Physics prospects at FCC(-ee) and some opportunities to contribute

FCC kick-off meeting for the Brazilian community,
March 7, 2023

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Introduction and outline

Current activities in physics analyses focus on FCC-ee.
For some benchmark measurements:

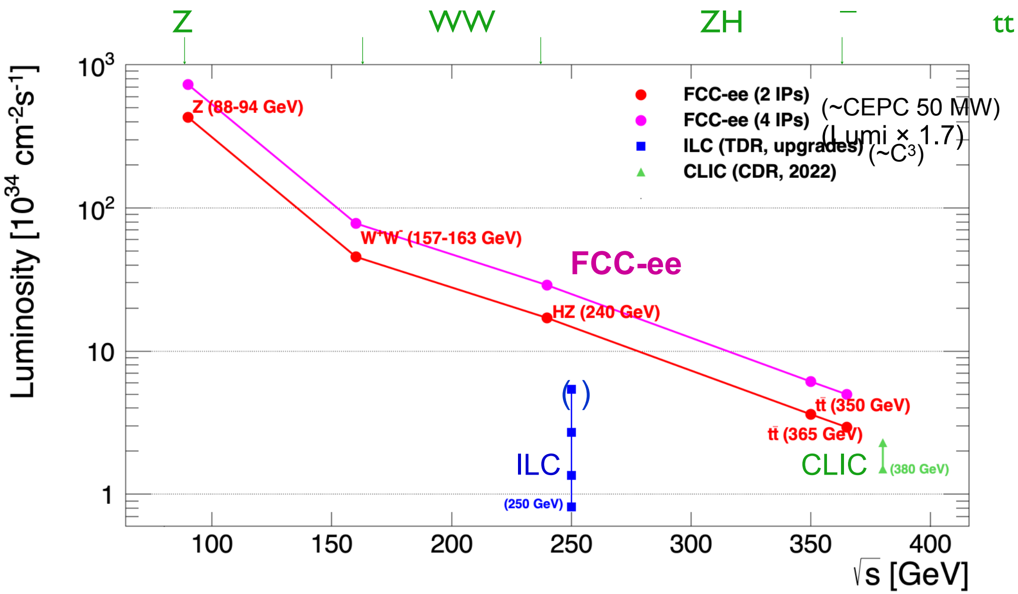
- Optimise the ultimate statistical sensitivity
- Identify and evaluate the limiting systematic uncertainties
- Establish detector requirements to match systematic uncertainties with statistical precision
    - Up to 4 interaction points, hence 4 detectors

Outline : quick overview of the physics, of the ongoing activities, and of opportunities, in :

- Higgs physics
- (non-Higgs) Precision measurements
- Physics at the intensity frontier
    - Direct searches for new physics
    - Flavour physics

THE UNIQUENESS OF FCC-ee

With respect to linear collider's 1st stage



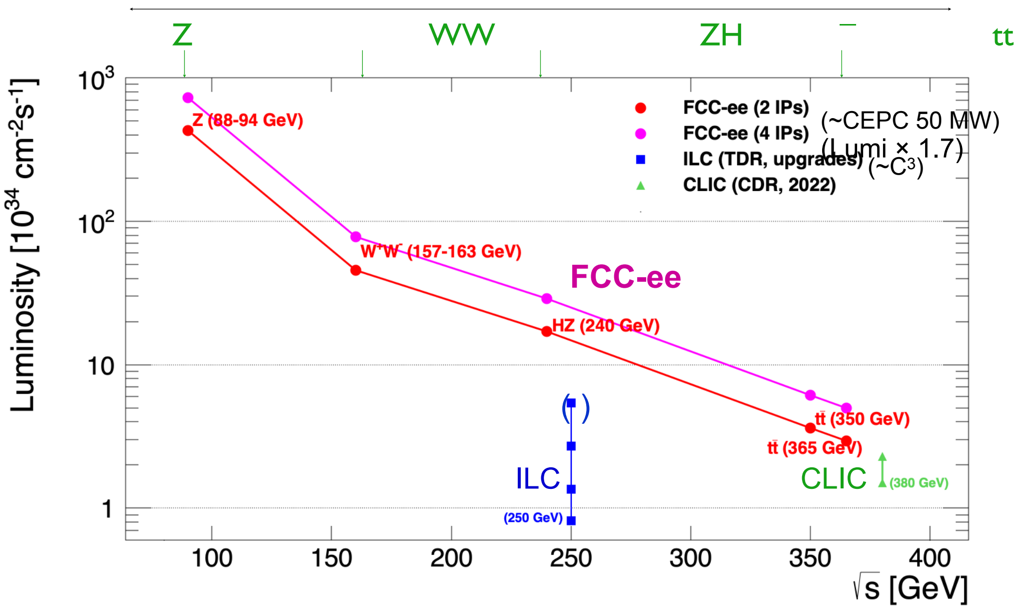
Slide from P. Janot

THE UNIQUENESS OF FCC-ee

With respect to linear collider's 1st stage

Optimal energy range for SM particles

Sharpen and challenge our knowledge of already existing physics



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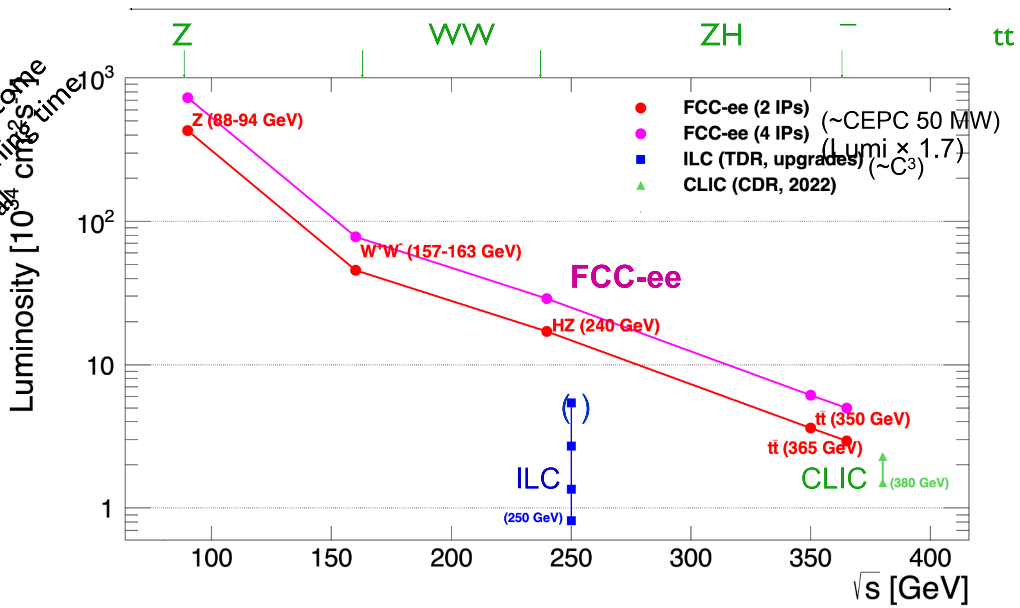
Highest luminosities

- Less running time for a given physics outcome
- Better physics outcome for a given running time
- Increase discovery potential



(~CEPC 50 MW)

(Lumi × 1.7)

$(\sim C^3)$

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LEP1 statistics in a few minutes

Detector calibration/alignment at all √s

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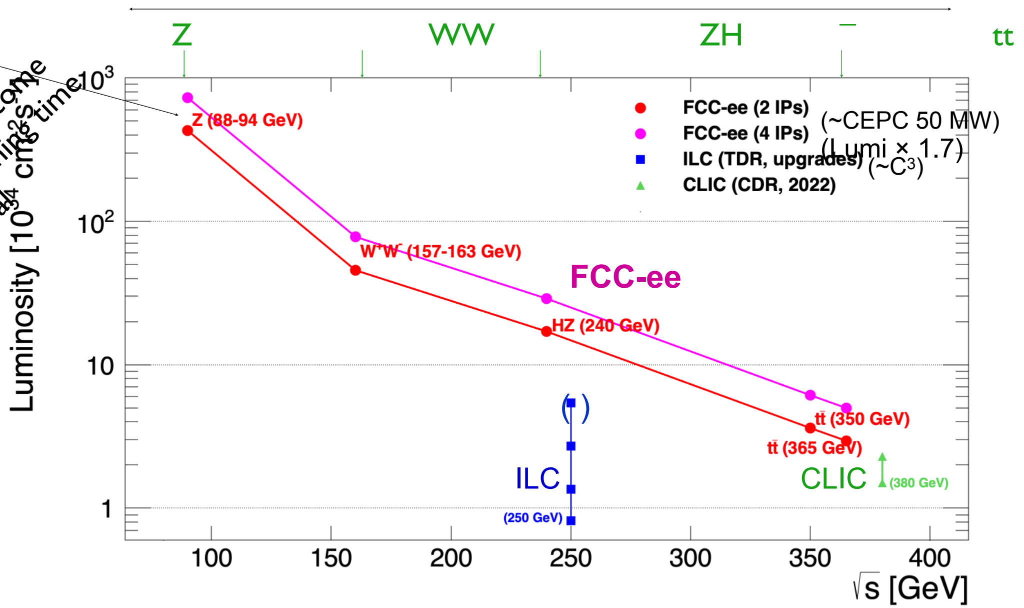

