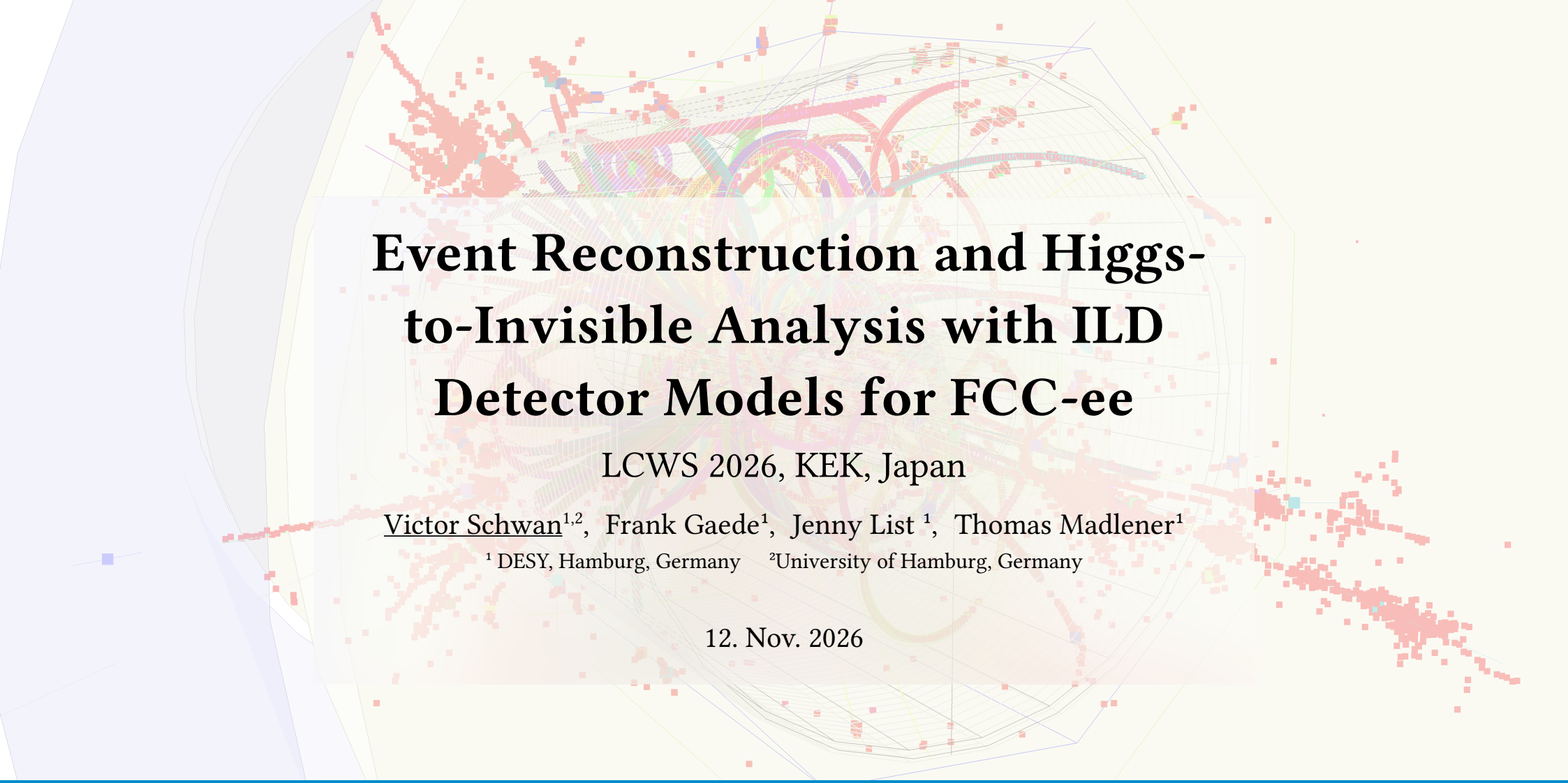


Event Reconstruction and Higgs-to-Invisible Analysis with ILD Detector Models for FCC-ee

LCWS 2026, KEK, Japan

Victor Schwan[1,2], Frank Gaede[1], Jenny List [1], Thomas Madlener[1]

[1] DESY, Hamburg, Germany [2]University of Hamburg, Germany

12. Nov. 2026

FCC ILD DESY. Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG HELMHOLTZ CLUSTER OF EXCELLENCE QUANTUM UNIVERSE PIER Partnership of University of Hamburg and DESY EAJADE Europe-America-Japan Accelerator Development Exchange Programme

Outline

Adapting ILD to FCC

Motivation: Higgs to Invisible

Recoil Mass: ILC vs FCC-ee

Comparison of Experimental Environments

	ILC250	**FCC-ee240**
B field	3.5 T	2 T
Half crossing angle	7 mrad	15 mrad
L*	4.1 m	2.4 m
$\sqrt{s}$ @ ZH	250 GeV	240 GeV
Beam polarisation	$P(e^-, e^+) = (\mp 0.8, \pm 0.3)$	none
Integrated luminosity	2 ab^{-1}, of which 0.9 ab^{-1} each for $(-0.8, +0.3)$ and $(+0.8, -0.3)$	10.8 ab^{-1} (4 Detectors)

