Exotic Higgs Studies at the FCC-ee

Summary talk

Axel Gallén – Uppsala University
obo the FCC BSM group

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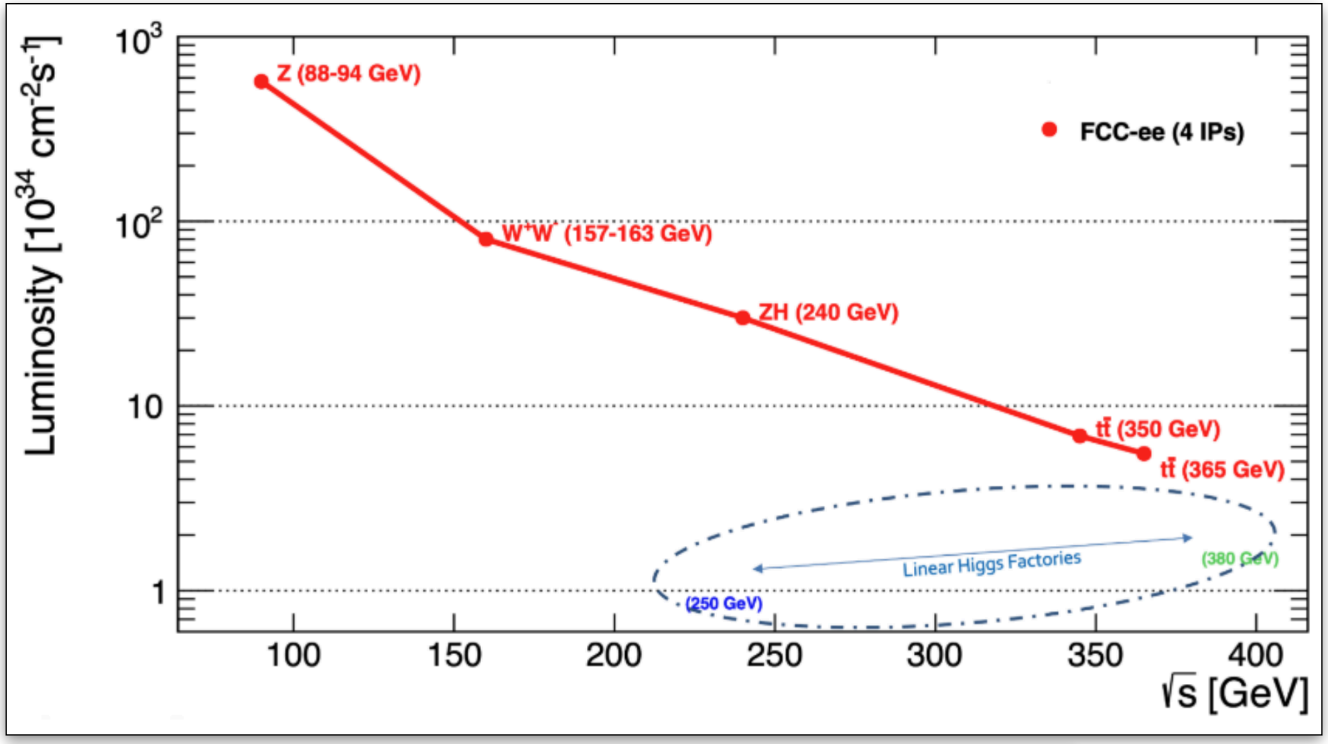
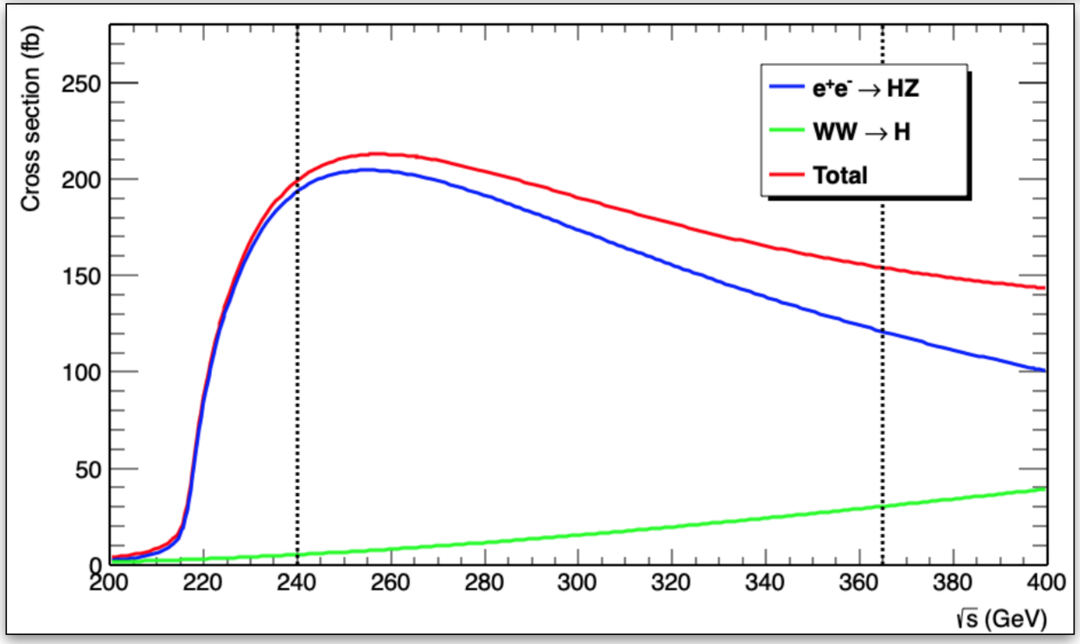
Introduction

- FCC-ee is a Higgs factory!
  - 240 GeV: 2.2M Zh / 65k VBF
  - 365 GeV: 370k Zh / 92k VBF
- Precision Higgs program will constrain BR(H→exotics) to <1%
- Still room for particles and sectors with small couplings to the Higgs boson
- Direct searches for new Higgs bosons and exotic Higgs boson decays are an important complement to the precision program
- This presentation will:
  - Show the progress of the Exotic Higgs studies at the FCC-ee





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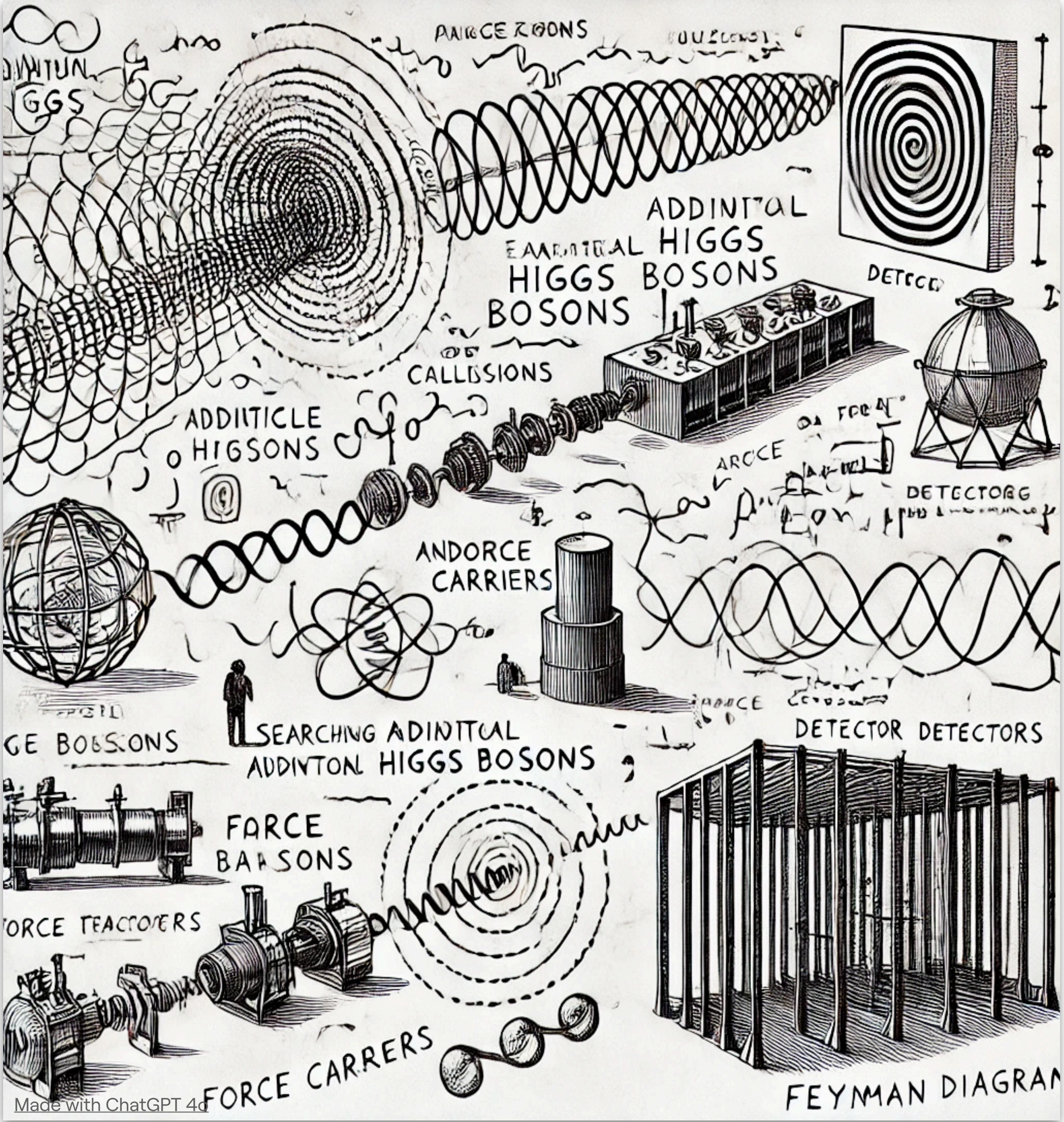

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Search for additional Higgs bosons

