# Results on SUSY and Higgs searches at CMS

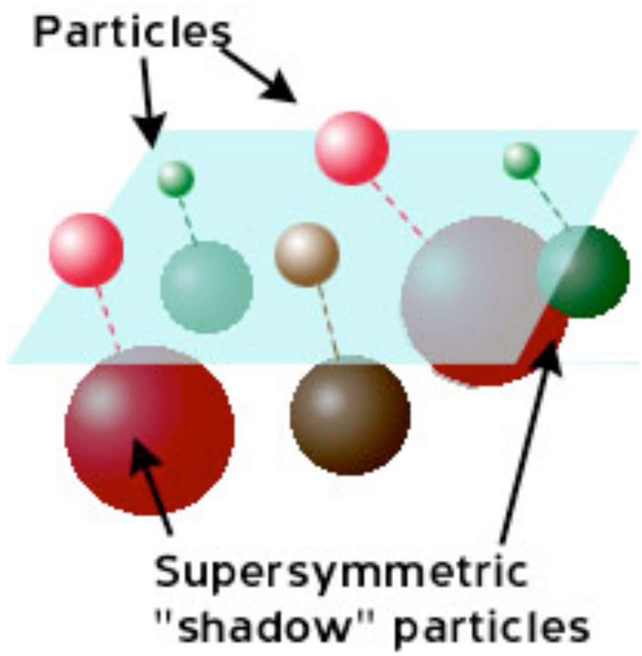
**Alex Tapper**

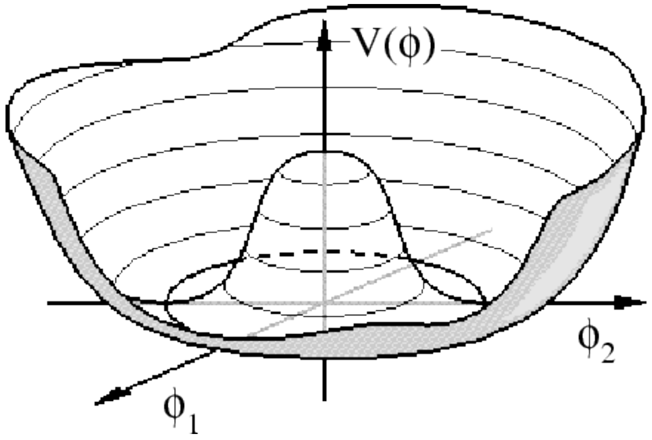
 CERN Joint EP/PP/LPCC Seminar, 15th March 2011.

Imperial College London

# Outline

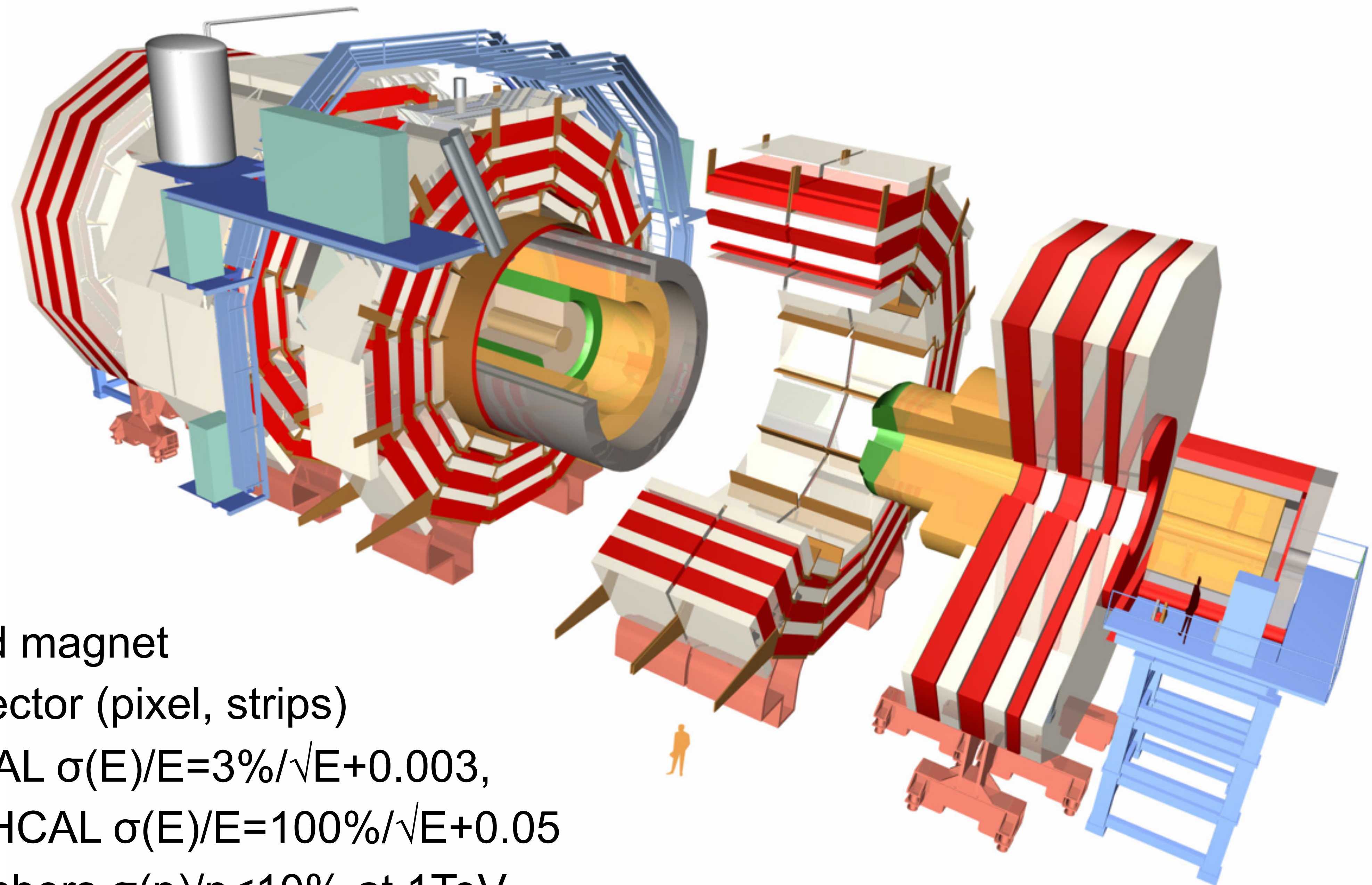
- CMS performance
  - Why you should believe our searches
- SUSY search programme
  - What to look for and how to look for it
  - All-hadronic searches
  - Searches with leptons
  - Searches with photons
- Higgs searches
  - Neutral Higgs searches
  - Charged Higgs searches
- Summary and conclusions



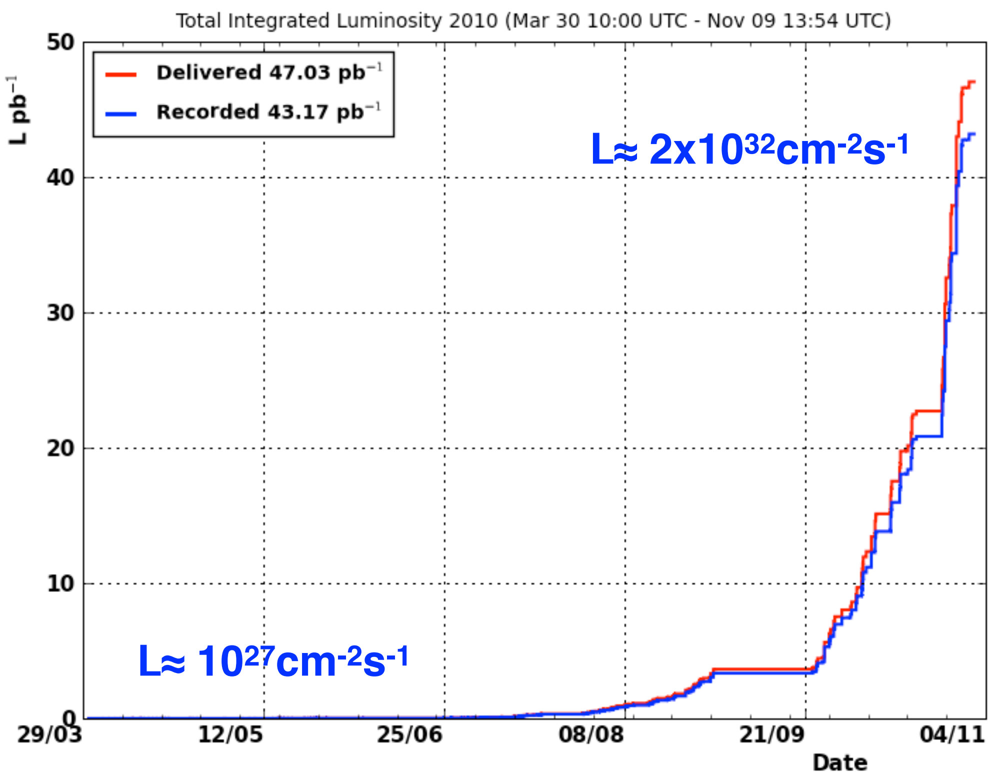
# The CMS detector

JINST3:S08004 (2008)



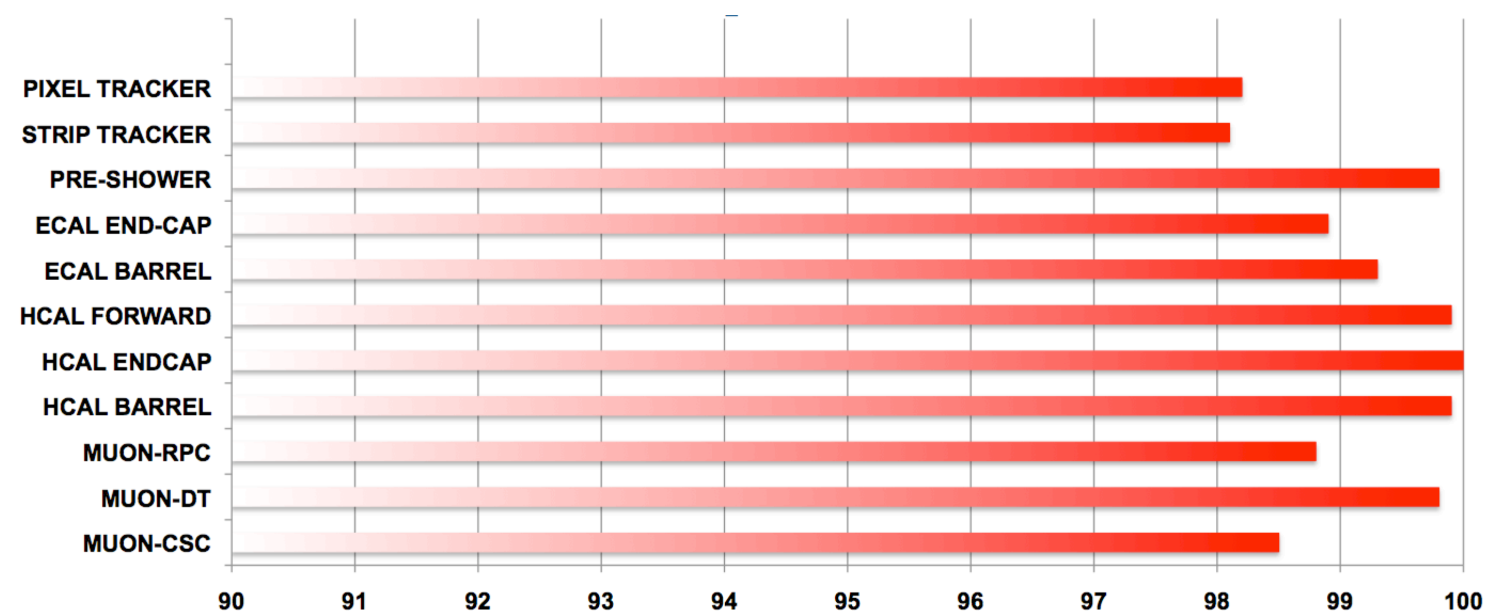
- 4T solenoid magnet
- Silicon detector (pixel, strips)
- Crystal ECAL $\sigma(E)/E=3\%/\sqrt{E}+0.003$,
- Brass/sci. HCAL $\sigma(E)/E=100\%/\sqrt{E}+0.05$
- Muon chambers $\sigma(p)/p<10\%$ at 1TeV

# The CMS detector in 2010




- LHC delivered ~47 pb$^{-1}$ (thanks!)
- CMS collected ~43 pb$^{-1}$ (~92%)
- Coped with 5 orders of increase in instantaneous luminosity
- Results based on ~35 pb$^{-1}$ (~85%)

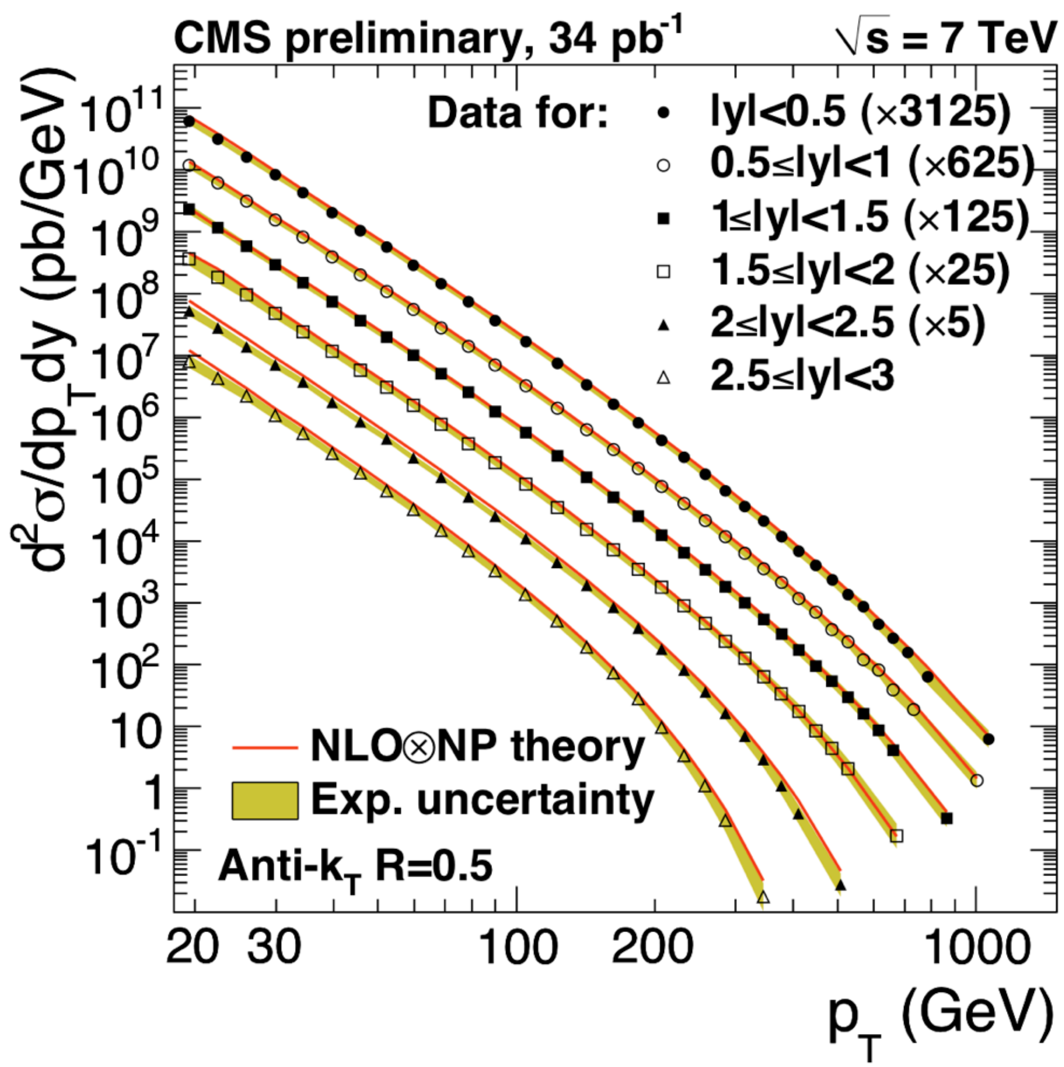
- Average fraction of functional detector channels > 99%
- Lowest still > 98%



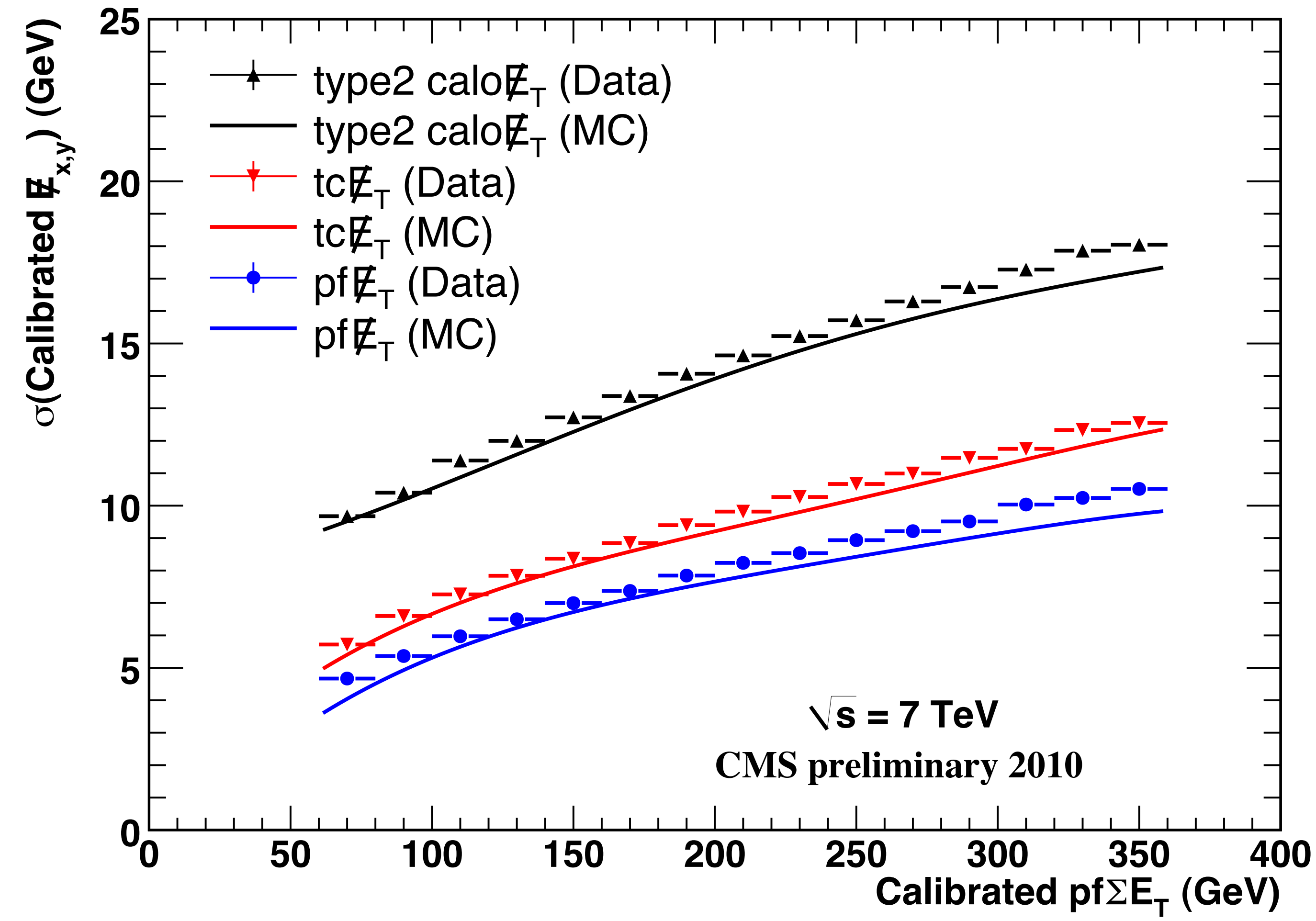

| | MUON-CSC | MUON-DT | MUON-RPC | HCAL BARREL | HCAL ENDCAP | HCAL FORWARD | ECAL BARREL | ECAL END-CAP | PRE-SHOWER | STRIP TRACKER | PIXEL TRACKER |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Series1 | 98.5 | 99.8 | 98.8 | 99.9 | 100 | 99.9 | 99.3 | 98.9 | 99.8 | 98.1 | 98.2 |

# Hadronic jets and MET

CMS-QCD-10-011




CMS-PAS-JME-10-004

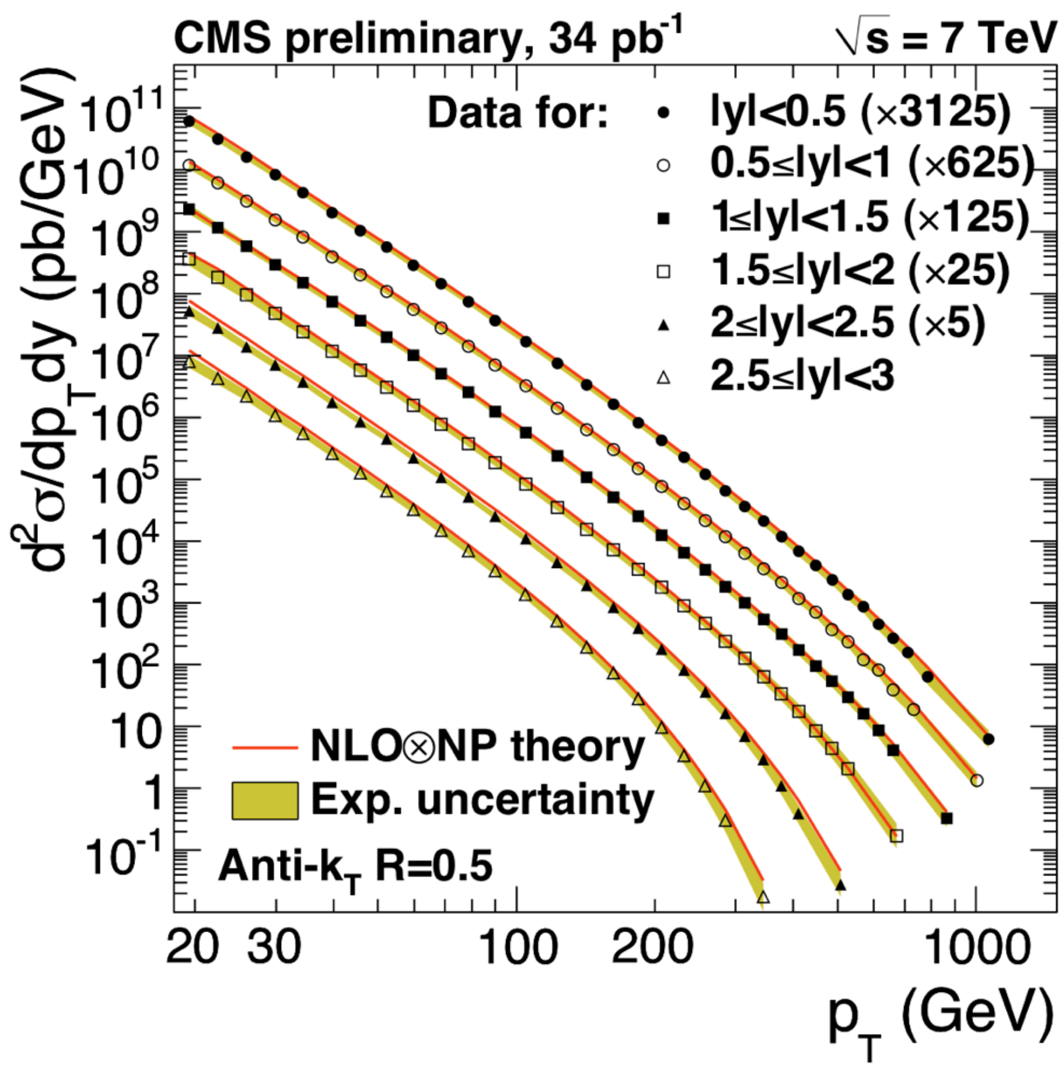


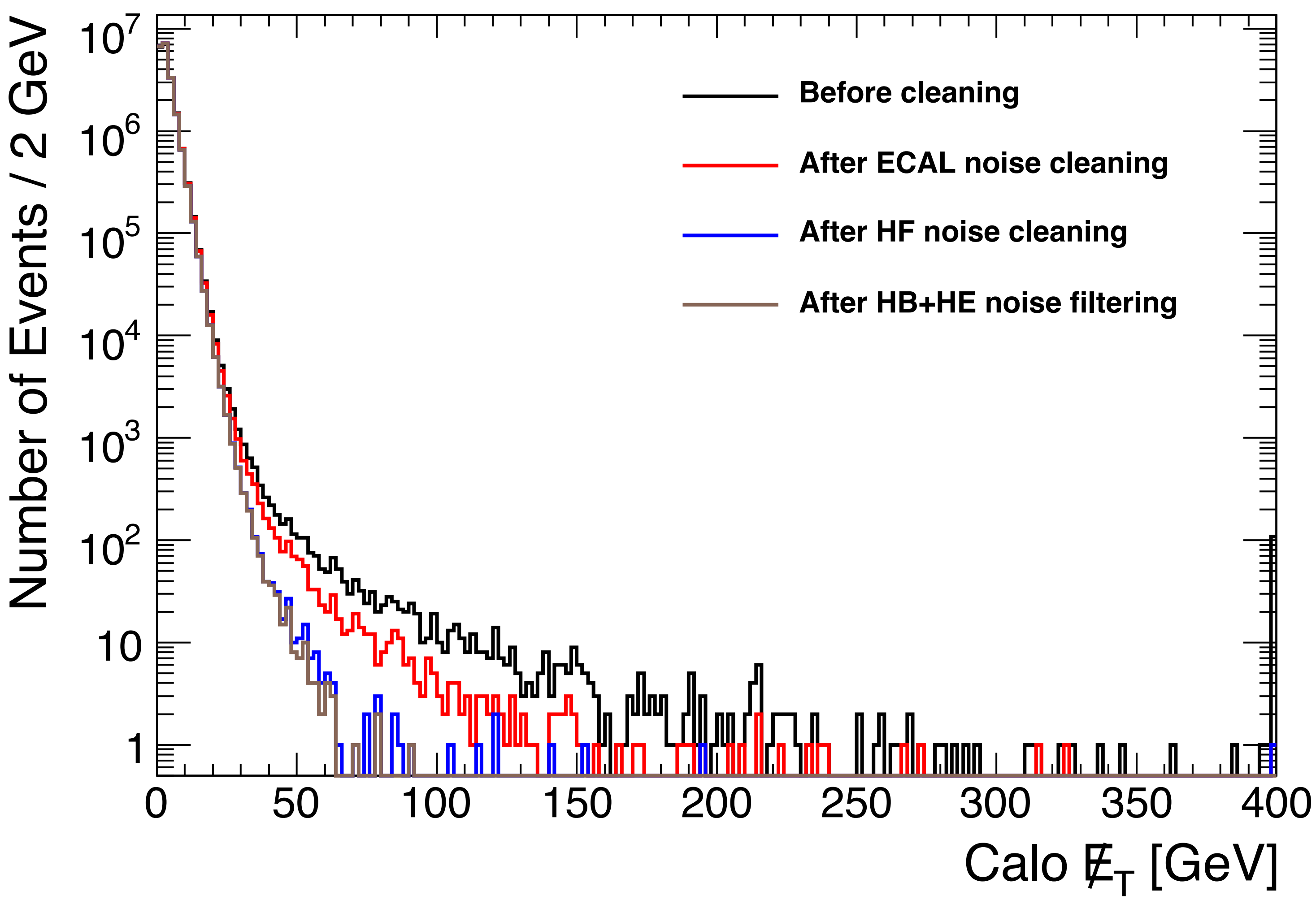

- Measurements of jet cross sections and MET resolution
- Jets and MET in good shape

# Hadronic jets and MET

CMS-QCD-10-011

CMS-PAS-JME-10-004

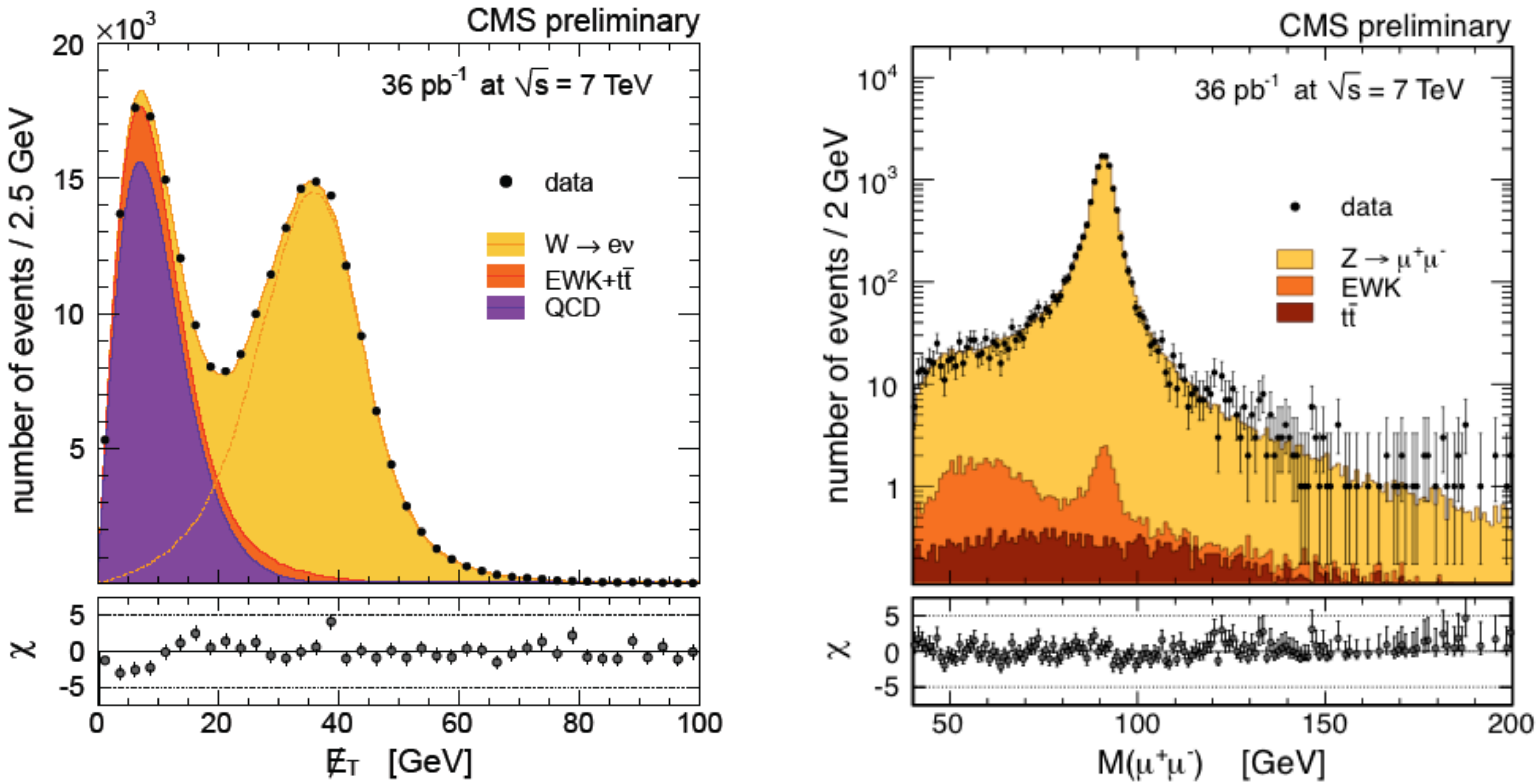



- Measurements of jet cross sections and MET resolution
- Jets and MET in good shape

