Prospects for Slepton and Electroweakino searches at CEPC

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CEPC味物理-新物理和相关探测技术研讨会

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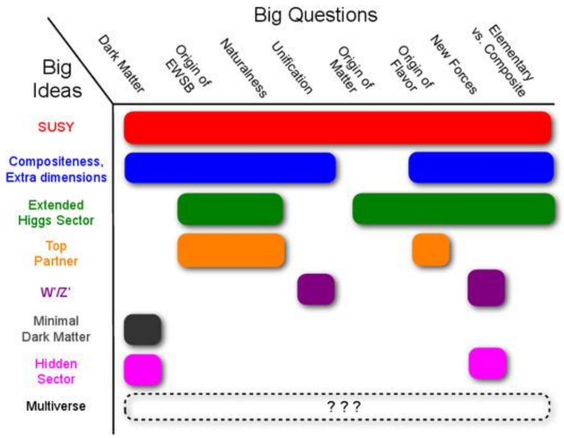
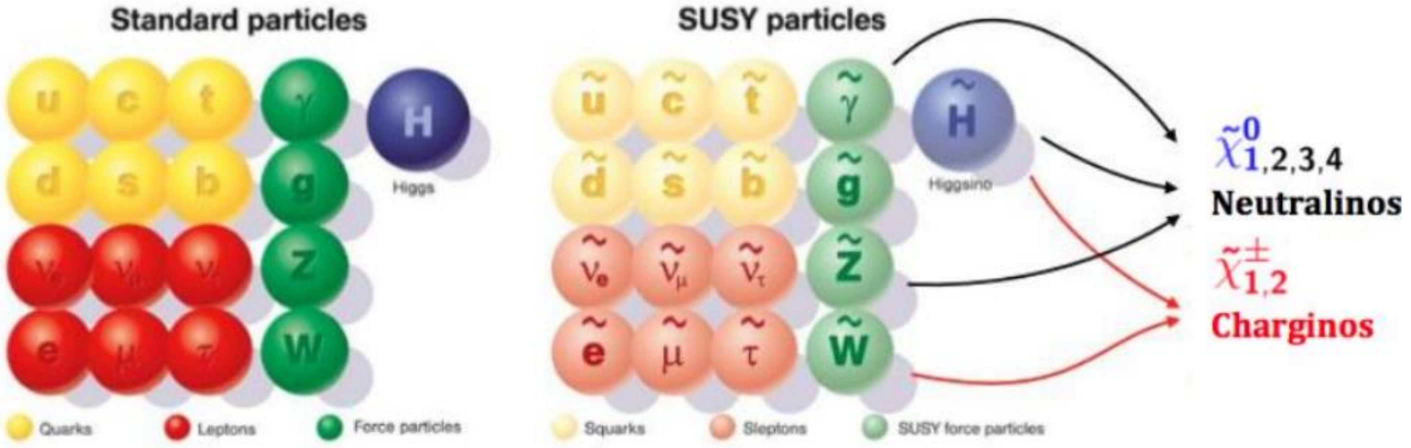
Introduction

- Standard Model (SM) of particle physics
  - Excellent agreement between the experimental observations and the predictions.
  - Some problems are still unsolved, such as dark matter, hierarchy problem, unification problem.
- Many beyond-SM theories are proposed to solve these problems.
- Supersymmetry (SUSY) is one of the most appealing BSM theories.
  - Introduces a new symmetry between bosons and fermions
  - Helps to explain dark matter, solve hierarchy problem and unification problem
- R-parity: $R_p = (-1)^{3B+L+2S} = \begin{cases} +1 \text{ for SM particles} \\ -1 \text{ for SUSY particles} \end{cases}$
- With R-parity conserved, SUSY particles are produced in pair, and the lightest supersymmetric particle (LSP) is stable.

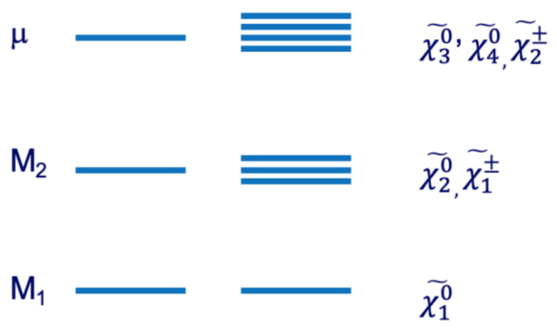




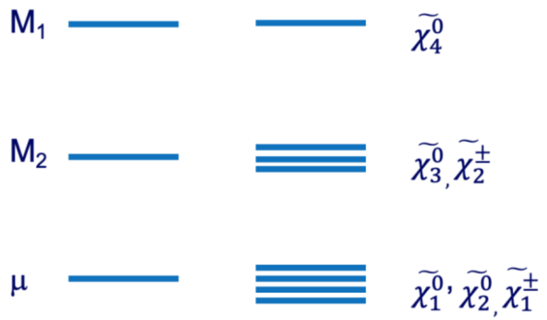
Introduction – Chargino Pair Production

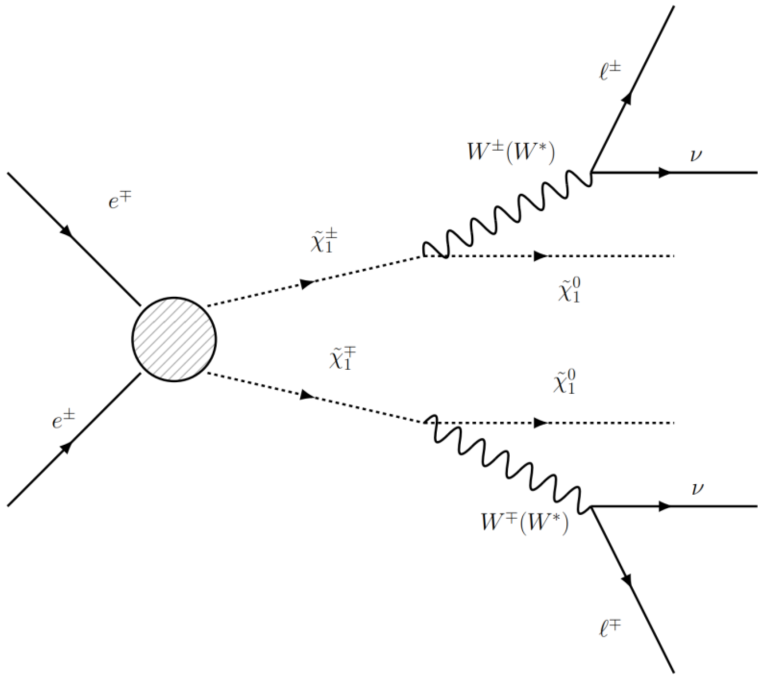
- This talk will present four prospective searches for slepton and electroweakino.
- The first two searches are for the chargino pair production.
- Bino-wino search via chargino pair production with **two muon**
  - Bino-like $\tilde{\chi}_1^0$, wino-like $\tilde{\chi}_1^\pm$
  - **Large mass-splitting** between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$
- Higgsino search via chargino pair production with **two muon**
  - Higgsino-like $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$
  - **Almost mass-degenerate** $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$
  - Natural SUSY models predict higgsino mass is about several hundred GeV.

