FCC

Overview and organisation of Physics & Performance Studies

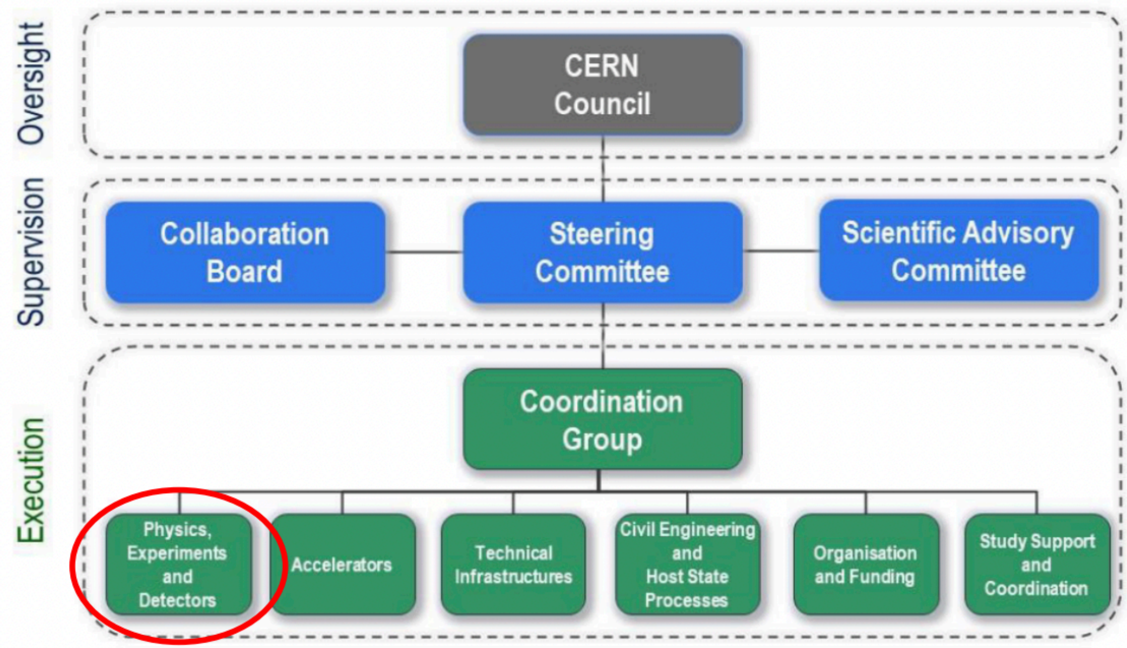
Swiss FCC Day - 07/09/2021

P. Azzi (INFN-PD/CERN)

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.

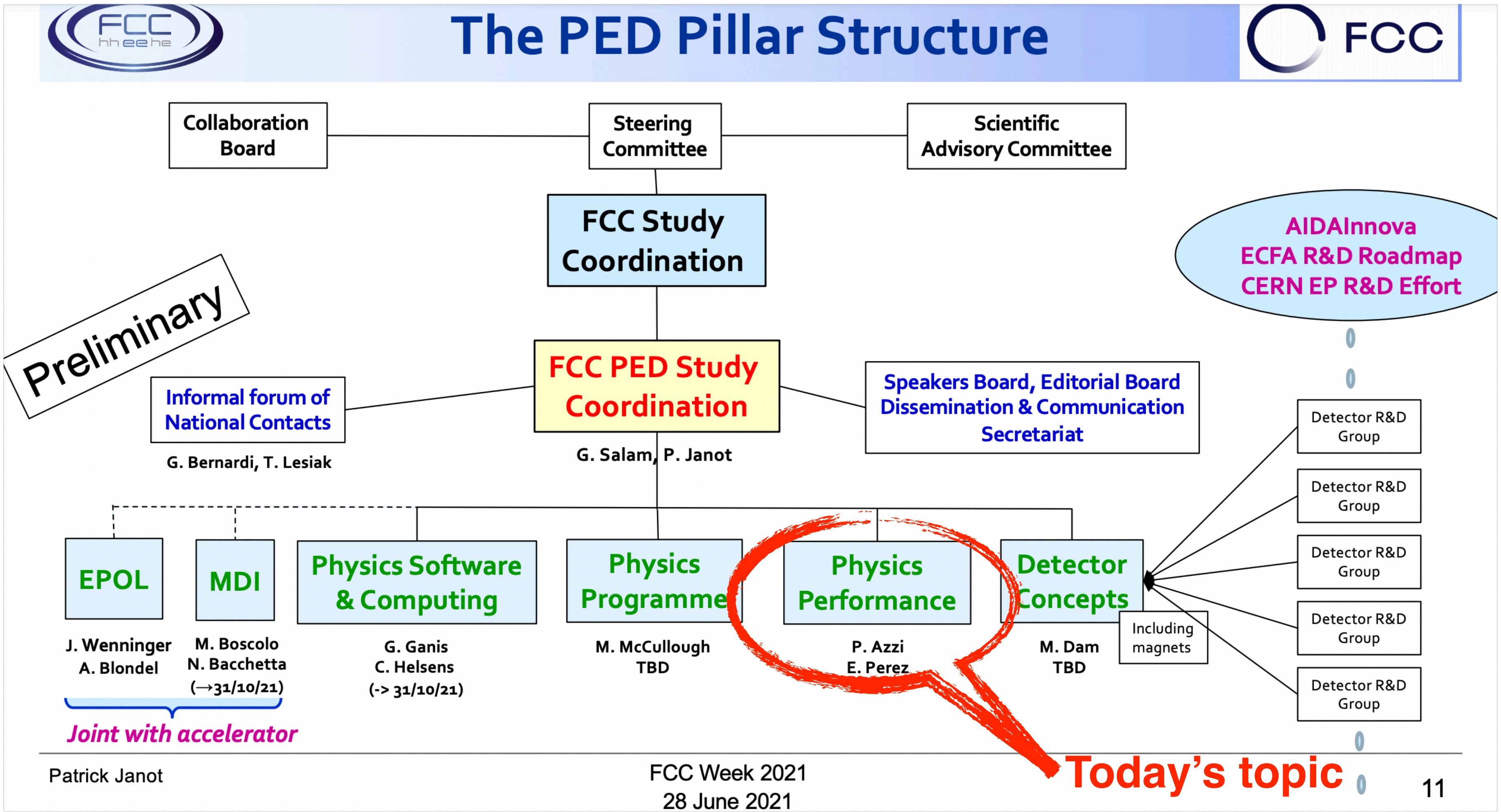
FCC Feasibility Study (2021-2025)



