Results on SUSY and Higgs searches at CMS

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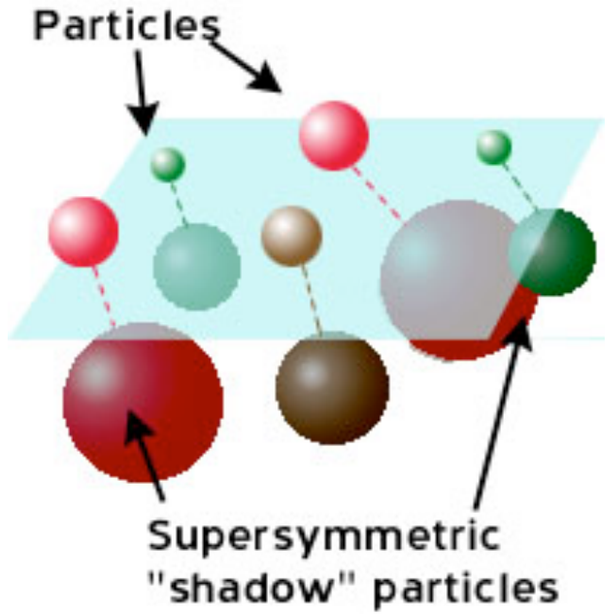
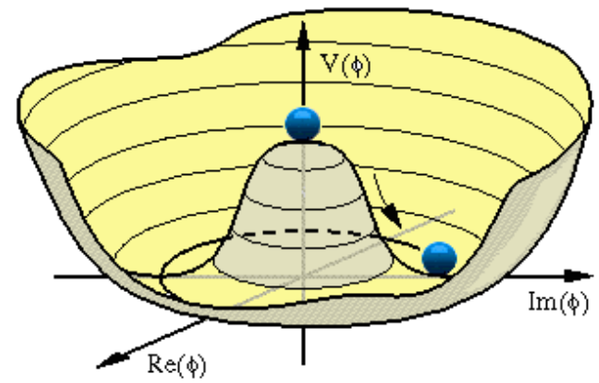
Outline

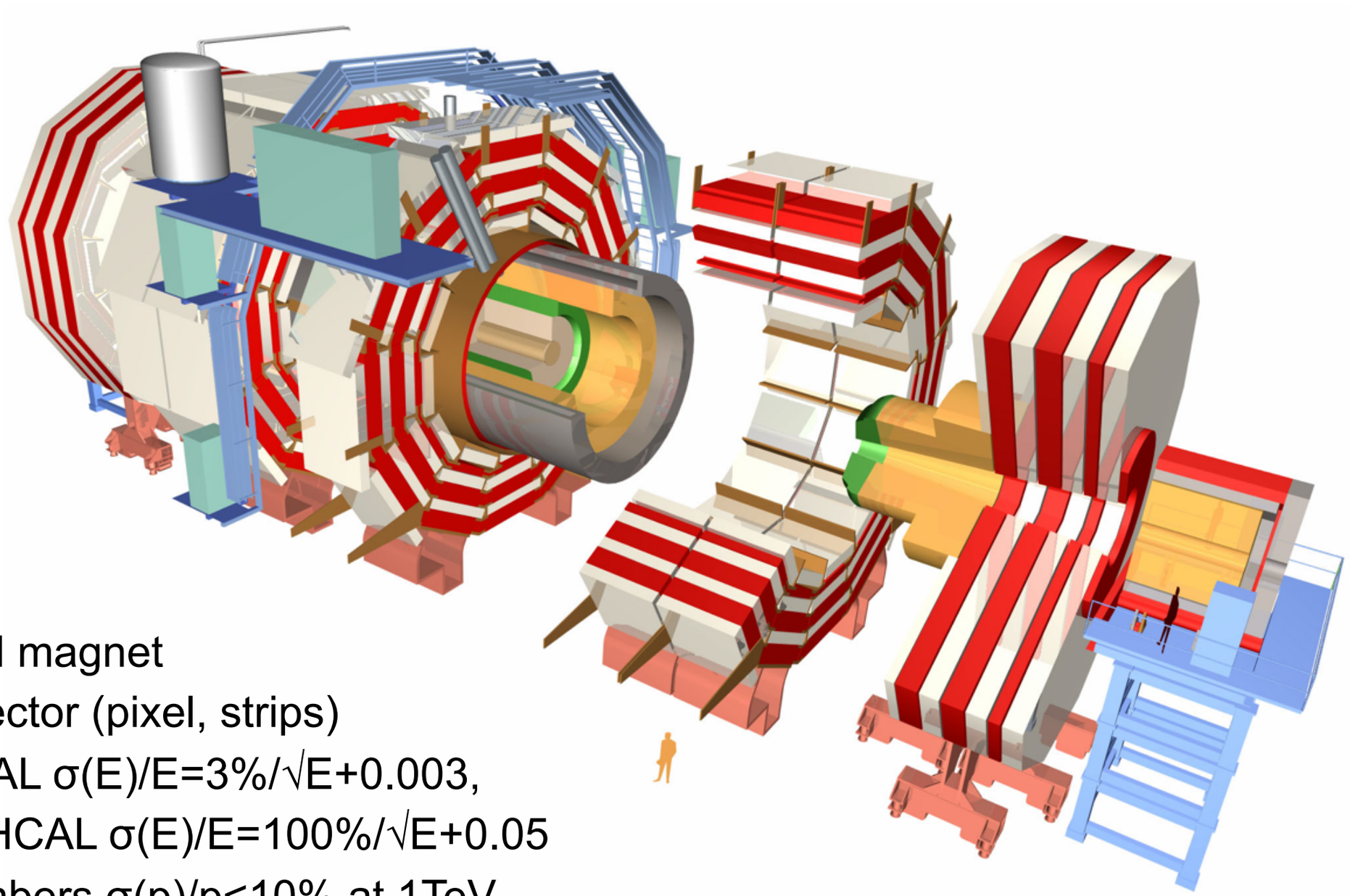
- CMS performance
  - Why you should believe our searches
- SUSY search programme
  - What to look for and how to look for it
  - All-hadronic searches
  - Searches with leptons
  - Searches with photons
- Higgs searches
  - Neutral Higgs searches
  - Charged Higgs searches
- Summary and conclusions





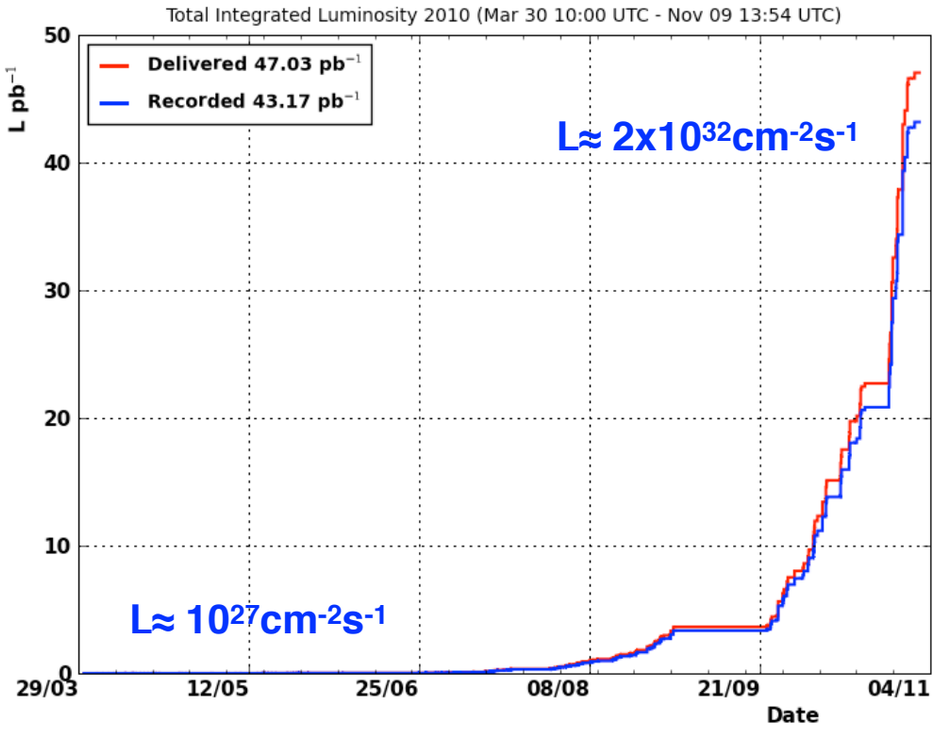
The CMS detector

JINST3:S08004 (2008)



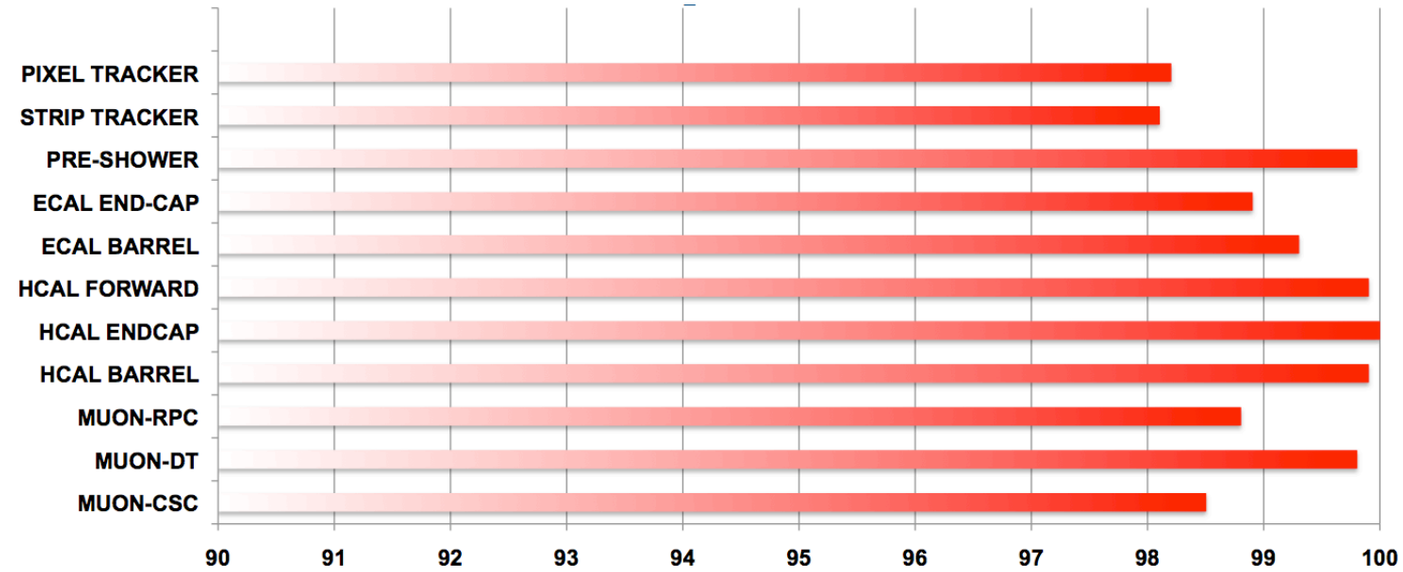
- 4T solenoid magnet
- Silicon detector (pixel, strips)
- Crystal ECAL $\sigma(E)/E=3\%/\sqrt{E}+0.003$,
- Brass/sci. HCAL $\sigma(E)/E=100\%/\sqrt{E}+0.05$
- Muon chambers $\sigma(p)/p<10\%$ at 1TeV

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%)

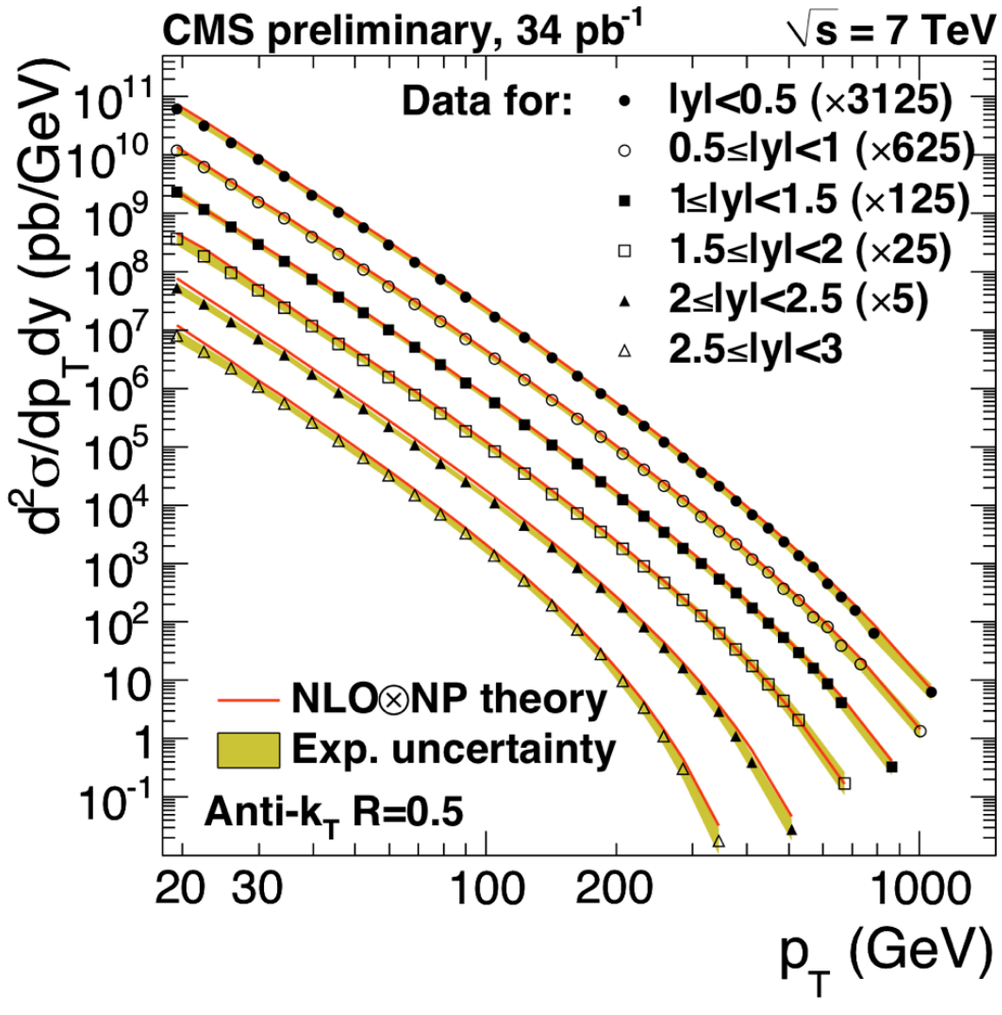
- Average fraction of functional detector channels > 99%
- Lowest still > 98%



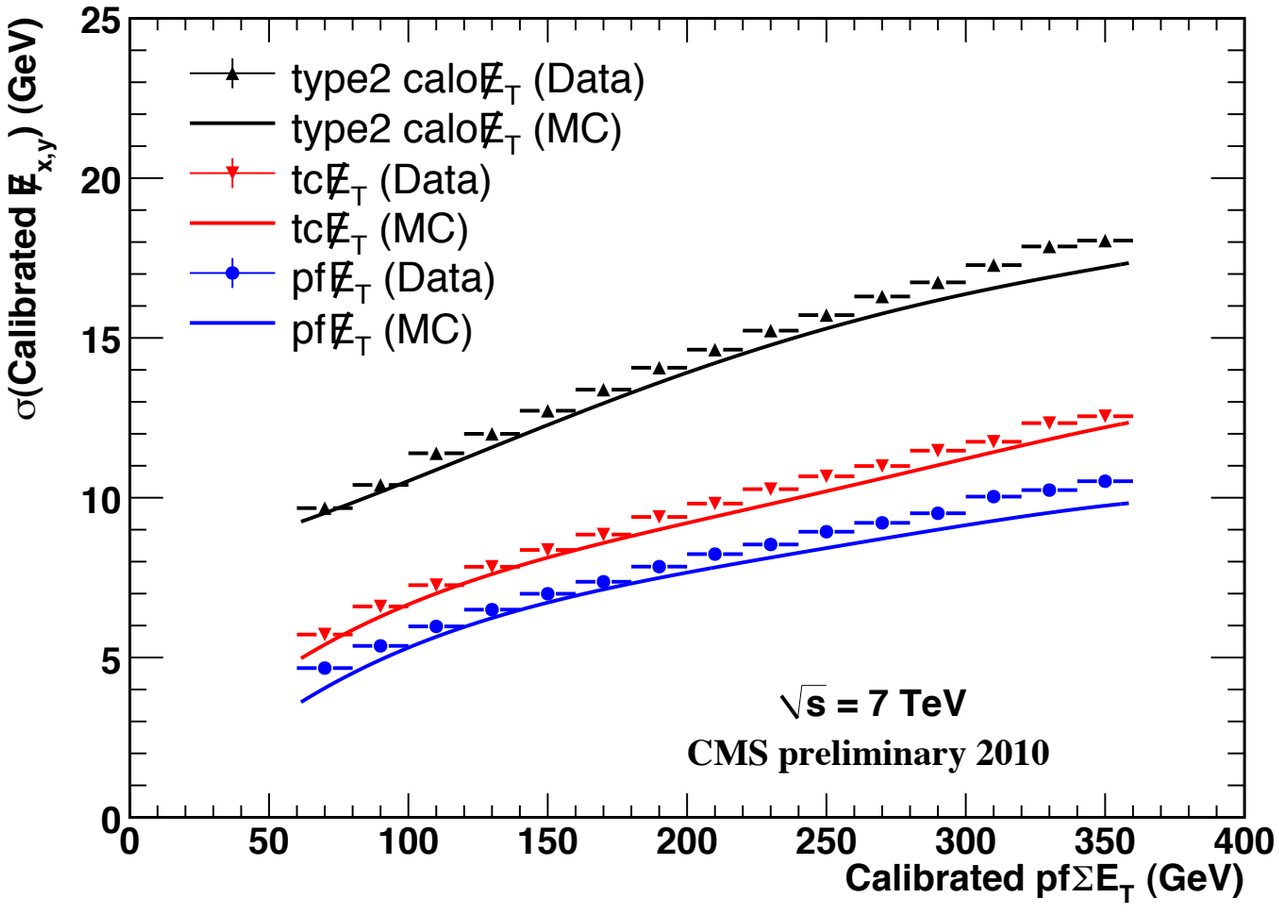
	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2

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

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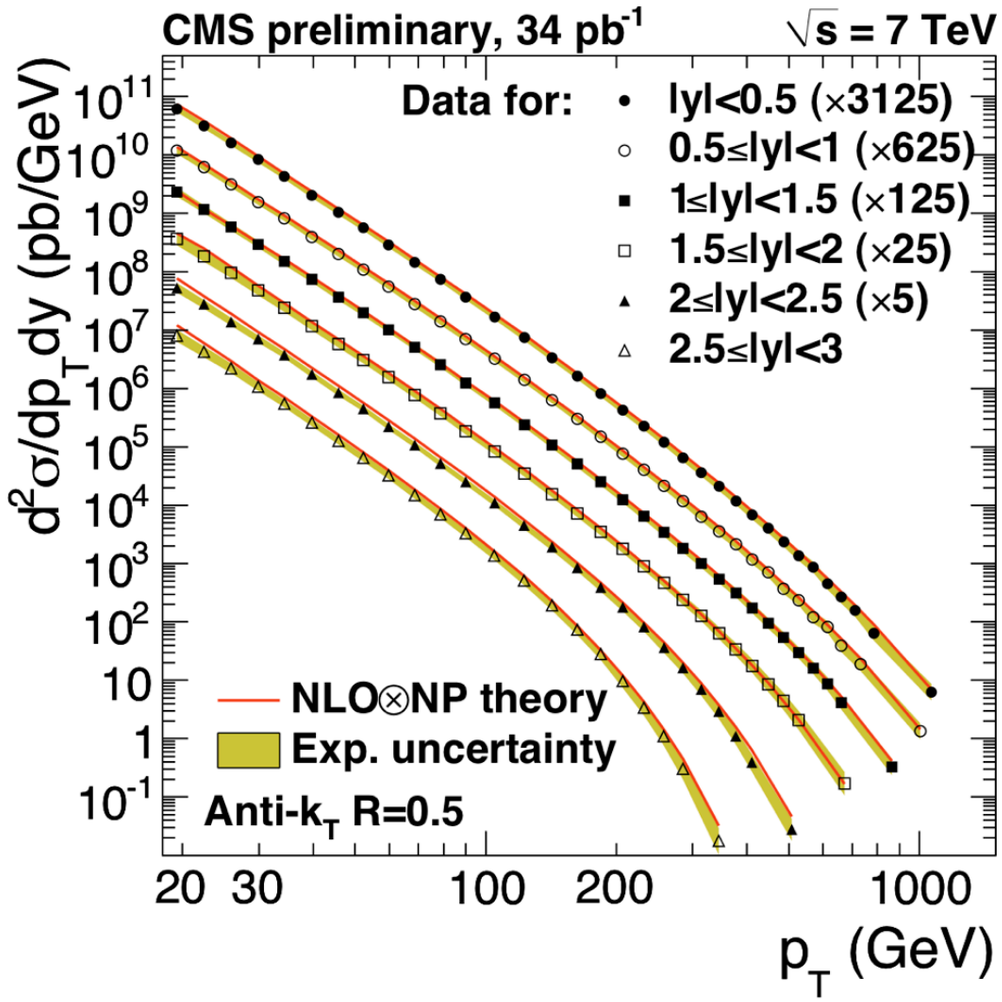

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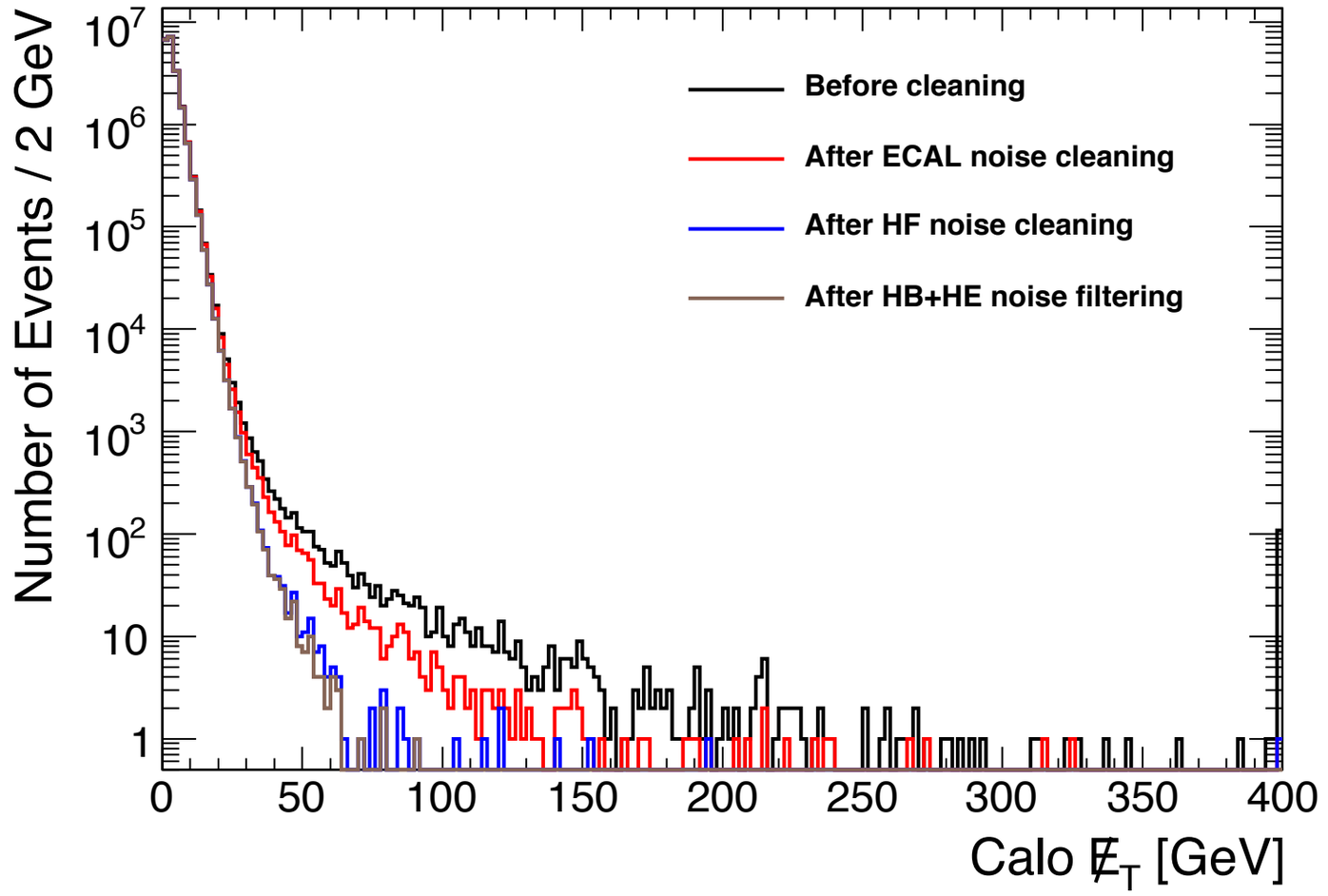
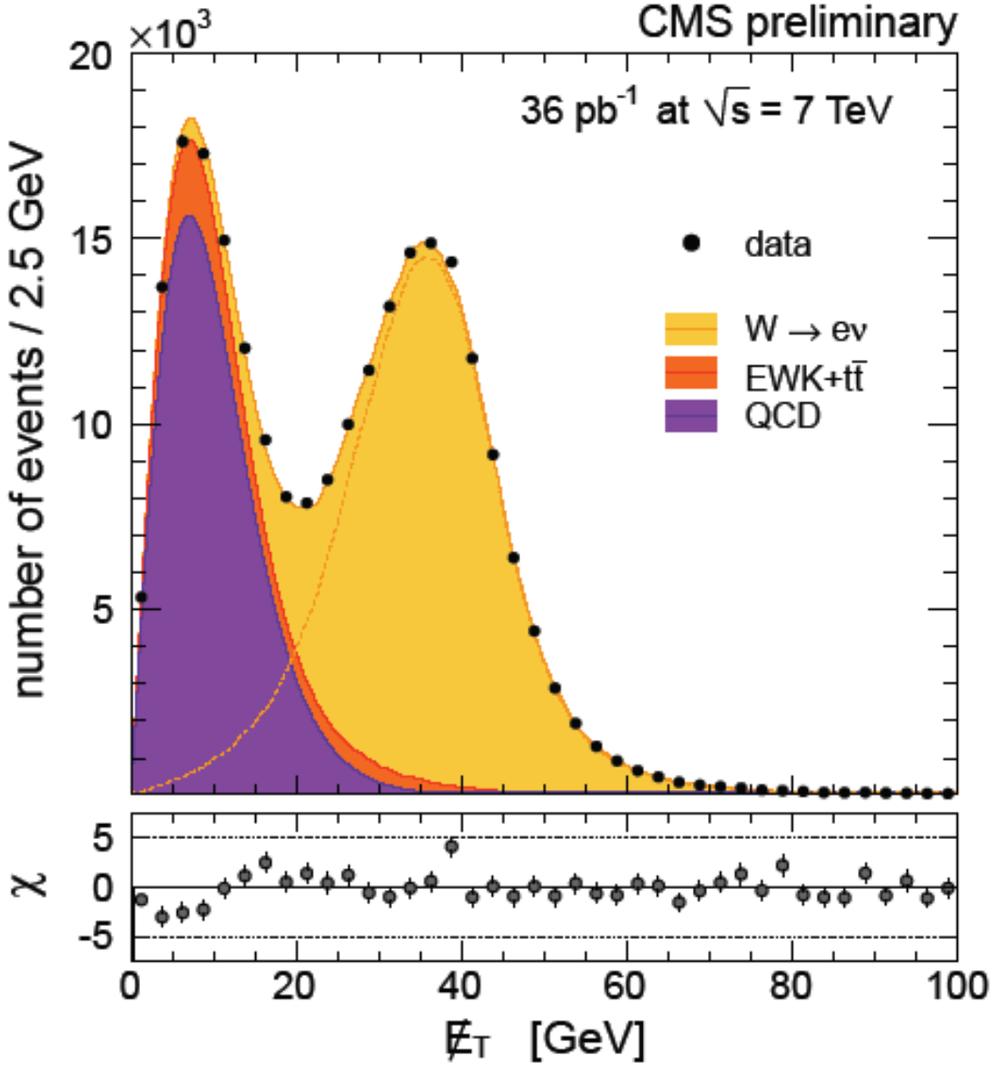
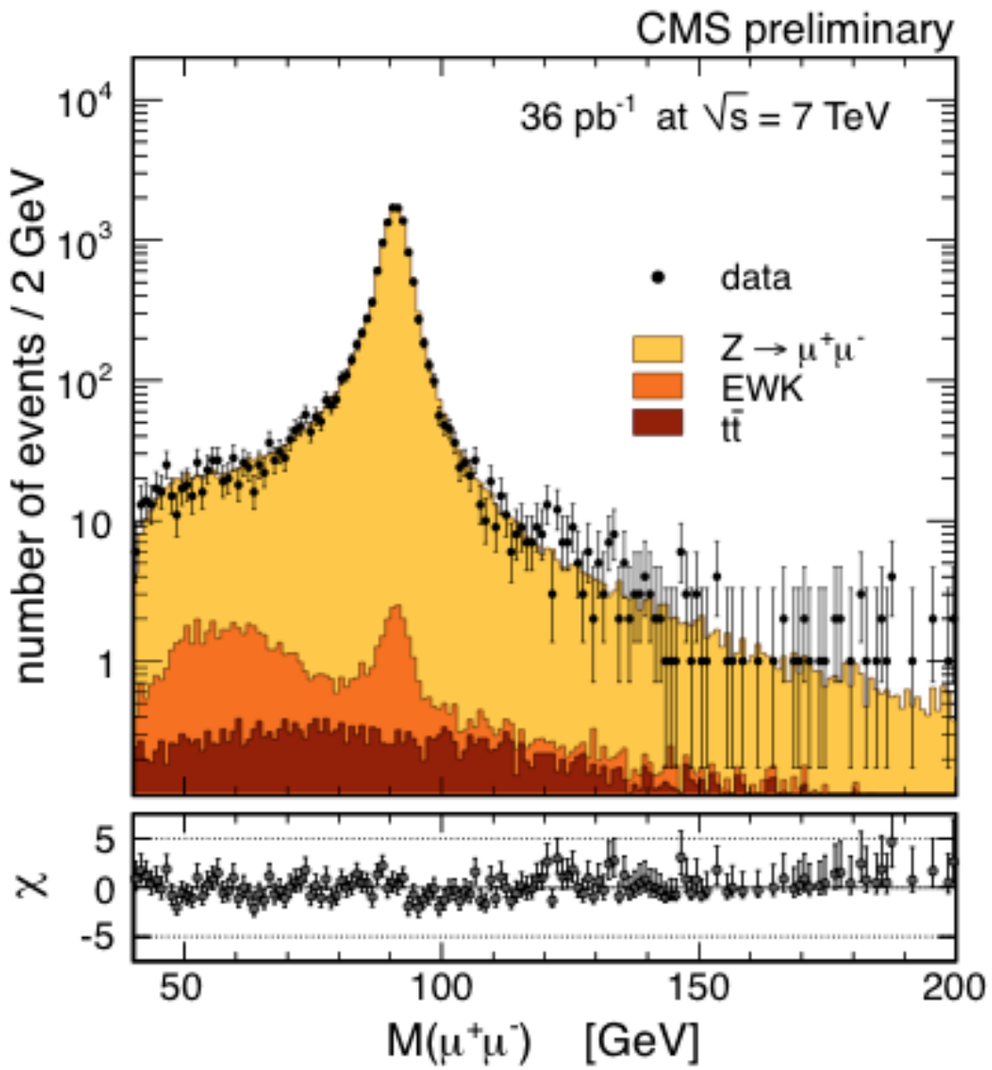


