FCC Feasibility Study [with a focus on Flavour Physics and precision opportunities]

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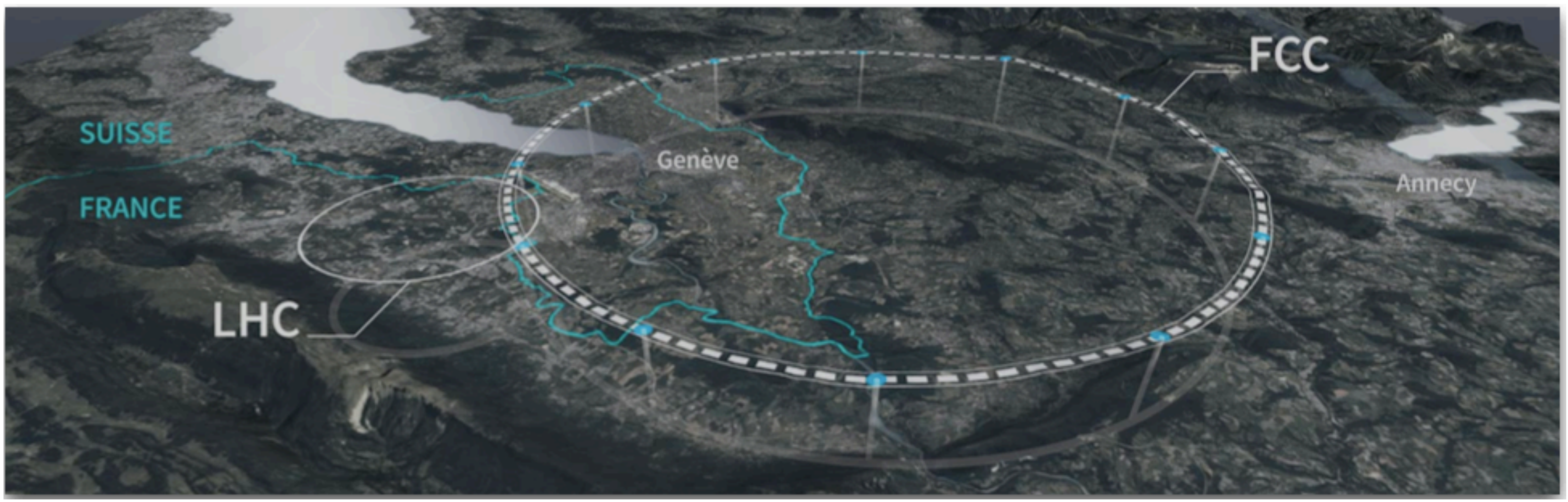
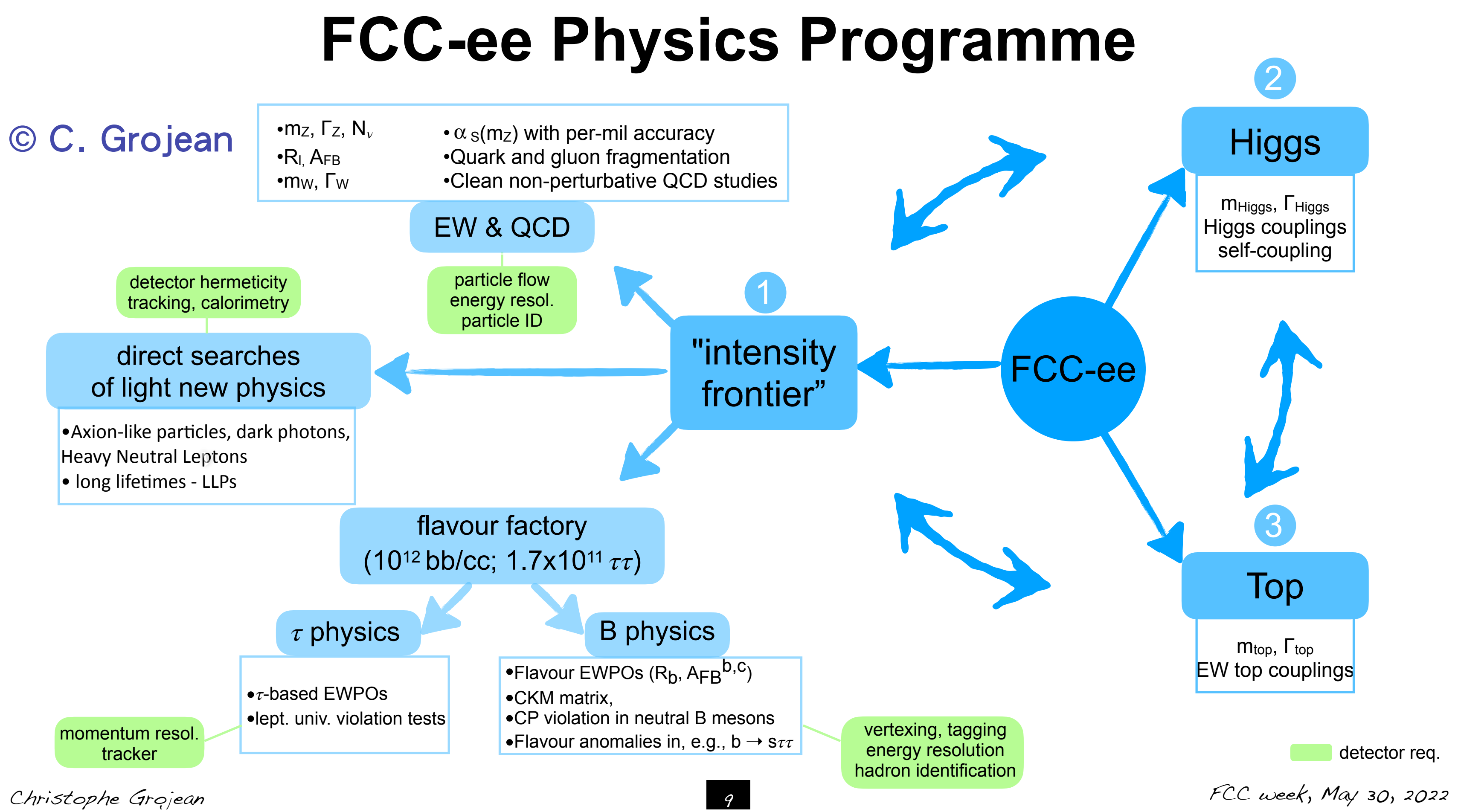
Outline

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. Review of current activities
6. Focus on two analyses
7. Connecting some dots: Flavours, EWPO@Z and top
8. Summary

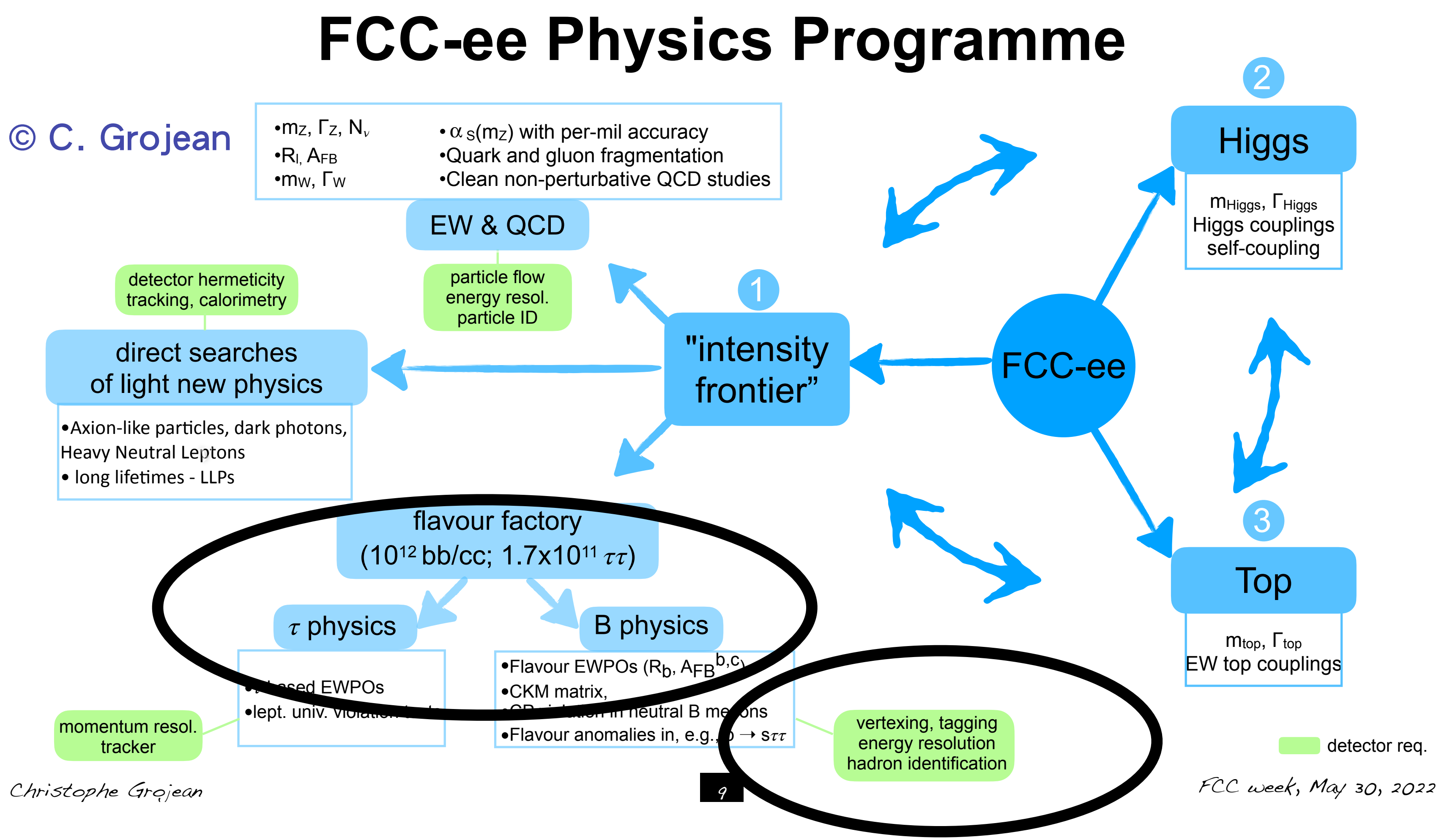
1. FCC-ee Feasibility Study. Motivation.

- 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.



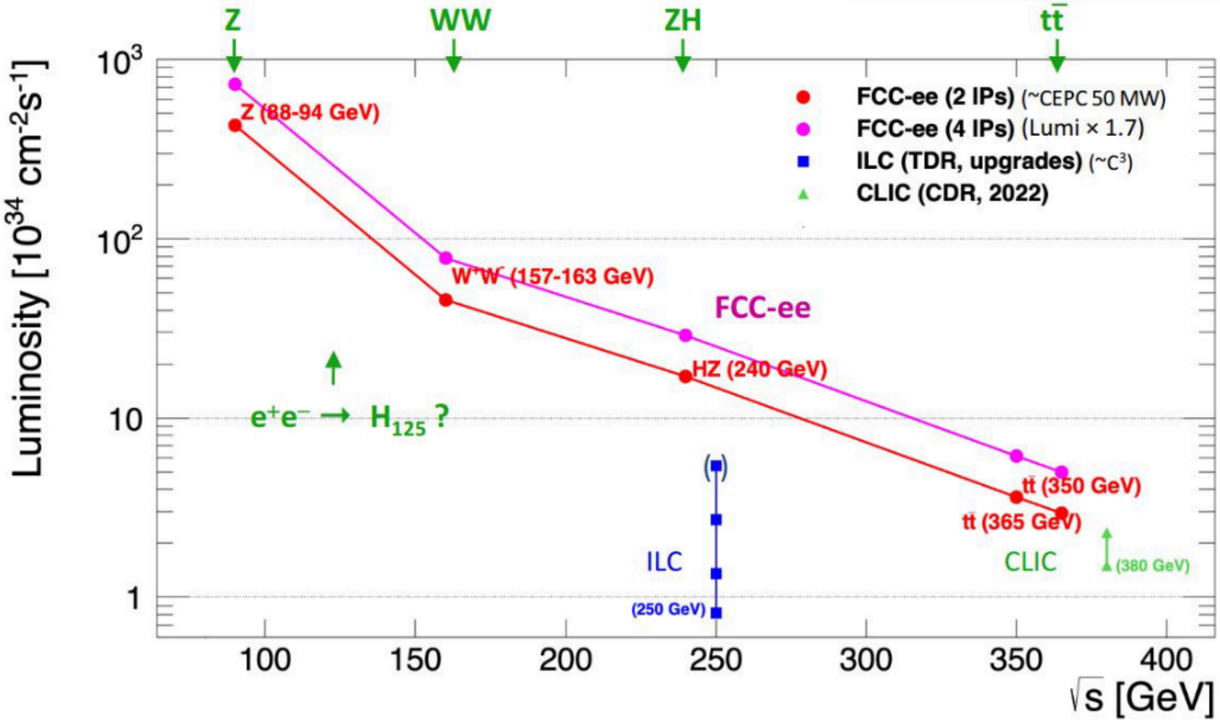


- Triptych: Higgs / Top / EW factory (Intensity).



- Probable imo that Flavour Physics requirements are the most demanding in vertexing, PID, calorimetry

2. Key points: FCC-ee luminosity and operation

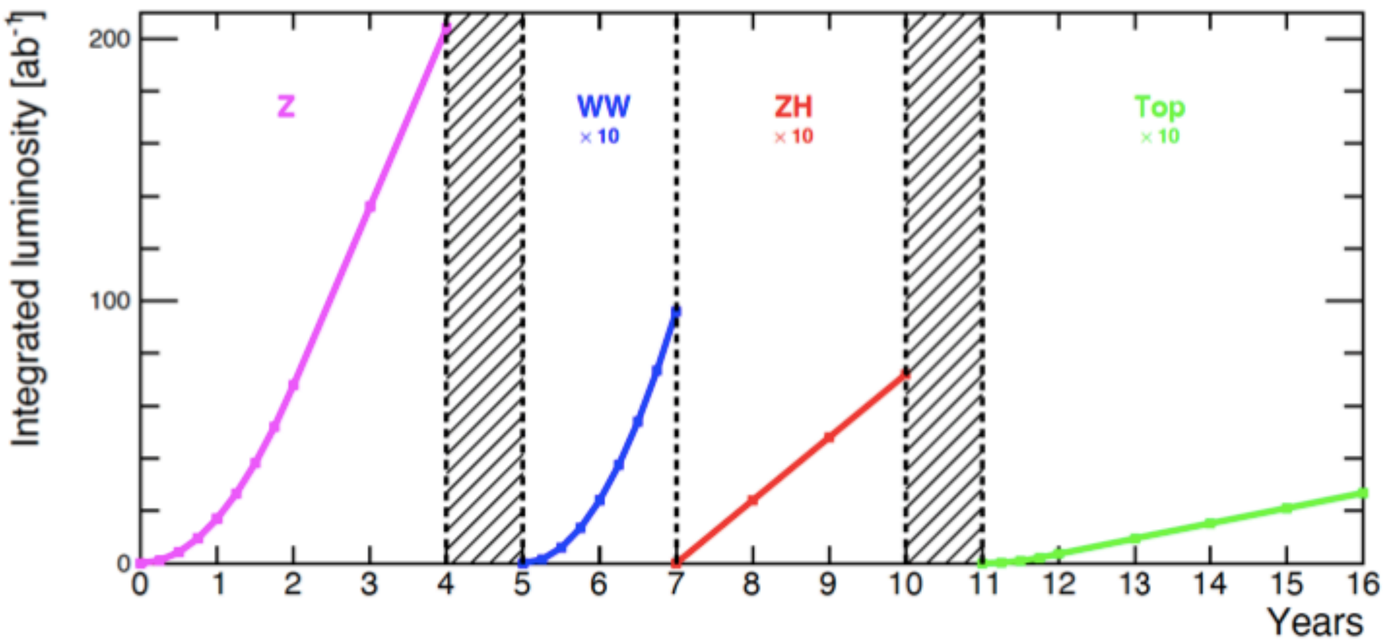


- We‘re speaking of 10^5 *Z*/s , 10^4 *W*/h, 1.5 10^3 *H* and top /d, in a very clean environment: no pile-up, controlled beam backgrounds, *E* and *p* constraints, ~w/o trigger loss.

- In particular, you do the LEP in a minute! Some Flavour measurements are still dominated by LEP experiments.

2. Key points: FCC-ee luminosity and operation

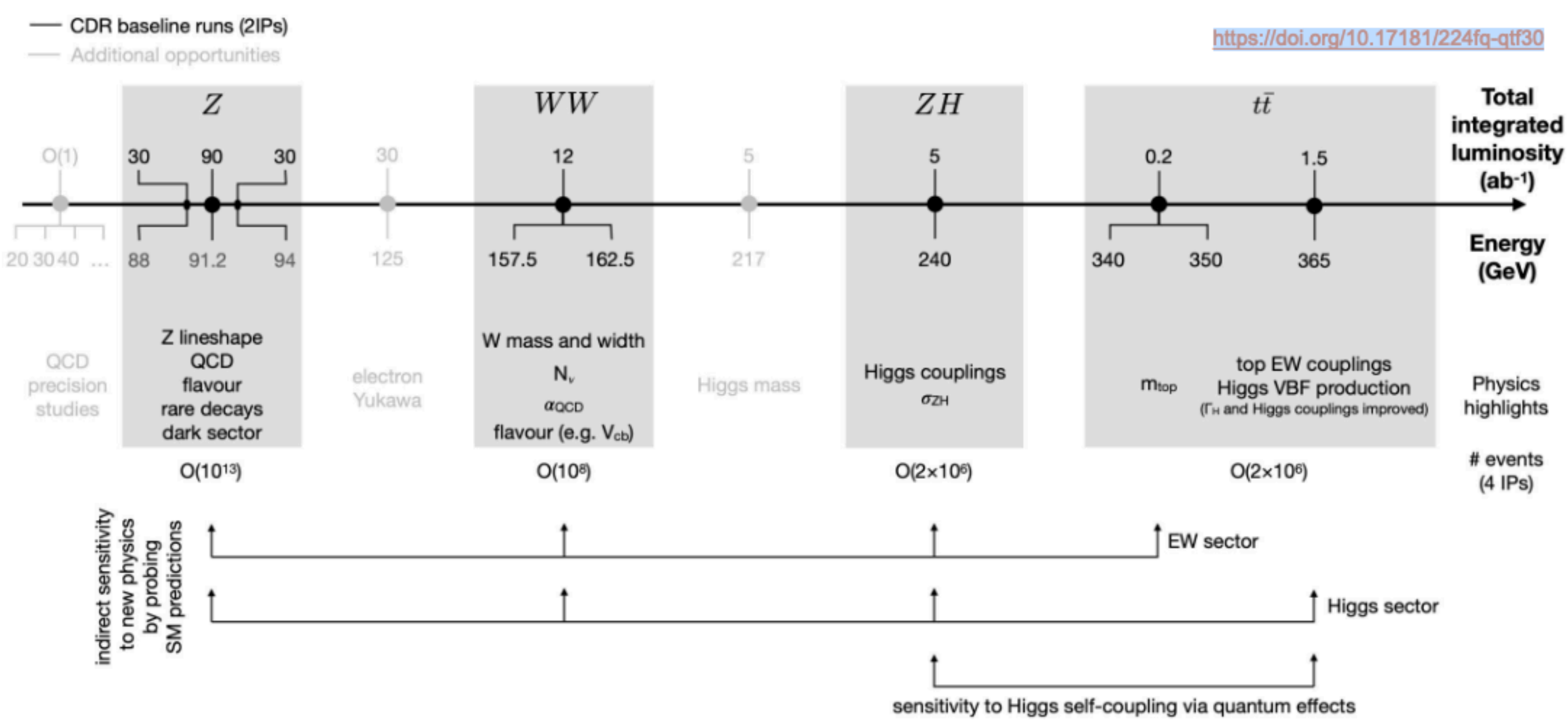
- Baseline:
  - 16 years nominal program.
  - 4 interaction points.
  - Versatility in run scenarii (*e.g.* could start w/ Higgs run)
  - Possibility of additional runs (*e.g.* e^- Yukawa w/ 125 GeV run).



