“Doing analysis for FCC-ee”

i.e. overview and organisation of Physics & Performance Studies

FNAL FCC Day - 10/28/2022

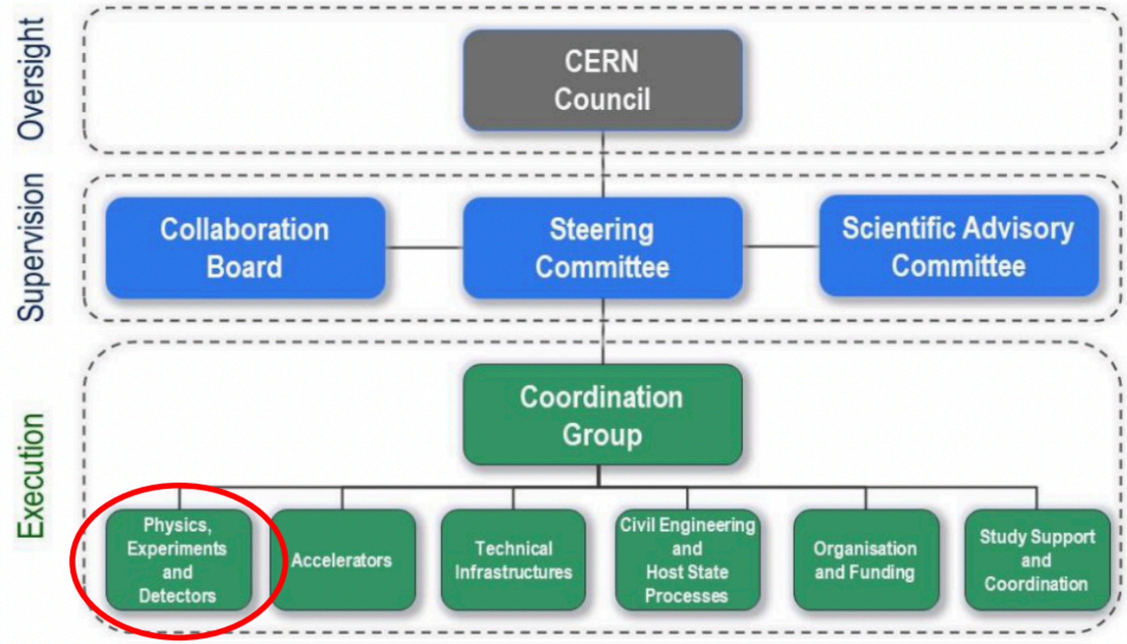
P. Azzi (INFN-PD/CERN)

With many thanks to E. Perez, G. Ganis, C. Helsens, J. Alimena, et al…

Introduction

- The physics landscape of the FCC-ee program extends in all possible directions:
  - the difference in the physics focus at the different $\sqrt{s}$
  - 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, the « case studies » that will be used to extract requirements on what is missing to achieve our ambitious goals: detector requirements, reconstruction tools, calibration techniques.

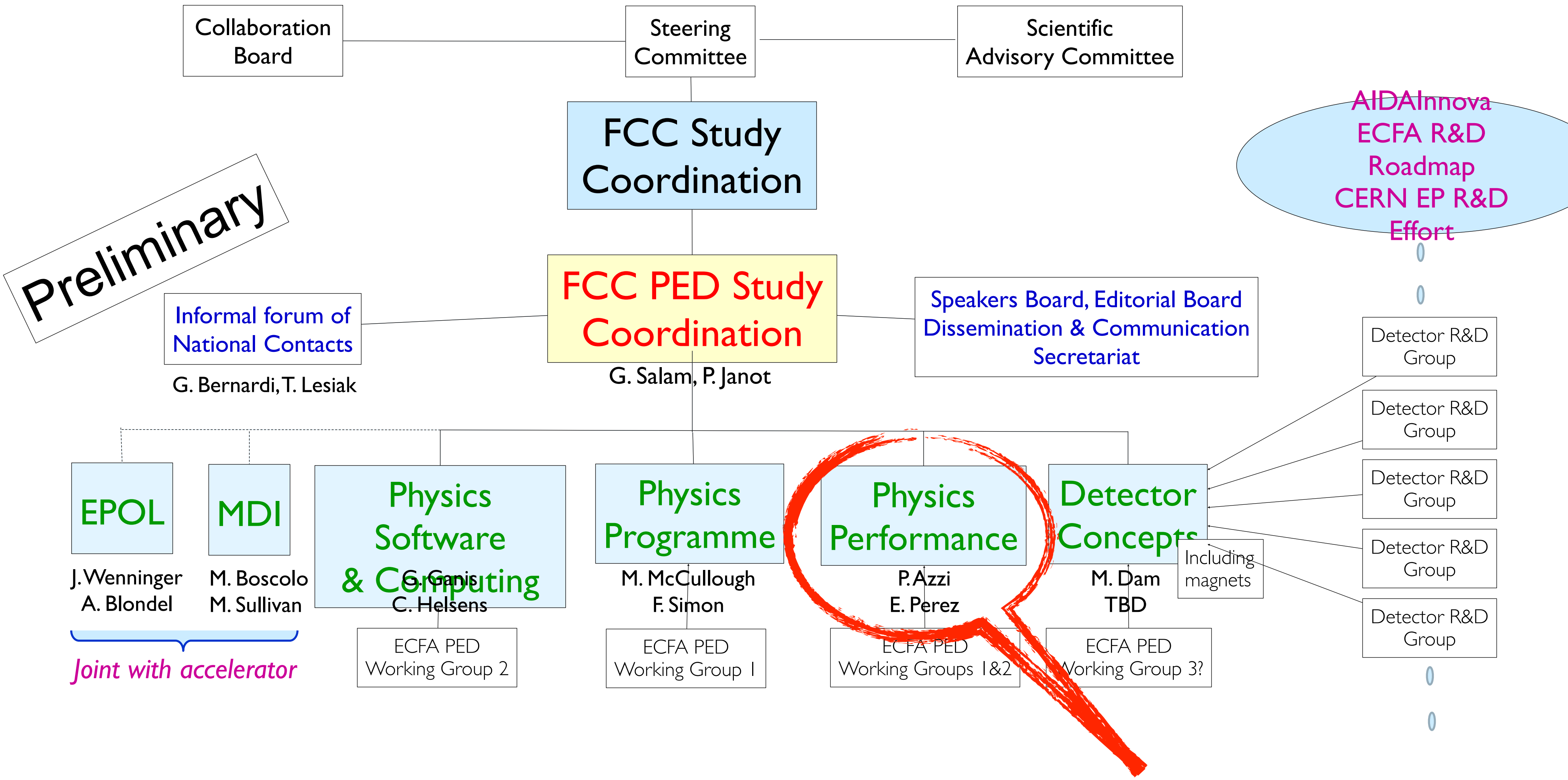
FCC Feasibility Study (2021-2025)



FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY: MAIN DELIVERABLES AND MILESTONES	CERN/SPC/1161 CERN/3588 Original: English 21 June 2021	**RESTRICTED COUNCIL** 203rd Session **17 June 2021**

- a committee including external experts will be established to review the cost of the first-stage project (the tunnel and the FCC-ee collider) by mid-2023; a second cost review will take place at the end of the Feasibility Study in 2025;

PED pillar organisation to tackle these



Physics Programme WP

- Six working groups (with at least one experimentalist and one theorist conveners, tbd)
  - Focus on the phenomenological aspects of the integrated FCC programme
    1. Precision Electroweak Physics
       - ➔ Z peak and WW threshold (ee)
       - ➔ High-energy diboson and difermion (hh)
    2. Higgs physics
    3. Flavour (c, b, τ) physics
    4. BSM Physics
       - ➔ Indirect sensitivity from precision measurements (ee and hh)
       - ➔ Direct BSM searches at the smallest couplings (ee and hh) and highest masses (hh)
    5. QCD
    6. Top physics
  - To be considered in addition
    - Physics at FCC-hh with dedicated experiments

