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MUSiC - Model Unspecific Search in CMS (CMS PAS EXO-14-016)

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Motivation

Challenge at the LHC

Many competing models!
Difficult to have dedicated analyses for all.
Are there models no one has thought of yet?

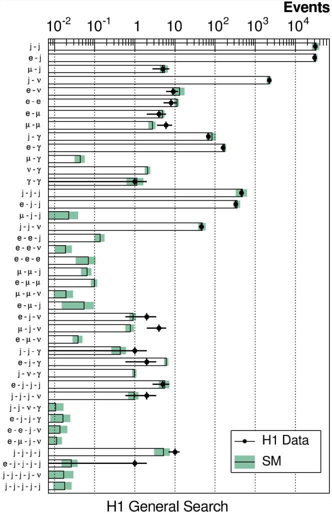
Alternative Approach

Model independent search!

- Assume only: **The Standard Model**.
- Search for deviations in many final states.

Previous Model Independent Searches

Performed at: L3, H1, D0 (SLEUTH), CDF (VISTA), **ATLAS**, **CMS**, ...



arXiv:hep-ex/0408044

Scope of MUSiC

What is MUSiC?

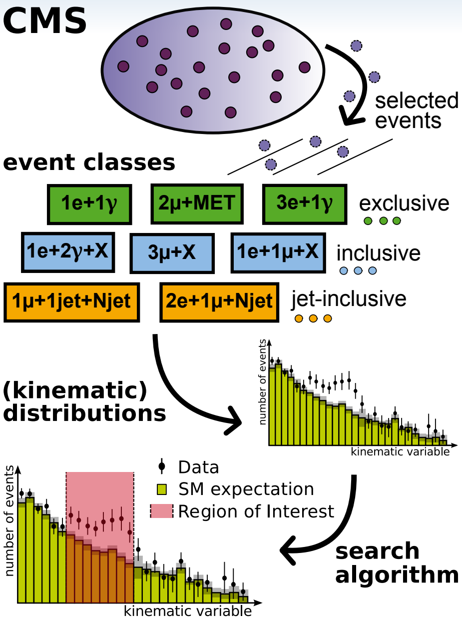
- A physics and detector monitor.
- An alarm system.
- Complementary to dedicated analyses.

What if MUSiC finds something?

- New physics?
- Inadequate detector simulation?
- Inadequate Monte-Carlo: tuning, missing (rare) processes, etc.?

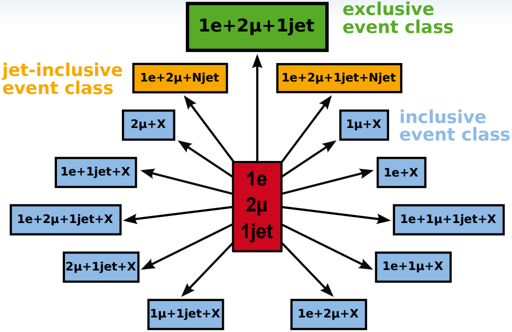
$\Longrightarrow$ Careful investigation is essential!

MUSiC Workflow



- Sort data and MC into **event classes** by physics object content of final state: e, μ, γ, jet, MET
- **Three distributions** per class: $\sum |\vec{p}_\mathrm{T}|$, $M_{(\mathrm{T})}$, MET
- Most significant region in each distribution: **Region of Interest**
- Determine look-elsewhere effect corrected ***p*-value** ($\tilde{p}$) for each event class distribution
- Compare distribution of $\tilde{p}$-values from data with SM MC

Event Classes



After Applying Selection Criteria

- Each **event** ends up in exactly one **exclusive** and in general in several **jet-inclusive** as well as **inclusive** event classes.
- Event classes with at least 6 jets are combined, e.g. $1\mu+\geq 6$jets.
- At 8 TeV: 337 (341, 321) exclusive (inclusive, jet-inclusive) event classes. Around 50% of event classes contain data.

