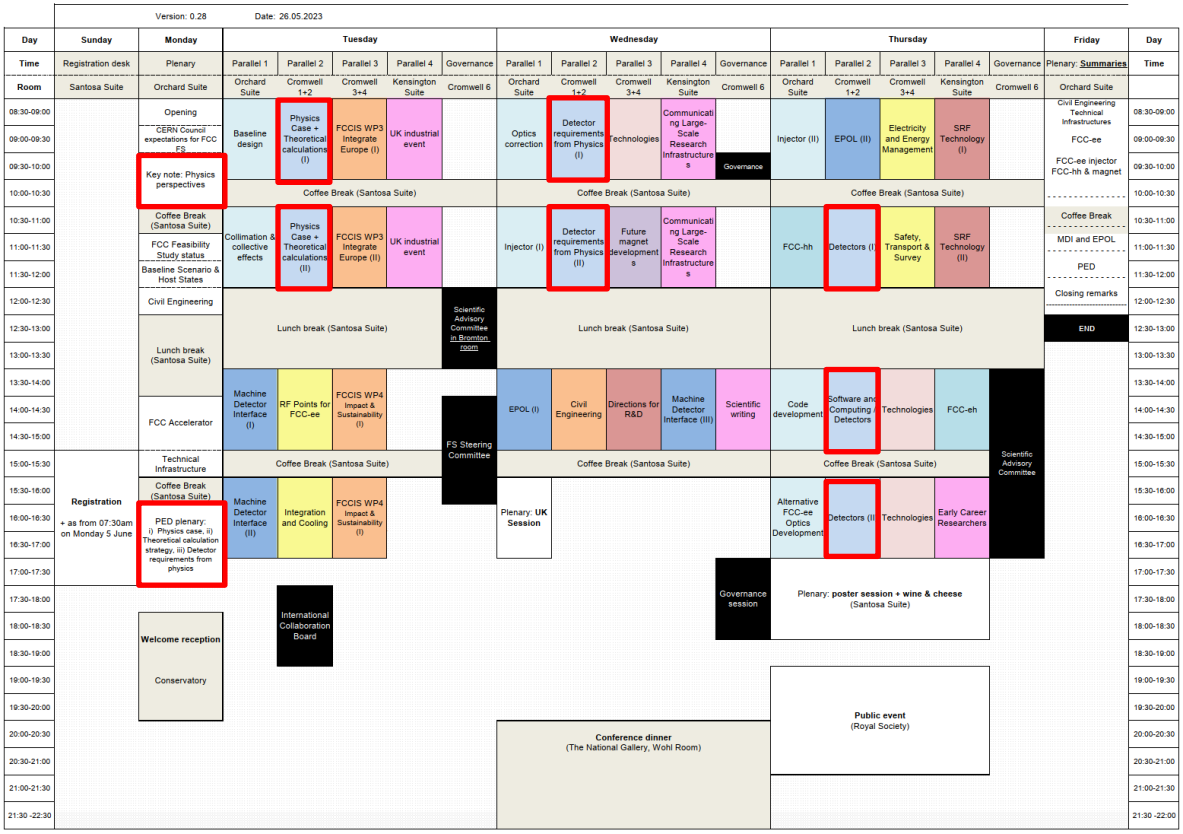
Physics, experiments and detectors summary: a pub perspective

Guy Wilkinson,
University of Oxford
9/6/23

What was expected of me

To attend all these sessions, and then present you with a carefully considered summary of the most important developments.



Version: 0.28 Date: 26.05.2023

Day	Sunday	Monday	Tuesday					Wednesday					Thursday					Friday	Day
Time	Registration desk	Plenary	Parallel 1	Parallel 2	Parallel 3	Parallel 4	Governance	Parallel 1	Parallel 2	Parallel 3	Parallel 4	Governance	Parallel 1	Parallel 2	Parallel 3	Parallel 4	Governance	Plenary: Summaries	Time
Room	Santosa Suite	Orchard Suite	Orchard Suite	Cromwell 1+2	Cromwell 3+4	Kensington Suite	Cromwell 6	Orchard Suite	Cromwell 1+2	Cromwell 3+4	Kensington Suite	Cromwell 6	Orchard Suite	Cromwell 1+2	Cromwell 3+4	Kensington Suite	Cromwell 6	Orchard Suite	
08:30-09:00		Opening	Baseline design	Physics Case + Theoretical calculations (I)	FCCIS WP3 Integrate Europe (I)	UK industrial event		Optics correction	Detector requirements from Physics (I)	Technologies	Communicating Large-Scale Research Infrastructures		Injector (II)	EPOL (II)	Electricity and Energy Management	SRF Technology (I)		Civil Engineering Technical Infrastructures	08:30-09:00
09:00-09:30		CERN Council expectations for FCC ES																FCC-ee	09:00-09:30
09:30-10:00		Key note: Physics perspectives										Governance						FCC-ee injector FCC-hh & magnet	09:30-10:00
10:00-10:30			Coffee Break (Santosa Suite)					Coffee Break (Santosa Suite)					Coffee Break (Santosa Suite)						10:00-10:30
10:30-11:00		Coffee Break (Santosa Suite)																Coffee Break	10:30-11:00
11:00-11:30		FCC Feasibility Study status	Collimation & collective effects	Physics Case + Theoretical calculations (II)	FCCIS WP3 Integrate Europe (II)	UK industrial event		Injector (I)	Detector requirements from Physics (II)	Future magnet development	Communicating Large-Scale Research Infrastructures		FCC-hh	Detectors (I)	Safety, Transport & Survey	SRF Technology (II)		MDI and EPOL	11:00-11:30
11:30-12:00		Baseline Scenario & Host States																PED	11:30-12:00
12:00-12:30		Civil Engineering																Closing remarks	12:00-12:30
12:30-13:00		Lunch break (Santosa Suite)	Lunch break (Santosa Suite)				Scientific Advisory Committee in Bromton room	Lunch break (Santosa Suite)					Lunch break (Santosa Suite)					END	12:30-13:00
13:00-13:30																			13:00-13:30
13:30-14:00			Machine Detector Interface (I)	RF Points for FCC-ee	FCCIS WP4 Impact & Sustainability (I)			EPOL (I)	Civil Engineering	Directions for R&D	Machine Detector Interface (III)	Scientific writing	Code development	Software and Computing & Detectors	Technologies	FCC-eh	Scientific Advisory Committee		13:30-14:00
14:00-14:30		FCC Accelerator					FS Steering Committee												14:00-14:30
14:30-15:00																			14:30-15:00
15:00-15:30		Technical Infrastructure	Coffee Break (Santosa Suite)					Coffee Break (Santosa Suite)					Coffee Break (Santosa Suite)						15:00-15:30
15:30-16:00	Registration + as from 07:30am on Monday 5 June	Coffee Break (Santosa Suite)	Machine Detector Interface (II)	Integration and Cooling	FCCIS WP4 Impact & Sustainability (I)			Plenary: UK Session					Alternative FCC-ee Optics Development	Detectors (II)	Technologies	Early Career Researchers			15:30-16:00
16:00-16:30		PED plenary: i) Physics case, ii) Theoretical calculation strategy, iii) Detector requirements from physics																	16:00-16:30
16:30-17:00																			16:30-17:00
17:00-17:30												Governance session	Plenary: poster session + wine & cheese (Santosa Suite)						17:00-17:30
17:30-18:00				International Collaboration Board															17:30-18:00
18:00-18:30		Welcome reception																	18:00-18:30
18:30-19:00		Conservatory																	18:30-19:00
19:00-19:30													Public event (Royal Society)						19:00-19:30
19:30-20:00																			19:30-20:00
20:00-20:30								Conference dinner (The National Gallery, Wohl Room)											20:00-20:30
20:30-21:00																			20:30-21:00
21:00-21:30																			21:00-21:30
21:30 -22:30																			21:30 -22:00

I faithfully attended (almost) all of them, and was greatly impressed by the work that is ongoing. But today I won't attempt a conventional summary.

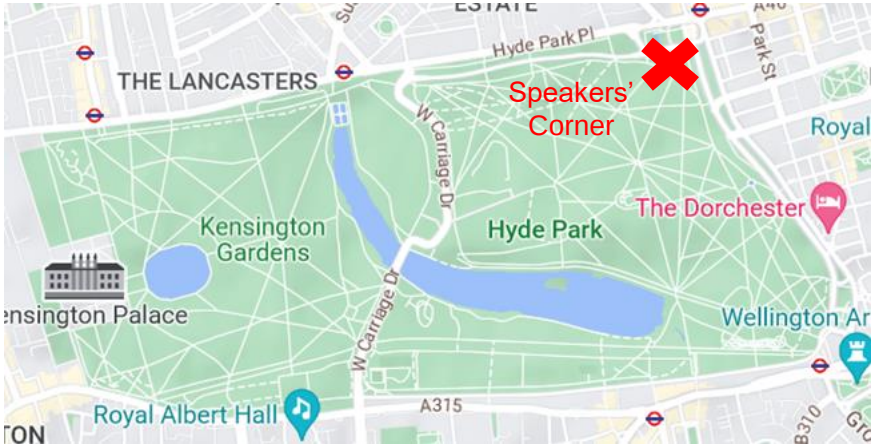
Where I have been ~~instead~~ in addition

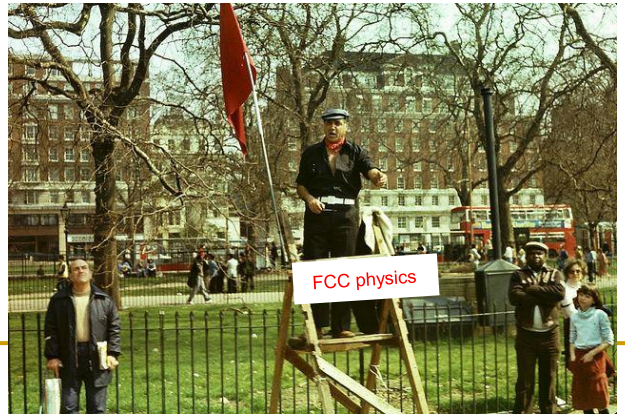
Much of most interesting discussion happens outside the sessions.

There you often hear the real questions and issues that concern people. Here I highlight the most frequent topics of conversations, and give some responses.

The spirit of Speakers' Corner

Warning – that than a conventional review, I am taking the opportunity to subject you to my own opinions about the FCC physics programme.



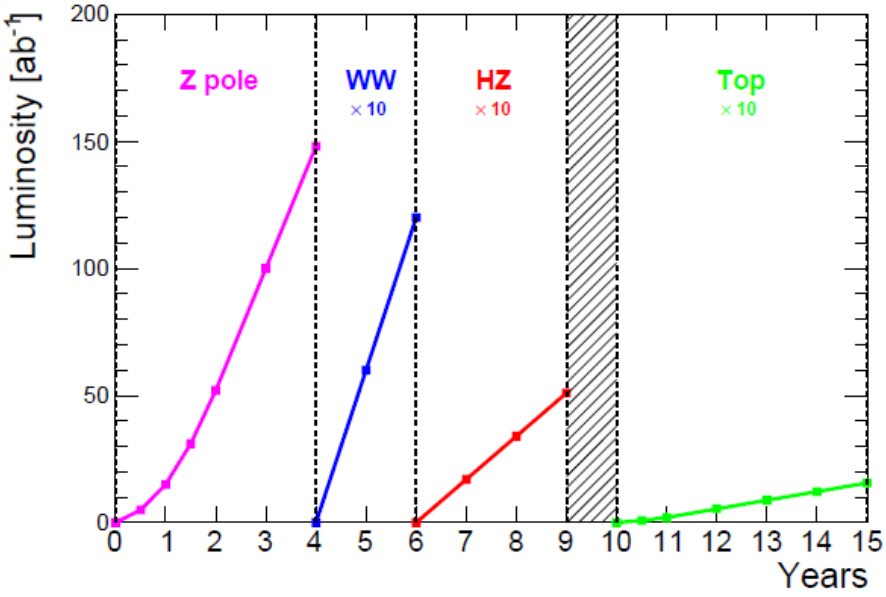


FCC physics programme – the pub perspective

The interconnectedness of all things

An ambitious programme !
But can it be descoped in anyway ?