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 Study Pillar Structure



Physics Programme WP

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- 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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- Coordinators nomination in progress

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

Targets and Progress Status

- 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 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.*

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)

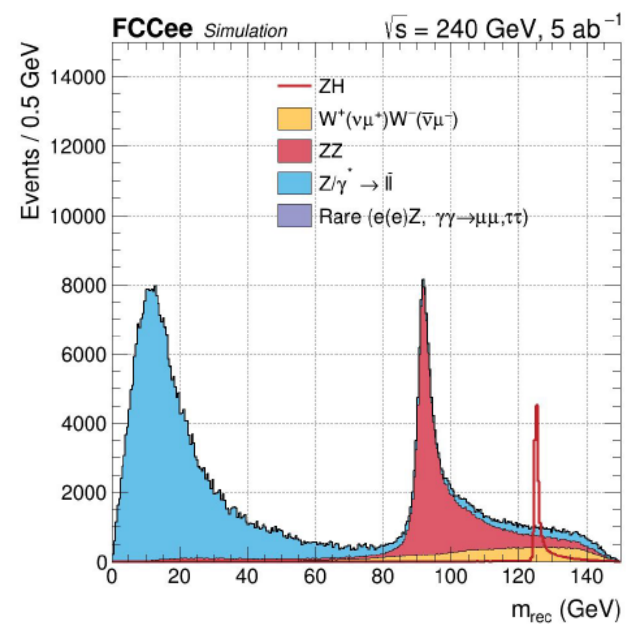
Example: Higgs mass with ZH events

- 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
  - accelerator operations detector design, analysis techniques
- 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**

Stat-only results

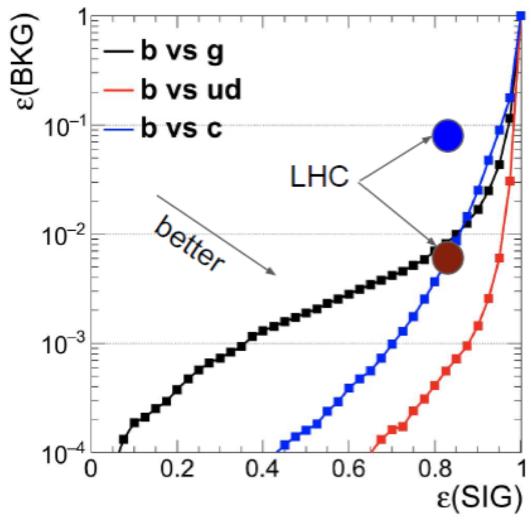
IDEA	Δm_H (MeV)	Δσ (%)
Nominal	**6.70**	**1.07**
FullSilicon	**9.01**	**1.12**
3T	**5.78**	**1.06**

