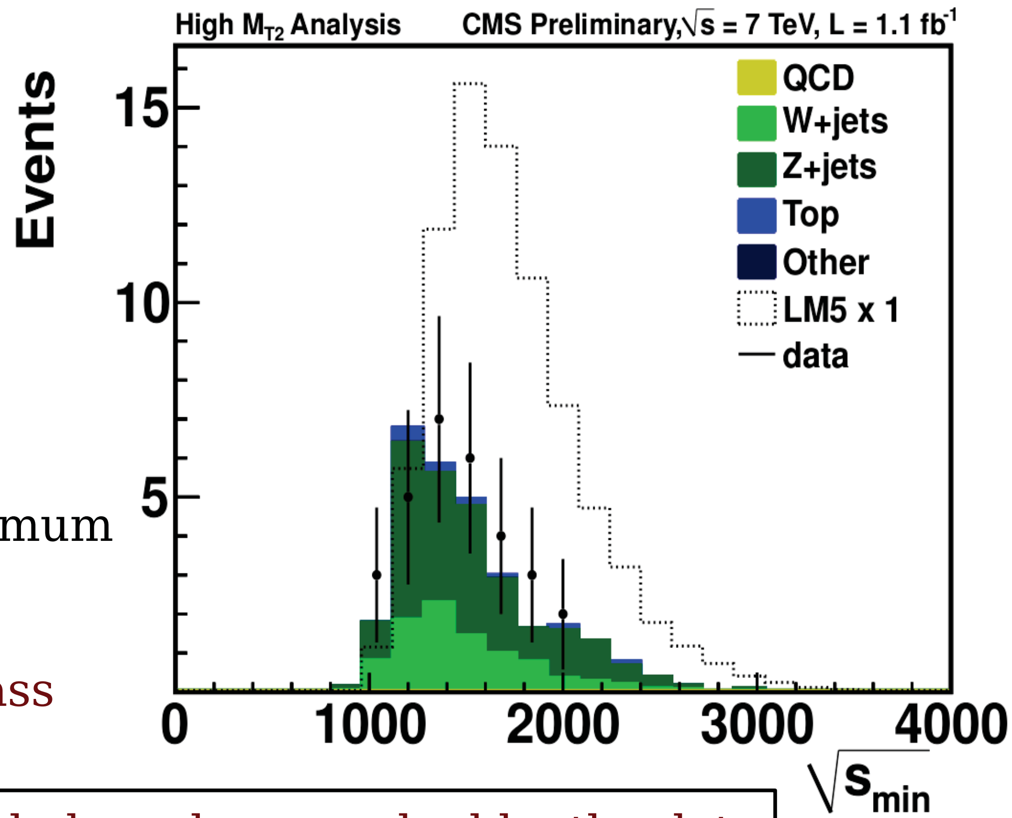
Explore variable sensitive to the observed heavy states (S_{min}):

$$\sqrt{s}_{min}(M_{miss,min}) = \sqrt{M^2_{vis} + P^2_{T,vis}} + \sqrt{M^2_{miss,min} + \not{E}_T{}^2}$$

Proposed in hep/ph/1006.0653

This variable attempts to compute a minimum value for the c.m.s energy.

LM5 peaks at 1.6 TeV, ~ 2 x sparticle mass

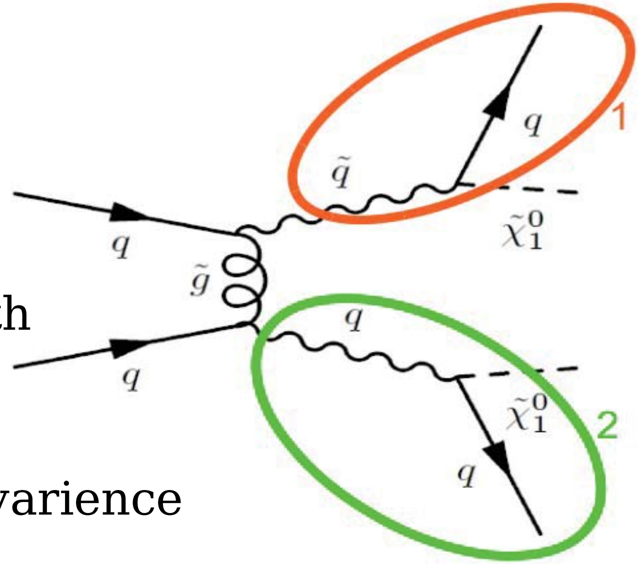


Maximum of ~2000/2 GeV of mass scale have been probed by the data

Inclusive search for squarks and gluinos - "Razor"

Use hemisphere algorithm to cluster events into an effective di-jet system.

C. Rogan, arXiv: 1006:2727



Define: $$M_{\Delta} = \frac{M_{\tilde{q}}^2 - M_{\chi^0}^2}{M_{\tilde{q}}}$$

This is the parton level estimator of the mass-scale with heavy quarks produced at rest.

Event-by-event estimator and with longitudinal boost invarience

$$M_R = 2\sqrt{\frac{(E_1 \cdot p_{z,2} - E_2 \cdot p_{z,1})^2}{(p_{z,1} - p_{z,2})^2 - (E_1 - E_2)^2}}$$

$$M_T^R = \sqrt{\frac{\not{E}_T(p_{T,1} + p_{T,2}) - \vec{\not{E}}_T(\vec{p}_{T,1} + \vec{p}_{T,2})}{2}}$$

→ Transverse estimator

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

→ Ratio of scales

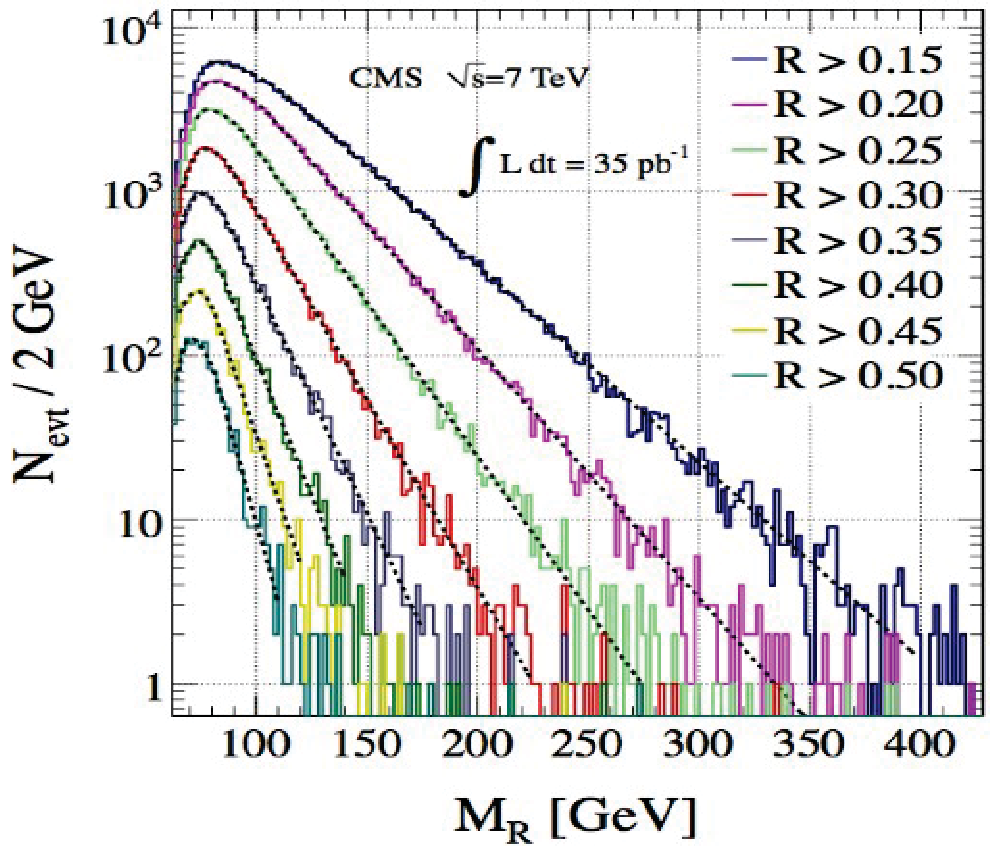
For the QCD background

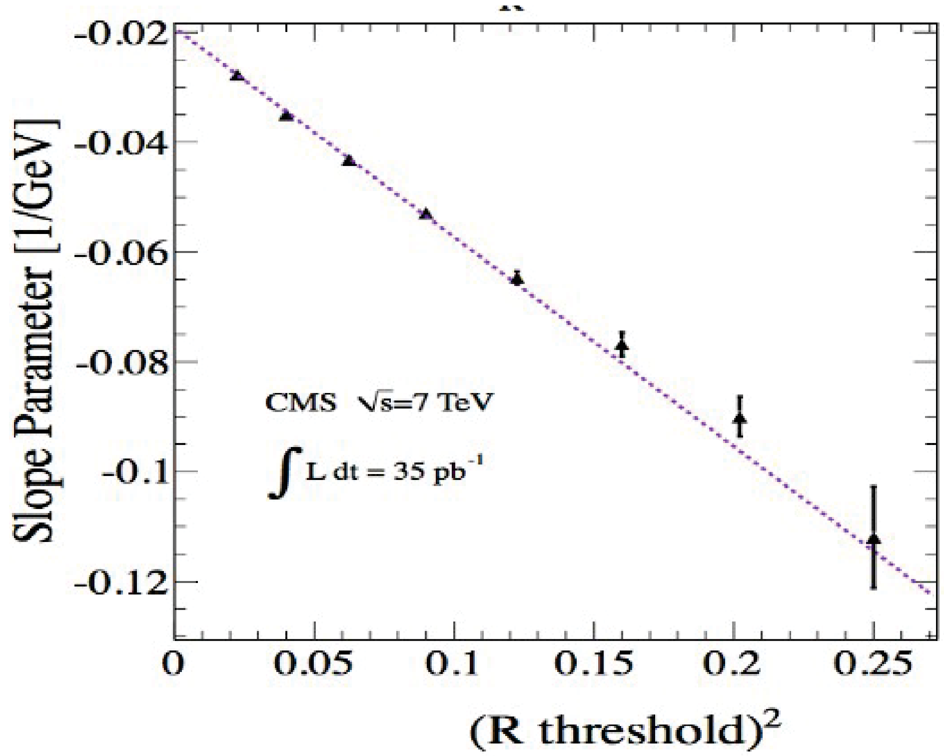
$$M_R = \sqrt{\hat{s}}$$

is falls like a power law

Let us look at the data → See next

Inclusive search for squarks and gluinos - “Razor”





QCD events (without well identified leptons):

- M_R falls exponentially
- Slope depends linearly on R^2

Prediction:

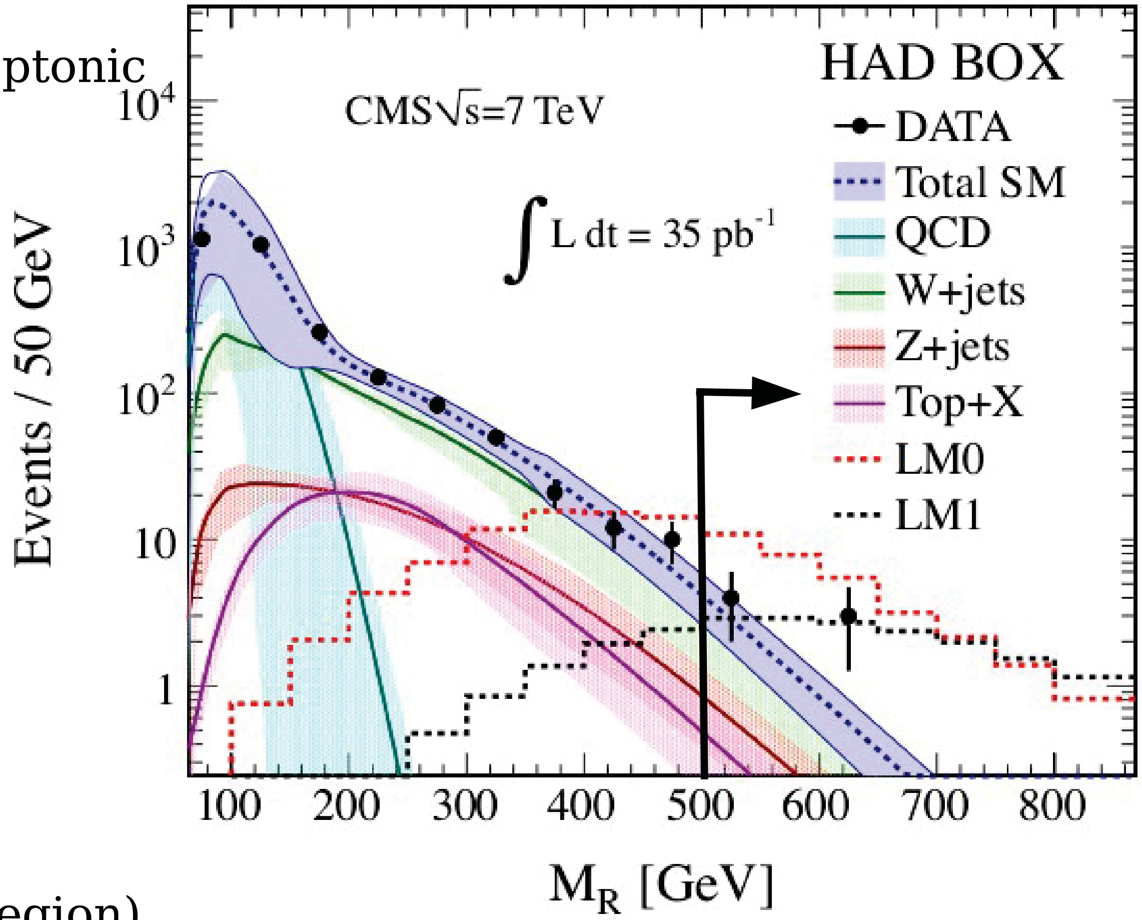
- Extrapolate to signal-region with M_R > 500 GeV, R > 0.5

Inclusive search for squarks and gluinos - "Razor"

Background modeling:

- Classify events as hadronic and leptonic
- Use shapes from leptonic boxes
- Use QCD shape from dijet data
- Fit in 80 < M_R (GeV) < 400
- Extrapolate in high M_R

arXiv:1107.1279 [hep-ex]



Event Selection:

- Njet ≥ 2 with p_T > 30 GeV
- Δφ (hemispheres) < 2.8
- R > 0.5, M_R > 500 GeV (Signal region)

	Expected	Observed
MR > 500 GeV	5.5 ± 1.4	7

Searches in leptonic modes in SUSY

- Searches using One lepton + Jets + MET (CMS SUS-11-015)

- Opposite sign di-leptons studies with Z veto (CMS SUS-11-011)

- Opposite sign di-leptons with Z

    - *Jet-Z* balance method (CMS SUS-11-012)

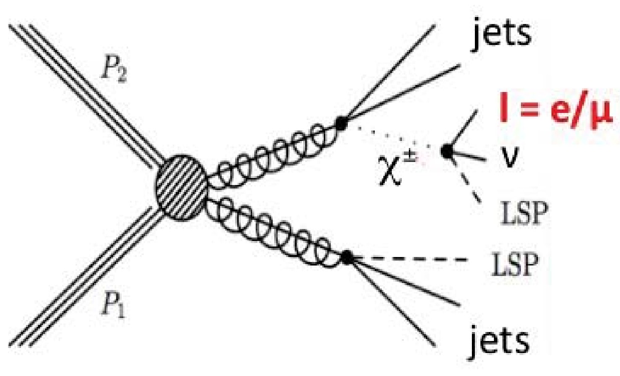
    - MET template method (CMS SUS-11-017)

- Same sign di-leptons searches (CMS SUS-11-010)

Note : Multi-lepton modes are currently being updated with full luminosity.

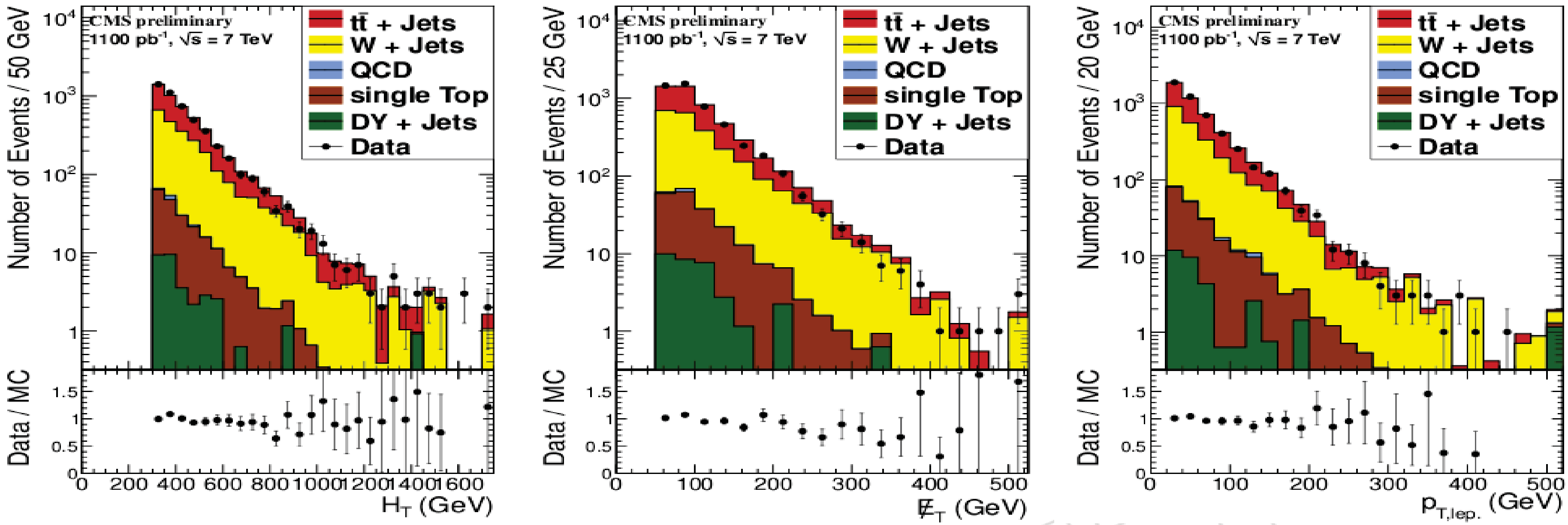
Single lepton search with Jets and MET

Signature: Exactly one lepton, Jets and large MET



- Require exactly one isolated lepton with p_T > 20 GeV
- At least 3 Jets with P_T > 40 GeV
- H_T > 300 GeV and MET > 60 GeV

Muons only, electrons similar. See backup



- SM simulations agree well with the data
- Dominant contributions are from ttbar, W + Jets (~90%)
- Determine the backgrounds from data using two complementary methods

