Search for Supersymmetry at the LHC

V. Daniel Elvira
Fermi National Accelerator Laboratory

- Three lectures ~1.5 hrs long each
- Focused on experimental techniques
- Based on public CMS material
- Targets all audiences but mainly students and post-docs not necessarily familiar with SUSY searches
- We want you to get enthusiastic about joining our SUSY efforts at the LPC

Bibliography

CMS Physics Results

http://cms.web.cern.ch/org/cms-papers-and-results

- Plots and Results
- Journal Publications
- Physics Analysis Summaries – public documents

The Challenge of Pileup

Origin and how to deal with a difficult problem

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What is Pileup?

Merriam-Webster

1 : a collision involving usually several motor vehicles

In Google Images:

“Huge car crash pileup”

“Boat Pileup”

What is Pileup?

Merriam-Webster

1 : a collision involving usually several motor vehicles

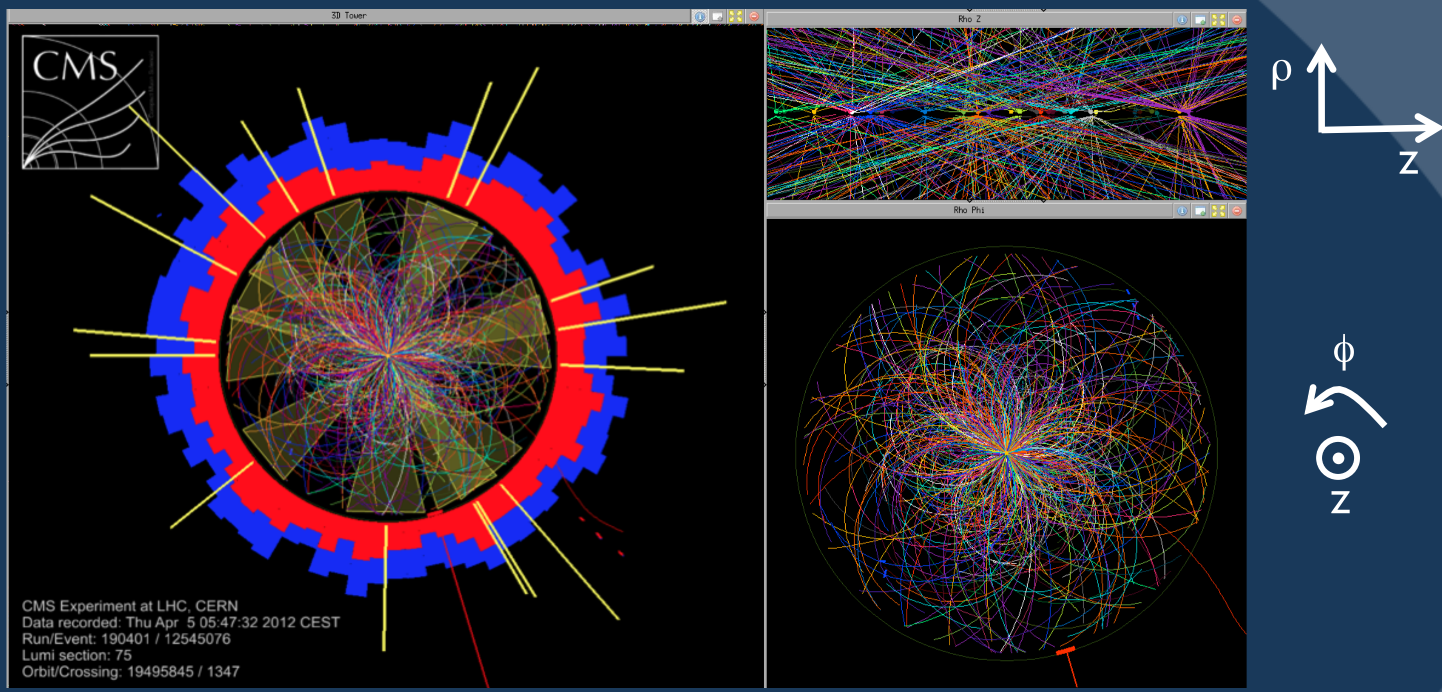
In Google Images:

"Pig pileup"

"Muti-ethnic male soccer players in pileup"

What is Pileup?

The effect of more than one proton-proton hard collision in a single crossing at the LHC ← in-time pileup

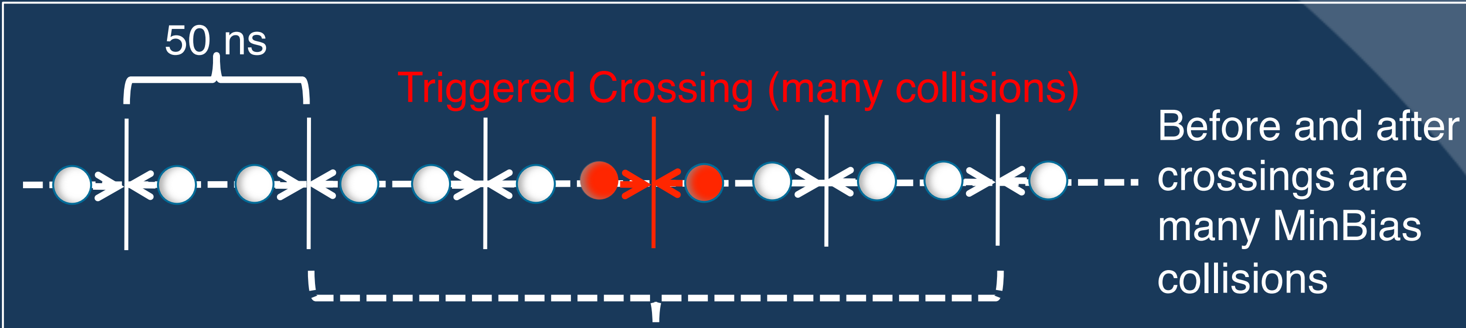


8 TeV collisions at CMS showing the effect of pileup – April 5th 2012

29 distinct primary vertices within the same crossing were reconstructed !

What is Pileup?

The effect of hard collisions occurring before and after the one that fired the trigger ← out-of-time pileup



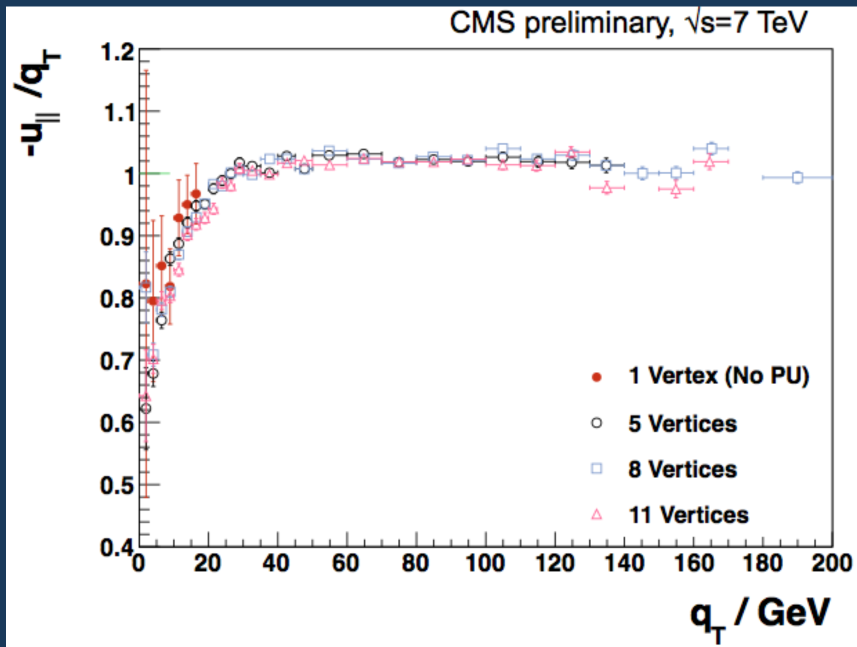
Detector electronics integrate the signal over a larger time window than the time interval between bunch crossings (tunable parameter)

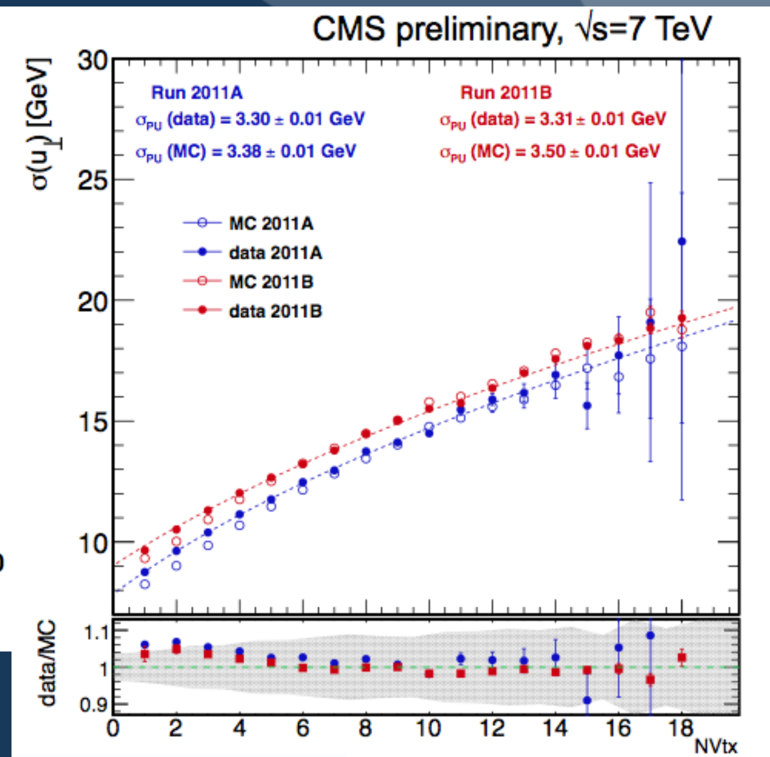
Pileup modifies the original triggered event:

- ➢ Track, cluster association with high p_T primary vertex difficult
- ➢ Many Soft jets from extra MinBias events
- ➢ Unclustered energy masks lepton isolation

Performance of physics objects algorithms could potentially deteriorate

Pileup and MET in Z(μμ)+jets





- PU has little effect on response
- MET resolution for 2011B run is worse due to larger out-of-time pileup
- PU equivalent to additional smearing of ~3-4 GeV on MET (in quadrature)

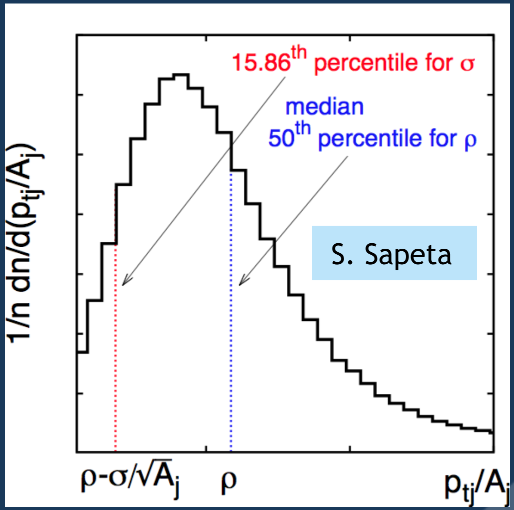
Excellent MC modeling

How to deal with Pileup

Pileup subtraction based on event-by-event p_T density estimation using FastJet tools Cacciari, Salam, Soyez (2008), http://fastjet.fr

- Add to the event a dense set of infinitely soft particles, ghosts, uniformly distributed in azimuth and rapidity
- Apply clustering algorithm and determine the area, A_j, for each jet
- From the list of all jets, calculate the energy density ρ as:

$$\rho = \text{median}\left[\left\{\frac{p_{T,j}}{A_j}\right\}\right]$$



This definition of ρ separates (median) the hard and soft parts of the event, limiting the bias from hard jets.

$$p_T^{sub} = p_T - f(y)\rho A$$

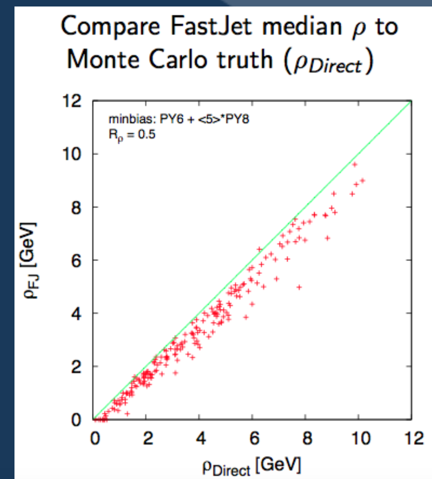
p_T^{sub} is the rapidity dependent corrected jet p_T

Pileup Subtraction Performance

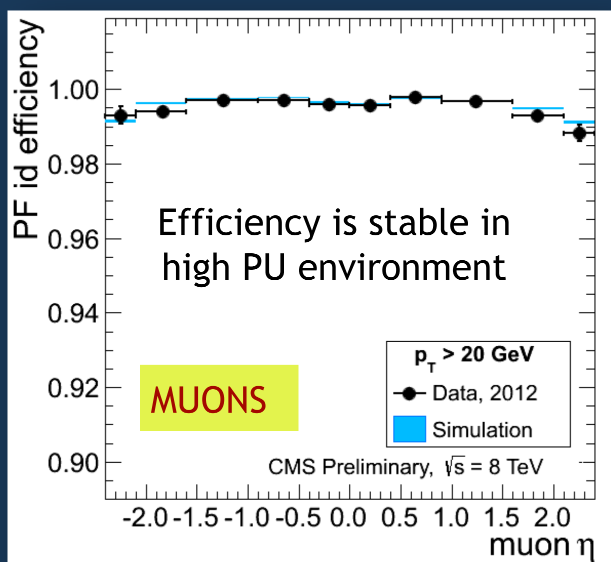
10 extra events contribute ≈ 10 GeV extra p_T per jet, with large fluctuations

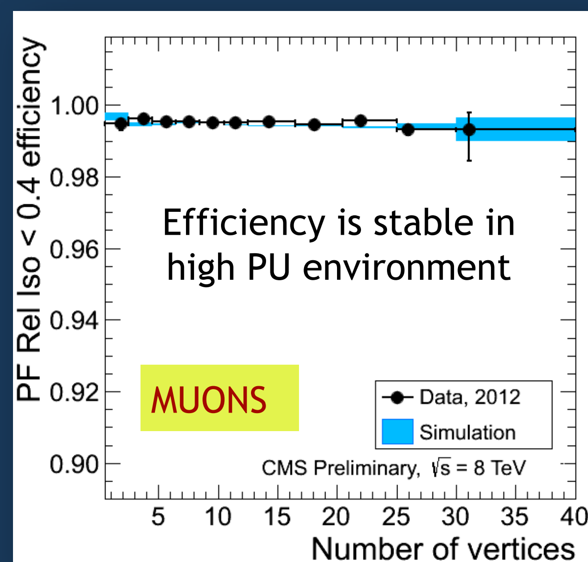
Bunch Spacing LHC 2012	Peak Luminosity	Integrated Luminosity (fb-1)	Pile Up
50ns	5.50E+33	~16	~26

S. Myers



Monte Carlo closure test





A (SUSY) Search Analysis:

How do we build the components and put everything together?

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Standard Model Measurements

Precise measurements of Standard Model (SM) “candles” essential to establish solid ground for searches

New physics signals appear as an excess of events with respect to the SM predictions

It is important to measure accurately cross sections for:

- Jets
- W/Z+jets
- Top

Described in the 2011 version of lectures
https://indico.cern.ch/categoryDisplay.py?categId=3654

This constitutes the background for SUSY searches

No understanding of background means no discovery

Search Deconstruction

The components of a search analysis:

- Theoretical models motivate the search, but they are not essential for a discovery – until you care about its nature

  (A statistically significant deviation of the data from the Standard Model predictions is a signature of new physics)

- Sensitive variables, used to observe the data – event counting is the simplest way
- Background predictions, # of events from SM processes is subtracted from observed data
- Interpretation
  - Statistically significant excess of events – discovery

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  - Statistically significant excess of events – discovery (and glory)

Search Deconstruction

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- Background predictions, # of events from SM processes is subtracted from observed data, in case of event counting
- Interpretation
  - No excess does not mean failure !