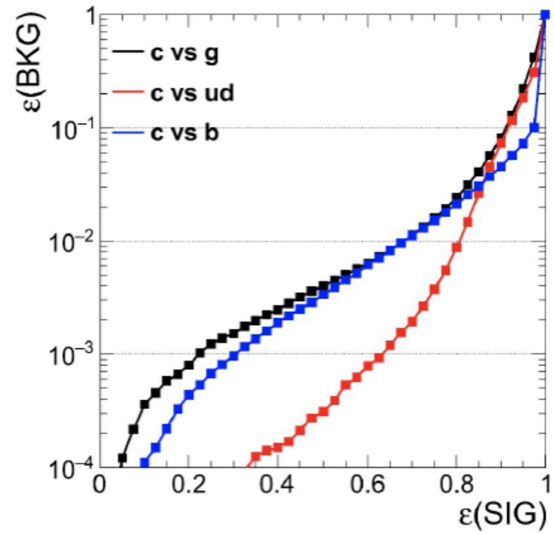
A. Li, J.Eysermans, S. Braibant, V. Diolaiti



Jet-flavor tagging

F. Bedeschi,
L. Gouskos,
M. Selvaggi





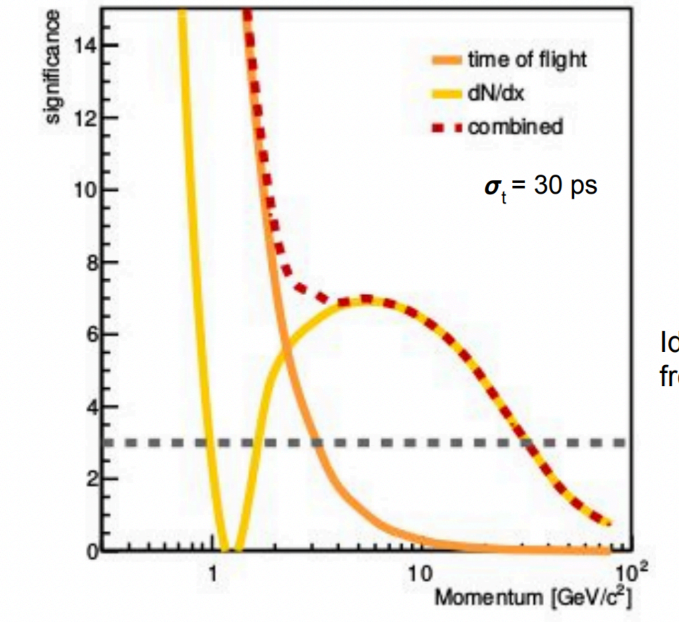
WP	Eff (b)	Mistag (g)	Mistag (ud)	Mistag (c)
Loose	90%	2%	0.2%	3%
Medium	80%	0.7%	<0.1%	0.4%

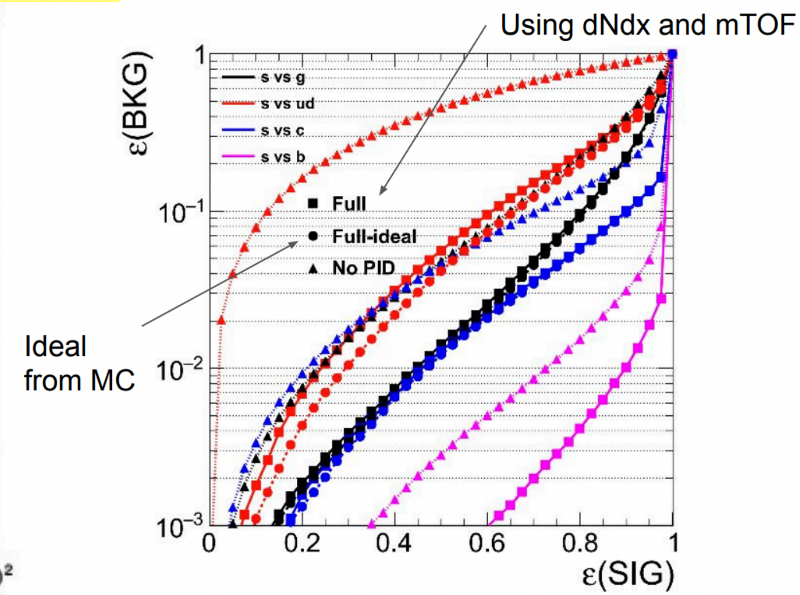
WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	8%	7.5%	5%
Medium	80%	3%	0.9%	2.5%

