Krakow, Jan. 23-27, 2023: https://indico.cern.ch/event/1176398/

— Summary of Physics Talks —

Christophe Grojean

General remarks

My personal impressions

- 196 registrants (incl. 104 registrants for remote participation).
- About 50+ participants in the room at any given time, and between 20-30 people connected on zoom in addition.
- Good participation of different subgroups, incl. young people.
- Many people made the efforts to spend a significant fraction of the week in Krakow and not simply coming for their talks/sessions.
- Participants appreciated to be able to get a global picture of what is going on even if some of the talks were not directly relevant for what they are doing. They got convinced that FCC is a (very) concrete project.
- It was great to have the opportunity that we very much missed in the past 3 years to meet in person. In Alain Blondel’s words: “great to be in the same place with people and finding again the chats, random walk between essential topics and people, direct questions and replies in private chat after the talks.”

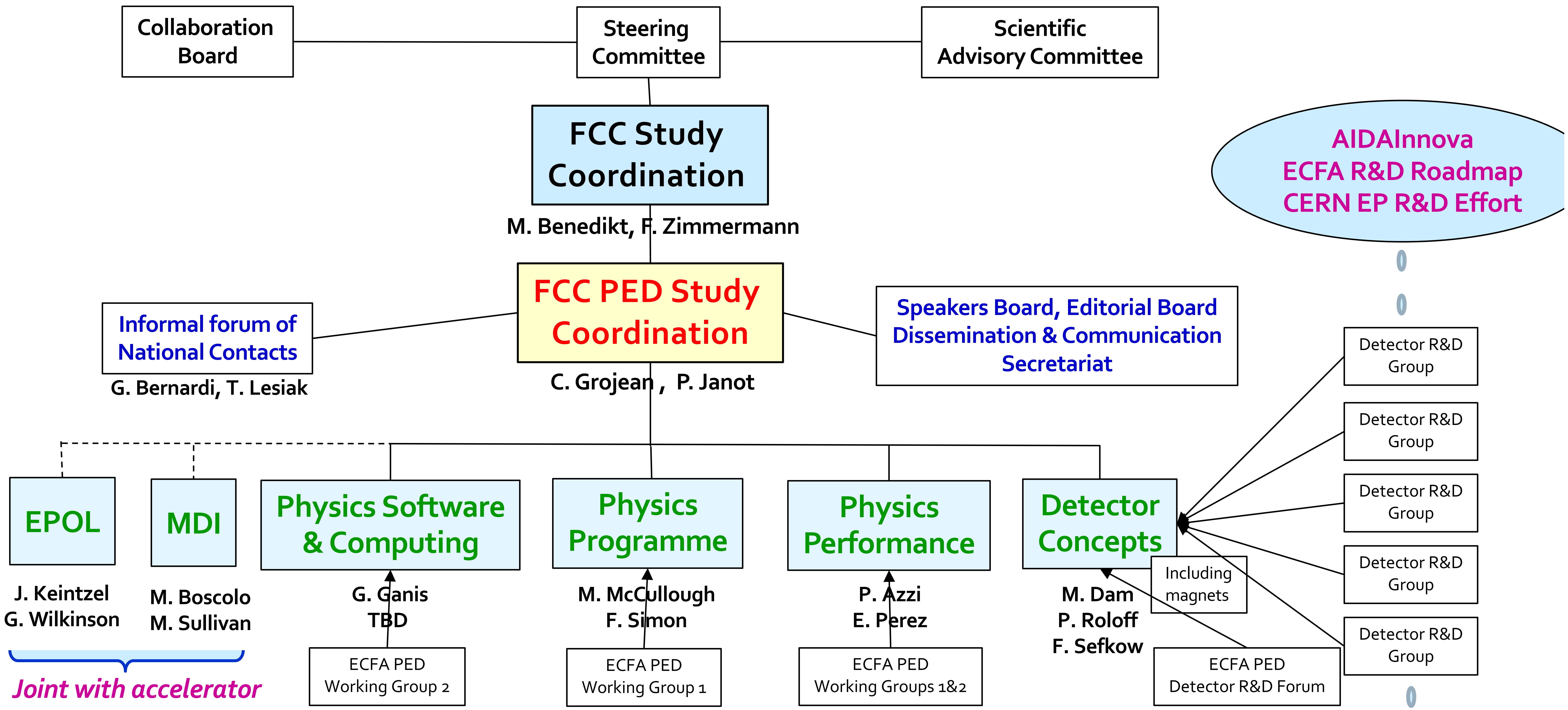
A Dense Programme

- 89 talks incl. 22 talks on zoom
- 33h20’ of talks/discussions
- 39 talks (15h30’) for physics programme/performance
  - QCD
  - EW
  - Higgs
  - Flavour
  - BSM

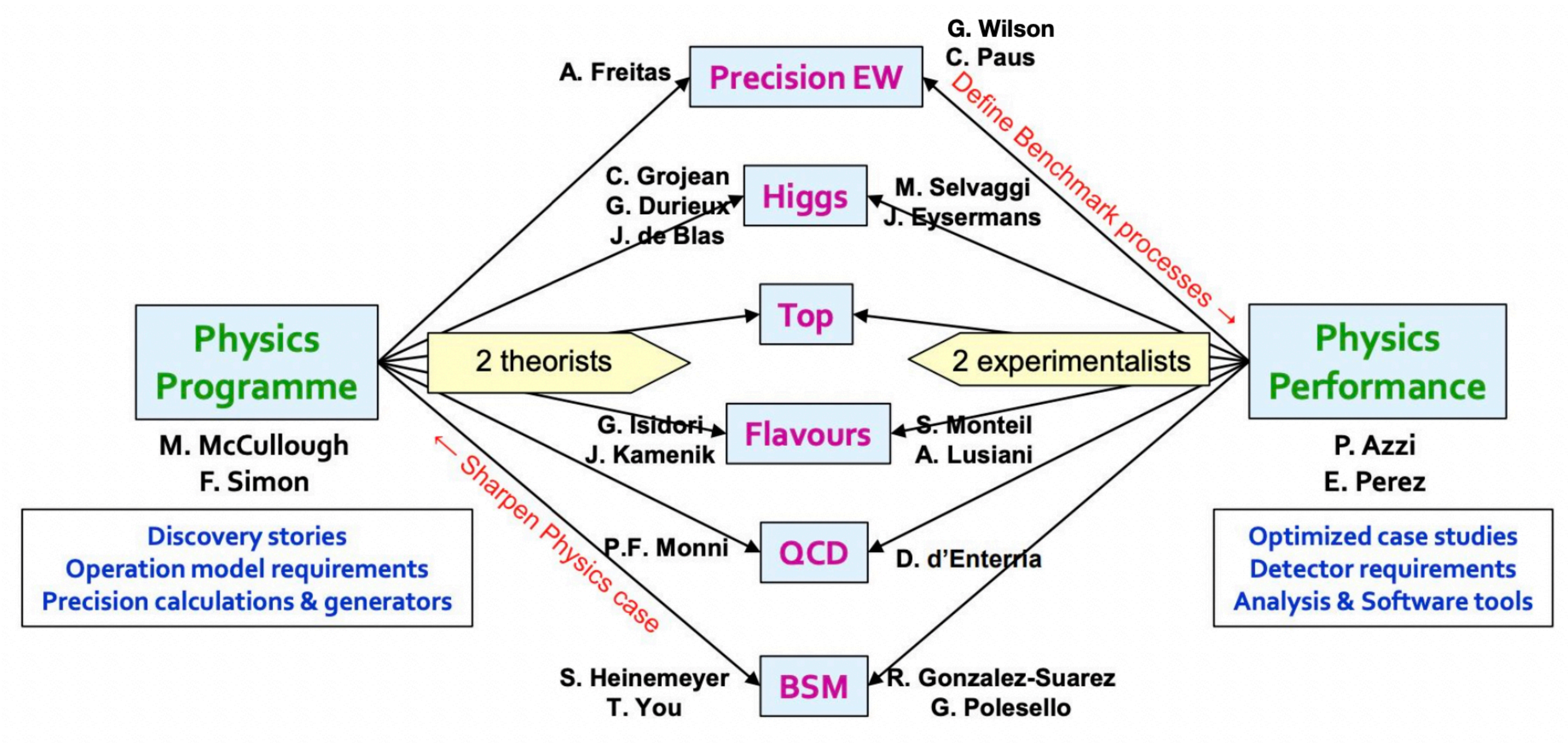
Krakow FCC physics week 2023 - Tentative Schedule

Day	Session	Speaker	Title	Remote?	Confirmed	Topics
Monday 23.01	**Opening**	Tadeusz Lesiak (IFJ PAN, PL) - 5'	Welcome		1	opening
	Mon 23.01	Marcin Chrząszcz (IFJ PAN, PL) - 10'	Welcome and local information		1	opening
	8:45-10:45	Michael Benedikt (CERN, CH)- 20'+10'	Status of FCC feasbility study		1	opening
		Aidan Robson (Edinburgh, UK) - 25'	ECFA Higgs factory studies and FCC feasibility studies: synergies and complementarities	1	1	opening
		Roberto Franceschini (Rome III, IT) - 20'+10'	FCC and muon collider: synergies and complementarities		1	opening
		Sarah Eno (Maryland U, US) - 15'+5'	US contributions to FCC after Snowmass		1	opening
	Chair: Alain Blondel (TBC)					
	Higgs	Michele Selvaggi (CERN, CH) - 20'	Higgs physics experimental overview		1	Higgs
	Mon 23.01	Jorde de Blas (Granada, ES) - 25'	Higgs coupling fits		1	Higgs
	11:15-12:50	Andrew Mehta (Liverpool U, UK) - 25'	Higgs to invisible	1	1	Higgs
		Ennio Salvioni (Padova, IT) - 25'	Geganbauers & Higgs Self-coupling		1	Higgs
	Chair: Gauthier Durieux					
	EW	Gauthier Durieux (CERN, CH) and Tevong You (KCL, UK) ' 40'	Physics motivations		1	opening
	Mon 23.01	Alain Blondel (LPNHE, FR) - 25'	Introduction to the session and the example of the Z lineshape		1	EW
	14:10-16:30	Giovanni Guerrieri (Udine U, IT) - 25'	Afb (focus on discussion of systematics control and evaluation)		1	EW
		Johannes Bluemlein (DESY, DE) - 25'	High-precision QED initial state corrections for e+e−→ γ∗/Z∗e+e−→ γ∗/Z∗ annihilation	1	1	EW
		Jean-Claude Brient (LLR, FR) - 25'	Measurement of tau polarisation	1	1	EW
	Chair: Roberto Tenchini					
	EPOL	Guy Wilkinson (Oxford, UK) - 30'	Status and prospects for the ECAL measurements		1	EPOL
	Mon 23.01	Maciej Skrzypek (INP Krakow, PL) - 25'	Study of Theoretical Luminosity Precision for Electron Colliders at Higher Energies		1	EPOL
	17:00-19:10	Angeles Faus-Golfe (IJCLab Orsay, FR) - 25'	Status and progress on monochromatization studies	1	1	EPOL
		Emmanuel Perez (CERN, CH) - 25'	Role of timing measurements in ECAL studies		1	EPOL
		Graham Wilson (Kansas U., US) - 25'	Studies with dileptons: machine parameters and EW studies	1	1	EPOL
	Chair: Alain Blondel					
TUESDAY 24.01	**SW**	Gerardo Ganis (CERN, CH) - 20'	Introduction and statuts of things		1	SW
	Tues 24.01	Gerardo Ganis (CERN, CH) - 25'	Key4hep and FCC software		1	SW
	9:00-10:35	Juraj Smiesko (CERN, CH) - 25'	Analysis and visiualisation		1	SW
		Andre Sailer (CERN, CH) - 25'	Tools for Monte Carlo productions		1	SW
	Chair: Paolo Giacomelli					
	Detector	Felix Sefkow (DESY, DE) - 20'	Intro by conveners		1	Detector
	Tues 24.01	Roberto Ferarri (INFN Pavia, IT) - 25'	Calorimetry		1	Detector
	11:00-13:00	Anna Collaleo (Universita e INFN Bari, IT) - 25'	Gaseous detectors	1	1	Detector
		Nicolo Cartiglia (INFN Torino, IT) - 25'	Silicon detectors	1	1	Detector
		Paul Colas (SPP Saclay, FR) - 25'	TPC operability		1	Detector
	Chair: Franco Bedeschi					
	BSM/Higgs	Giacomo Polesello (INFN, IT) - 20'	Intro by conveners		1	BSM
	Tues 24.01	Ben Allanach (Cambridge U., UK) - 25'	Exploring Z' models at FCC		1	BSM
	14:30-16:30	Biswajit Karmakar (U. Silesia, PL) - 25'	Z decay and heavy neutrinos at FCC-ee		1	BSM
		Simone Blasi (VUB, BE) - 25'	Electroweak phase transition		1	BSM
		Dave Sutherland (Glasgow, UK) - 25'	SMET vs HEFT		1	Higgs
	Chair: Ennio Salvioni					
	MDI/Detector	Manuela Boscolo (LNF, IT) - 20'	Intro by conveners		1	MDI
	Tues 24.01	Francesco Fransesini (LNF, IT) - 25'	Mechanical model of FCC-ee MDI		1	MDI
	17:00-19:00	Franco Bedeschi (INFN Pisa , IT) - 25'	Detectors integration in the MDI area		1	MDI
		Andrea Ciarma (CERN, CH) - 25'	Status and Perspectives for the FCC-ee Detector Backgrounds	1	1	MDI
		Anna Zaborowska (CERN, CH) - 25'	FCC-hh detector concept		1	Detector
	Chair: Gerardo Ganis					
WEDNESDAY 25.01	**QCD**	David d'Enterria (CERN, CH) - 20'	Intro by conveners		1	QCD
	Wed 25.01	Stefan Kluth (MPI Munich, DE) - 25'	Review of strong coupling at FCC-ee	1	1	QCD
	9:00-10:35	Pier Monni (CERN, CH) - 25'	Precision calculations at FCC-ee	1	1	QCD
		Simon Plaetzer (U. Graz, AT) - 25'	Monte Carlo challenges for FCC-ee and progress		1	QCD
	Chair: Andrzej Siodmok					
	Jt Detector/SW	Brieuc Francois (CERN, CH) - 25'	Strategy and plans for detector software		1	D&SW
	Wed 25.01	Martin Tat (Oxford, UK) - 25'	ARC: progress update and plans towards full simulation		1	D&SW
	11:00-13:05	Vincent Boudry (LLR, FR) - 25'	Modelling signal digitisation for test calorimeters: the CALICE experience	1	1	D&SW
		Riccardo Farinelli (INFN Ferrara, IT) - 25'	Modelling signal digitisation for trackers	1	1	D&SW
		Leila Freitag and Armin Ilg (UZH, CH) - 25'	Performance of an ALICE ITS3-like vertex detector for FCC-ee and progress on the IDEA vertex d		1	Detector
	Chair: Michele Selvaggi					
	Flavour/BSM	Stephane Monteil (LPC, FR) - 20'	Intro by conveners	1	1	Flavour
	Wed 25.01	Jure Zupan (Cicinnati, US) - 25'	Higgs and flavor (with a focus on FCNC)		1	Flavour
	14:05-16:30	Luiz Vale Silva (Valencia U, ES) - 25'	Projections of CKM global fits and meson mixings		1	Flavour
		Seddigheh Tizchang (IPM, IR) - 25'	Top FCNC	1	1	BSM
		Giulia Ripellino (Uppsala U., SE) - 25'	LLP experimental perspectives at FCC-ee: ALPS and exotic Higgs decays	1	1	BSM
		Suchita Kulkarni (Graz. U, AT) - 25'	LLP experimental perspectives at FCC-ee: HNL		1	BSM
	Chair: Giacomo Polesello					
	MDI	Mogens Dam (NBI, DK) - 25'	Summary of review on civil engineering and technical infrastructure requirements for FCC experimental sites		1	MDI
	Wed 25.01	Andrea Gaddi (CERN, CH) - 25'	Lessons learnt from CMS IR mock-ups	1	1	MDI
	17:00-19:05	Andrey Abramov (CERN, CH) - 25'	IR beams losses		1	MDI
		Kevin D.J. Andre (CERN, CH) - 25'	FCC-ee synchroton radiation collimators and masks	1	1	MDI
		Nikkie Deelen (CERN, CH) - 25'	Detector Stray Magnetic Fields		1	MDI
	Chair: Manuela Boscolo					
THURSDAY 26.01	**QCD**	Andrzej Siodmok (IPN, PL) - 25'	Modeling of hadronization		1	QCD
	Thurs 26.01	Loukas Gousksz (CERN, CH) - 25'	Flavour jet tagging at FCC-ee with ParticleNet		1	QCD
	9:00-9:50	~~Eduardo Ploerer (VUB/UZH, BE/CH) - 25'~~	~~Multi-flavour taggers from transformer graph DNN~~		~~cancelled~~	~~QCD~~
	Chair: David d'Enterria					
	Tau	Lukas Allwicher (U. Zurich, CH) - 25'	Universality tests in tau decays		1	Flavour
	Thurs 26.01	Alberto Lusiani (SNS, IT) - 25'	Tau lifetime		1	Flavour
	10:20-12:25	Tristan Miralles (U. Clermont Auvergne, FR) - 25'	B to K* tau tau		1	Flavour
		Zbigniew Was (INP Cracow, PL) - 25'	On precise tau simulations		1	Flavour
		Priyanka Lamba (Warsaw U., PL) - 25'	Quantum information and CP measurement in H->tau tau		1	BSM
	Chair: Matthew McCullough					
	IFNC	Gregorio Bernardini (APC, FR) - 5'	Introduction		1	IFNC
	Thurs 26.01	Patrizia Azzi (INFN Padova, IT) - 15'	Opportunities in FCC Physics and Performance Studies		1	IFNC
	13:30-15:10	Mogens Dam (NBI, DK) - 15'	Opportunities in FCC Detector concepts, R&D, MDI, EPO		1	IFNC
		Gerardo Ganis (CERN, CH) - 15'	Opportunities in FCC Software developments		1	IFNC
		All - 10'	Questions and discussions		1	IFNC
		All national contacts - 30'	Summary of activities in FCC by country		1	IFNC
		Gregorio Bernardini (APC, FR) - 10'	Summary of the activities and prospects		1	IFNC
	Chair: Sarah Eno					
FRIDAY 27.01	**Higgs**	Shankha Banerjee (CERN, CH) - 25'	Diboson at FCC-hh	1	1	Higgs
	Fri 27.01	Eleni Vryonidou (Manchester, UK) - 25'	Higgs/top interplay		1	Higgs
	9:00-10:40	Ang Li (APC, FR) - 25'	Higgs mass and ZH cross-section		1	Higgs
		Giovanni Marchiori (APC, FR) - 25'	Higgs to hadrons in ZH with Z→ll/νν		1	Higgs
	Chair: Jorge De Blas					
	EW	Paolo Azzurri (INFN Pisa, IT) -25'	Measurement of the W mass	1	1	EW
	Fri 27.01	Lisong Chen (Karlsruhe, DE) - 25'	GRIFFIN: A C++ library for EW radiative corrections in fermion scattering and decay processes		1	EW
	11:10-12:50	Lars Roehrig (Dortmund U., DE and LPC, FR) - 25'	Synergies in top-beauty and a first look at b-tagging with exclusive decays		1	EW
		Qian Song (Pittsburgh U, US) - 25'	NNLO corrections to H+Z - 2209.07612	1	1	EW
	Chair: Alberto Lusiani					
	Future plans	Marc-André Pleier (BNL, US) - 15'	Brookhaven National Lab contributions to the FCC-ee		1	clsoing
	Fri 27.01	Matthew McCullough (CERN, CH) - 15'	Future plans: physics program		1	closing
	14:00-15:50	Patrizia Azzi (INFN Padova, IT) - 15'	Future plans: physics performance		1	closing
		Mogens Dam (NBI, DK) - 15'	Future plans: Detectors		1	closing
		Gerardo Ganis (CERN, CH) - 15'	Future plans: Software		1	closing
		Jacqueline Keintzel (CERN, CH) - 15'	Future plans: EPOL	1	1	closing
		Manuela Boscolo (LNF, IT) - 15'	Future plans: MDI		1	closing
		Christophe Grojean (DESY, DE) and Patrick Janot (CERN, CH) - 5'	Close-up		1	closing
	Chair: Patrick Janot					
		# Talks foreseen →	90	22	89	
				↑ # remote	↑ # confirmed	