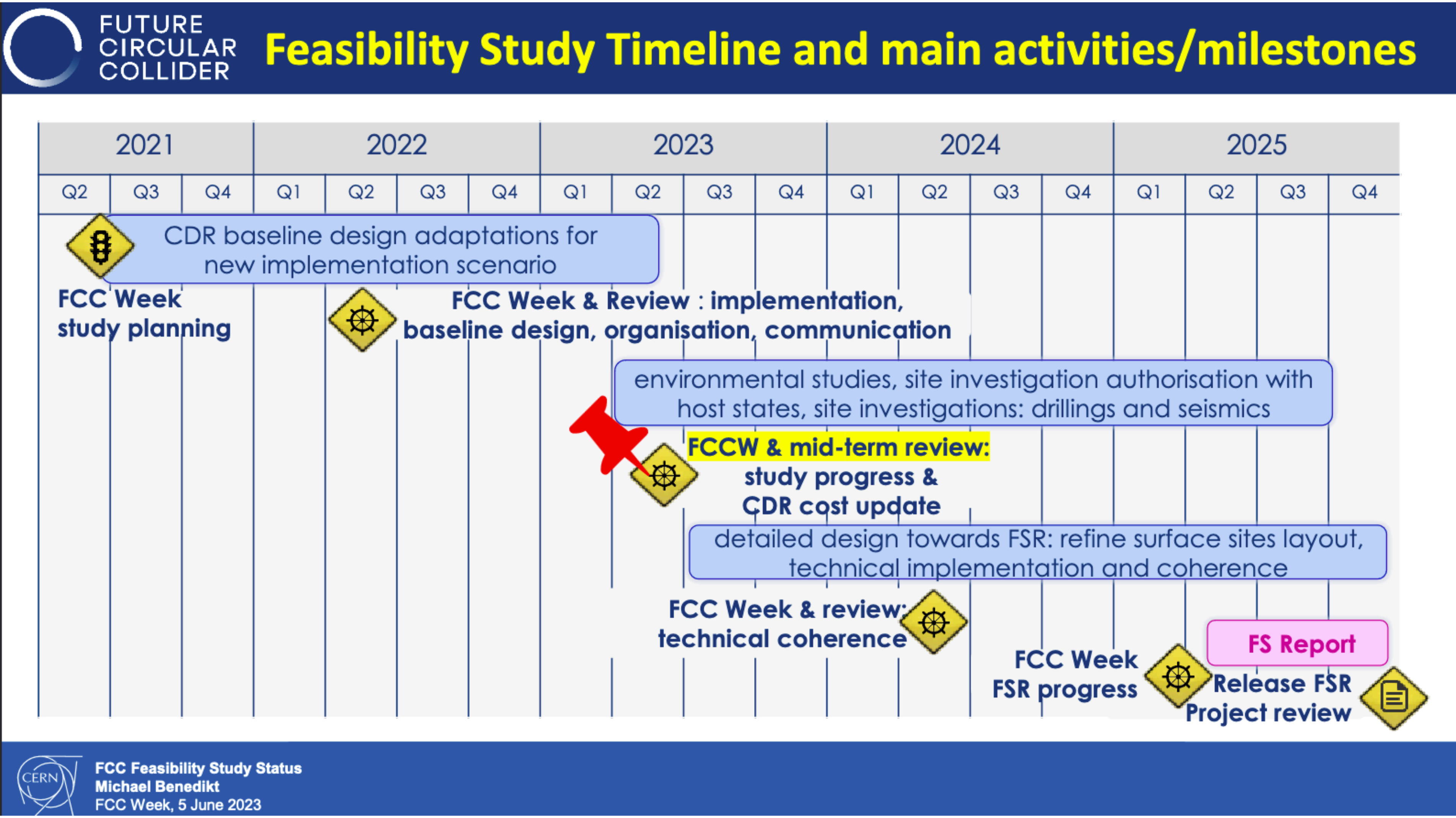
FCC feasibility Mid-term report - Physics and Experiments

2. Key points: FCC-ee luminosity and operation

- Baseline:
  - Flexibility is key, e.g. one year at the *Z* pole, installation of RF, one year for *WW*, then full *ZH* program, …



2. FCC-ee Feasibility Study timeline



2. FCC-ee Feasibility Study: mid-term review key points

- Racetrack placement and democratic reach-out:

FUTURE CIRCULAR COLLIDER

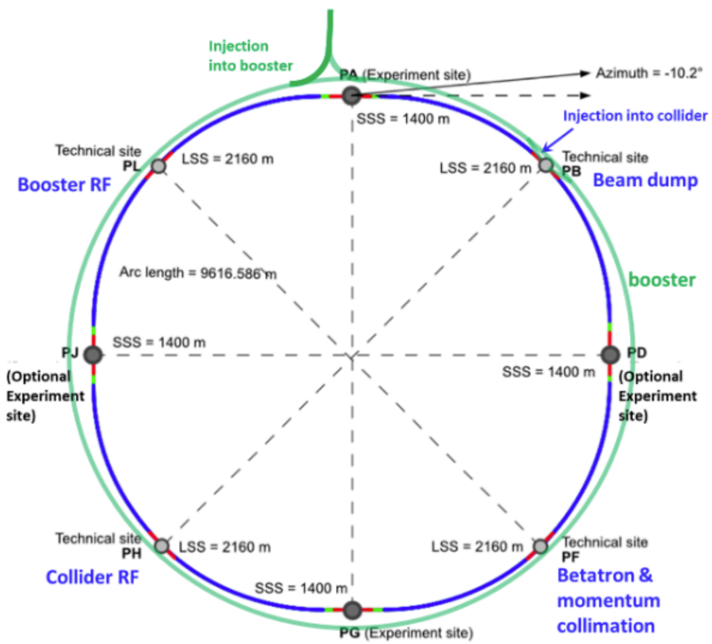
Optimized placement and layout for feasibility study

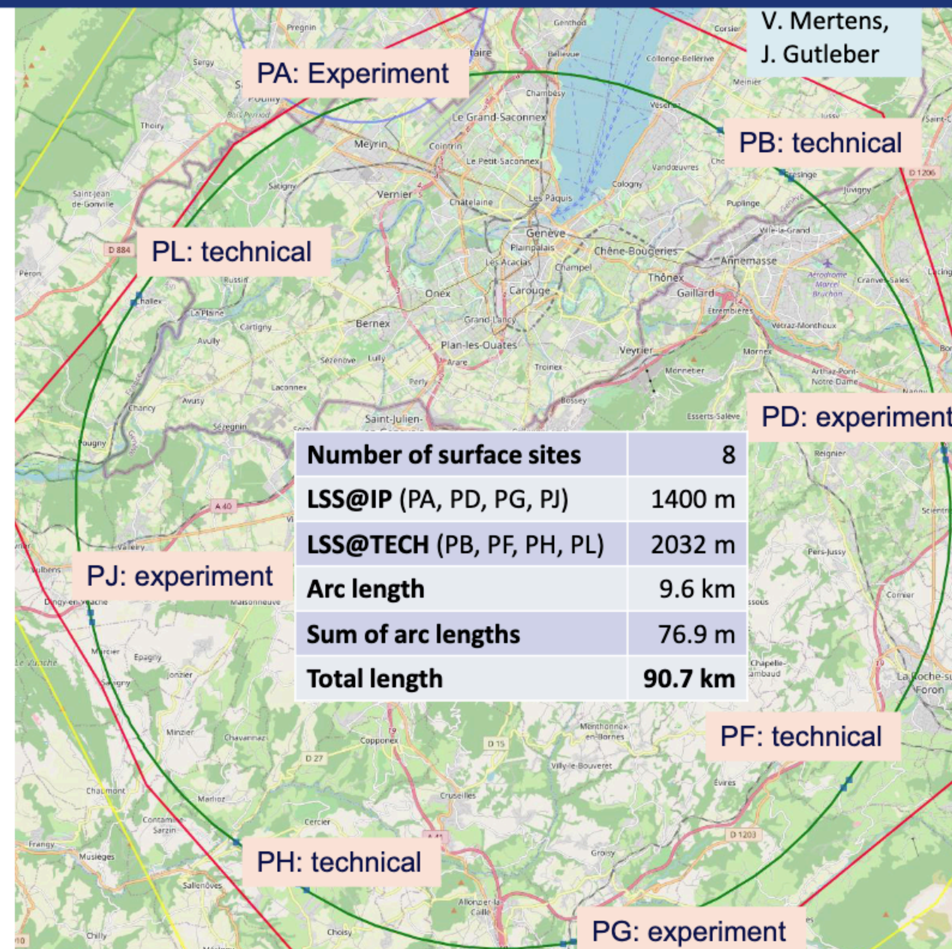
Major achievement: optimization of the ring placement

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: mid-term review key points

FCC

- Racetrack placement and democratic reach-out: © J. Gutleber

FUTURE CIRCULAR COLLIDER

implementation baseline PA31 90.7 km

Meetings with municipalities concerned in France (31) and Switzerland (10)

PA – Ferney Voltaire (FR) – site experimental

PB – Présinge/Choulex (CH) – site technique

PD – Nangy (FR) – site technique et experimental

PF – Roche sur Foron/Etaux (FR) – site technique

PG – Charvonnex/Groisy (FR) – site experimental

PH – Cercier (FR) – site technique

PJ – Vulbens/Dingy en Vuache (FR) site technique et experimental

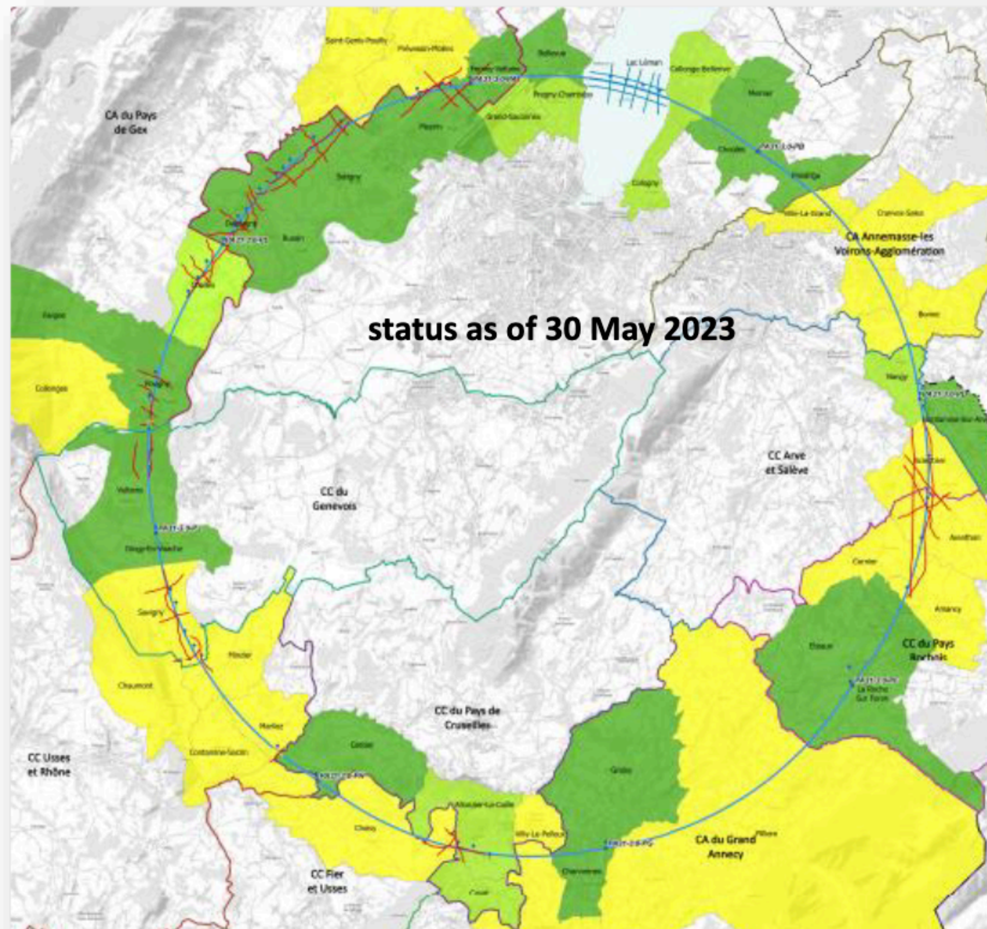
PL – Challex (FR) – site technique

Rencontrée individuellement

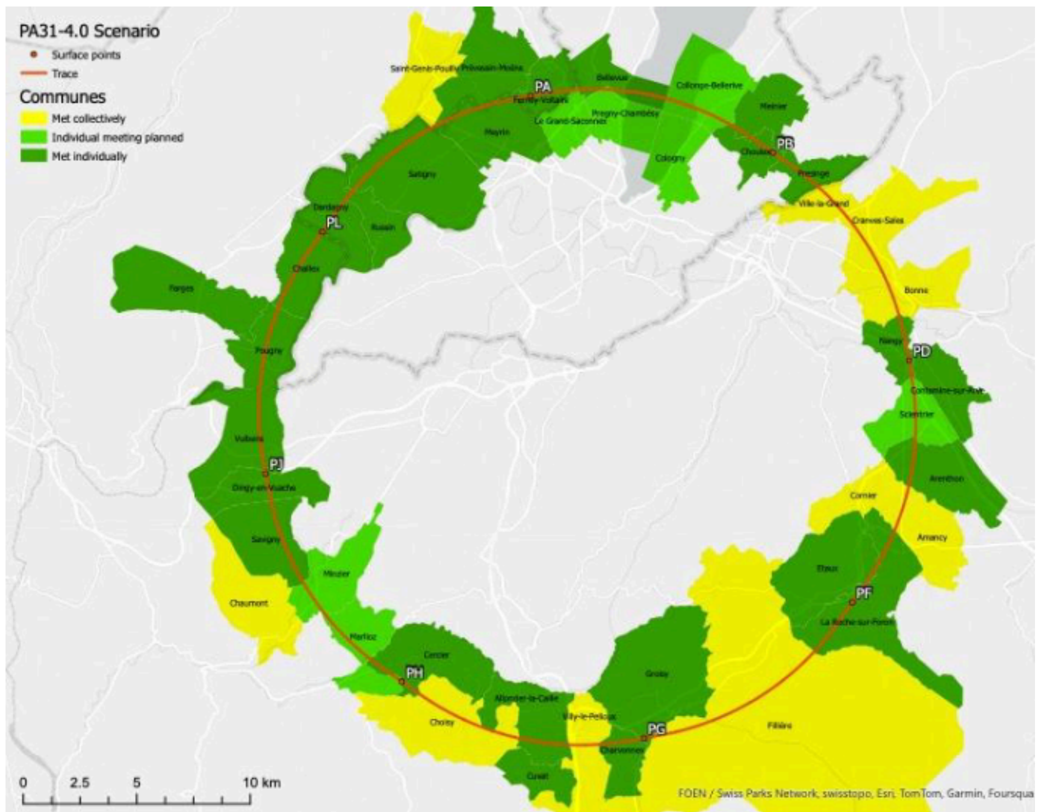
Rendez-vous proposé / programmé

Rencontre collective

Environmental studies and preparation of geological investigations (drillings and seismics) ongoing since February 2023



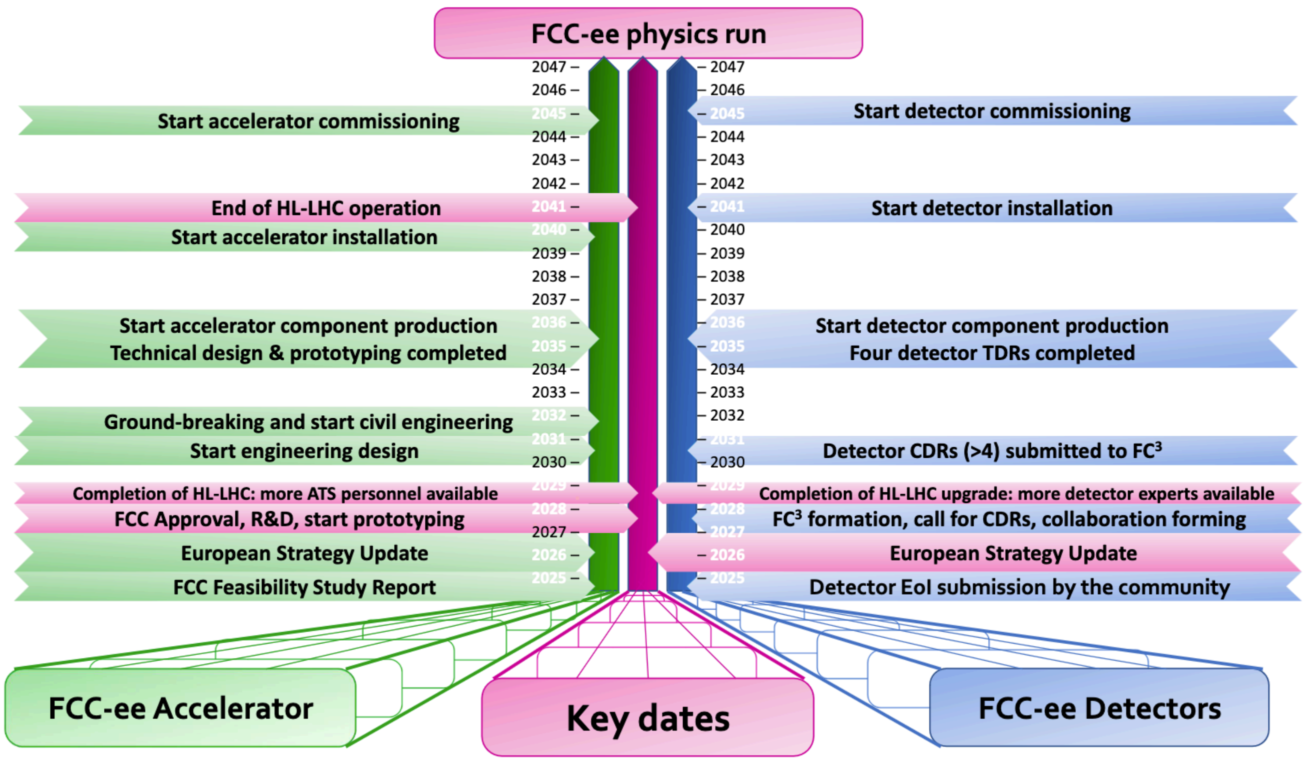
- Racetrack placement and democratic reach-out: (as of january 2024)



2. FCC-ee Feasibility Study: mid-term review key points

- Message#1: the machine design is matured as underlined by the mid-term review.

- Message#2: this schedule is (imo) the only conservative schedule of the projects on the market. Can be felt discouraging but realistically solid.



3. The Physics Case at large

3. The Physics Case at large: big picture

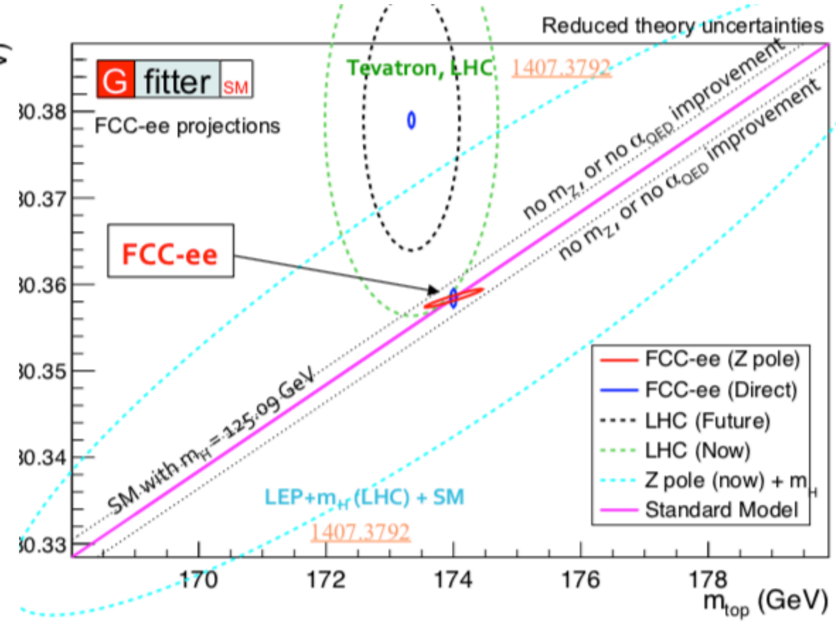
FCC

Z pole

WW thr.

