SUSY Searches at CMS

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On behalf of the CMS collaboration

Why SUSY

- SUSY has many virtues:
  - solves the hierarchy problem, provides Dark Matter candidates, has a better unification of couplings, ...
- And (at least) one vice:

  We do not know if it is there.
  - And if it is, which flavour of it.

- So we look. Everywhere.
- In this talk. First results from CMS on 35pb^{-1} data:
  - Jet+MET
  - Di-photon + MET
  - Di-lepton (OS) + MET

Jet+MET [SUS-10-003]

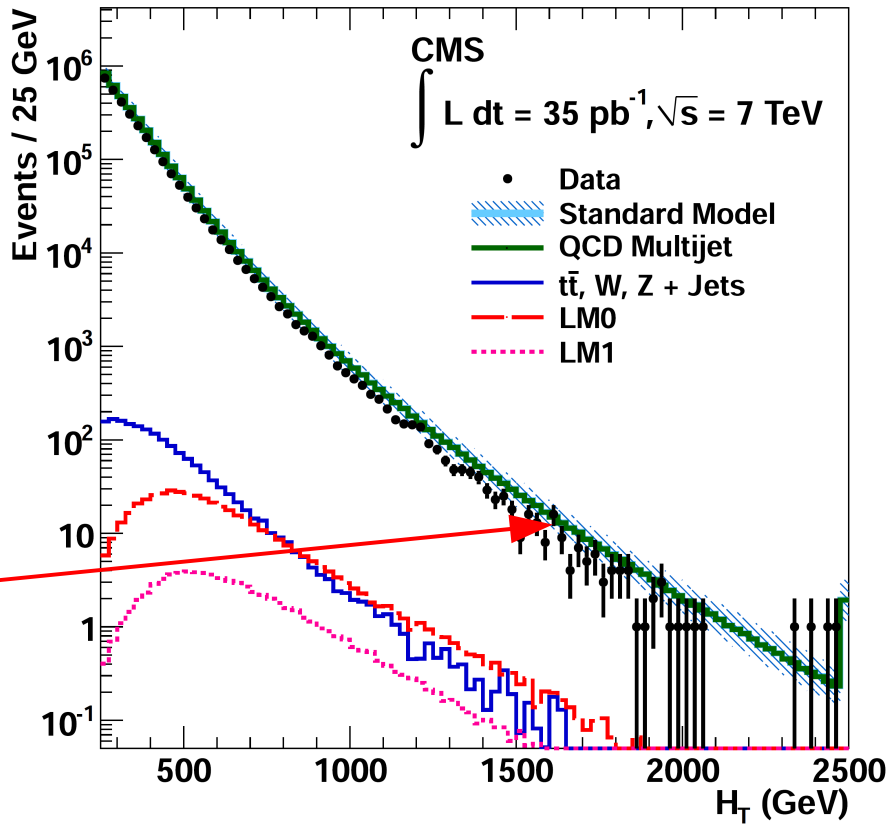
- The problem
- The variable α_T
- The background estimations
  - Inclusive
  - W+jets/ttbar and Z->$\nu\nu$
- Results

Jet+MET

- Events collected with a H_T trigger:
  - $H_T^{trigger}$ >150GeV

$$H_T = \sum_i^{N_{jet}} E_T^{j_i}$$

- Offline preselection based on calorimetric jets
  - >= 2jets
    - $E_T(j_1,j_2)$>100GeV
    - $|\eta|$<2.5
  - Other jets
    - $E_T(j)$>50GeV
    - $|\eta|$<3.0
  - H_T > 350GeV
  - Veto events containing:
    - Isolated leptons with p_T>10GeV
    - Isolated photons with E_T>25GeV
- After preselection the spectrum looks like this
  - We have a problem



α_T

- Use the kinematic variable α_T to reject the QCD background
  - Proposed in [Randall]

- Dijet definition

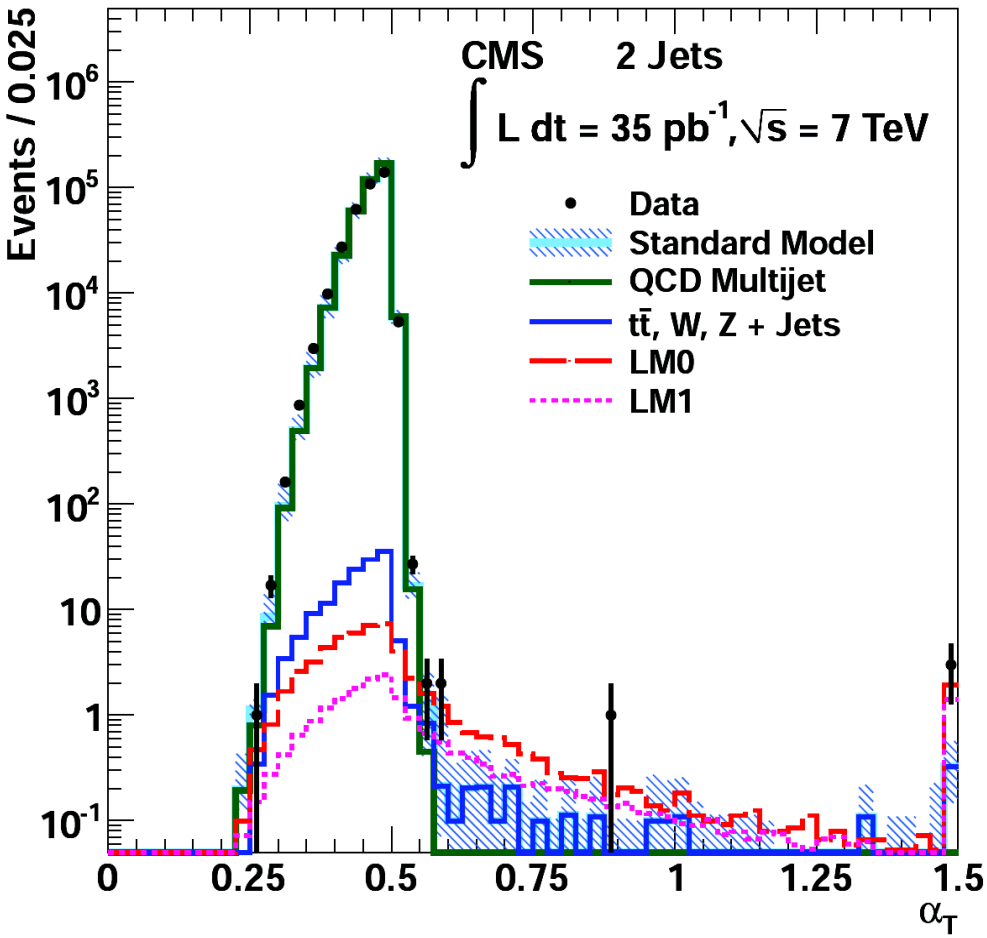
$$\alpha_T = E_T^{j2} / M_T$$

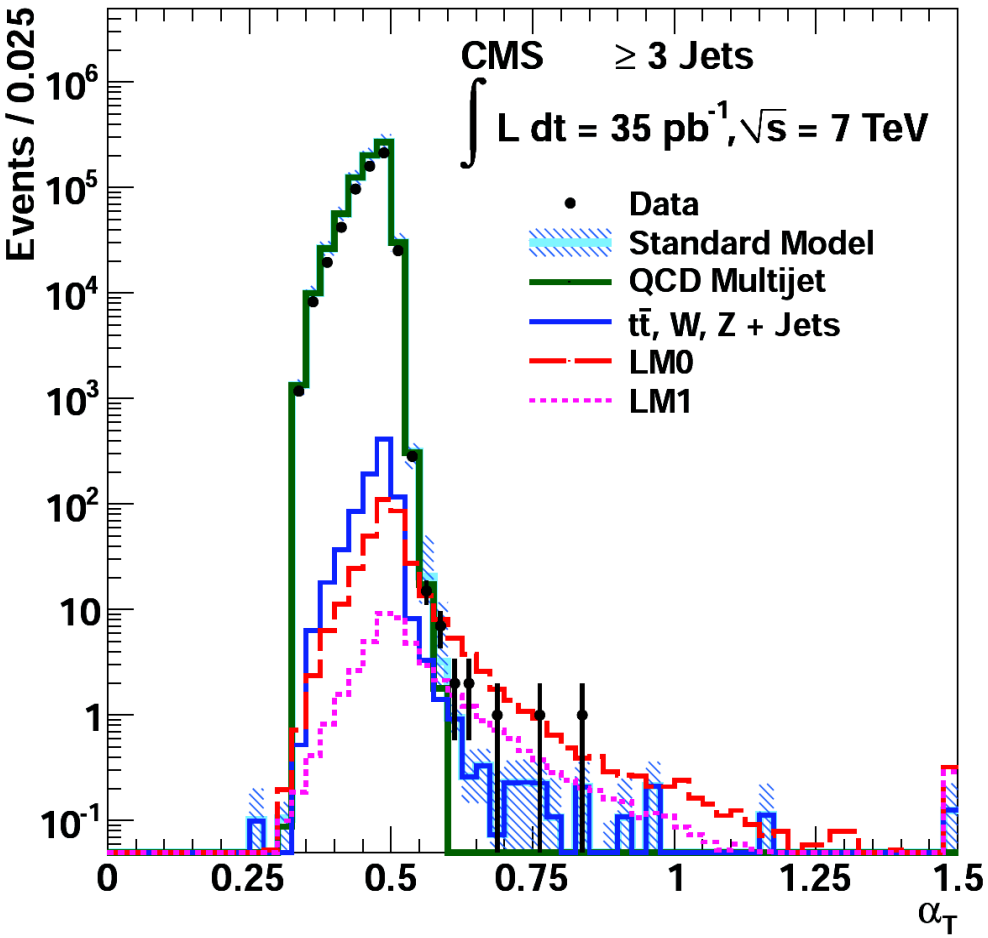
- Multijet extension
  - 2 pseudo jets w/ min(ΔH_T)

