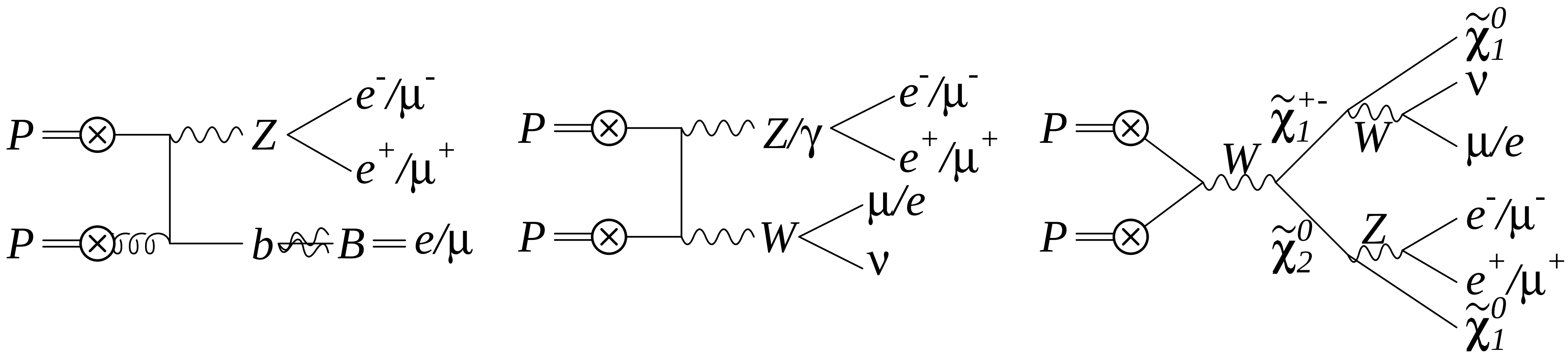
July 16 - 22, 2009

Trilepton Production

SUSY Signals and SM Backgrounds



Edmond Berger

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Based on E. Berger and Z. Sullivan, Phys Rev D **78**, 034030 (2008) and **74**, 033008 (2006)

Outline

1. Several (1, 2, ... N) *isolated* leptons are a signature for New Physics
2. Many Standard Model sources of isolated leptons
3. New: Isolated leptons from heavy flavor (b, c) decays and cuts that can be used to deal with this background
4. Dileptons and the Search for Higgs Bosons: Summary Berger and Sullivan, Phys Rev D **74**, 033008 (2006)
   - $H \rightarrow WW \rightarrow l^+ l^-$ plus missing energy vs. leptons from Standard Model Sources at the LHC
5. Trileptons and the Search for Supersymmetry
   - $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ ("Golden" SUSY channel) vs. leptons from Standard Model Sources at LHC
6. Conclusions

Isolated leptons from heavy-flavor decays

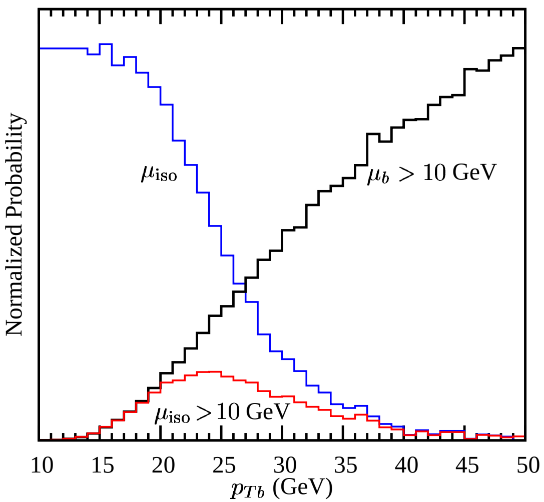
Generic definition of isolation:

- Locate a muon.
- Construct a cone ΔR in rapidity and azimuthal angle space around the track of the muon

Muon is "isolated" if the sum of the transverse energy of all other particles in the cone is less than a defined "isolation energy" $E_{\rm iso} \sim 4$ GeV

More sophisticated specifications are used in practice and in our analysis

Physics of isolated leptons from b decay



Prob. isolated μ w. $p_{T\mu} > 10$ GeV

$= $ Prob. producing muon

$\times$ Prob. B remnants missed

- Muons that pass isolation take substantial fraction of p_{Tb}
- Nearly all isolated muons point back to primary vertex.

