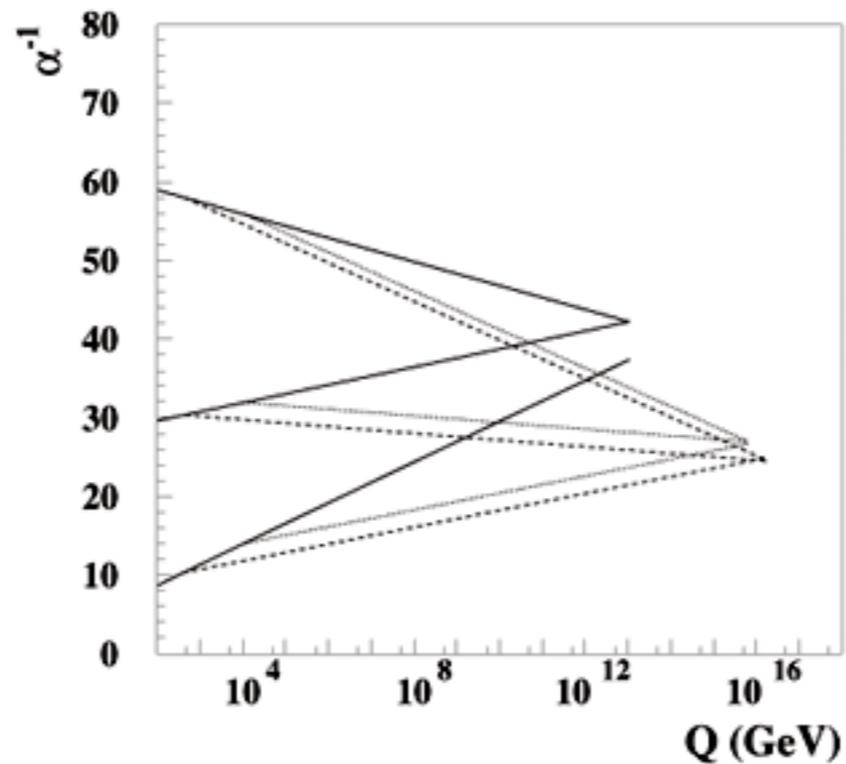
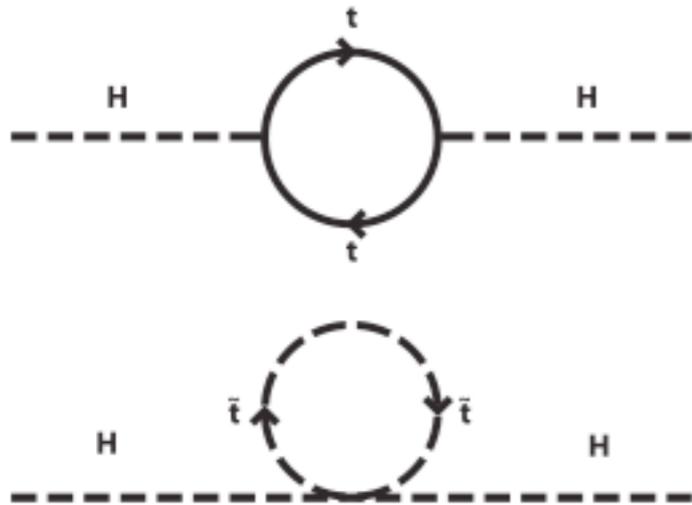
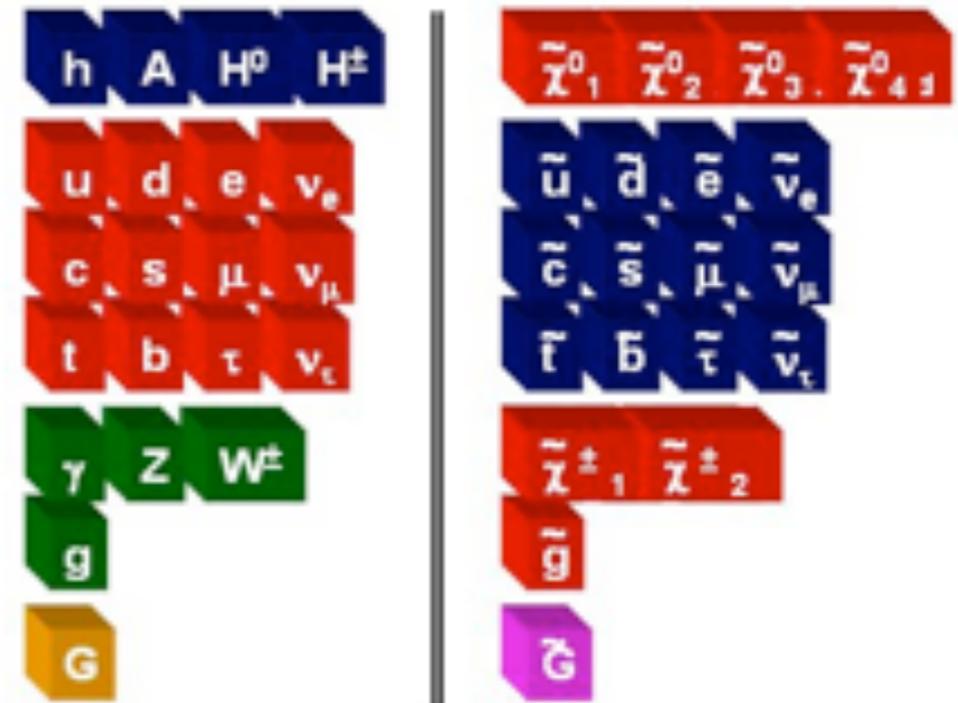


# Searches for supersymmetry with jets and missing $E_T$ and no leptons

Gheorghe Lungu  
*The Rockefeller University*

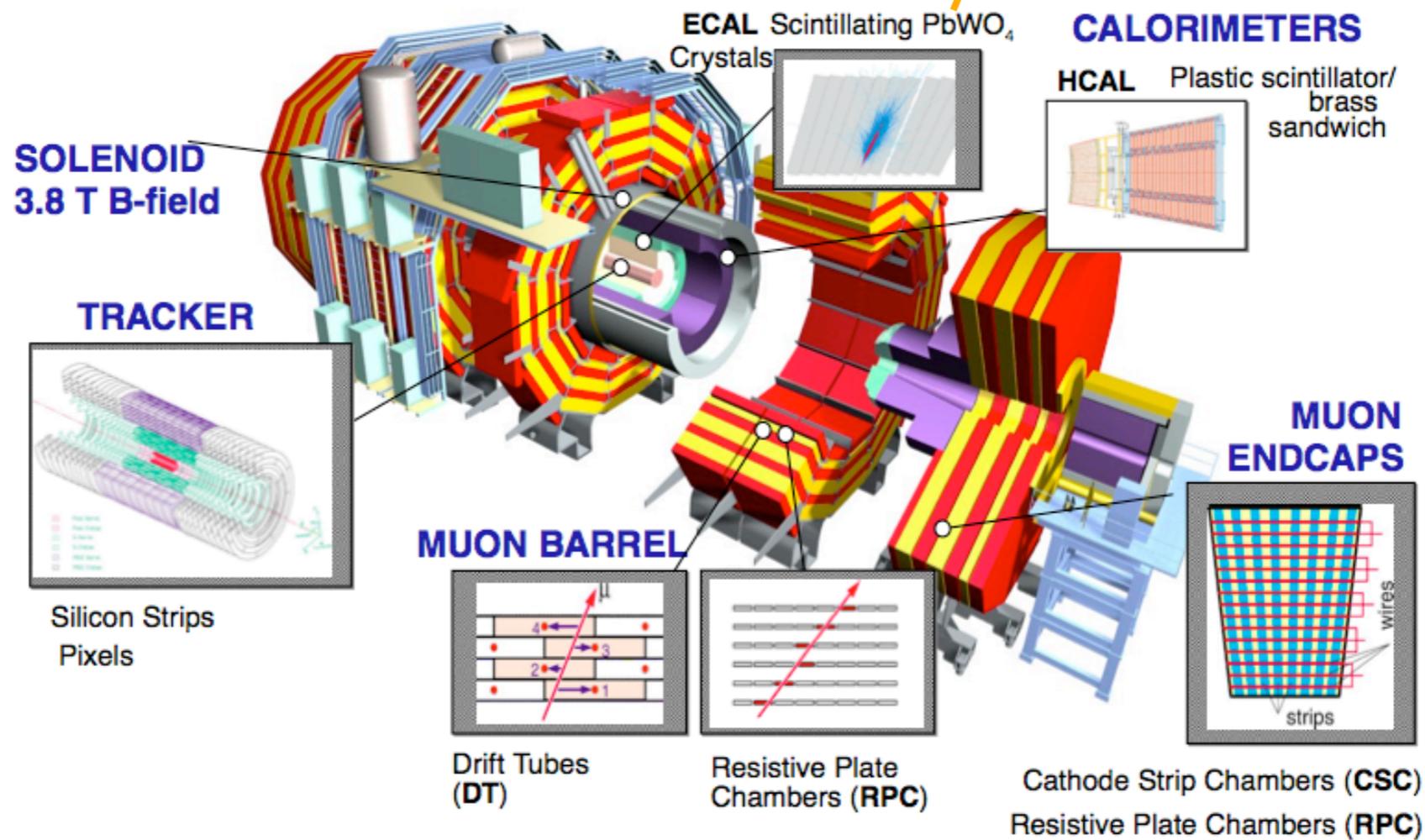
- Introduction to SUSY
- LHC and CMS detector
- Strategy for 2011 searches
- Standard Model background methods
- Results in 2011
- Conclusions

- SUSY = symmetry between fermions and bosons  $\Rightarrow$  new particles
- Solves the hierarchy problem in SM
- Unification of forces is realized
- R-parity conservation results in a dark matter candidate
- No new forces  $\Rightarrow$  hadronic channels the most sensitive