$$\alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{M_T}$$

- Features:
  - Events w/ no "intrinsic" MET have α_T=0.5
    - Jet resolution effects induce a migration to α_T<0.5
  - Spillover at α_T>0.5 due to:
    - Remnant QCD from severe energy mismeasurement.
      - E.g. due to dead towers in the electromagnetic calorimeter
    - Several low E_T jets conspiring
    - Processes w/ genuine MET

α_T





- The QCD contribution is mostly below α_T=0.5 with a drop by 4-5 orders of magnitude between 0.5 and 0.55.

Jet+MET backgrounds

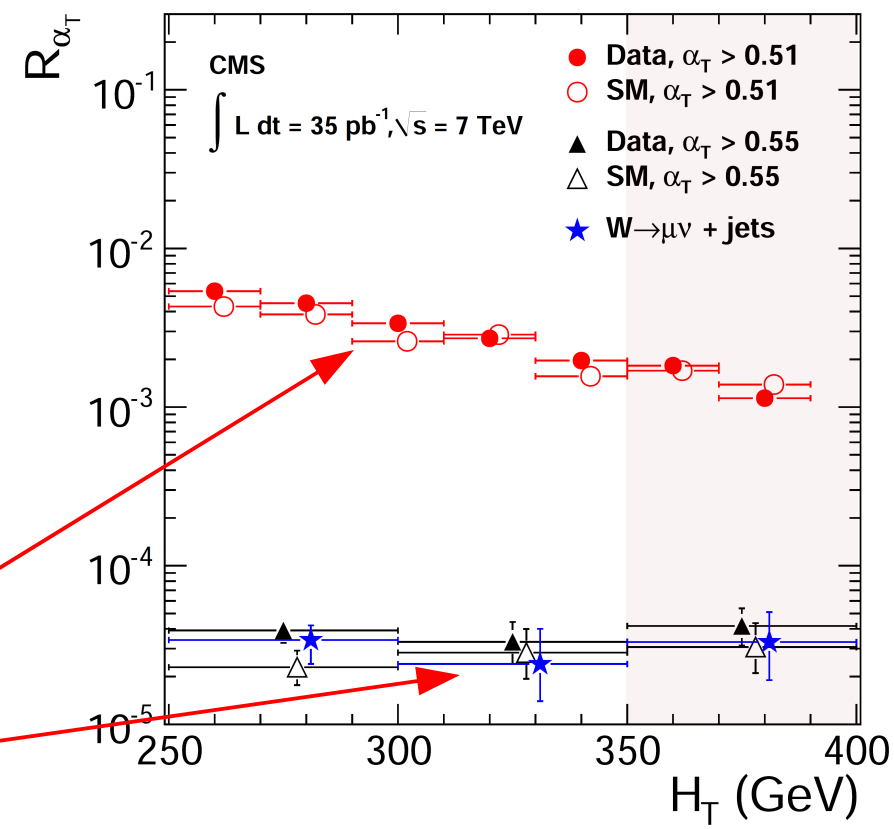
- After all the selections are applied, the signal region is defined with α_T>0.55

Selection	Data	SM	QCD multijet	$Z \to \nu\bar{\nu}$	W + jets	$t\bar{t}$
$H_T > 250\,\mathrm{GeV}$	4.68M	5.81M	5.81M	290	2.0k	2.5k
$E_T^{j2} > 100\,\mathrm{GeV}$	2.89M	3.40M	3.40M	160	610	830
$H_T > 350\,\mathrm{GeV}$	908k	1.11M	1.11M	80	280	650
$\alpha_T > 0.55$	37	30.5±4.7	19.5±4.6	4.2±0.6	3.9±0.7	2.8±0.1
$\Delta R_{\mathrm{ECAL}} > 0.3 \vee \Delta\phi^* > 0.5$	32	24.5±4.2	14.3±4.1	4.2±0.6	3.6±0.6	2.4±0.1
$R_{\mathrm{miss}} < 1.25$	13	9.3±0.9	0.03±0.02	4.1±0.6	3.3±0.6	1.8±0.1

- The MC simulation predicts yield in good agreement with the data and suggests that:
  - No QCD events survived
  - Z/W/ttbar are all important contributions
    - With $W \to \tau\nu(\tau \to \text{hadronic})$ or $W \to (e,\mu)\nu$ and e,μ not vetoed
- Still, use two independent data driven approaches to estimate all of them.

Jet+MET: inclusive background estimation

- Estimation of the combined background using the α_T ratio ($R_X = N_{\alpha T>X} / N_{\alpha T<X}$) from low H_T control regions
  - $250 < H_T < 300$ GeV and $300 < H_T < 350$ GeV
- Measure R_X VS H_T in data & MC
  - X=0.51 is monotonically falling as expected from QCD
  - X=0.55 is flat, no QCD
    - Confirmed in a data W sample



- $R_{0.55}$(HT350) estimated from the constant double ratio R_R

$$R_R = \frac{R_{0.55}(HT300)}{R_{0.55}(HT250)} = \frac{R_{0.55}(HT350)}{R_{0.55}(HT300)}$$

- Robustness check in MC:
  - extreme changes in the EWK cross-sections

W/ttbar and Z→νν background estimations

The EWK backgrounds are also separately measured in two data control samples

- W→μν control sample to predict W+jets/ttbar
  - A pure W→μν +jets sample selected on data.
    - Yields predicted by the MC in good agreement in several H_T regions
  - W/ttbar background in the signal (=hadronic) region predicted by MC translation

$$N_{\text{data}}^{\text{W; had}} = N_{\text{MC}}^{\text{W; had}} / N_{\text{MC}}^{\text{W; }\mu} \times N_{\text{data}}^{\text{W; }\mu} \approx 0.86 \times N_{\text{data}}^{\text{W; }\mu}$$

  - Also the Z→νν is estimated using this sample
- γ+jets control sample to predict Z→νν+jets
  - At high p_T the Z/γ cross-section ratio flattens out
    - Select events with high p_T isolated photons
    - Use MC to correct for the cross-section ratio and acceptance

