

Adapting the ILD Detector for HALHF

ILD Meeting @ CERN 16.09.2026

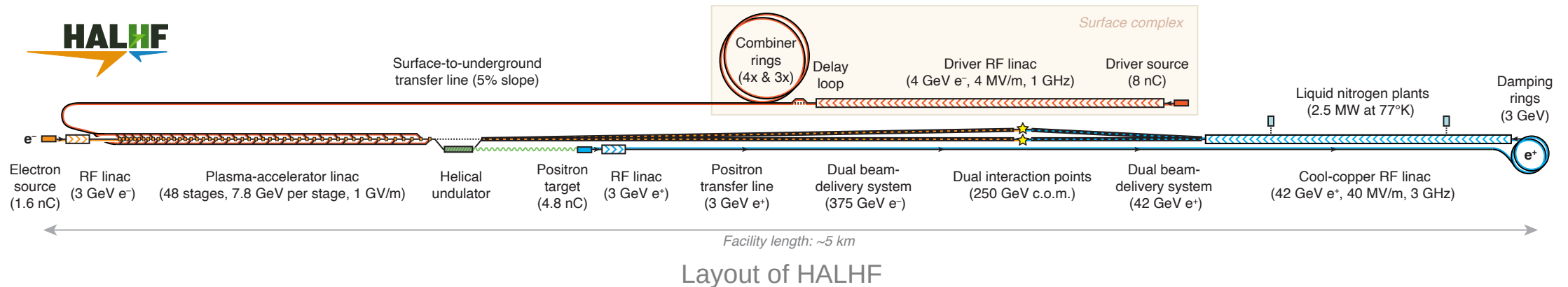
Shriyansh Ranjan, Jenny List, Mikael Berggren, Matthew Wing, Lucy Jane Bishop

Deutsches Elektronen-Synchrotron (DESY)



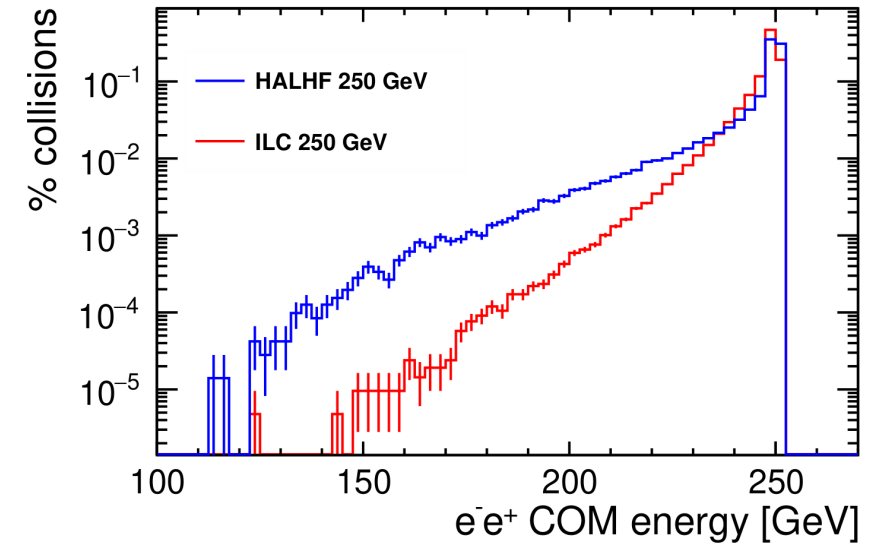
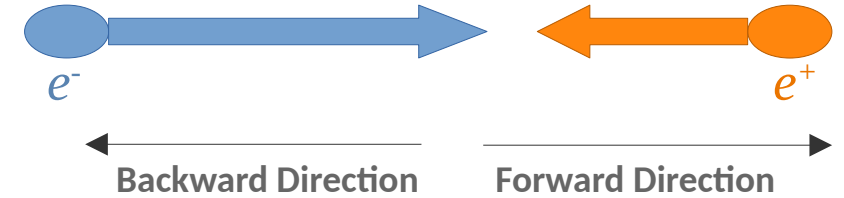
What is Hybrid Asymmetric Linear Higgs Factory (HALHF)?

- Proposed e^+e^- linear Higgs factory to study Higgs potential
- e^- beam (~ 400 to 800 GeV): Plasma Wakefield Acceleration (PWFA)
- e^+ beam (~ 40 to 90 GeV): RF acceleration
- High center-of-mass energy, highly asymmetric collisions



How is HALHF different from other Higgs factories?

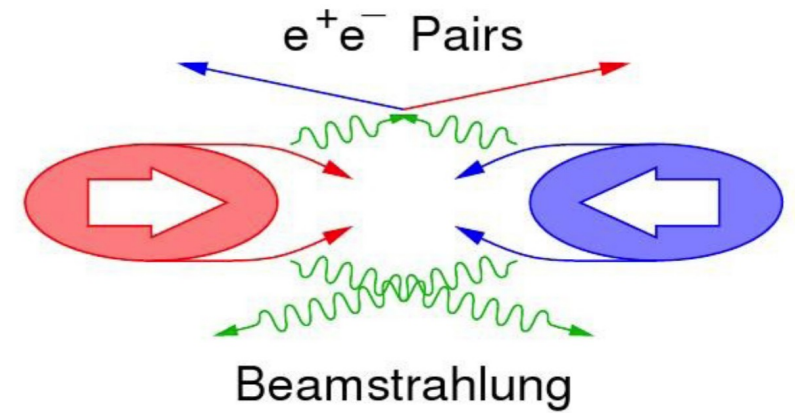
- COM frame **boosted** towards e- beam (forward direction)
 - Increased decay distances of heavy quarks: better tagging efficiencies
- Different **beam-beam interactions** in the two directions
 - Much more e+e- pairs from beamstrahlung in the electron beam direction
- Impacts **energy spectra** and **beam backgrounds**
 - Larger tail of HALHF compared to ILC but also a narrower peak!



e-e⁺ COM Energy Spectrum of
Symmetric and Asymmetric Colliders

Beam-beam effects at HALHF

- Beamstrahlung: Radiation from one beam in the field of the opposite beam
 - Increases energy spread of colliding particles
 - Leads to broad luminosity spectrum

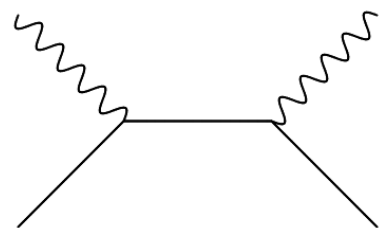
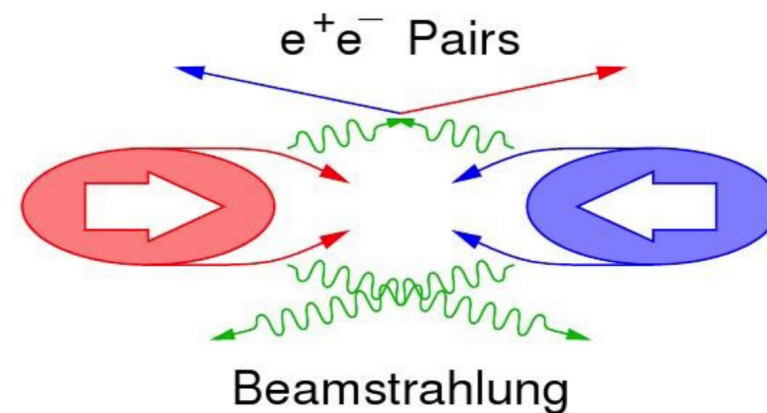


Beam-beam effects at HALHF

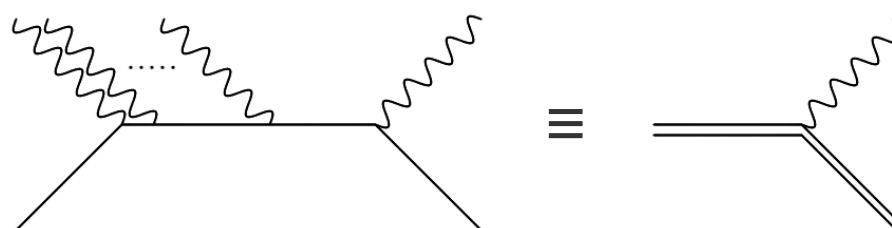
- Beamstrahlung: Radiation from one beam in the field of the opposite beam
 - Increases energy spread of colliding particles
 - Leads to broad luminosity spectrum
- Beamstrahlung parameter χ

$$\chi \approx \Upsilon = \gamma E/E_s$$

E_s : Schwinger Field $\sim 10^{18}$ V/m
Results in vacuum breakdown



Perturbative QED
($\Upsilon \leq 1$)



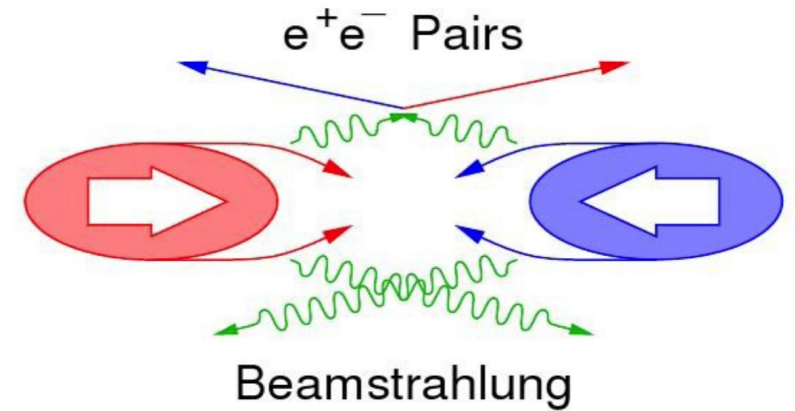
Strong-field QED
($\Upsilon \geq 1$)