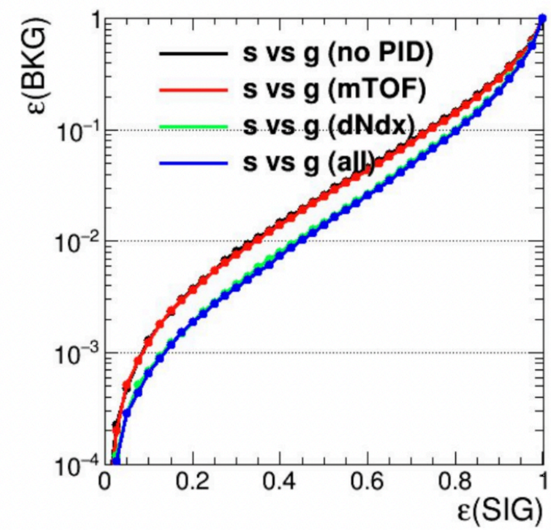
- New tagging algorithm developed based on DNN approach: DGCNN: [arXiv:1801.07829] ParticleNet: [arXiv:1902.08570]
- c-tagging efficiency is 80-90%, improves when beam pipe radius decreases
- $H \to c\bar{c}$ **coupling performance:** $\delta(\sigma \times BR)/(\sigma \times BR)\,\% \approx 0.6(\mathrm{stat\,.\,only})$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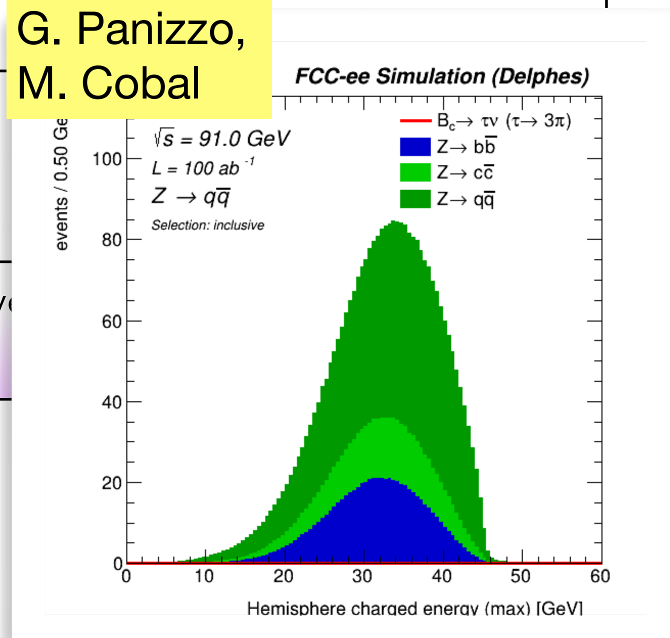
G. Panizzo, M. Cobal



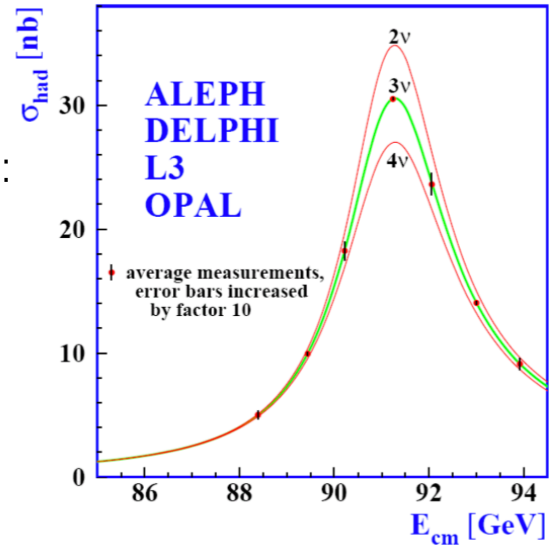
AFB(bb) analysis started on centrally produced samples.