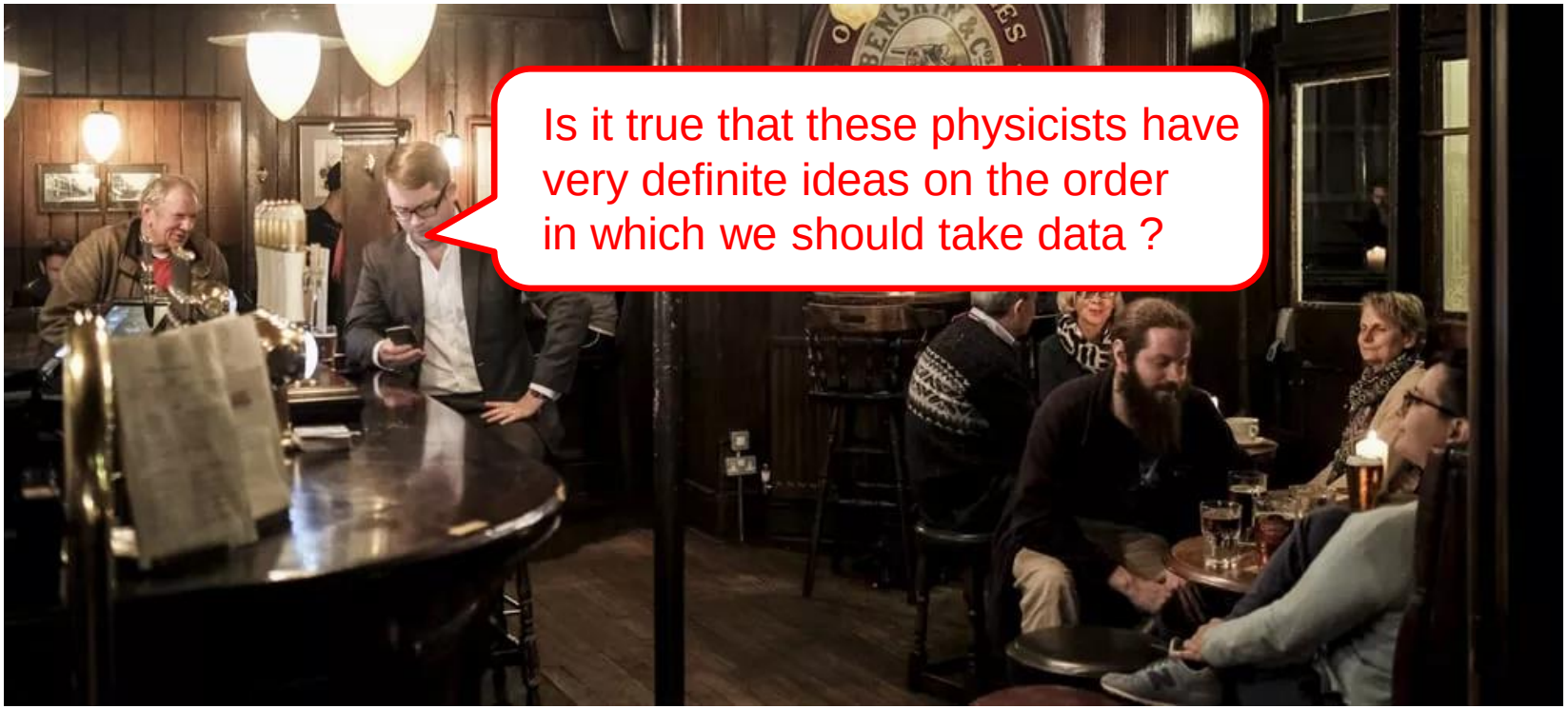
- Do we need all energy points ?
- Do we need so much running at Z ?
- Do we really need to run at the top threshold – this is very expensive and will be hard work.



No !!! All energy points are necessary, and the whole is greater than the sum of the parts, *e.g.*

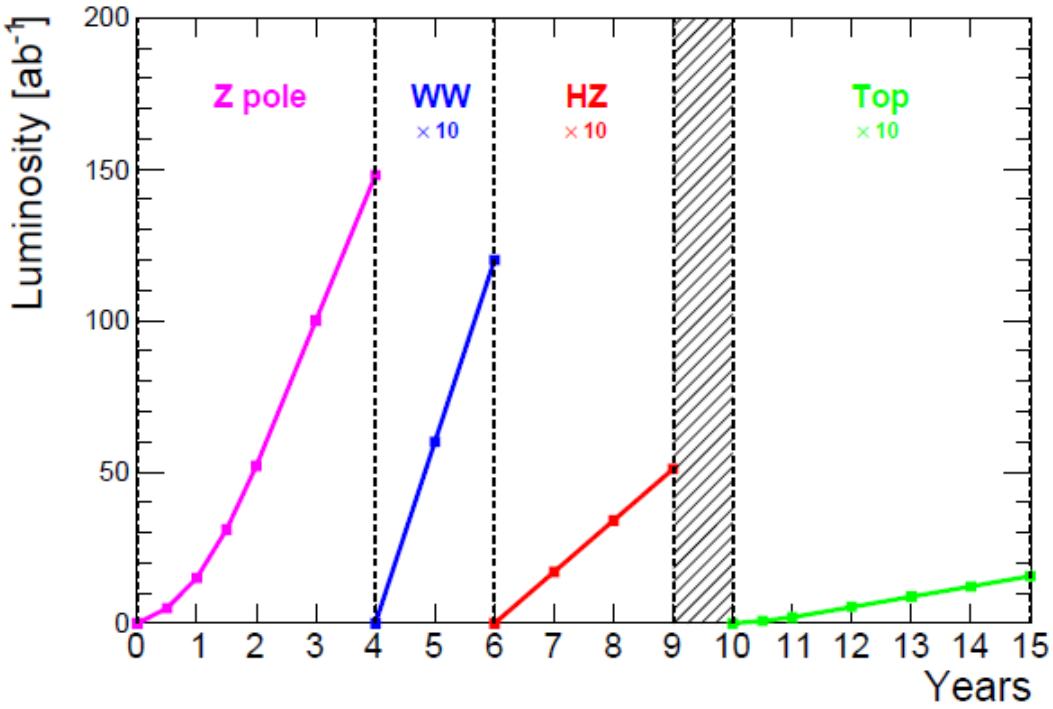
- m_W needs improved knowledge of $\alpha_{QED}(m_Z^2)$ from Z run;
- m_W measurement of little use, unless we have a much better measurement of m_t ;
- m_t needs improved knowledge of $\alpha_s(m_Z^2)$ from lower data points;
- 'Top' running is equally useful for the Higgs through $e^+e^- \rightarrow H^0\nu\bar{\nu}$. Essential for both improving knowledge of Higgs width, & for accessing Higgs self-interaction.

FCC physics programme – the pub perspective



So does the order matter ?

Are their any physics reasons to prioritise the sequence of data taking ?

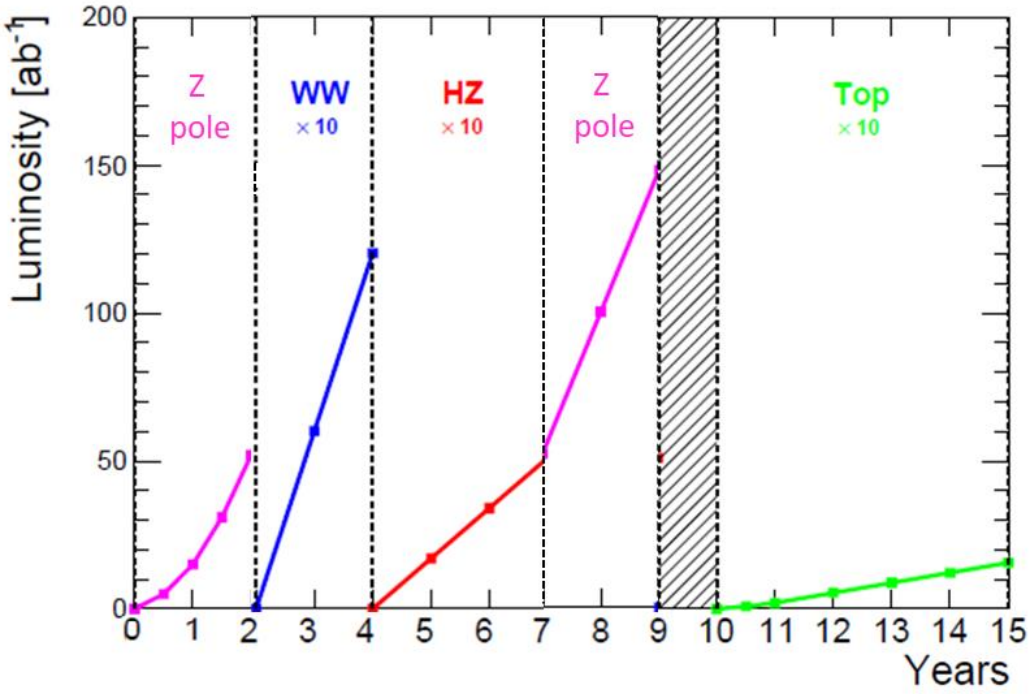


No – we need all data, but the sequence doesn't matter. (Even if the above is the most natural from an operational point of view.)

So does the order matter ?

However, the Z run is extremely demanding from a detector and energy calibration perspective. Getting everything right in the first few years of operation might be impossible – at LEP there was four years of operation before the first precision scan, then another year of consolidation before a second scan took place.

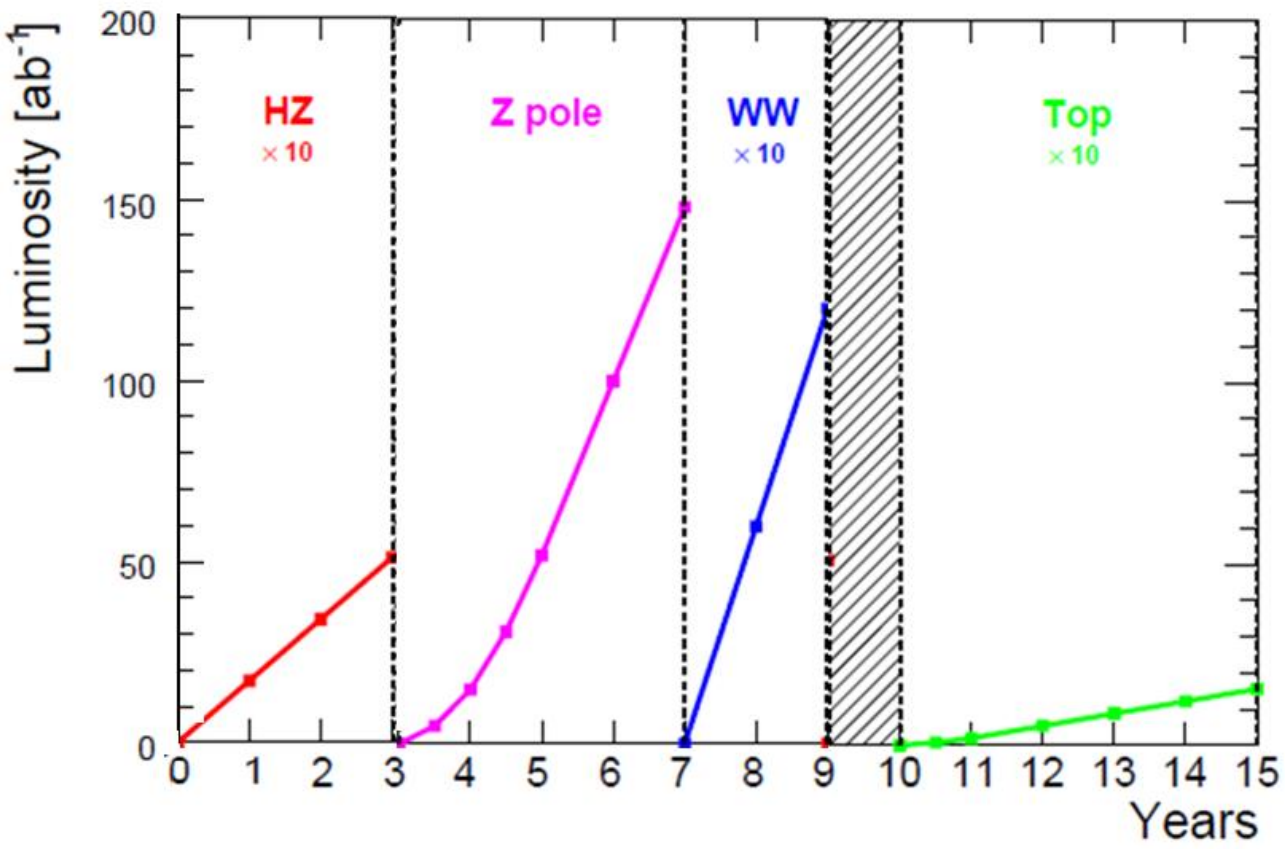
So dividing the Z operation into two separate periods would be wise, *e.g.*



This certainly poses issues for the machine, but for the physicist flexibility is key !

