FERMILAB-SLIDES-24-0061-T

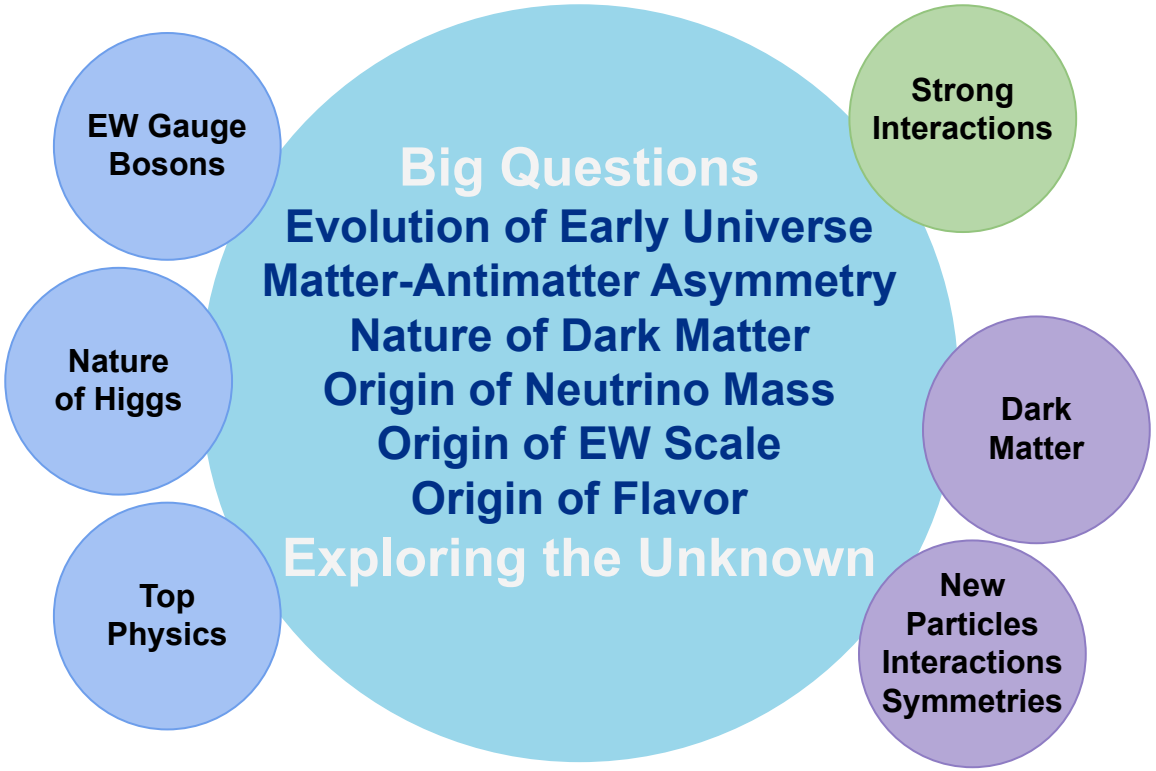
Summary on Theory and Measurements

Stefan Höche, Fermilab

Second annual U.S. FCC Workshop

March 27, 2024

Physics at the Energy Frontier – Snowmass 2021

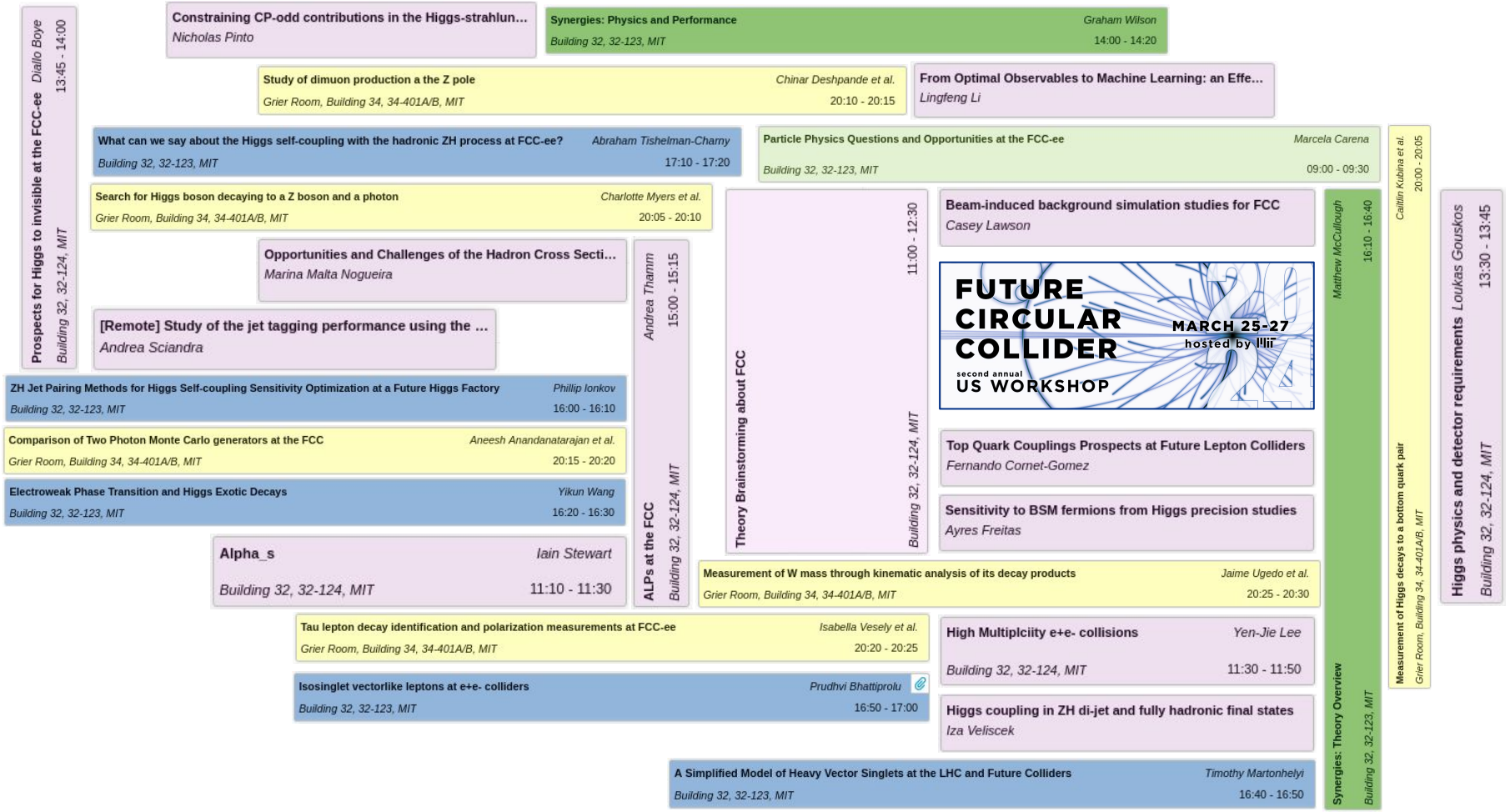


- What can we learn about the origin of the EW scale and the EW phase transition from an in-depth study of SM particles at colliders?
- What can we learn about the dynamics of strong interactions in different regimes?
- How can we build a complete program of BSM searches which includes both model-specific and model-independent explorations at high scales?

