Searches for Scenarios with Squeezed Spectra

(extremely preliminary)

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squeezed spectra

- basic scenario
  - dark matter χ is a gauge-singlet Majorana fermion ...
  - ... which couples to SM fermion f ...
  - ... through exchange of SM-charged scalar(s) $\tilde{f}_{1,2}$
  - χ and $\tilde{f}_{1,2}$ charged under Z_2 symmetry which stabilizes DM
- arises in a variety of frameworks
  - MSSM with bino-like LSP (our main example)
    - scalars = sfermions
  - WIMPless dark matter with DM = Majorana fermion (easy to generalize)
- we're interested in the case of a squeezed spectrum ...
  - small mass splitting between DM and lightest mediating scalar ($\mathcal{O}$(1-60) GeV)
- ... and when f = e or μ (leptons) or u, d, s (light quarks)
- interesting phenomenology for LHC, direct detection and early Universe

new features

- LHC (f = e, μ)
  - standard sfermion searches fail, since MET and visible fermions are soft
  - can use ISR jets to give transverse boost to system
  - we'll find that angular cuts can boost S/B and signal significance

- direct detection (f = u, d, s)
  - can get large enhancement in scattering cross section from resonance
  - boost sensitivity for SI, SD, or even v-suppressed cross sections

- early Universe (f = e, μ, u, d, s)
  - co-annihilation processes can widen mass range for which correct thermal relic density can be achieved

new features

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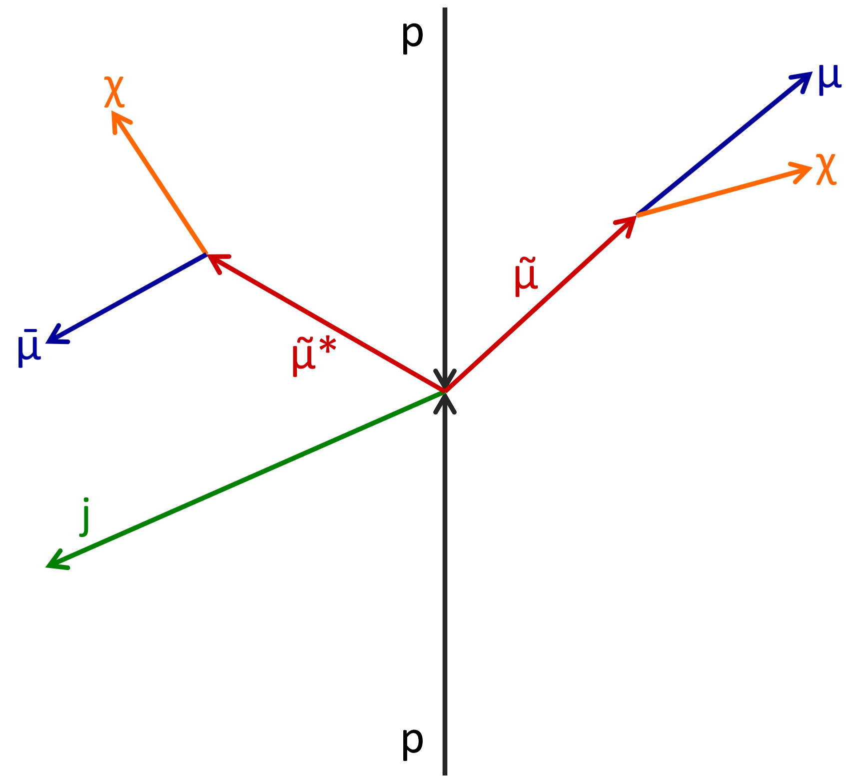
already interest LHC searches for compressed scenarios... (see Ismail's talk)

- a path for light sparticles to evade LHC, since all particles are soft
  - there is interest in closing the window
- for example, Han, Kribs, Martin, Menon (1401.1235) and Han, Liu (1412.0618)
  - use a monojet to boost give a transverse boost to sleptons
  - at worst, like a monojet dark matter search
  - can do better by demanding OS/SF leptons which satisfy cuts on kinematic variables (upper bound on M_{T2}) (1412.0618,1501.02251 (Barr, Scoville))
- upper bound kinematic cuts are a common theme
  - main SM backgrounds get charged leptons and MET through W, Z-decay
  - in "unboosted frame" the energy is ~ 40-50 GeV
  - for very compressed spectra, products from slepton decay are even softer
- we'll try another approach with angular distributions....
  - focus on region which is less squeezed, before non-monojet searches pick up again

