SUSY Search at the CEPC

Jiarong Yuan
Nankai University, Institute of High Energy Physics
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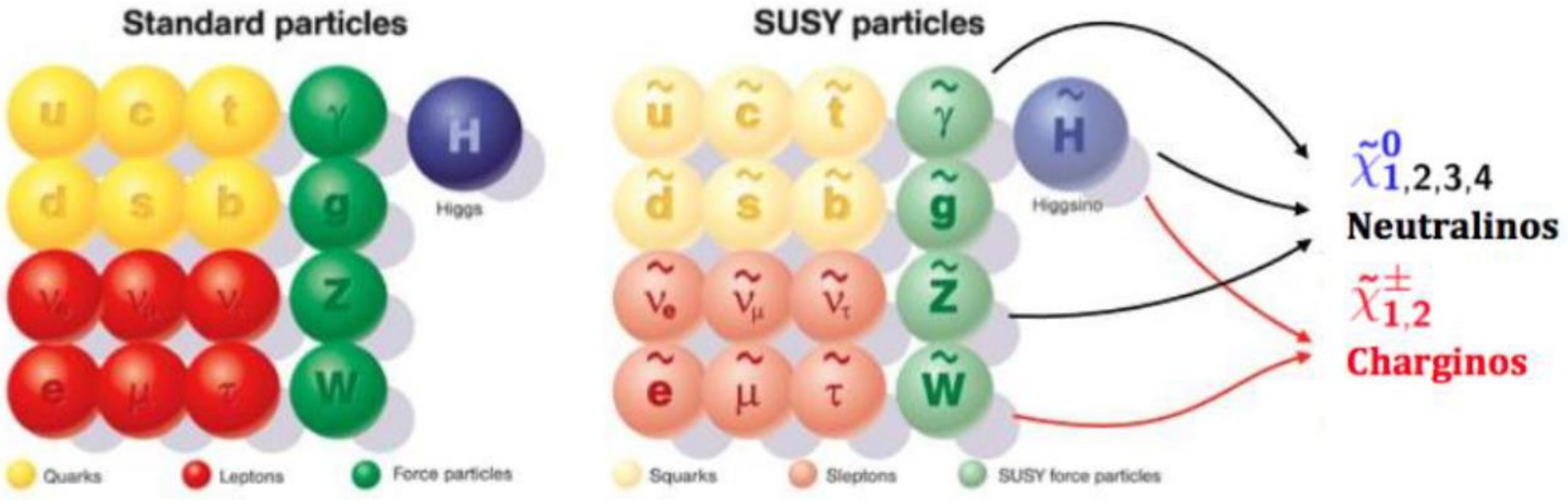
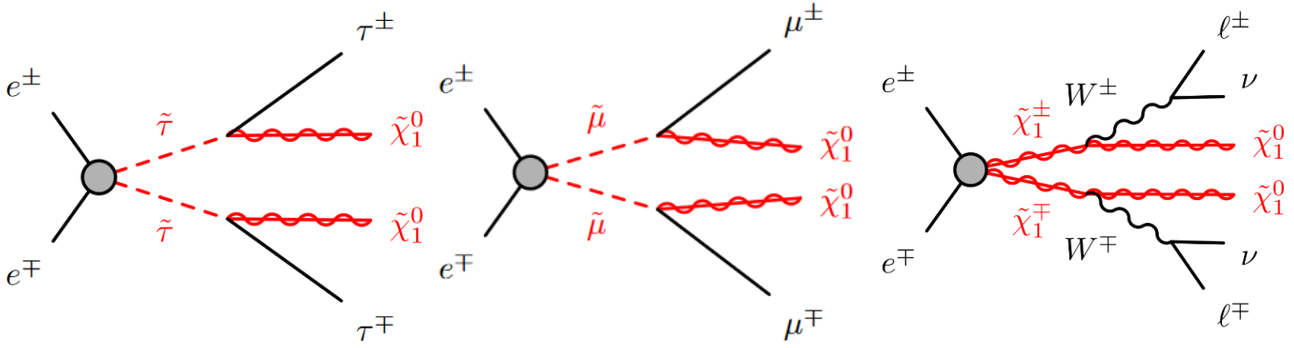
Supersymmetry Introduction

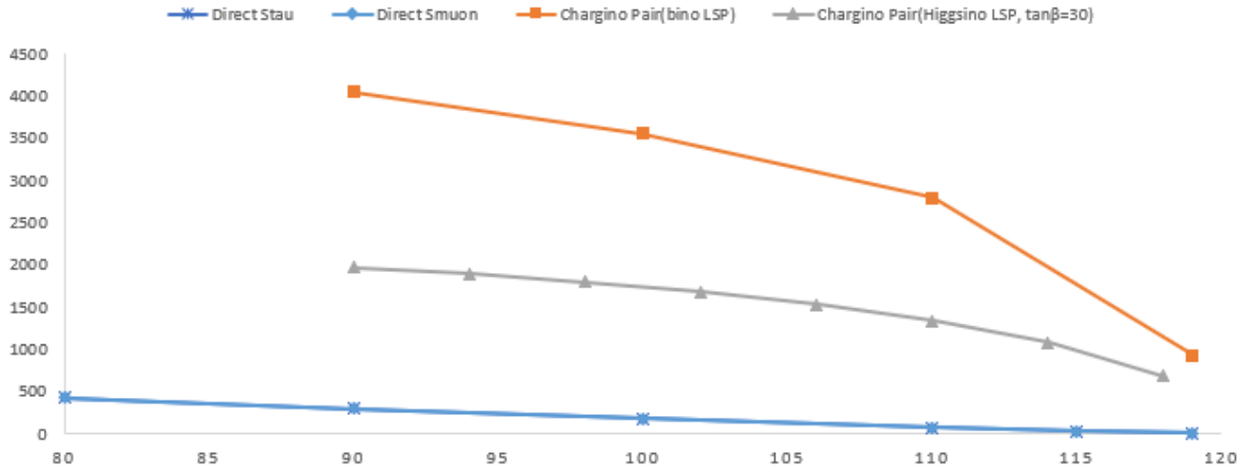


- The Supersymmetry is one of the most appealing BSM theories, which can be helpful for:
  dark matter candidate,
  hierarchy problem,
  grand unification of gauge couplings
  …

Overview

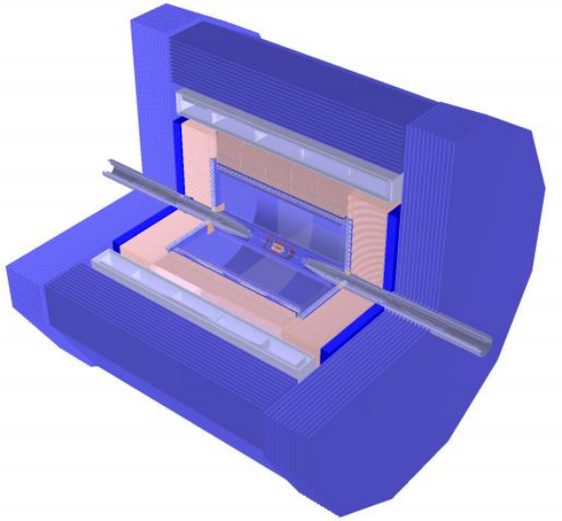
- Search for sleptons and electroweakinos at CEPC.
- Signal scenarios
  - Direct production of stau pairs (**DM relic density consistent with cosmology observation**)
  - Direct production of smuon pairs (can **explain g-2 excess**)
  - Production of chargino pairs decaying via W bosons (**Bino LSP**, **large cross section**)
  - Production of chargino pairs decaying via W bosons (**Higgsino LSP, interesting related with higgs**)
- Search results in final states with two opposite sign (OS) charged muons(in last 3 scenarios).





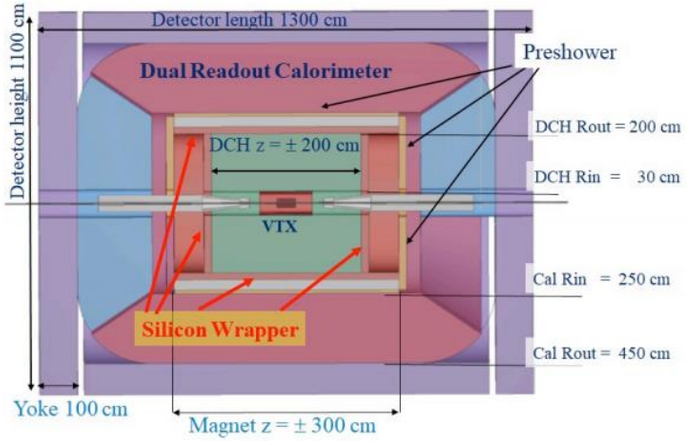
Cross-section based on Madgraph calculation

Technical detail

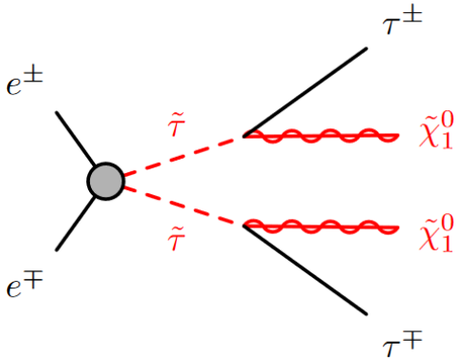


- About CEPC
  - ECM=240GeV, higgs factory, 100 km circumference, 2 interaction points.
  - ILD-like detector
- Software
  - **Signal samples:** **MadGraph+Pythia8**
  - Simulation: Mokka
  - Reconstruction: Marlin
- Normalized to $5050\ \mathrm{fb}^{-1}$
- **Dominant backgrounds:**
  - **SM processes with two-e or two-μ or two-τ and large missing energy final states.(DirectStau)**
  - **SM processes with two-μ or two-τ and large missing energy final states.(Other 3 scenarios)**

process	Cross Section [fb]
$\mu\mu$	4967.58
$\tau\tau$	4374.94
$WW \to \ell\ell$	392.96
$ZZorWW \to \mu\mu\nu\nu$	214.81
$ZZorWW \to \tau\tau\nu\nu$	205.84
$\nu Z, Z \to \mu\mu$	43.33
$ZZ \to \mu\mu\nu\nu$	18.17
$\nu Z, Z \to \tau\tau$	14.57
$ZZ \to \tau\tau\nu\nu$	9.2
$\nu\nu H, H \to \tau\tau$	3.07
$e\nu W, W \to \mu\nu$	429.2
$e\nu W, W \to \tau\nu$	429.42
$eeZ, Z \to \nu\nu$	29.62
$eeZ, Z \to \nu\nu\ or\ e\nu W, W \to e\nu$	249.34



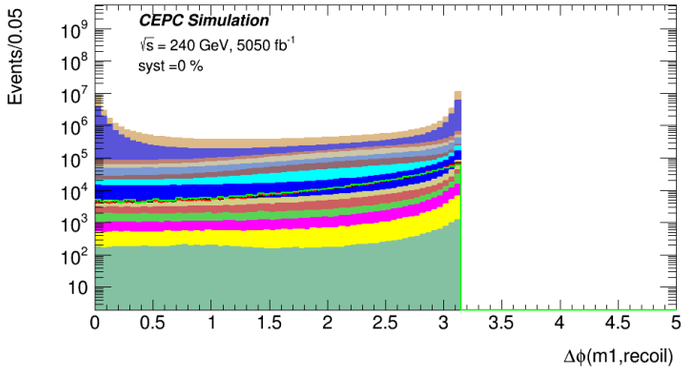
Direct stau: Optimization Strategy

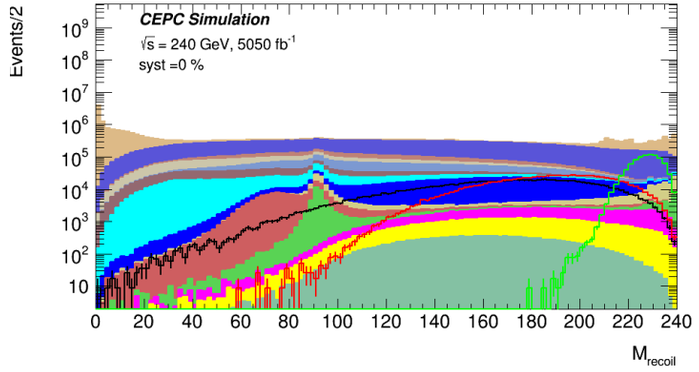


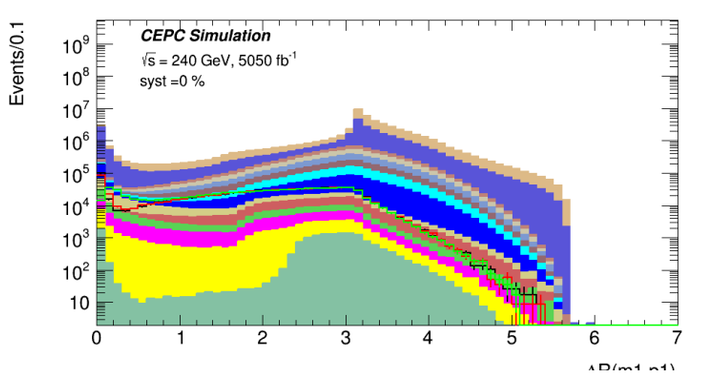
- Use the leading track with minus(positive) charge to represent the $\tau^-(\tau^+)$ for simplicity.
- Select events with 2 OS τ with energy > 0.5GeV.
- Perform a multi-dimension optimization, considering variables:

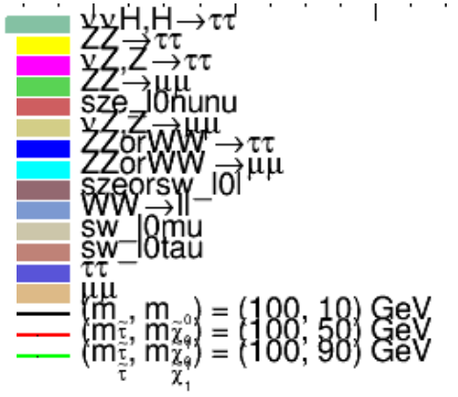
$$\Delta R(\tau,\tau), \Delta R(\tau, recoil), \Delta\varphi(\tau,\tau), \Delta\varphi(\tau, recoil), M_{\tau\tau}, M_{recoil}, E_\tau$$

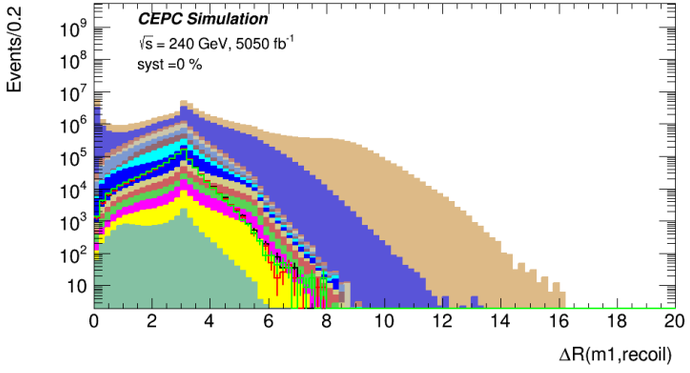
- Check for both upper cut and down cut for each variable.
- Use $\frac{S}{\sqrt{B+dB^2}}$ as a sensitivity measurement (consider statistical uncertainty and 5% systematic uncertainty).