C. Wolfe, CDF internal

- Isolation leaves $\sim 7.5 \times 10^{-3}$ μ/b $\gg 10^{-4}$ per light jet

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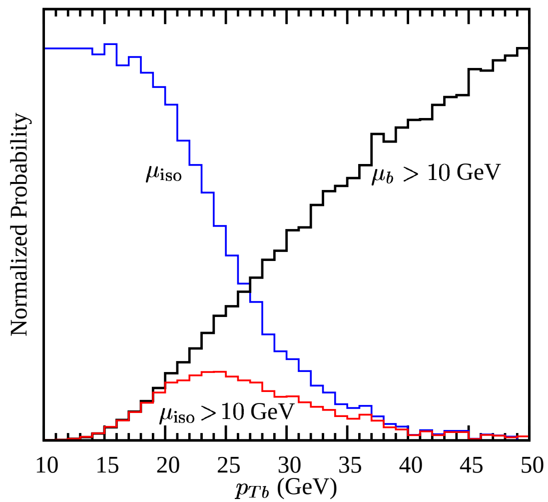

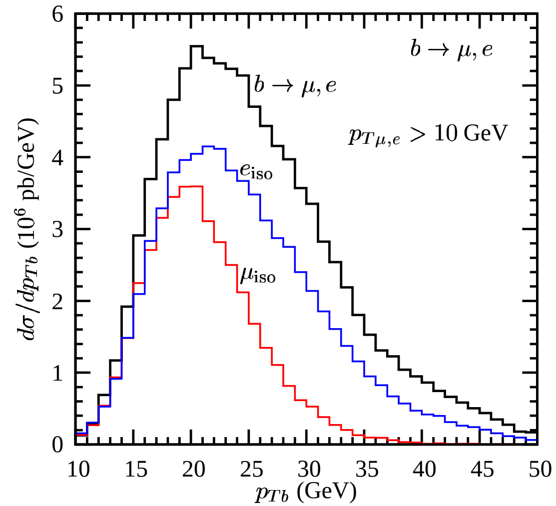

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Fold in $b\bar{b}$ cross section

- A large fraction of events with $b \to \mu/e$ have isolated μ/e
- Long tail that extends to large momentum, but
- $1/2$ of all isolated μ come from b with $p_{Tb} < 20$ GeV.

It is common for analyses to start simulations with $p_{Tb} > 20$ GeV

Limited impact of isolation cuts

For the isolated leptons, our simulations suggest:

- $\sim 1/2$ of the events pass the usual isolation cuts, because the remnant is just outside whatever cone is used for tracking/energy cuts.
- $\sim 1/2$ of the events pass because the lepton took nearly all of the energy. Hence, there is nothing left to reject on.

  These events are not good candidates to reject with impact parameter cuts — they tend to point back to the primary vertex.

It is possible to get factors of 2–3 suppression of the heavy-flavor background by using tighter cuts. Risk is that signal is also suppressed

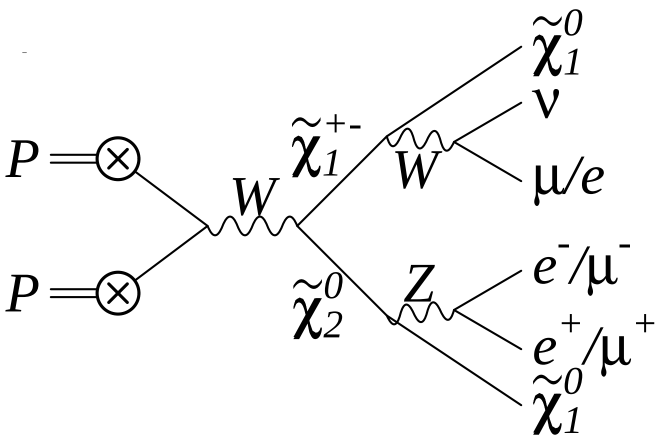
Nature of the problem: More than 0.5% of all produced b and c quarks are observed as isolated leptons AND $\sigma^{b\bar{b}}_{\rm inclusive} \sim 5 \times 10^8$ pb at LHC.

