Physics and detectors

Flavour Physics in Belle II

65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders - Frascati, 13.09.2022

Overview of tau physcis at present and future e^+e^- colliders

INTRODUCTION TO FLAVOUR PHYSICS

Searches for feebly interacting new particles at FCC-ee

Latest results on Kaon Physics at KLOE-2

STCF Detector and Physics Program

Higgs physics at CEPC

Flavor physics at Future Circular Lepton Collider

Detector requirements at FCC-ee

Dark sector in Belle II

MgB_2 CONDUCTORS FOR FUTURE DETECTOR MAGNETS

65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022)

B. Di Micco - Università degli Studi di Roma Tre e I.N.F.N.

Open questions and shortcomings of the SM

?	Need new matter (or even bigger modifications to the SM)
	Adjusting one SM parameter might do
	Adjusting several SM parameters might do
~~EFT~~	Separation of scales as an organizing principle might fail

- ? what is the dark matter in the Universe?
- why QCD does not violate CP?
- how have baryons originated in the early Universe?
- what originates flavor mixing and fermions masses?
- what gives mass to neutrinos?
- ~~EFT~~ why gravity and weak interactions are so different?
- ~~EFT~~ what fixes the cosmological constant?

EACH of these issues one day will teach us a lesson

the usual questions, with the "standard" answers

Open questions and shortcomings of the SM

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- ? • what is the dark matter in the Universe? **neutralino**
- • why QCD does not violate CP? **axions**
- • how have baryons originated in the early Universe? **B-L violation at big bang ?**
- • what originates flavor mixing and fermions masses? **?, no answer**
- • what gives mass to neutrinos? **heavy neutrinos**
- ~~EFT~~ • why gravity and weak interactions are so different? **SUSY**
- ~~EFT~~ • what fixes the cosmological constant? **?**

EACH of these issues one day will teach us a lesson

the usual questions, with the “standard” hoped answers

When ?

Open questions and shortcomings of the SM

? Need new matter (or even bigger modifications to the SM)
Adjusting one SM parameter might do
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~~EFT~~ Separation of scales as an organizing principle might fail

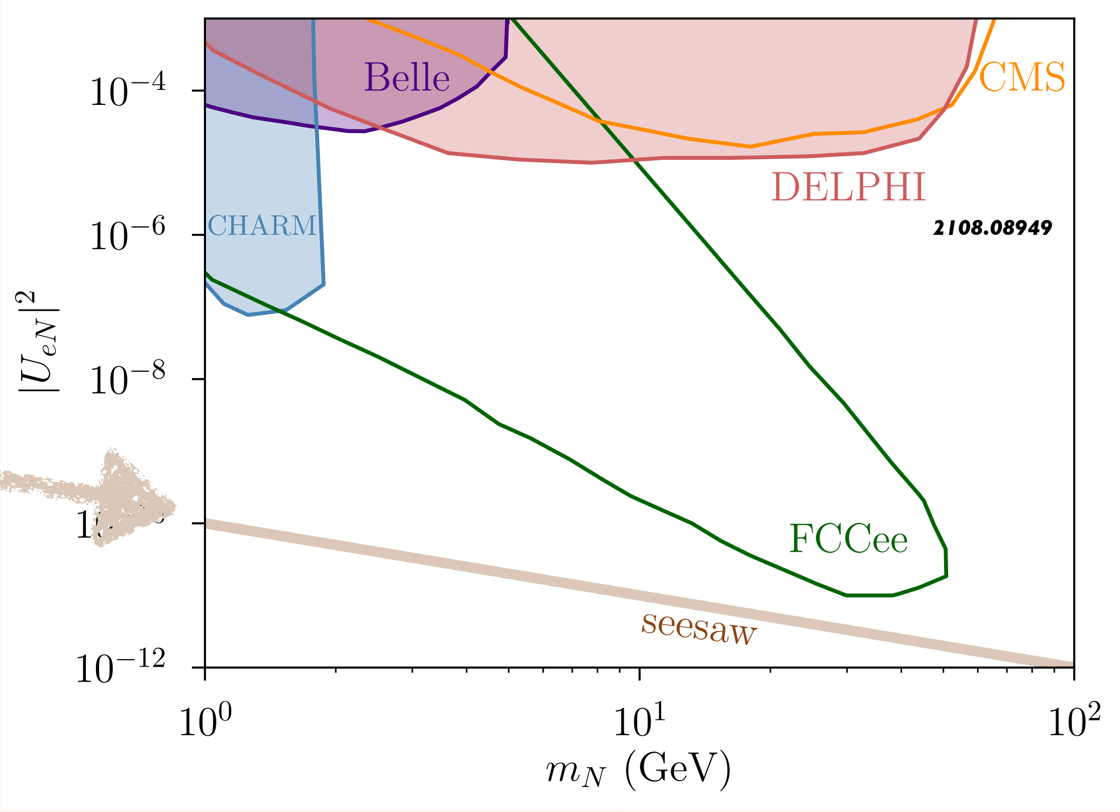
- ? what is the dark matter in the Universe? **neutralino (10 TeV SUSY?)**
- why QCD does not violate CP? **axions (aestethic) ?**
- how have baryons originated in the early Universe? **B-L violation in heavy neutrinos (planck mass cale ?)**
- what originates flavor mixing and fermions masses? **?, no answer**
- what gives mass to neutrinos? **heavy neutrinos (planck mass scale ?)**
- ~~EFT~~ why gravity and weak interactions are so different? **?**
- ~~EFT~~ what fixes the cosmological constant? **?**

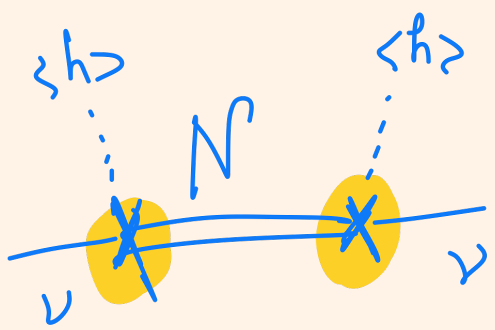
EACH of these issues one day will teach us a lesson

the usual questions, with the “standard” hoped answers

Very high-lumi Z-pole

$$m_\nu \simeq \frac{y_\nu^2 v^2}{M}$$





Long-lived signature

Prototypical: what if $m_N \sim M_{PL}$?

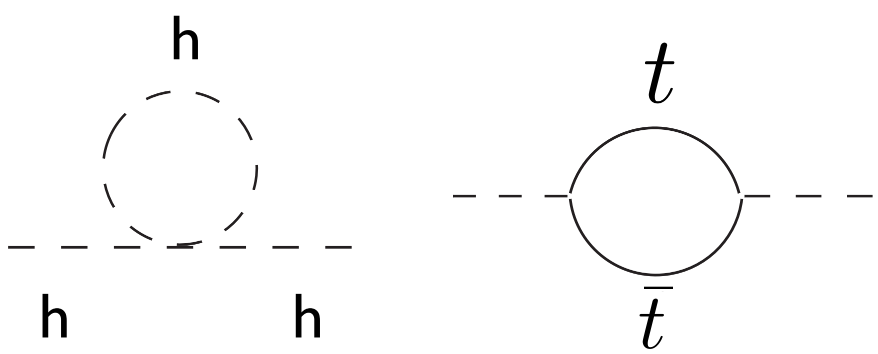
- depends crucially on lumi (within the mass range that can be probed by the machine)
- suggests a new signature (•‿•)
- there are alternative theoretical models (most of which cannot be probed at the same machine) ¯_(ツ)_/¯

The problem of post-LHC physics is not the missing of open problems, what we miss is a simple solution that we are able to explore with our tools.

It is a different way to phrase a no-loose theorem

The “old” naturalness problem

Quantum corrections at 1-loop give contribution to the Higgs boson mass.



At Planck scale M_{pl} = 1.2 × 10^{19} GeV, we expect gravity to enter in the game. The physics mass and the bare mass are linked by the relation:

Li-gong Bian, arXiv: 1303.2402

$$(m_H^0)^2 = (m_H)^2 + \frac{2\Lambda^2}{(4\pi)^2 v^2}\left[3(m_H)^2 - 12(m_t)^2 + 6(m_W)^2 + 3(m_Z)^2\right]$$

bare mass (parameter that we put in the lagrangian)

Physical mass (renormalised, 125 GeV)

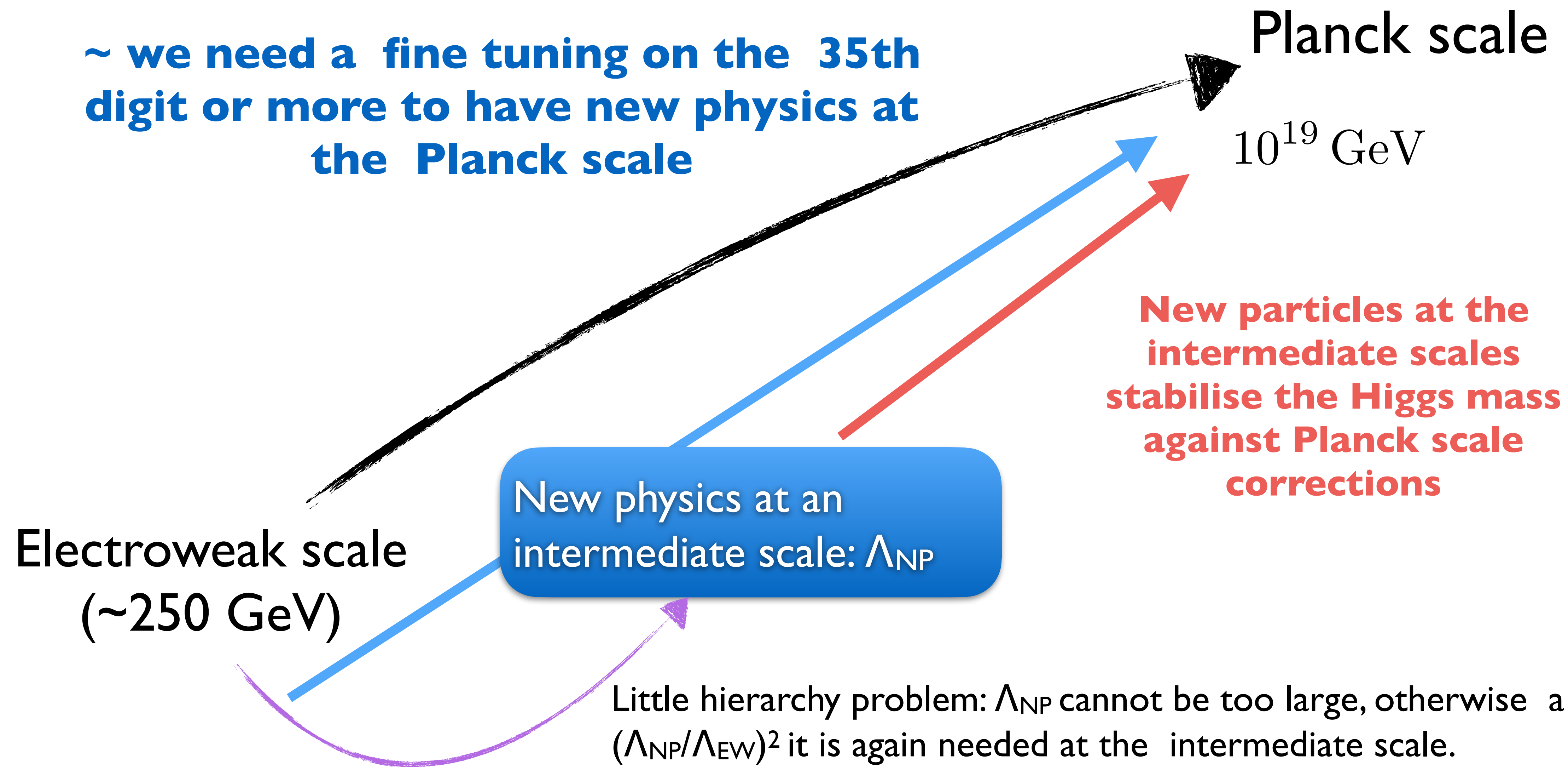
cut-off value, M_{pl}

h_0 ~ 246 GeV

$$(m_H^0)^2 = 15647.5081 - 0.05928573148564 \times 10^{38} = -5928573148563999999999999999984352.4919$$

$$m_H^2 = 0.05928573148564 \times 10^{38} - 5928573148563999999999999999984352.4919$$

If we want that the bare mass is fied by some more fundamental theory at the Planck mass such theory needs to tune the parameters of the Standard Model with a precision of 35 digits **(the fine tuning problem)**



Little hierarchy problem: Λ_{NP} cannot be too large, otherwise a fine tuning of $(\Lambda_{NP}/\Lambda_{EW})^2$ it is again needed at the intermediate scale.

$\Lambda_{NP} \sim 1$ TeV ~fine tuning 0.06
$\Lambda_{NP} \sim 10$ TeV ~ fine tuning $6\ 10^{-3}$
$\Lambda_{NP} \sim 100$TeV ~ fine tining $6\ 10^{-6}$

We didn't find new physics at TeV scale doesn't make the argument less valid (it is less strong, but we are still quite far from the 35 digits problem)

Today particle physics crisis holds because one wanted to have SUSY at the TeV scale, but it fixes a fine tuning of 6%, that is quite large !!

Natural fine tuning: $(m_n - m_p)/m_p \sim 0.3\%$!!

$m_n < m_p$ proton can decay, no atom can be formed

$m_n - m_p >$ few MeV neutron can decay inside nuclei (nothing more than hydrogen)

a 0.3% fine tuning looks natural

We don’t know where new physics is, but we know that there is new physics and higher it is in energy more fine tuned it looks!!

Looking under the corner is the way to go, and precision physics through indirect measurements is the most cost-effective way to scan large scales.

Direct searches can be done when we will know where new physics is and if we can reach that energy !!

Some people were not surprised to not have found new physics at LHC, flavour physics and LEP precision measurements already had told us that there was space only for the Higgs boson at the TeV scale.

This became evident once the Higgs boson was observed.

Now we need to go further and explore the 10 - 100 TeV scale !!

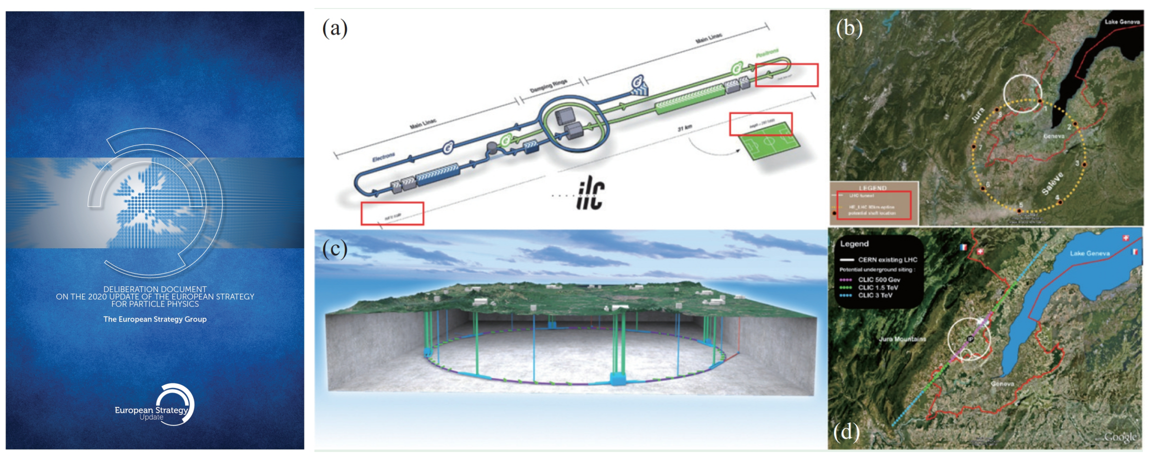
Present and next colliders

Electron Positron Higgs factories

High-priority future initiatives

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

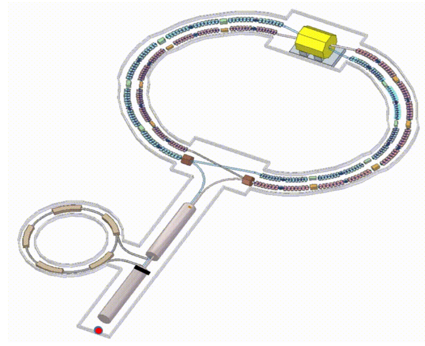
ILC (a):	TDR @ 2013
FCC (b):	CDR @ 2019
CEPC (c):	CDR @ 2018
CLIC (d):	CDR @ 2013



- all next collider projects, focus on e+ e- factories
- The main focus is precision physics, achievable with high luminosity e+ e- colliders

Super τ-charm factory

❖**STCF: a natural extension of the Beijing Electron-Positron Collider (BEPC II) and a viable option for a post-BEPCII HEP project in China.**

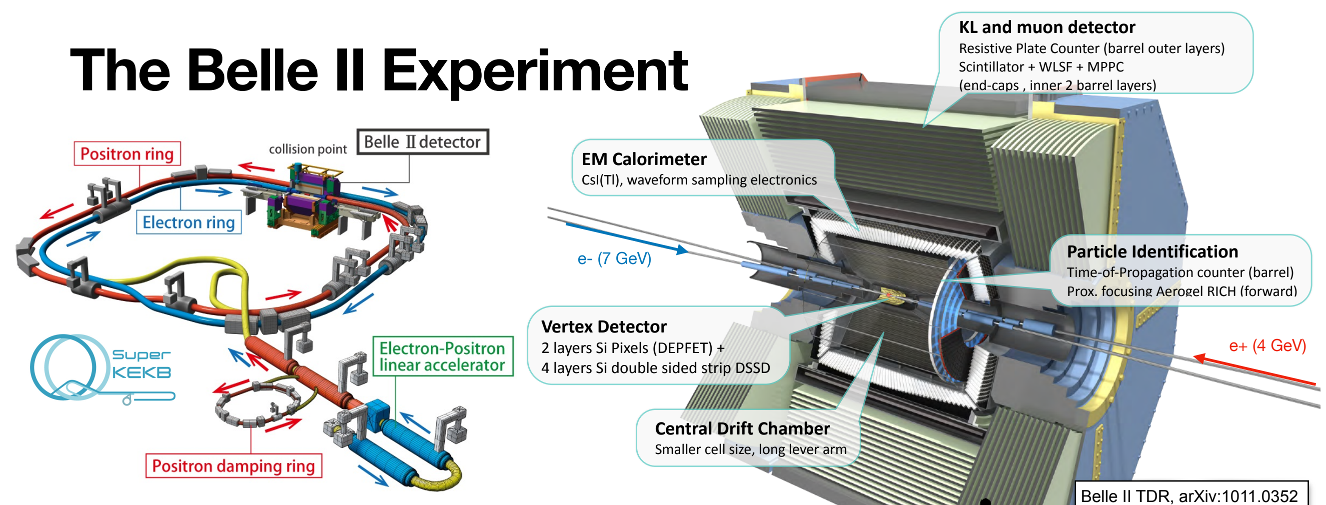


- **Extended energy region: E_{cm} = 2-7 GeV**
- **Super high luminosity: L >0.5×10^{35} $cm^{-2}s^{-1}$@4 GeV**
- Linac injector: ~300 m, storage ring: ~600 m
- Large Piwinski angle & Crab waist
- Potential for luminosity upgrade and a polarized electron beam

An super τ-c machine far beyond BEPCII

B factories

The Belle II Experiment



- **Belle II/SuperKEKB** succeed Belle detector and KEKB collider.
- **SuperKEKB:** Nano-beam scheme to achieve high luminosity.
- **Belle II:** new detector with improved vertex reconstruction and particle identification.

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Flavour projections

PROSPECTS: LHCb UPGRADES + BELLE II

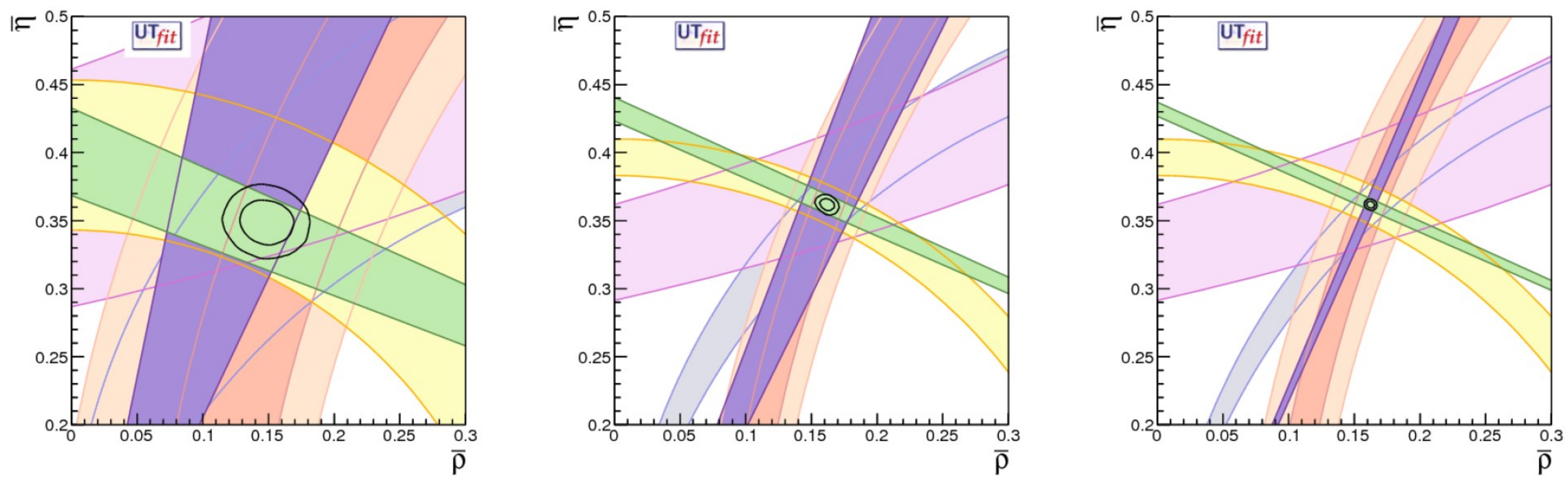


Fig. 23: Present (left) and future (center: phase 1, right: phase 2) constraints in the $(\bar{\rho}, \bar{\eta})$ plane (UTfit collaboration).

Phase I: 23/fb LHCb; Phase II: 300/fb LHCb, 50/ab Belle II

Table 10: Relative uncertainties on the predictions of UT parameters and angles, using current and extrapolated input values for measurements and theoretical parameters (UTfit collaboration).

	λ	$\bar{\rho}$	$\bar{\eta}$	A	$\sin 2\beta$	γ	α	β_s
Current	0.12%	9%	3%	1.5%	4.5%	3%	2.5%	3%
Phase 1	0.12%	2%	0.8%	0.6%	0.9%	0.9%	0.7%	0.8%
Phase 2	0.12%	1%	0.6%	0.5%	0.6%	0.8%	0.4%	0.5%

L. Silvestrini

1812.07638

PROSPECTS: FCC-ee

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-ee
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\lvert V_{ub}\rvert$ (precision)	5.9%	2.5%	6%	1%
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	same
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	same
a^d_{fs} (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
a^s_{fs} (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2

L. Silvestrini

FCC Phys. Opp.

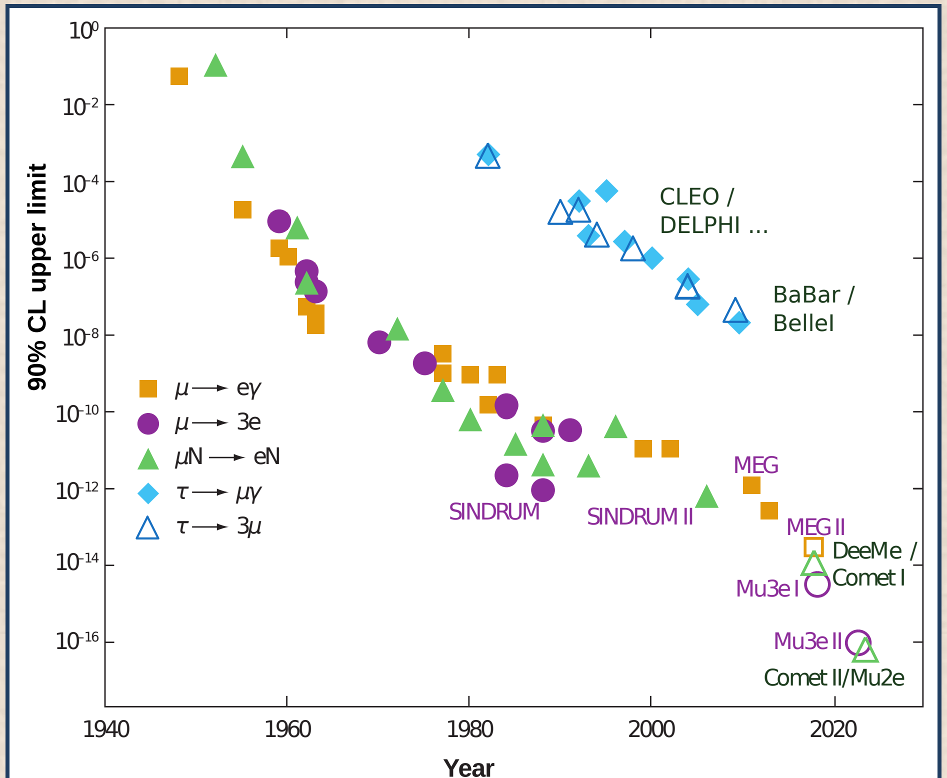
τ physics

A. Lusiani

	CLEO, CLEOIII	LEP 100	Belle, BABAR	Belle II	SCT	STCF	CEPC(Z)	FCC-ee(Z)
E_{CM} [GeV]	∼10.6	92	∼10.6	∼10.6	2 – 6	2 – 7	92	
$\int \mathcal{L}dt$ [ab^{-1}]	0.01		1.5	50	10			
tau pairs	$1{\cdot}10^7$	$0.8{\cdot}10^6$	$1.4{\cdot}10^9$	$46{\cdot}10^9$	$30{\cdot}10^9$		$30{\cdot}10^9$	$165{\cdot}10^9$

note: SCT & SCFT tau pairs estimate assuming 10 years of tau-pairs-optimized CM energies running

Lepton Flavour Violation



Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008)

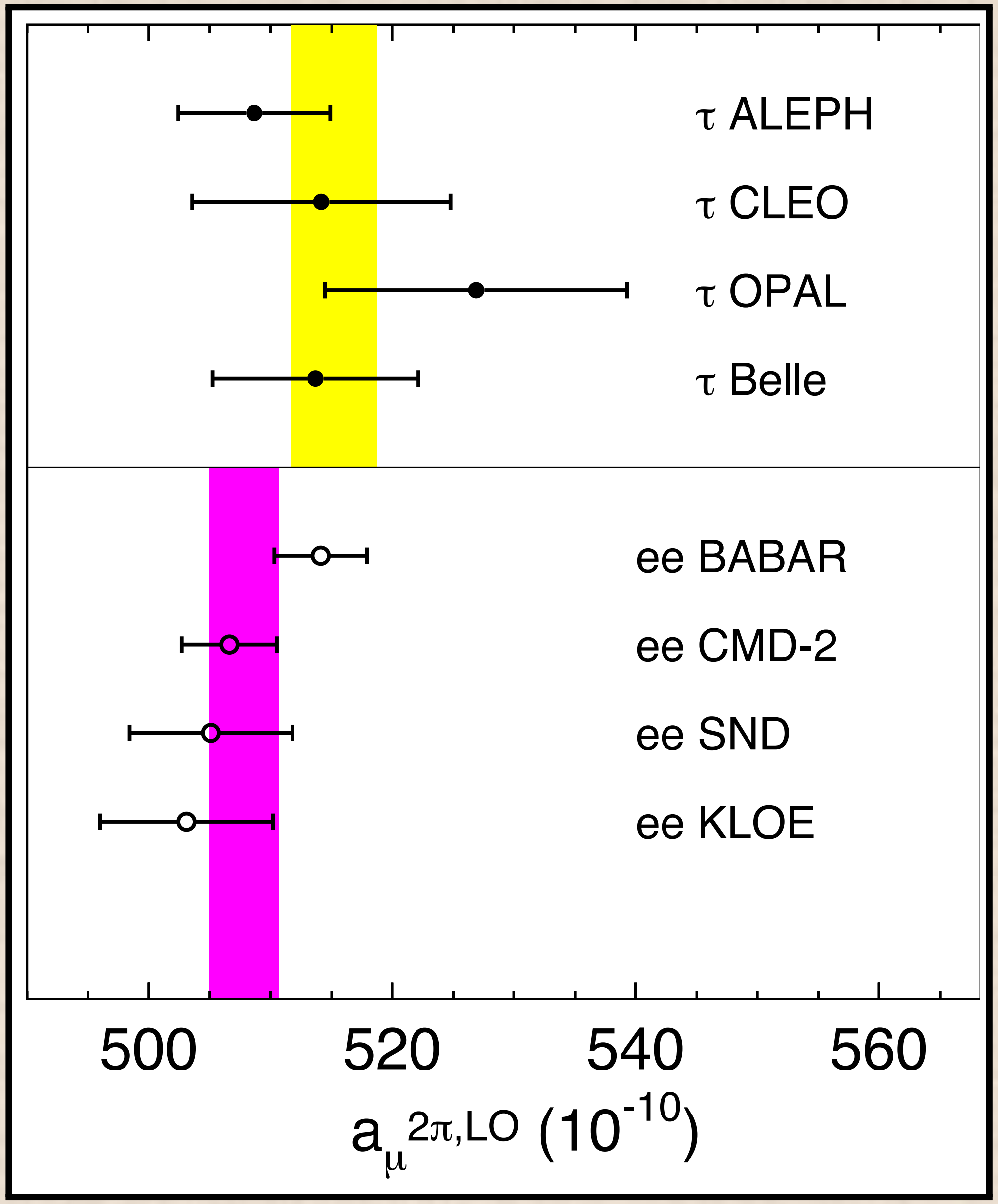
- NP effects usually scale as $\frac{m_\tau^2}{m_\mu^2}$
- muon LFV searches more powerful
- tau LFV has more channels
  ⇒ discrimination on NP models
  ⇒ more powerful for specific models