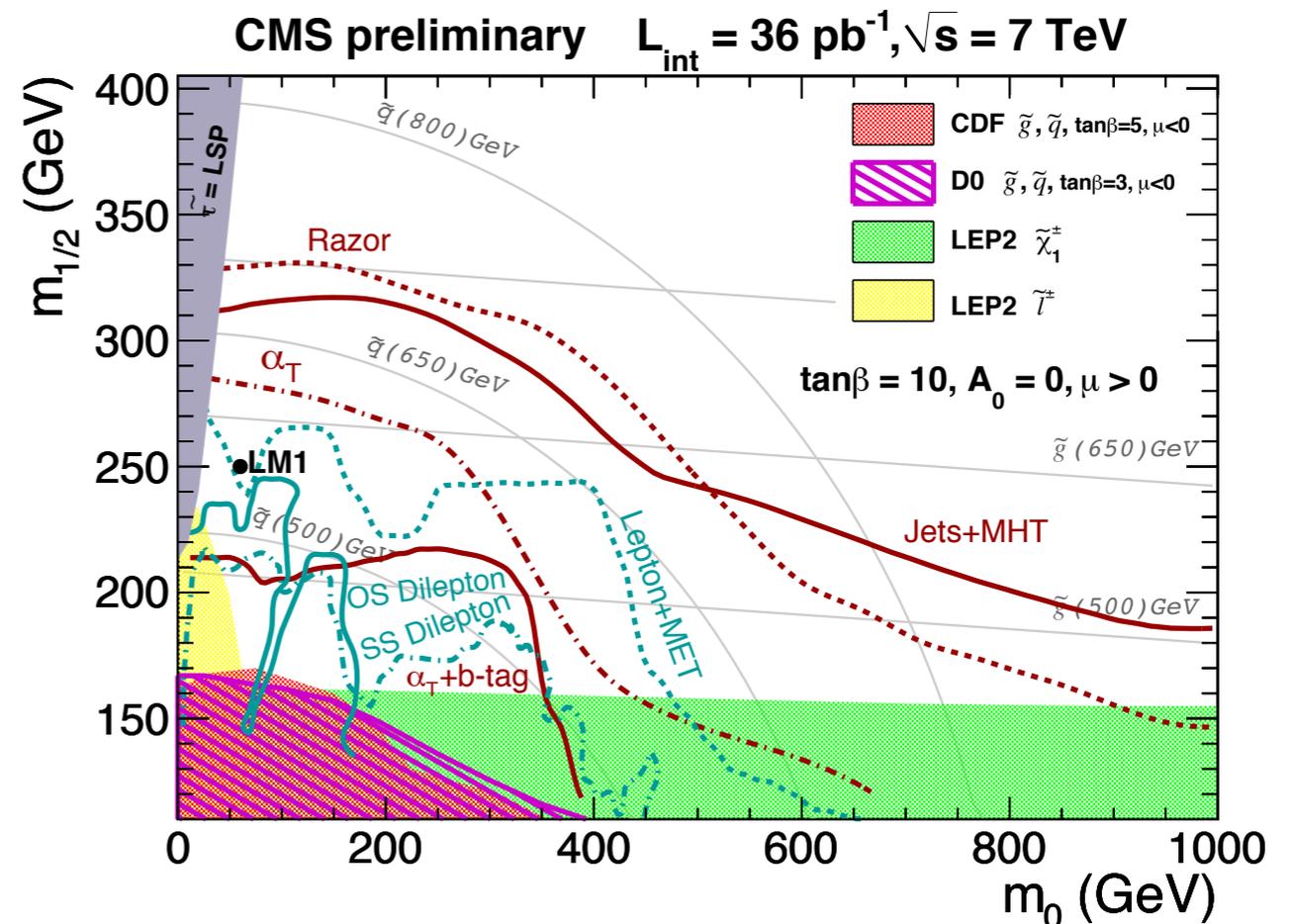
- Focus on final states containing many jets and large energy imbalance
- Reject events with good, isolated lepton
- Main SUSY signals
  - strong production of squark pairs, gluino pairs and squark-gluino
- Main SM backgrounds
  - QCD multijet production
  - $Z(\Rightarrow \nu\nu)+$ jets production
  - $W+$ jets production
  - $t\bar{t}+$ jets production

# LHC and the CMS detector



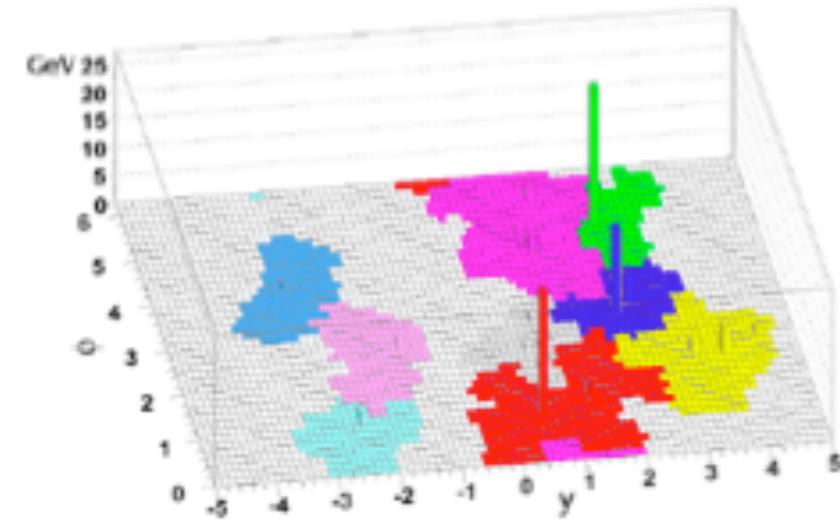
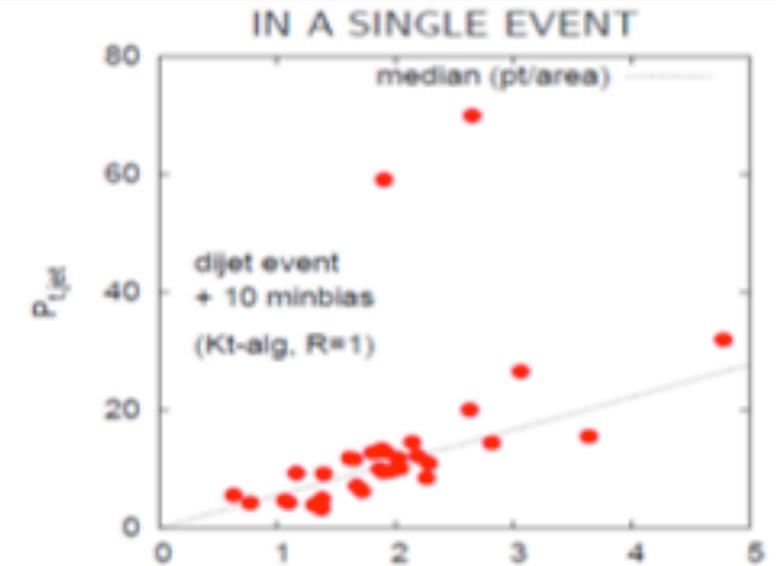
Azimuthal angle:  $\phi$   
 Polar angle:  $\theta$   
 Pseudorapidity:  $\eta = -\ln \tan(\theta/2)$

- Various hadronic searches
  - multijets + missing energy
  - fancy kinematic variables (razor,  $\alpha_T$ )
  - with b-jets
  - with  $\tau$  leptons
- Focus on data-driven SM background estimation
- As model independent as possible
- Extended the exclusion regions



- More or less a reload of the 2010 analyses
- More data ( $1.1 \text{ fb}^{-1}$ )
- Aim for the Summer conferences (EPS, LP, SUSY)
- Same focus on data-driven background estimation
- Deal with multiple interactions effects

- High instantaneous luminosity results in more multiple interactions (pile-up)
- Use jet-area based technique to subtract the pile-up from jets
- areas determined for each jet
- pile-up density determined for each event
- Jet resolutions are not significantly affected
- Details in hep-ph arXiv: 0707.1378v2, 0802.1188v2



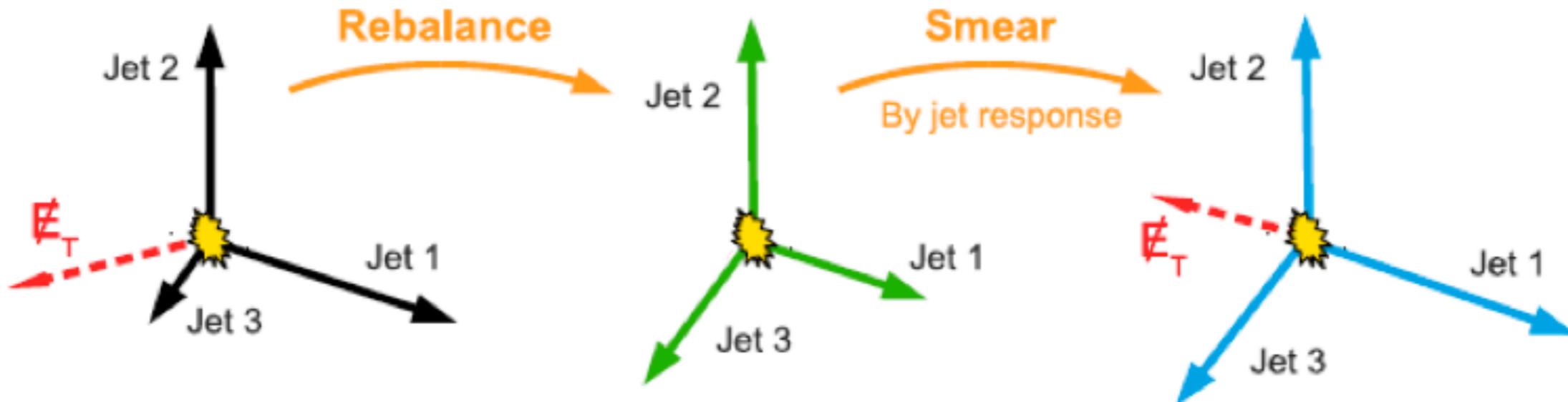
$$p_{t, \text{jet}}^{\text{subtracted}} = p_{t, \text{jet}} - \rho \times A_{\text{jet}}$$

$$A_{\text{jet}} = \text{jet area}$$

$$\rho = p_t \text{ per unit area from pileup}$$

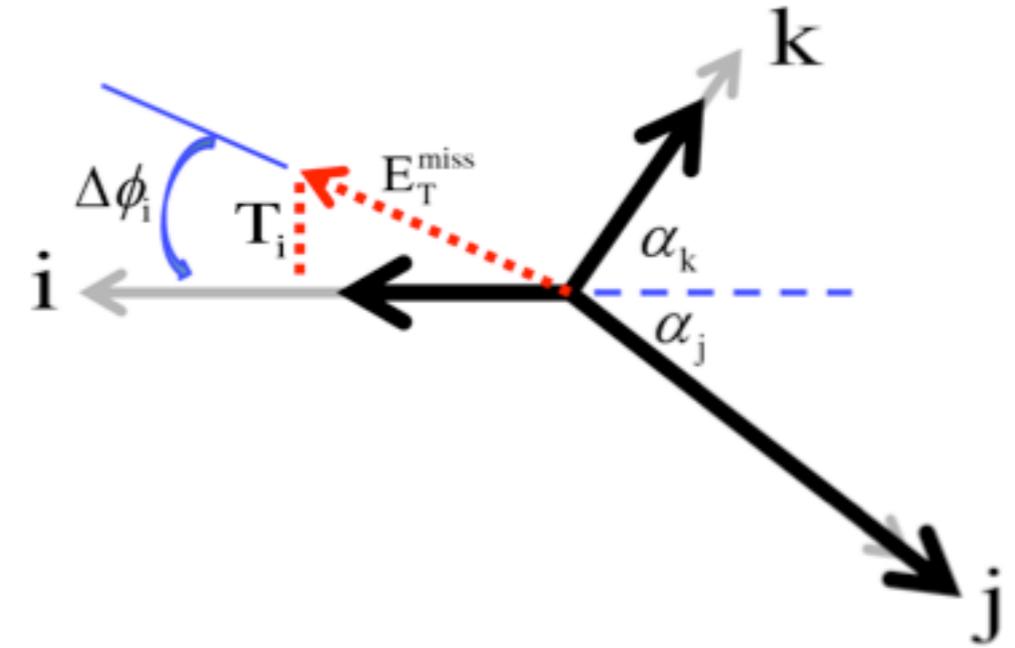
**Estimate  $\rho$ :**

$$\rho \simeq \text{median}_{\{\text{jets}\}} \left[ \frac{p_{t, \text{jet}}}{A_{\text{jet}}} \right]$$