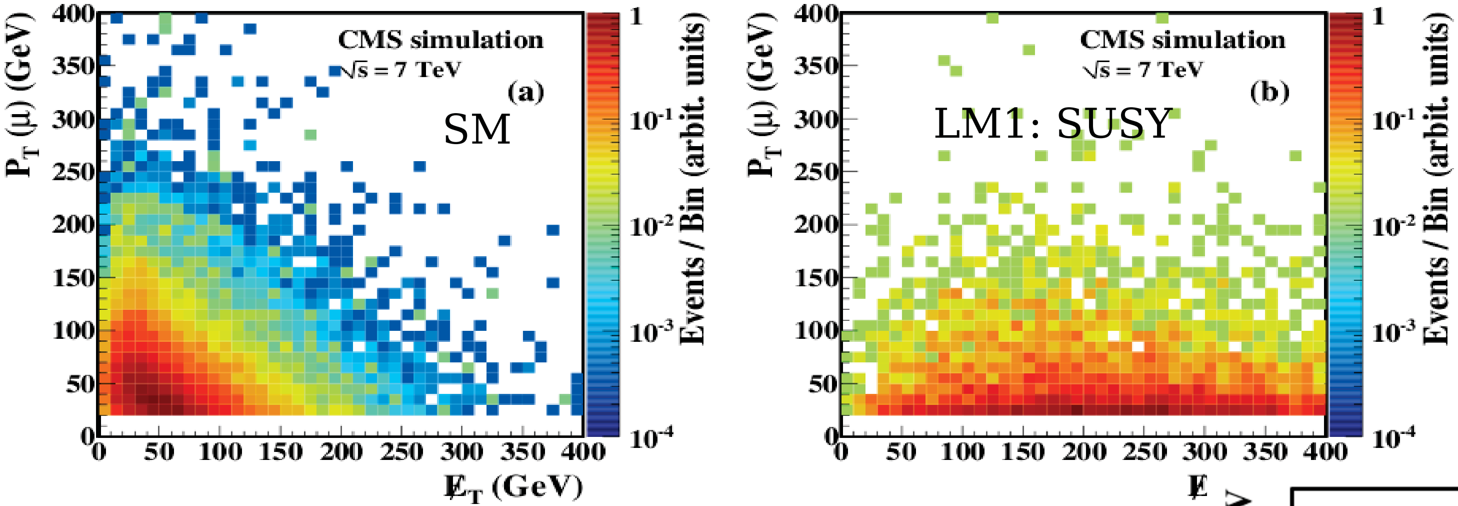
    a) Lepton Spectrum method, b) Lepton projection method

Lepton Spectrum method

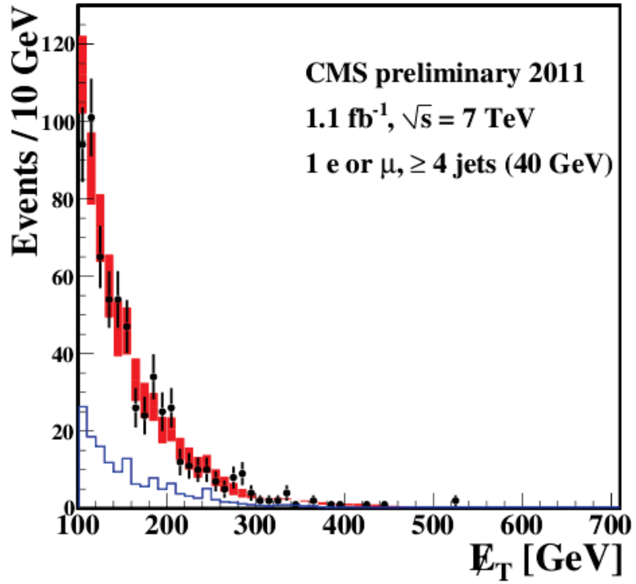
In SM events, the neutrino and lepton p_T are anti-correlated in an event

$\Rightarrow$ Overall spectra are similar

In SUSY event, the correlation between MET and lepton p_T is very different



- For ttbar & Wjets: use muon p_T spectrum
  - Correct for acceptance efficiency and polarization effects
  - Smear lepton p_T for instru. MET using QCD templates
- Residual bkg are from ttbar dileptons and tau decays
  - Use control samples with dileptons and emulate the mechanism to loose a lepton
  - Bkg from tau-to-lepton are modeled based on 1lep. Events
  - QCD is small (~1%), use ABCD between Rel Iso & MET



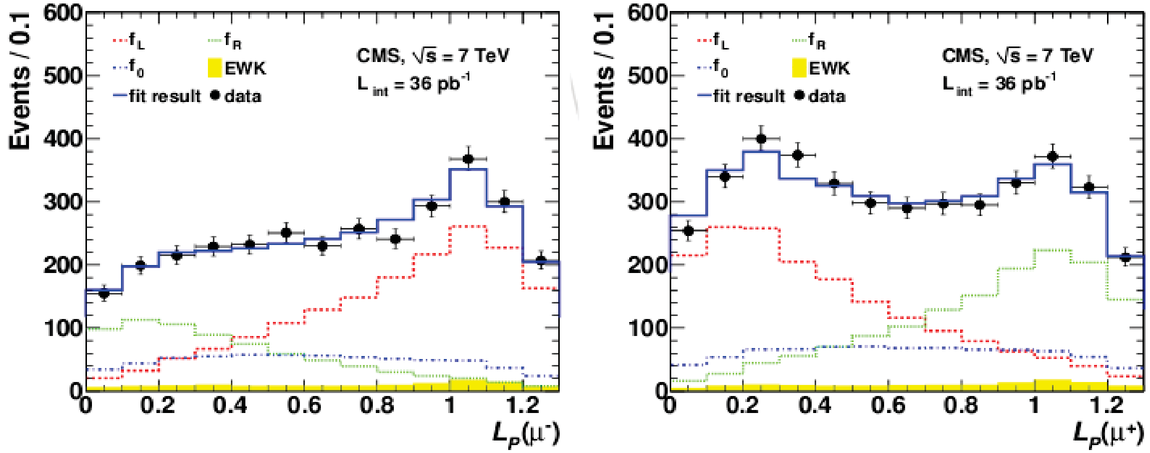
Lepton projection method

Sensitive to the helicity angle of the lepton in the W rest frame

PRL 107 (2011) 021802

$$L_P = \frac{\vec{p}_T(\ell)\cdot\vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

Left-handed W gives most of its momentum to left-handed lepton

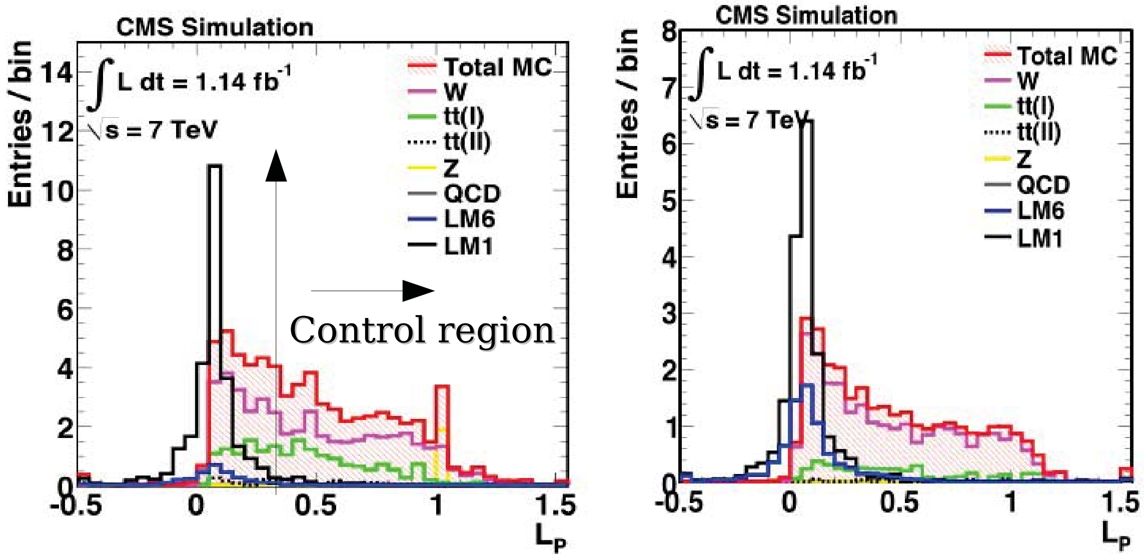


Left-handed = f_L; Longitudinal = f_0; Right-handed = f_R

Define leptonic mass scale:

$S_T^{lep} = p_T^{lep} + MET$

350 GeV < S_T^{lep} < 450 GeV   450 GeV < S_T^{lep}



<u>For SUSY:</u>

- Leptons can be soft
- Large angle between MET and the lepton ⇒ small L_p

Study in bins of S_T^{lep}:

Control region: $L_p > 0.3$

Signal region: $L_p < 0.15$

Extrapolate from control to signal region for the final bkg prediction

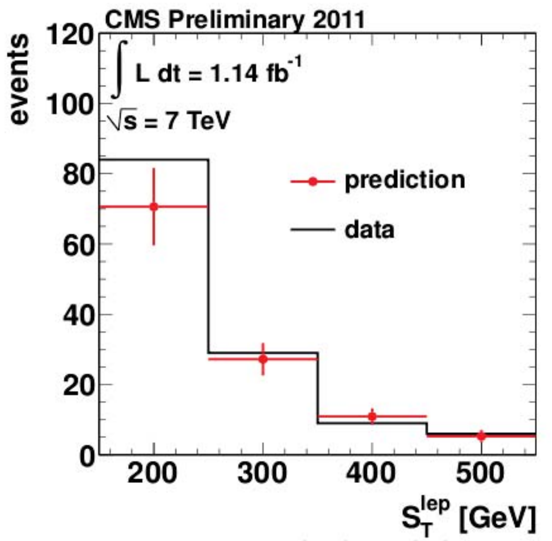
Single lepton search with Jets and MET

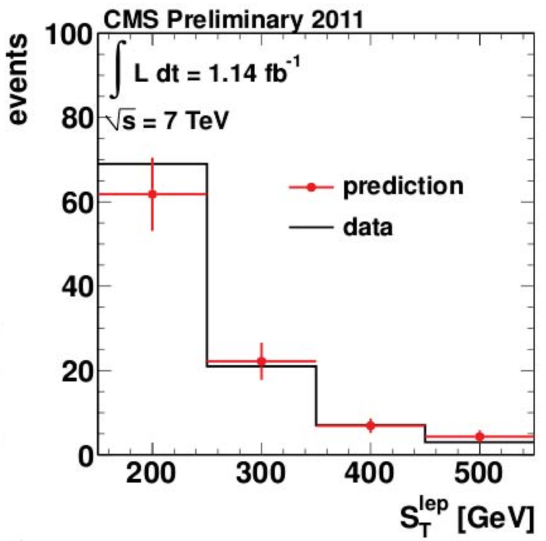
- **Lepton spectrum method:**

Sample	**Loose selection** H_T > 500 GeV, H_T^{miss} > 250 GeV	**Tight selection** H_T > 1 TeV, H_T^{miss} > 350 GeV
Total predicted SM	49.8 ± 8.8 ± 10.8	12.1 ± 4.3 ± 3.6
Data	52	8

- **Lepton projection method:**

S_T^{lep} range/GeV	**SM estimate μ**	**Data μ**	**SM estimate e**	**Data e**
150 – 250	70.6 ± 11	84	61.8±8.7	69
250 – 350	27.2 ± 4.6	29	22.2±4.4	21
350 – 450	10.9 ± 2.3	9	6.9±1.7	7
>450	5.3 ± 1.8	6	4.3±1.5	3





No observed excess

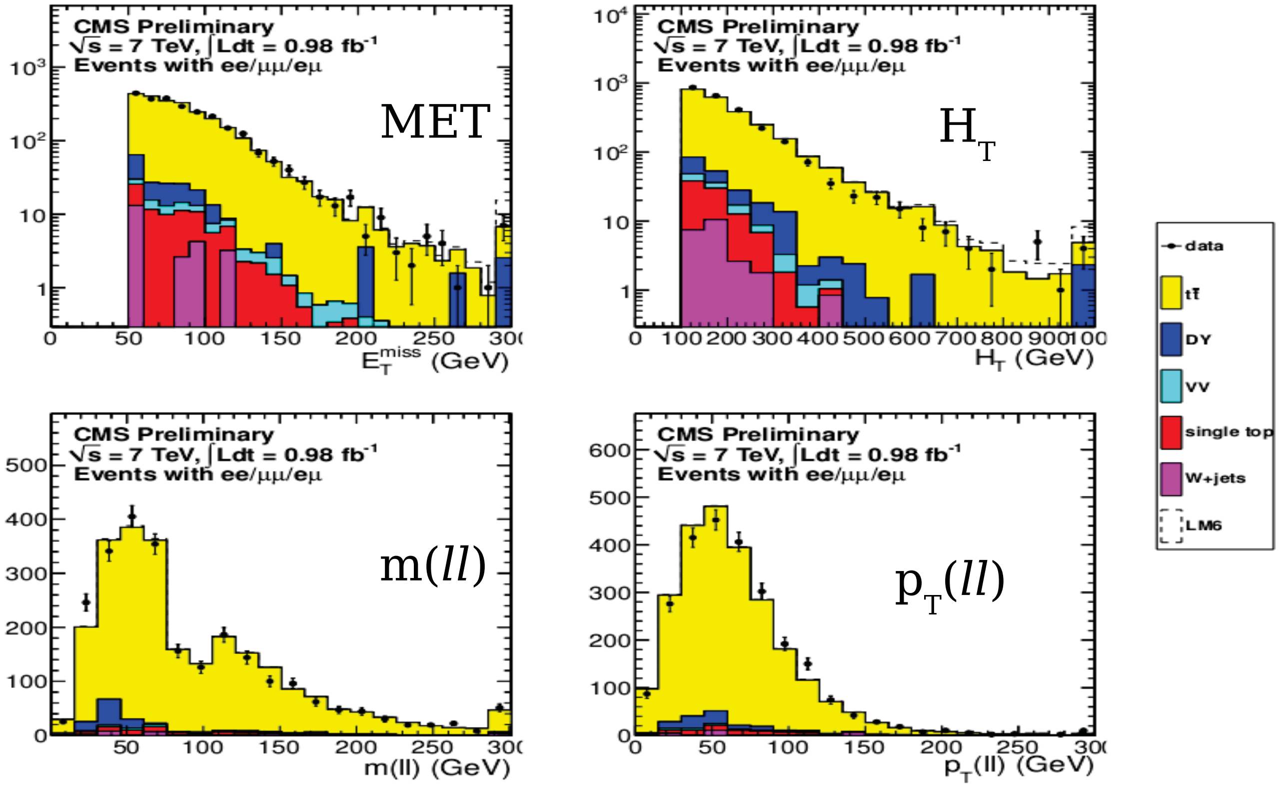
Opposite sign dilepton search

Requirement of di-leptons reduces W+Jets & QCD drastically, leaving mostly top

Use data driven techniques to predict bkg in tails of H_T and MET distribution

<u>Baseline selection:</u>

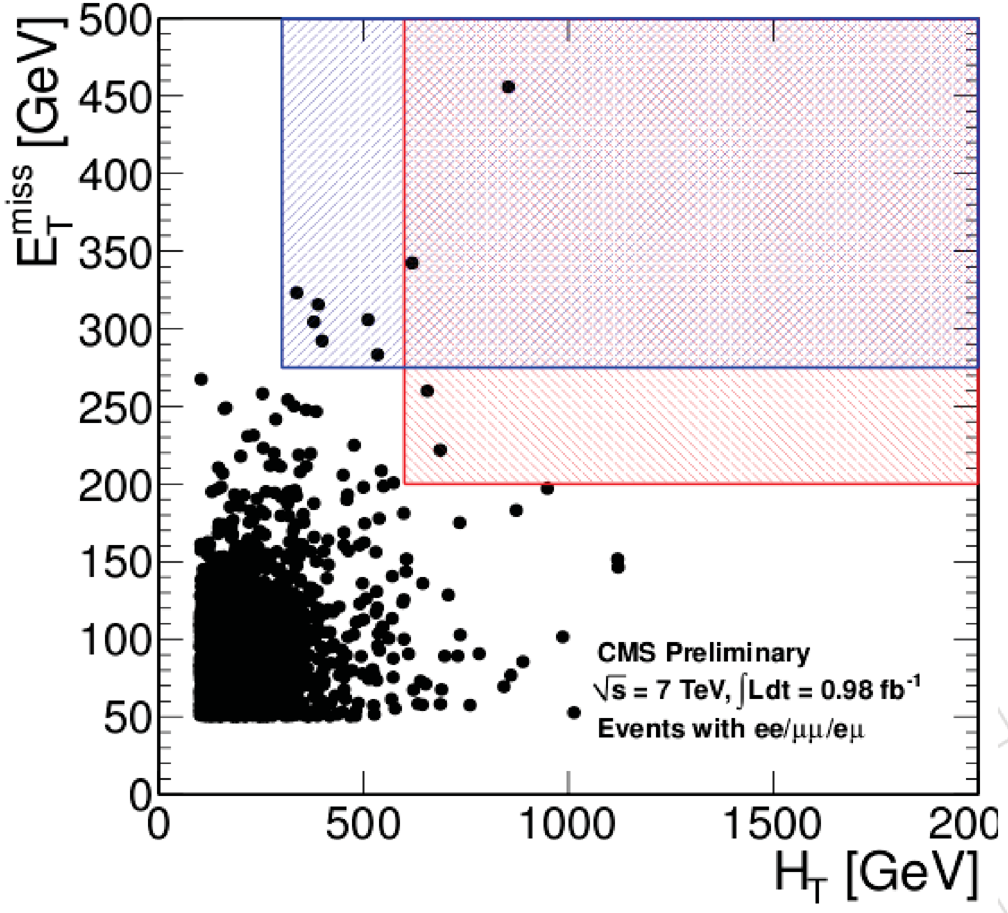
- Two isolated leptons (e, μ): one with p_T > 20 GeV, other with p_T > 10 GeV
- At least 2 jets with p_T > 30 and |η| < 3.0, MET > 30 GeV, H_T > 100 GeV
- Veto same-flavor pairs in Z mass window (76, 106) and m_{ll} < 12 GeV



Simulation shape agrees with the data in various distributions

Opposite sign dilepton search regions

Define signal regions in tails of MET and H_T



Derive data driven background Estimations ⇒ See Next

High MET signal region (MET > 275 GeV, H_T > 300 GeV)

High H_T signal region (MET > 200 GeV, H_T > 600 GeV)

Opposite sign dilepton search (Lepton spectrum method)

Two data driven methods used in this search:

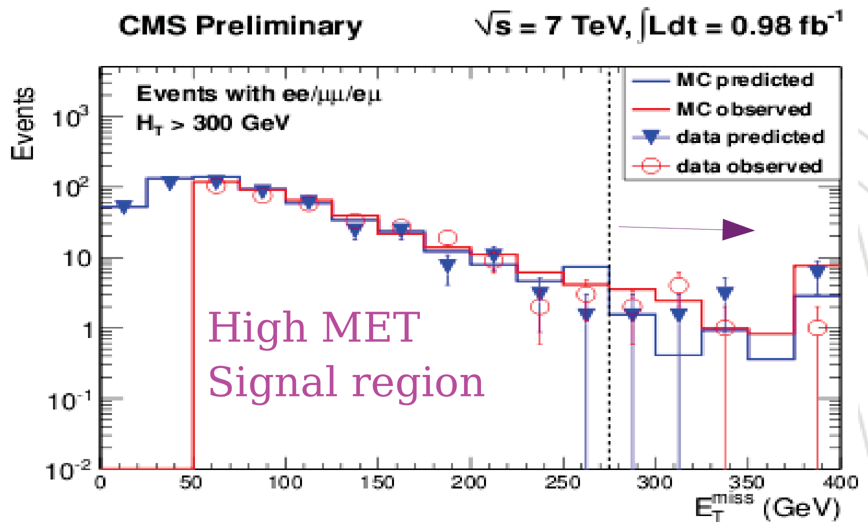
a) Lepton spectrum method ($p_T(ll)$) [V. Pavlunin, PRD 81, 035005 (2010)

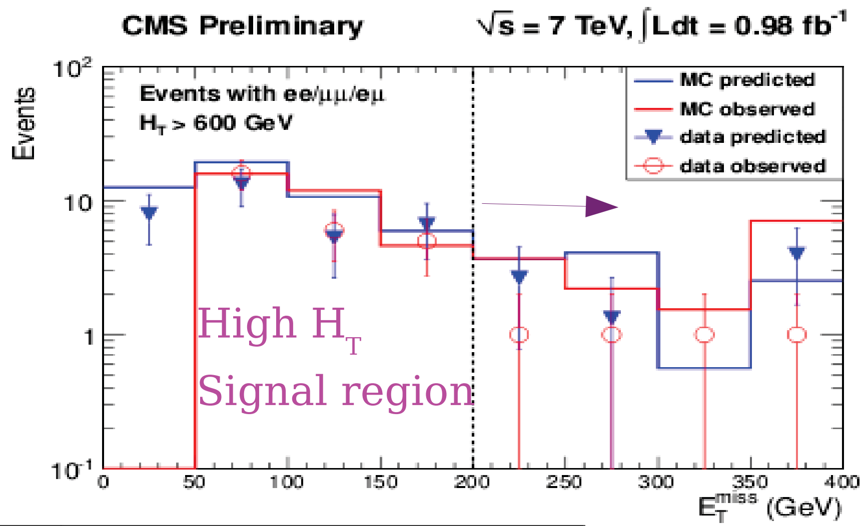
This method relies on the $p_T(ll)$ distribution to get $p_T(\nu\nu)$

In SM, the neutrino and the lepton p_T are anti-correlated in an given event

- Overall spectra are similar

Corrections are needed to account for cuts on MET, polarization effects due to Ws. Both of these are well modeled in MC.