Patrick Janot

FCC Week 2021
28 June 2021

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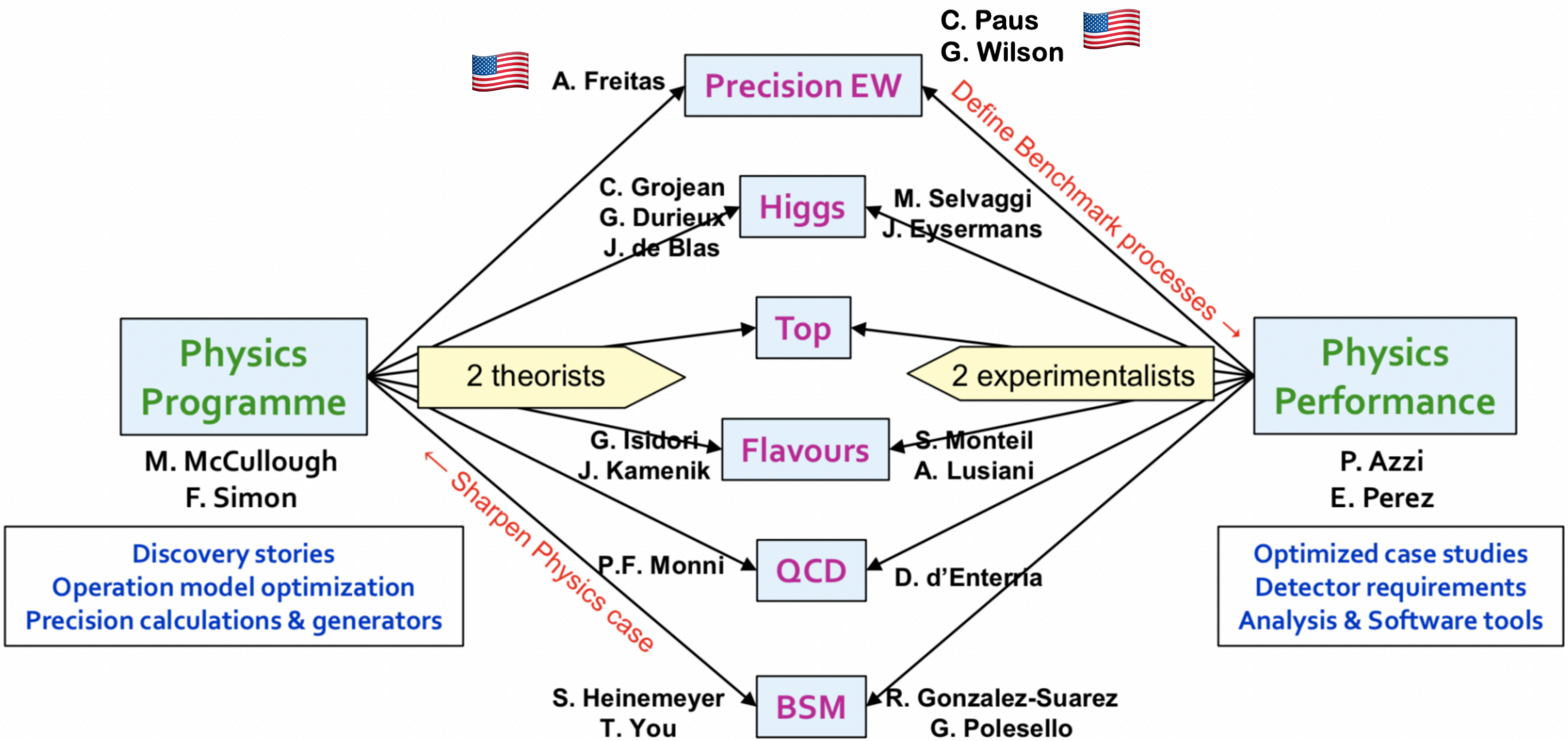
Physics Groups Structure



Transverse Activities

- Topics to be discussed in specific working meetings or in the general Physics Performance.

Jet reconstruction

Exploring most appropriate choices

MC Truth association

Particle ID

Implementing PID techniques in EDM4HEP

Vertexing

Studying displaced vertices

Isolation

Jet Flavour tagging

Several teams now, requires better organisation with dedicated working meetings

g different approaches

Kinematical fits

...more can come up!

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Physics Programme key deliverables

- **Within the domain of expertise of each working group**
  - **Bring together theorists and experimentalists**
  - **Report on recent results in the literature and develop new ideas**
    - **New models to probe; new experimental tests to implement; new observables to test**
    - **Examine different operation models (L vs $\sqrt{s}$: values and time ordering)**
    - **Propose ancillary (in situ) measurements of key accelerator/detector parameters**
  - **Propose physics benchmark measurements**
    - **Which may lead to new detector performance requirements or theory precision requirements**
  - **Plan for precision theory calculation development, to match experimental uncertainties**
    - **A strategic priority for FCC-ee – Such developments have focussed on LHC in the past 20 years.**
  - **Review existing MC generators**
    - **And plan for upgrade to include most recent theoretical progress**
  - **Deliver and test global fitting code and formulae**
    - **For standard model, specific BSM models, and generic Effective-Field-Theory (EFT) approach**
  - **Organize public documentation for the results of the working group**

Physics Performance WP

Physics Performance makes the link between:
- *Physics Benchmarks measurements,* proposed by the Physics Programme
- *Detector Requirements*, used by Detector Concepts

By means of concrete Physics Case Studies

- For each *Physics Benchmark* measurement:
  - Identify and implement one or several case studies to optimise the ultimate statistical sensitivity
  - Identify and evaluate the limiting systematic uncertainties
  - Establish detector requirements to match systematic uncertainties with statistical precision and pass them on to the Detector Concept WP

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

Where to start…

- Several "case studies" have started covering very different physics topics.
  - Documentation: https://hep-fcc.github.io/FCCeePhysicsPerformance/
  - They are at different level of maturity both from the analysis point of view but also from the software tools that are used.
- In collaboration with the Software Coordination, *common tools* are provided such as:
  - Delphes simulation samples within EDM4HEP centrally generated (and documented)
    - Common samples: http://fcc-physics-events.web.cern.ch/fcc-physics-events/FCCee/spring2021/Delphesevents_IDEA.php
    - Information here: https://bit.ly/35Lgft5
  - FCCAnalysis framework+examples (in git)
    - the latter benefits from stand-alone developments (as addition to dataframe tools) or developments within Delphes (e.g. vertex fitter, PID…)
- *However, in some cases, it was easier for the analysers to choose to use a standalone approach. This will require a porting of the analysis to the common code later on.*

