Searches for contact interactions and extra dimensions with non-resonant excesses at the TeV scale

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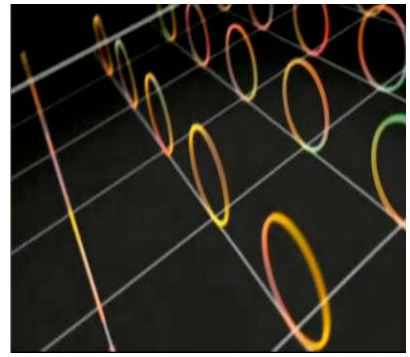
on behalf of the
ATLAS and CMS Collaborations

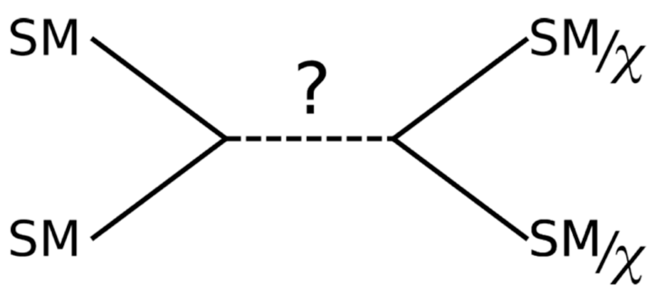
LHCP 2015
August 31 - September 5 2015
St. Petersburg, Russia

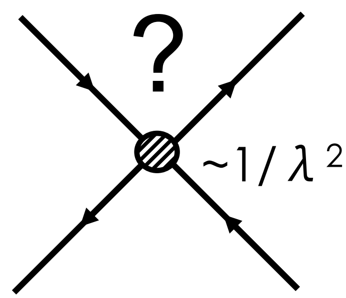
Introduction

- Final states studied for non-resonant excesses (covered in this talk)
  - Dilepton
  - Single lepton + Missing Energy
  - Dijet
  - Ditau
  - Monojets



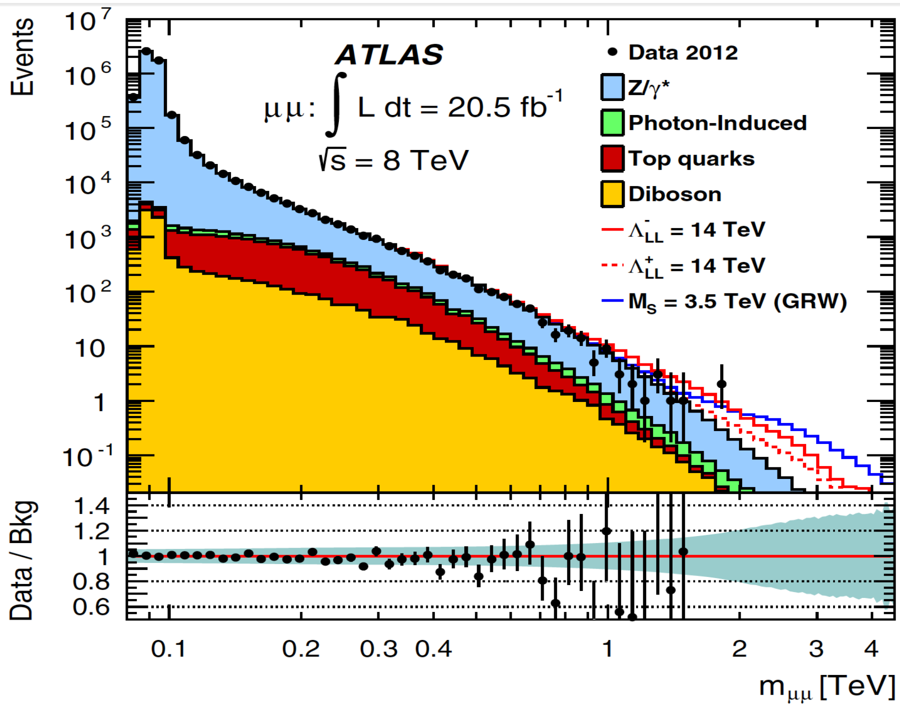
- Sensitive to contact interactions and extra dimensions
  - Benchmarks ADD and general contact interactions
- Same final states also sensitive to other models
  - new resonances, Dark Matter, SUSY….

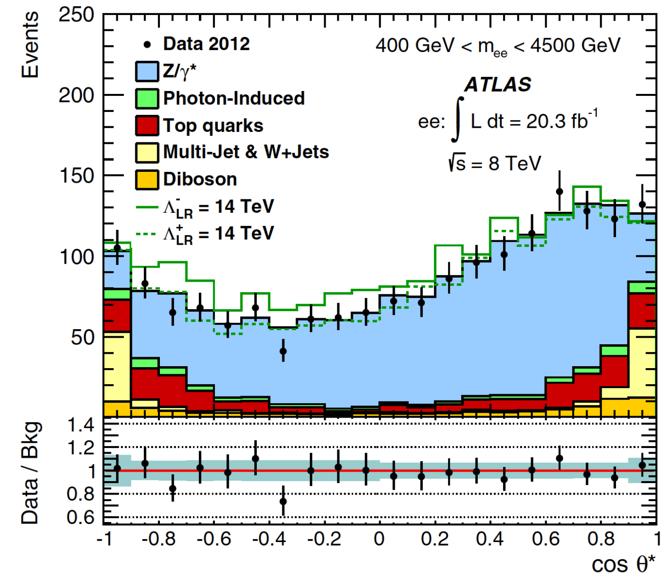


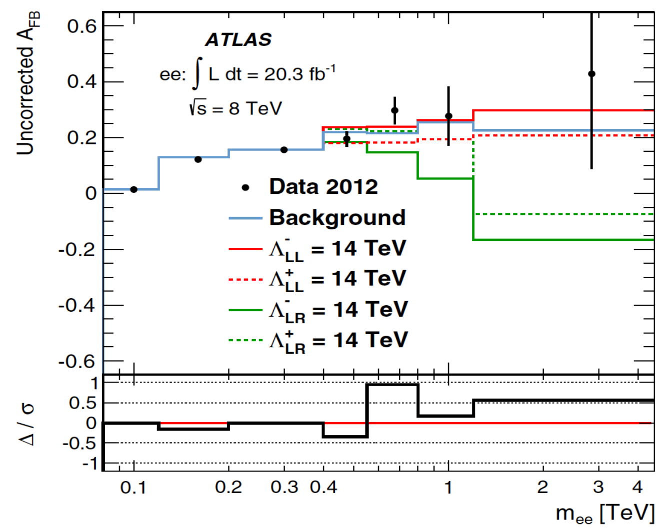


Dilepton Searches

- Two well reconstructed ee or μμ
  - Invariant mass distribution
  - cos θ*, angle btw CS-frame z-axis and l^-
  - A_{FB} distribution $A_{FB} = \frac{N_F - N_B}{N_F + N_B}$







Dimuon p-value of 8 % (6%) in the CI LL model with destructive interference (ADD GRW)

Dilepton Searches

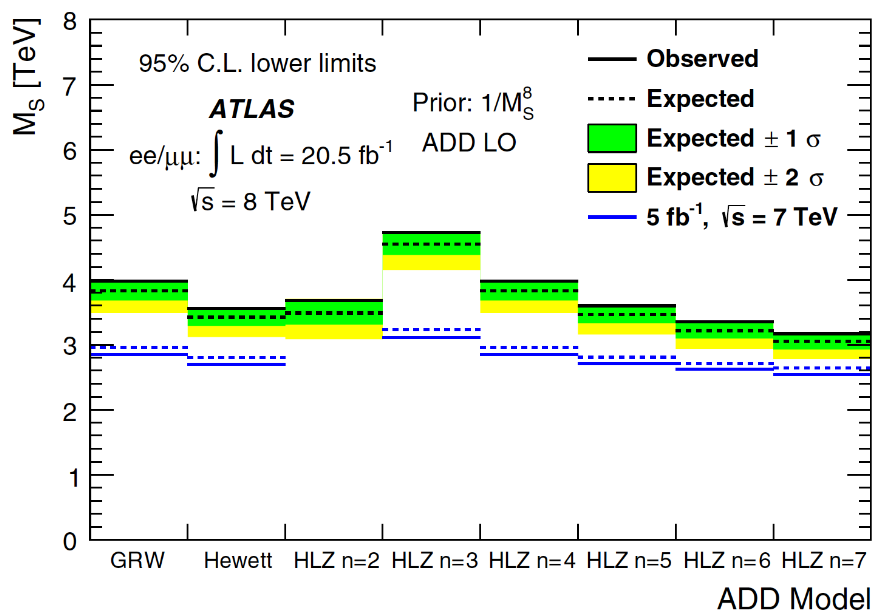
Eur. Phys. J. C (2014) 74:3134, arXiv:1407.2410

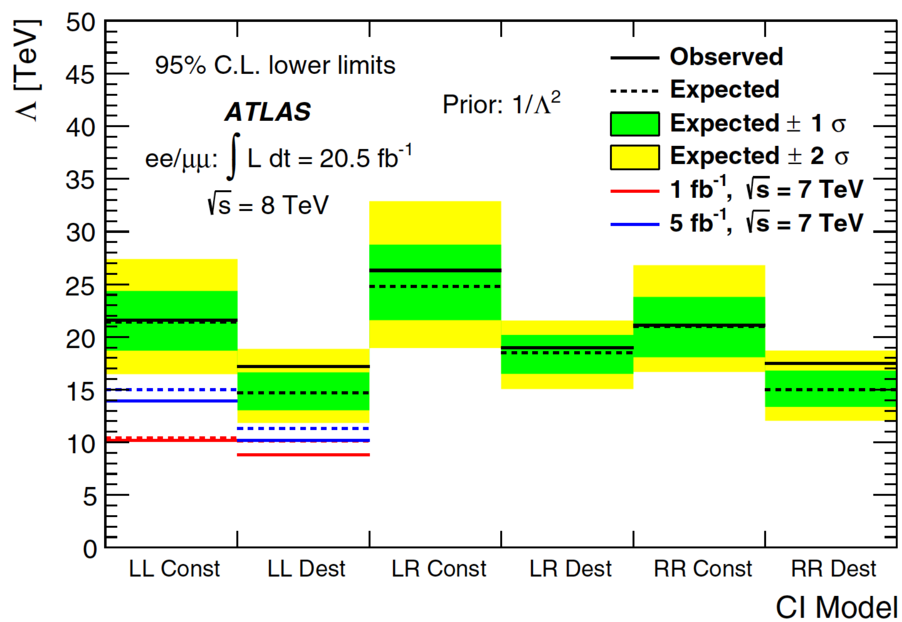
- Interpret in benchmark models
  - Contact interaction
  - ADD

$$M_{\mathrm{Pl}}^2 \sim M_{\mathrm{D}}^{n+2} R^n$$

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{DY}} + \mathscr{F}\frac{F_{\mathrm{int}}}{M_S^4} + \mathscr{F}^2\frac{F_G}{M_S^8}$$

$$\mathscr{L} = \frac{g^2}{\Lambda^2}\left[\eta_{\mathrm{LL}}(\overline{q}_{\mathrm{L}}\gamma_\mu q_{\mathrm{L}})(\overline{\ell}_{\mathrm{L}}\gamma^\mu \ell_{\mathrm{L}}) + \eta_{\mathrm{RR}}(\overline{q}_{\mathrm{R}}\gamma_\mu q_{\mathrm{R}})(\overline{\ell}_{\mathrm{R}}\gamma^\mu \ell_{\mathrm{R}}) + \eta_{\mathrm{LR}}(\overline{q}_{\mathrm{L}}\gamma_\mu q_{\mathrm{L}})(\overline{\ell}_{\mathrm{R}}\gamma^\mu \ell_{\mathrm{R}}) + \eta_{\mathrm{RL}}(\overline{q}_{\mathrm{R}}\gamma_\mu q_{\mathrm{R}})(\overline{\ell}_{\mathrm{L}}\gamma^\mu \ell_{\mathrm{L}})\right],$$