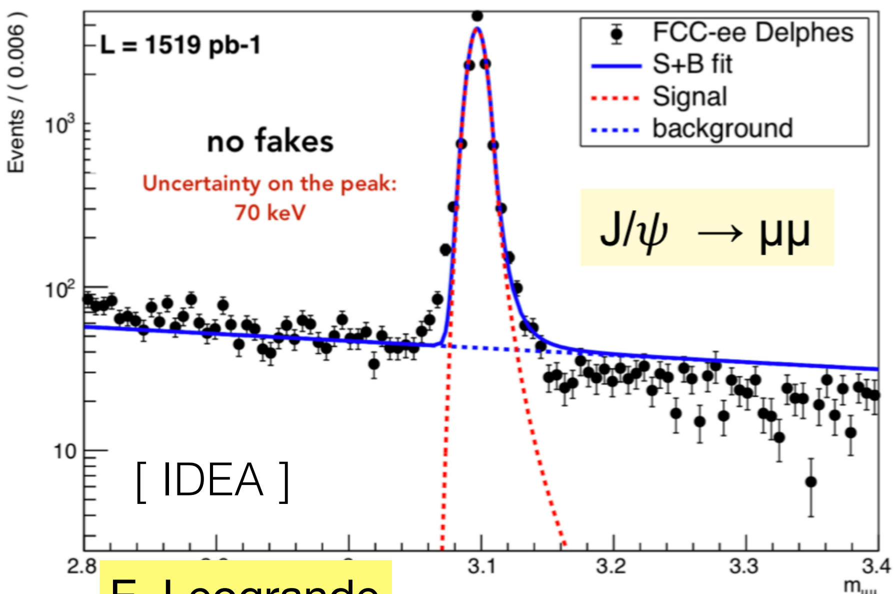
Example : Determination of the Z width

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 !**

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

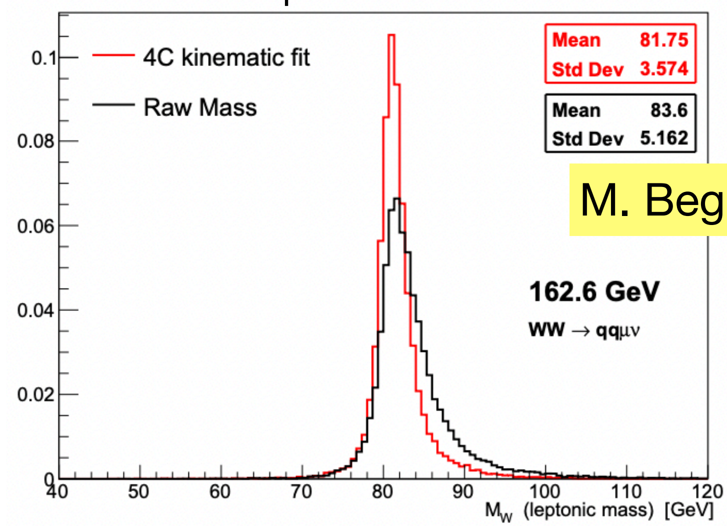
Example: W mass direct reco

- 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:

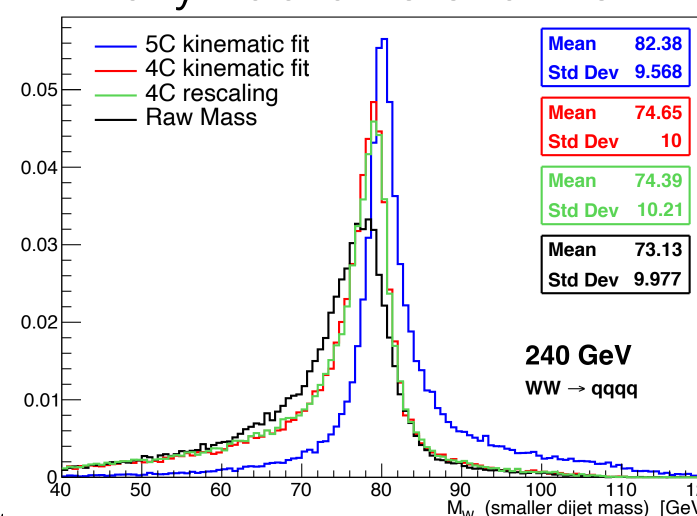
- Statistical and systematic uncertainties with templates fit
- W hadronic decay modelling systematics
- Exploiting also ZZ and Zγ events for constraints and calibration
- Thesis of M. Beguin available as starting point

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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Tau Lifetime	Construction and alignement of vertex detector
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Tau leptonic BR	
Tau polarisation and exclu	
Lepton Flavor Violation in decays	

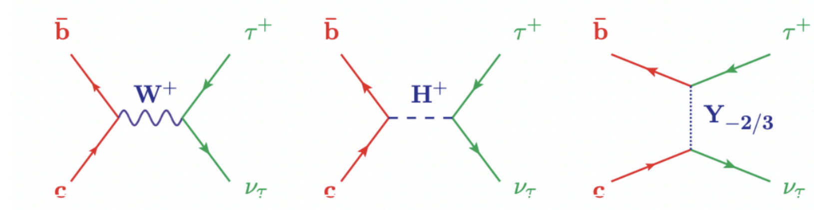
* Delphes samples of limited use for (several of) these tau studies.
* Goal of separation of tau decay modes has triggered FullSim studies:
    — Clustering developments in FCCSW with the LAr[NBI]
    — NN-based tau-ID in the IDEA calo [Roma]

FCC $B_c \to \tau\nu_\tau$

https://arxiv.org/abs/2105.13330

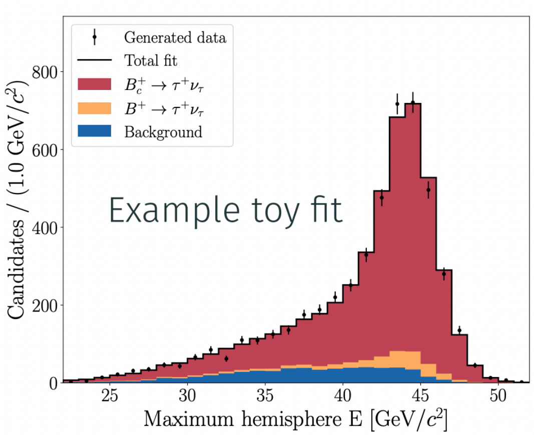
First published case study

- $B_c \to \tau\nu_\tau$ is a unique flavour opportunity at FCC-ee
    - Not possible at LHCb due to missing energy
    - No B_c^+ mesons produced at Belle II
- Involves the same Feynman vertex factors as $b \to c\tau\nu_\tau$ decays
    - Measurements of R(D) and R(D*) show a ~ 3-4σ tension with SM