FCC Software &computing structure

FCC S&C Coordinators

FCC S&C Feasibility Study Lead
FCC S&C Coordinators

Core SW Coordinator / key4hep liaison *K4, E4*

Generator Liaison *PP, GF*

Simulation, Digitization, Reconstruction Coord *DC, E4*

MC Production Coord
Dirac Liaison

FCCSW Release Coordinator *K4*

MDI Interface Coordinator
MDI Liaison *MDI*

Geometry Coordinator and DD4Hep Liaison *DC*

Resource Coordinator

FCC Analysis Coordinator *PP, E4*

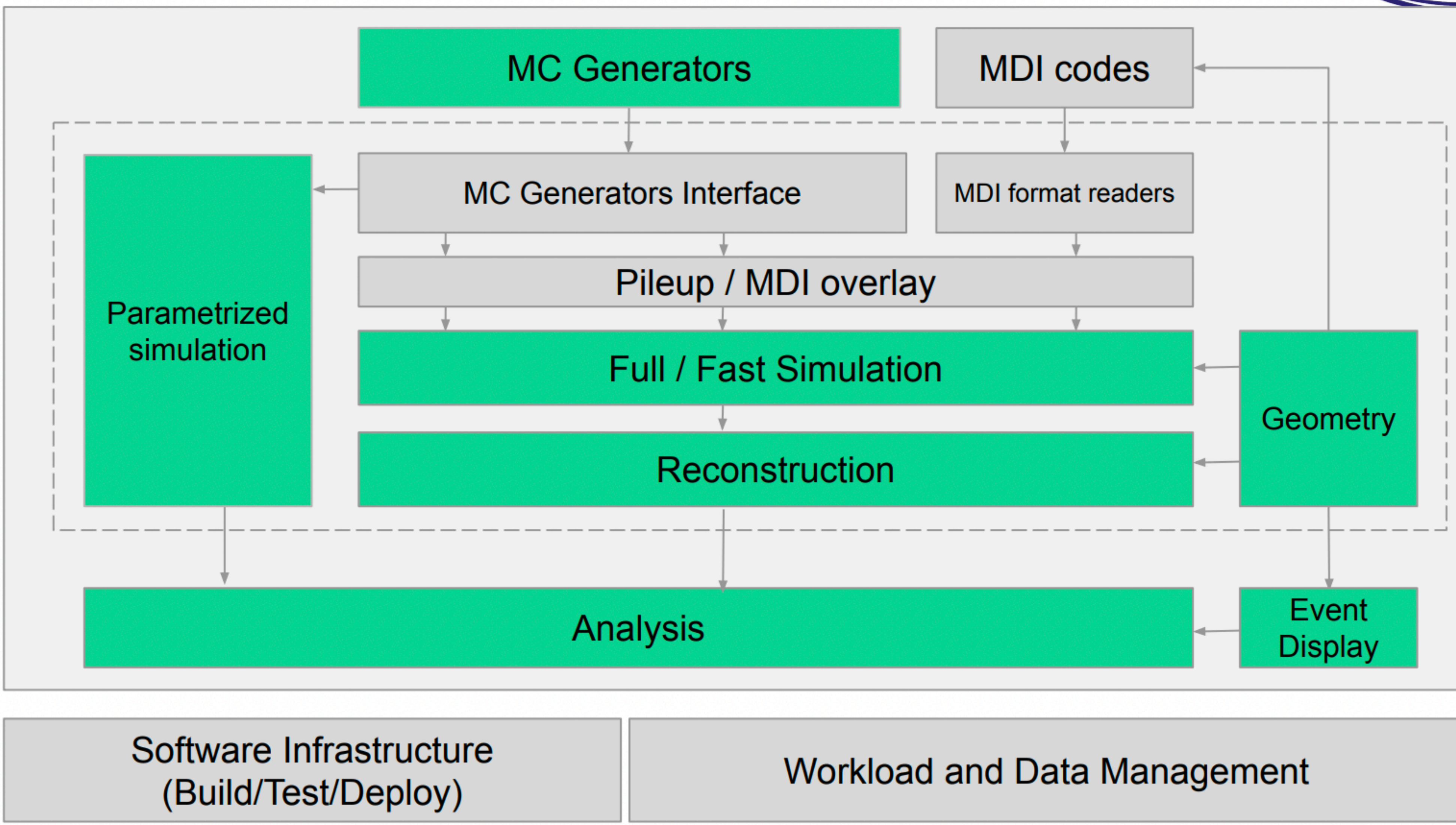
Documentation Coordinator
FCC S&C Coordinators

Training Coordinator
FCC S&C Coordinators

- Core software group at CERN
- External contributions warmly encouraged
- Connection with other PED groups

PP	Physics Performance
DC	Detector Concepts
MDI	Machine Detector Interface
K4	Key4hep
E4	EDM4hep
GF	Generator Forum

Typical workflows to support



Key4hep

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

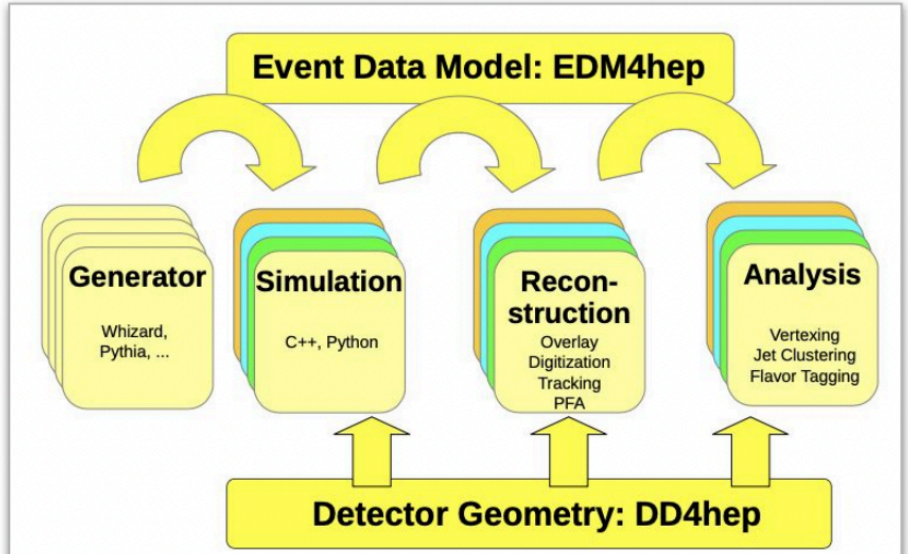
Common Core ingredients

- 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



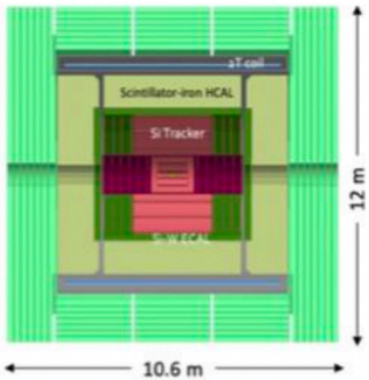
Kick-off meetings Bologna (6/2019), Hong Kong (1/2020)
Weekly working meetings
Deliverables already used in large scale production

Detector Concepts Fast Overview

CDR

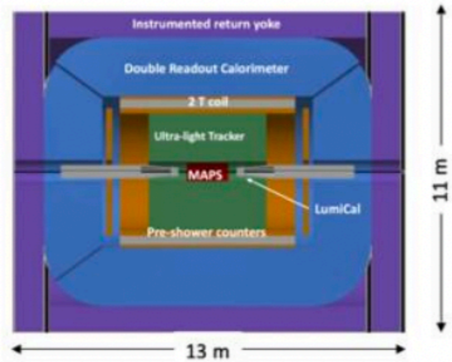
new

CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker; CALICE-like calorimetry; large coil, muon system
- Engineering still needed for operation with continous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - ...

IDEA



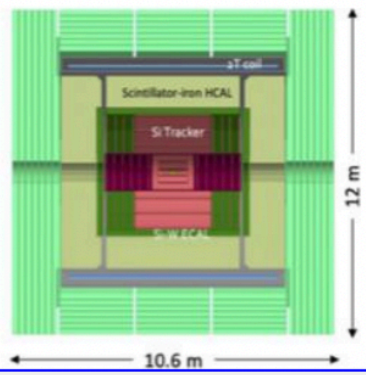
- Less established design
  - But still ~15y history: ILC 4th Concept
- Si vtx detector; ultra light drift chamber w powerfull PID; compact, light coil; monolitic dual readout calorimeter; muon system
  - Possibly augmented by crystal ECAL
- Very active community
  - Prototype designs, test beam campains, ...

Noble Liquid ECAL based

- A design in its infancy
- High granularity Noble Liquid ECAL is core
  - PB+LAr (or denser W+LKr)
- Drift chamber (or Si) tracking; CALICE-like HCAL; muon system.
- Coil inside same cryostat as LAr, possibly outside ECAL
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, ...
  - Software & performance studies

Detector Concepts Fast Overview

CLD

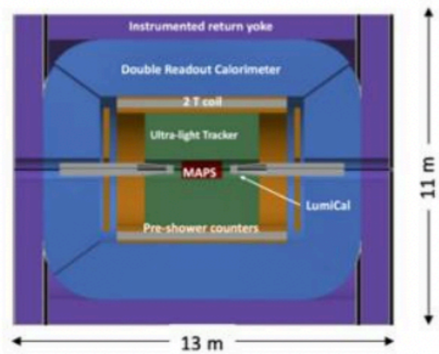


CDR

Full Sim
k4 w/ DDSim
Reco
k4 w/ iLCSoft@Wrapper

- ;
- continous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - ...

IDEA



Full Sim
Vertex, DC: standalone
DR Calo: k4 w/ k4SimG4
Reco
Vertex, DC: standalone
DR Calo: ?

Muon: in the works
Simplified Vertex+DC
Full Sim: k4 w/ k4SimG4
Reco: k4 w/ iLC@Wrapper ?

Noble Liquid ECAL based

new

Full Sim:
Simplified Vertex+DC,
ECAL: k4 w/ k4SimG4
Reco:
Tracker: k4 w/ iLC@Wrapper ?
ECAL: k4

HCAL, muon: in the works

Mogens Dam / NBI Copenhagen 4

https://indico.cern.ch/event/1165167/timetable/#20220622

Detector Concept kickoff meeting
Nice talks on requirements!

Software tools & tutorials

- Latest tutorial last week at CERN: https://indico.cern.ch/event/1182767/
- Needs to be run in person. Would like to propose it here in the near future.