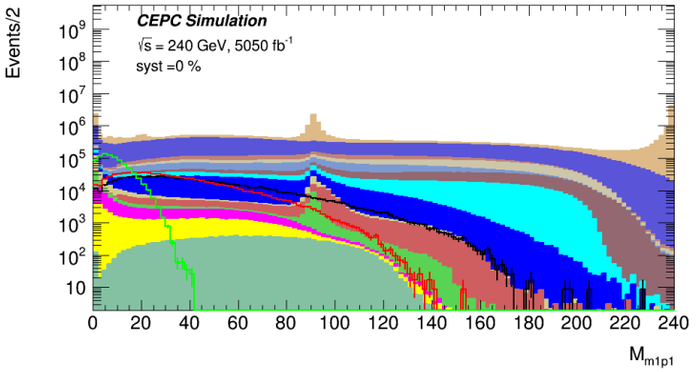


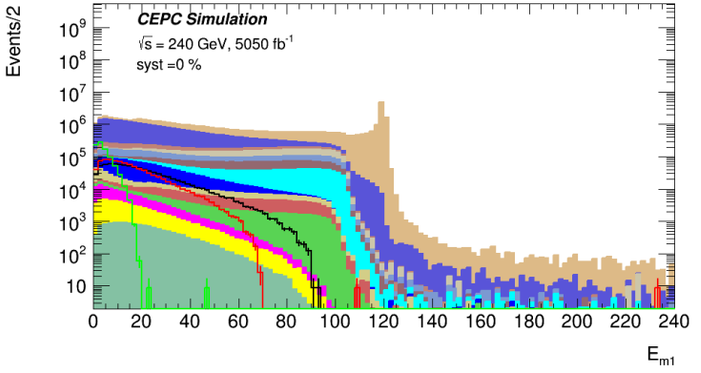












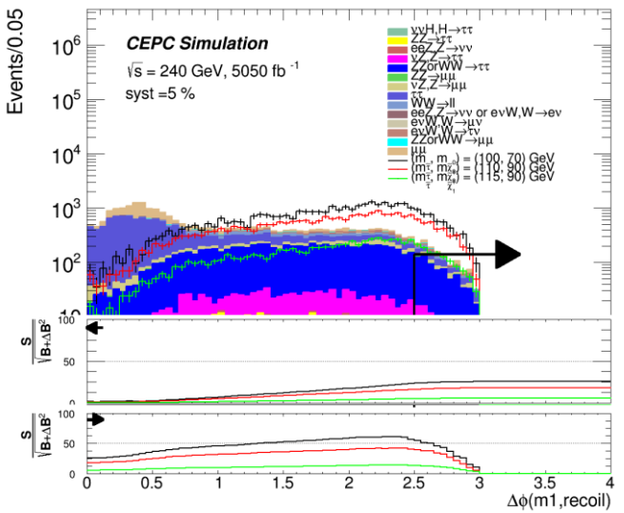
Direct stau: SR & Results

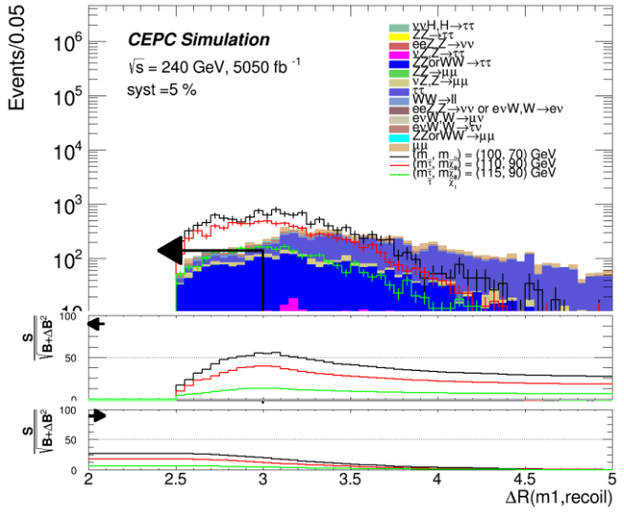
- Two SRs are defined for different $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$.

SR-lowDeltaM	SR2-highDeltaM
$\lvert\Delta\phi(\tau, recoil)\rvert > 2.5$	
$\Delta R(\tau, recoil) < 3$	
$\lvert\Delta R(\tau,\tau)\rvert > 1.2$	$\lvert\Delta R(\tau,\tau)\rvert > 0.6$
$E_\tau < 15GeV$	
$m_{\tau\tau} < 30GeV$	$m_{recoil} < 180GeV$
	$m_{\tau\tau} < 35GeV$

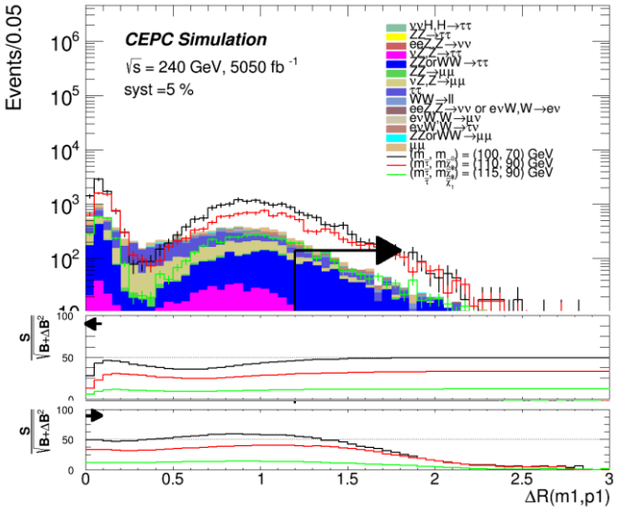
Process	SR-lowDeltaM	SR2-highDeltaM
$\tau\tau$	199.76±21.2945	6.81±3.93176
$\nu\nu H, H \to \tau\tau$	0.155±0.155	0.155±0.155
$ZZorWW \to \tau\tau\nu\nu$	611.82±25.1033	41.2±6.51429
$ZZ \to \tau\tau\nu\nu$	18.76±3.17102	7.504±2.00553
$\nu Z, Z \to \tau\tau$	50.388±6.11044	4.446±1.81507
$ZZorWW \to \mu\mu\nu\nu$	8.544±3.02076	1.068±1.068
$ZZ \to \mu\mu\nu\nu$	6.92±3.09472	0
$WW \to \ell\ell$	85.932±9.37595	12.276±3.54378
$\nu Z, Z \to \mu\mu$	106.848±10.9051	1.113±1.113
$\mu\mu$	121.74±27.2219	0
$e\nu W, W \to \mu\nu$	0	0
$e\nu W, W \to \tau\nu$	91.637±9.60617	45.315±6.75516
$eeZ, Z \to \nu\nu$	3.072±1.77362	0
$eeZ, Z \to \nu\nu$ or $e\nu W, W \to e\nu$	19.855±4.55505	5.225±2.33669
Total background	1325.43±47.0509	125.112±11.4571
(100,10)	1209.58±102.228	751.668±80.5873
(100,50)	2531.48±147.891	639.35±74.3229
(100,90)	7283.4±250.854	0

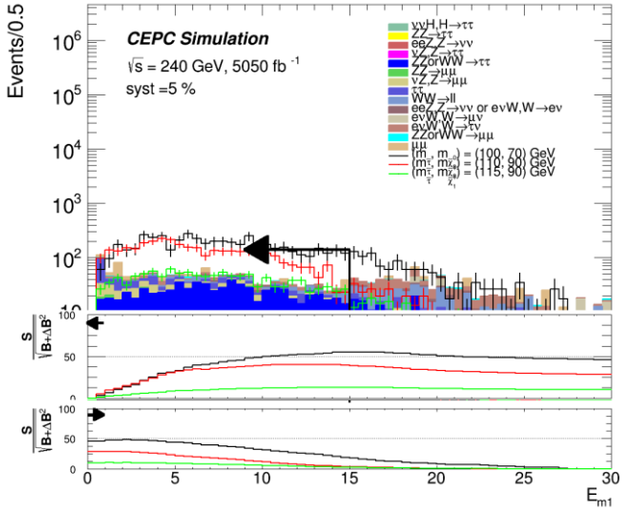
SR-lowDeltaM





$|\Delta\phi(\tau, recoil)| > 2.5: \tau\tau; ZZorWW \to \tau\tau\nu\nu; \mu\mu$ $\Delta R(\tau, recoil) < 3: \tau\tau; ZZorWW \to \tau\tau\nu\nu; \mu\mu$





$|\Delta R(\tau,\tau)| > 1.2: \tau\tau; ZZorWW \to \tau\tau\nu\nu; \nu Z, Z \to \mu\mu$ $E_\tau < 15GeV: WW \to ll; \mu\mu; e\nu W, W \to \tau\nu$

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$m_{\tau\tau} < 30GeV$	$m_{recoil} < 180GeV$
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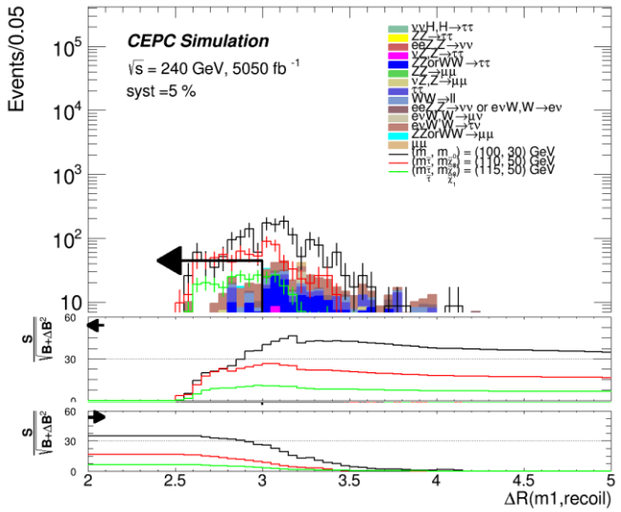
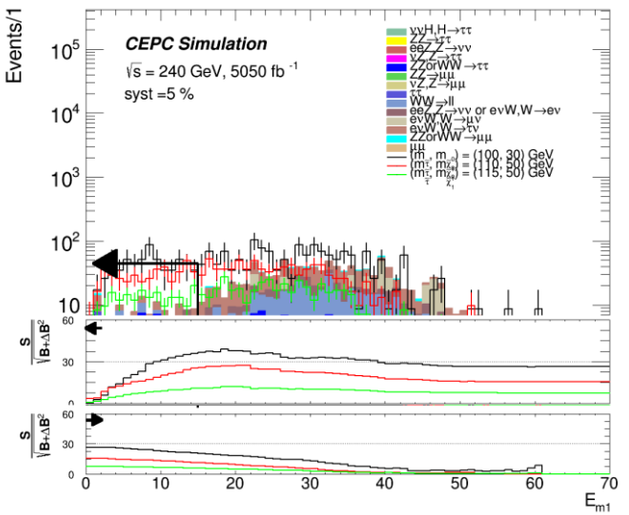
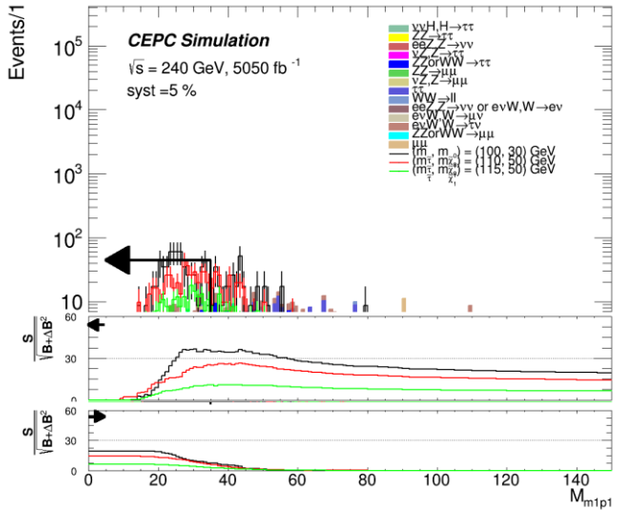
SR-highDeltaM

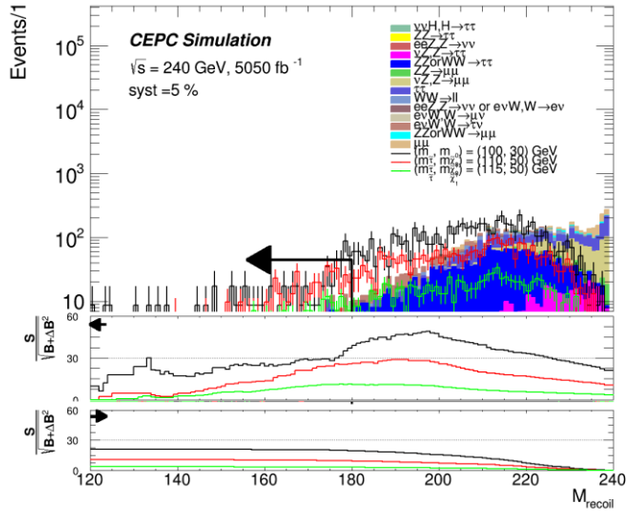




$\Delta R(\tau, recoil) < 3: \tau\tau; ZZorWW \to \tau\tau\nu\nu; e\nu W, W \to \tau\nu$ $E_\tau < 15GeV: WW \to ll; e\nu W, W \to \tau\nu$



