CepC Physics S~~ummary~~ Musings

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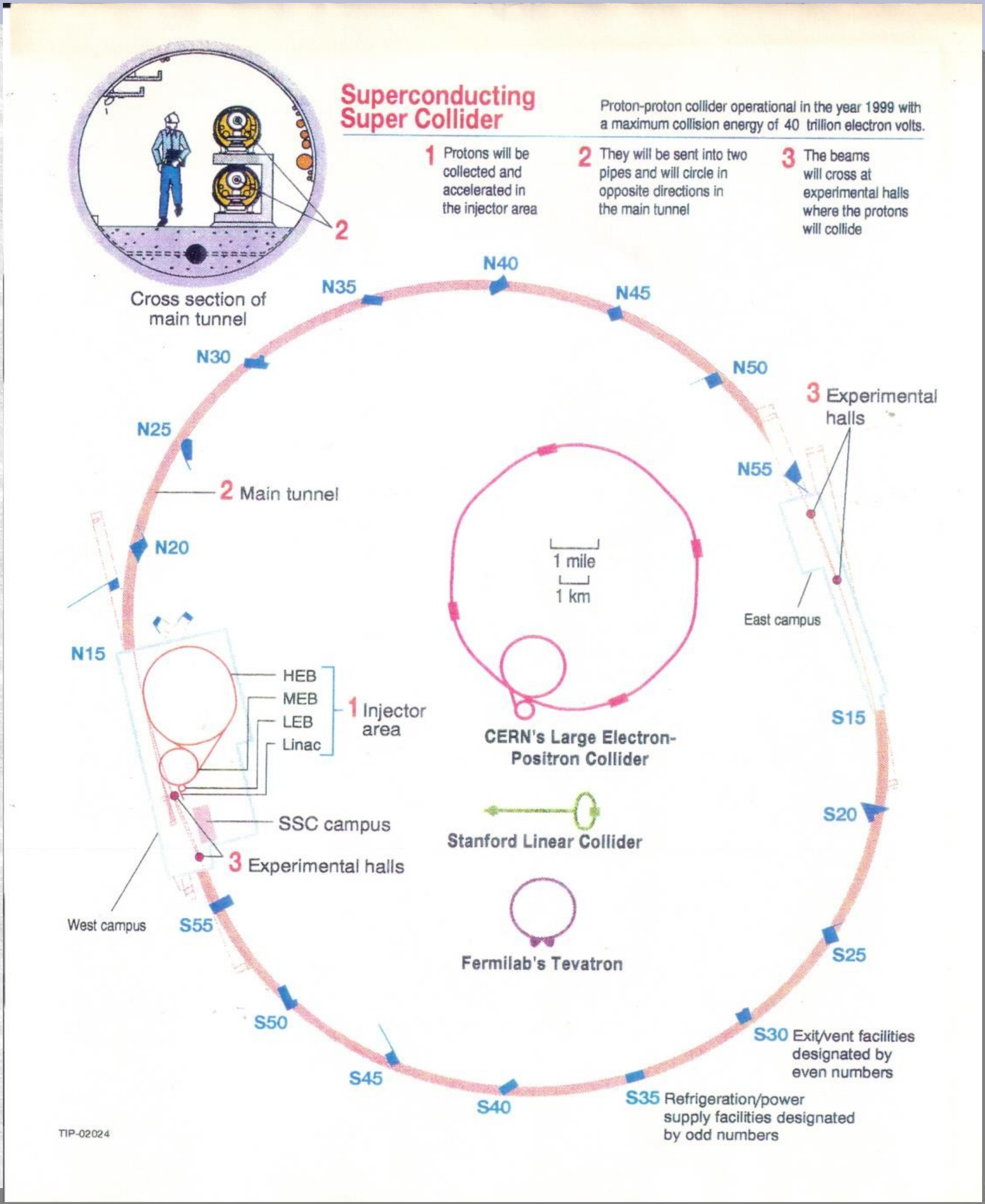
Edinburgh 6th July 2023

The SSC

- 40 TeV ‘Throw Deep’ pp collider sited in Texas
  - 87km ring
- Driven/funded mostly US
- Cost estimates:
  - 1982: $1-3 Billion
  - 1993’: $10.45 Billion
- Cancelled 1993
  - Ballooning costs
    - Inc. magnet bore increase
  - Annual funding vote
    - Political imperatives
- Major blow to US HEP



Cancelled: with a lot spent

North Campus

Tunnel

Problems facing the SM

- The hierarchy or naturalness problem
  - Why is the Higgs so light?
- Neutrino Mass
  - Neutrinos have mass – but how? We do not know
- Dark matter
  - Most matter in the Universe is something unknown
- Dark energy
  - What accelerates the Universe expansion?
- Matter-antimatter asymmetry
  - Where did the antimatter go after the big bang?
- Is the Higgs field real?
  - If so why didn't the Universe collapse already?
- **CepC might help with any of these**
- **But that is <u>not</u> why we should do it**

The three realms of Nature

- Matter 5thC BC:
  - Atomic theory can be traced to Leucippus of Miletus (and his disciple, Democritos
    - Who coined the word ‘atomos’
    - (And had some fundamentally un-British ideas about government)
- Forces 17th C CE:
  - Newton in Principia Mathematica codified forces
  - In Optiks: “There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the business of experimental Philosophy to find them out.”
- VeVs 20th C CE:
  - Higgs in PRL: One finds the possibility of two non-vanishing vacuum expectation values
- All three demand our detailed study
  - But only Higgs studies address the VeV sector

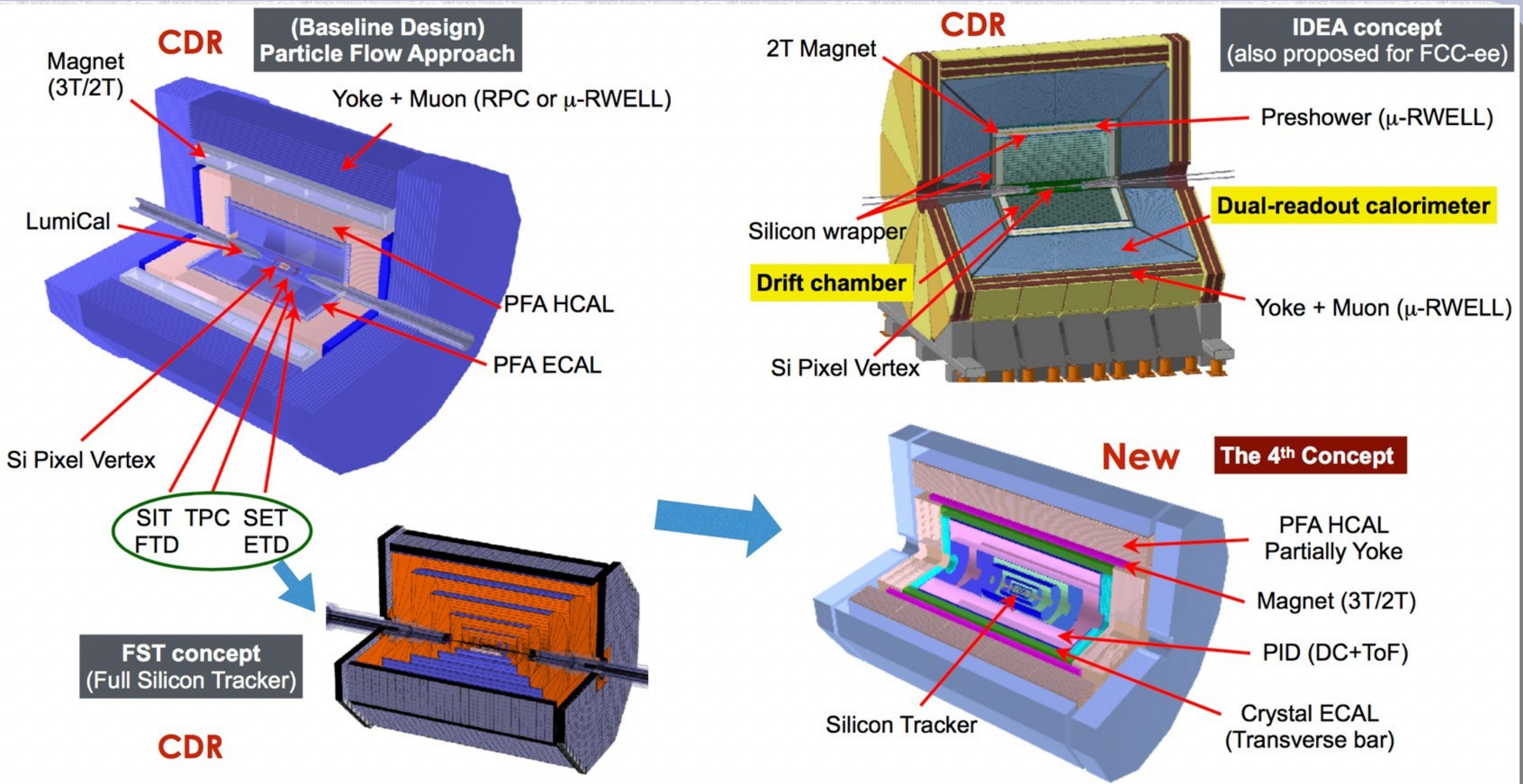
The Physics program

Operation mode	ZH	Z	WW	tt
√s	240	91	160	360
Run years	10	2	1	5
L/IP x $10^{34}cm^{-2}s^{-1}$	8	190	27	0.8
ab^{-1}, 2IPs	20	96	7	1
Event yield	4M	4000000M	50M	0.5M

- “An extremely versatile machine with a broad spectrum of physics opportunities
  → Far beyond a Higgs factory”

Jianbei Liu

CepC detectors

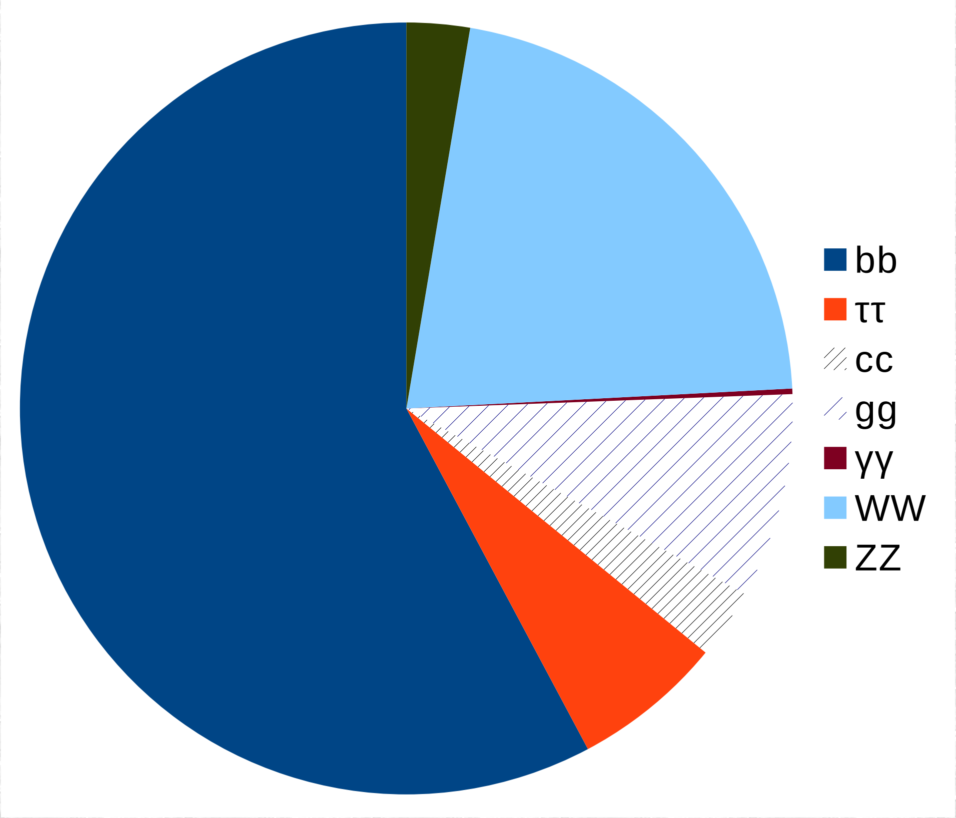


- Not the focus of this talk

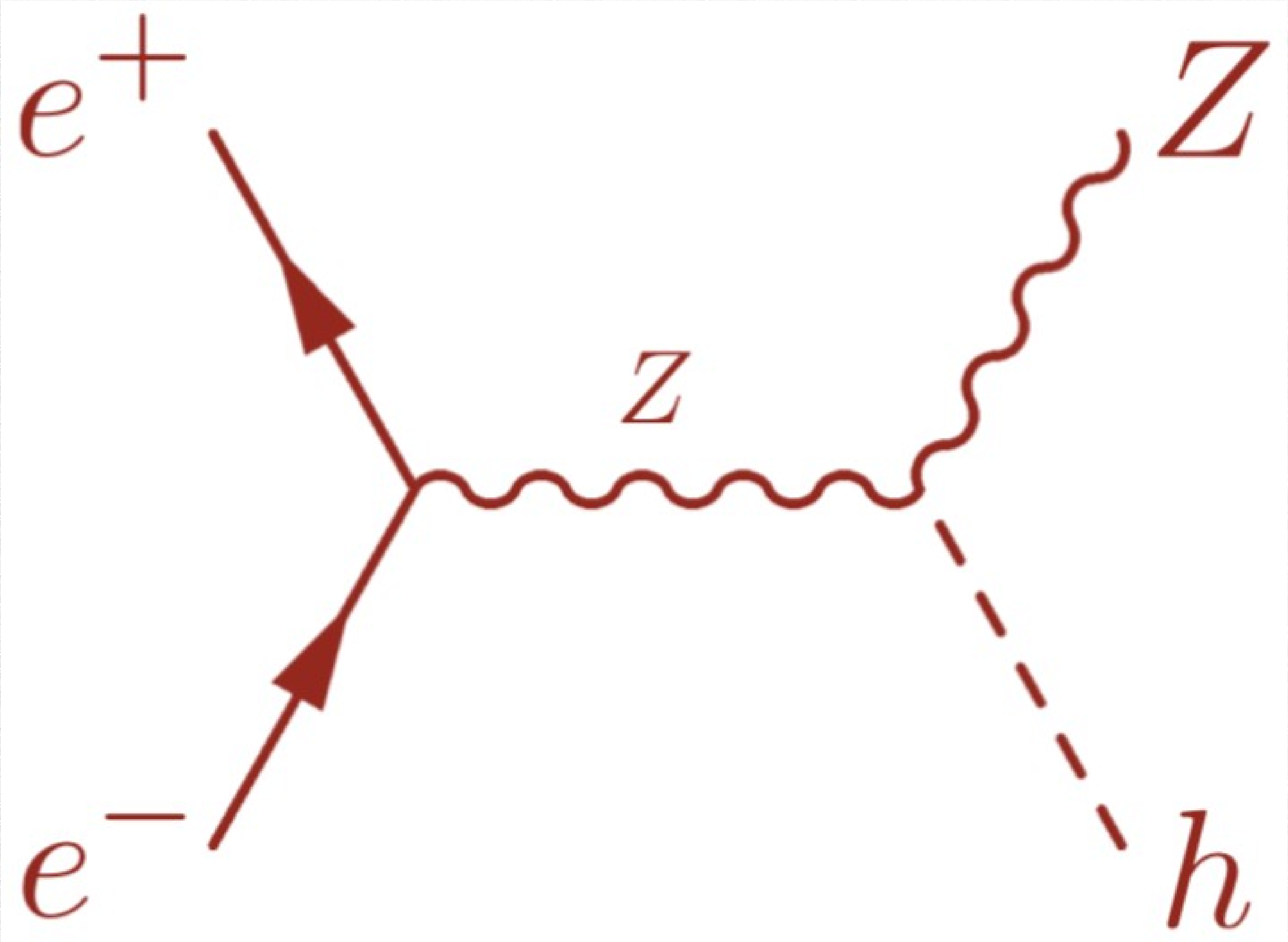
Higgs physics

The Higgs Boson

- Nature has dealt an odd hand at LHC
- Many people expected abundant SUSY to be obvious
  - And are frustrated
- But the Higgs we found has unreasonably many testable properties
  - It is a gift for a dedicated clean Higgs factory
  - All these decays and more can be measured well