S. Eno works on this!

- Added bonus of learning to do analysis for FCC-ee: DD4HEP and DataFrame now used for the LHC experiments.
- Documentation is still in constant evolution, but it has been improved recently.
  - NOTE: Active developers for framework and for analyses are still a small number, so direct contact is best (and some patience)

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New LLP tutorial

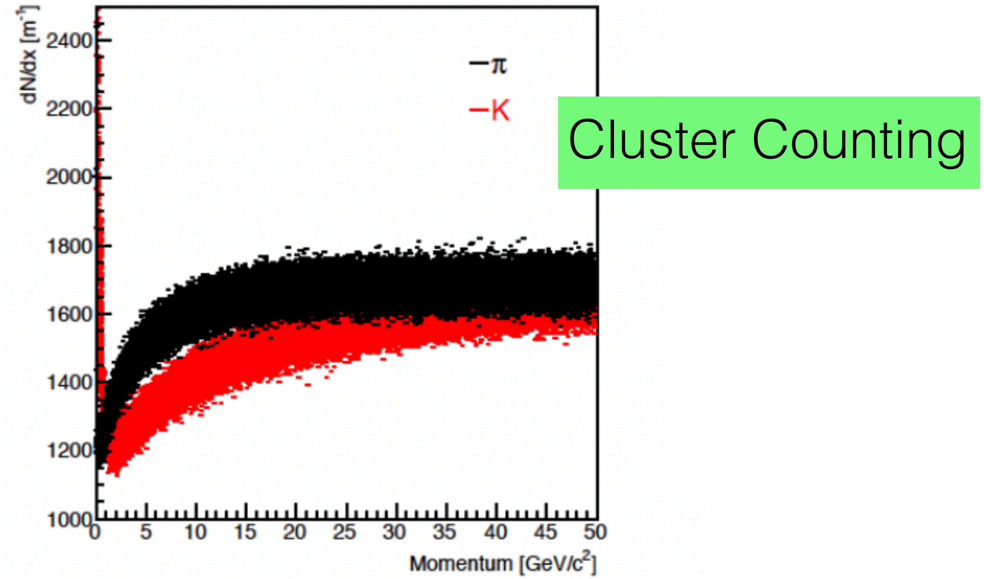
- Additional brand new tutorial for LLP from J. Alimena here (was created just for this crowd):
  - https://github.com/jalimena/LLPFCCTutorial/blob/main/README.md
- Gives a nice overview focused on the analyses steps for the search of Long Lived signatures.
- Interested people can reach out to me (and her) once they try it out if they have questions or comments.

Delphes "on steroids"

- For FCC-ee we decide to add more functionality to Delphes, since the FullSimulation of the detector concept in the key4hep is not ready yet (planned for next year).
- Delphes simulates the response of a multipurpose detector in a parameterised fashion
  - designed to deal with hadronic environment, is also well-suited also for e+e- studies
  - detector cards for: CMS (current/PhaseII) - ATLAS - LHCb - FCC-hh - ILD - CEPC - FCCee (IDEA/CLD)
- Delphes output in EDM4HEP format allows to run **same analysis code** on FullSim events output.
- More info here: https://indico.desy.de/event/33640/contributions/128007/attachments/77587/100359/delphes_ecfa2022.pdf

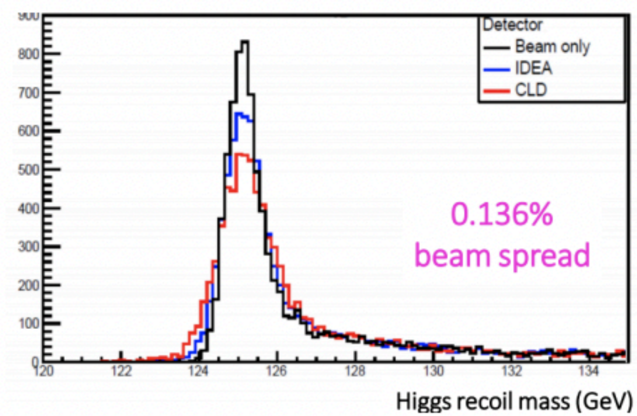
Additions for FCC-ee

- TrackCovariance
- Cluster counting for PID
- Time of flight
- Jet Clustering
- EDM4Hep event format



Track Smearing

- Simple tracker geometry implementation, **including material**
- Computes **full covariance matrix** (in present Delphes we have "diagonal" smearing in the 5 tracking parameters)
- Can be used for studying impact of material and realistic **HF tagging** simulation



Bedeschi, Gouskos, MS, [2202.03285]

HIGGS Measurement	Constraining
Higgs boson coupling to c quark	Flavour tagging, vertexing
σ(ZH) and mH, Z →leptons (Mrecoil); New scalars in Z + S	Lepton momentum & energy resolution
σ(ZH) and mH, Z → hadrons ; BR(Higgs invisible)	hadronic mass and hadronic recoil-mass resolution ; Maybe b-tagging
Γ(H) in ZH, H → ZZ*	Lepton ID efficiencies; jet clustering algorithms, jet directions, kinematic fits
Higgs boson mass in all exclusive final states (hadronic, taus, etc)	b-tagging eff and purity, jet angular resolution, jet reco, kin fits
Γ(H) with bbnunu events	Visible and missing mass resolutions
HZγ coupling	photon identification, energy and angular scale
e-e+->H production in s-channel at Higgs pole	q / g tagging CERN (former analysis exists & being revamped)

HIGGS MASS AND CROSS SECTION "CASE STUDY"

$e^+e^- \to ZH, Z \to \mu\mu$

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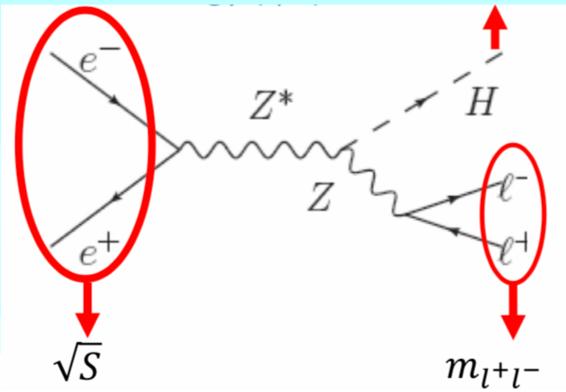
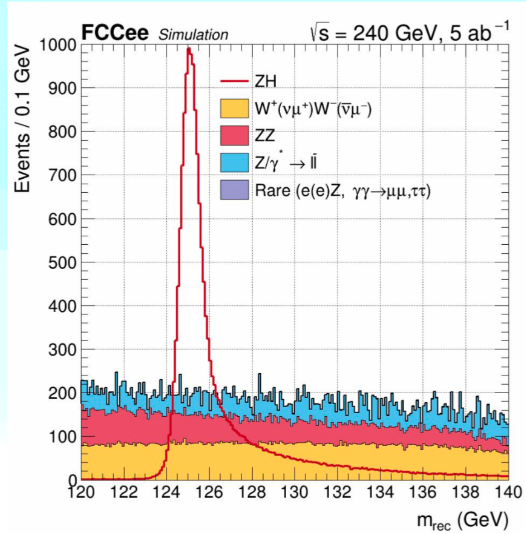
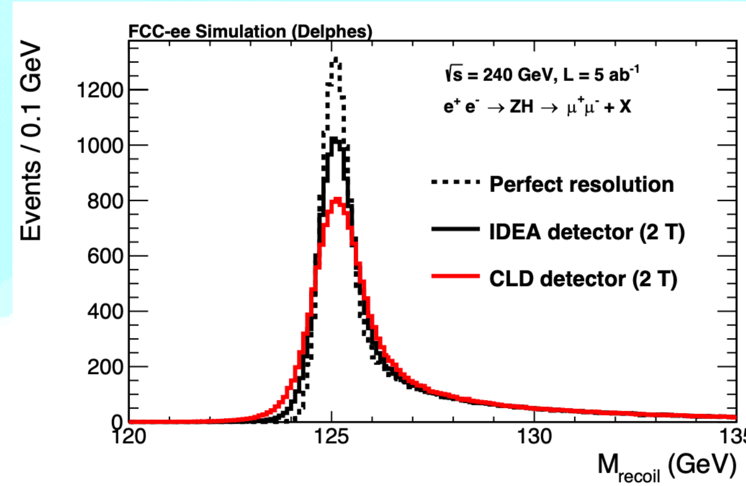






Main TK	Δm_H (MeV)	$\Delta\sigma$ (%)
IDEA 2T	**6.70**	**1.07**
CLD 2T	**9.01**	**1.12**
IDEA 3T	**5.78**	**1.06**
Perfect resol	**4.75**	**1.04**

$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

Recoil mass affected by :

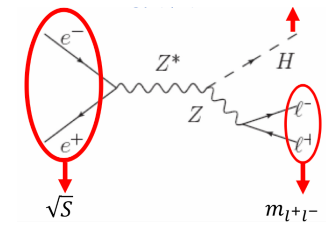
- The beam energy spread
- The momentum resolution (and the ISRs for the tail)

