FCC-ee PHYSICS & SOFTWARE

Overview and mid-term deliverables

Introduction

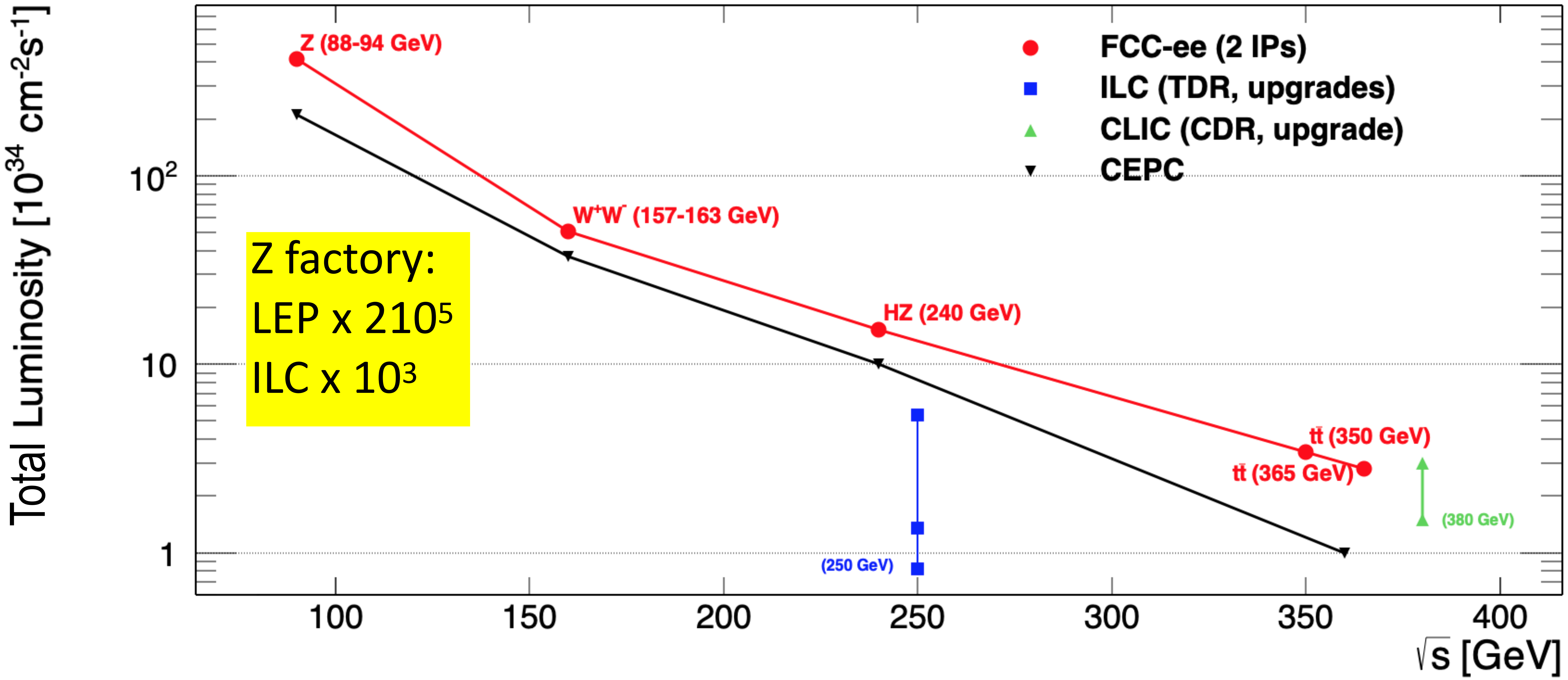
The physics landscape of the FCC-ee program extends in all possible directions:

- the difference in the physics focus at the different √s
- the difference in the event kinematic of running from 90GeV (and possibly below) up to 365GeV
- the challenge of being able to achieve superbe precision on SM processes but also perform unique direct searches for new physics

The list of interesting processes and measurement is extensive, and it has not been fully explored yet, even in terms of sensitivity.

From this richness, we need to extract concrete benchmark measurements that will be used to extract requirements on what is missing to achieve our ambitious goals: detector requirements, reconstruction tools, calibration techniques.

Can produce all the heaviest particles of the Standard Model



Z factory:
LEP x 210^5
ILC x 10^3

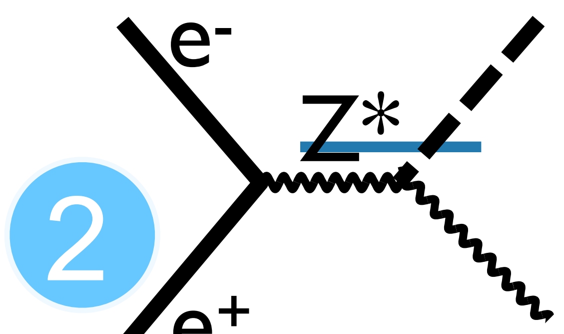
High integrated luminosity at the needed E_{cm}

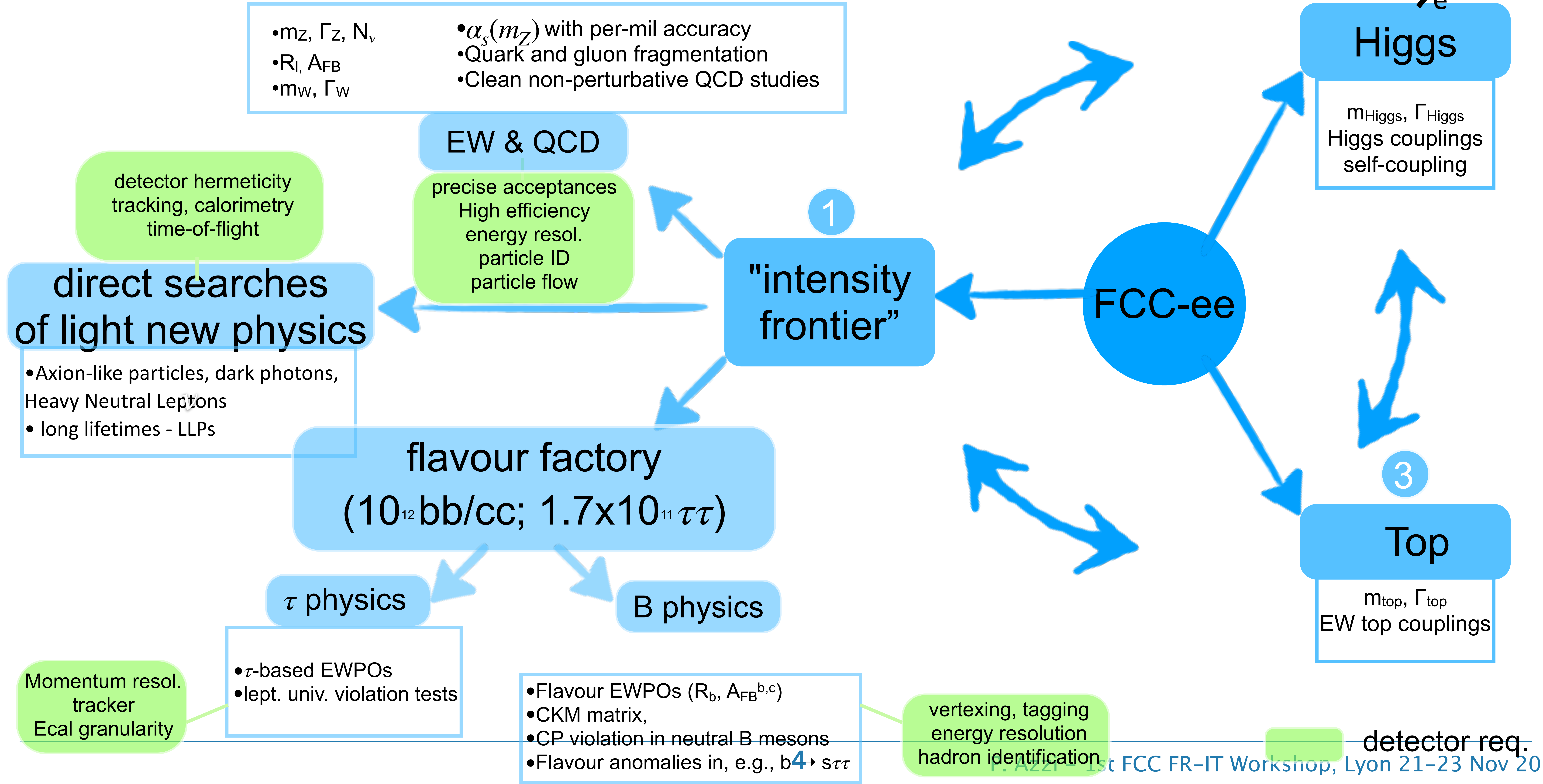
Clean environment

Precise knowledge of the center-of-mass energy and of the luminosity

						$\sqrt{s}$ errors
ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$\bar{t}t$ threshold	$\sqrt{s} \sim 350$ GeV	5 years	10^6	$e^+e^- \to \bar{t}t$	Never done	5 MeV
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	5×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 100 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$	LEP x 10^3	< 300 keV
s-channel H	$\sqrt{s} = 125$ GeV	? Years	~5000	$e^+e^- \to H$	Never done	< 200 keV

FCC-ee Physics Programme





- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_s(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

EW & QCD

precise acceptances
High efficiency
energy resol.
particle ID
particle flow

detector hermeticity
tracking, calorimetry
time-of-flight

direct searches of light new physics

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

1

"intensity frontier"

FCC-ee

2

Higgs

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

3

Top

m_{top}, Γ_{top}
EW top couplings

flavour factory
(10^{12} bb/cc; 1.7×10^{11} $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

Momentum resol.
tracker
Ecal granularity

B physics

- Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b\rightarrow s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

🟩 detector req.

The FCC Feasibility Study

Design new detector concepts to realise the physics potential of the FCC-ee

- both in term of precision and sensitivity

Focus on benchmark studies

- that represent the physics goals and allow to extract the detector requirements

Need to develop simulation and analysis tools to get this done

Timeline:
Feasibility study to provide input for the next EPPSU (~2026/7)
Mid-Term Report to be prepared in Fall 2023

Deliverables for Physics, Experiment & Detectors (1)

1. Documentation of the specificities of the FCC-ee and FCC-hh physics cases and their complementarity for the characterisation of the Standard Model Higgs boson and other processes;
    - Consolidation of the physics case and detector concepts for both colliders
    - …()… for FCC-ee several detector concepts are being considered and benchmarked to meet the requirements of ultra-precise Higgs boson and electroweak measurements.
    - …()…Detector design and R&D will proceed in collaboration with the R&D for future detectors initiative at CERN, and with the activities that will emerge from the Detector Roadmap being developed under the auspices of ECFA.

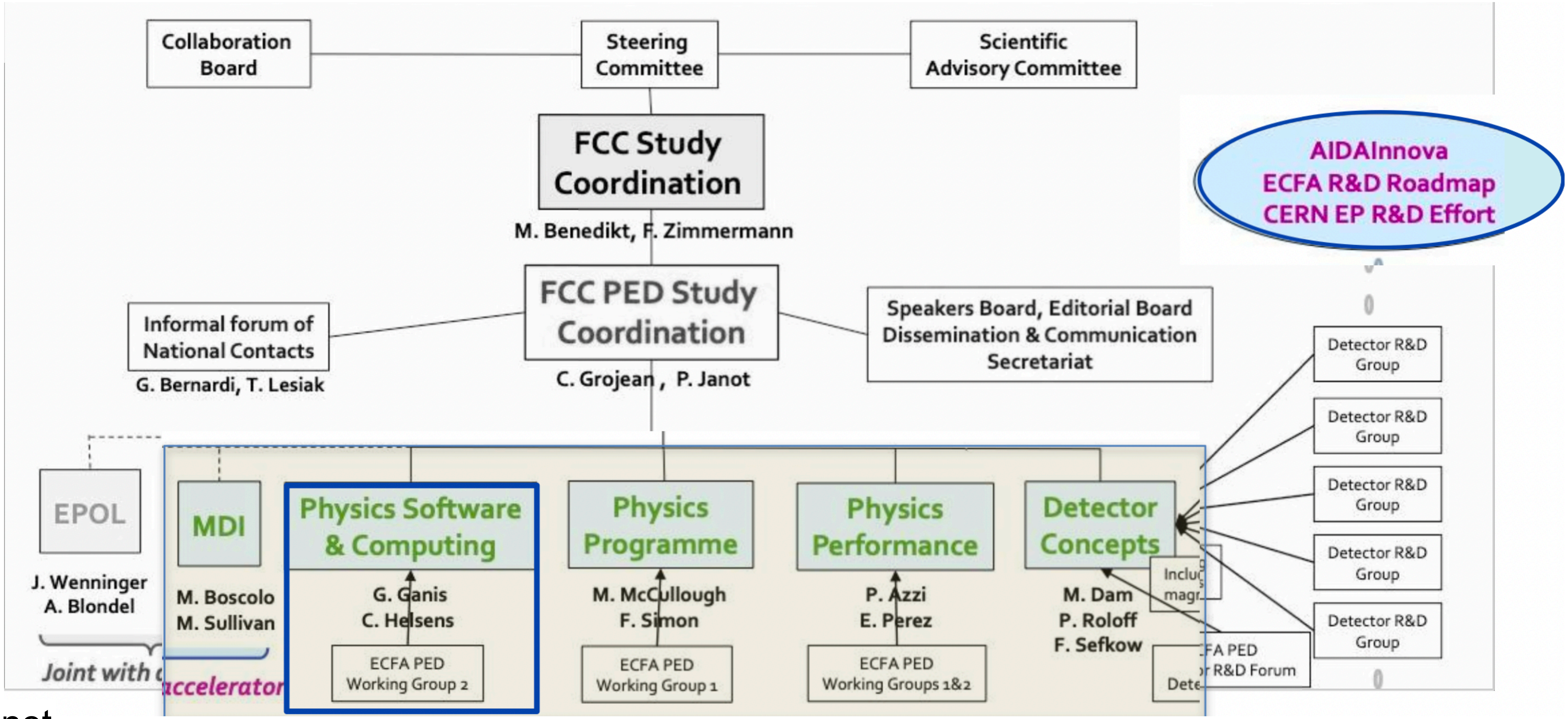
Deliverables for Physics, Experiment & Detectors (2)

2. Strategic plans for the **improved theoretical calculations** needed to reduce the theoretical uncertainties towards matching the FCC-ee expected statistical precision for the most important measurements.
   - See Fulvio Piccinini’s talk

3. First documentation of the **main detector requirements** to be able to fully exploit the FCC-ee physics opportunities, in particular to **reduce the experimental systematic uncertainties** with a view to matching the expected statistical precision for the most important measurements.
   - Improve the evaluation of the requirements for FCC-ee experiments using key physics processes that drive the physics case as benchmarks. This will be done using fast or fully simulated data, to extract the necessary performances that satisfy the ultimate desired measurement uncertainty.
   - Particular emphasis on identification of the main systematic uncertainties and on strategies to reduce them to meet the expected statistical precision. Development and evaluation of experiment concepts, for both general-purpose detectors and detectors primarily targeting specific physics c

CASE STUDIES

How to get there? – Tailored PED pillar organisation



Collaboration Board

Steering Committee

Scientific Advisory Committee

FCC Study Coordination

M. Benedikt, F. Zimmermann

AIDAInnova
ECFA R&D Roadmap
CERN EP R&D Effort

FCC PED Study Coordination

C. Grojean , P. Janot

Informal forum of National Contacts

G. Bernardi, T. Lesiak

Speakers Board, Editorial Board
Dissemination & Communication
Secretariat

Detector R&D Group

Detector R&D Group

Detector R&D Group

Detector R&D Group

Detector R&D Group

EPOL

J. Wenninger
A. Blondel

Joint with *accelerator*

MDI

M. Boscolo
M. Sullivan

Physics Software & Computing

G. Ganis
C. Helsens

ECFA PED Working Group 2

Physics Programme

M. McCullough
F. Simon

ECFA PED Working Group 1

Physics Performance

P. Azzi
E. Perez

ECFA PED Working Groups 1&2

Detector Concepts

M. Dam
P. Roloff
F. Sefkow

Inclu
magr

FA PED
r R&D Forum

Dete

P. Janot

How to get there? – Software & Computing

Main driver:

- One software to support all cases (FCC-ee, hh, eh) with a modular structure to allow for evolution

Neecessary functionalities:

- Parameterized (fast) simulation with same output as full simulation
  - Algorithm development before full simulation is available
- Sub-detector Plug&Play mechanism: easy switch of detector solution

Computing:

- FullSimulation of all cases unrealistic
- Interplay of full/fast/parameterized simulation crucial
  - Crucial synergy with Physics Performance and Detector WPs

Key4HEP, the common software vision

Create a software ecosystem integrating in optimal way various software components to provide a ready-to-use full-fledged data processing solution for HEP experiments

Complete set of tools

- Generation, simulation, reconstruction, analysis
- Build, package, test, deploy, run

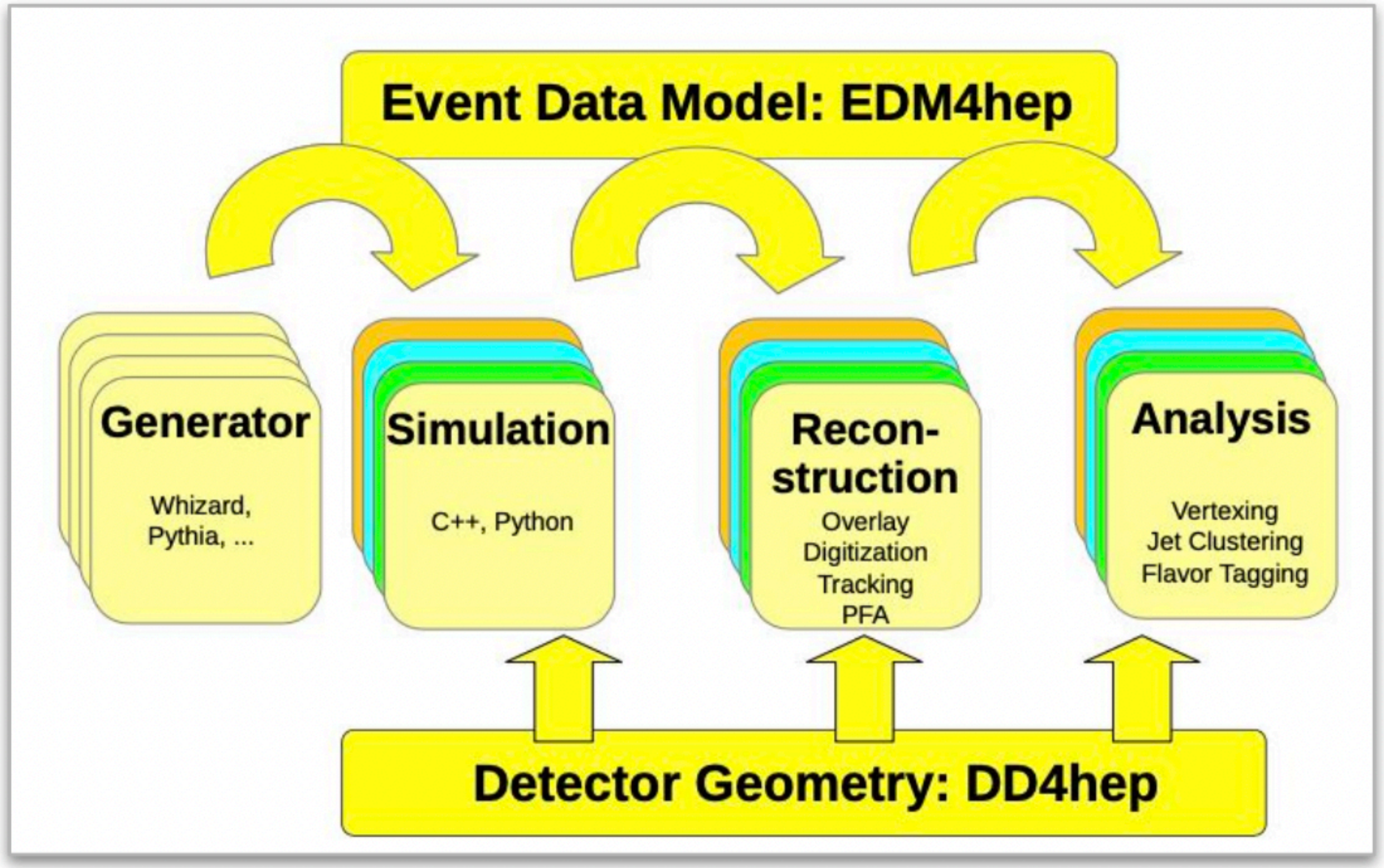
Common Core ingredients

- PoDIO for EDM4hep, based on LCIO and FCC-edm
- Gaudi framework, devel/used for (HL-)LHC
- DD4hep for geometry, adopted at LHC
- Spack package manager, lot of interest from LHC