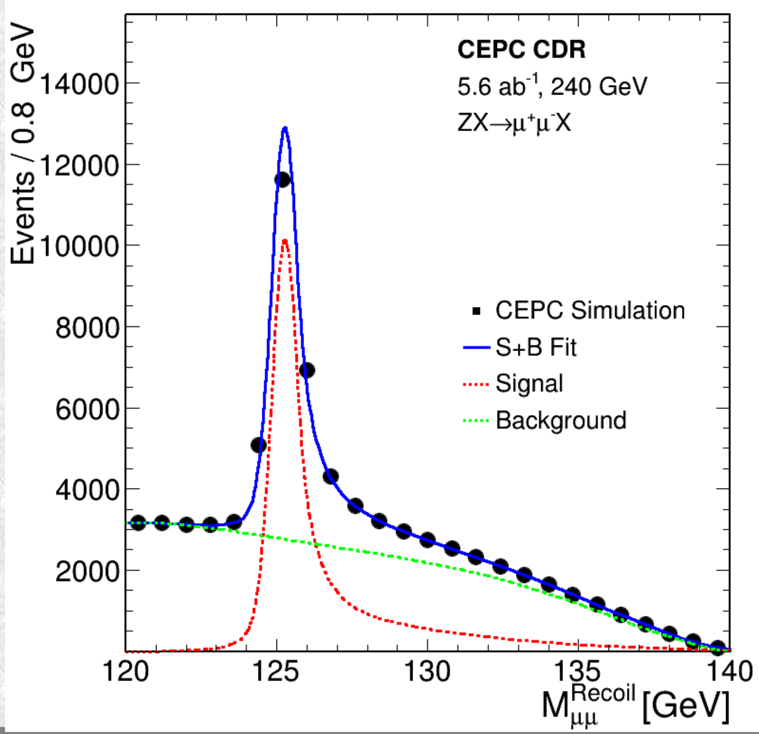


ee collider H target



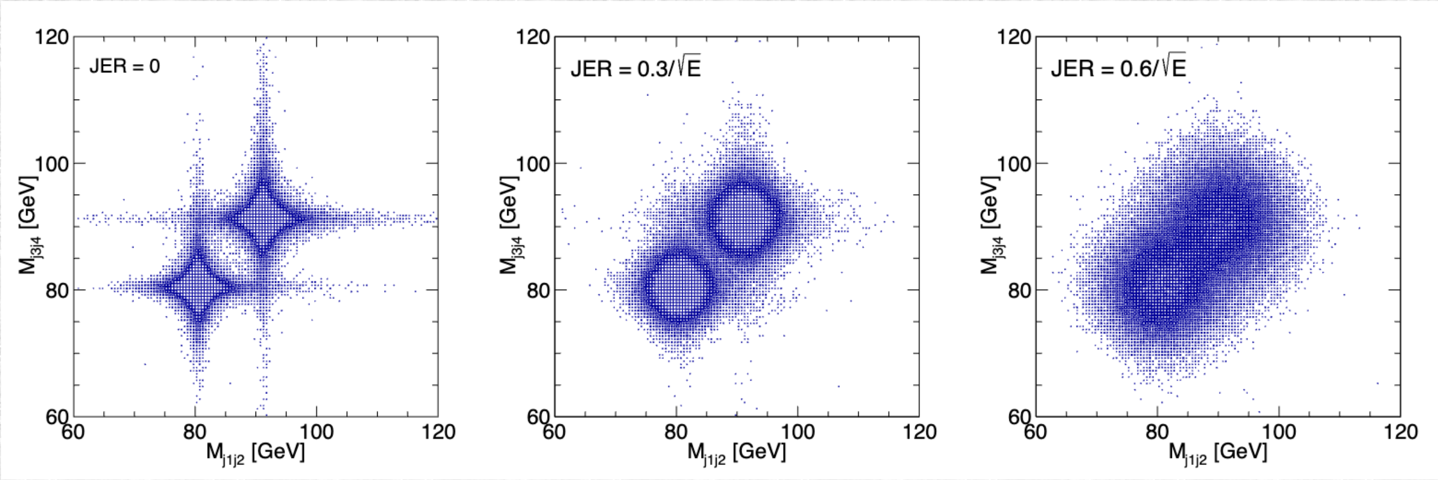
The method

- The Higgs-strahllung from known initial state is the unique and best feature of the Higgs factory
  - Higgs-tagging from the Z
    - Leptonic and hadronic z decays to maximise rate
  - Total width can be extracted
  - The result is g_{HZZ} is much the best measured Higgs coupling at CepC
- "Higgs tagging" allows unbiased study of the decay modes

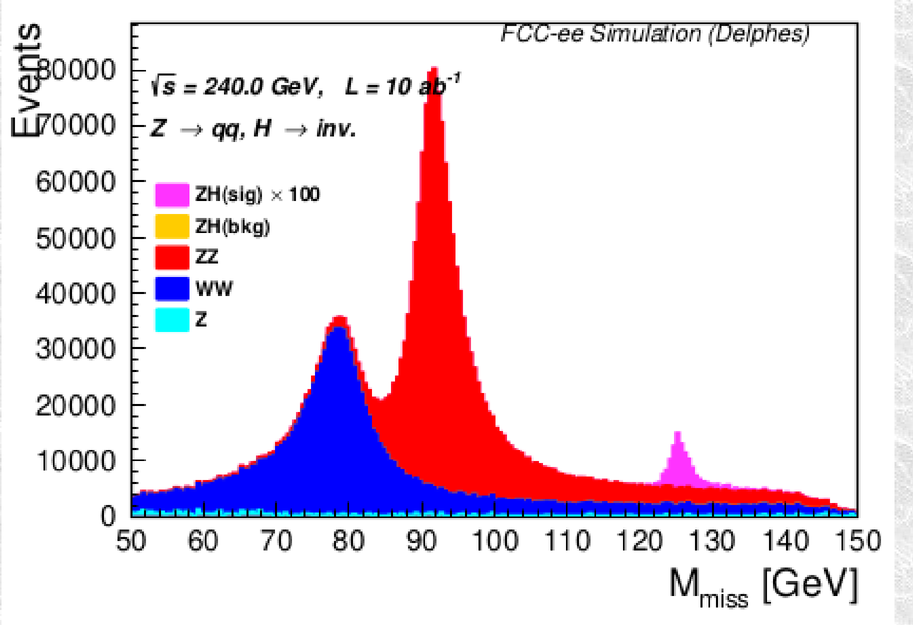


Jet energy resolution

- JES of 30%/√E can be motivated by WW/ZZ separation

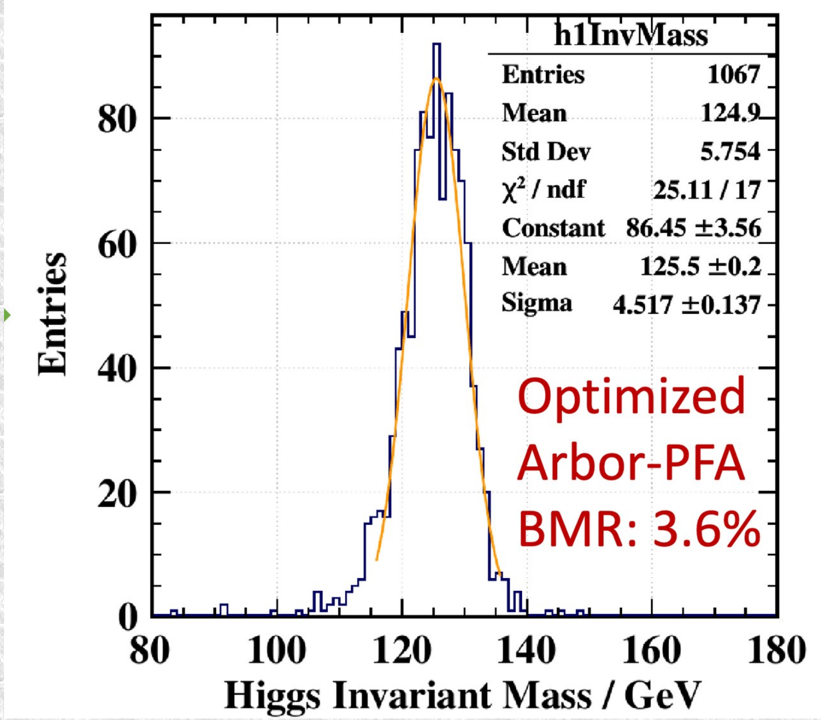


- Measuring H→χχ is a key target for CepC
  - Measured through missing mass, mostly qq channel
  - Controlling the jet resolution and tails is crucial



Jet energy reconstruction

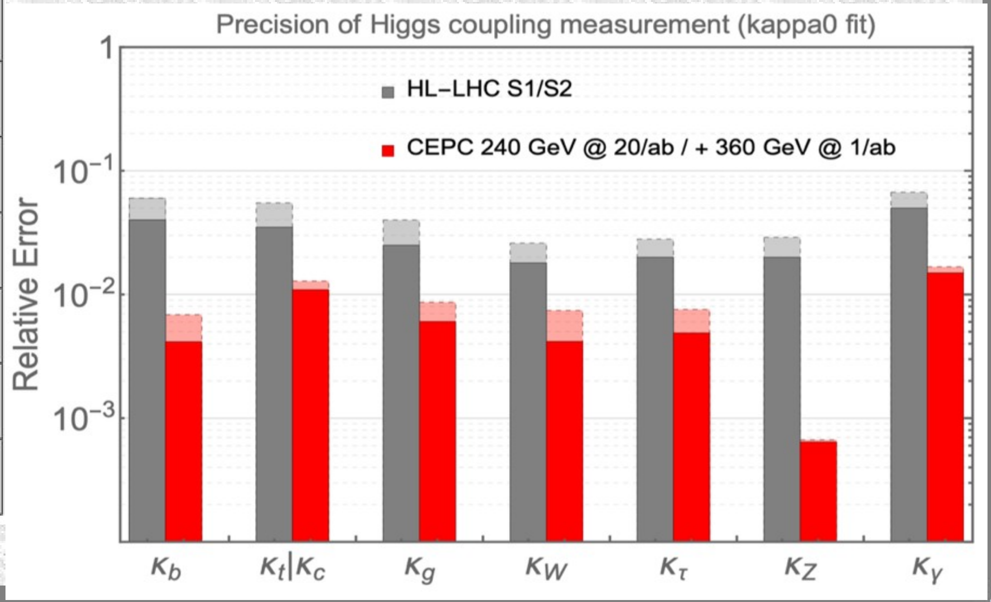
- Pandora PFA
  - Well established hand-tuned algorithm
  - Confusion about assigning energy to charged or neutral particles is a significant issue
- ArborPFA
  - Follow a tree structure
  - 3.6% boson mass resolution
- In 2030s?
  - Many AI options being tested
    - Ultimate performance unknown
  - Will do better than we think
  - Quantum machine learning?
    - Work ongoing already



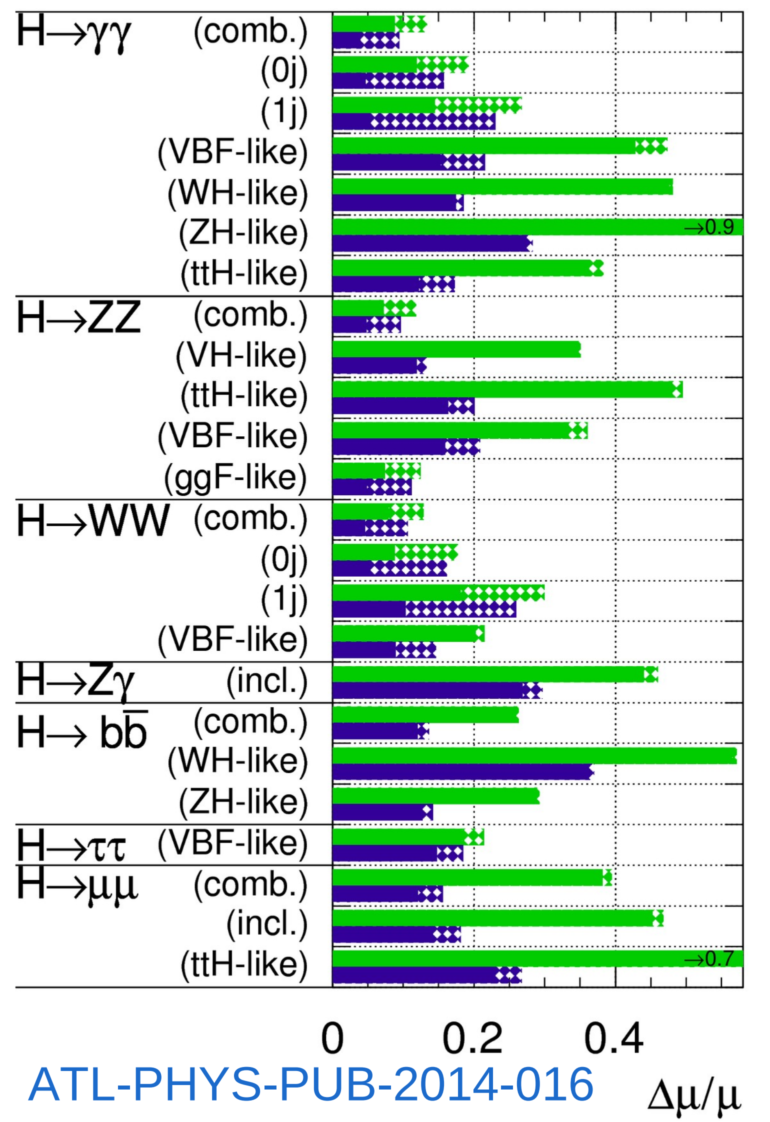
Higgs k-framework expectations

	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	vvH	ZH	vvH	eeH
inclusive	0.26%		1.40%	\	\
H→bb	0.14%	1.59%	0.90%	1.10%	4.30%
H→cc	2.02%		8.80%	16%	20%
H→gg	0.81%		3.40%	4.50%	12%
H→WW	0.53%		2.80%	4.40%	6.50%
H→ZZ	4.17%		20%	21%	
$H \to \tau\tau$	0.42%		2.10%	4.20%	7.50%
$H \to \gamma\gamma$	3.02%		11%	16%	
$H \to \mu\mu$	6.36%		41%	57%	
$H \to Z\gamma$	8.50%		35%		
$\mathrm{Br}_{upper}(H \to inv.)$	0.07%				
Γ_H	1.65%		1.10%		

- Higgs coupling precision factor ~10 better than LHC
- Where many models predict deviations

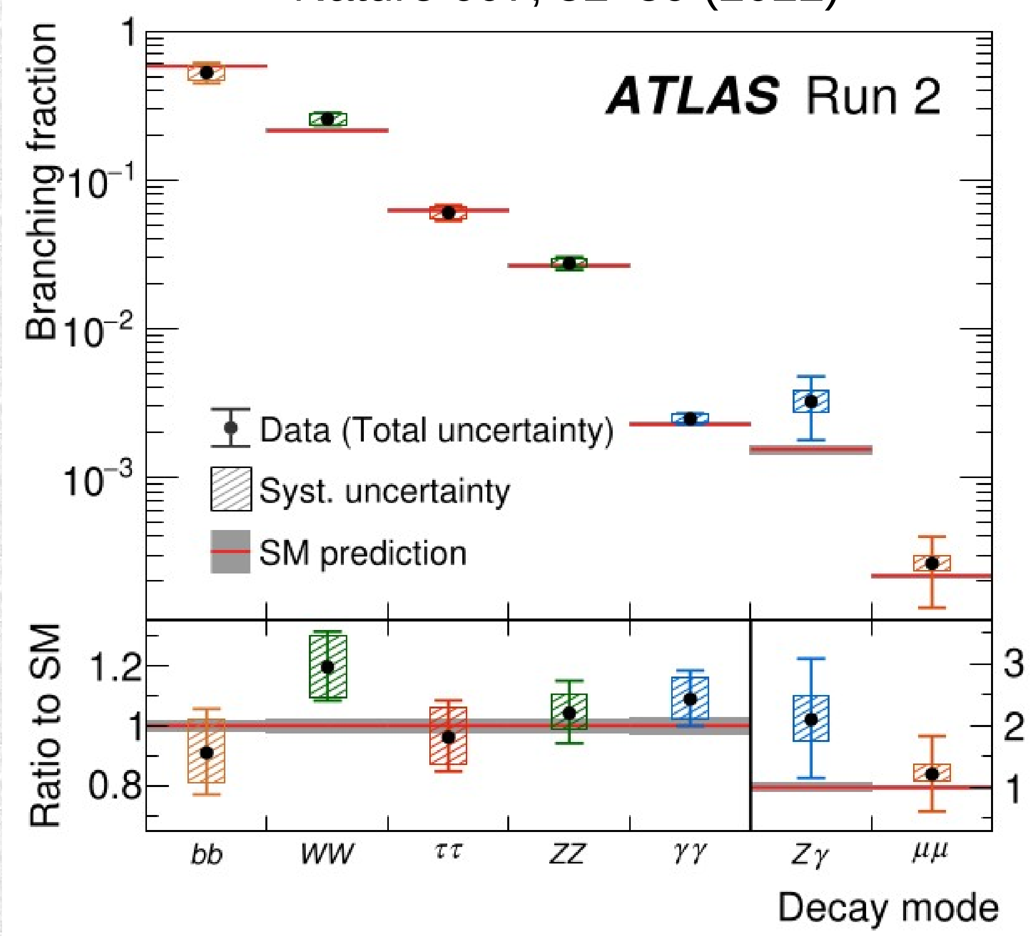


A warning on projections



ATL-PHYS-PUB-2014-016

Nature 607, 52–59 (2022)



- Run 2 results are comparable to 2014 HL-LHC expectations

Can we study all these channels?

