Physics Landscape for (at) Future Colliders

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Disclaimers

1. Mandate from the organisers was to not have another talk about Higgs physics. I tried indeed another approach (and probably will fail at).
   - Starting from what we know and how we know it
   - Discussing the experimental landscape at horizon 2040
2. Good to know from where people are speaking. I'm committed to FCCee since 2014.
3. We are orphan of the {Higgs or BSM} no-loose theorem. This talk aims at discussing elements to build the next theorem.

Outline

1. The free parameters of the Standard Model (SM)
2. The two pillars of the SM and the case for next machine.
3. Within the section 2, I'll discuss physics cases for the next machine (including Flavour program).
4. Conclusion: a desirable physics programme.

1. The SM seen from its free parameters

The free parameters of the SM:

- $SU(2)_L \otimes U(1)_Y$ unification:
  - the weak and electromagnetic coupling constants G_F / g_W and α_{EM}.
- After the spontaneous breaking of the symmetry:
  - The nine masses of the fermions: m_f.
  - The masses of the electroweak gauge bosons: m_Z and m_W.
  - The scalar sector parameters: $$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

  v (the v.e.v) and m_H .

1. The SM seen from its free parameters

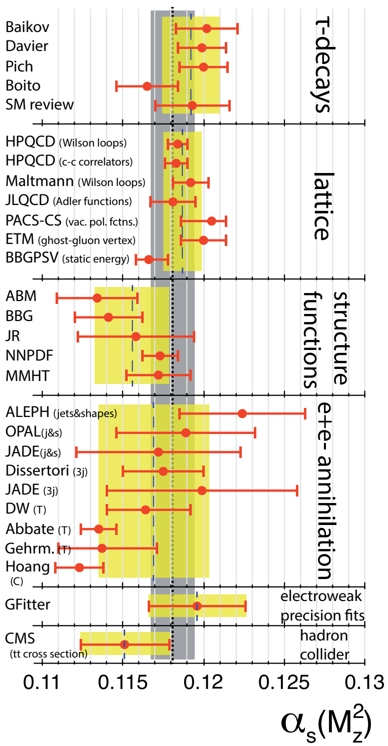
The free parameters of the SM

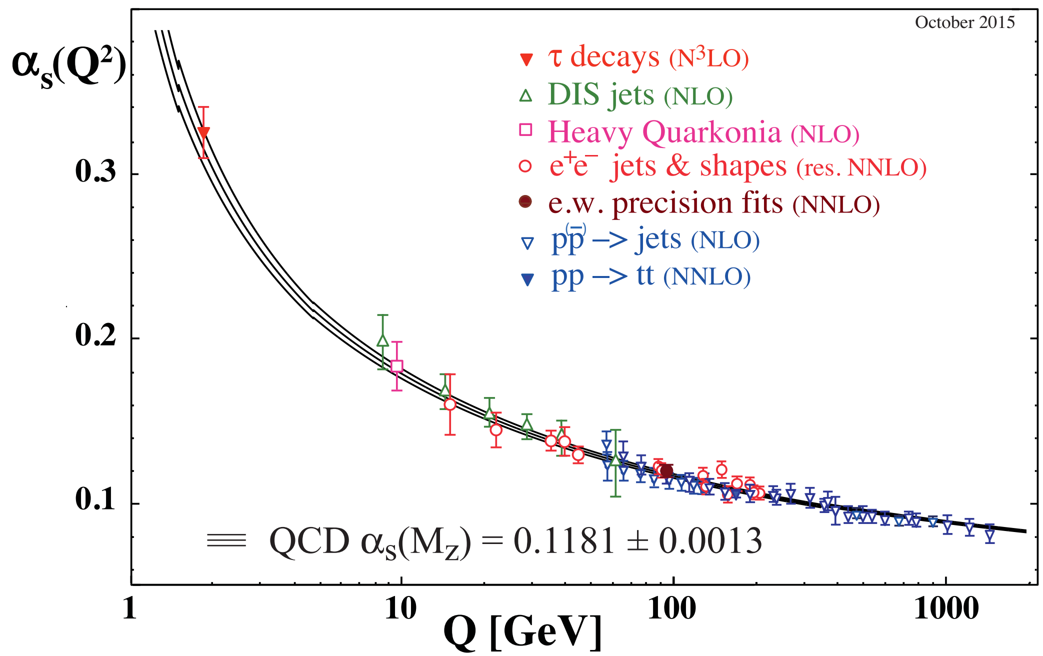
- The CKM matrix elements : it's a 3X3 complex and unitary matrix and hence can be described by means of only **4 independent parameters**. As the masses of the fermions (except for the top quark), these 4 parameters are decoupled from the rest of the theory. A consistency test of these parameters is in order.
- If you'd like like QCD in (and you should), just add $\alpha_{\mathbf{s}}$ (and $\theta^{S}{}_{CP}$).
- Neutrino oscillations are implying neutrinos to be massive and to mix → 7 parameters to minimally describe them.
- The number of parameters amounts to 20 (28 w/ neutrinos and strong *CP*). Not all of them are independent though.

1. The SM seen from its free parameters

Reorganisation:

- QCD and α_s : LEP, LHC and others did great already. Limitation of the consistency test is not yet fully on the theory side for most of the determinations.

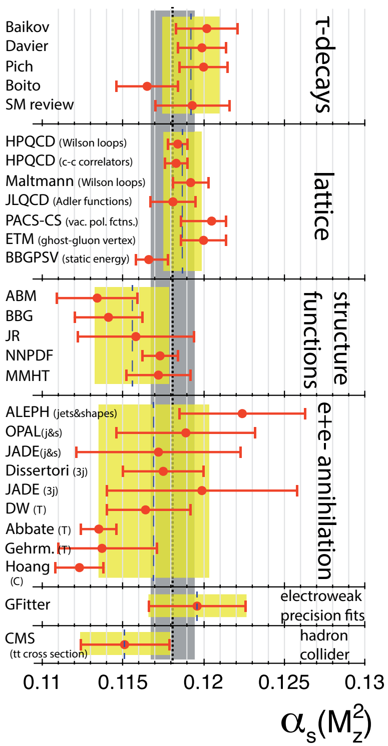


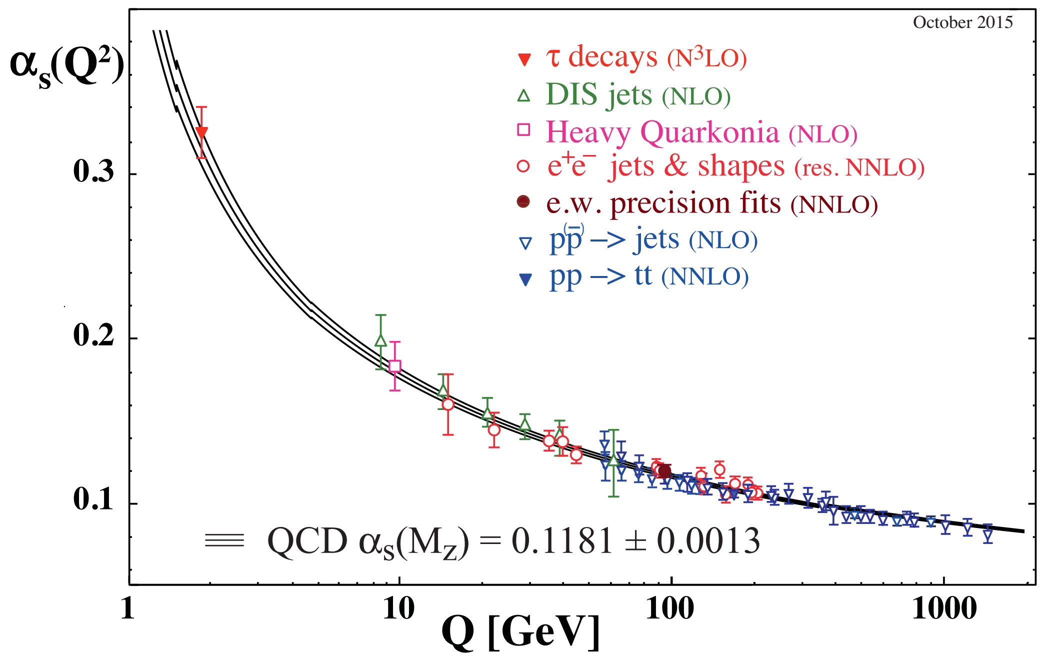


1. The SM seen from its free parameters

Reorganisation:

- QCD IS the theory of strong interactions. Beyond that provocative statement, improved determination of α_S, LQCD (getting mature in its predictions as well) tests and developments are desirable. Tau lepton physics and Z pole are keys to advance.

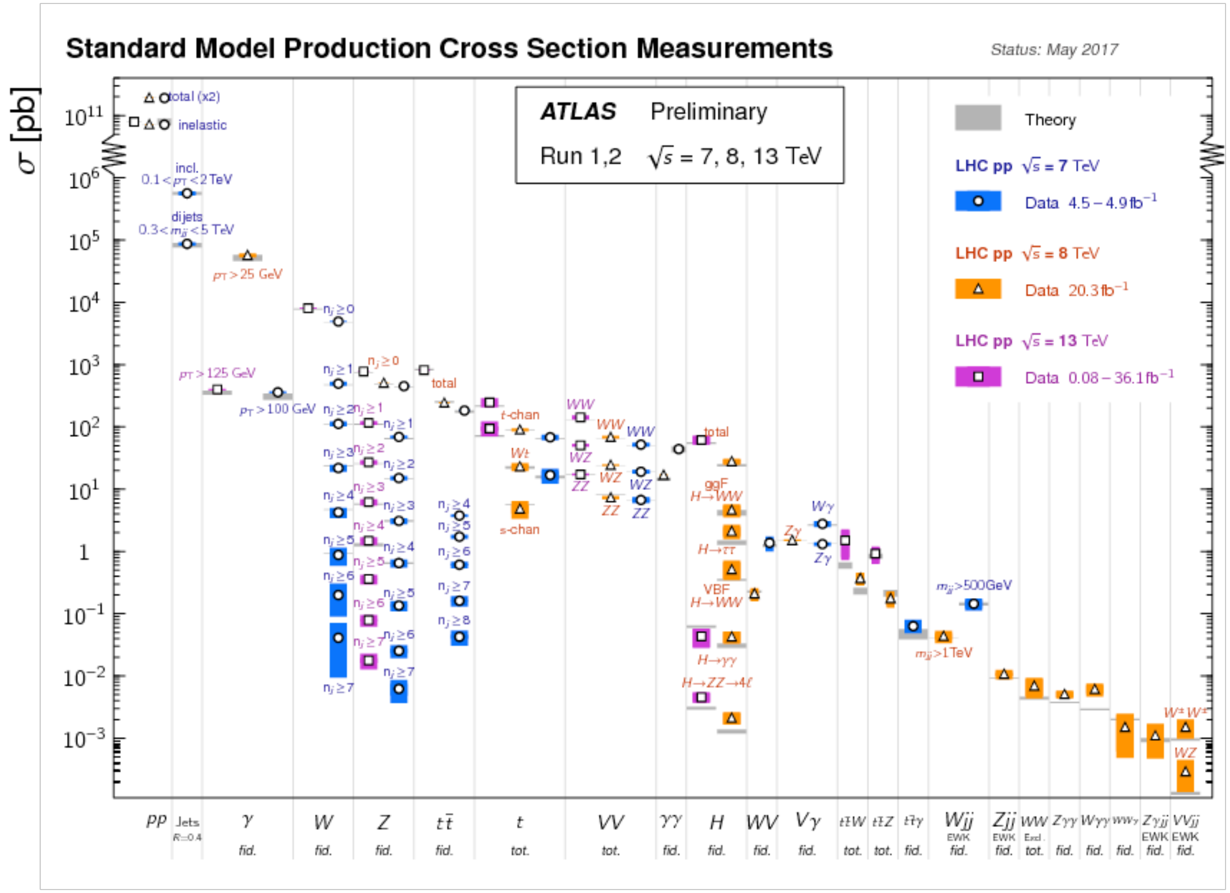




1. The SM seen from its free parameters

Reorganisation:

- This figure is often advocated as a tremendous success of the SM predictions over impressive order of magnitude. This is a QCD success at first.



1. The SM seen from its free parameters

Reorganisation:

- The nine masses of the fermions: m_f.
- They are for 8 of them decoupled from the rest of the SM parameters.
- One of the Flavour problems and there's nothing much to do here as well till the moment a theory comes with a prediction.
- They are however captured in the Yukawa couplings. We'll come back there.
- The top deserves a special mention.

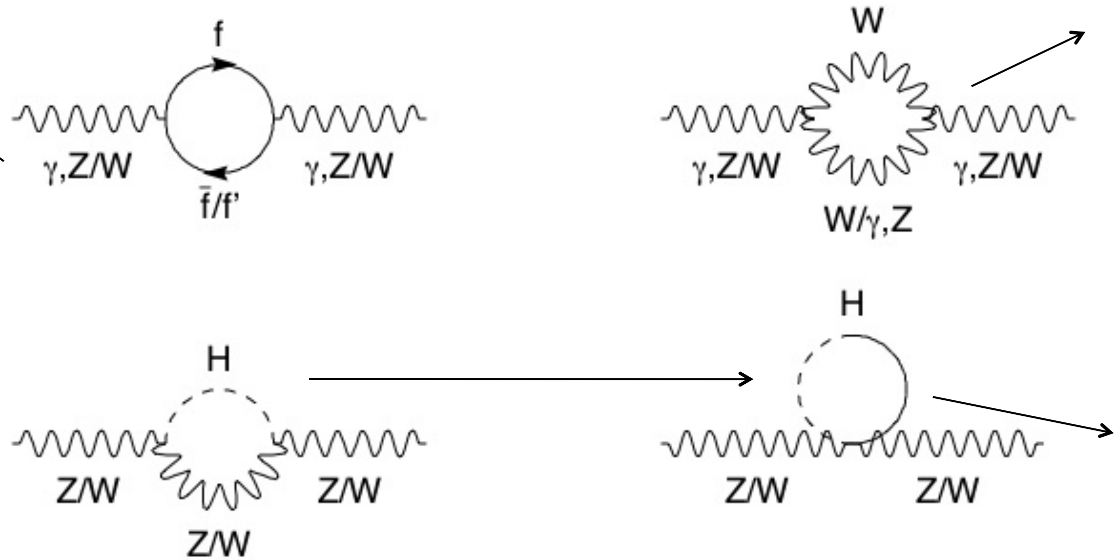
1. The SM seen from its free parameters

Reorganisation: the specific status of the top quark.

- The top quark has a specific status because it enters dominantly in the radiative corrections of the intermediate bosons mass propagators (in particular), *e.g.*

Top dominates. Mostly sensitive to m^2_t

Non abelian structure of the EW theory. TGC.



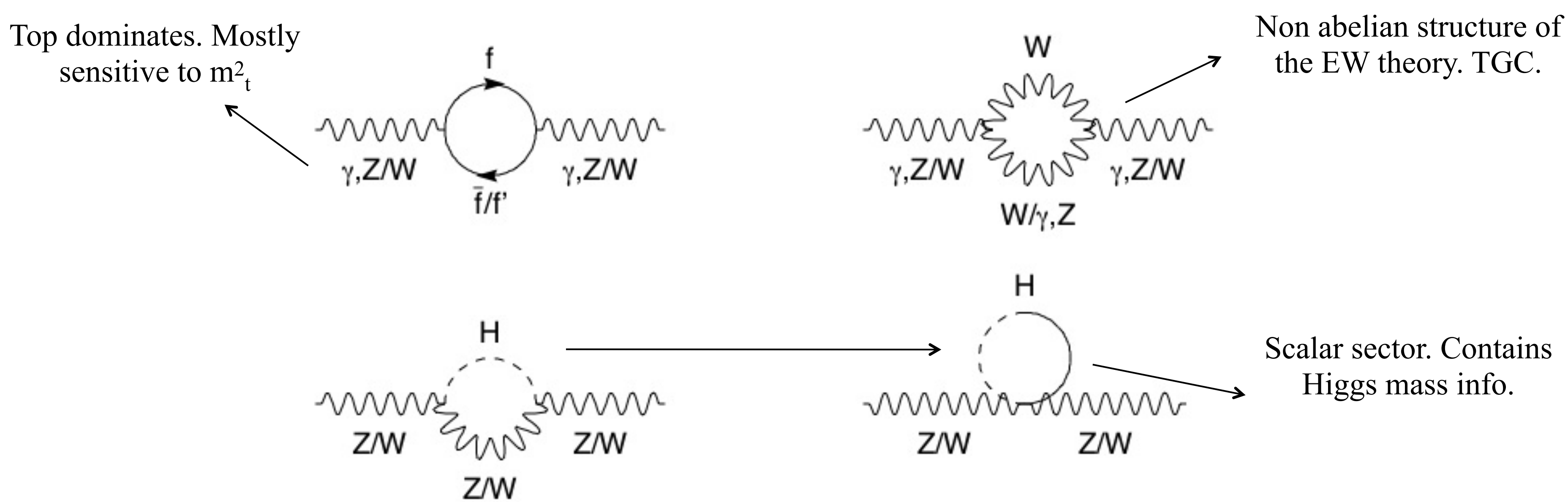
Scalar sector. Contains Higgs mass info ($\ln m_H$) !

- In turn, a prediction of the top quark mass in the SM is possible in the consistency fit of the SM hypothesis against the electroweak precision observables (gauge boson masses, widthes, electroweak couplings…)

1. The SM seen from its free parameters

Reorganisation: the specific status of the top quark.

- The top quark has a specific status because it enters dominantly in the radiative corrections of the intermediate bosons mass propagators (in particular), *e.g.*

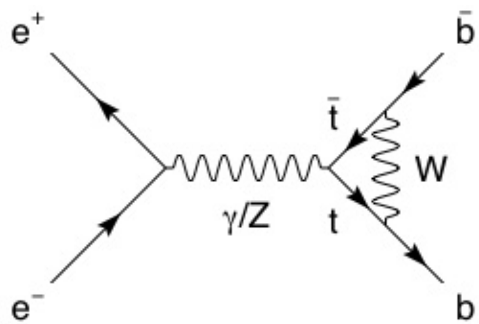


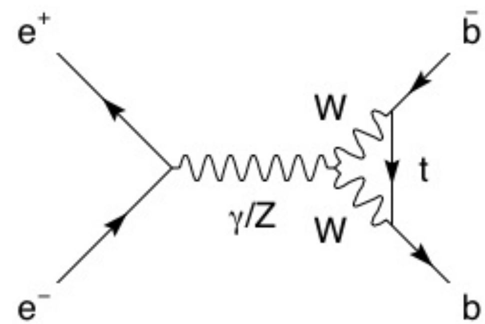
- *When the guys weighing 200 pounds are saying certain things, those of 100 pounds are listening (Michel Audiard, french screenplay writer).*
-

1. The SM became a theory

Reorganisation: the specific status of the top quark.