Muon $g-2$ hadronic contribution from tau

A. Lusiani

- $\alpha_\mu^{2\pi,\text{LO}}$ from
  - $\tau \to \pi\pi^0\nu$ spectral function
  - normalization could come from $\mathcal{B}(\tau \to \pi\pi^0\nu)$, τ_τ
  - isospin rotation (associated theory systematics)
- best experimental inputs e^+e^- facilities at the Z peak
  - modest experimental progress since LEP times
  - statistics, clean data, non-trivial analysis needed
- tau data $\Rightarrow$ reduced discrepancy with exp.
- presently e^+e^- data more precise and complete

Davier 2013



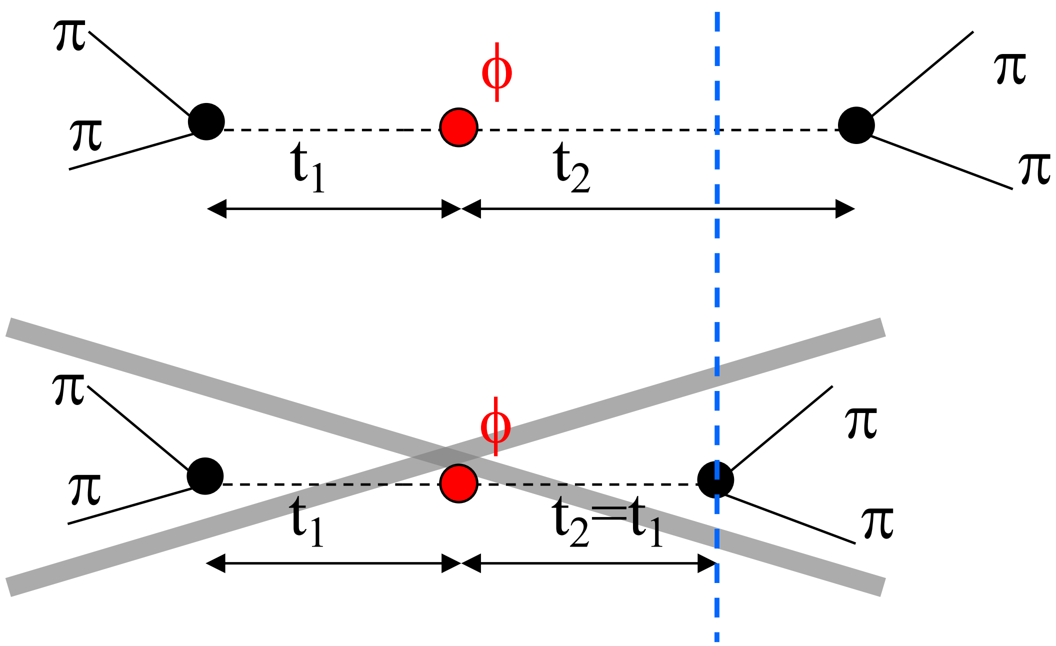
Requirements

- improved isospin-violating and EM corrections for $\tau \to \pi^0\pi\nu_\tau$
- tau spectral functions
- tau branching fractions

theoretical and experimental effort needed to reconcile τ data with e^+e^-

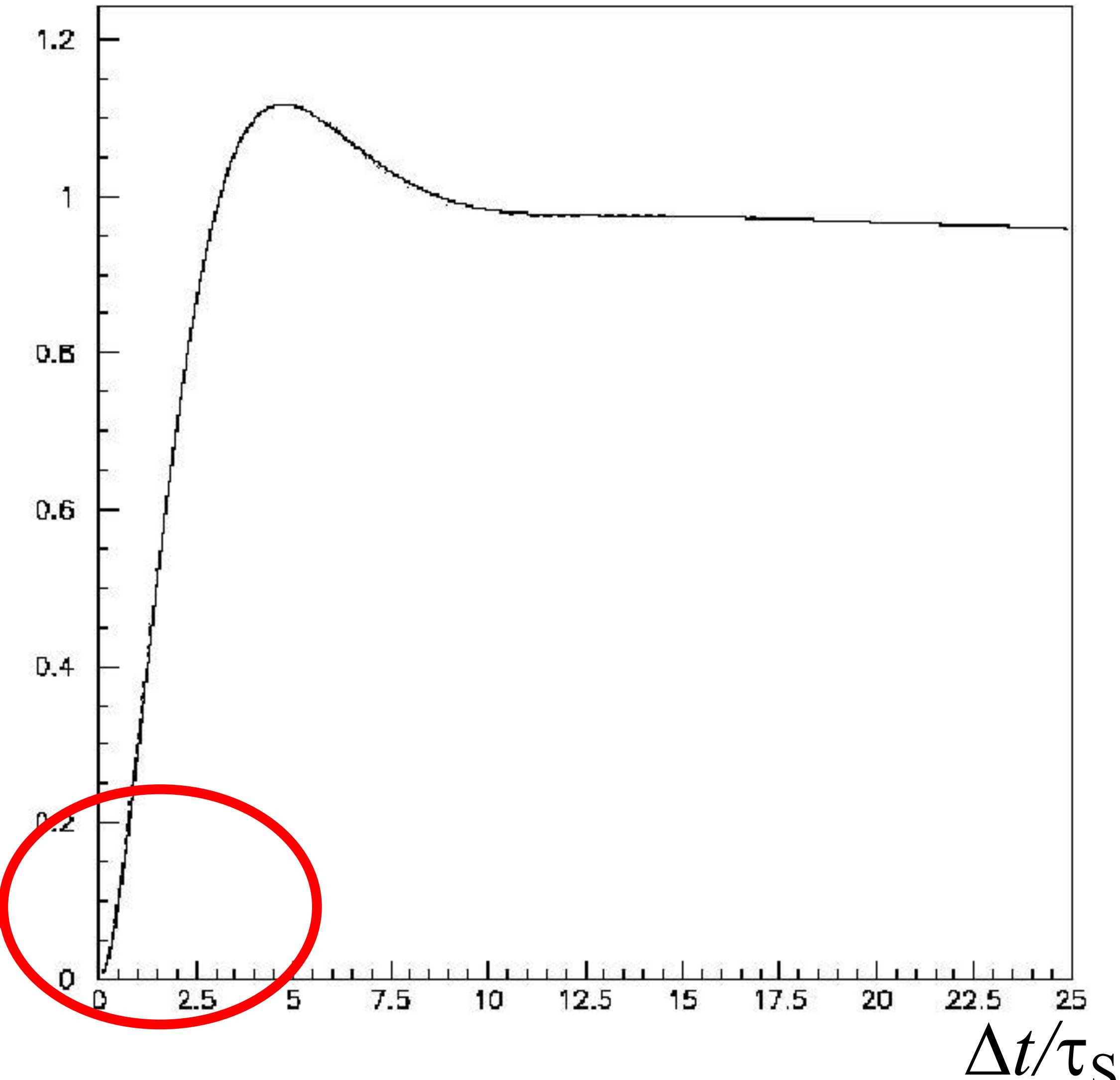
Planck scale test at KLOE with quantum decoherence

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$



Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$

(this specific channel is suppressed by CP viol. $|\eta_{+-}|^2 = |A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-)|^2 \sim |\varepsilon|^2 \sim 10^{-6}$)



EPR correlation:

no simultaneous decays (Δt=0) in the same final state due to the fully destructive quantum interference

A. Di Domenico

$\Delta t = |t_1 - t_2|$

Planck scale test at KLOE with quantum decoherence

KLOE-2 JHEP 04 (2022) 059

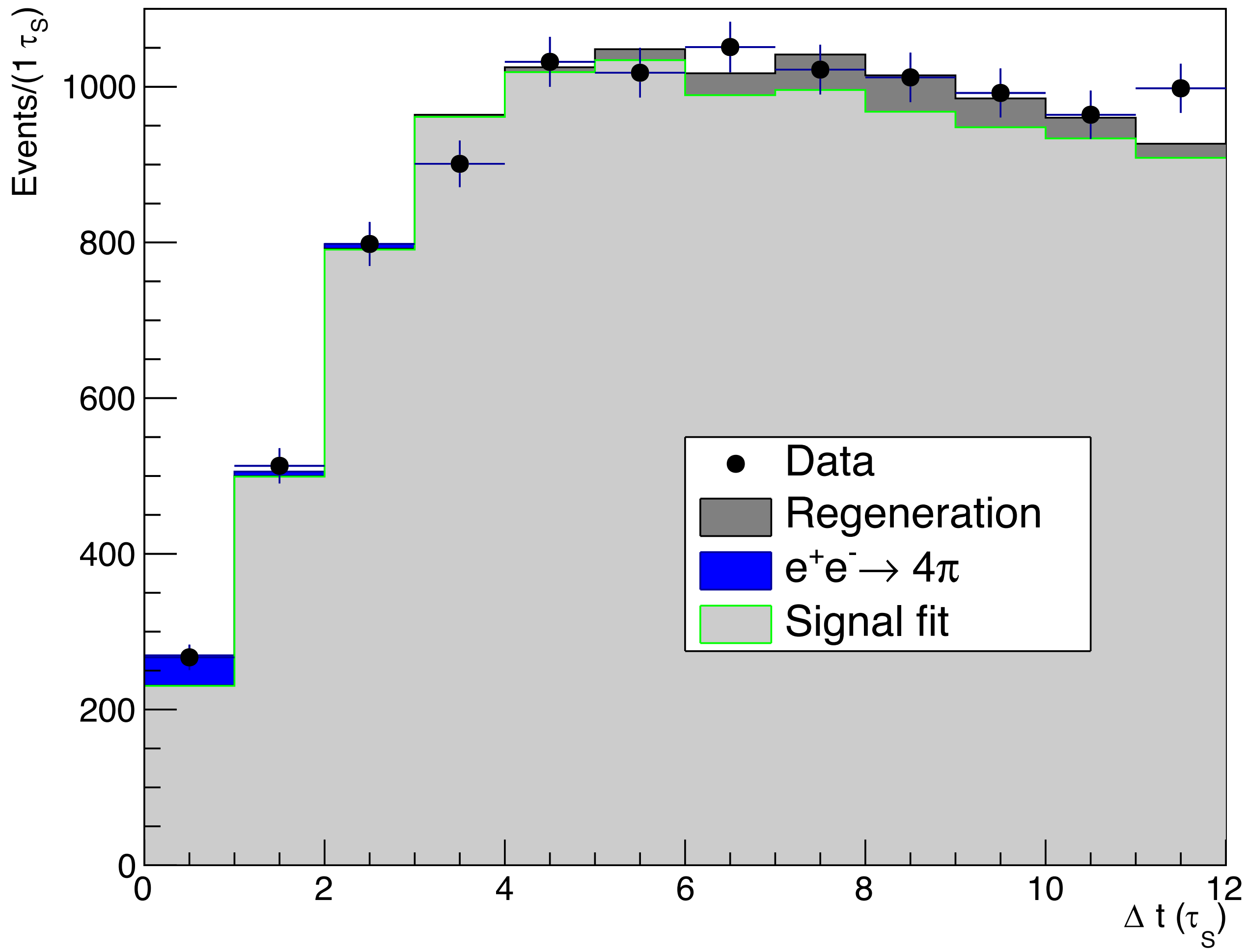
$$\boxed{\zeta_{0\bar{0}} = (-0.5 \pm 8.0_{stat} \pm 3.7_{syst})\times 10^{-7}}$$

CP violating process:
terms $\zeta_{00}/|\eta_{+-}|^2$ with $|\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6}$
=> high sensitivity to ζ_{00} ;
CP violation in kaon mixing acts as amplification mechanism

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

$$\zeta^{B}_{0\bar{0}} = 0.029 \pm 0.057$$

Possible decoherence due quantum gravity effects (apparent loss of unitarity) implying also CPT violation => modified Liouville – von Neumann equation for the density matrix of the kaon system depends on a CPTV parameter γ [J. Ellis et al. PRD53 (1996) 3846]



In this scenario γ can be at most:

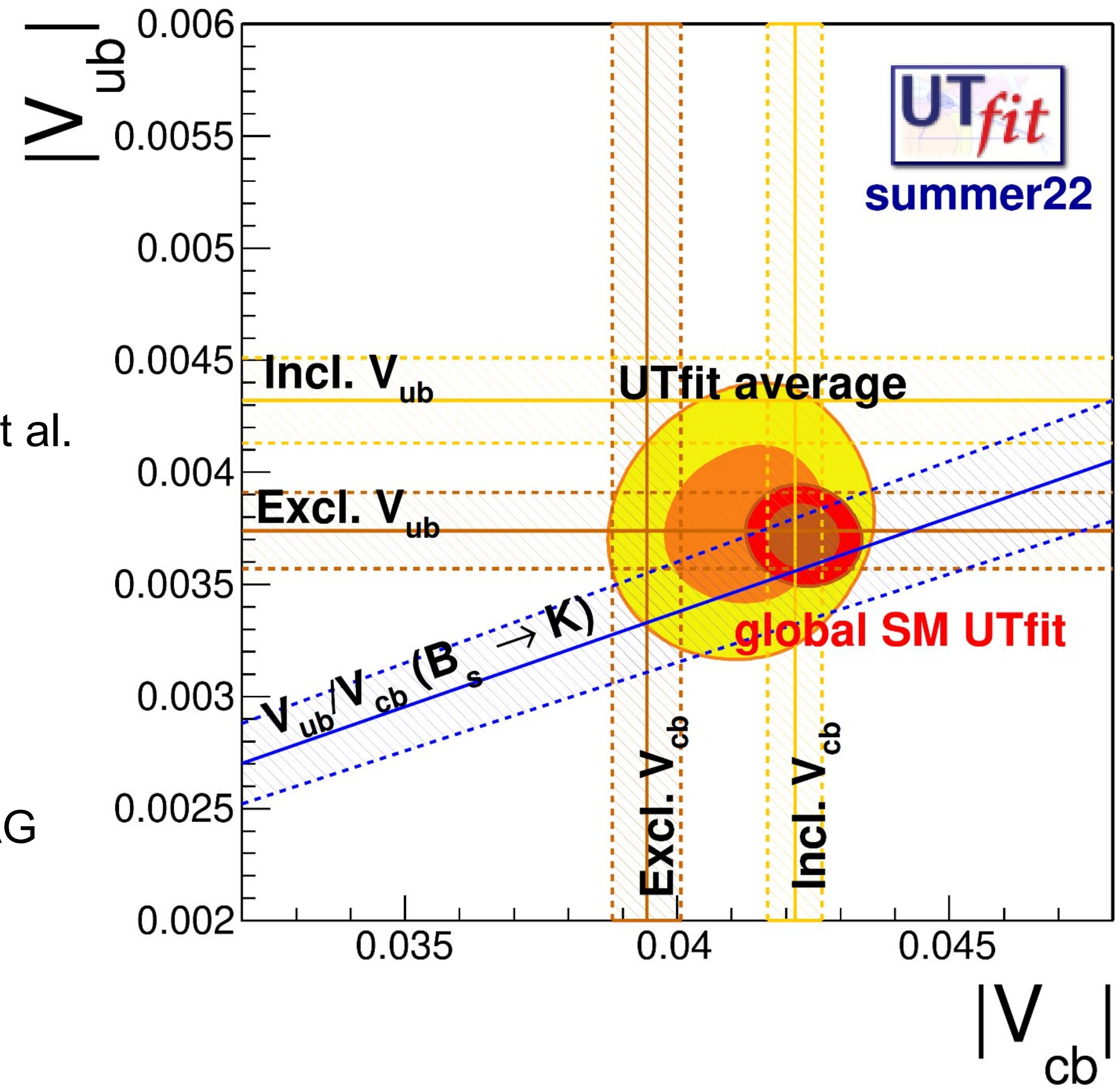
$$O(m_K^2/M_{PLANCK}) = 2\times 10^{-20}\ GeV$$

KLOE-2 result

$$\boxed{\gamma = (1.3 \pm 9.4_{stat} \pm 4.2_{syst})\times 10^{-22}\ \text{GeV}}$$

$|V_{ub}|$ AND $|V_{cb}|$ INCL. & EXCL.

- Skeptic 2D combination of inclusive and exclusive:
  - $|V_{cb}|_{excl} = (39.44 \pm 0.63)\ 10^{-3}$ UTfit
  - $|V_{cb}|_{incl} = (42.16 \pm 0.50)\ 10^{-3}$ Bordone et al.
  - $|V_{ub}|_{excl} = (3.74 \pm 0.17)\ 10^{-3}$ FLAG
  - $|V_{ub}|_{incl} = (4.32 \pm 0.29)\ 10^{-3}$ GGOU
  - $|V_{ub}/V_{cb}| = (8.44 \pm 0.56)\ 10^{-2}$ LHCb/FLAG
- we get:
  - $|V_{ub}| = (3.77 \pm 0.24)\ 10^{-3}$
  - $|V_{cb}| = (41.25 \pm 0.95)\ 10^{-3}$, ρ=0.11



- Global fit:
  $|V_{ub}| = (3.71 \pm 0.09)\ 10^{-3}$,
  $|V_{cb}| = (42.00 \pm 0.45)\ 10^{-3}$

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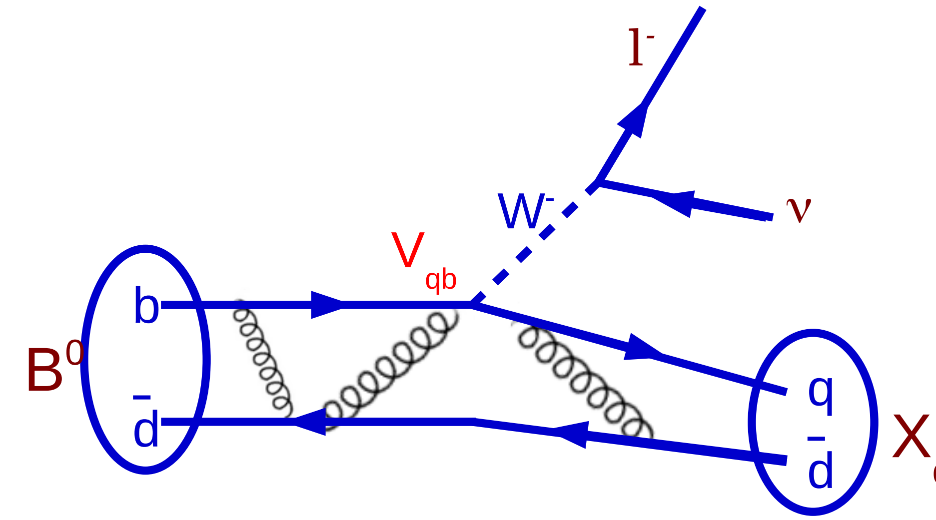
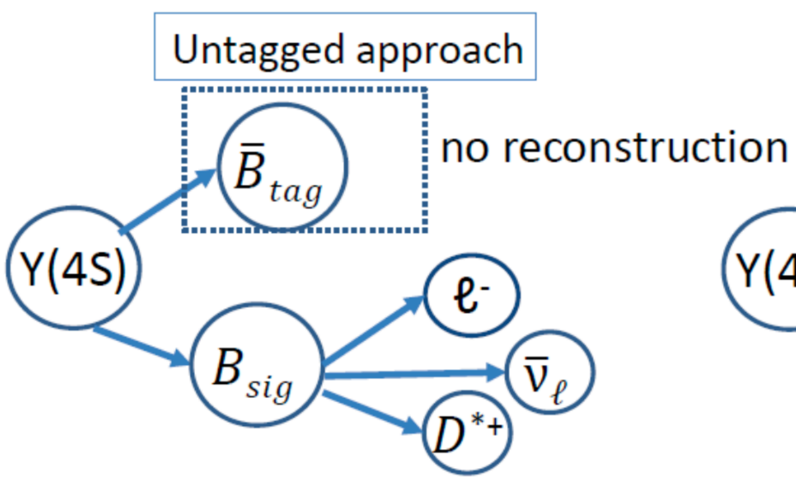
CKM measurements at Belle-2

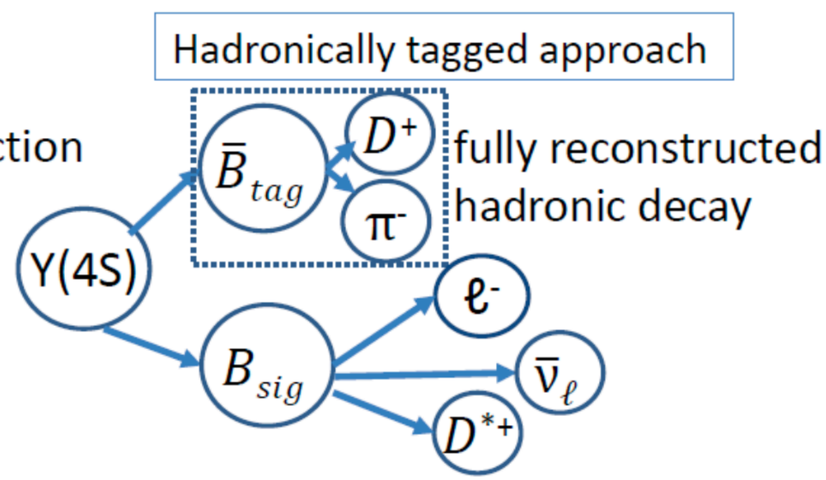
|Vxb| Determination at Belle II

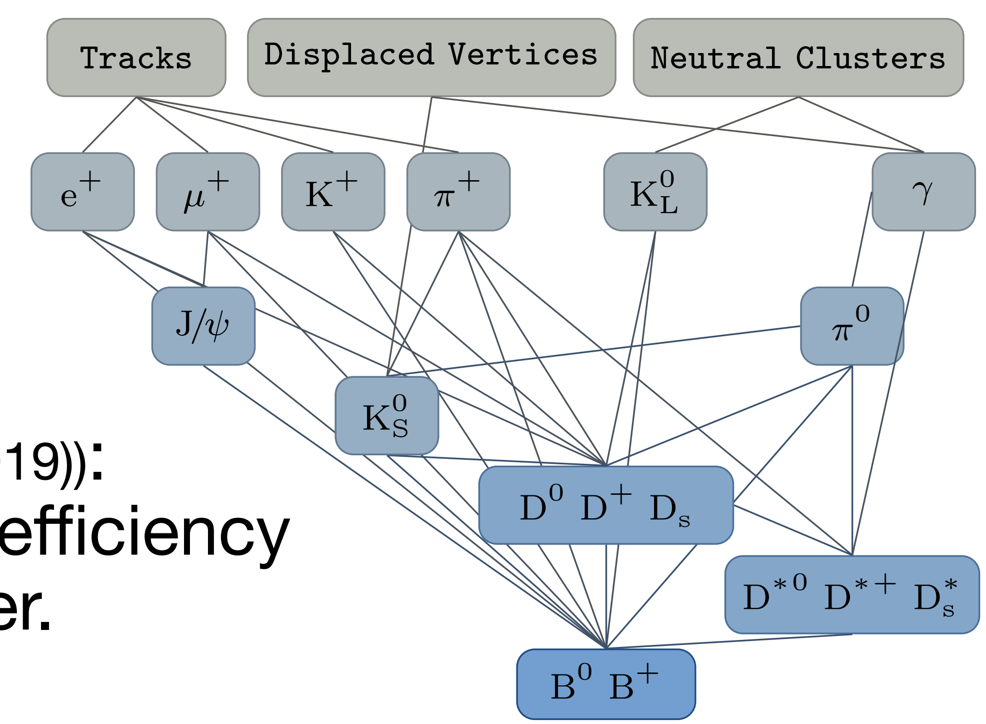


- Measured from tree level semileptonic decays assumed to be free of NP.

- **Belle II** can measure |Vxb| in multiple ways: **inclusive** and **<u>exclusive</u>**, **tagged** (high purity) and **untagged** (high statistics)
  → unique advantage







- **Full Event Interpretation** (Comput Softw Big Sci **3,** 6 (2019)): New tool for B-tag reconstruction with increased efficiency (0.5 (0.3)% for $B^+(B^0)$) using a multivariate classifier.

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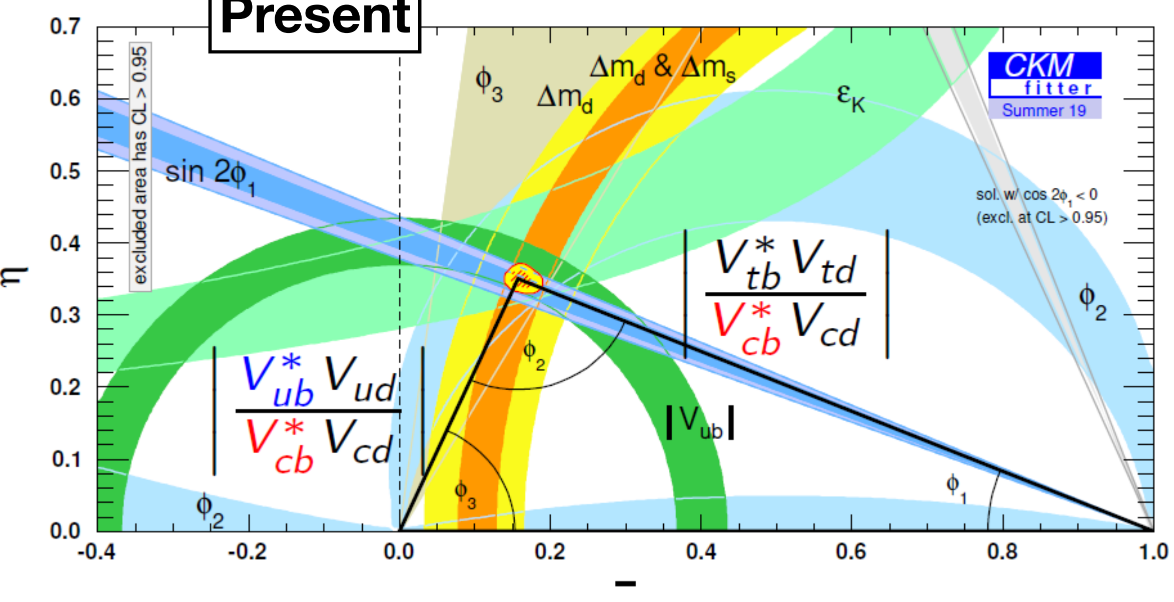
F. Tenchini

High luminosity prospects

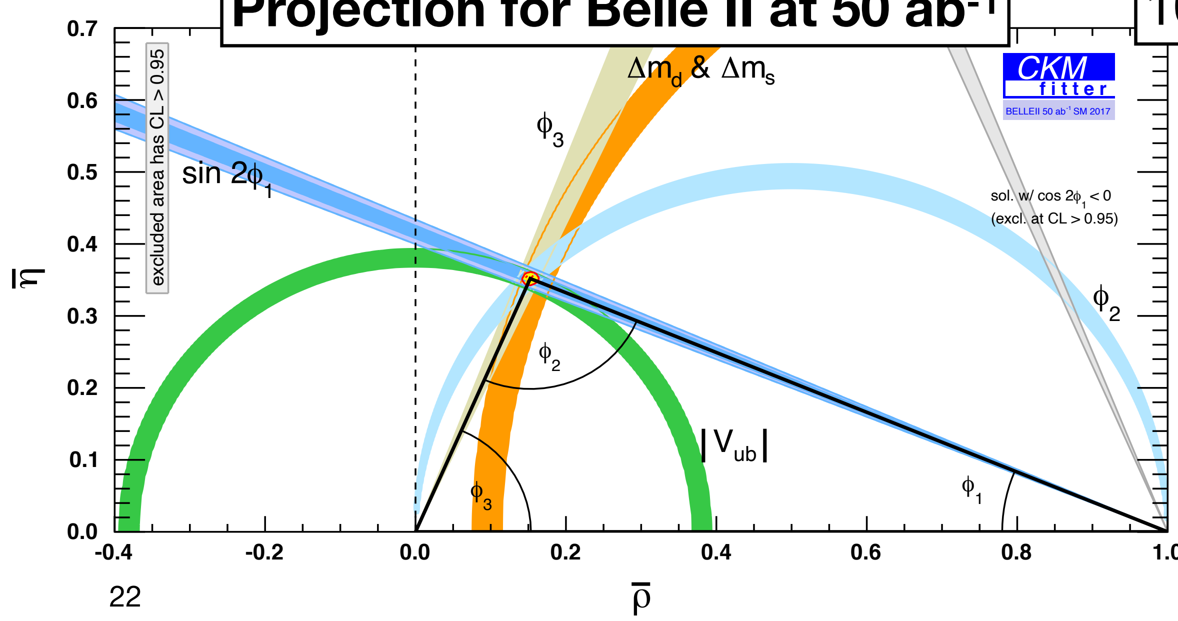
Uncertainties from arXiv: 2203.11349

Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	Belle-II 250 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005	0.002
γ/ϕ_3 (Belle+BelleII)	$11°$	$4.7°$	$1.5°$	$0.8°$
α/ϕ_2 (WA)	$4°$	$2°$	$0.6°$	$0.3°$
$\lvert V_{ub}\rvert$ (Exclusive)	4.5%	2%	1%	$< 1\%$