Community project

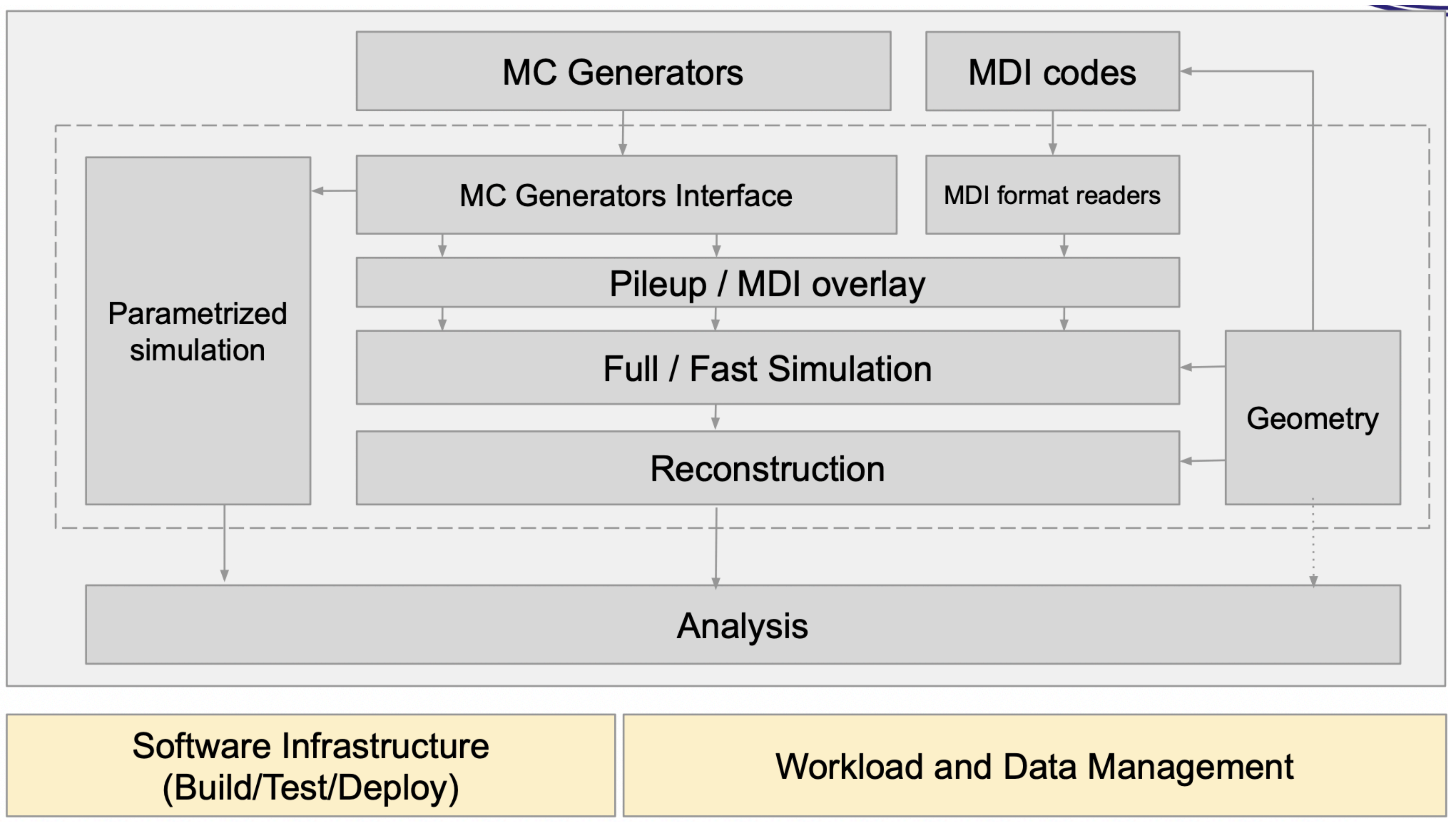
- Unifying communities, synergetic enterprise
- Contributions from CLIC, ILC, FCC, CEPC and EIC

Full support by ECFA, AIDA, CERN EP R&D



Kick-off meetings Bologna (6/2019), Hong Kong (1/2020)
Weekly working meetings
Deliverables already used in large scale production

Software & Computing: status



MC Generators
MDI codes
MC Generators Interface
MDI format readers
Parametrized simulation
Pileup / MDI overlay
Full / Fast Simulation
Geometry
Reconstruction
Analysis
Software Infrastructure (Build/Test/Deploy)
Workload and Data Management

Current workflows

- Parametrized simulation
  - Delphes based studies
    - Improved tracking: realistic output allows to design/develop advanced algorithms
- Analysis
  - Developed a framework based on latest ROOT technology being pushed for HL-LHC
  - Fully based on EDM4hep (Key4hep)
- Full simulation
  - Workflow being consolidated together w/ Physics Performance/Detector Concepts WGs
  - Extensive experience from Linear Collider community very important

Computing

- Home based solution for MC productions
  - Mostly based on CERN in-kind resources

G. Ganis

Software & Computing: next priorities

Simulation:

- Forming new experts in DD4HEP description. —> Streamline the sub-detector Plug&Play technology

Reconstruction

- Review/integrate the algorithms developed from the Linear Collider studies and LHC
- Foster integration in Key4Hep for packages such as Pandora (ParticleFlow) and ACTS(Tracking)

Analysis

- Consolidate current approach based on RDataFrame. Adding reduced format for simplified navigation
- New Tutorials and examples to help newcomers
- Provide visualisation tool (event Display)

Computing:

- Development of distributed computing model (CNAF, BARI, DESY) for central production of samples

Physics & Detector requirements Higgs/EW/Top

M. Dam

”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 $e^+e^- \to H$ @ √s = 125 GeV

DETECTOR REQUIREMENTS

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

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

- $5\mathrm{x}10^{12}$ Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ , R_b, α_s, m_W, Γ_W,…
- 10^6 tt
  - m_{top} , Γ_{top} , EW couplings

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

DETECTOR REQUIREMENTS

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. Γ_{had}/Γ_ℓ) to 10^{-5}
- Momentum resolution ”as good as we can get it”
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.

…are these requirements enough to design our best detector?

FCC-ee at the intensity frontier

TeraZ offers four additional pillars to the FCC-ee Higgs/EW/Top physics programme

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., $b \to s\tau\tau$

QCD programme

- Enormous statistics with $Z \to \ell\ell$, qq(g)
- Complemented by 100,000 $H \to gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Often statistics-limited
$5.\,10^{12}$ Z is a minimum

Tau physics programme

- Enormous statistics: $1.7\ 10^{11}$ $\tau\tau$ events
- Clean environment, boost, vertexing
- Much improved measurement of mass, lifetime, BR's

1. τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
2. Lepton universality violation tests
3. PMNS matrix unitarity
4. Light-heavy neutrino mixing

Rare/BSM processes, e.g. Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m_Z

- Signature: long lifetimes (LLP's)
- Other ultra-rare Z (and W) decays

1. Axion-like particles
2. Dark photons
3. Heavy Neutral Leptons

Slide by P. Janot Ecfa meeting 19 Nov 2021

FCC-ee at the intensity frontier

… which in turn provide specific detector requirements

Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z resonance

QCD + EW programme

- Particle-Flow reconstruction
- Lepton and jet angular and energy resolution ; Lepton ID

More case studies will lead to more detector requirements

Tau physics programme

- Momentum resolution
  Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  Lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation
  BR measurements, EWPOs, spectral functions

Rare/BSM processes, e.g. Feebly Coupled Particles

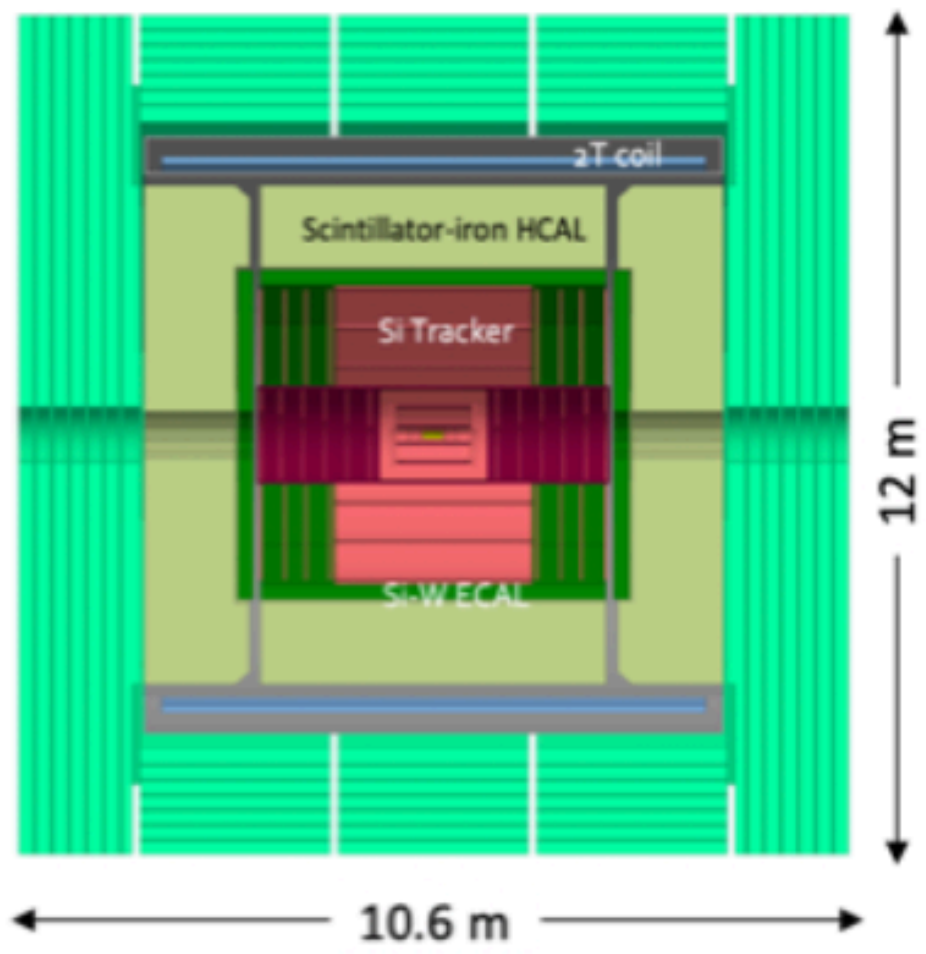
- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

If all these constraints are met, Higgs and top programme probably OK (tbc)

Slide by P. Janot Ecfa meeting 19 Nov 2021

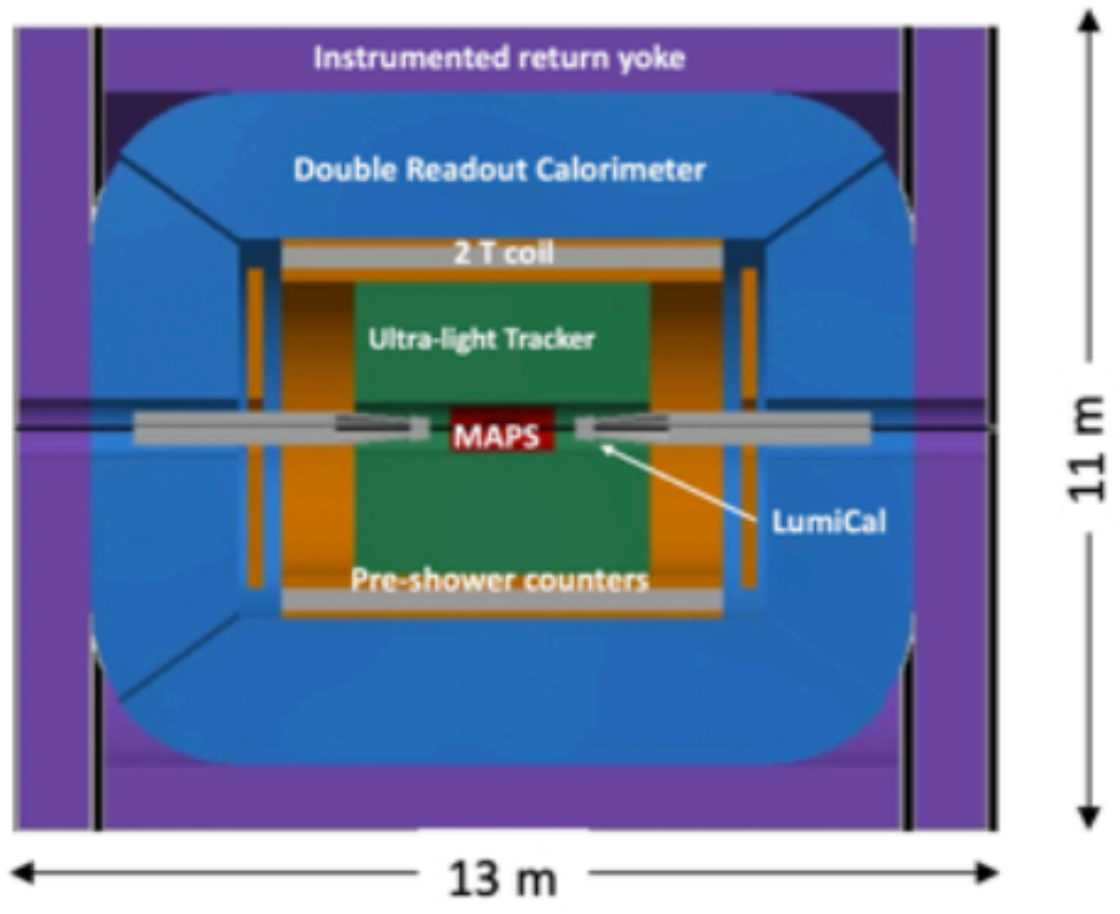
Current Detector concepts

CLD

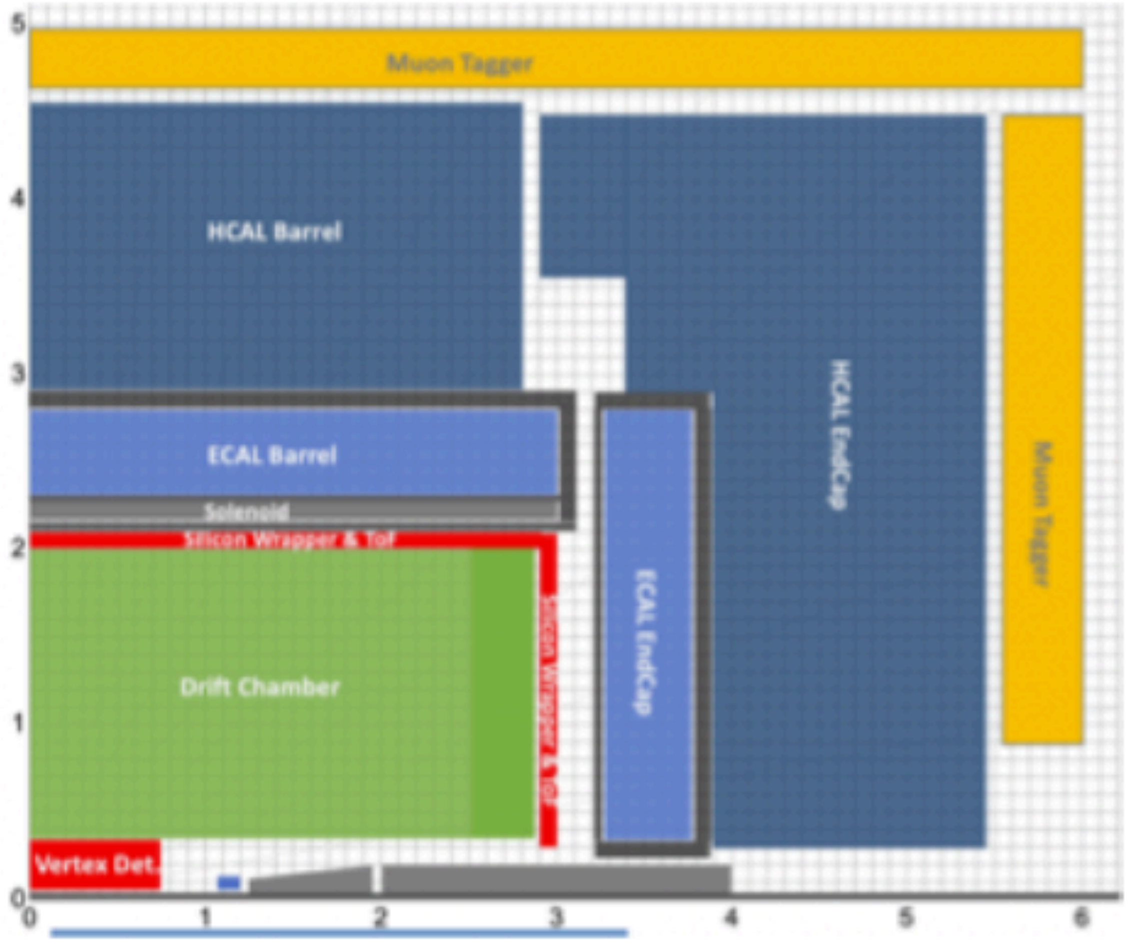


CDR

IDEA



Noble Liquid ECAL based



new

- CLIC detector -> CLD
- 2T solenoid outside Calo
- Full Si vtx + tracker
- CALICE-like calo
- RPC muon system

- 2T thin solenoid within Calo
- Si vtx detector
- Ultra light drift chamber
- Dual Readout calo+preshower
- Possible crystal ECAL
- MPGD (μ-rwell) muon system