Beam-beam effects at HALHF

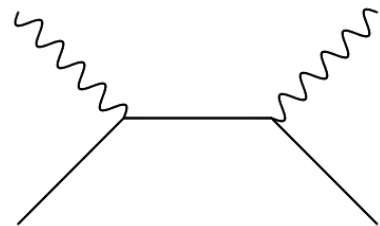
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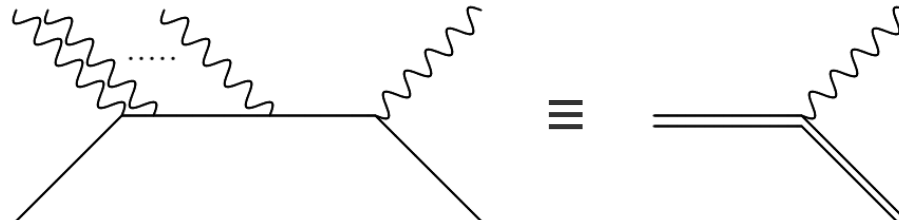
E_s : Schwinger Field $\sim 10^{18}$ V/m
Results in vacuum breakdown



- Using GuineaPIG and WarpX simulation tools to model these processes!



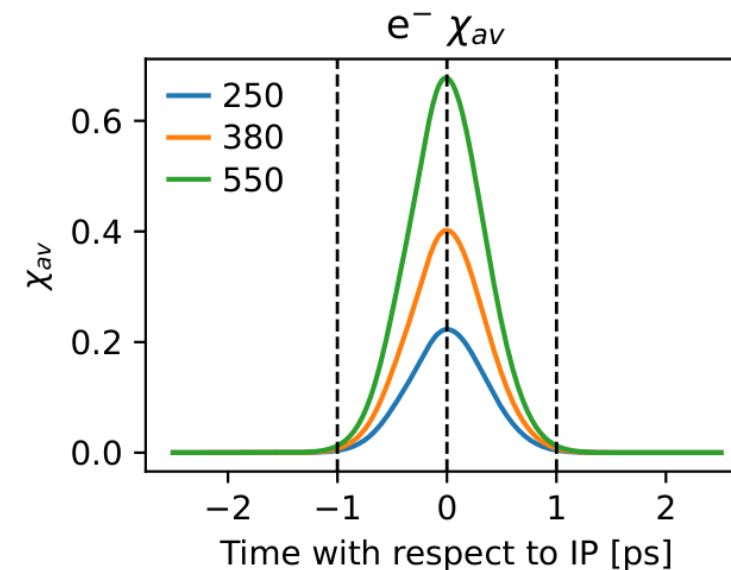
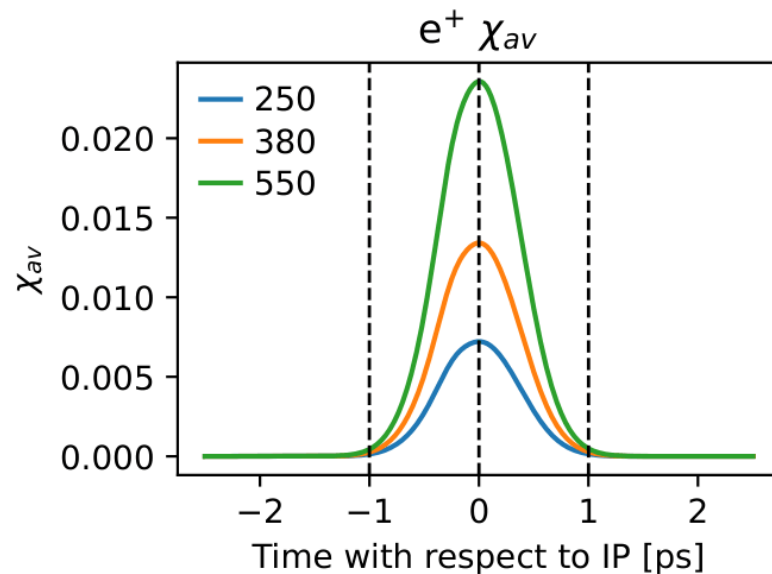
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Strong-field QED
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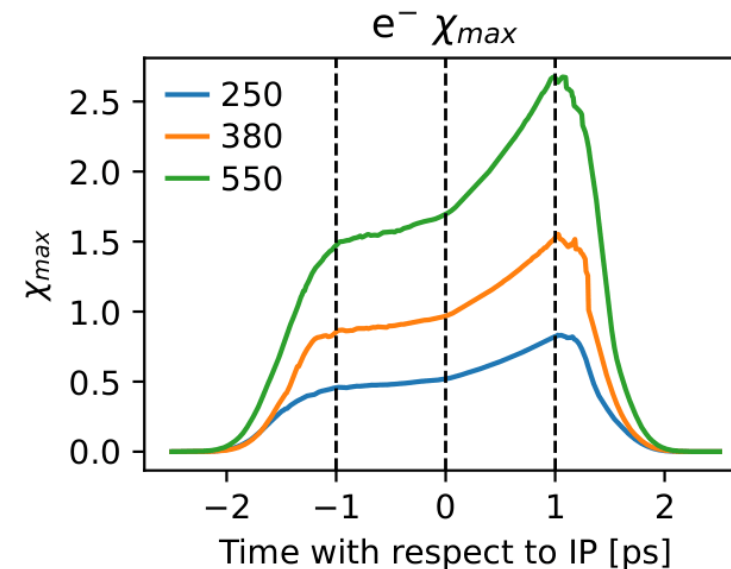
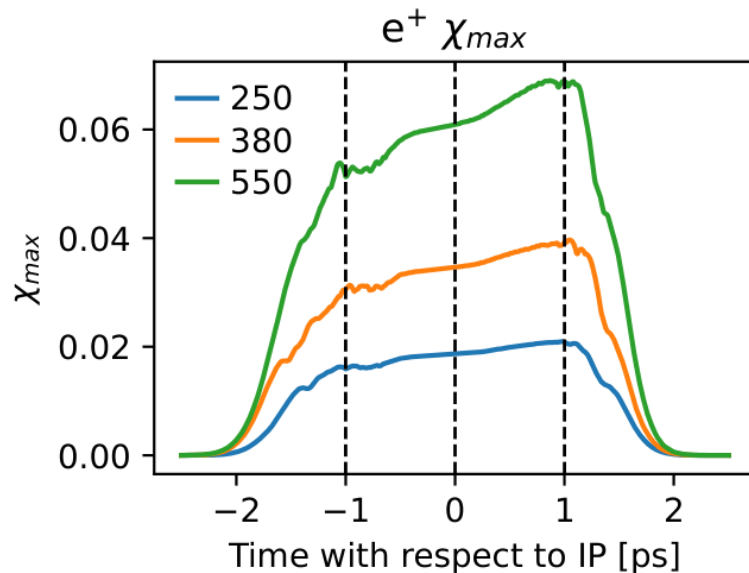
Beamstrahlung Parameter at HALHF collisions

- Evolution of χ during the collision (obtained from WarpX)
- Average χ is symmetric around the IP



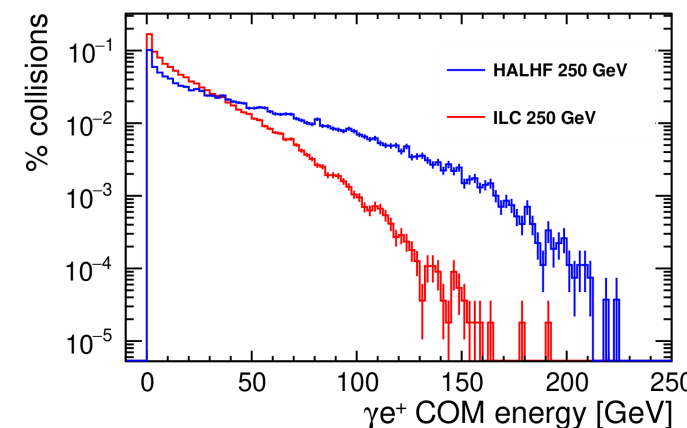
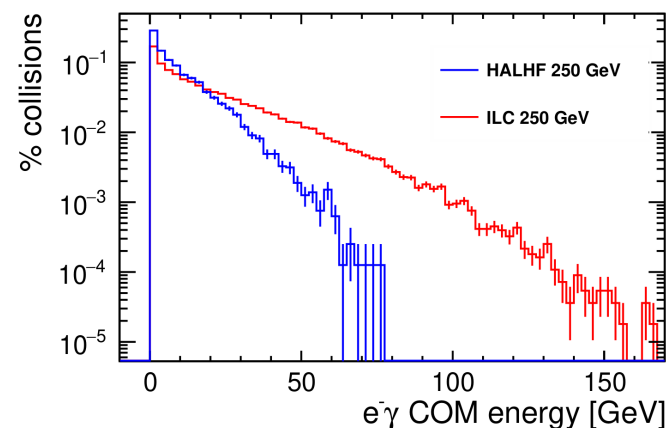
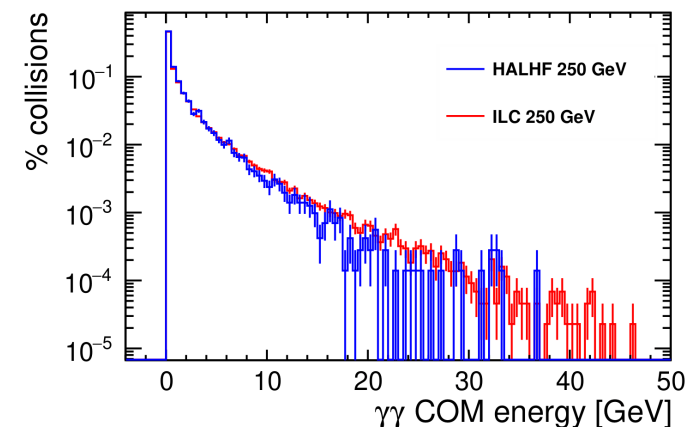
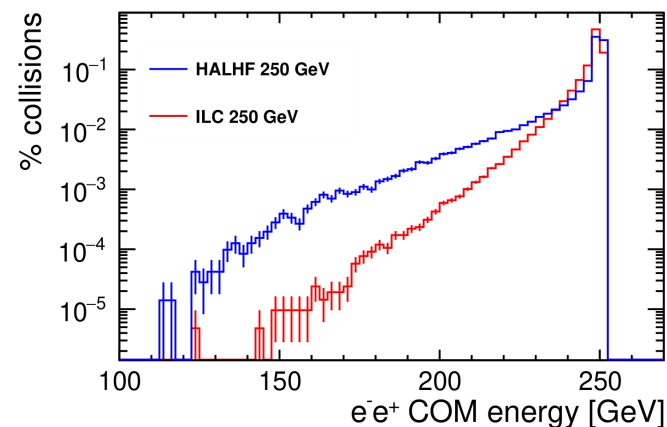
Beamstrahlung Parameter at HALHF collisions

