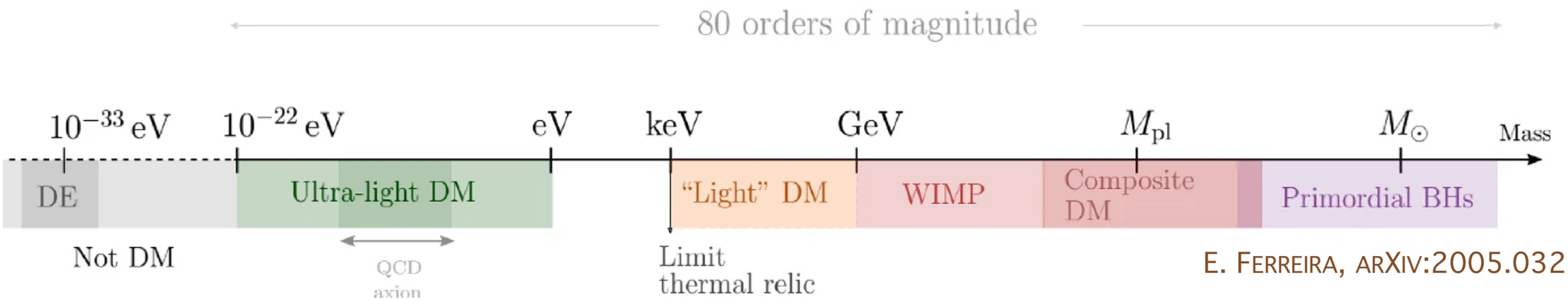
PHYSICS SUMMARY

ROBERT SZAFRON

Brookhaven
National Laboratory

Colliders are and always have been at the heart of particle physics!

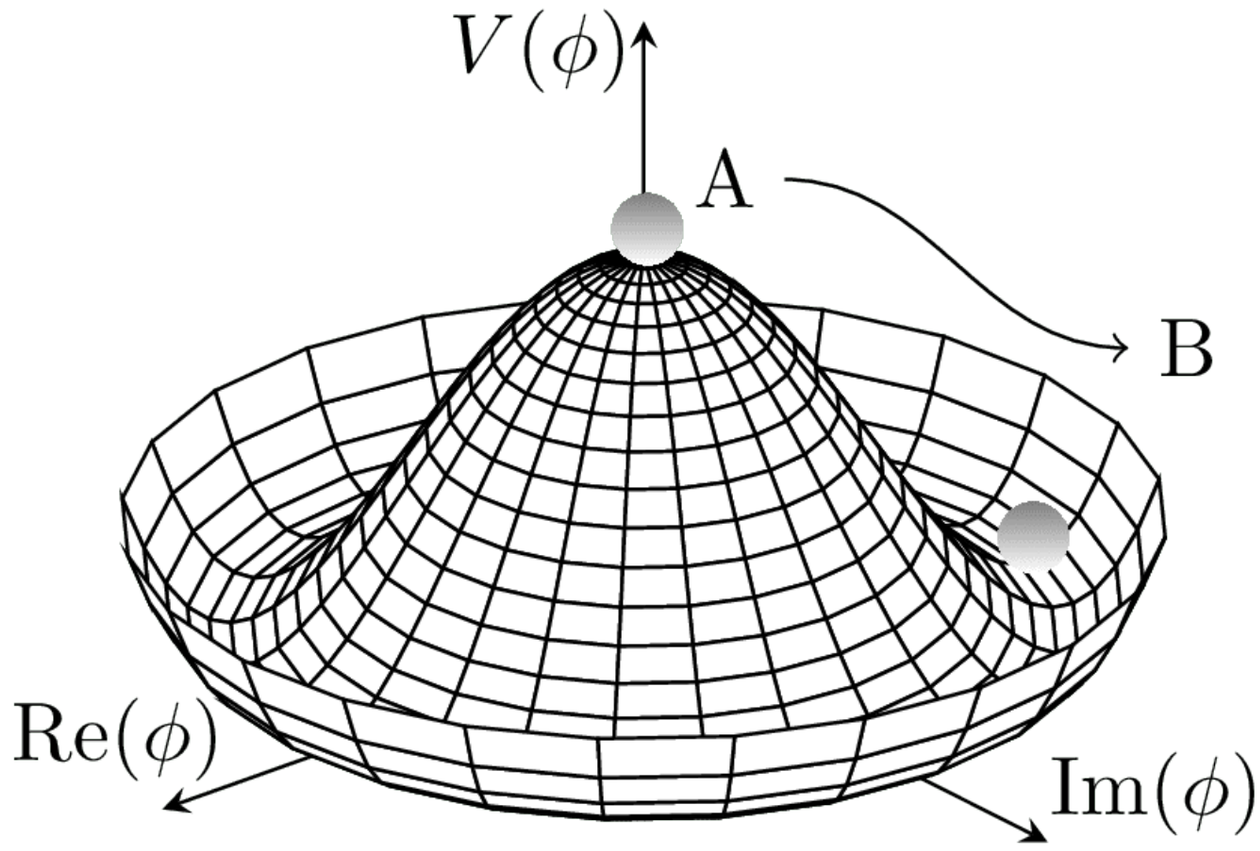
There are many open questions in particle physics and many paths to explore



E. Ferreira, arXiv:2005.03254

Most DM searches are bound to give null result

Colliders are and always have been at the heart of particle physics!



Colliders are the only place to probe Higgs boson

and in addition provide multitude of interesting measurements!