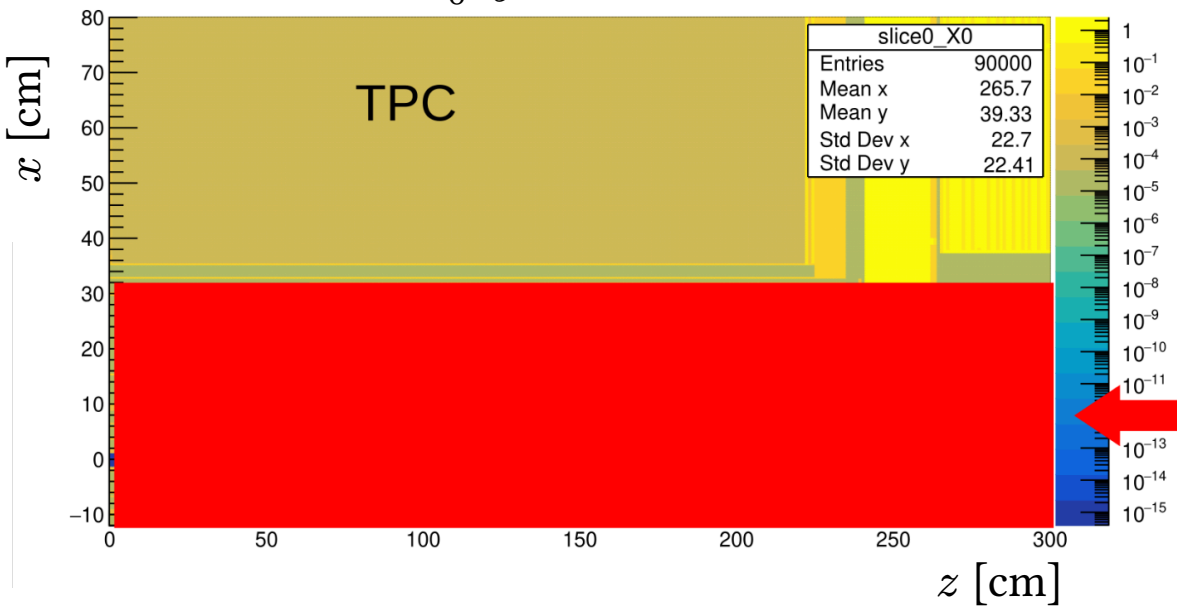
L*: distance from the interaction point to the first final-focus quadrupole