Selection at 8 TeV

Event Selection

Use inclusive lepton triggers to select events with at least one lepton:

≥ 1 **electron** with $p_T > 100\,\text{GeV}$
OR
≥ 2 **electrons** with $p_T > 25\,\text{GeV}$

≥ 1 **muon** with $p_T > 30\,\text{GeV}$
OR
≥ 2 **muons** with $p_T > 25\,\text{GeV}$

Object Selection

For all subsequent objects use well studied identification criteria:

Object	p_T/GeV	Identification Summary
e	> 25	track quality, isolation, calo signature
μ	> 25	track quality, isolation
γ	> 25	isolation, veto against e
jet	> 50	anti-k_t algorithm $(R = 0.5)$
MET	> 50	-

Systematic Uncertainties at 8 TeV

Apply to Simulated Background Events

Contribution	Value	Remarks
Luminosity	2.6 %	-
Parton density functions	varies	PDF4LHC recipe
Energy/momentum scales	1 % to 10 %	per object
MC Reconstruction efficiencies	1 % to 3 %	per object
MC Misidentification rates	50 % to 100 %	per object
SM cross sections	5 % to 50 %	process dependent
Number of MC events	varies	relative value $< 60\%$

MUSiC's p-value

Use a **Gaussian prior** to model the systematic uncertainties on the mean of a *Poisson counting experiment*.

$$p = \begin{cases} \underbrace{\sum_{i=N_{\text{obs}}}^{\infty} C}_{\text{normalization}} \cdot \int_0^\infty \mathrm{d}\theta \underbrace{\exp\left(-\frac{(\theta - N_{\text{SM}})^2}{2\,\sigma_{\text{SM}}^2}\right)}_{\text{systematics}} \cdot \underbrace{\frac{\theta^i\,\mathrm{e}^{-\theta}}{i!}}_{\text{statistics}} & \text{if } N_{\text{obs}} \geq N_{\text{SM}} \\ \sum_{i=0}^{N_{\text{obs}}} C \cdot \int_0^\infty \mathrm{d}\theta \exp\left(-\frac{(\theta - N_{\text{SM}})^2}{2\,\sigma_{\text{SM}}^2}\right) \cdot \frac{\theta^i\,\mathrm{e}^{-\theta}}{i!} & \text{if } N_{\text{obs}} < N_{\text{SM}} \end{cases}$$

with:

N_{obs} : Observed events in data

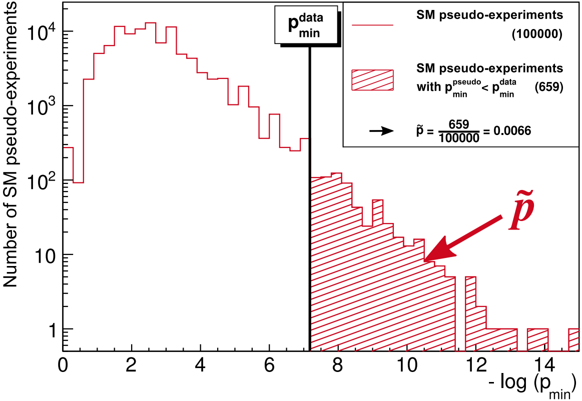
N_{SM} : Pure SM (Monte Carlo) expectation in region

σ_{SM} : Uncertainty on the SM MC prediction

Region with the smallest p-value: **Region of Interest**

"Look-Elsewhere Effect"

Considering **many regions** in each distribution makes it more probable to see a large deviation somewhere by chance due to statistical fluctuations.

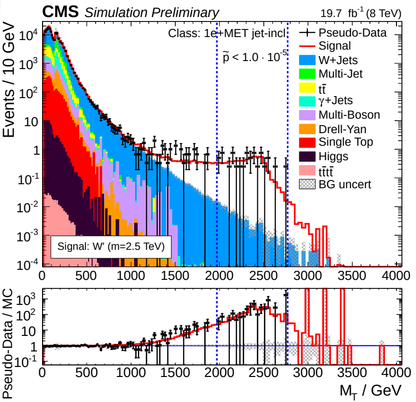


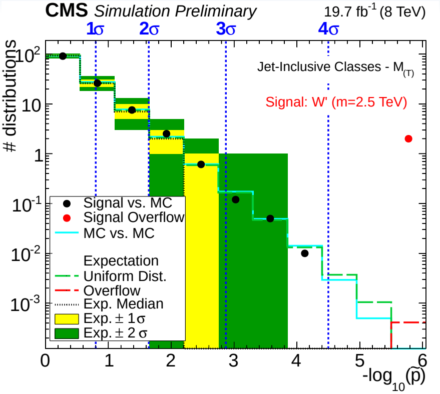
- Randomize SM MC expectation bin by bin, accounting for known uncertainties.
- Determine most significant region in pseudo data.