Edward Curtis, Anne-Marie Magnan & Tania Robens

ECFA 2024 presentation, CDS note

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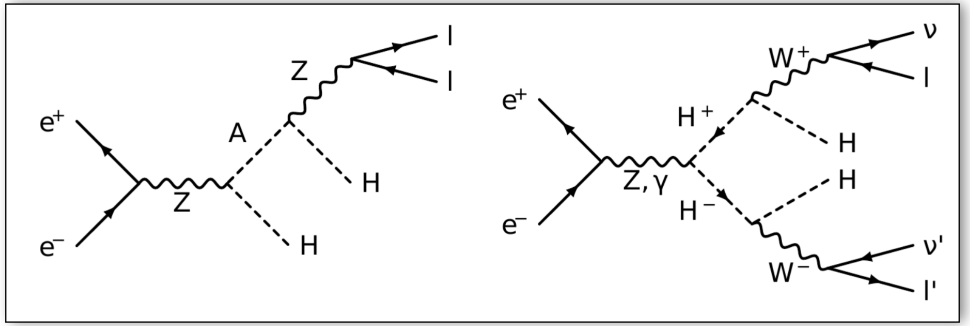
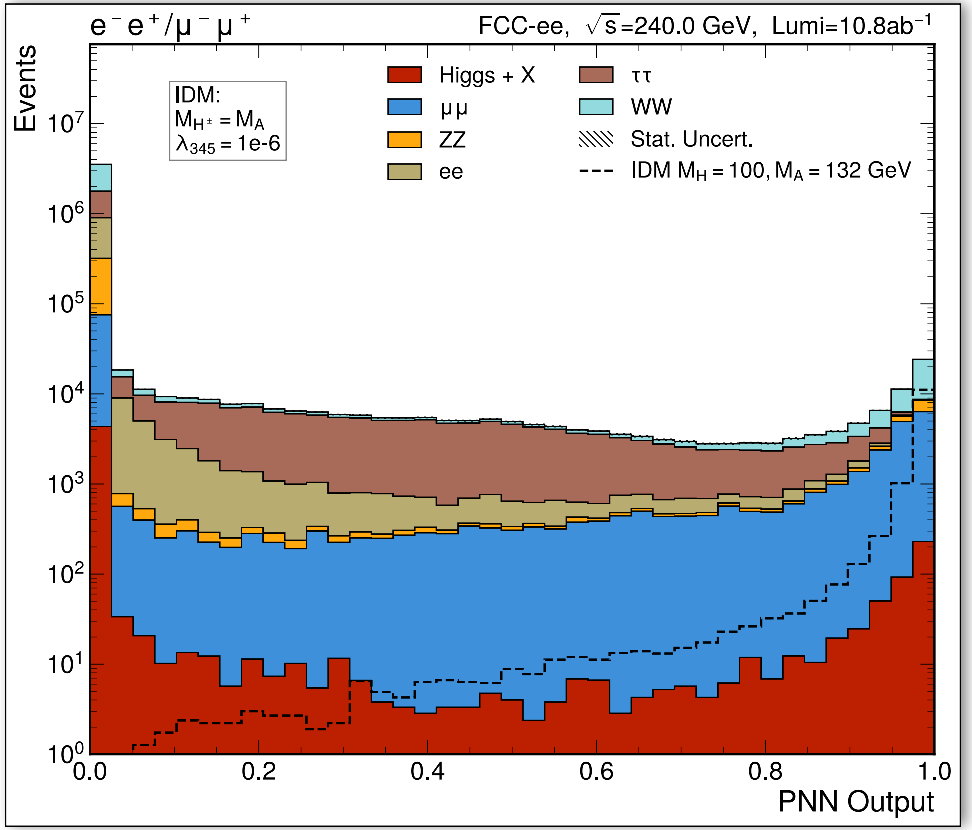
Analysis motivation & method

- Inert Two-Higgs-Doublet model (IDM)
  - Five new free parameters: $m_H, m_A, m_{H^\pm}, \lambda_{345}, \lambda_2$
- One new Dark matter candidate: H (invisible)
- Previous studies concerns IDM @ CLIC:
  - 2201.07146
  - 2002.11716
  - 1811.06952
- Study considers both Zh & $t\bar{t}$ runs
- Considered final state: HH + 2e (2μ)
  - MG5_aMC@NLO simulation
- Main backgrounds: $ee \rightarrow \ell\ell, WW, ZZ, Zh$
- Sensitivity mainly depending on m_H & $m_A - m_H$
- Further optimised with PNN for signal discrimination

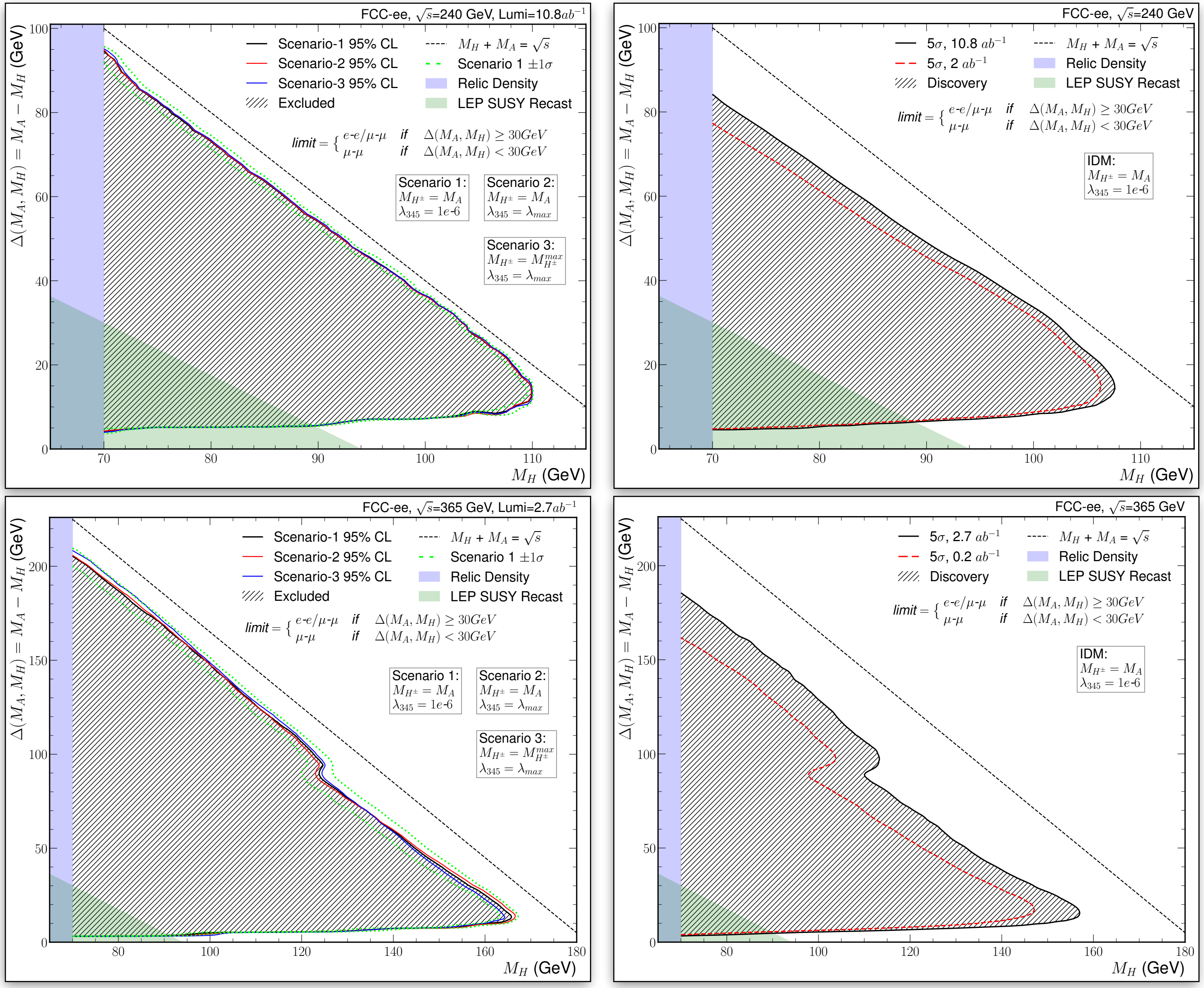




Edward Curtis, Anne-Marie Magnan & Tania Robens

Results & outlook

- IDM model explored at the FCC-ee using PNN
- Successfully reproduced CLIC setup results - extending the reach
    - Different free parameters scenarios explored
- Next steps:
    - Implement realistic systematic uncertainties



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Higgs to Dark Showers

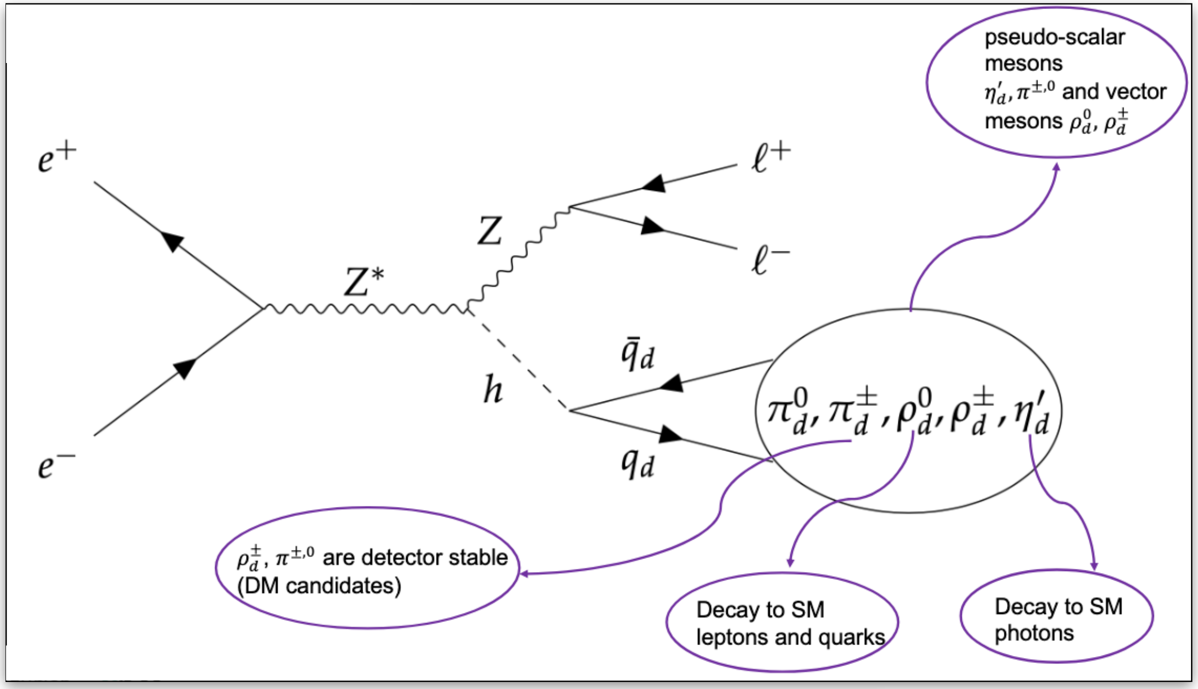
Emre Sitti, Cesare Cazzaniga, Annapaola de Cosa & Felix Kahlhoefer

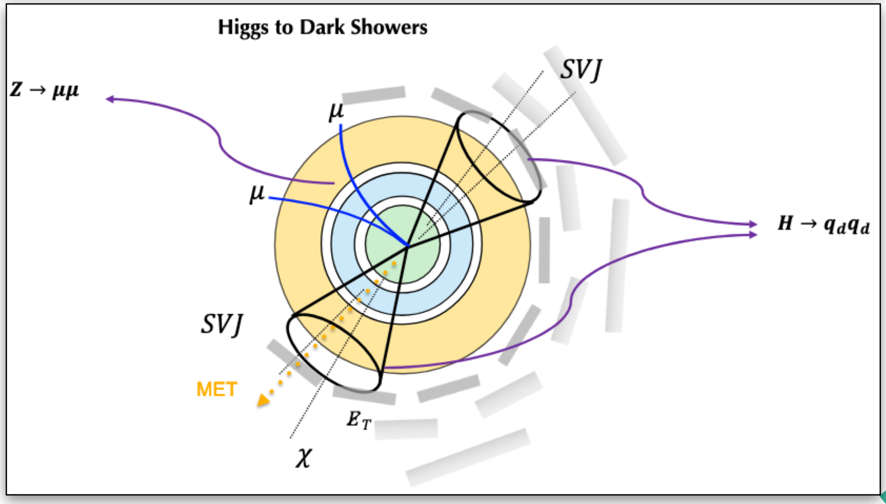
FCC BSM presentation, LHC Higgs workshop presentation