Jet+MET summary

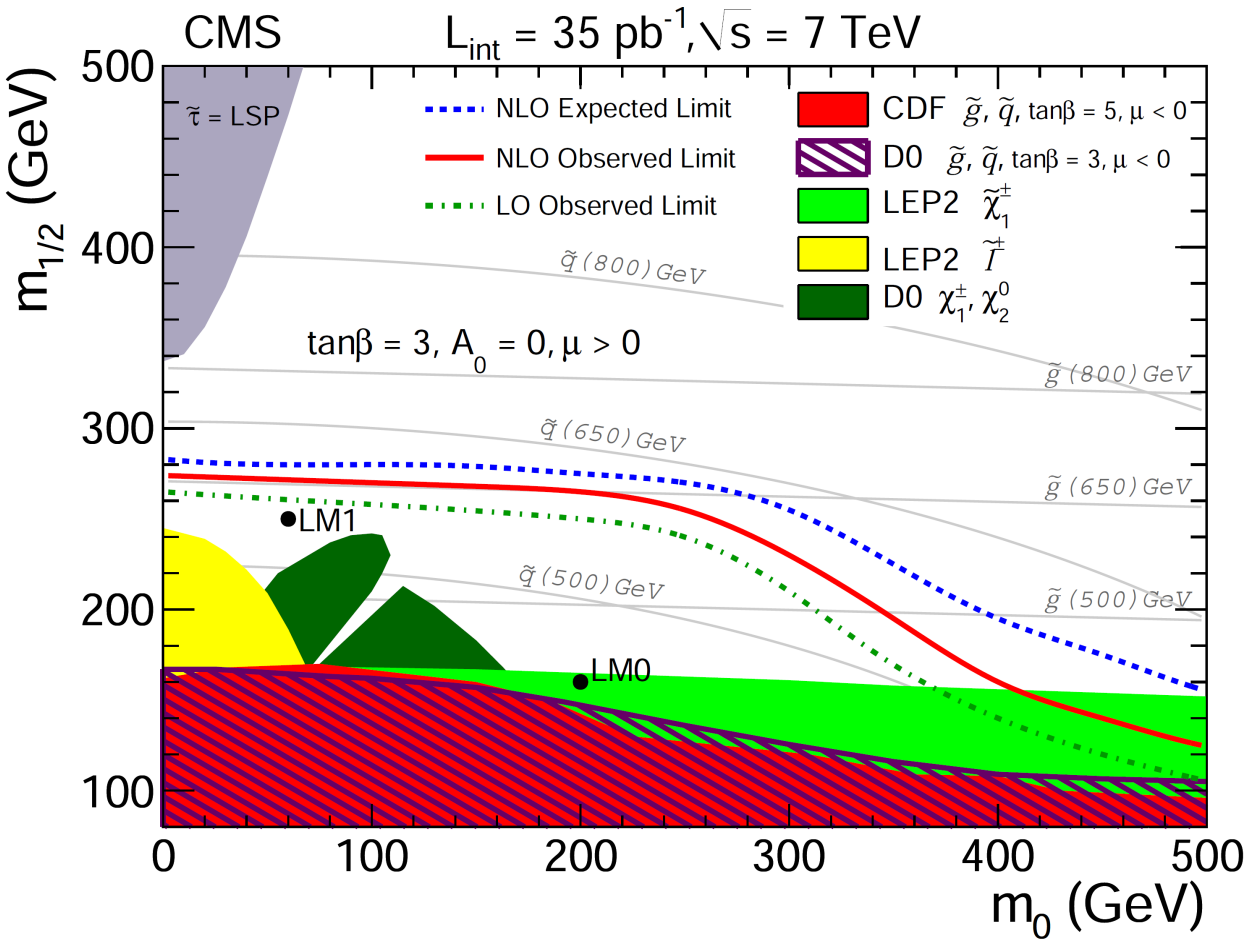
Background source	Method	Result	Total
Inclusive	Monte Carlo		9.3 ± 0.9
Inclusive	DD: R_R		$9.4^{+4.8}_{-4.0} \pm 1.0$
$W/t\bar{t}$	DD: $W \to \mu\nu$	$6.1^{+2.8}_{-1.9} \pm 1.8$	
$Z \to \nu\nu$	DD: γ+jets	$4.4^{+2.3}_{-1.6} \pm 1.8$	
Sum			$10.6^{+3.6}_{-2.5} \pm 2.5$
Data			13

- The two data driven (DD) methods are in good agreement between themselves
    - and with the MC expectation
  - Confirm that QCD is negligible
- Good agreement with the data (unfortunately)
- Both data driven results are used as input in the limit calculation.
- Can exclude with 95% CL points which yields more than 13.4 events

Jet+MET limits in mSUGRA

- Observed and expected limits in the m_0-$m_{1/2}$ plane for $\tan\beta=3$, $A_0=0$, $\mu>0$
  - Signal contamination in the background estimations, accounted for.

- Limits weakly dependent on value of $\tan\beta$
- In the same plot Tevatron limits w/ $2fb^{-1}$:
  - CDF w/ $\tan\beta=5$, $\mu<0$
  - D0 w/ $\tan\beta=3$, $\mu<0$



Photons+Jet+MET [SUS-10-002]

- Event selection
- Background estimations
  - EWK
  - QCD
- Results and limits

γs+Jet+MET event selection

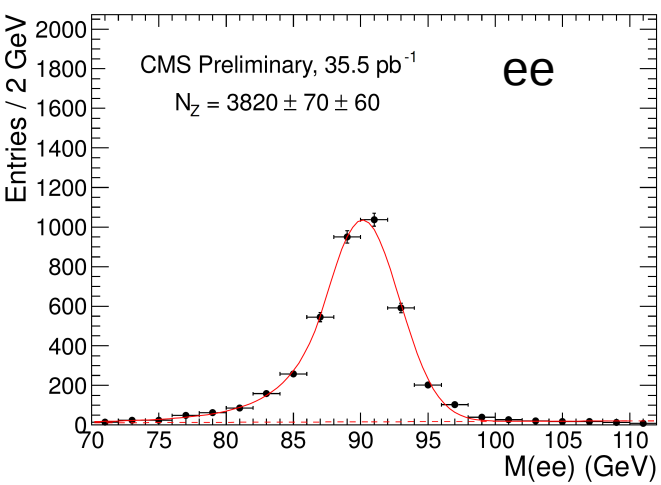
- Events collected by single and double photon triggers
  - SinglePhoton30 and DoublePhoton22
- Offline selections:
  - Two (or more) photons candidates in the ECAL with
    - E_T>30 GeV
    - $|\eta|$<1.4
    - Shower shape, Hadronic/EM and ECAL, HCAL, Track Isolation requirements applied
  - One (or more) jet with:
    - E_T>30 GeV
    - $|\eta|$<2.6
    - $\Delta R(j,\gamma)$>0.9 for at least one of the jets
    - Jets defined with the Jet Plus Track algorithm [JPT]. Calorimeter response is corrected by the pT of the tracks

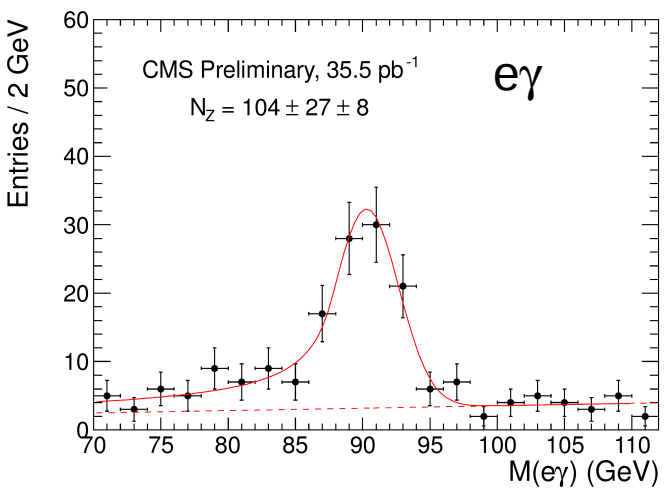
γs+Jet+MET backgrounds

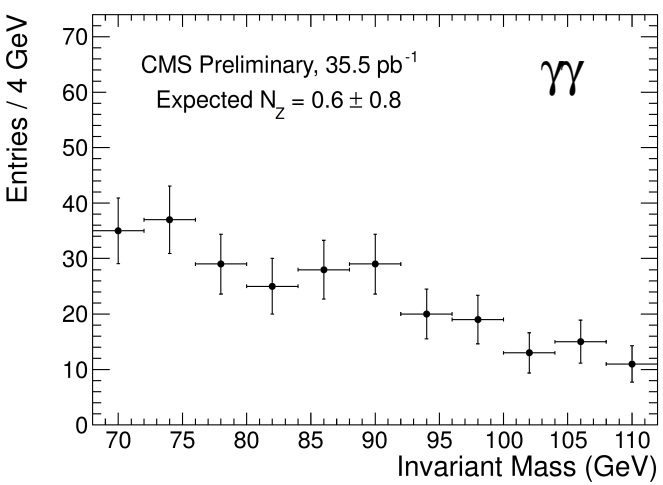
- Electroweak (real MET)
  - Irreducible:
    - $Z\gamma\gamma$, $W\gamma\gamma$, negligible at these luminosities
  - Electron mis-identification
    - $W\gamma$, W+jet with W decaying to electron that is mis-ID'ed as γ
- Fake MET
  - Mostly QCD ($\gamma\gamma$, γ+jet, multijet)
- Non-beam negligible after the jet requirement
  - cosmic muons' bremsstrahlung
  - beam halo muons' bremsstrahlung