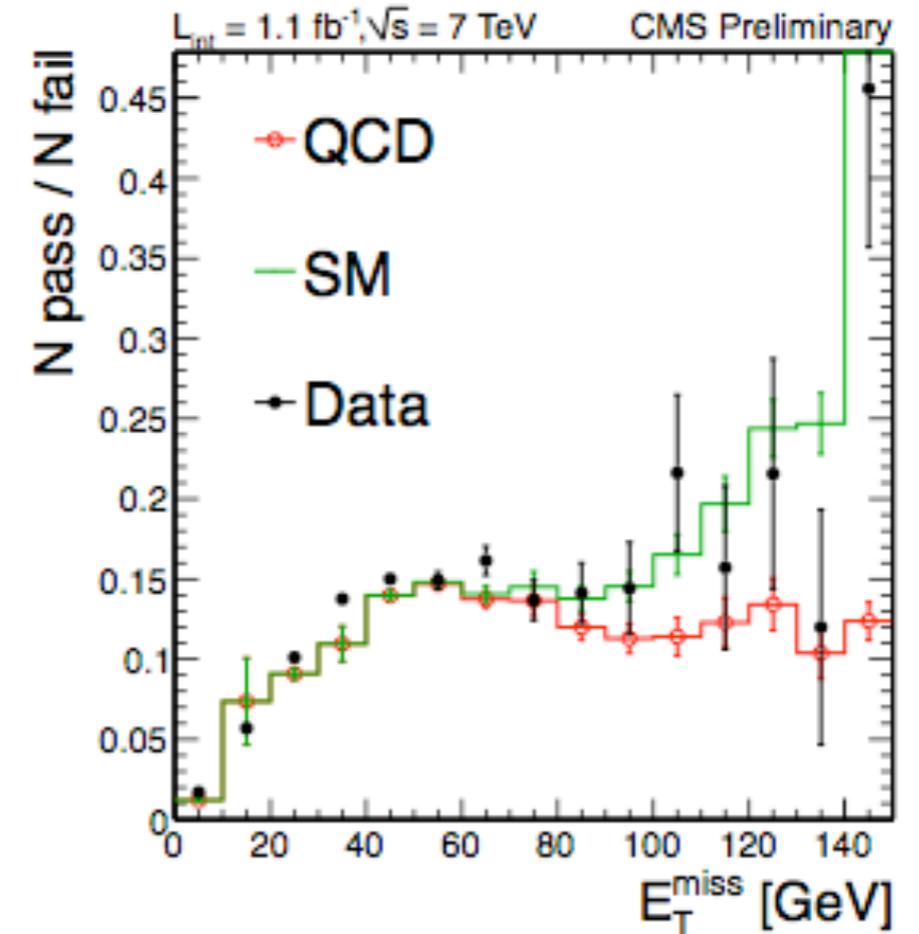


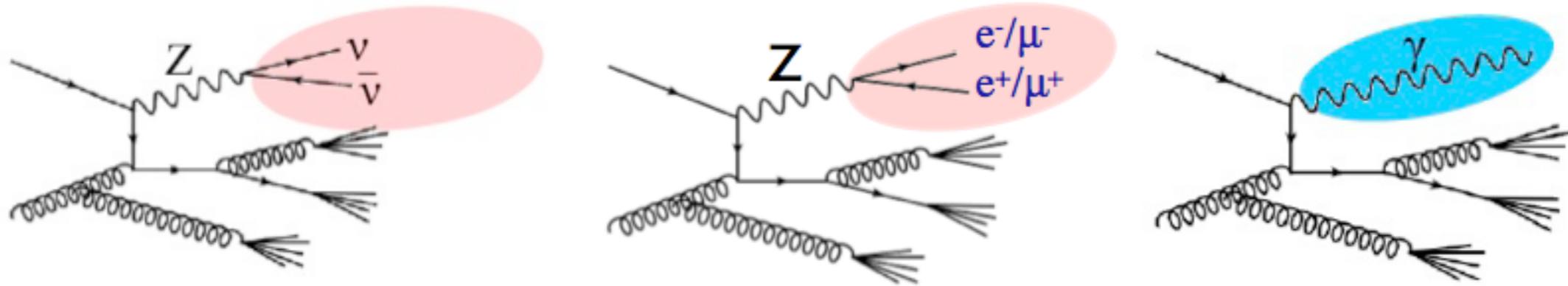
- QCD multijet events are balanced at the parton level
- The imbalance appears due to fluctuations in response of detector, malfunctions or semileptonic decays
- Rebalance: restore particle level jet  $P_T$  from detector level using inclusive multijet data via kinematic fit using jet resolution functions measured in data
- Smear: the rebalanced events are smeared using the measured jet resolution functions

- Generic strategy
  - find 2 uncorrelated variables
  - divide plane in 4 regions
  - use yields in 3 regions to predict the 4th



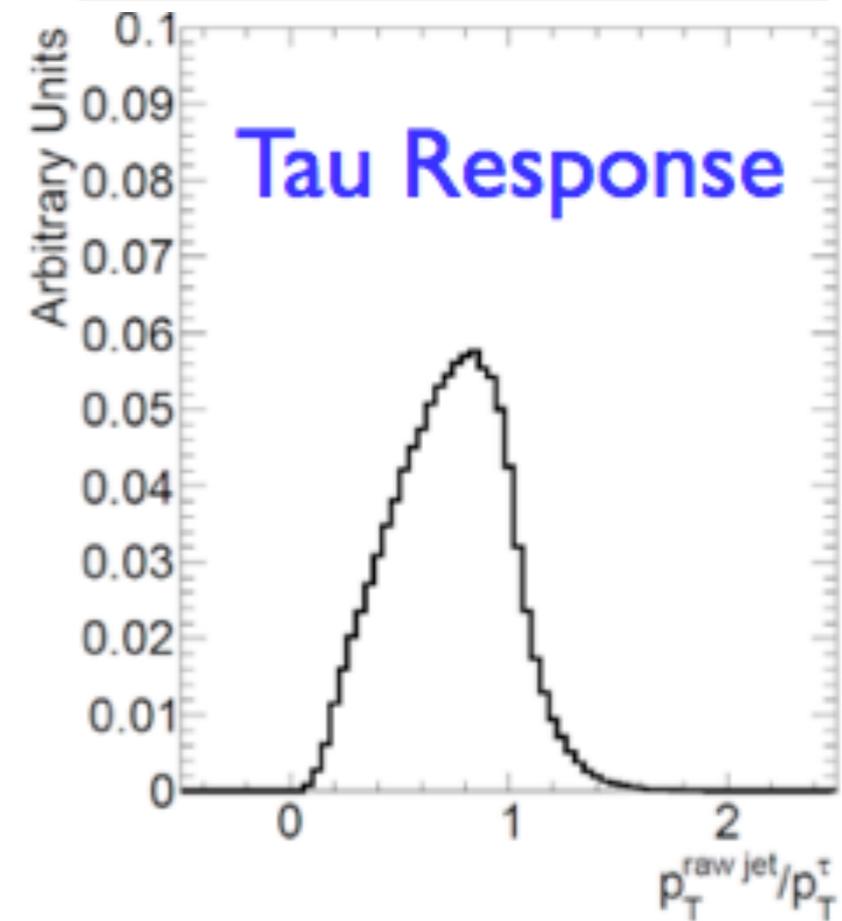
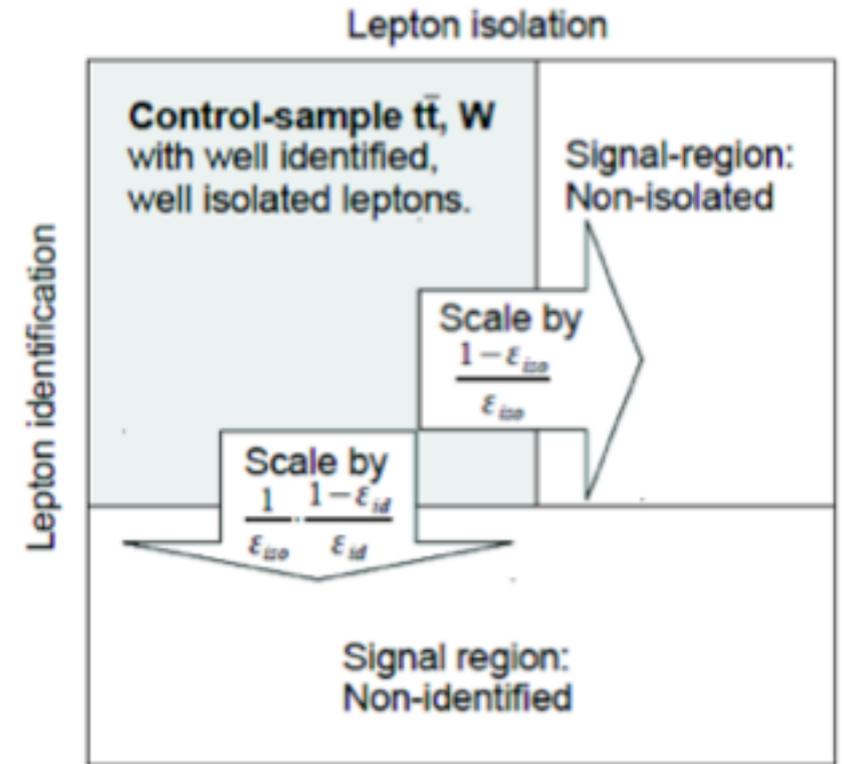
- Example:  $\Delta\varphi_{\min}^N$  vs MET
  - $\Delta\varphi_{\min}^N = \min(\Delta\varphi(j^i, MET) / \sigma_{\Delta\varphi})$
  - $\sigma_{\Delta\varphi} = \text{atan}(T/MET)$
  - QCD with MET 30  $\Rightarrow$  140 GeV has  $N(\Delta\varphi_{\min}^N > 4) / N(\Delta\varphi_{\min}^N < 4) \sim \text{flat}$  vs MET





