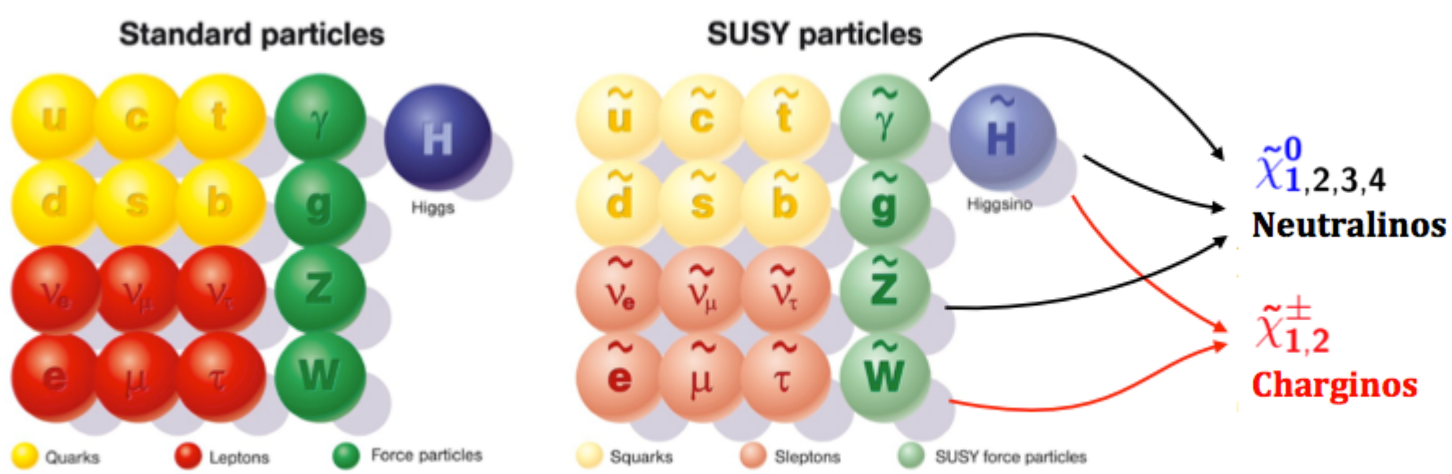
Prospects for supersymmetric searches at CEPC

Da XU (IHEP, CAS)
CEPC workshop 2021

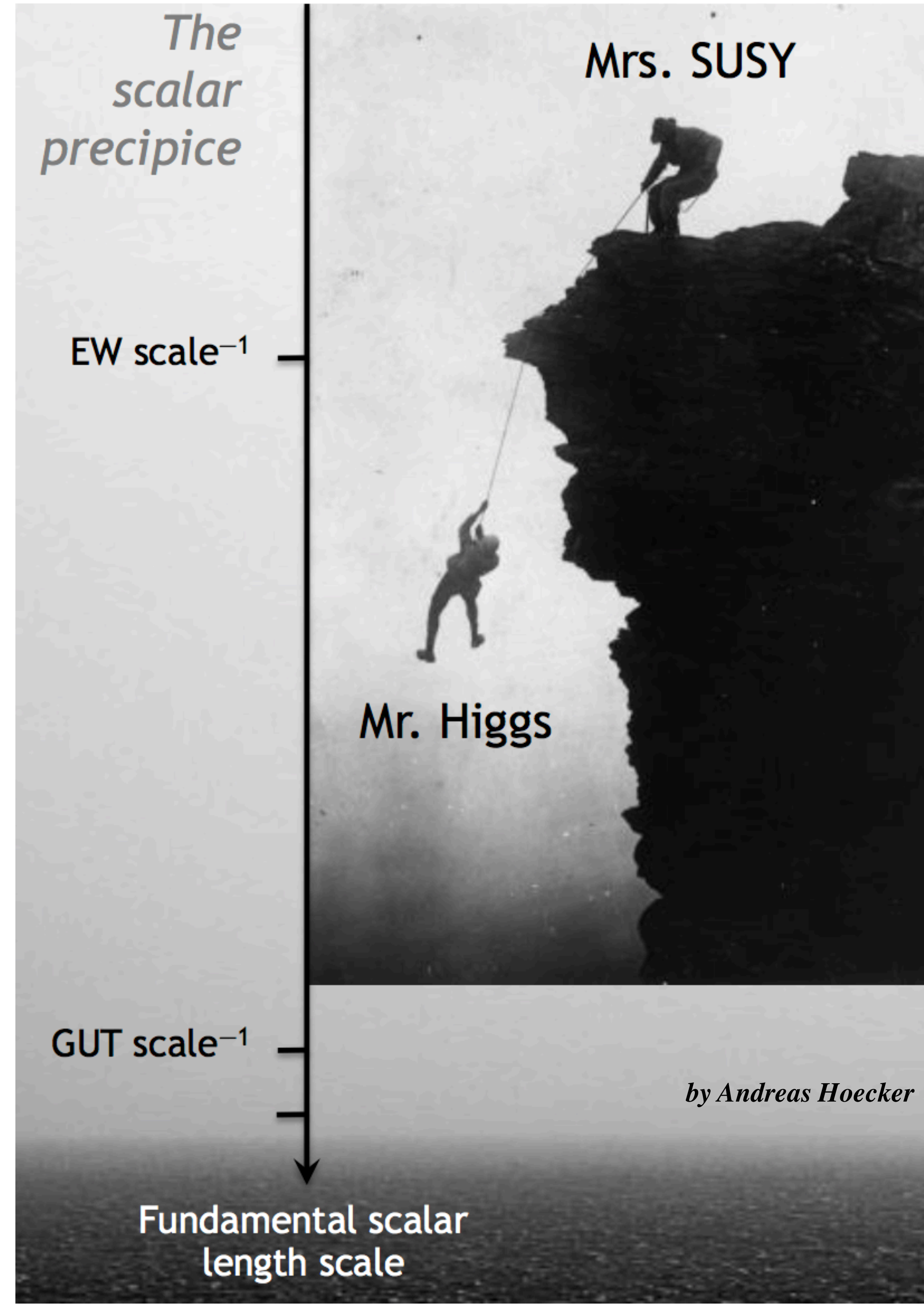
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

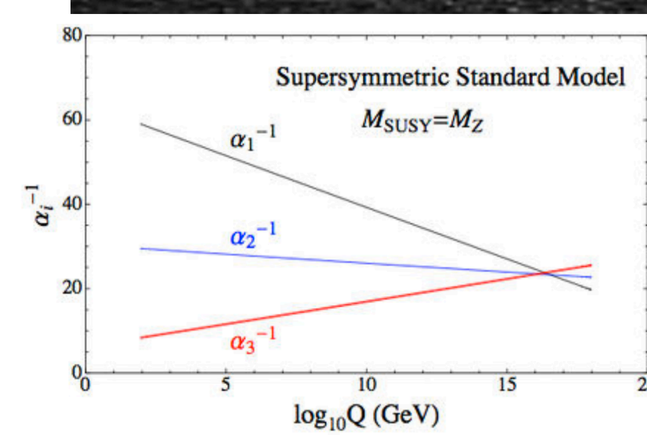
Supersymmetry



A theory to describe physics beyond the Standard Model, with additional symmetry introduced: fermions ~ bosons

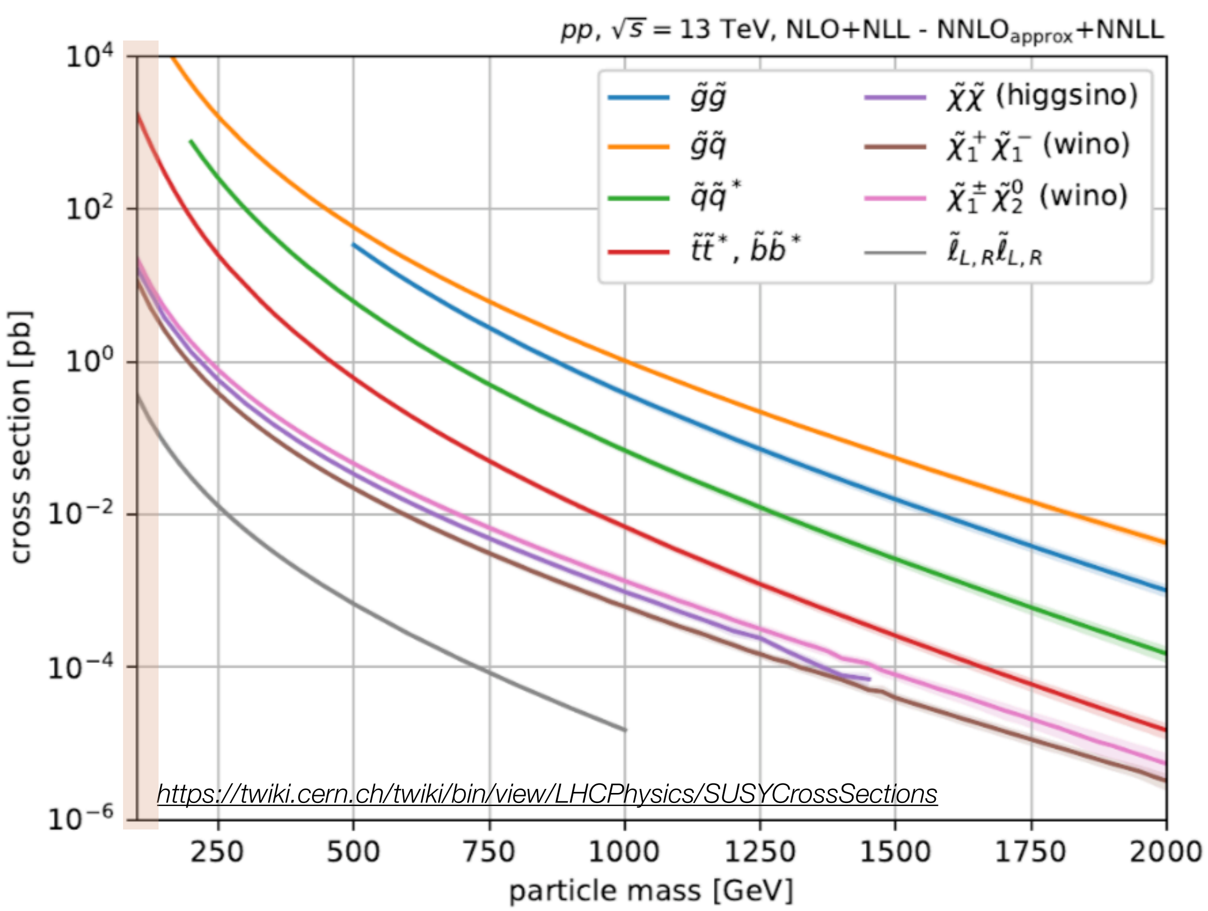
If weak-scale SUSY existed, it could…
Moderate the hierarchy problem
Realize grand unification of gauge couplings
Provide a suitable dark matter candidate



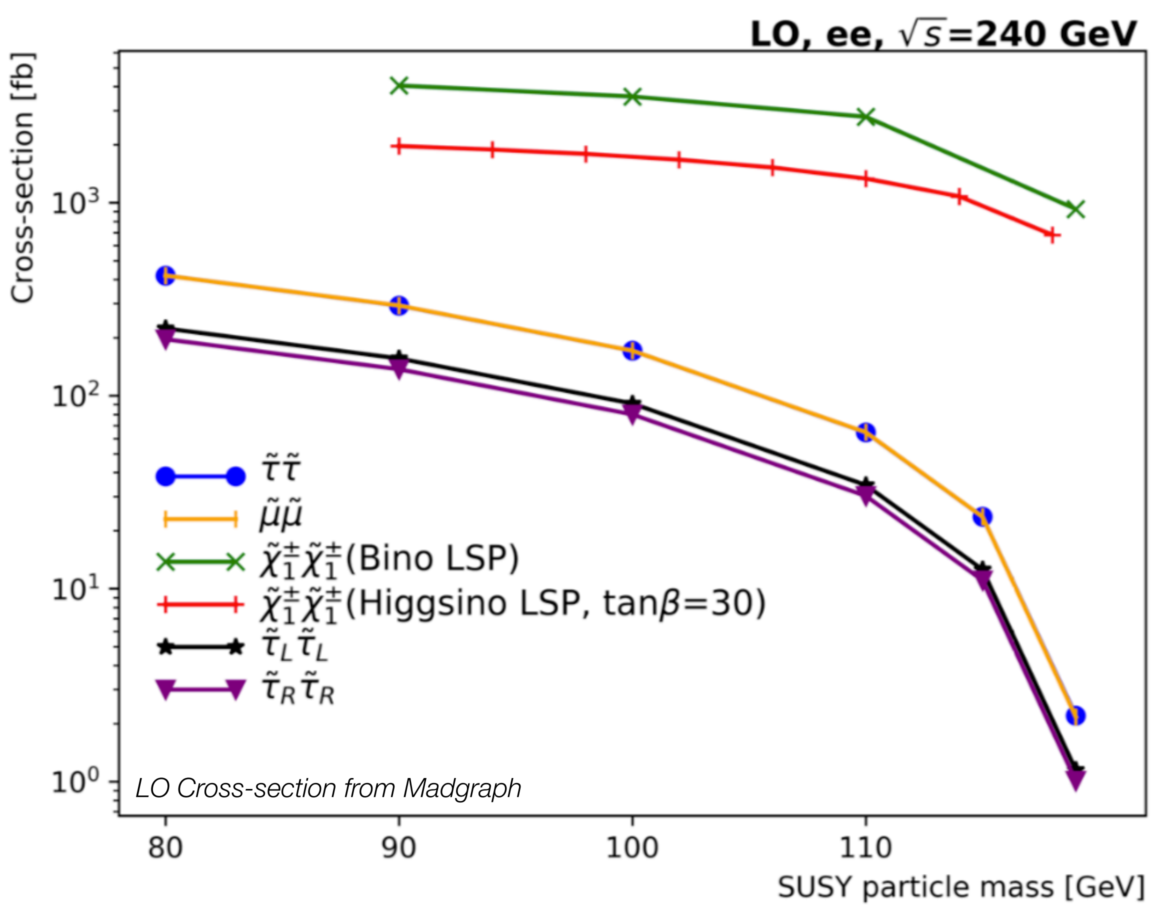


Where is SUSY hiding?

Hadron collider



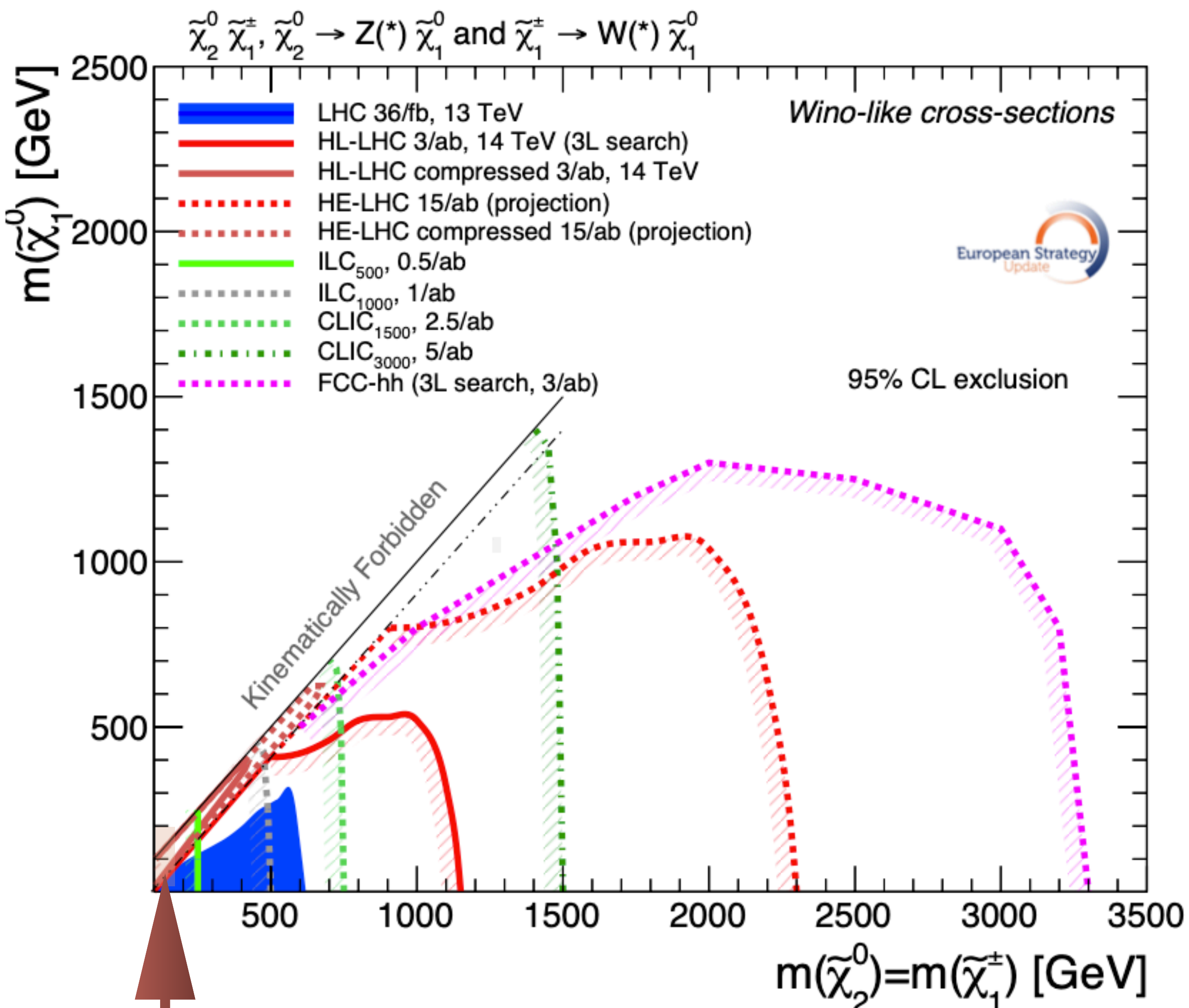
Lepton collider

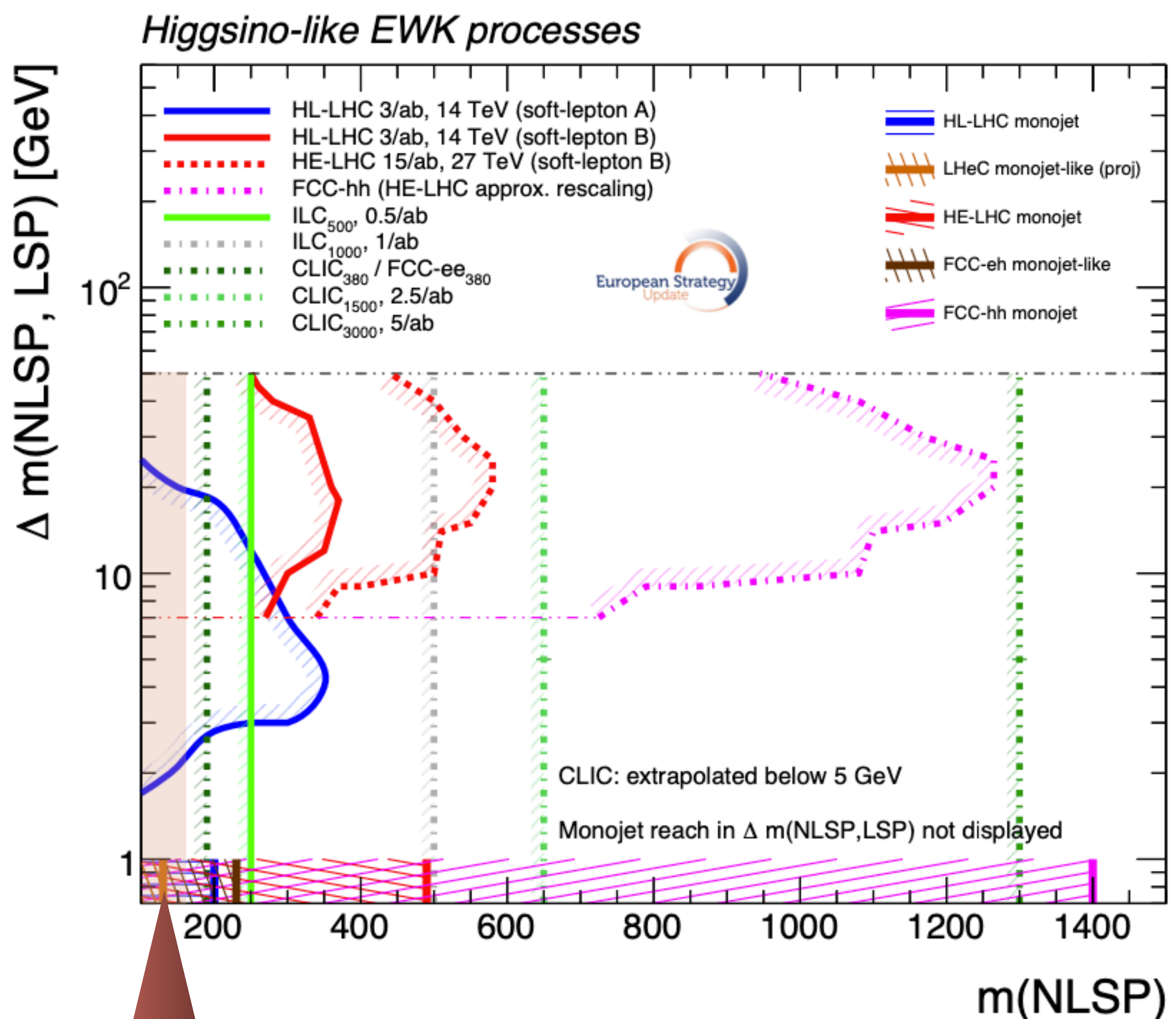


For slepton prod. of 100 GeV, similar scale in LHC (~10^-1 pb) and CEPC (~10^2 fb).
Lepton collider can be powerful to probe the low mass region.