EWK background

- This background has a W→eν plus a real or fake photon. It involves electron-photon mis-identification.
  - By design electrons and γ differ only by a pixel matching requirement
  - Measure the electron-γ mis-ID rate $f_{e\gamma}$ (=1.4±0.4%) by counting Z events in the ee, eγ, γγ samples
- Scale the eγ+(jets) sample by $f_{e\gamma}/(1-f_{e\gamma})$ to get the EWK background contribution in the γγ+(jets)
  - 43 events in eγ+(jets)

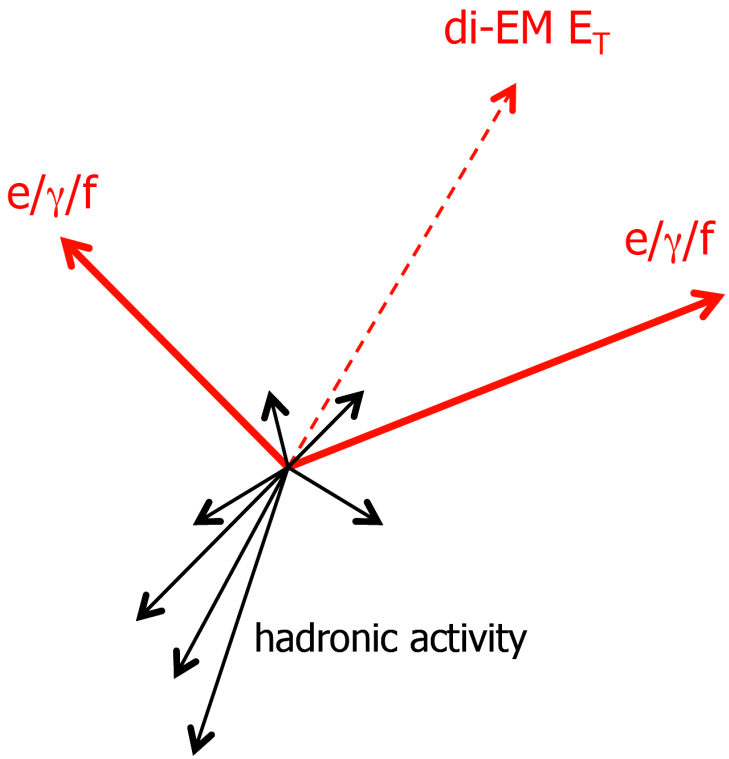






Fake MET background (QCD)

- Fake MET is mostly due to the hadronic component of the event
  - The EM energy resolution is much higher, everything is determined by hadronic recoil



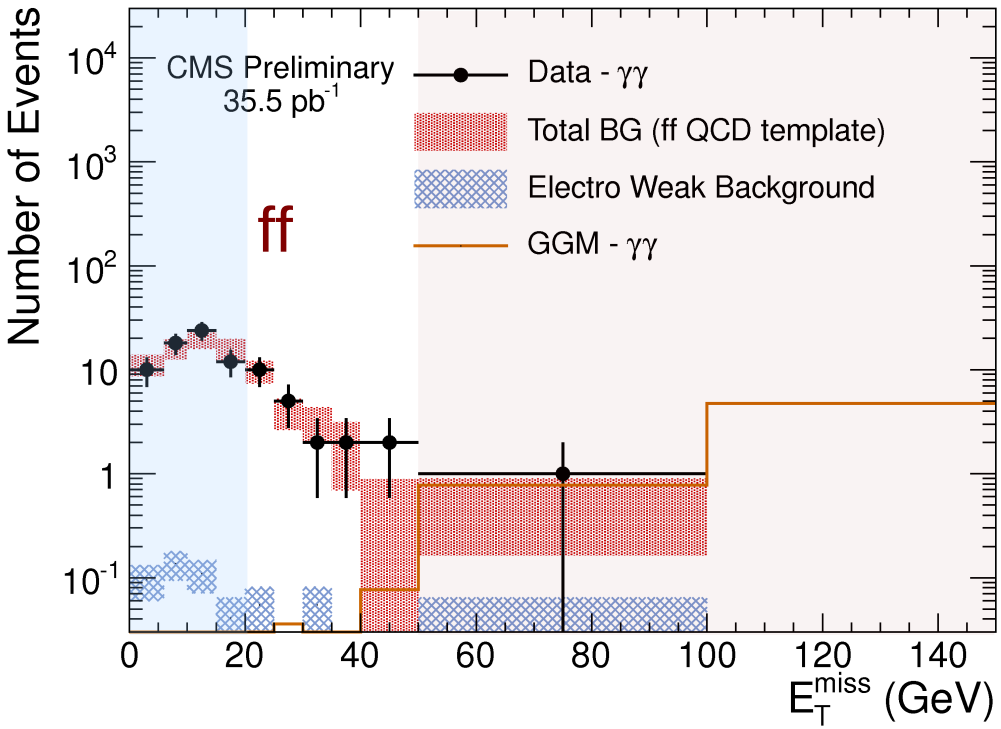
Idea

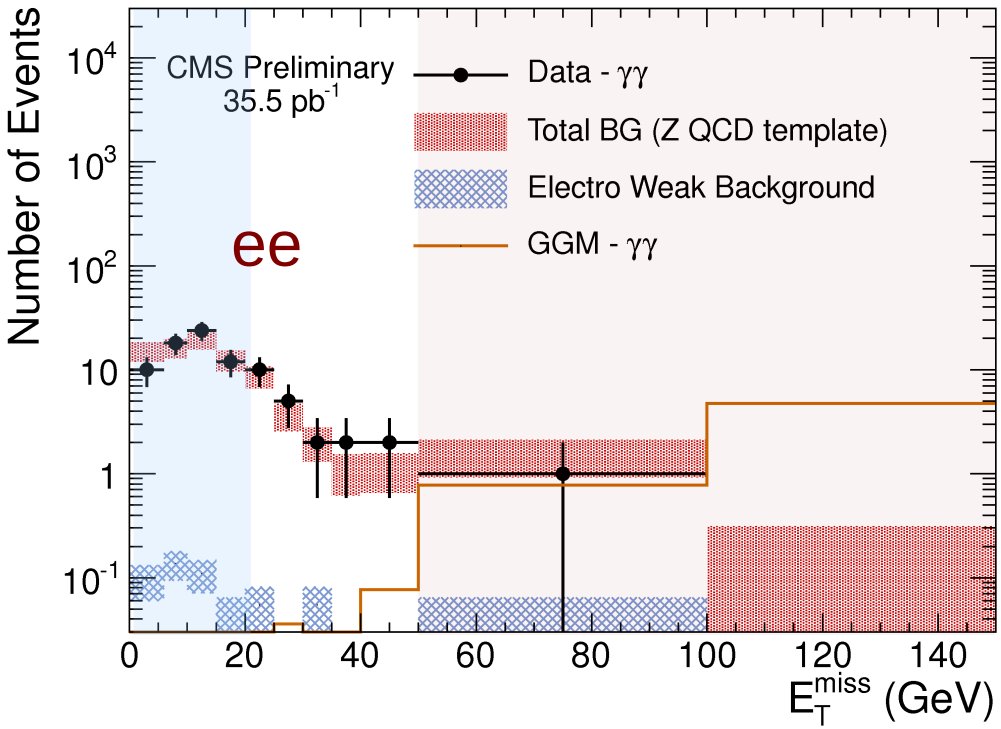
- Find sample with two EM objects and no true MET
- Re-weigh it so that the di-EM E_T matches the signal sample
  - After EWK subtraction
- Two control samples used:
  - Fake-fake (ff). A fake is defined as a photon that fails either the shower shape or track isolation.
    - dominated by QCD events w/ two "photon-like" jets
  - e^+e^- with $70<M(ee)<110$ GeV
    - Dominated by $Z\rightarrow ee$

Backgrounds

- Re-weigh the ff and ee samples to match the di-EM pT spectrum shape of the γγ sample
  → provides the E_T^{miss} templates
- Normalize the templates in the E_T^{miss} < 20 GeV region
  - negligible SUSY contribution there