Bino-wino case



Higgsino case

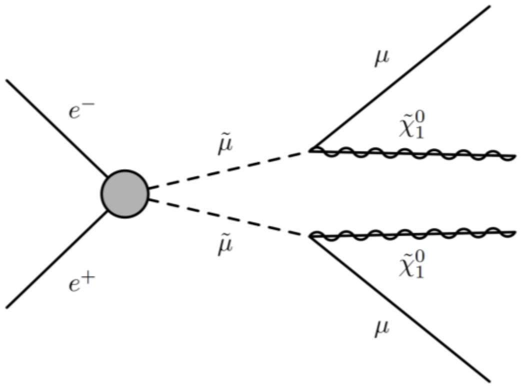


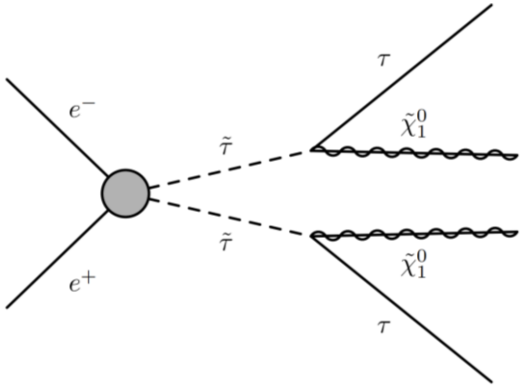


Jiarong Yuan et al, Chinese Phys. C 46 013104 (2022)

Introduction – Direct Slepton Production

- The last two searches are for direct slepton production.
- **Theoretical motivation** for light slepton scenarios
  - Models with light sleptons satisfy the dark matter relic density measurements.
  - Light sleptons can take part in the coannihilation of neutralinos.
  - Gauge-mediated and anomaly-mediated SUSY breaking models expect sleptons masses are several hundred GeV
- Direct smuon production with two muon
  - Light smuons can explain muon g-2 excess
- Direct stau production with **two hadronic tau**
  - The stau is lighter than other sleptons, squarks and gluinos, so there is higher possibility to find stau.

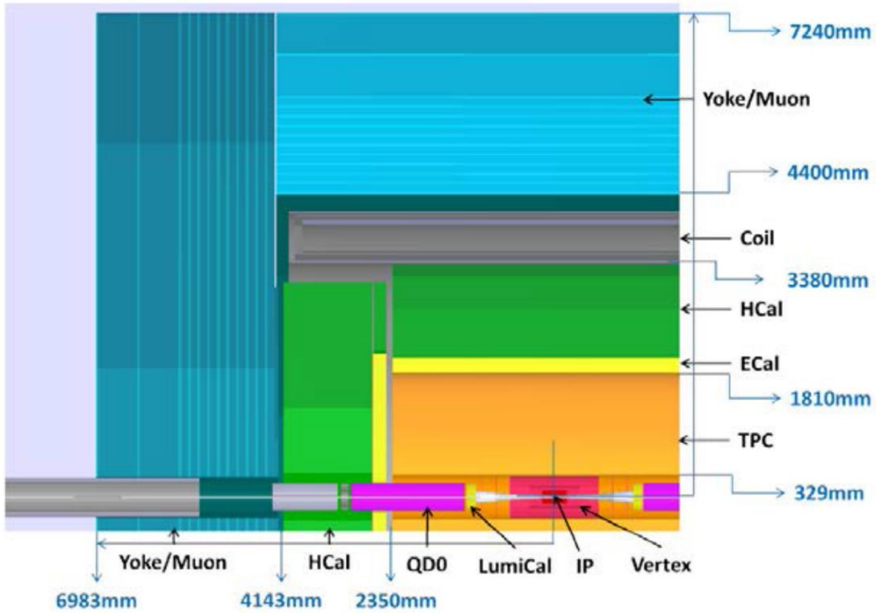




Jiarong Yuan et al, arXiv:2203.10580 (2022)

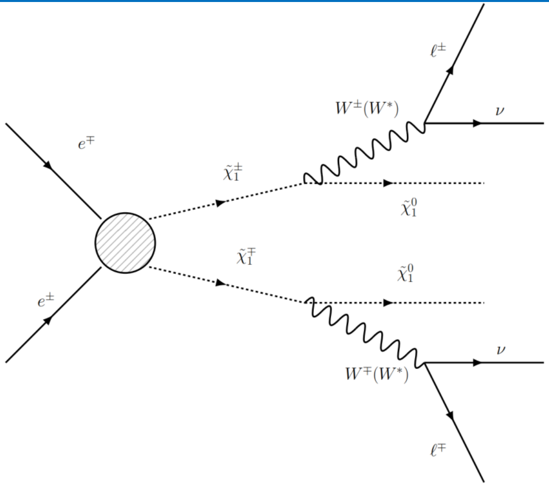
Techniques in CEPC Analysis

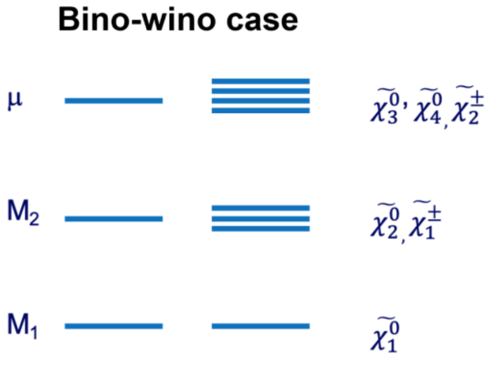
- Baseline CEPC detector design
  - a particle-flow oriented detector
  - Structure: vertex detector, silicon tracker, time projection chamber (TPC), electromagnetic calorimeter (ECAL), hadronic calorimeter (HCAL), solenoid + muon detector
- E_{cm}: 240 GeV, Luminosity: 5050 fb^{-1}
- **Software**
  - **Generation**
    - SUSY Signal sample: MadGraph 2.7.3 + Pythia 8.244
    - Standard Model MC sample: Whizard 1.95
  - **Simulation**: MokkaC
  - **Reconstruction**
    - Track reconstruction: Clupatra
    - Object reconstruction: Arbor(particle flow algorithm)
    - Lepton identification: LICH based on Multivariate Data Analysis (TMVA)