	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)

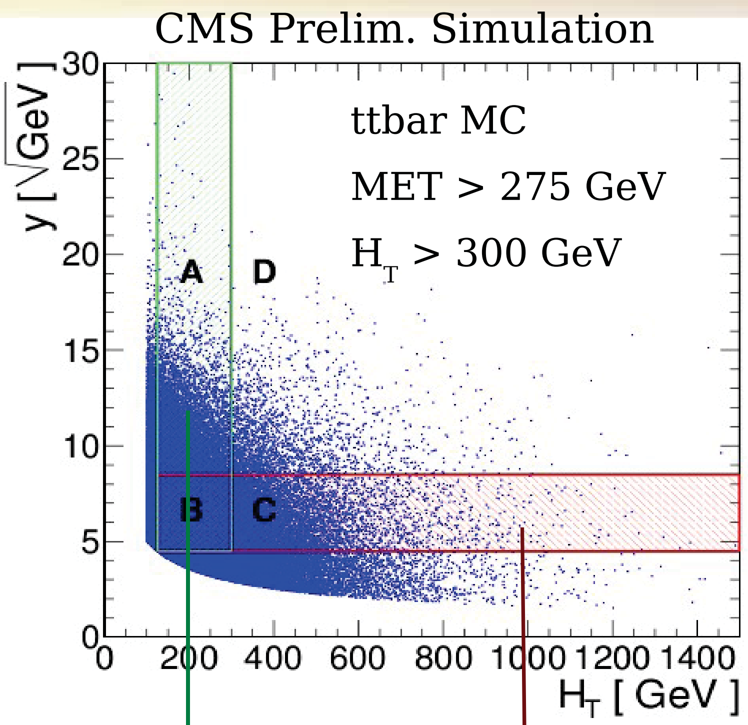
The observation is consistent with the prediction

Opposite sign dilepton search (ABCD' method)

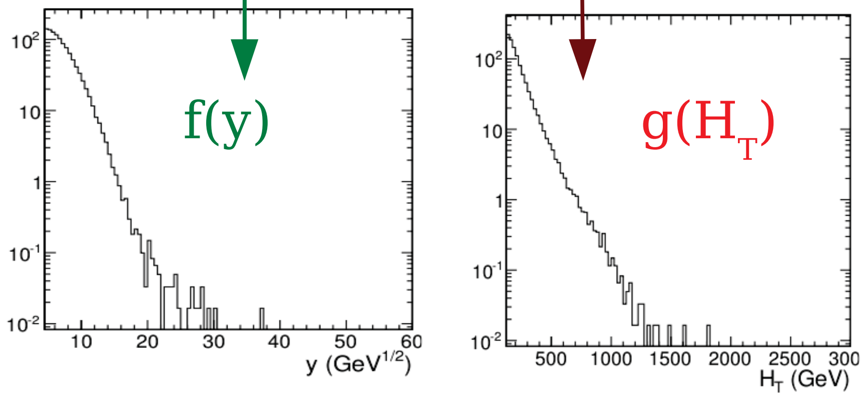
b) ABCD' method (Use weakly correlated variables, H_T & y)

- Measure in data the H_T & $y = MET/\sqrt{H_T}$ distributions f(y), g(H_T).
- Predict yields in a given region using:

$$\frac{\partial^2 N}{\partial y \partial H_T} = f(y)g(H_T)$$



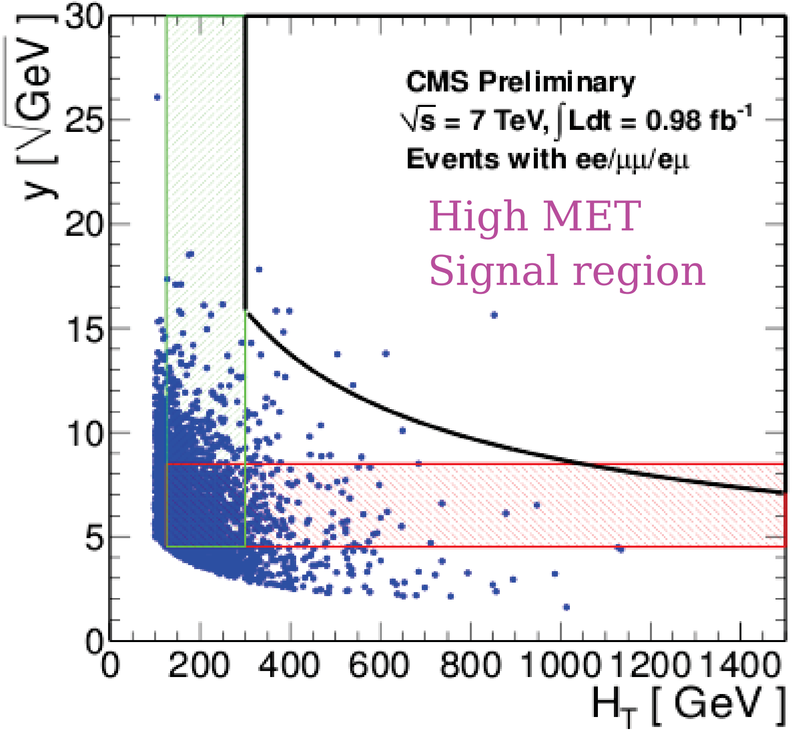
- Method validated using toy MC studies (~1fb^{-1})

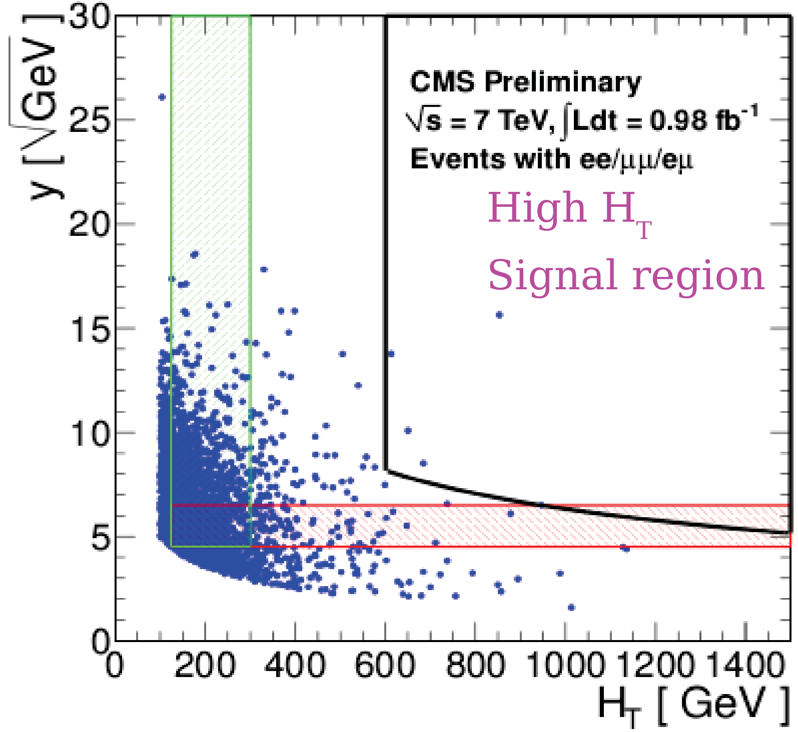


Bin contents of f(y) and f(H_T) are smeared according to their poisson uncertainties for stat uncert. in the bkg prediction.

Opposite sign dilepton search (ABCD' method)

b) ABCD' method





	high $E_{\mathrm{T}}^{\mathrm{miss}}$ 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)
[illegible]	[illegible]	[illegible]

Prediction yields are consistent with MC and the observation

Opposite sign dileptons – Opposite flavour Subtraction

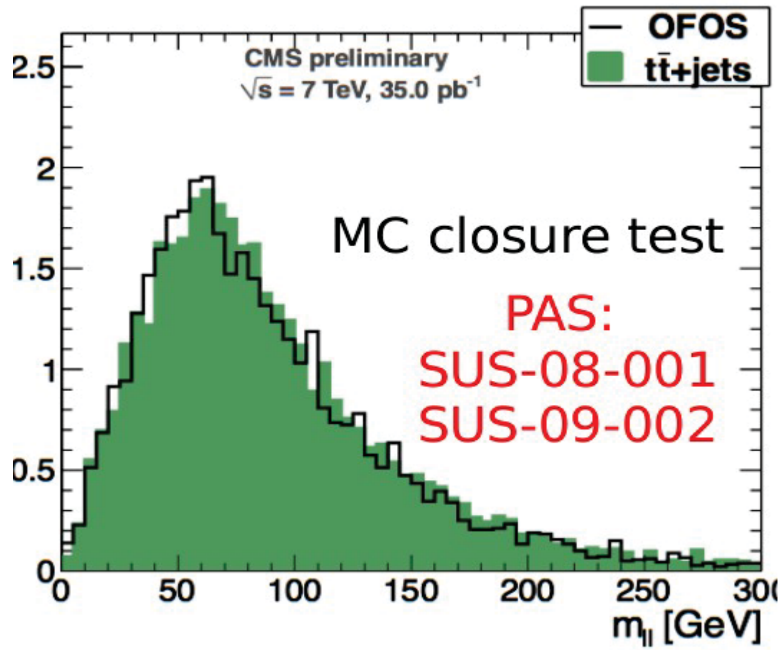
- Predict number of ttbar from dileptons μμ and ee from eμ events →

$$n_{ee} = \frac{1}{2} n_{e\mu} r_{\mu e}, \quad n_{\mu\mu} = \frac{1}{2} \frac{n_{e\mu}}{r_{\mu e}}$$

- Lepton p_T > 10 GeV

Relies on $r_{\mu e} = N(Z \to ee)/N(Z \to \mu\mu)$

- Known within 2% syst.



Quantify the excess of SF Vs OF events using:

$$\Delta = 1/r_{\mu e} N(ee) + r_{\mu e} N(\mu\mu) - N(e\mu)$$

Note: $\Delta = 0$ for dominant SM bkg's (ttbar, WW, DY $\to \tau\tau$)

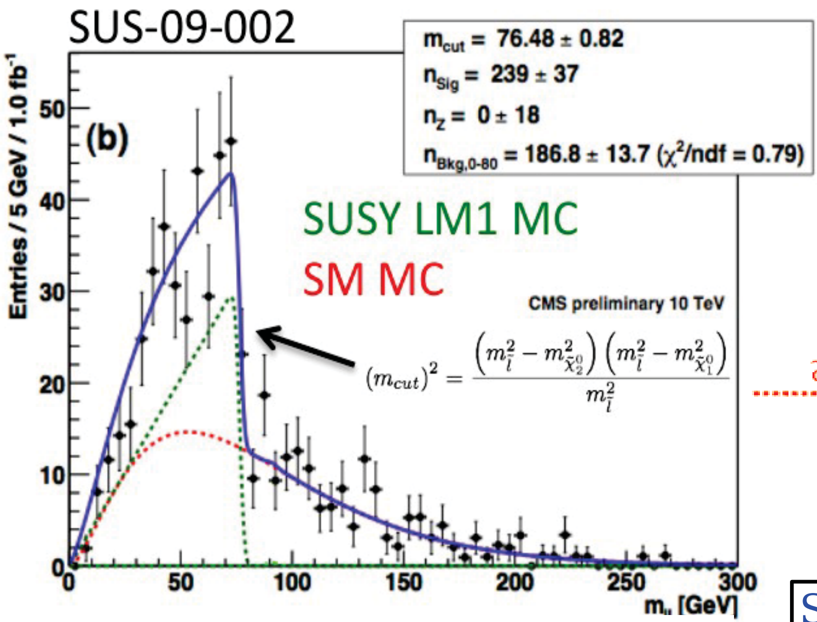
	high E_T^{miss} signal region	high H_T signal region
observed Δ	3.6 ± 2.9 (stat) ± 0.4 (syst)	-0.9 ± 1.8 (stat) ± 1.1 (syst)

No evidence of any excess

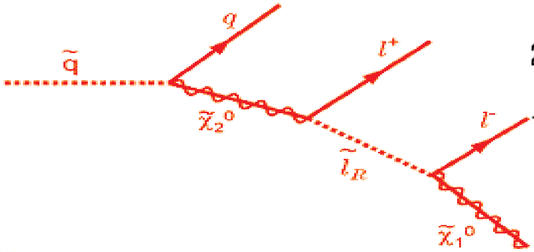
Search for kinematic edge in m(*ll*) distribution

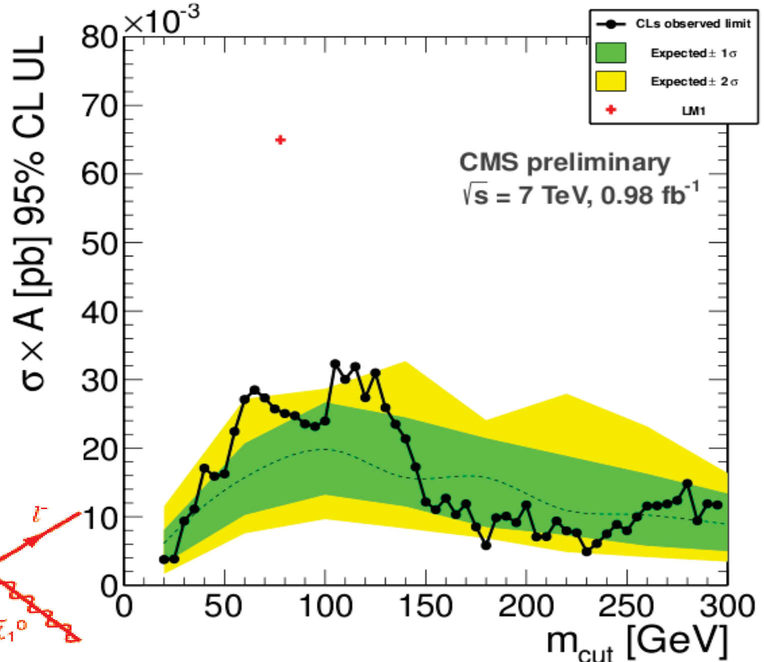
- Perform extended maximum likelihood fit simultaneously to ee, μμ, eμ events
  - ee/μμ with signal + Z + bkg
  - em: bkg only
- Validate fit in control region dominated by ttbar (MET > 100 GeV, 100 < H_T < 300)
- Search for NP in signal region (MET > 100 GeV, H_T > 300 GeV)
- Observe no evidence for kinematic edge ⇒ Set upper limit on the signal

$$\chi_2^0 \to \ell\tilde{\ell} \to \chi_1^0\ell^+\ell^-$$



$$T(m_{ll}) = \frac{1}{\sqrt{2\pi}\sigma}\int_0^{m_{cut}} dy \cdot y e^{\frac{-(m_{ll}-y)^2}{2\sigma^2}}$$





Shape depends on 1 parameter (position of the edge)
- Perform fit to m_{cut} for LM1 benchmark point
- Scan edge position and extract Upper limit

Opposite sign di-leptons with Z (*Jet-Z* balance method)

Search for SUSY in Z final state (e.g $\chi^2_0 \rightarrow Z\, \chi^1_0$)

- Two isolated leptons (e, μ): p_T > 20 GeV
- At least 3 jets with p_T > 30 and |η| < 3.0
- Require same-flavor pairs in Z mass window $|m_{ll} - Z| < 20$ GeV

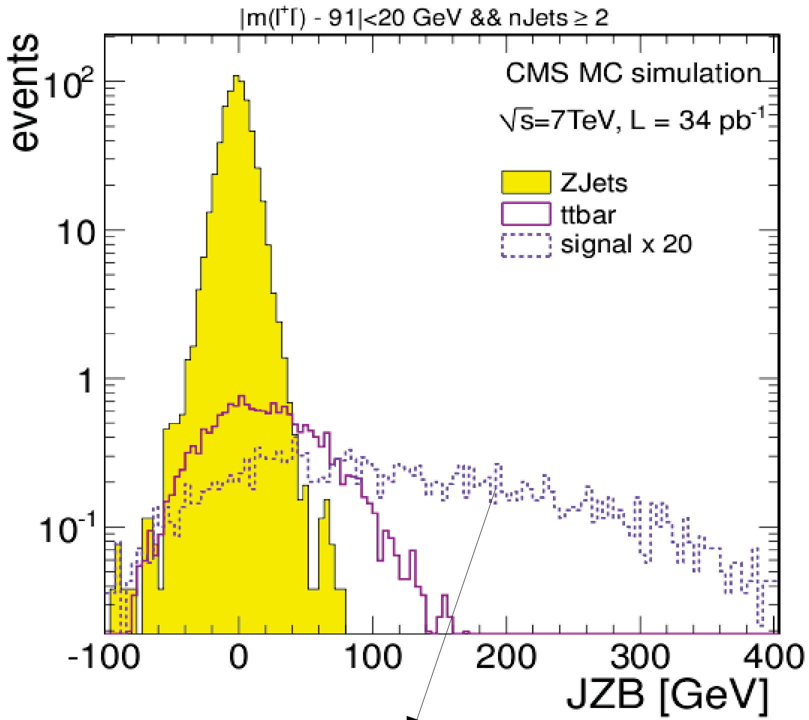
Backgrounds:

- Z + Jets + instrumental MET
- OSSF dileptons from ttbar
  (Predict using OSOF subtraction method)