New (post-trial) significance:

$$\tilde{p} = \frac{\text{number of pseudo experiments with } p^{\text{pseudo}}_{\text{min}} < p^{\text{data}}_{\text{min}}}{\text{total number of pseudo experiments}}$$

Sensitivity to BSM Signals

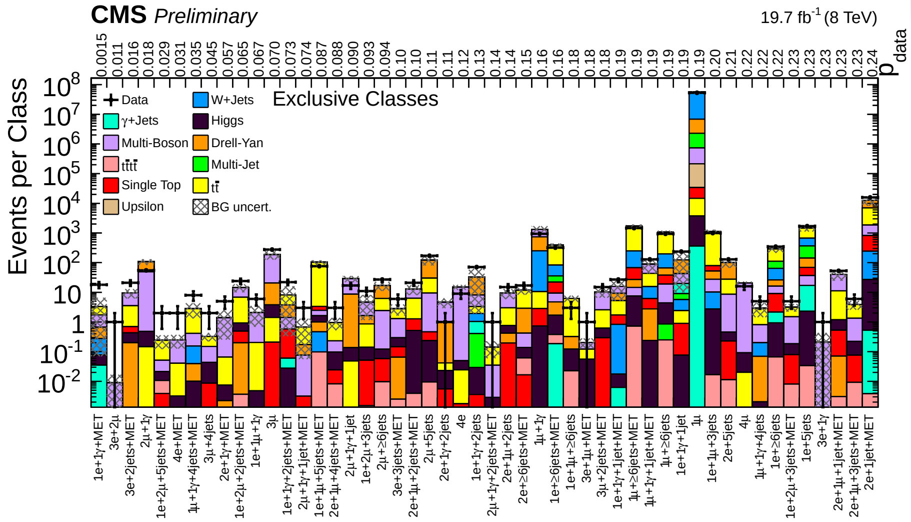




M_T of Jet-Inclusive Event Class

- Assume hypothetial leptonically decaying SSM W' boson and generate pseudo-data according to SM+W', compare with SM.
- On average 2 very significant event classes found for m(W') = 2.5 TeV.

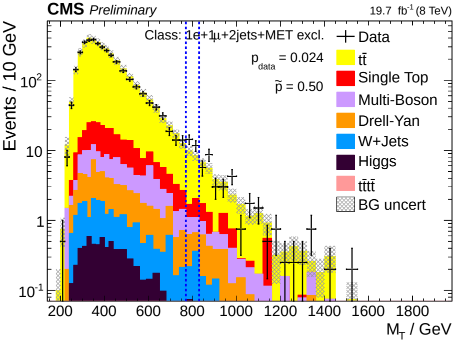
Total Event Yield Per Event Class

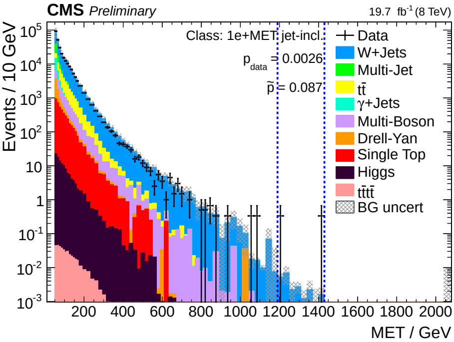


Exclusive Event Classes

All events condensed into a single bin, sorted here by significance.

Example Distributions





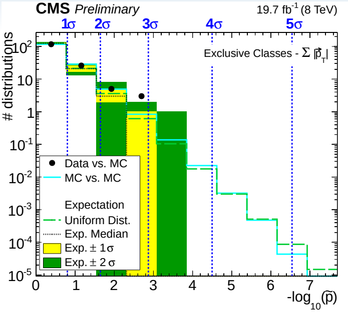
Exclusive Event Class

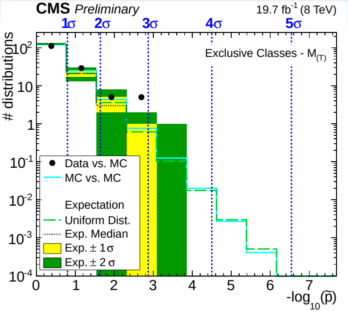
- Dominated by $t\bar{t}$ production
- Insignificant excess found in bulk