- High granularity ECAL
  - Pb+Lar (or W+LKr)
- Drift chamber (or Si) tracker; CALICE-like HCAL; muon sys.
- Coil in same cryostat as LAr

1911.12230, 1905.02520

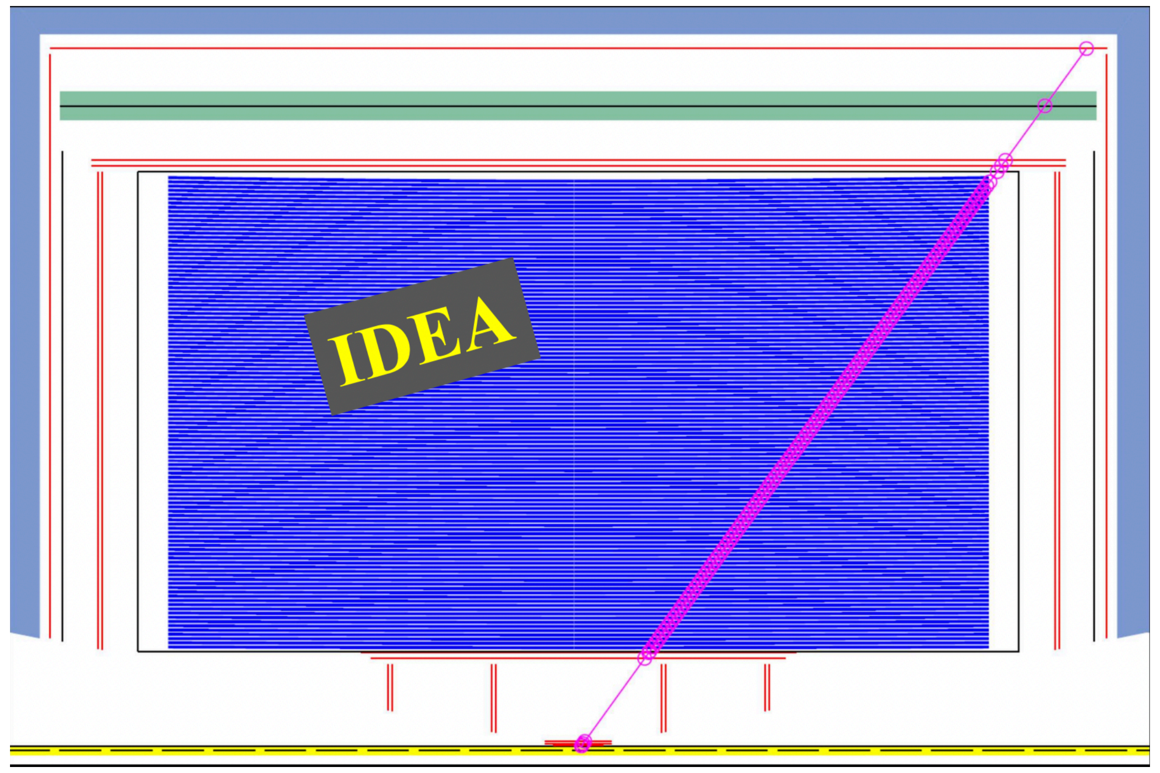
CERN-ACC-2018-0057

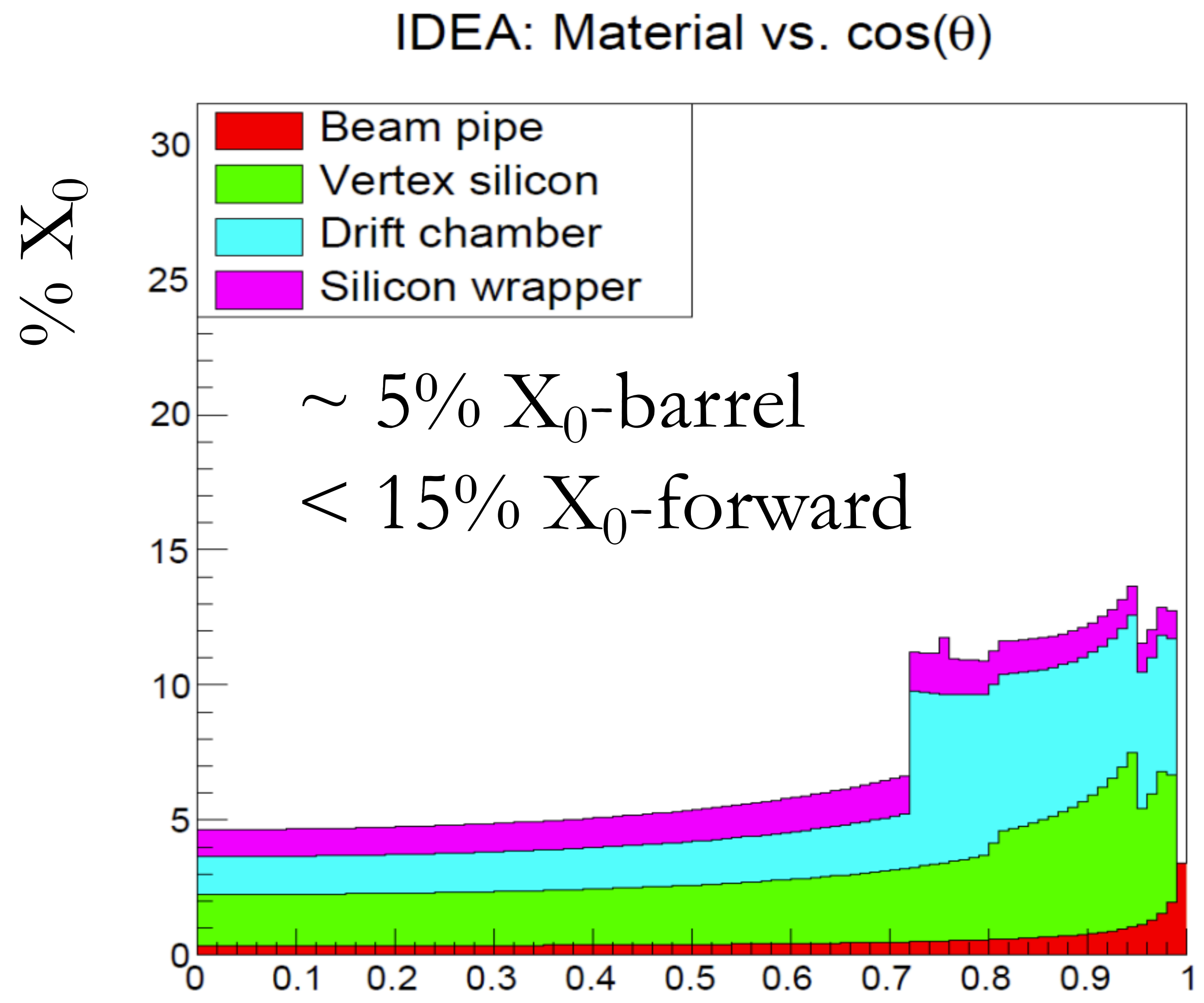
Detector Simulations

Full simulation:

10^2-10^3 s/ev

- simulates all particle-detector interaction (e.m/hadron showers, nuclear interaction, brem, conversions) with GEANT
- **In fast development, will be the standard for the final feasibility studies**

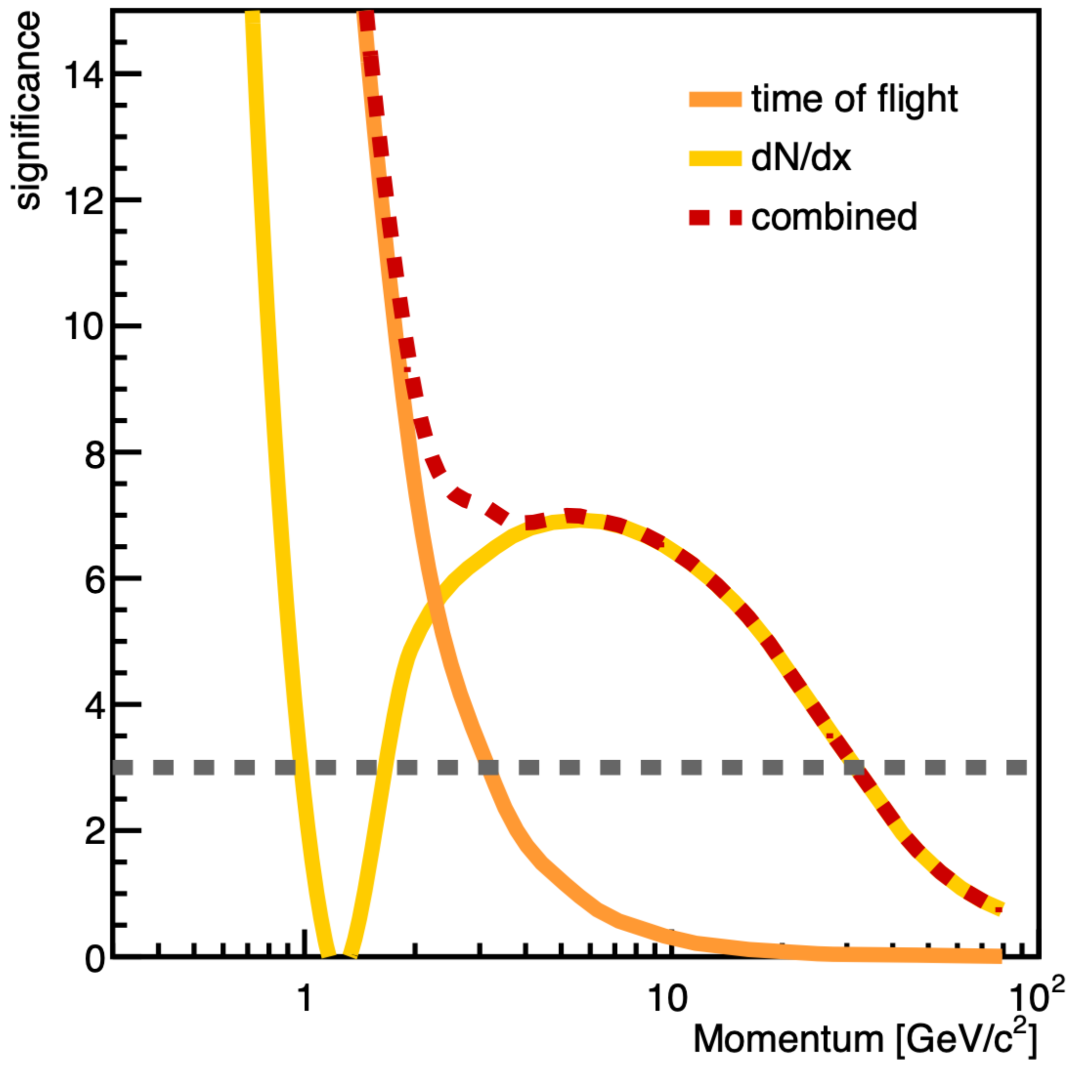


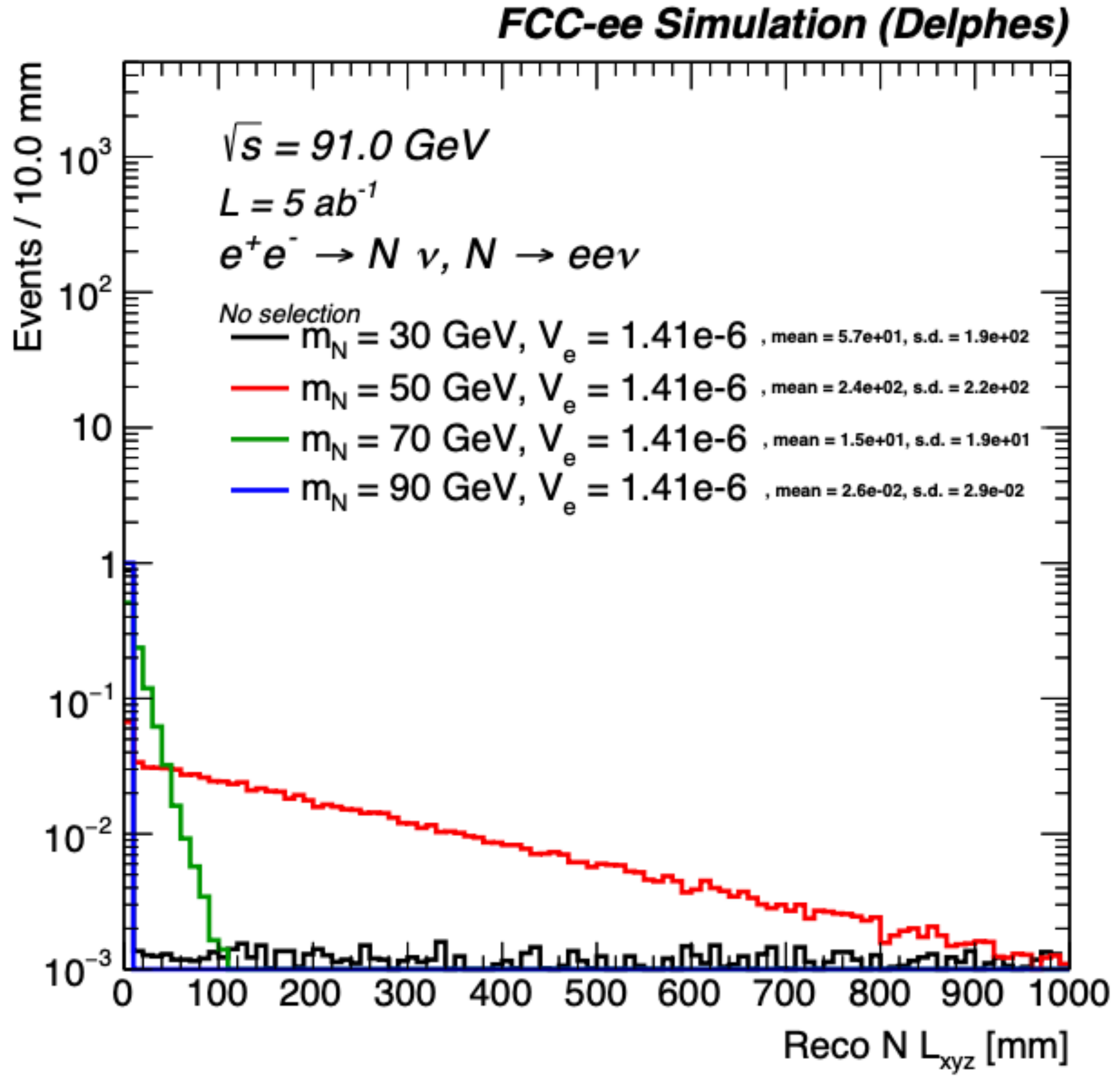


Parametric simulation (Delphes):

10^{-2}-10^{-1} s/ev

- parameterise detector response at the particle level (efficiency, resolution on tracks, calorimeter objects)
- reconstruct complex objects and observables(use particle-flow, jets, missing ET, pile-up ..)
- **Many features added: full covariance matrix for tracking, vertexing, LLP, PID with dN/dx, timing…**
- **Basis for the mid-term report**



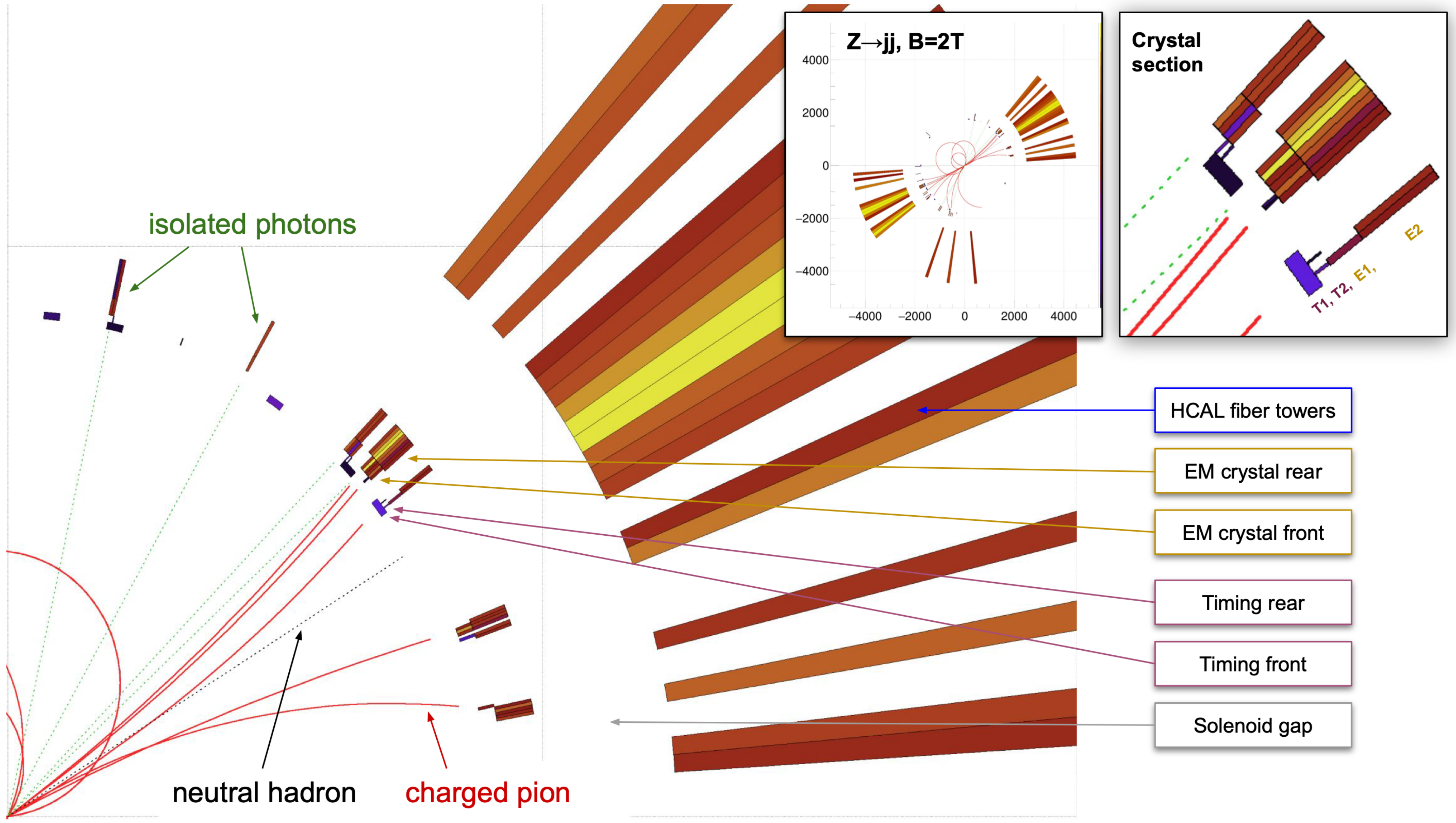


See M. Selvaggi shorturl.at/oruxA

Exploiting the detector potential

Particle Identification in DRCalo: γ/π^0 : The extremely high 2D-granularity of the IDEA Calorimeter brings to some spectacular results. An example is the π^0 identification from two γ-initiated showers

- **A quantitative analysis on the possibility to distinguish between π^0 and γ was performed using a convolutional neural network.** Results on events with no selection and fully digitised.