- On top of the (universal) propagator corrections, one finds vertex corrections



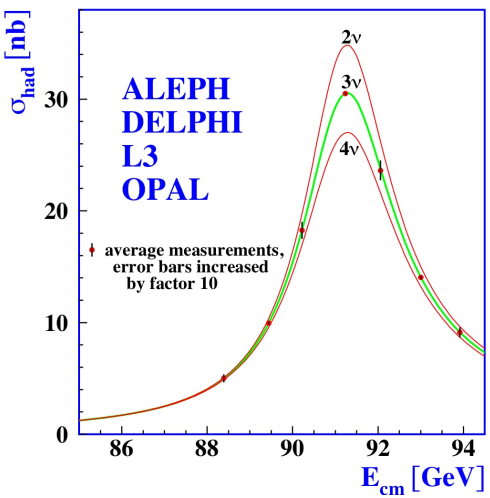


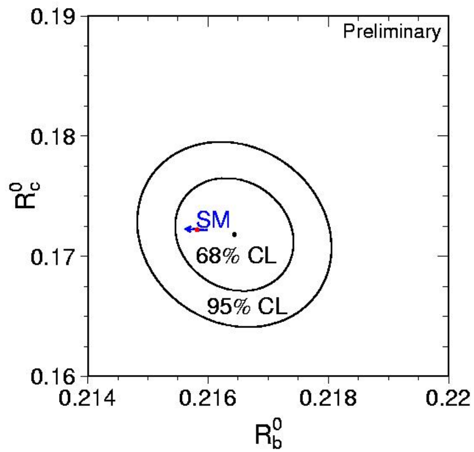
- In SM, these corrections are proportional to the CKM matrix elements V_{tq}.
- Hierarchy (within the SM): $|V_{tb}| \approx 1 \gg |V_{ts}| \approx 0.04 \gg |V_{td}| \approx 0.008$
- Vertex corrections are only relevant for *b* quarks: $\Delta\kappa_b = \frac{G_F m_t^2}{4\sqrt{2}\pi^2} + \ldots$
- A unique observable of interest there: $R_b = \mathrm{P}(Z \rightarrow bb) \,/\, \mathrm{P}(Z \rightarrow qq)$

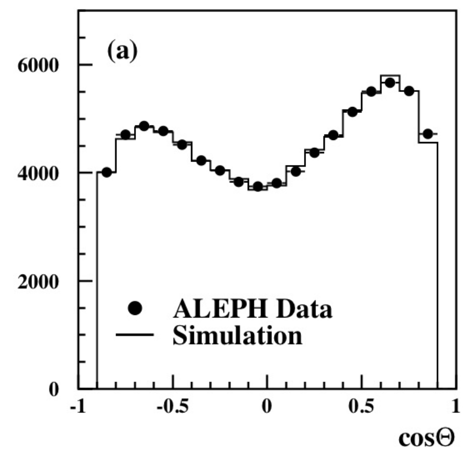
2. The two pillars of the SM: first pillar

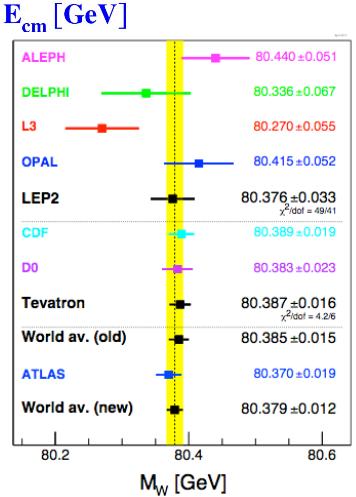
Reorganisation: the main observables

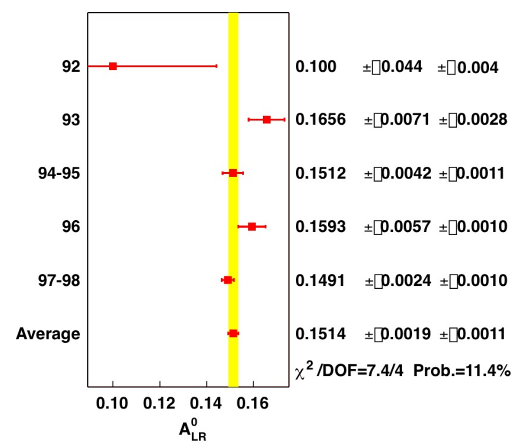
- Measurements at the *Z* pole and m_W : (universal) propagator corr.







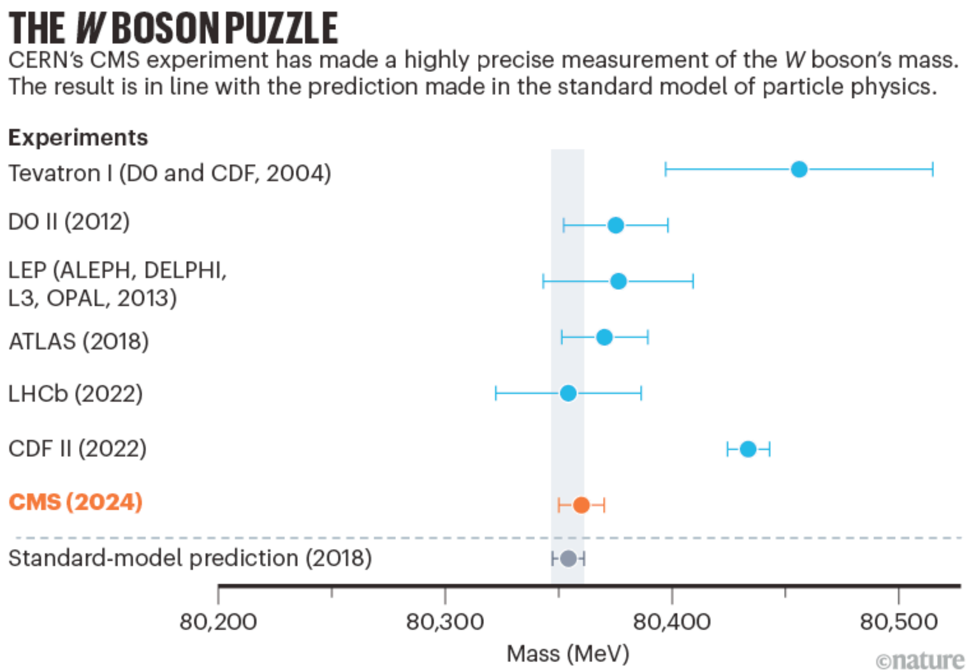


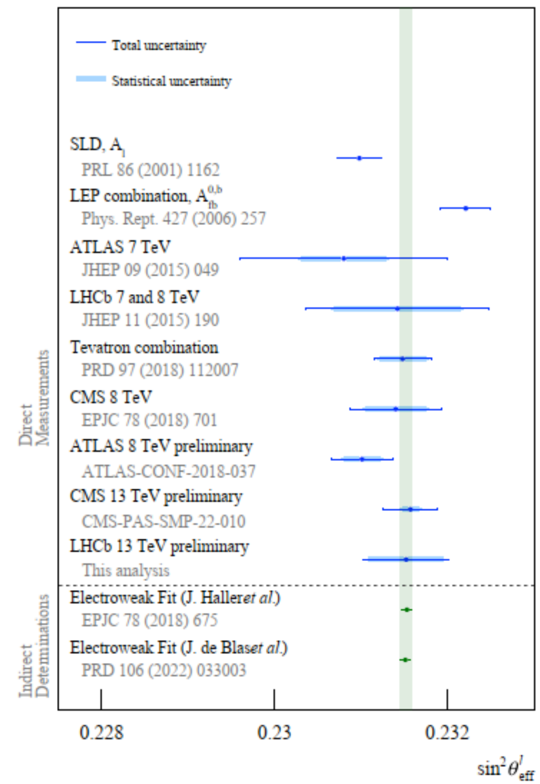


2. The two pillars of the SM: first pillar

Reorganisation: the main observables

- The Tevatron and LHC contributions (universal) propagator corr.



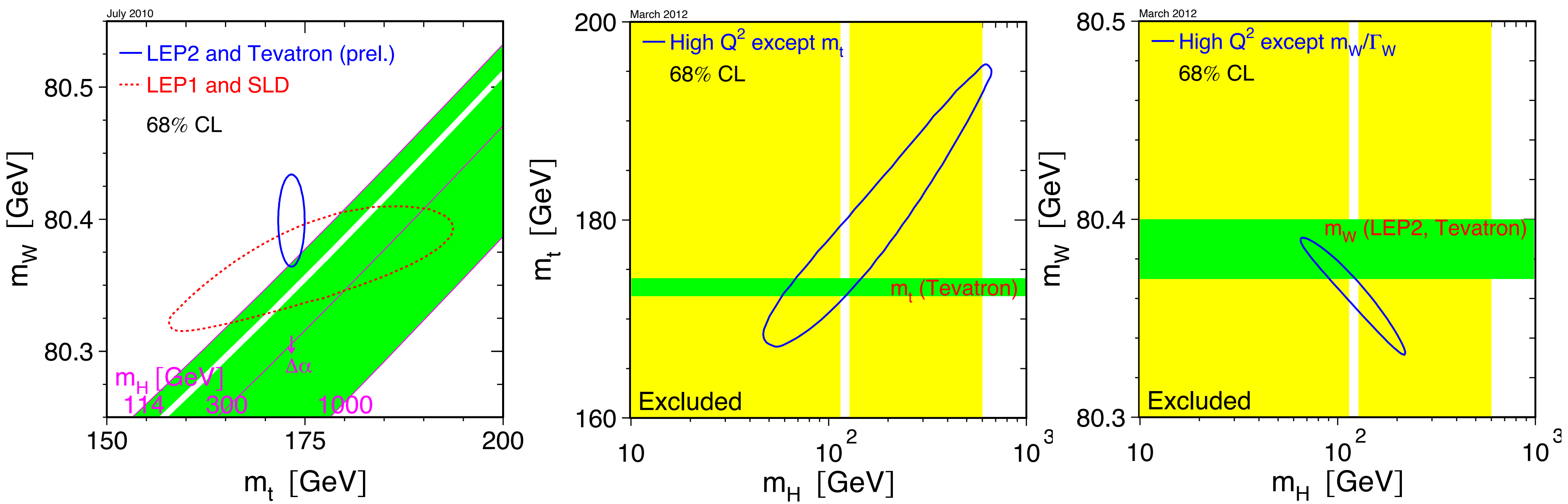


- Challenging the SLC / LEP precisions but syst. dominated

2. The two pillars of the SM: first pillar

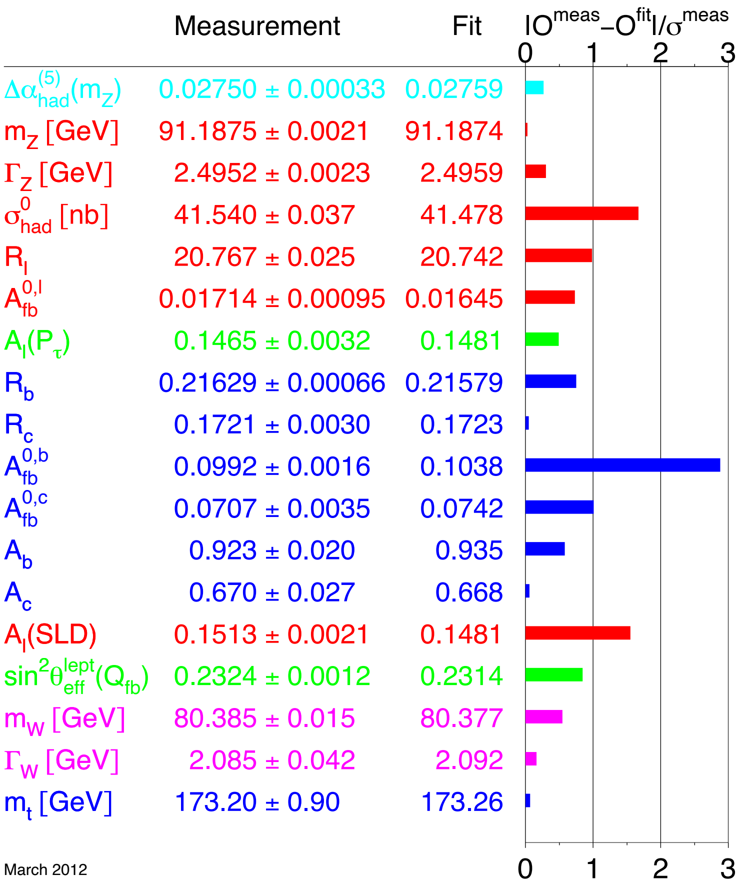
The global EWPO fit :

- Six free parameters are therefore part of the so-called electroweak precision observables consistency check. This is the first pillar of the SM. Fix G_F , α_{EM} and m_Z at their measured value and produce a prediction of m_{top} , m_W and m_H. A tremendous success !



2. The two pillars of the SM: first pillar

Spelling out the predictions.



- The SM EW global fit has a remarkable χ^2_{min}/d.o.f = 1.40 (p-value=15%).
- The SM hypothesis passes the test. It does not mean that SM IS the Nature. In Science, one can usually only say NO...
- Two (if we put aside m_W) observables depart « with some significance » from their prediction. It happens they are the two most important for the constraint on the Higgs boson.
- One can go one step further and make the metrology of the parameters.

2. The SM became a theory

Spelling out the predictions.

- We must now compare the direct and indirect determinations:

$$m_{\rm top} = 173.18 \pm 0.96 \text{ GeV}/c^2, \text{ [direct } - \text{ Tevatron]}$$
$$m_{\rm top} = 172.6^{+13.2}_{-10.2} \text{ GeV}/c^2, \text{ [indirect } - \text{ LEP1]}$$

$$m_{\rm top} = 172.44 \pm 0.48 \text{ GeV}/c^2, \text{ [direct } - \text{ LHC]}$$

- The agreement is remarkable.

- LEP/SLD + SM predicted the top quark mass.

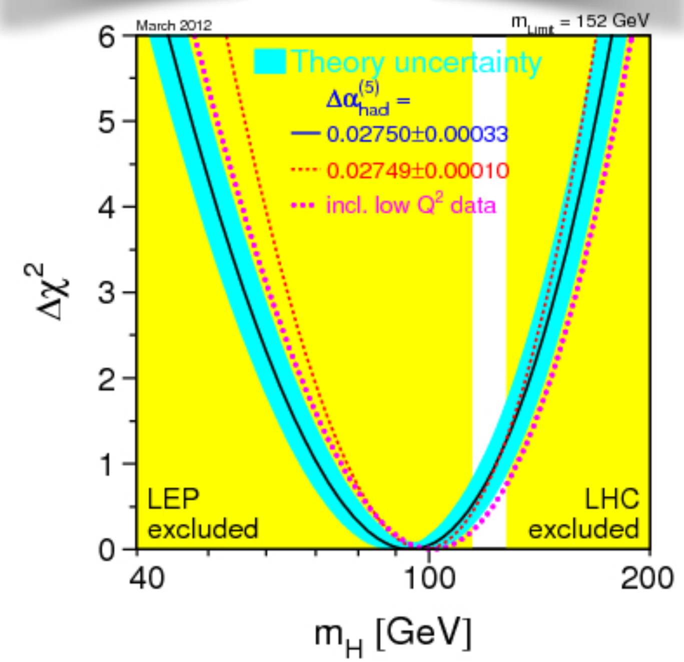
- This is simultaneously a triumph of the Standard Model and the HEP physics experiments. Probe quantum corrections of the electroweak theory to predict the existence of a particle in the Nature.

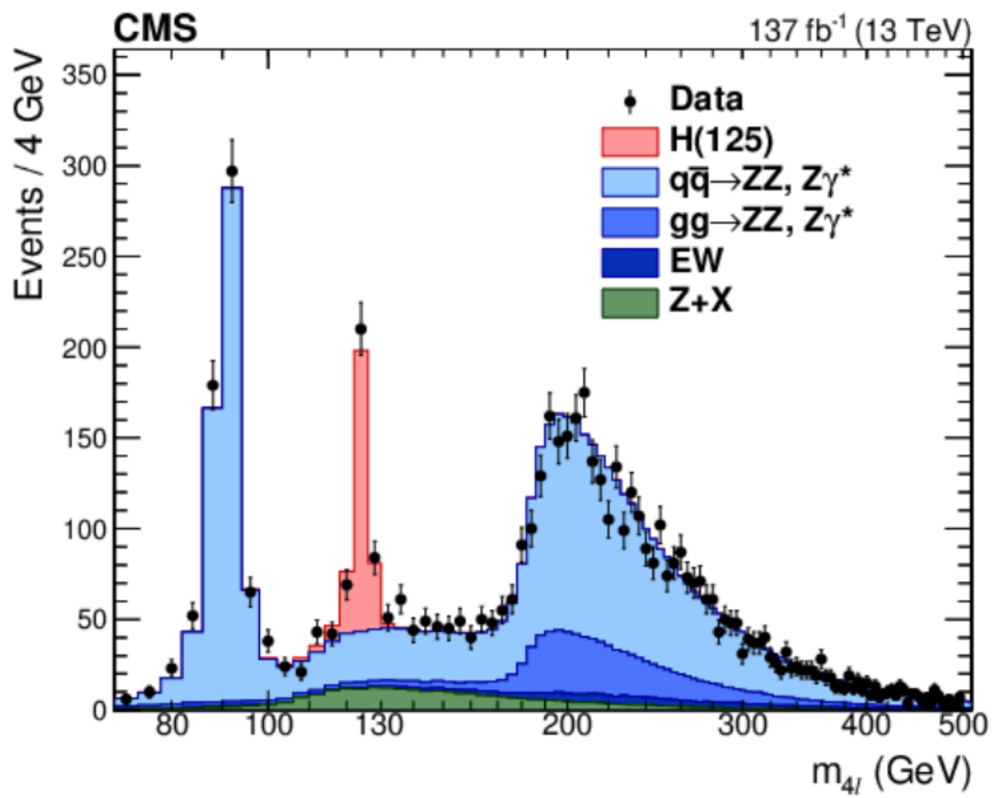
2. The two pillars of the SM: first pillar

Spelling out the predictions.