# Electrons and muons

CMS-EWK-10-005

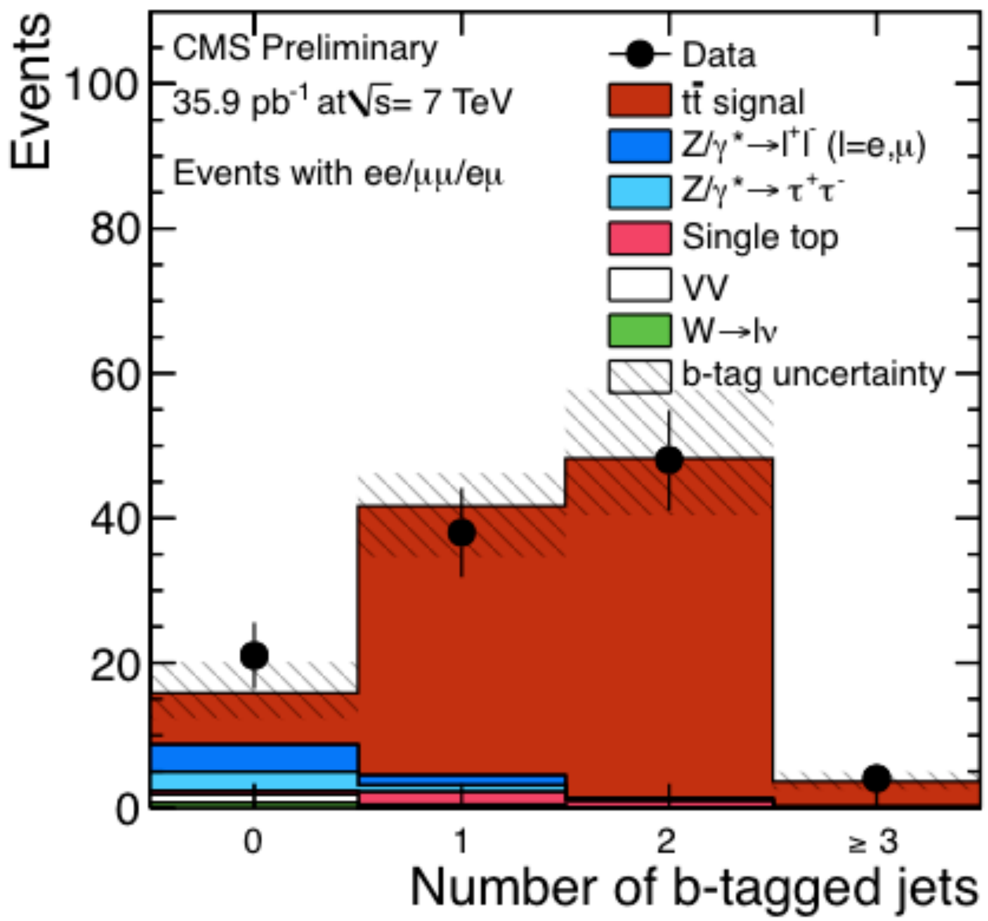


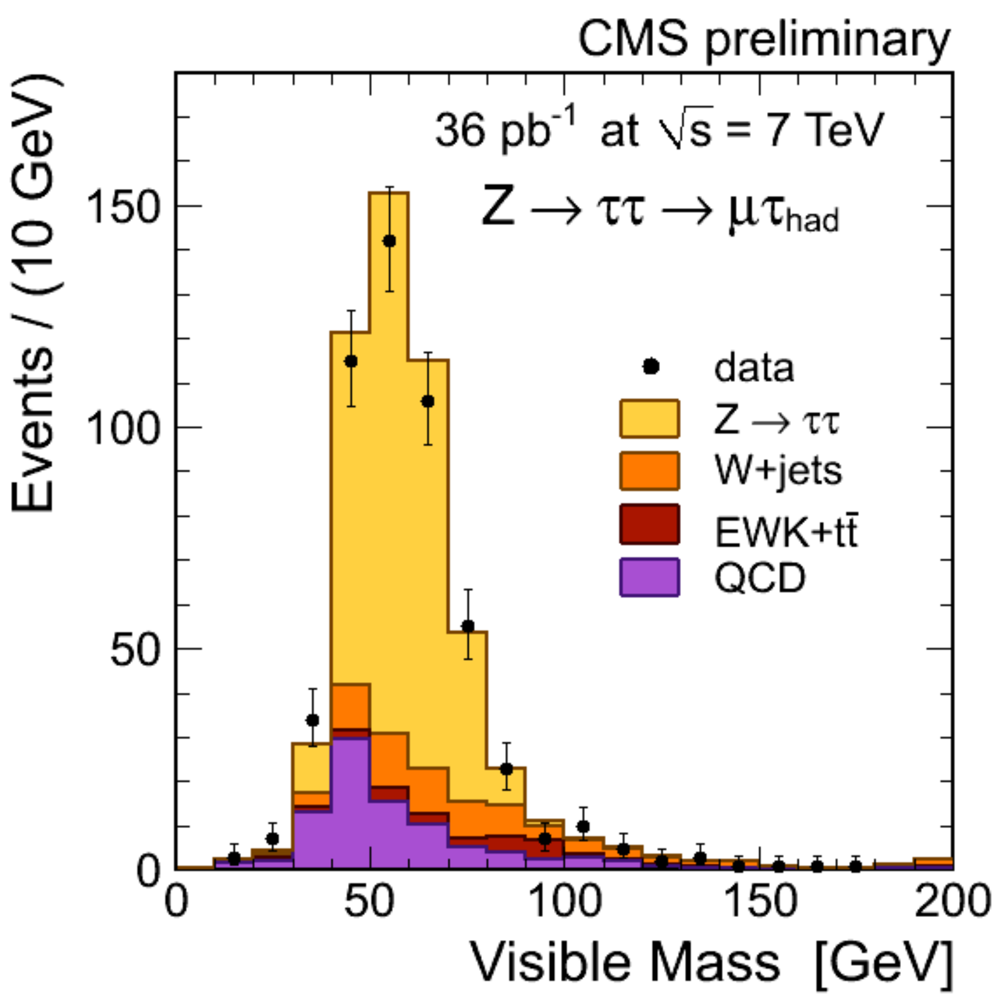

- Beautiful reconstruction of W and Z bosons
- Leptons and MET reconstruction performing well

# B and τ tagging

CMS-TOP-10-005

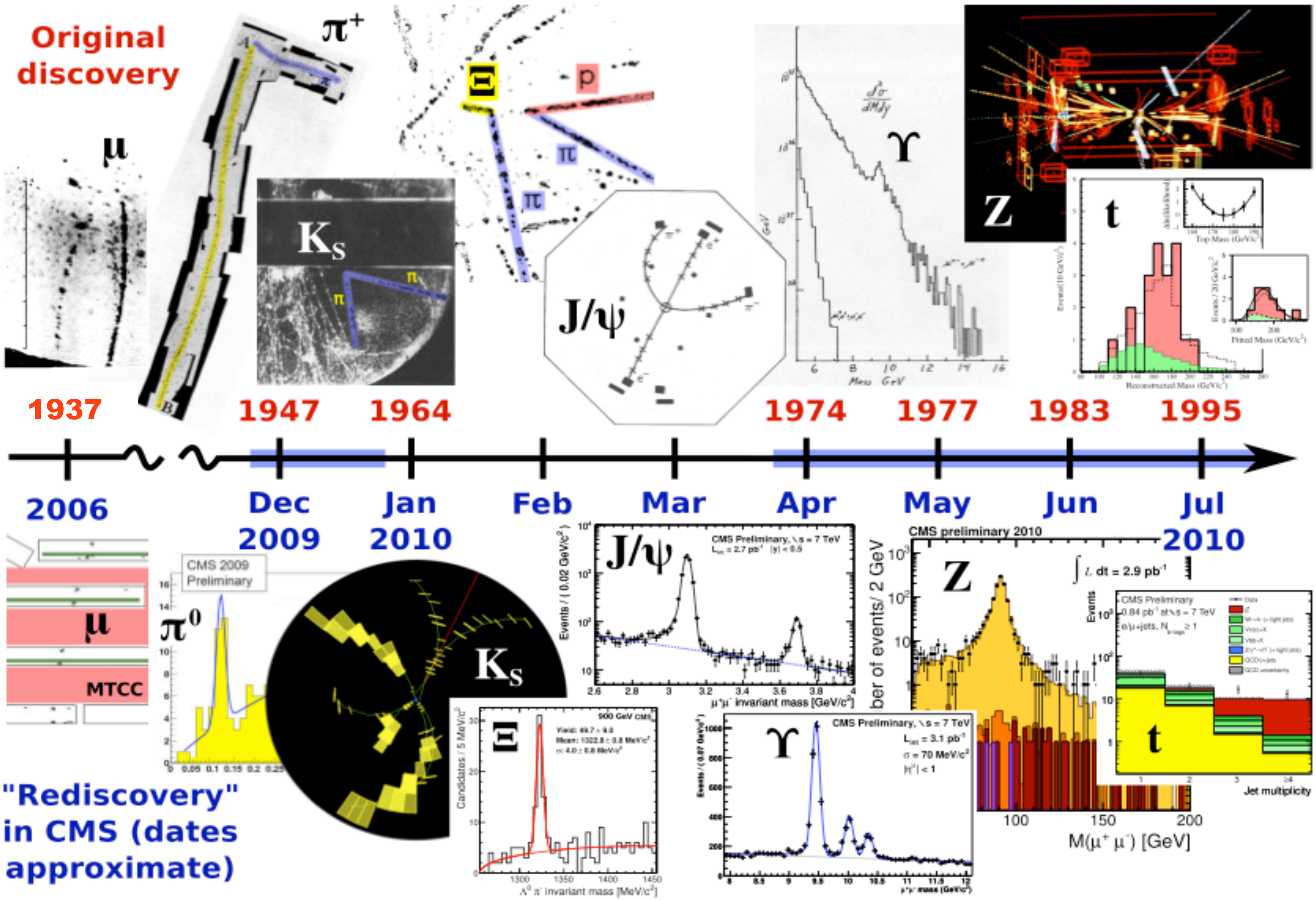
CMS-EWK-10-013



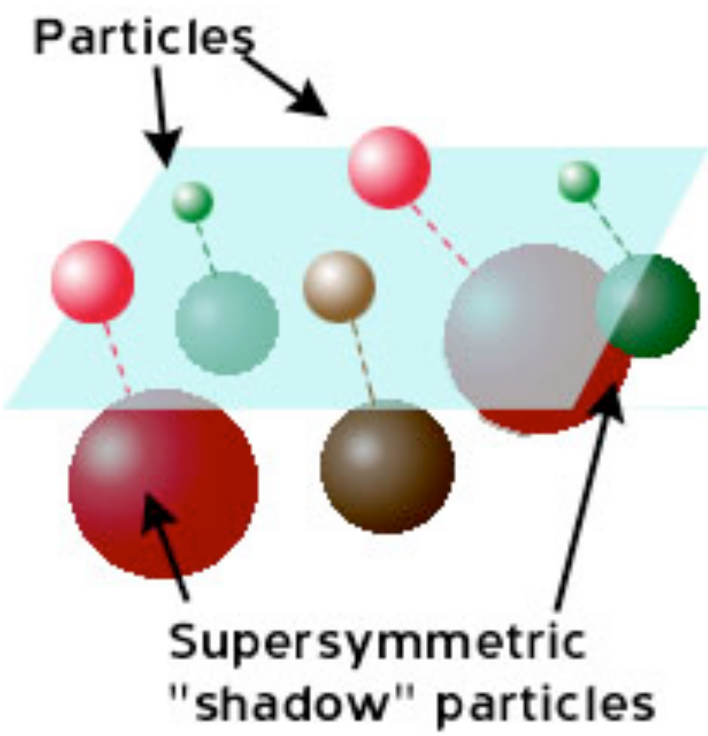

- Top-quark pair-production and Z➔ $\tau^+\tau^-$
- b-tagging and τ-tagging performing well

# Re-discovery of the Standard Model



# Supersymmetry

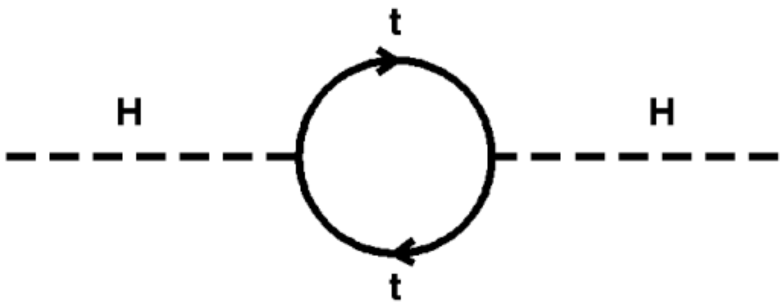
- The theory hypothesises a relationship between bosons and fermions
  - Leads to the prediction that every fermion has a bosonic super-partner and vice versa



# Supersymmetry

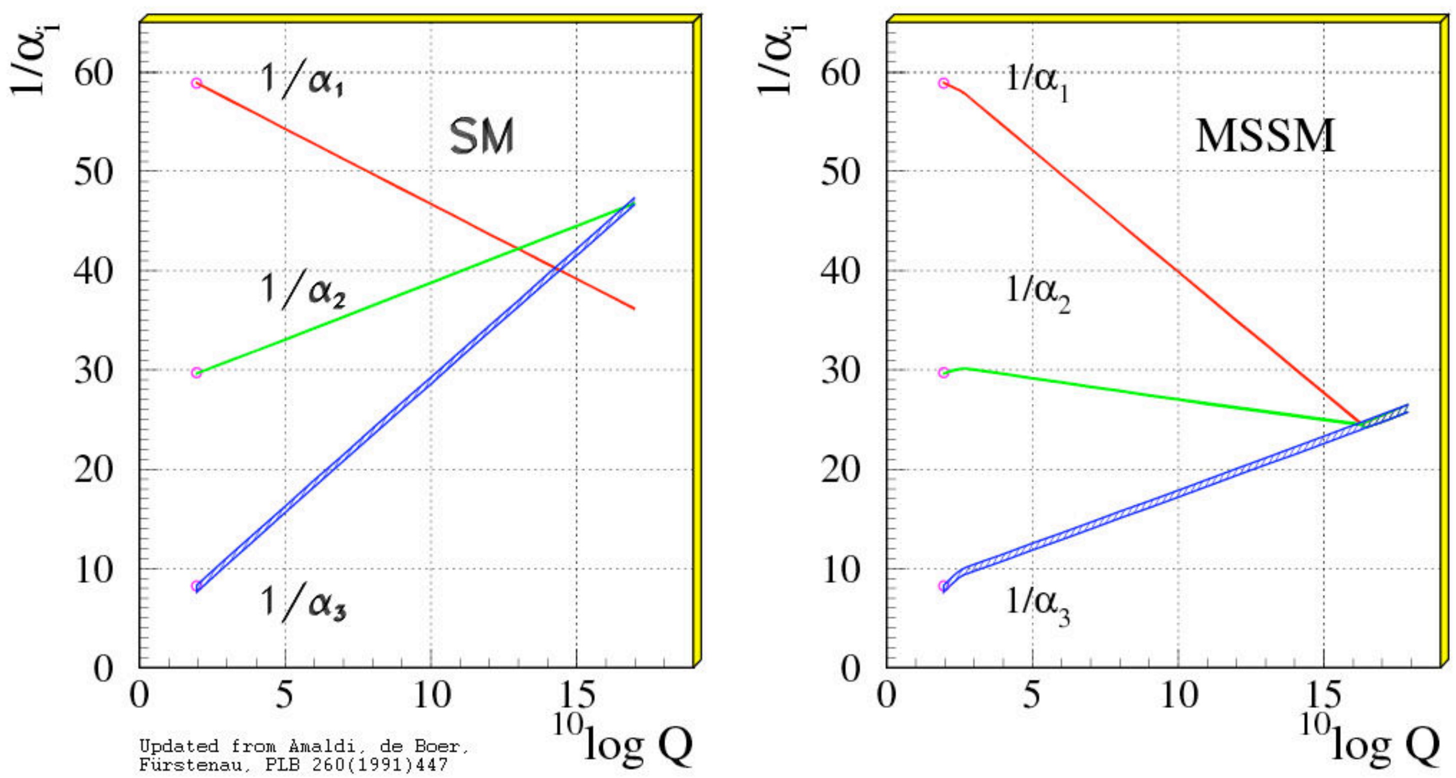
- The theory hypothesises a relationship between bosons and fermions
  - Leads to the prediction that every fermion has a bosonic super-partner and vice versa

- Theorists love SUSY (@ TeV scale) because
  - It provides a solution to the hierarchy problem




# Supersymmetry

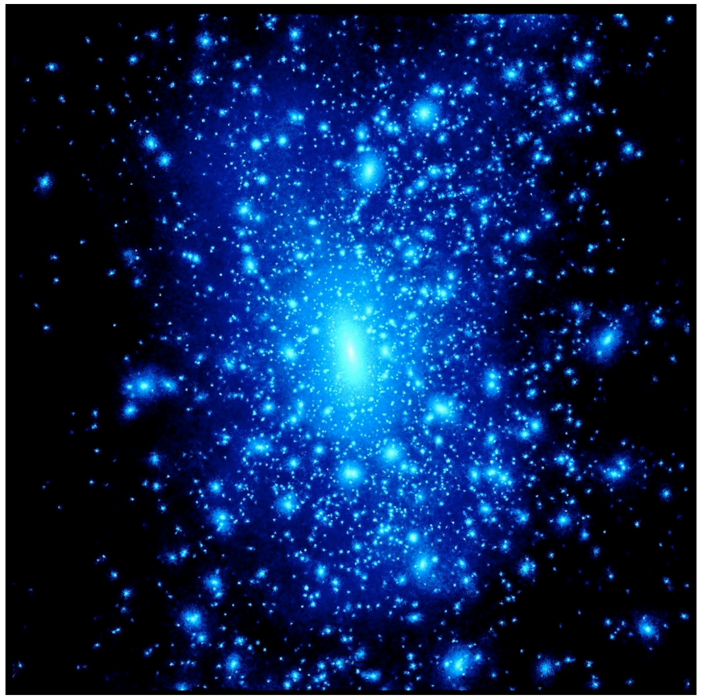
- The theory hypothesises a relationship between bosons and fermions
  - Leads to the prediction that every fermion has a bosonic super-partner and vice versa
- Theorists love SUSY (@ TeV scale) because:
  - It provides a solution to the hierarchy problem
  - It allows unification of the gauge couplings at high scales and perhaps a GUT?

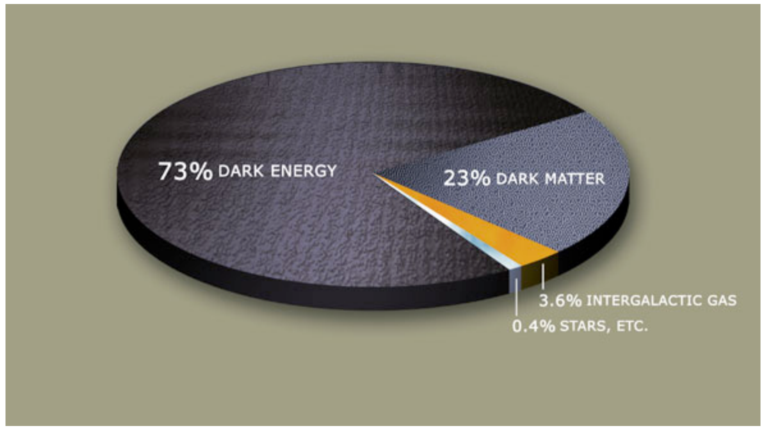


# Supersymmetry

- The theory hypothesises a relationship between bosons and fermions
  - Leads to the prediction that every fermion has a bosonic super-partner and vice versa

- Theorists love SUSY (@ TeV scale) because:
  - It provides a solution to the hierarchy problem
  - It allows unification of the gauge couplings at high scales and perhaps a GUT?
  - It can provide a dark matter candidate



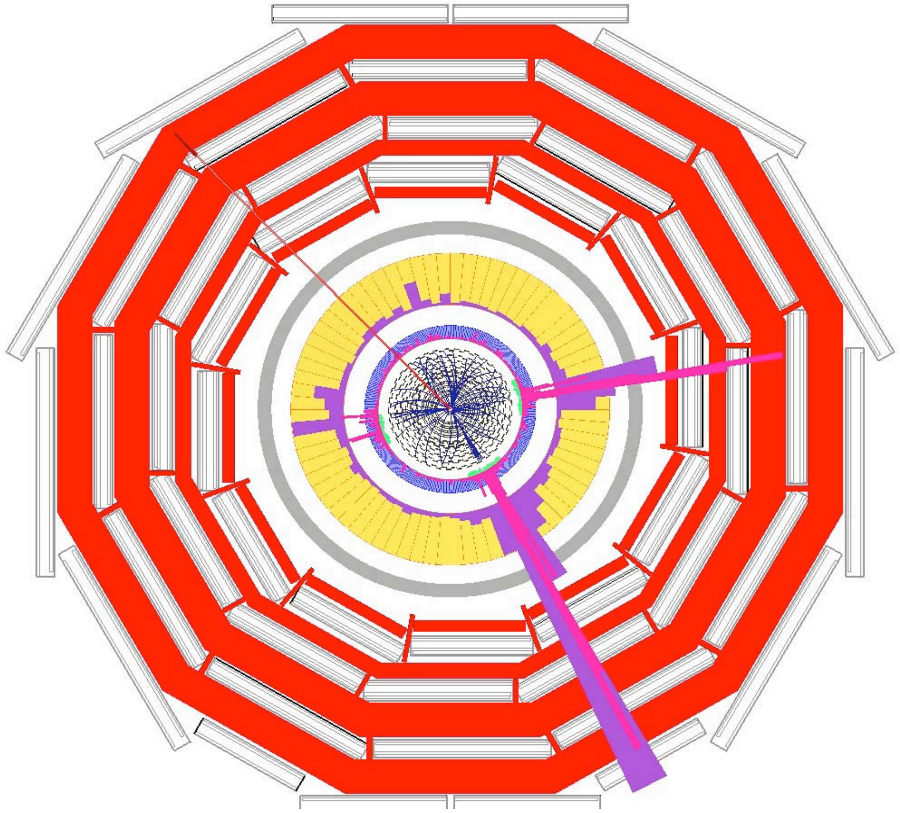


# Supersymmetry

- The theory hypothesises a relationship between bosons and fermions
  - Leads to the prediction that every fermion has a bosonic super-partner and vice versa

- Theorists love SUSY (@ TeV scale) because:
  - It provides a solution to the hierarchy problem
  - It allows unification of the gauge couplings at high scales and therefore a GUT?
  - It can provide a dark matter candidate

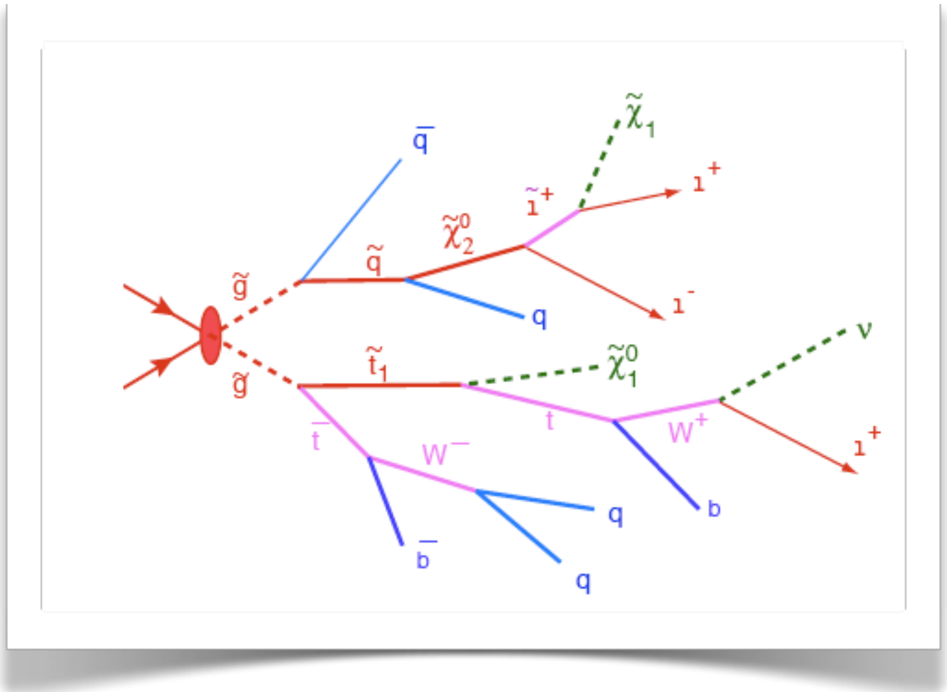
- Experimentalists love it because:
  - Plethora of new particles to discover and measure



# Supersymmetry

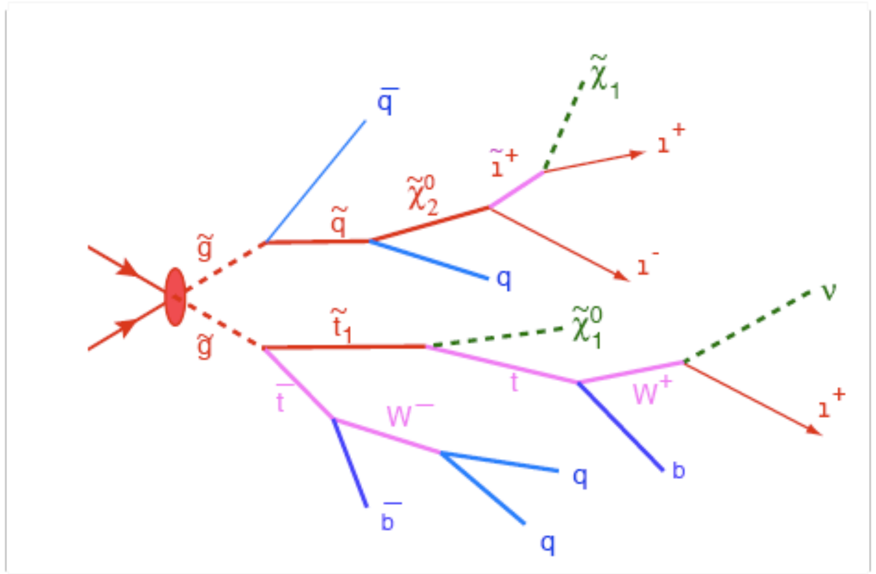
- The theory hypothesises a relationship between bosons and fermions
  - Leads to the prediction that every fermion has a bosonic super-partner and vice versa
- Theorists love SUSY (@ TeV scale) because:
  - It provides a solution to the hierarchy problem
  - It allows unification of the gauge couplings at high scales and therefore a GUT?
  - It can provide a dark matter candidate
- Experimentalists love it because:
  - Plethora of new particles to discover and measure
- Symmetry not exact
  - SUSY and Standard Model particles have different masses
  - SUSY is broken → what does it look like and how do we search?

# SUSY search strategy




- Production
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model

# SUSY search strategy




- Production
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model
- Decay
  - Details of decay chain depend on SUSY model (mass spectra, branching ratios, etc.)
  - Assume $R_P$ conserved ➔ decay to lightest SUSY particle (LSP)
  - Assume squarks and gluinos are heavy ➔ long decay chains
- Signatures
  - **MET** from LSPs, **high-$E_T$ jets** and **leptons** from long decay chain
- Focus on simple signatures
  - Common to wide variety of models
  - Let Standard Model background and detector performance define searches not models

# The key: backgrounds

- Physics
  - Standard Model processes that give the same signatures as SUSY
  - Cannot (yet?) rely on Monte Carlo predictions ➔ measure in data
- Detector effects
  - Detector noise, mis-measurements etc. that generate MET or extra jets
  - Commissioning and calibration ➔ good performance shown earlier
- Other
  - Beam-halo muons and cosmic-ray muons, beam-gas events
  - Data and simulation already ➔ measure in situ too

# Search strategy (what and how?)

| 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 |

- Generic missing energy signatures
- Categorised by numbers of leptons and photons
- Many include jet requirement ➔ strong production
- All counting experiments at this point

# Search strategy (what and how?)

| 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 |

- Very challenging due to large amount and wide range of backgrounds
- However most sensitive search for strongly produced SUSY
- CMS pursues several complementary strategies based on kinematics and detector understanding
- Extend to b, τ and top-tagged final states

# Search strategy (what and how?)

| 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 |

- Lepton (electron or muon) requirement reduces background considerably
- Only ttbar and W+jets left ➔ topological handles

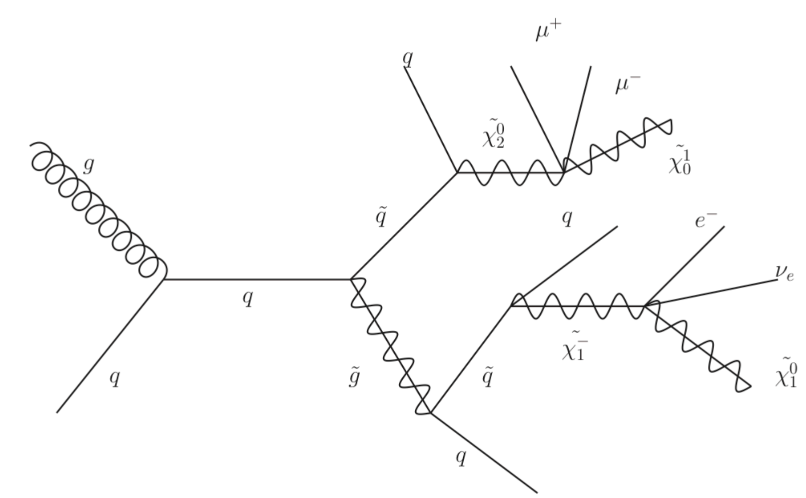
# Search strategy (what and how?)

| 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 |

- Adding a second lepton (electron or muon) reduced W background
- Two analyses here: inclusive and Z peak search
- Several techniques including opposite-sign opposite-flavour subtraction
- Shape information and mass edges

# Search strategy (what and how?)

| 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 |




- A natural SUSY signature
- Very small Standard Model backgrounds
- Include all three generations of leptons and all cross channels

# Search strategy (what and how?)

| 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 |

- Very clean events with very low Standard Model background
- Include all three generations of leptons and all combinations
- Search inclusively, on the Z peak, with and without MET
- Some striking Standard Model events observed already

# Search strategy (what and how?)

| 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 |

- Many gauge-mediated models predict photons in final state
- Di-photon searches dominated by QCD multijet and γ+jet backgrounds

# Search strategy (what and how?)

| 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 |

- Many gauge mediated models predict photons in final state
- Lepton reduces QCD multijet and γ+jet backgrounds

# Search strategy (what and how?)

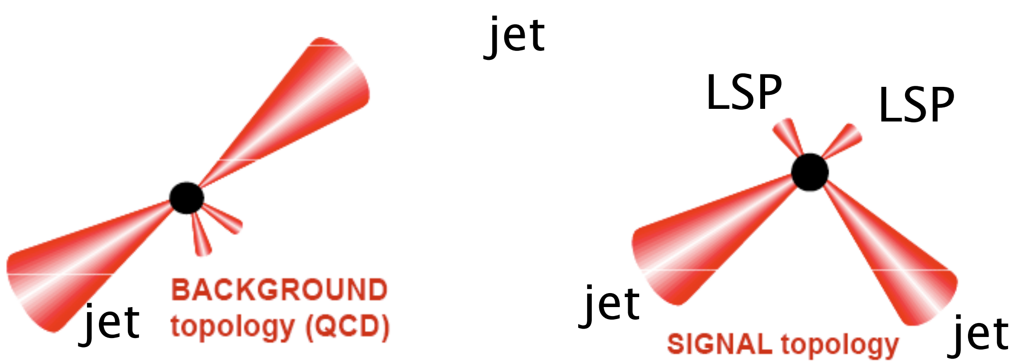
| 0-leptons | 1-lepton | OSDL | SSDL | ≥3 leptons | 2-photons | γ+lepton |
|---|---|---|---|---|---|---|
| Jets + MET | Single lepton + Jets + MET | Opposite-sign di-lepton + jets + MET | Same-sign di-lepton + jets + MET | Multi-lepton | Di-photon + jet + MET | Photon + lepton + MET |

| RPV | "Exotic" |
|---|---|
| R-Parity violating searches | Long-lived particles etc. |

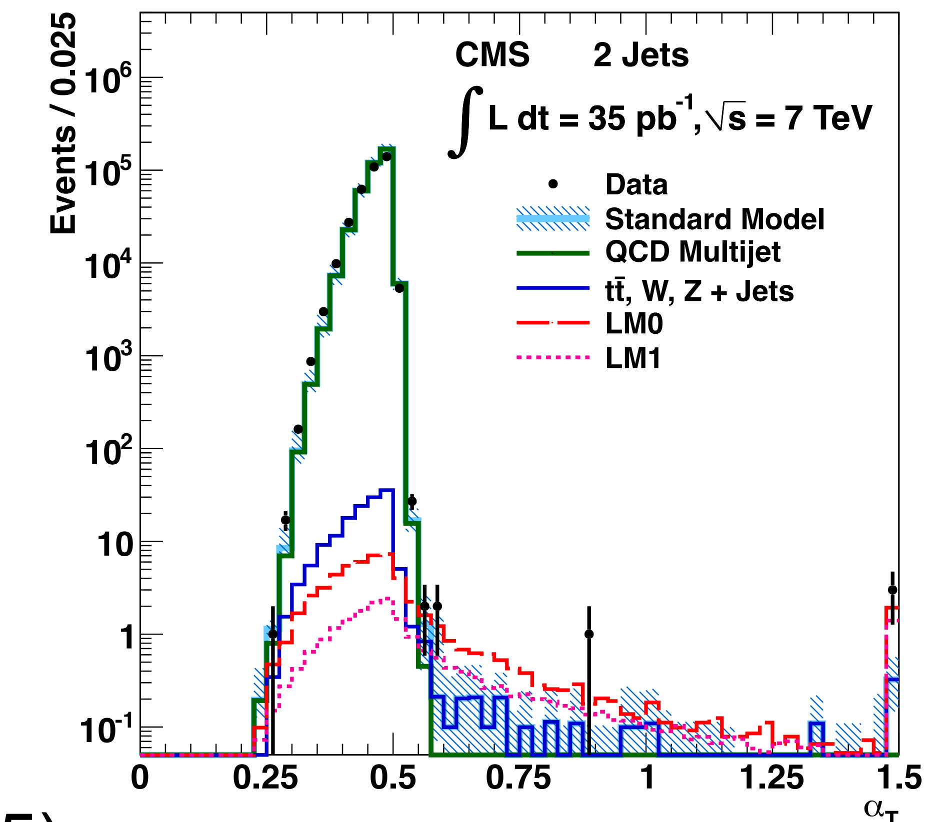
- Non-MET based searches
- R-parity conserving and "exotic" SUSY
- Examples are long-lived particles
- Not covered in this talk but well-studied in CMS
- See https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