Search Deconstruction

The components of a search analysis:

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- Sensitive variables, used to observe the data – event counting is the simplest way
- Background predictions, # of events from SM processes is subtracted from observed data, in case of event counting
- Interpretation
  - Observation consistent with SM prediction means that new physics is not present at the mass scale we are probing – limit on mass or x-section follows

Search Common Elements:

All searches are more or less affected by the same sources of background and interpreted in the light of theoretical models

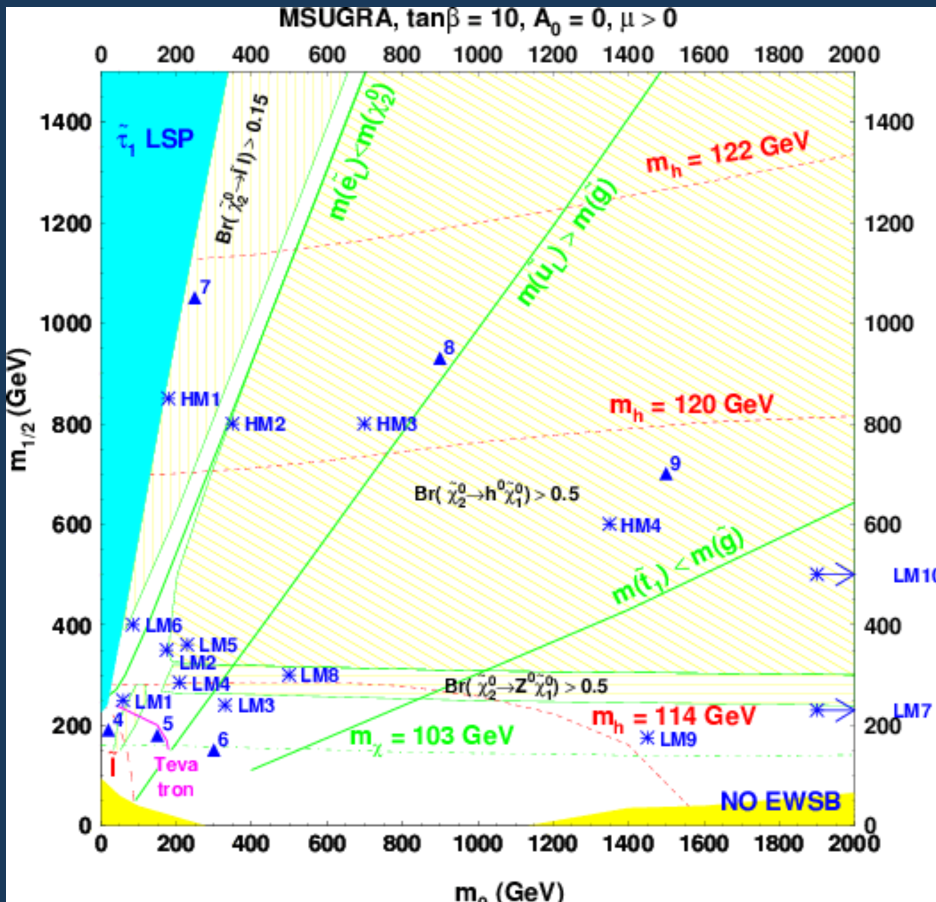
CMSSM Framework Parameters

The Constrained MSSM (CMSSM) framework includes mSUGRA

- Depends on a few independent parameters defined at the M_{GUT} scale
  - ✓ sleptons/squarks/Higgs have the same common scalar mass m_0
  - ✓ gauginos unify at the common mass $m_{1/2}$
  - ✓ Universal trilinear coupling (higgs-sfermion-sfermion) A_0
  - ✓ Ratio of the two higgs doublets VEVs is $\tan\beta$
  - ✓ Sign of higgs/higgsino mass parameter μ, $\mathrm{sgn}(\mu)$
- RGEs evolve parameters, compute couplings/masses at EWK scale
- LSP is often the neutralino

Different parameter values correspond to different production cross section for SUSY particles, flavor content, masses and mass hierarchy, length of the decay chain

CMSSM Benchmark Points (CMS)



- Low Mass points (LM1 to LM10), above TeV reach, target early LHC searches
- High Mass points (HM1 to HM4) defined for ultimate CMS reach

CMS Physics TDR, Vol.II, CERN/LHCC 06-021

Point	m_0	$m_{1/2}$	$\tan\beta$	sgn(μ)	A_0
LM1	60	250	10	+	0
LM2	185	350	35	+	0
LM3	330	240	20	+	0
LM4	210	285	10	+	0
LM5	230	360	10	+	0
LM6	85	400	10	+	0
LM7	3000	230	10	+	0
LM8	500	300	10	+	-300
LM9	1450	175	50	+	0
LM10	3000	500	10	+	0
HM1	180	850	10	+	0
HM2	350	800	35	+	0
HM3	700	800	10	+	0
HM4	1350	600	10	+	0

All Low Mass points were excluded by LHC experiments using ~ 1 fb^{-1} by the Summer of 2011

CMSSM Benchmark Points

Experiments use benchmark points as aid for comparative assessment

Define a grid of points in parameter space for setting exclusion limits

(In CMS, $m_{1/2}$ & m_0 were scanned in 10 GeV steps for tan β=3, 10, 50 using LO generators and NLO k-factors using PROSPINO. Events are then passed through detector simulation)

ATLAS Benchmark Points

	m_0 (GeV)	m_1/2 (GeV)	A0 (GeV)	tan(beta)	σ(NLO) (pb)	Comment
SU1	70	350	0	10	10.9	Soft leptons, taus
SU2	3550	300	0	10	7.2	gluino/gaugino production, heavy flavor decays
SU3	100	300	-300	6	27.7	Generic point
SU4	200	160	-400	10	402.2	Low mass point near Tevatron bound
SU6	320	375	0	50	6.1	Tau rich

The Simplified Models

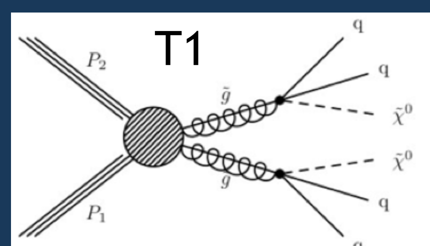
Final state kinematics from squark & gluino strong production determined mostly by pdfs and decay amplitudes, and little on the SUSY model details

Simplified Models (SMS)

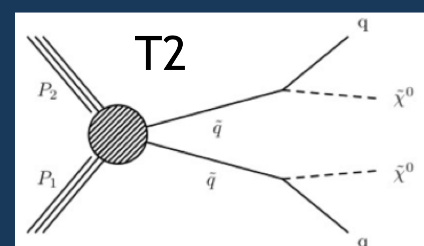
- SMS are defined for a limited set of hypothetical particles and decay chains introduced to produce a given topological signature that groups large sectors of phase space
- Production/decay amplitudes parameterized in terms of their masses and branching ratios
- SMS signal acceptance and cross section exclusion limit can be used as a reference to place limits on different theoretical models.

Alwall, Schuster, Toro: Phys. Rev. D79, 075020 (2009) arXiv:0810.3921[hep-ph]

CMS-PAS-SUS-11-016



Gluino pair production



squark pair production

The Simplified Models are generated with PYTHIA for a range of masses of the particles involved and passed through detector simulation

Background Sources

Background events are events that mimic the signal

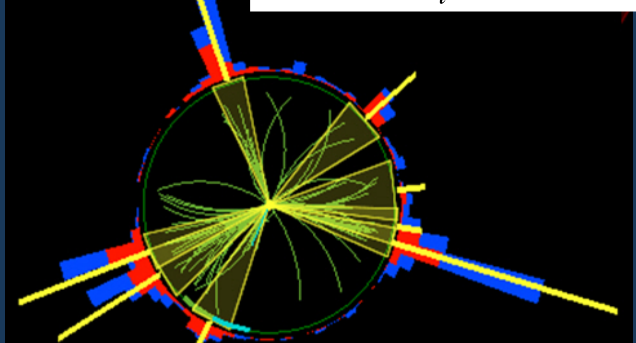
Concept

- Reducible: same final state but one or more objects are fake due to detector acceptance, response, efficiency
- Irreducible: indistinguishable from signal events, all objects are real

QCD background:

- Multijets come from QCD Standard Model production
- Large MET created by extreme detector response mis-measurement

$$\vec{p}_T^{\,event} = \sum_i \vec{p}_{Ti}^{\,jet} = 0$$ In the case of an ideal detector (perfect response)



QCD Multijet Event

Physics Background

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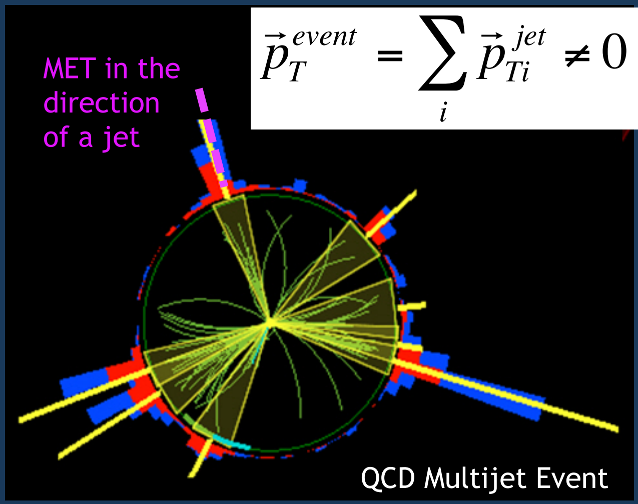
$$\vec{p}_T^{\,event} = \sum_i \vec{p}_{Ti}^{\,jet} \neq 0$$

Detector response <1
Fake MET



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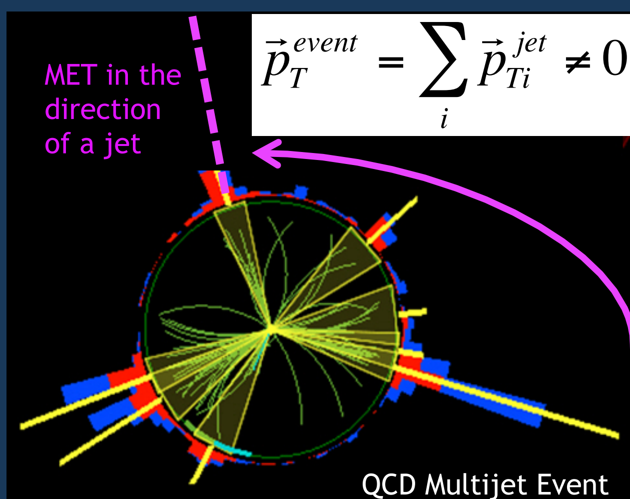
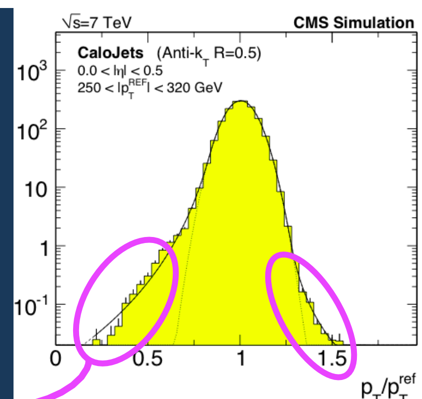




Extreme mis-measurement
⇓
Large fake MET consistent with SUSY signals

(events in the "tails")

Background Sources

QCD background:

- Jet response fluctuation

$$QCD\ multijet\ event \Rightarrow\ jets + MET$$

- One or more EM jets or γ's mis-identified as a lepton

$$QCD\ multijet\ event \Rightarrow\ jets + n \times l^{\pm} + MET$$

- One or more EM jets mis-identified as a γ, direct γ production

$$QCD\ multijet\ or\ \gamma's + jets\ event \Rightarrow\ jets + n \times \gamma + MET$$

QCD background is significant in the all jets and γ+jets final states but small as we require one or more leptons, a Z-boson, a γ+lepton

- Depends on *jet p_T response function*, jet-lepton and jet-γ fake rates
  - Change with detector conditions ➔ time (sample) dependence
- Mitigated with cuts, e.g. $\Delta\phi$(MET,jets), or kinematic based variables
- Typically not dominant but difficult to predict, extrapolate

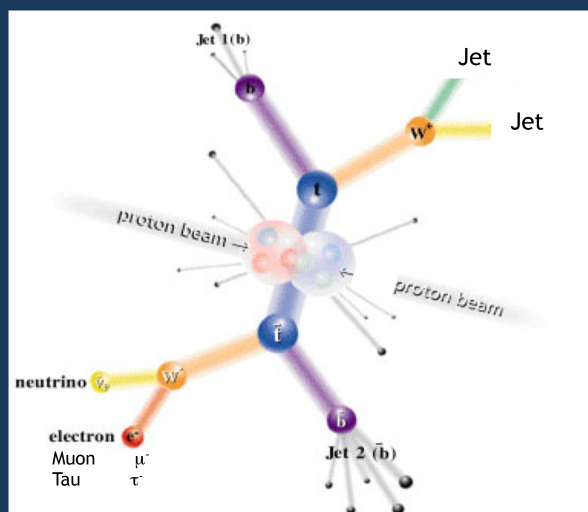
Background Sources

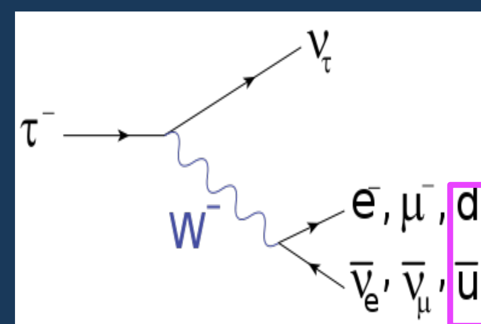
Electroweak (EWK) background:

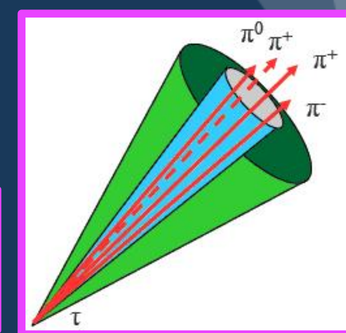
- W+jets and top production

  W decays hadronically
  W decays to $\tau\nu$ and τ decays hadronically
  W decays leptonically

  } Irreducible background







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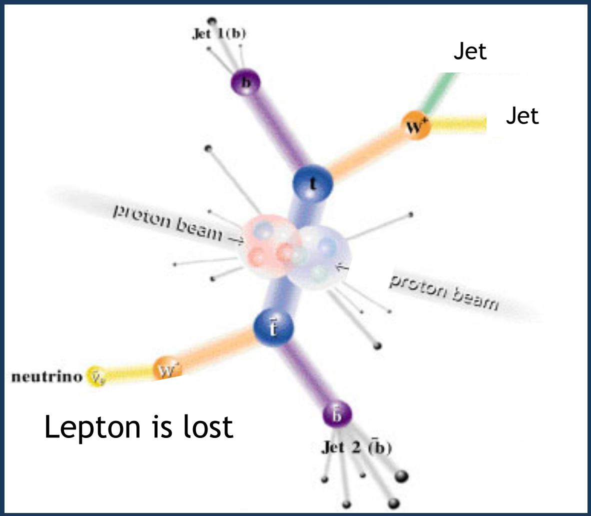

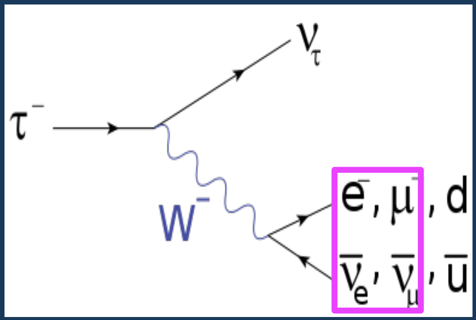

W decays leptonically and e/μ is "lost" (not detected or reconstructed)

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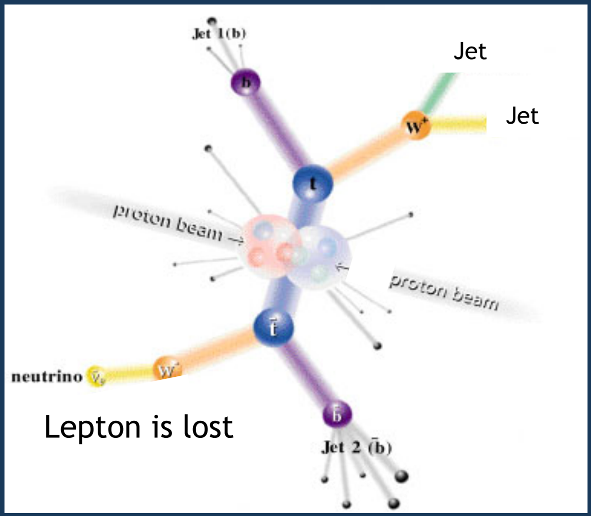
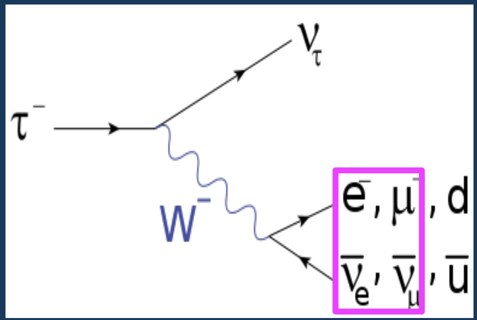




$$t\bar{t} \rightarrow W^+W^- b\bar{b} \Rightarrow$$
$$l^+ / jets + l^- / jets + 2b\ jets + MET$$