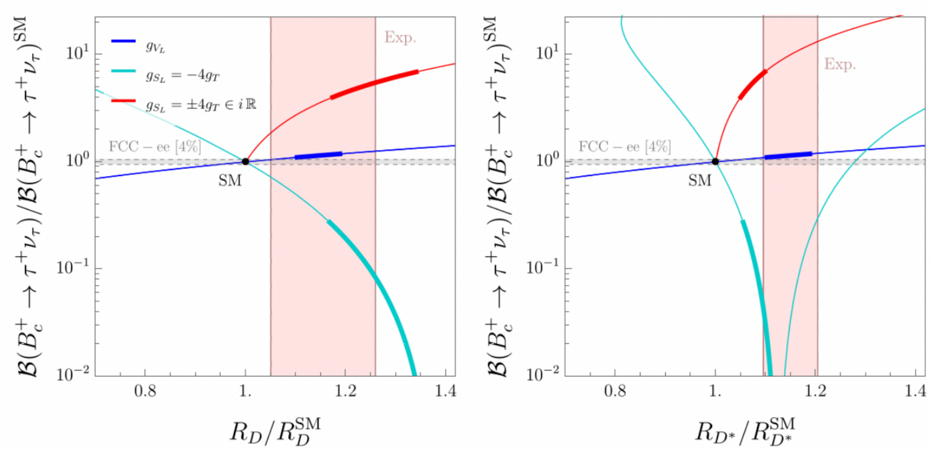


$BR(B_c^+ \to \tau^+\nu_\tau) = (1.941 \pm 0.175) \times 10^{-2}$

- Use tree-prong hadronic mode $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau$
    - Common software used throughout from EDM4hep to FCCAnalyses and common Python analysis tools
    - Using MVAs to reduce background and discriminate signal, toy fit to measure signal yield
- Signal yield measurement ~3% precision
    - but requires accurate $B(B_c^+ \to J/\psi\mu\nu_\mu)$ prediction to convert to $B(B_c^+ \to \tau^+\nu_\tau)$ now 8.1% unc. Dominating the error.



R_C at 4%
NP constraints



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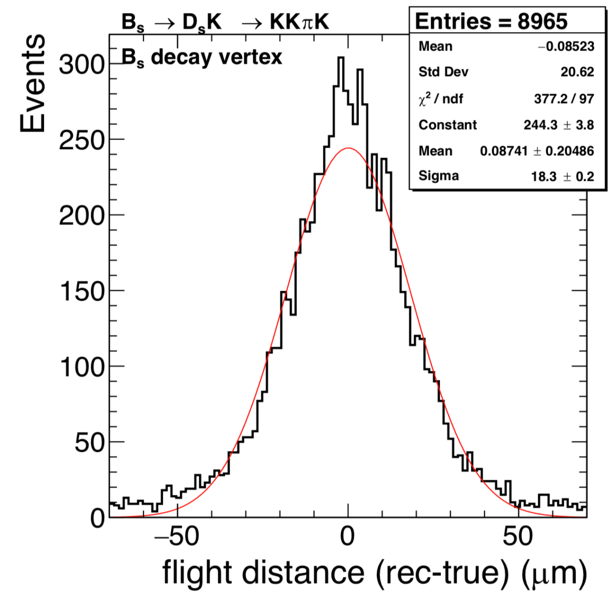
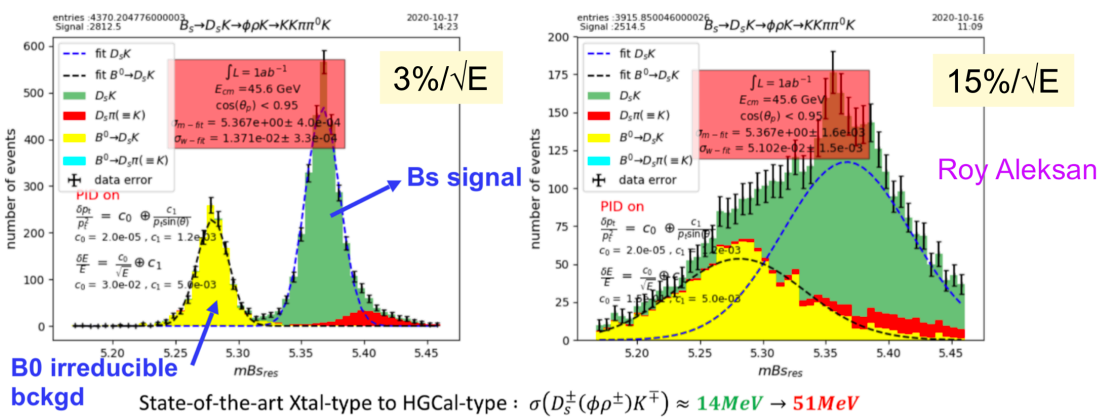
$B_s \to D_s K$