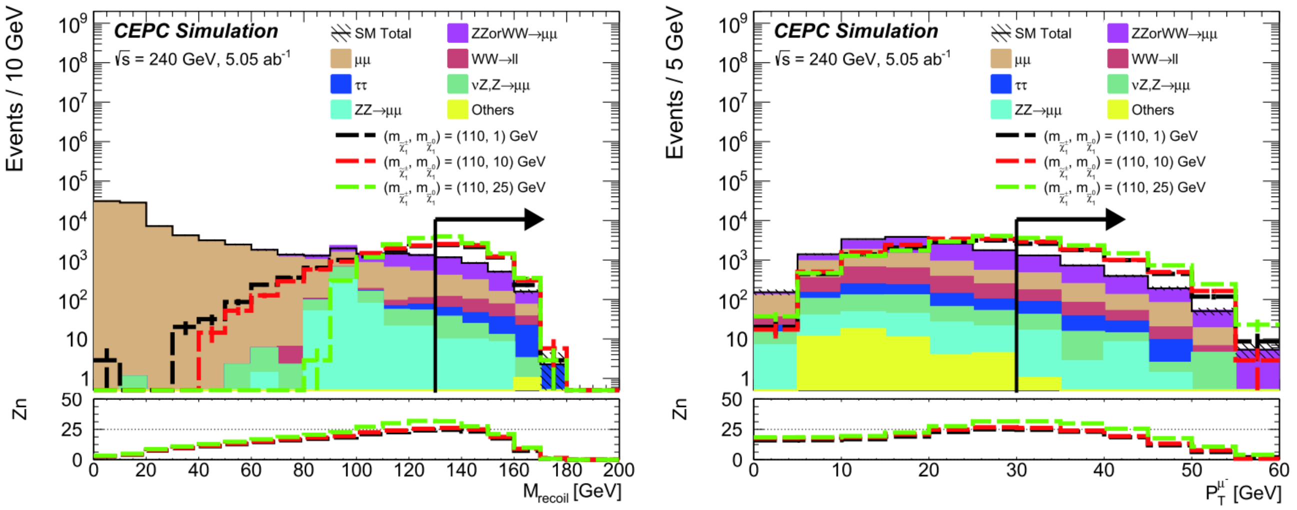
Bino-wino Search with Two Muons

- Signal scenario:
  - **Pair production of wino-like $\tilde{\chi}_1^{\pm}$ decaying via W boson**
  - Chargino mass ranges from 90 GeV(LEP limit) to ~<120 GeV (CEPC kinematic limit)
- Signature: **2 muons + large M_{recoil}**
  - Recoil mass M_{recoil} : the invariant mass of the system recoiling against the two leptons assuming the event total energy $\sqrt{s}$ and zero momentum
  - $M_{\ell\ell}^2 = (\sqrt{s} - E_{\ell\ell})^2 - p_{\ell\ell}^2 = s - 2\sqrt{s}E_{\ell\ell} + m_{\ell\ell}^2$
- Signal region
  - $P_T^{\mu} > 30$ GeV: suppress soft muon backgrounds
  - $M_{recoil} > 130$ GeV: **The most powerful cut.** Large for signal due to $\tilde{\chi}_1^0$ and ν





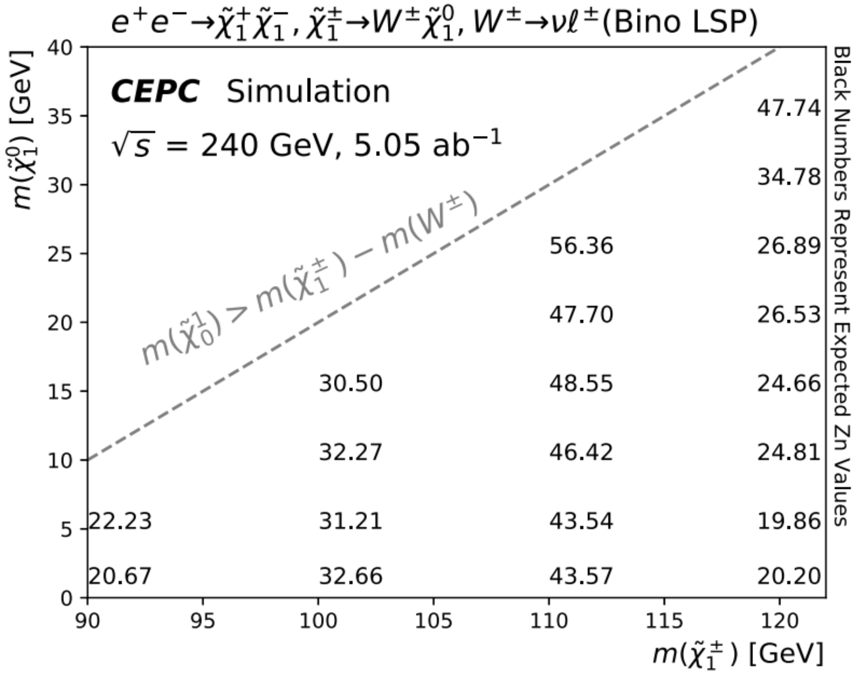
Signal Region
Exactly 2 OS muons
$E_{\mu} > 10$ GeV
$0.4 < \Delta R(\mu^+, \mu^-) < 1.6$
$P_T^{\mu} > 30$ GeV
$M_{recoil} > 130$ GeV



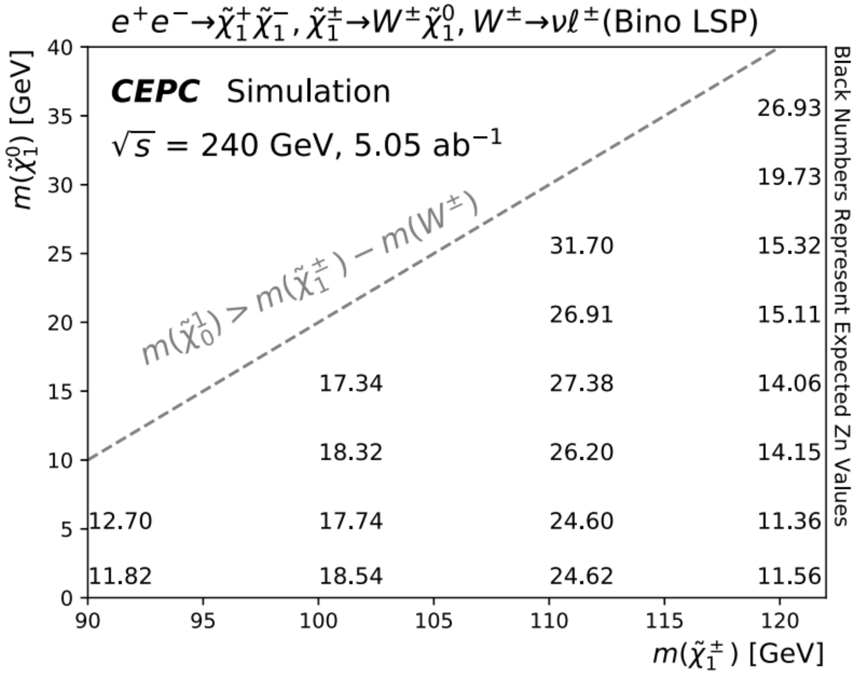
"N-1" plots: kinematic distributions in SR before the selection on that kinematic is made.

Bino-wino Search with Two Muons

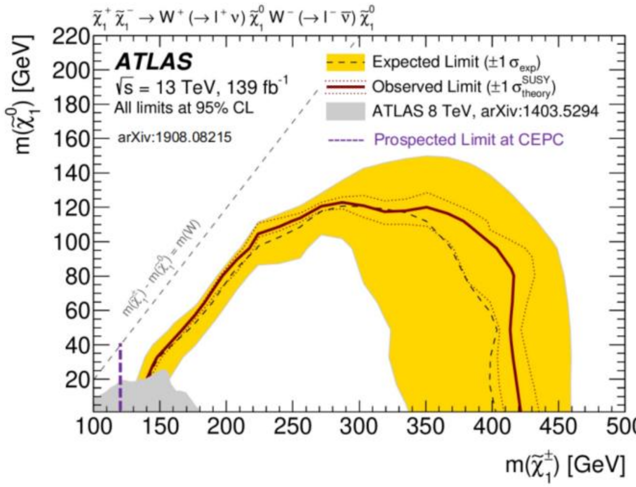
- The discovery potential can reach up to kinematic limit $\sqrt{s}/2$
- Cover the compressed region, which is challenging for hadron collider
- No large influence of systematic uncertainty on signal sensitivity