Birth of ILD@FCC

ILD@ILC

- ILC MDI
- Hybrid tracking layout

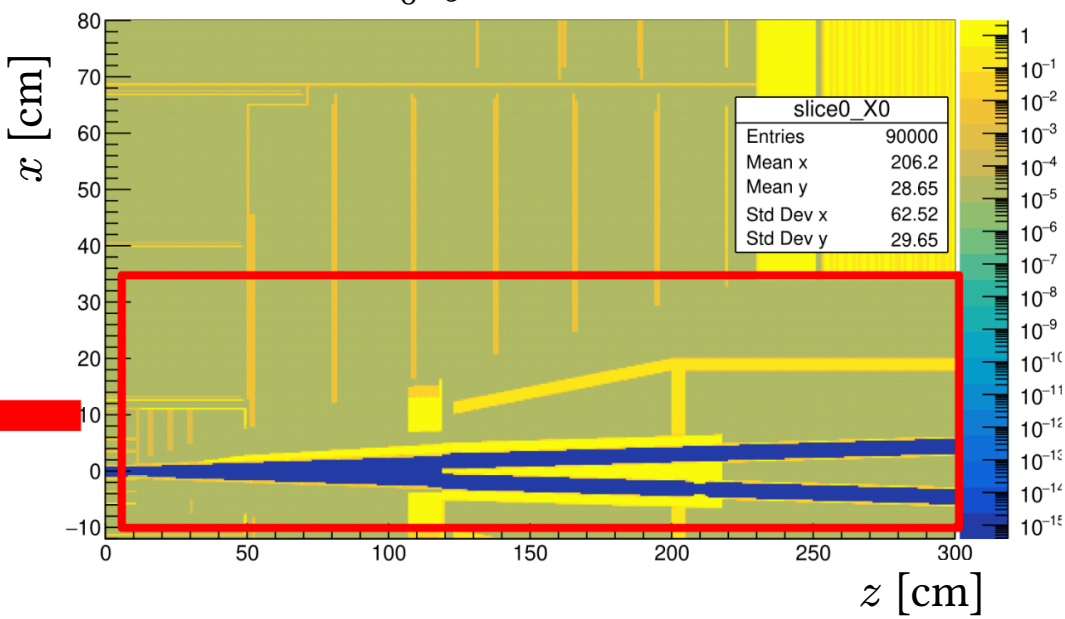
X_0, $y = 0.010$ cm



CLD@FCC

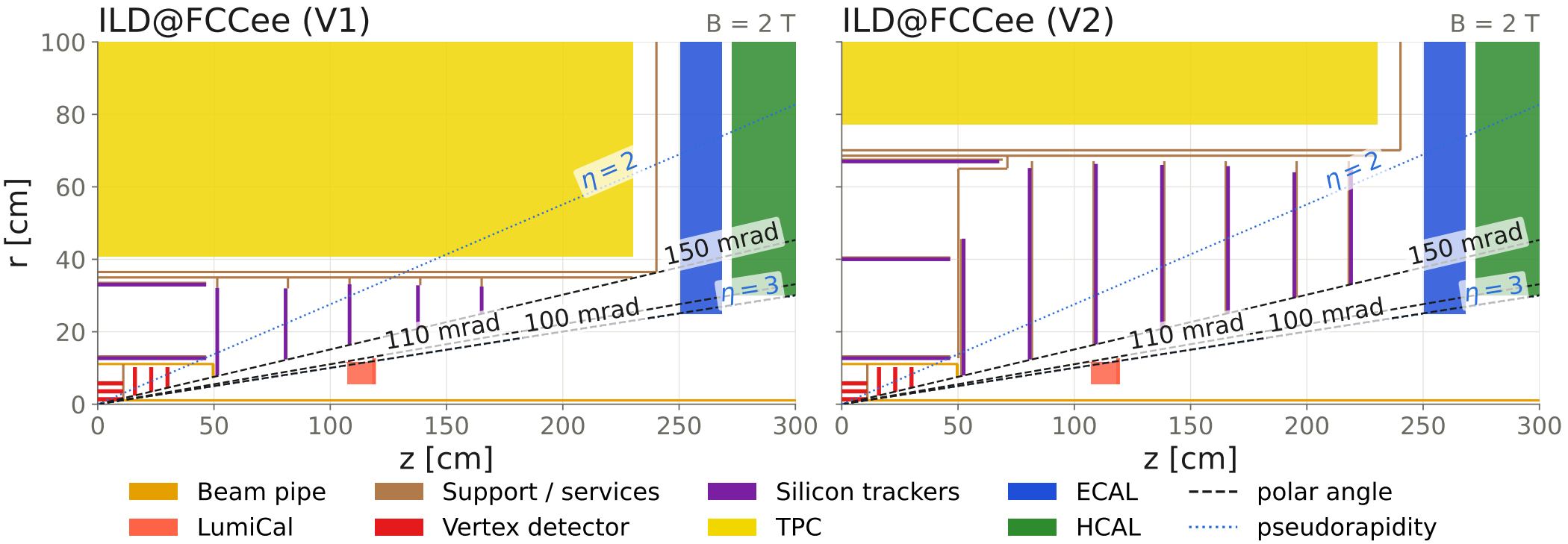
- FCC-ee MDI
- All-silicon tracking

X_0, $y = 0.010$ cm



Ansatz:
1) Remove everything inside of the TPC from ILD
2) Replace with CLD subdetectors

ILD@FCC Detector Models



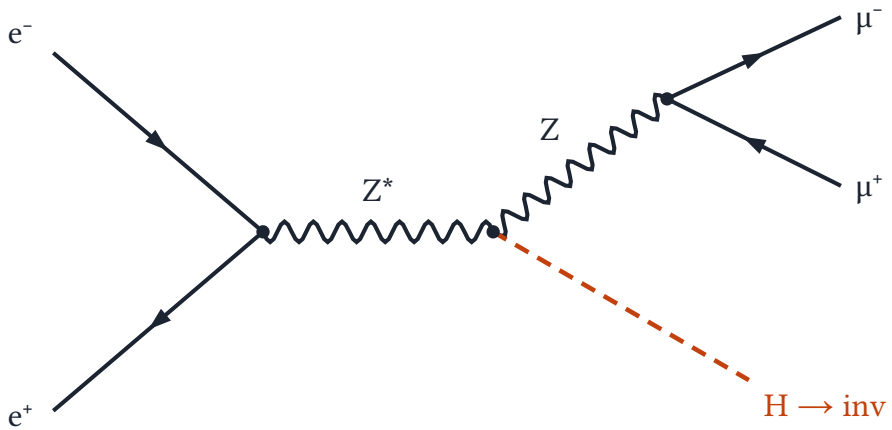
- CLD: 150 mrad stay-clear cone ⟹ silicon up to this line
- Feasibility Study: Interaction Region report [1]:
  - Machine within 100 mrad (hermeticity)
  - Free LumiCal view ⟹ detector elements > 110 mrad
- ECal: cone ⟶ cylindrical stay-clear volume
- Under study: higher solenoid field, magnetic compensation schemes
- MDI still under active development ⟹ fine-tune ILD models to a mature design with good BIB mitigation

Motivation: H ⟶ Invisible

- SM: BR($H \rightarrow \text{inv}$) ≈ 0.106 % [2]
  ($H \rightarrow ZZ^* \rightarrow 4\nu$)
- Enhancement ⟹ new physics
  (Higgs portal, dark matter: e.g. IDM)
- Sensitivity to MDI
- LHC, 95 % CL upper limits:

	Obs.	**Exp.**
ATLAS [3]	10.7 %	7.7 %
CMS [4]	15 %	8 %
HL-LHC [5], [6]	–	≈ 2.5 %

- e^+e^- Higgs factory: **recoil method** tags ZH independently of the Higgs decay
  ⟹ UL $\mathcal{O}(0.1\%)$, SM rate within reach:
  25 % [7] … 63 % [8] relative precision



Discrepancies Between Previous Analyses

Study	Sim.	$\sqrt{s}$ [GeV] / $\mathcal{L}$ [ab^{-1}]	Method	ee / $\mu\mu$	qq	Comb.
ILD@ILC [9]	full	250 / 2×0.9 pol.	cuts	0.57 ($\ell\ell$)[a]	0.25	**0.23**
SiD@ILC [10]	full	250 / 2×0.9 pol.	BDT	0.33 / 0.27	0.25	**0.16**
CEPC [8]	full+fast	240 / 5.6	cuts	0.96 / 0.31	0.29	**0.24**
CLD@FCC [11]	full	240 / 10.8	cuts	1.1 / 0.47	0.67	**0.28**[b]
IDEA@FCC [7]	Delphes	240+365 / 10.8+3	–	–	best	**0.052**[c]
IDEA@FCC [12]	Delphes	240 / 10.8	BDT	0.43 / 0.35	0.15	**0.15**

95 % CL expected upper limits on BR($H \to$ inv) in %. [a] leptonic result taken from an earlier ILD study; [b] headline value of the text, per-channel table 0.47–1.1 %; [c] stat. only, 5σ for BR > 0.13 %.