ETH zürich
Karlsruher Institut für Technologie

Analysis motivation & method

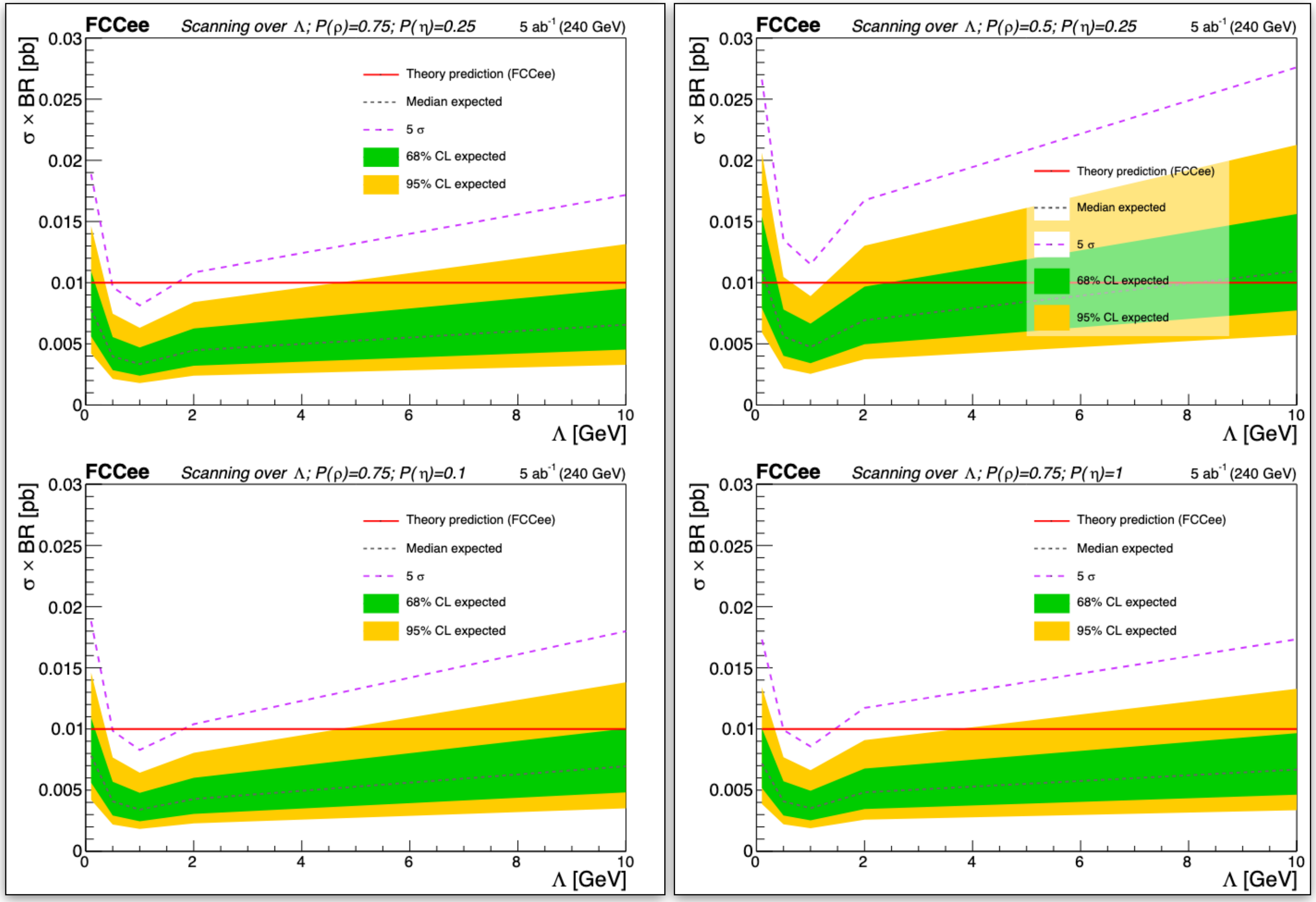
- Hidden valley which proposes feebly coupled hidden sector
  - Long Lived Particles (LLPs)!
  - → Exotic Higgs Decays!
- Signature: 2μ + 2 displaced Semi Visible Jets (SVJ)
  - Where SVJ → $2\gamma, 2\ell$
- Semi Visible Jets (SVJ) from Dark showers
  - SVJ: Jets which are not fully decaying into SM
- Main backgrounds: $ee \to ZZ, WW, Z(\mu\mu)h$
- Delphes Fast Sim with IDEA detector card
- Analysis done with FCCAnalyses Framework



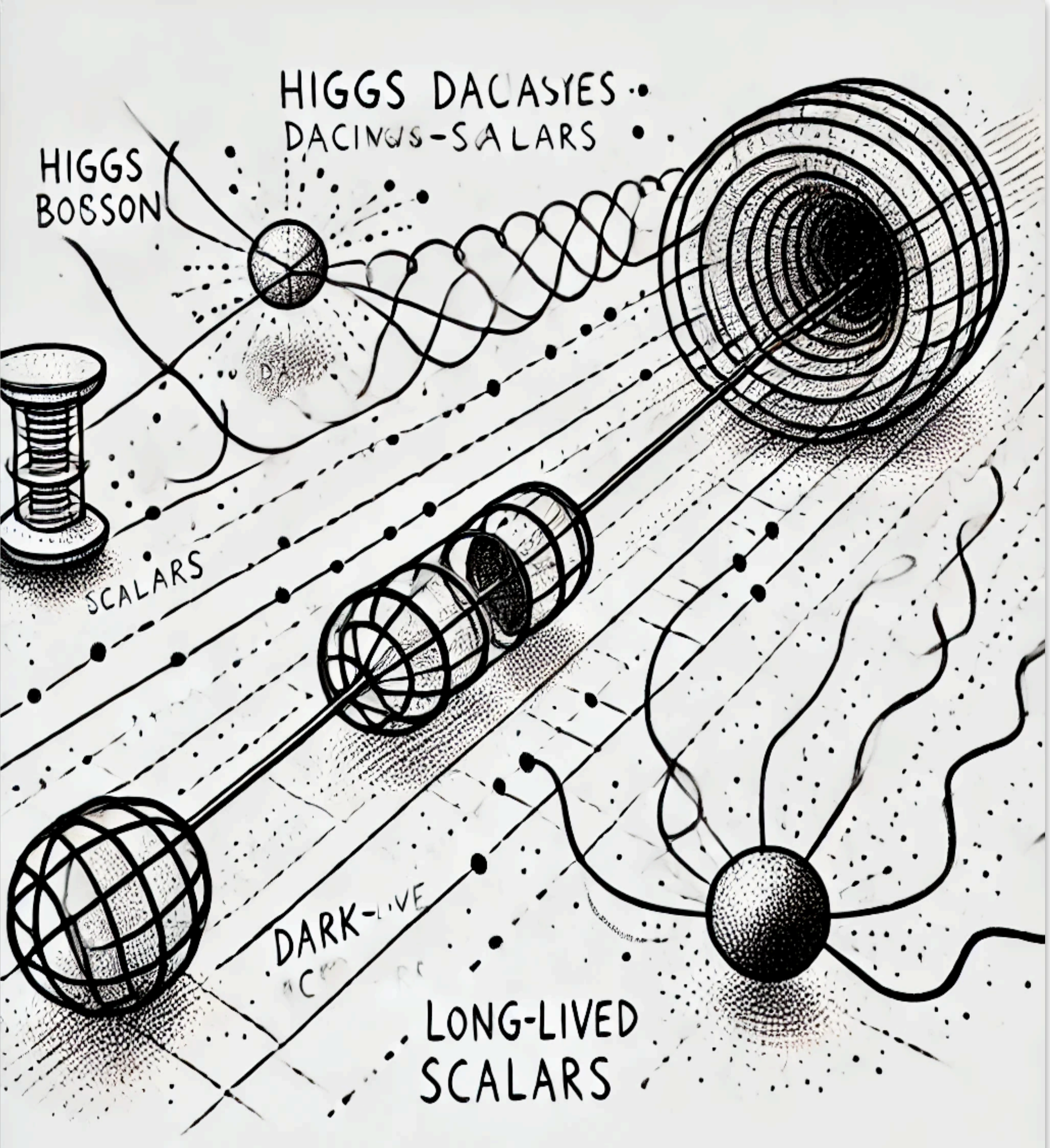


Results & outlook

- Study looking for Dark Showers via dark mesons from SVJs
- FCC-ee study which also can be probed at the HL-LHC
- Investigates low-mass mediator like Higgs
- Confinement scale scan yields limits on cross section given dark meson fractions
- Next steps:
  - Jet tagger
  - Electron category



Emre Sitti, Cesare Cazzaniga, Annapaola de Cosa & Felix Kahlhoefer



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Searching for Higgs decaying into long-lived dark scalars

Giulia Ripellino, Magdalena Vande Voorde, Axel Gallén & Rebeca Gonzalez Suarez

ECFA 2024 presentation, HIGGS 2024 presentation, CDS note, pre-print

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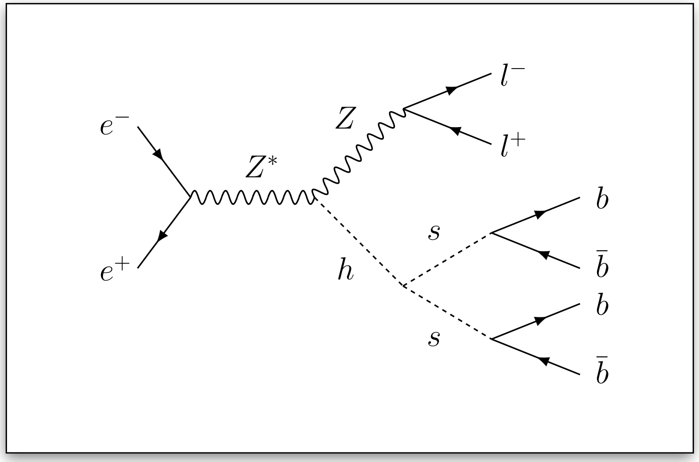
Analysis motivation & method

- Hidden sector model with scalar portal
  - New dark scalar s mixes with SM Higgs via $sin\theta$
- Exotic decay of SM Higgs, h, into new scalar s
  - s then decays into SM states
- Small mixing angles yields long-lived scalars
  - LLPs!
  - → Displaced Vertex (DV) search!
- Targets Zh stage; 240 GeV & 10.8 ab^{-1}
- Signature generated with HAHM model: $ee \rightarrow Zh, Z \rightarrow \ell^{\pm}\ell^{\mp}, h \rightarrow ss \rightarrow 4b$
- Main backgrounds: WW, ZZ, Zh
- Analysis done using FCCAnalyses Framework
  - "Winter 2023" backgrounds
  - Signal simulated with MadGraph5 HAHM model
  - Delphes Fast Sim with IDEA detector card



