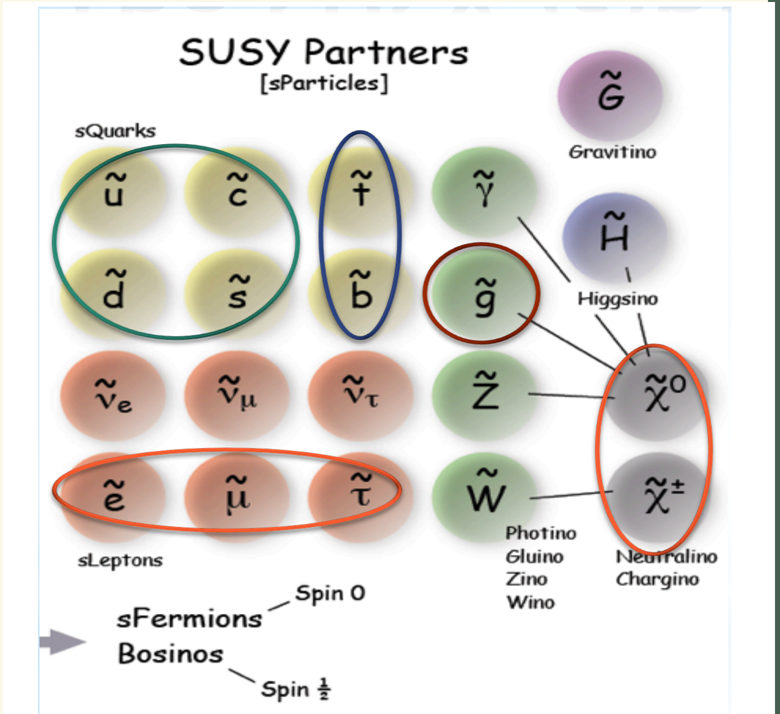


UNIVERSITY OF
LIVERPOOL

Disappearing track analyses for European Strategy

Monica D’Onofrio

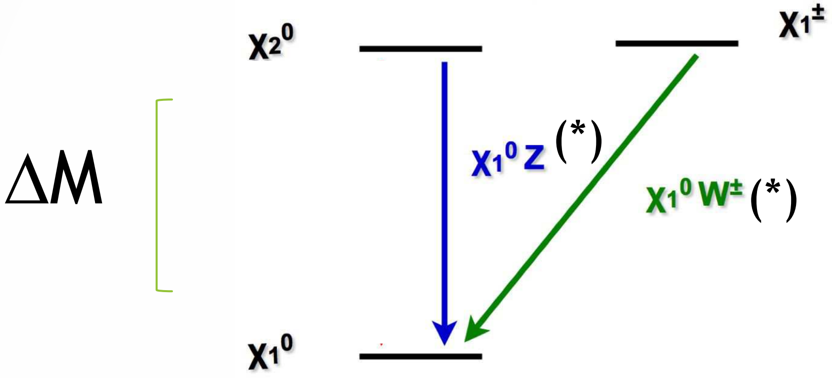
University of Liverpool

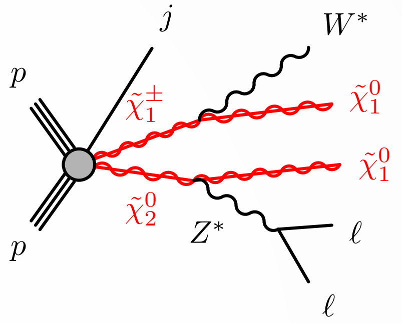
EF10-Snowmass meeting
4/6/2020

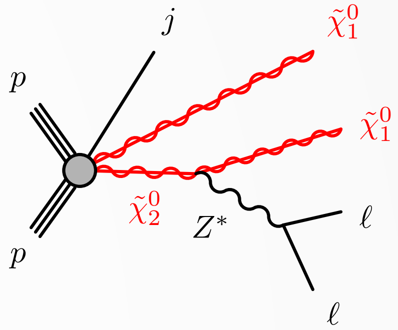
Higgsino EWK processes

Processes: $\chi^{+}_{1}\chi^{-}_{1},\ \chi^{\pm}_{1}\chi^{0}_{2},\ \chi^{0}_{1}\chi^{0}_{2}$

$\chi^{\pm}_{1}, \chi^{0}_{2}$ = NSLP, $m(\chi^{\pm}_{1}) \sim m(\chi^{0}_{2})$







Higgsino-like (i.e. large higgsino component but not pure):

→ ΔM(NLSP, LSP) ~ O(GeV)

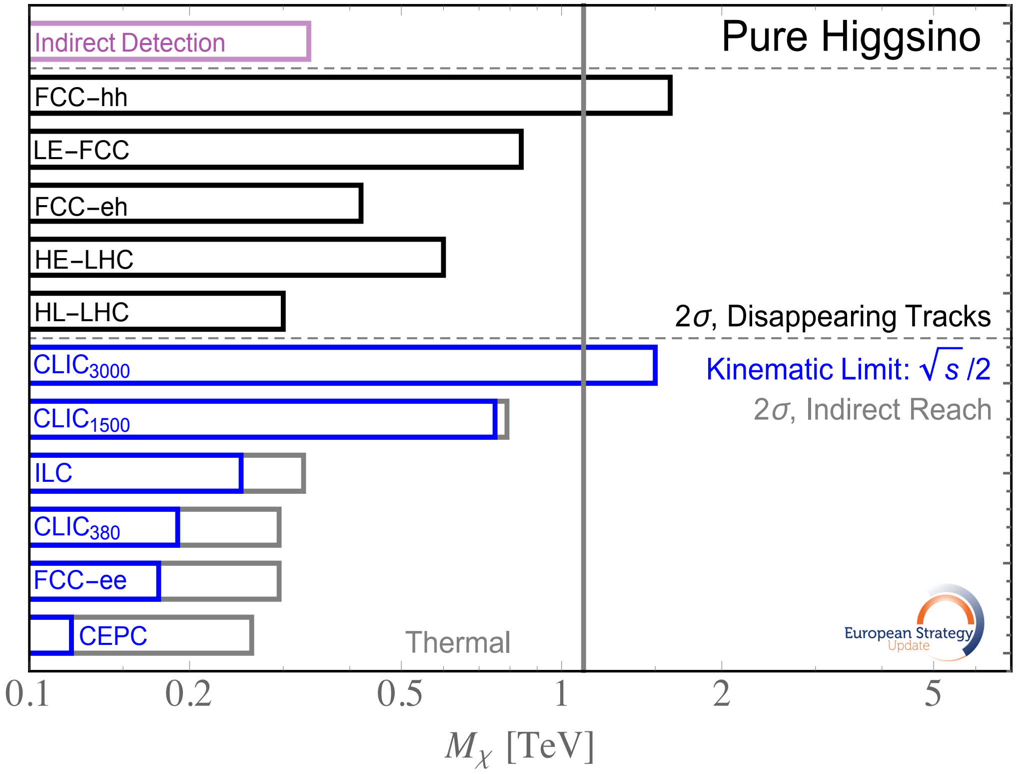
Pure-higgsino:

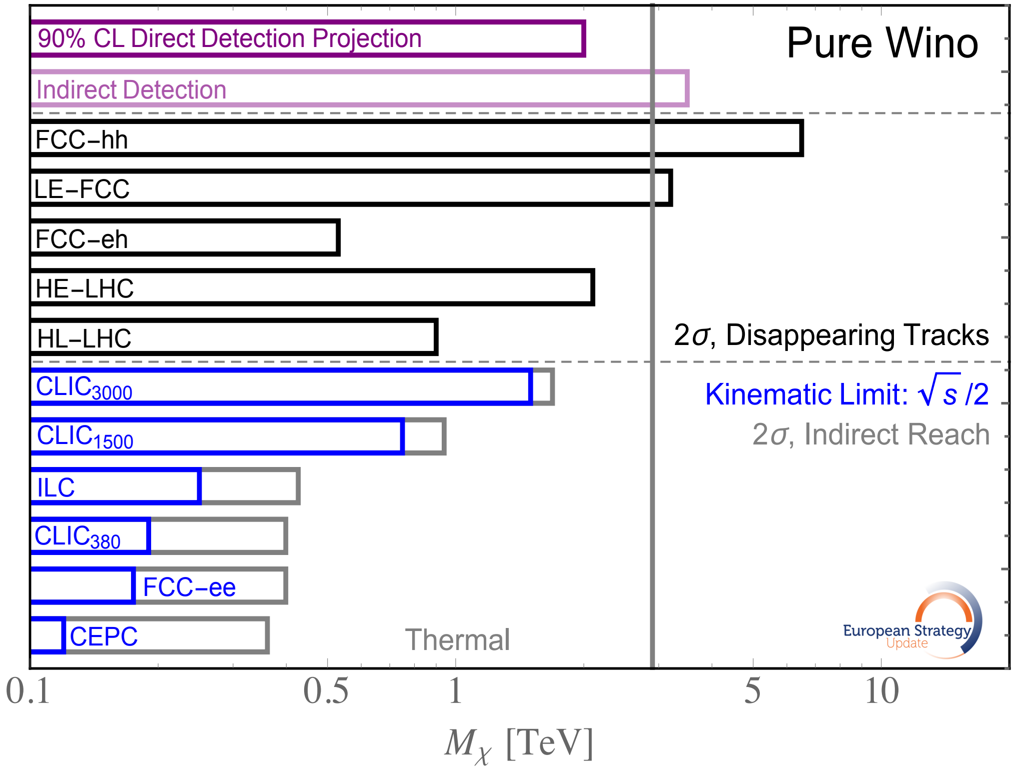
→ ΔM ~ 160 MeV – targeted by disappearing track analyses