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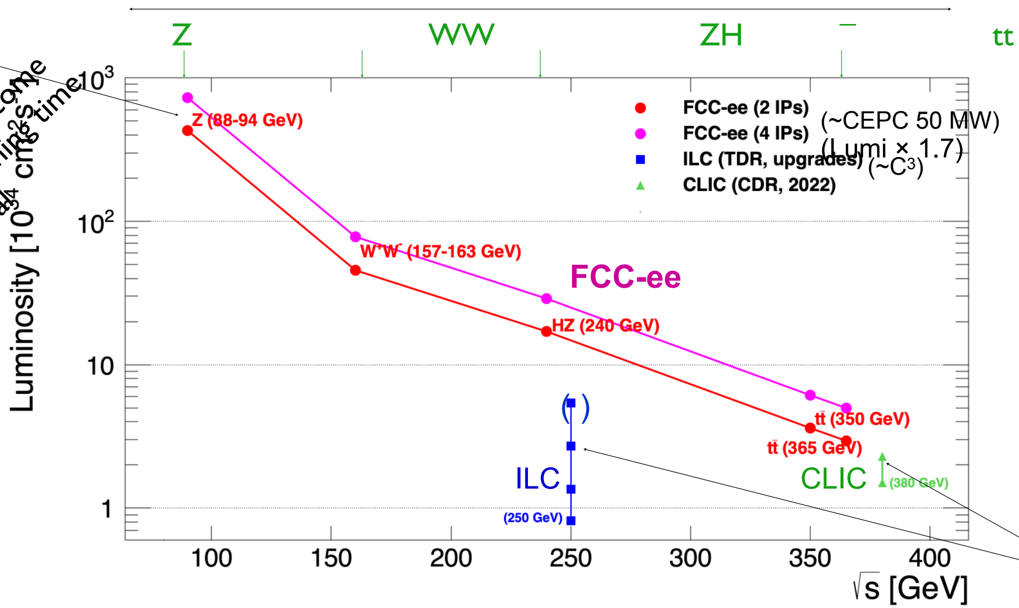

Motivates the competition

Luminosity is the name of the game

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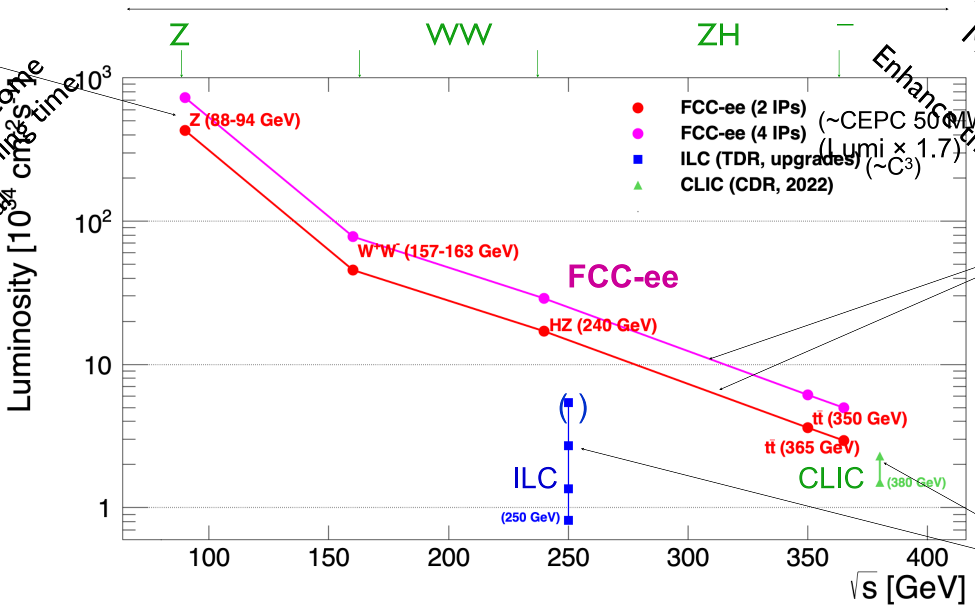
Serve up to 4 interaction points

Net overall gain in MW/ab^{-1} or CO2-eq/ab^{-1}
Essential redundancy for precision measurements
May satisfy all detector requirements
Increase discovery potential
Enhance the community (FCC/CERN clients)



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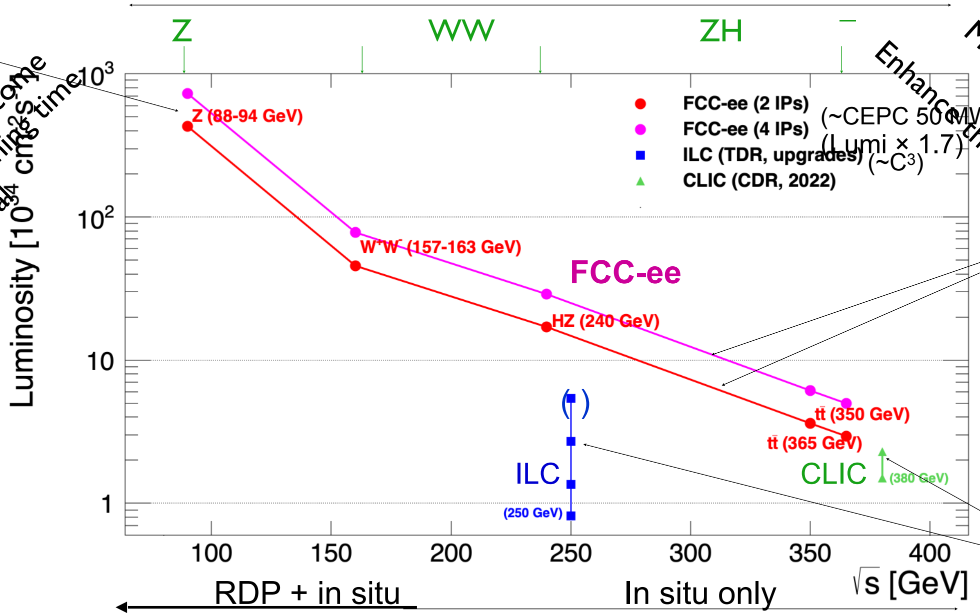

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Luminosity is the name of the game

Precise and continuous √s, √s spread, boost determination

Both with resonant depolarisation (RDP) and with collision events in up to four detectors

Essential for precision measurements

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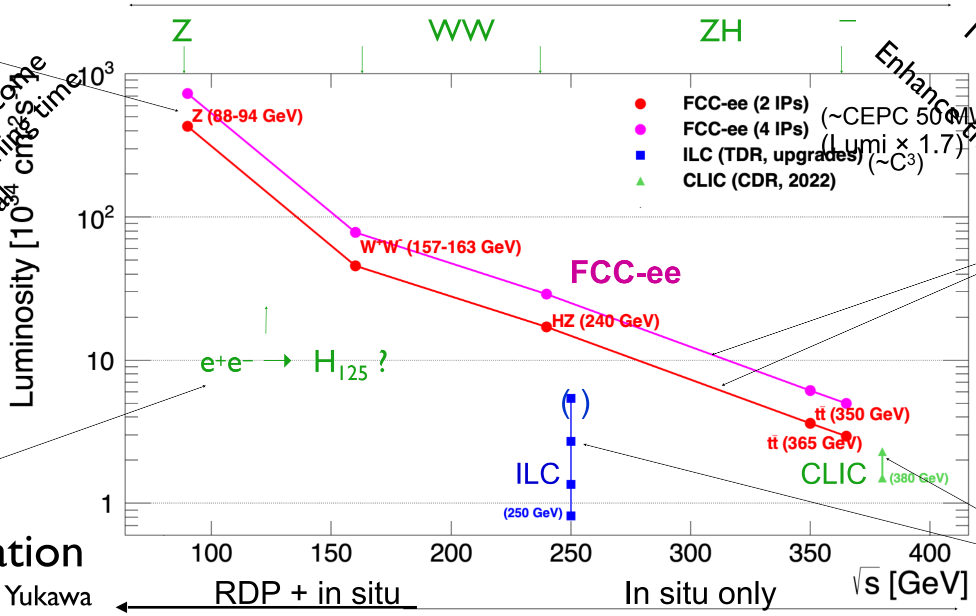

RDP + in situ

In situ only

√s Monochromatisation

Unique opportunity for electron Yukawa

Motivates the competition

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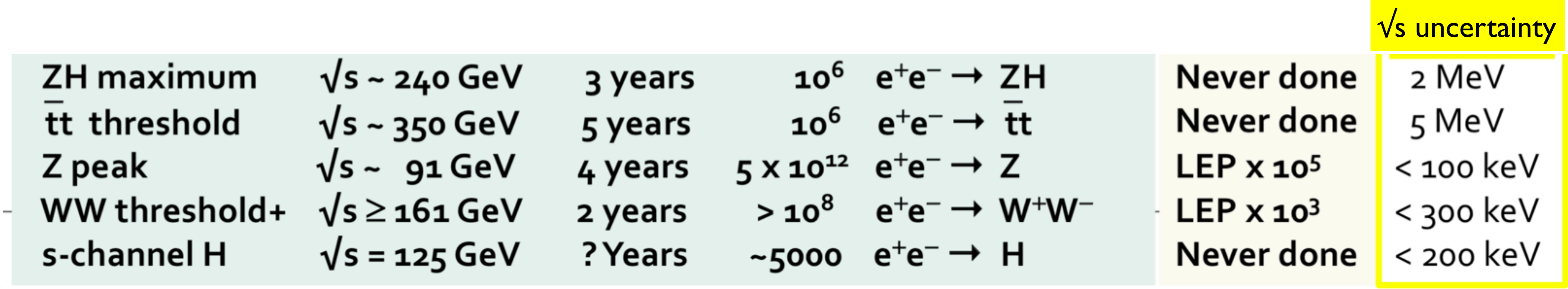
Slide from P. Janot

BASELINE RUN SCENARIO WITH 2IPs (FROM CDR)

- Numbers of events in 15 years, tuned to maximise the physics outcome:



						$\sqrt{s}$ uncertainty
ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s} \sim 350$ GeV	5 years	10^6	$e^+e^- \to t\bar{t}$	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

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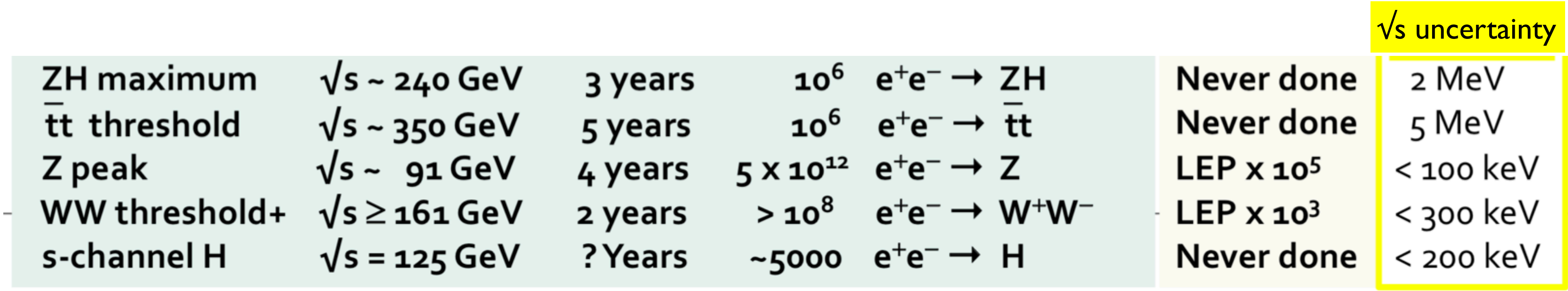