Define:

$$JZB = \left|\sum_{jets} \vec{p}_T\right| - \left|\vec{p}_T^{\,Z}\right|$$

JZB < 0: Control region

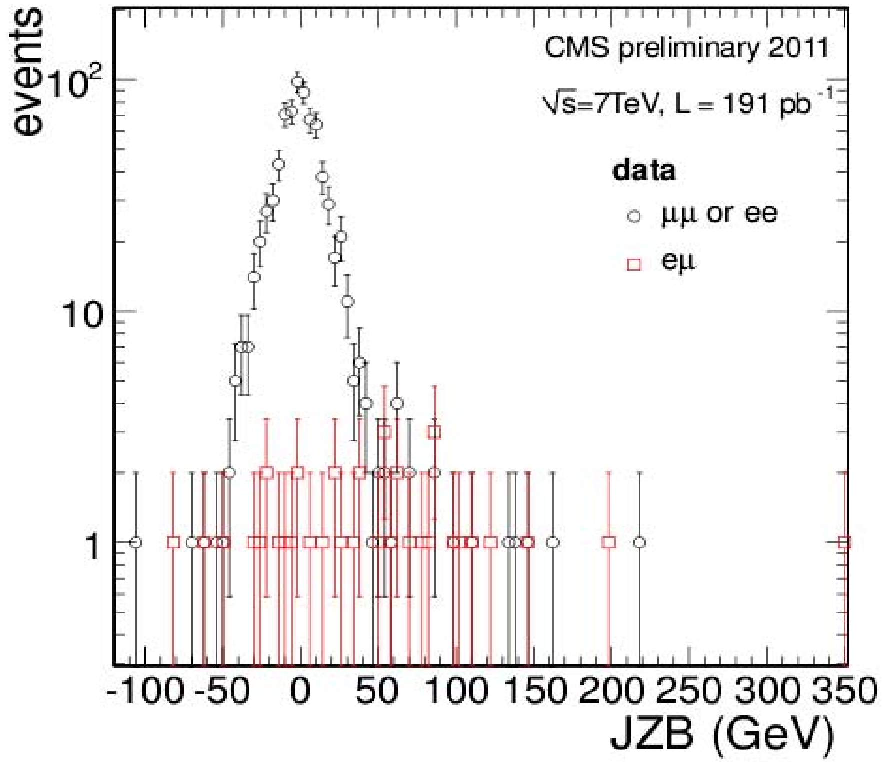


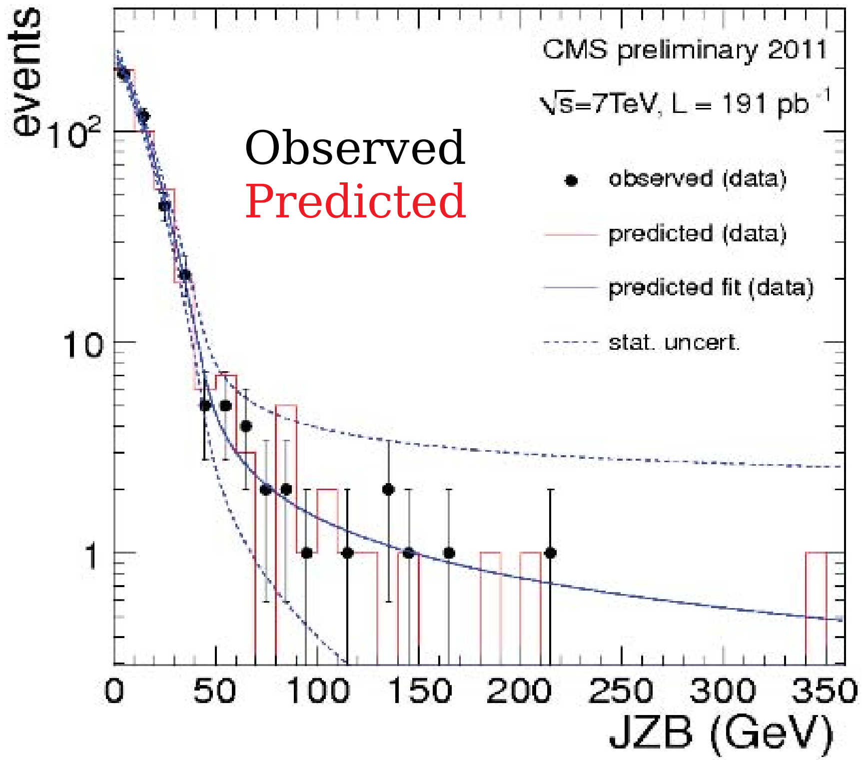
Use JZB (<0) peak events to predict
JZB (>0) peak events after the eμ subtraction

Substantial tail for SUSY in JZB > 0 events

Opposite sign di-leptons with Z (*Jet-Z* balance method)

Two regions defined: JZB > 50 GeV (reference region); JZB > 100 GeV (search region)





The background prediction has been fitted to ±σ display uncert. band

Region	Observed events	Background prediction	MC expectation
$JZB > 50\,\mathrm{GeV}$	20	$24 \pm 6(\mathrm{stat}) \pm 1.4(\mathrm{peak})^{+1.2}_{-2.4}(\mathrm{sys})$	16.0 ± 1.2 (MC stat)
$JZB > 100\,\mathrm{GeV}$	6	$8 \pm 4(\mathrm{stat}) \pm 0.1(\mathrm{peak})^{+0.4}_{-0.8}(\mathrm{sys})$	3.6 ± 0.4 (MC stat)

Prediction agrees well with the observation in both regions

Opposite sign di-leptons with Z (MET template method)

New physics search similar to previously outlined:

- It uses MET as the major discriminant

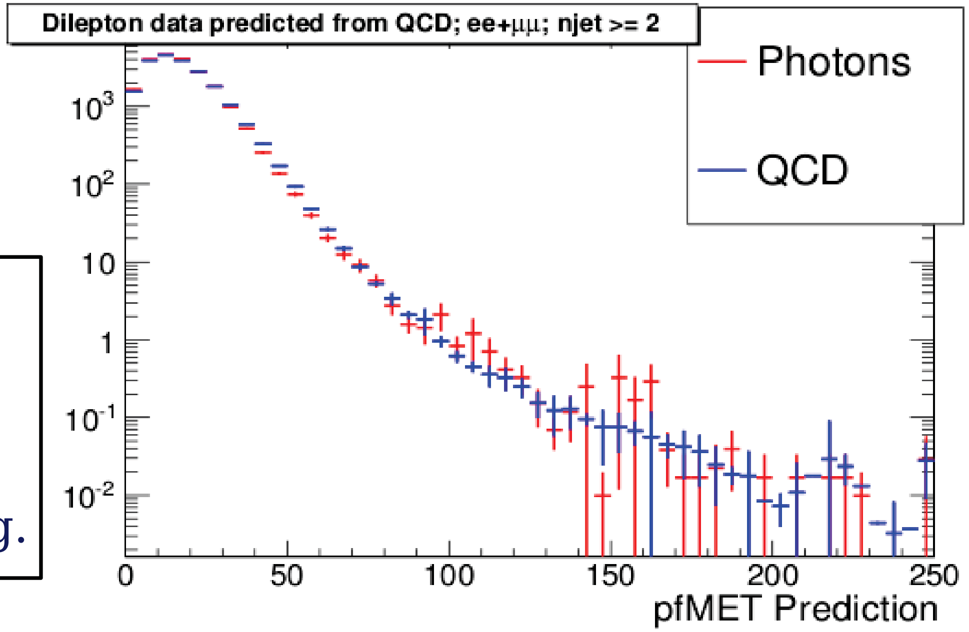
- Two isolated leptons (e, μ): p_T > 20 GeV
- At least 2 jets with p_T > 30 and |η| < 3.0
- Require same-flavor pairs in Z mass window (81 – 101) GeV

Predicted MET in Z events from 2 complementary control samples are consistent within uncertainties

Two signal regions:

Loose region: MET > 100 GeV

Tight region: MET > 200 GeV



Dominant bkg from: Z + Jets & ttbar.

Use data-driven bkg estimation:

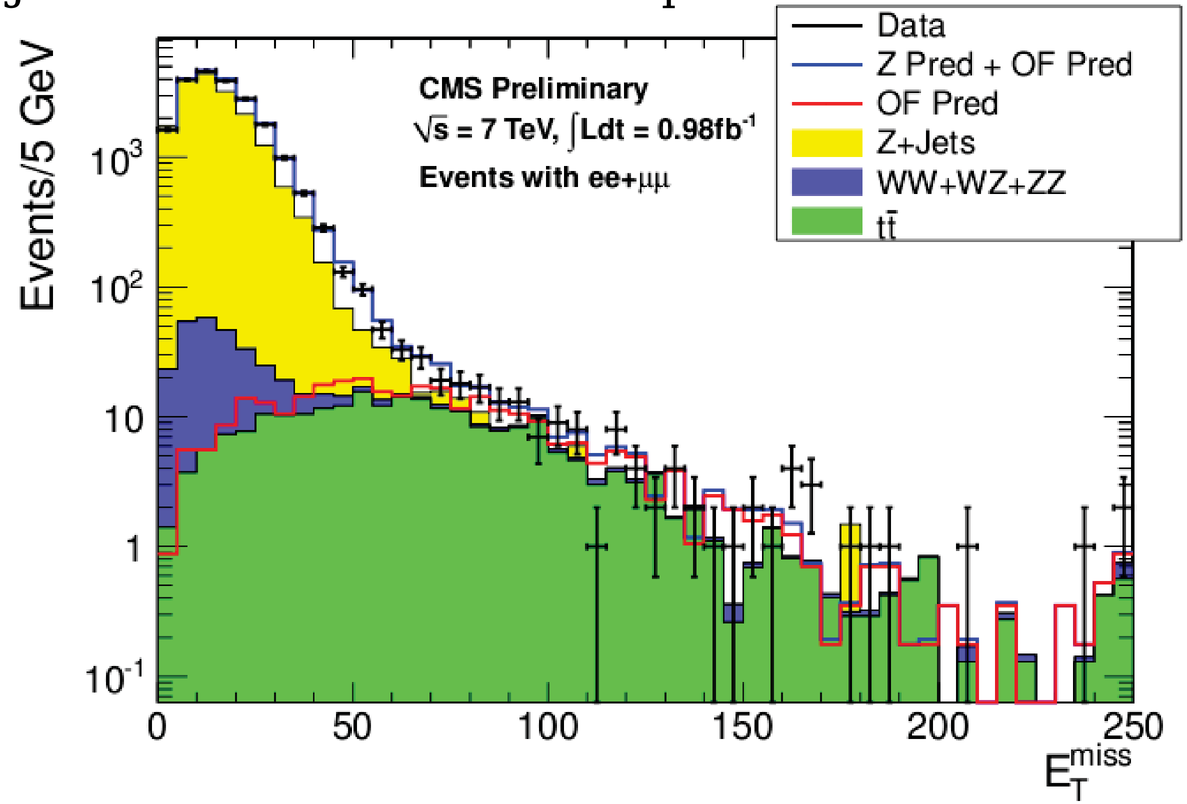
- MET template to model Z + Jets
- Flavor subtraction to model ttbar bkg.

Construct MET templates by studying MET in control samples (QCD & photon +Jets)

- Bin in Scalar sum p_T and njets
- Binning accounts for MET dependence on these two variables
- Form prediction by summing templates corresponding to sum jet P_T and njet of each Z event passing pre selection (Verified the prediction using MC)

Opposite sign di-leptons with Z (MET template method)

Use photon + Jets events for the MET template



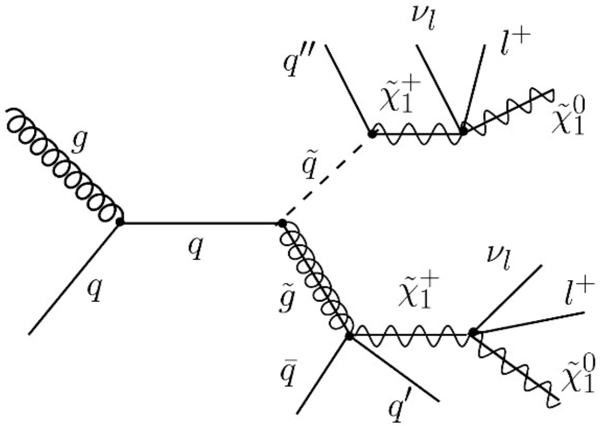
	$E_T^{miss} > 30$ GeV	$E_T^{miss} > 60$ GeV	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 200$ GeV
Z Pred	$2060.3 \pm 29.1 \pm 309.1$	$60.8 \pm 4.1 \pm 9.1$	$5.1 \pm 1.0 \pm 0.8$	$0.09 \pm 0.04 \pm 0.01$
$t\bar{t}$ Pred	$246.6 \pm 6.3 \pm 22.2$	$152.5 \pm 4.9 \pm 13.7$	$50.6 \pm 2.8 \pm 4.6$	$3.2 \pm 0.7 \pm 0.3$
Prediction	$2306.9 \pm 29.7 \pm 309.9$	$213.0 \pm 6.4 \pm 16.5$	$55.7 \pm 3.0 \pm 4.6$	$3.3 \pm 0.7 \pm 0.3$
Data	**2287 (1145,1142)**	**206 (114,92)**	**57 (25,32)**	**4 (1,3)**
UL	498	37	20	5.9

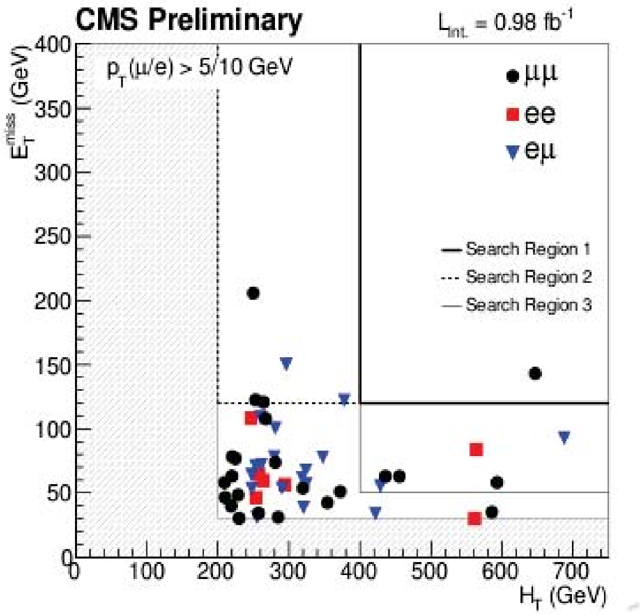
No excess of data over prediction in signal regions ⇒ Upper limit

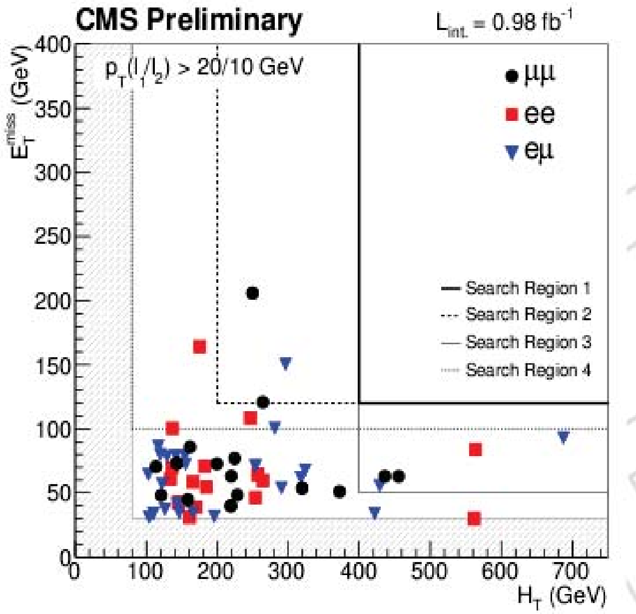
Same sign dilepton search

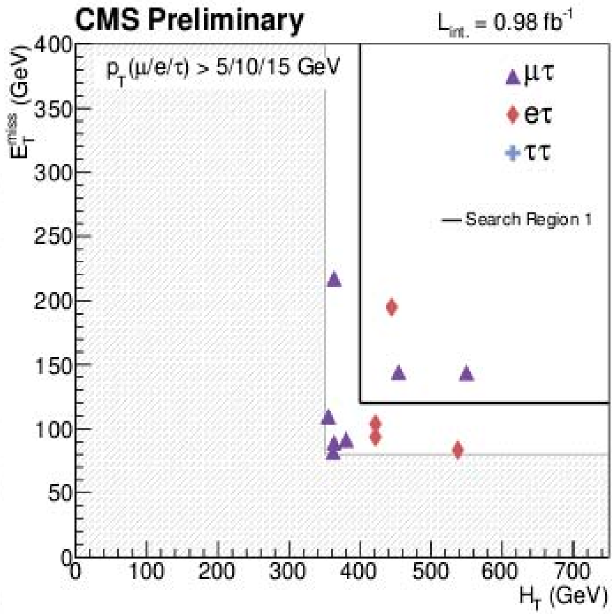
- Isolated same sign dileptons (SS) are very rare in the SM
- Several search regions with three lepton flavors (e, μ, τ) are studied
- A natural SUSY signature
- All cross channels are included in

three lepton flavors :





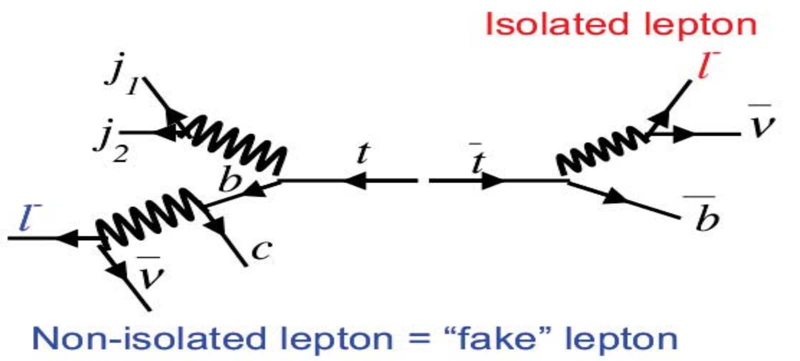




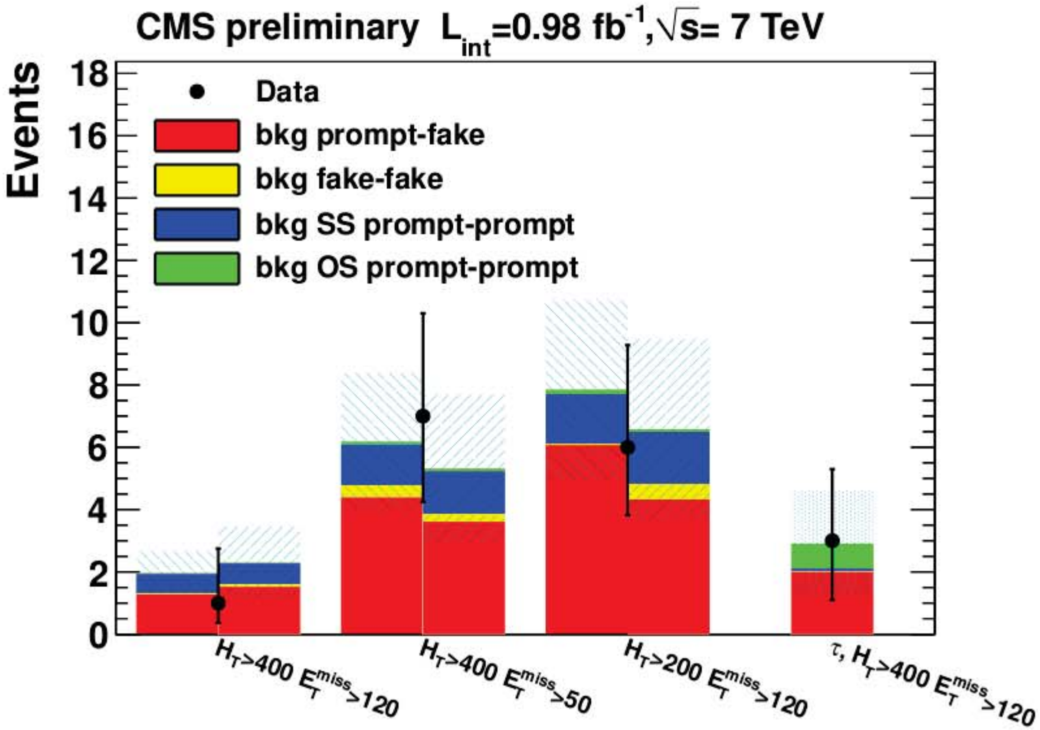
Same sign dilepton search

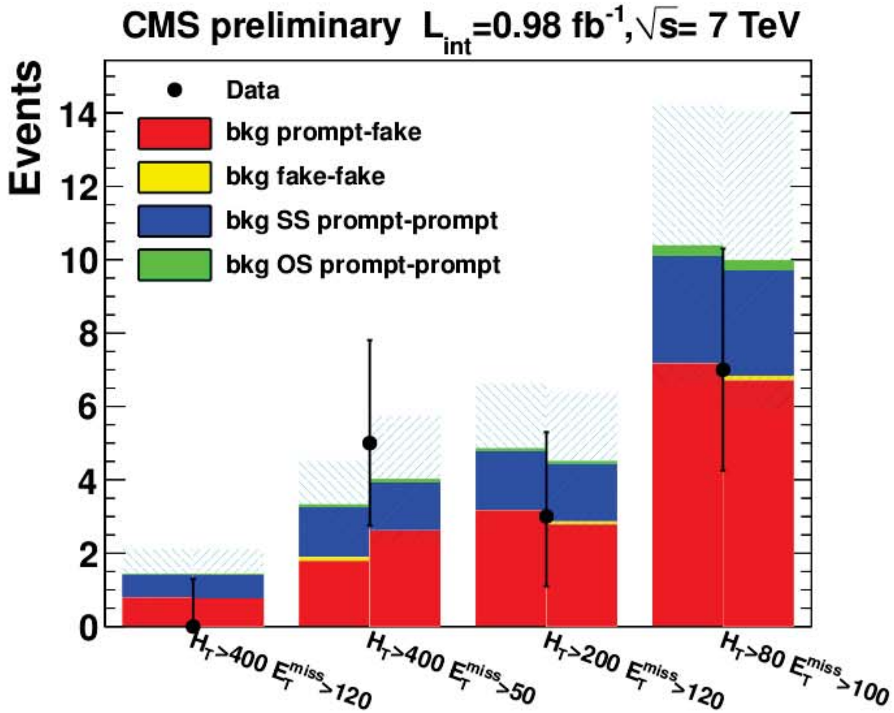
Major Backgrounds:

- "~Fake" leptons from ttbar (b/c → e,μ)
- Charge Mis-reconstruction
- QCD fakes in case of tau final states



Use multiple complementary data driven methods to estimate the backgrounds

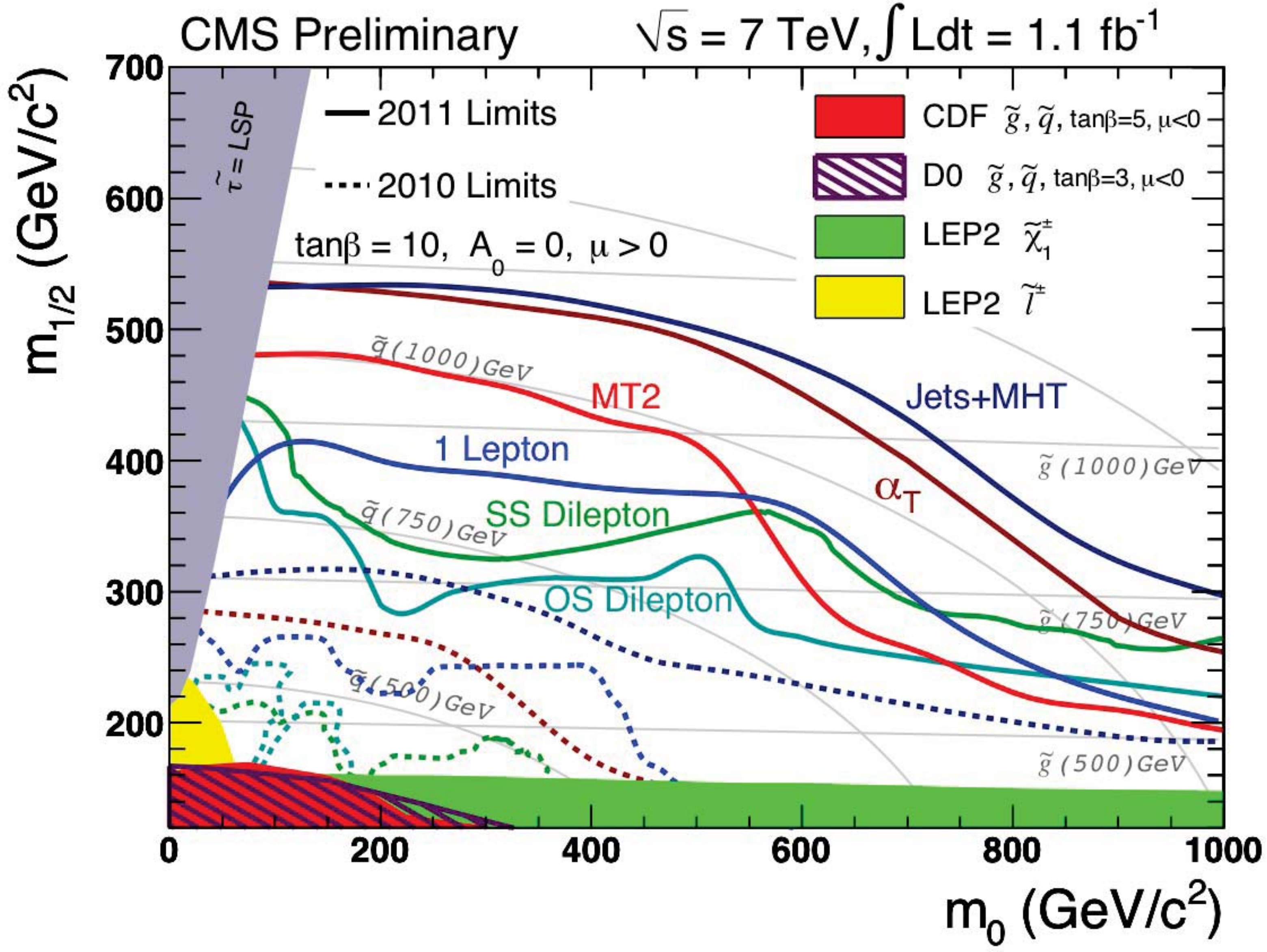




No sign of any new physics anywhere

Exclusion limits/Interpretation of results

Limits using CMSSM framework



For equal squark and gluino masses, this excludes ~ 1.2 TeV

Searches involving photons + MET in the final state

(CMS PAS-11-003)

Searches involving photons + MET in the final state

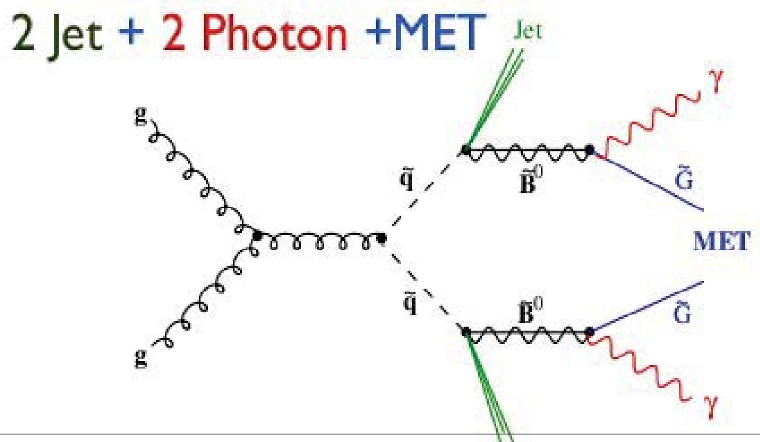
Use general gauge mediated susy breaking as the framework

Gravitino as the LSP

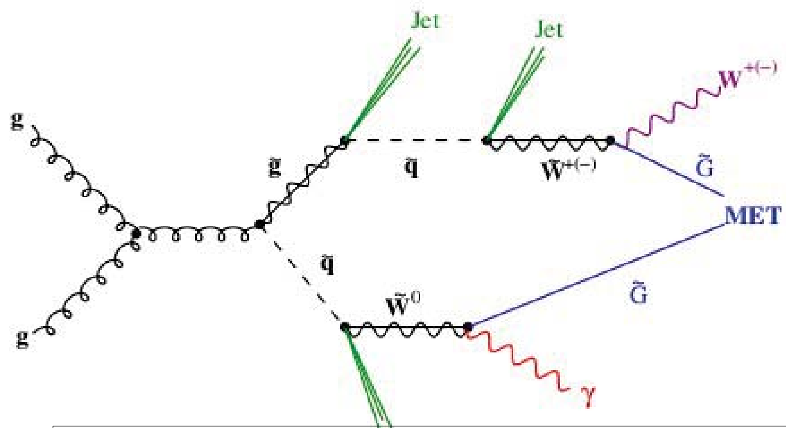
Neutralino as the NLSP

Neutralino generally would be some mixture of Binos, neutral winos, higgsinos

- With Bino like neutralino (diphoton + MET + Jets)
- If Wino has similar mass, this results in chargino-neutralino Co-NLSP
  - $\rightarrow$ single photon + Jets + MET signature



1 photon + Jets + MET



Require 2 photons with pT > 45, 30 GeV

Both in barrel region

At least 1 Jet with pT > 20 GeV

MET (GeV) > 50 (loose), 100 (tight)

Require 1 photon with pT > 75 GeV

In the barrel region

Atleast 3 jets, H_T > 400 GeV

MET > 200 GeV

Searches involving photons + MET in the final state

Two major backgrounds for both analysis:

- "Non-MET" backgrounds: those without intrinsic MET but acquire it via mis-reconstruction & resolution effects

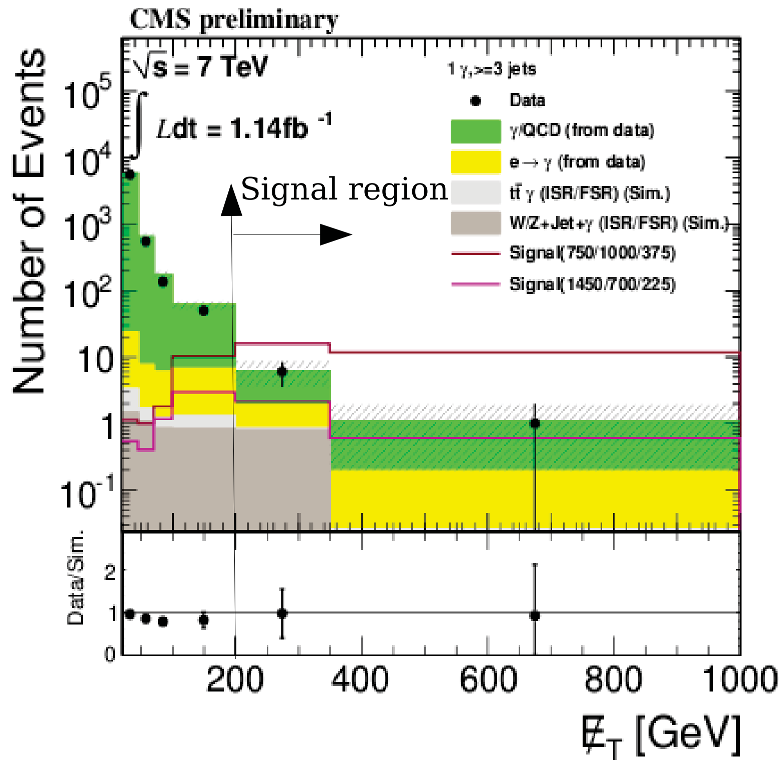
  - QCD, where jets "fake" photons.

  - measure it from data in orthogonal sample with similar hadronic env.

- "Intrinsic MET" backgrounds: those with actual MET which enter into the sample via electron mis-id as a photon, etc.

  - EWK background like Wγ, W+Jets

  - measure from data use e$\rightarrow\gamma$ fake rate.

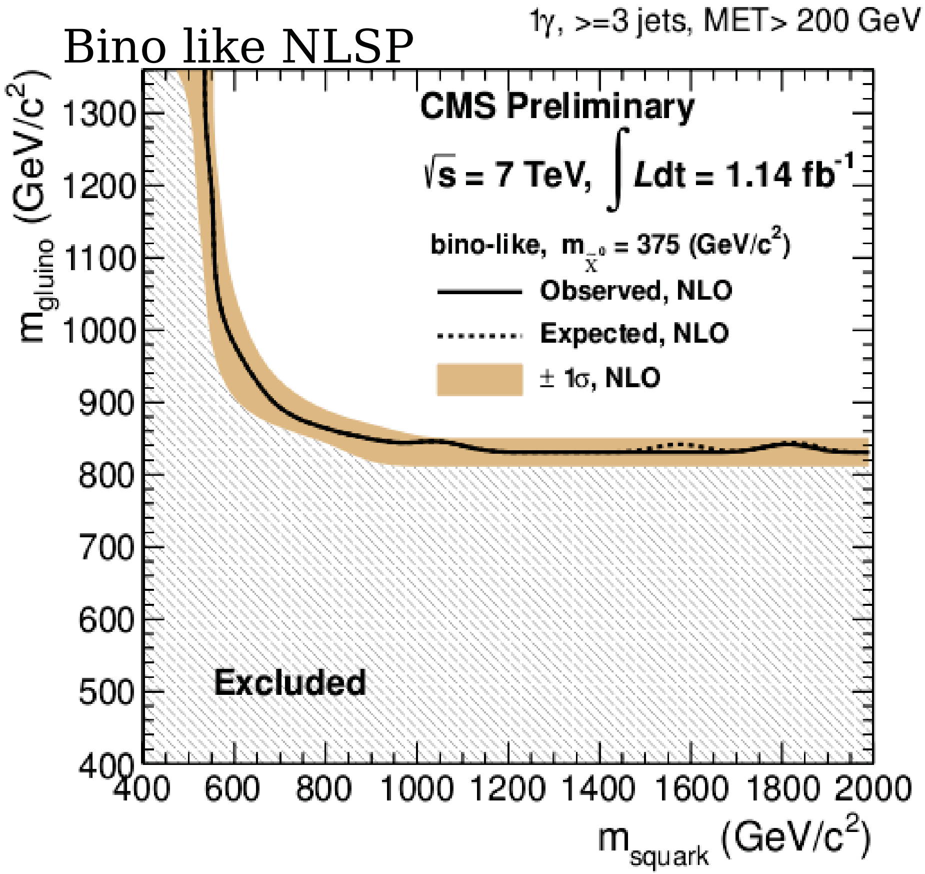


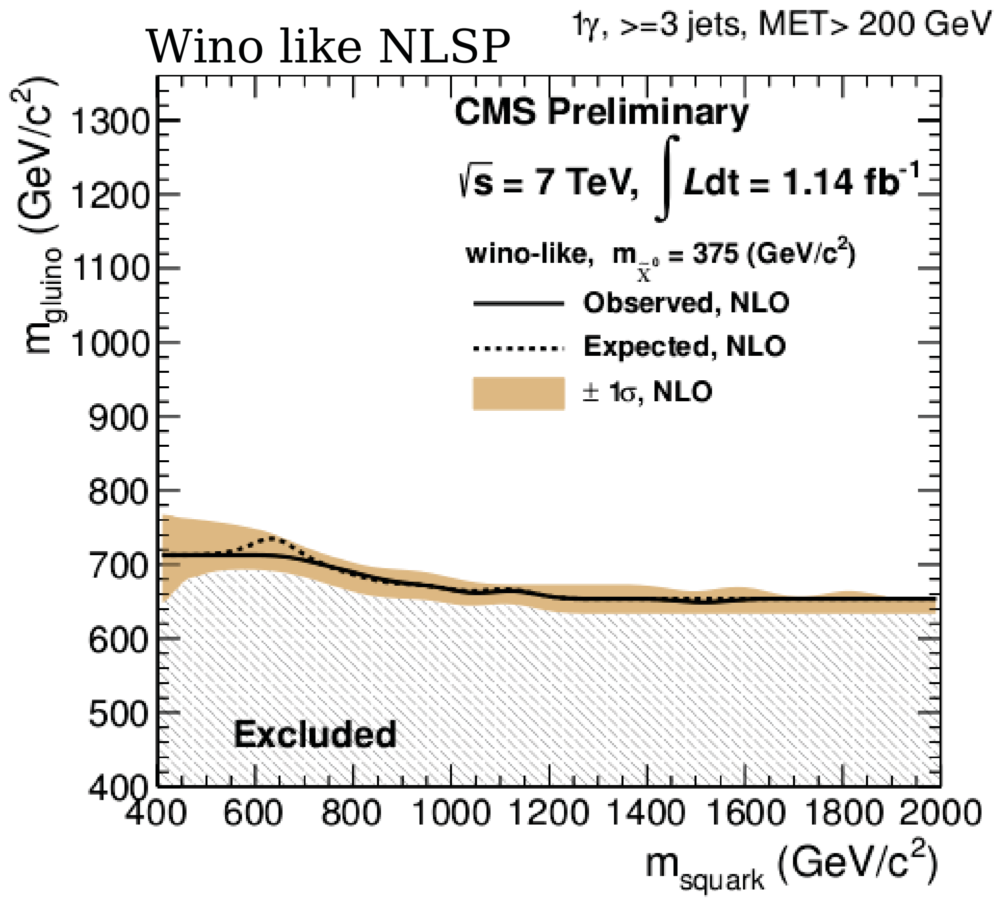
<u>Fake rate determination:</u>

Measure rate of events in Z region in eγ and ee sample:

$F_{e\rightarrow\gamma} = 0.014 \pm 0.0004$ (stat.) ± 0.002 (syst.)

Searches involving photons + MET in the final state





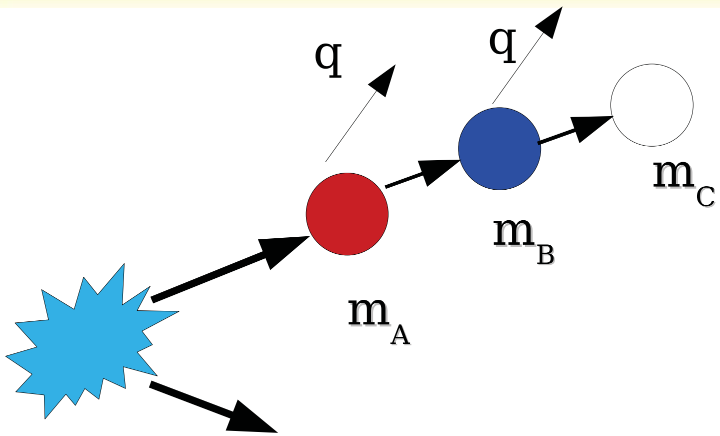
Good agreement between data and SM estimation

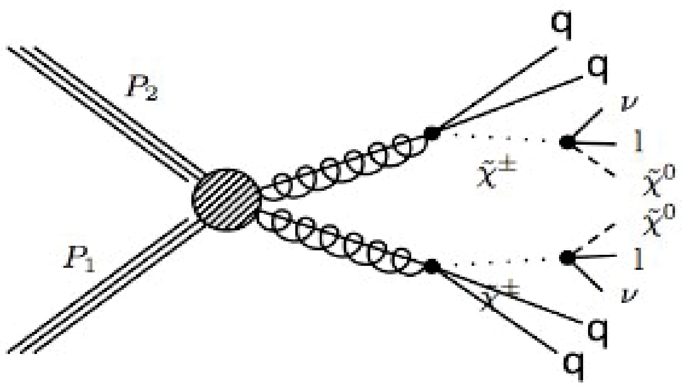
For the case chargino-neutralino mass is small. Chargino decays wino like to W + G ⇒ reduced photon activity

Sample	Event yield	(stat.)	(syst.)
Data	7		
QCD (est. from data)	5.16	±2.58	±0.62
EWK $e \to \gamma$ (est. from data)	1.22	±0.13	±0.04
FSR/ISR ($W \to \mu/\tau\nu, Z \to \nu\nu$) (Sim.)	0.80	±0.31	±0.80
FSR/ISR ($t\bar{t} \to \mu/\tau\nu + X$) (Sim.)	0.07	±0.05	±0.07
Total SM background estimate	7.24	±2.6	±1.53

Implication of these results on TeV scale physics

Simplified Topologies





Assume LSP

- LSP (m_C): 1st scale (expect MET)