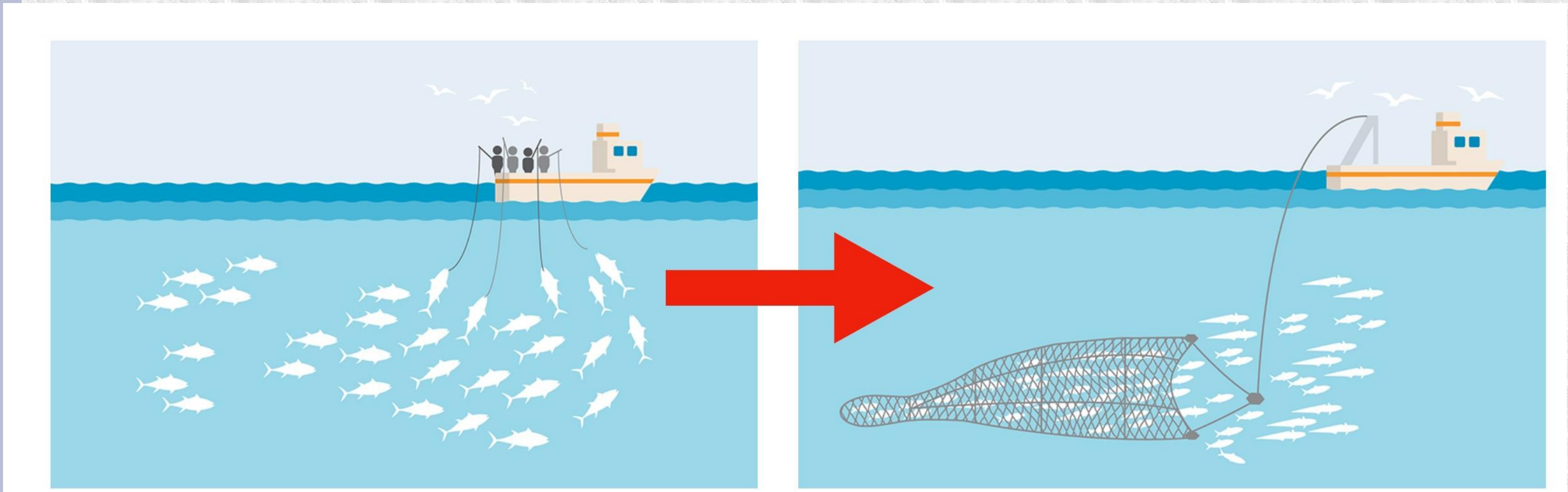
4 x 9 modes in this study, [**5 production and 13 (9) decay** modes in SM]

Prod/decay	cc	bb	μμ	ττ	γγ	gg	WW	ZZ	γZ	ee, uu,dd,ss
eeH (incl. Z fusion)	3	1	5	2	4	1	2	3	5	Not covered yet
μμH	3	1	5	2	4	1	2	3	5	
ττH	3	1	5	2	4	1	2	3	5	
qqH	4	1	2	1	2	5	5	5	3	
ννH (incl. W fusion)	5	1	3	2	3	5	4	2	4	

According to production rate, signal signature, backgrounds, complication of analysis, …

Global analysis

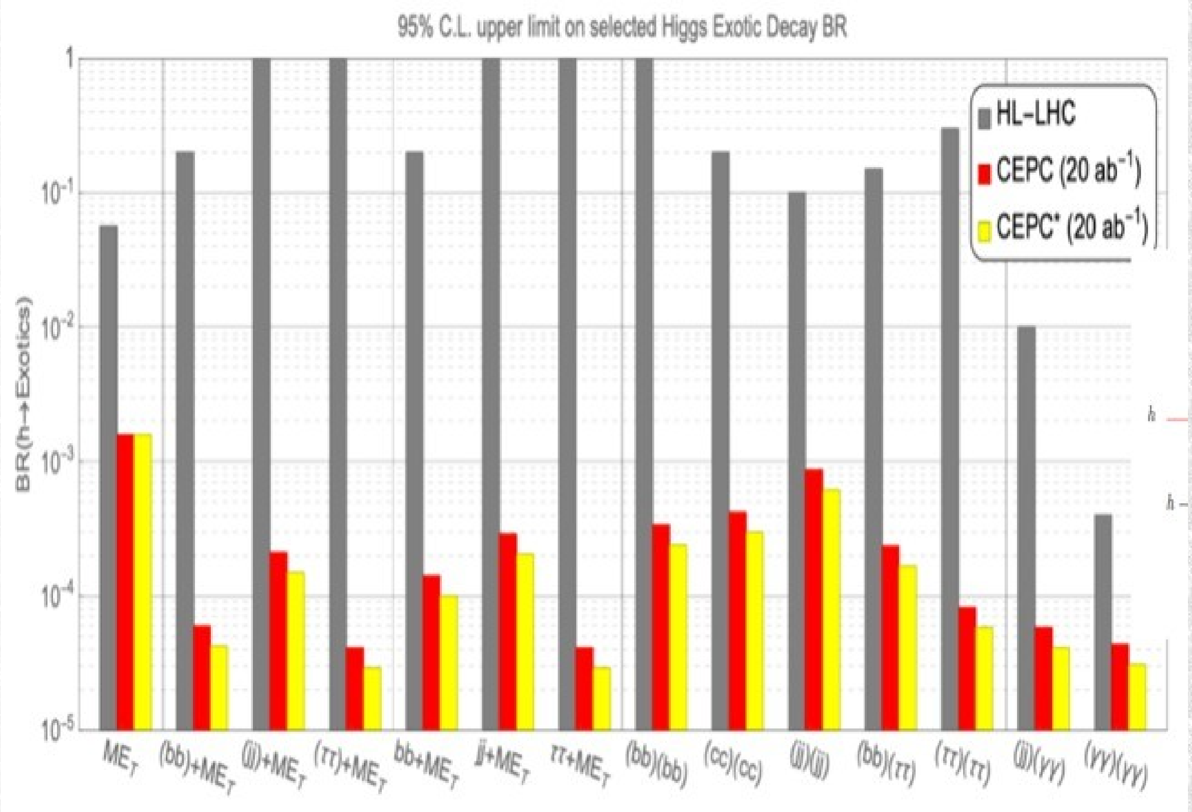
- ML makes it practical to study all these at once



- Avoids a common problem in projection studies:
  - Only using the most promising channels – which naturally leads to underestimating performance
- Not necessarily final approach, but very helpful

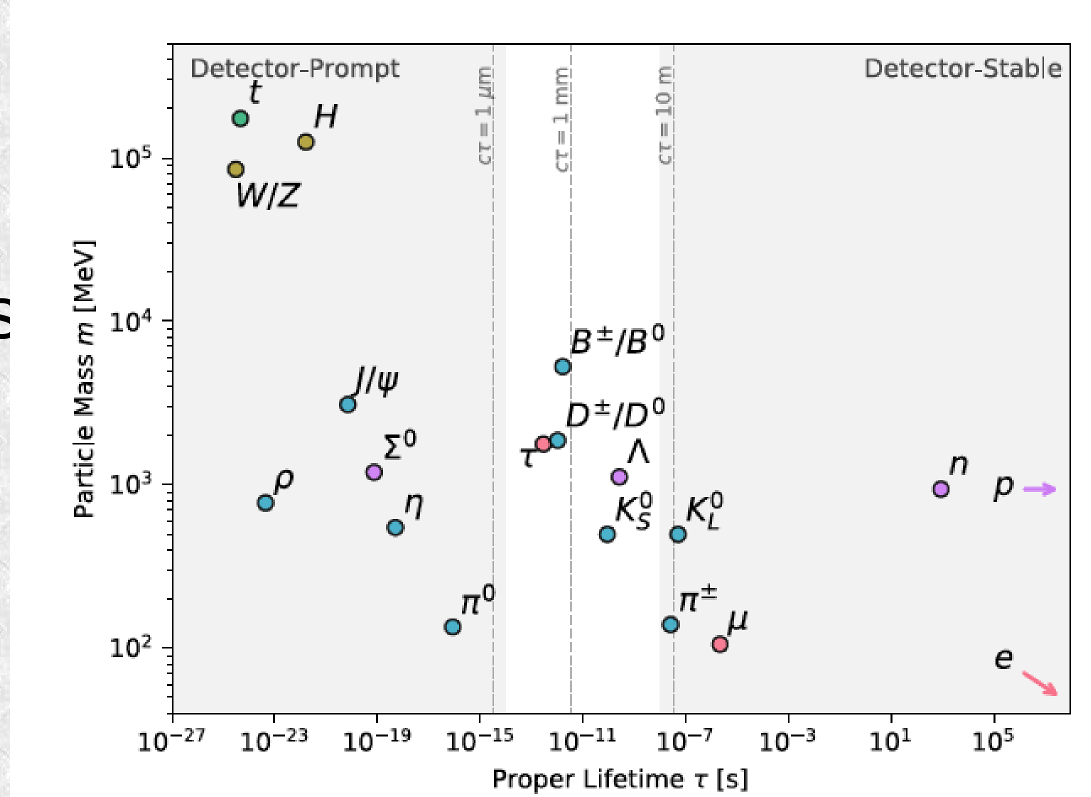
Exotic Higgs decays

- Huge potential for unexpected Higgs decay modes



- Many modes are dark sector – hard to test at LHC
- The Z run does theme – maybe more – for it.

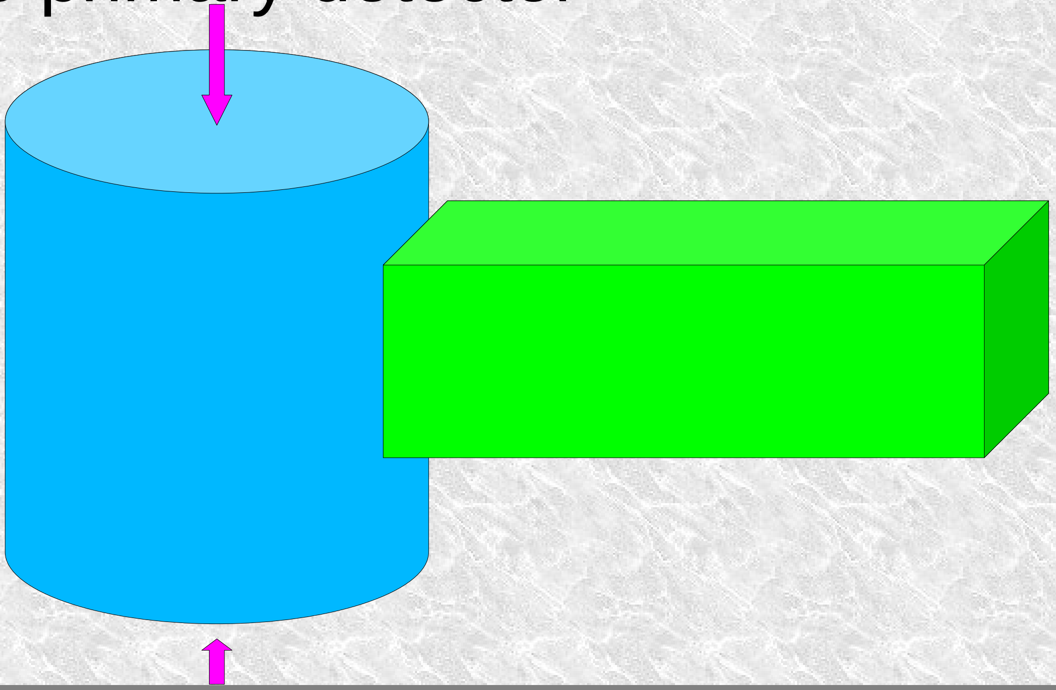
Long lived particles



- LHC designed for high mass prompt
  - Searches for long lived need bespoke solutions
- CepC should be ready for long lived
  - Weakly coupled/mass degenerate
  - 3µm resolution allows sub-fs lifetimes to be probed
  - axion: $H \rightarrow Za$, with $a \rightarrow ll$ or $\gamma\gamma$ could look like a π^0
- Leptogenesis also gives candidates e.g. in Z decay
- Detectors being optimised for this.