Although the decay leptons are "relatively soft", their associated backgrounds extend well into the signal region of relatively large mass New Physics, e.g . $H \to WW \to l^+ l^- \not{E}_T$ with $M_H \sim 150$ GeV and SUSY $\tilde{\chi}^+_1 \tilde{\chi}^0_2$ for mSUGRA points that exhibit a large trilepton signature.

Trileptons at LHC

SUSY chargino/neutralino production

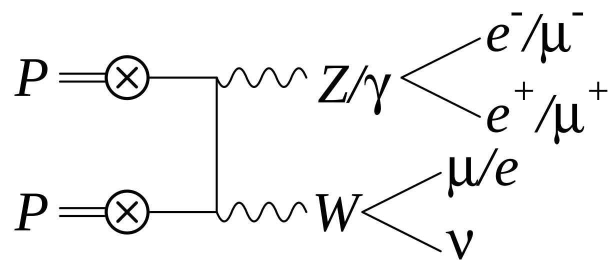
Trileptons at LHC



$\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0 \rightarrow l^+ l^- \, l^{\pm} + \not{E}_T$ is a golden signature of supersymmetry.

CMS and ATLAS have analyses designed to observe this signal.

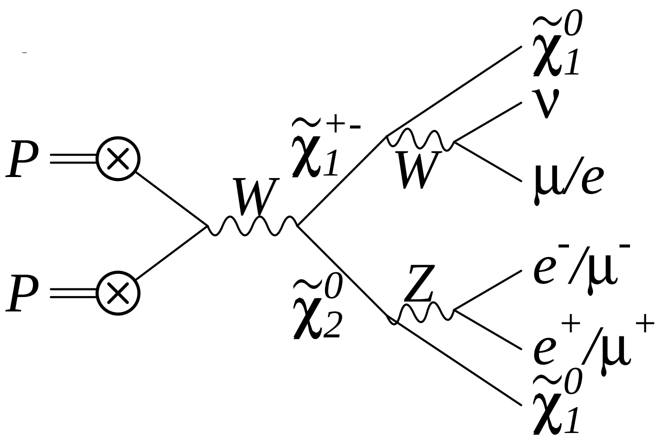
CMS TDR V.2&Note 2006/113; ATLAS CSC 7

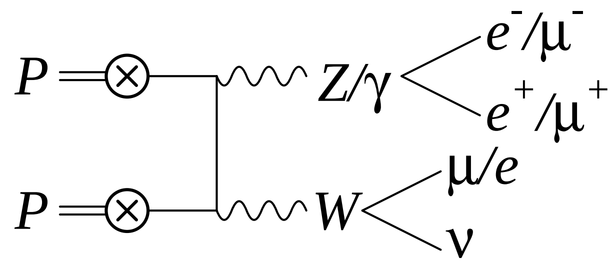


WZ is thought to be the largest source of low-p_T trileptons at LHC.

$W\gamma^*$ is not always included but should be.

Trileptons at LHC





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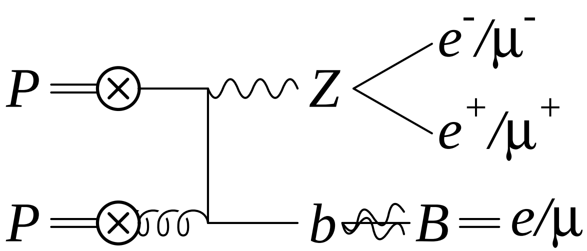


Many processes with heavy flavors:
bZ/γ, $b\bar{b}Z/\gamma$, cZ/γ, $c\bar{c}Z/\gamma$, $b\bar{b}W$, $c\bar{c}W$, $t\bar{t}$, tW, $t\bar{b}$

How important are leptons from heavy flavor (b, c) decays?

NOTE: All photons are virtual, and split to $l^+ l^-$

SUSY particle masses

We examined the trilepton SUSY signal and the SM backgrounds for 4 SUSY points (all masses in GeV units):

	$\widetilde{\chi}_1^0$	$\widetilde{\chi}_2^0$	$\widetilde{\chi}_1^{\pm}$
LM1	96.8	178.3	178.1
LM7	90.5	154.8	154.8
LM9	68.7	121.7	122.3
SU2	112.5	171.3	164.0

- LM1, LM7, and LM9 are the SUSY points investigated by CMS. They are a subset that exhibits a large trilepton signature from $\widetilde{\chi}_1^+\widetilde{\chi}_2^0$ decay.
- ATLAS point SU2 is in the focus point region of mSUGRA parameter space.
- These may already be excluded by WMAP, $b \to s\gamma$, or other data. We use them to make contact with the CMS and ATLAS simulations.