LHC searches

- focus f = μ, $\tilde{\mu}_1 = \tilde{\mu}_L$, $m_{\tilde{\mu}}$ = 110 GeV
- signal to look for
  - a single hard non-b jet
  - lepton pair ($\mu^+\mu^-$)
  - MET
- take $\Delta m \equiv m_{\tilde{\mu}} - m_\chi < 60$ GeV
  - else standard search is OK....
- main SM bgd. from $\bar{t}t(j)$, jZ, jVV
  - single top killed by OSSF cuts
- get leptons and MET from
  - $W^+W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$
  - $Z Z \rightarrow \bar{\nu} \nu \ell^+ \ell^-$
  - $Z \rightarrow \bar{\tau} \tau \rightarrow \ell^+ \ell^- + 4\nu$

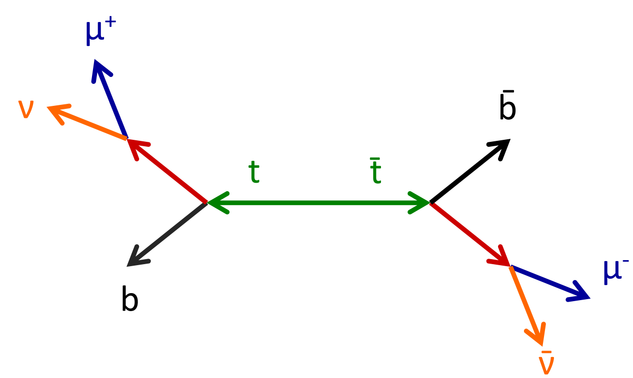


extra cuts

- can use $m_{\ell_1\ell_2}^2$ to reject $Z \to \ell\ell$
- can use $m_{\tau\tau}^2$ to reject $Z \to \bar{\tau}\tau$
  - assume MET comes from light invisible particles collinear with ℓ_1, ℓ_2
  - 2 unknowns, 2 constraint s (P_T)
  - reconstruct parent mass
- j/ℓ/MET for signal harder than $\bar{t}t$
  - need exactly one hard jet
  - $\bar{t}t$ decay gives 2 b-jets
    - need one missed, both mistagged
  - get p_T^{ℓ}, MET < 100 GeV
    - can boost with ISR jet or production above threshold
    - but harder to miss b-jets

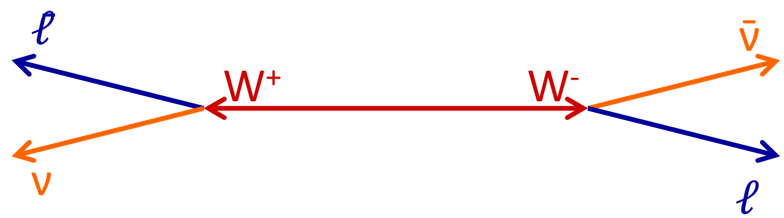
$$m_{\tau\tau}^2 \equiv -m_{\ell_1\ell_2}^2 \frac{\left(\vec{P}_T^{\ell_1} \times \vec{P}_T^{j}\right)\cdot\left(\vec{P}_T^{\ell_1} \times \vec{P}_T^{j}\right)}{\left|\vec{P}_T^{\ell_1} \times \vec{P}_T^{\ell_2}\right|^2}$$

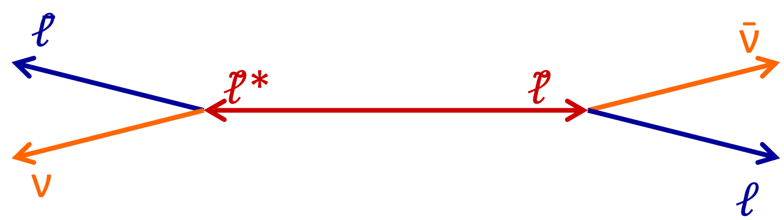
Ellis, Hinchliffe, Soldate, van der Bij (1988)
Baer, Mustafayev, Tata (1409.7058)



angular cuts

- decay products tend to be collimated when parent produced above threshold
  - WW, $\tilde{\ell}^*\tilde{\ell} \rightarrow$ leptons relatively anti-collimated
- jet boost smears out the collimation, but less smearing if intermediary heavy
  - $\bar{t}t$ similar to WW, but more smearing from b-jets
- look for events with leptons anti-collimated, collimated with MPT
- $\ell_1 \ell_2$ angle cut more effective as smuon gets heavier