Sample $(m_s, \sin\theta)$	$c\tau$ [mm]	BR$(h \to ss)$
20 GeV, 1×10^{-5}	3.4	8.1×10^{-4}
20 GeV, 3×10^{-6}	38	8.1×10^{-4}
20 GeV, 1×10^{-6}	340	8.1×10^{-4}
20 GeV, 1×10^{-7}	34 000	8.1×10^{-4}
40 GeV, 1×10^{-5}	1.4	10.2×10^{-4}
40 GeV, 1×10^{-6}	140	10.2×10^{-4}
40 GeV, 1×10^{-7}	14 000	10.2×10^{-4}
50 GeV, 3×10^{-6}	12	10.9×10^{-4}
50 GeV, 1×10^{-6}	110	10.9×10^{-4}
50 GeV, 3×10^{-7}	1200	10.9×10^{-4}
60 GeV, 1×10^{-5}	0.9	7.4×10^{-4}
60 GeV, 1×10^{-6}	88	7.4×10^{-4}
60 GeV, 1×10^{-7}	8800	7.4×10^{-4}

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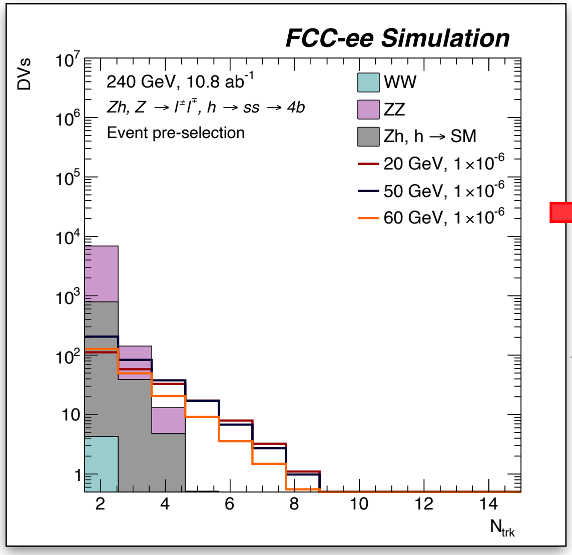
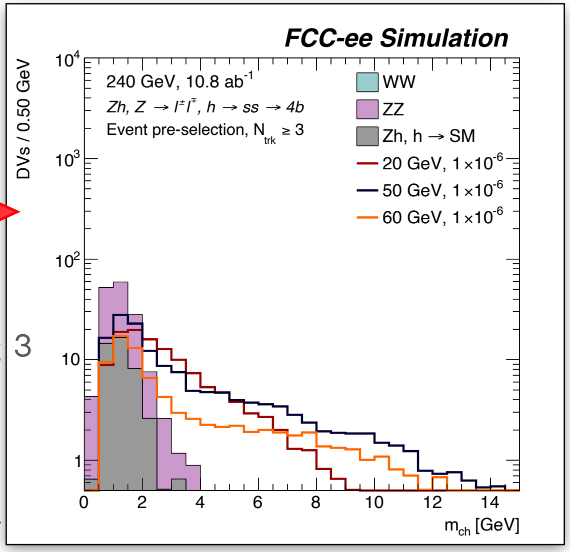
Event & Vertex Selection

- Secondary Vertex finder of LCFIPlus algorithm used
  - Custom track selection: $p_T > 1$ GeV & $|d_0| > 2$ mm

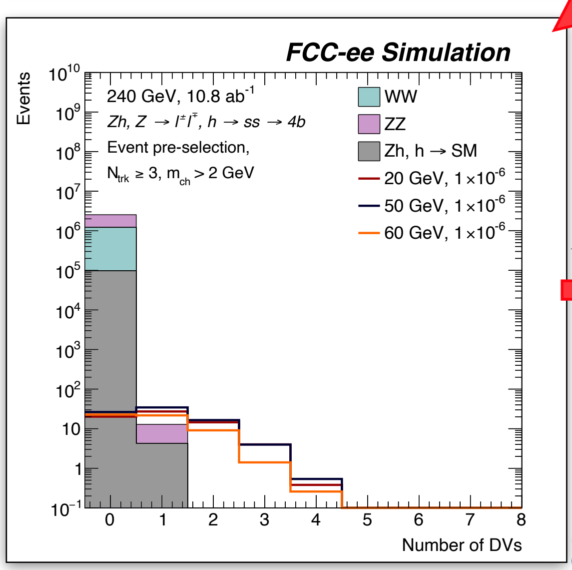
- Selections:
  - Event selection:
    - 2 iso. leptons (μ or e), opposite-sign, same flavour
    - 70 GeV < m_{ll} < 110 GeV
    - At least 2 DVs passing the full DV selection
  - DV selection:
    - $N_{trk} \geq 3$
    - $m_{ch} > 2$ GeV



$N_{trk} \geq 3$



$m_{ch} > 2$ GeV



$N_{DV} \geq 2$

Zero background!

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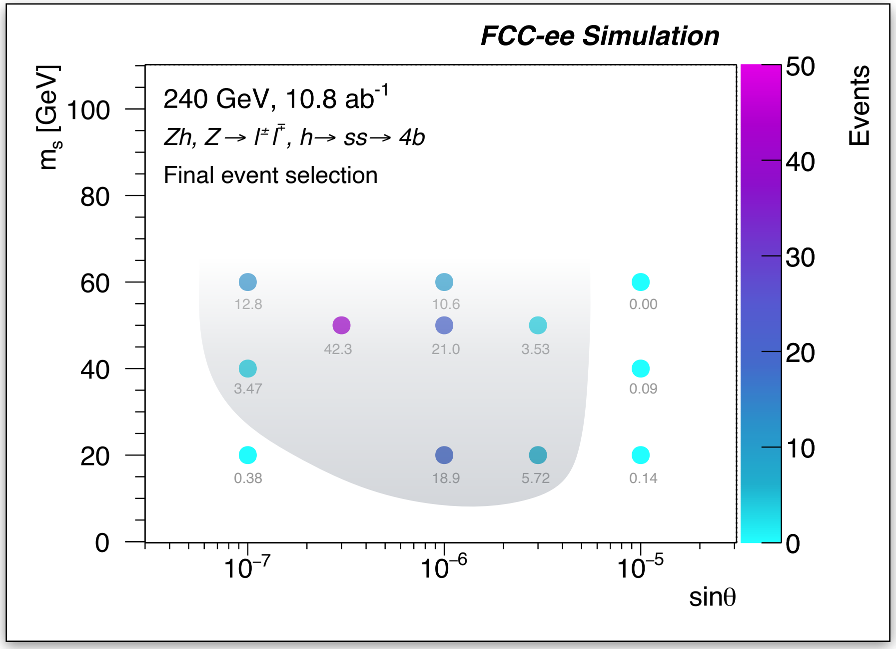
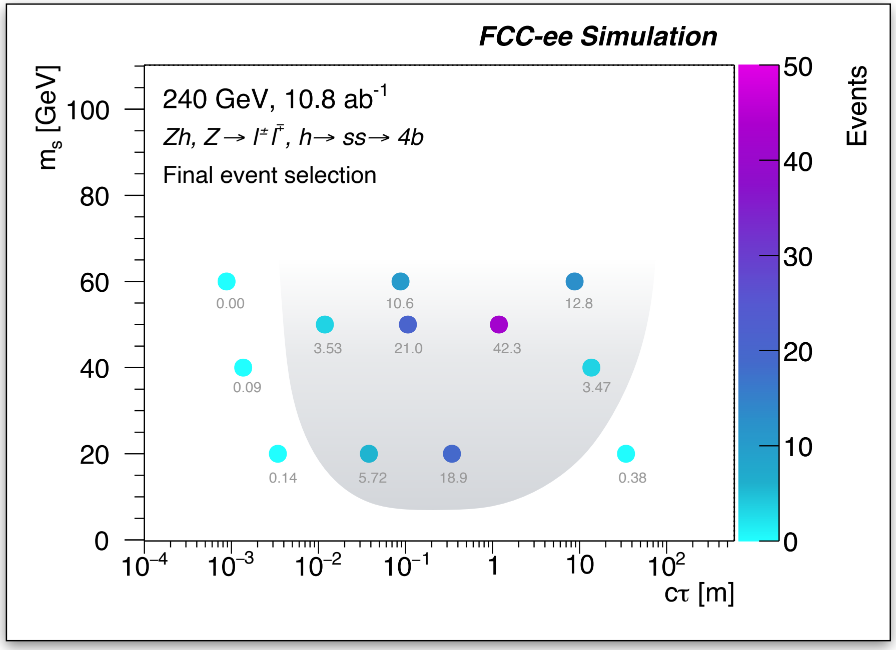
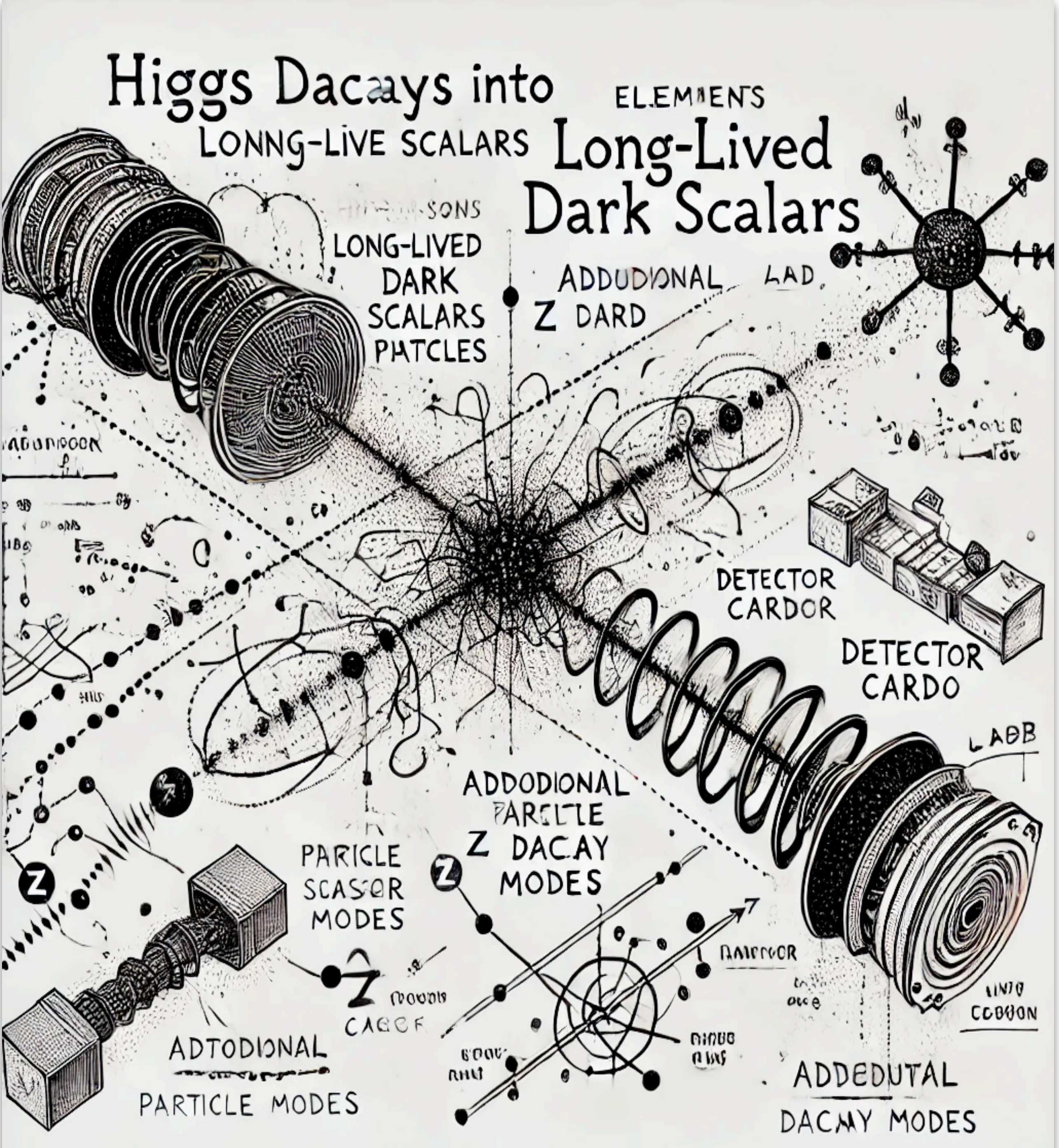
Results & outlook