(~ 350 MeV for wino-cases)

Thermal Higgsino/Wino dark matter

- Thermal freeze-out mechanism provides a cosmological clue for the observed DM density
- Most straightforward example of a DM thermal relic: massive particle with EW gauge interactions only
- Spin-1/2 particles transforming as doublets or triplets under SU(2) symmetry, usually referred to as Higgsino and Wino
  - Although they are not really "SUSY" related – phenomenology is equivalent



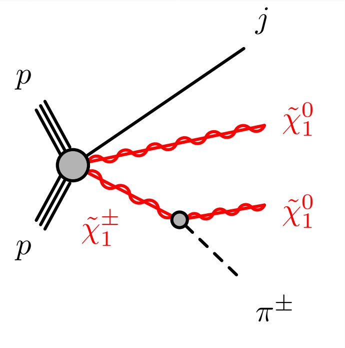


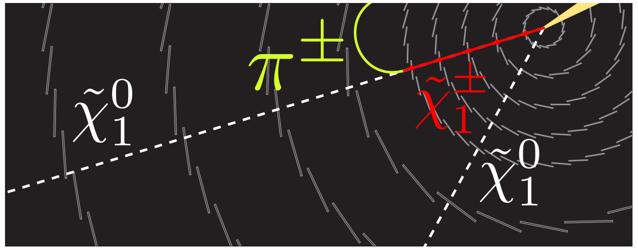
In the following, **direct searches** are presented in a bit more detail

HL-LHC: Disappearing track signatures

Section 4.1 of arxiv:1812.07831

ATL-PHYS-PUB-2018-031





Very challenging with high pile-up → not shown in this sketch

A disappearing track occurs when the decay products of a charged particle, like a supersymmetric chargino, are not detected (disappear) because they either interact only weakly or have soft momenta and hence are not reconstructed.

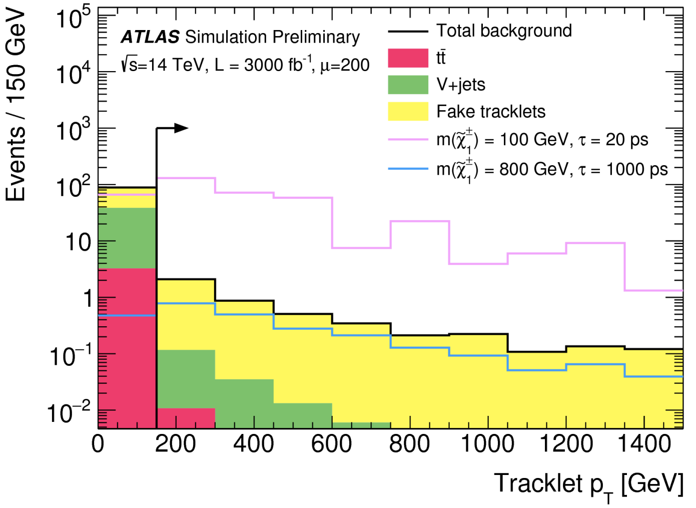
Variable	SR Selection
Lepton veto p_T [GeV]	>20
$\min\{\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})\}$	> 1
E_T^{miss} [GeV]	> 300
Leading jet p_T [GeV]	> 300
Leading tracklet p_T [GeV]	> 150
$\Delta\phi(E_T^{\text{miss}}, \text{trk})$	< 0.5

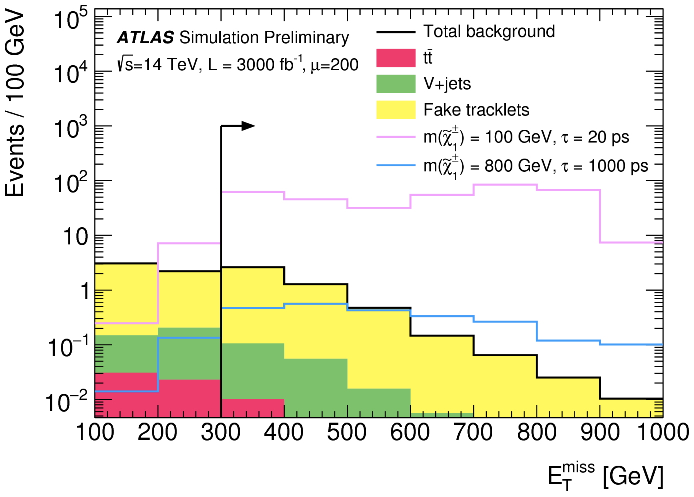
Tracklet reconstruction:

- "standard" tracks are reconstructed;
- track reconstruction is then rerun with looser criteria → >= 4 pixel hits using only input hits not associated with tracks
- Tracklets are then extrapolated to the strip detectors
- p_T > 5 GeV and $|\eta|$ < 2.2

Event selection:

- Use boosts from ISR jets to trigger events
- Lepton veto and kinematic selections applied to reduce background

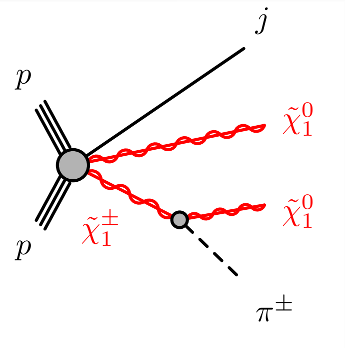


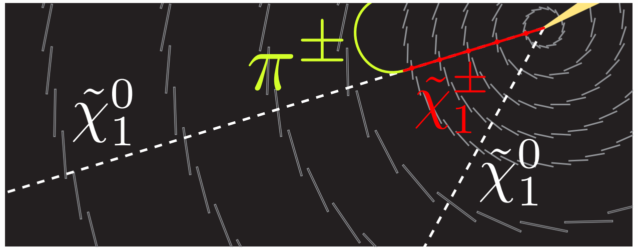


HL-LHC: Disappearing track signatures

Section 4.1.1 of arxiv:1812.07831

ATL-PHYS-PUB-2018-031





Very challenging with high pile-up → not shown in this sketch

A disappearing track occurs when the decay products of a charged particle, like a supersymmetric chargino, are not detected (disappear) because they either interact only weakly or have soft momenta and hence are not reconstructed.

Two sources of background contributions:

- SM particles that are reconstructed as tracklets, i.e. **hadrons** scattering in detector material or **electrons** undergoing bremsstrahlung

1) use samples of single e or π passing through the current ATLAS detector layout to estimate the probability that an isolated e or hadron leave a disappearing track
2) Scale it to account for ratio of material in the current ATLAS inner detector and the upgraded inner tracker

- Events which contain **fake tracklets**:
  - from Z → νν or W → lν where lepton is lost
  - Scaled by the expected fake tracklet probability
  - Fakes are also the largest source of uncertainties **(~30% of total background**)

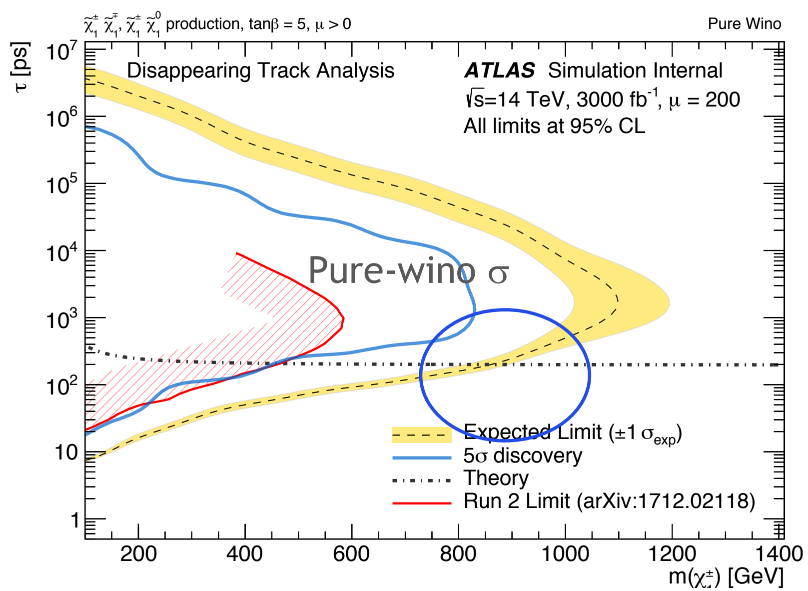
$$p^{\mathrm{ITk}}_{\mathrm{fake,tight}} = p^{\mathrm{ATLAS}}_{\mathrm{fake,tight}} \times \frac{R^{\mathrm{ITk}}_{\mathrm{fake,loose}}}{R^{\mathrm{ATLAS}}_{\mathrm{fake,loose}}} \times \frac{\epsilon^{\mathrm{ITk}}_{z_0}}{\epsilon^{\mathrm{ATLAS}}_{z_0}}.$$