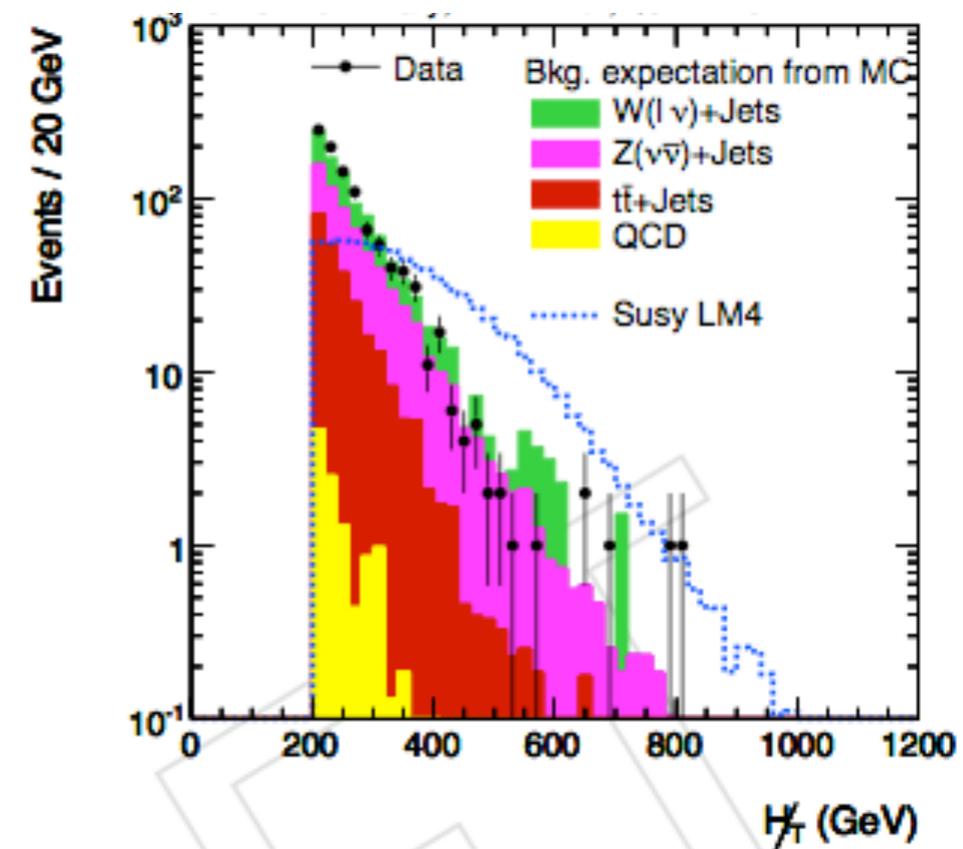
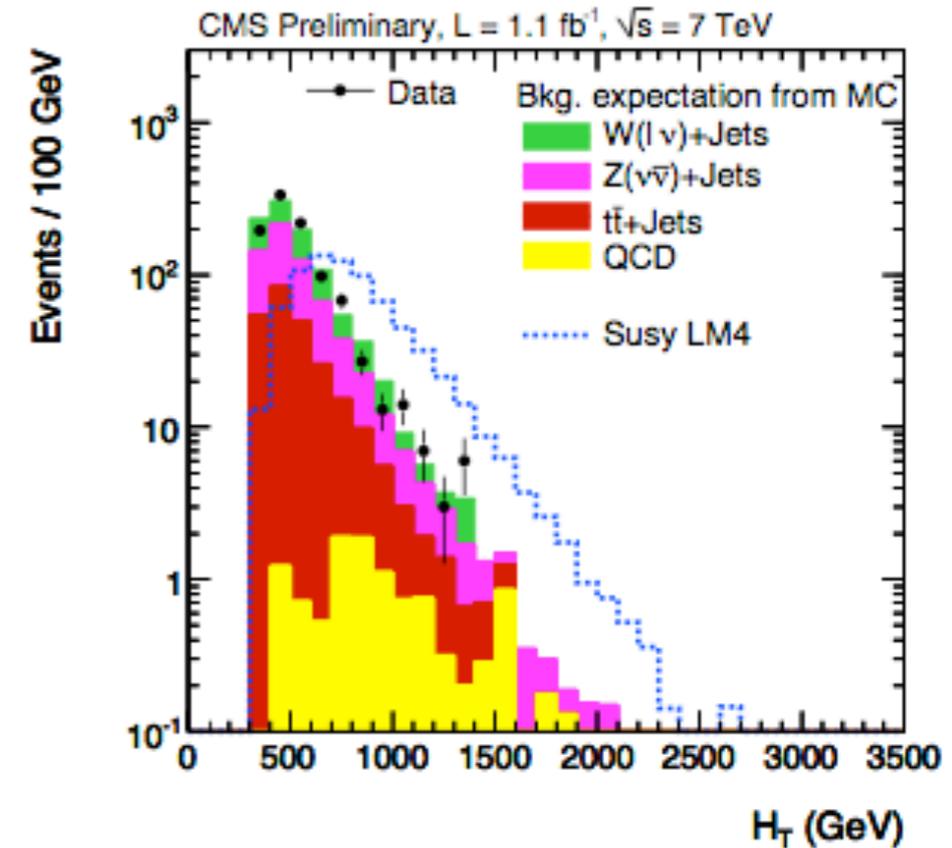
- At high  $P_T$  ( $\sim 200$  GeV) photon+jets kinematics are similar to Z+jets
- ignore photons, account for its reconstruction efficiency, ratio of cross-sections from theory
- high statistics sample, large systematics on theoretical factors
- More straightforward estimate via dilepton Z events
  - ignore leptons, account for leptonic reconstruction efficiency and geometrical acceptance, different branching ratios
  - low statistics in tight search regions
- Leptonic W candidates can also be used
  - deal with the lepton as in the dilepton case
  - larger statistics, larger backgrounds

- $W \Rightarrow e/\mu$  events with the lepton failing the lepton veto
- not reconstructed or not isolated
- estimate from a leptonic sample with inverted veto
- normalize yields with inverse of lepton efficiency
- $W \Rightarrow \tau \Rightarrow$  hadronic decay
- use a leptonic sample and replace the lepton with  $\tau$  via  $\tau$  jet response template from simulation
- account for lepton efficiencies, acceptance, branching ratios



$$\cancel{A}_T = \left| -\sum_i^{\text{jets}} \vec{p}_{T,i} \right| \quad H_T = \sum_i^{\text{jets}} \left| \vec{p}_{T,i} \right|$$

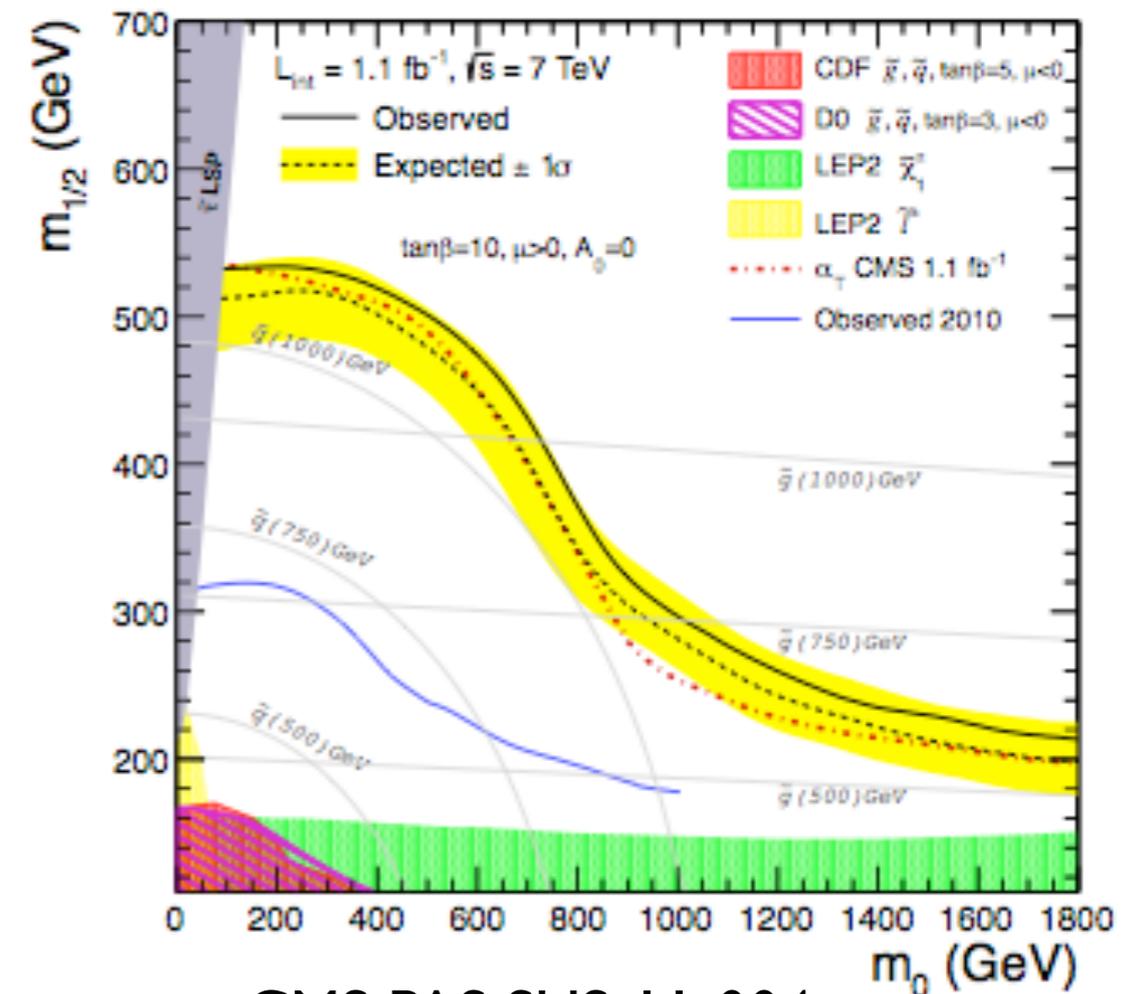
- $N_{\text{jets}} \geq 3$  ( $P_T > 50$  GeV,  $|\eta| < 2.5$ )
- HT computed from these jets
- MHT computed from jets with  $P_T > 30$ ,  $|\eta| < 5$
- $\Delta\varphi(\text{jets}[1,2,3], \text{MHT}) > [0.5, 0.5, 0.3]$
- Search regions:
  - $HT > 800, \text{MHT} > 200$
  - $HT > 800, \text{MHT} > 500$
- Data described well by the simulation
- Data-driven SM methods described earlier
- QCD R+S,  $Z \Rightarrow \nu\nu$  from  $\gamma + \text{jets}$ , W/tt lost lepton+hadronic  $\tau$



	Baseline ( $H_T > 350$ GeV) ( $\cancel{H}_T > 200$ GeV)	Medium ( $H_T > 500$ GeV) ( $\cancel{H}_T > 350$ GeV)	High $H_T$ ( $H_T > 800$ GeV) ( $\cancel{H}_T > 200$ GeV)	High $\cancel{H}_T$ ( $H_T > 800$ GeV) ( $\cancel{H}_T > 500$ GeV)
$Z \rightarrow \nu\bar{\nu}$ from $\gamma$ +jets	$376 \pm 12 \pm 79$	$42.6 \pm 4.4 \pm 8.9$	$24.9 \pm 3.5 \pm 5.2$	$2.4 \pm 1.1 \pm 0.5$
$t\bar{t}/W \rightarrow e, \mu + X$	$244 \pm 20^{+30}_{-31}$	$12.7 \pm 3.3 \pm 1.5$	$22.5 \pm 6.7^{+3.0}_{-3.1}$	$0.8 \pm 0.8 \pm 0.1$
$t\bar{t}/W \rightarrow \tau_h + X$	$263 \pm 8 \pm 7$	$17 \pm 2 \pm 0.7$	$18 \pm 2 \pm 0.5$	$0.73 \pm 0.73 \pm 0.04$
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	$928 \pm 103$	$73.9 \pm 11.9$	$79.4 \pm 12.2$	$4.6 \pm 1.5$
Observed in data	986	78	70	3