[Narain et al.] arXiv:2211.11084

Opportunities at the Future Circular Collider

- Many new ideas, reflected in a large number of contributions to this workshop
- Tremendous physics potential (and challenges) emphasized throughout



FCC-ee Opportunities – Precision and Exploration

ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \rightarrow ZH$
$t\bar{t}$ threshold	$\sqrt{s} \sim 365$ GeV	5 years	10^6	$e^+e^- \rightarrow t\bar{t}$
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	5×10^{12}	$e^+e^- \rightarrow Z$
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \rightarrow W^+W^-$
[s-channel H	$\sqrt{s} = 125$ GeV	5? years	~5000	$e^+e^- \rightarrow H_{125}$]

Higgs
factory

m_H, σ, Γ_H
self-coupling
$H \rightarrow$ bb, cc, ss, gg
$H \rightarrow$ inv
ee$\rightarrow$H
$H \rightarrow$ bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \rightarrow \tau\, \nu$
$B_s \rightarrow D_s$ K/π
$B_s \rightarrow K^* \tau\, \tau$
$B \rightarrow K^* \nu\, \nu$
$B_s \rightarrow \varphi\, \nu\, \nu$ ...

QCD - EWK
most precise SM test

m_Z, Γ_Z, Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

[Marcela Carena, Fermilab]

Theory Overview

- Tera-Z not just a LEP re-run, but a literal quantum leap towards smallest distances
- If new physics resides in the Higgs/EW sector, a full suite of Higgs/EW measurements required to fully explore it
- If new physics resides in flavour sector, it cannot generically be sequestered from precision EW

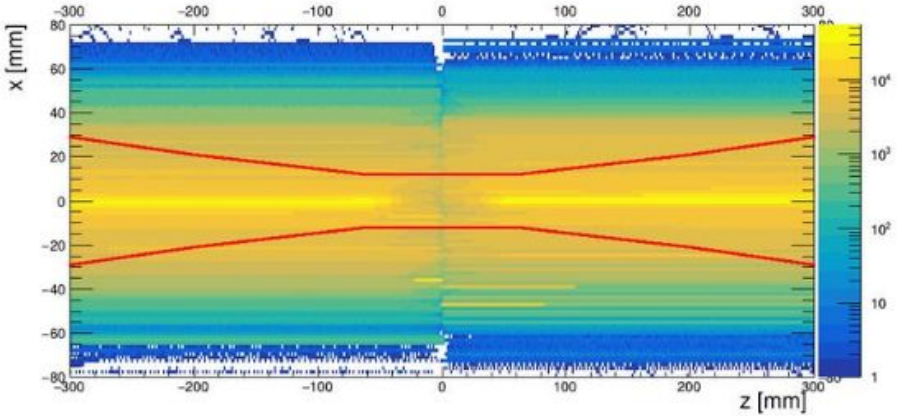
Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)
m_Z (keV/c^2)	91 186 700	±	2200	5	100
Γ_Z (keV)	2 495 200	±	2300	8	100
R_ℓ^Z ($\times 10^3$)	20 767	±	25	0.06	1
$\alpha_s(m_Z)$ ($\times 10^4$)	1196	±	30	0.1	1.6
R_b ($\times 10^6$)	216 290	±	660	0.3	<60
σ^0_{had} ($\times 10^3$) (nb)	41 541	±	37	0.1	4
N_ν($\times 10^3$)	2991	±	7	0.005	1
$\sin^2\theta^{eff}_W$($\times 10^6$)	231 480	±	160	3	2–5
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128 952	±	14	4	Small
$A^{b,0}_{FB}$ ($\times 10^4$)	992	±	16	0.02	<1
$A^{pol,\tau}_{FB}$ ($\times 10^4$)	1498	±	49	0.15	<2
m_W (keV/c^2)	803 500	±	15 000	600	300

- Enormous scope of flavour programme has begun to emerge, in particular as the most powerful b and τ factory ever constructed
- As exp error mitigation strategies evolve, so do theory targets. Require 3 and 4-loop precision SM predictions, understanding of hadronisation, EFT calculations, high-order QCD+EW, MCs

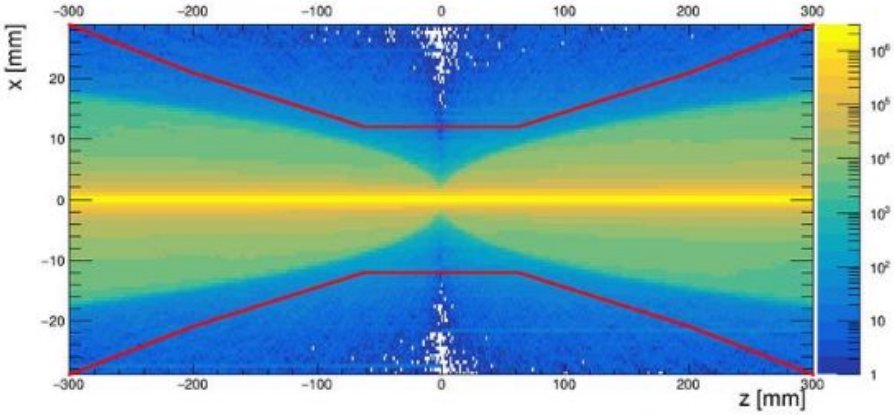
[Matthew McCullough, CERN]

FCC beam background studies with Guinea-Pig

FCC-EE ENVELOPE



C3 envelope:



- Smearing of envelope pattern
- Beam intensity is an order of magnitude lower than C3, meaning we can push much closer to the beam interaction region