# Hadronic search with $\alpha_T$

PRL101:221803 (2008) & arXiv:1101.1628

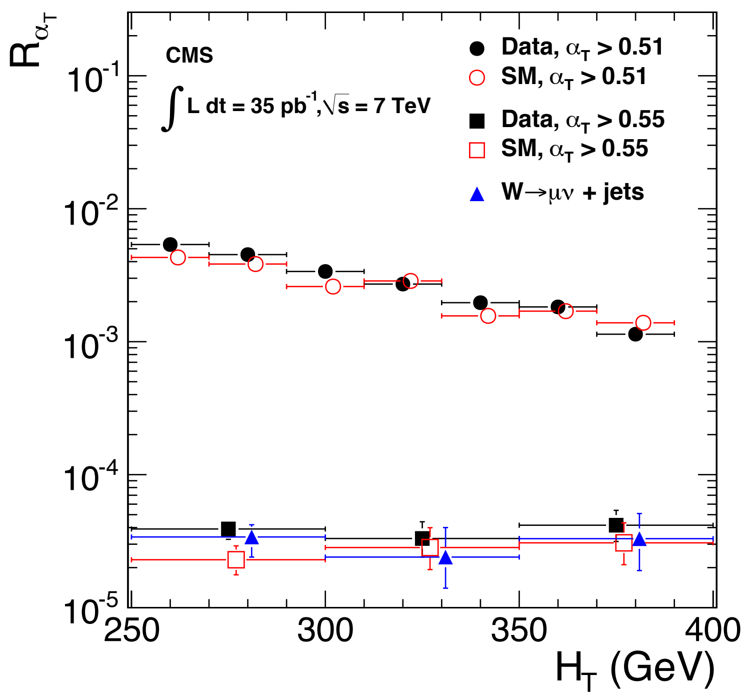



$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$




- At least 2 jets with $E_T$>50 GeV & $|\eta|$<3 anti-$k_T$ (0.5)
- Leading jet $|\eta|$<2.5 and $E_{Tj2}$>100 GeV
- Veto events isolated electrons, muons and photons
- Event cleaning cuts
- $H_T$ ($\Sigma E_{TJi}$) > 350 GeV (beyond previous searches) and $\alpha_T$>0.55

# Inclusive background estimate




- Use kinematics and control regions to estimate all backgrounds
  - Use lower $H_T$ bins 250-300 GeV and 300-350 GeV to extrapolate into signal region 350 GeV
  - Adjust cuts in control regions to preserve kinematics
  - Define $R\alpha_T = N(\alpha_T>x)/N(\alpha_T<x)$
  - For QCD (mismeasurement) expect this to fall as resolution improves with increasing $H_T$
  - For EWK (real MET) expect flat behaviour. Check with W/ttbar control sample
  - Indicates final selection is QCD free
  - Extrapolate for low to high $H_T$
  - Result is $9.4^{+4.8}_{-4.0}$ (stat.) ±1.0 (syst.)
  - 13 events observed in data

Other background determination methods discussed later:

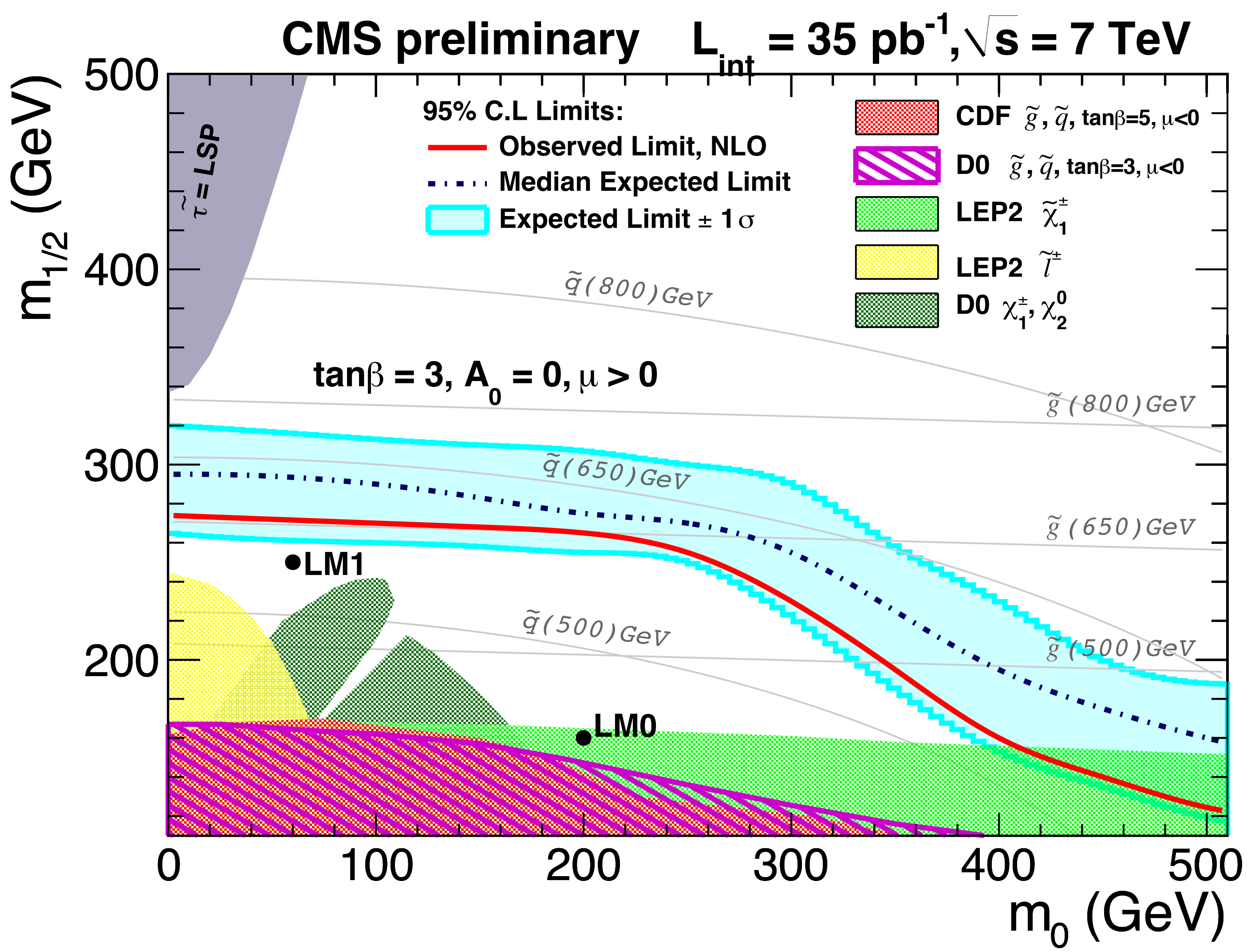
W and ttbar from muon control sample

Z to inv from photon+jets

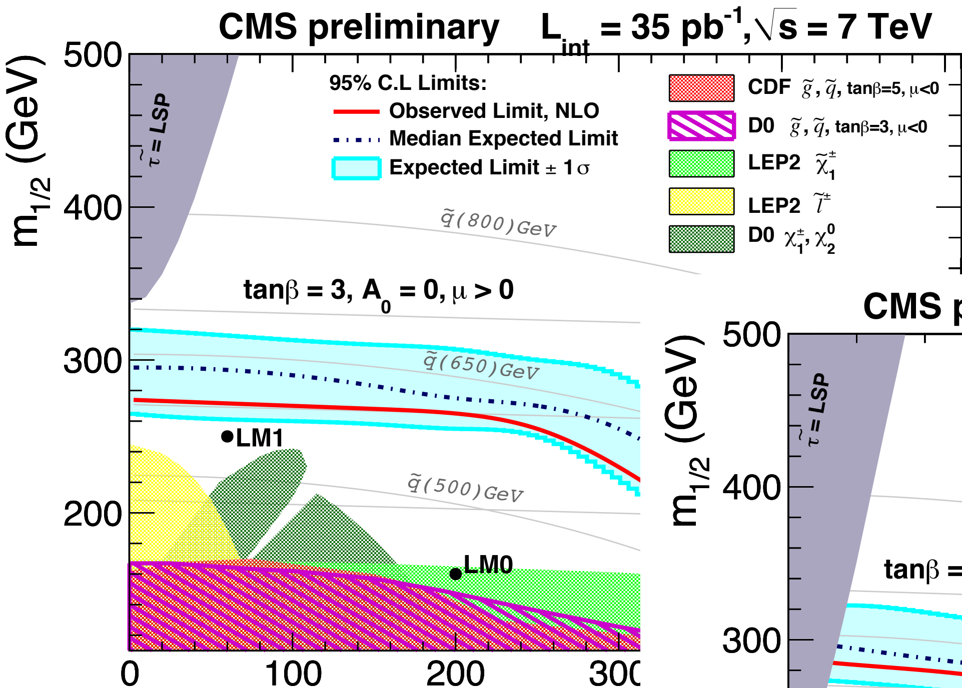
# Hadronic search with $\alpha_T$

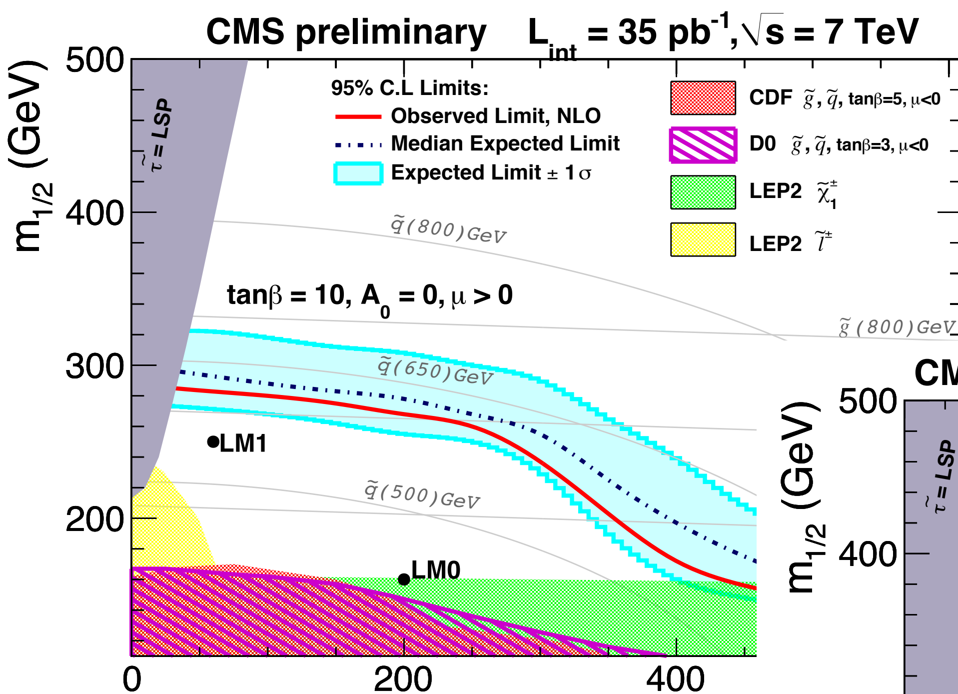
arXiv:1101.1628

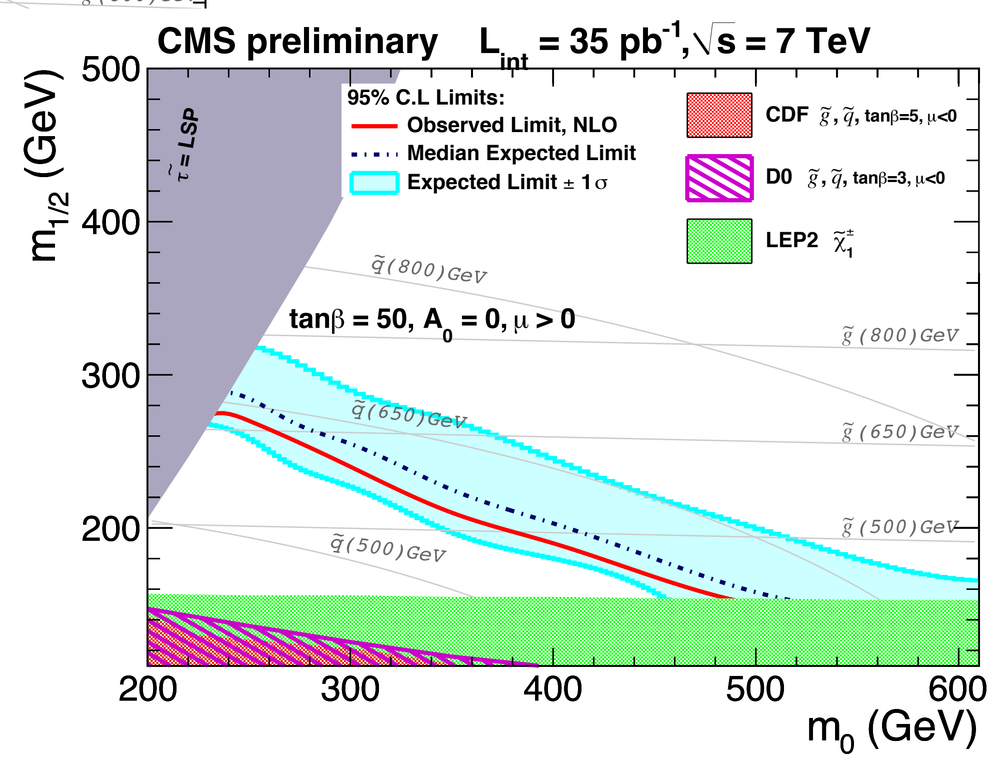
- Interpret in CMSSM for easy comparison with previous experiments
- $\tan\beta=3$ $A_0=0$ $\mu>0$
- Significant extension of excluded region over Tevatron experiments

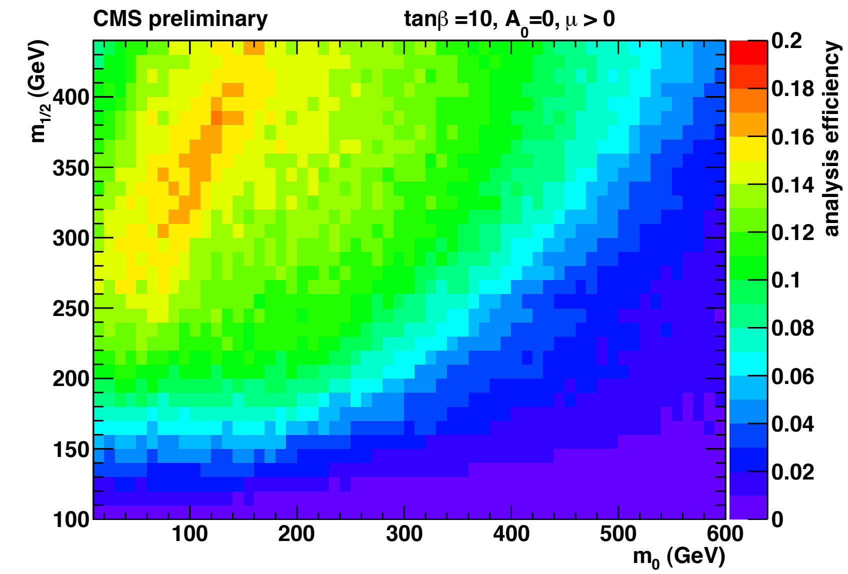


# Hadronic search with $\alpha_T$



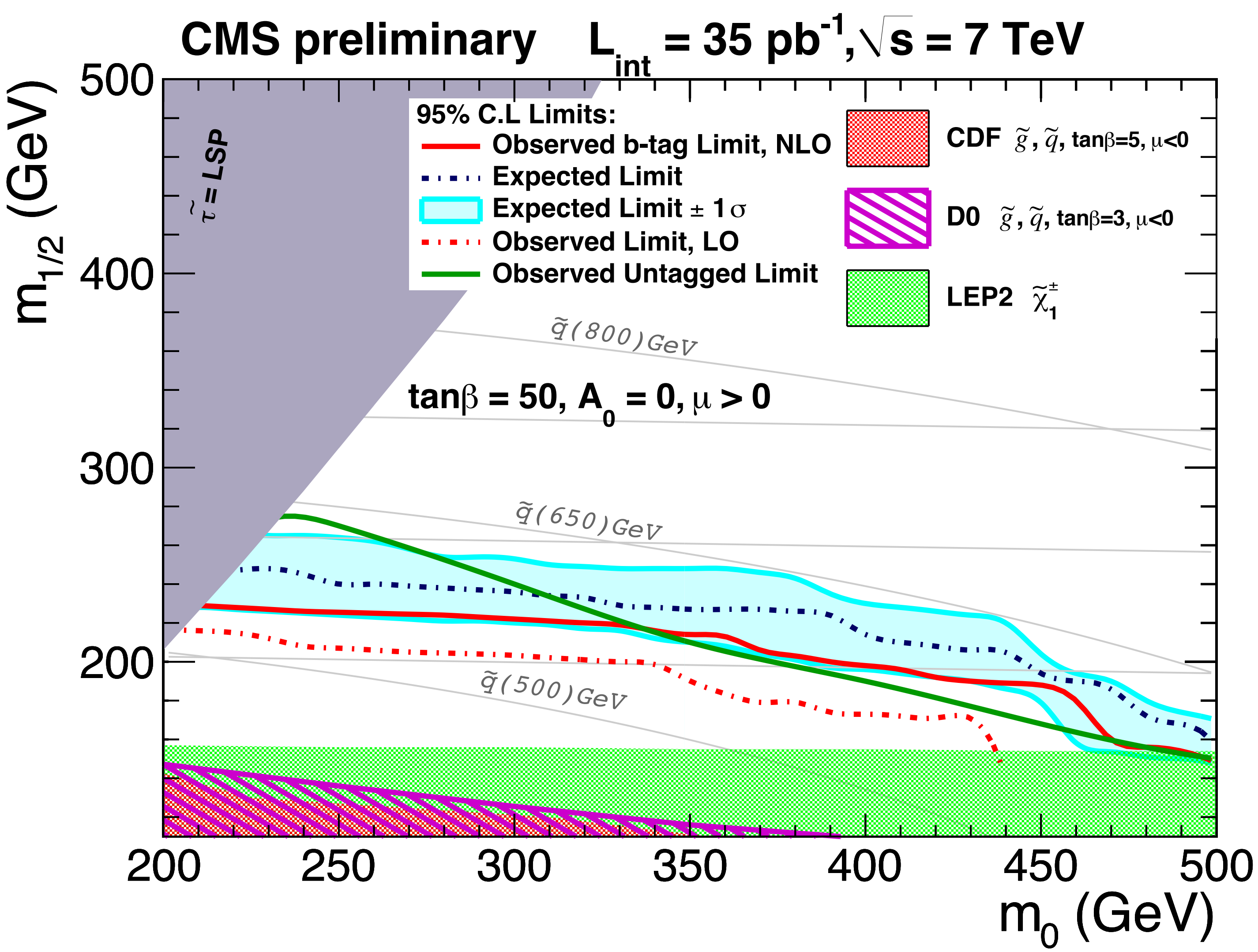




CMS-SUS-11-001

- Weak dependence on tanβ (3,10, 50)
- Efficiencies available as function of $m_0$ and $m_{1/2}$

# Hadronic search $\alpha_T$ + b-tag

CMS-SUS-10-011



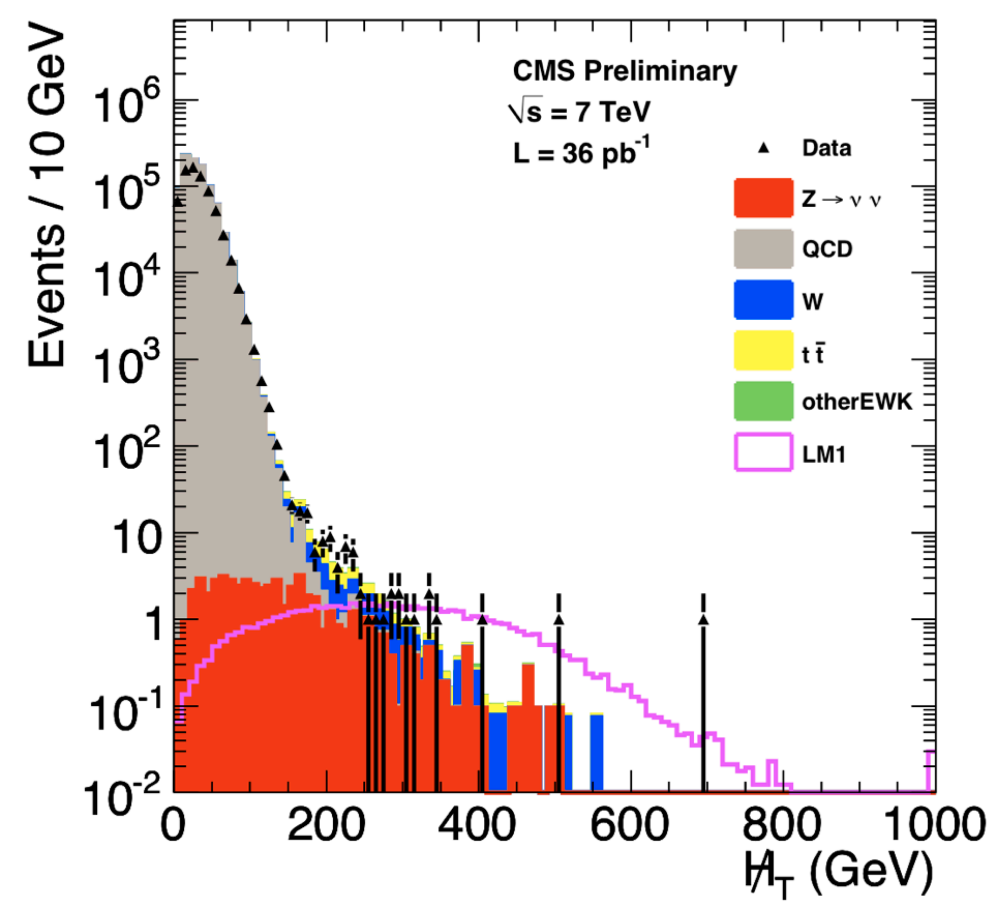

- Same as search with $\alpha_T$ but add the requirement that one of the jets must be b-tagged
- Reduces non-top backgrounds
- Increased sensitivity for b-rich models

- One event observed in data
- Expect $0.33^{+0.43}_{-0.33}$ (stat) ± 0.13 (syst) events

# Hadronic search with missing energy

CMS-SUS-10-005

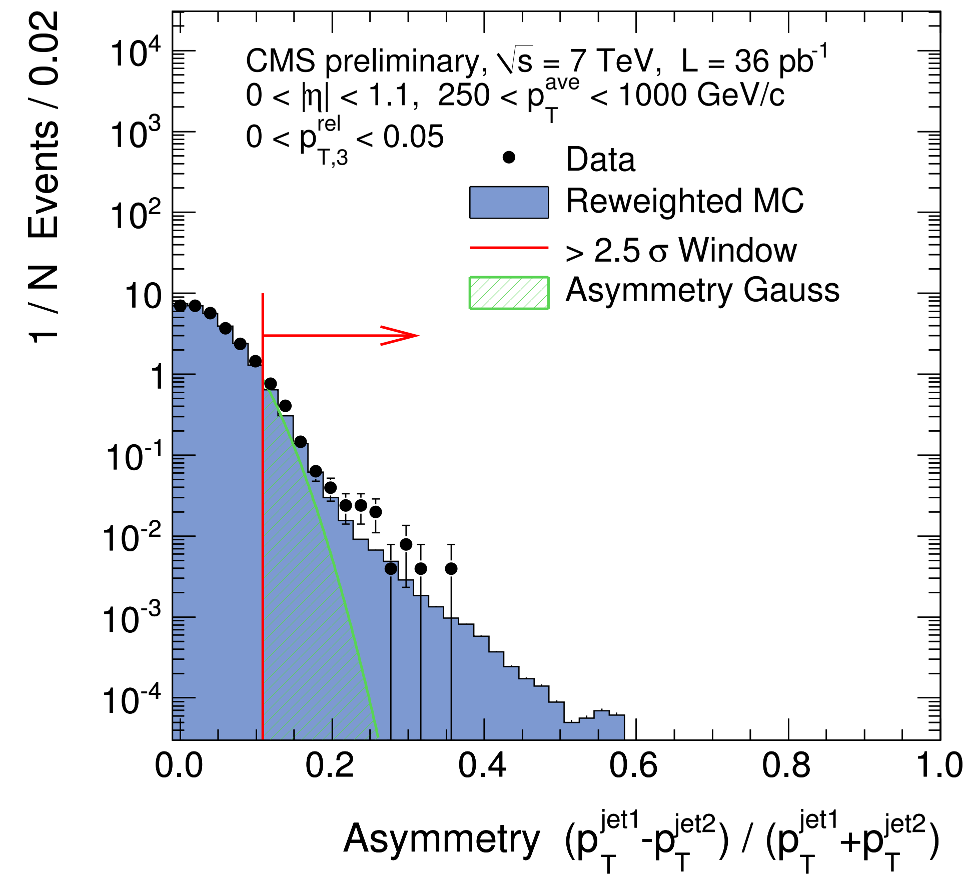
- Analysis based on understanding the detector response in detail
- Complementary to kinematics-based searches
- Baseline selection
  - At least 3 jets with $E_T$>50 GeV & |η| <2.5 anti-kT (0.5)
  - $H_T$>300 GeV and MHT > 150 GeV
  - Veto isolated electrons and muons
- Backgrounds from
  - Multi-jet QCD, Z ➔ νν, W+jets, ttbar
  - All determined from data-driven techniques ➔

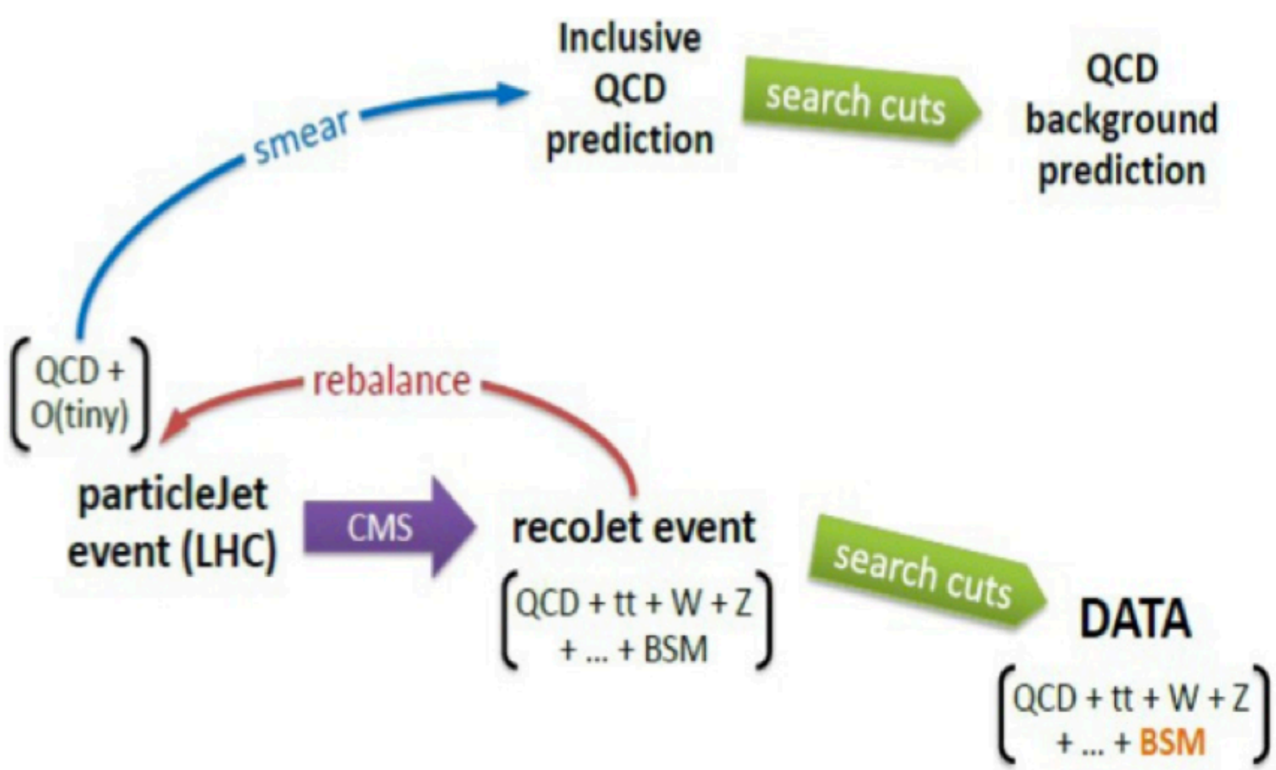



MC backgrounds (illustrative)

# Multi-jet QCD background

- Concept: derive a smearing function per jet from data and apply this to a seed sample to predict the high MET (MHT) tail in data
- Derive response function from γ+jets (core) and di-jets (non-Gaussian tails) ➔

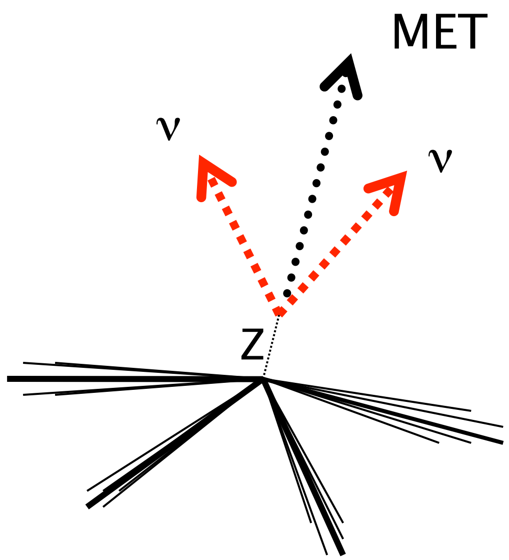


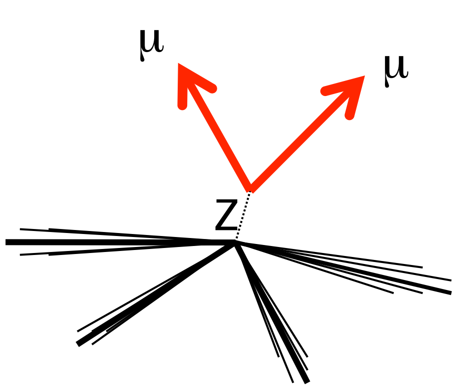




- Obtain a well-balance seed sample by rebalancing multi-jet events
- Makes electroweak and signal contamination negligible
- Apply smearing to each jet to get a background prediction

# $Z \rightarrow \nu\nu$ background

- $Z \rightarrow \nu\nu$ + jets ➔ irreducible background
- Replacement technique pursued with all three samples
- γ+jets sample currently used, other cross check

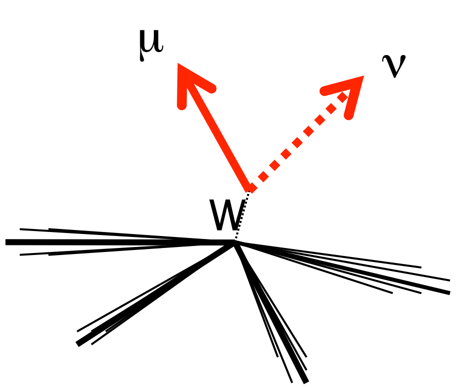



**$Z \rightarrow ll$ + jets**

Strength: very clean

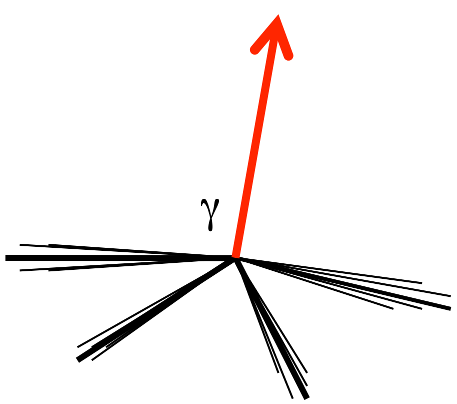
Weakness: low statistics




**$W \rightarrow l\nu$ + jets**

Strength: larger statistics

Weakness: background from SM and SUSY




**γ + jets**

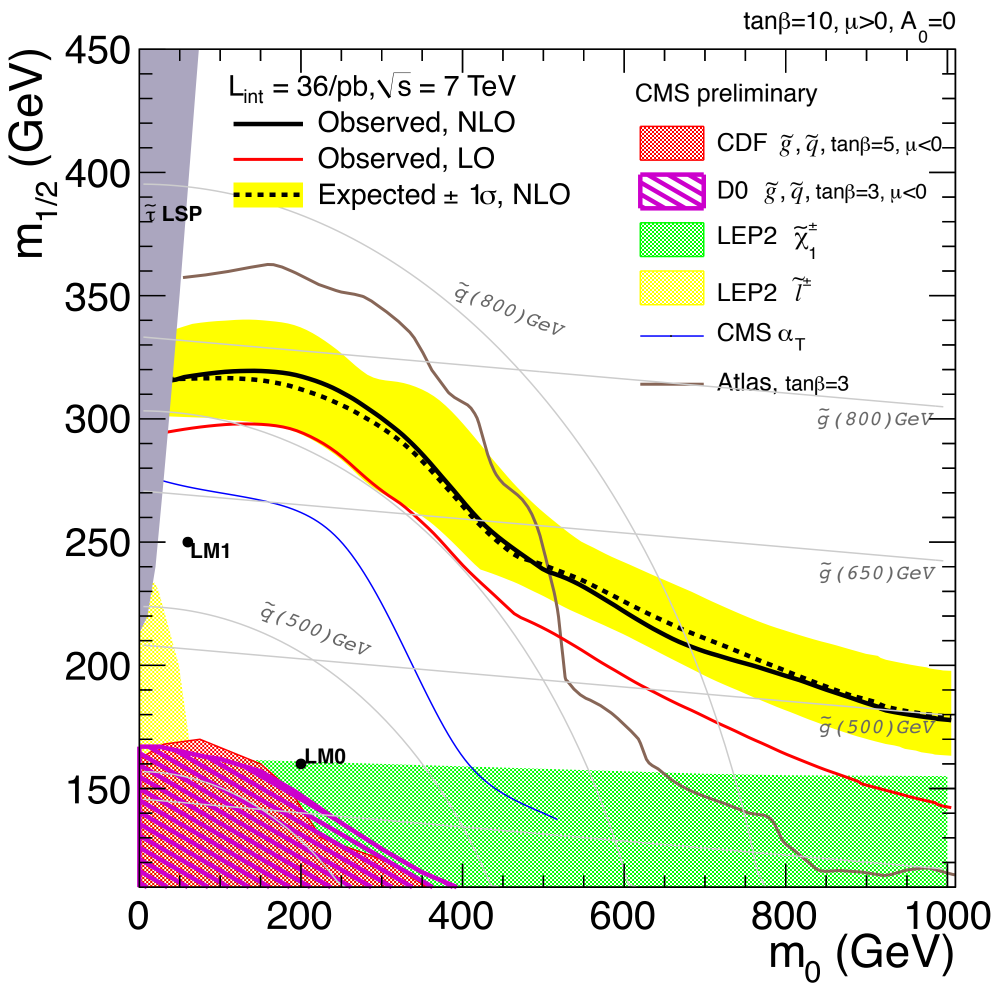
Strength: large statistics and clean at high $E_T$