- Measurements of jet cross sections and MET resolution
- Jets and MET in good shape

Electrons and muons

CMS-EWK-10-005

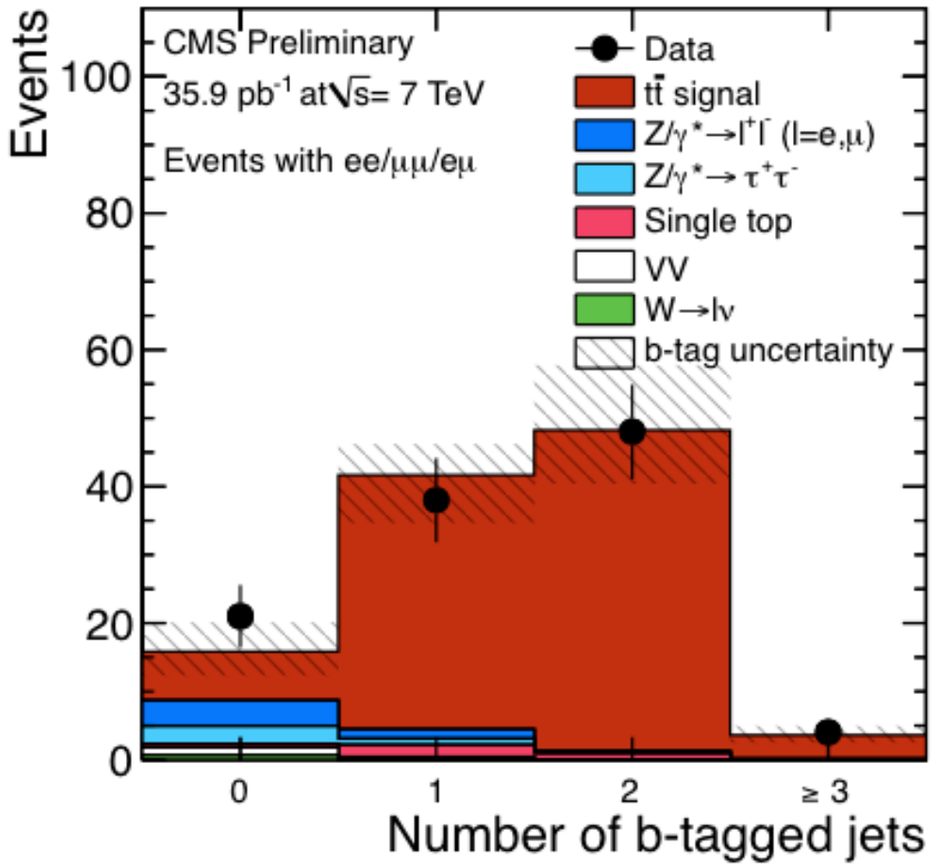




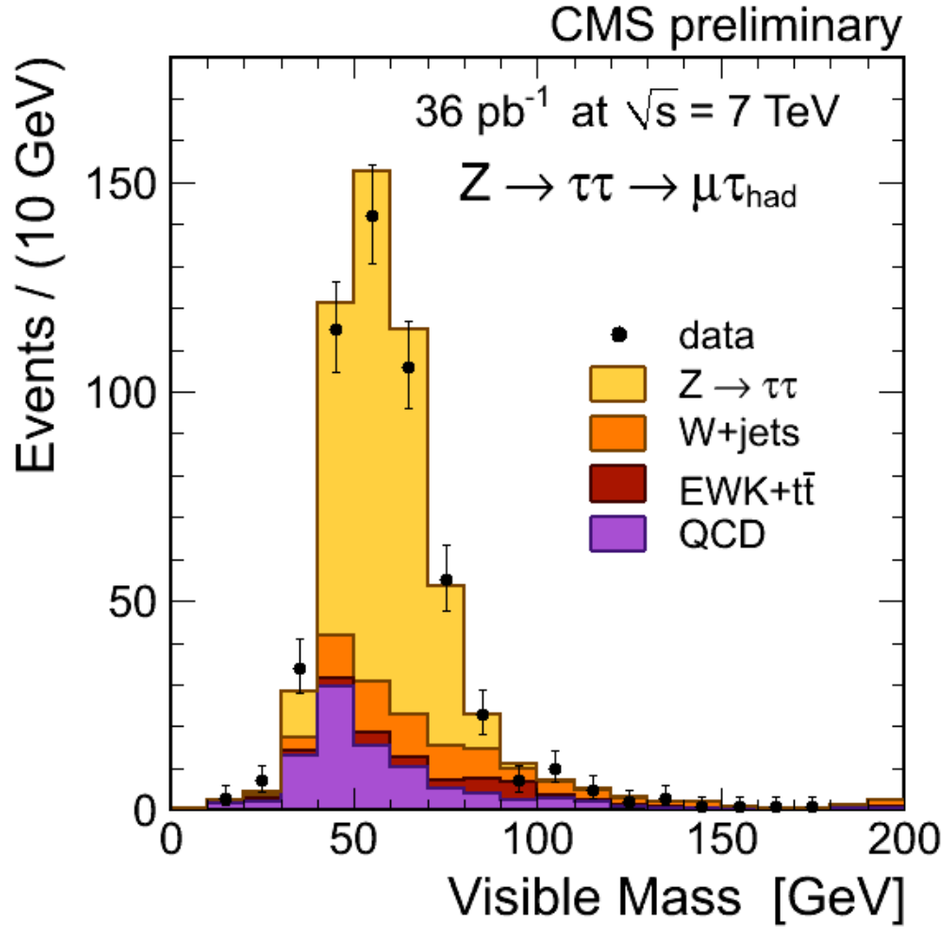
- Beautiful reconstruction of W and Z bosons
- Leptons and MET reconstruction performing well

B and τ tagging

CMS-TOP-10-005

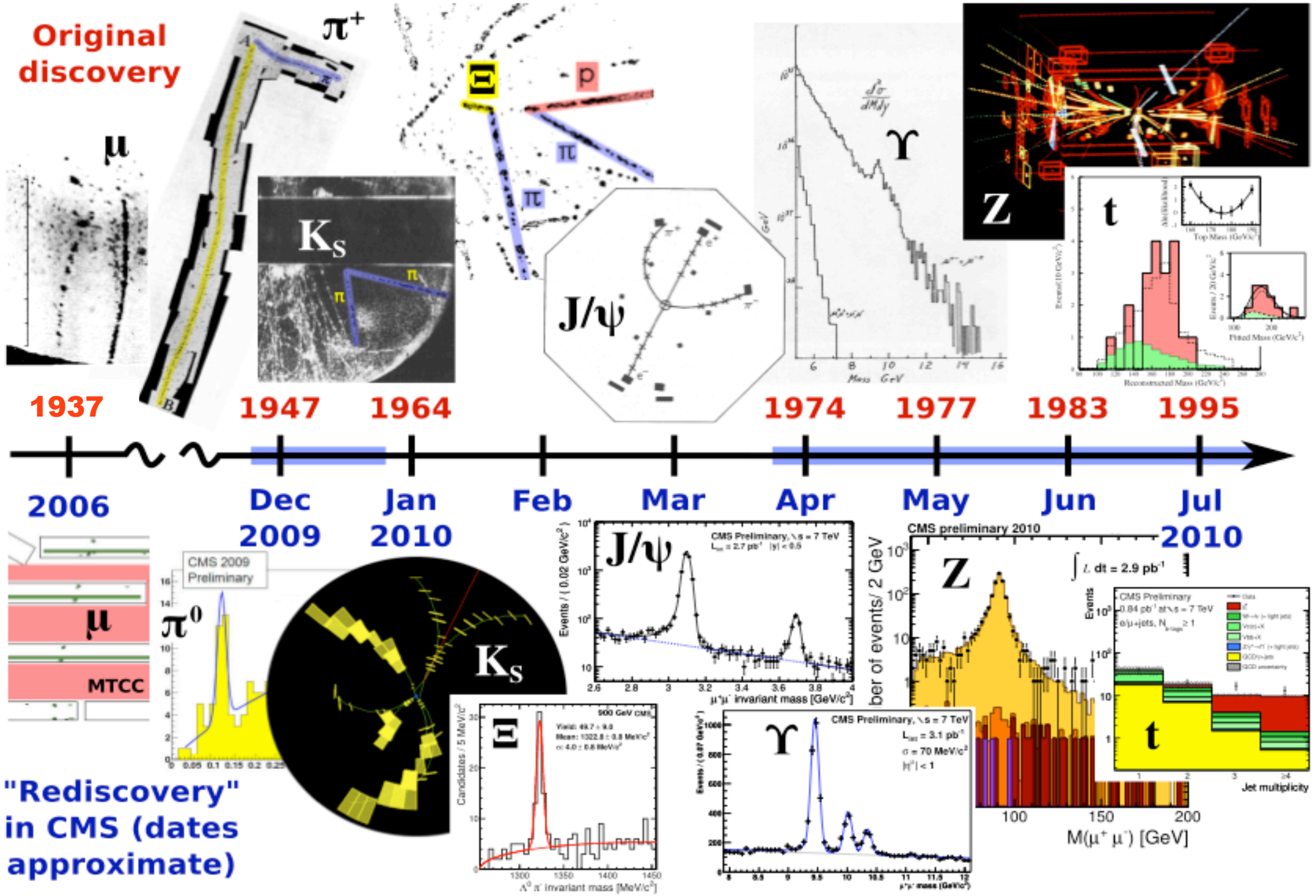


CMS-EWK-10-013



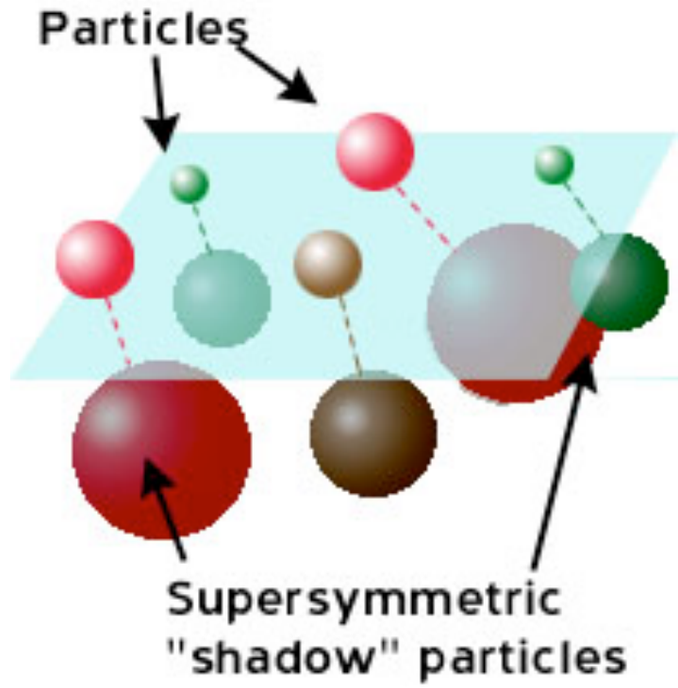
- Top-quark pair-production and Z→ $\tau^+\tau^-$
- b-tagging and τ-tagging performing well

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



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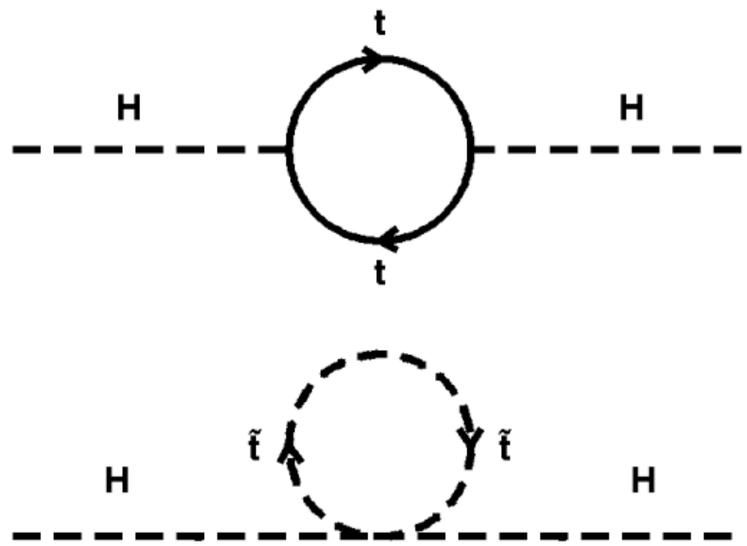
  - It provides a solution to the hierarchy problem



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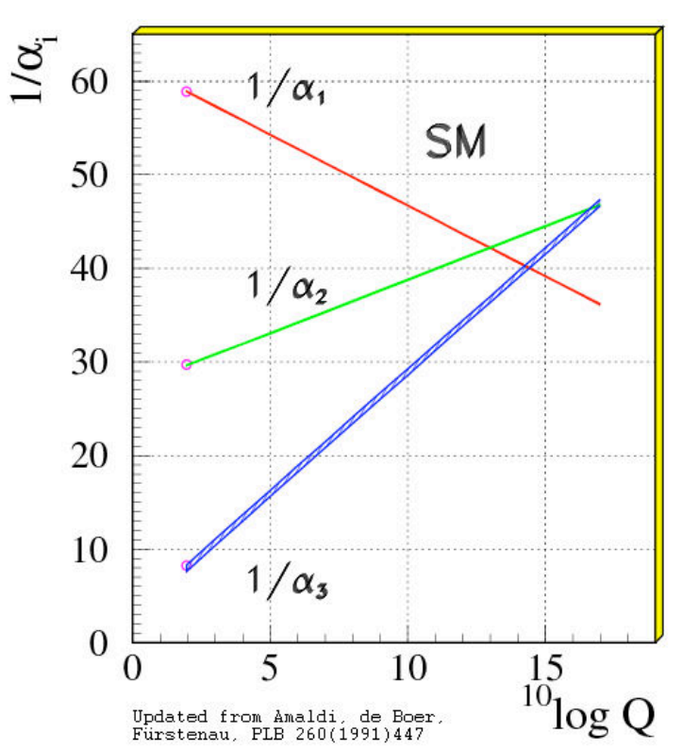

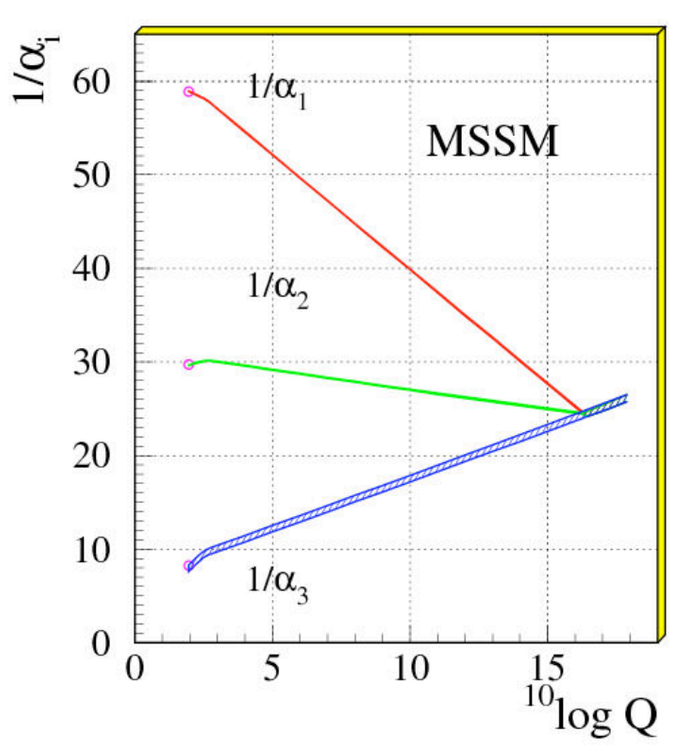

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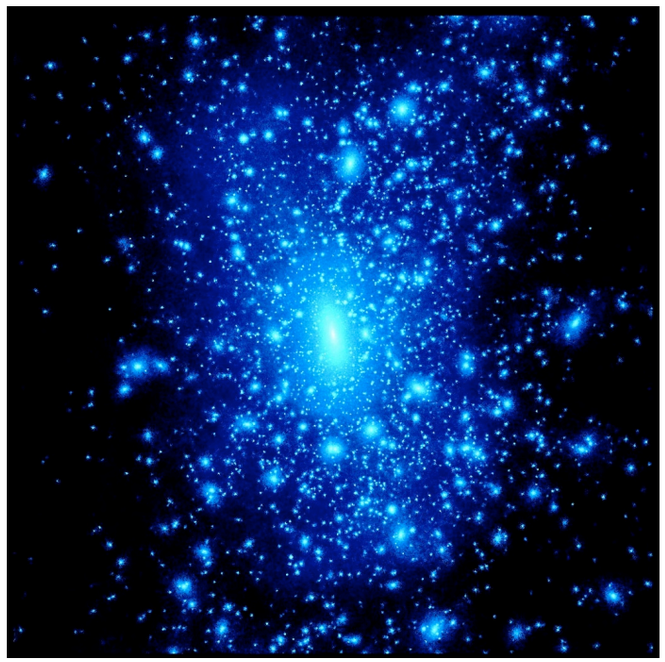

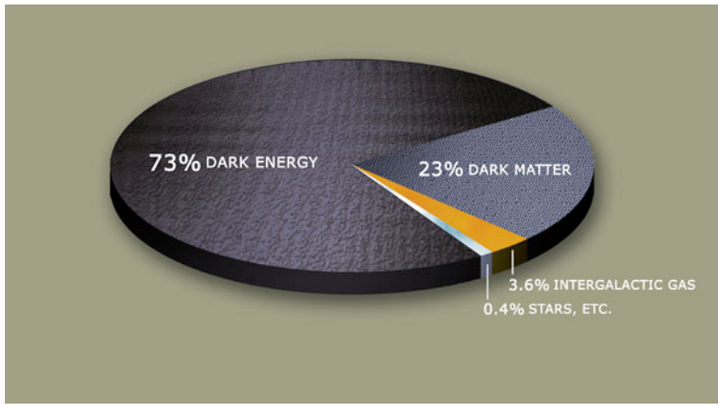

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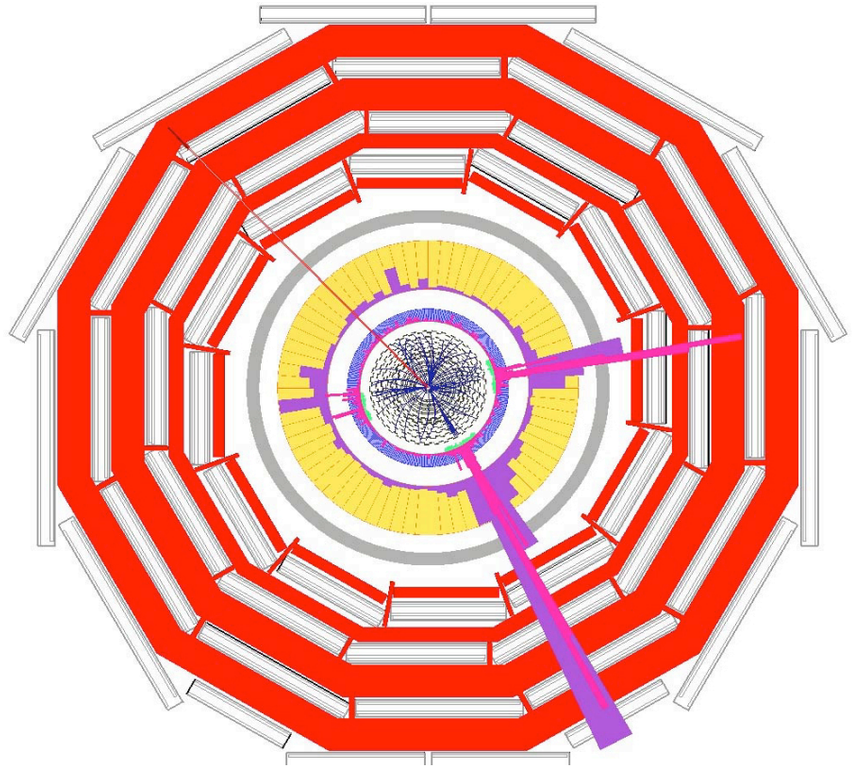
- Experimentalists love it because:
  - Plethora of new particles to discover and measure



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  - 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:
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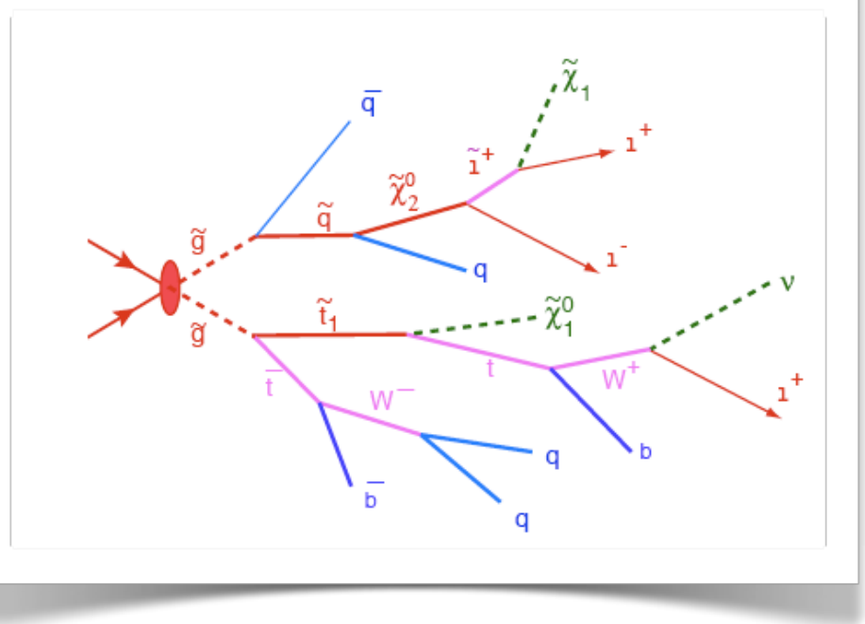
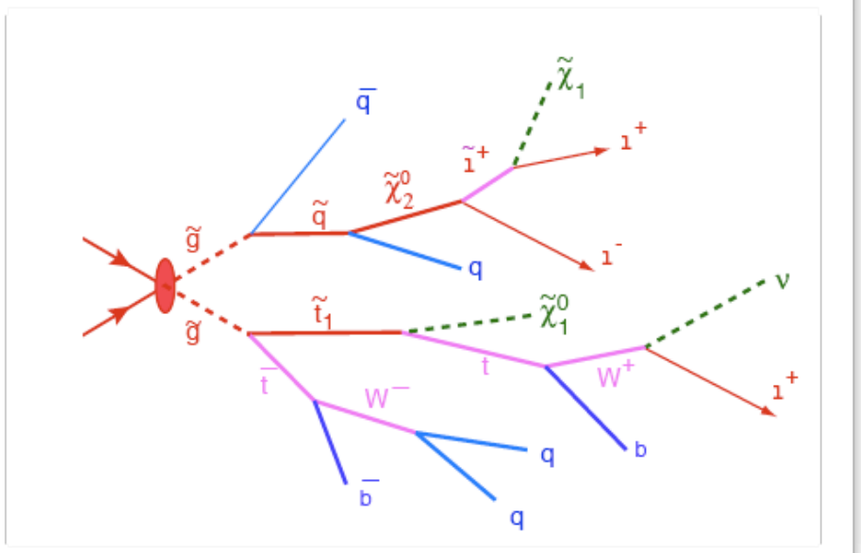
- Symmetry not exact
  - SUSY and Standard Model particles have different masses
  - SUSY is broken ➔ what does it look like and how do we search?

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?)

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- 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?)

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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?)

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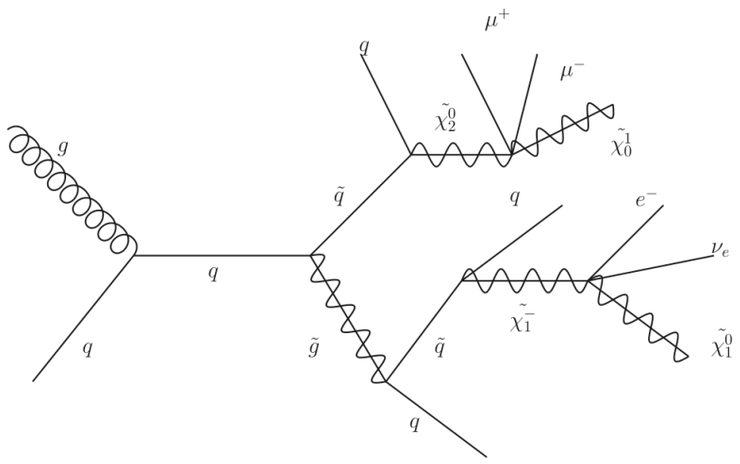

- A natural SUSY signature
- Very small Standard Model backgrounds
- Include all three generations of leptons and all cross channels

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?)

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- 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?)

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

Search strategy (what and how?)

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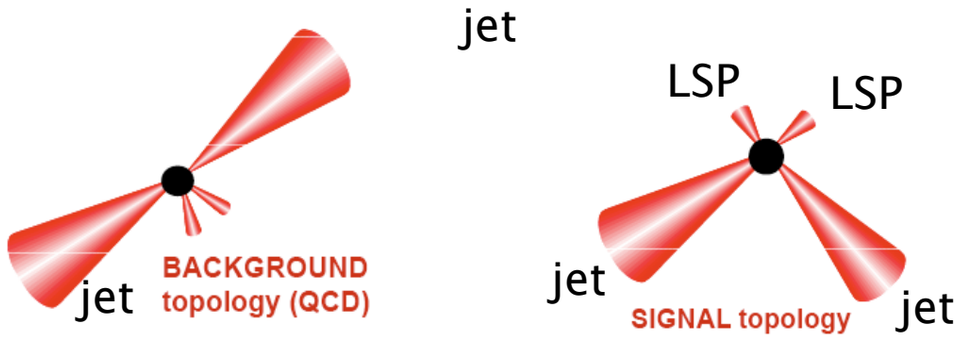
RPV	"Exotic"
R-Parity violating searches	Long-lived particles etc.