SUSY search in EU strategy

CERN-ESU-004

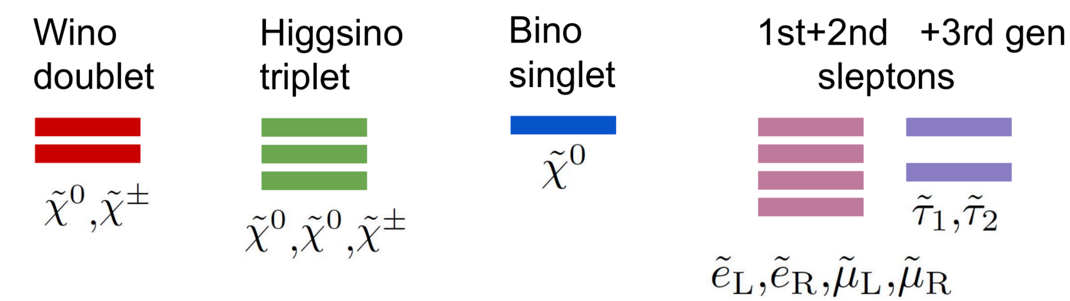




The discovery power is constrained by the experimental kinematic limit: $\sqrt{s}/2$.

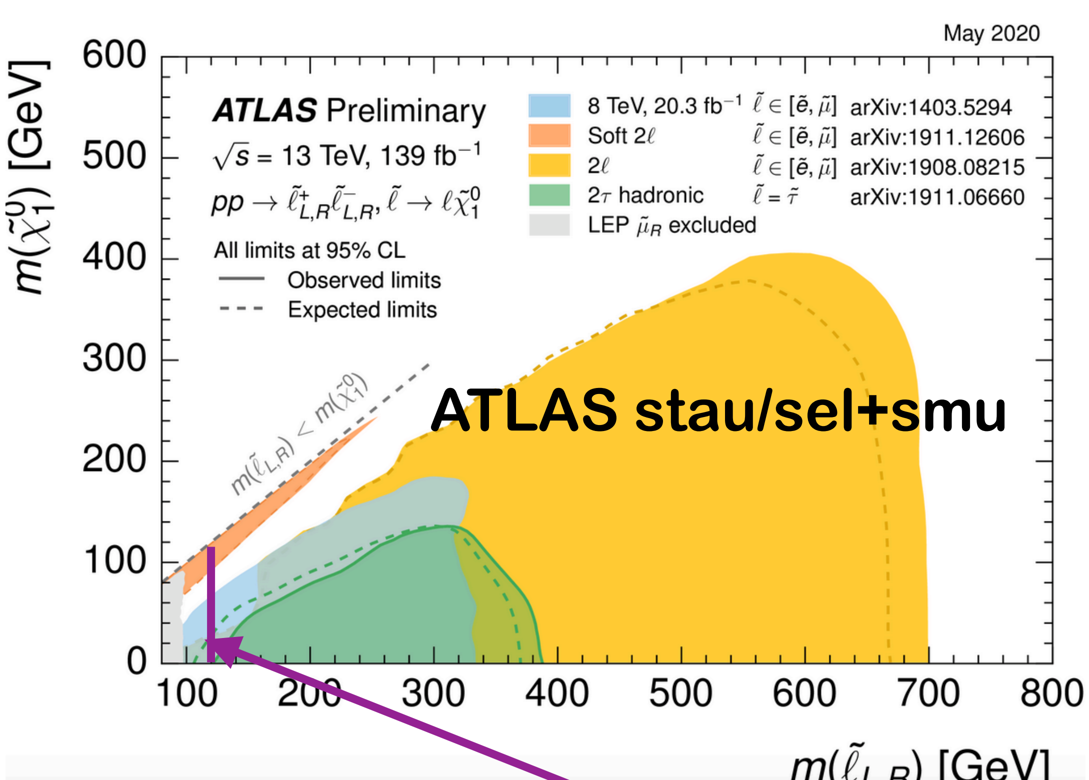
Gap in low NLSP mass region can be probed by CEPC.

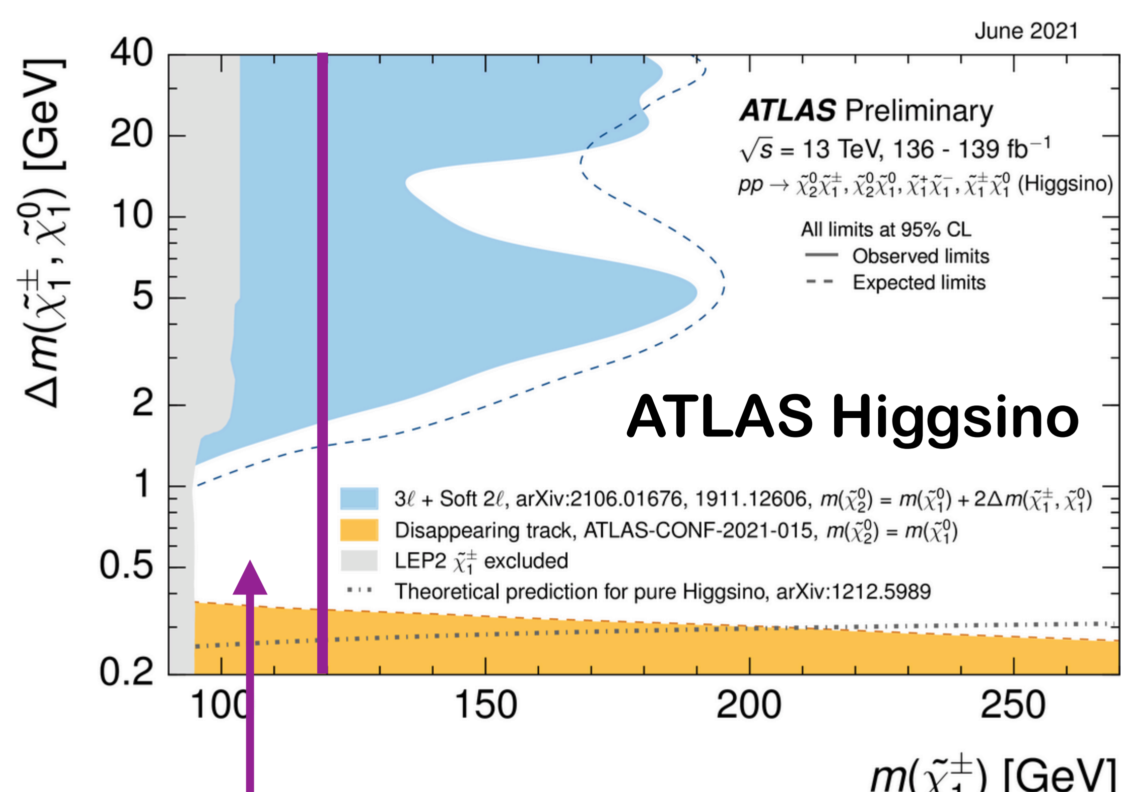
SUSY @ CEPC



The electroweak SUSY search is of great interest at CEPC: the generic searches for **wino/higgsino/bino/slepton**, as well as the relevant dark matter searches.

With cleaner collision environment and better efficiency for low energy particles, the search with CEPC has the capability of probing **super compressed scenarios** — extremely challenge for the LHC experiments!





CEPC potential coverage

SUSY topics in CEPC

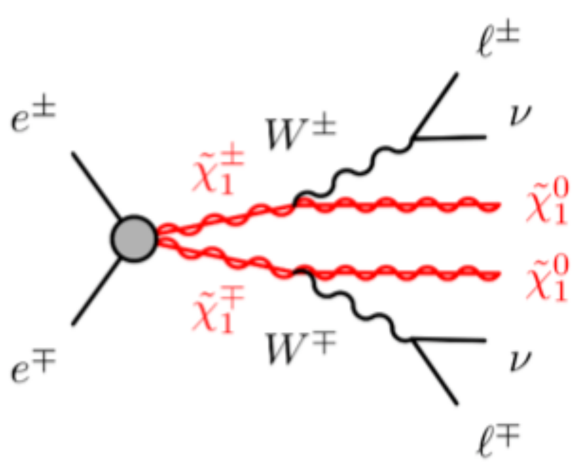
A wide range of SUSY topics has been studied

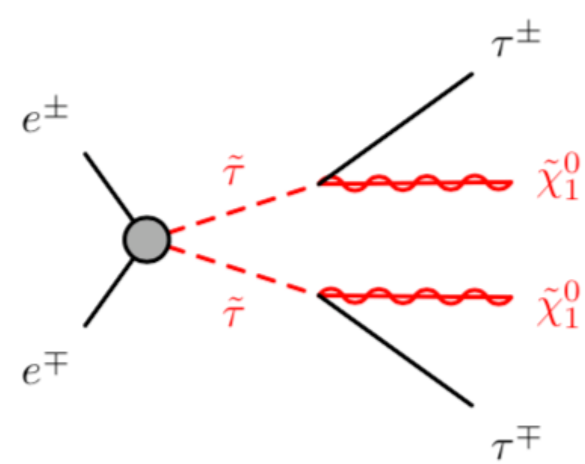
Wino-bino search via chargino pair

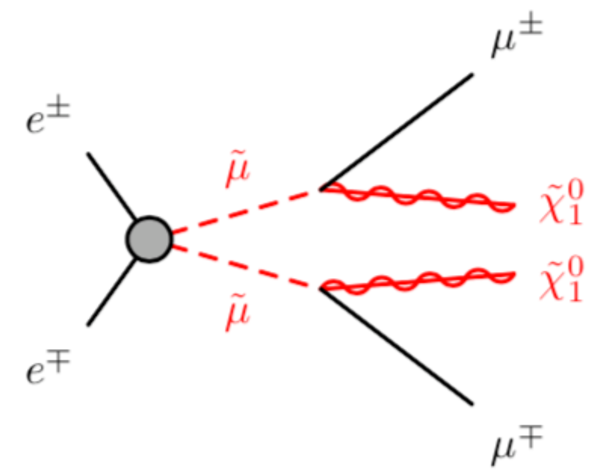
Higgsino search via chargino pair

Direct stau search

Direct smuon search







Techniques in CEPC analysis

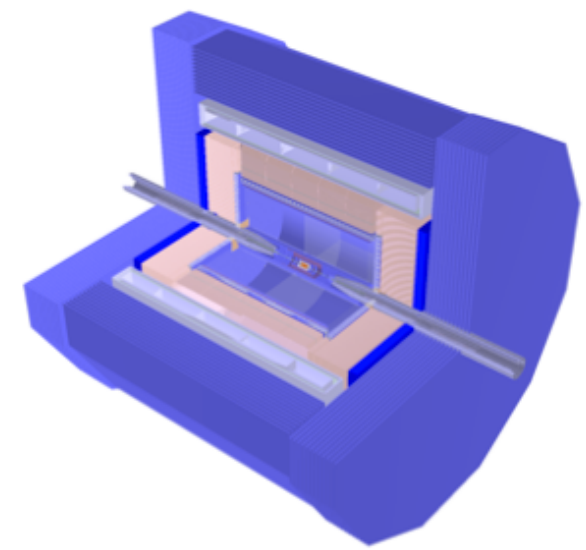
Ecm: 240 GeV   Tunnel ~100km   Luminosity: 5050 fb-1

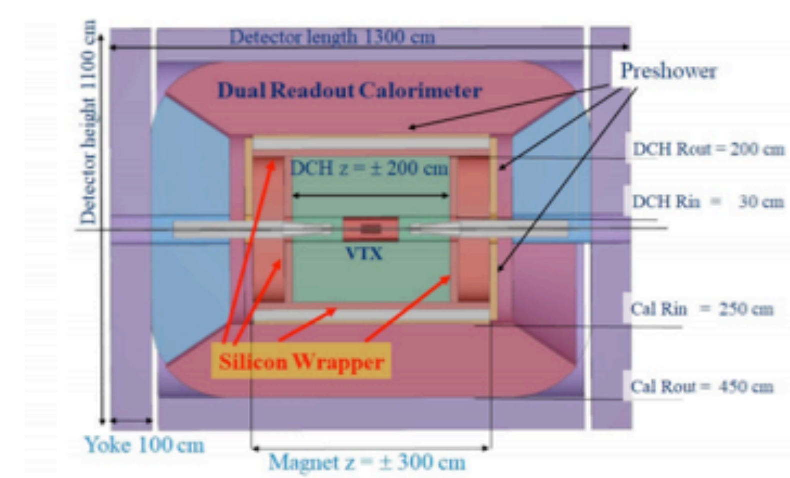
CEPC detector concepts

- a particle-flow oriented detector equipped with an ultra-high granularity calorimeter, a low-material tracker and a 3 Tesla solenoid

Software:

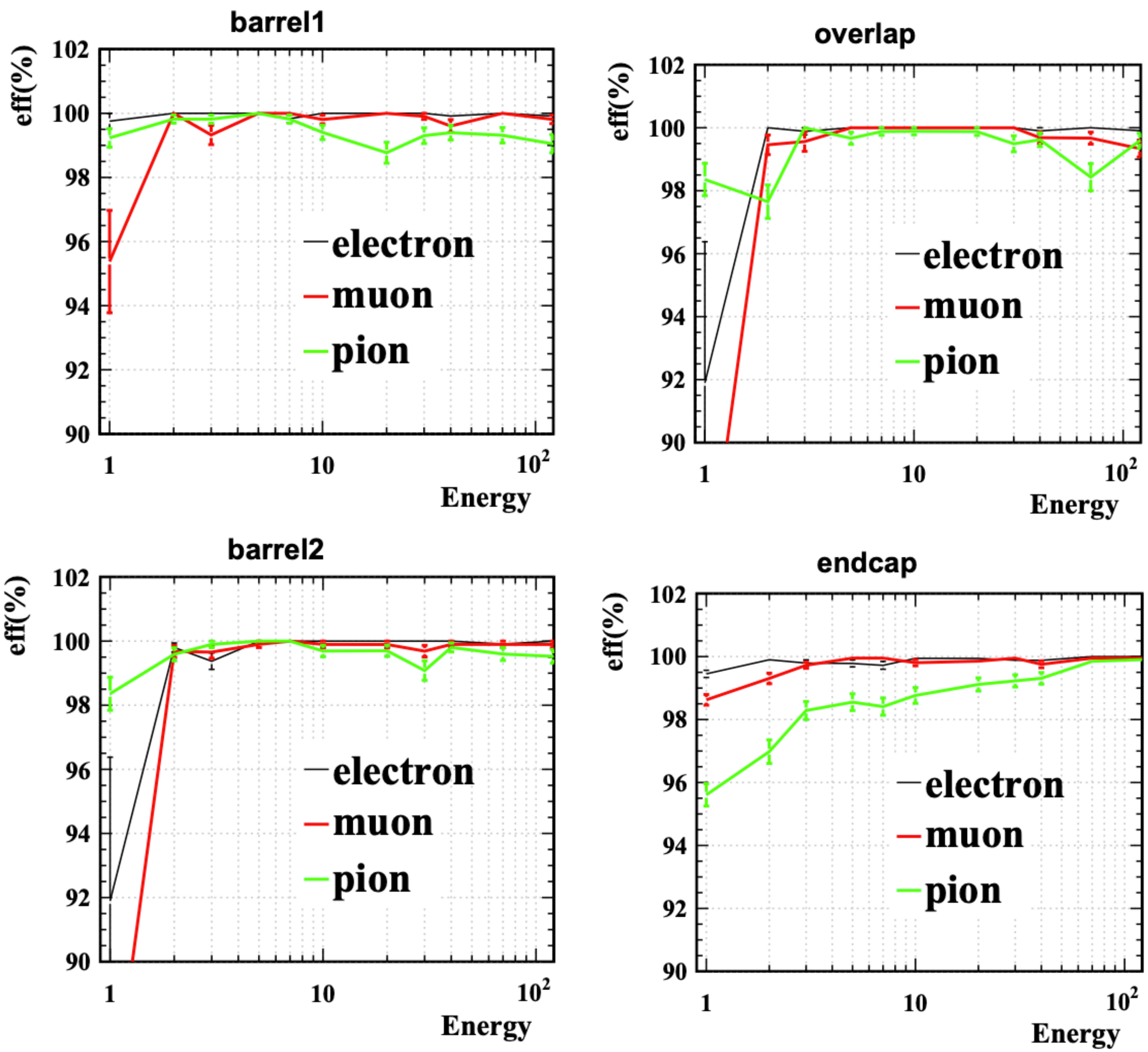
- SUSY Signal sample: MadGraph+Pythia
- Standard Model MC sample: Whizard
- Simulation (particle/detector): MokkaC
- Track reconstruction: Clupatra
- Object reconstruction: Arbor(particle flow algorithm)
- Lepton identification: LICH based on Multivariate Data Analysis (TMVA)





Muon ID in CEPC

Eur. Phys. J. C (2017) 77:591



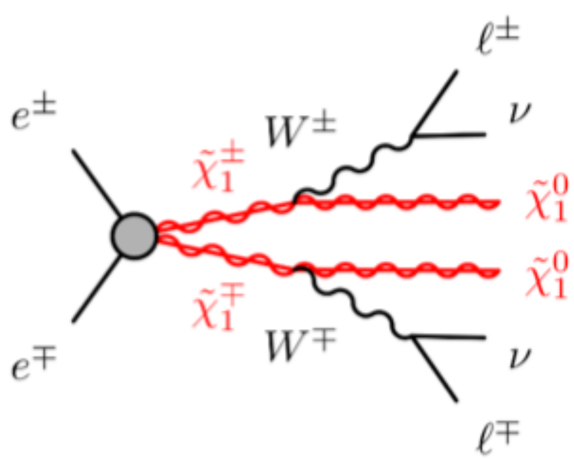
Muon is the main object of interest in the following analyses. The identification efficiency is :

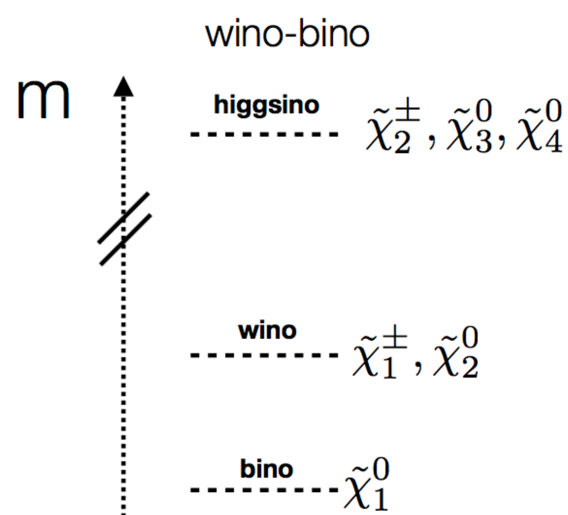
- ~ 99.9% with energy above 2 GeV;
- < 90% for energy below 1.3 GeV and at the edge of the barrel region (barrel2) or the overlap region.