Assume production via QCD

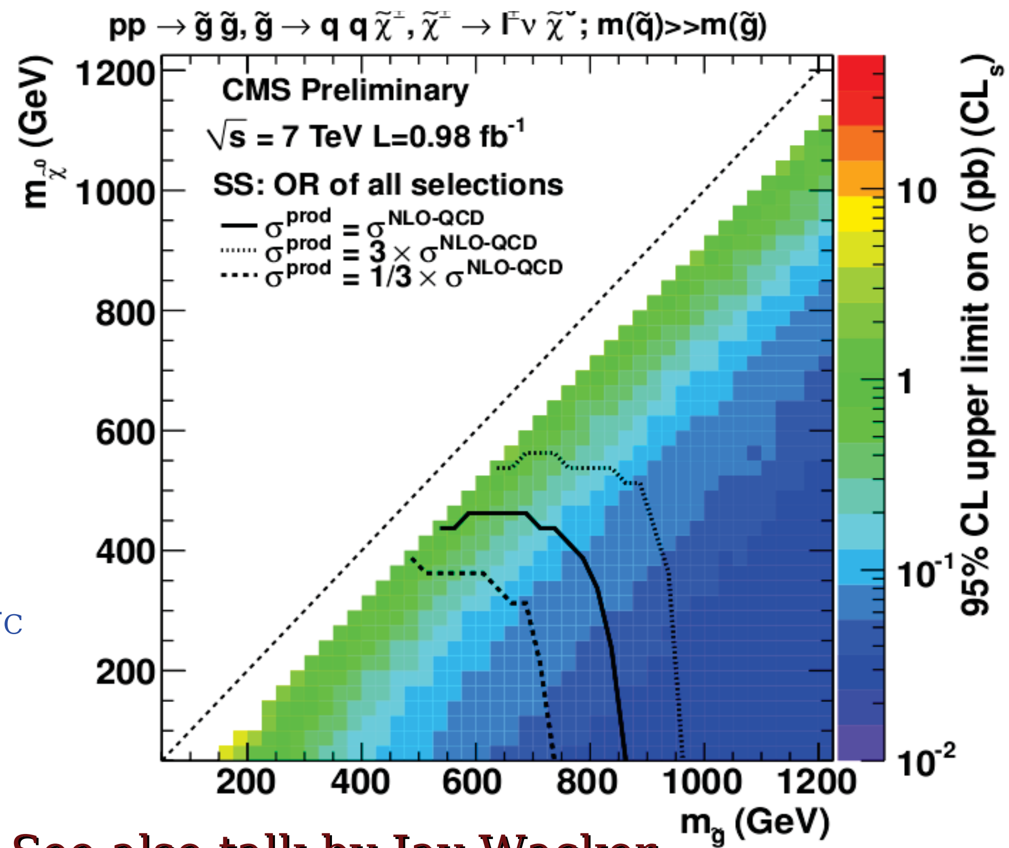
- squark/gluinos (m_A): 2nd scale
- large cross section

Assume charged EWK particle (m_B)

- if chargino mass is in between m_A & m_C

Example: $\tilde{g} \to qq\tilde{\chi}^{+}\,;\,\tilde{\chi}^{+} \to l^{+}\,\nu\tilde{\chi}^{0}$

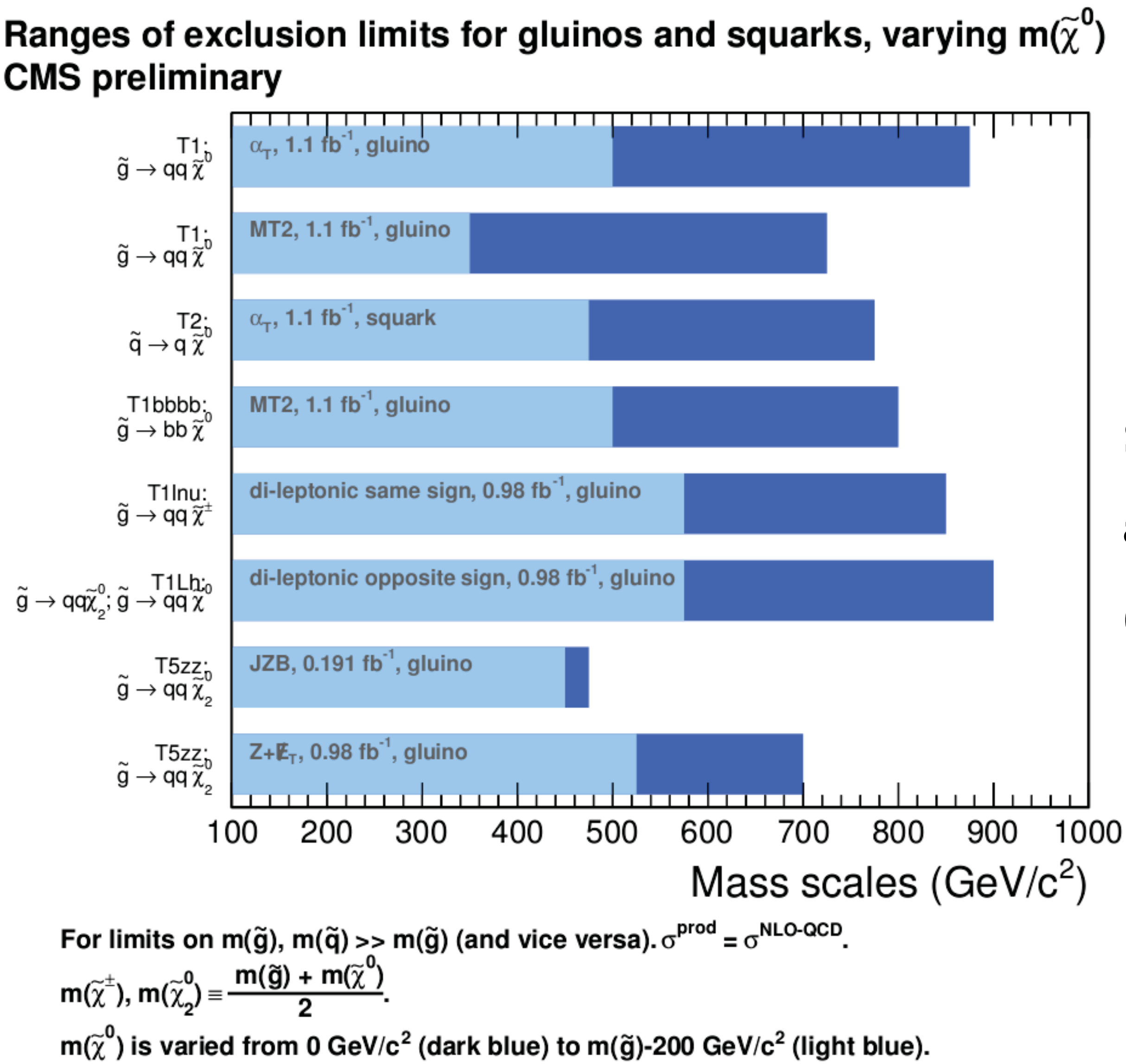
Final State : SS leptons + 4 jets + MET



See also talk by Jay Wacker

Results using simplified topology

CMSSM using similar squark and gluino masses are excluded ~ 1.2 TeV



Sensitivities vary based on analysis and the assumptions (Simplified Topologies)

Implication of these results on TeV scale physics

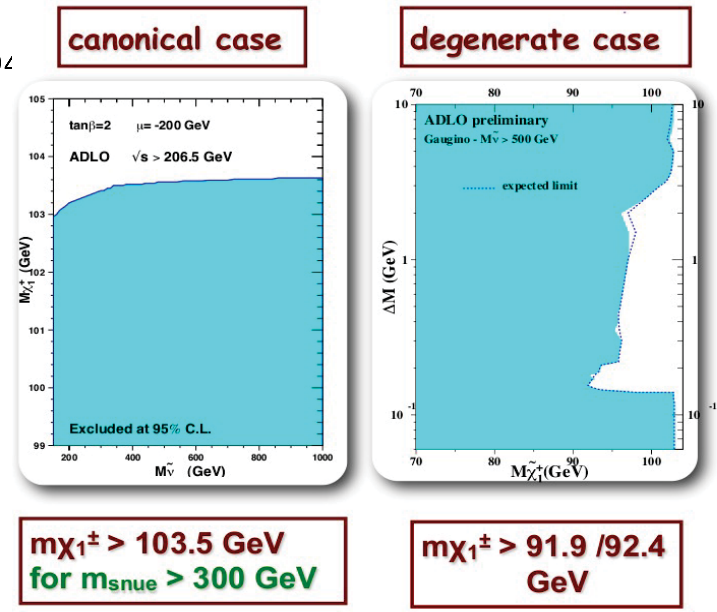
Assuming colored particles (1^{st} and 2^{nd} generation squarks) are beyond the LHC range:

a) Need dedicated exclusive studies to constrain stops and sbottoms

- With and without the cross section help from the colored particles
- e.g $\tilde{g}\tilde{g} \rightarrow tt\overline{t}\overline{t}\tilde{\chi}\tilde{\chi}$, direct stop pair production
- See also M. Papucci's EPS-2011 talk
- http://indico.in2p3.fr/contributionDisplay.py?contribId=904

b) Need dedicated activity on EWK inos

- Current limits on Chargino/neutralinos are low
- Explore LHC reach for the electroweak sector (See also Shufang Su SUSY-11 talk)



Summary and Conclusion

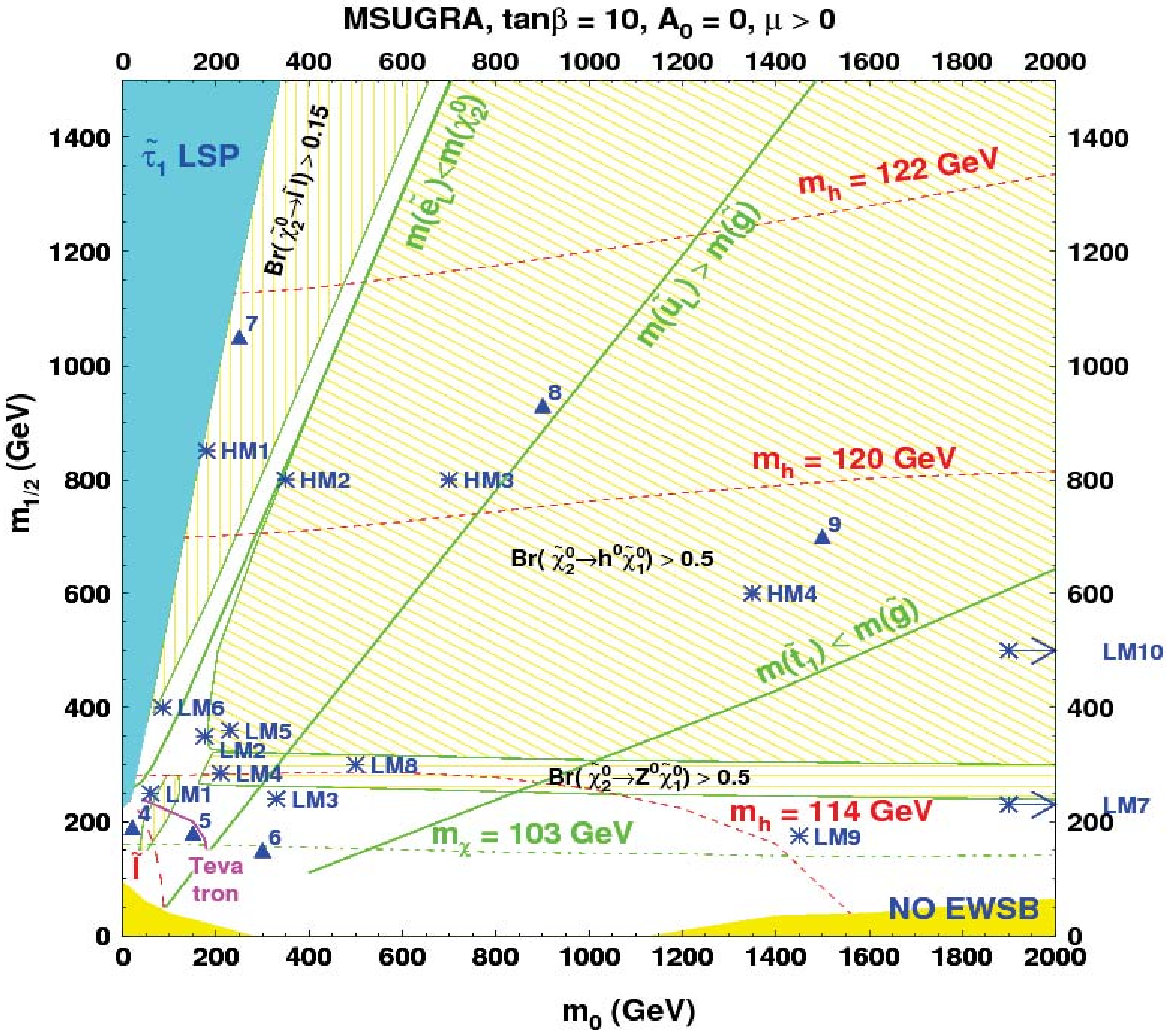
- Presented overview of searches with MET signatures
- In most cases, dominant backgrounds are estimated from the data itself with minimal reliance on Monte Carlo
- Unfortunately using ~ 1 fb^{-1} no new physics was found

  ⇒ We set limits using different SUSY & BSM frameworks
- Current limits in many cases enter into TeV scale territory
- Future:
  - Dedicated exclusive search for 3rd generation sparticles (still to come)
  - More studies are needed to explore LHC potential for EW particles

Plan to update results with ~5 fb^{-1} in next two months!, stay tuned

Backup Slides

CMS benchmark points



Upper Limits from Opposite sign dilepton studies

- Extract model independent limits on non-SM contributions to yields
- For generic search, use error-weighted average of 2 data-driven estimates
- Compute 95% CL UL, compare to the NLO yields from benchmark points*

Generic results ►

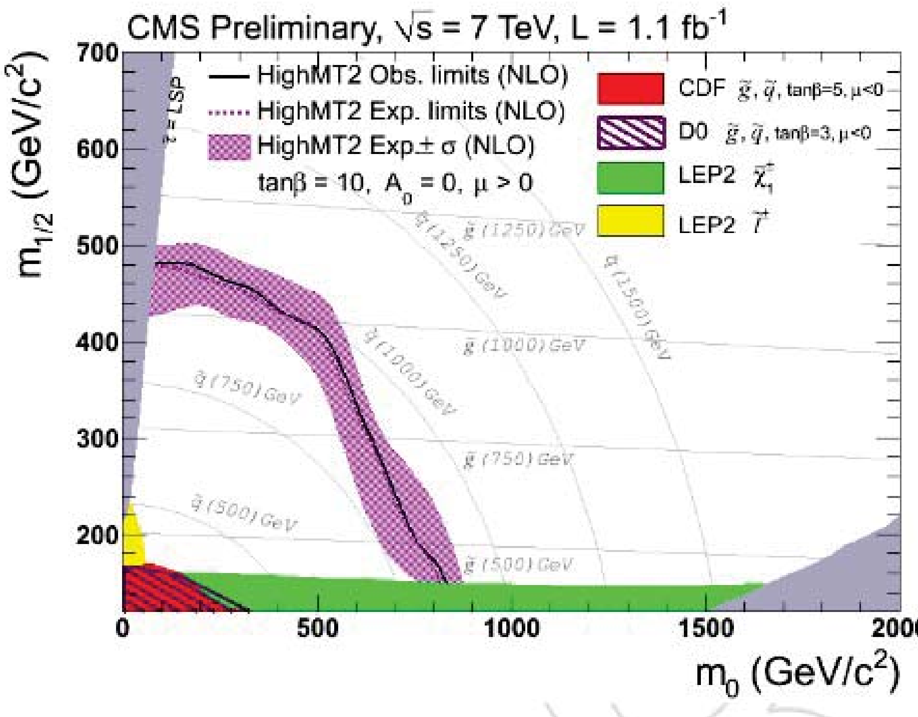
	high E_T^{miss} signal region	high H_T signal region
observed yield	8	4
MC prediction	7.3 ± 2.2	7.1 ± 2.2
ABCD′ prediction	4.0 ± 1.0 (stat) ± 0.8 (syst)	4.5 ± 1.6 (stat) ± 0.9 (syst)
$p_T(\ell\ell)$ prediction	14.3 ± 6.3 (stat) ± 5.3 (syst)	10.1 ± 4.2 (stat) ± 3.5 (syst)
N_{bkg}	4.2 ± 1.3	5.1 ± 1.7
non-SM 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

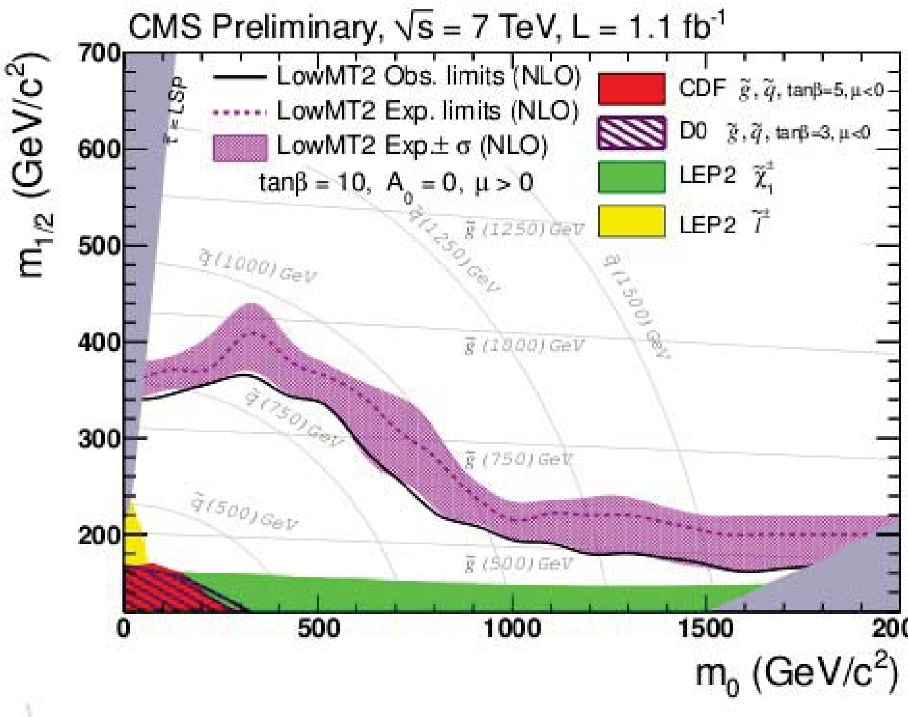
correlated flavor results ►

	high E_T^{miss} signal region	high H_T signal region
observed Δ	3.6 ± 2.9 (stat) ± 0.4 (syst)	-0.9 ± 1.8 (stat) ± 1.1 (syst)
UL	7.9	3.6
LM1	27 ± 6.0	24 ± 7.6
LM3	3.2 ± 0.9	3.3 ± 1.1
LM6	2.0 ± 0.2	1.9 ± 0.3