- SM background free search
- Rough contour of signal points with ≥3 events
- Successfully performed sensitivity analysis
  - BR($h \to ss$) probed to 10^{-4} for $c\tau \approx$ 1m

- pre-print on arXiv: 2412.10141
- Submitted to JHEP
- Possible future improvements:
  - Vertexing
  - Include hadronic & invisible Z decays in signal -> next slides!







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Detector card comparison and additional Z decay modes

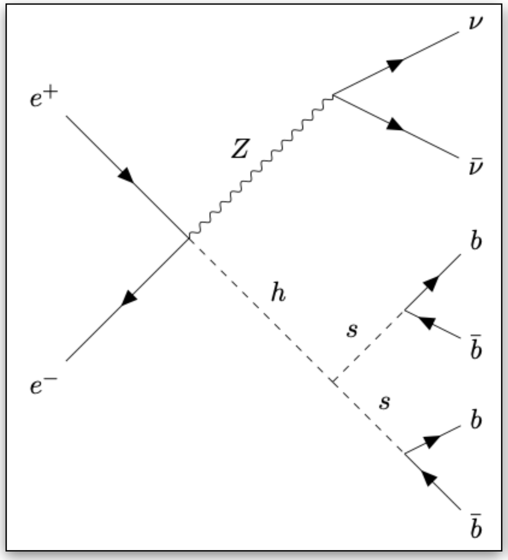
Mark Larson & Louise Skinnari

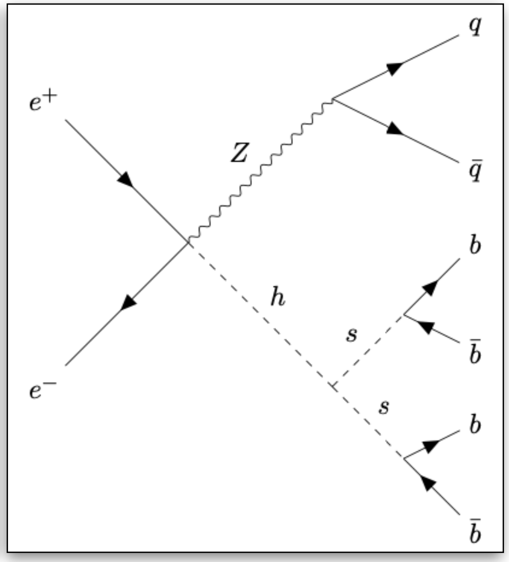
US FCC Workshop 2024

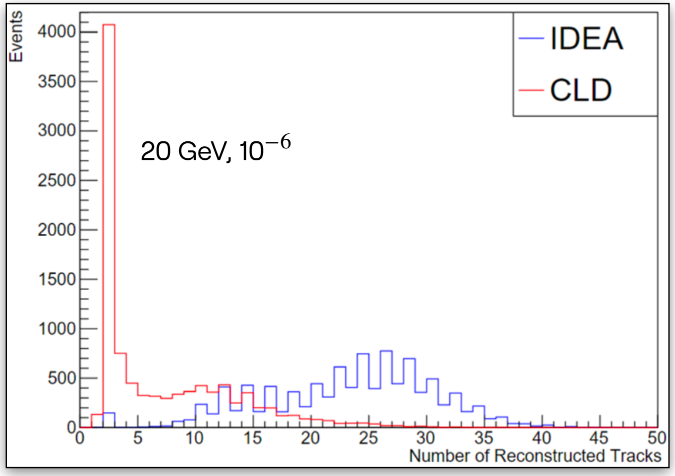
Northeastern University

Method & Results

- Spin-off of the previous analysis
  - Compares CLD and IDEA cards
  - Additionally includes invisible & hadronic Z decays for signal
    - $Z \to \nu\bar{\nu}$ & $Z \to q\bar{q}$
- Observed less reconstructed tracks per event in CLD compared to IDEA (for longer $c\tau$)
- Inclusion of more decay modes increases signal yield by ~13x
  - Note values here & on slide 12 not 1 - 1 comparison due to different luminosities (7.2 here vs 10.8 above)







Signal Processes					
20 GeV, 10^{-5}	20 GeV, 10^{-6}	20 GeV, 10^{-7}	60 GeV, 10^{-5}	60 GeV, 10^{-6}	60 GeV, 10^{-7}
54.56 ± 1.66	421.25 ± 4.60	10.32 ± 0.72	0.033 ± 0.023	123.0 ± 1.43	72.03 ± 1.09

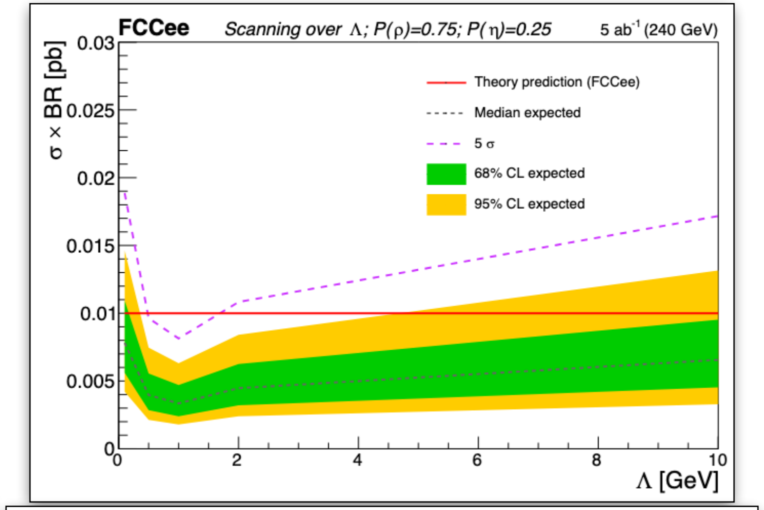
Background Processes		
WW	ZZ	Zh
1183.6	97.8	27.5

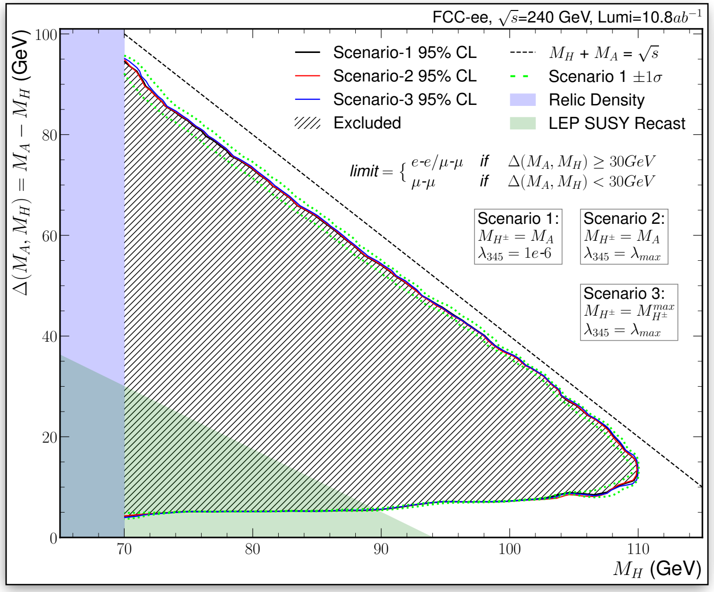
Northeastern University

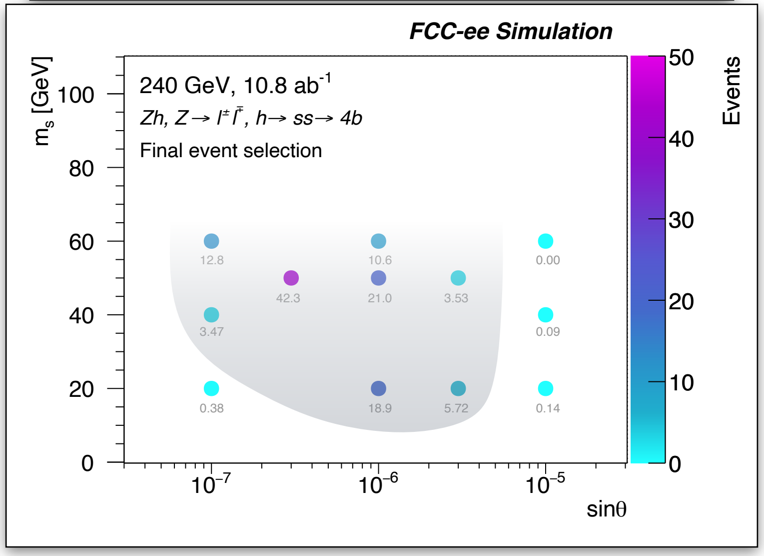
Mark Larson & Louise Skinnari

Conclusion & Summary

- A lot of work being done in the Exotic Higgs BSM sector
- FCC-ee will provide competitive sensitivity studies to exotic Higgs signatures
- Important for the FCC-ee case as a whole

