Search for Supersymmetry in States with Large Missing Transverse Momentum and Three Leptons including a Z-Boson

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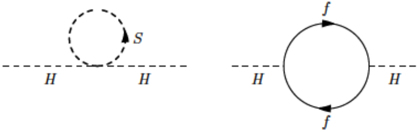
April 17^{th}, 2012

Abstract & Outline

- I present a search for supersymmetric particle production
- Signature is 3 leptons (e or μ) and large $E_{\mathrm{T}}^{\mathrm{miss}}$, with 2 of the leptons forming a same-flavor, opposite-sign pair within 10 GeV of the Z mass
- The data was taken at the ATLAS Detector with *pp*-collisions provided by the Large Hadron Collider (LHC) in 2011
- An upper limit on the cross section of processes beyond the standard model are set
- The results are also interpreted using General Gauge-Mediated (GGM) SUSY

Outline:

- Theoretical Motivation
- Experimental Apparatus
- Analysis
- Results
- Interpretation
- Future Studies



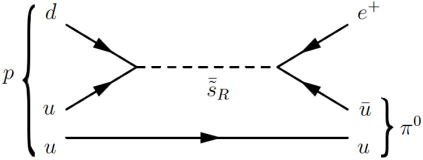
- Loop corrections to Standard m_H quadratically diverge
- SUSY adds partners fermion (boson) for each boson (fermion); "sparticles"
- Produces opposite sign contribution $\rightarrow$ cancellation
- SUSY is broken — 0.511 MeV charged bosons are not observed
- If sparticles have $m \sim \mathcal{O}(1\ \mathrm{TeV})$, the terms cancel acceptably

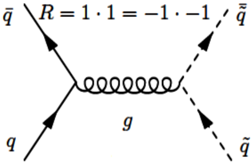
Minimal Supersymmetric Standard Model (MSSM)

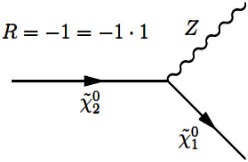
- Minimal additions necessary to bring supersymmetry into the Standard Model (SM)
- Higgs boson$\rightarrow$ Higgs Multiplet, h^0, H^0, $H^{\pm}$, A^0
- Higgsinos and gauginos mix to form charginos and neutralinos, $\tilde{\chi}^{\pm}_{i=1,2}$, $\tilde{\chi}^{0}_{i=1,2,3,4}$

R-Parity

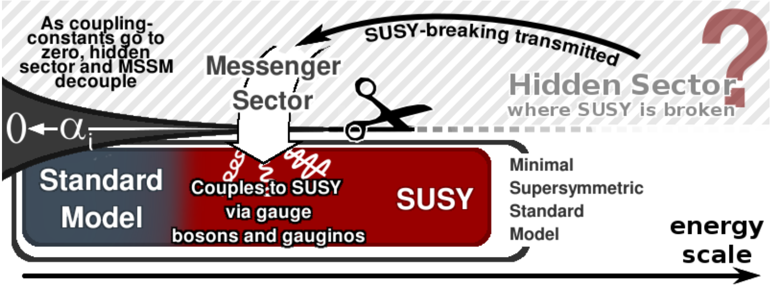
- Sparticles provide channels for proton decay (right top)
- $\lambda_{\text{proton}} > 10^{32}$ s, channels must be surpressed
- Sparticles get -1, SM particles get 1, multiplicative
- Results in Lightest Supersymmetric Particle (LSP)
- If weakly-interacting $\rightarrow E_{\mathrm{T}}^{\mathrm{miss}}$
- Bonus: LSP potentially Dark Matter candidate







General Gauge Mediation (GGM)



Wino co-NLSPs:

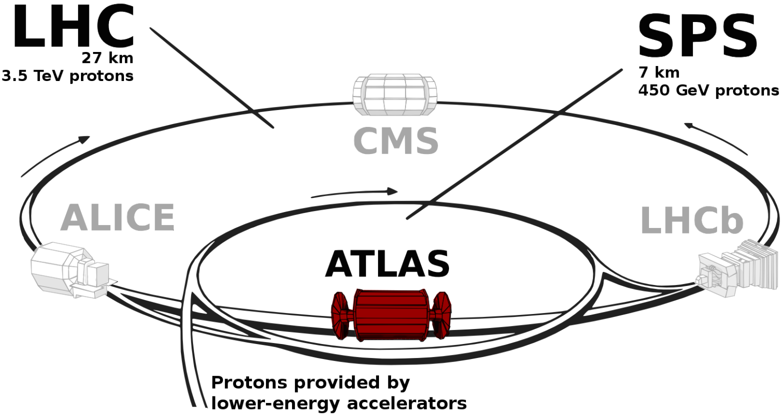
- $|m_2| \ll \mu$, $|m_2| < |m_1|$
- NLSP $\rightarrow \tilde{W}^0$ (wino)
- Charged wino, $\tilde{W}^{\pm}$, almost mass degenerate, effectively co-NLSPs
- $\tilde{W}^0 \rightarrow Z\tilde{G}$, $\tilde{W}^0 \rightarrow \gamma\tilde{G}$ and $\tilde{W}^{\pm} \rightarrow W^{\pm}\tilde{G}$

Z-rich Higgsino NLSP:

- $|\mu| \ll |m_1|,|m_2|$
- NLSP $\rightarrow \tilde{h}$
- Branching ratios for $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$ prominent

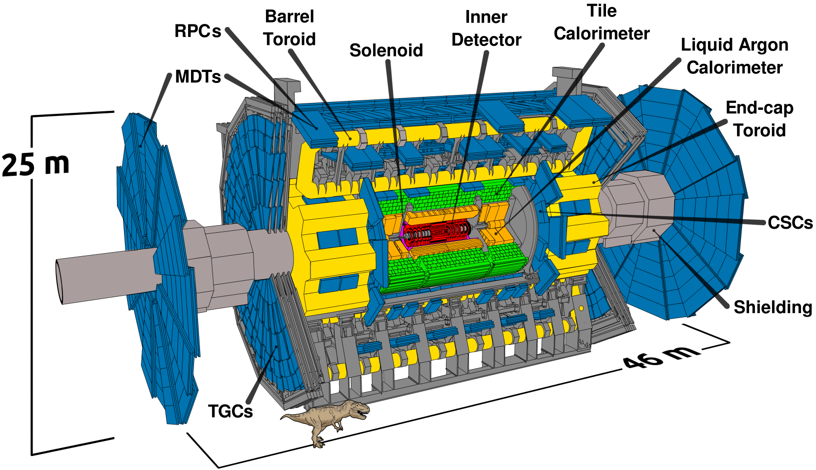
The prevalence of Z and W decays makes GGM intereresting from a multilepton analysis perspective

The CERN Accelerator Complex



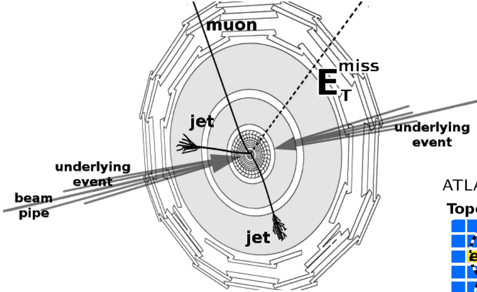
- Designed for $\sqrt{s} = 14$ TeV energy & $L = 10^{34}$ cm^{-2}s^{-1}
- 2011 operated at $\sqrt{s} = 7$ TeV CMS energy
- 2011 peak luminosity: $3.65 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Delivered 5.61 fb^{-1} of collisions in 2011

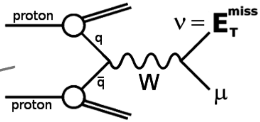
The ATLAS Detector

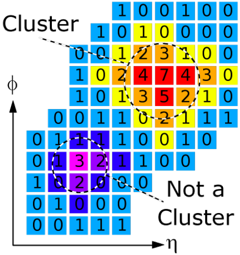


- Signal is defined by muons and electrons $\rightarrow$ measured using much of the ATLAS sub-systems
- Also, $E_{\mathrm{T}}^{\mathrm{miss}}$ calls on every major subcomponent $\rightarrow$ next slide...

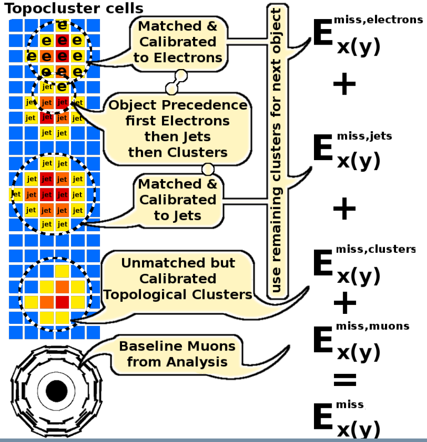
What is E_T^{miss} (missing transverse momentum/energy)







ATLAS E_T^{miss} Scheme:



Dataset

- 2.06 fb^{-1} of data used
- A good-runs-list is applied to our events, vetoing any event flagged as having detector problems during data taking and integrated luminosity used reflects this

Period	μ (pp/crossing)	$\int \mathcal{L}dt$ [pb^{-1}]	Dates	E_{T}^{e} [GeV] trigger	p_{T}^{μ} [GeV] trigger
B,D	5.9 ± 1.3	175	22 March — 28 April	20	18
E-H	5.6 ± 1.2	863	30 April — 28 June	20	18
I	6.1 ± 1.5	307	13 July — 29 July	20	18
J	7.2 ± 1.8	214	30 July — 4 August	20	18
K	7.3 ± 1.9	503	4 August — 22 August	22	18

μ in this case is the average number of visible interactions per bunch crossing

Object Selections

Muons:

- Require combination of ID and MS measurements or
- ID and energy in calorimeter
- p_{T} >10 GeV
- $|\eta| < 2.4$
- Signal muons are required to be isolated from other momentum tracks

Electrons:

- Reconstructed from combined track and calorimeter cluster
- E_{T} >10 GeV
- $|n_{cl}| < 2.47$
- Signal electrons are required to be isolated from other energy deposits

Jets:

- p_{T} >20 GeV
- $|\eta| < 2.8$

Drell-Yan Rejection:

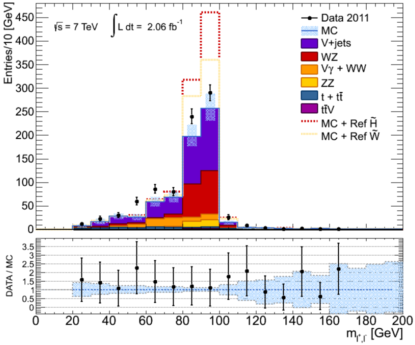
- Reject leptons with $M_{\ell^+\ell^-} < 20$ GeV

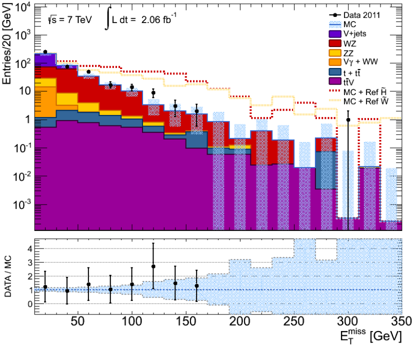
Signal Region

- $N_{\text{lepton}} = 3$, for signal leptons,
- $|m_{\ell^+\ell^-} - m_Z| < 10$ GeV, for any same-flavor, opposite-charge lepton pair,
- $E_T^{\text{miss}} > 50$ GeV.