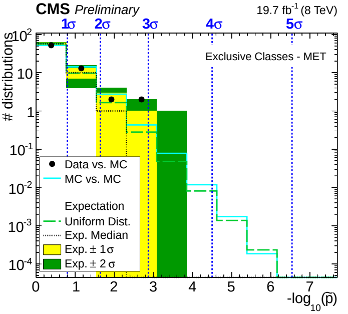
Jet-Inclusive Event Class

- Dominated by W+jets production
- Insignificant excess found in tail

Distribution of Deviations



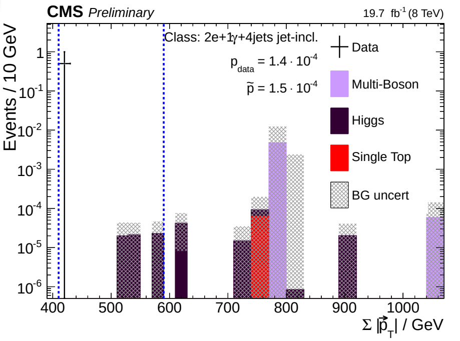


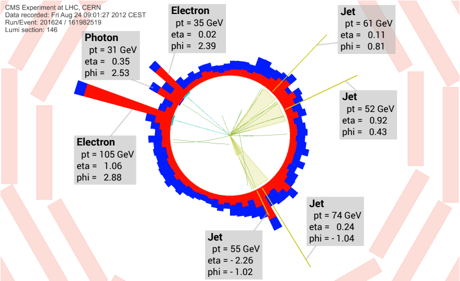


Global Overview

- Determined individually for each variable and event class type.
- Overall good agreement.
- Observed significances are compatible with SM fluctuations.

Most Significant Deviation





Jet-Inclusive Event Class

- Single data event and low SM MC event yield.
- $\sum |\vec{p}_{\mathrm{T}}| = 414\,\mathrm{GeV}$, $M_{(\mathrm{T})} = 718\,\mathrm{GeV}$, MET $= 27\,\mathrm{GeV}$
- Many vertices (30) $\rightarrow$ pileup
- $M_{\mathrm{inv}}(\mathrm{ee}\gamma) = 85\,\mathrm{GeV}$

Summary

MUSiC (CMS PAS EXO-14-016)

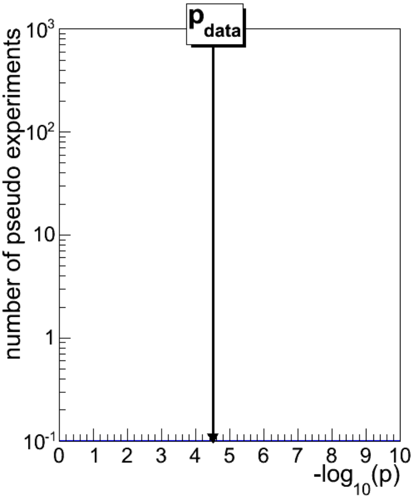
- Based on 8 TeV data in electron- and muon-triggered events, MUSiC has found no significant deviations beyond expected fluctuations.
- Good agreement between data and SM simulation over a wide range of final states.
- Sensitivity studies provide proof of MUSiC's discovery potential for specific signatures.

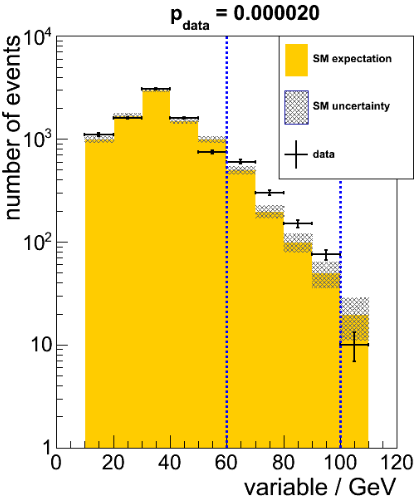
Outlook

- Expand analysis scope: photon and jet triggered events, b-tagged jets.
- Analysis of data collected at 13 TeV is ongoing.
- Stay tuned for results and updates on most significant deviations in 8 TeV data.