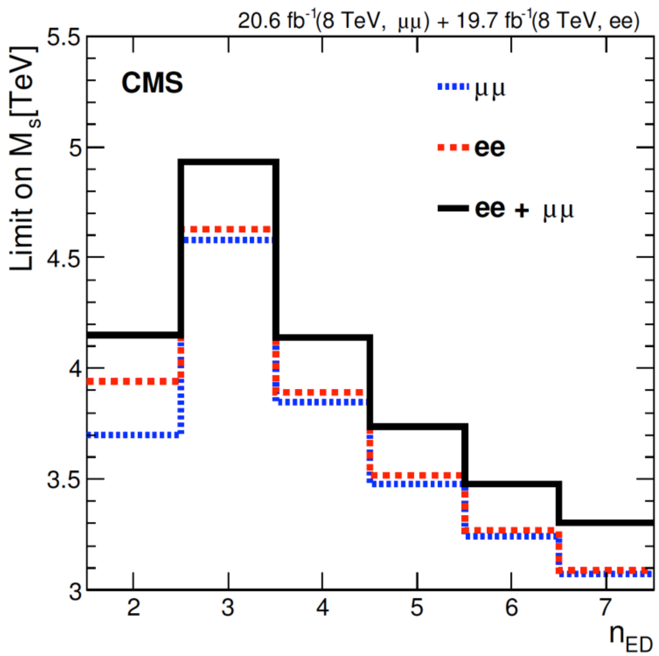


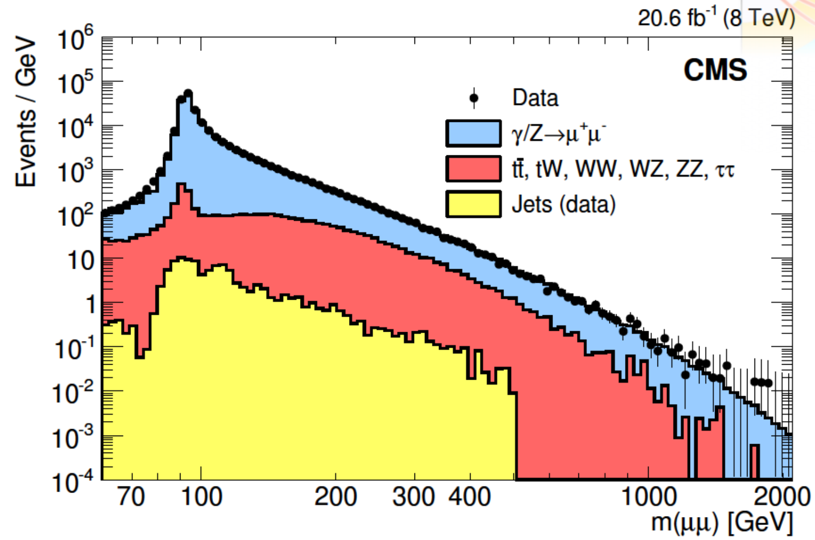


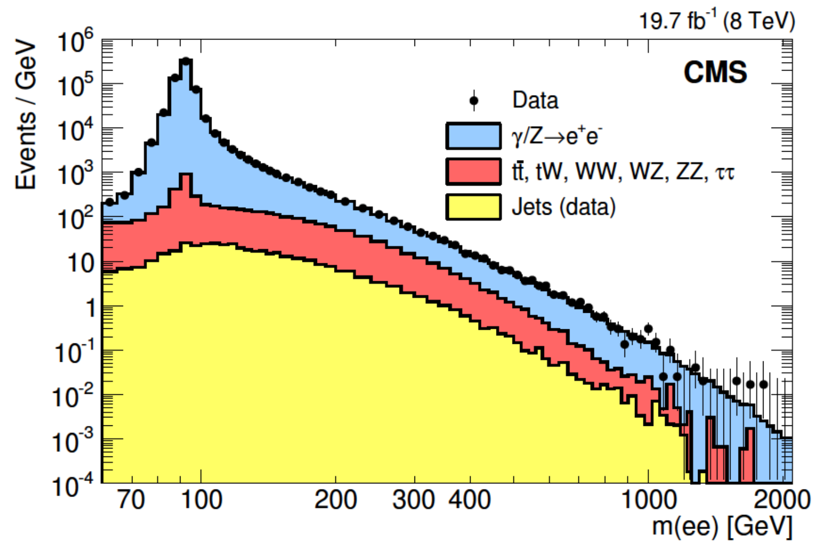
Dilepton Searches

10.1007/JHEP04(2015)025
arXiv:1412.6302

- ADD (GRW & HLZ) interpretation







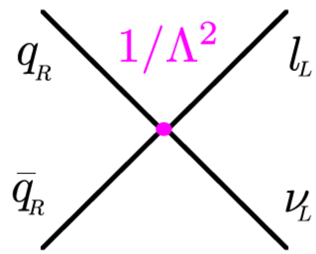
- Limits for LL isoscalar C.I. model
  - Dimuons 12.0 (15.2) TeV
  - Dielectrons 13.5 (18.3) TeV

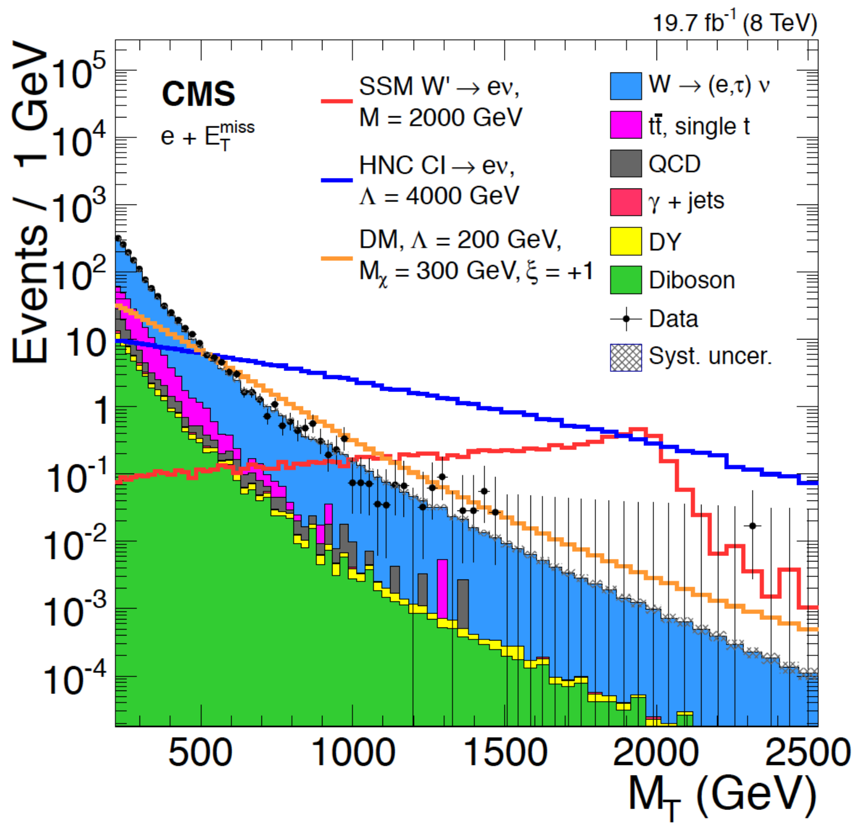
  for destructive (constructive) interference

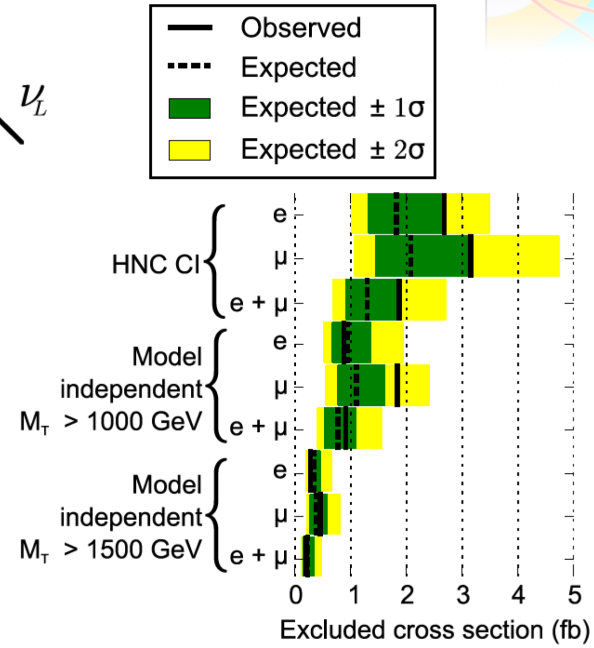
Lepton + Missing E_T

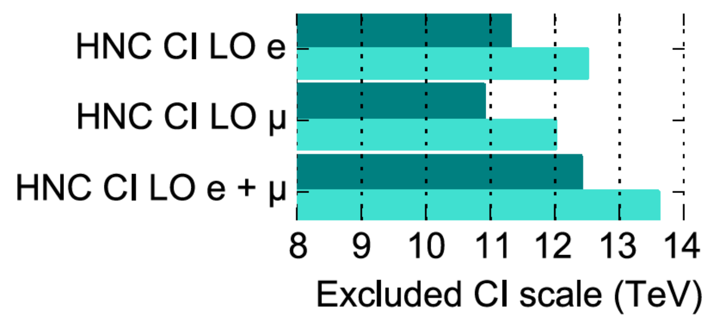
PRD 91 (2015) 092005
arXiv:1408.2745

- High E_T lepton and missing E_T
  - Model: Quarks and leptons are composite
  - At low Λ manifested by four fermion CI







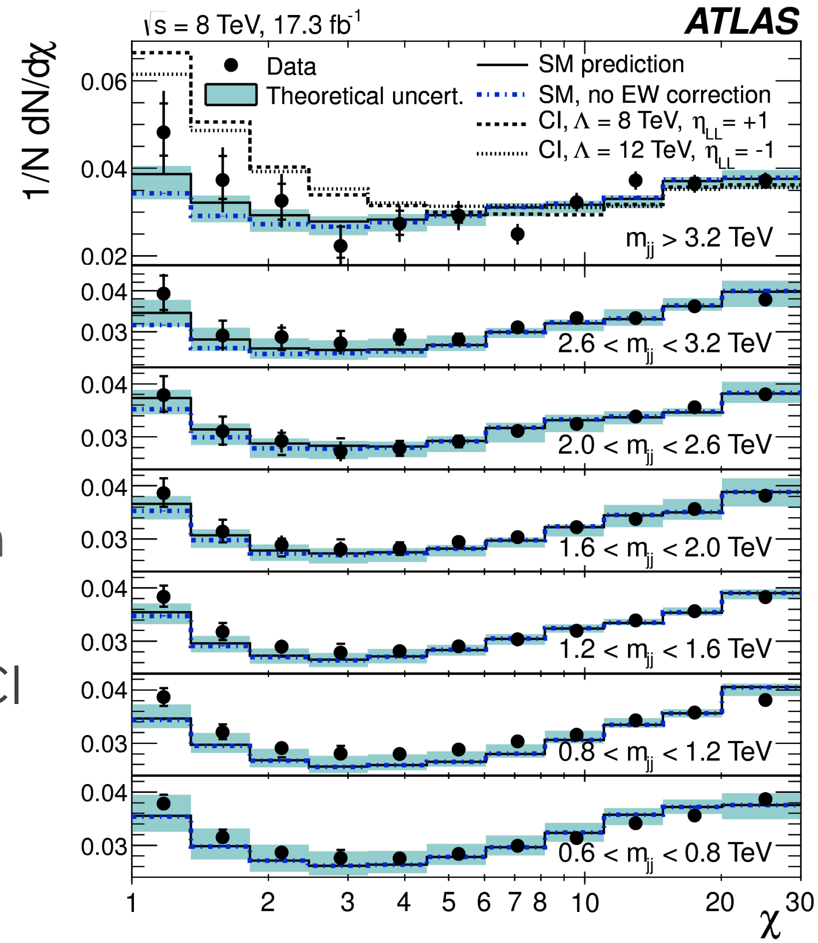


HNC: Helicity Non-Conserving

Dijet Searches

PRL 114, 221802 (2015)
arXiv:1504.00357

- Two high E_T jet candidates
- χ (dijet)= exp (|y_1-y_2|)
  - For massless partons, related to θ^*
  - χ (dijet)= (1+|cosθ^*|)/(1-|cosθ^*|)
- χ constructed, such that ~independent of the two-parton invariant mass
- Bins in χ ~calorimeter segmentation
- Exclusion in left-chiral color-singlet CI model
  - Λ>8.1 TeV destructive interference
  - Λ>12.0 TeV constructive interference

