The Future Circular Colliders project: a long term vision for particle physics — with a focus on flavour physics.

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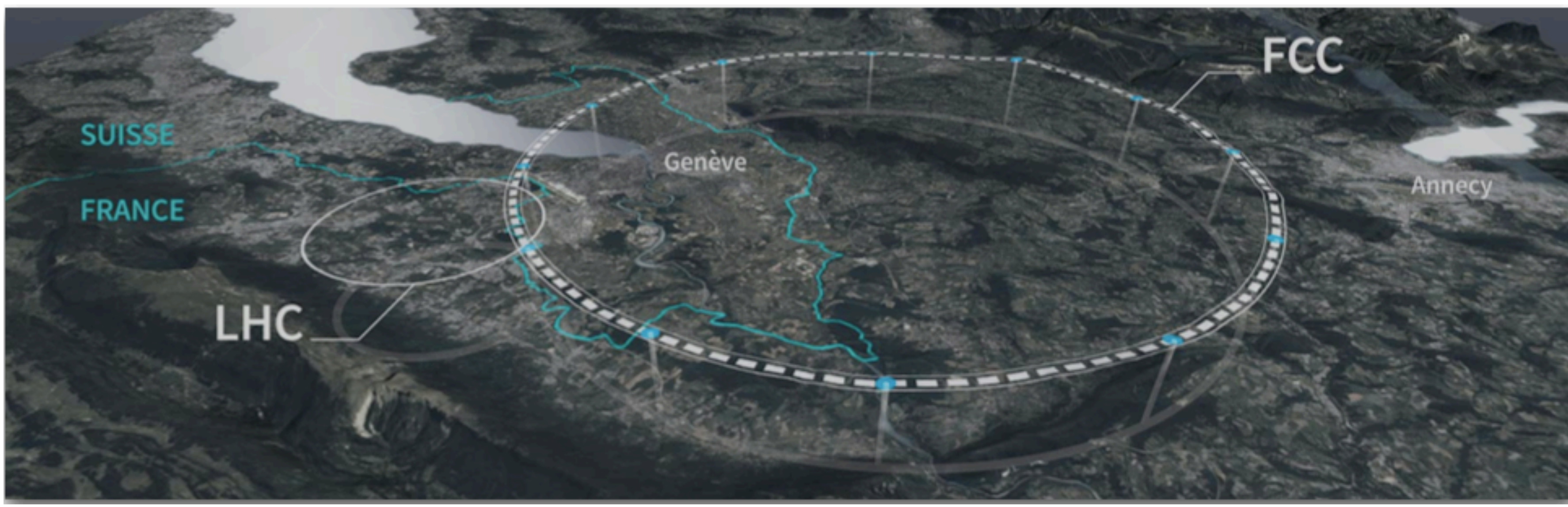
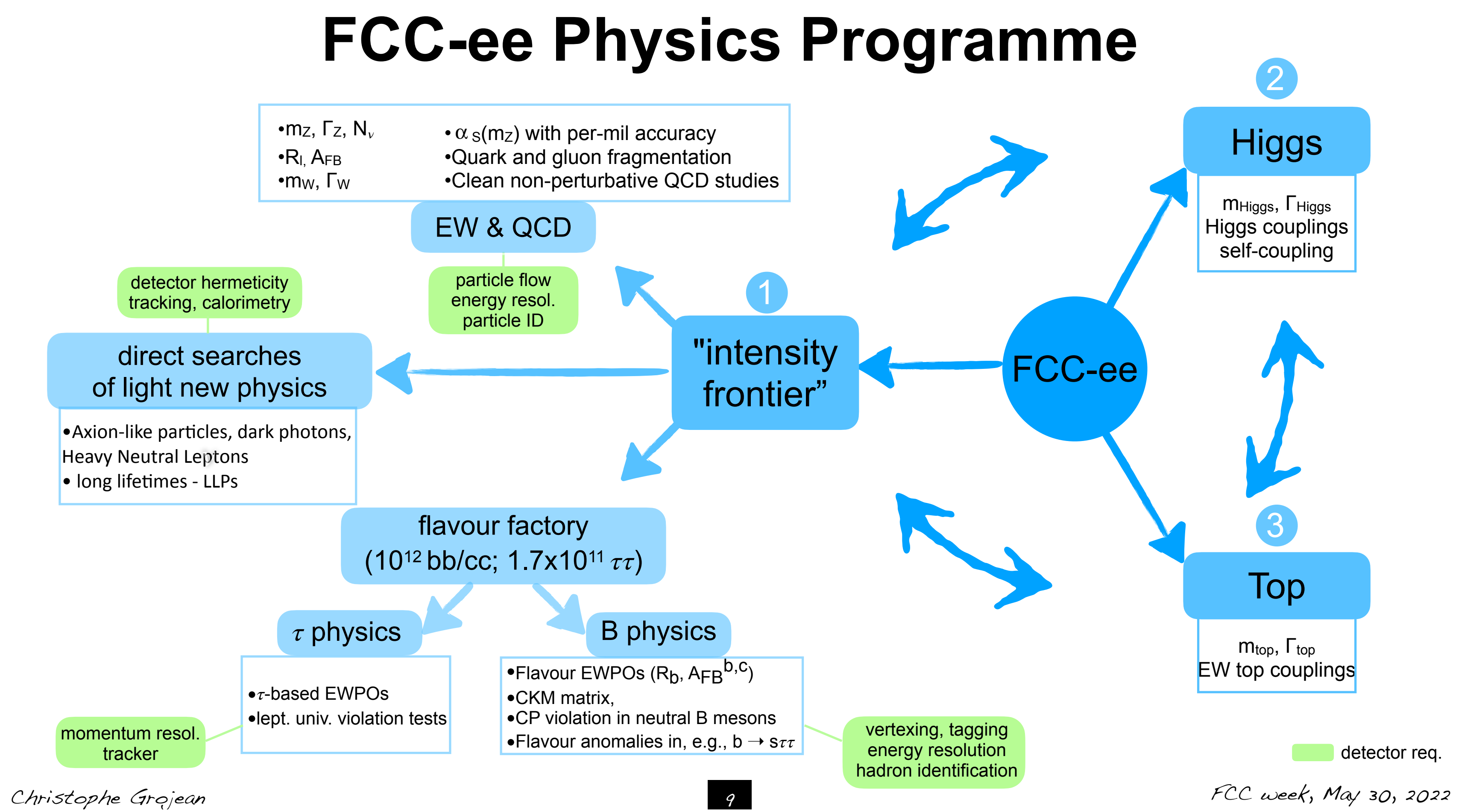
Outline

1. FCC-ee physics programme
2. Feasibility Study key points
3. The Physics case at large (and detectors)
4. Flavours@FCC-ee: setting the scene
5. The Flavoured Circular Collider Workshop
6. Summary

1. FCC-ee Feasibility Study. Motivation.

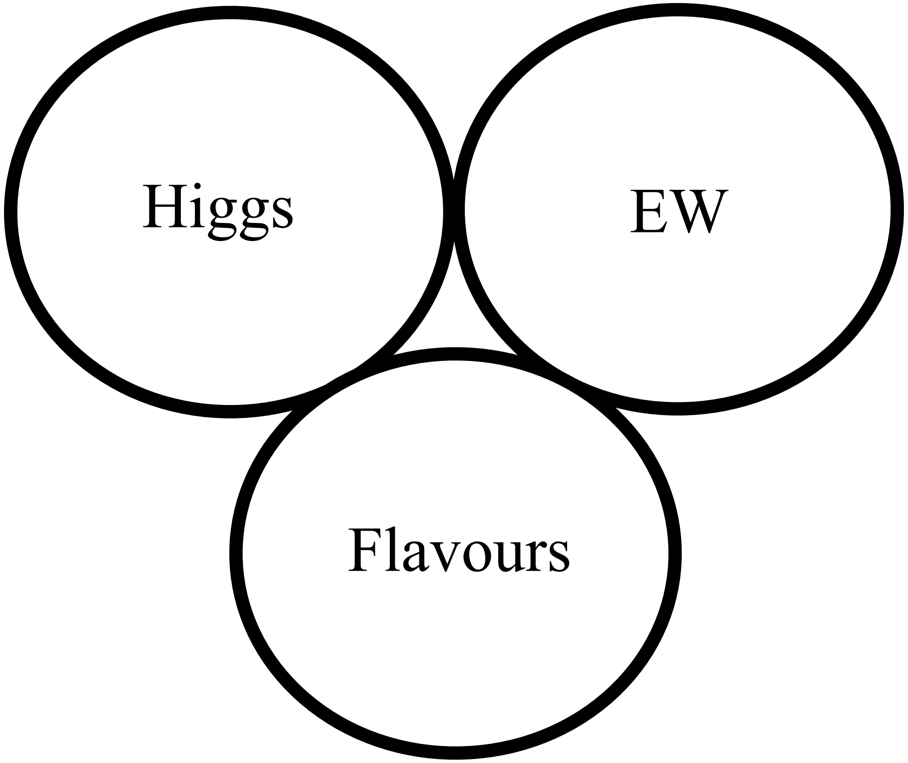
- Next-generation particle collider housed in a 90km underground tunnel
- Building-up on the CERN accelerator complex …
- … and building-up on the successful LEP / LHC strategy: implementation in stages with first an e^+e^- machine, followed by a high-energy hadron collider.



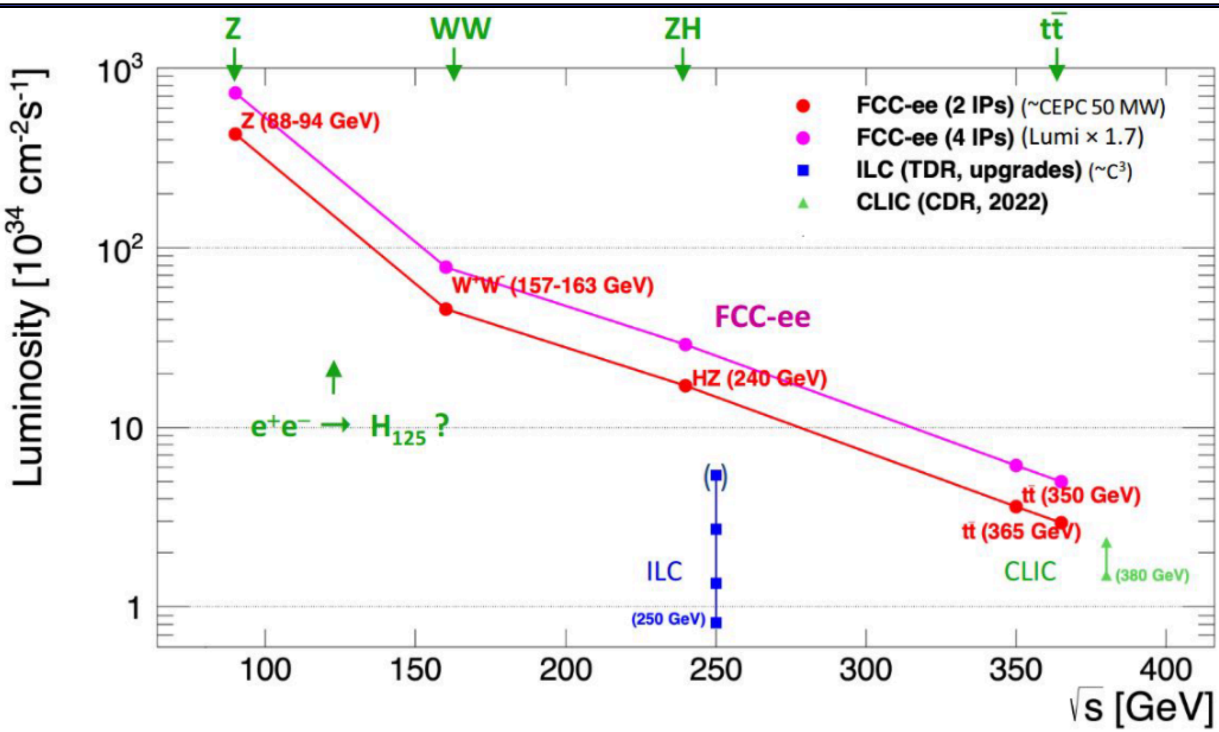


- Triptych: Higgs / Top / Intensity (EW, Flavours, light) .

FCC Physics programme: simplified view



2. Key points: FCC-ee luminosity and operation

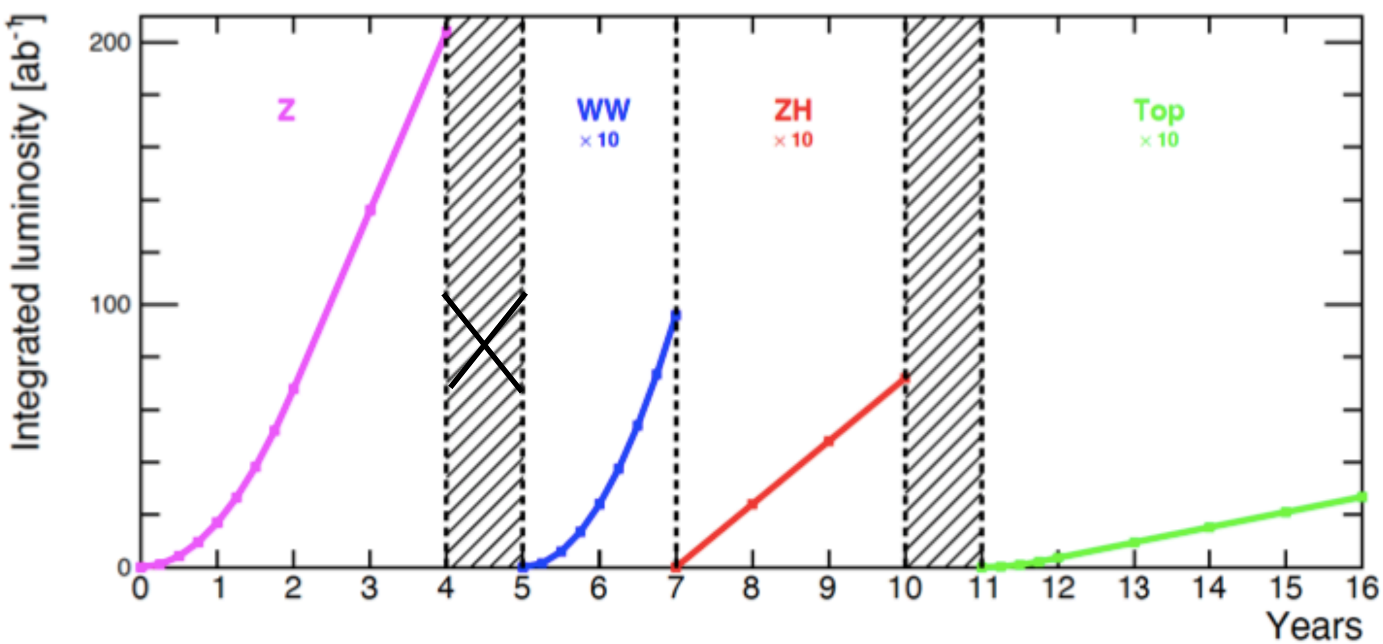


- We‘re speaking of 10^5 Z/s , 10^4 W/h, 1.5 10^3 H and top /d, in a very clean environment: no pile-up, controlled beam backgrounds, E and p constraints, ~w/o trigger loss.

- In particular, you do the LEP … in a minute!

2. Key points: FCC-ee luminosity and operation

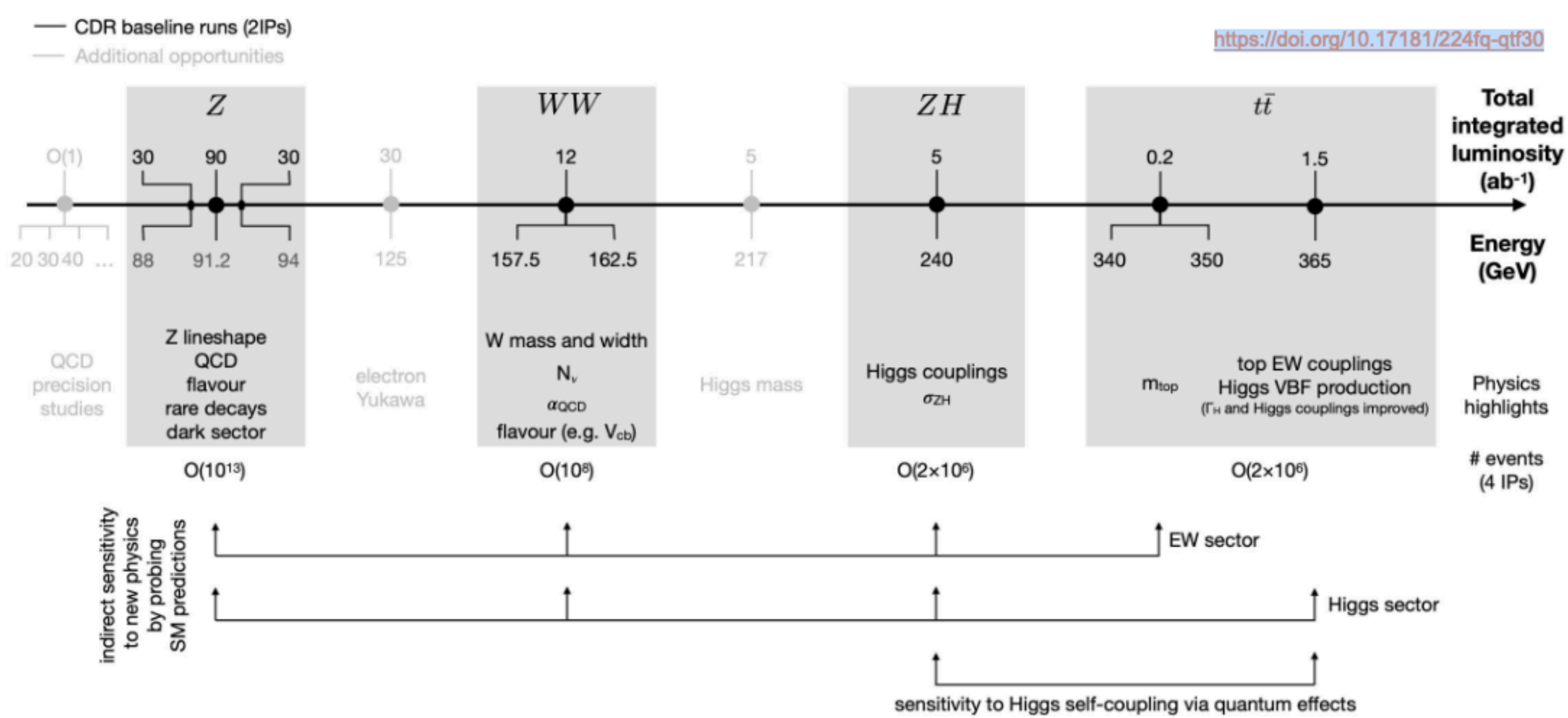
- Baseline:
  - 16 years nominal program.
  - 4 interaction points.
  - Versatility in run scenarii (*e.g.* could start w/ Higgs run)
  - Possibility of additional runs (*e.g.* e^- Yukawa w/ 125 GeV run).



FCC feasibility Mid-term report - Physics and Experiments

2. Key points: FCC-ee luminosity and operation

- Baseline:
  - Flexibility is key, and the feasibility study brought the possibility to navigate through the three “low energy” operation points seamlessly



2. FCC-ee Feasibility Study: key points

- Racetrack placement and democratic reach-out:

FUTURE CIRCULAR COLLIDER

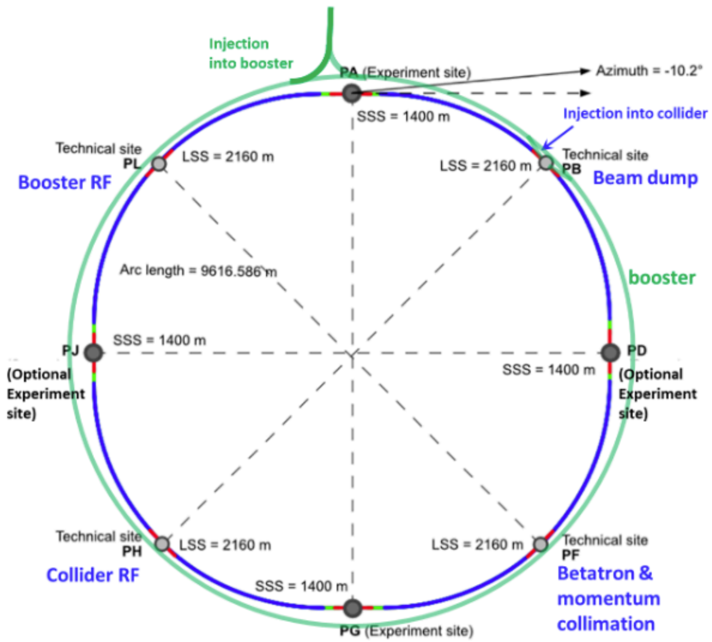
Optimized placement and layout for feasibility study

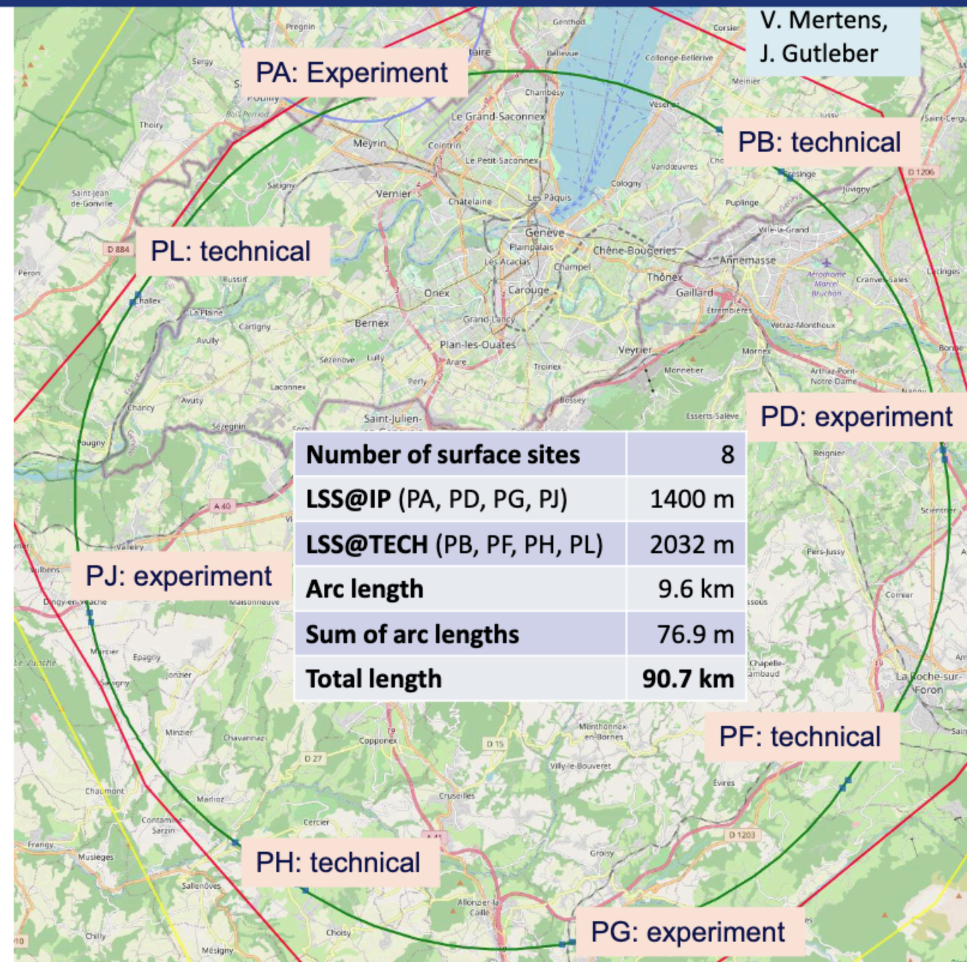
Major achievement: optimization of the ring placement

Layout chosen out of ~ 100 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment (protected zones), infrastructure (water, electricity, transport), etc. “Éviter, reduire, compenser” principle of EU and French regulations

Lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold superperiodicity, possibility of 2 or 4 IPs

Whole project now adapted to this placement

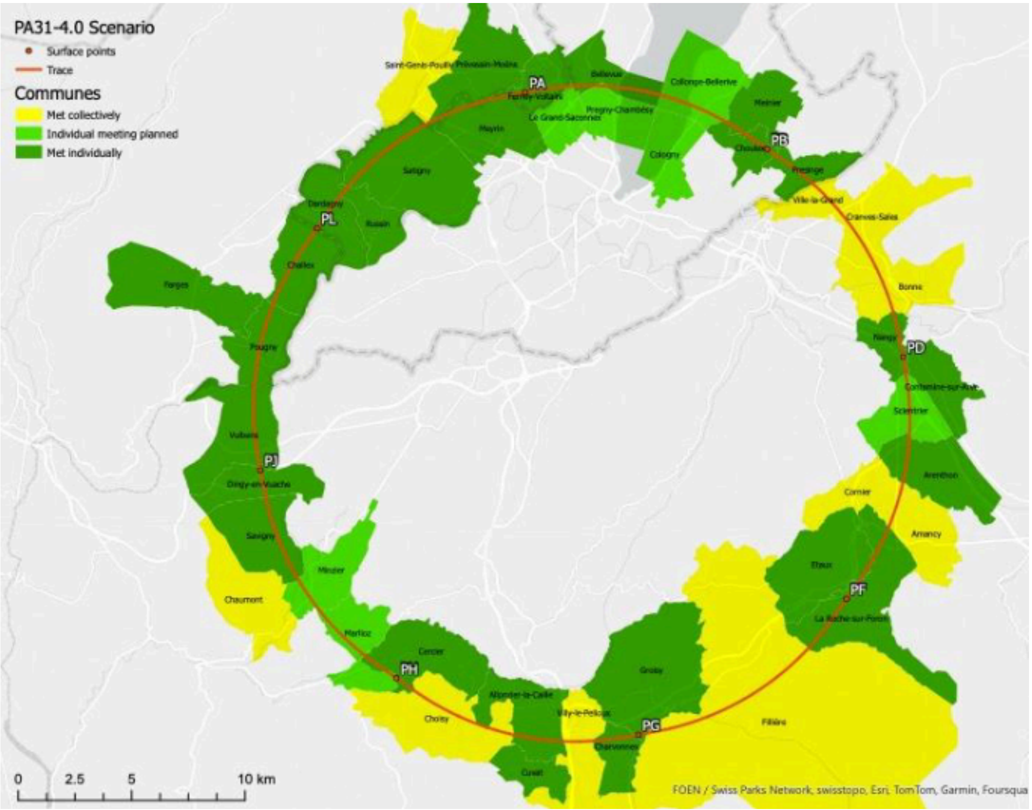




Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

2. FCC-ee Feasibility Study: key points

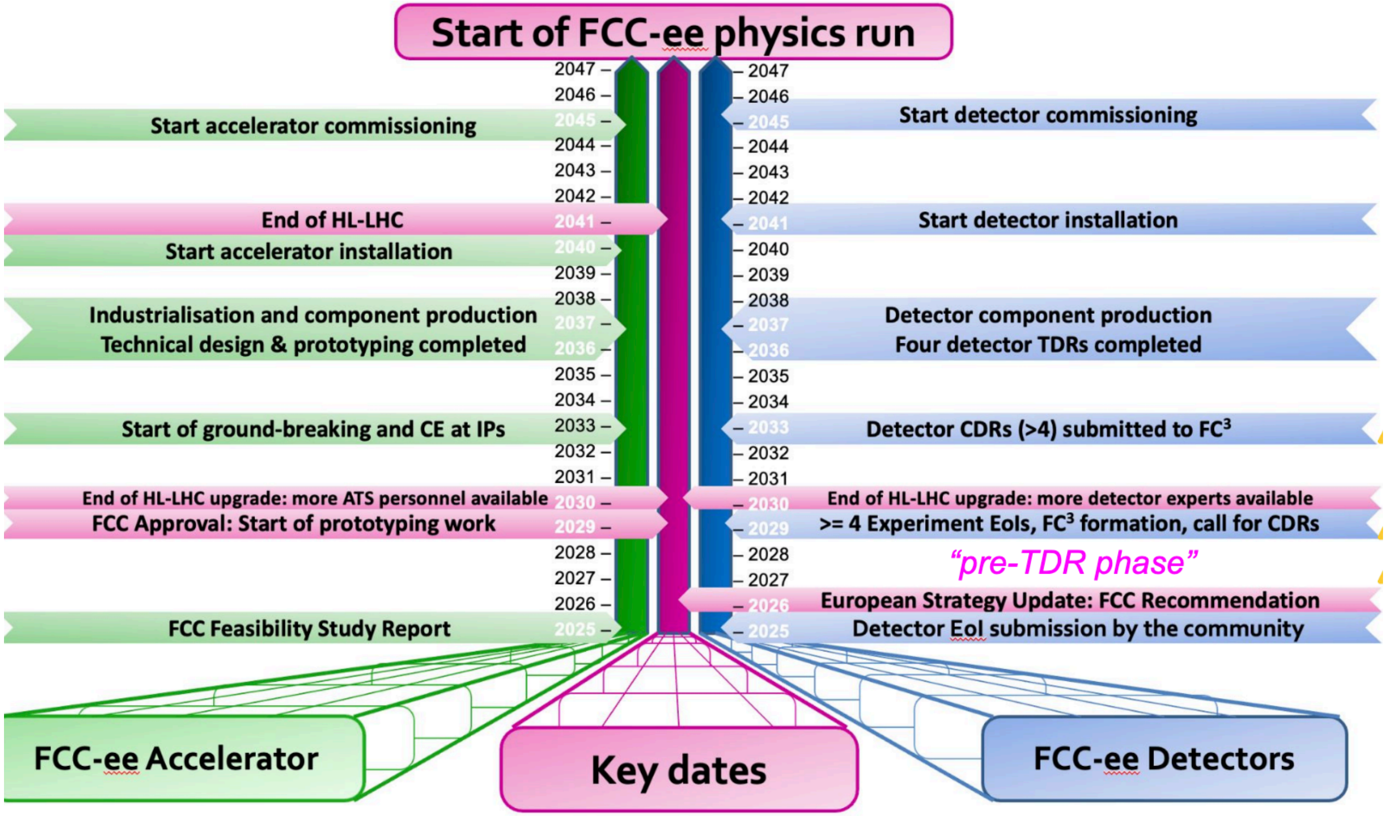
- Racetrack placement and democratic reach-out: (as of january 2024)



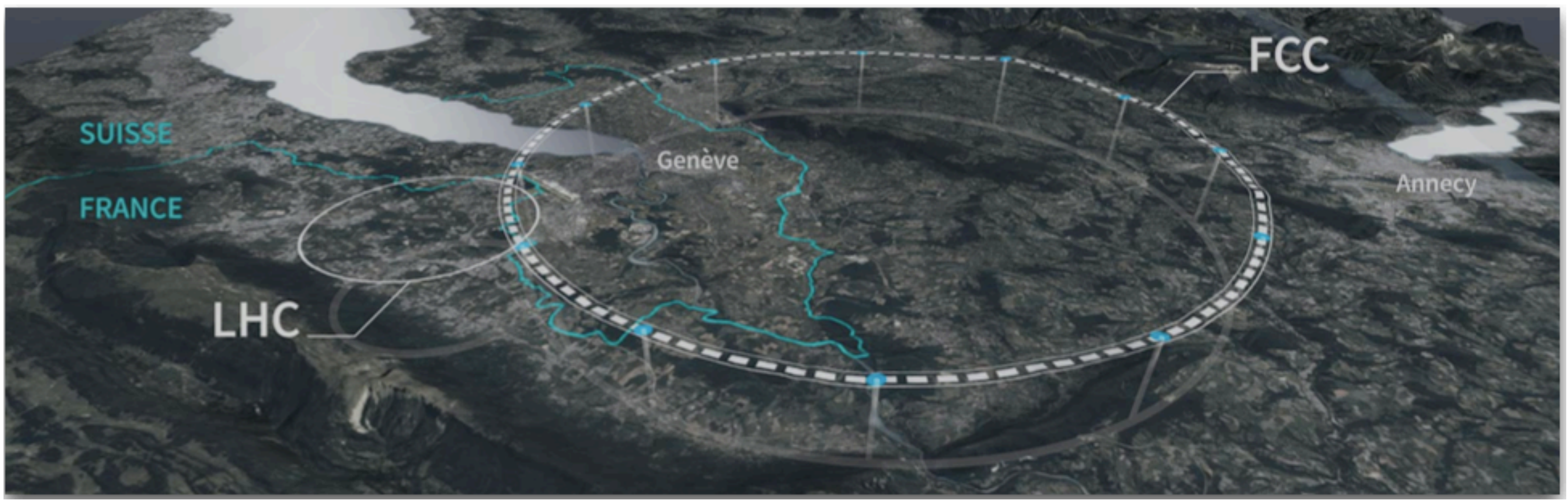
2. FCC-ee Feasibility Study:

- The machine design is matured as underlined by the accelerated schedule of the FS report.