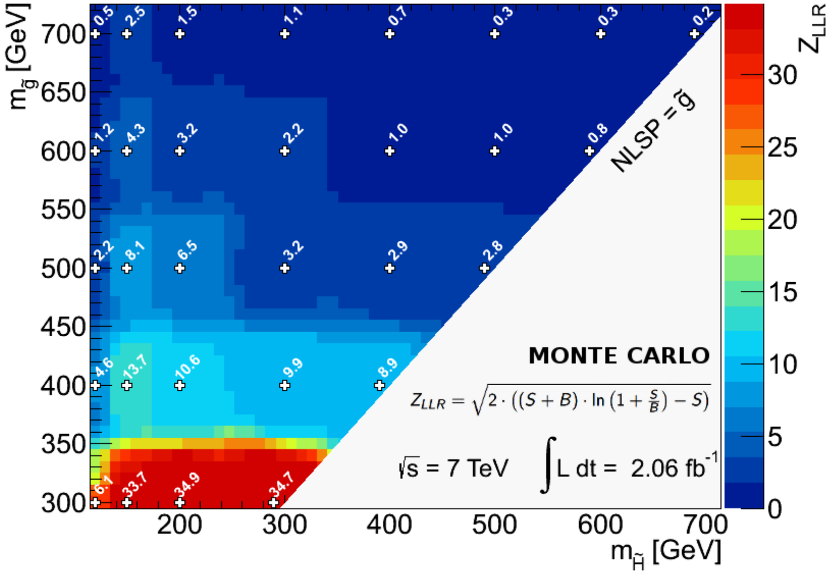
In a hadron collider, three leptons is a clean signal with little hadronic background

Good chance that anything new will stand out

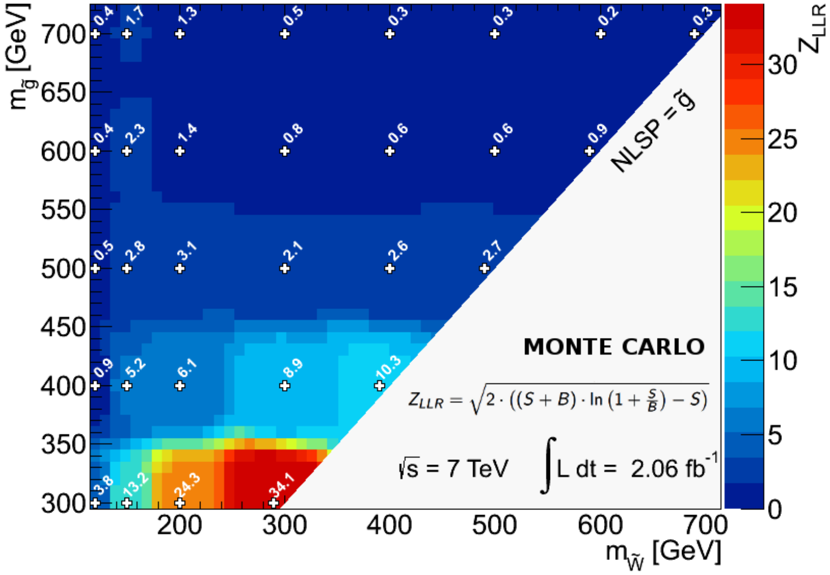




Sensitivity — Higgsino Grid



Sensitivity — Wino Grid



Irreducible Backgrounds — i.e., "real"

WZ, ZZ, and $t\bar{t}V$ (for V $= Z$ or W) have three real leptons

Contribution estimated with MC

Reducible Backgrounds — i.e., "fake"

Includes single-t, $t\bar{t}$, WW, $V\gamma$, and V + jets

$$\begin{pmatrix} N_{\mathrm{SSS}} \\ N_{\mathrm{SS\not{S}}} \\ N_{\mathrm{S\not{S}S}} \\ N_{\mathrm{S\not{S}\not{S}}} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\epsilon_2^c & \epsilon_1 f_2^c & f_1\epsilon_2^c & f_1 f_2^c \\ \epsilon_1^c\epsilon_2 & \epsilon_1^c f_2 & f_1^c\epsilon_2 & f_1^c f_2 \\ \epsilon_1^c\epsilon_2^c & \epsilon_1^c f_2^c & f_1^c\epsilon_2^c & f_1^c f_2^c \end{pmatrix} \cdot \begin{pmatrix} N_{RRR} \\ N_{RRF} \\ N_{RFR} \\ N_{RFF} \end{pmatrix}$$

- S is isolated lepton, $\not{S}$ fails isolation
- ϵ_i is the real efficiency, $\epsilon_i^c = 1 - \epsilon_i$
- f_i is the fake rate, $f_i^c = 1 - f_i$

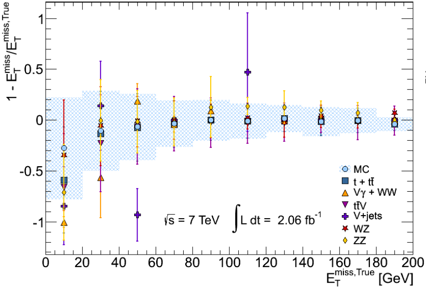
Invert matrix and use:

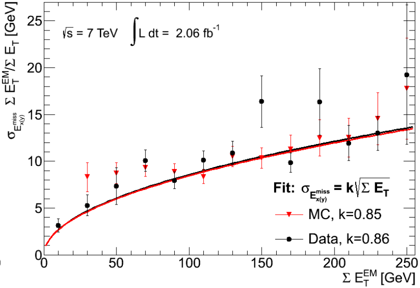
$$N_{\mathrm{RRF/RFR/RFF \to SSS}} = \epsilon_1 f_2 \cdot N_{\mathrm{RRF}} + f_1\epsilon_2 \cdot N_{\mathrm{RFR}} + f_1 f_2 \cdot N_{\mathrm{RFF}}$$

to estimate the reducible background

Control Region	$t\bar{t}V$	ZZ	WZ	Reducible Background	Total Background	Data
Low-$E_{\mathrm{T}}^{\mathrm{miss}}$	1.4±0.6	6.7±1.8	61.2±15.0	55.9±35.2	125.2±38.3	122
high-$E_{\mathrm{T}}^{\mathrm{miss}}$	0.7±0.6	0.03±0.04	0.4±0.2	13.5±8.7	14.7±8.7	12

E_T^{miss} is important to this analysis; thus an effort is made to ensure it is well-behaved





Left, E_T^{miss} linearity:

- Examined in MC
- $= (E_T^{\mathrm{miss,True}} - E_T^{\mathrm{miss}})/E_T^{\mathrm{miss,True}}$
- Require $N_\ell = 3$

Right, $\sigma_{E_T^{\mathrm{miss}}}$ vs ΣE_T

- Require $N_\ell = 3$
- E_x^{miss} & E_y^{miss} is binned in terms of ΣE_T^{EM}; fit with Gaussian
- Resolution scaled by $\Sigma E_T^{\mathrm{EM}}/\Sigma E_T$

MC Systematics:

	$t\bar{t}V$	ZZ	WZ	Total
Nominal	2.7	3.4	58.4	64.5
Statistical	±0.1	±0.4	±2.7	±2.7
JES	±0.1	±0.2	±0.2	±0.3
JER	±0.1	±0.0	±0.5	±0.5
EES	±0.0	±0.0	±0.8	±0.8
EER	±0.0	±0.0	±0.1	±0.1
MID	±0.1	±0.0	±1.1	±1.1
MMS	±0.1	±0.0	±1.3	±1.3
ESF	±0.1	±0.1	±2.0	±2.0
MSF	±0.0	±0.0	±0.5	±0.5
Trigger	±0.0	±0.0	±0.2	±0.2
Btag	±0.0	±0.0	±0.0	±0.0
Pileup	±0.0	±0.1	±0.2	±0.2
LArhole	±0.0	±0.1	±0.0	±0.1
PDF	—	±0.6	±8.9	±9.0
Cross Section	±2.1	±0.2	±4.090	±4.6
TOTAL	±2.1	±0.8	±10.5	±11.0

Reducible Backgrounds:

- Fake rate uncertainty: 0.4-45%
- Fake-rate scale factors uncertainty: 30-50% $\oplus$ 10% $\oplus$ 10%
- Process Fraction: 50-200%

Signal Grid Systematics:

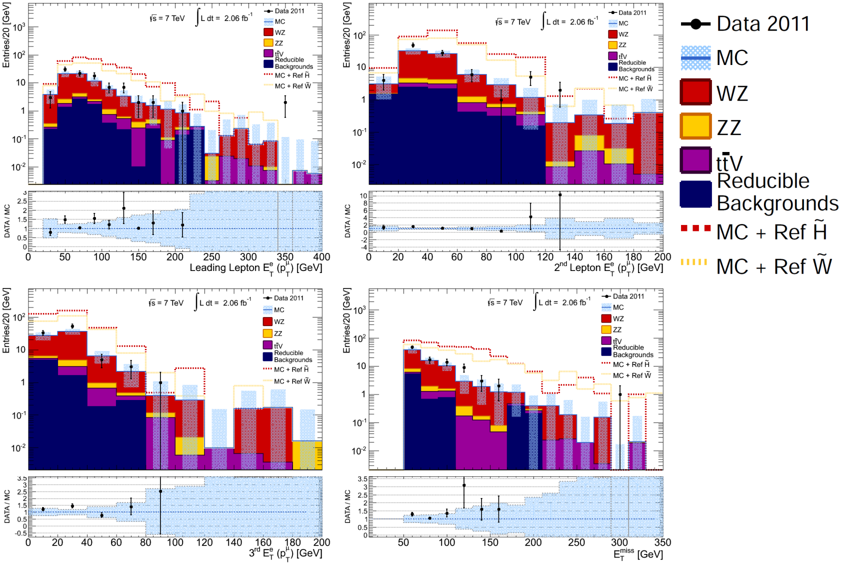
- Use MSTW 2008 NLO & CTEQ6.6M for scale & PDF uncertainties
- Set envelope $\sigma_{max} = \max(\mathrm{CTEQ}, \mathrm{MSTW})$ and $\sigma_{min} = \min(\mathrm{CTEQ}, \mathrm{MSTW})$
- $\sigma_{\mathrm{NLO}} = \frac{1}{2}\cdot(\sigma_{\mathrm{max}} + \sigma_{\mathrm{min}}) \pm \frac{1}{2}\cdot(\sigma_{\mathrm{max}} - \sigma_{\mathrm{min}})$
- Higgsino Grid $\sim$ 10%, Wino Grid $\sim$ 15%

Observed Events in Data

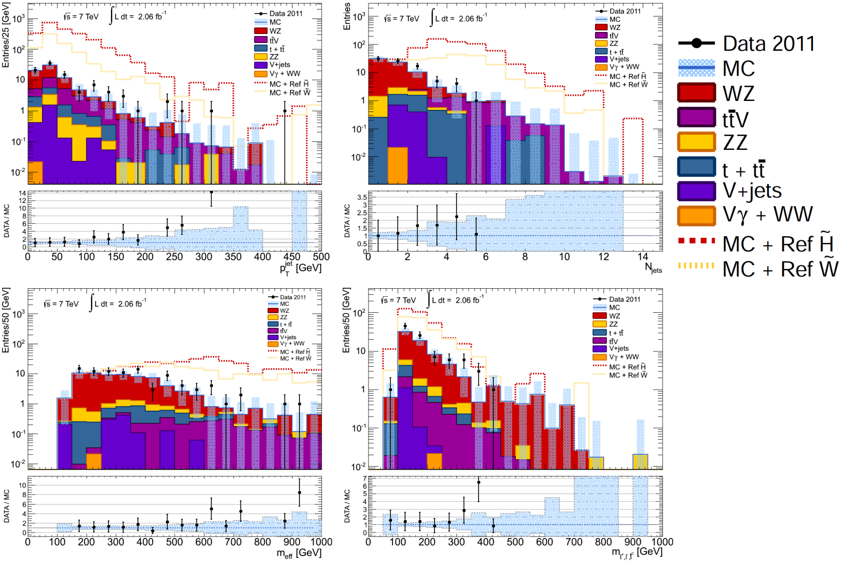
$t\bar{t}$	ZZ	WZ	Reducible Background	Total Background	Data
2.7 ± 2.1	3.4 ± 0.8	58 ± 11	7.5 ± 3.9	72 ± 12	95

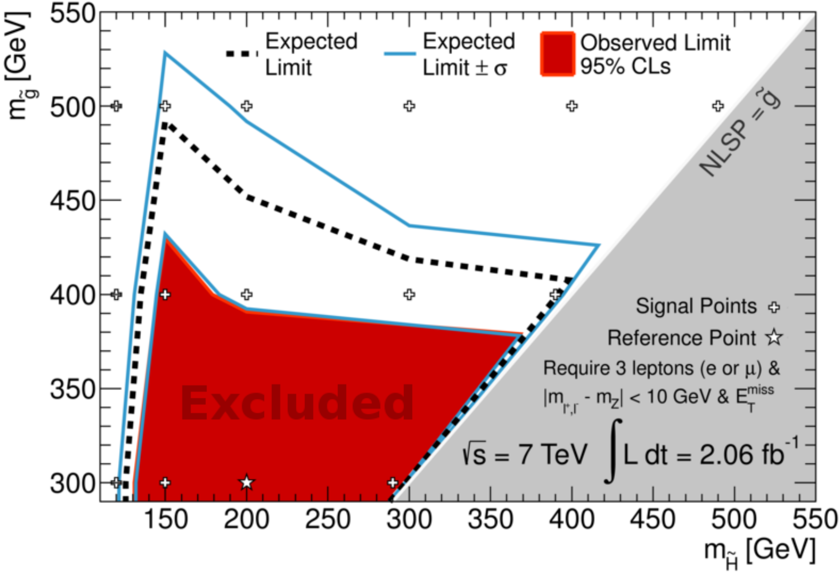
- p-value of 0.06 (1.6σ) using the CL_s method
- Any model which contributes more than 49.1 events in excess of the SM background is excluded at the 95% confidence level (CL) (expected limit 29.0 events)
- Limit of 23.8 fb on the visible cross section at the 95% confidence level (CL) (14.1 fb expected)