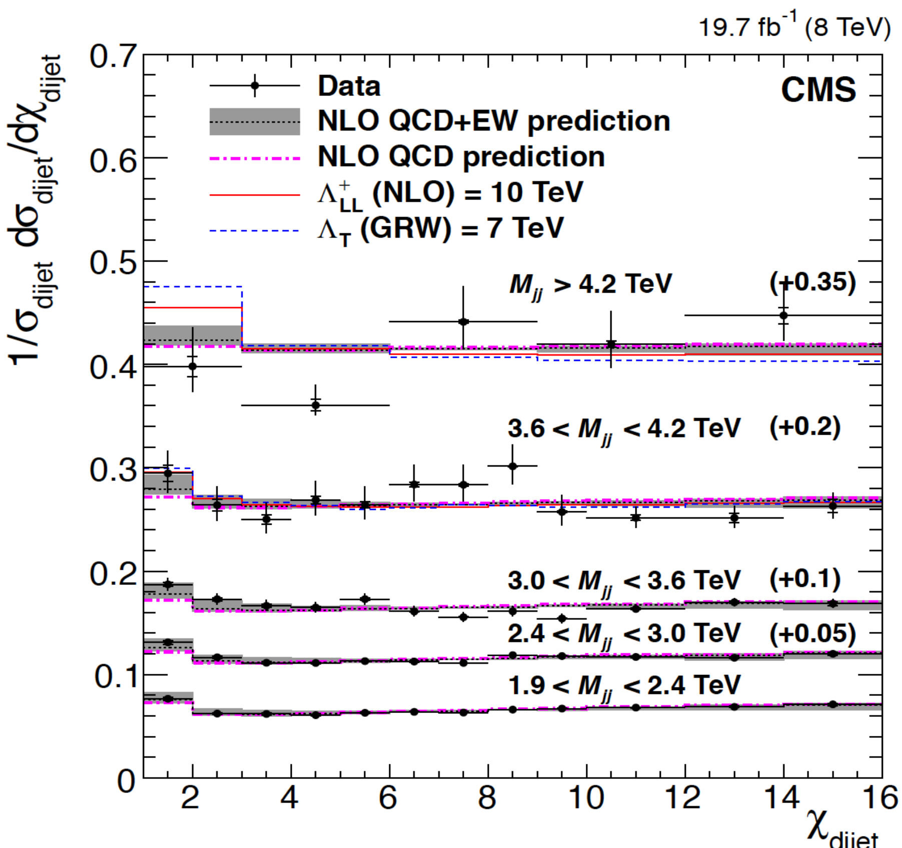


p –value is (0.25) 0.30 for the (second) highest m_{jj} bin

Dijet Searches

Phys. Lett. 04 (2015) 042
arXiv:1411.2646

- SM prediction NLO QCD + EWK
  - Red line: SM+CI
  - Blue line: ADD with Λ (GRW)=7 TeV



Smallest p-value is 17%, found in the M_{jj} range 3.0–3.6 TeV

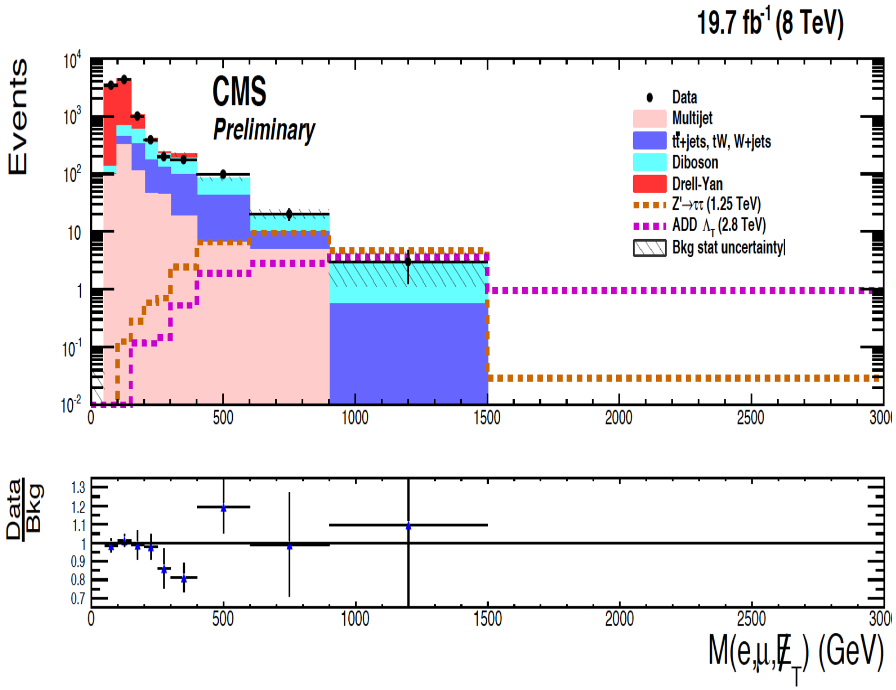
Model	Observed (TeV)	Expected (TeV)
$\Lambda^+_{LL/RR}$ (LO)	10.3	9.8 ± 1.0
$\Lambda^-_{LL/RR}$ (LO)	12.9	12.4 ± 2.2
$\Lambda^+_{LL/RR}$ (NLO)	9.0	8.7 ± 0.8
$\Lambda^-_{LL/RR}$ (NLO)	11.7	11.4 ± 1.8
Λ^+_{VV} (NLO)	11.3	10.8 ± 1.1
Λ^-_{VV} (NLO)	15.2	14.6 ± 2.6
Λ^+_{AA} (NLO)	11.4	10.9 ± 1.1
Λ^-_{AA} (NLO)	15.1	14.5 ± 2.6
$\Lambda^+_{(V-A)}$ (NLO)	8.8	8.5 ± 1.1
$\Lambda^-_{(V-A)}$ (NLO)	8.9	8.6 ± 1.2

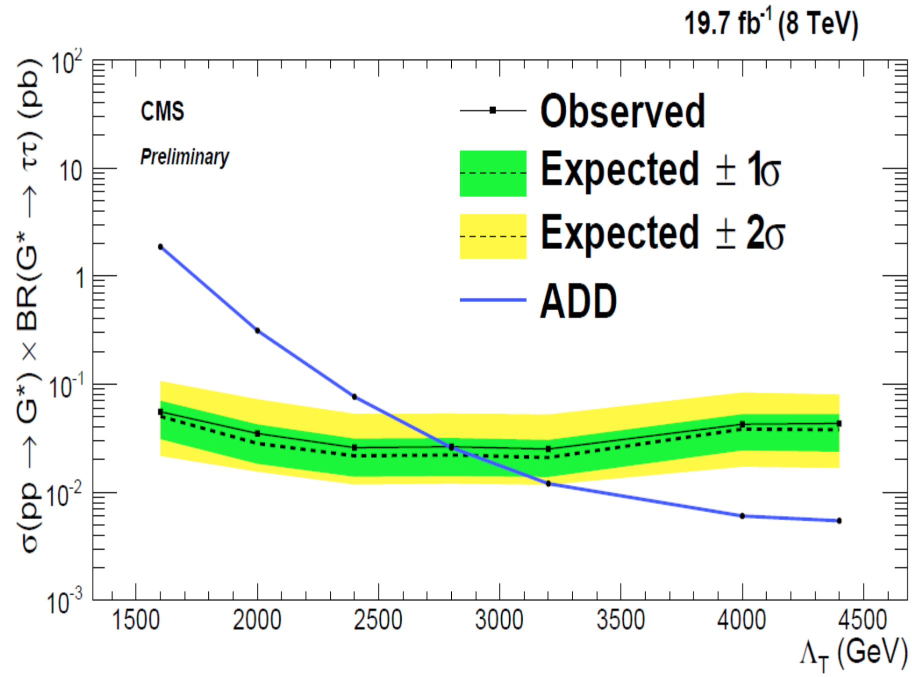
Model	Observed (TeV)	Expected (TeV)
ADD Λ_T (GRW)	7.1	6.8 ± 0.5
ADD M_S (HLZ) $n_{ED} = 2$	6.9	6.6 ± 0.4
ADD M_S (HLZ) $n_{ED} = 3$	8.4	8.0 ± 0.6
ADD M_S (HLZ) $n_{ED} = 4$	7.1	6.8 ± 0.5
ADD M_S (HLZ) $n_{ED} = 5$	6.4	6.1 ± 0.5
ADD M_S (HLZ) $n_{ED} = 6$	5.9	5.7 ± 0.4

Ditau Searches

CMS-PAS-EXO-12-046

- τ_e-τ_μ final states (eμ channel)
- Test a possible non universal coupling
- ADD (GRW, HLZ)



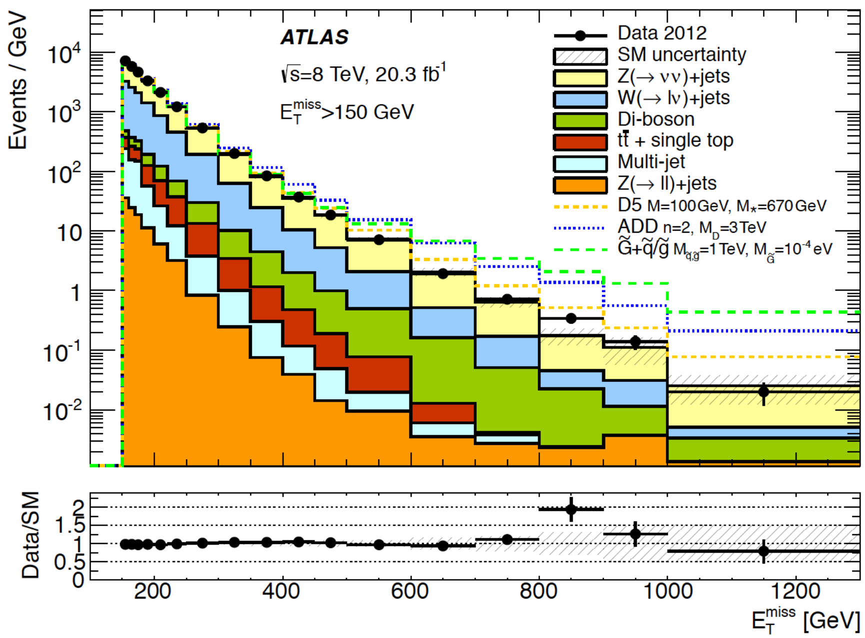


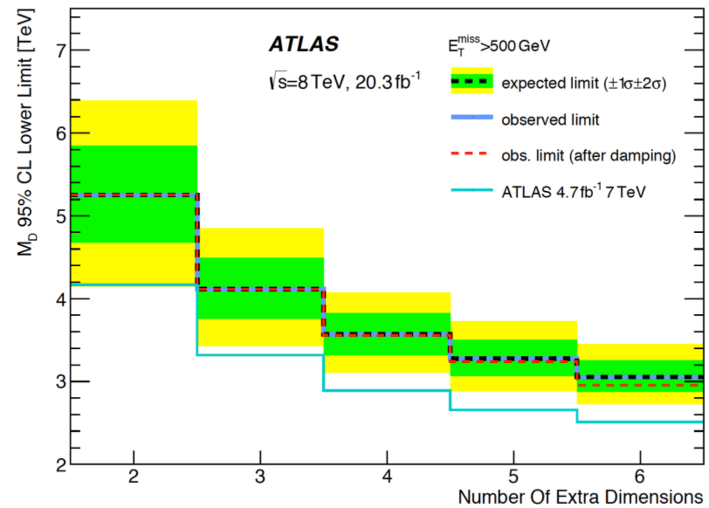
Limit	GRW	HLZ - M_S GeV				
	Λ_T (GeV)	n=3	n=4	n=5	n=6	n=7
Observed (K factor = 1.3)	2800	3330	2800	2530	2350	2230