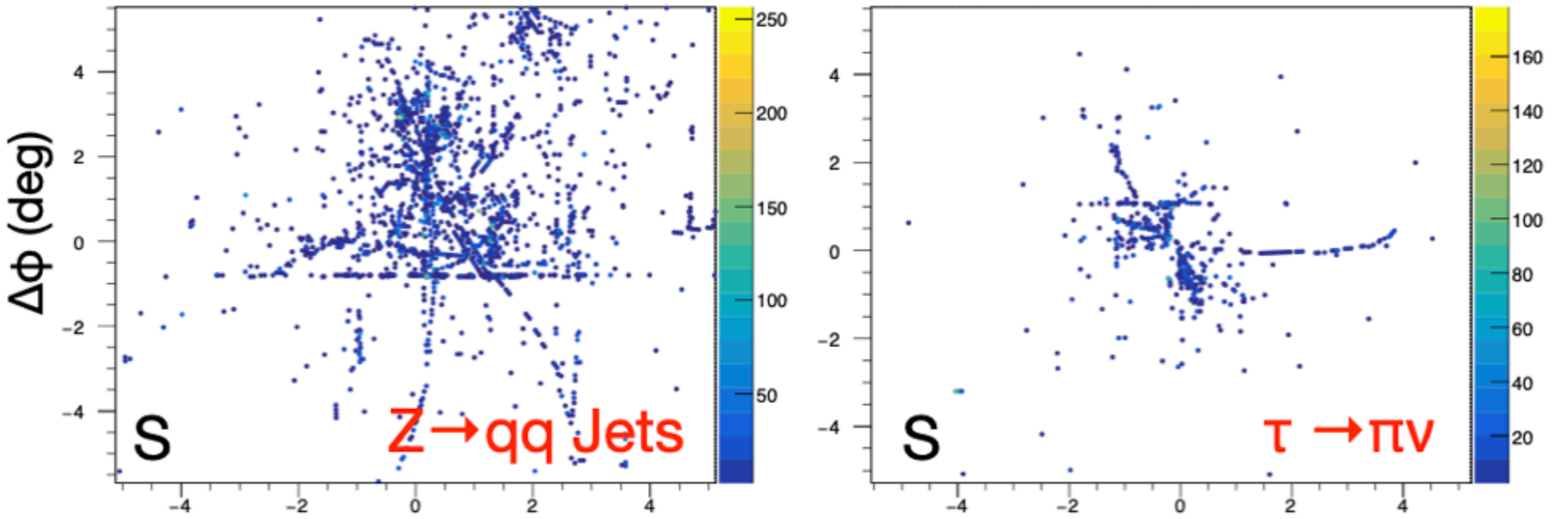


Develop powerful identification techniques to optimise physics potential for tau physics with the IDEA detector. Starting from DR Calorimeter information, to be extended

- Very promising realistic performances using full sim of DR Calorimeter + simulation of SiPM
- implementation of of individual object identification inside jet/tau images (e, mu, photons, pions, ...), as a first prototypal particle flow algorithm

PFLow with DR calo: NN based algorithm within the Pandora framework, started.

TALKS in PARALLEL SESSION TOMORROW!



CONVENERS
M. Selvaggi , J. Eysermans
C. Grojean, G. Durieux, J. De Blas

Case studies – Higgs Physics

Some **chosen** priority case studies for Higgs physics (of course not the FULL program!)

Goals of a “case study”:

- to identify major systematics
- dependence on detector performance or machine conditions
- Develop strategies for evaluation/reduction of systematics at the analysis level

M(H) and $\sigma(ZH)$ in HZ, Z in leptons **FR** **IT**

M(H) and $\sigma(ZH)$ in HZ, Z in hadrons

Invisible Higgs **FR**

$H \rightarrow b\bar{b}, c\bar{c}, s\bar{s}$ couplings **FR** **IT**

$\Gamma(H)$ in $ZH, H \rightarrow ZZ^*$

$\Gamma(H)$ in $bb\nu\nu$ events

$HZ\gamma$ coupling

Higgs self-coupling **FR**

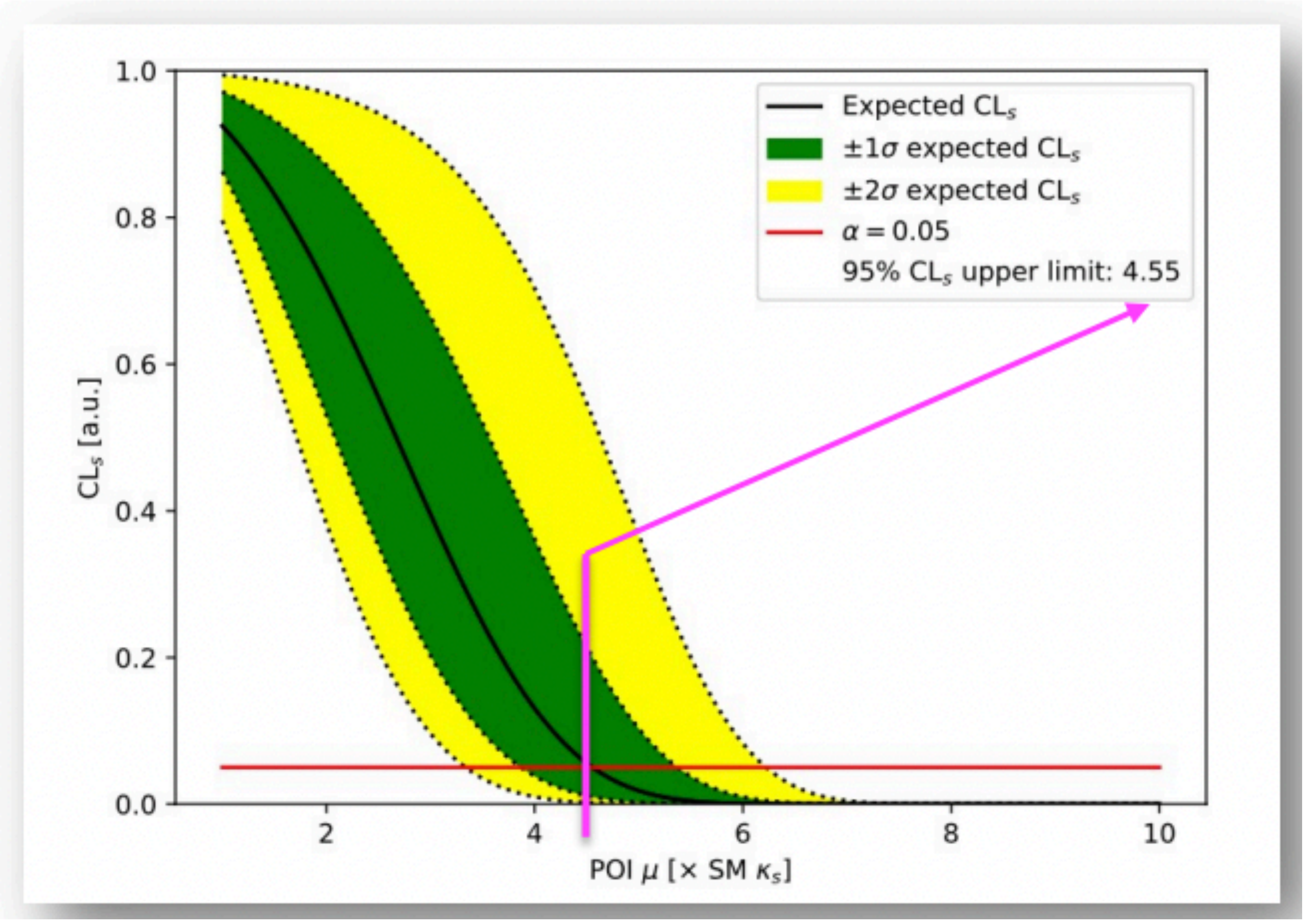
$ee \rightarrow H$, s-channel production

TALKS in PARALLEL SESSION TOMORROW!

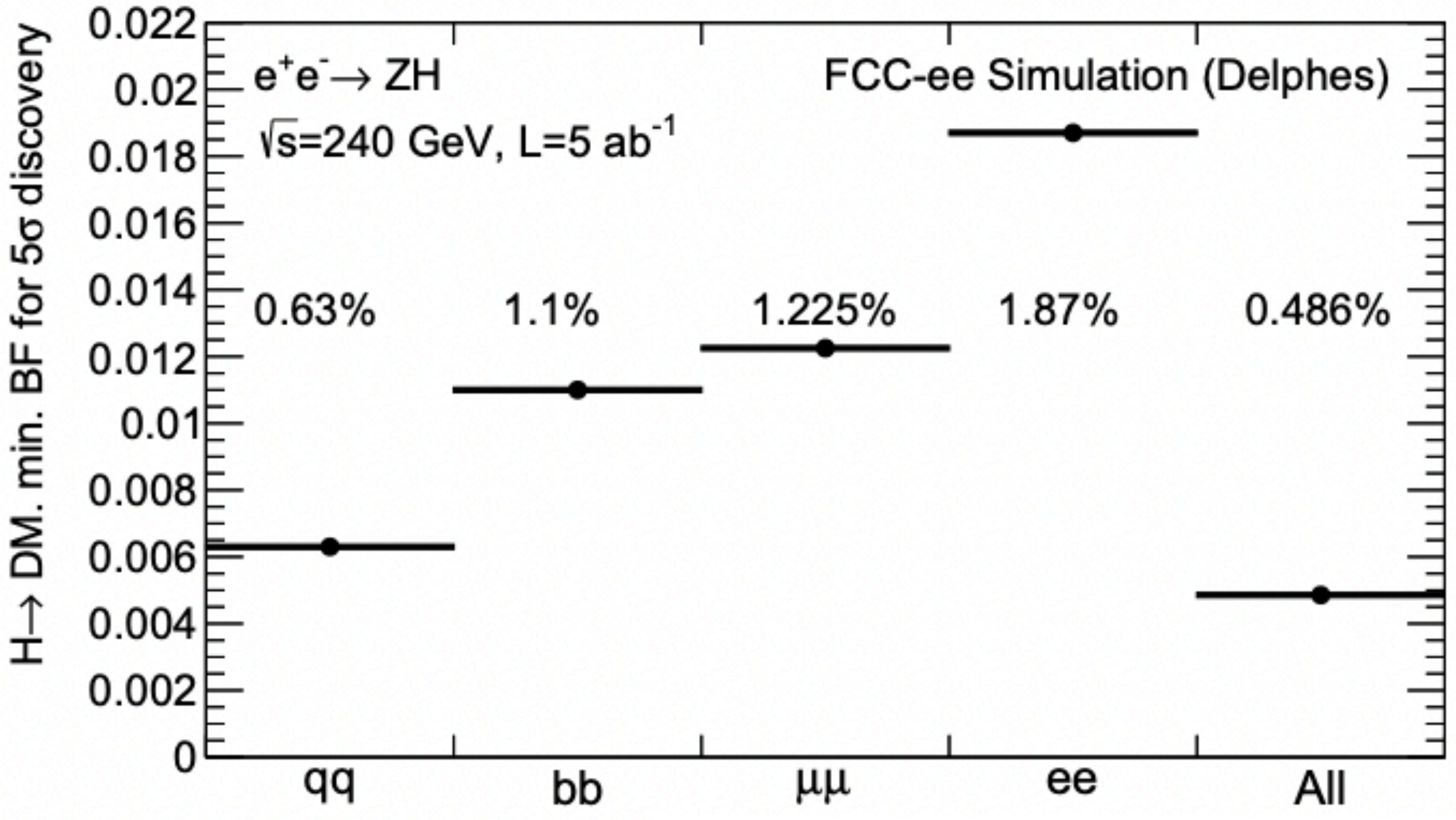
Other Higgs highlights

Recoil method the basis for many studies. First results with Z to leptons, now adding hadronic final states for Z and Higgs. Exploiting sophisticated flavour taggers with ML (ParticleNet)

- Rising interest in **Strange tagging** bringing constraints on detector PID performance, timing. For IDEA combined PID with dN/dx and TOF(30ps): $3\sigma\ K/\pi$ separation for p<30GeV
  - several active groups: *V. Cairo et al* using ILD tools proposing a RICH; *E. Ploerer, K. Gautam et al*. developing a new CNN approach



- **Higgs Invisible** studies: exploiting all channels to control uncertainties and push the sensitivity for the BR(H->DM)



A. Metha, N. Rompotis

V. Cairo et al

CONVENERS
S. Monteil , A. Lusiani
J. Kamenik, G. Isidori

The intensity frontier – Flavor physics

- 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

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

~15 times Belle's stat

Boost at the Z!

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	$\sim$ 2 000	$\sim$ 10	n/a (5)
LHCb Run I	150	-	$\sim$ 15 (–)
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)
FCC-ee	$\sim$ 200000	$\sim$ 1000	$\sim$1000 (100)

Yelds for flavor anomalies studies:

b→sll yelds and $B^0 \to K^{*0}\tau^+\tau^-$ 👍

Full reconstruction possible

Flavor physics– Case studies

Many ongoing activities, lots of work to do:

- Improved Delphes suitable for a first pass and setup of the analysis tools.
- Excellent benchmarks for track and vertex resolution, Particle ID, EM resolution for final states with neutrals
- Some arXiv available, need to be verified with proper simulation, reconstruction and analysis tools.

$B_u/B_c \to \tau\nu_\tau$: paper out, new improved version in progress

$B_s \to D_s K$: test bench for vertexing tools and EM calo requirement (including neutrals) https://arxiv.org/abs/2107.02002

IT

$B_s \to K^*\tau\tau$: testing effects of detector performance on background reduction (vertexing res., PID)

FR

$B_s \to \phi\phi$ https://arxiv.org/abs/2205.07823 strong requirements on mom resolution, vertexing, PID. Relevant for CP violation and NP

FR

$B^+ \to D^0K^+$: to measure γ_s. Study of effects of vertexing, resolution, but also comparing different performance of tracker concepts (2107.02002, 2107.05311)

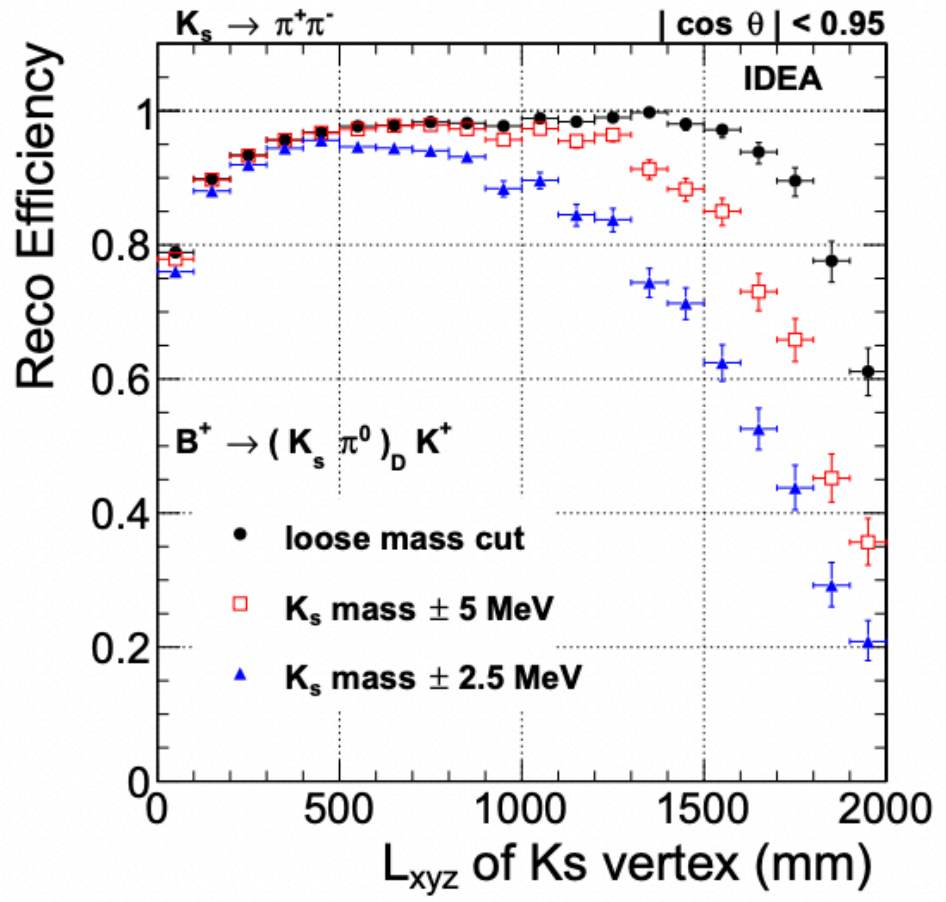
FR

$B_s \to K^*\nu\nu$: relevant for NP. Vertexing and PID crucial

FR

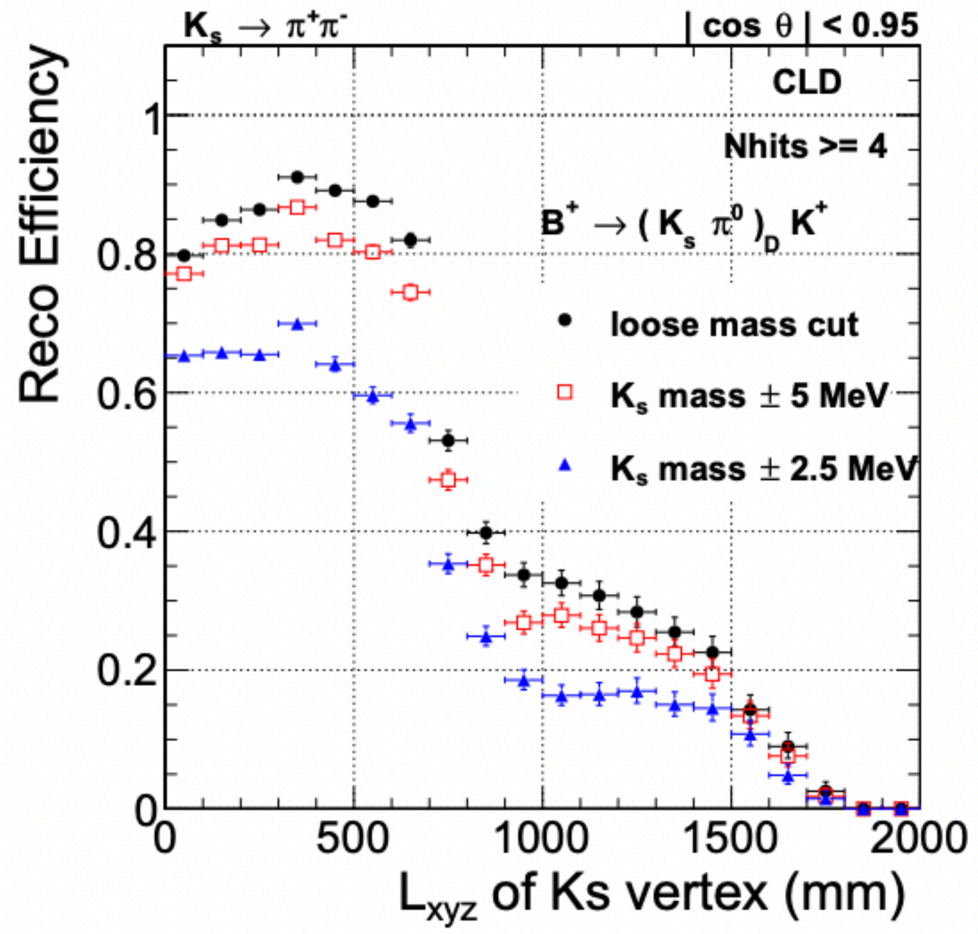
Study example for $B^+ \to D^0K^+$ with new tools *E. Perez*

https://arxiv.org/pdf/2107.05311.pdf



IDEA

Good efficiency also at big displacements



CLD big effect of losing a layer hit

Modified default card, similar vtx res, worse mass res.