FCC pairs / Occupancy

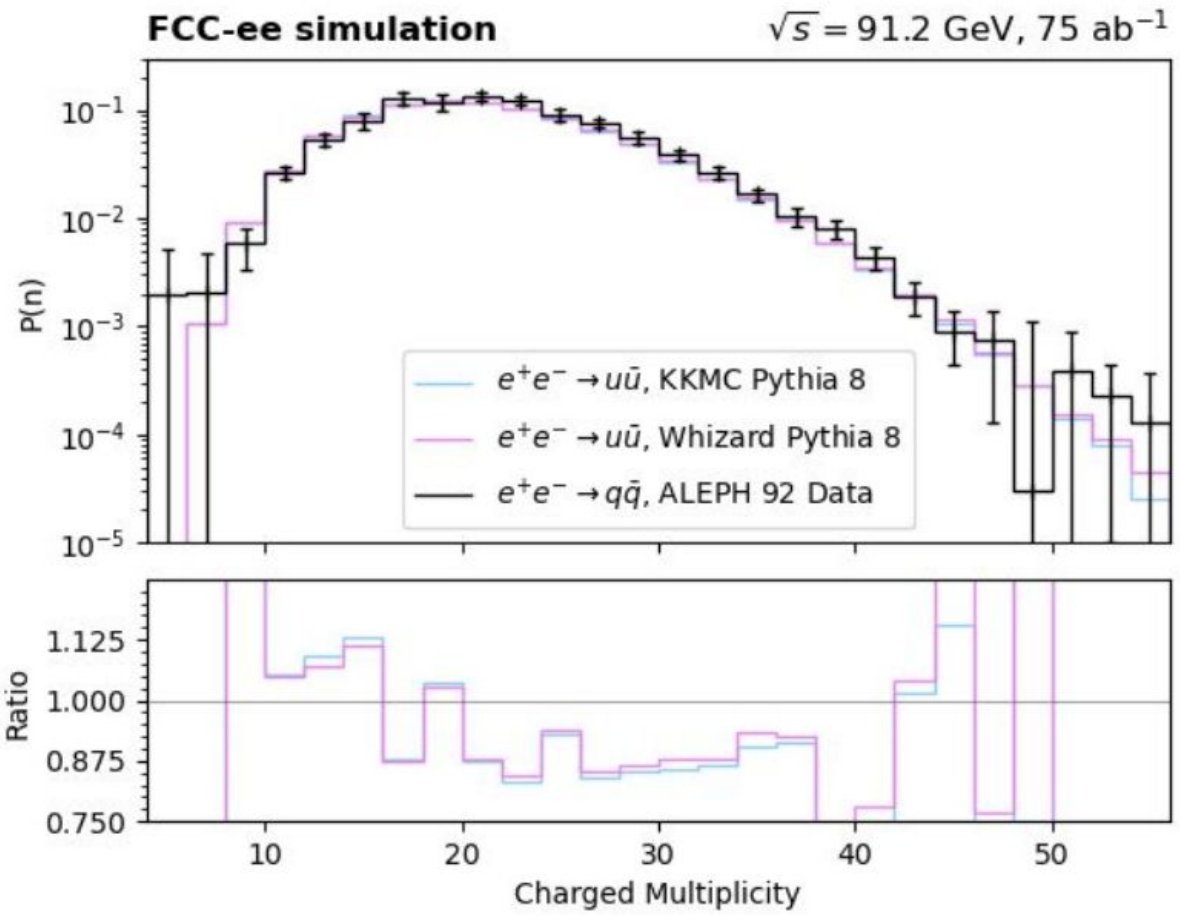
		Z	WW	ZH	$t\bar{t}$
1	Pairs/BX	1300	1800	2700	3300
10^{-6}	O_{max}(VXDB)	70	280	410	1150
10^{-6}	O_{max}(VXDE)	23	95	140	220
10^{-6}	O_{max}(TRKB)	9	20	38	40
10^{-6}	O_{max}(TRKE)	110	150	230	290

Main difference between FCC & C^3: beam crossing angle

Landau-Lifschitz process dominates, p_T typically very low

[Casey Laswon, MIT]

Hadron Cross-Section at the Z-pole



ALEPH Comparison

Both generators (gen-level) are in fair agreement with unfolded ALEPH data (in black), even though they might differ from each other in other measurements. The modelling of hadronization and multiplicities should still be improved for FCC-ee.

https://doi.org/10.1016/S0370-1573(97)00045-8

Generator level particles

KKMC & Whizard disagree; Still in need of better Monte Carlo to more accurately simulate hadronic events at the Z pole, hadronization & showering

[Marina Malta Nogueira, MIT]

From the past to the future: α_s in e^+e^-

$\alpha_s(m_Z)$ from e^+e^- jets, looking forward to the next e^+e^- collider

Theory wish list

- More rigorous treatment of 3-jet power corrections is crucial (including transition to 2-jet)
- Analyses with more observables (heavy-jet mass, EECs, ...), and combined observables while including all theory correlations
- Subleading power resummation, extension to N^4LL, ...

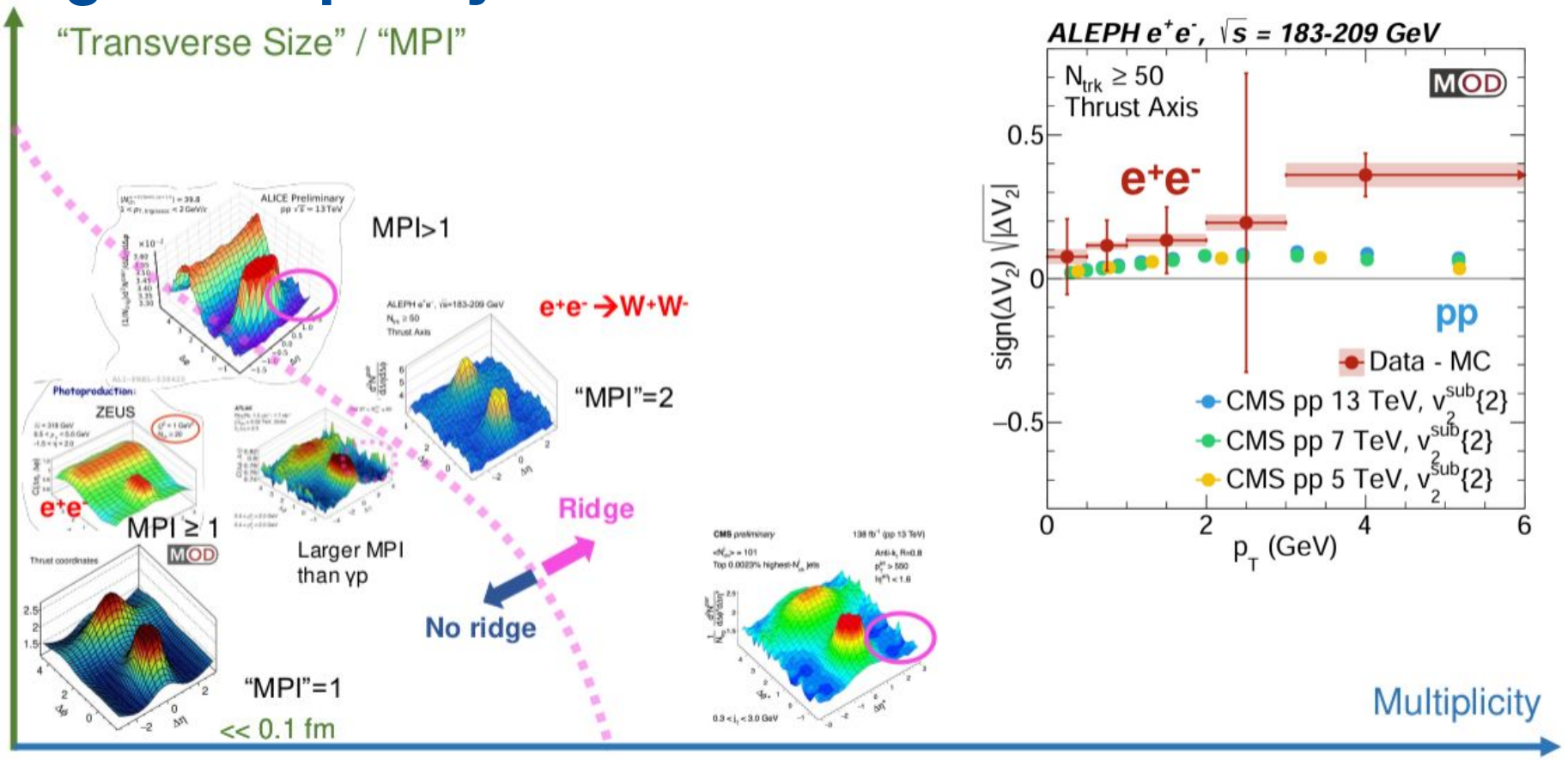
Synergy!

