EWK SUSY searches at FCC-eh

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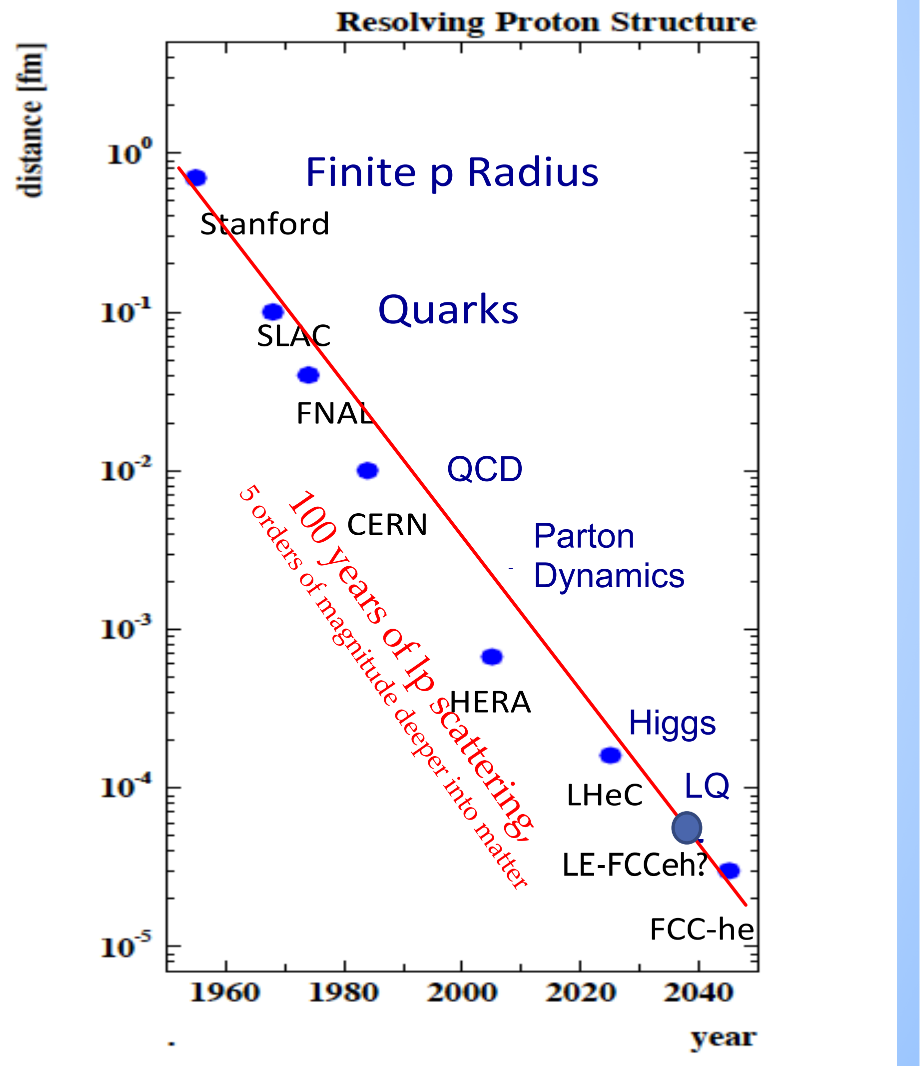
University of Liverpool

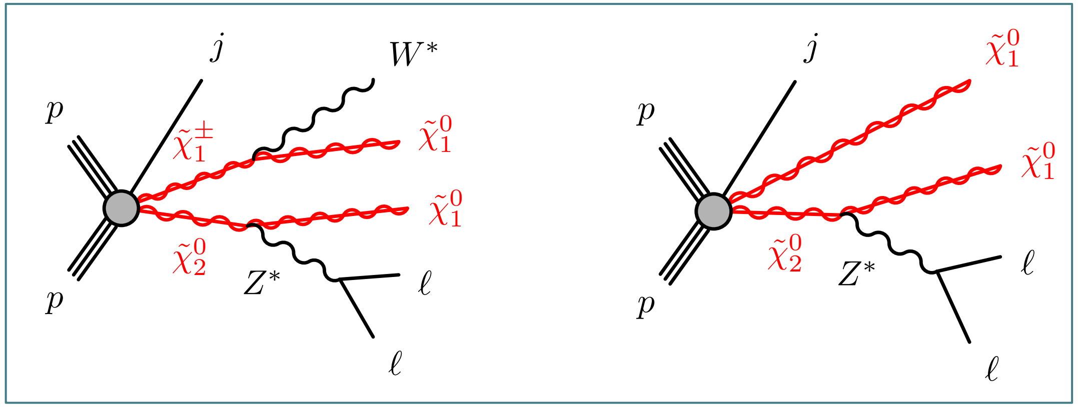
FCC Workshop

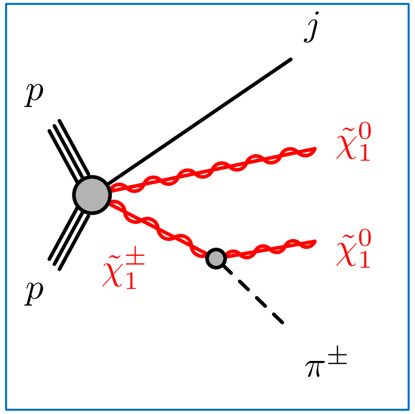
CERN, Switzerland, 16/1/2020



Introduction: the context

- Supersymmetric particles continue to be searched at the LHC
- At e-p, centre of mass energies are too low for strongly produced sparticles which remain domain of hadron colliders
  - Indirect *ep* impact: predictions of strong production cross sections at high mass, currently presenting 50-100% uncertainties due to PDF, can be improved
- EWK SUSY remains challenging at hh colliders, especially in compressed scenarios (and c.o.m. energy of FCC-ee is limited to m(sparticle) ~ 180 GeV)
  - Studies at HL-LHC and FCC-hh make very successful use of ISR-jets and soft leptons or disappearing-track analyses techniques





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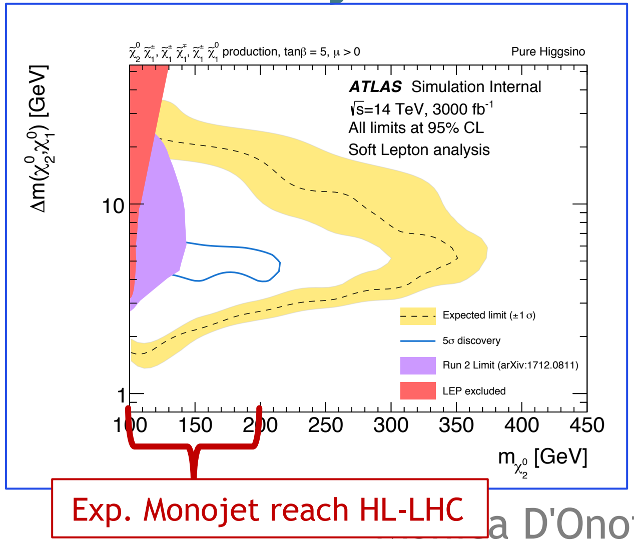
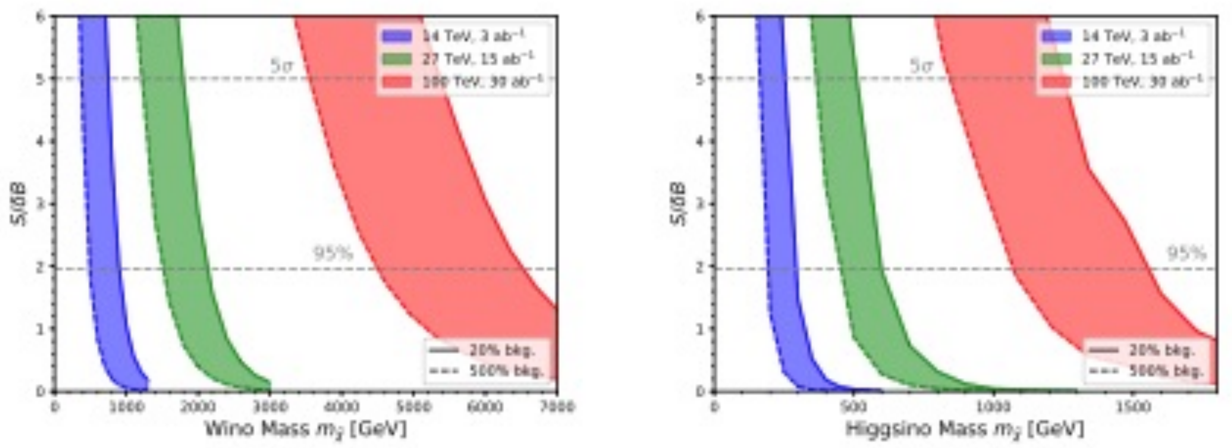
HL-LHC ISR-jets and soft leptons



HL/HE-LHC/FCC-hh disappearing-track analyses



E-p EWK SUSY: two studies

- There could remain uncovered regions of the SUSY parameter space after HL-LHC and, depending on the mass hierarchy in the EWK sector, FCC-eh might offer complementary sensitivity to that of FCC-hh.