Long lived particles: suggestion

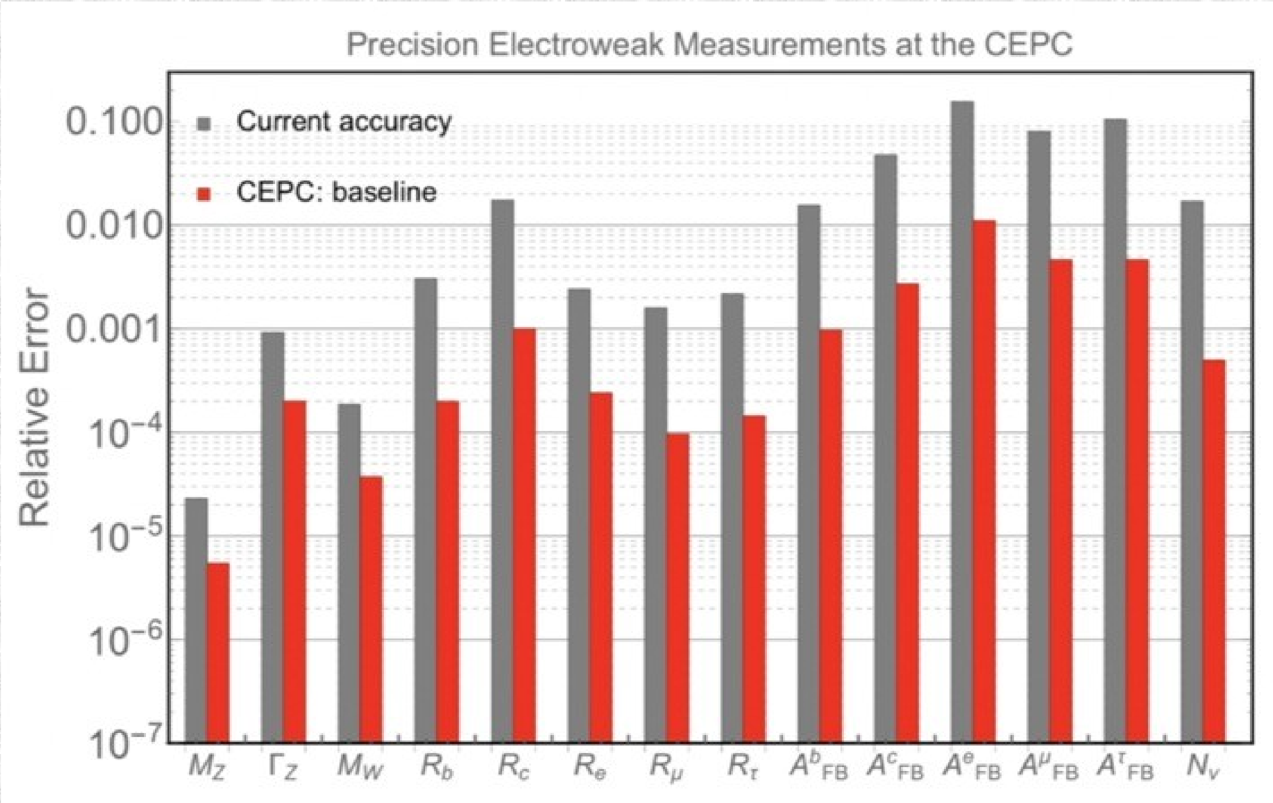
- One option is Methusla-like detectors 50m from IP
  - But the most probable decay length is always zero
  - Close to the IP means small (cheap?) detector
  - If the background can be kept low
- Could consider a single arm spectrometer?
  - Integrate extension into primary detector
  - Continuous sensitivity from IP to long range
  - Low background using inner tracking and calorimeter shielding
  - Possibly with extra shielding



Electroweak

Electroweak precision

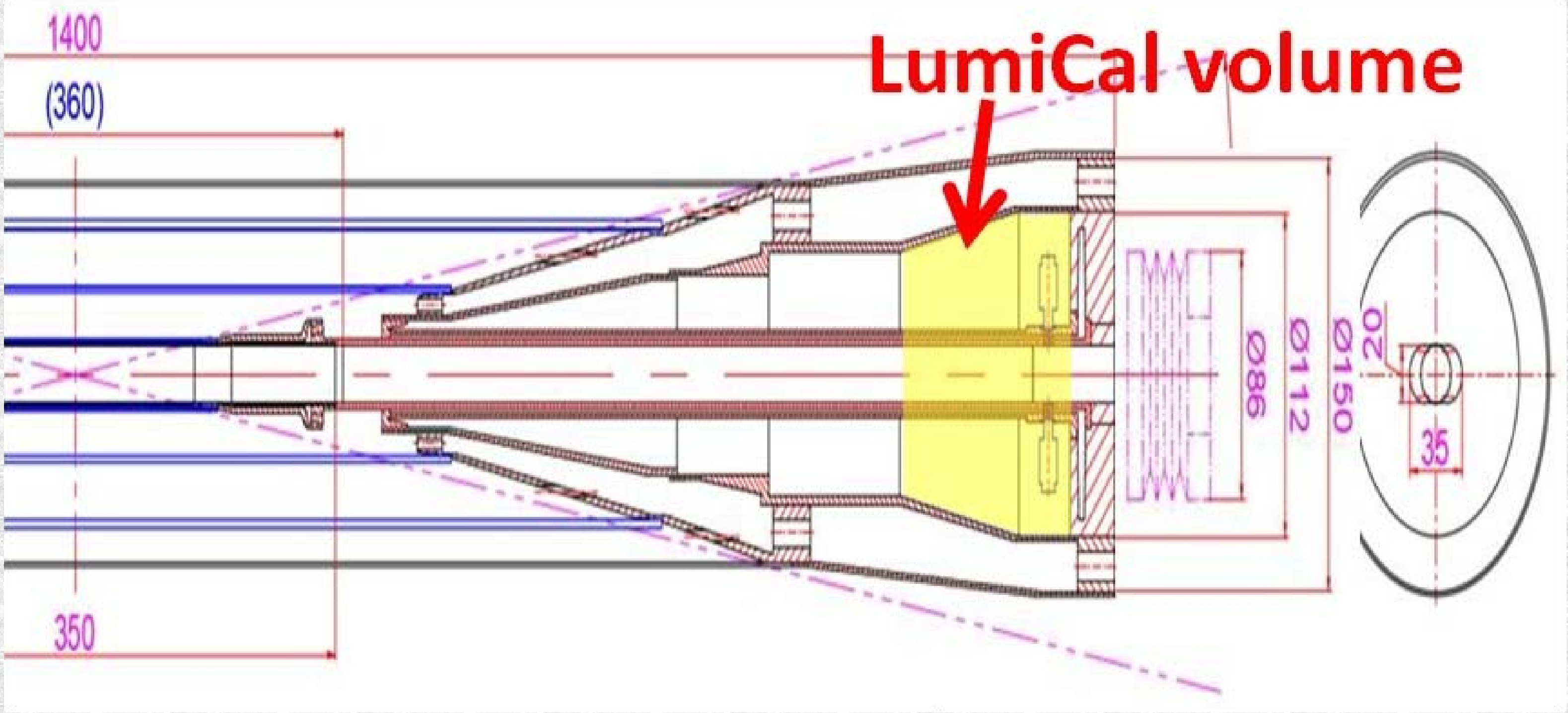
- CepC offers an order of magnitude over LEP in many key electroweak observables
  - Typically with systematics limiting



- Vital to keep this under active review
  - What limits precision: stat/expt. sys/external sys/theory
  - Much scope for ideas here.
    - e.g. What does transverse polarization really bring?

Luminosity

- Aiming for for 10^{-4} luminosity from ee→ee
  - QED: theory to << 0.1% ...needs improvement.
    - I have not stressed this, but in truth it applies everywhere



- Silicon detector planes define acceptance to ~μm
- Followed by 19Xo of LYSO complicated by bellows

Some personal Comments

- The CepC focuses on ZH much more than Fcc-ee
  - But there are calls for Fcc to prioritise it roo
  - The planning for these machines is converging
- Work on each machine acknowledges the other
  - Collaboration gives strength to all
- Ultimate exploitation of the giga-Z is all about control of systematics
  - Plan for multiple 1-year Z runs
    - With time to digest the data in between
  - One example: luminosity. We heard about 1 in 10^4 precision. But relative v absolute was not discussed (σ_Z v Γ_Z)

V_{cb} from WW run

- One of the fundamental parameters of SM
  - Just like m_H – and CKM clealry linked to Higgs
- Currently limited by discrepancy between V_{cb} from inclusive and exclusive B decays
  - With 2% errors
- Using ee→WW→lνcb allows direct measurement
  - Crucially dependent on flavour tagging performance
  - 20ab-1 @ 240 GeV gives 0.75/0.85% in eνcb / μνcb respectively
  - Efficiency controlled from Z data,
    - Backgrounds perhaps harder
  - Strongly dependent on charm tagging
    - Another motivation for excellent vertex detectors!

SMEFT sensitivity study

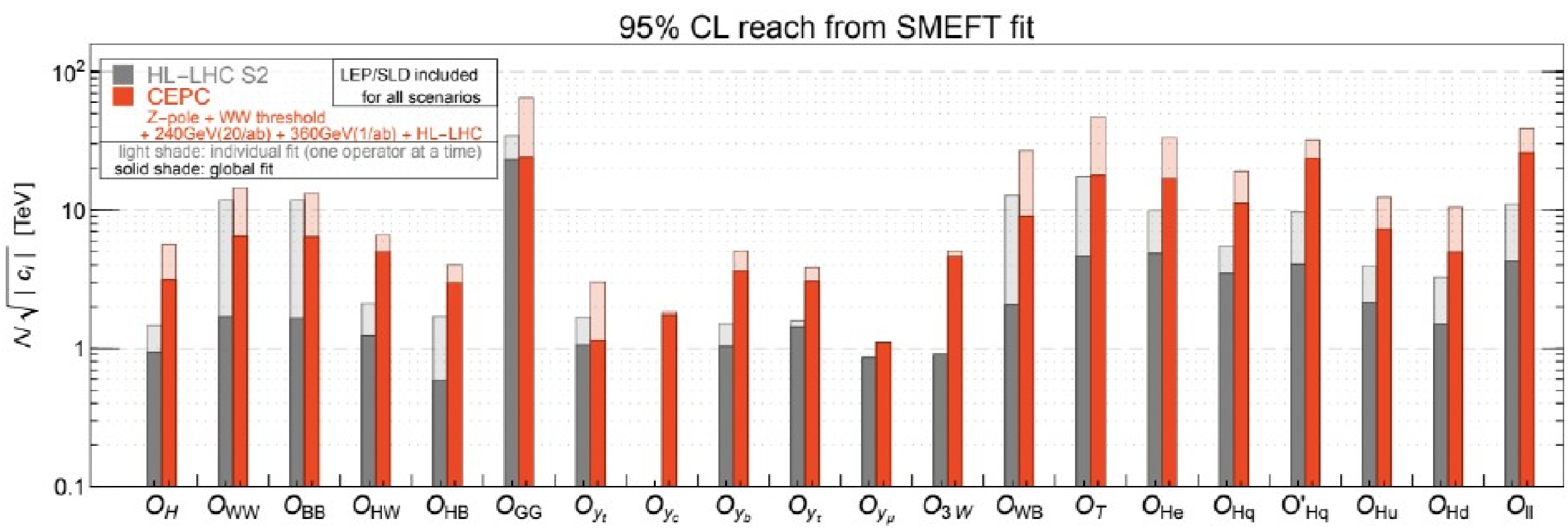
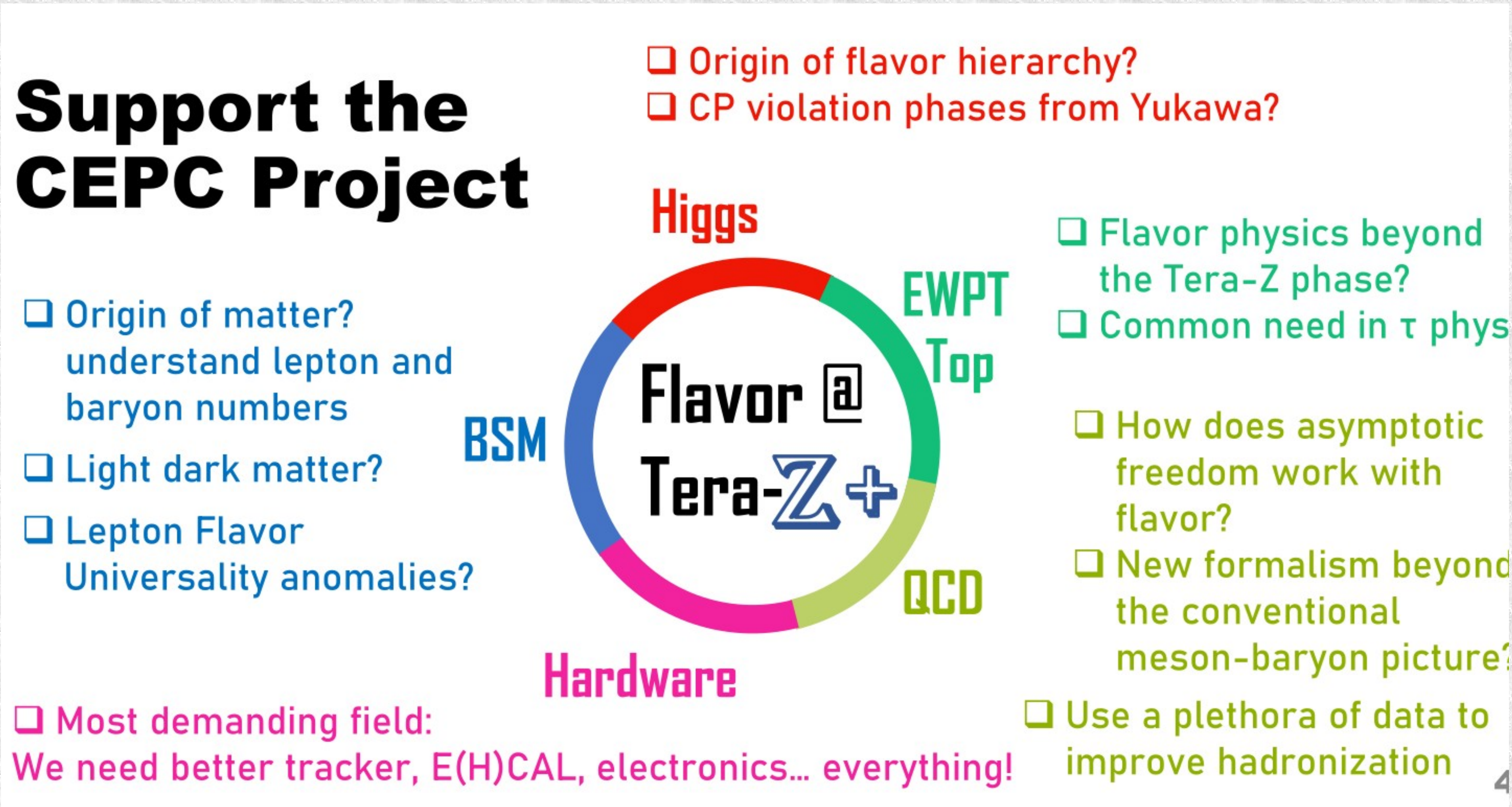


Figure 2.1: Covered energy scales of new physics from CPEC and HL-LHC, based on measurements of operators in the framework of the Standard Model Effective Field Theory (SMEFT). [1]

- 10 TeV physics can be probed in many operators
- SMEFT powerful tool for understanding importance of a measurement