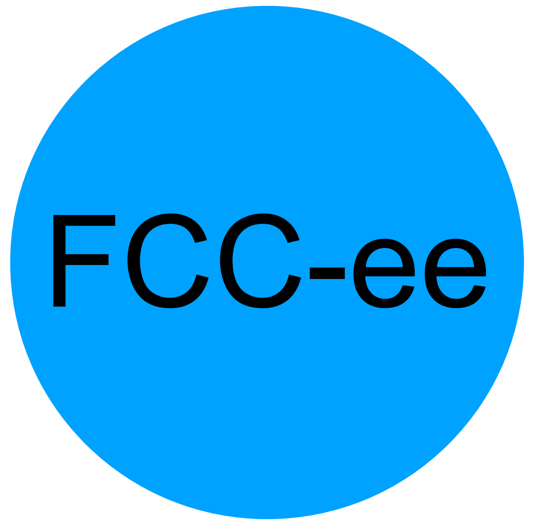
FCC Organisation



FCC Physics Organisation



FCC Physics Programme



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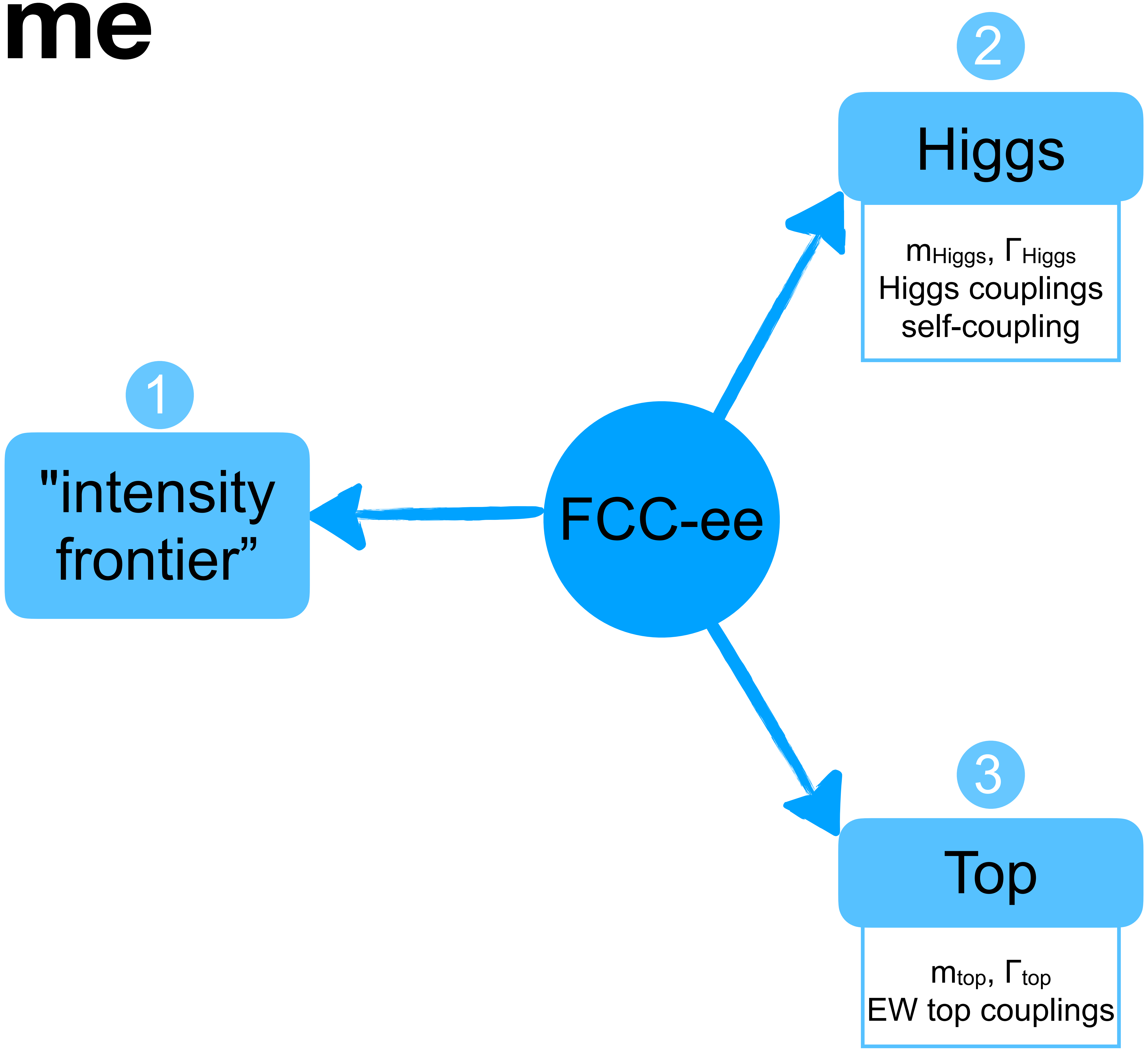

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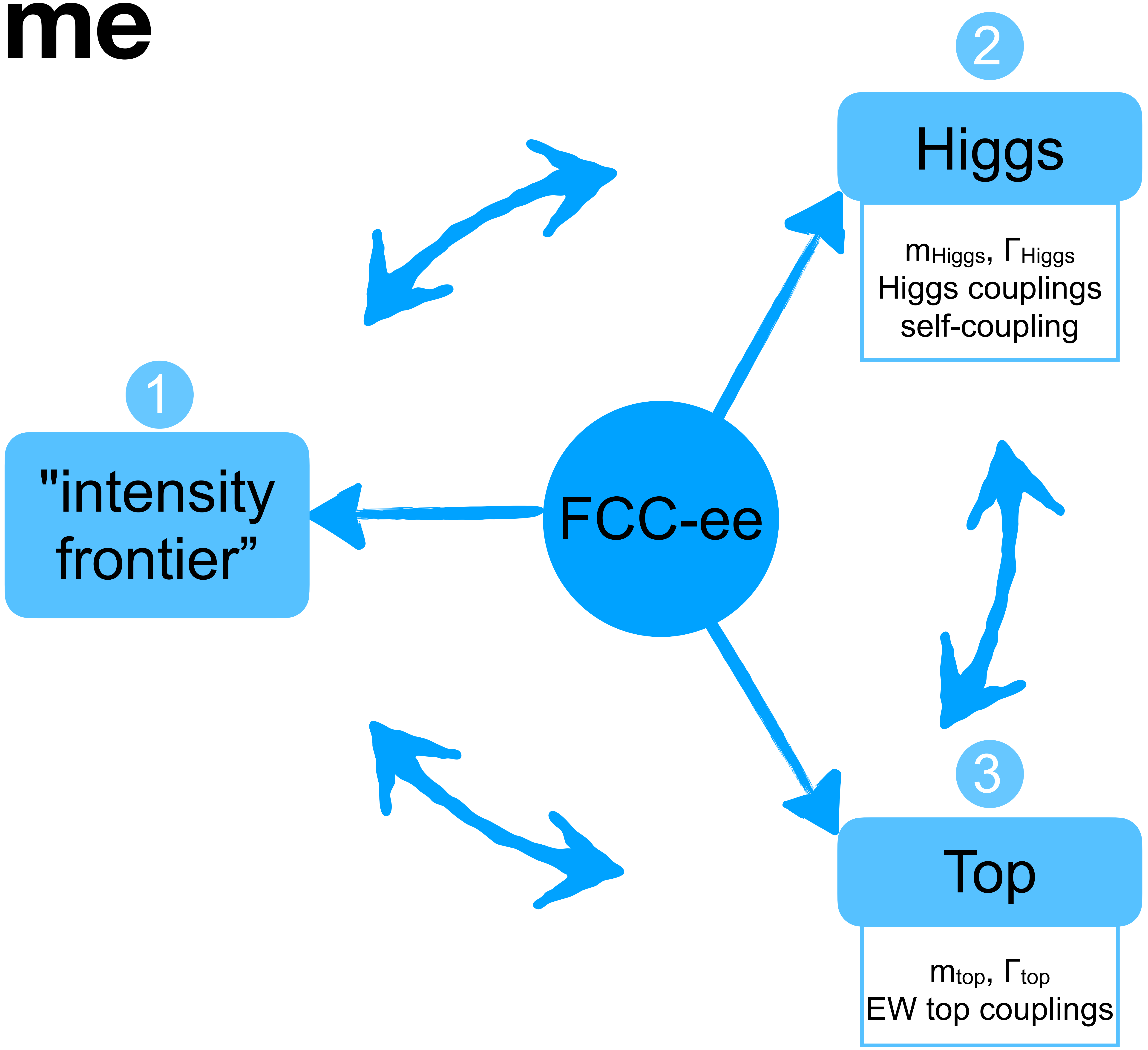