Higgs factory offers continued progress and guaranteed deliverables

FCC-ee Physics Programme

"Higgs Factory" Programme

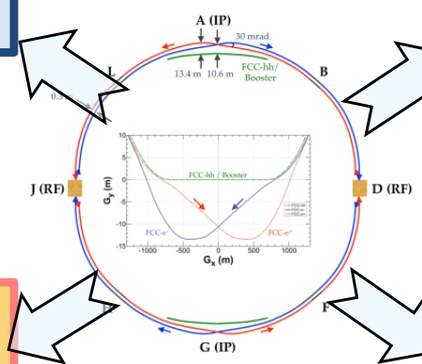
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- $6x10^{12}$ Z and $3x10^8$ WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…
- $2x10^6$ tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; $1.7x10^{11}$ ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

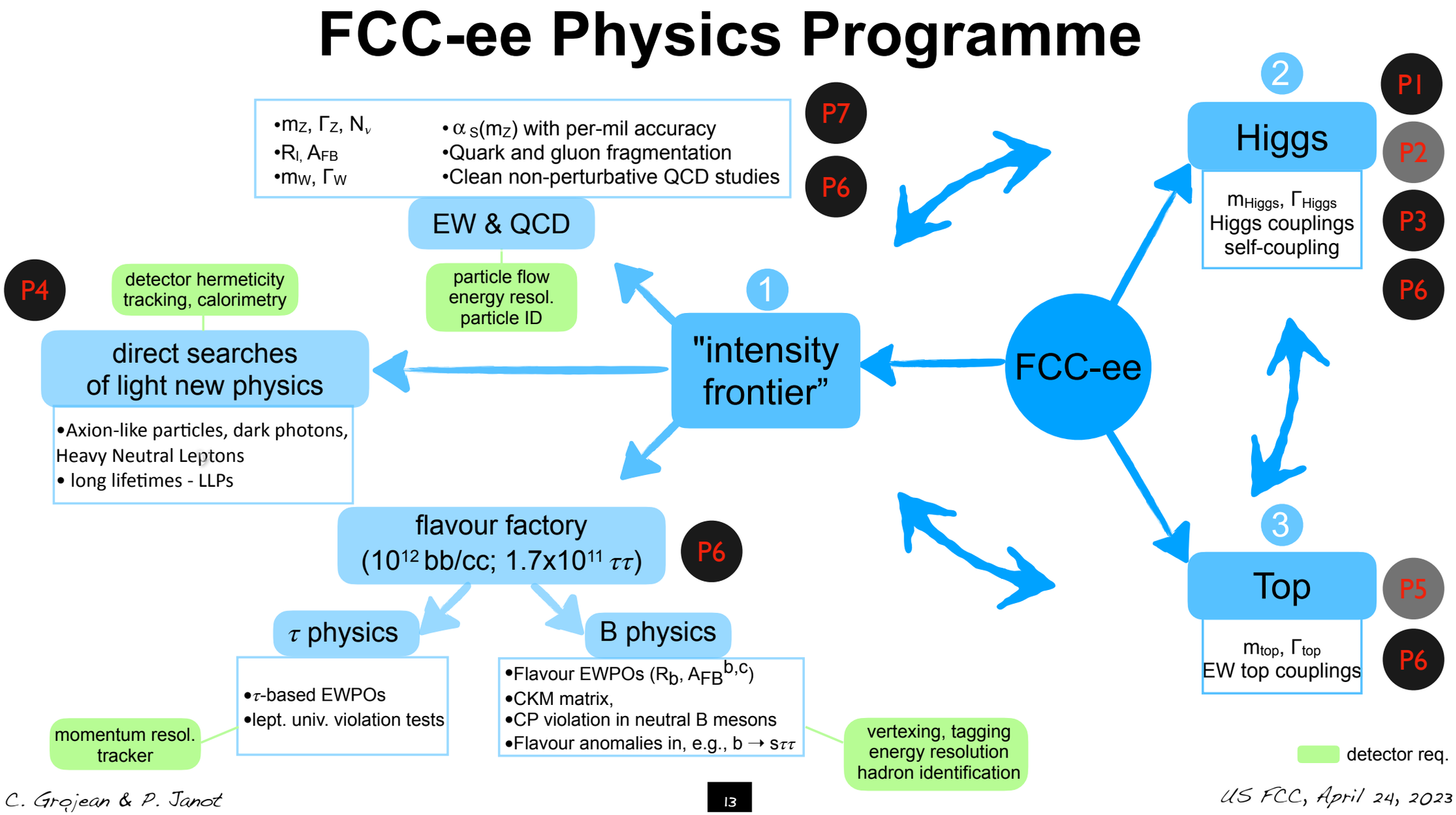
Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z:

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes – LLPs

Courtesy M. Dam

- *Model independent measurement of Higgs couplings*
- *$O(10^5)$ larger statistics than LEP at Z peak*
- *Order of magnitude more B mesons than flavor factories*

FCC (ee followed by hh) project offers unchallenged leadership in diversity of the physics program