  → provides the full E_T^{miss} spectrum



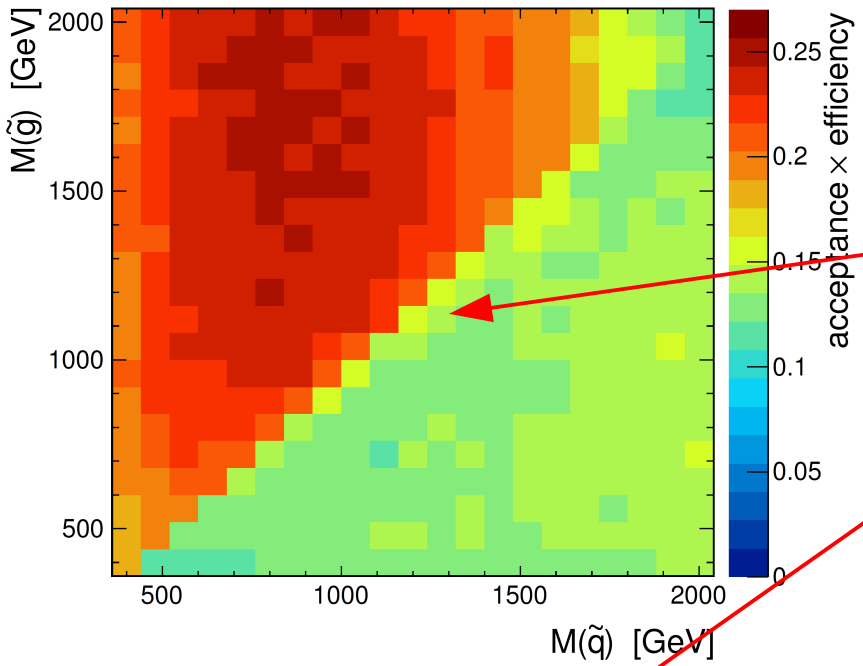


Results

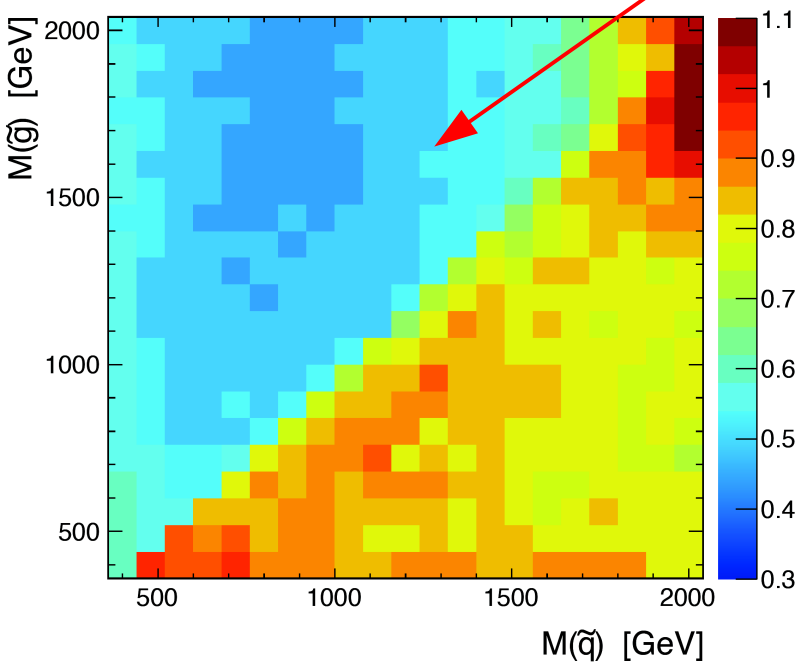
Type	Number of events	stat error	reweight error	normalization error
$\gamma\gamma$ events	1			
Electroweak background estimate	0.04 ± 0.03	± 0.02	± 0.0	± 0.01
QCD background estimate (ff)	0.49 ± 0.37	± 0.36	± 0.06	± 0.07
QCD background estimate (ee)	1.67 ± 0.64	± 0.46	± 0.38	± 0.23
Total background (using ff)	0.53 ± 0.37			
Total background (using ee)	1.71 ± 0.64			

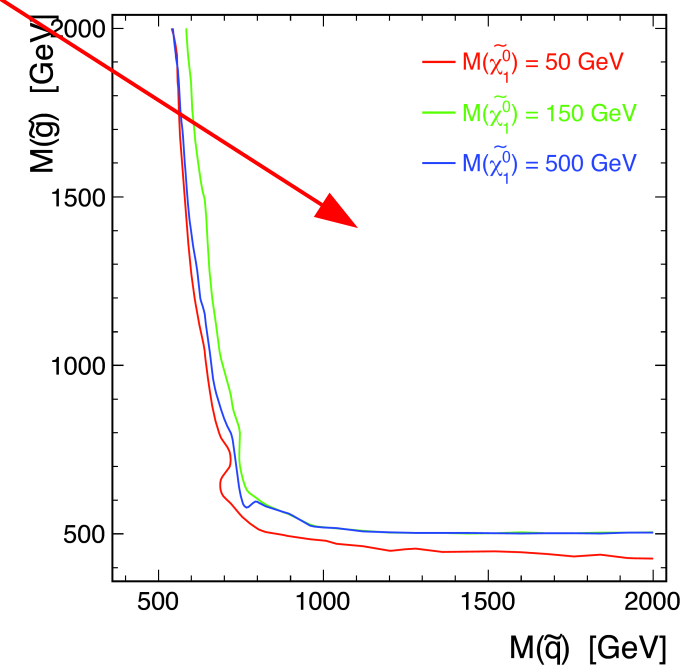
- One observed event in the signal region (E_T^{miss}>50 GeV)
- The total background estimation is 1.2±0.8 events from the average of ff and ee method, plus the eγ
- The uncertainties are due to:
  - Statistical uncertainties of the control samples
  - Statistical uncertainty on the di-EM distribution used for reweighing
  - Stat uncertainty on the normalization in E_t^{miss}<20GeV

M(g)-M(q) GGM limits



- Generated a grid of points scanning M(g), M(q) and M(χ^0).
  - Here: M(χ^0)=150 GeV
- Calculated the signal acceptance*efficiency for each point
- 95% CL upper limits on the production cross section
- 95% CL exclusion in M(g)-M(q)





Opposite sign dileptons+Jet+MET [SUS-10-007]

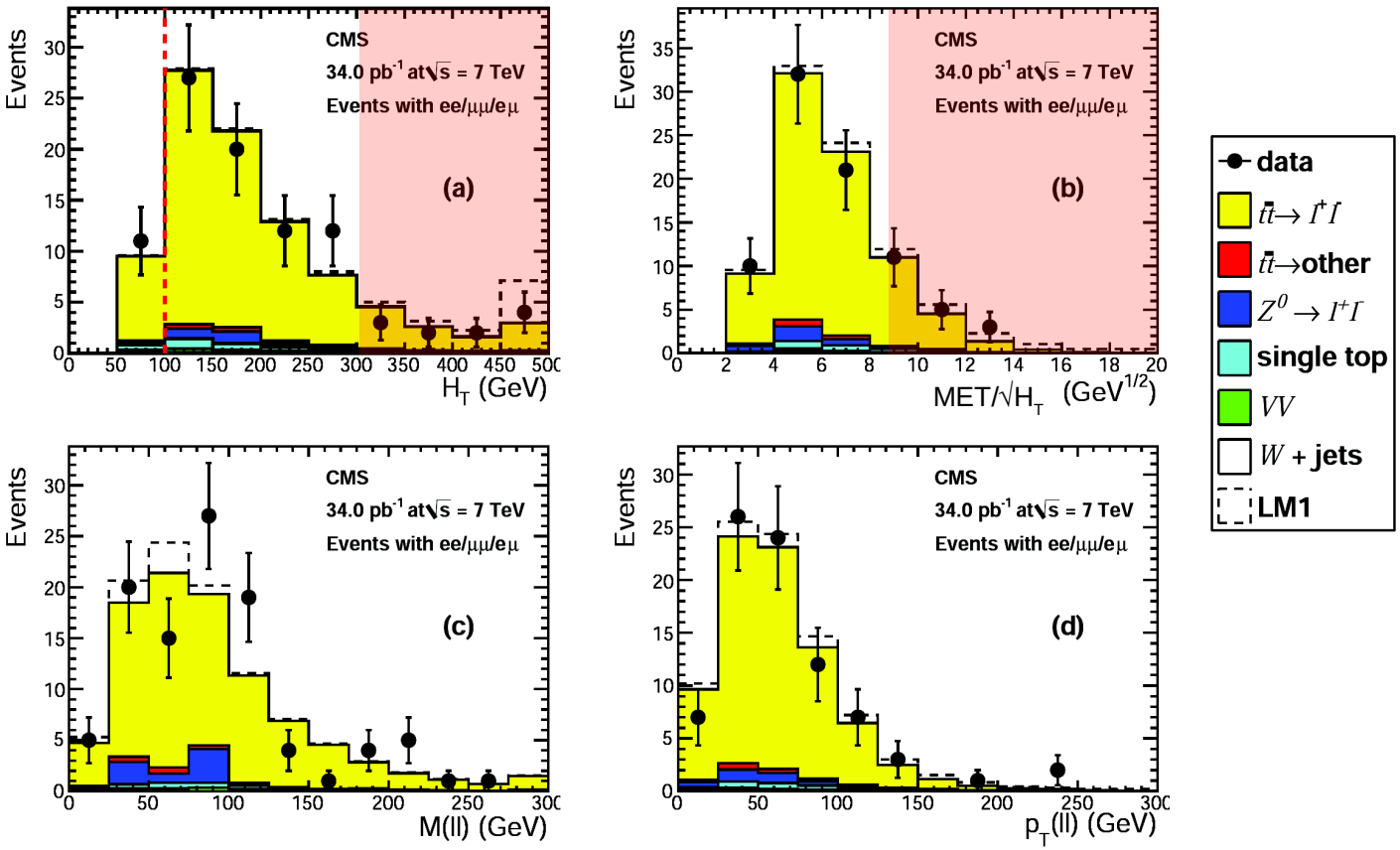
- Event selection
- Data/MC comparison
- Background estimations
  - ABCD
  - $P_T(ll)$
- Results