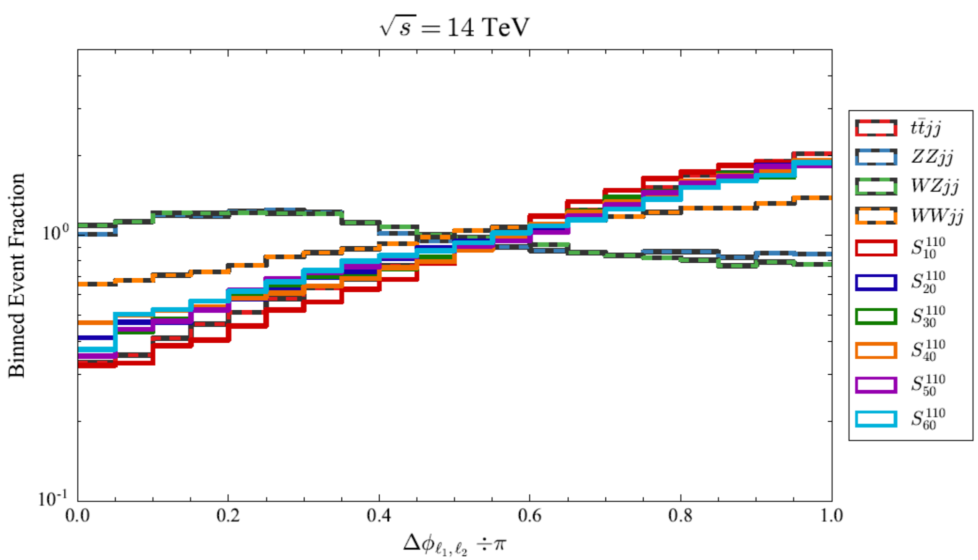




S/B and signal significance

- primary cuts
  - 1 jet , P_T^j > 100 GeV (no other jets > 30 GeV)
  - $\mu^+ \mu^-$
  - b-, τ-veto
  - MET > 100 GeV

- secondary cuts
  - $m_{\mu\mu} \notin m_Z \pm 10$ GeV
  - p_T^j , MET > 175 GeV
  - $m_{\tau\tau}^2$ > 175 GeV, M_{T2}^{WW} < 1 GeV
  - $P_T^{\ell 2}$ > 40 GeV
  - $\Delta\phi(\mu_1, \mu_2) > 0.5\,\pi$, $\Delta\phi(\mu_1, MPT) < 0.8\,\pi$



Δm	σ_{sig} (fb)
30 GeV	0.094
40 GeV	0.087
50 GeV	0.084
60 GeV	0.094

need about 200 fb^{-1} for 95%CL exclusion of model, 1 ab^{-1} for 5σ exclusion of SM

m_χ =110 GeV, $\sigma_{bgd} \approx 0.28$ fb, S/B ~ 1/3

upshot

- several interesting phenomenological features arise when dark matter and new charged mediators are similar in mass

- collider searches are weakened, due to softness of products...
- ... but can be improved by a transverse boost, plus dedicated cuts

- cuts on angular distribution of leptons and MET can distinguish signal from bgd events
  - also angle between jet and leptons/MET

- broadly applicable to degenerate window
  - cuts get better for heavier sleptons
  - though production cross section worse

m_χ (GeV)	σ_{sig} (fb)
110	0.087
160	0.051
200	0.034

Δm = 40 GeV

conclusion

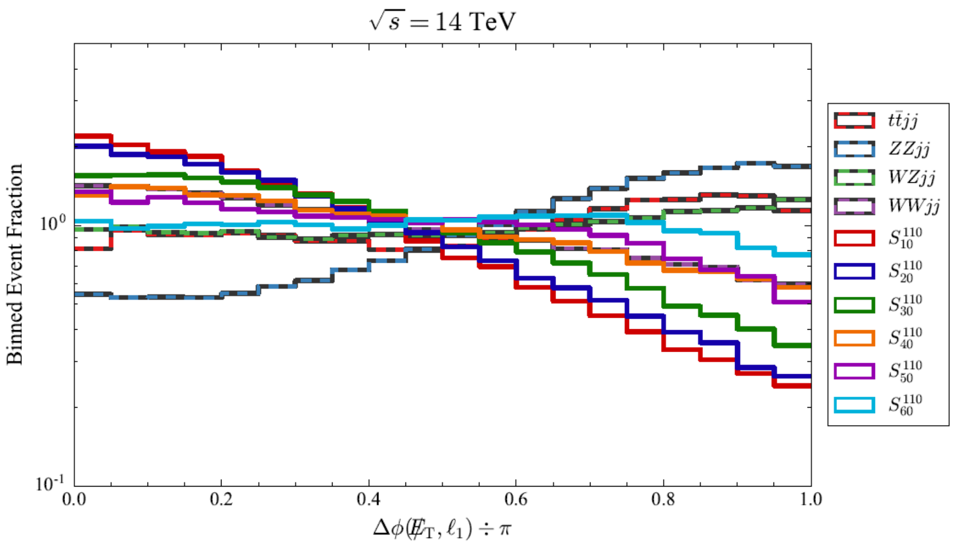
- a variety of new strategies are possible for the LHC to search for squeezed spectra
- this window could nicely correlate with getting the right relic density via co-annihilation, and enhanced prospects at direct detection experiments
- focus on leptons, angular cuts