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 : $\sigma(D_s^{\pm}(\phi\rho^{\pm})K^{\mp}) \approx 14MeV \to 51MeV$

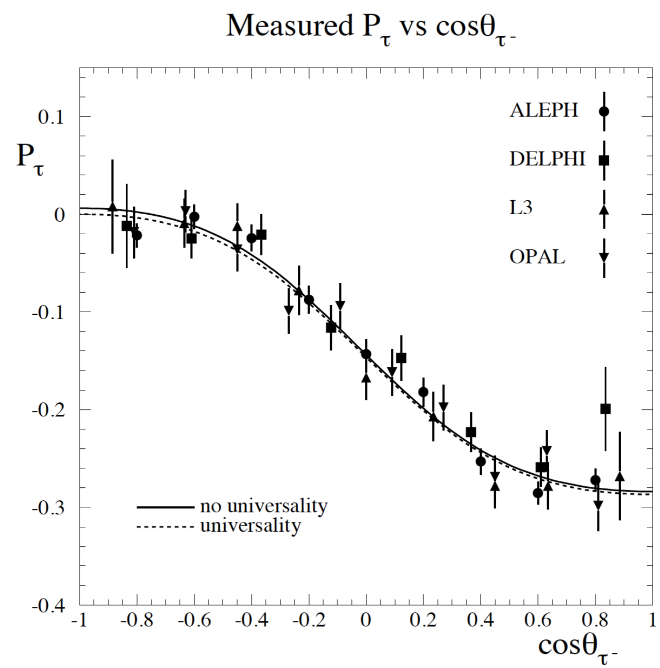
Good starting points exist. Need to put all bricks together in the common framework.

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

Example: Tau Polarisation

- Tau polarisation has a central role at the FCC-ee: crucial ingredient for $A_e, sin^2\theta_{eff}$ at a circular collider
  - Desired precision of few x10^{-6} on $sin^2\theta_{eff}$, similar to that from $A_{FB}^{\mu\mu}$ but model independent
- Very large tau statistics ($\approx 1.5 \times 10^{11}$). Not only leptonic decays. Can profit of hadronic decays and choose the best channels (avoiding modelling issues).
  - For instance use best decay channels such as $\tau \rightarrow \rho \nu_\tau$

$$P_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + \mathcal{A}_e(2\cos\theta)}{(1+\cos^2\theta) + \frac{4}{3}\mathcal{A}_{fb}(2\cos\theta)}$$



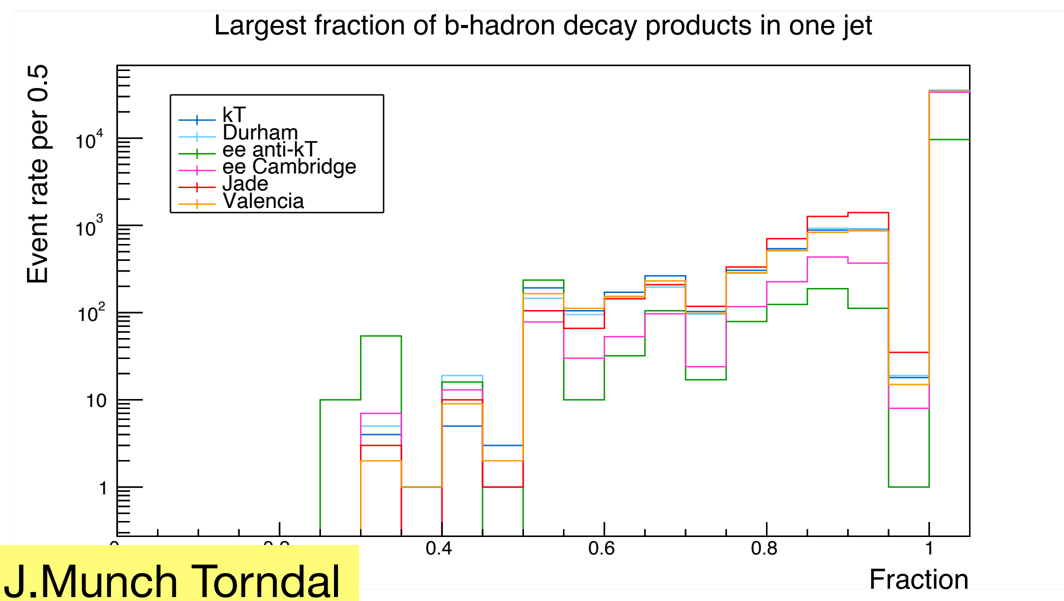
Excellent benchmark for detector performance in π^o/γ separation