Present



Projection for Belle II at 50 ab-1



10.1093/pt

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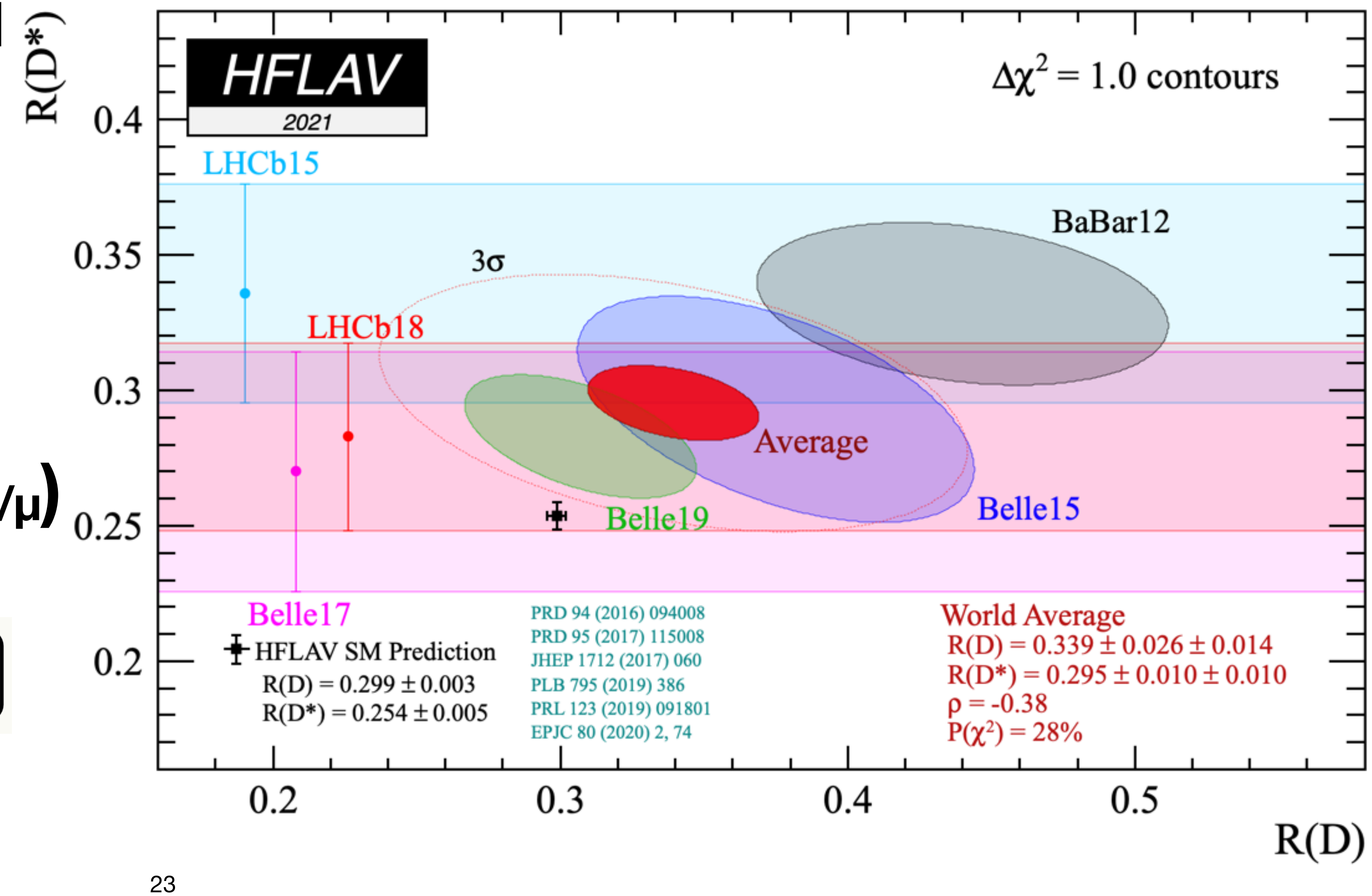
Lepton Flavour Universality

- EW coupling of gauge bosons is expected to be lepton-flavour-independent.
- Hints of LFU violation in charged current decays, e.g.:

$$R(D^{(*)}) = \frac{BF(B \to D^{(*)}\tau\nu_\tau)}{BF(B \to D^{(*)}\ell\nu_\ell)}$$



Independent test of LFU: R($X_{e/\mu}$)

- Result: $R(X_{e/\mu})^{p_\ell^*>1.3\mathrm{GeV}} = 1.033 \pm 0.010^{\mathrm{stat}} \pm 0.020^{\mathrm{syst}}$

- Paves the way for a measurement of $R(X_{\tau/\ell}) = BF(B \to X\tau\nu)/BF(B \to X\ell\nu)$

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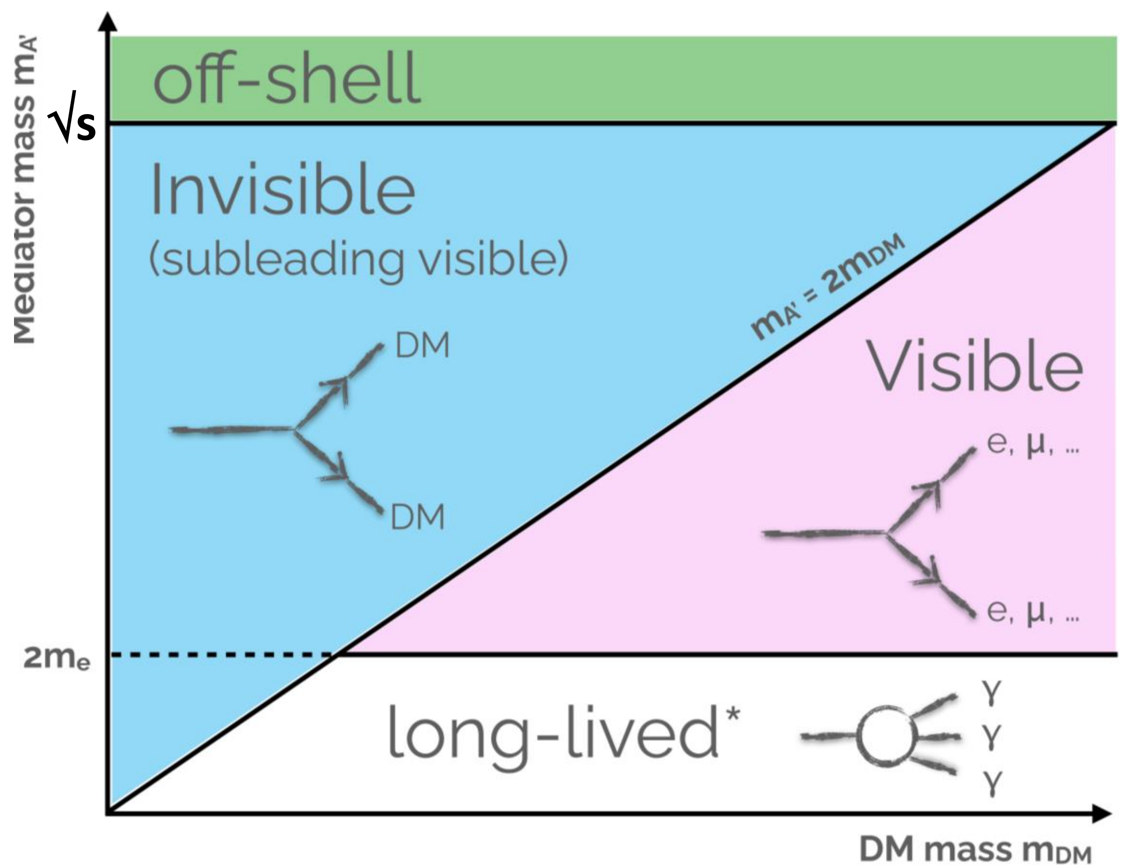
Light Dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

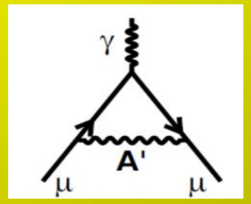


e+e- colliders

Probability of DM ↔ detector interaction negligible
- Mostly low multiplicity signatures
- Missing energy channels
- Invisible particles, often in closed kinematics regime
- Some fully neutral final states accessibility

Additional benefits

- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, …)
- Explanation of the $(g\text{-}2)_\mu$ effect →



- Explanation of some flavour anomalies (LHCB, Belle, …)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits

E. Graziani

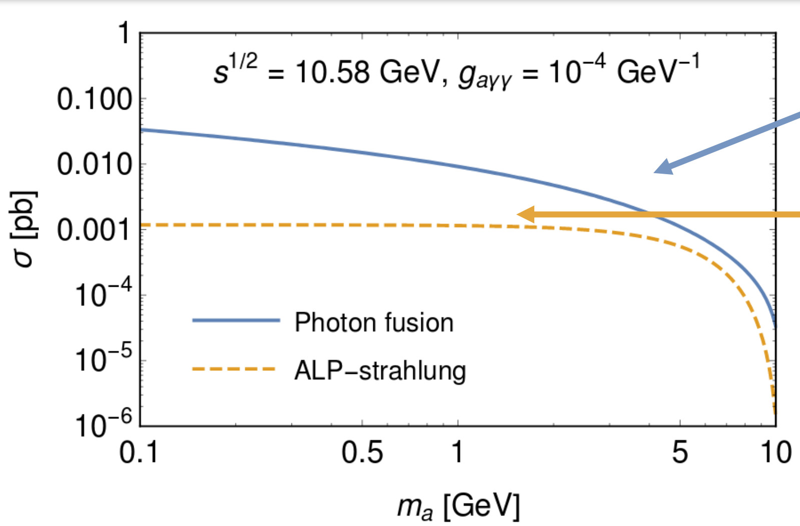
Axion Like Particles (ALPs)

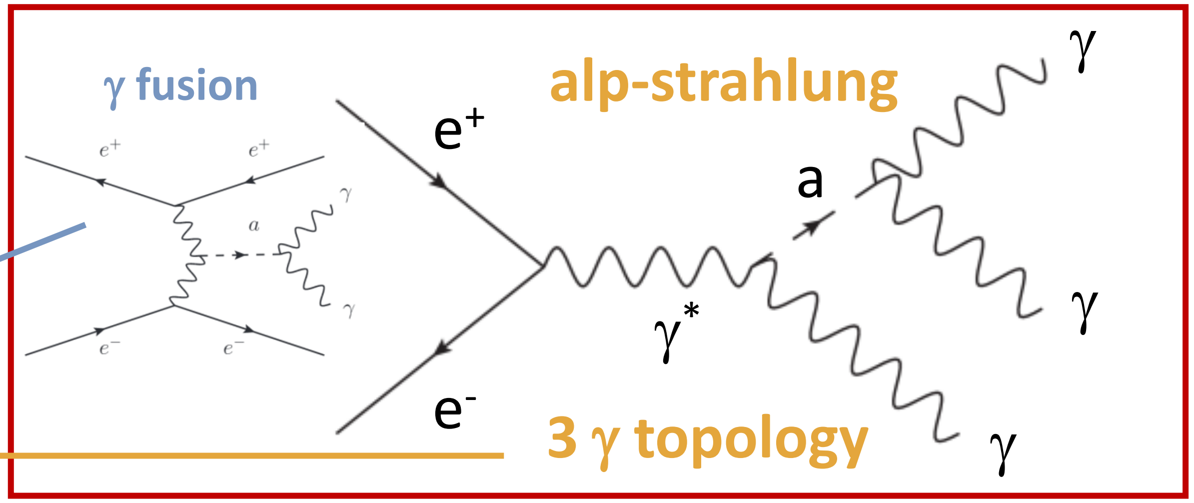
2020

- Appear in SM extensions after some global (i.e. family) symmetry breaking
- Pseudo-Goldstone bosons → Naturally light
- Cold dark matter candidates if m_a is sub MeV
- Couple naturally to photons
- Can couple LFV to fermions
- No mass↔coupling relationship (as for QCD)

Belle II

- Focus on coupling to photons: $g_{a\gamma\gamma}$
- **Alp-strahlung** + photon fusion production mechanisms
- $\tau \sim 1 / g_{a\gamma\gamma}^2 \, m_a^3$





photon fusion sensitivity under study

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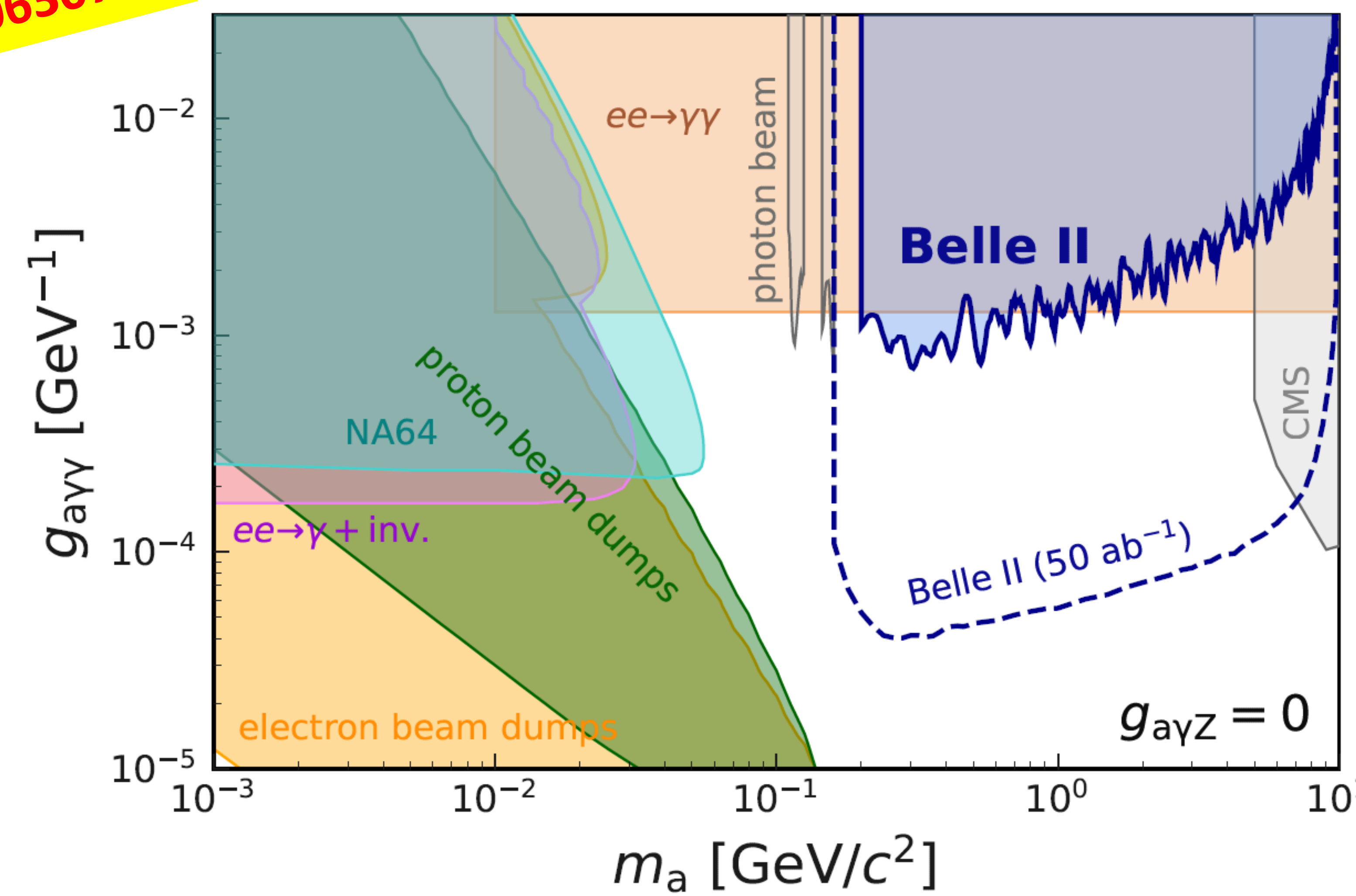
ALP →γγ : luminosity projections

Belle II physics reach @ Snowmass

arXiv: 2207.06307v1



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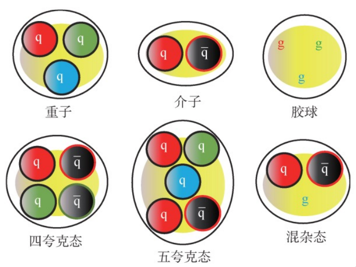
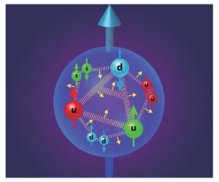
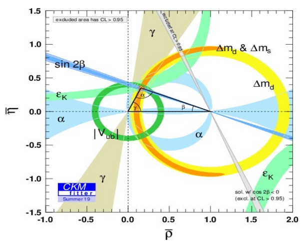
tau charm factory

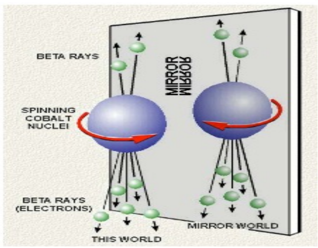
STCF Physics Program

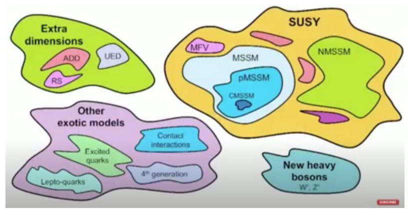




- **Physics at STCF**
  - **QCD and hadronic physics**
    - **XYZ Properties:** e+e-→Y→γX,ηX,ϕX; e+e-→Y→πZc, KZcs
    - **Hadron Spectroscopy:** Excited ccbar and their transition, Charmed hadron spectroscopy, Light hadron spectroscopy
    - **R value:** e+e-→inclusive; τ mass: e+e-→τ+τ-
    - **Nucleon Form Factors:** e+e-→BBbar from threshold
    - **Pentaquarks:** e+e-→J/ψppbar, Λc Dbar pbar, Σc Dbar pbar **Di-charmonium:** e+e-→J/ψηc, J/ψhc
    - **Muon g-2:** e+e-→π+ π-, π+ π- π0, 4π, K+ K-, γγ→π0, η(′),π+ π-
    - **Fragmentation functions:** e+e-→(π,K,p,Λ,D)+X, e+e-→(ππ,KK,πK)+X
  - **Flavor Physics and CP Violation**
    - **CKM matrix (Vcd, Vcs):** D_(s)+→l+v, D→P l+ v
    - **Charm hadron decay:** Λc+, Σc, Ξc, Ωc decay
    - **CPV in Hyperons:** J/ψ→ΛΛbar, ΣΣbar, Ξ- Ξ+bar, Ξ0 Ξ0bar
    - **D0-D0bar mixing:** ψ(3770)→(D0 D0bar)(CP=-), ψ(4140)→π0 (D0 D0bar)(CP=-) or γ(D0 D0bar)(CP=+)
    - **CPV in τ:** τ→Ks πv, EDM of τ, τ→π/K π0 v for polarized e- beam
    - **CPV in Charm:** D0→K+K-/π+π-, Λc→pK-π+π0/Λπ+π+π-/pKs π+π
    - **γ/ϕ3 measurement:** D0→K(s/L) π+ π-, K(s/L) K+ K-,K3π, 4π
    - **γ polarization:** D0→K1 e+ v_e
  - **Forbidden/Rare decay and New Particle**
    - **LNV, BNV:** D(s)+→l+ l+ X-, J/ψ→Λc e-, B→Bbar…
    - **Symmetry violation:** η(′)→llπ0, η′→ηll…
    - **FLV decays:** τ→γl, lll,l P1 P2 , J/ψ→ll′, D0→ll′ (l′≠l)…
    - **FCNC:** D→γV, D0→l+ l-, e+e-→D ∗ , Σ+→pl+ l-…
    - **Dark photon:** e+e-→γA′(→l+ l-), J/ψ→e+e-A′… **Millicharged:** e+e-→χχ̄γ…



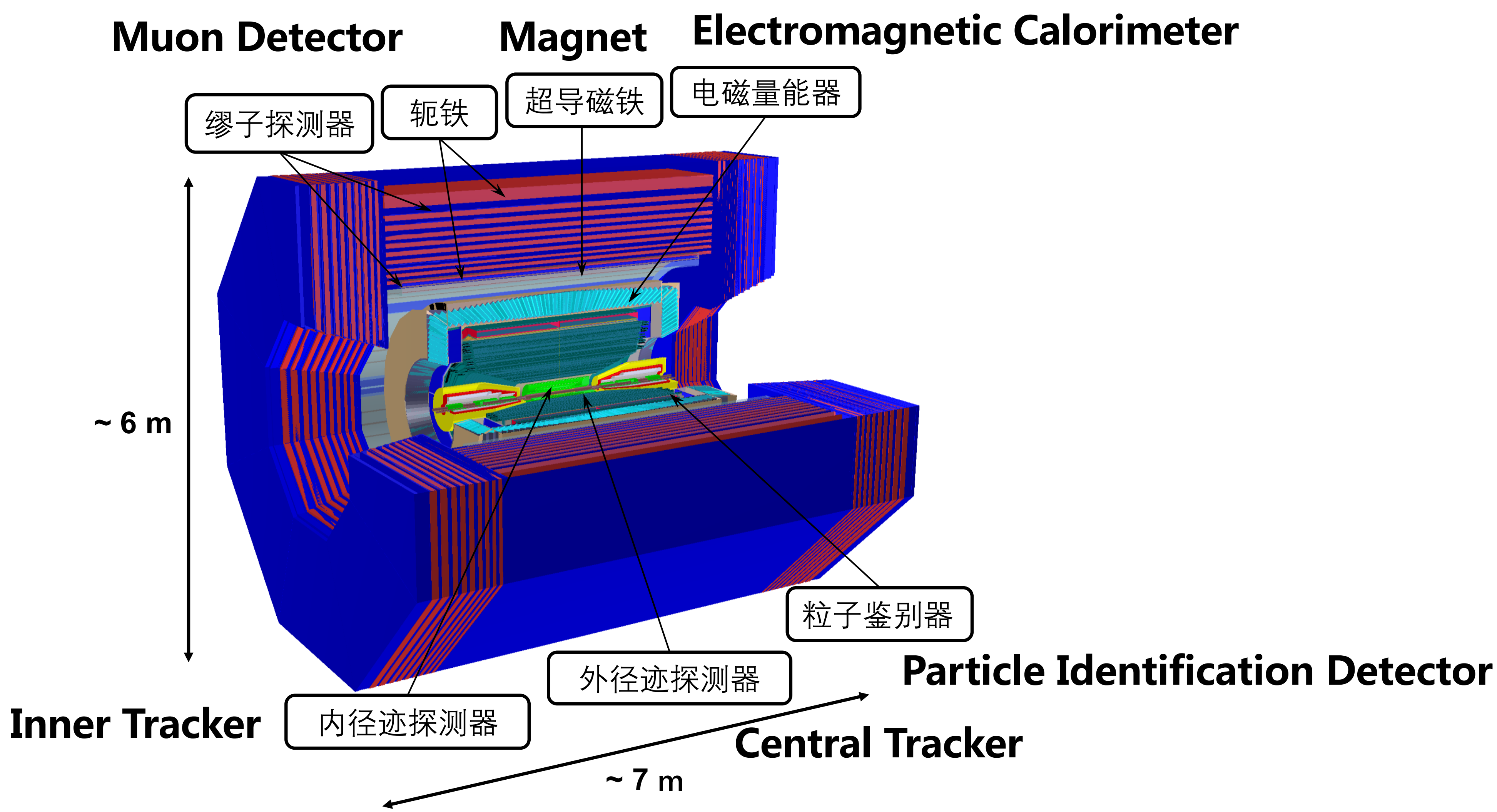




- **Leading role**
- Competing with Belle II/LHCb
- **Complementary to BelleII/LHCb/Eic/EicC**