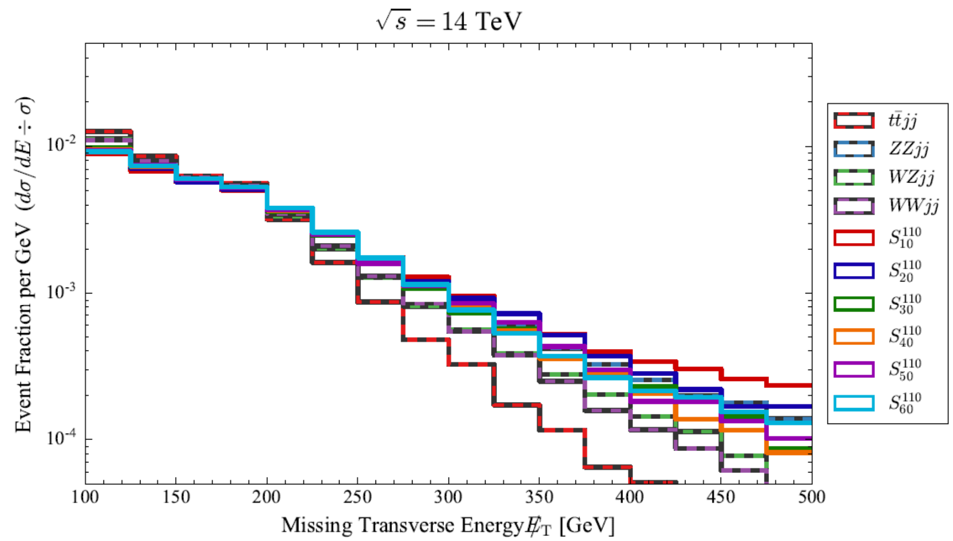
- could probe much of this degenerate region with 200 – 1000 fb^{-1}

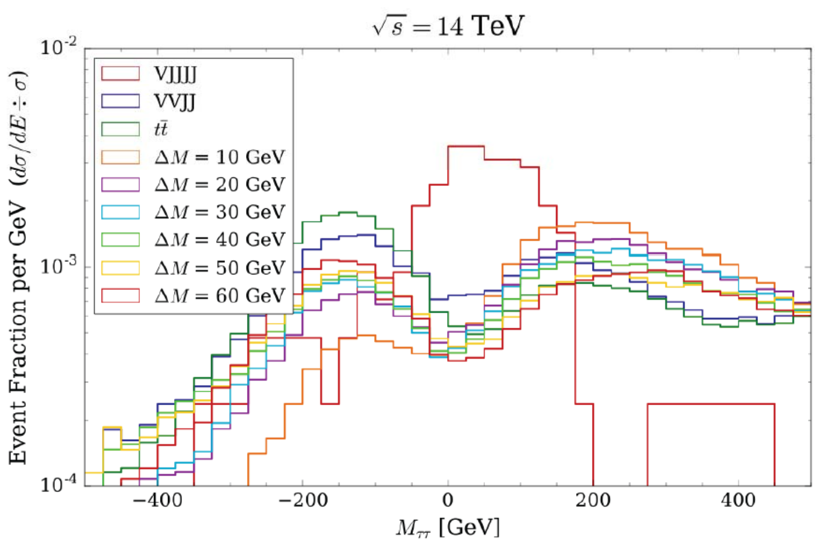
Mahalo!