• Once the top quark is known, it can enter in the EWP consistency and constrain further the rest of the parameters, and bound the Higgs boson mass:

$$m_{\mathrm{BEH}} < 152\ \mathrm{GeV}/c^2 \quad 95\%\ \mathrm{CL.}$$

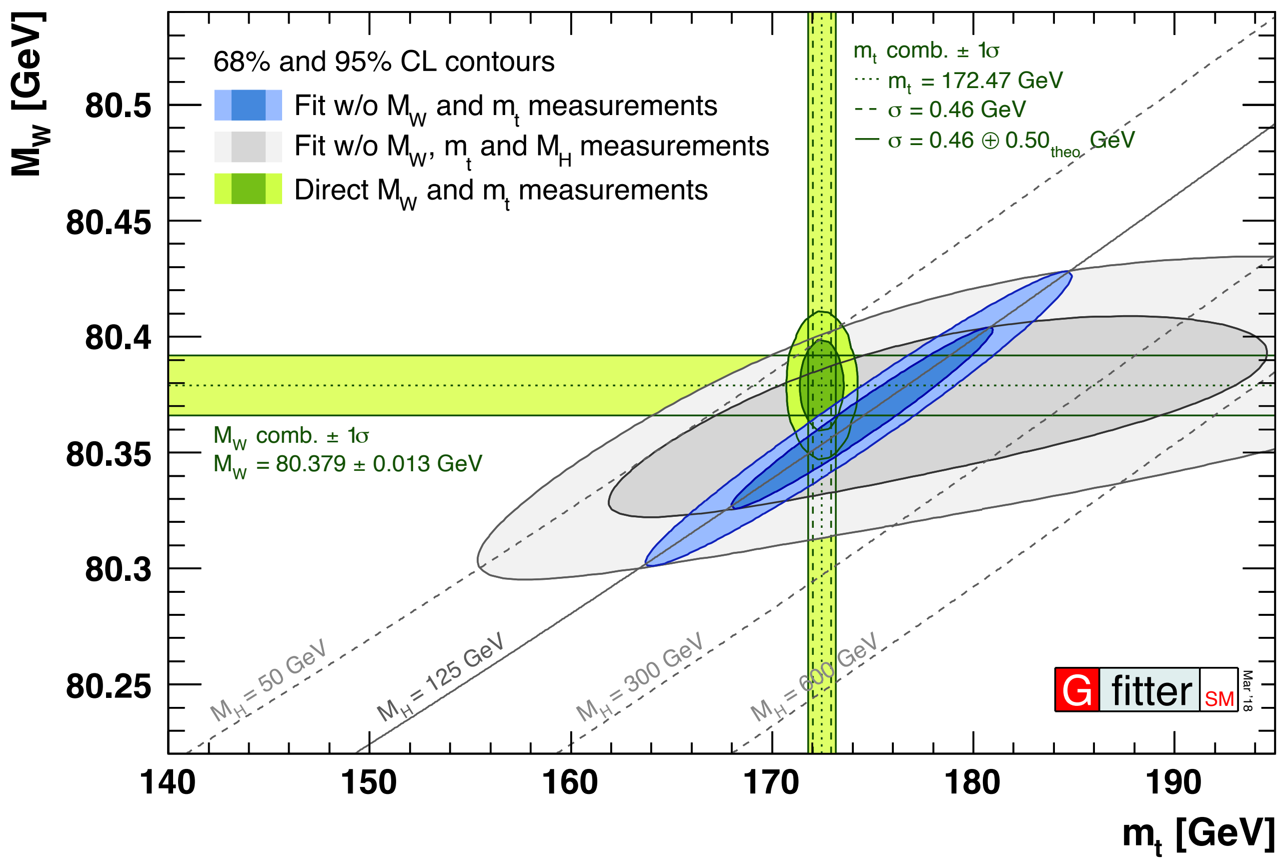




2. The two pillars of the SM: first pillar

Spelling out the predictions.

- The modern plot gathering all constraints



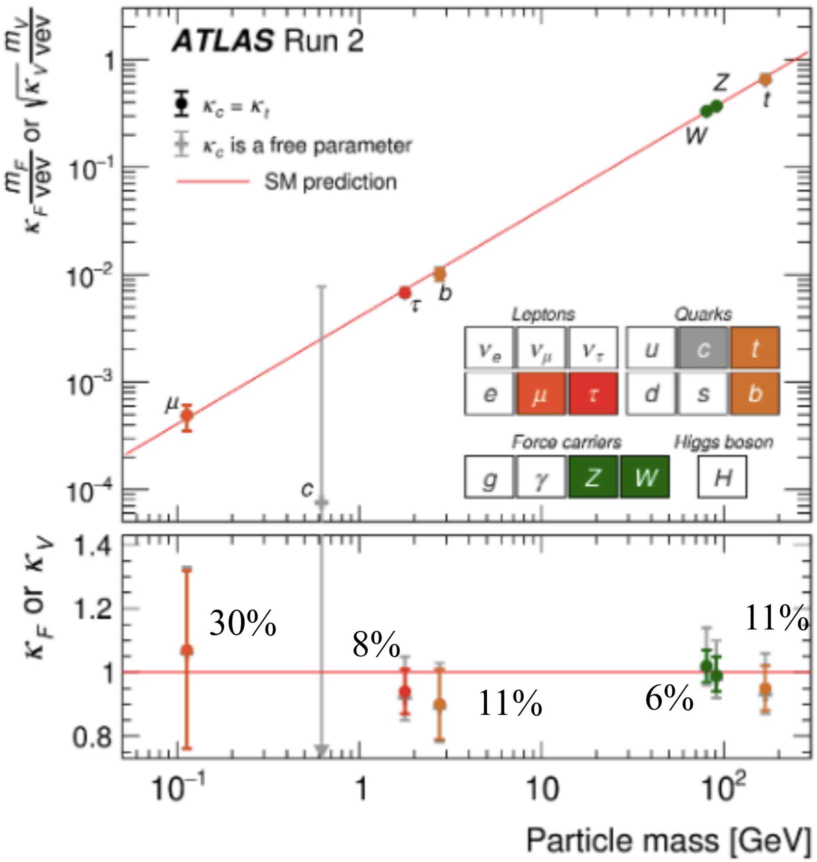
The case: narrow scalar physics as a portal to NP

- The measured couplings are so far (with a 10-30 % precision though) in good agreement with the SM predictions.

- HL-LHC will continue to improve this precision.

- The next duty is to bring the precision test at the level of the gauge sector test of the SM.

- This is the consensual outcome of the previous ESPP that an e+e- collider operated in particular at the Higgs threshold must be the next machine.



The case: narrow scalar physics as a portal to NP

- e+e- machines at 250 GeV are all the adequate tools to reach the needed precision.

- The duty is to bring the precision test at the level of the gauge one of the SM.

  - + Measure the Higgs width at 1%. Measure the invisible / exotic width.

  - + Measure the so far elusive couplings to charm and strange.

  - + And why not the electron Yukawa (FCCee)?

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ILC250	0.9ab^{-1} (-0.8,+0.3)		0.9ab^{-1} (+0.8,-0.3)		FCCee240 5ab^{-1}	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	1.07	-	1.07	-	0.5(0.537)	-
$\sigma \times BR_{bb}$	0.714	4.27	0.714	17.4	0.3(0.380)	3.1(2.78)
$\sigma \times BR_{cc}$	4.38	-	4.38	-	2.2(2.08)	-
$\sigma \times BR_{gg}$	3.69	-	3.69	-	1.9(1.75)	-
$\sigma \times BR_{ZZ}$	9.49	-	9.49	-	4.4(4.49)	-
$\sigma \times BR_{WW}$	2.43	-	2.43	-	1.2(1.16)	-
$\sigma \times BR_{\tau\tau}$	1.7	-	1.7	-	0.9(0.822)	-
$\sigma \times BR_{\gamma\gamma}$	17.9	-	17.9	-	9(8.47)	-
$\sigma \times BR_{\gamma Z}$	63	-	59	-	(17*)	-
$\sigma \times BR_{\mu\mu}$	37.9	-	37.9	-	19(17.9)	-
$\sigma \times BR_{inv.}$	0.336	-	0.277	-	0.3(0.226)	-

Self-contained program in which each machine brings nominally the needed breakthrough in precision.

2. The two pillars of the SM: second pillar

Back to quark masses and mass mixing matrix.

- Again, the name of the game consists in a global consistency check from a fit of the SM hypothesis against the relevant Flavour observable measurements.

- Most of the constraints are coming from *b*-hadron decays and neutral *B*-meson mixings. These can be *CP*-conserving or *CP*-violating observables.

- The global fit relies heavily, as far as *CP*-conserving observables are concerned, on QCD predictions, mostly numerically established (Lattice QCD).

- The observables related to the strange flavour (K decays and K^0 mixing) are also consistently described, though suffering from large(r) hadronic uncertainties (long distance physics where LQCD does not apply straightforwardly).

2. The two pillars of the SM: second pillar

Back to quark masses and mass mixing matrix.

- The 4 CKM matrix elements are decoupled from the rest of the theory. The consistency check of the SM hypothesis in that sector is the second pillar of the SM:

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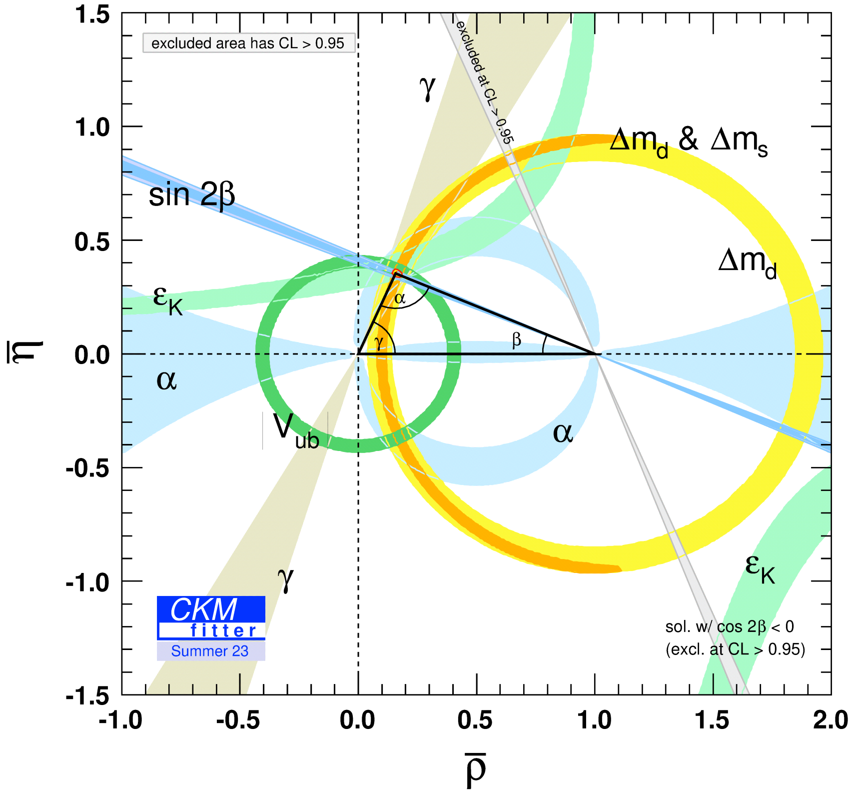
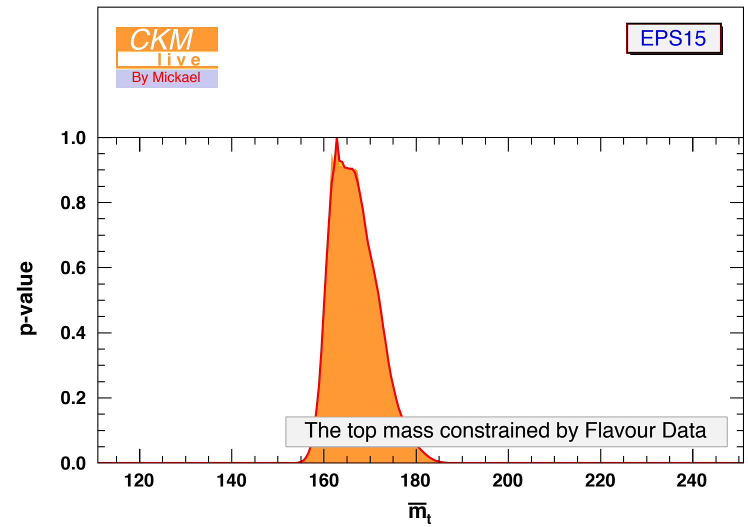
ckmlive.in2p3.fr



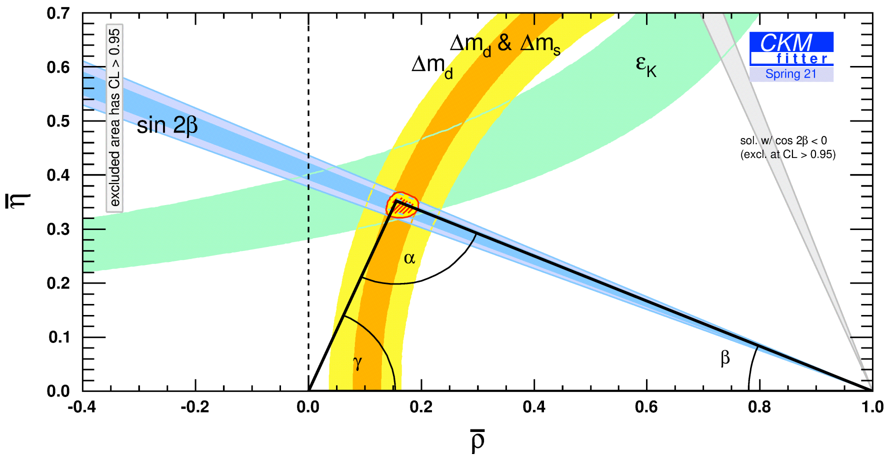


- Flavour observables are also predicting (well postdicting in that case) the top quark mass through mixing processes!

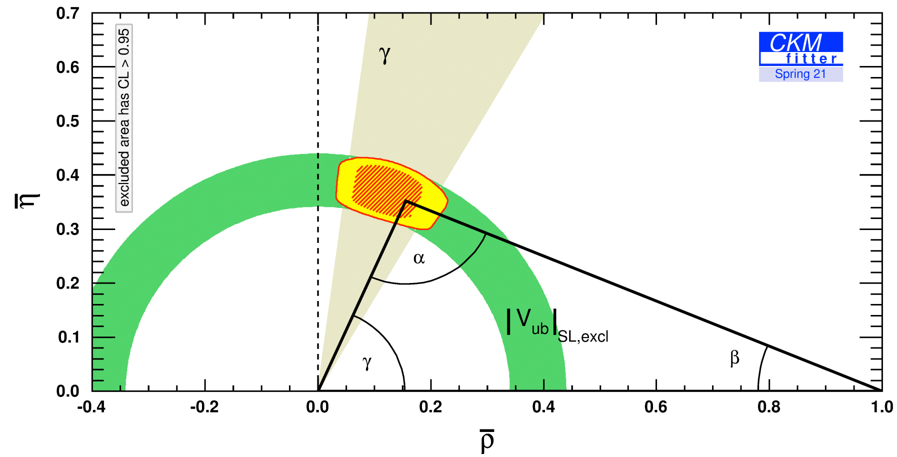
2. The two pillars of the SM: second pillar

Back to quark masses and mass mixing matrix.

- The 4 CKM matrix elements are decoupled from the rest of the theory. The consistency check of the SM hypothesis in that sector is the second pillar of the SM:



Loops - BSM friendly



Trees - supposedly SM friendly

- To date, remarkable agreement about the CKM profile. Beyond *CP* symmetry breaking physics, rare decays of heavy flavours are offering another vibrant territory for NP searches. No clear observation yet.

2. The second pillar: Flavour Physics

- Heavy Flavour Physics has a vibrant experimental program ahead, before the next Higgs / top / EW machine.

- LHCb collaboration operates (very successfully these days) its first upgrade and targets 50/fb (reasonably achievable). This shall constitute a first breakthrough for rare decays and *CP* violation program.

- SUPERKEKB and Belle II presents a program targeting at 50 /ab, and already reported world class results, such as the tau lepton mass measurement and the evidence of b->s nu nu decays.

- LHCb collaboration advocates an upgrade at the horizon of LHC Run 5 to reach 300 /fb.

- These two environments are complementary and will increase our knowledge by bringing the CKM profile in an era of precision at the horizon of 203x.

2. The second pillar: Flavour Physics

- The second upgrade of LHCb (not yet funded) is a must do to maximally exploit the physics potential of HL-LHC phase. High expectations there.

- A continuation of the Flavour program at the next e+e- (circular, one needs more than 10^{12} Z) collider is however possible and desirable, with strong and unique assets:

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

- Conclusions of the Feasibility Study:
  - Semileptonic rare decays with neutrinos and 3rd generation couplings,
  - Interpretation of the CKM profile with Vcb at WW, *CP* eigenstates
  - Tau physics (e.g. lepton unversality) etc …
  - Strong detector requirements (vertexing, PID, calorimetry)

The Case:

- The SM has (mostly) cleared **so far** the tests from SLC, LEP, TeVatron, *B*-factories, LHC and single-observables experiments.
- There are compelling theoretical arguments for Beyond Standard Model (BSM) Physics. There are strong cosmological indications (Dark matter, BAO). The neutrino masses make another evidence.
- But the next energy scale (where SM breaks) is unknown.
- The Higgs study case at e+e- machines is a straightforward and must-do physics case and can shed light to the next scale.
- Precision physics at the Z, W and top thresholds is a key in addition through improved consistency checks.

The Case: Physics scenarii for next machine (to be disputed)

1) Find a new heavy particle at the Run III of LHC:
- HL-LHC can study it to a certain extent.
- If mass is small enough (and couples to electrons), CLIC can be the way.
- Larger energies are needed to study (find) the whole spectrum.
- The underlying quantum structure must be studied.

2) Find no new particle, but non-standard *H* properties
- HL-LHC can study it to a certain extent.
- Higgs factory.
- *Z*, *W*, top factories for the quantum structure.
- Energy frontier (also for precision measurements)

3) Find no new particle, standard H properties but flavour observables departing from SM:
- Higgs factory.
- *Z*, *W*, top factories for the quantum and flavour structure.
- Energy frontier to find the corresponding spectrum.

4) Find no new particle, standard H properties and flavour observables in SM:
- Asymptotic *Z*, *W*, *H*, top factories for asymptotic precision.
- Push the energy frontier to the best of our knowledge.

4. Conclusions: a desirable programme.

- International Linear Collider project is proposed since a decade to be hosted by Japan. 250 GeV (Higgs factory) machine upgradable in energy.