- **Fast vs. full (FCC)**: Delphes 0.052 % ⟶ CLD full sim 0.28 % (≈ ×5)
  ECAL resolution in fast sim too optimistic, PFA m_{vis} shift, brems. recovery needed [11]

- **Background lists differ**: 3f $e\gamma \to eZ, \nu W$ = 36–39 % of SiD qq bkg; not in ILD (2f+4f+H) nor in IDEA@FCC study
- **Own estimate**, $\sqrt{\mathcal{L}}$ scaling to 10.8 ab^{-1}: ILD ≈ 0.09 %, CEPC ≈ 0.17 %
  (optimistic: no polarisation at FCC ⟶ WW not suppressed)

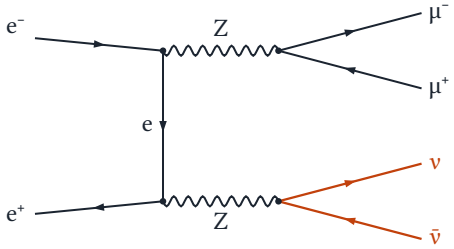
⟹ No consistent FCC expectation yet (0.05–0.28 %)

⟶ **ILD@FCC** full-sim study: complete background set, common statistical treatment

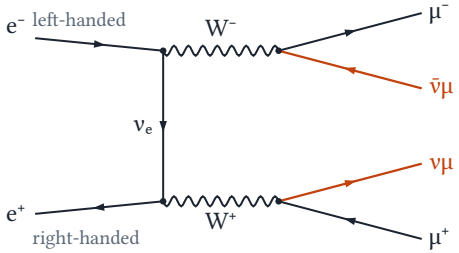
Dominant Backgrounds

$\mu\mu$ channel — reducible after p_T, $m_{\mu\mu}$, lepton-veto cuts except $\mu\mu\nu\nu$

$\mu\mu\nu\nu$

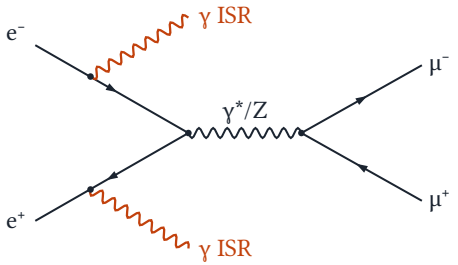


ZZ: irreducible



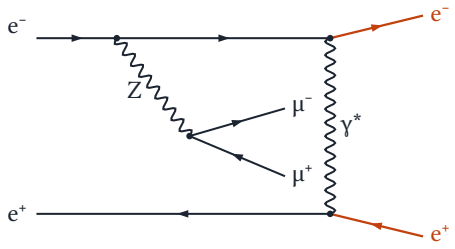
WW: mostly only for $e_L^- e_R^+$

$\mu\mu(\gamma)$



radiative return,
$p_T \approx 0$

$ee\mu\mu$



forward electrons lost,
usually 3–4 isolated leptons

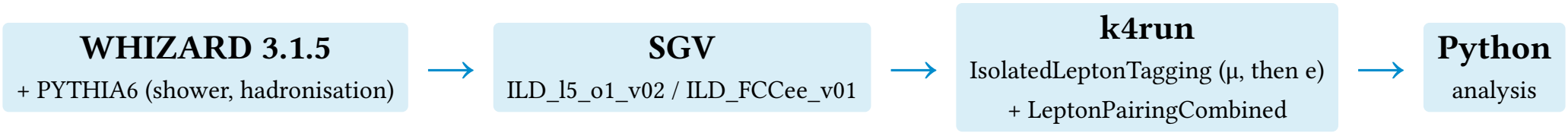
***ee* channel**

- weakest channel
- additional t-channel diagrams: single-boson eeZ ($Z \to \nu\nu$) and $e\nu W$ ($W \to e\nu$), 13 and 23 % of background @ SiD [10]
- radiation ⟶ wider windows than $\mu\mu$, e.g. M_{rec} 120–170 vs 120–150 GeV CEPC [8]