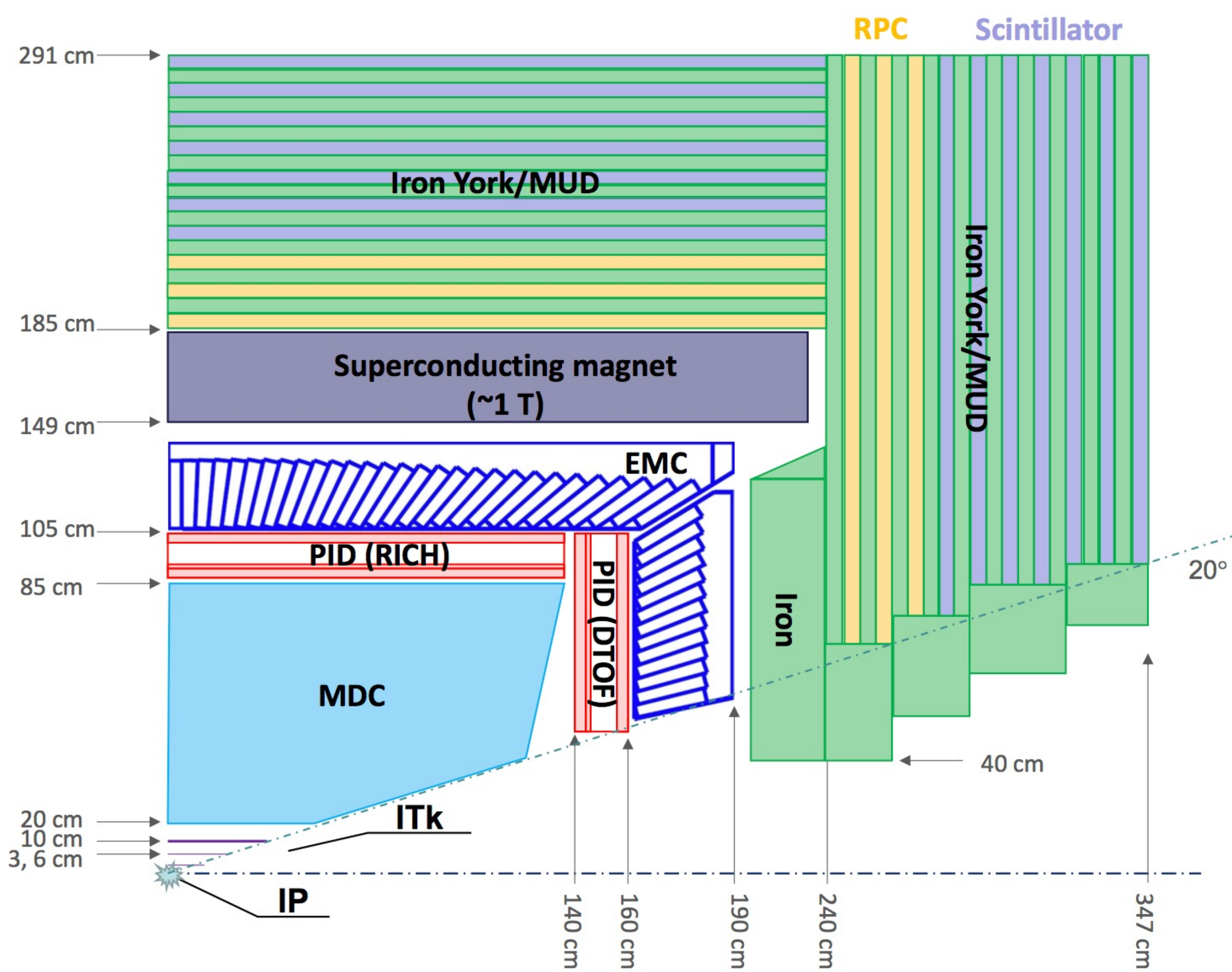
STCF detector

STCF Detector Concept



J. Liu

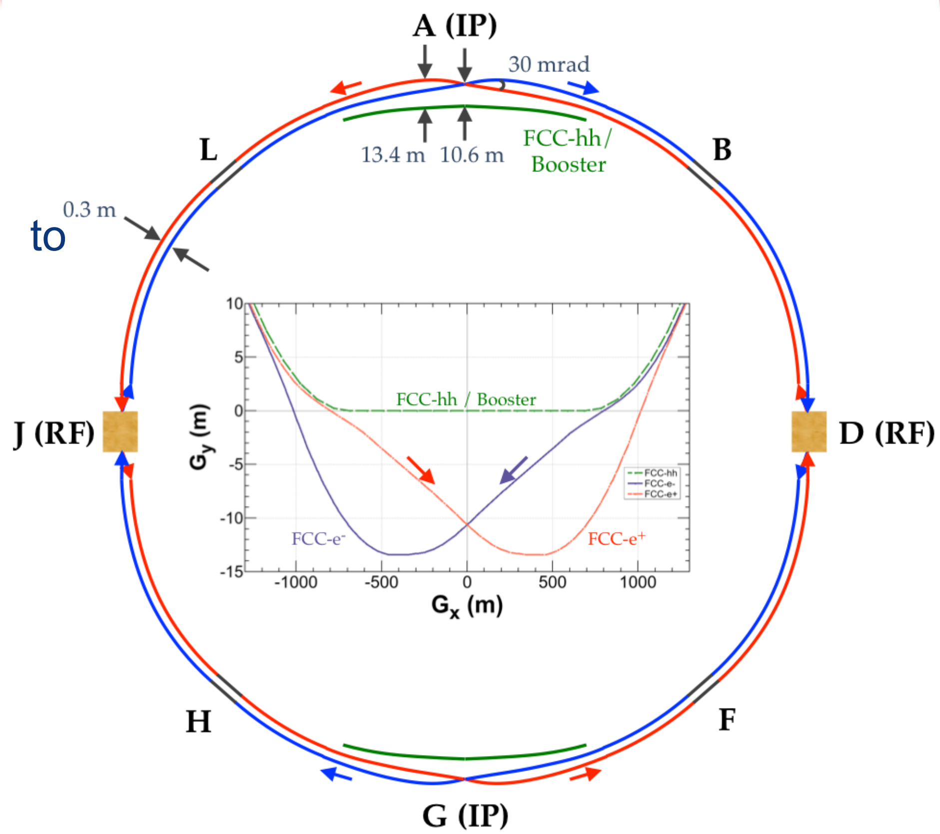
Detector Summary

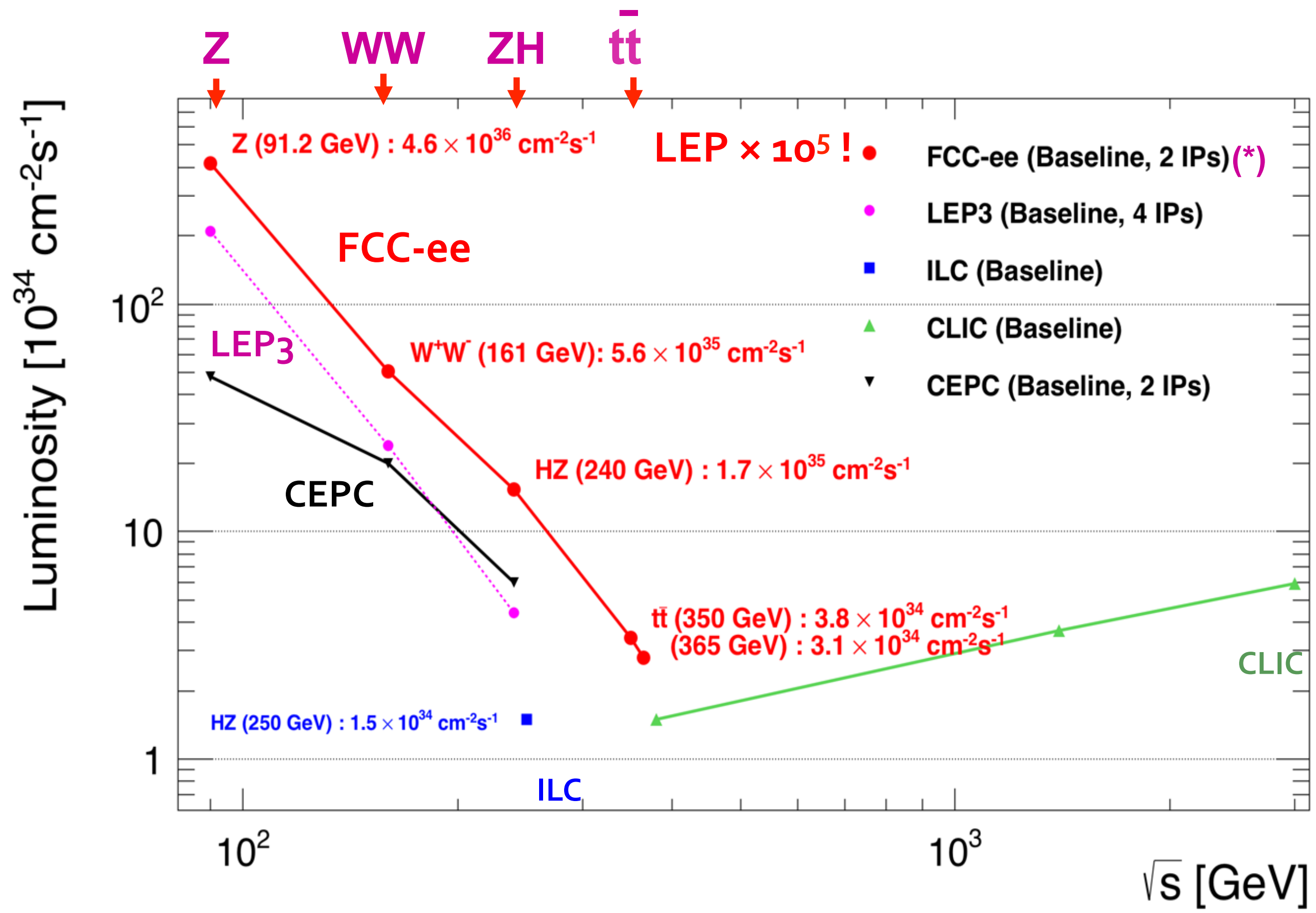


ITk • $< 0.25\% X_0$ / layer • $\sigma_{xy} < 100$ μm	Cylindrical μRWELL CMOS MAPS
MDC • $\sigma_{xy} < 130$ μm • $\sigma_p/p \sim 0.5\%$ @ 1 GeV • dE/dx~6%	Cylindrical Drift chamber
PID • π/K (and K/p) 3-4σ separation up to 2GeV/c	RICH with MPGD DIRC-like TOF
EMC E range: 0.025-3.5GeV σ_E (%) @ 1 GeV Barrel: 2 .5 Endcap: 4 Pos. Res. : 5 mm	pCsI + APD
MUD • 0.4 - 2 GeV • π suppression >30	RPC + scintillator

J. Liu

Detectors for future colliders





collider properties

- double accumulator ring, energy booster for acceleration, continuous injection, crossing angle (30 mrad), crab-waist techinque for luminosity optimisation
- minimal setup 2IP, optimal one with 4 IP

proposed timeline , energies and luminosity

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold...	... and above
√s (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4

Detectors at FCC

Higgs physics drivers

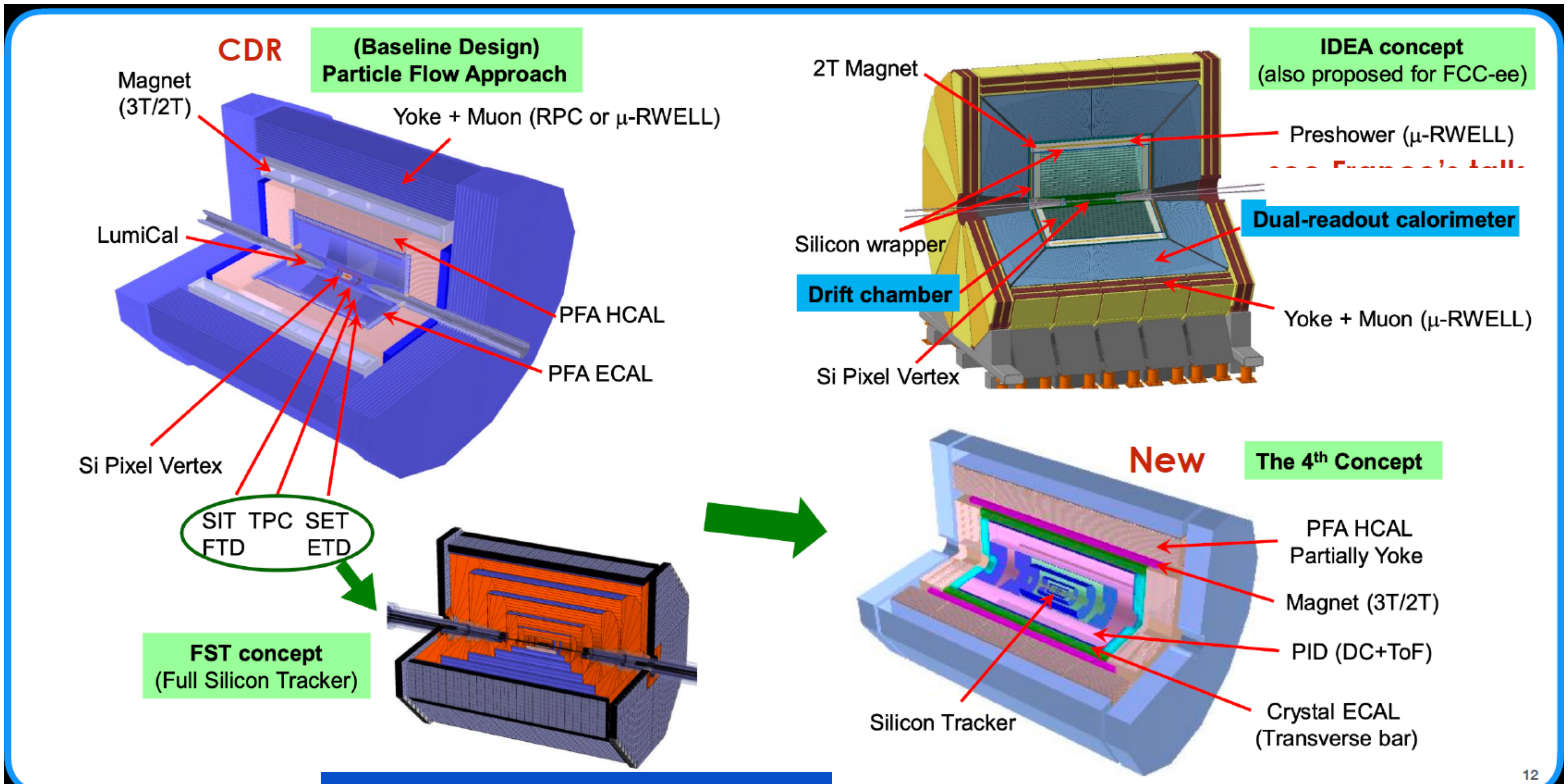
- Higgs total width → track momentum resolution
- Tagging specific Higgs final states
  - Beauty, Charm, (Strange ?) tagging → impact parameter resolution (PID)
  - ZZ vs WW → jet-jet invariant mass resolution
- Separating Higgs from background in VBF production → jet-jet resolution
  - E.g. ννH →ννqq' vs. ZZ →ννqq'

Requirements for EWK/HF physics

- EWK:
  - Extreme definition of luminosity and detector acceptance
    - Luminometer with high mechanical accuracy
    - Tracking with external silicon detector layer
    - Calorimetry with pre-shower/ high granularity EM
  - Extreme EM resolution (crystals) under study
    - Improved π^0 reconstruction
    - Physics with radiative return
- HF:
  - PID to accurately classify final states and flavor tagging
  - π^0 reconstruction efficiency
- Other requirements highly overlap with Higgs req.

F. Bedeschi

Detector concepts for CepC

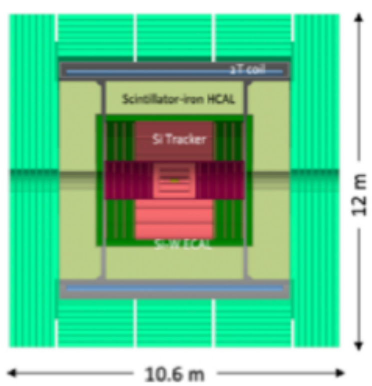


J. G. da Costa, INFN-IHEP 2022

F. Bedeschi

Detector concepts FCC-ee

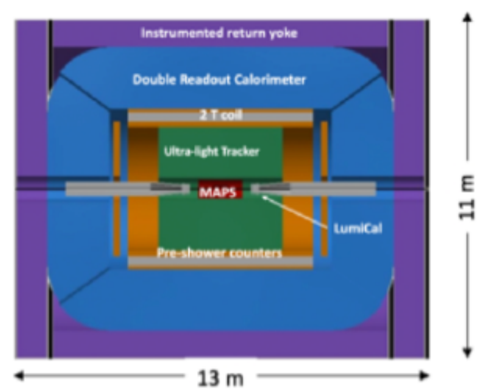
CLD



inside

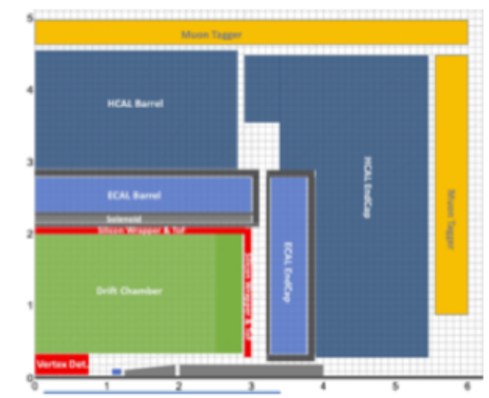
- Well established design
  - ILC -> CLIC detector -> CLD
- Engineering needed to make able to operate with continous beam (no pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations?
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

IDEA



- Less established design
  - But still ~15y history: 4th Concept
- Developed by very active community
  - Prototype construction / test beam compains
  - Italy, Korea,...
- Is IDEA really two concepts? Or will it be?
  - w, w/o crystals

Noble Liquid ECAL based



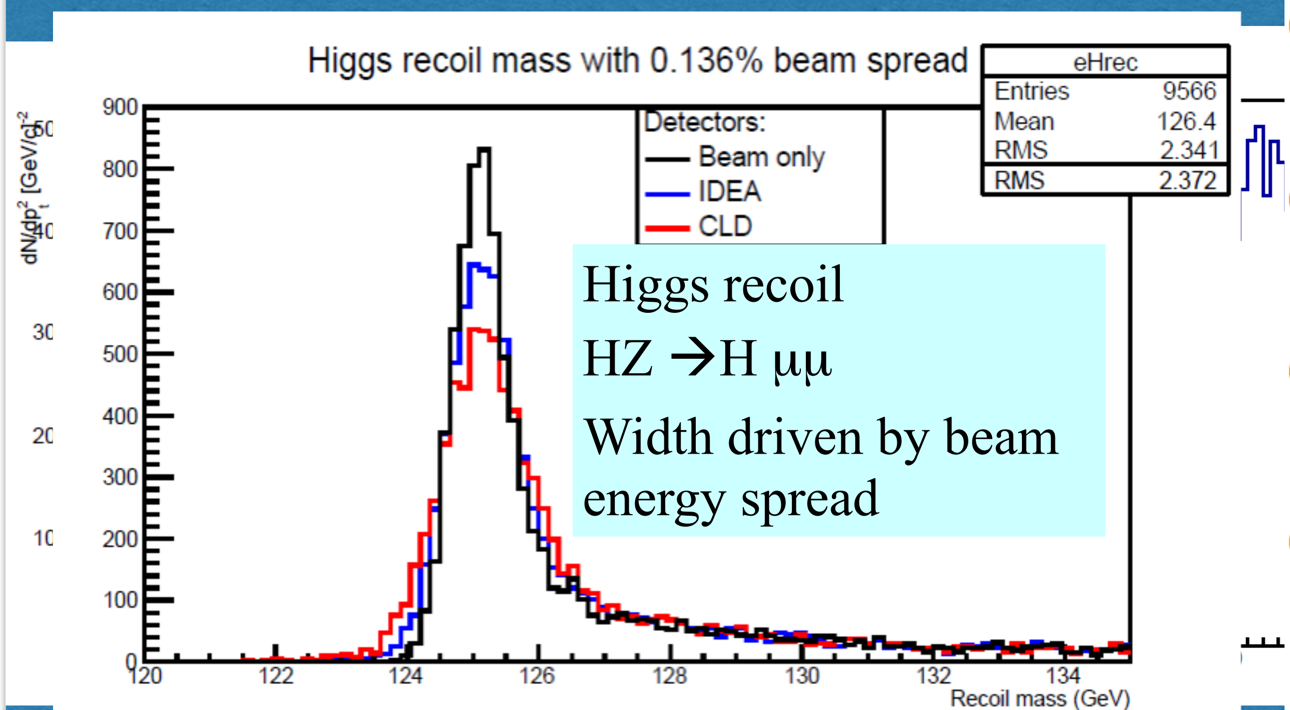
- A design in its infancy
- High granul Noble Liquid ECAL is the core
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, ...
  - Software & performance studies

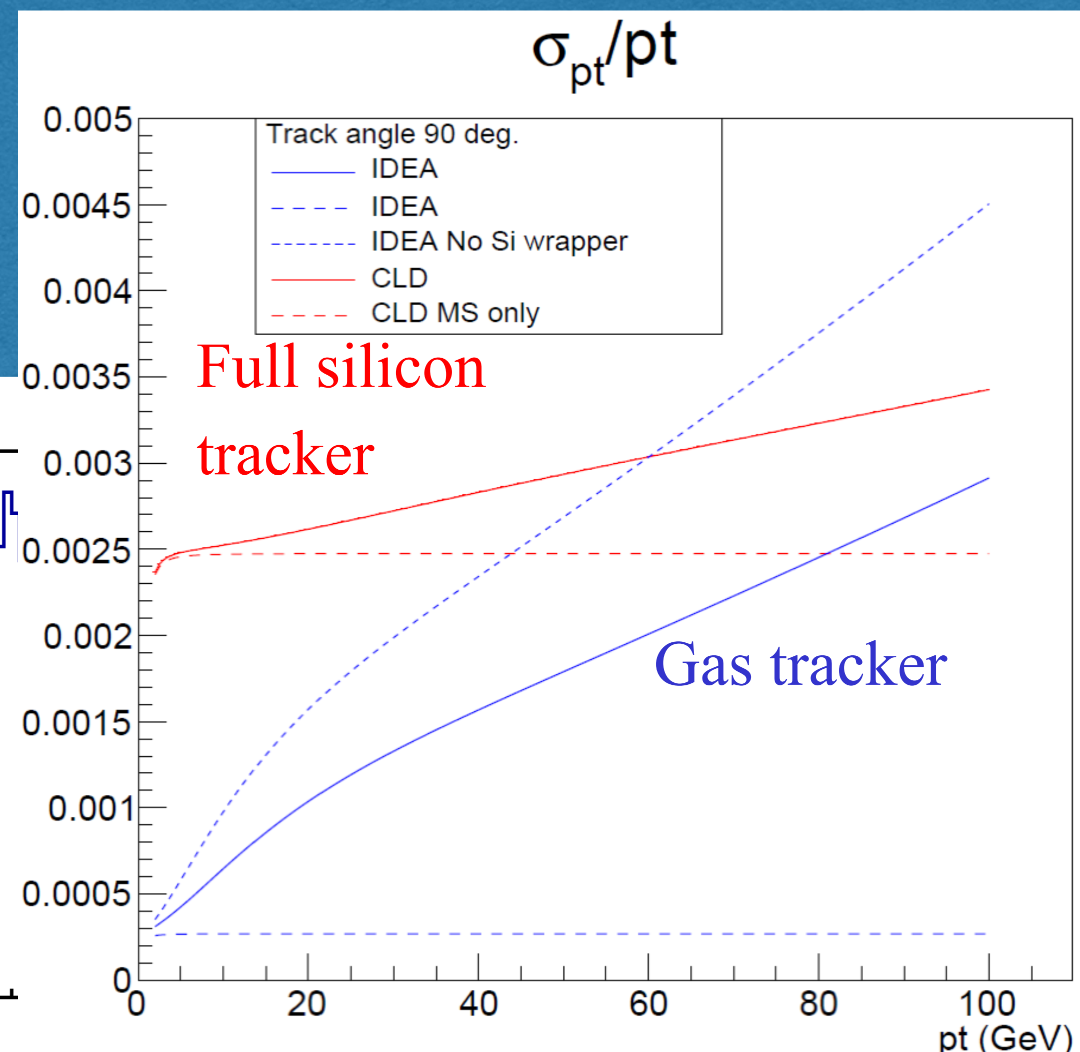
F. Bedeschi

FCC-ee detector studies

Momentum measurement

- Z or H decay muons in ZH events have rather small p_t
  - Transparency more relevant than asymptotic resolution





F. Bedeschi

CEPC detector studies

Impact of Vertex Optimization

$$Tr_{mig} = 2.118 + 0.054 \cdot log_2 \frac{R^0_{material}}{R_{material}} + 0.040 \cdot log_2 \frac{R^0_{resolution}}{R_{resolution}} + 0.098 \cdot log_2 \frac{R^0_{radius}}{R_{radius}}$$

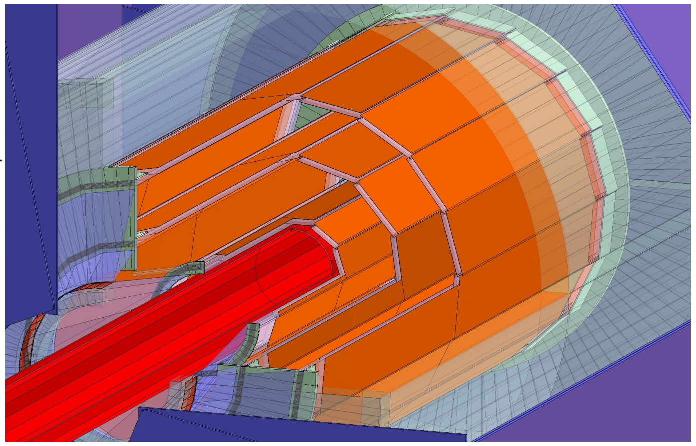
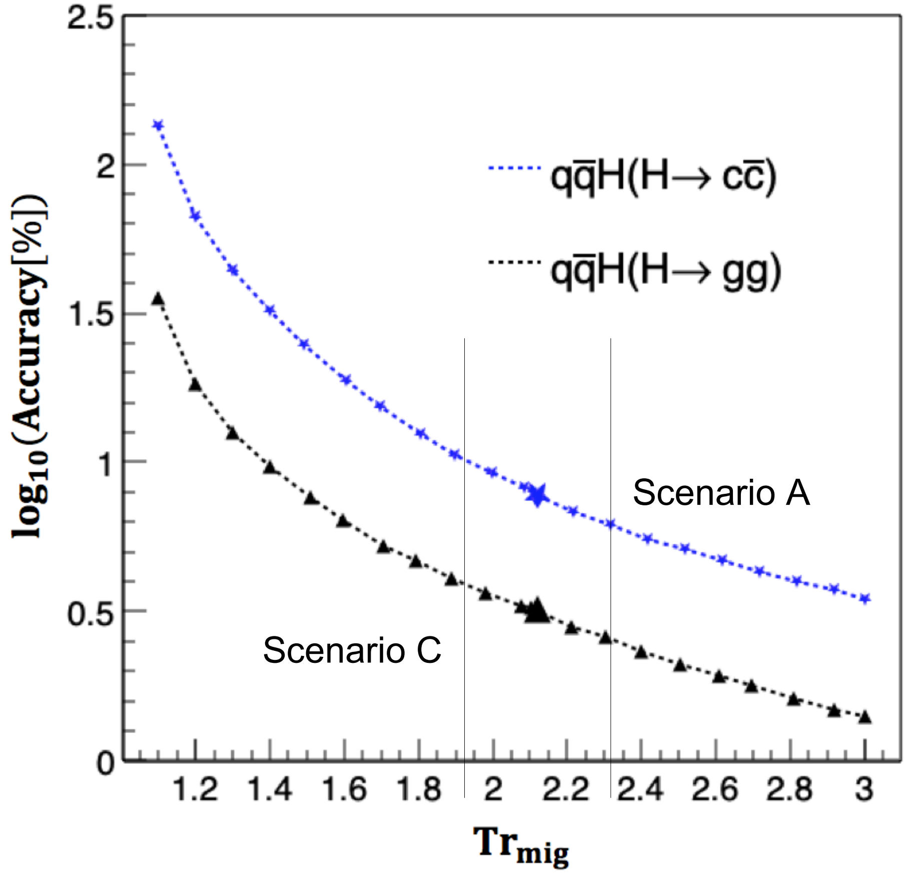


Table 2. Reference geometries.

	Scenario A (Aggressive)	Scenario B (Baseline)	Scenario C (Conservative)
Material per layer/X_0	0.075	0.15	0.3
Spatial resolution/µm	1.4 - 3	2.8 - 6	5 - 10.7
R_{in}/mm	8	16	23



Compared to the baseline:

- Perfect Flavor tagging improves the accuracy of qqH, H->cc measurement by 2 times
- Conservative & Aggressive scenario degrades/improves the accuracy by 30%
- Current Vertex design (with inner radius of 10 mm) improves the accuracy by 10%

M. Manqi

12/9/2022 eeFACT@INFN Frascati

Thin solenoids

SUPERCONDUCTING MAGNETS FOR PARTICLE DETECTORS

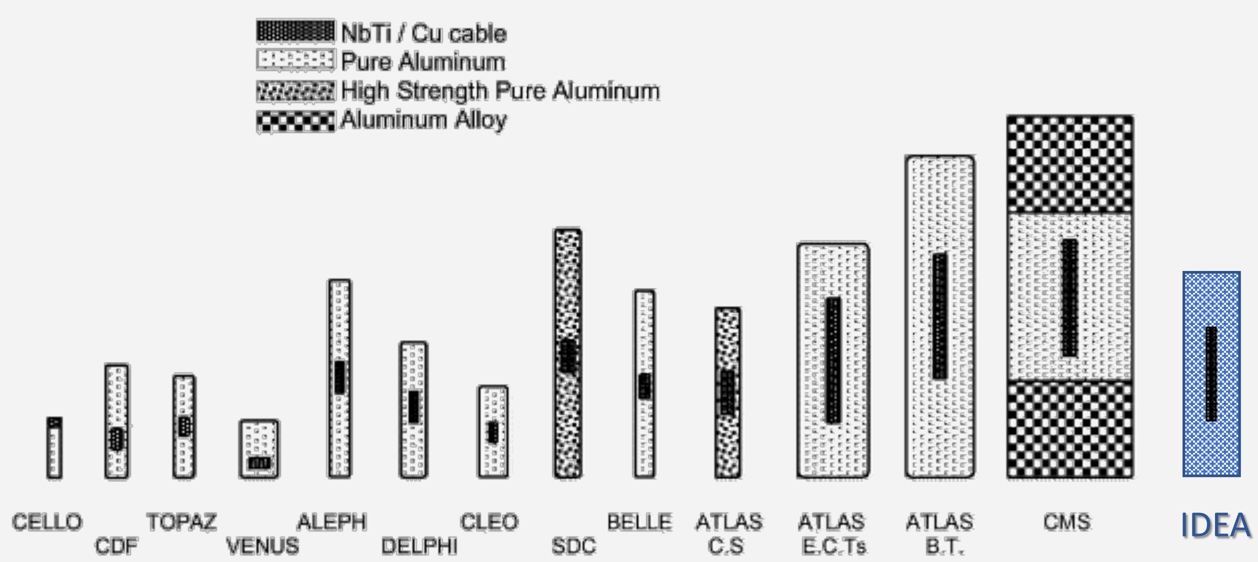
Main characteristics:

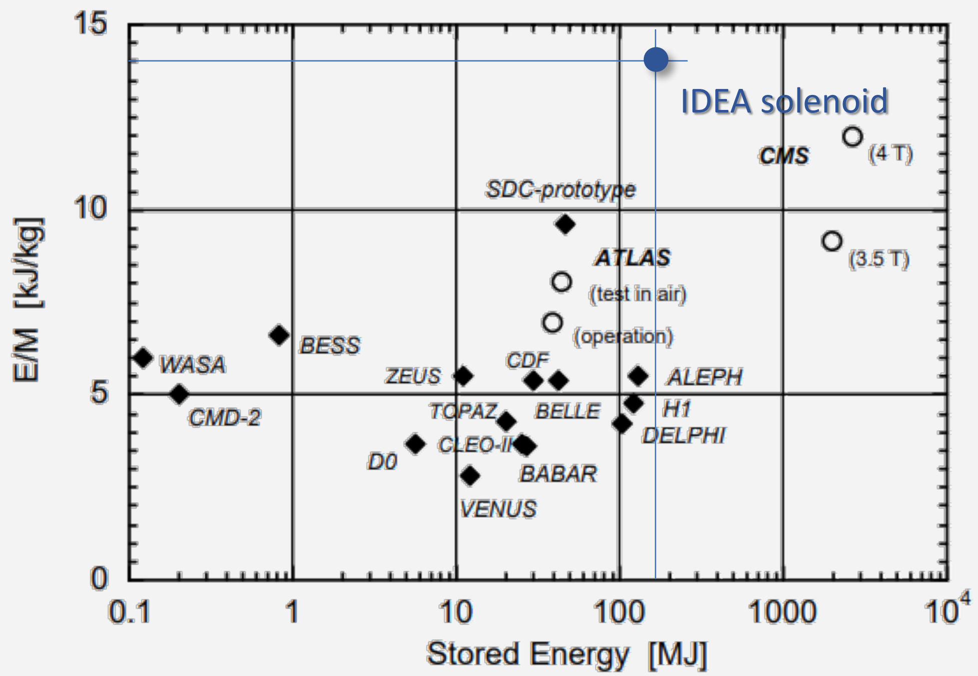
- Large volume
- Moderate magnetic field (0.5 to 4 T)
- Transparency to particles is often required
- Generally solenoidal or toroidal shape

S. Farinon

Thin solenoids

Thin solenoids evolution





A.Yamamoto and Y.Makida, *Nuclear Instruments and Methods in Physics Research* A 494 (2002)

IDEA data from N.Deelen *https://indico.cern.ch/event/1162992/contributions/4945512/* presented @ *Superconducting magnet Workshop,* Sept. 12th 2022

12

S. Farinon

we need high magnetic field and high volume to optimise momentum resolution, low material budget to mantain good calo resolution and efficiency: IDEA is a challange

Flavour physics at Tera-Z

Tera-Z as a Z and Flavor Factory

b-hadrons	Belle II (50+5 ab^{-1})	LHCb (300 fb^{-1})	Tera-Z
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	3.1×10^{10}
$B_c^\pm$	-	1×10^{11}	1.8×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	2.5×10^{10}
$c(\bar{c})$	2.6×10^{11}	$\gtrsim 10^{14}$	2.4×10^{11}
$\tau^\pm$	9×10^{10}	-	7.4×10^{10}

Lingfeng Li, Brown U.