W decays leptonically and e/μ is "lost" (not detected or reconstructed)

Background Sources

Electroweak (EWK) background:

- Z+jets

  Z ⟶ $\nu\nu$ or "Z to invisible" (irreducible – real jets and MET)

  Z ⟶ l^+l^- if $\tau\tau$, MET+jets or MET+e/μ

  if $e^\pm/\mu^\pm$, OS leptons+jets+MET

  if $e^\pm/\mu^\pm$ or jet mis-ID as γ, lepton/s+γ/s+jets+MET

  } Jet fluctuation creates MET

$$Z(\nu\bar{\nu}) + jets \Rightarrow jets + MET$$

$$Z + jets \Rightarrow \begin{array}{l} jets + OS\ leptons + MET \\ jets + lepton + \gamma + MET \\ jets + 2\gamma + MET \end{array}$$

- WW/WZ/ZZ+jets ➔ multileptons + jets + MET

EWK background is significant in hadronic/leptonic/γ searches

- Depends on *jets* ⟺ *l/γ fake rates, lepton ID/reco/iso efficiencies, jet p_T response fluctuation*
- Mitigated with cuts, e.g. lepton veto, in hadronic analyses

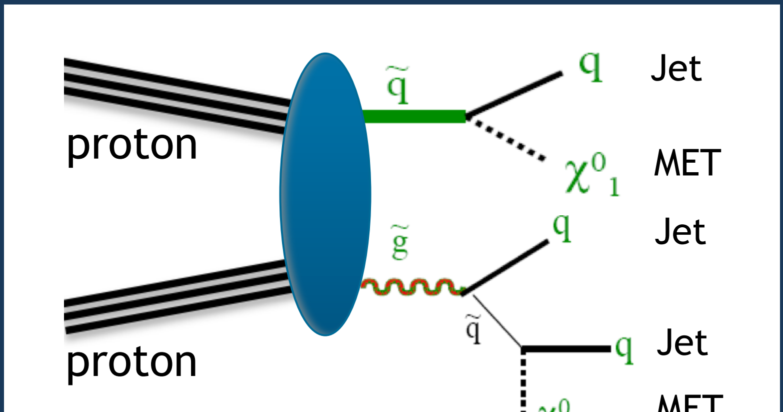
An Inclusive Search Example:

The MHT Search for jets and missing transverse momentum in the all-hadronic channel

Physics Signals

A generic search for jets and MET in the all hadronic channel is motivated by R-parity conserving SUSY

- Strong production of $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$
- Largest cross section, most sensitive channel - *if backgrounds are well understood*



Simplest Example

SUSY particles eventually decay to LSP (stable, neutral)

Experimental signature: Jets + Missing Transverse Momentum

In the example, LPS is χ^0_1 (neutralino)

Model independent analysis means:

Concept

- Inclusive sample selection
- High efficiency for a broad range of models associated with final state

Sample Selection

Analysis Strategy:

- Inclusive, model independent search with loose cuts to avoid kinematic bias
- Maximize signal acceptance at the cost of relatively large but well understood, accurately predicted, backgrounds
- HT and MHT are the search sensitive variables

Alternative: minimize bkgnds at the cost of signal acceptance

Baseline Event Selection (2011 full sample, 4.98 fb^{-1}):

- HT and HT_MHT triggers
- At least 3 JEC corrected jets with p_T>50 GeV, $|\eta|$<2.5 (central production)
- $\Delta\phi$(MET, jet[1,2,3])>[0.5,0.5,0.3] ← suppress QCD bkgnd
- Isolated electron and muon veto ← reduce W/top bkgnd
  p_T>10 GeV, $|\eta|$<2.4 (muons), 2.5 (electrons)

Selection	
H_T (GeV)	$\not{H}_T$ (GeV)
500–800	200–350
500–800	350–500
500–800	500–600
500–800	>600
800–1000	200–350
800–1000	350–500
800–1000	500–600
800–1000	>600
1000–1200	200–350
1000–1200	350–500
1000–1200	>500
1200–1400	200–350
1200–1400	>350
>1400	>200

14 Exclusive Search Regions in HT & MHT:

High MHT requirement ← generic DM candidate - good bkgd rejection

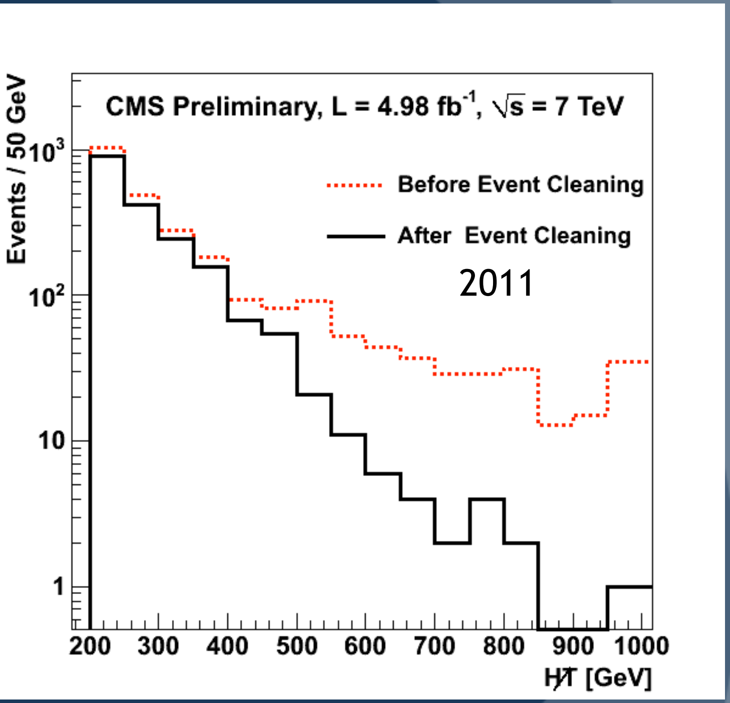
High HT requirement ← heavy particle - long cascade, high multiplicity

Object ID & Event Cleaning

The generic all-hadronic analysis is based on PF physics objects.
Jets reconstructed with Anti-k_T (D=0.5), JEC corrected

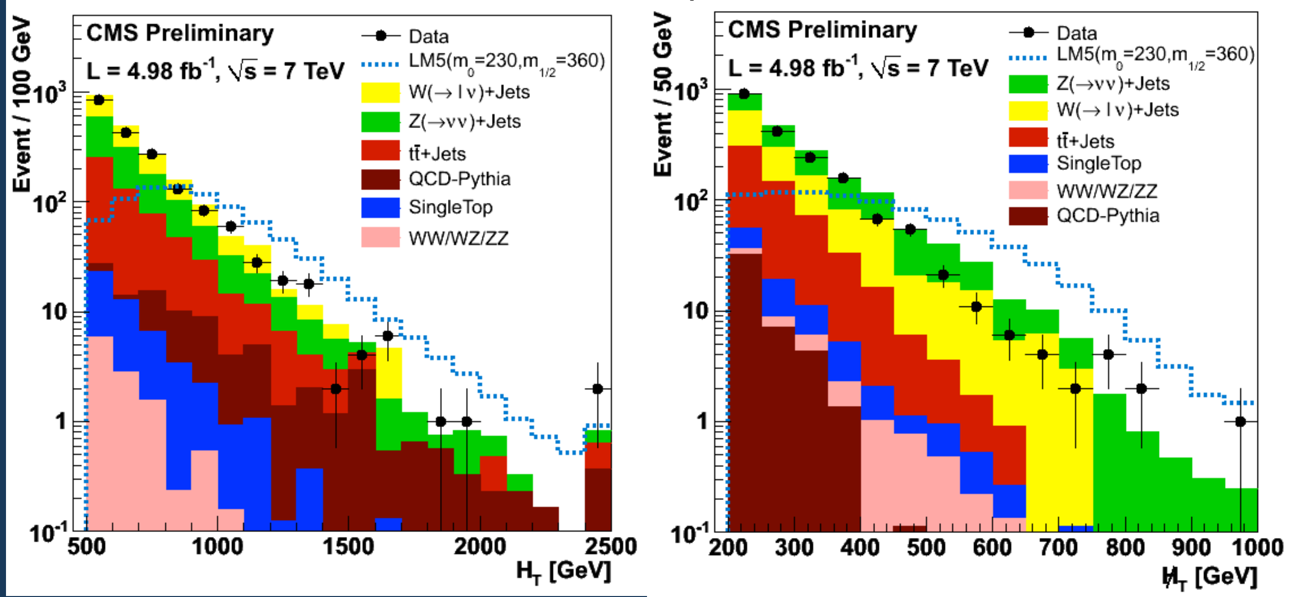
Event cleaning:

- Require at least one good vertex reconstructed
- Remove beam related, beamhalo, background events
- Apply Hcal & Ecal noise filters
- Reject events where substantial energy was lost in the 1% of Ecal towers masked for reconstruction: check parallel trigger readout path (TP saturation veto), or enforce the energy in neighboring crystals to be < 10 GeV



HT & MHT Distributions

2011 Sample



Observed data & MC background prediction

On left (right), baseline selection applied except for 200 GeV (500 GeV) MHT (HT) cuts

LM5 benchmark for illustration

Physics generators not accurate enough (QCD multijets, W/Z+jets)

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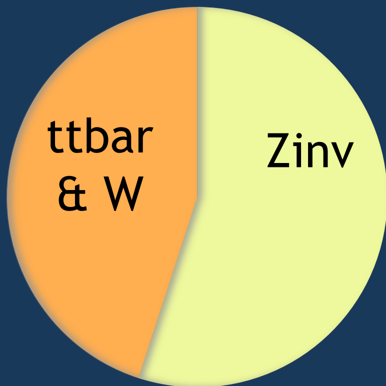
Background predictions extracted from data

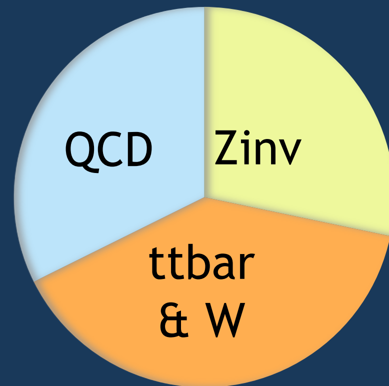
Background Predictions

High MHT: 500 GeV<HT<800 GeV, MHT>600 GeV



$Z(\nu\nu)$ dominates, about 2/3
QCD negligible

High HT: HT>1.4 TeV, MHT>200 GeV



$Z(\nu\nu)$ + ttbar/W about 2/3
QCD about 1/3

Data based predictions of backgrounds are the backbone of the analysis

Data Driven Method for background predictions

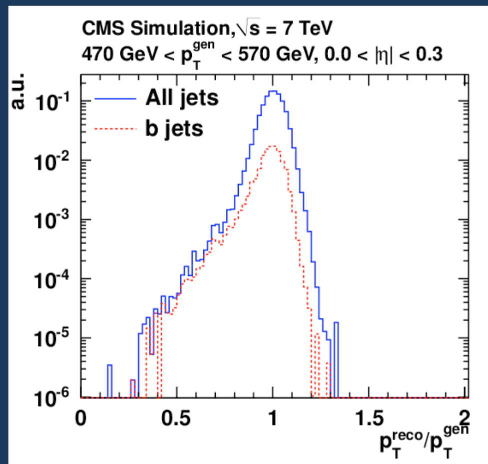
Concept

- Use "control data samples" or "control regions in data"
- Control sample/region: signal depleted sample/region from which to infer the bkgd in the signal region by use of event properties, physics laws, etc
- Signal: area of phase space where the signal is enhanced = search region (good s/b)

Background Prediction Methods

- QCD background
  - Rebalance & Smear (R+S): "unfold" data to particle level (R) and re-smear with measured jet resolutions (S).
  - Factorization: extrapolate two-variable correlation to search region
- W/top background
  - Lost lepton: use inverted lepton veto in a μ+jets control sample
  - Hadronic tau: replace muon by tau response template in a μ+jets control sample
- $Z(\nu\nu)$ background
  - From γ+jets: remove photon and scale by $Z(\nu\nu)$+jets/γ+jets ratio. High stats but non-trivial theory correspondence
  - From W+jets: remove lepton and scale by $Z(\nu\nu)$+jets/$W(l\nu)$+jets ratio. Less stats but easier theory correspondence
  - From Z+jets: remove leptons and scale by $Z(\nu\nu)$+jets/$Z(\mu\mu)$+jets ratio. Straight forward correction but limited yield

QCD Background: smearing effect

+ 

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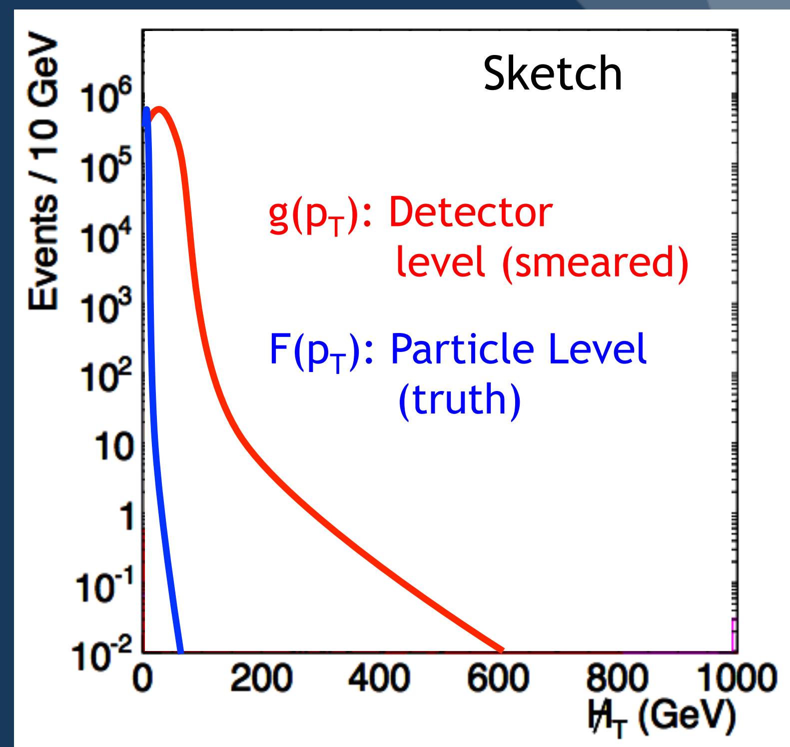
True distribution "smeared" due to the finite detector energy resolution

$$g^{smeared}(p_T^{meas}) = \int_0^{\infty} F^{true}(p_T^{true}) R(p_T^{meas}, p_T^{true}) \, dp_T^{true}$$



Jets that fluctuate to high/low response create spurious MHT tail

QCD Background: R+S concept

- Rebalance

  Jet particle level p_T restored from detector level inclusive multi-jet data sample by maximum likelihood using:

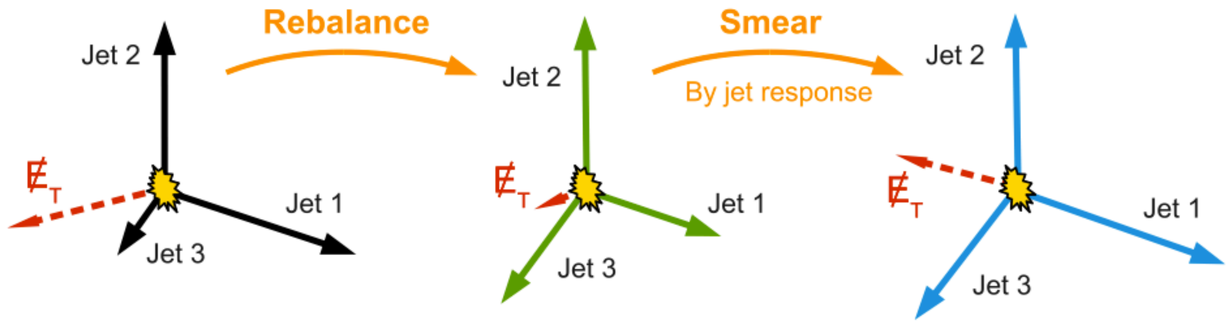
  ✓ Measured jet p_T response probability density functions