***qq* channel**

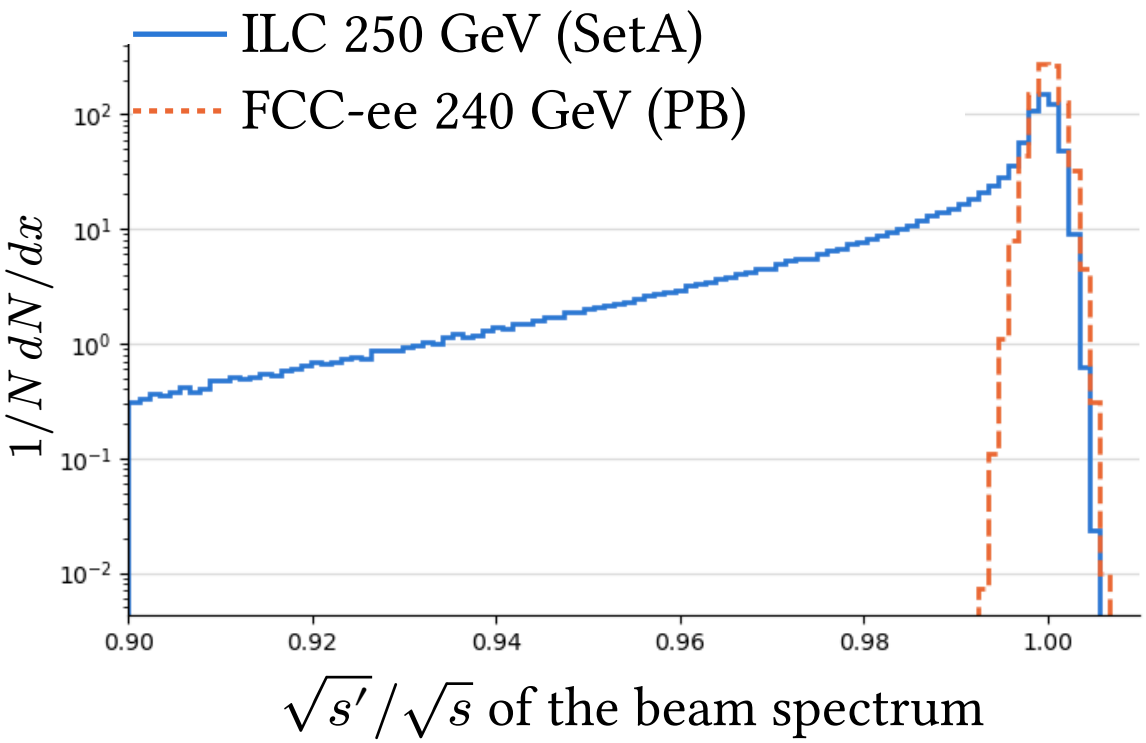
- provides the strongest constraint
- owing to the large Z ⟶ qq̄ branching fraction (70% vs 3.4% for leptons)
- for completeness: (SiD, after loose BDT, $e_L^- e_R^+$ / $e_R^- e_L^+$) [10]:
  3f $e\gamma \to eZ, \nu W$: 36 / 39 %, $WW \to \ell\nu qq$: 27 / 3 %,
  $\nu\nu Z$: 21 / 18 %, $ZZ \to \nu\nu qq$: 12 / 33 %

Simulation Chain



- Beam spectra from ECFA study based on 2025 machine designs:
  ILC SetA (250 GeV), FCC-ee 2025 ZH (240 GeV, IP PB) [13]
- ILC vs FCC differences: $\sqrt{s}$, beam spectrum, crossing angle, detector model

Bare Beam Spectra from the `circe2` Files



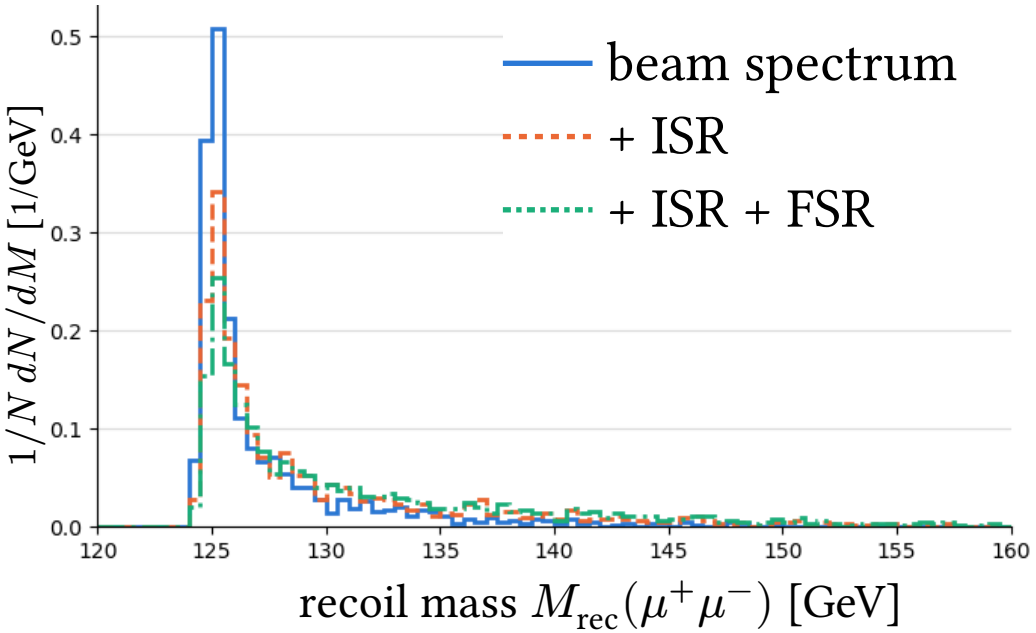
- Sampled directly from the circe2 files (`circe2_generate`): **no cross-section weighting**; FCC-ee: [13]

	ILC	FCC-ee
spread e^- †	0.18 %	0.19 %
spread e^+ †	0.15 %	0.19 %
mean loss / beam	1.1 %	0.0 %
$x < 0.9$	1.0 %	0.0 %
lowest x	0.627	0.993