Physics for everyone - crucial for sustaining HEP community in the US

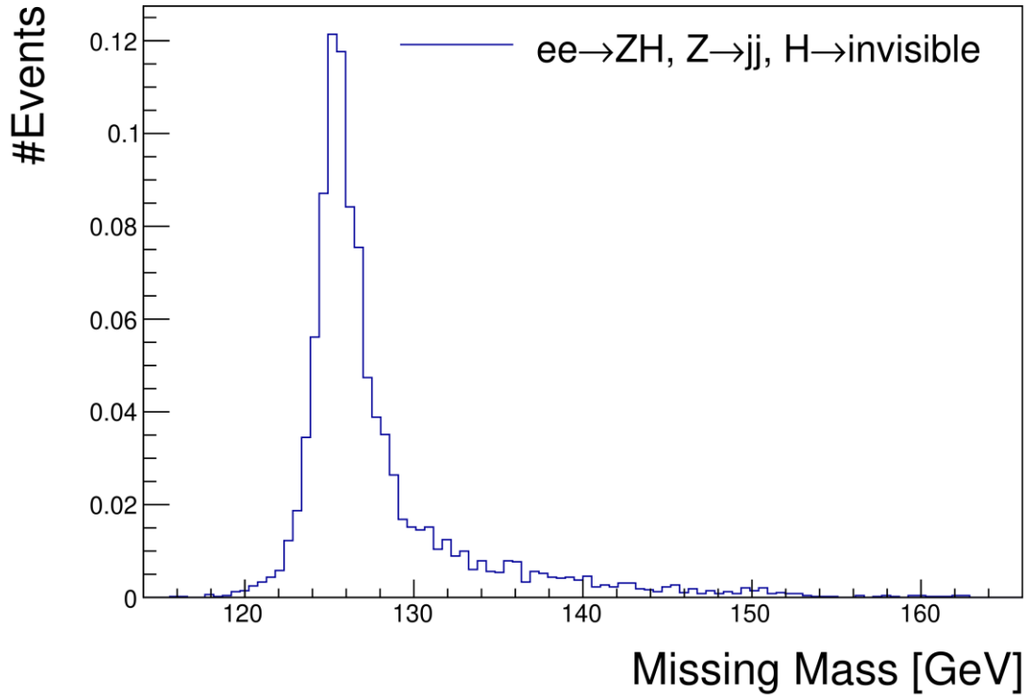
Much grater diversity of physics program that can be achieved by multiple small and medium size experiments

$H\rightarrow$invisible benchmarking

- Use invisible reconstructed mass resolution in $H \rightarrow$ invisible , $Z \rightarrow qq$ as benchmark for calorimeter comparison and optimization

- Preliminary Selection:
  - Exactly two jets, zero muons, zero electrons
  - Reconstruct Z from jets
  - Get invisible mass from Z recoil
  - $\text{MET} > 10\ \text{GeV}, 60\ \text{GeV} < m_Z < 100\ \text{GeV}$

- Currently using centrally produced FCCee Monte Carlo samples, reconstructed with the IDEA detector http://fcc-physics-events.web.cern.ch/fcc-physics-events/FCCee/winter2023/Delphesevents_IDEA.php



Invisible mass distribution, based on Higgs→invisible, with $Z \rightarrow jj$ and the Idea detector

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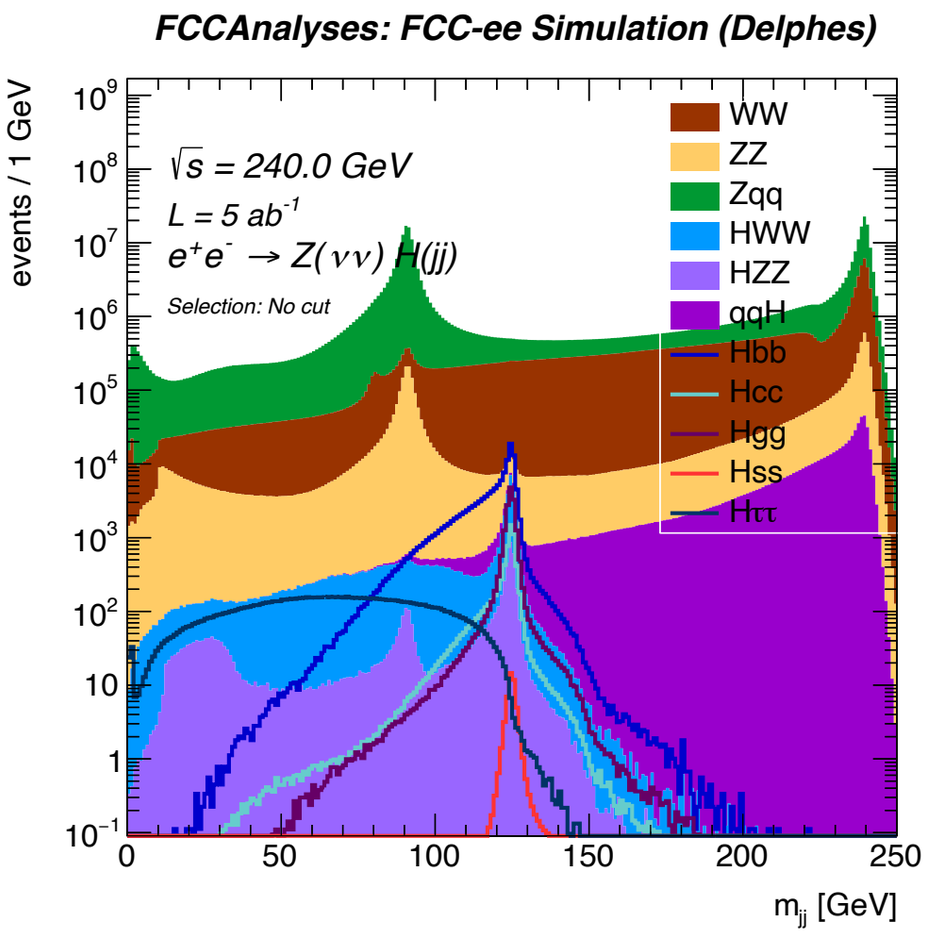
FCC-ee offers access to Higgs couplings that are challenging to measure at the LHC

Statistics

- Initial yield at (scaled for lumi): $\sqrt{s} = 240\,\text{GeV}, \mathscr{L} = 5\,\text{ab}^{-1}$