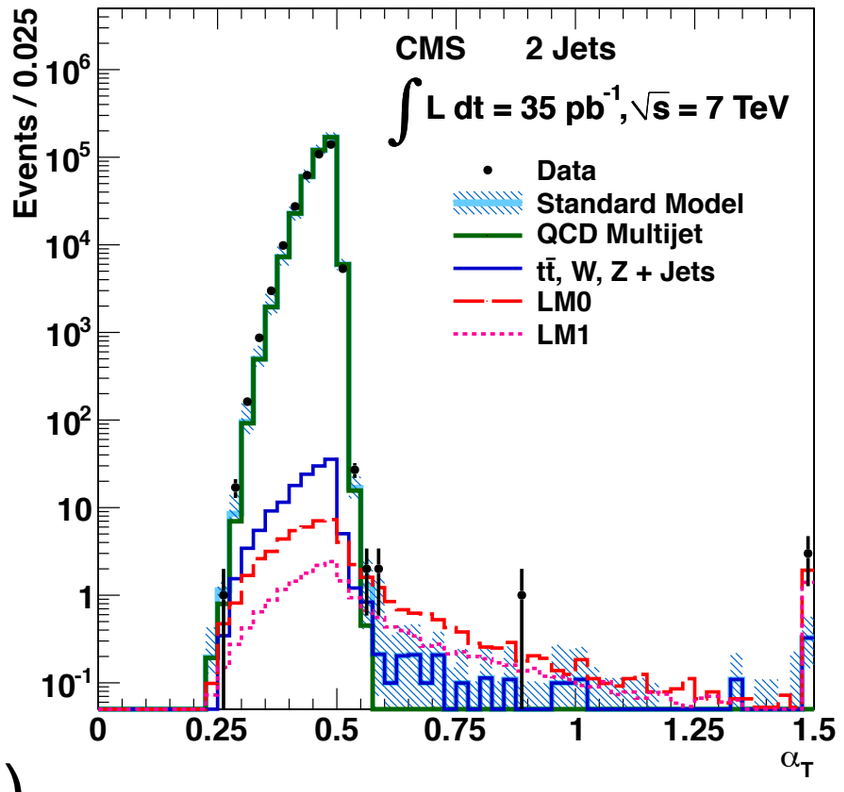
- Non-MET based searches
- R-parity conserving and "exotic" SUSY
- Examples are long-lived particles
- Not covered in this talk but well-studied in CMS
- See https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

Hadronic search with α_T

PRL101:221803 (2008) & arXiv:1101.1628

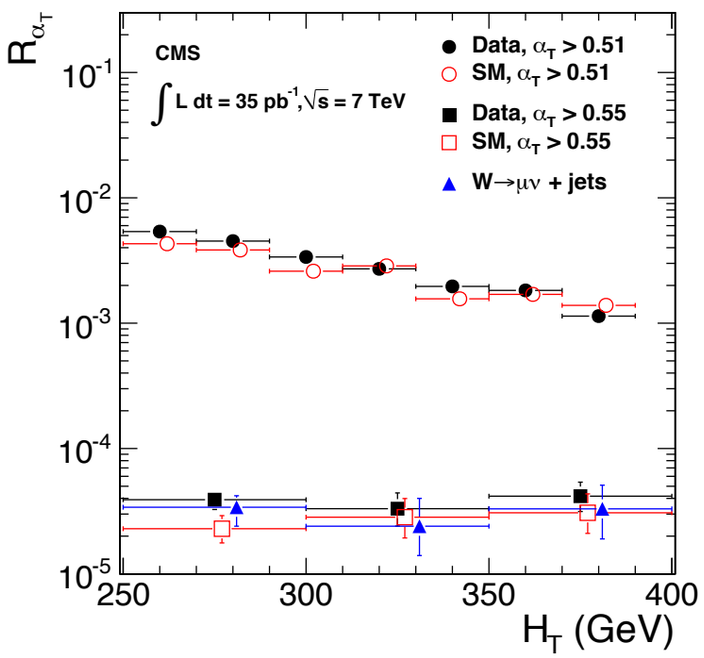


$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1\,j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$



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

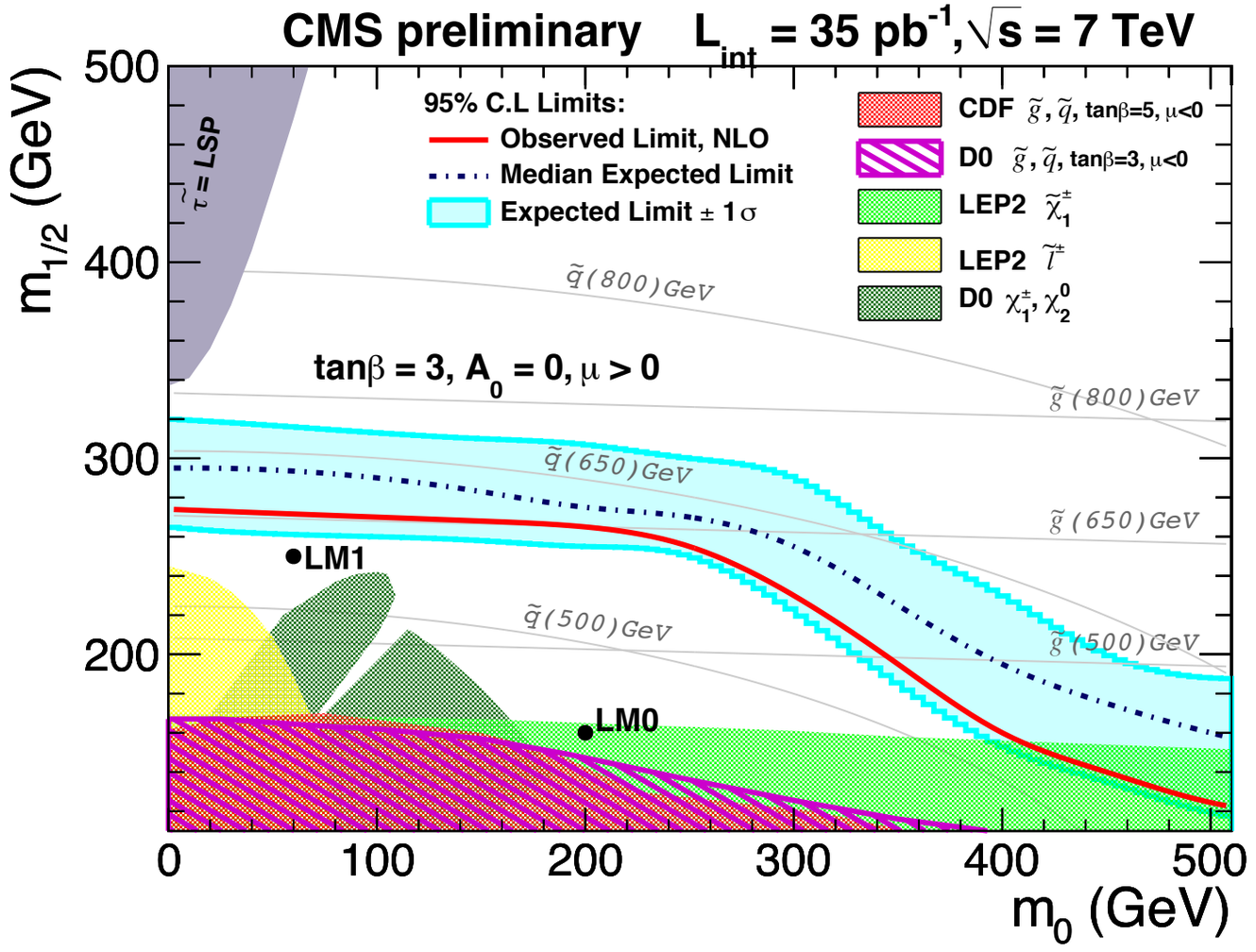
W and ttbar from muon control sample

Z to inv from photon+jets

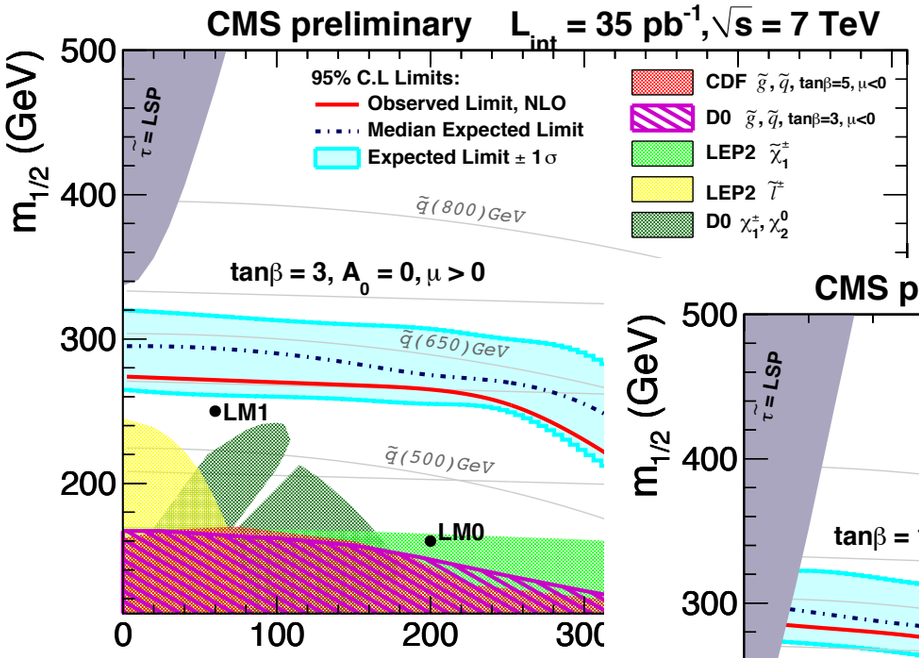
Hadronic search with α_T

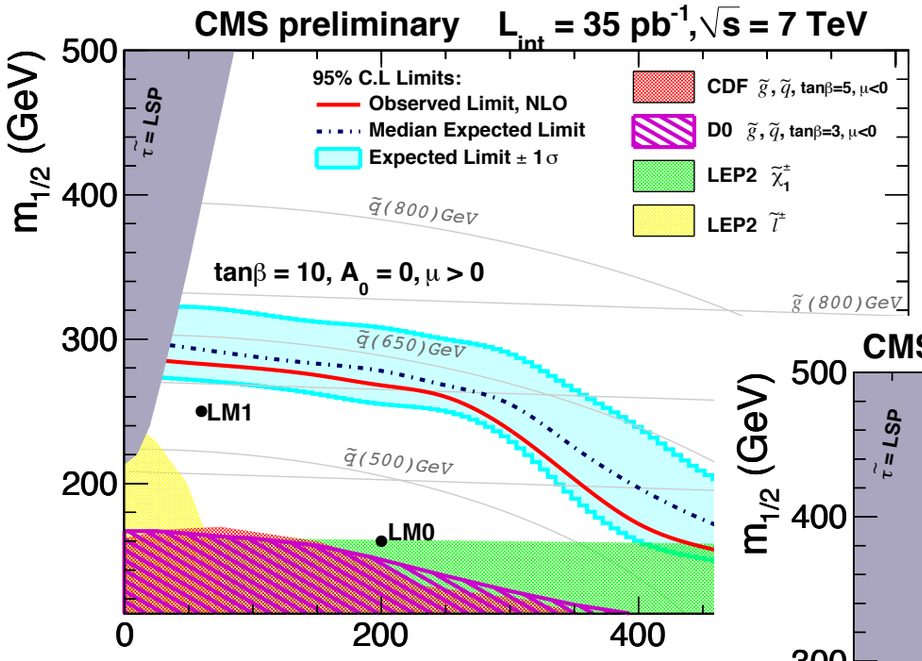
arXiv:1101.1628

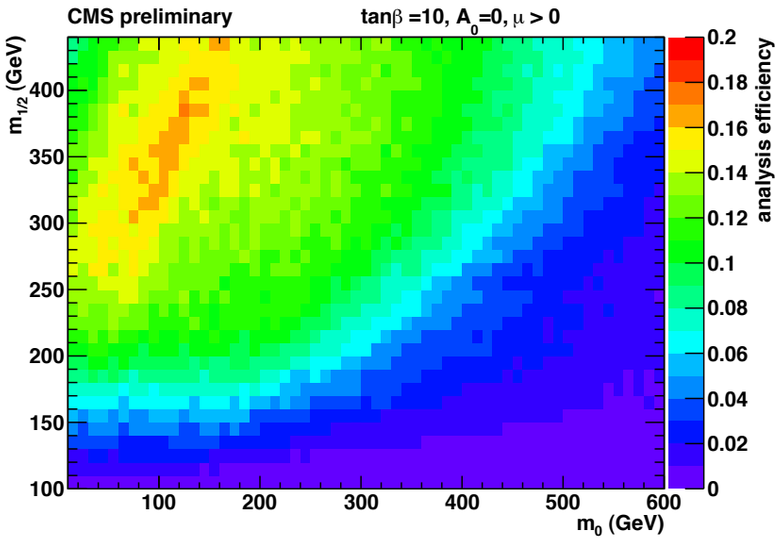
- Interpret in CMSSM for easy comparison with previous experiments
- $\tan\beta=3$ $A_0=0$ $\mu>0$
- Significant extension of excluded region over Tevatron experiments

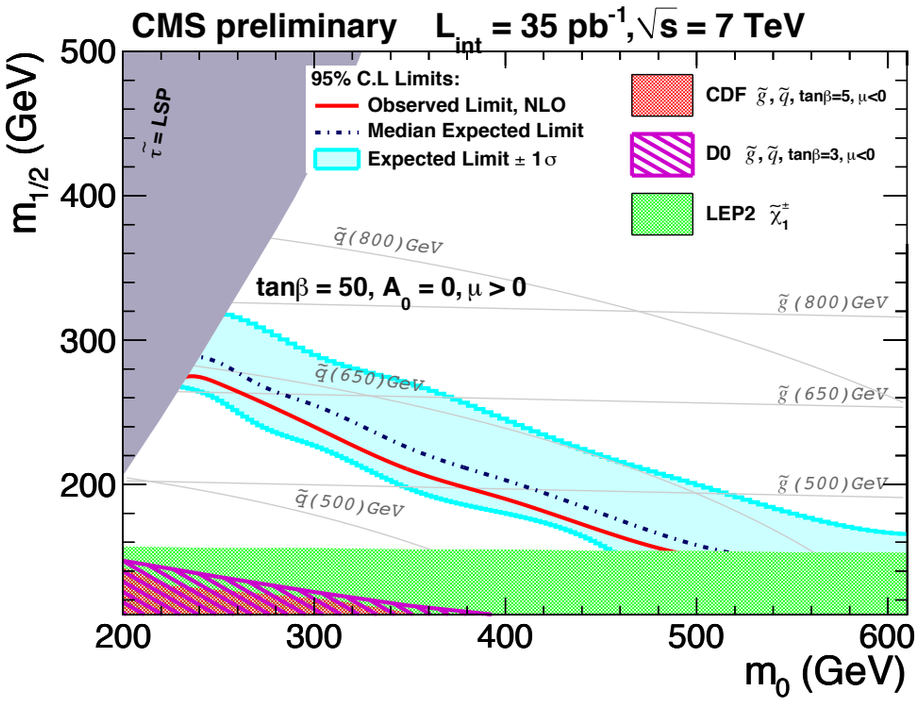


Hadronic search with α_T







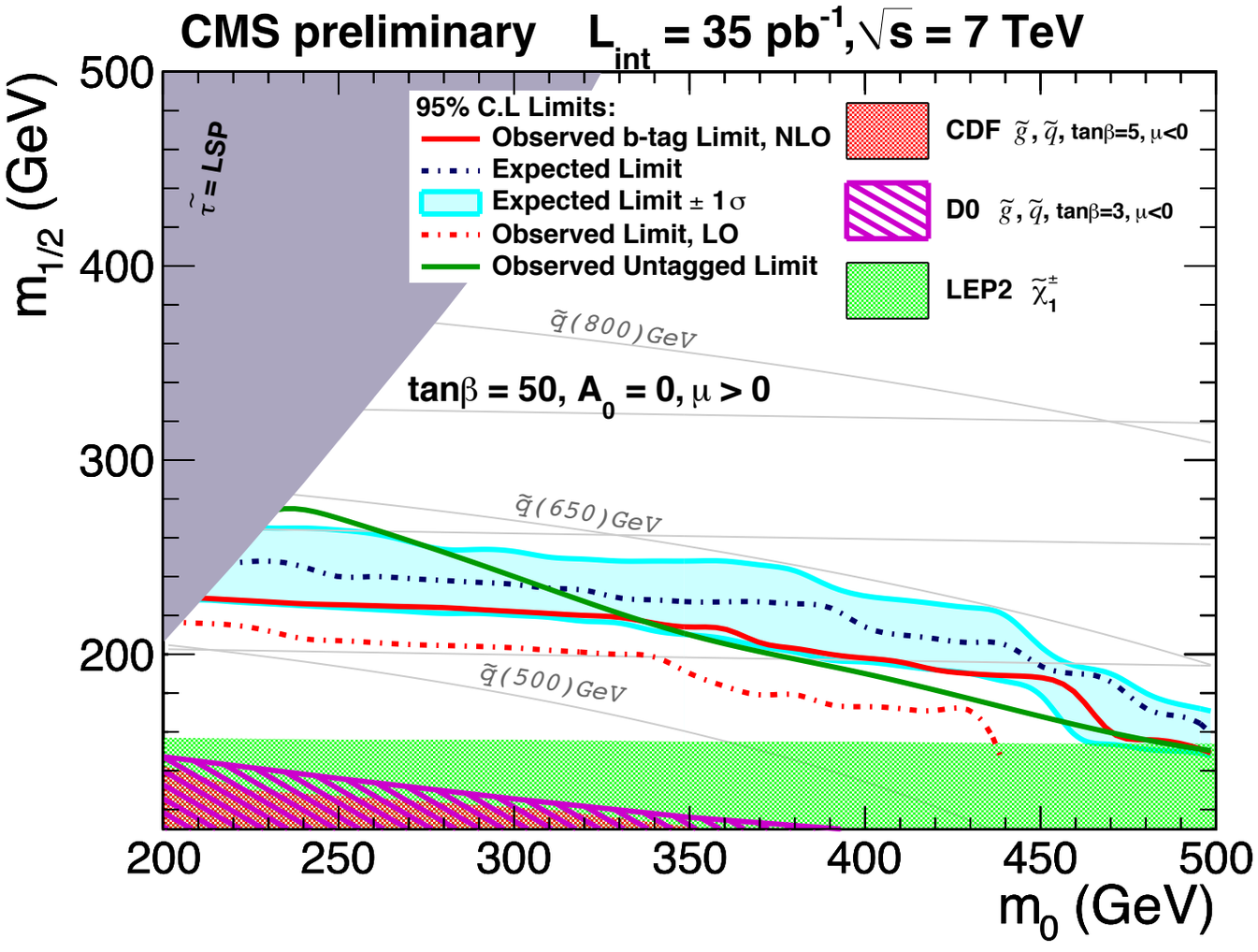


CMS-SUS-11-001

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

Hadronic search α_T + b-tag

CMS-SUS-10-011



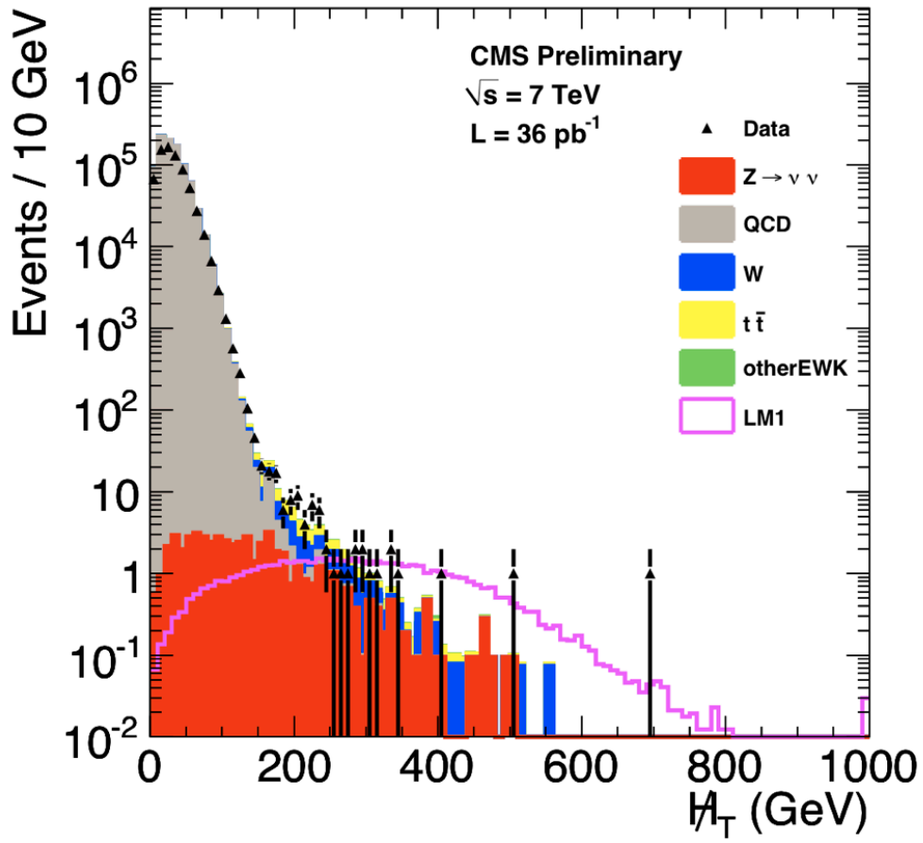
- Same as search with α_T but add the requirement that one of the jets must be b-tagged
- Reduces non-top backgrounds
- Increased sensitivity for b-rich models

- 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

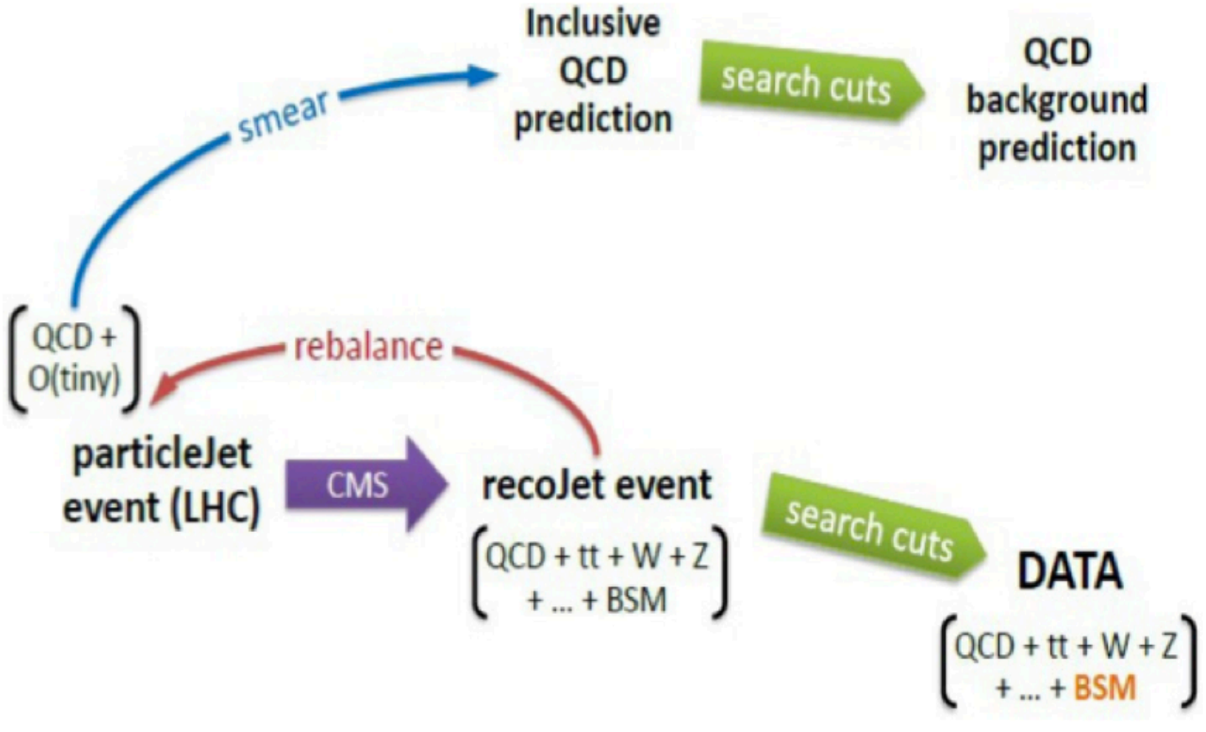
- Analysis based on understanding the detector response in detail
- Complementary to kinematics-based searches
- Baseline selection
  - At least 3 jets with E_T>50 GeV & |η| <2.5 anti-kT (0.5)
  - H_T>300 GeV and MHT > 150 GeV
  - Veto isolated electrons and muons
- Backgrounds from
  - Multi-jet QCD,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

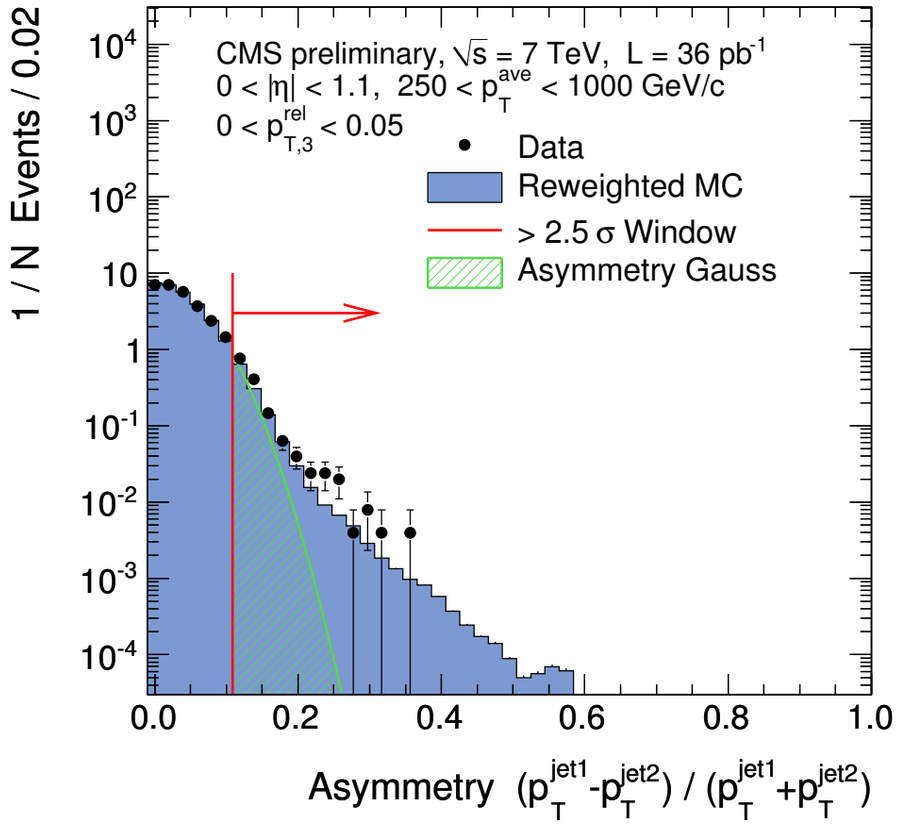


MC backgrounds (illustrative)

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) ➔

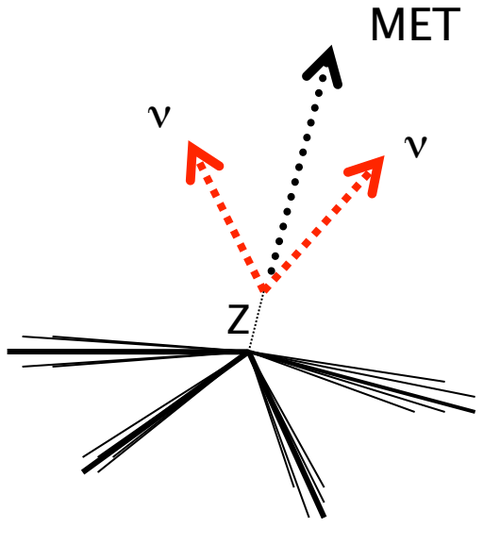


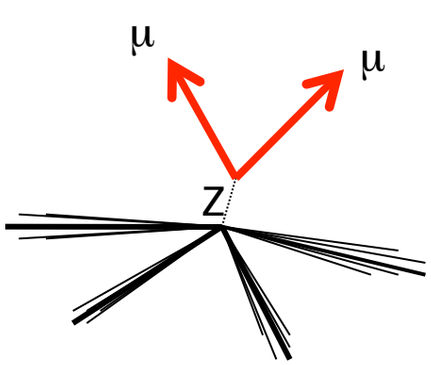


- Obtain a well-balance seed sample by rebalancing multi-jet events
- Makes electroweak and signal contamination negligible
- Apply smearing to each jet to get a background prediction

Z → νν background

- Z → νν + jets → irreducible background
- Replacement technique pursued with all three samples
- γ+jets sample currently used, other cross check

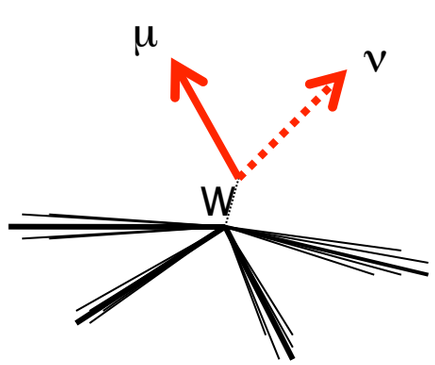




Z → ll + jets

Strength: very clean

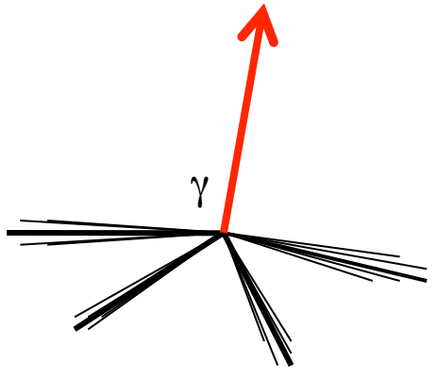
Weakness: low statistics



W → lν + jets

Strength: larger statistics

Weakness: background from SM and SUSY



γ + jets

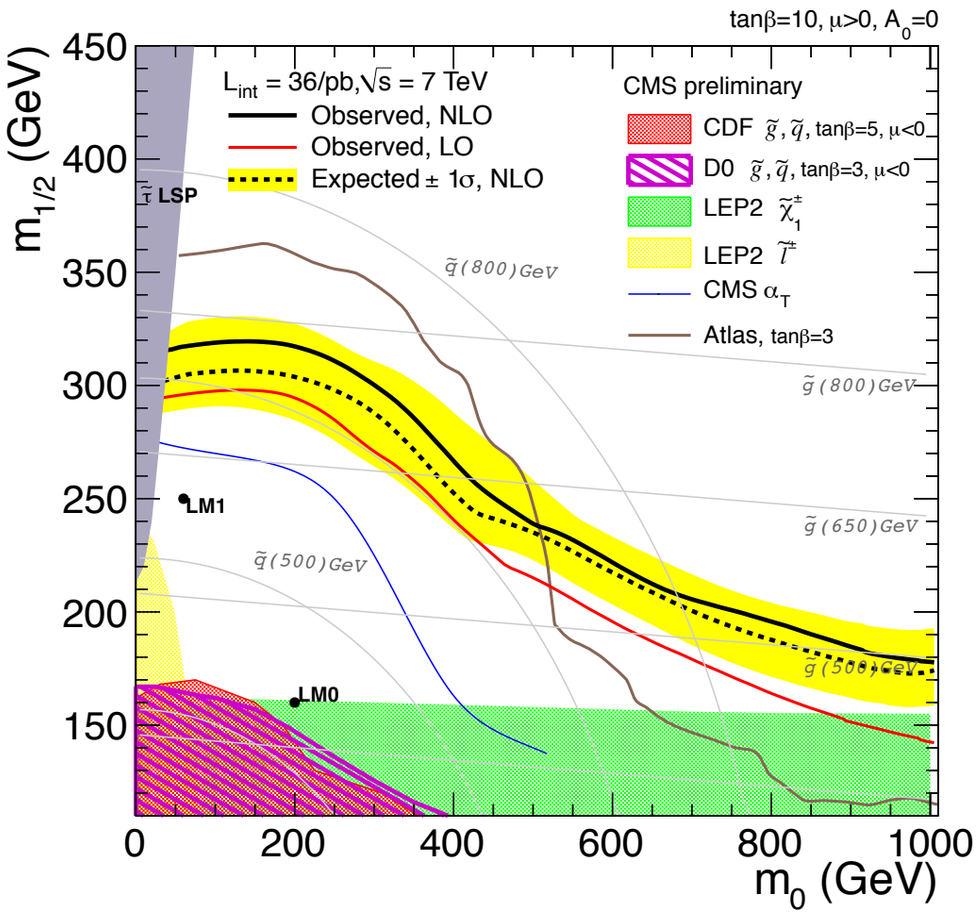
Strength: large statistics and clean at high E_T