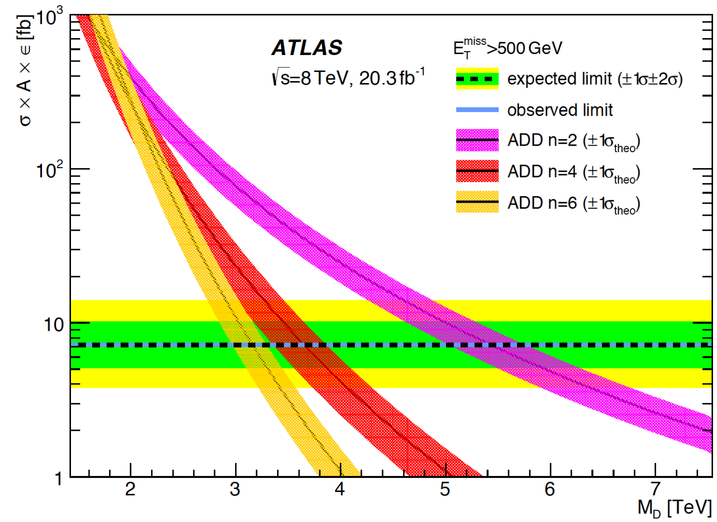
Mono-Jet Searches

Eur. Phys. J. C (2015) 75:299
arXiv:1502.01518

- Monojet: invisible particle (Graviton) is produced
  - large Missing E_T can be detected if recoiling jet present
- Signal region has no leptons
  - Different Missing E_T cuts