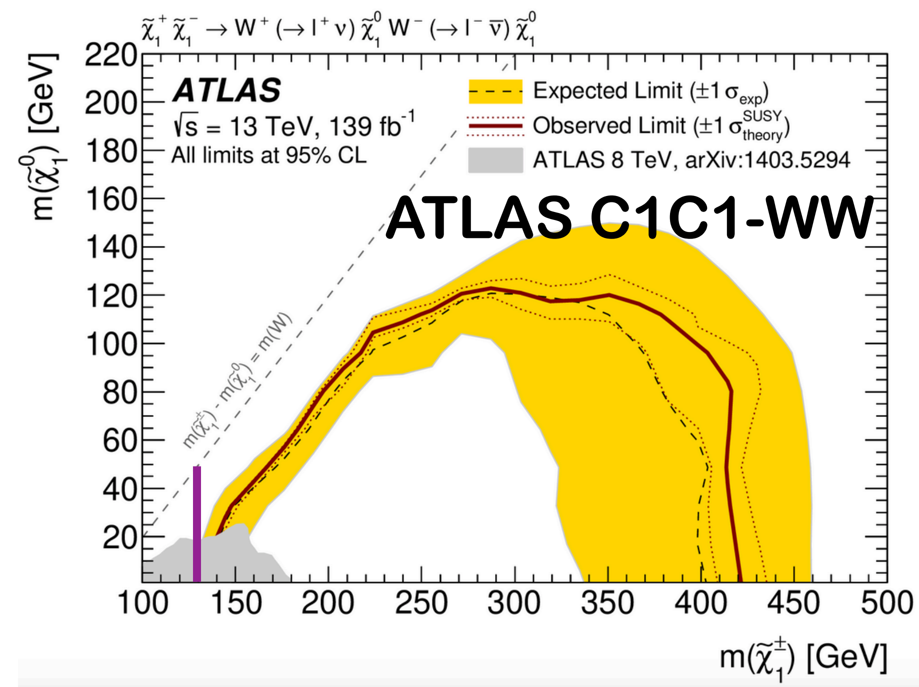
Wino-bino search

arXIV:2105.06135

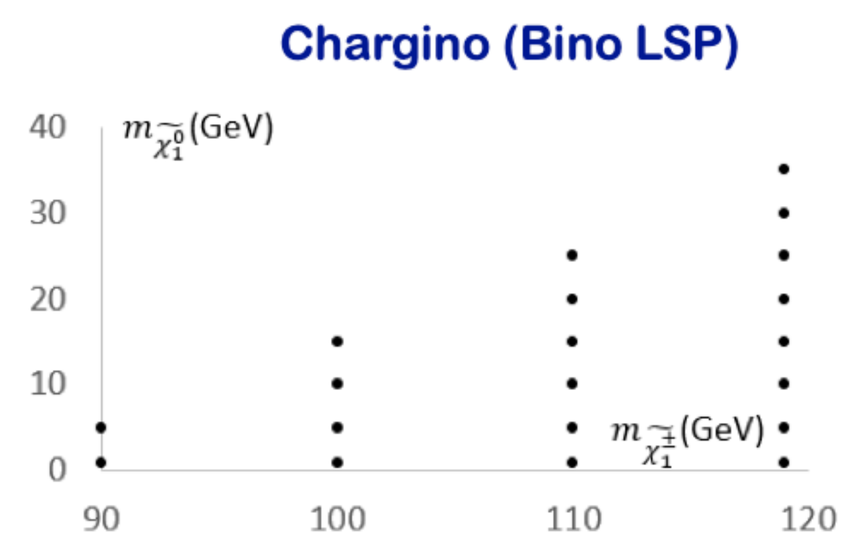
A challenge scenario for LHC experiment in the low mass region!





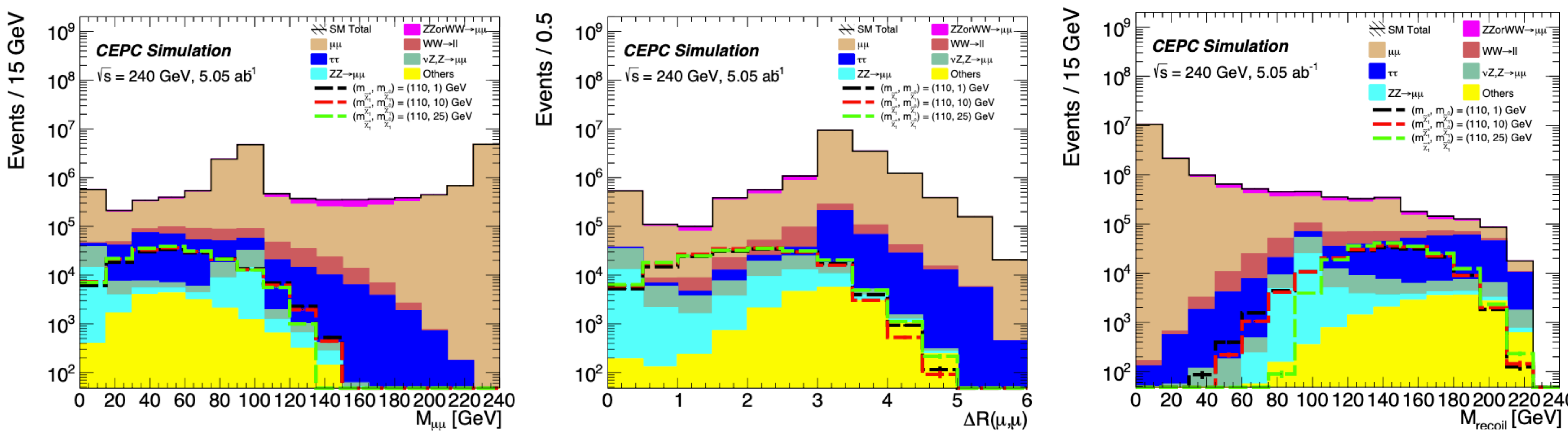


- Study wino mass ranging from 90GeV (LEP limit) to ~<120GeV(CEPC limit)
- Signal generated with 100% BR of C1->W
- Ref. Point: 100_1, 100_10, 100_25 with cross-section (LO) = 2789 fb



Wino-bino search

First look after two OS muons (E^{μ}>10GeV) selection



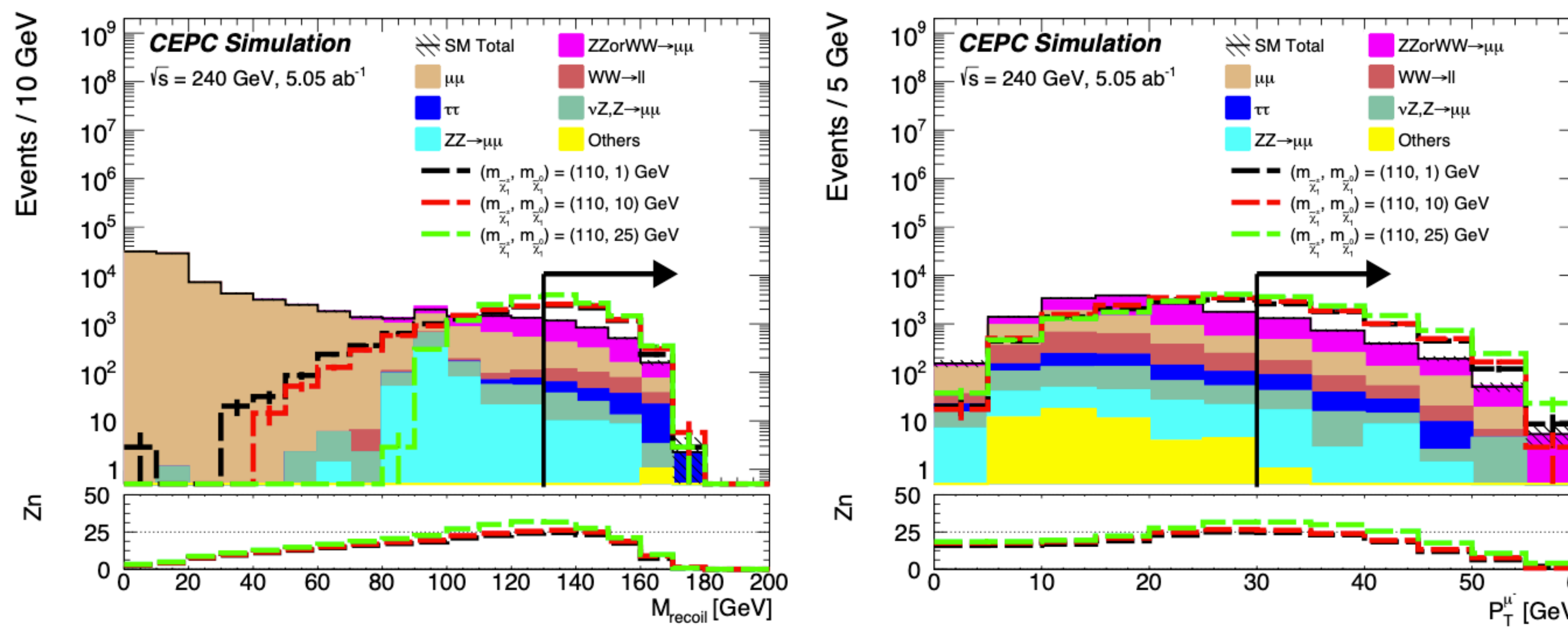
- Background: peak ~ Z(->mumu) mass region and tend to have large deltaR
- Recoil system is then defined as all particles except two OS muons: signal has larger recoil mass due to missing energy.

Wino-bino search

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

- **ΔR(μ⁺,μ⁻): reject ττ and μμ**
- **$P^{\mu^\pm}$ > 30 GeV: suppress soft muon processes**
- **Mrecoil: high in signal case due to large missing energy from N1 -> most powerful cut**
- **Dominant background: ZZ or WW → μμνν and μμ**

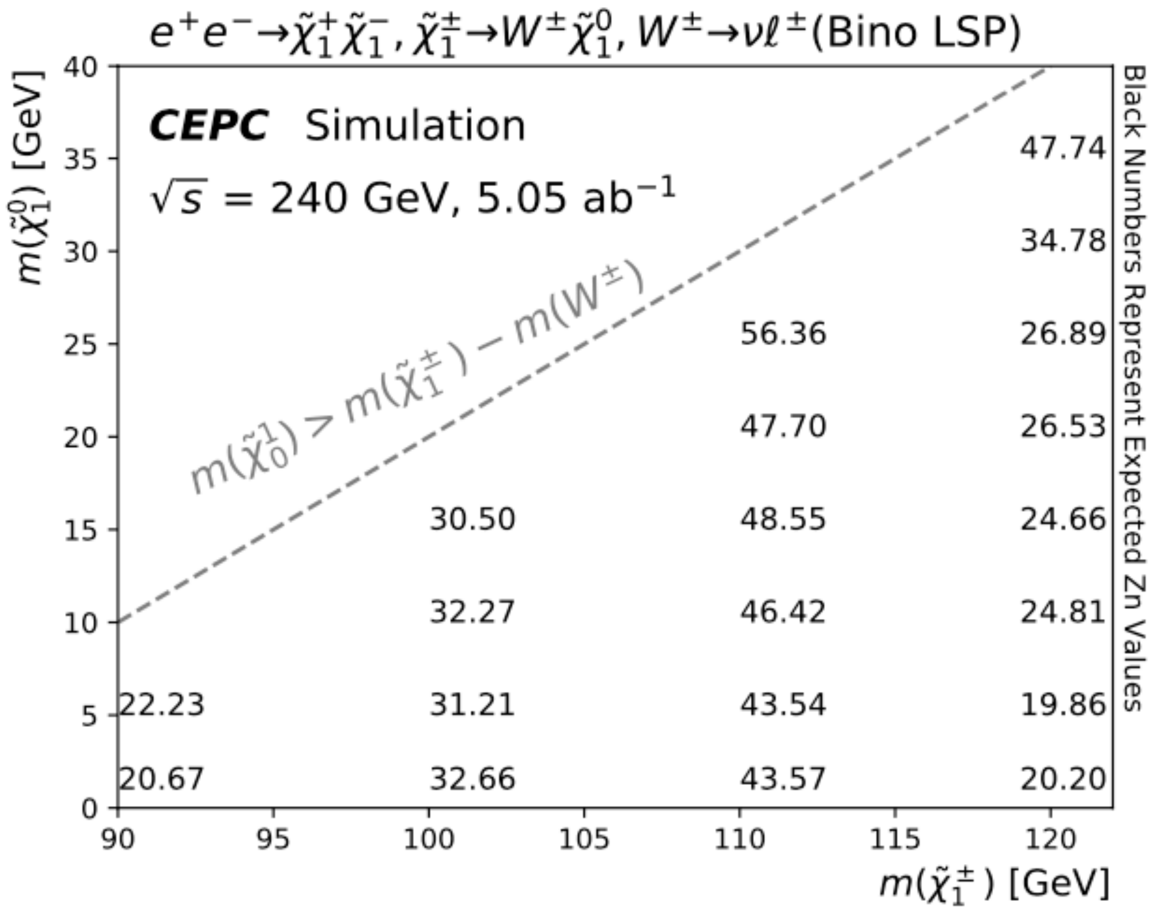
Process	Yields
$ZZorWW \to \mu\mu\nu\nu$	1632±42
$\mu\mu$	609±61
$WW \to \ell\ell$	163±13
$\tau\tau$	88±14
$\nu Z, Z \to \mu\mu$	47.9±7.3
$ZZ \to \mu\mu\nu\nu$	27.7±6.2
Others	0.74±0.74
Total background	2568 ± 77
m ($\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$) = (110 , 1) GeV	5940 ± 130
m ($\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$) = (110 , 10) GeV	6470 ± 140
m ($\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$) = (110 , 25) GeV	8470 ± 160



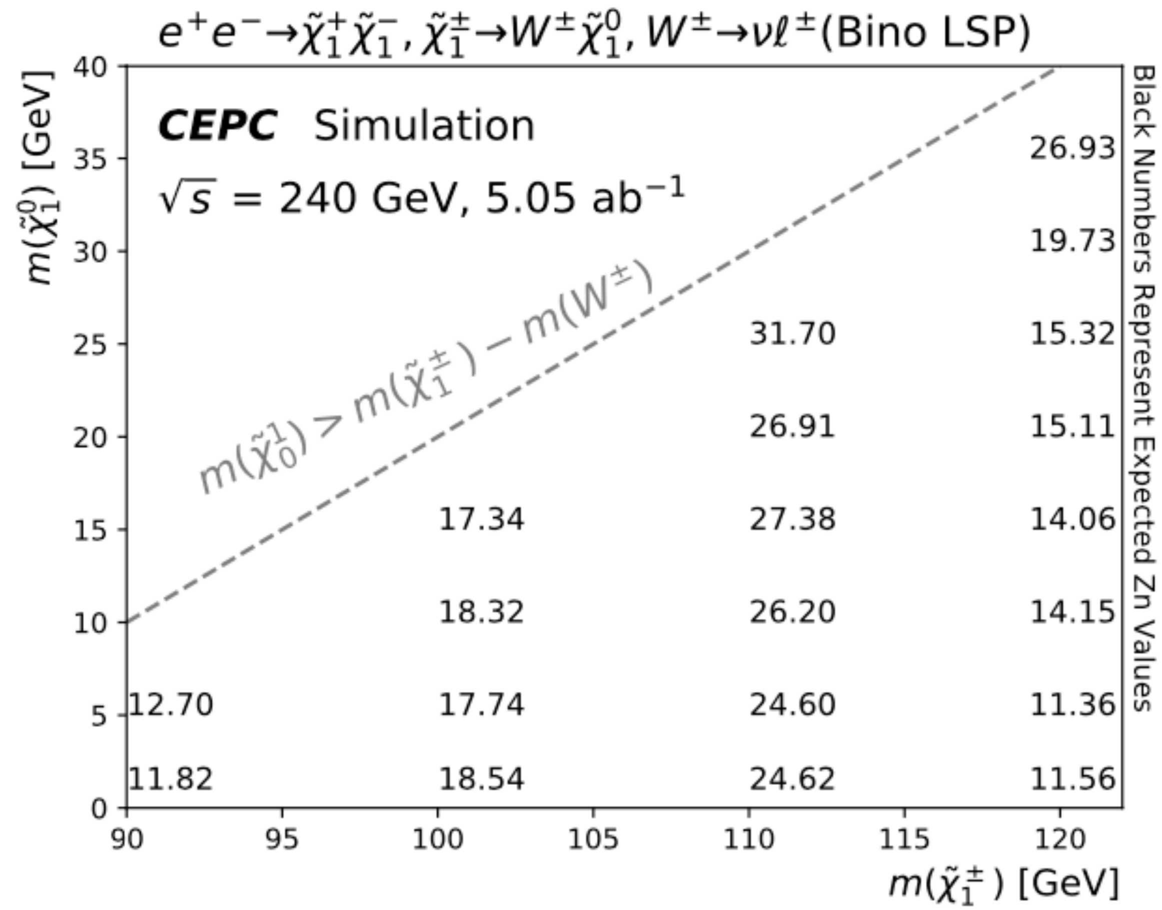
(a) M_{recoil} (M_{recoil} >130 GeV)   (b) $P_T^{\mu^-}$ ($P_T^{\mu^-}$ >30 GeV)

$$Zn = \left[2\left((s+b)\ln\left[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right] - \frac{b^2}{\sigma_b^2}\ln\left[1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right]\right)\right]^{1/2}$$

Wino-bino search



(a) systematic uncertainty = 0%



(b) systematic uncertainty = 5%

Great discovery sensitivity coverage, up to the detector constraint.