	Before selection
Hbb	1.34e+05
Hcc	6.68e+03
Hgg	1.66e+04
Hss	5.08e+01
H$\tau\tau$	1.26e+04
HWW	4.80e+04
HZZ	5.77e+03
qqH	6.82e+05
WW	7.99e+07
ZZ	6.48e+06
Zqq	2.62e+08

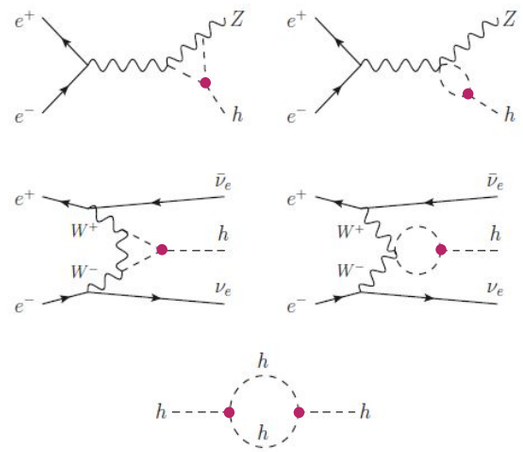


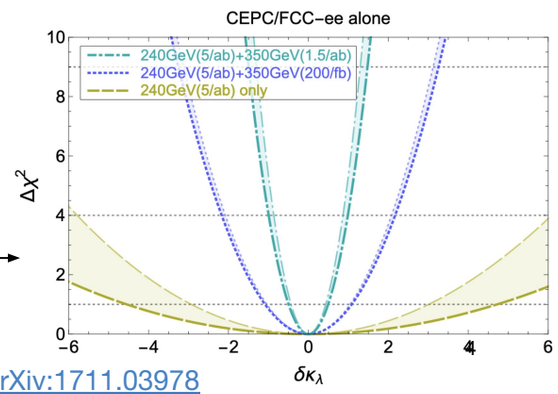
LOUKAS GOUSKOS, GEORGE IAKOVIDIS, MICHELE SELVAGGI

Higgs self-coupling can be measured indirectly

How to measure the Higgs self-coupling at the FCC-ee?

- The self-coupling measurement depends on measurements of Higgs production cross sections and decays to other particles.
- The κ analysis is expected to reach **~20%** accuracy [arXiv:1905.03764], while the global effective field theory fit will reach **~30%** [arXiv:1711.03978] (in combination with HL-LHC projections!)
- **The ZH cross section (240 GeV run) is most sensitive to changes in the self-coupling**
  - 365 GeV run is crucial for reducing uncertainties!