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



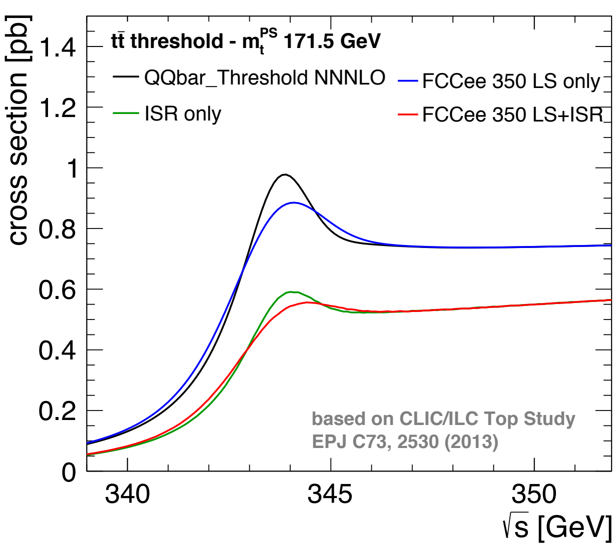
J.Munch Torndal

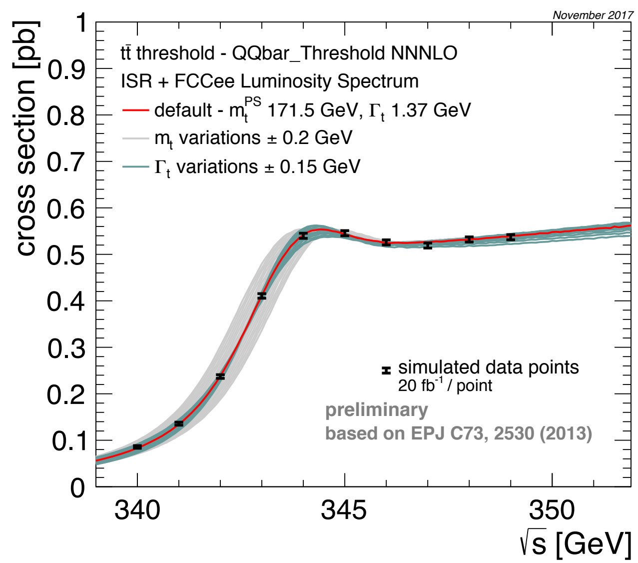
EWK Coupling of the top:

- 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 $\rightarrow$ aγ $\rightarrow$ 3γ	- 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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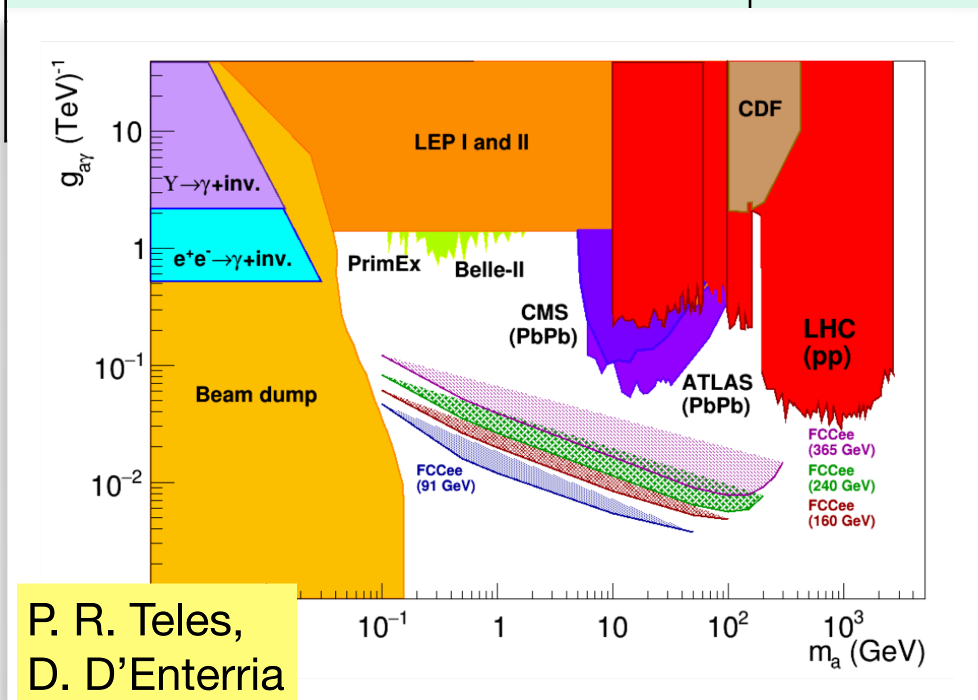

P. R. Teles, D. D'Enterria

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 not really suitable. Will profit largely of FullSim tracking in EDM4Hep
- Area with documentation & initial code in the PhysicsPerformance Github: https://hep-fcc.github.io/FCCeePhysicsPerformance/case-studies/BSM/LLP/

Why Physics Performance is the right place to join?

- 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
- Documentation: https://hep-fcc.github.io/FCCeePhysicsPerformance/

The Path Ahead

- « 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

This year has been quite intense and has brought much progress in the development of the first “case studies”. This is just the beginning!