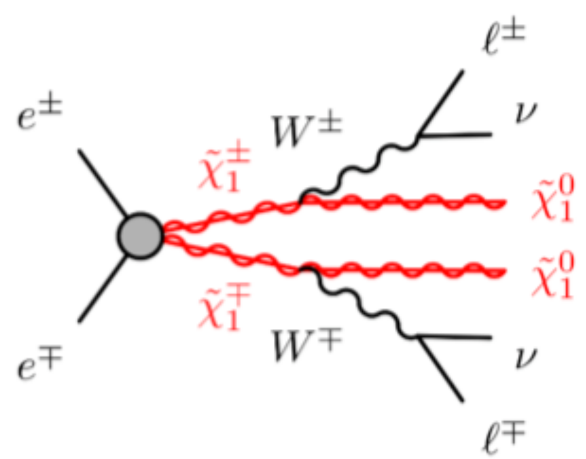
Fill in the LHC challenge region.

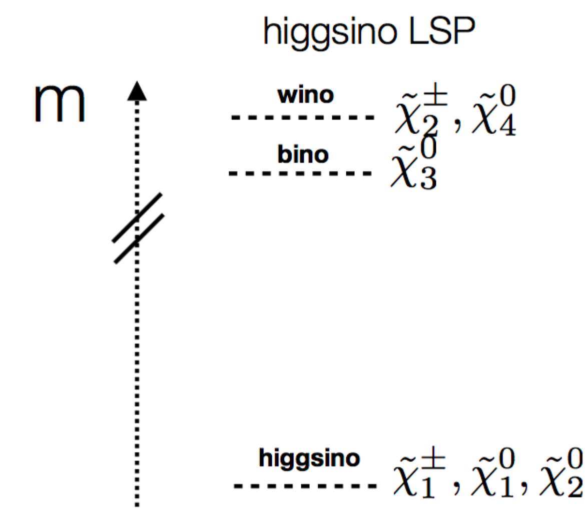
No large impact from the uncertainty on the discovery sensitivity.

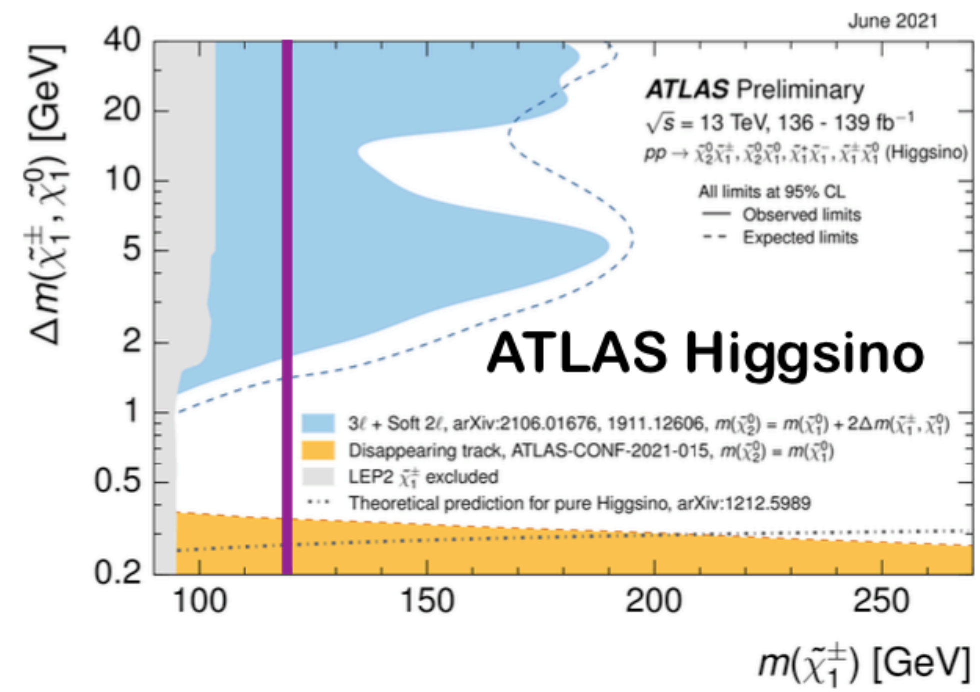
Higgsino search

arXIV:2105.06135

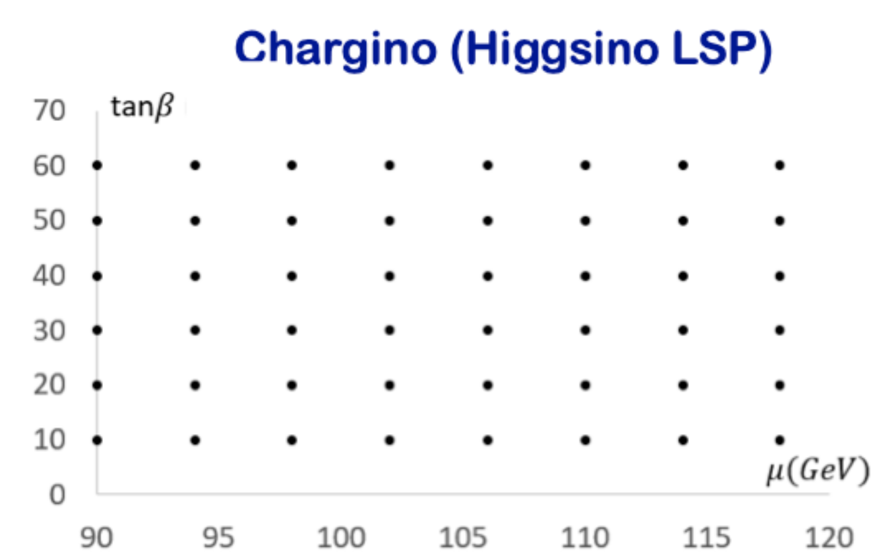
Motivated by Naturalness; challenge in compressed region.





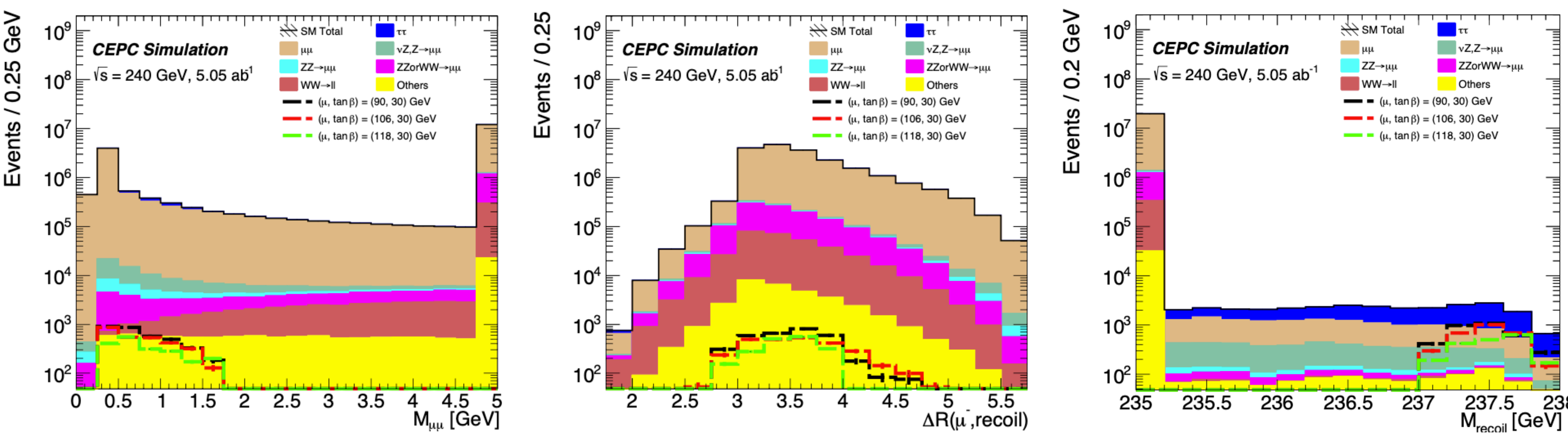


- Higgsino is designed for μ-tanβ phase space
- Corresponding to low mass splitting of dM(c1,n1)~<2GeV
- Signal with 100% BR of C1->W
- Ref. Point: 90_30, 106_30, 118_30 with cross-section (LO) = 1966 fb, 1522.9 fb and 681.2 fb.



Higgsino search

First look after two OS muons (E^{μ}>1GeV) selection



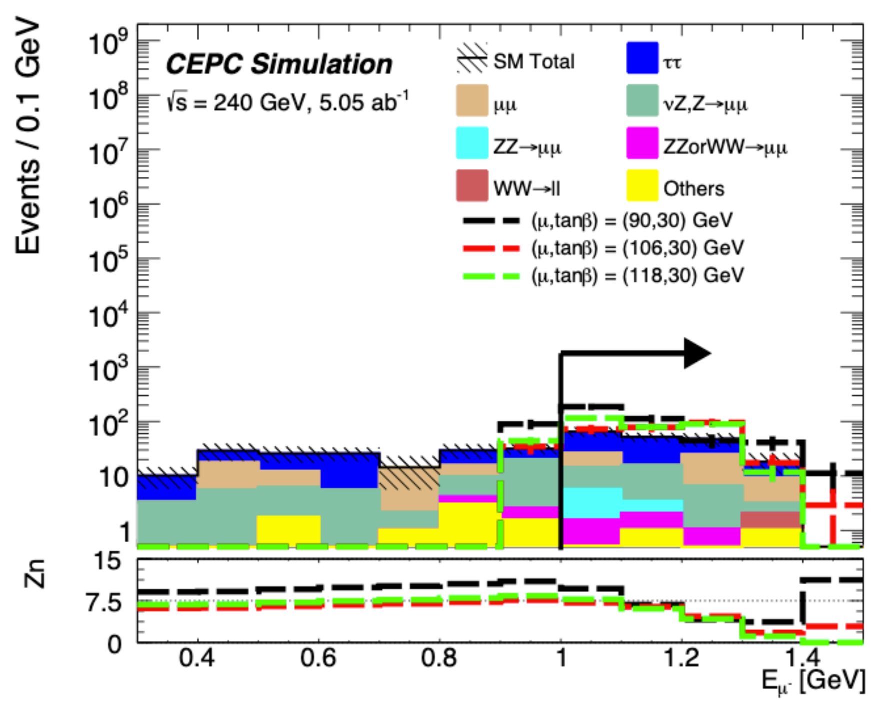
- **Unlike wino-bino case, the higgsino signal has much softer muons while much larger recoil mass!**

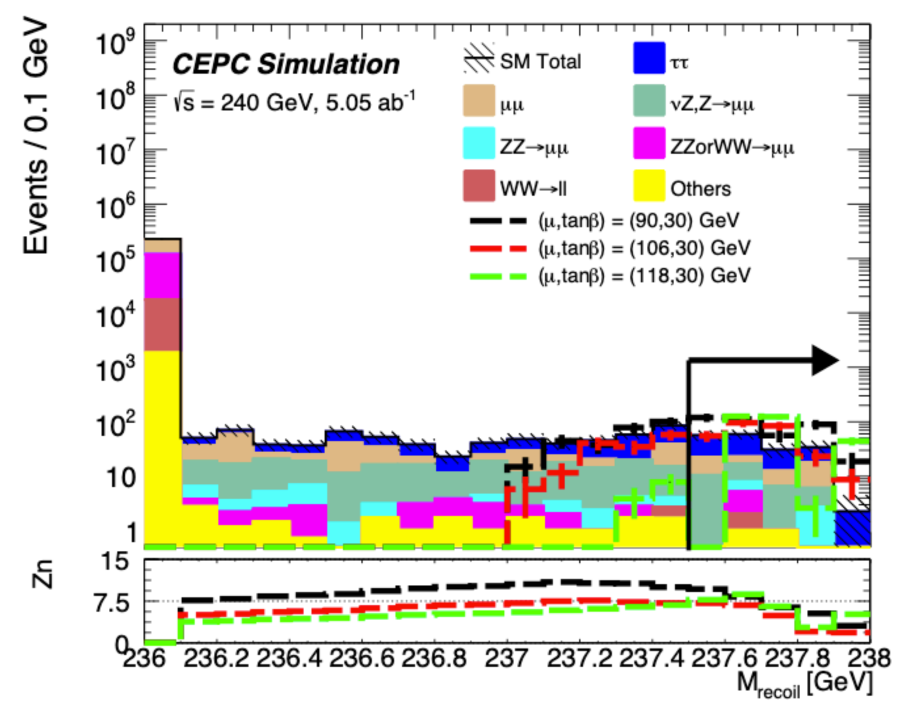
Higgsino search

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

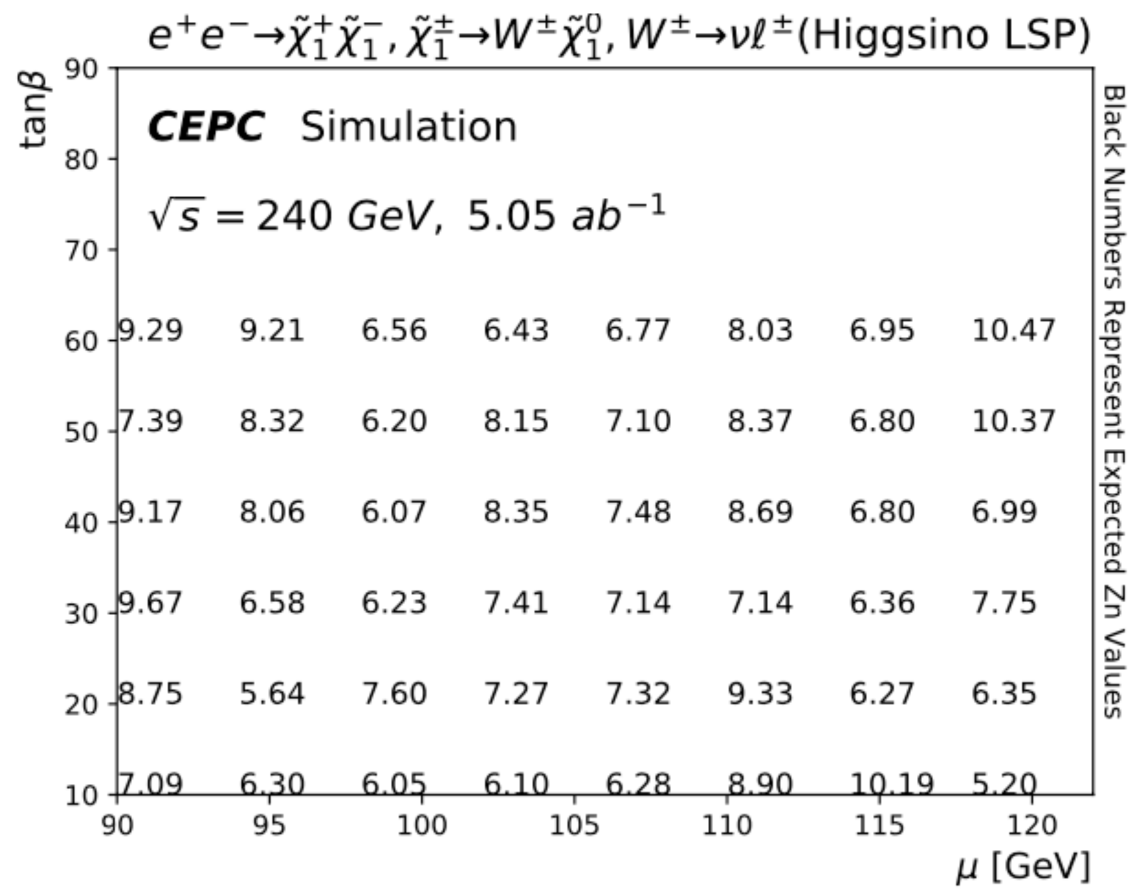
- Softer muon due to small signal mass splitting
- ΔR(μ,recoil): retain signal/suppress background
- |Δϕ(μ⁺,μ⁻)| < 1.4: suppress two muons back to back
- Mrecoil: much significant for signal, tighter than the wino case due to higher missing energy
- Dominant background: ττ

Processes	Yields
$\tau\tau$	107±16
$\mu\mu$	37±15
$\nu Z, Z \to \mu\mu$	27.8±5.6
$ZZ \to \mu\mu\nu\nu$	5.5±2.8
ZZ or $WW \to \mu\mu\nu\nu$	3.2±1.8
$WW \to \ell\ell$	1.0±1.0
Others	2.6±1.6
Total background	183±23
(μ , $\tan\beta$) = (90 GeV , 30)	396±39
(μ , $\tan\beta$) = (106 GeV , 30)	267±28
(μ , $\tan\beta$) = (118 GeV , 30)	296±20

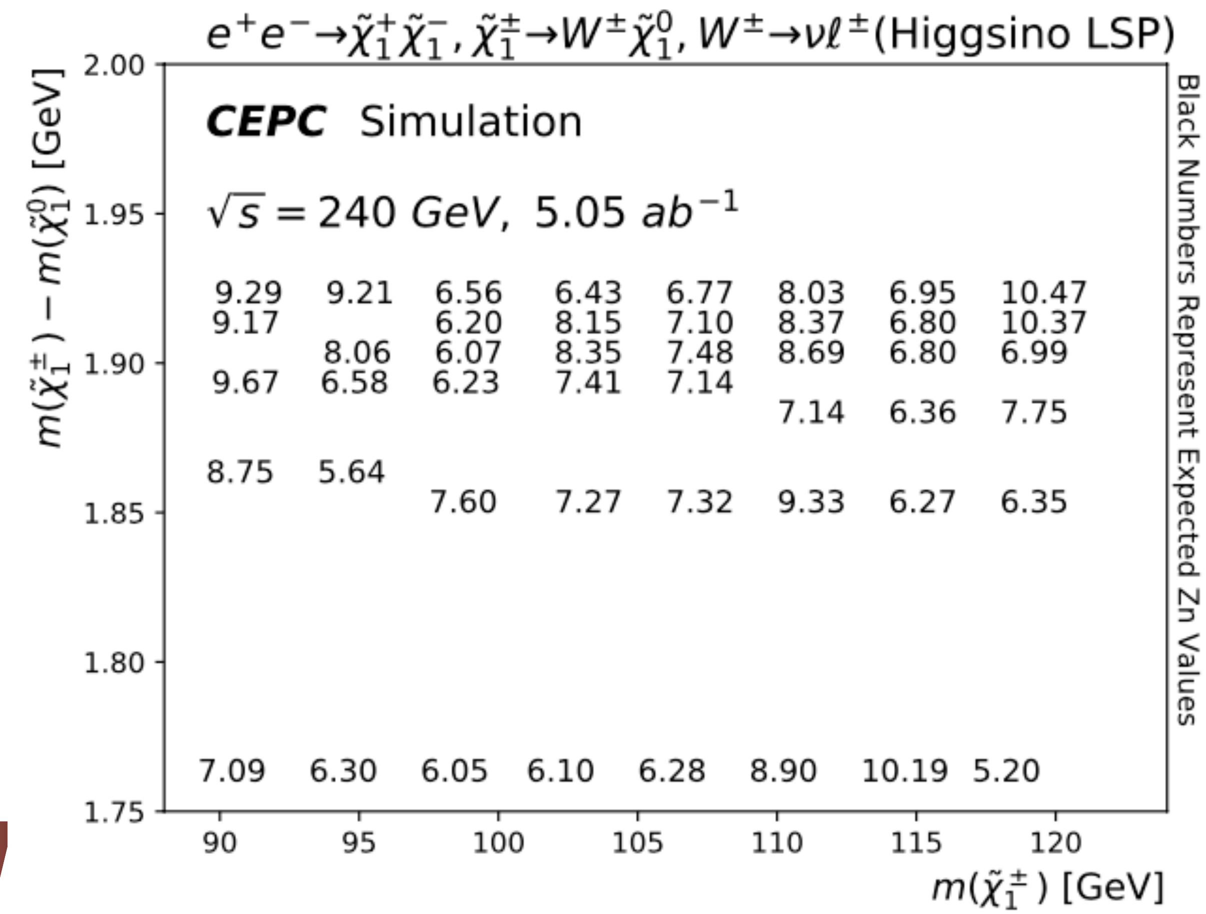




Higgsino search



(b) systematic uncertainty =5%



(d) systematic uncertainty =5%

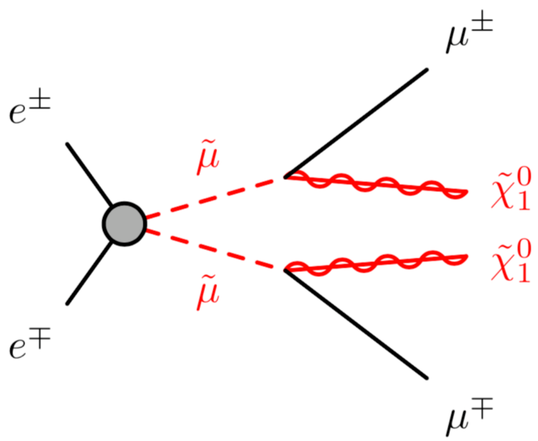
Nice discovery sensitivity coverage, up to the detector constraint.