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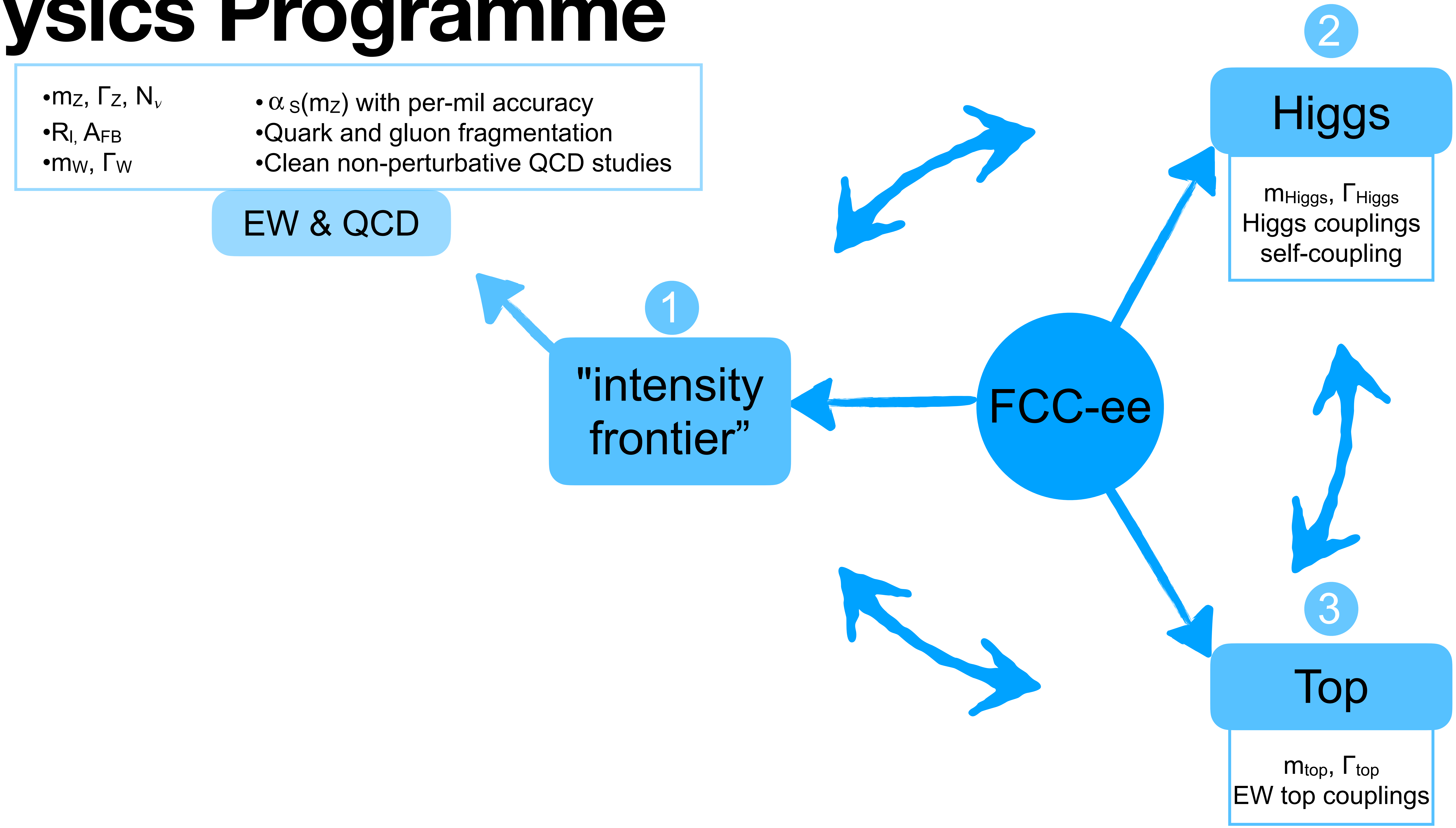

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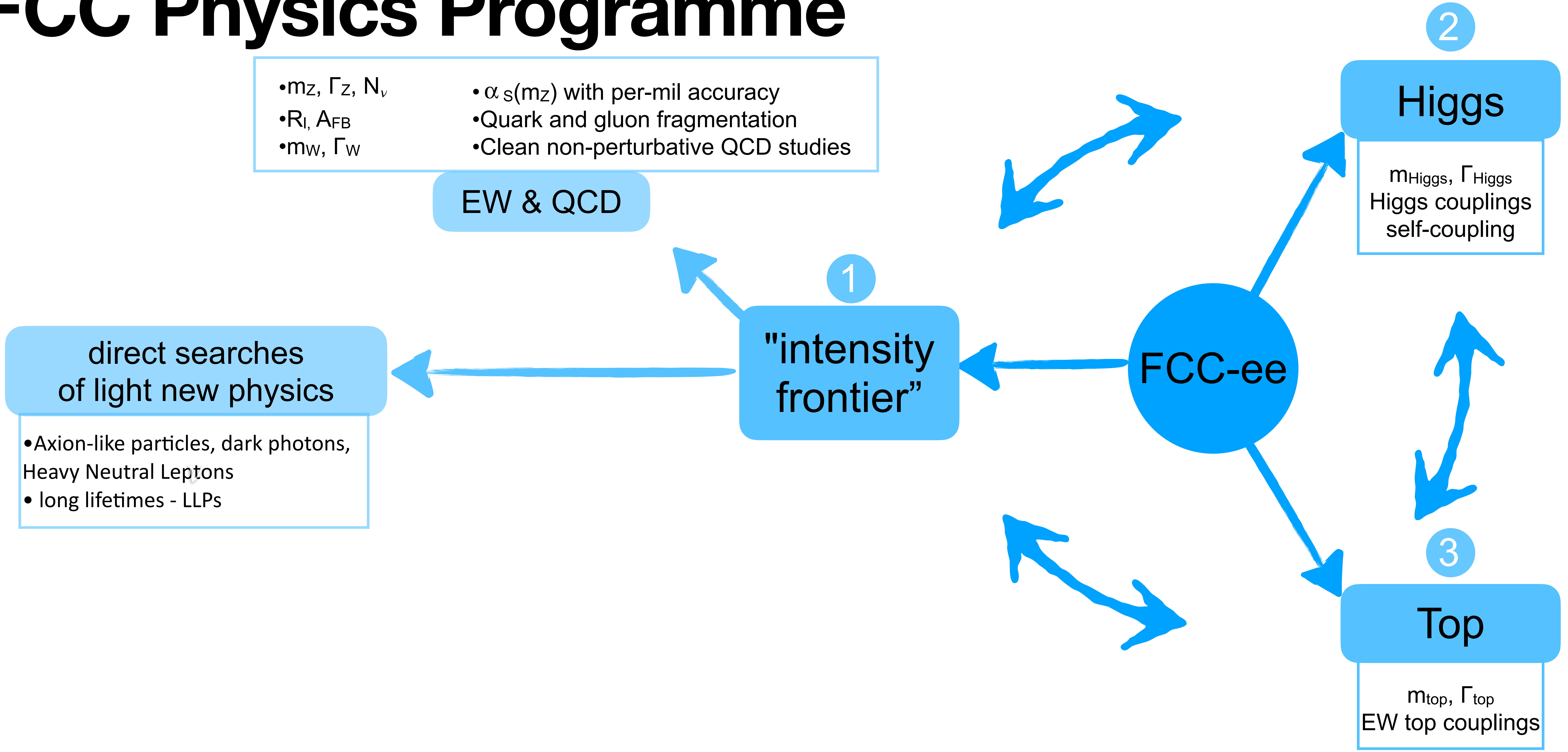

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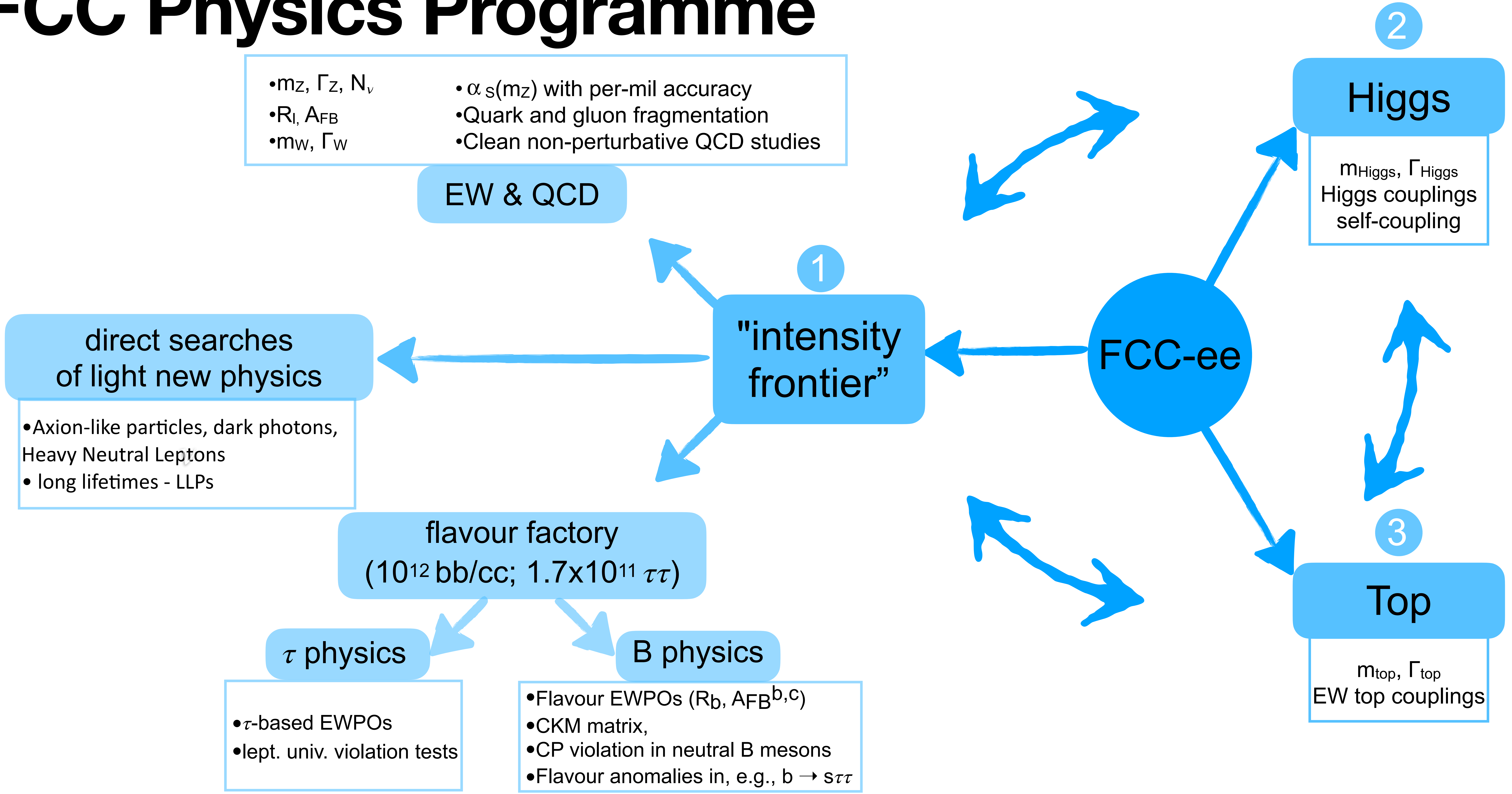

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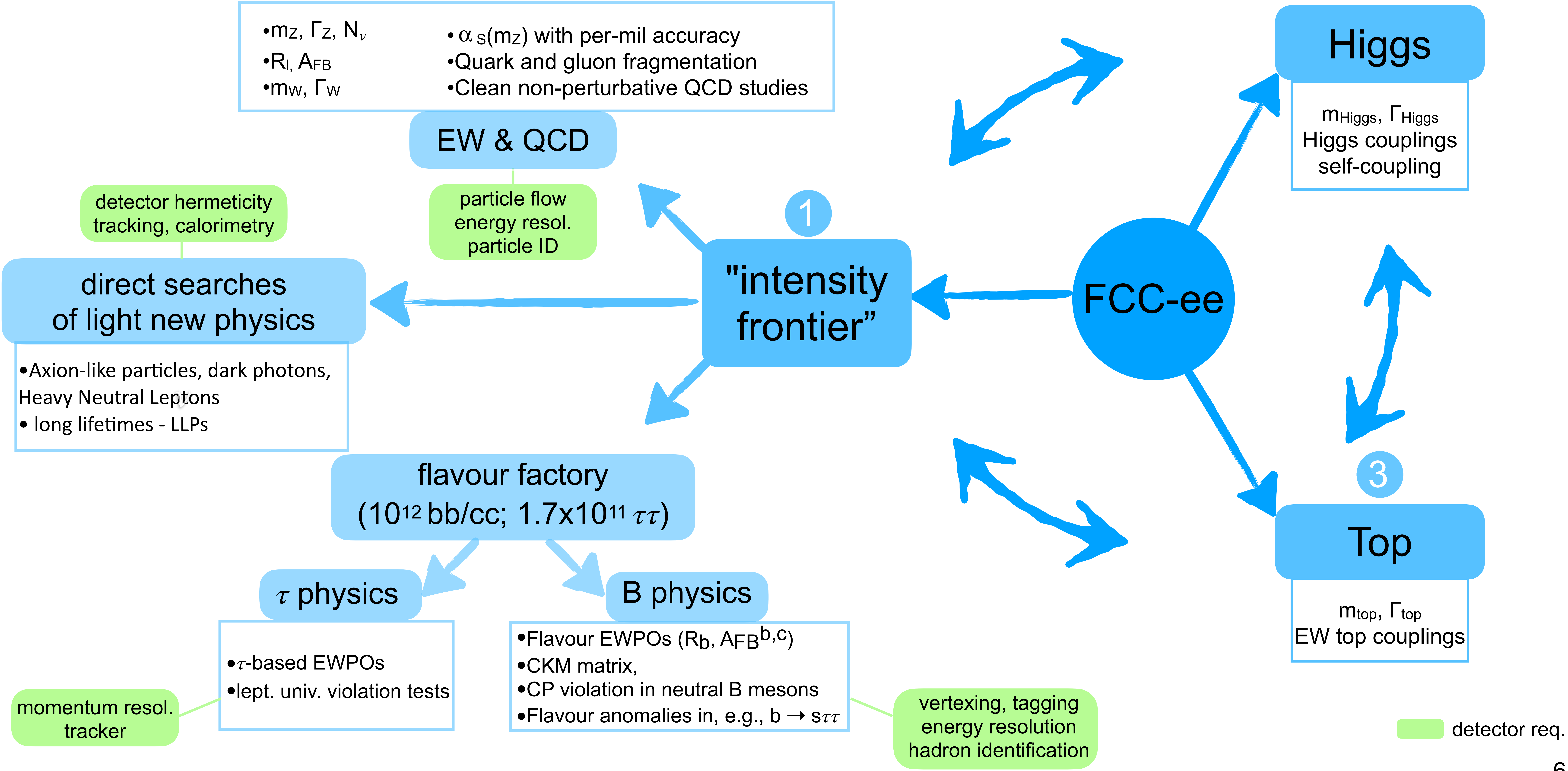


Physics Performance

where are we now – Active case studies

- M(H) and σ(ZH) in HZ, $Z \rightarrow ll/jj$
- Invisible Higgs
- Higgs couplings (bb, cc, s, gg)
- $ee \rightarrow H$ coupling, s-channel prod.