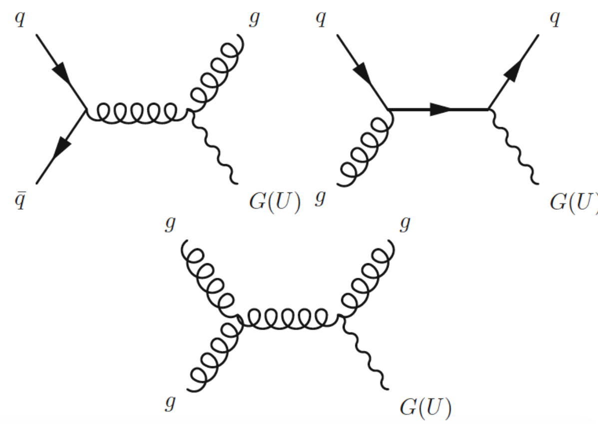


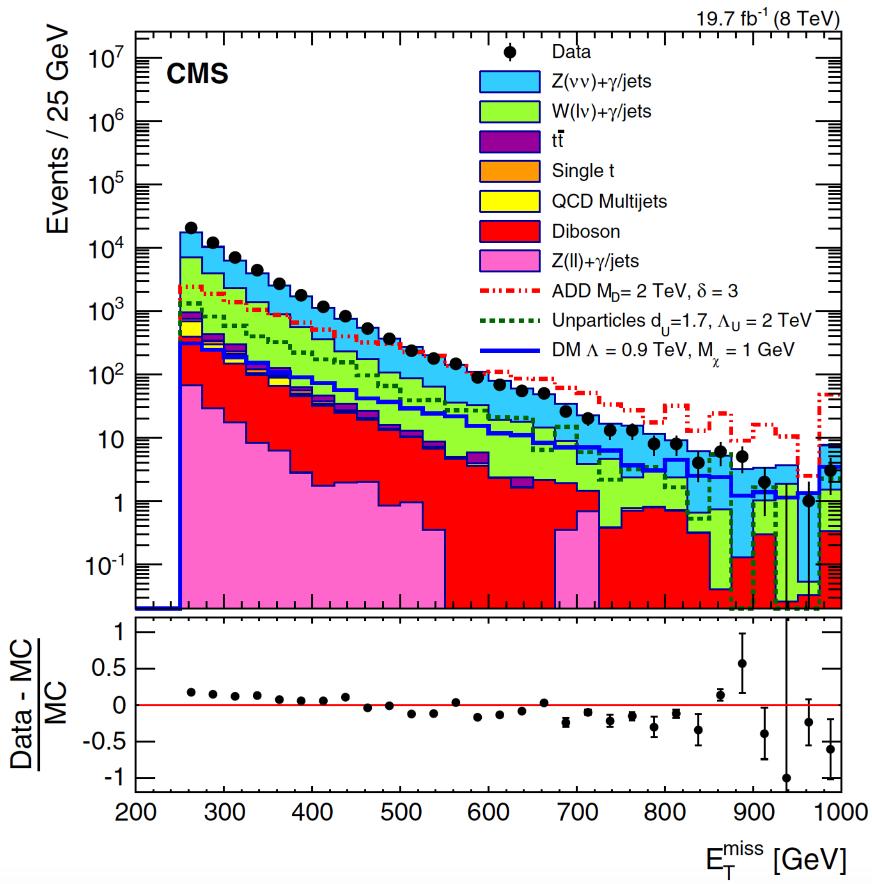


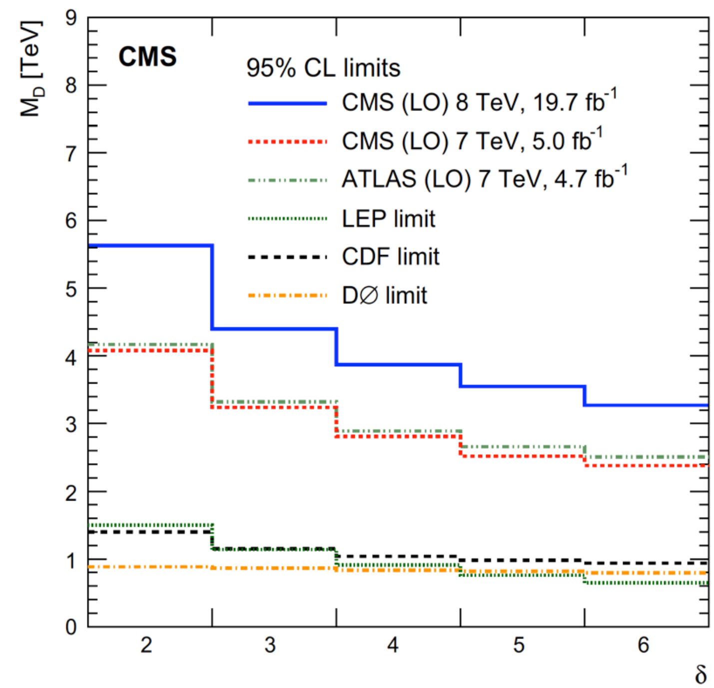
Mono-Jet Searches

Eur. Phys. J. C (2015) 75:235
arXiv:1408.3583

- Dominant background is from Z(νν)+jets
- Constraint from control regions

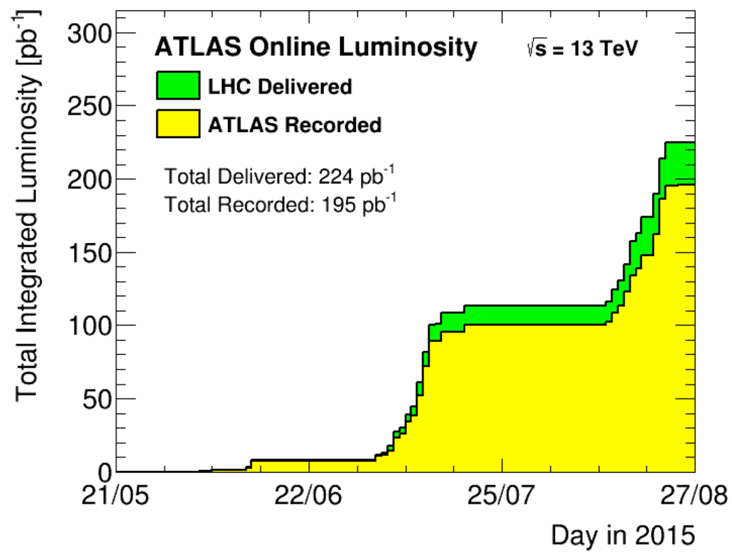


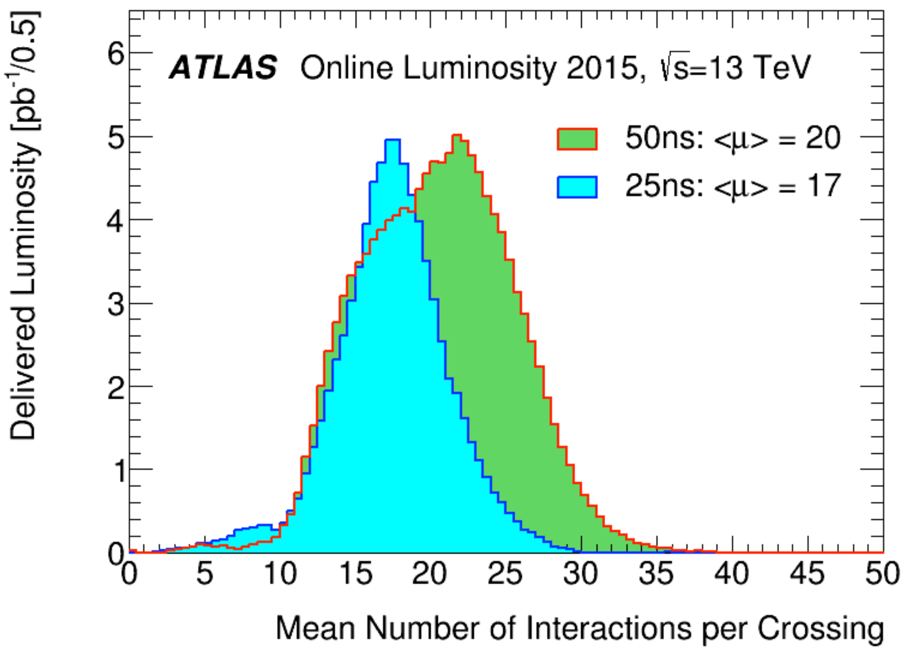


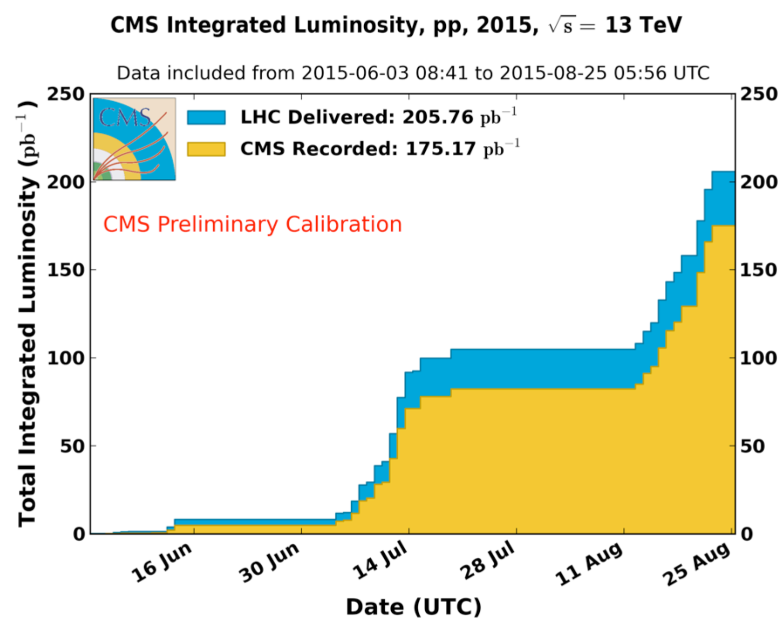


First Look at 13 TeV Data

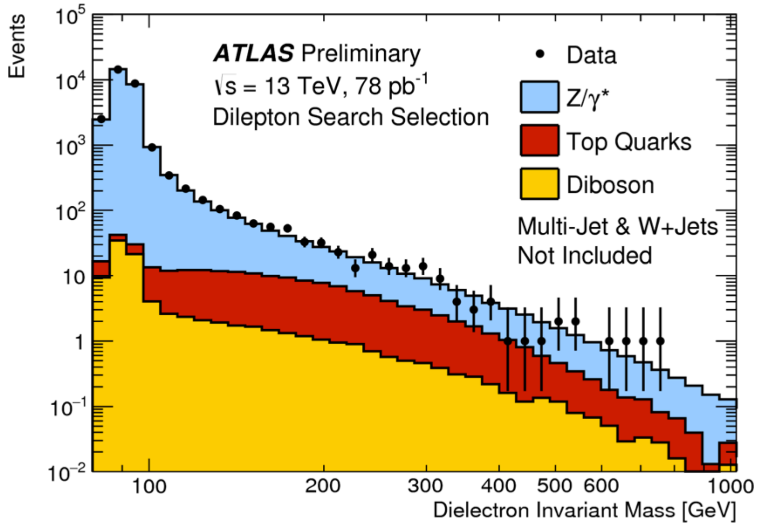
- Since June/July: runs with 50 ns bunch spacing, since August runs with 25ns
- Average number of interactions per bunch crossing
  - $<\mu> = 19$