- **Two sets of studies:**
  - prompt production of chargino/neutralino with/without sleptons
    - https://arxiv.org/pdf/1912.03823 New
      [K. Wang, S. Iwamoto, G. Azuelos, MD]
  - Non-prompt production of chargino/neutralino → long-lived particles
    - https://arxiv.org/abs/1712.07135
      [O. Fischer, D. Curtin, K. Deshpande, J. Zurita]

Prompt SUSY EWK production

- Target two kind of EWK mass spectra:

”Classic” compressed spectrum
→ **“decoupled-slepton scenario”**

“compressed-slepton scenario”

Slepton mass

Large gap

Chargino ~ Neutralino1 masses
Mass difference ~ 1-2 GeV

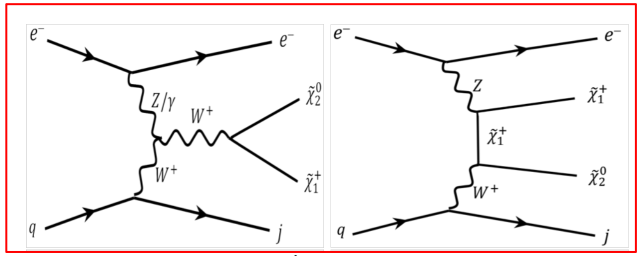
Slepton (selectron) mass

~35 GeV

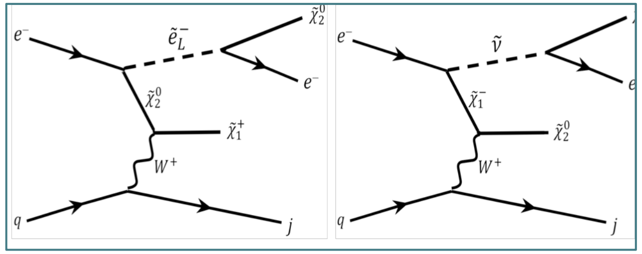
(Note: as sleptons are heavier than charginos and neutralinos, they do not play a role in the pp cross sections)

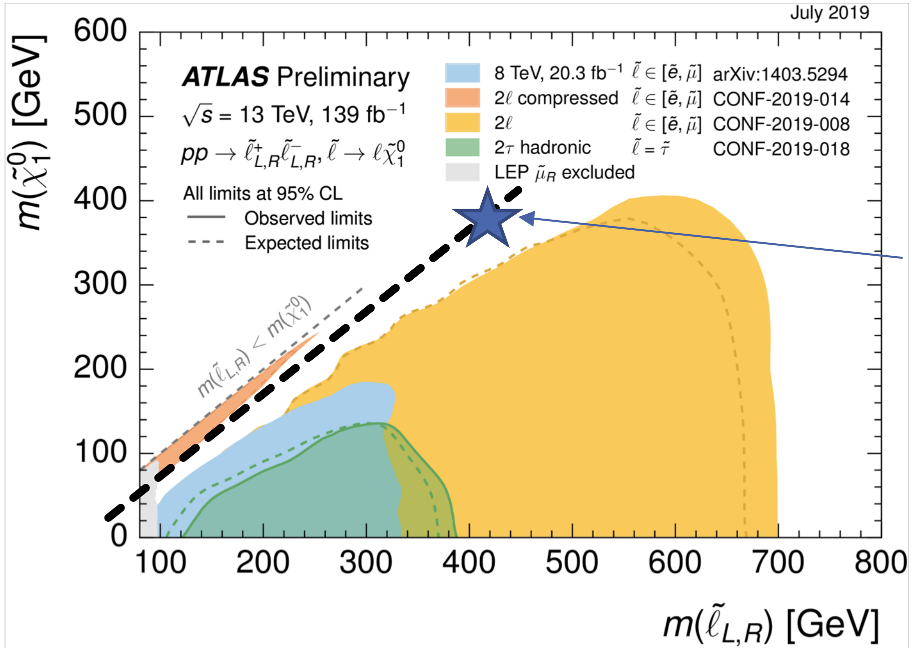
$$pe^- \rightarrow je^-\tilde{\chi}\tilde{\chi}\ (\tilde{\chi} = \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm)$$

VBF production



$$+\ pe^- \rightarrow j\tilde{\chi}\tilde{e}_L^-,\ j\tilde{\chi}\tilde{\nu} \rightarrow je^-\tilde{\chi}\tilde{\chi}$$





Benchmark slepton mass

Prompt SUSY EWK production

- Target two kind of EWK mass spectra:

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Slepton mass

Large gap

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"compressed-slepton scenario"

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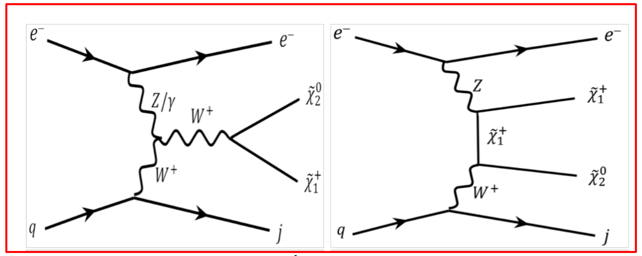
~35 GeV

Higher order corrections might be as high as 20% as for pp collisions - not taken into account (conservative!)

$$pe^- \to je^-\tilde{\chi}\tilde{\chi}\ (\tilde{\chi} = \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm)$$