  ✓ Transverse momentum conservation $\sum_{i=1}^{n} \vec{p}_{T,i}^{\,true} + \vec{p}_{T,soft}^{\,true} = 0$

  ✓ Events with real MET are turned to QCD multi-jet events automatically

- Smear

  Rebalanced distribution is smeared by the measured jet pT resolution functions including the tails



"Data Driven" (DD) technique

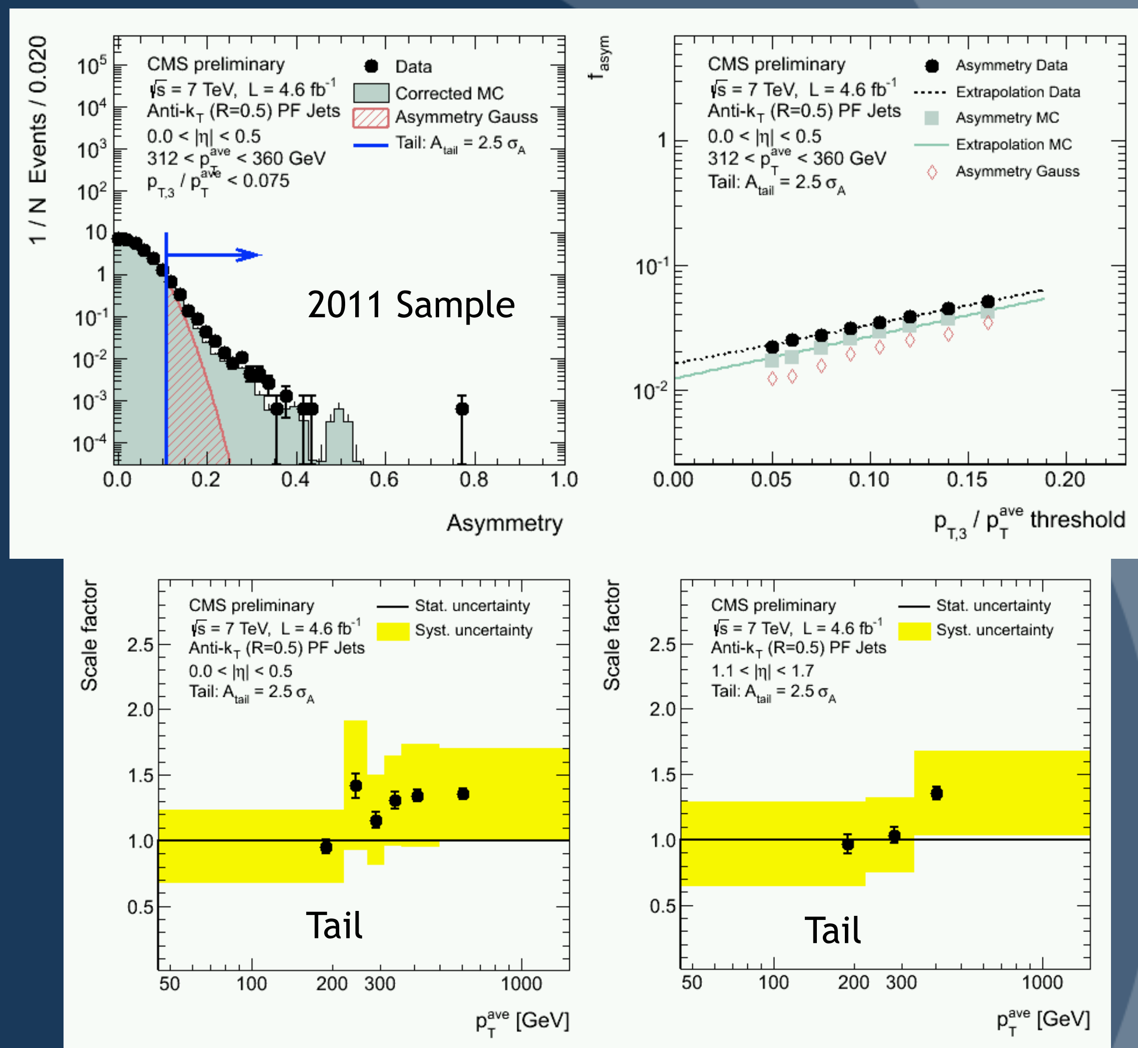
QCD Background: R+S ingredients

Jet p_T resolution functions are the main ingredient to R+S

Measured from data using object p_T balance (see lecture on physics objects)

For the Gaussian core and tails the data/MC ratio was measured

MC truth resolution functions * (data/MC) were used in R+S

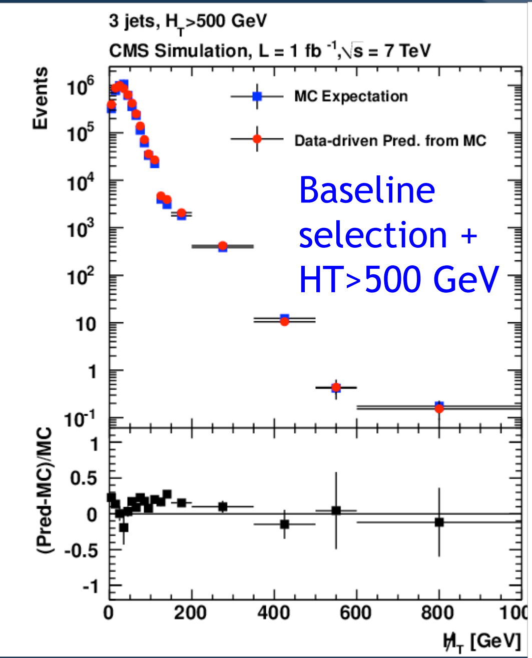


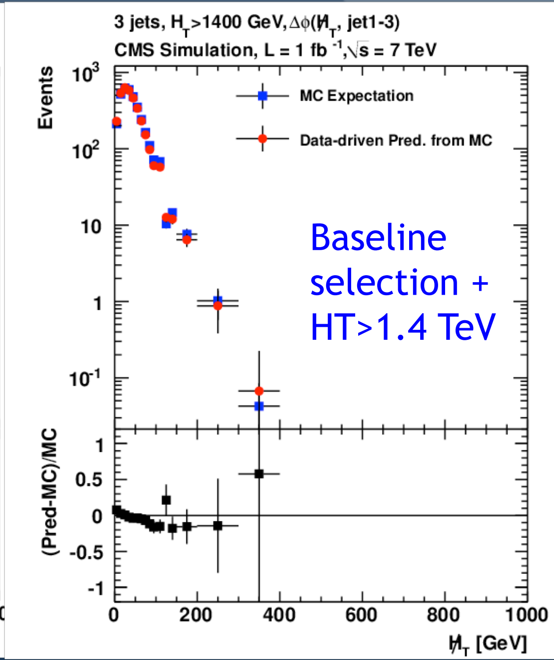
CMS-PAS-SUS-12-011

QCD Background: R+S closure

MC closure test of the method:

➢ Ratio of MC (R+S) predicted MHT (treated as data) to MC detector level MHT





Closure Test

Concept

➢ Using MC: evaluates the validity and accuracy of a method by comparing the "measured prediction" with the "truth" information (e.g. above)

➢ Using data: idem by comparing the measured prediction to the straight detector level distribution in a control region

(e.g. R+S distribution compared to observed MHT in a signal depleted region)

QCD Background: R+S results

QCD background prediction including uncertainty components

HT | MHT | QCD bkgnd | Total Syst. Error

H_T (GeV)	$\not{H}_T$ (GeV)	Pred.	Stat.	Core	Tail	Bias	HF	PU	Tot. Sys.
500…800	200…350	118	12	$^{+14\%}_{-10\%}$	$^{+33\%}_{-34\%}$	43%	10%	29%	$^{+76}_{-76}$
500…800	350…500	2.1	1.6	$^{+40\%}_{-11\%}$	$^{+46\%}_{-3\%}$	43%	10%	29%	$^{+1.8}_{-1.2}$
500…800	500…600	0.02	0.14	$^{+50\%}_{-50\%}$	$^{+50\%}_{-100\%}$	43%	10%	29%	$^{+0.02}_{-0.02}$
500…800	600…	-	-	-	-	-	-	-	-
800…1000	200…350	35	5.3	$^{+14\%}_{-12\%}$	$^{+32\%}_{-34\%}$	40%	10%	40%	$^{+23}_{-24}$
800…1000	350…500	1.2	1.1	$^{+14\%}_{-25\%}$	$^{+5\%}_{-34\%}$	40%	10%	40%	$^{+0.7}_{-0.8}$
800…1000	500…600	0.03	0.17	$^{+33\%}_{-0\%}$	$^{+100\%}_{-100\%}$	40%	10%	40%	$^{+0.04}_{-0.03}$
800…1000	600…	0.01	0.10	$^{+100\%}_{-100\%}$	$^{+0\%}_{-100\%}$	40%	10%	40%	$^{+0.01}_{-0.02}$
1000…1200	200…350	19.7	4.4	$^{+19\%}_{-13\%}$	$^{+37\%}_{-29\%}$	31%	10%	40%	$^{+13}_{-12}$
1000…1200	350…500	0.44	0.61	$^{+23\%}_{-9\%}$	$^{+39\%}_{-30\%}$	31%	10%	40%	$^{+0.30}_{-0.26}$
1000…1200	500…	0.04	0.2	$^{+0\%}_{-100\%}$	$^{+50\%}_{-25\%}$	31%	10%	40%	$^{+0.03}_{-0.05}$
1200…1400	200…350	11.6	3.4	$^{+20\%}_{-24\%}$	$^{+32\%}_{-29\%}$	34%	10%	39%	$^{+7.5}_{-7.6}$
1200…1400	350…	0.24	0.53	$^{+33\%}_{-33\%}$	$^{+4\%}_{-54\%}$	34%	10%	39%	$^{+0.15}_{-0.20}$
1400…	200…	11.9	3.8	$^{+23\%}_{-17\%}$	$^{+28\%}_{-27\%}$	47%	10%	36%	$^{+8.4}_{-8.1}$

For a fixed HT bin, QCD background falls versus MHT cut

Uncertainty very large, 60-100% depending on HT & MHT bin

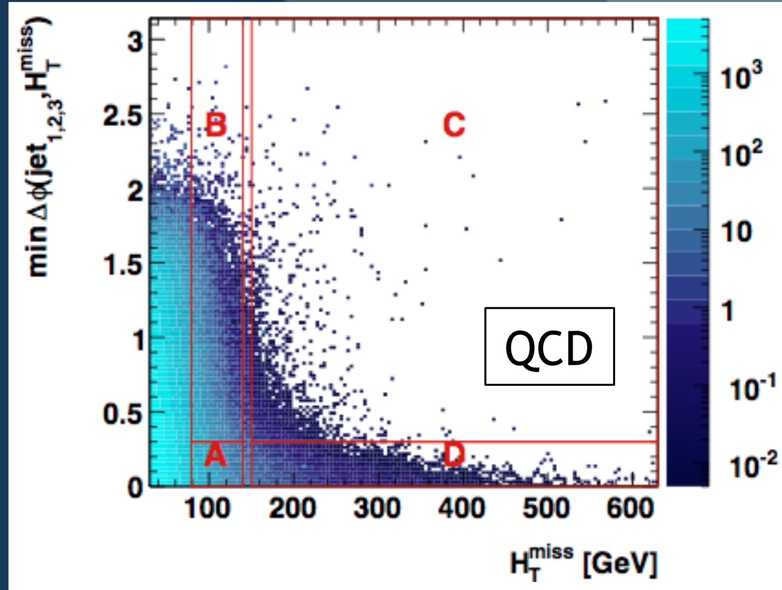
QCD Background: factorization

- A, B, D are background dominated regions
- C is the signal region

min $\Delta\phi$ (jet,MHT)>0.3, MHT>150 GeV

If variables uncorrelated:

$$N_C = N_B / N_A * N_D$$



“Data Driven” (DD) technique illustrated on MC

If variables are correlated and $r(MHT)=N_B/N_A$ is understood :

$$N_C = r(MHT) * N_D$$

with r(MHT) extrapolated to the signal region

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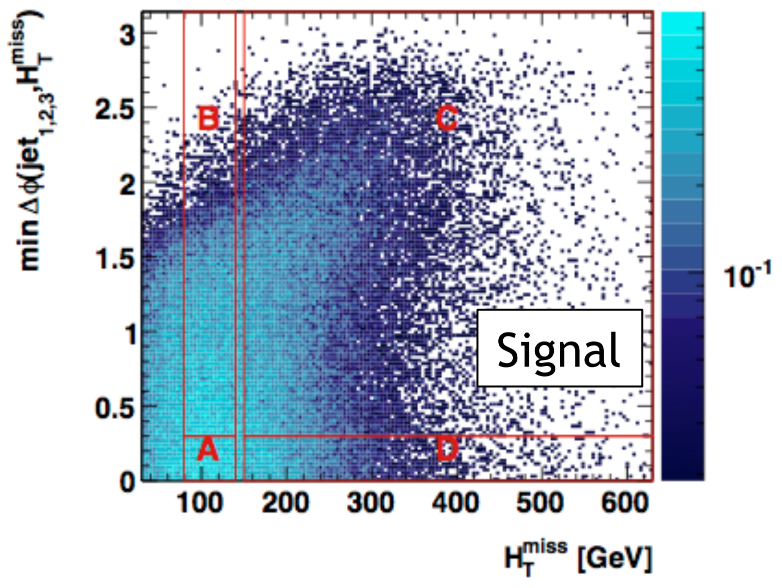


“Data Driven” (DD) technique illustrated on MC

If variables are correlated and $r(MHT)=N_B/N_A$ is understood :

$$N_C = r(MHT) * N_D$$

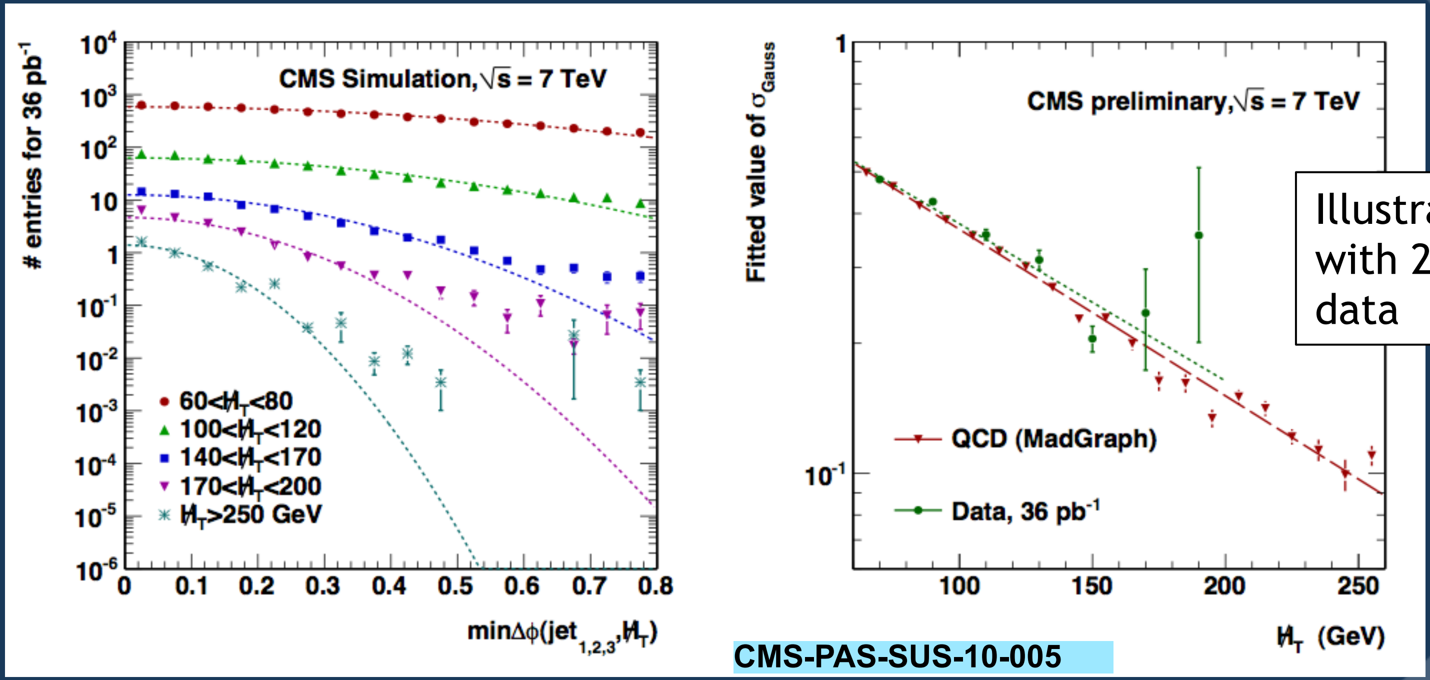
with r(MHT) extrapolated to the signal region