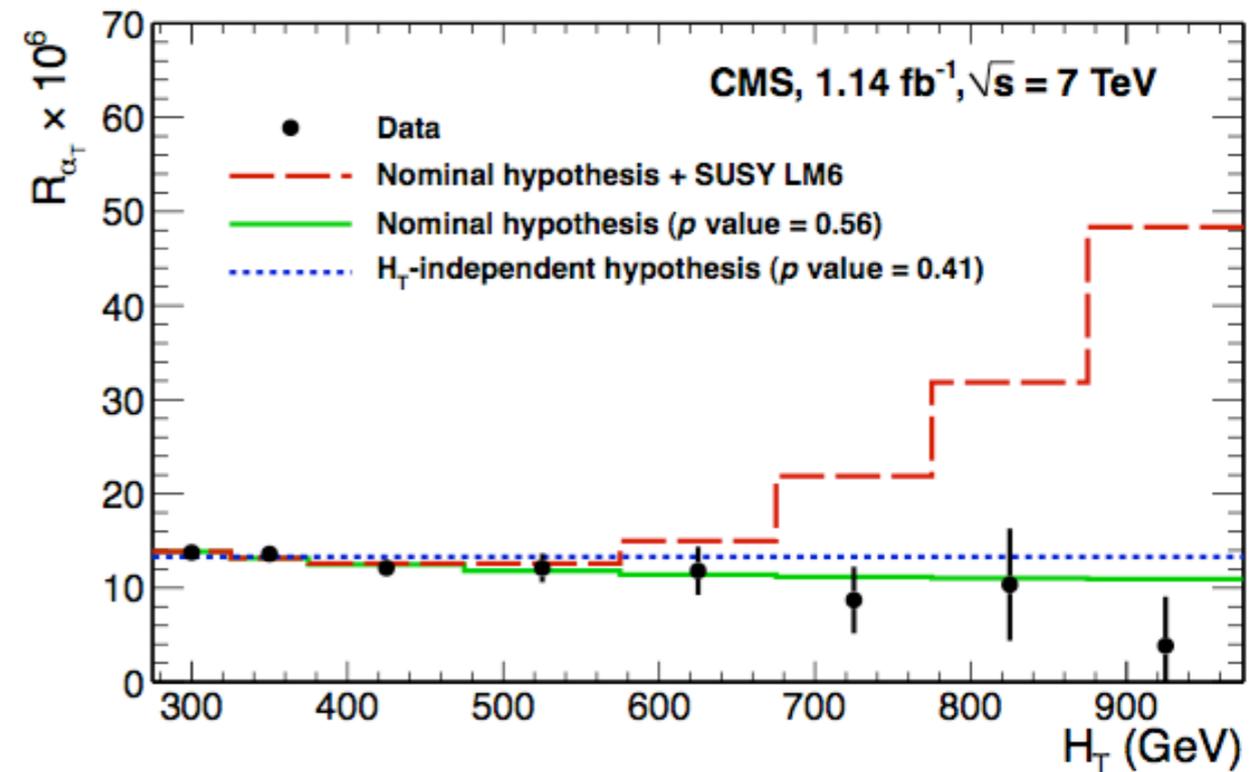
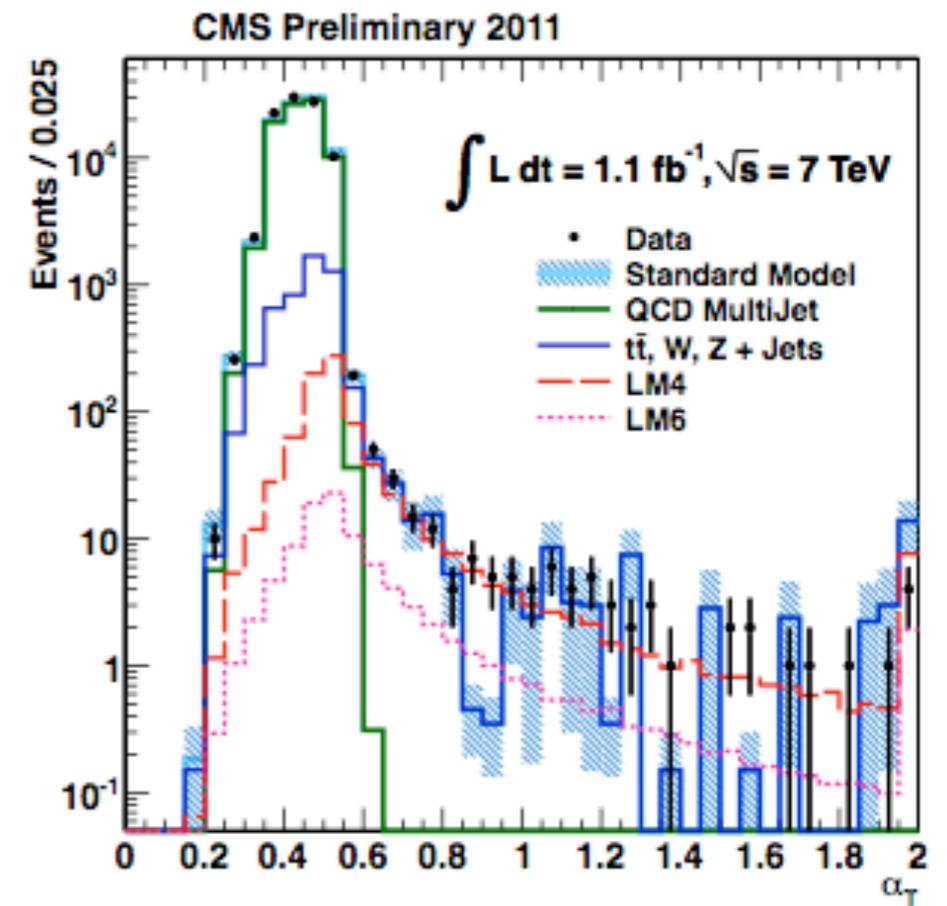
CMS Preliminary

- No excess over SM found in the data  $\Rightarrow$  set limits
- mSUGRA exclusion region
  - $m_0 = 100$  GeV,  $m_{1/2} > 530$  GeV
  - $m_0 = 1500$  GeV,  $m_{1/2} > 230$  GeV



CMS PAS SUS-11-004

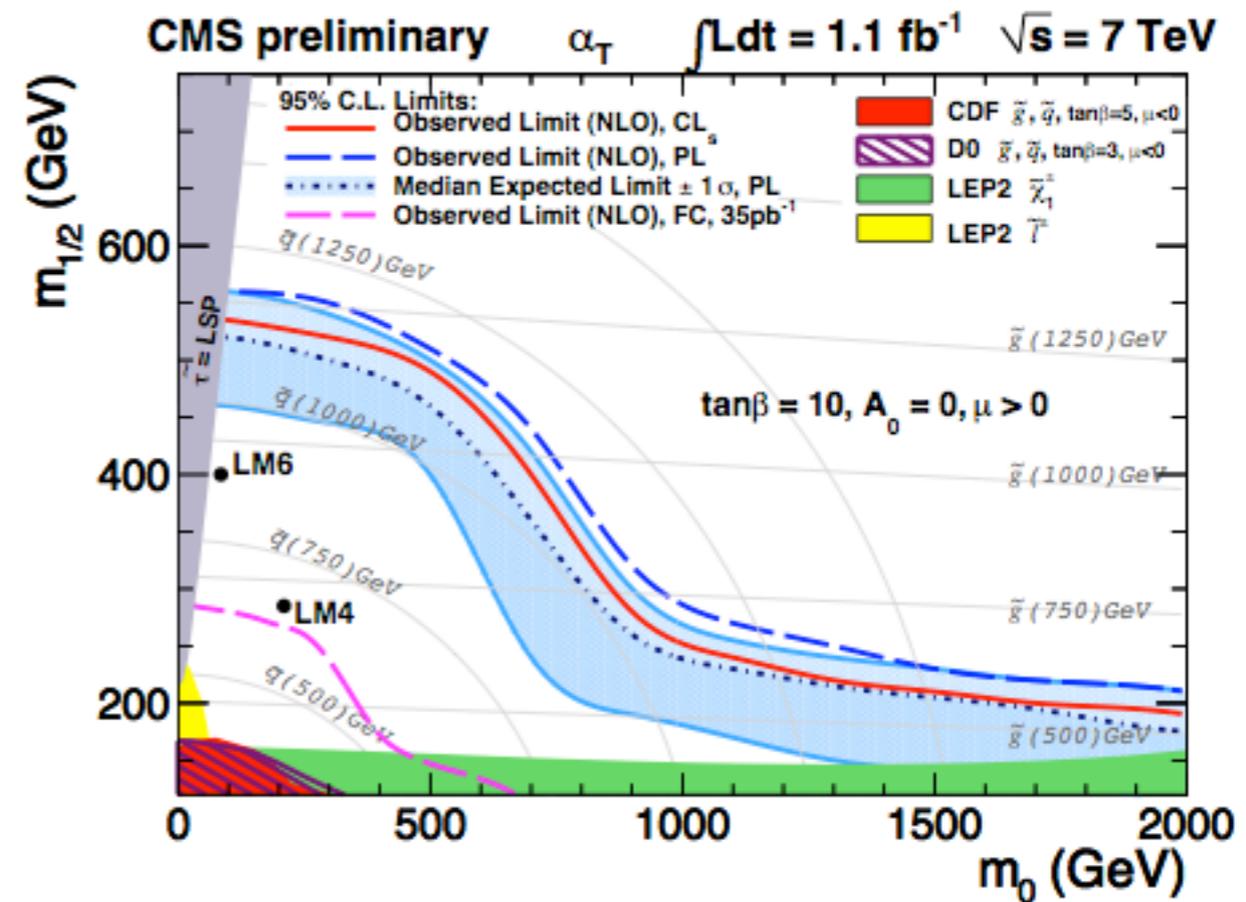
- $N_{\text{jets}} \geq 2$  ( $P_T > 50$  GeV,  $|\eta| < 3$ )
- 1st jet  $|\eta| < 2.5$
- Analyze 8 exclusive regions in HT
- first 2 jets:  $P_T > 100$  GeV except for 2 low HT regions
- Signal region:  $\alpha_T (= E_T^{j2} / M_T^{j1j2}) > 0.55$ 
  - if  $> 2$  jets  $\Rightarrow$  form 2 pseudo-jets  $\Rightarrow \alpha_T$
- Data described well by the simulation
- Exploit flatness of  $R_{\alpha_T}$  vs HT to estimate QCD
  - $R_{\alpha_T} = N^{\alpha_T > 0.55} / N^{\alpha_T < 0.55}$
- $\mu$  &  $\gamma$  control samples for EWK background estimation
- Simultaneous fit of SM backgrounds across hadronic and leptonic regions



# AlphaT results

$H_T$ bin (GeV)	275–325	325–375	375–475	475–575	575–675	675–775	775–875	>875
SM hadronic	$787^{+32}_{-22}$	$310^{+8}_{-12}$	$202^{+9}_{-9}$	$60.4^{+4.2}_{-3.0}$	$20.3^{+1.8}_{-1.1}$	$7.7^{+0.8}_{-0.5}$	$3.2^{+0.4}_{-0.2}$	$2.8^{+0.4}_{-0.2}$
Data hadronic	782	321	196	62	21	6	3	1
SM $\mu$ + jets	$367^{+15}_{-15}$	$182^{+8}_{-9}$	$113^{+8}_{-7}$	$36.5^{+3.8}_{-3.3}$	$13.4^{+2.2}_{-1.8}$	$4.0^{+1.4}_{-1.2}$	$0.8^{+0.9}_{-0.1}$	$0.7^{+0.9}_{-0.1}$
Data $\mu$ + jets	389	156	113	39	17	5	0	0
SM $\gamma$ + jets	$834^{+28}_{-30}$	$325^{+17}_{-17}$	$210^{+12}_{-12}$	$64.7^{+6.9}_{-7.0}$	$21.1^{+3.9}_{-4.3}$	$10.5^{+2.5}_{-2.6}$	$6.1^{+0.9}_{-1.7}$	$5.5^{+0.9}_{-1.6}$
Data $\gamma$ + jets	849	307	210	67	24	12	4	4

- No excess over SM yields found in data
- Similar exclusion region in the mSUGRA plane as the HT&MHT analysis