Event simulations

We reproduced the analysis chains described in

1. CMS: CMS TDR V.2&Note 2006/113
2. ATLAS: ATLAS CSC 7

but we included, in addition, the contributions from processes with heavy flavors: bZ/γ, $b\bar{b}Z/\gamma$, cZ/γ, $c\bar{c}Z/\gamma$, $b\bar{b}W$, $c\bar{c}W$, $t\bar{t}$, tW, $t\bar{b}$

Simulation method

- Matrix elements computed in MadEvent (spin correlations included)
- MadEvent results fed through PYTHIA showering.

PYTHIA output is fed through a modified PGS detector simulation that reproduces CMS and ATLAS full detector results to 10%.

Important Analysis Cuts

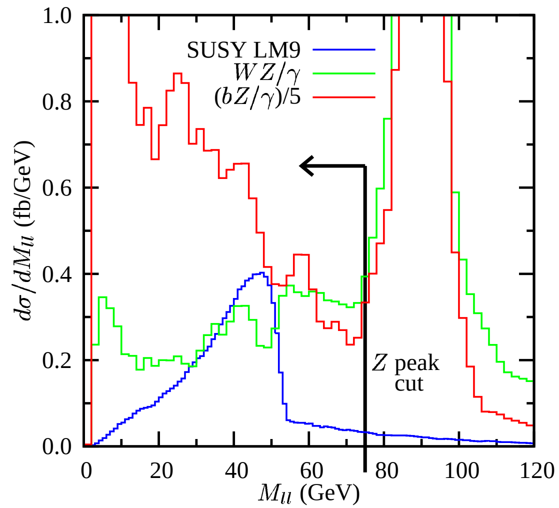
- Require 3 isolated leptons
- Require no jets with $E_T > 30$ GeV
- Require $M_{ll}^{\rm OSSF} < 75$ GeV

Trileptons: SUSY & SM at CMS w/ 30 fb^{-1}

Channel	$N^l = 3$, NoJets	$M_{ll}^{\rm OSSF} < 75$ GeV
LM9	248	243
LM7	126	123
LM1	46	44
WZ/γ	1880	538
$t\bar{t}$	1540	814
tW	273	146
$t\bar{b}$	1.1	1.0
bZ/γ	14000	6870
cZ/γ	3450	1400
$b\bar{b}Z/\gamma$	8990	2220
$c\bar{c}Z/\gamma$	4680	1830
$b\bar{b}W$	9.1	7.6
$c\bar{c}W$	0.19	0.15

Analysis cuts:

- 3 leptons
- No jets ($E_{Tj} > 30$ GeV)
- Remove Z peak (demand $M_{ll}^{\rm OSSF}) < 75$ GeV

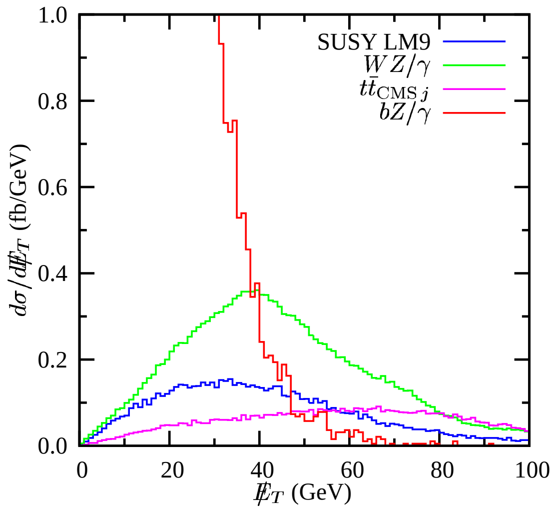


Z+heavy flavor decays are $10\times$ $WZ/\gamma + t\bar{t}$!