arXiv:1711.03978

Brookhaven National Laboratory

ABRAHAM TISHELMAN-CHARNY, BNL

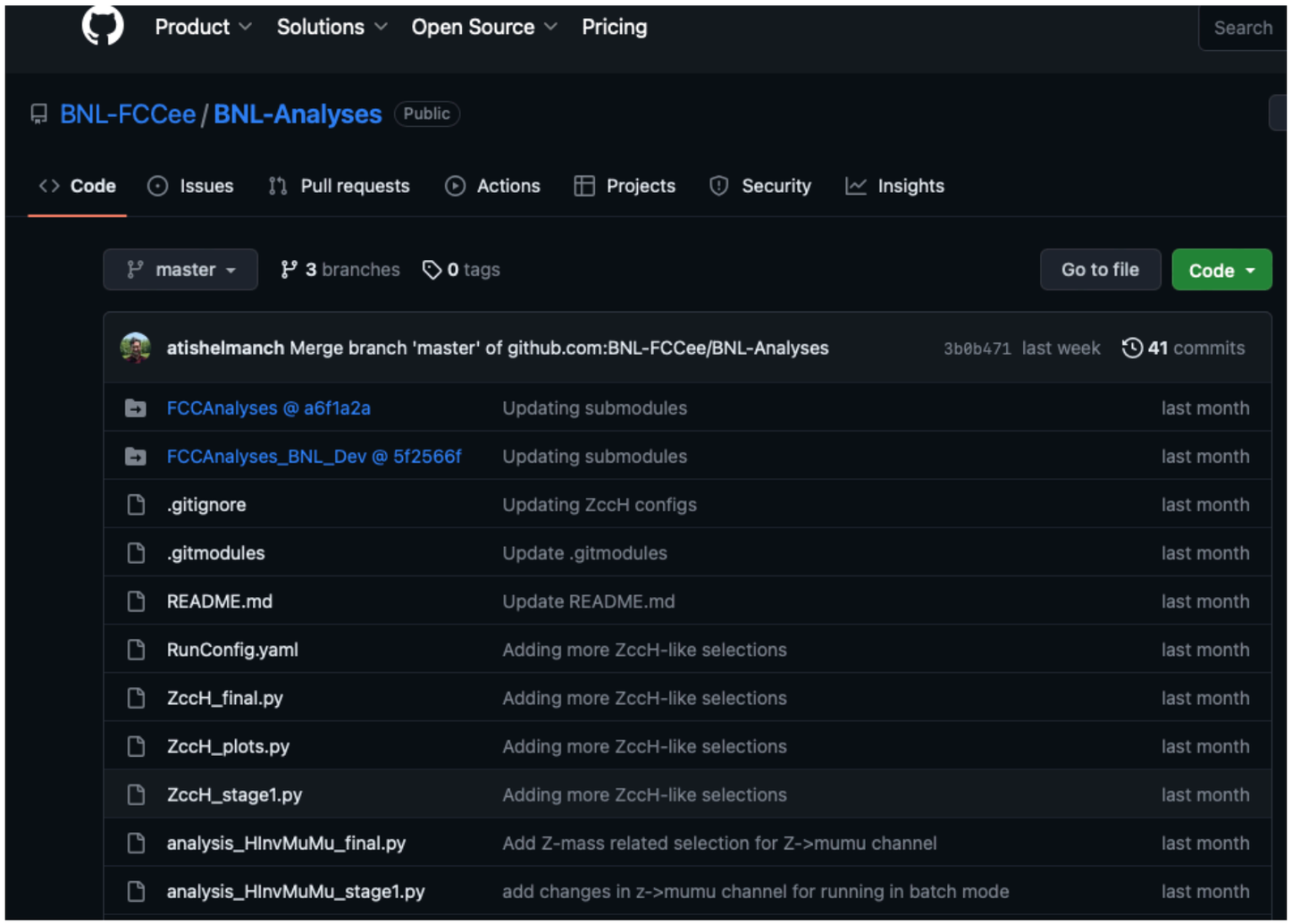
BNL thrusts

BNL efforts are progressing well

Focus: Higgs@FCC-ee

We are looking for people to join our efforts

Contact:
Marc-Andre Pleier



https://github.com/BNL-FCCee/BNL-Analyses

Standard Model precision is crucial

ACCEPTANCE FOR FCC

$e^+e^- \rightarrow \mu^+\mu^-$

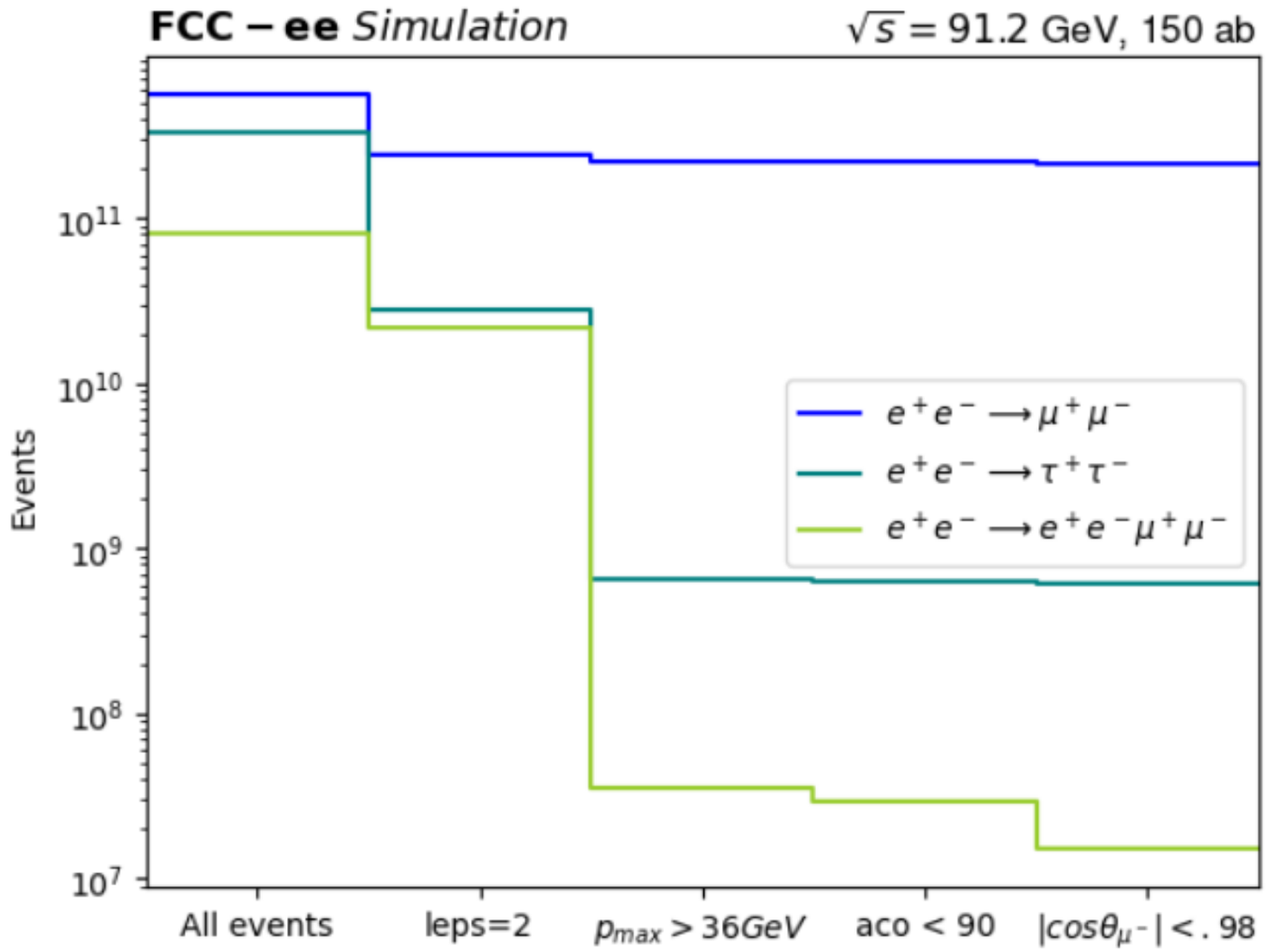
$Acceptance = 94.25\ \%$

$e^+e^- \rightarrow \tau^+\tau^-$

$Acceptance = .23\%$

$e^+e^- \rightarrow e^+e^-\mu^+\mu^-$

$Acceptance = 1.8 * 10^{-4}\ \%$



CASEY LAWSON, MIT

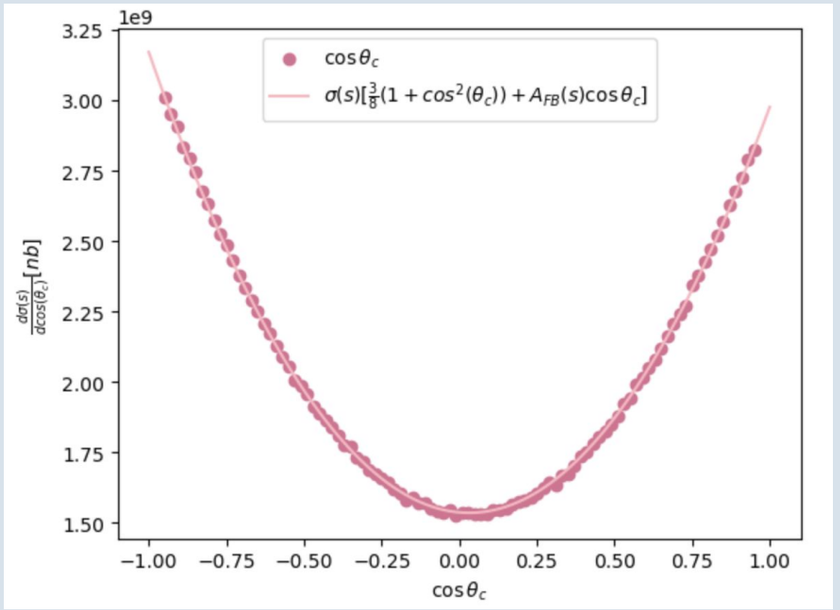
Muon forward backward asymmetry

χ^2 Goodness of Fit Test

- Plotted $\mu^+\mu^-$ as a scatter plot
- Fitted with the differential cross section for muon pair production ("Born" form)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}cos\theta} = \sigma(s)\cdot\left\{\frac{3}{8}(1+cos^2\theta_c) + A_{FB}(s)\cdot cos\theta_c)\right\}$$

- χ^2 test statistic = 0.068
  - greater than significance level 0.05, so reject null
  - conclusion: this is a good fit for the data!

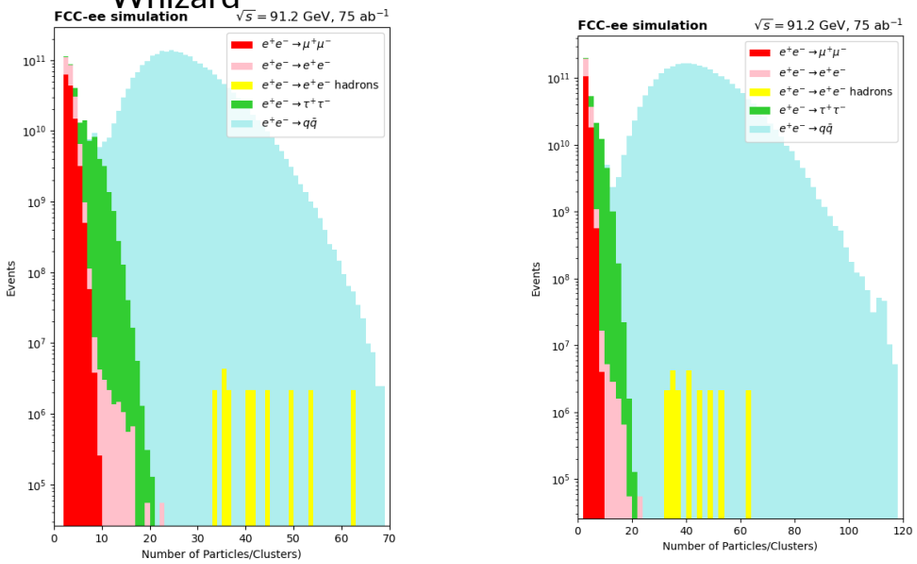