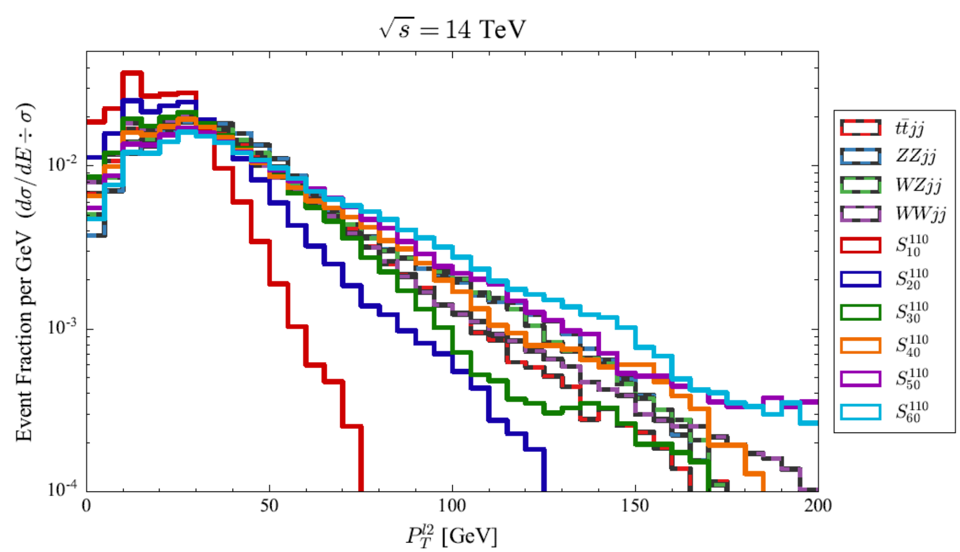
Back-up slides

other distributions

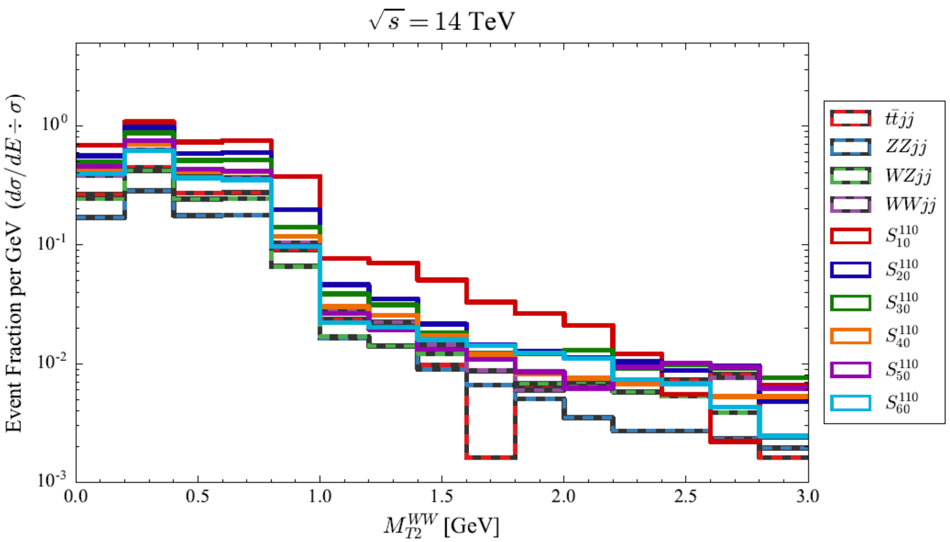








other distributions



simulation details

- MadGraph5/MadEvent/Pythia/Delphes (no k-factor, yet)
- MLM jet matching
  - up to two jets simulated for ditop or VV, up to four jets for single V
- single jet with p_T>30 GeV, η < 4.5; this jet must have p_T > 100 GeV, η < 2.5
- b-tagging eff. = 70%, τ-tagging eff. = 60% (mistag ~ 1%)
- minimal muon threshold, $p_T \geq 10$ GeV