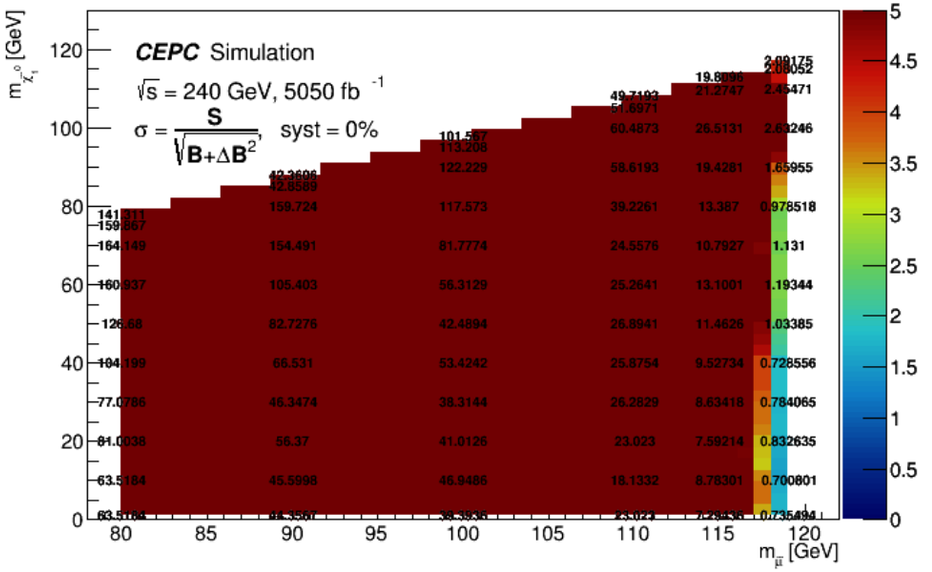
$m_{\tau\tau} < 35GeV$:
$\tau\tau; ZZorWW \to \tau\tau\nu\nu; \nu Z, Z \to \mu\mu$

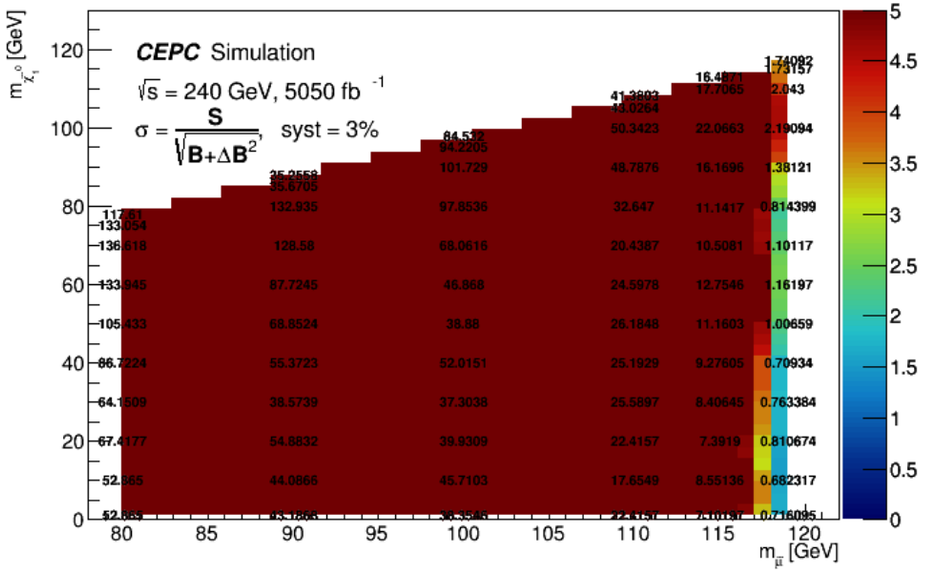


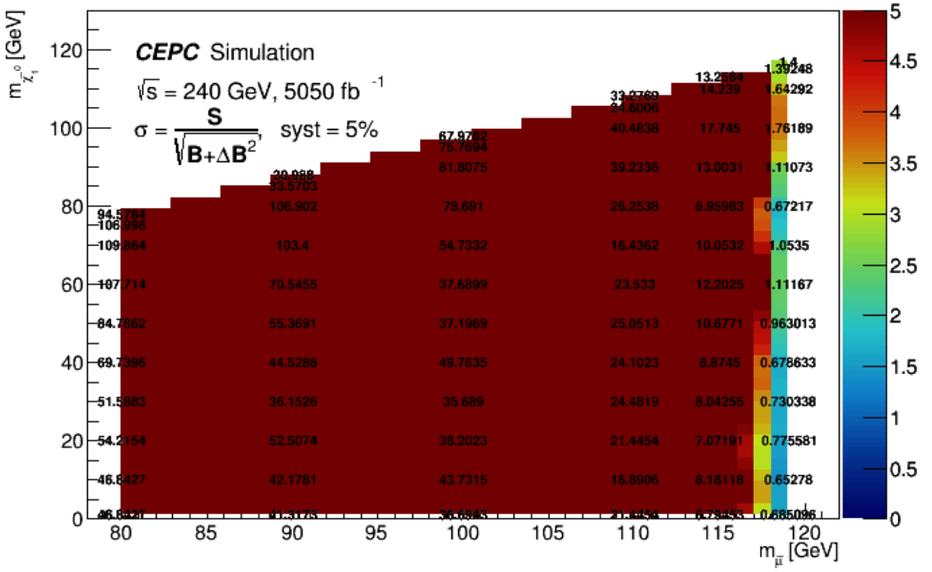
$m_{recoil} < 180GeV$:
$\tau\tau, ZZorWW \to \tau\tau; e\nu W, W \to \tau\nu$

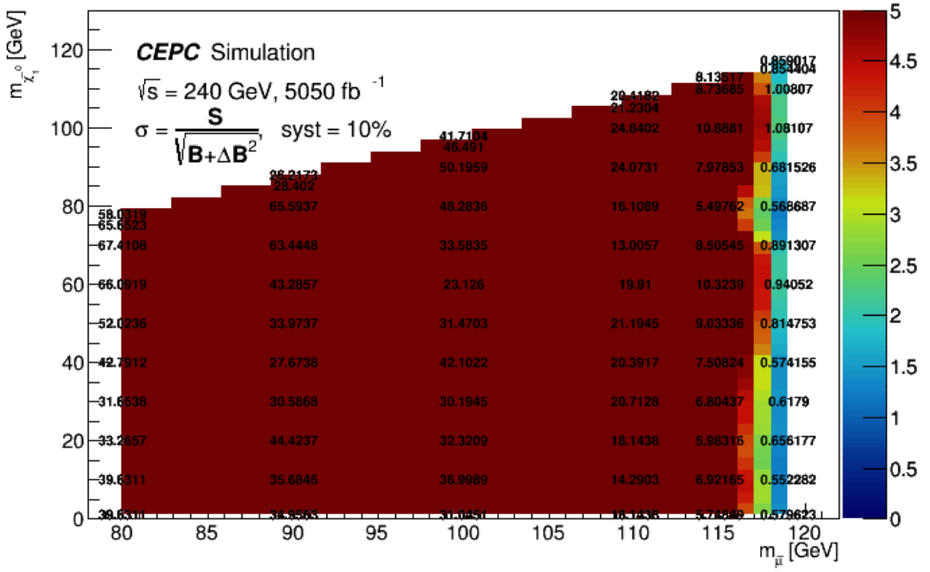
Direct stau: Sensitivity map

- Assuming 10% systematic uncertainty, the discovery sensitivity reaches up to 115 GeV.

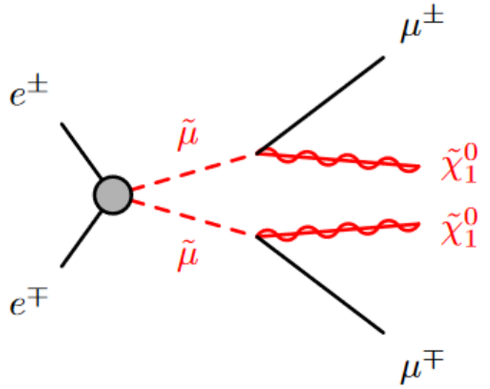








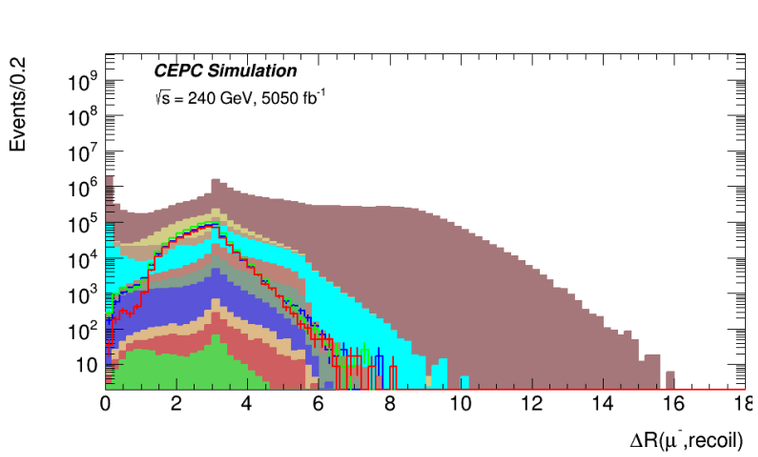
Direct smuon: Optimization Strategy

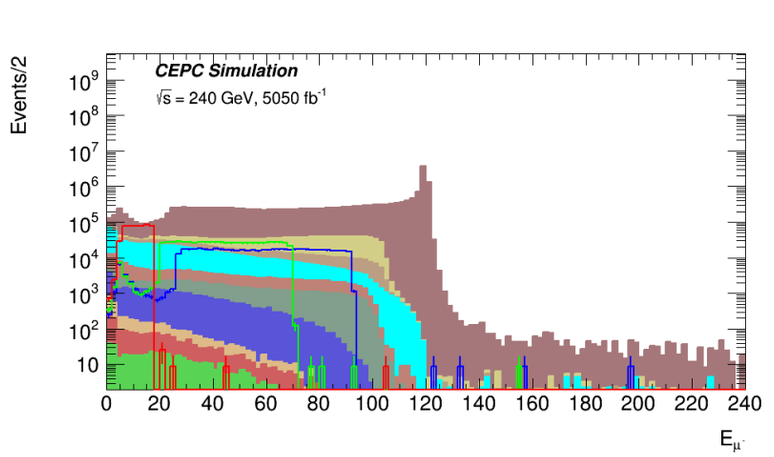


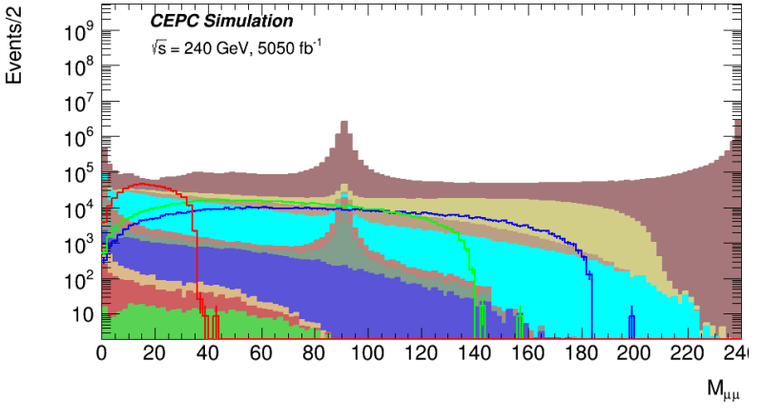
- Select events with 2 OS muons with energy > 0.5GeV.
- Perform a multi-dimension optimization, considering variables:

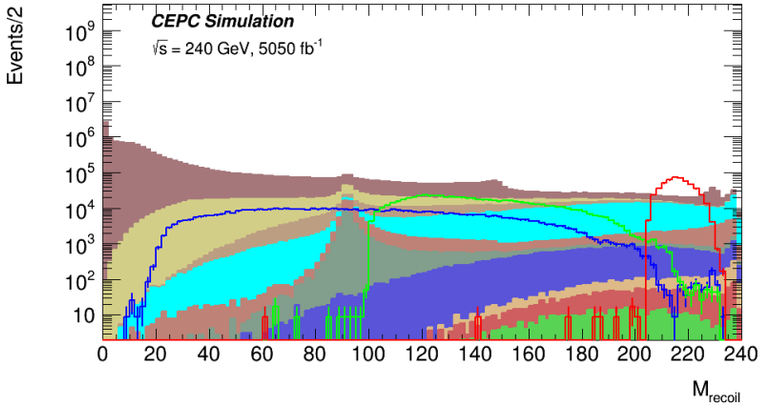
$$\Delta R(\mu,\mu), \Delta R(\mu, recoil), \Delta\varphi(\mu,\mu), \Delta\varphi(\mu, recoil), M_{\mu\mu}, M_{recoil}, E_{\mu\mu}, P_T^{\mu\mu}, E_{\mu}, P_T^{\mu}$$

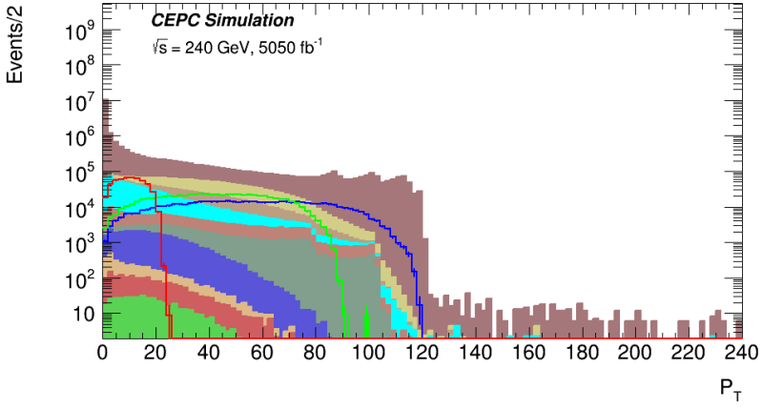
- Check for both upper cut and down cut for each variable.
- Use $\frac{S}{\sqrt{B+dB^2}}$ as a sensitivity measurement (consider statistical uncertainty and 5% systematic uncertainty).