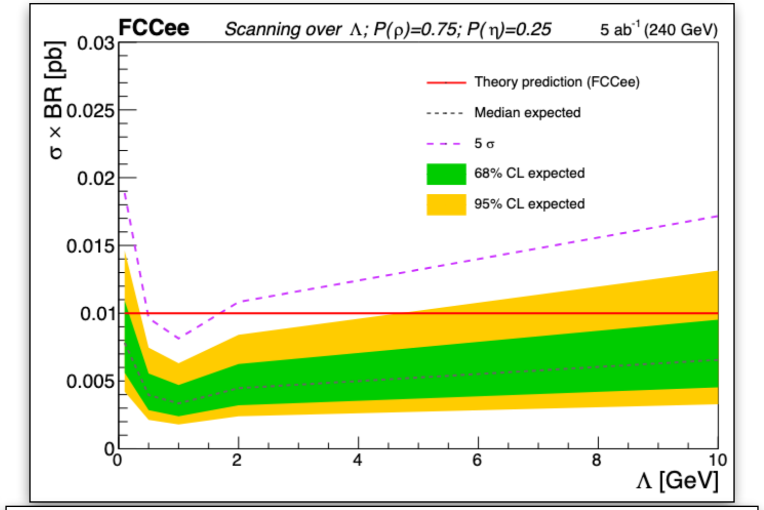


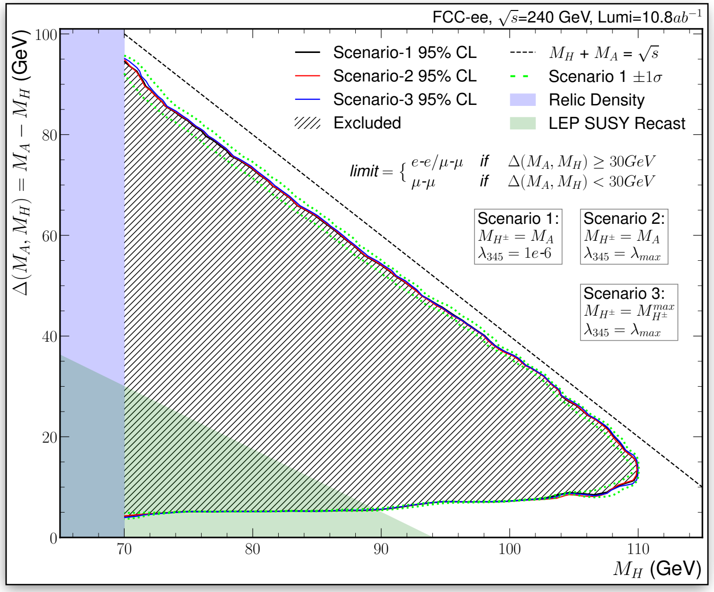


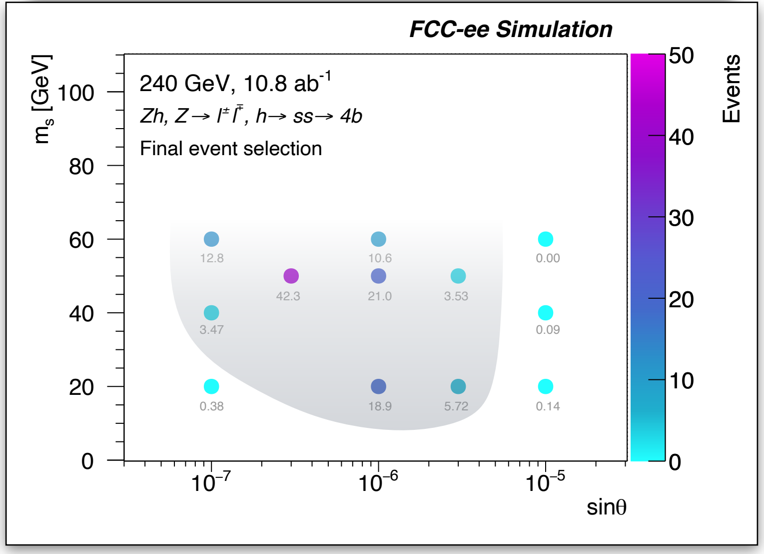


Conclusion & Summary

- A lot of work being done in the Exotic Higgs BSM sector
- FCC-ee will provide competitive sensitivity studies to exotic Higgs signatures
- Important for the FCC-ee case as a whole
- Thank you for listening!







Backup

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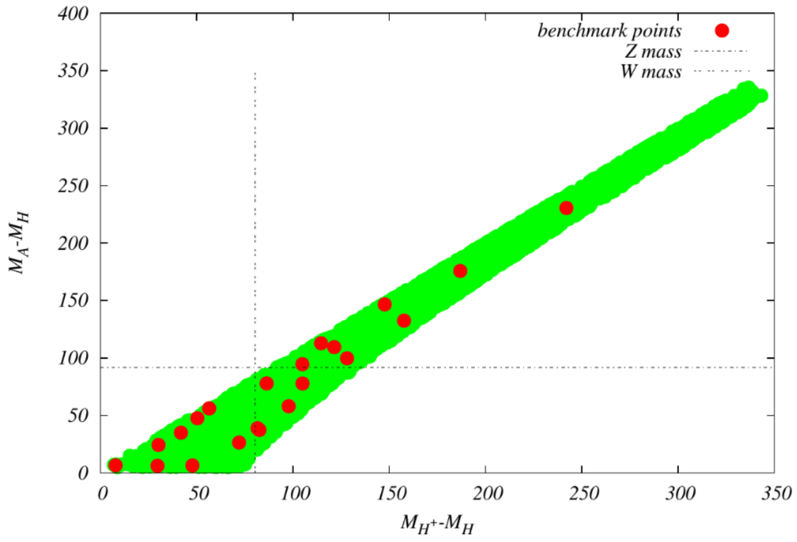
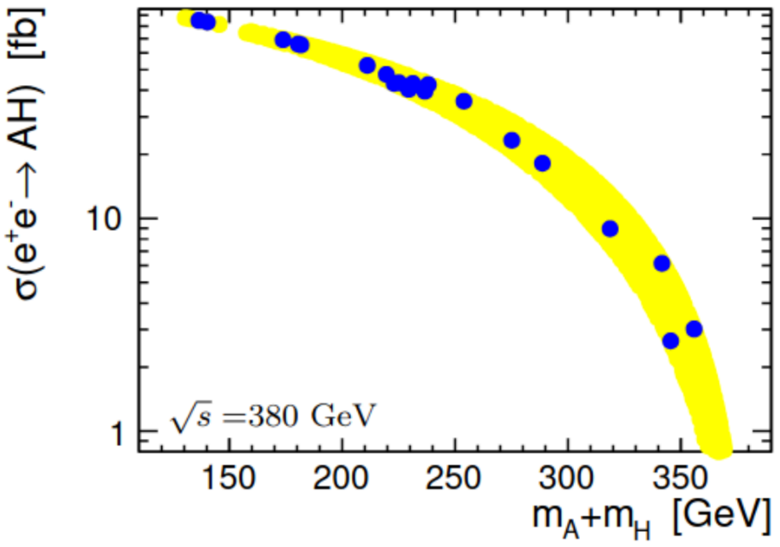
Additional Higgs Bosons

- Constraints from all experimental results: set of 20 low-mass benchmark points relevant for FCC-ee [JHEP 1812 (2018) 081]

No.	M_H	M_A	$M_{H^\pm}$	$\sigma(250)$	$\sigma(380)$	$\sigma(500)$
BP1	72.77	107.803	114.639	77.2	65.9	45.7
BP2	65	71.525	112.85	155	85.1	53.4
BP3	67.07	73.222	96.73	149	83.5	52.8
BP4	73.68	100.112	145.728	89.2	69.1	46.9
BP6	72.14	109.548	154.761	75.1	65.4	45.4
BP7	76.55	134.563	174.367	31.2	52.3	40.1
BP8	70.91	148.664	175.89	20	47.5	38.1
BP9	56.78	166.22	178.24	14.1	43	36
BP10	76.69	154.579	163.045	9.44	43	36.2
BP11	98.88	155.037	155.438	-	35.6	33.2
BP12	58.31	171.148	172.96	9.01	40.4	34.8
BP13	99.65	138.484	181.321	5.17	42.5	36.2
BP14	71.03	165.604	175.971	5.13	39.6	34.7
BP15	71.03	217.656	218.738	-	18.2	24.2
BP16	71.33	203.796	229.092	-	23.3	26.9
BP18	147	194.647	197.403	-	6.14	18.7
BP19	165.8	190.082	195.999	-	3.02	16.6
BP20	191.8	198.376	199.721	-	-	11.3
BP21	57.475	288.031	299.536	-	2.66	12.6
BP22	71.42	247.224	258.382	-	8.94	18.6
BP23	62.69	162.397	190.822	13.2	43.3	36.2





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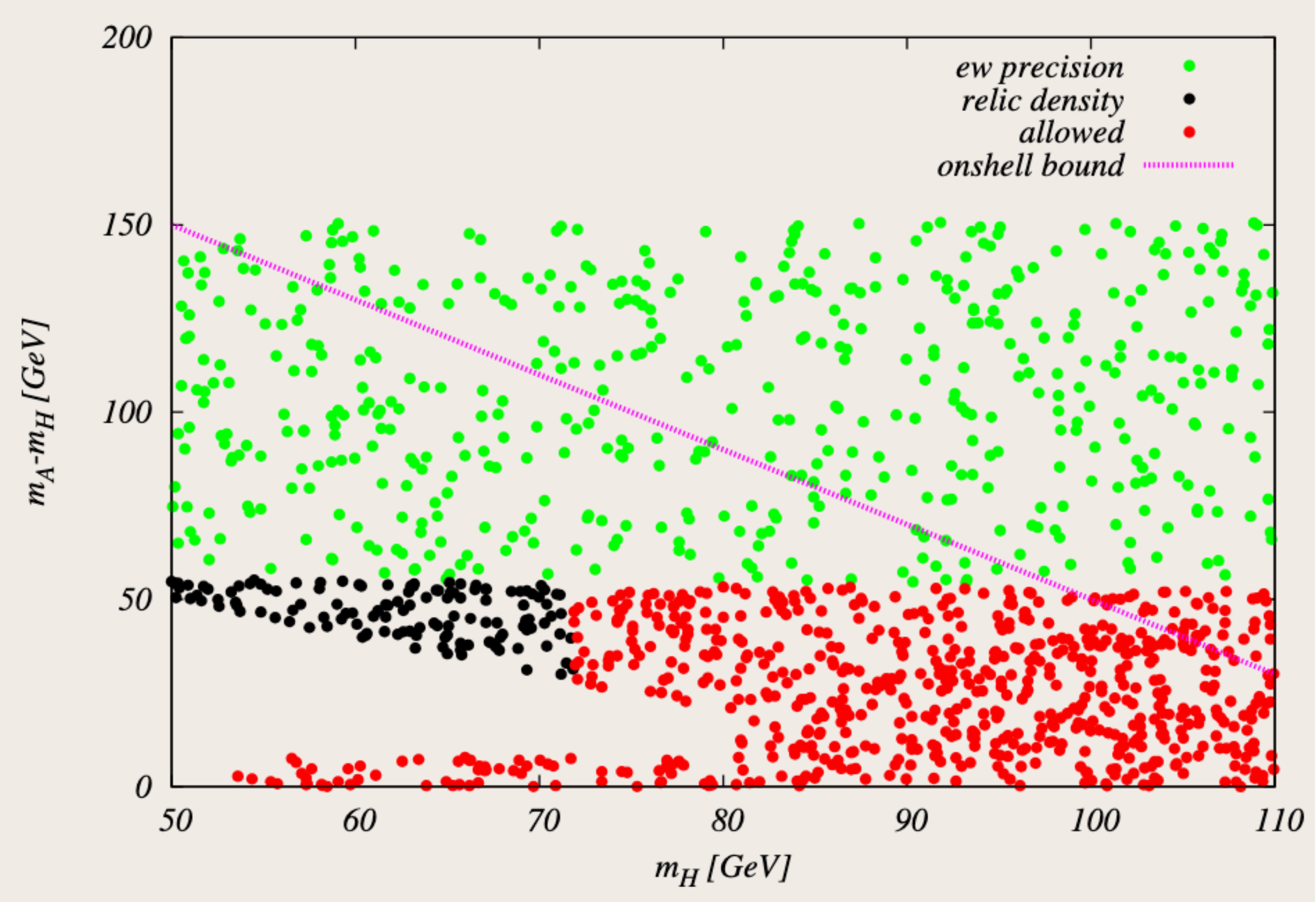
Additional Higgs Bosons

- λ_{345}, λ_2: Little impact on dominant production processes (fixed at 0 or small value)
- Dominant sensitivity from AH production: also very little impact from $m_{H^\pm}$, "artificially" fixed at m_A + 50 GeV
- 5-σ discovery possible up to m_A + m_H = 220 GeV with 1 ab^{-1} at $\sqrt{s}$ = 250 GeV.