- The project's timetable (slightly updated from Feas. Study.



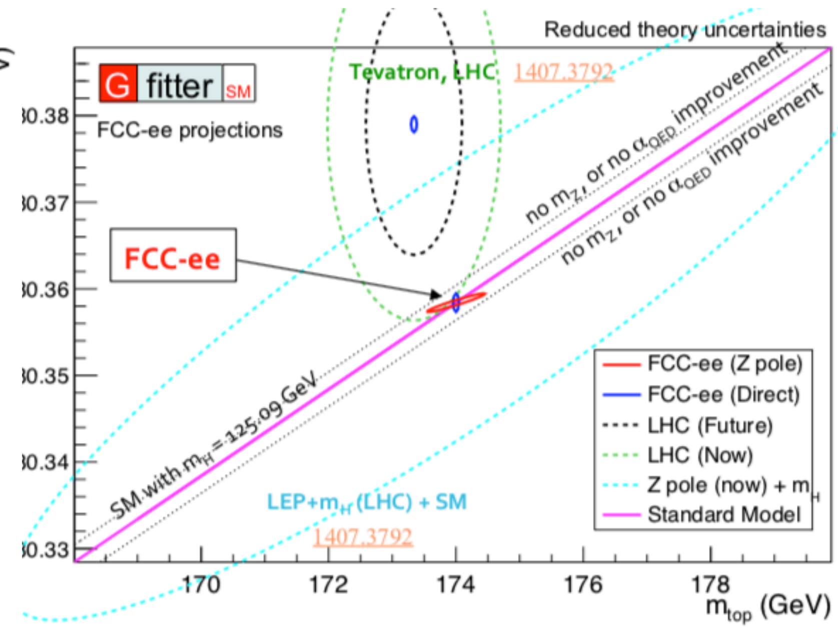
3. The Physics Case at large



3. The Physics Case at large: big picture

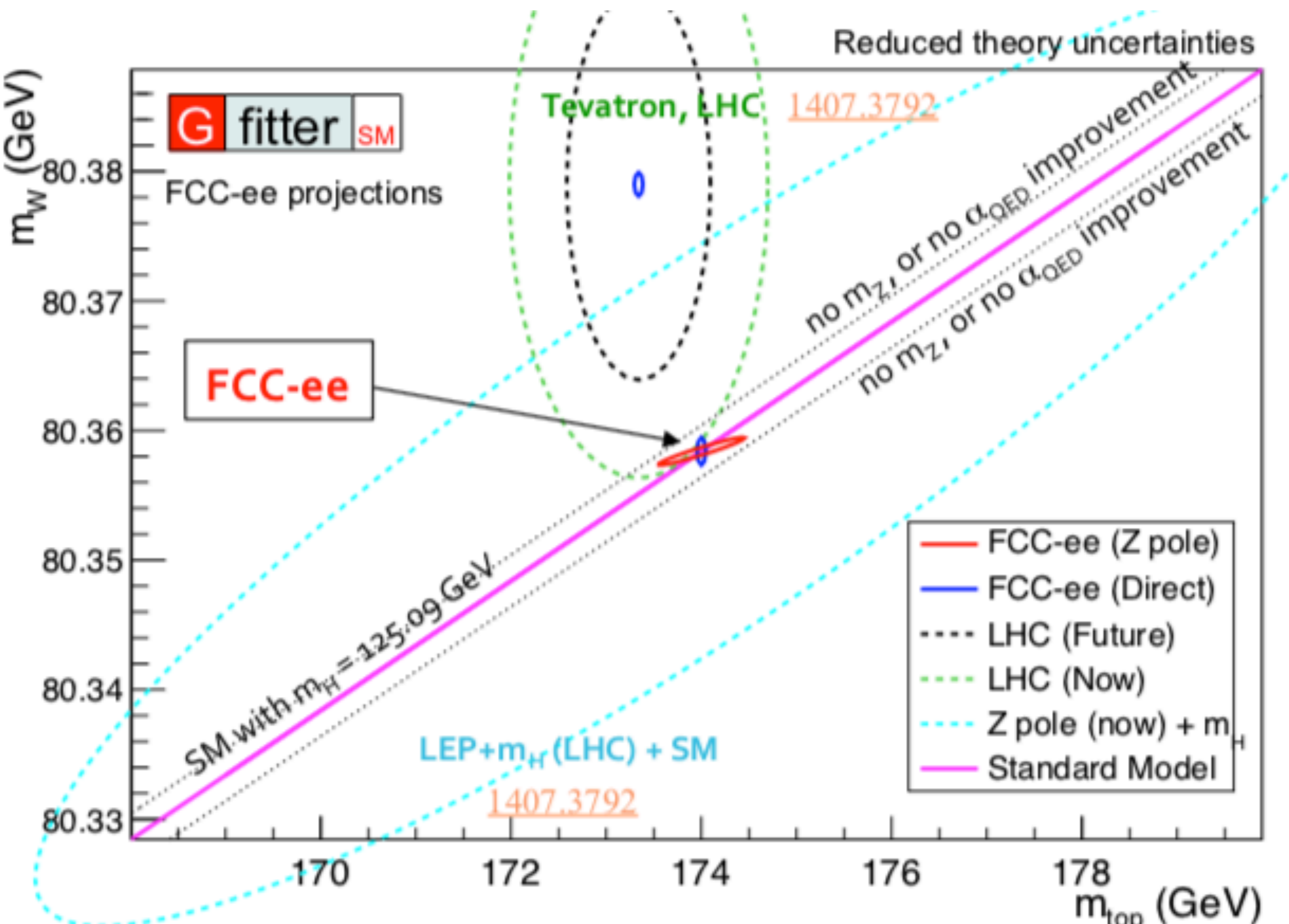
Z pole / WW thr. / tt thr.

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	Momentum scale
τ leptonic ($\mu\nu_\mu\nu_\tau$) B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010 ± 270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run



- Ultimate quantum completeness consistency test of the SM.
- The improvements in theory prediction precision is part of the FCC program.

3. The Physics Case at large: the indirect constraints



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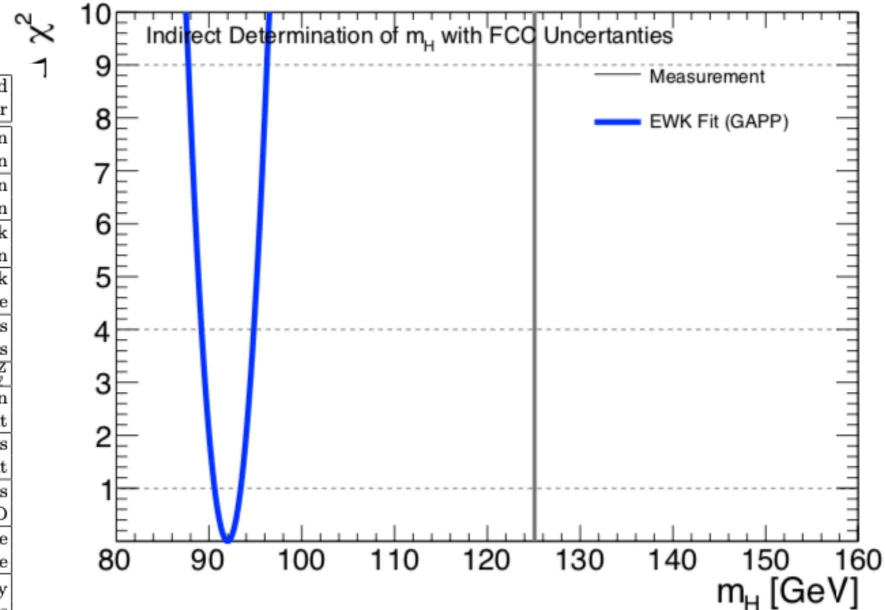
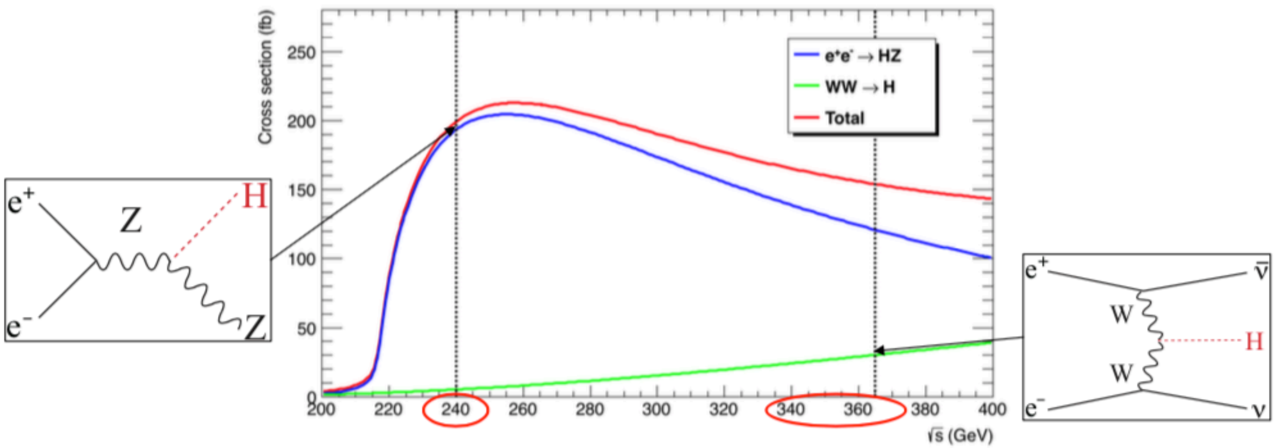


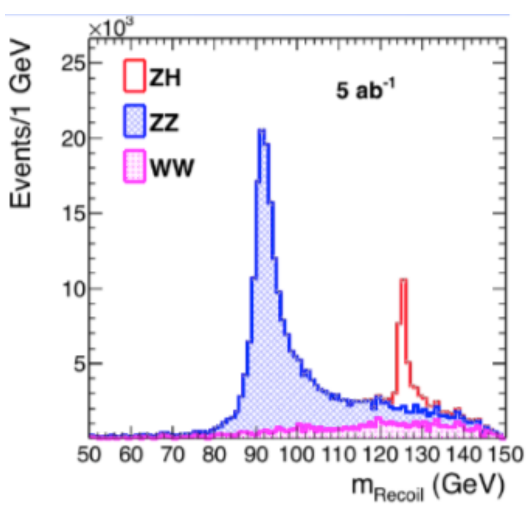
- Ultimate quantum completeness consistency test of the SM.

- The improvements in theory prediction precision is a grand challenge and a part of the FCC program. σ (m_H) = 1.4 GeV.

- Two energy points (240 and 360 GeV) for the program



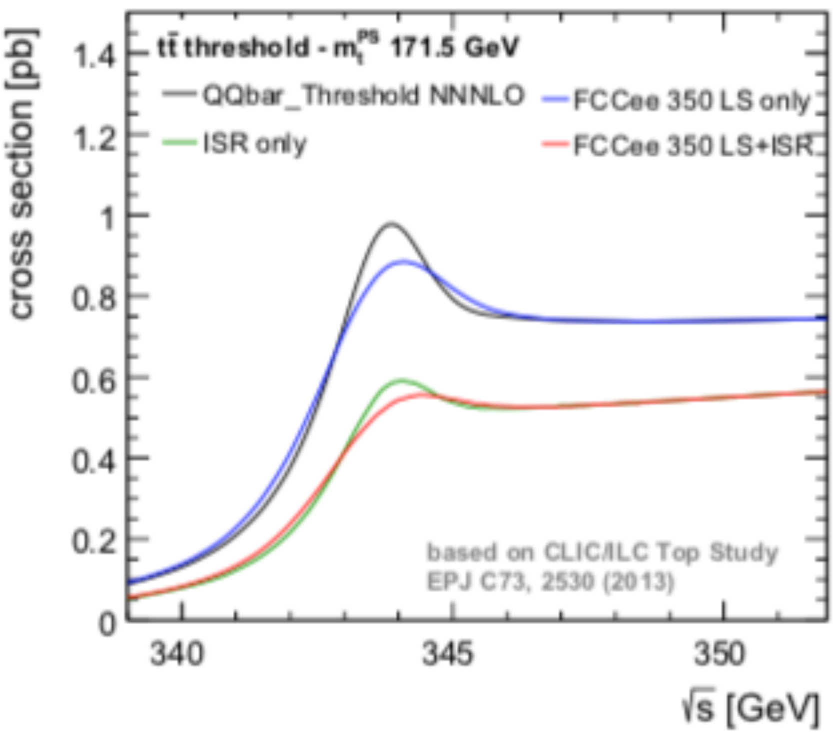
- Invincible precision on the absolute couplings and width. Interplay with HL-LHC.

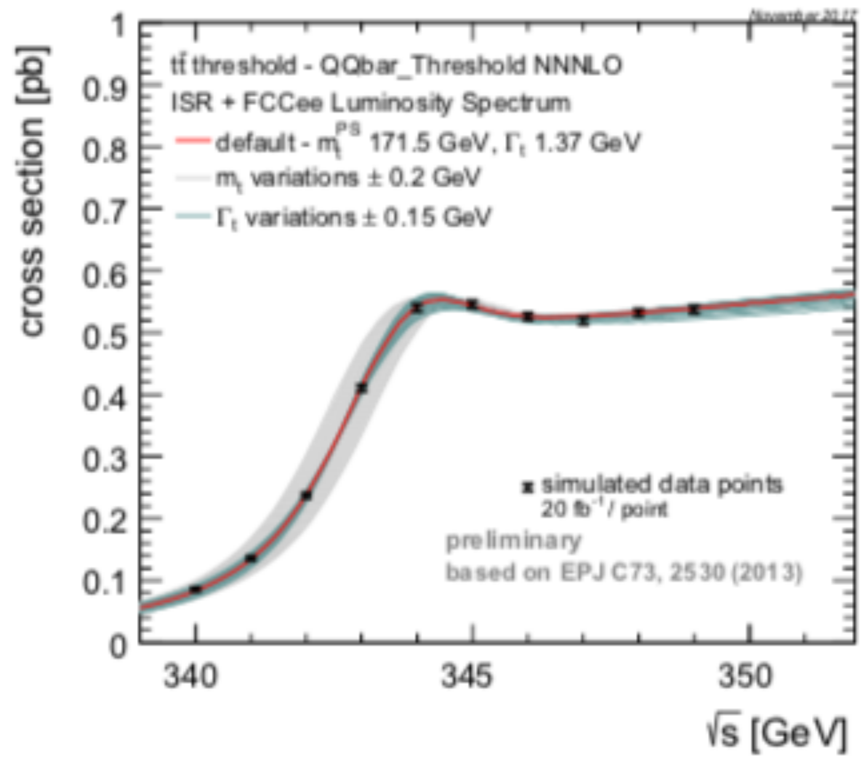


Collider	HL-LHC	FCC-ee		
Luminosity (ab^{-1})	3	5 @ 240GeV	+1.5 @ 365GeV	+HL-LHC
Years	25	3	**+4**	-
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	**0.61**	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	1.6	**1.01**	0.83
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.4	**0.74**	0.64
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	10.1	**9.0**	3.9
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	4.8	**3.9**	1.1
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	**–**	2.4
BR_{EXO} (%)	SM (0.0)	<1.2	**<1.0**	<1.0

Results as in the CDR 2018

3. The Physics Case at large: the top threshold





- Can get the top quark mass at the level of 20 MeV. Top width at 50 MeV.

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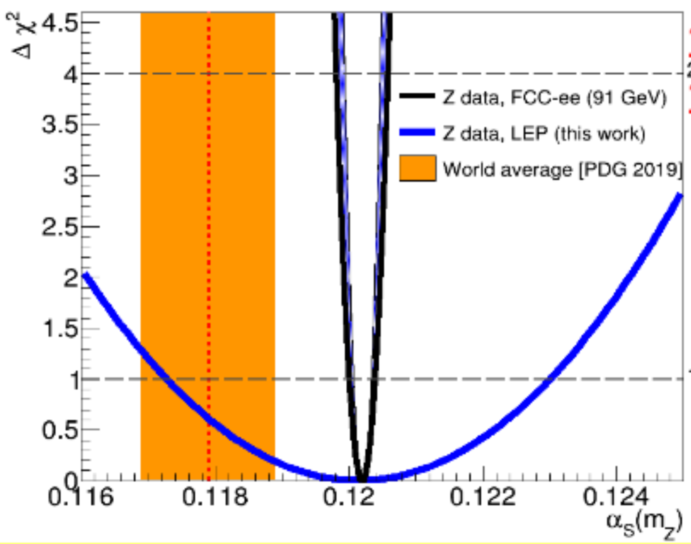
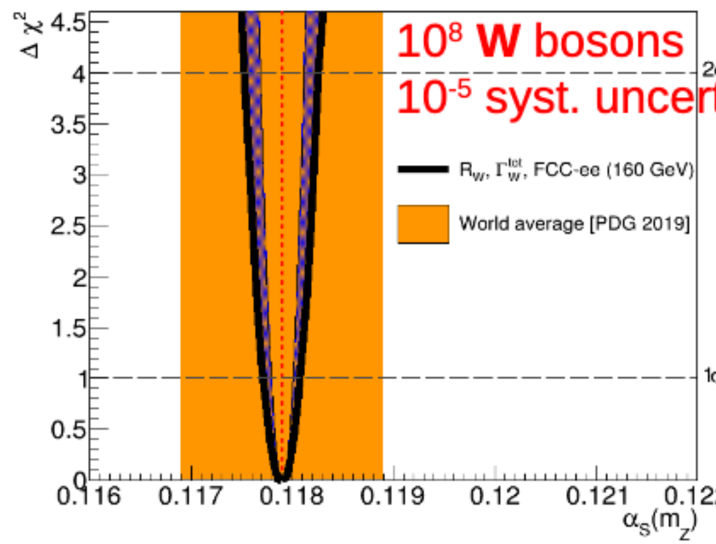
■ Future: Permille uncertainty possible only with a machine like FCC-e^+e^-



10^{12} **Z** bosons
10^{-5} syst. uncerts.

Strong SM "stress test"



10^8 **W** bosons
10^{-5} syst. uncerts.

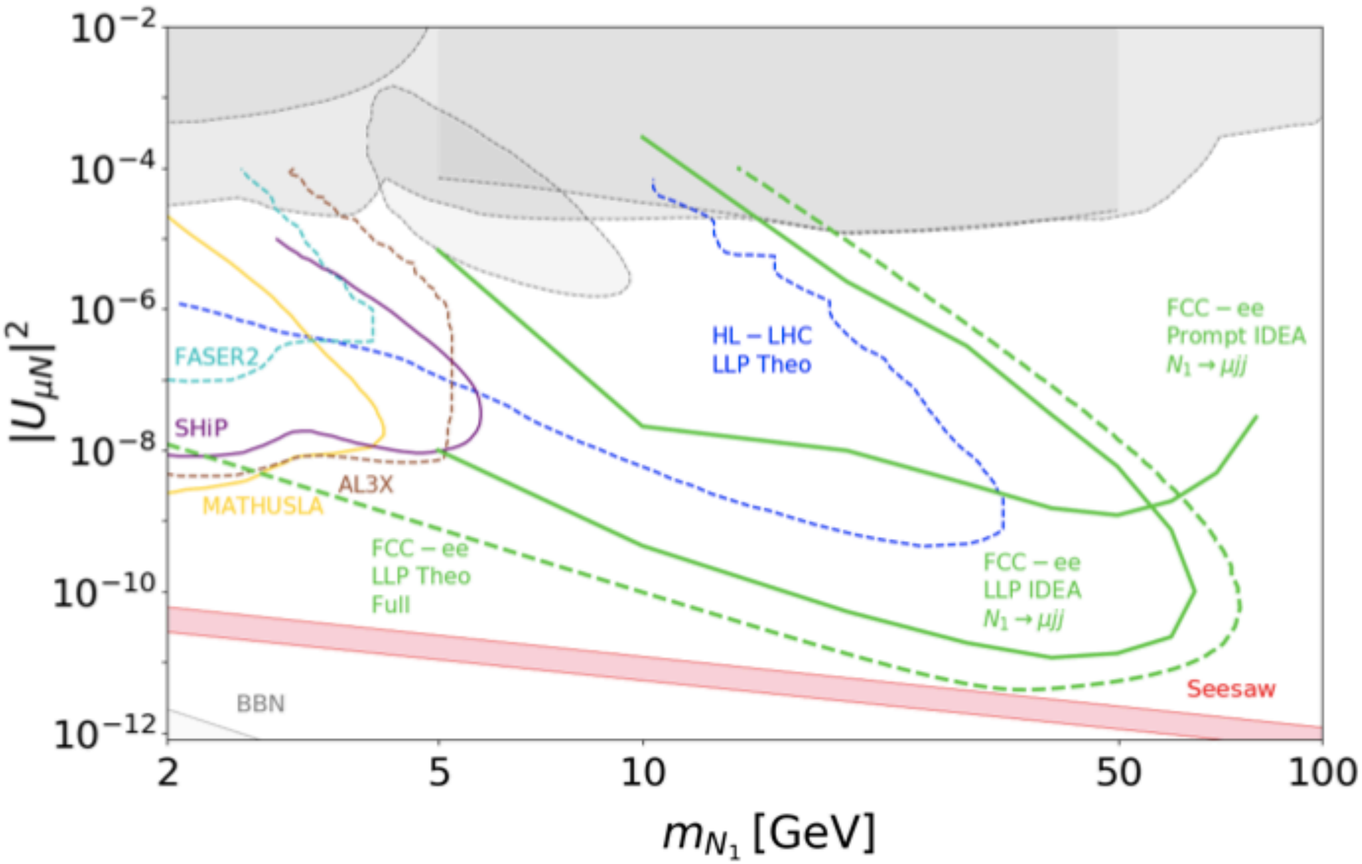
$\alpha_s(m_z) = 0.12030 \pm 0.00028$ ±0.2% (tot), ±0.1% (exp)

$\alpha_s(m_z) = 0.11790 \pm 0.00023$ ±0.2% (tot), ±0.1% (exp)

- The prospects for the strong coupling constant at Z and WW threshold.

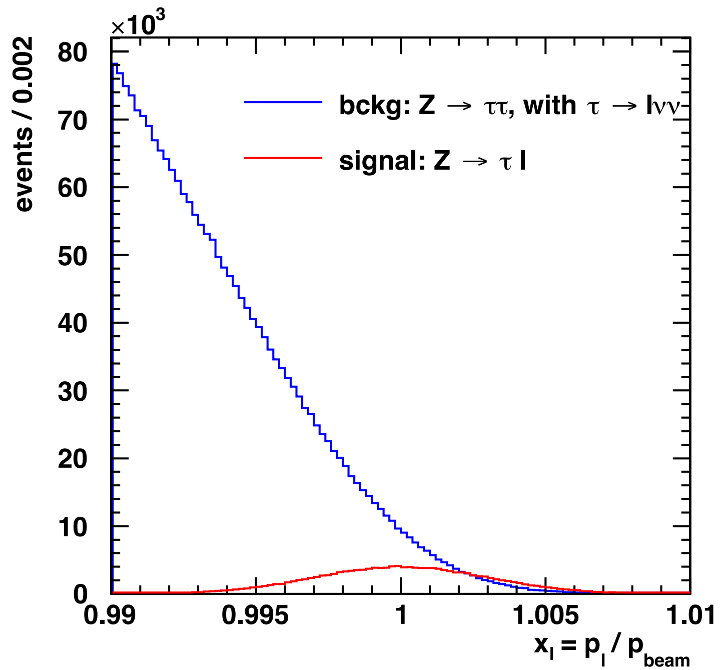
3. The Physics Case at large: discovery potential

- Much more than what I'm flashing here for Heavy Neutral Leptons. Full program feature searches for Axion-like Particles, dark sectors etc…



3. The Physics Case at large: discovery potential

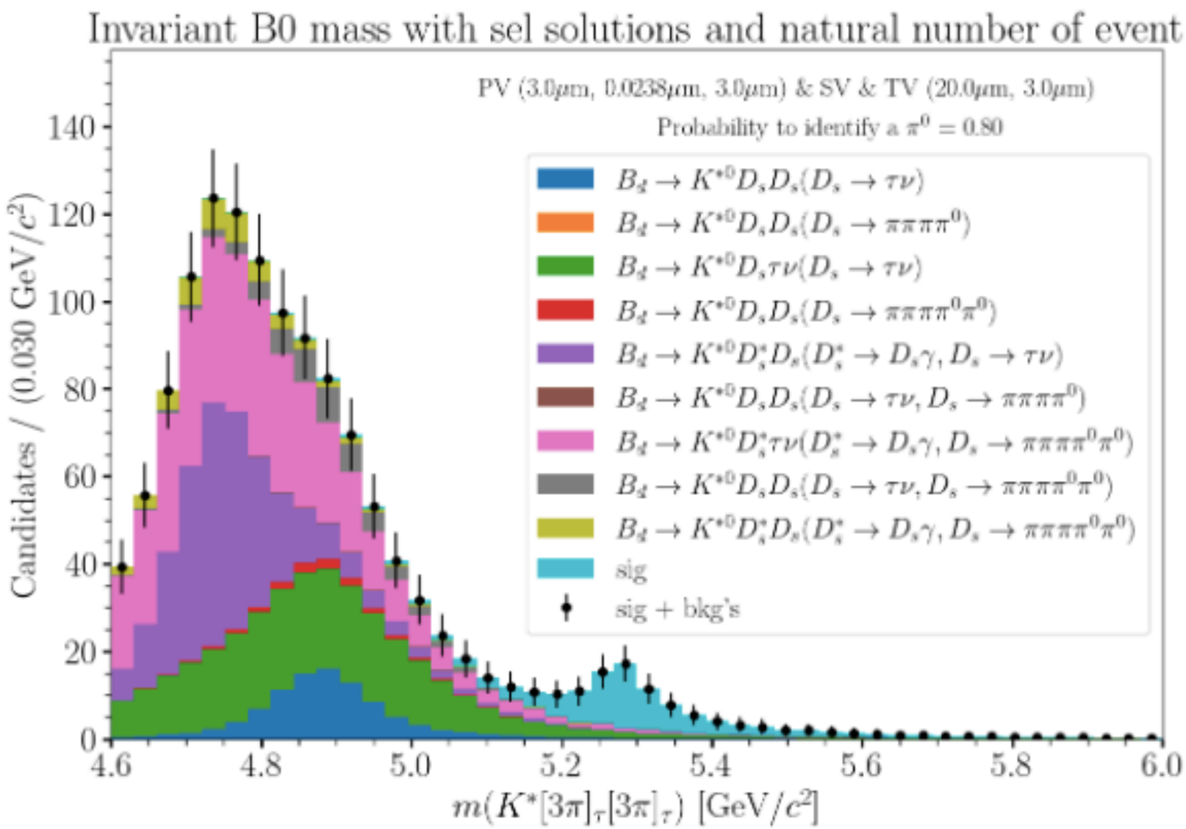
- The Z pole can be a rich factory of Lepton Flavour violation processes. We'll see later for the tau lepton.
- Lepton Flavour-Violating *Z* decays in the SM with lepton mixing are typically < 10^{-50}.
- Any observation of such a decay would be an indisputable evidence for New Physics. FCC-*ee* exploration [JHEP 1504 (2015) 051]. $Z \to \tau\mu/e$ is unique at FCC.
- The dominant background is ($Z \to \tau\tau$), where one tau decays into a close to beam energy lepton. The search is therefore limited by the couple (beam spread energy, momentum resolution). A lot of phenomenology to explore yet.



Bottomline: With the expected tracking performance at FCC-*ee* (beam spread equivalent resolution at 45 GeV), the current limits are pushed by three orders of magnitude, *e.g.* $O(10^{-9} - 10^{-10})$.

3. The Physics Case at large: one Flavour example

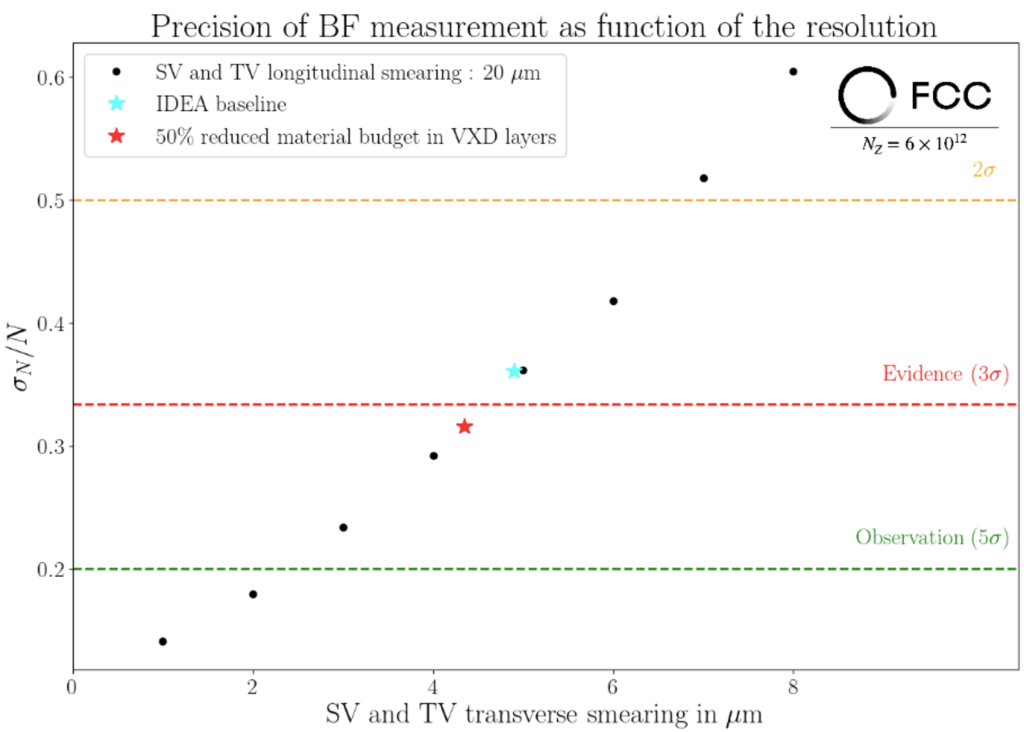
- $B^0 \to K^{*0}\ \tau^+\tau^-$: topological reconstruction + selection



- $B^0 \to K^{*0}\ \tau^+\tau^-$: we could see unambiguously the SM signal with this emulated detector! But it is an arbitrarily good one.

3. The Physics Case at large: one Flavour example

- $B^0 \to K^{*0}\ \tau^+\tau^-$: Checking how much to improve a vertex detector design? The IDEA example @ FCC-ee.



- One lesson: need to reduce the material of the beam pipe, or better, put the vertex detector in the beam pipe.