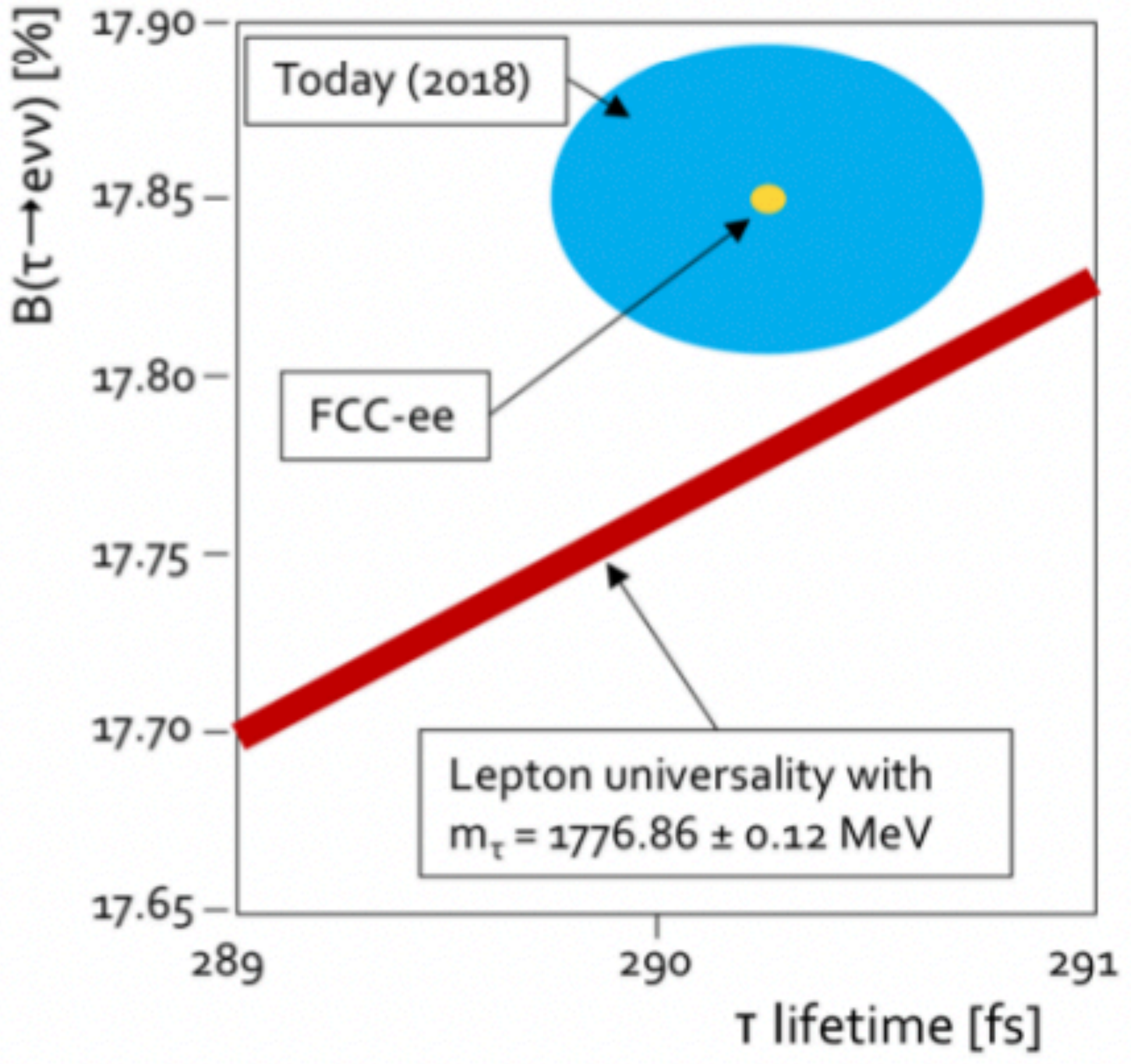
TALKS in PARALLEL SESSION TO

Tau Physics Case Studies

Tau physics very rich source of measurements constraining the detector requirements.

Some initial studies starting with Delphes, focusing on tool development for tau identification.

- FullSimulation necessary for further steps and detector requirements
- Some initial studies already happening in the context of the development of reconstructions tools (such as Tau ID in DR Calorimeter) **IT**



Tau lifetime

Tau mass

Tau leptonic BR

Tau polarisation and exclusive BR

LFV in Z and tau decays

LFU tests

- * NP expectation from current anomalies in the range (0.2 – 4.0) × 10-3 (SM theory precision ~ 10-5)
- * Belle-II can (at most) reach an error ~ 0.3 × 10-3
- * FCC-ee could go below 10-4

sensitivity good enough to probe BSM models "explaining" current flavour R_K anomalies ($b \rightarrow c\tau\nu$)

Electroweak & QCD Case Studies

EWK (Z)

Z width

R_b, R_c, R_ℓ

$A_{FB}(bb, cc)$ **IT**

$A_{FB}(muons)$

Luminosity from di-photons/NP

Coupling of Z to ν_e (NP)

EWK (W)

W polarisation

M(W) from direct reconstruction

$\sigma(WW)$ for M(W), **TGCs** **FR**

Vcb from $W \to cb$

W leptonic BRs

√s via radiative returns

QCD

$\alpha_S(M_Z)$

Quark and Gluon

fragmentation studies

CONVENERS EWK
C. Paus
G. Wilson
A. Freitas

CONVENERS QCD
D. D'Enterria
P.F.Monni

Tera-Z program is a dream for EWK measurements. Bound to bring very strong requirements also on acceptance and stability and alignment of the detector (construction tolerance, design choices)

Some preliminary papers/studies with parameterised approach.

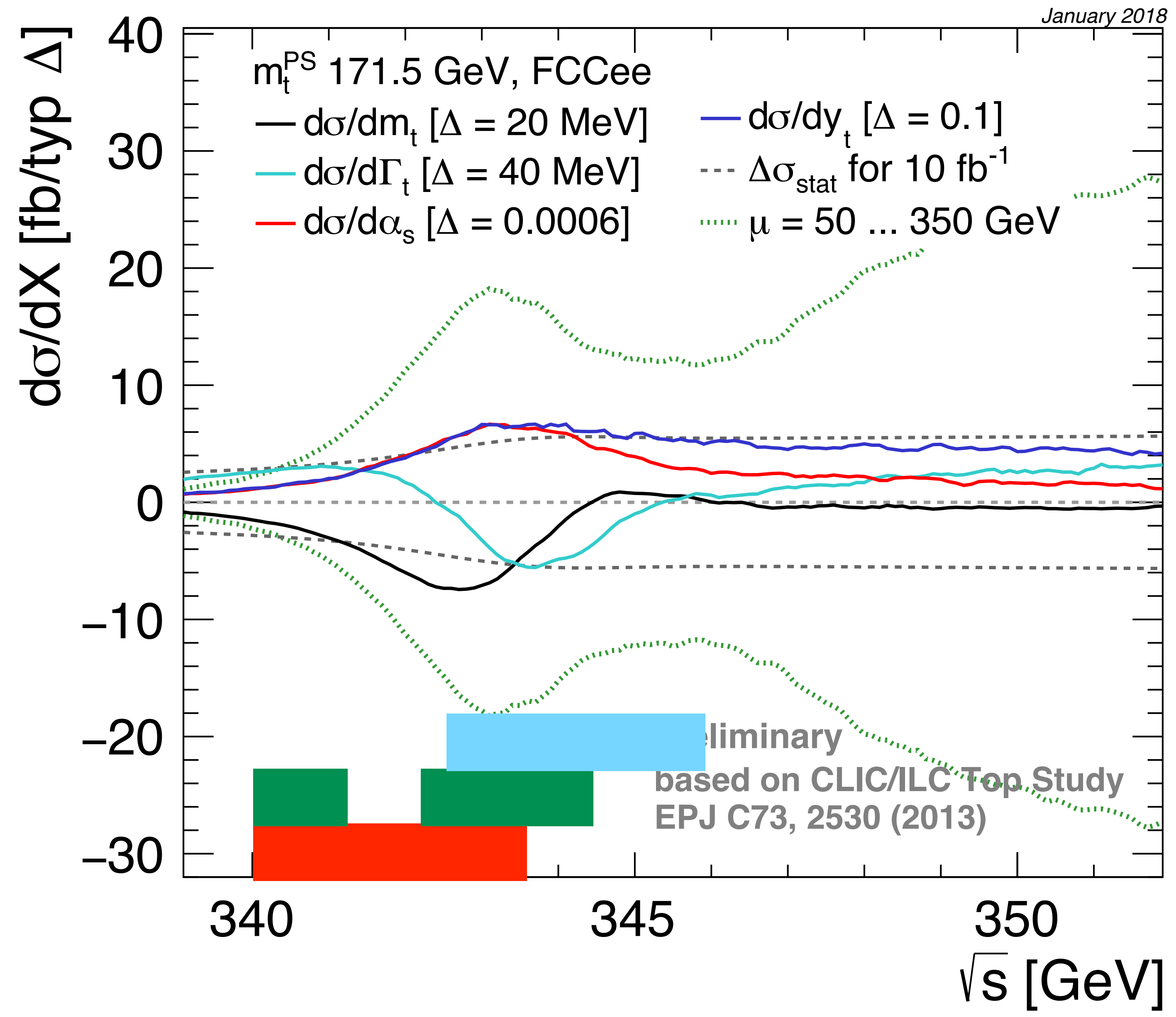
- Few studies started with new tools and detector simulation: $A_{FB}(bb, cc)$, TGCs, Z width

CONVENERS
…In progress

Top physics – Case Studies

sensitivity to:
🟥 mass
🟩 width
🟦 Yukawa

F. Simon



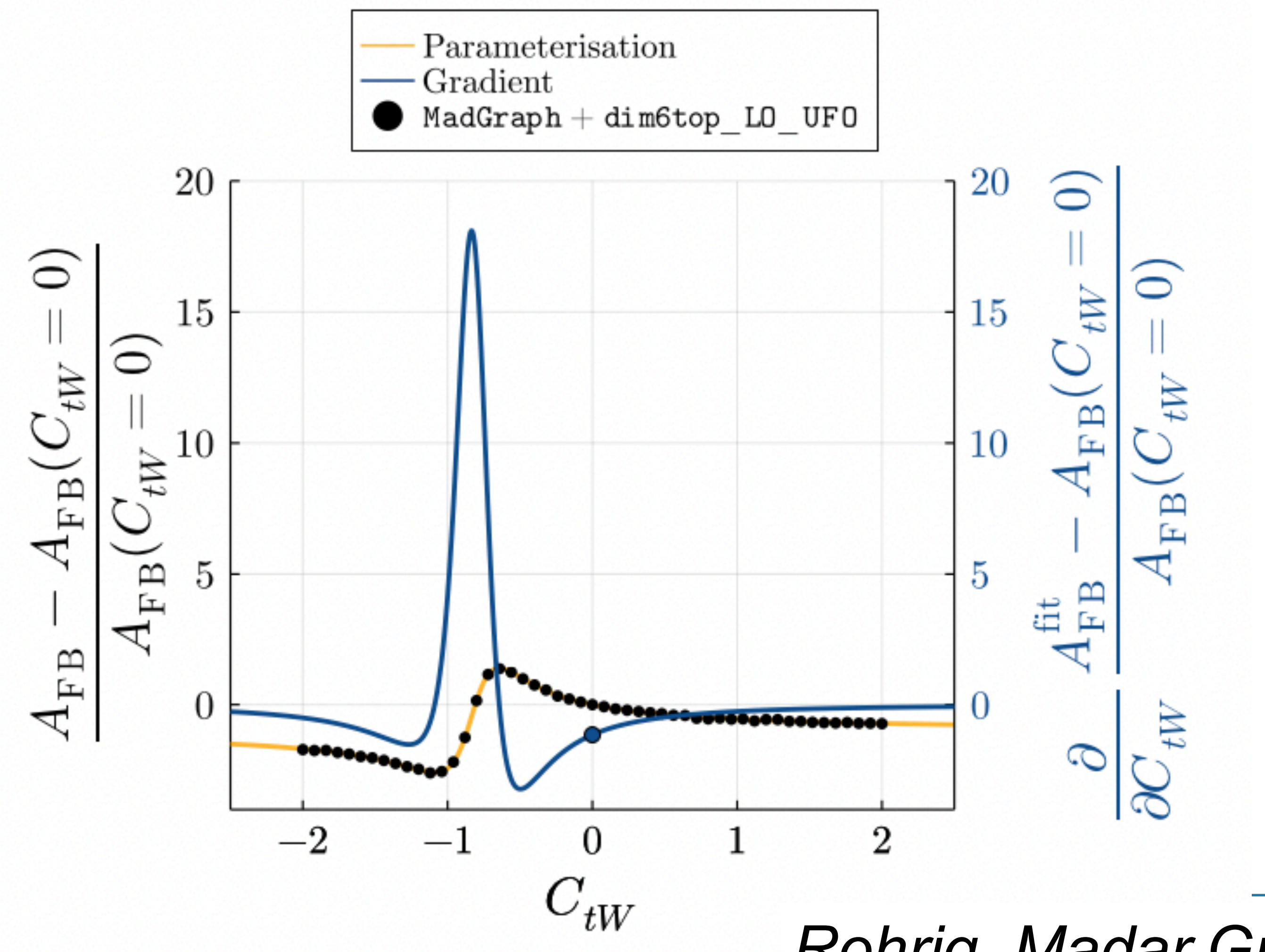
Top physics studies can happen during different running phases:

- **Threshold run** for ultra-precise mass measurement and other properties
  - Needs excellent control of beam energy, beam energy spread, luminosity spectrum $(\Delta m/m \approx 3MeV)$ and ISR : generator description to study effects
- **√s=365GeV for measurement of other properties** such as Electroweak couplings or anomalous couplings (FCNC). Also possible at **√s=240GeV** for anomalous single top production
  - Constraints on jet reconstructions, b-tagging, fitting algorithms, overall performance of detectors in full event reconstruction

Top events due to their large number and variety of particles in the final state are a fundamental validation tool for the software and detector performance!

Properties at threshold(mass, width, Yukawa)
EWK couplings
Anomalous Couplings(FCNC)
EFT Interpretations

IT
FR



Study of dim6 op. on Afb(tt)

Rohrig, Madar,Guerry, et al.

TALKS in PARALLEL SESSION TOMORROW!

Direct BSM Case Studies

CONVENERS BSM
R. Gonzalez-Suarez, G. Polesello
S. Heinemeyer, T. You

Tera-Z statistics pushes the limits of the sensitivity to feebly interacting particles.

In particular, can explore the range of small coupling and potentially large displacements.

Rich interaction between phenomenologist and experimentalist especially for the LLP case https://arxiv.org/abs/2203.05502

Heavy Neutral Lepton
Exotic Higgs
Dark Photons
Axion Like Particles

FR
IT

Detector Requirements

- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity
- Timing???

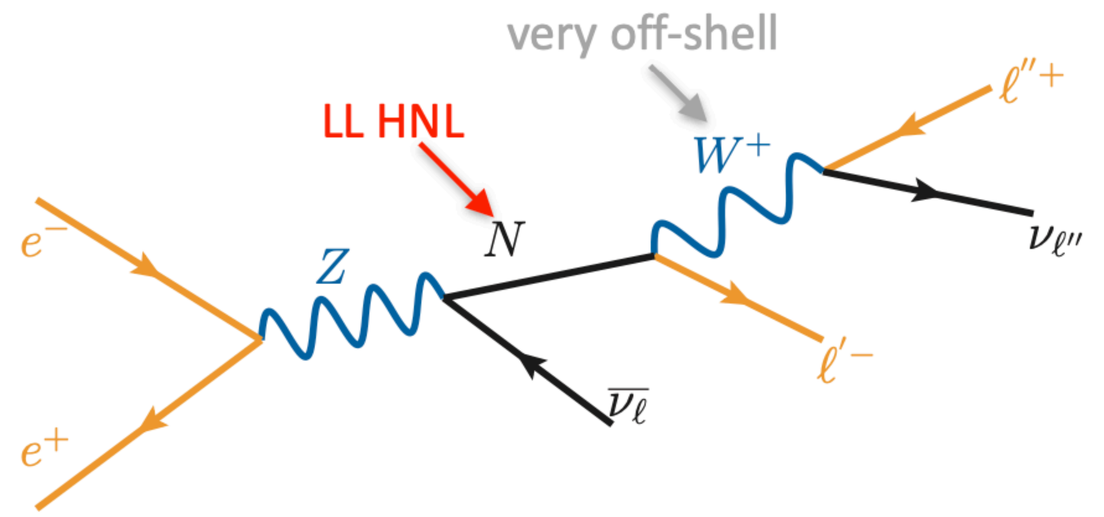
- Help develop/validate new tools for analysis with Delphes
- FullSim, advancement in Geant simulation, machine backgrounds etc, needed to fully explore the ultimate sensitivity reach.