So does the order matter ?

Nor can I see any physics objection to starting with HZ. In this case much of the preparatory work for the Z scans could be done during Z-pole calibration runs.



FCC physics programme – the pub perspective

A false dichotomy

Sometimes we mislead ourselves (and the public), by making a misleading distinction between the categories of experimental programmes we pursue.

Direct discovery vs. Precise measurement

A false dichotomy

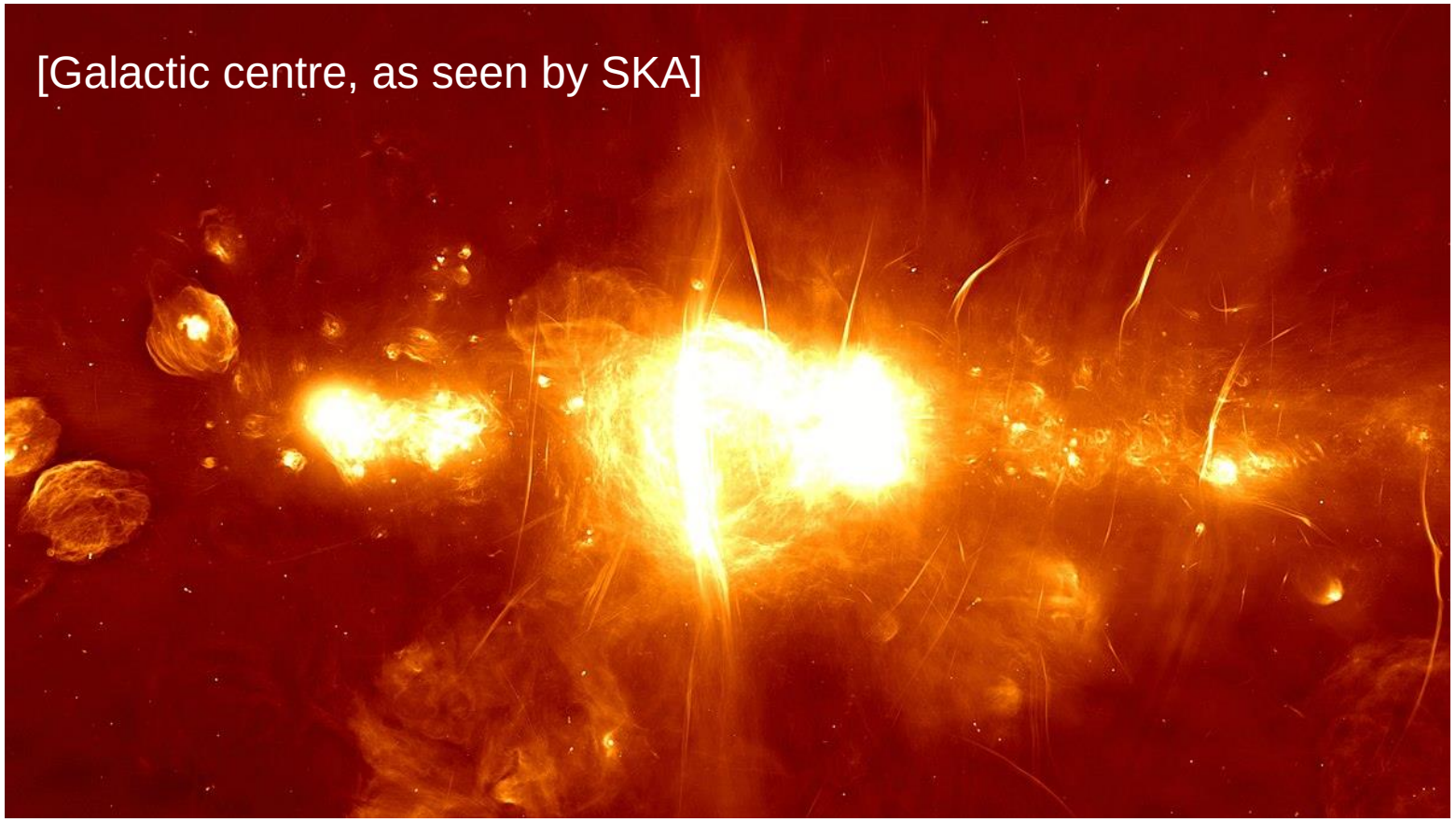
Sometimes we mislead ourselves (and the public), by making a misleading distinction between the categories of experimental programmes we pursue.

Direct discovery vs. Precise measurement

Of course precise measurement *is* a powerful method of discovery !

By forgetting this, we downplay the real excitement of the FCC-ee physics programme (which of course, also has avenues of direct discovery, *e.g.* LLPs).

Other disciplines (and the public) understand the importance of improved measurements very well

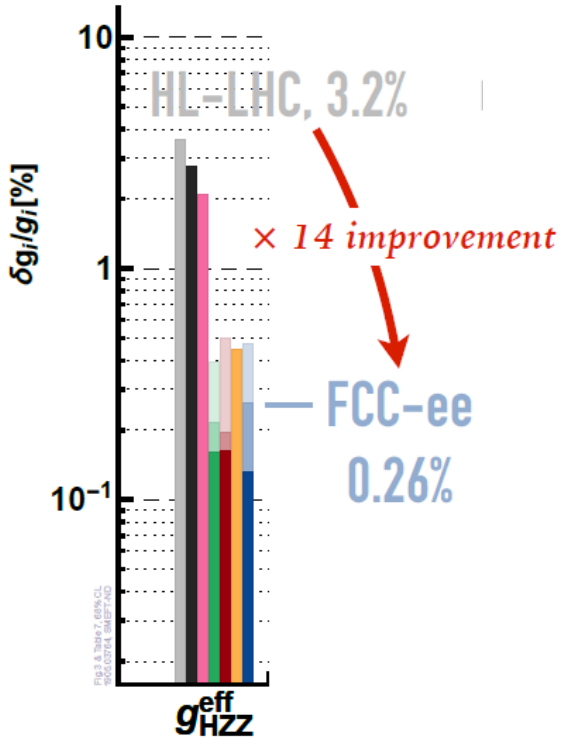


Other disciplines (and the public) understand the importance of improved measurements very well

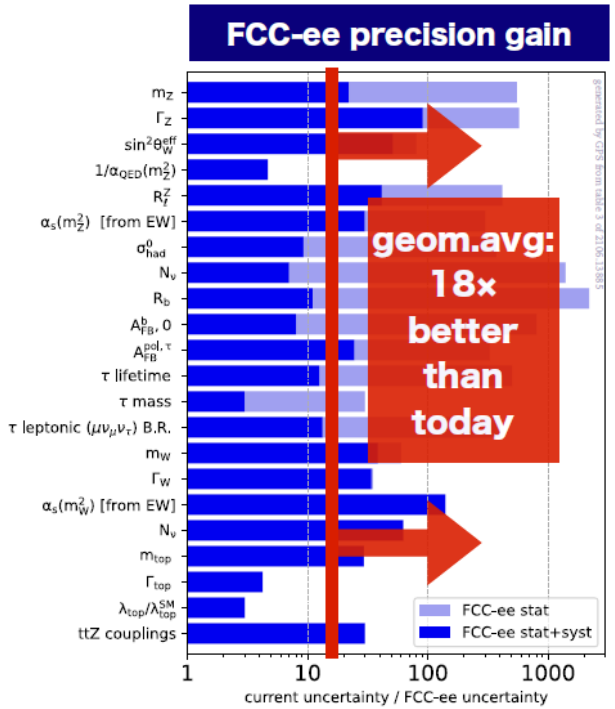
The large and enthusiastic audience last night seemed to ‘get it’.

Precision – a route to discovery

Higgs couplings



Electroweak Precision Observables

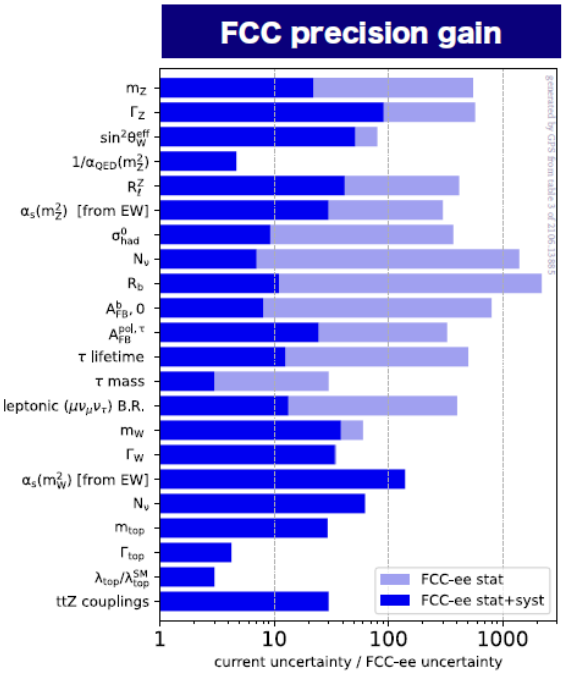


[Gavin Salam]

These sort of improvements in sensitivity will bring us 4-5 x higher reach in mass, which is very roughly the sort of gain we will get in direct searches from FCC-hh.