Two additional cuts: $\not{E}_T$ and angular correlations

Leptons from SUSY decays are SOFT $\Rightarrow$ Cannot raise p_{Tl} cut.

Missing E_T



Z/γ+heavy flavors – no intrinsic $\not{E}_T$

Comes from misreconstruction, energy lost down beam pipe

Natural $\not{E}_T$ in SUSY points low as well

$\tilde{\chi}_1^0$'s partially balance out

A $\not{E}_T$ cut demanding

$\not{E}_T > 30$–40 GeV is very effective

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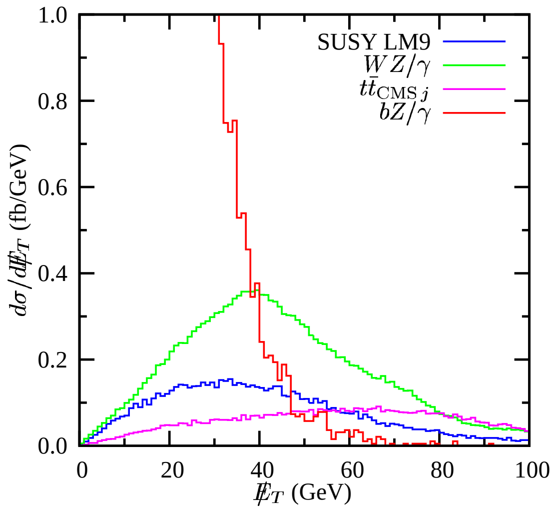

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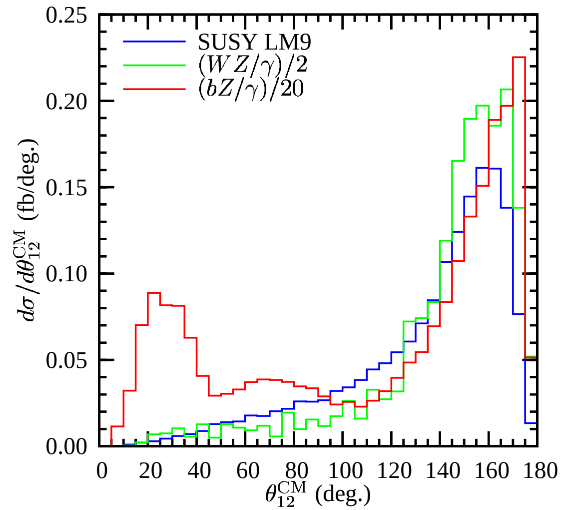
Caution: $\not\!\!E_T$ is poorly measured

Angular correlations



Angles measured extremely well

All combinations different ($\theta_{12}^{\mathrm{CM}}$ shown)

Demand $\theta_{12}^{\mathrm{CM}} > 45^\circ$, $\theta_{13}^{\mathrm{CM}} > 40^\circ$, $\theta_{23}^{\mathrm{CM}} < 160^\circ$

Reduces B by 30% for 5% loss of S

Not optimized

Trileptons: SUSY & SM at CMS (+new cuts)

Channel	$N^l = 3$, NoJets	$M_{ll}^{\mathrm{OSSF}} < 75$ GeV	$\not{E}_T > 30$ GeV	Angular cuts
LM9	248	243	160	150
LM7	126	123	89	85
LM1	46	44	33	32
WZ/γ	1880	538	325	302
$t\bar{t}$	1540	814	696	672
tW	273	146	123	121
$t\bar{b}$	1.1	1.0	0.77	0.73
bZ/γ	14000	6870	270	177
cZ/γ	3450	1400	45	35
$b\bar{b}Z/\gamma$	8990	2220	119	103
$c\bar{c}Z/\gamma$	4680	1830	69	35
$b\bar{b}W$	9.1	7.6	5.6	5.3
$c\bar{c}W$	0.19	0.15	0.12	0.11

Flavor and Sign Combinations

1. For SUSY trilepton signals and SM backgrounds no difference in production rates for $\mu\mu\mu$, $e\mu\mu$, $ee\mu$, and eee
2. Any observed differences come from larger acceptance for isolated e over isolated μ, balanced against larger rejection of e from Z mass cut
   - may be useful as check of detector performance, but no power to resolve the signal
3. Some enhancement of l^+l^+ over l^-l^- from $W^\pm Z/\gamma$, $b\bar{b}W^\pm$, etc., because PDFs for p favor W^+ over W^-
   - may be possible to use this sign difference to constrain the total $W + X$ background