Higgs mass measurement:

$$\Delta(m_H) < O(\Gamma_H)$$ i.e. 4 MeV desirable in view of $e^+e^- \to H$

Example: Higgs mass with ZH events

- Precise mass motivation, with O(10MeV) already matches the statistical precision on the Higgs, BR, but to constrain or measure electron Yukawa, would need better than the Higgs width (<4.1MeV).
- This is an ambitious goal that poses challenges and constraints on the measurement with the ZH events
- Preliminary recoil method determination using $Z \rightarrow \mu\mu$ decays shows Δm(H)~few MeV with systematics effects from:
  - Beam energy spread , Lepton and jet angular resolution, acceptance , Momentum scale and its stability (as will be shown for the example at the Z)
- **Exploring other channels with hadronic decays of the Z and H will add statistics, but challenge also the performance for reconstruction of jets and kinematical fitting**



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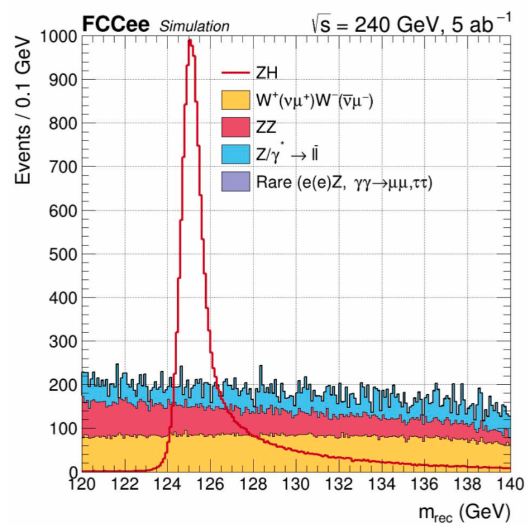
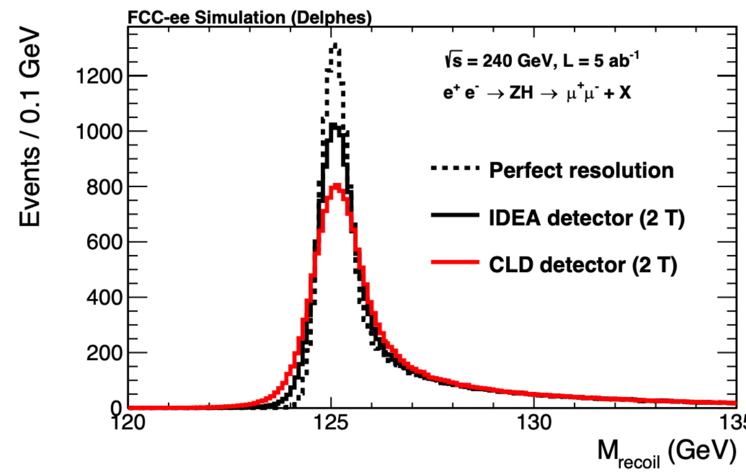
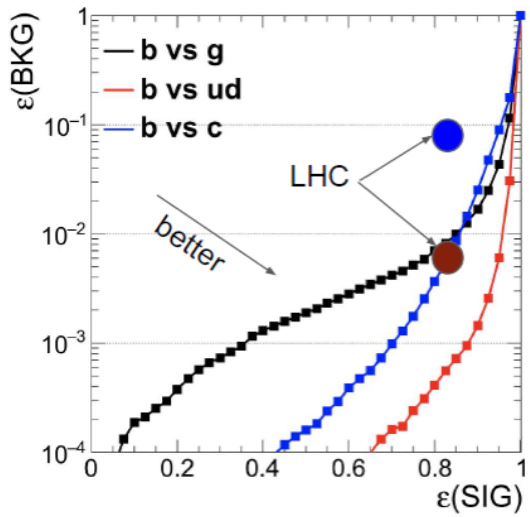
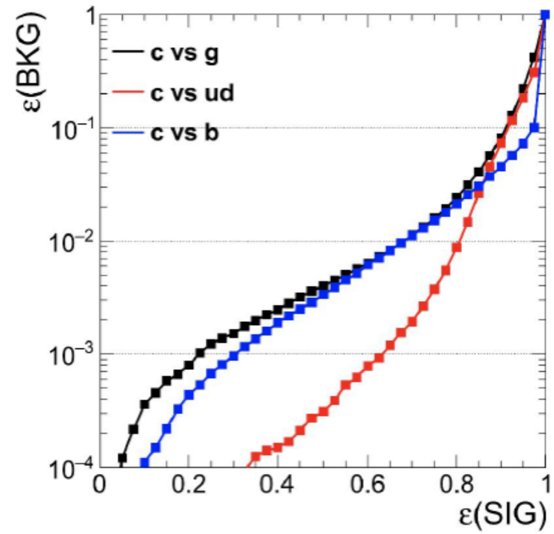




Jet-flavor tagging

F. Bedeschi,
L. Gouskos,
M. Selvaggi





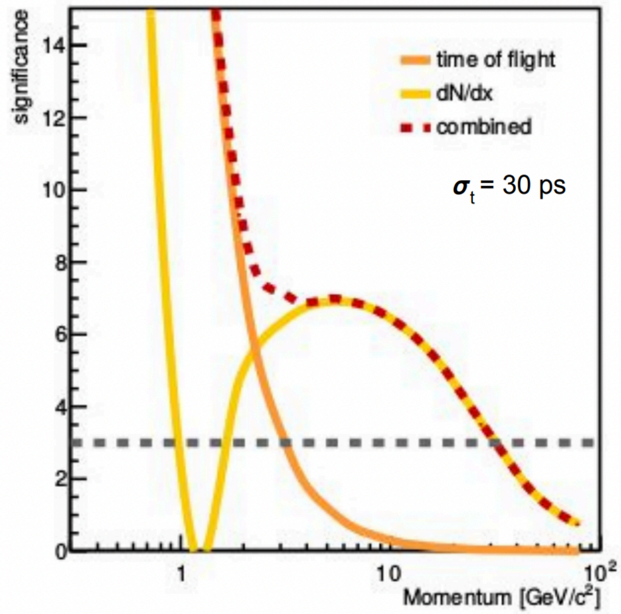
WP	Eff (b)	Mistag (g)	Mistag (ud)	Mistag (c)
Loose	90%	2%	0.2%	3%
Medium	80%	0.7%	<0.1%	0.4%

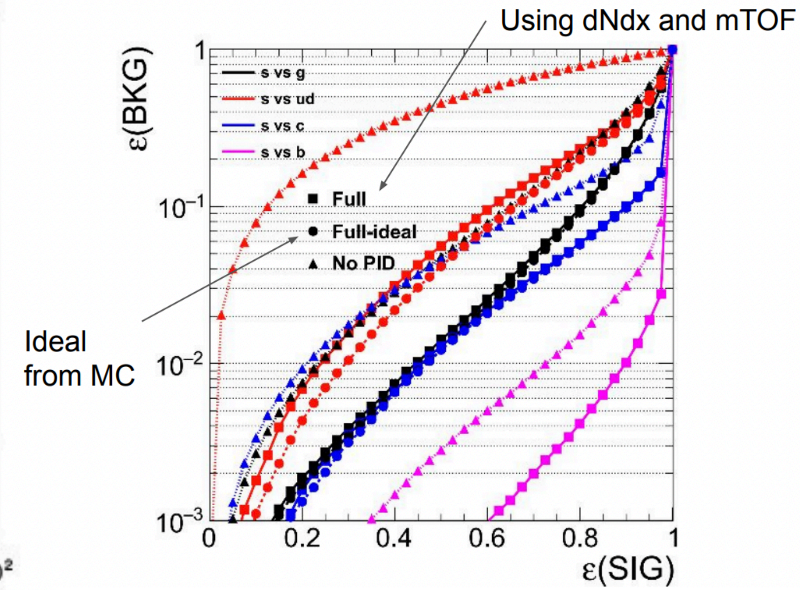
WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	8%	7.5%	5%
Medium	80%	3%	0.9%	2.5%

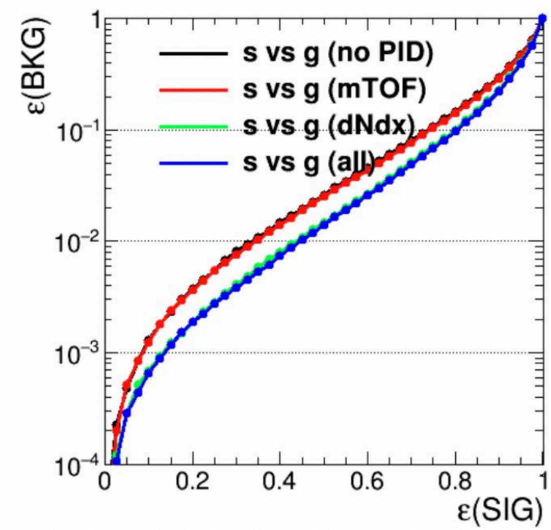
- New tagging algorithm developed based on DNN approach: DGCNN: [arXiv:1801.07829] ParticleNet: [arXiv:1902.08570]
- c-tagging efficiency is 80-90%, improves when beam pipe radius decreases
- $H \to c\bar{c}$ **coupling performance:** $\delta(\sigma \times BR)/(\sigma \times BR)\,\% \approx 0.6(\text{stat. only})$ or $2.9(\text{no Bkg rej})$: promising!