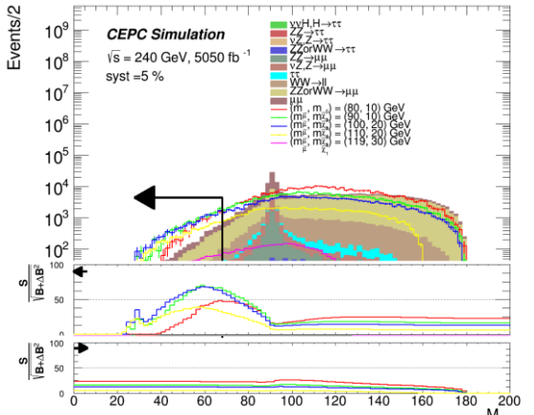


Direct smuon: SR & Results

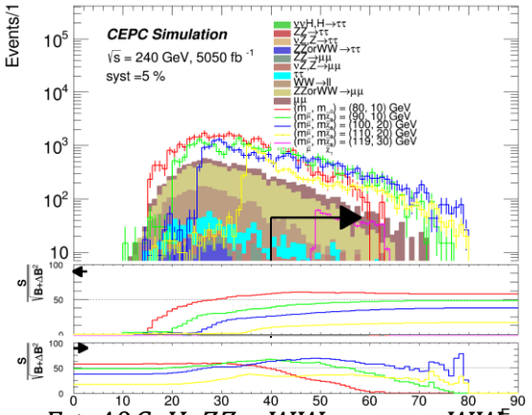
- Three SRs are defined for different $\Delta m(\tilde{\mu}, \tilde{\chi}_1^0)$.

SR-highDeltaM	SR-midDeltaM	SR-lowDeltaM
2 μ (OS, both energy > 0.5GeV)		
$\Delta R(\mu, recoil) < 2.9$ E_μ>40GeV $M_{\mu\mu} < 68GeV$ $M_{recoil} > 60GeV$	$\Delta R(\mu, recoil) < 2.6$ $E_\mu < 50GeV$ $p_T > 50GeV/c$	$\Delta R(\mu, recoil) < 2.7$ $M_{\mu\mu} < 85GeV$ $M_{recoil} > 135GeV$

process	SR-highΔm	SR-midΔm	SR-lowΔm
$\tau\tau$	72.64±12.84	68.1±12.43	5361.74±110.32
$\nu\nu H, H \to \tau\tau$	0	0	60.76±3.07
$ZZorWW \to \tau\tau\nu\nu$	3.09±1.78	1.03±1.03	2242.31±48.0581
$ZZ \to \tau\tau\nu\nu$	1.07±0.76	0	68.608±6.06
$\nu Z, Z \to \tau\tau$	0	0	115.60±9.26
$ZZorWW \to \mu\mu\nu\nu$	1561.42±40.84	624.78±25.83	19535.9±114.45
$ZZ \to \mu\mu\nu\nu$	69.2±9.79	15.22±4.59	218.67±17.40
$WW \to \ell\ell$	163.68±12.94	154.47±12.57	7589.64±88.11
$\nu Z, Z \to \mu\mu$	96.83±10.38	12.24±3.69	736.81±28.64
$\mu\mu$	1095.66±81.67	298.26±42.61	11060.10±259.47
total background	3063.59±94.22	1174.11±53.21	46990.10±334.20
Ref. point (100,10)	8817.9±276.10	587.86±71.29	19771.1±413.43
Ref. point (100,50)	8186.81±266.04	3423.42±172.42	61094.20±726.75
Ref. point (100,90)	0	0	139210±1094.03



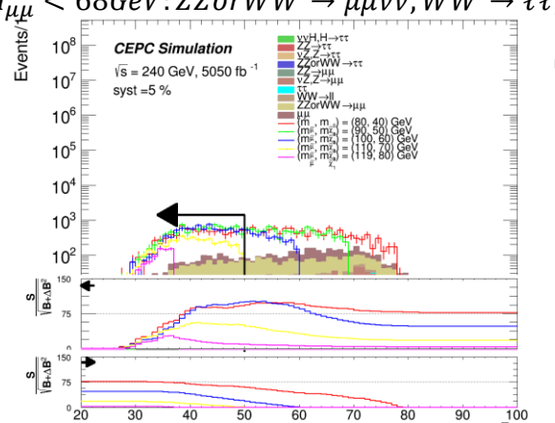
$M_{\mu\mu} < 68GeV: ZZorWW \to \mu\mu\nu\nu, WW \to \ell\ell$



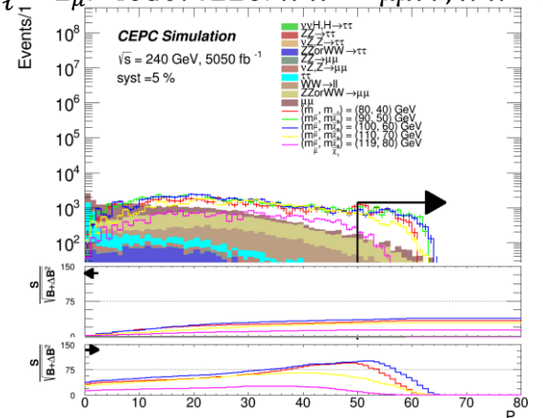
E_μ>40$GeV: ZZorWW \to \mu\mu\nu\nu, WW \to \ell\ell, \mu\mu$

SR-highDeltaM

- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (119, 1) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (119, 20) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (119, 40) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (119, 60) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (100, 10) GeV



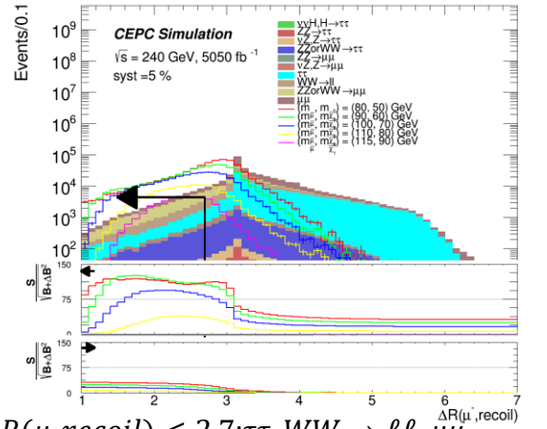
$E_\mu < 50GeV: ZZorWW \to \mu\mu\nu\nu, \mu\mu$



$p_T > 50GeV/c: ZZorWW \to \mu\mu\nu\nu, WW \to \ell\ell, \mu\mu$

SR-midDeltaM

- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (80, 30) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (90, 40) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (100, 50) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (110, 60) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (115, 60) GeV



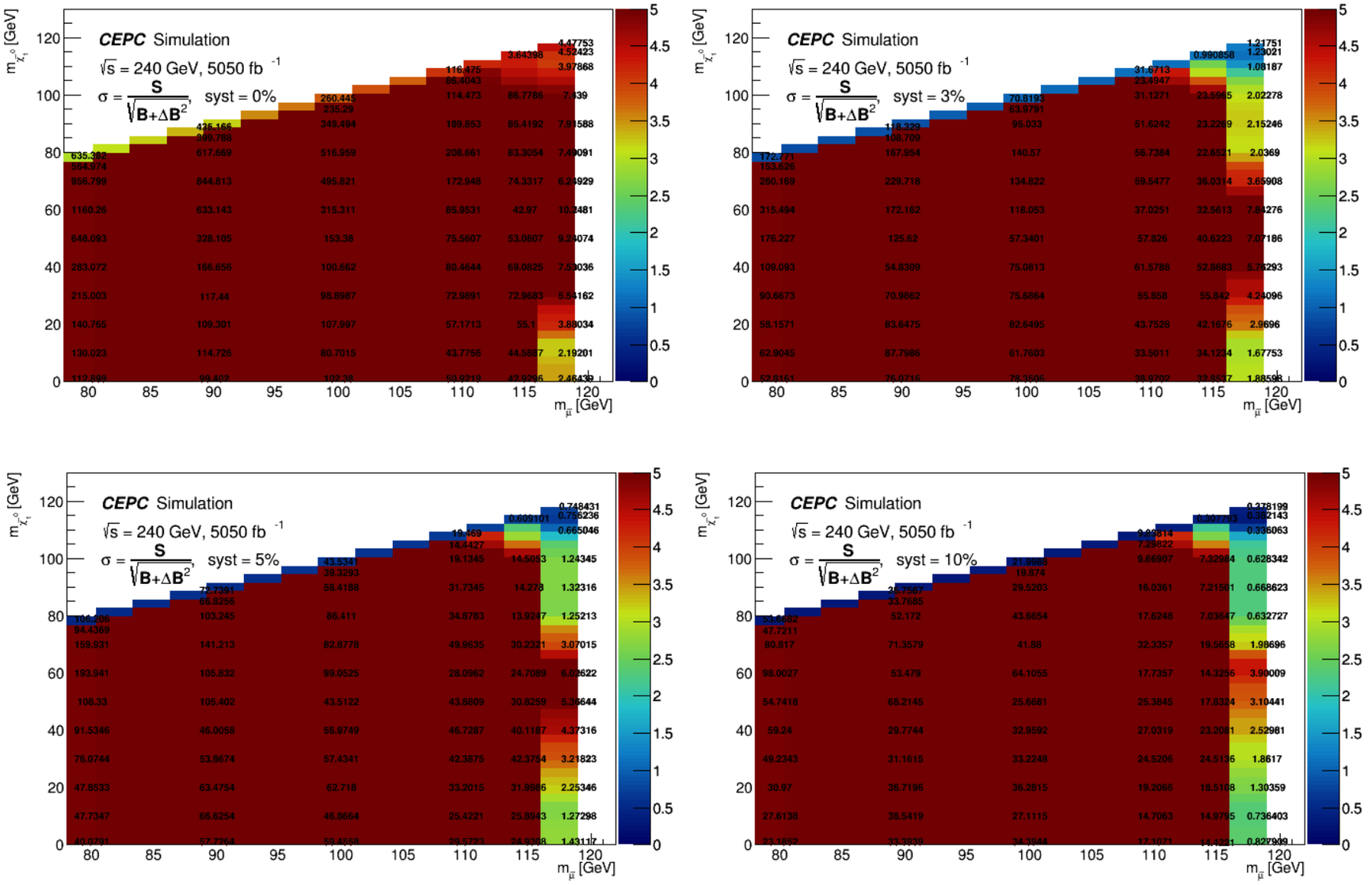
$\Delta R(\mu, recoil) < 2.7: \tau\tau, WW \to \ell\ell, \mu\mu$

SR-lowDeltaM

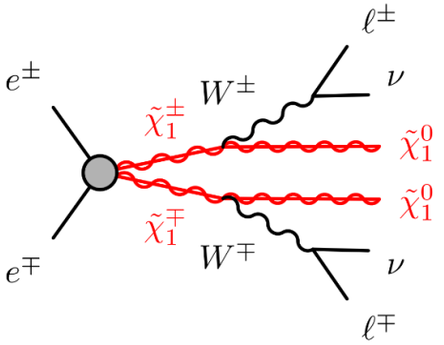
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (119, 90) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (119, 100) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (119, 110) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (119, 115) GeV
- ($m_{\tilde{\mu}}$, $m_{\tilde{\chi}_1^0}$) = (100, 90) GeV

Direct smuon: Sensitivity map

- Assuming 10% systematic uncertainty, the discovery sensitivity reaches up to 115 GeV.



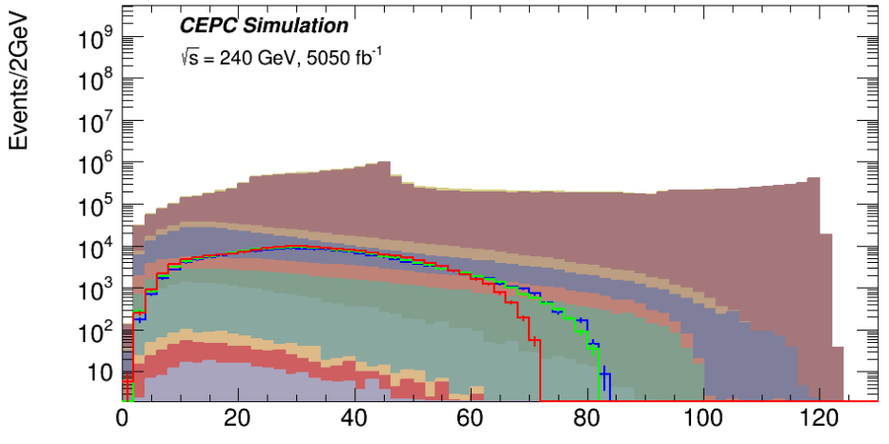
Chargino pair (Bino LSP): Optimization Strategy

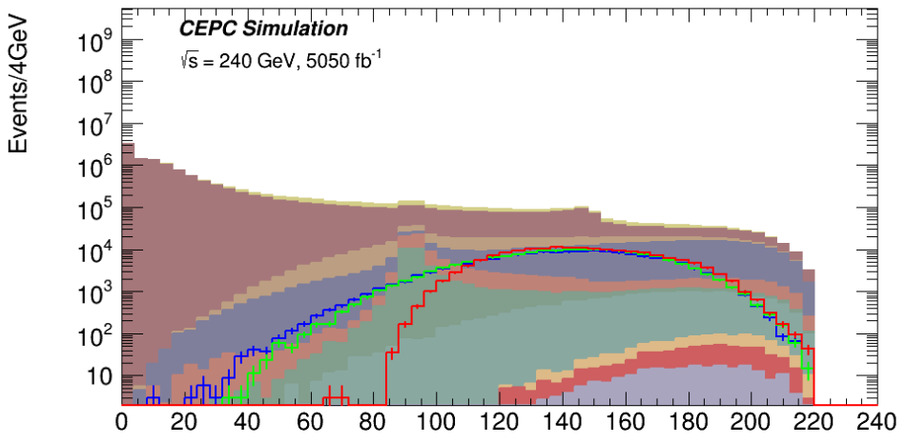


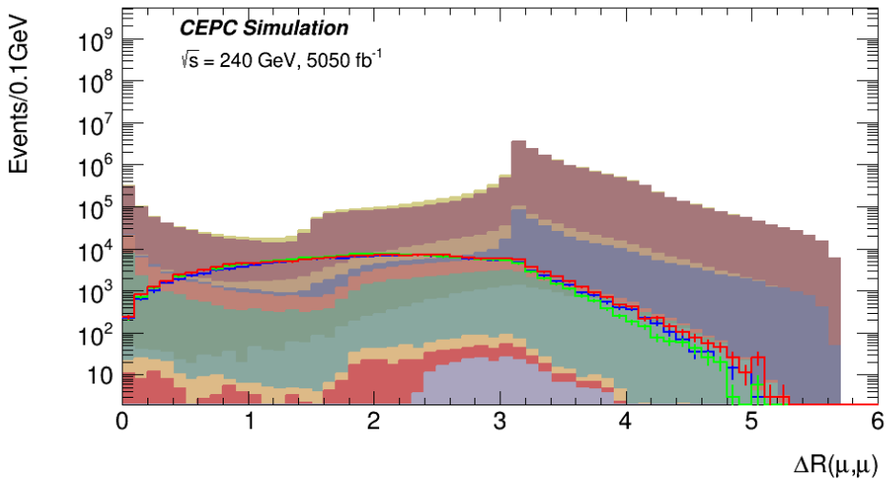
- Select events with 2 OS muons with energy > 10 GeV.
- Perform a multi-dimension optimization considering variables:

$$\Delta R(\mu,\mu), \Delta R(\mu, recoil), \Delta\varphi(\mu,\mu), \Delta\varphi(\mu, recoil), M_{\mu\mu}, M_{recoil}, E_{\mu\mu}, P_T^{\mu\mu}, E_{\mu}, P_T^{\mu}$$

- Check for both upper cut and down cut for each variable.
- Use $\frac{S}{\sqrt{S+B+dB^2}}$ as a sensitivity measurement (consider statistical uncertainty and 5% systematic uncertainty).