Observed Data Distributions

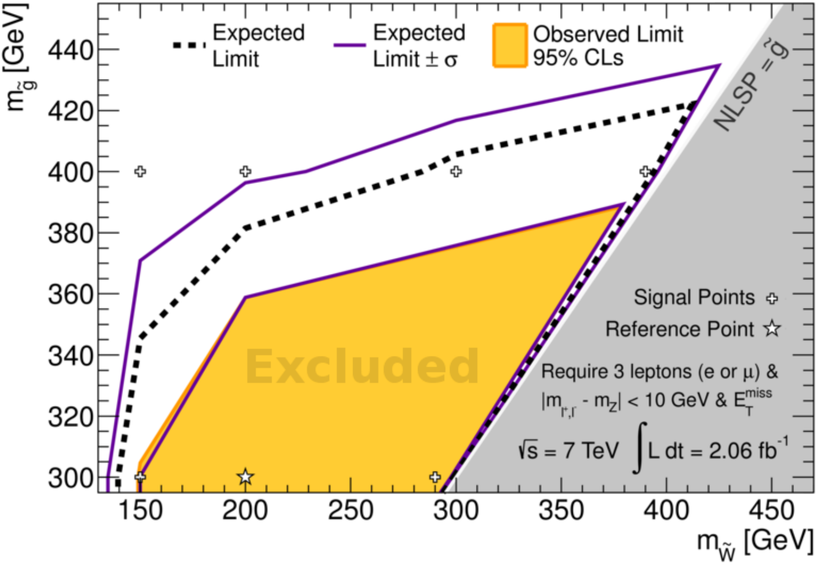


Observed Data Distributions



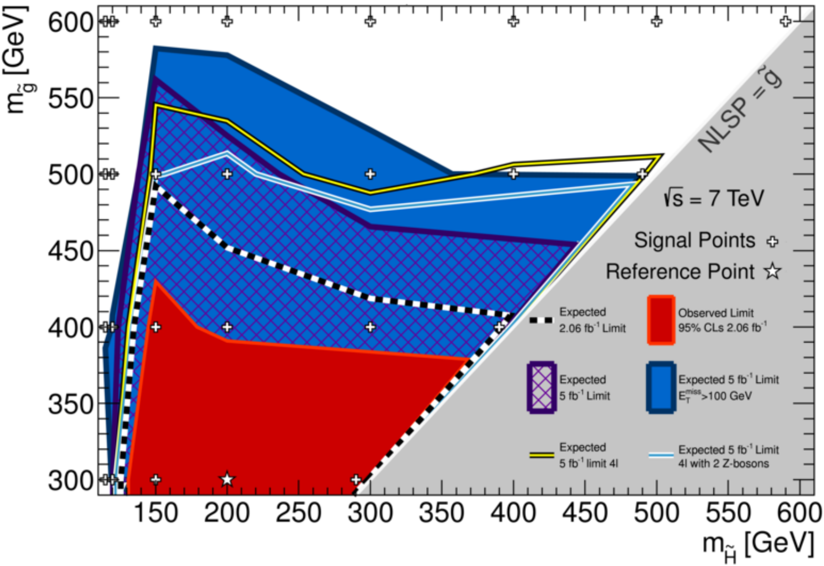

Expected Limit
Expected Limit ± σ
Observed Limit 95% CLs
NLSP = g̃
Signal Points
Reference Point
Require 3 leptons (e or μ) &
$|m_{l^+,l^-} - m_Z| < 10$ GeV & E_T^{miss}
$\sqrt{s}$ = 7 TeV $\int L\,dt$ = 2.06 fb^{-1}
Excluded
$m_{\tilde{g}}$ [GeV]
$m_{\tilde{H}}$ [GeV]
550
500
450
400
350
300
150
200
250
300
350
400
450
500
550

GGM Interpretation of Results — Wino Grid



Future Studies — Higgsino Grid

- 2011 total dataset ~ 5 fb^{-1}
- Next slide looks at exclusion potential for this expanded dataset
- Also look at alternative selections:
  - Extending the $E_{\mathrm{T}}^{\mathrm{miss}}$ selection to $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV (keep three-lepton and Z requirements)
  - Change three-lepton selection to ≥ 4 leptons ($E_{\mathrm{T}}^{\mathrm{miss}}$ & Z the same)
  - Change three-lepton selection to $\geq$ leptons and require 2 Zs from leptons ($E_{\mathrm{T}}^{\mathrm{miss}}$ the same)



600
550
500
450
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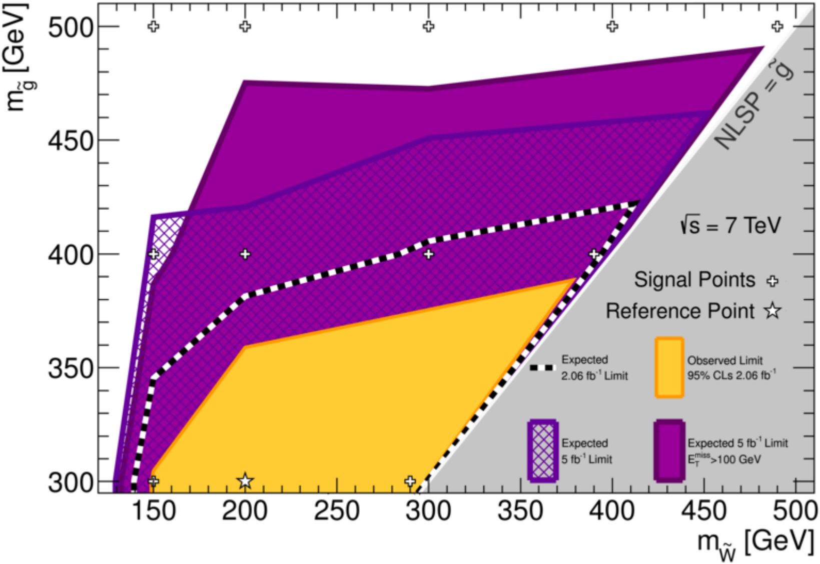
350
300
$m_{\tilde{g}}$ [GeV]
150
200
250
300
350
400
450
500
550
600
$m_{\tilde{H}}$ [GeV]
NLSP = $\tilde{g}$
$\sqrt{s}$ = 7 TeV
Signal Points
Reference Point
Expected 2.06 fb^{-1} Limit
Observed Limit 95% CLs 2.06 fb^{-1}
Expected 5 fb^{-1} Limit
Expected 5 fb^{-1} Limit E_T^{miss}>100 GeV
Expected 5 fb^{-1} limit 4l
Expected 5 fb^{-1} Limit 4l with 2 Z-bosons

Future Studies — Wino Grid

- 2011 total dataset $\sim 5\ \mathrm{fb}^{-1}$
- Next slide looks at exclusion potential for this expanded dataset
- Also look at alternative selection:
  - Extend the $E_{\mathrm{T}}^{\mathrm{miss}}$ selection to $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV (keep three-lepton and Z requirements)
  - A ≥ 4 lepton selection was found to reduce the wino grid event yields to nothing


$m_{\tilde{g}}$ [GeV]
500
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250
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350
400
450
500
$m_{\tilde{W}}$ [GeV]
NLSP = $\tilde{g}$
$\sqrt{s}$ = 7 TeV
Signal Points
Reference Point
Expected 2.06 fb^{-1} Limit
Observed Limit 95% CLs 2.06 fb^{-1}
Expected 5 fb^{-1} Limit
Expected 5 fb^{-1} Limit E_T^{miss}>100 GeV

Conclusion

- I presented a supersymmetric search for events with large values of $E_{\mathrm{T}}^{\mathrm{miss}}$ and three leptons, further requiring that two of the leptons form a same-flavor, opposite-sign pair with an invariant mass within 10 GeV of the Z mass
- 95 events observed in data and 72 ± 12 were expected
- Upper limit of 23.8 fb was set at 95% confidence level on the visible cross section for processes beyond the standard model which result in this signature
- Interpetation of this upper limit was performed using two models from GGM supersymmetry; one model in which the NLSP is a Z-rich higgsino and another model featuring wino co-NLSPs
- These exclusion intervals confirm existing interpretations of prior searches at the ATLAS detector

Back-Up Slides

General Gauge Mediation (GGM)

Gauge Mediated Supersymmetry Breaking (GMSB):

- SUSY is broken in a hidden sector, communicated to the MSSM sector by a messenger sector that couples to the gauge bosons
- Gauginos couple directly, generate $m_i = \frac{\alpha_i \Lambda}{4\pi}$
- Sfermions do not couple to messenger sector directly, require two loops giving mass-sqared contribution, $m^2 \propto (\alpha\Lambda)^2$
- For $\lambda \sim \mathcal{O}(100\ \mathrm{TeV})$, sparticle masses are $\sim \mathcal{O}(1\ \ \mathrm{TeV})$
- Sfermions masses only depend on gauge quantum numbers $\rightarrow$ degenerate
- Degeneracy prevents SUSY contribution to Flavor-Changing Neutral Currents, which depend on sfermion mass splittings
- LSP tends toward the gravitino in these models

General Gauge Mediation:

- Generic framework for GMSB models
- As $\alpha_i \rightarrow 0$, theory decouples to MSSM and hidden sector, messenger inbetween
- Information needed from hidden sector (due to strong coupling) are parameterized
- Modified mass relationship preserves scale and degeneracy, but doesn't force color-states to high mass
- LSP is the gravitino; makes the Next-to-LSP (NLSP) the interesting particle
- The MSSM's 105 parameters are reduced to:
  - m_1, U(1) gaugino mass
  - m_2, SU(2) gaugino mass
  - $m_{\tilde{g}}$, gluino mass
  - μ, SUSY Higgs mass parameter
  - tan β, ratio of SUSY Higgs vacuum-expectation values
  - $c\tau_{\mathrm{NLSP}}$, characteristic NLSP decay range, determined by the scale of supersymmetry breaking

GGM Models

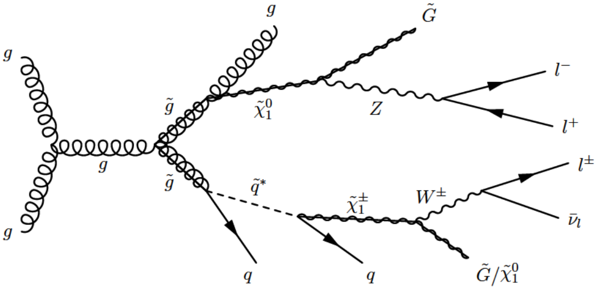
Wino co-NLSPs:

- $|m_2| \ll \mu$, $|m_2| < |m_1|$
- NLSP $\to \tilde{W}^0$ (wino)
- Charged wino, $\tilde{W}^{\pm}$, almost mass degenerate, effectively co-NLSPs
- $\tilde{W}^0 \to Z\tilde{G}$, $\tilde{W}^0 \to \gamma\tilde{G}$ and $\tilde{W}^{\pm} \to W^{\pm}\tilde{G}$
- Grid runs over $300 < m_{\tilde{g}} < 1000$ GeV and $120 < m_{\tilde{W}} < 990$ GeV
- 2 lepton filter applied; for $m_{\tilde{W}} = 120$ GeV, $Z \to \ell^+\ell^-$ filter applied

Z-rich Higgsino NLSP:

- $|\mu| \ll |m_1|,|m_2|$
- NLSP $\to \tilde{h}$
- Branching ratios for $\tilde{\chi}_1^0 \to Z\tilde{G}$ prominent
- $M_1 = M_2 = 1$ TeV, $\tan\beta$ =1.5, and $c\tau_{NLSP}$ =0.1 mm
- Grid runs over $300 < m_{\tilde{g}} < 1000$ GeV and $110 < m_{\tilde{H}} < 990$ GeV
- $Z \to \ell^+\ell^-$ filter applied, 19% efficiency

The GGM grids were produced with PYTHIA 6.423 with mass spectra calculated using SUSPECT 2.41 and SDECAY 1.3
Next-to-Leading-Order (NLO) calculated using Prospino 2.1
Next-to-Leading-Log (NLL) cross section for $\tilde{g}\tilde{g}$-production calculated using NLL_FAST



Object Selections

Electrons:

- electrons identified using shower shape, hadronic leakage, and ID hits ("medium" electrons)
- $E_{\mathrm{T}} > 10$ GeV
- $|n_{cl}| < 2.47$
- Electrons vetoed if pass through LAr dead cell
- if $1.37 < |n_{cl}| < 1.52$, $E_{\mathrm{T}} > 15\ GeV$
- MC is resolution smeared to match data
- data energy scale is calibrated to match $Z/J/\psi$-candle measurements
- Signal Electrons: $\sum_{\Delta R<0.2} E_{\mathrm{T}}/E_{\mathrm{T}^e} < 0.1$ and require tightened track & cluster criteria

Muons:

- Require combination of ID track and MS track or
- ID track matching MS segments, calorimeter deposits
- $p_{\mathrm{T}} > 10$ GeV
- $|\eta| < 2.4$
- Require 1 pixel hit, and 6 SCT hits
- TRT requirements, for $n = n_{TRT}^{hits} + n_{TRT}^{outliers}$:
  - if $|\eta| < 1.9$, require $n > 5$ and $n_{TRT}^{outliers} < 0.9n$
  - if $|\eta| \geq 1.9$ and $n > 5$ require $n_{TRT}^{outliers} < 0.9n$
- MC resolution smeared to match data
- Signal Muons: $\sum_{\Delta R<0.2} p_{\mathrm{T}}^{\mathrm{tracks}} < 1.8$ GeV

Jets:

- Anti-k_{T}, $\Delta R - 0.4$, EMJES scale
- $p_{\mathrm{T}} > 20$ GeV
- $|\eta| < 2.8$

Overlap Removal:

- if $\Delta R_{jet,electron} < 0.2$, select electron
- if $\Delta R_{jet,lepton} < 0.4$, select jet
- if $\Delta R_{muon,electron} < 0.1$, both muon & electron rejected

Drell-Yan:

- Reject leptons with $M_{\ell+\ell-} < 20$ GeV

Missing Transverse Momentum:

- $E_{\mathrm{T}}^{\mathrm{miss}}$ recipe: $E_{x(y)}^{\mathrm{miss}} = E_{x(y)}^{\mathrm{miss,e}} + E_{x(y)}^{\mathrm{miss,jets}} + E_{x(y)}^{\mathrm{miss,cl}} + E_{x(y)}^{\mathrm{miss,\mu}}$
- Correction for electron-jet overlap applied; if cluster energy sum is 110% of electron energy, spills over to jets
- Check for: $|\vec{E}_T^{\mathrm{miss,jets}} + \sum_{jets} \vec{p}_T^{jet}|/E_T^{\mathrm{miss,e}} \leq 1$
- Fix: $E_{x(y)}^{\mathrm{miss,jets}} = -\frac{e}{h} \cdot E_{x(y)}^{\mathrm{miss,e}} - \sum_{jets} \vec{p}_T^{jet}$

Event Handling

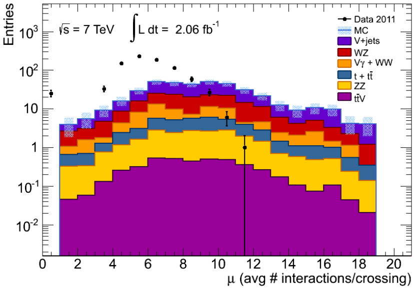
- Data Triggers:
  - Triggers change as luminosity forced them to pre-scale
  - EF_e20_medium — calorimeter seeded, $E_{\mathrm{T}} > 20$ GeV
  - EF_e22_medium — calorimeter seeded, $E_{\mathrm{T}} > 22$ GeV
  - EF_mu18 — requires ID/MS muon $p_{\mathrm{T}} > 18$ GeV
  - EF_mu18_medium — requires ID/MS muon $p_{\mathrm{T}} > 18$ GeV Seeded by L1 MU11 trigger instead of L1 MU10 (lower frequency)

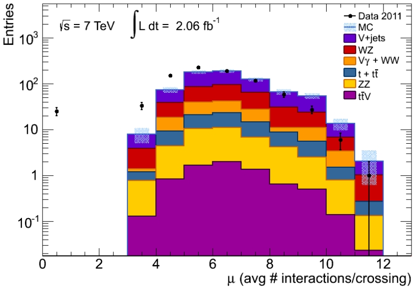
  Also require that a lepton be matched to the trigger object $\Delta R < 0.15$ and be in the plateau, $p_{\mathrm{T}} > 25$ (20) GeV for electrons (muons)
  MC is not triggered; instead each event is scaled by a trigger efficiency determined from the leptons in the event
- Require the primary vertex has $\geq$5 tracks
- If an event has a jet that meets certain criteria associated with calorimeter energy spikes, noise, and non-collision backgrounds, the event is vetoed
- LAr-hole Veto: For 41.9% of the dataset, an electronic failure caused a dead region in the LAr calorimeter, $-0.1 < \eta < 1.5$ and $-0.9 < \phi < -0.5$; data events in this period are vetoed if an electron passes through, or if a jet is estimated to leave more than 40 GeV in the region; a proportionate amount of MC also receives this treatment
- Events showing excessive noise in LAr are vetoed
- Events with $|d_0^{PV}| \geq 0.2$ mm or $|z_0^{PV}| \geq 1.0$ mm for a muon are vetoed (cosmics)
- Events with badly measured muons, $\frac{\sigma_{q/p}}{|q/p|} \leq 0.2$, are vetoed

MC corrections:

- Reconstruction efficiencies: events are scaled to correct the reconstruction efficiency in MC to that seen in data, based on the number, $E_{\mathrm{T}}/p_{\mathrm{T}}$, and η of the leptons
- *b*-tagging: events are scaled to match the MC *b*-tagging efficiency to that seen in data
- Pile-up: the MC was generated with a pile-up distribution different from data; MC events are re-weighted by the μ to match that seen in data

Pile-Up Re-weighting





Background Estimation

Irreducible: A SM contribution is considered “irreducible” if it produces three “real” leptons.
This includes diboson (WZ, ZZ) and $t\bar{t}V$ (for $V = Z, W$).
The contribution of these backgrounds is estimated using MC

Reducible: A background is deemed “reducible” if it includes at least one “fake” electron or muon
A lepton produced in a semi-leptonic decay of a heavy-flavor quark or a photon conversion mis-identified as an electron
The reducible background includes single-t, $t\bar{t}$ production, WW, and V produced with jets and photons
A matrix method similar is used to estimate these backgrounds
Except for internal conversions of photons mis-identified as a signal muon, which makes use of a re-weighting technique

To measure the internal conversion to muons:

- All object selections and event cleaning is applied, as is the $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV selection
- Take ratio of trilepton events satisfying $m_Z - m_{\ell^+\ell^-\ell^\pm}| < 10$ GeV over dilepton events with $m_Z - m_{\ell^+\ell^-}| < 10$ GeV
- This is then applied in the signal region to estimate the internal conversion faking muons rate, which gives a total of 0.7$\pm$0.1$\pm$0.7 events

Matrix Method

- We assume leading lepton is real (99% true)

$$\begin{pmatrix} N_{SSS} \\ N_{SS\not{S}} \\ N_{S\not{S}S} \\ N_{S\not{S}\not{S}} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\epsilon_2^c & \epsilon_1 f_2^c & f_1\epsilon_2^c & f_1 f_2^c \\ \epsilon_1^c\epsilon_2 & \epsilon_1^c f_2 & f_1^c\epsilon_2 & f_1^c f_2 \\ \epsilon_1^c\epsilon_2^c & \epsilon_1^c f_2^c & f_1^c\epsilon_2^c & f_1^c f_2^c \end{pmatrix} \cdot \begin{pmatrix} N_{RRR} \\ N_{RRF} \\ N_{RFR} \\ N_{RFF} \end{pmatrix}$$

- S is a signal lepton, $\not{S}$ fails signal selection
- ϵ_i is the real identification efficiency, $\epsilon_i^c = 1 - \epsilon_i$
- f_i is the fake rate, $f_i^c = 1 - f_i$
- Invert matrix and use
  $N_{\mathrm{RRF/RFR/RFF} \rightarrow \mathrm{SSS}} = \epsilon_1 f_2 \cdot N_{\mathrm{RRF}} + f_1 \epsilon_2 \cdot N_{\mathrm{RFR}} + f_1 f_2 \cdot N_{\mathrm{RFF}}$
  to estimate the reducible background
- ϵ_i is measured using tag-and-probe on the Z-candle
- f_i is measured in MC and scaled to data based on low-$E_{\mathrm{T}}^{\mathrm{miss}}$ control region, and depends on whether the lepton comes from heavy flavor or a photon conversion, and from top versus Z backgrounds, and the relative contribution of each background

The background estimation is tested in two control regions, 1) a low-$E_{\mathrm{T}}^{\mathrm{miss}}$ region with $30 < E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV and 2) a high-$E_{\mathrm{T}}^{\mathrm{miss}}$ control region with $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and a veto on same-flavor, opposite-charge pairs:

Control Region	$t\bar{t}V$	ZZ	WZ	Reducible Background	Total Background	Data
Low-$E_{\mathrm{T}}^{\mathrm{miss}}$	1.4 ± 0.6	6.7 ± 1.8	61.2 ± 15.0	55.9 ± 35.2	125.2 ± 38.3	122
high-$E_{\mathrm{T}}^{\mathrm{miss}}$	0.7 ± 0.6	0.03 ± 0.04	0.4 ± 0.2	13.5 ± 8.7	14.7 ± 8.7	12

Systematics

On MC:

	$t\bar{t}V$	ZZ	WZ	Total
Nominal	2.7	3.4	58.4	64.5
Statistical	± 0.1	± 0.4	± 2.7	± 2.7
JES	± 0.1	± 0.2	± 0.2	± 0.3
JER	± 0.1	± 0.0	± 0.5	± 0.5
EES	± 0.0	± 0.0	± 0.8	± 0.8
EER	± 0.0	± 0.0	± 0.1	± 0.1
MID	± 0.1	± 0.0	± 1.1	± 1.1
MMS	± 0.1	± 0.0	± 1.3	± 1.3
ESF	± 0.1	± 0.1	± 2.0	± 2.0
MSF	± 0.0	± 0.0	± 0.5	± 0.5
Trigger	± 0.0	± 0.0	± 0.2	± 0.2
Btag	± 0.0	± 0.0	± 0.0	± 0.0
Pileup	± 0.0	± 0.1	± 0.2	± 0.2
LArhole	± 0.0	± 0.1	± 0.0	± 0.1
PDF	—	± 0.6	± 8.9	± 9.0
Cross Section	± 2.1	± 0.2	± 4.1	± 4.6
TOTAL	± 2.1	± 0.8	± 10.5	± 11.0

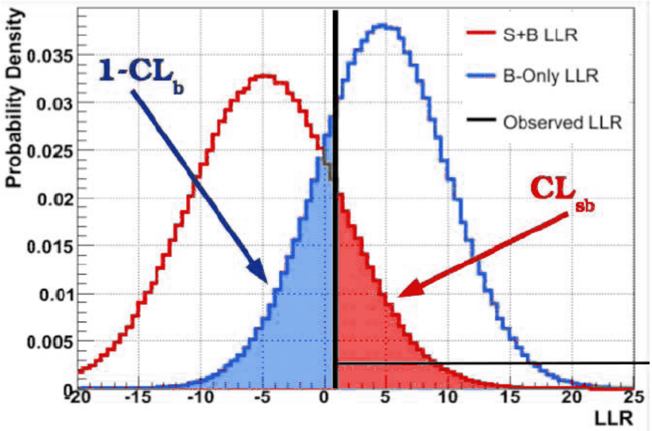
On reducible backgrounds:

- Fake rate — are measured in both low- and high-$E_{\mathrm{T}}^{\mathrm{miss}}$ regions, but the low-$E_{\mathrm{T}}^{\mathrm{miss}}$ region is used (higher statistics); the difference is used as a systematic and gives 0.4-35%, but is as high as 82% for heavy flavor electrons from $V + \mathrm{jets}$
- Fake-rate scale factors — estimated by varying the Z-mass window (30-50%); for heavy flavor also take difference between p_{T} fit and any variation in η (10%); a 10% systematic due to differences in MC shower shapes is also added
- Process fraction — The actual contribution due to each background is unknown, so the fake rates are varied by the same systematics as the irreducible backgrounds and give an estimate of 50% in low-$E_{\mathrm{T}}^{\mathrm{miss}}$ region and 50-200% in high-$E_{\mathrm{T}}^{\mathrm{miss}}$ region.

Signal Systematics:

- Use MSTW2008NLO for PDF and scale uncertainties and CTEQ6.6M for scale, PDF, and α_S uncertainties
- Set envelope $\sigma_{max} = \max(\mathrm{CTEQ}, \mathrm{MSTW})$ and $\sigma_{min} = \min(\mathrm{CTEQ}, \mathrm{MSTW})$
- $\sigma_{\mathrm{NLO}} = \frac{1}{2} \cdot (\sigma_{\mathrm{max}} + \sigma_{\mathrm{min}}) \pm \frac{1}{2} \cdot (\sigma_{\mathrm{max}} - \sigma_{\mathrm{min}})$
- Higgsino grid the mean uncertainty is 10% with some regions of the parameter space having an uncertainty as high as 35%
- Wino grid the mean uncertainty is 15% with some regions reaching as high as 44%
- The table of systematics is also applied to signal MC

Statistical Interpretation



Statistical Interpretation

Results interpreted using modified-frequentist approach

- Confidence level of the signal+background hypothesis is normalized to the background-only hypothesis, $\mathrm{CL_s} = \mathrm{CL_{s+b}}/\mathrm{CL_b}$
- Test statistic constructed using:
- Log Likelihood function

  $L(n, \theta^0|\mu, b, \theta) = P(n|\lambda_S(\mu, b, \theta)) \cdot P_{Syst}(\theta^0, \theta)$

  - n is the number of events observed in data,
  - μ is the predicted SUSY signal strength for each test, normalized to unity,
  - b is the estimate of the background contribution,
  - θ represents the systematic uncertainties in the form of nuisance parameters,
  - θ^0 represents the nominal values about which θ is varied.
  - $P(n|\lambda_S(\mu, b, \theta))$ is a Poisson distribution describing the probability of observing n given an expectation generated by $\lambda_S(\mu, b, \theta)$ based on the signal estimate, the background estimate, and systematic uncertainties. $P_{Syst}(\theta^0, \theta)$ is a probability density function composed of the product of unit normal distributions, $G(\theta^0 - \theta)$, for each of the systematic uncertainties accounted for.