VBF production



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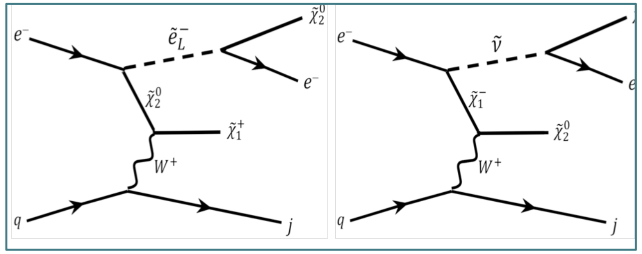
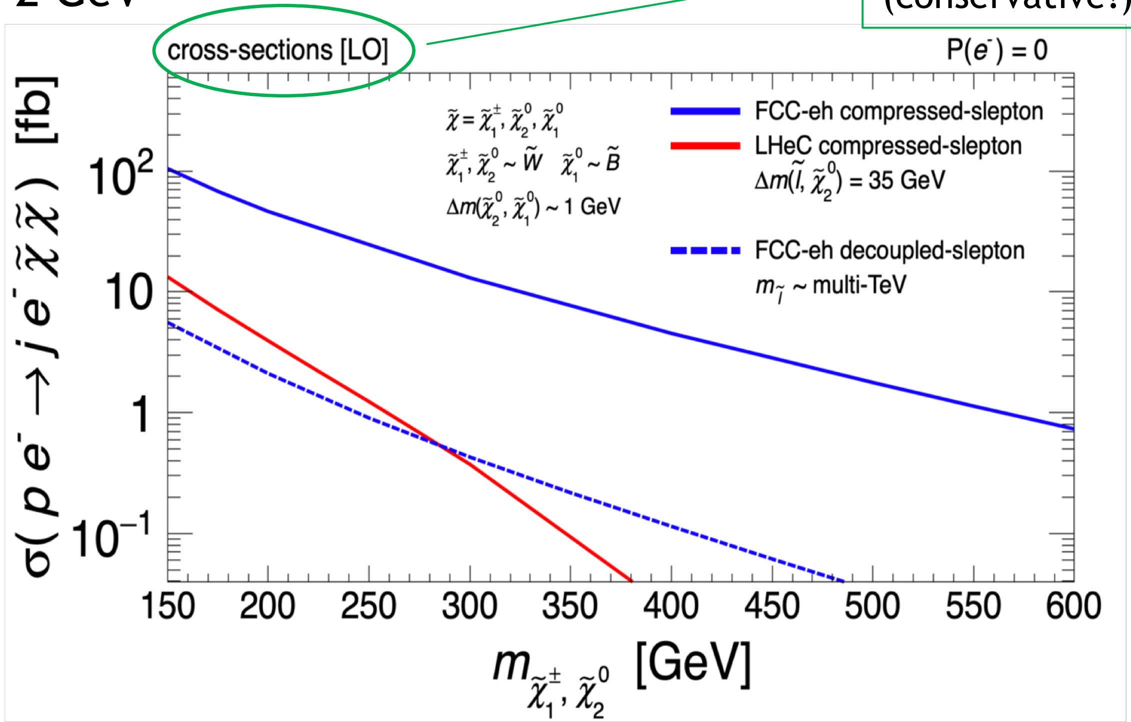
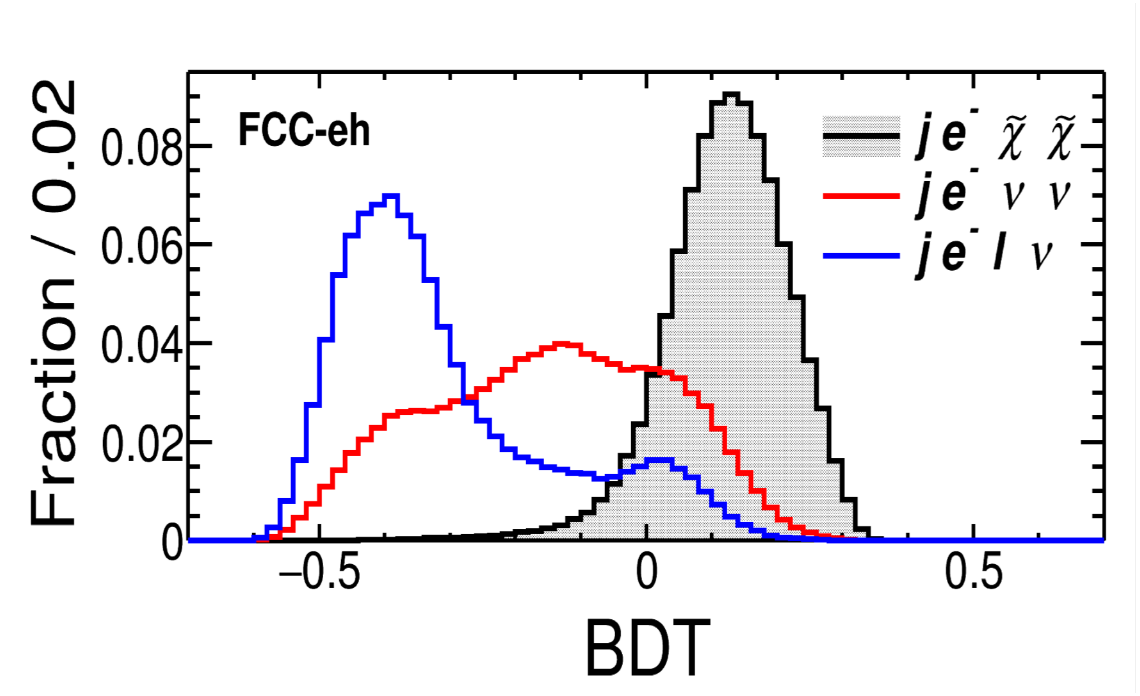




Compressed slepton scenarios: the analysis

- **Final state**: 1 e- + 1 j + MET
- Analysis at detector-level using a simple Boost Decision Tree.
- Backgrounds: all processes with one or two neutrinos (to also take into account mis-identified leptons): $p e^- \to j e^- \nu\nu$, $p e^- \to j e^- \ell\nu$
- Pre-selections:
  - At least one jet with $p_T > 20$ GeV, $|\eta| \leq 6.0$;
  - Exactly one electron with $p_T > 10$ GeV, $-5.0 < \eta < 5.2$;
  - No b-jet with $p_T > 20$ GeV;
  - No muon or tau with $p_T > 10$ GeV;
  - Missing transverse momentum $E^{miss}_T > 50$ GeV
- Use BDT with simple kinematic variables

and angular correlations as input



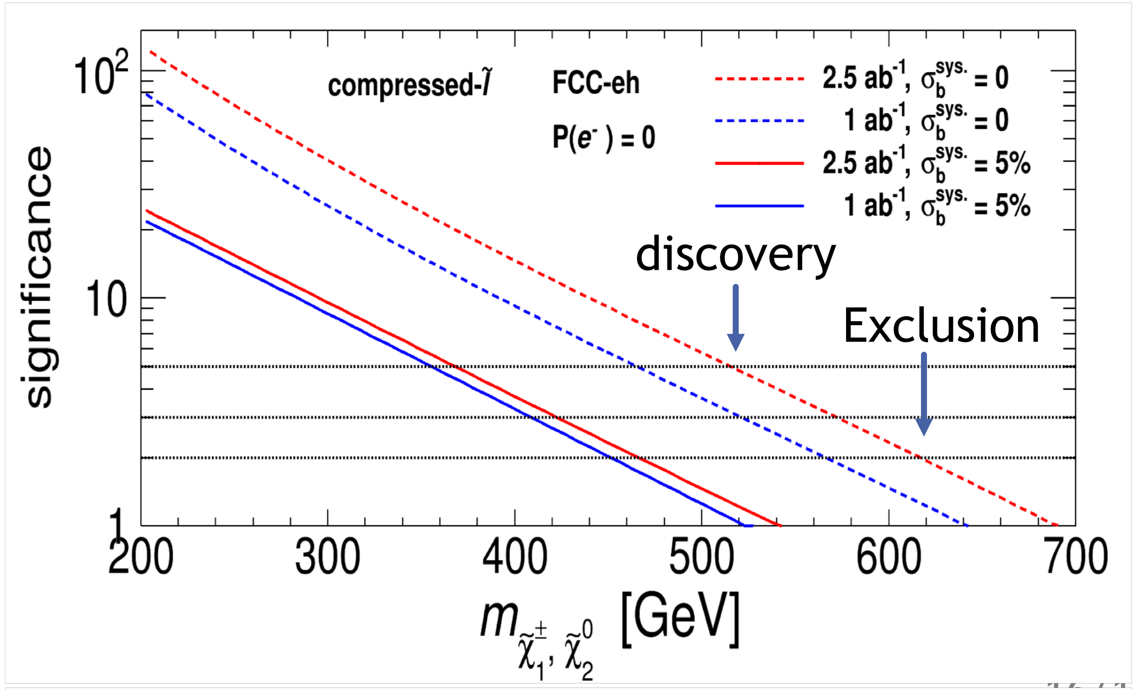
Compressed slepton scenarios: results

- Evaluate significance with statistical and systematic uncertainties

$$\sigma_{\text{stat}} = \sqrt{2[(N_s + N_b)\ln(1 + \frac{N_s}{N_b}) - N_s]}.$$

$$\sigma_{\text{stat+syst}} = \left[2\left((N_s + N_b)\ln\frac{(N_s + N_b)(N_b + \sigma_b^2)}{N_b^2 + (N_s + N_b)\sigma_b^2} - \frac{N_b^2}{\sigma_b^2}\ln\left[1 + \frac{\sigma_b^2 N_s}{N_b(N_b + \sigma_b^2)}\right]\right)\right]^{1/2}.$$

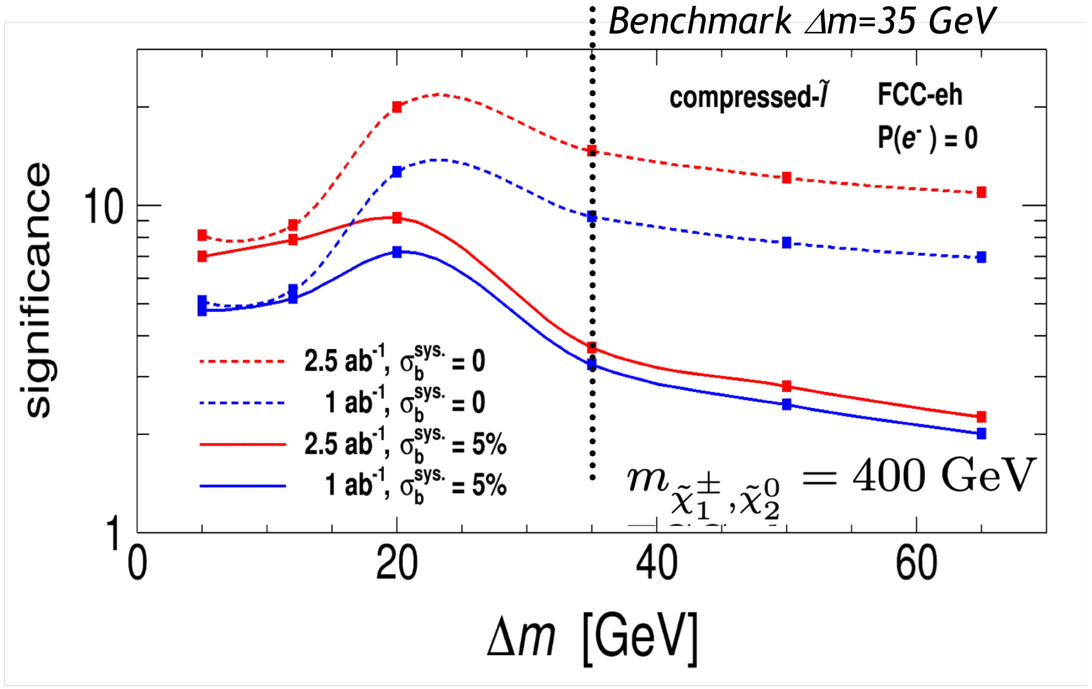
FCC-eh [1 ab^{-1}]	Signal	Background	
$m_{\tilde{\chi}_1^\pm,\tilde{\chi}_2^0}$ [GeV]	400	$j\,e^-\,\nu\nu$	$j\,e^-\,\ell\nu$
$m_{\tilde{\ell}}$ [GeV]	435		
initial	4564	1.08×10^6	7.96×10^6
Pre-selection	3000	3.87×10^5	5.71×10^5
BDT > 0.262	149	600	86
$\sigma_{\text{stat+syst}}$	3.3		