Precision – a route to discovery

Looking more closely…

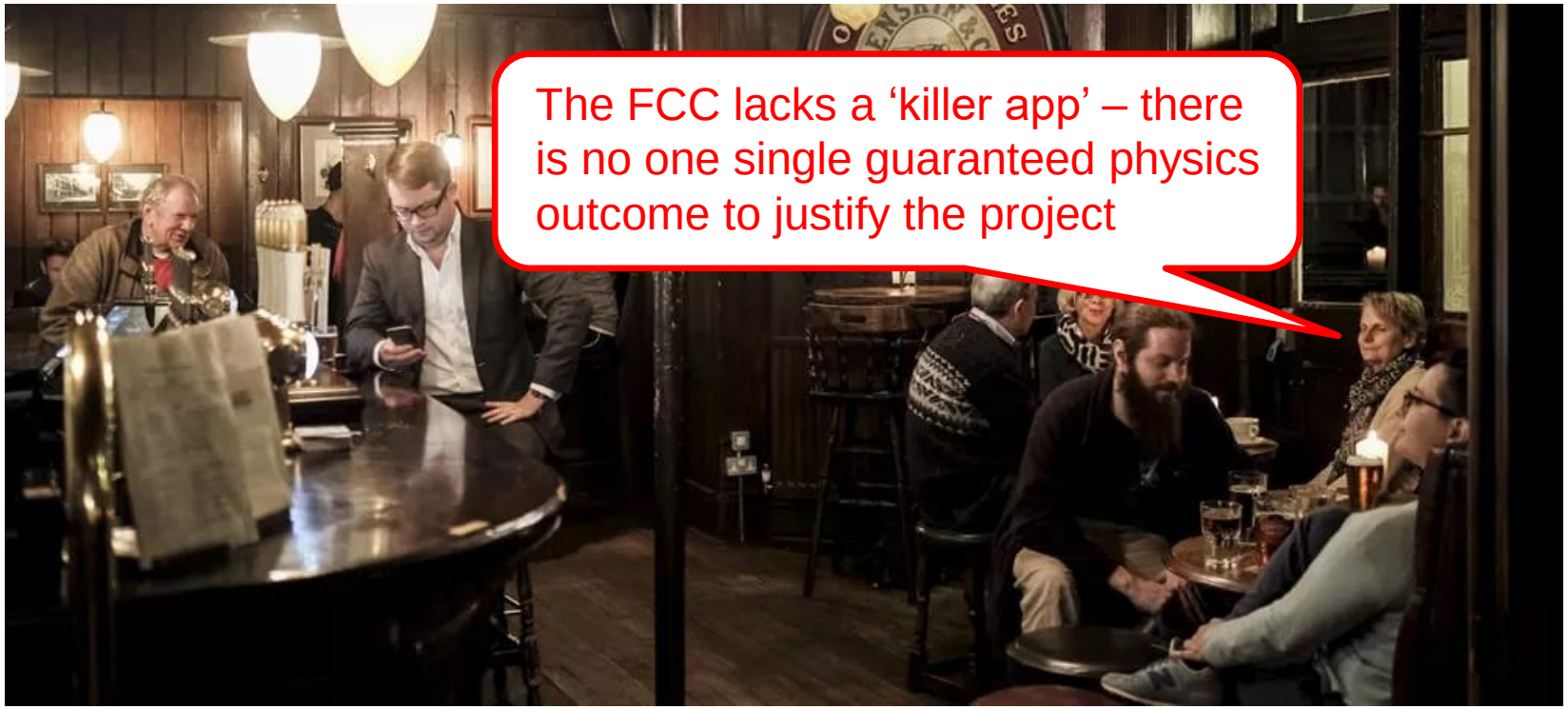


The gains are potentially much, much larger if we can gain greater systematic control (particularly at Z) !

A challenge for the machine, experimentalists *and* theorists [Gluza].

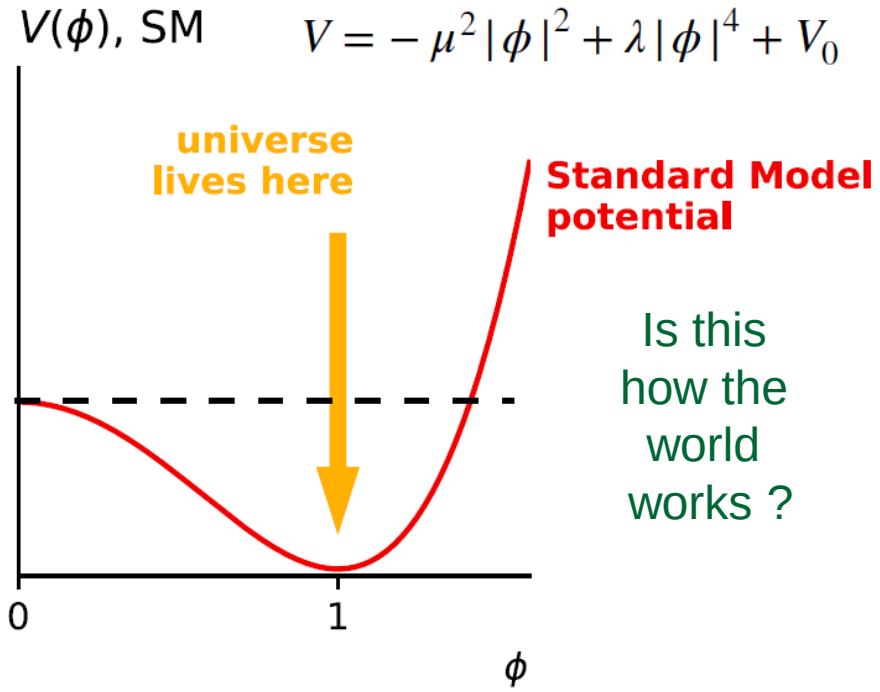
These sort of improvements in sensitivity will bring us 4-5 x higher reach in mass, which is very roughly the sort of gain we will get in direct searches from FCC-hh.

FCC physics programme – the pub perspective



No-lose theorem of the FCC – observation of the Higgs self interaction

Several speakers [Salam, McCullough, de Blas] reminded us of the critical importance of measuring the Higgs self-interaction, and characterising nature of potential.



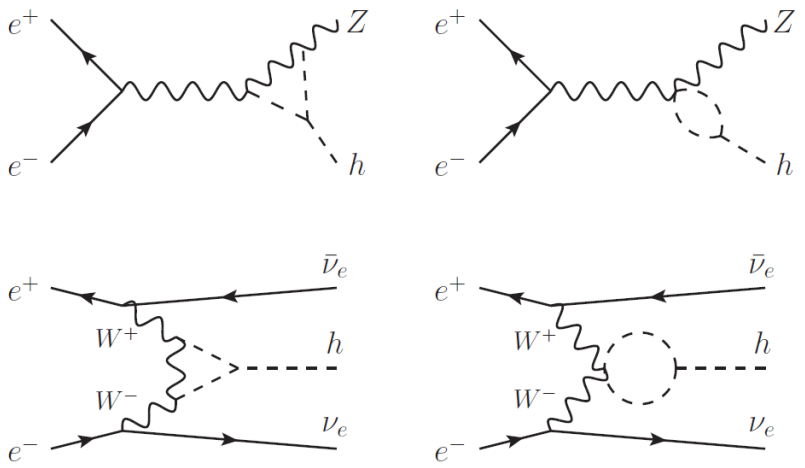
Is this how the world works ?

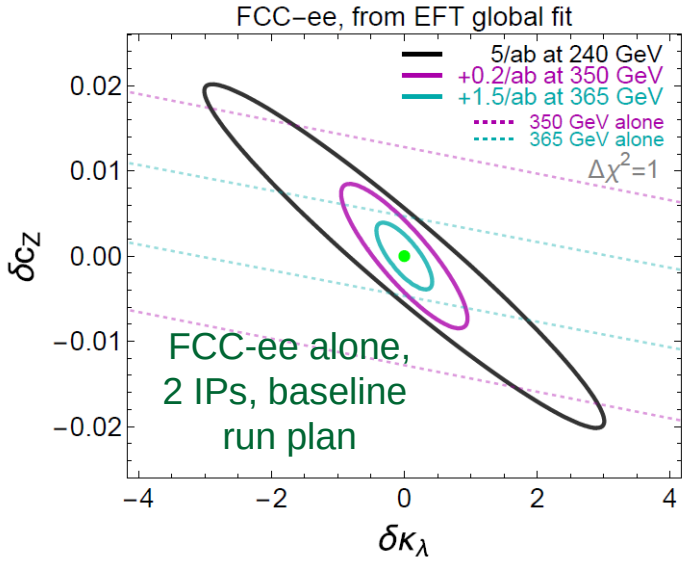
Something we need to know, as it plays a critical role in both the beginning, and possibly the end, of the history of universe…

…and is also an observable where major non-SM effects can lurk, which would not manifest themselves elsewhere.

Higgs self coupling at FCC-ee

FCC-ee will not observe HH production directly, but can access it indirectly [McCullough, PRD 90 (2014) 015001] through combination of precise cross-section measurements at 240 and 365 GeV [Blondel and Janor, arXiv:1809.10041].





Improving sensitivity of this measurement is one of (many) reasons to go to four interaction points, and, if possible, find other ways to boost luminosity.

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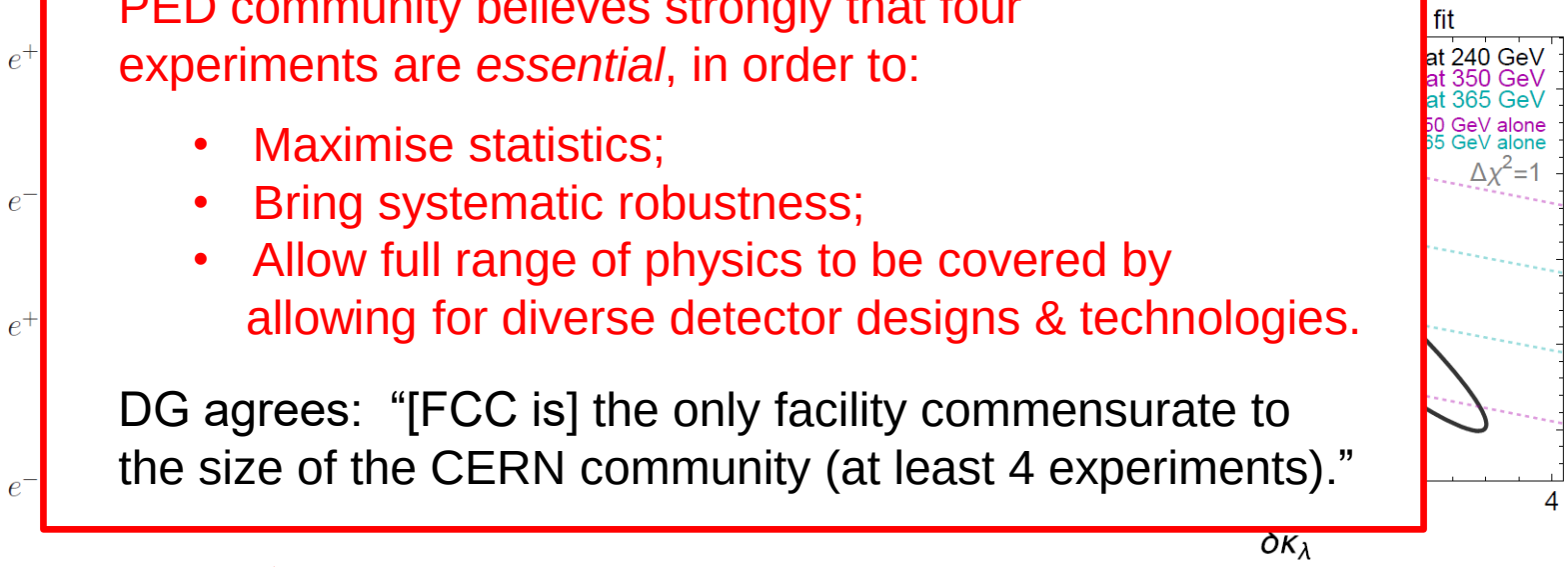
PED community believes strongly that four experiments are *essential*, in order to:

- Maximise statistics;
- Bring systematic robustness;
- Allow full range of physics to be covered by allowing for diverse detector designs & technologies.

DG agrees: "[FCC is] the only facility commensurate to the size of the CERN community (at least 4 experiments)."