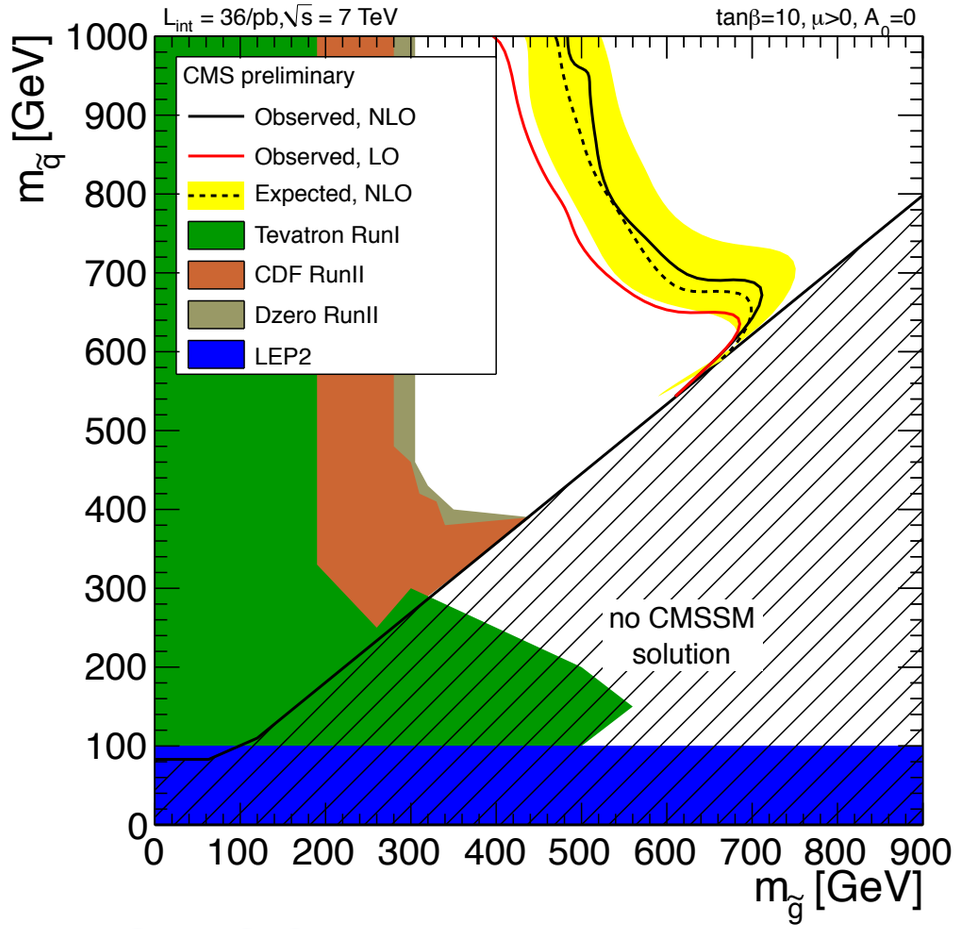
Weakness: background at low E_T, theoretical errors

Hadronic search with missing energy

	Predicted	Observed
MHT > 250 GeV	18.8 ± 3.5	15

	Predicted	Observed
H_T > 500 GeV	43.8 ± 9.2	40





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

CMS-SUS-10-005

Hadronic search with “Razor”

- Introducing the “Razor” variables: M_R and R

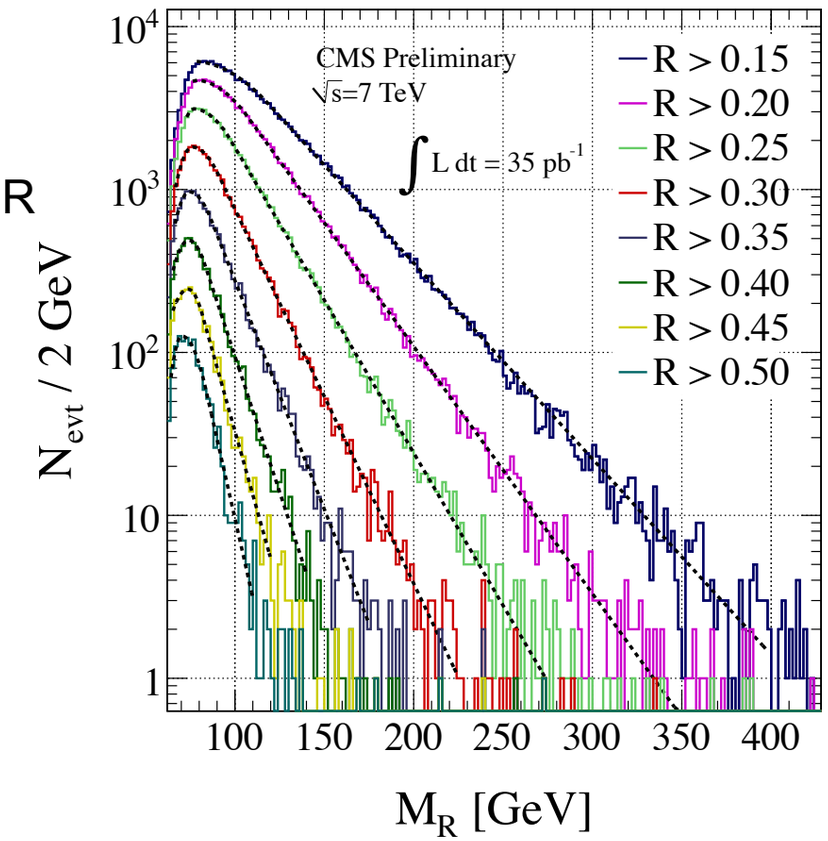
arXiv:1006.2727

  - 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

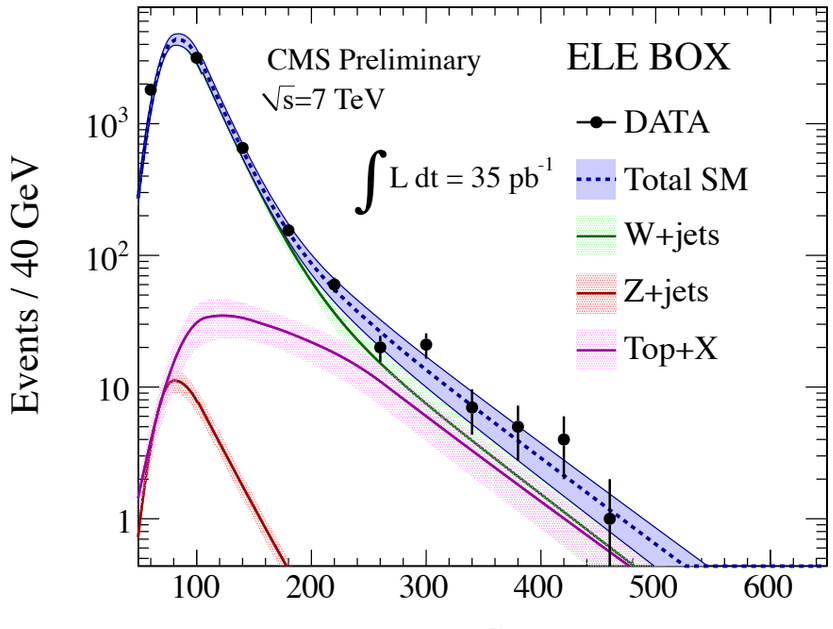
- M_R distribution after R cut shows exponential scaling behaviour ➔

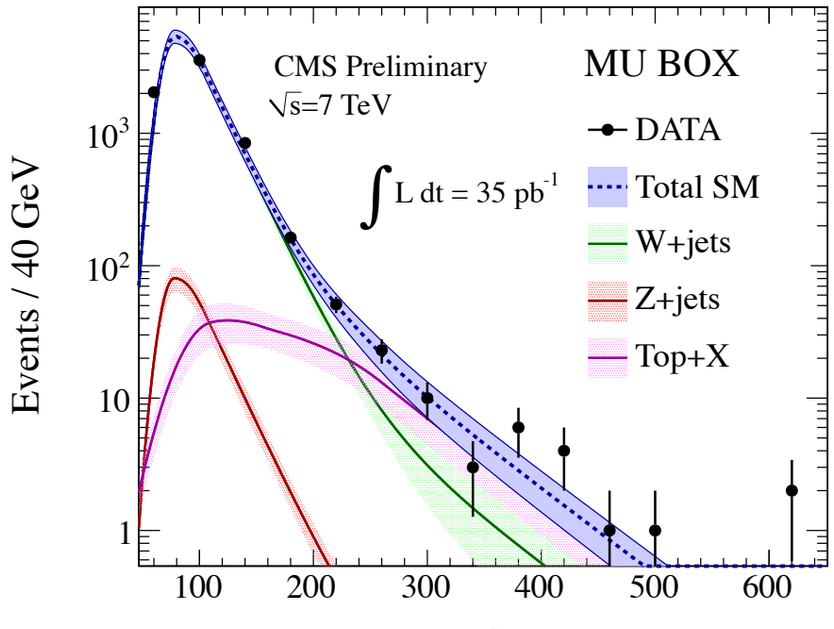


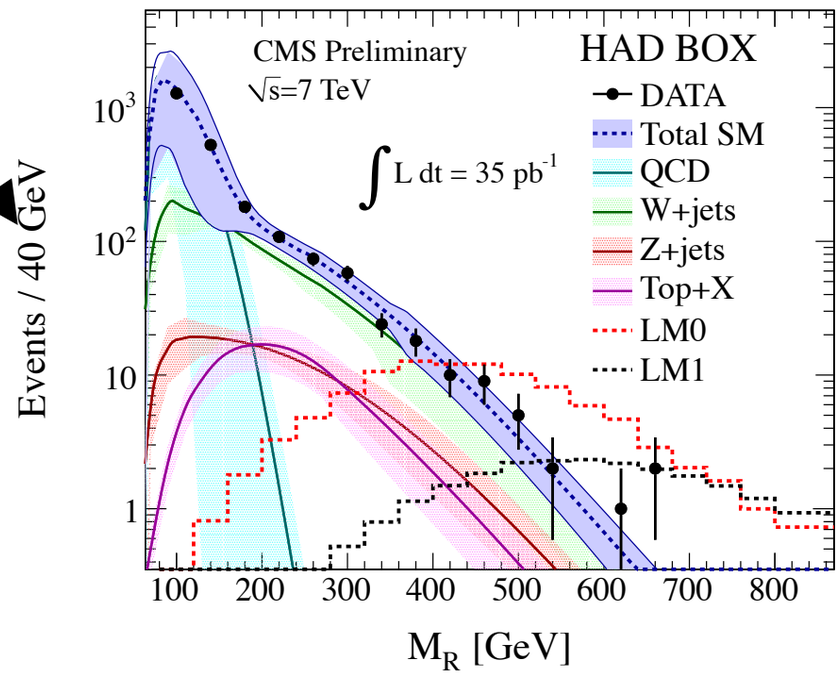
CMS-SUS-10-009

Background estimation

- Exponential scaling property in M_R used for background estimation







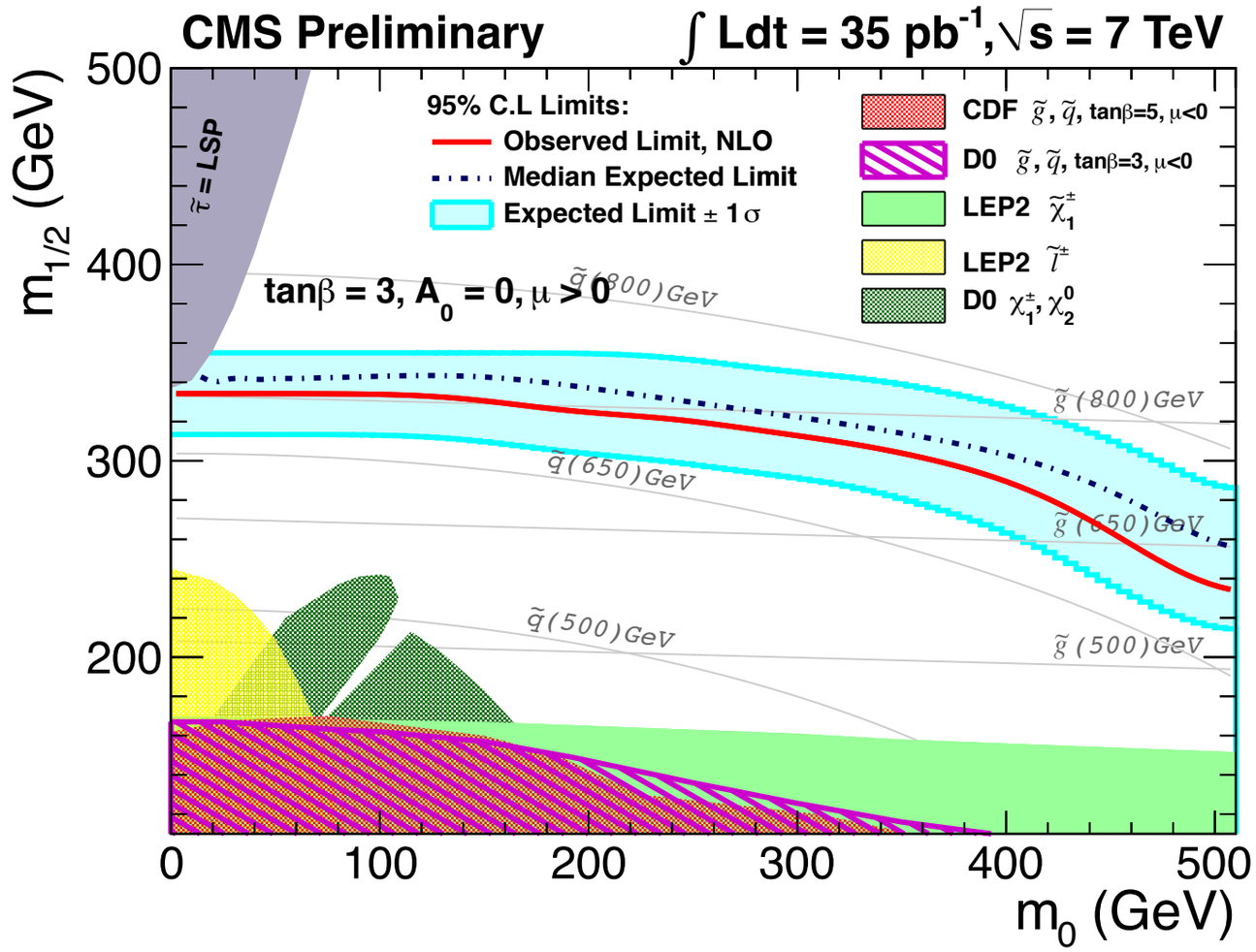
Use electron, muon and low M_R hadronic control samples to predict background in hadronic signal region

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

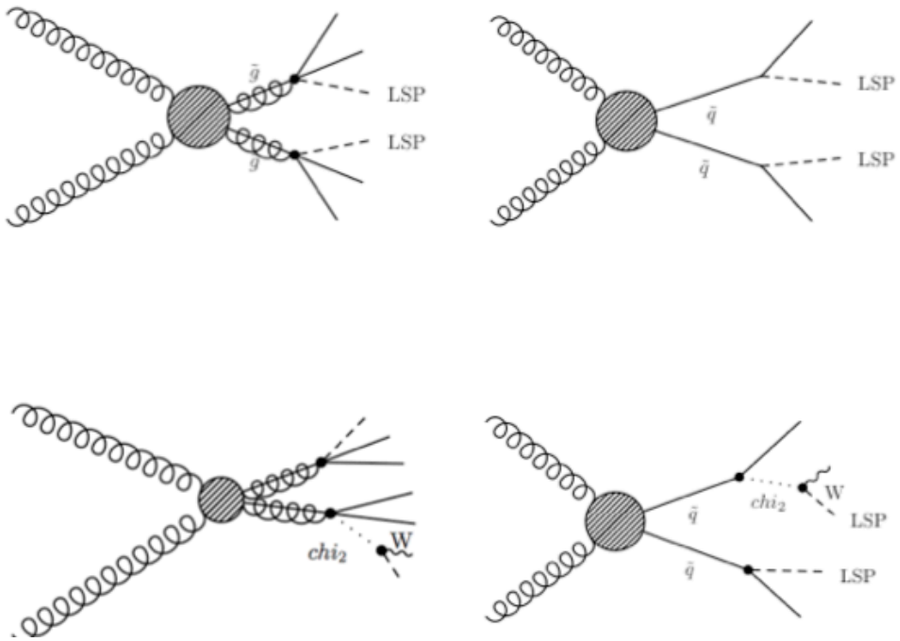
R>0.5	Predicted	Observed
M_R>500 GeV	5.5 ± 1.4	7



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

Interpretation Intermezzo

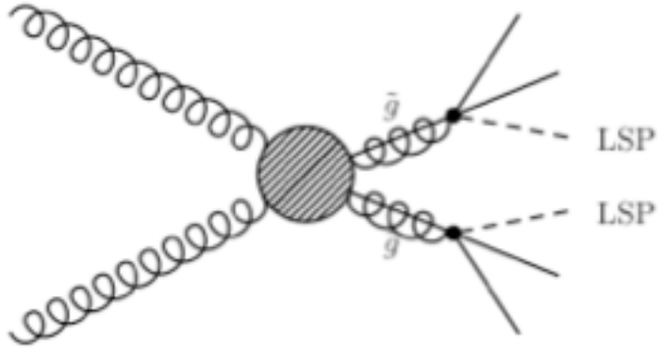
- Working with theorists in context of LPCC
  - Models proposed at: http://www.lhcnewphysics.org
  - Agreed on reference topologies for early searches
  - Cover what one might see in the first ~50 pb^{-1}
  - All initiated by strong production

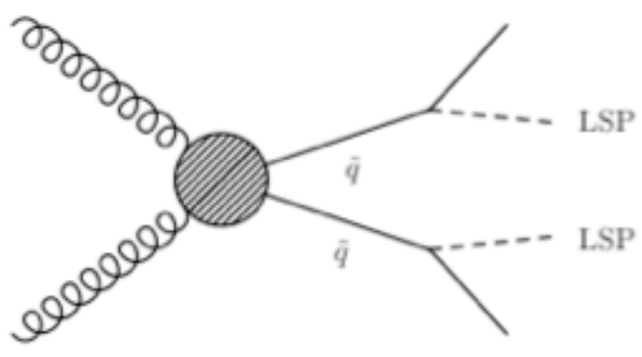


- Hadronic searches
  - Squark anti-squark pair production with decay squark → q + χ
  - Gluino pair production with decay gluino → qqbar + χ
  - χ can be the LSP or an intermediate state, decaying to W + LSP
  - Kinematics specified by masses
  - Direct case $m_{gluino}(m_{squark})$ vs m_{LSP} 2D plot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

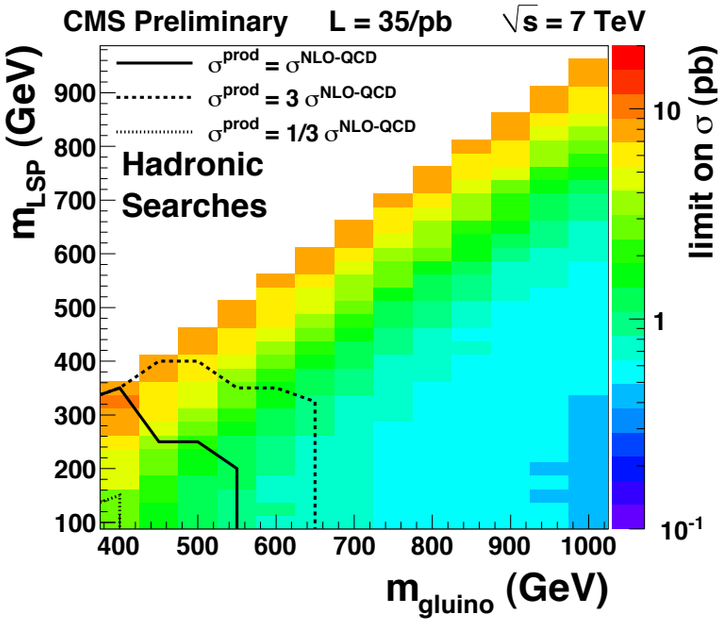
Simplified Model Spectra

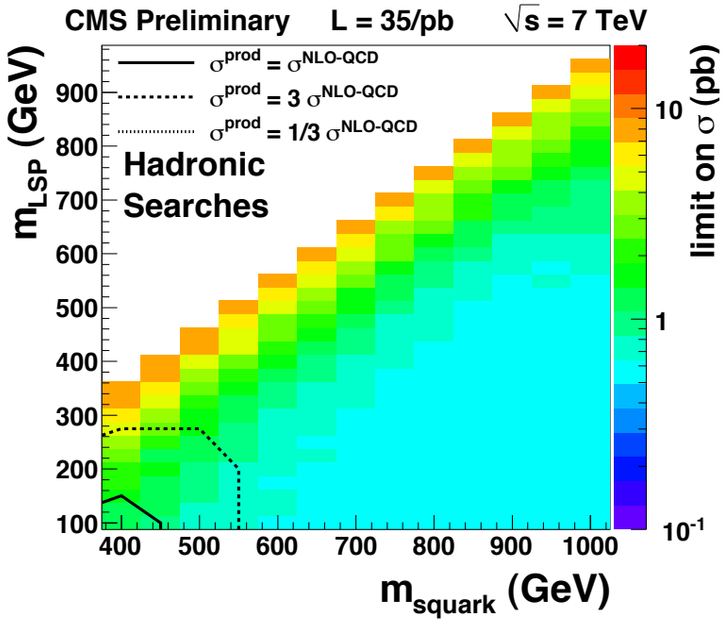
- So far considered squark and gluino pair-production topologies
- Limits are best of three hadronic searches (not a combination)
- Black lines are QCD-like cross sections
- Theoretical uncertainties like ISR simulation under studied
- Will provide all information that goes into this electronically





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 |η|<2.4

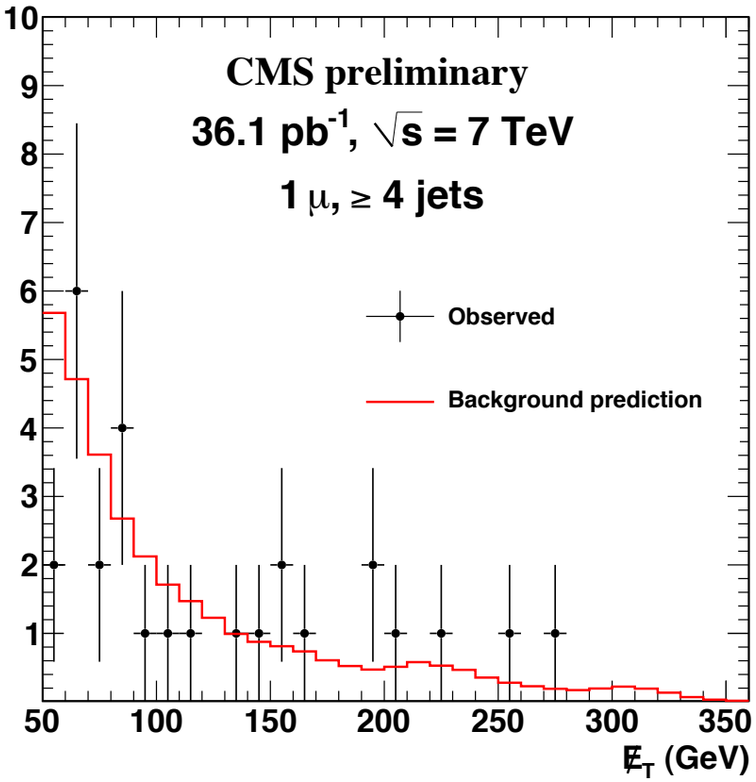
- Study selected events
  - Simulation predicts background from top and W+jets
  - General event properties well understood

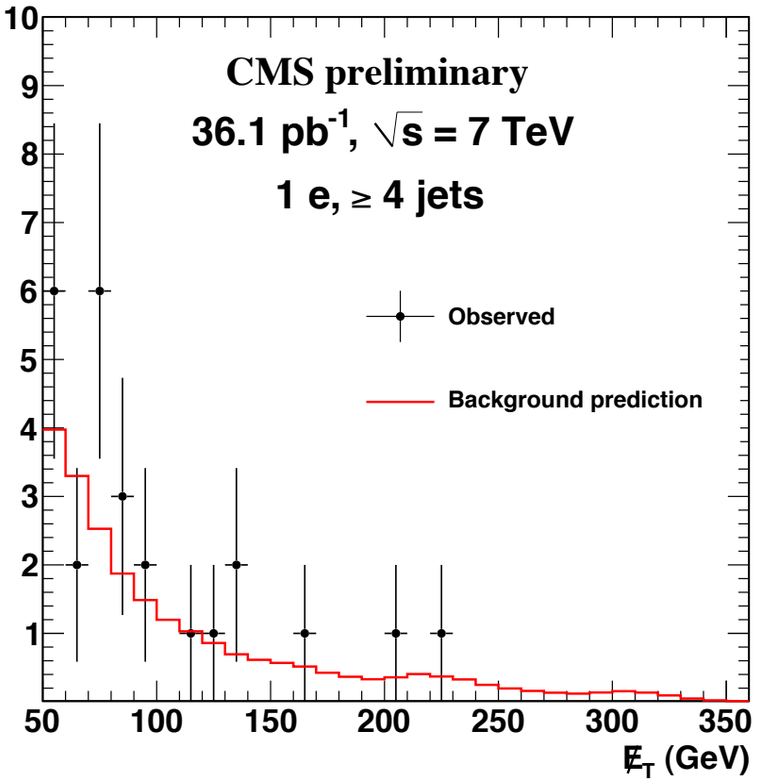
- Determine backgrounds from data ➔

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





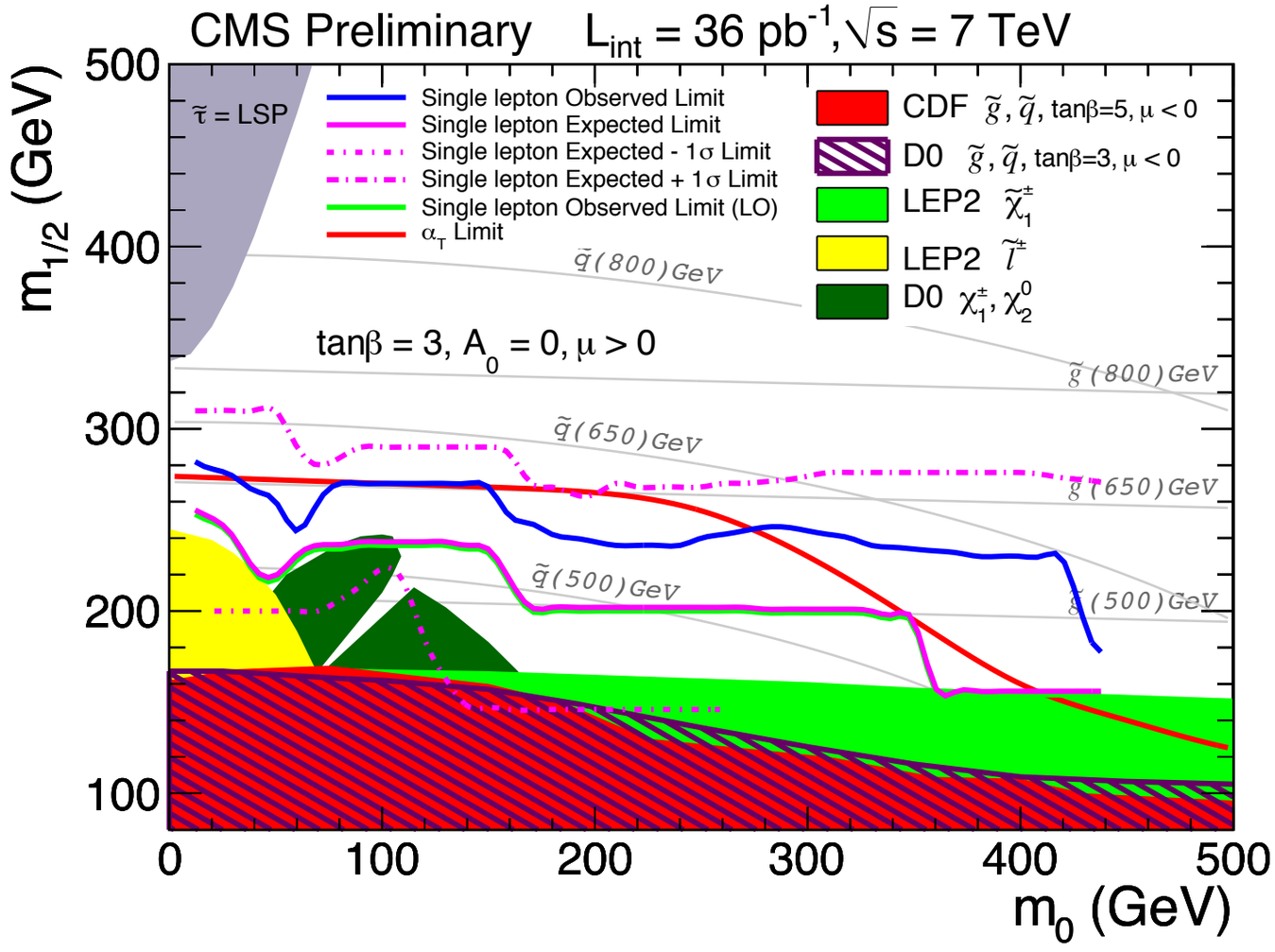
- Take muon p_T spectrum (cleaner than electron)
- Correct for acceptance, efficiency and polarisation effects
- MET resolution worse than for e/μ ➔ measure in data and smear
- Powerful technique based on fundamental physics
- Other techniques for smaller backgrounds (ttbar to dileptons, QCD etc.)
- 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 ℓ	1.7 ± 1.4	1.2 ± 1.0
Predicted SM dilepton	$0.0^{+0.8}_{-0.0}$	$0.0^{+0.6}_{-0.0}$
Predicted single τ	0.29 ± 0.22	$0.32^{+0.38}_{-0.32}$
Predicted QCD background	0.09 ± 0.09	$0.0^{+0.16}_{-0.0}$
Total predicted SM	2.1 ± 1.5	1.5 ± 1.2
Observed signal region	2	0