- Profile LLR:

  $\Lambda(\mu) \equiv \Lambda(\mu, n, \theta^0) \equiv -2\ln\left(\frac{L(n,\theta^0|\mu,\hat{\hat{b}},\hat{\hat{\theta}})}{L(n,\theta^0|\hat{\mu},\hat{b},\hat{\theta})}\right)$
- maximum of the likelihood occurs at $\hat{\mu}$, $\hat{b}$, $\hat{\theta}$
- For a fixed signal strength, μ, the maximum likelihood is given by $\hat{\hat{b}}$ and $\hat{\hat{\theta}}$
- Pseudo-experiments are used to calculate p-values
- $L(n, \theta^0|\mu, b, \theta)$ is used to make pseudo-measurements to obtain new values of n and θ^0, and then calculate a new value of $\Lambda(\mu)$, called q
- Then integrate over all $q' < q_{\mathrm{nominal}}$ to get p-values for signal hypothesis and SM hypothesis
- For signal, p-values < 0.05 are excluded

$e^+e^-e^\pm$											
Run #	Event #	Flavor	p_T^ℓ [GeV]	m_T [GeV]	$m_{l^+,l^{-1}}$ [GeV]	$m_{l^+,l^{-1},l'^\pm}$ [GeV]	N_{jets}	Jet p_T [GeV]	m_{eff} [GeV]	E_T^{miss} [GeV]	δE_T^{miss} (%)
180164	98593931	$e^-e^+e^+$	71.7, 54.0, 33.4	132.0, 77.3, 56.6	203.3, 86.8	247.0	0		222.0	60.8	1.9
180225	38923591	$e^+e^-e^-$	37.3, 36.1, 15.8	89.5, 1.1, 63.7	89.2, 37.8	108.1	1	56.9	152.1	64.3	9.5
180309	14077706	$e^-e^+e^-$	46.7, 29.1, 16.1	26.2, 89.3, 69.9	102.6, 89.6	150.7	2	46.4, 39.7	175.8	83.9	12.6
182787	56439353	$e^+e^-e^-$	94.8, 22.0, 11.2	129.6, 13.3, 64.8	90.7, 55.5	113.3	1	109.7	223.3	96.4	7.8
183003	5466177	$e^+e^-e^-$	84.7, 27.3, 19.6	64.0, 19.9, 75.2	32.5, 91.9	108.6	1	162.5	206.4	74.6	16.8
183003	61556406	$e^-e^+e^-$	51.5, 44.9, 12.4	52.9, 70.9, 52.6	95.0, 51.0	121.7	2	47.6, 23.4	166.3	57.5	14.8
183129	16288174	$e^-e^+e^-$	80.6, 21.1, 13.2	196.4, 63.6, 80.1	96.9, 23.7	107.5	1	44.8	239.9	124.9	4.9
183426	10151435	$e^-e^+e^+$	63.2, 31.7, 25.6	109.5, 67.7, 78.2	87.1, 65.8	122.9	0		182.9	61.7	0.8
184022	21785917	$e^-e^+e^+$	56.7, 56.4, 12.6	56.0, 7.0, 50.9	86.7, 58.4	116.8	3	71.6, 47.1, 39.1	177.7	52.6	24.3
184022	128414499	$e^-e^+e^+$	89.7, 22.3, 20.7	146.4, 59.2, 13.0	89.5, 84.6	128.5	1	37.6	204.5	71.5	4.3
185644	25257494	$e^+e^-e^-$	139.9, 124.8, 14.7	118.4, 36.7, 92.2	85.6, 101.3	163.0	2	236.1, 125.6	426.0	146.7	14.4
186049	1958828	$e^+e^-e^-$	52.2, 43.9, 43.7	103.5, 87.6, 35.4	159.6, 89.2	264.2	0		193.2	51.3	7.0
186729	243498369	$e^-e^-e^+$	48.9, 34.5, 29.5	133.7, 67.0, 34.7	91.2, 112.1	352.9	4	59.2, 41.1, 29.8, 25.8	215.6	102.6	8.4
186753	3683826	$e^+e^-e^-$	110.4, 62.0, 41.9	73.8, 65.0, 94.6	201.1, 87.4	248.3	2	139.6, 35.0	287.4	72.4	12.4
187219	31582796	$e^-e^+e^+$	41.1, 28.0, 27.9	89.2, 64.9, 83.5	85.7, 65.8	111.6	2	42.7, 33.2	162.0	65.1	3.1
187811	62120095	$e^-e^+e^-$	71.7, 34.6, 29.0	33.4, 62.7, 95.3	256.3, 91.3	290.3	2	107.5, 54.7	236.3	101.0	9.0
186965	28815719	$e^+e^-e^-$	131.0, 42.2, 21.5	257.4, 48.6, 102.4	161.9, 96.3	196.0	0		322.9	128.3	3.5
186965	120508399	$e^+e^+e^-$	83.9, 18.5, 15.5	161.9, 92.4, 6.2	88.1, 33.8	120.2	2	80.3, 31.4	242.1	124.2	6.3
186965	155446128	$e^-e^-e^+$	45.9, 38.0, 36.2	61.8, 89.6, 25.4	84.4, 82.8	126.8	3	154.2, 41.5, 20.4	181.8	62.1	2.5

$e^+e^-\mu^\pm$											
Run #	Event #	Flavor	p_T^ℓ [GeV]	m_T [GeV]	$m_{l^+,l^{-1}}$ [GeV]	$m_{l^+,l^{-1},l'^\pm}$ [GeV]	N_{jets}	Jet p_T [GeV]	$m_{\rm eff}$ [GeV]	$E_T^{\rm miss}$ [GeV]	$\delta E_T^{\rm miss}$ (%)
182456	55533226	$e^-e^+\mu^+$	96.7, 30.4, 18.3	184.8, 103.0, 85.4	85.1	172.0	1	41.4	249.2	102.7	1.6
182486	16677615	$e^-\mu^-e^+$	107.2, 39.7, 38.8	200.6, 38.9, 104.6	88.2	171.7	0		279.8	94.1	6.1
182486	21528951	$e^-\mu^-e^+$	120.8, 17.4, 16.1	202.1, 58.9, 14.2	90.0	113.4	0		239.2	84.6	3.7
182879	19439981	$e^-e^+\mu^-$	52.3, 50.1, 19.0	89.1, 90.0, 52.8	89.8	113.6	0		172.0	50.7	5.1
183021	69425573	$e^-e^+\mu^+$	50.3, 28.6, 26.5	97.2, 43.3, 72.5	90.8	179.7	0		155.6	50.2	3.2
183286	97150217	$e^-\mu^+e^+$	66.5, 39.6, 15.5	40.3, 64.8, 49.0	89.2	139.3	2	124.2, 21.6	189.1	68.2	11.4
183780	108727692	$e^-\mu^-e^+$	89.7, 38.5, 23.4	129.0, 46.7, 45.2	86.9	154.7	0		204.2	52.7	3.0
186169	16345995	$e^-e^+\mu^-$	41.5, 27.2, 11.4	18.9, 74.4, 26.9	82.3	95.0	1	20.3	131.1	51.0	10.5
186216	27680559	$e^-\mu^-e^+$	58.8, 45.5, 22.4	110.4, 95.5, 27.8	90.0	208.6	0		187.0	60.8	2.8
185761	18433702	$e^+\mu^-e^-$	67.0, 20.3, 11.8	129.4, 71.1, 6.4	90.7	105.2	0		162.3	63.2	4.5
185998	4354615	$e^+e^-\mu^+$	83.7, 38.9, 34.2	149.5, 101.9, 1.5	94.3	294.0	2	21.1, 20.6	225.8	66.8	4.3
186729	81190803	$e^-e^+\mu^+$	213.4, 105.5, 35.5	359.0, 254.2, 10.1	91.5	329.5	2	73.9, 64.6	508.8	154.0	4.7
186729	159856729	$e^-\mu^+e^+$	98.0, 19.9, 18.4	145.3, 48.8, 43.5	88.4	108.9	2	39.0, 27.9	195.6	59.3	5.0
186877	21782291	$\mu^-e^+e^-$	51.0, 37.2, 33.0	103.5, 84.8, 30.9	92.4	154.5	4	116.7, 41.4, 22.2, 20.3	174.8	53.4	11.6
186923	59240008	$e^+\mu^-e^-$	110.3, 46.6, 29.6	177.4, 111.6, 34.7	86.4	173.9	1	49.2	271.5	85.2	3.0

Backup —$\mu^+\mu^- e^\pm$

$\mu^+\mu^- e^\pm$											
Run #	Event #	Flavor	p_T^ℓ [GeV]	m_T [GeV]	$m_{l^+,l^{-1}}$ [GeV]	$m_{l^+,l^{-1},l'^\pm}$ [GeV]	N_{jets}	Jet p_T [GeV]	m_{eff} [GeV]	E_T^{miss} [GeV]	δE_T^{miss} (%)
180448	1483181	$\mu^-e^-\mu^+$	46.8, 43.0, 39.6	111.5, 65.6, 70.0	91.1	147.7	5	80.1, 55.9, 46.8, 37.8, 27.4	209.8	80.4	5.8
180139	47529321	$\mu^+\mu^-e^+$	91.6, 30.8, 15.7	151.6, 69.4, 14.7	85.8	119.8	0		203.8	65.7	4.3
180400	1649049	$\mu^+e^+\mu^-$	112.7, 103.6, 67.0	202.9, 55.7, 159.2	93.0	305.6	0		378.1	94.6	1.4
182787	18945920	$\mu^+\mu^-e^-$	46.0, 43.1, 29.6	74.1, 91.8, 65.1	93.2	135.7	0		173.4	54.7	2.6
182787	117824417	$\mu^-e^-\mu^+$	122.1, 37.1, 35.0	223.0, 21.3, 102.9	95.9	192.0	0		297.3	103.2	0.4
183054	25255214	$e^-\mu^+\mu^-$	128.6, 104.6, 83.4	12.3, 189.1, 167.5	82.3	358.6	2	52.8, 20.6	403.4	86.9	2.9
183081	160821752	$\mu^+e^-\mu^-$	179.2, 128.6, 24.7	256.1, 73.6, 96.7	97.6	397.5	0		427.0	94.7	2.5
183407	36412879	$\mu^+\mu^-e^-$	59.0, 36.2, 31.0	110.4, 50.1, 59.5	88.1	135.4	0		178.4	52.1	1.3
183462	137952124	$\mu^-e^-\mu^+$	87.6, 35.5, 31.3	155.8, 78.5, 39.8	91.6	141.7	0		224.2	69.8	1.1
183462	149168776	$\mu^+\mu^-e^-$	52.8, 32.9, 26.0	106.4, 46.8, 75.6	90.9	132.7	0		166.9	55.2	2.2
184130	43351005	$\mu^+\mu^-e^+$	65.7, 28.8, 27.3	113.4, 72.1, 28.8	92.8	158.8	0		176.4	55.5	2.2
183780	40559312	$\mu^+\mu^-e^-$	50.3, 45.5, 33.2	92.9, 83.2, 82.1	90.6	166.4	1	31.0	182.6	53.3	6.9
184169	35750750	$e^+\mu^+\mu^-$	87.8, 77.5, 67.0	141.3, 196.7, 156.5	90.9	335.7	1	21.5	357.7	125.3	1.9
184169	105464632	$\mu^-\mu^+e^-$	54.3, 33.9, 33.7	62.1, 91.0, 92.1	92.1	159.6	3	39.4, 28.8, 21.0	185.3	63.4	6.4
184130	44517484	$\mu^+e^-\mu^-$	59.6, 24.9, 20.9	21.2, 9.2, 65.7	99.1	152.3	1	138.2	157.5	52.5	16.1
183780	49478936	$\mu^+\mu^-e^-$	66.2, 25.8, 23.9	130.7, 0.6, 76.1	87.2	109.4	0		180.7	64.7	1.2
183780	62734339	$\mu^+e^+\mu^-$	81.5, 24.5, 14.9	152.1, 75.6, 70.1	94.1	127.8	2	74.9, 22.0	204.9	84.1	1.5
184072	10617609	$e^+\mu^+\mu^-$	23.1, 20.1, 20.0	75.6, 89.1, 43.2	86.5	117.7	1	91.0	177.1	113.9	6.4
186182	7407118	$\mu^-e^+\mu^+$	140.6, 30.3, 17.5	258.0, 42.1, 14.1	99.1	280.1	0		308.9	120.5	3.3
186169	17499798	$\mu^-\mu^+e^-$	53.4, 35.8, 30.1	47.2, 79.0, 77.6	88.8	136.0	2	44.0, 21.9	171.0	51.8	4.9
186169	60145885	$\mu^+\mu^-e^+$	72.8, 46.2, 31.9	157.5, 96.9, 92.4	89.3	184.9	0		238.7	87.8	1.1
186361	18855850	$\mu^+e^-\mu^-$	346.4, 45.9, 36.8	380.9, 65.7, 120.6	94.1	305.0	1	248.2	534.7	105.9	11.8
186721	30840259	$e^+\mu^-\mu^+$	128.1, 108.1, 60.0	88.7, 213.1, 173.4	91.0	304.8	2	25.3, 23.0	421.3	125.3	7.3
186669	42109584	$\mu^-\mu^+e^-$	54.6, 48.3, 13.7	83.1, 100.5, 53.2	94.4	124.7	0		176.4	59.7	3.9
186934	75059135	$\mu^-e^-\mu^+$	66.2, 40.7, 22.7	111.2, 54.4, 66.3	87.3	153.3	0		185.3	55.7	2.2
187763	61044675	$\mu^+e^+\mu^-$	128.4, 30.3, 23.2	232.9, 48.6, 59.3	91.5	155.5	0		287.2	105.7	0.5
187811	15210356	$\mu^+\mu^-e^-$	72.2, 45.7, 32.6	139.7, 133.7, 14.7	87.5	142.7	1	74.1	253.0	102.5	3.9
186877	126711223	$\mu^-e^-\mu^+$	95.4, 75.9, 30.6	59.2, 86.8, 139.5	100.0	135.9	3	251.5, 26.8, 24.0	365.3	163.4	9.6
186923	10398981	$e^-\mu^-\mu^+$	36.0, 28.8, 18.6	89.7, 39.0, 43.0	89.9	233.7	2	94.4, 20.6	167.3	84.0	8.8
187219	43654572	$\mu^-\mu^+e^-$	46.5, 33.6, 14.8	67.3, 67.8, 52.3	91.1	110.9	3	22.1, 21.5, 21.0	145.9	51.0	9.1