- Evolution of χ during the collision (obtained from WarpX)
- Average χ is symmetric around the IP
- Maximum χ peaks towards the end of the collision!
- Higher overall χ observed by the e- beam due to the asymmetric energies and bunch charges



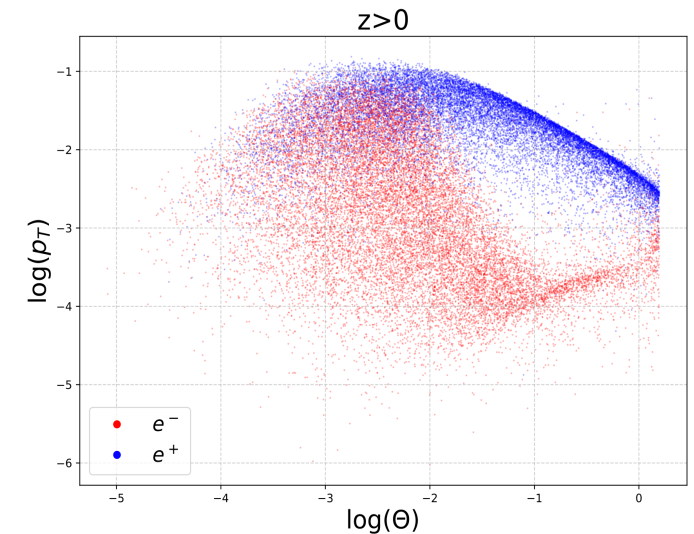
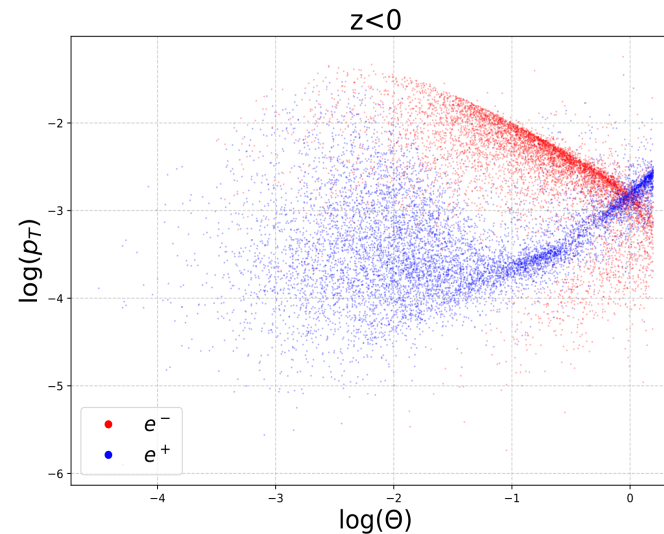
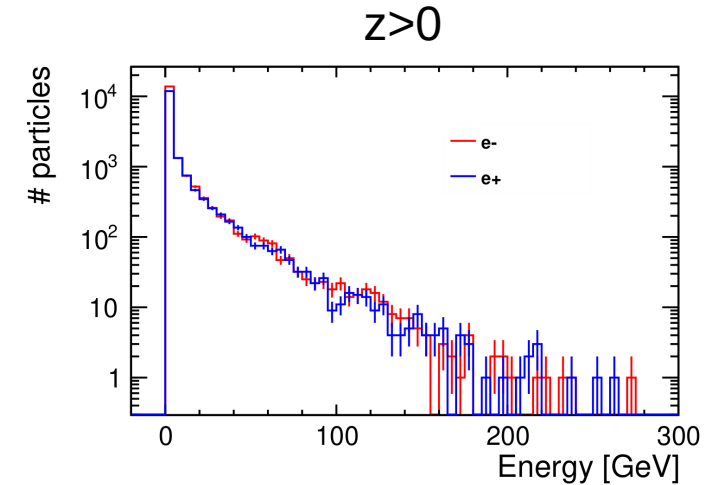
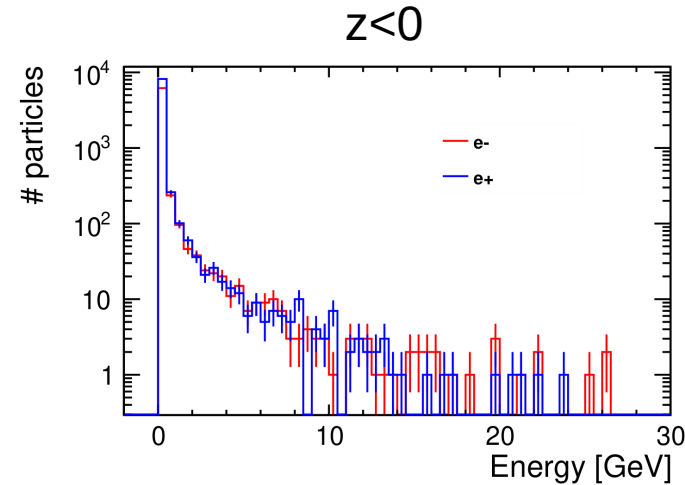
Luminosity Spectra at HALHF

- Luminosity spectra for different interactions during the bunch crossing compared to symmetric configuration (ILC).
- e^-e^+ luminosity has a higher tail but narrower peak
 - Advantage for measurements accounting for COM energies (Higgs recoil-mass)
- $e^-\gamma$ much softer than γe^+
 - Due to different χ parameters observed
- $\gamma\gamma$ luminosity similar to ILC

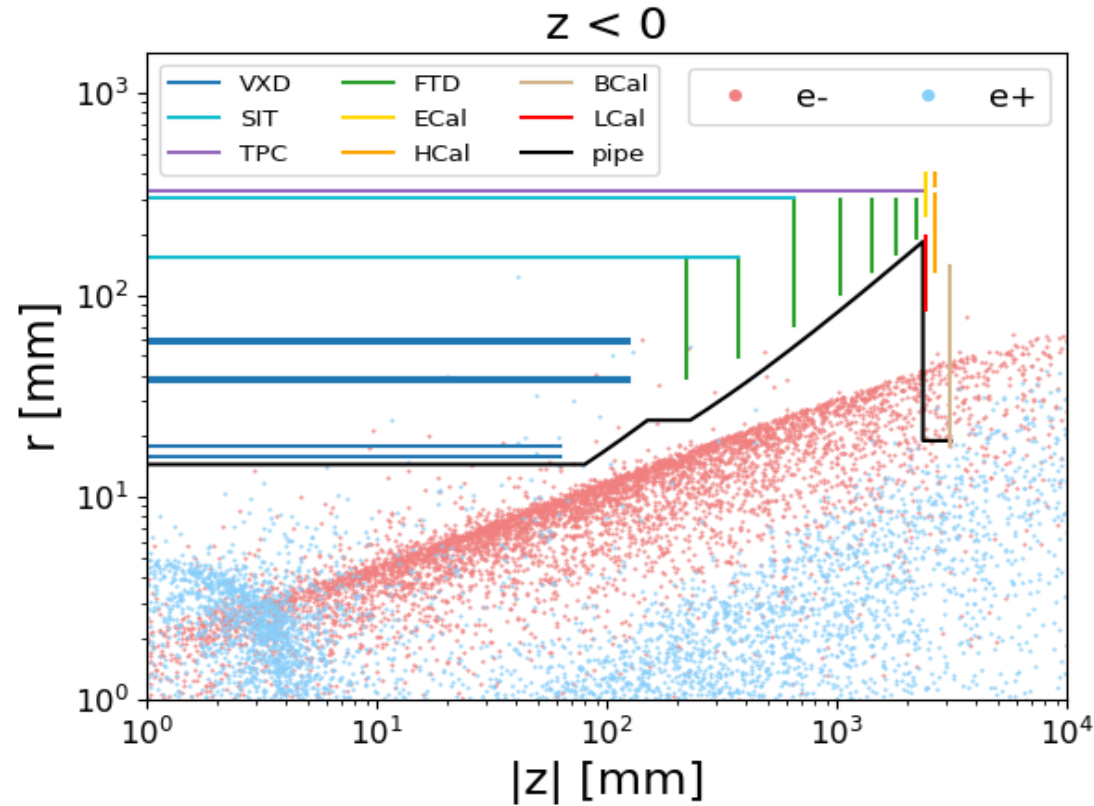


Beam-induced Backgrounds

- e^- and e^+ produced during the beam-beam collision have more energy in the forward direction.
- High p_T and θ pairs might hit the detector instrumentation and saturate it.
- Have to adjust the ILD detector to stay clear of these asymmetric backgrounds while still providing competitive performance!