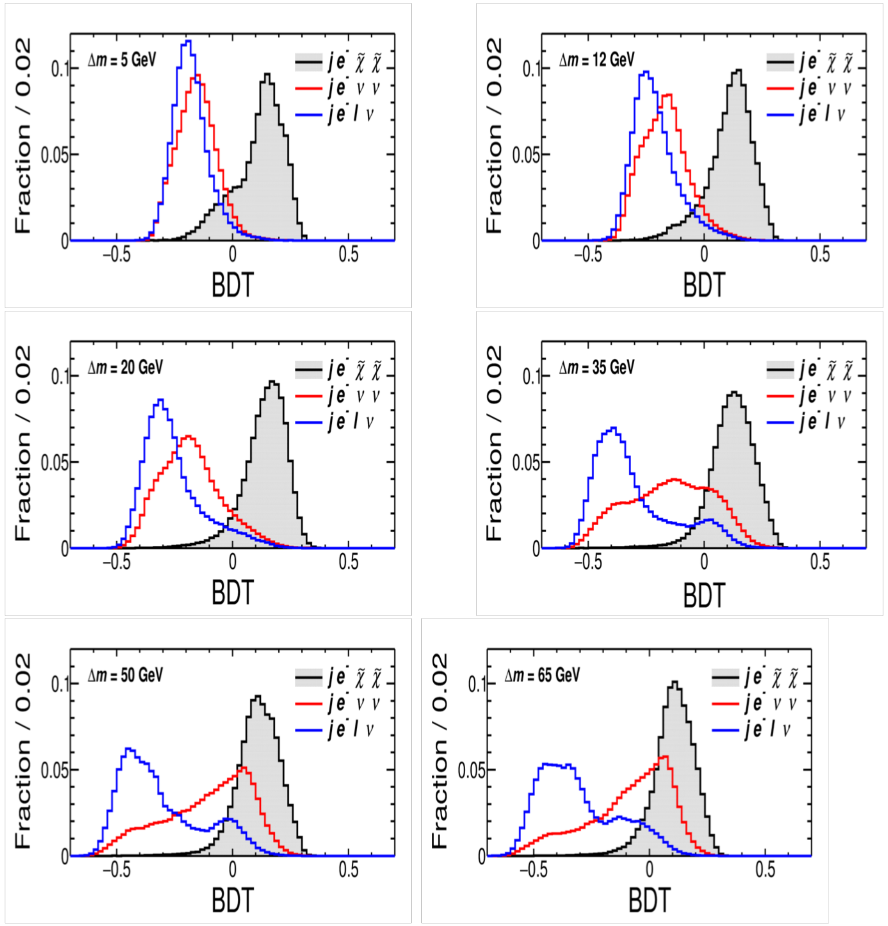


- Of course, systematic uncertainties play a crucial role, as in monojet searches at pp
  - → **Here we consider 0-5%**
  - → Projections for HL-LHC consider 1-3%

Dependence on slepton mass and polarization

- dependence on mass difference between sleptons and EWKinos due to kinematic selections on lepton p_T

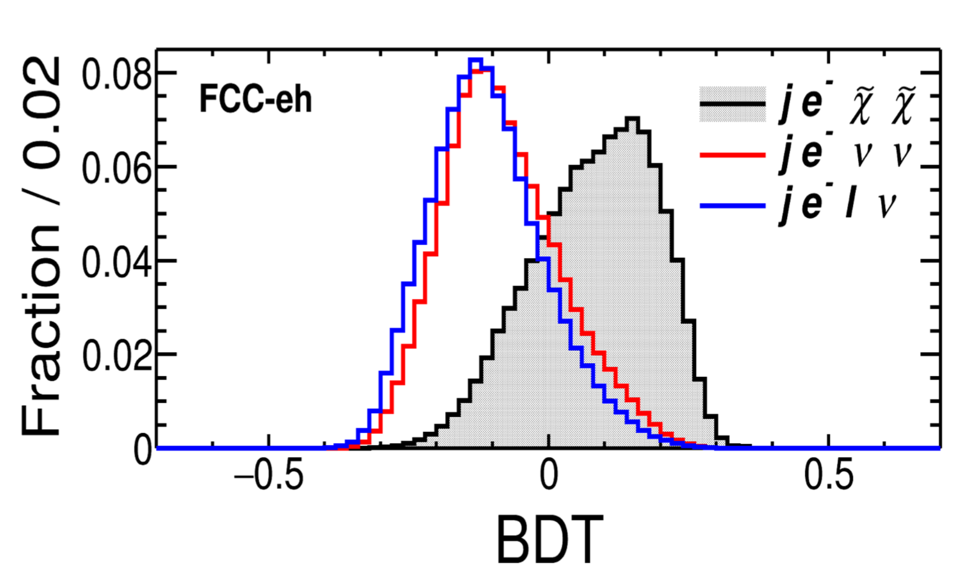




- Polarized beams: increase (decrease) the signal cross section by ~ **80% for P(e-) = - 80% (+80%)**
  - SM Background x-sections change by a maximum of 50-60% → for negative polarization of the electron beam, the net effect is to increase the sensitivity up to **about 40%**

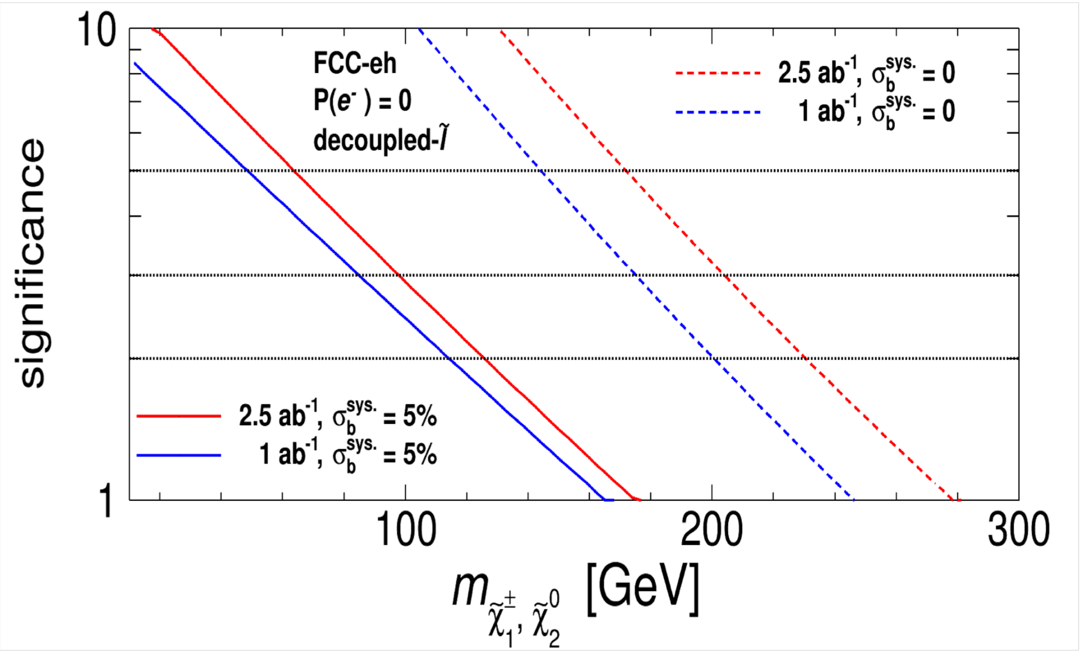
Decoupled-slepton ("classic compressed") scenarios

- In case of decoupled slepton scenarios, signatures are mono-jet like
  - Lower production cross section, more difficult to distinguish signal from background



FCC-eh [1 ab^{-1}]	Signal	Background	
$m_{\tilde{\chi}_1^\pm,\tilde{\chi}_2^0}$ [GeV] / $m_{\tilde{\ell}}$ [GeV]	250 / -	$j\,e^-\,\nu\nu$	$j\,e^-\,\ell\nu$
initial	909	1.08×10^6	7.96×10^6
Pre-selection	399	3.87×10^5	5.71×10^5
BDT > 0.251	14	326	357
$\sigma_{stat+syst}$	0.3		

Assumption on systematics are very relevant!