(a) systematic uncertainty = 0%

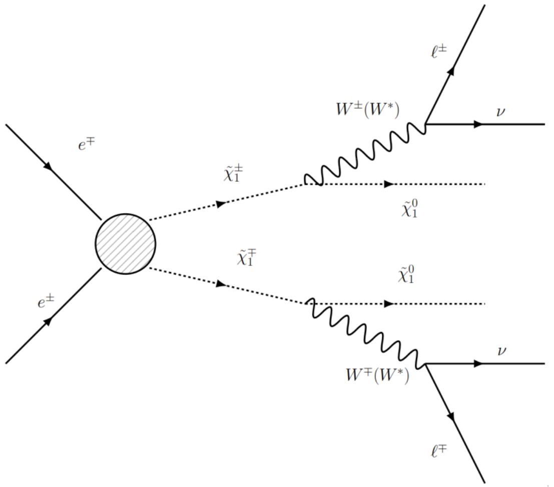


(b) systematic uncertainty = 5%

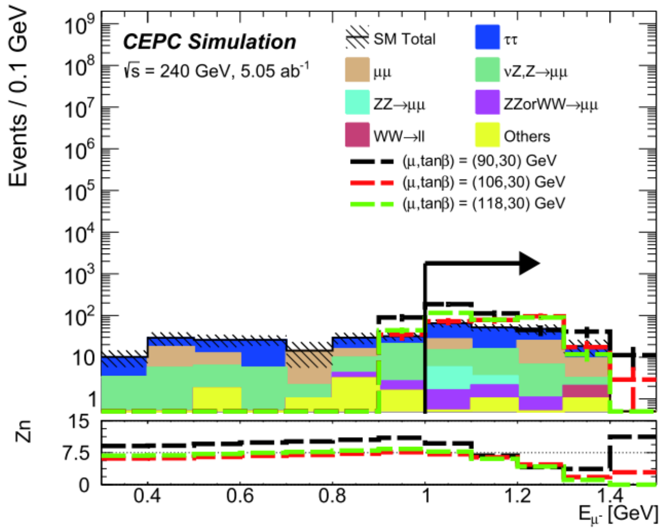


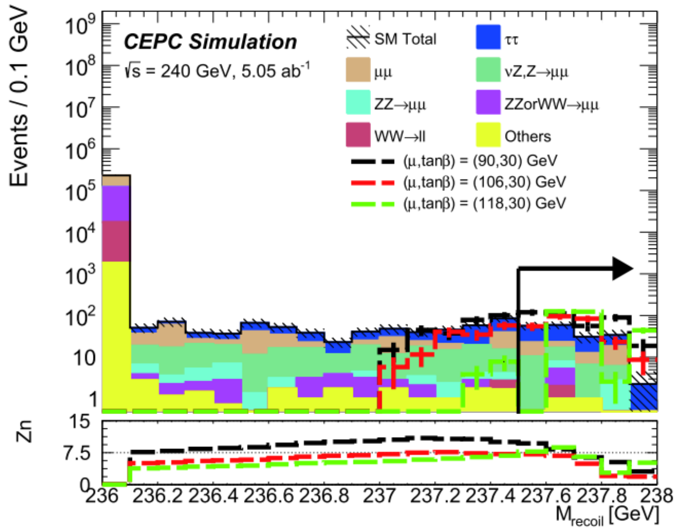
Higgsino Search with Two Muons

- Signal scenario:
  - **Pair production of higgsino-like $\tilde{\chi}_1^{\pm}$ decaying via off-shell W boson**
  - Signal grid is designed for $\mu - \tan\beta$ phase space, where μ ranges from 90 GeV (LEP limit) to ~<120 GeV (CEPC kinematic limit)
  - Almost mass-degenerate $\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0$: $\Delta M(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) < 2$ GeV
- Signature: **2 soft muons + large M_{recoil}**
- Signal region
  - M_{recoil}: **The most important selection.** Large for signal due to small mass splitting.
  - Although muon energy is low in SR, we still get good results due to **high muon ID efficiency in low-pt region**.
    - *Muon ID efficiency is ~ 99.9% with energy above 2 GeV, and < 90% for energy below 1.3 GeV at the overlap region or the edge of barrel region.*



Signal Region
Exact 2 OS muons
$E_\mu > 1.0$ GeV
$3.2 < \Delta R(\mu, recoil) < 4.6$
$\lvert\Delta\phi(\mu, recoil)\rvert < 2.9$
$\lvert\Delta\phi(\mu^+, \mu^-)\rvert < 1.4$
$M_{recoil} > 237.5$ GeV