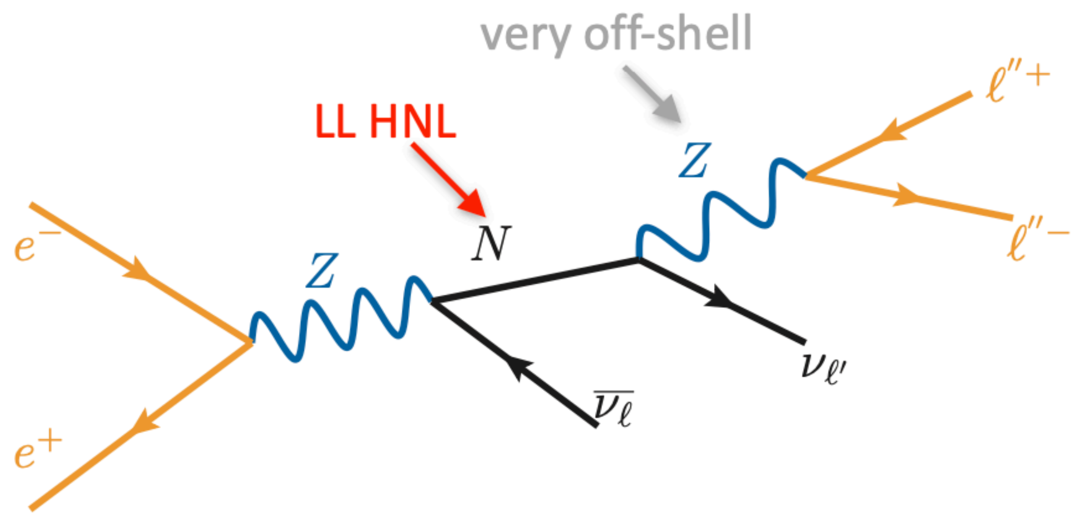
Example: Long Lived HNL CASE STUDY

HNL “case study” in progress. Upgraded Delphes for LLP

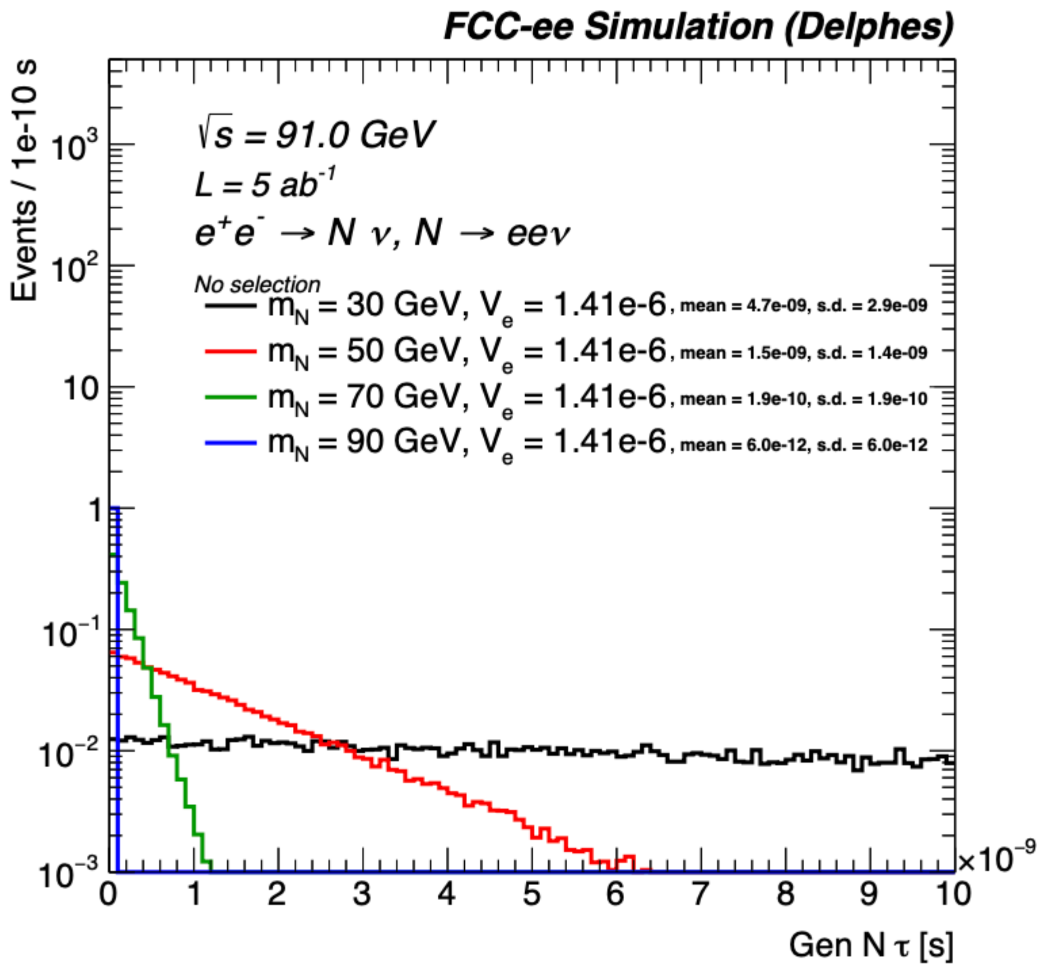
$$L \sim 0.025\mathrm{m}\left(\frac{10^{-6}}{V_l}\right)^2\left(\frac{100\ \mathrm{GeV}}{m_N}\right)^5$$

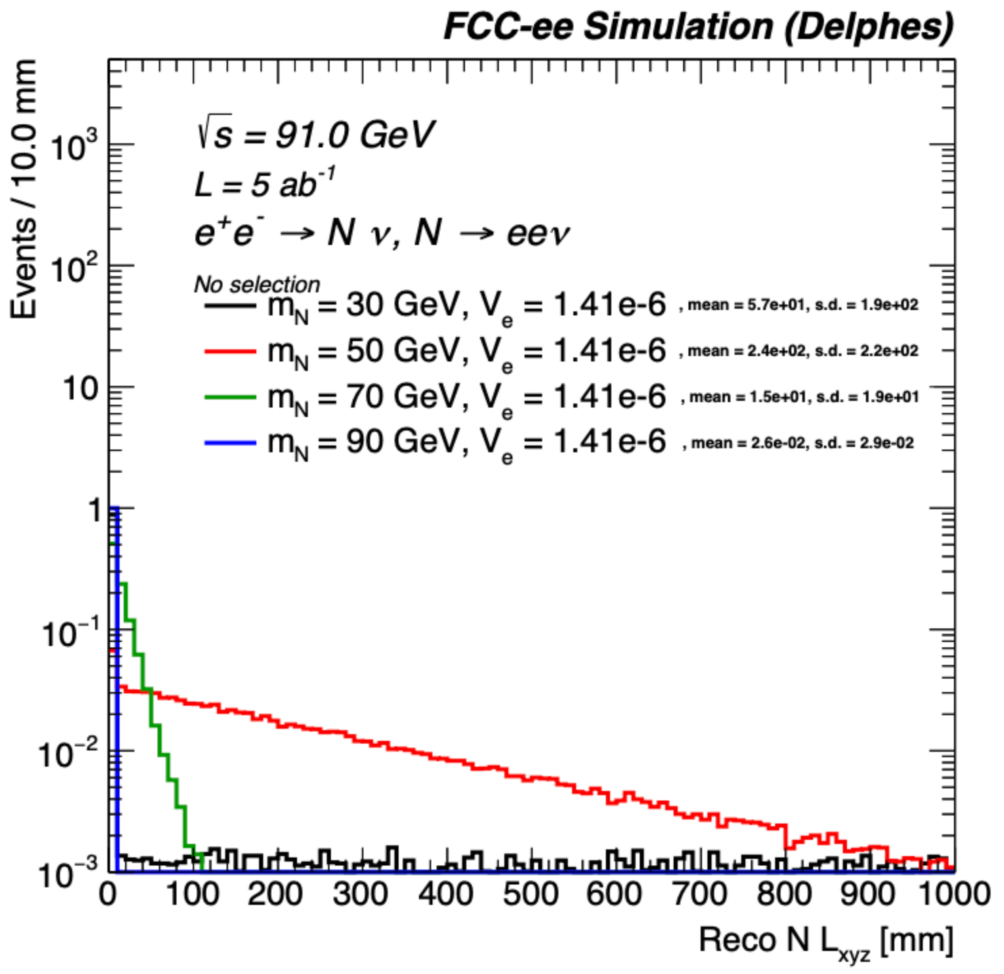
[Valid when $m_N \lesssim 100$ GeV, arXiv:1905.11889]



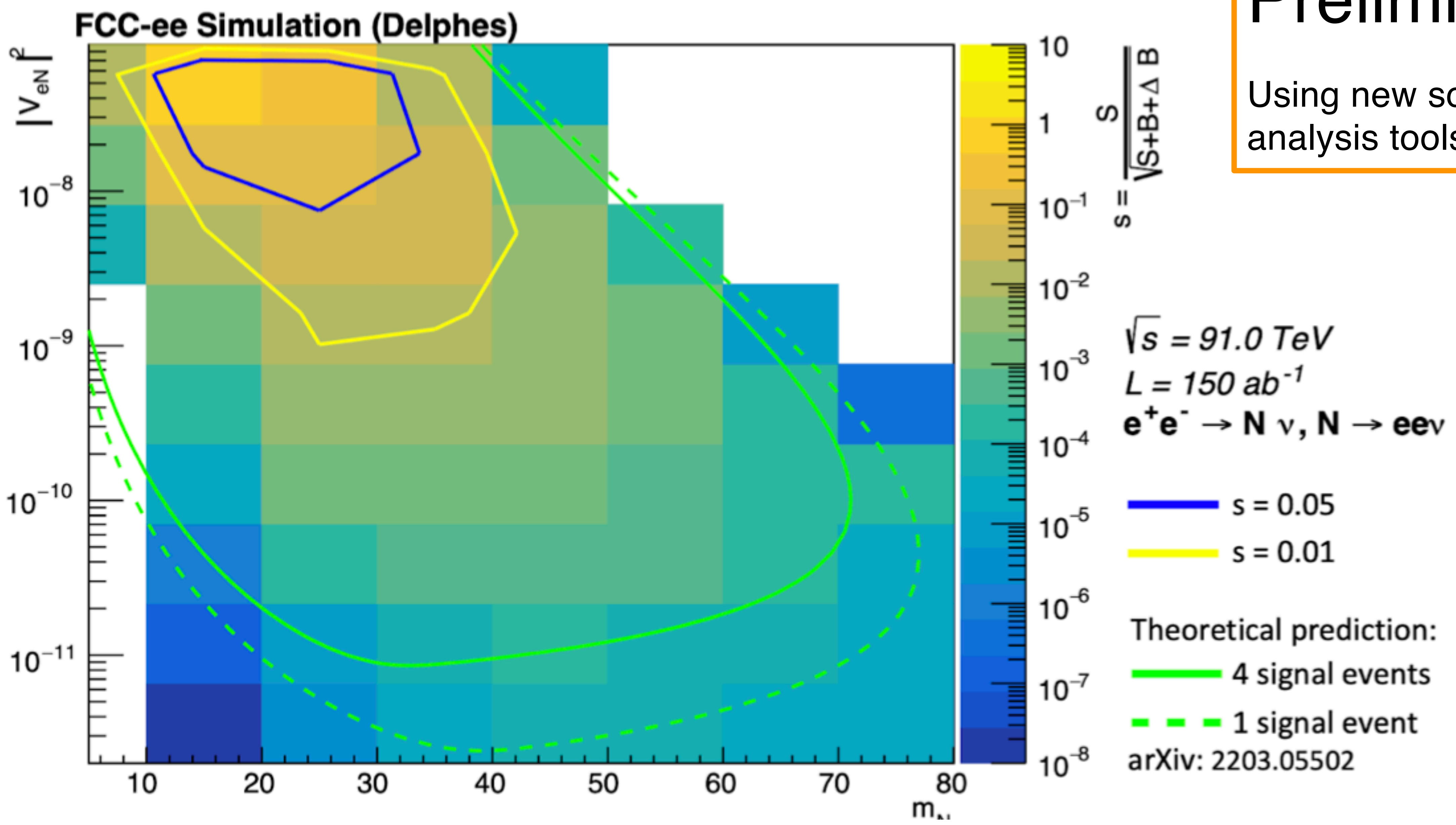


Get long-lived HNLs when coupling and mass are small





J. Alimena, L.Rygaard



Preliminary

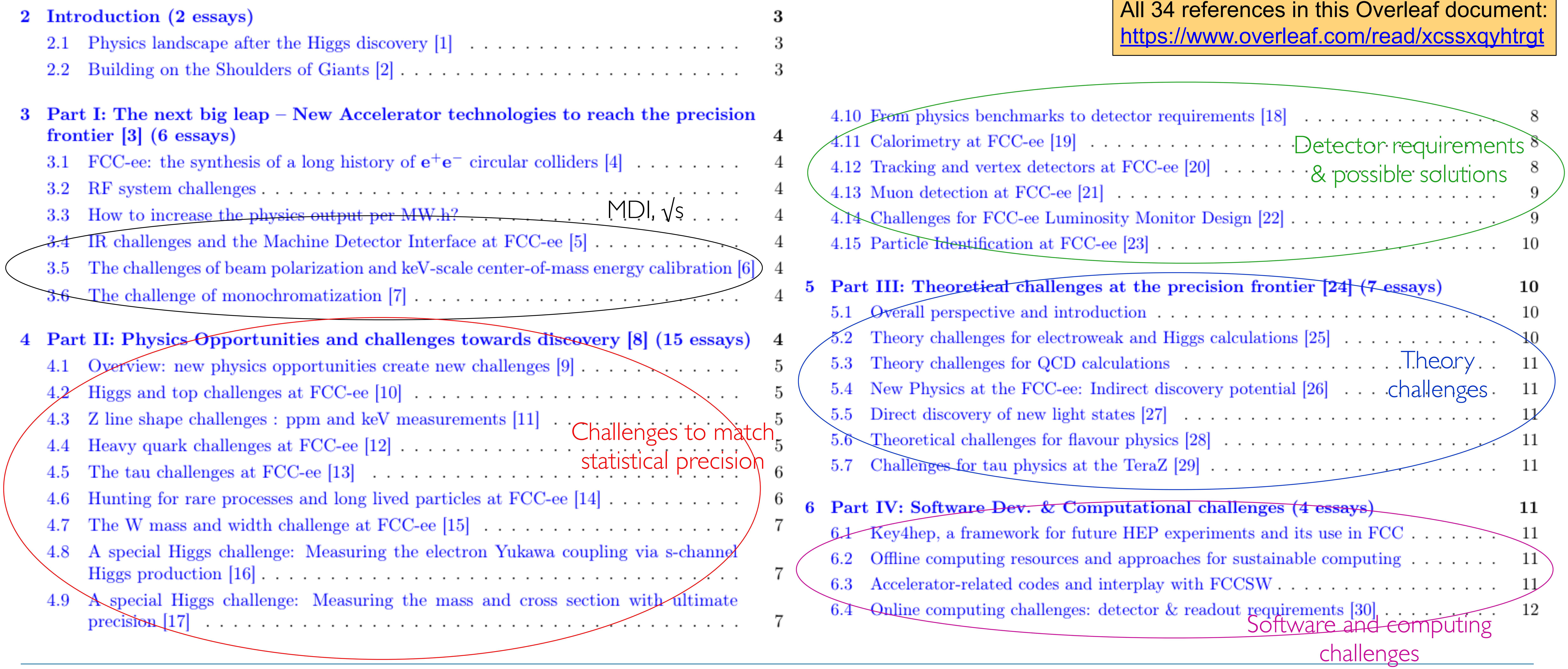
Using new software and analysis tools!

- LOIs to Snowmass, **challenges**: https://indico.cern.ch/event/951830/

EPJ+ special issue “A future Higgs and EW Factory: Challenges towards discovery”

EXCELLENT STARTING POINT!

All 34 references in this Overleaf document:
https://www.overleaf.com/read/xcssxqyhtrgt



MDI, √s

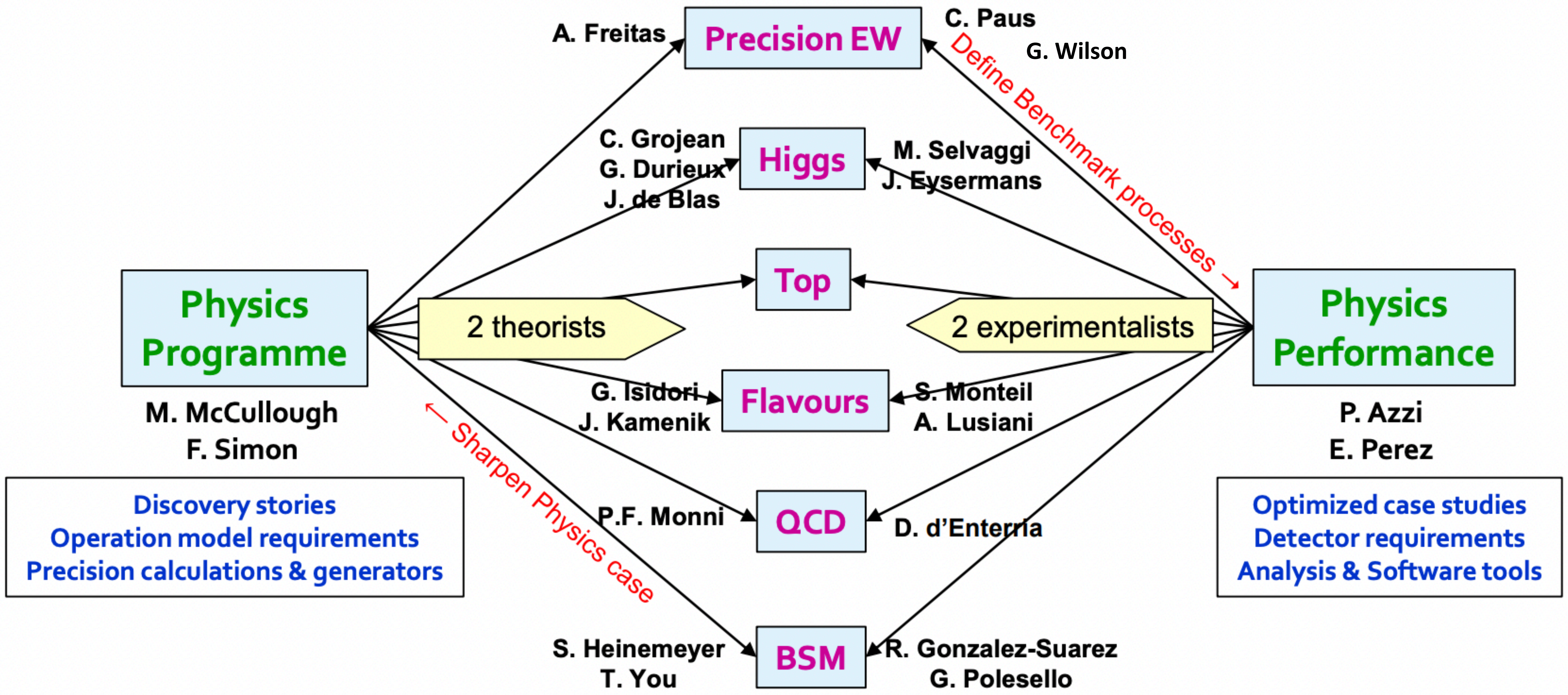
Challenges to match statistical precision

Detector requirements & possible solutions

Theory challenges

Software and computing challenges

Integrated organization of the Physics WPs



A. Freitas **Precision EW** C. Paus G. Wilson

C. Grojean G. Durieux J. de Blas **Higgs** M. Selvaggi J. Eysermans

Top

Physics Programme

M. McCullough
F. Simon

Discovery stories
Operation model requirements
Precision calculations & generators

2 theorists

2 experimentalists

Physics Performance

P. Azzi
E. Perez

Optimized case studies
Detector requirements
Analysis & Software tools

G. Isidori J. Kamenik **Flavours** S. Monteil A. Lusiani

P.F. Monni **QCD** D. d'Enterria

S. Heinemeyer T. You **BSM** R. Gonzalez-Suarez G. Polesello

Define Benchmark processes →

← Sharpen Physics case

Full integration between Phys.Programme and Phys. Performance

Integration with new Detector Concept WP ramping up

Monthly Physics meetings with flexible agenda to accomodate "transverse" topics

Take away message

A first round of analyses to frame the impressive physics case of the FCC-ee was summarized in the CDRs

CURRENT focus on « case studies » to determine the detector requirements needed to achieve the desired precision and to inform the technology choices for detector concepts

- Working in the new software framework (KEY4HEP), common to all future projects
- An organisation in place to help get started quickly and efficiently to cover as many topics as possible
- Timeline: Analyses ready by June FCC Week for mid-term report

Mid-Term Report of the FCC Feasibility Study to appear at the end of 2023 with new & updated detector concept proposals to realise the needs of the physics programme