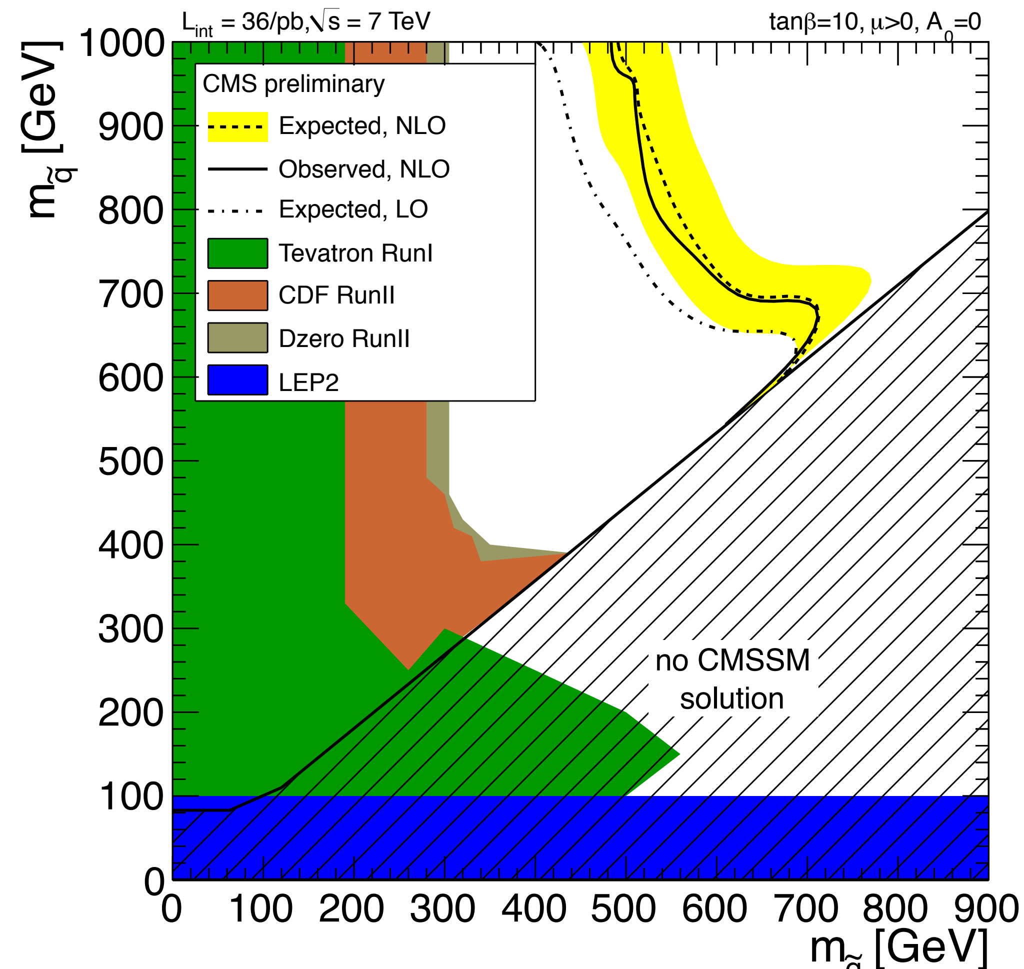
Weakness: background at low $E_T$, theoretical errors

# Hadronic search with missing energy

| | Predicted | Observed |
|---|---|---|
| MHT > 250 GeV | 18.8 ± 3.5 | 15 |

| | Predicted | Observed |
|---|---|---|
| $H_T$ > 500 GeV | 43.9 ± 8.8 | 40 |




- Results expressed in terms of 95% C.L. in CMSSM
- Extends limit from $\alpha_T$ search and Tevatron

CMS-SUS-10-005

# Hadronic search with "Razor"

arXiv:1006.2727

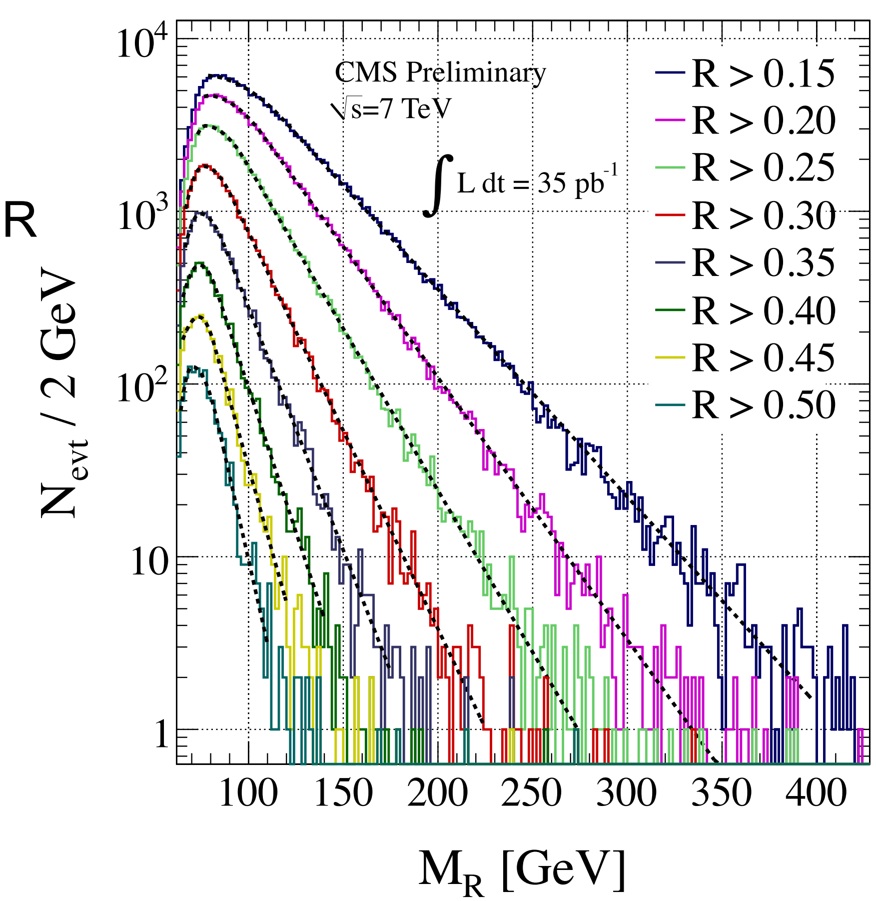
- Introducing the "Razor" variables: $M_R$ and R
  - Designed to characterise pair-production of heavy particles
  - Combine all particles into two hemispheres and boost back to rest frame

  - $M_R$ is a measure of the mass and peaks at the scale of the production

$$M_R \sim \frac{M_{squark}-M_{\chi}}{M_{squark}}$$

  - $M_R^T$ averaged transverse mass with endpoint $M_R$
  - R then the ratio $M_R/M_R^T$

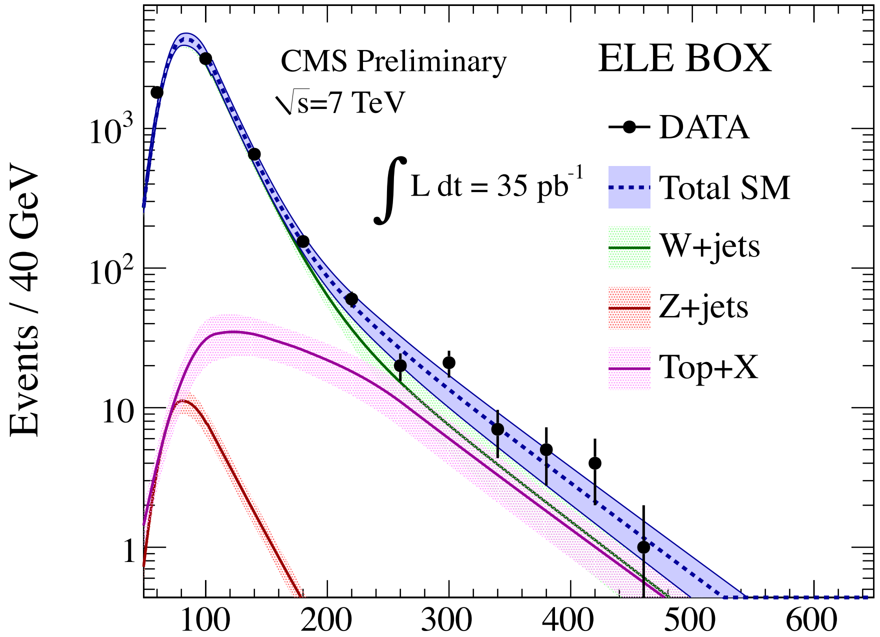
- $M_R$ distribution after R cut shows exponential scaling behaviour ➔

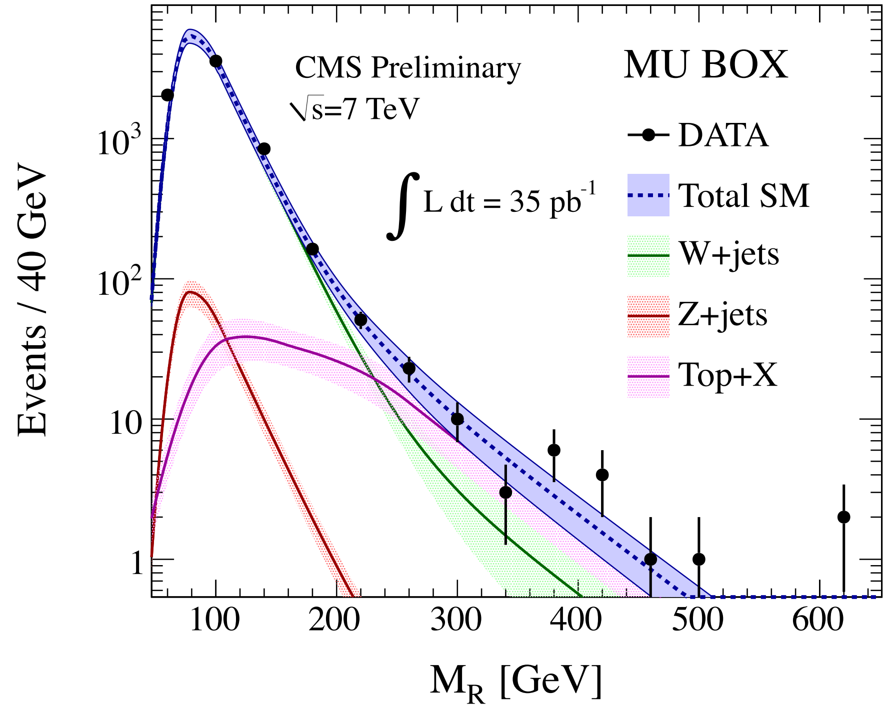



CMS-SUS-10-009

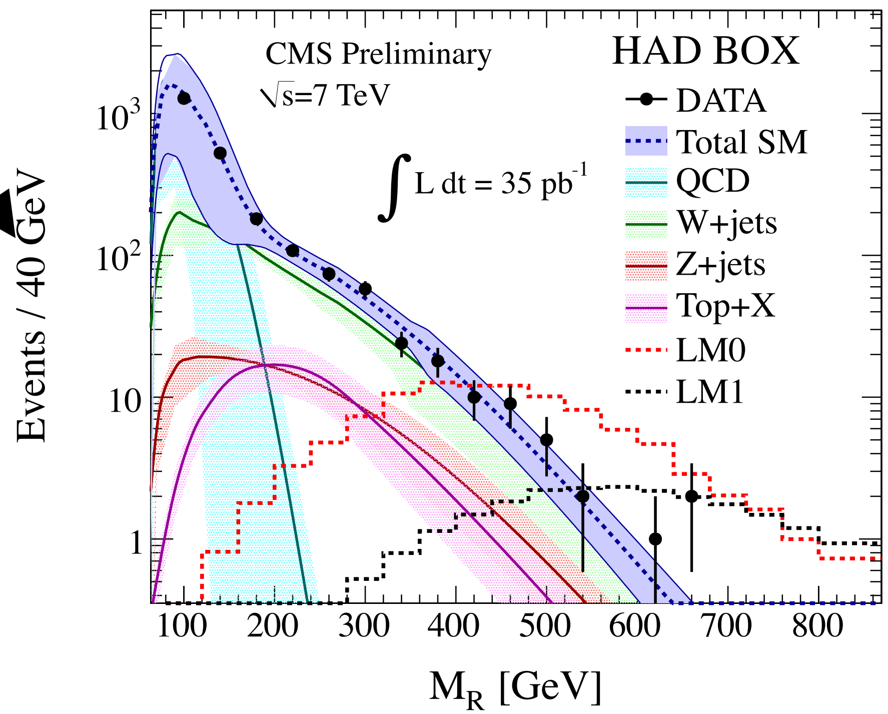
# Background estimation

- Exponential scaling property in $M_R$ used for background estimation




Use electron, muon and low $M_R$ hadronic control samples to predict background in hadronic signal region

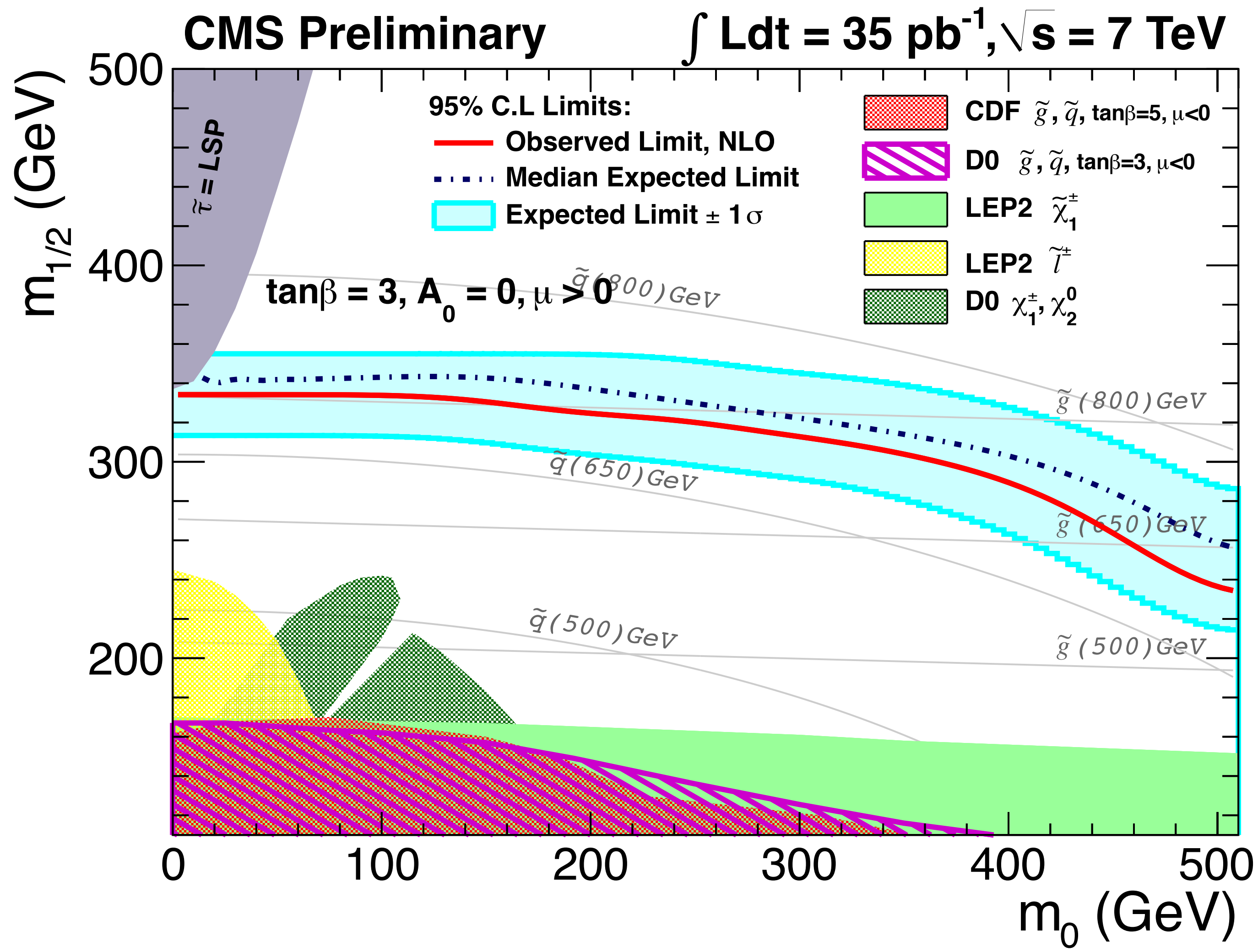



Only low $M_R$ regions used to determine backgrounds. Higher $M_R$ regions in e/μ control boxes are also searches

# Hadronic search with “Razor”

CMS-SUS-10-009

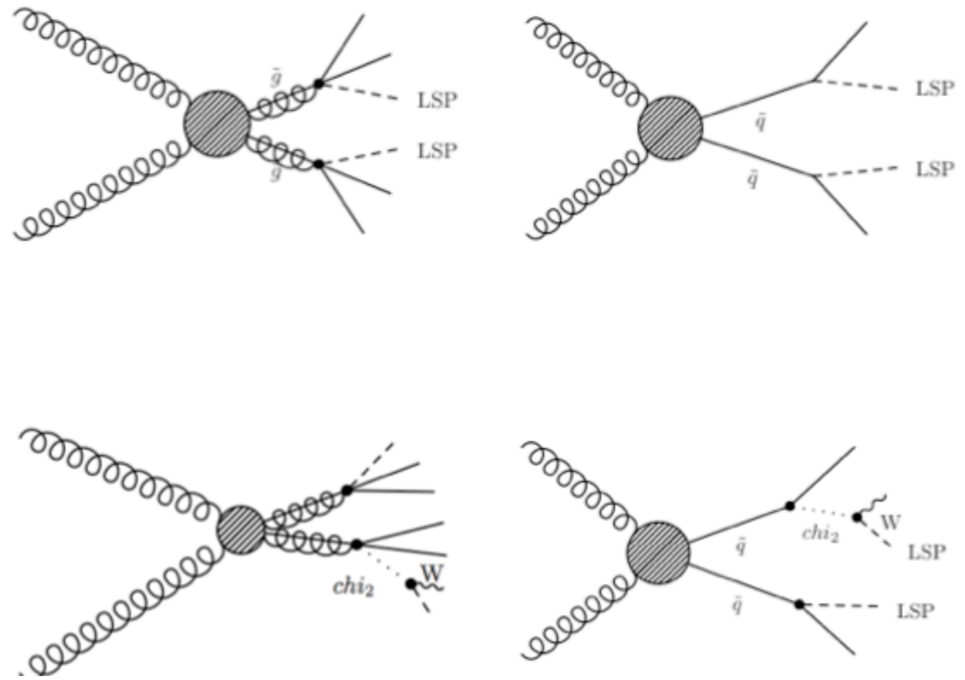
| R>0.5 | Predicted | Observed |
|---|---|---|
| MR>500 GeV | 5.5 ± 1.4 | 7 |




- Similar limits to jets+MHT analysis
- Complementary use of kinematics instead of detailed detector understanding

# Interpretation Intermezzo

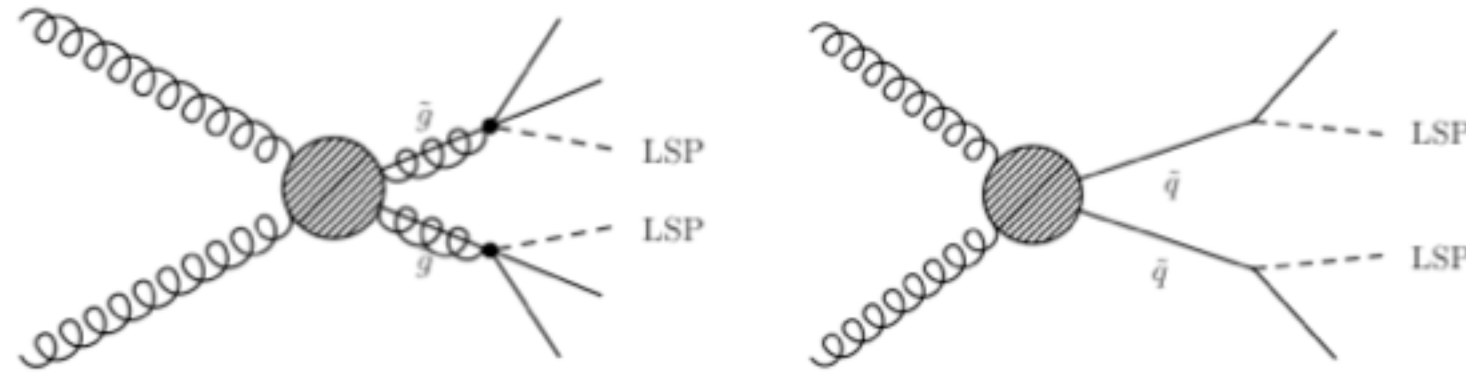
- Working with theorists in context of LPCC
  - Models proposed at: http://www.lhcnewphysics.org
  - Agreed on reference topologies for early searches
  - Cover what one might see in the first ~50 $pb^{-1}$
  - All initiated by strong production



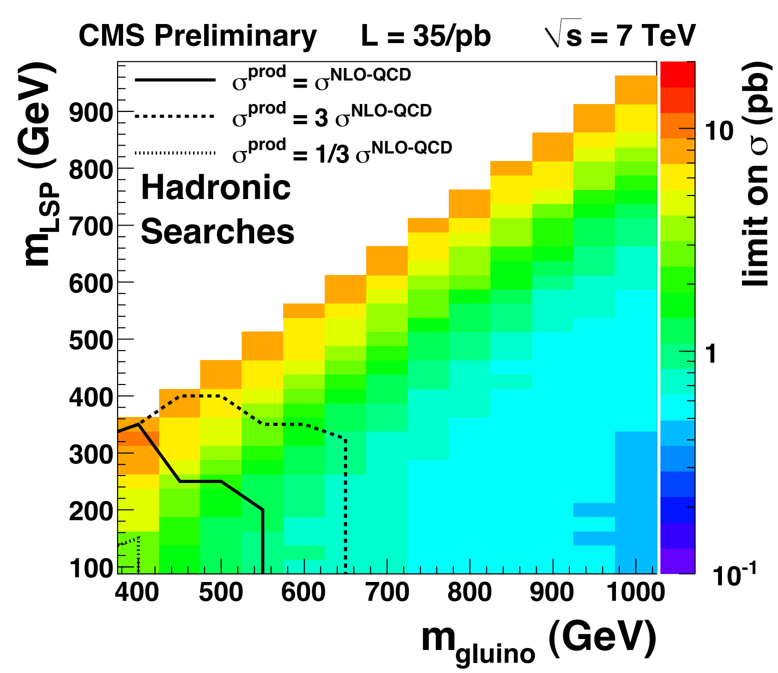

- Hadronic searches
  - Squark anti-squark pair production with decay squark → q + χ
  - Gluino pair production with decay gluino → qqbar + χ
  - χ can be the LSP or an intermediate state, decaying to W + LSP
  - Kinematics specified by masses
  - Direct case $m_{gluino}(m_{squark})$ vs $m_{LSP}$ 2D plot
  - For cascade decays (arbitrary) slices of intermediate particle
  - "Reference" cross sections given to illustrate limits

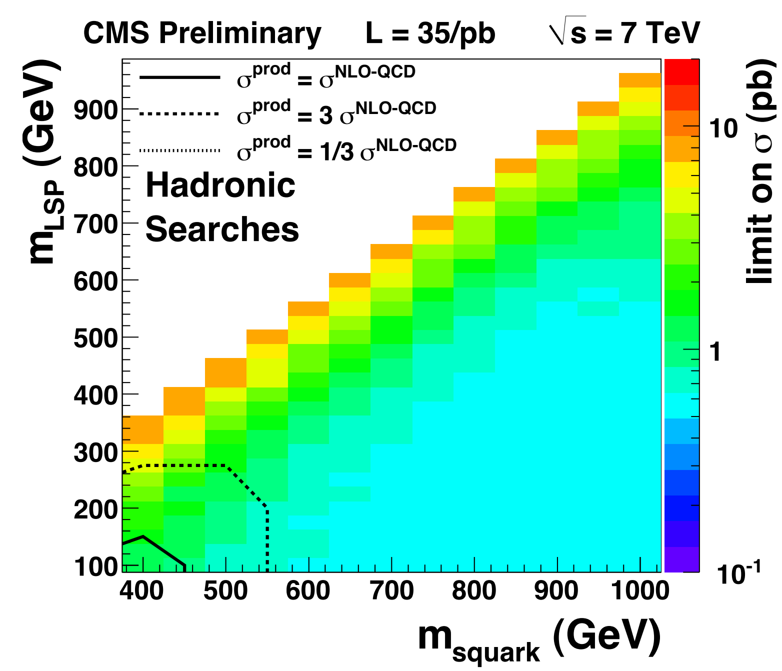
# Simplified Model Spectra

- So far considered squark and gluino pair-production topologies
- Limits are best of three hadronic searches (not a combination)
- Black lines are QCD-like cross sections
- Theoretical uncertainties like ISR simulation under studied
- Will provide all information that goes into this electronically




**Feedback welcome!**




Theoretical uncertainties not included

# Search in single lepton events

CMS-SUS-10-006

- Adding a lepton requirement to the hadronic searches changes the background composition significantly

- Baseline selection
  - Exactly one isolated electron or muon $p_T$>20 GeV
  - At least 4 jets $E_T$>30 GeV $|\eta|$<2.4

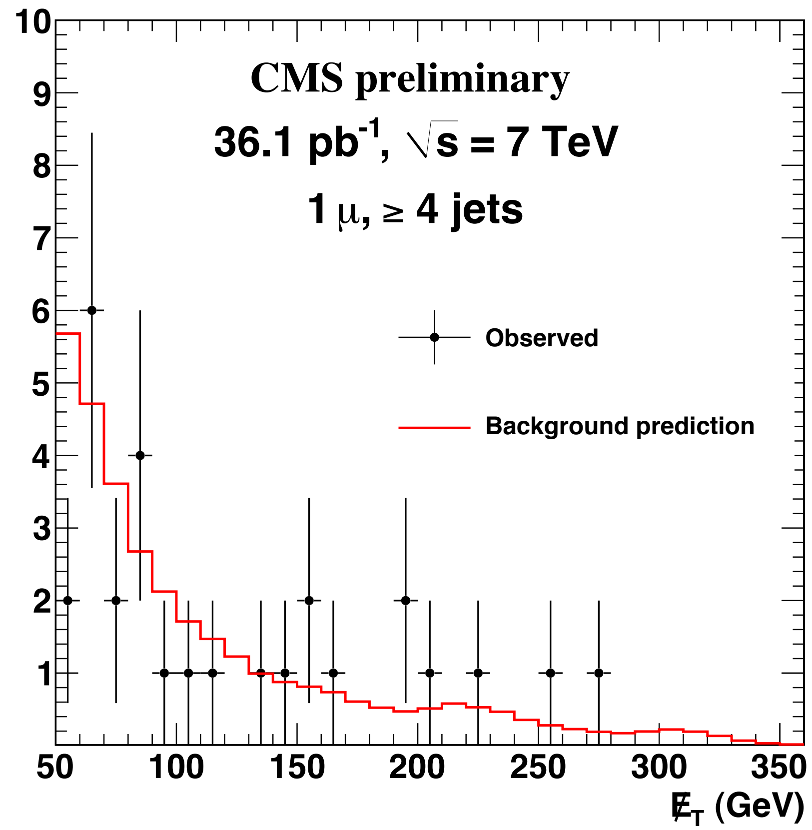
- Study selected events
  - Simulation predicts background from top and W+jets
  - General event properties well understood

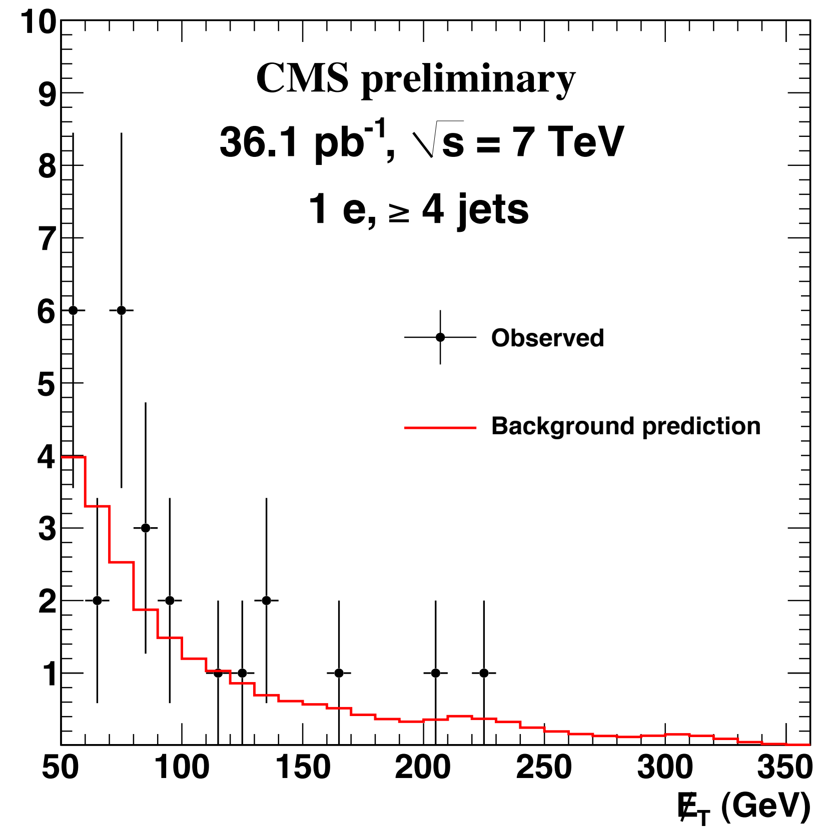
- Determine backgrounds from data ➔

# Background determination

Exploit the fact that for W decays the charged lepton and neutrino $p_T$ spectra are on average approximately the same

Use lepton $p_T$ spectra to predict MET



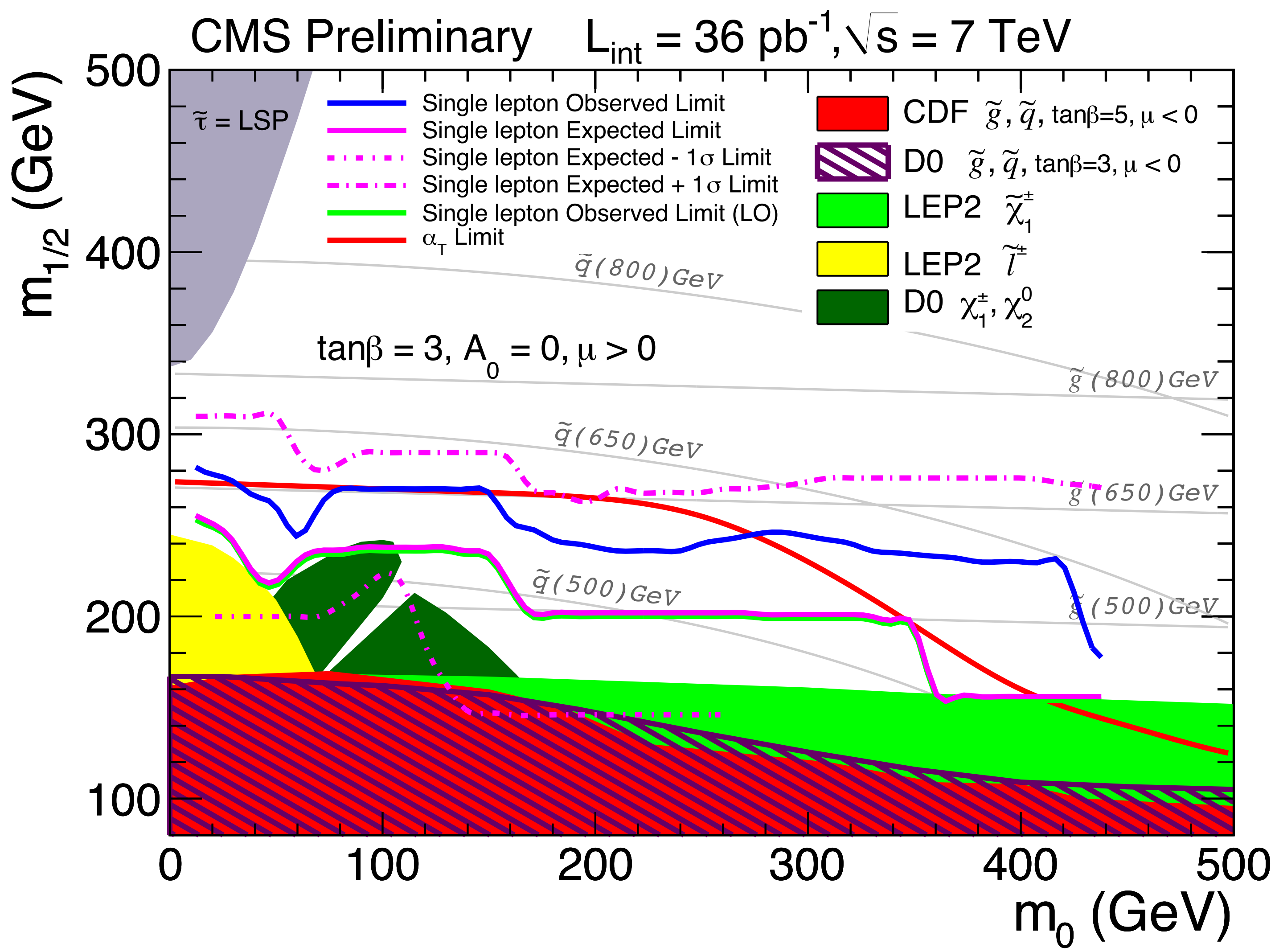

- Take muon $p_T$ spectrum (cleaner than electron)
- Correct for acceptance, efficiency and polarisation effects
- MET resolution worse than for e/μ ➔ measure in data and smear
- Powerful technique based on fundamental physics
- Other techniques for smaller backgrounds (ttbar to dileptons, QCD etc.)
- All backgrounds also determined using ABCD/matrix method (described later)