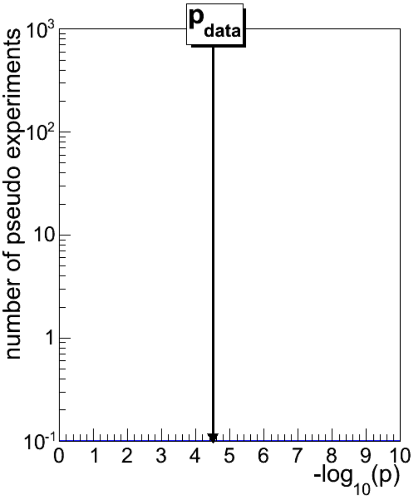
Additional Information

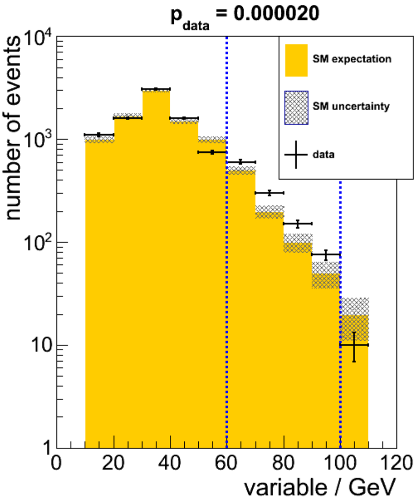
Dicing of Pseudo-Experiments



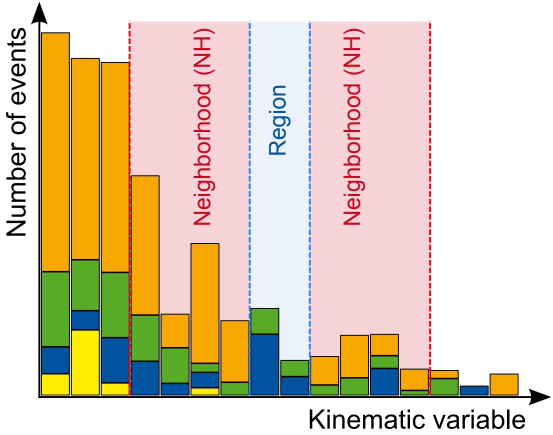


Dicing of Pseudo-Experiments





Region-Veto Method



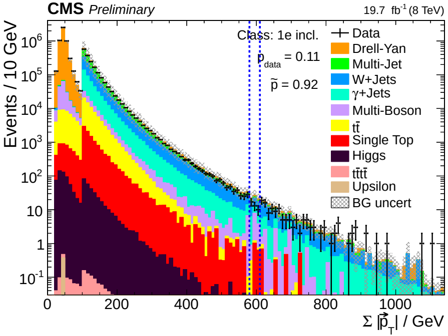
SM MC Data sets

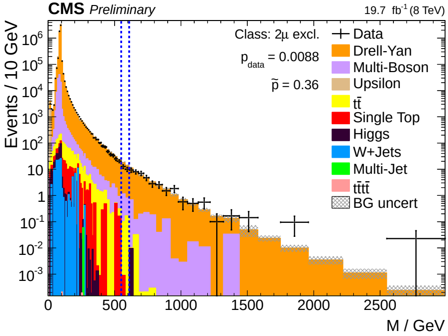
Process	Details	Generator	k-factor (order)	# Events
γ+Jets		PYTHIA6	1.3 (NLO)	$1.6 \cdot 10^6$
W+Jets		MADGRAPH	1.21 (NNLO)	$6.0 \cdot 10^7$
	$M_{l^\pm\nu} > 200$ GeV	MADGRAPH	1.21 (NNLO)	$1.2 \cdot 10^6$
	$H_T > 150$ GeV	MADGRAPH	1.21 (NNLO)	$4.3 \cdot 10^7$
	Wbb $\rightarrow l^\pm \nu$bb	MADGRAPH	1.79 (NLO)	$2.0 \cdot 10^7$
Drell-Yan	$M_{l^\pm l^\pm} > 10$ GeV	MADGRAPH	1.2 (NNLO)	$6.0 \cdot 10^7$
	$p_T(Z) > 50$ GeV	MADGRAPH	1.0 (LO)	$3.8 \cdot 10^8$
	$M_{l^\pm l^\pm} > 200$ GeV	POWHEG	1.02 (NNLO)	$2.2 \cdot 10^6$
	Z+Jets $\rightarrow \nu\nu$	MADGRAPH	1.0 (LO)	$3.0 \cdot 10^7$
Multi-Boson	$\gamma\gamma$	PYTHIA6	1.0 (LO)	$7.7 \cdot 10^6$
	WW	PYTHIA6	1.63 (NLO)	$1.0 \cdot 10^7$
	$W^\pm W^\pm$	MADGRAPH	1.0 (LO)	$1.8 \cdot 10^5$
	WW via DPS	PYTHIA6	1.0 (LO)	$8.0 \cdot 10^5$
	gg $\rightarrow$ WW	gg2VV	1.4 (NLO)	$1.0 \cdot 10^5$
	ZZ $\rightarrow 4l^\pm$	POWHEG	1.0 (NLO)	$1.5 \cdot 10^7$
	ZZ $\rightarrow 2l2$q	MADGRAPH	1.0 (LO)	$2.7 \cdot 10^6$
	gg $\rightarrow$ ZZ	gg2VV	1.0 (NLO)	$9.0 \cdot 10^5$
	WZ	MADGRAPH	1.0 (LO)	$7.9 \cdot 10^6$
	Vγ	MADGRAPH	1.2 (NLO)	$1.0 \cdot 10^7$
	WWW	MADGRAPH	0.98 (NLO)	$2.0 \cdot 10^5$
	ZZZ	MADGRAPH	1.2 (NLO)	$2.0 \cdot 10^5$
	WWZ	MADGRAPH	0.92 (NLO)	$2.0 \cdot 10^5$
	WZZ	MADGRAPH	1.02 (NLO)	$2.0 \cdot 10^5$
	WWγ	MADGRAPH	1.0 (LO)	$5.0 \cdot 10^5$
	W$\gamma\gamma$	MADGRAPH	1.0 (LO)	$2.0 \cdot 10^6$