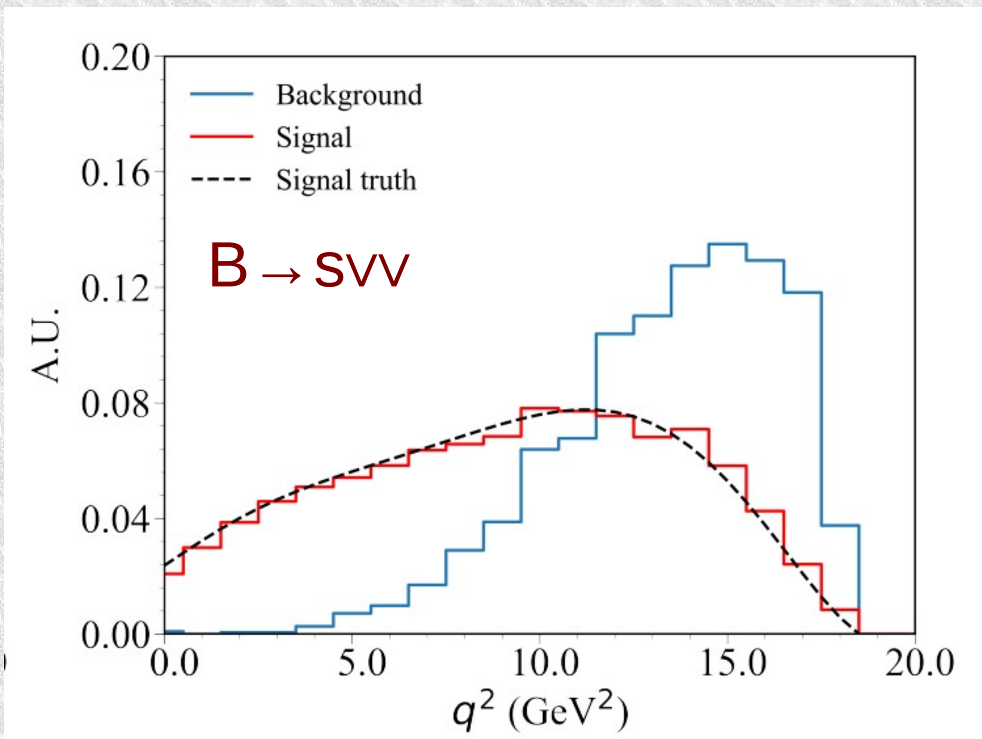
QCD, b, etc

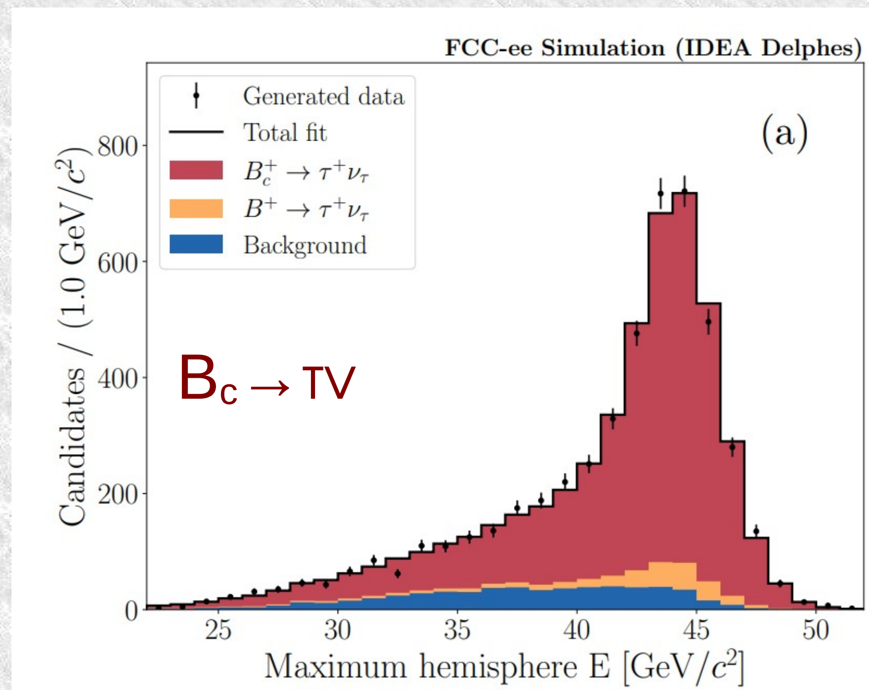
Flavour physics



B physics

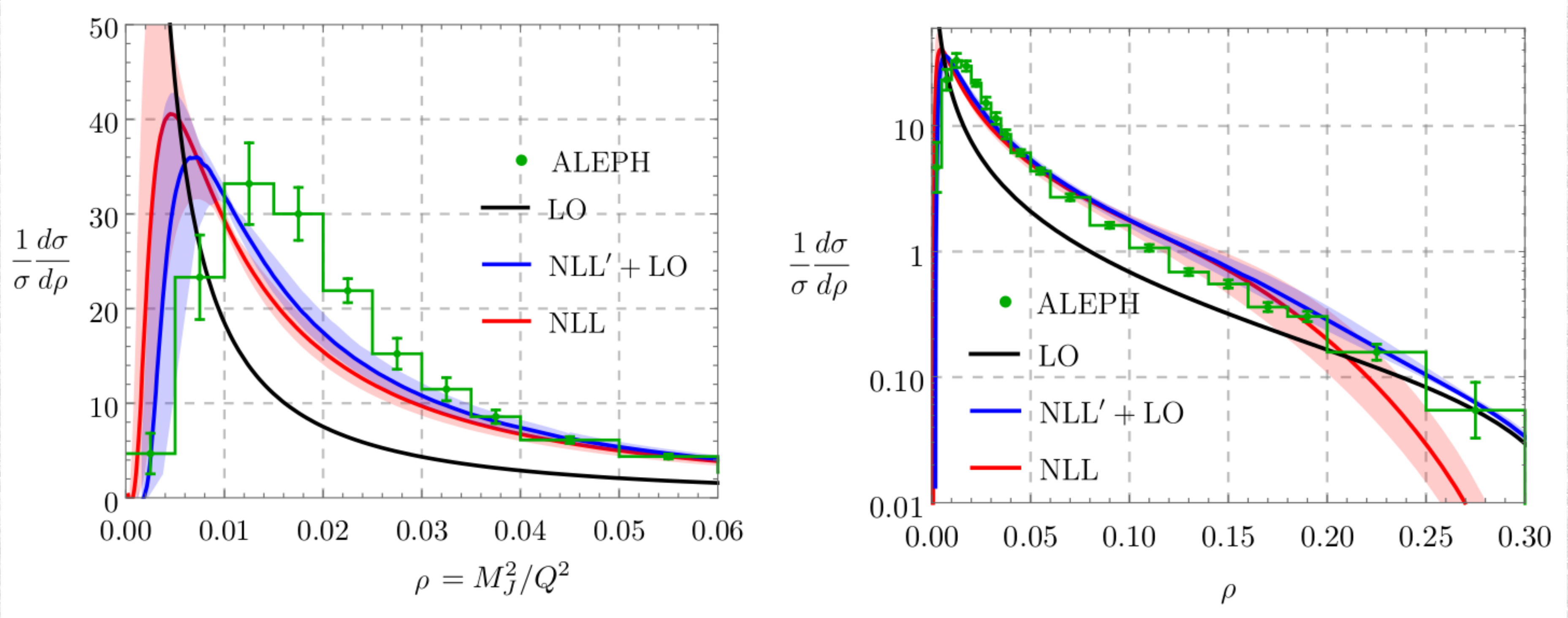
- Much work ongoing in B physics
  - But there is a lot more undone.
- At Z peak, larger yield of B_s, B_c, Λ_b than Belle-II
  - But the environment allows neutral (π^0 / ν) modes
    - More easily than LHCb





QCD studies

- Non-linear soft gluon evolution & Non-global logs resummation
  - Extending jet mass calculation beyond NLL
  - Important e.g. when separating quark states from hadronic boson decays

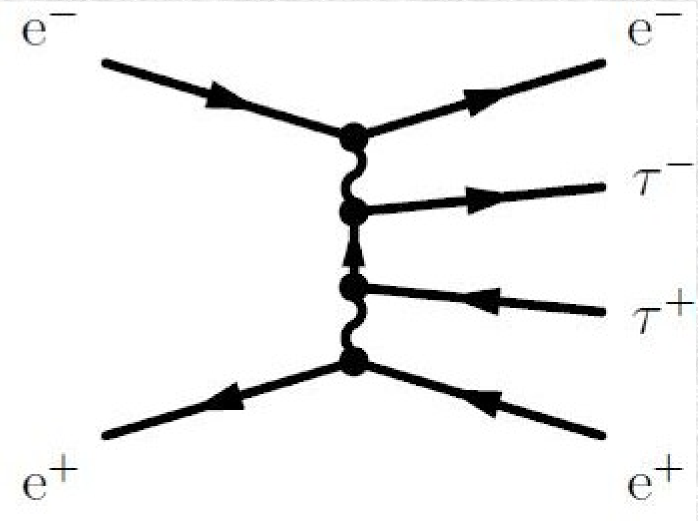


γγ physics and radiative return

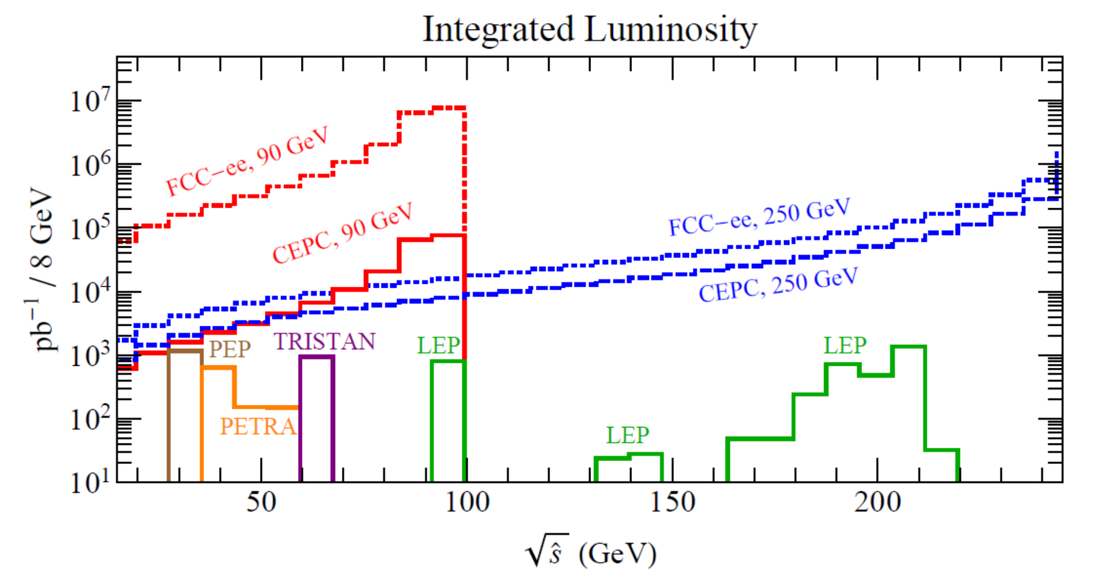
- Two photons:
  - dominate rate at 240 Gev
  - e.g. a_τ was measured best via

$\gamma\gamma \to \tau\tau$ at LEP

    - At 1% level
    - CepC can give major improvement



  - Photon structure function can also be studied
- Radiative return
  - Exceeding many previous colliders
  - Hadron spectroscopy
  - Unexplored thresholds
    - e.g. $B_c\bar{B}_c$
- Nb: This is forward...



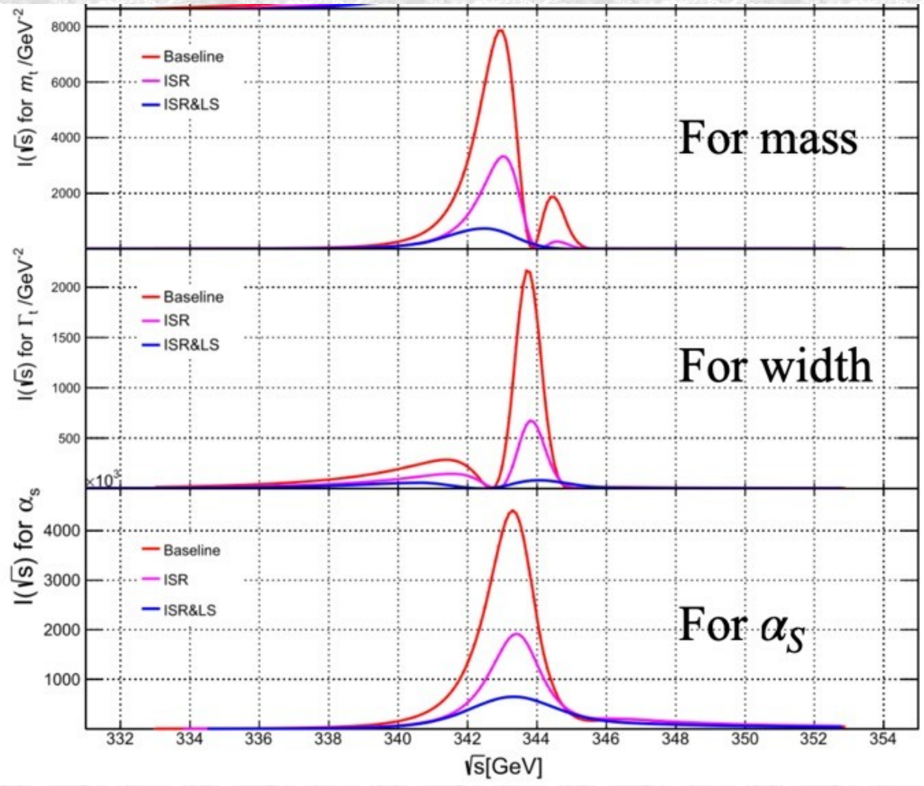
Top physics?

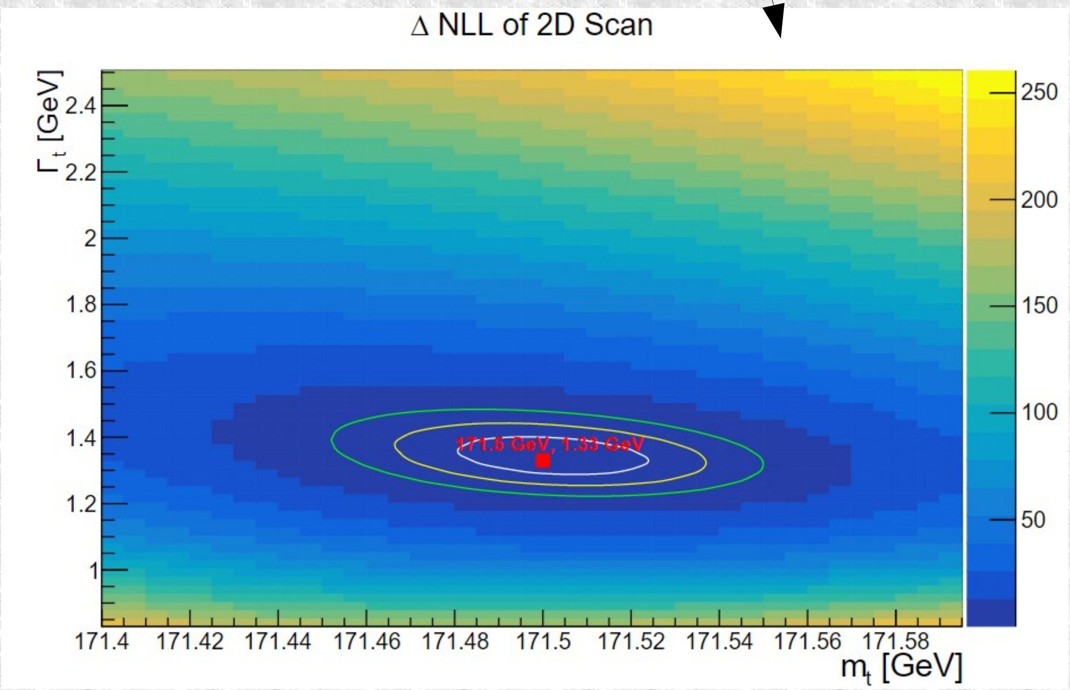
$t\bar{t}$ at CepC

- Precision measurement of Z, W and H is baseline
  - But m_t will limit precision of EW tests
- Adding $t\bar{t}$ run is coming closer to real axis
  - The 100km ring exceeds all other proposed
  - It makes sense – but would benefit from additional funding agency support
- Running at top threshold hugely sharpens the electroweak tests
  - And provides additional constraints..e.g. improving the Higgs width

Optimising the top run

- Sensitivity to $m_t/\Gamma_t/\alpha_s$ from σ at one energy – left
- Fit m_t/Γ_t at once: 21 MeV on mass, 57 on width.
  - Systematics will adds tens of MeV to each
- An orer of magnitude improvement