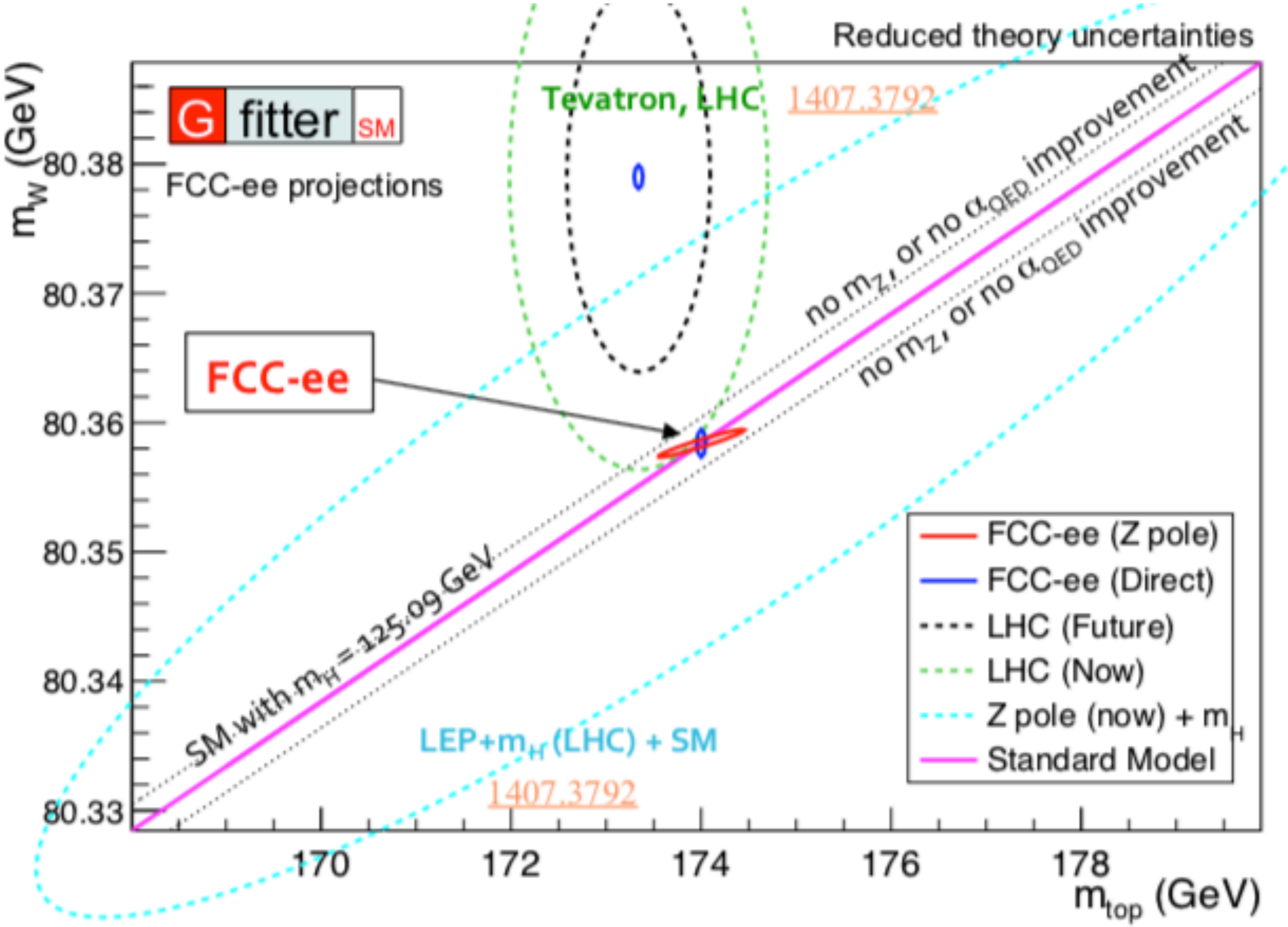
tt thr.

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
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480 ± 160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)(\times 10^3)$	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
$\sigma^0_{\rm had}$ $(\times 10^3)$ (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
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	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
$m_{\rm top}$ (MeV)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	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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Z pole | *WW* thr. | tt thr.

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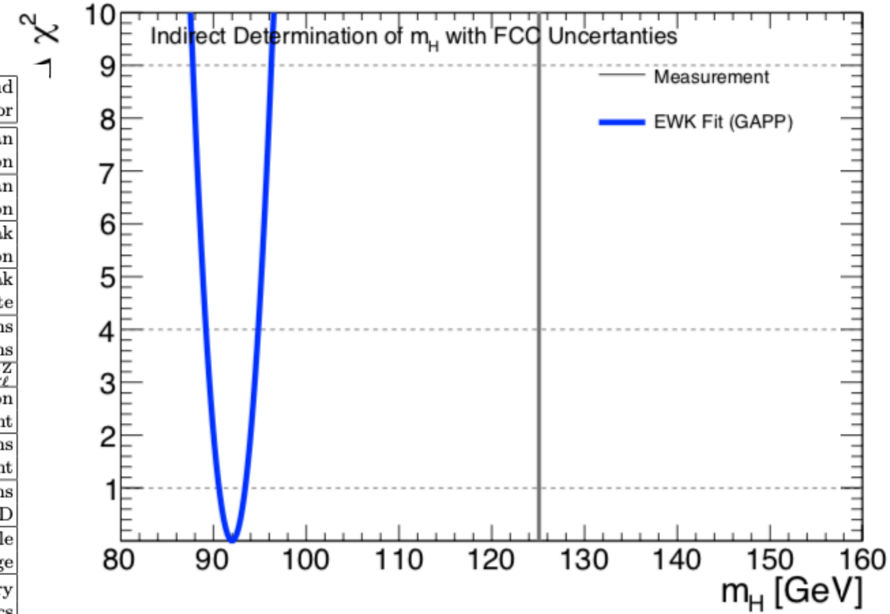
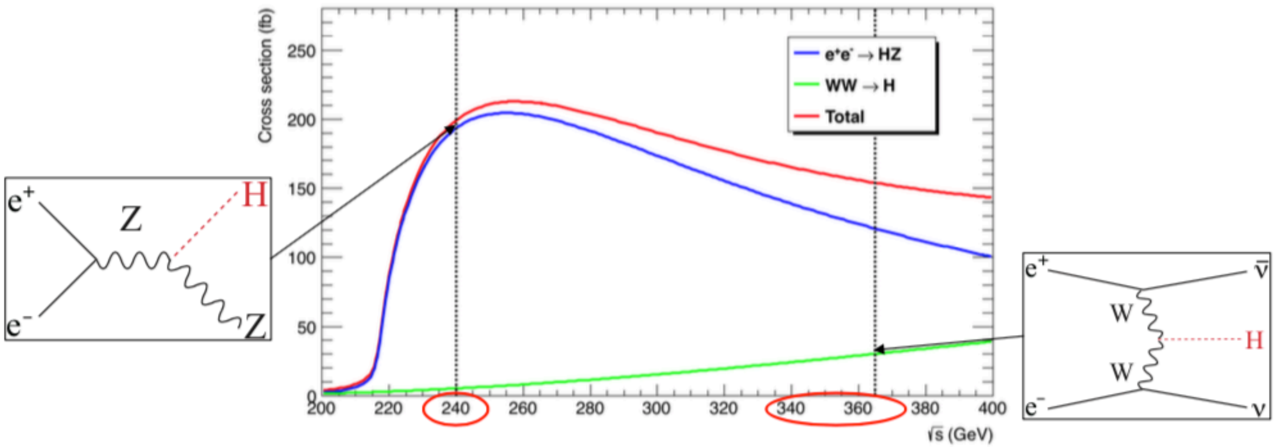


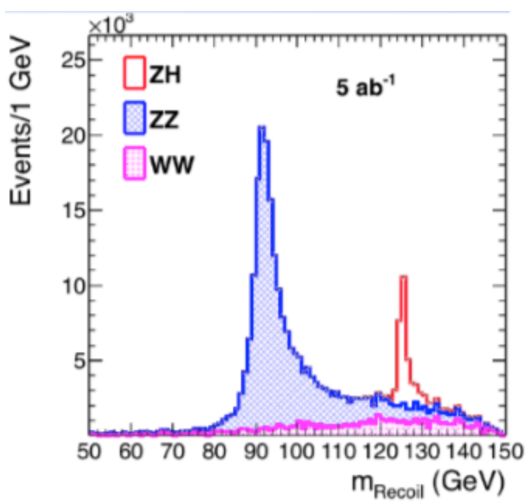
- Ultimate quantum completeness consistency test of the SM.
- The improvements in theory prediction precision is part of the FCC program. Precision 1.4 GeV.

3. The Physics Case at large: the Higgs factory

- 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 Higgs factory

- It is interesting to note that the extrapolations provided for the CDR have mostly received confirmation from the latest studies, featuring more realistic detectors

Parameter	FCC-ee CDR	FCCee today
$H \to WW$	1 %	2.0 %
$H \to ZZ$	3.6 %	4.6 %
$H \to gg$	1.6 %	0.78 %
$H \to \gamma\gamma$	7.5 %	3.5 %
$H \to cc$	1.8 %	1.6 %
$H \to bb$	0.25 %	0.18 %
$H \to \mu\mu$	15.8 %	19.5 %
$H \to \tau\tau$	0.75 %	0.9%
$H \to Z\gamma$		
$H \to ss$	–	103 %
Invisible	< 0.25 %	< 0.18 %
m_H	5 MeV	4 MeV
Γ_H	1 %	4%
κ_λ	42 %	30%

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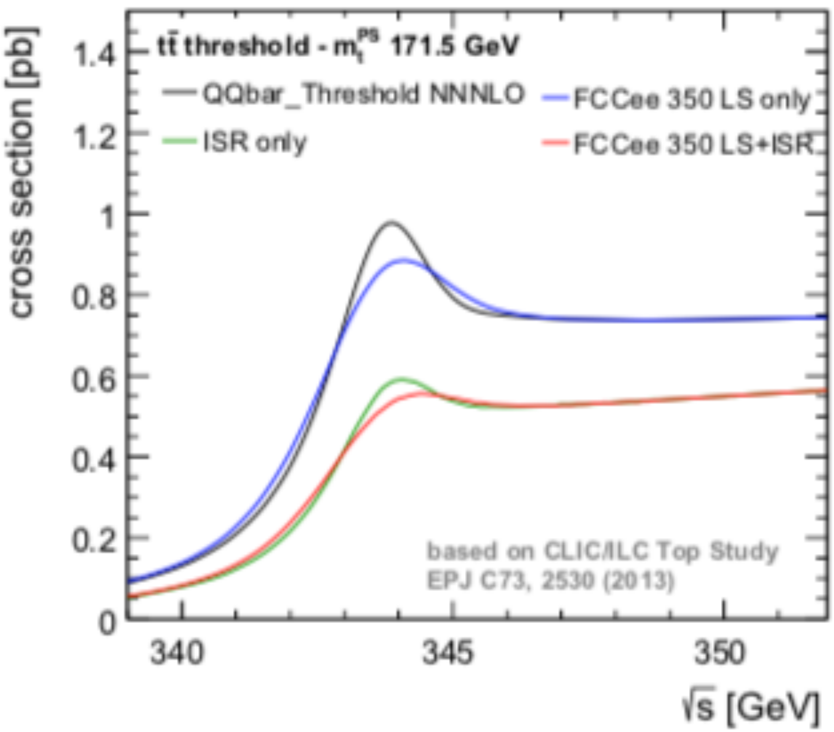
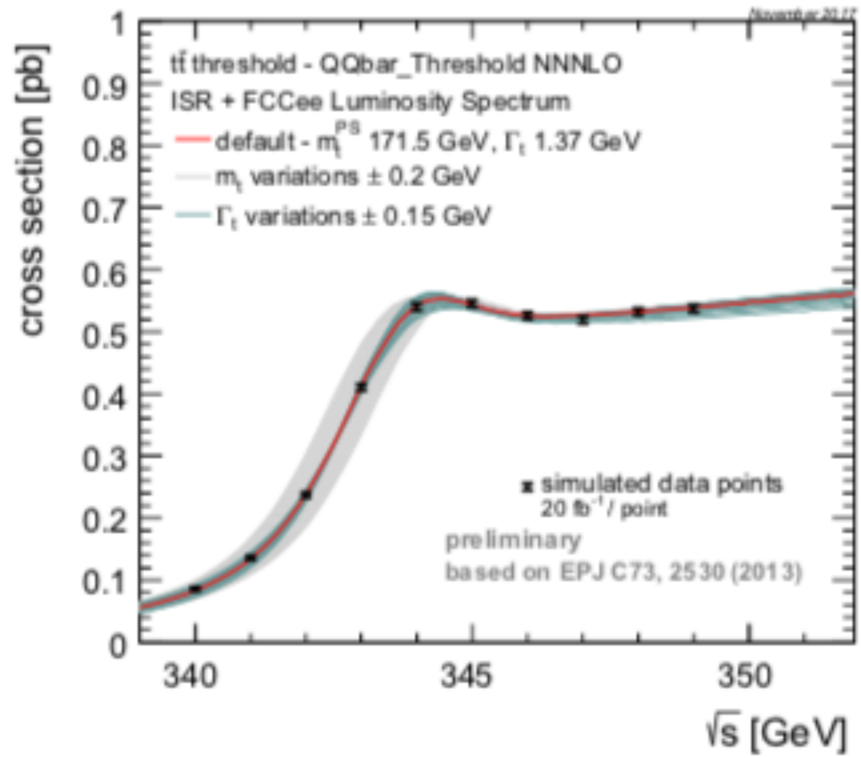
3. The Physics Case at large: the top threshold





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

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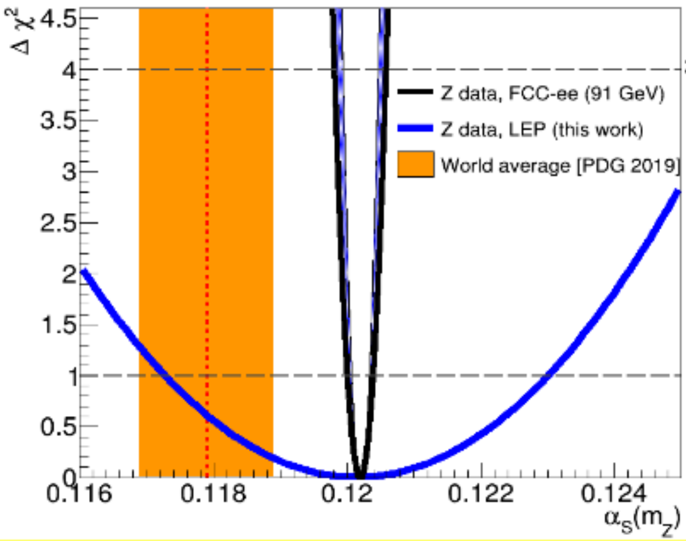
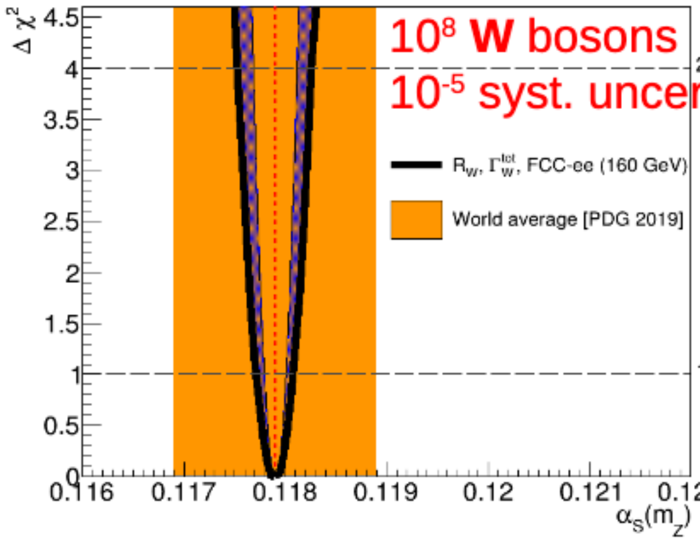
■ Future: Permille uncertainty possible only with a machine like FCC-e^+e^-



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

Strong SM "stress test"



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

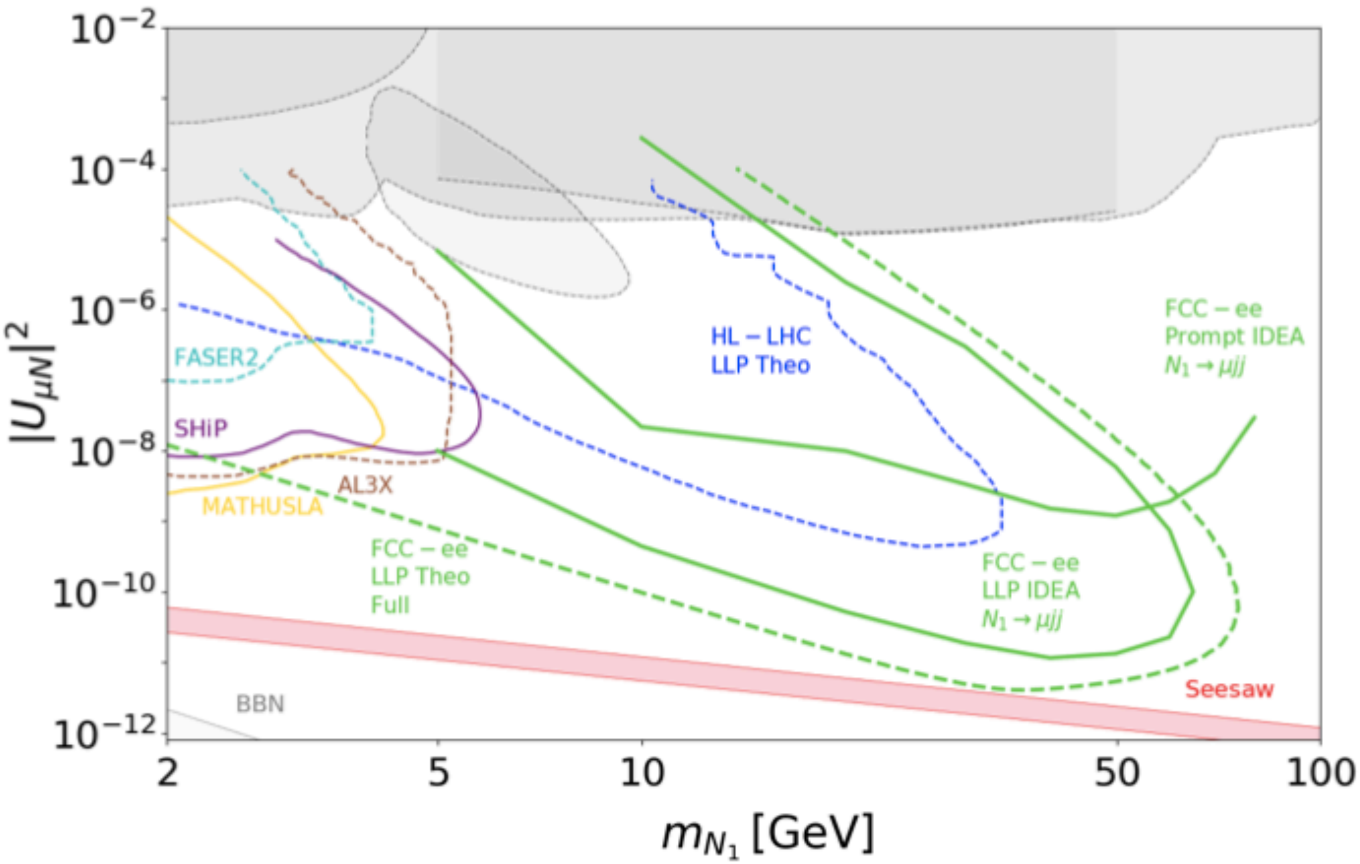
$\alpha_s(m_z)$ = 0.12030 ± 0.00028 ±0.2% (tot), ±0.1% (exp)

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

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

3. The Physics Case at large: discovery potential

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



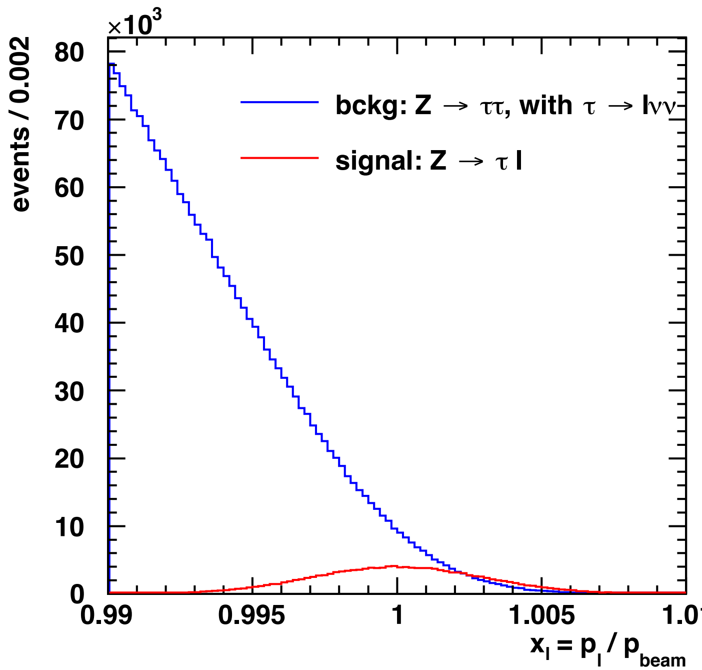
3. The Physics Case at large: discovery potential

- 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 limited by the momentum resolution. A lot of phenomenology to explore yet.

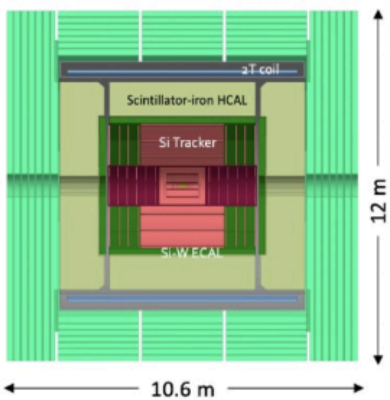


Bottomline: With the expected tracking performance at FCC-*ee* (beam spread equivalent resolution at 45 GeV), the current limits are pushed by three orders of magnitude, *e.g.* $O(10^{-9} - 10^{-10})$.