SM MC Data sets

Multi-Jet		PYTHIA6	1.0 (LO)	$4.5 \cdot 10^8$
Single Top		POWHEG	1.04-1.34 (NNLL)	$5.2 \cdot 10^6$
$t\bar{t}$		POWHEG	1.0 (NNLO)	$2.6 \cdot 10^7$
	$t\bar{t}$ ($M_{tt} > 700$ GeV)	POWHEG	1.11 (NNLO)	$4.0 \cdot 10^6$
	$t\bar{t}\gamma$	MADGRAPH	1.0 (LO)	$1.0 \cdot 10^6$
	$t\bar{t}W$	MADGRAPH	1.08 (NLO)	$1.0 \cdot 10^5$
	$t\bar{t}Z$	MADGRAPH	1.2 (NLO)	$2.0 \cdot 10^5$
	$t\bar{t}WW$	MADGRAPH	1.0 (LO)	$2.0 \cdot 10^5$
$t\bar{t}t\bar{t}$		MADGRAPH	1.28 (NLO)	$9.0 \cdot 10^4$
Higgs	$gg \rightarrow ZZ$	MiNLO	1.0 (NLO)	$8.0 \cdot 10^5$
	$gg \rightarrow bb, \gamma\gamma, \tau\tau, Z\gamma, WW$	POWHEG	1.0 (NLO)	$2.6 \cdot 10^6$
	$VBF \rightarrow bb, \gamma\gamma, \tau\tau, Z\gamma, VV$	POWHEG	1.0 (NLO)	$2.5 \cdot 10^6$
	$WH \rightarrow \mu\mu, bb$	POWHEG	1.0 (NLO)	$1.1 \cdot 10^6$
	$ZH \rightarrow \mu\mu, bb$	POWHEG	1.0 (NLO)	$2.9 \cdot 10^6$
	$TTH \rightarrow bb, \gamma\gamma, Z\gamma$	PYTHIA6	1.0 (NLO)	$1.2 \cdot 10^6$
	$WH, ZH \rightarrow \gamma\gamma, Z\gamma$	PYTHIA6	1.0 (NLO)	$1.1 \cdot 10^6$
	$WH, ZH, TTH \rightarrow \tau\tau, VV$	PYTHIA6	1.0 (NLO)	$9.0 \cdot 10^5$
Upsilon	$\Upsilon(1S)/\Upsilon(2S)/\Upsilon(3S) \rightarrow \mu\mu$	EVTGEN	1.0 (LO)	$5.0 \cdot 10^6$

Example Distributions





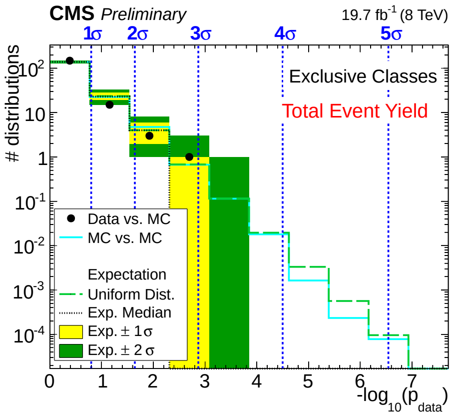
Jet-Inclusive Event Class

- Effect of different muon trigger thresholds visible
- Insignificant deficit identified in RoI