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Additional Higgs Bosons - PNN

- Set of input variables with discriminating features, similar to arXiv:2002.11716.
- Problem with BDT approach: how to categorise by signal features / interpolate between signal points.

- the dilepton pair $E_{\ell\ell}$,
- the dilepton pair $p_T^{\ell\ell}$,
- the dilepton invariant mass $M_{\ell\ell}$,
- the dilepton recoil mass calculated assuming the nominal $\sqrt{s}$,
- the dilepton $p_z^{\ell\ell}$,
- the dilepton Lorentz boost $p_{\ell\ell}/E_{\ell\ell}$,
- the polar angle of the dilepton pair $\cos\theta$,
- the leptons p_T,
- the leptons $\cos(\Delta\phi)$,
- ℓ^- production angle with respect to the beam direction calculated in the dilepton centre-of-mass frame $\cos(\theta*)$,
- ℓ^- production angle with respect to the dilepton pair boost direction, calculated in the dilepton centre-of-mass frame $\cos(\theta R)$

- One solution: parametric Neural Network, input signal masses as additional variables $\Rightarrow$ training incorporates signal features, and can interpolate between simulated grid points.

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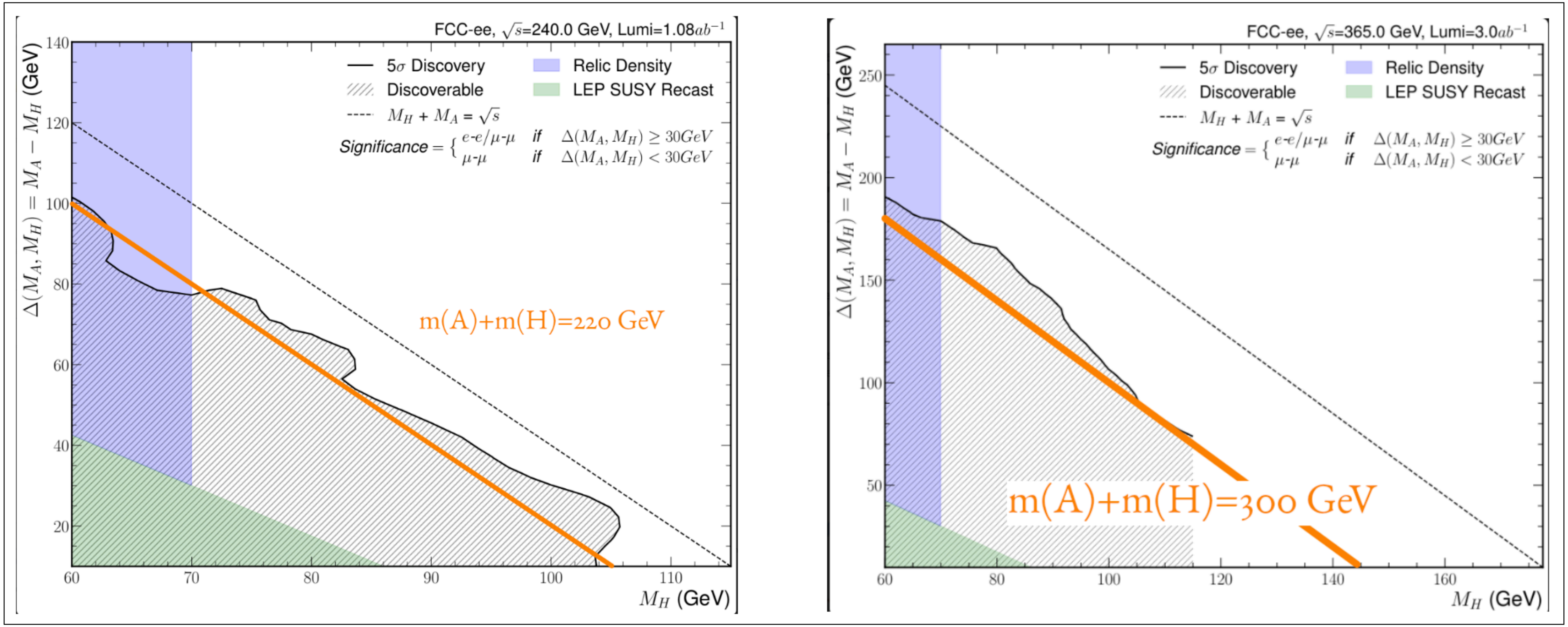
Additional Higgs Bosons - CLIC/ILC comparison



NOTE OLD LIMIT PLOTS

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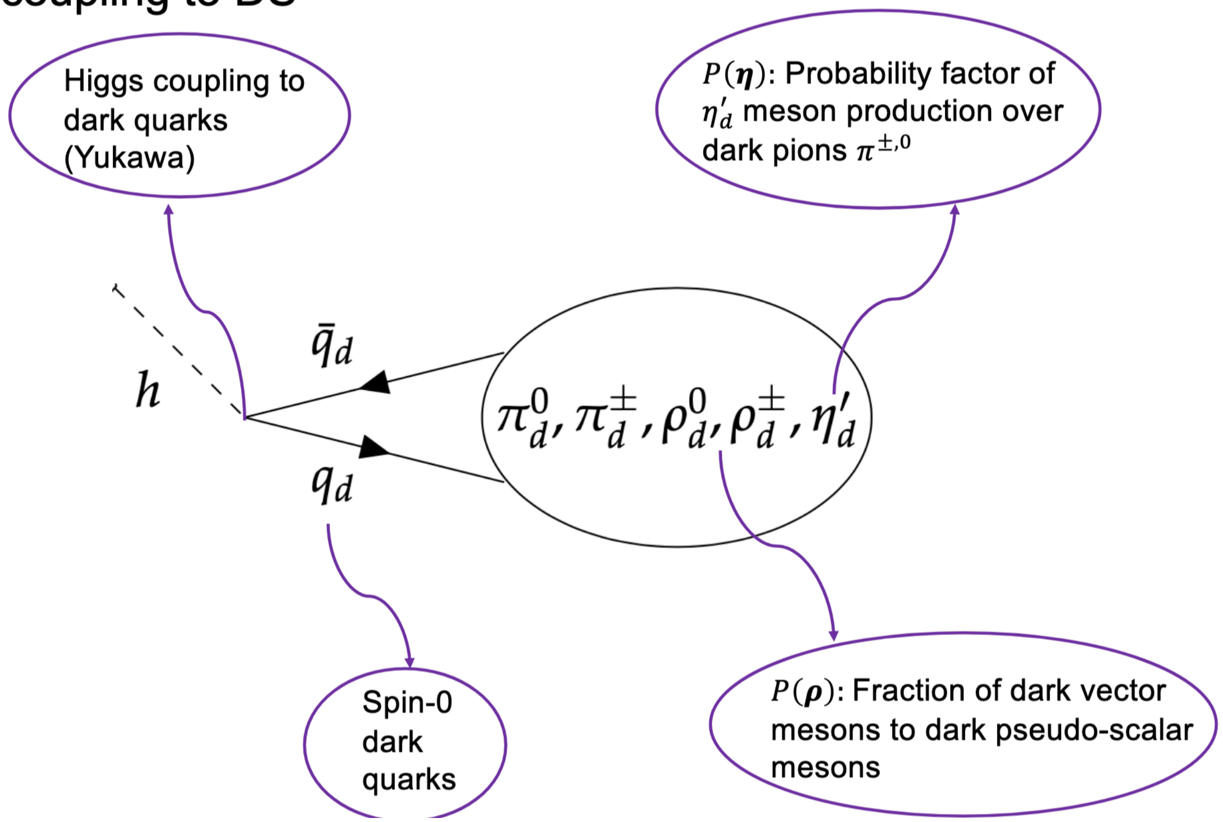
Higgs to Dark Showers

Higgs coupling to DS

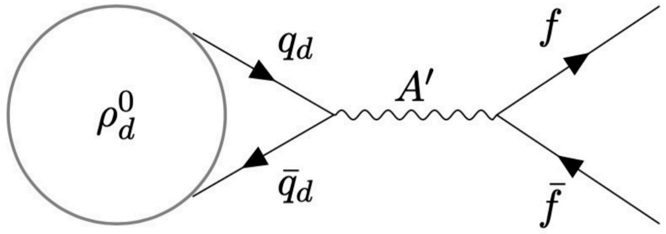


Higgs to Dark Showers

ρ-Decay

$$\Gamma(\rho_d^0 \to q\bar{q}) = N_c \times \frac{\kappa^2 e^2 m_{\rho_d^0}}{12\pi}\left(1 + 2\frac{m_q^2}{m_{\rho_d^0}^2}\right)\sqrt{1 - 4\frac{m_q^2}{m_{\rho_d^0}^2}}.$$

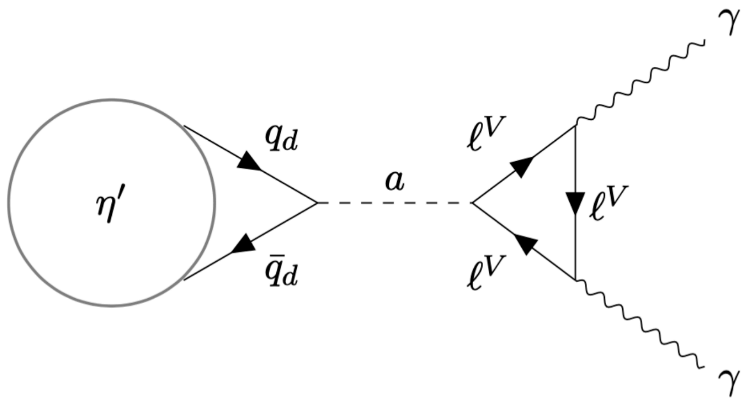
$$\Gamma(\rho_d^0 \to \ell^+\ell^-) = \frac{\kappa^2 e^2 m_{\rho_d^0}}{12\pi}\left(1 + 2\frac{m_\ell^2}{m_{\rho_d^0}^2}\right)\sqrt{1 - 4\frac{m_\ell^2}{m_{\rho_d^0}^2}}.$$