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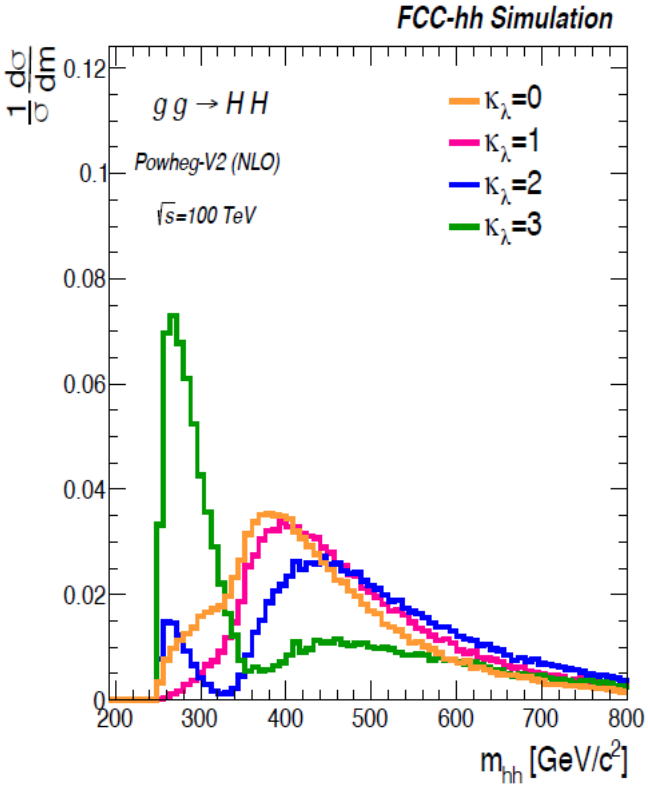
Higgs self coupling at FCC-hh

Even a strong indirect signal of Higgs self coupling would not be sufficient for such an important component of nature (and nor would 3 sigma 'evidence' at a 500 GeV linear collider). Need direct and precise observation at FCC-hh.

Remark, if we can build the machine then the signal will be there awaiting discovery – in that sense 'no lose'…

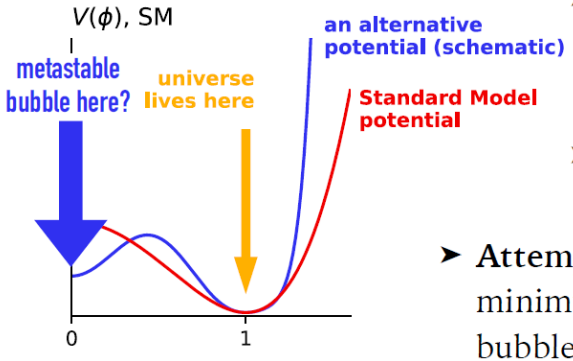
…but enormous effort still required to design and build the detectors that can operate in this environment, and deliver the goods.



The Higgs potential – practical applications ?

The slide that Gavin almost dared not show…

A wildly speculative aside [science fiction!]



- common argument for fundamental research: it may pay off in terms of technological advances in a century or two
- in particle physics, it's hard to conceive of a way in which this could be true
- **Attempt at counterexample:** if there were 2nd minimum in Higgs potential, could we create metastable bubbles of alternative vacuum? (cf. EW phase transition)

Practical applications: unlimited fusion power ?

…in case any journalist got to hear of it.

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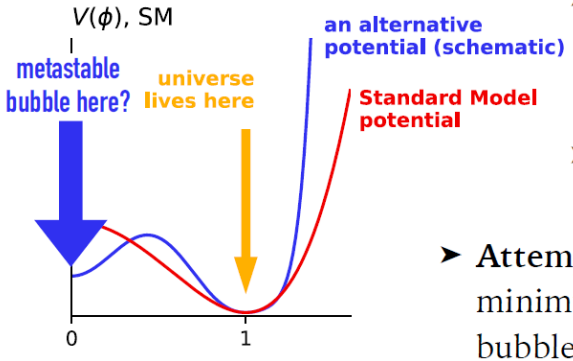

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Practical applications: unlimited fusion power ?

…in case any journalist got to hear of it. Too late !

Boffins promise unlimited power from new super atom smasher

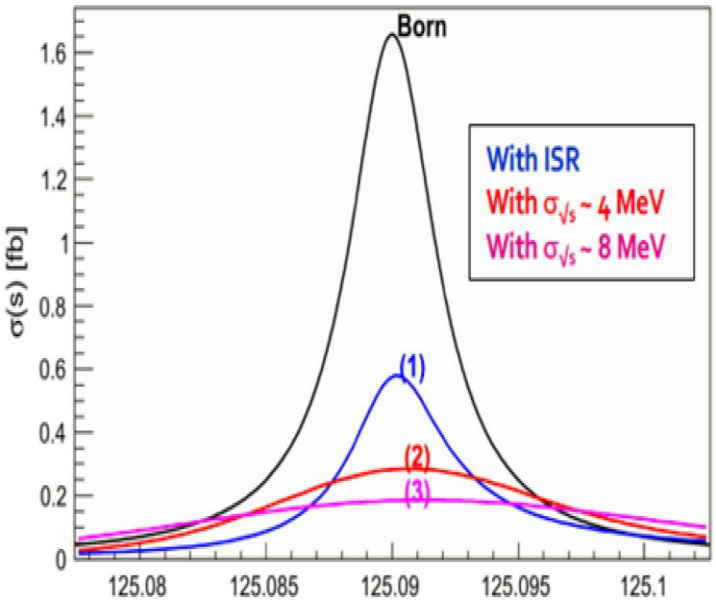
By MATTHEW CHALMERS

A new super atom-smasher, dubbed the Future Circular Collider (FCC), will transform our lives, providing unlimited power and removing the need for ever using fossil fuels again. The FCC will be built at the physics laboratory CERN, in Geneva, and will study the God Particle, also known as the Higgs. Top scientist Gavin Salam of Oxford University told us "I am convinced that our studies of the God Particle will unlock the door to unlimited power. They will also bring about world peace. Probably."

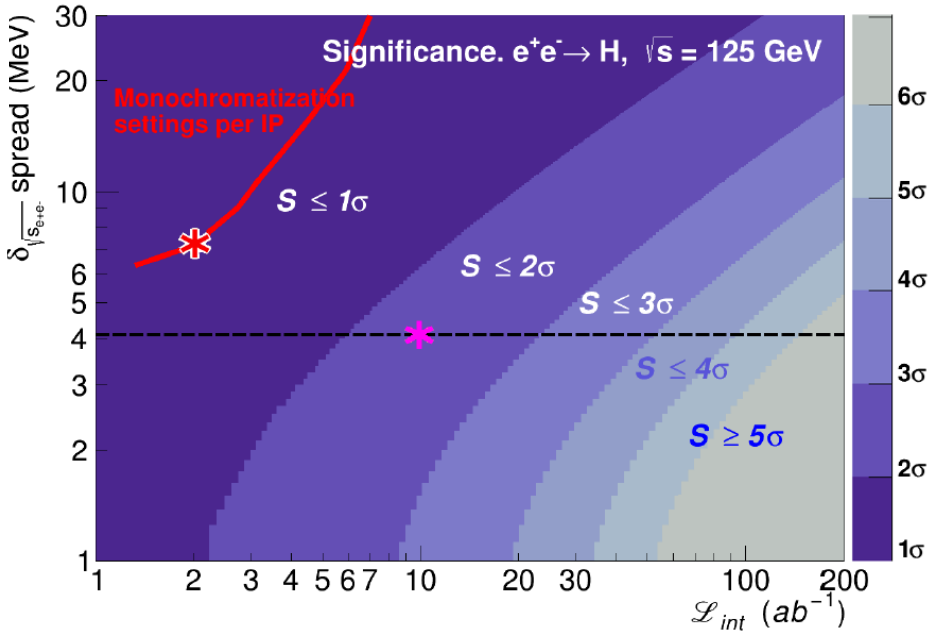
Reuters

Other no-lose theorems at the FCC ?

Measuring the Higgs' coupling to strange and (especially) the electron would be major scientific advances. These have not been part of the baseline FCC programme, but they nonetheless look tantalisingly close to achievable.



$e^+e^- \rightarrow H$ signal per IP per year



[EPJC 137 (2022) 201]

Keep working, keep thinking, and ensure the running programme remains *flexible* !

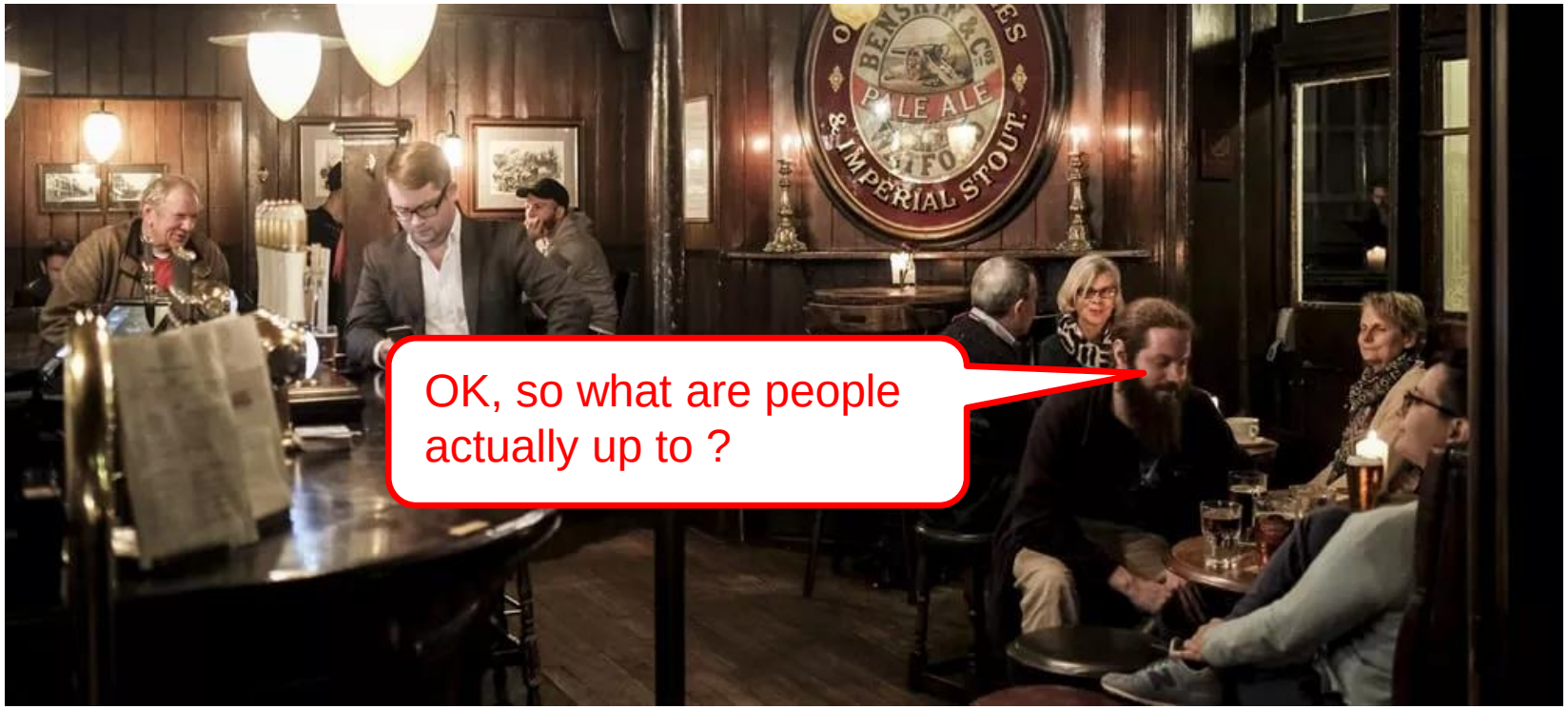
FCC physics programme – the pub perspective

Reasons to develop FCC-hh physics case still further

FCC-hh no longer the only high energy future collider in town.
The muon collider, presumed long dead is rising from the grave…

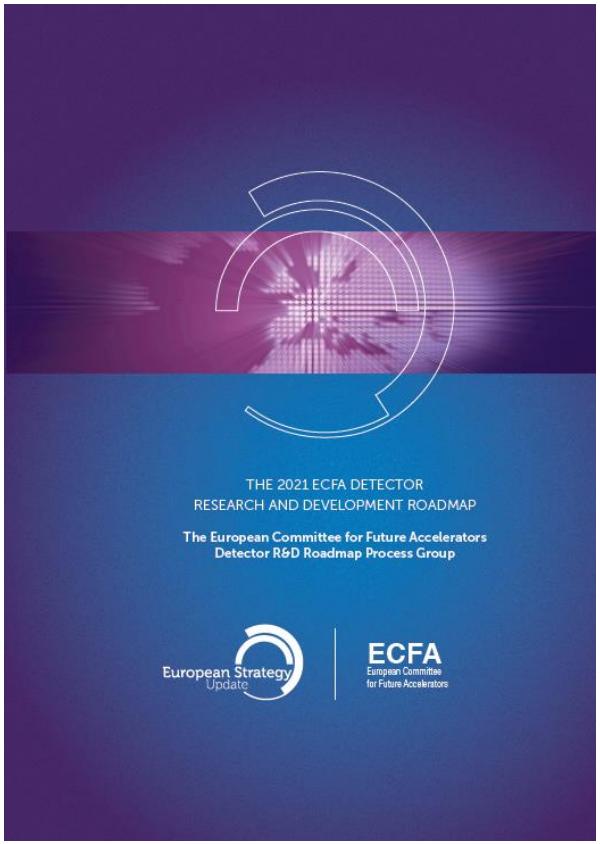
We must be prepared for a constructive discussion of the relative physics merits.