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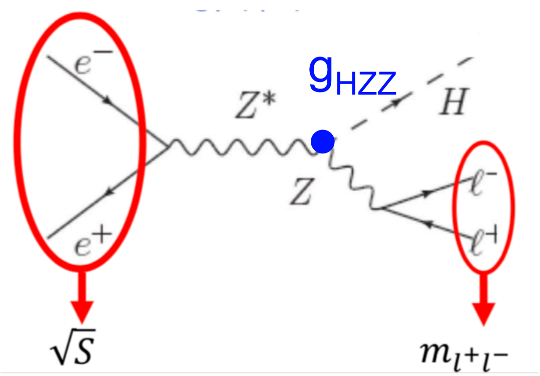
- Exact durations depend on a number of factors (to be studied by the FCCC in 2048-2063)
  - Overall duration: Are the FCC-hh magnets ready ? New physics in FCC-ee data ?
  - Step duration: What is the actual luminosity at each √s? How many IPs? Alternative physics optimization?

- Exact sequence of events is a multi-faceted issue (which can also be decided later)

FCC-ee as a Higgs factory



Key process: Higgsstrahlung $\sigma\,(ZH) \propto g^2_{HZZ}$

√s well known: ZH events tagged by the Z, without reconstructing the Higgs decay (recoil mass). Unique to lepton colliders.

Hence an absolute deterrmination on g_{HZZ} (indep. of Higgs decay mode).

Once g_{HZZ} is known: measure σ x BR for specific Higgs decays

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

- H → ZZ* provides Γ_H
- H → XX provides g_{HXX}

Hence a model-indep determination of all Higgs couplings.

FCC-ee prospects :

- HZZ coupling to the per-mil level, most other couplings < 1%
- *Ultimate precision on Hγγ, Hμμ and HZγ from FCC-hh (synergy with FCC-ee)*
- Self-coupling from precise measurement of σ(ZH) at 240 and 365 GeV
    - precision on λ of ~ 25% with 4 IPs at FCC-ee [to 3-8% at FCC-hh]
- $\sqrt{s} = m_H$: Electron Yukawa coupling: sensitivity close to the SM is at reach

Higgs measurements

Requirements on detector performance from Higgs physics: a priori already explored by ILC, but must be revisited :

- different environment (less beamstrahlung, no power-pulsing of electronics, etc)
- More ambitious goals on m_H (for ee → H) and on σ(ZH) (for self-coupling)
- Unique: possible run at the Higgs pole

Higgs analyses that are already covered :

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

For most of these analyses: see reports at the Krakow workshop

https://indico.cern.ch/event/1176398/

Higgs measurements: not covered yet

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

P. Azzi, E.Perez

Example: direct measurement of m_H

For a run at the Higgs pole: m_H must be known with a precision < 4 MeV (Γ_H).

mH from a fit to the recoil mass in Z(ll)H may not reach that precision.

→ complement with direct reconstruction of ZH → 4 jets

Z (and H) → hadrons or taus: cluster events to four jets and fix all jet velocities $\beta_i = p_i/E_i$

➔ **Determine all jet energies by solving (with a matrix inversion):**

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\ \beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\ \beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

followed by $m_H^{est} = m_{12} + m_{34} - m_Z$

+ template fits, bias understanding, combination, etc .

➔ **Can/should also try a full 5C kinematic fit (with E, p, m_Z constraints)**

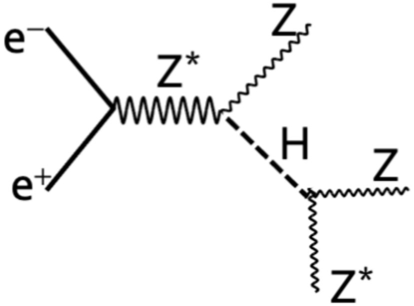
Calibration of the method on ee → ZZ → qqbb

➢ requirements on the jet angular resolutions, on the b-tagging efficiency and purity (and on the determination of the beam energy spread)

➢ Code for kinematic fits, could be used in other analyses.

Example: Higgs width

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



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

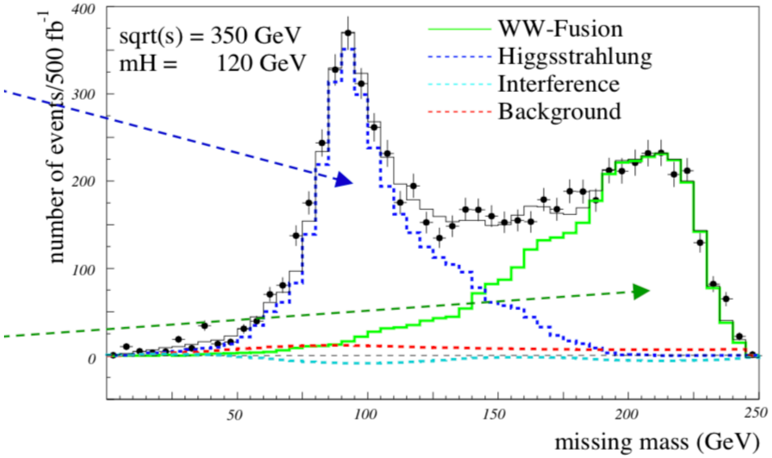
- From measurement of $\nu\nu$H(bb) events at 365 GeV :

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

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

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

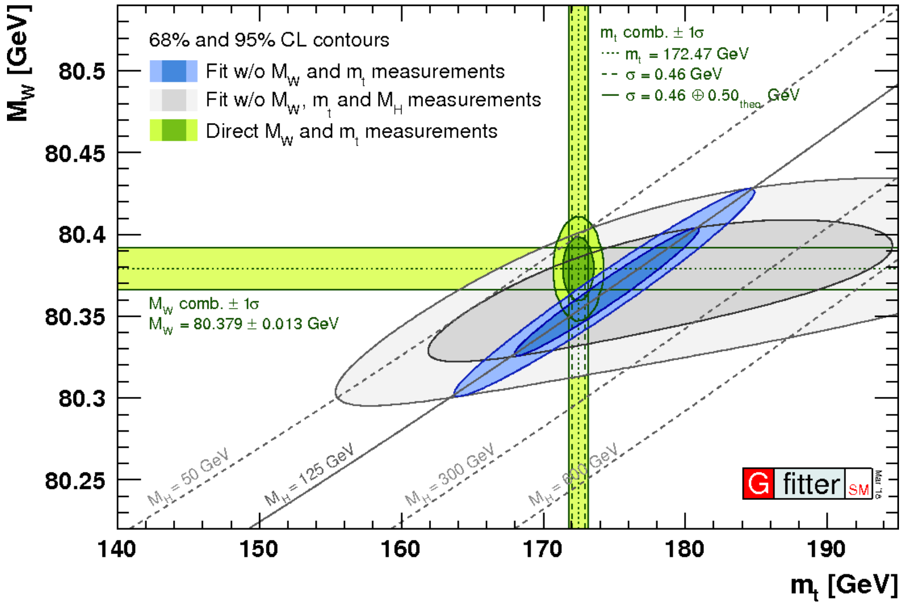
From early ILC studies



FCC-ee as an Electroweak factory

With highest luminosities at 91, 160 and 350-365 GeV: complete set of EW observables can be measured with a precision dramatically improved w.r.t. today.

With m_{top}, m_W and m_H fixed by measurements: the SM has nowhere to go !



Increased precision could show first hints of physics beyond the SM.

- Improve the direct determination of MW and Mtop
  - PDG 2020: MW to 12 MeV
- And the SM fit prediction for these quantities, e.g. :

$$m_W = 80.3584 \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{\text{theory}}\ \text{GeV} = 80.358 \pm 0.008_{\text{total}}\ \text{GeV},$$

Estimates from S.

Requires improved measurements of m_{top}, m_Z, $\alpha_{QED}(m^2_Z)$, α_S… and more generally all usual EWPO included in the EW fits.

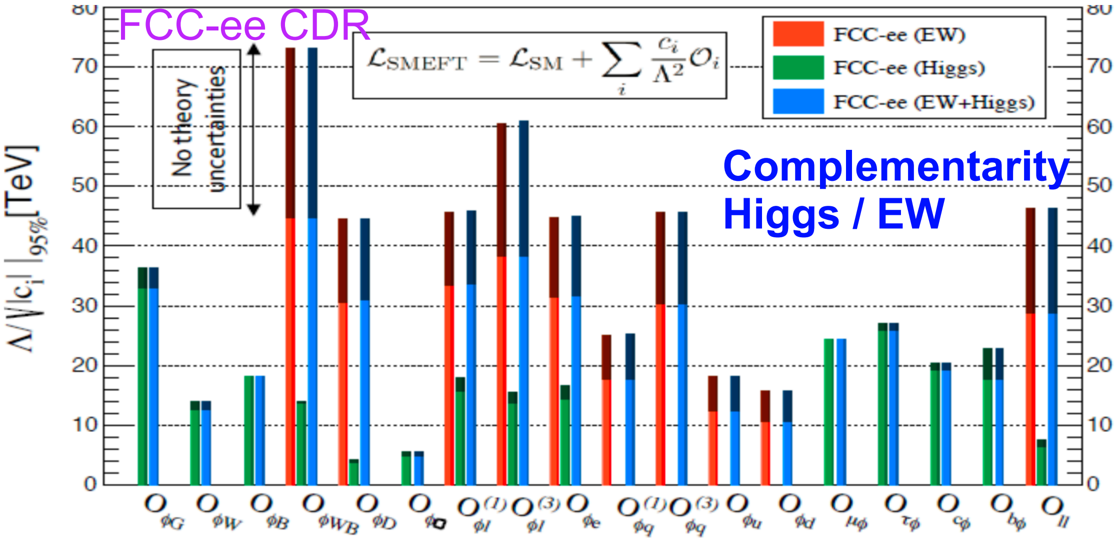
EW & QCD precision measurements: examples

(*) current guess

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

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

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



FCC-ee CDR

Complementarity Higgs / EW

In terms of weakly-coupled new physics: FCC-ee precision corresponds to sensitivity on Λ_{NP} up to 70 TeV, anticipating what FCC-pp would focus on.