3. A word on the European Strategy for PP

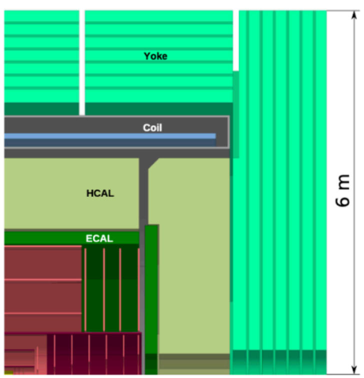
- The ESPP symposium in Venice (Summer 2025) established a community consensus towards the FCCee project as the next European flagship machine.
- The European Strategy Group (January 2026) proposed:
  - Plan A: FCCee;
  - Plan B: FCCee descoped, but reversible [power, w/o top threshold, 2 IPs]
- The next step is the examination of the European strategy by the CERN council for a final decision (likely) targeted for autumn 2028.
- Meanwhile, strengthen the case, provide detector requirements and work on detector concepts: the Flavoured Circular Collider Workshop, a.k.a Flavour at FCC Workshop.

3. The Physics Case at large: detector concepts

- The physics reach is intimately related to the detector performance
- Four detector concepts / benchmarks (more to come) defined by calorimetry

Detector Concepts Currently under study

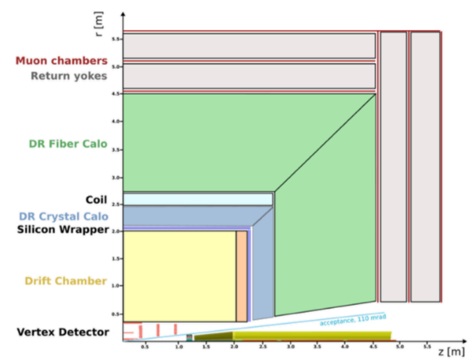
CLD



- Well established design
  - ILC → CLIC detector → CLD
- Full Si VXD + tracker
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

IDEA



- Design developed specifically for FCC-ee and CEPC
- Si VXD; ultra-light drift chamber with powerful PID
- Crystal ECAL w. dual readout
- Compact, light coil;
- Dual readout fibre calorimeter
- Muon system

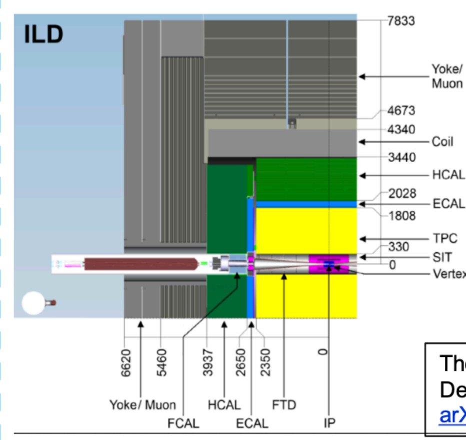
https://doi.org/10.48550/arXiv.2502.21223

Allegro

- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
  - Pb+LAr (or denser W+LKr)
- Si VXD
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391

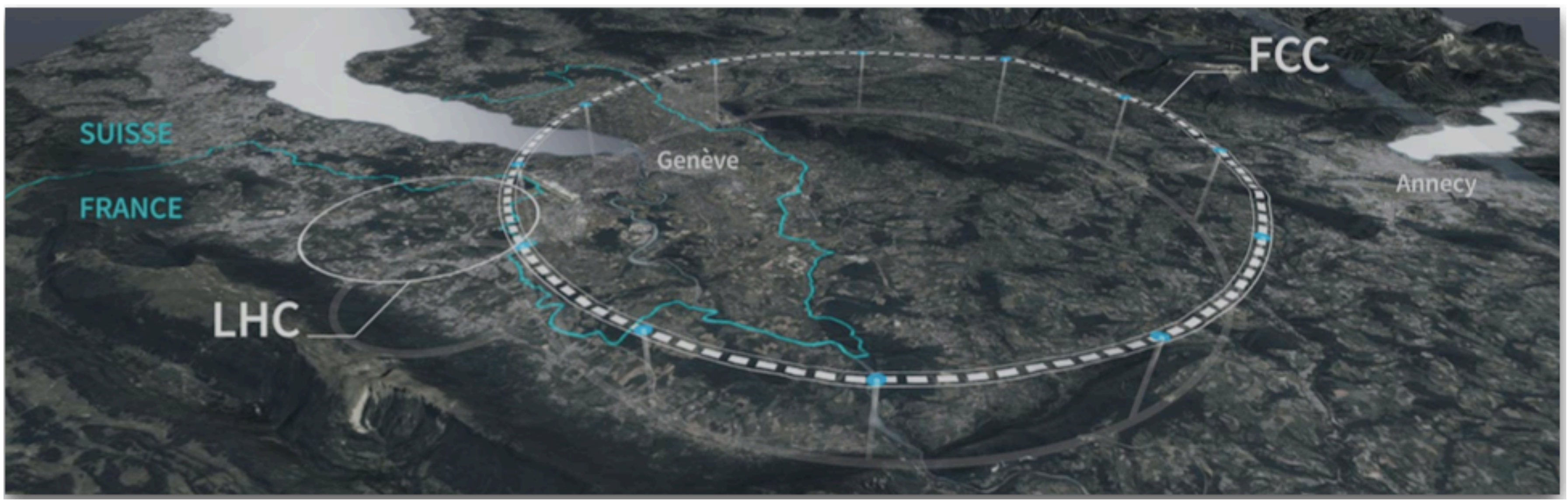
ILD



- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
  - Large-volume time projection chamber (TPC)

The International Linear Collider Technical Design Report - Volume 4: Detectors
arXiv:1306.6329

4. Flavours at FCC-ee: setting the scene



4) FCC-ee ABCD specifics for Flavour Physics.

FCC

A- Particle production at the Z pole:

- About 15 times the nominal Belle II anticipated statistics for B^0 and B^+.
- All species of b-hadrons are produced.

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm^{-2}s^{-1}}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year ($\mathrm{ab^{-1}}$)	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

Particle species	B^0	B^-	B^0_s	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

Table 1: Particle abundances for $6 \cdot 10^{12}$ Z decays. Charge conjugation is implied.

4) FCC-ee ABCD specifics for Flavour Physics.

B- The Boost at the *Z*: $\langle E_{X_b} \rangle = 75\% \times E_{\rm beam}; \langle \beta\gamma \rangle \sim 6.$

- Fragmentation of the *b*-quark:
- Makes possible a topological rec. of the decays w/ miss. energy.

C- Versatility : the *Z* pole does not saturate all Flavour possibilities. Beyond the obvious flavour-violating Higgs and top decays, the *WW* operation will enable to collect several 10^8 *W* decays on-shell AND boosted. Direct access to CKM matrix elements.

D- Comparison w/ LHC and B-factory. Advantageous attributes:

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

4) FCC-ee ABCD specifics for Flavour Physics.

D- Comparison w/ LHC and B-factory. Advantageous attributes:

Important note: there's a hole in this table. The Heavy Quarks production at the LHC is invincible. The exquisite luminosity at the *Z* pole mitigates this LHC(b) advantageous attribute to a certain extent. Yet, the statistics at play for fully charged modes can be commensurate with those of LHCb-Upgrade II, and in general less with muons in the final state. The watershed is about for 3-body decays.

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

4) FCC-ee ABCD specifics for Flavour Physics.

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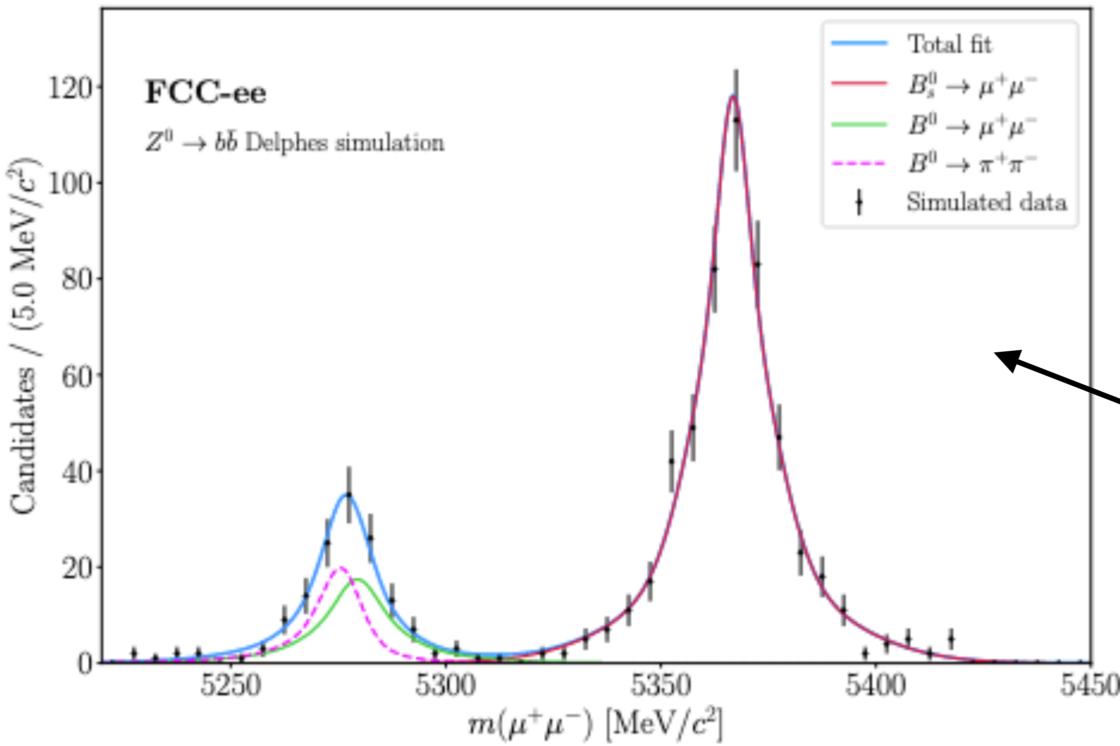

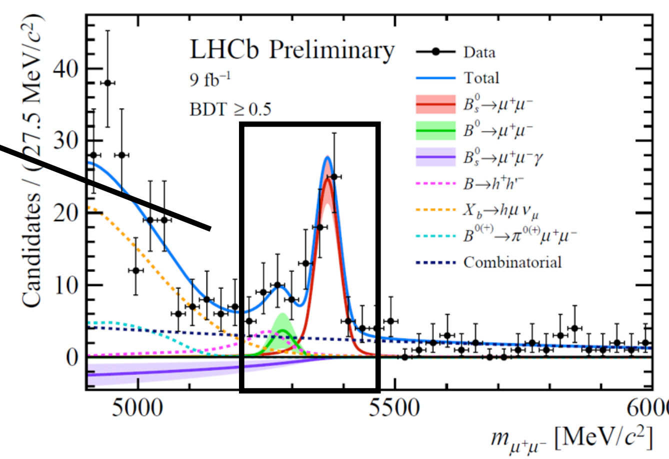

4) FCC-ee ABCD specifics for Flavour Physics.

Invariant-mass resolution is a must: exquisite tracking is necessary and at reach. Invariant-mass resolution as it is in the current state of IDEA fast simulation:

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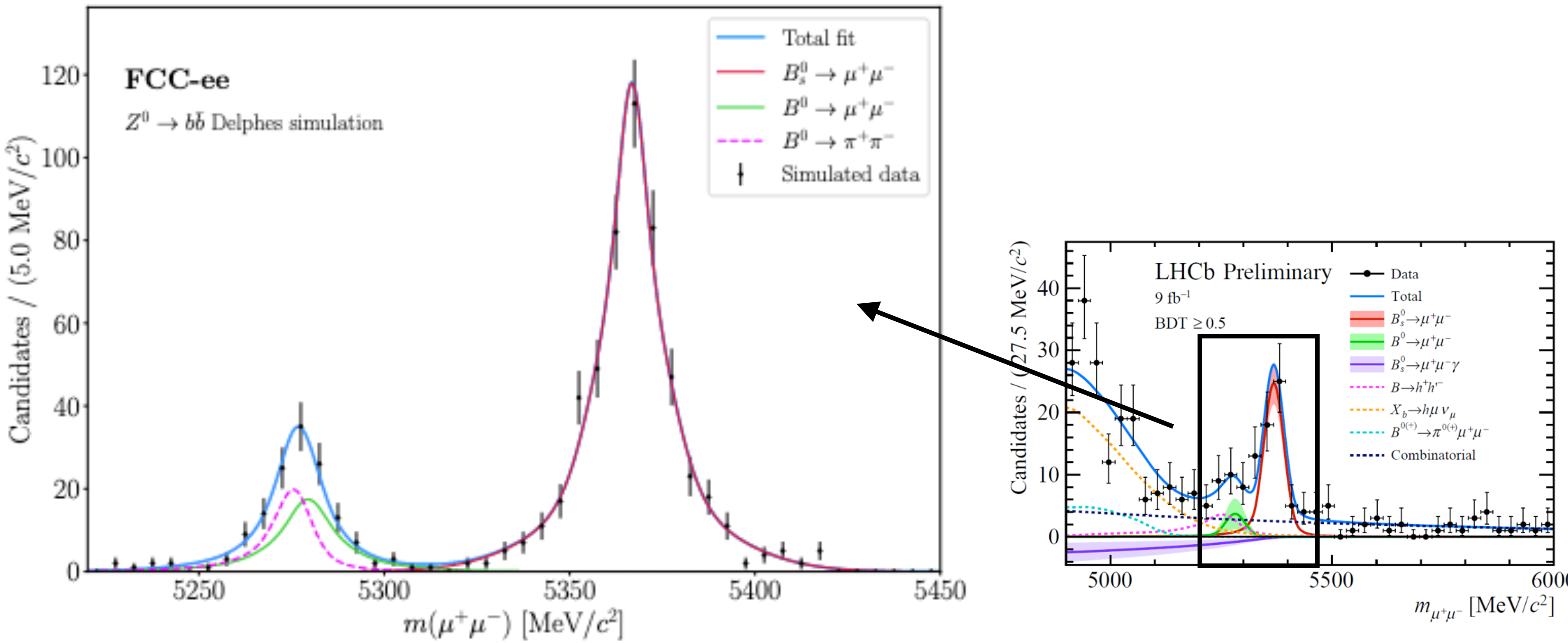


Seems granted w/ state-of-the-art tracker. Ultra-high resolution calorimetry is in addition desirable to touch high performance for modes w/ neutrals

4) FCC-ee ABCD specifics for Flavour Physics.

FCC

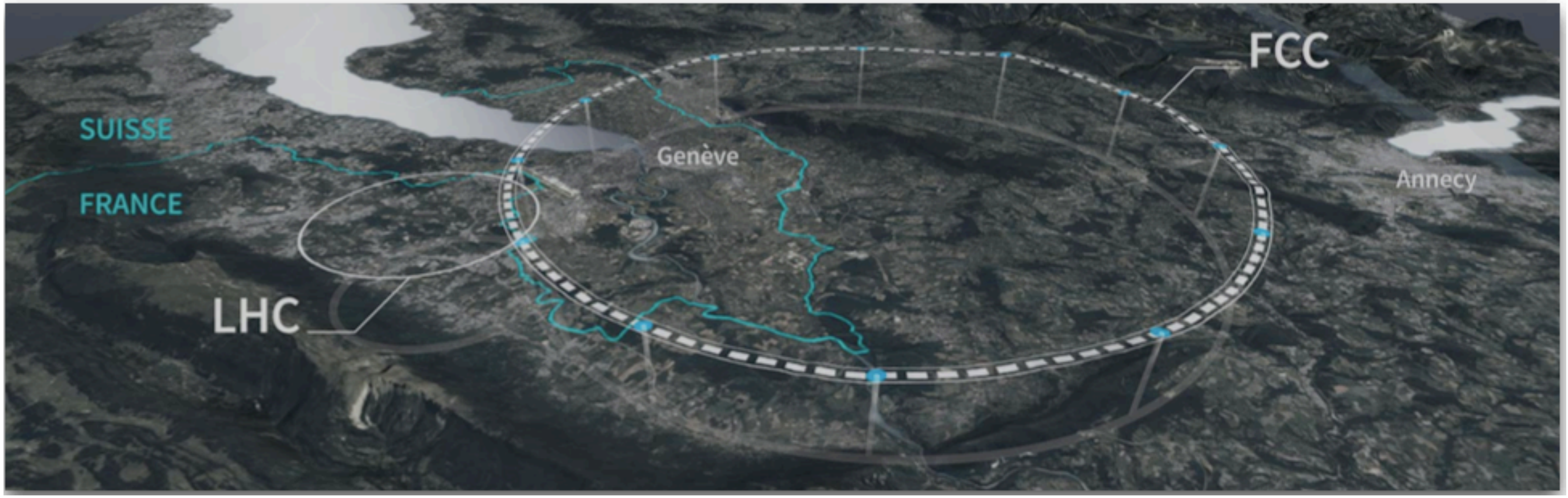
Final remarks on this section -

Advantageous attributes / detector requirements

- The boost of the Z makes the b-flavoured (tau) particles fly ~3 (2) mm on average. Flavour Physics successful if those are resolved with high precision in particular when the mom. of the tracks is low
  —> go beyond the state-of-the art.
- *CP* violation studies requires excellent K_S and neutral pions reconstruction. In order to make full advantage of the available statistics, exquisite energy and angular reconstruction in calorimetry
  —> go beyond the state-of-the art.
- Hadronic p / K / π Particle IDentification has to come from the dE/dx (dN/dx) or a Cerenkov detector to fit in front of the ECAL
  —> go beyond the state-of-the art.

Four IPs provide opportunities for a flavour-oriented detector concept.

Aparté



Aparté

Aparté

- The different tracking systems (be they Si-based or continuous-gaseous) on the table are already very powerful and are mostly meeting physics requirements. Some subtleties could however enhance the Flavour case, such as placing the vertex detector within the beam pipe … !
- But …
- … Detector Concepts are building on calorimetry.
- The Physics Case at large requires high granularity calorimeters, ideally both transverse granularity and longitudinal segmentation.
- Flavour Physics requires in addition high energy-resolution. Here follows a novel idea.

GRAiNITA: towards fine sampling crystal grain calorimetry for HEP.

Stéphane Monteil,
Clermont University, LPCA-IN2P3-CNRS.

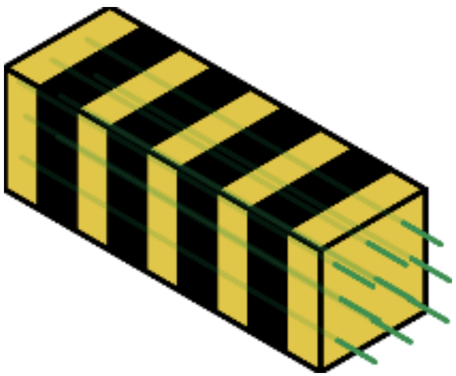
On behalf of the GRAiNITA Group:
IJCLab: S. Barsuk, I. Boyarintseva, D. Breton, G. Hull, J. Lefrançois, J. Maalmi, MH.Schune; ISMA: A. Boyarintsev, I. Tupitsyna, LPClermont: H. Chanal, Y. Hou, M. Magne, S. Monteil, D. Picard, M. Yeresko; TSNUK: O. Bezshyyko, A. Dubovik, D. Klekots, A. Kotenko, N. Semkiv. CERN: D. Abbaneo, M. DeFranchis, D. d'Enterria, B. François, F. Guo, P. Janot, E. Perez, M. Selvaggi, A. Silva.

Five institutes: CERN, IJCLab, ISMA (Ukraine), LPCA, TSNUK (Ukraine).

Aparté 1. Principles of GRAiNITA

- The equation: reaching an exquisite cost-effective energy resolution while preserving high transverse granularity for the full FCC physics program.

Typical sampling calorimeter (e.g. Shashlik)

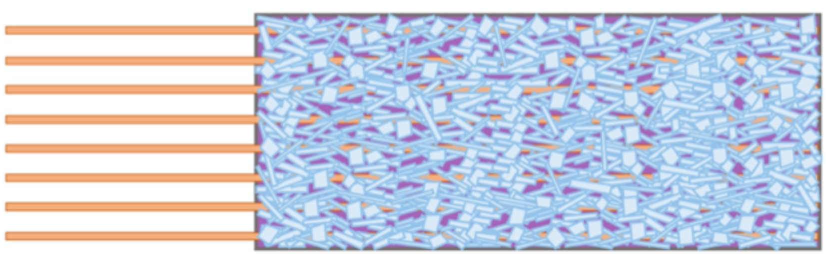


$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}}$$

Crystal calorimeter

$$\frac{\sigma_E}{E} \sim \frac{1-2\%}{\sqrt{E}}$$

- Can we make the best of the two approaches?
  - Fine sampling, scint. light containment
  - Potentially cost-effective: grains can be 2.5 cheaper than homogeneous crystals



Aparté 2. The grains, the fibres, the liquid

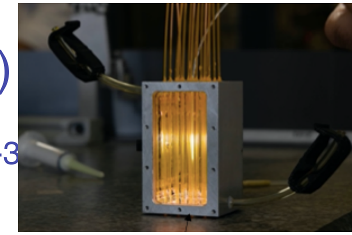
Table 1. Properties of interest for the GRAiNITA study of the the BGO and $ZnWO_4$ materials.

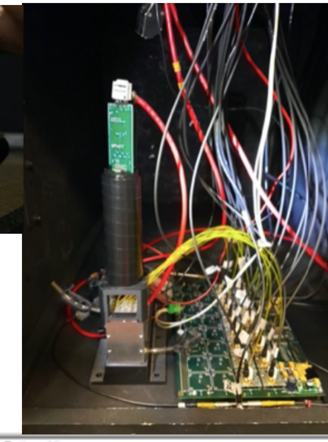
	BGO	$ZnWO_4$
Effective Z	74	61
Density (g/cm^3)	7.13	7.87
Refractive index	2.15	2.0 - 2.3
Light yield (photons/MeV)	~ 9000	~ 9000
Peak emission wavelength (nm)	480	480
Decay time (μs)	0.3	20
Radiation length (cm)	1.12	1.20
Molière radius (cm)	2.26	1.98

- Possible candidate for the grains: $ZnWO_4$.
- ISMA: dedicated R&D to produce $ZnWO_4$ grains with the flux method (cost effective). Production technique mastered.
- Scintillation decay time ok for FCC-ee (~50 kHz at the Z pole).
- About 1 kg produced.
- Options under consideration, *e.g.* $CaWO_4$, $Ca/PbWO_4$ (faster, flux method).

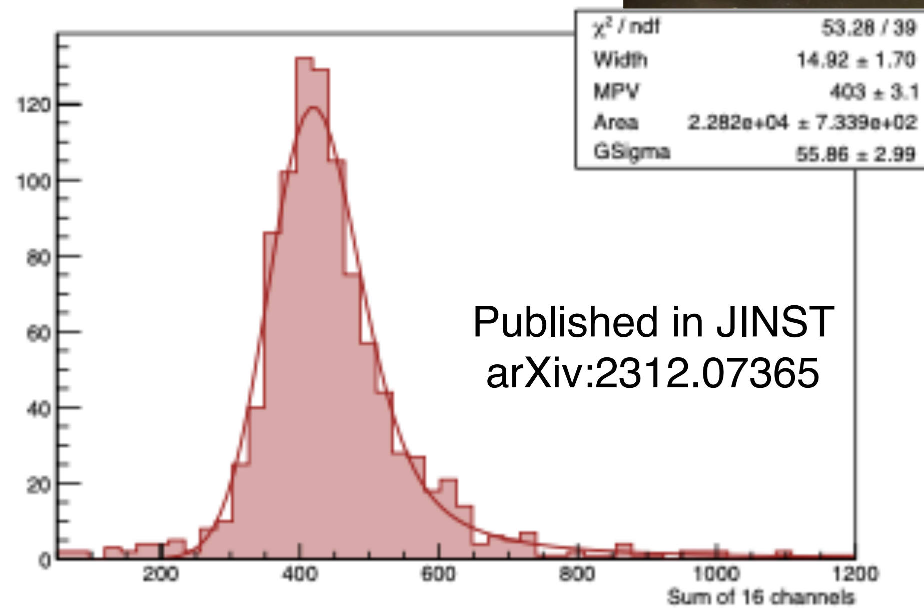
Aparté 3. Cosmic test bench: towards the stochastic term

- Average dE/dx for mu in prototype: ~1.5 MeV / (g.cm^{-2})
- Density of the proto is ~half that of $ZnWO_4$ (~4.5 g.cm^{-3})
- The length of proto seen by a cosmic mu is about 6 cm
- The energy deposited in the proto by a mu is *O*(40 MeV)





- Selected "central" muons
- About 400 photo-electrons
- About 10 p.e. per MeV, *e.g.* 10000 p.e. per GeV. !!
- More to study: mirror ends on fibres, heavy liquid …



Published in JINST
arXiv:2312.07365

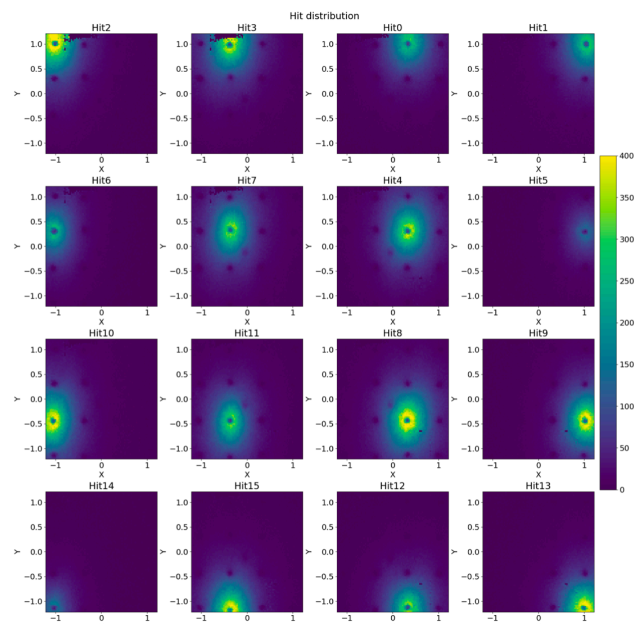
Should these numbers be confirmed, the

2% stochastic target is at reach !

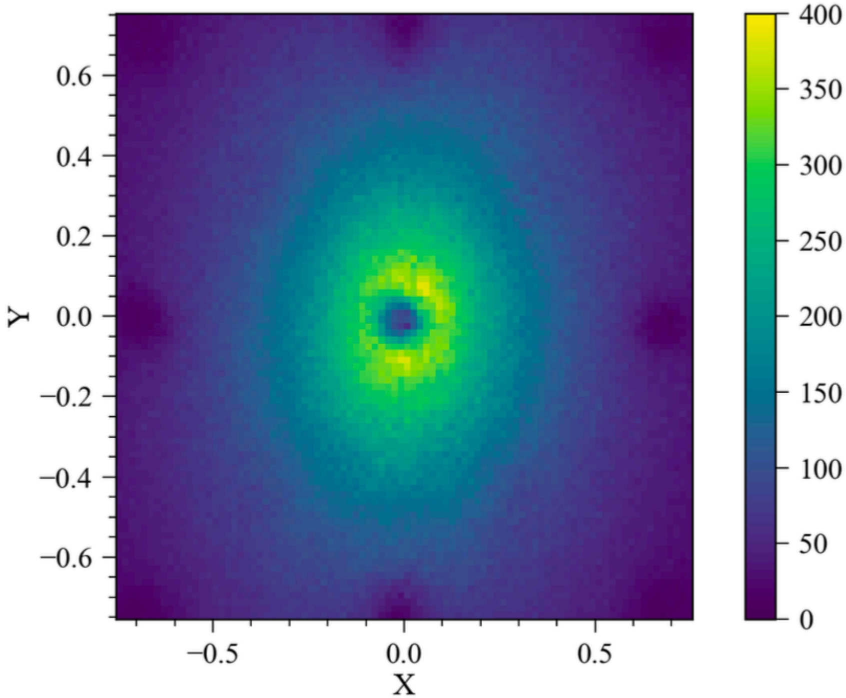
Aparté 4. Test beam at SPS: towards the constant term

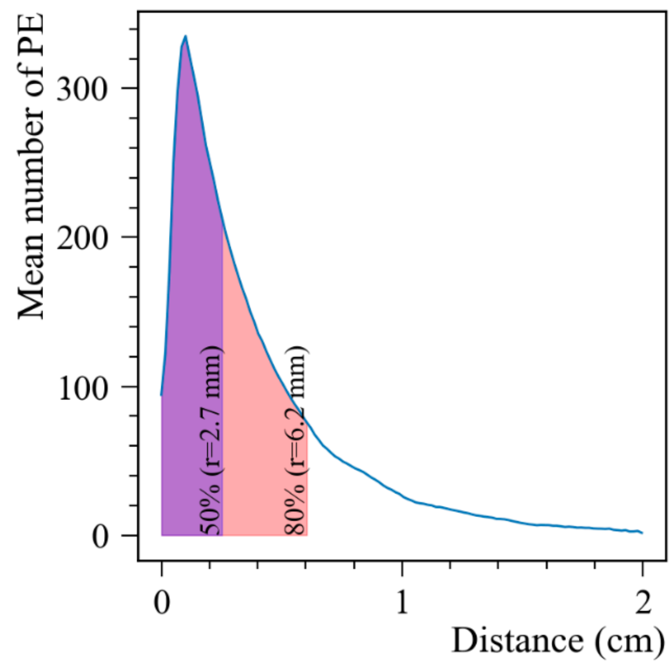
- We got the opportunity to benefit of two days of parasitic testbeam (muons and pions) at CERN SPS. Thanks to out LHCb colleagues for all the help.
- Tested two trolls (same small prototypes as in home test benches)
- Could check Water and Heavy Liquid
- Objective was to understand if there's not an irremediable constant term.
- Check the non-uniformity of the answer and input the result into simulations (WIP).

- On the way, one confirms that the 2% stochastic target is at reach.
- Confirms also that the scintillation light is confined close to the fibre.
- Note to read the plot: the entrance point in (x,y) (2.5 x 2.5) cm² of the beam track is represented here. The colour sketches the mean response of each of the 16 fibres.



4. Test beam at SPS: light confinement in more detail

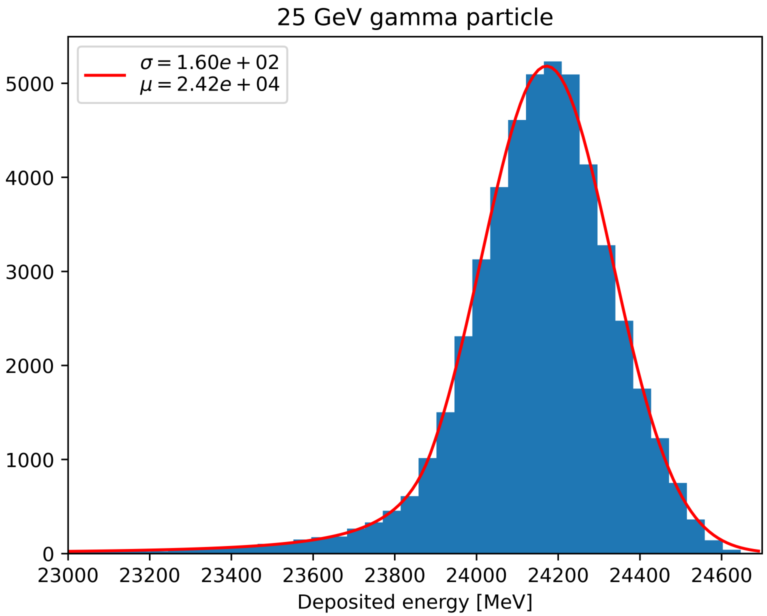


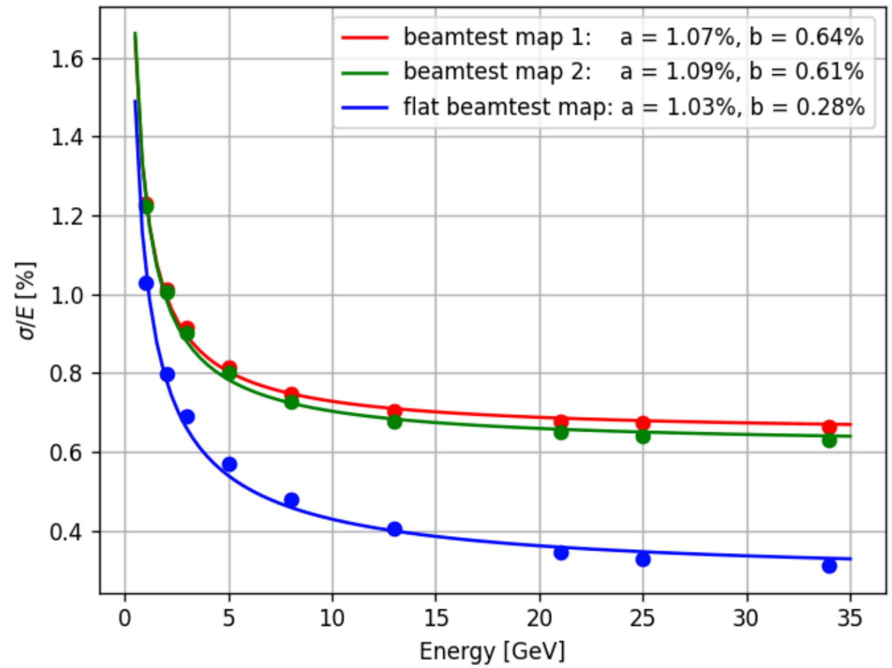


- The figures above are obtained using muon particles and the 4 most central fibres, to mitigate boundary effects.
- The (x,y) is the entrance point of the muon; the *z* (colour) scale is the number of photoelectrons..
- 75% of the scintillation light is collected by the 4 closest WLS fibers (7mmx7mm).