- Limit similar to hadronic α_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 |η|<2.5

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

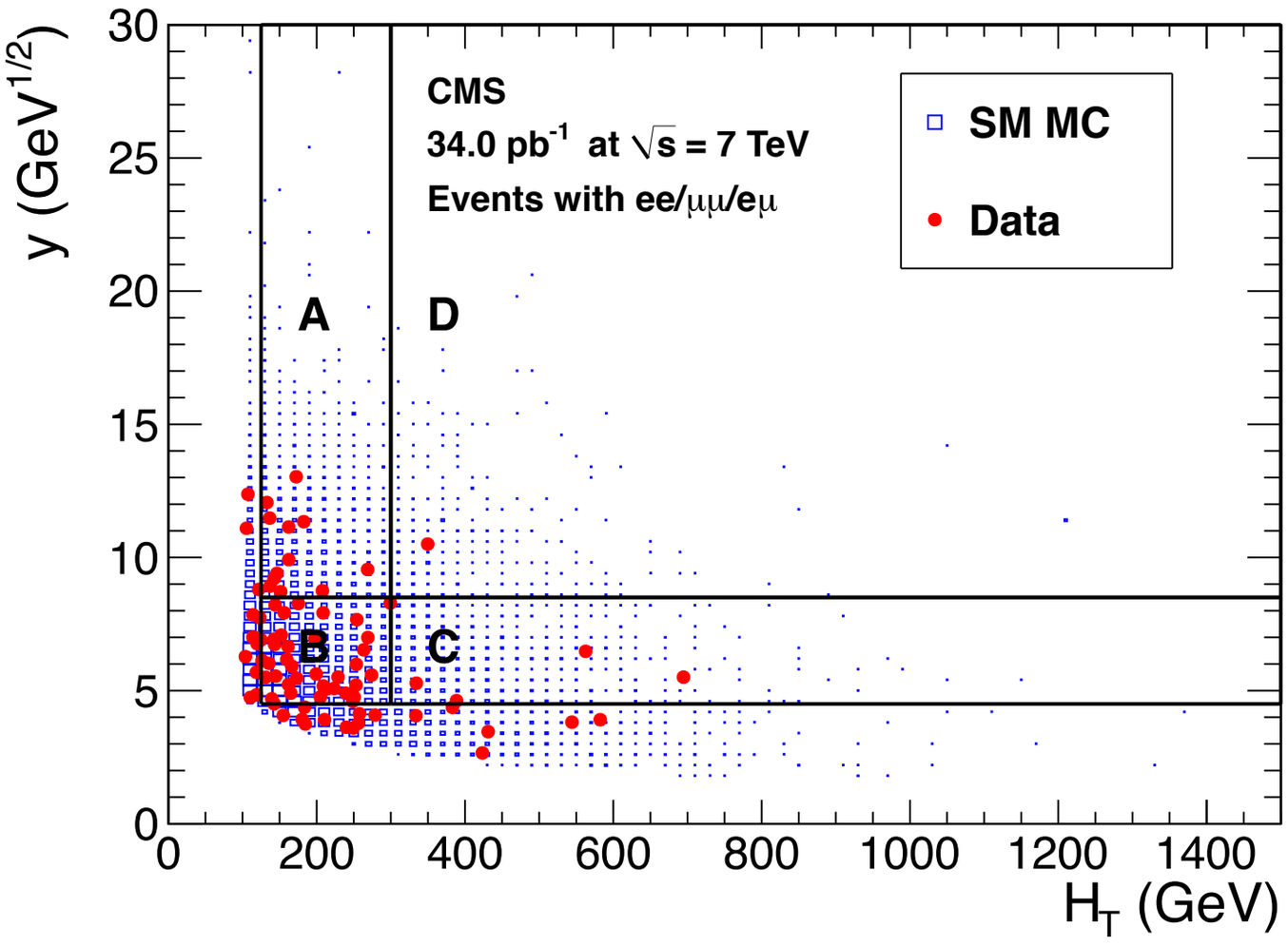
- Determine backgrounds from data ➔

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

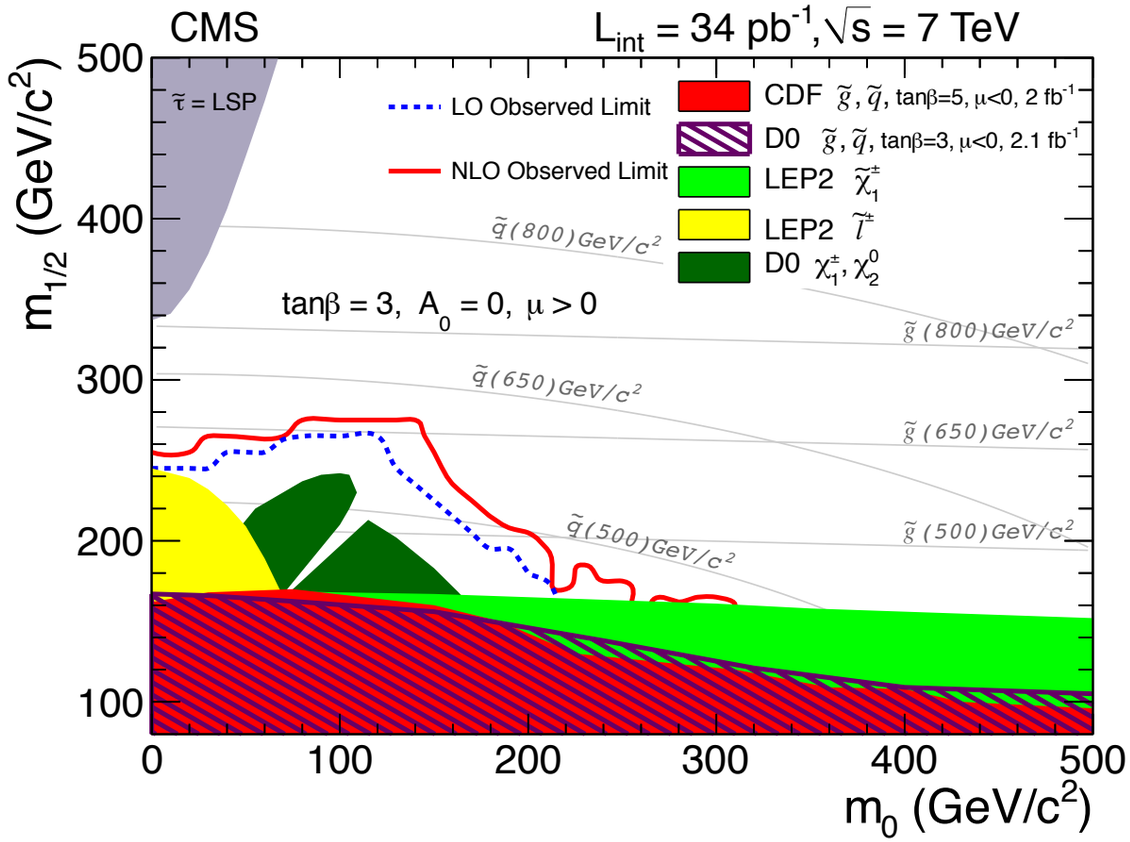


- Also use lepton p_T spectrum method described earlier

Opposite-sign dilepton result

arxiv:1103.1348

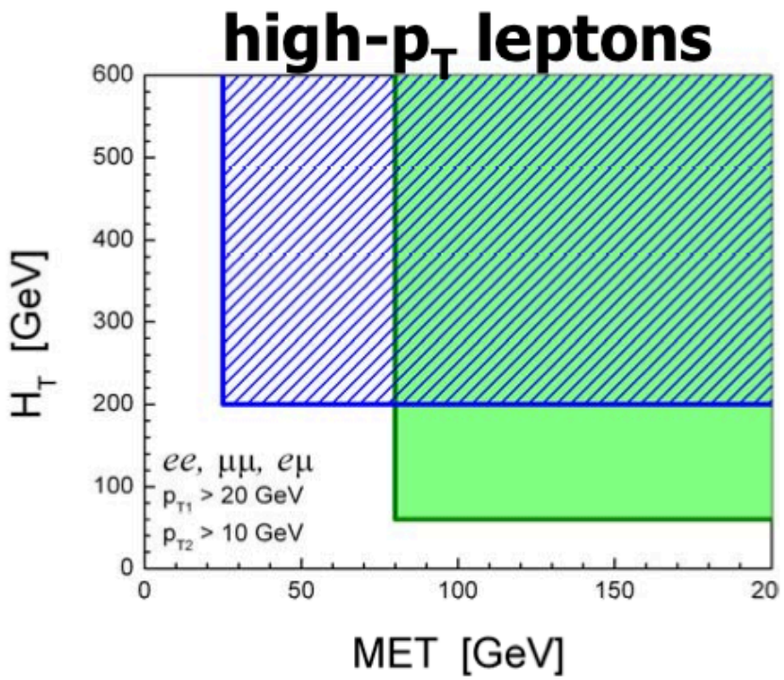
	Predicted	Observed
Region D	1.3 ± 0.8	1

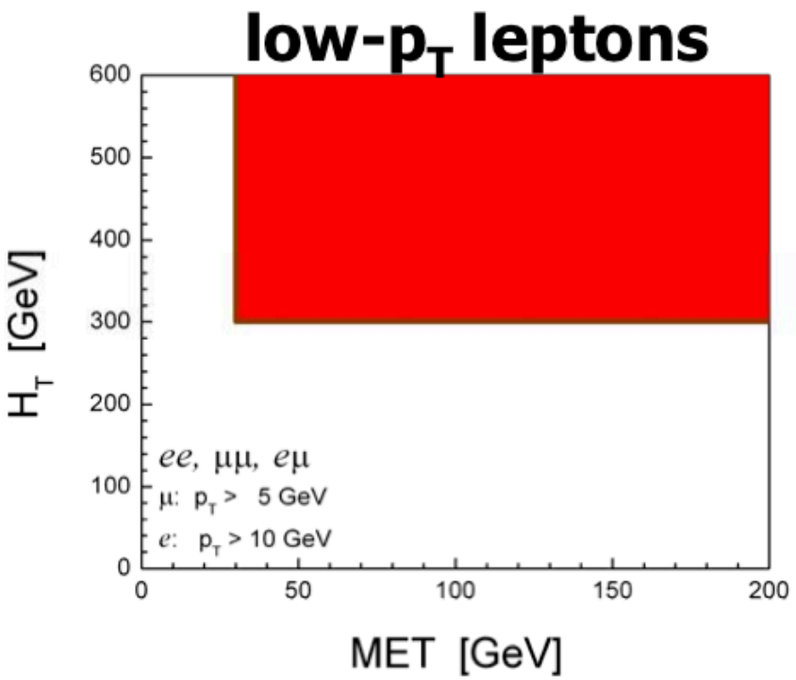


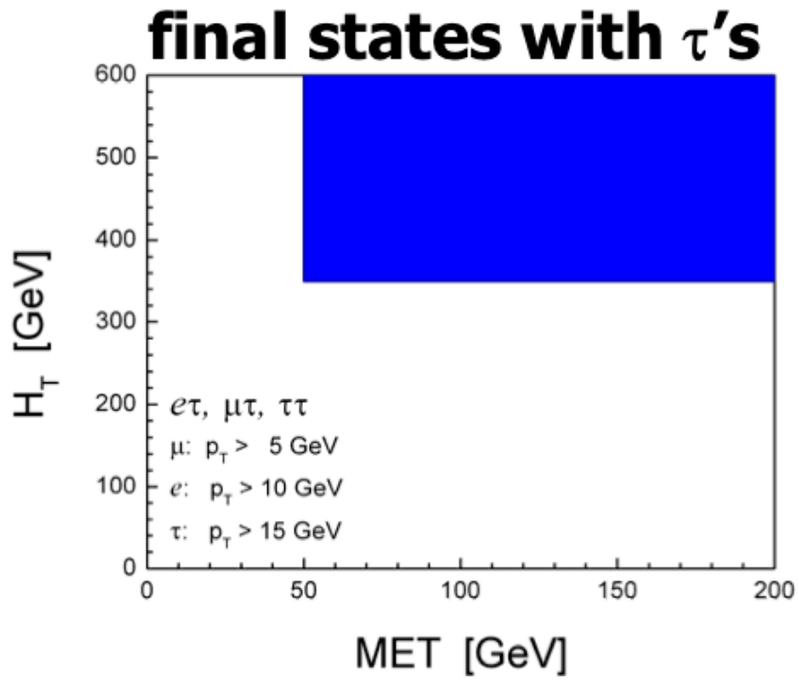
- Limit in CMSSM beyond previous Tevatron searches
- Also result from opposite-sign opposite-flavour subtraction
  - Observed in data: ee:0 μμ:0 Predicted background: ee: $0.1^{+1}_{-0.4}$ μμ: $0.5^{+1.2}_{-0.4}$
  - Powerful technique to obtain mass edge in the case of SUSY

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



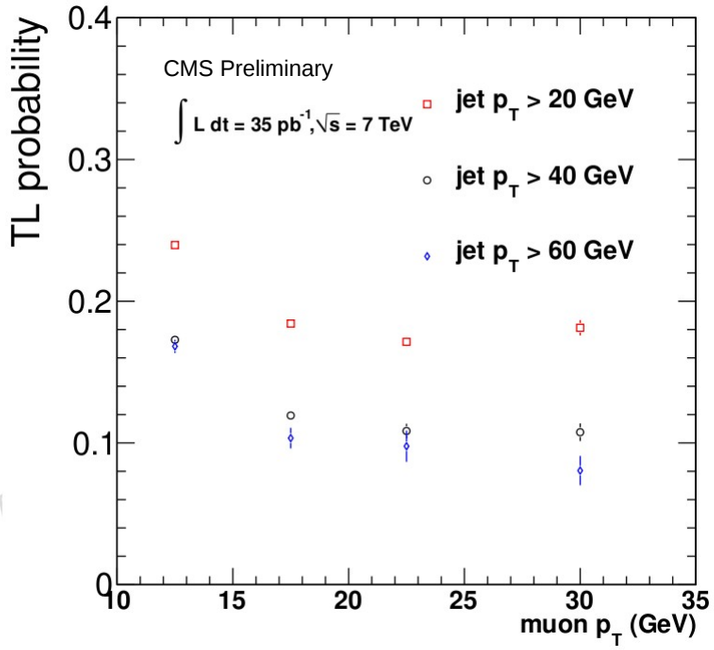


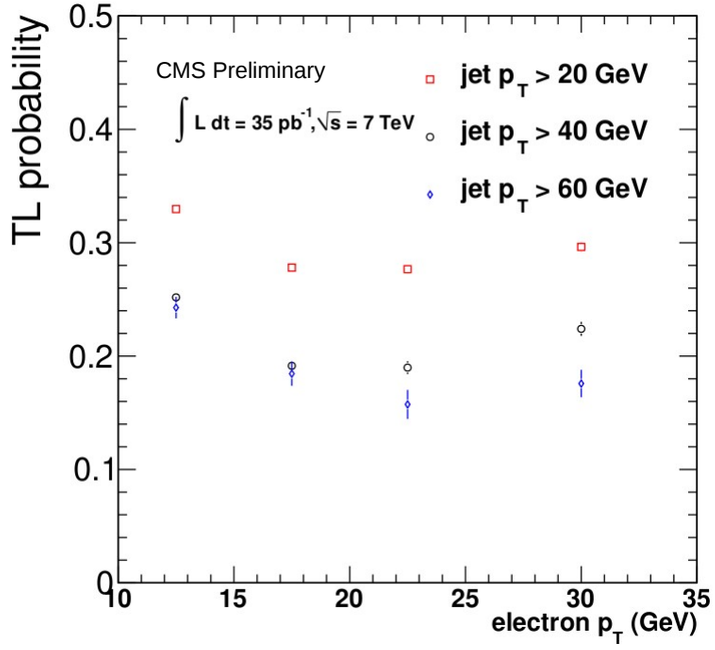


- Dominant backgrounds
  - ttbar: one isolated lepton from W, one from semi-lep b/c decay in jet
  - QCD: larger for hadronic τ final states

Background from ttbar

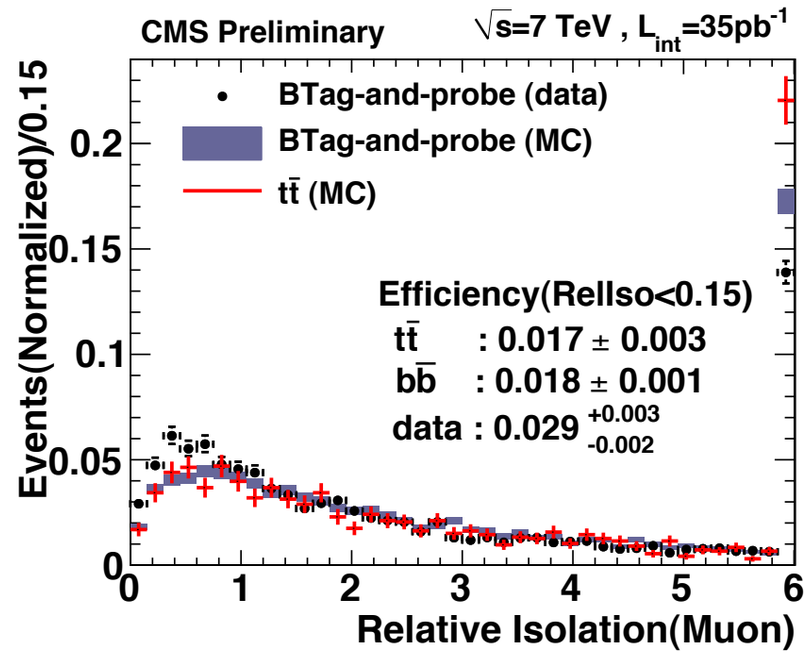
- Measure background from b/c ➔ e/μ in two slightly different ways
  - Tight to Loose lepton ID probability from multi-jet sample
  - Apply measured probability to side-band sample with loose lepton ID to predict background with tight lepton ID
  - Uncertainty from jet kinematics ~50%

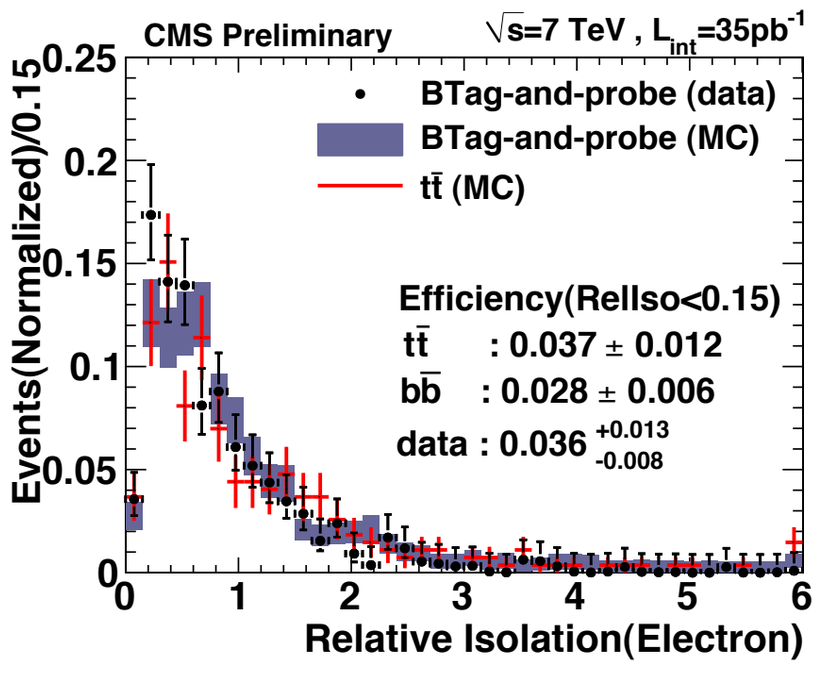




Background from ttbar

- 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

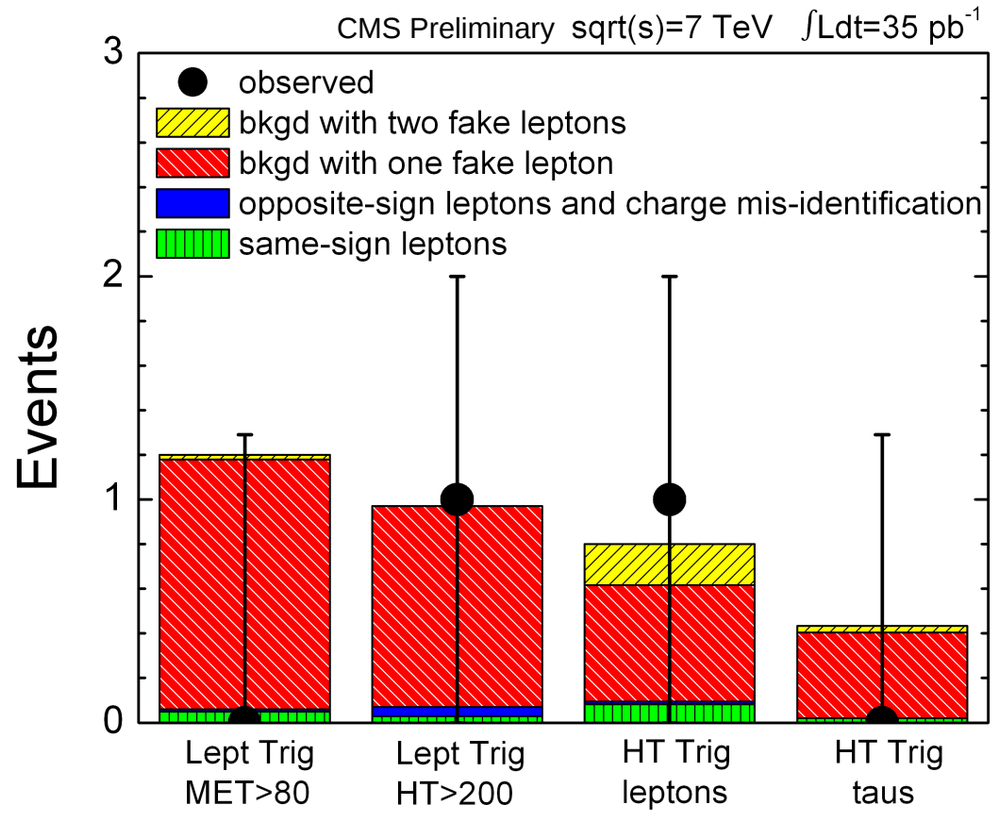




Hadronic τ channels

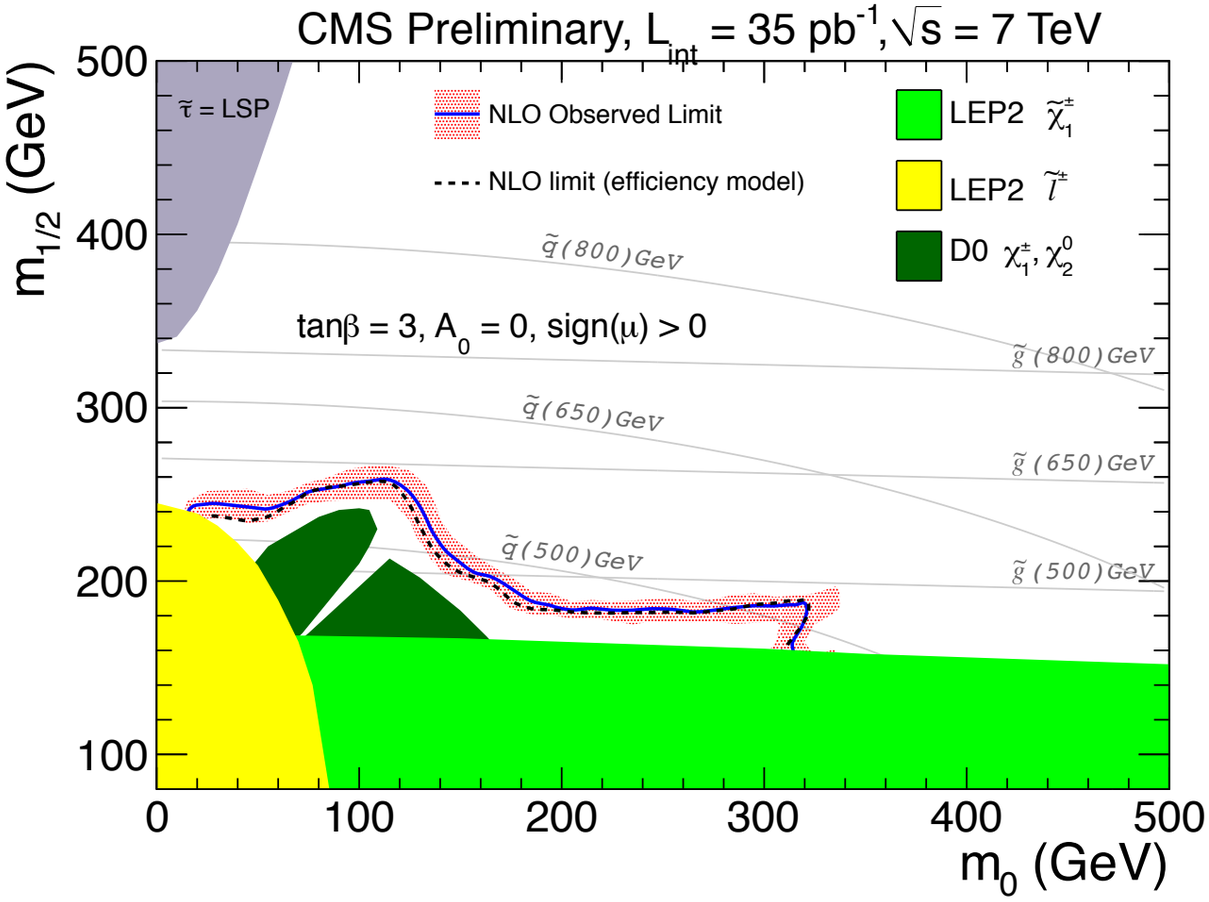
- Include hadronic τ channels e-τ, μ-τ and τ-τ
  - Increased background from QCD jets faking hadronic τ
  - Use similar tight to loose probability

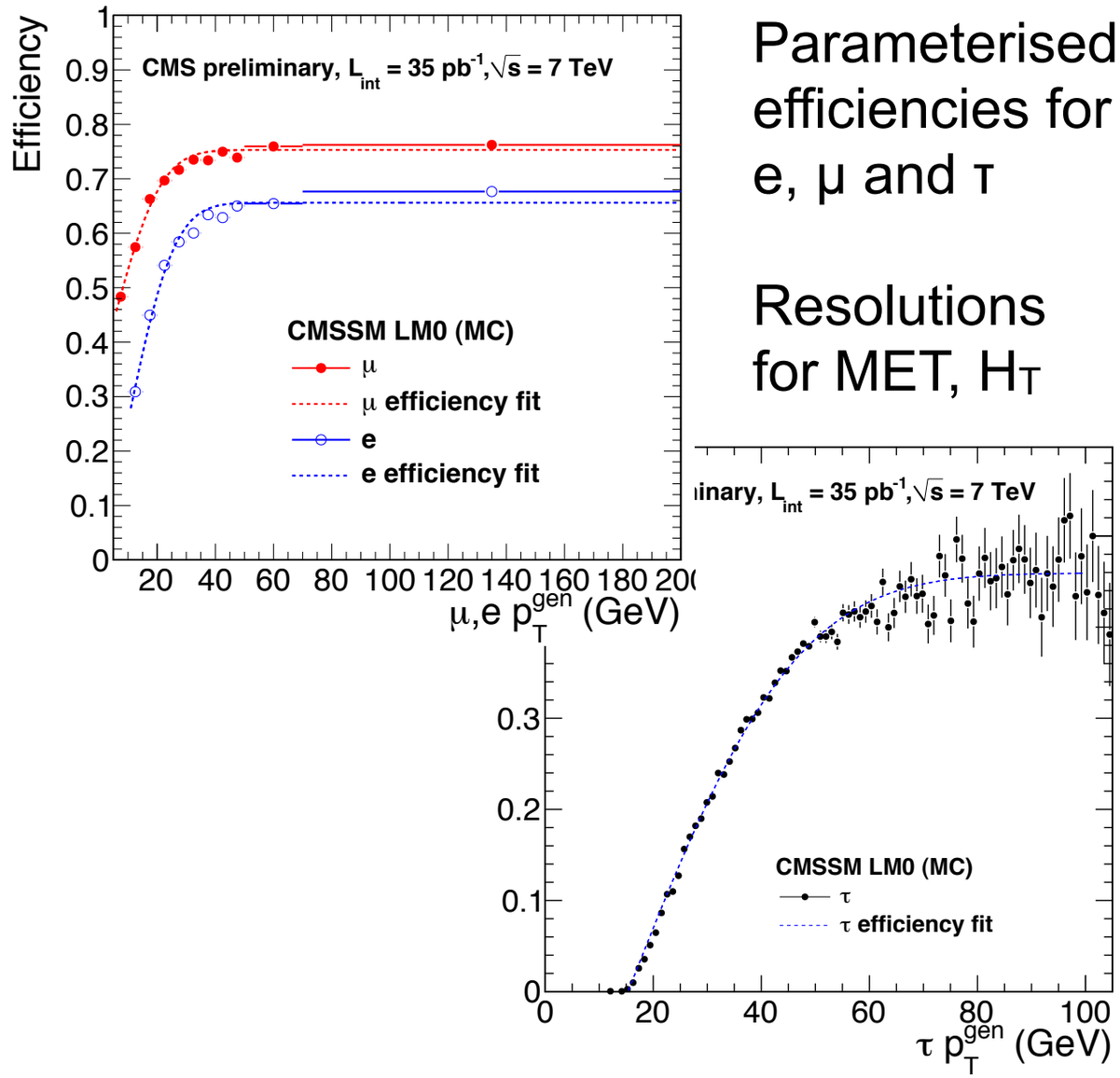
- Final background estimates:
  - No sign of new physics ➔
  - Set limits….