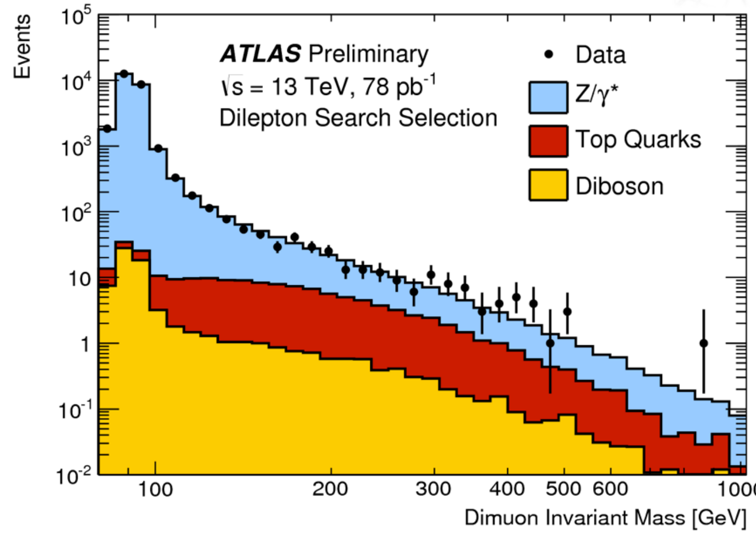


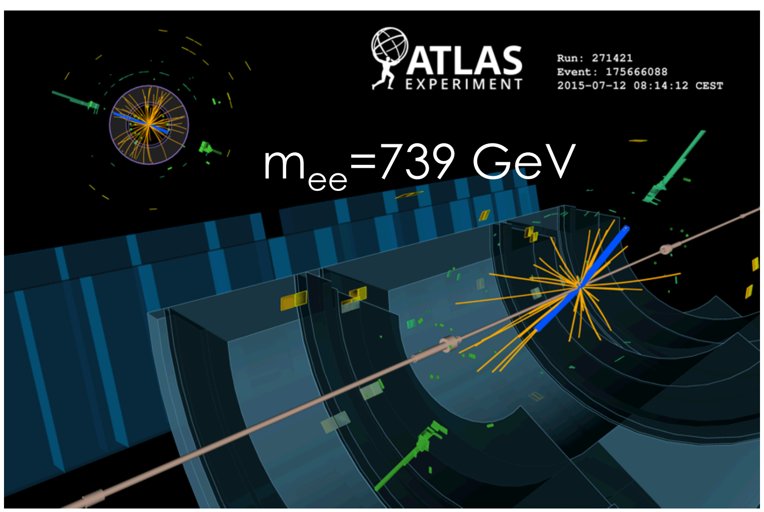


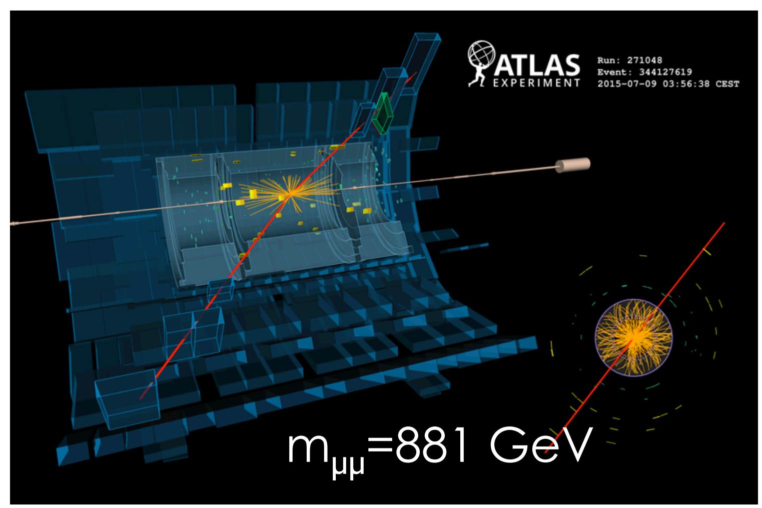


13 TeV data: Dilepton search



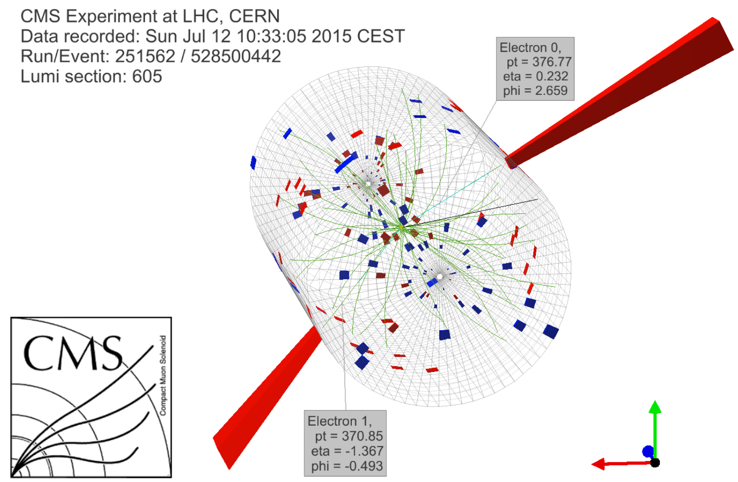


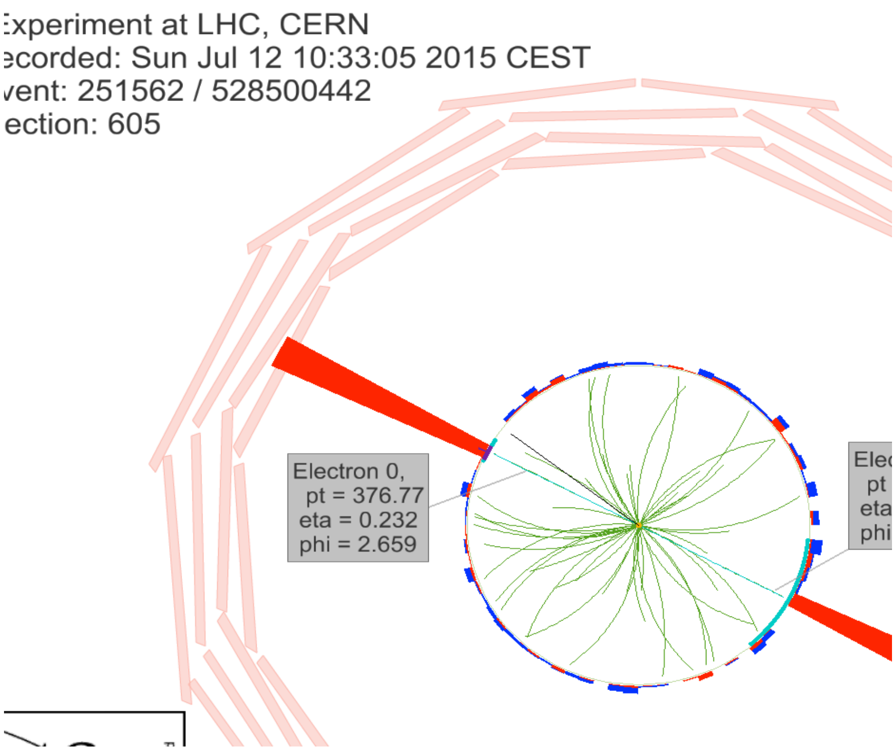


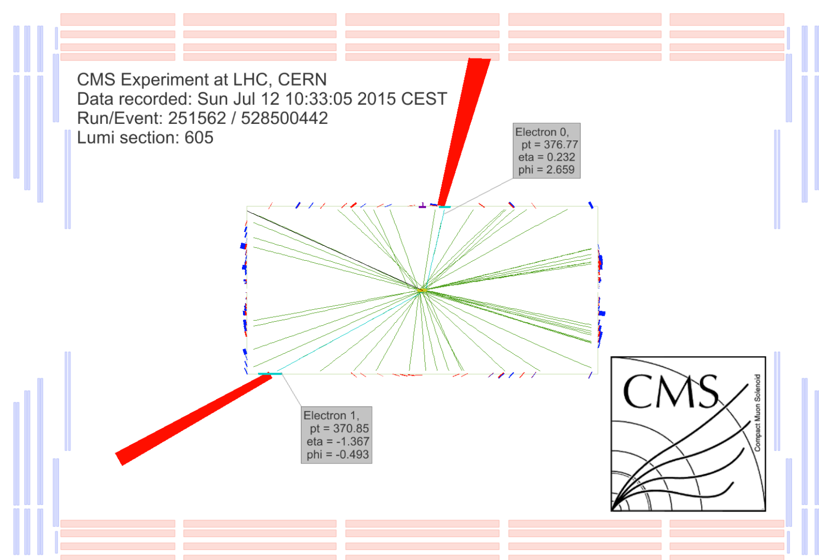


13 TeV data: Highest Mass Dilepton Event

- Dielectron event M=999 GeV
- 3.5 events expected, 3 observed for M>500 GeV

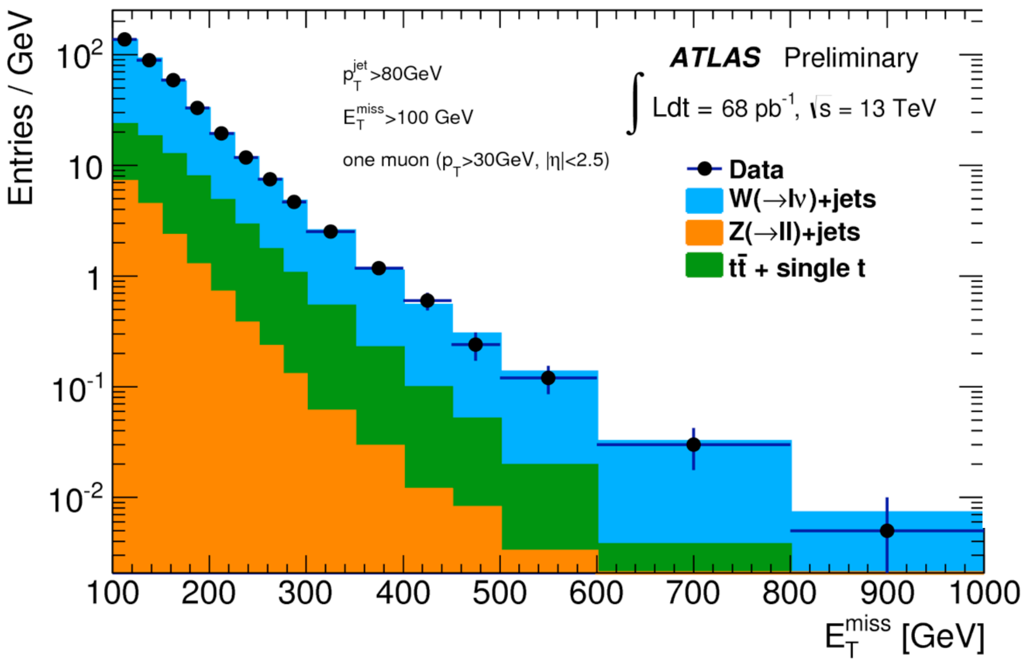


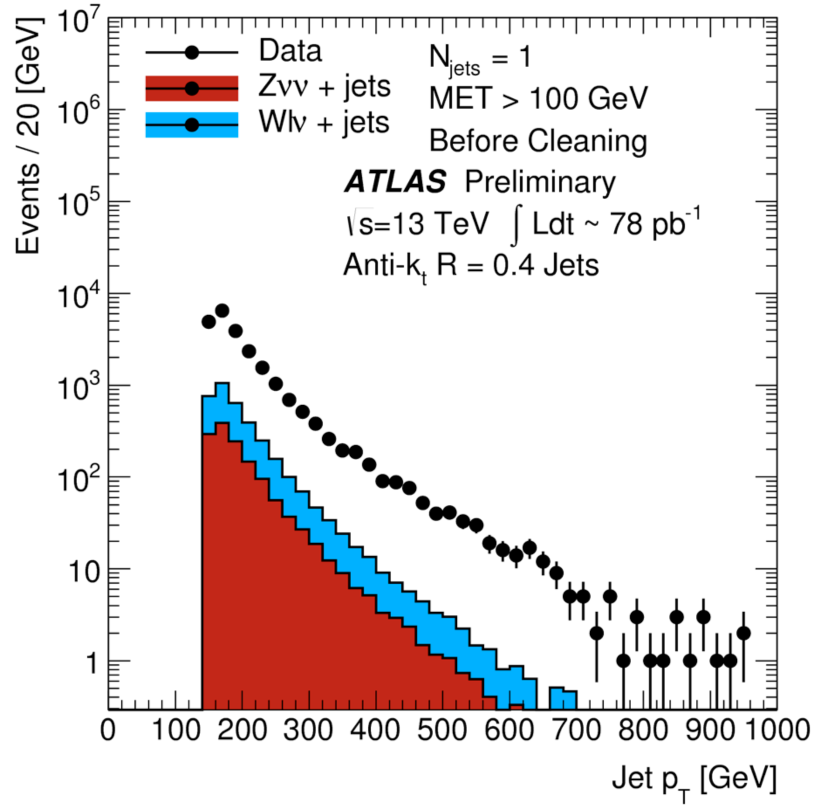




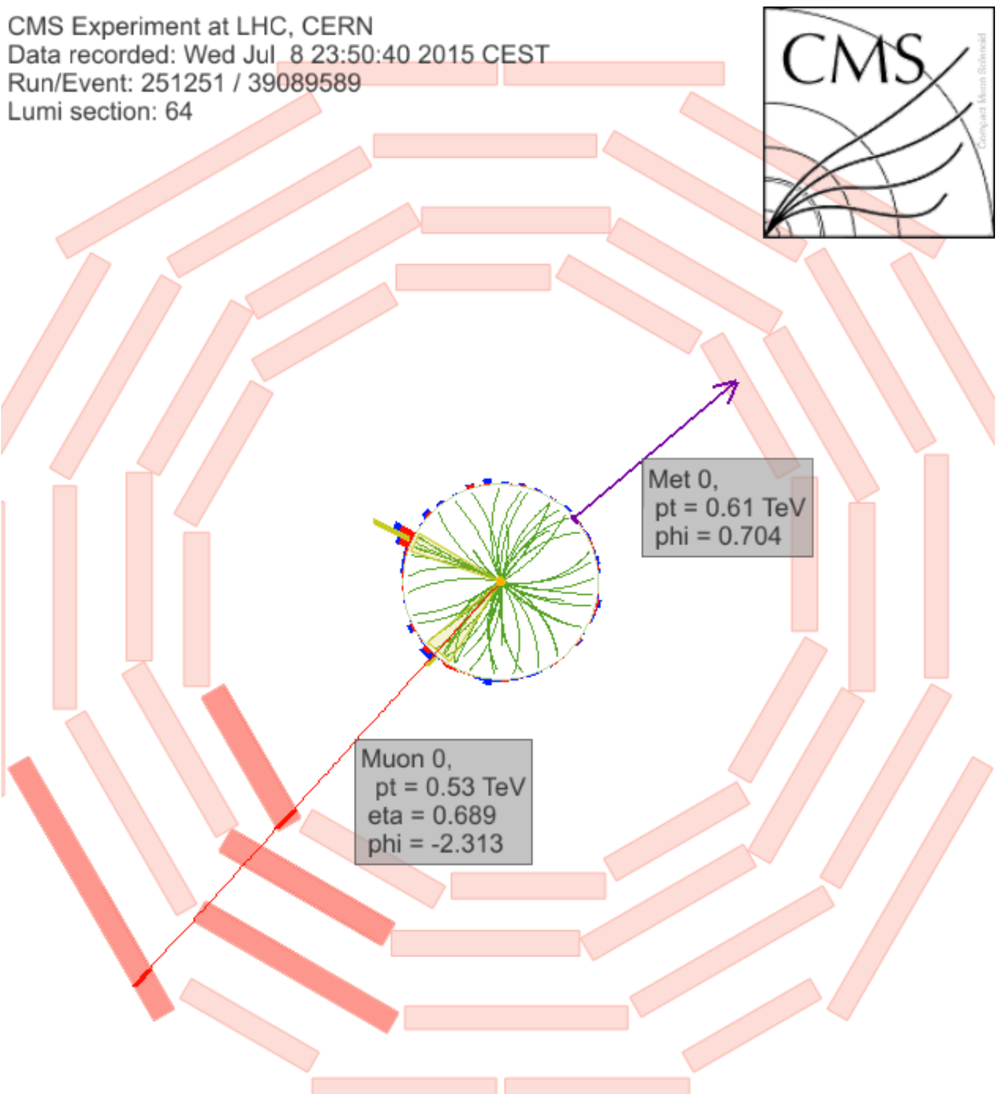
13 TeV data: Monojet Search

- Change to Run 1:
  - Allow only 4 jets in the event
- Jet cleaning cuts are applied in order to suppress non-collision backgrounds





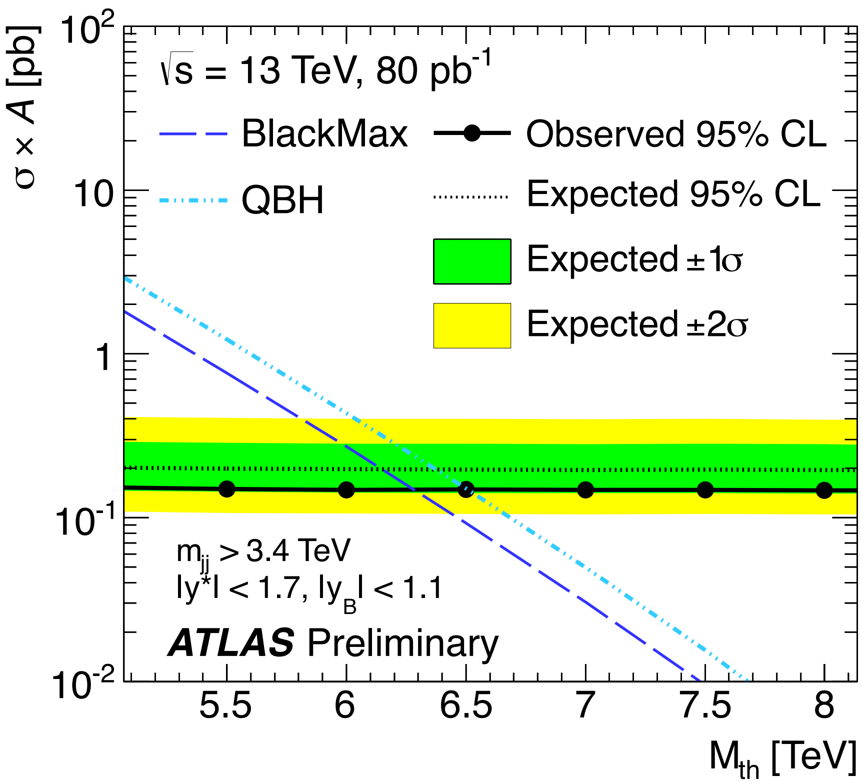
13 TeV data: Highest Mass μν Event

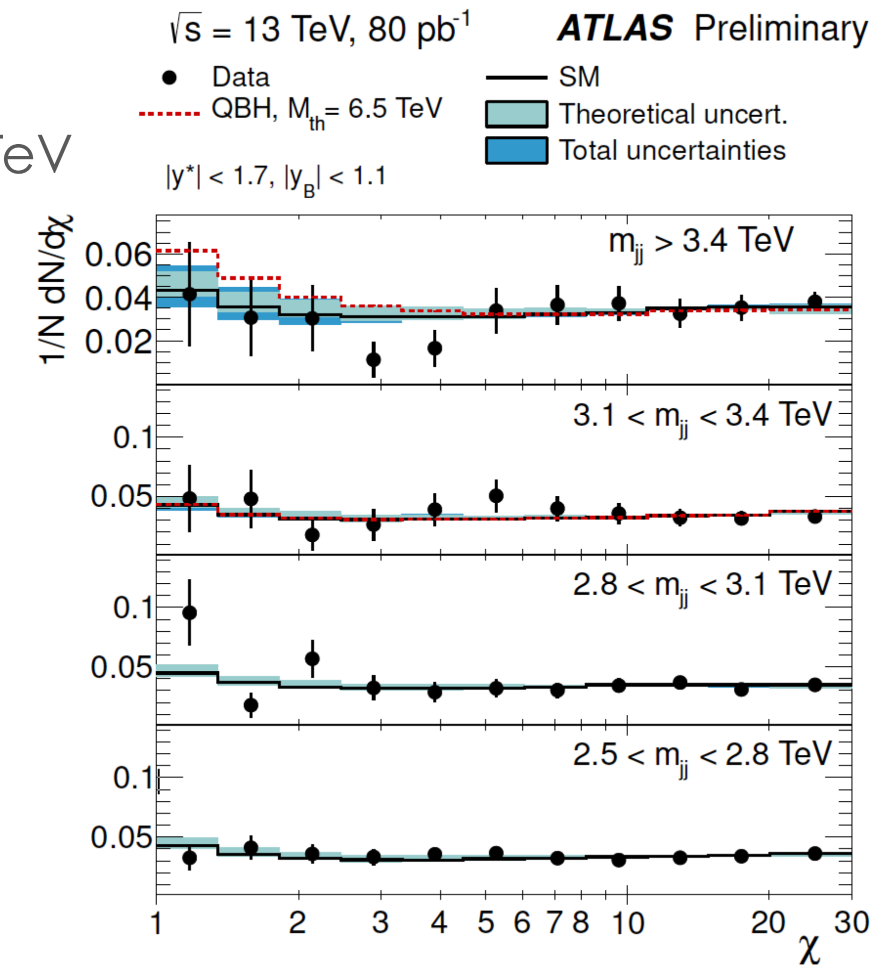


- Transverse Mass M_T=1.1 TeV
  - Muon p_T=0.53 TeV
  - Missing E_T=0.62 TeV
  - ΔΦ(Muon-Missing E_T)=3.0
- 1 events expected, 1 observed for M_T>700 GeV