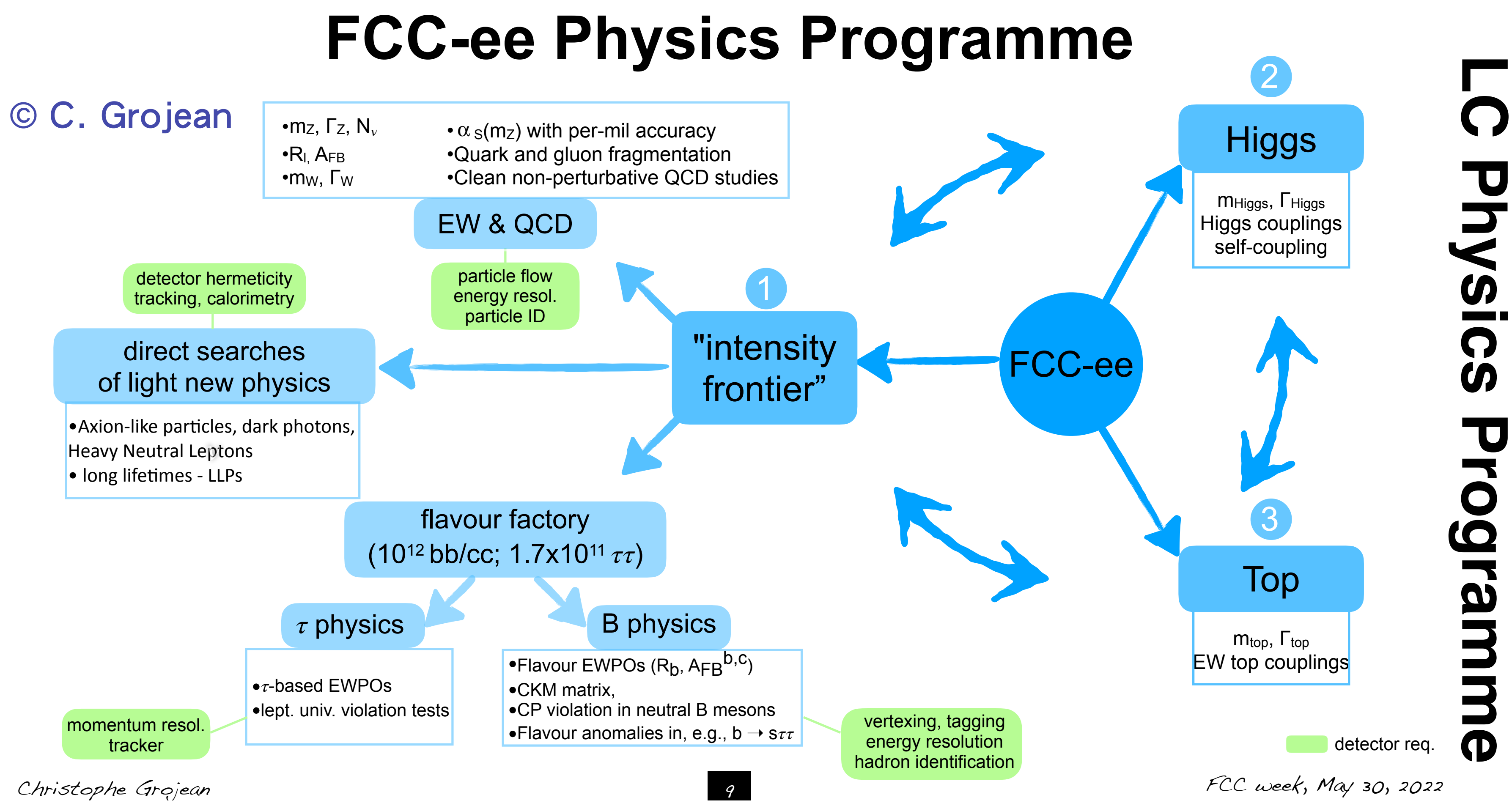
- FCC-ee project is the proposal at CERN for the next e^+e^- Higgs factory. It is more than a Higgs factory:
  - Z factory [$O(10^{13})$]
  - b, τ, c factories [$O(10^{12})$]
  - W factory [$O(5.10^{8})$]
  - top factory [$O(10^{6})$]

- You can make there the LEP in a minute!

- Before this: 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 in particular for a continuation of the Flavour program and to deepen it further.

4. Conclusion: a desirable programme.



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

4. Conclusions: a desirable programme.

- 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

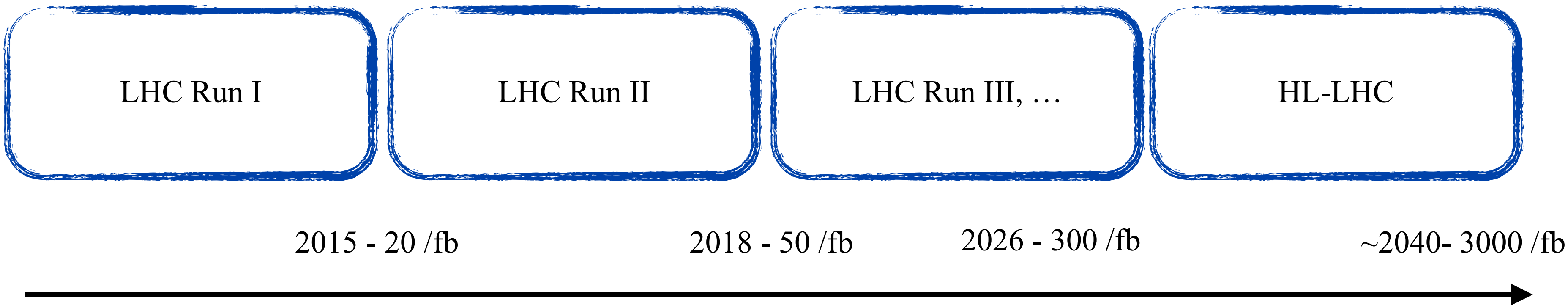
- The new one in Europe guarantees that we're closing the Higgs and Electroweak gauge chapters with a precision machine and let options opened to high energy protons if a compelling case is made.

Les Renforts! The back-ups

Scientific context: historical timelines

1964 Electroweak unification	1971 EW loops and RN	1973 *CP* violation	1964 Fundamental Scalar
	Top quark mass predicted by LEP, CERN (from M_Z and other EWPO).	The *B*-factories establish that the KM paradigm is the dominant source of *CP* violation in *K* and *B* particle systems.	Higgs boson mass cornered by LEP (EWPO) and Tevatron (top and *W* mass).
Neutral current discovery in 1973 by Gargamelle (CERN).	Top quark discovered by CDF, FNAL.		An alike Higgs boson discovered where said at LHC.
1979 Glashow, Salam and Weinberg get the Nobel.	1999 t'Hooft and Veltman get the Nobel.	2008 Kobayashi and Maskawa get the Nobel.	2013 Englert and Higgs get the Nobel.

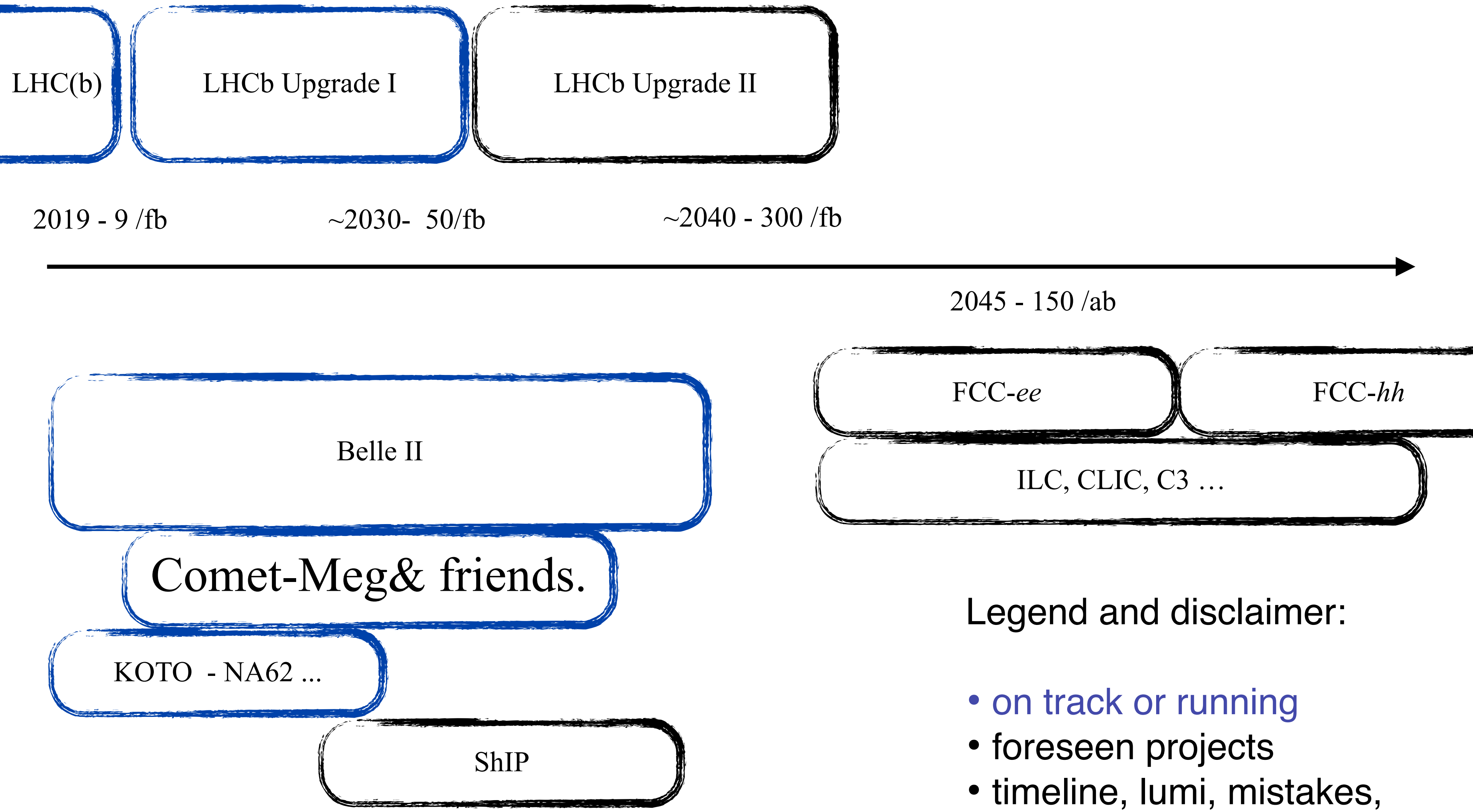
Scientific context: LHC timeline (GPD-wise)



Legend and disclaimer:

- on track or running
- foreseen projects
- timeline mistakes, lumi. approximation, omissions are mine.

Landscape of future colliders - Flavour_centered



Legend and disclaimer:

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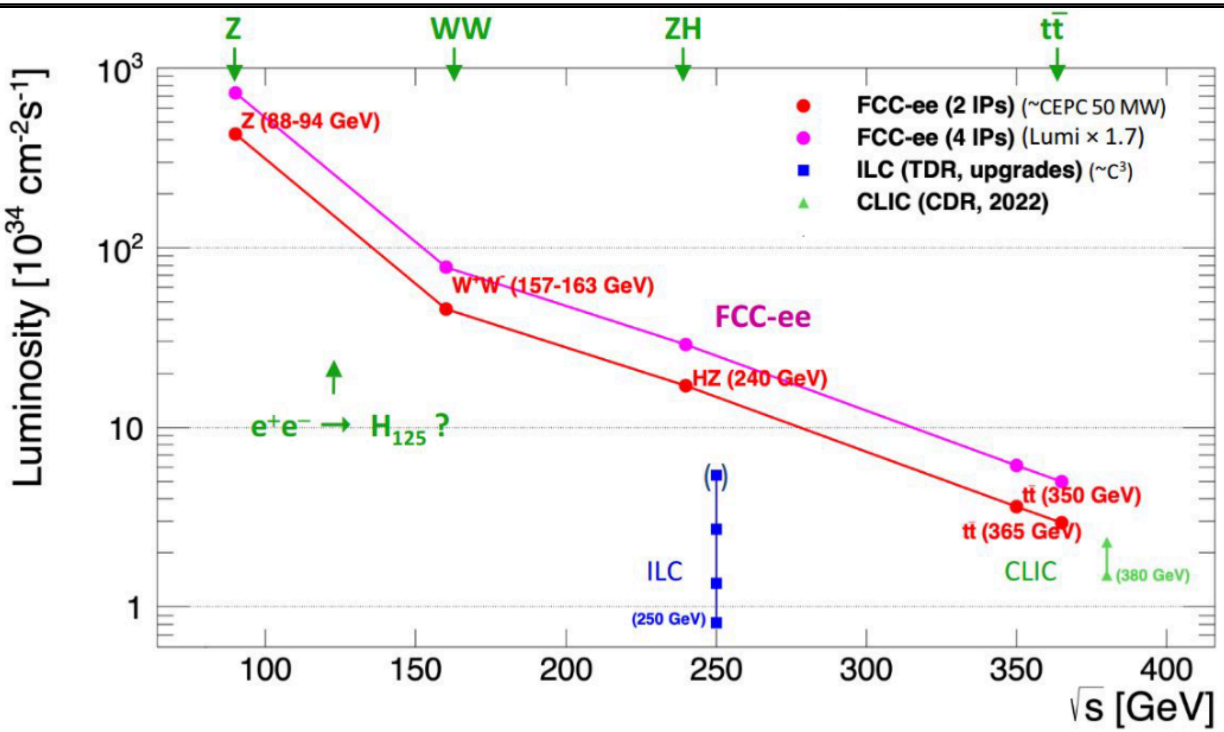
- foreseen projects
- timeline, lumi, mistakes, omissions are mine.

- Aparté: how NP can show up in Flavour data or how strong is the CKM consistency check?
  - Back in early 2010s, the *B*-factories results had established the KM paradigm as a tremendous success of the SM.
  - Yet, a single measurement at the time (it was the first observation of $B^+ \to \tau^+ \nu$:) came and has shaken the edifice.
  - It was receiving a "natural" explanation with additional amplitudes contributing to the neutral meson mixing processes.
  - The precision improved and SM stroke back but the precision nowadays is yet limited at 25% on the BF.
  - Re-enforces the need to get that measurement better and the quasi-model-independent NP in mixings at the adequate precision.

Key points: luminosity and operation

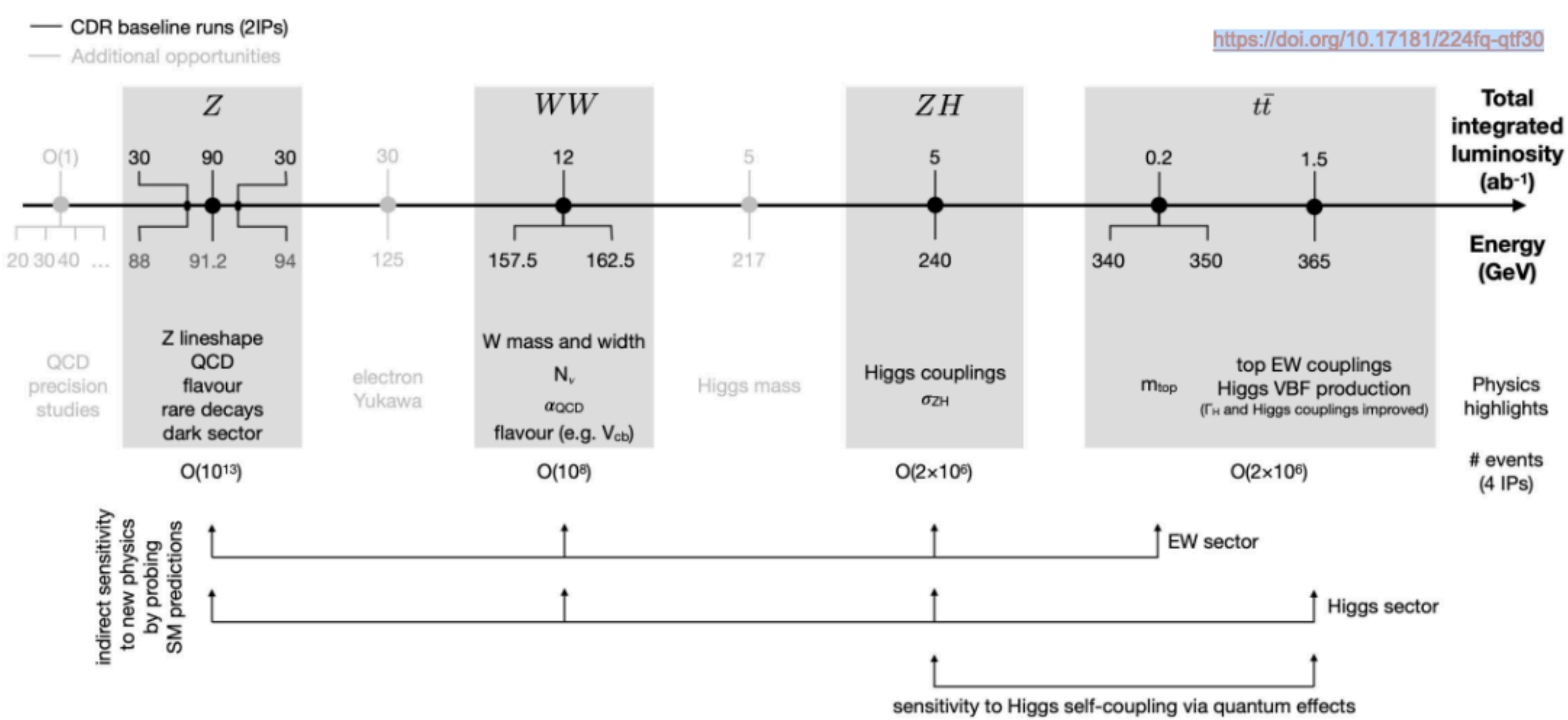


- We‘re speaking of 10^5 *Z*/s , 10^4 *W*/h, 1.5 10^3 *H* and top /d, in a very clean environment: no pile-up, controlled beam backgrounds, *E* and *p* constraints, ~w/o trigger loss. In particular, you do the LEP in a minute! We’ve seen that a significant part of our knowledge is still coming from the LEP experiments.

Try me

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, …



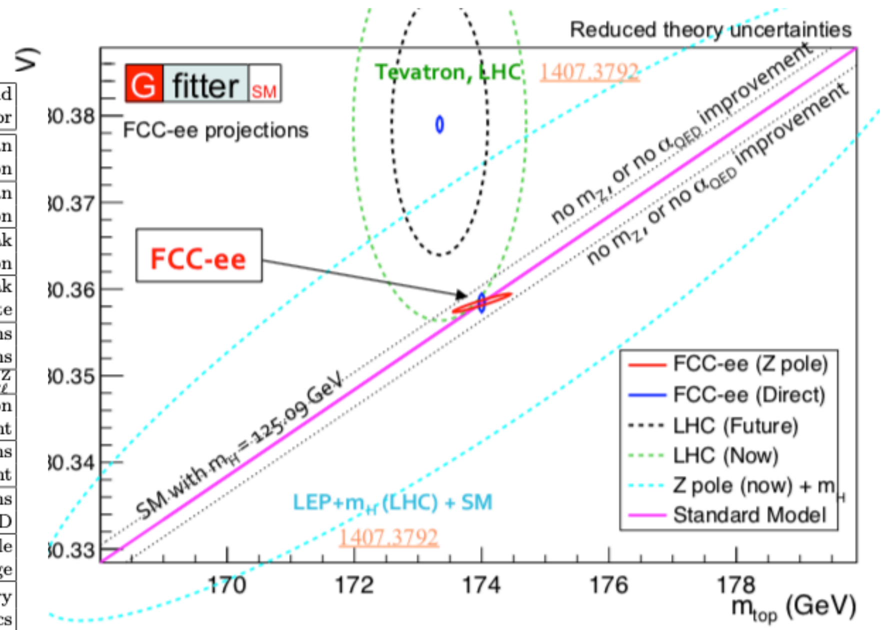
The Physics Case at large: big picture

Z pole

WW thr.