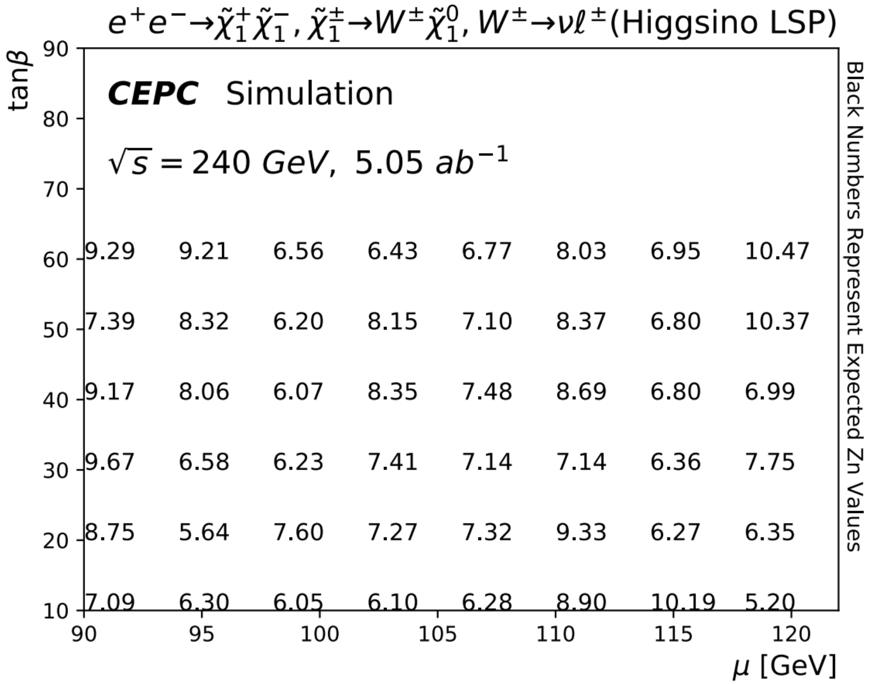




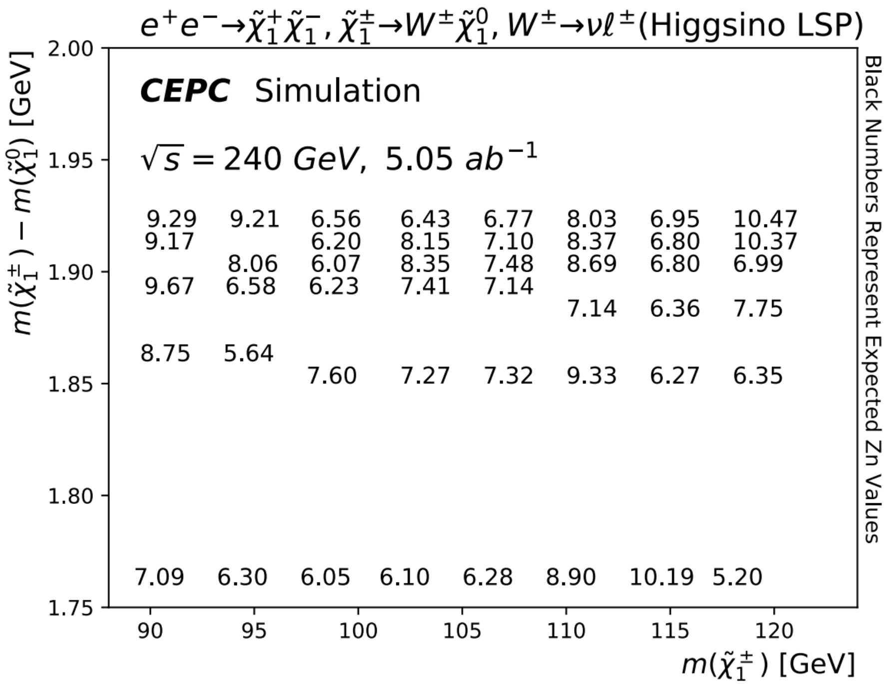
"N-1" plots

Higgsino Search with Two Muons

- Sensitivity maps in both $\mu - \tan\beta$ and $m(\tilde{\chi}_1^\pm) - \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ phase space
- The discovery potential can reach up to detector kinematic limit $\sqrt{s}/2$
- There is good discovery ability at compressed region.



systematic uncertainty =5%

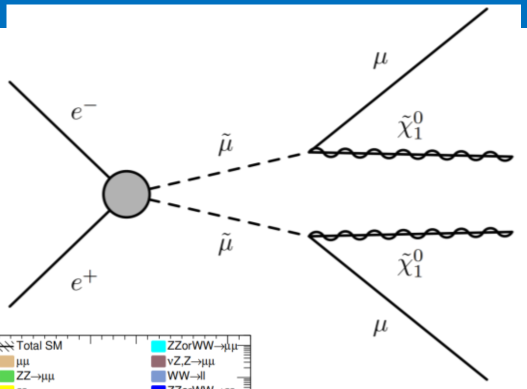


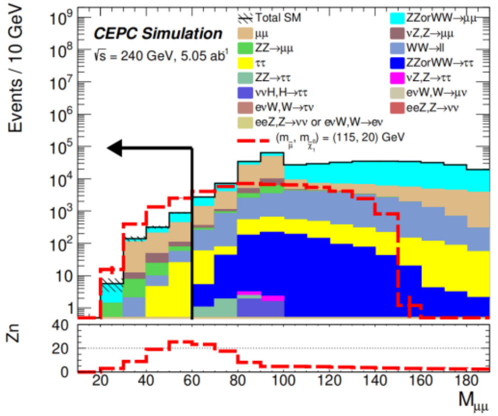
systematic uncertainty =5%

Direct Smuon Production with Two Muons

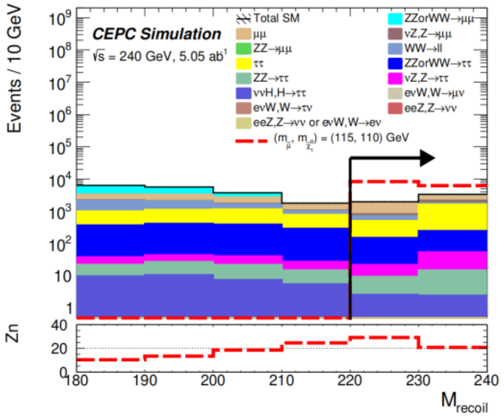
- Signal scenario:
  - **Direct production of smuon**, whose mass is bounded by LEP, CEPC limits (from 90 GeV to ~120 GeV).
- Signature: **2 muons + M_{recoil}**
- Signal region
  - Three signal regions aiming for different mass difference between $\tilde{\mu}$ and $\tilde{\chi}_1^0$
  - $M_{\mu\mu}$: reject $Z \rightarrow \mu\mu$ backgrounds in ~Z mass region
  - M_{recoil}: large for signal due to $\tilde{\chi}_1^0$

SR-highDeltaM	SR-midDeltaM	SR-lowDeltaM
	Exact 2 OS muons	
	$E_\mu > 1.0$ GeV	
$E_\mu > 40$ GeV	9 GeV $< E_\mu <$ 48 GeV	–
$\Delta R(\mu, recoil) < 2.9$	$1.5 < \Delta R(\mu, recoil) < 2.8$	
$M_{\mu\mu} < 60$ GeV	$M_{\mu\mu} < 80$ GeV	–
$M_{recoil} > 40$ GeV	–	$M_{recoil} > 220$ GeV