4. Test beam at SPS: constant term non-uniformities

- Map the GRAiNITA surface by steps of 1mm with pion samples.
- Quantify the non-uniformities (on average smaller than 10%) and input those into demonstrator simulations (see Denys' talk this afternoon).
- Fluctuations in the response (part of the contant term) is about 0.7% of the deposited energy.





Aparté 4. Test beam at SPS: DRD Calo paper in JINST

FCC

Studying the GRAiNITA concept: first test beam results

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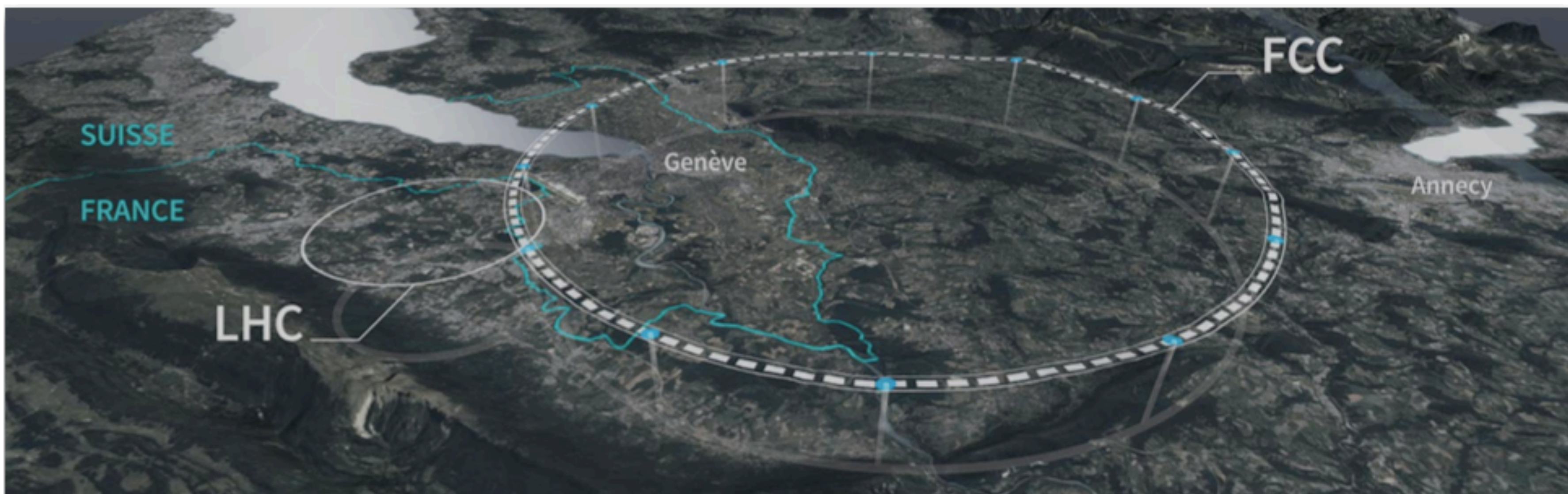
Abstract: Data collected over a two-day period in June 2024 at the CERN SPS H9 test beam using a small-scale GRAiNITA prototype have been analyzed to characterize the detector's energy-resolution performance. The measurements allow for a first estimate of the constant term associated with detector non-uniformity. Although the evaluation is limited by the small prototype size and the use of pion beams, the results indicate that the non-uniformity-related constant term is significantly below 1%. Furthermore, the test-beam data confirm that the contribution to the energy resolution arising from photo-electron statistics is approximately $1\%/\sqrt{E}$. These findings validate the expected calorimetric performance of the GRAiNITA concept and provide important input for the design and optimization of future full-scale detectors.

Fin de l'aparté



5) The Flavoured Circular Collider WS

- A look back:
  - The Flavour Program was not explored in the very-initial works about FCC-ee (but a mention to tau final states). It is now part of the program on its own right.
  - The case has to be thought of out of the anticipated very-rich experimental landscape at the horizon 2040 : there are LHCb Upgrade 2 (not yet secured but highly desirable — 300 /fb), Belle II (some thoughts about Belle III — 250 /ab) and Super Tau-Charm Factory (STCF).
  - The question was: is there a valuable addition to the vibrant Flavour physics case that will be developed in the next two decades? The answer was YES, established with studies of modes likely unique to FCC-ee.
  - The objective, after the ESPP update, is now to address the case as comprehensively as possible and to assess detector requirements: Flavour@FCC WS.

5) The Flavoured Circular Collider WS design

- The workshop, under aegis of PED, spans over 1.5 - 2 years in order to provide a clear Flavour view (case and detector requirements) at the time decision (autumn 2028), along with the Higgs and EWK cases.

- Kick-off and three week-long in person events (one per semester), all plenary. Intermediate zoom meetings to prepare.

- 5 WGs and more conveners than would seem necessary;
  - The WS is experiment-driven: mostly four EXP and two TH.
  - EXP: empowering those who can be in charge when data are coming.
  - To spark discussions and ideas
  - Everyone has a day job to run

- Given the short time-span, focus on key benchmarks but attempt to drive detector requirements up to full simulation studies.

- Keep eyes open to new ideas and cases: beyond WG sessions.

5) The Flavoured Circular Collider WS design

The Working Groups and WG conveners:

WG1 b-FCNCs: Thibaud Humair (DESY, Belle II), Renato Qualigliani(CERN, LHCb), Niharika Rout (DESY, Belle II), Eluned Smith (MIT, LHCb), Wolfgang Altmannshofer (UCSC, Th.), Marzia Bordone (Zurich, Th.)

WG2 CPV: Alberto Bragagnolo (CERN, CMS), Laurent Dufour (EPFL, LHCb), Matt Kenzie (Cambridge, LHCb), Michele Veronesi (IPMU, Belle II), Stefan Schacht (Durham, Th.), Jure Zupan (Cincinatti, Th.).

WG3 CPC: Christina Agapopoulou (IJClab, LHCb), Markus Prim (Bonn, Belle II), Raynette von Tonder (KIT, Belle II), Xunwu Zuo (EPFL, LHCb), Andreas Juettner (CERN, Th.) Dean Robinson (LBL, Th.)

WG4 Charm: Michel Bertemes (Vienna, Belle II), Nathan Jurik (CERN, LHCb), Dominik Mitzel (TuDO, LHCb), Gudrun Hiller (TuDO/CERN, Th.), Jernej Kamenik (Ljubljana, Th.)

WG5 Tau and selected EW: Maria Cepeda (CIEMAT, CMS), Romain Madar (Clermont, ATLAS), Aurélien Martens(IJCLab, Belle II), Laura Zani (Roma, Belle II) , Emilie Passemar (Valencia, Th.), Olcyr Sumensari (IJClab, Th.)

In addition, other topics will be pursued outside WG structure, *e.g.* spectroscopy, absolute BF measurements, hadronisation fractions, strangeness physics, prospects w/ FCC-hh *etc.*, and may form new WGs in future if reach critical mass.

5) The Flavoured Circular Collider WS mandate

— Obtain realistic estimates for precision on key flavour benchmarks;

— Identify and develop strategies for potentially limiting syst. (exp. and th.)

— Investigate requirements on and impact of various detector designs

— Formulate new meas. strategies and identify new decay of interest;

— Understand the complementarities with the HL-LHC;

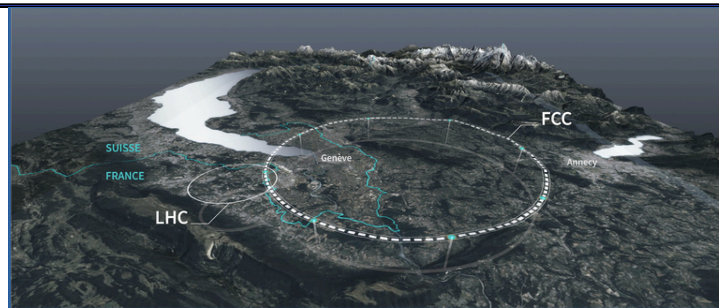
— Explore the interplay with the Higgs, EWK, and possible hidden sectors;

— Assess whether there exists a physics case beyond $6\ 10^{12}$ Z decays.

— Address transversal questions: normalising BF measurements, hadronis. fraction measurements, modelling parton shower and fragmentation, …

Some illustrations in the remaining slides (highlight det. contributions).

5) Flavour@FCC — Cherry-picked highlights



Flavours at FCC Workshop

19–21 Nov 2025
CERN
Europe/Zurich timezone

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- CERN's Values and Code of Conduct
- Hands-on tutorial: introduction to FCC analyses

Contact the organisers
stephane.monteil@cern....
guy.wilkinson@cern.ch

Physics at the Flavoured Circular Collider: preparing for heavy quark and lepton studies in the post HL-LHC/Belle II era

Experimentalists and theorists from the world-wide particle physics community are invited to participate in an extended workshop, beginning autumn 2025 and scheduled to continue until summer 2027 to deepen our understanding of the potential of the FCC-ee for heavy-flavour physics in the quark and lepton sector. This will build on the studies performed for the Conceptual Design Report and Feasibility Study Report and seek to set the agenda, and prepare the tools, for physics in the post HL-LHC and Belle II era.

The workshop will be focused on the physics opportunities and challenges at FCC-ee, with the following goals:

- Obtain realistic estimates for precision on key flavour benchmarks;
- Identify and develop strategies for potentially limiting systematics from experiment and theory;
- Work closely with the physics performance and detector-concept groups to investigate the requirements on and impact of various detector designs;
- Formulate new measurement strategies and identify new decay modes of interest;
- Understand the complementarities with the HL-LHC;
- Explore the interplay with the Higgs, electroweak, and possible hidden sectors;
- Assess whether there exists a physics case for extending the TeraZ programme beyond 6×10^{12} decays.

As well as pure flavour studies, the workshop will address electroweak measurements at the Z pole involving fully reconstructed heavy-flavour final states, and will also consider the rich possibilities that exist in hadron spectroscopy with the TeraZ dataset. In addition, consideration will be given to how the

Introductory materials used here can be found in the FCC Flavour document for ESPP: https://doi.org/10.17181/jnzpp-1fw39, the yellow rep. from the ECFA group and the FCCee Feasibility Study Rep.

The rest of the materials is in the indico of the workshop: https://indico.cern.ch/event/1588013/. I just indicated the talks from where I picked the material.

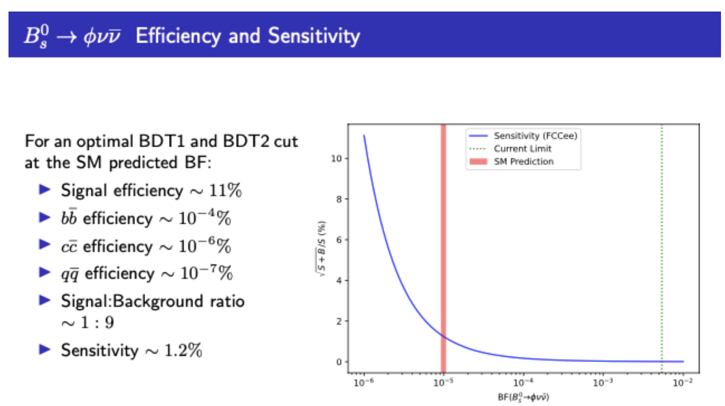
5) Flavour@FCC — Cherry-picked highlights, RD

- The b-flavoured rare decays: the programme is clear-cut as it comes to the modes where there is missing energy:

  - Promote the already studied transitions where FCCee reach is unique $\{b \to s\nu\bar{\nu}\,, b \to s\tau^+\tau^-, b \to \text{inv}\,. \ldots\}$ to full simulation. In particular unique vertex detector requirements.

  - Using the *b*-baryon polarisation as a new territory to capture BSM patterns (see Eluned Smith). Promising directions are the exploration of the final state with electrons, and the systematic studies of $b \to d$ transitions, and $B_s \to \tau\tau$. Studies engaged.

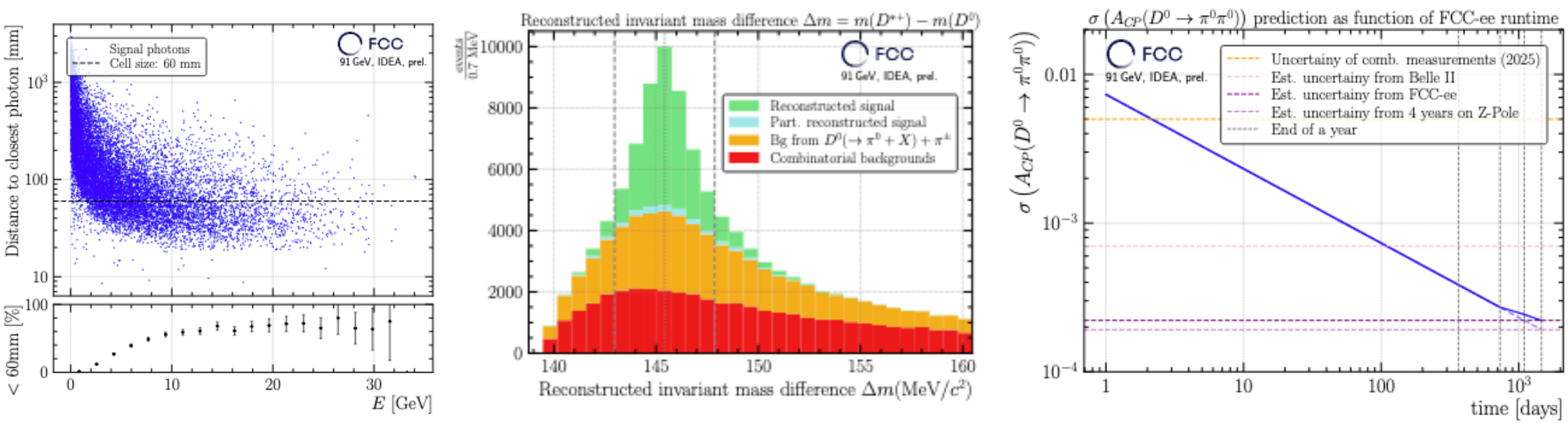
© A. Wiederhold, M. Kenzie
arXiv:2309.11353



5) Flavour@FCC — Cherry-picked highlights, charm

- The direct *CP* violation in charm decays has been observed by LHCb in 2-body charged modes. The interpretation of its magnitude is disputed.

  - We need to complement our anticipated knowledge with neutral modes. A first exploration took place w/ $D^0 \to \pi^0\pi^0$ (see W. Weber)

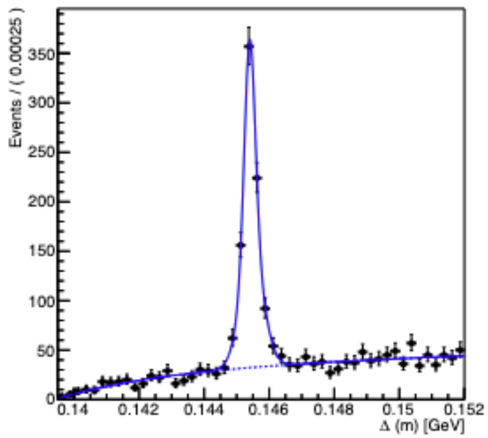


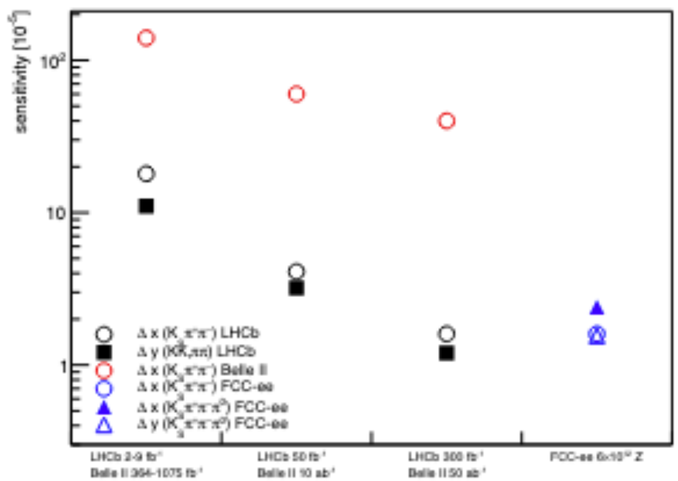
  - Despite a non-optimal electromagnetic calorimeter (6 cm cell size), large improvements expected. Promising other channels, e.g. $D^0 \to K_S\pi^0$ …

  - One immediate further perspective is $D^0 \to \gamma\gamma$, calo. requirements.

5) Flavour@FCC — Cherry-picked highlights, charm

- More is to study with CP violation in mixing (not observed to date). The relevant modes are here $D^0 \to K_S\pi^+\pi^-\pi^0$ and $D^0 \to K_S\pi^+\pi^-$



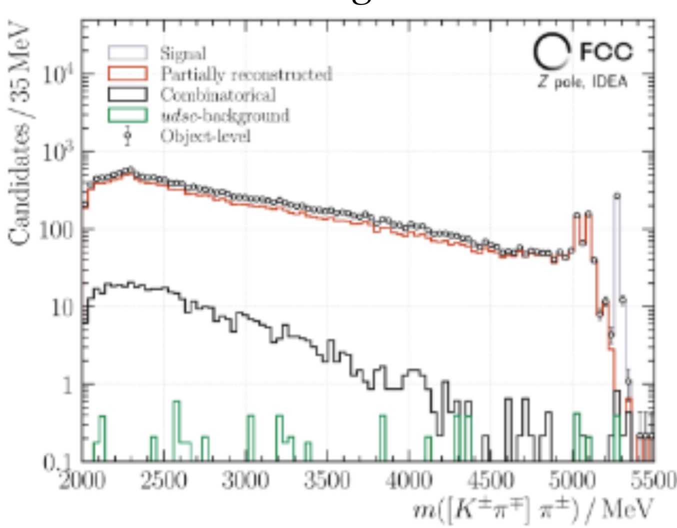


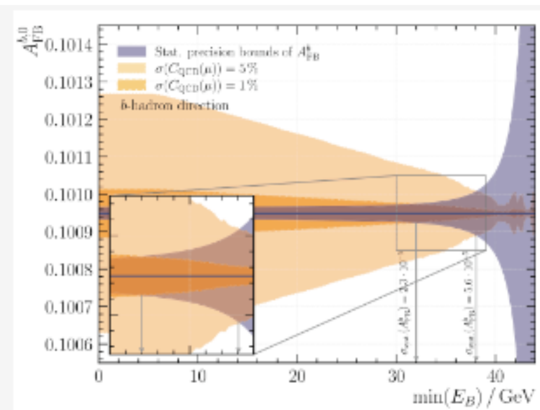
- Nathan Jurik's conclusion: FCC-ee will clearly be able to have significant impact on our knowledge of time-dependent *CP* violation! V0 tracking requirements and calorimeter requirements

- Rare decays program, *e.g.* in particular $c \to u\nu\bar{\nu}$ is unique to FCC-ee. (See Dominik Suelmann)

- Global SMEFT fits at FCCee aiming at sorting out the BSM patterns do use jointly electroweak and flavour observables.
- This WG gathers the tau properties (flavour and electroweak) and the *b* and *c* quark electroweak properties using *flavoured* experimental techniques, *e.g.* exclusive decay tagger (see Romain Madar).

$e.g.\ B^0 \to D^0\pi$





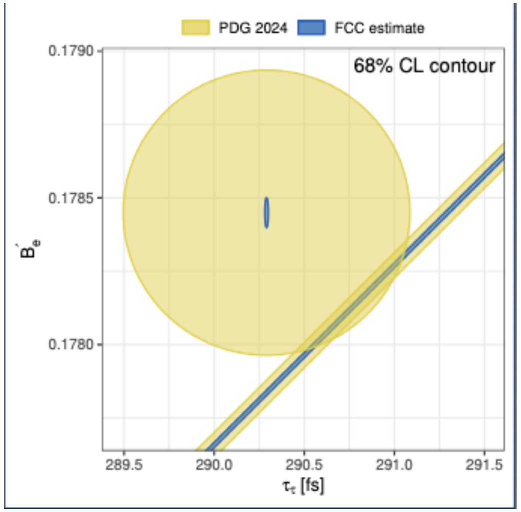
$\sigma_{A_{FB}^b} = (2.3 \oplus 2.3) \times 10^{-5}$, assuming $\sigma_{C_{QCD}} = 1\%$
$\to$ factor ~ 3 on $\sin^2\theta_W$ precision compared to A_{FB}^{μ}

5) Flavour@FCC — Cherry-picked highlights, tau/EWK

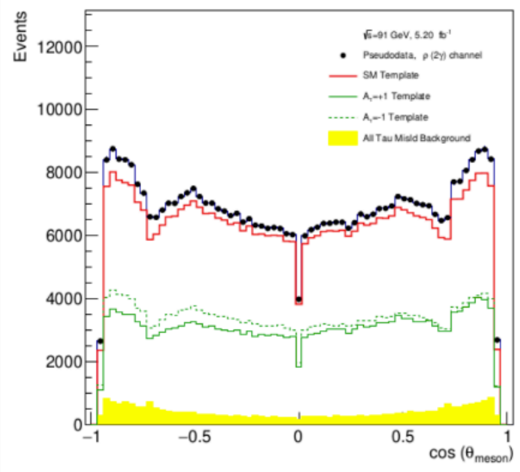
- First look at Forward-Backward tau asymmetry benefitting of the excellent 3-prongs vertexing and the exquisite knowledge of the luminous region.

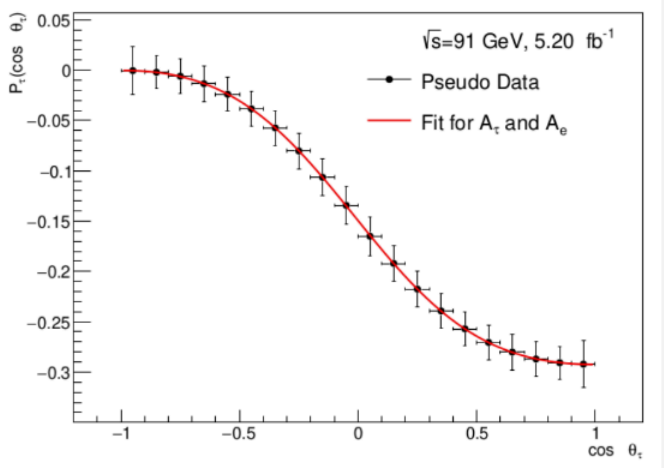
- Serves as well the tau lifetime measurement (central to Lepton Flavour Universality) (see Alberto Lusiani)

Vertexing and calorimetry measurements: lifetime and $\tau \rightarrow \pi\pi^0\nu_\tau$



- Tau polarisation looked after as well (M. Cepeda)





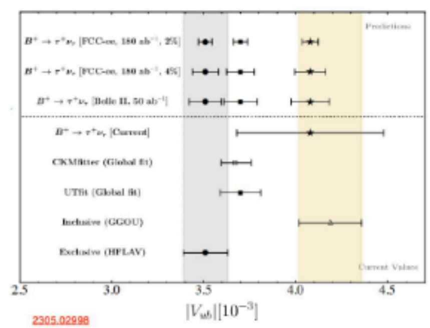
- Pick the summary slide here (more in the back-up if you're interested into the physics with *W* pairs)

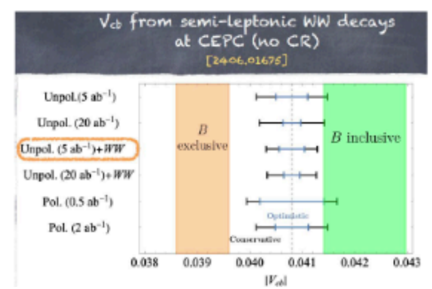
WG3: Charged-current processes

Experiment

(Semi)-leptonic decays:
- How precisely can we determine the fragmentation functions? They will be limiting any absolute measurements. Do/Will standard candles from the B factories have sufficient precision (sub-permille)
- B-tagging algorithms will allow for new kinds of measurements, prominent example is inclusive (not sum-of-exclusive) measurements

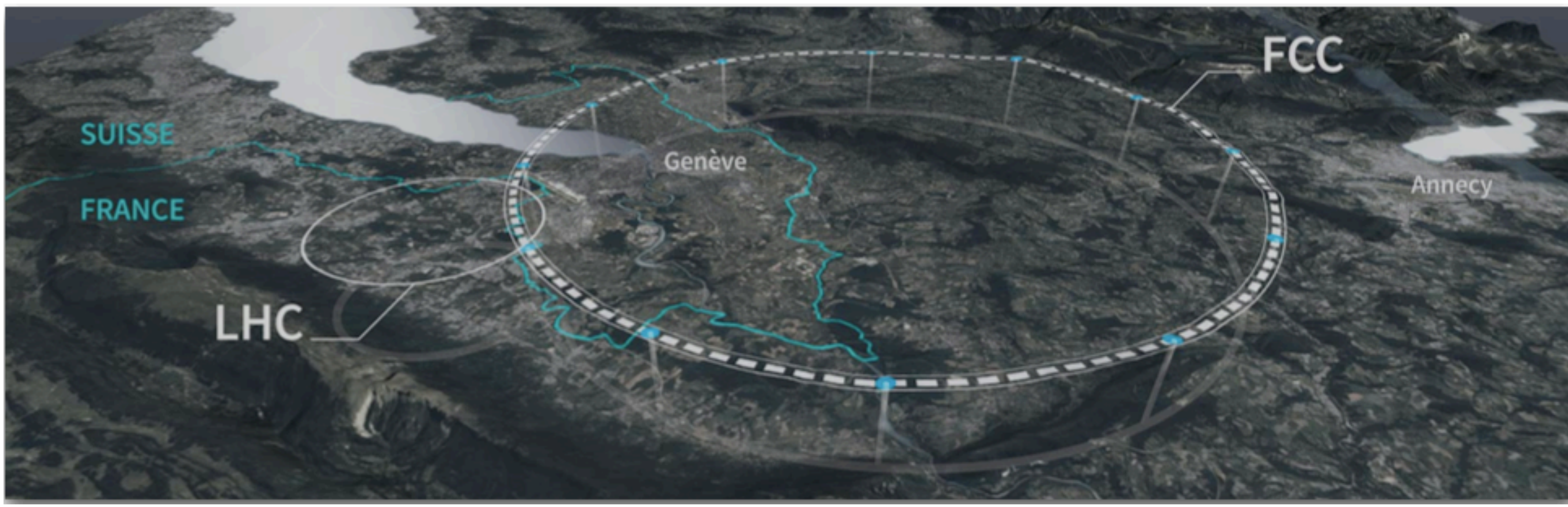
Vcb in particular:
- The Inclusive-exclusive tension has been with us for over a decade, and will or will not be resolved at the B factories.
- The key point: The tension drives our understanding of Vcb, and not the precision of the individual measurements
- A new measurements that has different systematics: on-shell W, but what are the systematics and how well are they understood?
- How precisely can we calibrate the jets at the Z-pole AND propagate these results from the Z-pole to the WW threshold?
- And what happens if that is incompatible with inclusive and exclusive Vcb?





- The unique cases are not forgotten, *e.g.* $B_c^+ \to \tau^+ \nu_\tau$.

8) Conclusions



6) Summary I

- FCC-ee is the proposal for the next flagship project at CERN (community and ESG recommandation)

- It is much more than a Higgs factory:

  - Z factory [$\mathcal{O}(10^{13})$]

  - b, τ , c factories [$\mathcal{O}(10^{12})$]

  - W factory [$\mathcal{O}(5.10^{8})$]

  - top factory [$\mathcal{O}(10^{6})$]

  - Discovery machine at low couplings / masses

- The decision on the machine by the CERN council is expected in autumn 2028.

6) Summary II

- FCC-ee is the proposal for the next flagship project at CERN (community and ESG recommandation)

- There's a vibrant program for Flavour Physics for the next two decades: the completion of Belle II and the desirable advent of the second LHCb upgrade (300 /fb). Our knowledge will improve a lot.

- FCC-ee is allowing for a continuation of the Flavour program and to deepen it further. And much more: we'll have within the same experiments the two pillars of our current knowledge (electroweak precision tests and CKM profile). Share experimental tools and interpretation frameworks.

- The Flavoured Circular Collider Workshop provides the adequate platform to welcome your questions curiosities, questions and studies. Next event: https://indico.cern.ch/event/1644557/

6) Summary III.

- Is it reasonable to plan a Physics program for seventy years? It was.
- The previous HEP European planning was only for … 60 years!

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field, H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann, K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter, C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

- The FCC plan guarantees that we're asymptotically pushing the precision on Flavours, Higgs and Electroweak gauge knowledge and let options opened to high energy protons if the case is made.
- And remember: the SM has nowhere to go.

8) Final remark:

- If interested in joining the effort, many (many) opportunities.

FCC-PED-PhysicsGroup-Flavours-Rare@cern.ch
To subscribe: https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Flavours-Rare
FCC-PED-PhysicsGroup-Flavours-CPV@cern.ch
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Subscribing to any of these makes you a member of
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which will be used for general announcements. (Can subscribe directly:
https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Flavours)

Please use institutional email addresses, as you have to be approved.

7) Back-up: les renforts !

- Example: 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.

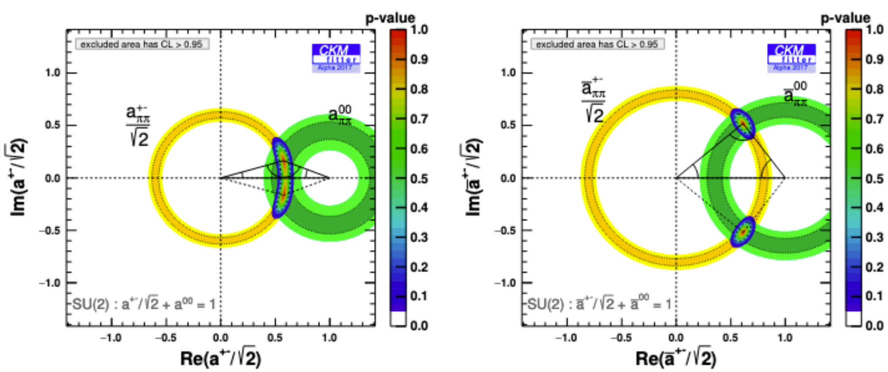


Figure 4: *Constraint on the reduced amplitude* $a^{+-} = A^{+-}/A^{+0}$ *in the complex plane for the* $B \to \pi\pi$ *(left) and* $\bar{B} \to \pi\pi$ *systems (right). The individual constraint from the* $B^0(\bar{B}^0) \to \pi^+\pi^-$ *observables and from the* $B^0(\bar{B}^0) \to \pi^0\pi^0$ *observables are indicated by the yellow and green circular areas, respectively. The corresponding isospin triangular relations* $a^{00} + a^{+-}/\sqrt{2} = 1$ *(and CP conjugate) are represented by the black triangles.*

- 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.