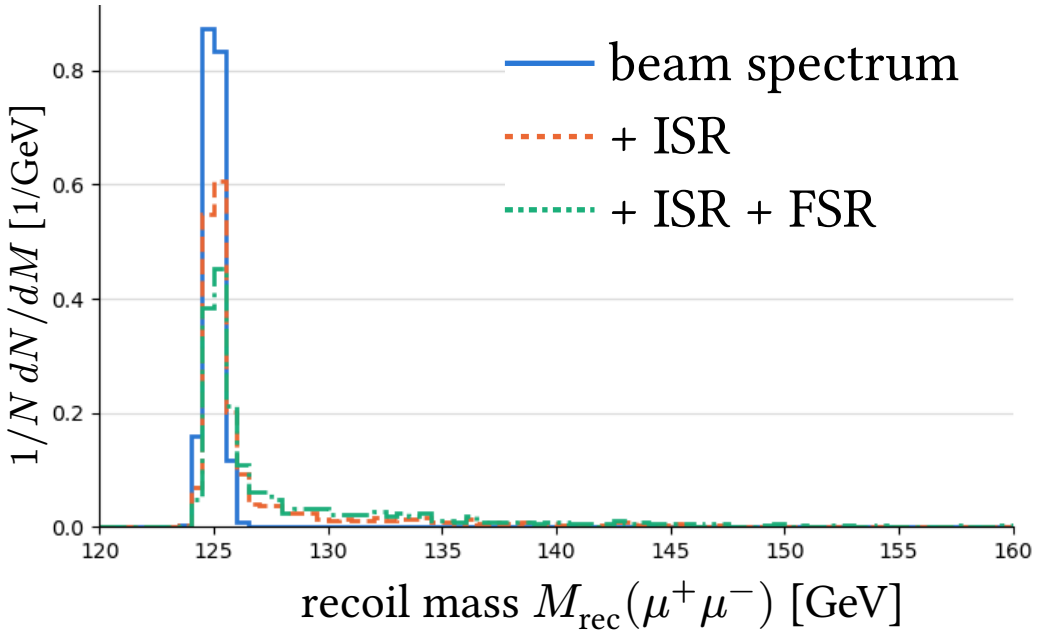
† energy spread: RMS of the part above nominal energy (beamstrahlung only lowers the energy)

Truth Level Recoil Mass Step by Step

ILC



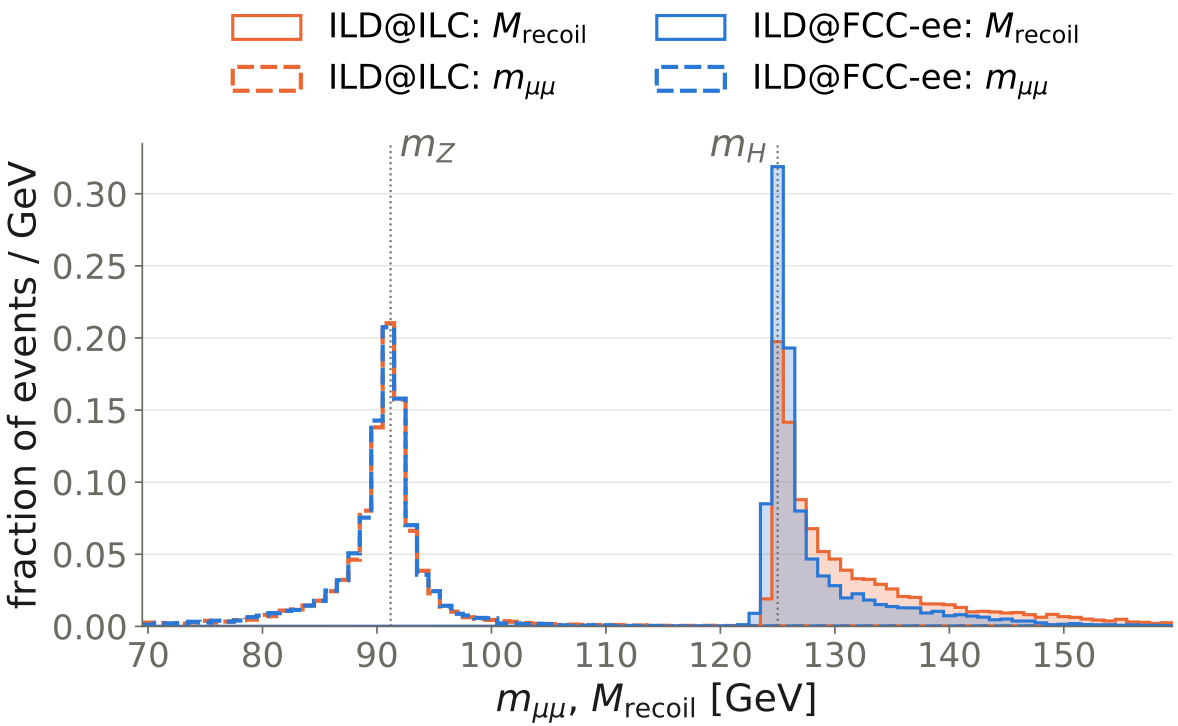
FCC-ee



- Starting with bare beam spectrum, adding ISR and lastly also FSR
- FSR recovery promising

$\lvert M_{\text{rec}} - 125\ \text{GeV}\rvert < 1\ \text{GeV}$	**Beam spectrum**	**+ ISR**	**+ ISR + FSR**
ILC	59 %	40 %	30 %
FCC-ee	99 %	71 %	55 %