Backup — $\mu^+\mu^-\mu^\pm$

$\mu^+\mu^-\mu^\pm$											
Run #	Event #	Flavor	p_T^ℓ [GeV]	m_T [GeV]	$m_{l^+,l^{-1}}$ [GeV]	$m_{l^+,l^{-1},l'^\pm}$ [GeV]	N_{jets}	Jet p_T [GeV]	$m_{\rm eff}$ [GeV]	$E_T^{\rm miss}$ [GeV]	$\delta E_T^{\rm miss}$ (%)
179739	23068430	$\mu^+\mu^+\mu^-$	73.0, 44.8, 30.6	112.4, 85.6, 36.1	95.0, 41.5	141.3	1	30.0	202.5	54.0	4.6
180124	68526315	$\mu^+\mu^+\mu^-$	62.7, 43.0, 34.5	90.2, 92.3, 54.0	93.7, 73.2	154.7	0		192.0	51.7	1.1
180164	73825441	$\mu^-\mu^+\mu^+$	67.0, 24.6, 13.2	117.2, 7.7, 41.6	90.7, 78.1	124.7	1	20.9	156.7	51.8	6.6
180309	31818991	$\mu^+\mu^-\mu^-$	52.6, 33.8, 27.7	80.3, 36.5, 71.9	81.4, 85.7	123.4	1	73.1	182.2	68.1	7.8
182454	4702311	$\mu^+\mu^-\mu^-$	109.2, 100.5, 53.8	128.5, 88.4, 2.8	57.6, 91.1	131.0	1	315.3	377.3	113.8	12.3
182456	37283247	$\mu^-\mu^+\mu^-$	86.4, 76.2, 30.1	129.3, 130.0, 61.5	88.6, 65.5	120.6	1	145.6	248.2	55.5	13.9
182796	41972295	$\mu^+\mu^+\mu^-$	94.4, 70.9, 34.4	101.5, 66.8, 66.8	113.9, 94.3	248.3	2	67.1, 21.6	251.7	51.9	11.8
183054	21026988	$\mu^+\mu^-\mu^+$	62.4, 36.8, 36.8	137.6, 119.2, 51.0	90.2, 78.1	155.3	1	159.1	271.3	135.4	5.6
183286	53451031	$\mu^+\mu^+\mu^-$	83.5, 29.5, 19.9	115.7, 64.0, 24.4	83.7, 73.7	233.5	1	22.8	183.5	50.5	5.5
183412	2242543	$\mu^-\mu^+\mu^-$	163.8, 29.2, 19.5	251.7, 69.3, 40.2	101.9, 86.7	234.7	1	56.0	309.2	96.8	3.8
182747	112682971	$\mu^+\mu^-\mu^-$	60.1, 53.6, 29.2	111.9, 106.5, 14.5	84.3, 83.6	153.4	1	28.5	195.8	52.9	5.8
182787	34276063	$\mu^-\mu^+\mu^-$	55.0, 41.9, 14.9	158.9, 27.7, 69.1	90.9, 50.7	113.6	1	111.8	234.8	123.0	4.7
182787	103600363	$\mu^-\mu^-\mu^+$	104.2, 31.7, 29.7	7.8, 6.2, 97.3	88.4, 93.5	139.2	4	116.1, 110.6, 34.5, 22.0	299.1	133.5	12.3
184130	35410477	$\mu^+\mu^+\mu^-$	40.4, 25.6, 11.1	106.0, 55.9, 56.4	53.2, 98.6	134.8	1	22.4	150.0	73.0	3.7
184022	43591184	$\mu^-\mu^-\mu^+$	45.0, 18.7, 13.7	115.8, 65.1, 61.5	91.9, 58.5	109.4	0		151.9	74.6	2.1
186049	70818458	$\mu^-\mu^+\mu^-$	94.8, 80.3, 21.3	157.9, 105.2, 65.7	82.3, 100.8	164.1	3	48.0, 30.4, 25.2	269.8	73.4	0.8
186179	5228295	$\mu^-\mu^+\mu^-$	79.2, 41.1, 32.7	119.8, 35.6, 95.4	93.1, 51.7	141.6	4	441.4, 193.0, 58.4, 25.5	245.6	92.6	8.2
186169	47351357	$\mu^-\mu^+\mu^-$	56.3, 32.8, 32.3	101.2, 40.6, 83.8	90.5, 89.1	141.4	0		175.7	54.4	0.6
186216	11067182	$\mu^-\mu^+\mu^-$	57.4, 31.7, 31.2	101.4, 68.6, 79.8	89.1, 27.2	137.9	0		185.2	64.9	5.8
186729	54074612	$\mu^-\mu^+\mu^+$	58.8, 36.4, 11.8	131.5, 85.2, 59.1	90.5, 42.5	124.9	0		186.8	79.8	2.7
186729	175034387	$\mu^-\mu^+\mu^-$	61.4, 43.8, 15.6	94.8, 120.8, 24.8	91.9, 53.7	131.6	1	69.6	205.3	84.6	4.3
186923	146860679	$\mu^-\mu^+\mu^+$	77.4, 37.5, 20.9	128.2, 73.2, 3.1	110.2, 92.6	150.1	0		193.5	57.7	1.5
186965	15778260	$\mu^-\mu^+\mu^+$	63.3, 57.8, 28.4	99.1, 134.1, 69.3	92.2, 102.7	169.9	1	31.4	227.4	77.9	2.1
186965	63620161	$\mu^-\mu^+\mu^-$	45.5, 41.1, 35.6	56.2, 81.6, 85.4	91.4, 40.7	128.8	0		173.5	51.2	2.6
186965	155056482	$\mu^-\mu^-\mu^+$	100.3, 40.6, 14.5	56.7, 90.0, 53.4	92.2, 41.0	322.5	1	92.2	205.6	50.2	7.6
186965	180209937	$\mu^+\mu^-\mu^-$	141.2, 46.1, 18.1	112.6, 97.4, 59.7	280.6, 88.7	297.0	4	56.4, 53.0, 25.3, 23.8	257.0	51.5	3.8
187219	68267656	$\mu^-\mu^-\mu^+$	347.8, 77.3, 36.0	607.8, 23.3, 149.2	95.8, 102.2	423.8	1	286.7	758.3	297.2	1.9
187811	67845541	$\mu^-\mu^+\mu^-$	71.9, 37.6, 37.3	135.4, 91.5, 52.4	88.7, 77.0	182.4	1	23.3	211.5	64.6	2.3
187811	68065554	$\mu^-\mu^+\mu^-$	50.7, 27.6, 17.0	107.2, 38.0, 61.2	87.3, 60.6	170.5	0		152.7	57.4	2.4
187812	11122323	$\mu^-\mu^+\mu^-$	70.9, 59.6, 40.1	107.7, 113.6, 44.1	93.7, 92.2	176.9	0		227.9	57.3	0.9
187763	79698027	$\mu^-\mu^+\mu^+$	73.0, 52.2, 46.9	151.7, 135.9, 70.9	95.5, 168.2	290.2	0		263.0	90.9	1.6

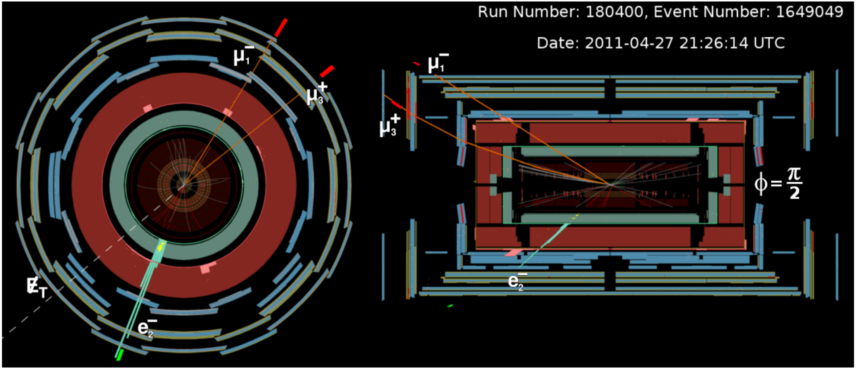


Figure: Event display for Event 1649049 from run 180400. The indices are indicative of lepton p_{T} order. This event is notable for having two leading muons with $p_{\mathrm{T}} > 100$ GeV, 112.7 GeV and 103.6 GeV.

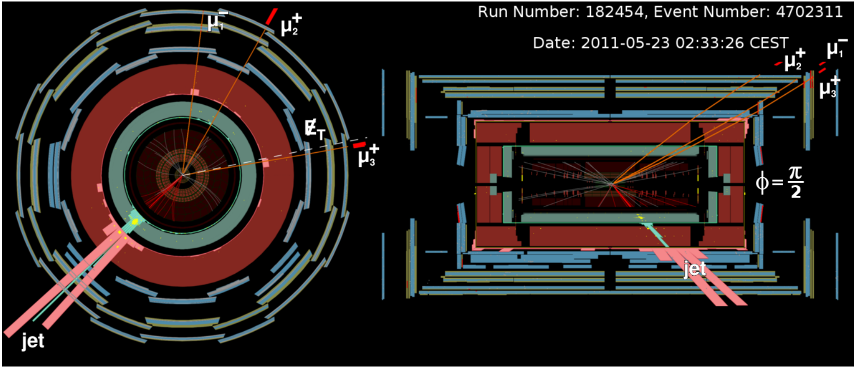


Figure: Event display for Event 4702311 from run 182454. The indices are indicative of lepton p_{T} order. This event is notable for having muons with $p_{\mathrm{T}} = 109.2$ GeV and 100.5 GeV and a jet with $p_{\mathrm{T}} = 315.3$ GeV, as well as $E_{\mathrm{T}}^{\mathrm{miss}} = 113.8$ GeV.

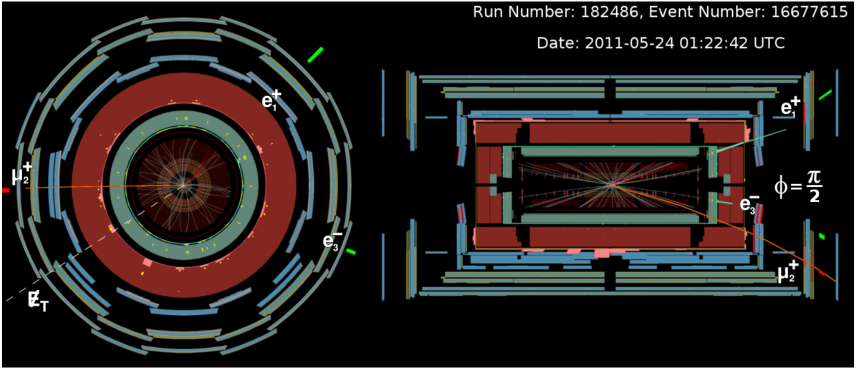


Figure: Event display for Event 16677615 from run 182486. The indices are indicative of lepton p_{T} order. This event is notable for a $p_{\mathrm{T}} = 107.2$ GeV lead-electron and a high transverse mass, $m_{\mathrm{T}} = 200.6$ GeV.

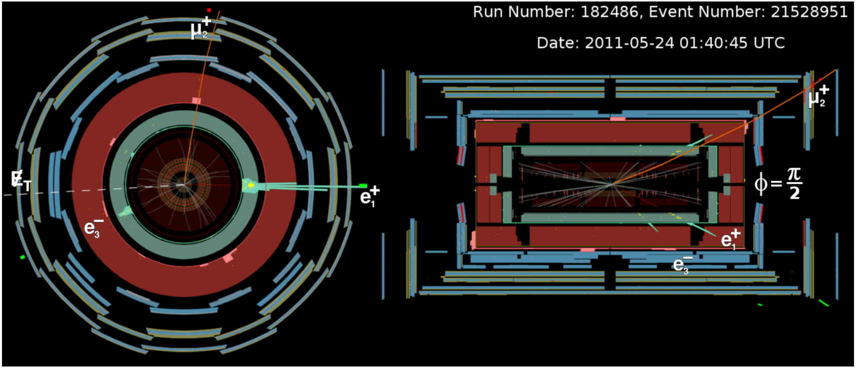


Figure: Event display for Event 21528951 from run 182486. The indices are indicative of lepton p_{T} order. This event is notable for a high-p_{T} lead-electron, $p_{\mathrm{T}} = 120.8$ GeV, and a high transverse mass, $m_{\mathrm{T}} = 202.1$ GeV.

Event Displays...