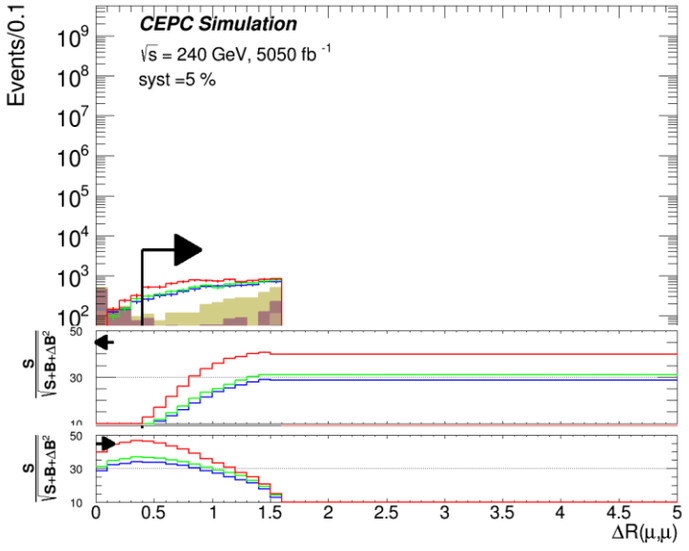


Chargino pair (Bino LSP): SR & Results

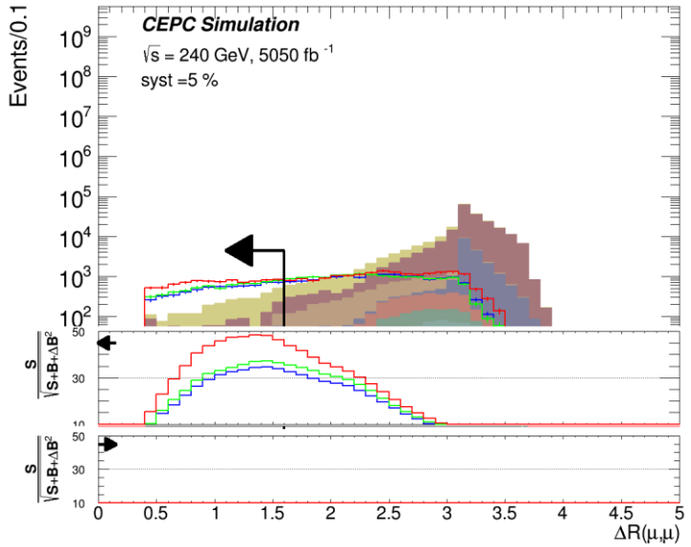
- One signal region is defined.

Signal Region
2 μ (OS, both energy > 10GeV)
$0.4 < \Delta R(\mu,\mu) < 1.6$
$M_{recoil} > 130$ GeV
$p_T^{\mu} > 30$ GeV/c

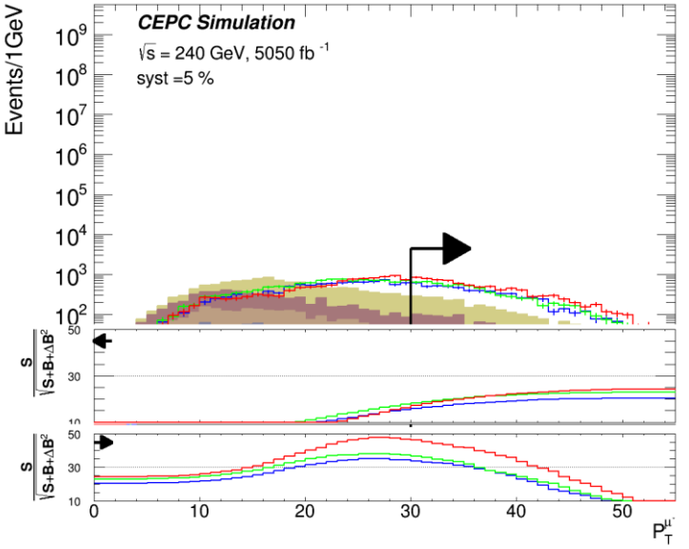
Process	Yield
$\tau\tau$	88.47±14.17
$\nu\nu H, H \to \tau\tau$	0
$ZZorWW \to \tau\tau\nu\nu$	0.74±0.74
$ZZ \to \tau\tau\nu\nu$	0
$\nu Z, Z \to \tau\tau$	0
$ZZorWW \to \mu\mu\nu\nu$	1637.9±41.75
$ZZ \to \mu\mu\nu\nu$	27.68±6.19
$WW \to \ell\ell$	162.66±12.90
$\nu Z, Z \to \mu\mu$	47.86±7.30
$\mu\mu$	608.7±60.87
total background	2568.01±76.86
Ref. point (110,1)	5937.33±130.879
Ref. point (110,10)	6468.17±136.60
Ref. point (110,25)	8470.36±156.32



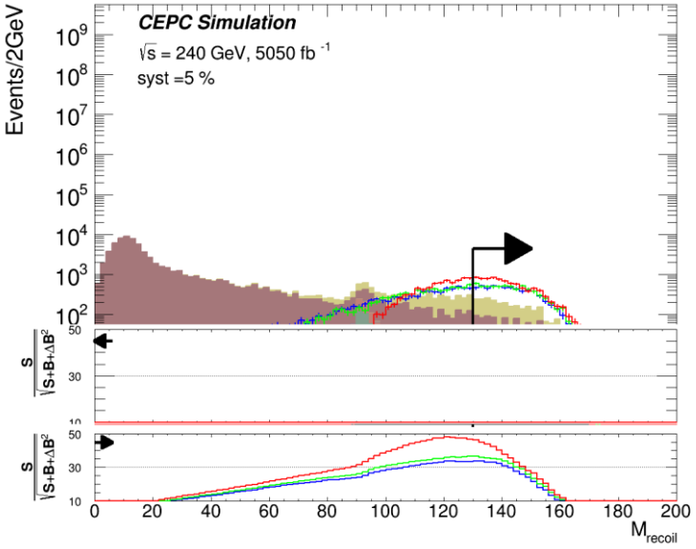
$\Delta R(\mu,\mu) > 0.4$: $\mu\mu$



$\Delta R(\mu,\mu) < 1.6$: $\mu\mu, ZZorWW \to \mu\mu\nu\nu$



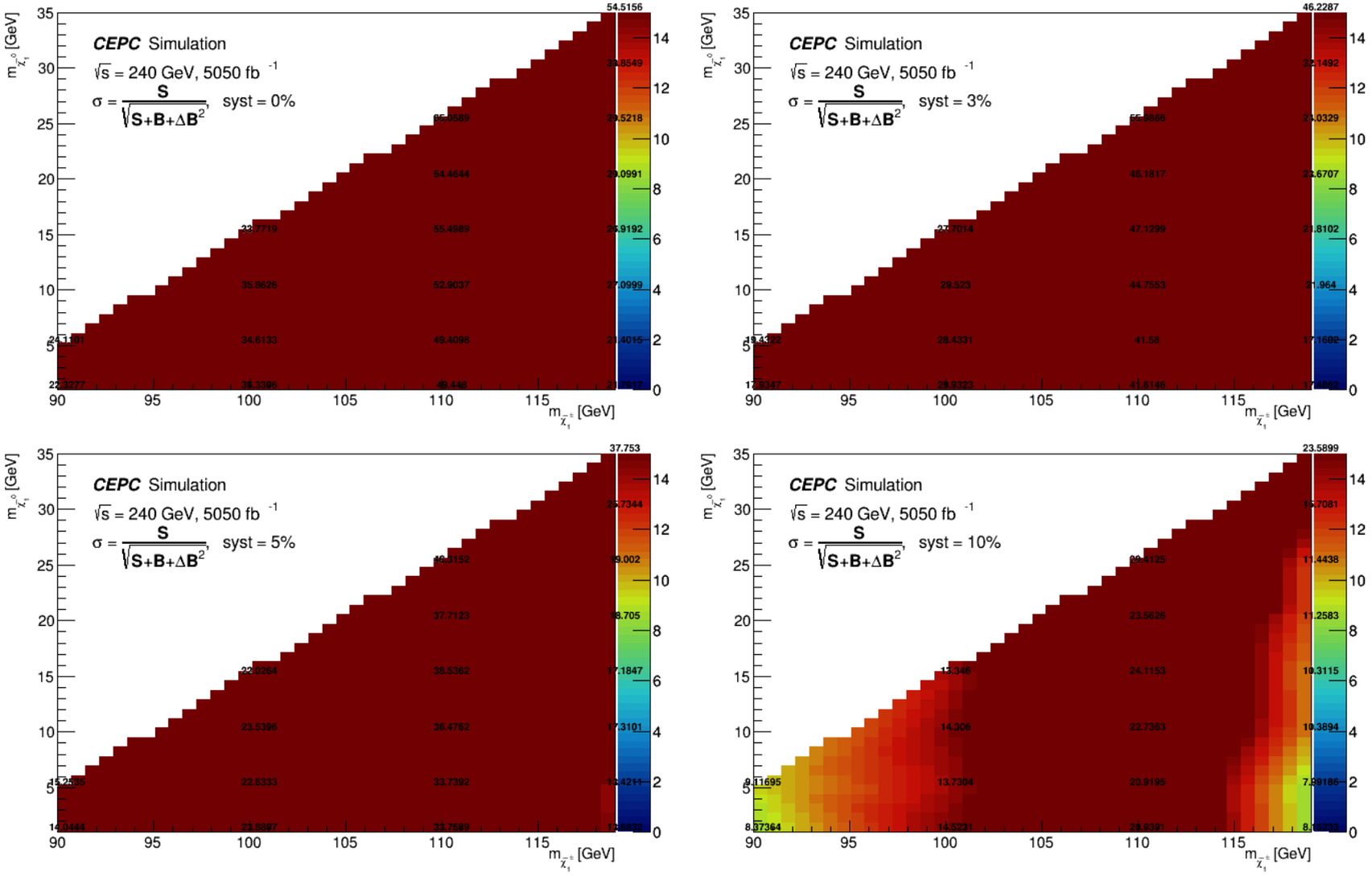
$M_{recoil} > 130$GeV: $\mu\mu, ZZorWW \to \mu\mu\nu\nu$



$p_T^{\mu} > 30$ GeV/c: $\mu\mu, ZZorWW \to \mu\mu\nu\nu$

Chargino pair (Bino LSP): Sensitivity map

- Assuming 10% systematic uncertainty, the discovery sensitivity can still reach up to all the mass phase space.

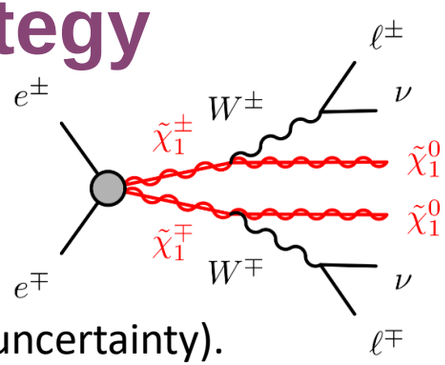


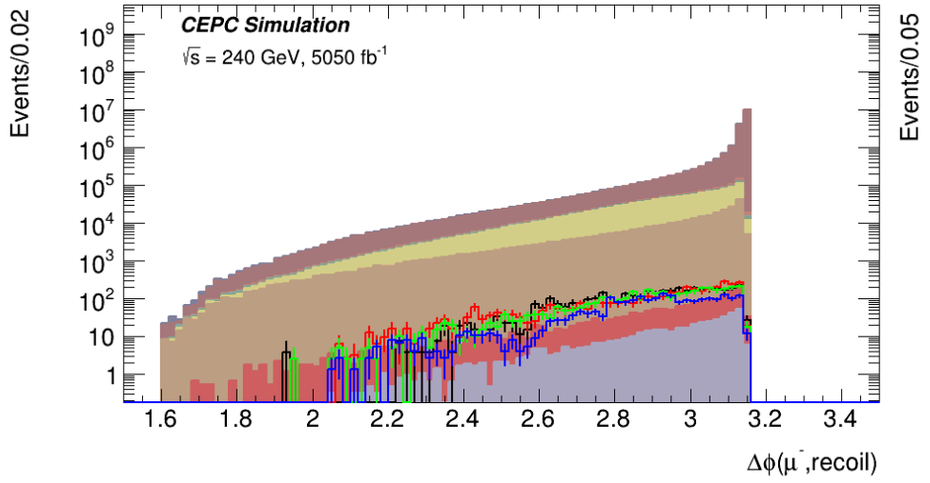
Chargino pair (Higgsino LSP): Optimization Strategy