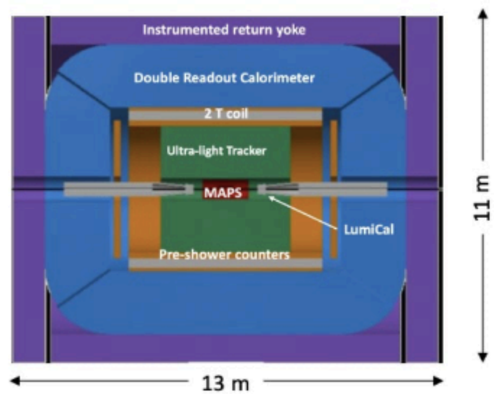
3. The Physics Case at large: detector concepts

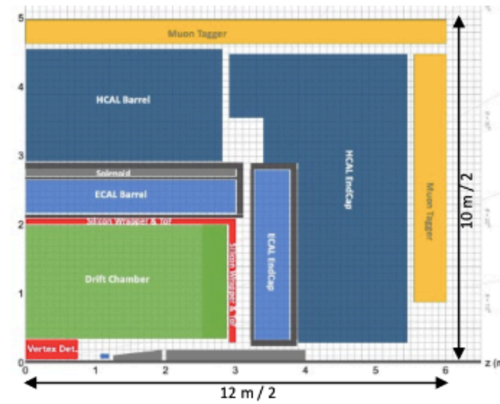
- The physics reach is obviously intimately related to the detector performance
- So far three detector concepts defined by calorimetry

CLD | **IDEA** | **ALLEGRO**



CDR





CLD

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

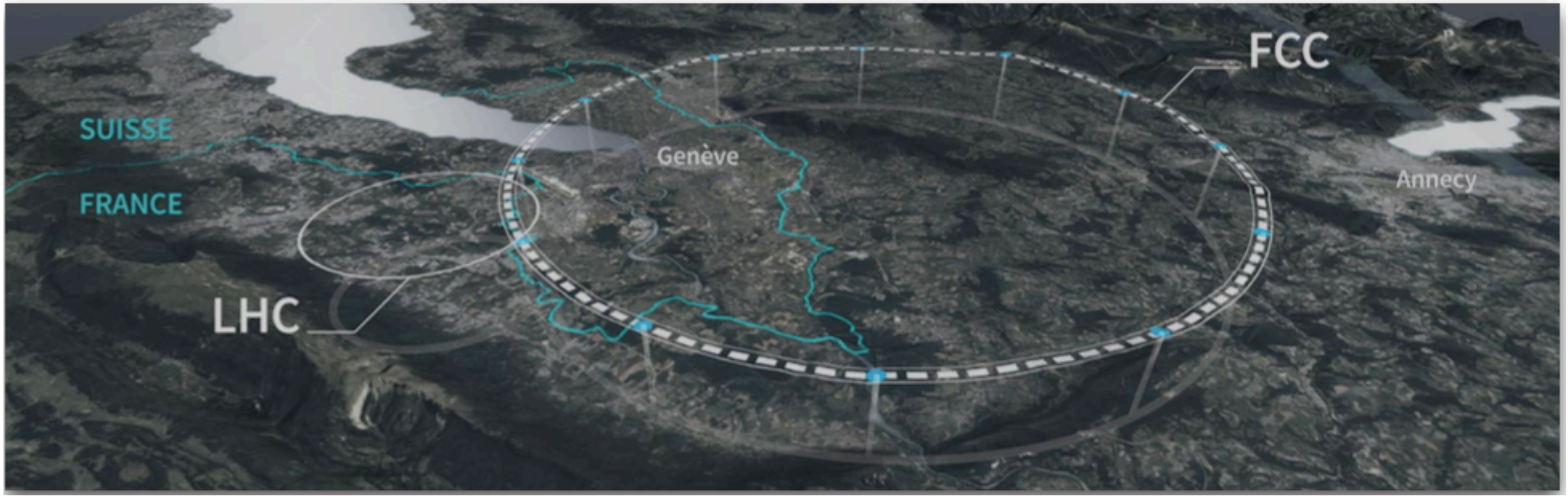
IDEA

- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber with powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

ALLEGRO

- The "new kid on the block"
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

4. Flavours at FCC-ee: setting the scene



4) FCC-ee ABCD specifics for Flavour Physics.

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 ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (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 $6\cdot10^{12}$ Z decays. Charge conjugation is implied.

4) FCC-ee ABCD specifics for Flavour Physics.

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

- 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^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
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 is commensurate with those of LHCb-Upgrade II.

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

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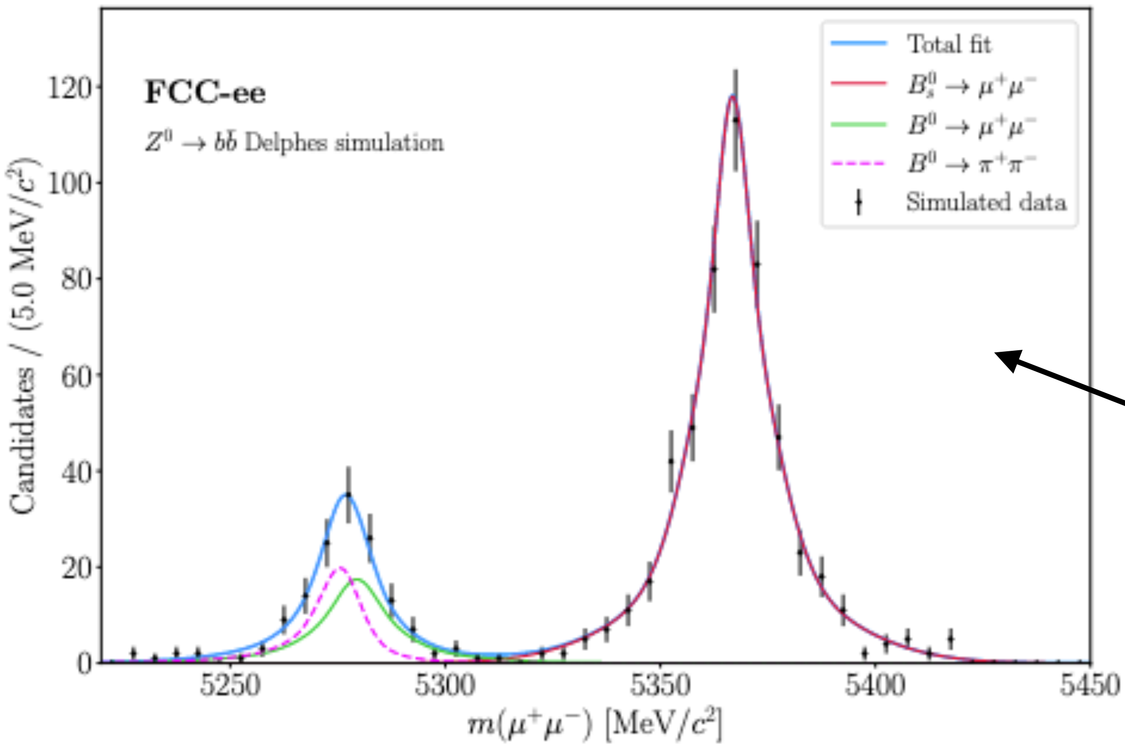
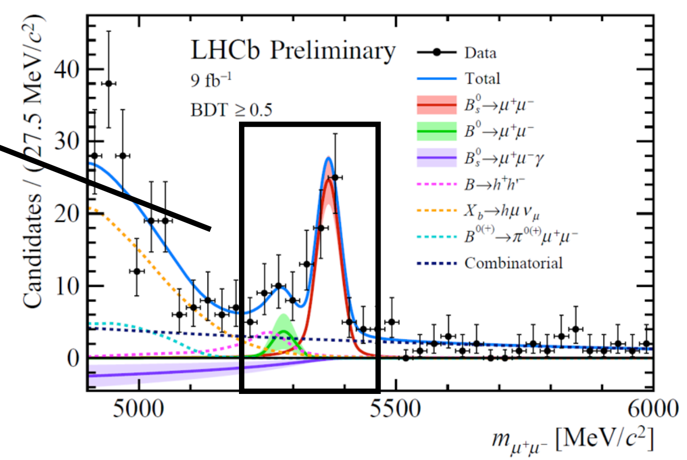

FCC-ee
$Z^0 \to b\bar{b}$ Delphes simulation
Total fit
$B_s^0 \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
$B^0 \to \pi^+\pi^-$
Simulated data
Candidates / (5.0 MeV/c^2)
$m(\mu^+\mu^-)$ [MeV/c^2]
0
20
40
60
80
100
120
5250
5300
5350
5400
5450


LHCb Preliminary
9 fb^{-1}
BDT ≥ 0.5
Data
Total
$B_s^0 \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
$B_s^0 \to \mu^+\mu^-\gamma$
$B \to h^+h'^-$
$X_b \to h\mu\nu_\mu$
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$
Combinatorial
0
10
20
30
40
5000
5500
6000
$m_{\mu^+\mu^-}$ [MeV/c^2]

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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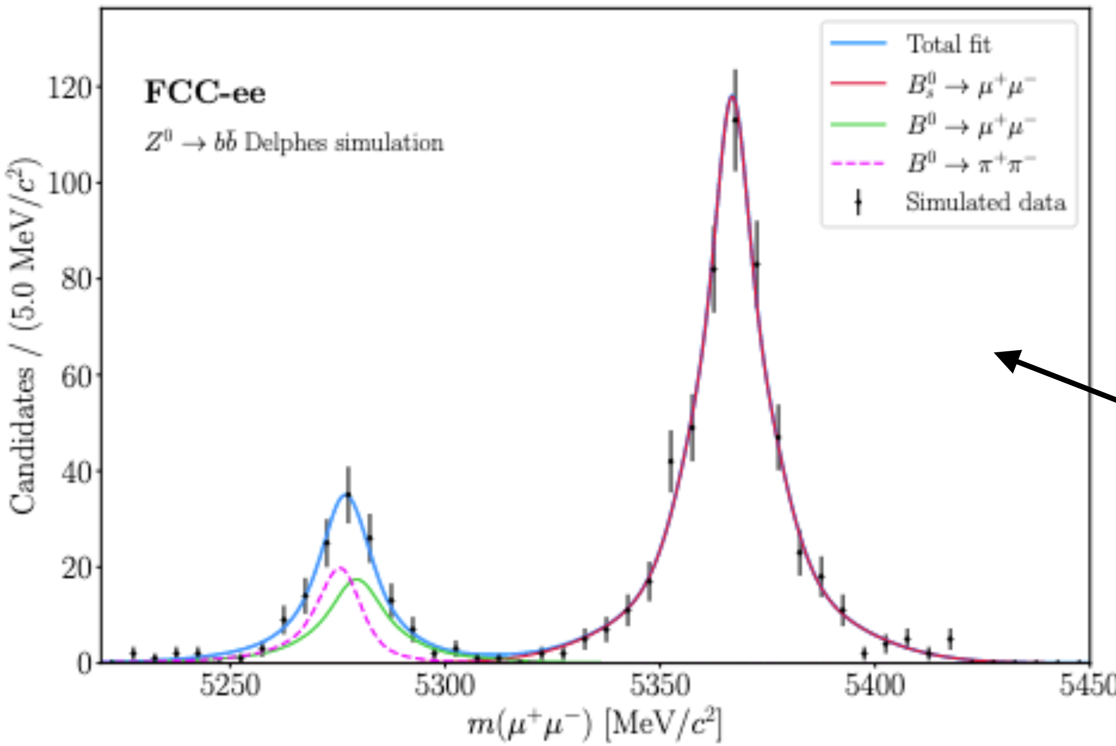
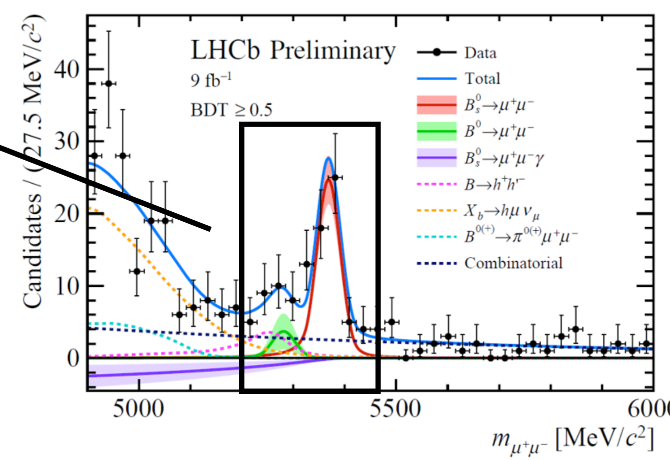




Seems granted w/ state-of-the-art tracker. Ultra-high resolution calorimetry is in addition desirable to touch high performance for modes w/ neutrals

4) FCC-ee ABCD specifics for Flavour Physics.

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.

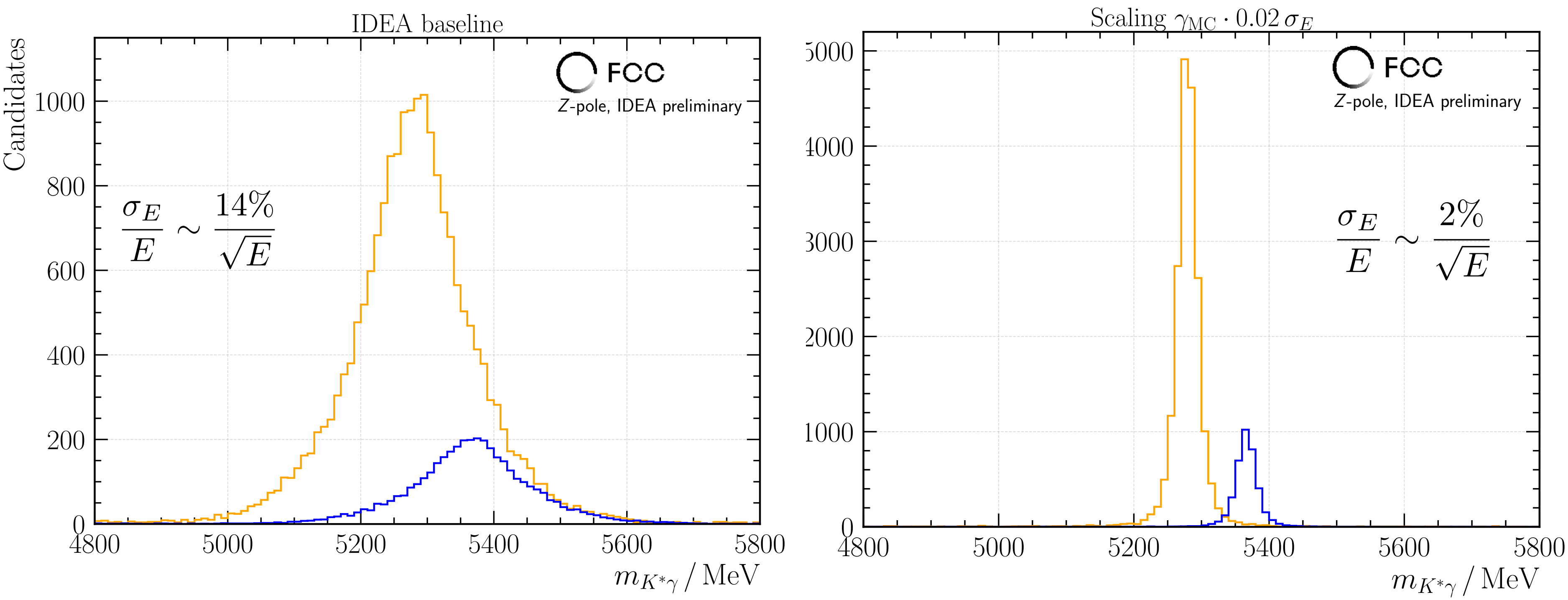
Aparté

Aparté

Aparté

- The different tracking systems on the table are already very powerful and are meeting physics requirements. Some subtleties from Flavour Physics however, such as placing the vertex detector within the beam pipe …
- But …
- … Detector Concepts built 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.

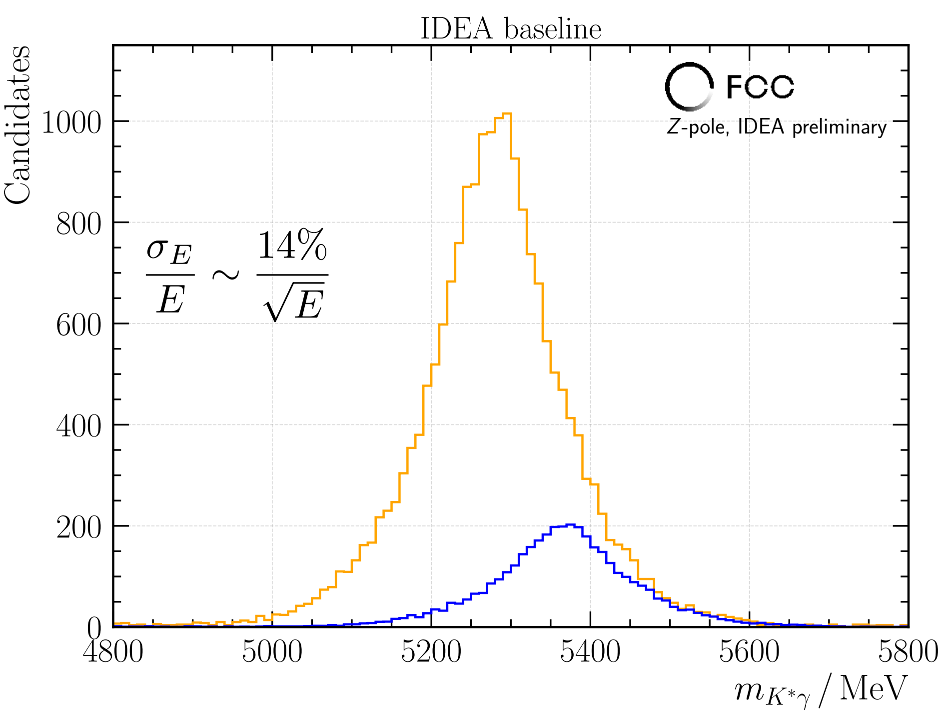
Aparté

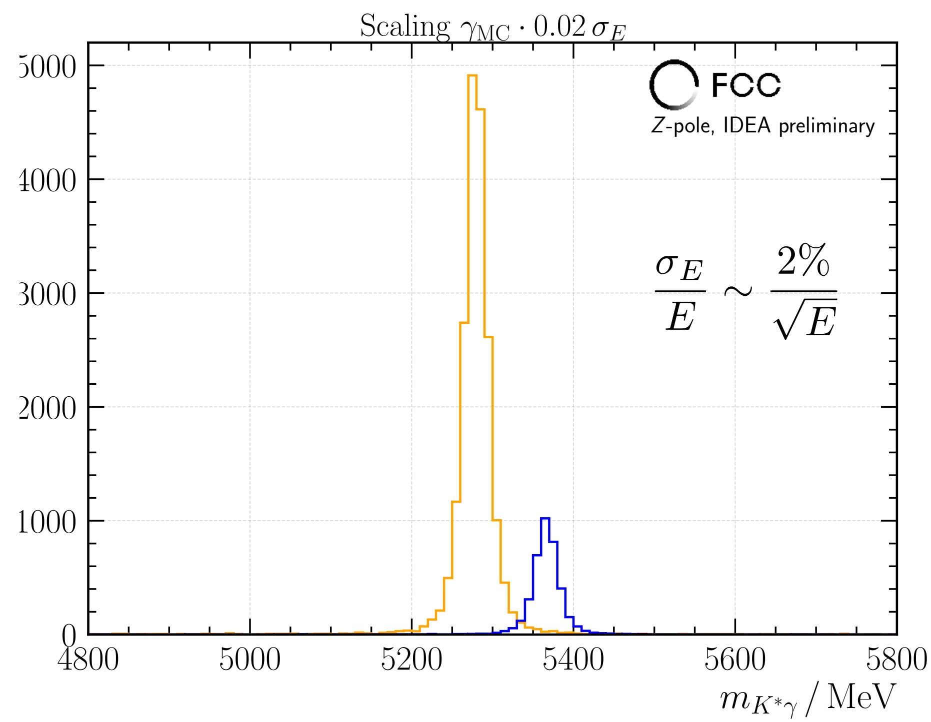


- There's a difference! addressing or not this Physics. Target: 2%!

Aparté

Flavour Physics requires in addition high energy-resolution, *e.g.* 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. Target: 2%!

Aparté

FCC PED Week — Annecy — January 2024

GRAiNITA: fine sampling crystal grain calorimetry.

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

On behalf of the GRAiNITA Group:
IJCLab: S.Barsuk, I.Boyarintseva, D.Breton, G.Hull, J.Lefrançois, 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, A.Kotenko, N.Semkiv.