Sofia Lara, Brenda Chow, MIT

Hadron production

Event Generator Discrepancy

KKMC
Whizard



Background: Whizard Samples
Signal: KKMC/Whizard

Determine source of discrepancy between event generators

Has significant impact on optimal cut parameters

Marina Malta Nogueira, Tim Neumann, MIT

Lineshape measurement

How good can the determination be?

Extract Pseudo Observables: m_Z, Γ_Z and $\sigma_{0,hadr}$; Inputs: hadronic cross sections, 5 points, 30/ab each

1. Start with statistical uncertainty on hadrons and the fully correlated systematic uncertainty as large as peak stat. uncertainty
2. Add stat. uncertainty on luminosity corresponding to 14 nb cross section
3. Add 10^{-4} syst. fully correlated, and another 10^{-5} uncorrelated (this might still improve)
4. Add 10 keV correlated uncertainty on ECMS
5. Or alternatively 100 keV correlated uncertainty on ECMS

Setup	delta(m_Z)	delta(Γ_Z)	delta($\sigma_{0,\,hadr}$)
units	[keV]	[keV]	[pb]
1	1.2	3.4	0.0441
2	1.7	5.2	0.076
3	8.4	26	4.2
4	13	26	4.2
5	101	26	4.2

We find a best uncertainty of 1.2 keV as opposed to an uncertainty of 4 keV. commonly quoted. Why is that?