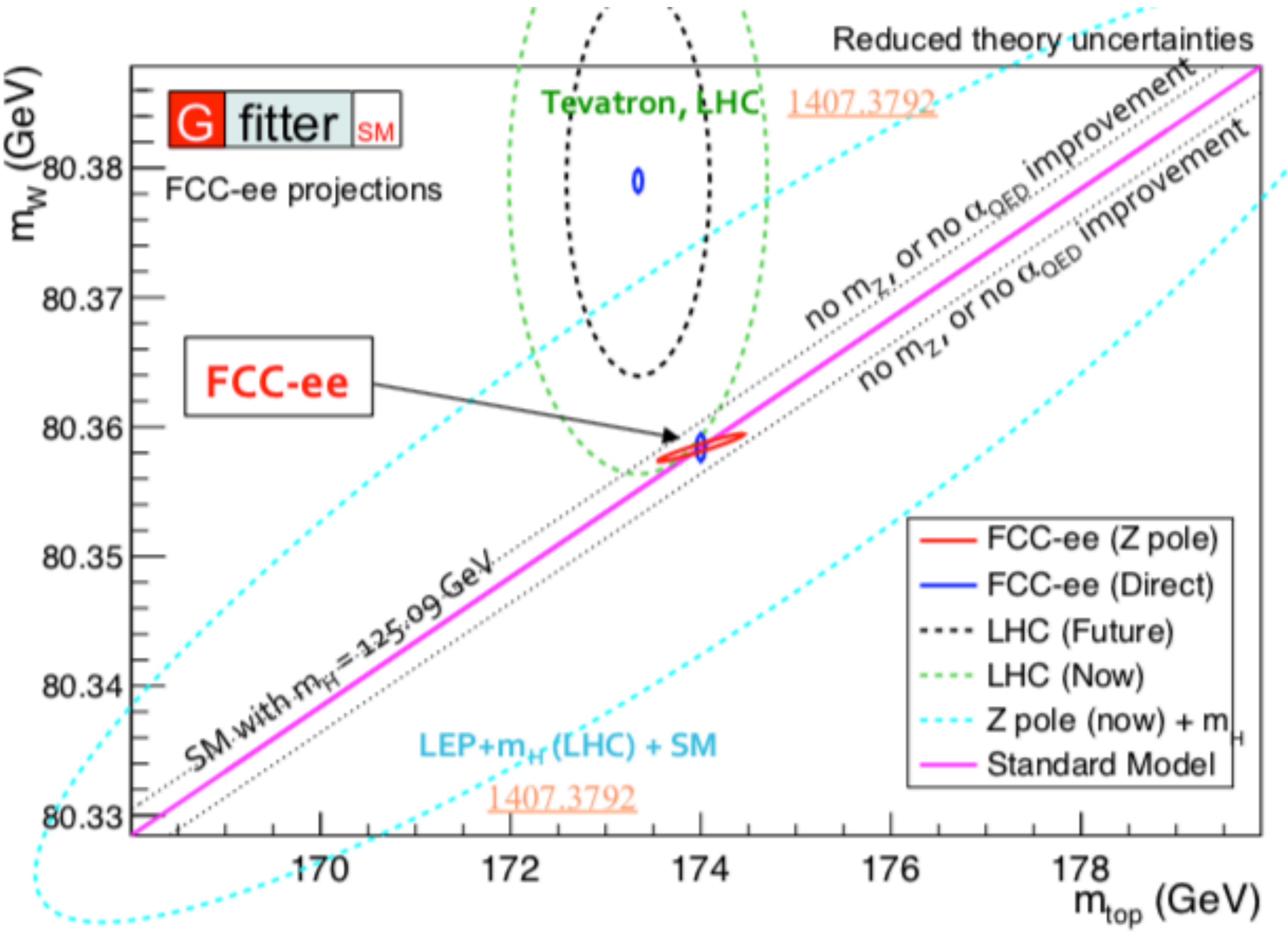
tt thr.

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



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

The Physics Case at large: the indirect constraints



The Physics Case at large: the big picture

Z pole / WW thr. / tt thr.

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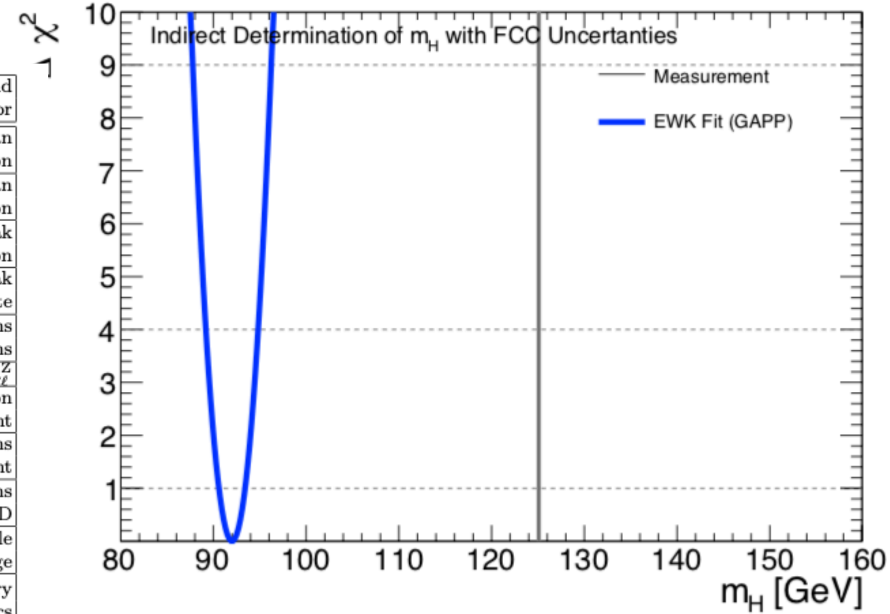


- Ultimate quantum completeness consistency test of the SM.
- The improvements in theory prediction precision is part of the FCC program. Precision 1.4 GeV.

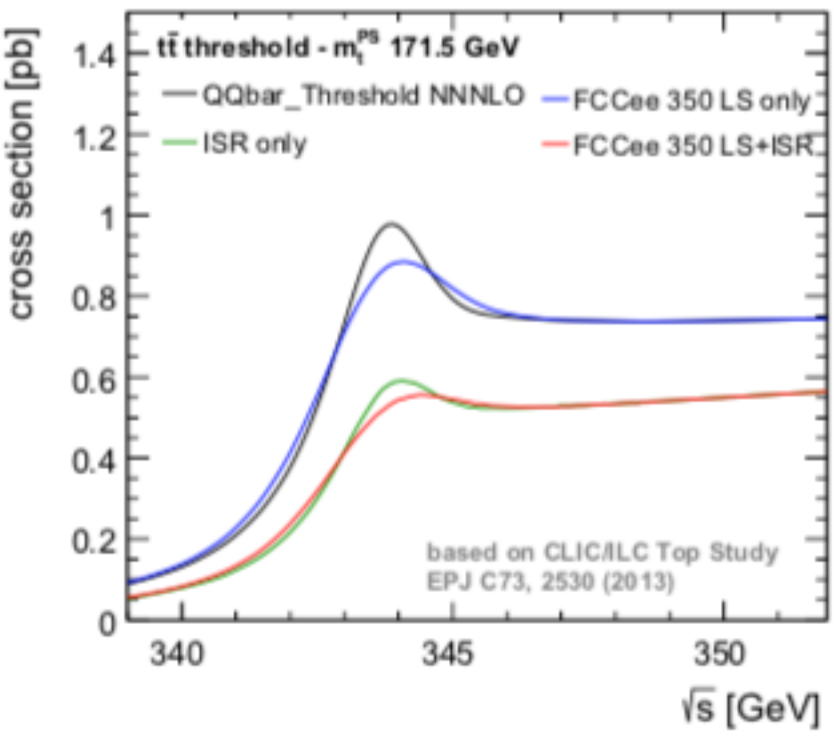
The Physics Case at large: the Higgs factory

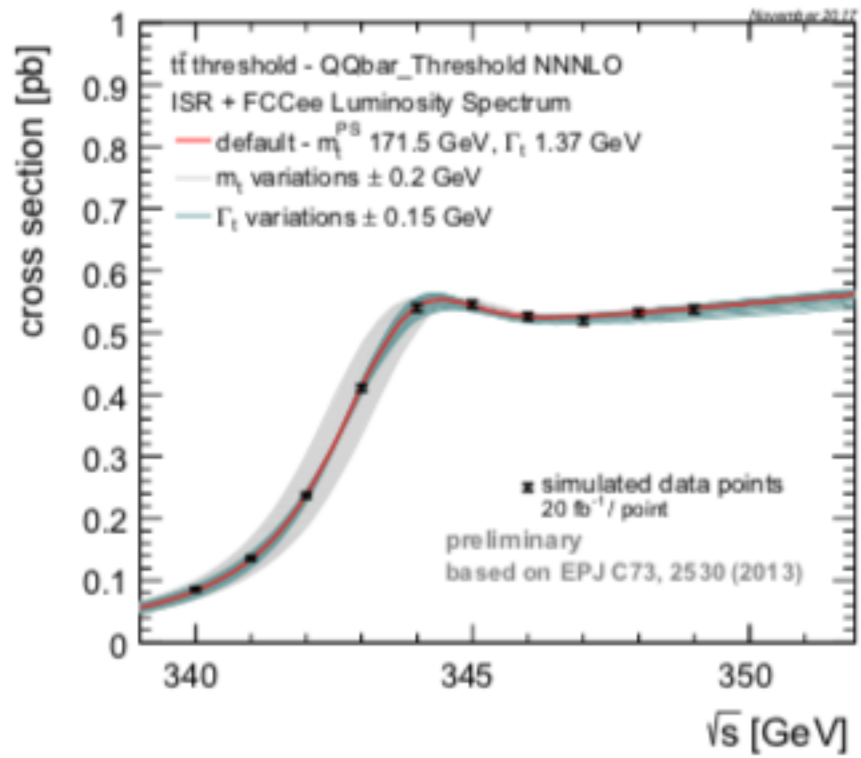
- It is interesting to note that the extrapolations provided for the CDR have mostly received confirmation from the latest studies, featuring more realistic detectors

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%

© J. Eysermans, as was shown end of january 2024.

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.

The Physics Case at large: the strong coupling constant

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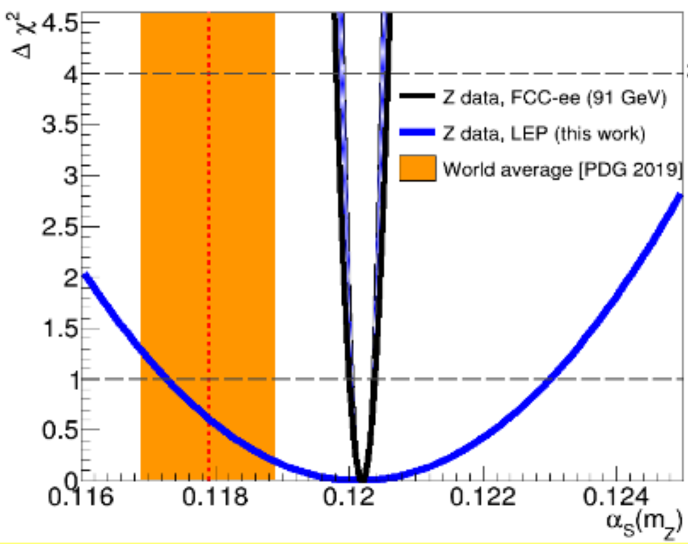
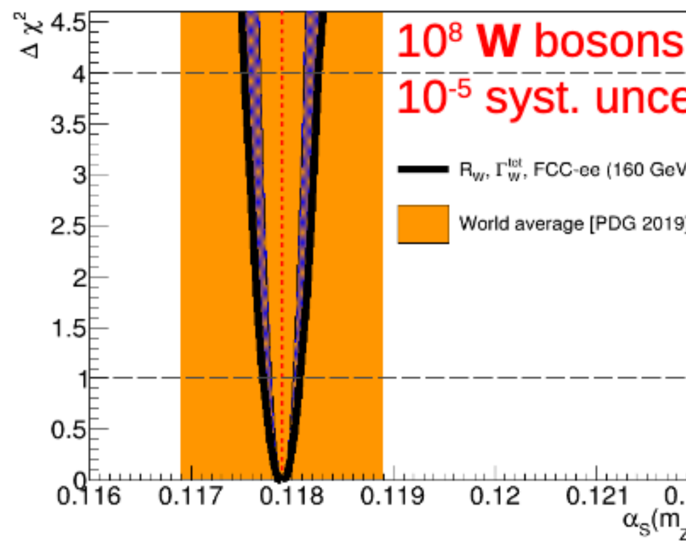
- Future: Permille uncertainty possible only with a machine like FCC-e^+e^-



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

Strong SM "stress test"



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

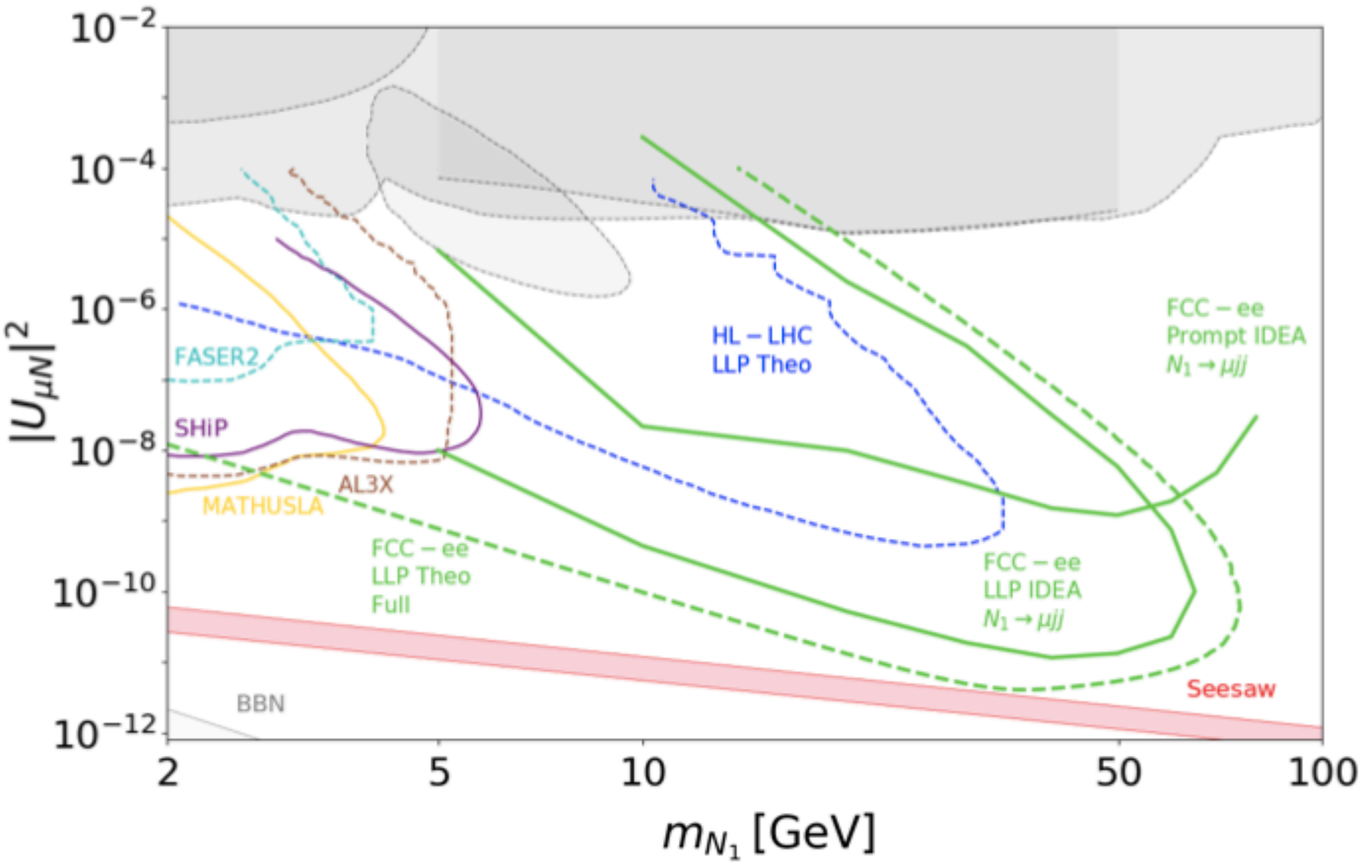
$\alpha_s(m_z)$ = 0.12030 ± 0.00028 ±0.2% (tot), ±0.1% (exp)

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

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

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…



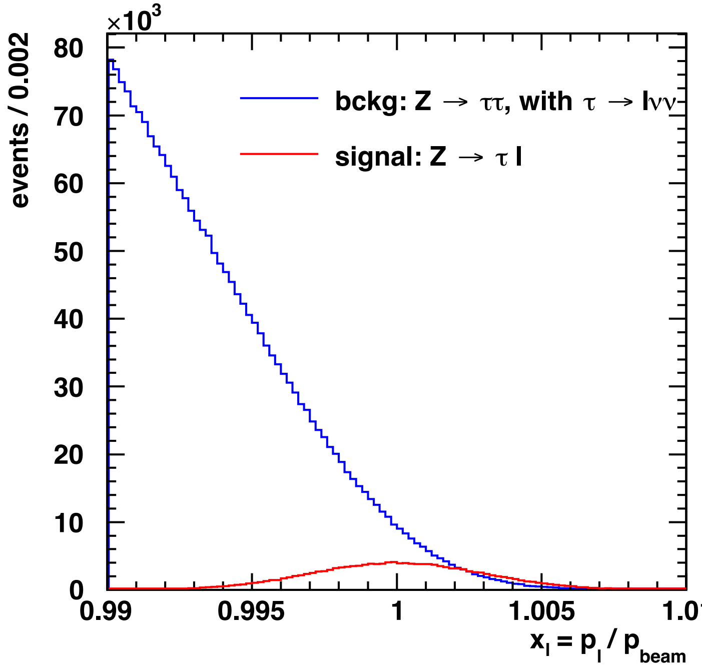
The Physics Case at large: discovery potential

- 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.* $O(10^{-9} - 10^{-10})$.

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	$\mathrm{t\bar{t}}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm^{-2}s^{-1}}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year ($\mathrm{ab^{-1}}$)	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	$1.9\times10^{6}\,\mathrm{t\bar{t}}$ +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*: $\langle E_{X_b} \rangle = 75\% \times E_{\text{beam}}; \langle \beta\gamma \rangle \sim 6.$

- 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 can be commensurate with those of LHCb-Upgrade II, and in general less with muons in the final state.