Experimental wish list

- More kinematic info: multi-differential distributions, jet substructure, ...
- Full correlation matrices
- Impact of using modern Monte Carlo generators when comparing to LEP

[Iain Stewart, MIT]

High-multiplicity e^+e^- collisions



MC based "Non-flow subtraction": $\Delta v_2 = v_{2,Data} - v_{2,MC}$

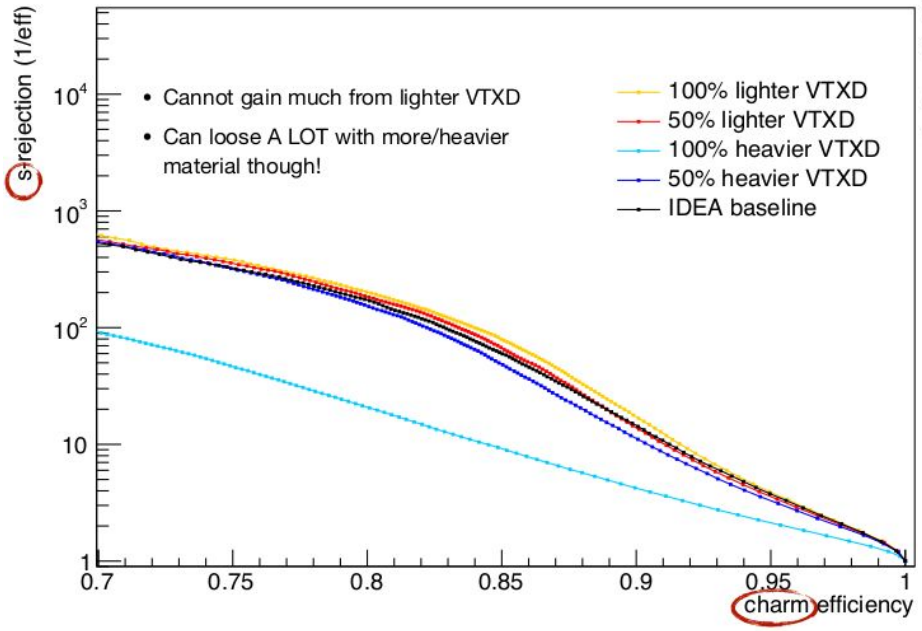
Similar increasing trend in e^+e^- and pp data as a function of p_T

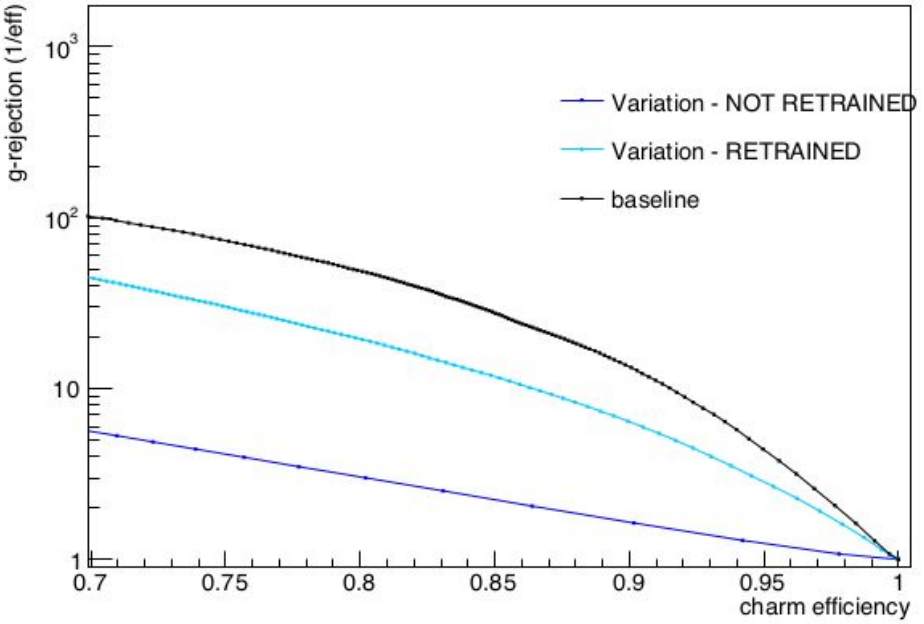
Significant increase in multiplicity reach at FCC-ee: ~ central p-Pb collisions

[Yen-Jie Lee, MIT]

FCCee ParticleNet Tagger & IDEA Detector Tracker

- **Significant effects observed in efficiency(rejection) at fixed rejection(efficiency) for different (IDEA) VTXD properties**
  - Re-training against each configuration allows for partial performance recovering
- In near future, **may expand studies** beyond "simple" changes in silicon vertex detector
  - Material-budget interplay between beam pipe & first silicon layer
  - **PID & timing studies** possible with setup in place