Exclusive Event Class

- Dominated by Drell-Yan production
- Insignificant deficit identified in RoI

Scan of Total Event Yield

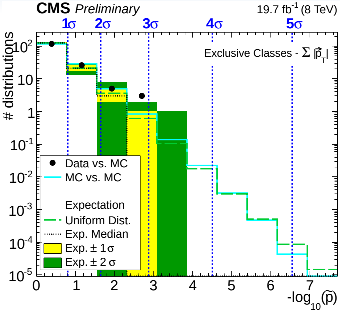


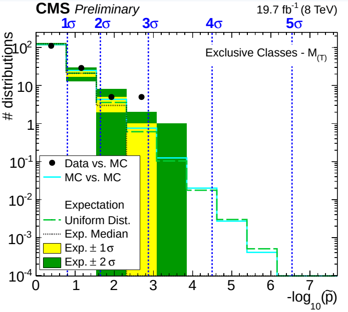
Yield in Exclusive Event Classes

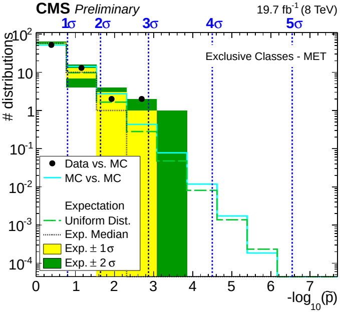
Global overview of all event classes:

- Determined individually for each kinematic variable and event class type.
- $\tilde{p}$-values from data vs. SM MC comparison (black markers).
- $\tilde{p}$-values from SM pseudo-data vs. SM MC comparison from LEE correction (blue line).
- Expectation assuming a uniform distribution given along with 68% and 95% interval.