- A_{FB}(bb,cc)
- *aTGCs with WW*

- Anomalous coupling of the top (FCNC) at $\sqrt{s}=240$ and $\sqrt{s}=365$GeV
- EFT interpretations
- *Electroweak Couplings*

- $B_u/B_c \rightarrow \tau\nu$ (paper under review)
- $B_s \rightarrow D_s K$
- $B_s \rightarrow K^*\tau\tau$
- $B_s \rightarrow \phi\phi$
- $B^+ \rightarrow D^0 K^+$
- $B \rightarrow s\nu\nu$

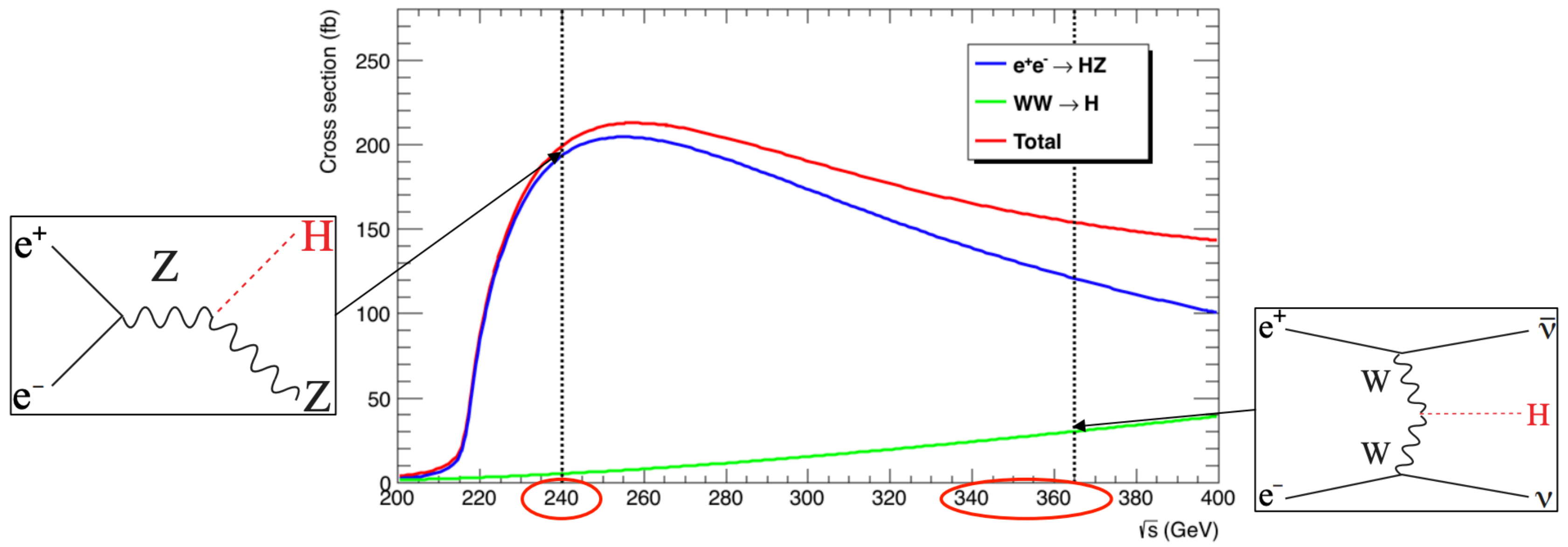
- Heavy Neutral Leptons
- ALPS
- Exotic Higgs

Many talks given at this Physics Week

Detector Requirements from Physics Studies

- → from Higgs mass: Track momentum resolution
- → from Higgs hadronic decays: Calorimeter resolution
  - for now using Delphes to smear the resolution of jets, missing mass, etc.
- → from B^0->pi^0pi^0, (H->$\gamma\gamma$?): ECAL resolution
- → from B->K*tautau: vertexing resolution
- → from invisible BSM final states: hermeticity
- → from BSM LLP studies: several options, need to define clear benchmarks

Higgs Measurements



	$L = 5\ ab^{-1}$	$L = 1.5\ ab^{-1}$
2IP	$ZH = 10^6$	$ZH = 2.5\times10^5$
	$VBF = 2\times10^4$	$VBF = 5\times10^4$

- Intrinsic properties
  - mass   O(few MeV) precision on m_H
  - ZH cross section (decay mode independent)   O(<%) on cross-section
  - width
  - self-coupling (FCC-ee/hh)
    - 19% kl alone vs 33% full (EFT projected) with 2IPs
    - 14% kl alone vs 24% full (EFT projected) with 4IPs

- Higgs couplings
  - vector bosons
  - jets
    - bb/cc/gg/ss
  - electron (production)
  - taus
  - rare (μμ/γγ/Zγ)

Higgs Measurements

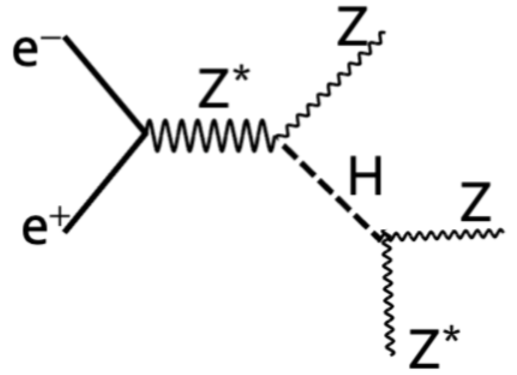
Higgs analyses that are already covered :

- $\sigma(ZH)$ and mH from Higgs recoil, $Z \to ll$
- Higgs couplings to b, c, g, s
- Higgs to invisible
- Higgs self-coupling from precise $\sigma(ZH)$ measurements at 240 and 365 GeV
- ee → H production in s-channel at 125 GeV
- *$\sigma(ZH)$ in $Z \to qq$ (starting – challenge = model independent σ meas.)*

Measurement	Requirements
Direct reconstruction of mH in hadronic final states	jet angular resolution, kinematic fits, b-tag effi & purity *(Possible link with meas. of σ(ZH) in Z → qq)*
Γ(H) • H → ZZ • ZH(WW), ZH(bb), $\nu\nu$H(bb)	• Lepton ID efficiencies; jet clustering algorithms, jet directions, kinematic fits • Visible and missing mass resolutions
HZγ coupling (production and decay)	photon identification, energy and angular scale
Rare decays: H → $\gamma\gamma$ and H → μμ (unlikely to do better than HL-LHC..)	Photon ID and resolution, track resolution
H → $\tau\tau$ and CP studies	Tau reconstruction, Pi0 id

Higgs width

❑ From ZH(ZZ) i.e. ZZZ* : $\sigma(ZH) \times BR(H \to ZZ)\ \alpha\ g^4_{HZZ} / \Gamma_H$



- 3 or 4 leptons: ~ bckgd free but low stat
- ≤ 2 leptons : key = jet clustering and kinematic fits
  - Many constraints: (E, p), M(H), M(Z) x2
  - Angles very well measured → Over-constrained fit for final state with 6 parton
  - Separation of signal from ZH(WW) background will set detector requirements

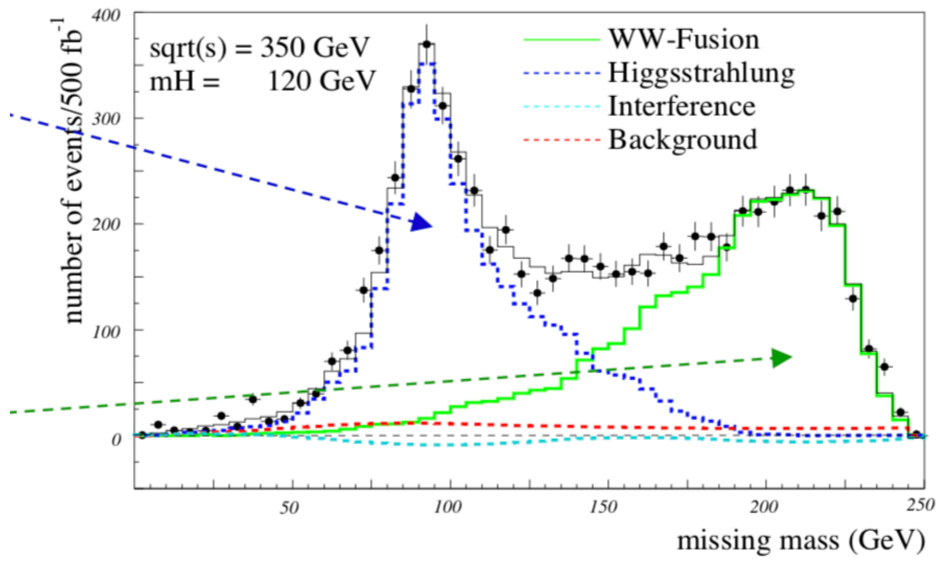
❑ From measurement of $\nu\nu$H(bb) events at 365 GeV :

$$\frac{\sigma_{WW\to H}\times BR(H\to bb)\times\sigma^2_{HZ}}{\sigma_{ZH}\times BR(H\to bb)\times\sigma_{ZH}\times BR(H\to WW^*)}$$

- Background esp. from $Z(\nu\nu)H(bb)$
  - Sig. & back: hadronic mass peaks at mH
  - Background: missing mass peaks at mZ

- Will set requirement on resolutions of hadronic mass, missing mass, Particle Flow reco, calorimeter granularity

From early ILC studies



Higgs → inv

- Estimate sensitivity of $H \to$ invisible using ZH events in e^+e^- simulated data
- Only studied $\sqrt{s} = 240$ GeV events
- Assume $\int L = 5$ ab^{-1}
- Using $Z \to ee$, $\mu\mu$, bb and qq channels
- Delphes simulation
- Backgrounds dilepton (Z), ZZ, WW and ZH
- Some diagrams not included in ZZ and WW samples labelled 'WZ'
- Will need dedicated four fermion samples with interference, but not expected to make a large difference to results
- SM $ZH \to \nu\nu\nu\nu$ treated either as a background when determining limits or a signal when determining precision on measurement
- Taus not studies yet but could be useful in reducing backgrounds

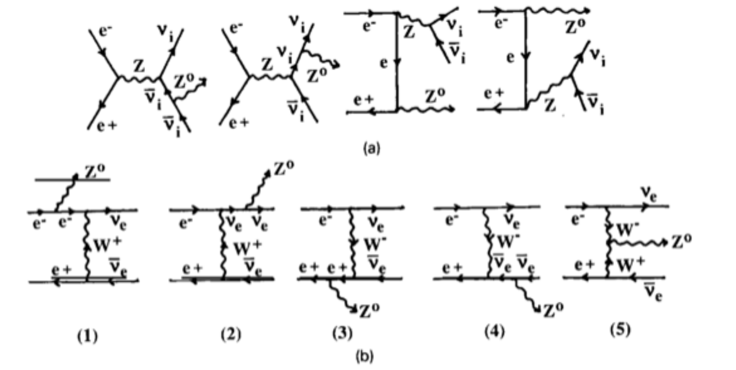
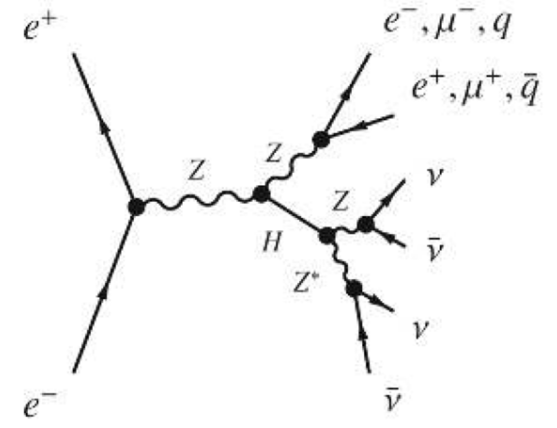
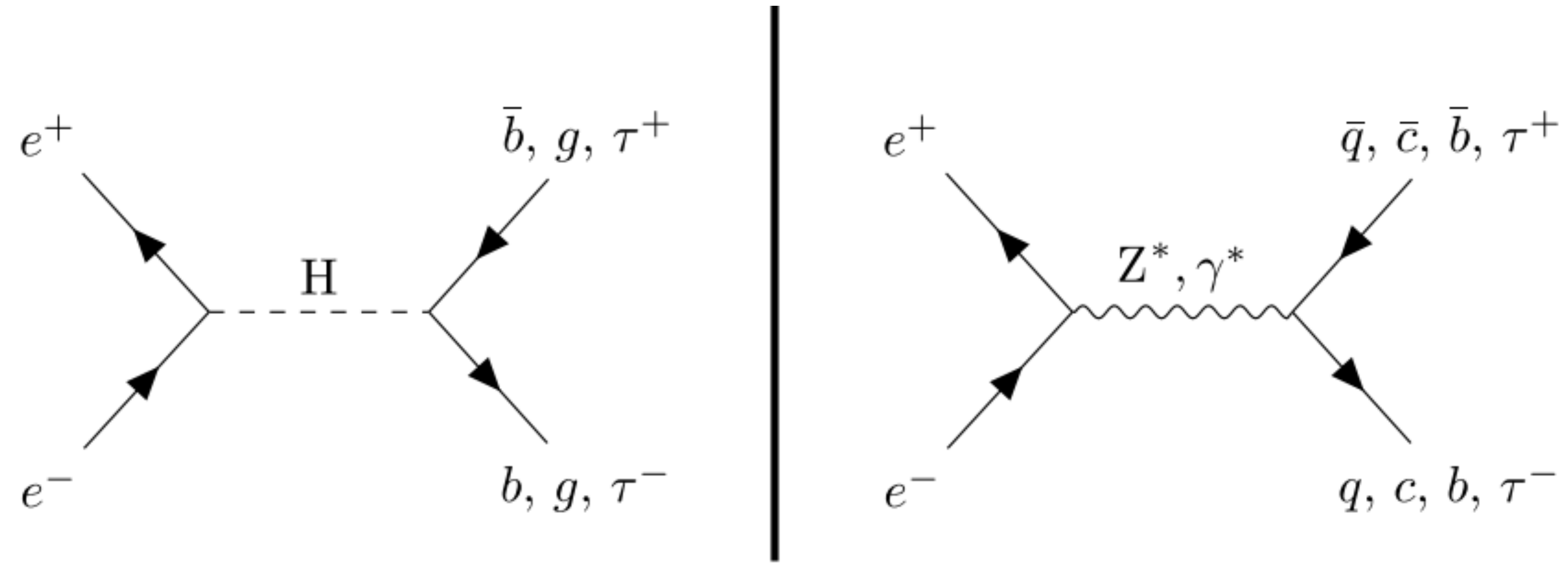


Fig. 1. Feynman diagrams contributing to the process $e^+e^- \to Z^0\nu\bar{\nu}$: (a) Z-exchange diagrams (with Z^0 in the s-channel); (b) W-exchange diagrams (with $W^{\pm}$('s) in the t-channel).