OS dilepton preselection

- Events collected by single and double-lepton triggers.
  - Efficiency>99%
- Preselection:
  - 2 isolated leptons with opposite charge (e^+e^-, $e^\pm\mu^\pm$, $\mu^+\mu^-$)
    - $p_T(l_1) > 20$GeV, $p_T(l_2) > 10$GeV, Veto ee/μμ pairs in Z mass window
  - 2 jets (jet+tracks) with $p_T > 30$ GeV, $|\eta|<2.5$
    - Separated from the leptons by $\Delta R>0.4$
  - $H_T > 100$ GeV, $E_T^{miss} > 50$ GeV
- Monte Carlo and data yields in very good agreement

Sample	ee	$\mu\mu$	$e\mu$	tot
$t\bar{t} \to \ell^+\ell^-$	14.50 ± 0.24	17.52 ± 0.26	41.34 ± 0.40	73.36 ± 0.53
$t\bar{t} \to$ other	0.49 ± 0.04	0.21 ± 0.03	1.02 ± 0.06	1.72 ± 0.08
$Z^0 \to \ell^+\ell^-$	1.02 ± 0.21	1.16 ± 0.22	1.20 ± 0.22	3.38 ± 0.37
$W^\pm$ + jets	0.19 ± 0.13	0.00 ± 0.00	0.09 ± 0.09	0.28 ± 0.16
W^+W^-	0.15 ± 0.01	0.16 ± 0.01	0.37 ± 0.02	0.68 ± 0.03
$W^\pm Z^0$	0.02 ± 0.00	0.02 ± 0.00	0.04 ± 0.00	0.09 ± 0.00
Z^0Z^0	0.01 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.05 ± 0.00
single top	0.46 ± 0.02	0.55 ± 0.02	1.24 ± 0.03	2.25 ± 0.04
total SM MC	16.85 ± 0.34	19.63 ± 0.34	45.33 ± 0.47	81.81 ± 0.67
data	15	22	45	82

Data/MC comparisons – signal selection



- MC describes well the data in various distributions
- Define the signal region with the further requirements:

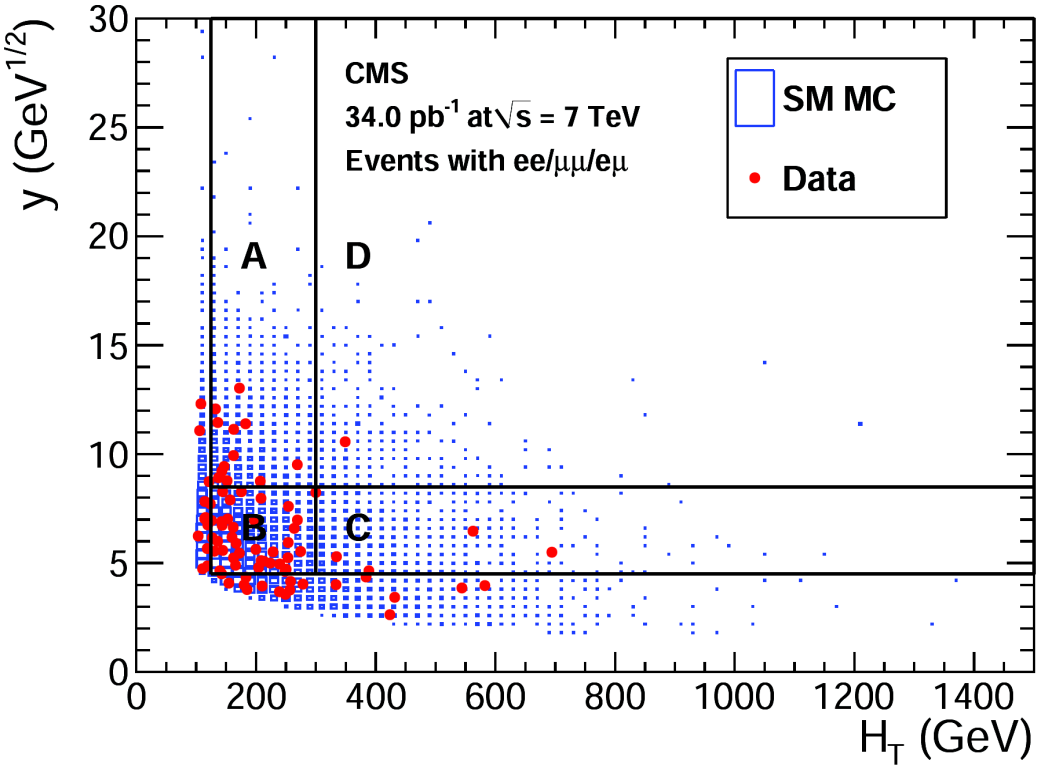
  $H_T > 300$ GeV and $y := E_T^{miss}/\sqrt{H_T} > 8.5$ GeV$^{1/2}$
- one event is left in the data
  - Consistent with 1.3 events predicted by MC

(Residual) background predictions

Developed two independent data-driven methods to estimate the ttbar background in the signal region

- First: ABCD method in the y vs H_T plane
  - H_T and y are basically uncorrelated for tt→dilepton
- Second: in dilepton ttbar events the l and ν from W have similar P_T spectra [MET_VplusJets]
    - Except for W polarization effects
  - Use the observed P_T(ll) distribution to model P_T(νν)
- Finally check that the backgrounds from fake leptons are negligible.
    - Sources: leptons from b or c, muon decays, pions misID as electrons
  - Estimated in events with one lepton tight, one loose
    - =Fakeable Object
    - Weigh events with FR/(1-FR) with FR(P_T,η). See [ttbar-dilepton].
  - Zero events expected, assumed $0.00^{+0.04}_{-0.00}$

ABCD background predictions



- Verified that chosen ABCD variables $E_T^{miss}/\sqrt{H_T}$, H_T are weakly correlated (<5%)
- Observed good agreement between data and MC yields
- Assess 20% uncertainty for:
  - MC stats in closure test,
  - non tt→dilepton bkgs
  - variation of ABCD boundaries from hadronic energy scale uncertainty