- N_C: Number of QCD colors
- κ: The mixing parameter
- q_f: The fermion charge
- m_q: SM Quark mass
- m_l: SM Lepton mass
- $m_{\rho_d^0}$: ρ_d^0 mass
- e: Electric charge

η' -Decay

$$\Gamma(\eta'_d \to \gamma\gamma) = \frac{\alpha^2}{256\pi^2}\frac{m_{\eta'_d}^3}{f_{\eta'_d}^2}.$$



- α : Fine structure constant
- $m_{\eta'_d}$: Mass of η'_d
- $f_{\eta'_d}$: η'_d decay constant

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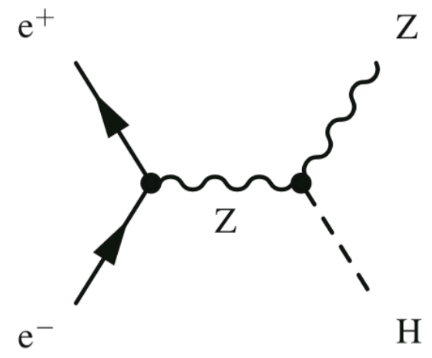
Higgs to Dark Showers

Analysis & Selections

- Backgrounds: **ZZ, Z$\mu\mu$H, WW**
  - similar signatures, need to be carefully differentiated from the signal
- ***Selections:***
  - **Cut 1** : 2 OS muons with $E \geq 10$ GeV and $\eta < 2.4$
  - **Cut 2** : Veto isolated electrons with $E \geq 10$ GeV and $\eta < 2.4$
  - **Cut 3** : Dimuon mass window > 89 GeV and < 92 GeV
  - **Cut 4** : At least two jets with $E \geq 10$ GeV and $\eta < 2.4$
  - **Cut 5** : Higgs recoil mass > 120 GeV and < 130 GeV
    - $M_{rec}^2 = \left(s - E_{ff}\right)^2 - \left|\vec{p}_{ff}\right|^2$



Mass Reflects Higgs Decays: The jet mass provides direct information about Higgs boson decay products, especially for hadronic decays like $H \rightarrow$ bbar, making it crucial for Higgs reconstruction.
Recoil Mass for Background Rejection Recoil mass is more suited for rejecting backgrounds, isolating events like Zh, but does not directly contribute to reconstructing the Higgs properties.

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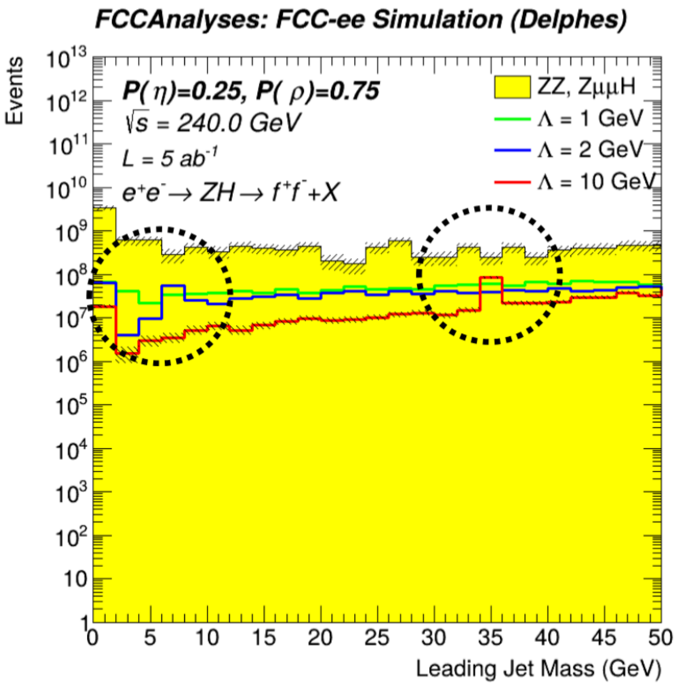
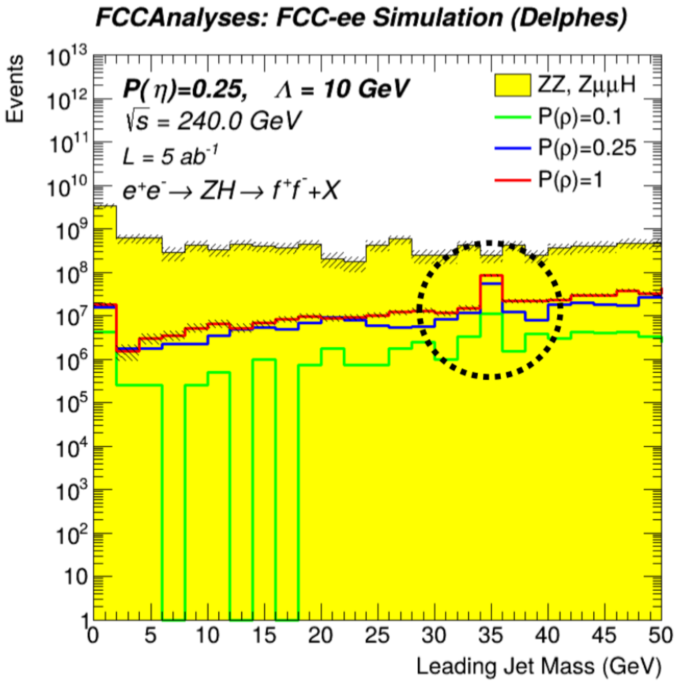
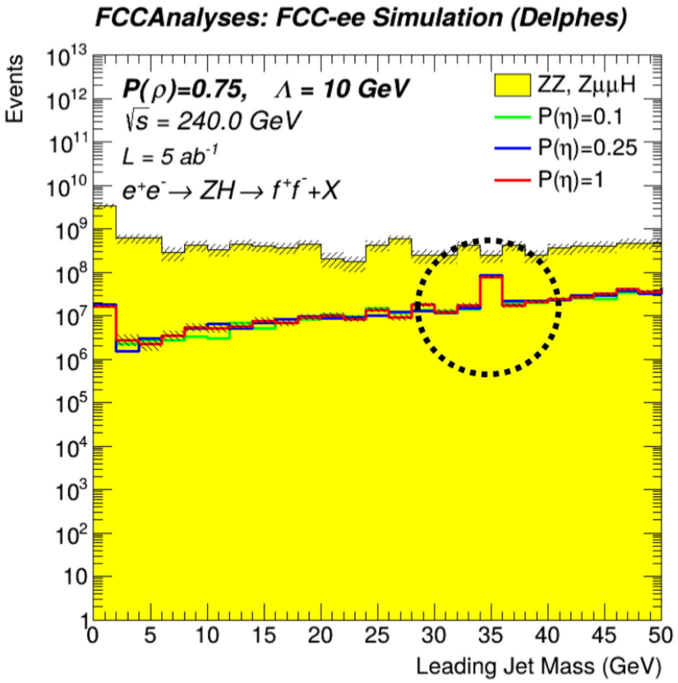
Higgs to Dark Showers

Leading Jet Mass







Lattice QCD: $\frac{m_{\pi_d^0}}{\Lambda} = 2$, $\Lambda = 10\ \mathrm{GeV} \rightarrow m_{\rho_d^0} = 34.3\ \mathrm{GeV}$

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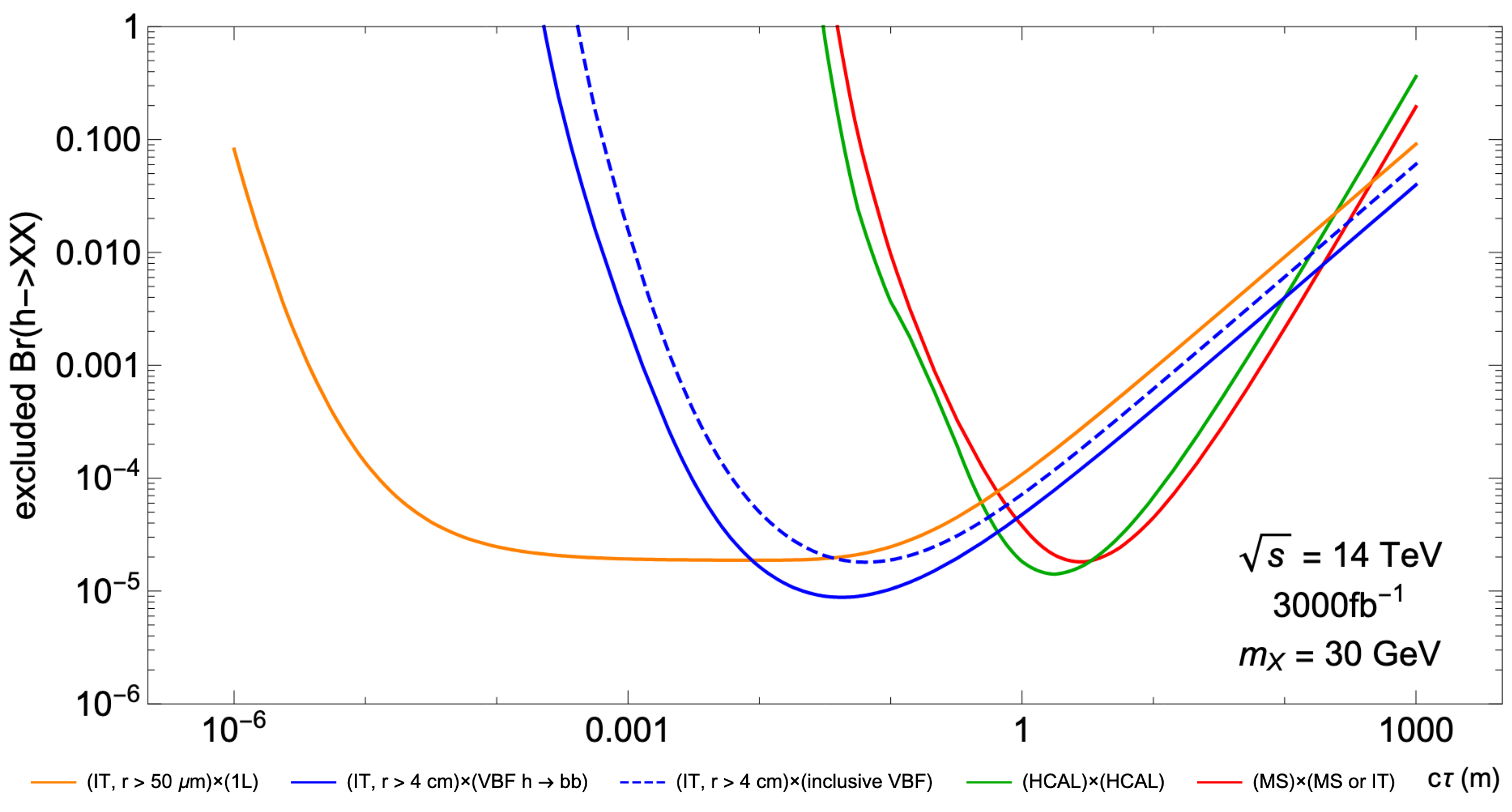
Projected HL-LHC limits for exotic Higgs decays



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