Based on arXiv:2312.07365

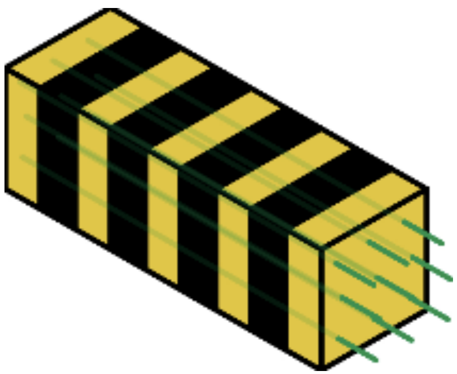
S. Monteil GRAiNITA@ FCC

Hot from the press: accepted by JINST

Aparté: principles of GRAiNITA

- Reaching an exquisite energy resolution while preserving high transverse granularity

Typical sampling calorimeter (e.g. Shashlik)

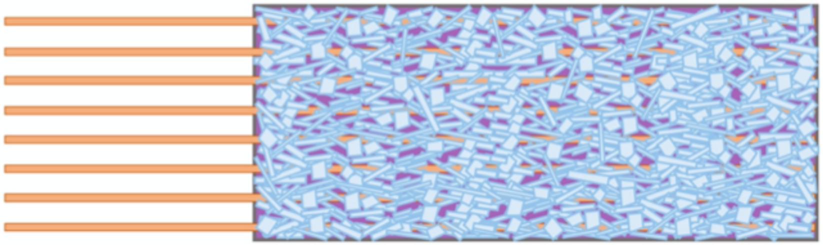


$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}}$$

Crystal calorimeter

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

- Can we make the best of the two approaches ?
- Fine sampling
- Local containment of the scint.light (inspired by A. Cabrera et al. LiquidO Commun Phys 4, 273 (2021)



Aparté: the grains, the fibres, the liquid

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

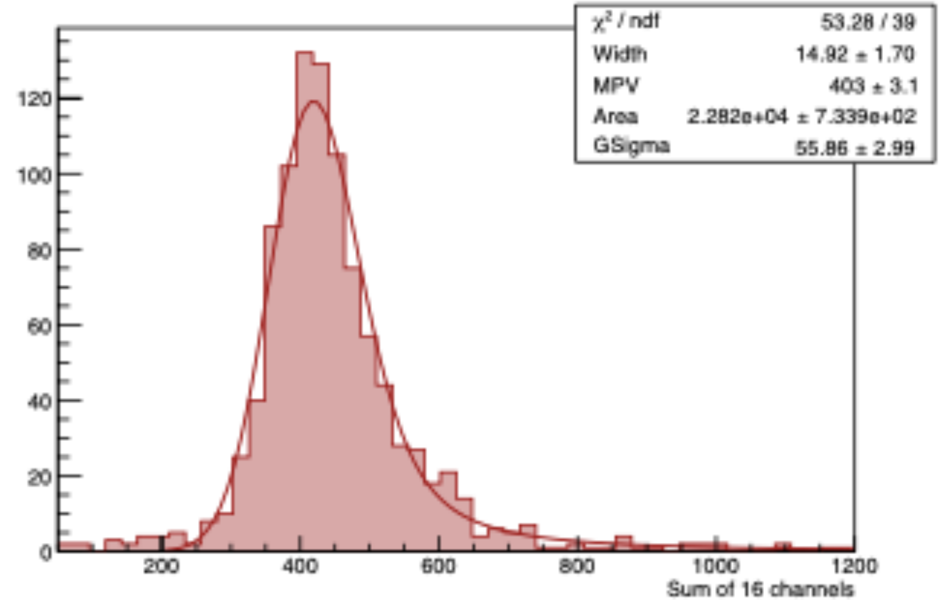
	BGO	$ZnWO_4$
Effective Z	74	61
Density (g/cm^3)	7.13	7.87
Refractive index	2.15	2.0 - 2.3
Light yield (photons/MeV)	~ 9000	~ 9000
Peak emission wavelength (nm)	480	480
Decay time (μs)	0.3	20
Radiation length (cm)	1.12	1.20
Molière radius (cm)	2.26	1.98

©A. Contamine and C. Fayard

- Possible candidate for the grains: $ZnWO_4$
- ISMA: dedicated R&D to produce $ZnWO_4$ grains with the flux method (inexpensive method). Production technique mastered.
- Scintillation decay time ok for FCC-ee (~75 kHz at the Z pole).
- About 1 kg produced.
- Other options under consideration, *e.g.* BGO.

Aparté: the first paper result.

- Average dE/dx for muons in the prototype: ~1.5 MeV / (g.cm^{-2})
- Density of the prototype is about half that of $ZnWO_4$ (~4 g.cm^{-3})
- The length of prototype seen by a muon is about 6 cm
- The energy deposited in the prototype by a cosmic muon is *O*(40 MeV)

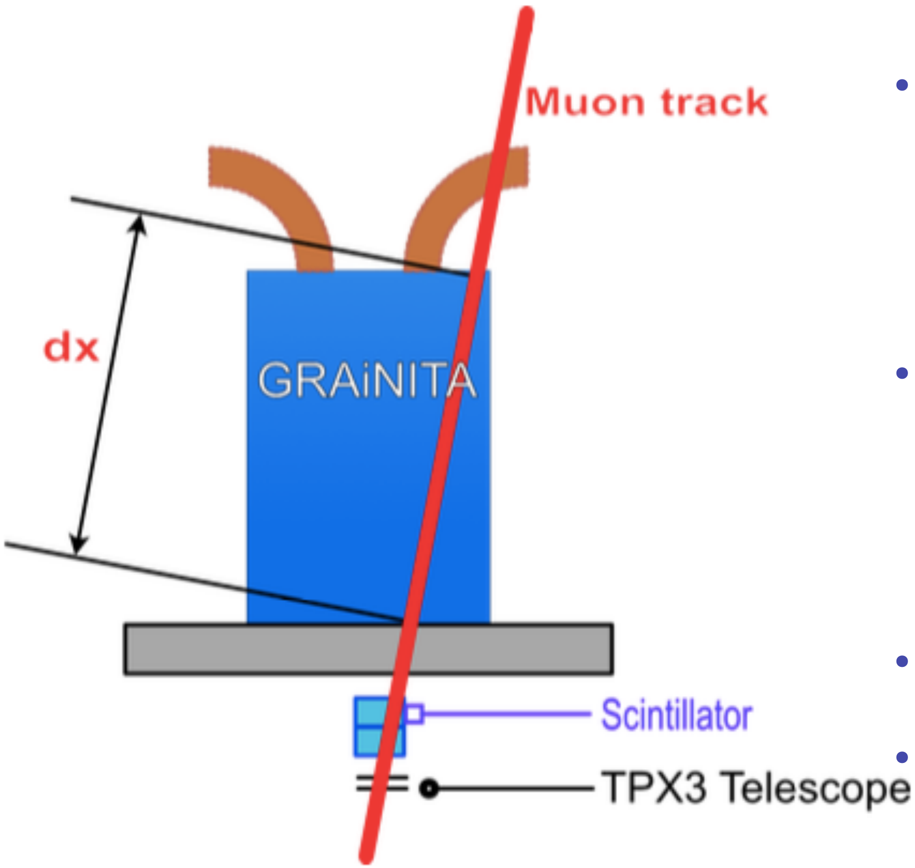


- About 400 photo-electrons
- About 10 p.e. per MeV, *e.g.* 10000 p.e. per GeV. !!
- More to study: mirror ends on fibres, heavy liquid …

Should these numbers be confirmed, the

1% stochastic target is at reach ! arXiv:2312.07365

Aparté: the Clermont test bench. Towards constant term



- Accurate (1mm at 15 cm) knowledge of the muon trajectory in the prototype thanks to a Si telescope prototype (TPX3)
- Aim at measuring the response of the GRAiNITA prototype as a function of the actual (length) passage of the particle, the distance to the fibre etc…
- Start to address the non-uniformities.
- To be used further in muon test beam.

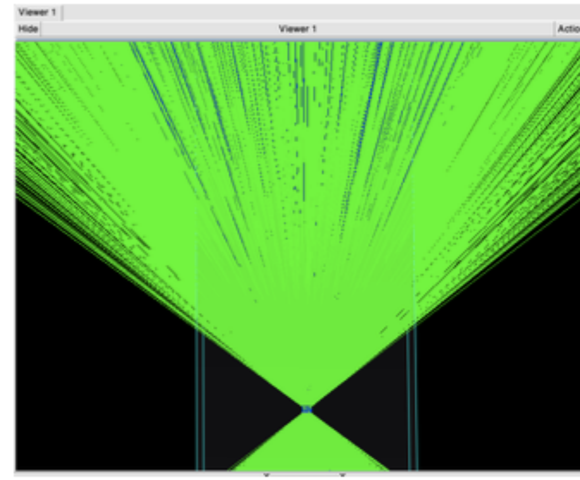
Aparté: the Clermont test bench. Towards constant term

- TPX3 qualification:
  - comparison of the angular distribution of muons (use seven days sent by the manufacturer) with the canonical model

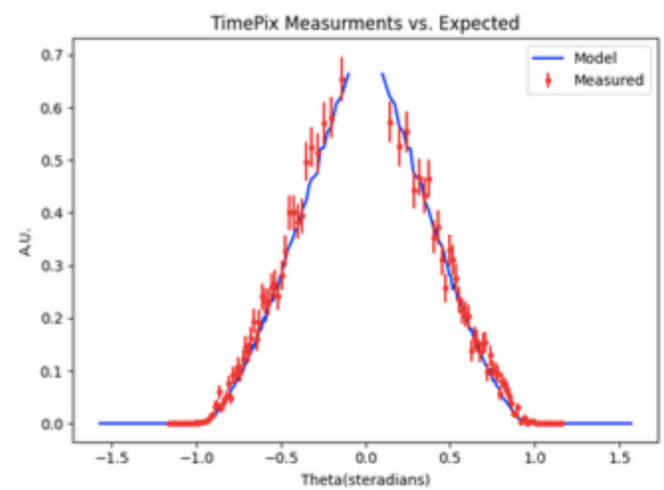
    $$I(\theta)=I_0 \cos^{2.22}(\theta)\ \mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

  - works fine: 0.73 muons /min observed while 0.74 / min were predicted
- Status of the bench:
  - commissioning

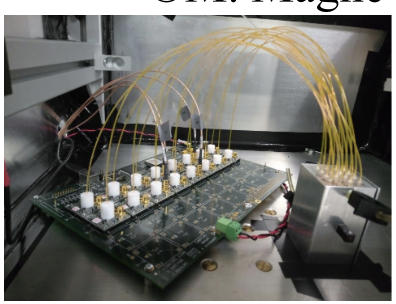
©H. Chanal



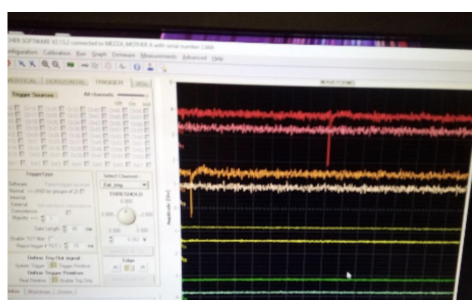
Event viewer



©M. Magne



First photon seen 2 weeks ago!



Aparté: the Clermont test bench. Towards constant term

- Pulse Shape Discrimination

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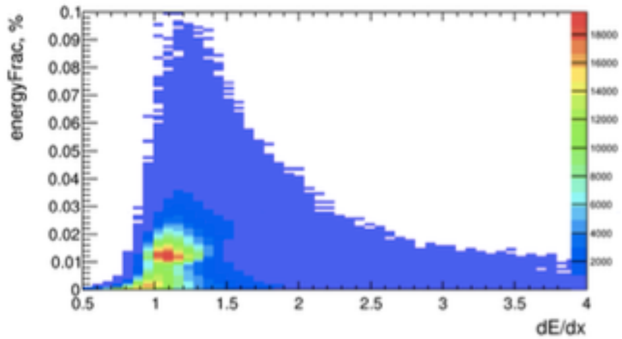
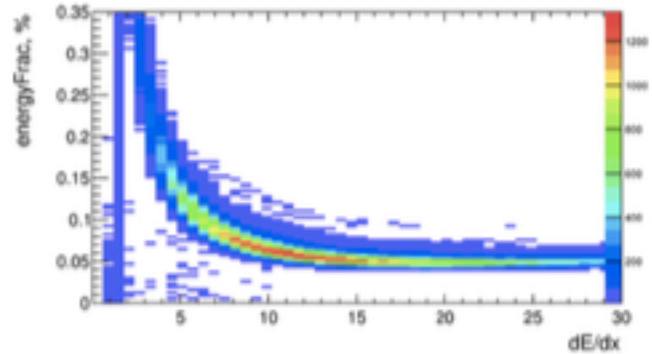
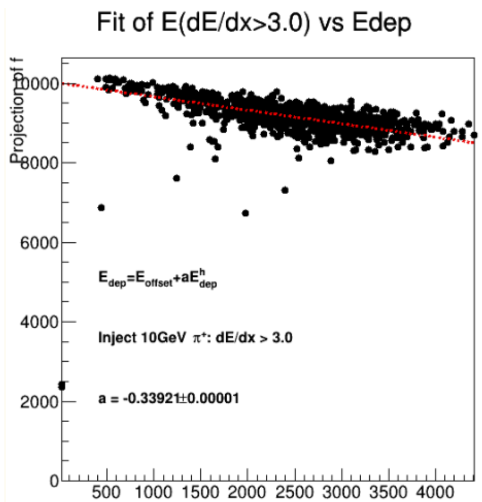
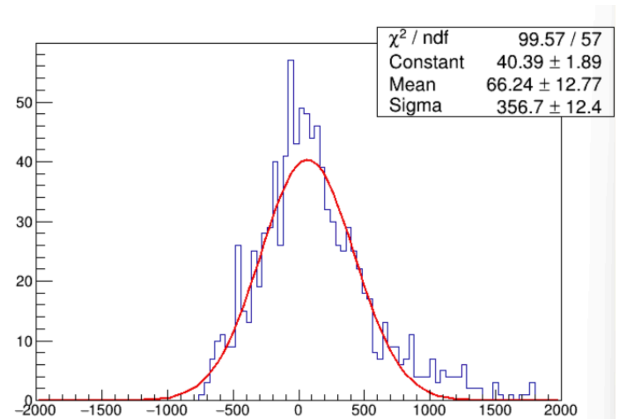








- Different ways to deposit the energy shall reflect into different scintillation times: next step is to educate an optical model (test beam at low energy first and simulations).

5) Reviews of current activities (Design/Feas. Study)

- 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 approved 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 Flavour physics case that will be developed in the next two decades?
  - The answer is: YES. Focus was put on the study of modes that are likely unique to FCC-ee. It happens in addition that there is no place where FCC-ee does not compete valuably, and hence provides at least a useful comparison.

5) Reviews of current / foreseen activities (Feas. Study)

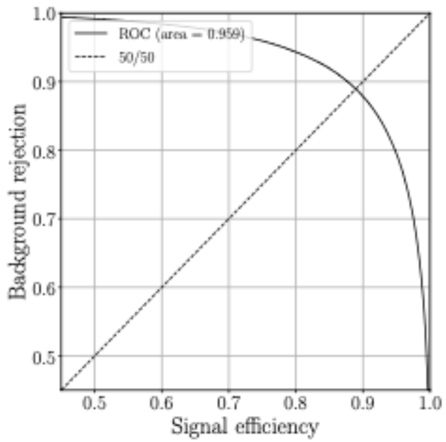
- Rare semileptonic decays and leptonic decays:
  - $b \to s\tau^+\tau^-$, e.g. $B^0 \to K^{*0}\ \tau^+\tau^-$. (case for mid-term review)
  - $b \to s\nu\nu$, e.g. $B_s \to \phi\nu\nu$
  - $Bc \to \tau\nu$; $b \to s(d)\,\ell\ell$

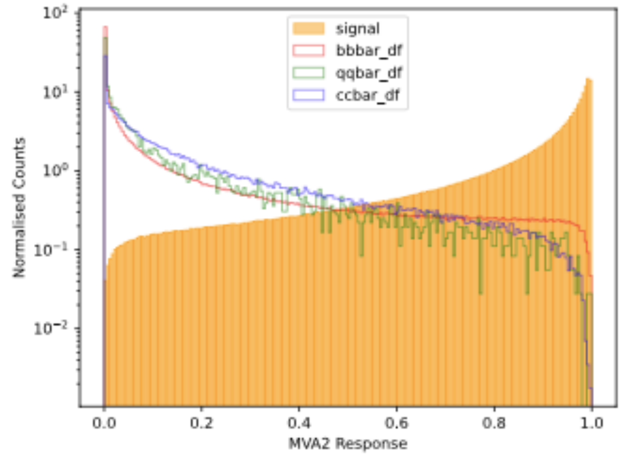
- *CP* violation studies:
  - The CKM γ angle, e.g. $B_s \to D_s K$.
  - The semileptonic asymmetries (*CP* breaking in mixing).
  - The CKM α angle, e.g. $B^0 \to (\pi^0\pi^0)$.
  - The matrix elements V_{ub} and V_{cb} ….

- Tau Physics:
  - Lepton flavour violating τ decays
  - Lepton-universality tests in τ decays.

- Charm Physics:
  - The rare decays, e.g. $D \to \pi\nu\nu$, $D^0 \to \gamma\gamma$
  - The hadronic decays, $D^+ \to \pi^+\pi^0$ …

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





© A. Wiederhold, M. Kenzie
arXiv:2309.11353

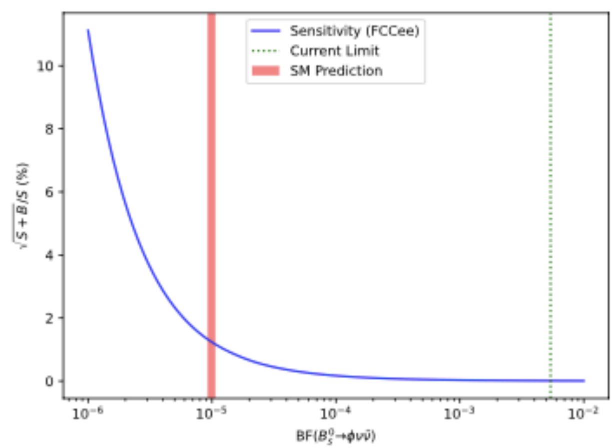
First indication of such a transition just came from Belle II (2023).