Interpreted in both μ-tanβ and C1-dM scenarios.

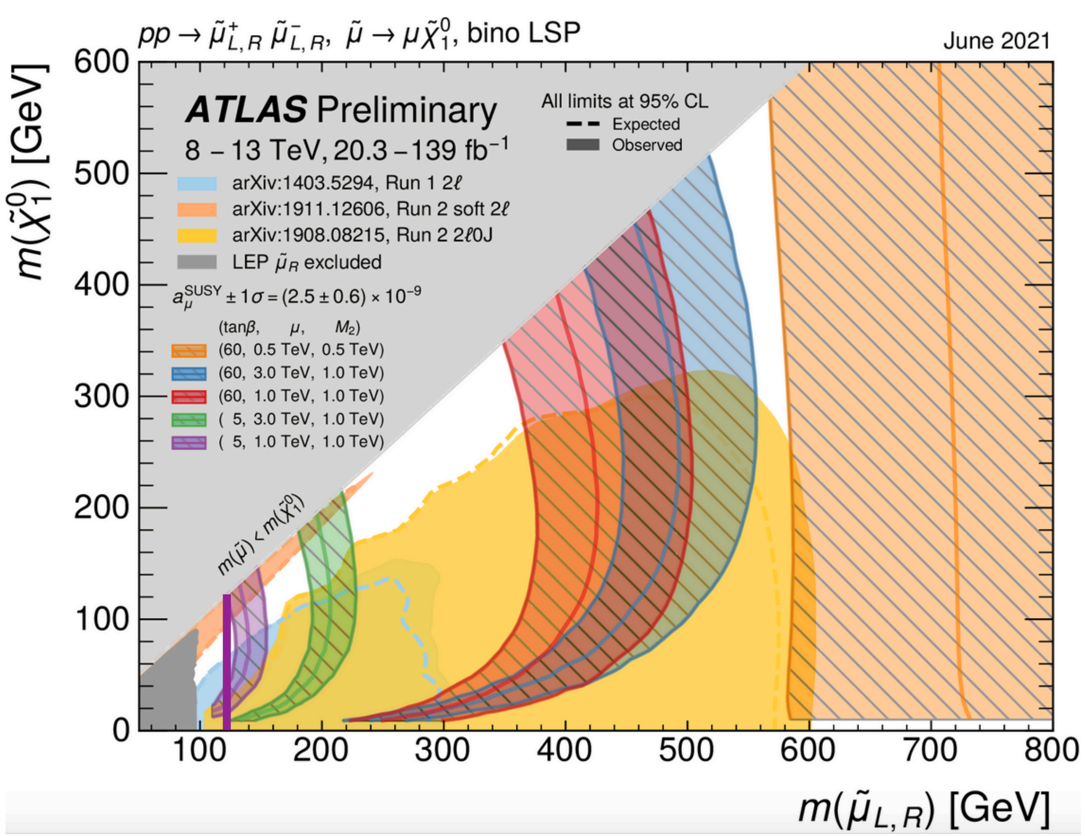
According to the current result, there are large potential to explore to even compressed region!

Smuon search

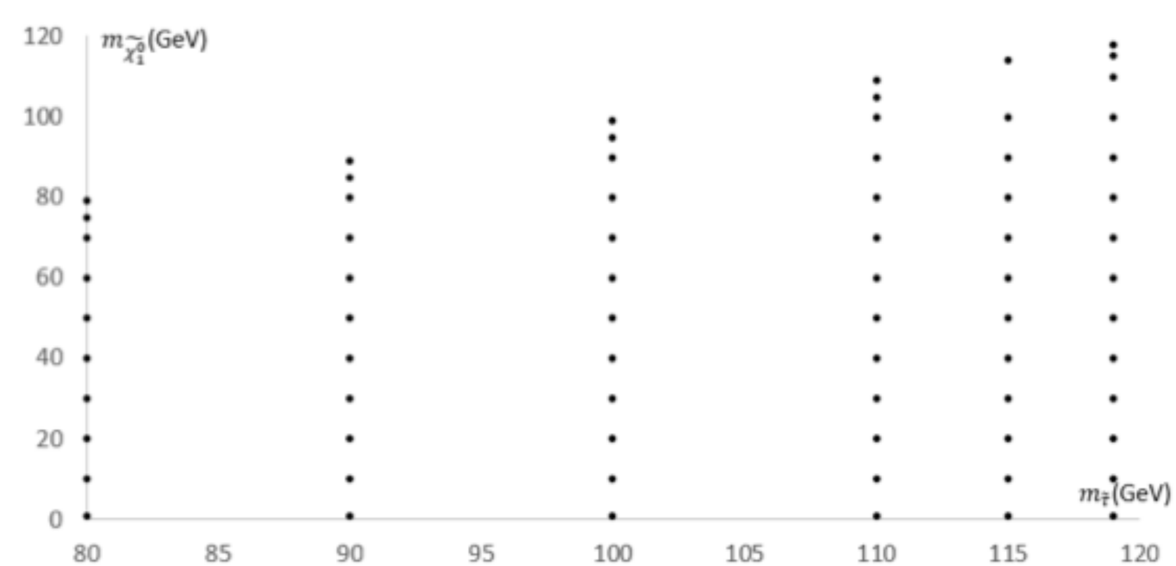
Favored by muon g-2 excess. Explore soft smuon in CEPC.



- Signal sample designed in μ˜ and LSP mass phase space
- μ˜ mass is bounded by LEP/CEPC limit; LSP is bounded by the μ˜ mass
- Slepton decay into a lepton and a LSP with 100% BR
- Ref. Point: 115_20, 115_70, 115_110 with cross-section (LO) = 23.6 fb



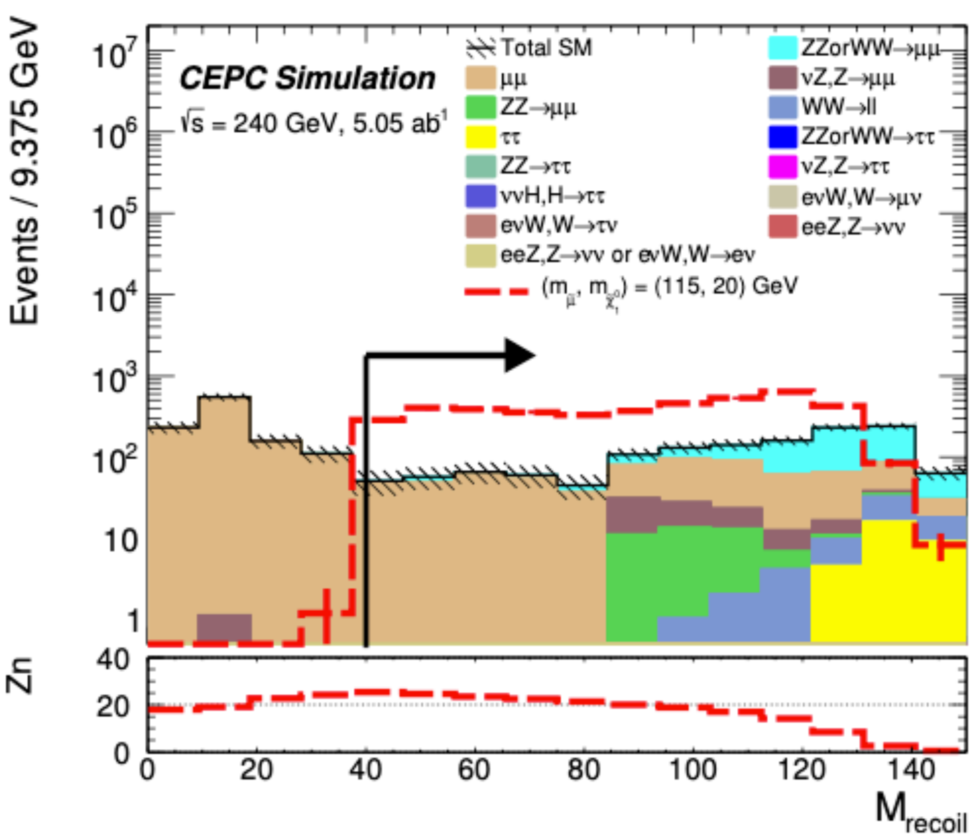
Direct stau/smuon



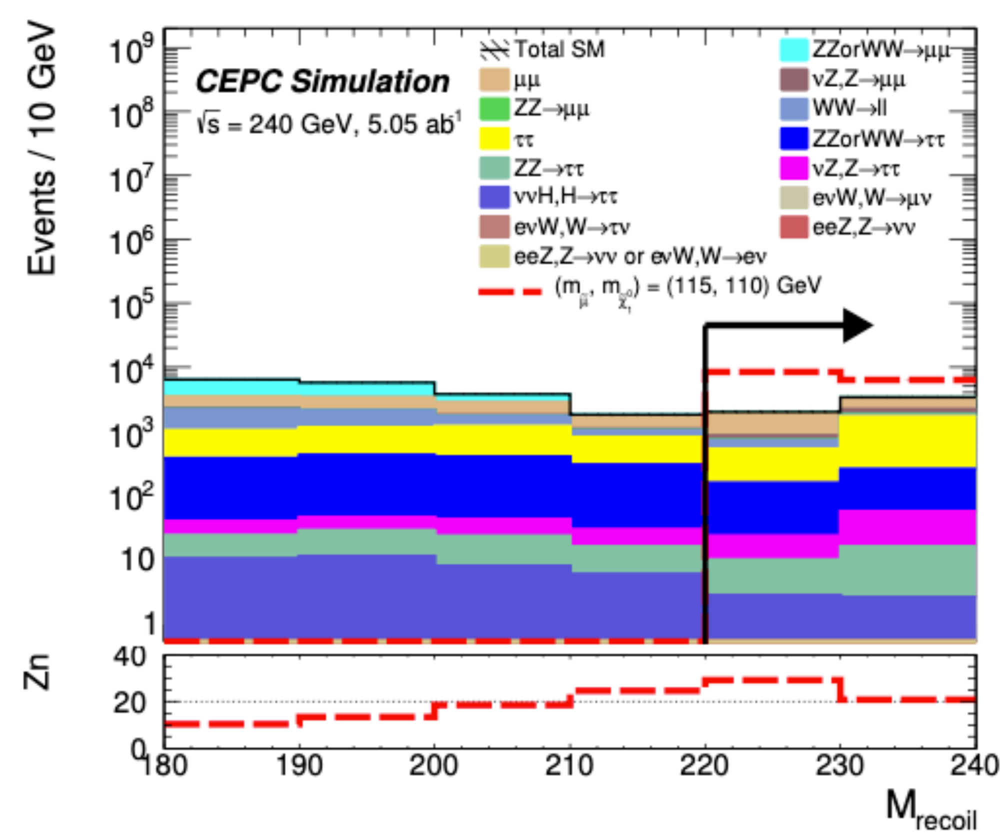
Smuon search

SR-highDeltaM	SR-midDeltaM	SR-lowDeltaM
== 2 muons (OS, both energy >0.5 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

- 3 SR categories according to different mass splitting
- For large dM, high μ energy
- For small dM, high Mrecoil

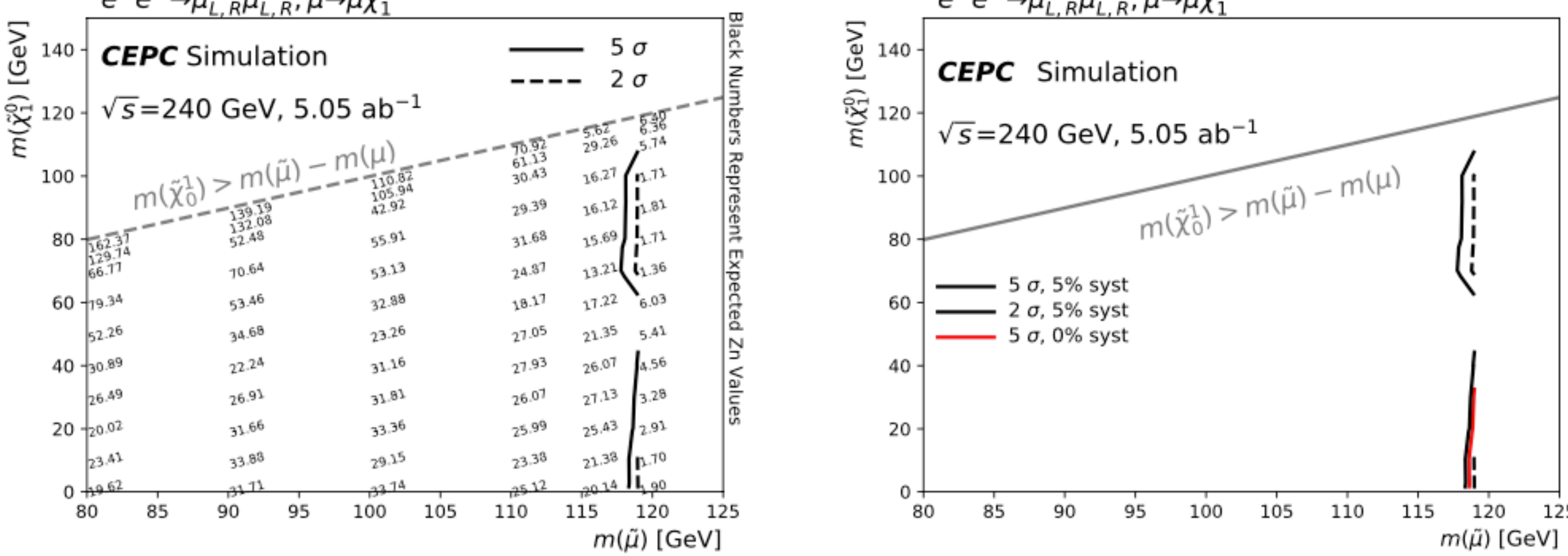


(a) SR-highDeltaM:M_{recoil}



(e) SR-lowDeltaM:M_{recoil}

Smuon search



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

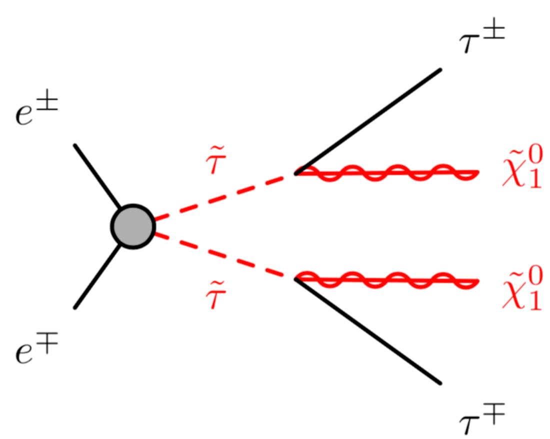
Great discovery sensitivity coverage, up to the detector constraint.

With flat 5% systematic, the discovery sensitivity can reach up to 117 GeV in smuon mass.

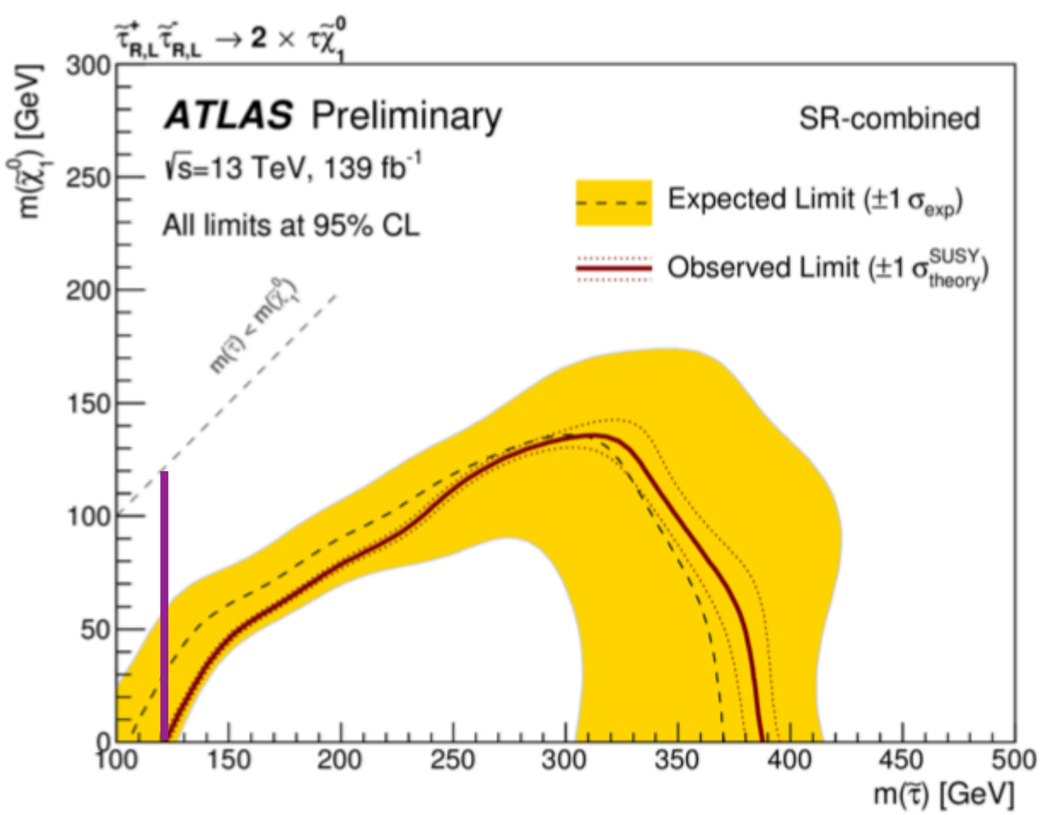
Fill in the LHC challenge region. No large impact from the uncertainty.