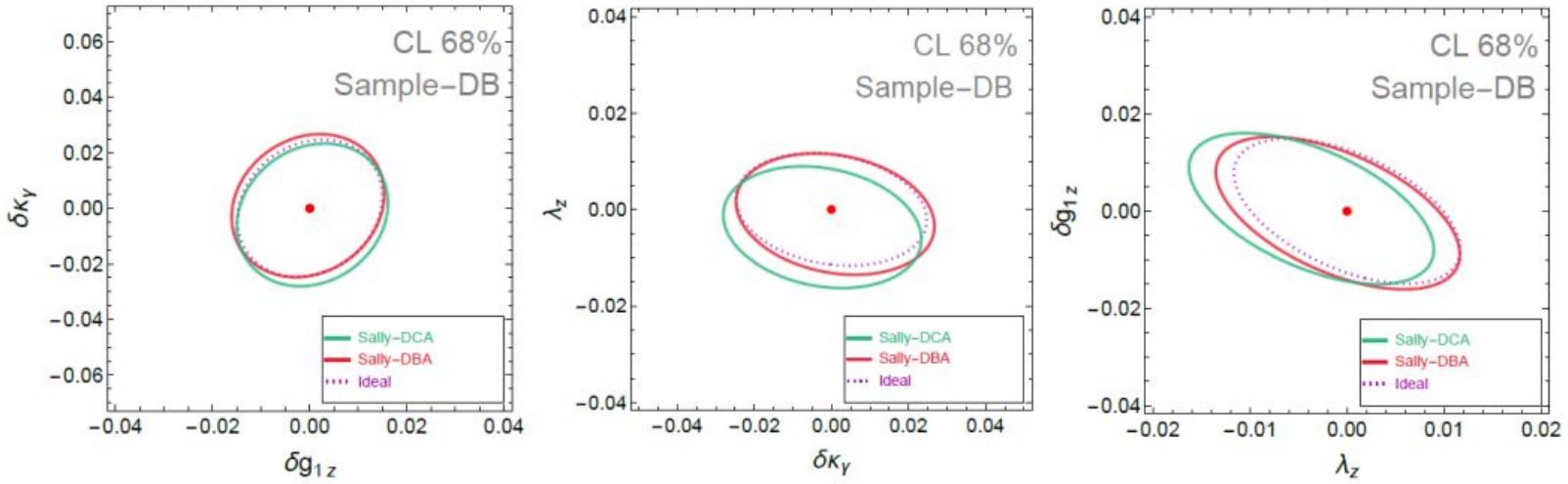
[Andrea Sciandra, BNL]

Unbinned approach to aTGC searches

SALLY (Score approximates likelihood locally) algorithm, the Optimal Observable extension in ML J. Brehmer, K. Cranmer, G. Louppe and J. Pavez 1805.00013 , 1805.00020

$$L = \sum |\hat{\alpha}_i(x) - \alpha_i|^2$$

Loss function(al) — Inferenced from observables — Truth value

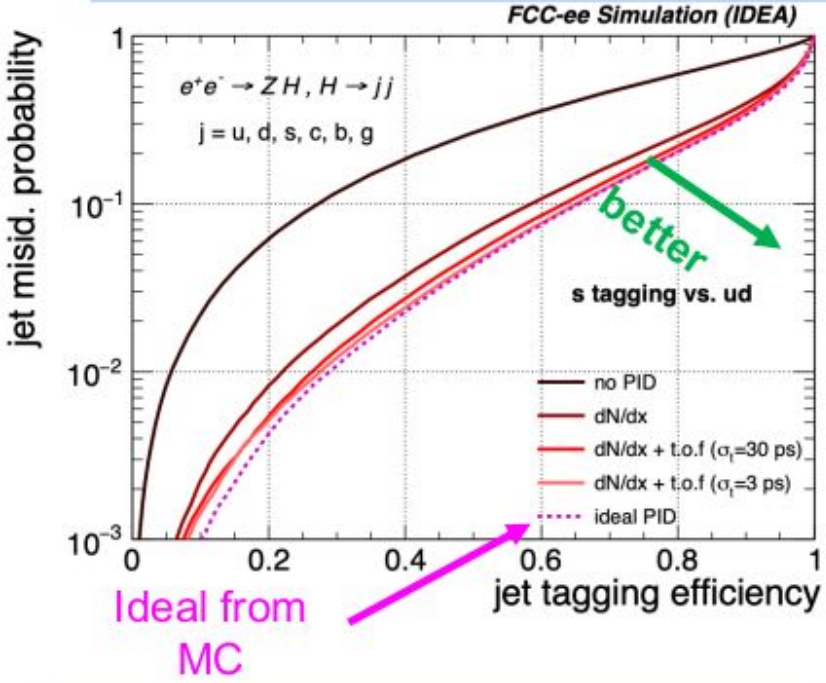


[Lingfeng Li, Brown University]

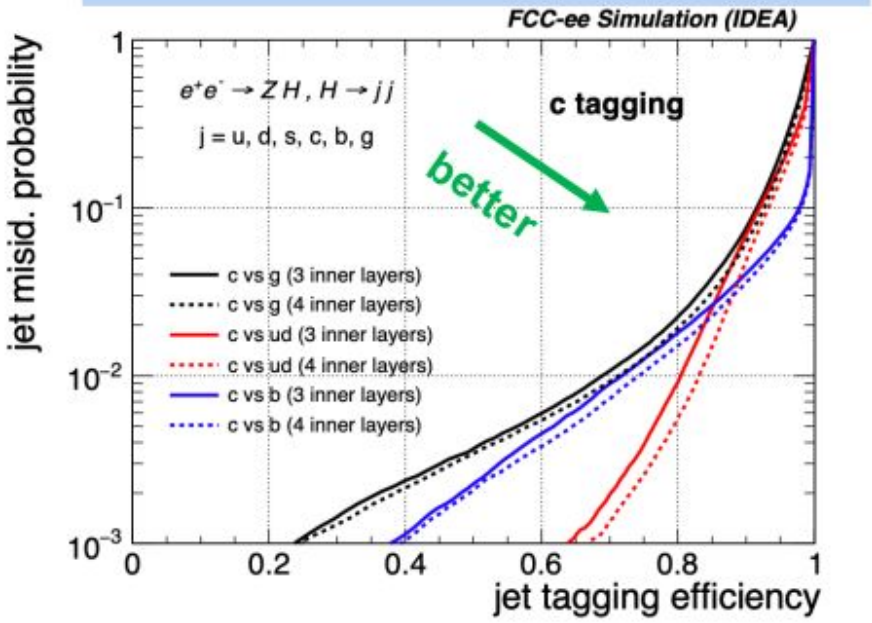
Higgs physics and detector requirements

EPJ C 82 646 (2022)

strange-tagging (timing)



charm-tagging [PIX layer]



dN/dx brings most of the gain additional gain w/ TOF (30ps)

→TOF (3ps): marginal improvement

Additional PIX layer:

→ 2x improved BKG rej. in c-tag

→ Marginal/no improvement in b-tag

With aim to complete 2nd gen Yukawas, s tagging is crucial

[Loukas Gouskos, Brown University]