Strange tagging

F. Bedeschi, L. Gouskos, M. Selvaggi







- Combined PID with dN/dx and TOF(30ps): 3σ K/π separation for p<30GeV
  - Using IDEA concept with Drift Chamber
- First look. Investigating possible improvements, maybe 30ps not enough?

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

EWK Measurements at the Z	Constraining
Total width of the Z *(see next slide)*	Track momentum (and angular) resolution, scale (magnetic field) stability
Rb, Rc, AFB of heavy quarks	Flavour tagging, acceptance, QCD corrections
alphaS measurement	Z -> jets
Ratio R_ℓ	Geometrical acceptance for lepton pairs
AFB (muons) and $\alpha(QED)$	EW corrections and control of IFI (initial-final state radiation interference)
Luminosity from diphoton events ; NP in diphotons	e/gamma separation, gamma acceptance

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Total width of the Z *(see next slide)*	Track momentum (and angular) resolution, scale (magnetic field) stability
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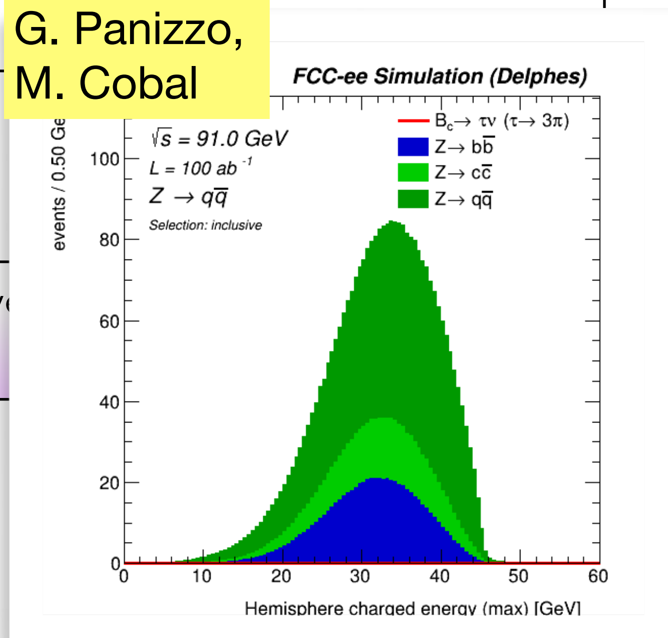
G. Panizzo,
M. Cobal



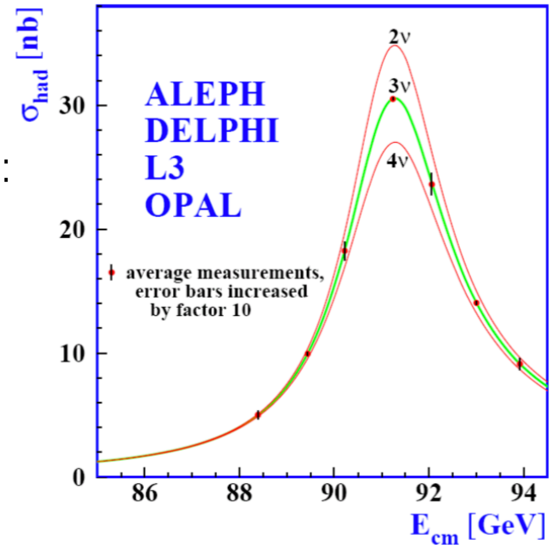
A_{FB}(bb) analysis started on centrally produced samples.

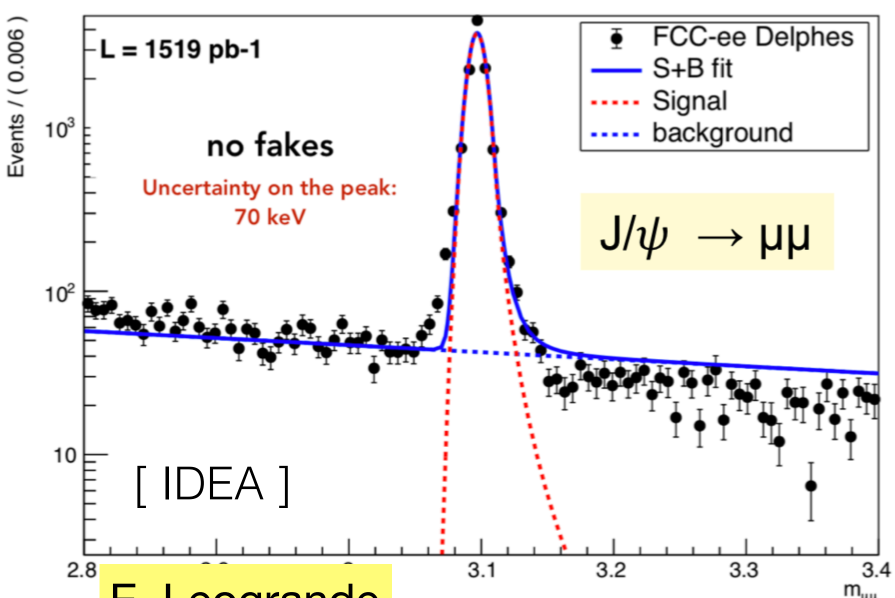
Example : Determination of the Z width

Key = Relative uncertainty of √s between the different energy points of the lineshape scan.

Can be controlled via the direct measurement of Mμμ in di-muon events : compare the peak positions at the different √s points.

- σ(Mμμ) : statistical potential to control relative δ(√s) to O(40 keV)
- Requires the stability of the momentum scale, esp. of B, to that level, i.e. 40 keV / 90 GeV < 10^{-6}





E. Leogrande
E. Perez

In-situ, using the large statistics of well-known resonances, e.g. J/ψ → μμ

First studies: Target seems within reach with an IDEA-like resolution.

- post-doc left, but code available!
- **candidate analysis to move asap to FullSim tracks !**

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EWK Measurements at the WW	Constraining
Coupling of Z to nu_e (also, at the Z peak: invisible ALP, dark γ)	Photon energy resolution, acceptance, track efficiency
M_W from WW -> had, semi-lep	Lepton and jet angles, Kinem fits
(d)σ(WW) for M_W, TGCs	Lepton ID, angular resolutions
Vcb via W -> cb	Flavour tagging
W leptonic BRs	Lepton ID, acceptance
Meas of $\sqrt{s}$ via radiative return	lepton and jet angular resolutions, acceptance

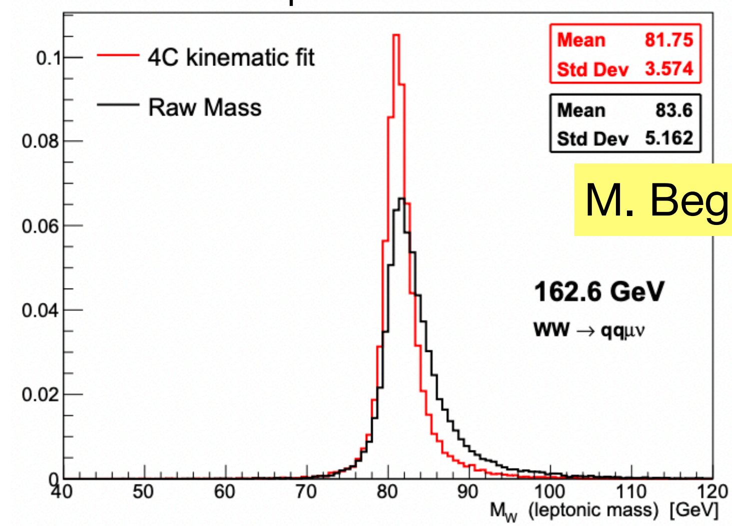
Example: W mass direct reco

- Precise M(W) from threshold run ~400keV (stat)
- **M(W) direct reconstruction from decay products useful at any √s>threshold**
- Competitive as statistical uncertainty but different challenges to be considered:
  - Event reconstruction, choice of jet algorithms
  - Lepton momentum scale and resolution
  - Kinematical fitting