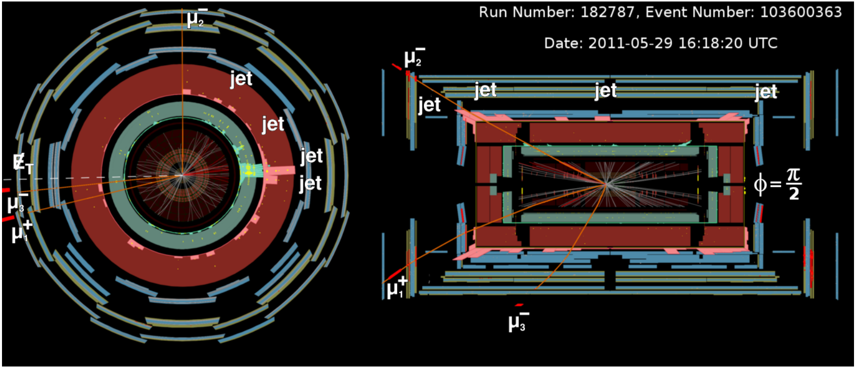


Figure: Event display for Event 103600363 from run 182787. The indices are indicative of lepton p_{T} order. Notable features of this event are the $p_{\mathrm{T}} = 104.2$ GeV muon, as well as the large $E_{\mathrm{T}}^{\mathrm{miss}}$ value of 133.5 GeV. This event also has a relatively high jet multiplicity, with four jets.

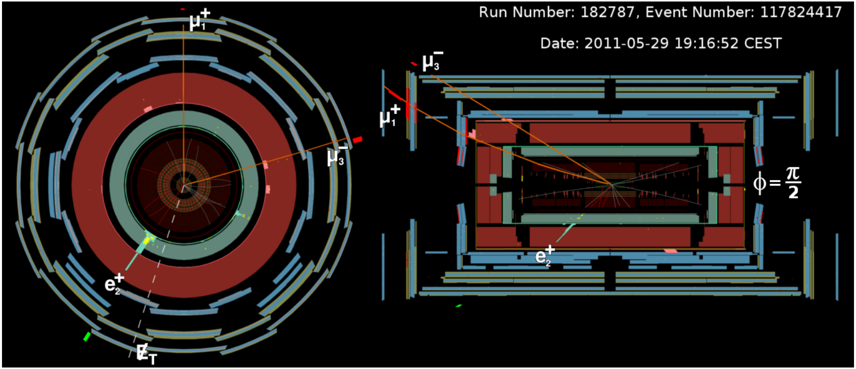


Figure: Event display for Event 117824417 from run 182787. The indices are indicative of lepton p_{T} order. This event is notable for the $p_{\mathrm{T}} = 122.1$ GeV muon and $E_{\mathrm{T}}^{\mathrm{miss}} = 103.2$ GeV.

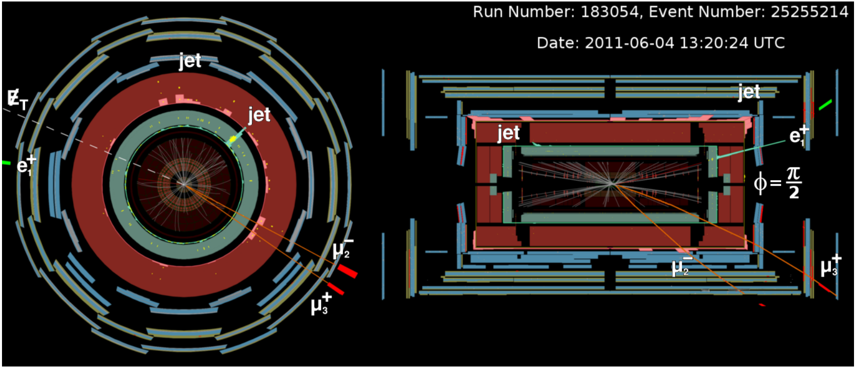


Figure: Event display for Event 25255214 from run 183054. The indices are indicative of lepton p_{T} order. The $p_{\mathrm{T}} = 128.6$ GeV electron and $p_{\mathrm{T}} = 104.6$ GeV muon make this event notable. Additionally, it has a trilepton invariant mass of 358.6 GeV.

Event Displays...

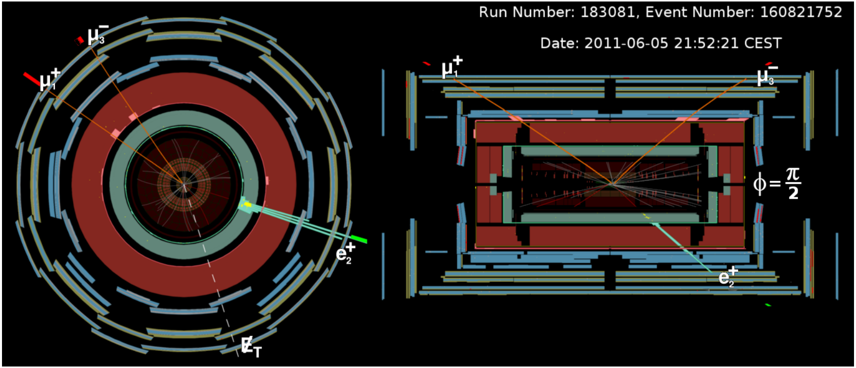


Figure: Event display for Event 160821752 from run 183081. The indices are indicative of lepton p_{T} order. This event is notable for featuring a $p_{\mathrm{T}} = 179.2$ GeV muon, a $p_{\mathrm{T}} = 128.6$ GeV electron, and a trilepton mass of 397.5 GeV.

Event Displays...

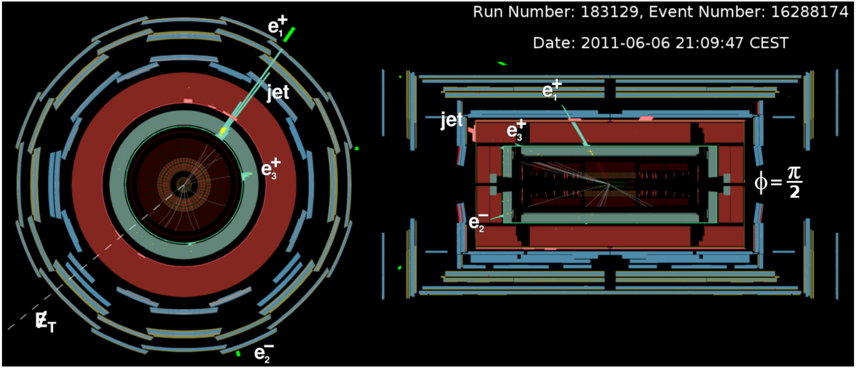


Figure: Event display for Event 16288174 from run 183129. The indices are indicative of lepton p_{T} order. This event has 124.9 GeV of $E_{\mathrm{T}}^{\mathrm{miss}}$.

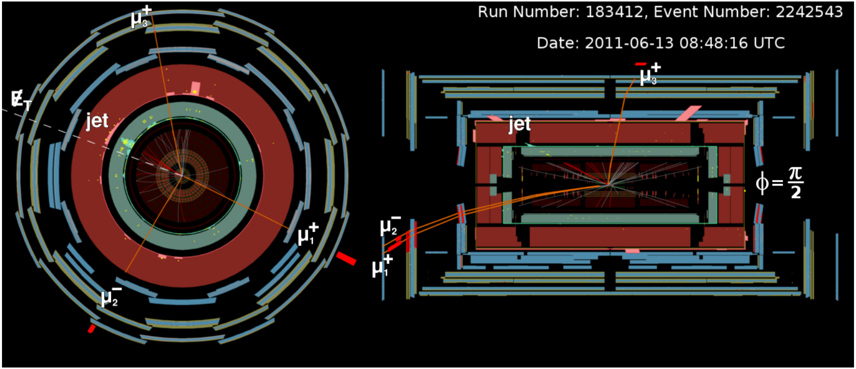


Figure: Event display for Event 2242543 from run 183412. The indices are indicative of lepton p_{T} order. This event is notable for its $p_{\mathrm{T}} = 163.8$ GeV lead muon.

Event Displays...

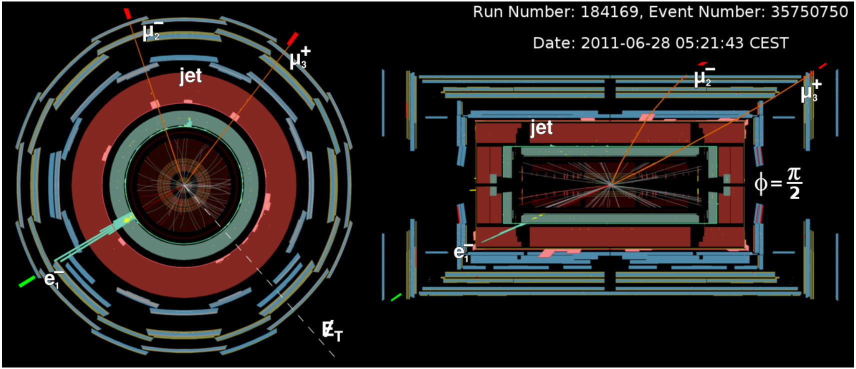


Figure: Event display for Event 35750750 from run 184169. The indices are indicative of lepton p_{T} order. The $E_{\mathrm{T}}^{\mathrm{miss}} = 125.3$ GeV makes this event remarkable.

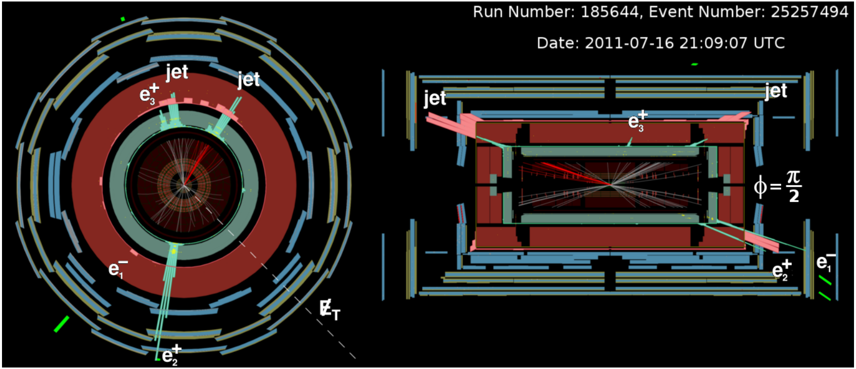


Figure: Event display for Event 25257494 from run 185644. The indices are indicative of lepton p_{T} order. This event has a sizable amount of $E_{\mathrm{T}}^{\mathrm{miss}}$, 146.7 GeV, and leading electrons with $p_{\mathrm{T}} = 139.9$ and 124.8 GeV.

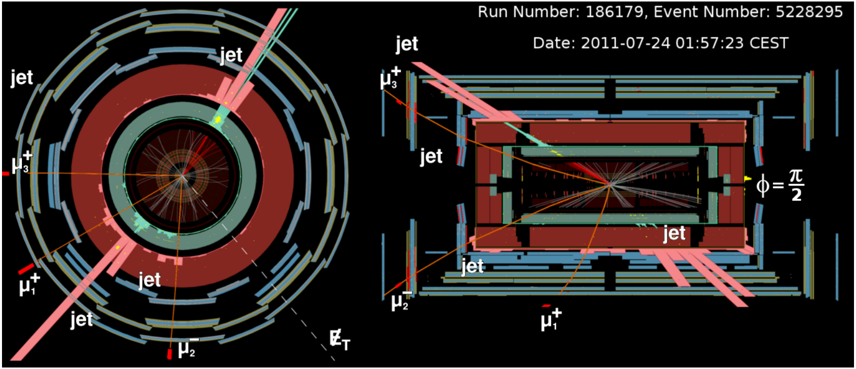


Figure: Event display for Event 5228295 from run 186179. The indices are indicative of lepton p_{T} order. This event is notable for having a jet with $p_{\mathrm{T}} = 441.4$ GeV, on top of a relatively large jet multiplicity.

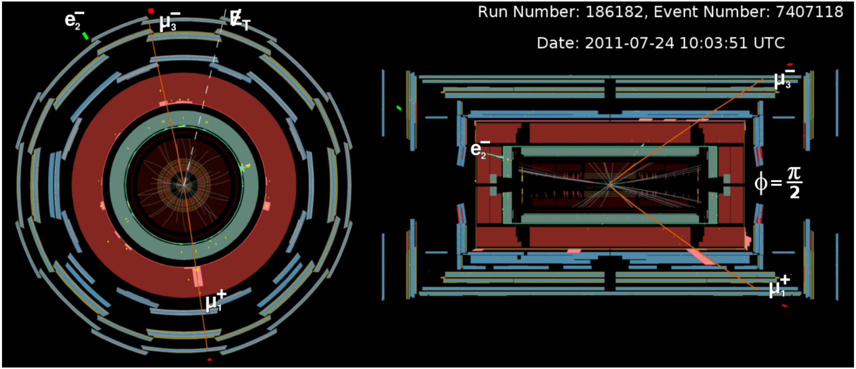


Figure: Event display for Event 7407118 from run 186182. The indices are indicative of lepton p_T order. This event is notable for having a $p_T = 140.6$ GeV muon and a trilepton mass of 280.1 GeV.

Event Displays...