E.Perez

Precision measurements

For many measurements. :

- Early studies (CDR) for a first estimate of the stat uncertainty & main systematics
  - Often made with simple tools

- Some more evolved studies were started with simulations of an FCC-ee detector, but manpower left. E.g. :
  - Measurement of the W mass (PhD thesis)
  - Determination of EW top couplings (master thesis)

- Very large room for contributions !
  - Only one analysis currently ongoing
    - A_{FB} of b quarks (one group only)
  - Starting point :
    - reproduce the early studies (with state of the art MCs and simulations, realistic beam conditions, with backgrounds, etc)
    - And/or reproduce the LEP analyses

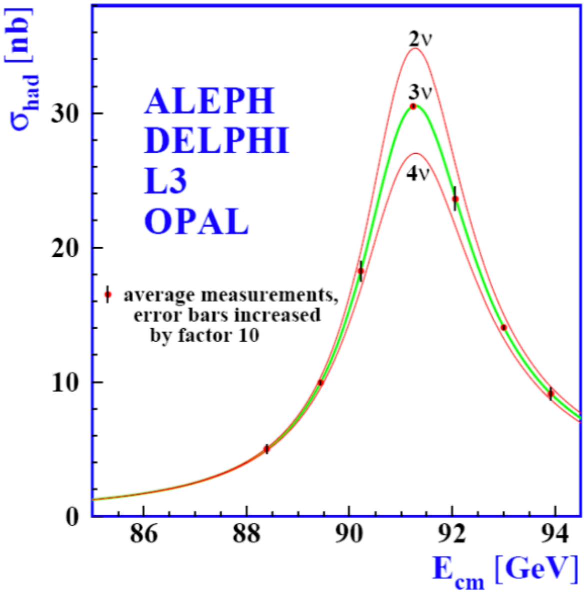
- Next page: a list of “open” studies, a few being illustrated in the following slides.

EW measurements currently uncovered

	Measurement	**Requirements**
Z peak	Total width of the Z	scale (magnetic field) stability
	Rb, Rc, (A_{FB})	Flavour tagging, acceptance, QCD corrections
	Ratio Rl = Gamma_had / Gamma_l	Geometrical acceptance for lepton pairs
	Tau polarisation	ECAL granularity
	A_{FB} (muons)	QED corrections
	Luminosity from diphoton events	e/gamma separation, gamma acceptance
WW threshold	Coupling of Z to nu_e	Photon energy resolution, acceptance, track eff
	$\sigma(ee \to WW)$ and MW (threshold scan ; direct reco also above threshold)	$\sqrt{s}$ determination, bckgd control; angles, kinem. fits
	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
ttbar	Top properties from threshold scan	Jet reco, b-tagging, kine fits
	EW couplings of the top	Jet reco, b-tagging, kine fits

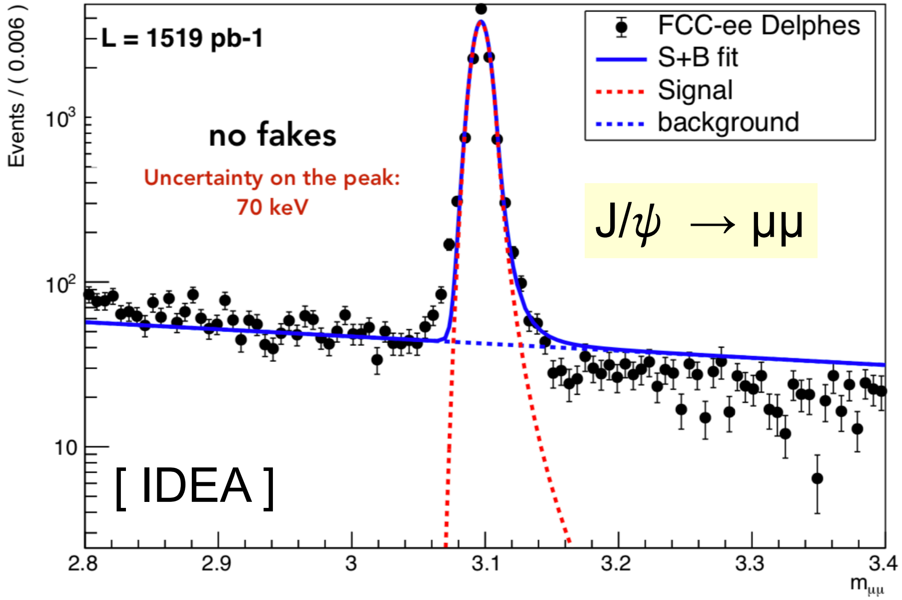
Example: Determination of the Z width

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



Can be controlled via the direct measurement of $M_{\mu\mu}$ in dimuon events : compare the peak positions at the different √s points.

- σ($M_{\mu\mu}$) : 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}



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

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

post-doc left, but code in place, should be easy to take over !

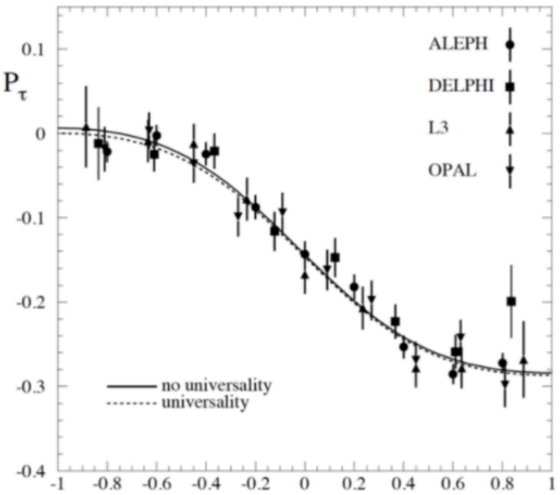
Example: Tau polarisation

Dedicated talk at Krakow, from JC Brient (ALEPH expert)

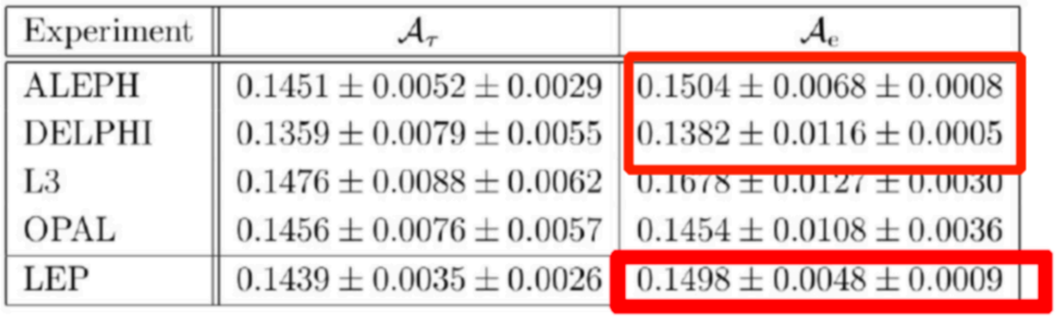
- Tau polarisation has a central role at the FCC-ee: crucial ingredient for A_e, $sin^2\theta_{eff}$ at a circular collider
  - Desired precision of few x10-6 on $sin^2\theta_{eff}$, similar to that from $A_{FB}^{\mu\mu}$ but model independent
- Very large tau statistics ($\approx 1.5 \times 10^{11}$). 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 τ→ρντ
- Fit of $\mathscr{P}(\tau)$ vs cosθ : Ae much less affected by syst. than A. Could achieve $\Delta(sin^2\theta_{eff}) \sim 3 \cdot 10^{-6}$

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

Measured P_τ vs $\cos\theta_{\tau^-}$



Crucial to have excellent $\pi^{\pm}/\pi^{0}$ separation (for the rho channel), hence ECAL granularity requirement



Experiment	$\mathcal{A}_\tau$	$\mathcal{A}_e$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$	$0.1504 \pm 0.0068 \pm 0.0008$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$	$0.1382 \pm 0.0116 \pm 0.0005$
L3	$0.1476 \pm 0.0088 \pm 0.0062$	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$	$0.1454 \pm 0.0108 \pm 0.0036$
LEP	$0.1439 \pm 0.0035 \pm 0.0026$	$0.1498 \pm 0.0048 \pm 0.0009$

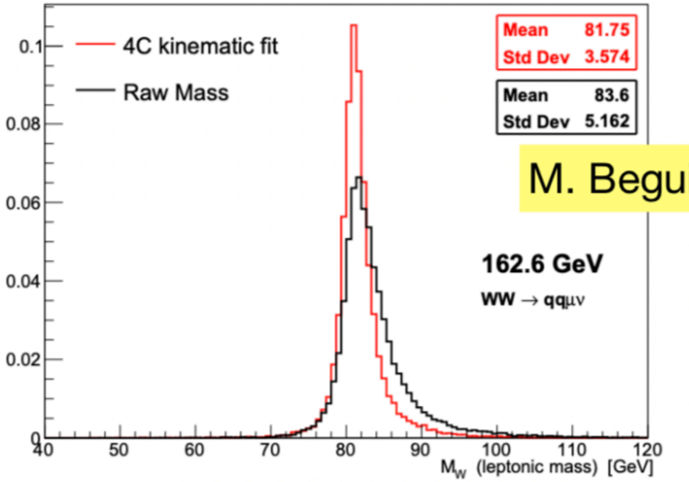
Example: W mass direct reco

- 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:

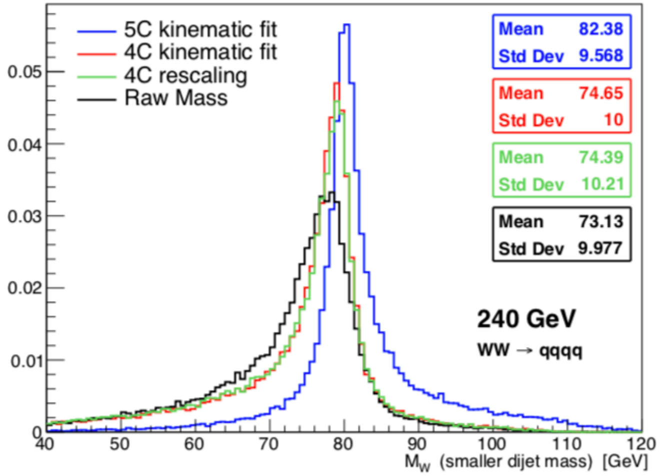
- Statistical and systematic uncertainties with templates fit
- W hadronic decay modelling systematics
- Exploiting also ZZ and Zγ events for constraints and calibration
- Thesis of M. Beguin available as starting point

Semi-leptonic channel



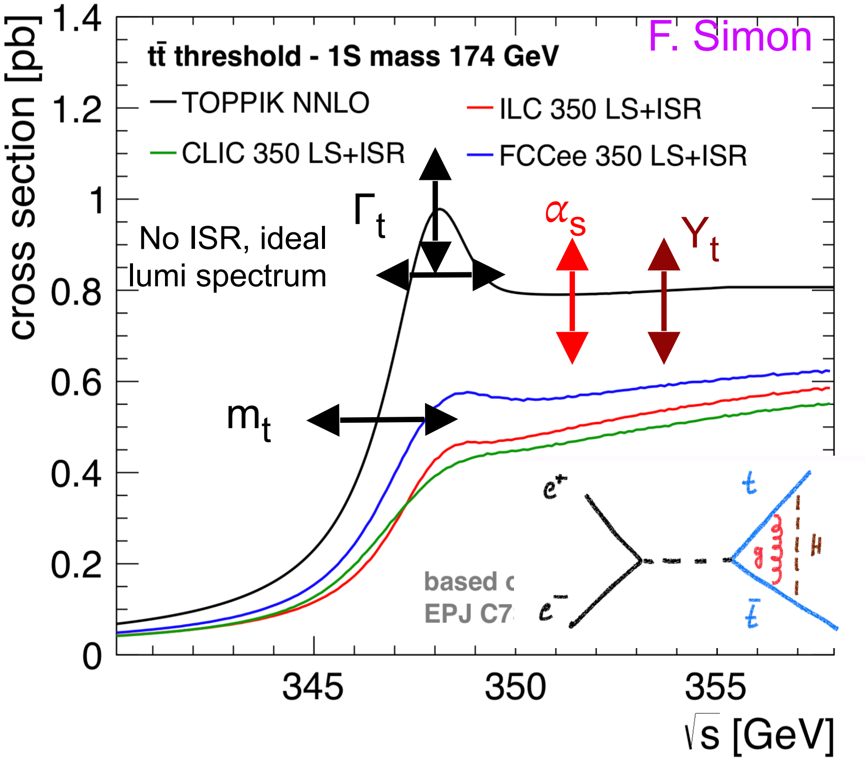
M. Beguin

Fully hadronic channel



Example: Top mass and width, Yukawa coupling

Short scan at the tt threshold. Determines m_{top} in a theoretically clean way, Γ_{top}, and the Yukawa coupling of the top.



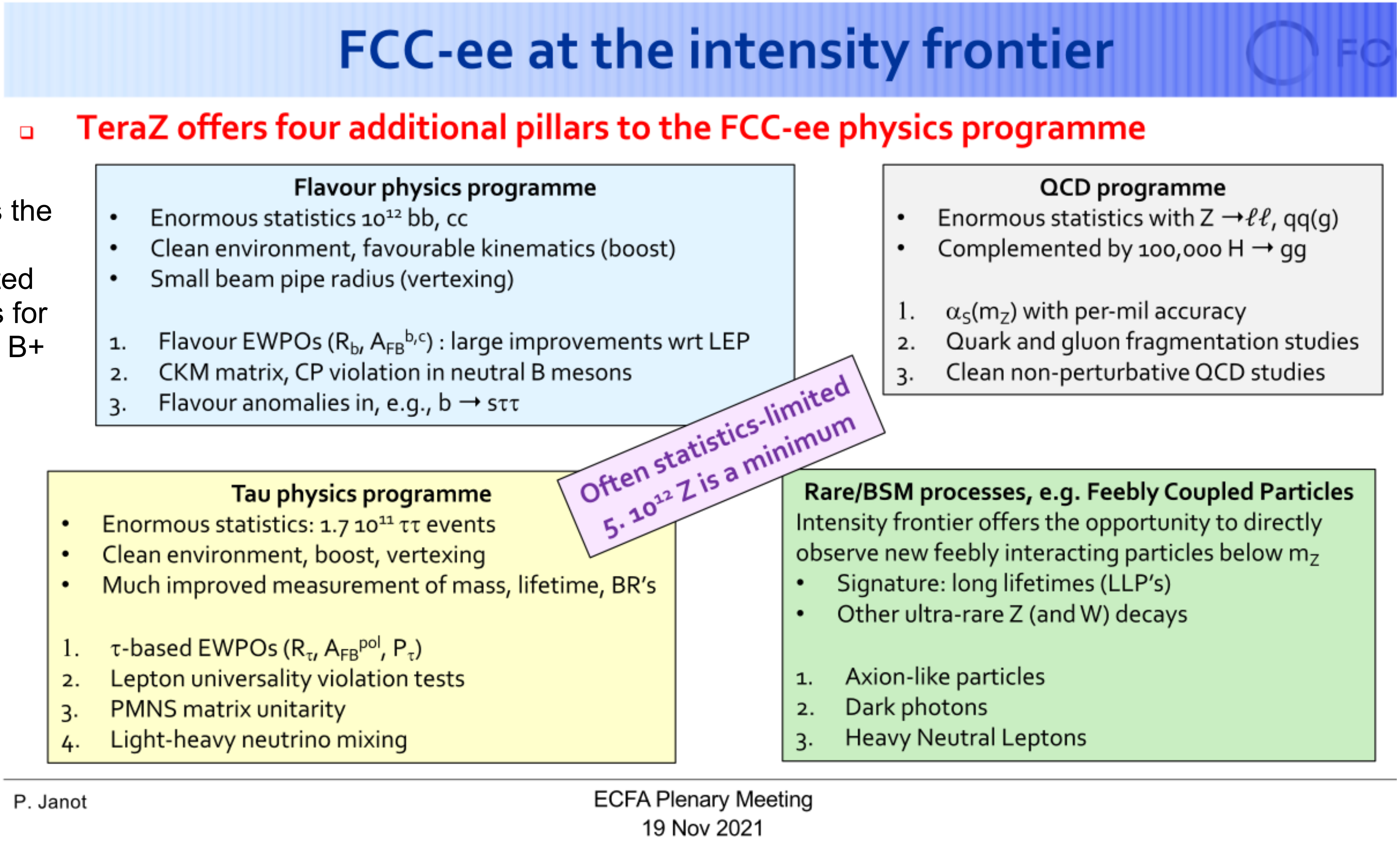
Threshold shape affected by ISR & lumi spectrum (= main difference between the ee colliders).

Measure σ at a few points around $2m_{top}$, e.g. 200 fb^{-1}

- M_{top} determined with a stat uncertainty of 15-20 MeV (theory syst ~ 40 MeV)
- y_{top} to about 10% - 20%

Possible project:
Optimise the scan, i.e. √s points & luminosity at each point) - re-optimisation of the scan made recently for CLIC conditions showed a sizable improvement !)

15 times the BelleII anticipated statistics for B0s and B+



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

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

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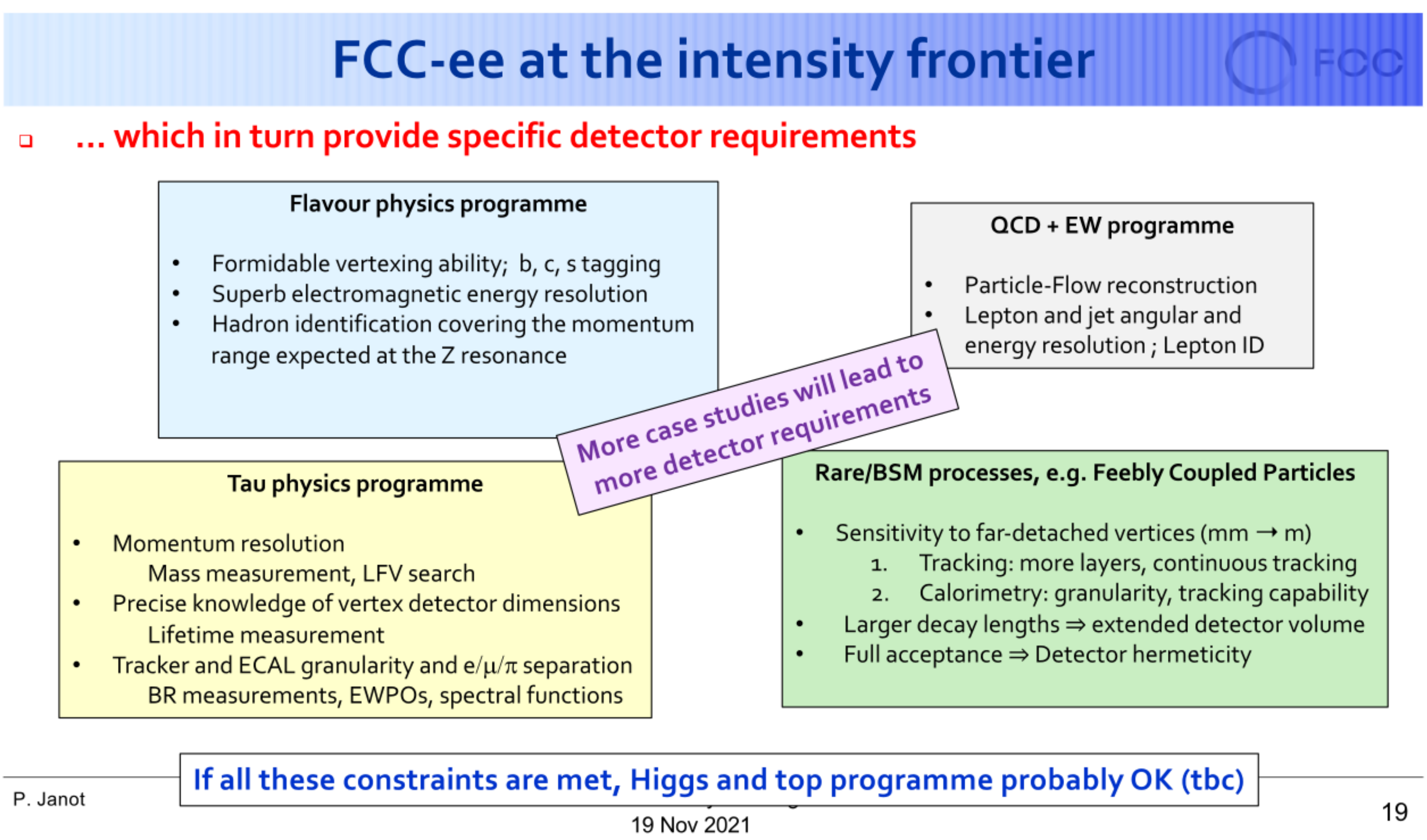