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.

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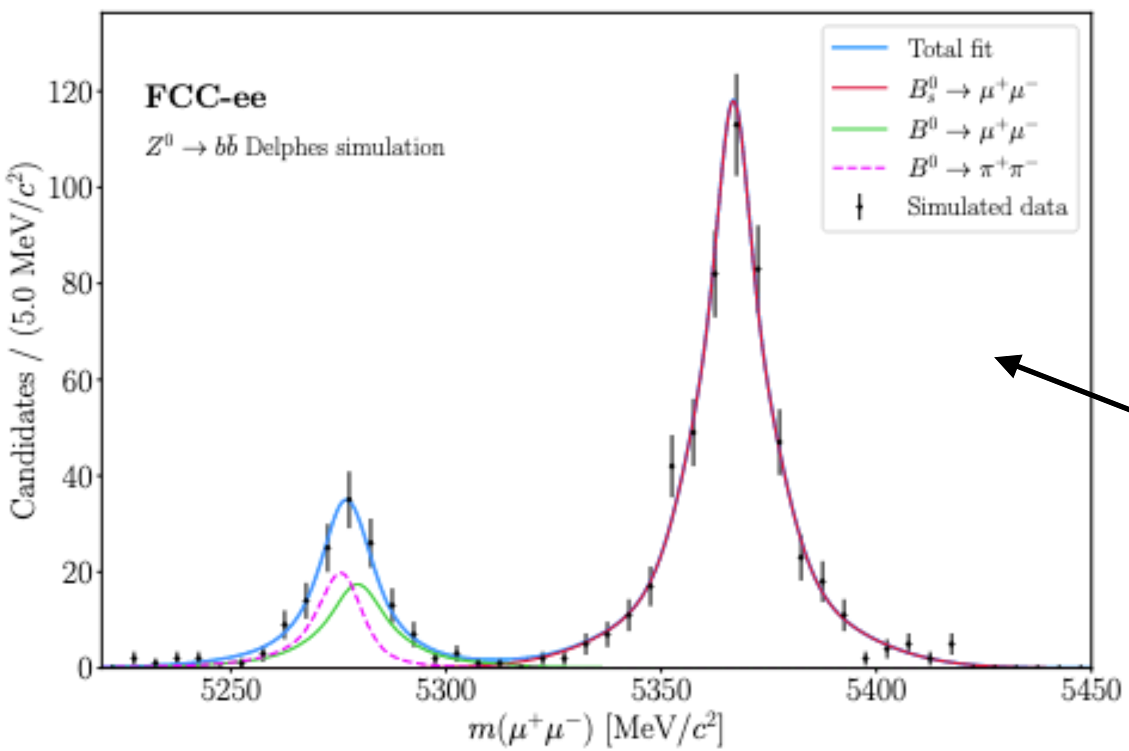

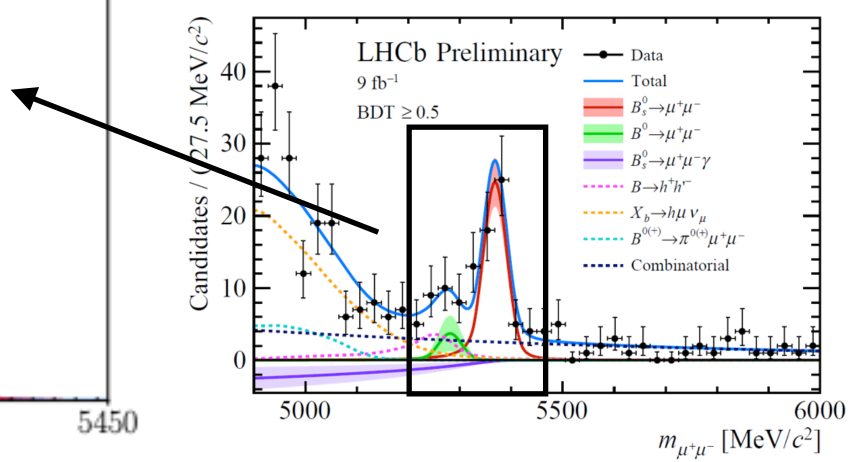

4) FCC-ee ABCD specifics for Flavour Physics.

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

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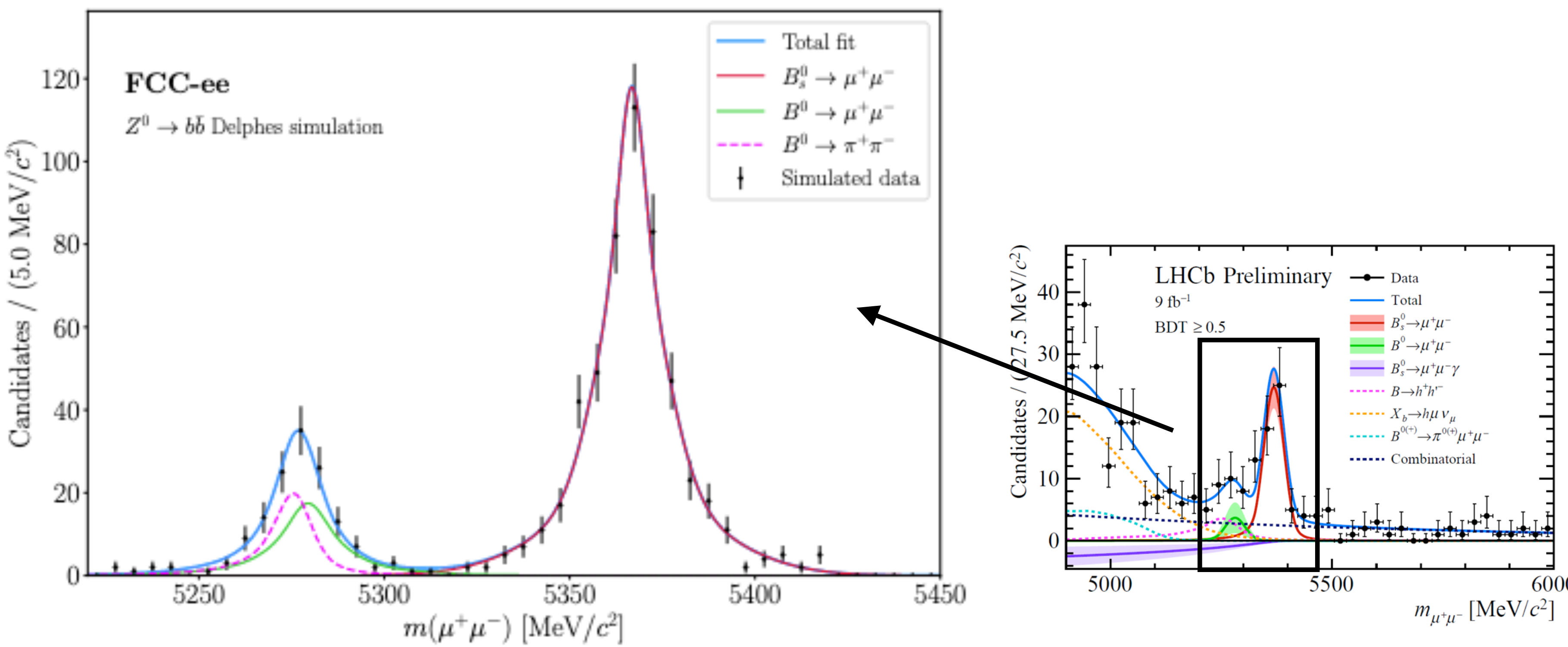


Seems granted w/ state-of-the-art tracker. Ultra-high resolution calorimetry is in addition desirable to touch high performance for modes w/ neutrals

4) FCC-ee ABCD specifics for Flavour Physics.

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.

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. $B_s \to \phi\nu\nu$
  - $Bc \to \tau\nu$; $b \to s(d)\ \ell\ell$

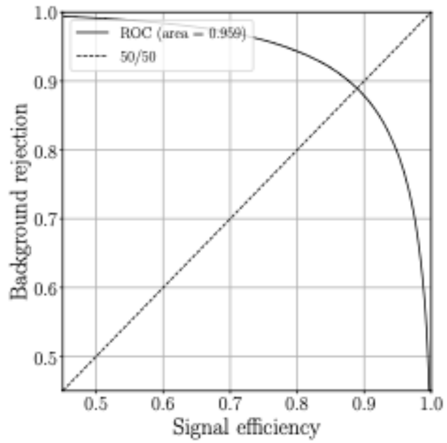
- *CP* violation studies:
  - The CKM γ angle, e.g. $B_s \to D_s K$.
  - The semileptonic asymmetries (*CP* breaking in mixing).
  - The CKM α angle, e.g. $B^0 \to (\pi^0\pi^0)$.
  - The matrix elements V_{ub} and V_{cb} ….

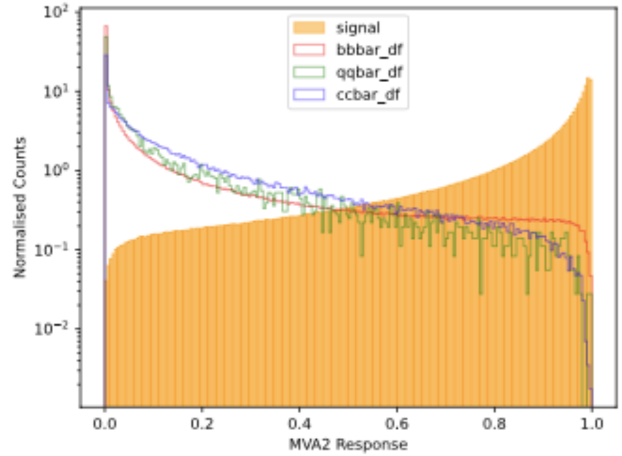
- Tau Physics:
  - Lepton flavour violating τ decays
  - Lepton-universality tests in τ decays.

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

5) Reviews of current activities (Feas. Study)

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





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arXiv:2309.11353

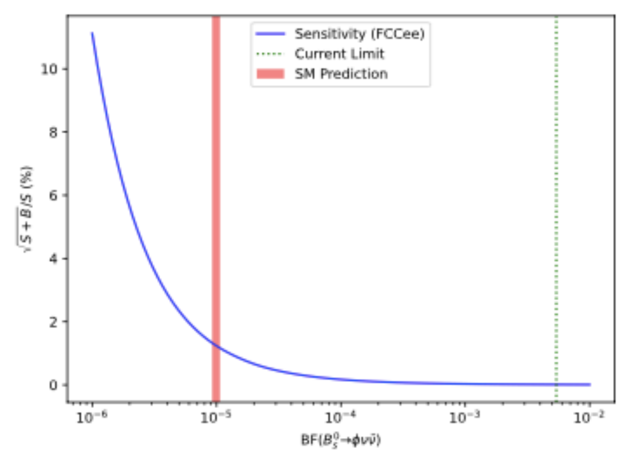
First indication of such a transition just came from Belle II (2023).

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

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

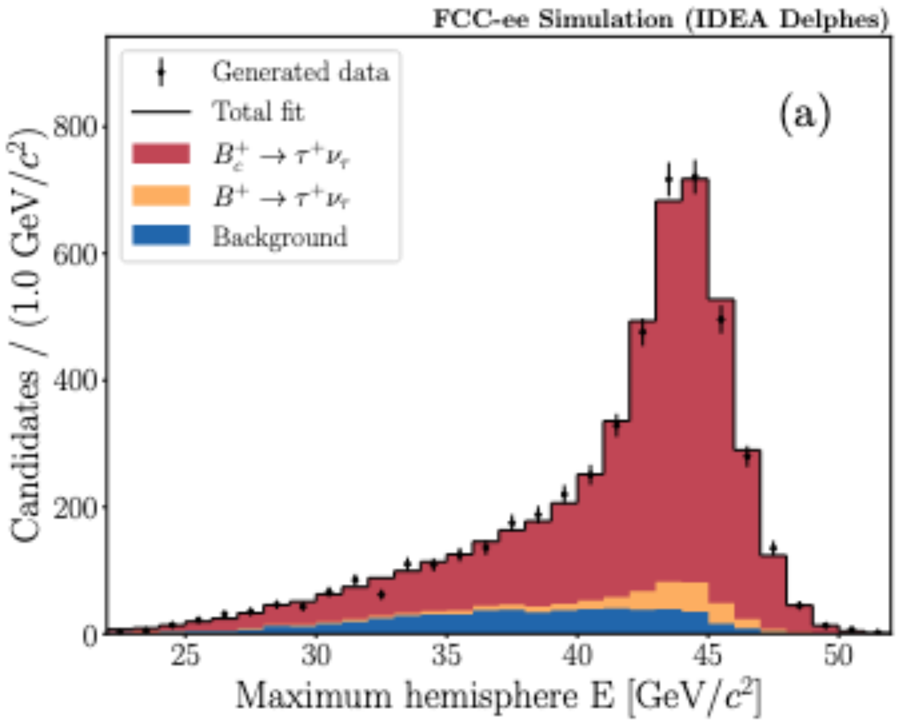
For an optimal BDT1 and BDT2 cut at the SM predicted BF:

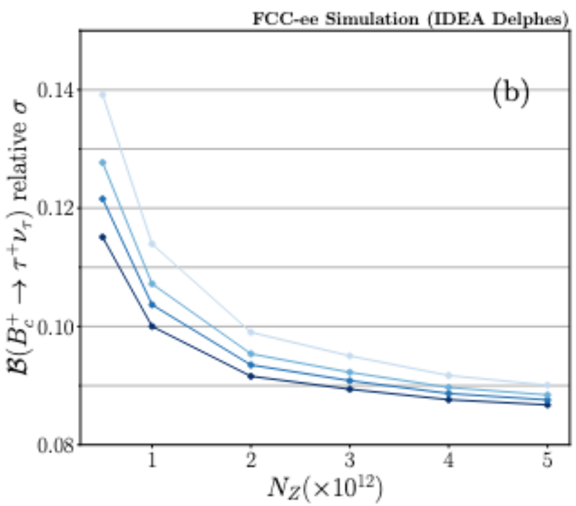
- Signal efficiency $\sim 11\%$
- $b\bar{b}$ efficiency $\sim 10^{-4}\%$
- $c\bar{c}$ efficiency $\sim 10^{-6}\%$
- $q\bar{q}$ efficiency $\sim 10^{-7}\%$
- Signal:Background ratio $\sim 1:9$
- Sensitivity $\sim 1.2\%$



5) Reviews of current activities (Feas. Study)

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





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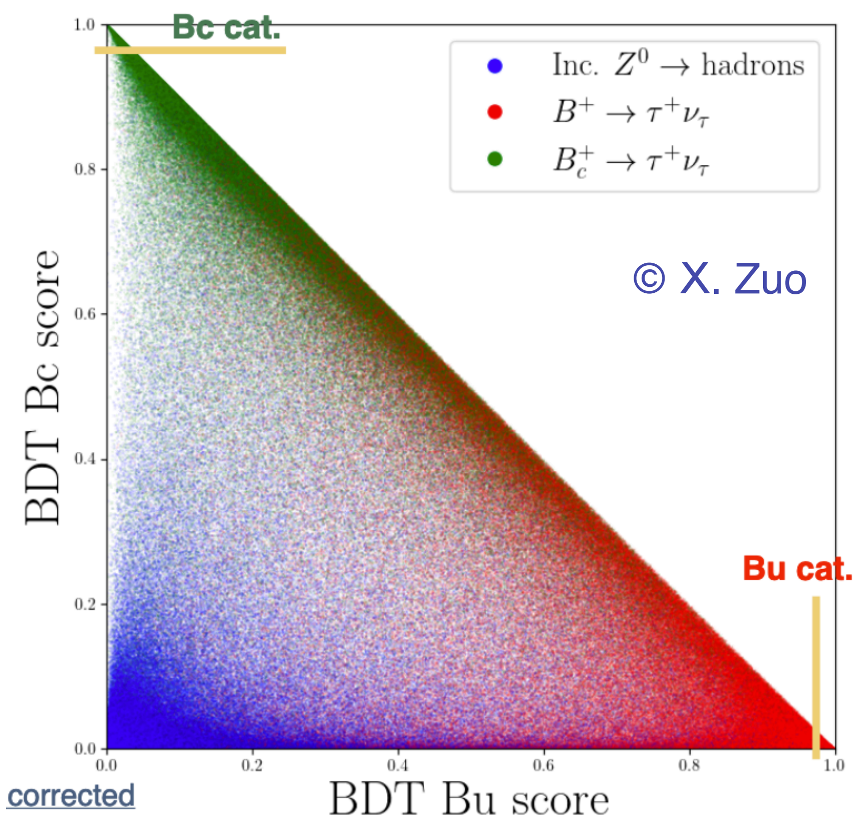
Bottomline: few percent precision mostly limited yet by the knowledge of the normalisation BF ($J/\psi\mu\nu$).