# Results and interpretation

Final selection:

MET > 250 GeV $H_T$ > 500 GeV

| Sample | $\ell = \mu$ | $\ell = e$ |
|---|---|---|
| Predicted SM 1 $\ell$ | $1.7 \pm 1.4$ | $1.2 \pm 1.0$ |
| Predicted SM dilepton | $0.0^{+0.8}_{-0.0}$ | $0.0^{+0.6}_{-0.0}$ |
| Predicted single $\tau$ | $0.29 \pm 0.22$ | $0.32^{+0.38}_{-0.32}$ |
| Predicted QCD background | $0.09 \pm 0.09$ | $0.0^{+0.16}_{-0.0}$ |
| Total predicted SM | $2.1 \pm 1.5$ | $1.5 \pm 1.2$ |
| Observed signal region | 2 | 0 |




- Limit similar to hadronic $\alpha_T$ search in CMSSM

# Opposite-sign dilepton search

arxiv:1103.1348

- Adding a second lepton rejects W+jets leaving mostly top background

- Baseline selection
  - Two isolated leptons (e or μ); one with $p_T$>20 GeV, other with $p_T$>10 GeV
  - Veto same-flavour pairs in Z mass window and $m_{ll}$<10 GeV
  - At least 2 jets with $p_T$>30 and $|\eta|$<2.5

- Study selected events
  - Simulation predicts background from top
  - General event properties well understood

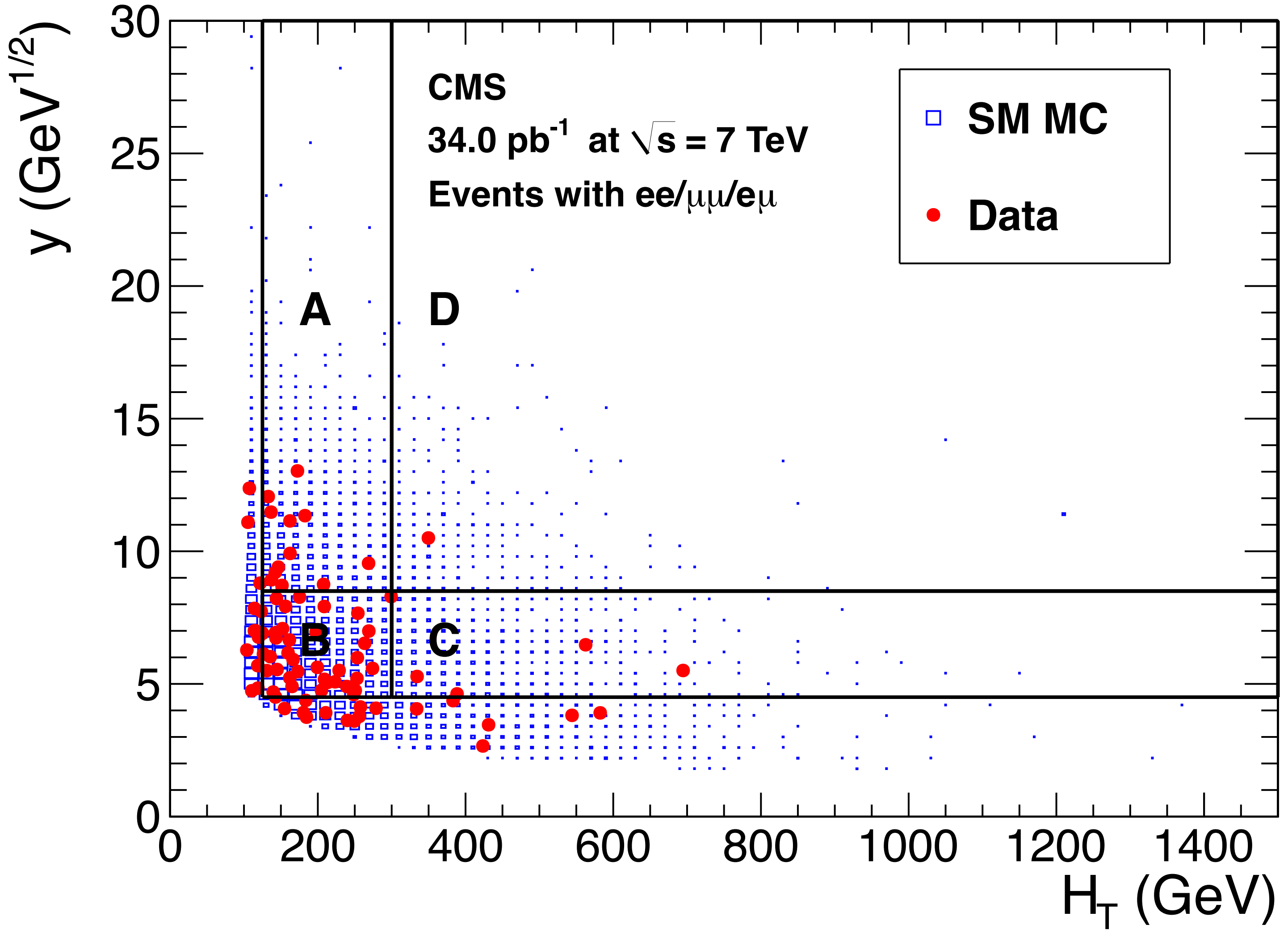
- Determine backgrounds from data →

# Top background from ABCD

- Exploit the observation that $H_T$ and $y=MET/\sqrt{H_T}$ are almost uncorrelated

- Define signal region:
  - $H_T > 300$ GeV
  - $y > 8.5\ \sqrt{\text{GeV}}$

- Use ABCD/matrix method to determine background

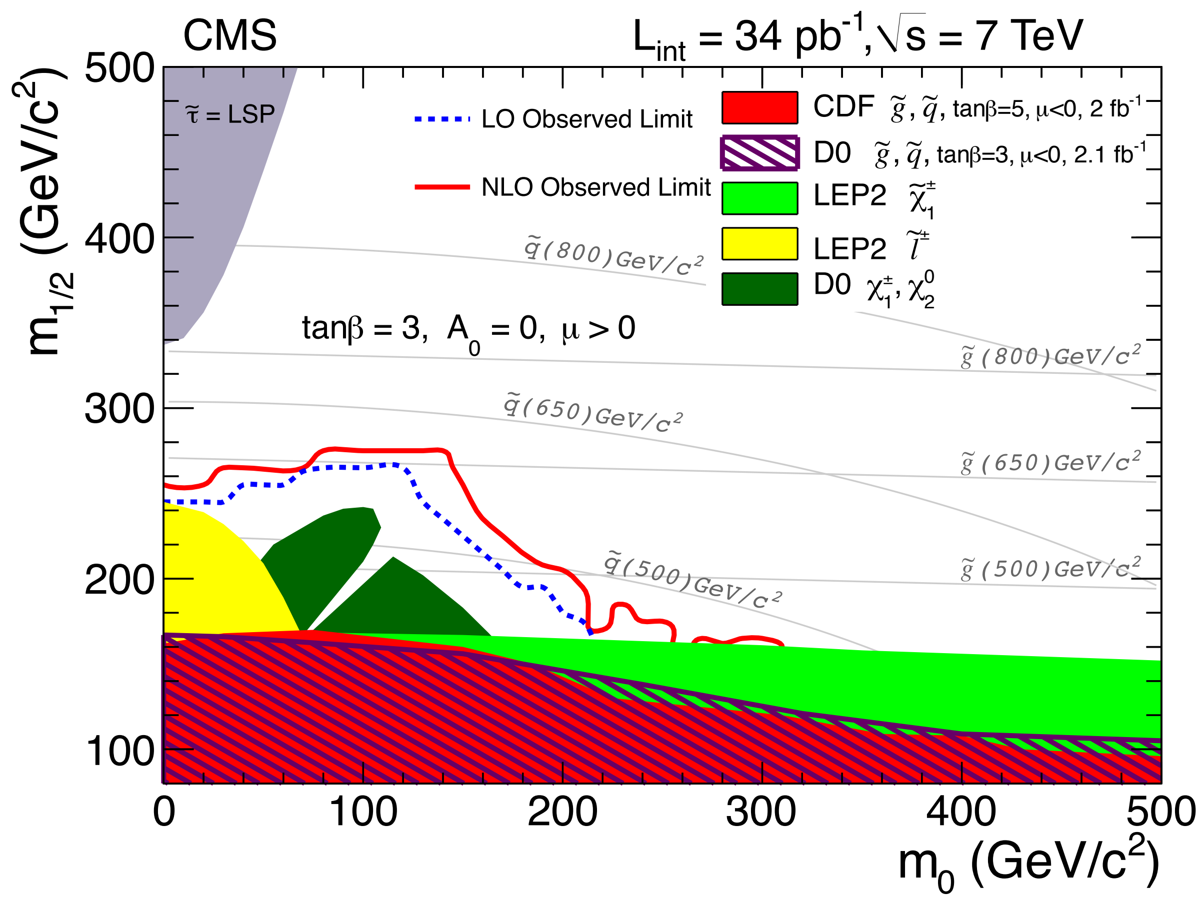



- Also use lepton $p_T$ spectrum method described earlier

# Opposite-sign dilepton result

arxiv:1103.1348

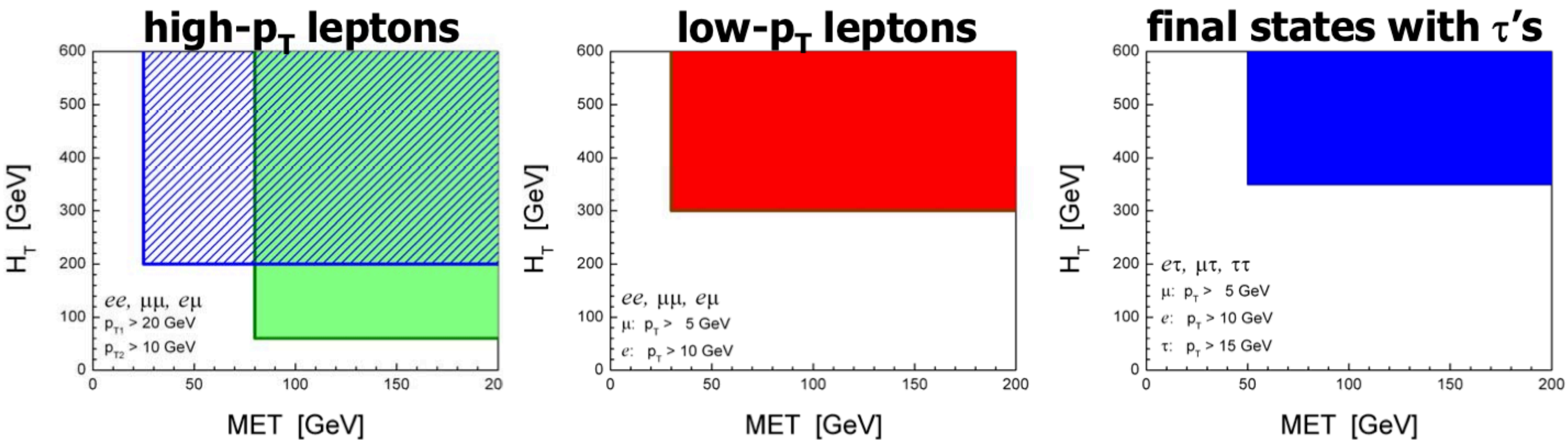
| | Predicted | Observed |
|---|---|---|
| Region D | 1.3 ± 0.8 | 1 |




- Limit in CMSSM beyond previous Tevatron searches
- Also result from opposite-sign opposite-flavour subtraction
  - Observed in data: ee:0 μμ:0  Predicted background: ee: $0.1^{+1}_{-0.4}$ μμ: $0.5^{+1.2}_{-0.4}$
  - Powerful technique to obtain mass edge in the case of SUSY

# Same-sign dilepton search

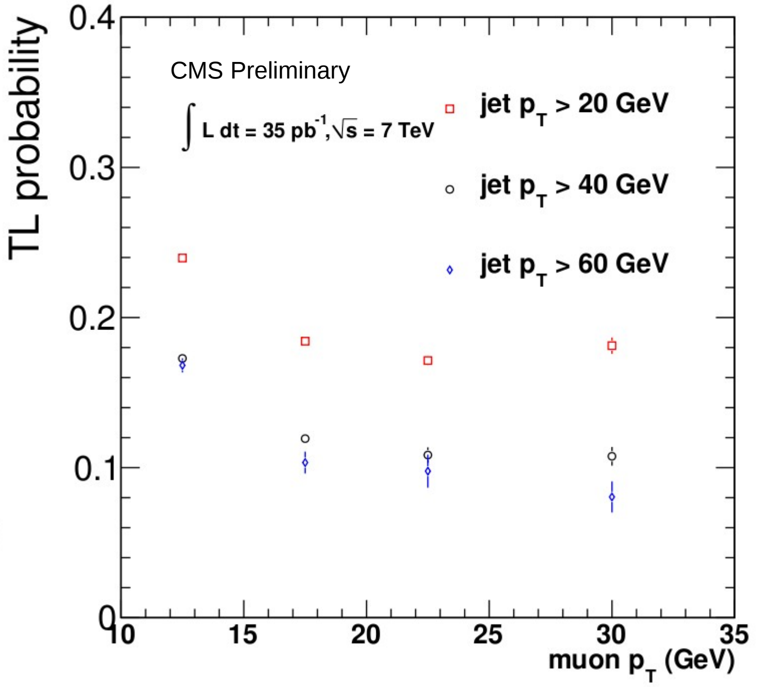
- Isolated same-sign lepton signature essentially absent in the Standard Model
- Search in all three lepton species and four search regions

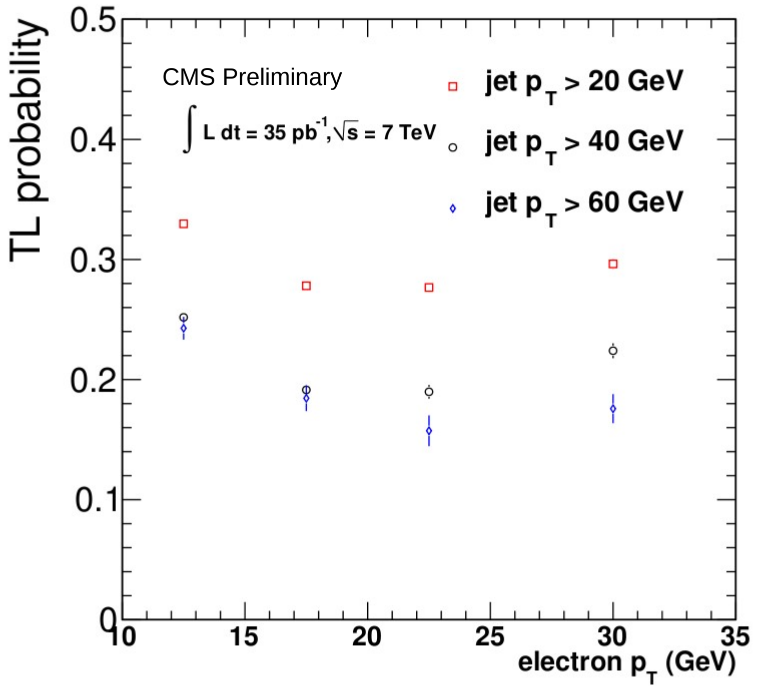



- Dominant backgrounds
  - ttbar: one isolated lepton from W, one from semi-lep b/c decay in jet
  - QCD: larger for hadronic τ final states

# Background from ttbar

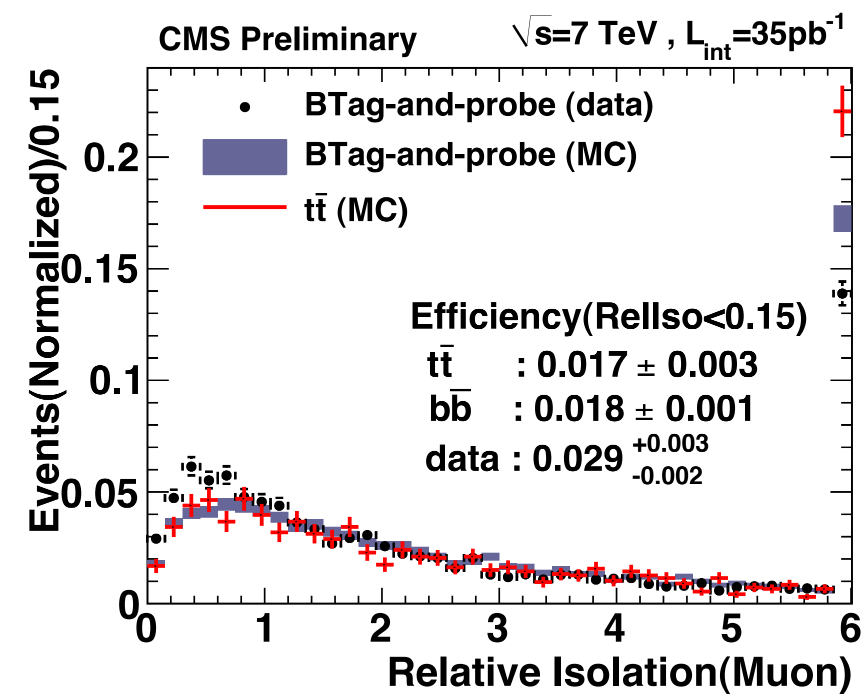
- Measure background from b/c ➔ e/μ in two slightly different ways
  - Tight to Loose lepton ID probability from multi-jet sample
  - Apply measured probability to side-band sample with loose lepton ID to predict background with tight lepton ID
  - Uncertainty from jet kinematics ~50%

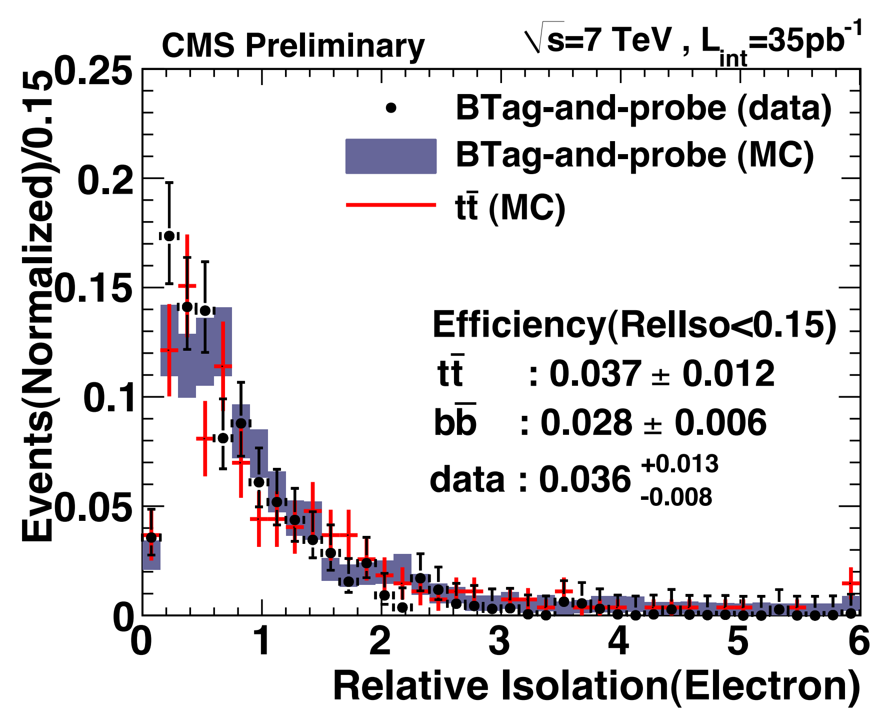


# Background from ttbar

- Measure background from b/c ➔ e/μ in two different ways
  - Use tag and probe in bbbar (QCD) events to measure isolation efficiency
  - Reweight this distribution to that of ttbar using simulation
  - Use this isolation efficiency to determine background

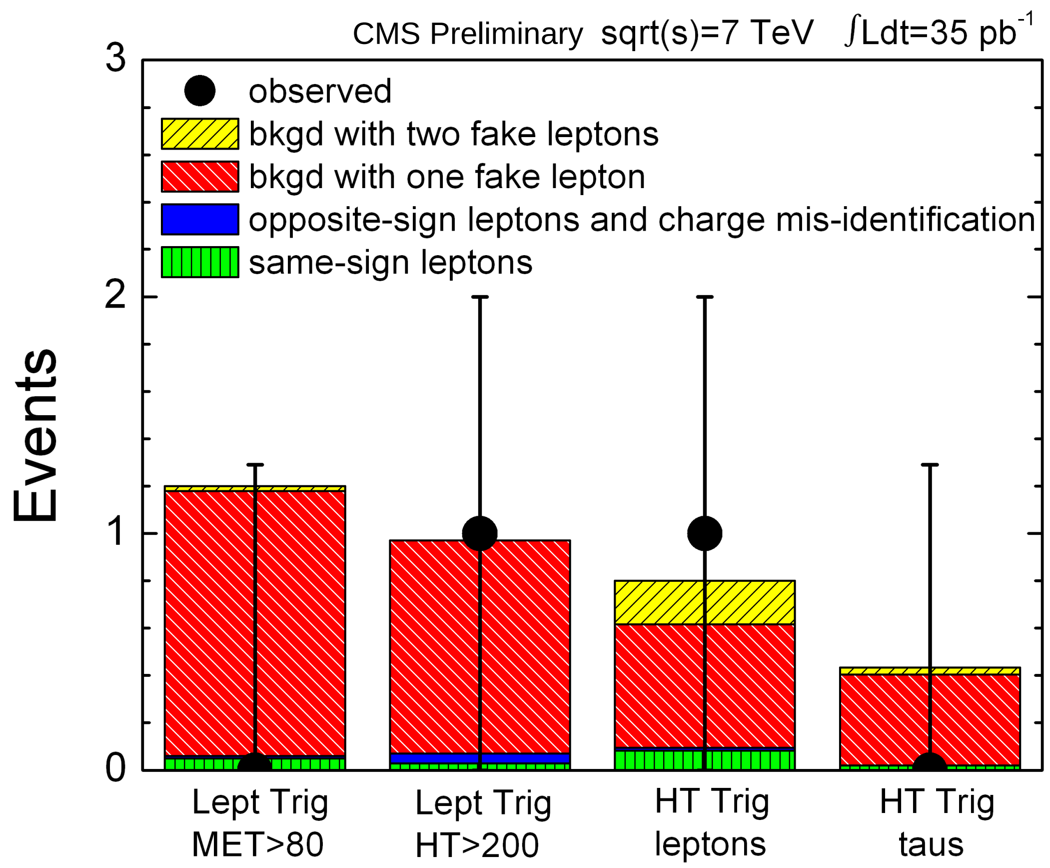


# Hadronic τ channels

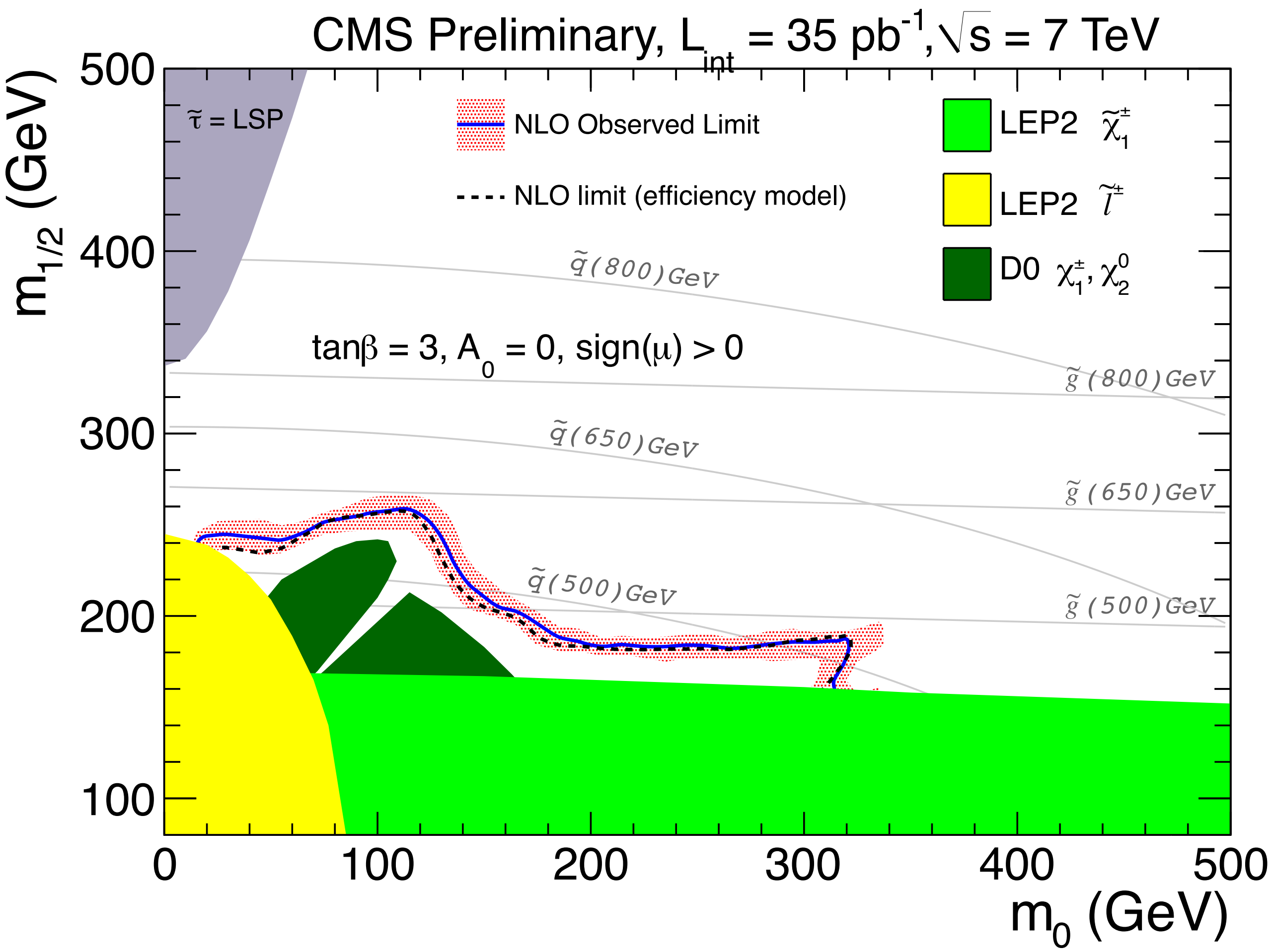
- Include hadronic τ channels e-τ, μ-τ and τ-τ
  - Increased background from QCD jets faking hadronic τ
  - Use similar tight to loose probability

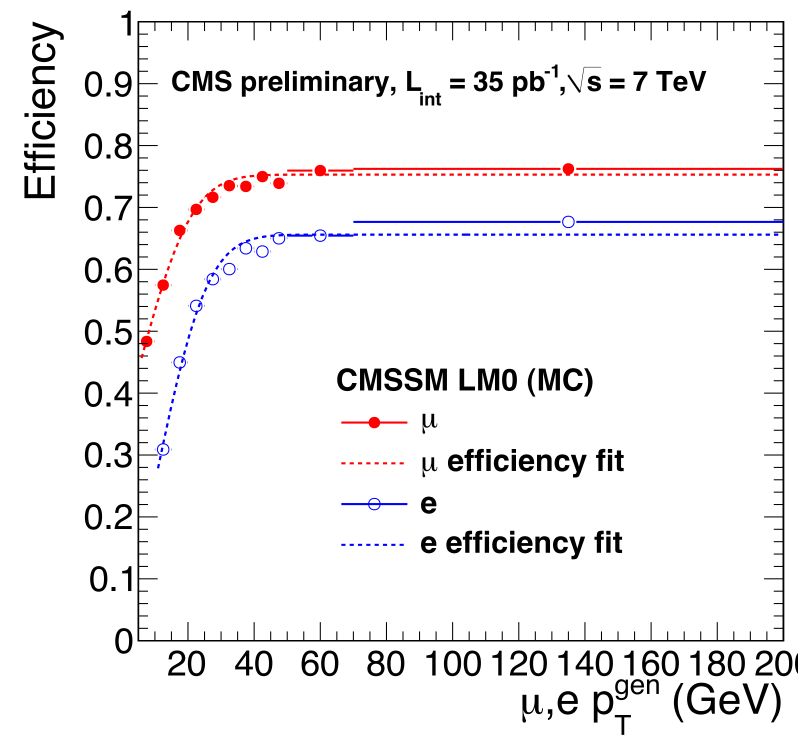
- Final background estimates:
  - No sign of new physics ➔
  - Set limits….