Definition of W mass estimators and study and optimisation of:

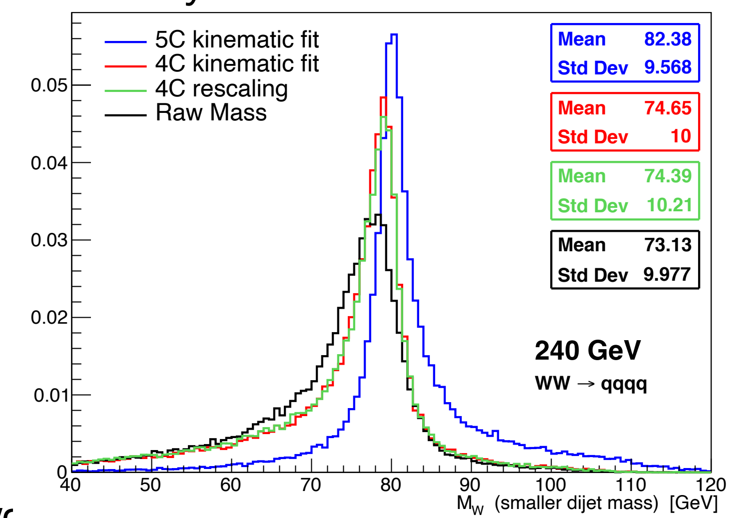
- Statistical and systematic uncertainties with templates fit
- W hadronic decay modelling systematics
- Exploiting also ZZ and Zγ events for constraints and calibration
- Thesis of M. Beguin available as starting point

Semi-leptonic channel



M. Beguin

Fully hadronic channel



Flavour and tau physics

Measurement	Constraining
B_s -> D_s K	Many things.. Vertexing, PID, EM resolution
Bc -> tau nu	Flight distance resolution (vertexing)
B -> K* tau tau	Flight distance resolution (vertexing)
Modes with pi0's	EM resolution
Tau Lifetime	Construction and alignement of vertex detector
Tau mass	Track momentum scale (in multi-track collimated environment)
Tau leptonic BR	Electron and muon ID
Tau polarisation and exclusive BR	Photon, Pi0, neutrals, K/pi separation
Lepton Flavor Violation in Z and tau decays	Lepton momentum scale

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Flavour and tau physics

Measurement	Constraining
B_s -> D_s K	Many things.. Vertexing, PID, EM resolution
Bc -> tau nu	Flight distance resolution (vertexing)
B -> K* tau tau	Flight distance resolution (vertexing)
Modes with pi0's	EM resolution
Tau Lifetime	Construction and alignement of vertex detector
Tau mass	Track momentum scale (in multi-track collimated environment)
Tau leptonic BR	
Tau polarisation and exclu	
Lepton Flavor Violation in decays	

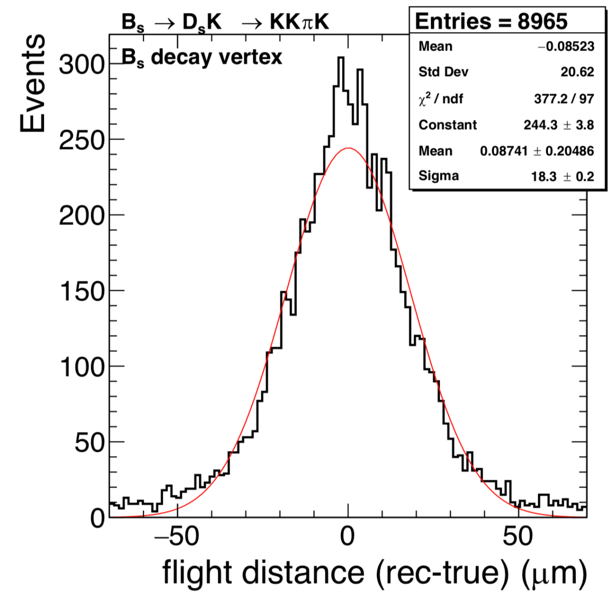
* Delphes samples of limited use for (several of) these tau studies.
* Goal of separation of tau decay modes has triggered FullSim studies:
    — Clustering developments in FCCSW with the LAr[NBI]
    — NN-based tau-ID in the IDEA calo [Roma]

$B_s \to D_s K$

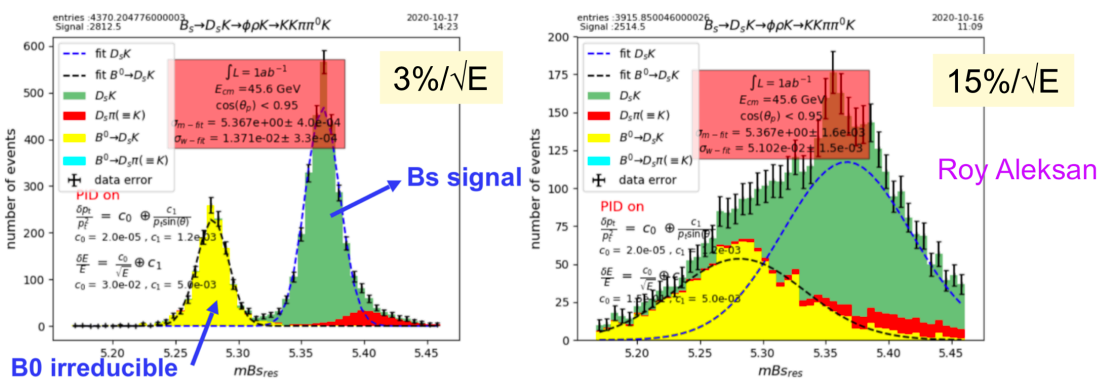
https://arxiv.org/abs/2107.02002

Excellent benchmark for several detector requirements !

- **Precise reconstruction of displaced vertices**
  - Esp. for CP violation measurements
  - Vertexing tools implemented within FCCAnalyses



- **Excellent EM resolution**
  - Mandatory to see the signal in modes with neutrals !



State-of-the-art Xtal-type to HGCal-type : $\sigma(D_s^{\pm}(\phi\rho^{\pm})K^{\mp}) \approx 14MeV \to 51MeV$

Good starting points exist. Need to put all bricks together in the common framework.

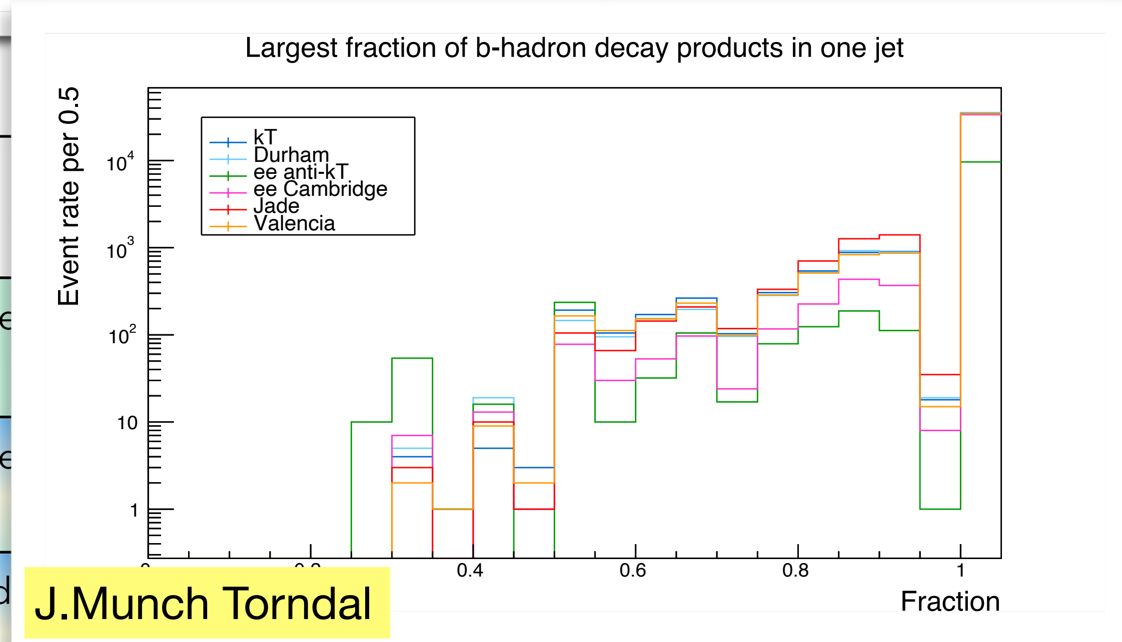
- **Good π / K separation**
  - PID tools recently implemented in Delphes