FCC-ee at the intensity frontier

- **... 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)

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^0_s	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

Analyses in Flavour physics

Ongoing analyses in b physics :

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

Many interesting opportunities in tau physics.
- Existing FastSim samples of limited use for several tau studies
- But FullSim is coming up

Looking for interested contributors.

Tau lifetime. Flagship measurement, work is starting by one of the conveners (A. Lusiani). Dedicated talk here: https://indico.cern.ch/event/1176398/contributions/5207209/

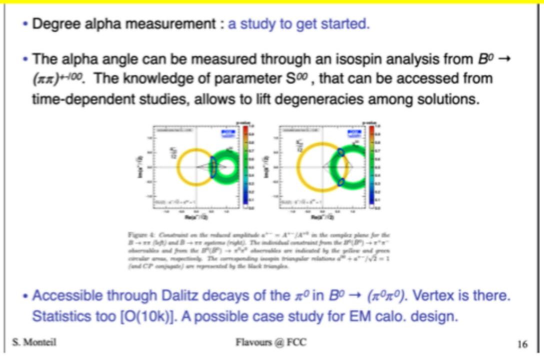
Flavour physics analyses currently uncovered

	Measurement	**Requirements**
Z peak	CP violation in Bs → ΦΦ	PID, vertex, track resolution
	B0 → π0π0 (→ eeγ)	Low energy γ ‘s in jets (ECAL resolution and granularity)
	Bs → τ τ	Vertexing
	Meas of γ from B+ → DK+	Ks reconstruction
	τ → 3μ, τ → μγ	resolutions
	τ lifetime	Alignment, scale of vertex detector,
	τ BRs	Lepton ID, PID, e/pi separation
	τ mass	Track reco & resolution (in multi-track collimated environment)
	Charm physics	
	Masses, spectroscopy, exotics…	
WW	EW parameters, exclusive modes (Vcb, etc)	Flavour tagging

P. Azzi, E.Perez

Example: CP study of B → $\pi 0 \pi 0$

Monteil @FCCWeek



- Degree alpha measurement : a study to get started.
- The alpha angle can be measured through an isospin analysis from $B^0 \rightarrow (\pi\pi)^{+-/00}$. The knowledge of parameter S^{00} , that can be accessed from time-dependent studies, allows to lift degeneracies among solutions.
- Accessible through Dalitz decays of the π^0 in $B^0 \rightarrow (\pi^0\pi^0)$. Vertex is there. Statistics too [O(10k)]. A possible case study for EM calo. design.

S. Monteil Flavours @ FCC 16

- Relevant for the angle α is the measurement of the time-dependent CP asymmetries in $B^0 \rightarrow \pi^0\pi^0$. It can be achieved with Dalitz decays.

- We expect 2500 $B^0 \rightarrow \pi^0(\rightarrow \gamma\gamma)\pi^0(\rightarrow e^+e^-\gamma)$ with efficiency for $\pi^0 \rightarrow \gamma\gamma$ reco such as LEP -> improve efficiency with ECAL design
- Use the electron for the vertex information to extract the time dependence

A very interesting study that needs to get started !

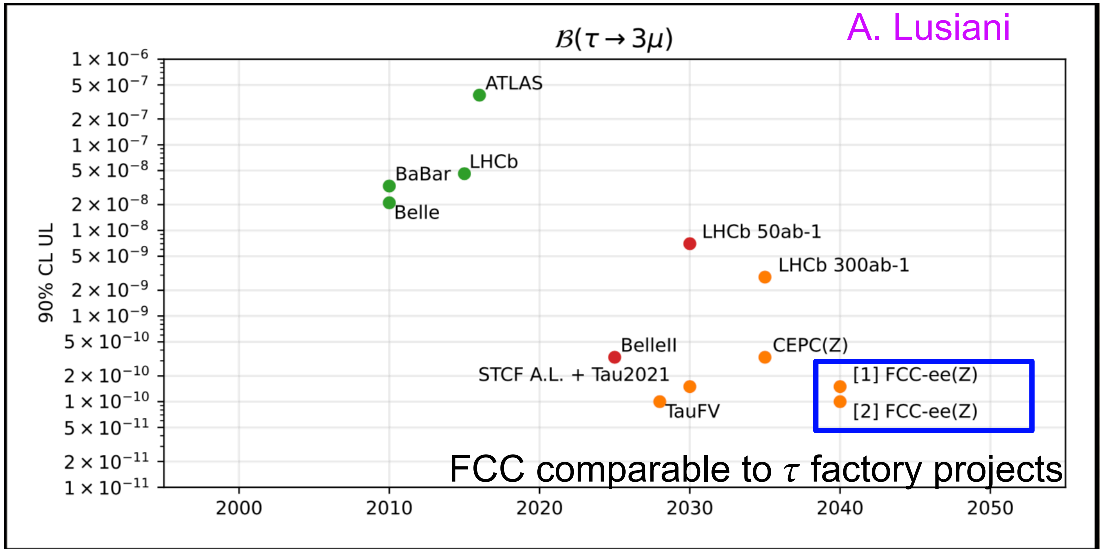
Example: Lepton Flavour Violating decays with taus

$\tau \rightarrow 3\mu$

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

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

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



FCC comparable to τ factory projects

Consolidate the guessed sensitivity shown above by a full analysis, including simulated backgrounds (mostly fakes from tau -> 3pi nu decays).

Starting point: an exercise was set up for this study in the last SW tutorial, see https://hep-fcc.github.io/fcc-tutorials/fast-sim-and-analysis/fccanalyses/doc/starterkit/FccFastSimVertexing/

Direct searches for new particles

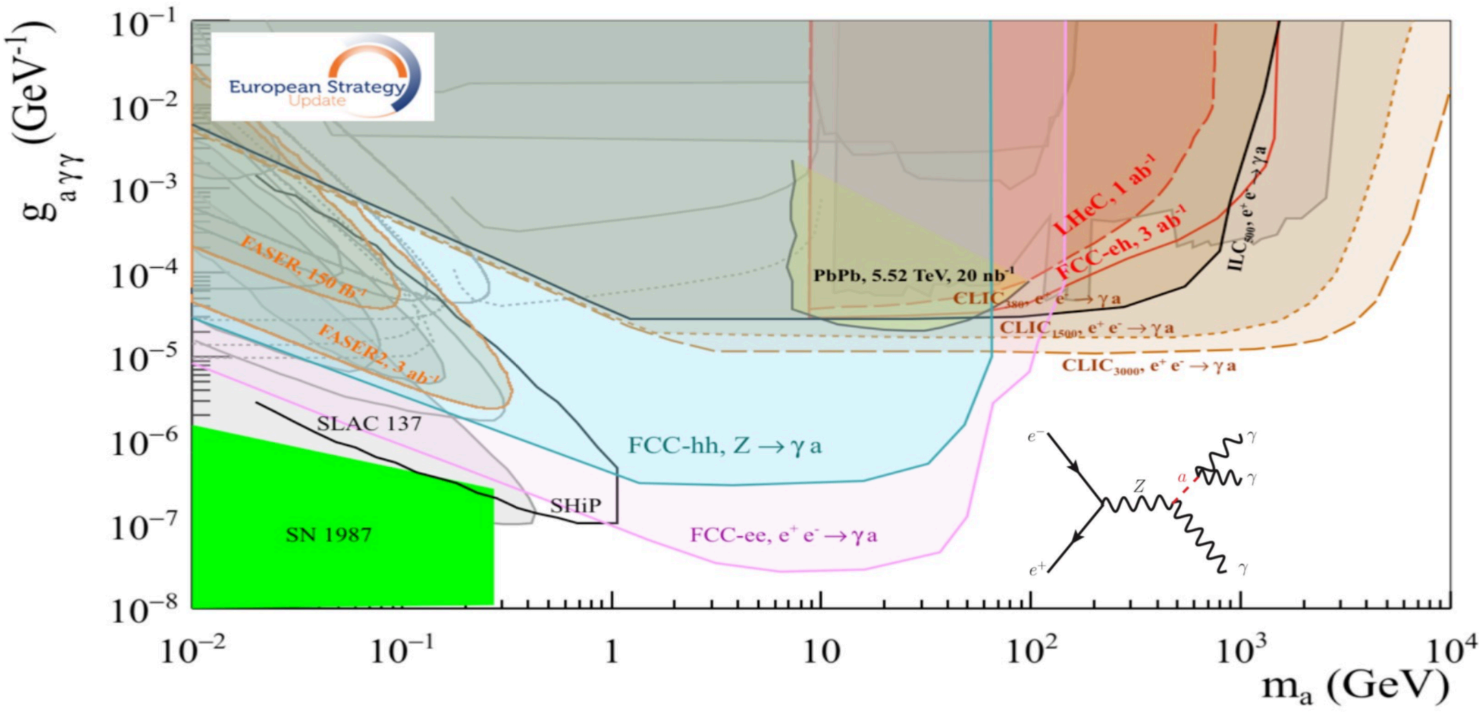
Areas with active analyses :

- Exotic particles produced at 91 GeV:
  - Heavy Neutral Leptons (ee → νN)
  - Axion-like particles / dark photons (ee → γa or $\gamma\gamma_D$)
- Exotic Higgs decays to LLPs

Large phase space to cover, different signatures, large range of decay lengths etc: ready for more people to step in !