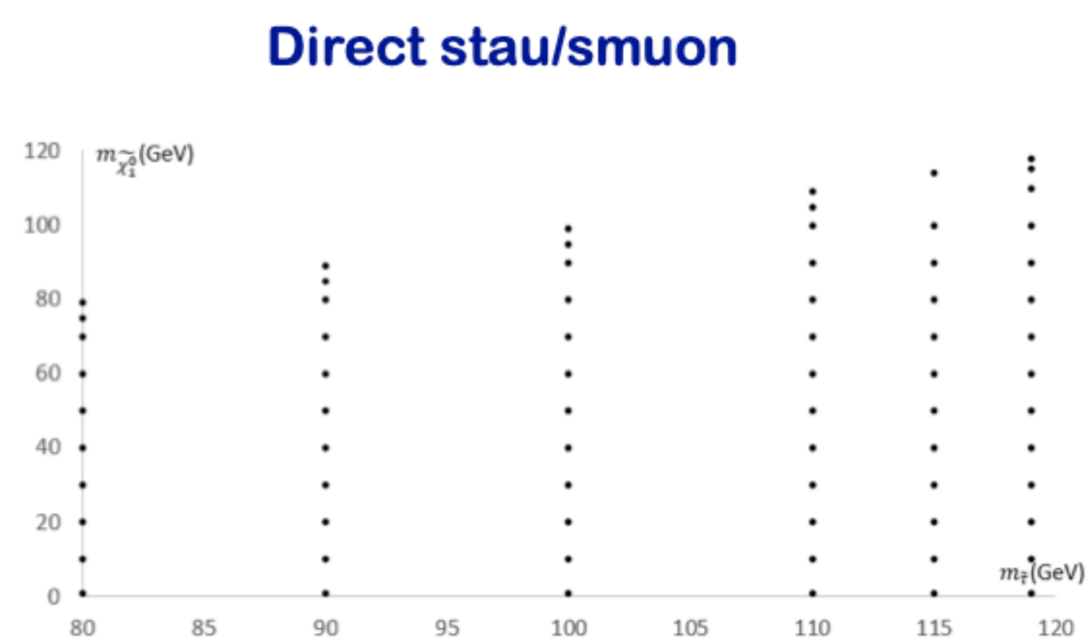
Stau search

Favored by dark matter relic density measurement. Explore soft stau in CEPC.



- **Signal sample designed in $\tilde{\tau}$ and LSP mass phase space**
- **$\tilde{\tau}$ mass is bounded by LEP/CEPC limit; LSP is bounded by the $\tilde{\tau}$ mass**
- **Stau decay into a tau and a LSP with 100% BR**
- **Ref. Point: 115_20, 115_60, 115_100 with cross-section (LO) = 23.6 fb**

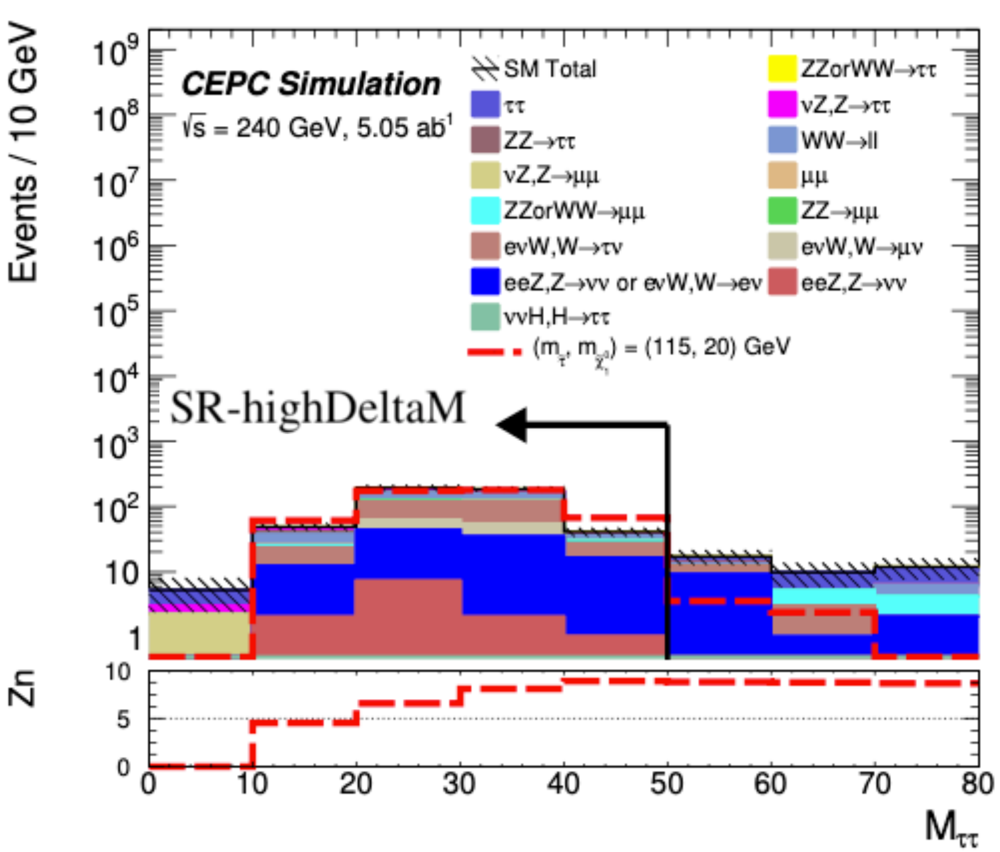


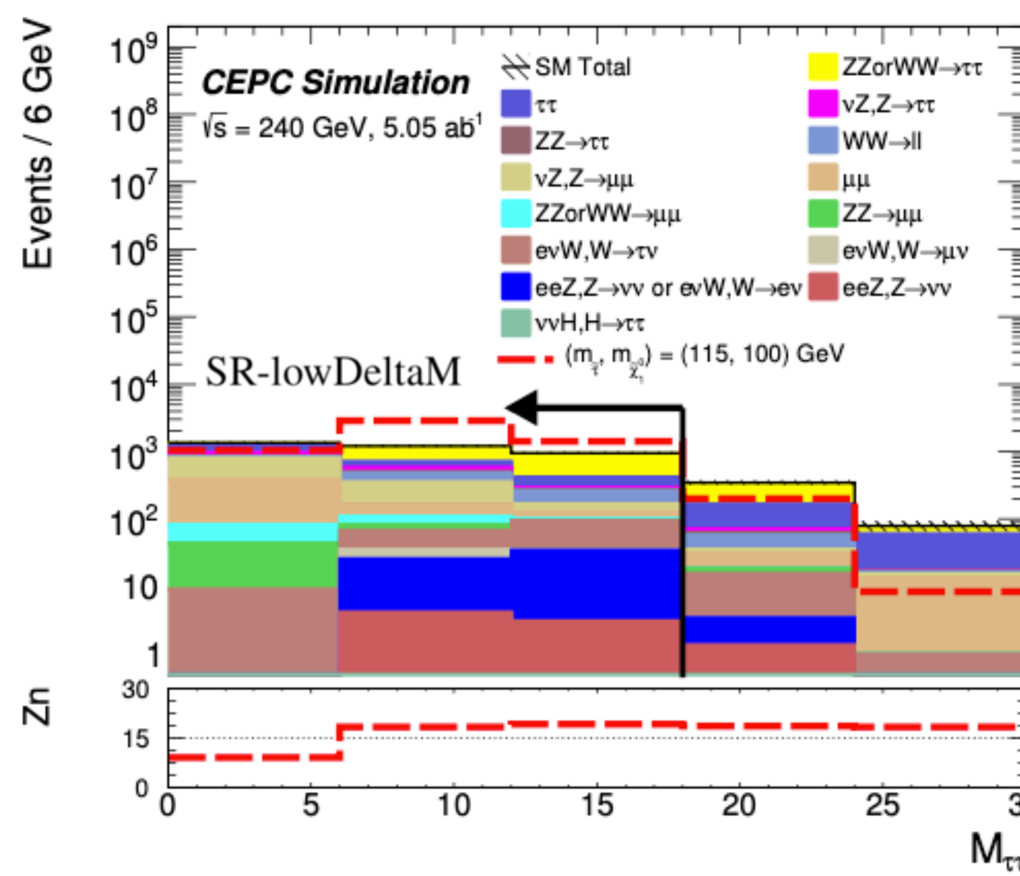


Stau search

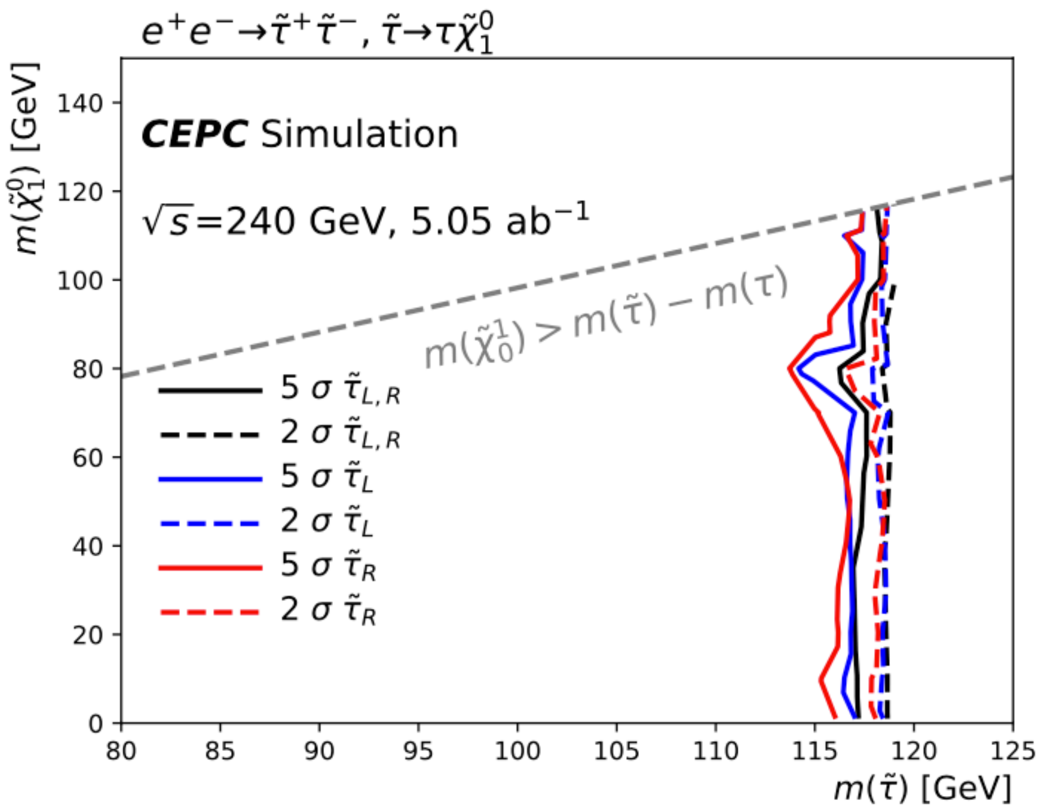
SR-highDeltaM	SR-midDeltaM	SR-lowDeltaM
$E_{\tau^\pm}$ <34 GeV	$E_{\tau^\pm}$ <15 GeV	
sumP_T >70 GeV	sumP_T >40 GeV	-
-	$0.2 < \|\Delta\phi(\tau,\tau)\| < 1.2$	$\|\Delta\phi(\tau,\tau)\| > 0.6$
$2.4 < \|\Delta\phi(\tau^\pm, recoil)\| < 3$		$\|\Delta\phi(\tau^\pm, recoil)\| > 2.3$
$0.4 < \Delta R(\tau,\tau)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

- 3 SR categories according to different mass splitting
- For large dM, high τ energy
- For small dM, high Mrecoil

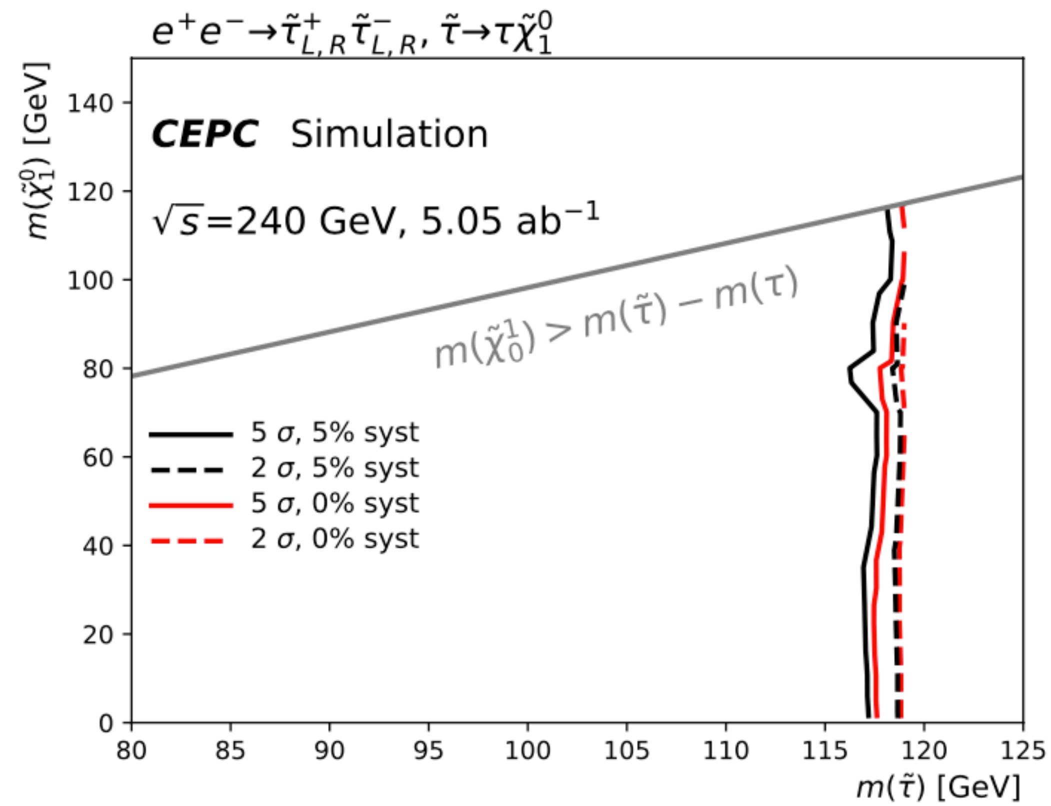




Stau search



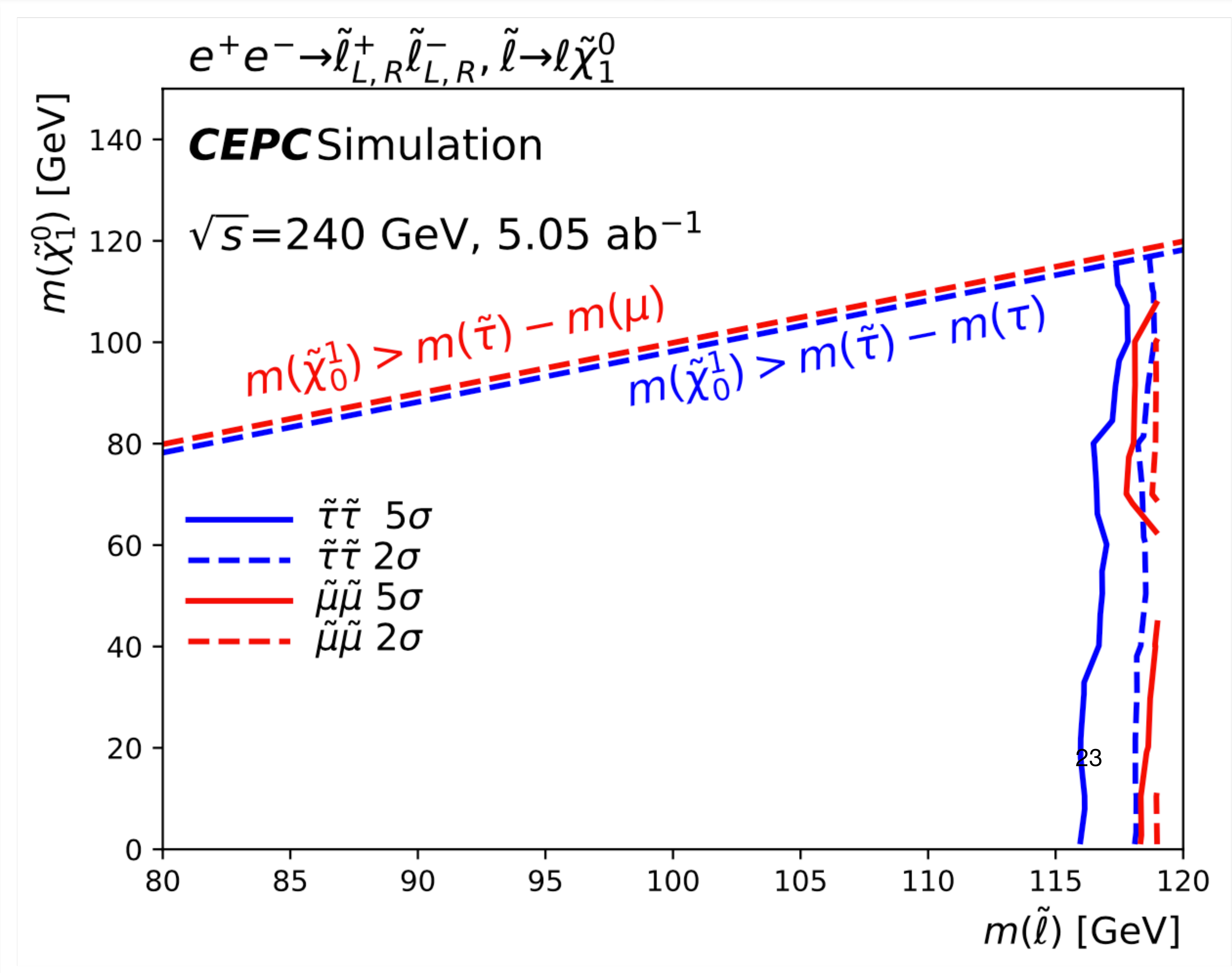
(a) systematic uncertainty = 5%



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

For direct stau production with left-/right- combined(only) stau, assuming flat 5% systematic uncertainty, the discovery sensitivity can reach up to 116 GeV (113 GeV) in stau mass.

Great power to fill the LHC gap!



$e^+e^-\to\tilde{\ell}^+_{L,R}\tilde{\ell}^-_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$
CEPC Simulation
$\sqrt{s}$=240 GeV, 5.05 ab^{-1}
$m(\tilde{\chi}^1_0) > m(\tilde{\tau}) - m(\mu)$
$m(\tilde{\chi}^1_0) > m(\tilde{\tau}) - m(\tau)$
$\tilde{\tau}\tilde{\tau}$ 5σ
$\tilde{\tau}\tilde{\tau}$ 2σ
$\tilde{\mu}\tilde{\mu}$ 5σ
$\tilde{\mu}\tilde{\mu}$ 2σ
$m(\tilde{\chi}^0_1)$ [GeV]
$m(\tilde{\ell})$ [GeV]
23

Summary

- Various prospective searches for sleptons and electroweakinos have been performed with CEPC.

- The discovery potential is high, close to the kinematic limit of the detector: $\sqrt{s}/2$.