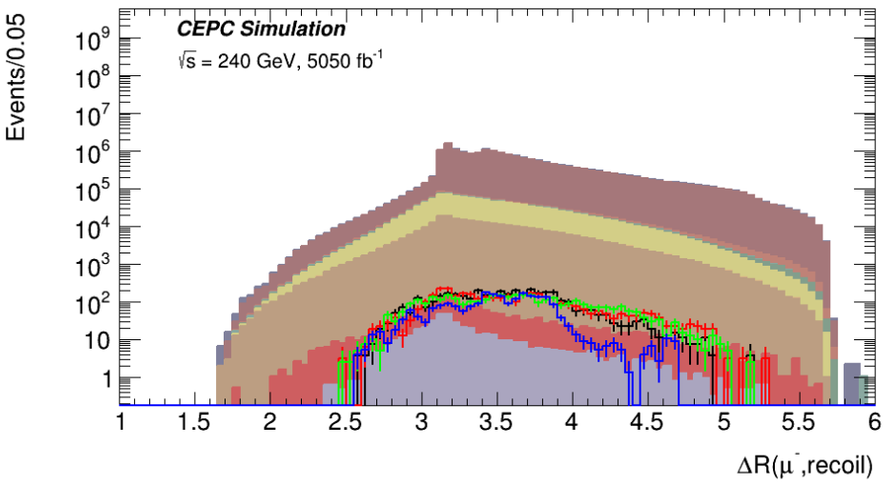
- Select events with 2 OS muons.
- Perform a multi-dimension optimization considering variables:

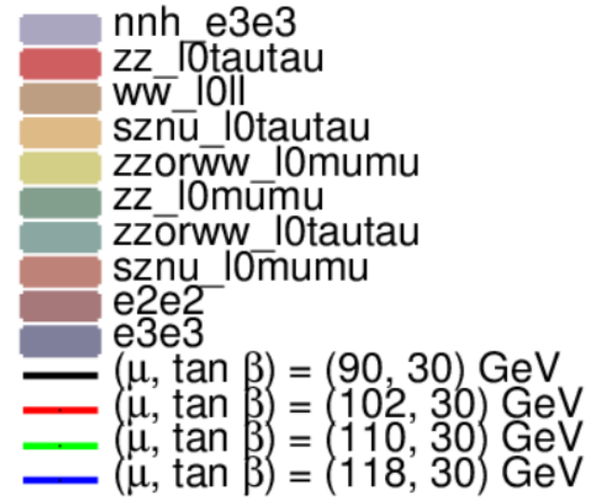
$$\Delta R(\mu,\mu), \Delta R(\mu, recoil), \Delta\varphi(\mu,\mu), \Delta\varphi(\mu, recoil), M_{\mu\mu}, M_{recoil}, E_{\mu\mu}, P_T^{\mu\mu}, E_\mu, P_T^\mu$$

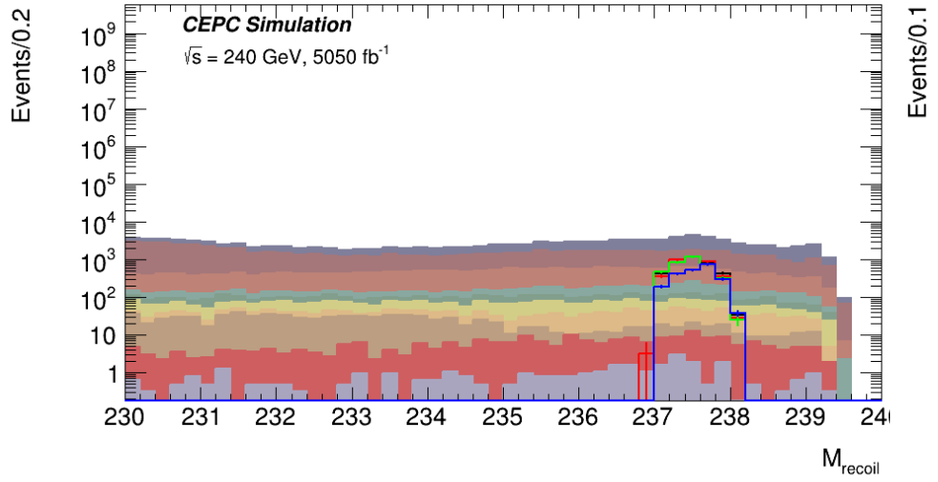
- Check for both upper cut and down cut for each variable.
- Use $Z_n = \sqrt{2}\,\mathrm{erf}^{-1}(1-2p)$ as a sensitivity measurement (consider statistical uncertainty and 5% systematic uncertainty).

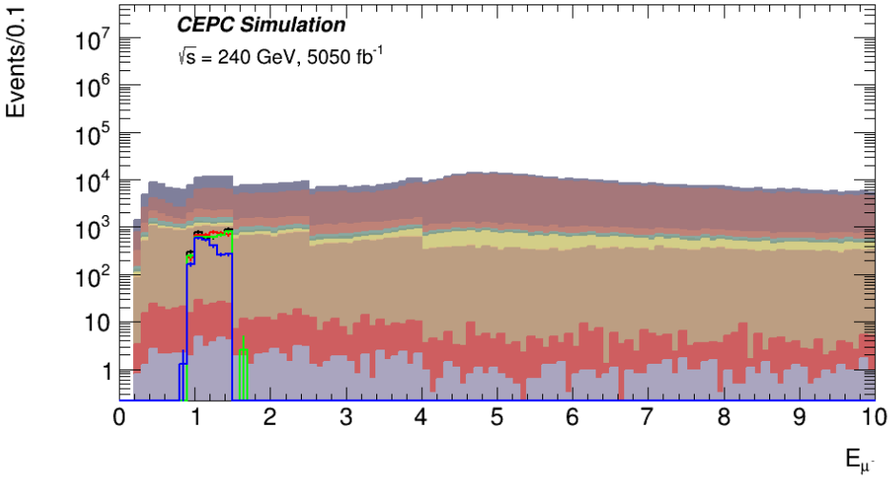










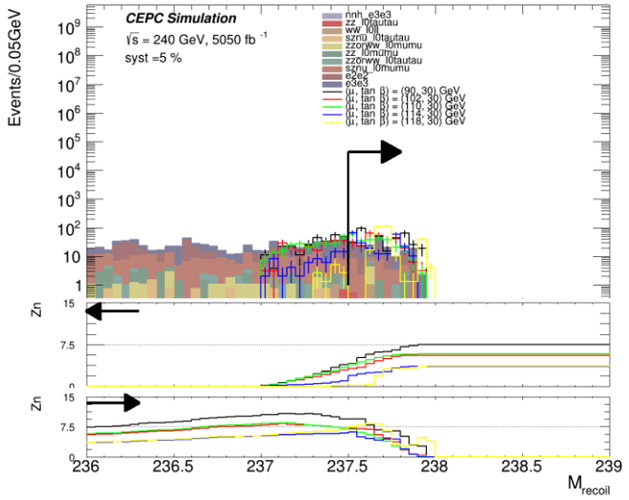


Chargino pair (Higgsino LSP): SR & Results

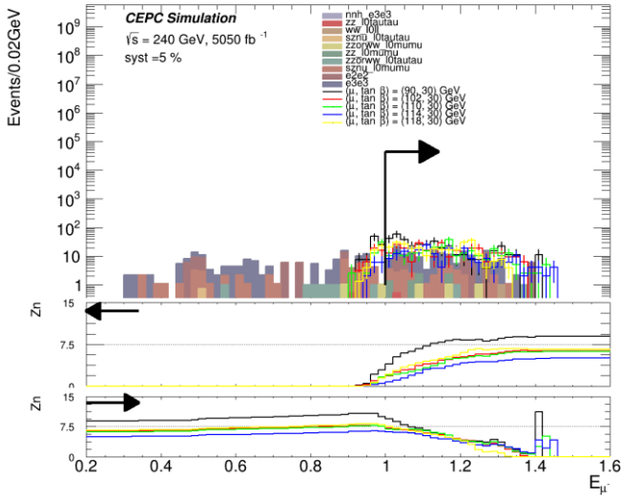
- One signal region is defined.

Signal Region
2 OS μ
$M_{recoil} > 237.5GeV$
E_{μ}>1GeV
$3.2 < \Delta R(\mu, recoil) < 4.6$
$\Delta\phi(\mu, recoil) < 2.9$

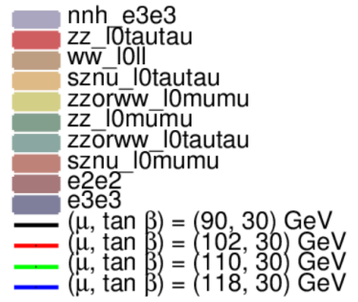
Selection	Yields
$\tau\tau$	106.62±15.55
$\nu\nu H, H \to \tau\tau$	0
$ZZorWW \to \tau\tau\nu\nu$	2.07±1.46
$ZZ \to \tau\tau\nu\nu$	0.53±0.53
$\nu Z, Z \to \tau\tau$	0
$ZZorWW \to \mu\mu\nu\nu$	3.20±1.85
$ZZ \to \mu\mu\nu\nu$	5.54±2.77
$WW \to \ell\ell$	1.02±1.02
$\nu Z, Z \to \mu\mu$	27.83±5.57
$\mu\mu$	42.61±16.10
total background	189.40±23.38
Ref. point (90,30)	400.18±38.69
Ref. point (102,30)	279.84±29.83
Ref. point (110,30)	266.70±26.03
Ref. point (118,30)	296.40±19.63

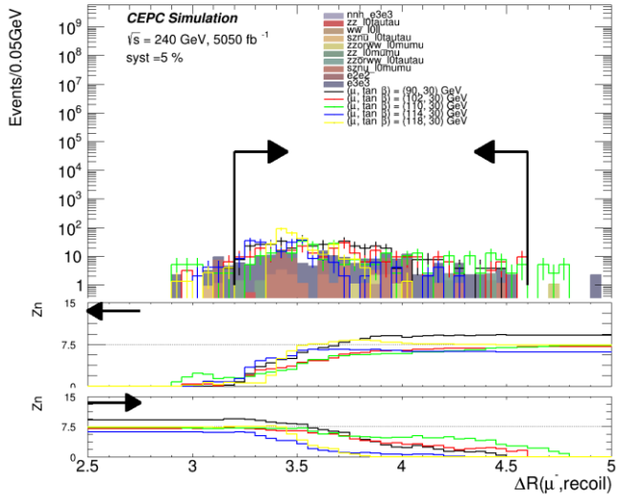


$M_{recoil} > 237.5GeV$: $ZZorWW \to \mu\mu\nu\nu, \mu\mu$

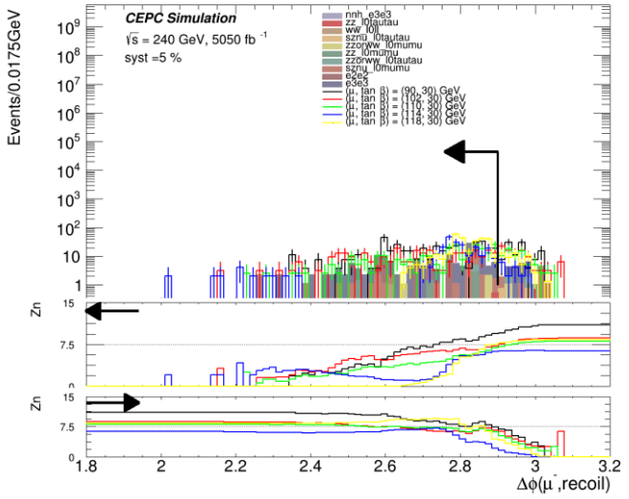


E_{μ}>1GeV: $\nu Z, Z \to \mu\mu, \mu\mu$





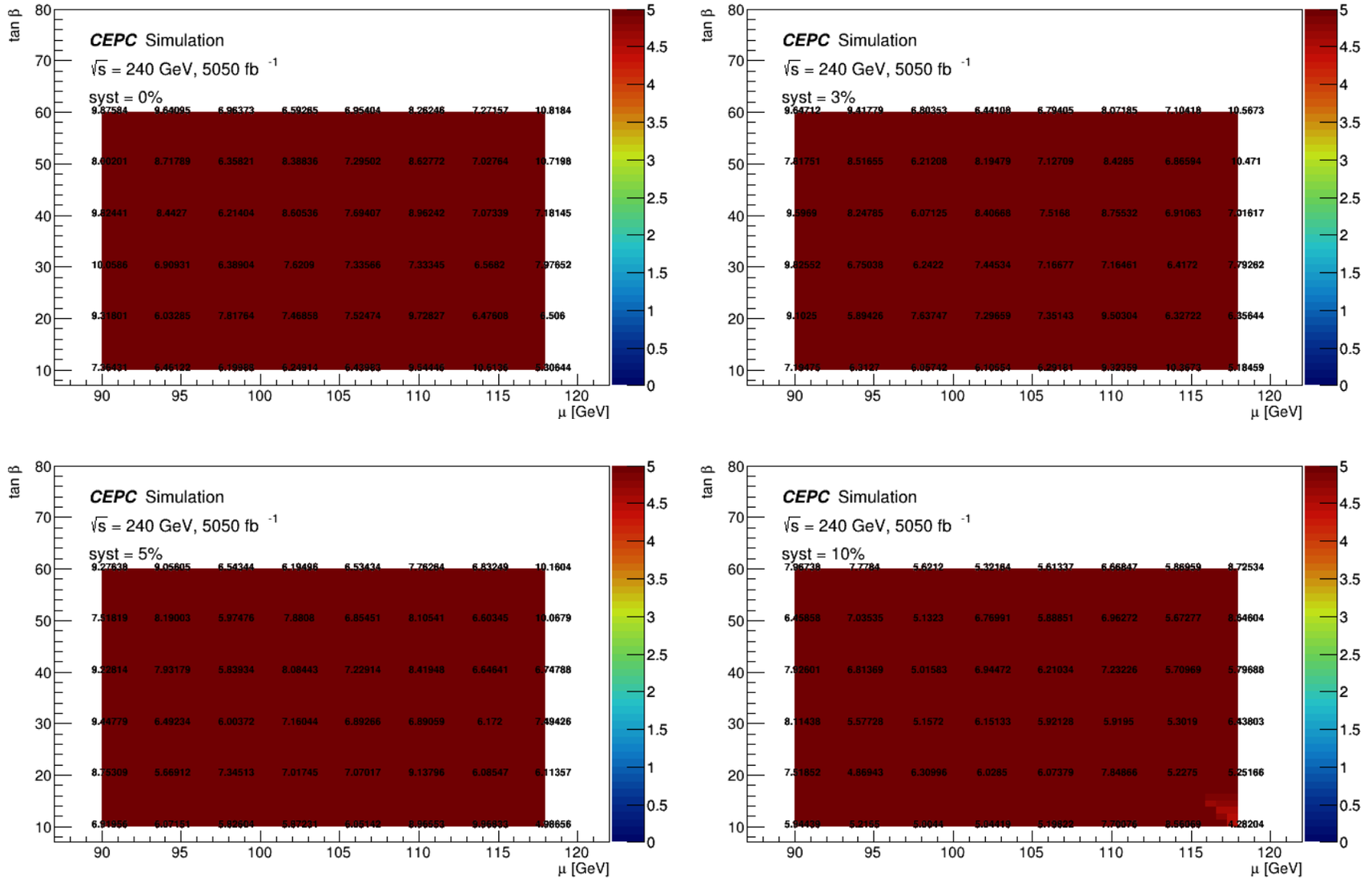
$3.2 < \Delta R(\mu, recoil) < 4.6$: $\tau\tau, \mu\mu$



$\Delta\phi(\mu, recoil) < 2.9$: $\tau\tau$

Chargino pair (Higgsino LSP): Sensitivity map

- Assuming 10% systematic uncertainty, the discovery sensitivity can reach up to 118 GeV except a corner at high-μ region.