Summary of trileptons

(E. Berger and Z. Sullivan, PDR **78**, 034030 (2008), hep-ph:0805.3720)

1. Heavy-flavor (b, c) decays to leptons dominate low-p_T isolated leptons at LHC
   Trileptons from Z/γ^*+heavy flavors (HF) $\sim 10\times$ all other backgrounds
2. Raising minimum p_T is not viable for SUSY signal, but other cuts work:
   (a) Require $\not{E}_T > 30$ GeV, $Z/\gamma^* + \mathrm{HF} \rightarrow Z/\gamma^* + \mathrm{HF}/30$ Hard to measure low $\not{E}_T$
   (b) Impose cuts on well-measured angles, Z/γ^*+HF reduced by 30%
3. Overall normalization is dominated by assumptions regarding ISR
   Large uncertainty in the effectiveness of jet veto
   If large ISR exists, may want to loosen jet veto to recover SUSY signal
   ISR questions should be resolved with initial data from LHC
4. Any signal that has low-p_T leptons MUST consider the background from heavy flavor (b, c) decays. Analyses of SUSY exclusion limits should include this (neglected) background.

Overall lesson: precise understanding of all SM physics processes will enable confident discovery claims.

BACKUPS

SUSY (mSUGRA) mass parameters

We examined the trilepton SUSY signal and the SM backgrounds for 4 SUSY points:

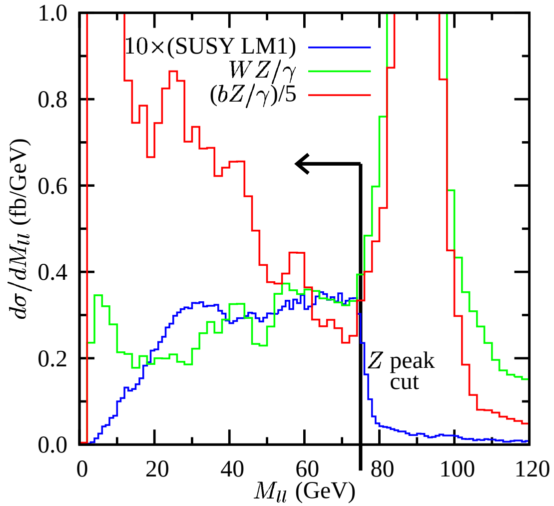
	A_o	μ	m_o	$m_{1/2}$	$\tan\beta$
LM1	0	> 0	60	250	10
LM7	0	> 0	3000	230	10
LM9	0	> 0	1450	175	50
SU2	0	> 0	3550	300	10

- LM1, LM7, and LM9 are the SUSY points investigated by CMS. They are a subset that exhibits a large trilepton signature from $\widetilde{\chi}_1^+ \widetilde{\chi}_2^0$ decay.
- ATLAS point SU2 is in the focus point region of mSUGRA parameter space.
- These may already be excluded by WMAP, $b \to s\gamma$, or other data. We use them to make contact with the CMS and ATLAS simulations.