SGV Event Reconstruction

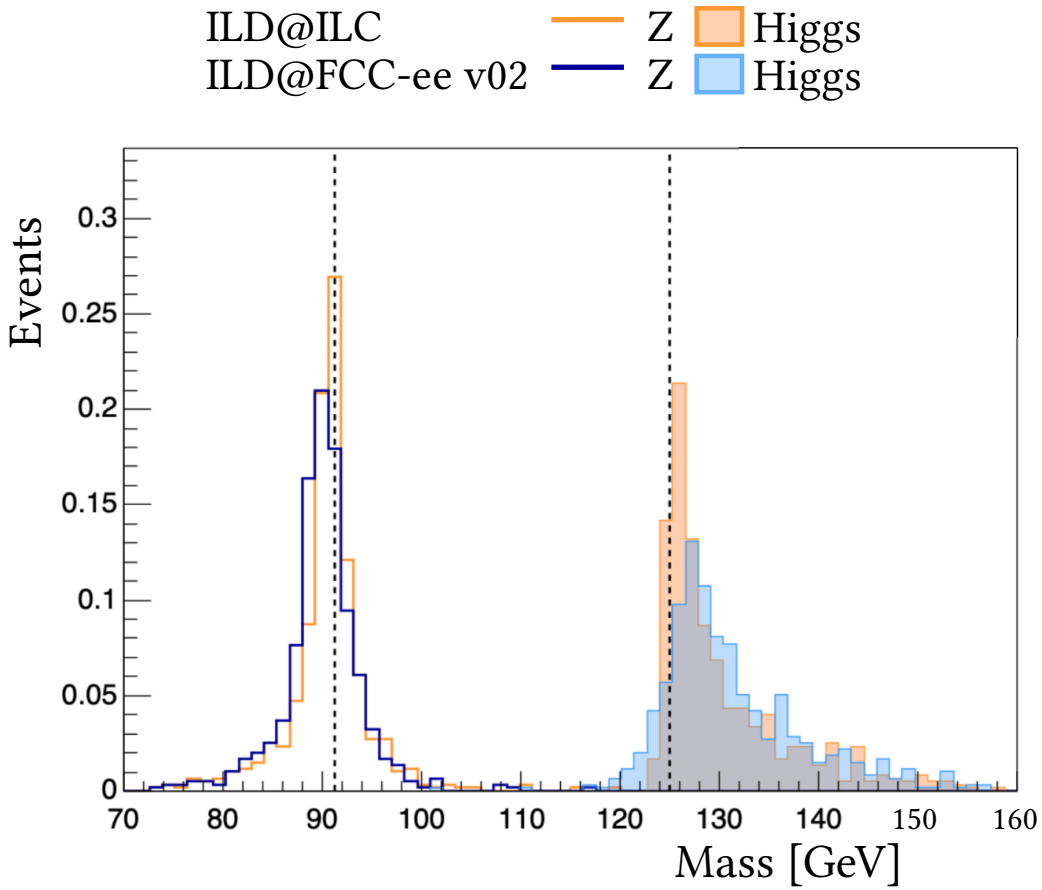


SGV, $ZH \to \mu\mu + \text{inv}$, events with a $\mu^+\mu^-$ pair; ILC 250 GeV eL.pR (ILD_l5_o1_v02), FCC-ee 240 GeV (ILD_FCCee_v01); normalised

	ILC	**FCC-ee**
Events losing > 0.5 % of $\sqrt{s}$	38 %	0 %
Spread of $\sqrt{s'}$ (core)	0.16 %	0.13 %
M_{rec} peak FWHM: truth → reco	1.2 → 1.5 GeV	1.0 → 1.6 GeV
$\lvert M_{\text{rec}} - 125\ \text{GeV}\rvert < 1$ GeV	30 %	50 %
$M_{\text{rec}} > 140$ GeV	15 %	6 %

- $m_{\mu\mu}$ alike: $\Gamma_Z \gg$ momentum resolution
- **ILC**: beamstrahlung ⟹ tail, median +2 GeV
- **FCC-ee**: no beamstrahlung; **detector** (2 T) dominates the peak width
- FSR not recovered: doubles the FCC-ee tail (3 → 6 %)

First Full-Simulation Shot



Full simulation, Summer 2026

First $ZH \to \mu\mu + \text{inv}$ in full simulation

- Z peak at m_Z for both detectors
  $\Rightarrow$ tracking, lepton ID and pairing work
- Recoil peak at m_H for both

Known limitations at the time

- ILC beam spectrum also fed into ILD@FCC-ee
  $\Rightarrow$ broadened FCC-ee recoil peak
- Tracking: barrel region only, unoptimized for FCC

Now: FCC-ee beam spectrum in the samples
$\Rightarrow$ narrower FCC-ee tail expected (previous slide)

First shot: full-sim reconstruction works for ILD@FCC-ee, differences understood

Plot: Fatma Tekaslan

Summary & Outlook

Summary

- ILD@FCC-ee models in `k4geo` & SGV, SGV geometry check against `DD4hep` WIP
- Several analyses done, no consistent expectation for ILD@FCC
- Recoil mass, same chain for both colliders:
  - ILC: beamstrahlung tail
  - FCC-ee: peak width set by the detector (2 T)
- First full-sim shot: reconstruction chain operational for ILD@FCC-ee

Outlook

- Full simulation with the FCC-ee beam spectrum with refined detector models
- FSR / photon recovery for the recoil mass
- Validate SGV momentum resolution against full sim
- Selection and expected limit on BR($H \to$ inv): $\mu\mu$, then ee and qq
- Comparison of physics reach: ILC vs FCC-ee

Thank You for Your Attention!

This work was partially supported by the European Union's Horizon Europe Marie Sklodowska-Curie Staff Exchanges programme under grant agreement no. 101086276.