See reports at the Krakow meeting:

- https://indico.cern.ch/event/1176398/contributions/5208459/attachments/2581524/4452667/LLPs_FCCPhysicsWorkshop2023_Ripellino.pdf
- https://indico.cern.ch/event/1176398/contributions/5208460/attachments/2581820/4453258/Kulkarni_FCC_week_Krakow.pdf

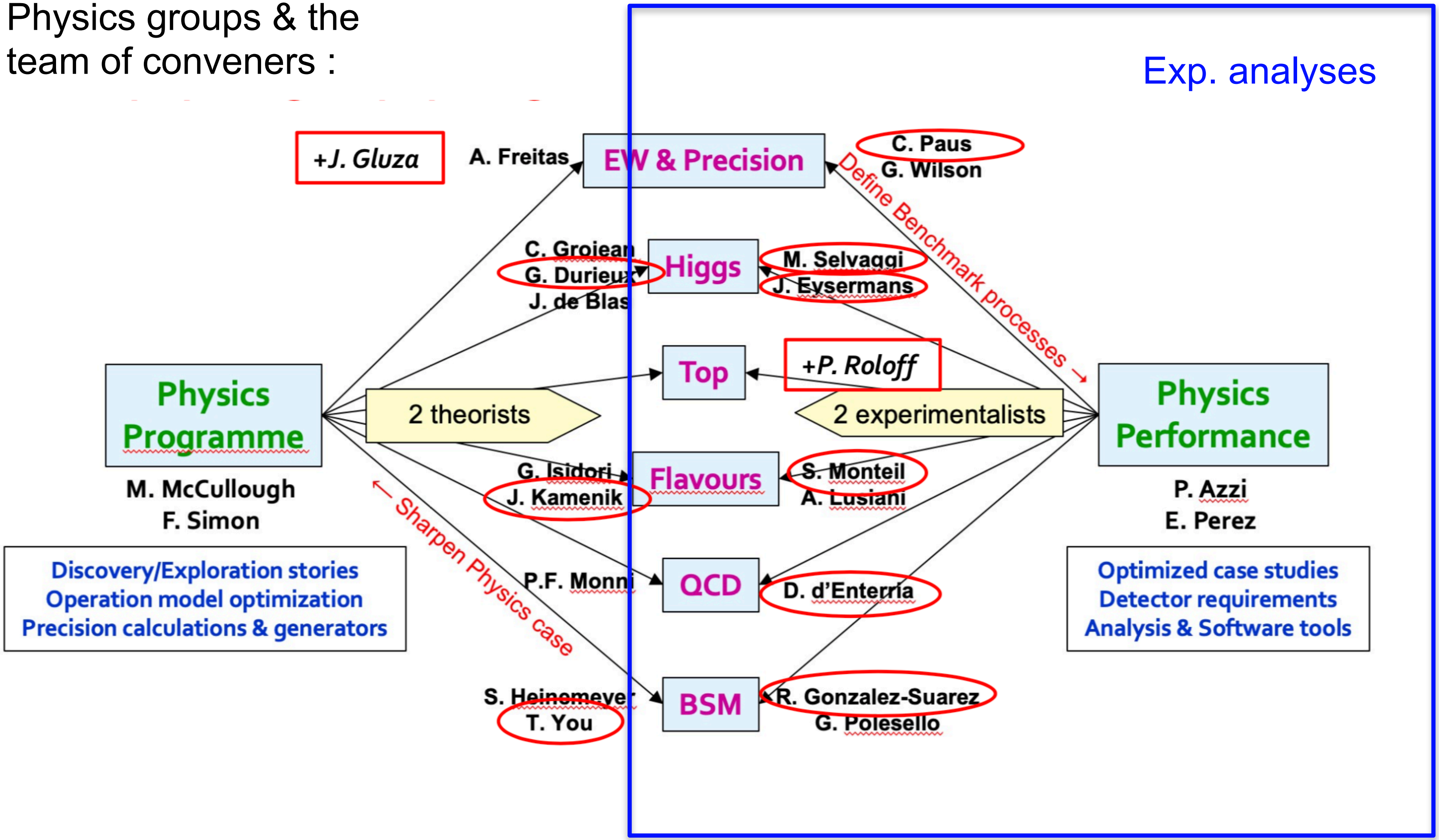


ALPS

E.Perez

How to start exp. analyses / whom to contact

Physics groups & the
team of conveners :



Exp. analyses

Physics Programme

M. McCullough
F. Simon

Discovery/Exploration stories
Operation model optimization
Precision calculations & generators

2 theorists

← Sharpen Physics case

+J. Gluza

A. Freitas — **EW & Precision** — C. Paus, G. Wilson

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

Top — *+P. Roloff*

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 →

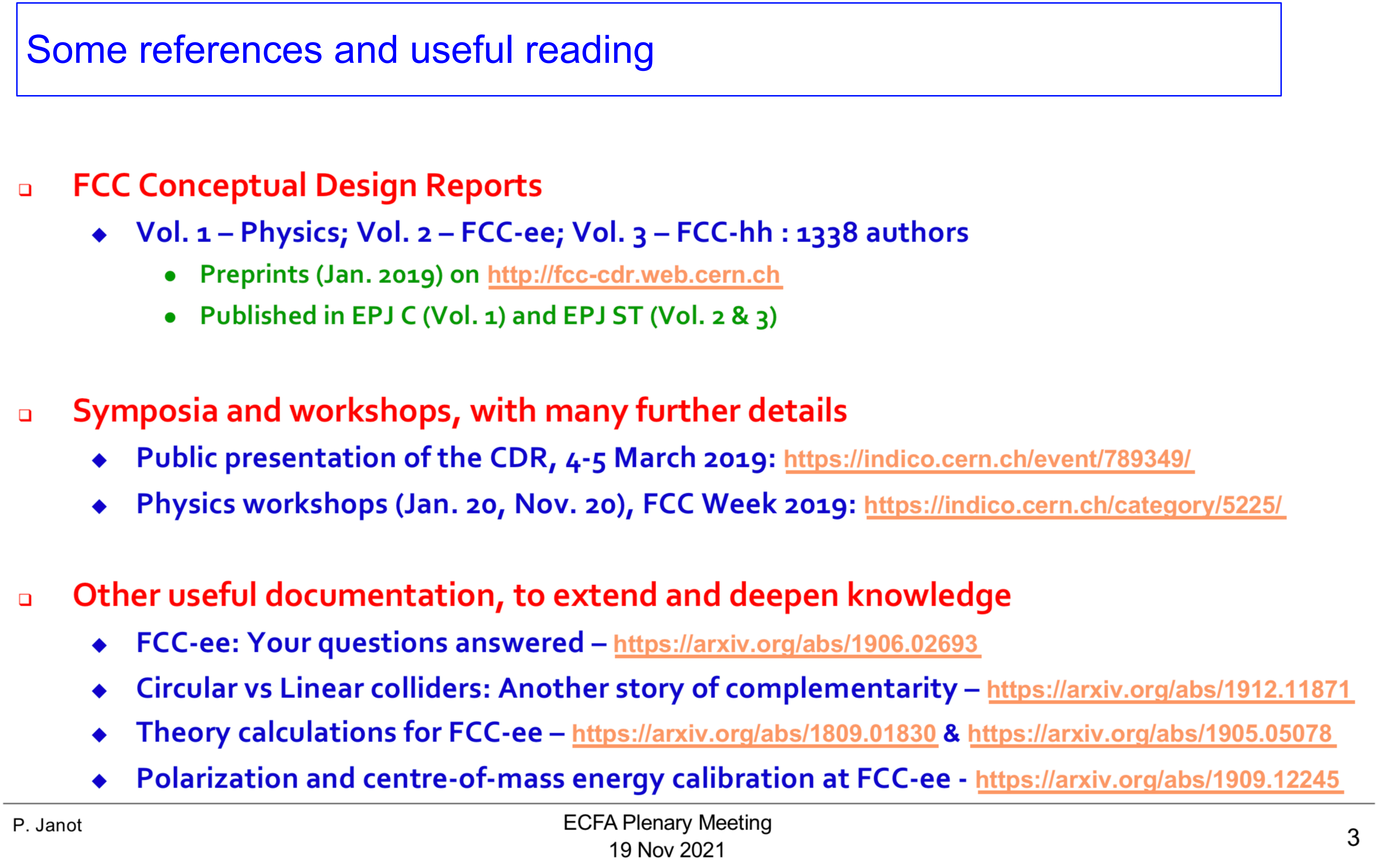
2 experimentalists

Physics Performance

P. Azzi
E. Perez

Optimized case studies
Detector requirements
Analysis & Software tools

(Slide taken from a summary at the June 2022 FCC week. red ellipses = people who gave a talk there)



Some references and useful reading

- **FCC Conceptual Design Reports**
  - Vol. 1 – Physics; Vol. 2 – FCC-ee; Vol. 3 – FCC-hh : 1338 authors
    - Preprints (Jan. 2019) on http://fcc-cdr.web.cern.ch
    - Published in EPJ C (Vol. 1) and EPJ ST (Vol. 2 & 3)
- **Symposia and workshops, with many further details**
  - Public presentation of the CDR, 4-5 March 2019: https://indico.cern.ch/event/789349/
  - Physics workshops (Jan. 20, Nov. 20), FCC Week 2019: https://indico.cern.ch/category/5225/
- **Other useful documentation, to extend and deepen knowledge**
  - FCC-ee: Your questions answered – https://arxiv.org/abs/1906.02693
  - Circular vs Linear colliders: Another story of complementarity – https://arxiv.org/abs/1912.11871
  - Theory calculations for FCC-ee – https://arxiv.org/abs/1809.01830 & https://arxiv.org/abs/1905.05078
  - Polarization and centre-of-mass energy calibration at FCC-ee - https://arxiv.org/abs/1909.12245