FCC physics programme – the pub perspective



Detector R&D – getting organised

ECFA Roadmap defined a way forward for all main detector technologies.



DRD collaborations now being established in most of these areas, and should be in place by the end of the year [reports this week].

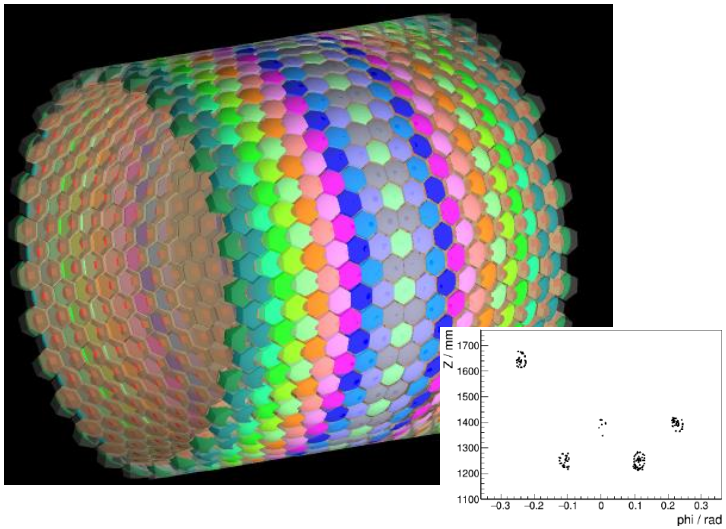
TF#1	TF#2	TF#3	TF#4	TF#5
Gaseous Detectors	Liquid Detectors	Solid State Detectors	Photon Detectors & PID	Quantum & Emerging Technologies
Anna Colaleo Leszek Ropelewski	Roxanne Guenette Jocelyn Monroe	Nicolo' Cartiglia Giulio Pellegrini	Neville Harnew Peter Krizan	Marcel Demarteau Michael Doser

TF#6	TF#7	TF#8	TF#9
Calorimetry	Electronics & On-detector Processing	Integration	Training
Roberto Ferrari Roman Poeschl	Dave Newbold Francois Vasey	Frank Hartmann Werner Riegler	Johann Collot Erika Garutti

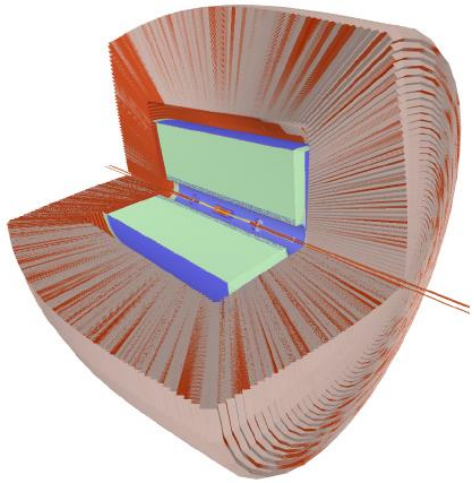
These are not for FCC alone, but FCC requirements are a major driver.

Progress in implementing many subdetectors in Key4HEP

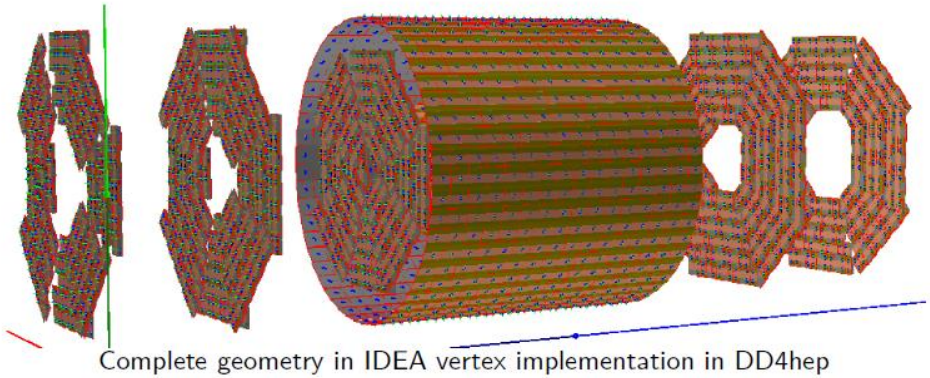
ARC (*i.e.* RICH) [Delgardo]



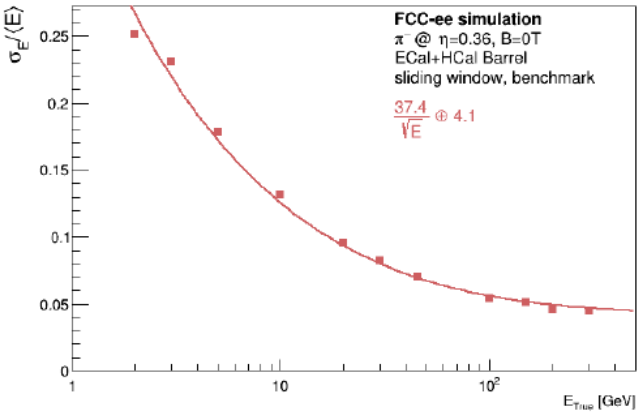
Dual-readout calorimeter [Ko]



IDEA vertex and drift detectors [Ilg]


Complete geometry in IDEA vertex implementation in DD4hep

LAr + tilecal [Mlynarikova]



Progress in implementing many subdetectors in Key4HEP

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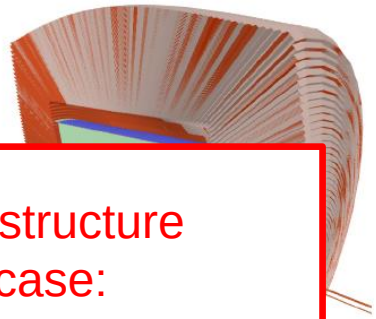
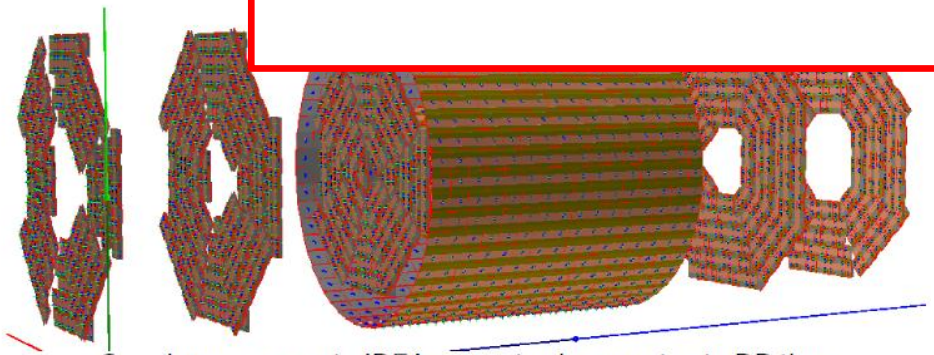


Progress also reported in software infrastructure [Smiesko], however, as it generally the case:

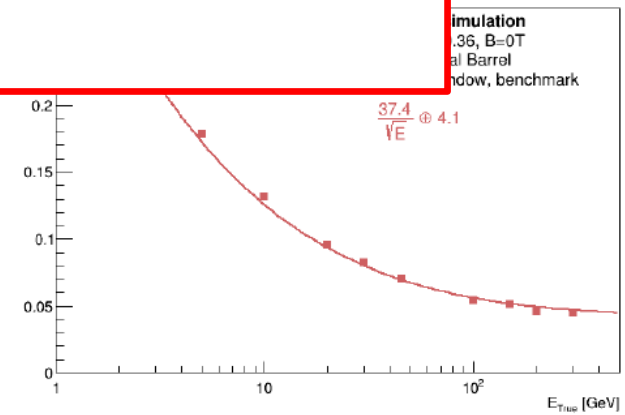
More heads are welcome!

Babyface from Toy Story, Pixar

IDEA vert rikova]