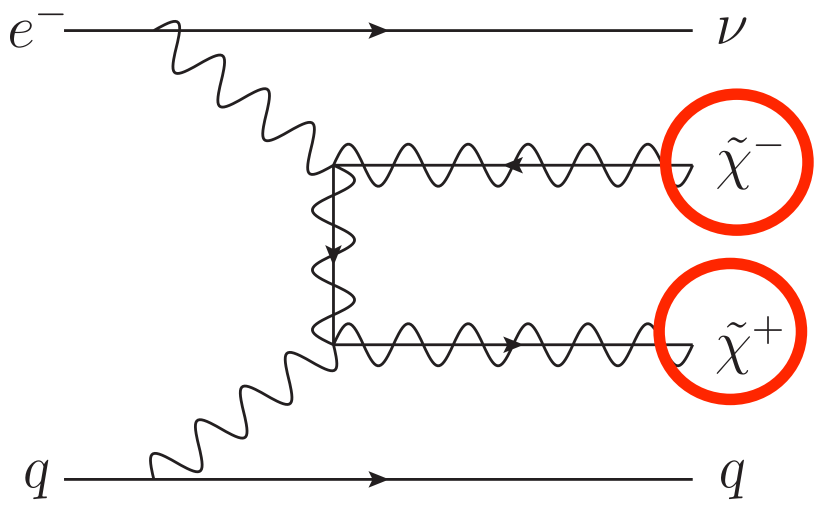
A negative polarization of the electron beam increases the significance by up to 30%

What if the m(chargino)~m(neutralino1)?

- The decay of chargino is **NOT prompt → long-lived particles (LLP)**!

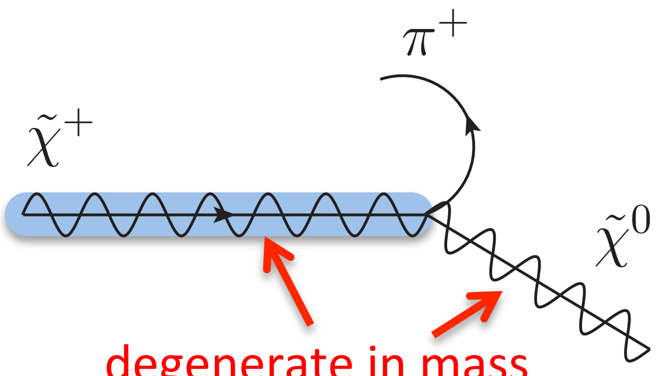
Simplest models at FCC-he: four-body process and tiny cross section

- Charginos (Wino or Higgsino)



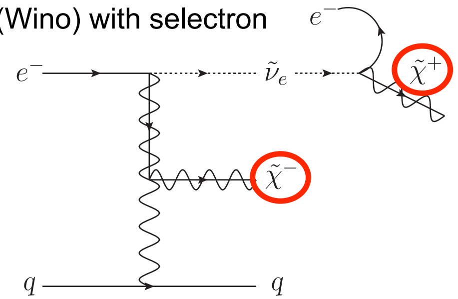
LLCPs

disappearing track



Cross section enhanced with "co-production"

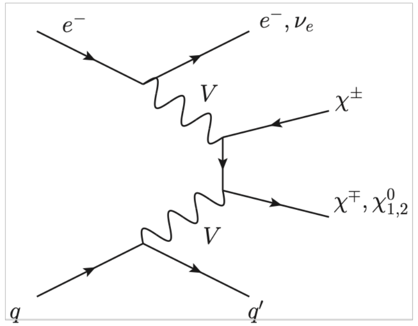
- Chargino (Wino) with selectron

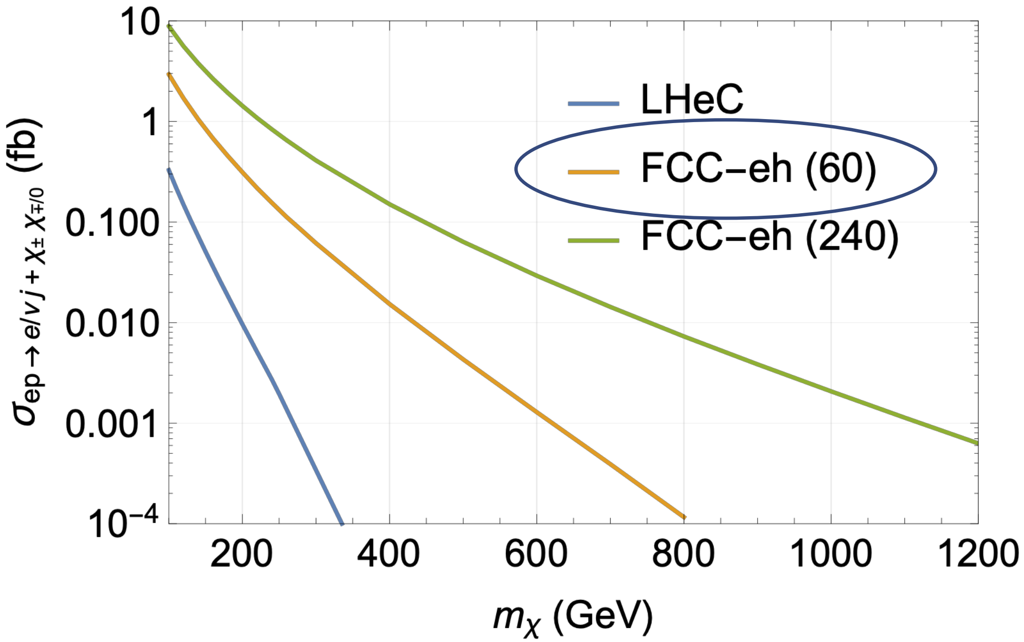


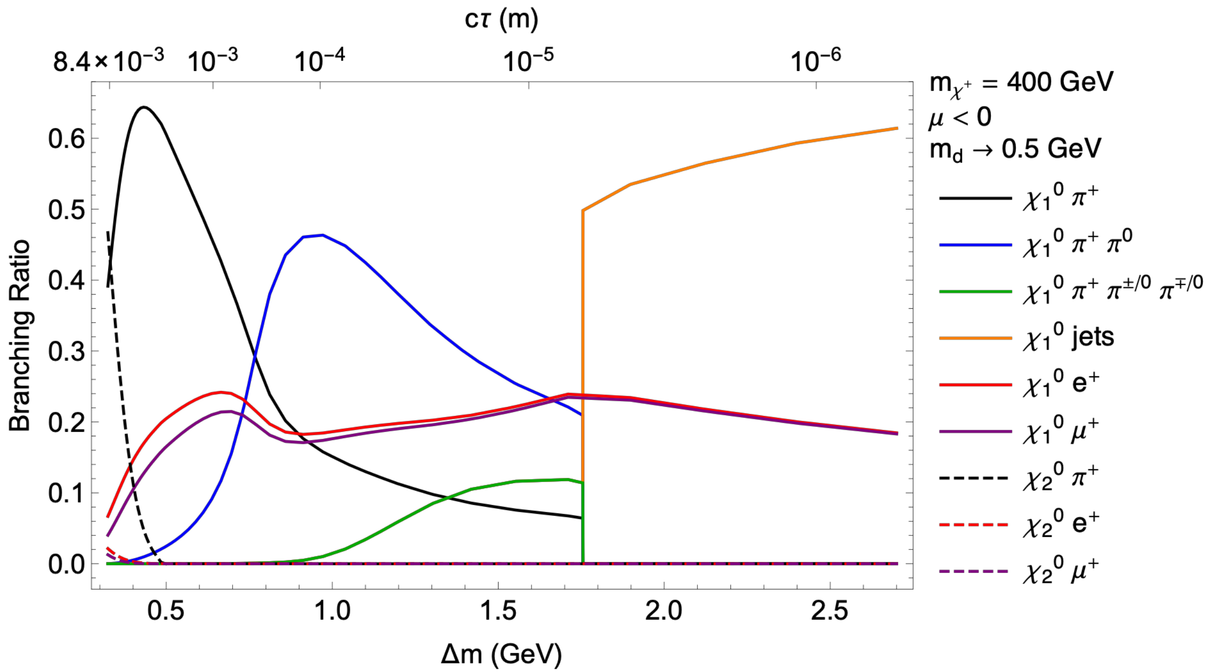
In this case, only the scenario with heavy (decoupled) sleptons is considered (most conservative)