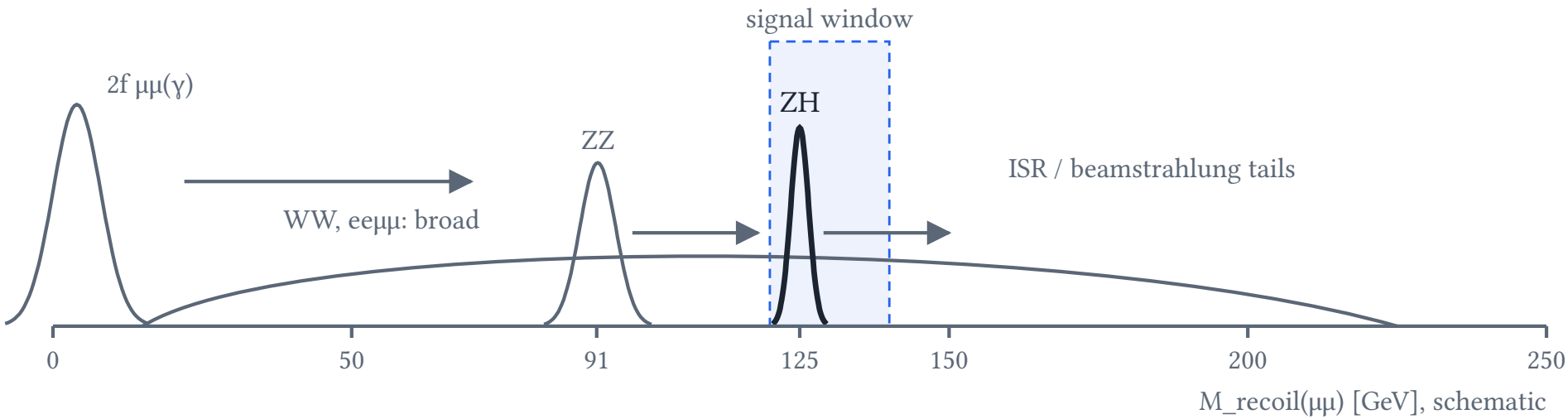
Backup

Recoil Method

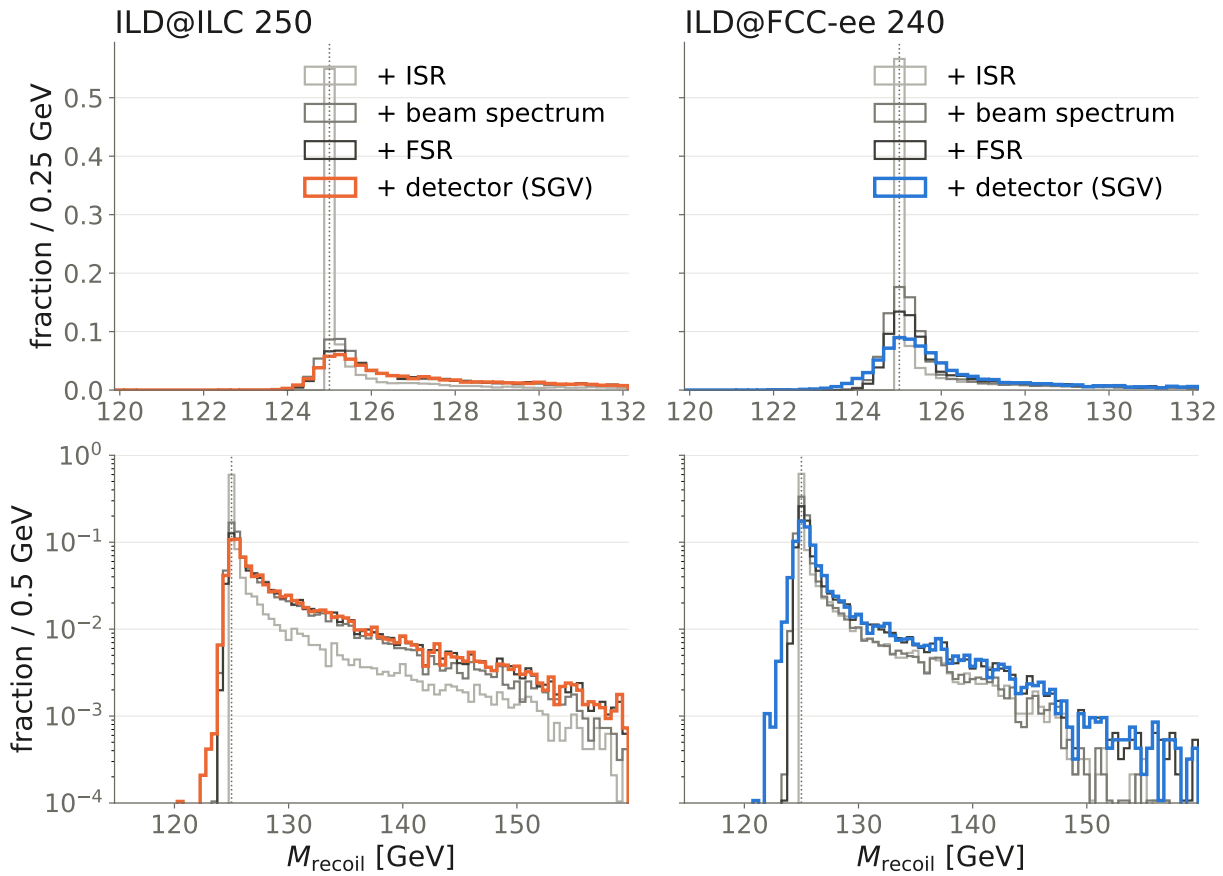
$$M^2_{\text{recoil}} = \left(\sqrt{s} - E_{\mu\mu}\right)^2 - |\vec{p}_{\mu\mu}|^2$$

evaluated with the true initial state, incl. the crossing-angle boost

- Topology: two isolated muons, $m_{\mu\mu} \approx m_Z$, nothing else
- ISR and beamstrahlung shift M_{recoil} upwards



Backup: Recoil Mass incl. Detector, Effect by Effect



SGV signal; '+ ISR' uses the beams after the beam spectrum (generator status 2), all other curves the nominal beams. Top: peak region, bottom: full range (log).

Backup: Lepton Object Definition

IsolatedLeptonTagging (k4run)

- $p > 5$ GeV
- Muons: $E_{\text{cal}}/p < 0.3$
- Isolation MVA with the ILD full-simulation weights
- Applied to SGV **without re-tuning**
- Two passes: muons first, then electrons

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