Prospects for Higgs to invisible at the FCC-ee

Signal (H→ inv)	Energy	Luminosity	Selection on channels	Bkg
ZH	240 GeV	5 ab^{-1}	$ee, \mu\mu, qq$	ZZ and ZH

Limit set on $\mathcal{B}(H \rightarrow \text{inv})$ in%					
channel	-2σ	-1σ	Limit	+1σ	+2σ
ee	0.15	0.20	0.28	0.40	0.54
$\mu\mu$	0.08	0.11	0.15	0.21	0.29
qq	0.09	0.12	0.16	0.23	0.31

- A comparison on the lepton reconstruction between CLD full simulation and Delphes simulations of CLD and IDEA is shown.
- A study of the efficiency and resolution are performed for this comparison.
  - A nearly identical efficiency is observed for IDEA and CLD fast sim.
  - Electron efficiency is worse for full sim than for fast sim, especially at low p_T.
  - Muon efficiency is very similar for full and fast simulation.
  - The resolution in one p_T slice shows a low-end tail on the electron distribution in full sim which is not reproduced in fast sim.

[Diallo Boye, BNL]

ZH→jjjj

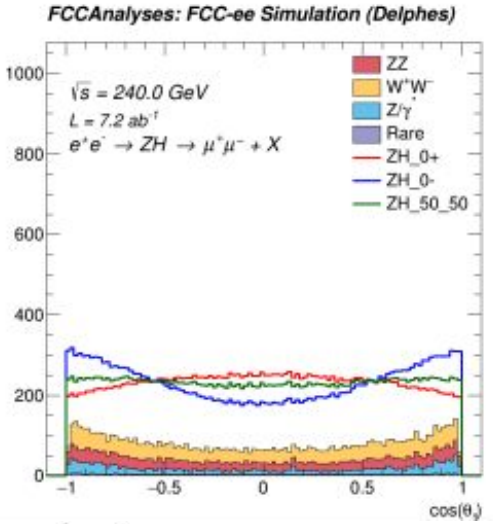
- **IDEA baseline very close to ideal vertex & calo detector**
- Robust analysis strategy
  - Small change in event selection
  - Main effect is migrates events between categories, dues to changes in performance
- No change in μ_{Hgg} as expected
  - G-score not varied nor truth gluon jet score corrected
- Largest impact on μ_{Hcc} w/ CLD trained tagger
- Caveats remainder!
  - Only approximate propagation of tagging effects
  - Ignored correlations of between b/c/s with g and light scores

variation \ 68% CL precision	μ_{Hbb}	μ_{Hcc}
BASE	±0.3%	±3.9%
idealVXDCalo	±0.3%	+3.9% -3.8%
lighterVXD_100pc	±0.3%	±3.9%
heavierVXD_100pc	±0.4%	+4.6% -4.5%
CLD	±0.4%	±4.3%

[Iza Veliscek, BNL]

FCC-ee Higgs CP Study

- Likelihood fit from angular distributions represents a realistic constraints on f_{CP}^{HZZ}.

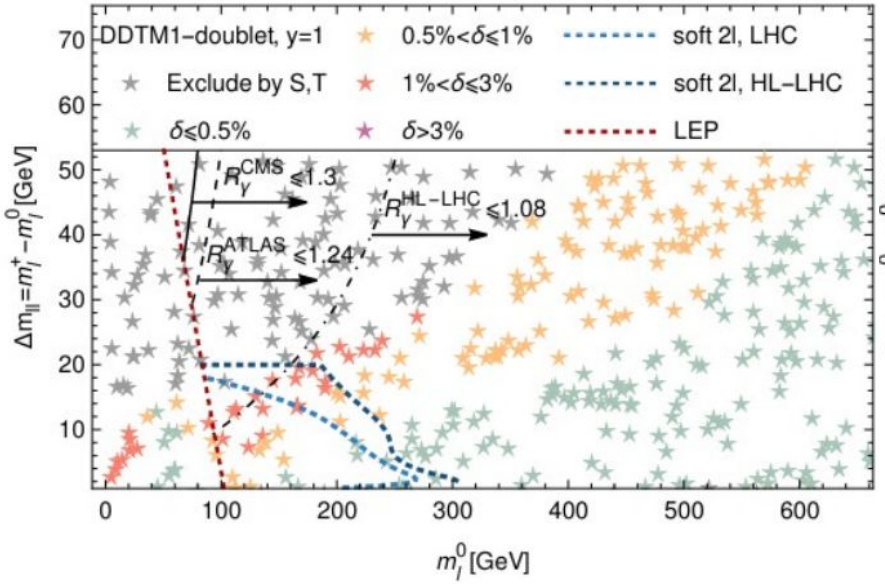


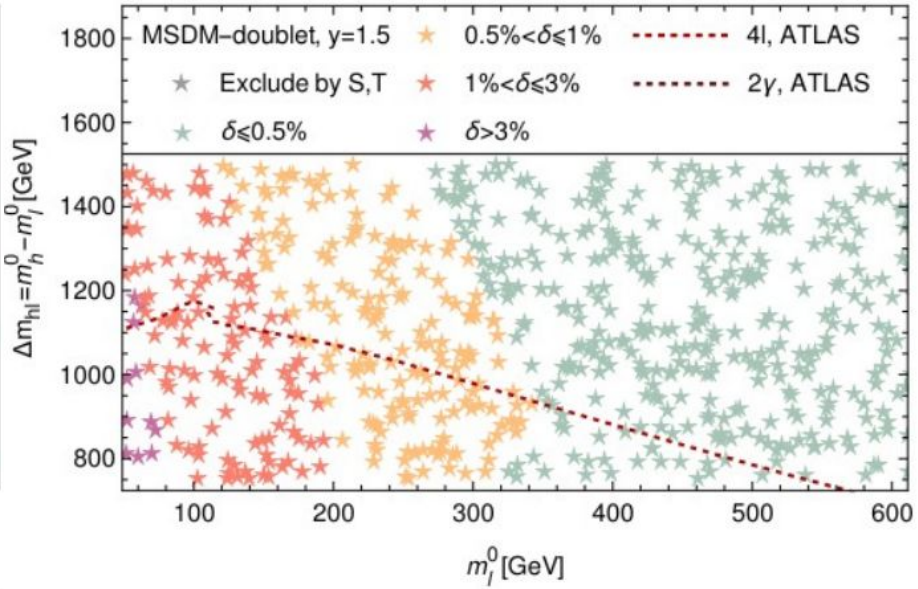
- MELA functional within FCC framework.
  - Pending review to be officially incorporated.
- Update to this study using discriminants in the works!
- Plans to extend this study:
  - $Z \rightarrow e^+e^-$ final state
  - Alternative couplings: $f_{CP}^{HZ\gamma*}$, $f_{CP}^{H\gamma*\gamma*}$
- MELA can probe couplings besides f_{CP}^{HZZ}.
  - $f_{CP}^{HZ\gamma*}$, $f_{CP}^{H\gamma*\gamma*}$ studies also possible within FCC framework.