Higgsino production in disappearing tracks

- https://arxiv.org/abs/1712.07135





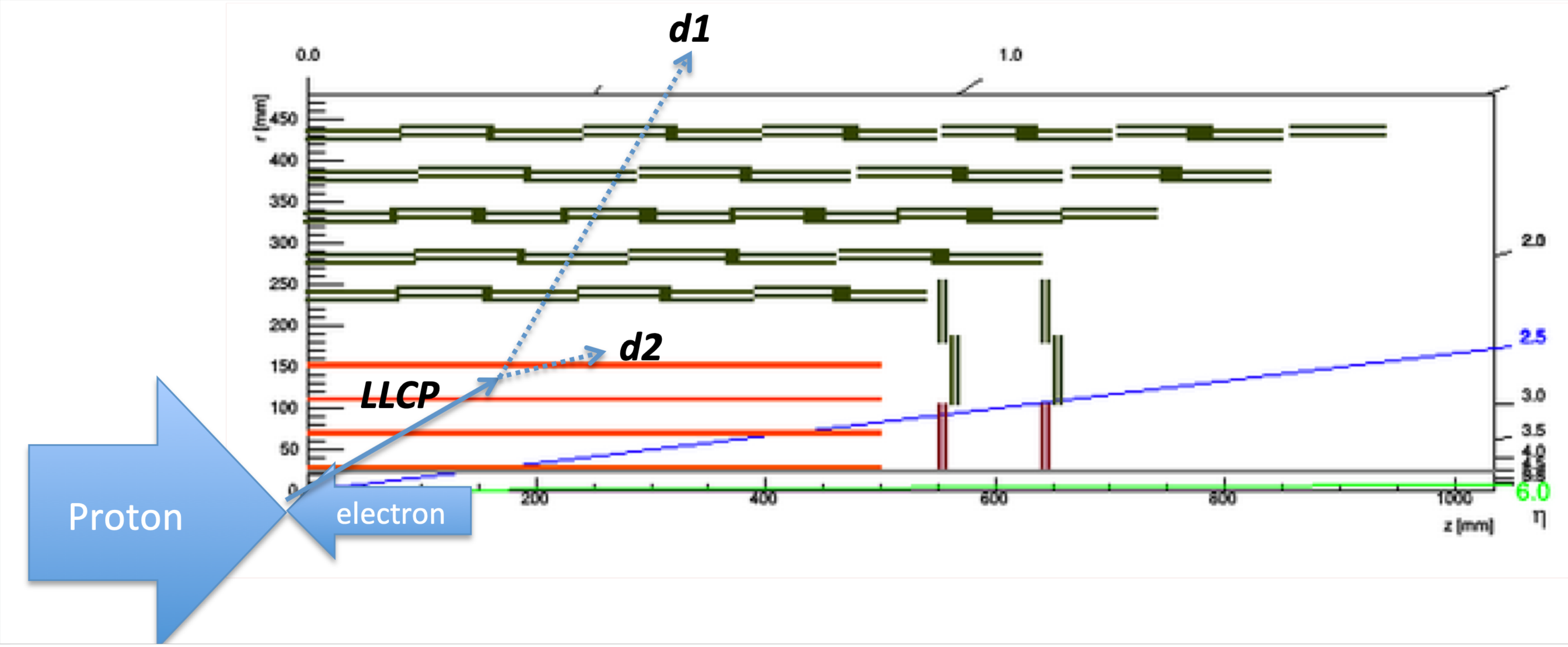


Minimal mass splitting is given by $\Delta_{1\text{-loop}}$ and larger mass splittings are possible when the MSSM M_1 is closer to μ,

Higgsino cross sections lower than wino ones

Long-lived EWKinos: disappearing tracks

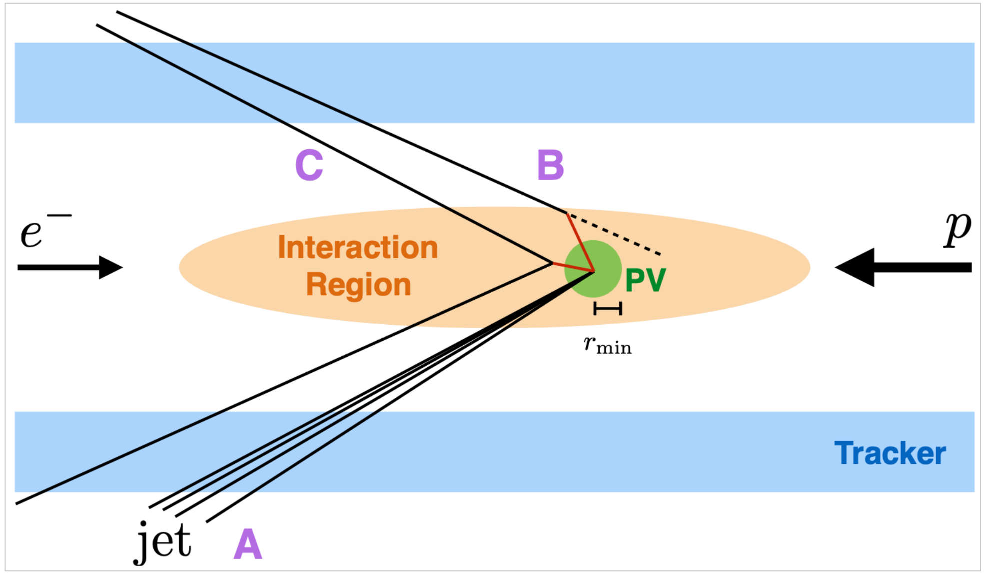
- long lived charginos are typically significantly boosted along the proton beam direction, which increases their lifetime in the laboratory frame. $b_{\rm com} \approx \frac{1}{2}\sqrt{E_e/E_p} \approx 5.5$



3-4 hits only in the inner-most tracker àmissing (disappearing track)
(or a "kink" if the harder daughter ***d1*** is charged)

Analysis strategy

- One or two charginos are produced at the PV, which is identified by the triggering jet (A).
- A chargino decaying to a single charged particle (B)
- If the impact parameter with respect to the PV is greater than a given r_{min} we can tag this track as originating from an LLP decay



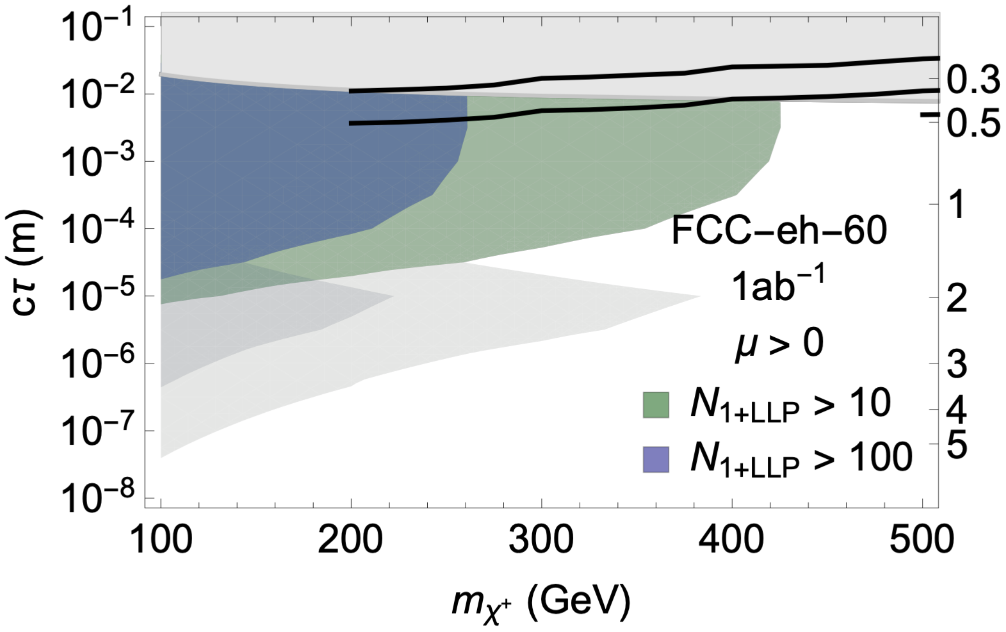
- heavily relies on backgrounds due to pile-up being either absent or controllable.
  - benchmark value is r_{min} = 40μm (~ 5 nominal detector resolutions); p_T threshold for reconstruction of a single charged particle is chosen as 100 MeV
  - Assume 100% efficiency
- Estimate probability of detecting 1 or 2 LLP