13 TeV data: Dijet Search NEW!

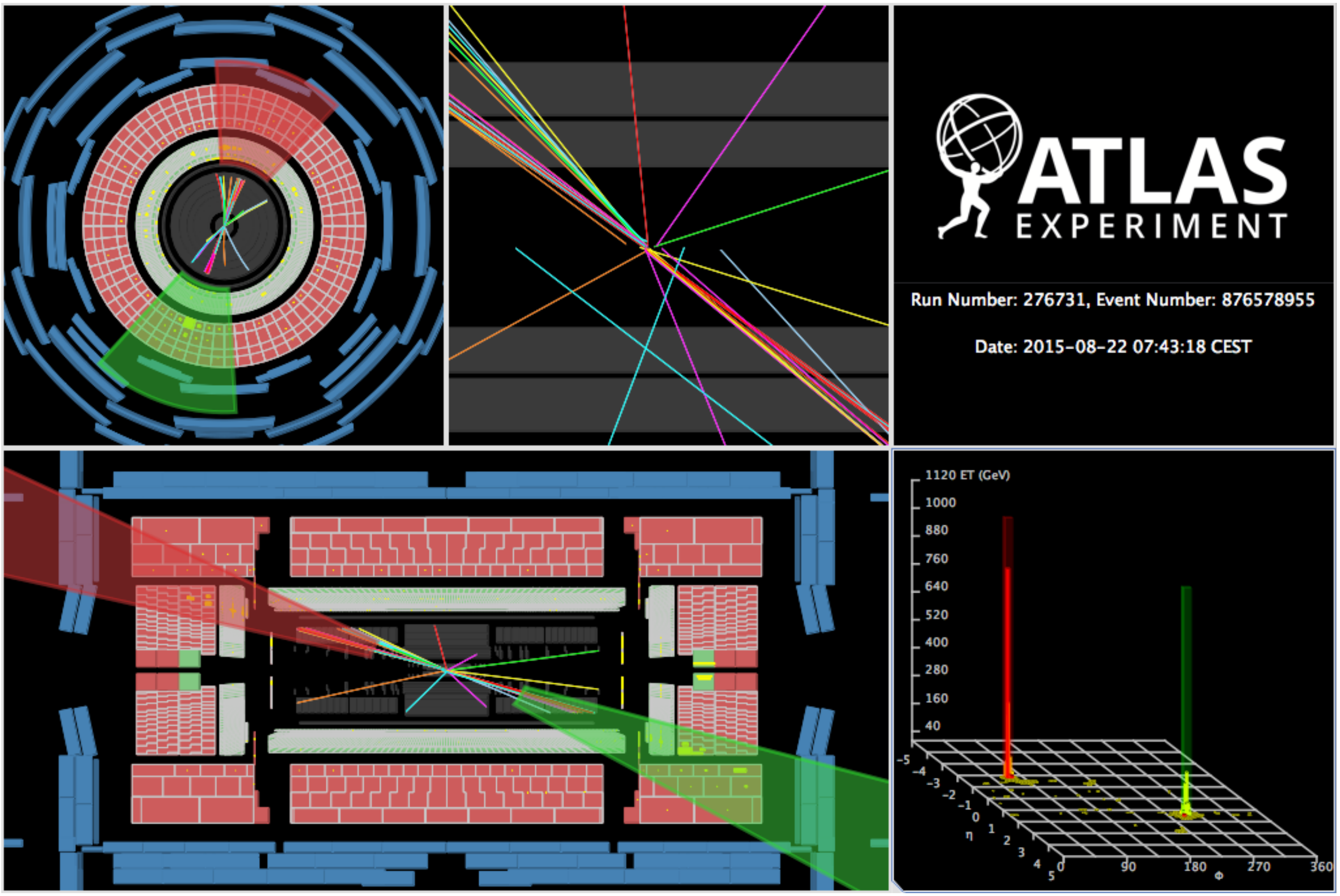
- LHC could produce quantum black holes (QBH) with masses near M_D
- ADD with n = 6 and $M_D = M_{th}$, we exclude QBH with M_{th} below 6.5 TeV





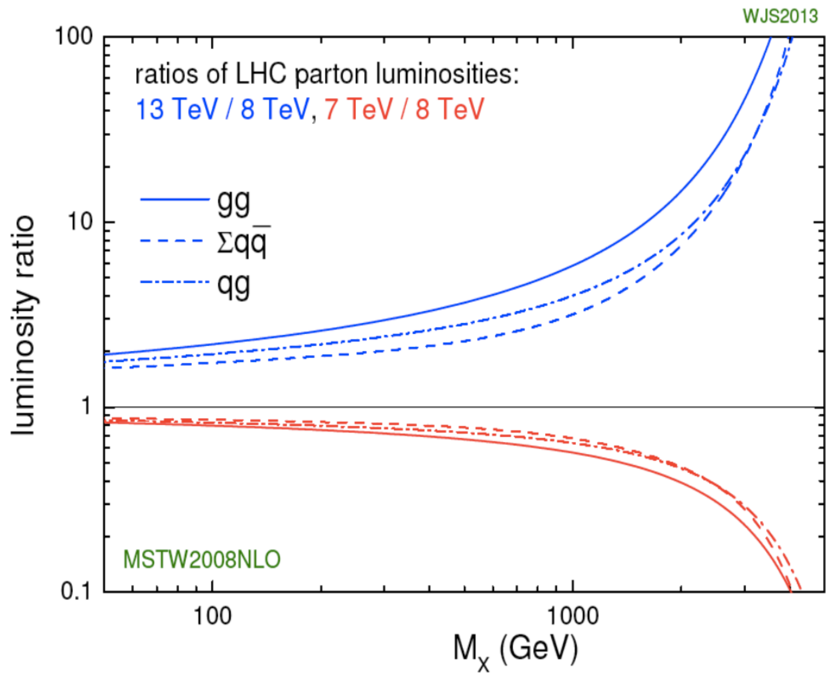
13 TeV data: Dijet Search NEW!

- Highest mass event in angular analysis: 6.9 TeV



Summary

- ATLAS and CMS and the LHC performing well
- Several final states searched for Beyond the Standard Model non-resonant excesses
  - So far good agreement with the Standard Model
- Run 2 is well underway!
  - Cross sections for many new physics scenarios increased significantly
- First results at 13 TeV
  - New energy regime!
  - Discoveries might just be around the corner…



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Extras

Dilepton Searches

Eur. Phys. J. C (2014) 74:3134, arXiv:1407.2410

Table 1 Summary of MC sample information for signal and background processes used in this search. The columns from left to right give the process of interest, generator, matrix-element order, parton shower program, and PDF utilized

Process	Generator	Order	Parton Shower / Hadronization	PDF
$q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$	POWHEG [26]	NLO	PYTHIA 8.165 [28]	CT10 [27]
$\gamma\gamma/\gamma q/\gamma\bar{q} \to \ell^+\ell^-$	PYTHIA 8.165 [28]	LO	PYTHIA 8.165 [28]	MRST2004QED [32]
$t\bar{t} \to \ell X$, $Wt \to X$	MC@NLO 4.06 [33]	NLO	JIMMY 4.31 [34] + HERWIG 6.520 [35]	CT10 [27]
$WW, WZ, ZZ \to \ell X/\ell\nu/\ell\ell$	HERWIG 6.520 [35]	LO	HERWIG 6.520 [35]	CTEQ6L1 [37]
CI: $q\bar{q} \to \ell^+\ell^-$	PYTHIA 8.165 [28]	LO	PYTHIA 8.165 [28]	MSTW2008LO [30,31]
ADD: $q\bar{q}/gg \to G^* \to \ell^+\ell^-$	SHERPA 1.3.1 [7]	LO (multi-leg)	SHERPA 1.3.1 [7]	CTEQ6L1 [37]

Table 5 Summary of the systematic uncertainties taken into account for the total expected number of events. Values are provided at $m_{\ell\ell}$ = 1 TeV (2 TeV) to give representative estimates relevant to this search. The PDF variation values shown for signal are based on CI. For the ADD signal they are uniform at 6 % and 3 % in the dielectron and dimuon channels, respectively. Signal systematic uncertainties are assessed as a function of the corresponding parameter of interest but are not found to vary greatly. N/A indicates that the uncertainty is not applicable

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	4.0 % (4.0 %)	N/A	4.0 % (4.0 %)	N/A
PDF Variation	<0.1 % (0.2 %)	5.0 % (11.0 %)	<0.1 % (<0.1 %)	5.0 % (12.0 %)
PDF Choice	N/A	1.0 % (7.0 %)	N/A	1.0 % (6.0 %)
α_S	N/A	1.0 % (3.0 %)	N/A	1.0 % (3.0 %)
EW Corrections	N/A	1.0 % (2.0 %)	N/A	1.0 % (3.0 %)
Photon-Induced	N/A	7.0 % (12.0 %)	N/A	6.5 % (9.5 %)
Efficiency	1.0 % (2.0 %)	1.0 % (2.0 %)	3.0 % (6.0 %)	3.0 % (6.0 %)
Scale & Resolution	1.2 % (2.4 %)	1.2 % (2.4 %)	1.0 % (4.0 %)	1.0 % (4.0 %)
Electron Charge Misident.	1.2 % (2.0 %)	1.2 % (2.0 %)	N/A	N/A
Multi-Jet & W+Jets	N/A	3.0 % (5.0 %)	N/A	N/A
Beam Energy	1.0 % (3.0 %)	1.0 % (3.0 %)	1.0 % (3.0 %)	2.0 % (3.0 %)
MC Statistics	3.0 % (3.0 %)	0.5 % (0.5 %)	3.0 % (3.0 %)	0.5 % (0.5 %)
Total	5.5 % (6.9 %)	9.5 % (19.4 %)	6.0 % (9.3 %)	9.2 % (18.7 %)

Dilepton Searches

Eur. Phys. J. C (2014) 74:3134,
arXiv:1407.2410

$$M_S = 2\sqrt{\pi}\left[\Gamma\left(\frac{n}{2}\right)\right]^{1/(n+2)} M_D.$$

$$\sigma_{tot} = \sigma_{DY} + \mathscr{F}\frac{F_{int}}{M_S^4} + \mathscr{F}^2\frac{F_G}{M_S^8}$$

The strength of the interaction is characterized by $F/M_S{}^4$, where the dimensionless parameter F varies in the different calculations provided by Giudice–Rattazzi–Wells (GRW), Hewett and Han–Lykken–Zhang (HLZ)

$$\mathscr{F} = 1, \quad \text{(GRW)}$$
$$\mathscr{F} = \frac{2\lambda}{\pi} = \frac{\pm 2}{\pi}, \quad \text{(Hewett)}$$
$$\mathscr{F} = \log\left(\frac{M_S^2}{s}\right) \quad \text{for } n = 2, \quad \text{(HLZ)}$$
$$\mathscr{F} = \frac{2}{n-2} \quad \text{for } n > 2. \text{ (HLZ)}.$$

Dilepton Searches

10.1007/JHEP04(2015)025
arXiv:1412.6302

$m_{\mu\mu}$ range (GeV)	Data	Total background	Z/γ^*	$t\bar{t}$ + other prompt bkgd	Jet mis-reconstruction
120–400	96299	96800 ± 4300	86800 ± 3800	9900 ± 420	147 ± 18
400–600	1367	1460 ± 80	1180 ± 60	276 ± 13	3 ± 3
600–900	273	283 ± 19	246 ± 16	37 ± 4	—
900–1300	55	46 ± 4	40 ± 4	5 ± 1	—
1300–1800	8	6.1 ± 0.8	5.7 ± 0.8	0.4 ± 0.2	—
>1800	2	0.8 ± 0.2	0.8 ± 0.2	—	—