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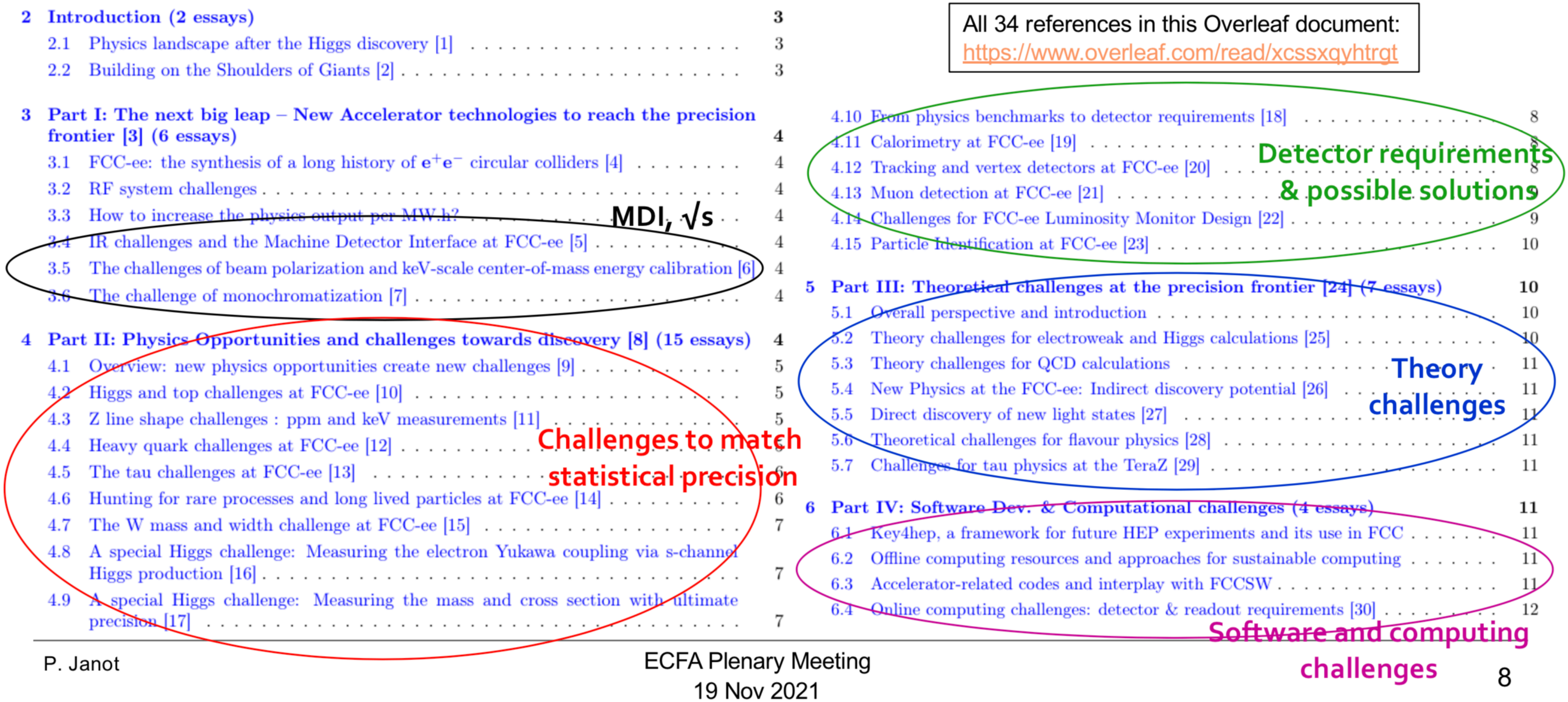
Some useful reading beyond the CDR

- **EPJ+ special issue "A future Higgs and EW Factory: Challenges towards discovery"**

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

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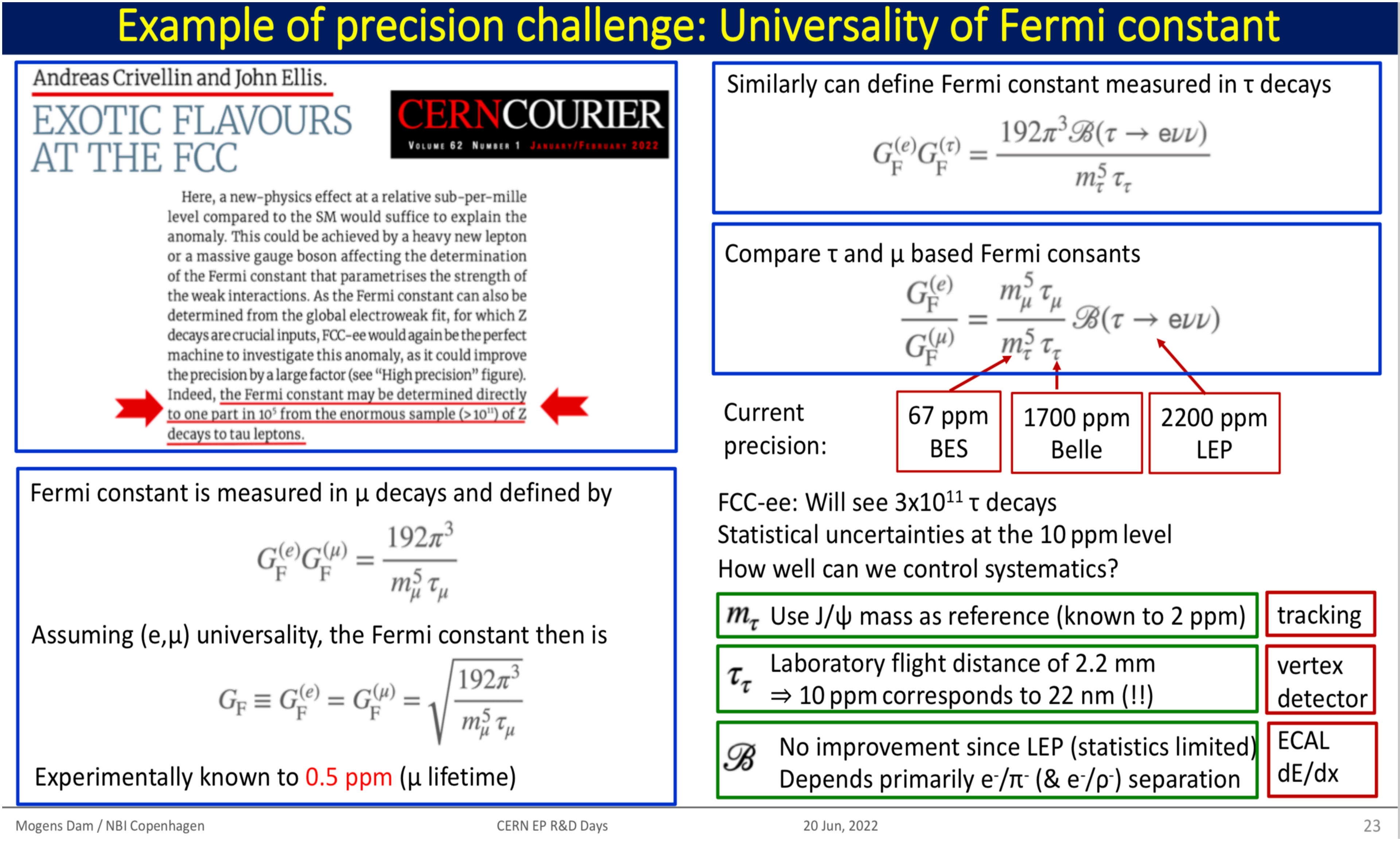
Backup

Example: Tau lifetime, BRs (and mass)



Example of precision challenge: Universality of Fermi constant

Andreas Crivellin and John Ellis.

EXOTIC FLAVOURS AT THE FCC

CERNCOURIER Volume 62 Number 1 January/February 2022

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

Fermi constant is measured in μ decays and defined by

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

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

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

Experimentally known to 0.5 ppm (μ lifetime)

Similarly can define Fermi constant measured in τ decays

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

Compare τ and μ based Fermi consants

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

Current precision:

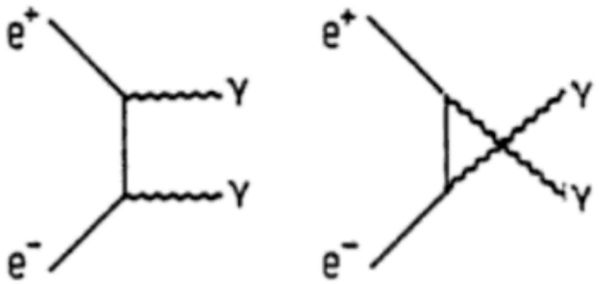
67 ppm BES	1700 ppm Belle	2200 ppm LEP

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

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

Mogens Dam / NBI Copenhagen CERN EP R&D Days 20 Jun, 2022 23

Alternative measurement of the luminosity : ee $\longrightarrow \gamma\gamma$ at large angles



- Pure QED process (at LO)
- Well controlled theoretically

Much smaller σ than small angle Bhabhas, but statistics still adequate for a precision of 10^{-4}

Example:

θ_{min} = 20 deg

Huge contamination from $e^+e^- \longrightarrow e^+e^-$ before any id cut (20 - 100x signal)

Energy	Process	Cross Section	Large angle $e^+e^- \rightarrow \gamma\gamma$	Large angle $e^+e^- \rightarrow e^+e^-$
90 GeV	$e^+e^- \rightarrow Z$	40 nb	0.039 nb	2.9 nb
160 GeV	$e^+e^- \rightarrow W^+W^-$	4 pb	15 pb	301 pb
240 GeV	$e^+e^- \rightarrow ZH$	0.2 pb	5.6 pb	134 pb
350 GeV	$e^+e^- \rightarrow tt$	0.5 pb	2.6 pb	60 pb

Need a good control of the e/γ separation (γ conversions, e $\longrightarrow \gamma$ fake rate).

e.g. with ε (γ id) = 99% and fake(e $\longrightarrow \gamma$) = 1%, would need to know the γ id inefficiency to the % level and the fake rate to a few per-mille.

Worth to take a closer look – systematics completely different from small angle Bhabhas (and no beam induced effect !)