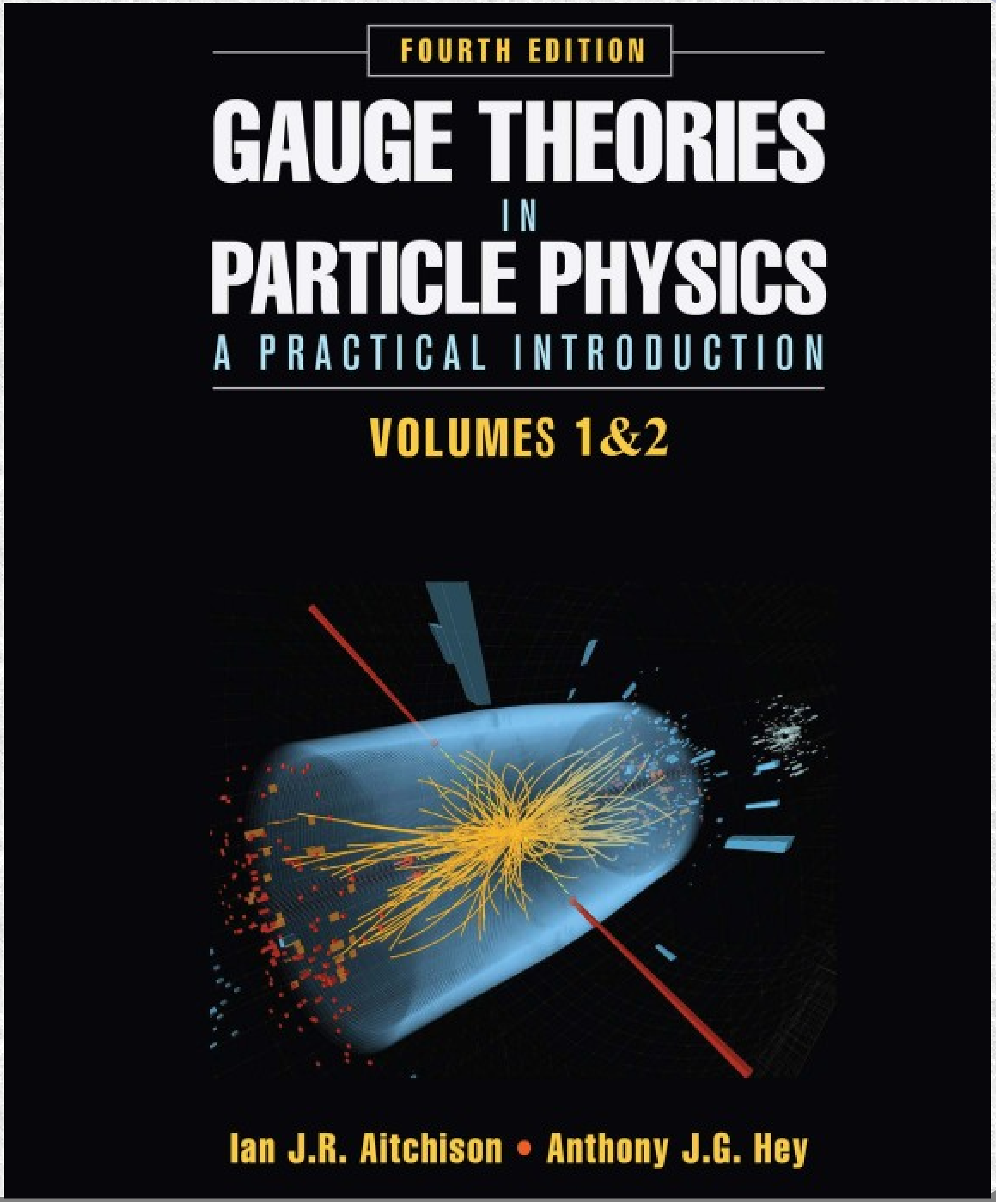




Conclusions

A personal word

- Our education has a lasting impression on us
- When I was an undergraduate, Ian Aitchison tried to teach me theoretical physics
  - Its not his fault I had to become an experimentalist
  - And he wrote a good book
- On the Higgs model he insisted: "It's too naive. The truth will be more complete"
- I don't know whether he was right
- But millennia of progress tell us we have to try to find out



Conclusions

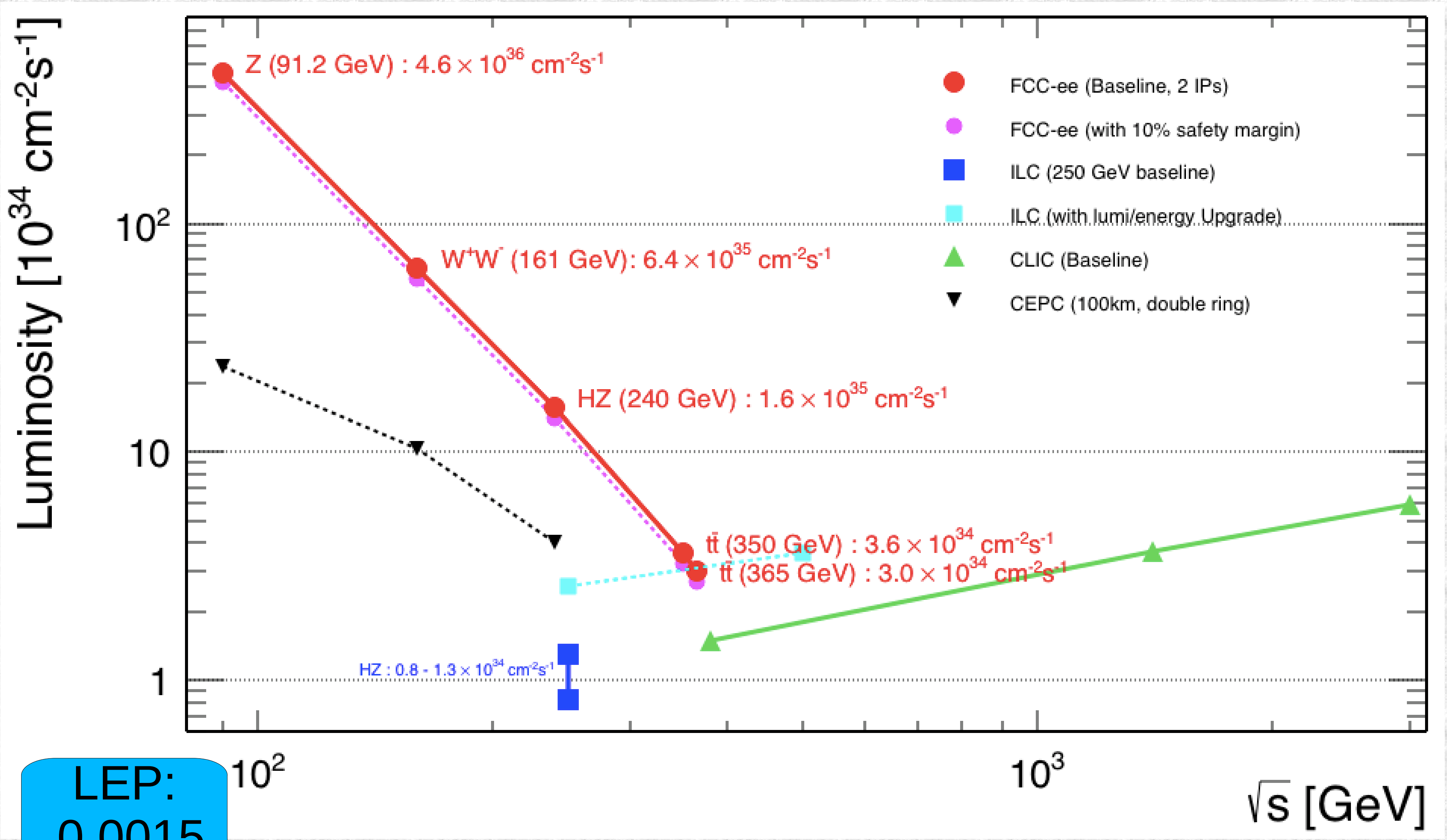
- The CepC can bring clean Higgs studies
  - in a timescale that people can grasp
- The strength of the physics programme is diversity:
  - Unprecedented H coupling to known particles
  - Out of this world Precision electroweak
  - Powerful QCD studies
  - Many Higgs/Z decays to dark sector
  - Flavour physics
  - Awesome feebly coupled particle sensitivity
- We need to change mindset.
  - Forget ‘Discover particle’ or ‘Confirm SM’
  - Theory needs experimental input. Measure the unknown. Whatever we find is new

Backup

A reminder of brehmstrahlung

- Electron synchrotron's energy is limited by brehmstralung losses
  - Proportional to E^4/r^2
- LEP at 103 GeV/beam had 18 MW of synchrotron radiation
  - It needed 3.6 GV acceleration,
- Double LEP's energy would have needed 288 MW
  - 57 GeV lost per turn for 206 GeV beams
    - Its approaching a linear accelerator
    - But without the tiny spot sizes
- But with 100km tunnel power is divided by 16

Luminosity v energy



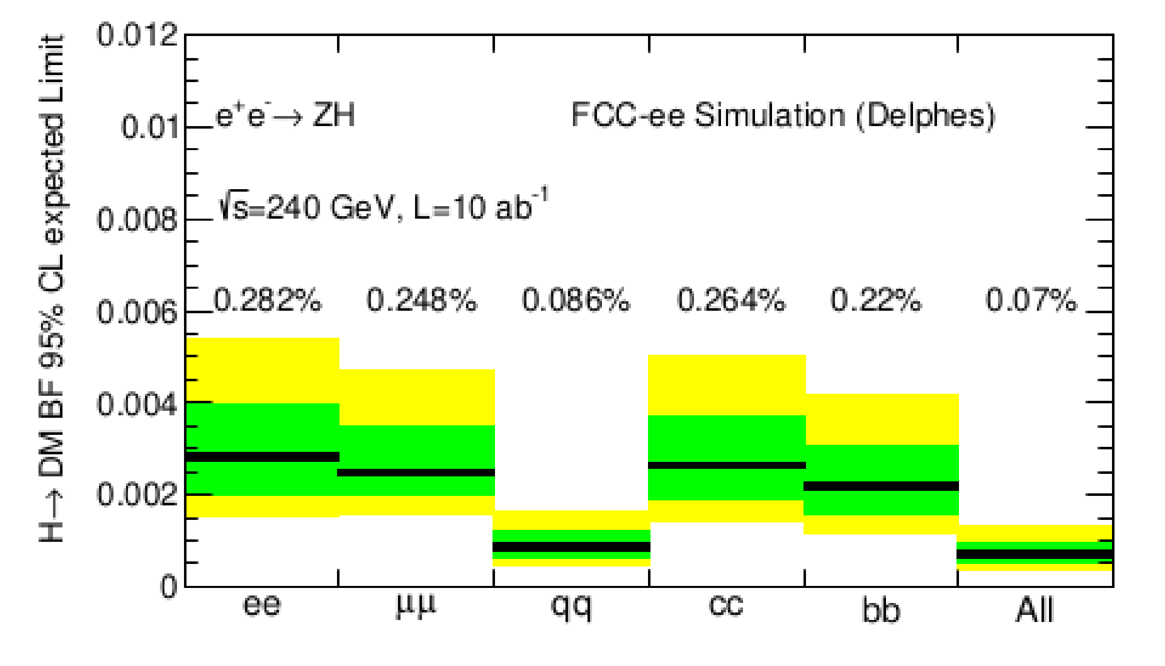
LEP: 0.0015

Fcc ee (CepC) parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390 (460)	147 (88)	29 (17)	5.4
no. bunches/beam	16640 (12000)	2000 (1524)	393 (242)	48
bunch intensity [10^{11}]	1.7 (0.8)	1.5 (1.2)	1.5 (1.5)	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15 (0.2)	0.2 (0.36)	0.3 (0.36)	1
vertical beta* [mm]	0.8 (1.5)	1 (1.5)	1 (1.5)	1.6
horiz. geometric emittance [nm]	0.27 (0.18)	0.28 (0.54)	0.63 (1.21)	1.46
vert. geom. emittance [pm]	1.0 (4)	1.7 (1.6)	1.3 (3.1)	2.9
bunch length with SR / BS [mm]	3.5 / 12.1 (2.4)	3.0 / 6.0 (3.0)	3.3 / 5.3 (2.7)	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230 (16/32)	28 (10)	8.5 (2.9)	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

Dark matter

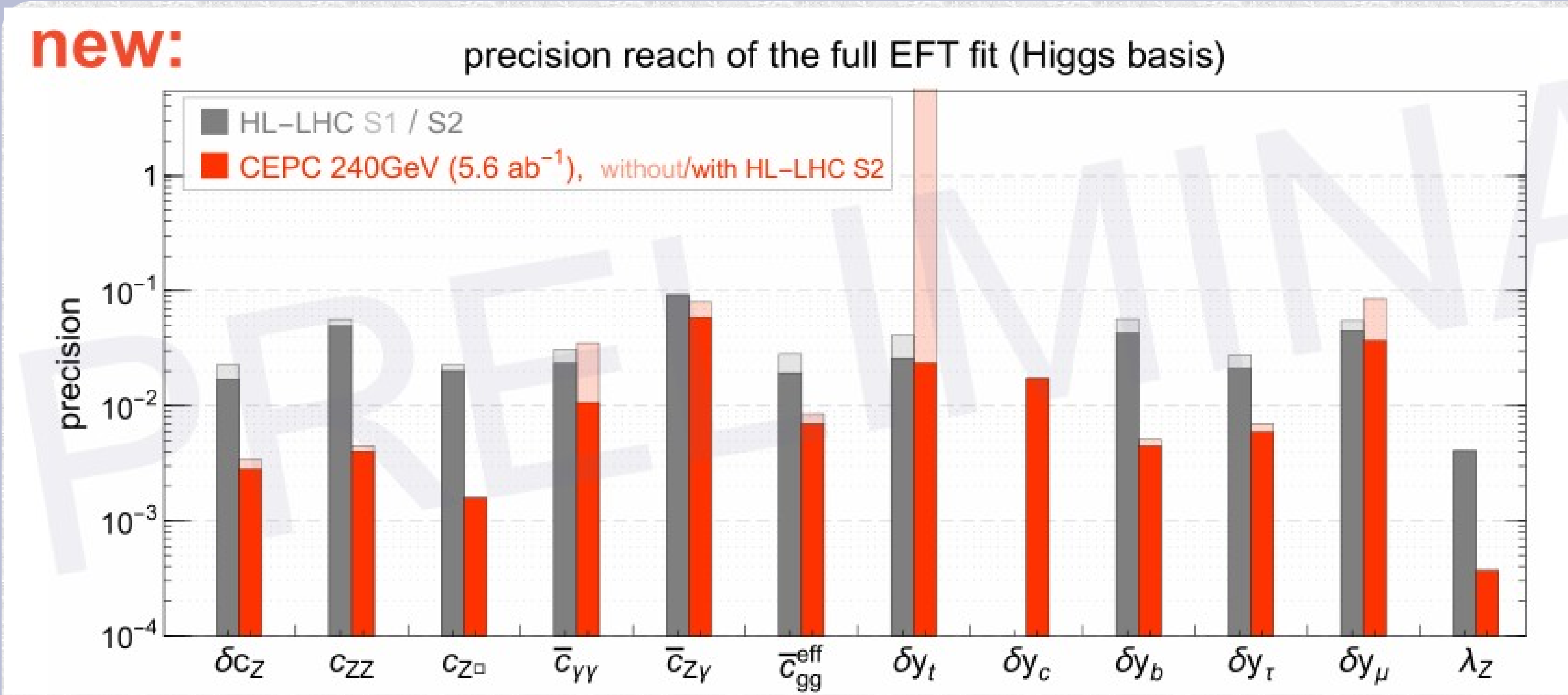
- The Z decay to $q\bar{q}$ clearly dominates
- Reducing the resolution tail on the



What drives detector specs?