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

Top physics

Measurement		
EW couplings of the top	Je	
Top properties from threshold scan	Je	
FCNC couplings	Id	

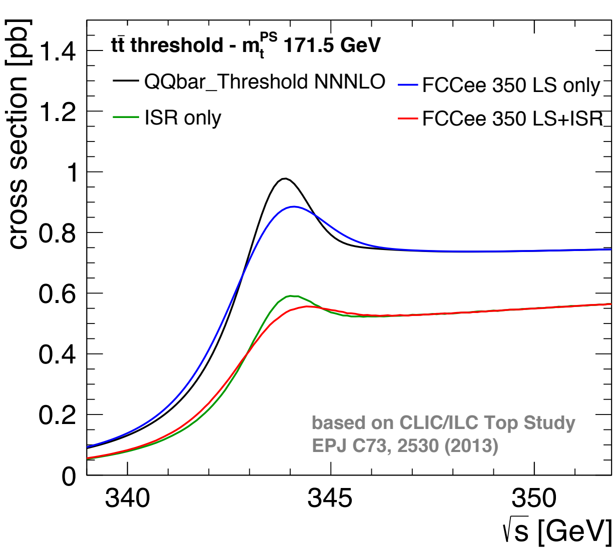


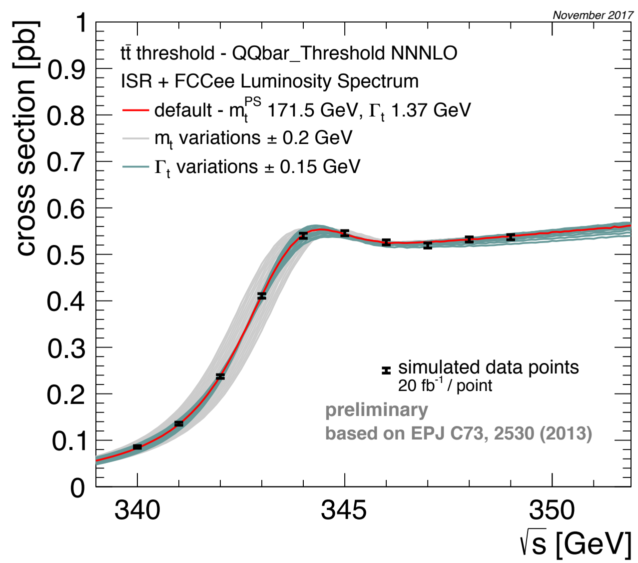
EWK Coupling of the top:

- Study of different jet clustering algorithm in top l+jets events
- Development of code to rerun jet clustering after Delphes
- Addition of parameterised B-tagging in FCCAnalysis
- Reoptimization of event selection
- Development of fitting code in progress

Example: Top mass at threshold

- **Most precise top mass measurement method with specific threshold scan of 100fb^{-1}**
- Theory available at NNNLO/NNLO+NNLL: $\Delta m/m \approx 40MeV$ from scale. Generators description of the threshold region important
- No need for kinematic fit, counting experiment: optimisation of threshold scan strategy important
- **Needs excellent control of beam energy, beam energy spread, luminosity spectrum ($\Delta m/m \approx 3MeV$) and ISR** : generator description to study effects
- **Needs excellent b-tagging, jet algorithm reconstruction:** systematics effects from selection to be studied
  - If α_S from TeraZ $\Delta m/m \approx 5MeV$ (30MeV for parametric uncertainty if current value)





For differential studies at threshold will need direct top reconstruction and fitting: control combinatorial effects, association, etc…

BSM Direct searches

HNL	- displaced vertices - specific tracking	Uppsala/Graz/Geneva
ALPS: ee $\rightarrow a\gamma \rightarrow 3\gamma$	- Photon resolution - separation of close-by photons - displaced γ vertices	Pavia FullSim needed…
ALPS: $\gamma\gamma \rightarrow \gamma \rightarrow \gamma\gamma$	Photon resolution	CERN / Rio
Dark Photons $ee \rightarrow \gamma\bar{\gamma}$	Photon resolution	Udine [2020] https://arxiv.org/abs/2006.15945

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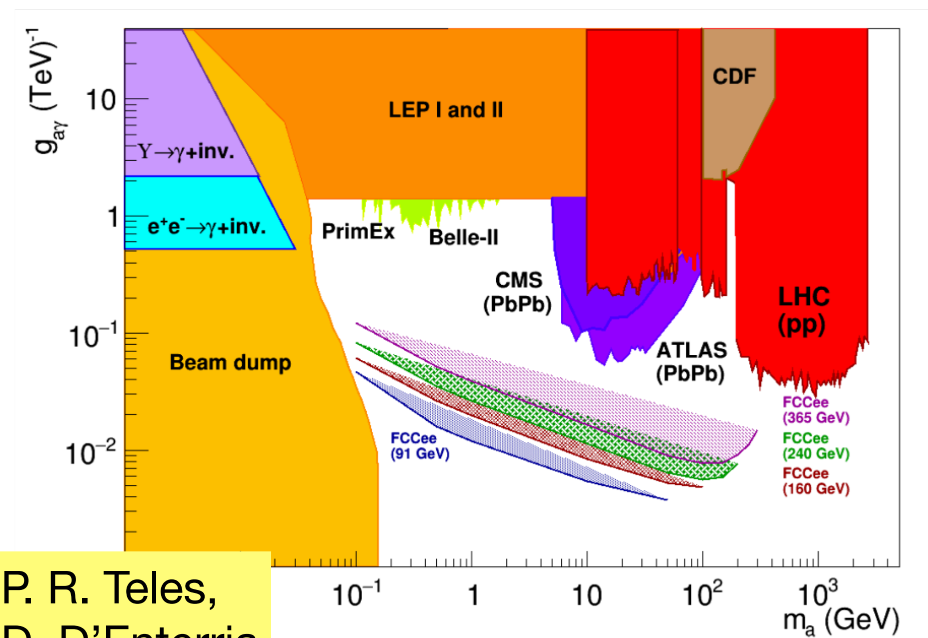

P. R. Teles, D. D'Enterria

Parton level sensitivities extracted on light-by-light production of ALPS. Results with IDEA Delphes card in progress

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LLP Direct searches

- BSM processes with with very long lived particles, or unusual signatures, can be probed particularly well at a lepton collider with a large statistics such a Tera-Z.
  - For a general overview of the challenges EPJ+ essay: https://arxiv.org/abs/2106.15459 (under review)
- Given the rich list of models proposed, theorist and experimentalist have been meeting up regularly in an "informal group" focusing on:
  - defining benchmarks models, with different signal characterisation
    - analysis code in place for validation of MC signals in Delphes for HNL
  - defining "case studies": to extract detector requirements
    - Delphes being updated to allow developments while FullSim becomes ready.
- Area with documentation & initial code in the PhysicsPerformance Github: https://hep-fcc.github.io/FCCeePhysicsPerformance/case-studies/BSM/LLP/

What if I am curious?

- Perfect entry point for a newcomer.
- Easy to find a topic matching your expertise:
  - future physics studies while working at an LHC experiment
  - trying new technologies & new algorithms, pushing the limits of detector and analysis performance
  - Favorite detector technology that can be connected to a physics study
- Regular monthly meetings 3rd Monday of the month afternoon
- Documentation: https://hep-fcc.github.io/FCCeePhysicsPerformance/

What next?

- « case studies » have generated a very nice momentum!
  - the FCCAnalysis model has proven to be easy to use and it allows a collaborative modus operandi that speeds up work
- The start of the Physics Programme activities will nicely merge and complement ongoing work
  - through the proposal of new benchmarks to extend the physics potential exploration using the tools developed within PPC
- The start of the Detector Concept Coordination area will help speed up the development of FullSimulation response to explore new design and technologies
  - A nice feedback from “case studies” result will inform and guide detector designs

A concrete goal of the mid-term document end of 2023 coming up with new detector concepts is a fun challenge to try.
Recycling/exchange of knowledge and skills back to LHC or other future projects is possible
Definition of tasks allows to progress even with small FTE available