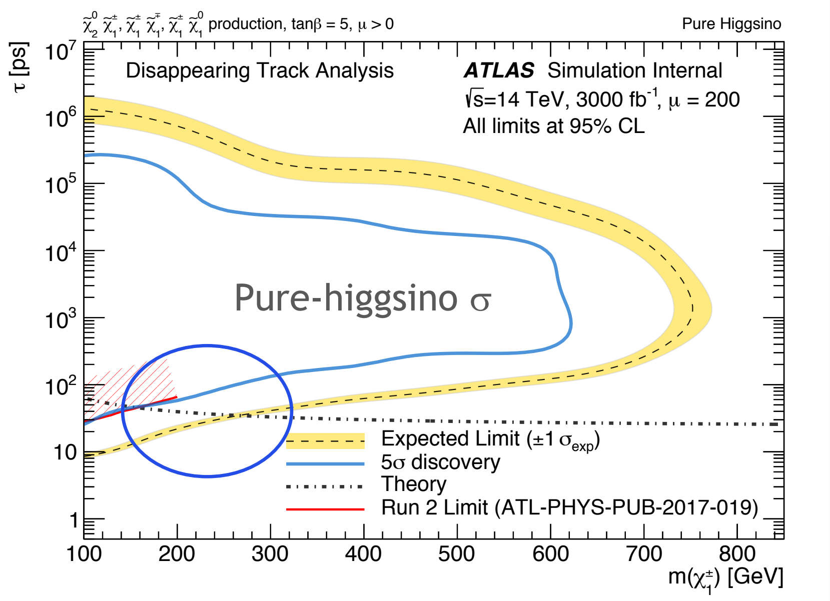
~ 200 (depends strongly on pile up)

~ 0.12 (due to differences in tracket selection)

HL-LHC: Disappearing track signatures

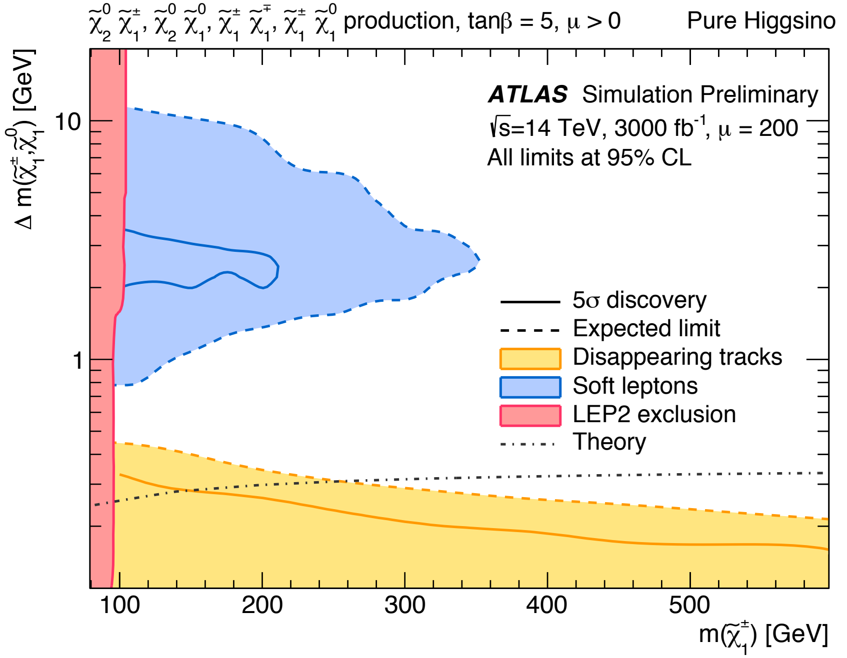
	SR
Total SM	4.6 ± 1.3
V+jets events	0.17 ± 0.05
$t\bar{t}$ events	0.02 ± 0.01
Fake tracklets	4.4 ± 1.3





Fakes mostly arising from Z→νν

Wino: ~ 850 GeV exclusion (~500 GeV discovery)
Higgsino: ~ 260 GeV exclusion (~150 GeV discovery)



Complementarity with soft-lepton analysis in higgsino-like scenarios

HE-LHC and FCC-hh

Section 4.1.3 of arxiv:1812.07831

https://arxiv.org/pdf/1805.00015.pdf

- Extrapolation of ATLAS-36/fb analysis for disappearing track to HL, HE and FCC-hh

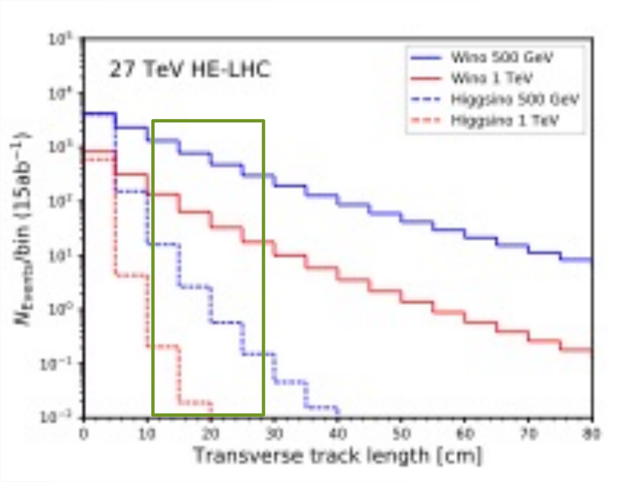
  transverse charged track length must be in specific ranges to retain sensitivity

$$S/\sqrt{B+(\Delta_B B)^2+(\Delta_S S)^2}$$

$$\Delta_B \;=\; 20\% \text{ and } \Delta_S \;=\; 10\%$$

$\sqrt{s}$	$\not{E}_T$ [GeV]	p_{T,j_1} [GeV]	p_{T,j_2} [GeV]	$p_{T,\mathrm{track}}$ [GeV]
14 TeV	150	150	70	250
27 TeV	400 – 700	400 – 600	140	400 – 700
100 TeV	1000 – 1400	700 – 1400	500	1000 – 1400

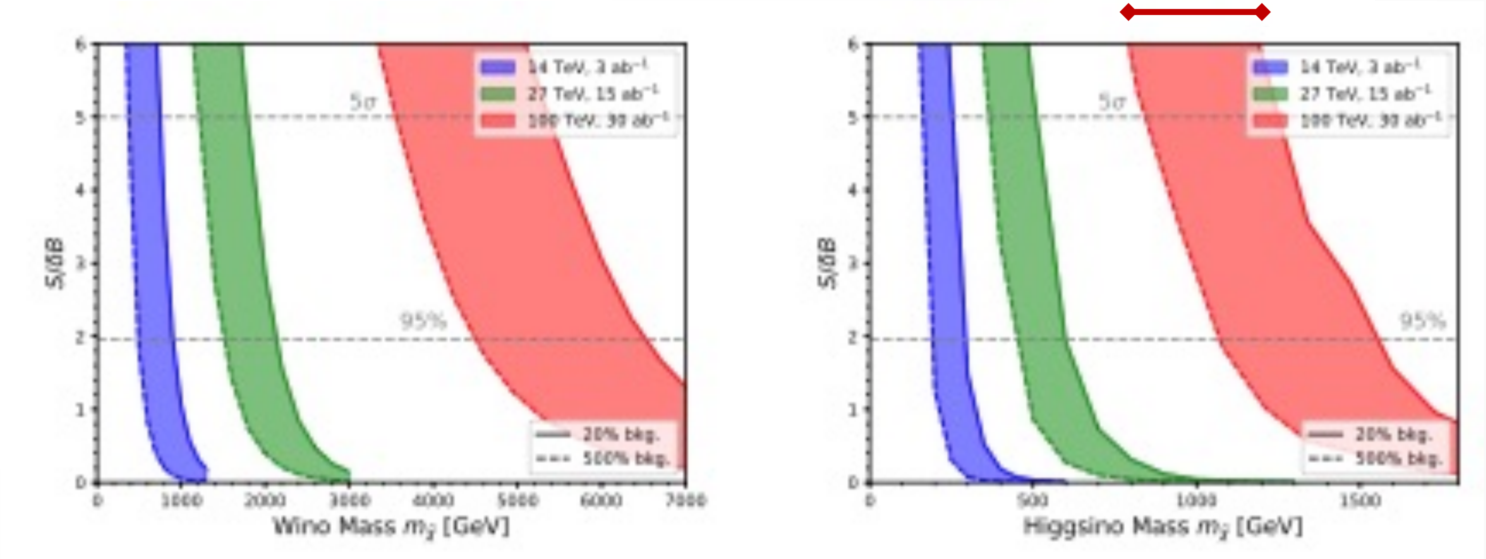
95% C.L.	Wino Monojet	Wino Disappearing Track	Higgsino Monojet	Higgsino Disappearing Track
14 TeV	280 GeV	900 GeV	200 GeV	300 GeV
27 TeV	700 GeV	2.1 TeV	490 GeV	600 GeV
100 TeV	2 TeV	6.5 TeV	1.4 TeV	1.6 TeV