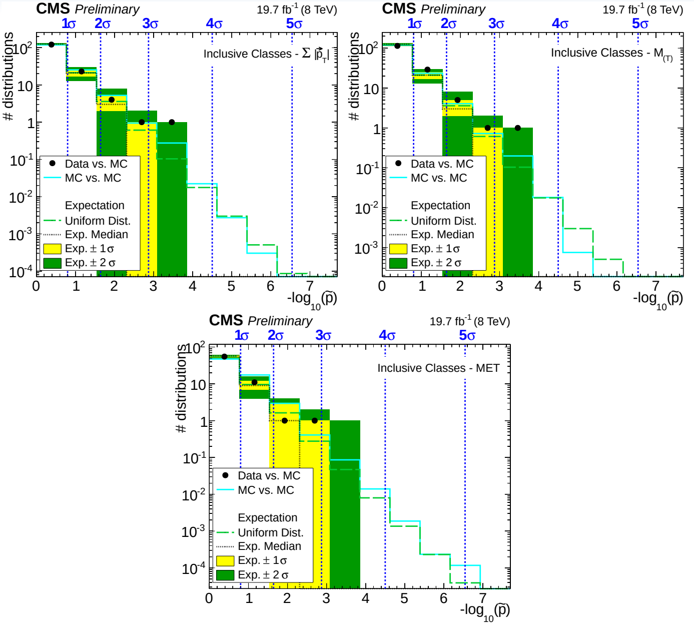
Distribution of $\tilde{p}$-values



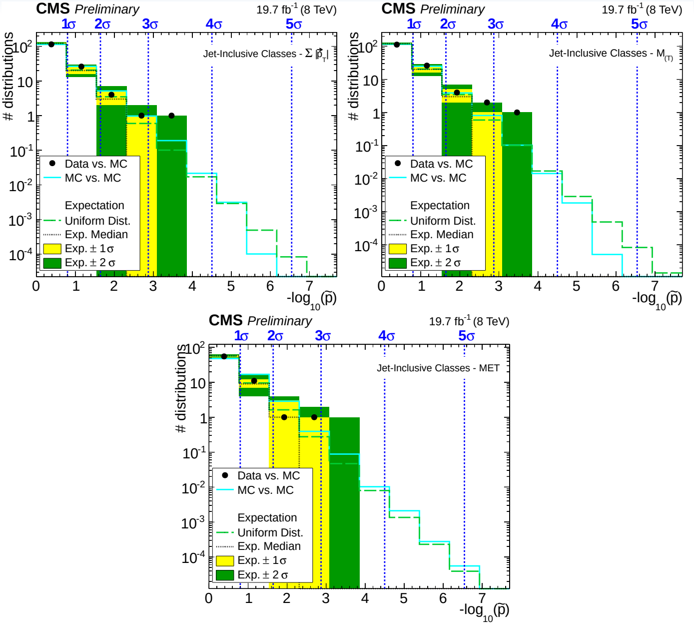




Distribution of $\tilde{p}$-values



Distribution of $\tilde{p}$-values

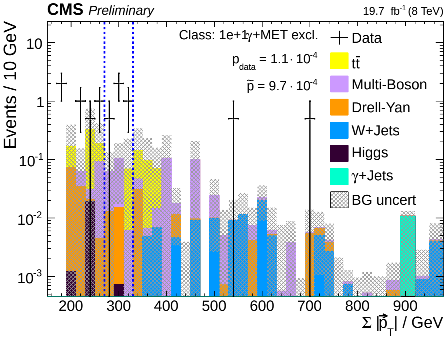


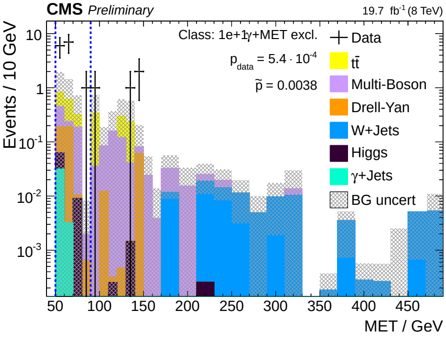
Most Significant Deviations

Table 3: Overview of the two most significant event classes from each scan type. Corresponding significance values are given in each case, where the p-value represents the full significance in the scan of total event yield. The $\tilde{p}$-value is stated for scans of kinematic distributions.

Scan type		Most significant		Second most significant	
		Event class	$\tilde{p}$ (p)	Event class	$\tilde{p}$ (p)
Total Event Yield	excl.	1e+1γ+MET	(0.0015)	3e+2μ	(0.011)
	incl.	3e+2jets+MET+X	(0.014)	3e+2μ+X	(0.019)
	jet-incl.	3e+2jets+MET+Njet	(0.012)	2μ+1γ+Njet	(0.015)
$\sum \lvert\vec{p}_{\mathrm{T}}\rvert$	excl.	1e+1γ+MET	0.00097	3e+2jets+MET	0.0027
	incl.	2e+1γ+4jets+X	0.00069	3e+2μ+X	0.0041
	jet-incl.	2e+1γ+4jets+Njet	0.00015	3e+2μ+Njet	0.0040
$M_{(T)}$	excl.	1e+1γ+MET	0.0020	1μ+1γ	0.0021
	incl.	2e+1γ+4jets+X	0.00071	2μ+1jet+X	0.0016
	jet-incl.	2e+1γ+4jets+Njet	0.00017	2μ+1jet+Njet	0.0014
MET	excl.	1e+1γ+MET	0.0038	2μ+1γ+1jet+MET	0.0039
	incl.	2μ+1γ+1jet+MET+X	0.0013	3e+2jets+MET+X	0.013
	jet-incl.	2μ+1γ+1jet+MET+Njet	0.0013	3e+2jets+MET+Njet	0.0095

Most Significant Deviations

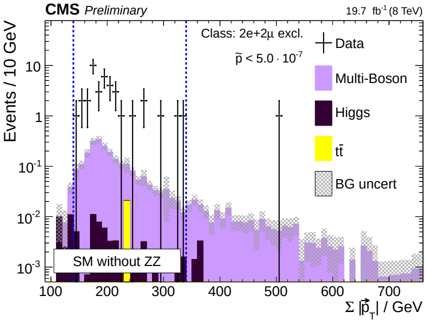


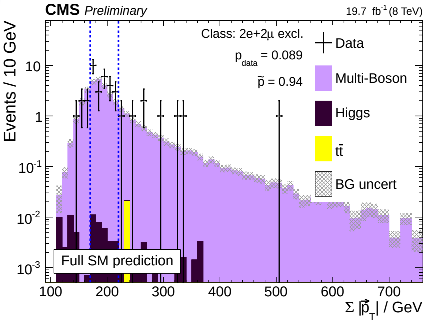


Exclusive Event Class

- Most significant exclusive event class.

Sensitivity to SM Processes

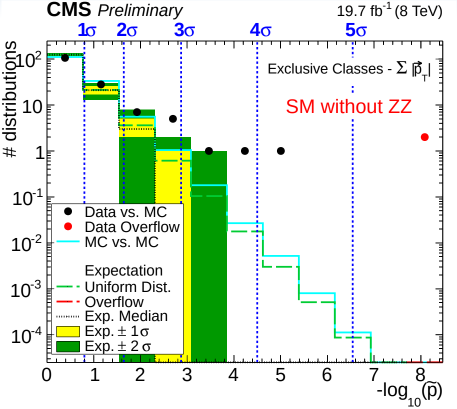




$\sum |\tilde{p}_t|$ of Exclusive Event Class

- Remove ZZ production from SM description.
- Perform comparison with measured 8 TeV data.
- Most significant deviation observed in 2e+2μ exclusive event class.
- Similar results for $M_{(T)}$, whereas MET (>50 GeV) is not sensitive.

Sensitivity to SM Processes



$\sum |\tilde{p}_t|$ of Exclusive Event Class

- Remove ZZ production from SM description.
- Perform comparison with measured 8 TeV data.
- Event classes with 4 leptons show strongest deviations.