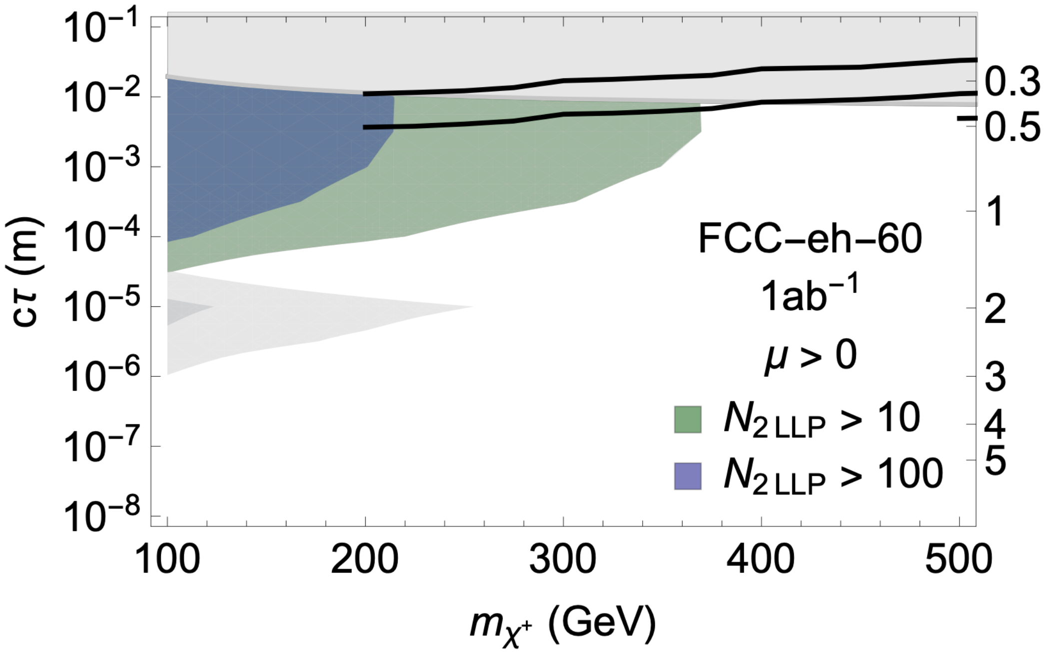
Backgrounds:

- Taus: proper lifetime of ~ 0.1mm and beta-decay into the same range of final states as the charginos.
- suppressed considerably with simple kinematic cuts as it is central in eta
- **rejection of 10^{-4}(10^{-5}) for 1(2)τ**

Results for disappearing track analysis

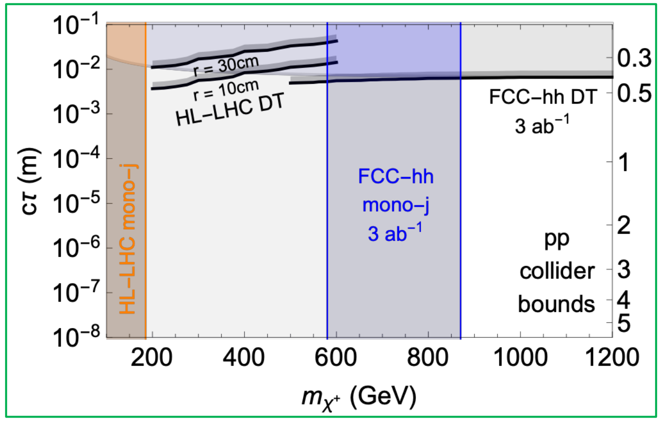
- contours of N_{1+LLP} and $N_{2\ LLP}$





green region: 2σ sensitivity estimate in the presence of τ backgrounds

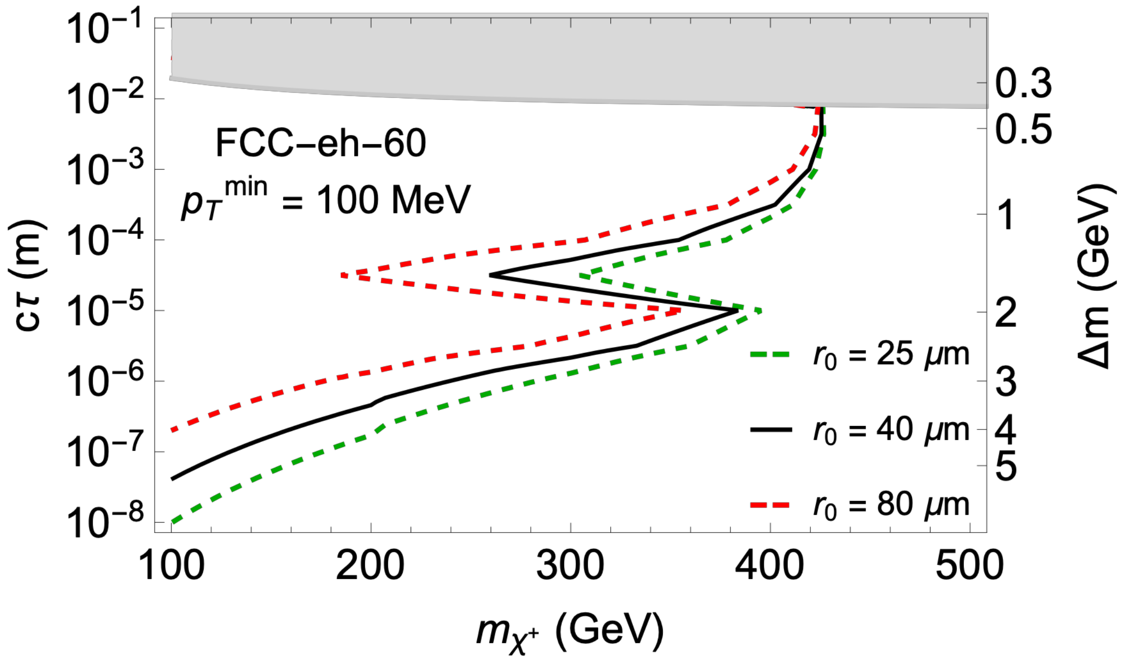
black curves: projected bounds from disappearing track searches for HL-LHC (optimistic and pessimistic) and the FCC-hh