QCD Background: factorization

r(MHT) dependence determined empirically

- Gaussian fit to min ΔΦ(jet,MHT): $r(\not{H}_T) = \frac{1}{\mathrm{erf}\left(\frac{\Delta\phi^{\mathrm{cut}}_{\mathrm{min}}}{\sqrt{2}\cdot\sigma_{\mathrm{Gauss}}(\not{H}_T)}\right)} - 1$ + C

  C taken from MC
- Exponential fit: $r(MHT) = a + \exp(-b/MHT) + c$



Illustrated with 2010 data

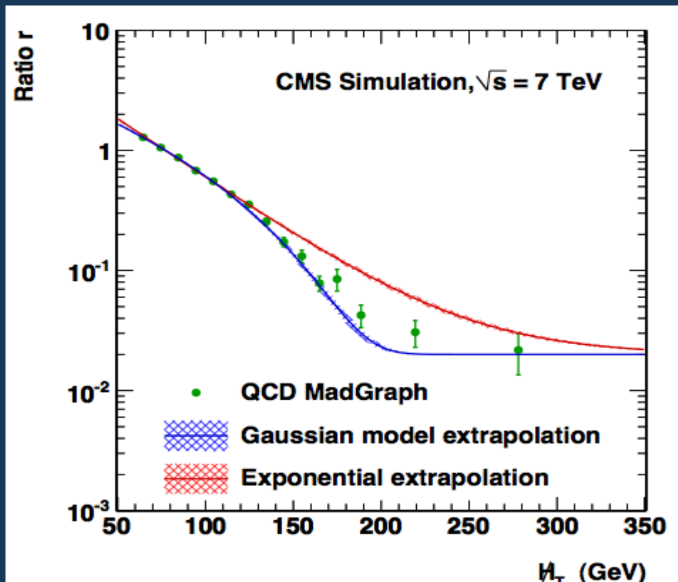
min ΔΦ resolution better as MHT increases (more likely single mis-measured jet), non-Gaussian tails more prominent → C constant added

QCD Background: factorization

Expo and Gauss models bracket the true # of QCD events

- Gaussian underestimates, exponential overestimates

MC closure test



CMS-PAS-SUS-10-005

2011 full dataset
QCD bkgnd prediction →

HT & MHT		Exp. Model	Gauss. Model
500-800	200-350	245.04	80.90
500-800	350-500	2.74	2.31
500-800	500-600	0.04	0.04
500-800	>600	0.00	0.00
800-1000	200-350	53.97	21.32
800-1000	350-500	1.17	1.10
800-1000	500-600	0.06	0.06
800-1000	>600	0.07	0.07
1000-1200	200-350	22.34	10.98
1000-1200	350-500	0.81	0.78
1000-1200	>500	0.13	0.13
1200-1400	200-350	9.97	5.15
1200-1400	>350	0.73	0.72
>1400	>200	11.98	6.91

W/top Background: lost lepton

Lepton veto not fully efficient rejecting W/top background. Lepton is "lost" and the event not rejected if:

- ✓ Not reconstructed
- ✓ Not Isolated
- ✓ Out of detector acceptance

Pythia prediction for events with lost leptons passing lepton veto

36 pb^{-1}	ttbar		W+jets	
Baseline selection	electron	muon	electron	muon
Not reconstructed	1.5	0.4	0.4	0.1
Not isolated	3.2	3.8	0.6	0.6
Out of acceptance	5.5	4.8	2.1	1.9
total	10.2	9.0	3.1	2.6

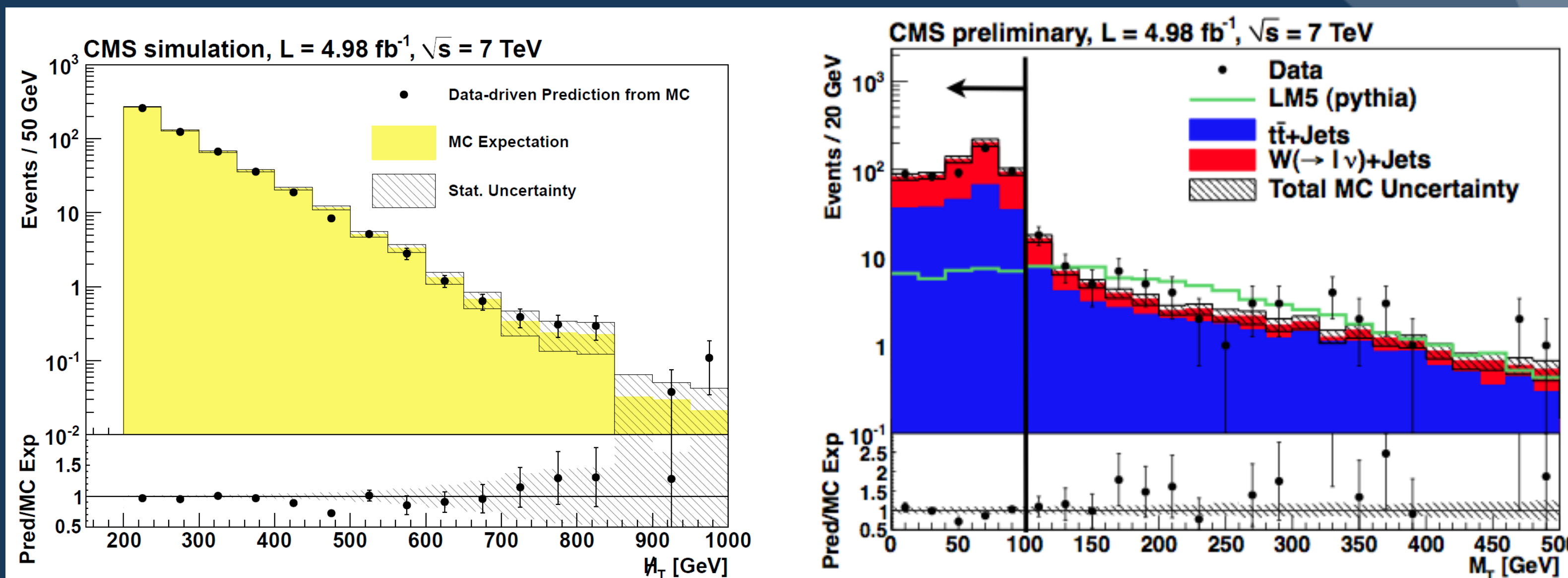
Invert lepton veto technique on μ+jets control sample (97% of events are ttbar or W+jets)

- ✓ All cuts but require one iso muon
- ✓ Events scaled by → $$\frac{1}{\varepsilon_{iso}} \frac{1-\varepsilon_{id}}{\varepsilon_{id}}$$
- ✓ ε_{iso} parameterized in p_T, $\Delta R(l,jet)$ from Z using tag and probe
- ✓ ε_{id} parameterized in p_T, η also using tag and probe
- ✓ Residual corrections (<10%) applied for differences between Z and W/top kinematics

W/top Background: lost lepton

MC test using ttbar and W+jets

- ✓ Simulation (truth) and estimate (prediction) agree within stat errors
- ✓ MC expectation / data prediction agreement excellent (a bonus)



Closure Test of the lost lepton "Data Driven" (DD) technique

Use events with MT(W) < 100 GeV (reduce signal contamination)

W/top Background: lost lepton

Events predicted: from 326 for HT=[500, 800] GeV & MHT=[200, 350] GeV to almost zero for high HT, MHT

Systematic Uncertainties:

- ✓ Bias from closure test (4-20%)
- ✓ Efficiency measurement and parameterization (~10%)
- ✓ SM background contamination in control sample: QCD, Z, di-boson (~3%)

Selection H_T (GeV)	Selection $\not{H}_T$ (GeV)	$t\bar{t}/W \to e,\mu+X$	
500–800	200–350	326.5	± 47.0
500–800	350–500	47.8	± 9.2
500–800	500–600	5.0	± 2.2
500–800	>600	0.8	± 0.8
800–1000	200–350	57.7	± 15.3
800–1000	350–500	5.4	± 2.3
800–1000	500–600	2.4	± 1.5
800–1000	>600	0.7	± 0.7
1000–1200	200–350	13.7	± 3.8
1000–1200	350–500	5.0	± 4.4
1000–1200	>500	1.6	± 1.2
1200–1400	200–350	4.2	± 2.1
1200–1400	>350	2.3	± 1.4
>1400	>200	2.7	± 1.6

W/top Background: hadronic τ

Hadronic τ method combined with lost lepton method to predict total W/top background

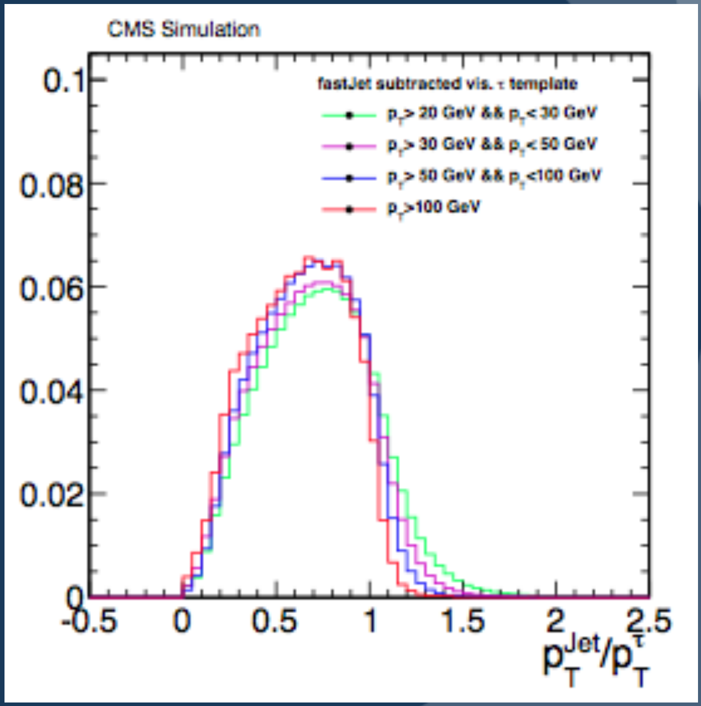
- ✓ Lost lepton: W/ttbar $\rightarrow$ e, μ + X
- ✓ Hadronic τ: W/ttbar $\rightarrow$ τ_{had}+ X

"Data Driven" (DD) technique

Use μ+jets control sample, muon ID & ISO with p_T^{μ}> 20 GeV, $|\eta|$<2.1

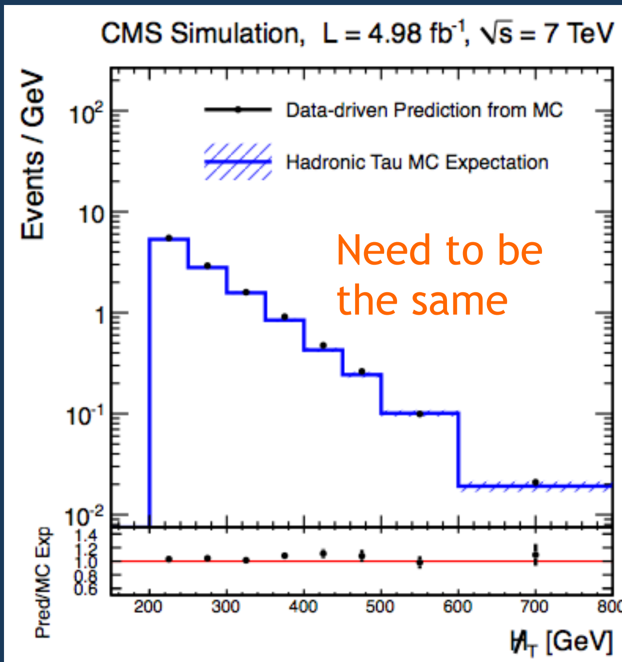
- ✓ Muons replaced by τ-jets
- ✓ τ-jet momentum obtained from simulated template of p_T^{jet}/p_T^{τ}
- ✓ Recalculate HT, MHT
- ✓ correct for muon trigger, acceptance, reco & iso efficiencies, and branching ratio

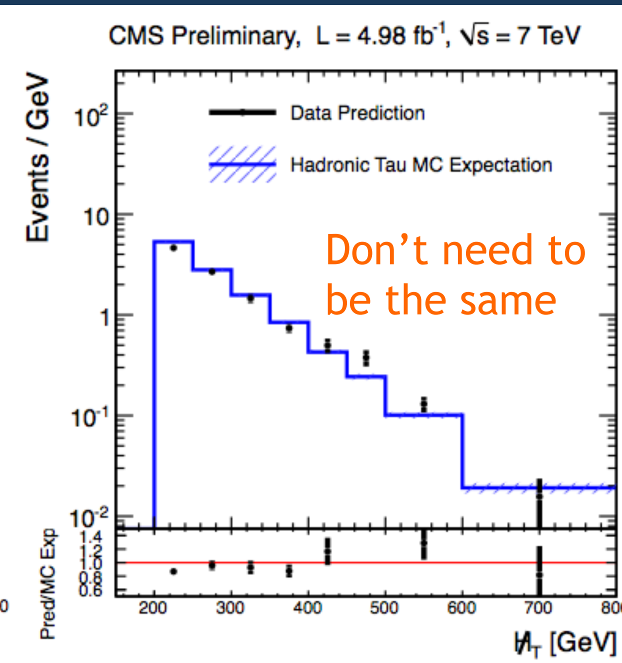
$BR(W\rightarrow\tau)/BR(W\rightarrow\mu) * BR(\tau\text{->Hadrons})$



W/top Background: hadronic τ

Hadronic τ method closure test (left), data driven estimation compared to MC prediction (right)





Selection		$t\bar{t}/W$	
HT	MHT	$\rightarrow \tau_{hadr}+X$	
500-800	200-350	348.5	± 40.1
500-800	350-500	62.5	± 8.7
500-800	500-600	8.7	± 2.5
500-800	>600	2.0	± 1.8
800-1000	200-350	56.3	± 8.3
800-1000	350-500	7.2	± 2.0
800-1000	500-600	1.3	± 0.6
800-1000	>600	1.0	± 0.3
1000-1200	200-350	21.9	± 4.6
1000-1200	350-500	2.9	± 1.3
1000-1200	>500	2.3	± 1.0
1200-1400	200-350	6.2	± 1.8
1200-1400	>350	0.6	± 0.8
>1400	>200	1.1	± 0.5
Total		522.4	± 67.0

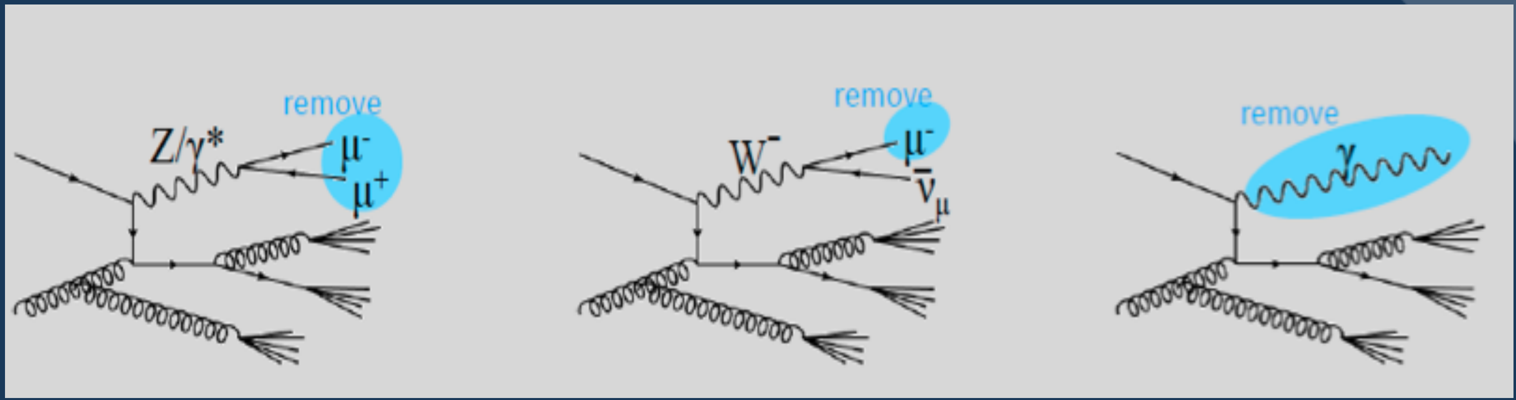
Systematic Uncertainties: tau energy scale and acceptance (2-20%, 5-12%), background subtractions (1-2%), muon ID & ISO efficiencies (1-2%), trigger efficiency (1%), closure (6-12%)