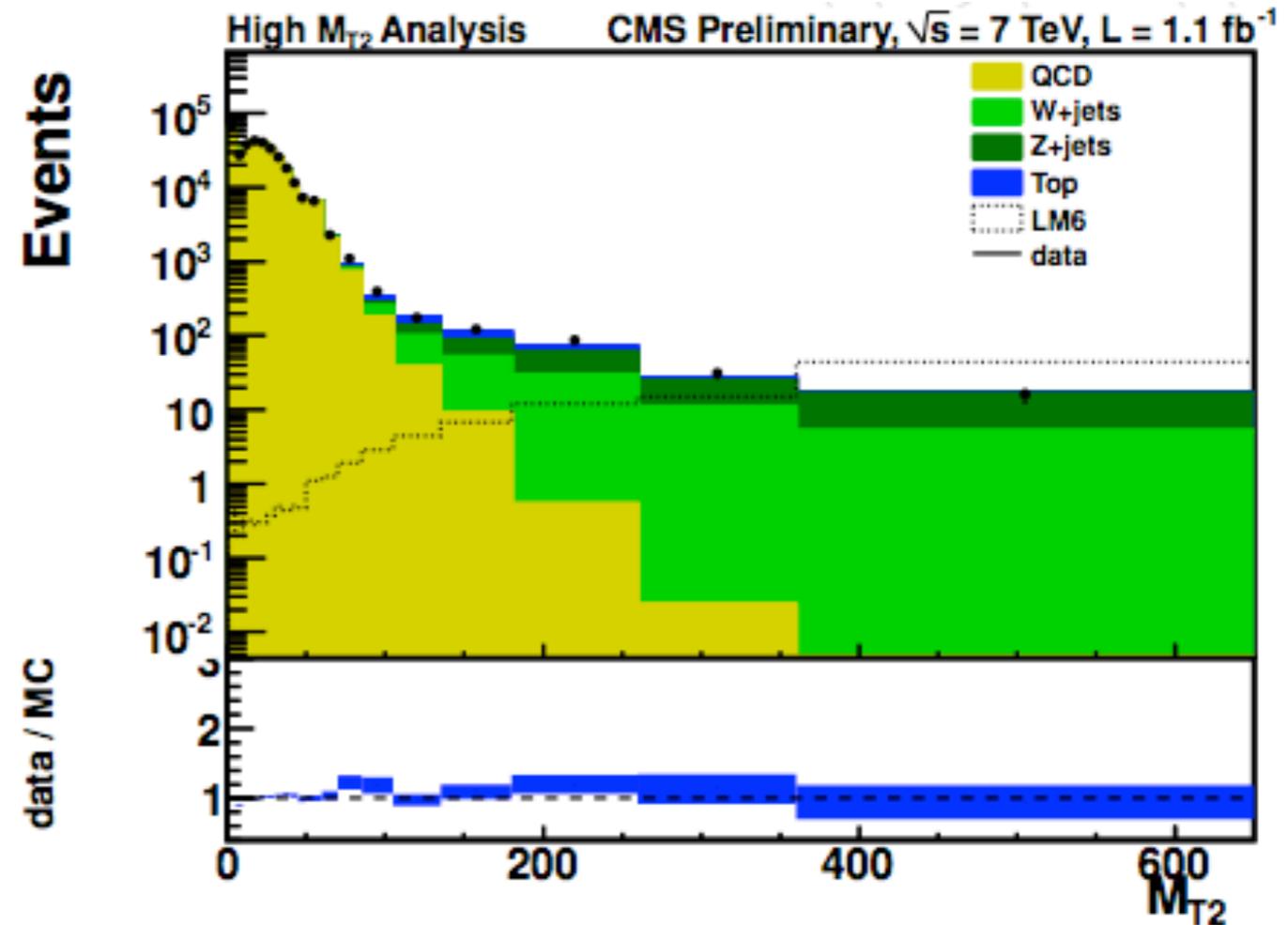


CMS PAS SUS-11-003

- $N_{\text{jets}} \geq 3$  ( $P_T > 20$  GeV,  $|\eta| < 2.4$ )
- Leading 2 jets:  $P_T > 100$  GeV
- $HT > 600$  GeV
- $\Delta\phi_{\text{min}}(\text{jets}, \text{MET}) > 0.3$
- High  $M_{T2}$  region:  $M_{T2} > 400$  GeV
- Low  $M_{T2}$  region:  $M_{T2} > 150$  GeV
  - $N_{\text{jets}} \geq 4$ ,  $\geq 1$  b-jet
  - $HT > 650$  GeV,  $P_T^{j1} > 150$  GeV,  $P_T^{j2} > 100$  GeV
- more sensitive to low  $m_{1/2}$ , high  $m_0$
- Data described well by the simulation
- QCD estimate in  $\Delta\phi_{\text{min}}$  vs  $M_{T2}$  plane,  $Z \Rightarrow \nu\nu$  from  $W$ 's,  $W/tt$  from MC

$$M_{T2}(m_\chi) = \min_{\vec{v}_\pm^{\chi(1)} + \vec{v}_\pm^{\chi(2)} = \vec{v}_\pm^{\text{miss}}} \left[ \max \left( m_T^{(1)}, m_T^{(2)} \right) \right]$$

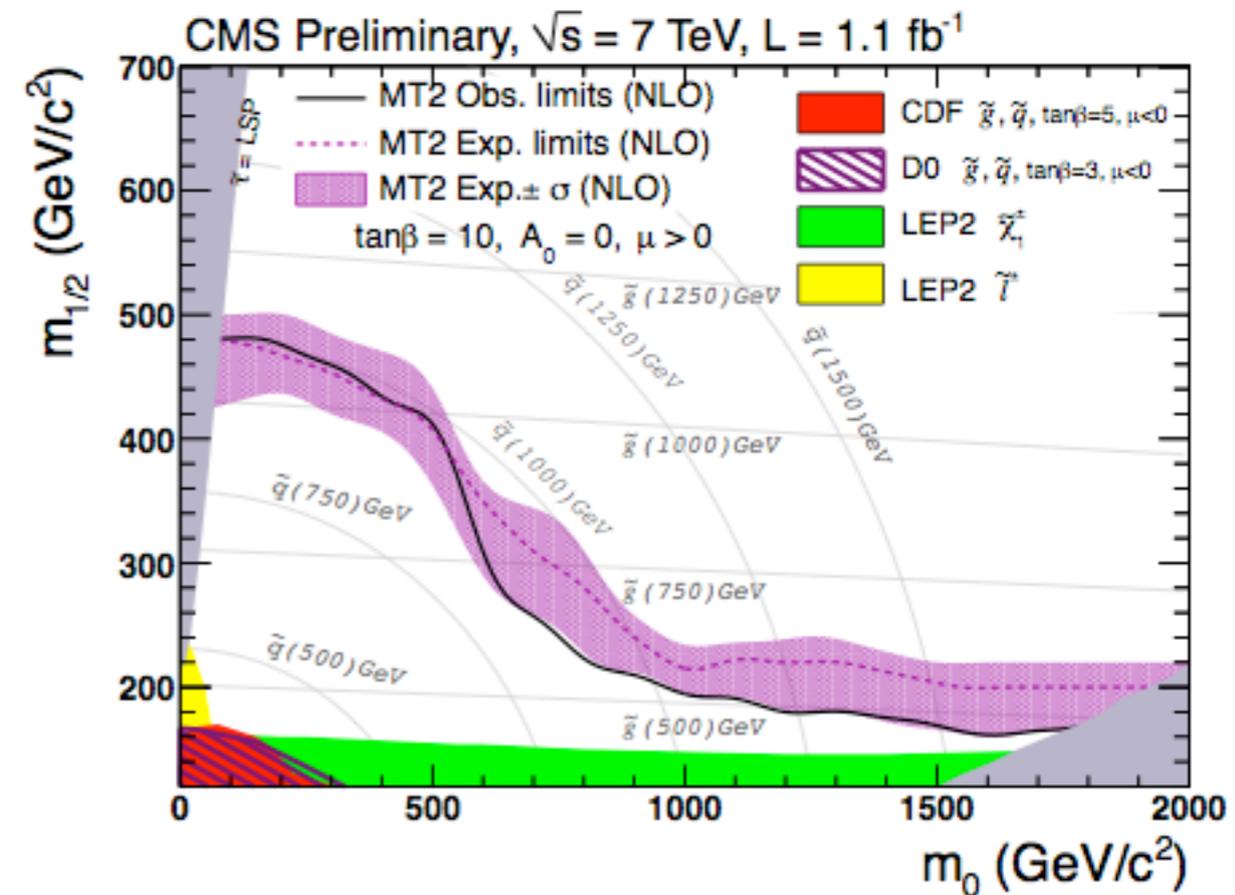
$$(m_T^{(i)})^2 = (m^{\text{vis}(i)})^2 + m_\chi^2 + 2 \left( E_T^{\text{vis}(i)} E_T^{\chi(i)} - \vec{p}_T^{\text{vis}(i)} \cdot \vec{p}_T^{\chi(i)} \right)$$



# MT2 results

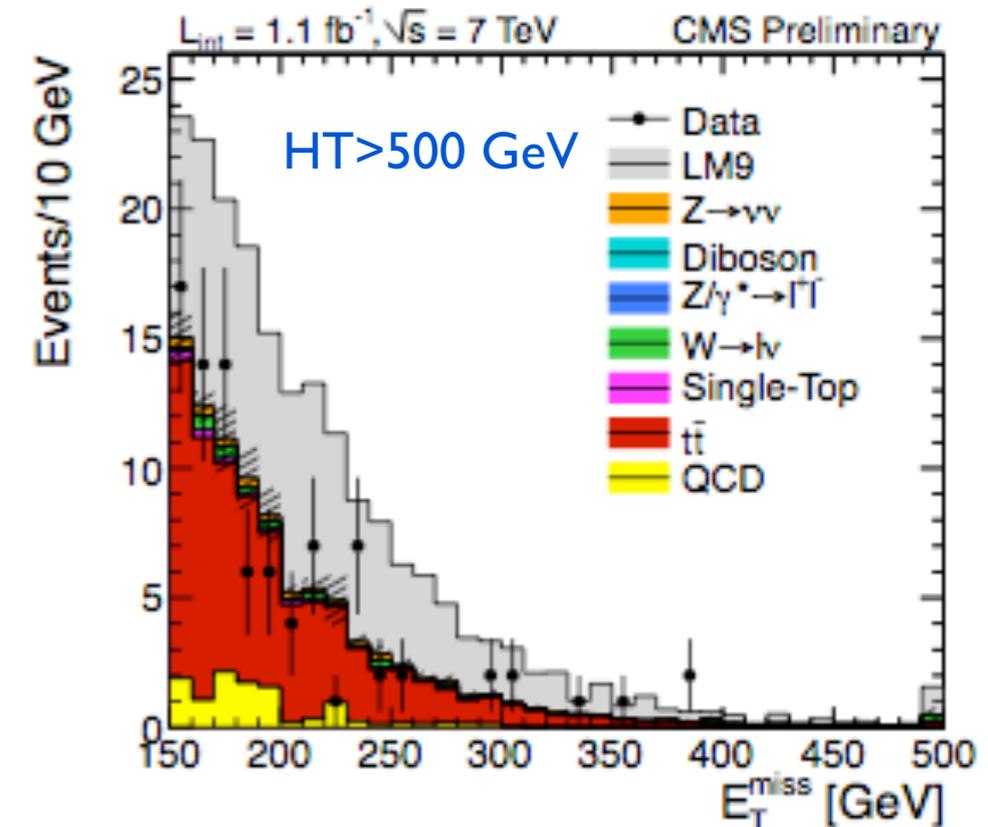
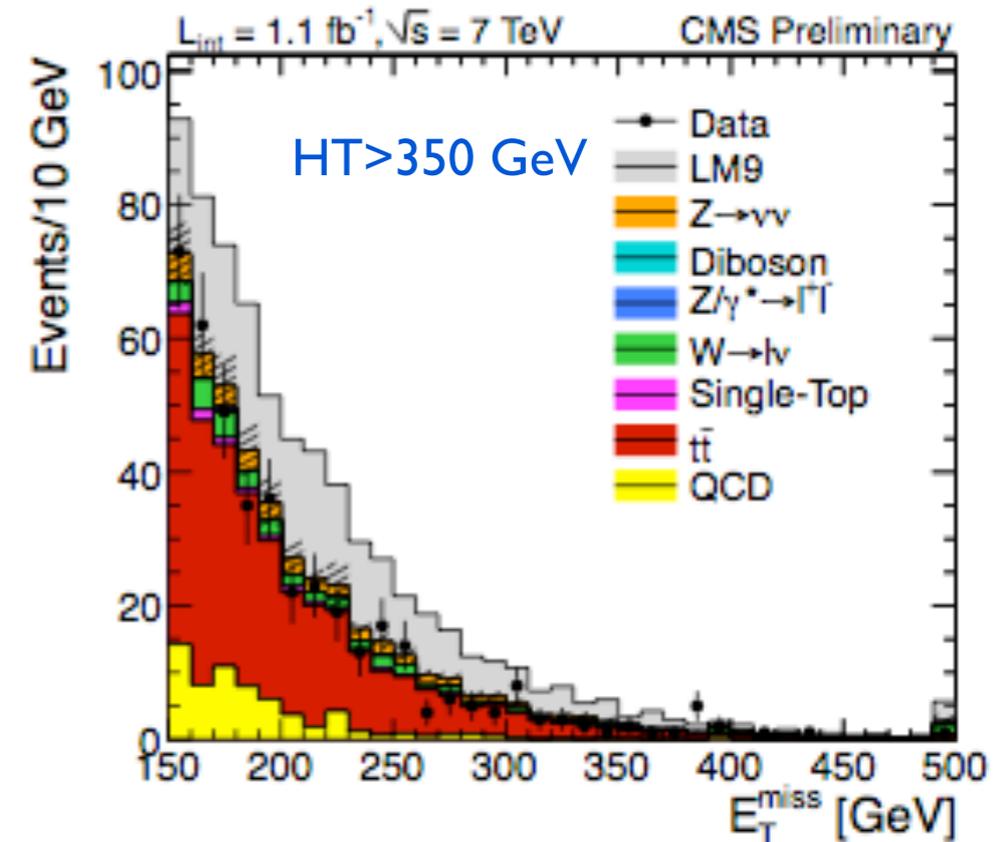
Regions	High $M_{T2}$	Low $M_{T2}$
SM prediction	$12.6 \pm 1.3 \pm 3.5$	$10.6 \pm 1.9 \pm 4.8$
Data	12	19