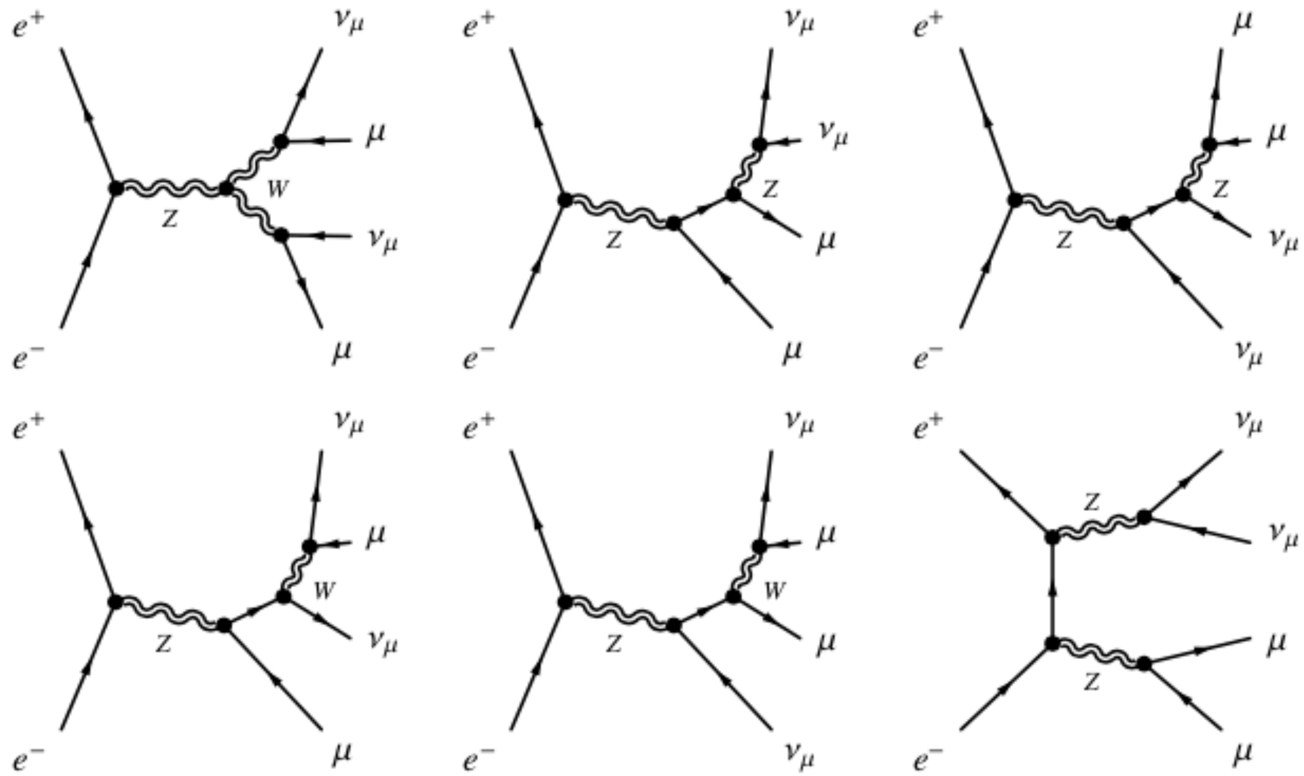
- The results can be referenced by other lepton colliders as ILC, FCC-ee etc.

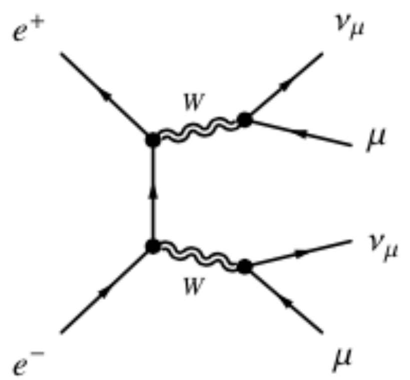
- A lepton collider is not just a precision-measurement machine, it has the discovery advantage in many challenge scenarios which can be difficult for a hadronic collider.

Extra slides

6.26 zzorww_l0mumu

$\nu_\mu\bar{\nu}_\mu\mu\bar{\mu}$,

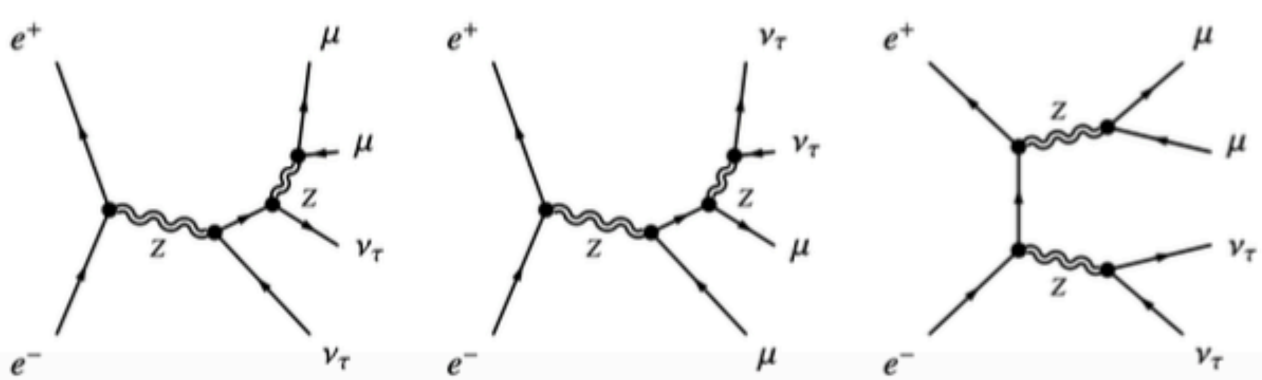




Some combinations could come from both Z and W boson, the corresponding processes form the mixing samples.

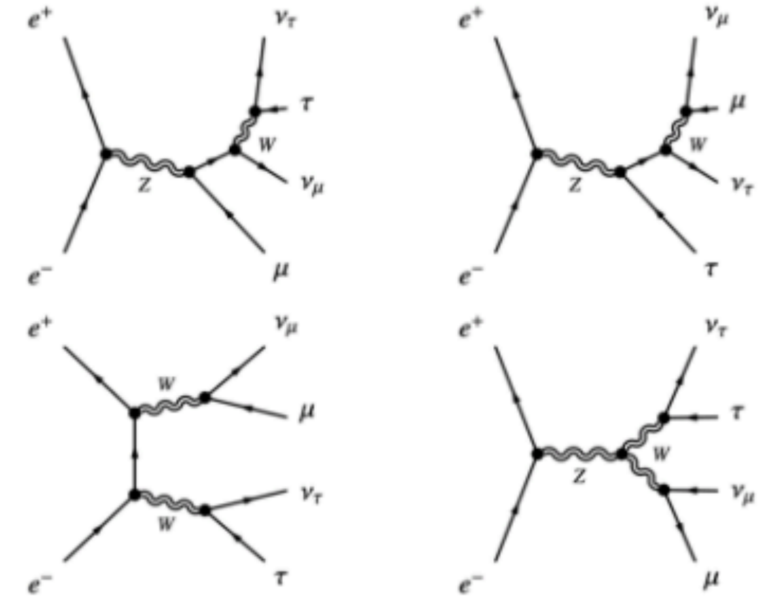
6.14 zz_l0mumu

Different flavor between lepton and neutrino.



6.23 ww_l0ll

Different flavor between lepton and neutrino.



3 The two fermions background

There are two different topological structure of two fermions Feynman diagrams. One is in s-channel, like in Fig.2, the other is in t-channel, shown as Fig.2. The t-channel can be classified still further according to its intermediate state. The information about the two fermions samples is listed in Tab.6.

Table 6: The cross section for the 2 fermions background

Process	Cross section [fb]	Error [fb]	ILC result [fb]
uu	9995.35	23.2	10110.43
dd	9808.71	25.7	10010.07
cc	9974.20	28.9	10102.75
ss	9805.39	74.7	9924.40
bb	9803.04	25.5	9957.70
qq	49561.30	120.0	50105.35
e2e2	4967.58	35.0	4991.91
e3e3	4374.94	10.5	4432.18
bhabha	24992.21	41.50	24937.95

It should be noted that the two fermions samples are generated under the averaged polarization.

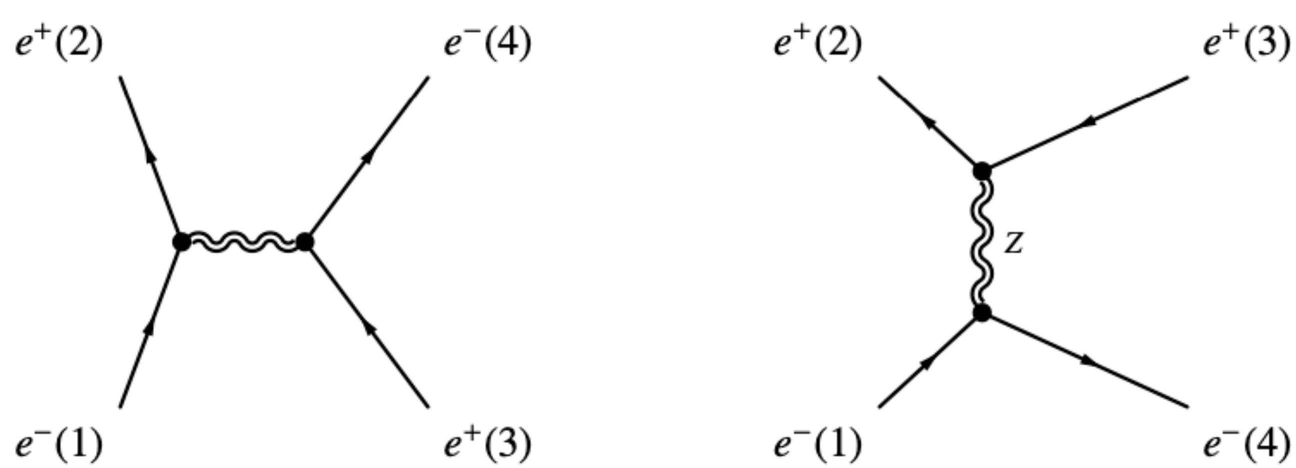
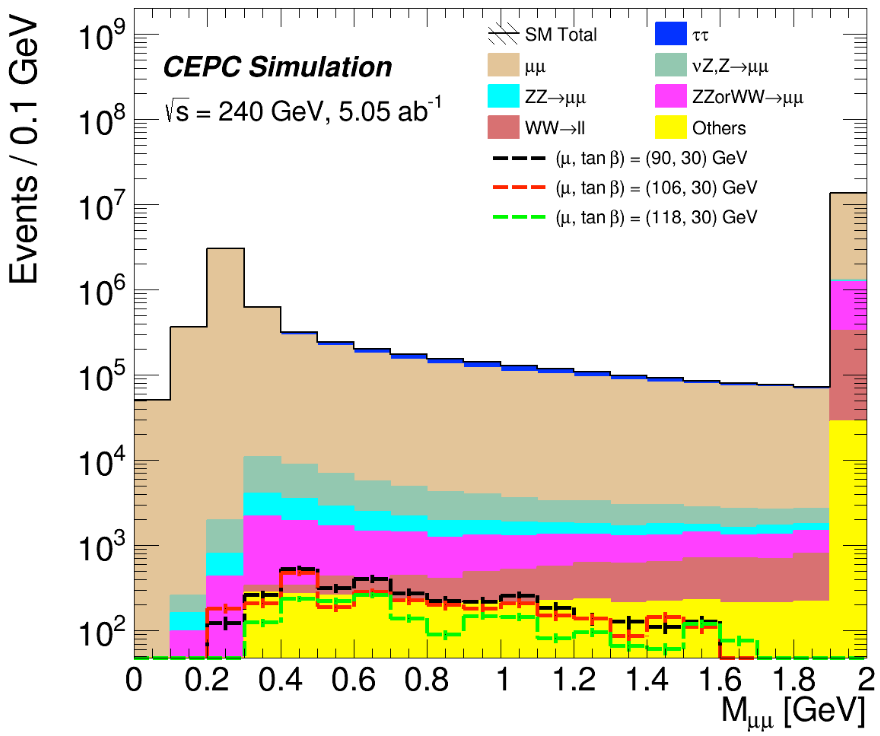
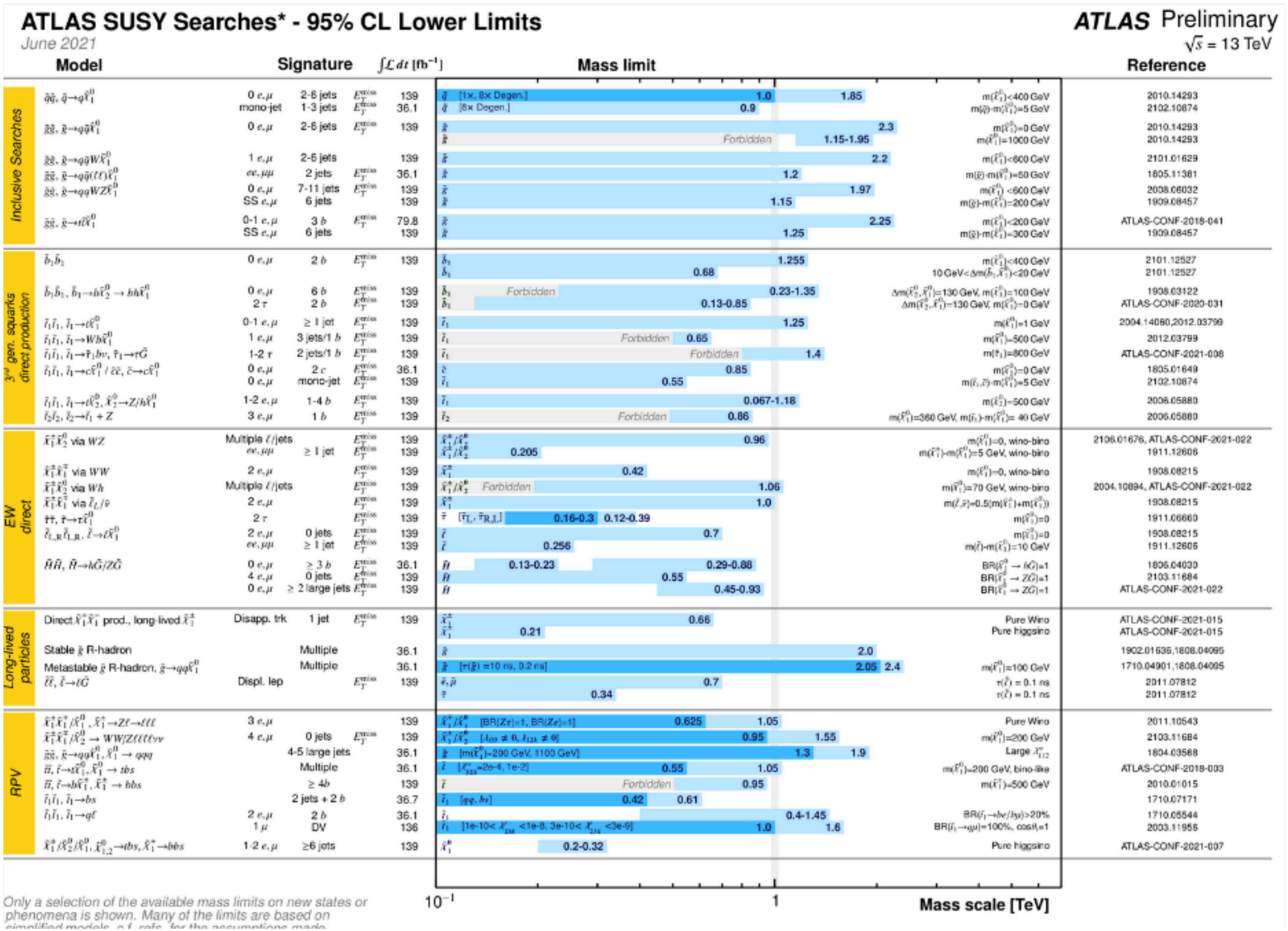


Figure 2: The diagrams of the two fermions processes



process	=2μ(OS,energy¿10GeV)	0.4¡$\Delta R(\mu,\mu)$¡1.6	M_{recoil} ¿ 130 GeV	P_T^{μ} ¿ 30 GeV/c
(110,1)	161984±683.611	46791.8±367.416	32560.1±306.49	5937.33±130.879
(110,10)	170754±701.874	52547.4±389.357	37620.4±329.446	6468.17±136.604
(110,25)	174808±710.156	51278±384.626	37559.8±329.181	8470.36±156.323
$\tau\tau$	322331±855.076	2808.2±79.812	2592.71±76.6886	88.4652±14.1658
$\nu\nu H, H\to\tau\tau$	229.299±5.96235	-	-	-
$ZZorWW\to\tau\tau\nu\nu$	11912.5±93.9421	280.774±14.4224	280.774±14.4224	0.740828±0.740828
$ZZ\to\tau\tau\nu\nu$	403.726±14.5777	33.1614±4.17794	32.1086±4.11109	-
$\nu Z, Z\to\tau\tau$	720.662±27.2774	61.948±7.99745	61.948±7.99745	-
$ZZorWW\to\mu\mu\nu\nu$	872793±965.476	41217.3±209.81	23016.5±156.785	1631.9±41.7477
$ZZ\to\mu\mu\nu\nu$	40228.7±235.959	4367.9±77.7508	871.92±34.7381	27.68±6.18944
$WW\to\ell\ell$	228461±483.442	7432.1±87.1954	6559.48±81.9167	162.657±12.8995
$\nu Z, Z\to\mu\mu$	60942.3±260.44	7349.14±90.4411	3333.44±60.9107	47.859±7.29843
$\mu\mu$	1.58973e+07±9837.01	232292±1189.1	19374.9±343.417	608.7±60.87
$e\nu W, W\to\mu\nu$	-	-	-	-
$e\nu W, W\to\tau\nu$	9.063±3.021	-	-	-
$eeZ, Z\to\nu\nu$	-	-	-	-
$eeZ, Z\to\nu\nu$ or $e\nu W, W\to e\nu$	-	-	-	-
total background	1.74353e+07±9939.68	295843±1219.21	56123.8±400.392	2568.01±76.8585

process	=2μ(OS)	E_{μ}¿0.95GeV	3.2¡$\Delta R(\mu, recoil)$ ¡ 4.6	$\Delta\phi(\mu, recoil)$ ¡2.9	M_{recoil} ¿ 237.5 GeV
(90,30)	3867.16±120.263	3803.58±119.27	2434.74±95.425	826.54±55.5991	546.04±45.1906
(118,30)	2245.1±54.0243	2198.3±53.4583	1280.5±40.8001	412.1±23.1458	400.4±22.8149
(118,10)	1621.62±48.1551	1578.72±47.5139	785.07±33.506	207.35±17.2195	201.63±16.9803
$\tau\tau$	601598±1168.19	557650±1124.71	362032±906.219	2635.88±77.3255	117.957±16.3577
$\nu\nu H, H\to\tau\tau$	451.05±8.36138	424.855±8.11496	148.49±4.79749	18.135±1.67658	0.155±0.155
$ZZorWW\to\tau\tau\nu\nu$	31629.6±180.714	29273.4±173.853	14978.5±124.359	1824.43±43.4019	3.0975±1.78834
$ZZ\to\tau\tau\nu\nu$	1395.49±27.1032	1200.19±25.1353	463.232±15.6155	38.4272±4.49756	0.5264±0.5264
$\nu Z, Z\to\tau\tau$	2390.56±42.0824	1845.33±36.9733	690.426±22.6156	61.4864±6.74901	-
$ZZorWW\to\mu\mu\nu\nu$	906723±984.063	905997±983.669	502054±732.252	105817±336.174	4.272±2.136
$ZZ\to\mu\mu\nu\nu$	49490.5±261.715	48878.7±260.093	21301.1±171.7	1238.68±41.4045	5.536±2.768
$WW\to\ell\ell$	315375±568.004	304846±558.442	158570±402.762	16007.9±127.969	1.023±1.023
$\nu Z, Z\to\mu\mu$	105339±342.406	99931.8±333.503	46372±227.183	3165.37±59.3554	36.729±6.3937
$\mu\mu$	1.77661e+07±10399.1	1.77487e+07±10394	1.21686e+07±8606.42	103881±795.187	48.696±17.2166
$e\nu W, W\to\mu\nu$	-	-	-	-	-
$e\nu W, W\to\tau\nu$	24.168±4.93327	24.168±4.93327	19.133±4.38941	1.007±1.007	1.007±1.007
$eeZ, Z\to\nu\nu$	-	-	-	-	-
$eeZ, Z\to\nu\nu$ or $e\nu W, W\to e\nu$	-	-	-	-	-
total background	1.97805e+07±10536.5	1.96987e+07±10525.8	1.32753e+07±8699.85	234690±880.273	218.999±24.9529


ATLAS SUSY Searches* - 95% CL Lower Limits
June 2021
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model
Signature
$\int \mathcal{L}\,dt$ [fb^{-1}]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
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[8× Degen.] 0.9 2102.10874
2.3 2010.14293
Forbidden 1.15-1.95 2010.14293
2.2 2101.01629
1.2 1805.11381
1.97 2008.06032
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0.13-0.23 0.29-0.88 1806.04030
0.55 2103.11684
0.45-0.93 ATLAS-CONF-2021-022
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ Disapp. trk 1 jet 139 0.66 Pure Wino ATLAS-CONF-2021-015
0.21 Pure higgsino ATLAS-CONF-2021-015
Stable $\tilde{g}$ R-hadron Multiple 36.1 2.0 1902.01636,1808.04095
Metastable $\tilde{g}$ R-hadron Multiple 36.1 [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4 1710.04901,1808.04095
Displ. lep 139 0.7 2011.07812
0.34 2011.07812
0.625 1.05 Pure Wino 2011.10543
0.95 1.55 2103.11684
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1.0 1.6 2003.11956
0.2-0.32 Pure higgsino ATLAS-CONF-2021-007
10^{-1}
1
Mass scale [TeV]
Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on
simplified models, c.f. refs. for the assumptions made.