Impact on Detector Design

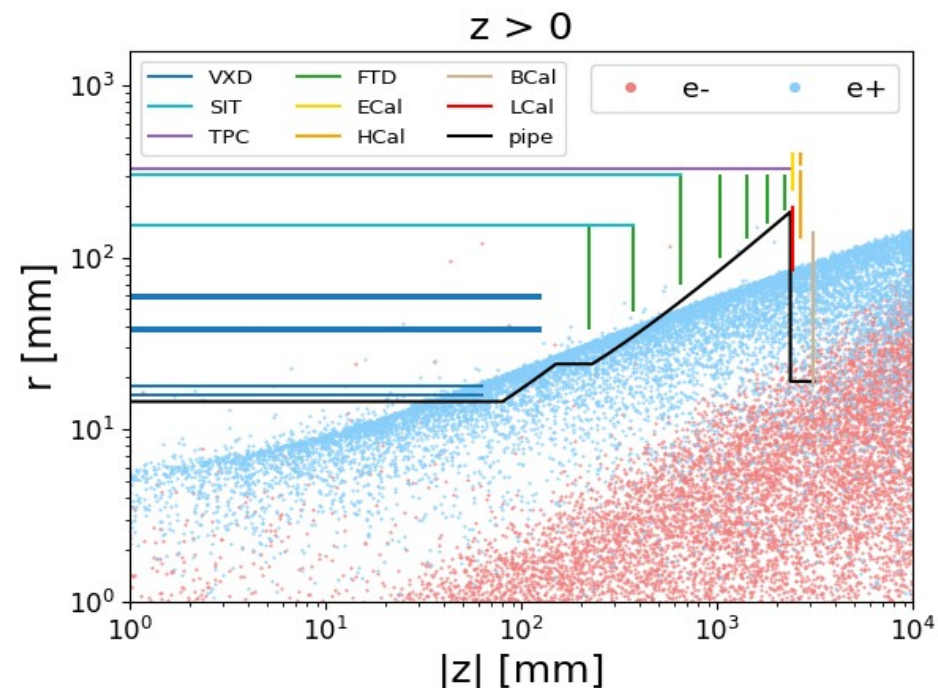
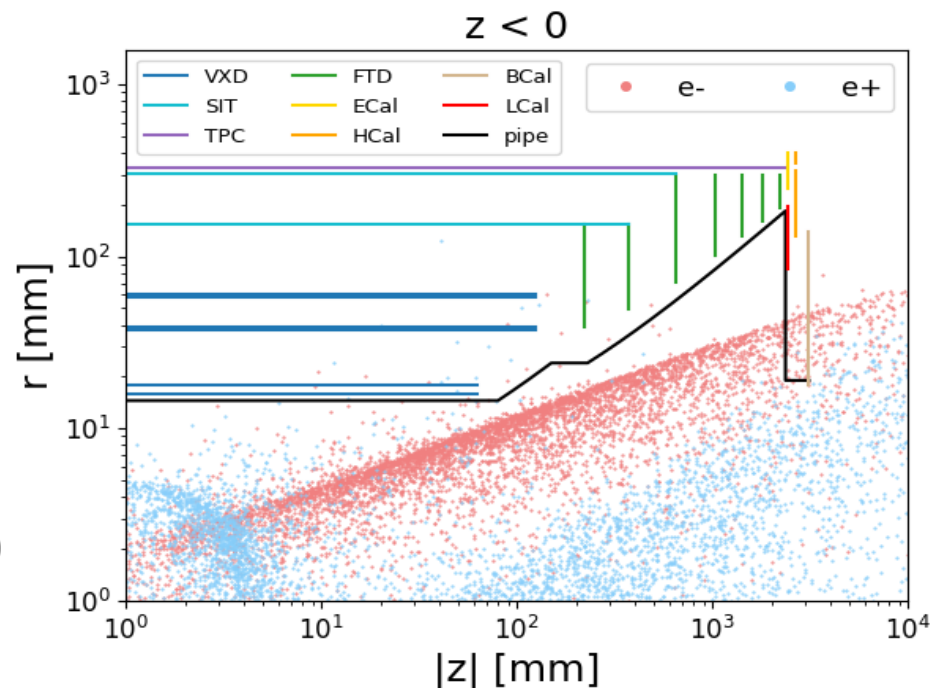


- Pairs produced in 1 bunch crossing
- r and z calculated corresponding to the particle reaching its maximum r (assuming 3.5T magnetic field)
- The symmetric ILD@ILC detector is overlaid

Impact on Detector Design

ILD

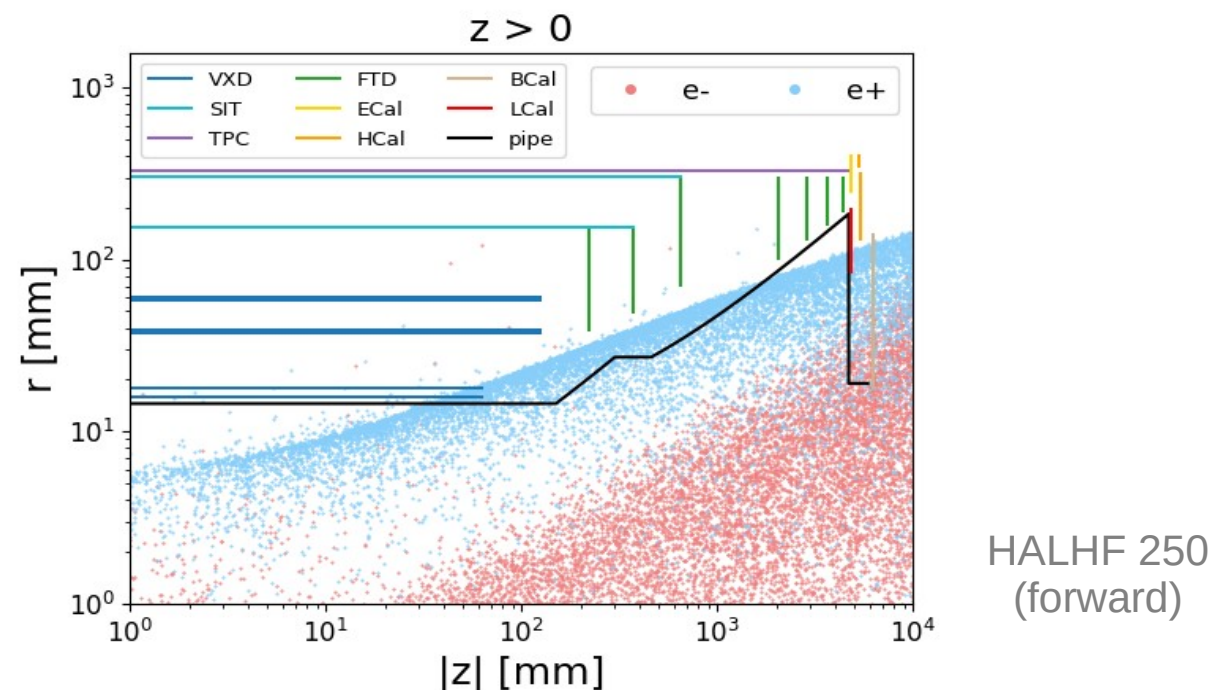
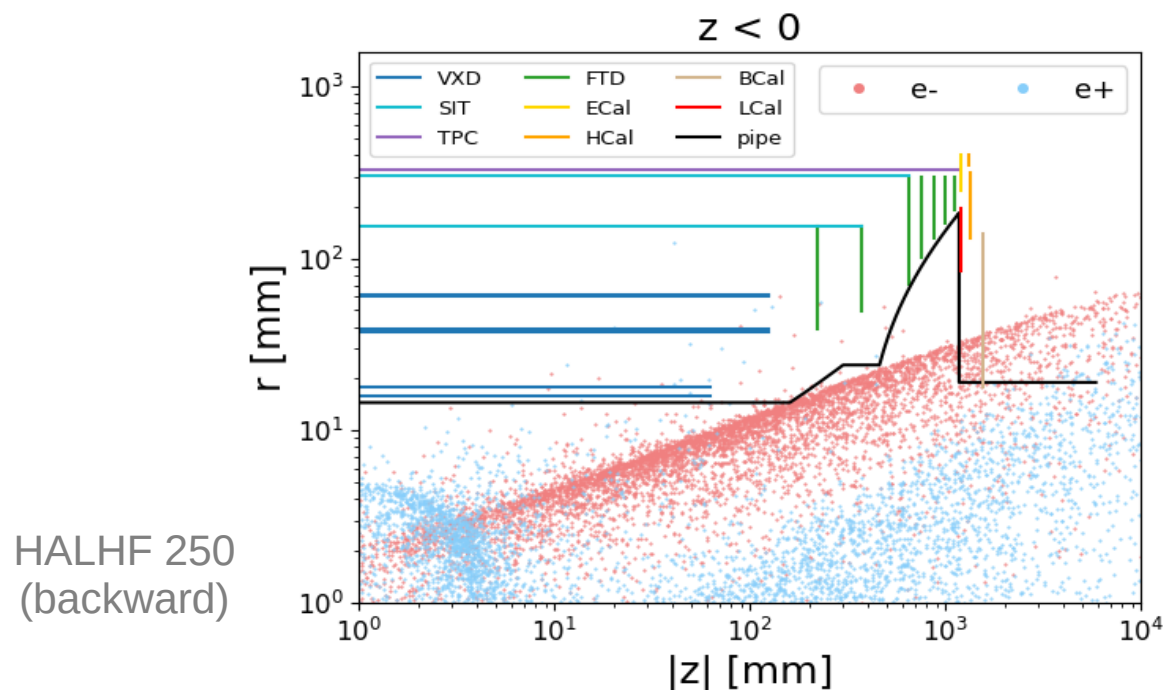
- The pairs in the forward direction hit the VXD and LCAL!
- Using the pair cone to adjust the asymmetric ILD@HALHF (e-ILD)