7) Back-up

- Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements. The feasibility study entangles the Physics performance and detector concepts. Flavour physics places most demanding requirements for vertexing and calorimetry.

- The feasibility study will be used to systematically address the physics case while placing requirements on the detectors. Hadron particle identification deserves a special treatment and Flavour physics is at the heart of it.

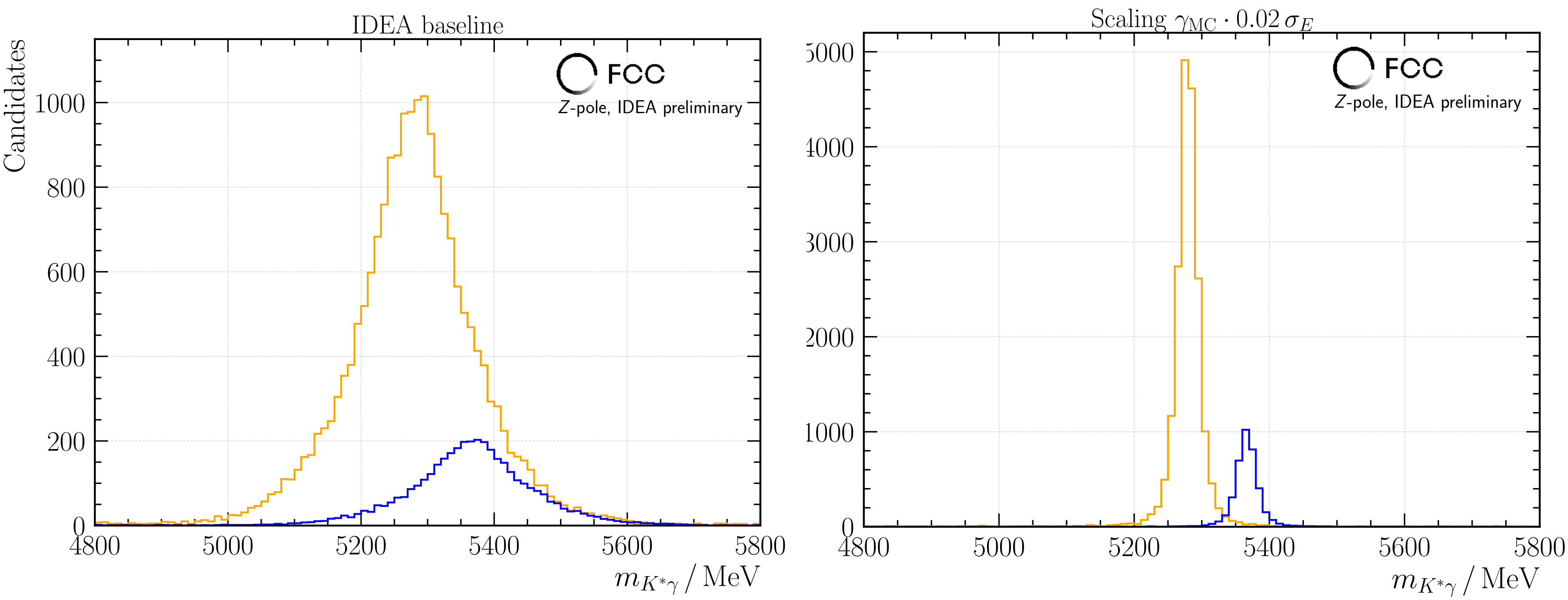
- All studies at the Z pole shown above are made for 5.10^{12} Z decays. Most of flavour observables will remain statistically limited. More would be desirable ! The machine study from two IPs to four IPs is positive and would bring about a factor 2 (1.7) in integrated luminosity.

- Four experiments can as well allow for different experiment designs, including a flavour-oriented concept.

- Engage and reach out to make this plan happening.

7) Back-up

- Two illustrations:
  - 2) From radiative decays: separation of $b \to s\gamma$ and $b \to d\gamma$. *Academic exercise w/ $B^0 \to K^*\gamma$.*



- There's a difference! addressing or not this Physics.

6) Back-up:

- Example: degree alpha measurement : a study to get started.

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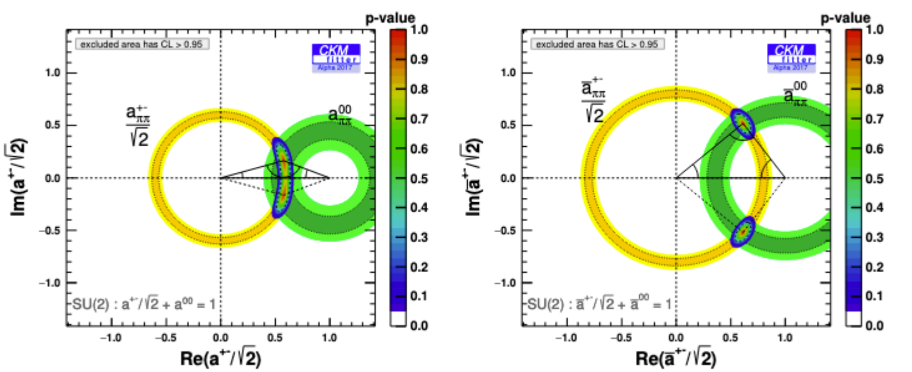

Figure 4: *Constraint on the reduced amplitude $a^{+-} = A^{+-}/A^{+0}$ in the complex plane for the $B \to \pi\pi$ (left) and $\bar{B} \to \pi\pi$ systems (right). The individual constraint from the $B^0(\bar{B}^0) \to \pi^+\pi^-$ observables and from the $B^0(\bar{B}^0) \to \pi^0\pi^0$ observables are indicated by the yellow and green circular areas, respectively. The corresponding isospin triangular relations $a^{00} + a^{+-}/\sqrt{2} = 1$ (and CP conjugate) are represented by the black triangles.*

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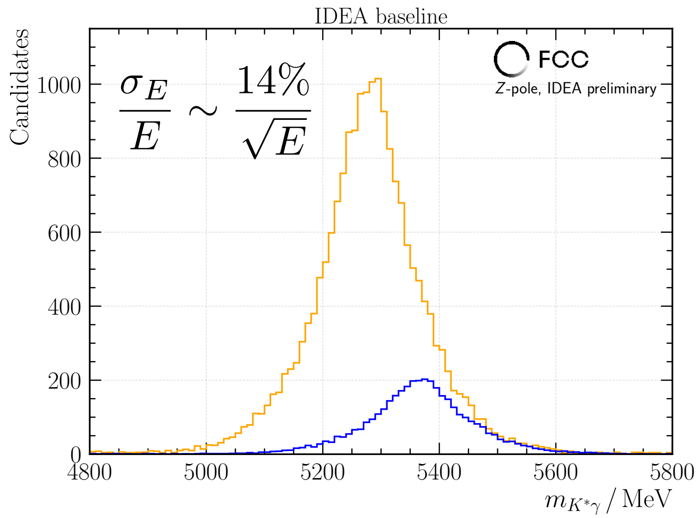
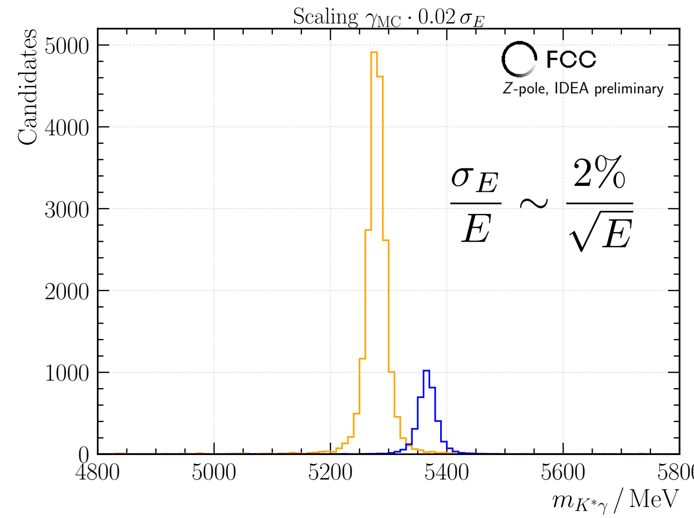
6) Back-up: GRAiNITA a novel idea for calorimetry

- Flavours: exquisite EM energy resolution in order!

G. Hull, J. Lefrançois et al. 2312.07365





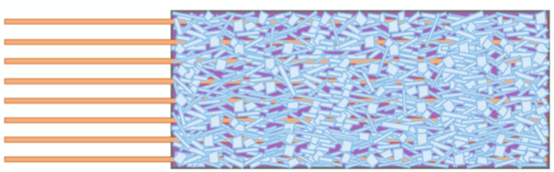
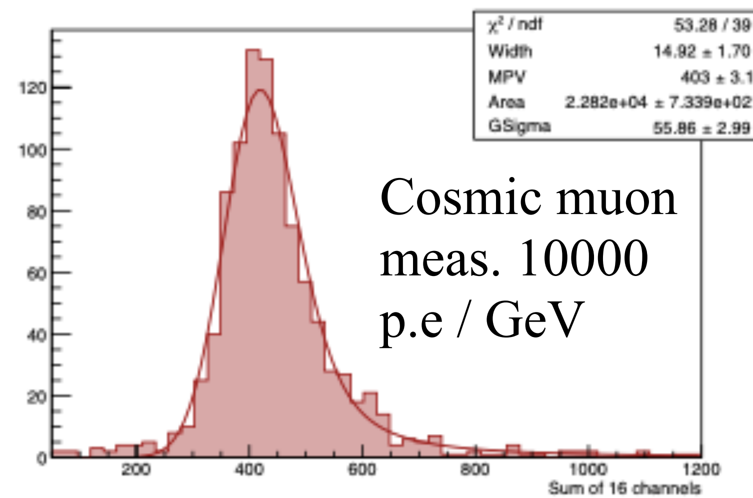


Table 1. Properties of interest for the GRAiNITA study of the the BGO and $ZnWO_4$ materials.

	BGO	$ZnWO_4$
Effective Z	74	61
Density (g/cm^3)	7.13	7.87
Refractive index	2.15	2.0 - 2.3
Light yield (photons/MeV)	~ 9000	~ 9000
Peak emission wavelength (nm)	480	480
Decay time (μs)	0.3	20
Radiation length (cm)	1.12	1.20
Molière radius (cm)	2.26	1.98



Should these numbers be confirmed, the 1% stochastic target is at reach ! Constant term to study …

6) Back-up:

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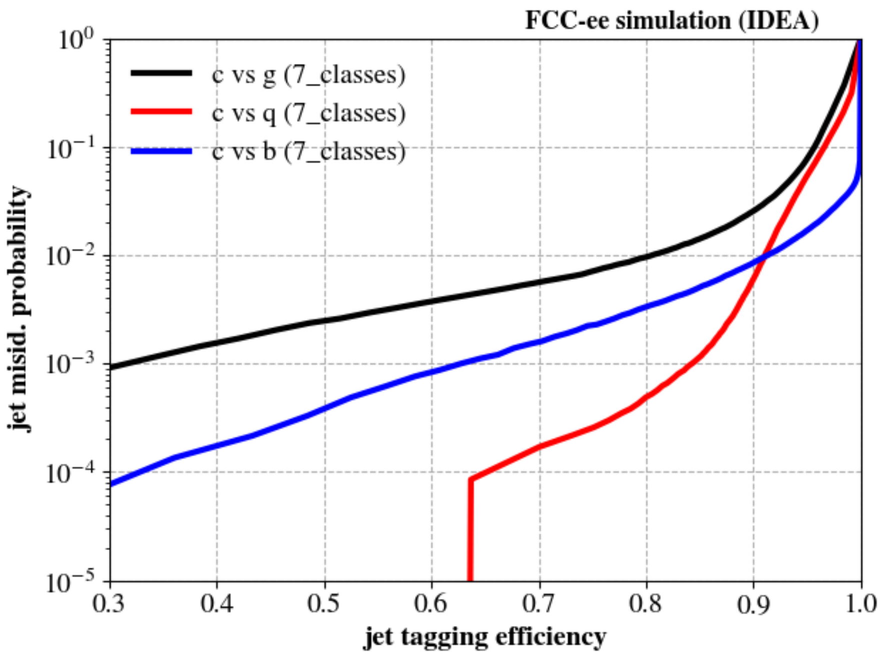
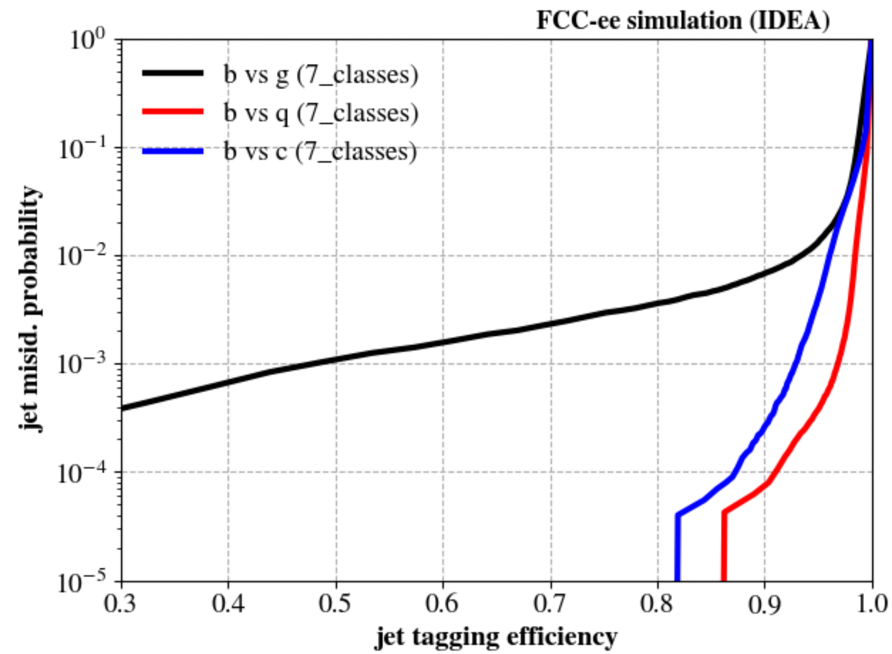
6) Back-up: $|V_{cb}|$ and CKM

- From Michele Selvaggi





- Racetrack placement and population reach-out:

FUTURE CIRCULAR COLLIDER

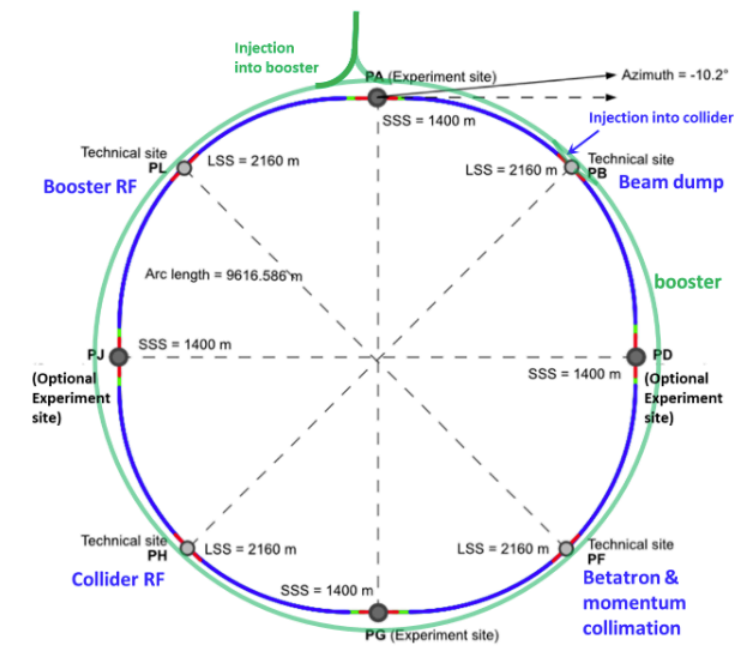
Optimized placement and layout for feasibility study

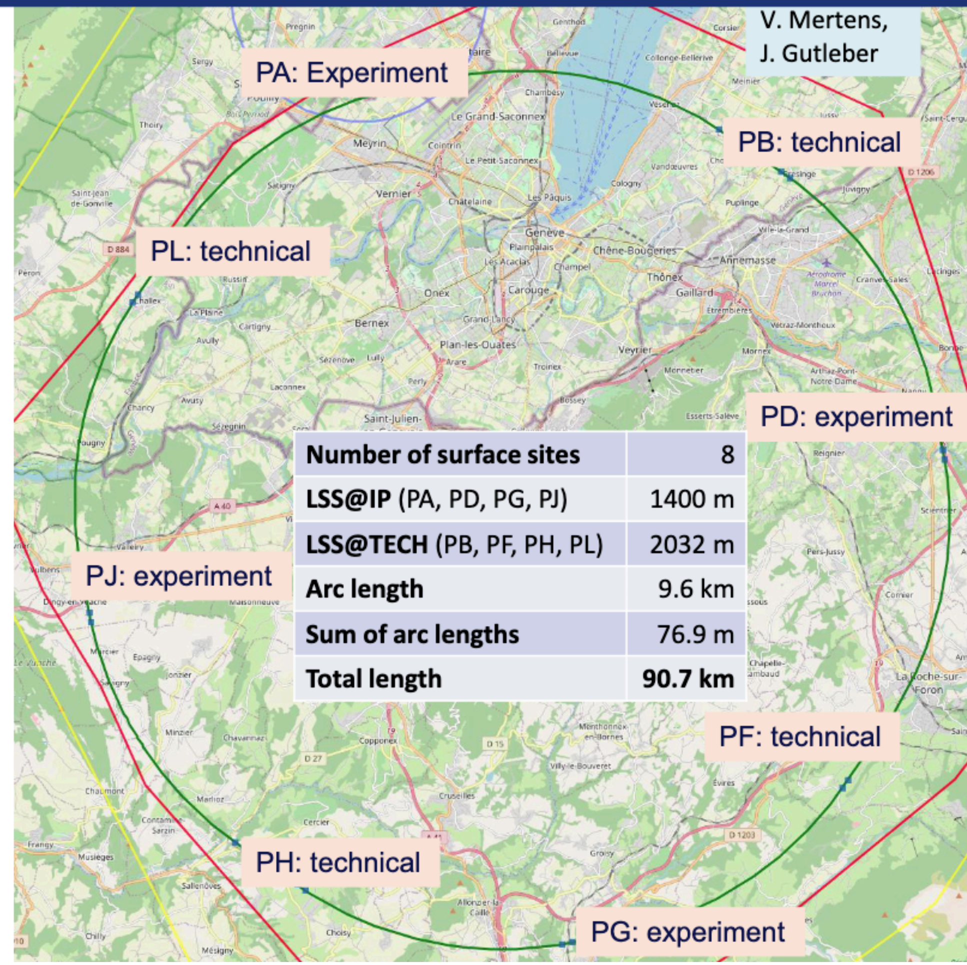
Major achievement: optimization of the ring placement

Layout chosen out of ~ 100 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment (protected zones), infrastructure (water, electricity, transport), etc.
"Éviter, reduire, compenser" principle of EU and French regulations

Lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold superperiodicity, possibility of 2 or 4 IPs

Whole project now adapted to this placement

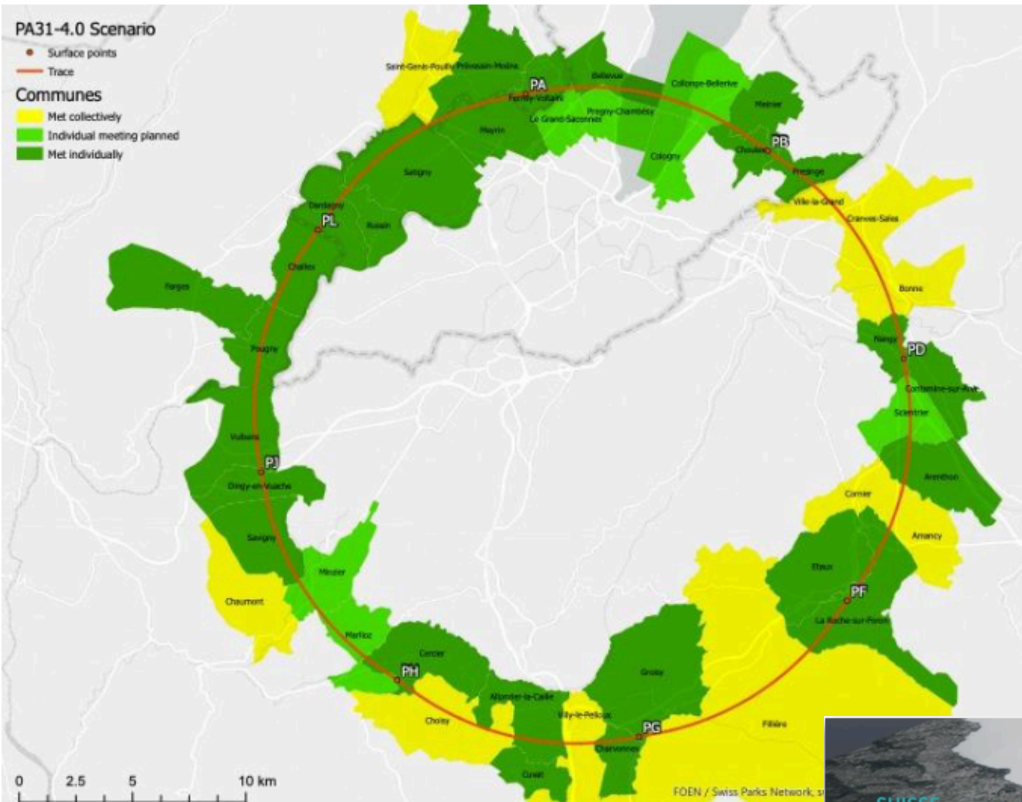




Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

6) Back-up: implementation

- Racetrack placement and population reach-out:



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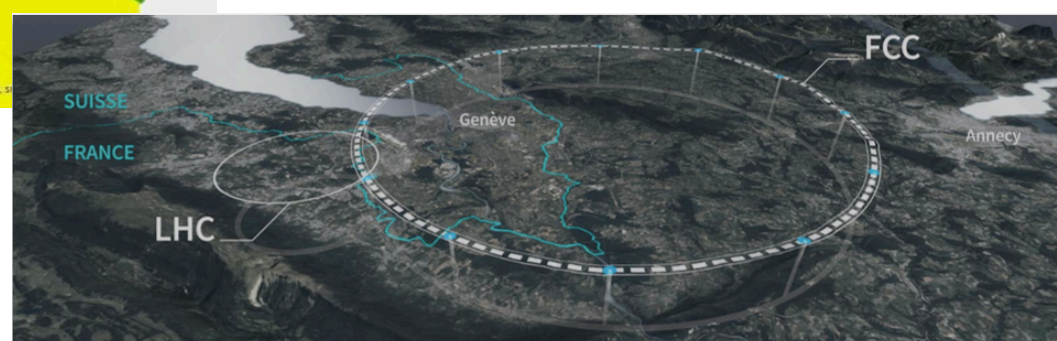
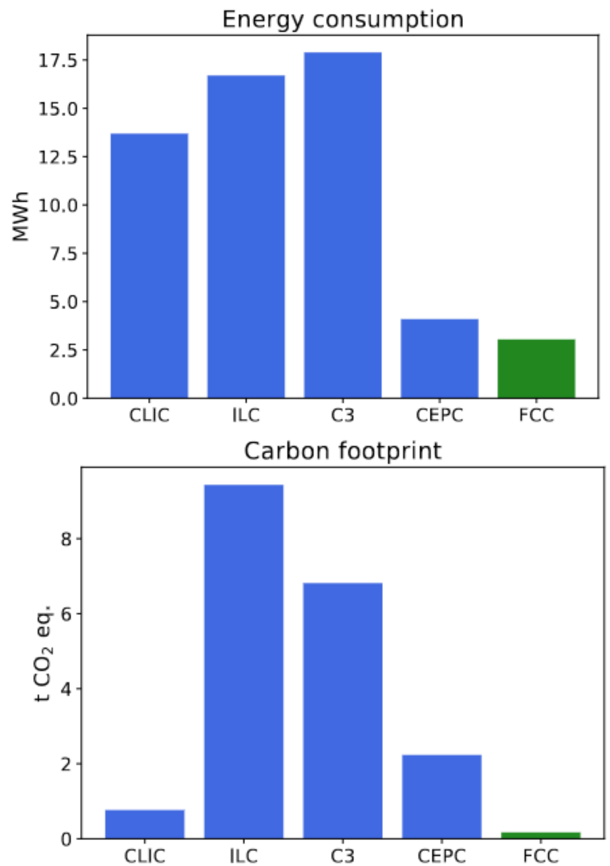


6) Back-up: implementation

- Energy consumption, carbon footprint, and excavation materials matter most.

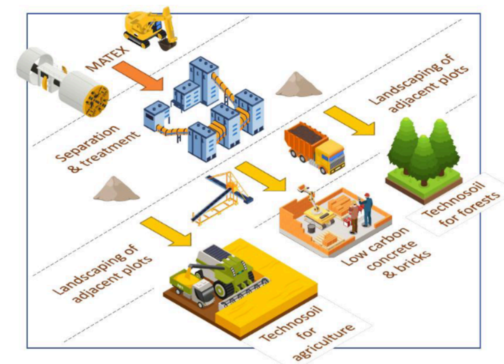
[2208.10466](https://arxiv.org/abs/2208.10466)

Fig. 2: Energy consumption (top) and carbon footprint (bottom) for the five Higgs factory projects (CLIC at 380 GeV, ILC/C[3] at 250 GeV, and CEPC/FCC-ee at 240 GeV), per Higgs boson produced, i.e., for an equivalent physics outcome. In these plots, FCC-ee is assumed to operate only two detectors. With four detectors, the FCC-ee estimators would be divided by a factor 1.7.



Management of the excavated materials: a key topic

- **Priority : reuse, minimize disposal**
  - Feasible disposal concept exists, but is very costly and comes with nuisances
- **Avoid and reduce transport**
  - In particular with trucks
- Industrialisation of re-use pathways according to available resources
  - Value creation for agriculture and reforestation
  - Improvement of acid and polluted plots
  - Recovery of wastelands
  - Use as construction materials within the project (e.g. compressed blocks)



MATEX Open Innovation Example

"Mining the Future®" competition carried out in the frame of the FCCIS H2020 project revealed a number of credible processes and technologies to

- Develop approaches to **manage the 8 million m³** of materials once excavated (foisonné) and
- contribute in meaningful and relevant ways to the **ever critical issue in Europe of disposing (waste) excavated materials** from construction projects.

A consortium with academic & industrial partners is built to provide tangible evidence with a multi-year agricultural trial **on 10'000 m² at LHC P5 in Cessy** to
- convert **molasse to arable soil**,
- **promote reforestation** with climate fit trees and
- **reduce the carbon footprint** of construction projects
- **bring quality assured processes to market**

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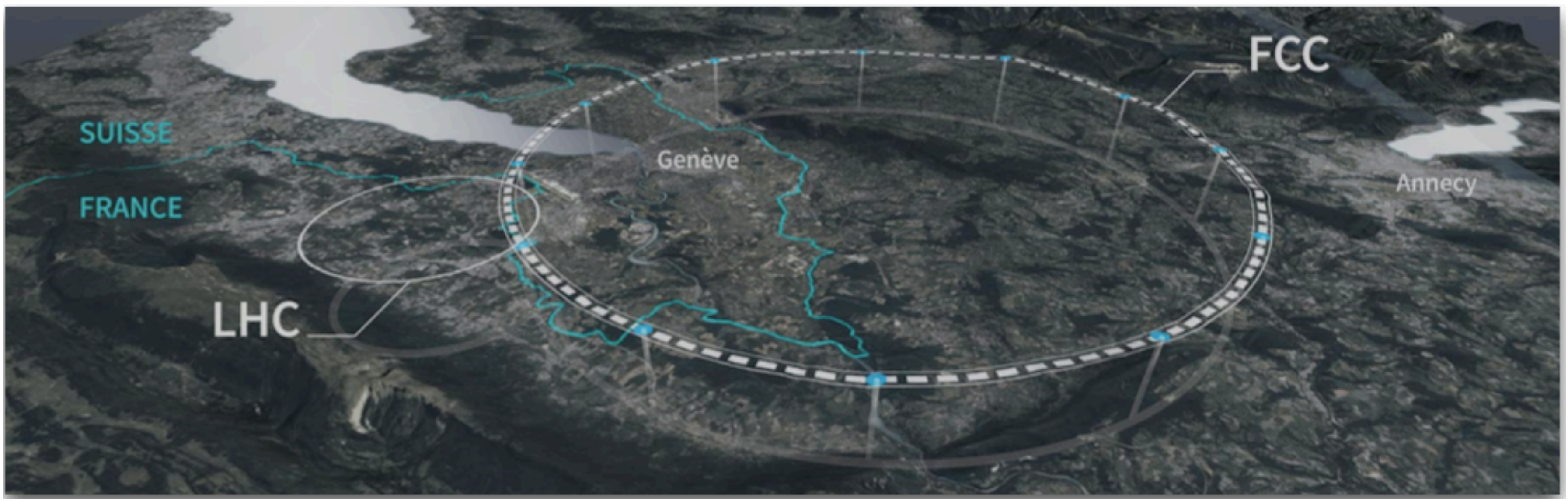
Focus on two analyses



6) Focus#1: the CKM matrix element V_{cb}

- At the horizon of the next electron collider, the knowledge of the CKM profile is expected to have been deeply revisited by LHCb and Belle II/III.

- The CKM angle γ might be known at the sub-degree precision; as will the angle β.

- One relevant figure of merit to devise the possible bottlenecks in precision that would alter the global interpretation of the CKM profile is a quasi-model-independent analysis of the BSM contributions in neutral kaon and beautiful-meson mixing phenomena.

- Bottomline: one needs the matrix element $|V_{cb}|$ at a much-higher precision than what semileptonic *B* decays can provide. The next couple of slides to justify the statement. $|V_{cb}|$ is the normalisation of the UT in the SM and beyond (in a large class of BSM models).

- Longstanding tensions in exclusive / inclusive determinations to be fixed!

6) Focus#1: the CKM matrix element V_{cb}

- Model-independent approach to constrain BSM Physics in neutral meson mixing processes

$$\langle B_q | \mathcal{H}^{\mathrm{SM+NP}}_{\Delta B=2} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}^{\mathrm{SM}}_{\Delta B=2} | \bar{B}_q \rangle \times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))$$

$$\mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}$$

Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Grossman, Nir & Worah, PLB 407, 307 (1997)

Assumptions:

✓only the short distance part of the mixing processes might receive NP contributions.

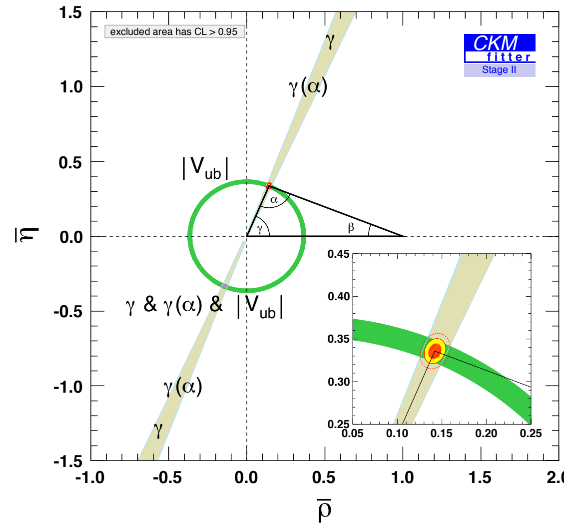
✓Unitary 3x3 CKM matrix (Flavour violation only from the Yukawas-MFV hypothesis).

✓ tree-level processes are not affected by NP (so-called SM4FC: $b \rightarrow f_i f_j f_k$ ($i \neq j \neq k$)). As a consequence, the quantities which do not receive NP contributions in that scenario are:

$$|V_{ud}|,\ |V_{us}|,\ |V_{ub}|,\ |V_{cb}|,\ B^+ \rightarrow \tau^+ \nu_\tau \text{ and } \gamma$$

6) Focus#1: the CKM matrix element V_{cb}

- The unitarity triangle: fixing CKM parameters w/ $|V_{ub}|$, $|V_{cb}|$ and gamma. This is the anticipated landscape after Belle II and LHCb Upgrade I.