- No excess over SM in data
- Combine exclusion regions from low and high  $M_{T2}$  searches



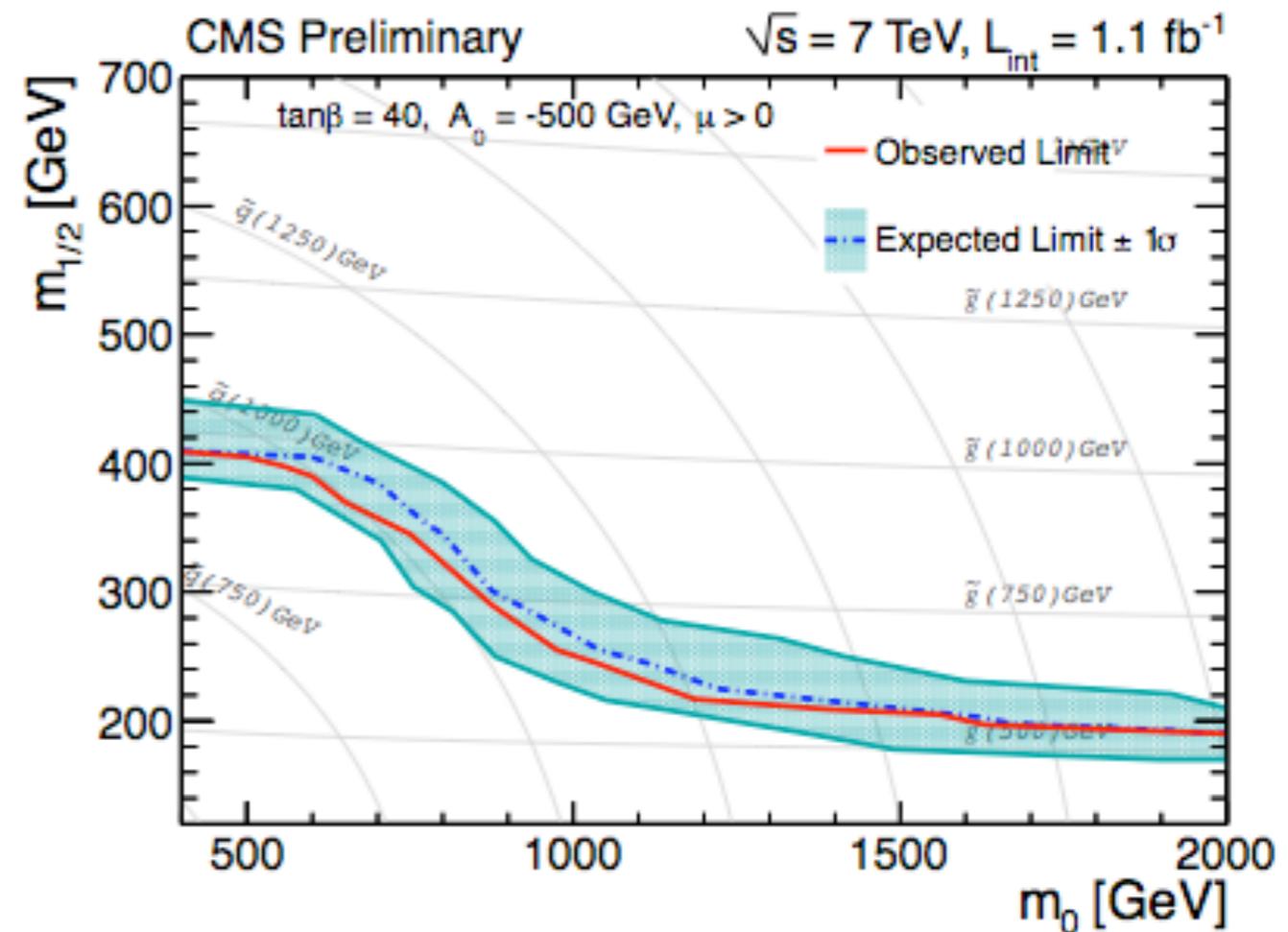
CMS PAS SUS-11-005

- $N_{\text{jets}} \geq 3$  ( $P_T > 50$  GeV,  $|\eta| < 2.4$ )
- $\geq 1$  b-jet ( $P_T > 30$  GeV)
- $\Delta\varphi_{\min}^N(\text{jets}^{1,2,3}, \text{MET}) > 4$ 
  - $\Delta\varphi_{\min}^N = \min(\Delta\varphi/\sigma_{\Delta\varphi})$
- Two search regions
  - HT > 350 GeV, MET > 200 GeV
  - HT > 500 GeV, MET > 300 GeV
- Data described well by the simulation
- QCD estimate in  $\Delta\varphi_{\min}^N$  vs MET plane,  $Z \Rightarrow \nu\nu$  from dileptons, W/tt with MET templates from leptonic samples
- Simultaneous likelihood fit of SM yields in signal and control regions

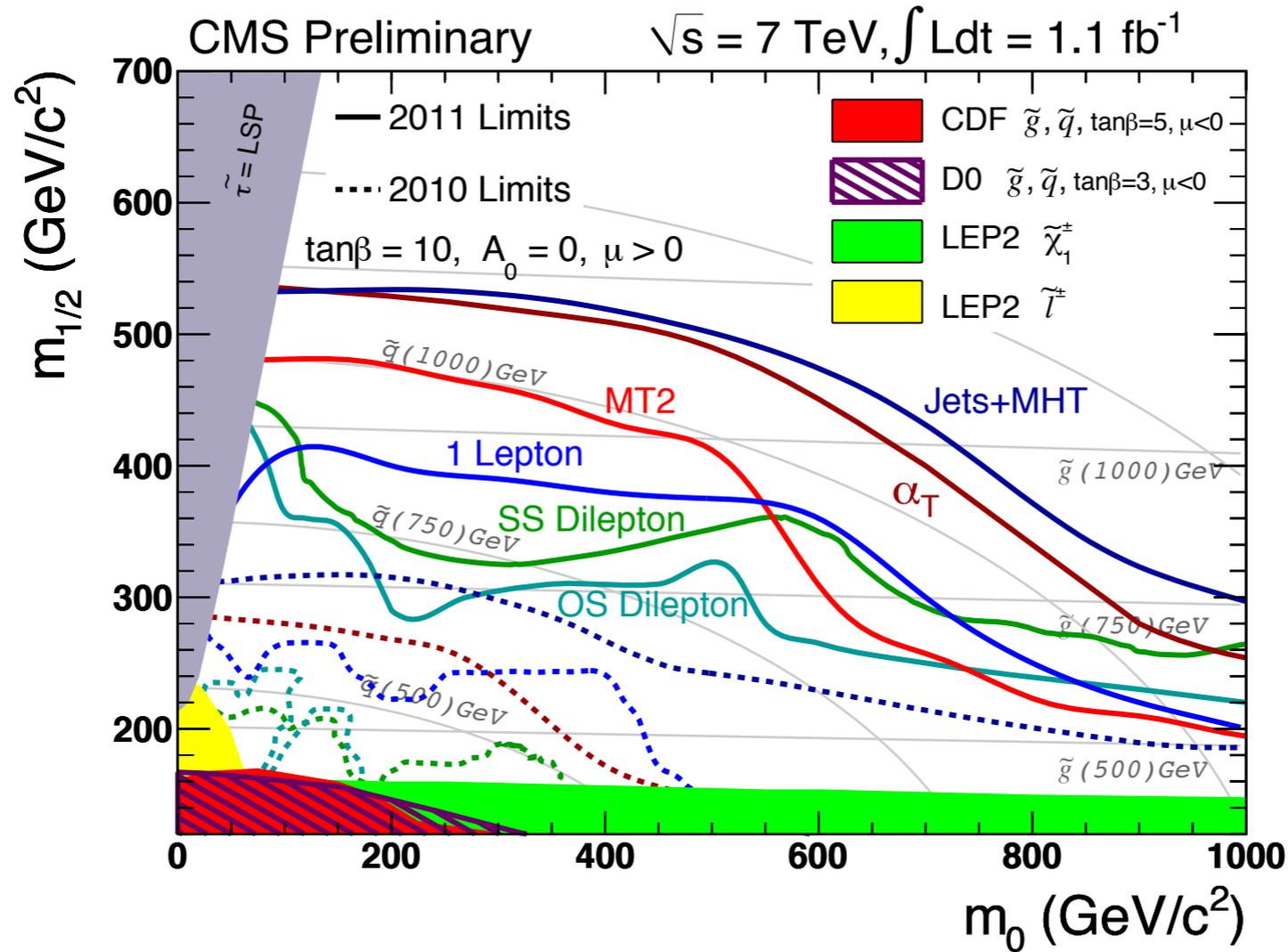


	Loose search region		Tight search region	
	$\geq 1 b$	$\geq 2 b$	$\geq 1 b$	$\geq 2 b$
QCD	$9.7^{+10.1}_{-8.4}$	$0.0^{+3.7}_{-0.0}$	$0.2^{+0.8}_{-0.2}$	$0.1^{+0.6}_{-0.1}$
top and W+jets	$115 \pm 15$	$24.5 \pm 5.5$	$13.9^{+4.6}_{-4.3}$	$5.0^{+2.4}_{-1.9}$
$Z \rightarrow \nu\bar{\nu}$	$29^{+14}_{-11}$	$5.2^{+4.6}_{-2.9}$	$5.3^{+3.6}_{-2.7}$	$0.6^{+0.9}_{-0.6}$
Total SM (LH)	152.8	29.7	19.5	5.7
Data	155	30	20	5