Z(νν) Background

Z(νν) background is a large component of the total background

Three independent data driven methods are used based on Boson substitution with MHT

Z(ll)+jets | W(lν)+jets | γ+jets



Z(ll)+jets
- Same kinematics
- Trivial Br correction $Br(Z \to \mu\bar{\mu})/Br(Z \to \nu\bar{\nu}) = 1/6$
- Lower stats than γ/W+jets

W(lν)+jets
- Similar kinematics
- Large backgrounds
- More stats than Z(νν) and 2.5 more than Z(μμ)

γ+jets
- Similar kinematics as Z+jets at high p_T and MHT
- Large and complex theory corrections
- High statistics

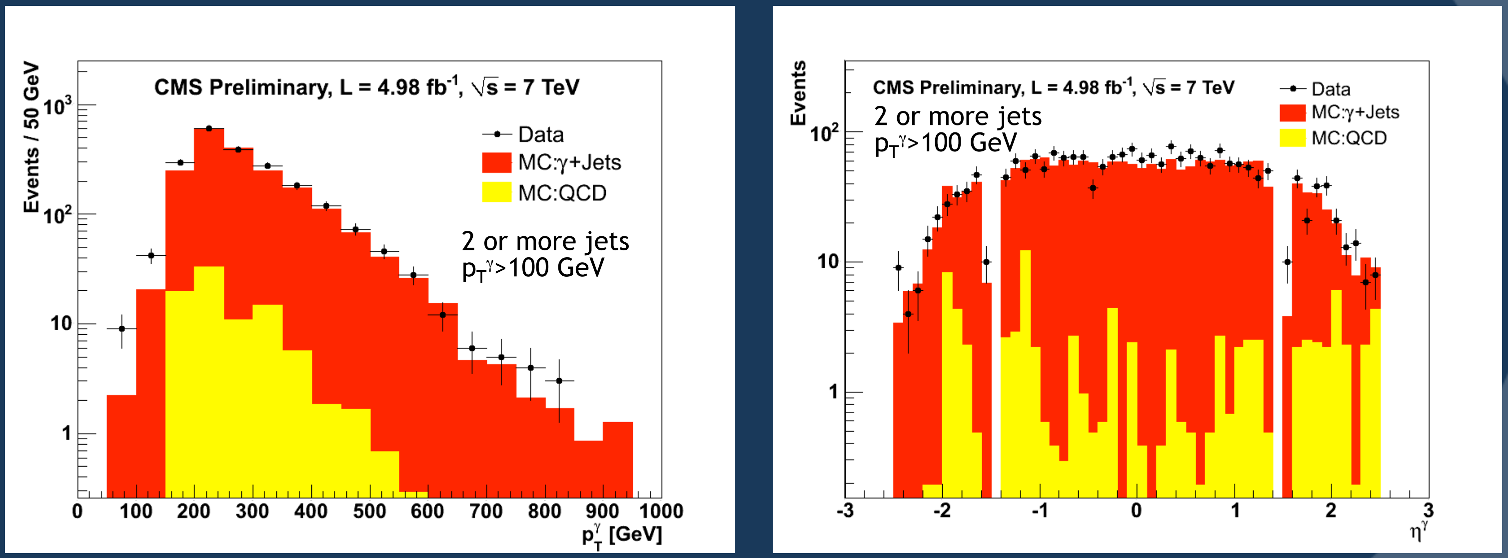
γ+jets prediction is used for the limit, Z/W+jets are cross checks

Z($\nu\nu$) Background: γ+jets sample

Single photon trigger and standard cuts to select isolated photons with p_T >100 GeV in a γ+jets sample

Photon categories

- Direct: well isolated photon from hard scatter ← selected for estimate
- Fragmented: from parton shower, non-isolated, reconstructed inside a jet
- Decay: from π, η mesons



MC: Madgraph LO + detector simulation (normalized)
Excellent description of prompt photons, backgrounds

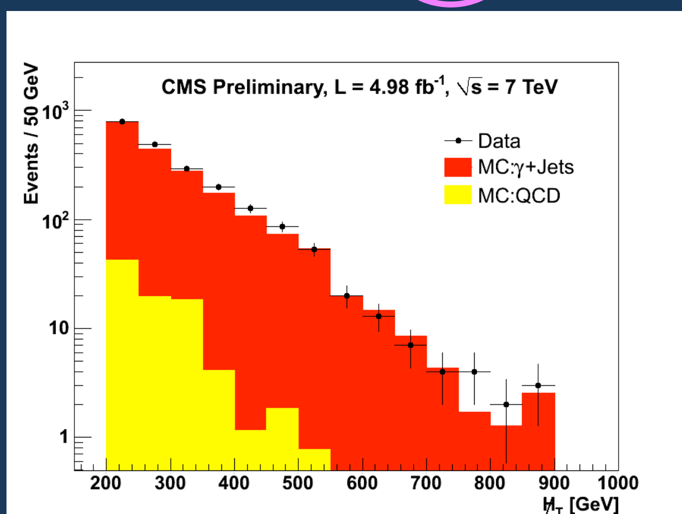
Z(νν) Background: γ+jet procedure

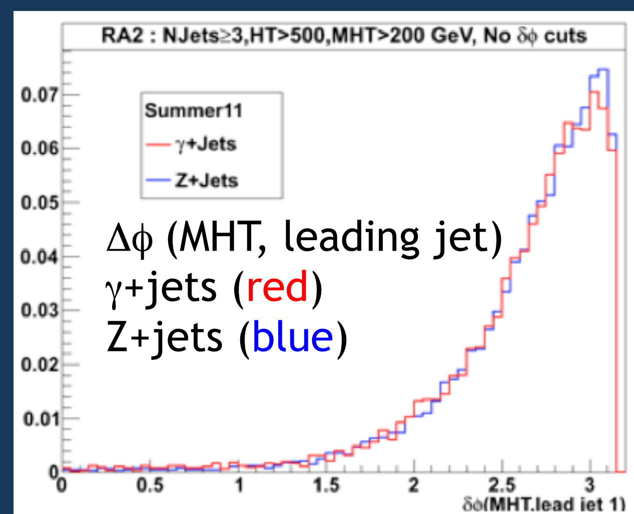
At p_T > 200 GeV, γ and Z spectra is similar but not the same due to the different couplings

- Background subtracted from photon sample after isolation: fragmentation photons are 5% (NLO JetPHOX), photon pairs from mesons
- LO γ+jets/LO Z+jets (Madgraph LO + parton shower + detector simulation) is computed for each of the 14 search selections
- Detector acceptance correction folded into the γ-Z correspondence

$$N^{Z(\nu\nu)+jets}(\mathbf{data}) = \frac{Z+\mathbf{jets}}{\gamma+\mathbf{jets}} \cdot \mathbf{Purity} \cdot N^{\gamma+\mathbf{jets}}(\mathbf{data})$$

Correction factor ~ 0.3





Z(νν) Background: γ+jet results

Data driven predictions of Z(νν) background in 14 HT, MHT bins

Systematic Uncertainties:

- Theory uncertainty on γ/Z ratio (21-42%)
  - ✓ Computed from NLO/LO + parton shower calculation for γ/Z + 2 jets

From Black Hat Collaboration

- Fragmented photon subtraction (5%)
- Detector acceptance (5%)
- Trigger efficiency (1-2%)
- Photon purity (~2%)

Selection H_T (GeV)	$\not{H}_T$ (GeV)	$Z \to \nu\bar{\nu}$ from γ+jets	
500–800	200–350	359.2	± 82.2
500–800	350–500	112.3	± 27.4
500–800	500–600	17.6	± 5.6
500–800	>600	5.5	± 3.1
800–1000	200–350	48.4	± 19.1
800–1000	350–500	16.0	± 7.3
800–1000	500–600	7.1	± 4.5
800–1000	>600	3.3	± 2.0
1000–1200	200–350	10.9	± 5.5
1000–1200	350–500	5.5	± 3.5
1000–1200	>500	2.2	± 2.9
1200–1400	200–350	3.1	± 2.0
1200–1400	>350	2.3	± 2.3
>1400	>200	3.2	± 2.4

Z(νν) Background from Z(μμ) Sample

Start with di-muon events M=60-120 GeV, background small and ignored, remove di-muon and recalculate HT and MHT

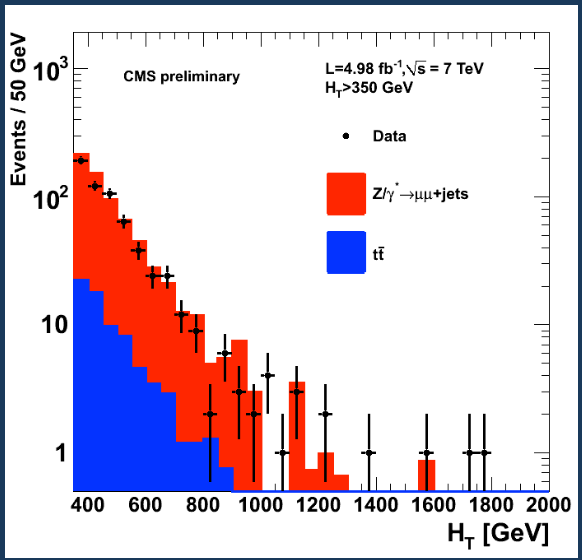
$$N(Z \to \nu\nu) = \frac{N_Z^{obs} - N_Z^{bkg}}{A_Z \cdot \varepsilon_Z \cdot L} \cdot R\left(\frac{Z \to \nu\nu}{Z \to ll}\right)$$

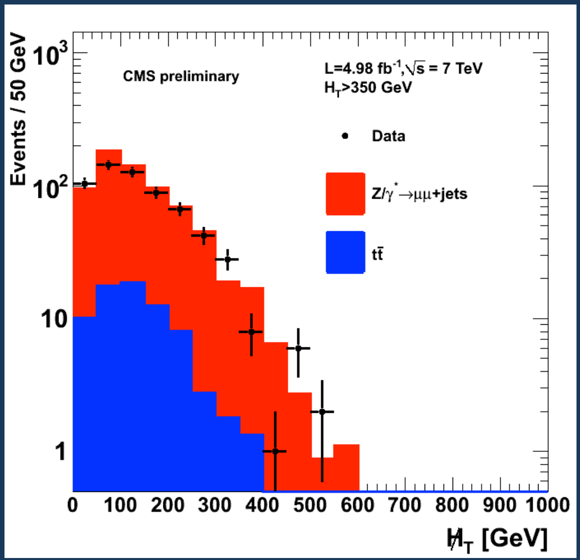
$$R\left(\frac{Z \to \nu\nu}{Z \to ll}\right) = 5.95 \pm 0.02$$

$$\varepsilon_{lepton} = \varepsilon_{Iso} \cdot \varepsilon_{RECO} \cdot \varepsilon_{trig}$$

$$\varepsilon_Z = (\varepsilon_{leptopn})^2 \cdot \varepsilon_{trig},$$

where $\varepsilon_{trig} = 1 - (1 - \varepsilon_{HLT})^2$

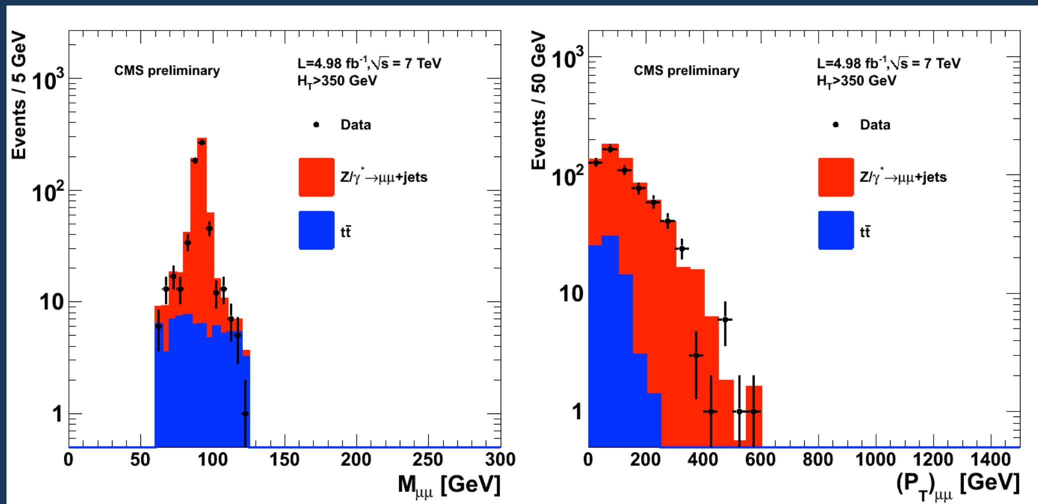




Simulation describes the di-muon HT and MHT distributions well

Z(νν) Background from Z(μμ) Sample

Data driven predictions of Z(νν) backgrounds using di-muon samples



Simulation describes the di-muon p_T spectrum and invariant mass well

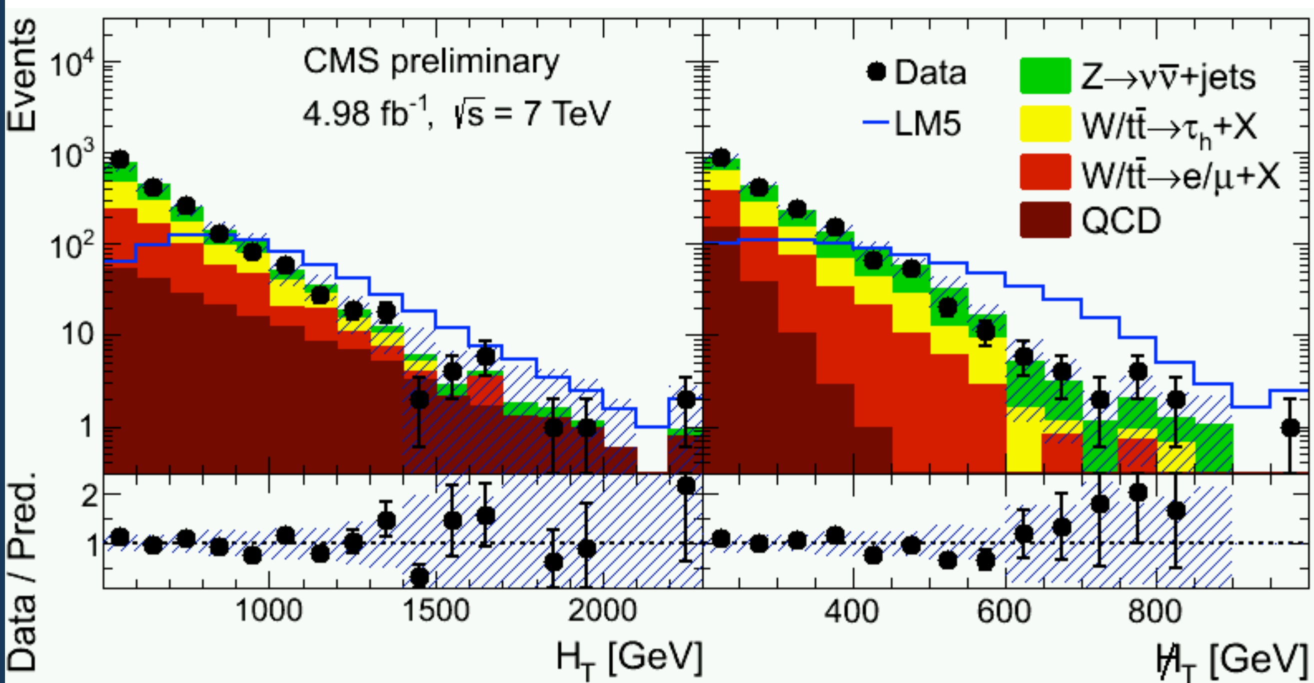
(HT)(MHT)	$\mu^+\mu^-$ +Jets	γ +Jets	MC- Z(νν)+Jets
(500-800), (200-350)	390 ± 76.3	359 ± 82	447 ± 6
(500-800), (350-500)	88.8 -28.2 + 31	112 ± 26.9	131 ± 3
(500-800), (500-600)	15.1 - 8.8 + 16.8	17.6 ± 5.5	25.3 ± 1.4
(800-1000), (200-350)	49.3 - 18.3 + 25.7	48.4 ± 19.1	56.0 ± 2.2
(800-1000), (350-500)	12.6 - 7.7 +17.1	16.0 ± 7.3	17.8 ± 1.2

Predictions from γ+jets and Z+jets are consistent within uncertainties
… but less precise and not used in the limit calculation