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

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

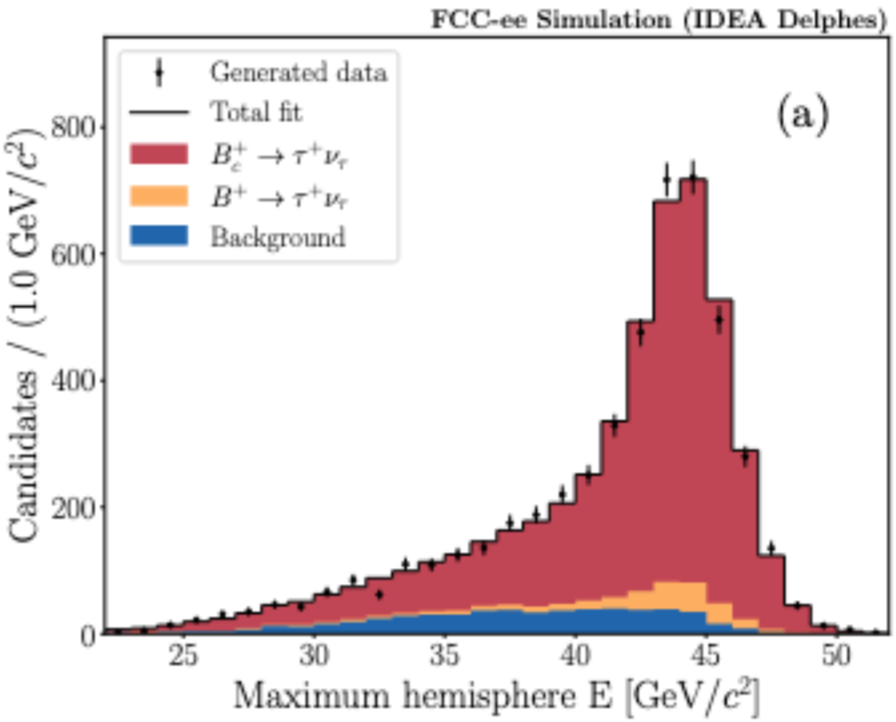
For an optimal BDT1 and BDT2 cut at the SM predicted BF:

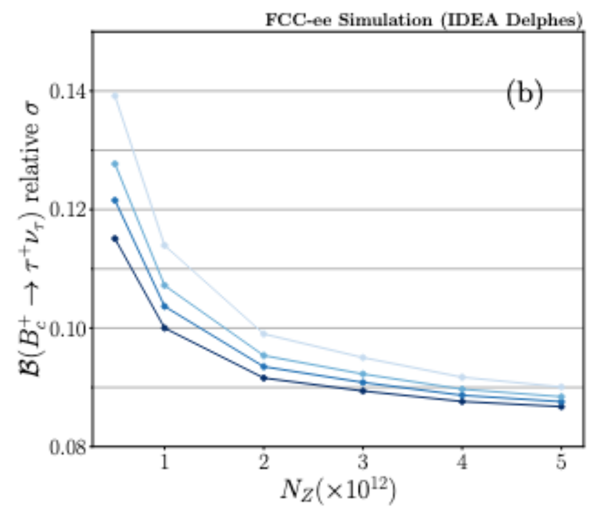
- Signal efficiency $\sim 11\%$
- $b\bar{b}$ efficiency $\sim 10^{-4}\%$
- $c\bar{c}$ efficiency $\sim 10^{-6}\%$
- $q\bar{q}$ efficiency $\sim 10^{-7}\%$
- Signal:Background ratio $\sim 1:9$
- Sensitivity $\sim 1.2\%$



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]



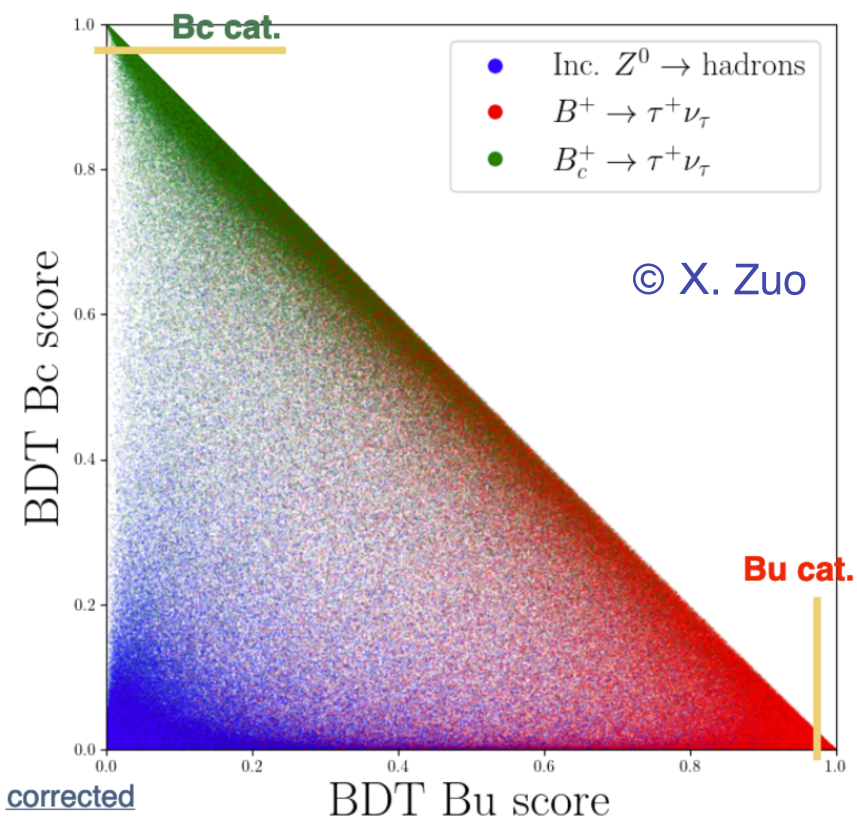


© X. Zuo et al.

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.



© X. Zuo et al.

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)

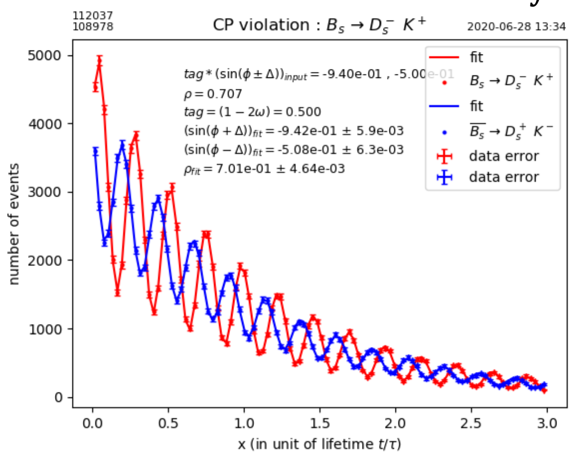
- Sub-degree gamma angle measurement with just one mode :

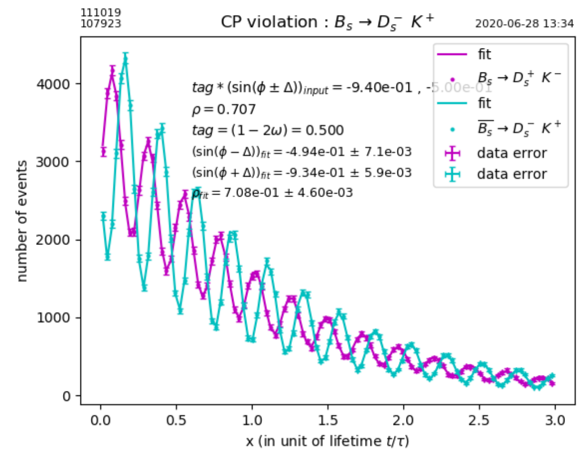
Measurement of CP violation with $B_s \to D_s K$

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

PDG: $\gamma = (71.1^{+4.6}_{-5.3})°$

© R. Aleksan





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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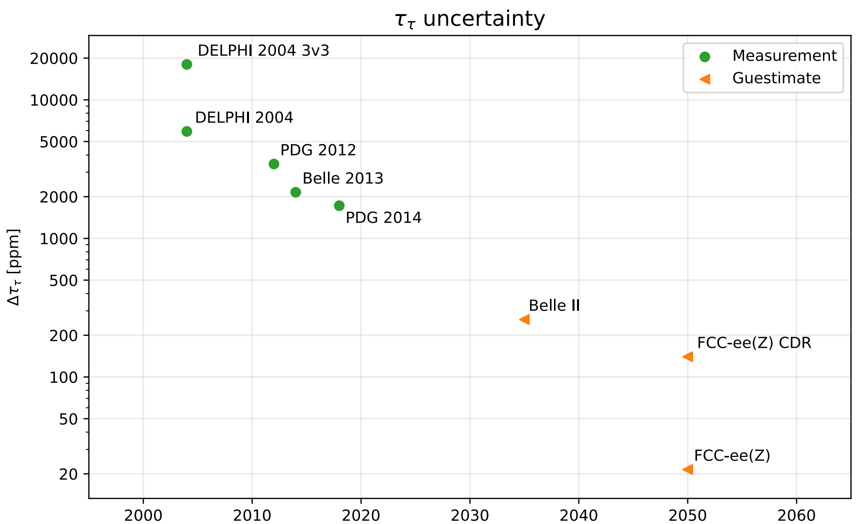

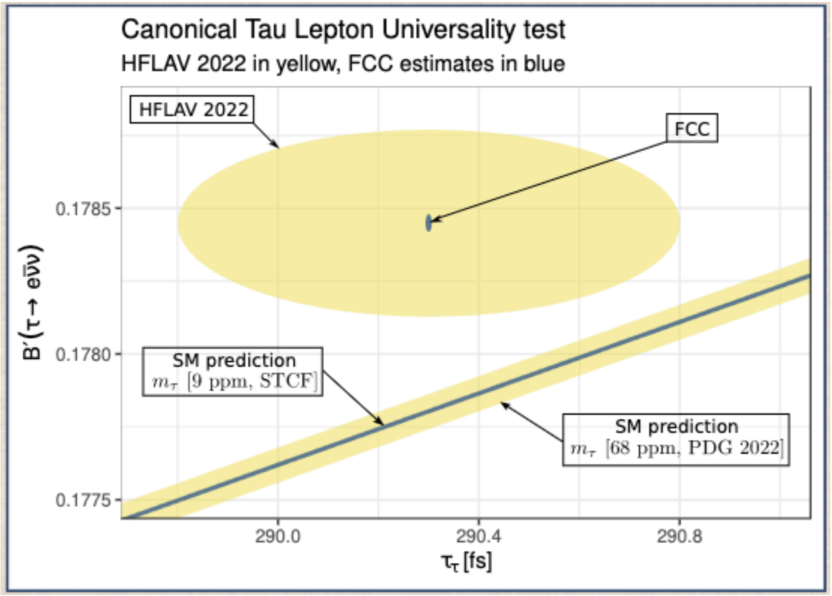

Comment: B-factories did not improve (much) LEP measurements (Belle II might). FCC-ee has much better experimental conditions than LEP and about 5× the statistics of tau pairs w.r.t. Belle II.

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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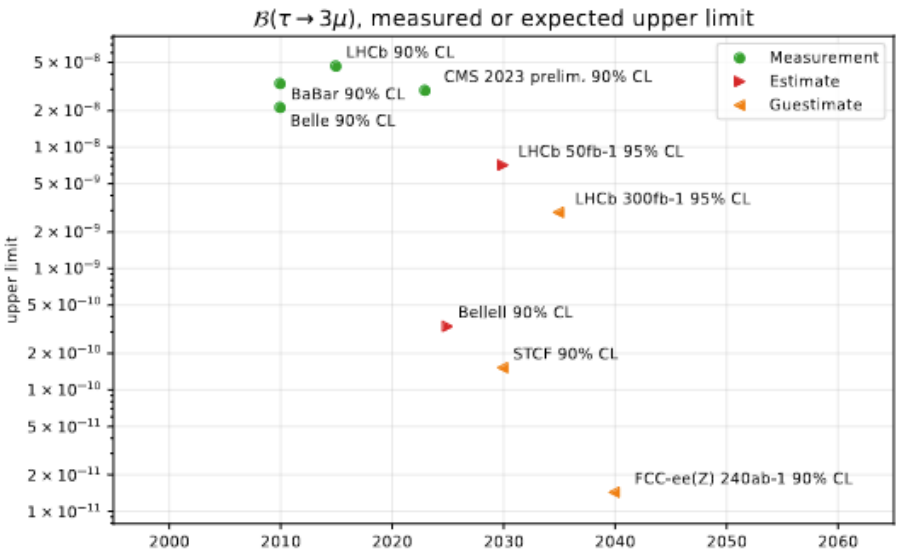
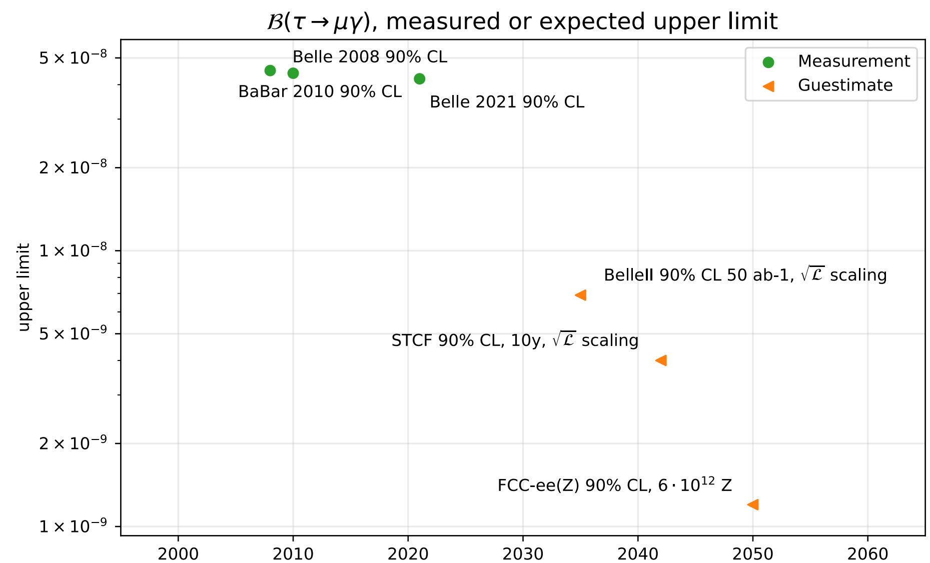
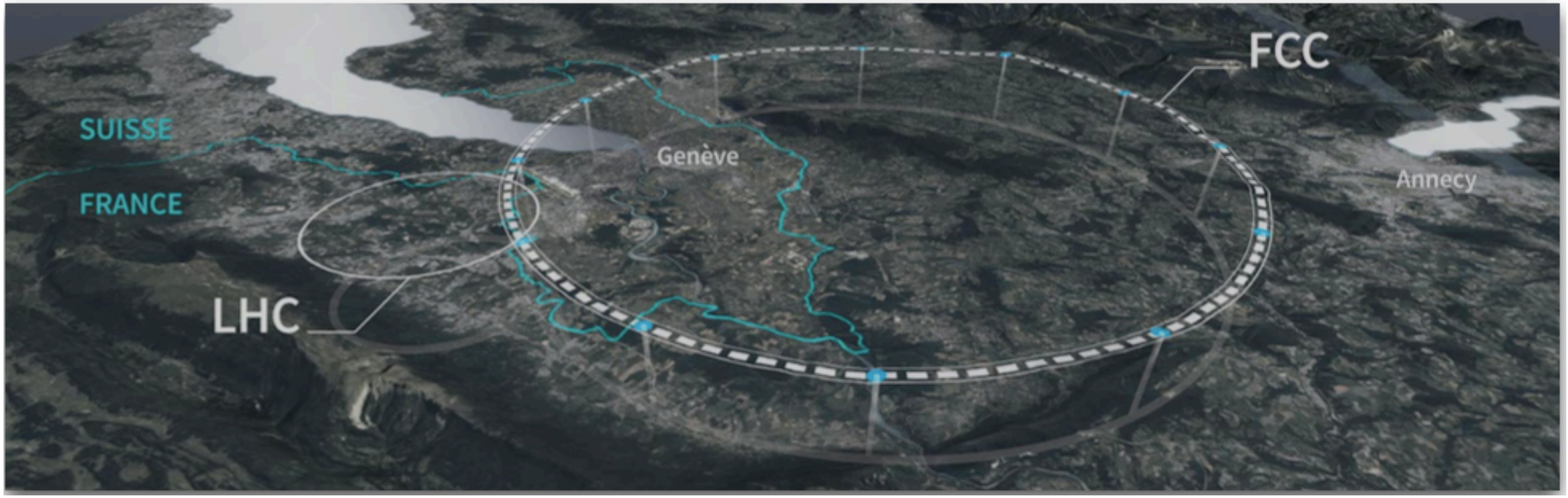




Bottomline: improved sensitivity by about two orders of magnitude.

6) 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!

- 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.

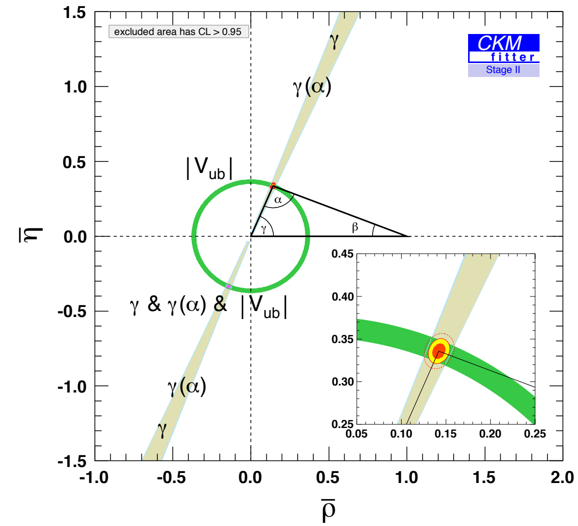
✓Unitary 3x3 CKM matrix (Flavour violation only from the Yukawas-MFV hypothesis).

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

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

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}

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

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

hep-ph 2006.04824

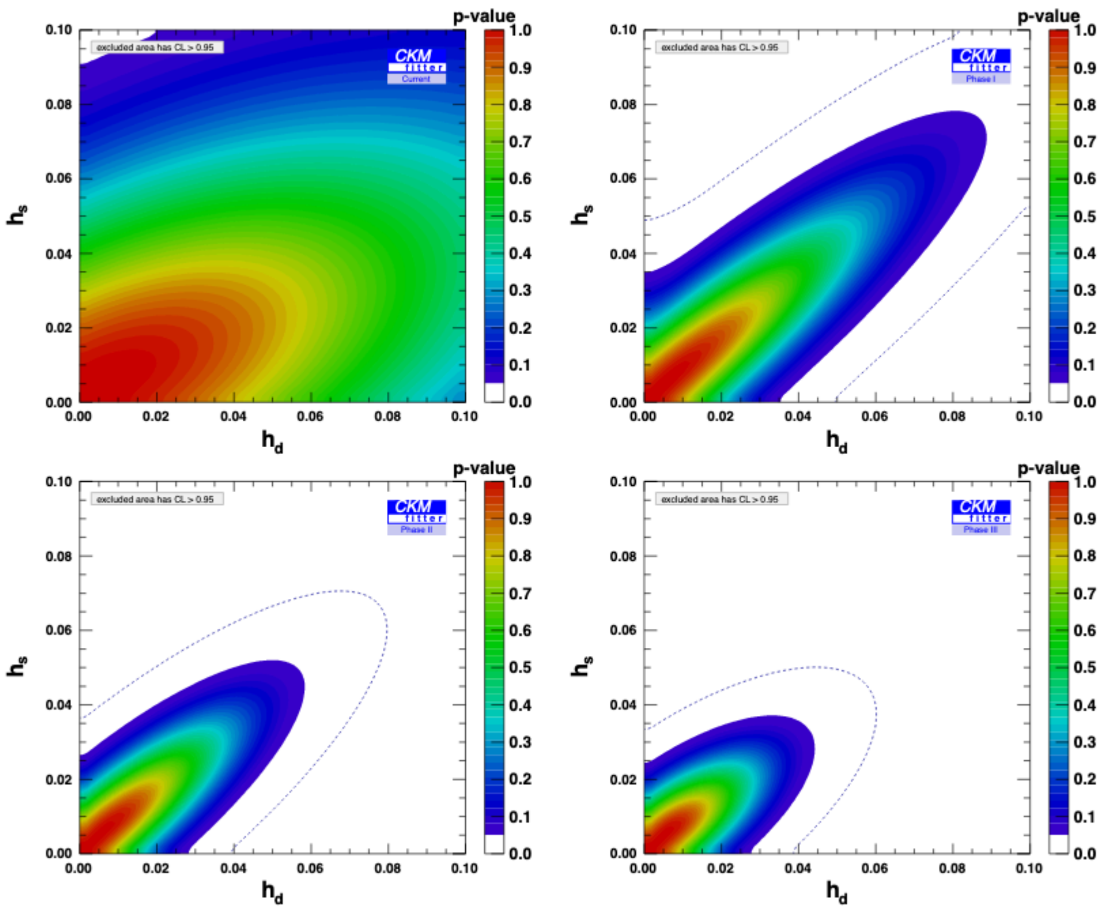


FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ)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

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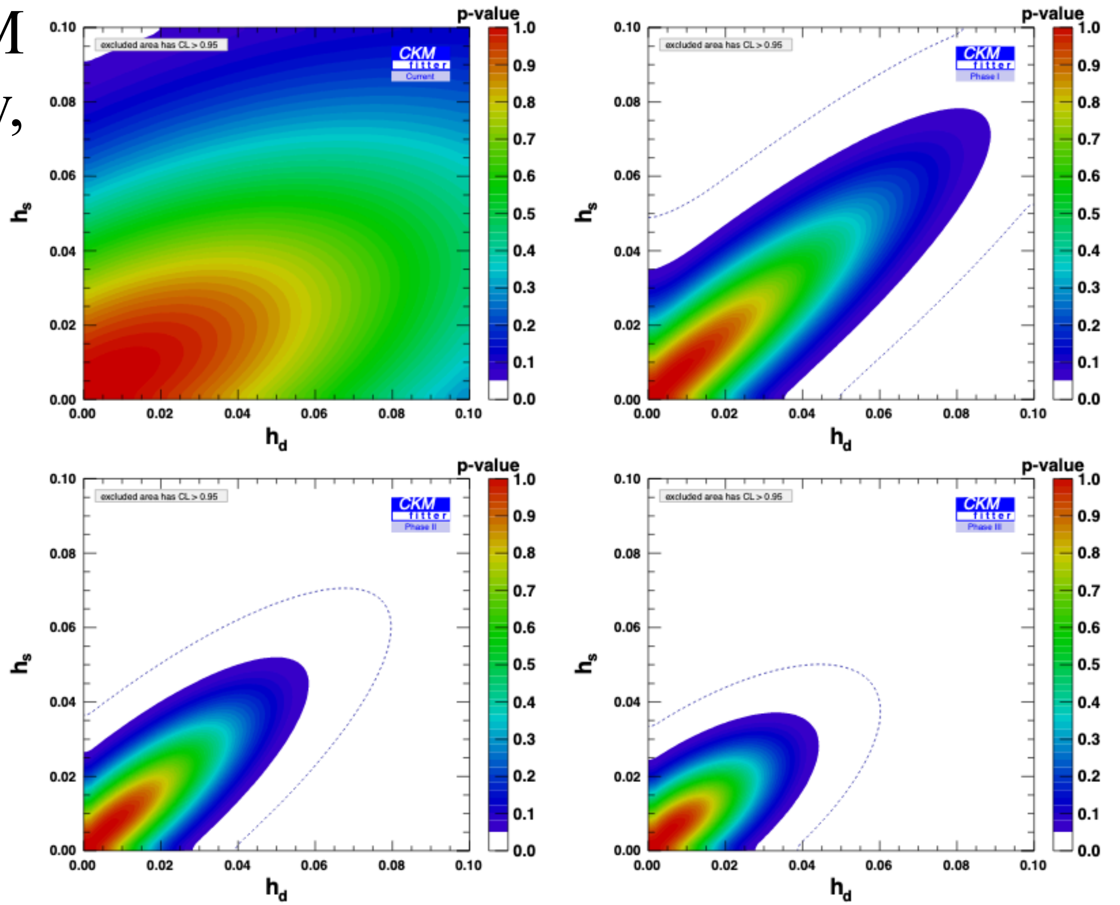