Table 2. The number of dimuon events in various invariant mass ranges for an integrated luminosity of 20.6 fb^{-1}. The total background is the sum of the events for the standard model processes listed. The yields from simulation are normalized relative to the expected cross sections, and overall the simulation is normalized to the data using the number of events in the mass window 60–120 GeV acquired using a prescaled low threshold trigger. Uncertainties include both statistical and systematic components, summed in quadrature. A dash (—) is used to indicate negligibly small contributions.

m_{ee} range (GeV)	Data	Total background	Z/γ^*	$t\bar{t}$ + other prompt bkgd	Jet mis-reconstruction
120–400	87117	88700 ± 3900	77100 ± 3900	10130 ± 680	1500 ± 300
400–600	1266	1240 ± 100	970 ± 100	226 ± 15	40 ± 8
600–900	259	245 ± 21	211 ± 21	27 ± 2	7 ± 1
900–1300	41	39 ± 3	35 ± 3	3.5 ± 0.2	1.2 ± 0.2
1300–1800	4	5.2 ± 0.5	4.8 ± 0.5	0.36 ± 0.02	0.005 ± 0.001
>1800	0	0.64 ± 0.06	0.64 ± 0.06	—	—

Table 3. The number of dielectron events in various invariant mass ranges for an integrated luminosity of 19.7 fb^{-1}. The total background is the sum of the events for the standard model processes listed. The yields from simulation are normalized relative to the expected cross sections, and overall the simulation is normalized to the data using the number of events in the mass window 60–120 GeV. Uncertainties include both statistical and systematic components, summed in quadrature. A dash (—) is used to indicate negligibly small contributions.

Lepton + Missing E_T

PRD 91 (2015) 092005
arXiv:1408.2745

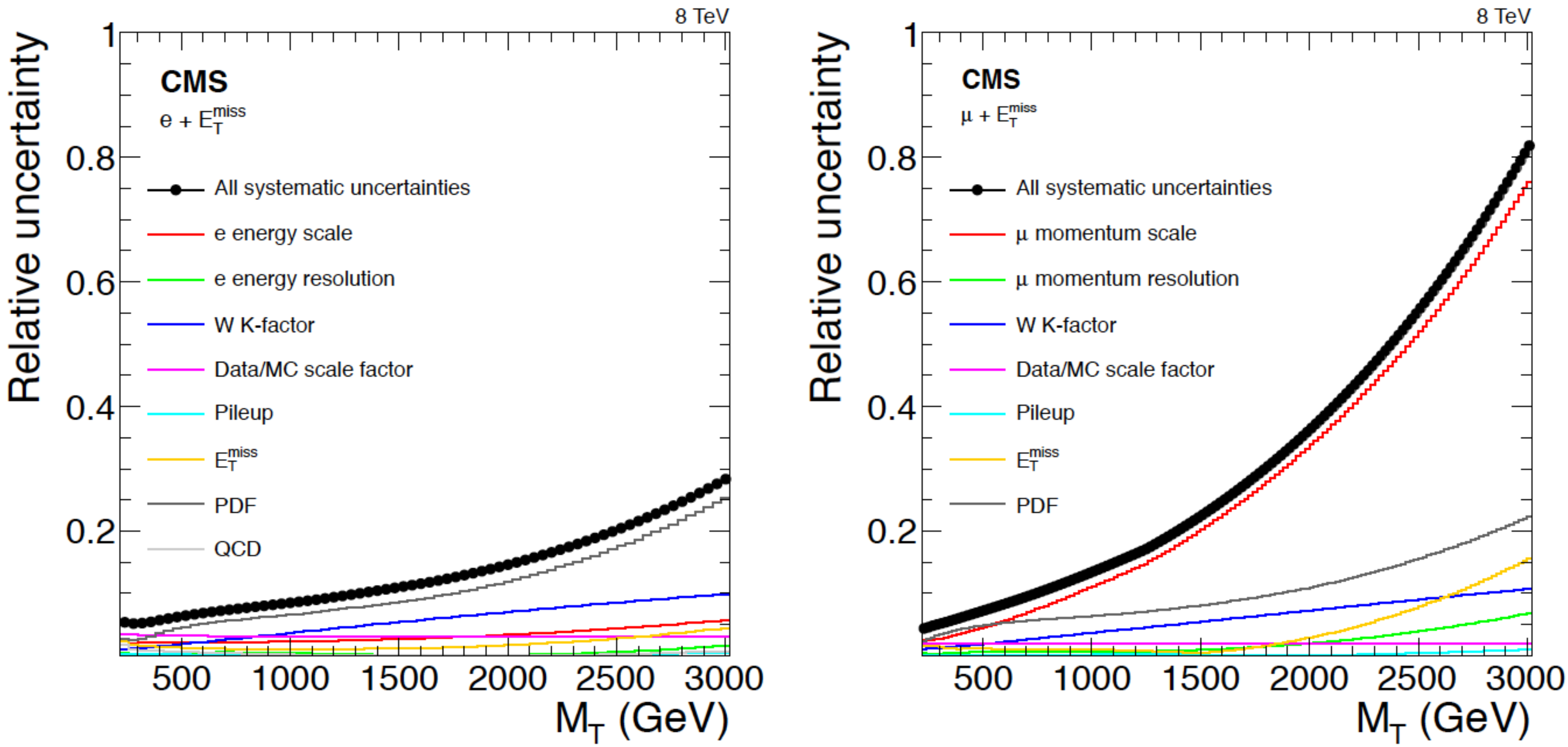

Figure 9: Individual contributions of relative systematic uncertainties on the background event yields in the electron (left) and muon (right) channels.

HNC: Helicity Non-Conserving

Dijet Searches

PRL 114, 221802 (2015)
arXiv:1504.00357

- The data are selected using a trigger that requires a single high-pT jet above one of eight thresholds, ranging from 25 GeV to 220 GeV
- Individual jets are reconstructed using the anti-kt jet clustering algorithm with radius parameter R = 0.6.
- Events are required to have at least two jets, each with $p_T > 50$ GeV, the dijet system, defined as the two jets with largest pT , is required to have $y^*<1.7$, $y_B<1.1$ and $m_{jj}>600$ GeV, where $y^* = ½(y_1-y_2)$ and $y_B=½(y_1+y_2)$
- The largest uncertainty due to choice of generator is at the lowest m_{jj} values, where it approaches 20%, while for the highest m_{jj} values and smallest χ , it ranges from 10% to 14%
- The experimental uncertainty is dominated by the η dependence of the jet energy scale calibration. This uncertainty varies from approximately 15% at small values of χ for the highest m_{jj} values, to a few percent at lower m_{jj} values and higher χ values.

Dijet Searches

Phys. Lett. 04 (2015) 042
arXiv:1411.2646

Table 1: Summary of the experimental and theoretical uncertainties in the normalized χ_{dijet} distributions. For the lowest, second highest and highest M_{jj} ranges, the relative shift (in %) of the lowest χ_{dijet} bin from its nominal value is quoted. While in the statistical analysis each systematic uncertainty is represented by a change of the χ_{dijet} distribution correlated among all χ_{dijet} bins, this table summarizes each uncertainty by a representative number to demonstrate the relative contributions.

Uncertainty	$1.9 < M_{jj} < 2.4$ TeV (%)	$3.6 < M_{jj} < 4.2$ TeV (%)	$M_{jj} > 4.2$ TeV (%)
Statistical	1.0	2.3	47
Jet energy scale	2.0	2.1	2.5
Jet energy resolution (tails)	1.0	2.0	13
Jet energy resolution (core)	0.5	0.6	1.5
Unfolding, modeling	0.1	1.2	1.2
Unfolding, detector simulation	0.4	1.0	5.0
Pileup	<0.1	<0.1	<1.0
Total experimental	2.5	4.1	49
QCD NLO scale (6 variations of μ_R and μ_F)	$^{+9.0}_{-3.4}$	$^{+11}_{-4.0}$	$^{+18}_{-6.3}$
PDF (CT10 eigenvectors)	0.6	0.7	1.0
Non-perturbative effects	<1.0	<1.0	<0.2
Total theoretical	9	11	18

Mono-Jet Searches

Eur. Phys. J. C (2015) 75:299
arXiv:1502.01518

ATLAS EXPERIMENT

Table 2 Event selection criteria applied for the selection of monojet-like signal regions, SR1–SR9.

Selection criteria									
Preselection									
Primary vertex $E_T^{miss} > 150$ GeV Jet quality requirements At least one jet with $p_T > 30$ GeV and $\|\eta\| < 4.5$ Lepton and isolated track vetoes									
Monojet-like selection									
The leading jet with $p_T > 120$ GeV and $\|\eta\| < 2.0$ Leading jet $p_T/E_T^{miss} > 0.5$ $\Delta\phi(\text{jet}, \mathbf{p}_T^{miss}) > 1.0$									
Signal region	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9
Minimum E_T^{miss} [GeV]	150	200	250	300	350	400	500	600	700

Table 3 Summary of the methods and control samples used to constrain the different background contributions in the signal regions.

Background process	Method	Control sample
$Z(\to \nu\bar{\nu})$+jets	MC and control samples in data	$Z/\gamma^*(\to \ell^+\ell^-)$, $W(\to \ell\nu)$ $(\ell = e, \mu)$
$W(\to e\nu)$+jets	MC and control samples in data	$W(\to e\nu)$ (loose)
$W(\to \tau\nu)$+jets	MC and control samples in data	$W(\to e\nu)$ (loose)
$W(\to \mu\nu)$+jets	MC and control samples in data	$W(\to \mu\nu)$
$Z/\gamma^*(\to \ell^+\ell^-)$+jets $(\ell = e, \mu, \tau)$	MC-only	
$t\bar{t}$, single top	MC-only	
Diboson	MC-only	
Multijets	data-driven	
Non-collision	data-driven	

$$N_{\text{signal}}^{Z(\to\nu\bar{\nu})} = \frac{(N_{W(\to\mu\nu),\text{control}}^{\text{data}} - N_{W(\to\mu\nu),\text{control}}^{\text{non}-W/Z})}{N_{W(\to\mu\nu),\text{control}}^{\text{MC}}} \times N_{\text{signal}}^{\text{MC}(Z(\to\nu\bar{\nu}))} \times \xi_\ell \times \xi_{\text{trg}},$$

Mono-Jet Searches

Eur. Phys. J. C (2015) 75:235
arXiv:1408.3583

Table 1 Summary of the statistical and systematic contributions to the total uncertainty on the $Z(\nu\nu)$ background

E_T^{miss} (GeV) →	>250	>300	>350	>400	>450	>500	>550
(1) $Z(\mu\mu)$ + jets statistical unc.	1.7	2.7	4.0	5.6	7.8	11	16
(2) Background	1.4	1.7	2.1	2.4	2.7	3.2	3.9
(3) Acceptance	2.0	2.1	2.1	2.2	2.3	2.6	2.8
(4) Selection efficiency	2.1	2.2	2.2	2.4	2.7	3.1	3.7
(5) R_{BF}	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Total uncertainty (%)	5.1	5.6	6.6	7.9	9.9	13	18

Table 2 Summary of the statistical and systematic contributions to the total uncertainty on the W + jets background from the various factors used in the estimation from data

E_T^{miss} (GeV) →	>250	>300	>350	>400	>450	>500	>550
(1) $W(\mu\nu)$ + jets statistical unc.	0.8	1.3	1.9	2.8	3.9	5.5	7.3
(2) Background	2.3	2.3	2.2	2.3	2.4	2.6	2.8
(3) Acceptance and efficiency	4.5	4.6	4.9	5.2	5.7	6.4	7.6
Total uncertainty (%)	5.1	5.3	5.7	6.4	7.3	8.8	11