Impact on Detector Design

e-ILD_v1

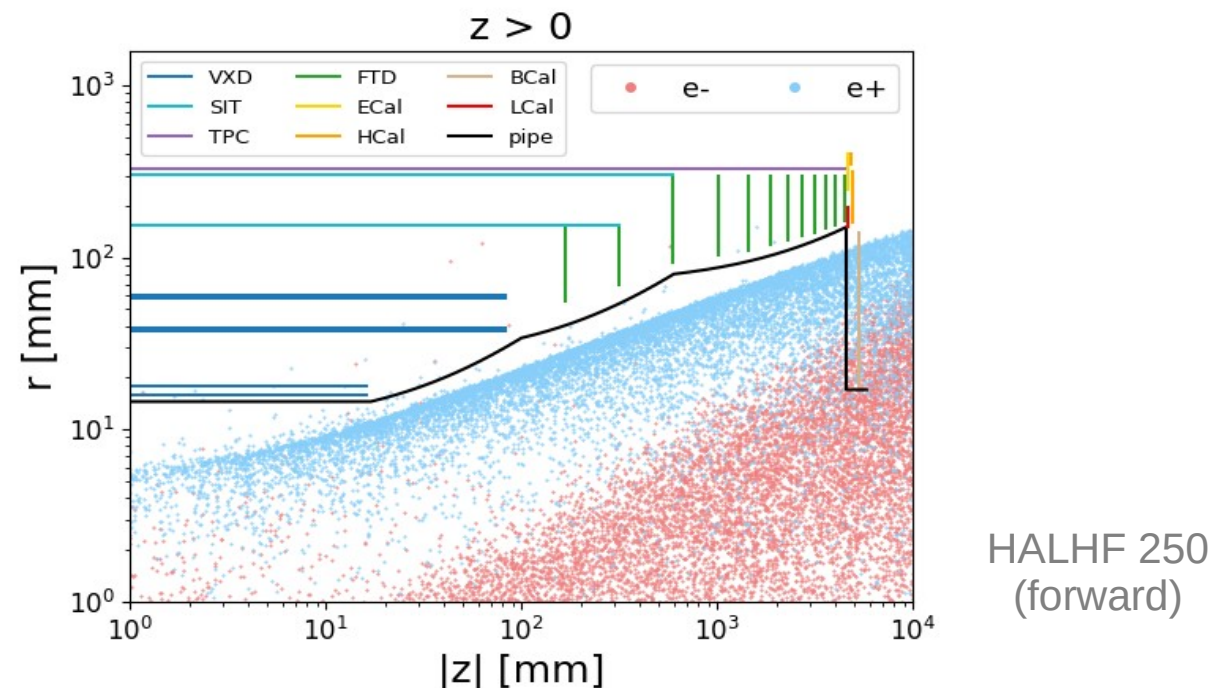
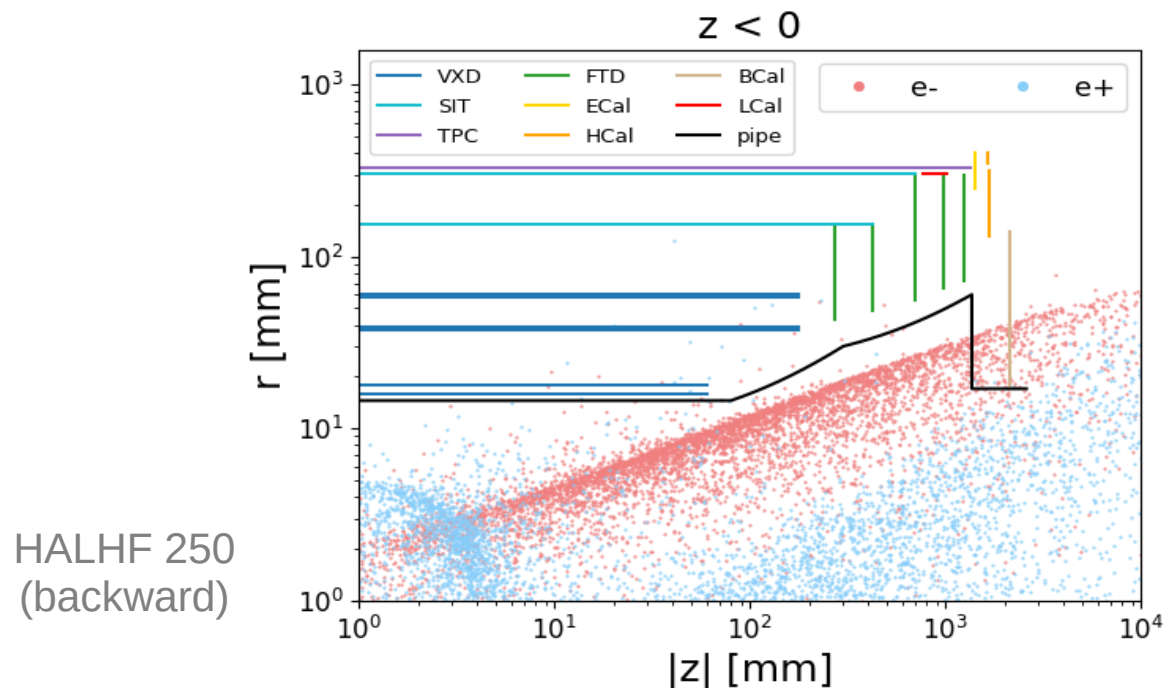
- Developed earlier by Mikael Berggren to provide similar Higgs recoil-mass performance to ILC
- 2x forward barrel length, $\frac{1}{2}$ x backward barrel length



Impact on Detector Design

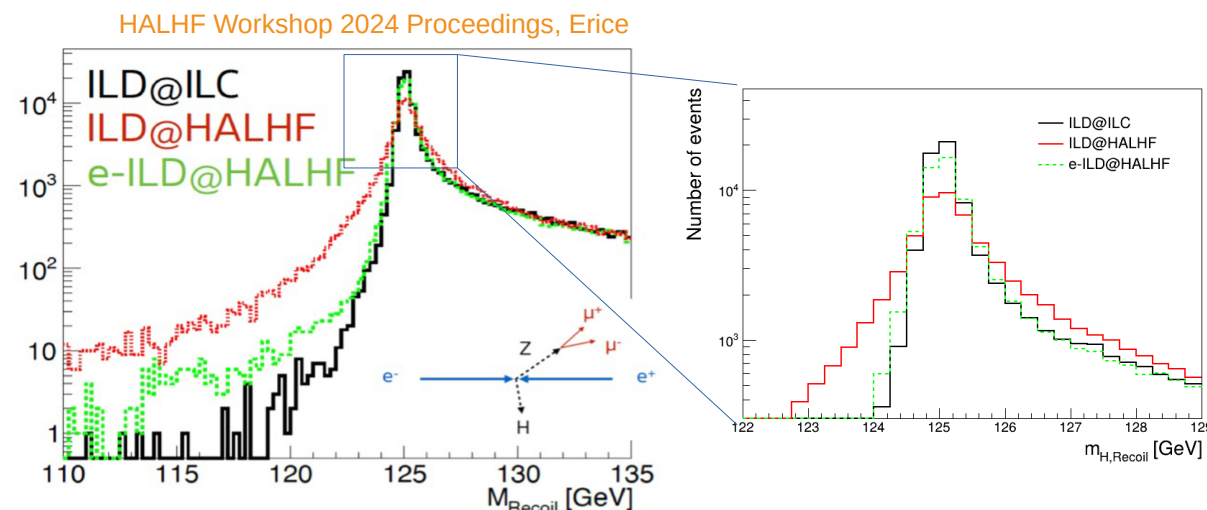
e-ILD_v2

- Newest iteration of e-ILD
- Beampipe above the pair background envelope
- Location of LumiCAL changed to capture the boosted Bhabha-scattered pairs



Impact on Physics Analysis

- Higgs recoil-mass measurement
- Whizard for process generation ($e^+ e^- \rightarrow HZ \rightarrow H\mu\mu$)
- SGV detector simulations for symmetric (ILD) and asymmetric (e-ILD) detectors
- Only boost: Worse Higgs peak for HALHF. Improved with extended ILD (e-ILD)