[Nicholas Pinto, Johns Hopkins University]

Sensitivity to BSM fermions from Higgs precision

- Lightest fermion can (but need not) be DM
- Larger parameter region and wider set of (HL-)LHC constraints than prev. work

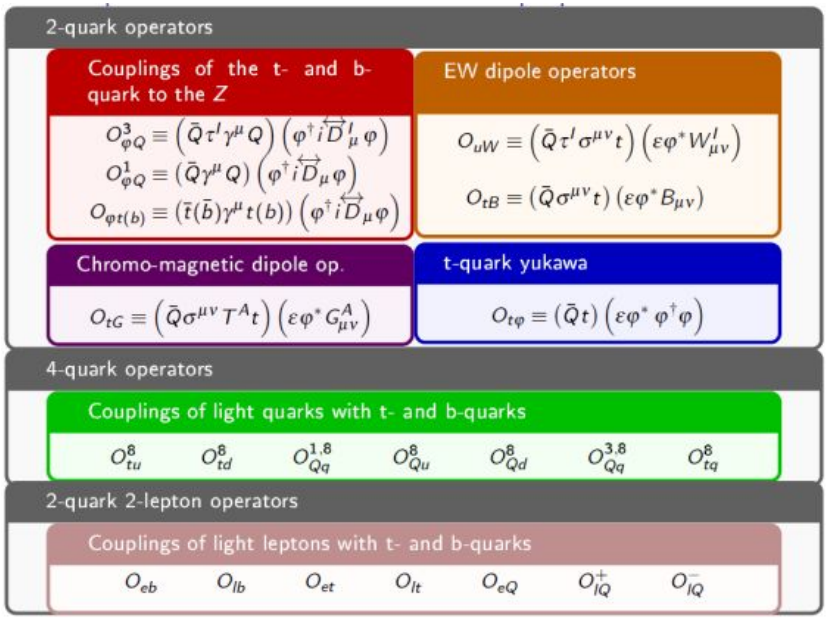


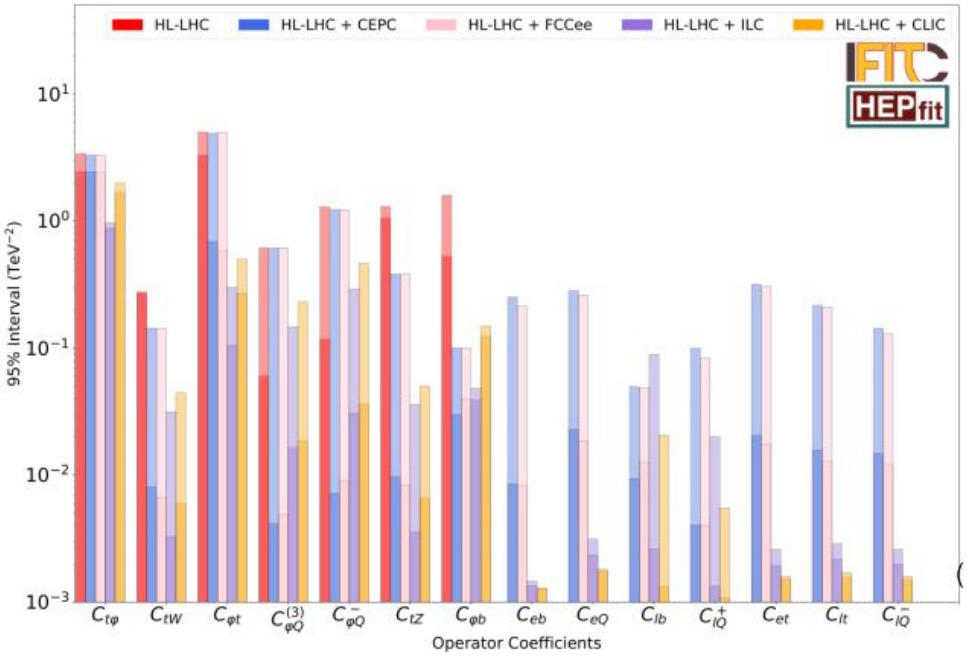


- New parameter space probed by Higgs factories (beyond current and projected HL-LHC bounds)
  - in particular for Majorana models
  - also in regions of small Δm

[Ayres Freitas, University of Pittsburgh]

Top Quark Couplings Prospects



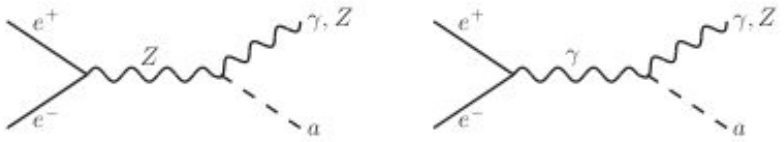


- Optimal observables maximally exploit the information in the fully diferential $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ dist. [1807.02121], constraining:
  - The 2-fermion coefficients: $C^-_{\varphi Q}$, $C_{\varphi t}$, C_{tW} , C_{tZ}
  - The 2-quark 2-lepton: C^-_{lQ} , C_{lt} , C_{et} , C_{eQ}
  - Two different energies above the top-pair threshold are needed to constrain all the 2- and 4-fermion operators (constant/linear vs quadratically with energy)

[Fernando Cornet-Gomez, Case Western Reserve University]