# Same-sign dilepton search

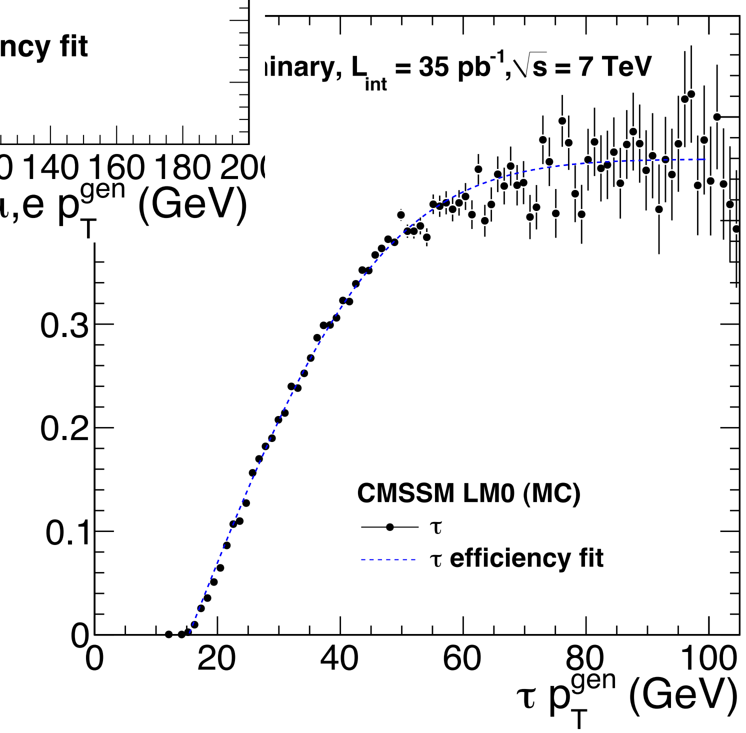
CMS-SUS-10-004




Parameterised efficiencies for e, μ and τ

Resolutions for MET, $H_T$



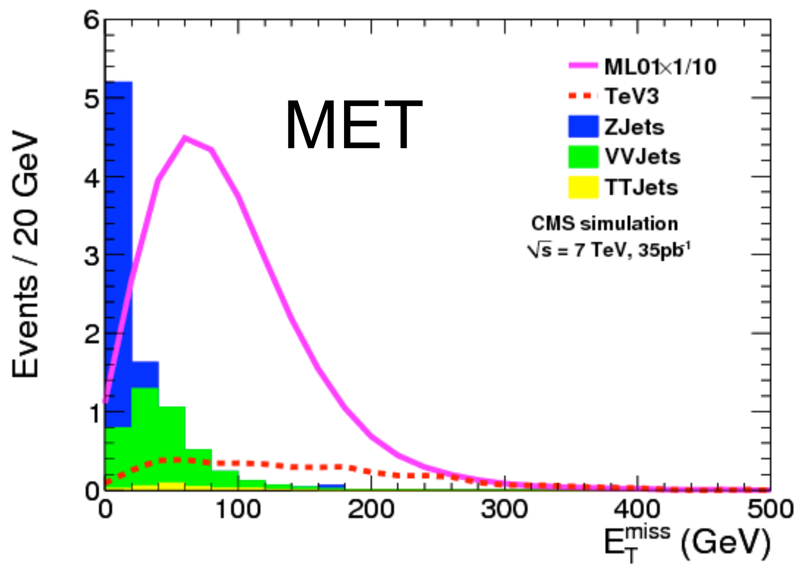

- Limit in CMSSM
  - Also provide information on efficiencies for model builders
  - Test this ourselves and reproduce our limit well (dashed line)

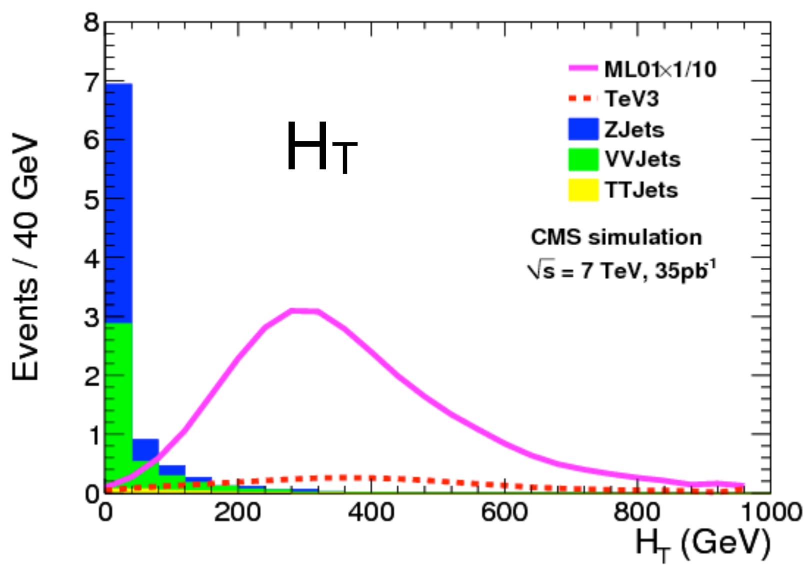
# Multi-lepton search

CMS-SUS-10-008

- Search in events with at least three isolated leptons
  - Backgrounds suppressed drastically
  - More inclusive search ➔ wide phase space
- Baseline
  - At least three leptons (e,μ,τ) with $p_T$ thresholds from 8 GeV
  - Require one non-τ lepton (trigger)
- Two final selections
  - MET > 50 GeV
  - $H_T$ > 200 GeV

MET and $H_T$ both suppress background effectively, but probe complementary SUSY phase space

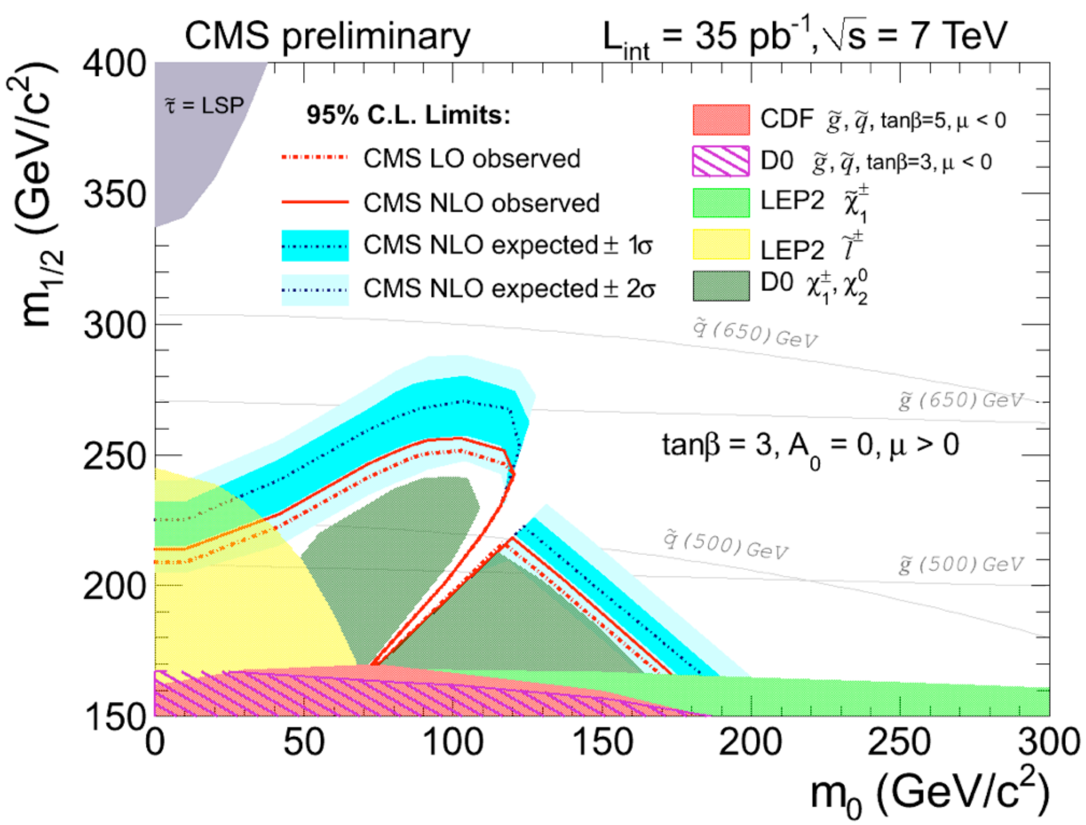


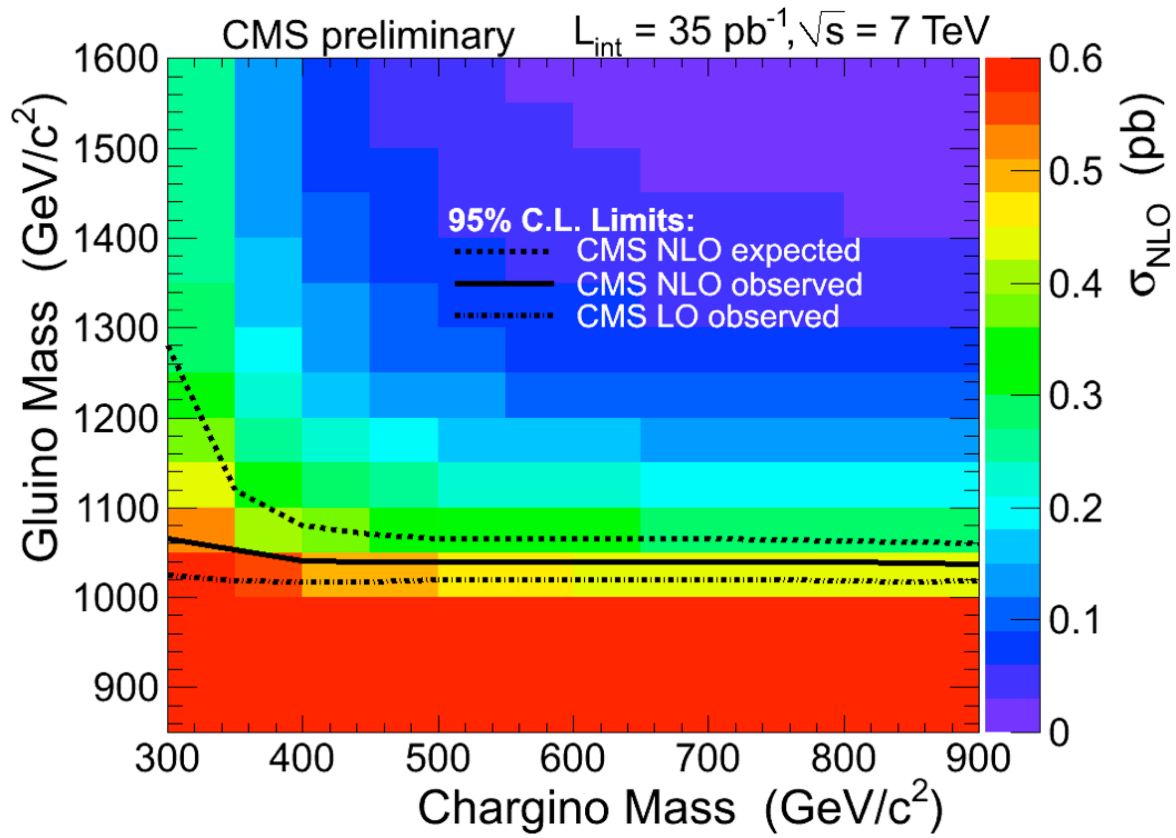



# Multi-lepton analysis

- Backgrounds:
  - Irreducible: WZ+Jets, ZZ+Jets - estimated from simulation
  - ttbar - simulation
  - Z+Jets, WW+Jets, W+Jets, QCD - data-driven using fake rate
- Analysis based on combination 55 exclusive channels
  - Opposite-sign/same-sign/Z peak/off peak/MET/$H_T$….
  - Channels combined statistically to give final result
  - No excess observed (but some beautifully events)

# Multi-lepton search




- Set limits in CMSSM for comparison with previous expts.
- Also consider more phenomenological interpretation in GGM model
- Multi-lepton signatures also arise naturally in co-NLSP model with mass degenerate sleptons decaying to leptons and Gravitino

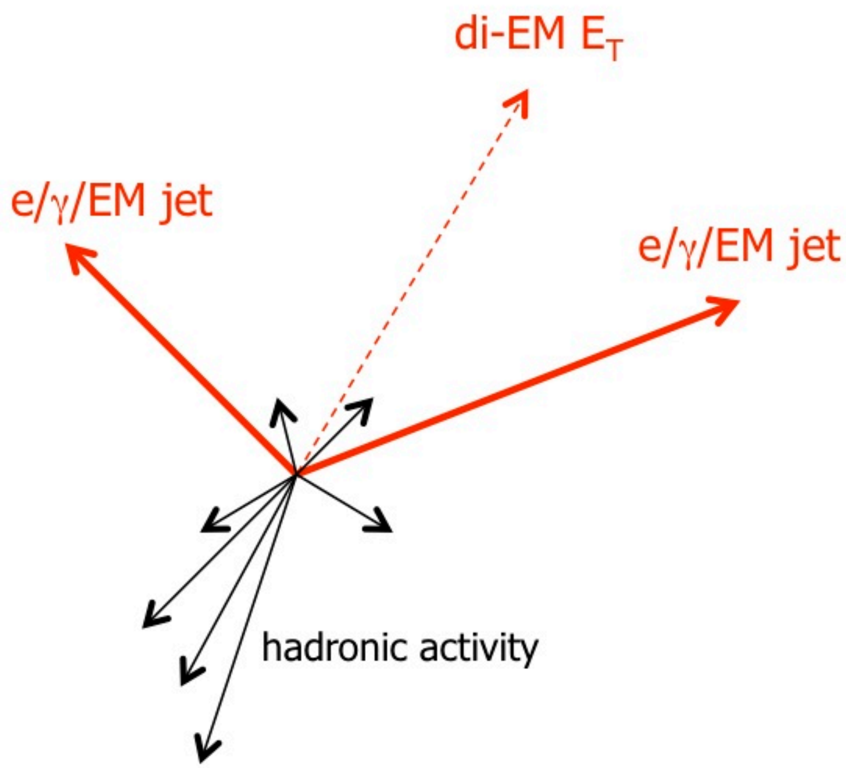
# Searches with photons

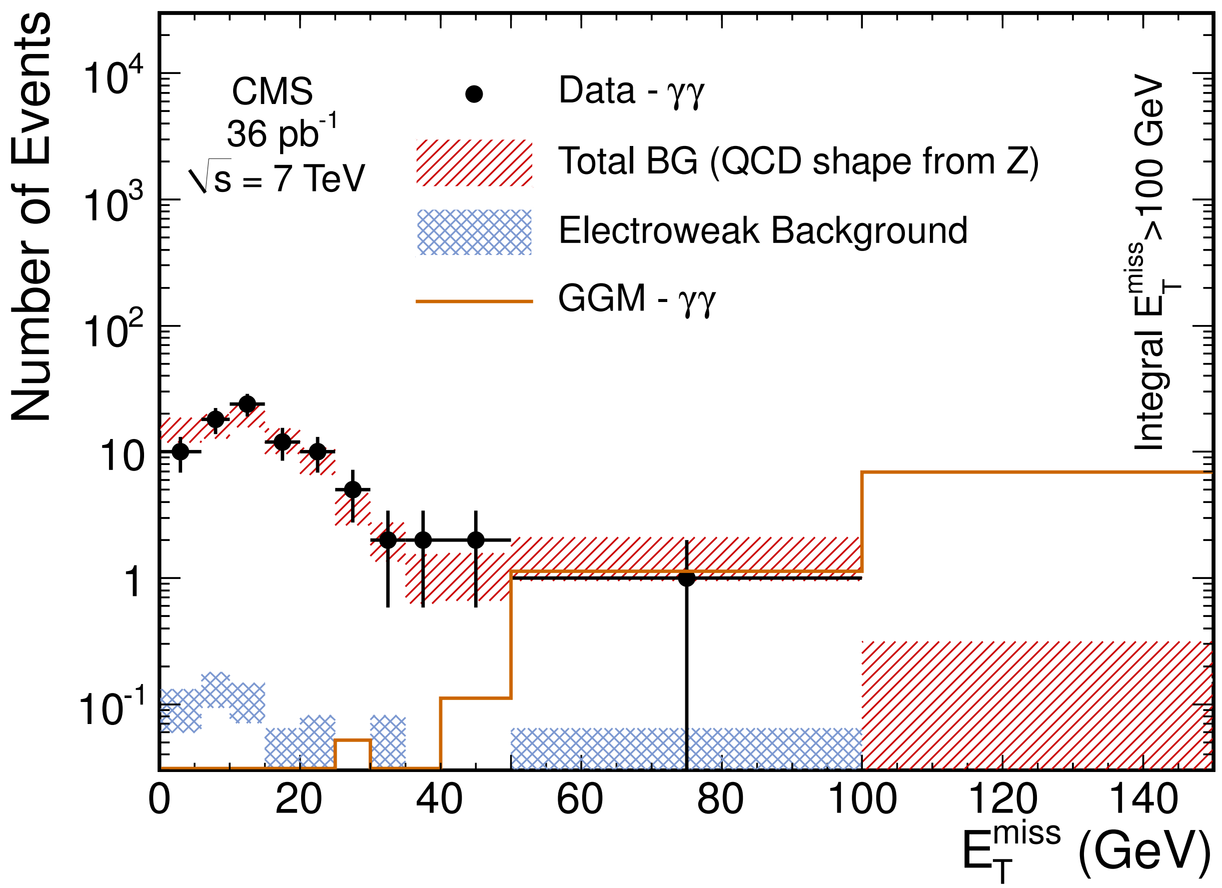
arxiv:1103.0953

- Pre-selection
  - Trigger: single photon $P_{T\gamma}$ > 30 GeV
  - Require two photons with $P_{T\gamma}$ > 30 GeV and $|\eta_\gamma| < 1.4$
  - Shower shape ID cuts and H/E veto (<5%)

  - Distinguish electrons and photons by track in pixel detector
  - At least one jet $E_T$>30 GeV (cleans up beam and cosmic backgrounds)
- Define two control samples for background estimation
  - fake-fake - fail track isolation or shower shape
  - $Z \rightarrow e^+e^-$ - two electrons and Z mass window cut (90 ± 20 GeV)

# QCD backgrounds

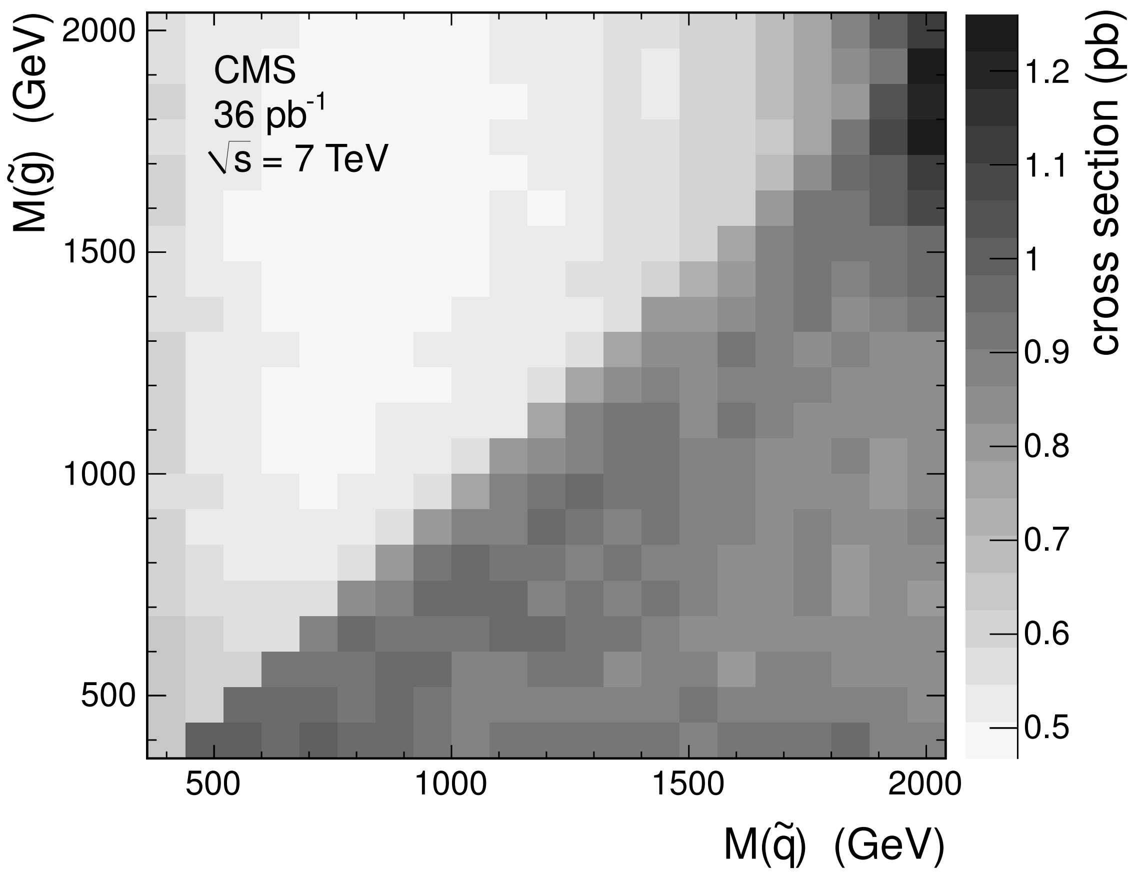


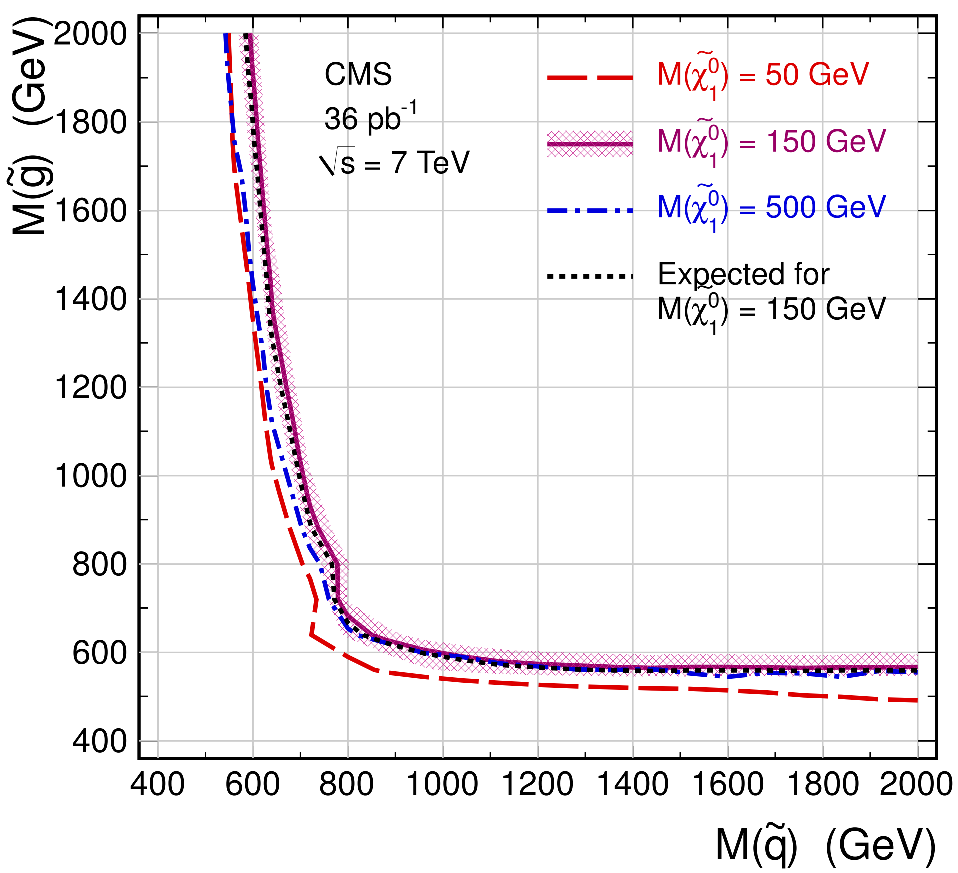




- EM objects better measured than hadronic objects
- MET dominated by hadronic resolution
- Reweight control samples to signal γγ $E_T$ spectrum
- Normalise at low MET (<20 GeV)

# Diphoton search

- Observe 1 event MET >50 GeV consistent with 1.2 ± 0.8 background



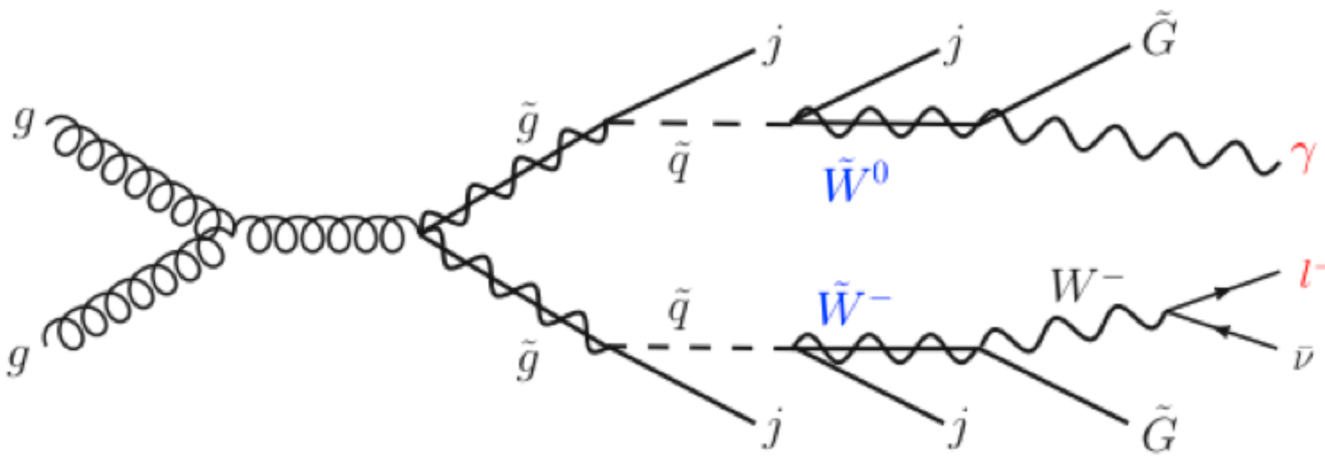




- Consider GGM model with neutralino (bino), gluino, and squark decaying to jets + two photons + two Gravitinos
- 95% CL upper limit this simple model for neutralino mass = 150 GeV
- Upper limits between 0.5 and 1.1 pb depending on masses
- Beyond previous experiments

# Lepton + photon search

CMS-SUS-11-002

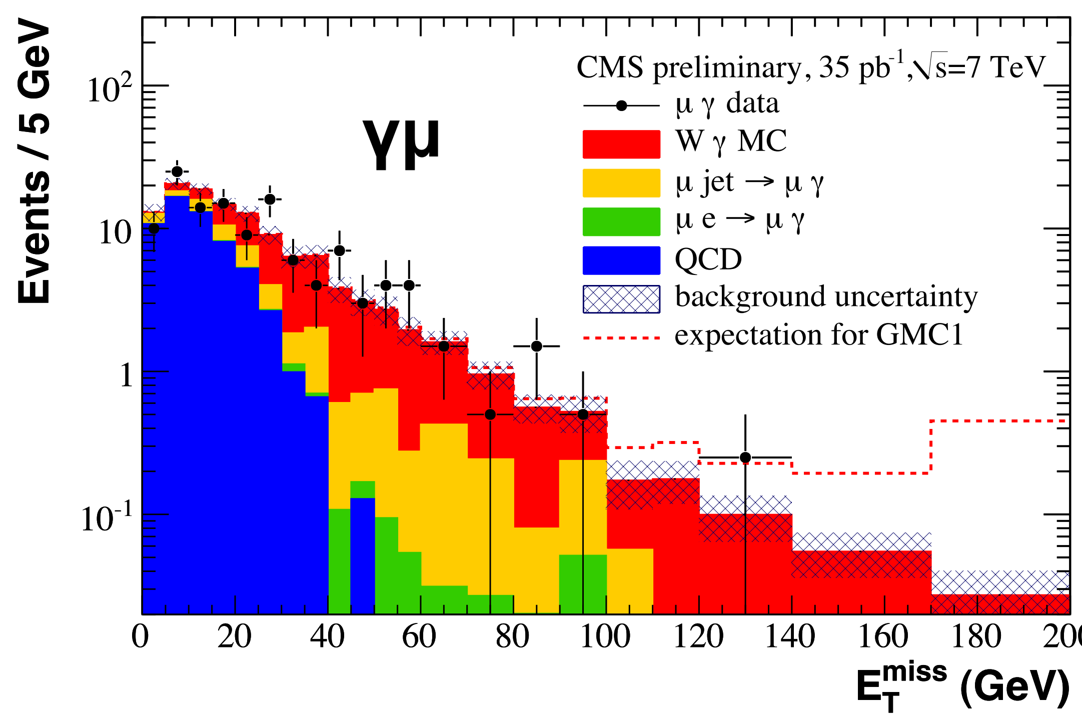
If wino and bino are mass degenerate NLSPs then di-photon signature replaced by lepton+photon signature.

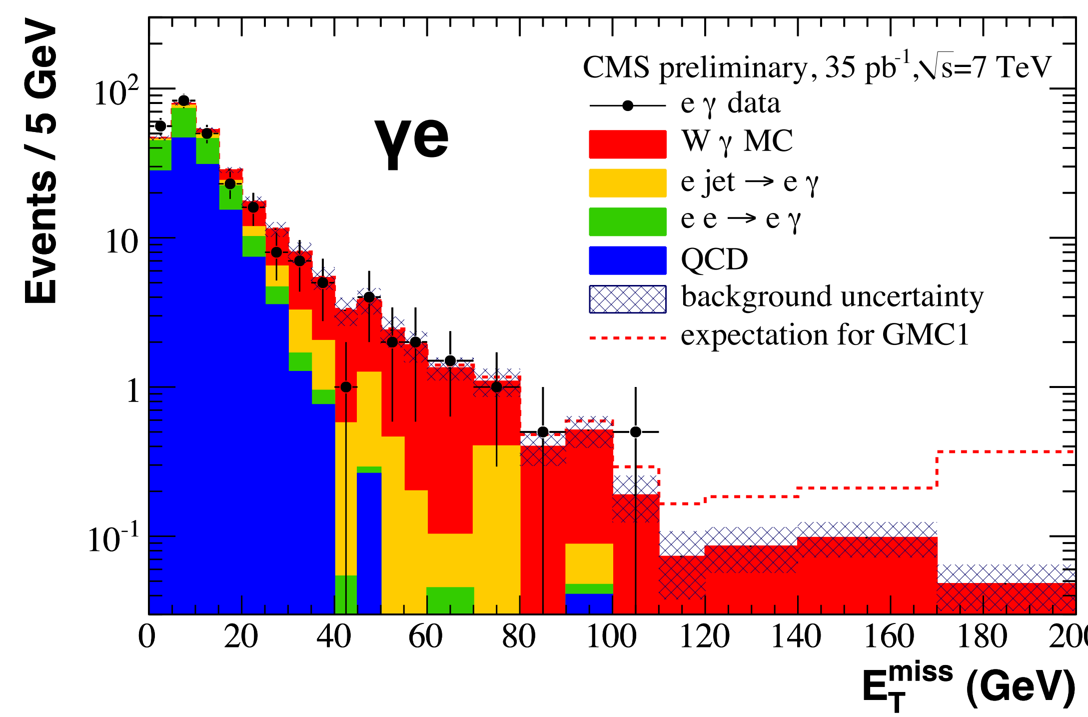


- Baseline selection
  - Isolated lepton (e or μ) with $p_T$>20 GeV
  - Isolated photon with $p_T$>30 GeV

- Dominant background is Wγ
  - Cross section measured by CMS [CMS EWK-10-008]
  - Taken from simulation

# Lepton + photon search



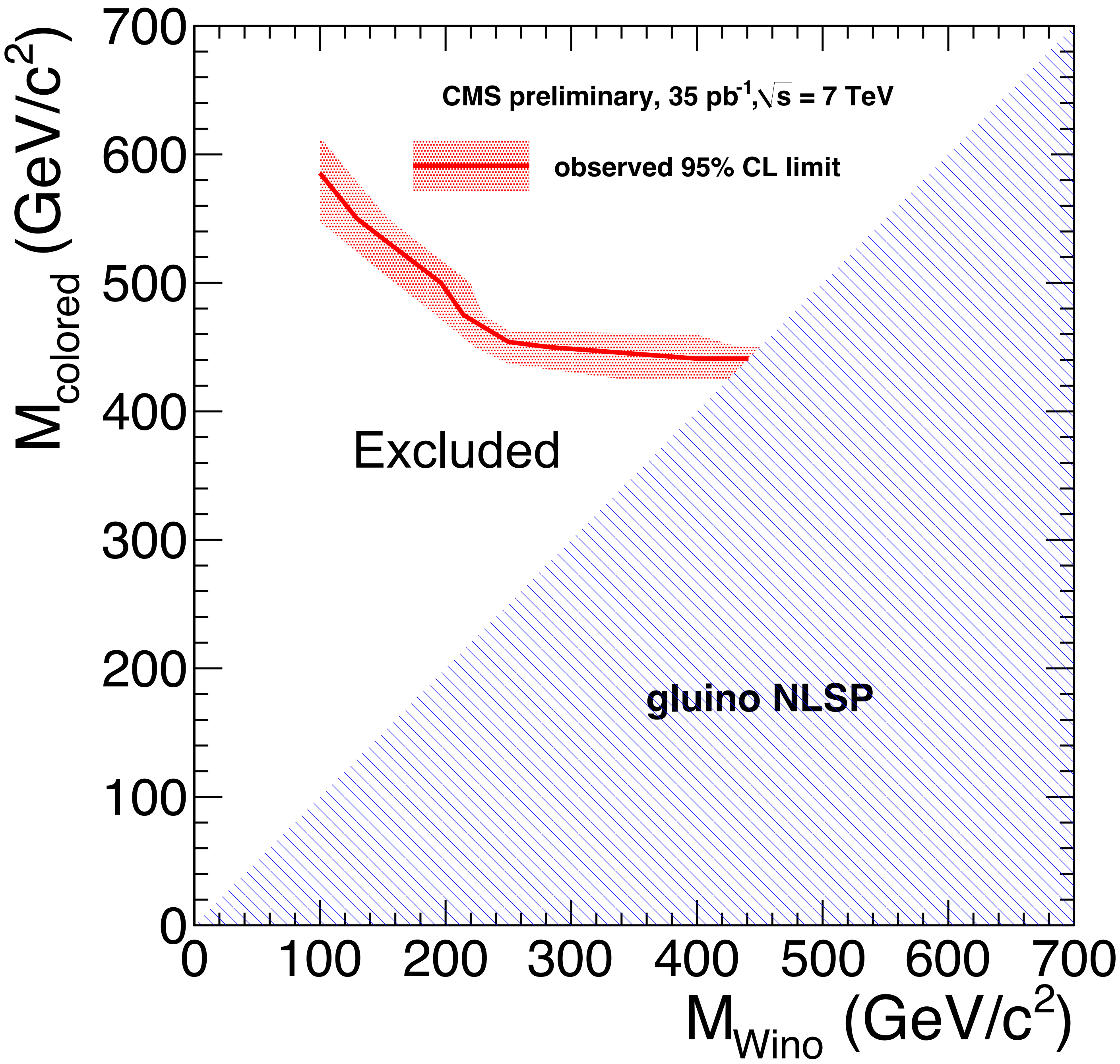




| | Predicted | Observed |
|---|---|---|
| MET > 40 GeV | 20.1 ± 3.7 | 27 |
| MET > 100 GeV | 1.59 ± 0.39 | 1 |

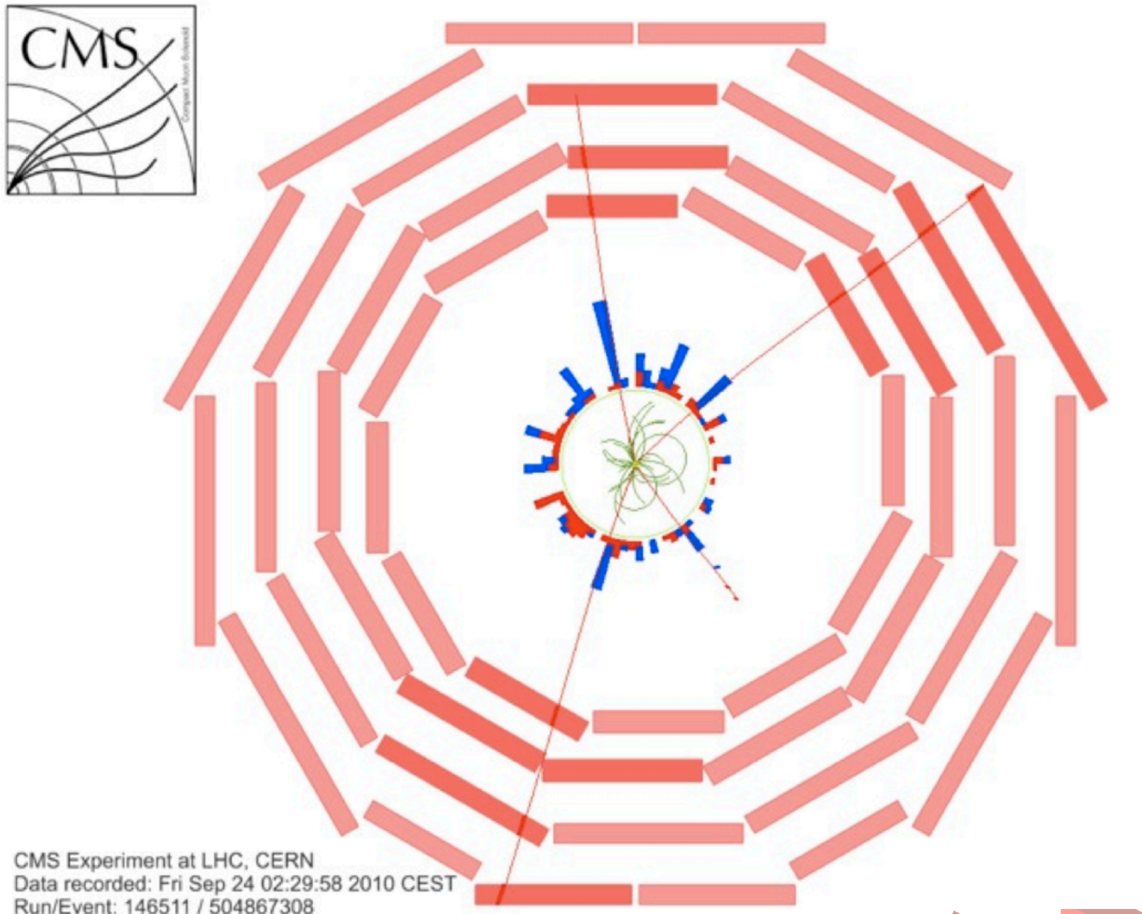
| | Predicted | Observed |
|---|---|---|
| MET > 40 GeV | 19.9 ± 3.7 | 16 |
| MET > 100 GeV | 1.74 ± 0.43 | 1 |