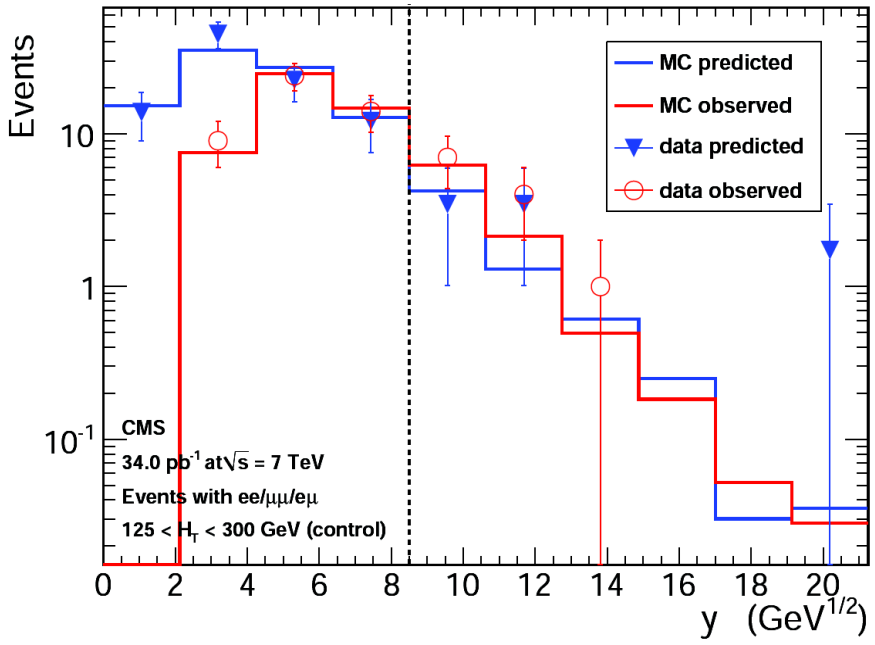
sample	A	B	C	D	A × C / B
$t\bar{t} \to \ell^+\ell^-$	8.44 ± 0.18	32.83 ± 0.35	4.78 ± 0.14	1.07 ± 0.06	1.23 ± 0.05
$t\bar{t} \to$ other	0.12 ± 0.02	0.78 ± 0.05	0.16 ± 0.02	0.02 ± 0.01	0.02 ± 0.01
$Z^0 \to \ell^+\ell^-$	0.17 ± 0.08	1.18 ± 0.22	0.04 ± 0.04	0.12 ± 0.07	0.01 ± 0.01
$W^\pm$ + jets	0.00 ± 0.00	0.09 ± 0.09	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
W^+W^-	0.11 ± 0.01	0.29 ± 0.02	0.02 ± 0.01	0.03 ± 0.01	0.01 ± 0.00
$W^\pm Z^0$	0.01 ± 0.00	0.04 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Z^0Z^0	0.01 ± 0.00	0.02 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
single top	0.29 ± 0.01	1.04 ± 0.03	0.04 ± 0.01	0.01 ± 0.00	0.01 ± 0.00
total SM MC	9.14 ± 0.20	36.26 ± 0.43	5.05 ± 0.14	1.27 ± 0.10	1.27 ± 0.05
data	12	37	4	1	1.30 ± 0.78

$P_T(ll)$ background prediction

- This method relies on the $P_T(ll)$ distribution to get $P_T(\nu\nu)$
- A couple of corrections are needed to account for:
  - The dilepton event selection includes a $E_T^{miss} > 50$ GeV.
  - The Ws from top decay are polarized → the νs carry on average a larger momentum than the l.
    - These two effects are well modelled by MC and a correction factor can be derived. K = 2.1±0.6

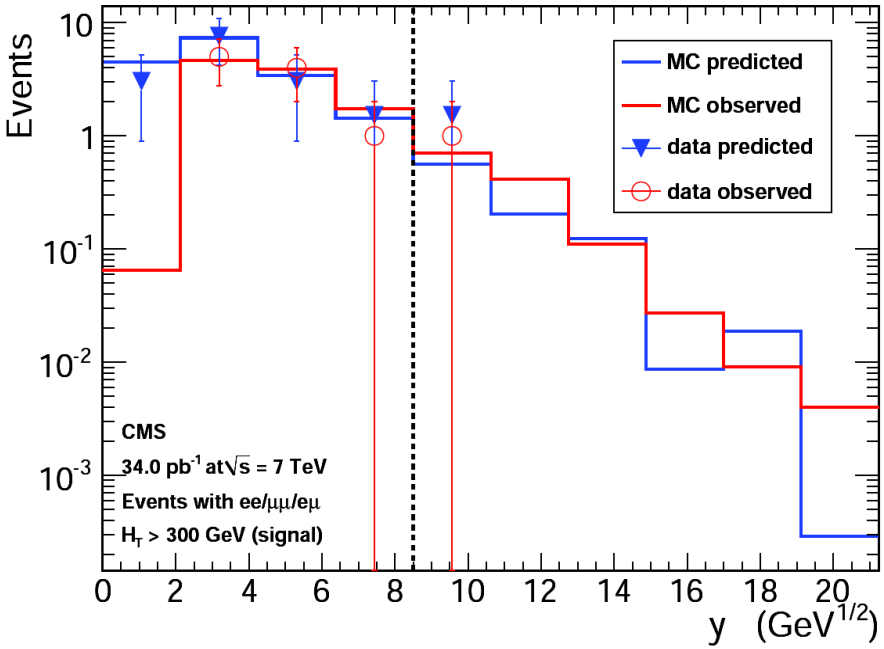
- Closure tested in region A

  ($125<H_T<300$ GeV and $y=E_T^{miss}/\sqrt{H_T}>8.5$ GeV$^{1/2}$)
  - 5 events in the A' region
    - ($E_T^{miss}/\sqrt{H_T} \rightarrow P_T(ll)/\sqrt{H_T}$)
  - Subtract expected DY there: $N_{DY}=1.3\pm0.9$
  - Predicted: $N_A = K\cdot(N_{A'}-N_{DY})= 9.0\pm6.0$. Observed=12



P_T(ll) background prediction - Summary

- Finally the method is applied in (signal) region D and (D')
  - 1 event in D' region
  - Predicted: $N_D = K\cdot(N_{D'}-N_{DY})$ $=2.1\pm2.1(stat)\pm0.6(syst)$



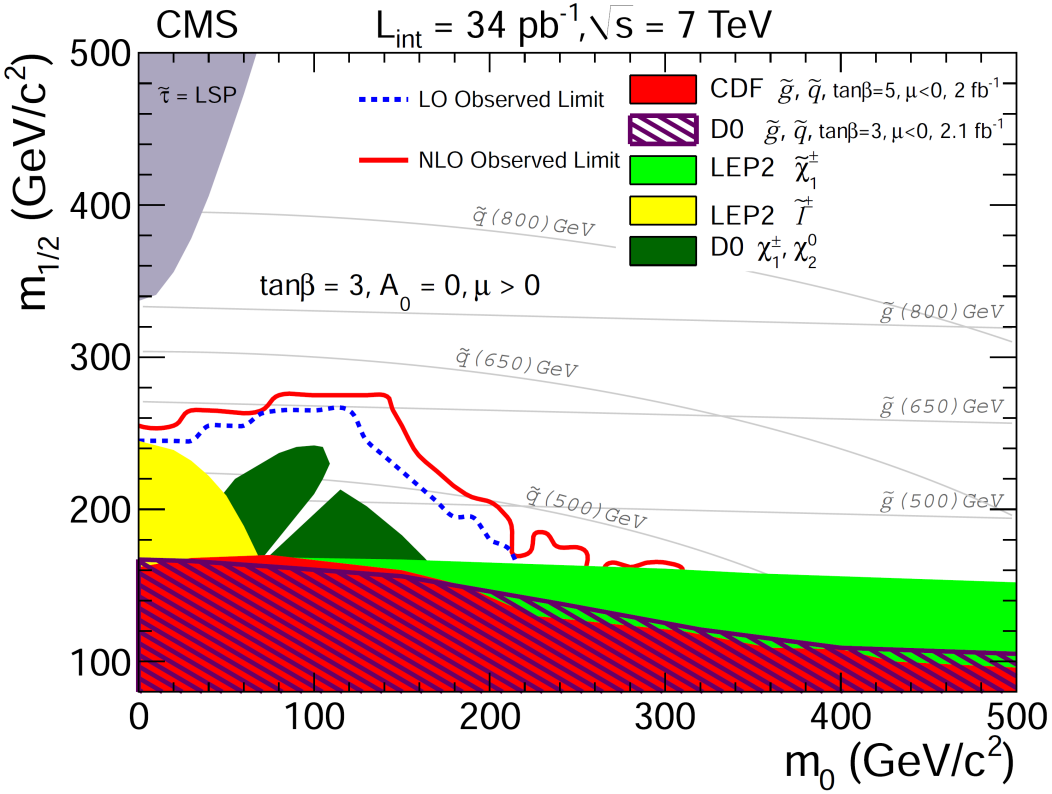
- Background summary

Observed yield:	**1 event**
MC predicts:	**1.3 events**
ABCD method predicts:	**1.3 ± 0.8 (stat) ± 0.3 (syst) events**
p_T(ll) method predicts:	**2.1 ± 2.1 (stat) ± 0.6 (syst) events**

- Weighted average of the two DD predictions: 1.4±0.8

Results

- Limit on signal yield:
  - 4.1 events at 95% CL
- mSUGRA limits:
  - Uncertainties and signal contamination fully accounted for



Eff_{μ}^{ID}	$\approx 95\%$
$Eff_{e}^{ID}(10GeV)$	$\approx 63\%$
$Eff_{e}^{ID}(>30GeV)$	$\approx 91\%$
$Eff_{\mu}^{Iso}(10GeV)$	$\approx 83\%$ in $t\bar{t}$
$Eff_{\mu}^{Iso}(>60GeV)$	$\approx 95\%$ in $t\bar{t}$
$Eff_{e}^{Iso}(10GeV)$	$\approx 89\%$ in $t\bar{t}$
$Eff_{e}^{Iso}(>60GeV)$	$\approx 95\%$ in $t\bar{t}$
	$\approx 5-10\%$ lower in LM0
H_T response	1.02 ± 0.05
y response	0.94 ± 0.05

- Additional information to facilitate generator-level studies.