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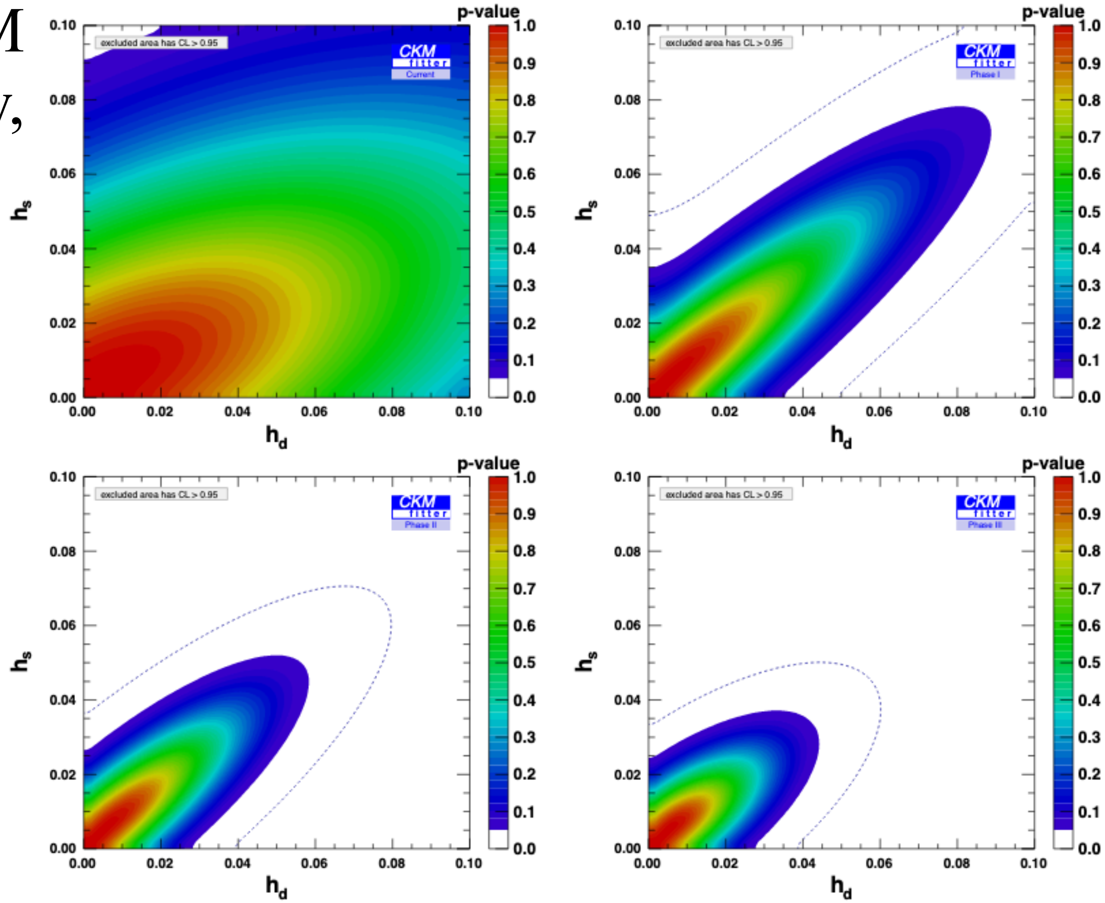
hep-ph 2006.04824

rescaled to SM — Now,

after LHCb-U1 and Belle II — 2030



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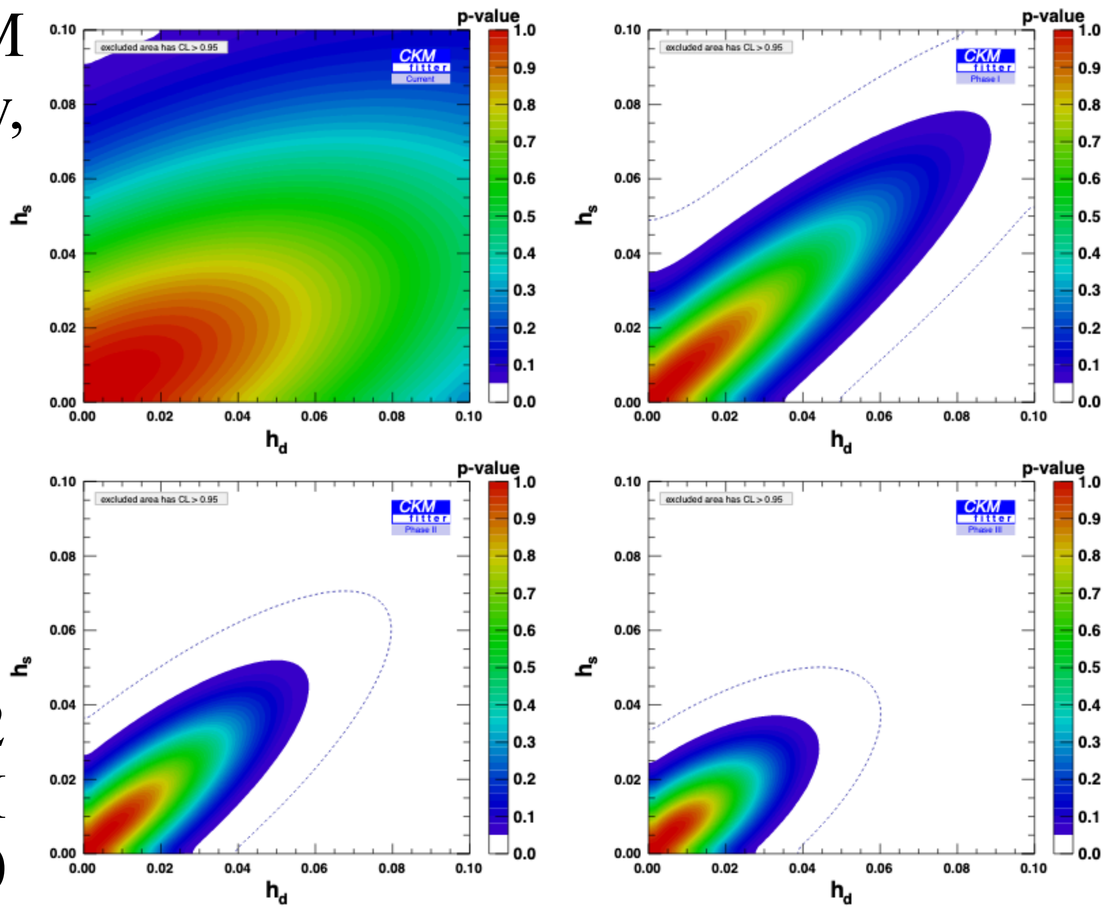
hep-ph 2006.04824

rescaled to SM — Now,

after LHCb-U1 and Belle II — 2030

after LHCb U2 and Belle III — 2040



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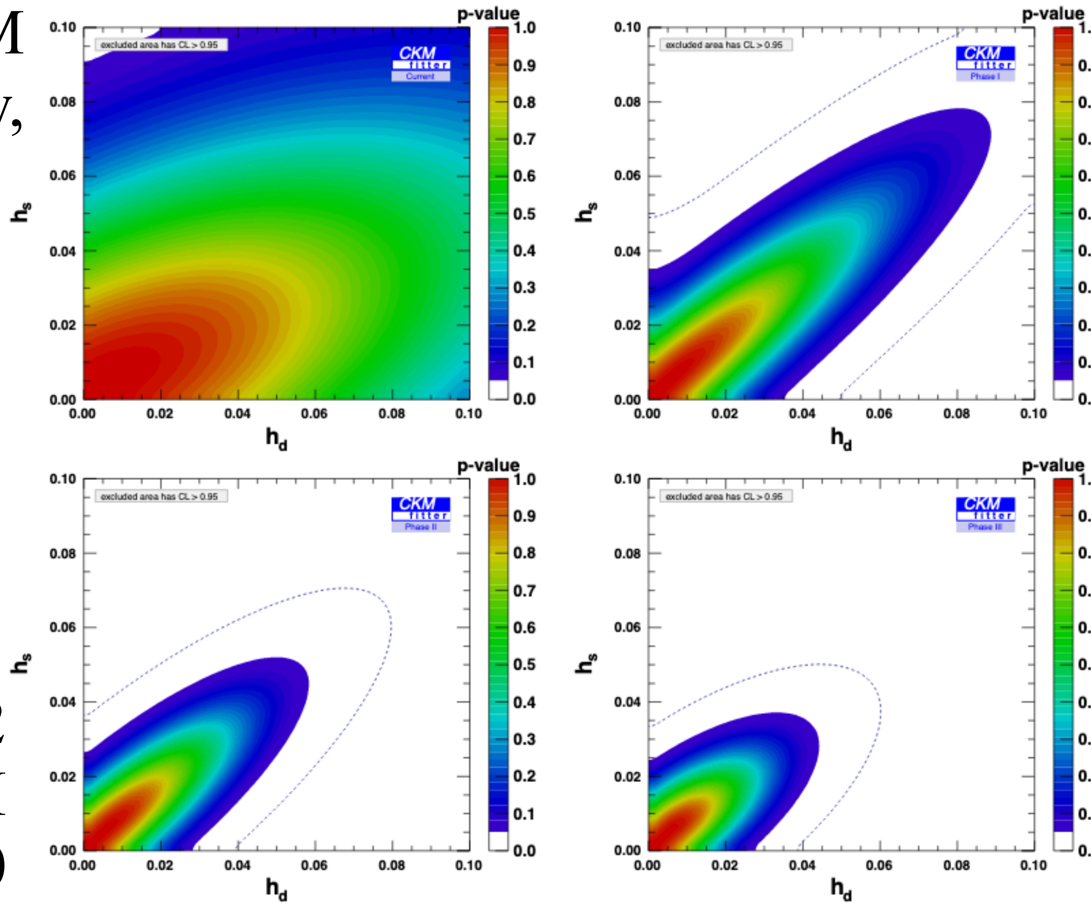
hep-ph 2006.04824

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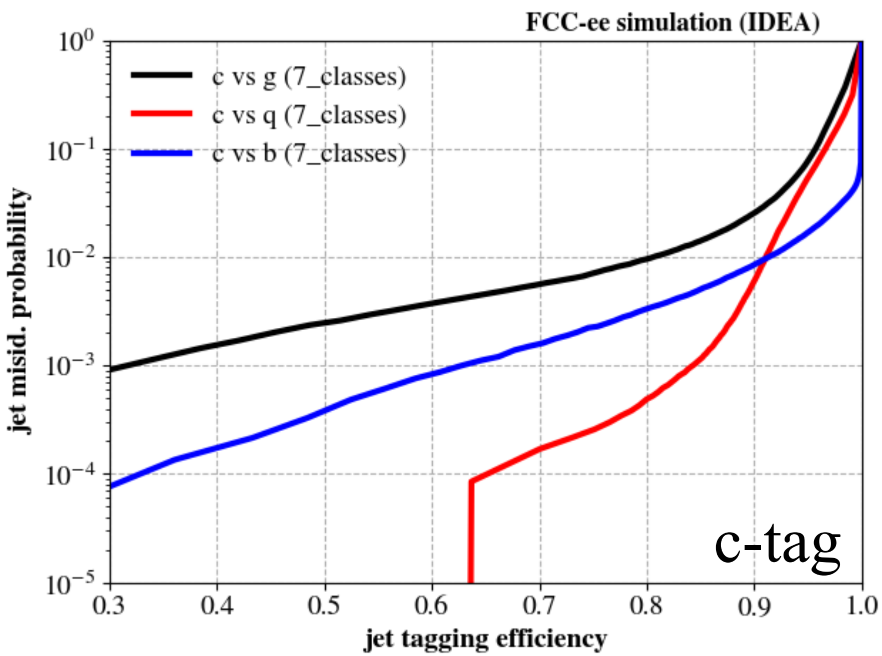
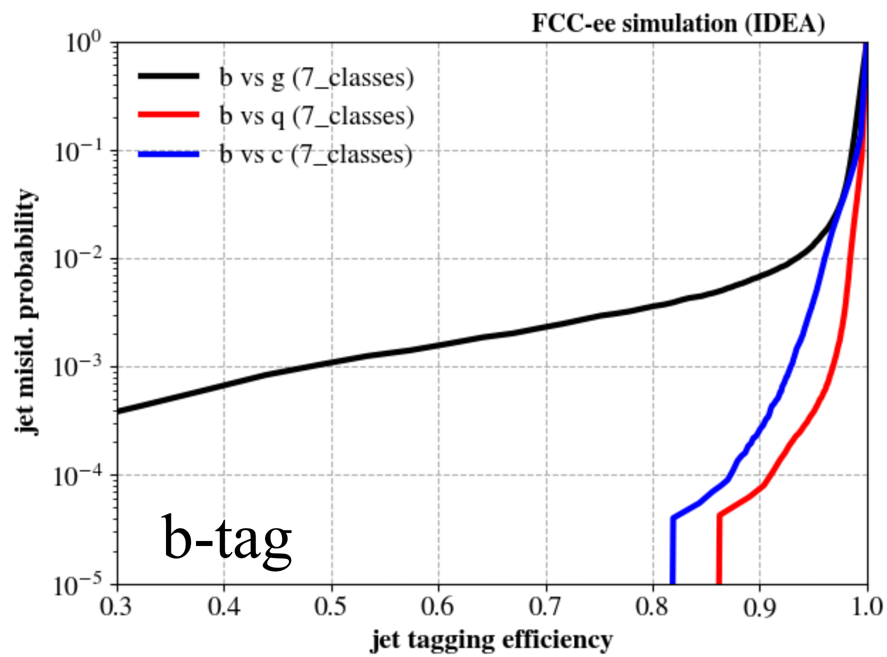
6) Focus#1: the CKM matrix element V_{cb}

- 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.

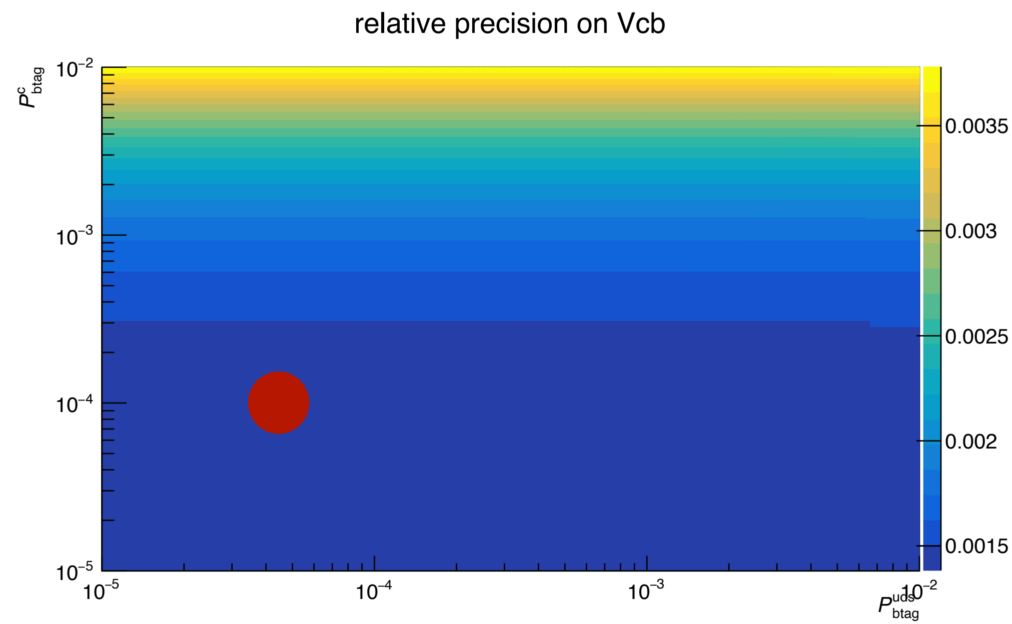




6) Focus#1: the CKM matrix element V_{cb}

- 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	1	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

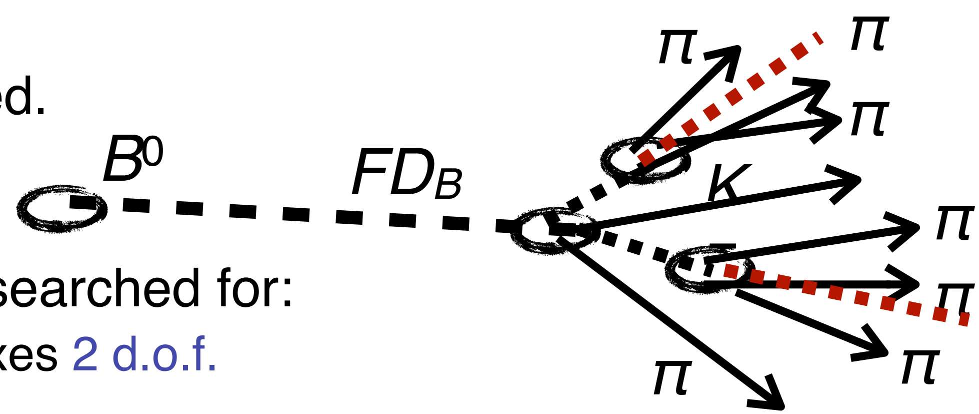
6) Focus#2: the transition $b \to s\tau^+\tau^-$

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.