FIP particle search at FCC-ee

Genesis of the feebly interacting particles FIPs

How to couple light degrees of freedom to the SM while being consistent with all possible constraints: its symmetries and mass spectra, respect the actual phenomenologies?

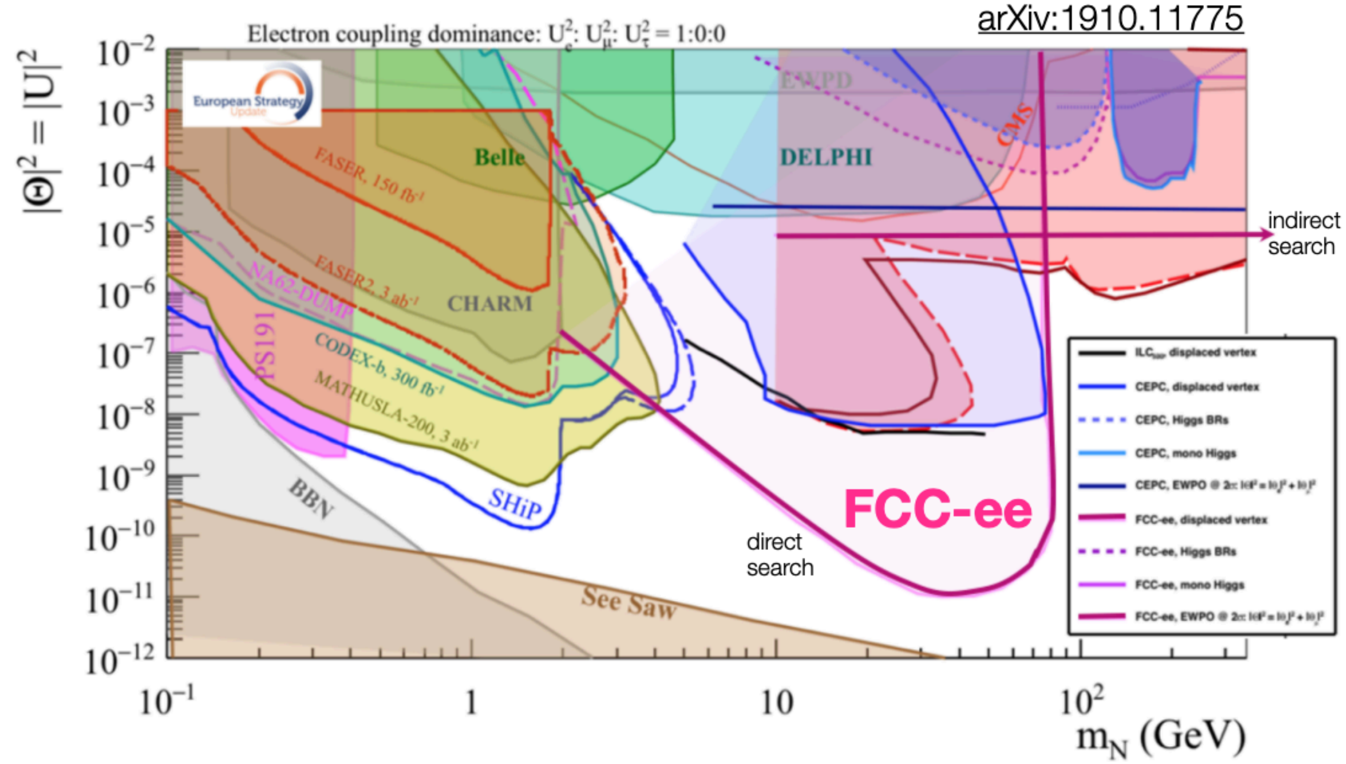
- Idea: add new particle feebly coupled to the SM via a portal term (suppressed).

$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{NON-SM} + \mathscr{L}^{Portal}_{INT}$$

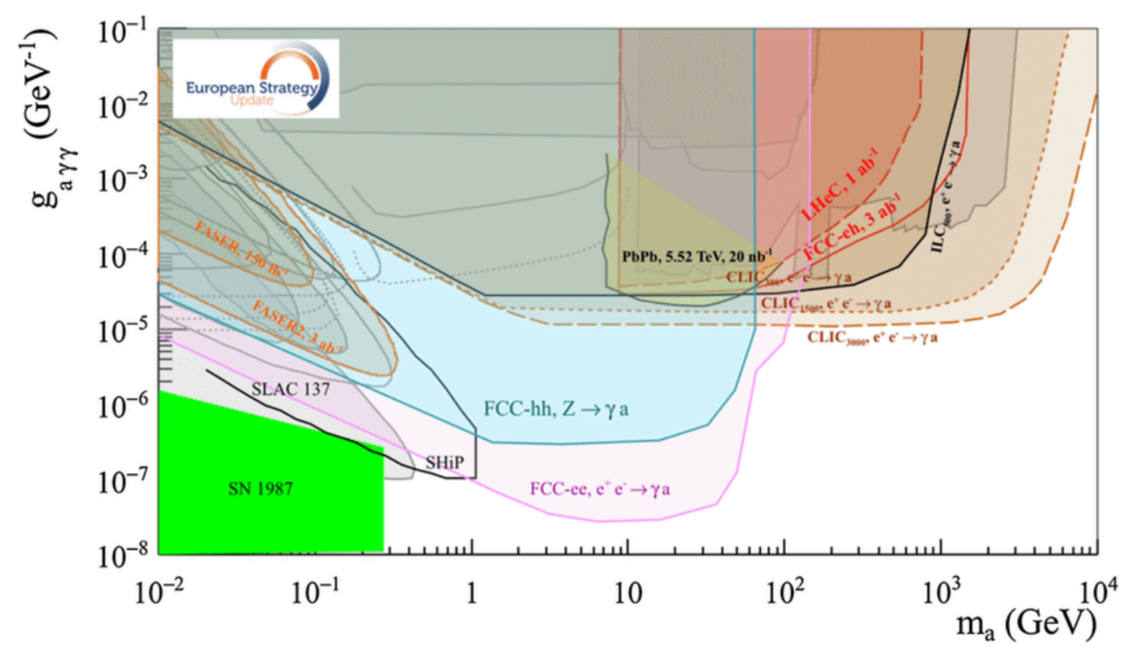
Portal Type	SM Operator	FIP Operator	Dark Sector /FIP	
Scalar Portal	$\lvert H \rvert^2 (d=2)$	$\lvert S \rvert^2$	Dark Higgs	Mixes with standard Higgs
Vector Portal	$F_{\mu\nu}(d=2)$	$F'^{\mu\nu}$	Dark Photon	Mixes with photon
Neutrino Portal	$LH\ (d=5/2)$	N	HNL	Mixes with neutrino
Pseudoscalar Portal	$\bar{f}_i \Gamma^\mu f_j (d=3)$	$\partial_\mu a$	ALP	Direct interaction with fermion
Fermion Portal	$\bar{f}_i \Gamma^\mu f_j (d=3)$	$\Psi \Gamma_\mu \Psi$	dark fermion	

M. Verducci

FCC will probe space not constrained by astrophysics or cosmology, complementary to accelerator and neutrino prospects



Axion-Like Particle



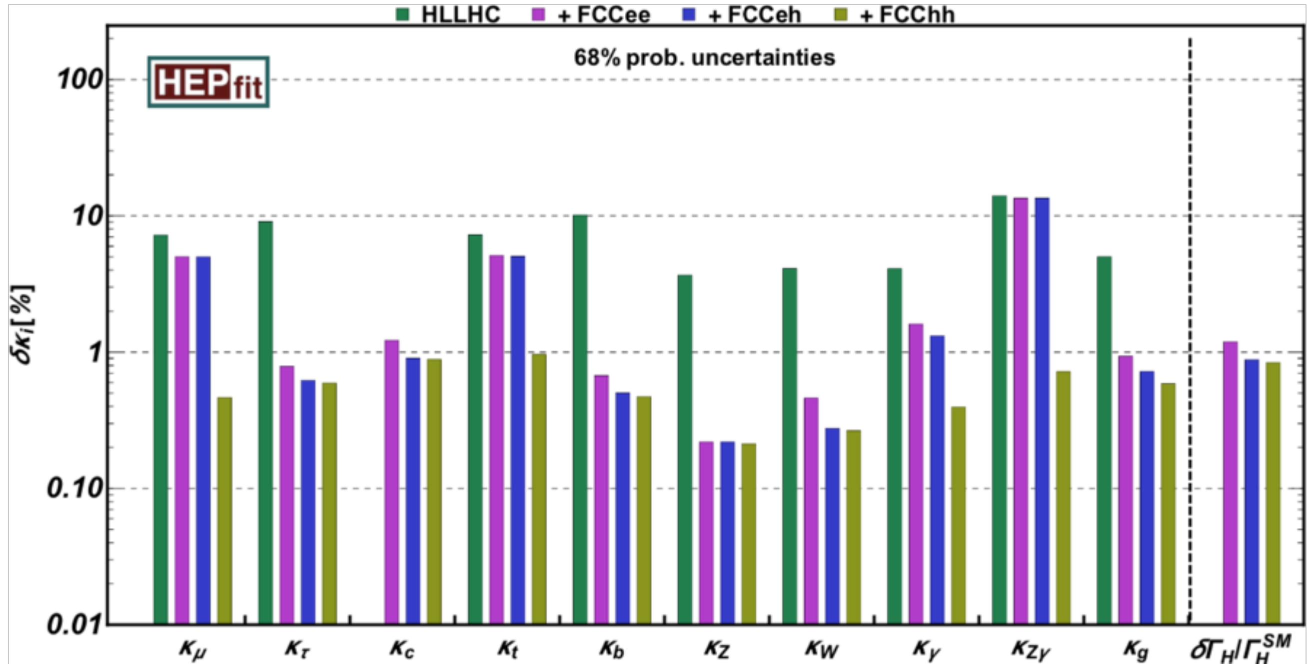
M. Verducci

- FCC-ee will push the intensity frontier of particle physics , in particular we expected to collect 5×10^{12} Z bosons at Z-Tera Runs
- **Feebly interacting new particles**, could be investigated in a phase space where no other experiment will ever have sensitivity
  - HNL and ALP sensitivity presented.
- **Detector requirements:**
  - Need to be sensitive to vertices from mm to m (displaced vertices identification)
  - Calorimetry system with high granularity.
  - Extended sensitive material (additional detectors?)
  - Trigger (online) selection prepared to filter these events

M. Verducci

FCC-ee physics goals

Higgs boson couplings



BSM sensitivity

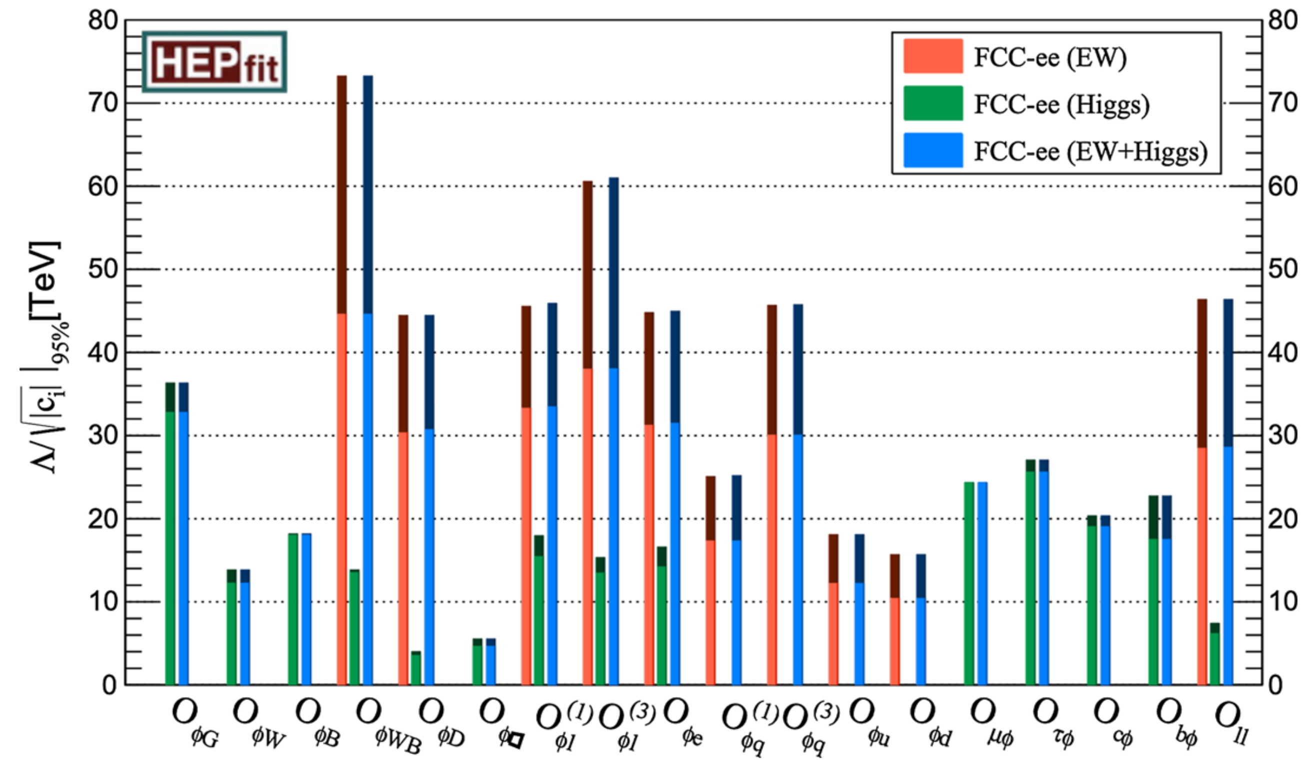
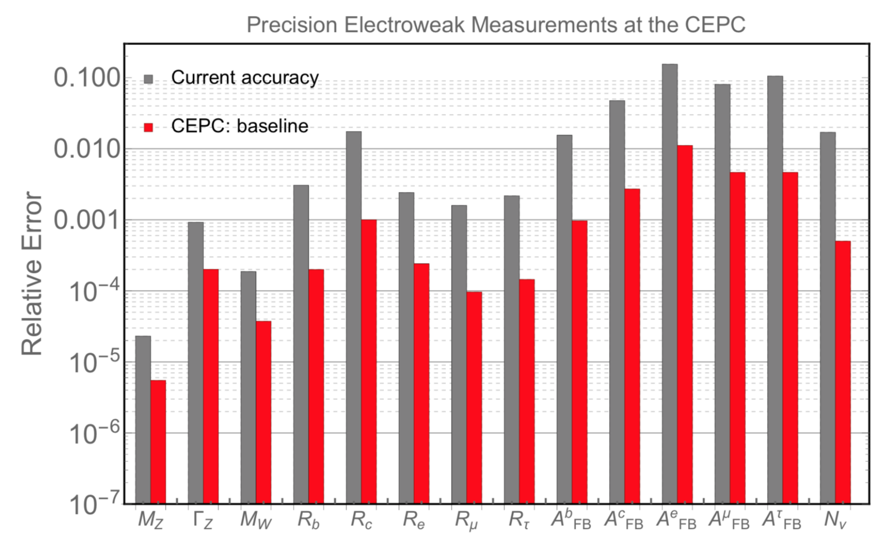


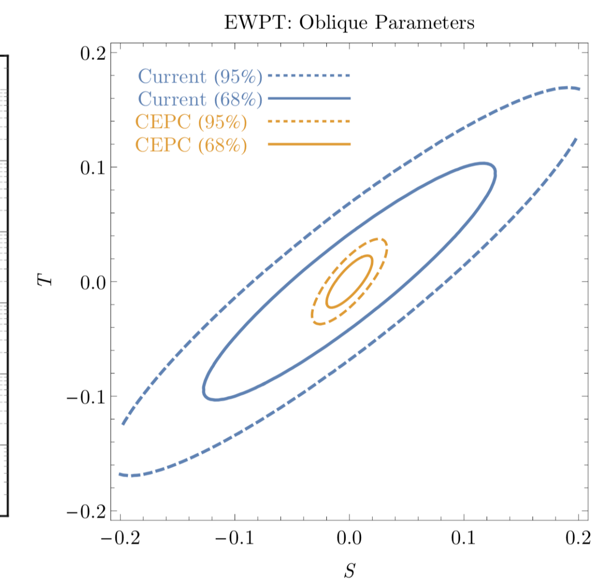
Fig. 5 Electroweak (red) and Higgs (green) constraints from FCC-ee, and their combination (blue) in a global EFT fit. The constraints are presented as the 95% probability bounds on the interaction scale, $\Lambda/\sqrt{c_i}$, associated to each EFT operator. Darker shades of each colour indicate the results when neglecting all SM theory uncertainties

CEPC projections

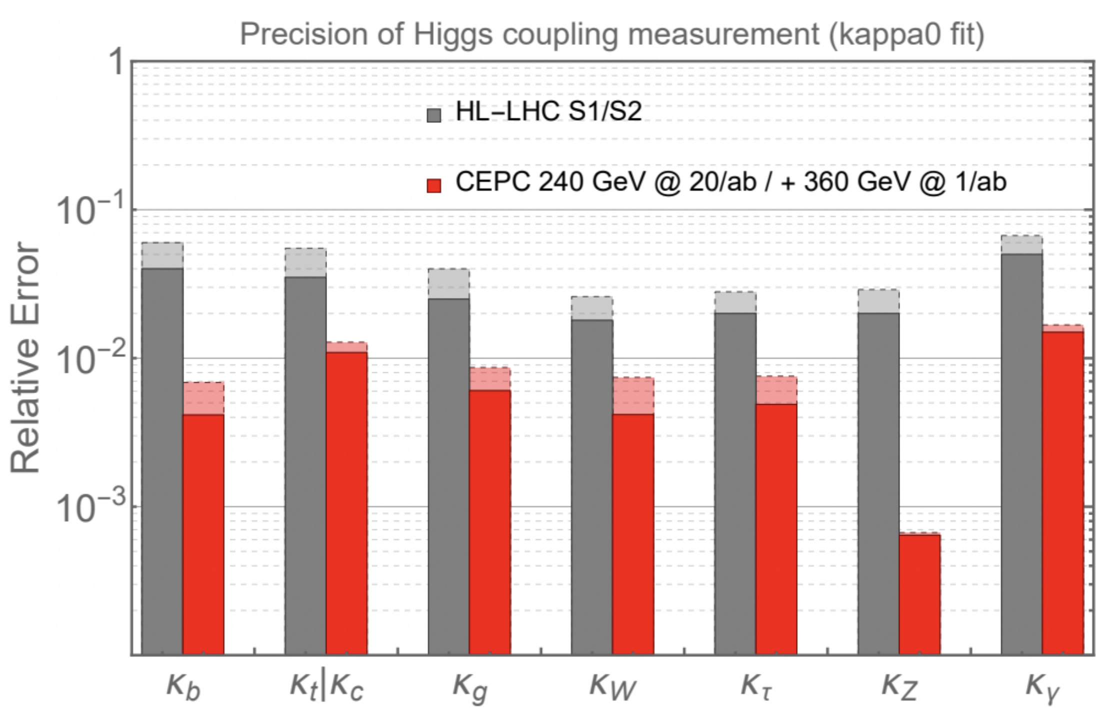
EW

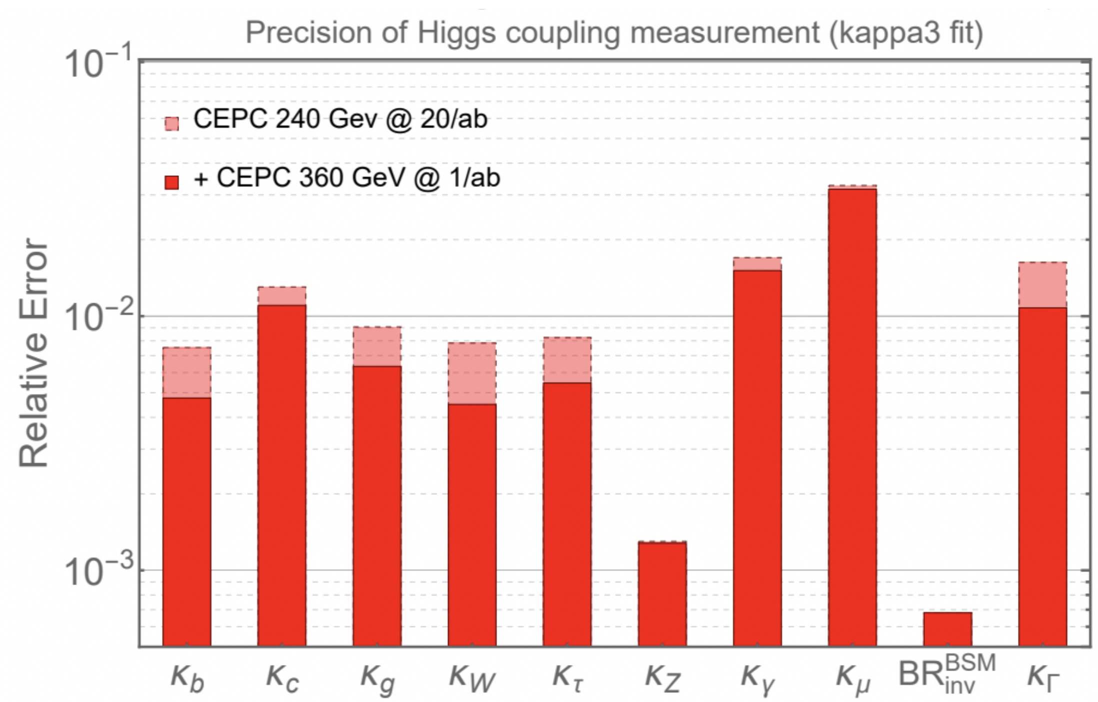
R. Manqi





With 2 years of Z pole operation (~ 1 Tera Z) and 1 year of W mass scan (~1E7 W)





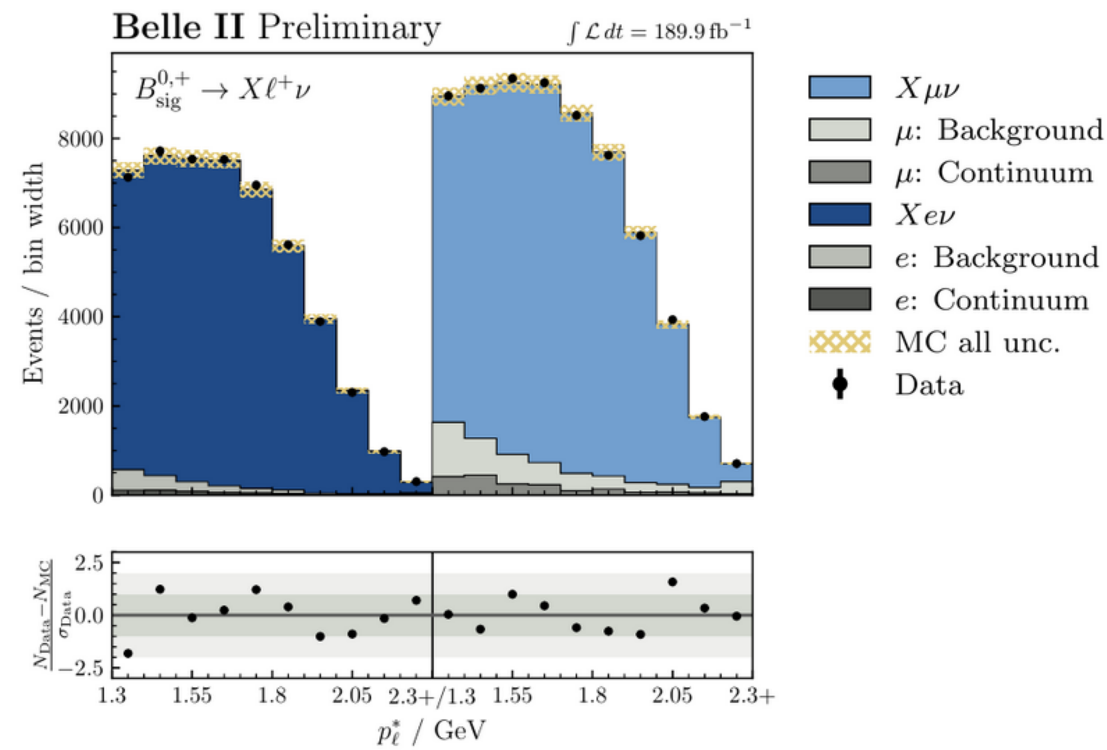
Conclusions

- Higgs boson at 125 GeV and nothing else disproves any further “no loose” theorem
- there are still strong reasons to believe that the SM is not the final story, but the energy scale is uncertain
- naturalness argument still holds, telling us that the New Physics scale cannot be too high
- priority is to scan directly or indirectly the largest possible scale
- the most cost effective way to make such scan is through precision physics at high luminosity factories: flavour factories, Z,W,H, top factories
- there is a long period ahead of us where current facilities: LHC, HL-LHC and Belle2 could give surprises
- the highest priority is to study with maximum precision the new discovered particle: the Higgs boson with the highest possible accuracy

Henrik Junkerkalefeld
@ICHEP2022

Independent test of LFU: R($X_{e/\mu}$)

- $R(X_{e/\mu}) = \dfrac{BF(B \to Xe\nu)}{BF(B \to X\mu\nu)}$ with hadronic tag.
- Binned template fit on CM lepton momentum.
- Backgrounds fixed from off-resonance data and sidebands while Xlν floats freely.
- Result: $\boxed{R(X_{e/\mu})^{p_\ell^*>1.3\text{GeV}} = \mathbf{1.033 \pm 0.010^{stat} \pm 0.020^{syst}}}$



- Most precise measurement, in agreement with SM and previous Belle measurement.
- Systematically dominated → can be improved with better lepton ID
- Paves the way for a measurement of $R(X_{\tau/\ell}) = BF(B \to X\tau\nu)/BF(B \to X\ell\nu)$

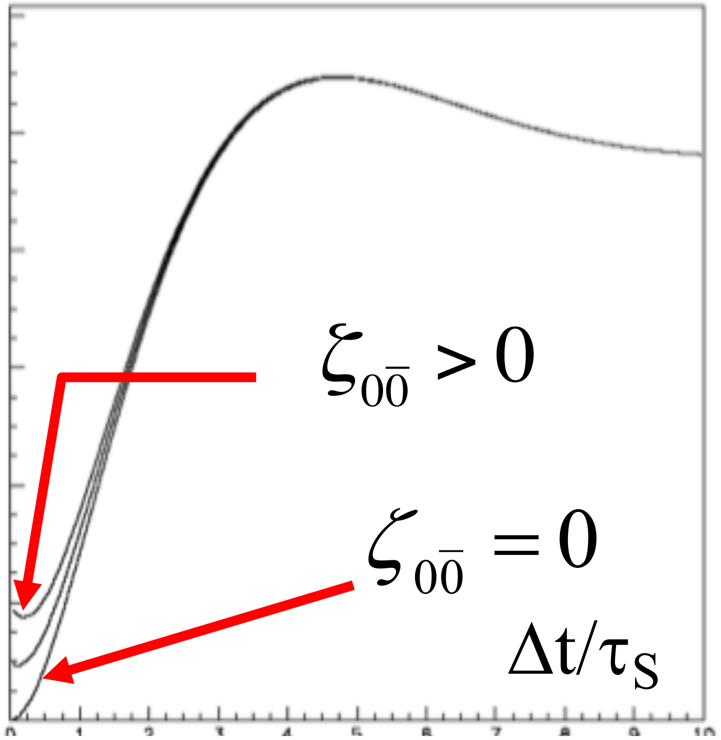
F. Tenchini

Planck scale test at KLOE with quantum decoherence

$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0\right\rangle\left|\overline{K}^0\right\rangle - \left|\overline{K}^0\right\rangle\left|K^0\right\rangle\right]$$

$$I\left(\pi^+\pi^-,\pi^+\pi^-;\Delta t\right) = \frac{N}{2}\left[\left|\left\langle\pi^+\pi^-,\pi^+\pi^-\left|K^0\overline{K}^0(\Delta t)\right.\right\rangle\right|^2 + \left|\left\langle\pi^+\pi^-,\pi^+\pi^-\left|\overline{K}^0K^0(\Delta t)\right.\right\rangle\right|^2\right.$$
$$\left.-\left(1-\zeta_{0\bar{0}}\right)\cdot 2\Re\left(\left\langle\pi^+\pi^-,\pi^+\pi^-\left|K^0\overline{K}^0(\Delta t)\right.\right\rangle\left\langle\pi^+\pi^-,\pi^+\pi^-\left|\overline{K}^0K^0(\Delta t)\right.\right\rangle^*\right)\right]$$

I(Δt) (a.u.)