3) Reviews of current activities (Feas. Study)

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



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

3) Reviews of current activities (Feas. Study)

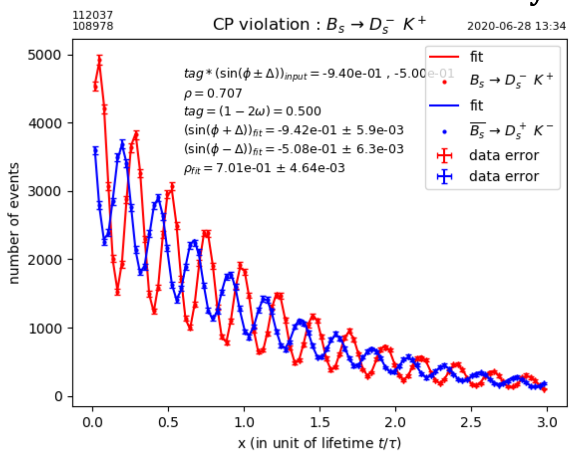
- Sub-degree gamma angle measurement with just one mode :

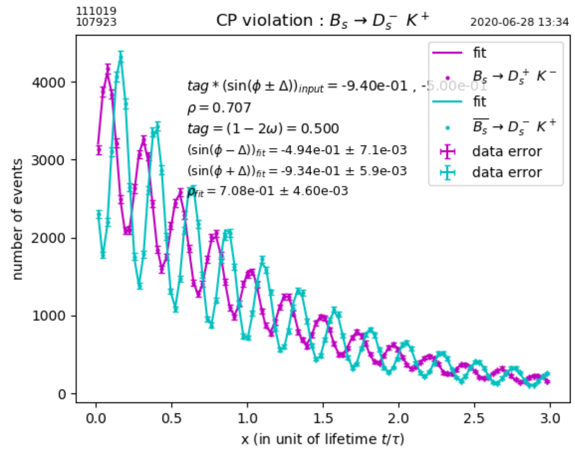
Measurement of CP violation with $B_s \rightarrow D_s K$

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

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 $D_s^{\pm} \rightarrow K^{*0}K^{\pm}, \phi\rho^{\pm}$, … but background needs to be studied (see later)+
Additionnal potential gain (another factor ~2) with $B_s \rightarrow D_s^{*\pm}K^{\mp}, D_s^{\pm}K^{*\mp}, D_s^{*\pm}K^{*\mp}$, 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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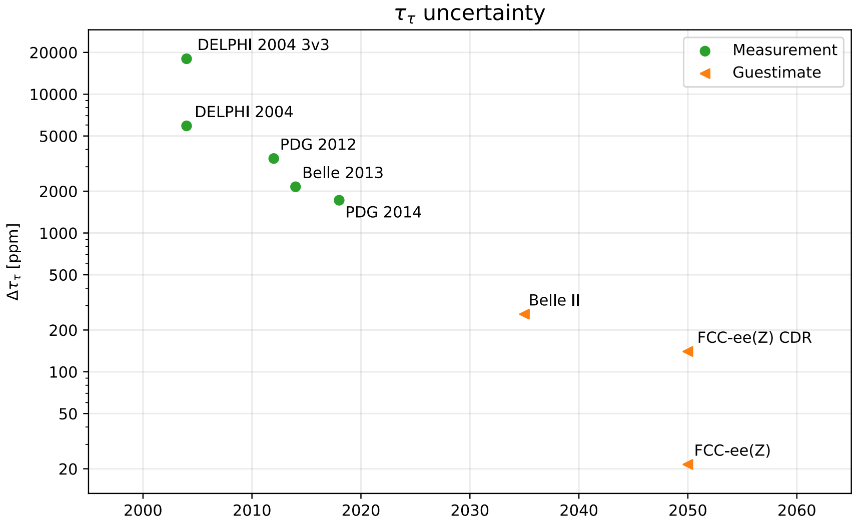

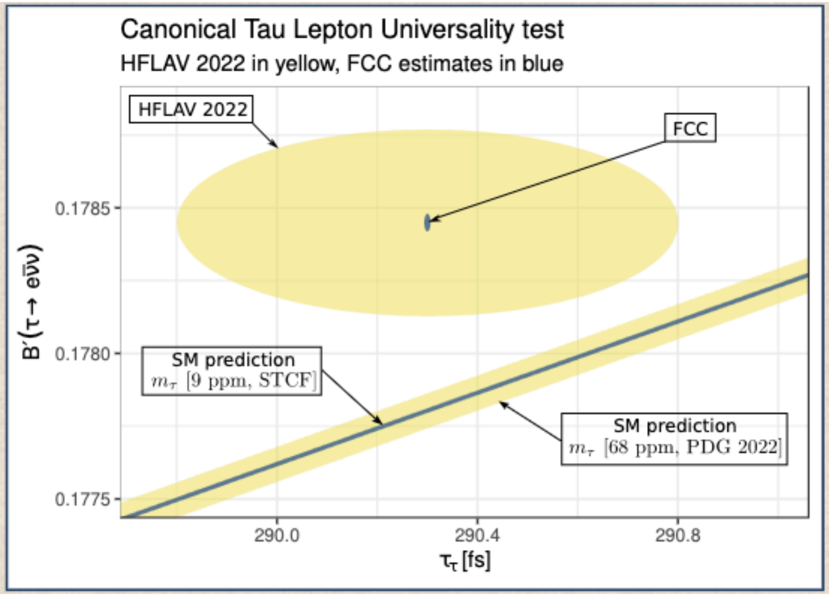

Comment: B-factories did not improve (much) LEP measurements (Belle II might). FCC-ee has much better experimental conditions than LEP and about 5× the statistics of tau pairs w.r.t. Belle II.

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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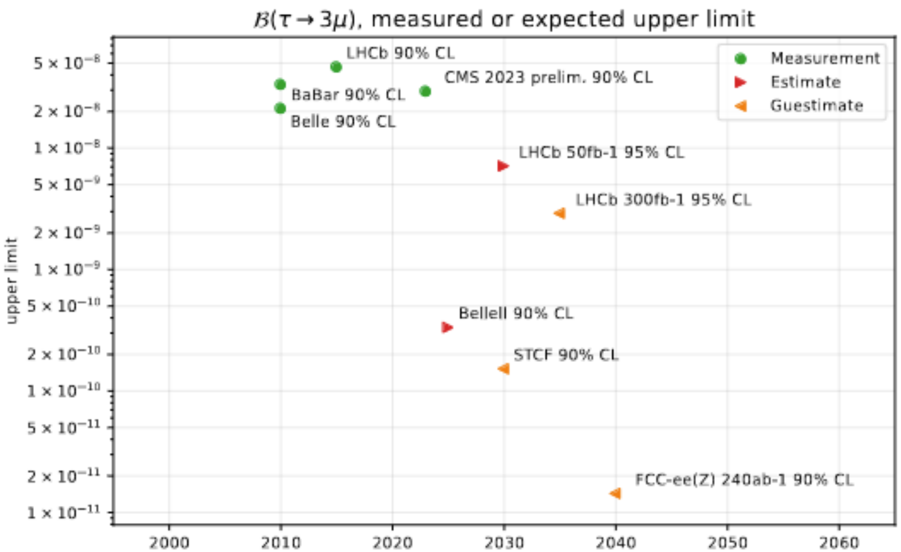
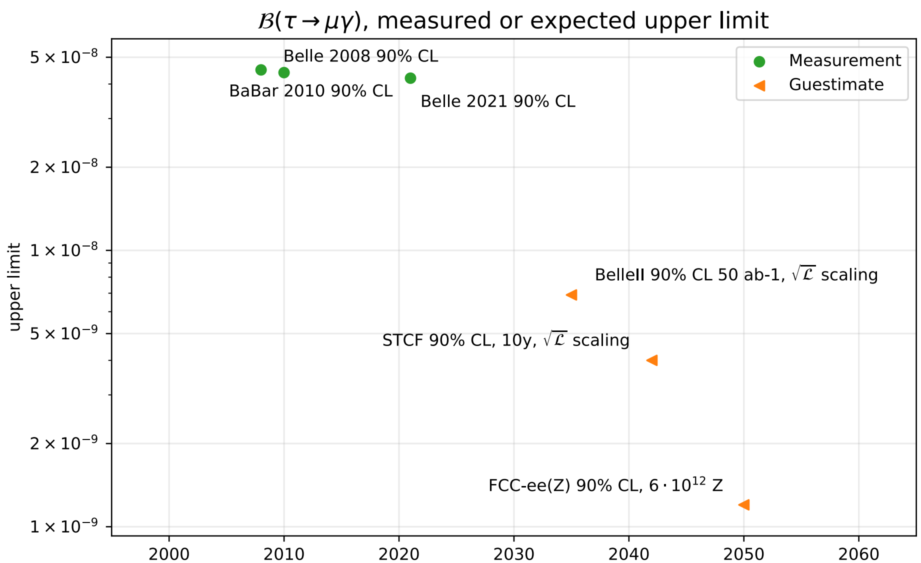
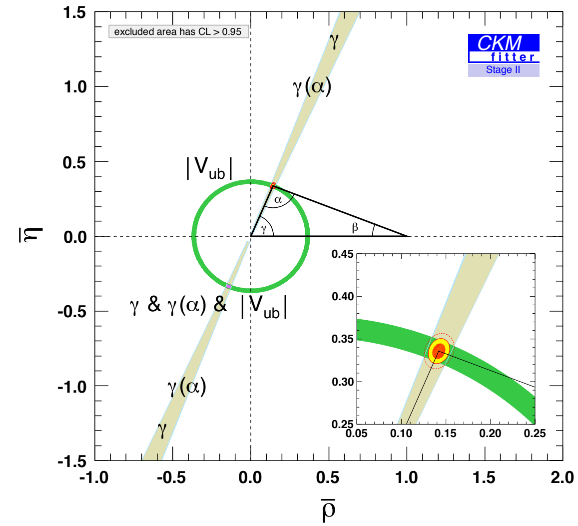




Bottomline: improved sensitivity by about two orders of magnitude.

6) Focus#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

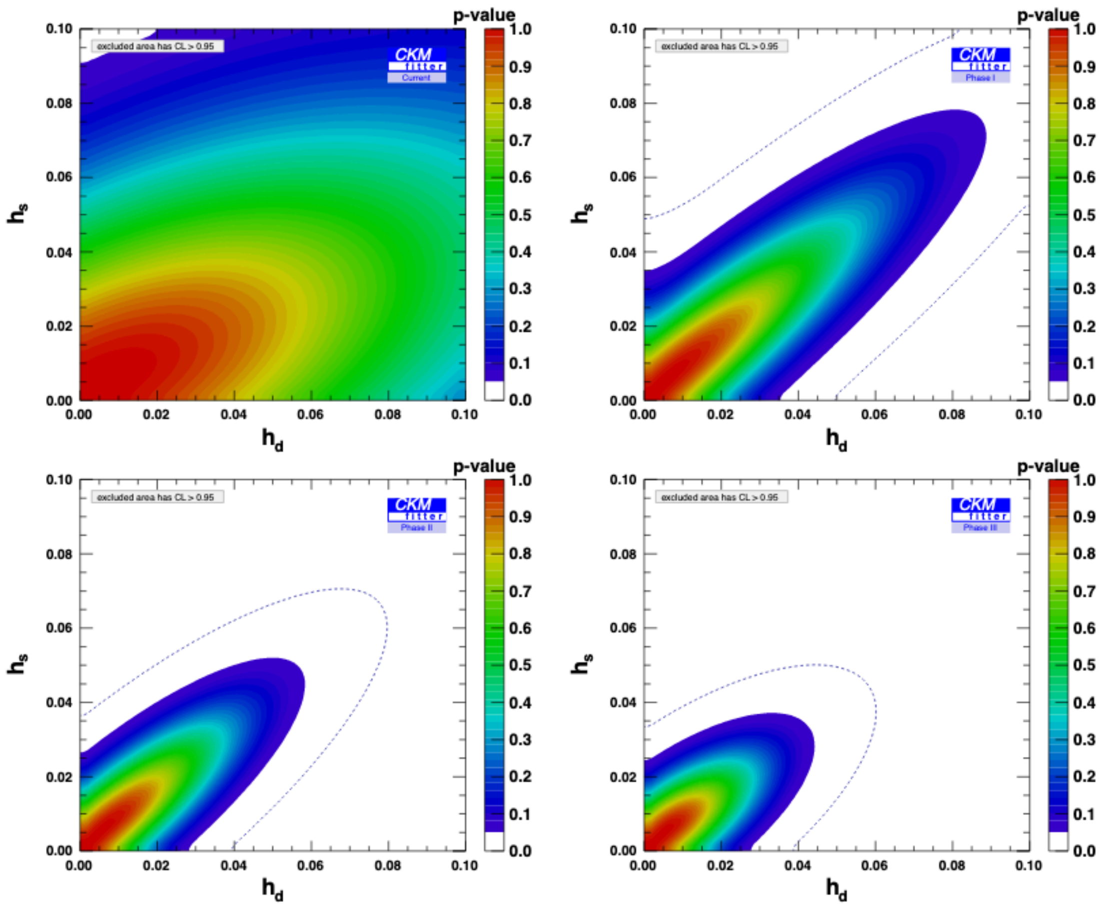


FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ)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

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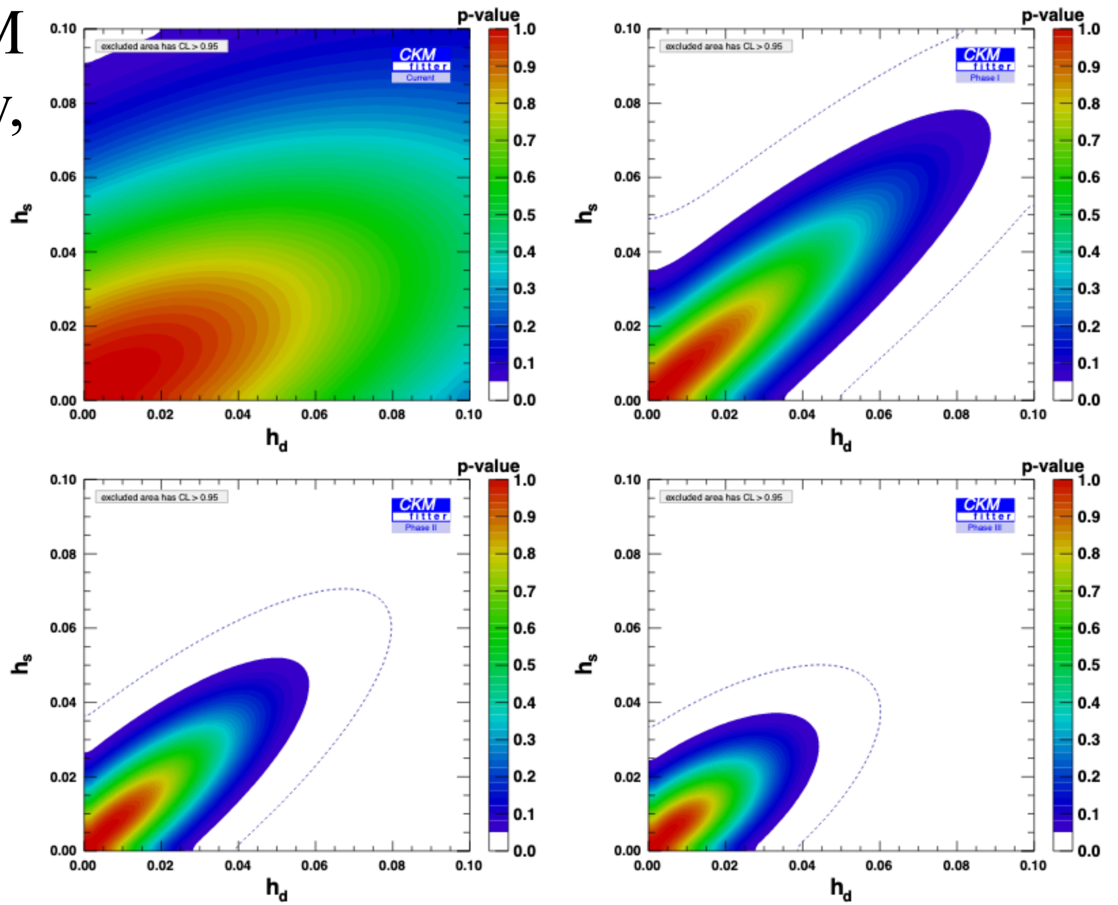
hep-ph 2006.04824

rescaled to SM

— Now,



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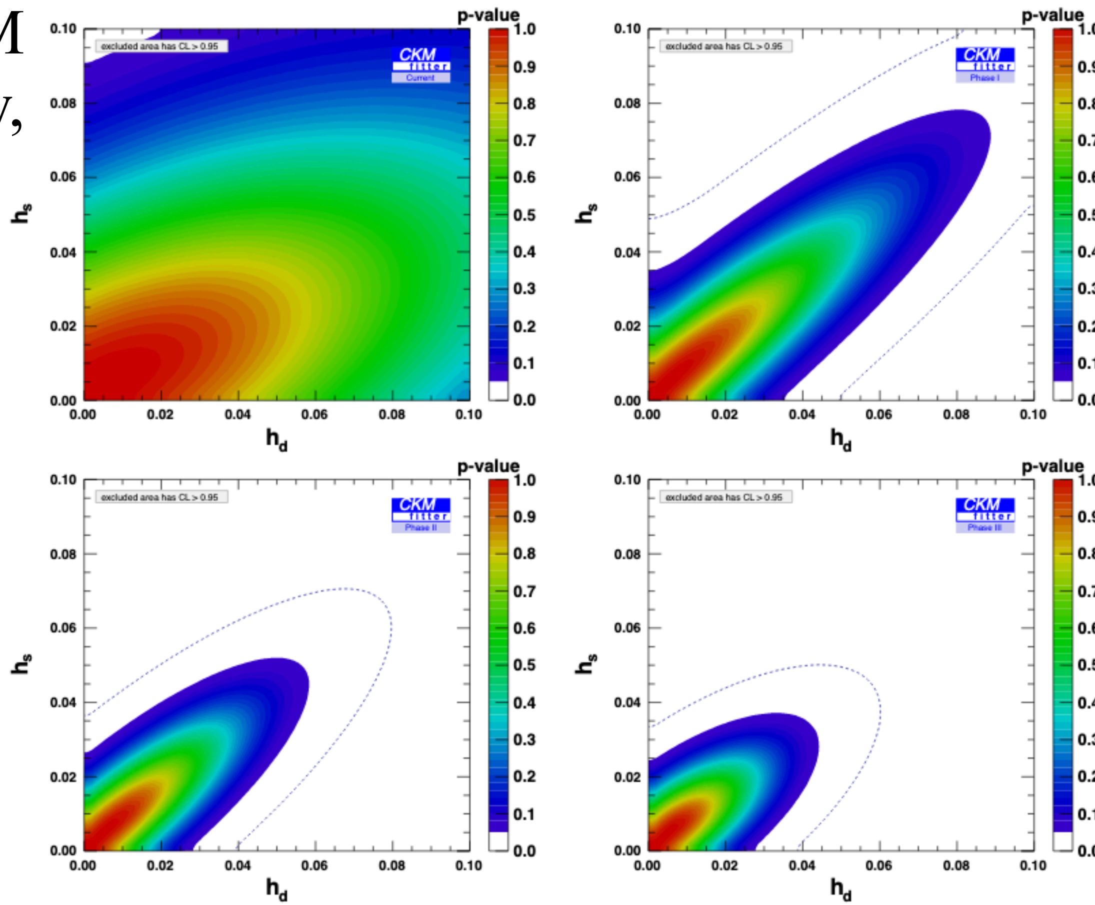
hep-ph 2006.04824

rescaled to SM

— Now,

after LHCb-U1 and Belle II — 2030



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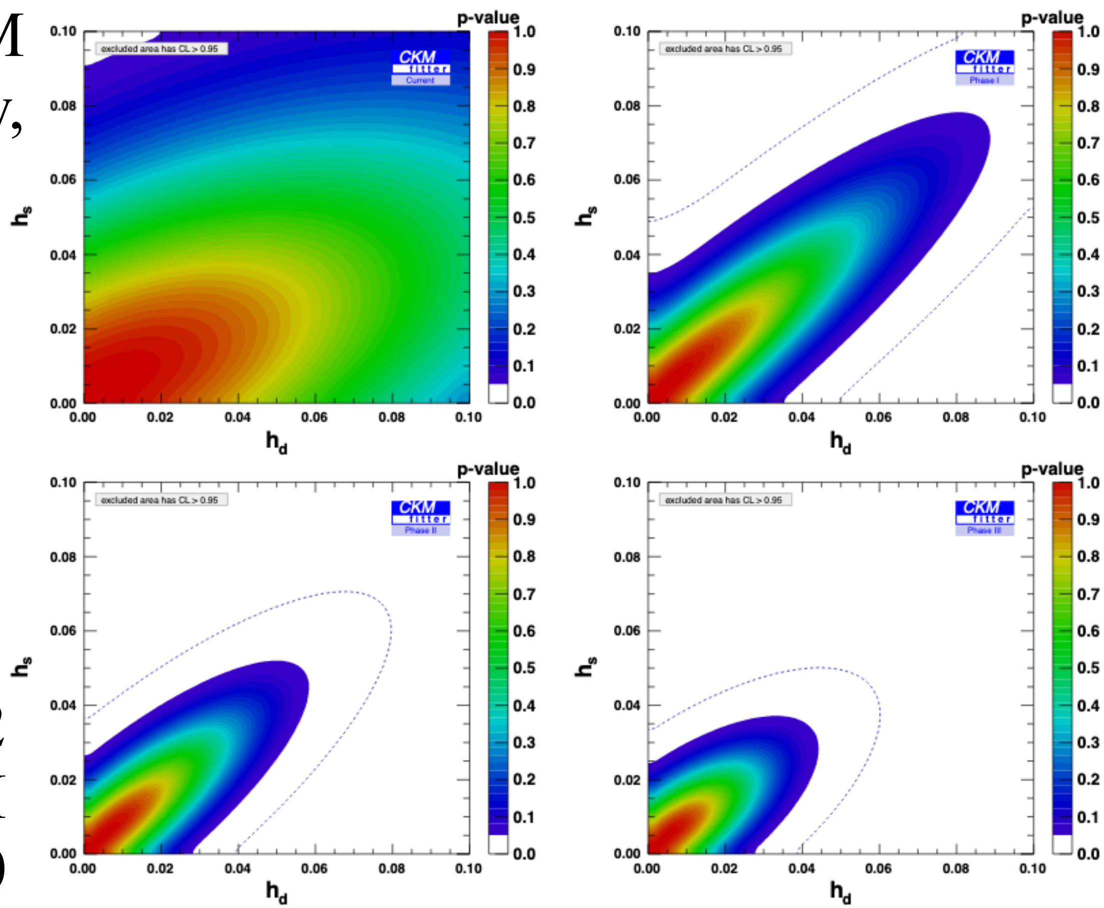
rescaled to SM — Now,

after LHCb-U1 and Belle II — 2030

after LHCb U2 and Belle III — 2040



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after LHCb-U1 and Belle II — 2030