BACKUP

FCC-ee as a Higgs factory and beyond

Higgs provides a very good reason why we need both e$^+$e$^-$ <u>AND</u> pp colliders

- FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from σ_{ZH}
  - Γ_H, g_{Hbb}, g_{Hcc}, $g_{H\tau\tau}$, g_{HWW} follow
  - Standard candle fixes all HL-LHC couplings
- FCC-hh produces over 10^{10} Higgs bosons
  - (1st standard candle →) $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}
- FCC-ee measures top EW couplings (e$^+$e$^-$ → tt)
  - Another standard candle
- FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
  - (2nd standard candle →) g_{Htt} and g_{HHH}

–

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95
g_{HHH} (%)	50.	44./33. 27./24.	2-3
Γ_H (%)	SM	1.1	0.91
BR$_{inv}$ (%)	1.9	0.19	0.024
BR$_{EXO}$ (%)	SM (0.0)	1.1	1

ee

pp

ee

pp

ee

FCC-ee + FCC-hh is outstanding

- All accessible couplings with per-mil precision; self-coupling with per-cent precision

FCC-ee is also the most effective way toward FCC-hh

FCC-ee AS AN ELECTROWEAK FACTORY

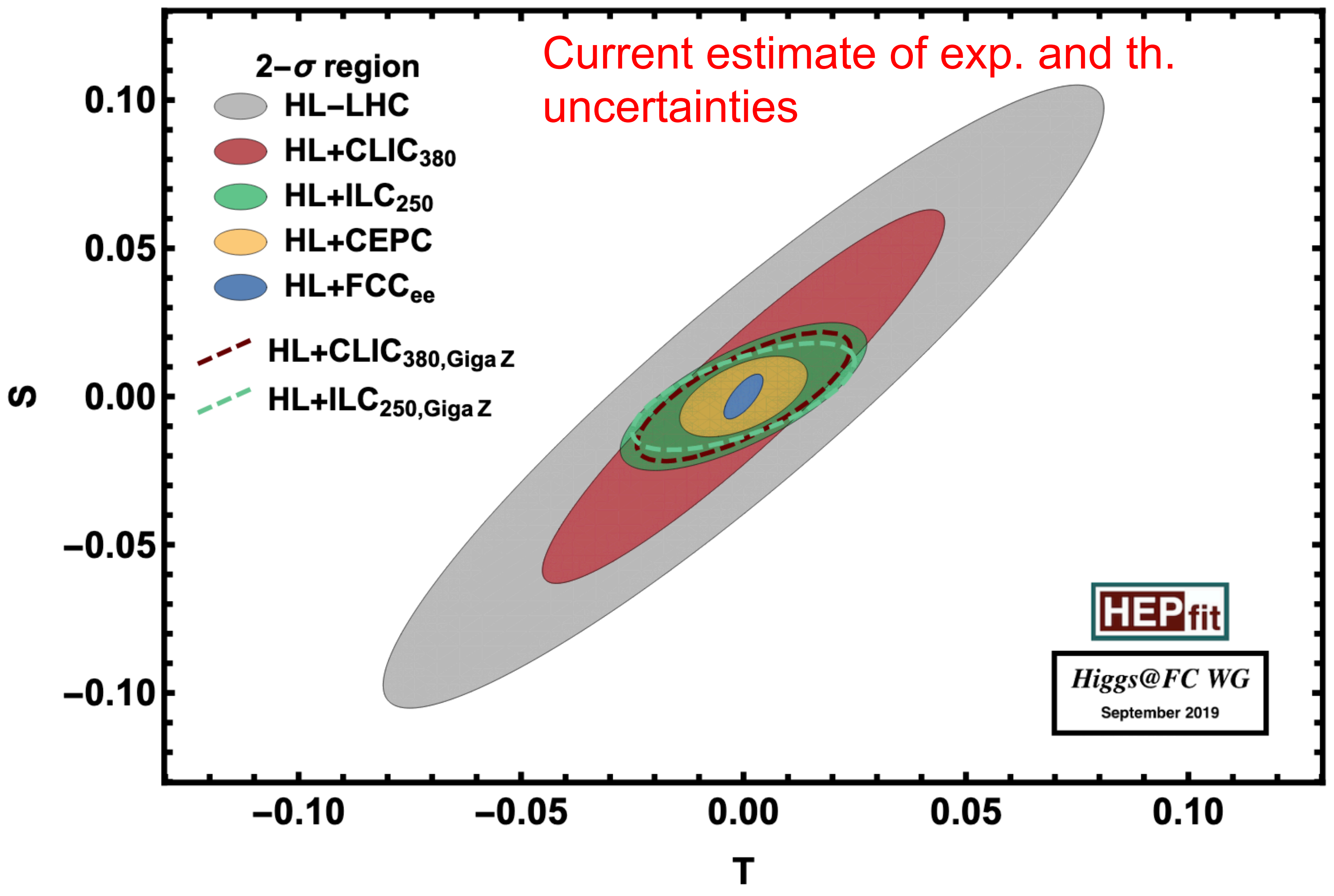
- With highest luminosities at 91, 160 and 350 GeV
  - Complete set of EW observables can be measured
    - Precision (10^{-3} today) down to few 10^{-6}

e.g., m_Z (100 keV), Γ_Z (25 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5}), $\sin^2\theta_W$ ($3.\ 10^{-6}$), m_W (<500 keV), m_{top} (20 MeV)

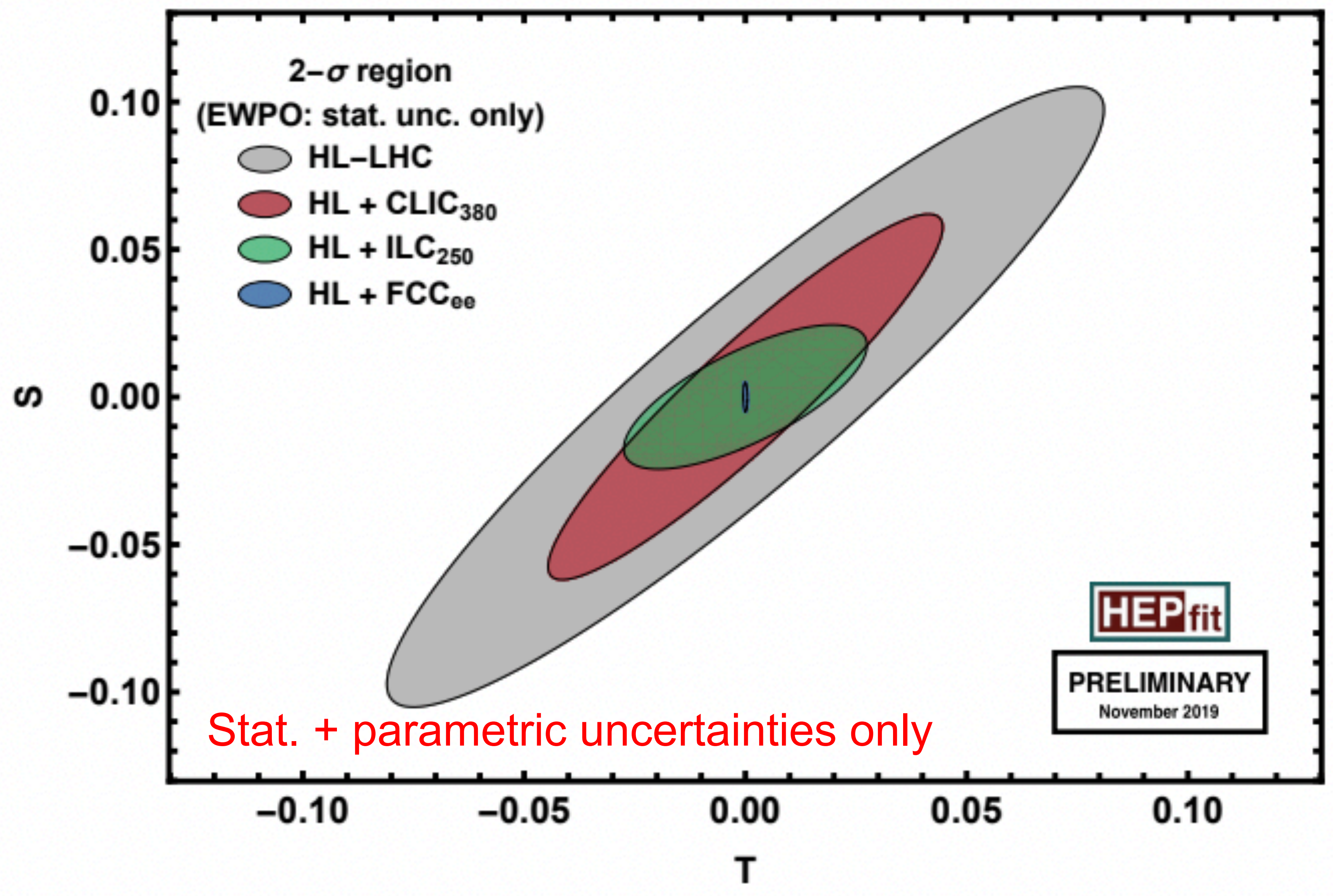
Benefiting from √s calibration with resonant depolarisation at 91 and 160 GeV

- Precision unique to FCC-ee, with smallest parametric errors
  - Challenge: match syst. uncertainties to the stat. precision
    - A lot more potential to exploit with good detector design than the present treatment suggests
    - Theory work is critical and initiated
- Precision = discovery potential (e.g., NP in Z/W propagators)
  - Generic discovery potential: Show that SM does not suffice
  - Challenge: test specific models with ALL information
    - Clarify the need for precision from a theoretical perspective
    - Explain how FCC-ee go towards answering big questions in fundamental physics

S ↘ ↙ T



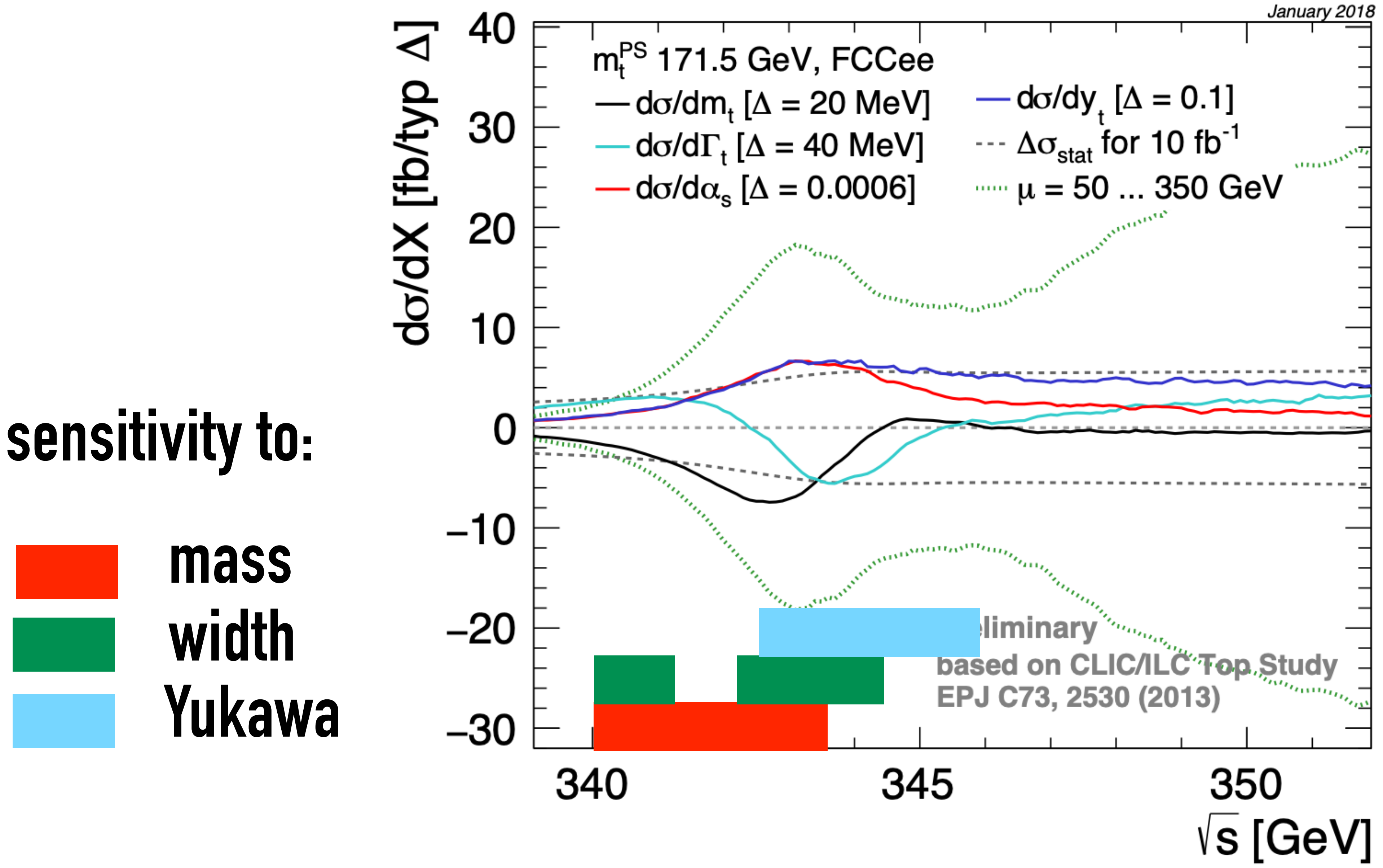
Current estimate of exp. and th. uncertainties

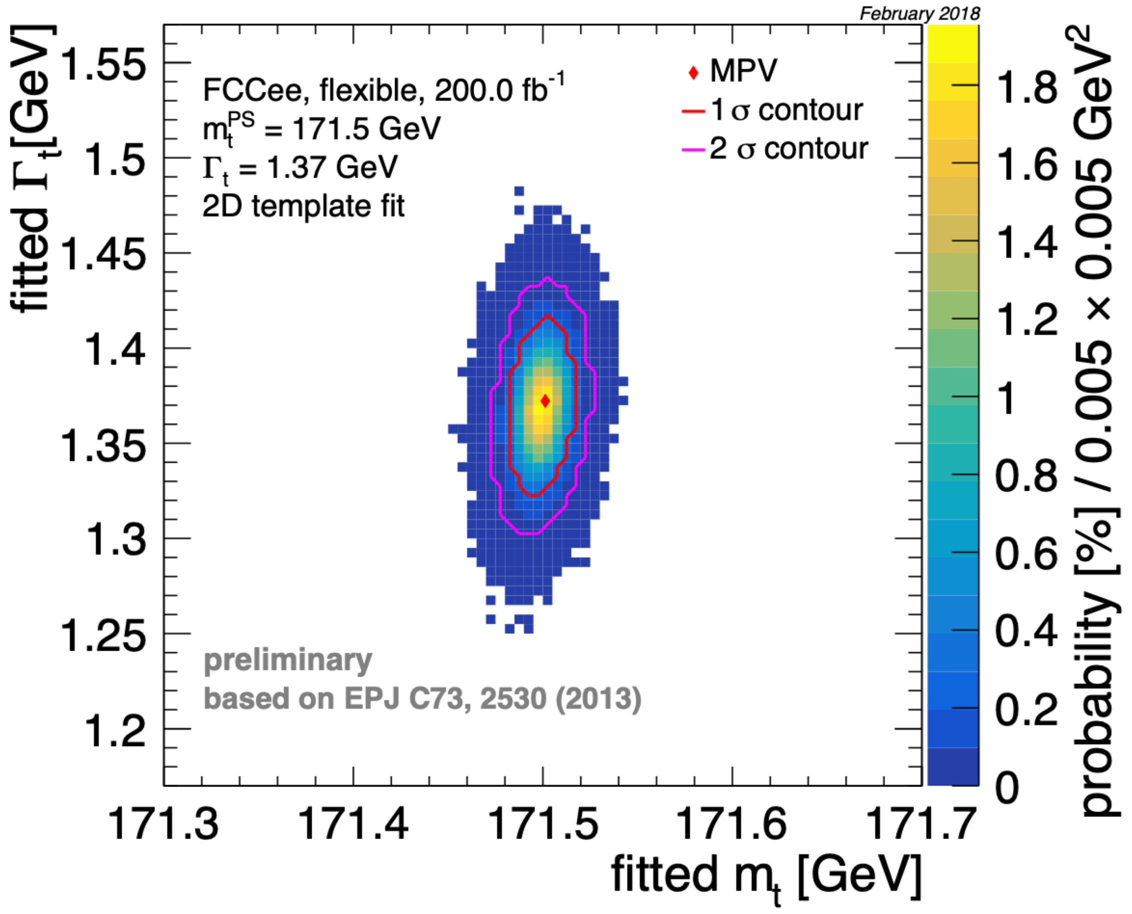


Stat. + parametric uncertainties only

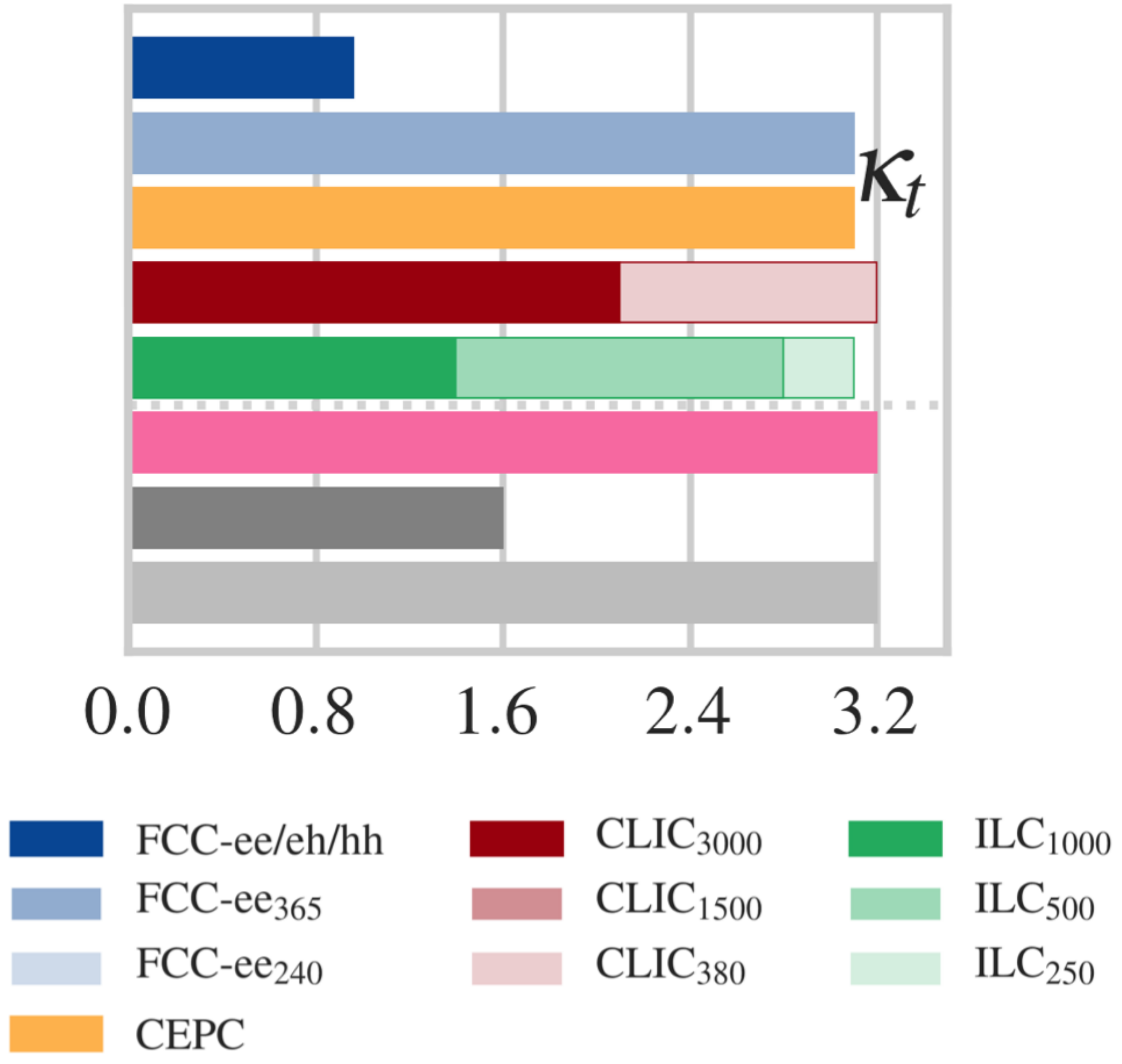
TOP PHYSICS AT FCC-ee

- Threshold region allows most precise measurements of top mass, width, and estimate of Yukawa coupling. Scan strategy can be optimized
  - FCC-ee has some standalone sensitivity to the top Yukawa coupling from the measurements at thresholds for a 10% precision (profiting of the better αS).
    - But, HL-LHC result of about 3.1% already better (with FCC-ee Higgs measurements removing the model dependence)





Mass only: 8.8 MeV (stat), 5.4 MeV (αs [2 x 10-4]), 44 MeV (theo)



- Run at 365 GeV used also for measurements of top EWK couplings (at the level of 10^{-2}-10^{-3}) and FCNC in the top sector.