SUSY results: outreach

- How to maximize the information content of our papers?
  - mSUGRA limits
  - pMSSM limits
  - Efficiencies and detector responses
  - ...
- Also:
  - describe discoveries and exclusions in terms of simplified models. Decouple all mass parameters, couplings, etc.
    - See workshop ”Global BSM fits and LHC data”, Feb 10-11
    - http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=118137
    - “CMS: progress on searches using simplified models” , W. Waltenberger

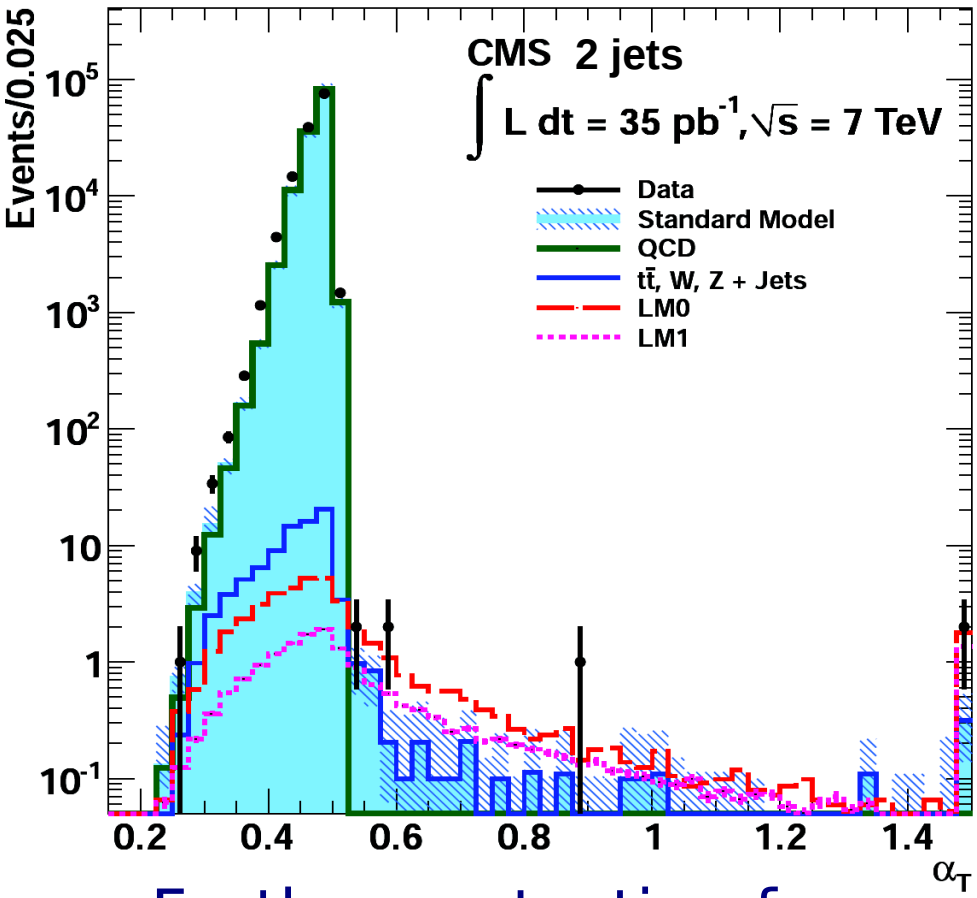
Conclusions

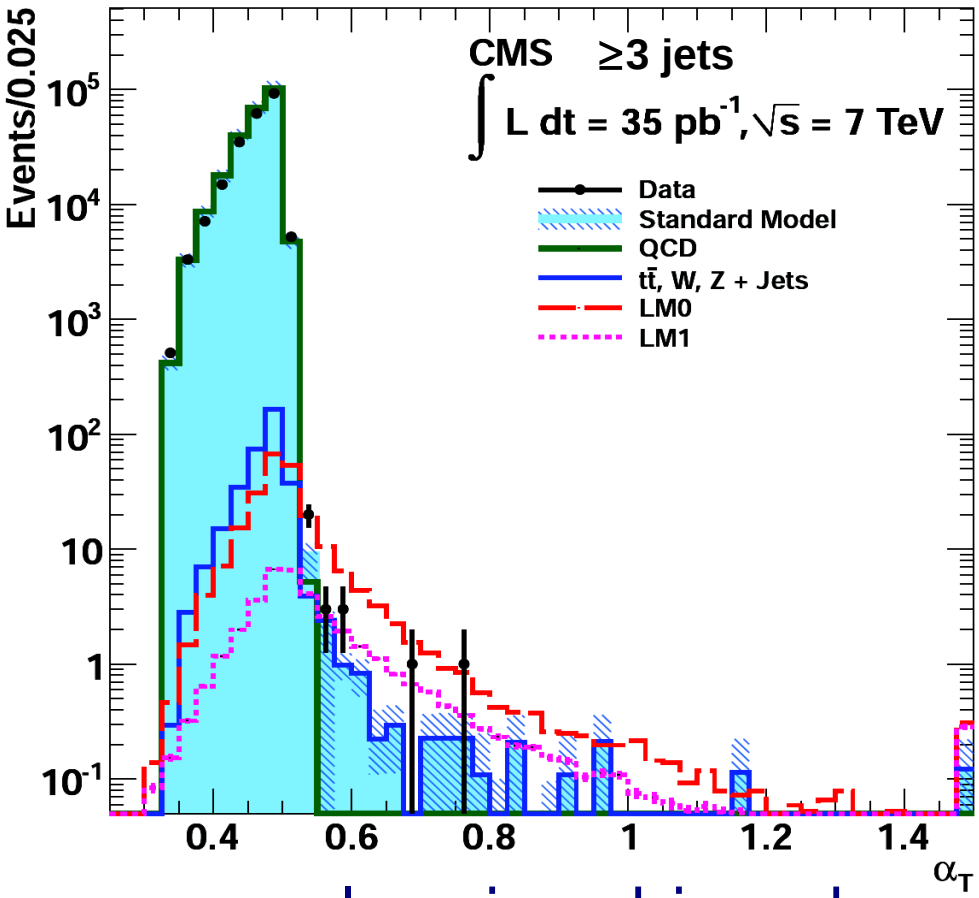
- With just 35 pb^{-1} of data CMS entered into new territory
- Performed searches with E_T^{miss} signatures in a variety of final states
  - Extended previously explored range of model parameters
- Many more to follow
- Before the 2013 shut-down LHC will deliver O(fb^{-1}) of data.

No more “limits” this/next year?

Backup/References

α_T





- Further protection from severe energy loss is achieved by removing events with:
  - Jets falling into an ECAL masked tower
  - Multiple jets failing the E_T>50GeV requirement.
    - Event is rejected if $R_{miss} = \not{H}_T / \not{E}_T{}^{calo} > 1.25$

Jet+MET: ECAL masked towers protection

- The variable:

$$\Delta\phi^* = \min_k \left(\Delta\phi \left(\left(\sum_{i=0}^{n} -\vec{j}_i \right) + \vec{j}_k ; \vec{j}_k \right) \right)$$

- is the (minimal) azimuthal distance between the jets and their recoils.
- The jet which minimizes $\Delta\phi^*$ is likely the one which gave the largest contribution to

$$\vec{\not{H}}_T = -\sum_{jets} \vec{p}_{T_{jet}}$$

- Events with $\Delta\phi^*<0.5$ AND $\Delta R_{ECAL} <0.3$ are rejected
  - ΔR_{ECAL} is the distance between the selected jet and a ECAL masked tower

References

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  - “Modelling missing transverse energy in V+jets at CERN LHC”. V. Pavlunin, (UC, Santa Barbara), Phys.Rev.D81:035005 (2010).