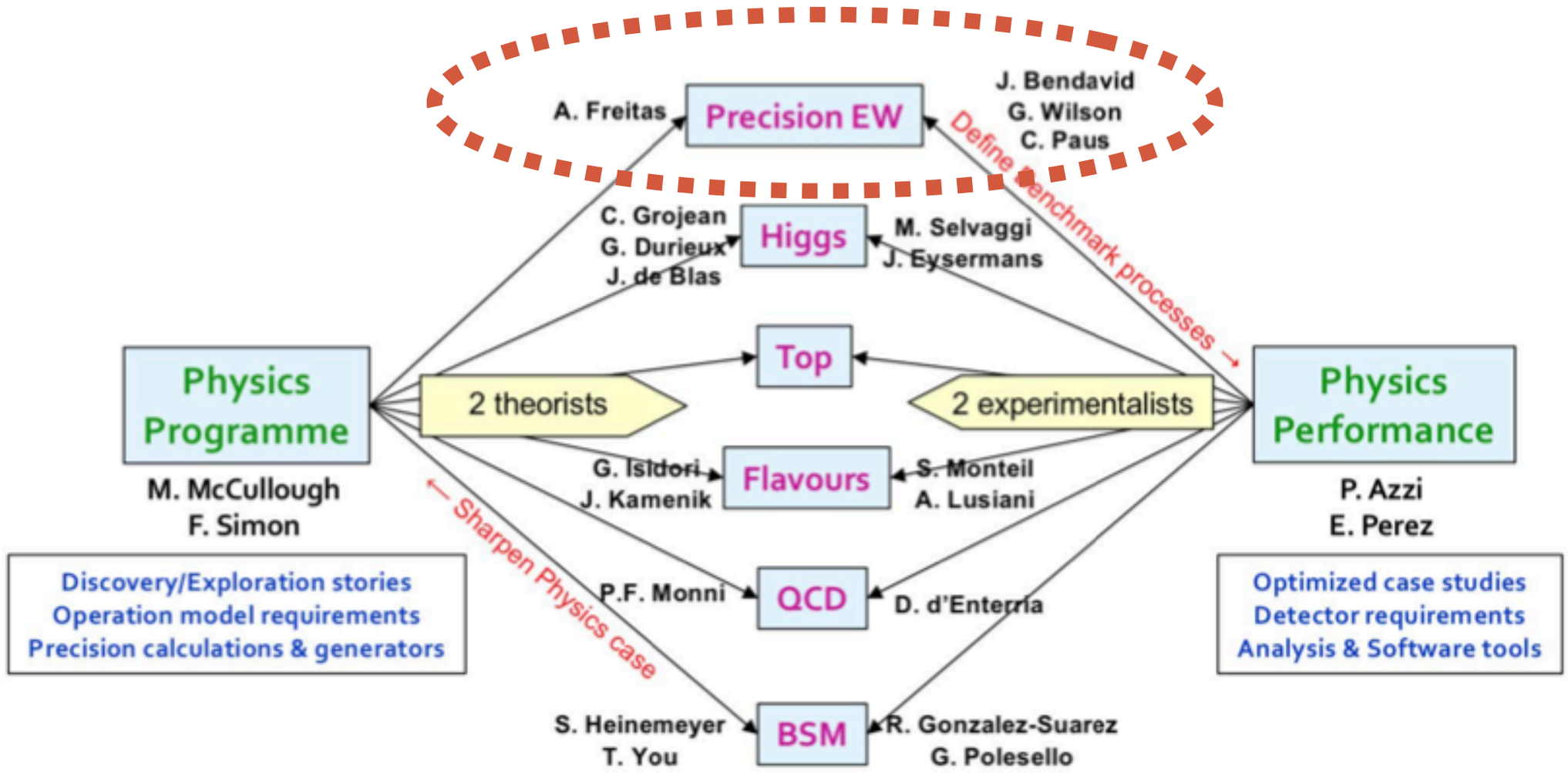
RUJUTA SANE, DENIS SIMINIUC, ISABELLA TORRES, MIT

MIT thrusts

Focus: Electroweak

Excellent progress on electroweak physics

Contact:
Christoph Paus



FCC-ee needs to take advantage of recent theory developments

Partnership with generator theory community

- Implement state-of-the-art event generator workflows with the most precise predictions available
- Design workflow for centralized Monte Carlo production
- Partnership with generator theory community is crucial
- Downstream steps include detector simulation
  - Use GEANT or Delphes for most physics studies?
  - Three different detector technologies proposed: full simulation to be run centrally or by individual groups and compare performance?

Martin Aleksa's talk

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Saptaparna Bhattacharya, Northwestern University

Round table discussion

Physics questions that can be addressed by the US community

Ideas collected in Google docs

Feel free to add your name and new ideas

Leverage existing expertise — establish US leadership in selected areas

Build community oriented towards FCC project

The goal of the document is to write down a few bullets for projects and questions we need to address to accomplish the FCC-ee feasibility study physics goals.

General

1. Precise luminosity measurement is limited by the absolute theory uncertainty on the small angle bhabha scattering (The two photon cross section overall is severely limited due to it small production cross section but precise in terms of theory uncertainties) Ayres et al.
2. Beam energy calibration is essential as it introduces a significant uncertainty for basic pseudo observables at the Z pole, A.Blondel et al.
3. Study energy calibration using muon events for example at higher energies (J.Eysermans et al.)
4. Detailed Monte Carlo to describe the multiplicity more precisely, in particular at lower momenta. This is an issue already identified at LEP and it was never really 'resolved'.
5. Find someone to port the ALEPH/OPAL/DELPHI? data to the FCC data format.
6. Generators: two photon collision event generators are not modeling the data very well, particularly bad is the hadron production in two photons (Sebastian Jaskiewicz., F. Kraus)
7. Detailed charm taggers and charm fragmentation function (George Iakovidis, Marc-Andre Pleier, Abe T.-C., Elisabeth Brost)
8. Gluon tagging (M.Begel)
9. Study background using potential 125 GeV run (C.Paus et al.)