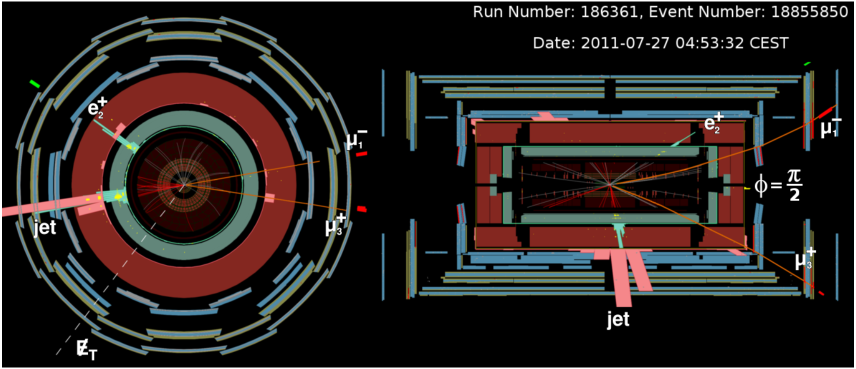


Figure: Event display for Event 18855850 from run 186361. The indices are indicative of lepton p_{T} order. This event is remarkable by virtue of including a $p_{\mathrm{T}} = 346.4$ Gev muon and having a trilepton mass of 305.0 GeV.

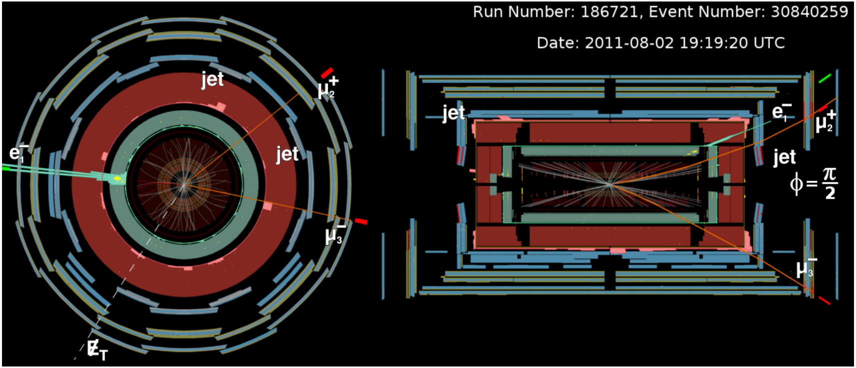


Figure: Event display for Event 30840259 from run 186721. The indices are indicative of lepton p_{T} order. This event is notable for having a $p_{\mathrm{T}} = 128.1$ GeV electron and a $p_{\mathrm{T}} = 108.1$ GeV muon. It also has a 304.8 GeV trileptonic mass and 125.3 GeV of $E_{\mathrm{T}}^{\mathrm{miss}}$.

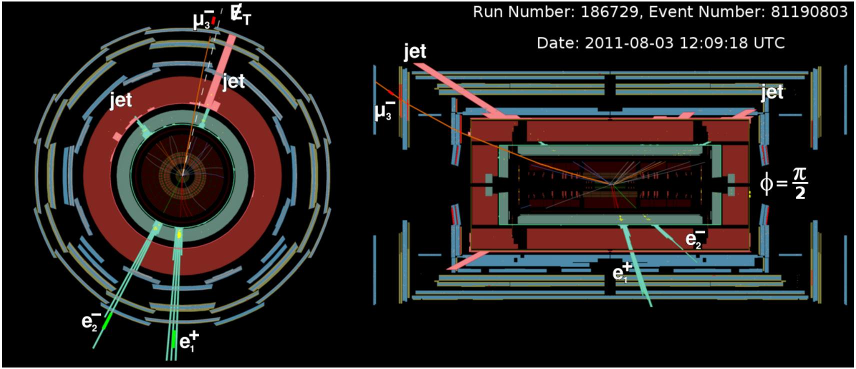


Figure: Event display for Event 81190803 from run 186729. The indices are indicative of lepton p_T order. This event is notable for its $p_T = 213.4$ GeV lead electron and $E_T^{miss} = 154.0$ GeV. It also has $m_{\ell^+\ell^-,\ell'^{\pm}} = 329.5$ GeV.

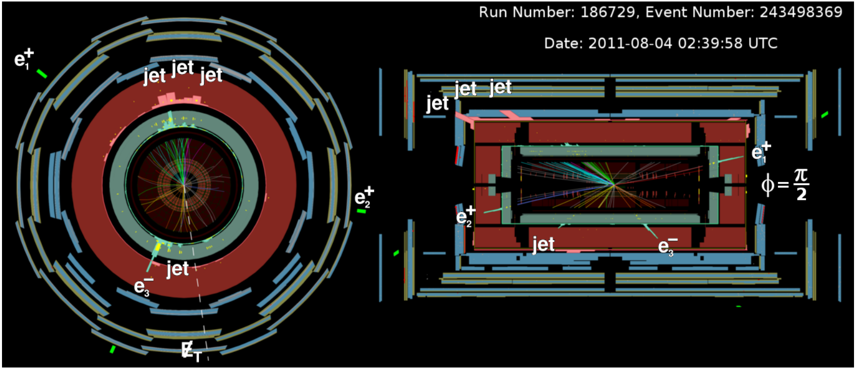


Figure: Event display for Event 243498369 from run 186729. The indices are indicative of lepton p_{T} order. This event features a large trilepton mass, $m_{\ell^+\ell^-,\ell'^\pm} = 352.9$ GeV and large $E_{\mathrm{T}}^{\mathrm{miss}}$, 102.6 GeV.

Event Displays...

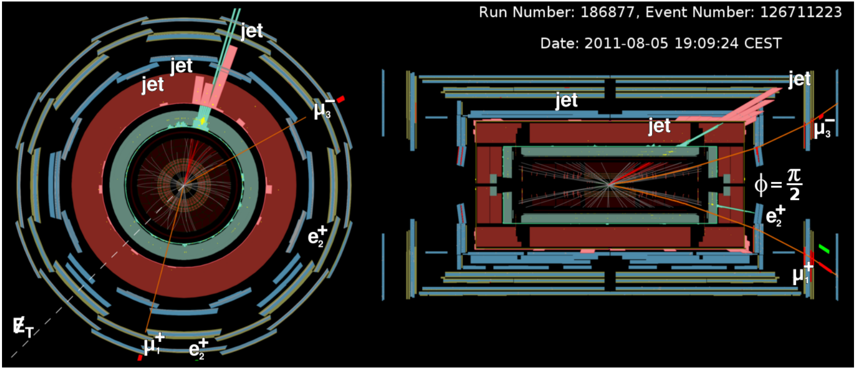


Figure: Event display for Event 126711223 from run 186877. The indices are indicative of lepton p_{T} order. This event has a jet with $p_{\mathrm{T}} = 251.5$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} = 163.4$ GeV.

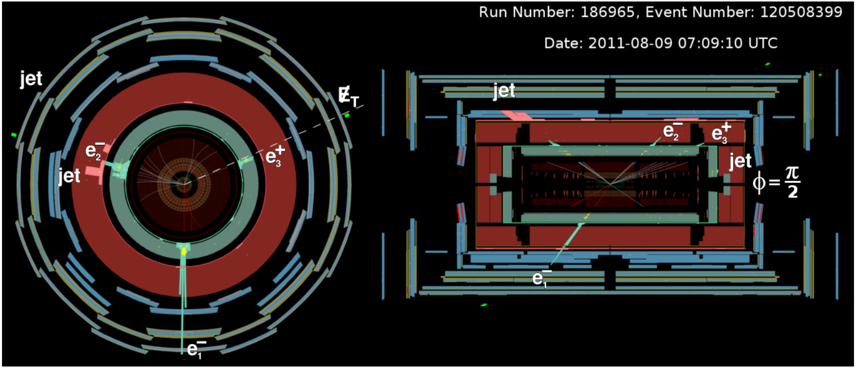


Figure: Event display for Event 120508399 from run 186965. The indices are indicative of lepton p_{T} order. This event contains 124.2 GeV of $E_{\mathrm{T}}^{\mathrm{miss}}$.

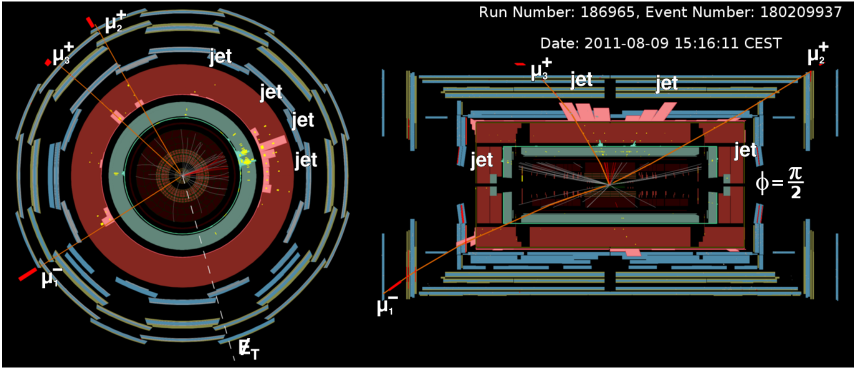


Figure: Event display for Event 180209937 from run 186965. The indices are indicative of lepton p_{T} order. This event is notable for having a $p_{\mathrm{T}} = 141.2$ GeV muon and $m_{\ell^+\ell^-,\ell'^\pm} = 297.0$ GeV.

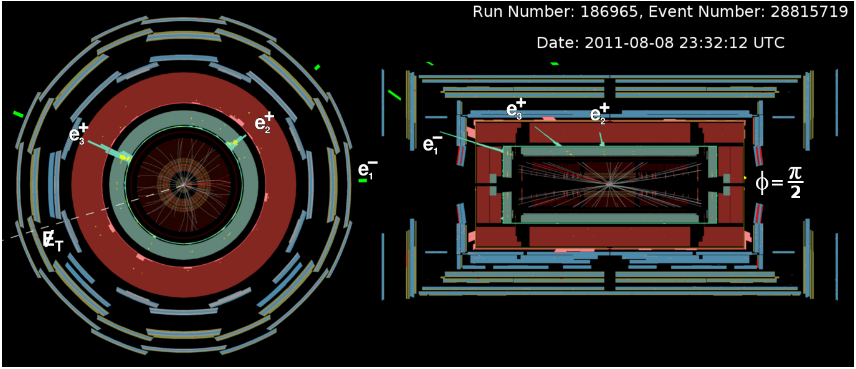


Figure: Event display for Event 28815719 from run 186965. The indices are indicative of lepton p_{T} order. This is another event with a large amount of $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}} = 128.3$ GeV and an electron with $p_{\mathrm{T}} = 131.0$ GeV.

Event Displays...

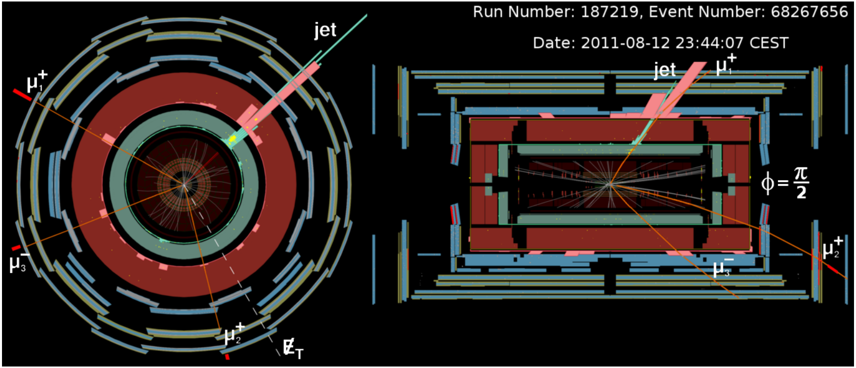


Figure: Event display for Event 68267656 from run 187219. The indices are indicative of lepton p_{T} order. This event is notable for having a $p_{\mathrm{T}} = 347.8$ GeV muon, as well as a $p_{\mathrm{T}} = 286.7$ GeV jet and $E_{\mathrm{T}}^{\mathrm{miss}} = 297.2$ GeV. The trilepton mass is 423.8 GeV. This event has been super-sized.

Event Displays...

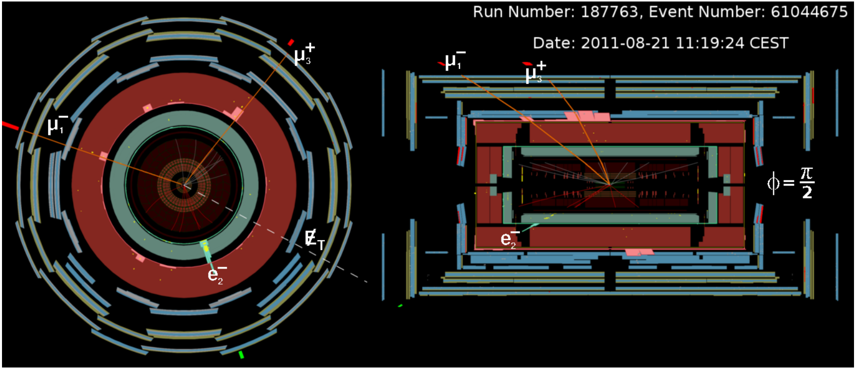


Figure: Event display for Event 61044675 from run 187763. The indices are indicative of lepton p_{T} order. This event is notable for having a $p_{\mathrm{T}} = 128.4$ GeV muon.