Summary

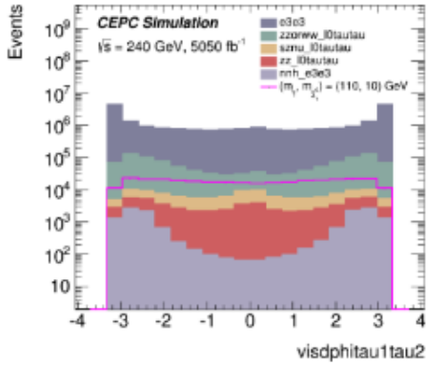
- A preliminary SUSY sensitivity study has been performed to direct stau production, direct smuon production and chargino pair production (Bino LSP and Higgsino LSP) in CEPC, which is promising. With assuming 10% systematic uncertainty:
  - For direct stau production, the discovery sensitivity reaches up to 115 GeV.
  - For direct smuon production, the discovery sensitivity reaches up to 115 GeV.
  - For chargino pair production (Bino LSP), the discovery sensitivity can still reach up all the mass phase space.
  - For chargino pair production (Higgsino LSP), the discovery sensitivity can reach up to 118 GeV.

Thank you.

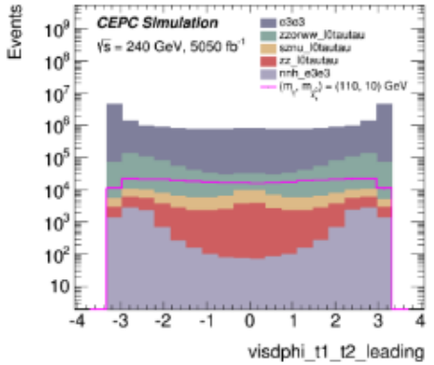
Backup

Validation of the angular between tracks vs truth taus

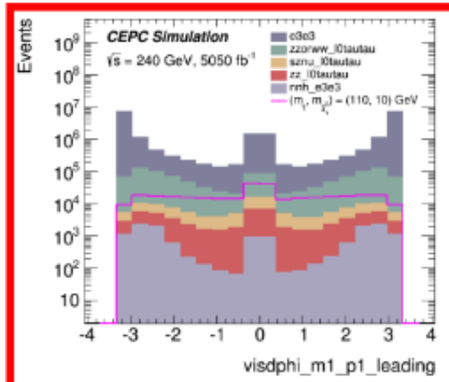
- **Compare the angular at different truth levels**
  - Between two truth tau leptons
  - Between two leading tracks originating from tau leptons
  - Between two leading tracks with opposite sign → least truth info



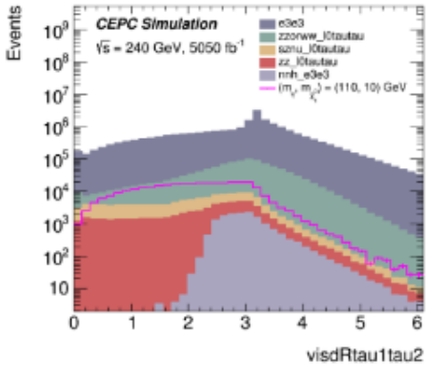
(a) truth tau leptons



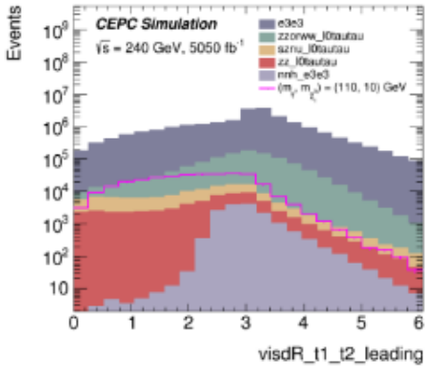
(b) leading track from tau lepton



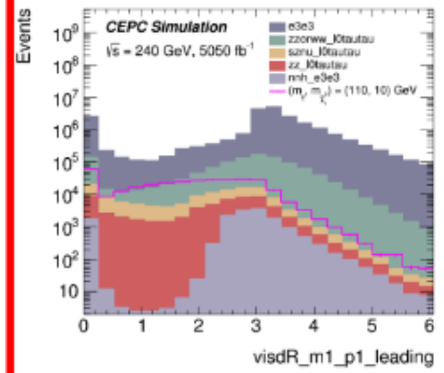
(c) Recon leading OS tracks



(d) truth tau leptons



(e) leading track from tau lepton

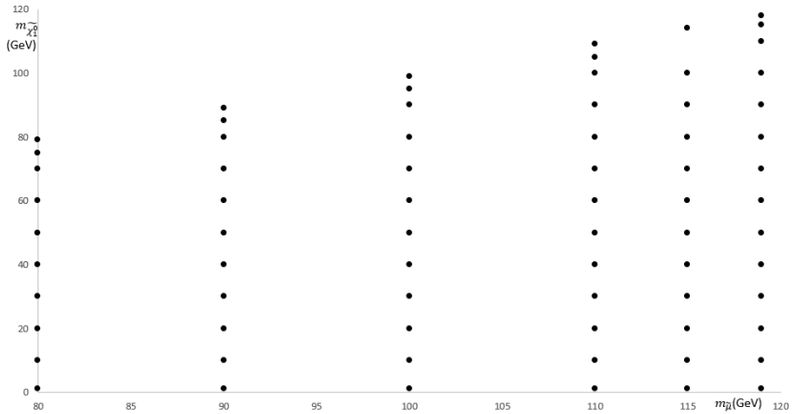


(f) Recon leading OS tracks

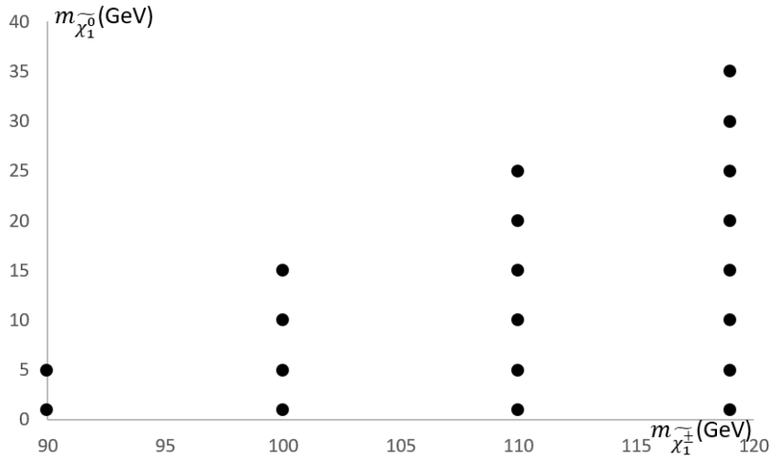
- Many OS tracks generated from the same parent → very close to each other
- Observed in both signal and backgrounds
- **In general, promising to use the angular of the OS leading tracks**

Samples

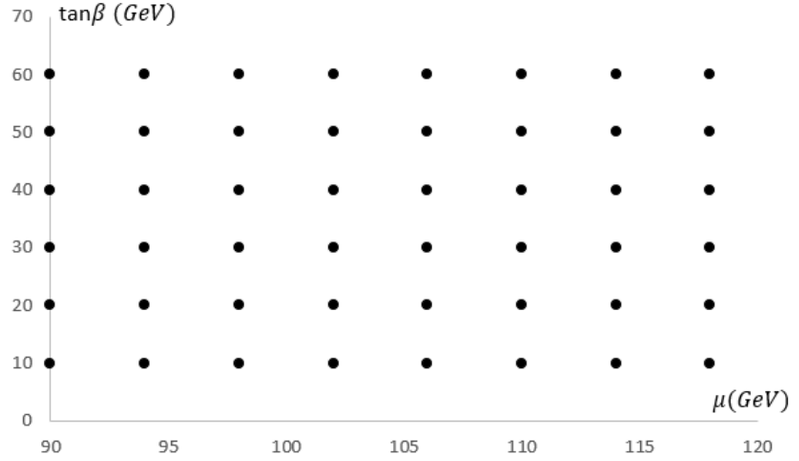
- Direct smuon



- Chargino pair (Bino LSP)



- Chargino pair (Higgsino LSP)

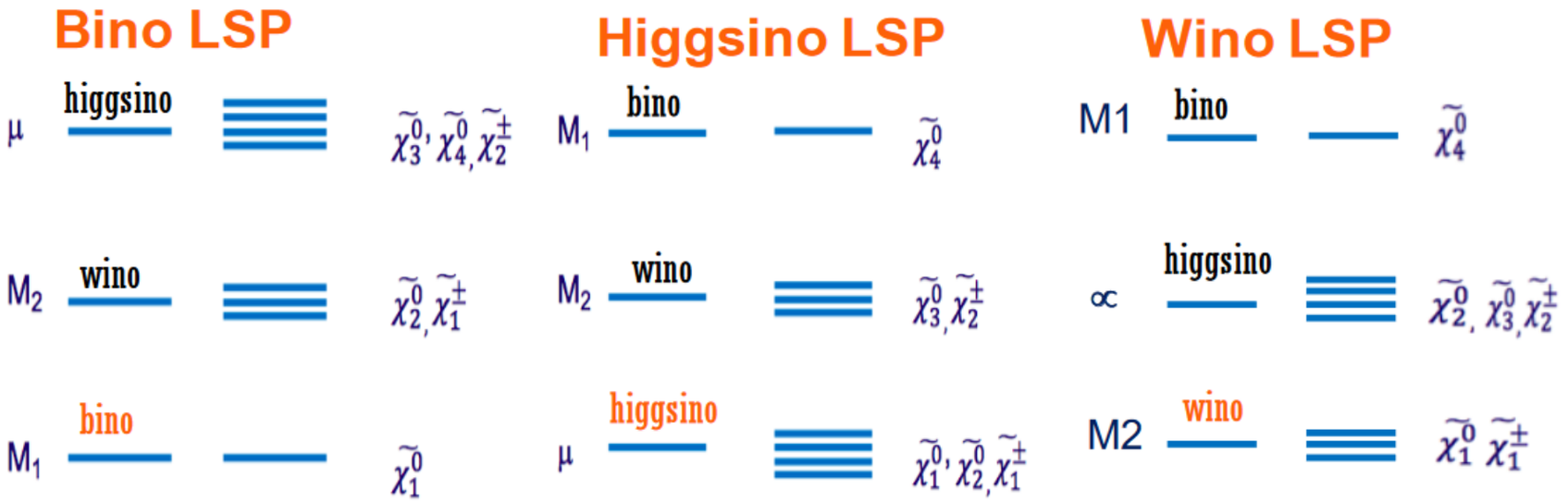


Zn

Signal significance Z_n

$Z_n = \sqrt{2}\,\mathrm{erf}^{-1}(1-2p)$, where $p \propto \int_0^\infty dbG(b; N_b, \delta b) \sum_{i=N_s+b}^{\infty} \frac{e^{-b} b^i}{i!}$

Electrowikinos mass split



Standard wino-bino case: large Δm between N1 and C1/N2;