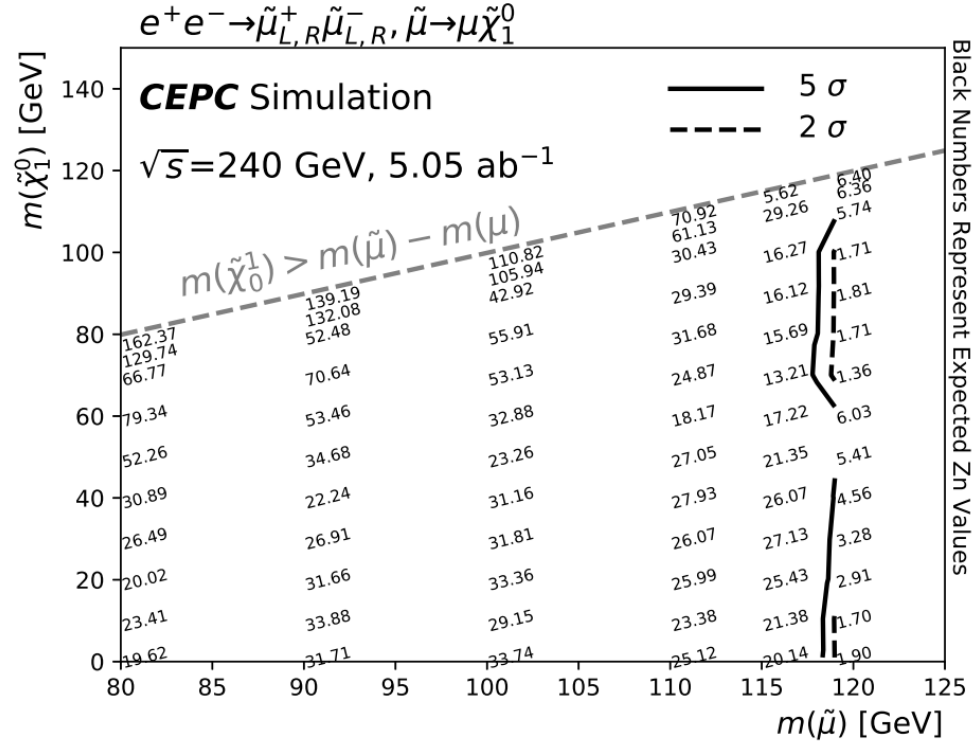
SR-high $M_{\mu\mu}$ N-1 distributions



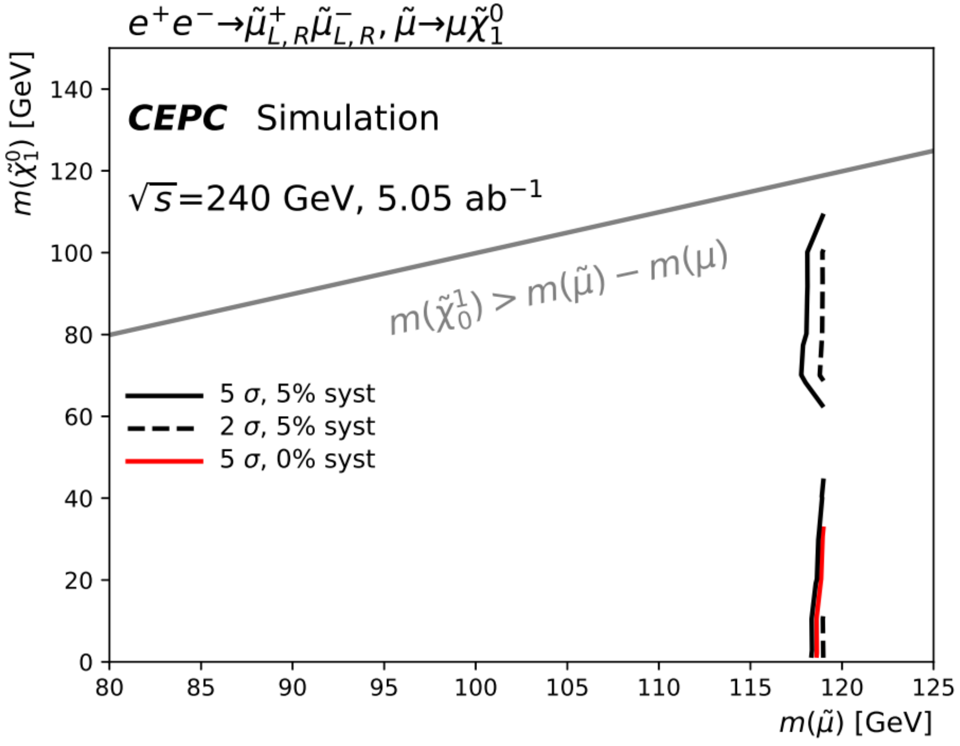
SR-low M_{recoil} N-1 distributions

Direct Smuon Production with Two Muons

- With flat 5% systematic, the discovery sensitivity can reach up to 117 GeV in smuon mass.
- Cover the region with compressed mass spectrum.
- No large impact from systematic uncertainty.



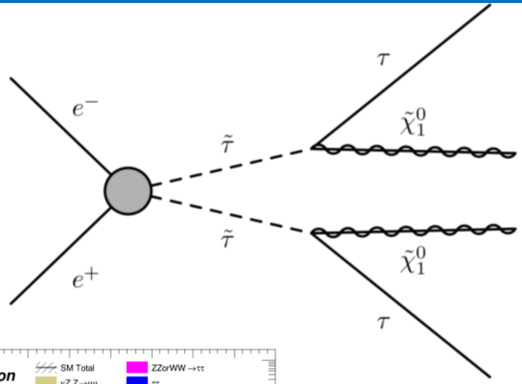
(a) systematic uncertainty = 5%



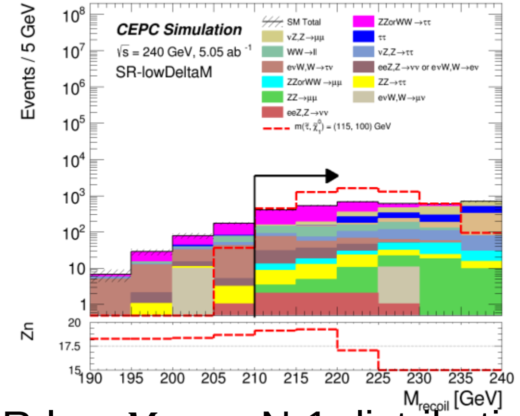
(b) comparison between systematic uncertainty = 0% and 5%

Direct Stau Production with Two Hadronic Taus

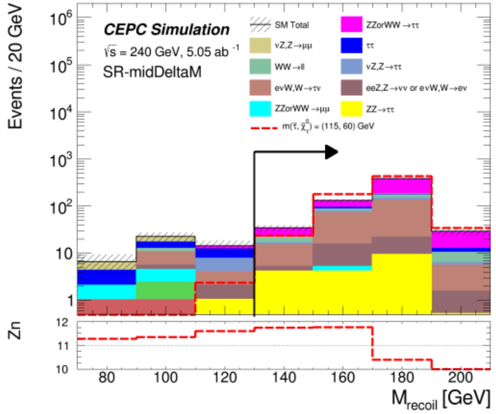
- Signal scenario:
  - **Direct production of stau**, whose mass is bounded by LEP, CEPC limits (from 90 GeV to ~120 GeV).
- Signature: **2 hadronic tau + M_{recoil}**
- Signal region
  - Use leading and subleading tracks as 2 taus.
  - Three signal regions according to different mass splitting between $\tilde{\tau}$ and $\tilde{\chi}_1^0$
  - High mass splitting leads to high tau energy
  - Low mass splitting leads to high recoil mass



SR-highDeltaM	SR-midDeltaM	SR-lowDeltaM
	Exact 2 OS taus	
	$E_\tau > 1.0$ GeV	
$E_\tau < 34$ GeV	$E_\tau < 15$ GeV	
$sumP_T > 70$ GeV	$sumP_T > 40$ GeV	-
-	$0.2 < \lvert\Delta\phi(\tau,\tau)\rvert < 1.2$	$\lvert\Delta\phi(\tau,\tau)\rvert > 0.6$
$2.4 < \lvert\Delta\phi(\tau, recoil)\rvert < 3$		$\lvert\Delta\phi(\tau, recoil)\rvert > 2.3$
$0.4 < \Delta R(\tau,\tau) < 1$	$0.4 < \Delta R(\tau,\tau) < 1.6$	-
$\Delta R(\tau,\tau) < 3.1$		$\Delta R(\tau, recoil) < 2.9$
$M_{\tau\tau} < 50$ GeV	$M_{\tau\tau} < 40$ GeV	$M_{\tau\tau} < 18$ GeV
$M_{recoil} > 90$ GeV	$M_{recoil} > 130$ GeV	$M_{recoil} > 210$ GeV