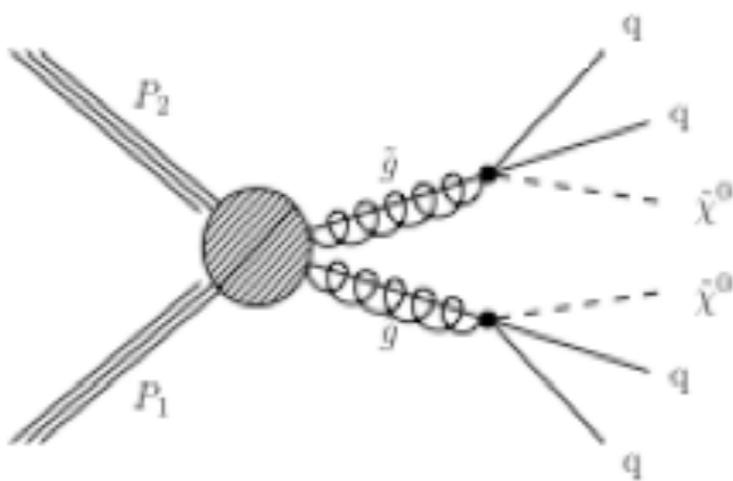
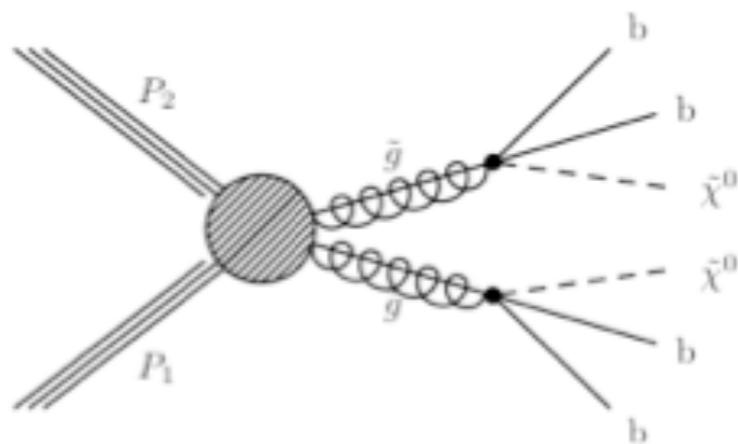
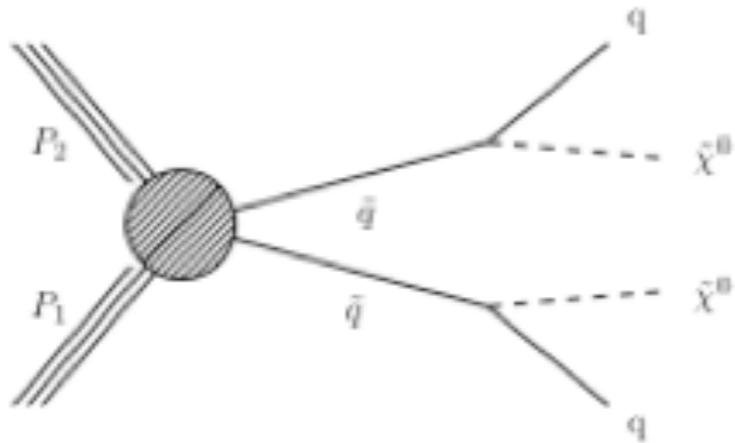
- No excess over the SM prediction in data
- Analysis mostly targeting high  $m_0$  region
- Exclusion regions shown for tight region &  $\geq 1$  b-jet



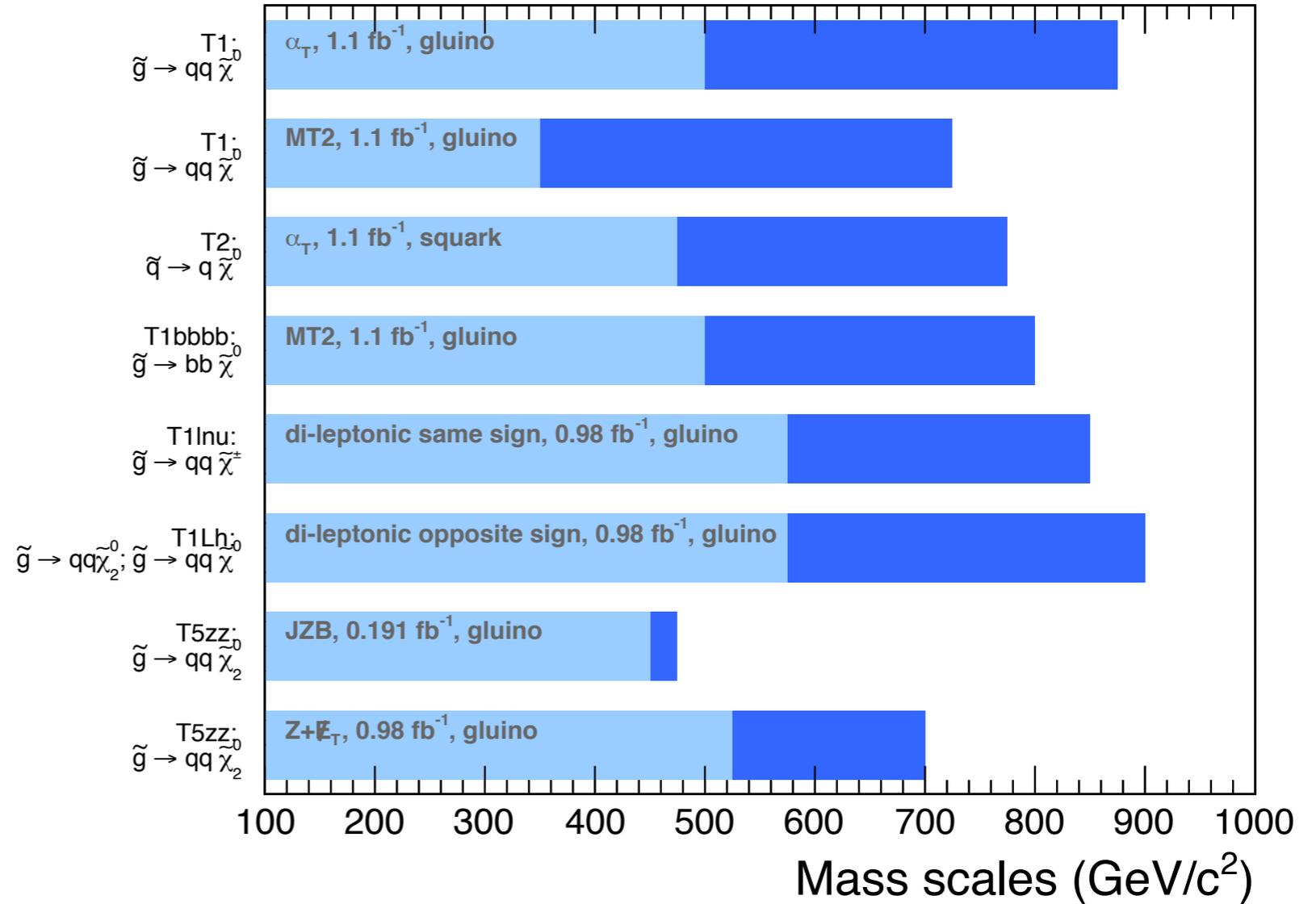
CMS PAS SUS-11-006



- As expected the exclusion regions from hadronic searches exceed those from leptonic searches
- not shown the b-jet analysis results
- New results extend dramatically the previous exclusion regions set with 2010 dataset



## Ranges of exclusion limits for gluinos and squarks, varying $m(\tilde{\chi}^0)$ CMS preliminary



For limits on  $m(\tilde{g}), m(\tilde{q}) \gg m(\tilde{g})$  (and vice versa).  $\sigma^{\text{prod}} = \sigma^{\text{NLO-QCD}}$ .

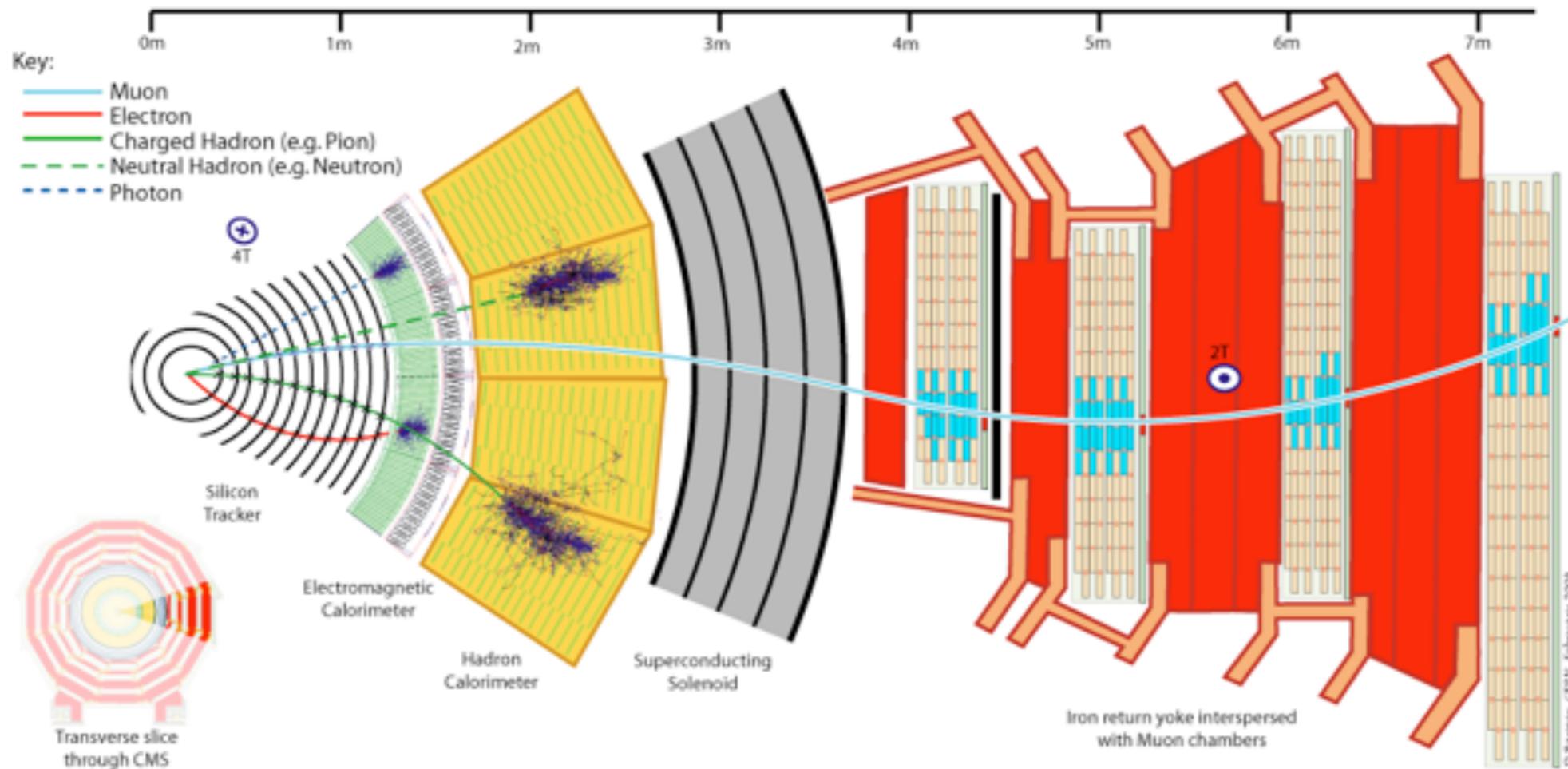
$$m(\tilde{\chi}^\pm), m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$$

$m(\tilde{\chi}^0)$  is varied from 0  $\text{GeV}/c^2$  (dark blue) to  $m(\tilde{g})-200 \text{ GeV}/c^2$  (light blue).

- Summarized the CMS hadronic searches prepared during the 2011 summer on  $1.1 \text{ fb}^{-1}$
- No excess found over the SM predictions
- Extended greatly previous exclusion regions
- Looking ahead at repeating these (and more) analyses with  $\sim 5 \text{ fb}^{-1}$  of projected total 2011 dataset

# BACK-UP

- $\geq 1$  well-defined primary vertex ( $|z| < 24\text{cm}, \rho < 2\text{cm}, N_{\text{dof}} > 4$ )
- reject events with small fraction of high quality tracks
- require  $\sum P_{\text{T}}^{\text{tracks}} > 0.1 \sum P_{\text{T}}^{\text{jets}}$
- reject beam halo events
- reject events with jets pointing to  $> 1\%$  of the masked ECAL cells
- reject events with calorimeter noise (HCAL & ECAL)



- Events reconstructed with Particle Flow algorithm
  - combines information from tracker, ECAL, HCAL and muon detectors
  - obtain energy, direction and identity of particles
    - jets, photons, electrons, muons
  - jets are typically clustered with antiKT05 algorithm

- luminosity measurement: 4.5%
- jet energy scale and jet resolution: 2.5%
- NLO cross-section and proton PDF choice: 10%
- modeling of lepton veto: 2.5%
- ECAL masked region: 3%