12 < d < 30 cm

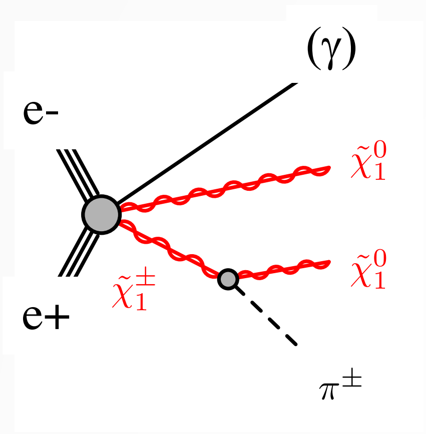
Only slightly more optimistic for HL-LHC wrt experimental search

Variation of bkg by factor 5



CLIC: Disappearing track signatures

https://arxiv.org/pdf/1812.02093.pdf



In this case, the chargino leaves a “charged” track-stub in the detector. Two analyses:

- **charge-stub only**
- **charge-stub + photon**

$d_{min}(\theta)$ = minimum distance a single χ± must travel in the detector before decaying in order to register **4 hits in the CLIC tracker**

$$d_{\rm min}(\theta) = \begin{cases} \dfrac{4.4\,{\rm cm}}{\sin\theta} & 19^\circ < \theta < 90^\circ \\ \dfrac{22\,{\rm cm}}{\cos\theta} & 13^\circ < \theta < 19^\circ \\ \dfrac{29\,{\rm cm}}{\cos\theta} & 8^\circ < \theta < 13^\circ \end{cases} ,$$

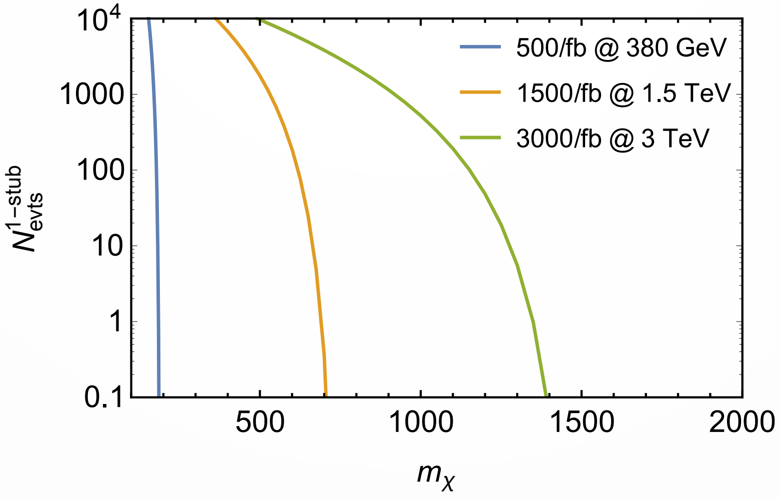
Particles produced at polar angles θ < 8° are assumed to exit the detector without registering hits.

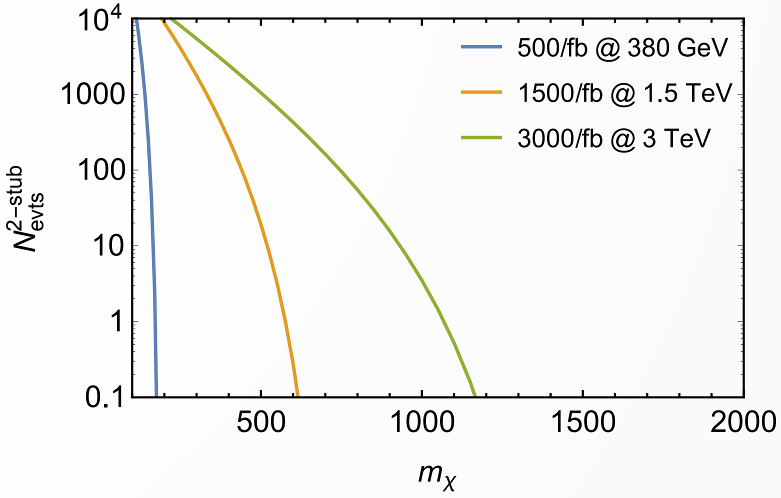
$$\begin{aligned} N_{\rm evts}^{1-{\rm stub}} &= \mathcal{L}_{\rm int} \times \int_{-1}^{1} \frac{d\sigma(e^+e^- \to \chi^+\chi^-)}{d\cos\theta} [2P_{\rm s}(d_{\rm min}) - P_{\rm s}(d_{\rm min})^2]\, d\cos\theta \,, \\ N_{\rm evts}^{2-{\rm stub}} &= \mathcal{L}_{\rm int} \times \int_{-1}^{1} \frac{d\sigma(e^+e^- \to \chi^+\chi^-)}{d\cos\theta} P_{\rm s}(d_{\rm min})^2\, d\cos\theta \,. \end{aligned}$$

$$P_{\rm s}(d_{\rm min}) = e^{-m_\chi d_{\rm min}\Gamma_\chi/|\vec{p}_\chi|}$$

Survival probability

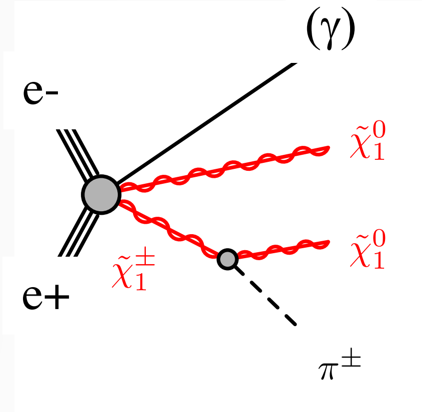
charge-stub only





CLIC: Disappearing track signatures

https://arxiv.org/pdf/1812.02093.pdf



In this case, the chargino leaves a “charged” track-stub in the detector. Two analyses:

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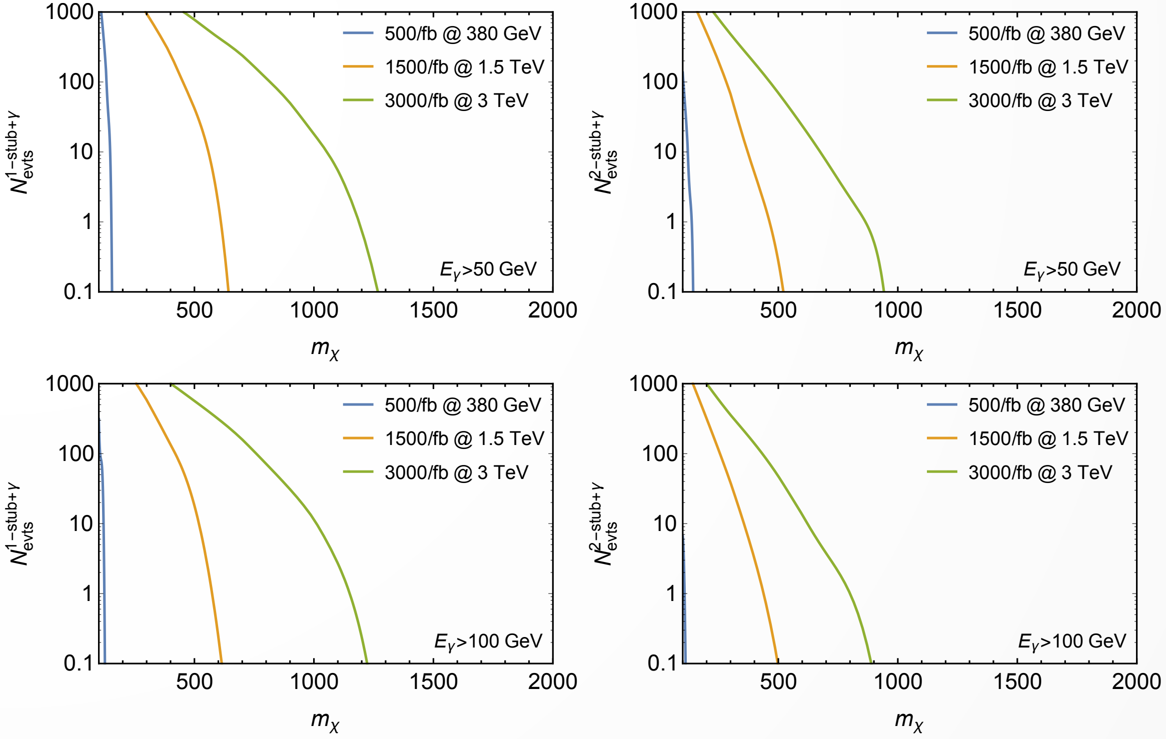
Particles produced at polar angles θ < 8° are assumed to exit the detector without registering hits.

charge-stub + photon

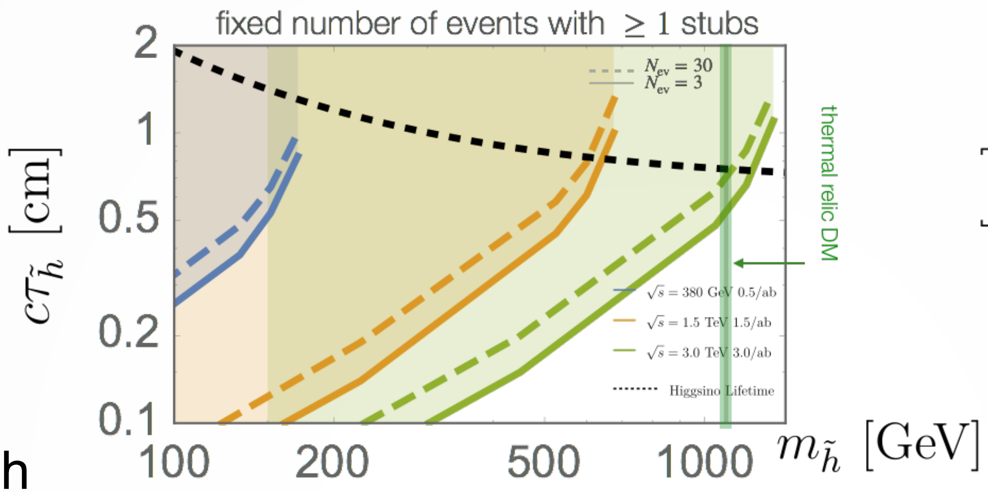
require sufficiently hard initial state radiation (ISR) in conjunction with one or more charged stubs.