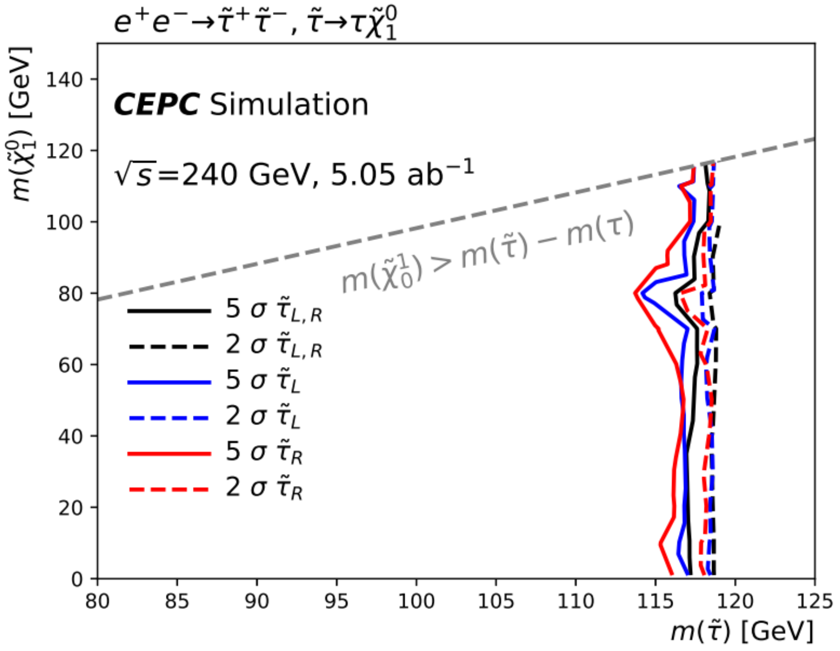
SR-low M_{recoil} N-1 distributions



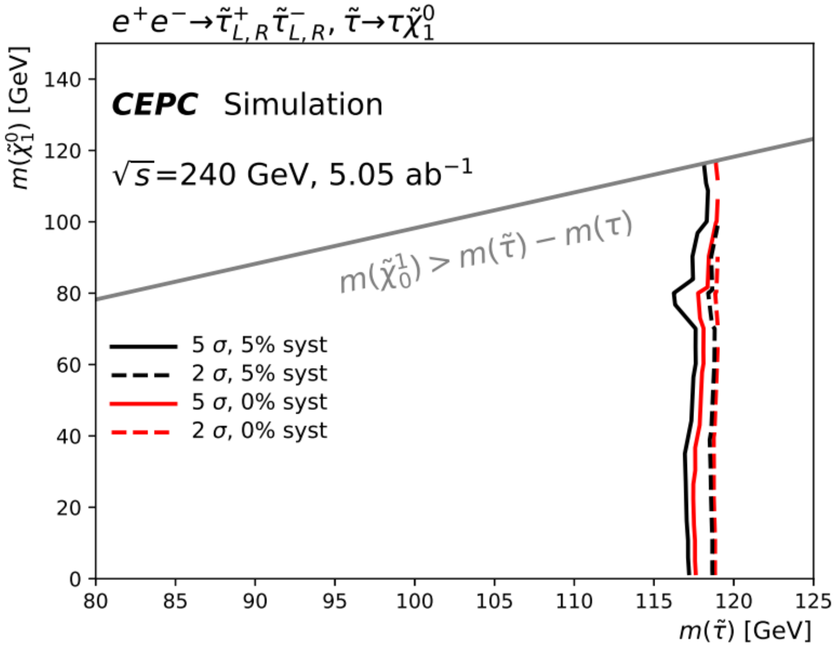
SR-mid M_{recoil} N-1 distributions

Direct Stau Production with Two Hadronic Taus

- Assuming flat 5% systematic uncertainty, with **left-handed and right-handed stau**, the discovery sensitivity can reach up to **116 GeV** in stau mass.
- *Assuming flat 5% systematic uncertainty, with **left/right-handed stau**, the discovery sensitivity can reach up to **113 GeV** in stau mass.*
- Cover the region with compressed mass spectrum.
- No large impact from systematic uncertainty.