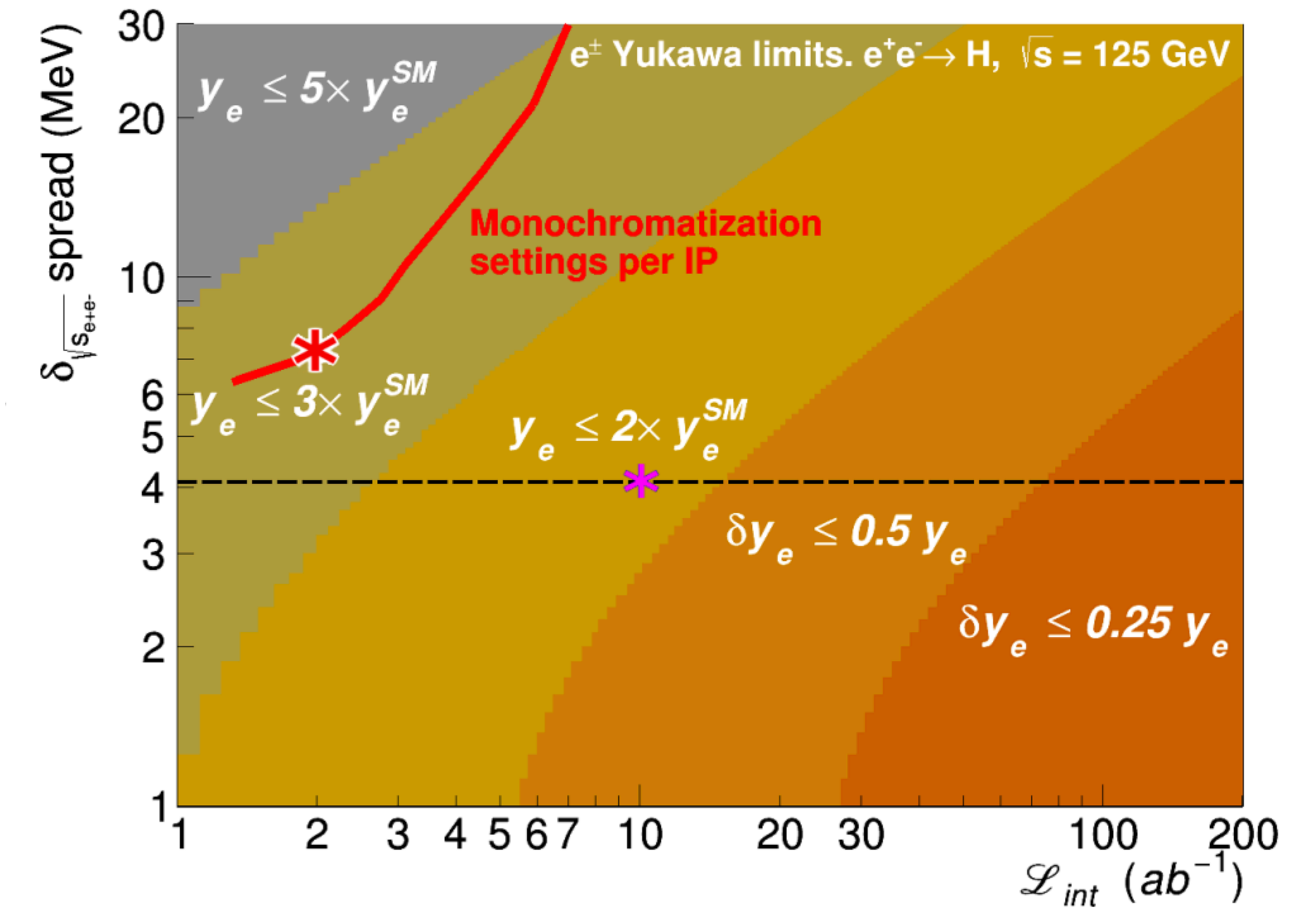
Reach SM precision of $\simeq 0.1\%$

Higgs: Electron Yukawa



Higgs decay channel	BR	$\sigma\times$ BR (ISR⊗spread incl.)
$H\to b\bar{b}$	58.2%	164 ab
$H\to gg$	8.2%	23 ab
$H\to\tau\tau$	6.3%×60%×60%	6.5 ab
$H\to c\bar{c}$	2.9%	8 ab
$H\to WW\to \ell\nu\,2j$	21.4%×67.6%×32.4%×2	26 ab
$H\to WW\to 2\ell\,2\nu$	21.4%×32.4%×32.4%	6.3 ab
$H\to WW\to 4j$	21.4%×67.6%×67.6%	28 ab
$H\to ZZ\to 2j\,2\nu$	2.6%×70.%×20.%×2	2 ab
$H\to ZZ\to 2\ell\,2j$	2.6%×70.%×10.%×2	1 ab
$H\to ZZ\to 2\ell\,2\nu$	2.6%×20.%×10.%×2	0.3 ab
$H\to\gamma\gamma$	0.23%	0.65 ab

- s-channel production with beam mono-chromatisation at √s = 125 GeV
  - ISR+FSR leads to 40% + with beam spread ~ Γ_H another 45% (σ ~ 280 ab^{-1})
    - plus potentially uncertainty on the Higgs mass
  - can hope for y_e < 1.6 y_e (SM) with 4 (2) years of running with 2 (4) IPs
    - potentially improve with exclusive ee→gg(cc)



EW & QCD Precision Measurements

	stat	w/ syst (*)	improvement
M_W	400 keV	500 keV	30
M_Z	4 keV	< 100 keV	> 20
Γ_Z	4 keV	< 25 keV	> 100
$\sin^2\theta_{eff}$ (τ pol)		3 10 $^{-6}$	60
$\alpha_{QED}(m^2{}_Z)$	3 10-5	3 10 $^{-5}$	4 (stat. lim. !)
Rb	3 10-7	2 10 $^{-5}$	30
alphaS(m2Z)	10-5	10-4	30
Mtop	20 MeV	40 MeV	12

- Huge statistics: very small stat errors call for very small syst uncertainties too.
  - E.g. acceptances, should be known to 10-4 – 10-5
- Goal: σ(exp syst) ≈ σ(stat)
- Work on theo. side also critical (and initiated, 1809.01830)

One key experimental handle: knowledge of √s (exquisite at circular collider with resonant depolarisation method, at Z & WW)

EW & QCD Precision Measurements

Advancing understanding of precision and QCD challenges, bottlenecks, and mitigation strategies.

- **First full two-loop calculations of the Z total width Γ_Z in the Standard Model**

J. Gluza

Dubovyk et al, https://doi.org/10.1016/j.physletb.2018.06.037

	$\Gamma_e, \Gamma_\mu, \Gamma_\tau$	$\Gamma_{\nu_e}, \Gamma_{\nu_\mu}, \Gamma_{\nu_\tau}$	Γ_d, Γ_s	Γ_u, Γ_c	Γ_b	Γ_Z
Born	81.142	160.096	371.141	292.445	369.56	2420.2
$\mathcal{O}(\alpha)$	2.273	6.174	9.717	5.799	3.857	60.22
$\mathcal{O}(\alpha\alpha_s)$	0.288	0.458	1.276	1.156	2.006	9.11
$\mathcal{O}(N_f^2\alpha^2)$	0.244	0.416	0.698	0.528	0.694	5.13
$\mathcal{O}(N_f\alpha^2)$	0.120	0.185	0.493	0.494	0.144	3.04
$\mathcal{O}(\alpha^2_{\mathrm{bos}})$	0.017	0.019	0.058	0.057	0.167	0.505

the bosonic 2-loop corrections shift the value of Γ_Z by 0.51 MeV

Will require three- or four-loop calculations (!)

To meet projected exp. uncertainty (0.025 MeV)

(This uncertainty may still decrease ...)

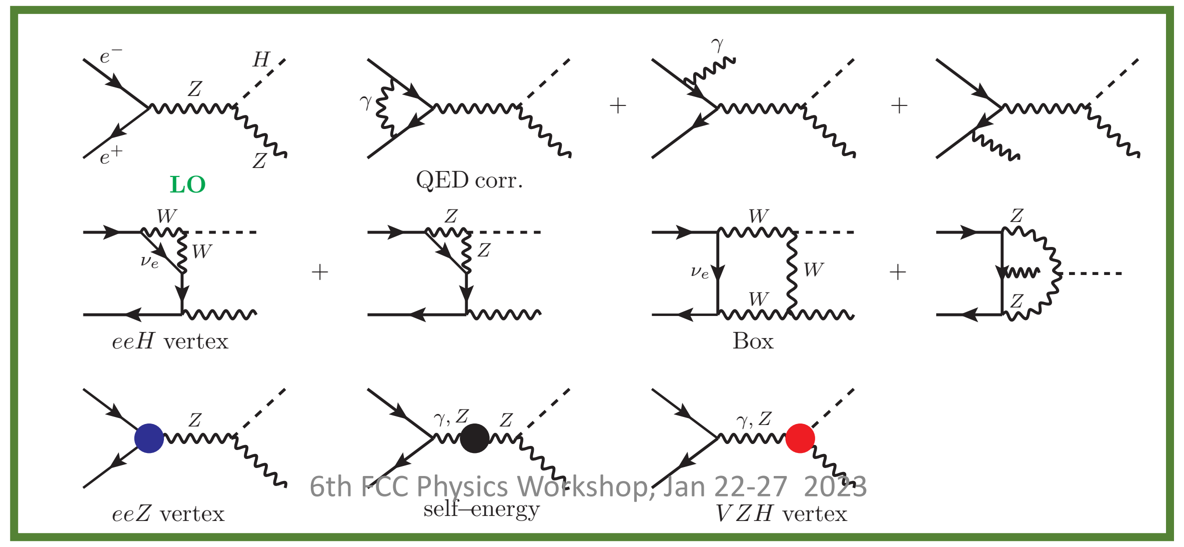
Eur. Phys. J. Plus (2022) 137:92 arXiv:2106.13885 Page 9 of 19 92

Table 3 Measurement of selected precision measurements at FCC-ee, compared with present precision. Statistical errors are indicated in boed phase. The systematic uncertainties are initial estimates, aim is to improve down to statistical errors. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in specific new physics (non-decoupling) models

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\mathrm{eff}}$ ($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	Small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2–1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4–1.6	From R_ℓ^Z above
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	Peak hadronic cross section Luminosity measurement
N_ν ($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216290 ± 660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons

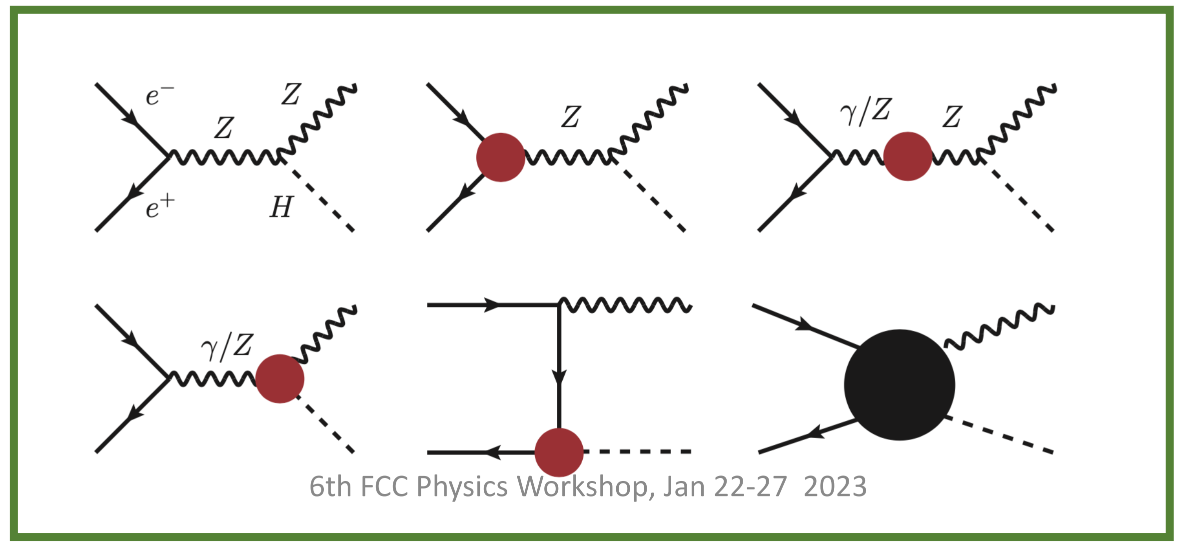
NNLO electroweak corrections for $ee \to ZH$

NNLO(EW+QCD): 0.4-1.3% ($\alpha(0), \alpha(M_Z), G_\mu$); 1.3% ($\overline{MS}, \alpha(M_Z)$)



Qian Song(U. Pitt)

NNLO(EW+EW): largest missing part



Qian Song(U. Pitt)

NNLO(EW+EW) correction with fermion loops increases LO cross section about 0.7% , comparable with experimental precision

MW mass

- Two independent W mass and width measurements @FCCee :

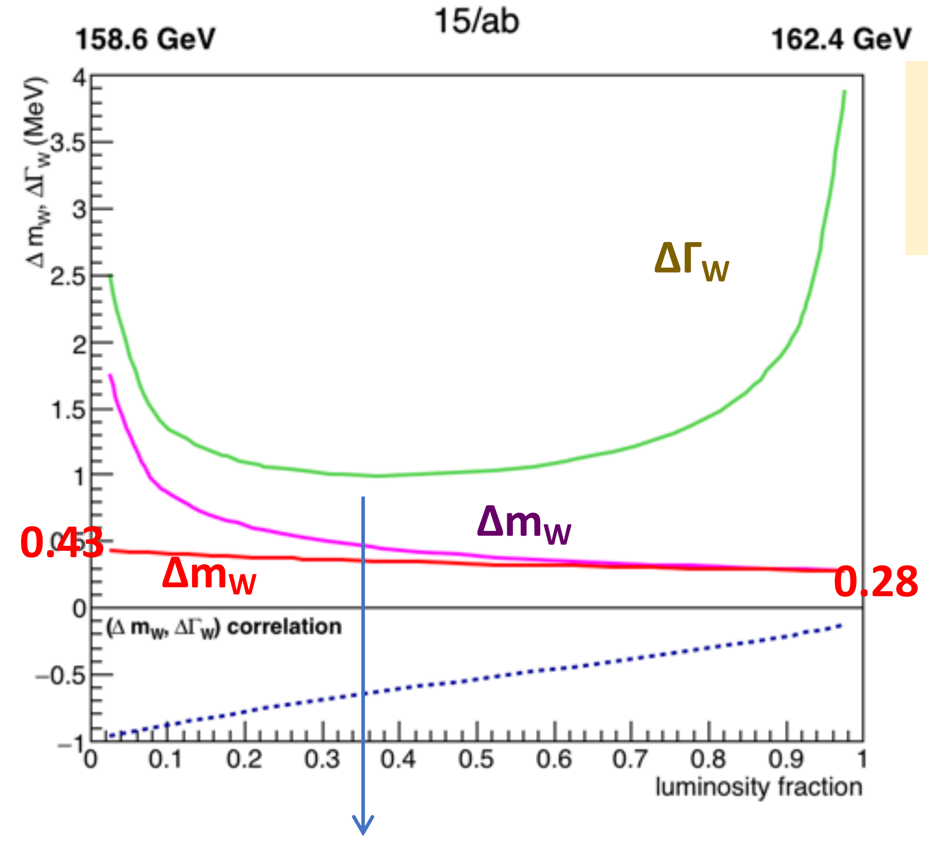
1. The m_W and Γ_W determinations from the WW threshold cross section lineshape, with 12/ab at $E_{CM} \simeq$ 157.5-162.5 GeV

Δm_W=0.4 MeV $\Delta\Gamma_W$=1 MeV

2. Other measurements of m_W and Γ_W from the decay products kinematics at $E_{CM} \simeq$ 162.5-240-365 GeV

Δm_W , $\Delta\Gamma_W$= 2-5 MeV ?