**benchmark points are defined in backup slides*

Limits using CMSSM framework

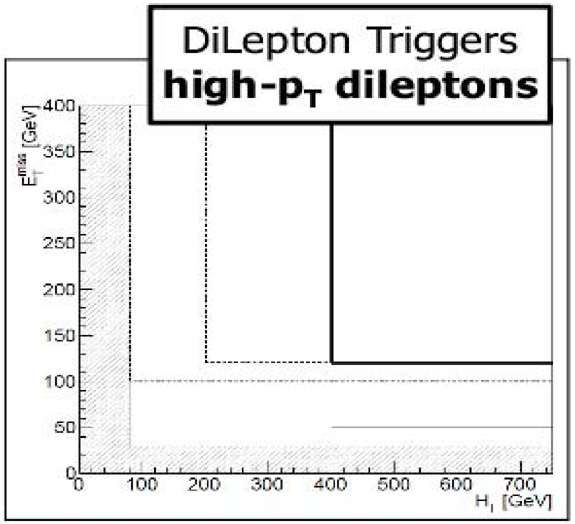


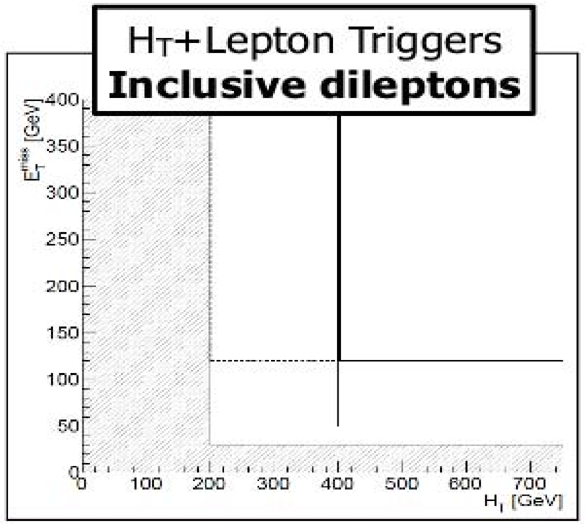


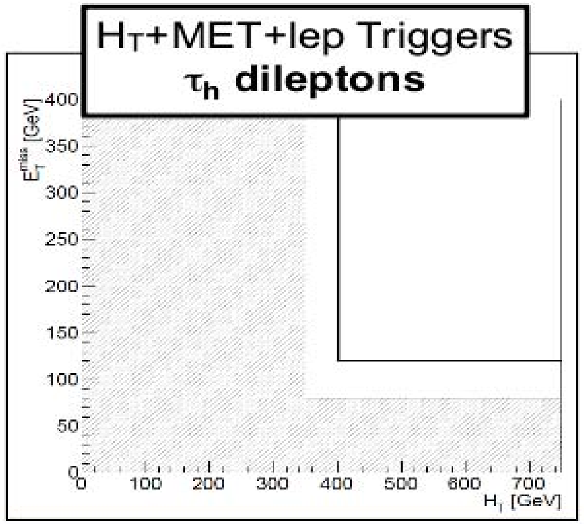
Same sign dilepton search

Isolated same sign dileptons (SS) are very rare in the SM

Several search regions with three lepton flavors (e, μ, τ) are studied







Region 1 $(ee, \mu\mu, e\mu)$: **leptons p_T > 20/10** **H_T > 400 MET > 120**	**Region 1** $(ee, \mu\mu, e\mu)$: **mu p_T > 5, ele p_T>10** **H_T > 400 MET > 120**	**Region 1** $(e\tau, \mu\tau, \tau\tau)$: **mu p_T > 5, ele p_T > 10, tau p_T> 15** **H_T > 400 MET > 120**
Region 2 $(ee, \mu\mu, e\mu)$: **leptons p_T > 20/10** **H_T > 200 MET > 120**	**Region 2** $(ee, \mu\mu, e\mu)$: **mu p_T > 5, ele p_T>10** **H_T > 200 MET > 120**	
Region 3 $(ee, \mu\mu, e\mu)$: **leptons p_T > 20/10** **H_T > 400 MET > 50**	**Region 3** $(ee, \mu\mu, e\mu)$: **mu p_T > 5, ele p_T>10** **H_T > 400 MET > 50**	
Region 4 $(ee, \mu\mu, e\mu)$: **leptons p_T > 20/10** **H_T > 80 MET > 100**		

SS Background estimation – Method A

Define a “Tight” and a “Loose” lepton selection:

- “Loose” is essentially extrapolation in isolation

Measure “Tight-to-Loose Ratio” a.k.a “Fake Rate” in an unbiased sample

FR = (# evts passing tight)/ (# evts passing loose)

Measure this as a function of f(p_T, η).

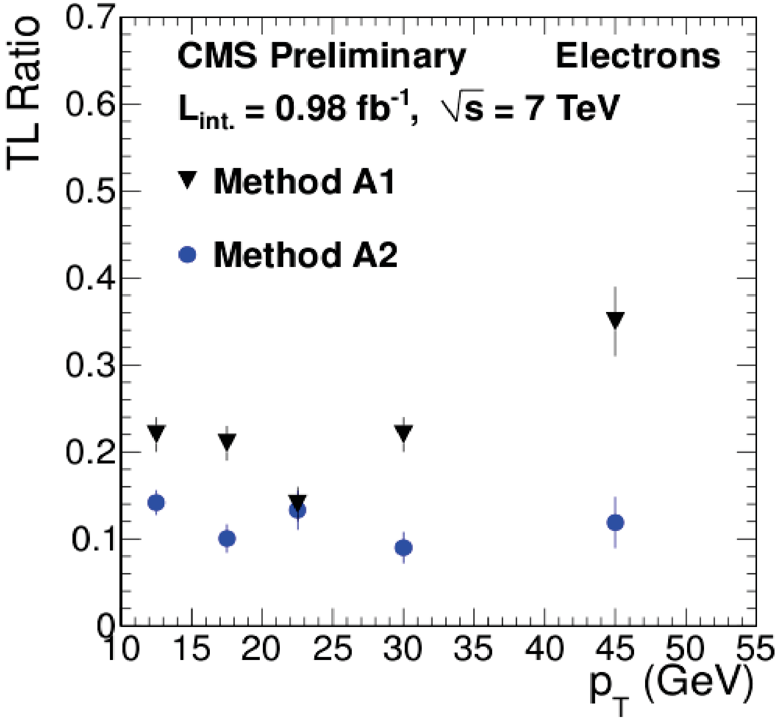
Apply to f(p_T, η) sample with:

- Two loose to estimate double fake (QCD)
- One tight one loose to estimate single fakes
- Total = Combination of the above two estimates

Methods A1(A2) use different extrapolations.

- A1 uses extrapolation in lepton isolation
- A2 uses extrapolation in ID and Isolation

Muons similar, see backup



The systematic uncert. is evaluated based on closure tests and dependence of the TL ratio on the away jet p_T and the sample composition

Same Sign dilepton search

Results with High-p_T dileptons

Search Region (minimum H_T / E_T^{miss})	ee	$\mu\mu$	$e\mu$	Total	95% CL UL yield
Region 1 (400/120)					
Predicted background by (A1)	0.4 ± 0.3	0.4 ± 0.3	0.7 ± 0.4	1.4 ± 0.7	
Predicted background by (A2)	0.7 ± 0.5	0.4 ± 0.3	0.4 ± 0.3	1.4 ± 0.7	
Observed	0	0	0	0	3.0
Region 2 (400/50)					
Predicted background by (A1)	1.4 ± 0.8	1.3 ± 0.8	1.3 ± 0.6	4.0 ± 1.7	
Predicted background by (A2)	1.5 ± 0.8	0.8 ± 0.4	1.0 ± 0.5	3.3 ± 1.2	
Observed	1	2	2	5	7.5
Region 3 (200/120)					
Predicted background by (A1)	1.2 ± 0.7	1.5 ± 0.8	1.8 ± 0.8	4.5 ± 1.9	
Predicted background by (A2)	1.3 ± 0.7	1.8 ± 0.8	1.8 ± 0.7	4.9 ± 1.8	
Observed	0	2	1	3	5.2
Region 4 (80/100)					
Predicted background by (A1)	2.5 ± 1.2	2.6 ± 1.2	4.9 ± 2.2	10 ± 4	
Predicted background by (A2)	2.4 ± 1.0	3.6 ± 1.6	4.4 ± 1.6	10 ± 4	
Observed	3	2	2	7	6.0

No sign of any new physics anywhere

Same Sign dilepton search

Results with inclusive dileptons with H_T trigger

Search region (minimum H_T / E_T^{miss})	ee	$\mu\mu$	$e\mu$	Total	95% CL UL yield
Region 1 (400/120)					
Predicted background by (B)	0.2 ± 0.1	0.9 ± 0.3	0.9 ± 0.3	2.0 ± 0.7	
Predicted background by (A1)	0.4 ± 0.4	1.2 ± 0.8	0.7 ± 0.4	2.3 ± 1.2	
Observed	0	1	0	1	3.7
Region 2 (400/50)					
Predicted background by (B)	1.0 ± 0.4	2.3 ± 0.7	3.0 ± 1.0	6.2 ± 2.2	
Predicted background by (A1)	1.3 ± 0.7	2.5 ± 1.5	1.4 ± 0.7	5.3 ± 2.4	
Observed	1	4	2	7	8.9
Region 3 (200/120)					
Predicted background by (B)	0.8 ± 0.4	3.6 ± 1.3	3.4 ± 1.3	7.8 ± 2.9	
Predicted background by (A1)	1.5 ± 0.9	3.0 ± 1.6	2.1 ± 1.0	6.6 ± 2.9	
Observed	0	4	2	6	7.3

Include hadronic τ channels: eτ, μτ and ττ

- Backgrounds from QCD jets faking hadronic τ's
- Use similar tight to loose probability to predict the background

Search Region (minimum H_T / E_T^{miss})	$e\tau$	$\mu\tau$	$\tau\tau$	Total	95% CL UL yield
Region 1 (400/120)					
Predicted background	1.1 ± 0.4	1.8 ± 1.4	0.0 ± 0.2	2.9 ± 1.7	
Observed	1	2	0	3	5.8

No sign of any new physics anywhere

QCD background estimation using “Re-balance & Smear”:

Detector effects: Jet resolution, dead ECAL cells, Punch through ...

Physics: Leptonic heavy flavor decays

→ mismeasured jets (→ large MHT)

Full jet response (incl. tails) measured from data

↓

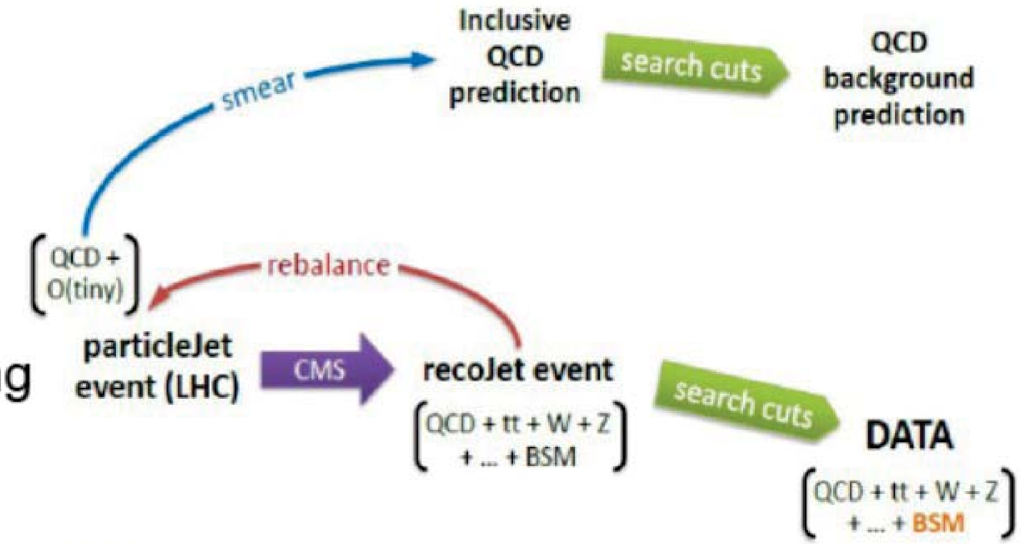
Select or mimic particle jets (rebalance seed events):

↓

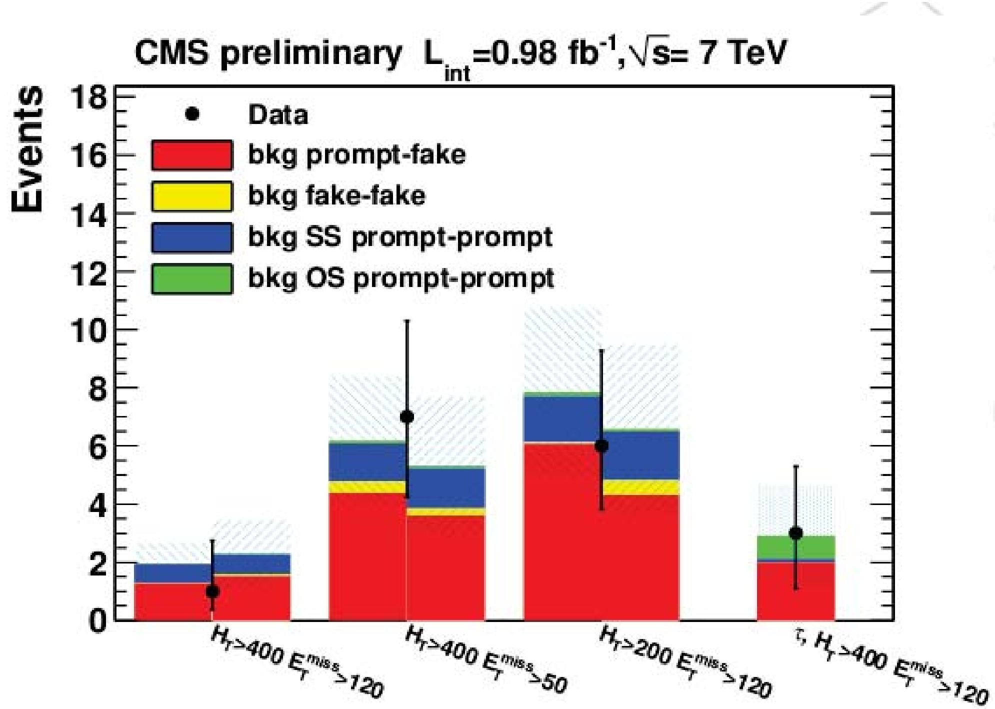
Smear seed events according to measured jet resolutions

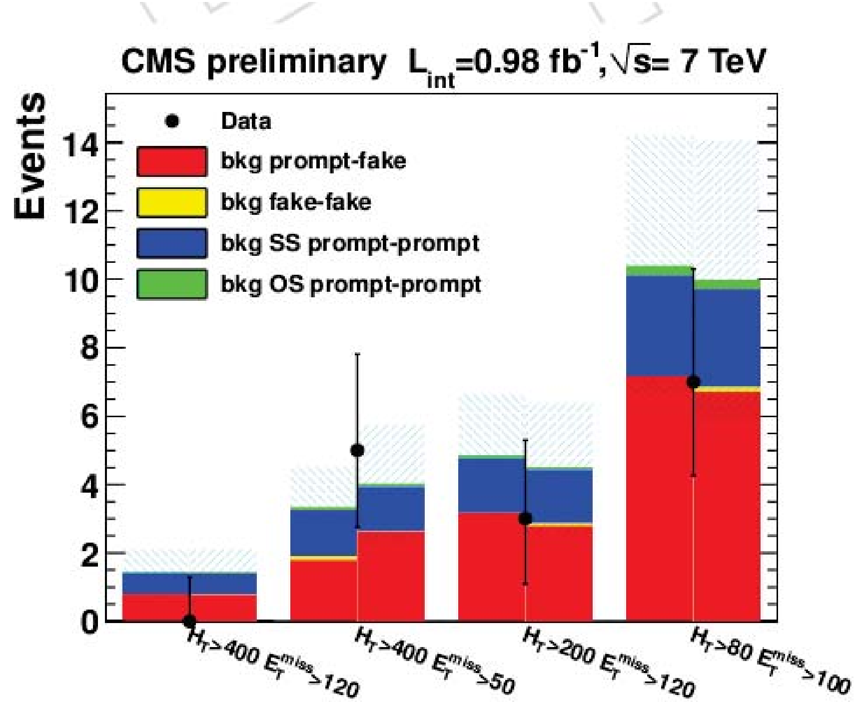
↓

Obtain a data driven estimation of full kinematics of QCD multijet events (can predict HT, MHT, ...)



SS Yields -signal regions



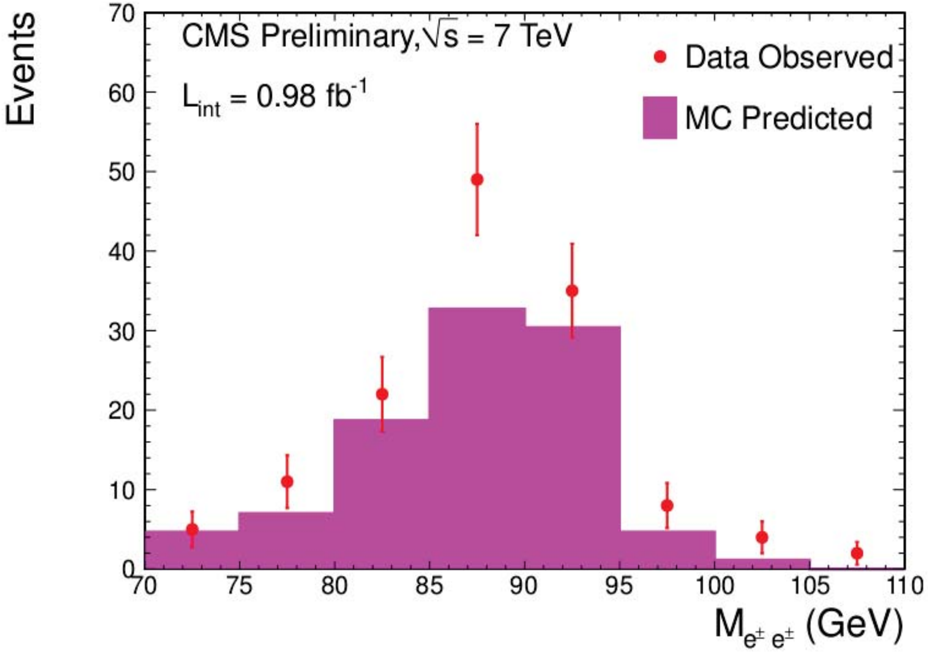


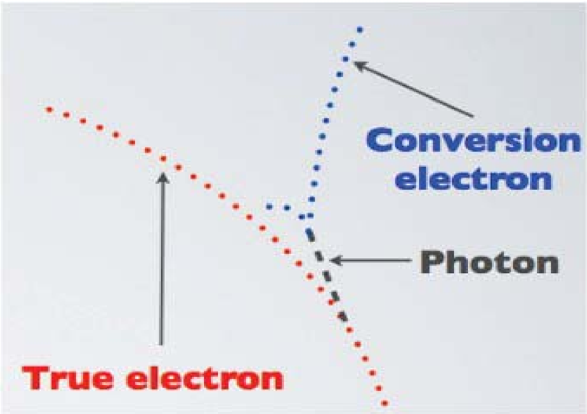
SS Background estimation – Charge Mis-reconstruction

Electron momentum is measured (mostly) by ECAL

Electron charge is measured (mostly) by tracker

- Charge mis-measurement leaves the momentum unchanged





Hard brems followed by conversion can lead to Charge mismeasurement

Same sign Z to ee in data and MC (veto W using MET < 20 and M_T < 25 GeV requirements)

Measure the mis-measurement rates in data Or MC [e.g: SS/(OS + SS) Z bosons]

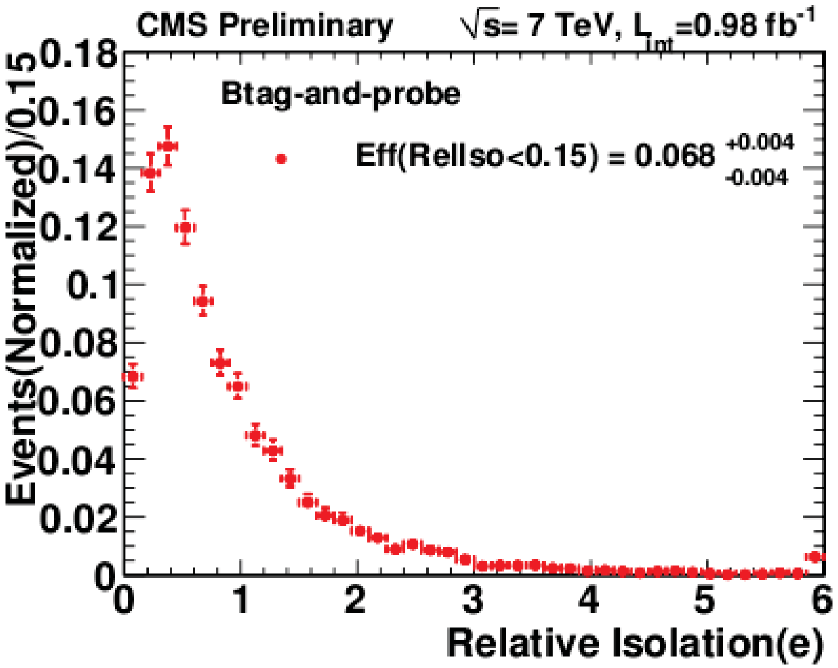
- Mis-Charge Rate $\sim 10^{-4}$ in barrel, and $\sim 10^{-3}$ at $|\eta| \sim 1.5$.