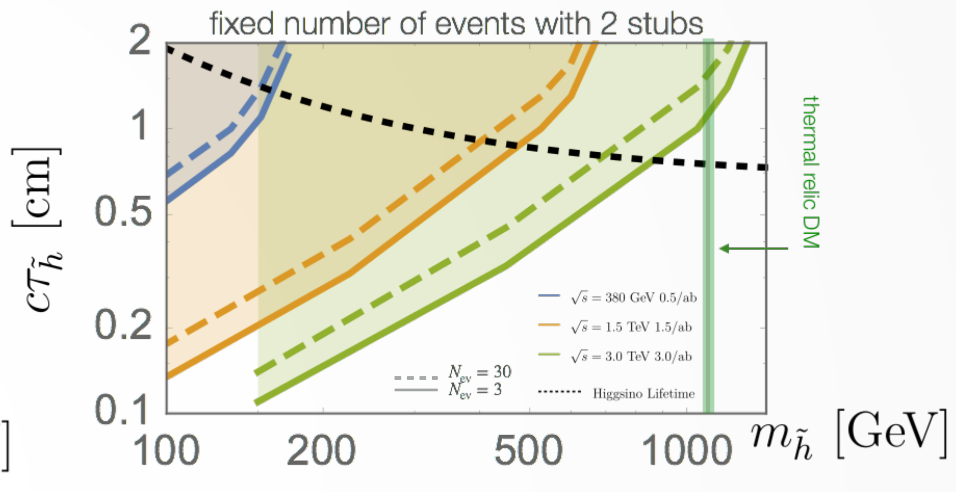


CLIC: disappearing track analysis

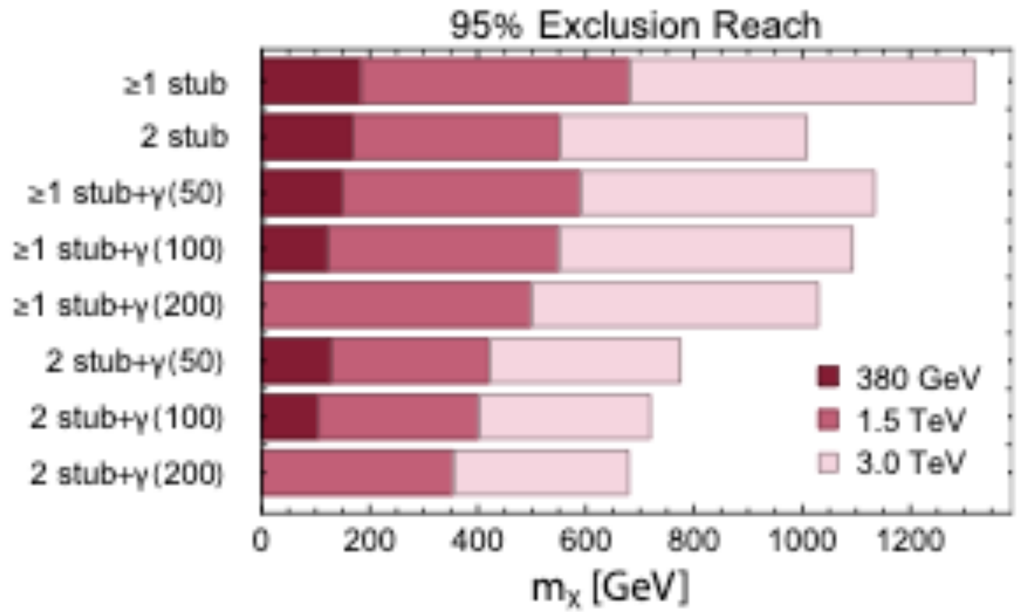
Charged stub

+ photon analysis





Overall results and reach



95% CLIC exclusion reach for pure higgsinos in each of the eight analysis strategies, **assuming zero background in each analysis**

A word on ILC chargino and neutralino searches

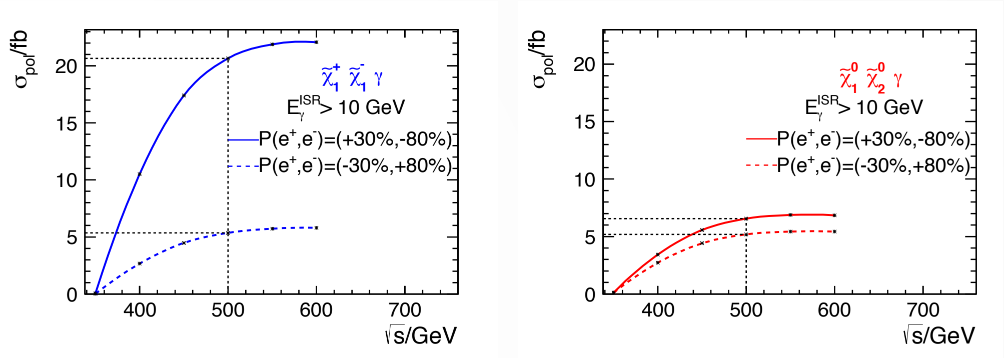
https://arxiv.org/pdf/1307.3566.pdf

- Parameters considered for the original studies:

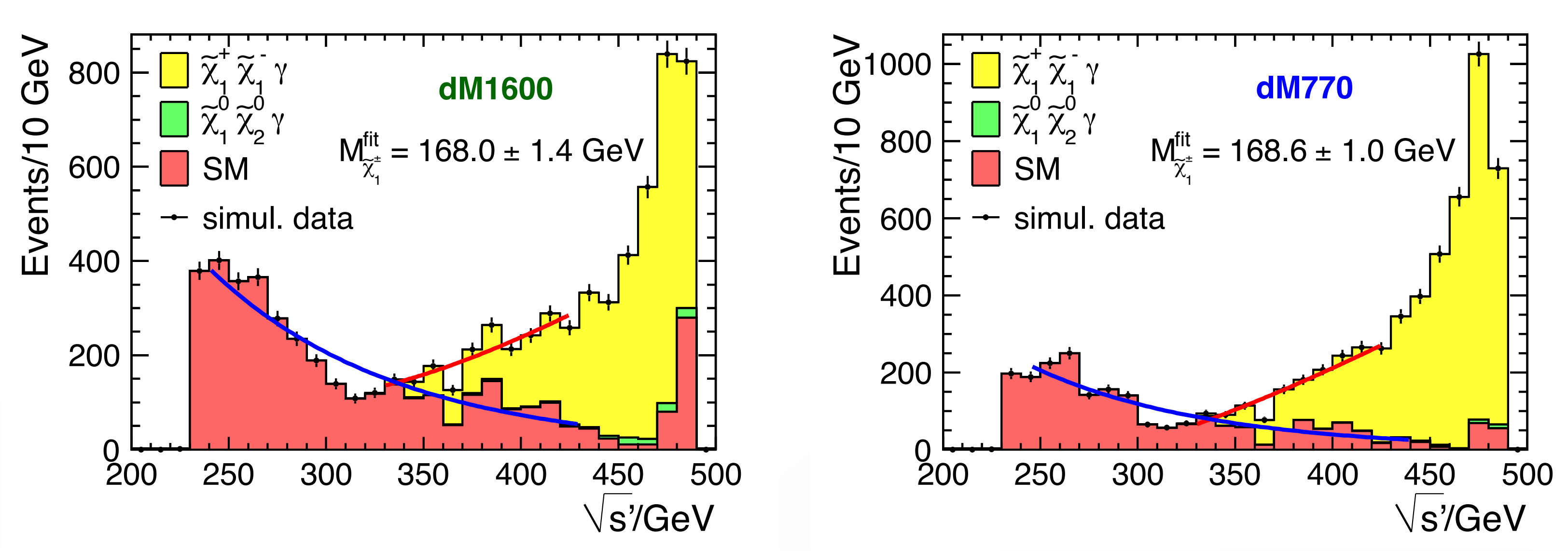
$$\begin{array}{ll}
\text{dM1600} & M_1 = 1.70\,\text{TeV},\ M_2 = 4.36\,\text{TeV},\ \mu = 165.89\,\text{GeV},\ \tan\beta|_{m_Z} = 44, \\
 & M_{\tilde{\chi}_1^\pm} = 165.77\,\text{GeV},\ M_{\tilde{\chi}_1^0} = 164.17\,\text{GeV},\ M_{\tilde{\chi}_2^0} = 166.87\,\text{GeV},\ m_h = 124\,\text{GeV}; \\
\text{dM770} & M_1 = 5.30\,\text{TeV},\ M_2 = 9.51\,\text{TeV},\ \mu = 167.40\,\text{GeV},\ \tan\beta|_{m_Z} = 48, \\
 & M_{\tilde{\chi}_1^\pm} = 167.36\,\text{GeV},\ M_{\tilde{\chi}_1^0} = 166.59\,\text{GeV},\ M_{\tilde{\chi}_2^0} = 167.63\,\text{GeV},\ m_h = 127\,\text{GeV}.
\end{array}$$