Decoherence parameter:

$\zeta_{0\bar{0}} = 0 \quad \rightarrow \quad$ QM

$\zeta_{0\bar{0}} = 1 \quad \rightarrow \quad$ total decoherence

(also known as Furry's hypothesis or spontaneous factorization)
W.Furry, PR 49 (1936) 393

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

The SM after the Higgs boson discovery and gravitational waves observation

Einstein-Hilbert action

$$S = \int \left[\frac{1}{2} M_{\rm pl}^2 R + \mathcal{L} \right] d^4x \sqrt{-g}$$

gravity

matter and gauge force fields

gravity

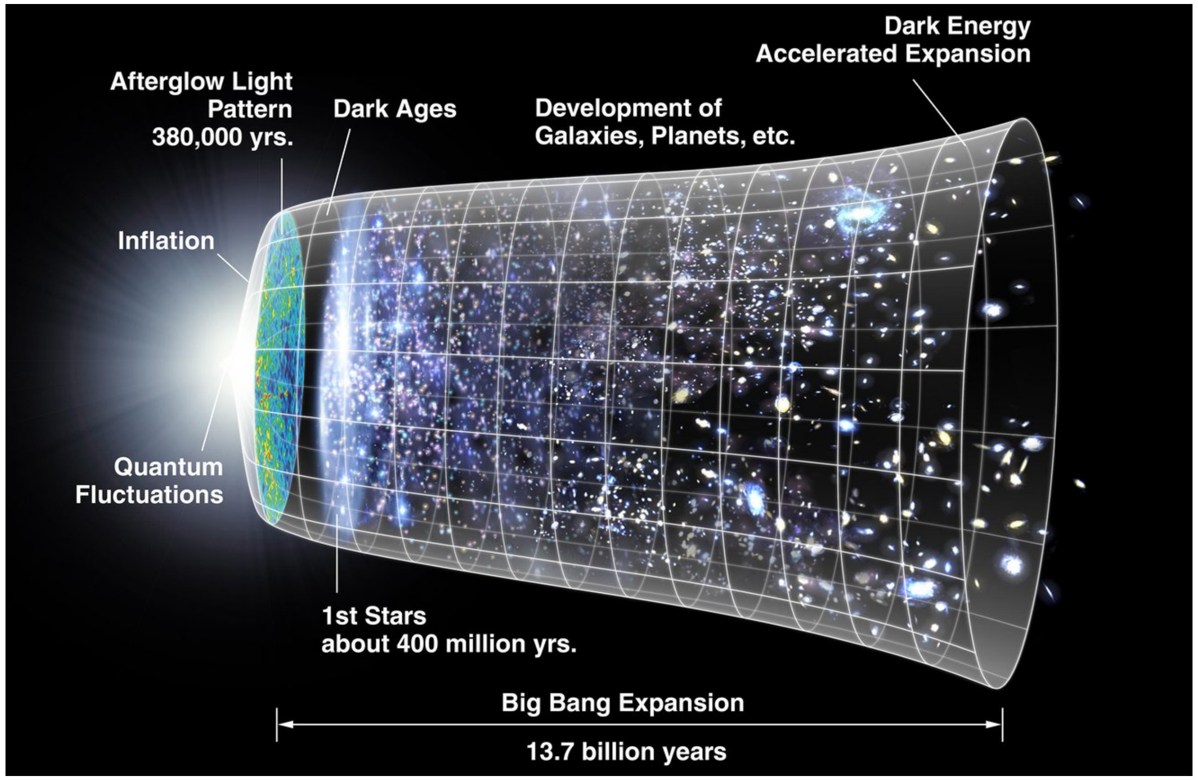
$$\mathcal{L} = -\frac{1}{4g'^4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a} + \bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{\ell}_i i \not{D} \ell_i + \left(Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_l^{ij} \bar{L}_i \ell_j H + c.c. \right) - \lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H$$

not observed in: e, μ, c, u, d, s

still not observed

Higgs boson couplings to ordinary matter still need to be observed !!

The Higgs boson and the inflation

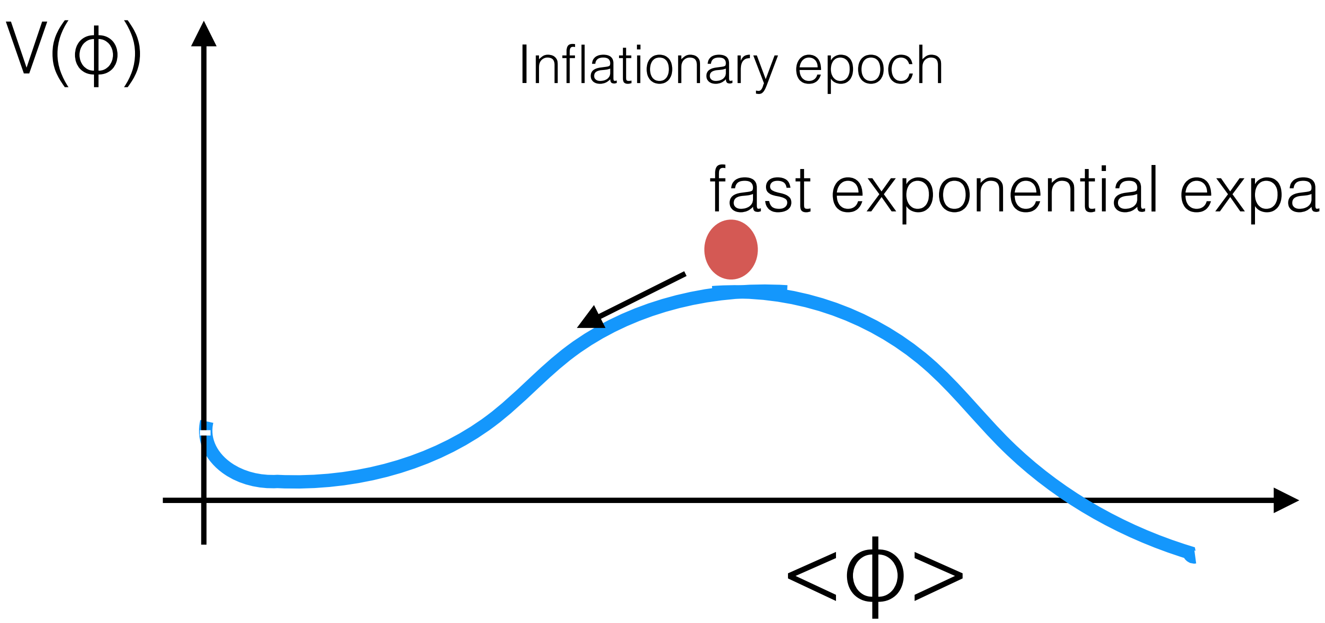


- **Exponential expansion of the universe at the starting age, it involves one scalar ϕ with a properly shaped energy potential $V(\phi)$. This energy behaves like dark-energy inducing universe acceleration (inflaton field)**

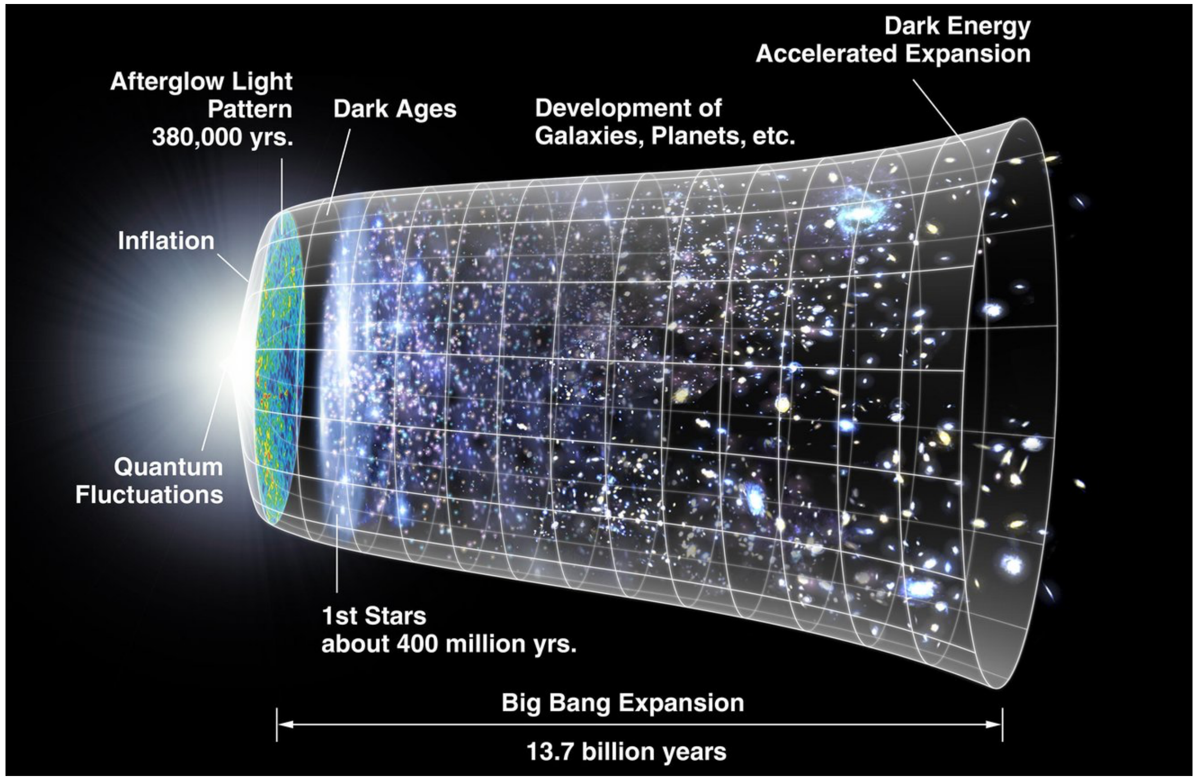
- **The Higgs potential could have such role if its potential is properly shaped**

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \longrightarrow H^2 = \frac{8\pi G}{3} V(\phi) \simeq const. \longrightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a}\right)$$

a(t) universe expansion parameter



The Higgs boson and the inflation



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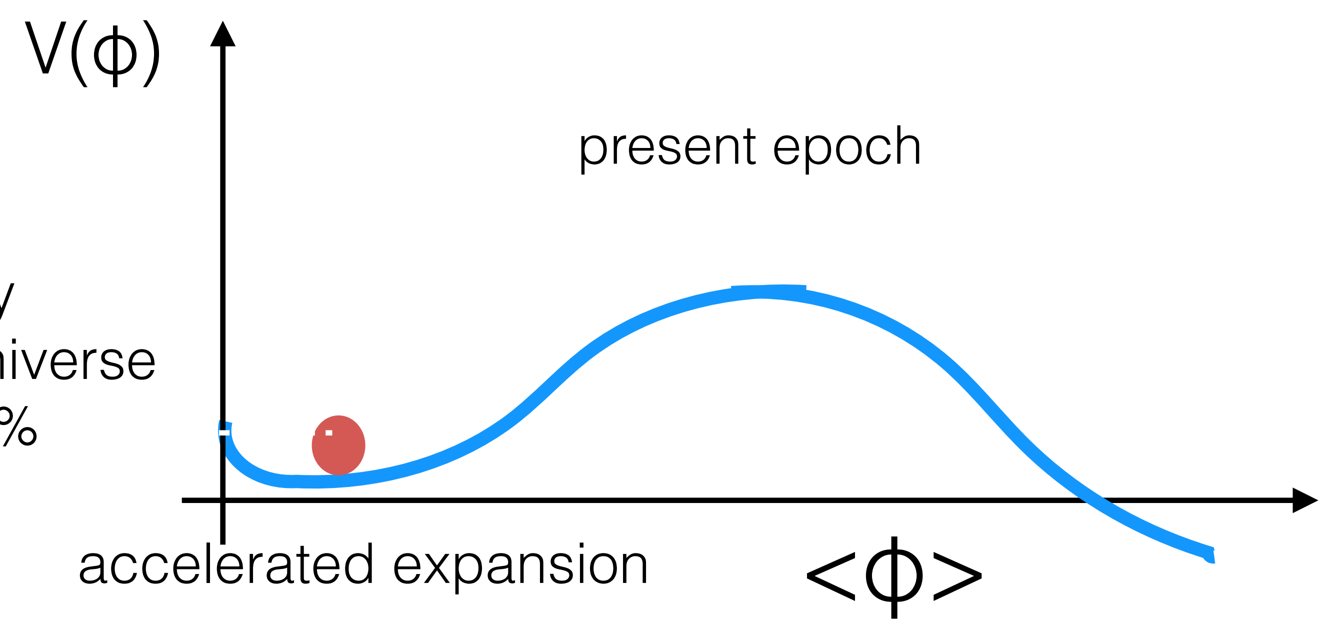
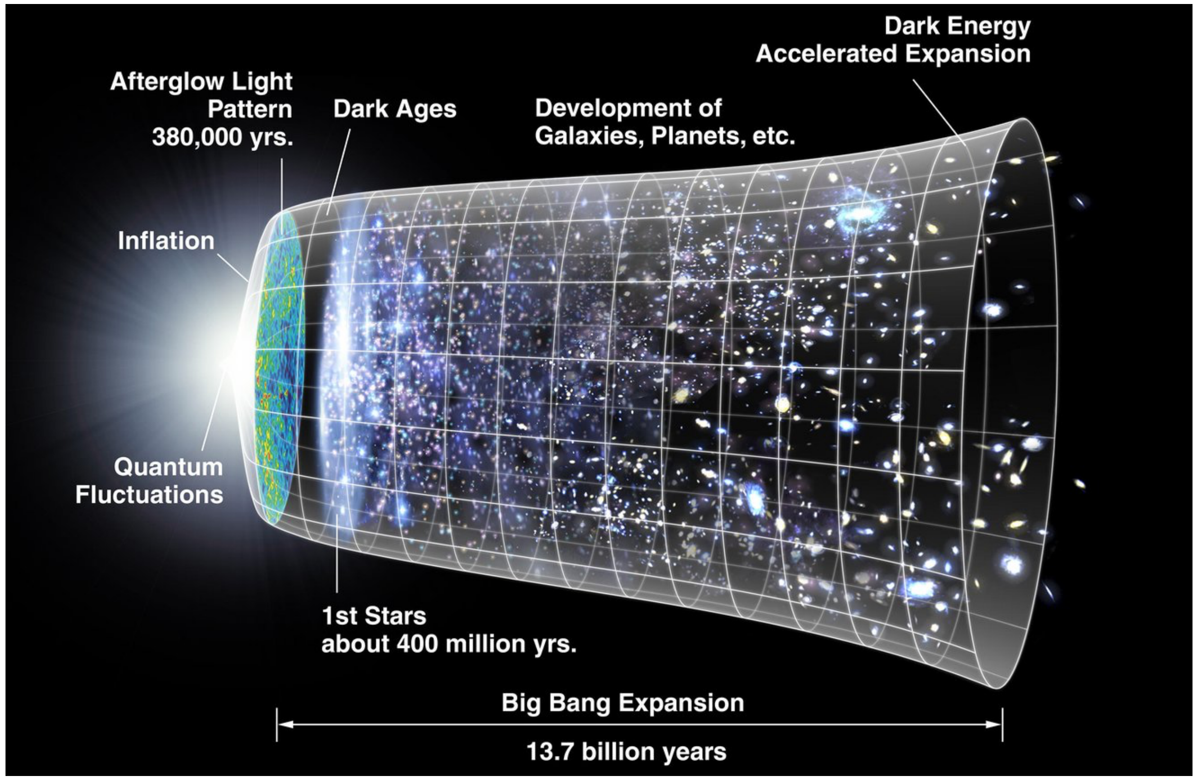
a(t) universe expansion parameter

dark energy
contribution to universe
evolution 70%



The Higgs boson and the inflation



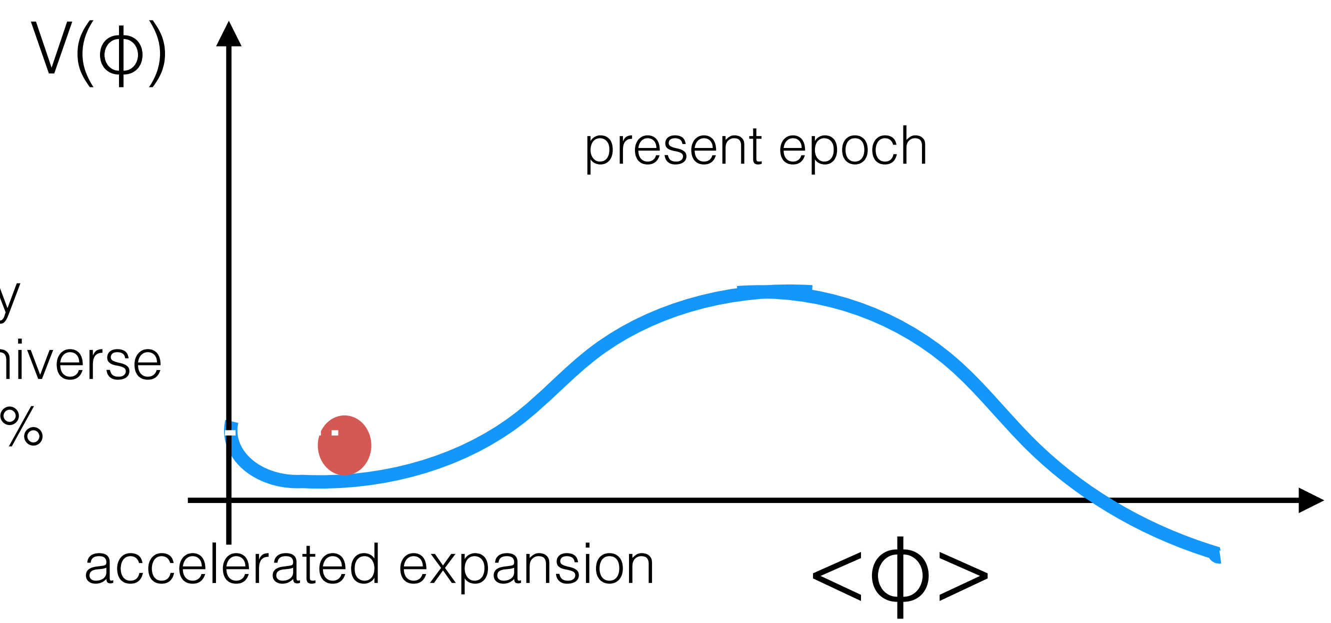
- **Exponential expansion of the universe at the starting age, it involves one scalar ϕ with a properly shaped energy potential V(ϕ). This energy behaves like dark-energy inducing universe acceleration (inflaton field)**

- **The Higgs potential could have such role if its potential is properly shaped**

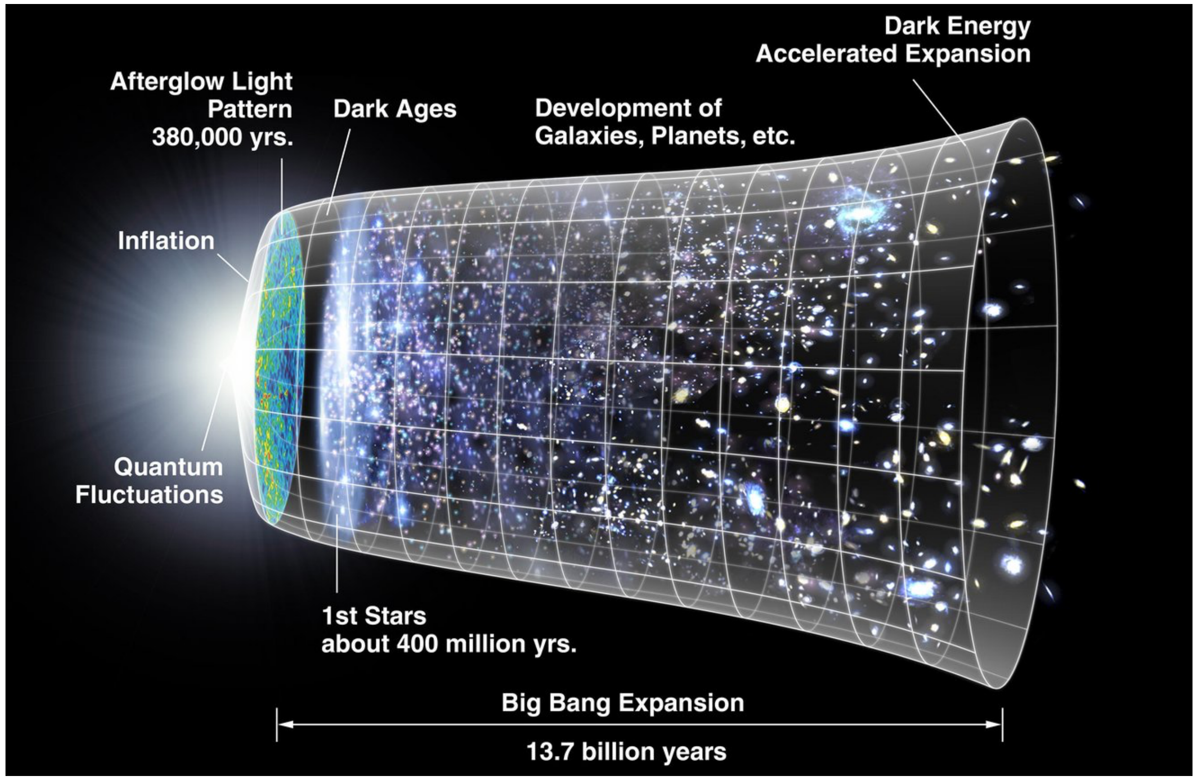
$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \longrightarrow H^2 = \frac{8\pi G}{3} V(\phi) \simeq const. \longrightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a}\right)$$

a(t) universe expansion parameter

dark energy
contribution to universe
evolution 70%



The Higgs boson and the inflation



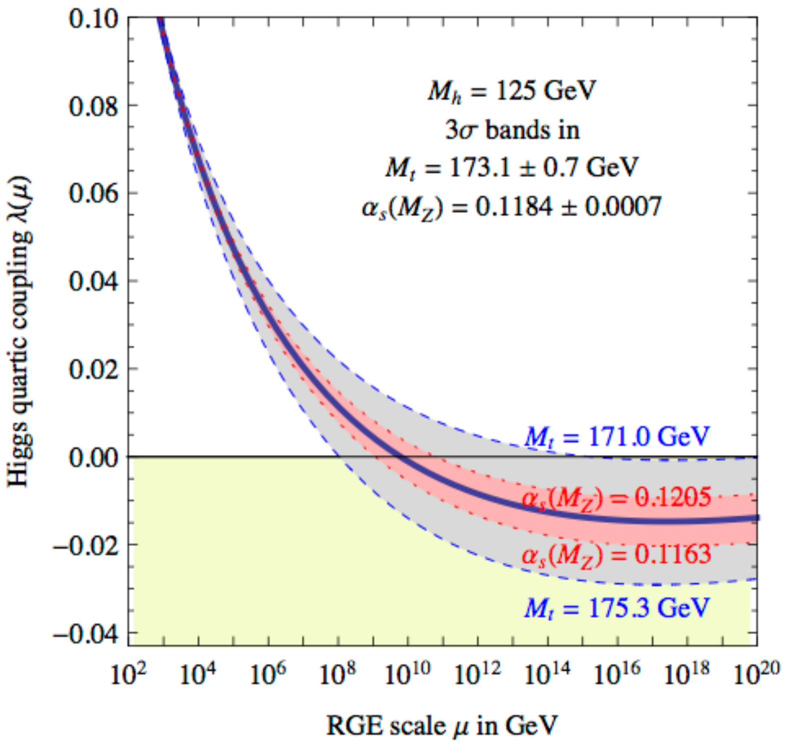
- Exponential expansion of the universe at the starting age, it involves one scalar φ with a properly shaped energy potential V(φ). This energy behaves like dark-energy inducing universe acceleration (inflaton field)

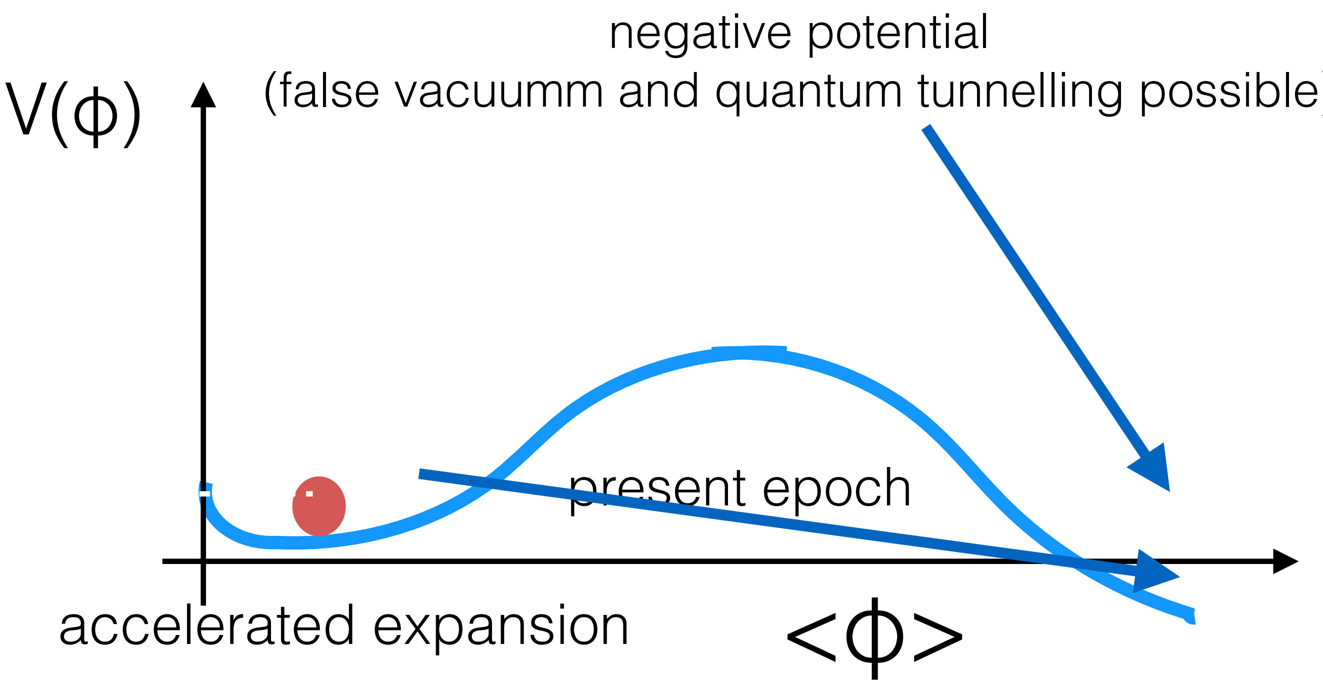
- The Higgs potential could have such role if its potential is properly shaped

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \longrightarrow H^2 = \frac{8\pi G}{3} V(\phi) \simeq const. \longrightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a}\right)$$

$$V(\phi) \sim \lambda\phi^4$$

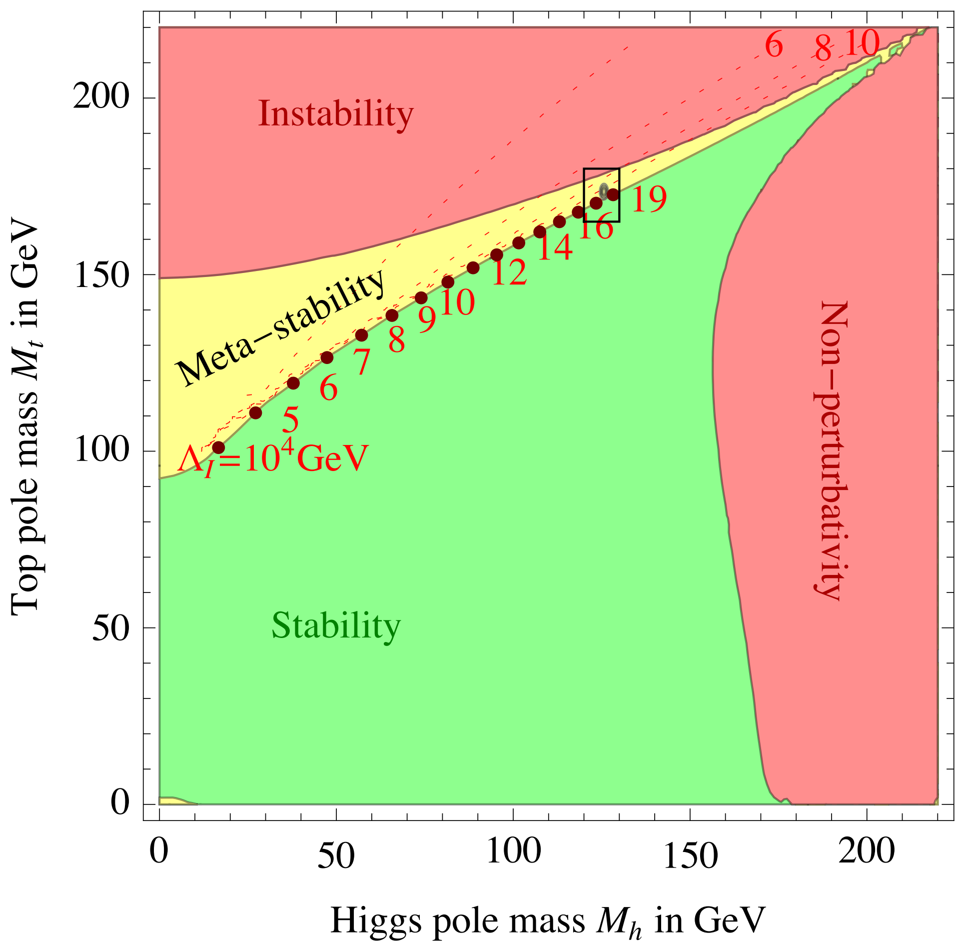
λ energy scale dependence is function of M_h, M_t and the strong coupling constant at Mz