QCD

1. Events shapes and alpha_s (Chris Lee, Jesse Thaler, Iain Stewart, Jennifer Roloff (BNL), R.Szafron)
2. Colorflow at the Higgs factory (Michael Begel)

Electroweak Precision

1. Extraction scheme of pseudo observables in LEP style is likely not going to scale to FCC-ee, is there a new and better way of extracting pseudo observables?
2. Two photon production processes, in particular production of hadrons in the two photon interactions, are in need of better MC.
3. BES/acceptance effects on hadronic final states (J.Eysermans et al.)
4. Various pieces on the W mass measurements (J.Eysermans et al.)
5. Electron structure function (R.Szafron)

Higgs Physics

1. Inclusive versus exclusive jets in the ccbar final state (Abe)
2. Establish Standard Model level sensitivity and what limit are possible.

Round table discussion

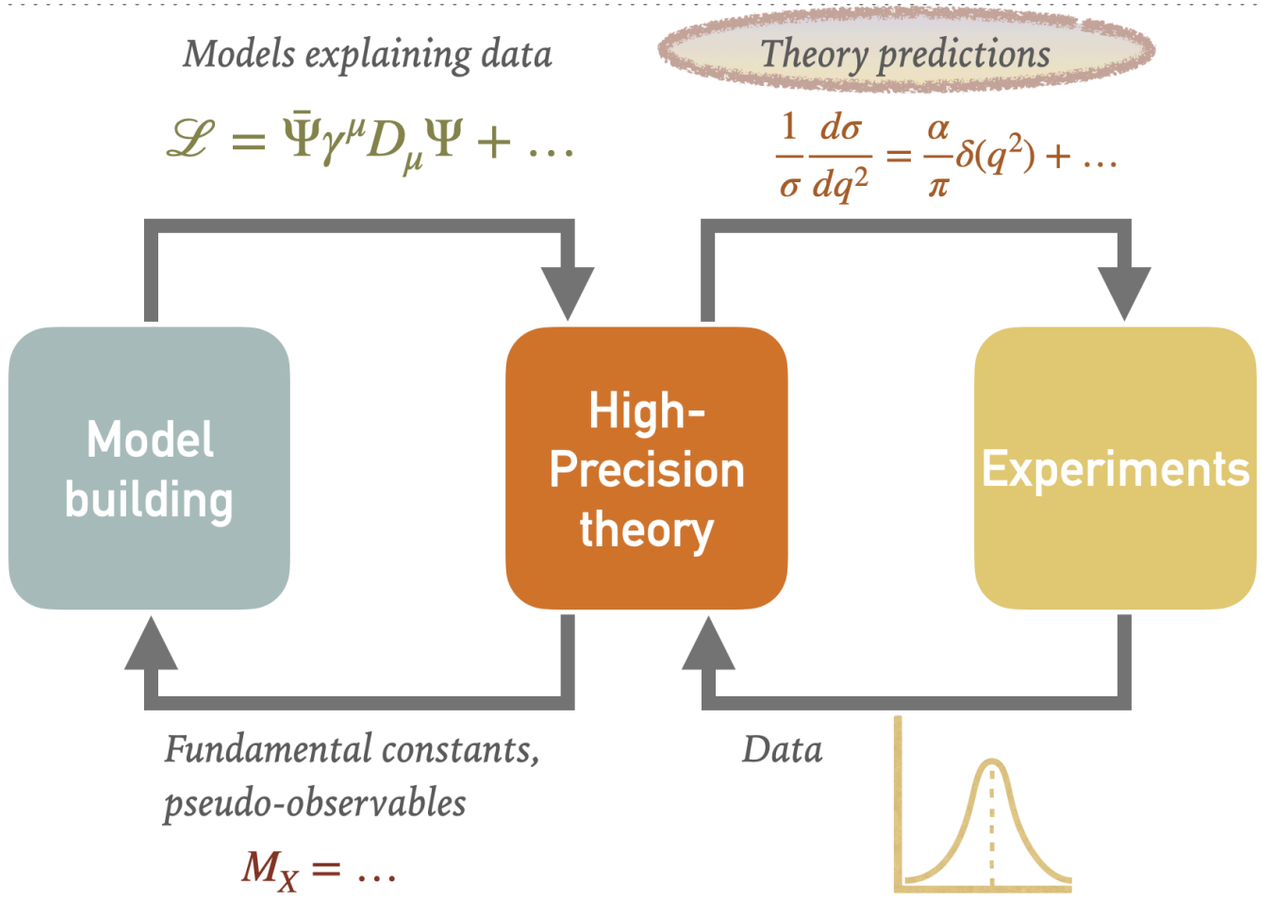
- *Luminosity measurements (old theory, can be improved with modern methods)*
- *Energy calibration*
- *Charm and gluon tagging*
- *Background and additional physics potential of 125 GeV run*
- *QCD at FCC*
- *Electroweak precision (pseudo-observables vs modern EFT based approach)*
- *Threshold production theory and experiments*

Many opportunities to contribute!

Theory for FCC-ee

We need strong theory support:

- *Standard Model precision*
  - *Electroweak (with focus on QED)*
  - *QCD*
  - *Generators*
    - *Resummation*
- *Discovering New Physics indirectly rather than focusing on direct signatures*



Experiment and theory need to work together for the FCC

Summary

- *e+e- collider the only way to explore Higgs sector in a near future*
- *FCC project offers natural path towards 100 TeV*
- *Partnership with CERN is crucial given the budget constraints and the need for broad physics program*
- *P5 report and update of European strategy will be critical for the future of particle physics*

US community needs to establish leadership in selected areas of FCC program

ROBERT SZAFRON, FIRST US FCC WORKSHOP, BROOKHAVEN NATIONAL LABORATORY, APRIL 26, 2023