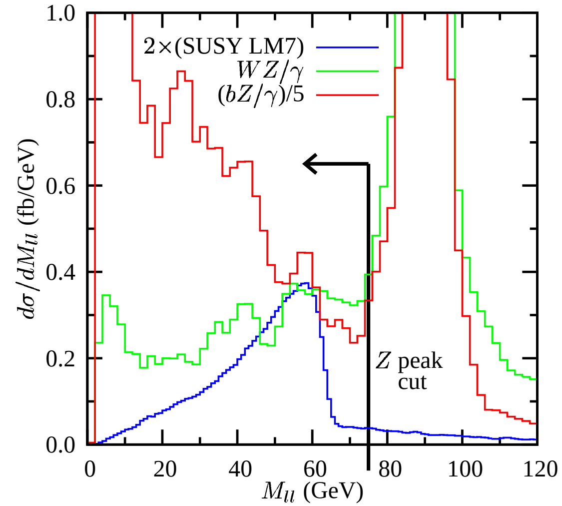
CMS SUSY points LM1, LM7

Representative opposite-sign same-flavor (OSSF) invariant masses

LM1



LM7

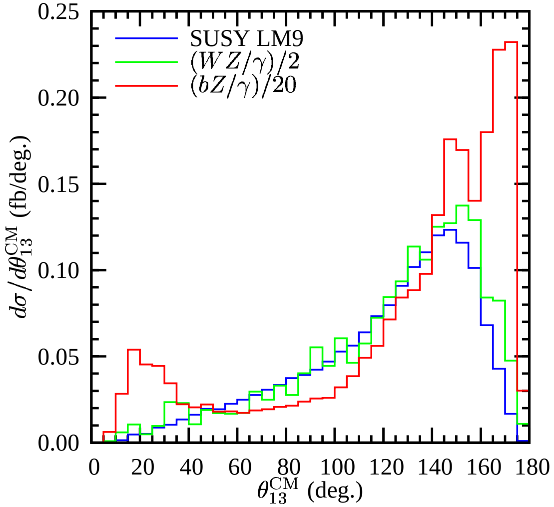


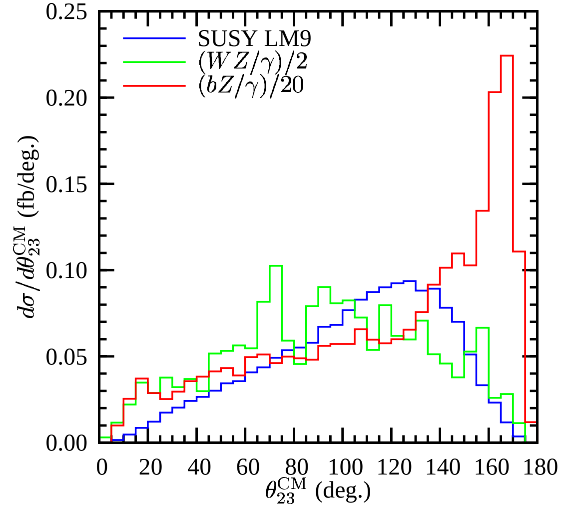
Signal endpoint above Z-peak cut and signal is small

LM7 similar to LM9, but smaller

Other angular correlations

Angles are well-measured, and defined in the trilepton CM frame.





Suggested cut: $\theta_{13}^{\rm CM} > 40°$

Suggested cut: $\theta_{23}^{\rm CM} < 160°$

These cuts are almost free, and not optimized.

5% signal decrease, but 30% backgound decrease

Significance of SUSY point LM9 in 30 fb^{-1}

1. Our calculations are LO.
   NLO K-factors are large (1.5–2) on most processes,
   BUT, jet veto will reduce this effect.
2. Initial state raditation/showering (ISR) is not well determined
   The rate of > 30 GeV jets can be changed by a factor of 4 depending on assumptions in PYTHIA about ISR. Need a NLO PYTHIA-like shower code battle-tested against LHC data.

We present our calculation, and one that scales B down by 4 to show the range of possible significances

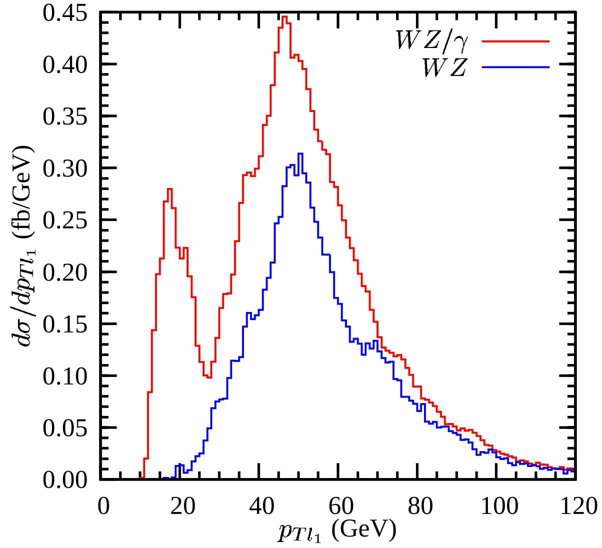
	$N^l = 3$, NoJets	$M_{ll}^{\mathrm{OSSF}} < 75$ GeV	$\not{E}_T > 30$ GeV	Angular cuts
$S/\sqrt{B}_{\mathrm{LM9}}$	1.33	2.07(1.79)	3.93(3.74)	3.94(3.79)
$S/\sqrt{B}_{\mathrm{LM9}}^{\mathrm{CMS}\,j}$	2.63	4.09(3.54)	7.78(7.39)	7.79(7.49)