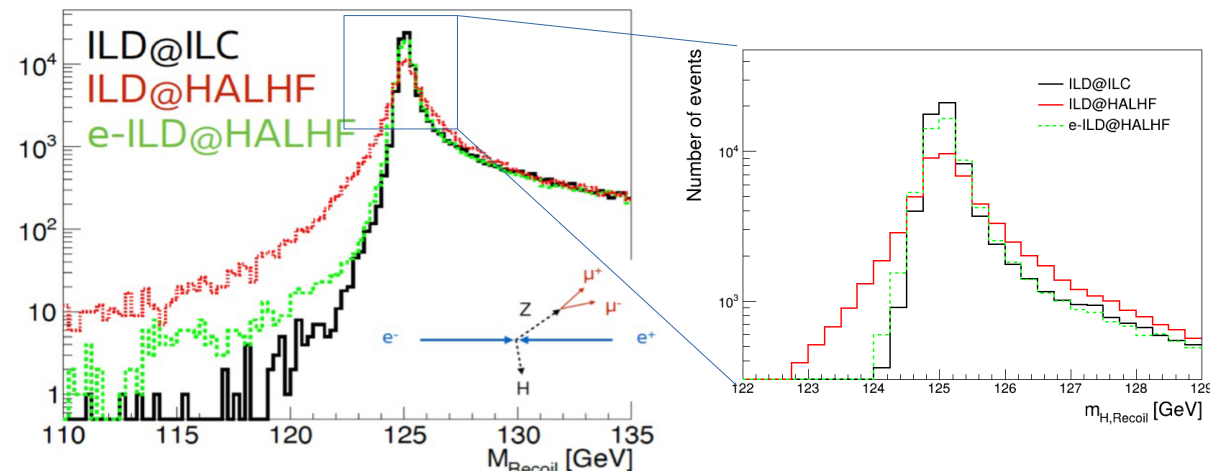


No beam-spectrum

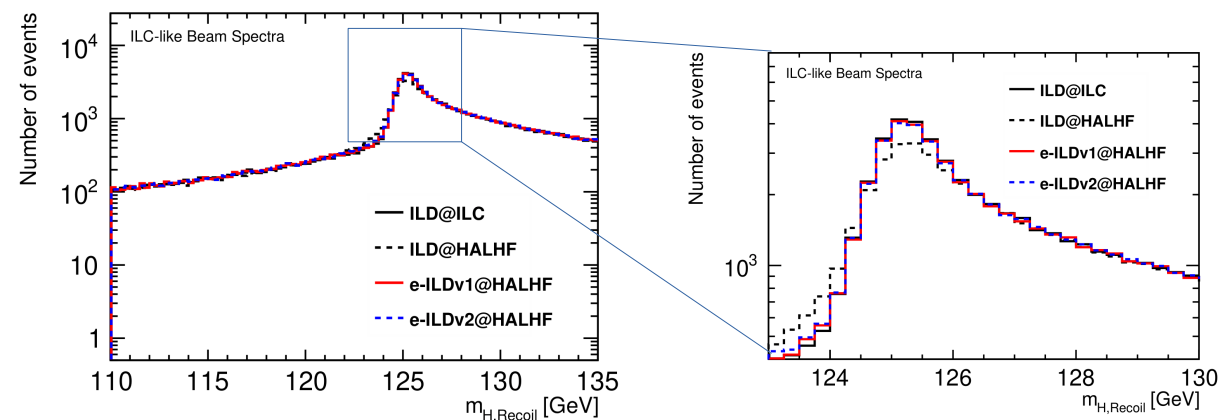
Impact on Physics Analysis

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- Only boost: Worse Higgs peak for HALHF. Improved with extended ILD (e-ILD)
- With beam spectrum: Less difference
- e-ILD_v2 still achieves comparable performance to e-ILD_v1

HALHF Workshop 2024 Proceedings, Erice



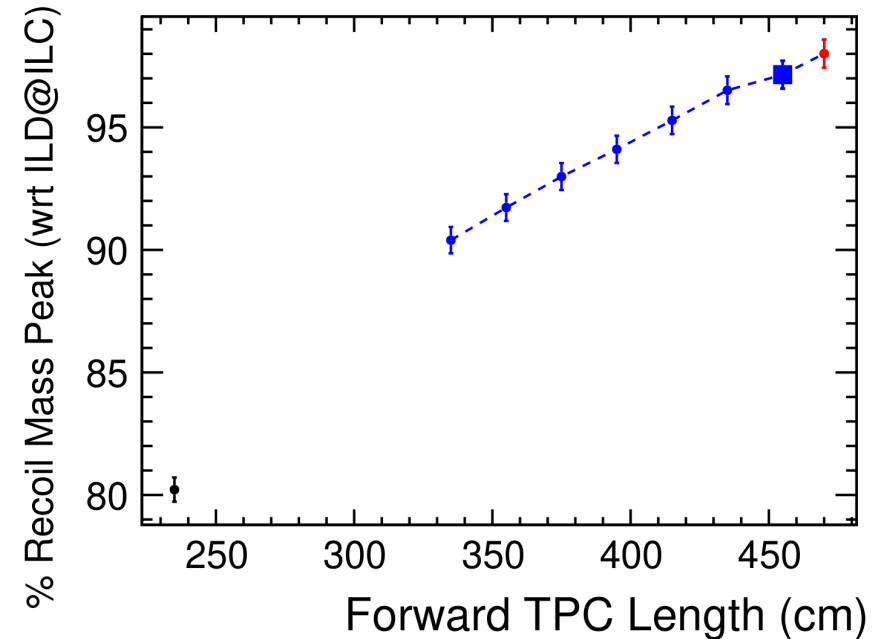
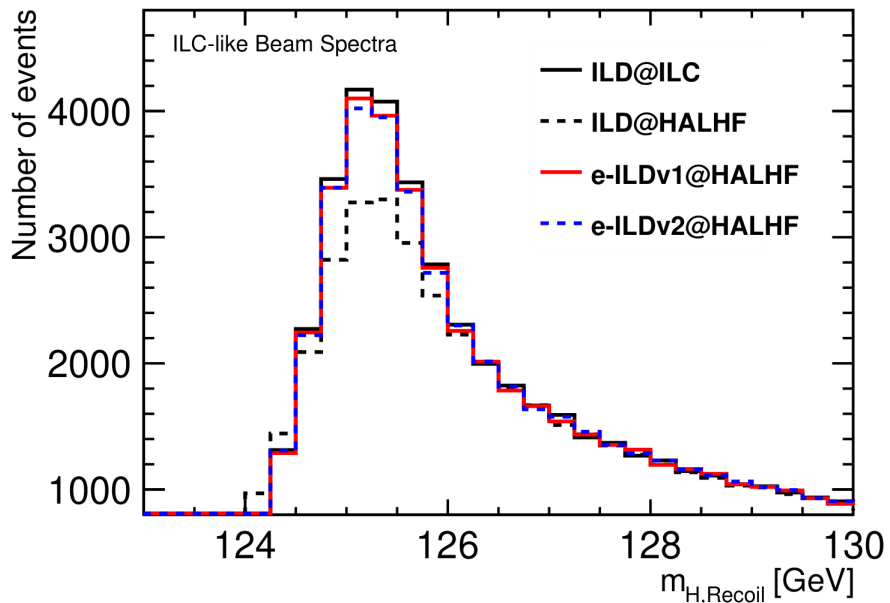
No beam-spectrum



ILC-like beam-spectrum

Impact on Physics Analysis

- Forward TPC length contributes significantly to the Recoil-Mass performance
- v2 achieves 97% peak integral vs 98% of v1 wrt ILD@ILC



Next Steps

- Incorporating HALHF beam-spectra to the Higgs recoil-mass plots
 - Might result in even better performance compared to ILC
- Demonstrating a concept for luminosity measurement at HALHF.
 - Optimize LumiCAL positioning
 - Study the effect of tracker material and deflection from bunch fields to the Bhabha scattered pairs
- Optimizing the auxiliary silicone tracking for impact parameter resolution and studying the flavour-tagging capabilities.
 - $H \rightarrow c\bar{c}$ as a benchmark
- Studying the impact of a higher magnetic field (4T?)
 - Would improve track resolution
 - Narrower pair cone could allow detector instrumentation to come closer to the beam