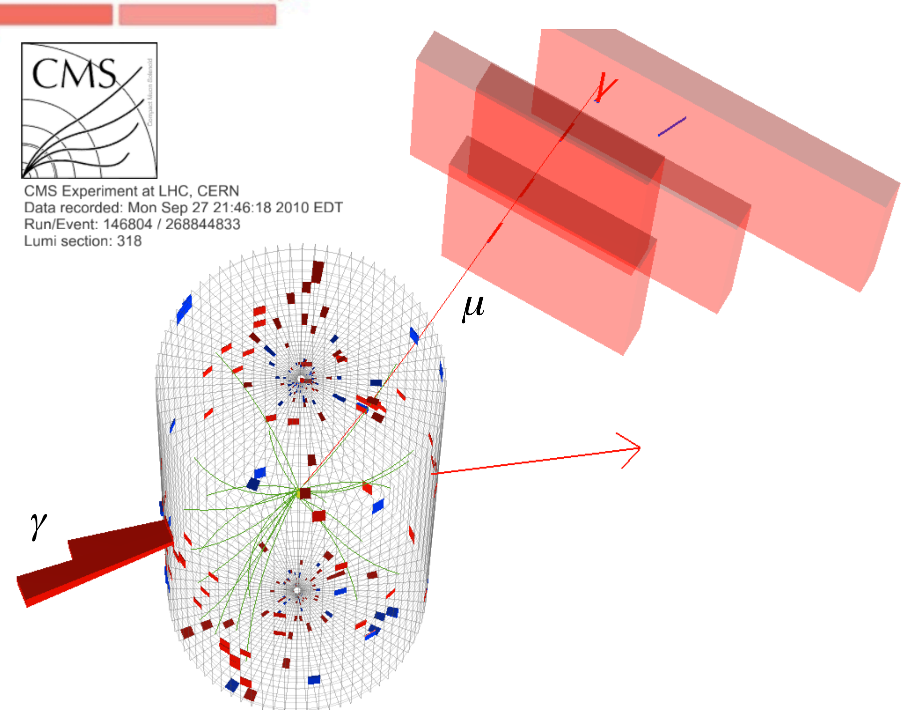
# Lepton + photon search

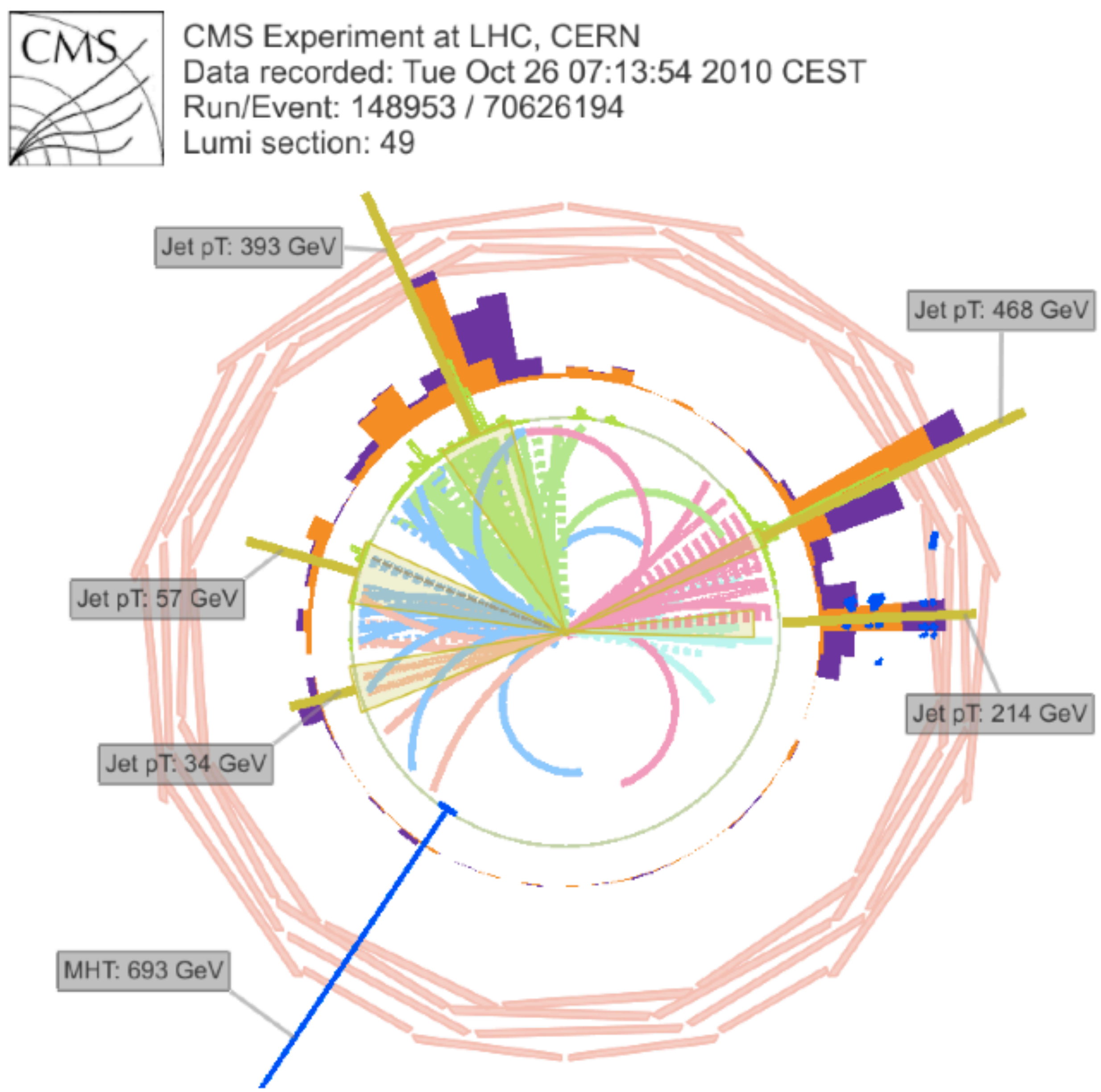
- Final selection MET > 100 GeV
- $M_{squark}$=$M_{gluino}$
- $M_{Wino}$ = $M_{Bino}$
- Area under the red line excluded
- Band from theoretical error on NLO calculation



# No SUSY but many pretty background events

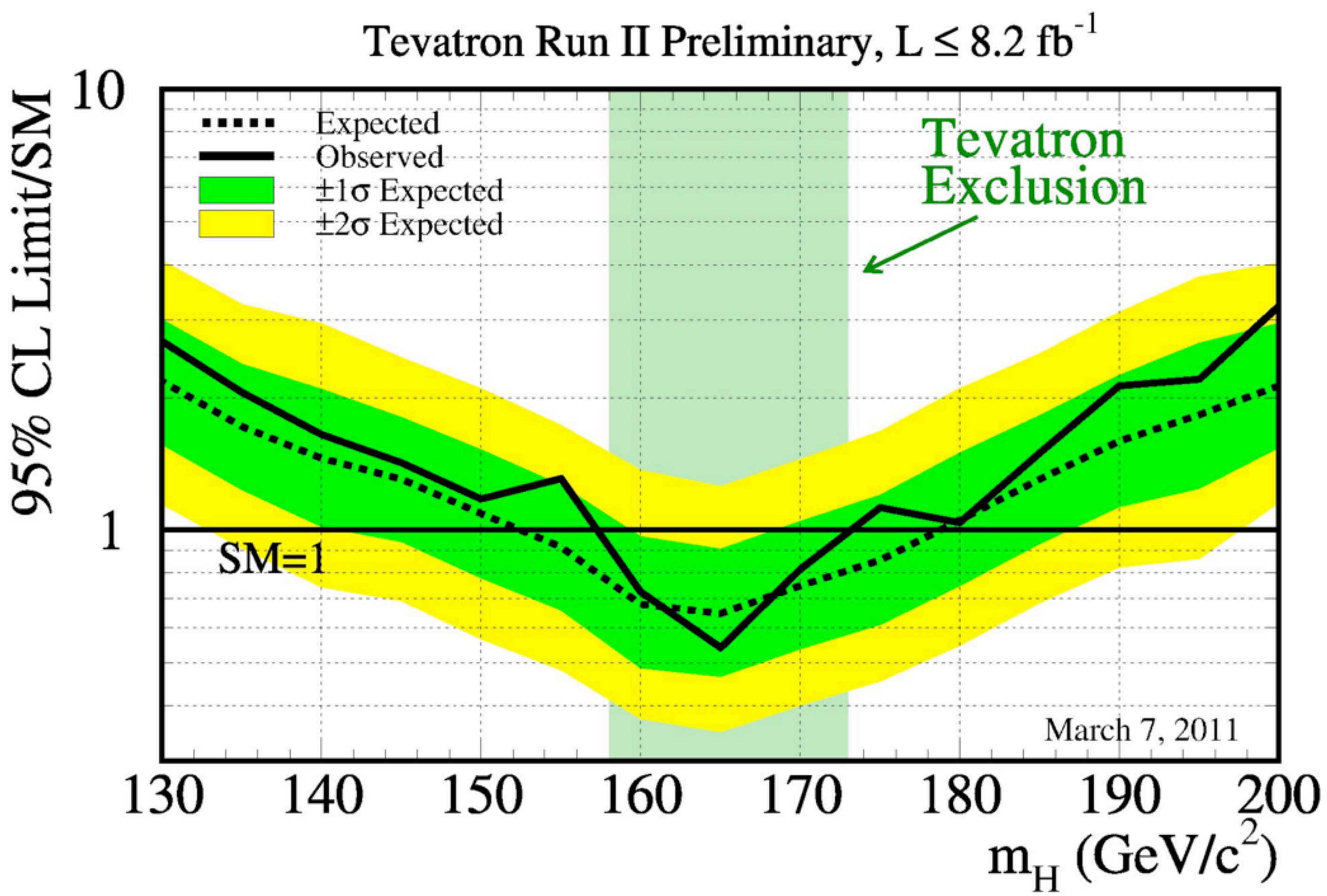


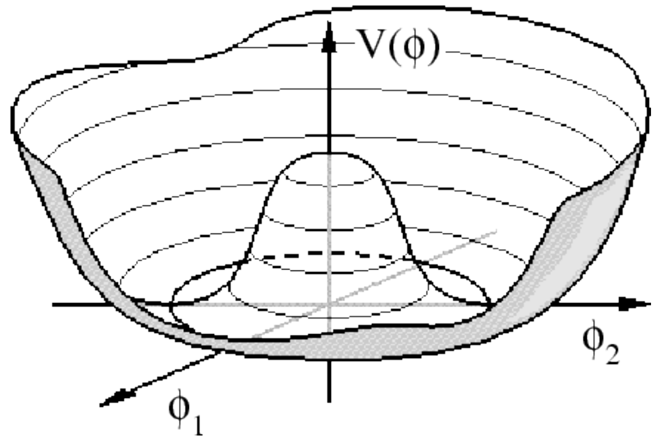



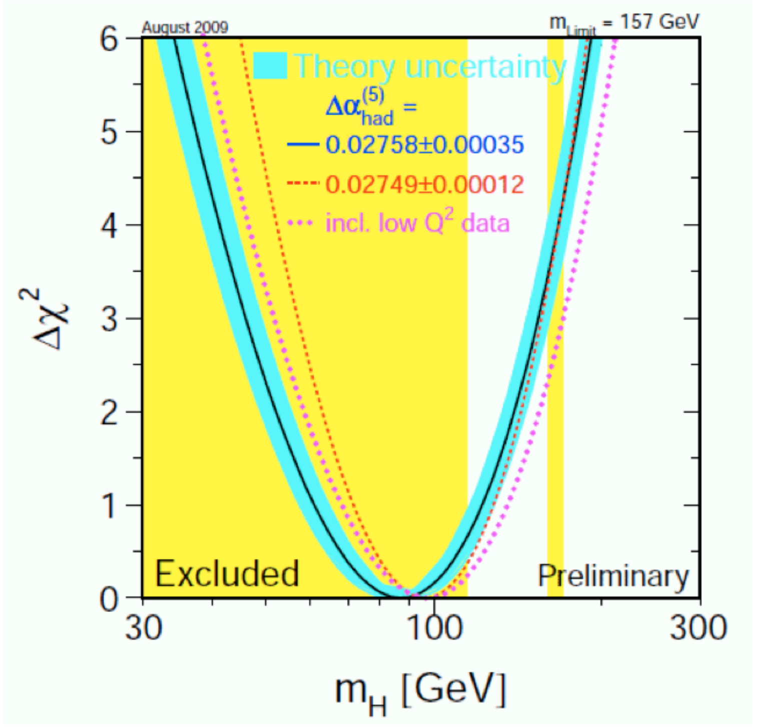



# Higgs searches

- State of Standard Model Higgs searches




- No sensitivity to Standard Model Higgs boson with current data sample (at least with three generations...)

# $H \rightarrow WW \rightarrow ll\nu\nu$

CMS-HIG-10-003

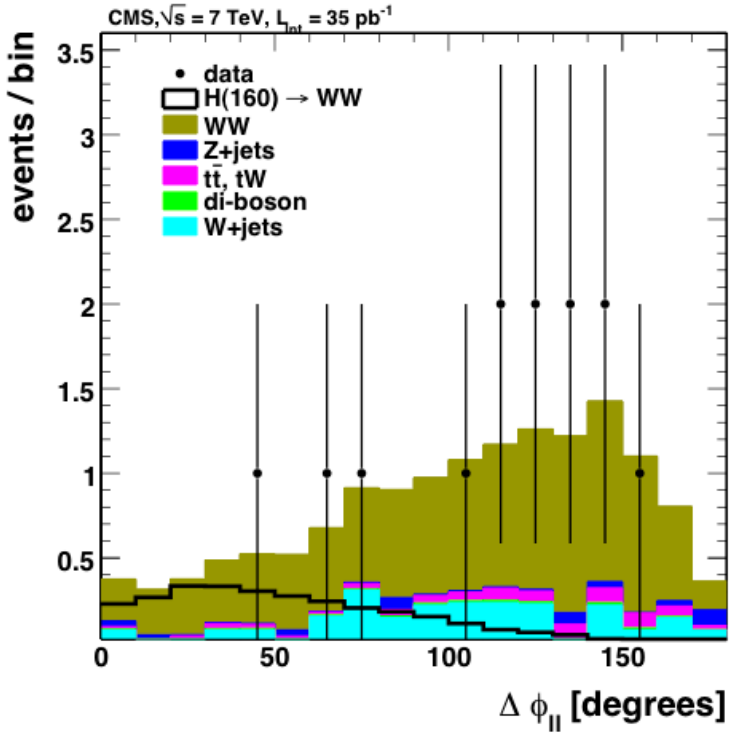
- Signature:
  - Two high $p_T$ leptons
  - Large missing transverse momentum from two neutrinos

- Two techniques: Cut based & boosted decision tree

- Cut based (example, optimised for $m_H$)
  - Two isolated leptons (e,μ) with $p_T$>20 GeV
  - *projected* MET > 35 (20) GeV for ee/μμ (eμ) final states
  - Z mass veto (± 15 GeV)
  - 3$^{rd}$ lepton veto
  - Jet veto and b-tag veto to remove top events

# H → WW → llνν search

- Boosted Decision Tree
  - Uses variable define previously
  - Differences in position between leptons
  - Transverse masses between leptons and MET




- Backgrounds from data
  - W+jets: fake-rate method as described earlier
  - Top: count b-tagged jets and correct for tagger inefficiency
  - Z/γ: Use MC ratio to extrapolate data inside Z window to outside
  - WW continuum: Measured in data away from the Higgs mass window

# H → WW → llνν

- Results
  - Cut based analysis

| Mass (GeV) | SM Higgs | $4^{th}$ Gen | Bgnd. | Data |
|---|---|---|---|---|
| 130 | 0.3 ± 0.01 | 1.73 ± 0.04 | 1.67 ± 0.10 | 1 |
| 160 | 1.23 ± 0.02 | 10.35 ± 0.16 | 0.91 ± 0.05 | 0 |
| 200 | 0.47 ± 0.01 | 3.94 ± 0.07 | 1.47 ± 0.09 | 0 |
| 250 | 0.26 ± 0.00 | 1.98 ± 0.04 | 1.64 ± 0.08 | 1 |

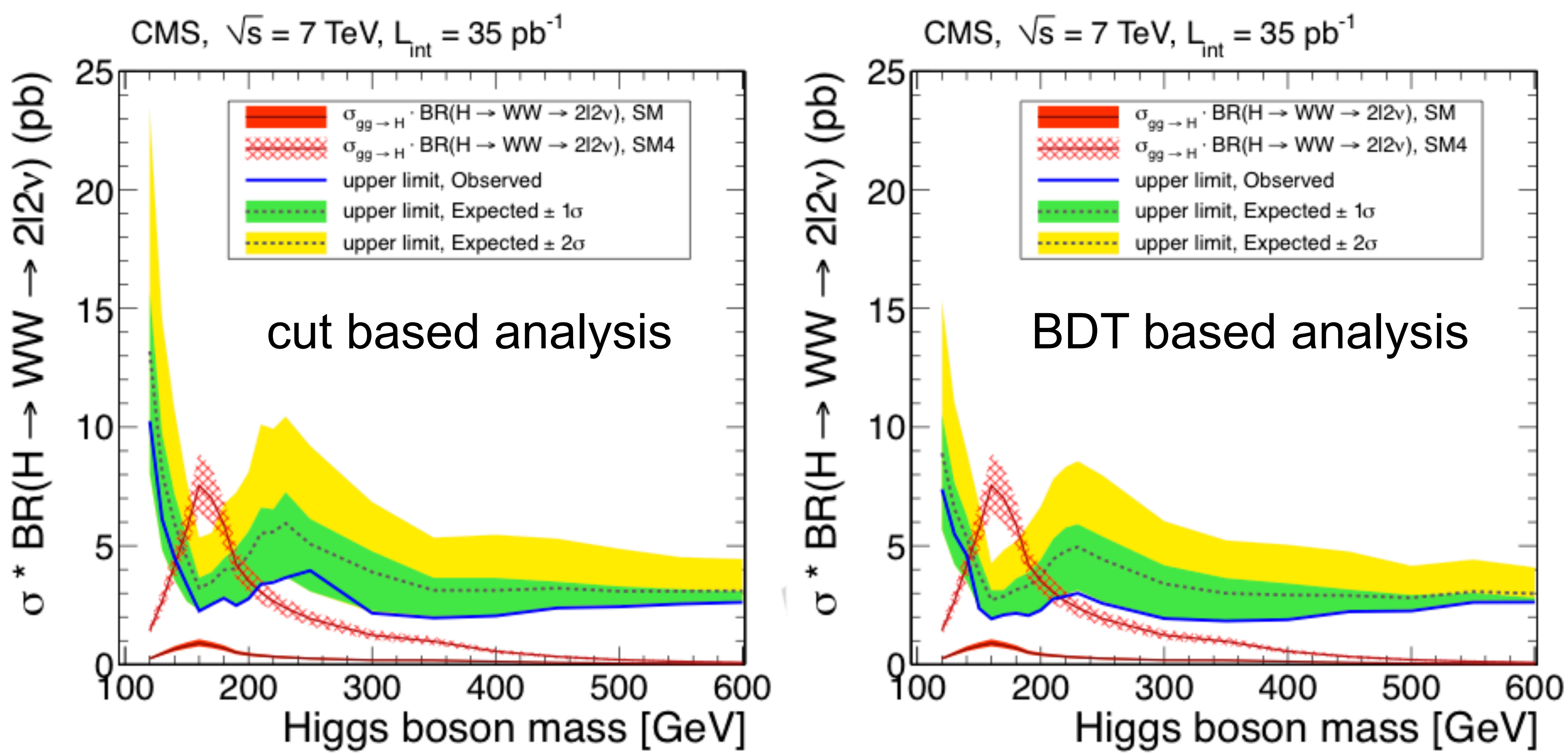
  - Boosted decision tree

| Mass (GeV) | SM Higgs | $4^{th}$ Gen | Bgnd. | Data |
|---|---|---|---|---|
| 130 | 0.34 ± 0.01 | 1.98 ± 0.04 | 1.32 ± 0.18 | 1 |
| 160 | 1.47 ± 0.02 | 12.31 ± 0.17 | 0.92 ± 0.10 | 0 |
| 200 | 0.57 ± 0.01 | 4.76 ± 0.07 | 1.47 ± 0.07 | 0 |
| 250 | 0.30 ± 0.00 | 2.30 ± 0.04 | 1.67 ± 0.10 | 0 |

- No signal observed ➔ set limits

# H → WW → llvv limits

- Limit above Standard Model Higgs cross section (factor 3 @ 160 GeV)




- Fourth generation model with infinite quark masses (conservative) excluded mass in the range from 144 to 207 GeV at 95% C.L.
- Competitive with Tevatron limits

# MSSM Higgs searches

- Looking beyond the Standard Model the Higgs sector becomes much richer
  - In the Minimal Supersymmetric Standard Model (MSSM) two Higgs doublets ➔ five Higgs bosons
  - Three neutral: h (light scalar), H (heavy scalar) & A (neutral CP odd)
  - Two charged: $H^{\pm}$
  - Couplings of Higgs to down-type quarks enhanced at high tanβ
- Other less constrained models predict more Higgs bosons including doubly-charged Higgs

# $\phi \rightarrow \tau\tau$ search

CMS-HIG-10-002

- Search for pp $\rightarrow \phi$ + X
  - $\phi$ = h,H,A mass degenerate depending on regime
- Higgs decays to tau-pairs with BR~10%
  - (b-quark pairs higher BR but huge background from QCD)
- Three decay channels considered:
  - $H \rightarrow \tau\tau \rightarrow e\text{-}\mu$
  - $H \rightarrow \tau\tau \rightarrow e\text{-}\tau_h$ ($\tau_h$=hadronic decay)
  - $H \rightarrow \tau\tau \rightarrow \mu\text{-}\tau_h$
- Selection:
  - Electron/muon pT> 15 GeV
  - $\tau_h$ $p_T$>20 GeV
  - $l\text{-}\tau_h$: $M_T=\sqrt{2p_T^l \cdot MET \cdot (1-\cos\Delta\phi)} < 40$ GeV
  - $e\text{-}\mu$: $M_T < 50$ GeV

# Backgrounds

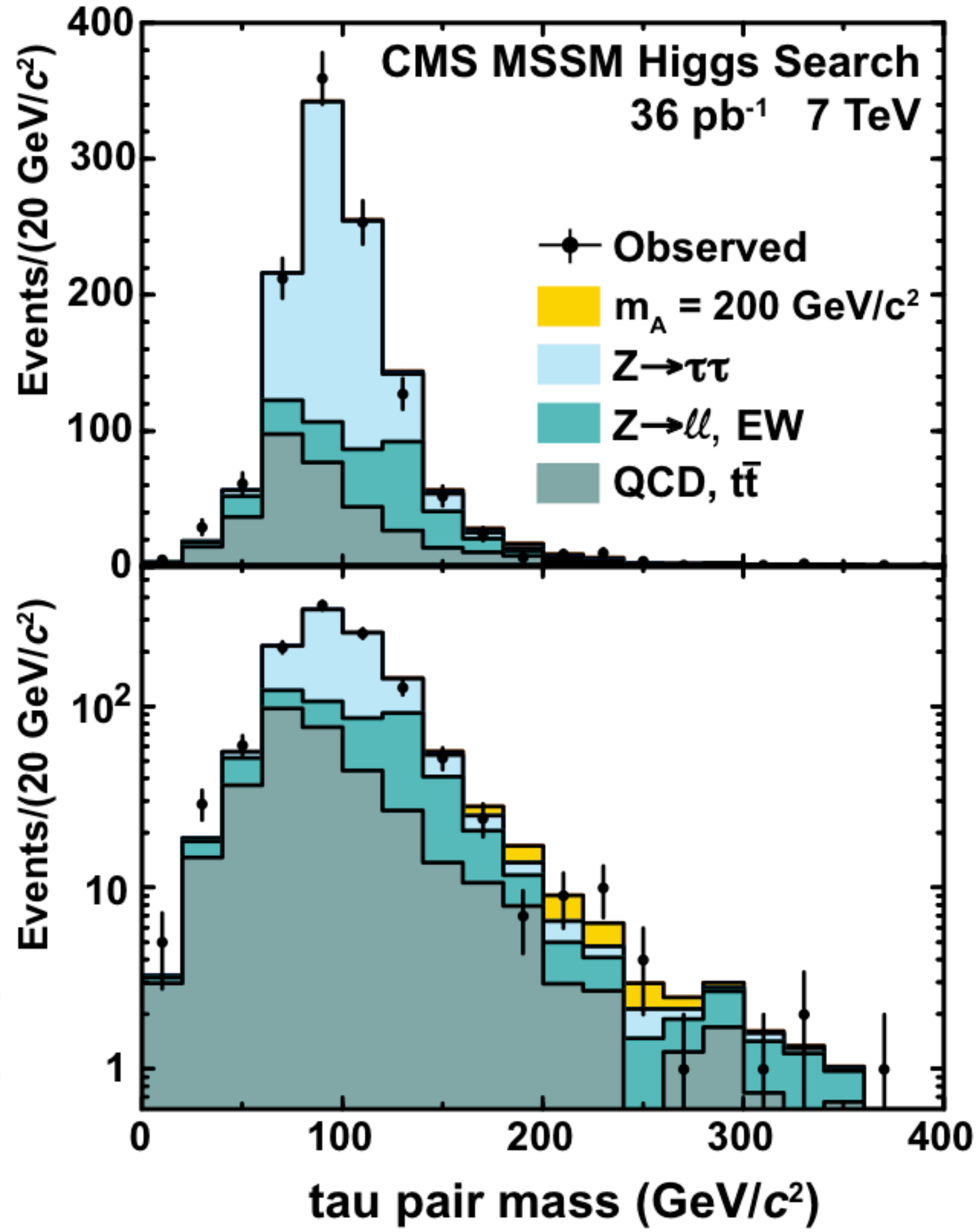
- Main background from Standard Model Z ➔ ττ
  - Taken from simulation and normalised to Z ➔ μμ data

- Backgrounds from QCD multi-jets determined in two ways
  - From ratio of SS to OS dilepton events
  - From tau fake rate studies in QCD multi-jet sample

| Process | $\mu\tau_h$ | $e\tau_h$ | $e\mu$ |
|---|---|---|---|
| $Z \to \tau\tau$ | 329±77 | 190±44 | 88±5 |
| $t\bar{t}$ | 6±3 | 2.6±1.3 | 7.1±1.3 |
| $Z \to \ell\ell$, jet $\to \tau_h$ | 6.4±2.4 | 15±6.2 | |
| $Z \to \ell\ell$, $\ell \to \tau_h$ | 13.3±3.6 | 119±28 | |
| $W \to \ell\nu$ | 54.9±4.8 | 30.6±3.1 | 3.9±1.2 |
| $W \to \tau_\ell\nu$ | 14.7±1.3 | 7.0±0.7 | |
| QCD | 132±14 | 181±23 | |
| WW/WZ/ZZ | 1.6±0.8 | 0.8±0.4 | 3.0±0.4 |
| Total | 558±79 | 546±57 | 102±5 |
| Observed | 540 | 517 | 101 |
| Signal Efficiency ($m_A$=120 GeV/$c^2$) | 0.0253 | 0.0156 | 0.00561 |

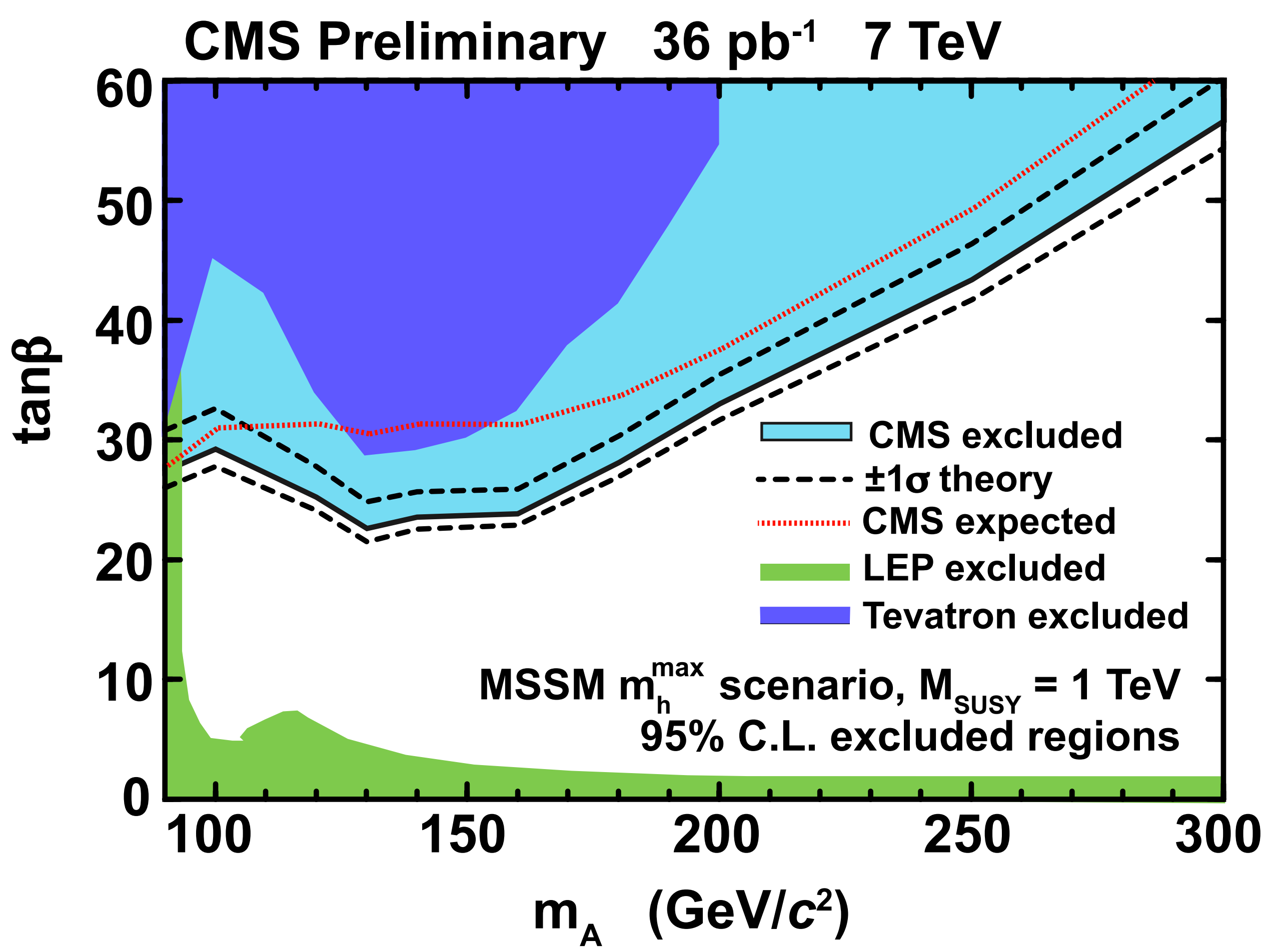
# τ pair mass reconstruction

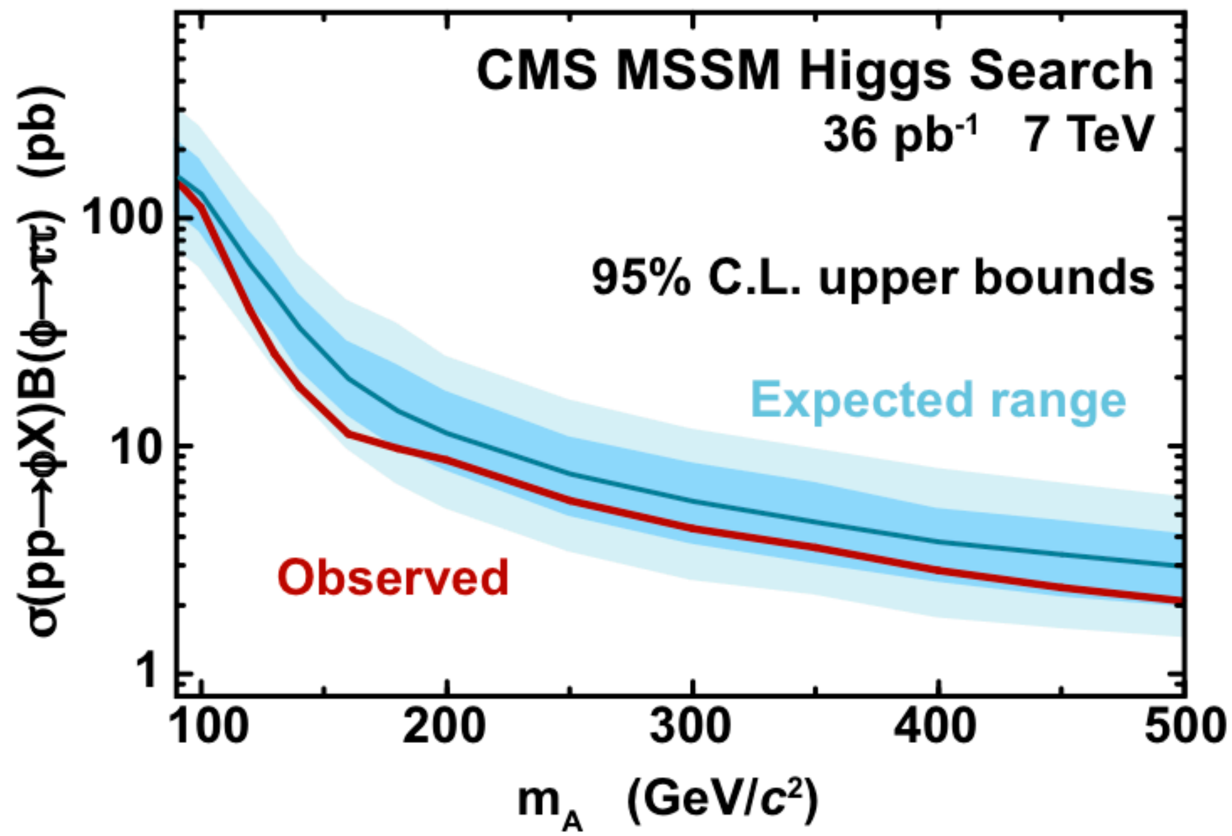
- Likelihood fit to τ momenta
- Use all available kinematic information and probability density for τ $p_T$ spectra
- Improvement in resolution compared to visible mass