(Parentheses include leptons from fakes from CMS Table 6, Note 2006/113)

We will not know which ISR estimate is correct until we measure it at LHC

Importance of the virtual photon

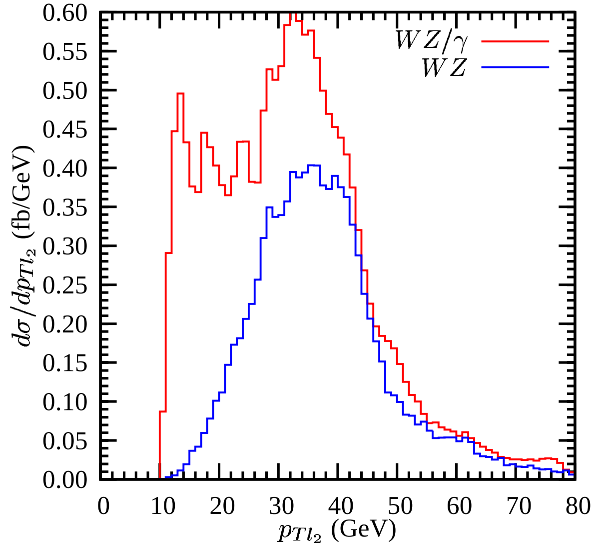
Simulations of WZ based on PYTHIA do not include virtual photons.

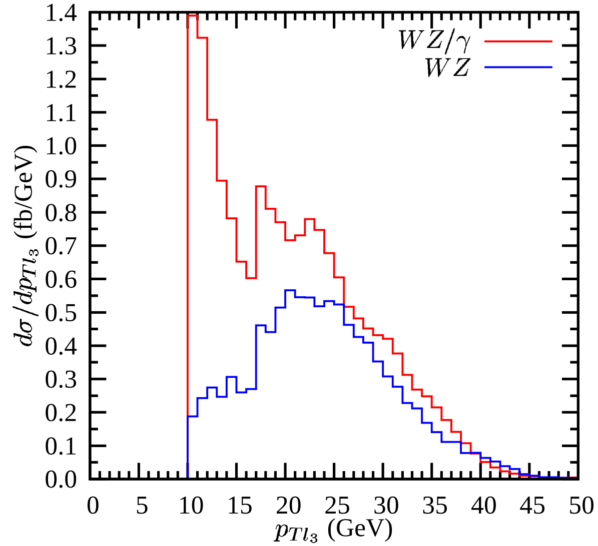


Nearly $1/2$ of the trilepton background from WZ/γ is from $W\gamma^*$ alone.

Matrix elements that include virtual photons are important for studies of low-p_T leptons.

(p_{Tl} spectra after M_{ll}^{OSSF} cut)





Pure QCD background to trileptons

CMS estimates $jjj \to lll < 5$ events in 30 fb^{-1}

What about $b\bar{b}b\bar{b}$, $b\bar{b}c\bar{c}$, $c\bar{c}c\bar{c}$?

We cannot simulate this directly in our lifetimes ($\sim 10^3$ CPU years)

Estimate 3 sources of $b\bar{b}b\bar{b}$ for 30 fb^{-1}

1. Direct $b\bar{b}b\bar{b}$: ~500 events
   Use $Wb\bar{b}$ to estimate $P(b \to \mu_{\rm iso})$: $\sigma_{b\bar{b}b\bar{b}} \times (7.5 \times 10^{-3})^3$
2. Multiple interactions: ~600 events
   10 interactions $\times \sigma^2_{b\bar{b}} / \sigma^{\rm Tot}_{\rm inelastic}$
3. Multiple scattering, gluon splitting: $\sim 10^3$ events

Note that K factors could be as high as 5.5

A. Del Fabbro, D. Treleani, PRD66, 074012 (02)

Scaling results from E. Berger and Z. Sullivan, PRD 74, 033008 (06), we expect that the $\not{E}_T$ cut should remove nearly all of these.