$\tilde{\chi}_1^+$ decay mode	BR(dM1600)	BR(dM770)
$e\nu\tilde{\chi}_1^0$	17.3%	15.0%
$\mu\nu\tilde{\chi}_1^0$	16.6%	13.7%
$\pi^+\tilde{\chi}_1^0$	16.5%	60.4%
$\pi^+\pi^0\tilde{\chi}_1^0$	28.5%	7.3%
$\pi^+\pi^0\pi^0\tilde{\chi}_1^0$	7.5%	0.03%
$\pi^+\pi^+\pi^-\tilde{\chi}_1^0$	7.1%	0.03%
$\pi^+\pi^+\pi^-\pi^0\tilde{\chi}_1^0$	2.4%	–
$\pi^+\pi^0\pi^0\pi^0\tilde{\chi}_1^0$	0.5%	–
$K^+\tilde{\chi}_1^0$	1.2%	3.5%
$K^0\pi^+\tilde{\chi}_1^0$	1.0%	0.03%
$K^+\pi^0\tilde{\chi}_1^0$	0.5%	0.02%

$\tilde{\chi}_2^0$ decay mode	BR(dM1600)	BR(dM770)
$\gamma\tilde{\chi}_1^0$	23.6%	74.0%
$\nu\bar{\nu}\tilde{\chi}_1^0$	21.9%	9.7%
$e^+e^-\tilde{\chi}_1^0$	3.7%	1.6%
$\mu^+\mu^-\tilde{\chi}_1^0$	3.7%	1.5%
hadrons $+\tilde{\chi}_1^0$	44.9%	12.7%
$\tilde{\chi}_1^\pm + X$	1.9%	0.4%

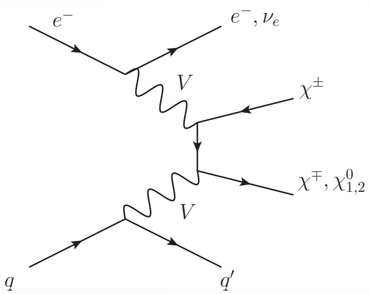


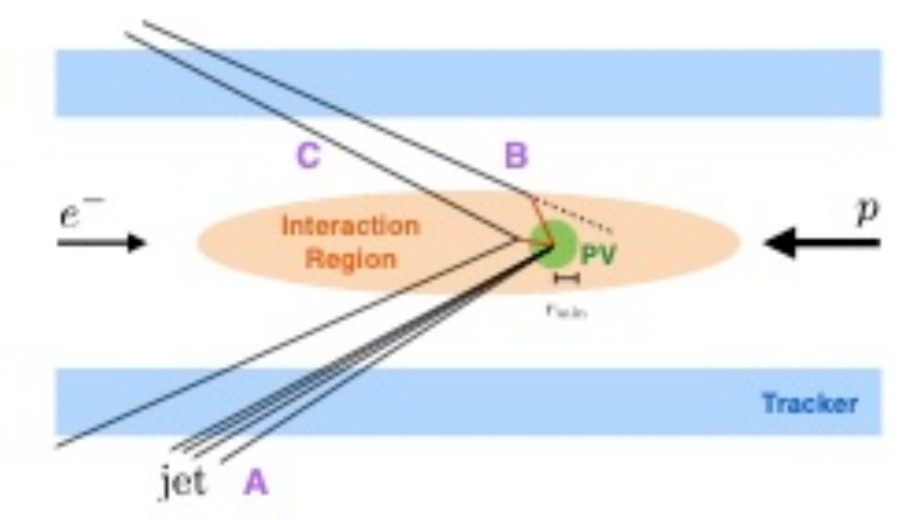
Use reduced centre-of-mass energy of the system recoiling against the photon (s' = s – 2 sqrt(s) E$_g$) → while this is not a dedicated analysis, reach down to low Δm



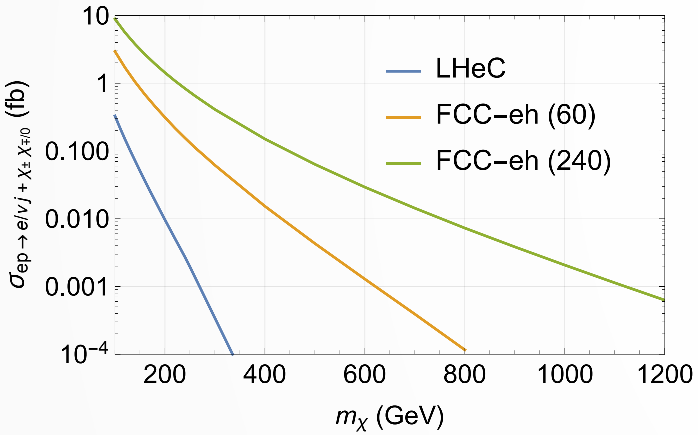
LHeC and FCC-eh: disappearing track

Section 4.1.2 of HL-LHC report
https://arxiv.org/pdf/1712.07135.pdf



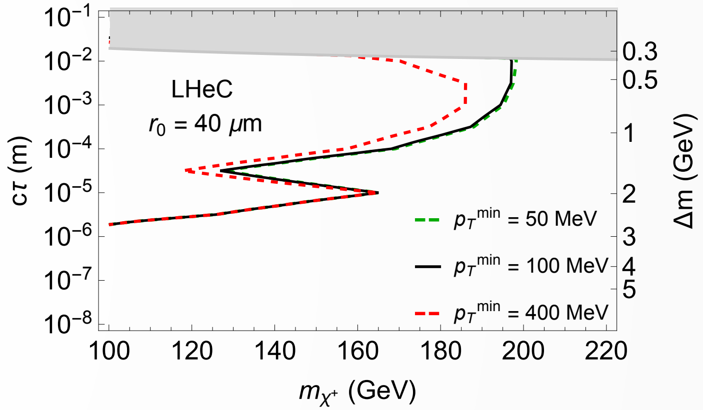


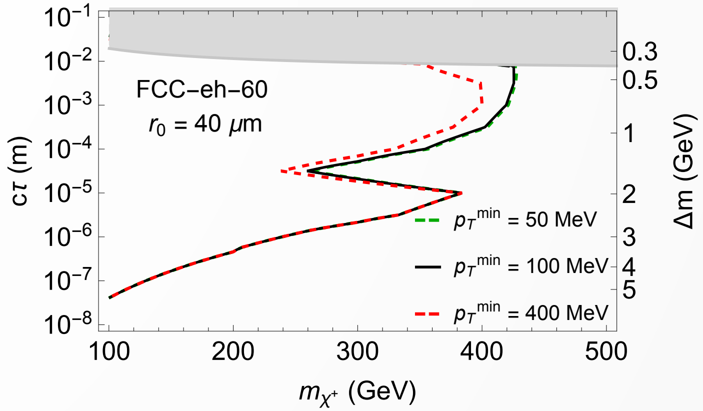
Higgsino cross-section @ e-p



probability of detecting it as an LLP

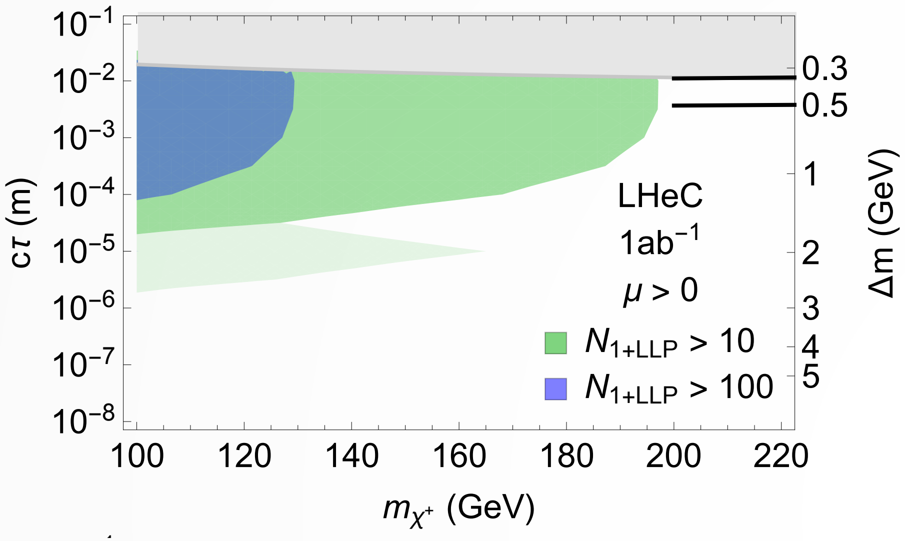
$$P^{(k)}_{\rm detect} = \sum_i {\rm Br}_i(\Delta m(c\tau))P_i(c\tau)$$