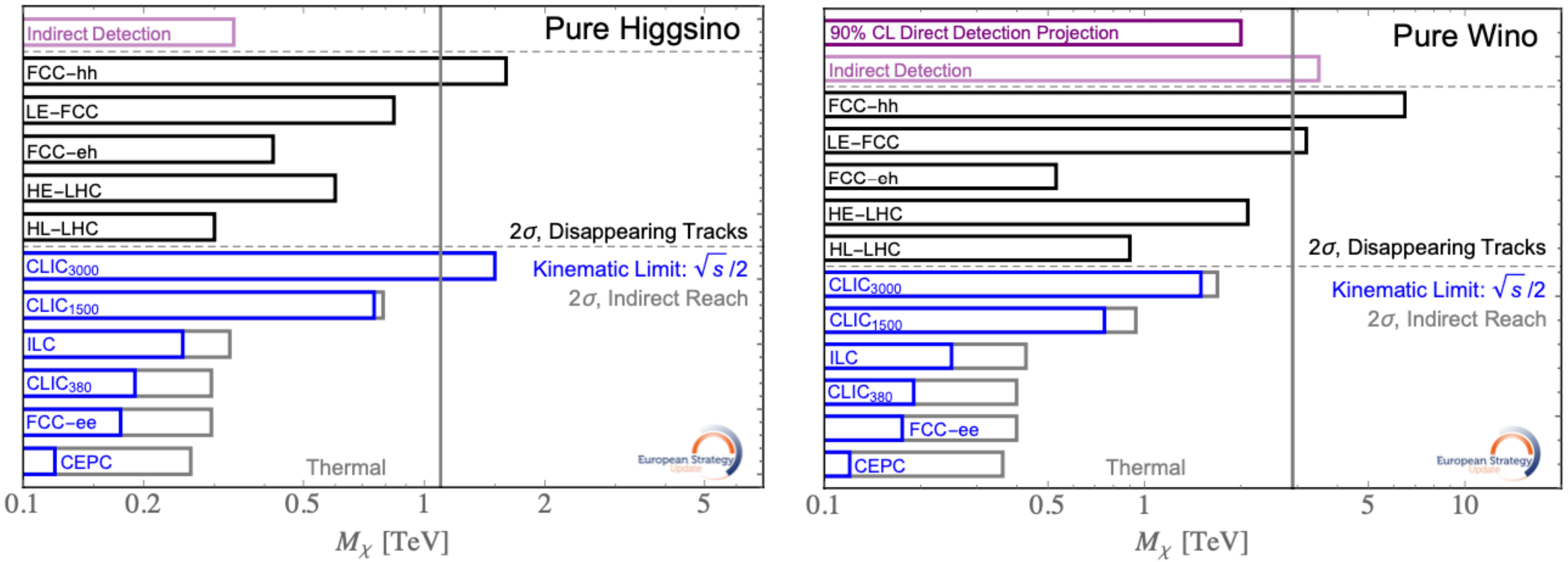
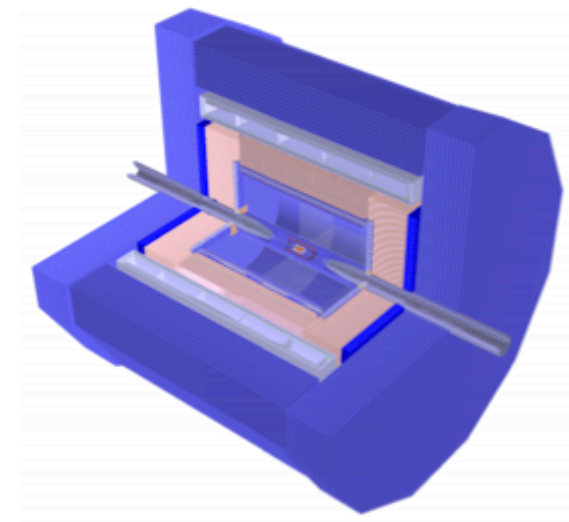


Fig. 8.14: Summary of 2σ sensitivity reach to pure Higgsinos and Winos at future colliders. Current indirect DM detection constraints (which suffer from unknown halo-modelling uncertainties) and projections for future direct DM detection (which suffer from uncertainties on the Wino-nucleon cross section) are also indicated. The vertical line shows the mass corresponding to DM thermal relic.

TECHNICAL DETAIL



- About CEPC

  ECM=240GeV, higgs factory, 100 km circumference, 2 interaction points.

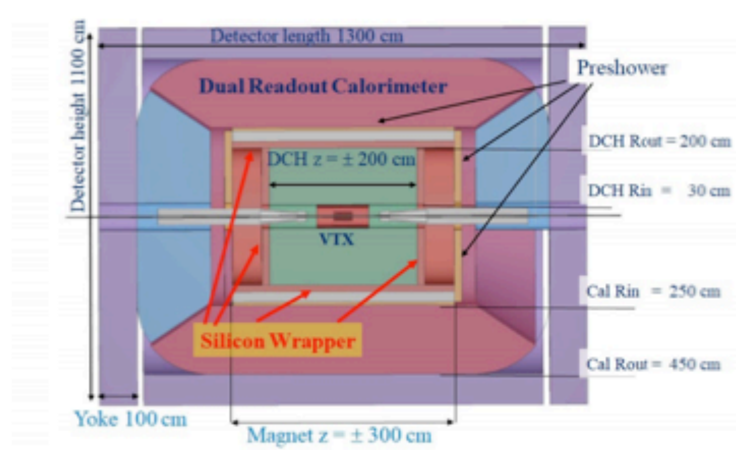
  ILD-like detector
- Software

  Signal samples: MadGraph+Pythia8

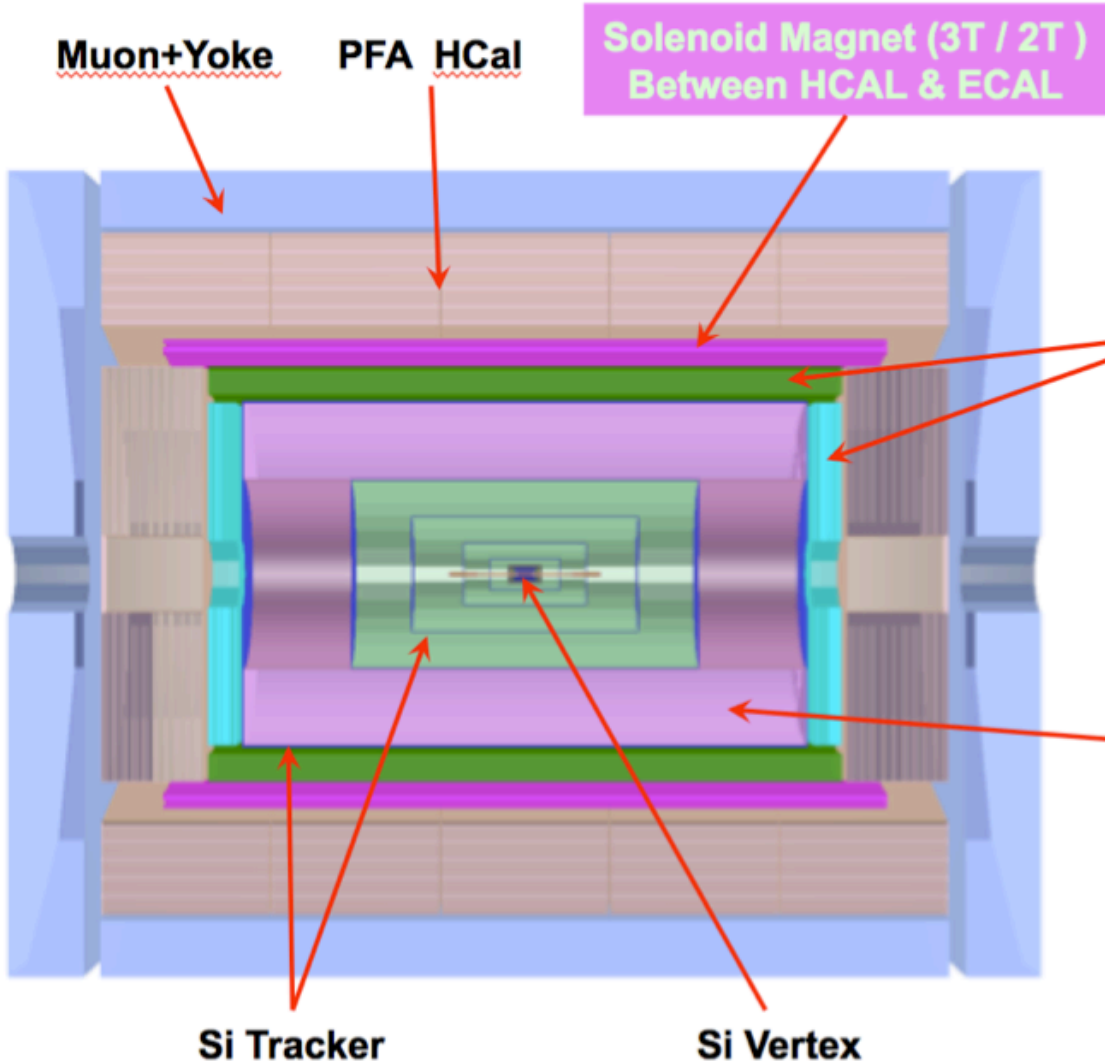
  Simulation: Mokka

  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.**

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



The 4th Conceptual Detector Design



Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Transverse Crystal bar ECAL

Advantage: better π^0/γ reconstruction.

Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

Drift chamber that is optimized for PID

Advantage: Work at high luminosity Z runs

Challenges: sufficient PID power; thin enough not to affect the moment resolution.

32

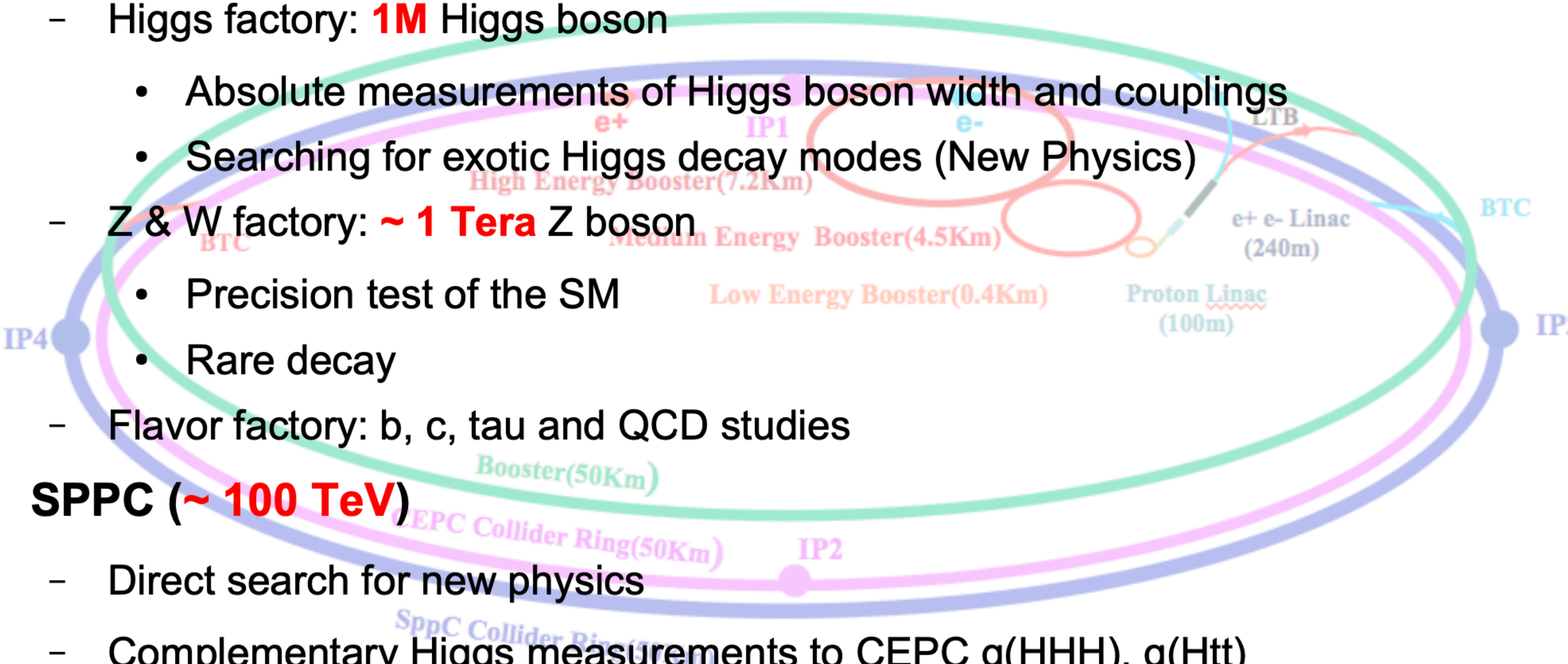
6

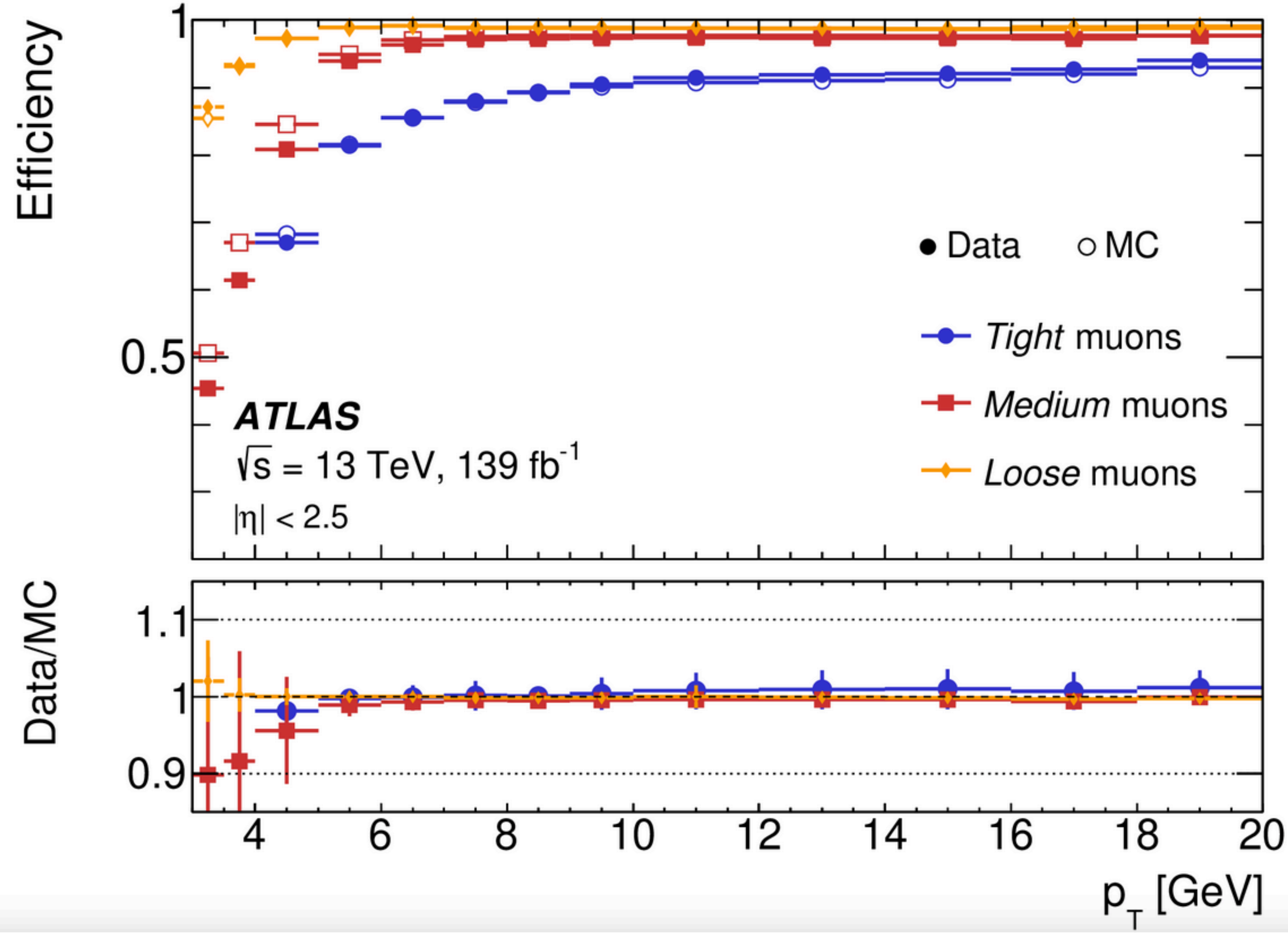
+ requirement & hardware studies
& Innovative software developments;

Key parameters of the CEPC-SPPC

- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **~ 1 Tera** Z boson
    - Precision test of the SM
    - Rare decay
  - Flavor factory: b, c, tau and QCD studies
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...
- **Heavy ion, e-p collision...**

Complementary





Efficiency
Data/MC
1
0.5
1.1
1
0.9
4
6
8
10
12
14
16
18
20
p_T [GeV]
● Data ○ MC
Tight muons
Medium muons
Loose muons
ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$|\eta|$ < 2.5