- Lepton resolution for ZH$\rightarrow$llX requires excellent momentum
- $\pi^0 \rightarrow \gamma\gamma$ separation forces calorimeter granulairty
- Jet energy measurement to tens of GeV req

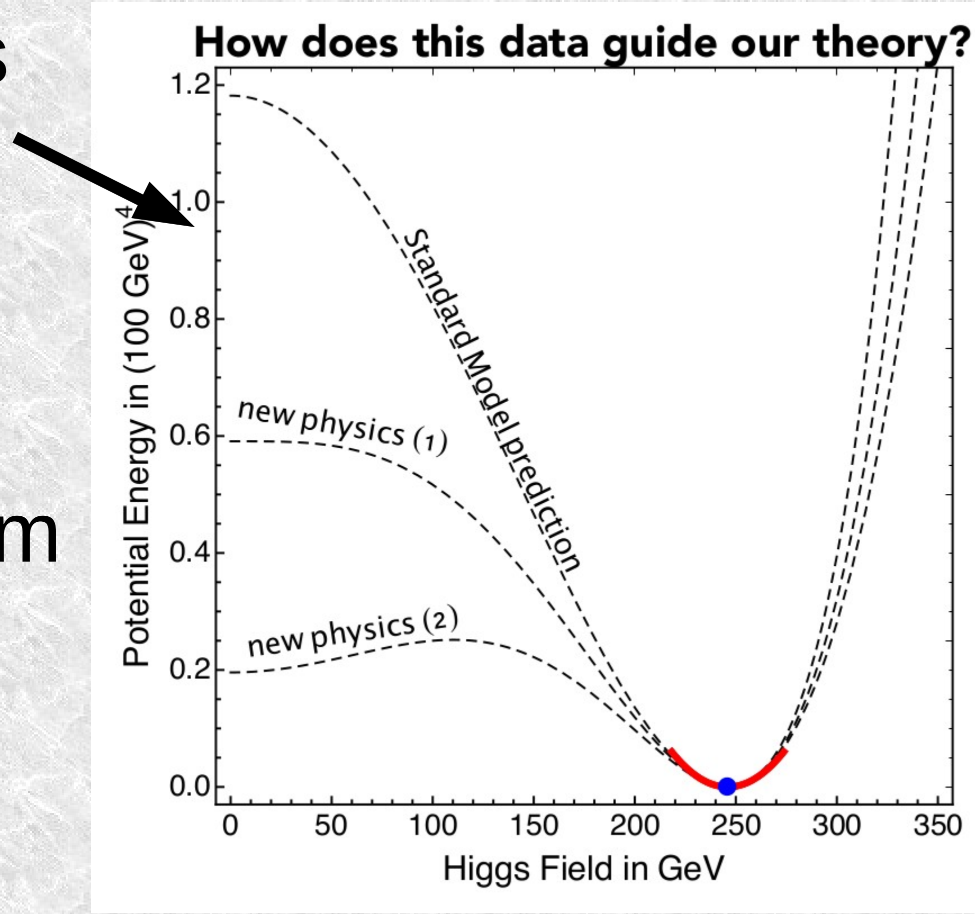
Higgs couplings precision



- Big gains expected
  - Especially on Z couplings & b/c interactions

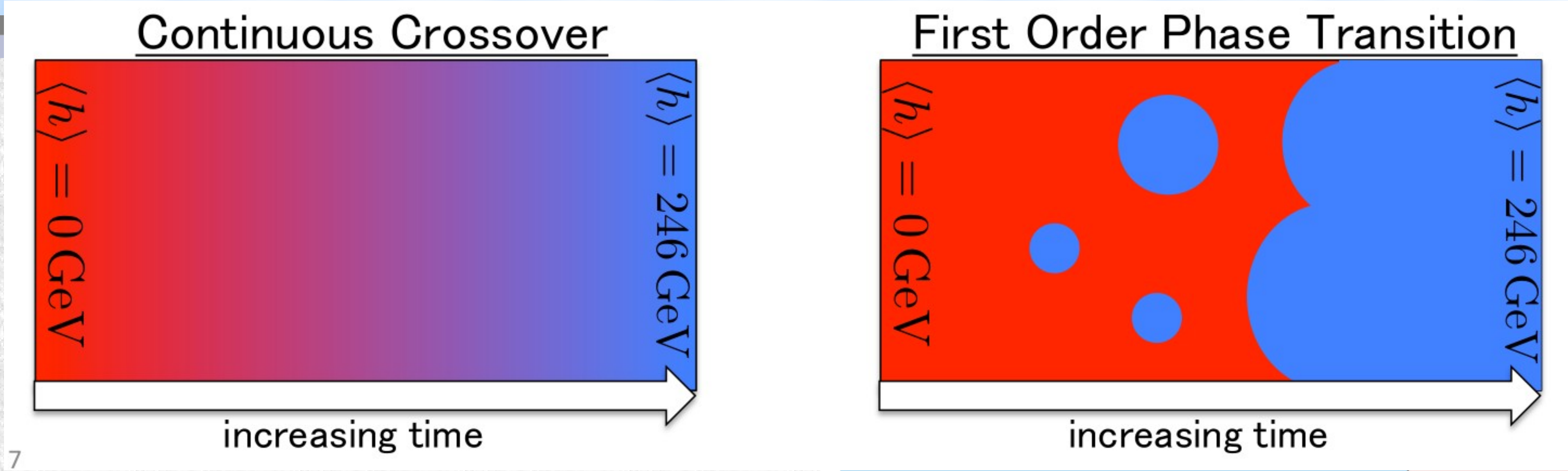
First order phase transition

- So far we probe the Higgs potential near 250GeV
- There could be a barrier between the origin and vacuum?
- If so the symmetric vacuum is meta-stable
- Universe does not smoothly evolve to the observed Higgs VeV
- But will start from local fluctuations which spread

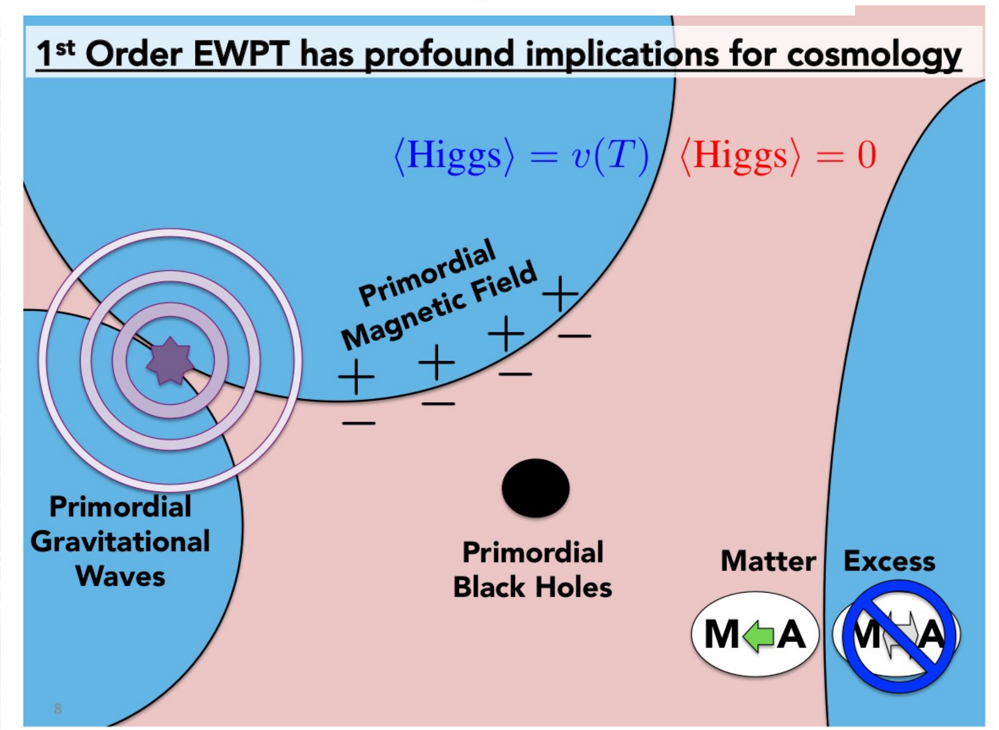


Long

Why do we care?

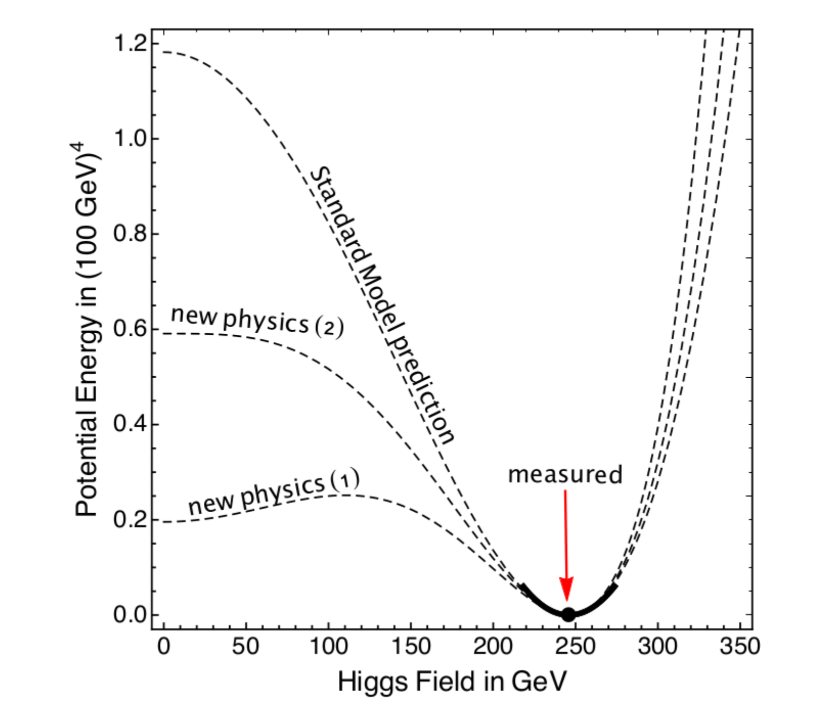


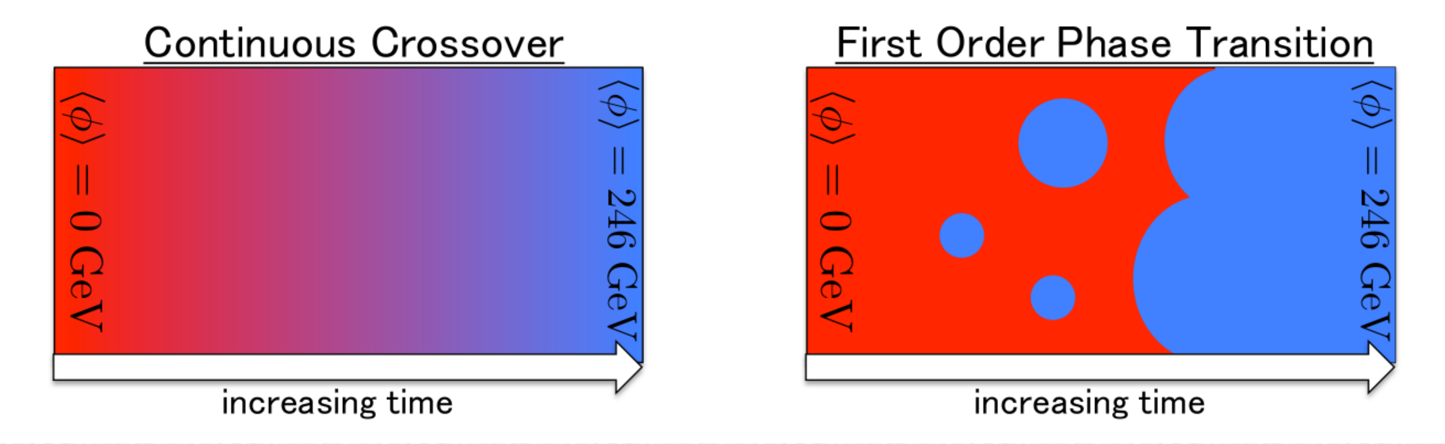
- The inhomogeneities associated could drive matter asymmetry,
- create gravitational waves
- Or seed primordial black holes



Higgs couplings and CPV

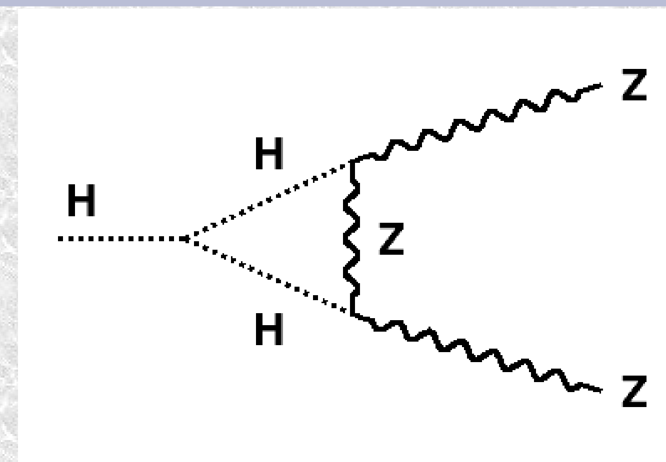
- The Higgs potential may not be simple $-m\varphi^2+\varphi^4$
- Add a singlet and you can deform the potential
- If the potential is metastable then phase transition is first order
  - Bubbles of expanding real vacuum
- This can yield matter domination!

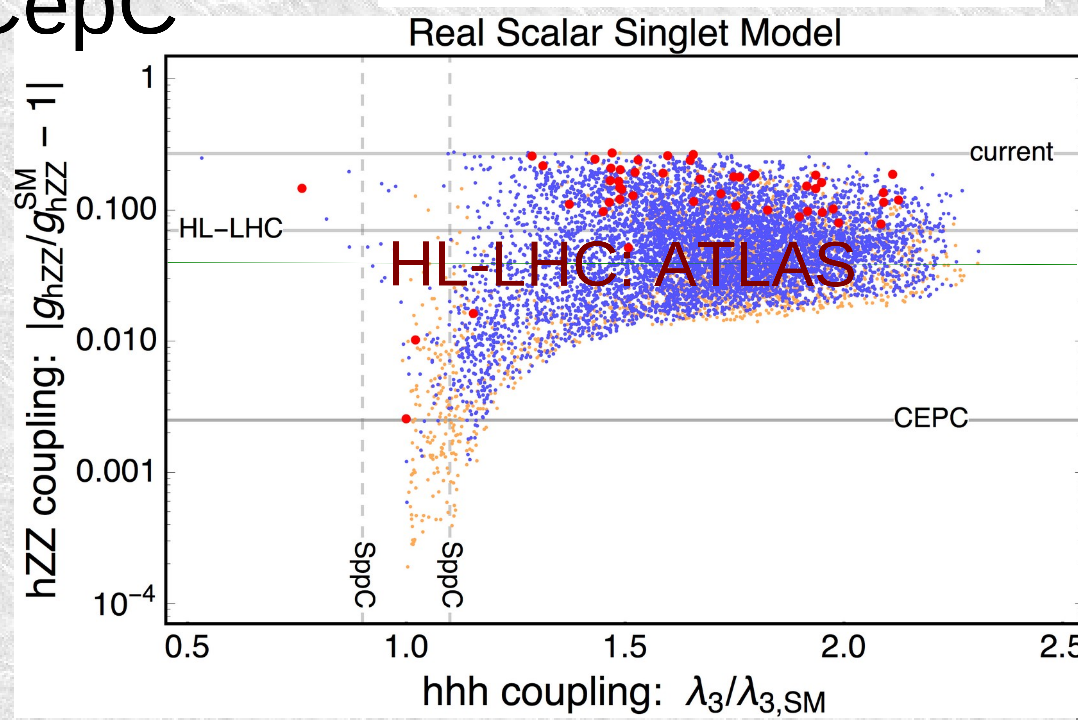




What do couplings teach?