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

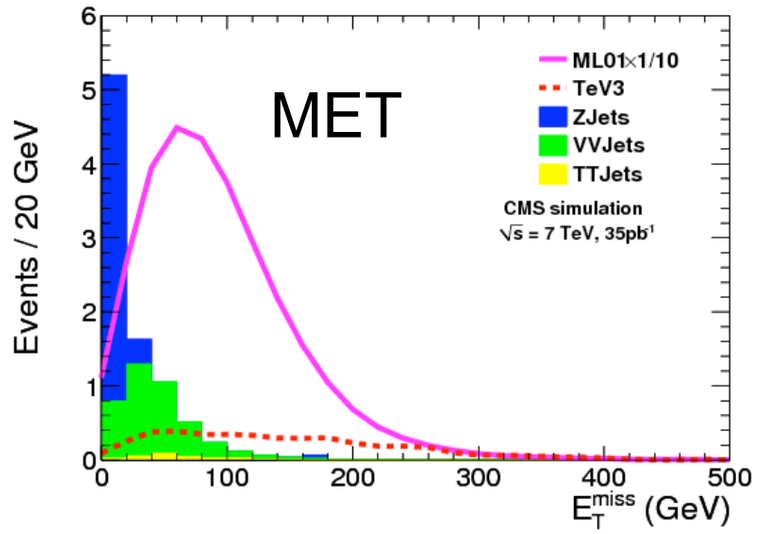
CMS-SUS-10-008

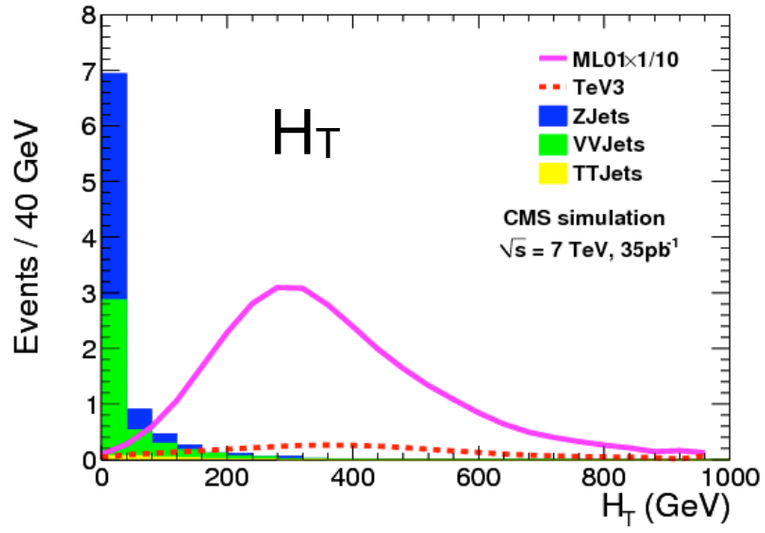
- Search in events with at least three isolated leptons
  - Backgrounds suppressed drastically
  - More inclusive search ➔ wide phase space

- 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



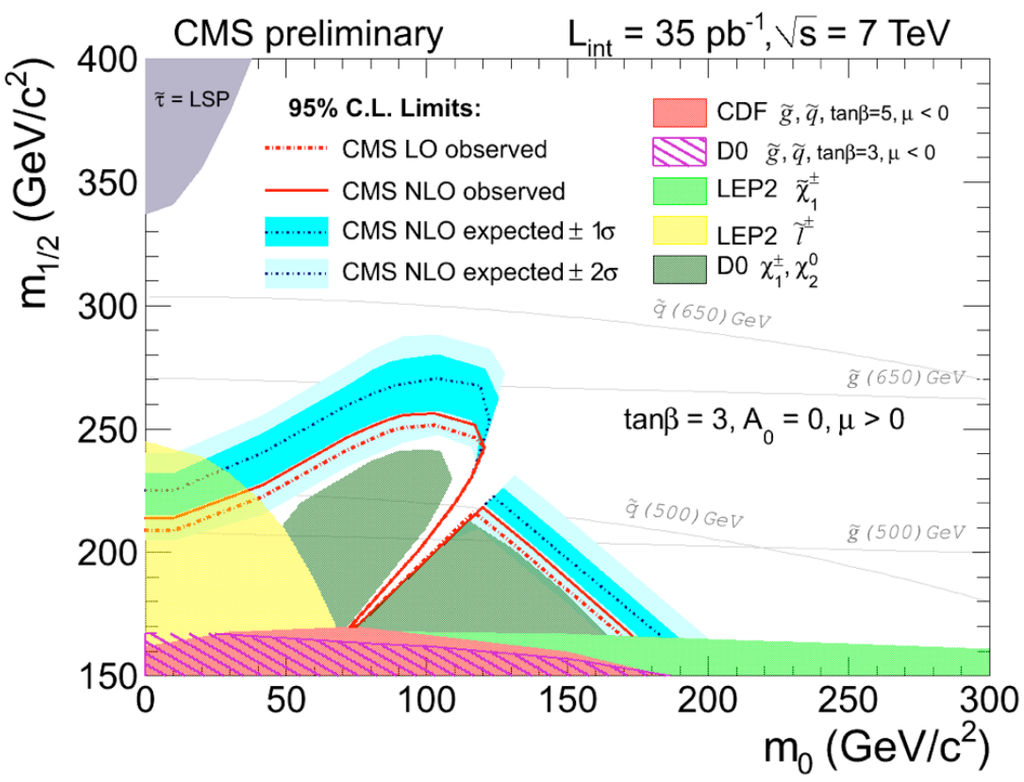


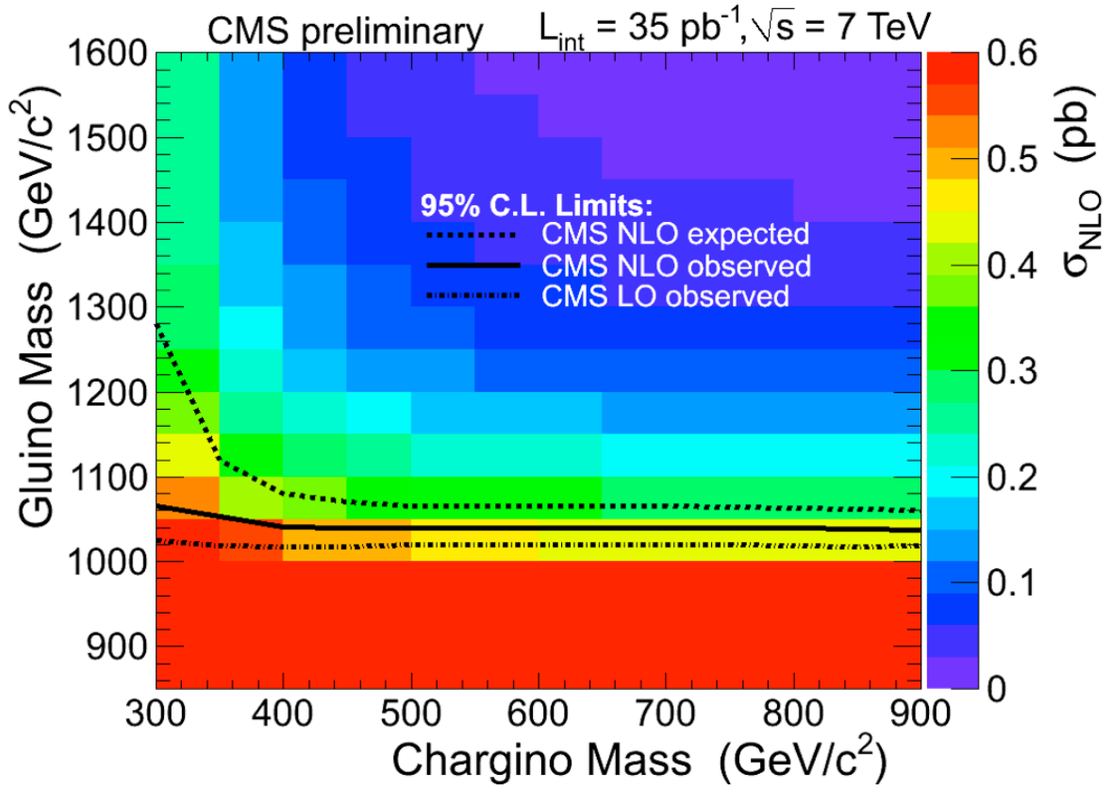
Multi-lepton analysis

- 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





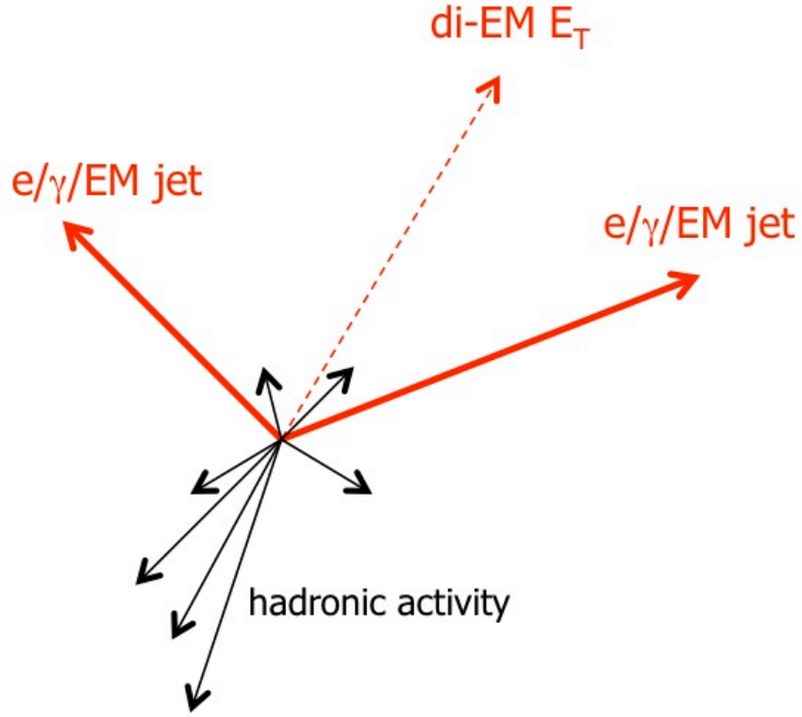
- Set limits in CMSSM for comparison with previous expts.
- Also consider more phenomenological interpretation in GGM model
- Multi-lepton signatures also arise naturally in co-NLSP model with mass degenerate sleptons decaying to leptons and Gravitino

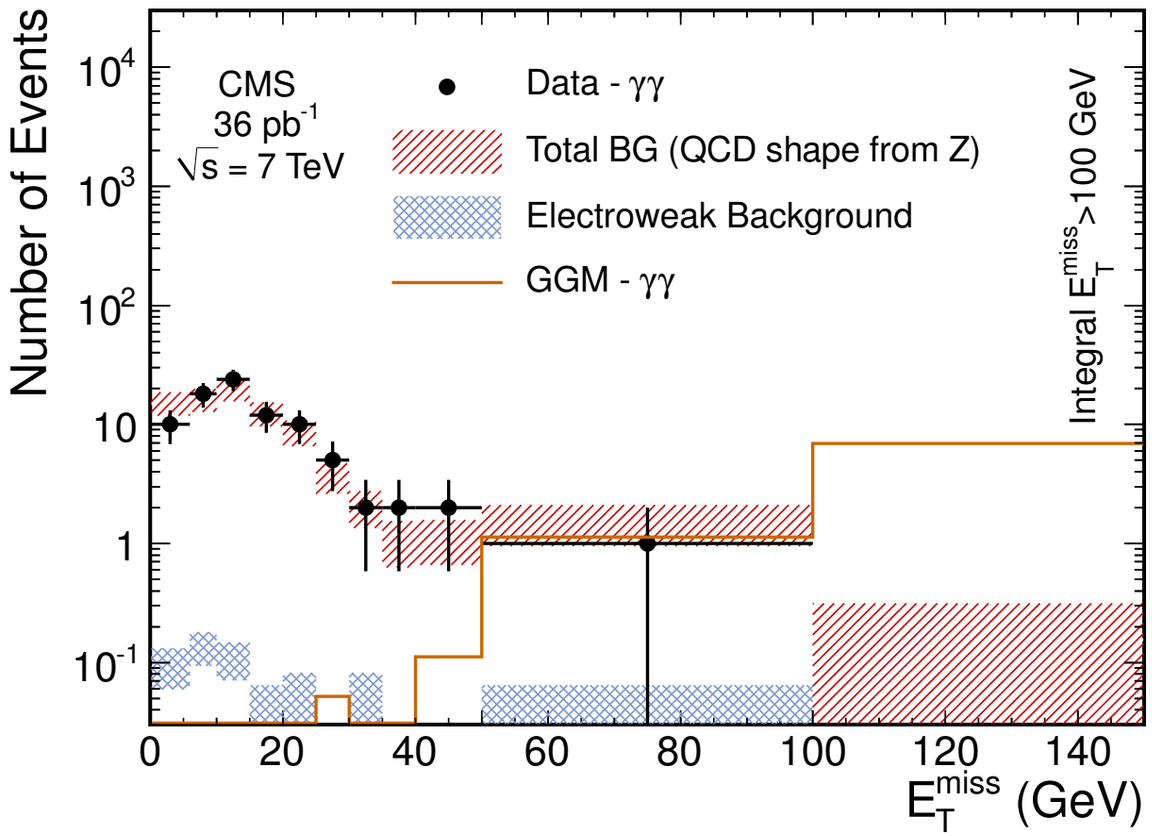
Searches with photons

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

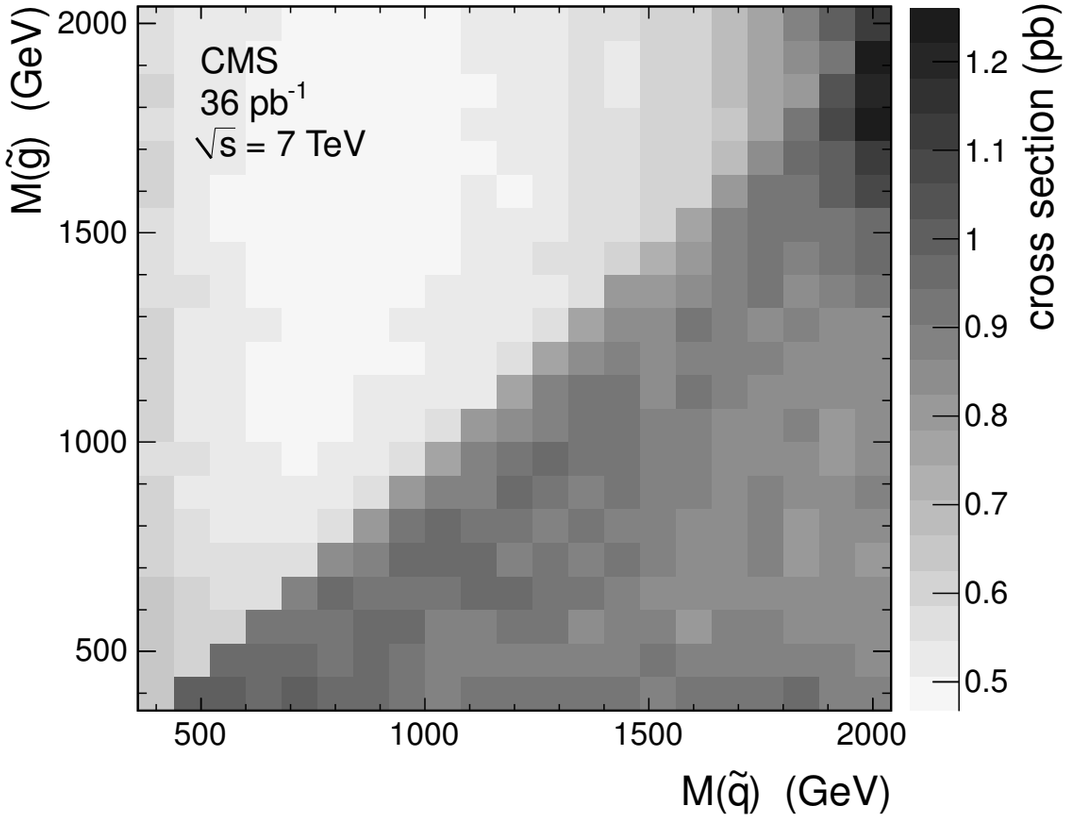


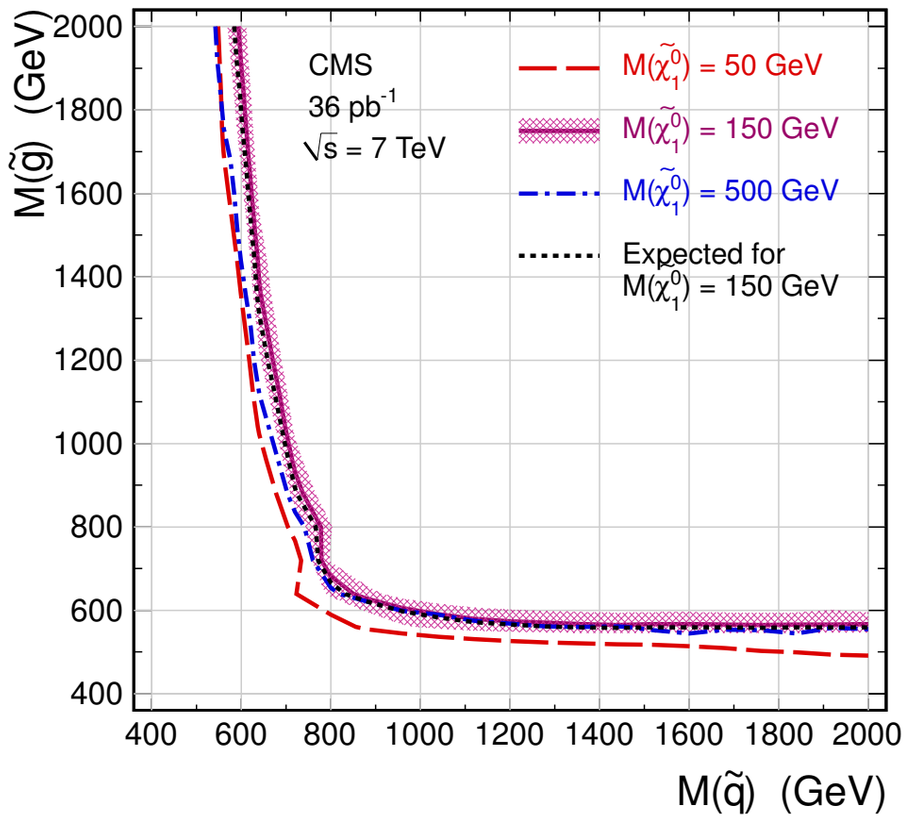


- EM objects better measured than hadronic objects
- MET dominated by hadronic resolution
- Reweight control samples to signal γγ E_T spectrum
- Normalise at low MET (<20 GeV)

Diphoton search

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



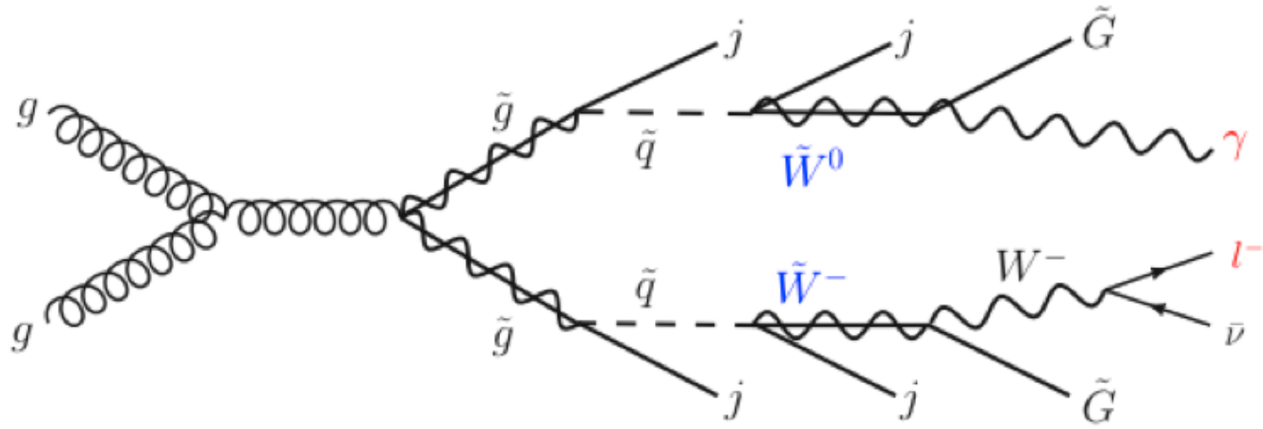


- Consider GGM model with neutralino (bino), gluino, and squark decaying to jets + two photons + two Gravitinos
- 95% CL upper limit this simple model for neutralino mass = 150 GeV
- Upper limits between 0.5 and 1.1 pb depending on masses
- Beyond previous experiments

Lepton + photon search

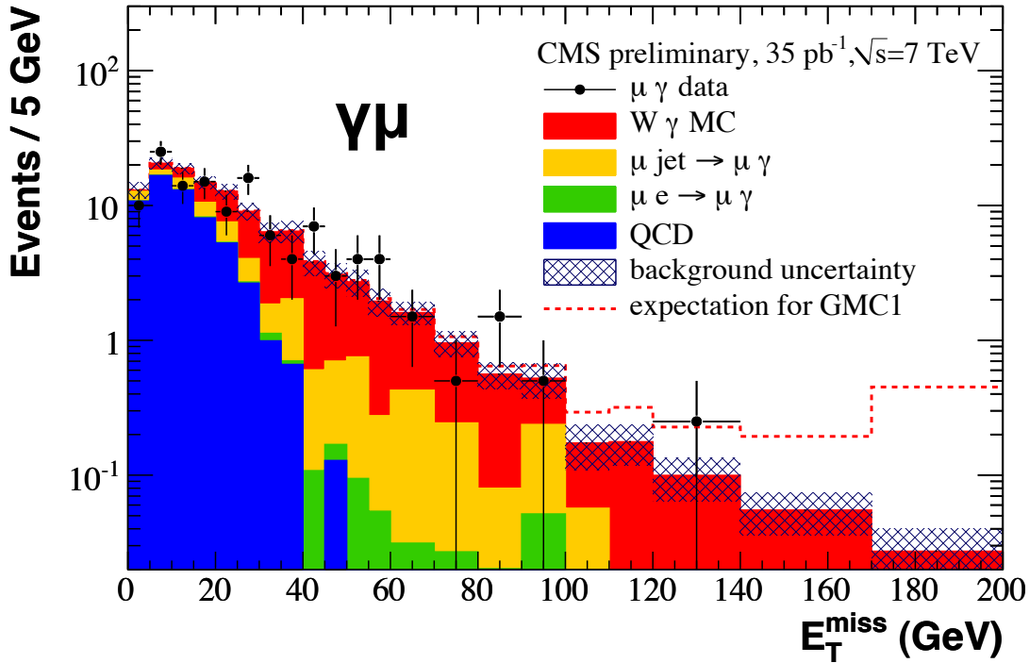
CMS-SUS-11-002

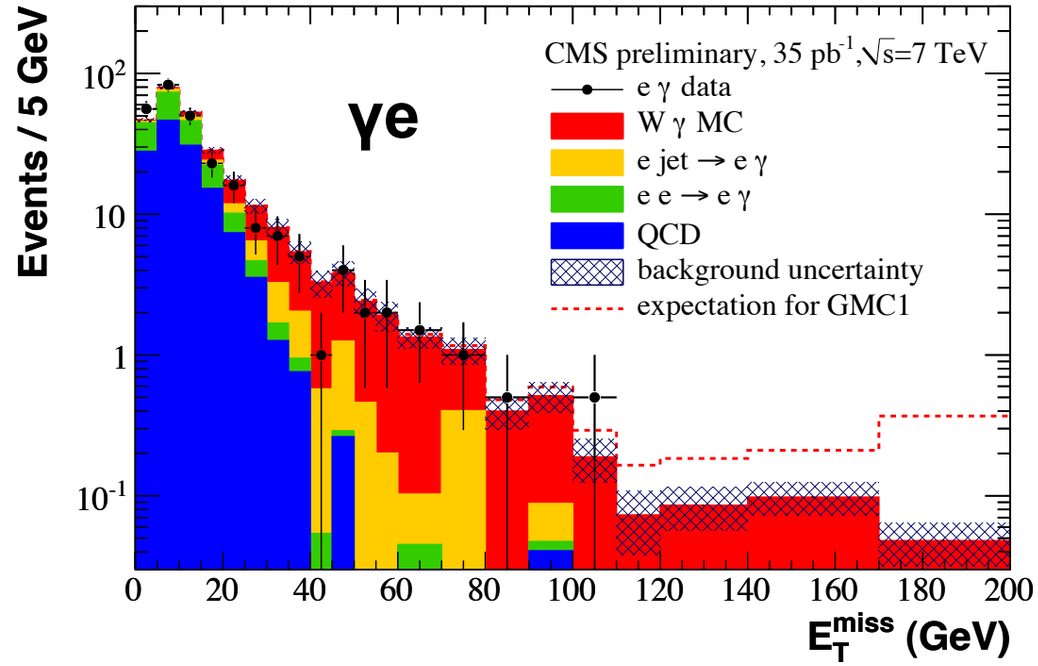
If wino and bino are mass degenerate NLSPs then di-photon signature replaced by lepton+photon signature.