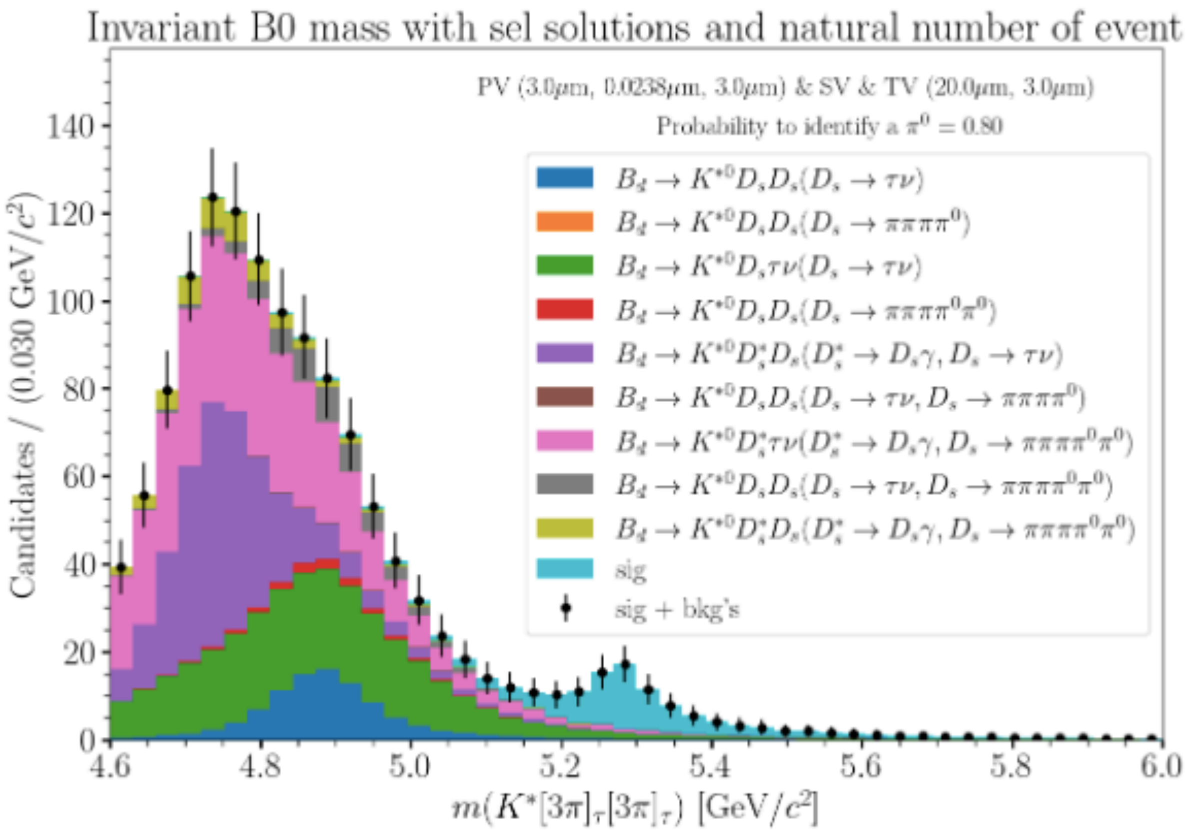


- Six momentum components to be searched for:
  - B^0 momentum direction from $K\pi$ fixes 2 d.o.f.
  - τ momenta direction fixes 4 d.o.f.
  - Mass of the τ provides 2 additional constraints
  - Since both tau legs provide quadratic equations, one ends up w/ 4 solutions.
  - Yet, the system is over-constrained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

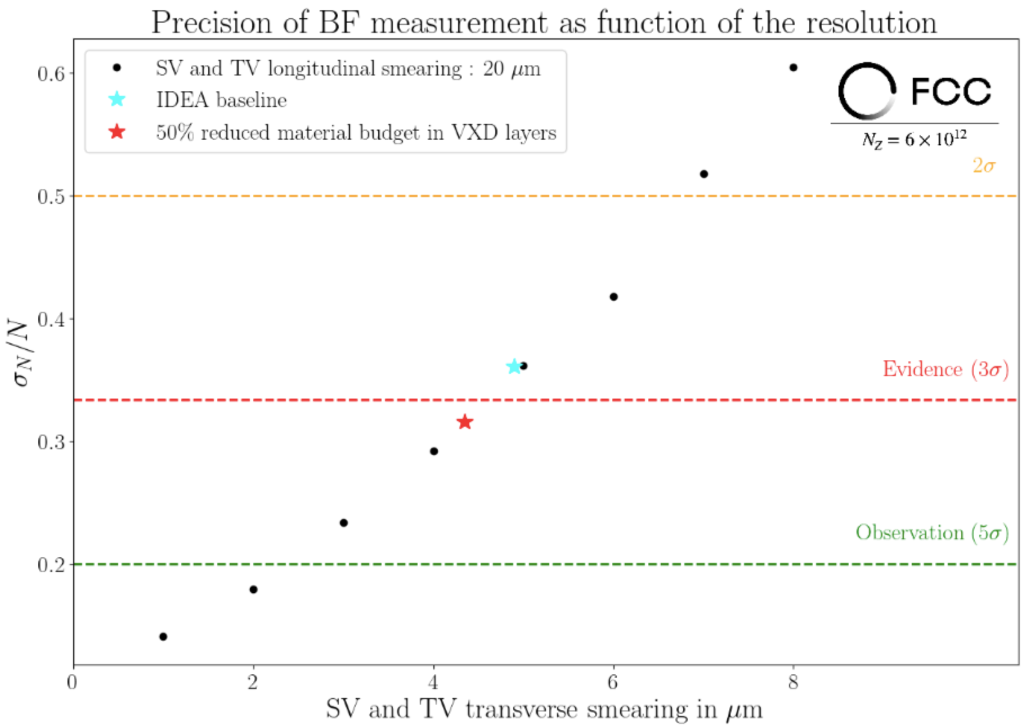
- $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$: topological reconstruction + selection



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

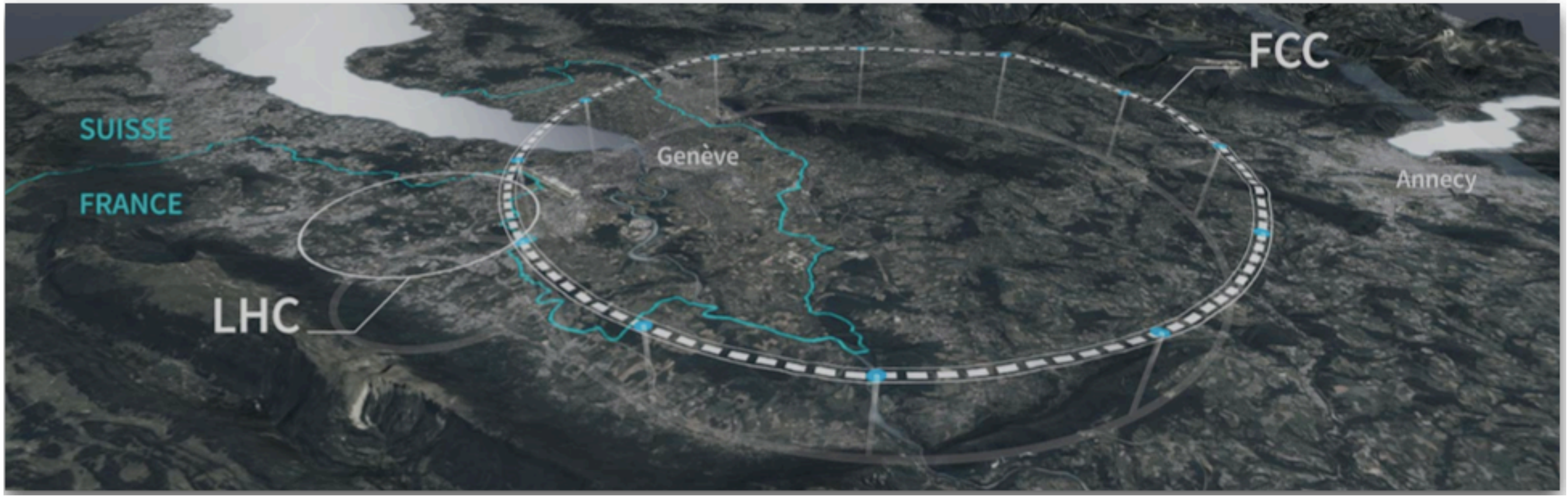
6) Focus#2: the transition $b \to s\tau^+\tau^-$

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

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

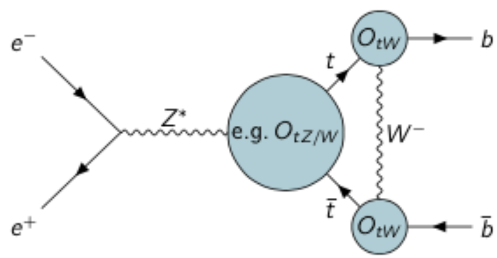


7) Connecting the dots: EWPO at the Z pole

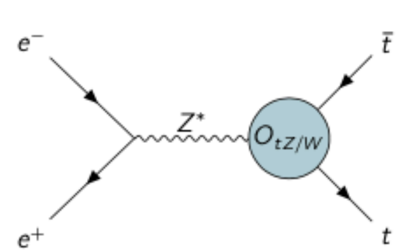
Motivation I

- 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 $4.2 \cdot 10^{12}$ $Z \to q\bar{q}$ (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

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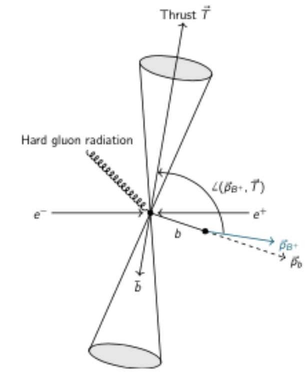
Exclusive *b*-hadron decays

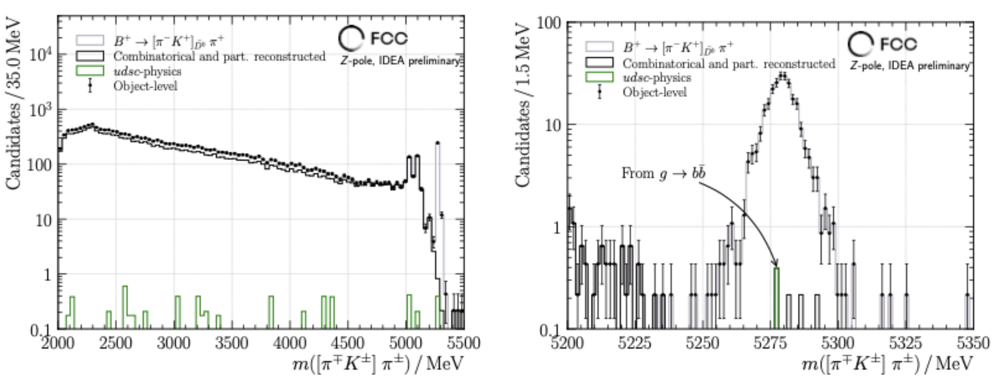
- LEP $\sigma_{\text{syst.}}$ dominated by *udsc*-physics and hemisphere correlations
- With Tera-Z $\sigma_{\text{stat.}}$ in reach: measurement limited by systematic uncertainties
- Reconstruct exclusive *b*-hadron: determine quark-flavour with 100 % purity
  $\rightarrow$ Stick to **ultra-pure mass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



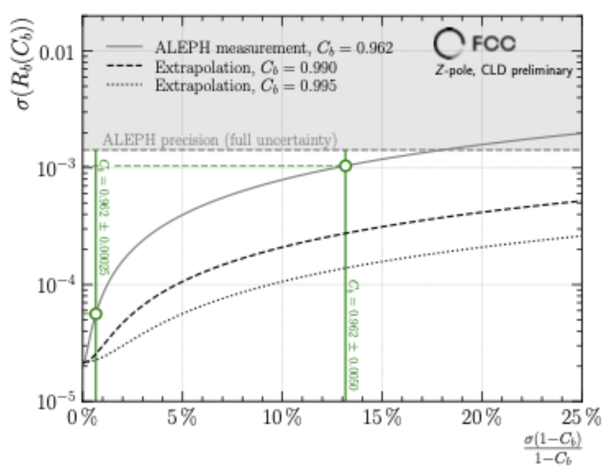
- C_b and QCD corrections evaluated on **Full Simulation sample** and forced decays $(B^\pm \rightarrow [K^+\pi^-]_{\bar{D}^0}\,\pi^+)$

- 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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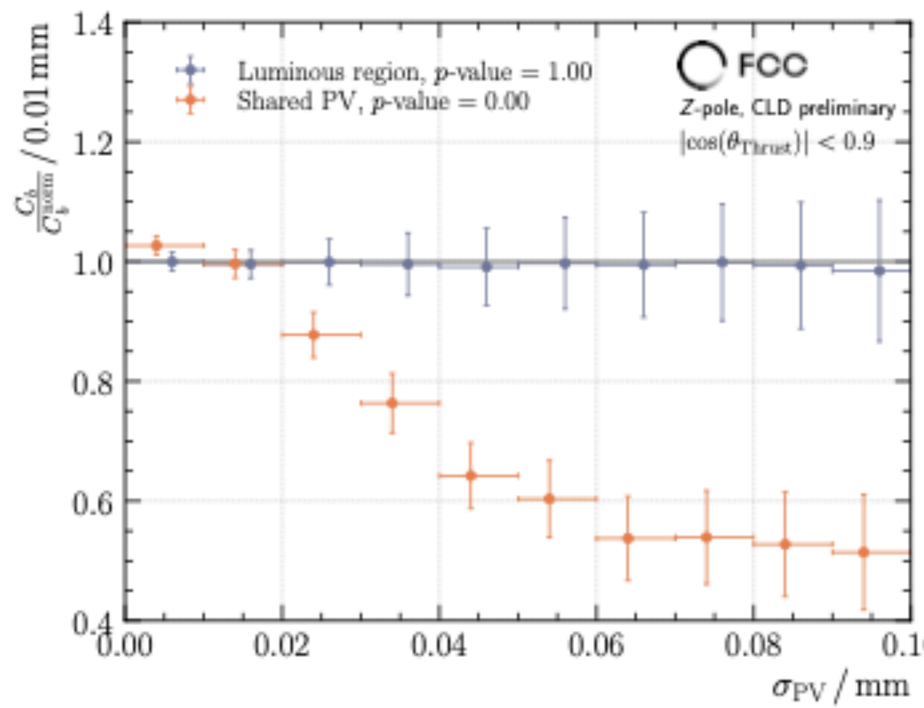


S. Monteil

7) Connecting the dots: EWPO at the Z pole

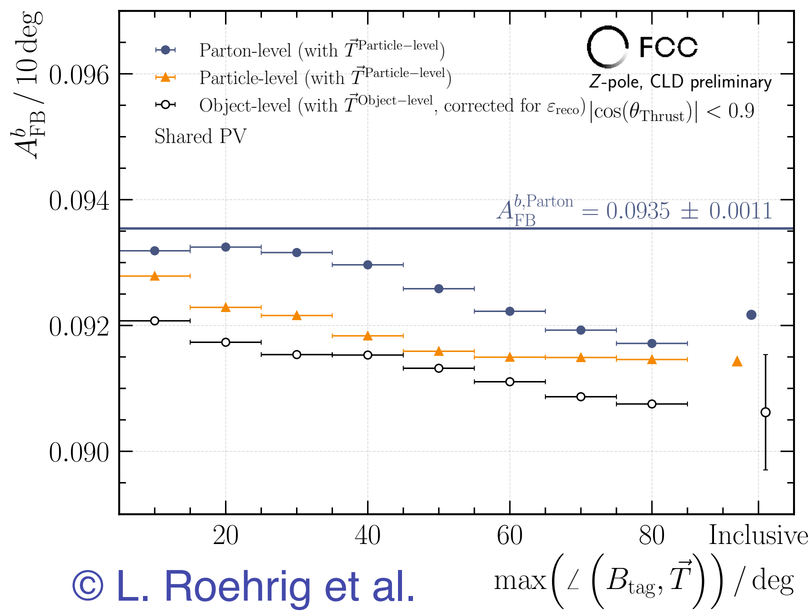
- Exclusive decays as a tagger can also help to reduce the systematic uncertainties on the bb forward-backward asymmetry

- 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.

- Seems as well promising.

- Work in progress!



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8) Conclusions

8) Summary I

- FCC-ee is the proposal at CERN for the next e^+e^- Higgs factory.

- It is much more than a Higgs factory:

  - *Z* factory [*O*(10^{13})]
  - *b*, *τ* , *c* factories [*O*(10^{12})]
  - *W* factory [*O*(5.10^{8})]
  - top factory [*O*(10^{6})]

- The mid-term review went well (I was told). Conclusions to be analysed / endorsed by the CERN council (02/02/2024).

- 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. Four IPs —> one flavour-oriented detector.

8) Summary II.

- 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 new one guarantees that we're closing the Higgs and Electroweak gauge chapters with a precision machine and let options opened to high energy protons if the case is made.

- Rendez-vous en 2026 pour la mise à jour de la stratégie européenne de la physique des particules!

7) Back-up

7) Back-up

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

- The alpha angle can be measured through an isospin analysis from $B^0 \to (\pi\pi)^{+-/00}$. The knowledge of parameter S^{00}, that can be accessed from time-dependent studies, allows to lift degeneracies among solutions.

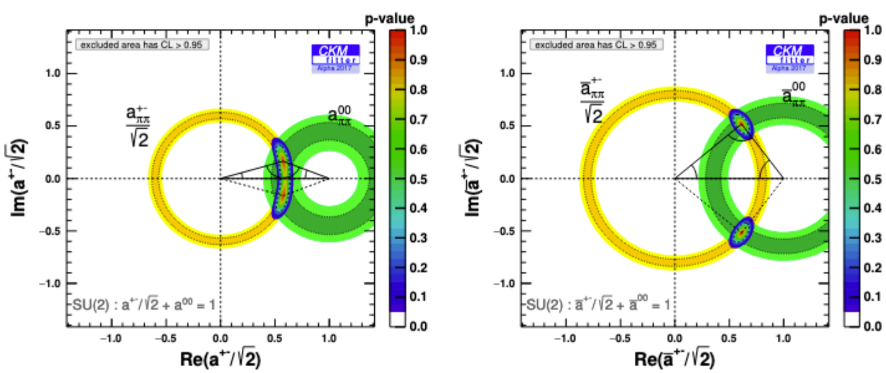


Figure 4: *Constraint on the reduced amplitude $a^{+-} = A^{+-}/A^{+0}$ in the complex plane for the $B \to \pi\pi$ (left) and $\bar{B} \to \pi\pi$ systems (right). The individual constraint from the $B^0(\bar{B}^0) \to \pi^+\pi^-$ observables and from the $B^0(\bar{B}^0) \to \pi^0\pi^0$ observables 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 $B^0 \to (\pi^0\pi^0)$. 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.

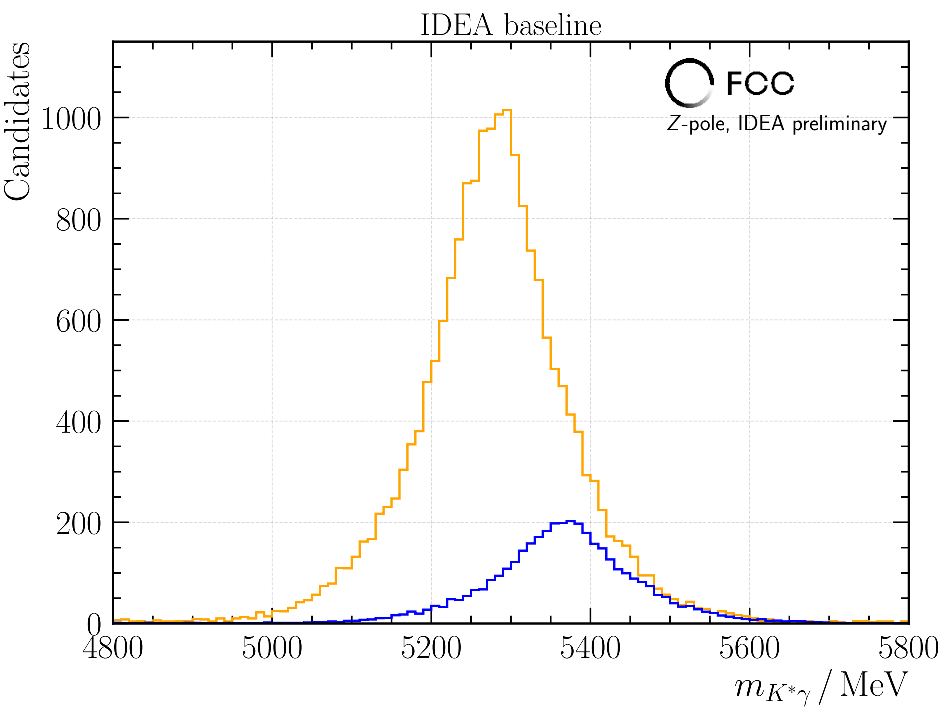
- The feasibility study will be used to systematically address the physics case while placing requirements on the detectors. Hadron particle identification deserves a special treatment and Flavour physics is at the heart of it.

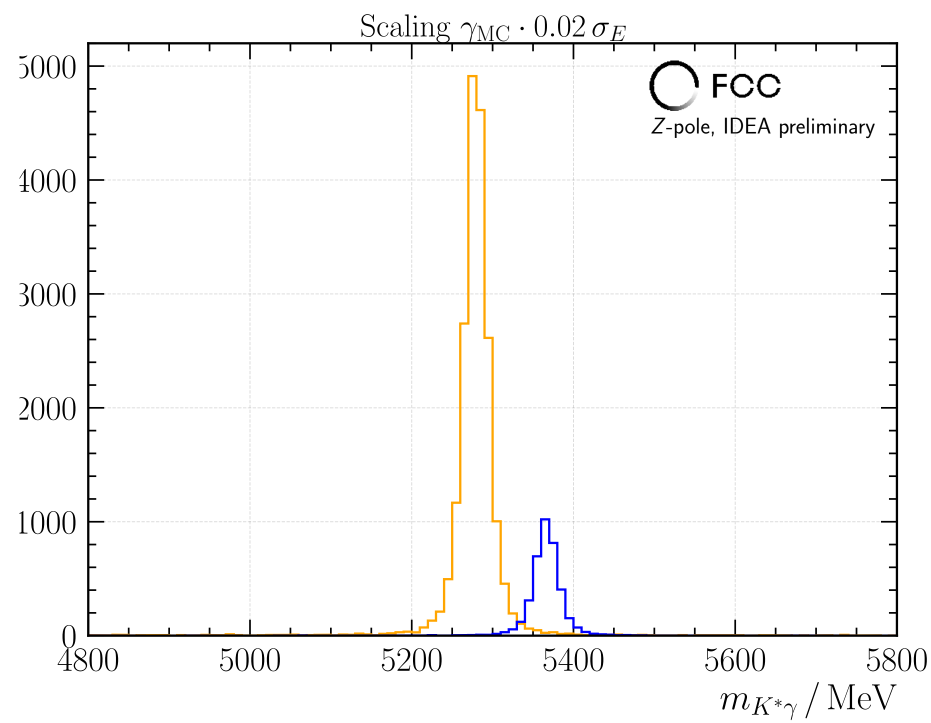
- All studies at the Z pole shown above are made for 5.10^{12} Z decays. Most of flavour observables will remain statistically limited. More would be desirable ! The machine study from two IPs to four IPs is positive and would bring about a factor 2 (1.7) in integrated luminosity.

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

- Engage and reach out to make this plan happening.

- 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.