Observed Data & Estimated Background

Observed data HT and MHT distributions agree with the total data driven predicted background within systematic uncertainties

Baseline Selection



LM5 cMSSM benchmark point included for illustration (clearly excluded):
M_0=230 GeV, $m_{1/2}$=360 GeV, tan β=10, sgn(μ)=+, A_0=0

Search Results in all HT, MHT Bins

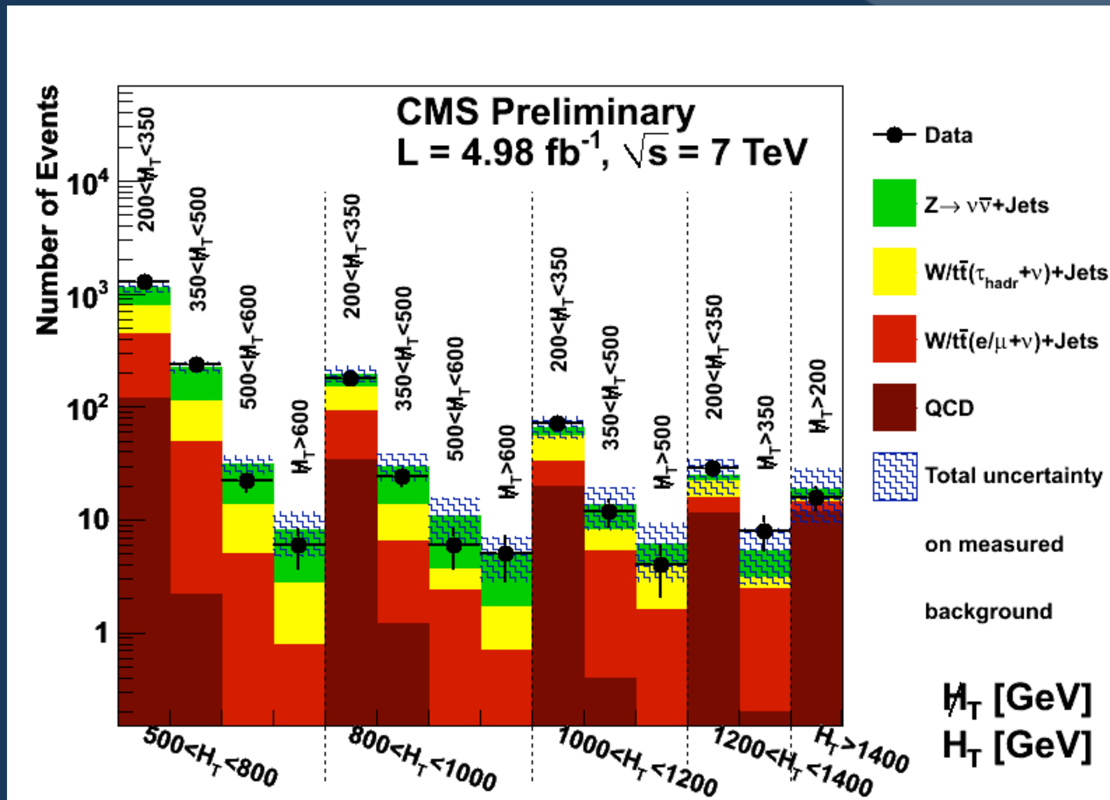
No excess of events is observed in either of the 14 HT, MHT bins in the for 5 fb^{-1} full 2011 data sample

Selection H_T (GeV)	$\not{H}_T$ (GeV)	$Z \to \nu\bar{\nu}$ from γ+jets		$t\bar{t}$/W $\to$ e, μ+X		$t\bar{t}$/W $\to \tau_{hadr}$+X		QCD multijets		Total background		Data
500–800	200–350	359.2	± 82.2	326.5	± 47.0	348.5	± 40.1	118.6	± 76.9	1152.8	± 128.4	1269
500–800	350–500	112.3	± 27.4	47.8	± 9.2	62.5	± 8.7	2.2	± 2.2	224.8	± 30.3	236
500–800	500–600	17.6	± 5.6	5.0	± 2.2	8.7	± 2.5	0.0	± 0.1	31.3	± 6.5	22
500–800	>600	5.5	± 3.1	0.8	± 0.8	2.0	± 1.8	0.0	± 0.0	8.3	± 3.6	6
800–1000	200–350	48.4	± 19.1	57.7	± 15.3	56.3	± 8.3	34.6	± 24.0	197.0	± 35.3	177
800–1000	350–500	16.0	± 7.3	5.4	± 2.3	7.2	± 2.0	1.2	± 1.3	29.8	± 8.0	24
800–1000	500–600	7.1	± 4.5	2.4	± 1.5	1.3	± 0.6	0.0	± 0.2	10.8	± 4.8	6
800–1000	>600	3.3	± 2.0	0.7	± 0.7	1.0	± 0.3	0.0	± 0.1	5.0	± 2.2	5
1000–1200	200–350	10.9	± 5.5	13.7	± 3.8	21.9	± 4.6	19.7	± 13.3	66.2	± 15.5	71
1000–1200	350–500	5.5	± 3.5	5.0	± 4.4	2.9	± 1.3	0.4	± 0.7	13.8	± 5.8	12
1000–1200	>500	2.2	± 2.9	1.6	± 1.2	2.3	± 1.0	0.0	± 0.2	6.1	± 3.3	4
1200–1400	200–350	3.1	± 2.0	4.2	± 2.1	6.2	± 1.8	11.7	± 8.3	25.2	± 9.0	29
1200–1400	>350	2.3	± 2.3	2.3	± 1.4	0.6	± 0.8	0.2	± 0.6	5.4	± 2.9	8
>1400	>200	3.2	± 2.4	2.7	± 1.6	1.1	± 0.5	12.0	± 9.1	19.0	± 9.6	16

At the 95% C.L. the data is consistent with no more than 7.1 (13.9) signal events for the high-MHT(HT) search regions

- If I repeat the experiment N→∞ times, 95% of the times the background will fluctuate to accommodate zero to no more than 7.1 (13.9) signal events

Search Results in all HT, MHT Bins



The 14 search regions are used as separate statistically independent channels in limit calculation

No Excess Means … Limits

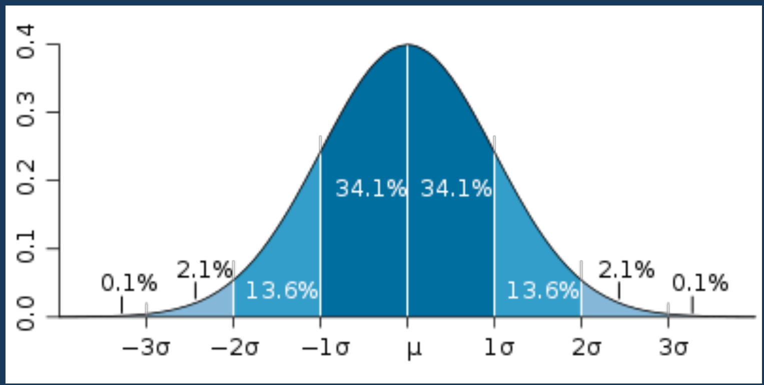
Confidence Intervals (C.I.)

A confidence interval gives an estimated range of values which is likely to include the unknown true value μ of a population parameter

$$\hat{\mu} = \langle X \rangle = \frac{1}{N}\sum_{i=1}^{n} X_i$$

The estimator of the true parameter value $\hat{\mu}$ is calculated as the mean value $\langle X \rangle$ in a given data sample

I repeat the experiment N (e.g. 100) times, each experiment generating M (e.g. 1000) values of X



Central C.I. for Normal Distribution

1σ ➔ 68.27%

2σ ➔ 95.45%

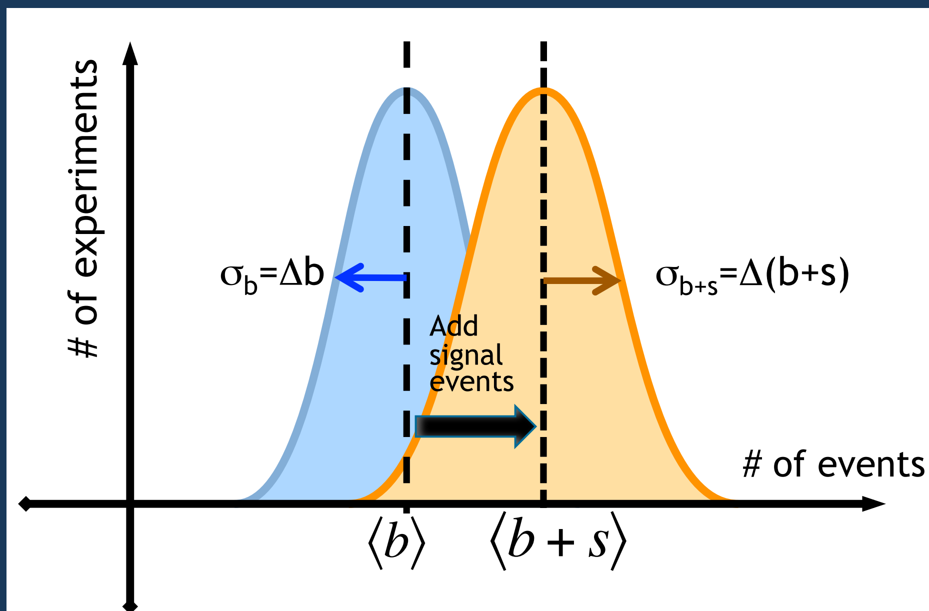
3σ ➔ 99.75%

5σ ➔ 99.99994%

The "level" of a confidence interval (C.L. 90%, 95%, 99%, ...) refers to the number of times (n/N*100 experiments) the interval will contain the true value

Expected Limit

- Generate ensemble of N experiments using the measured <b>+Δb distribution (<b> is mean of a Poisson, Δb is Gaussian)
- Question: how many signal events (s) can I add so that the b+s C.I. includes the background only prediction, <b>, 95% of the times?



Expected Limit on signal at the 95% C.L.

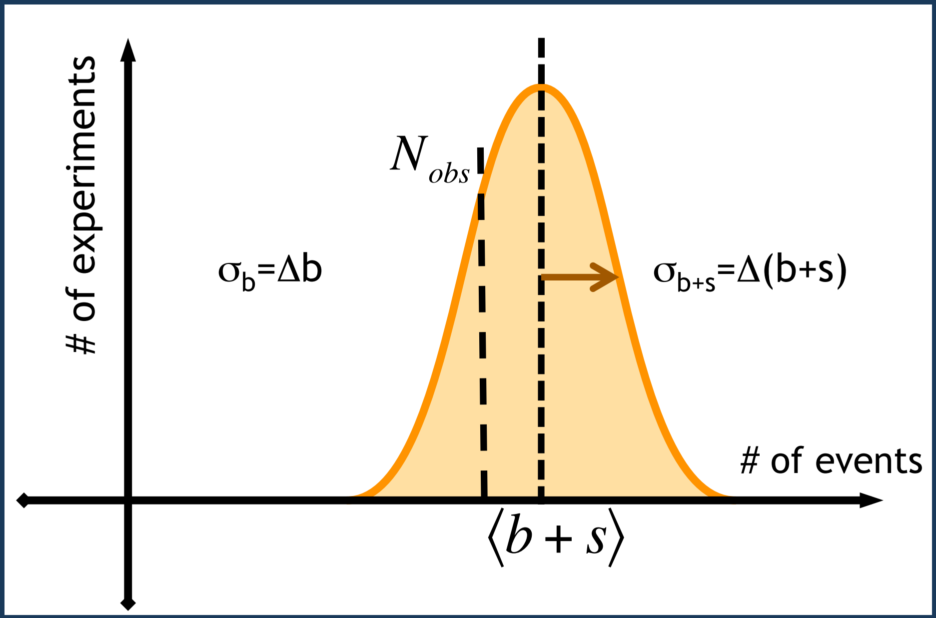
- maximum # of signal events the sample may contain consistent with <b>
- Signal events generated as explained later
- Limit translated to production x-section or masses

  (theory models and signal acceptance/efficiency)

Observed Limit

- Generate ensemble of N experiments using the measured <b>+Δb distribution (signal contamination 3-20% subtracted)

- Question: how many signal events (s) can I add so that the b+s C.I. includes the # of observed events, N_{obs}, 95% of the times?



Observed Limit on signal at the 95% C.L.

- maximum # of signal events the sample may contain consistent with N_{obs}
- Signal events generated as explained later
- Limit translated to production x-section or masses

  (theory models and signal acceptance/efficiency)

Comments on Limits

- Expected Limit is expressed as a band consistent with <b>±Δb
- If N_{obs} is greater than <b>, the observed limit is less than the expected
  - ✓ Small excess not "significant", most probably occurred by chance
- If N_{obs} is less than <b>, the observed limit is greater than the expected
  - ✓ Deficit means that data fluctuated low
- Zero background hypothesis is the most conservative for setting a limit
  - ✓ Lowest limit
- Zero background hypothesis is the least conservative for a discovery
  - ✓ Largest probability of wrongly accepting the signal hypothesis

Statistical Tests for Limits

CMS uses the Modified Frequentist Procedure (CL_s)

- ✓ Avoids excluding or discovering signals that the analysis is not really sensitive to.
- ✓ Reduce dependency on uncertainty from background

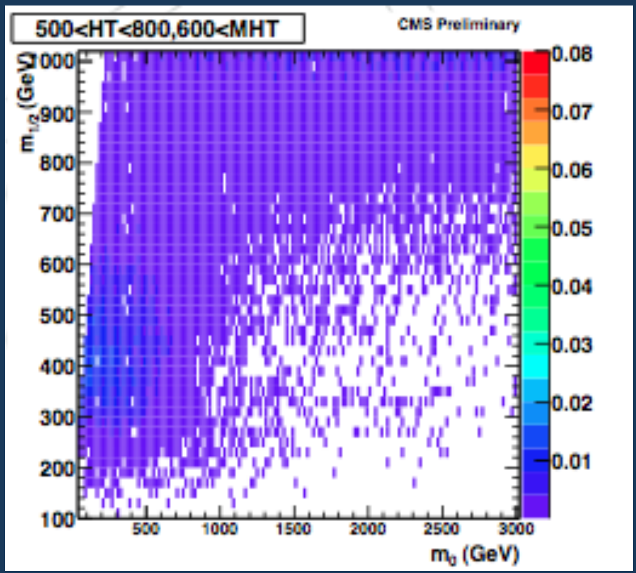
CMS also uses Bayesian Framework (flat prior for the signal)

- ✓ Frequentist probability is the limit of a frequency
- ✓ Bayesian probability is a subjective degree of believe (The prior is the probability of a theory)

Signal Acceptance/Efficiency

The expected number of signal events for a given model and event selection is estimated from simulated signal samples (generation + detector simulation)

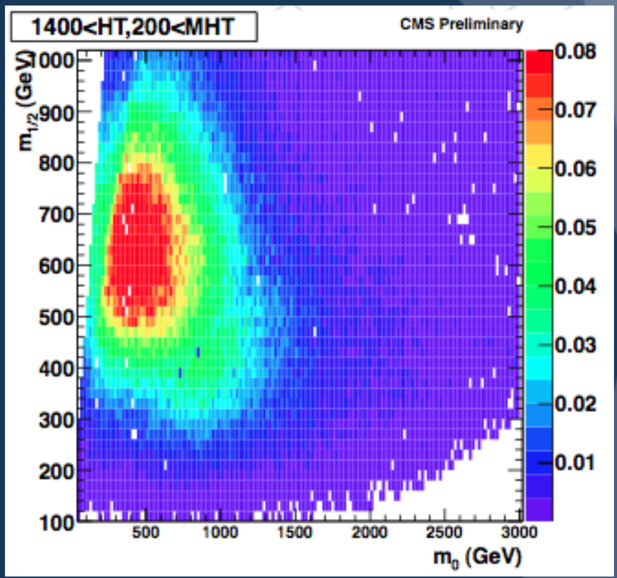
- Experimental and theoretical uncertainties from event selection, reconstruction, calibration
- Theoretical uncertainties related to event generation
- Overall luminosity uncertainty



Signal A_{cc} x E_{ff}

Acceptance (Acc): fraction of events passing the topology & kinematics requirement

Efficiency (Eff): Fraction of "accepted" events that were triggered, reconstructed, identified