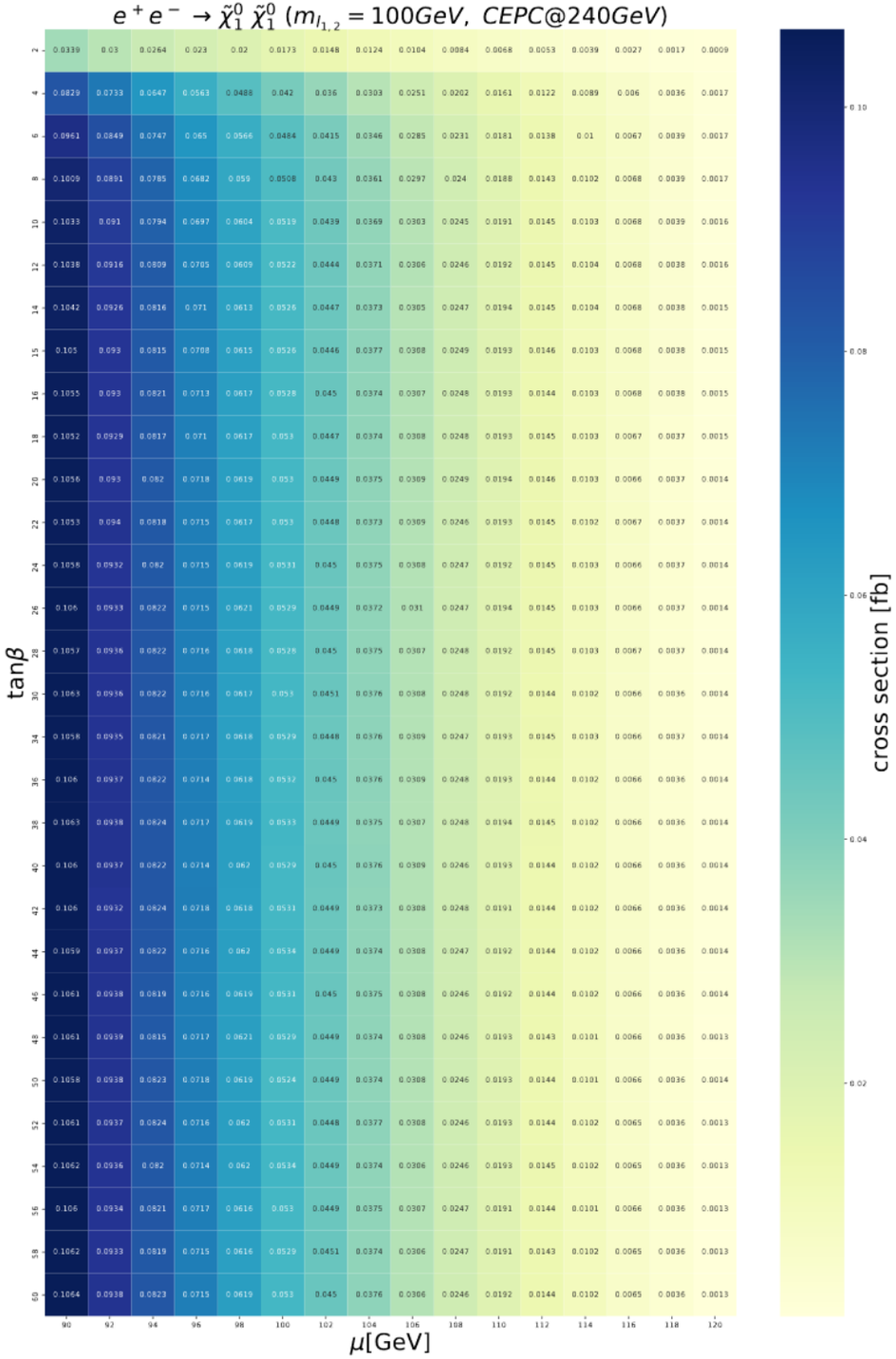
➔ MET + hard leptons

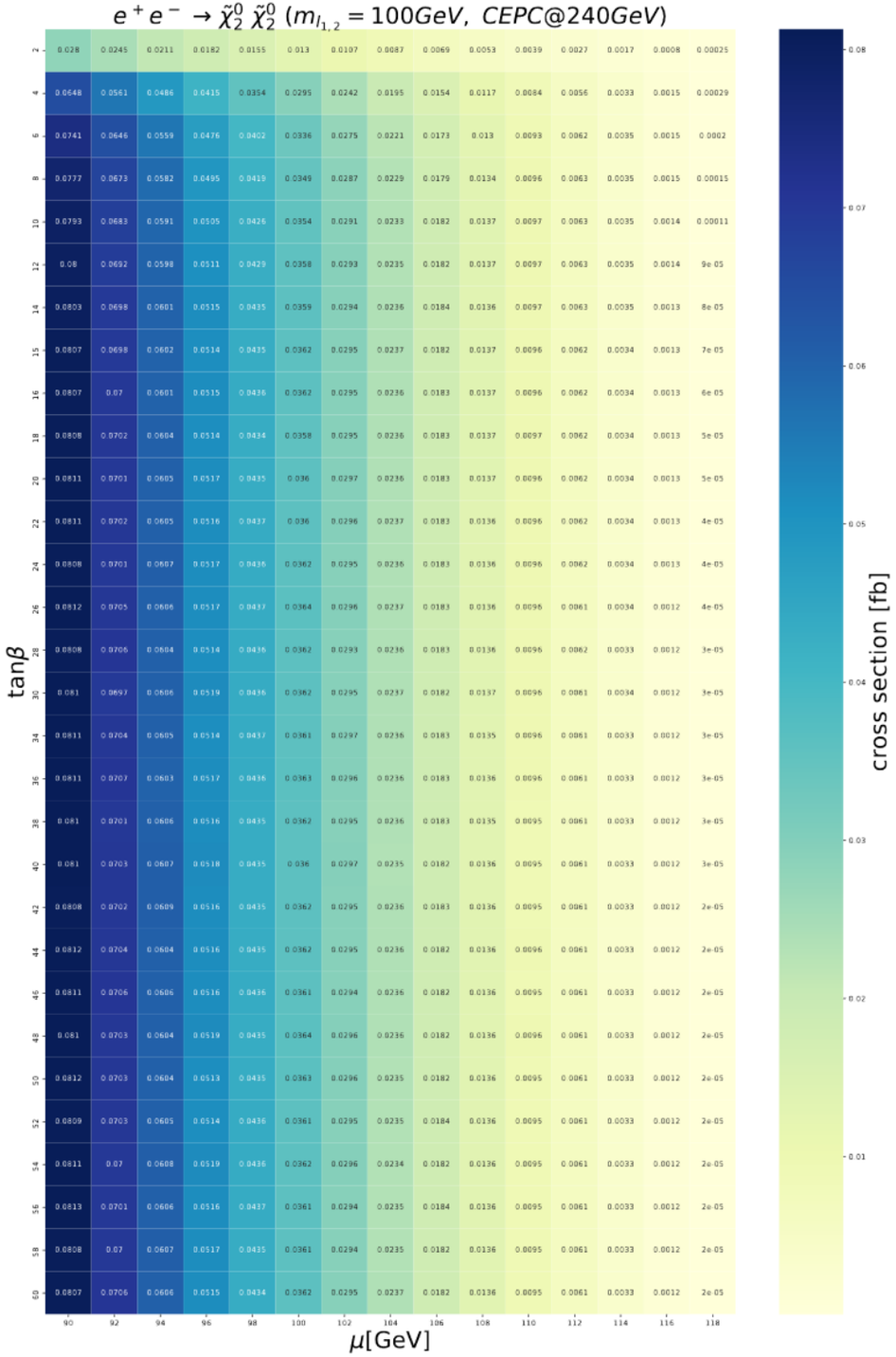
N1,N2,C1 almost degenerate: experimental challenging;

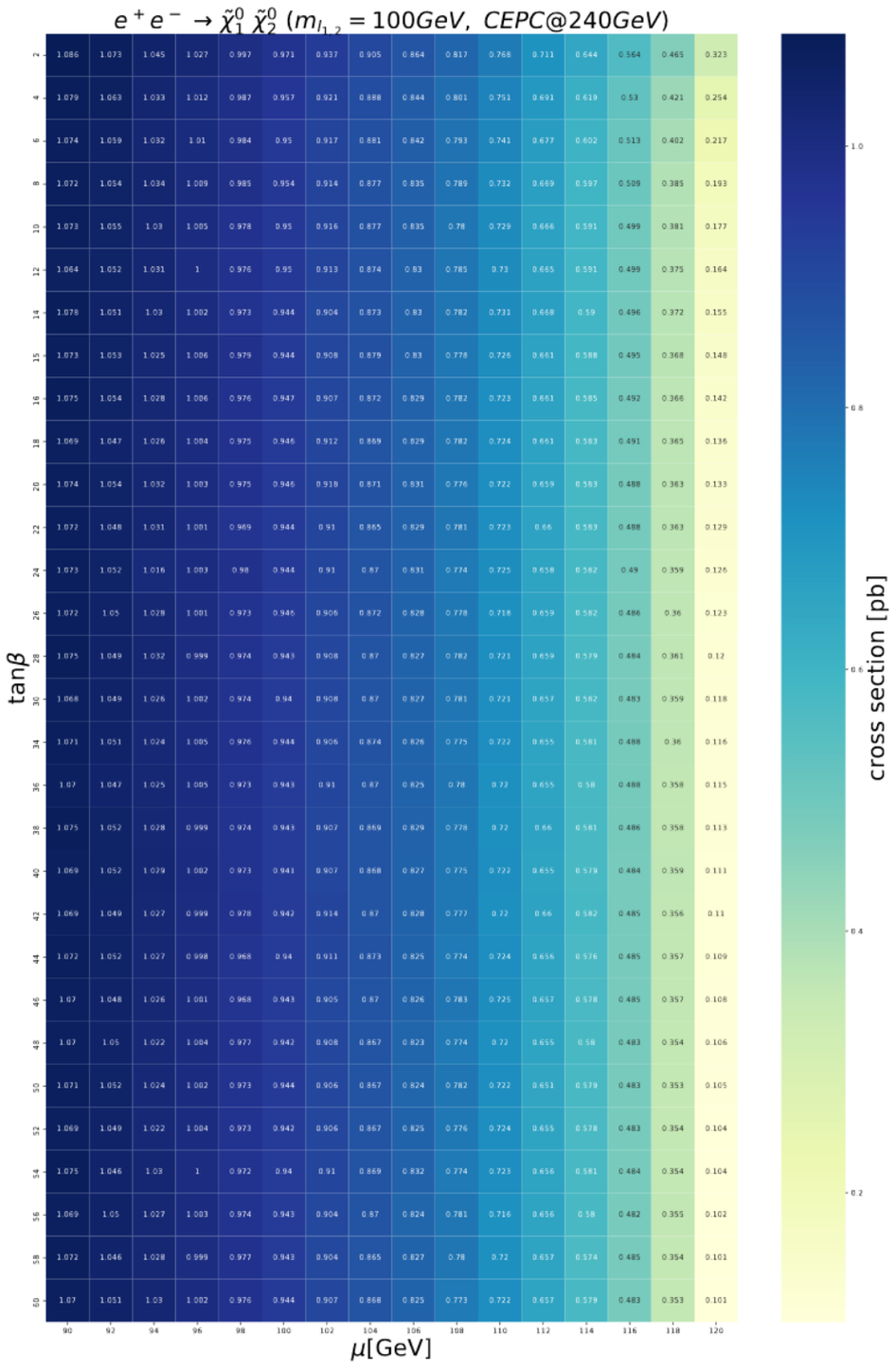
➔ MET + soft leptons

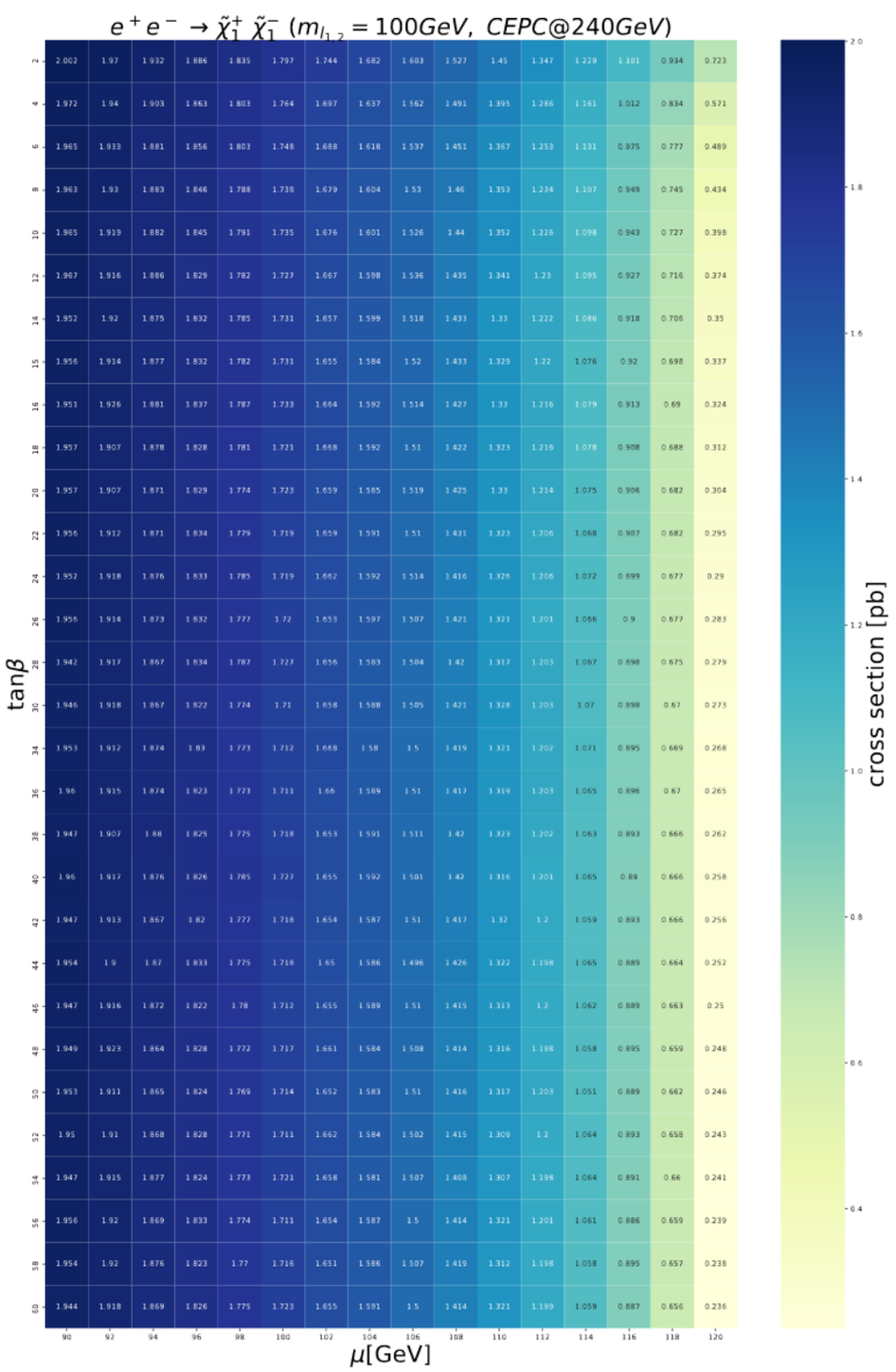
➔ Lower xsec than higgsino LSP;

➔ WW+MET dominant;


$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ($m_{l_{1,2}} = 100GeV$, $CEPC@240GeV$)
tanβ
μ[GeV]
cross section [fb]


$e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$ ($m_{l_{1,2}} = 100GeV$, $CEPC@240GeV$)
tanβ
μ[GeV]
cross section [fb]


$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$ ($m_{l_{1,2}} = 100GeV$, $CEPC@240GeV$)
tanβ
μ[GeV]
cross section [pb]


$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$ ($m_{l_{1,2}} = 100GeV$, $CEPC@240GeV$)
tanβ
μ[GeV]
cross section [pb]