- Knowing the CKM parameters, one can introduce the constraints of the *B* mixing observables depending on the NP complex number (here parameterised as Δ).

parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\rm NP}\rvert \times \Delta m_q^{\rm SM}$
2β	$2\beta^{\rm SM} + \Phi_d^{\rm NP}$
$2\beta_s$	$2\beta_s^{\rm SM} - \Phi_s^{\rm NP}$
2α	$2(\pi - \beta^{\rm SM} - \gamma) - \Phi_d^{\rm NP}$
$\Phi_{12,q} = {\rm Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\rm SM} + \Phi_q^{\rm NP}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\rm SM}} \times \frac{\sin(\Phi_{12,q}^{\rm SM}+\Phi_q^{\rm NP})}{\lvert\Delta_q^{\rm NP}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\rm SM} + \Phi_q^{\rm NP})$

6) Focus#1: the CKM matrix element V_{cb}

FCC

hep-ph 2006.04824

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2} \left(\frac{4.5\,\mathrm{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg\left(C_{ij}\, \lambda^{t*}_{ij}\right),$$

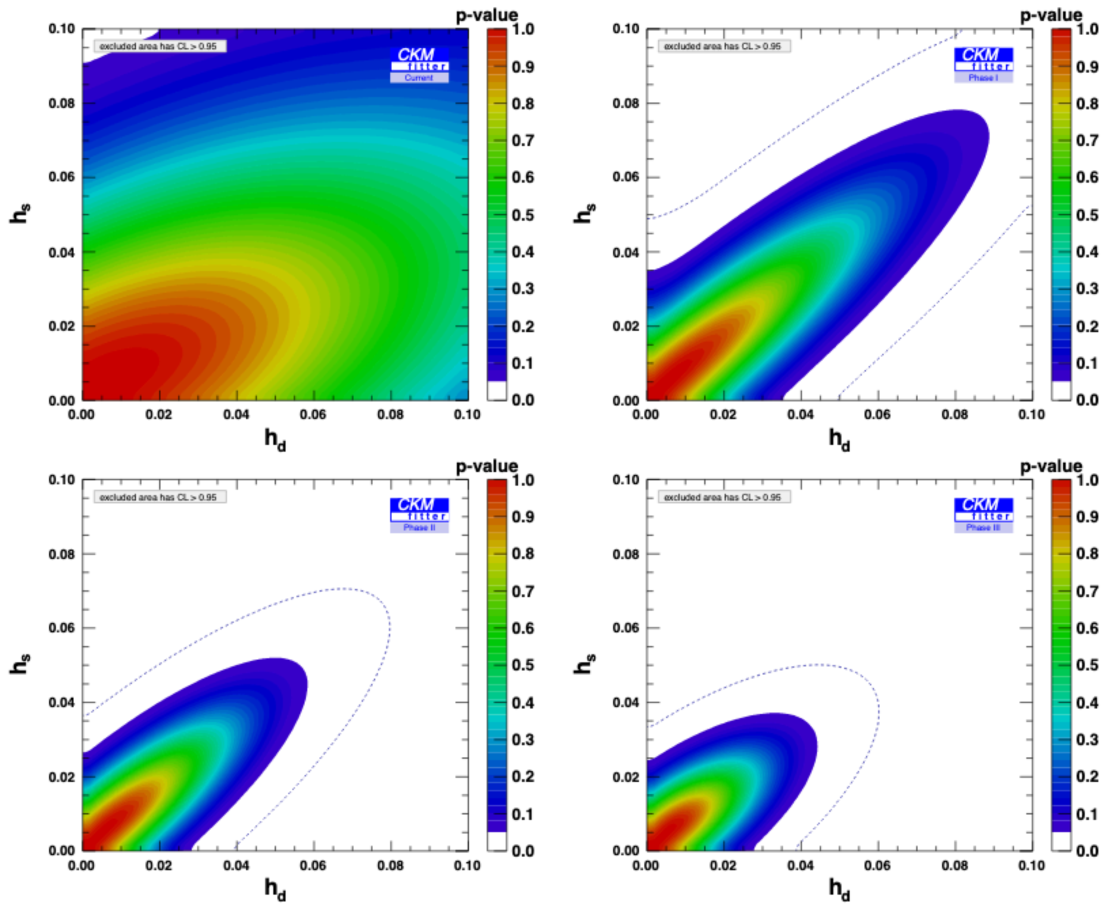


FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

6) Focus#1: the CKM matrix element V_{cb}

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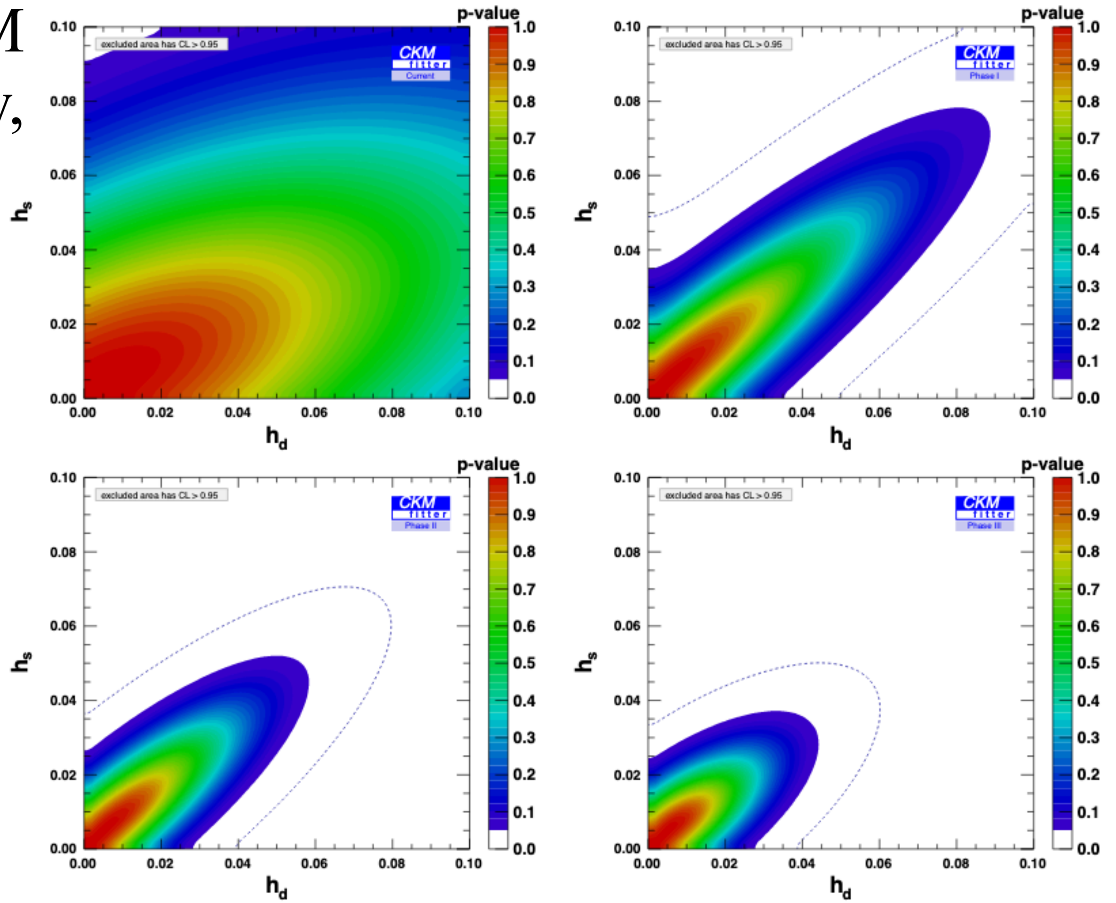
hep-ph 2006.04824

rescaled to SM

— Now,



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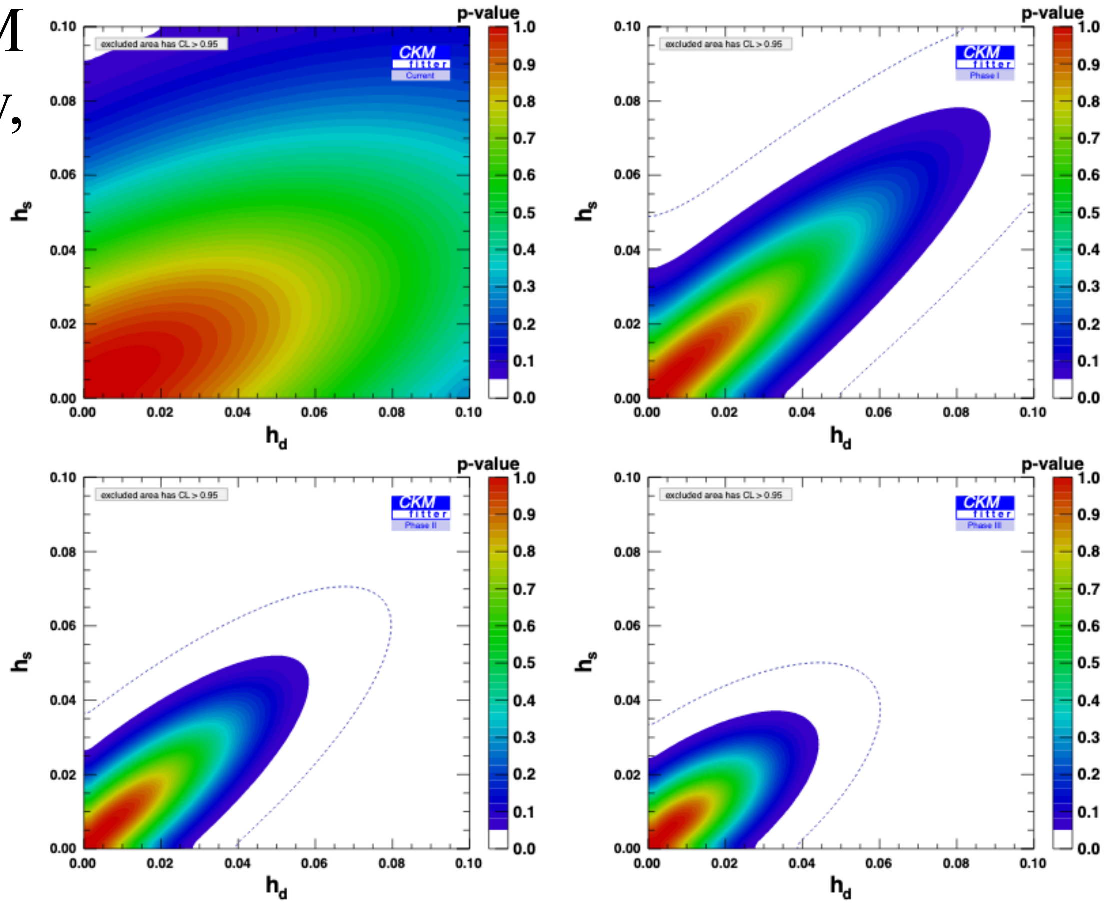
hep-ph 2006.04824

rescaled to SM
— Now,

after LHCb-U1
and Belle II
— 2030



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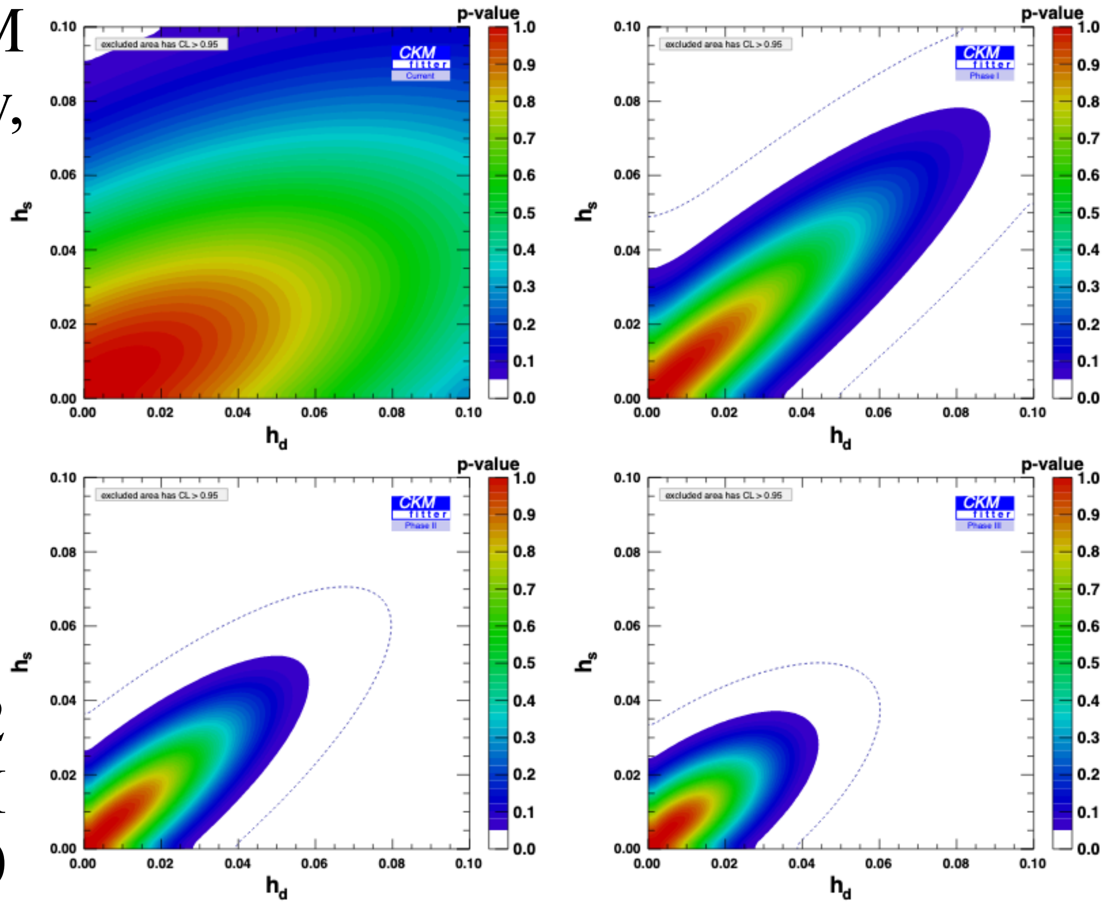
$$\sigma = \arg(C_{ij}\,\lambda_{ij}^{t*}),$$

hep-ph 2006.04824

rescaled to SM — Now,

after LHCb-U1 and Belle II — 2030

after LHCb U2 and Belle III — 2040



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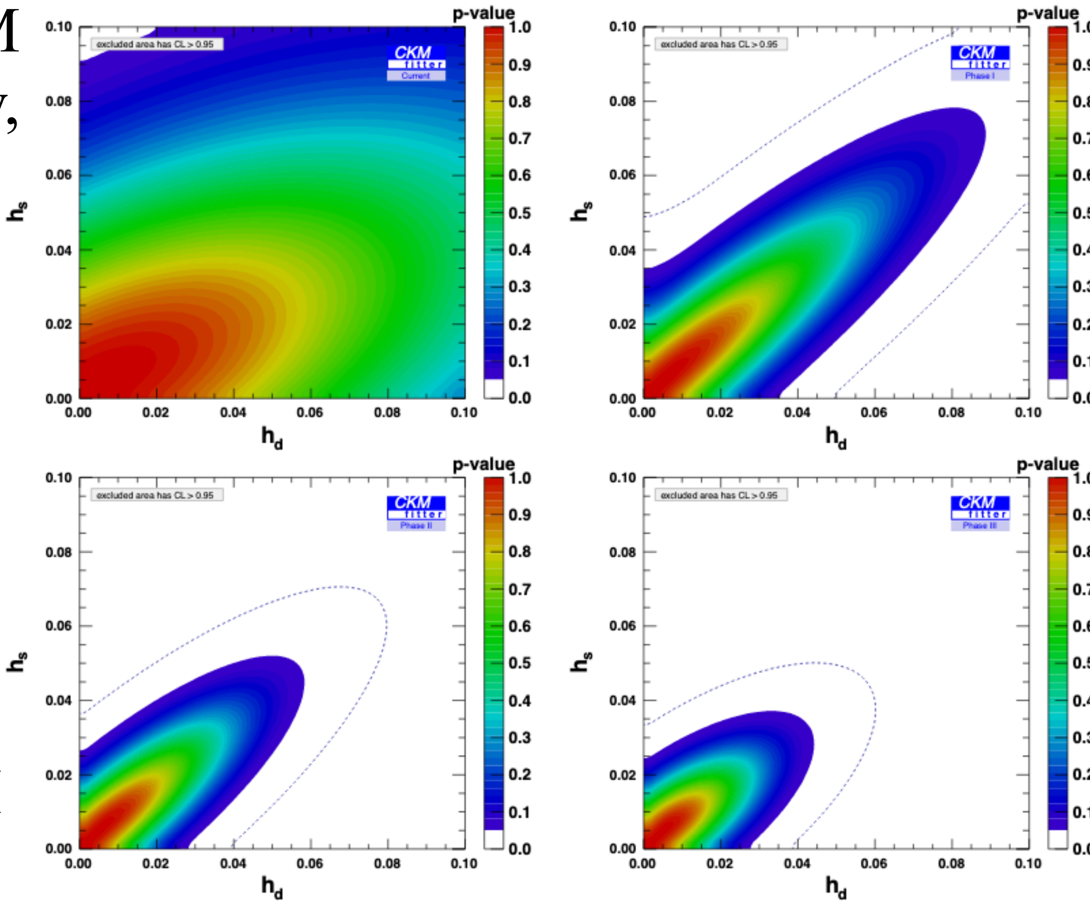
hep-ph 2006.04824

rescaled to SM — Now,

after LHCb-U1 and Belle II — 2030

after LHCb U2 and Belle III — 2040

Vcb improved LQCD not



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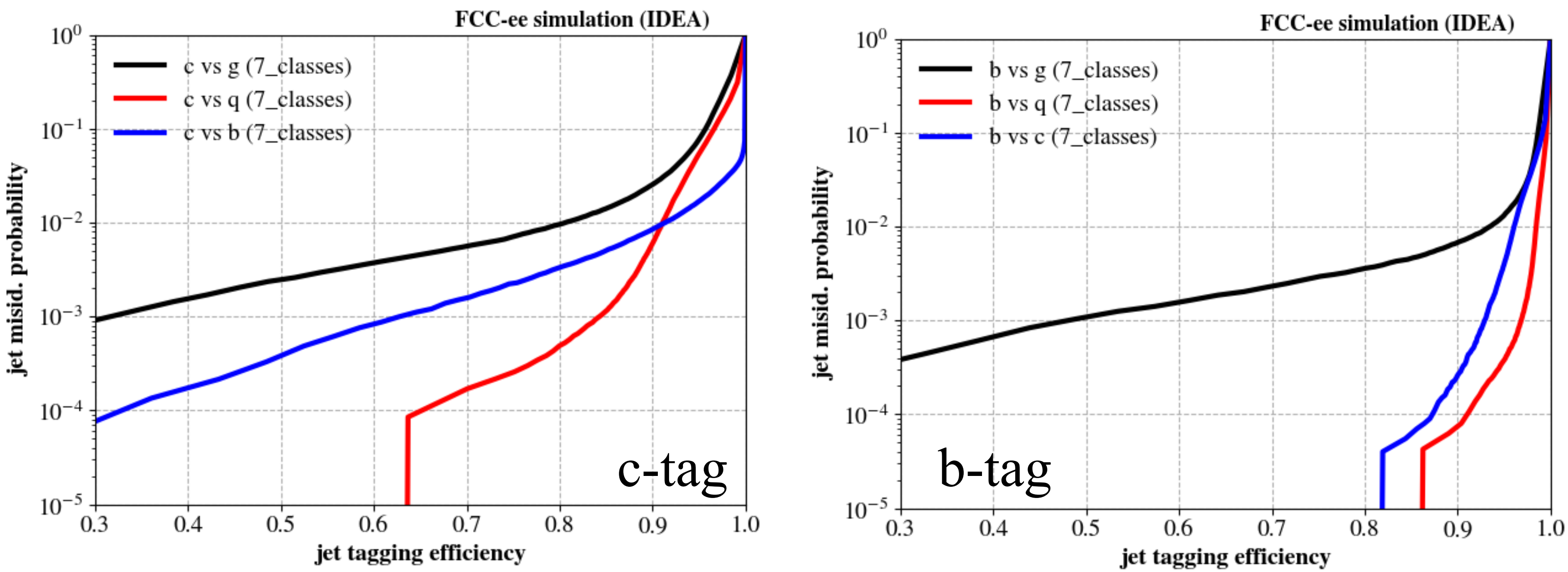
6) Focus#1: the CKM matrix element V_{cb}

- Theory: none at WW threshold and beyond! Marginal correction to the B scale. Clean observable and hence becomes a benchmark to test the Lattice-QCD predictions.

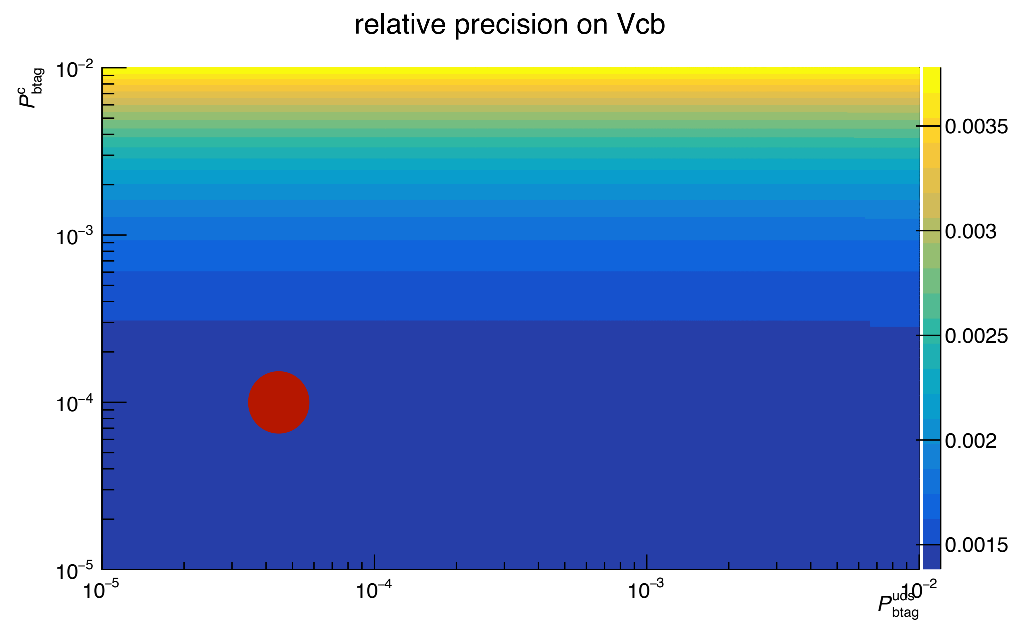
- Experiment: this study can be a test bench for jet-flavour tagging algorithms. The latest (or close) performance of FCC-ee is tested today.



6) Focus#1: the CKM matrix element V_{cb}

- Jet tagging performance supposed as in the previous slide
- Consider (academic) $N_{WW} = 10^8$; count the signal and background.

Eff. \	*b*	*c*	*uds*
b-tag	0.87		
c-tag	0.001	0.65	0.0001



- $|V_{cb}|$ measurement precision can be 0.15 %, one order of magnitude better than the current precision and close to the asymptotic stat. precision.
- Jet-tagging efficiencies shall be determined from data at *Z*-pole

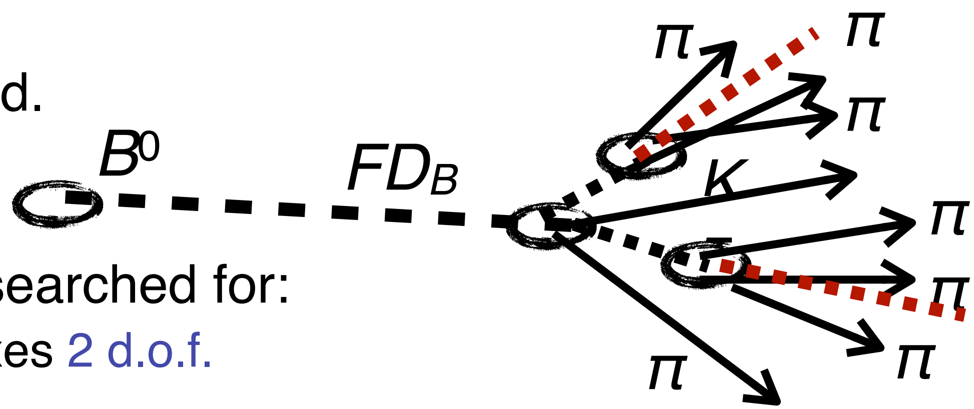
6) Focus#2: the transition $b \to s\tau^+\tau^-$

The scope:

- Semileptonic decays (Electroweak penguins in the SM) with tau in the final states are not measured. First evidence with neutrinos just out!
- One of the flavour physics sectors that are beyond the reach of the current experimental programme(s). Boost at the *Z* / case for luminosity at the Z (FCC-ee).
- Occupied some space as a change of paradigm for the search of New Physics from the Flavour problem(s). Though the excitement has lowered with better measurements from LHCb, third fermion generation couplings are a must to study
- The canonical decays with taus places ultra-demanding requirements on the vertex detector (fully solvable kinematics provided the decay vertices are known).

6) Focus#2: the transition $b \to s\tau^+\tau^-$

- $B^0 \to K^{*0}\ \tau^+\tau^-$: some vertices indeed.



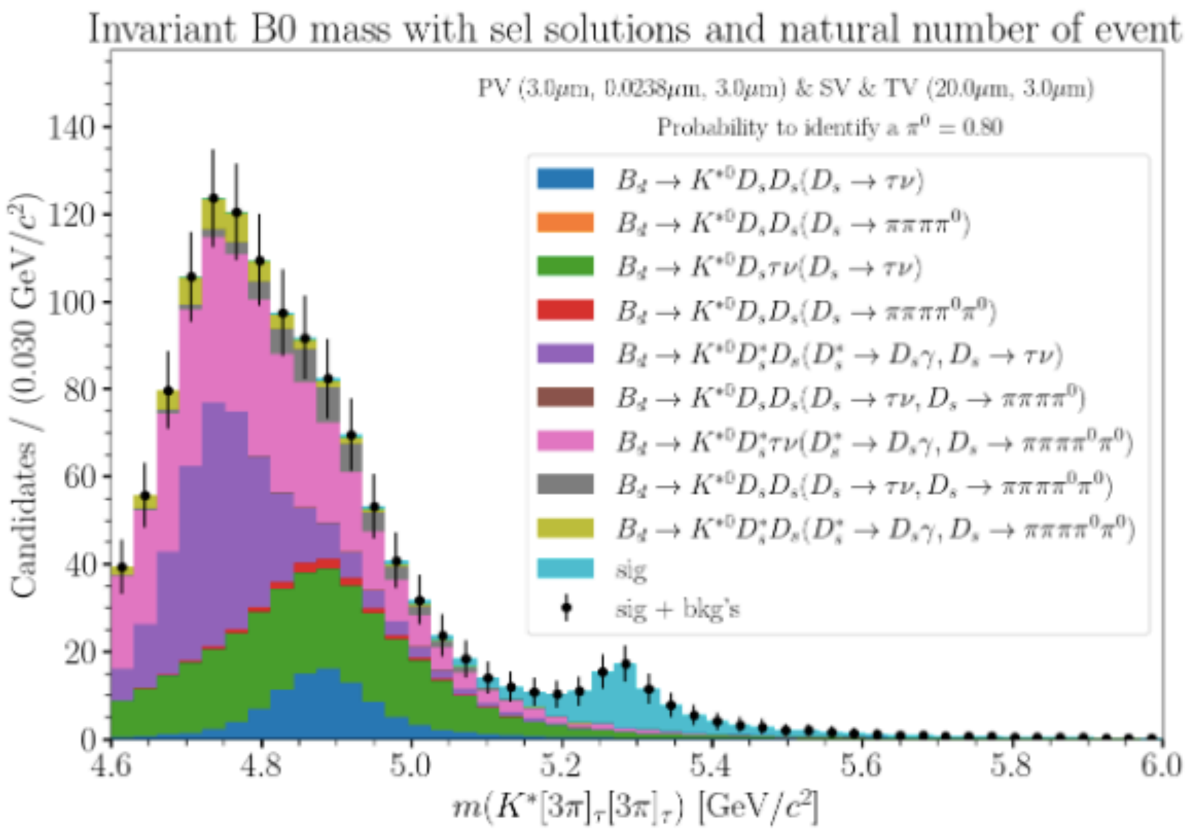
- Six momentum components to be searched for:
  - B^0 momentum direction from $K\pi$ fixes 2 d.o.f.
  - τ momenta direction fixes 4 d.o.f.
  - Mass of the τ provides 2 additional constraints
  - Since both tau legs provide quadratic equations, one ends up w/ 4 solutions.
  - Yet, the system is over-constrained and in principle fully solvable.

- $B^0 \to K^{*0}\ \tau^+\tau^-$: some backgrounds as well

Decay	BF (SM/meas.)	Intermediate decay	BF_had	Additional missing particles
Signal : $B^0 \to K^*\tau\tau$	1.30×10^{-7}	$\tau \to \pi\pi\pi\nu$, $K^* \to K\pi$	9.57×10^{-11}	
Backgrounds $b \to c\bar{c}s$:				
$B^0 \to K^{*0} D_s D_s$	2.78×10^{-4}	$D_s \to \tau\nu$	5.79×10^{-10}	2ν
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$	6.52×10^{-10}	ν , π^0
		$D_s \to \pi\pi\pi\pi^0$	7.35×10^{-10}	$2\pi^0$,
		$D_s \to \tau\nu, \pi\pi\pi\pi^0\pi^0$	5.47×10^{-9}	ν , $2\pi^0$
		$D_s \to \pi\pi\pi 2\pi^0$	5.17×10^{-8}	$4\pi^0$,
$B^0 \to K^{*0} D_s D_s^*$	8.78×10^{-4}	$D_s \to \tau\nu$	1.83×10^{-9}	2ν, γ/π^0
		$D_s \to \pi\pi\pi\pi^0\pi^0$	1.63×10^{-7}	$4\pi^0$, γ/π^0
Backgrounds $b \to c\tau\nu$:				
$B^0 \to K^{*0} D_s \tau\nu$	9.17×10^{-6}	$D_s \to \tau\nu$	3.59×10^{-10}	2ν
$B^0 \to K^{*0} D_s^* \tau\nu$	2.03×10^{-5}	$D_s \to \pi\pi\pi\pi^0\pi^0$	7.51×10^{-9}	ν, γ, $2\pi^0$

6) Focus#2: the transition $b \to s\tau^+\tau^-$

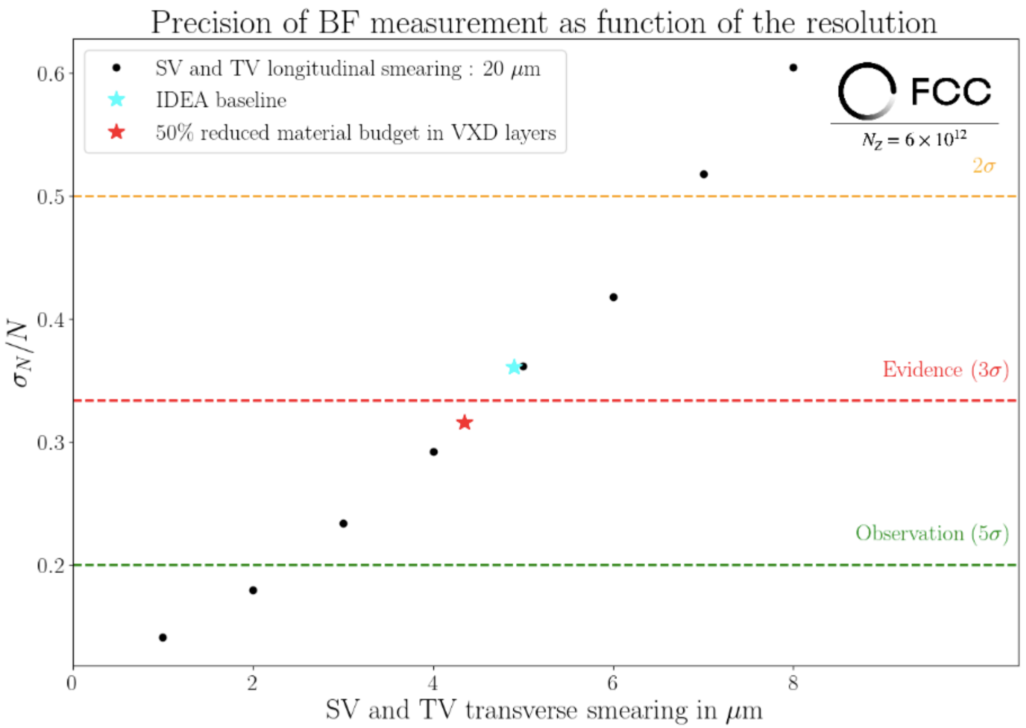
- $B^0 \to K^{*0}\ \tau^+\tau^-$: topological reconstruction + selection



- $B^0 \to K^{*0}\ \tau^+\tau^-$: we could see unambiguously the SM signal with this emulated detector! But it is an arbitrarily good one.