- 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



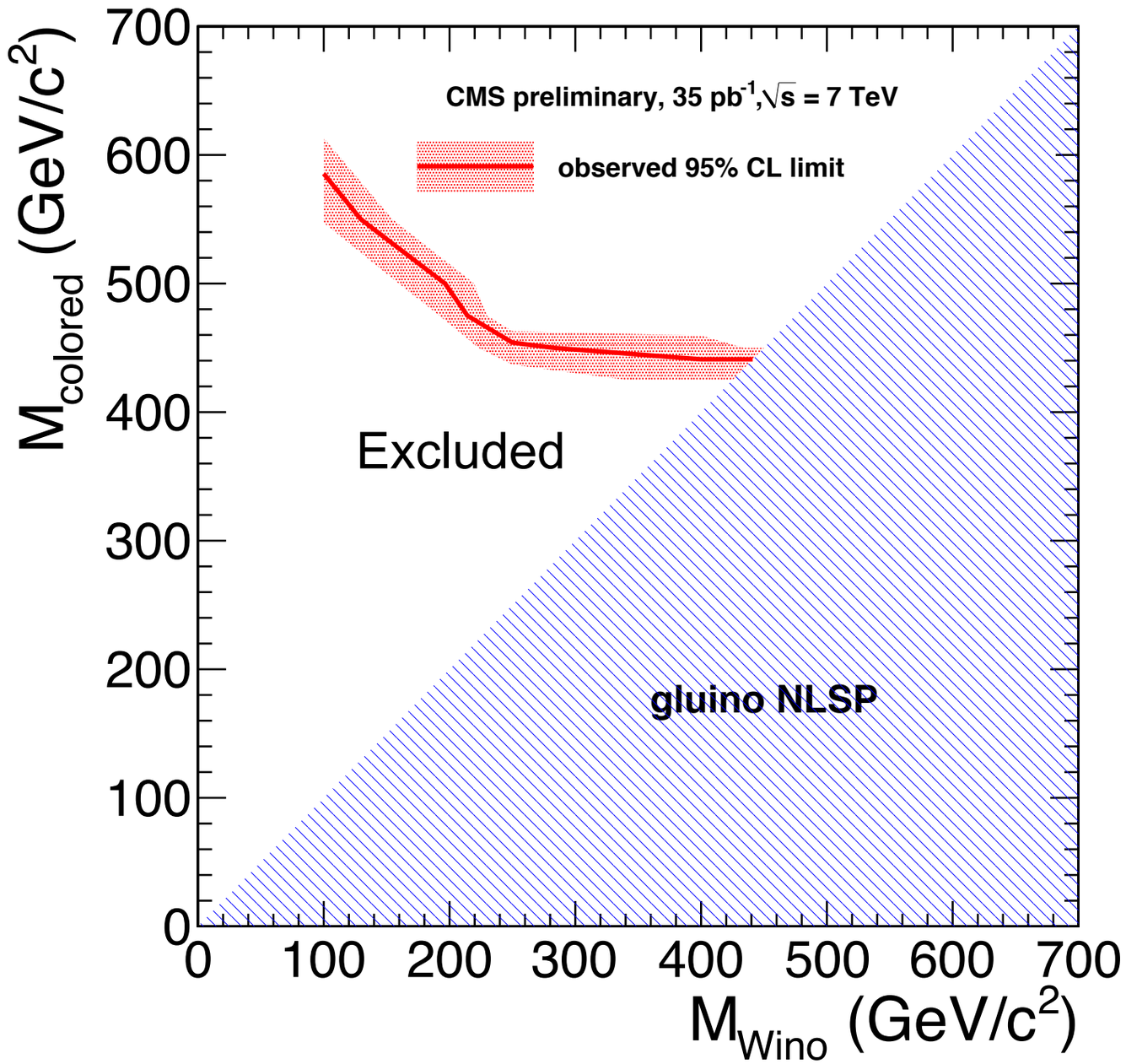


	Predicted	Observed
MET > 40 GeV	20.1 ± 3.7	27
MET > 100 GeV	1.59 ± 0.39	1

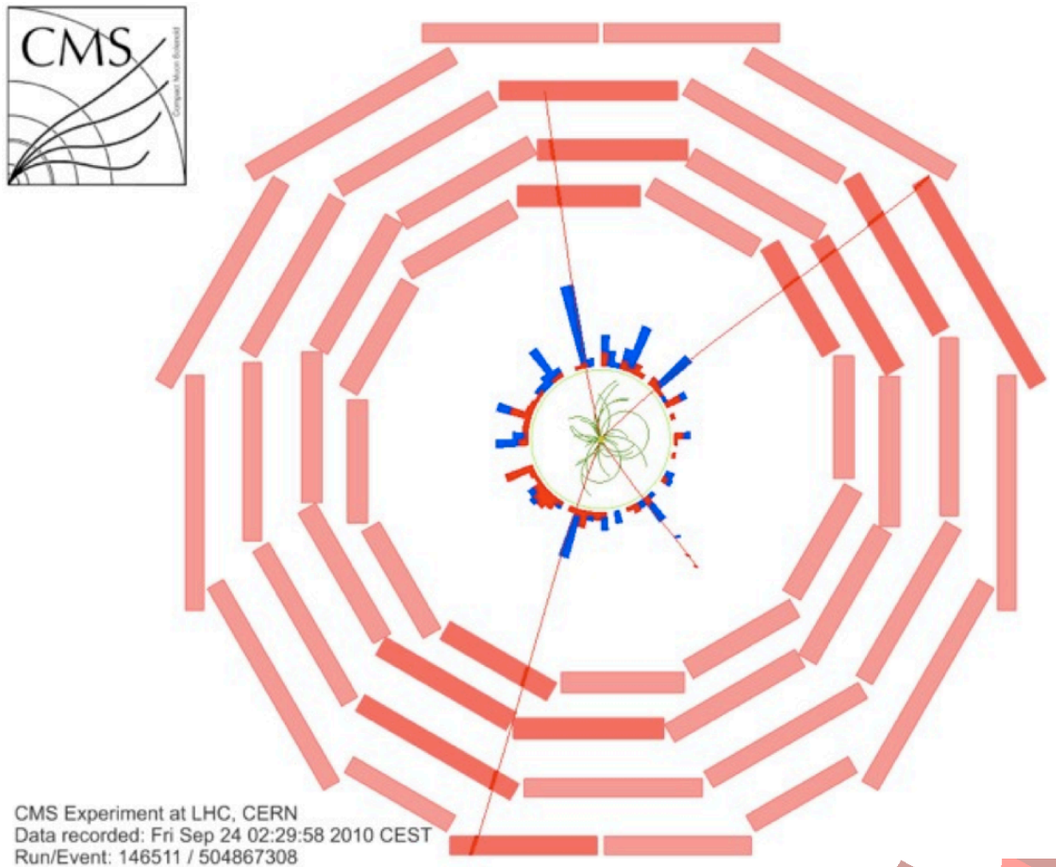
	Predicted	Observed
MET > 40 GeV	19.9 ± 3.7	16
MET > 100 GeV	1.74 ± 0.43	1

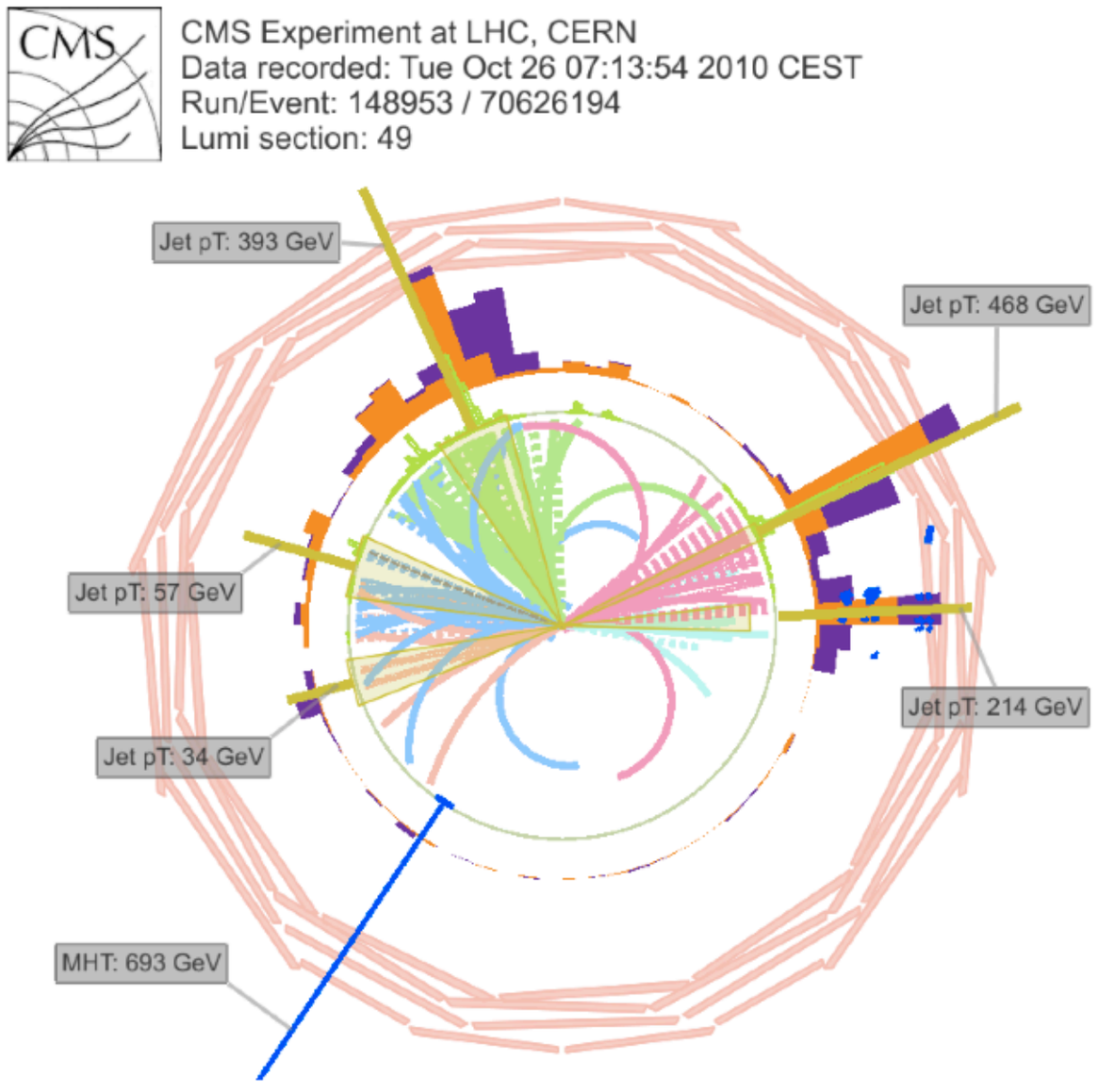
Lepton + photon search

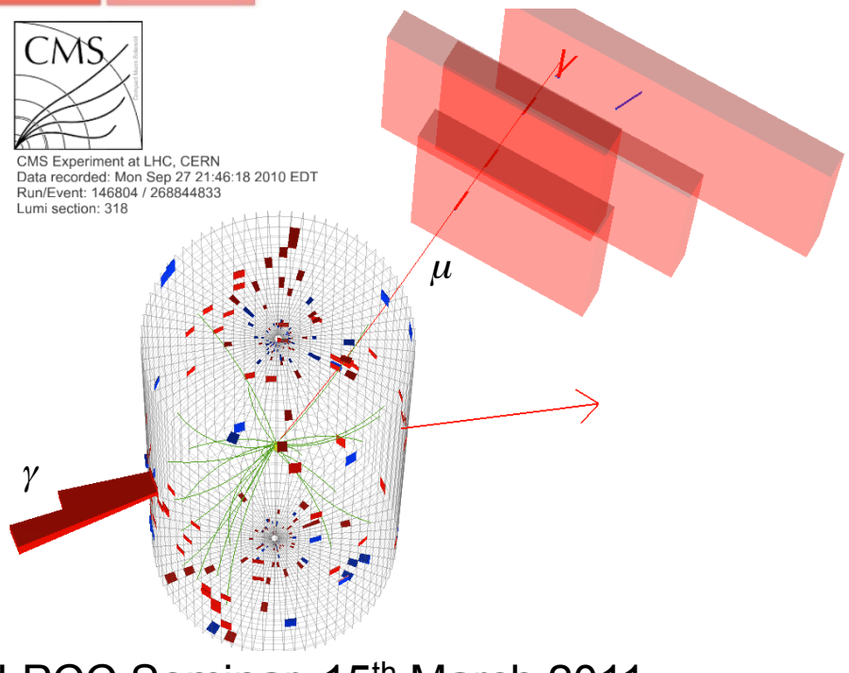
- Final selection MET > 100 GeV
- $M_{squark}=M_{gluino}$
- $M_{Wino} = M_{Bino}$
- Area under the red line excluded
- Band from theoretical error on NLO calculation



No SUSY but many pretty background events

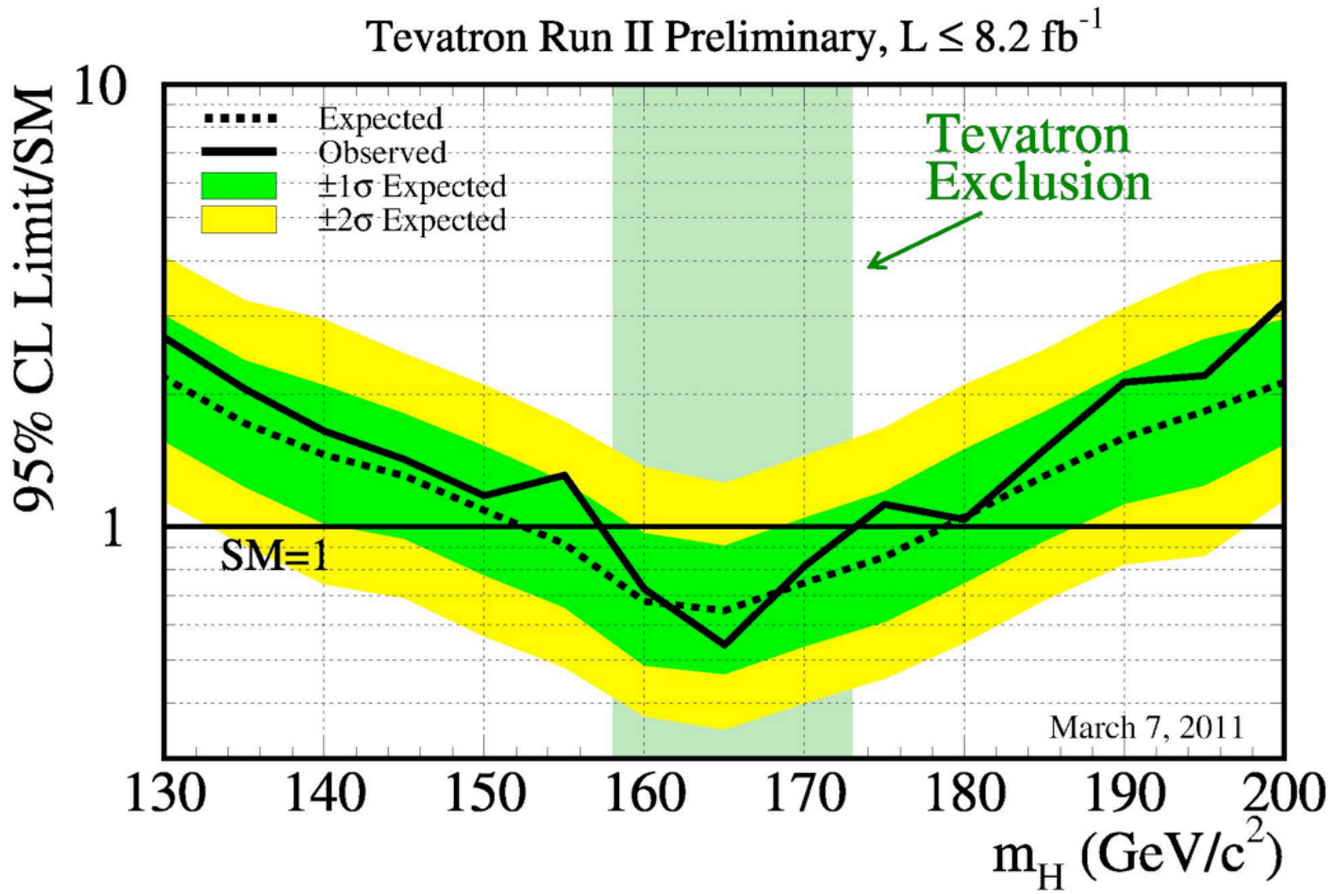


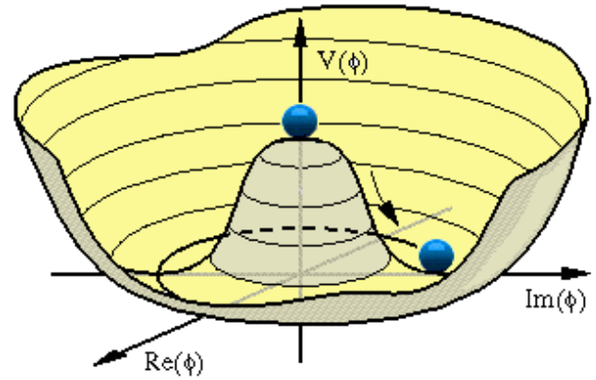


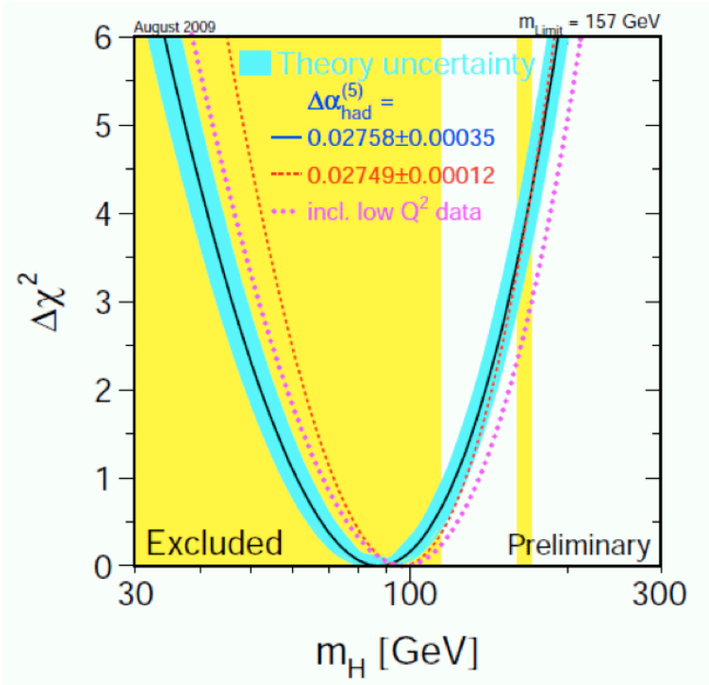


Higgs searches

- State of Standard Model Higgs searches







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

H → WW → lνlν

CMS-HIG-10-003

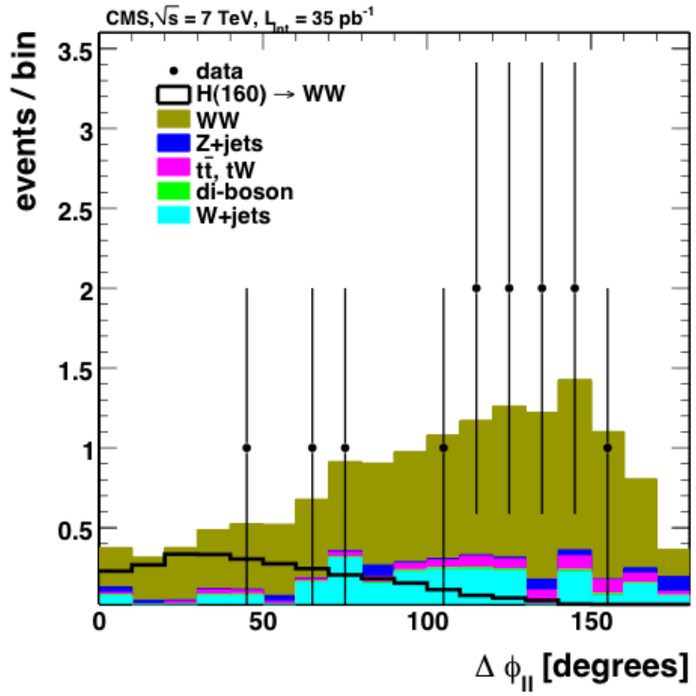
- Signature:
  - Two high p_T leptons
  - Large missing transverse momentum from two neutrinos

- 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)
  - 3rd 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 → lνlν

- Results
  - Cut based analysis

Mass (GeV)	SM Higgs	4th 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

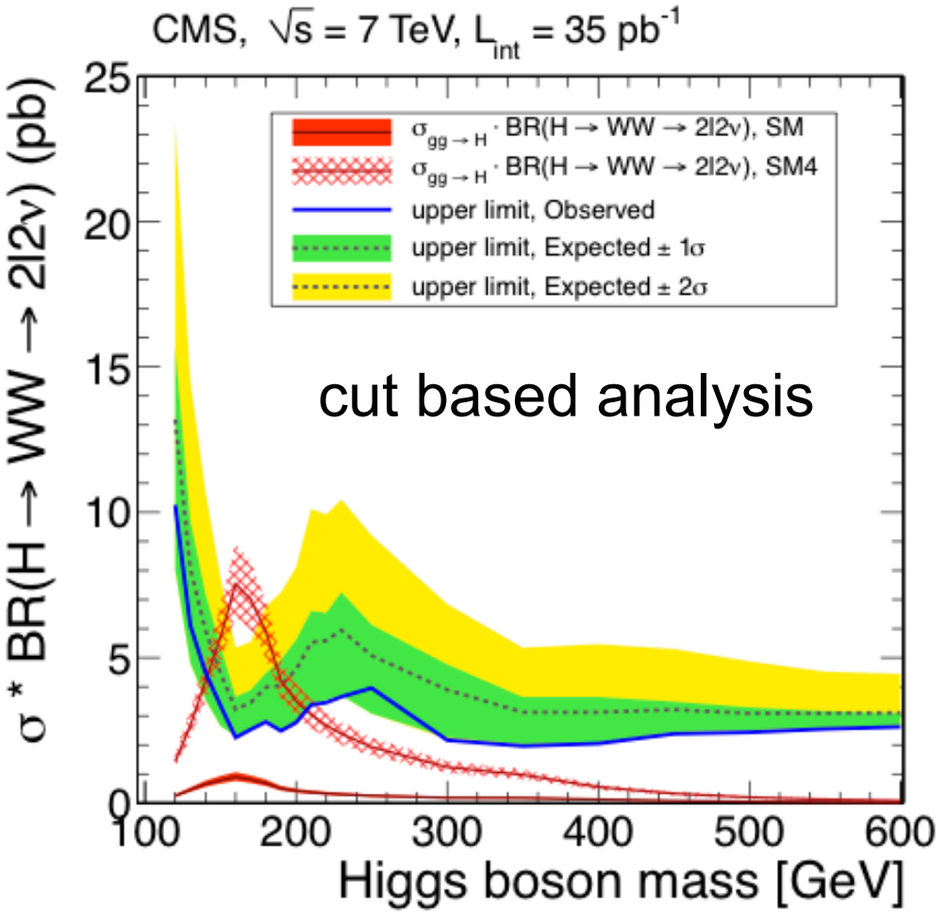
  - Boosted decision tree

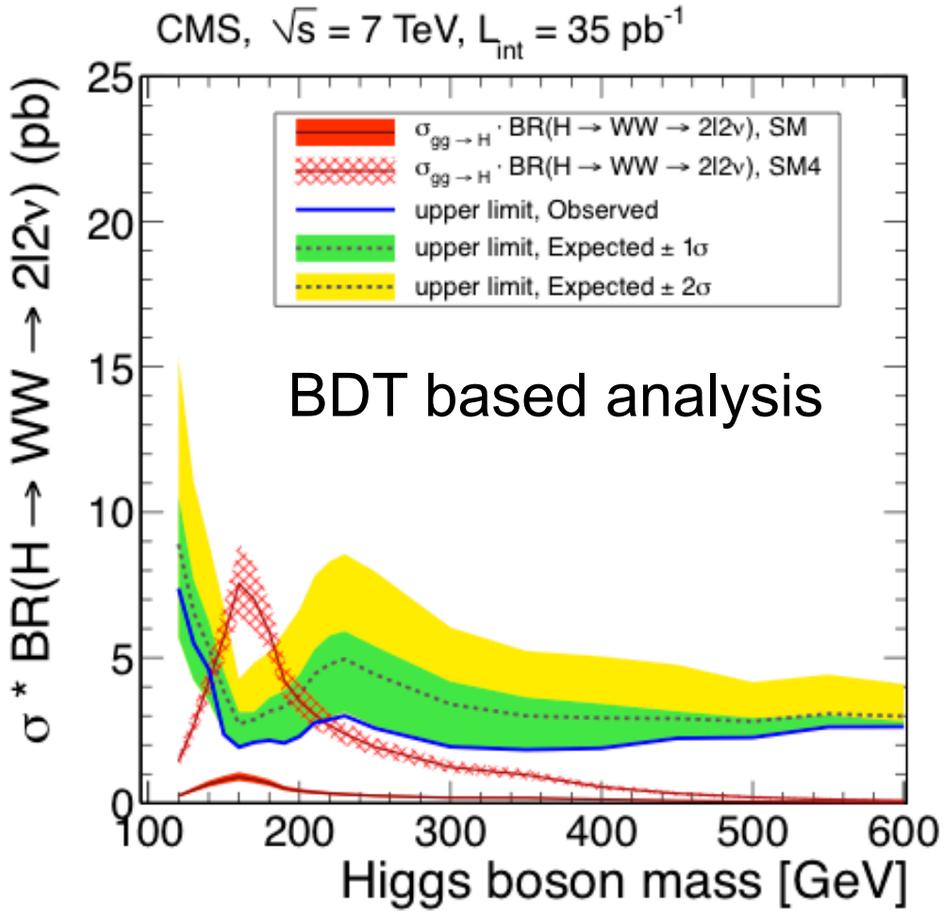
Mass (GeV)	SM Higgs	4th Gen	Bgnd.	Data
130	0.34 ± 0.01	1.98 ± 0.04	1.32 ± 0.18	1
160	1.47 ± 0.02	12.31 ± 0.17	0.92 ± 0.10	0
200	0.57 ± 0.01	4.76 ± 0.07	1.47 ± 0.07	0
250	0.30 ± 0.00	2.30 ± 0.04	1.67 ± 0.10	0

- No signal observed → set limits

H → WW → lνlν 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 → ϕ + X
  - ϕ = 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 → ττ → e-μ
  - H → ττ → e-τ_h (τ_h=hadronic decay)
  - H → ττ → μ-τ_h

- Selection:
  - Electron/muon pT> 15 GeV
  - τ_h p_T>20 GeV
  - l-τ_h: $M_T=\sqrt{2p_T^l \cdot MET \cdot (1-\cos\Delta\phi)} < 40$ GeV
  - e-μ: $M_T < 50$ GeV

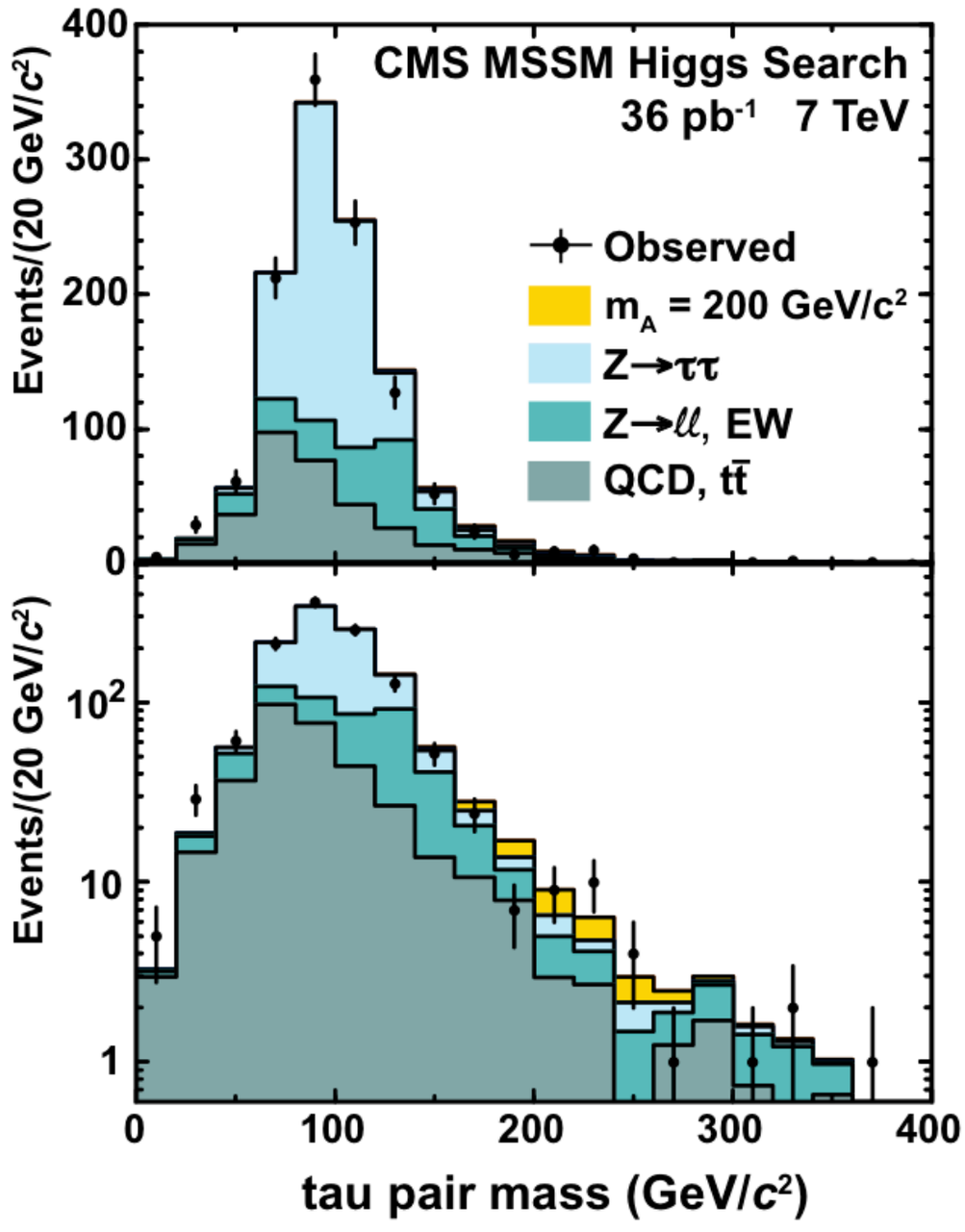
Backgrounds

- 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	
$W \to \tau_\ell\nu$	14.7±1.3	7.0±0.7	3.9±1.2
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