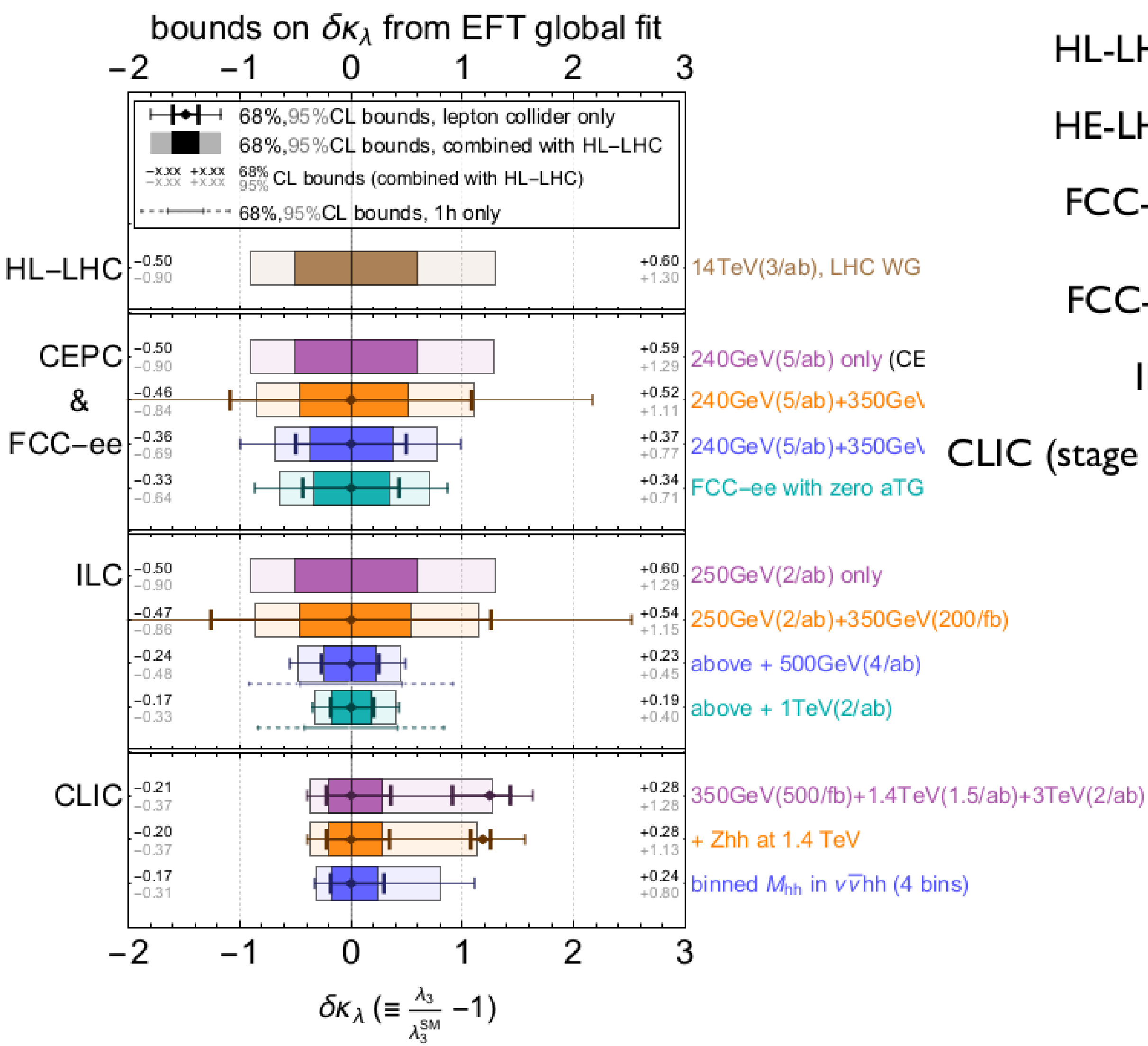
- Vertex corrections mix HHH and ZZH couplings real vacuum
- Large distortions to the triple coupling will shown up in g_{hZZ}
- Bottom right plot (from CepC CDR) shows much of parameter space accessible
- HL-LHC may find hints to origin of Universe

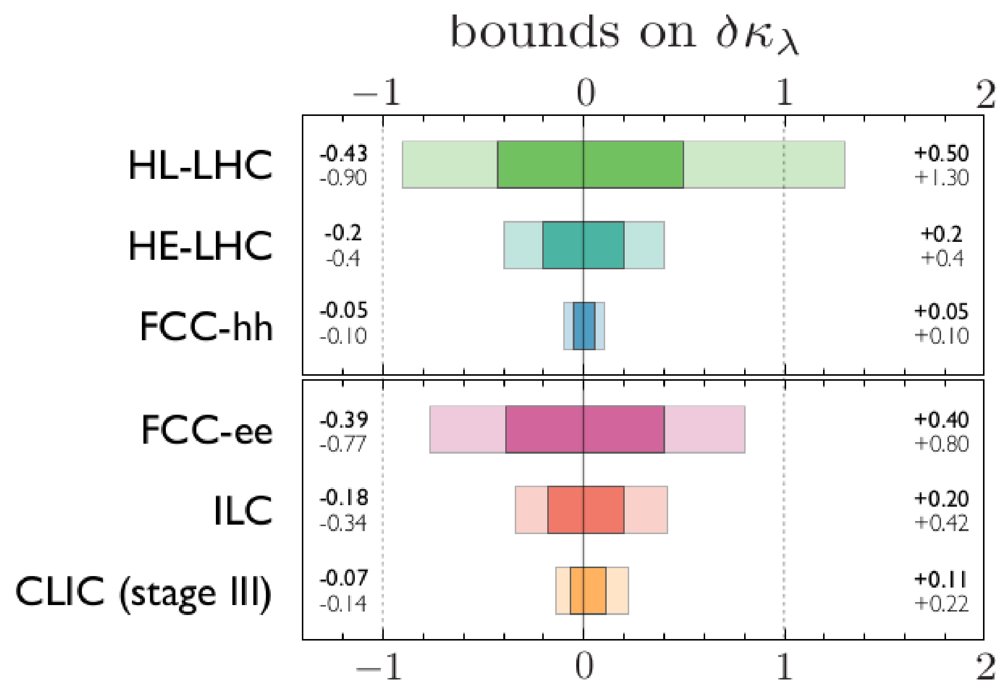




h^3 prospects

DiVita et al, arXiv: 1711.03978
(updated with latest HL-LHC) projections





Dark: 68%CL, Light: 95%CL

ee colliders
will establish at 95%CL that the Higgs self-coupling exists
ILC will establish it at 5σ
FCC-hh will probe the quantum corrections of the Higgs potential

B physics at CepC

Beauty hadrons @CEPC

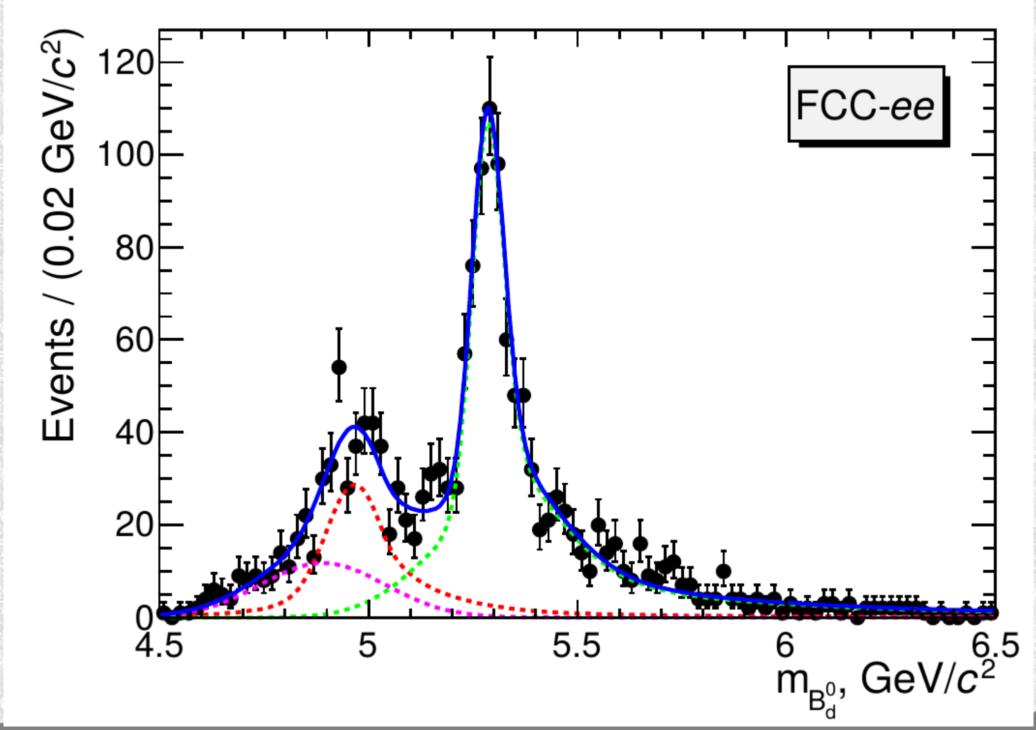
	CEPC (10^{12} Z)	Belle II (50 ab^{-1} @$\Upsilon(4S)$ & 5 fb^{-1} @$\Upsilon(5S)$)	LHCb (50 fb^{-1})
$B^{\pm}/B^0$	6×10^{10}	3×10^{10}	3×10^{13}
B_s	2×10^{10}	3×10^{8}	8×10^{12}
B_c	10^{8}	-	6×10^{10}
b baryons	10^{10}	-	10^{13}

- Yields match or exceed Belle
  - Though well below LHCb
- But:
  - B's are produced back to back, unlike LHCb
  - With predictable momenta, unlike LHCb

B hadrons

Altmannshofer & Charles

- Tau decay modes should be accessible at CepC?
  - $Bs \rightarrow \tau\tau$ or $B \rightarrow K\tau\tau$
  - The B flavor anomalies make this very interesting
  - $B \rightarrow K\tau\tau$ with 3-prong tau decays allows 4 vertex positions and thus full mass reconstruction
    - O(100) events seen with CepC?
    - DD background in LHCb
  - Belle-II/LHCb fail here?
- B to $K\nu\nu$ CepC can look for MET+K – promising
- $B_c \rightarrow \tau\nu$ also promising



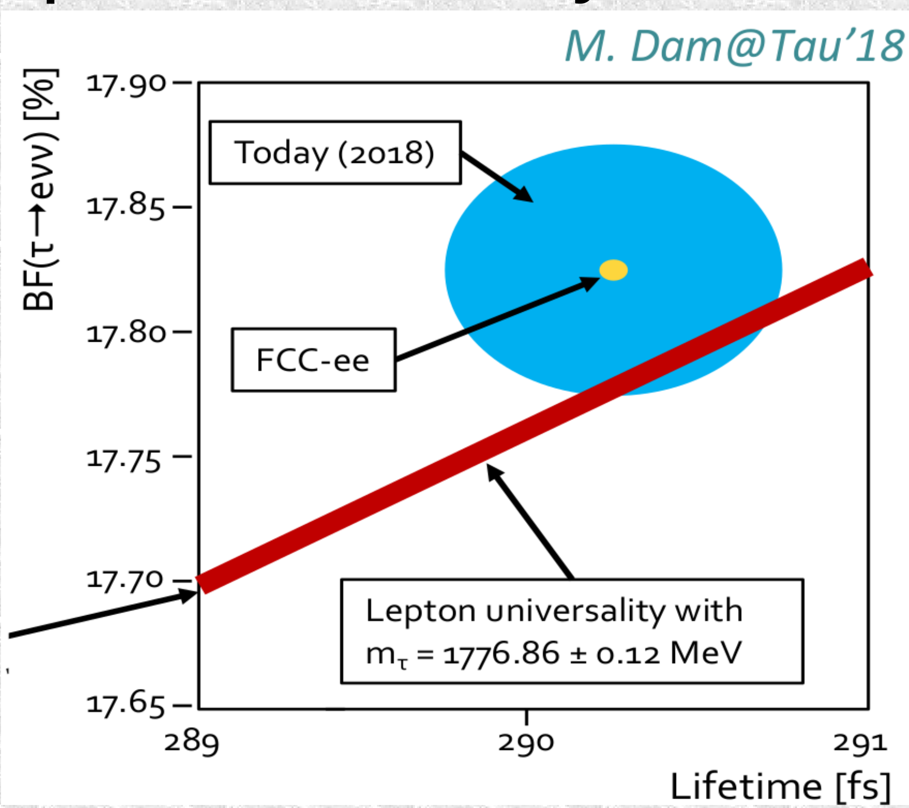
Rare Z decays

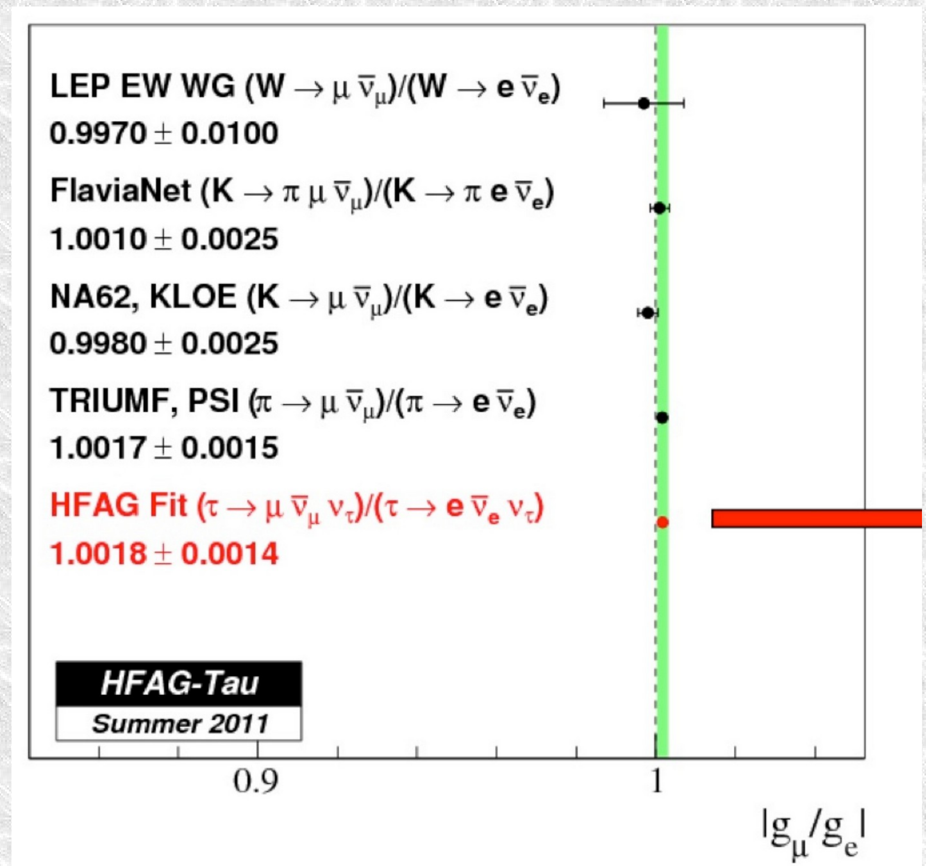
- $Z \to \mu e$, $e\tau$ or $\mu\tau$
  - Sensitivity should be 2 orders of magnitude better than HL-LHC
  - There are constraints from $\mu \to e\gamma$, $\mu \to 3e$ etc
    - Strongly constraining for μe case
    - But not so for decays with taus
- Lepton universality in Z decay
  - ee:μμ:ττ
  - 3 per mille constraints from LEP
  - These are important constraints on the B flavour anomalies
  - CepC will have to understand e/μ/τ efficiencies well
    - Question to experimentalists: What can be achieved here?

Tau working group

Passemar

- In several areas LEP results still dominate
  - Large B-factory tau yields but poor efficiency
- With 10^6 more tau CepC has a rich tau program
- μ/e universality is one key





QCD studies

- α_s measurement
- Non-linear soft gluon evolution & Non-global logs resummation
- Hadronization models & Monte-Carlo tuning
- Fragmentation function
- Interplay with Higgs & Electroweak physics
- Charmonium physics
- Top quark physics

Dreaming of top

- Fcc-ee (& ILC, CLIC) plan top threshold scan
- m_t errors:
  - 20-30 MeV statistical
  - 25-50 MeV systematic
  - 40MeV theoretical
- Autoscan – radiative return
  - 100 MeV stat
  - 100 MeV theoretical
- Top polarization is a sensitive measurement too
- CepC does not have energy reach….or does it?