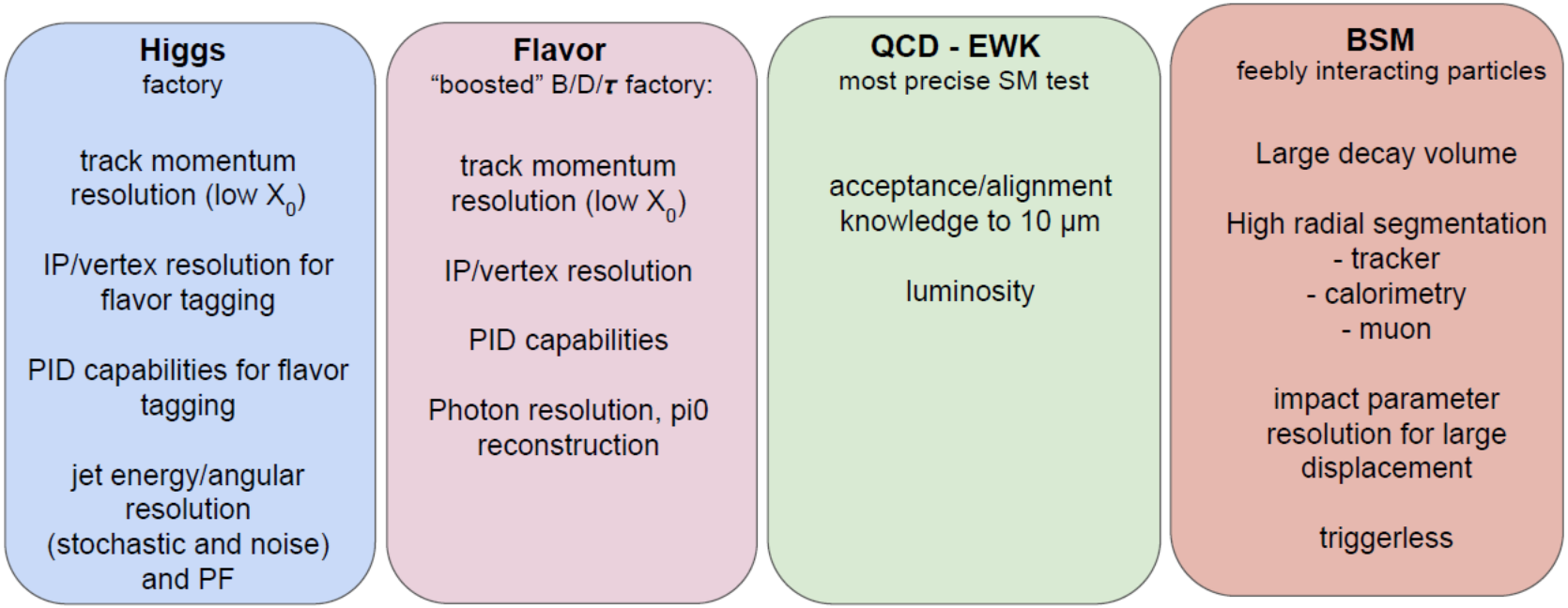


Complete geometry in IDEA vertex implementation in DD4hep



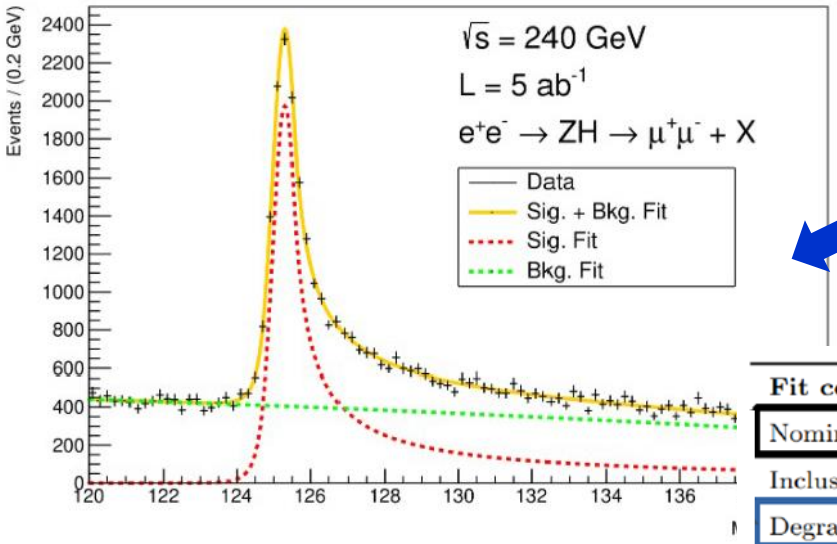
Growing focus on detector requirements

Progress in many physics studies presented – too many to summarise. One of most important deliverables of these studies is to define detector requirements.



[Michele Selvaggi]

Impact of detector on physics performance, *e.g.* m_H



Recoil mass in ZH analysis

Fit configuration	$\mu^+\mu^-$ channel	e^+e^- channel	combination
Nominal	3.49 (4.27)	4.38 (4.72)	2.67 (3.28)
Inclusive	4.11 (4.79)	5.26 (5.73)	3.19 (3.89)
Degradation electron res.	3.49	5.09	2.82
Magnetic field 3T	2.89	3.59	2.20
CLD 2T (silicon tracker)	4.56	4.93	3.26
BES 6% uncertainty	3.49 (4.35)	4.38 (5.00)	2.67 (3.42)
Disable BES	1.92	2.52	1.50
Ideal resolution	2.67	3.29	2.02
Freeze backgrounds	3.49	4.38	2.67
Remove backgrounds	2.86	3.26	2.11

[Li, Eysermans, Bernardi]

Variations in sensitivity with various detector (and other) variations

Clear idea of impact of different detector choices on physics performance !

FCC-ee as a flavour factory

In flavour physics, in comparison with Belle II and the LHC, FCC-ee will have almost the best of both worlds - although missing out on the entangled signal-only initial state of the B factories, and the eye-wateringly large cross section at the LHC.

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

In crude terms, the event yields will be one order of magnitude higher than those hoped for at Belle II with 50 ab^{-1} (trigger prevents no general comparison with LHCb).

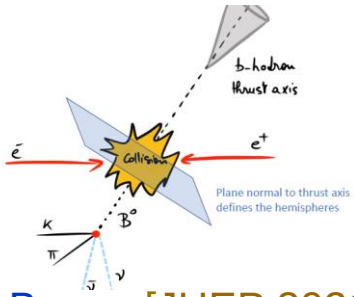
Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

If the detectors have the right characteristics, then great physics can be done over all areas. But in which measurements can FCC-ee be *truly* transformative ?

(Some) transformative measurements in flavour at FCC-ee

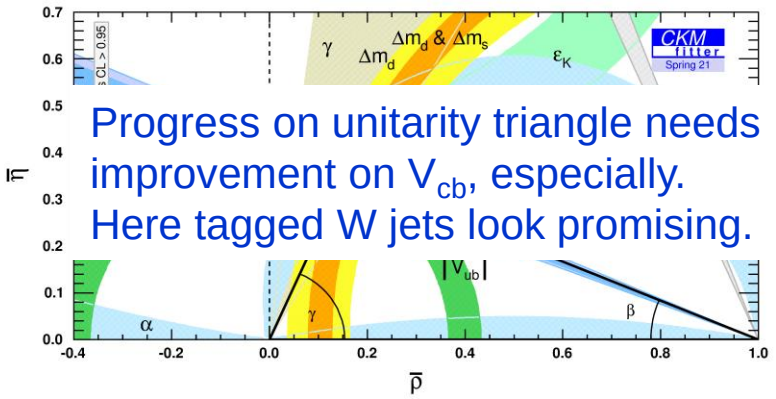
Leptonic and semi-leptonic decays

B→K*νν, Bs→ϕνν [Kenzie]



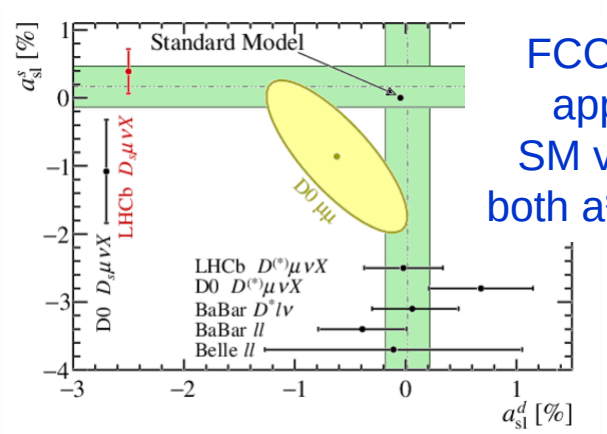
also $B_c \to \tau\nu$ [JHEP 2021 133]

Measurements of CKM elements



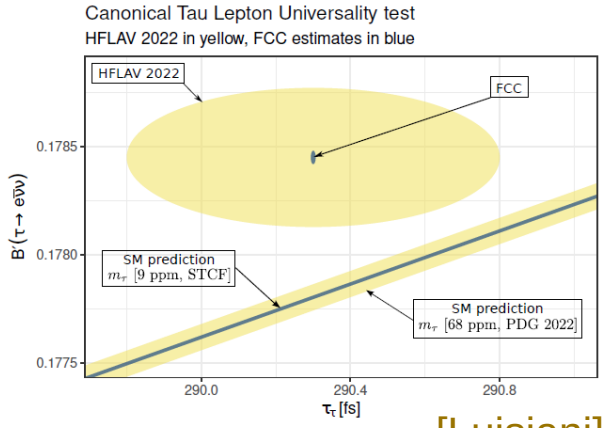
Progress on unitarity triangle needs improvement on V_{cb}, especially. Here tagged W jets look promising.

CPV mixing asymmetries



FCC-ee can approach SM values of both a^s_{sl} and a^d_{sl}.

Tau physics



and flavour-violating decays

[Luisiani]

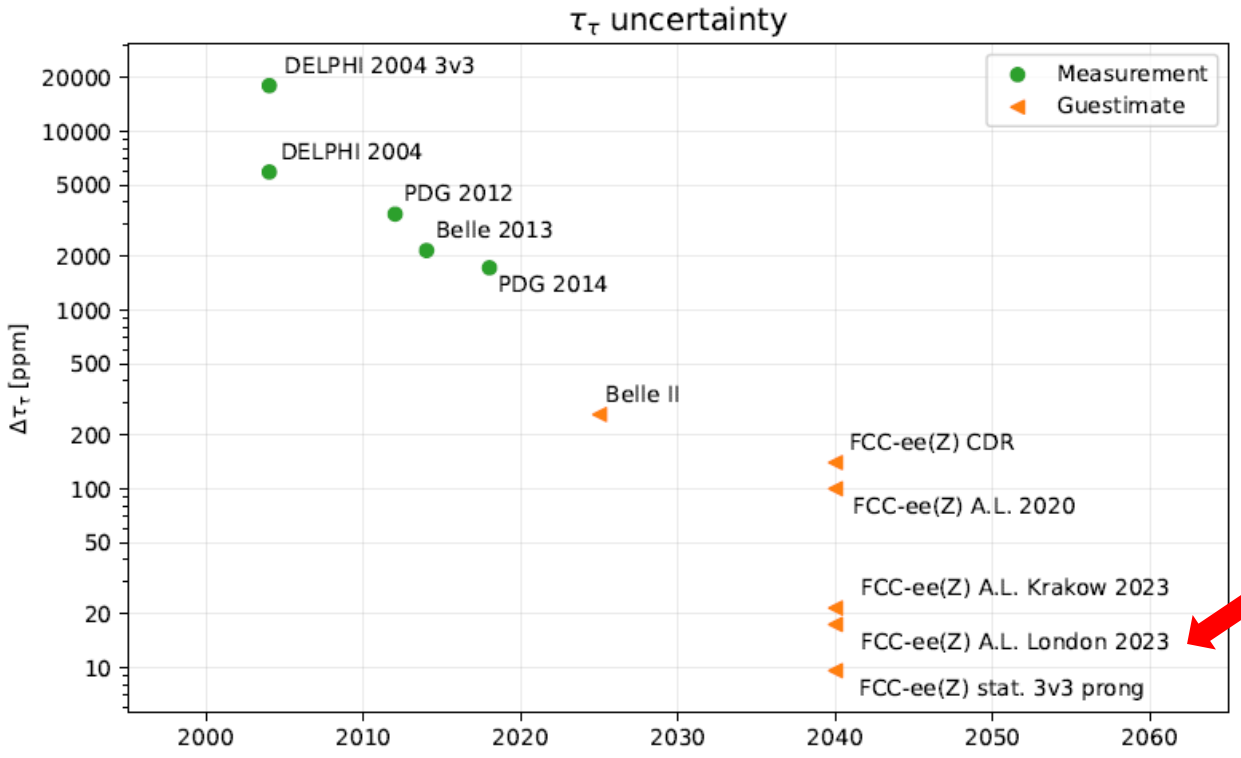
Many flavour updates presented this week, *e.g.* on tau-physics measurements

Serious consideration on systematics – *e.g.* the tau lifetime [Luisiani]

- consider just tau pairs in 3-prong vs. 3-prong topology (3v3)
  - Belle 2013 best measurement uses these events
  - τ direction reconstruction using vertices reduces importance of simulation
- extrapolate FCC-ee statistical precision starting from Delphi 2004 3v3 events statistical precision
  - expect no significant differences on selection efficiency
  - Delphi 2004 3v3 precision by rescaling 3v1+3v3 measurement to number of 3v3 candidates
  - τ_τ measurement is a measurement of transverse i.p. $\langle d_0 \sin\theta \rangle \approx 70\,\mu$m
  - Delphi 2004 3v3 precision consistent with a d_0 resolution $\approx 70\,\mu$m (tracking, beam spot)
  - assume FCC-ee has both transverse beam spot and can have d_0 resolution $\ll 70\mu$m
    $\Rightarrow$ precision improvement factor $\sim(70\,\mu\text{m} \oplus 70\,\mu\text{m})/70\,\mu\text{m} \simeq 1.41$
- assume DELPHI systematics for background, reconstruction bias and alignment (total 1.3 fs) scale with luminosity to 3.5 ppm at FCC-ee
  - very optimistic, and revised w.r.t. estimate in Krakow 2023, which was 12 ppm
- assume 30$\times$ better KKMC simulation can reduce uncertainty on ISR+FSR energy loss in tau pair production to reduce the associated systematic contribution from 350 ppm to 12 ppm
- assume 9 ppm tau mass measurement at SCT/STCF or at FCC-ee
- assume 2 ppm vertex detector length scale (possible with optical methods)
- see Krakow Jan 2023 presentation for more details