# $\phi \rightarrow \tau\tau$ limits

Limit on σxBR for tanβ=30



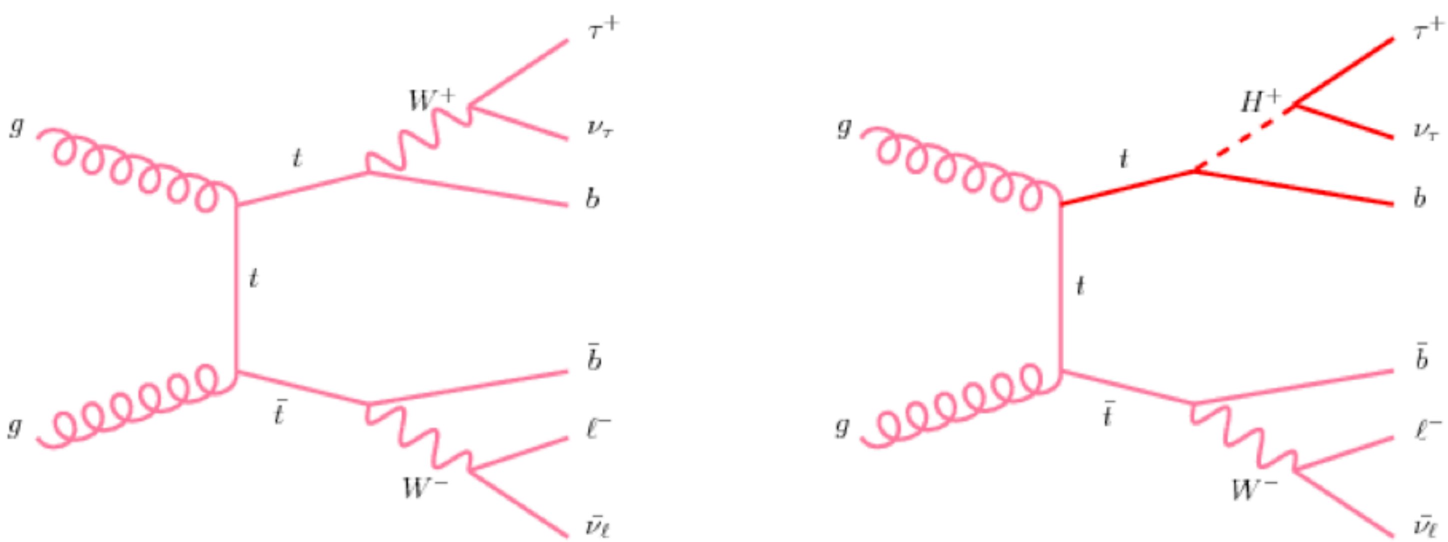




Excluded region in MSSM $m_h^{max}$ scenario

Significantly extends previous limits

# Charged Higgs search

- Charged MSSM Higgs bosons may contribute to ttbar decays

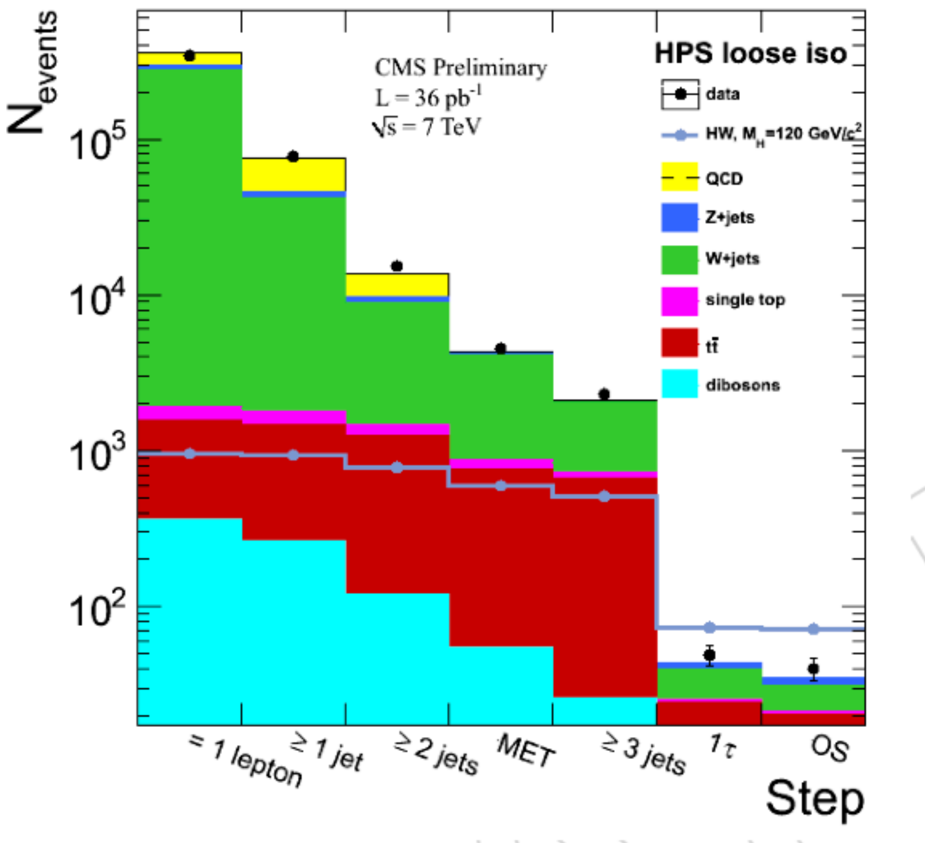


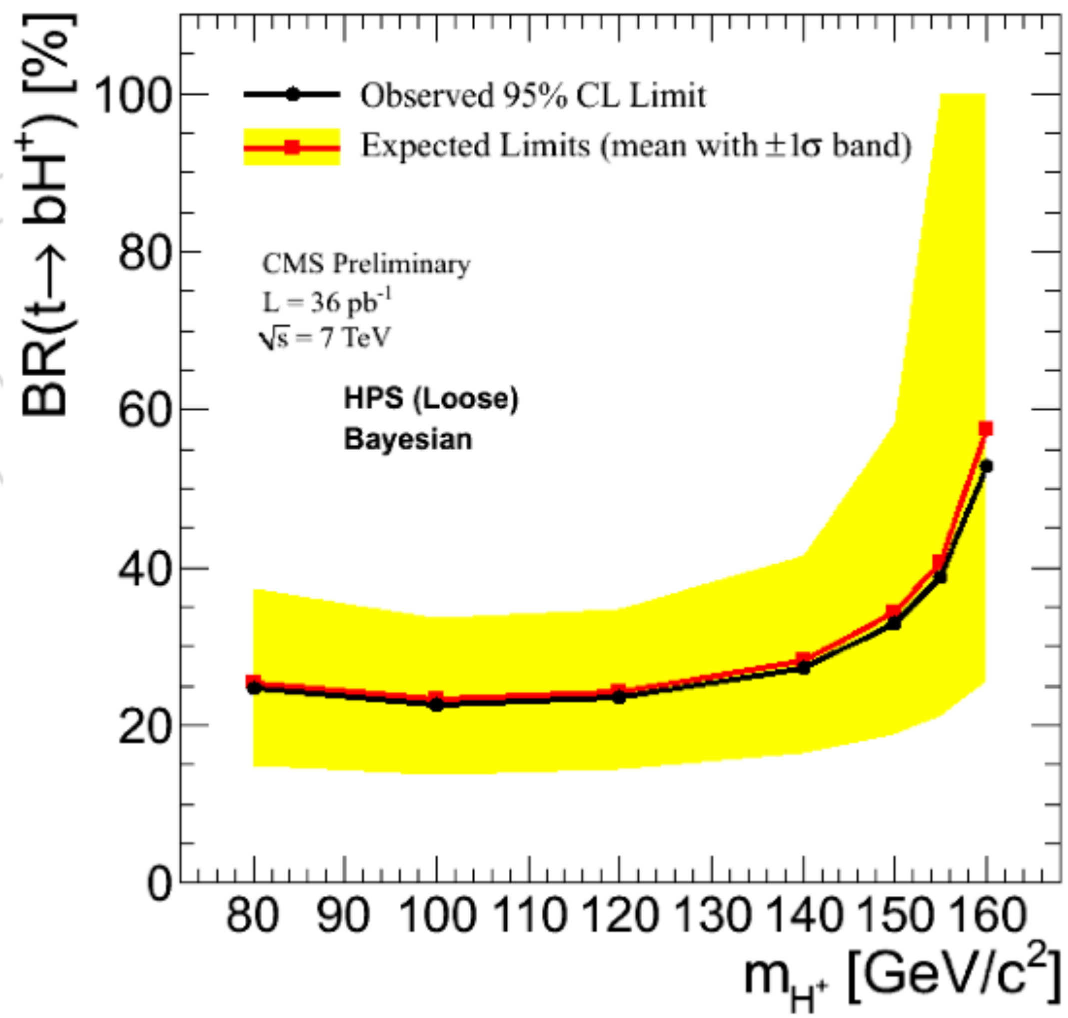

Substitute $H^{\pm}$ for $W^{\pm}$ in ttbar decays to τ

- Selection as for ttbar cross section measurement [CMS PAS-TOP-10-002]
  - One electron (muon) with $p_T$ > 30 (20) GeV
  - At least two jets $E_T$ > GeV
  - MET > 40 GeV
  - Hadronic τ $p_T$ > 20 GeV
- Backgrounds in two categories:
  - Fake hadronic τ: use fake rate method to estimate from data
  - Real hadronic τ: use simulation to estimate background

# Charged Higgs

CMS-HIG-11-002

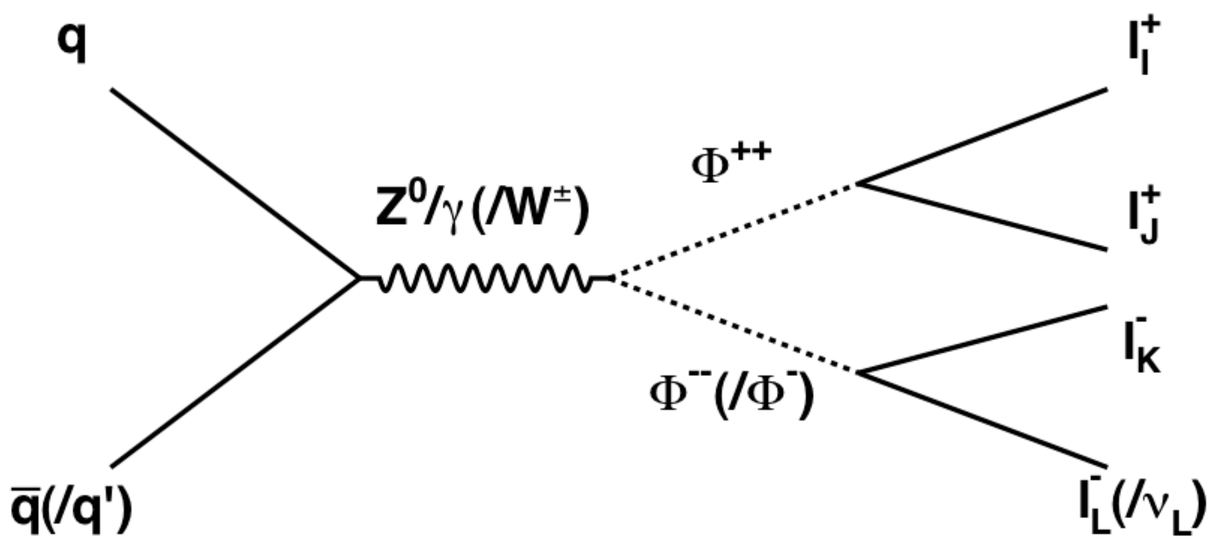



- No signal observed
  - Set 95% C.L on BR (t➔bH$^+$) assuming BR(H$^+$➔ τ$^+$ν)=1
  - Limit ~0.25-0.30 for 80 GeV < $m_H^+$ < 140 GeV
  - Limits comparable with Tevatron

# Doubly charged Higgs

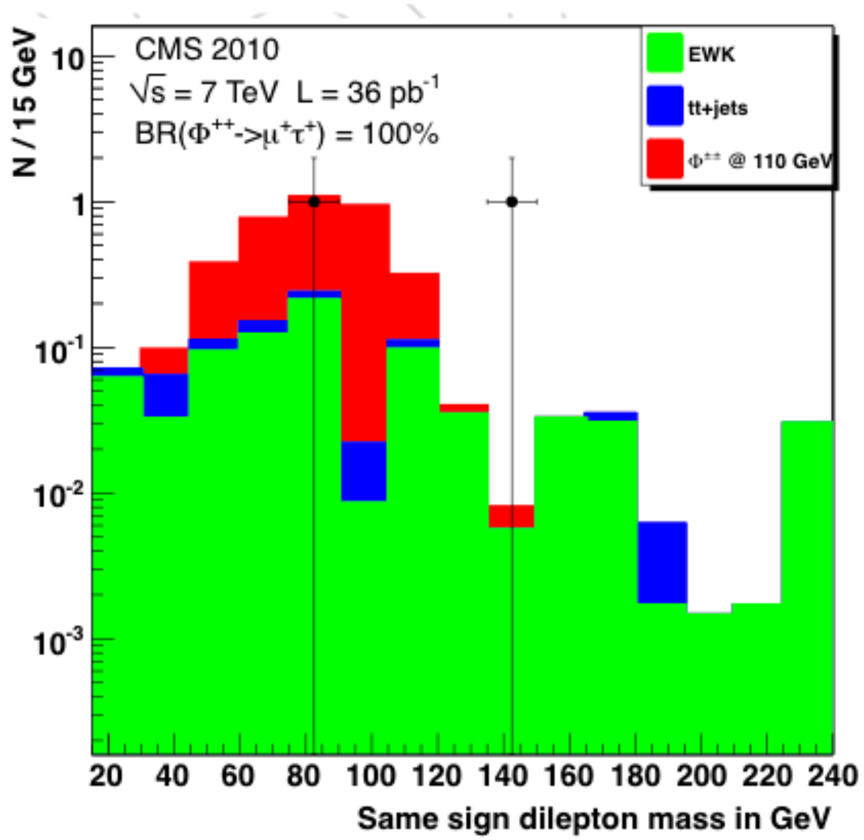
- Extend Standard Model adding scalar triplet: $\Phi^{\pm\pm}$, $\Phi^{\pm}$ and $\Phi^{0}$
- Triplet responsible for neutrino masses

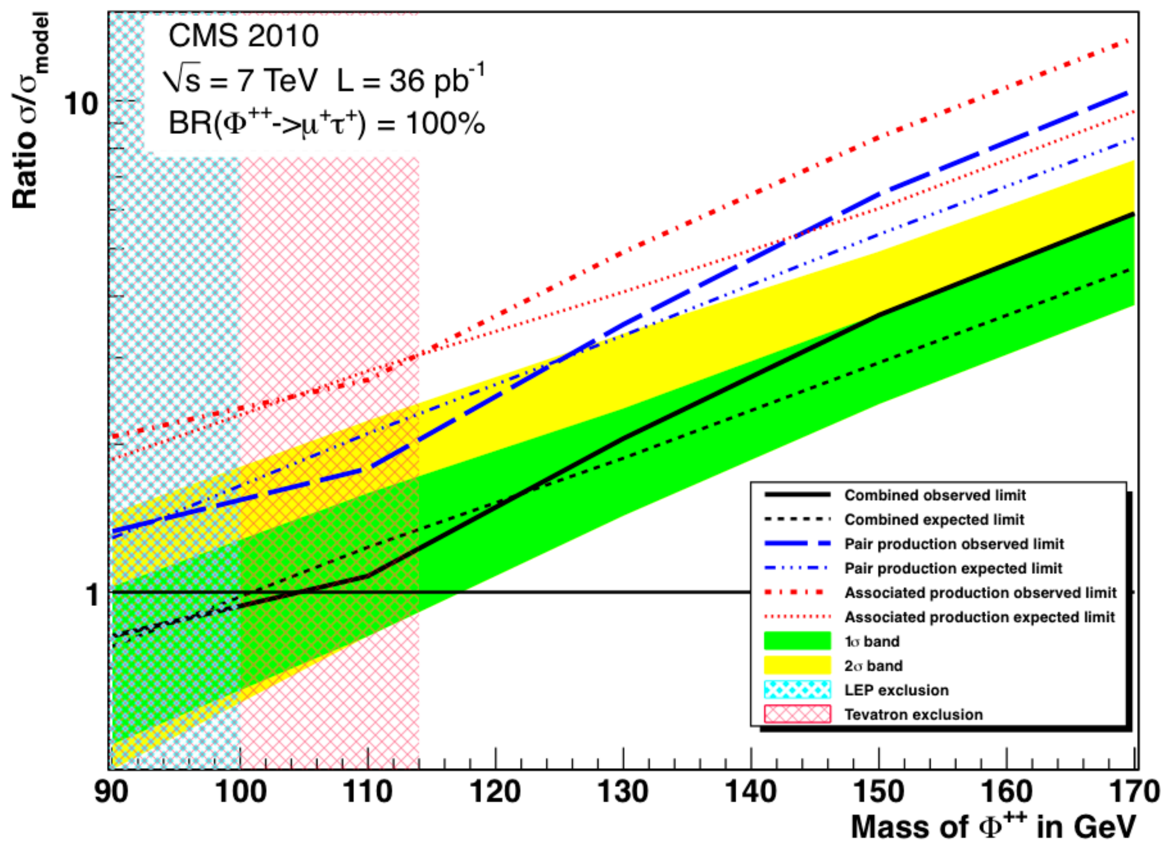



- Consider model where BR($\Phi^{\pm\pm}$ ➔ ll)=100%
- Final states with three or four isolated leptons (earlier multi-lepton search)
- Look for resonance peaks in dilepton mass distributions ➔

# Doubly charged Higgs

- Example for $\mu^+\tau^+$ final state (one of many considered)




- No peak observed → set limit extending reach of previous experiments

CMS-HIG-11-001

# Summary and conclusions

- First SUSY and Higgs searches from CMS
- Unfortunately no observations ➔ set limits
- Commissioned all our tools for searches
- Wide range of searches underway, with novel techniques
- **Ready to make discoveries in 2011/12!**


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

# Backup: Benchmark points

### Low mass (LM) mSUGRA benchmarks

| Benchmark | m0 | m1/2 | A0 | tanb | sgn(mu) | Notes |
|---|---|---|---|---|---|---|
| LM0 | 200 | 160 | –400 | 10 | 1 | |
| LM1 | 60 | 250 | 0 | 10 | + | |
| LM2 | 185 | 350 | 0 | 35 | + | |
| LM2mhf360 | 185 | 360 | 0 | 35 | + | |
| LM3 | 330 | 240 | 0 | 20 | + | |
| LM4 | 210 | 285 | 0 | 10 | + | |
| LM5 | 230 | 360 | 0 | 10 | + | |
| LM6 | 85 | 400 | 0 | 10 | + | |
| LM7 | 3000 | 230 | 0 | 10 | + | |
| LM8 | 500 | 300 | –300 | 10 | + | |
| LM9 | 1450 | 175 | 0 | 50 | + | |
| LM9p | 1450 | 230 | 0 | 10 | + | |
| LM9t175 | 1450 | 175 | 0 | 50 | + | mtop = 175 |
| LM10 | 3000 | 500 | 0 | 10 | + | |
| LM11 | 250 | 325 | 0 | 35 | + | |
| LM12 | | | | | | TBD |
| LM13 | | | | | | focus point, TBD |

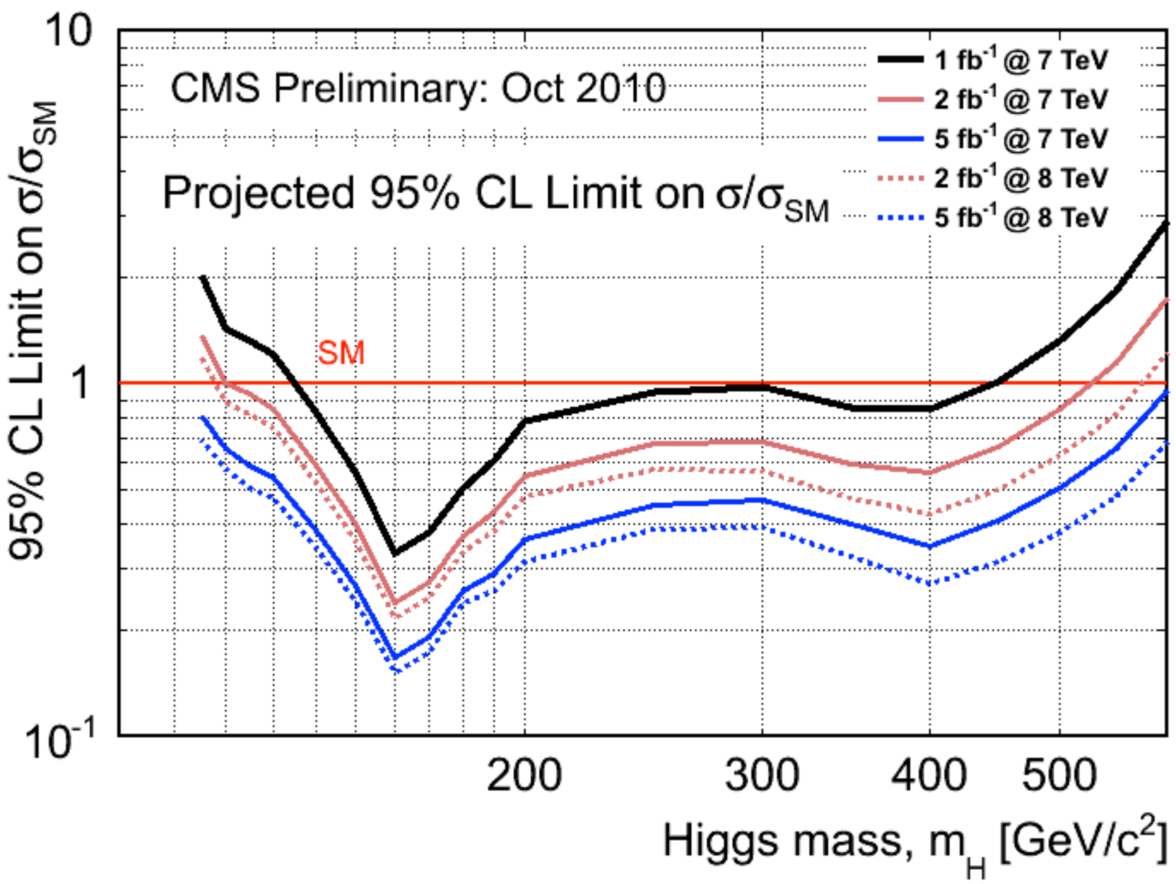
### High mass (HM) mSUGRA benchmarks

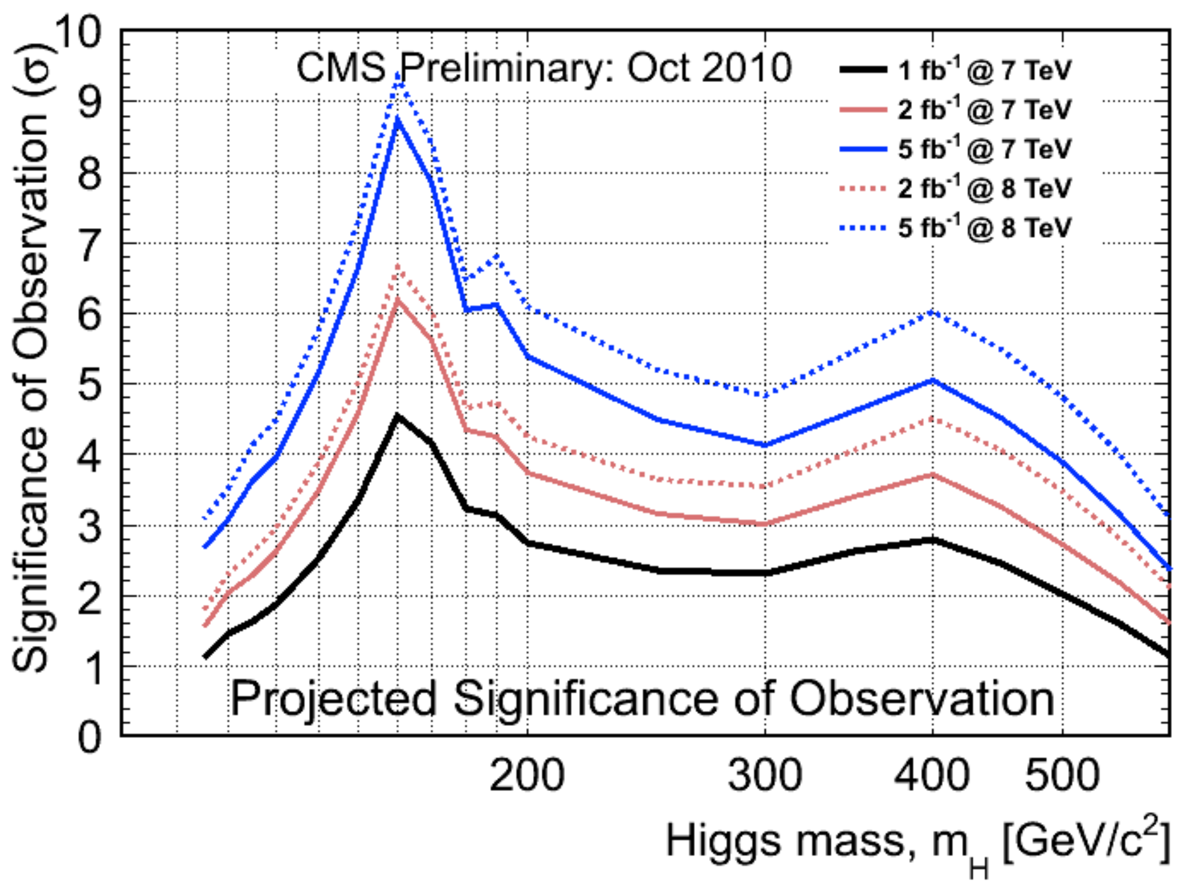
| Benchmark | m0 | m1/2 | A0 | tanb | sgn(mu) | Notes |
|---|---|---|---|---|---|---|
| HM1 | 180 | 850 | 0 | 10 | + | |
| HM2 | 350 | 800 | 0 | 35 | + | |
| HM3 | 700 | 800 | 0 | 10 | + | |
| HM4 | 1350 | 600 | 0 | 10 | + | |

### GMSB (GM) benchmarks

| Benchmark | Lambda | M_mess | N5 | C_Grav | tanb | sgn(mu) | Notes |
|---|---|---|---|---|---|---|---|
| GM1b | 80 | 160 | 1 | 1 | 15 | + | |
| GM1c | 100 | 200 | 1 | 1 | 15 | + | |
| GM1d | 120 | 240 | 1 | 1 | 15 | + | |
| GM1e | 140 | 280 | 1 | 1 | 15 | + | |
| GM1f | 160 | 320 | 1 | 1 | 15 | + | |
| GM1g | 180 | 360 | 1 | 1 | 15 | + | |

# SM Higgs reach in 2011/12

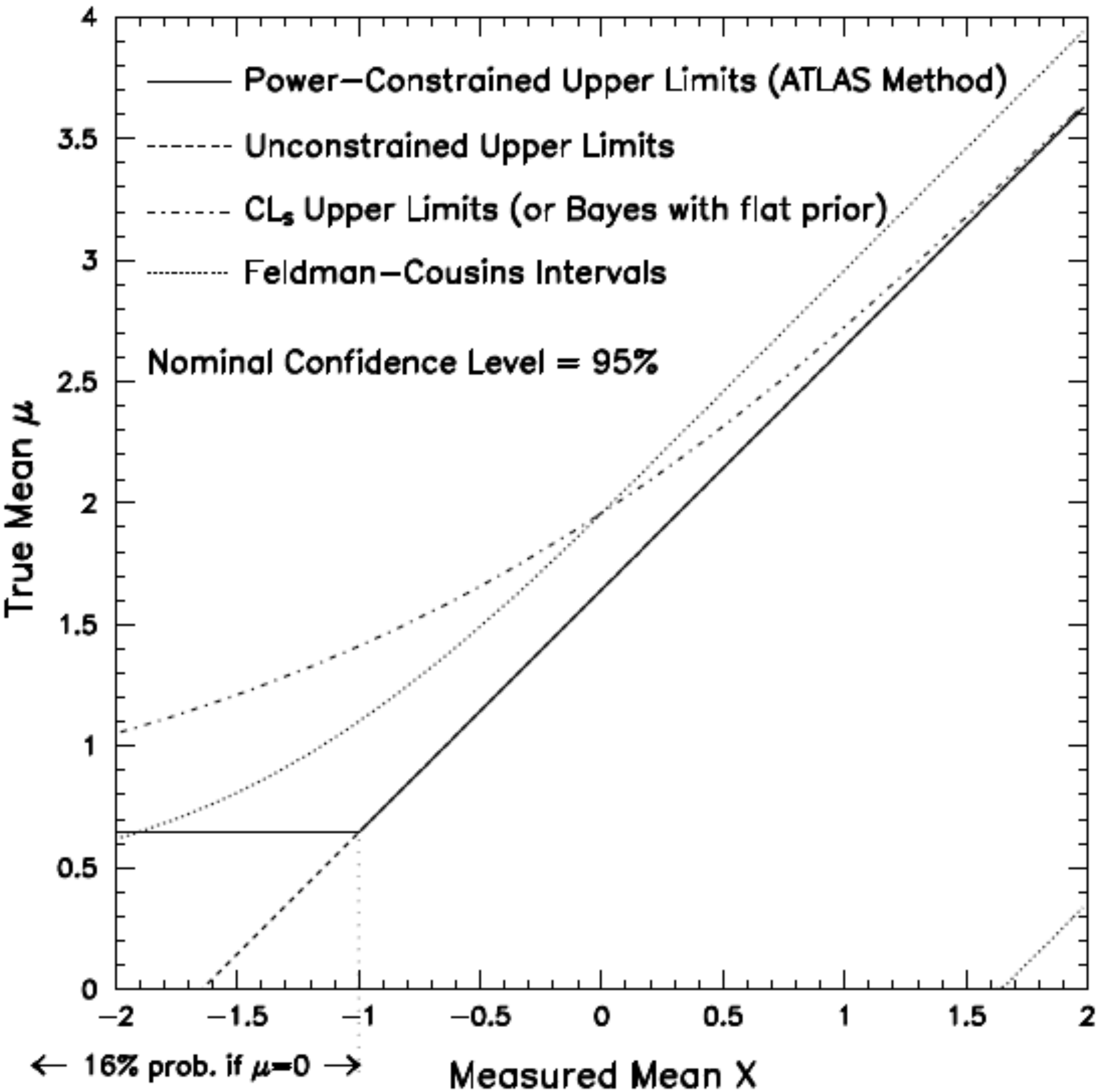


# Intervals and Limits for a Physically Bounded $\mu$

- Prototype: measurement *x* is unbiased Gaussian estimate of $\mu$. (Let $\sigma$=1.) What is 95% C.L. Upper Limit (UL)?
- 1986: Six methods for UL surveyed by V. Highland (VH) include U.L. = max(0, *x* + 1.64) and U.L. = max(0,*x*) + 1.64.
- RPP 1986: Bayesian: uniform prior on the mean $\mu$ for $\mu \geq 0$, prior prob = 0 for $\mu < 0$. (VH's other five not mentioned.)
- 1994,96: 3 ad-hoc frequentist recipes, one using max(*x*,0).
- 1998: Feldman & Cousins (FC) "Unified Approach" in (Kendall and Stuart) replaces ad hoc frequentist
- 2002: $CL_S$ from LEP added to Bayesian and FC.
- CMS Statistics Committee recommends using (at least) one of the three (red) methods in 2002-present PDG RPP.
- ATLAS SC method implies U.L. = max(0, *x* + 1.64) before power constraint (PC), U.L. = max(-1,*x*) + 1.64 after PC.

# Comparison of ATLAS PCL with the three methods in PDG




(Atlas unconstrained U.L. is zero, not null, for x < −1.64)

**ATLAS PCL re-opens discussion on use of diagonal line along with ad hoc constraint, out of favor for many years, not recommended by CMS SC.**

**CMS and ATLAS SC's are reviewing arguments and what has been learned in 25+ years. Academic statisticians have commented as well.**

**Just tip of iceberg: Poisson example brings in other issues. Nuisance parameters yet more. Choice of test statistic varies.**