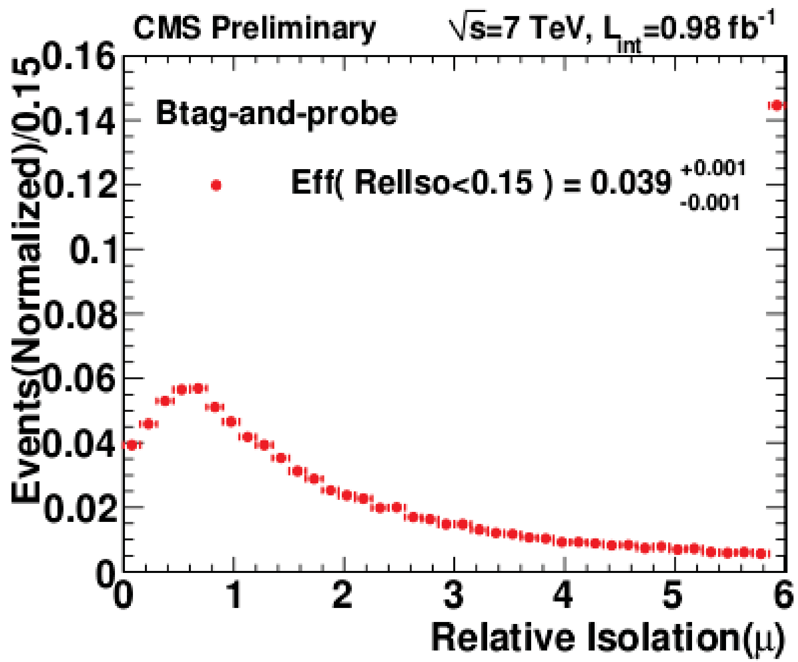
Apply the rate to OS dilepton sample with exact same selections to get a prediction:

Control region: N(Observed) = 129, N(Predicted) = 100 ± 0.3, Expect 8 ± 4 from fake electrons

SS Background estimation – (Method B)

Measure background from b/c → e,μ





- Use tag and probe in bbbar (QCD) events to measure isolation efficiency
- Re-weight this distribution to reflect lepton p_T and Njets in

  ttbar expectation
- Use this isolation efficiency to determine background

Trigger Rates in Hz

Hadronic triggers (a few examples from recent runs):

Path	Rate @ 2.3e32	Rate @ 5e32	Estimate @ 5e32
HT250_MHT60	6.5	14.1	14.0
HT300_MHT75	1.8	3.9	3.8
Meff440	6	13.0	
Meff520	2.8	6.1	9.4*

Leptonic triggers (a few examples from recent runs):

Path	Rate @ 2.3e32	Rate @ 5e32	Estimate @ 5e32
DoubleMu6	4.2	9.1	
DoubleMu7	2.2	4.8	5.9
Ele17_CaloIdL_CaloIsoVL_Ele8_CaloIdL_CaloIsoVL	3	6.5	11
Mu17_Ele8_CaloIdL	0.8	1.7	2
Mu8_Ele17_CaloIdL	2	4.3	7

Trigger Rates in Hz

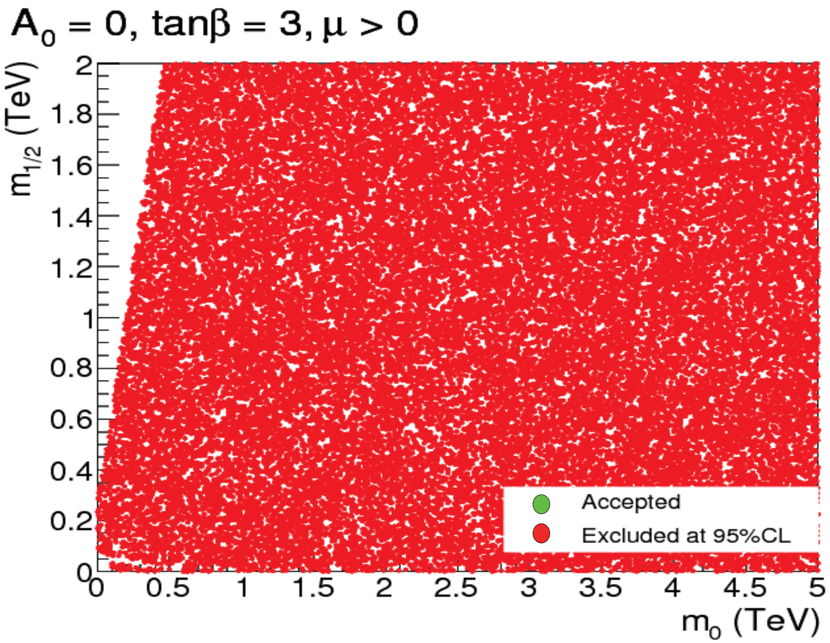
Cross triggers (a few examples from recent runs):

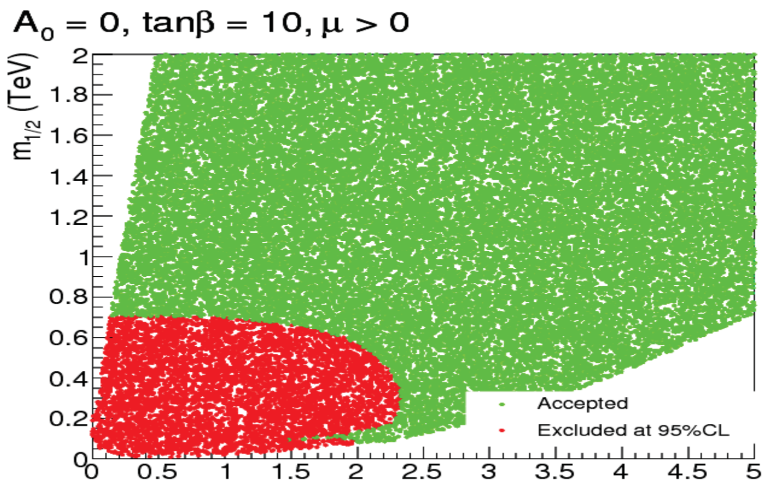
Path	Rate @ 2.3e32	Rate @ 5e32	Estimate @ 5e32
Ele10_CaloIdL_CaloIsoVL_TrkIdVL_TrkIsoVL_HT20	2.6	5.7	~7 Hz
Ele10_CaloIdT_CaloIsoVL_TrkIdT_TrkIsoVL_HT200	1.1	2.4	
Mu5_HT200	5	10.9	
Mu8_HT200	2.5	5.4	5.5
DoubleMu3_HT160	0.4	0.9	2.0
DoubleMu3_HT200	0.25	0.5	1.0
Mu3_Ele8_CaloIdL_TrkIdVL_HT160	1.3	2.8	3
Mu3_Ele8_CaloIdLT_TrkIdVL_HT160	0.5	1.1	1.5
DoubleEle8_CaloIdL_TrkIdVL_HT160	1.2	2.6	2
DoubleEle8_CaloIdT_TrkIdVL_HT160	0.3	0.7	1

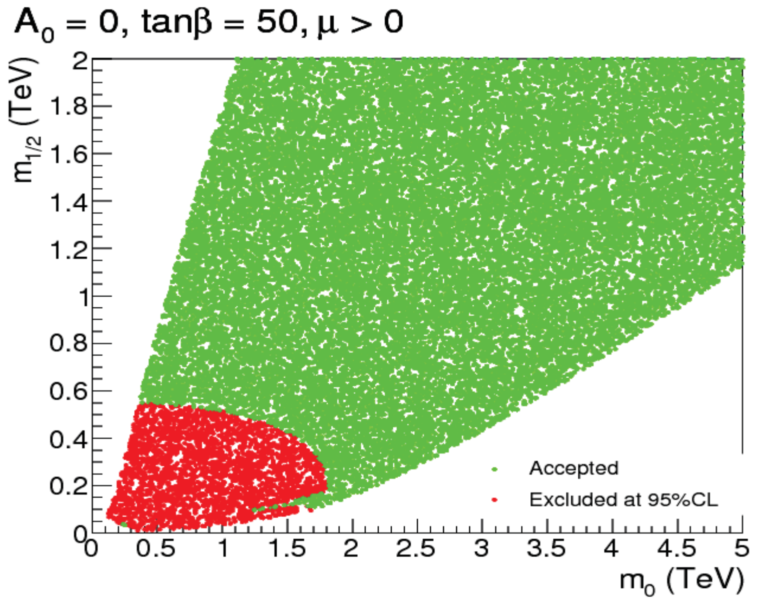
Limits using CMSSM framework

Consider Higgs mass limits from LEP (without uncert.)

Using Softsusy + Higgsbounds (SLHA interface via SuperIso 3.0): Plots by Sezen Sekmen







Results from hadron colliders (Tevatron, LHC) can probe direct squarks/gluino production to the highest scales in the world.

Major region of phase space is already excluded based on LEP higgs mass limit with this “EXACT” choice of parameters in the model

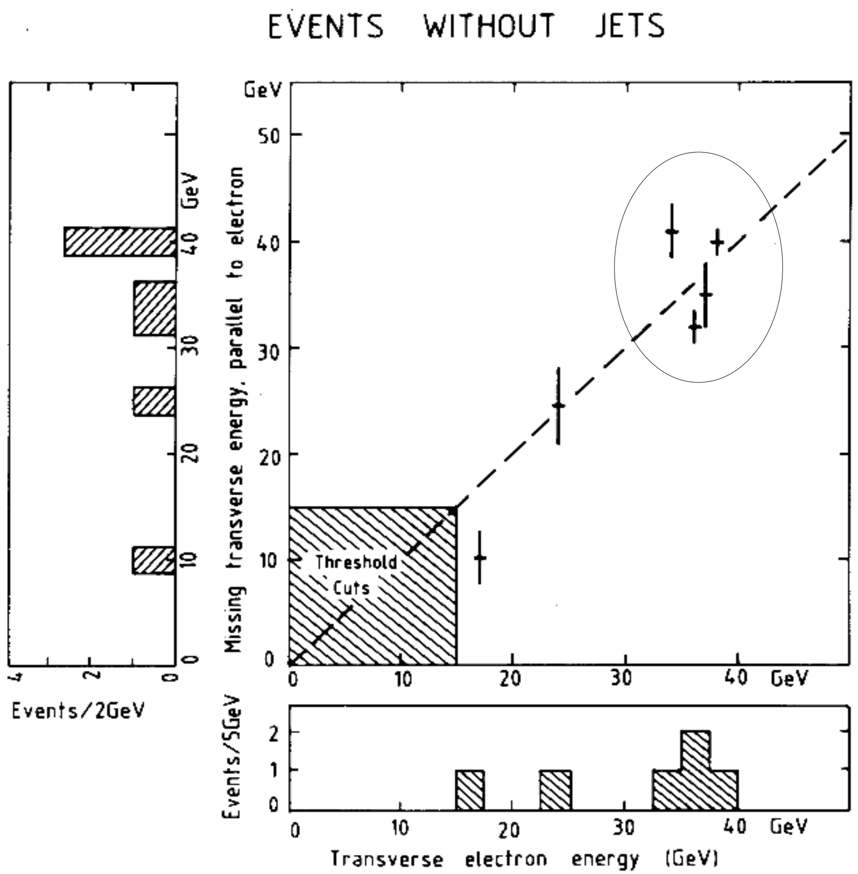
We use them in order to compare with previous LEP/Tevatron results

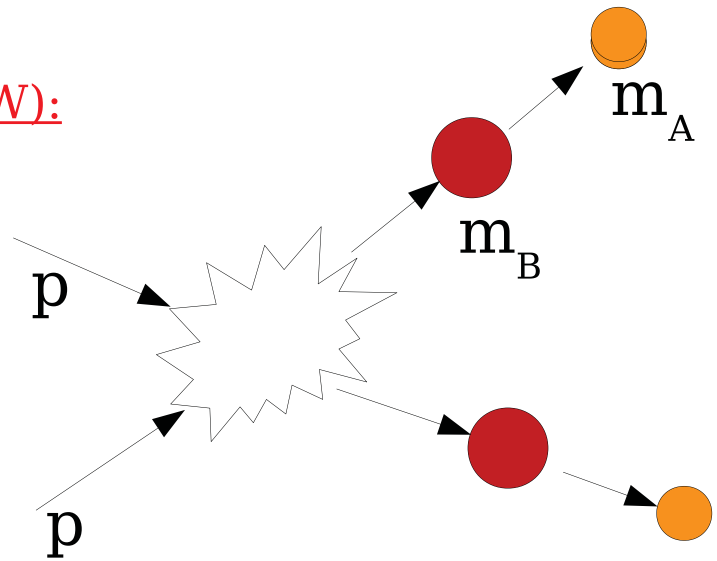
MET

WIKIPEDIA: "Missing energy is commonly used to infer the presence of non-detectable particles such as the standard model neutrino and is expected to be a signature of many new physics events".

Classic example of a MET search (Observation of W):

Physics Letters 122B (1983) p103:





ΔM_{BA} drives the MET

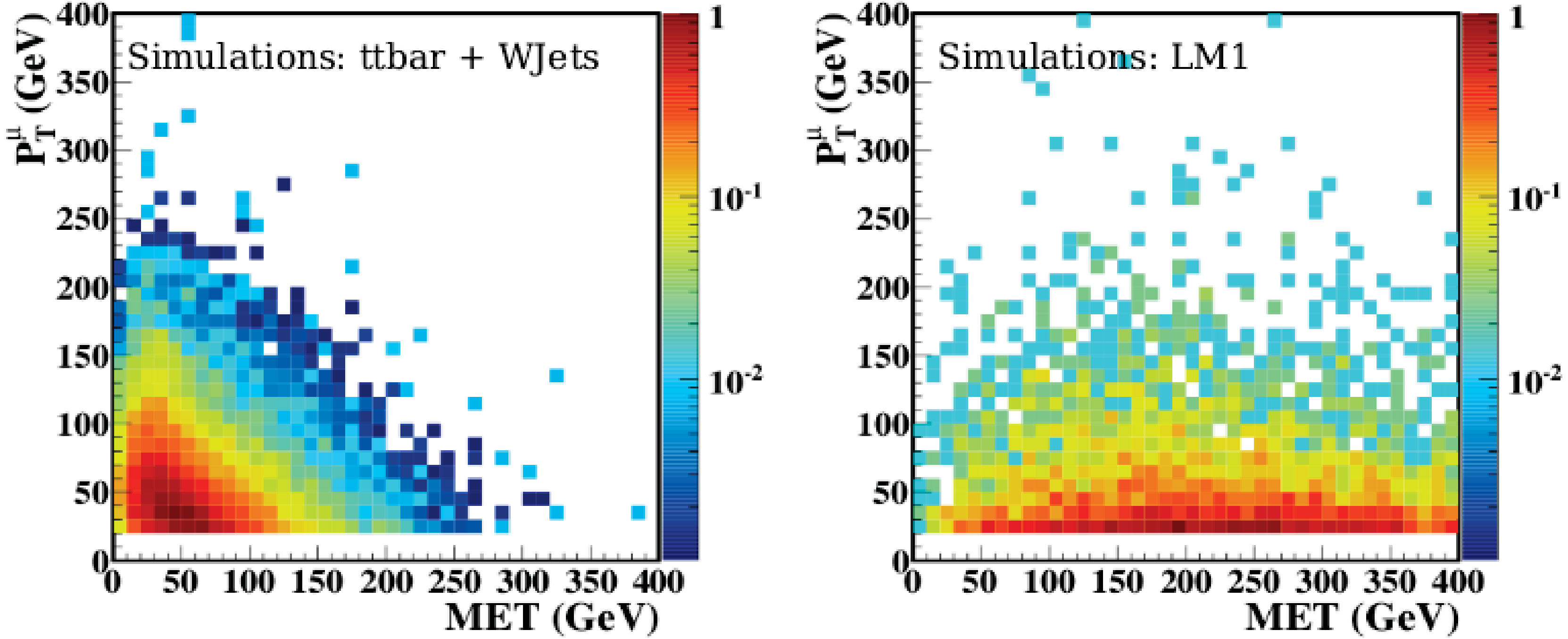
However, MET can also arise from mis-measurement of the underlying reconstructed objects/ingredients

Lepton spectrum method

In SM events, the neutrino and lepton p_T are anti-correlated in a given event

$\Rightarrow$ Overall spectra are similar

In SUSY event, the correlation between MET and lepton p_T is very different.



- Main backgrounds: ttbar, W + Jets
- Use the muon p_T spectrum to predict the MET spectrum
- MET resolutions and W polarization effects are accounted for

Lepton spectrum method

- While lepton and neutrino p_T spectra are different in a given event, their spectra are very similar in SM processes
- Strong physics foundation for method but many details to check before lepton spectrum can be used to quantitatively predict the MET for SM
  - MET resolution/scale: Resolution of MET and lepton p_T are quite different and energy scale uncertainty on MET much be taken into account
  - W polarization: Due to V-A effects, W polarization of the W boson, in either Wjets or ttbar can lead to different angular distributions for the lepton and neutrino in the W rest frame. This can produce differences in lepton, neutrino p_T in lab frame
  - Non single lepton background: Lepton spectrum method predicts single lepton events but not tau→μ,e background and feed down from dilepton ttbar events
  - Threshold on lepton p_T: not applied to neutrino

Have investigated all these points and many more

Lepton spectrum method

Helicity fractions of W bosons from top quark decays at NNLO in QCD

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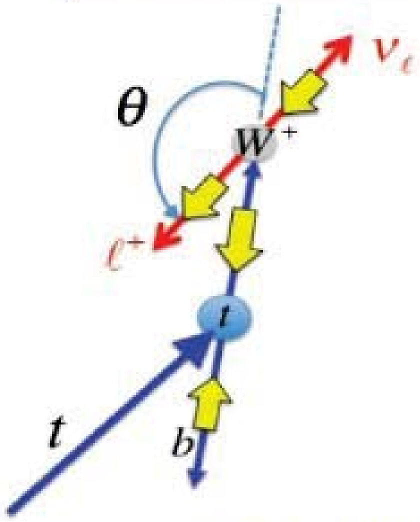
(Dated: May 18, 2010)

Decay rates of unpolarized top quarks into longitudinally and transversally polarized W bosons are calculated to second order in the strong coupling constant α_s. Including the finite bottom quark mass and electroweak effects, the Standard Model predictions for the W boson helicity fractions are $\mathcal{F}_L = 0.687(5)$, $\mathcal{F}_+ = 0.0017(1)$, and $\mathcal{F}_- = 0.311(5)$.



$\lambda(W) = -1$ (30%)
$\lambda(W) = 0$ (70%)

- Helicity fractions are very precise prediction in SM theory, have been calculated with QCD corrections to NNLO.
- Errors on F_L and F_- are O(1%); due to m(top) uncertainty
- Reduces uncertainties due to W polarization in top events to very low level
- The boost is the same for lepton, neutrino
- Lepton, neutrino spectra are result of polarizations
- In ttbar understand fully where any differences in lepton, neutrino spectrum come from