6) Focus#2: the transition $b \rightarrow s\tau^+\tau^-$

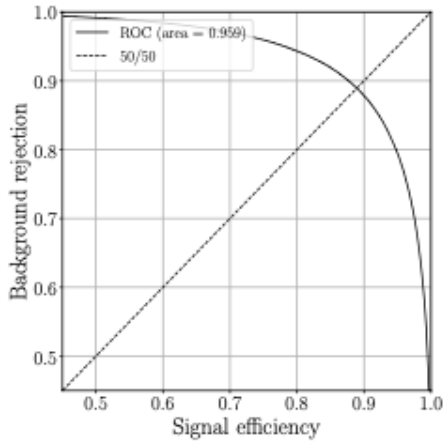
- $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$: Checking how much to improve a vertex detector design? The IDEA example @ FCC-ee.

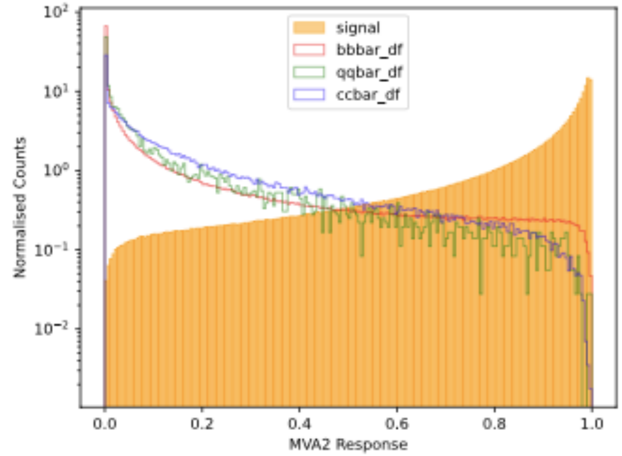


- One lesson: need to reduce the material of the beam pipe, or better, put the vertex detector in the beam pipe.

5) Reviews of current activities (Feas. Study)

- Flashing some of the recent studies: *b→svv*





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arXiv:2309.11353

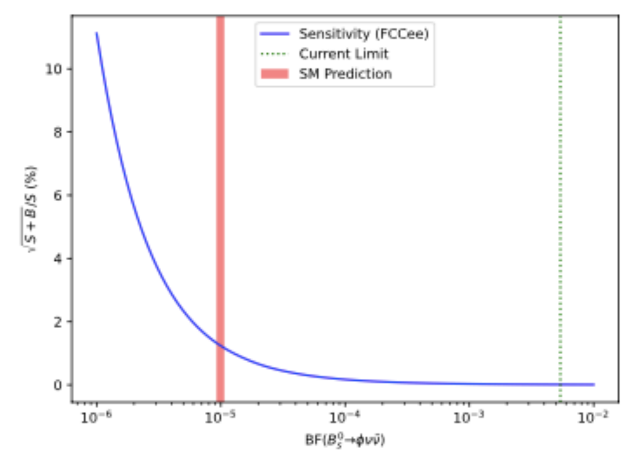
First indication of such a transition just came from Belle II (2023).

Analysis based on the hemisphere missing energy measurement confronting the event properties.

$B_s^0 \to \phi\nu\bar{\nu}$ Efficiency and Sensitivity

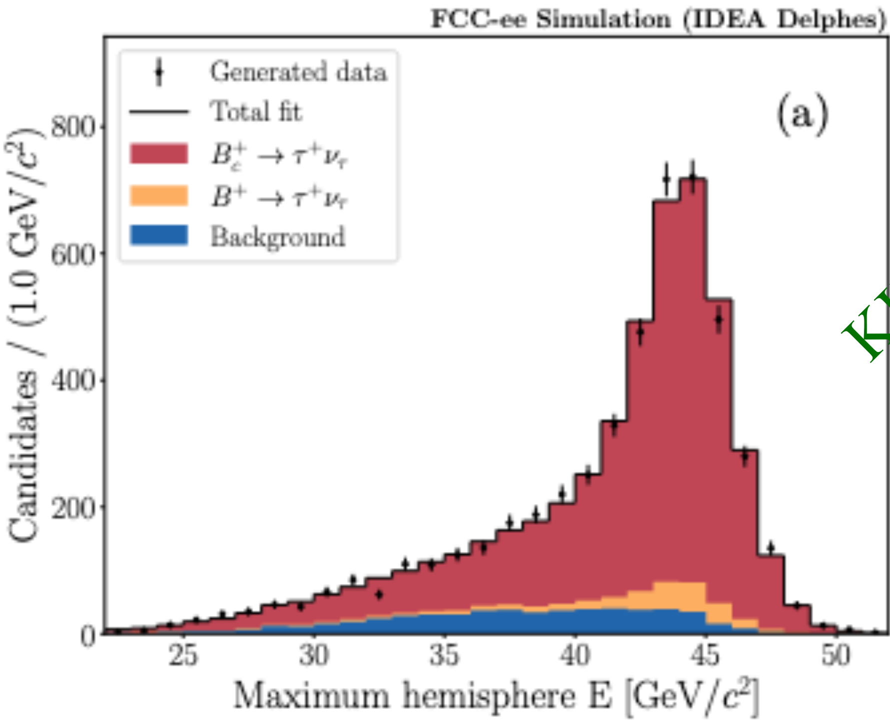
For an optimal BDT1 and BDT2 cut at the SM predicted BF:

- Signal efficiency $\sim 11\%$
- $b\bar{b}$ efficiency $\sim 10^{-4}\%$
- $c\bar{c}$ efficiency $\sim 10^{-6}\%$
- $q\bar{q}$ efficiency $\sim 10^{-7}\%$
- Signal:Background ratio $\sim 1:9$
- Sensitivity $\sim 1.2\%$

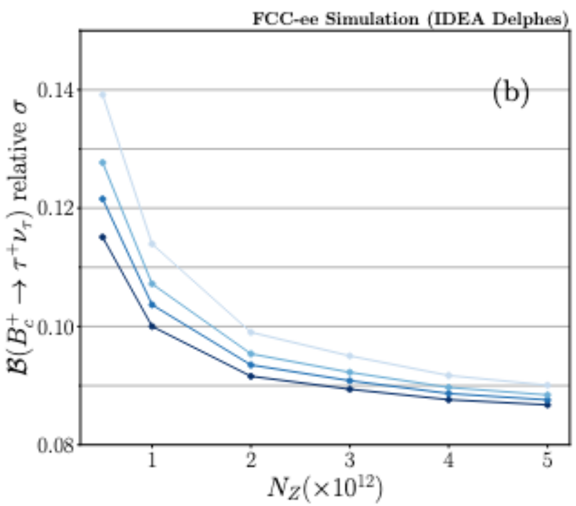


5) Reviews of current activities (Feas. Study)

- $B_c \to \tau^+\nu$: another fundamental test of lepton universality. Counterpart of R_{D,D^*}. A promising study lies here [2105.13330, see also 2007.08234]



KIT !



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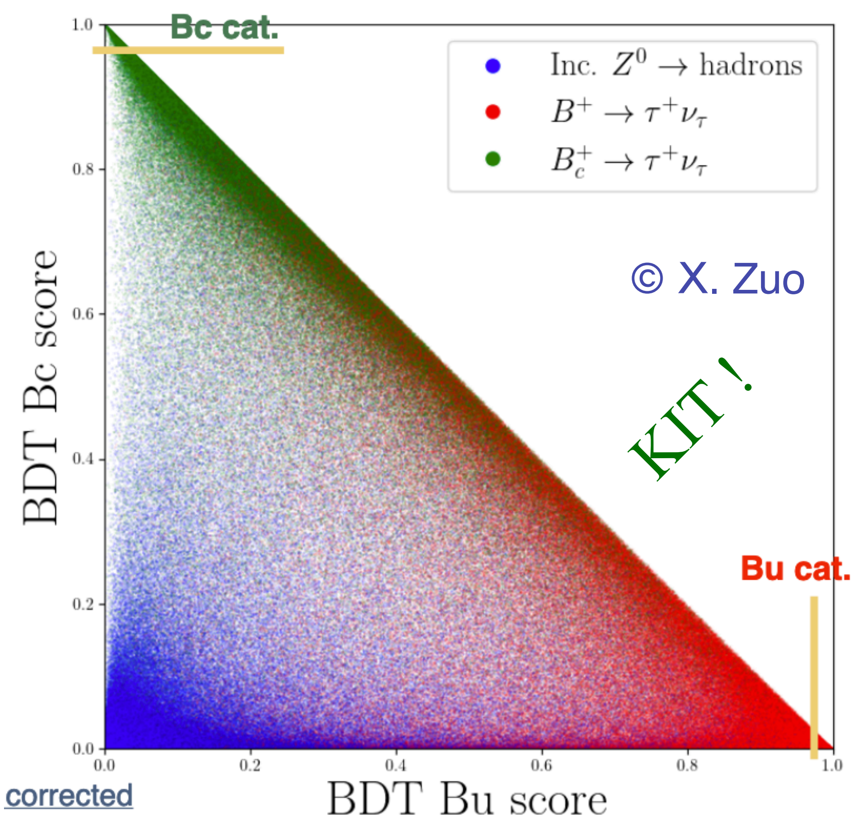
Bottomline: few percent precision mostly limited yet by the knowledge of the normalisation BF ($J/\psi\mu\nu$).

3) Reviews of current activities (Feas. Study)

- $B^+ \to \tau^+\nu$: access $|V_{ub}|$ with the only knowledge of the decay constant.



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Bottomline: similar yields / purities as for $B_c \to \tau^+\nu$. A paper out. *arXiv 2305.02998* that makes the synthesis of both analyses.

3) Reviews of current activities (Feas. Study)

- Sub-degree gamma angle measurement with just one mode :

Measurement of CP violation with $B_s \to D_s K$

$\int Ldt = 150\ ab^{-1}$

PDG: $\gamma = (71.1^{+4.6}_{-5.3})°$

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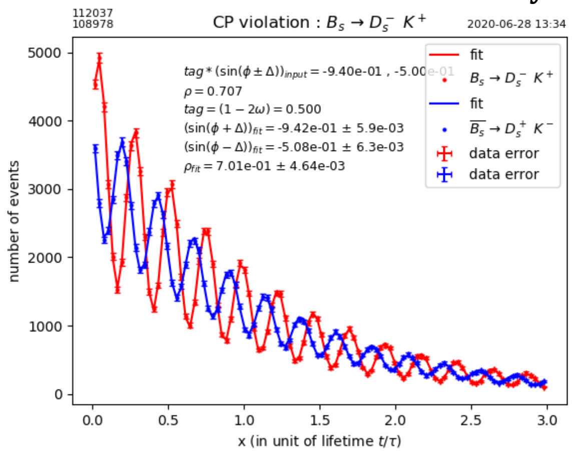

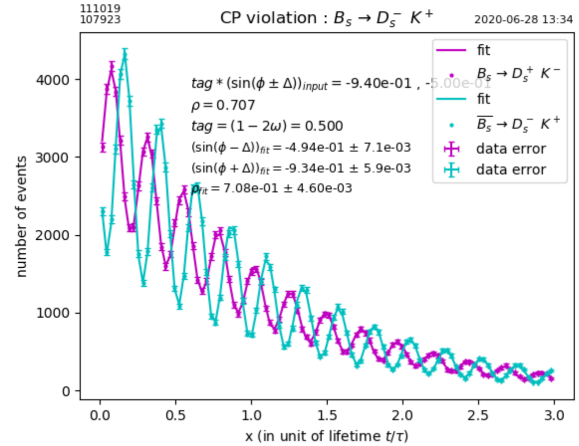

Result 3 :

$\delta(\rho) \approx 3.2 \times 10^{-3} (stat.)$

$\delta(sin^2\phi_{CKM}) \approx \delta(sin^2\gamma) \approx 5 \times 10^{-3} (stat.) \cong \delta(\gamma) \approx 0.4° (stat.)$

Potential statistical gain of factor 4-5 with $D_S^{\pm} \to K^{*0}K^{\pm}, \phi\rho^{\pm}$, … but background needs to be studied (see later)+
Additionnal potential gain (another factor ~2) with $B_s \to D_s^{*\pm}K^{\mp}, D_s^{\pm}K^{*\mp}, D_s^{*\pm}K^{*\mp}$, most modes including γ(s)

- A lot more to do with neutrals !
- Several null tests of the SM accessible w/ potentially unprecedented precision, *e.g.* semileptonic asymmetries, ϕ_s in penguin-dominated diagrams …

5) Reviews of current activities (Feas. Study)

- Tau Physics: Lepton Flavour Universality

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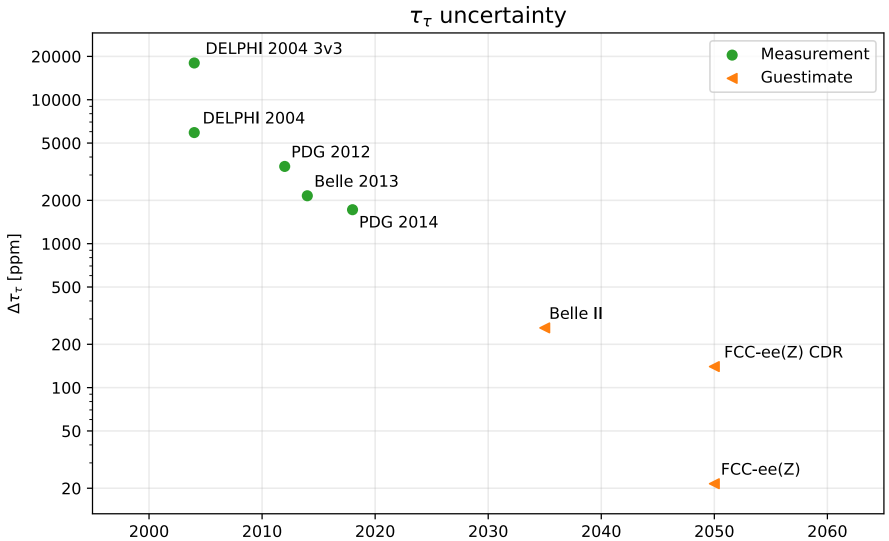

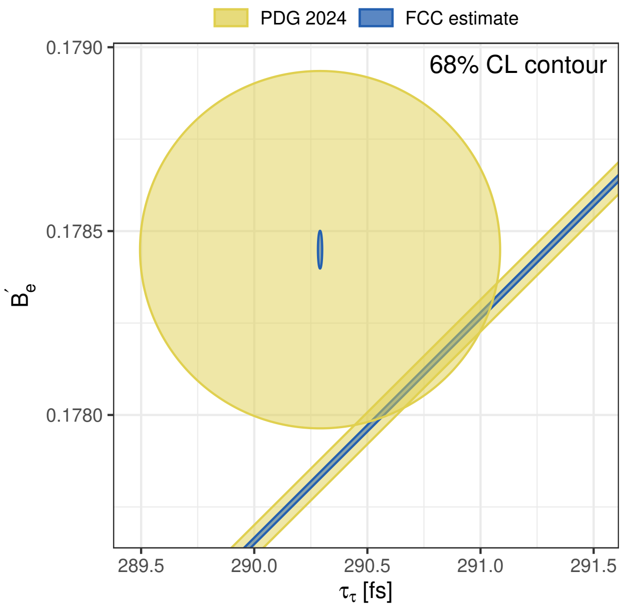

Comment: B-factories did not improve (much) LEP measurements (Belle II might). FCC-ee has much better experimental conditions than LEP and about 5× the statistics of tau pairs w.r.t. Belle II.

Bottomline: lifetime resolution obtained with three-prongs decays. Orders of magnitude improvements.

5) Reviews of current activities (Feas. Study)

- Tau Physics: Lepton Flavour Violation

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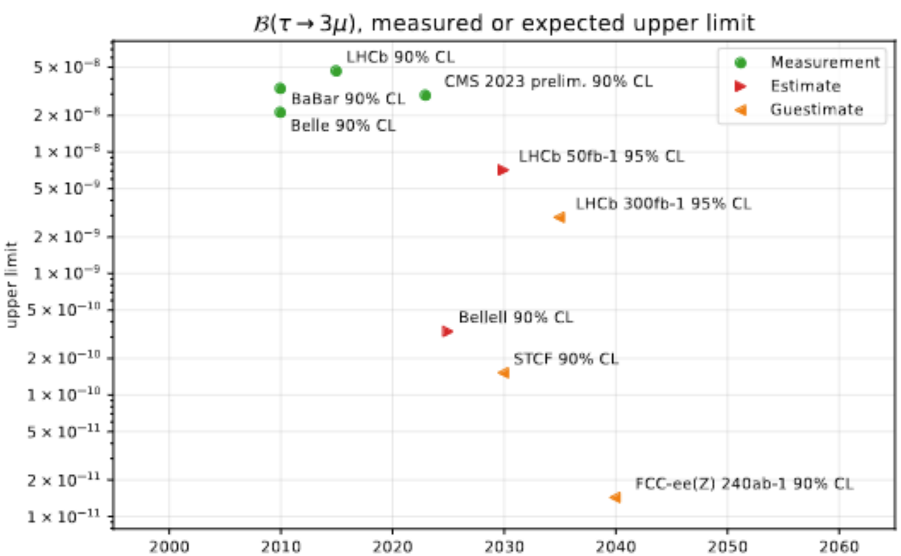
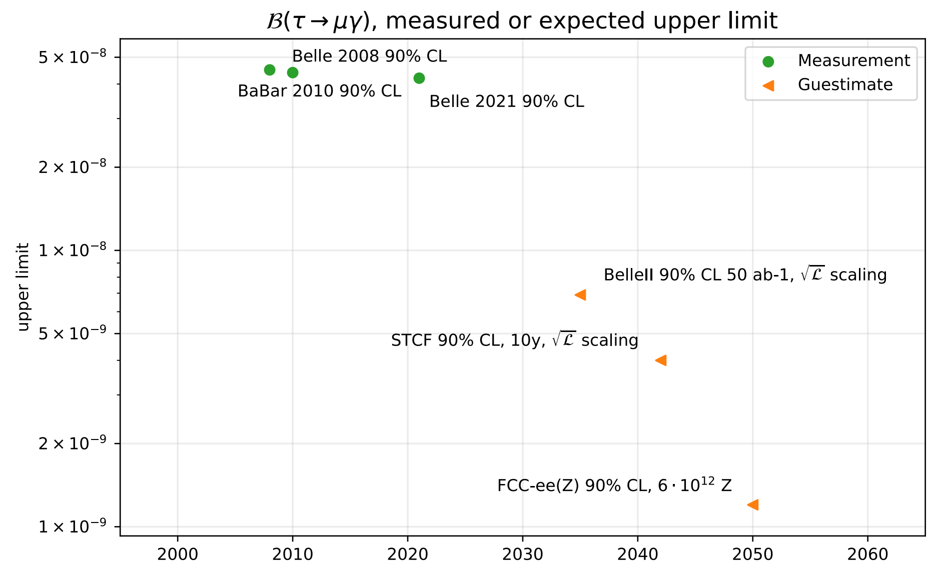
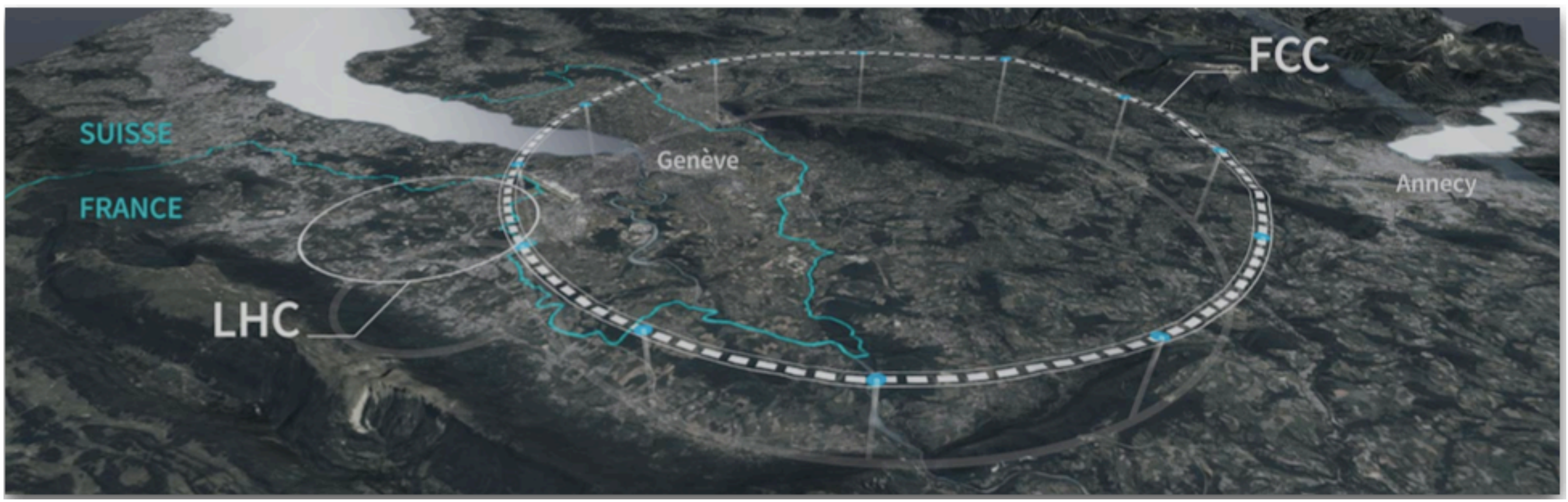




Bottomline: improved sensitivity by about two orders of magnitude.

7) Connecting the scales: Flavours, Z pole, top

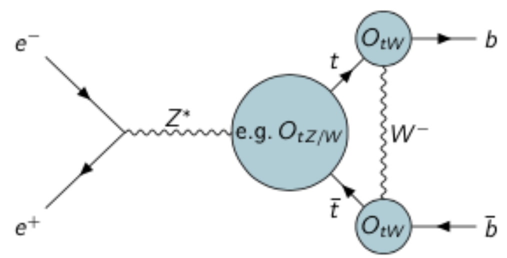


7) Connecting the dots: EWPO at the Z pole

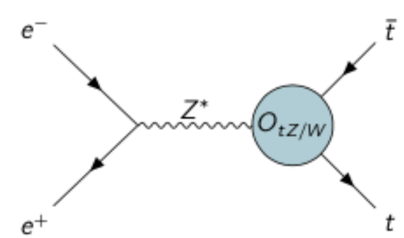
Motivation I

- Possible anomalies translate over a range of energy scales: from Z-pole to top threshold
- Heavy-quark EW measurements as a **probe for new physics** with a common set of dimension-6 operators

$\mathcal{O}(m_Z) \sim 90$ GeV



$\mathcal{O}(m_t) \sim 350$ GeV to 365 GeV



Today:

- Measurements at the Z-pole with $4.2 \cdot 10^{12}$ $Z \rightarrow q\bar{q}$ (4 IPs):
  - $R_b = \frac{\sigma_{b\bar{b}}}{\sigma_{\text{had.}}}$
  - $A^b_{\text{FB}} = \frac{N_\text{F} - N_\text{B}}{N_\text{F} + N_\text{B}}$

$\rightarrow$ Likely **dominated by systematic uncertainties**

$\rightarrow$ Explore Tera-Z regime with **exclusive b-hadron decay reconstruction as new tagger**

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Novel methods in order

7) Connecting the dots: EWPO at the Z pole

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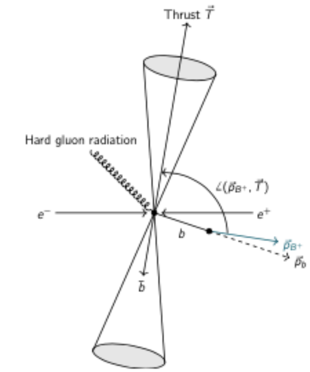
Exclusive b-hadron decays

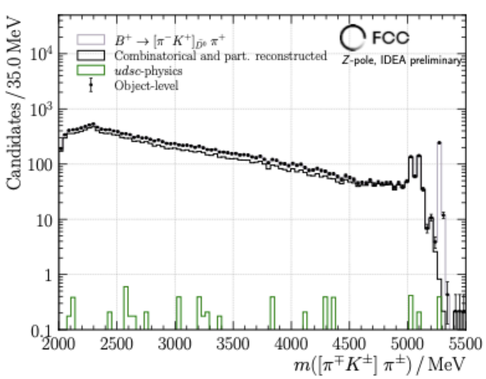
- LEP $\sigma_{\text{syst.}}$ dominated by *udsc*-physics and hemisphere correlations
- With Tera-Z $\sigma_{\text{stat.}}$ in reach: measurement limited by systematic uncertainties
- Reconstruct exclusive b-hadron: determine quark-flavour with 100 % purity
  $\rightarrow$ Stick to **ultra-pure mass region** to assess remaining systematic uncertainties $\rightarrow \varepsilon_b = 1\,\%$

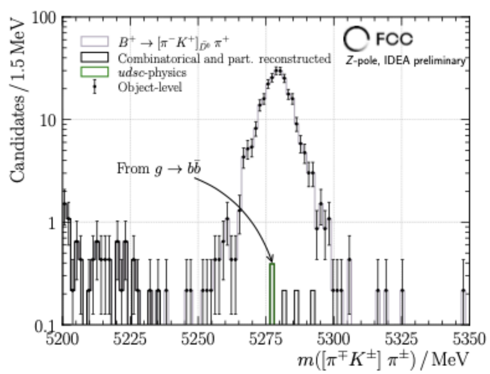
Observable	R_b	A^b_{FB}
b-hadrons	$B^+, B^0_d, B^0_s, \Lambda^0_b$	B^+, Λ_b
Knowledge of...	Flavour	Flavour, $\vec{p}$ & Q
Advantages	Remove *udsc*-physics contribution	Remove *udsc*-physics contribution; Overcome mixing dilutions and hemisphere confusion
Remaining $\sigma_{\text{syst.}}$	Hemisphere correlation C_b	QCD corrections



- C_b and QCD corrections evaluated on **Full Simulation sample** and forced decays ($B^\pm \rightarrow [K^+\pi^-]_{\bar{D}^0}\,\pi^+$)

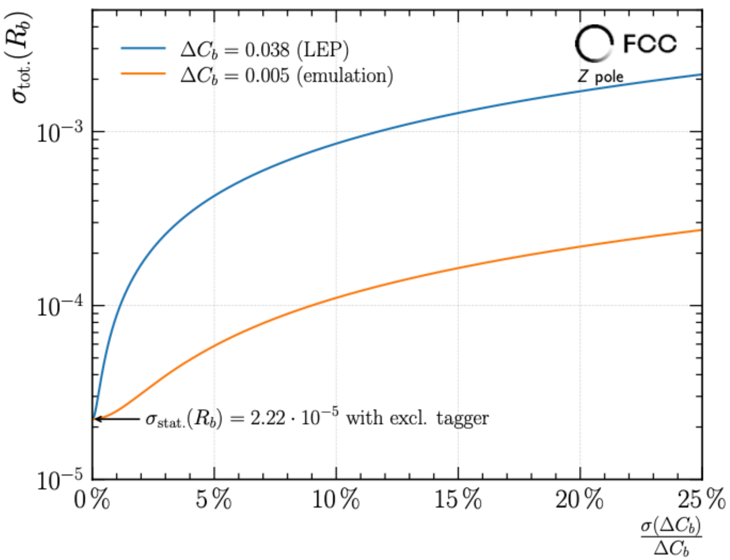
- Here: $B^+ \rightarrow [K^+\pi^-]_{\bar{D}^0}\,\pi^+$ with $E_B > 20$ GeV to reduce background





7) Connecting the dots: EWPO at the *Z* pole

- Understanding hemisphere correlations as the ultimate systematics
- LEP found that PV resolution was driving the correlation. LEP did separate PV measurement per hemisphere.
- At FCC-ee, one can use the luminous region to reduce the correlation.



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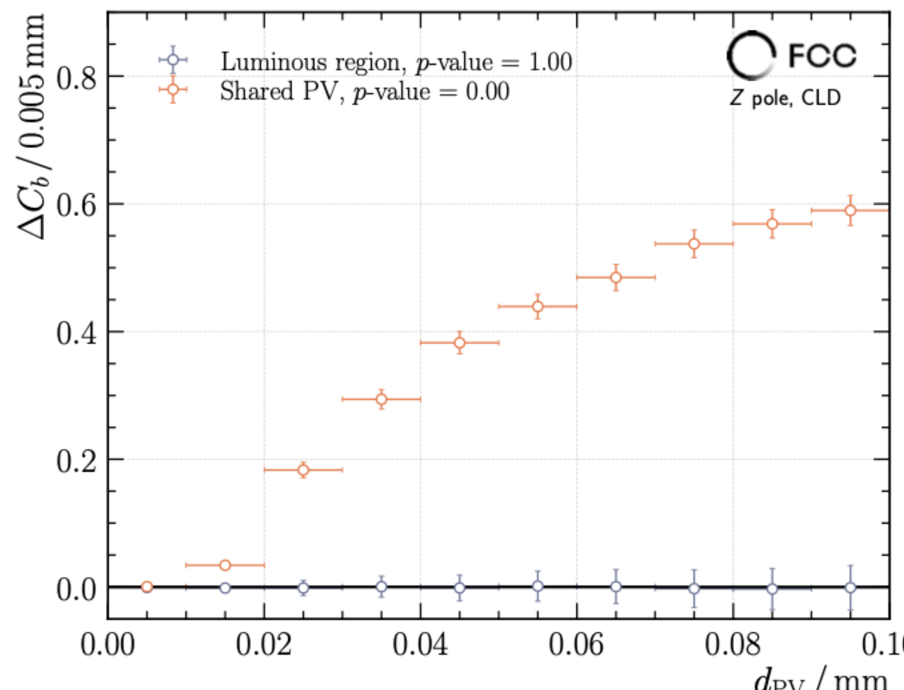

7) Connecting the dots: EWPO at the Z pole

- Exclusive decays as a tagger can also help to reduce the systematic uncertainties on the bb forward-backward asymmetry

- Light quark contamination and mixing dilution are removed by the performance of the tagger.

- Remaining uncertainty to tackle are therefore QCD corrections. Could be controlled by the angle b/w thrust and the b-hadron candidate or the hadron energy.

- Works fine.

Reaching three times the precision on the electroweak mixing angle obtained with muons !