Scans of possible E_1 E_2 data taking energies and luminosity fractions f (at the E_2 point)



A -minimum of **$\Delta\Gamma_W$=0.91 MeV** with **Δm_W=0.55 MeV** taking data at E_1=**156.6** GeV E_2=**162.4** GeV f=**0.25** yields **Δm_W=0.47 MeV** (as single par)

B- minimum of **Δm_W=0.28 MeV** **$\Delta\Gamma_W$=3.3 MeV** with E_1=**155.5** GeV E_2=**162.4** GeV f=**0.95** yields **Δm_W=0.28 MeV** (as single par)

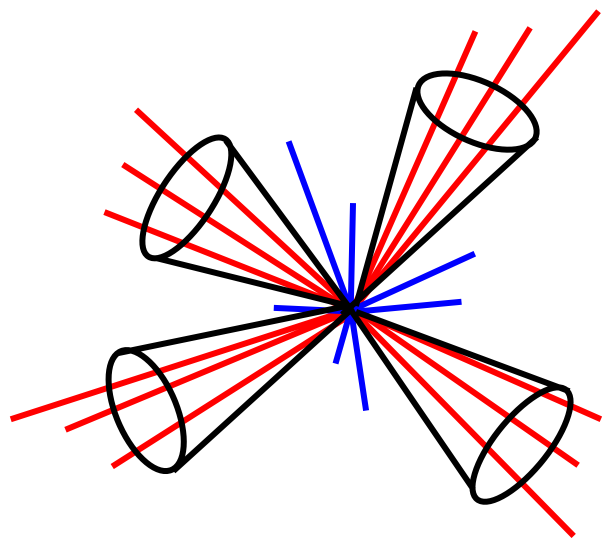
C- minimum of **$\Delta\Gamma_W$=0.96 MeV** +**Δm_W=0.41 MeV** with E_1=**157.5** GeV E_2=**162.4** GeV f=**0.45** yields and **Δm_W=0.37 MeV** (as single par)

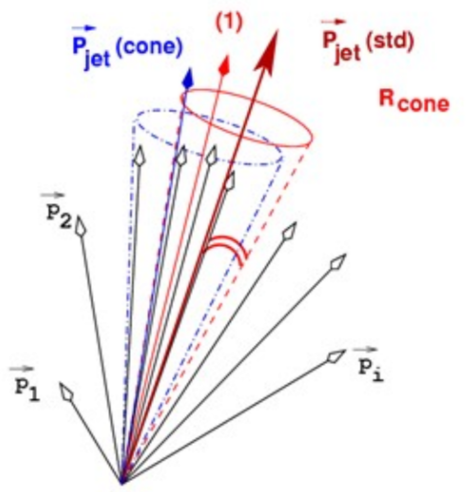
Δm_W =0.45 MeV , $\Delta\Gamma_W$=1 MeV (r=-0.6)
Δm_W=0.35 MeV

Δm_W , $\Delta\Gamma_W$: error on W mass and width from fitting both
Δm_W : error on W mass from fitting only m_W

Table 8: Summary of the systematic errors on m_W and Γ_W averaged over 183-209 GeV in the $q\bar{q}q\bar{q}$ channel for the standard, PCUT (= 3.0 GeV/c) and CONE (R=0.4) reconstructions.

	Δm_W (MeV/c^2)			$\Delta\Gamma_W$ (MeV)		
Source	standard	PCUT	CONE	standard	PCUT	CONE
Jet energy scale/linearity	2	2	3	2	12	4
Jet energy resoln	0	1	0	7	9	10
Jet angle	6	6	6	1	3	3
Jet angle resoln	1	3	2	15	18	9
Jet boost	14	15	11	5	5	4
Fragmentation	10	20	20	20	40	40
Radiative Corrections	2	2	2	5	7	7
LEP energy	9	10	10	7	7	7
Ref MC Statistics	2	3	3	5	7	7
Bkgnd contamination	8	5	5	29	31	32
Colour reconnection	79	28	36	104	24	45
Bose-Einstein effects	6	2	3	20	10	10

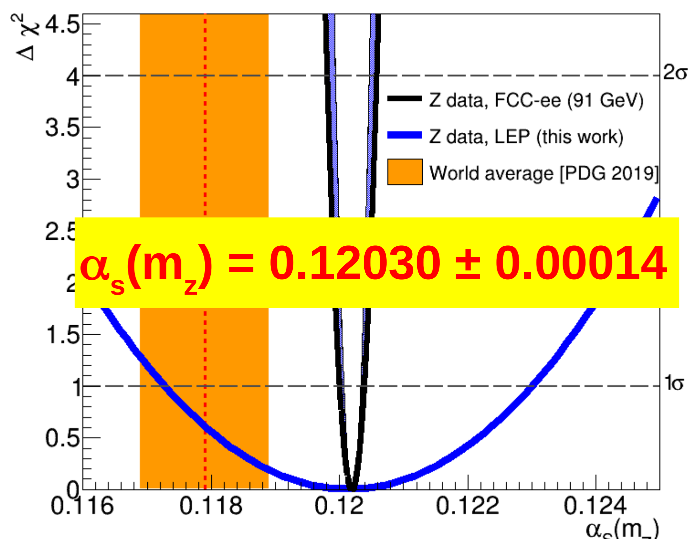


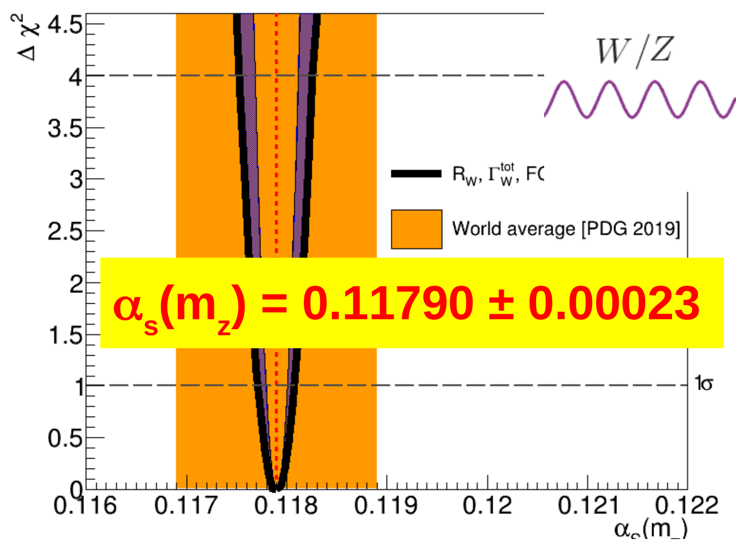


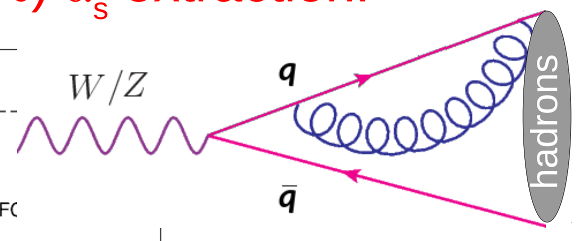
QCD

1. Precise α_s determination is needed to accurately & precisely predict all SM x-sections & decay rates (Higgs, top, EWPOs,...)
2. Higher-order (N^{n}LO, N^{n}LL) calculations crucial to gain precise control over hadronic final states and jet dynamics.
3. Heavy/light quark & gluon separation (flavour tagging, substructure,...) is key for multiple SM measurements (e.g. H Yukawas) and BSM searches (e.g. X→jj decays).
4. Non-perturbative QCD (hadronisation, colour reconnection,...) impacts studies with hadronic final states: $e^+e^-\to$WW,ttbar (→jets), m_W, m_{top} extractions.
5. @ FCC-hh, accurate knowledge of parton densities at high-*x* (BSM) and saturation dynamics at small-*x*, MPI dynamics,… is fundamental.

■ Z,W hadronic widths provide the most precise (0.1%) α_s extraction:

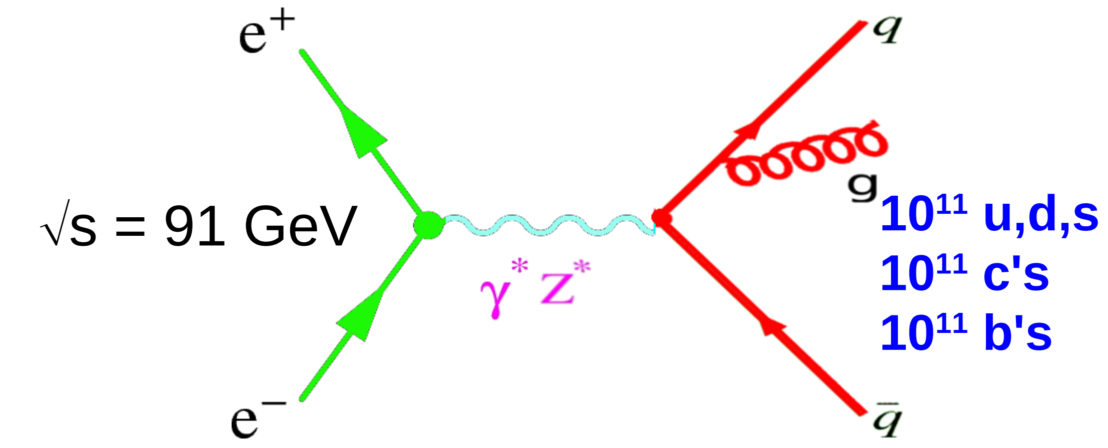


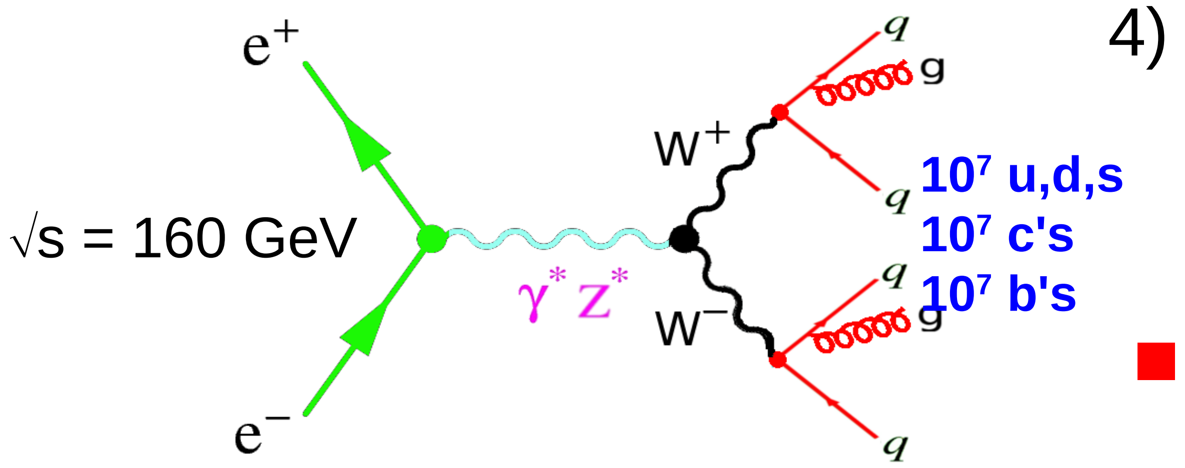


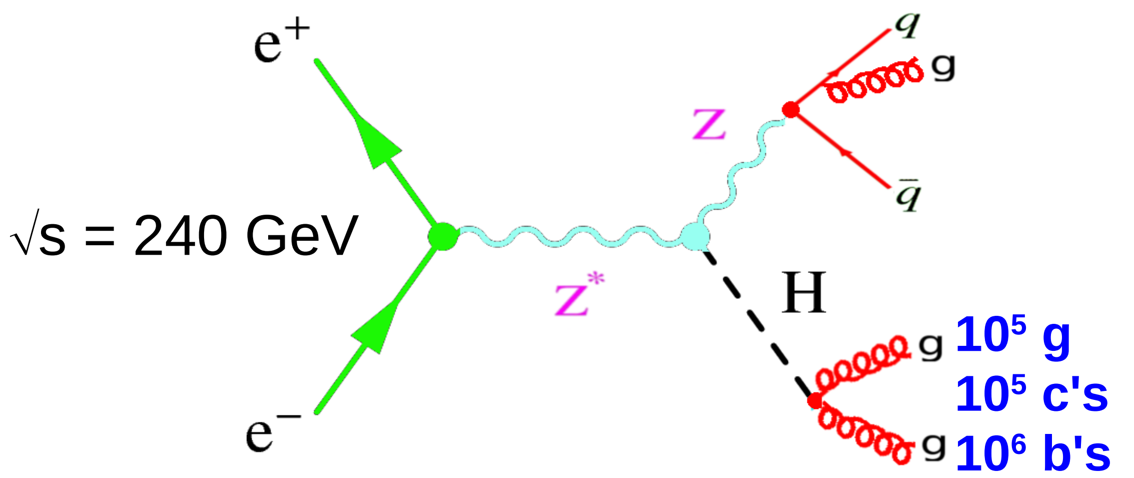


Strong (B)SM consistency test

■ e^+e^- collisions provide an extremely clean environment with fully-controlled initial-state to probe very precisely q,g dynamics:

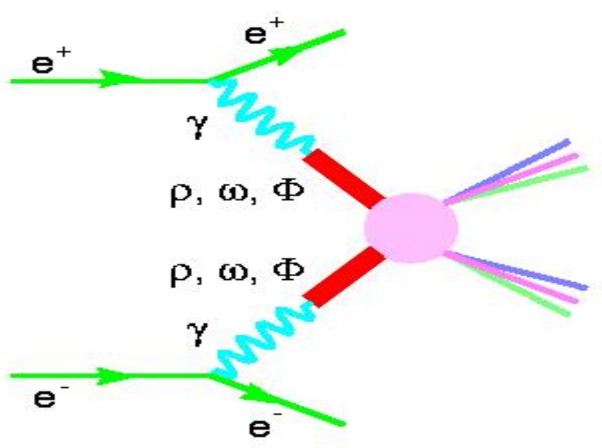




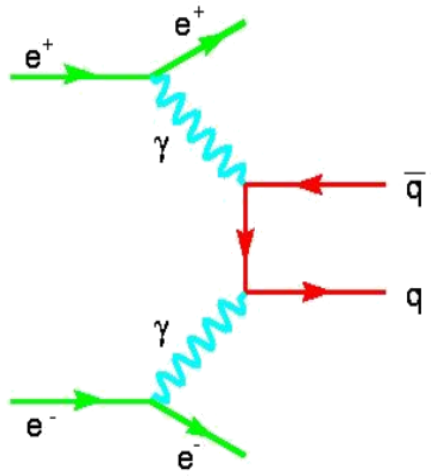


Advantages compared to p-p collisions:
1) QED initial-state with known kinematics
2) Controlled QCD radiation (only in final-state)
3) Well-defined heavy-Q, quark, gluon jets
4) Smaller non-pQCD uncertainties:
no PDFs, no QCD "underlying event",…
Direct clean parton fragmentation & hadroniz.