Summary

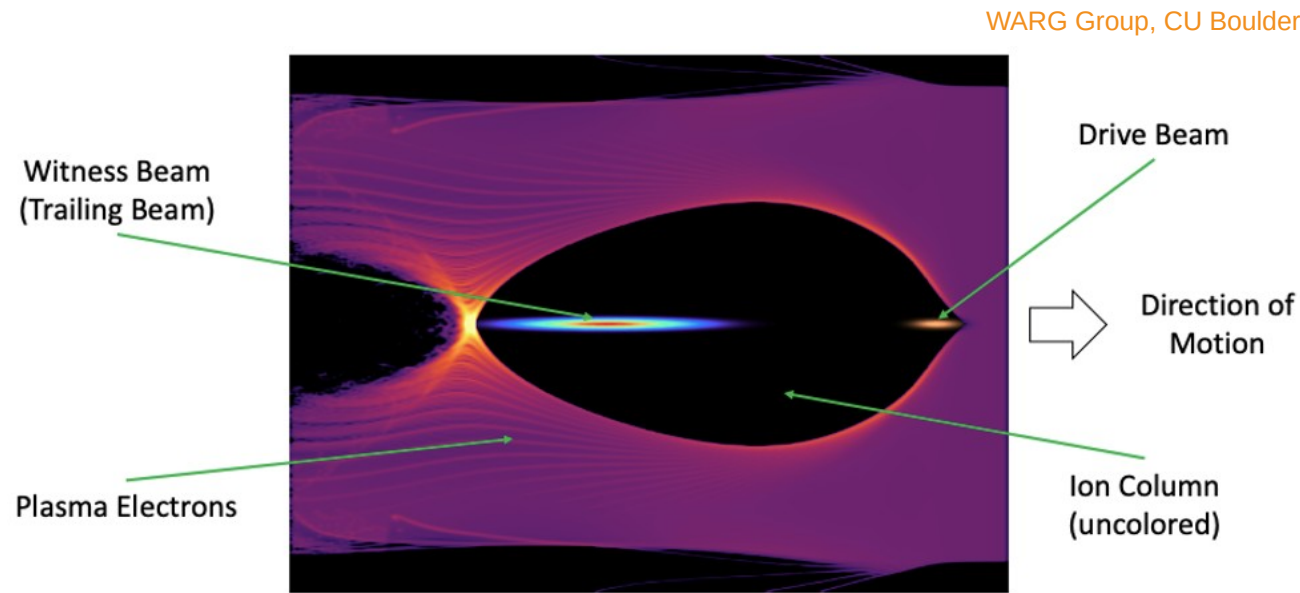
- HALHF is a cost-effective linear collider conducive to Higgs studies.
- The high-energy, tight beams result in various beam-beam effects, affecting physics observables and detector designs.
- Need to model these effects through simulation tools like GuineaPIG and WarpX.
- Compared HALHF to symmetric ILC collider wrt energy spectra and luminosities.
- Displayed the effect of beam backgrounds on detector design.
- Analyzed the impact of pair backgrounds, boost and energy spectra on physics analyses at HALHF.
- The study implies that the physics goals of a symmetric linear collider can also be achieved with little or no degradation at HALHF.
- pre-CDR almost out ;)

Thank you

Backup

Plasma Wakefield Acceleration

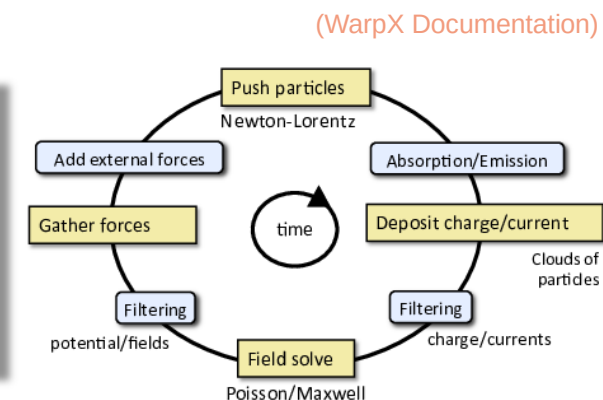
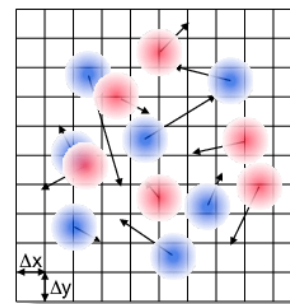
- Drive beam pushes through plasma, expelling plasma electrons outwards
- Ions remain effectively stationary in the timescale of electron motion
- While coming back, electrons generate a trailing plasma density oscillation (wakefield)
- Witness beam surfs along the wakefield, experiencing high accelerating gradients



Simulation Tools

WarpX, GuineaPIG and CAIN use **PIC (Particle-In-Cell)** approach.

- Divide the space into a grid with fields calculated at each nodes.
- Divide beams into macroparticles for easier tracking.
- Calculate forces and push particles at each time-step.
- Recalculate fields at the next time step.



GuineaPIG slices beams longitudinally and only calculates transverse fields (ultra-relativistic approximation).

- Very fast and efficient for high-energy linear colliders.
- Includes all the coherent and incoherent processes.
- However, cannot perform e- γ simulations!

Simulation Tools

Ptarmigan is used mainly for e-laser simulations.

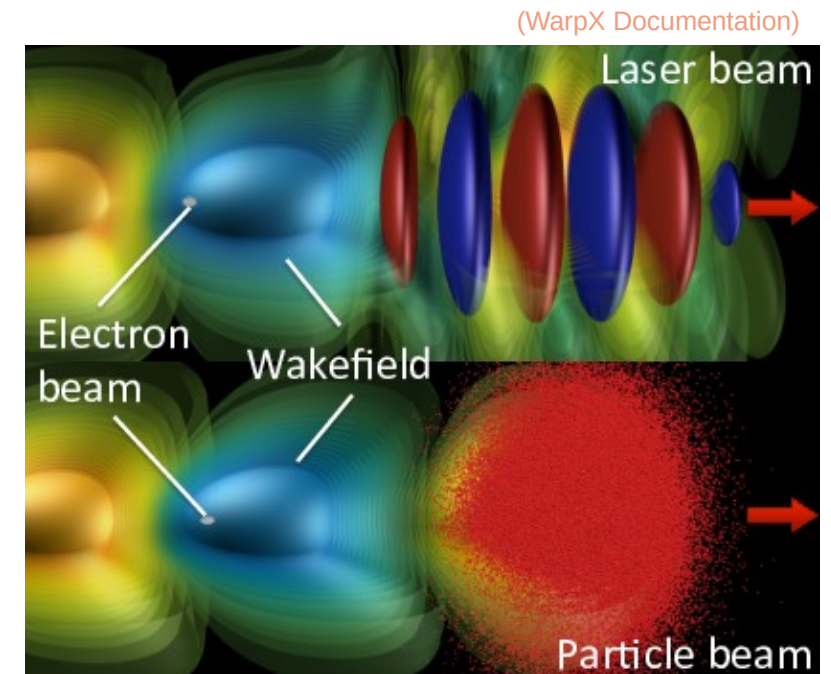
- Simulates strong-field QED accurately.
- It does not simulate e^+e^- collisions.

CAIN does both e^+e^- and e-laser simulations.

- Also slices beams longitudinally for 2D simulations.

WarpX is a general purpose simulation software that does the full 3D simulation.

- Can simulate various particle physics phenomena (PWFA, plasma mirror)
- Can use GPU programming to increase speed.
- Incoherent processes under development.



HALHF Parameters (Old and New)

arXiv:2503.23489 [physics.acc-ph]

B Foster et al 2023 New J. Phys. 25 093037

Machine parameters	Unit	Value (250 GeV)		Value (380 GeV)		Value (550 GeV)	
Centre-of-mass energy	GeV	250		380		550	
Centre-of-mass boost		1.67		1.67		1.67	
Bunches per train		160		160		160	
Train repetition rate	Hz	100		100		100	
Average collision rate	kHz	16		16		16	
Luminosity	$\text{cm}^{-2} \text{ s}^{-1}$	1.2×10^{34}		1.7×10^{34}		2.5×10^{34}	
Luminosity fraction in top 1%		63%		53%		46%	
Quantum parameter (Υ)		0.9		1.6		2.8	
Estimated total power usage	MW	106		154		218	
Total site length	km	4.9		6.5		8.4	
Colliding-beam parameters		e^-	e^+	e^-	e^+	e^-	e^+
Beam energy	GeV	375	41.7	570	63.3	825	91.7
Bunch population	10^{10}	1	3	1	3	1	3
Bunch length in linacs (rms)	μm	40	150	40	150	40	150
Bunch length at IP (rms)	μm		150		150		150
Energy spread (rms)	%	0.15		0.15		0.15	
Horizontal emittance (norm.)	μm	90	10	90	10	90	10
Vertical emittance (norm.)	μm	0.32	0.035	0.32	0.035	0.32	0.035
IP horizontal beta function	mm	3.3		3.3		3.3	
IP vertical beta function	mm	0.1		0.1		0.1	
IP horizontal beam size (rms)	nm	636		519		429	
IP vertical beam size (rms)	nm	6.6		5.2		4.4	
Average beam power delivered	MW	9.6	3.2	14.6	4.9	21.1	7.0
Bunch separation	ns	16		16		16	
Average beam current	μA	26	77	26	77	26	77