Selection	$t\bar{t}jj$	$ZZjj$	$WZjj$	$WWjj$	S^{110}_{10}	S^{110}_{20}	S^{110}_{30}	S^{110}_{40}	S^{110}_{50}	S^{110}_{60}
Matched Production	6.1×10^5	1.3×10^4	4.2×10^4	9.5×10^4	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2
τ-veto	5.4×10^5	1.2×10^4	4.0×10^4	8.9×10^4	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2
OSSF muon	3.5×10^3	3.2×10^2	5.8×10^2	5.1×10^2	3.9×10^1	6.8×10^1	8.1×10^1	8.8×10^1	8.9×10^1	9.1×10^1
only 1J $P_T > 30$	6.6×10^2	9.4×10^1	1.5×10^2	1.1×10^2	7.6×10^0	1.3×10^1	1.6×10^1	1.7×10^1	1.7×10^1	1.8×10^1
Jet b-veto	1.9×10^2	8.0×10^1	1.4×10^2	1.1×10^2	7.5×10^0	1.3×10^1	1.6×10^1	1.7×10^1	1.7×10^1	1.8×10^1
$\not{E}_T > 100$ GeV	3.2×10^1	4.3×10^0	7.8×10^0	1.7×10^1	1.3×10^0	2.1×10^0	2.5×10^0	3.4×10^0	3.8×10^0	4.8×10^0
Jet $P_T > 100$ GeV	1.2×10^1	1.4×10^0	4.0×10^0	1.0×10^1	1.3×10^0	1.8×10^0	1.8×10^0	1.9×10^0	1.8×10^0	1.9×10^0
$m_{\ell\ell} \notin M_Z \pm 10$ GeV	1.1×10^1	1.0×10^{-1}	1.0×10^0	8.9×10^0	1.2×10^0	1.5×10^0	1.6×10^0	1.6×10^0	1.5×10^0	1.7×10^0
$m_{\tau\tau} > 175$ GeV	4.8×10^0	2.0×10^{-2}	3.3×10^{-1}	4.5×10^0	8.1×10^{-1}	9.0×10^{-1}	9.3×10^{-1}	9.3×10^{-1}	9.3×10^{-1}	9.6×10^{-1}
$\not{E}_T > 175$ GeV	7.5×10^{-1}	8.3×10^{-3}	9.9×10^{-2}	1.3×10^0	2.9×10^{-1}	3.5×10^{-1}	3.5×10^{-1}	3.1×10^{-1}	3.2×10^{-1}	3.5×10^{-1}
Jet $P_T > 175$ GeV	3.7×10^{-1}	6.6×10^{-3}	8.7×10^{-2}	1.2×10^0	2.9×10^{-1}	3.3×10^{-1}	3.3×10^{-1}	2.6×10^{-1}	2.6×10^{-1}	2.7×10^{-1}

secondary cuts

Selection	$t\bar{t}jj$	$ZZjj$	$WZjj$	$WWjj$	S_{10}^{110}	S_{20}^{110}	S_{30}^{110}	S_{40}^{110}	S_{50}^{110}	S_{60}^{110}
$M_{T2}^{WW} < 1$ GeV	2.4×10^{-1}	3.9×10^{-3}	7.0×10^{-2}	8.6×10^{-1}	2.7×10^{-1}	3.0×10^{-1}	2.8×10^{-1}	2.1×10^{-1}	2.0×10^{-1}	1.9×10^{-1}
$0.8 < P_T^j \div \not{E}_T < 1.8\}$	2.1×10^{-1}	3.9×10^{-3}	5.6×10^{-2}	7.5×10^{-1}	2.7×10^{-1}	3.0×10^{-1}	2.7×10^{-1}	1.9×10^{-1}	1.7×10^{-1}	1.7×10^{-1}
$\Delta\phi(\not{E}_T, \ell_1) \div \pi < 0.8$	1.8×10^{-1}	3.9×10^{-3}	5.4×10^{-2}	7.2×10^{-1}	2.7×10^{-1}	3.0×10^{-1}	2.6×10^{-1}	1.9×10^{-1}	1.6×10^{-1}	1.6×10^{-1}
$\Delta\phi(\ell_1, \ell_2) \div \pi > 0.5$	1.5×10^{-1}	2.7×10^{-3}	3.1×10^{-2}	5.6×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	1.6×10^{-1}	1.2×10^{-1}	1.4×10^{-1}
$P_T^{\ell 2} > 40$ GeV	3.9×10^{-2}	0	1.1×10^{-2}	2.3×10^{-1}	2.0×10^{-2}	8.1×10^{-2}	9.4×10^{-2}	8.7×10^{-2}	8.4×10^{-2}	9.4×10^{-2}
Events at $\mathcal{L} = 300$ fb^{-1}	11.8	0.0	3.4	68.5	6.0	24.3	28.2	26.1	25.2	28.2
$S \div B$	-	-	-	-	0.07	0.29	0.34	0.31	0.30	0.34
$S \div \sqrt{B}$	-	-	-	-	0.7	2.7	3.1	2.9	2.8	3.1
Poisson Significance	-	-	-	-	1.2	2.8	3.2	3.0	2.9	3.2