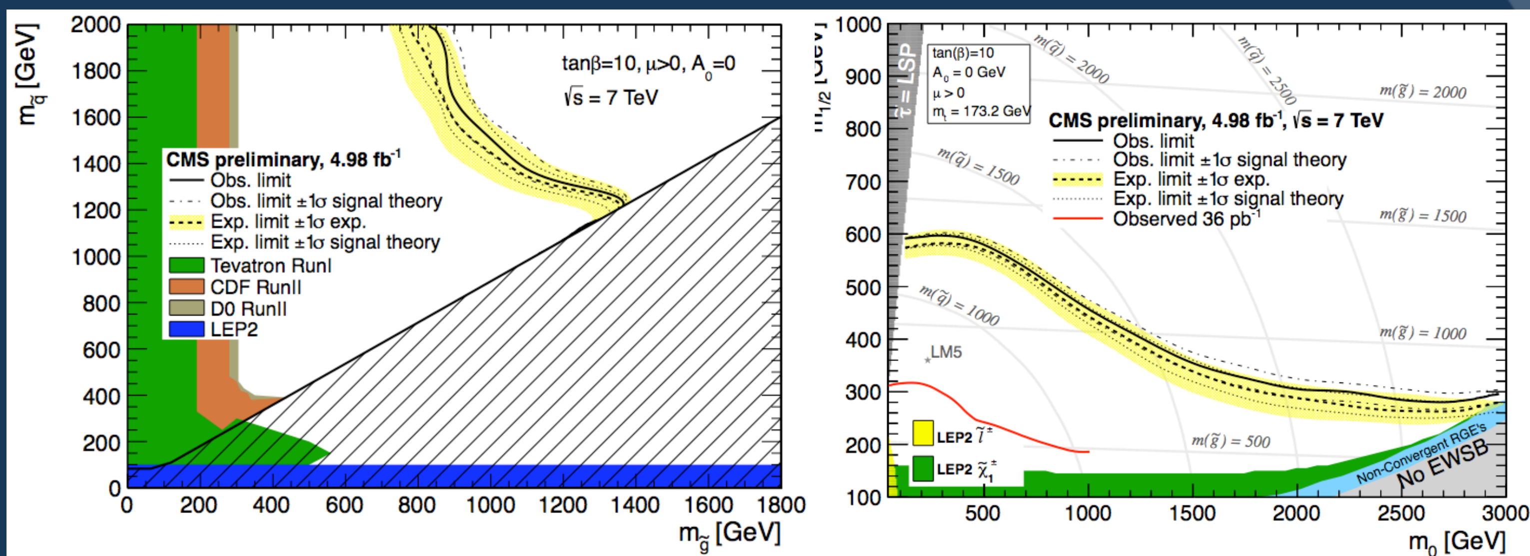
Signal Uncertainties:

JEC (8%), JER (2%), lepton veto/trigger efficiency (4%), event cleaning (3%), luminosity (2.2%), PDFs (6%)

Interpretation within the CMSSM

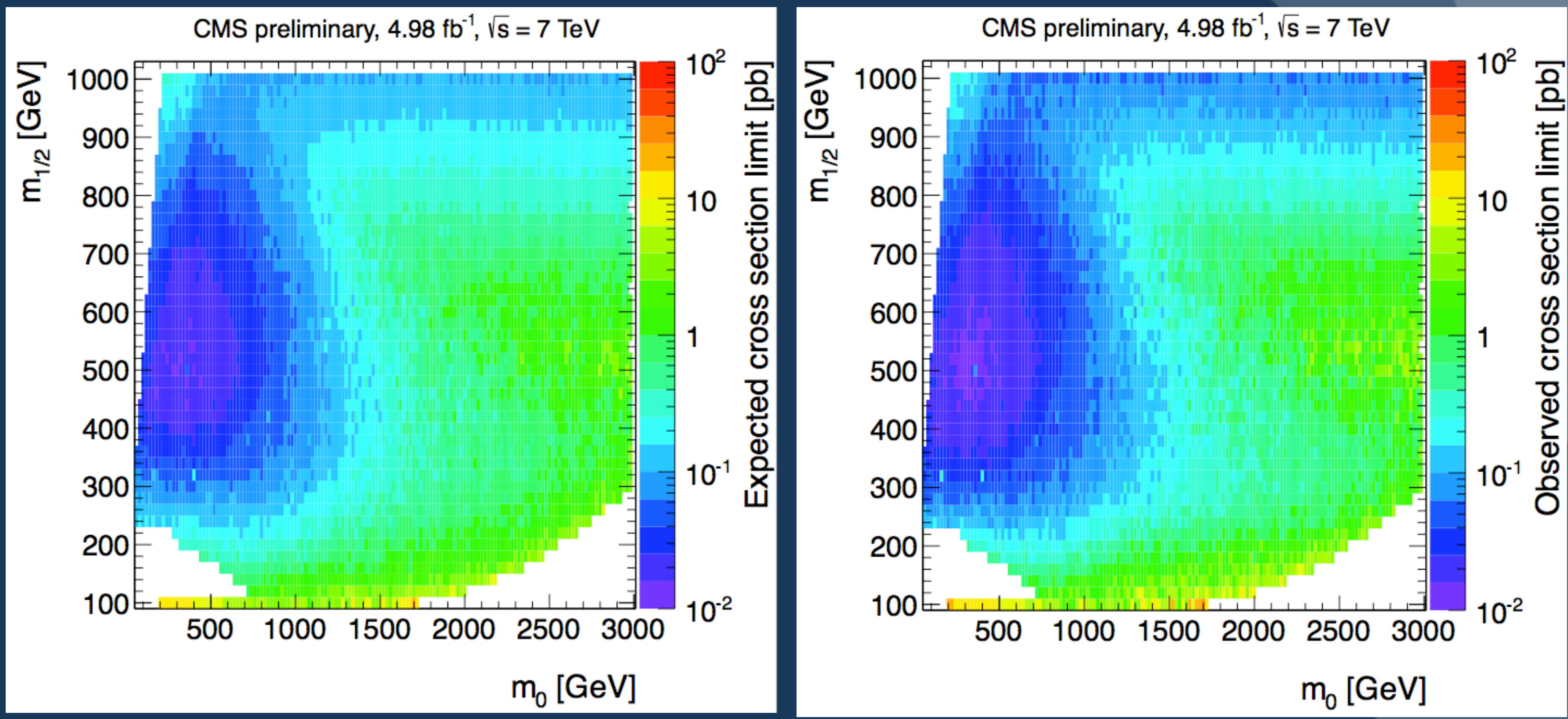
The contours are the envelope with respect to the best sensitivity of the 14 HT and the MHT search bins

- $m_{1/2}$ > 600 GeV for m_0 ~200 GeV, $m_{1/2}$ > 350 GeV for m_0 ~1500 GeV at the 95% C.L.
- Squark and gluinos with mass < 1.3 TeV are excluded at the 95% C.L. for M_{gluino} ~M_{squark} and for M_{squark} > M_{gluino} , gluinos of mass < 800 GeV



Interpretation within the CMSSM

Cross Section Limits < 5 pb^{-1} in the $m_{1/2}$ vs m_0 explored



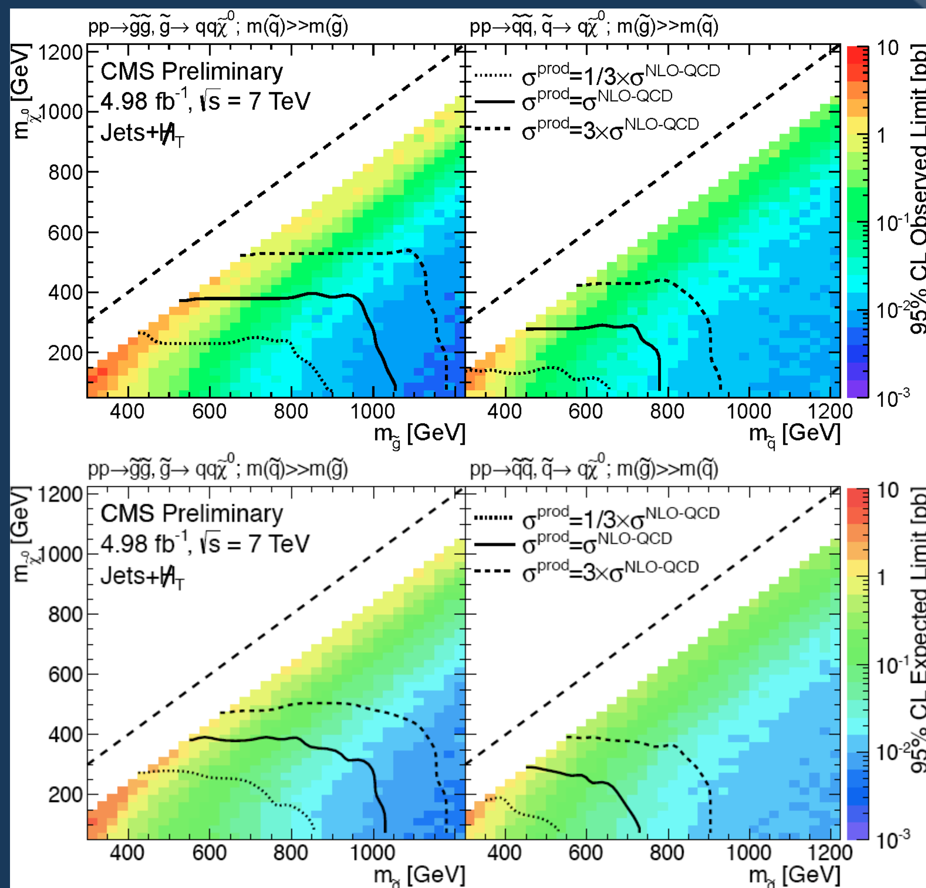
Interpretation with Simplified Models

Production cross section excluded above 5×10^{-3}-4 pb at the 95% C.L. depending on the particle masses in the decay chain (m_{gluino} < 1 TeV and m_{squark} < 0.76 TeV are excluded for $m\chi^0$ < 200 GeV)

As illustration, limit is translated to the case of cMSSM with

$\sigma^{prod} = 1/3\sigma^{NLO-QCD}$
$\sigma^{prod} = \sigma^{NLO-QCD}$
$\sigma^{prod} = 3\sigma^{NLO-QCD}$

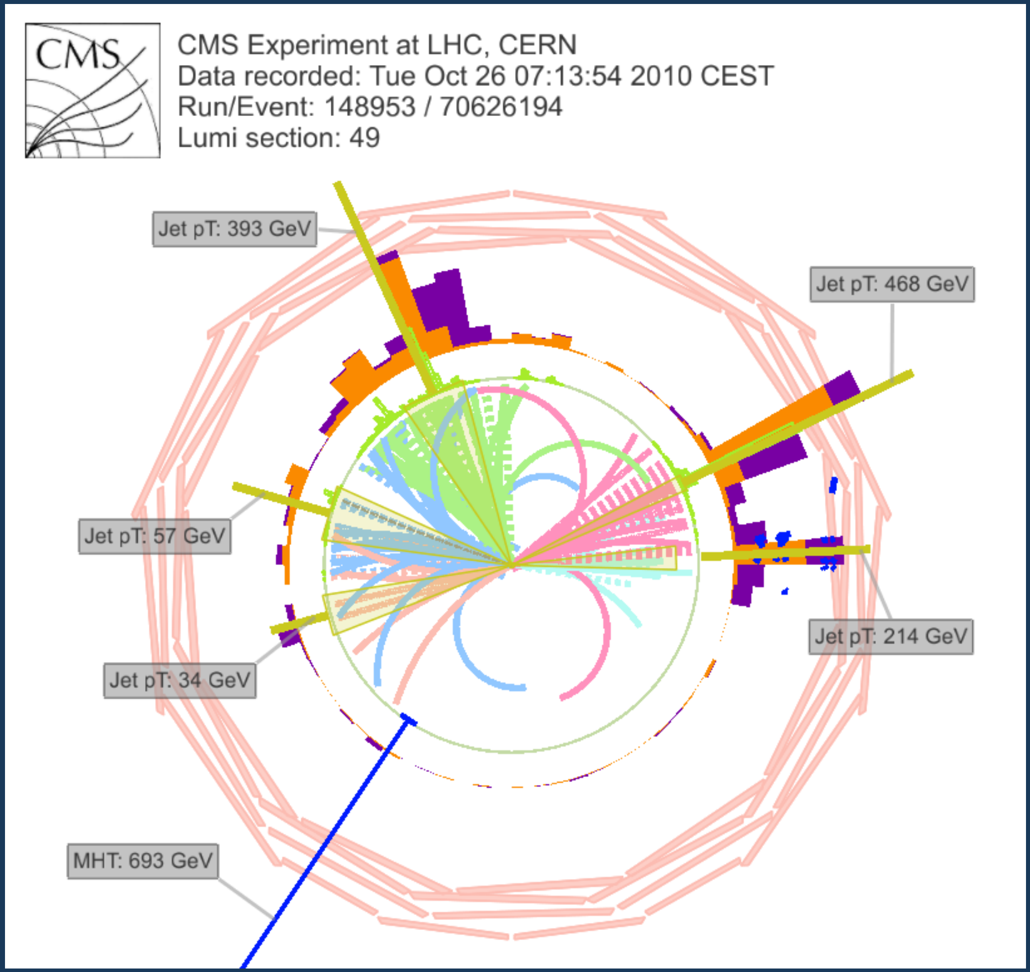
(PROSPINO)



Observed

Expected

A Candidate Event

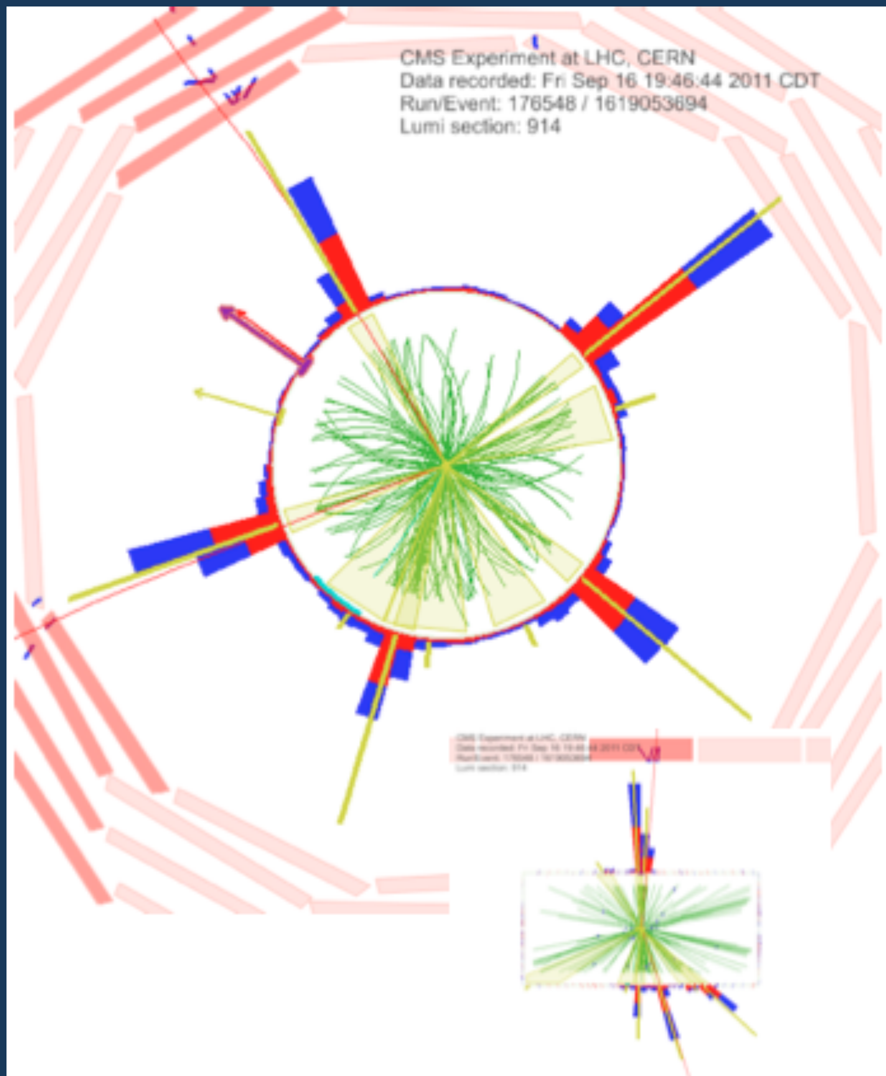


Medium HT, high MHT Event

5 jets + MHT

MHT = 693 GeV
HT= 1132 GeV
M_{eff}= MHT+HT = 1.83 TeV
No b-tagged jet
No isolated lepton
Incompatible with W or top mass

Another Candidate Event



High HT, relatively low MHT

5 jets + MHT

MHT = 212 GeV
HT= 2577 GeV
Leading jet p_T= 693 GeV
No b-tagged jet
No isolated lepton
Incompatible with W or top mass