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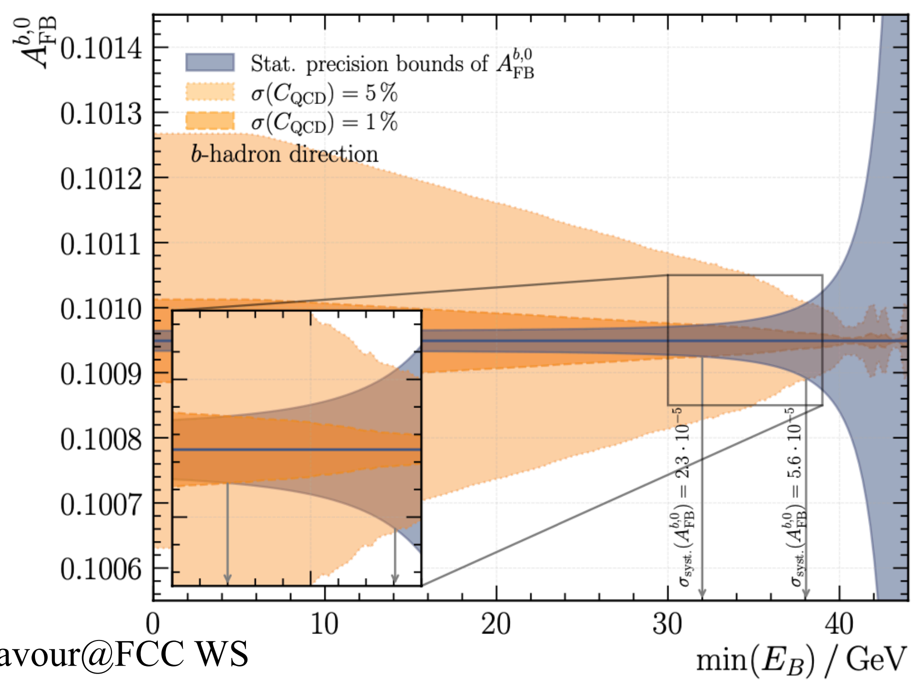
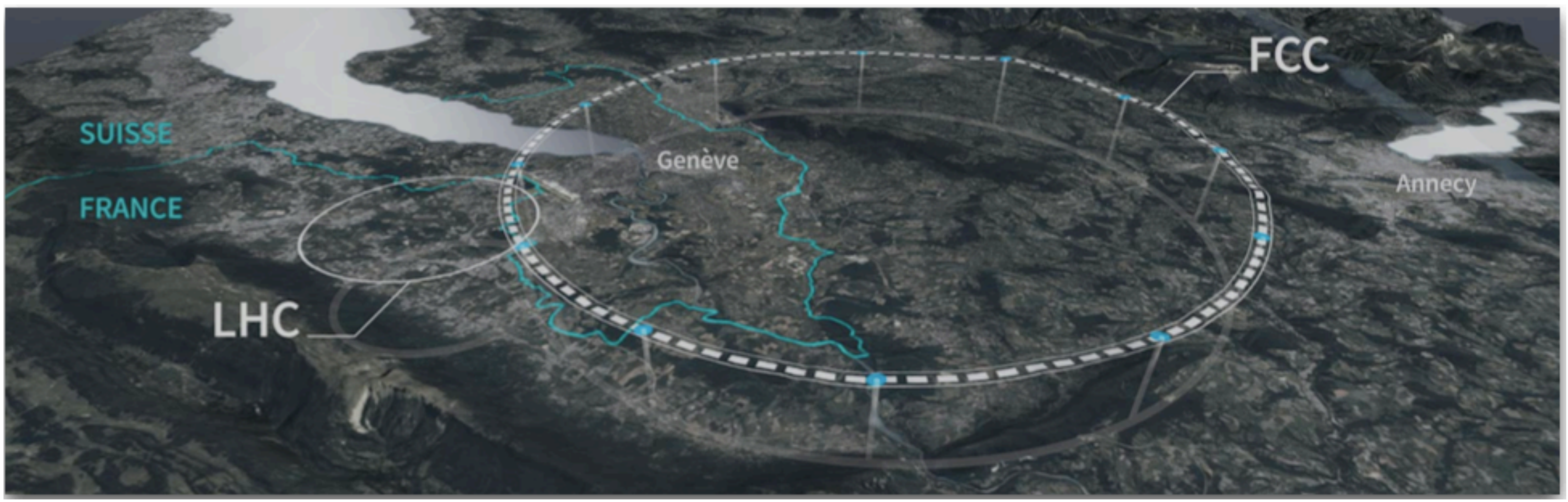


Aparté



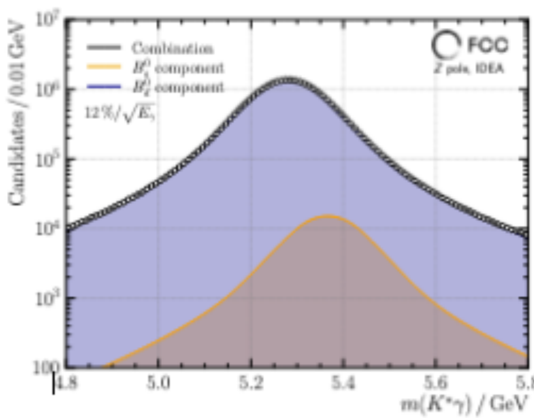
Aparté

Aparté

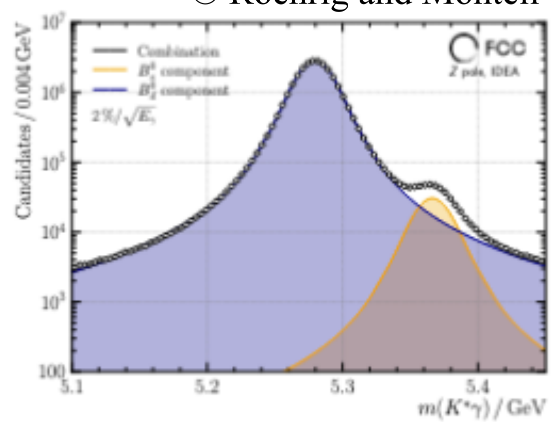
- The different tracking systems (be they Si-based or continuous-gaseous) on the table are already very powerful and are mostly meeting physics requirements. Some subtleties could however enhance the Flavour case, such as placing the vertex detector within the beam pipe … !
- But …
- … Detector Concepts are building on calorimetry.
- The Physics Case at large requires high granularity calorimeters, ideally both transverse granularity and longitudinal segmentation.
- Flavour Physics requires in addition high energy-resolution. Here follows a novel idea.

Aparté 1. Motivations for high *E*-resolution calorimetry

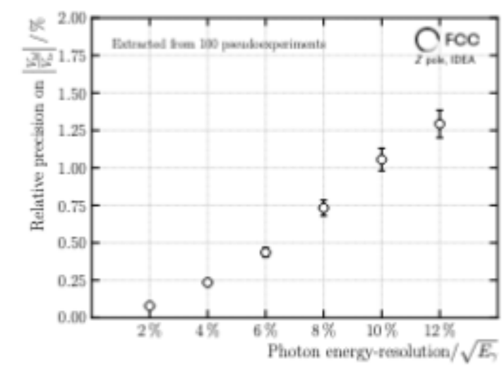
- The *CP*-violation and rare decays programs benefit from an excellent electromagnetic energy resolution for the reconstruction of *b*-flavoured hadron decays: radiative decays $b \to s(d)\gamma$ and final states with neutral pions. Does not saturate the requirement: tau, ALPs…
- Two illustrations from the Flavoured Circular Collider Workshop:
  - 1) From radiative decays: separation of $b \to s\gamma$ and $b \to d\gamma$. *Academic exercise w/* $B^0, B_s \to K^*(892)\gamma$



(a) IDEA baseline scenario with a dual-readout calorimeter, $r = 0.12$.



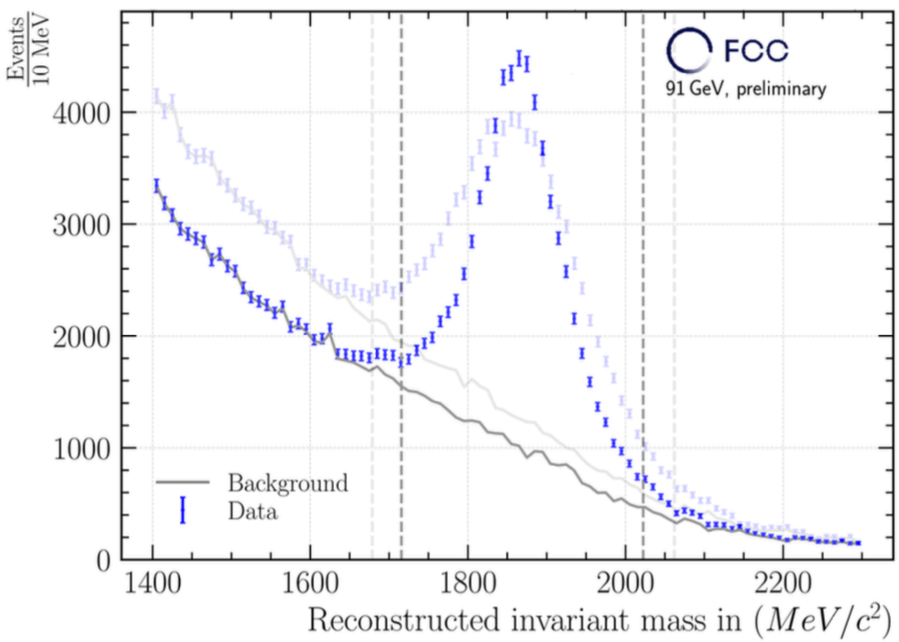
(b) High photon-energy resolution from crystals, $r = 0.02$.

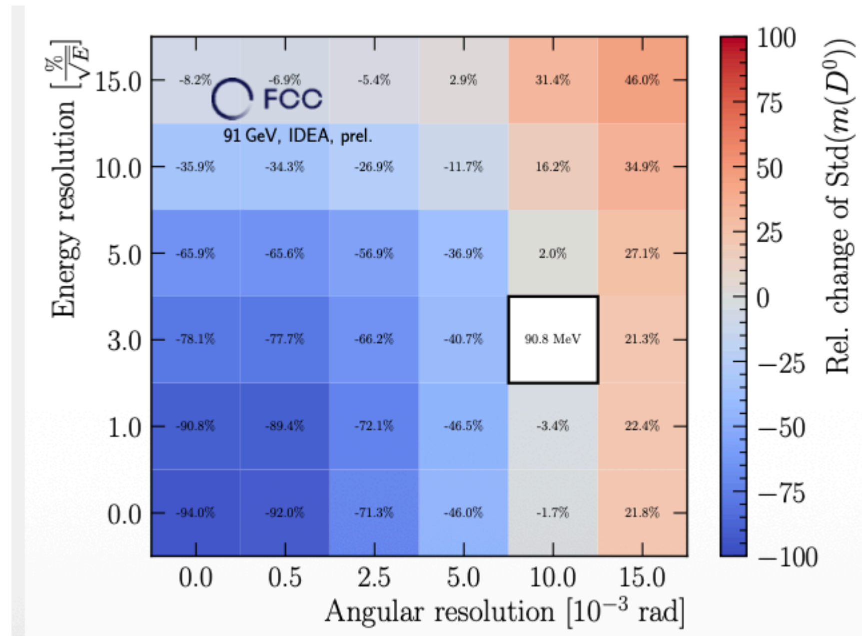


(b) The relative precision as a function of the energy resolution.

Aparté 1. Motivations for high *E*-resolution calorimetry

- Two illustrations:
  - 2) From *CP* breaking in $D^{*+} \to D^0(\to \pi^0\pi^0)\pi^+$ — W. Weber et al.



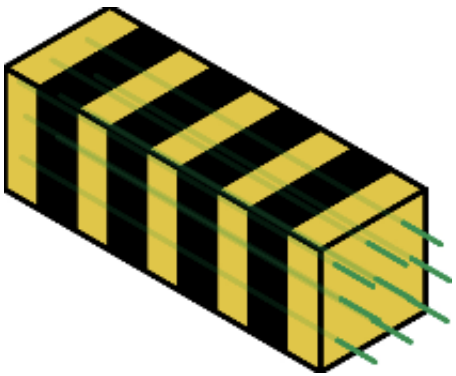


- Study to be ironed out but the lower quarter of the figure of the merit seems a right place to be.

Aparté 1. Principles of GRAiNITA

- The equation: reaching an exquisite cost-effective energy resolution while preserving high transverse granularity for the full FCC physics program.

Typical sampling calorimeter (e.g. Shashlik)

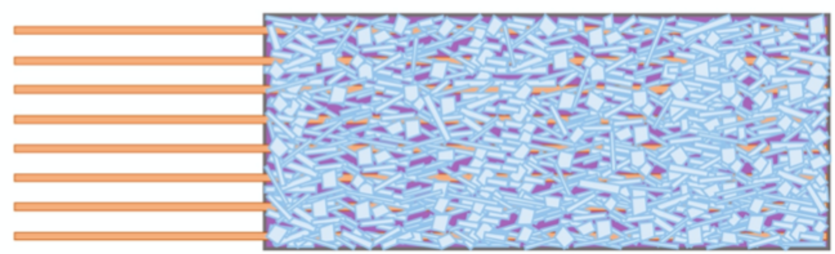


$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}}$$

Crystal calorimeter

$$\frac{\sigma_E}{E} \sim \frac{1-2\%}{\sqrt{E}}$$

- Can we make the best of the two approaches?
  - Fine sampling, scint. light containment
  - Potentially cost-effective: grains can be 2.5 cheaper than homogeneous crystals



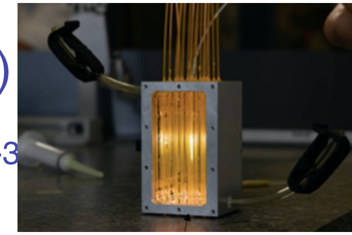
Aparté 2. The grains, the fibres, the liquid

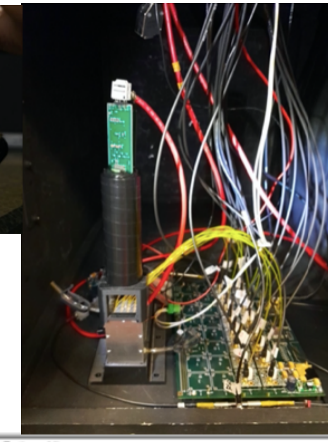
Table 1. Properties of interest for the GRAiNITA study of the the BGO and $ZnWO_4$ materials.

	BGO	$ZnWO_4$
Effective Z	74	61
Density (g/cm^3)	7.13	7.87
Refractive index	2.15	2.0 - 2.3
Light yield (photons/MeV)	~ 9000	~ 9000
Peak emission wavelength (nm)	480	480
Decay time (μs)	0.3	20
Radiation length (cm)	1.12	1.20
Molière radius (cm)	2.26	1.98

- Possible candidate for the grains: $ZnWO_4$.
- ISMA: dedicated R&D to produce $ZnWO_4$ grains with the flux method (cost effective). Production technique mastered.
- Scintillation decay time ok for FCC-ee (~50 kHz at the *Z* pole).
- About 1 kg produced.
- Options under consideration, *e.g.* $CaWO_4$, $Ca/PbWO_4$ (faster, flux method).

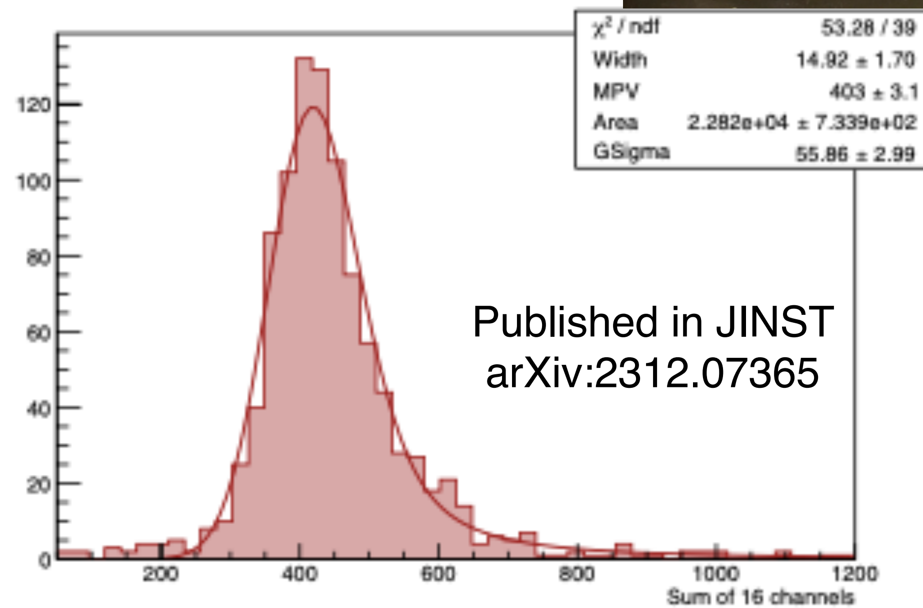
Aparté 3. Cosmic test bench: towards the stochastic term





- Average dE/dx for mu in prototype: ~1.5 MeV / (g.cm^{-2})
- Density of the proto is ~half that of $ZnWO_4$ (~4.5 g.cm^{-3})
- The length of proto seen by a cosmic mu is about 6 cm
- The energy deposited in the proto by a mu is *O*(40 MeV)

  - Selected "central" muons
  - About 400 photo-electrons
  - About 10 p.e. per MeV, *e.g.* 10000 p.e. per GeV. !!
  - More to study: mirror ends on fibres, heavy liquid …



Published in JINST arXiv:2312.07365

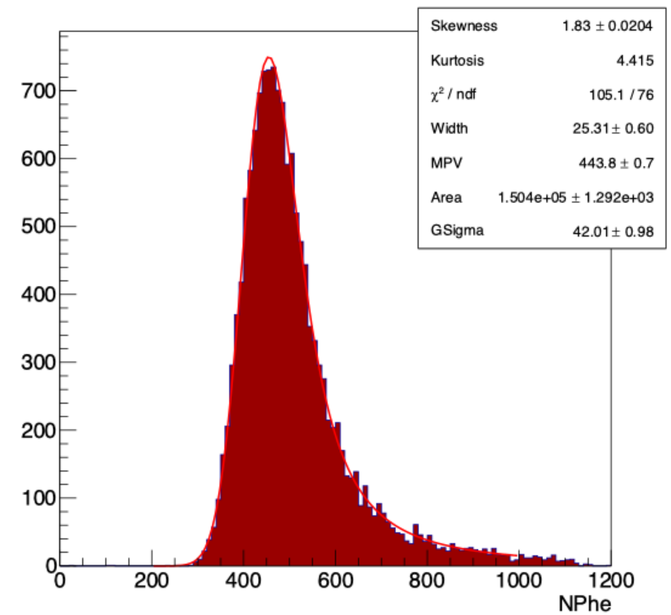
Should these numbers be confirmed, the

2% stochastic target is at reach !

Aparté 4. Test beam at SPS: in the shadow of LHCb PicoCal

- We got the opportunity to benefit of two days of parasitic testbeam (muons and pions) at CERN SPS.
- Tested two trolls (same small prototypes as in home test bench).
- Could check Water and fastfloat Heavy Liquid.
- Objective was to understand if there's not an irremediable constant term.
- Check the non-uniformity of the answer and input the result into simulations.

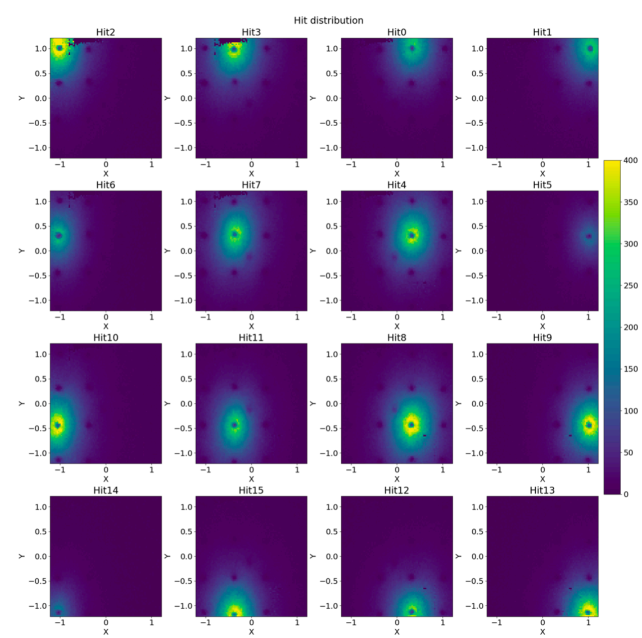
  - On the way, one confirms the 1% photoelectron statistics contribution to the stochastic term (water and HL).



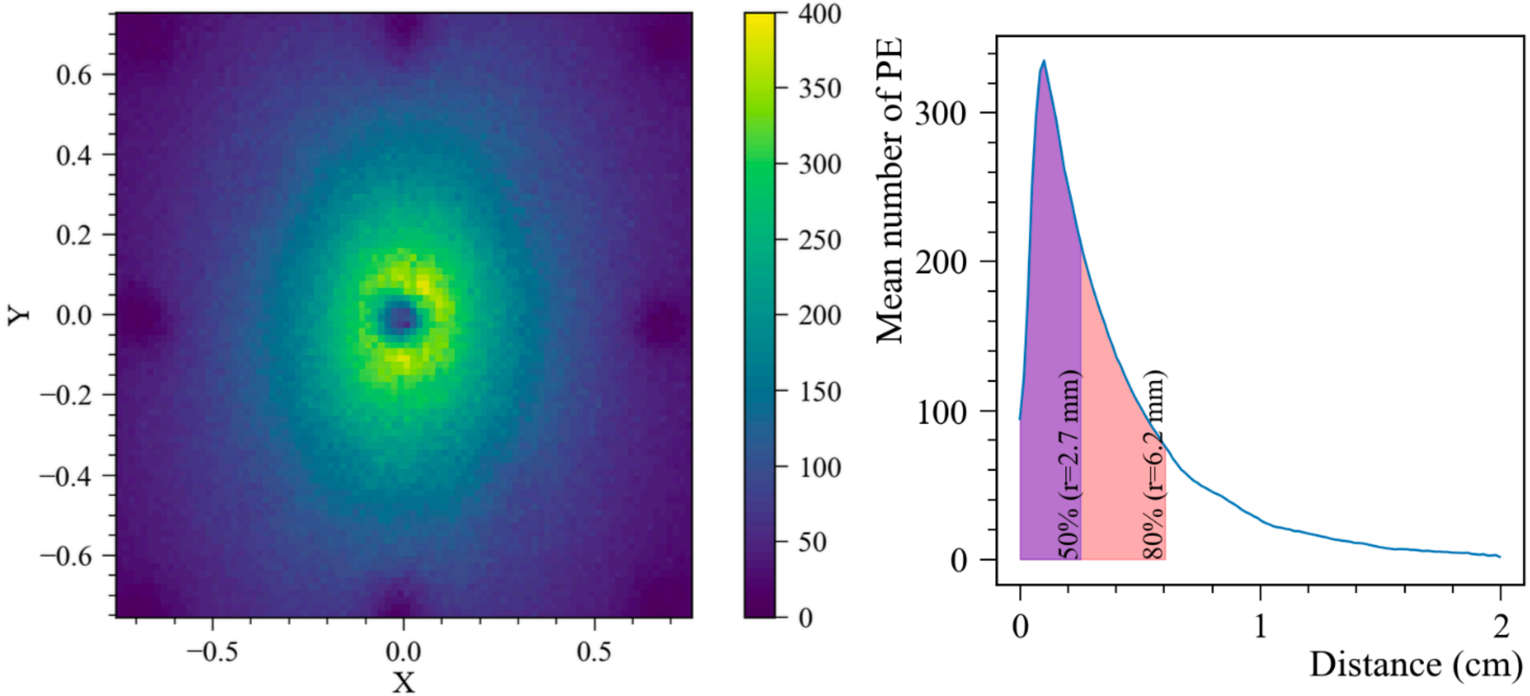
Aparté 4. Test beam at SPS: towards the constant term

- We got the opportunity to benefit of two days of parasitic testbeam (muons and pions) at CERN SPS. Thanks to out LHCb colleagues for all the help.
- Tested two trolls (same small prototypes as in home test benches)
- Could check Water and Heavy Liquid
- Objective was to understand if there's not an irremediable constant term.
- Check the non-uniformity of the answer and input the result into simulations (WIP).

  - On the way, one confirms that the 2% stochastic target is at reach.
  - Confirms also that the scintillation light is confined close to the fibre.
  - Note to read the plot: the entrance point in (x,y) (2.5 x 2.5) cm^2 of the beam track is represented here. The colour sketches the mean response of each of the 16 fibres.



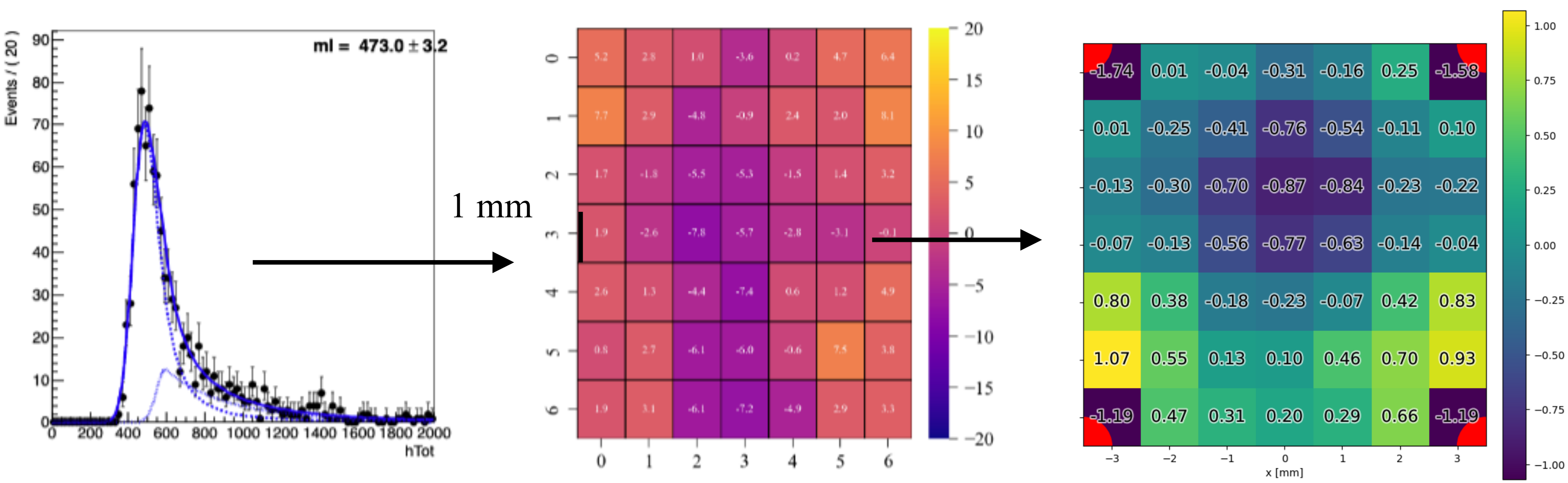
4. Test beam at SPS: light confinement in more detail



- The figures above are obtained using muon particles and the 4 most central fibres, to mitigate boundary effects.
- The (x,y) is the entrance point of the muon; the *z* (colour) scale is the number of photoelectrons..
- 75% of the scintillation light is collected by the 4 closest WLS fibers (7mmx7mm).

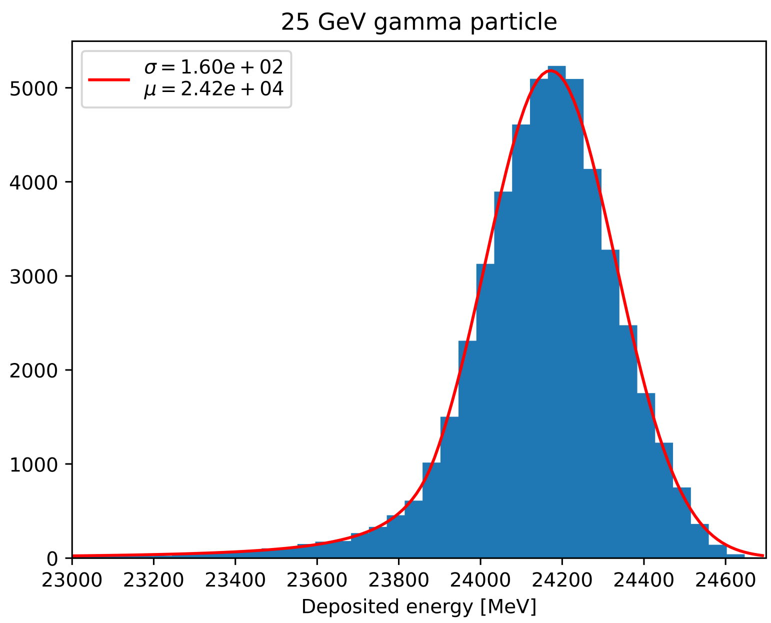
Aparté 4. Test beam at SPS: constant term non-uniformities

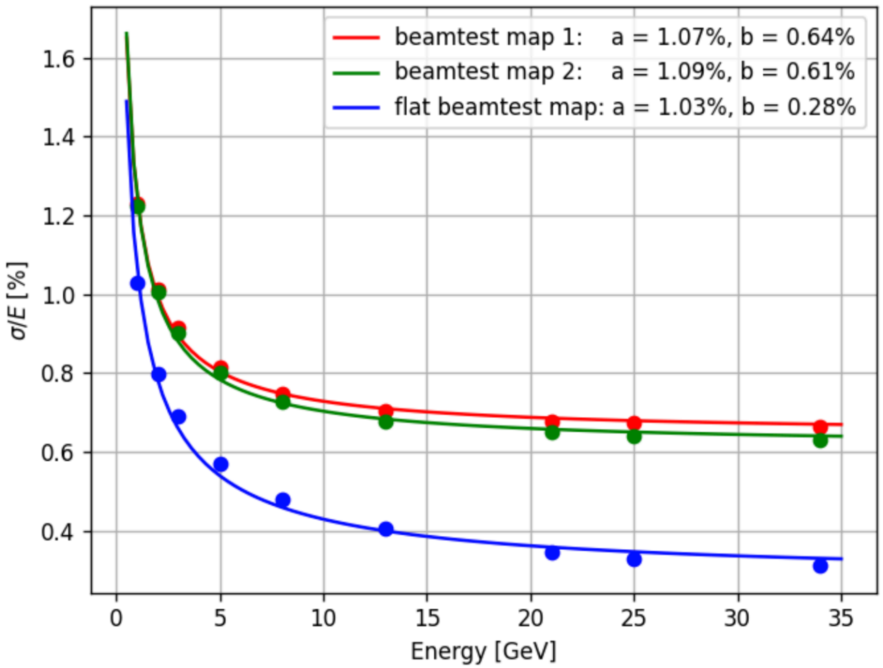
- Map the GRAiNITA surface by steps of 1mm with pion samples.
- Quantify the non-uniformities (on average smaller than 10%) and
- input those into the ZnWO4/HL demonstrator simulations with 25 GeV photons (see Denys' talk this afternoon).



4. Test beam at SPS: constant term non-uniformities

- Map the GRAiNITA surface by steps of 1mm with pion samples.
- Quantify the non-uniformities (on average smaller than 10%) and input those into demonstrator simulations (see Denys' talk this afternoon).
- Fluctuations in the response (part of the contant term) is about 0.7% of the deposited energy.





Aparté 4. Test beam at SPS: DRD Calo paper in JINST

Studying the GRAiNITA concept: first test beam results

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Abstract: Data collected over a two-day period in June 2024 at the CERN SPS H9 test beam using a small-scale GRAiNITA prototype have been analyzed to characterize the detector's energy-resolution performance. The measurements allow for a first estimate of the constant term associated with detector non-uniformity. Although the evaluation is limited by the small prototype size and the use of pion beams, the results indicate that the non-uniformity-related constant term is significantly below 1%. Furthermore, the test-beam data confirm that the contribution to the energy resolution arising from photo-electron statistics is approximately $1\%/\sqrt{E}$. These findings validate the expected calorimetric performance of the GRAiNITA concept and provide important input for the design and optimization of future full-scale detectors.