Flavor physics potential

- 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

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

~15 times Belle's stat

Boost at the Z!

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	∼ 2 000	∼ 10	n/a (5)
LHCb Run I	150	-	∼ 15 (–)
LHCb Upgrade	∼ 5000	-	∼ 500 (50)
FCC-ee	∼ 200000	∼ 1000	∼1000 (100)

Yelds for flavor anomalies studies:

b→sll yelds and $B^0 \to K^{*0}\tau^+\tau^-$👍

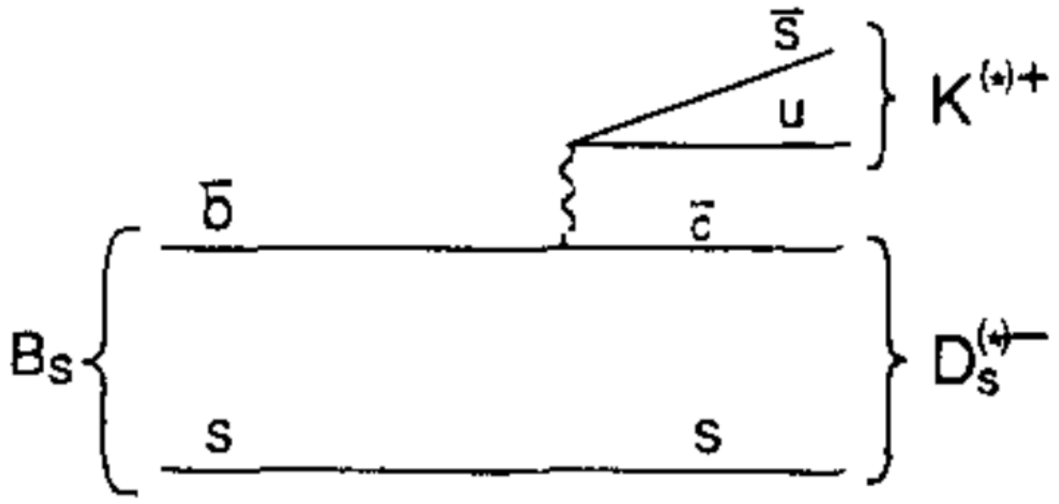
Full reconstruction possible

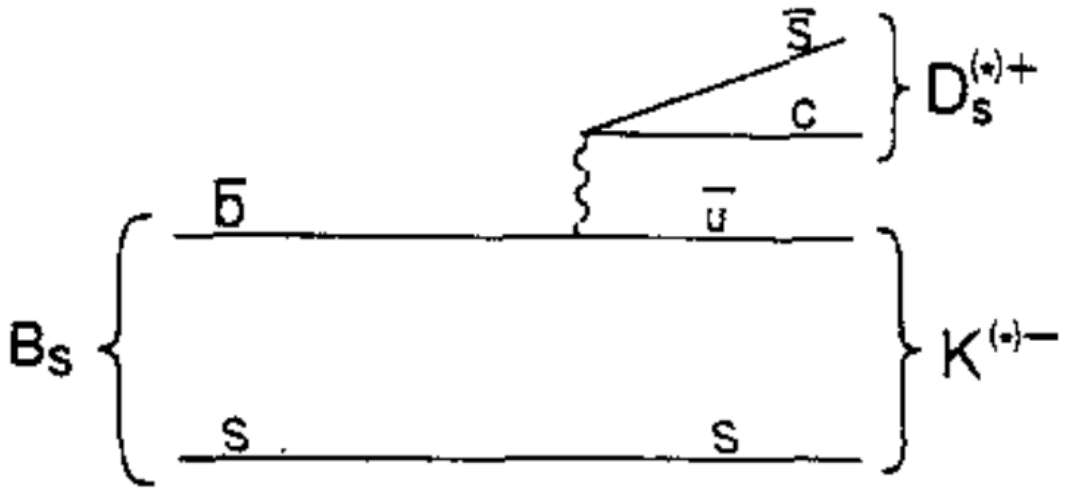
THE ANALYSIS

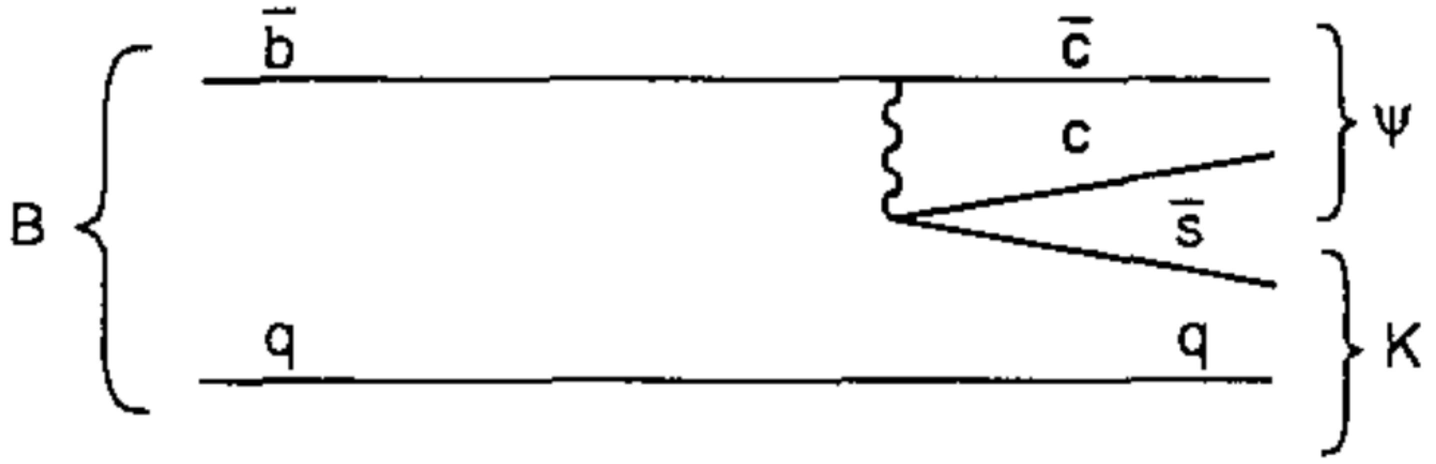
Study the decays:

1. $B^0_s \rightarrow D^{\pm}_s K^{\mp}$
2. $B_s \rightarrow J/\psi\ \varphi$

with the final objective (for the *fast-sim*) to estimate $\varphi = \gamma_{CKM} + \gamma_{ds} - 2\beta_s$ and $2\beta_s$







With 75 (310) billions of B^0_s (B^0) a statistical precision of 0.4° on γ ($3.4° \times 10^{-2}$ on β_s) is expected and can be compared with the present measurements...

$$\gamma = (72.1^{+4.1}_{-4.5})^{\circ} \qquad 2\beta_s = 0.051 \pm 0.023$$

$$2\beta_s = 0.0383^{+0.0012}_{-0.0011}$$

To be tested against a very precise SM prediction

2021 PLAN

Familiarise with the software k4SimDelphes

Reproduce and develop the many results already presented in the meetings

Simulate the signal decay chain and produce the necessary datasets

Perform a preliminary analysis on the *fast-sim* to understand the behaviour of the two channels

FCC-ee at the intensity frontier

❑ TeraZ offers four additional pillars to the FCC-ee physics programme

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., $b \rightarrow s\tau\tau$

QCD programme

- Enormous statistics with $Z \rightarrow \ell\ell$, qq(g)
- Complemented by 100,000 $H \rightarrow gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Often statistics-limited
5. 10^{12} Z is a minimum

Tau physics programme

- Enormous statistics: 1.7 10^{11} $\tau\tau$ events
- Clean environment, boost, vertexing
- Much improved measurement of mass, lifetime, BR's

1. τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
2. Lepton universality violation tests
3. PMNS matrix unitarity
4. Light-heavy neutrino mixing

Rare/BSM processes, e.g. Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m_Z

- Signature: long lifetimes (LLP's)
- Other ultra-rare Z (and W) decays

1. Axion-like particles
2. Dark photons
3. Heavy Neutral Leptons

FCC-ee at the intensity frontier

- … which in turn provide specific detector requirements

Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z resonance

QCD + EW programme

- Particle-Flow reconstruction
- Lepton and jet angular and energy resolution ; Lepton ID

More case studies will lead to more detector requirements

Tau physics programme

- Momentum resolution
  Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  Lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation
  BR measurements, EWPOs, spectral functions

Rare/BSM processes, e.g. Feebly Coupled Particles

- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

If all these constraints are met, Higgs and top programme probably OK (tbc)

Case Studies

>>>“Case Studies”: reverse engineering of a chosen benchmark process. The elements contributing to the final results are “unpacked” to allow maximal optimisation on all aspects.

extract detector requirements to achieve desired performance

develop a detector simulation that allows this performance to be merged in the full analysis

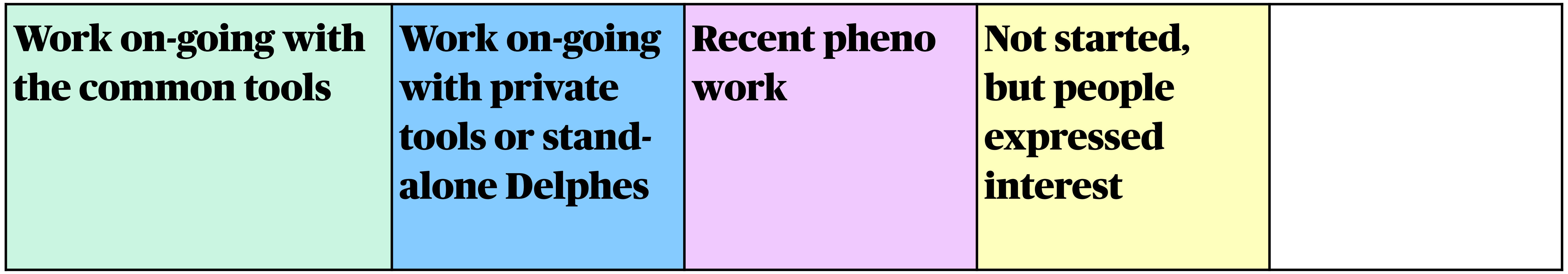
develop reconstruction algorithms that fully exploit the detector information

develop calibration strategies and analysis techniques to shrink the uncertainties as needed

Extract requirements on event generation and simulation of machine effects to ensure realistic predictions

Status of analysis efforts that were reported to PP meetings

Summarized in the next slides, color-coding :



Work on-going with the common tools	**Work on-going with private tools or stand-alone Delphes**	**Recent pheno work**	**Not started, but people expressed interest**	

with some "shading" too

"Common tools" means :

- Delphes simulation samples within EDM4HEP,
- FCCAnalysis framework
  - the latter benefits from stand-alone developments or devels within Delphes (e.g. vertex fitter, soon PID modules)

In most cases, 1 group = 1-2 people, part-time.

Higgs measurements

Measurement	Constraining	Person-power
Higgs boson coupling to c quark	Flavour tagging, vertexing	CERN Also interest from APC
σ(ZH) and mH, Z ➔leptons (Mrecoil); New scalars in Z + S	Lepton momentum & energy resolution	APC / Bologna / MIT (CERN) Good candidate to move to FullSim "soon".
σ(ZH) and mH, Z ➔ hadrons ; BR(Higgs invisible)	hadronic mass and hadronic recoil-mass resolution ; Maybe b-tagging	MPI Munich
Γ(H) in ZH, H ➔ ZZ*	Lepton ID efficiencies; jet clustering algorithms, jet directions, kinematic fits	CERN fellow expressed interest
Higgs boson mass in hadronic final states	b-tagging eff and purity, jet angular resolution, jet reco, kin fits	

Higgs measurements (2)

Measurement	Constraining	Person-power
$\Gamma(H)$ with bbnunu events	**Visible and missing mass resolutions**	
HZγ coupling	**photon identification, energy and angular scale**	
ee->H production in s-channel at Higgs pole	**- q / g tagging**	**CERN (former analysis exists)**

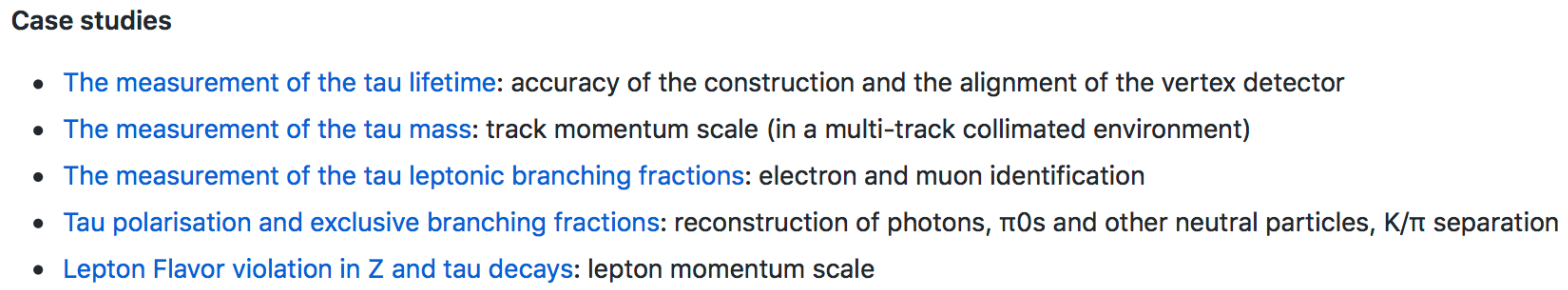
EW measurements at the Z peak

Measurement	Constraining	Person-power
Total width of the Z	**Track momentum (and angular) resolution, scale (magnetic field) stability**	**CERN [but fellow left]** **Good candidate to move to FullSim "soon".**
Rb, Rc, AFB of heavy quarks	**Flavour tagging, acceptance, QCD corrections**	**QCD corr. studied at CIEMAT ;** **Udine**
alphaS measurement	**Z -> jets**	**LPNHE [report soon]**
Ratio Rl	**Geometrical acceptance for lepton pairs**	
AFB (muons)	**QED corrections**	
Luminosity from diphoton events ; **NP in diphotons**	**e/gamma separation, gamma acceptance**	**CIEMAT (NP, pheno)**

EW measurements at WW

Measurement	Constraining	Person-power
Coupling of Z to nu_e (also, at the Z peak: invisible ALP, dark γ)	**Photon energy resolution, acceptance, track efficiency**	**Saclay Udine**
MW from WW -> had, semi-lep	**Lepton and jet angles, Kinem fits**	**Saclay [2019]**
(d)σ(WW) for MW, TGCs	**Lepton ID, angular resolutions**	**LAPP**
Vcb via W -> cb	**Flavour tagging**	**Pisa + interest from postdoc?**
W leptonic BRs	**Lepton ID, acceptance**	
Meas of √s via radiative return	**lepton and jet angular resolutions, acceptance**	

Tau physics



Case studies

- The measurement of the tau lifetime: accuracy of the construction and the alignment of the vertex detector
- The measurement of the tau mass: track momentum scale (in a multi-track collimated environment)
- The measurement of the tau leptonic branching fractions: electron and muon identification
- Tau polarisation and exclusive branching fractions: reconstruction of photons, π0s and other neutral particles, K/π separation
- Lepton Flavor violation in Z and tau decays: lepton momentum scale

- Delphes samples of limited use for (several of) these studies
- Goal of separation of tau decay modes has triggered FullSim studies:
  - Clustering devels in FCCSW with the LAr [NBI]
  - NN-based tauID in the IDEA calo [Roma]

Flavour physics

Measurement	Constraining	Person-power
Bs to Ds K	**Many things.. Vertexing, PID, EM resolution**	**Saclay / Ferrara (CERN)**
Bc -> tau nu	**Flight distance resolution (vertexing)**	**EPFL / CERN / Orsay**
B -> K* tau tau	**Flight distance resolution (vertexing)**	**Former work at Clermont**
Modes with pi0's	**EM resolution**	

Top physics

Measurement	Needs good:	Person-power
EW couplings of the top	Jet reco, b-tagging, kine fits	NBI
Top properties from threshold scan	Jet reco, b-tagging, kine fits	Strasbourg/Padova
FCNC couplings	Idem + photon reco	Tehran/Behshahr

ALPs / LLPs / Heavy Neutrinos

- "Informal group" regular meetings involving both theorists and experimentalists. Focus:
  - defining model benchmarks
  - better defining case studies to perform: they include both characterization of signals and detector requirements
  - first pass at having analysis code in place for validation of MC signals in Delphes
  - need to develop specific tools to use Delphes in this context. Will profit largely of FullSim tracking in EDM4Hep
- Informal group mailing list ~50 names (including Uppsala, Graz, Geneva, Bologna, PD, CERN...)

Area with documentation in the Physics Performance Github collecting documentation and other info
https://hep-fcc.github.io/FCCeePhysicsPerformance/case-studies/BSM/LLP/

HNLs	- **displaced vertices** - **specific tracking**	**Uppsala/Graz/Geneva**
ee ➔ aγ ➔ 3γ	- **Photon resolution** - **separation of close-by photons** - **displaced γ vertices**	**Pavia** **FullSim needed...**
$\gamma\gamma \rightarrow$ a $\rightarrow \gamma\gamma$	**Photon resolution**	**CERN / Rio**