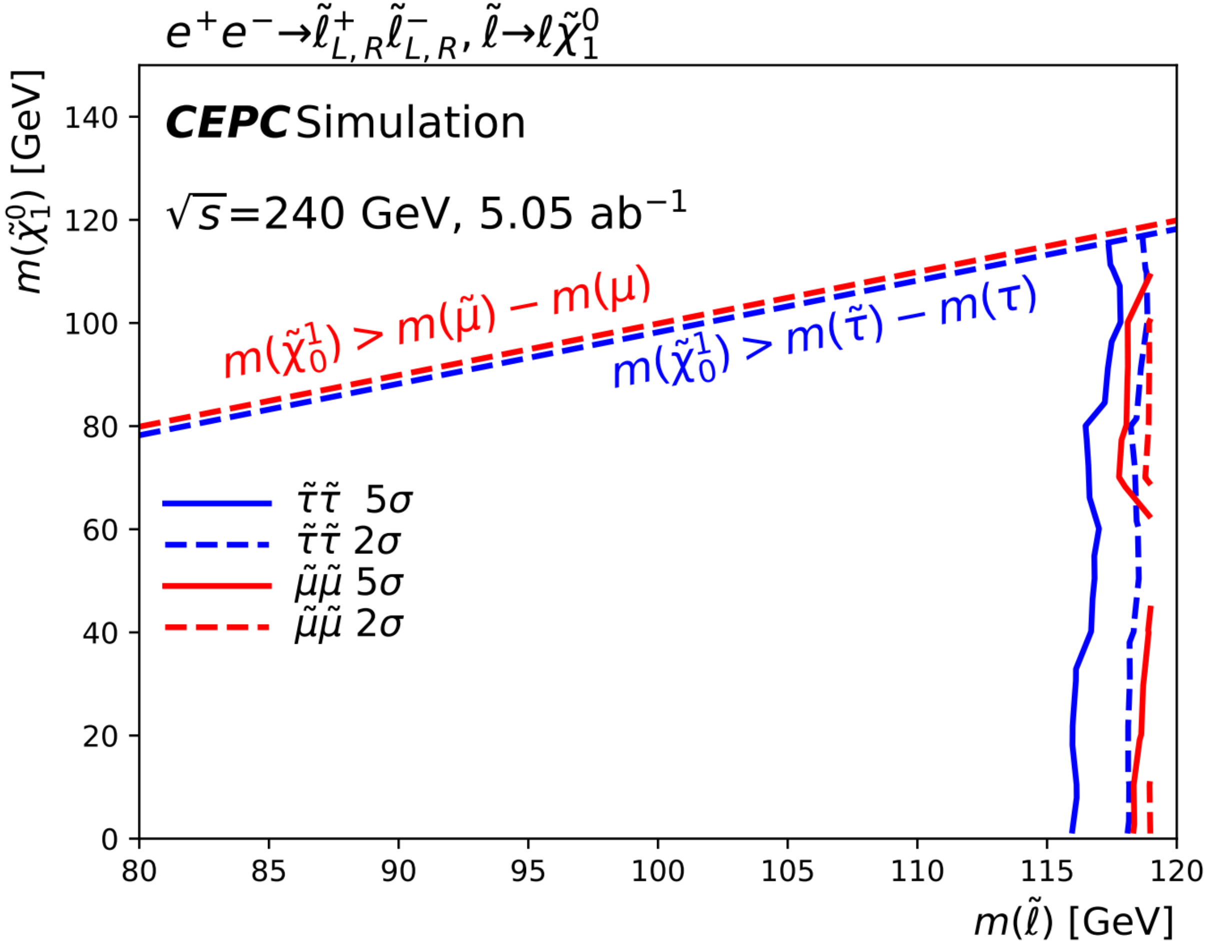
(a) systematic uncertainty = 5%



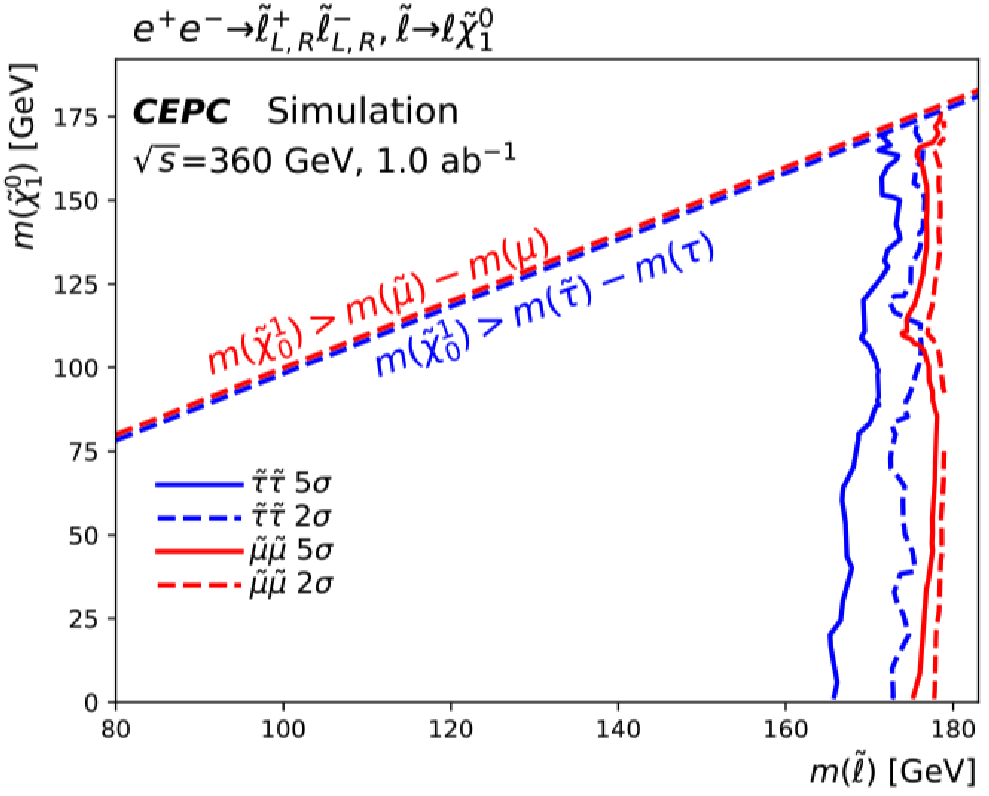
(b) comparison between systematic uncertainty = 0% and 5%

Stau, Smuon Sensitivity Map

Sensitivity map for direct slepton$(\tilde{\tau}, \tilde{\mu})$ production with 5% flat systematic uncertainty.



360 GeV preliminary results
reference from Feng LU



Summary

- Several prospective searches for slepton and electroweakino have been performed with CEPC.
- The discovery potential is close to the kinematic limit $\sqrt{s}/2$
- The results can be used as a reference for searches at other electron-positron experiments, such as ILC and FCC-ee.

THE END

Backup

Naturalness

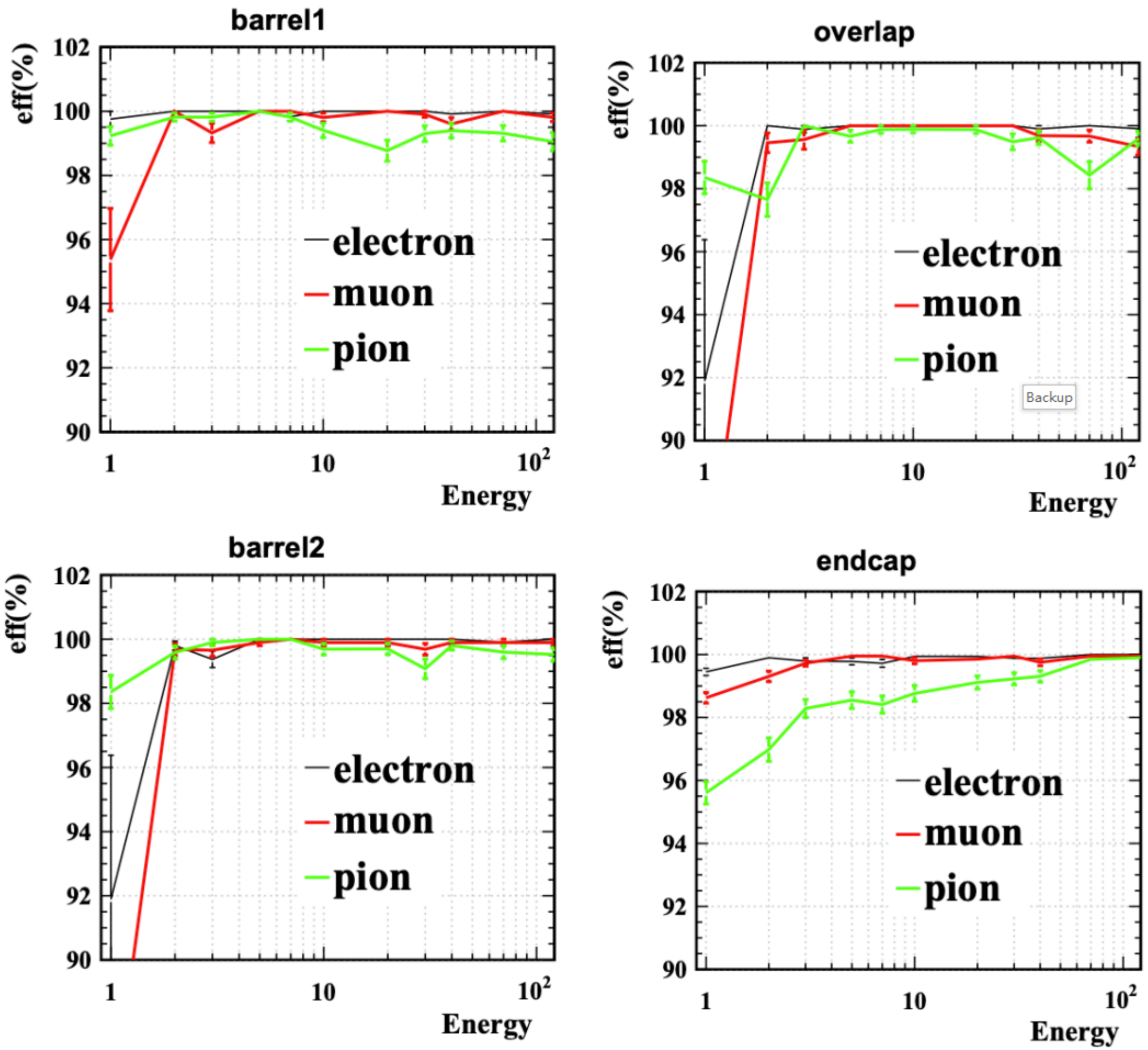
- Everything should be made as simple as possible, but not simpler. (A. Einstein)
- The appearance of **fine-tuning** in a scientific theory is like a cry of distress from nature, complaining that something needs to be better explained. (S. Weinberg)
- The most direct relation between **the observed value of the weak scale** and **elements of the SUSY Lagrangian** comes from minimizing the MSSM scalar potential.

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \Sigma_u^u - \mu^2$$

- All terms on RHS should be comparable to or smaller than $m_Z^2/2$
- The soft parameter $m_{H_u}^2$ is driven radiatively to small negative values at the weak scale
- Radiative corrections $\Sigma_u^u \lesssim m_Z^2/2$ leads to top-squarks are highly mixed and not too far beyond the few TeV range.
- $\mu \sim 100 - 300$ GeV. **Higgsino-like gaugino mass should be around 100-300 GeV.**

Howard Baer, Mikael Berggren et al., PoS ICHEP2016 156 (2016)

Muon ID Efficiency at CEPC



Dan Yu, Manqi Ruan et al., Eur. Phys. J. C 77, 591 (2017).