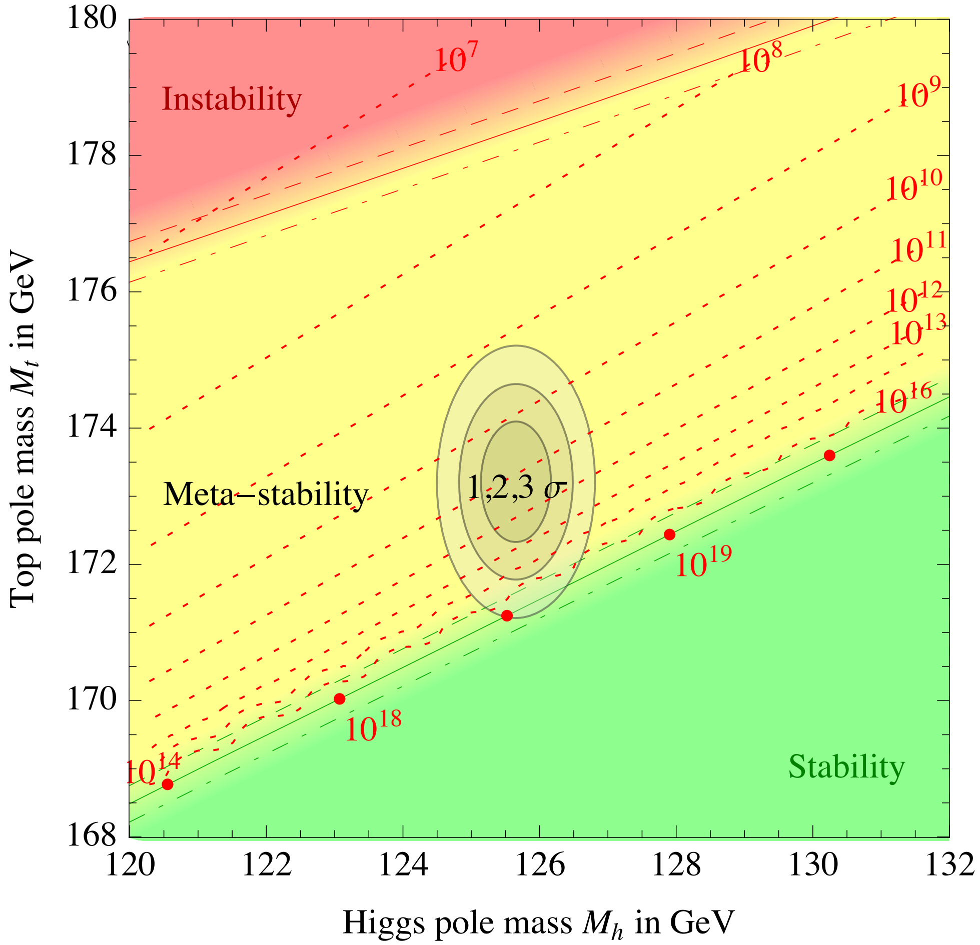




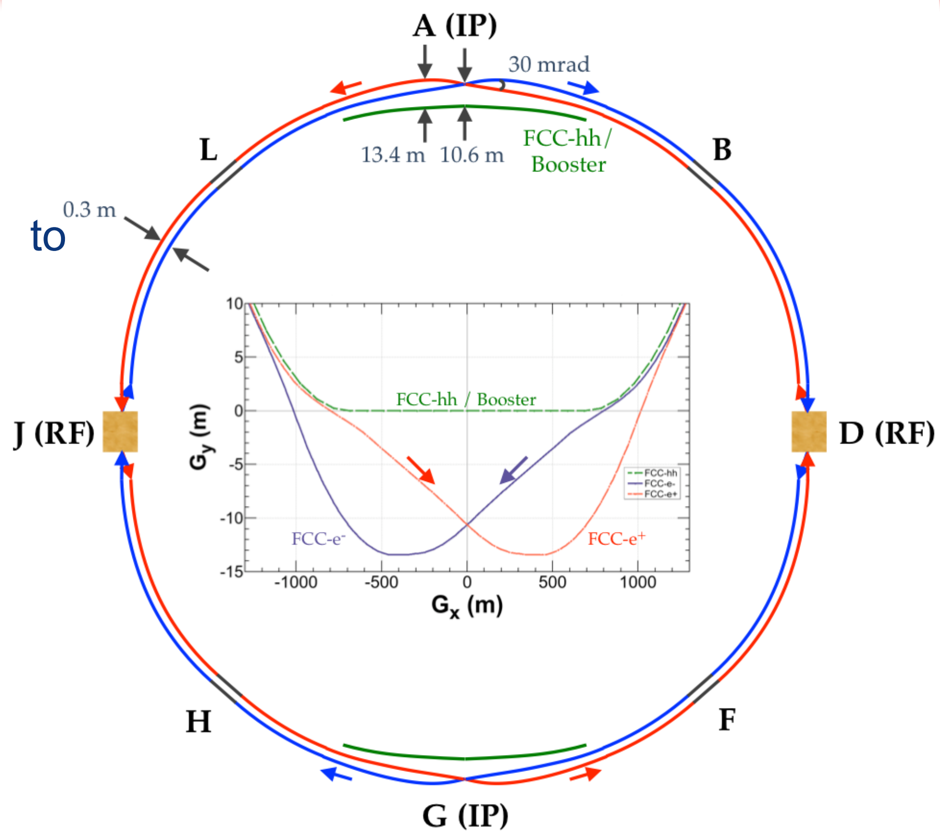
Vacuum stability

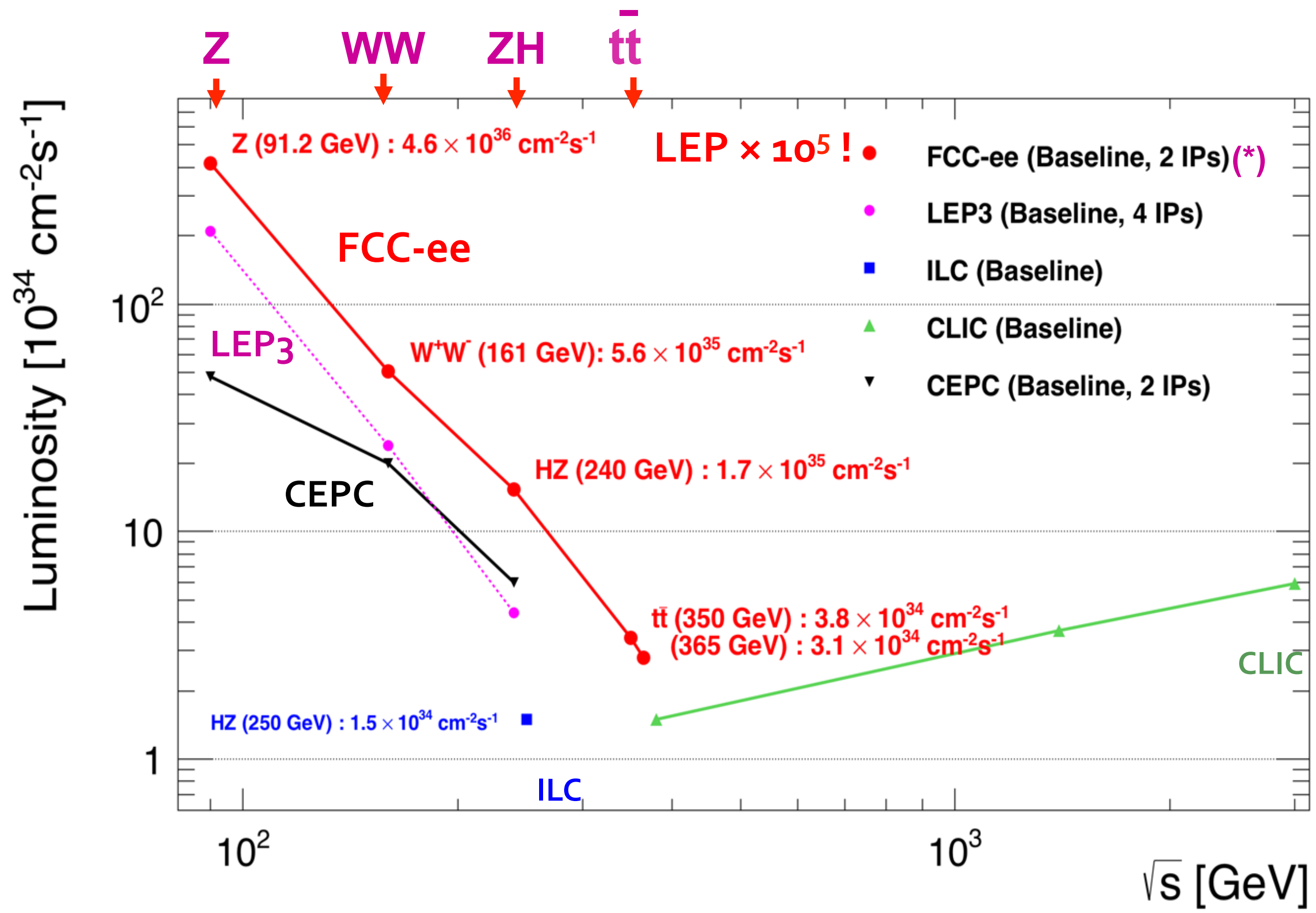
It is critical for our understanding of universe evolution to measure the Higgs boson self-coupling, the Higgs, the W and the top mass with the highest possible accuracy





FCC-ee: Machine scheme and luminosity





collider properties

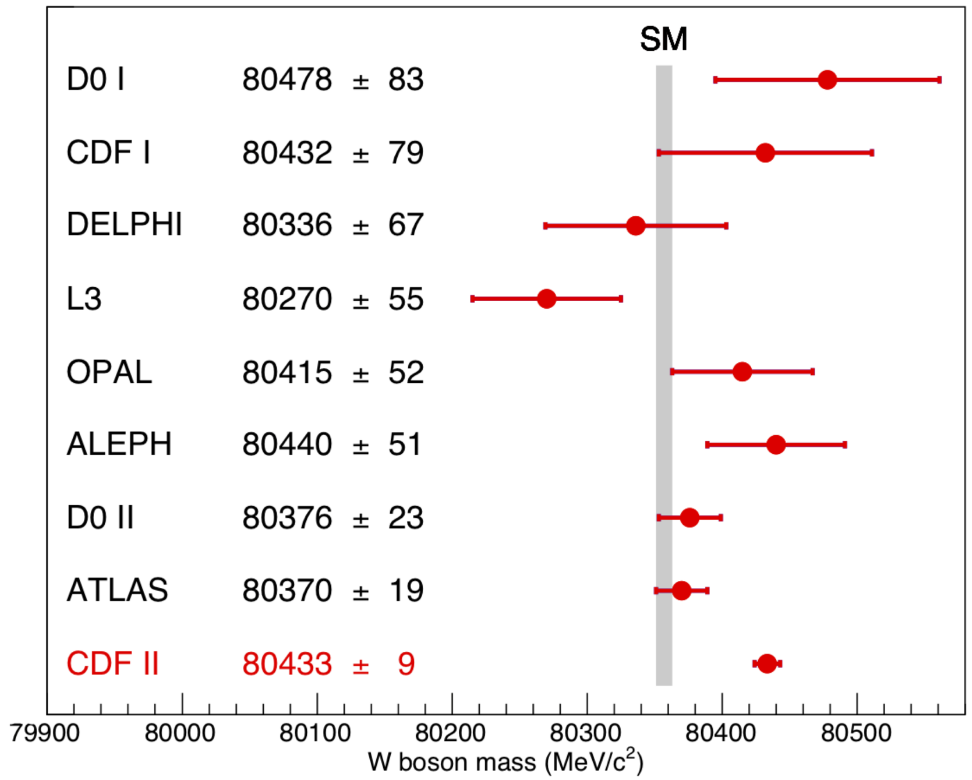
- double accumulator ring, energy booster for acceleration, continuous injection, crossing angle (30 mrad), crab-waist techinque for luminosity optimisation
- minimal setup 2IP, optimal one with 4 IP

proposed timeline , energies and luminosity

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold...	... and above
√s (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4

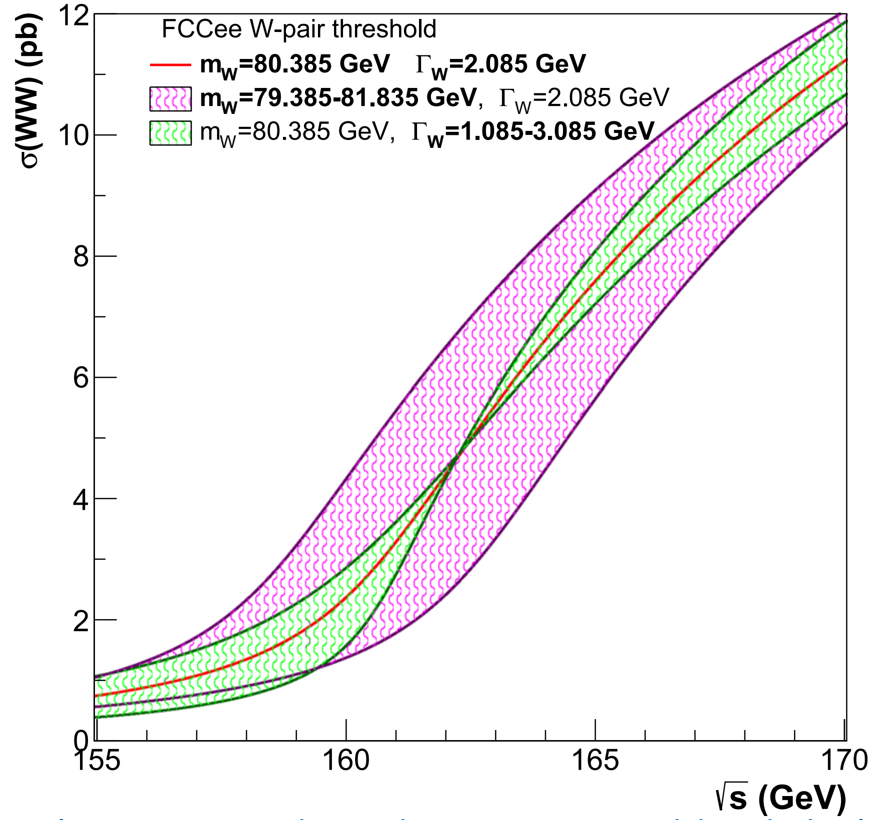
Measurement of m_W

present status



- Large number of measurements from LEP, Tevatron, LHC
- Recent CDF RunII results greatly reduce the error keeping the previous central value
- compatibility among the measurements at the 0.2% level

FCC-ee can measure m_W and Γ_W using a scan of $\sigma(e^+e^- \to W^+W^-)$ as a function of $\sqrt{s}$

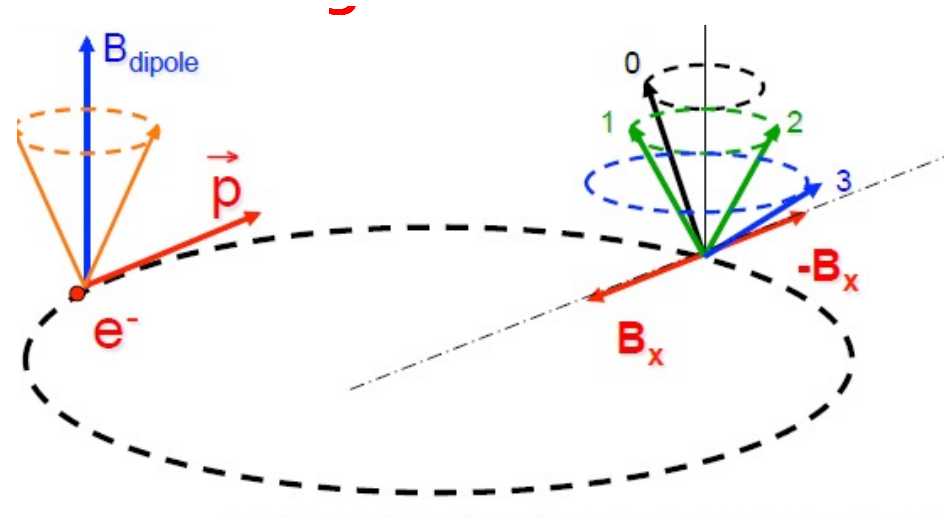


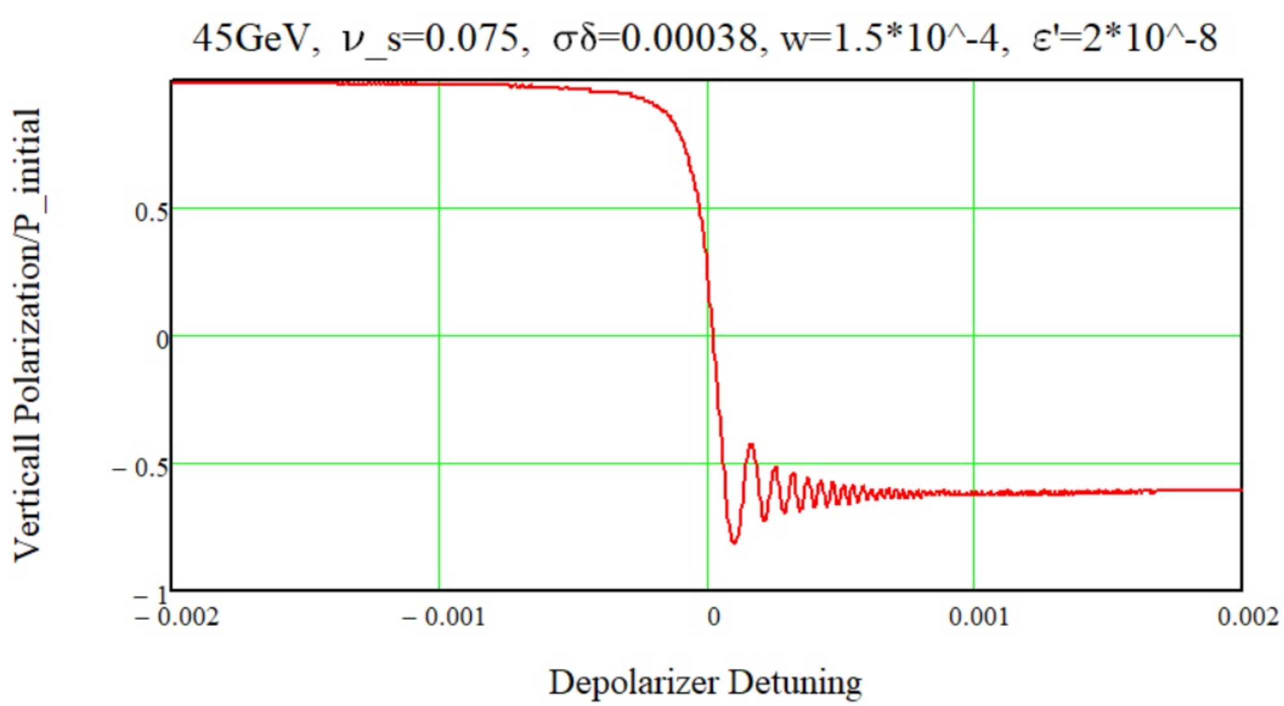
- the WW final state needs to be measured both in leptonic and hadronic channels to maximise statistics
- measuring the XS at a single energy point a statistical precision of 0.3 MeV on m_W can be obtained with 12 ab^{-1} of data, beam energy spread ΔE_{beam} < 0.35 MeV is needed;
- using 2 energy points E_1 = 157.1 GeV, E_2 = 162.3 GeV, L_{int} = 12 ab^{-1}, 40% of the luminosity at E_2 : Δm_W = 0.5 MeV , $\Delta\Gamma_W$ = 1.2 MeV (stat. only.)
- It is crucial to have low beam-energy spread and accurate absolute beam energy measurement

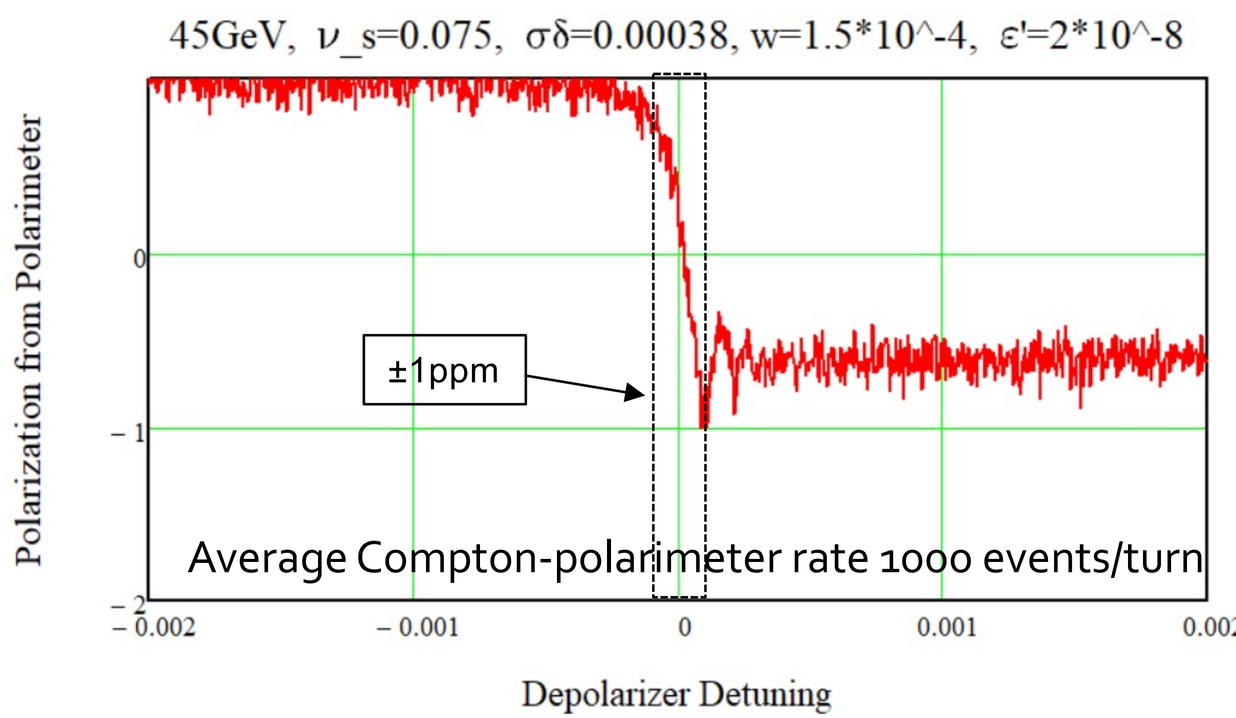
Absolute determination of √s

Continuous resonant depolarisation to measure the beam energies

- electrons are transverse-polarised using Wigglers
- spin precession frequency $\nu_0 \sim E_{beam}$
- beams are depolarised by a kicker at frequency ν_0
- polarisation measurement through Compton backscattering

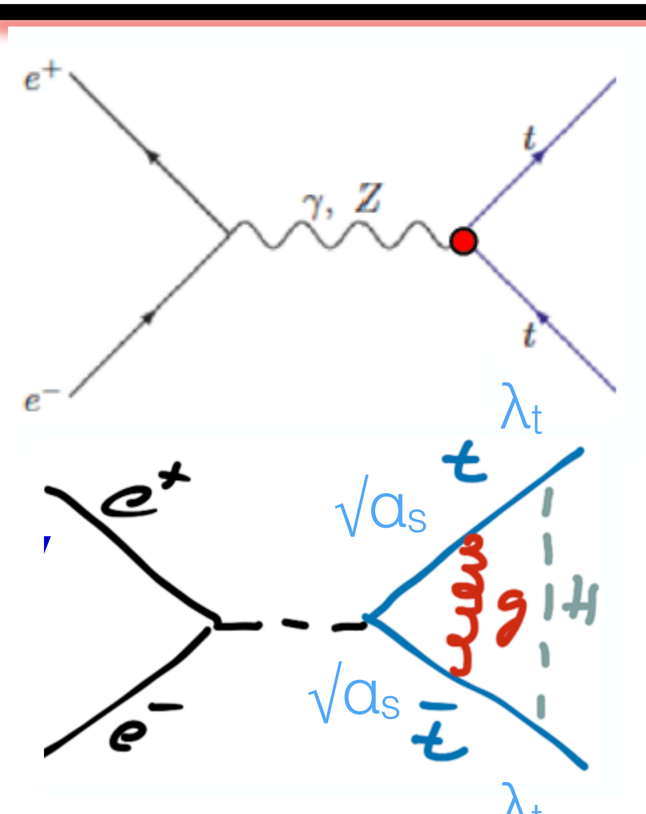


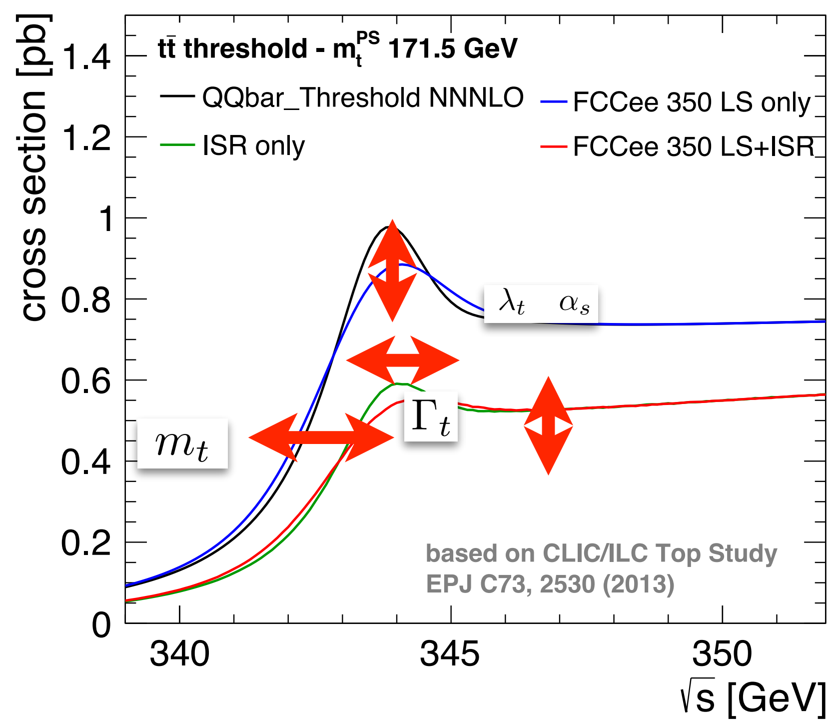


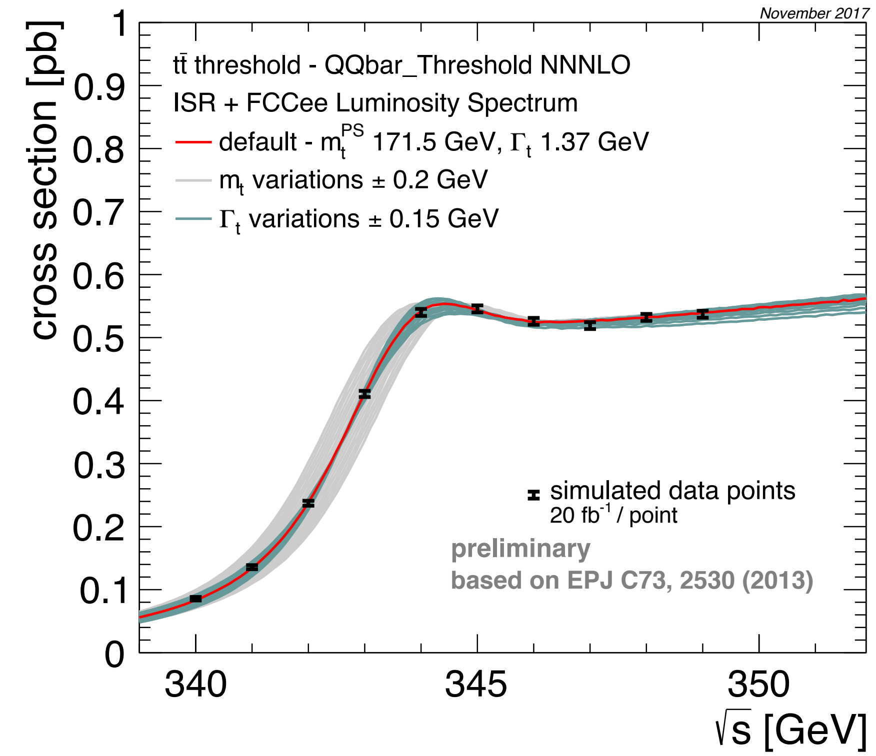


1 ppm accuracy on beam energy is feasible
accuracy at level of 100 keV at the Z pole