New Parameters

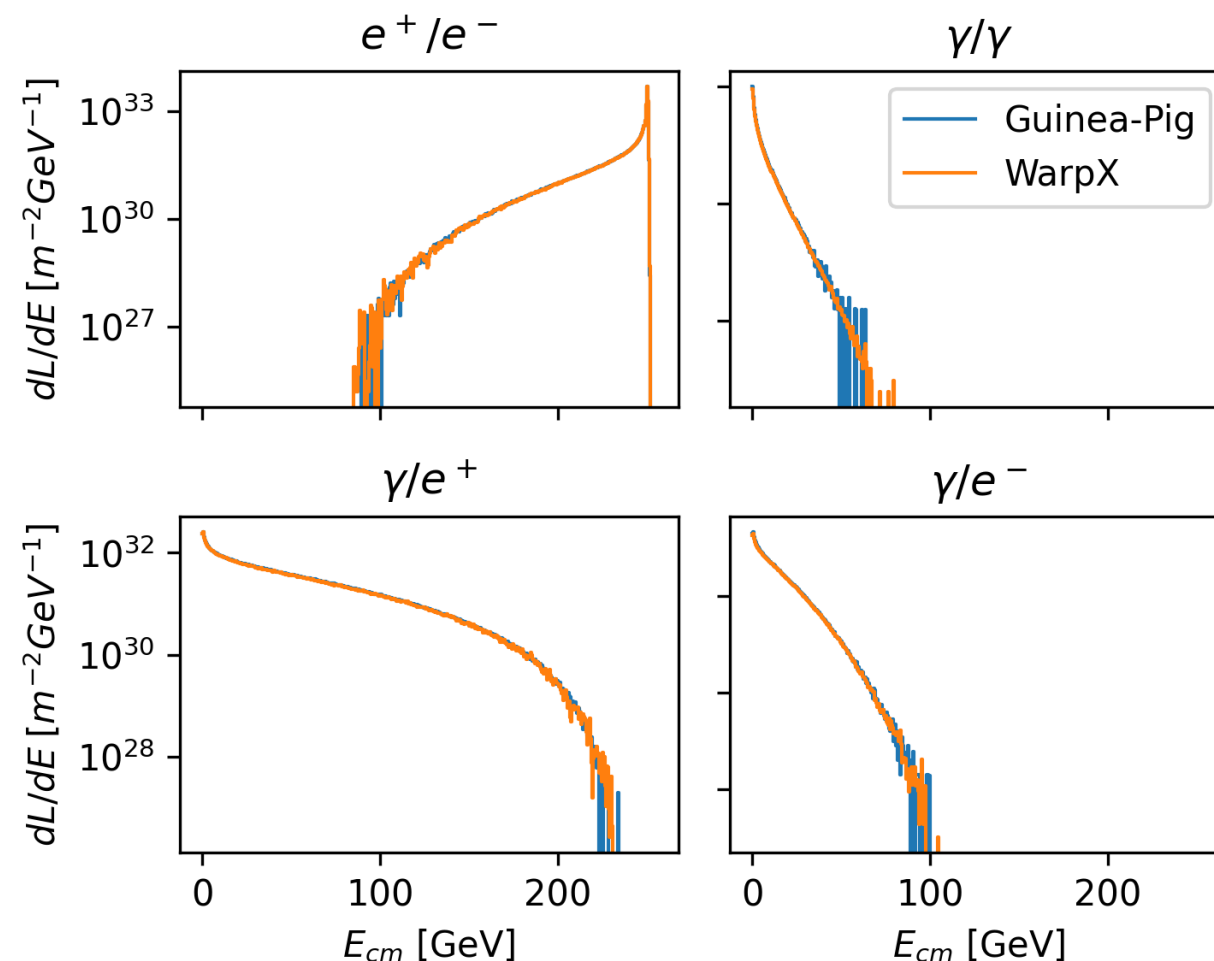
Machine parameters	Unit	Value	
Centre-of-mass energy	GeV	250	
Centre-of-mass boost		2.13	
Bunches per train		100	
Train repetition rate	Hz	100	
Average collision rate	kHz	10	
Luminosity	$\text{cm}^{-2} \text{s}^{-1}$	0.81×10^{34}	
Luminosity fraction in top 1%		57%	
Estimated total power usage	MW	100	
Colliding-beam parameters		e^-	e^+
Beam energy	GeV	500	31.25
Bunch population	10^{10}	1	4
Bunch length in linacs (rms)	μm	18	75
Bunch length at IP (rms)	μm	75	75
Energy spread (rms)	%	0.15	0.15
Horizontal emittance (norm.)	μm	160	10
Vertical emittance (norm.)	μm	0.56	0.035
IP horizontal beta function	mm	3.3	3.3
IP vertical beta function	mm	0.1	0.1
IP horizontal beam size (rms)	nm	729	729
IP vertical beam size (rms)	nm	7.7	7.7
Average beam power delivered	MW	8	2
Bunch separation	ns	80	80
Average beam current	μA	16	64

Old Parameters

: Parameters used as GuineaPIG input

Comparing the Simulation Tools

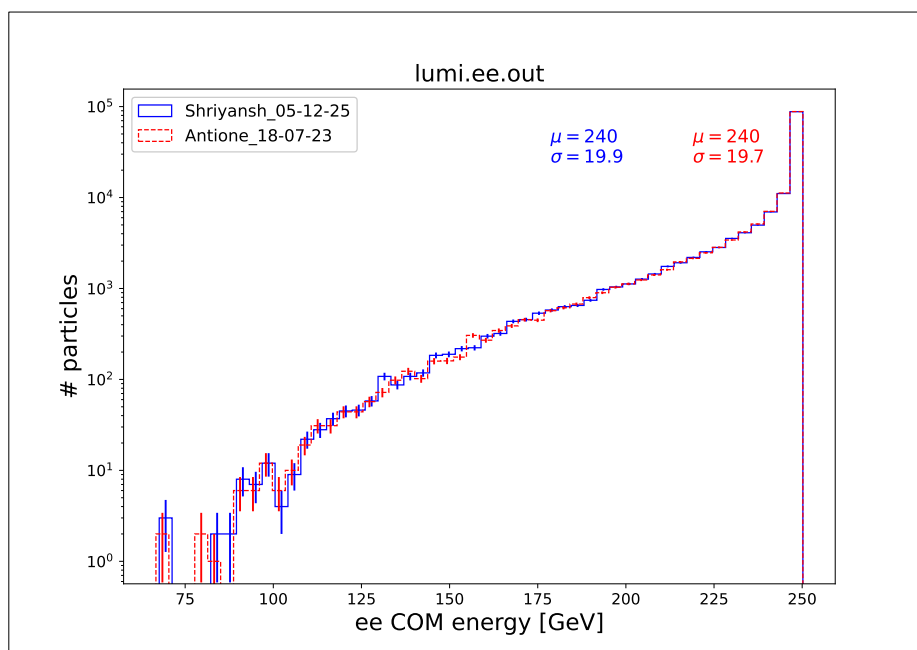
- HALHF250 collisions simulated with GuineaPig and WarpX.
- Luminosity distributions for different interactions agree well!



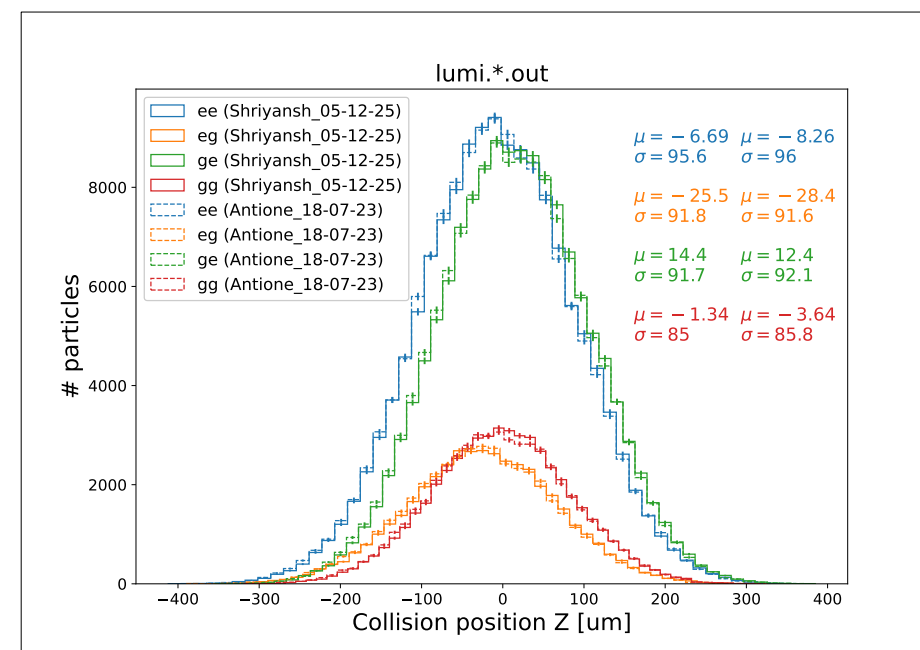
Luminosities for Different Interactions during 1 Bunch Crossing at HALHF250

HALHF Validation with GuineaPIG

- Validated my setup through energy spectrum and luminosity plots using old HALHF 250 GeV parameters.
- Obtained a good agreement.



e+e- COM energy spectrum



Luminosity wrt z-position of collisions

Incorporating Beam Spectra

A First Comparison

- For physics analyses, convenient to reuse ILC samples and boost them
- Caveat: ILC beam spectrum different than HALHF beam spectrum
 - HALHF spectra have much higher tail at low E_{CM}
 - ... but also narrower close to nominal E_{CM} (most relevant for recoil spectrum)
- For first estimate, use ILC beam spectrum for HALHF too

Collision Energy Spectra

Issues

- Generating asymmetric events with Whizard (v2.8.5) poses problems with Pythia 6 in hadronization process.
- Currently: Generate symmetric collisions, then boost later on in SGV to restore asymmetry.
- Possible solutions:
 - Use Whizard with Pythia 8 (setup would take time)
 - HALHF beam-beam simulation results (Guinea-PIG) boosted to symmetric → input to Whizard to generate events → boost back to HALHF in SGV

Conclusion

- Updated the Higgs recoil-mass plot with new HALHF configuration
- Factors affecting Higgs recoil-mass measurement:
 - ☒ Boost
 - ☐ Beam energy spectrum
 - ☒ Beam-beam background
- Effect of boost is overrated
- Next: Test the workarounds to use HALHF energy spectrum for the respective plots