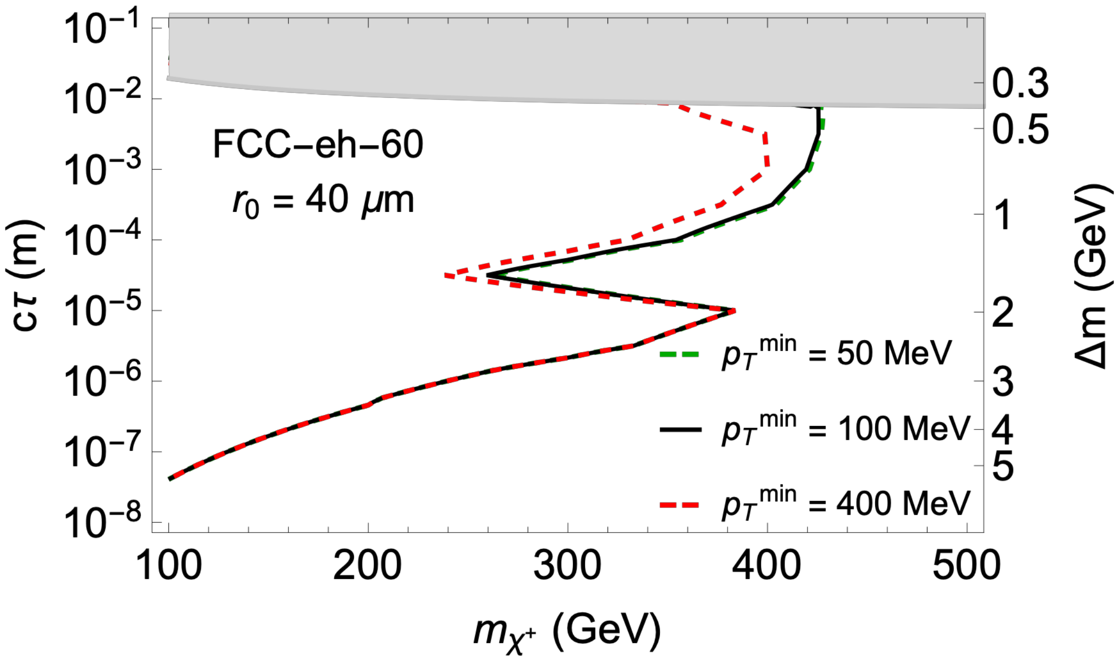


Sensitive to very short lifetimes exceeds that of hh colliders

Results for disappearing track analysis

- Dependence on pT and r_min selections

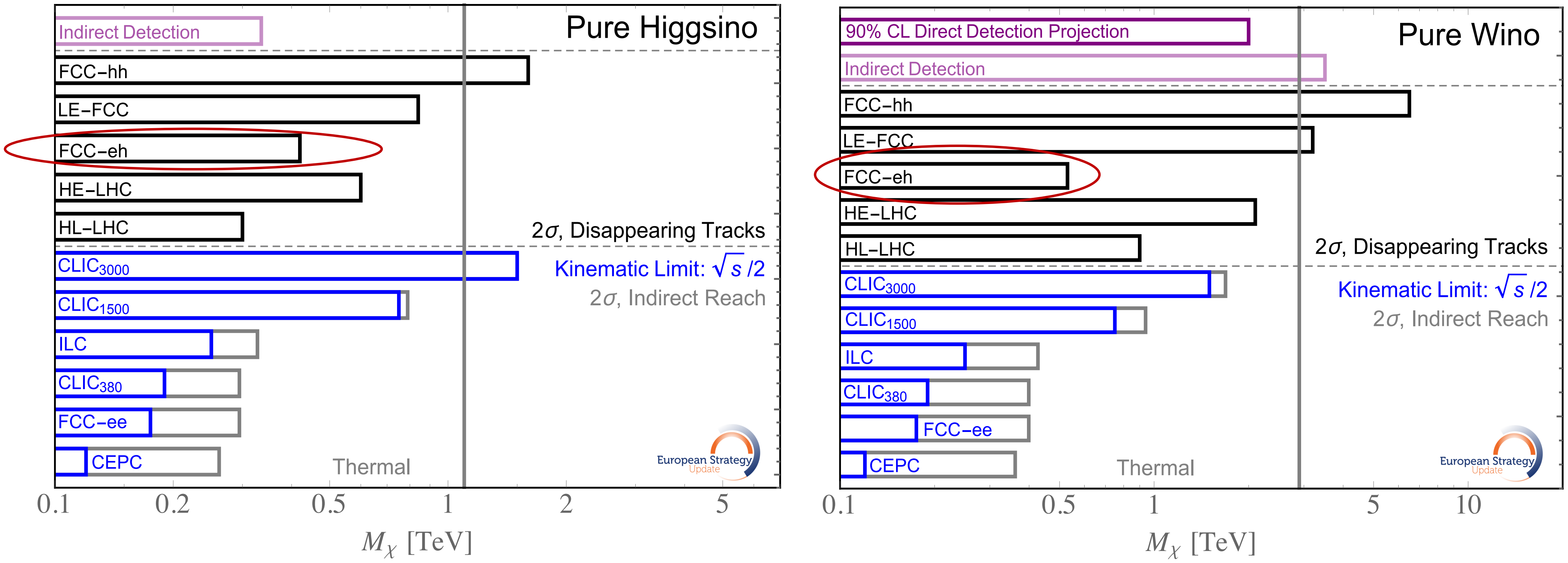




Sensitivity almost unchanged

Comparisons with other facilities

- Thermal Higgsino/Wino dark matter mass
- Comparisons computed for the European strategy



- FCC-eh not directly competitive with FCC-hh but **still reasonable reach**
- In all cases FCC-eh sensitivity to **short decay lengths**, possibly much less than a single micron, improves with respect to what the FCC-hh can accomplish with disappearing track searches

conclusions

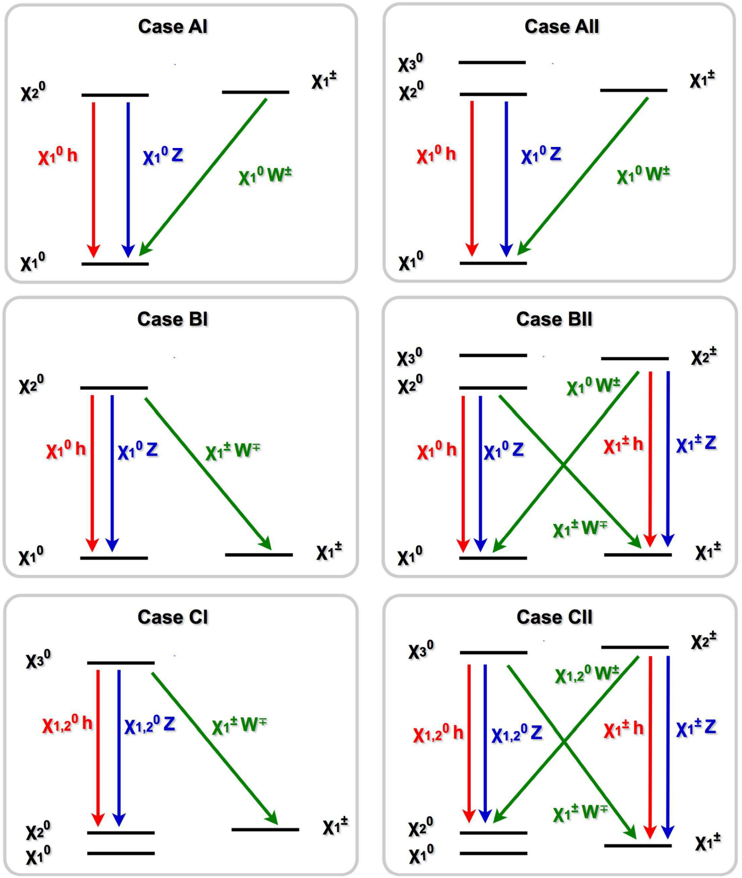
- Studies on the FCC-eh potential for SUSY EWK particles have been performed
- As expected, coverage is reduced with respect to hh colliders because of low production cross section. Nonetheless:
  - EWK prompt: Rate might be higher in case slepton (selectron) masses are just a bit higher than chargino and neutralino masses: sensitivities up to 600 GeV, strong dependence on systematic assumptions, as well as beam polarization
  - EWK LLP: Low background conditions allow sensitivity to short decay lengths, possibly much less than a single micron, making disappearing track searches at e-p complementary to those at hh collider

[more on the exploitation of LLP at FCC-eh in other talks at this workshop, e.g. Oliver Fischer, Sudip Jana]

Back up

SUSY EWK production: Phenomenology

- Mass and hierarchy of the four neutralinos and the two charginos, as well as their production cross sections and decay modes, depend on the M_1, M_2, μ (bino, wino, higgsino) values and hierarchy
  - EWK phenomenology broadly driven by the LSP and Next-LSP nature
  - Examples of classifications (cf: arXiV: 1309.5966)



- **Scenario A:** $M_1 < M_2, |\mu|$

  Bino LSP

- **Scenario B:** $M_2 < M_1, |\mu|$

  Wino LSP

- **Scenario C:** $|\mu| < M_1, M_2$

  Higgsino LSP

Used as benchmarks:

- Bino LSP, wino-bino cross sections
  (1) Mass($\chi^{\pm}_1$) = Mass (χ^0_2)
  (2) $\chi^{+}_1\chi^{-}_1$ and $\chi^{\pm}_1\chi^0_2$ processes

- Higgsino-LSP, higgsino-like cross sections
  (1) Small mass splitting χ^0_1, $\chi^{\pm}_1$, χ^0_2
  (2) Consider triplets for cross sections
  (3) Role of high-multiplicity neutralinos and charginos also relevant

$$\sigma_H(\chi^{\pm}_1\chi^0_2 + \chi^{+}_1\chi^{-}_1 + \chi^{\pm}_1\chi^0_1) < \text{or} << \sigma_W(\chi^{\pm}_1\chi^0_2)$$

[depending on masses!]

Input kinematic variables

FIG. 9. Kinematial distributions of some input obervables for signal $j\,e^-\,\tilde{\chi}\tilde{\chi}$ with $m_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0} = 400$ GeV (black with filled area) in the compressed-slepton scenario, and for the SM background of the $j\,e^-\,\nu\nu$ (red) and $j\,e^-\,\ell\nu$ (blue) processes after applying the pre-selection cuts at the FCC-eh with an unpolarized electron beam.