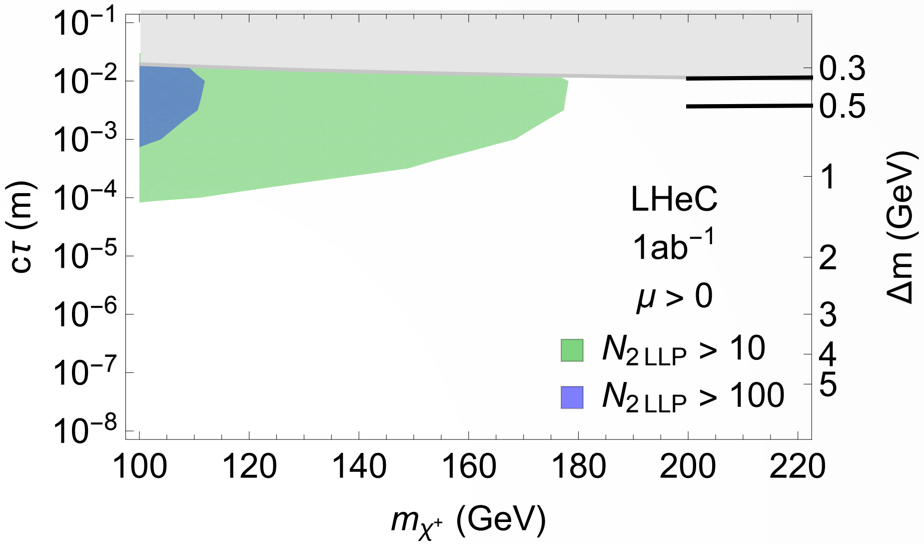


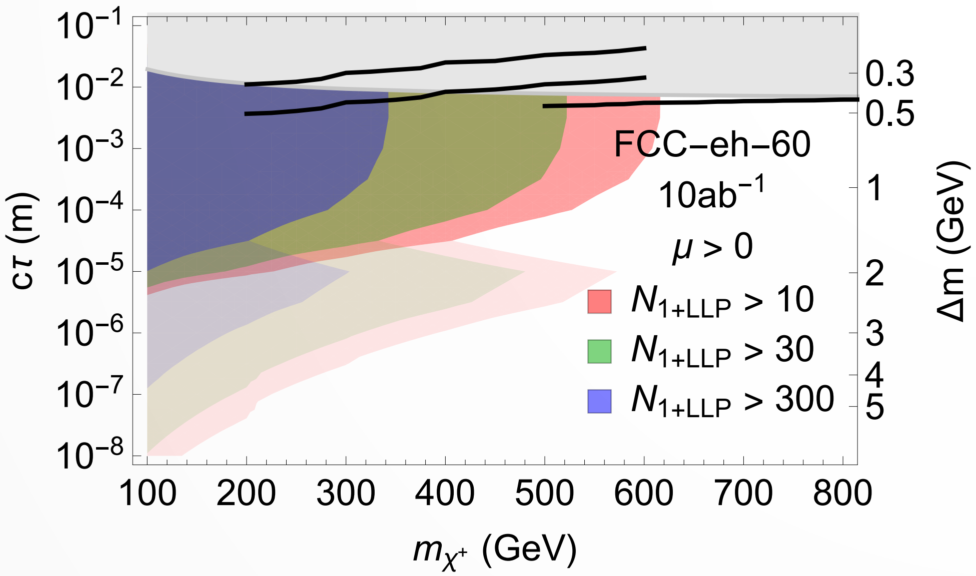


Single low-energy charged tracks are reconstructed if the minimum displacement between primary and secondary vertex (r0) is at least 40μm, and the minimum p_T of the charged SM particle is at least 100 MeV.

LHeC and FCC-eh: disappearing track





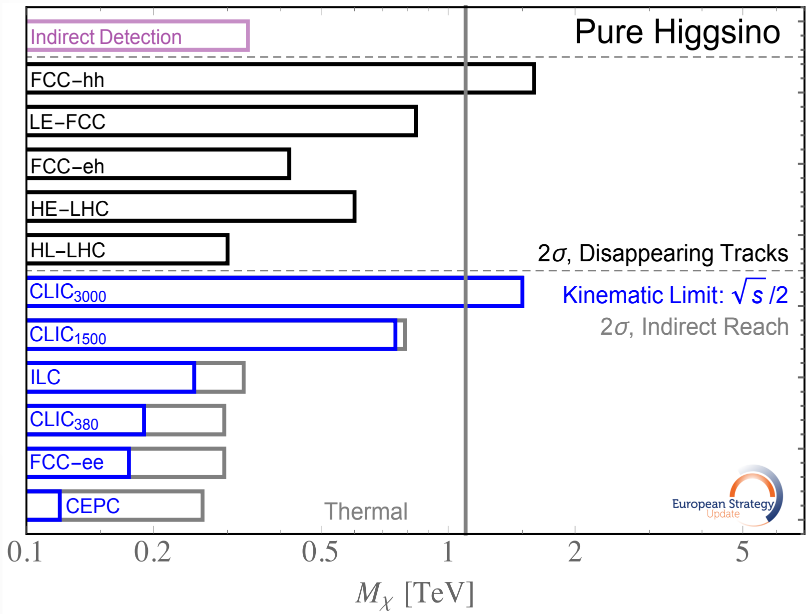


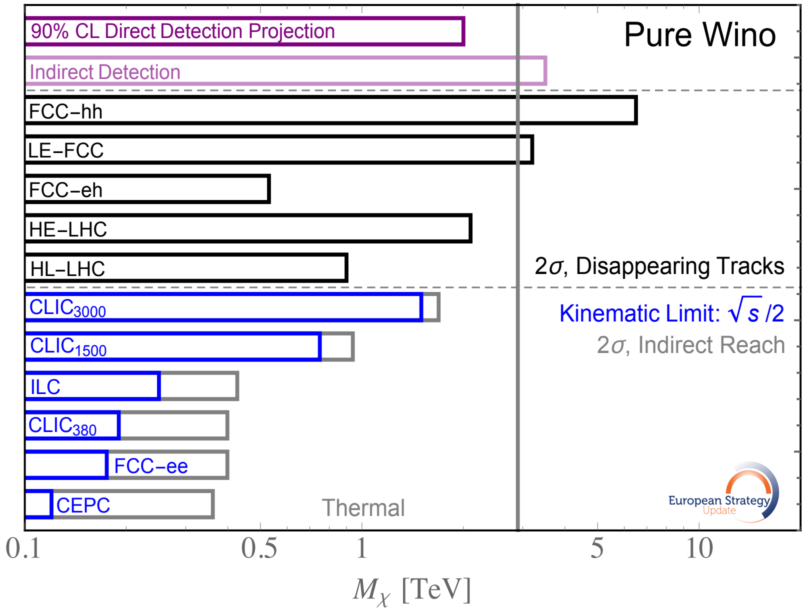
Sensitive to lifetimes as short as microseconds which makes it also complementary to pp searches

Good reach also for wino-like cases (as the production cross section is bigger)

Lessons learned: pure-wino/higgsino and analyses

- Disappearing tracks analysis very challenging:
  - Review of the assumptions made for fake backgrounds by the ATLAS prospect studies might be good (e.g. extrapolation of bkg using 3 hits instead of 4 for tracklet reconstructions)
  - Prospect studies from CMS based on the recently published disappearing track analysis would be excellent
- Are prospects for FCC-hh realistic? Are zero—background hypothesis too optimistic?
  - Dedicated analyses with specific assumptions (optimistic or pessimistic) on the detectors layout and level of pile-up / background should be made to assess the reach



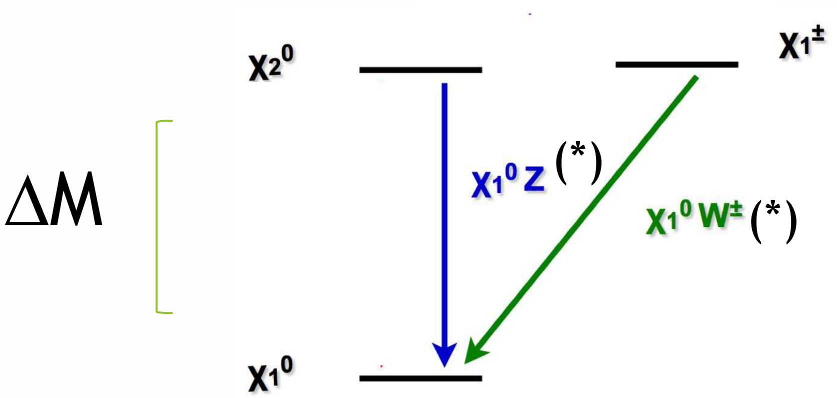


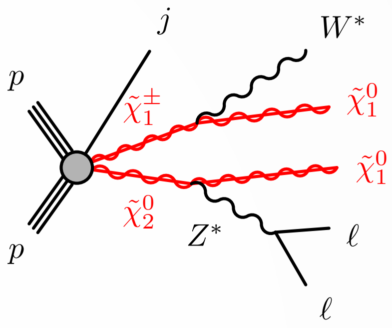
Back up

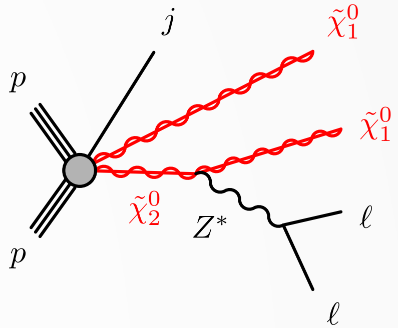
Higgsino-like EWK processes

Processes: $\chi^{+}{}_{1}\chi^{-}{}_{1}$, $\chi^{\pm}{}_{1}\chi^{0}{}_{2}$, $\chi^{0}{}_{1}\chi^{0}{}_{2}$