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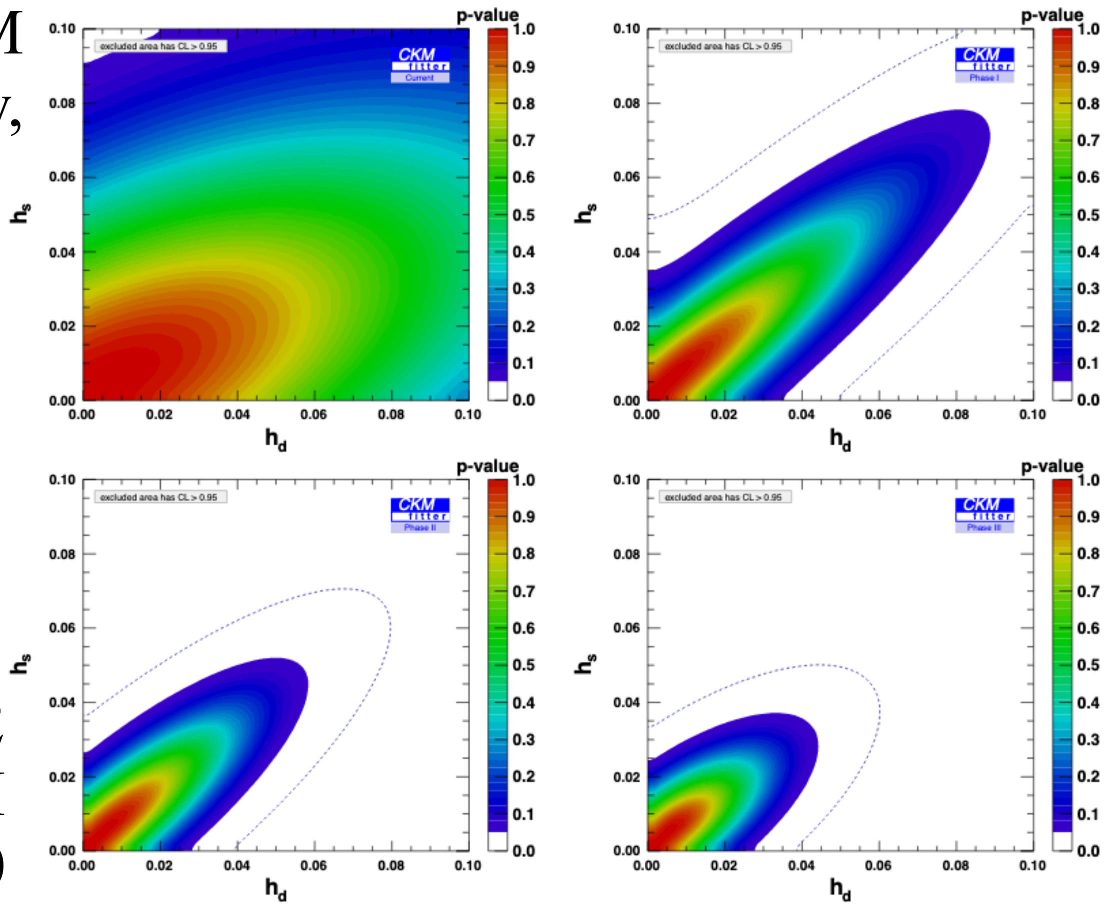
Vcb improved LQCD not



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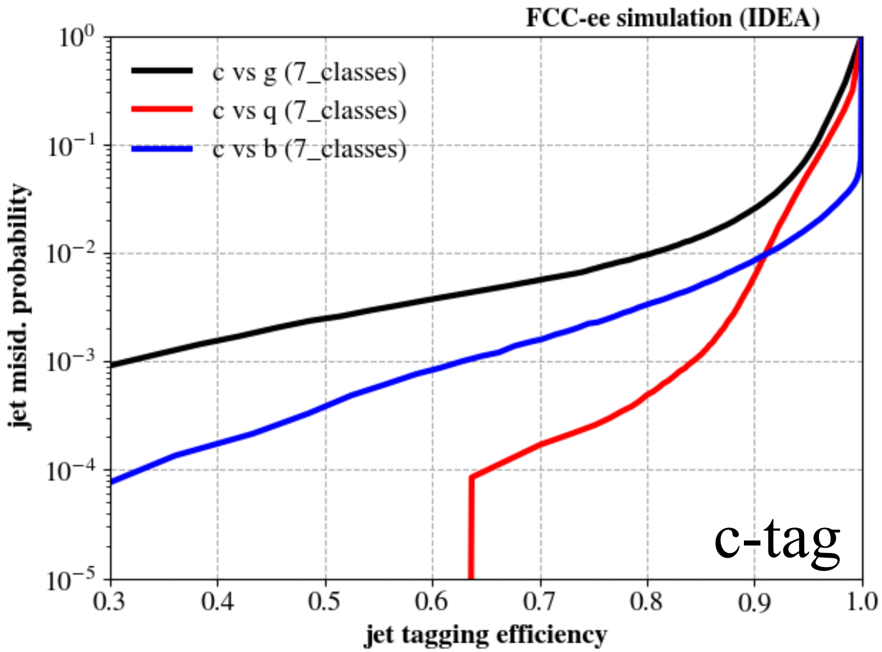
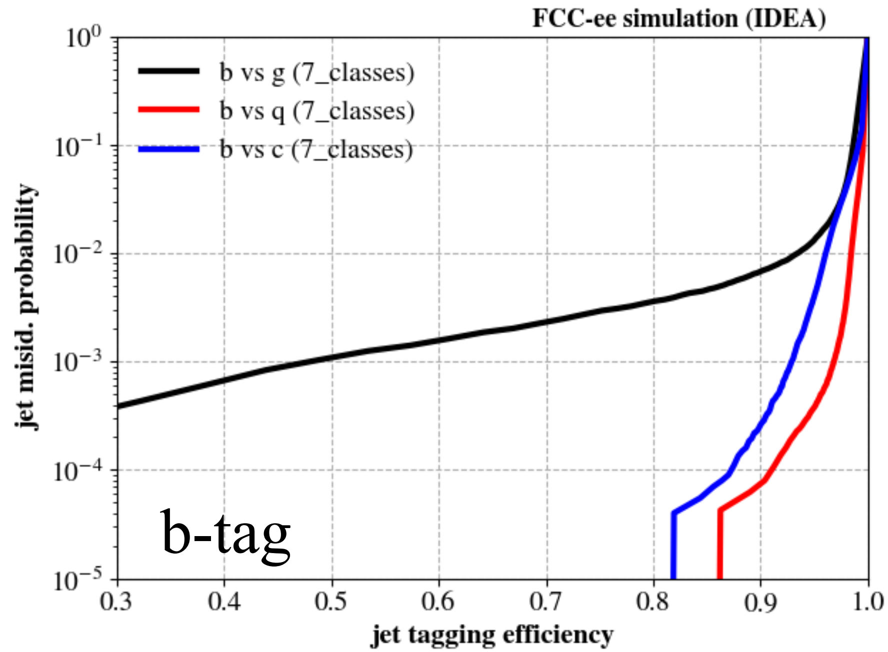
6) Focus#1: the CKM matrix element V_{cb}

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

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

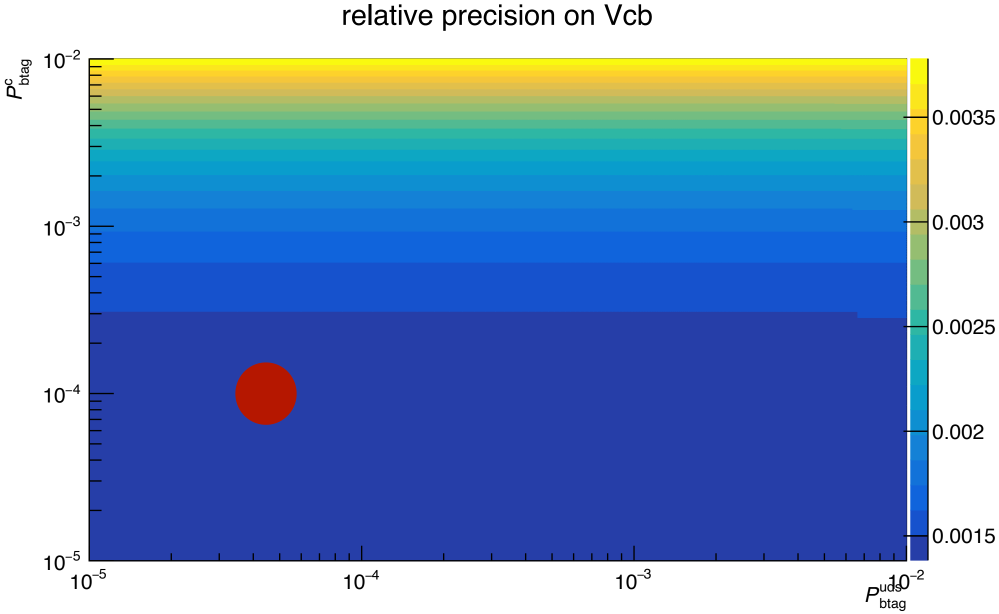




6) Focus#1: the CKM matrix element V_{cb}

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

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



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

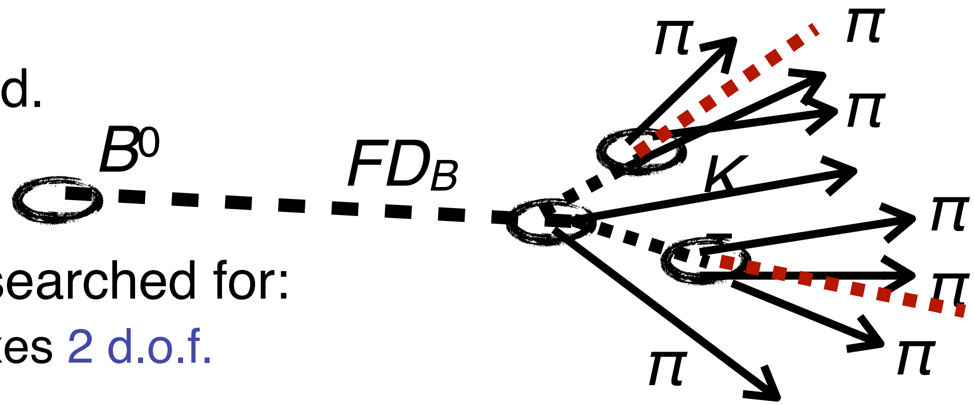
6) Focus#2: the transition $b \to s\tau^+\tau^-$

The scope:

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

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

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



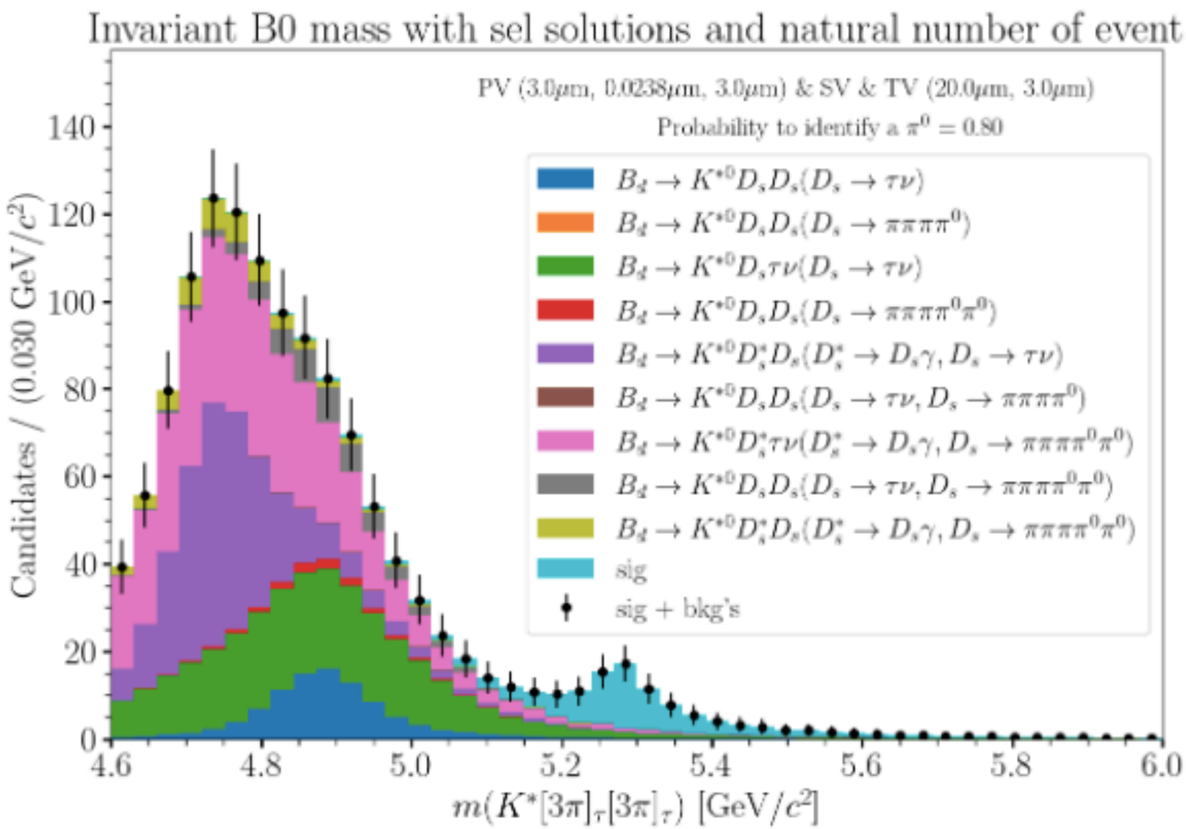
- Six momentum components to be searched for:
  - B^0 momentum direction from $K\pi$ fixes 2 d.o.f.
  - τ momenta direction fixes 4 d.o.f.
  - Mass of the τ provides 2 additional constraints
  - Since both tau legs provide quadratic equations, one ends up w/ 4 solutions.
  - Yet, the system is over-constrained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

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

Decay	BF (SM/meas.)	Intermediate decay	BF_had	Additional missing particles
Signal : $B^0 \to K^*\tau\tau$	1.30×10^{-7}	$\tau \to \pi\pi\pi\nu$, $K^* \to K\pi$	9.57×10^{-11}	
Backgrounds $b \to c\bar{c}s$:				
$B^0 \to K^{*0}D_sD_s$	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, $2\pi^0$

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

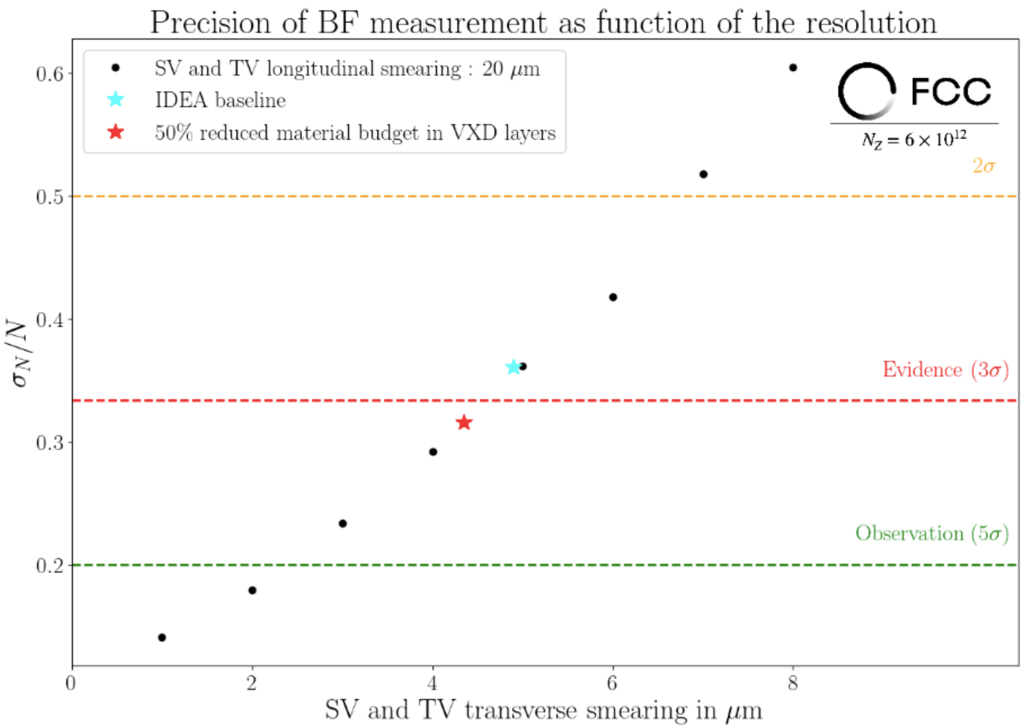
- $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$: topological reconstruction + selection



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

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

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



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