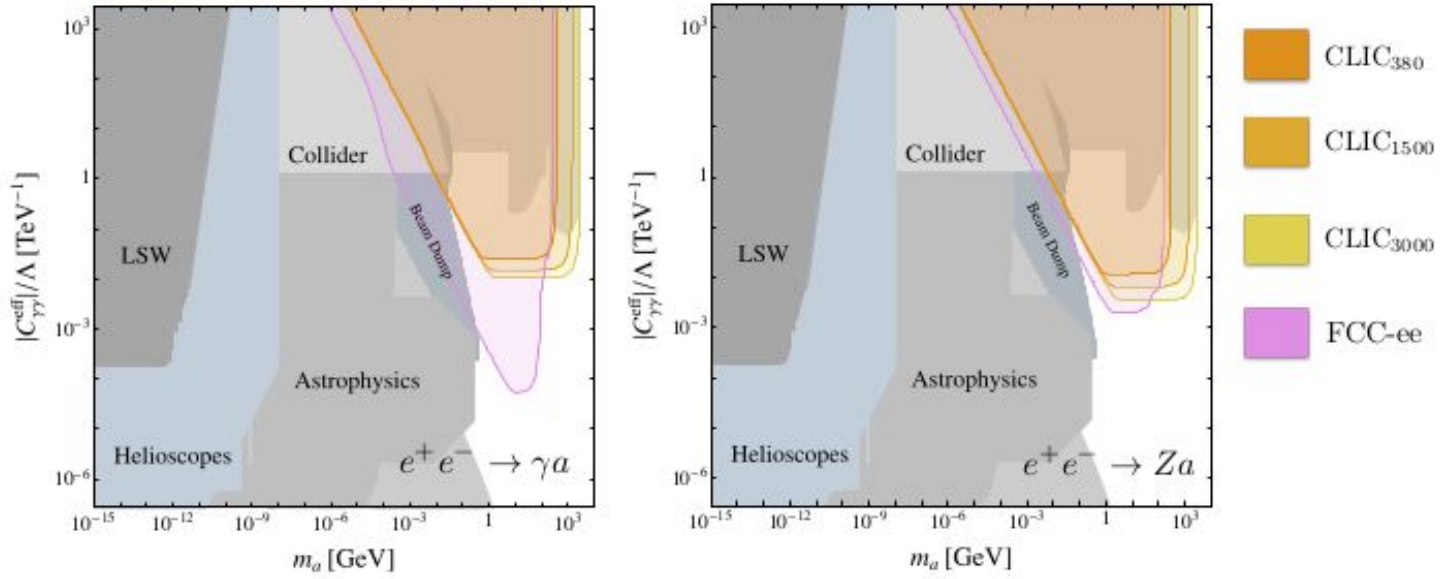
ALPs at the FCC-ee

- ALP associated production with a photon or Z



- ALP decay into photons

[Bauer, Heiles, Neubert, Thamm: 1808.10323]



[see also Tian, Wang, Wang: 2201.08960]

[Andrea Thamm, University of Massachusetts]

Theory brainstorming

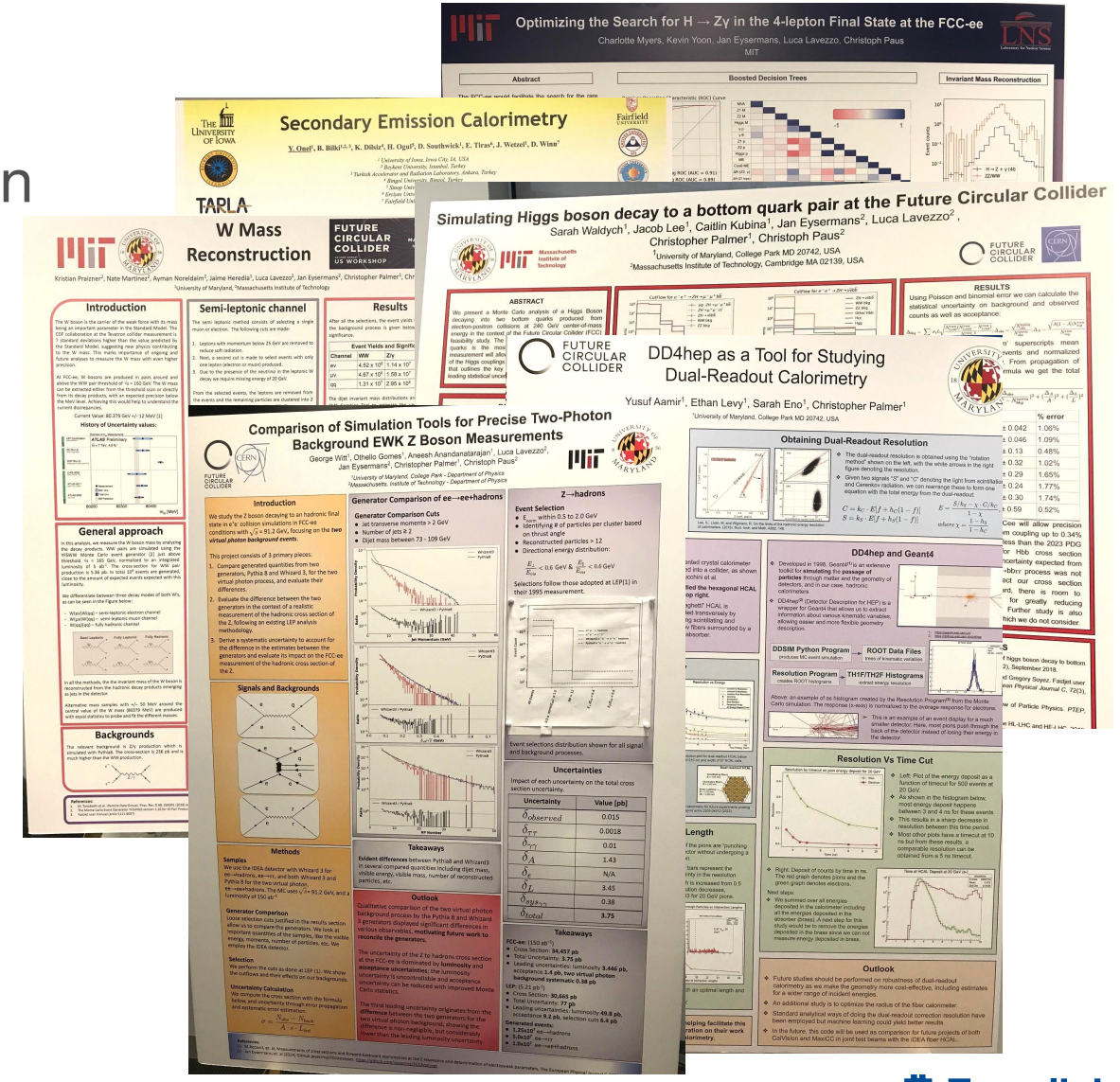
- Various interesting questions
  - Exploration of parasitic detectors at FCC to maximize the physics potential
  - Flavor physics and EW physics are largely intertwined (seen e.g. in arXiv:2311.00020, ↗ M. McCullough's talk)
  - How beneficial would a 125 GeV run be and under which circumstances?
- Theory effort in U.S. might benefit from more coherence
  - Especially as experimental community begins to invest
  - Some theory projects might require larger, organized effort
  - Many physics scenarios overlooked or not fully explored

Poster session contributions

Discussion of physics opportunities in

- H→bb
- H→Zγ
- γγ→qq
- W mass
- Calorimetry

Promising studies, also indicating the need for more theory & MC support



- FCC-ee is a new frontier, both from experimental and from theoretical perspective
- A path towards understanding big physics questions formulated during Snowmass 2021
- Many exciting opportunities

Many thanks to the organizers for an exciting and inspiring workshop!