■ Plus QCD physics in γγ (EPA) collisions:



(soft, VDM)



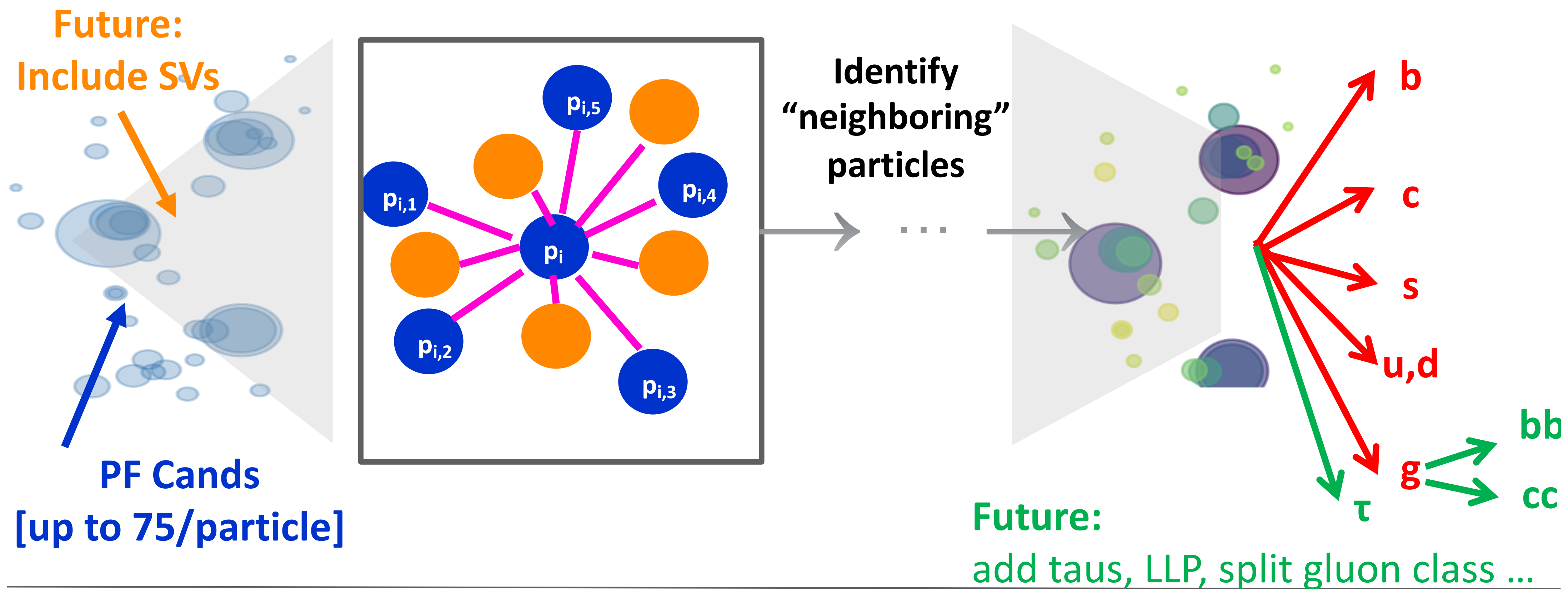
(direct)

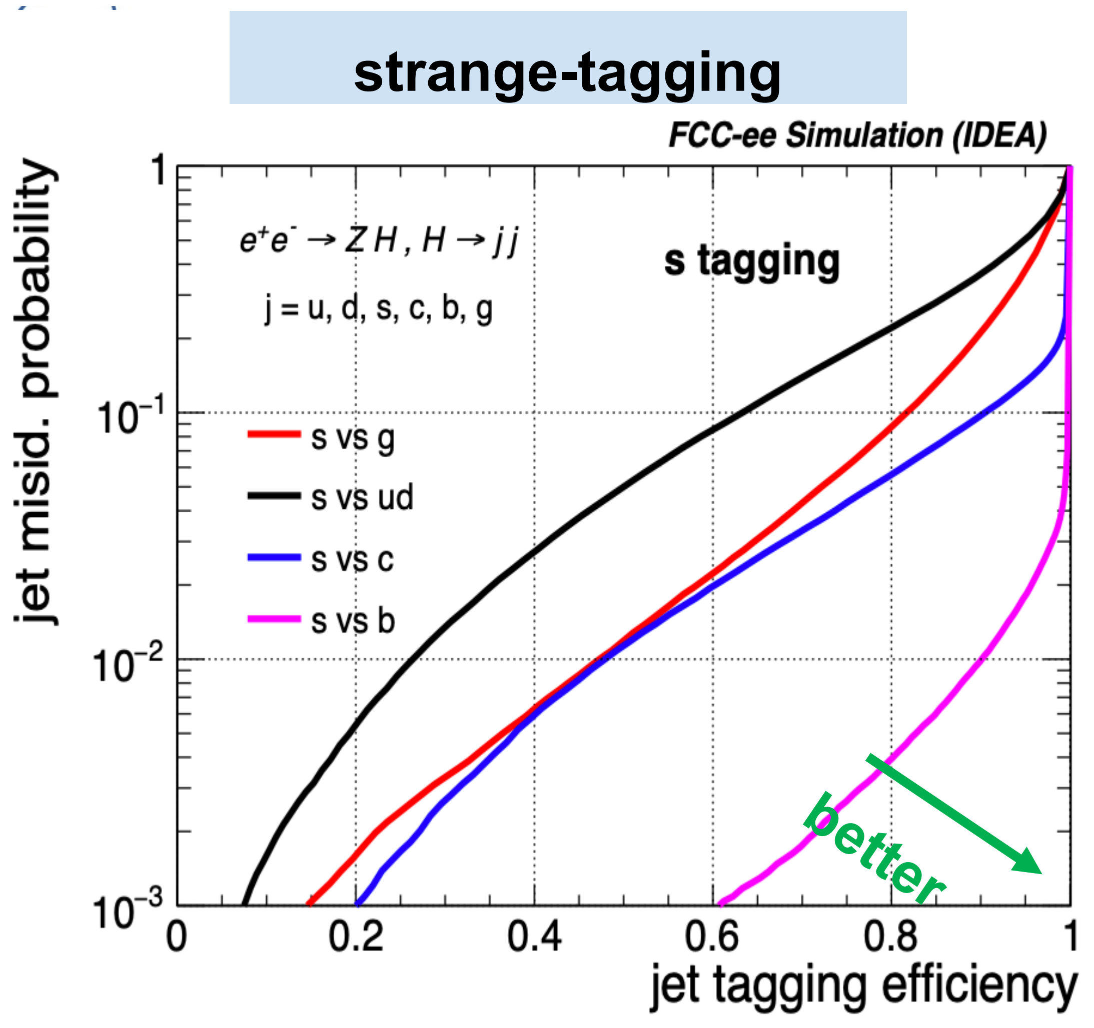
Jet Flavour Identification

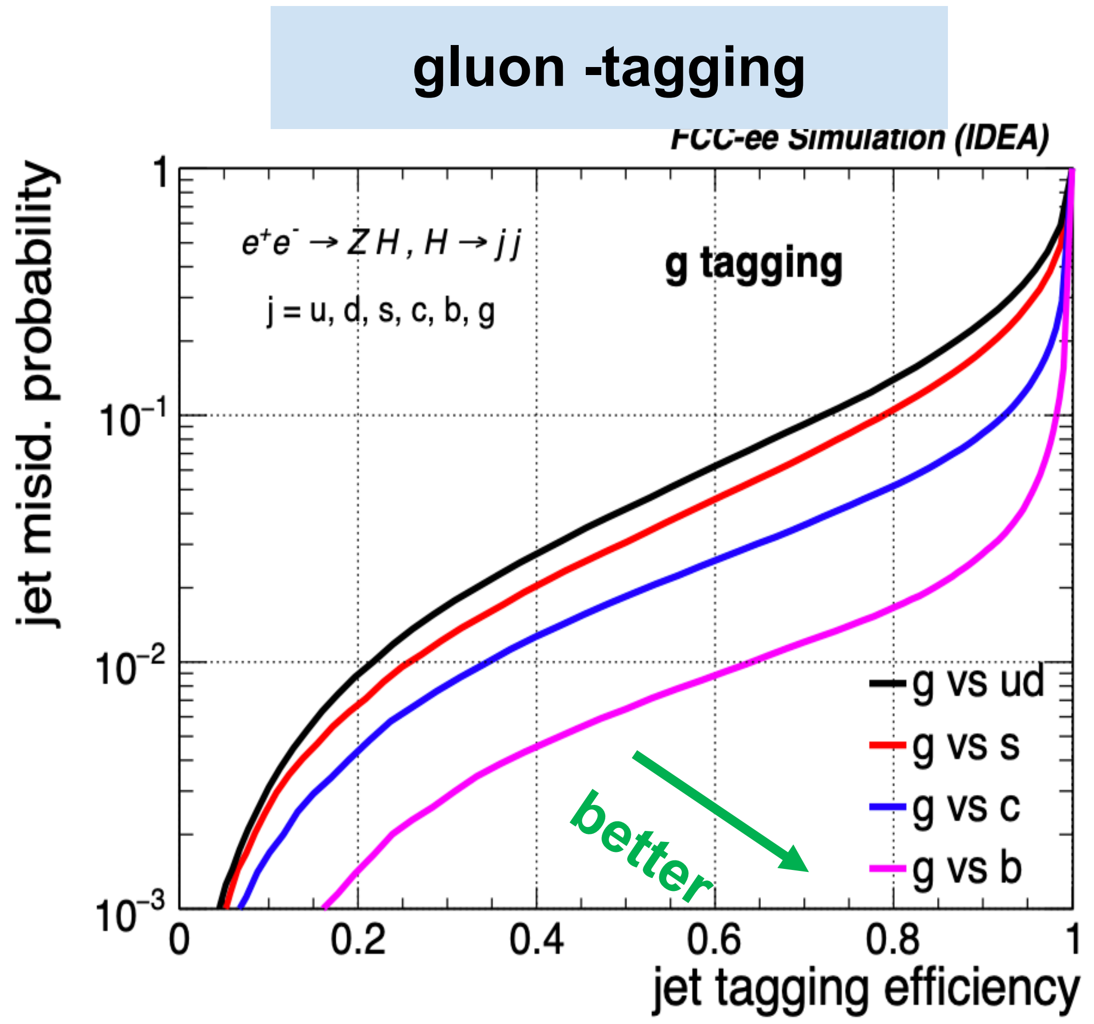
ParticleNet(-ee)

H. Qu and LG
PRD 101 056019 (2020)
F. Bedeschi, M. Selvaggi, LG
EPJ C 82 646 (2022)

- Jet representation: *"Point Cloud"* → *"Particle Clouds"*
  - Treat the jet as an unordered set of particles
- Network architecture: Graph Neural Networks
  - Particle cloud represented as a graph
    - Each particle: **vertex** of the graph; Connections between particles: the **edges**
- Follow a hierarchical learning approach
  - First learn local structures → then move to more global ones







WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	9%	20%	6%	0.4%

WP	Eff (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	25%	7%	2.5%
Medium	80%	15%	5%	2%

Flavour Physics

Flavour physics programme

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., b → sττ

Ongoing analyses in b physics :

- Bc (and Bu) to tau nu - New physics, access to Vcb, Vub
- B → K* tau tau - very rare decay, high interest in view of LFU
- CP violation in B → Ds K ((re-) starting) - meas. of γ to < 1 degree
- b to s nu nu - sensitive to new physics
- Semi-leptonic CP asymetries - BSM contributions in mixing

Measurement	Requirements
CP violation in Bs → ΦΦ	PID, vertex, track resolution
B0 → $\pi 0 \pi 0$ (→ eeγ) Example in Backup	Low energy γ 's in jets (ECAL resolution and granularity)
Bs → $\tau\tau$	Vertexing
Meas of γ from B+ → DK+	Ks reconstruction
τ → 3μ, τ → μγ Example in Backup	resolutions
τ lifetime talk at Krakow Lusiani Example in Backup	Alignment, scale of vertex detector,
τ BRs	Lepton ID, PID, e/pi separation
τ mass	Track reco & resolution (in multi-track collimated environment)
Charm physics	
Masses, spectroscopy, exotics…	

Many interesting opportunities in tau physics.

- Existing FastSim samples of limited use for several tau studies
- But fullSim is coming up

Looking for interested contributors.

talk at Krakow: Miralles

Flagship measurement, tau lifetime, work is starting by one of the conveners (A. Lusiani)

Tau Physics

Example of precision challenge: Universality of Fermi constant

Andreas Crivellin and John Ellis.

EXOTIC FLAVOURS AT THE FCC

CERNCOURIER Volume 62 Number 1 January/February 2022

Here, a new-physics effect at a relative sub-per-mille level compared to the SM would suffice to explain the anomaly. This could be achieved by a heavy new lepton or a massive gauge boson affecting the determination of the Fermi constant that parametrises the strength of the weak interactions. As the Fermi constant can also be determined from the global electroweak fit, for which Z decays are crucial inputs, FCC-ee would again be the perfect machine to investigate this anomaly, as it could improve the precision by a large factor (see "High precision" figure). Indeed, the Fermi constant may be determined directly to one part in 10^5 from the enormous sample (>10^{11}) of Z decays to tau leptons.

Fermi constant is measured in μ decays and defined by

$$G_F^{(e)} G_F^{(\mu)} = \frac{192\pi^3}{m_\mu^5 \tau_\mu}$$

Assuming (e,μ) universality, the Fermi constant then is

$$G_F \equiv G_F^{(e)} = G_F^{(\mu)} = \sqrt{\frac{192\pi^3}{m_\mu^5 \tau_\mu}}$$

Experimentally known to 0.5 ppm (μ lifetime)

Similarly can define Fermi constant measured in τ decays

$$G_F^{(e)} G_F^{(\tau)} = \frac{192\pi^3 \mathscr{B}(\tau \to e\nu\nu)}{m_\tau^5 \tau_\tau}$$

Compare τ and μ based Fermi consants

$$\frac{G_F^{(e)}}{G_F^{(\mu)}} = \frac{m_\mu^5 \tau_\mu}{m_\tau^5 \tau_\tau} \mathscr{B}(\tau \to e\nu\nu)$$

Current precision:	67 ppm BES	1700 ppm Belle	2200 ppm LEP

FCC-ee: Will see 3×10^{11} τ decays
Statistical uncertainties at the 10 ppm level
How well can we control systematics?