Many flavour updates presented this week, *e.g.* on tau-physics measurements

Serious consideration on systematics – *e.g.* the tau lifetime [Luisiani]

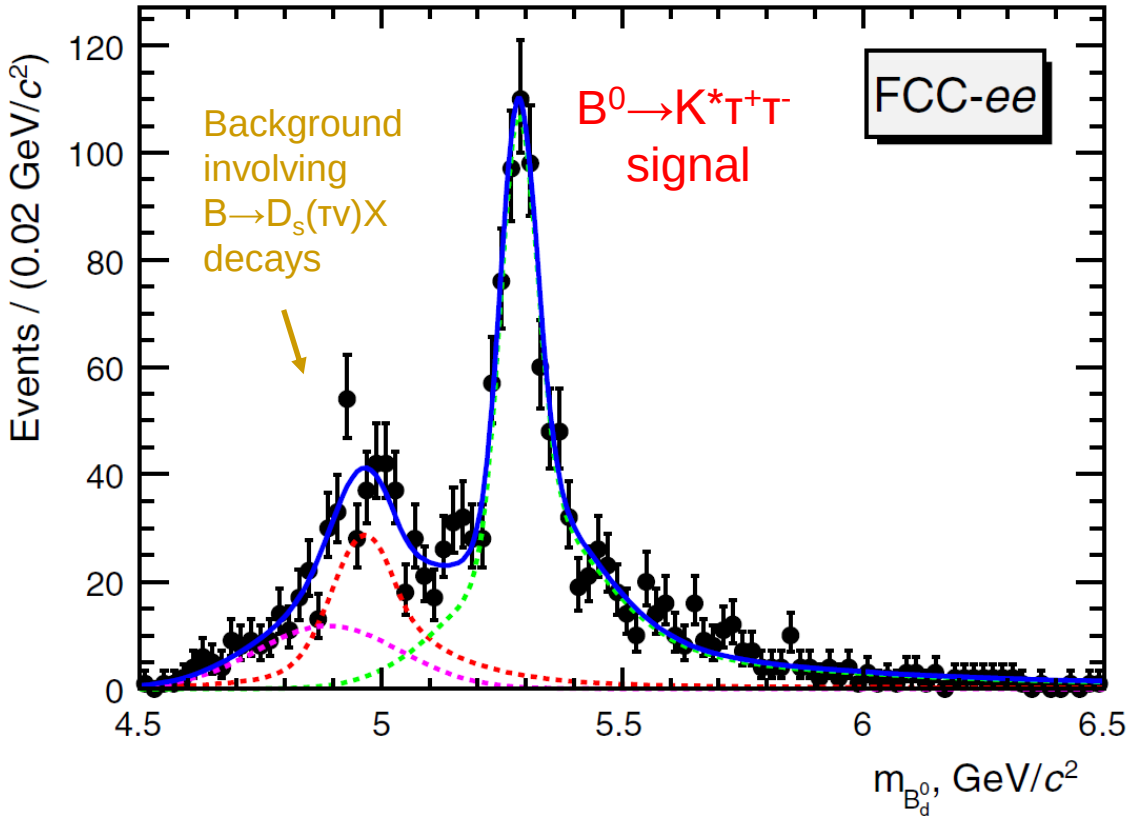


looking promising !

(the branching fractions seem tougher)

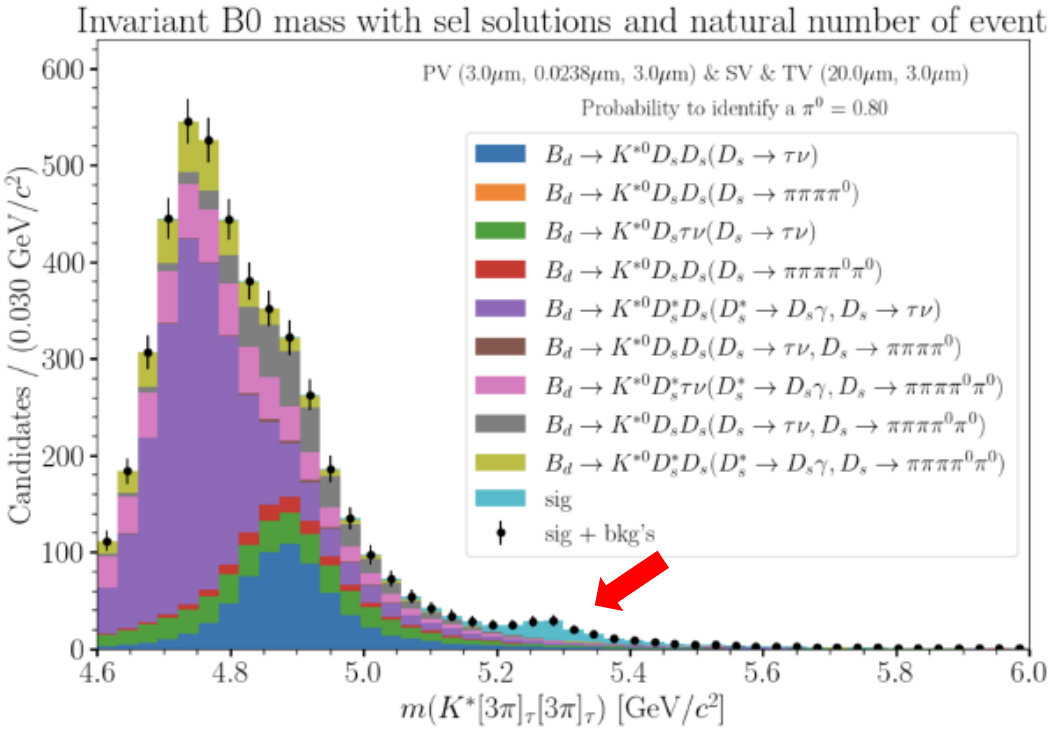
Taking a closer look sometimes makes clear how demanding some of these measurements are

This used to be the poster child of FCC-ee flavour physics



Taking a closer look sometimes makes clear how demanding some of these measurements are

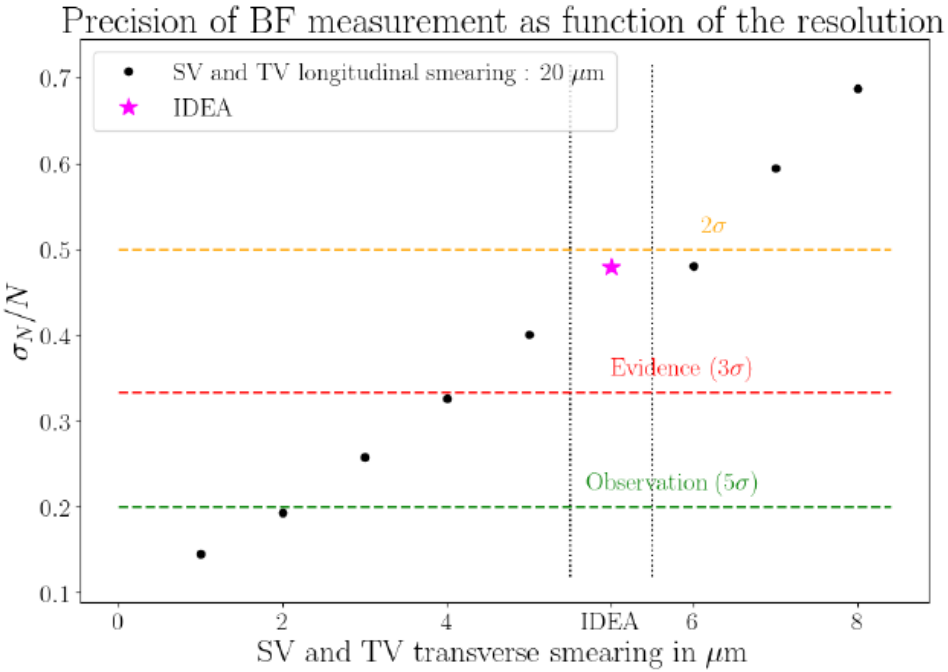
Including more realistic backgrounds, and reconstruction, but taking a less idealistic performance for the vertex resolutions.



[Tristan Miralles]

Taking a closer look sometimes makes clear how demanding some of these measurements are

And now scaling over transverse vertex resolution, and finally comparing to performance expected by one detector concept (IDEA).



[Tristan Miralles]

No need to panic yet – this may be 'merely' a material issue. The purpose of this study is indeed to *define* detector requirements ! Also, made with τ→3πν alone.

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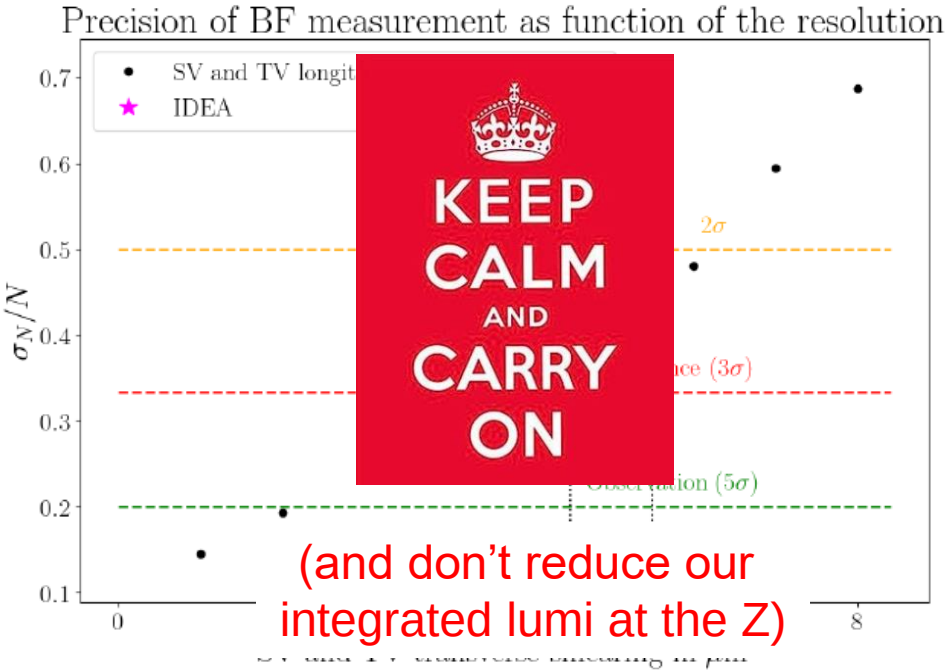

[Tristan Miralles]

(and don't reduce our integrated lumi at the Z)

No need to panic yet – this may be 'merely' a material issue. The purpose of this study is indeed to *define* detector requirements ! Also, made with τ→3πν alone.

Conclusions

The integrated FCC programme offers unparalleled exploration potential over the widest physics frontier.

There are guaranteed no-lose outcomes, but the real interest will be the unexpected. Let us measure, and see what comes of our measurements.

Flexibility will be key !

Many measurements will be challenging, and work is required now, as solutions define detector requirements.

Thank you for your attendance, and have a safe trip home !