$\chi^{\pm}{}_{1}$, $\chi^{0}{}_{2}$ = NSLP, m($\chi^{\pm}{}_{1}$) ~ m($\chi^{0}{}_{2}$)







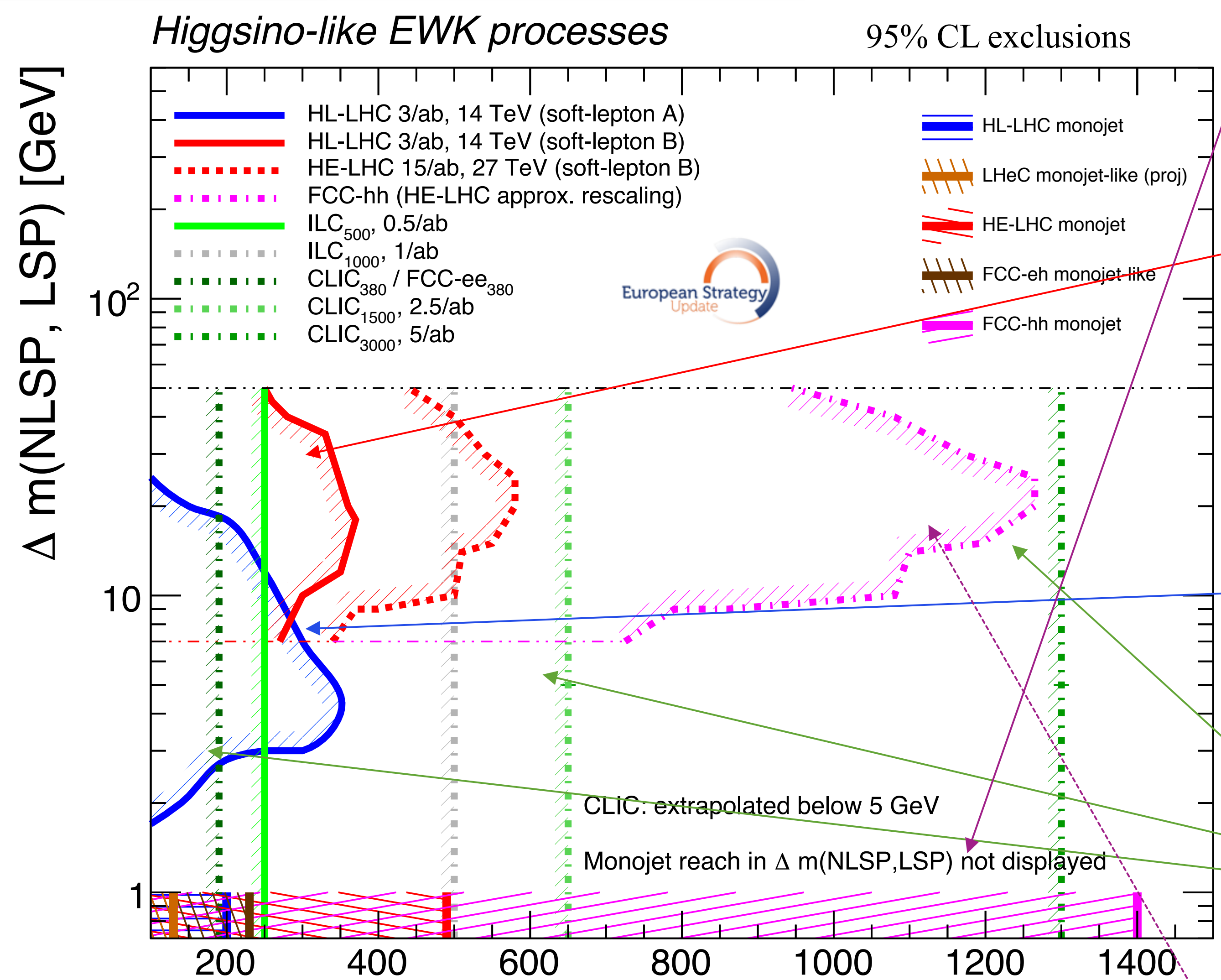
Higgsino-like (i.e. large higgsino component but not pure):

→ ΔM(NLSP, LSP) ~ O(GeV)

Pure-higgsino:

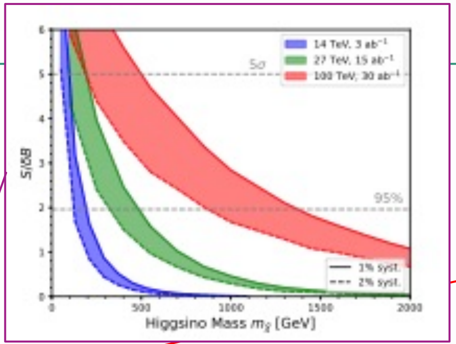
→ **ΔM ~ 160 MeV** – targeted by disappearing track analyses

Higgsino-like EWK processes

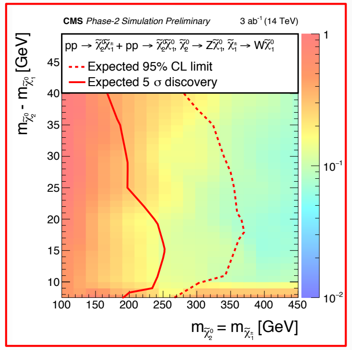


ILC sensitive up to sqrt(s)/2 and down to O(100 MeV)

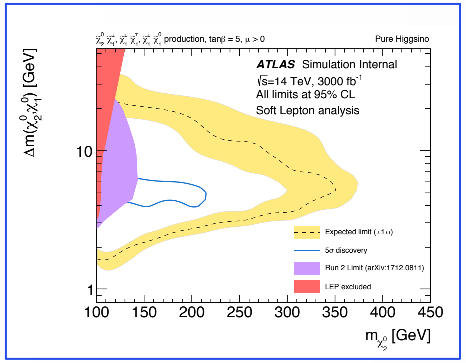
Monojets (HL/HE/FCC-hh/LHeC/FCC-eh)



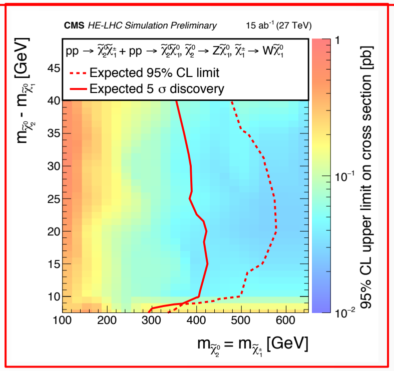
HL-LHC soft lepton analysis CMS

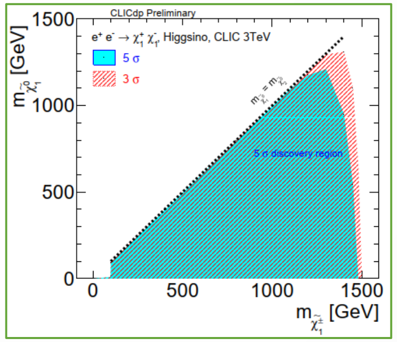


HL-LHC soft lepton analysis ATLAS



HE-LHC soft lepton analysis





CLIC 3 TeV, results rescaled also for CLIC1.5, CLIC380, FCC-ee **(tbc)**
Analysis done for DM(NLSP,LSP)=5 GeV – below: extrapolated

Indicative partonic rescaling of HE for FCC-hh soft-lepton

Lessons learned: higgsino-like scenarios

- At the time of the Yellow Report and ES document ATLAS and CMS managed to reach an excellent set of results in compressed scenarios → one could envisage a **better coherence on the model assumptions** used for the soft lepton analyses
- As compressed scenarios are the most interesting for complementarities with e+e- colliders, **reinterpretation of monojet analyses** in the higgsino-like scenario as a function of ΔM would be fundamental, i.e. in the 1-20 GeV range
  - we can expect some sensitivity there!
  - It is very important to understand (1) complementarities with e+e- and e-p colliders (2) impact on systematics and discovery potential
- There are **no dedicated studies for FCC-hh**, only extrapolations → would be very important to perform a more realistic and dedicated set of analyses!
- Follow up on possible deviations observed at HL-LHC should be made