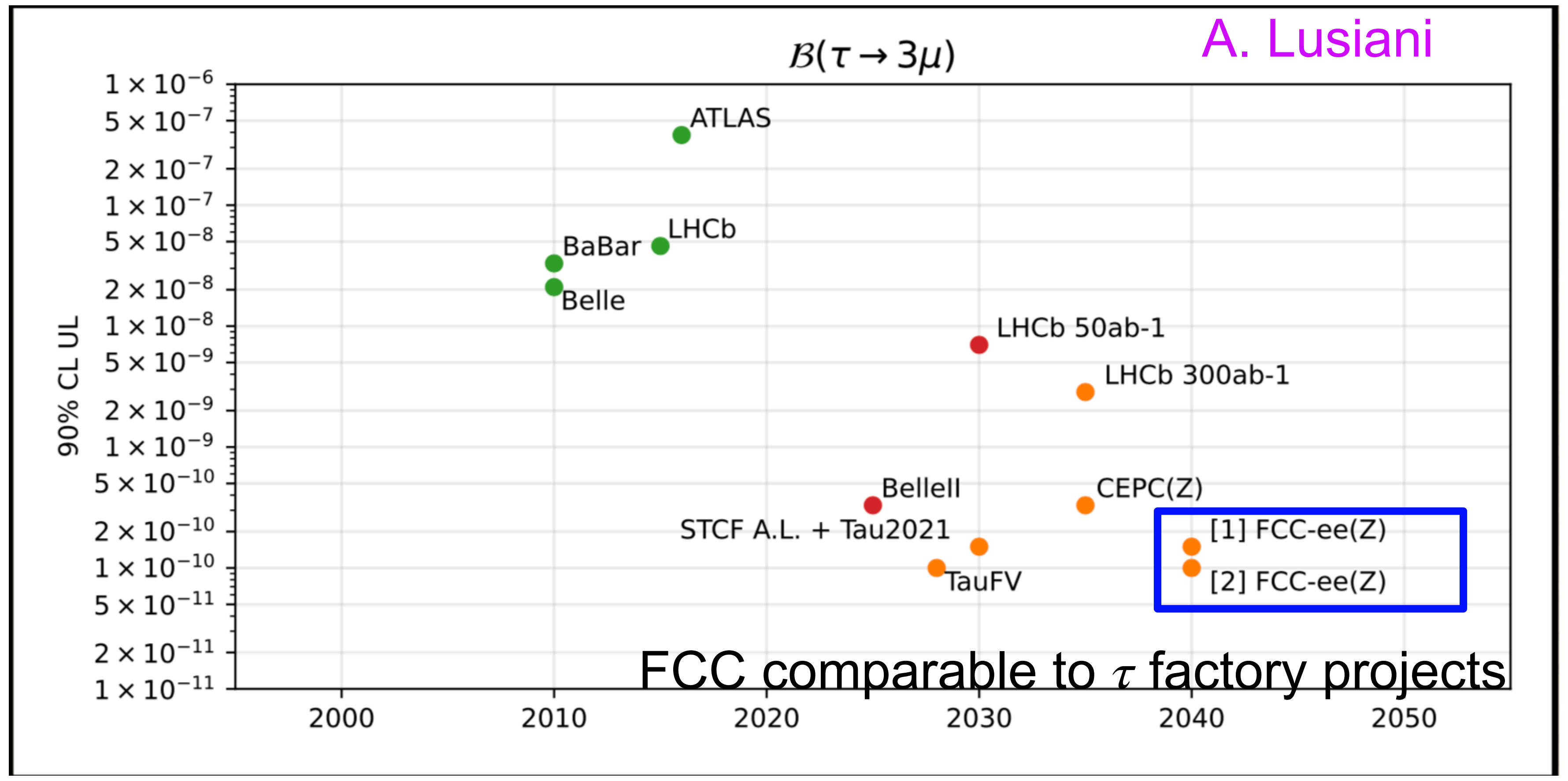
m_τ	Use J/ψ mass as reference (known to 2 ppm)	tracking
τ_τ	Laboratory flight distance of 2.2 mm ⇒ 10 ppm corresponds to 22 nm (!!)	vertex detector
$\mathscr{B}$	No improvement since LEP (statistics limited) Depends primarily e^-/π^- (& e^-/ρ^-) separation	ECAL dE/dx

$\tau \to 3\mu$

Remember: about 1.7 10^{11} $Z \to \tau\,\tau$ decays !

Present bound ~ 10^{-8} (B factories). FCC could bring 2 orders of magnitude.

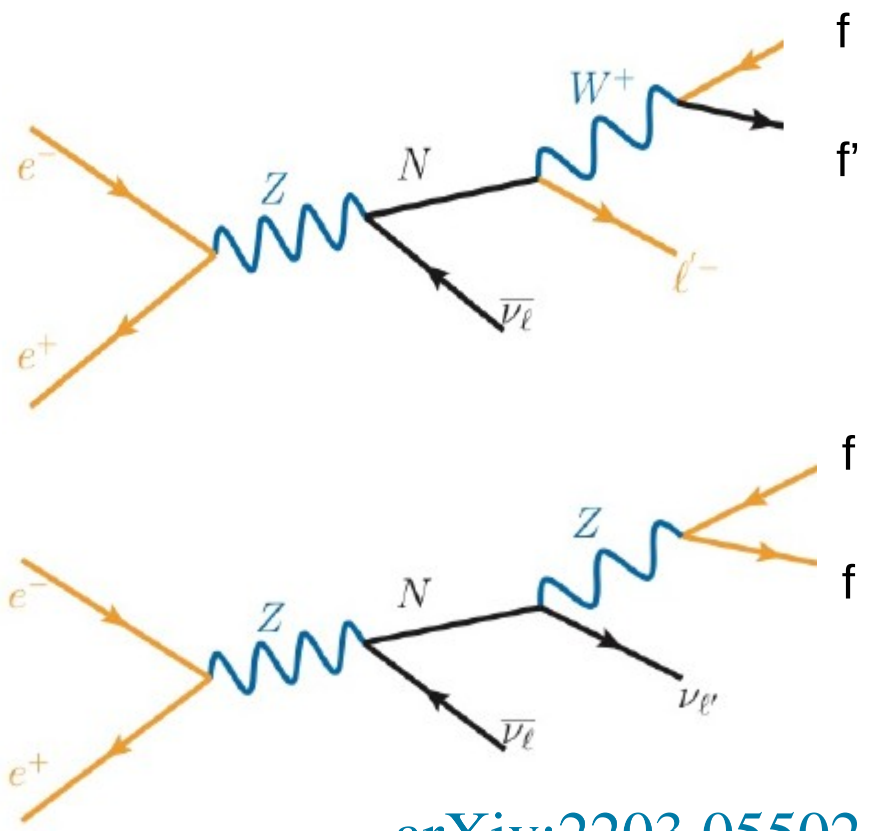
Channel also tests the reco of collimated tracks and purity of muon-ID.

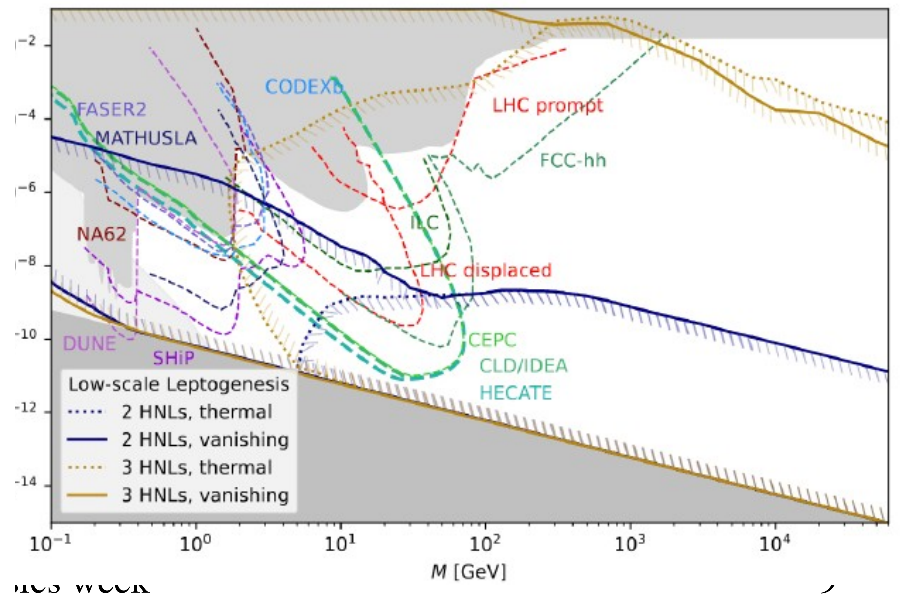


BSM

- Heavy Neutral Leptons *
- Exotic Higgs boson decays *
- Light SUSY scenarios and scenarios with light scalars
- Axion-like particles (ALP) *
- Z’, dark photons and other light mediator scenarios

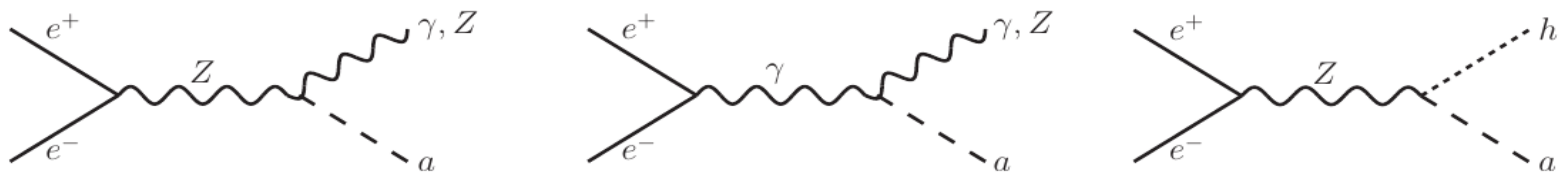
HNL

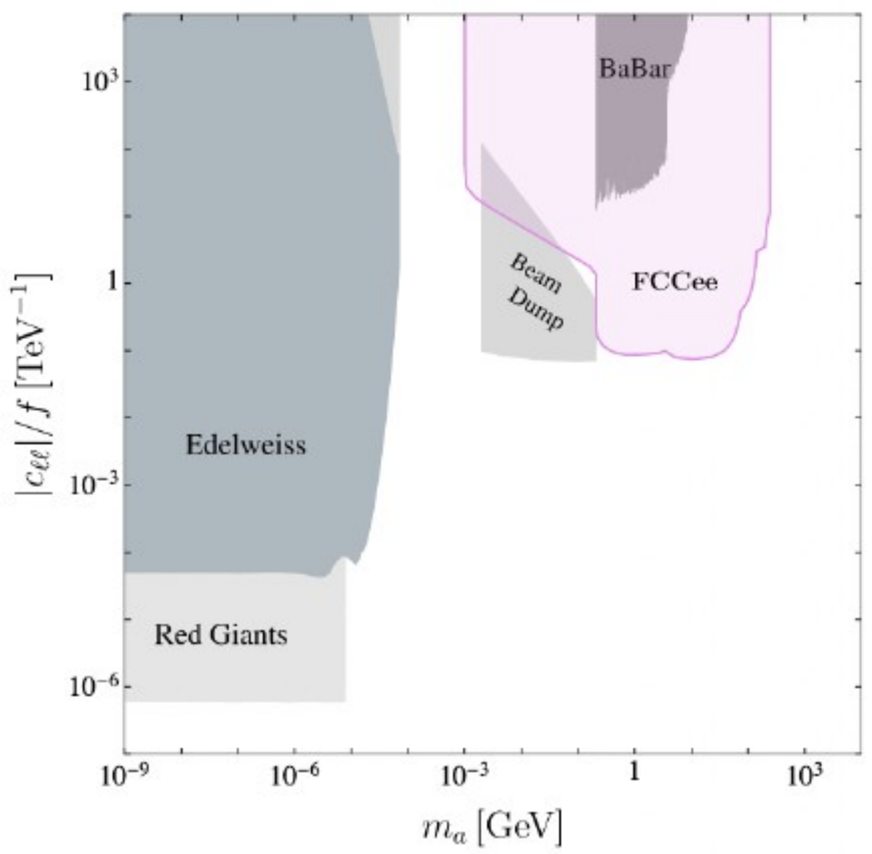




arXiv:2203.05502

ALP

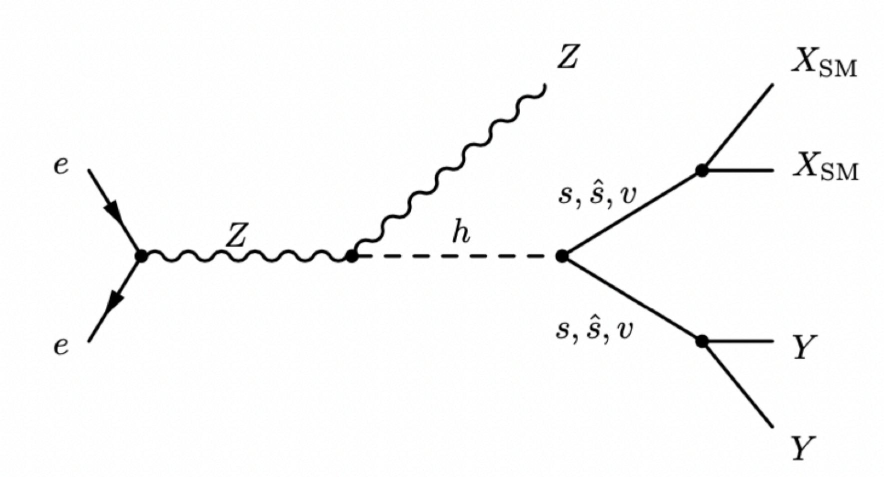




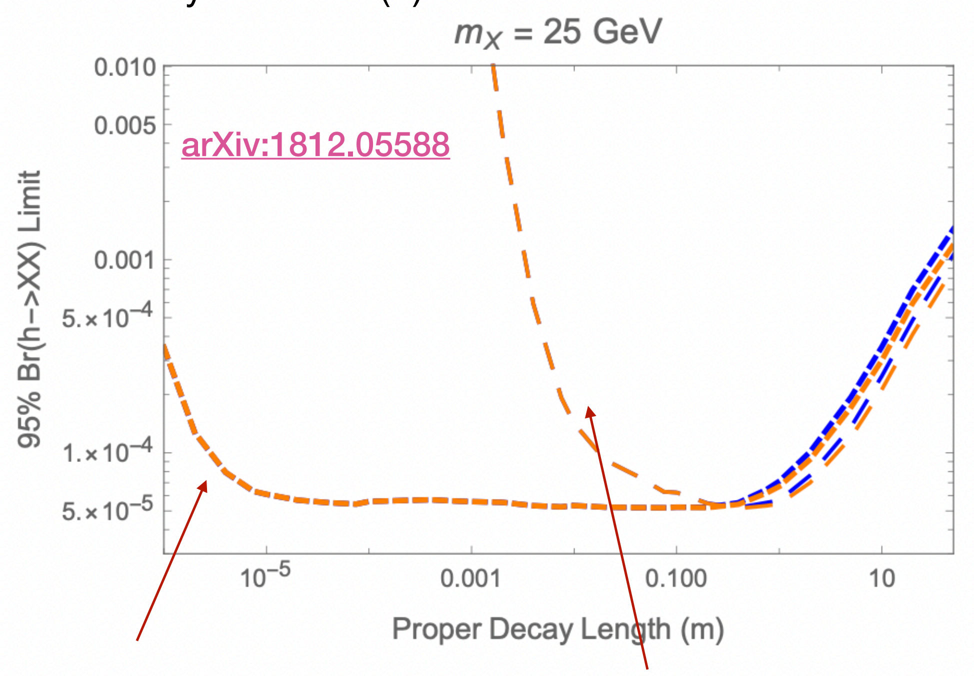
Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

Exotic Higgs Decays

Example production of LLPs through exotic decays of the Higgs boson to scalars, pseudo-scalars, or vectors:



- Sensitivity of FCC-ee to exotic Higgs boson decays to LLPs (X)



Invariant mass cut to retain sensitivity to shorter decay lengths

Cuts optimised for longer decay lengths