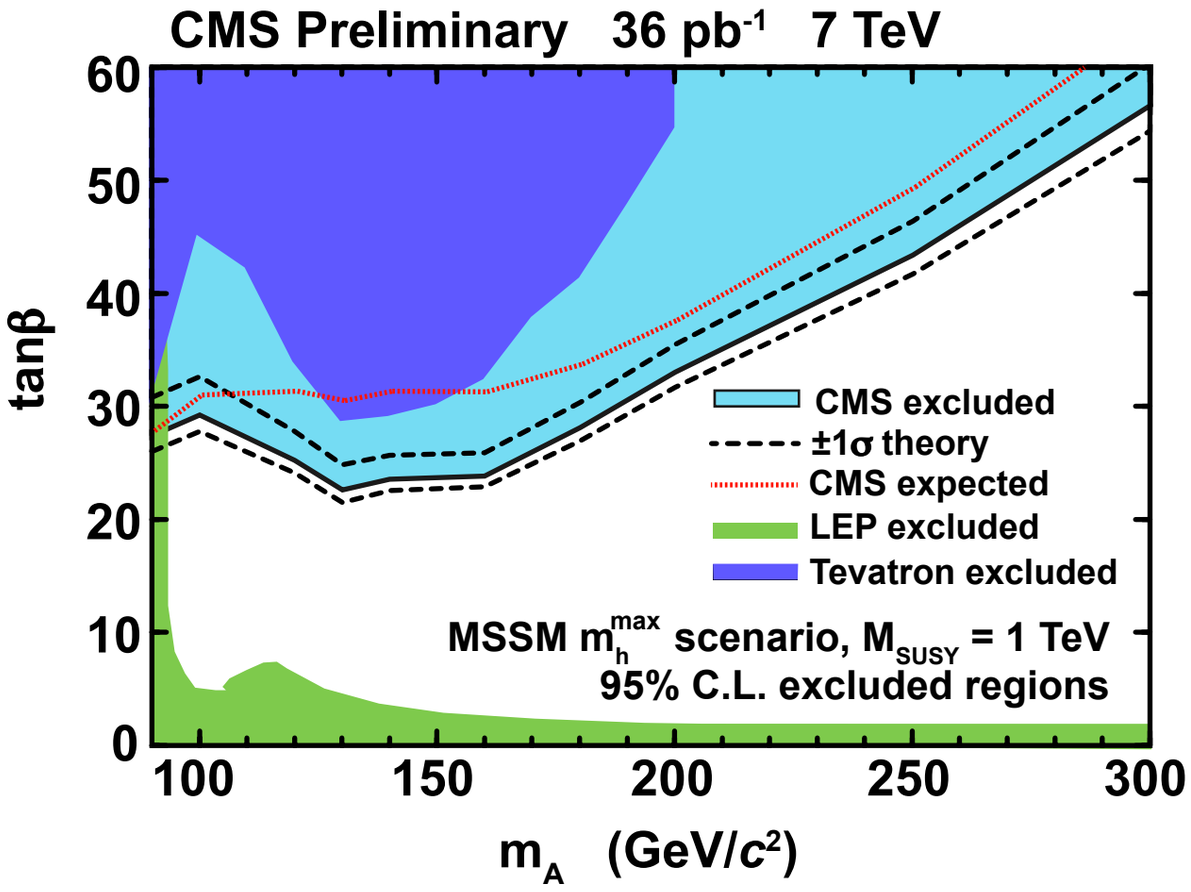
τ pair mass reconstruction

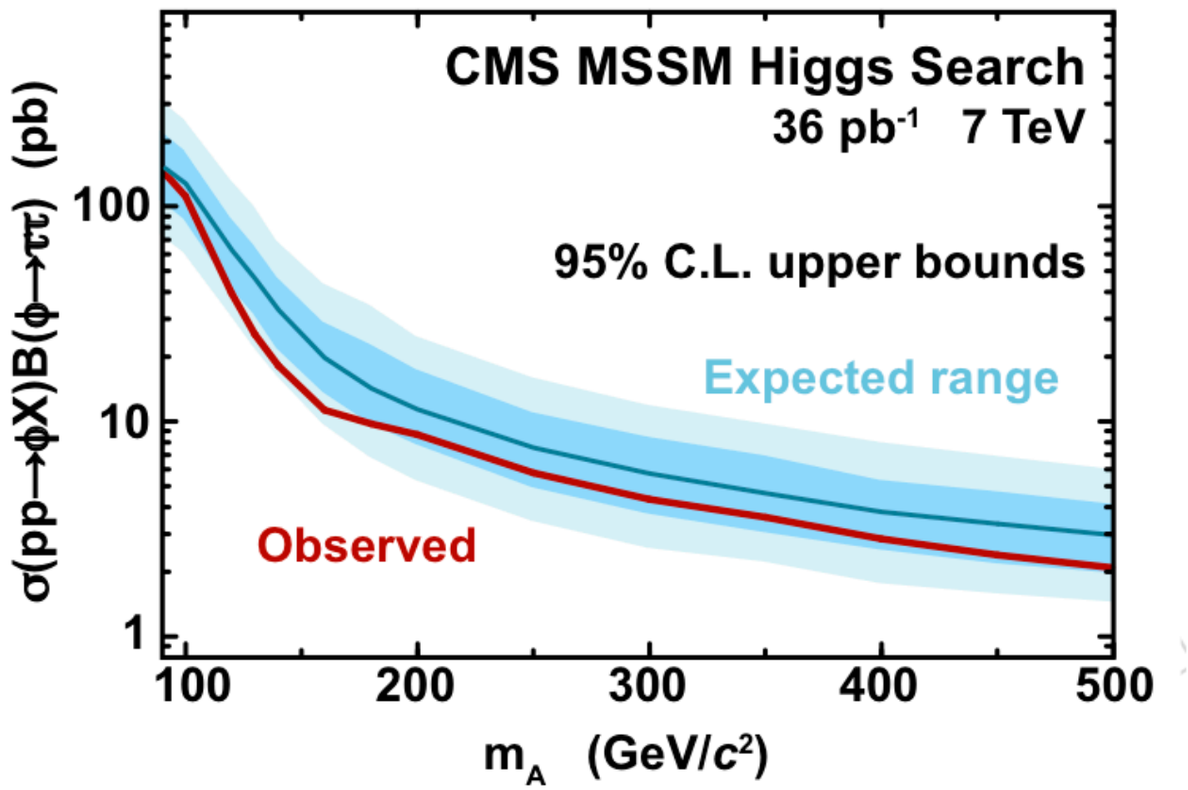
- Likelihood fit to τ momenta
- Use all available kinematic information and probability density for τ p_T spectra
- Improvement in resolution compared to visible mass



ϕ → ττ limits

Limit on σxBR for tanβ=30



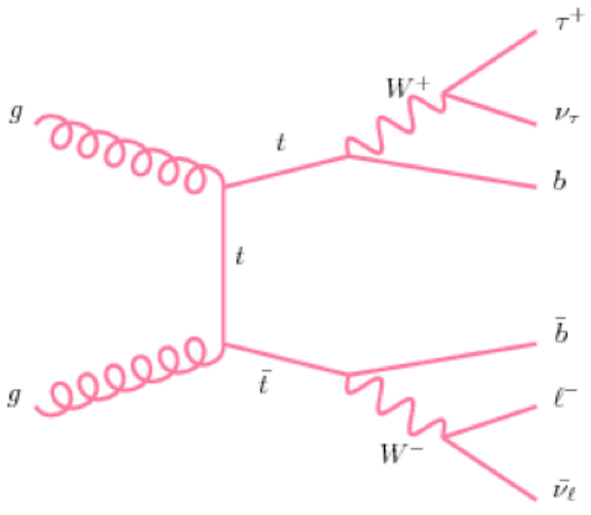


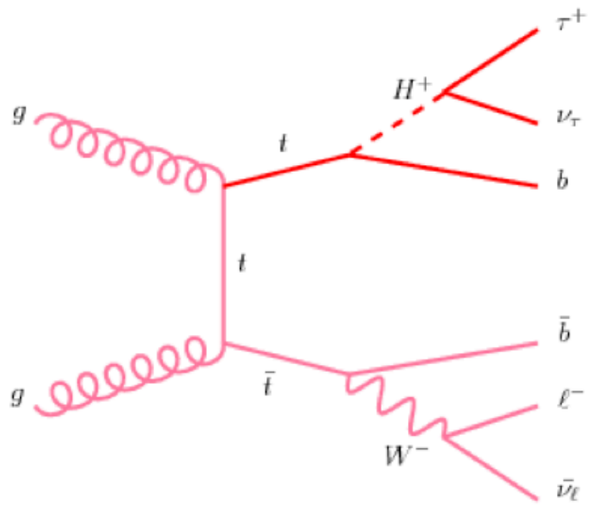
Excluded region in MSSM m_h^{max} scenario

Significantly extends previous limits

Charged Higgs search

- Charged MSSM Higgs bosons may contribute to ttbar decays



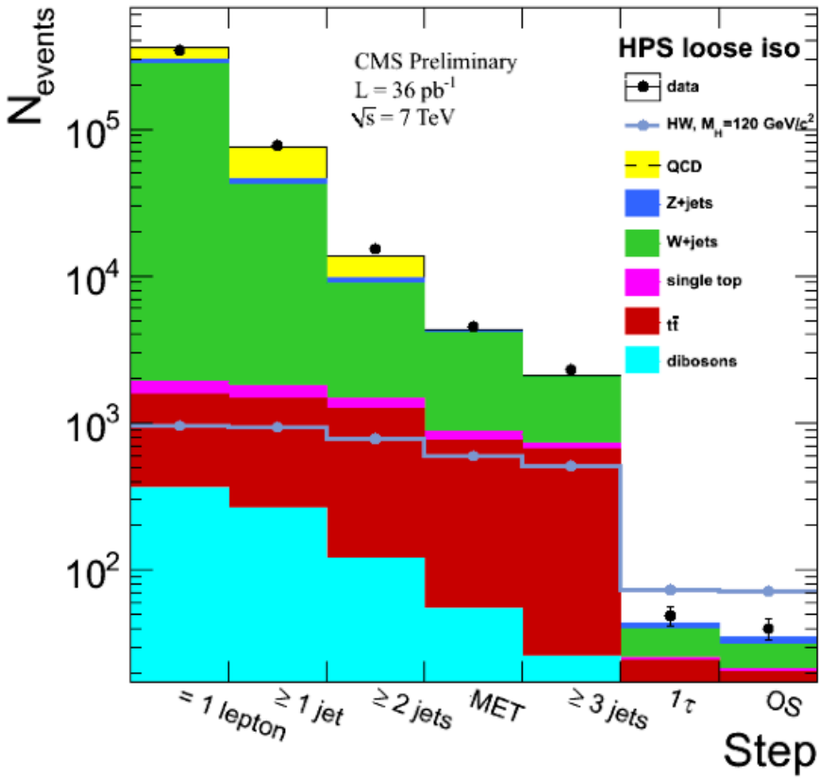


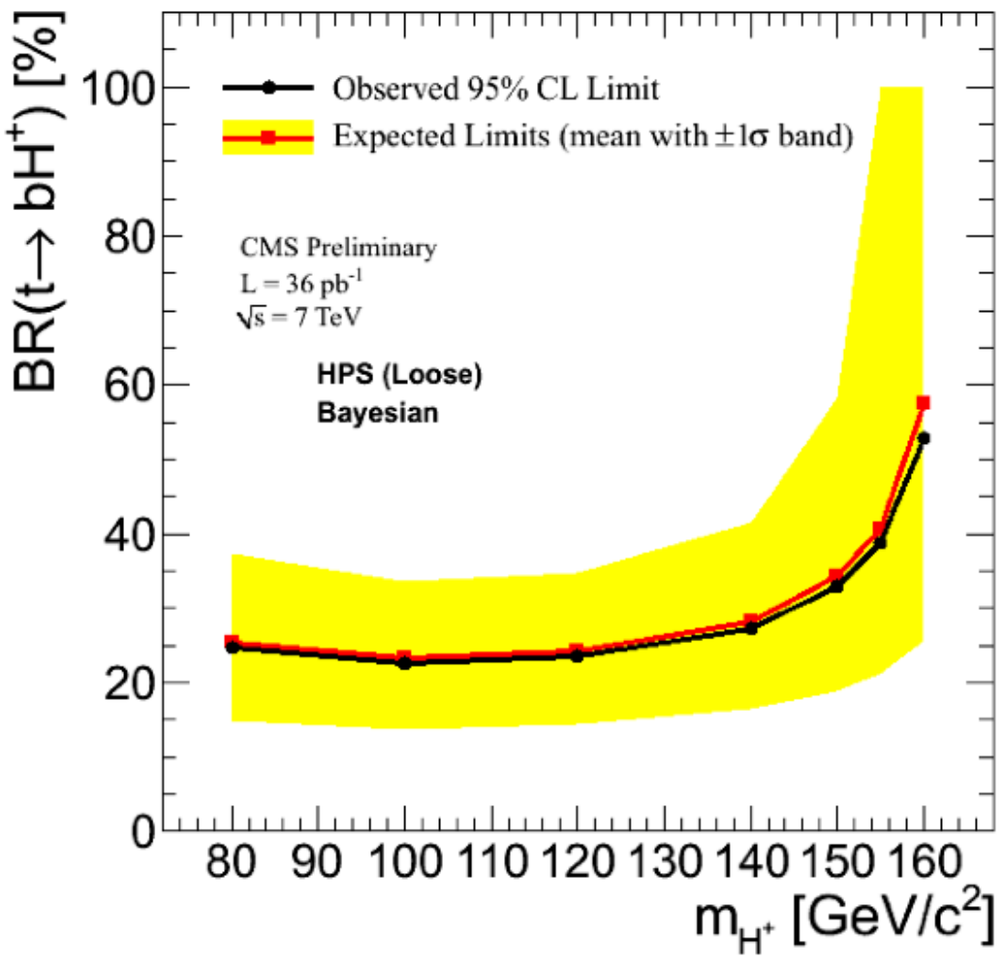
Substitute $H^\pm$ for $W^\pm$ in ttbar decays to τ

- 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



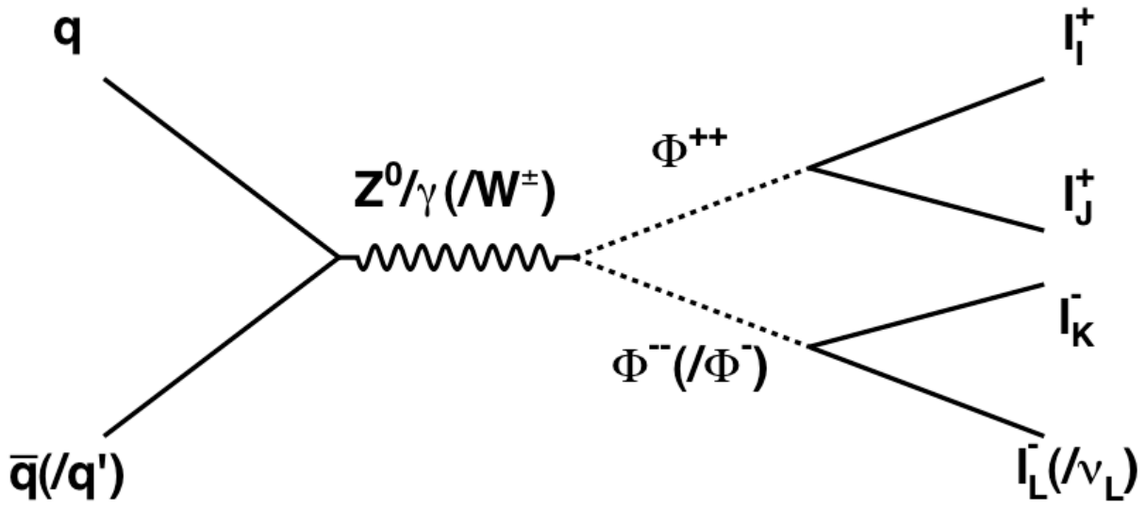


- No signal observed
  - Set 95% C.L on BR ($t \rightarrow bH^+$) assuming BR($H^+ \rightarrow \tau^+\nu$)=1
  - Limit ~0.25-0.30 for 80 GeV < m_{H^+} < 140 GeV
  - Limits comparable with Tevatron

Doubly charged Higgs

- Extend Standard Model adding scalar triplet: $\Phi^{\pm\pm}$, $\Phi^{\pm}$ and Φ^{0}

- Triplet responsible for neutrino masses



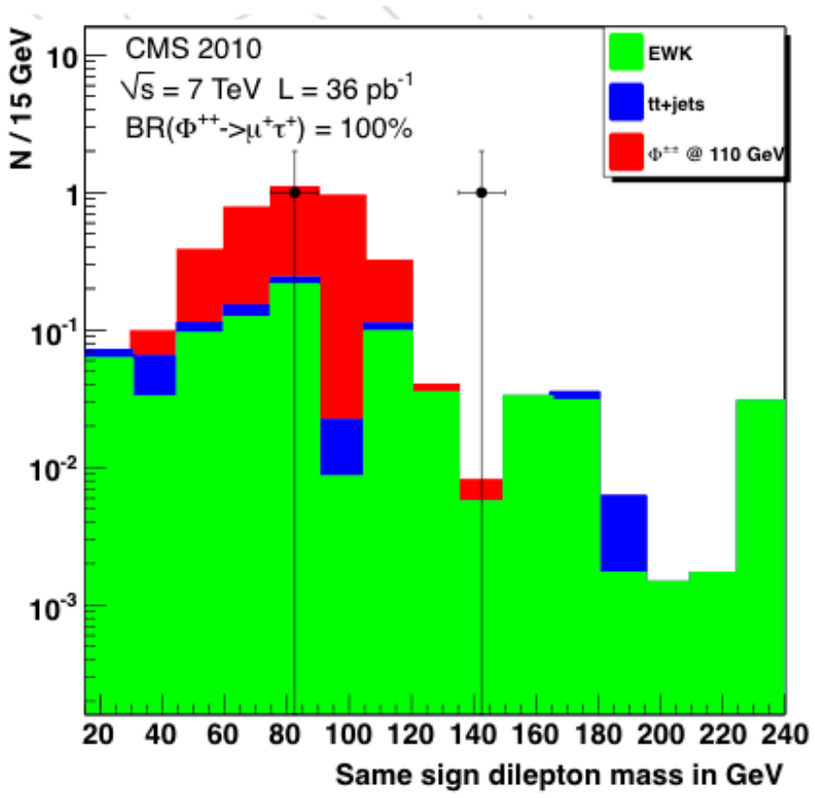
- Consider model where BR($\Phi^{\pm\pm}$ ➔ ll)=100%

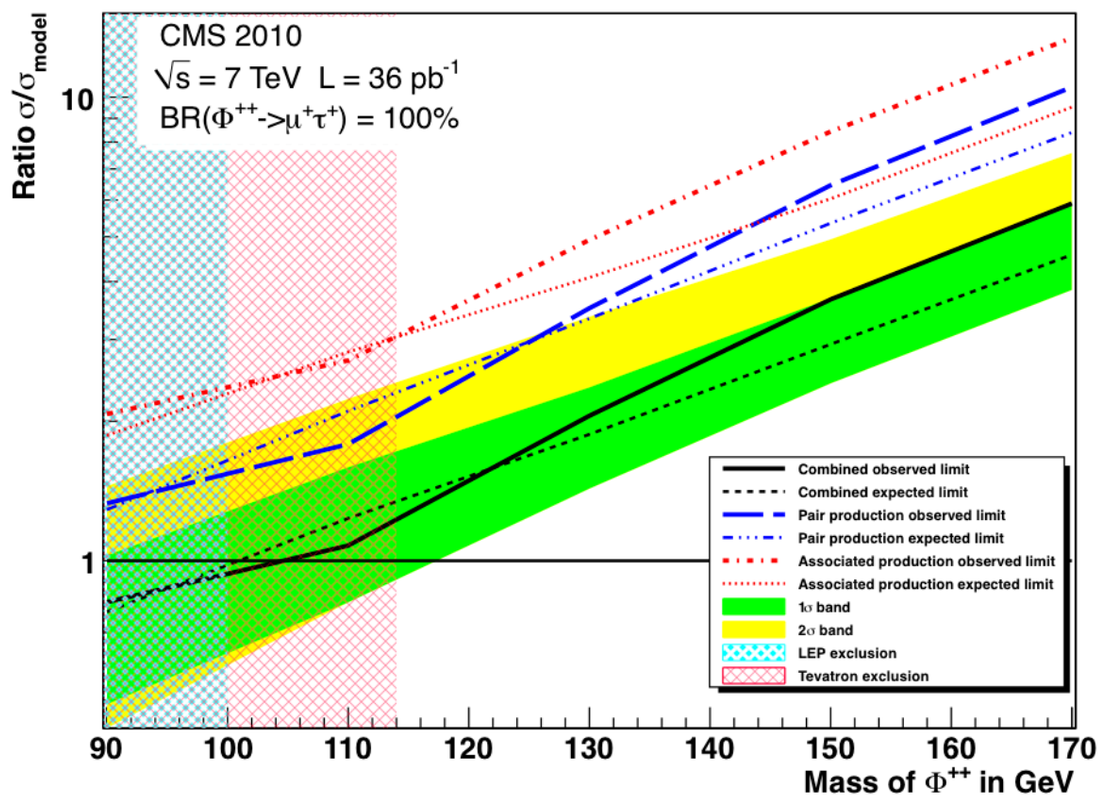
- Final states with three or four isolated leptons (earlier multi-lepton search)

- 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

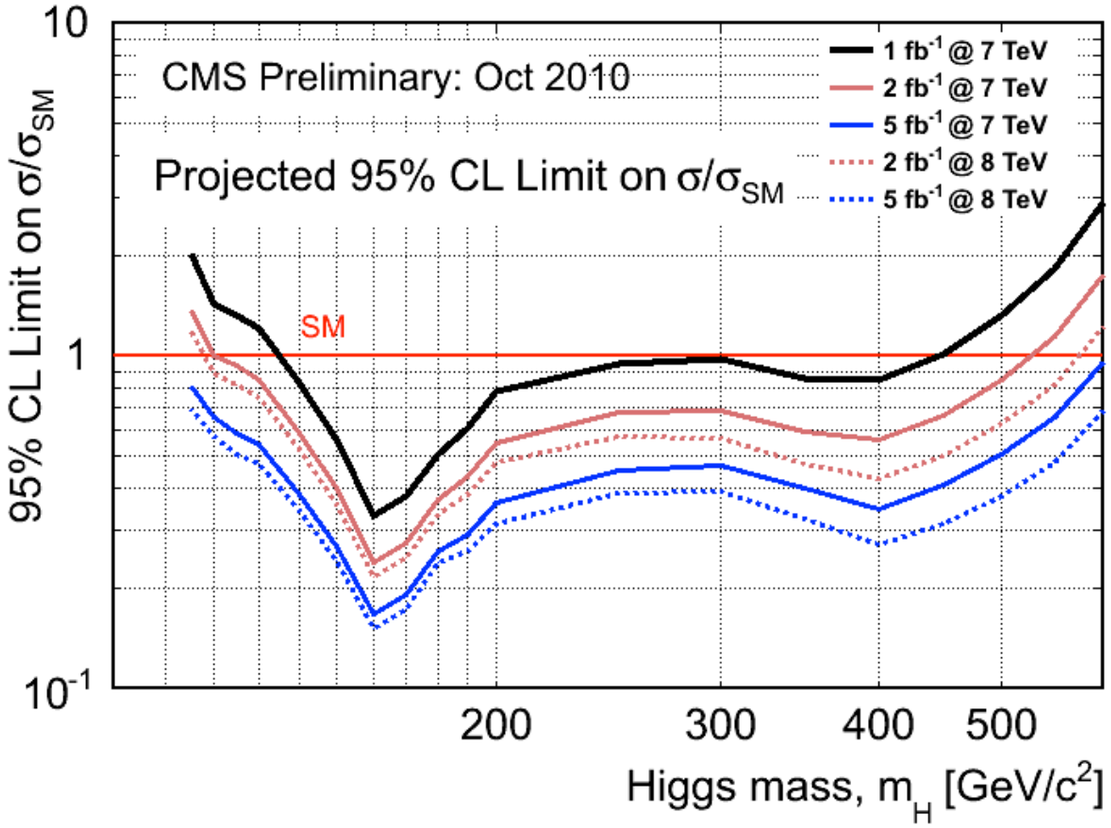
High mass (HM) mSUGRA benchmarks

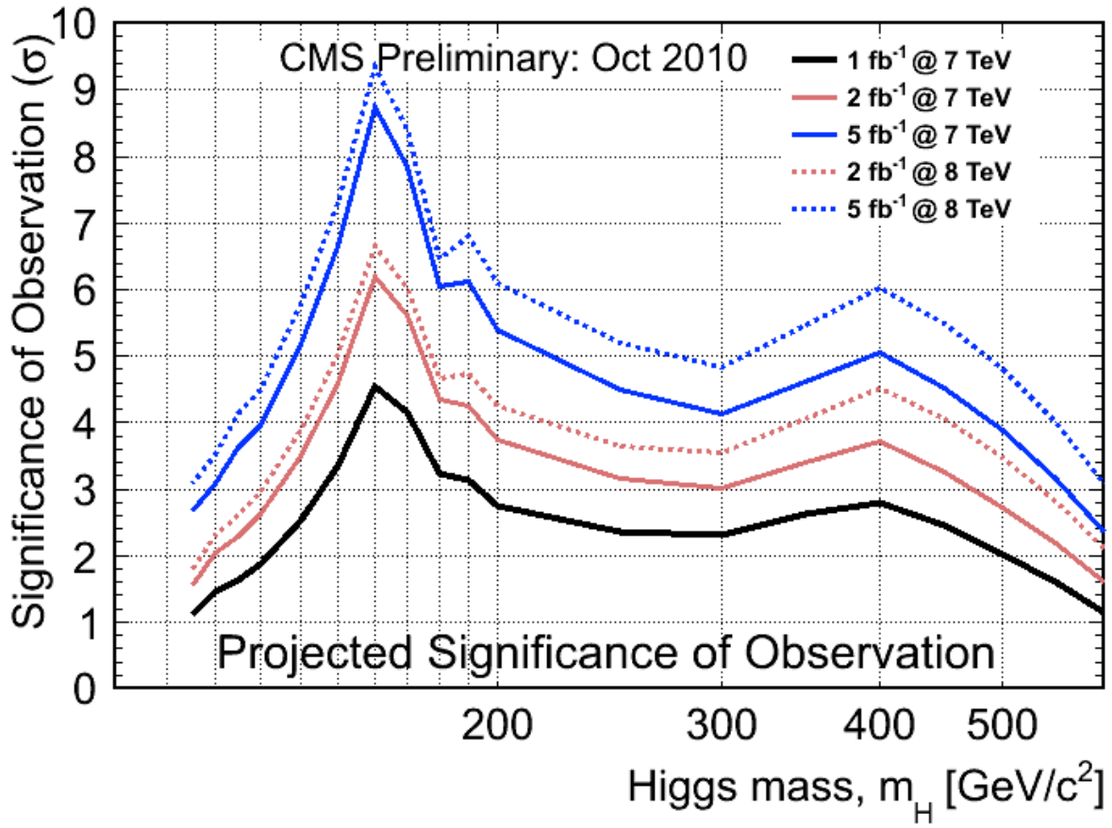
Benchmark	m0	m1/2	A0	tanb	sgn(mu)	Notes
HM1	180	850	0	10	+	
HM2	350	800	0	35	+	
HM3	700	800	0	10	+	
HM4	1350	600	0	10	+	

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

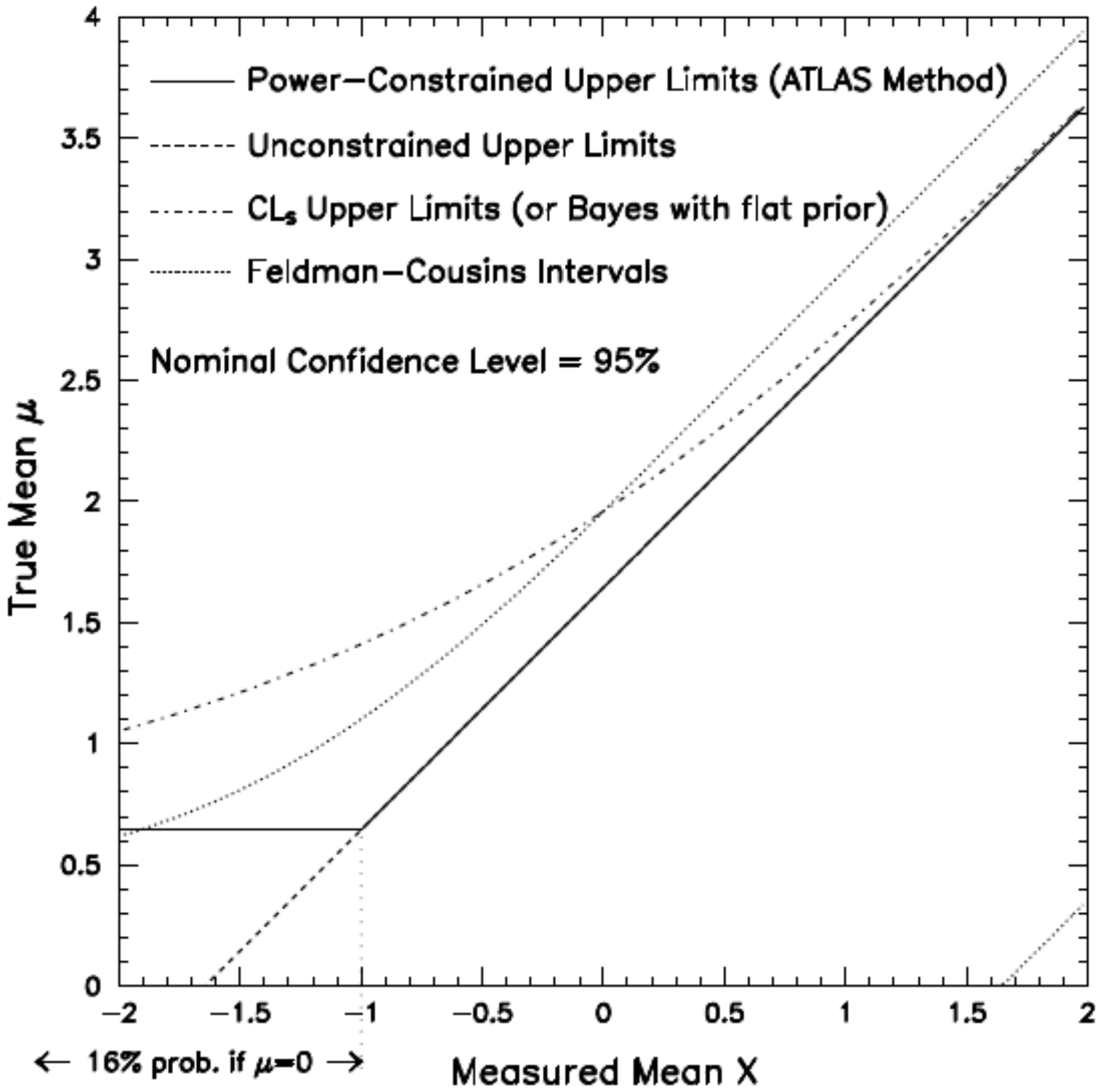




Intervals and Limits for a Physically Bounded μ

- Prototype: measurement *x* is unbiased Gaussian estimate of μ. (Let σ=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 μ 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.