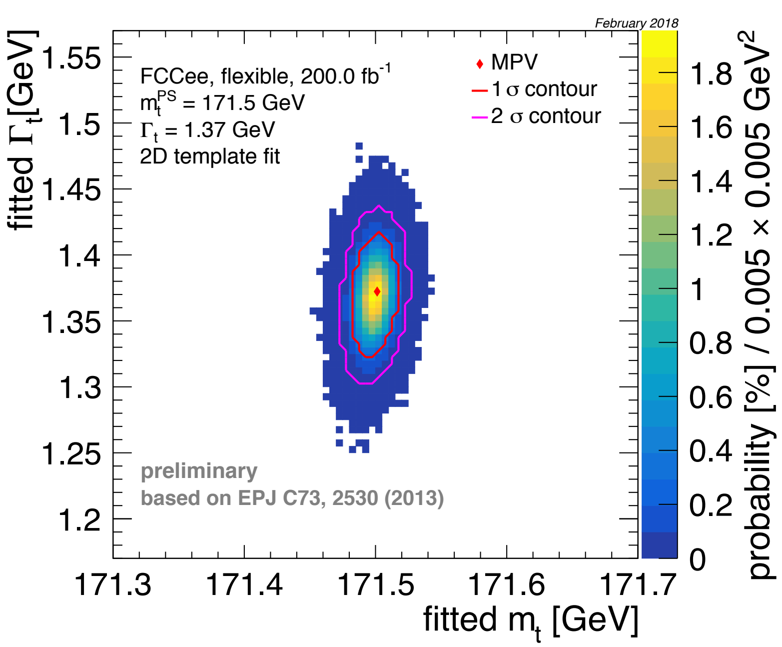
Measurement of the top mass

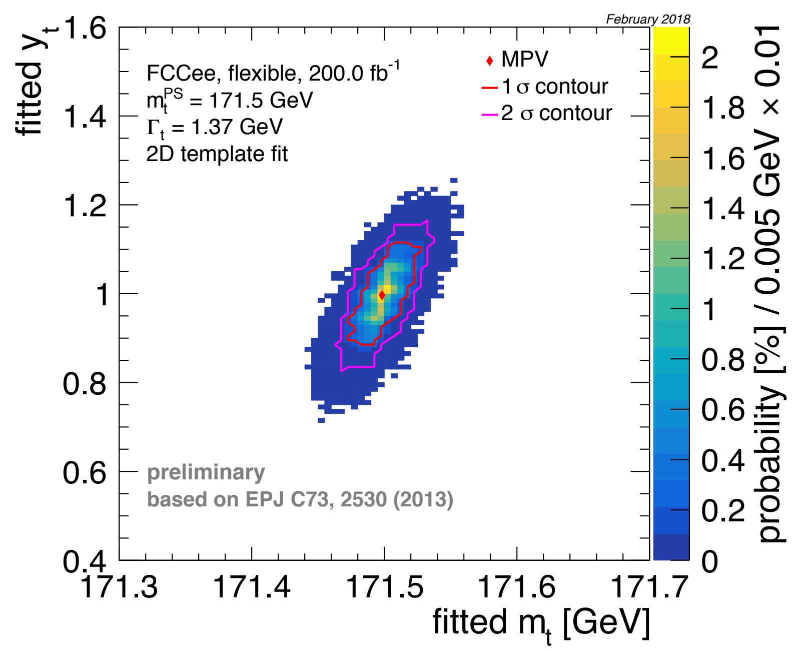


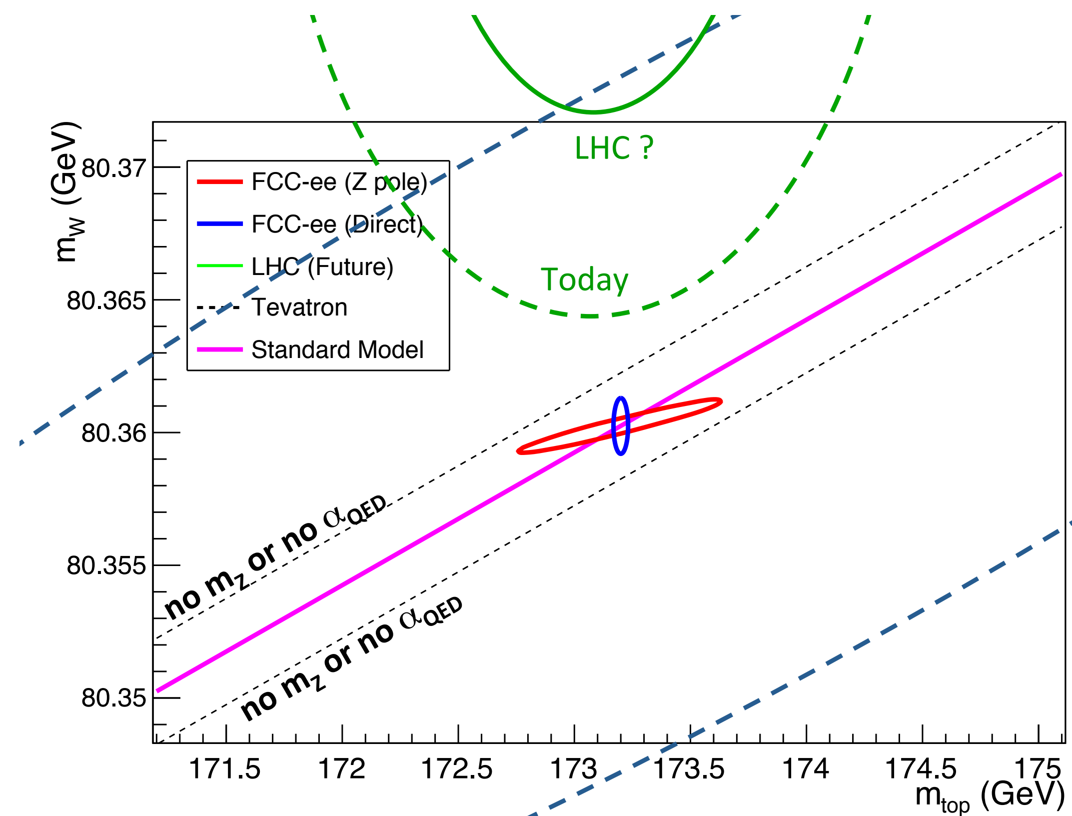




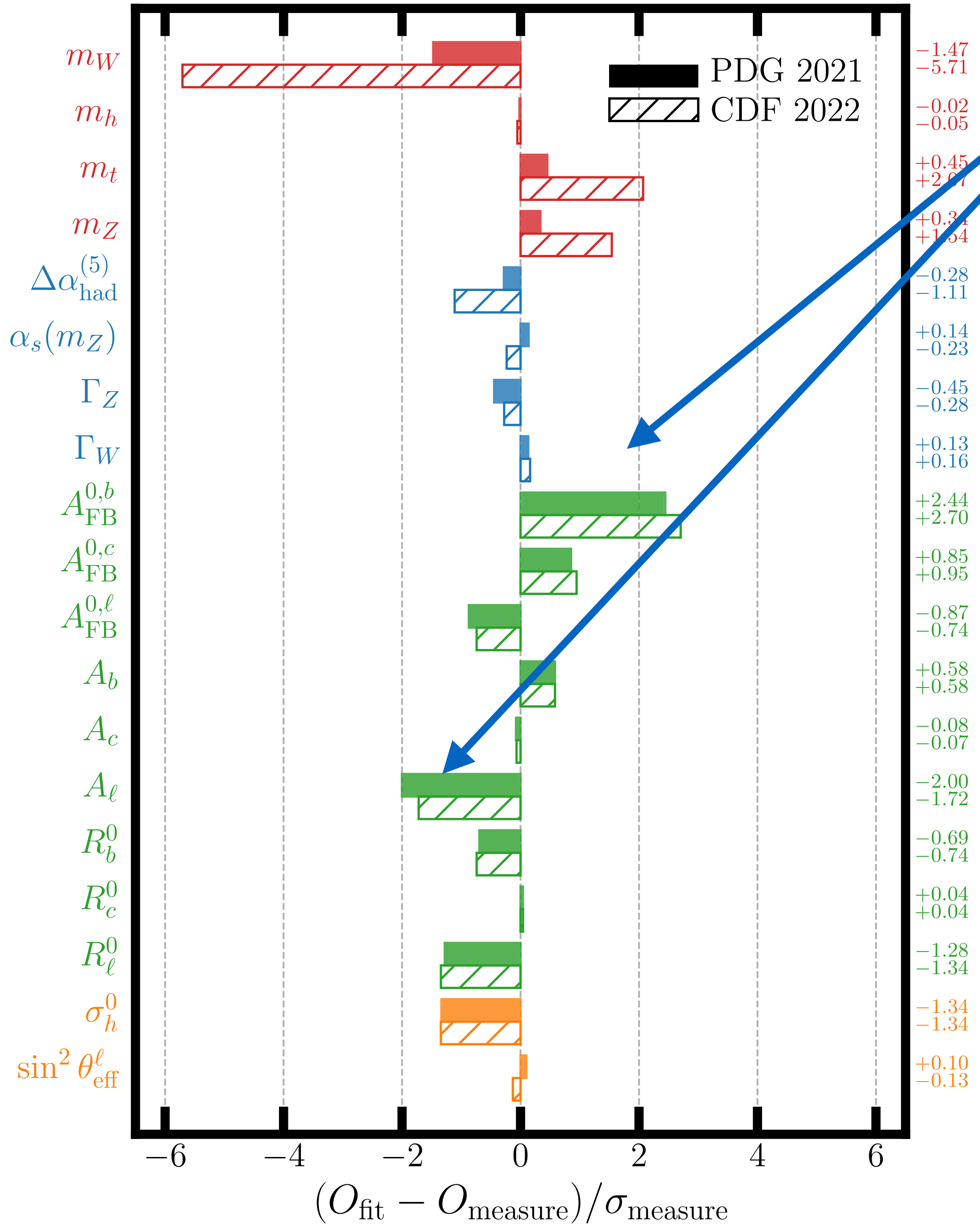
Yukawa coupling and α_S through loop higher orfer corrections







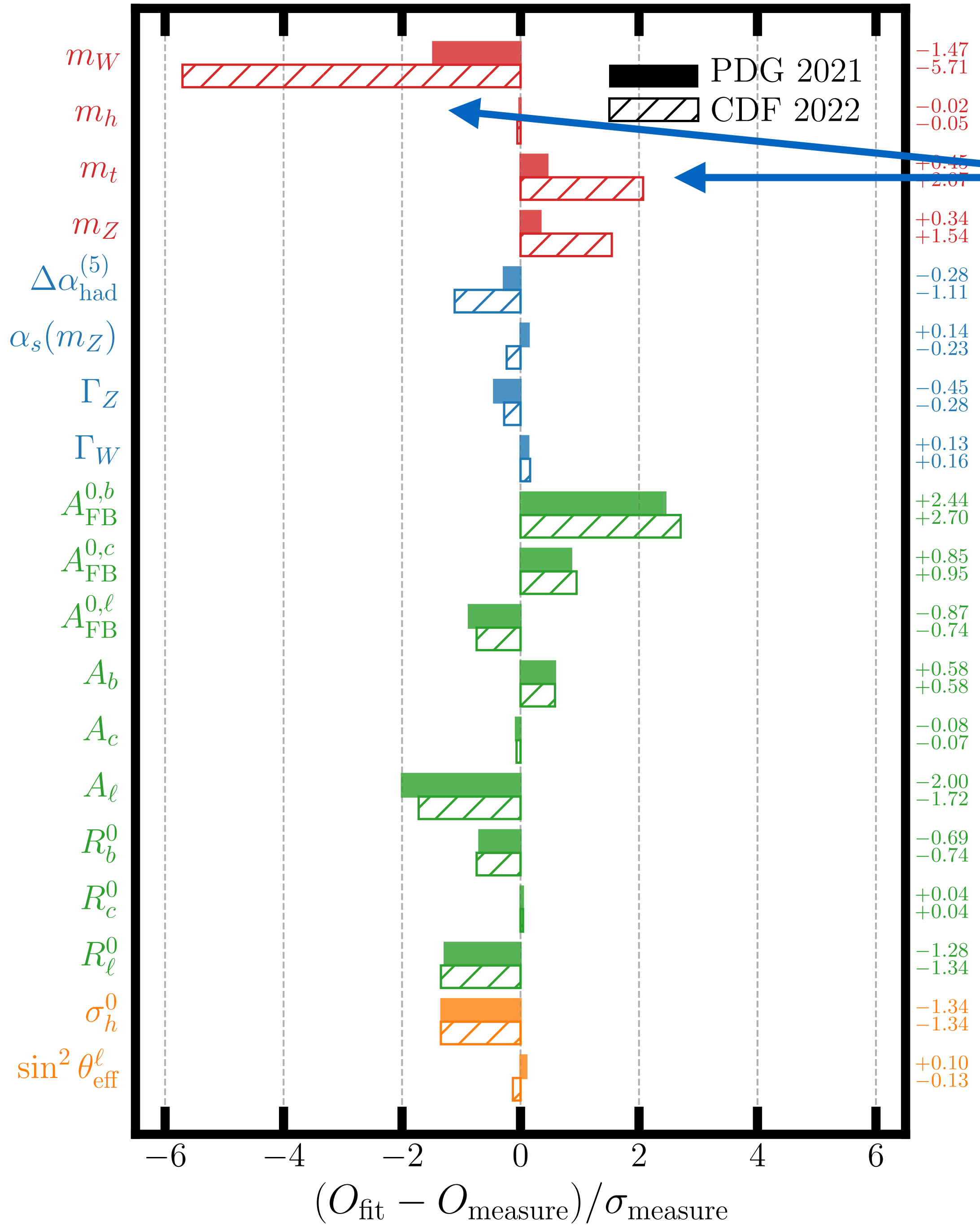
Electroweak precision measurements



C.T. Lu et al., Phys. Rev. D 106, 035034 (2022)

- **new CDFII measurement increases tension in the fit**
- **usual border-line measurements are still there**

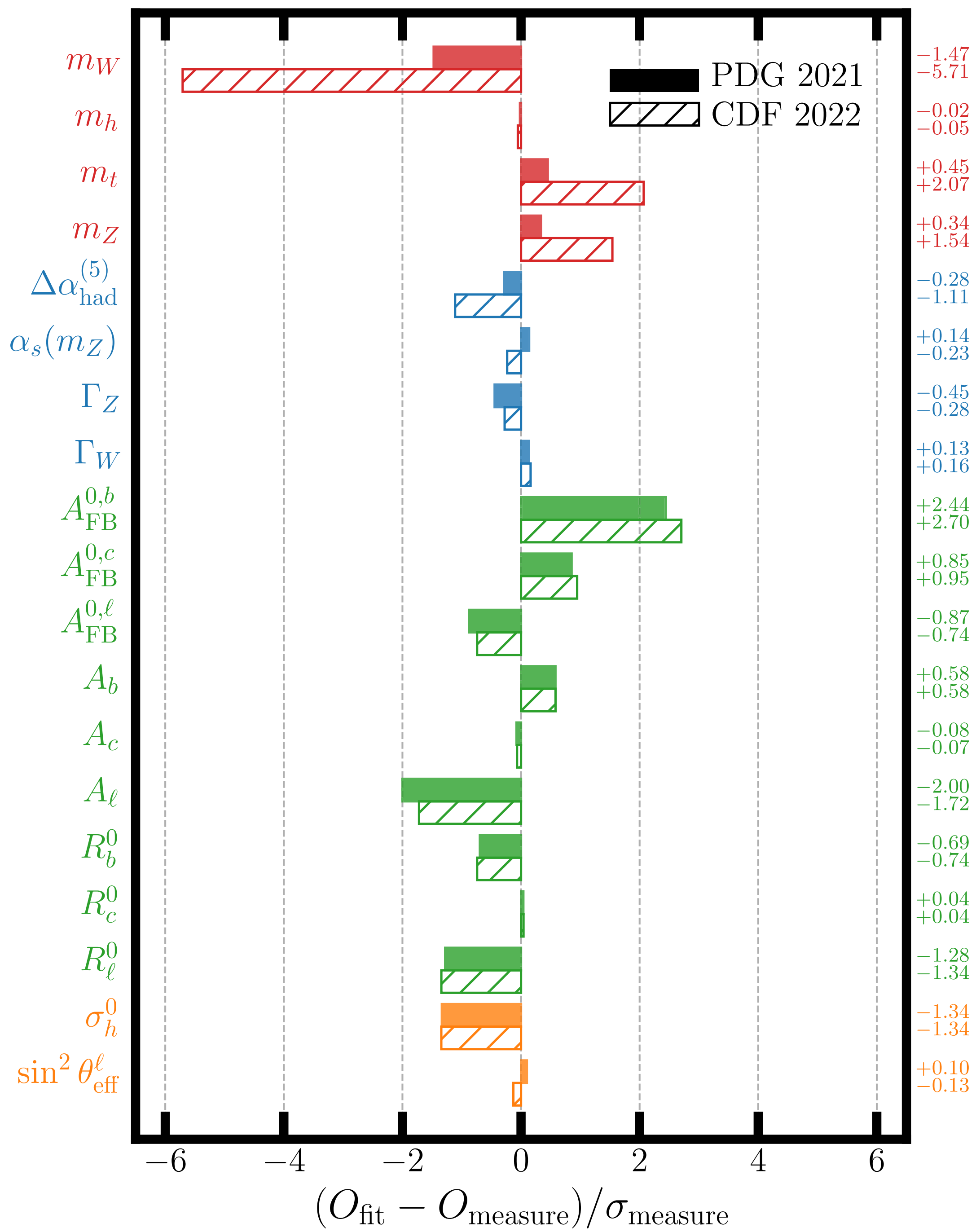
Electroweak precision measurements



- **new CDFII measurement increases tension in the fit**
- **usual border-line measurements are still there**
- **new incompatibilities show up :-)**

C.T. Lu et al., Phys. Rev. D 106, 035034 (2022)

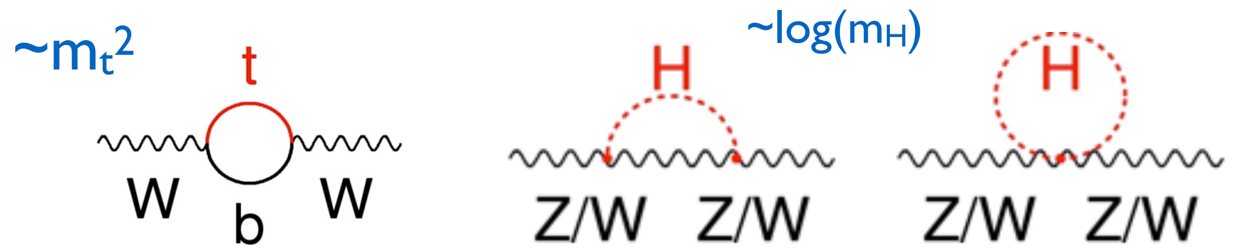
Electroweak precision measurements

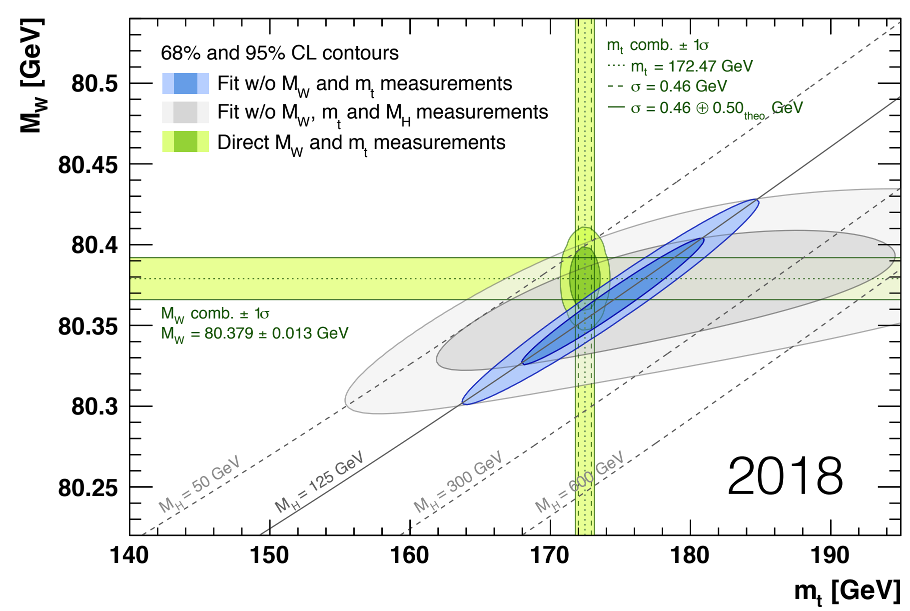


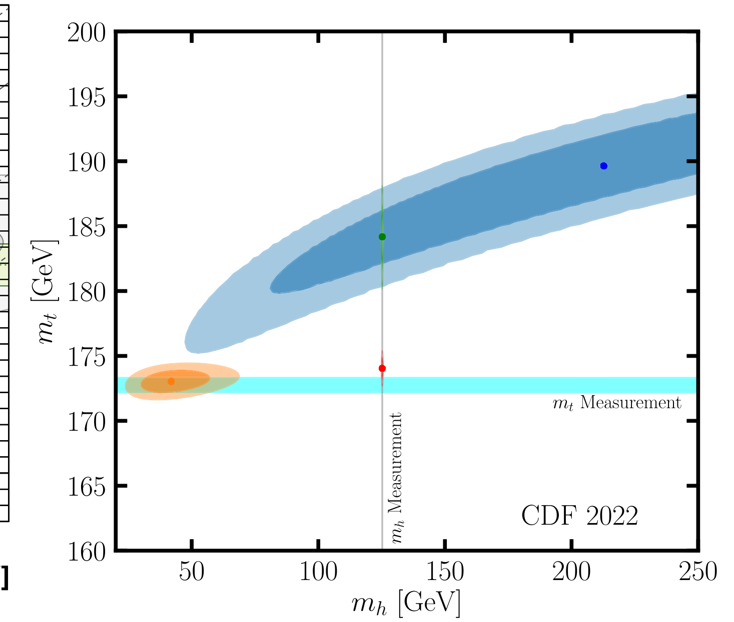
C.T. Lu et al., Phys. Rev. D 106, 035034 (2022)

- new CDFII measurement increases tension in the fit
- usual border-line measurements are still there
- new incompatibilities show up :-)
- hopefully LHC will clarify (or add confusion) to the m_W puzzle
- other tensions will remain, will it be the next e^+e^- collider to address this issue (and find new ones ?)

W mass gets top and Higgs mass correction through loops

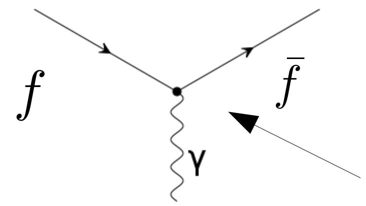




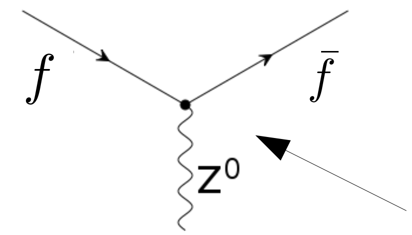


Fermionic asymmetries measurements

$$A^f_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

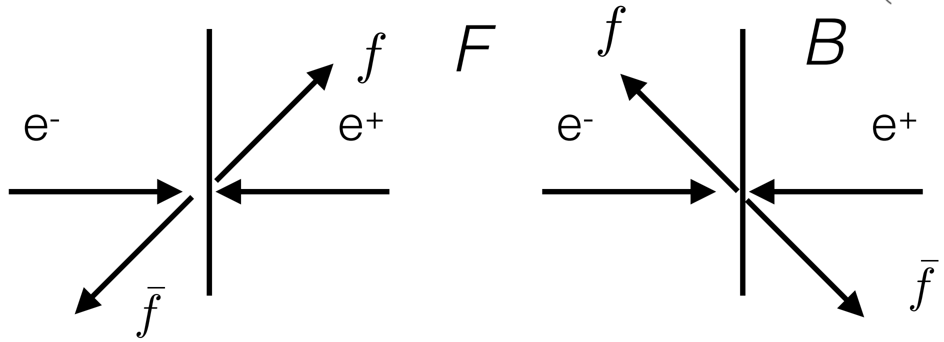


$-ieQ^f\gamma^\mu$



$$\frac{-ig}{cos\theta_W}\gamma^\mu\frac{g_{Vf} - g_{Af}\gamma_5}{2}$$

$$\mathcal{A}_f = \frac{2g_{Vf}g_{Af}}{1 + (g_{Vf}/g_{Ae})^2}$$



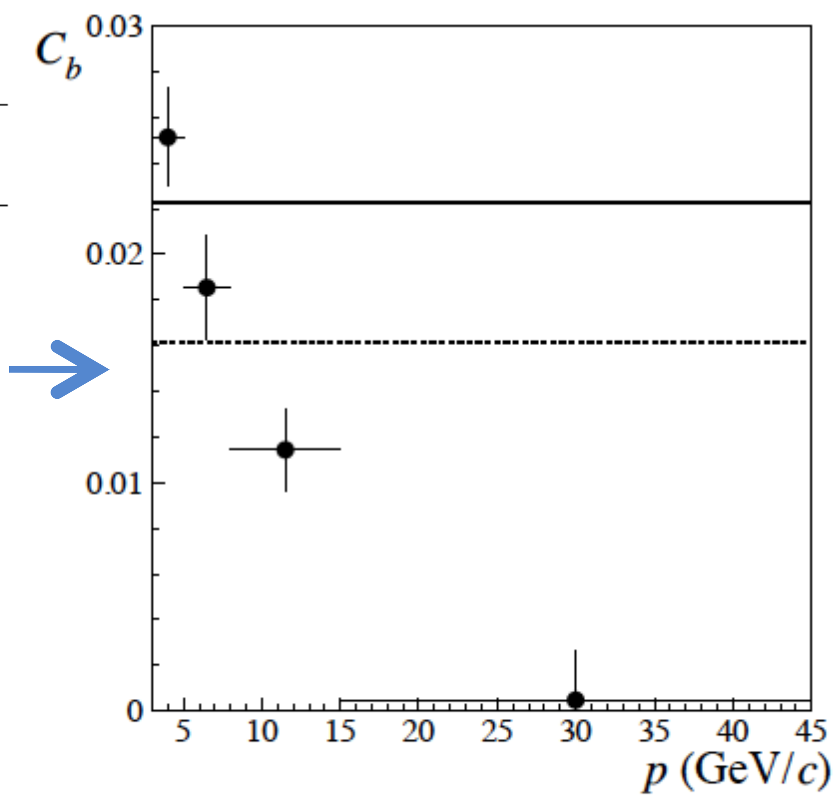
$$\mathcal{A}^f_{\rm FB}(\sqrt{s} = m_Z) = \mathcal{A}^{0,f}_{\rm FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
$\mathcal{A}_e$	$5. \times 10^{-5}$	$1. \times 10^{-4}$	50
$\mathcal{A}_\mu$	2.5×10^{-5}	1.5×10^{-4}	30
$\mathcal{A}_\tau$	$4. \times 10^{-5}$	$3. \times 10^{-4}$	15
$\mathcal{A}_b$	2×10^{-4}	30×10^{-4}	5
$\mathcal{A}_c$	3×10^{-4}	80×10^{-4}	4
$\sin^2\theta_{W,eff}$ (from muon FB)	10^{-7}	$5. \times 10^{-6}$	100
$\sin^2\theta_{W,eff}$ (from tau pol)	10^{-7}	6.6×10^{-6}	75

Profiting of the high available statistics hard cuts can be used to reduce the impact of systematic errors

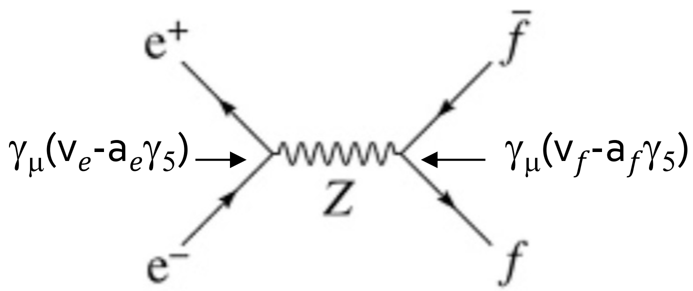
	LEP	FCC-ee
statistics	0.00156	0.00002
unc. sys.	0.00061	orig. stat.
QCD corr	0.00030	tagli su p_T^l

impact of QCD correction



$\sin^2\theta_{eff}$ from τ polarisation

Parity-violating (L ≠ R) weak couplings at the Z pole



$a_f = \pm 1/2$
$v_f = a_f(1 - 4|Q_f| \sin^2\theta^{\ell}_{eff})$

Asymmetry parameter

$$\boxed{A_f = \frac{2 a_f v_f}{v_f^2 + a_f^2}}$$

- At linear colliders it is possible to increase the sensitivity using longitudinally polarised beams $P = \frac{P_{e^-} - P_{e^+}}{(1 - P_{e^-} P_{e^+})}$

$$\boxed{A_{LR} = \frac{\sigma_{tot}(P) - \sigma_{tot}(-P)}{\sigma_{tot}(P) + \sigma_{tot}(-P)} = P A_e}$$

$$\boxed{A_{FB}^{polf} = \frac{\sigma_{Ff}(P) - \sigma_{Ff}(-P) - [\sigma_{Bf}(P) - \sigma_{Bf}(-P)]}{\sigma_{totf}(P) + \sigma_{totf}(-P)} = \frac{3}{4} P A_f}$$

- Polarisation is present also in the final state fermions, it can be measured in the τ case using the angular distribution of the decay products

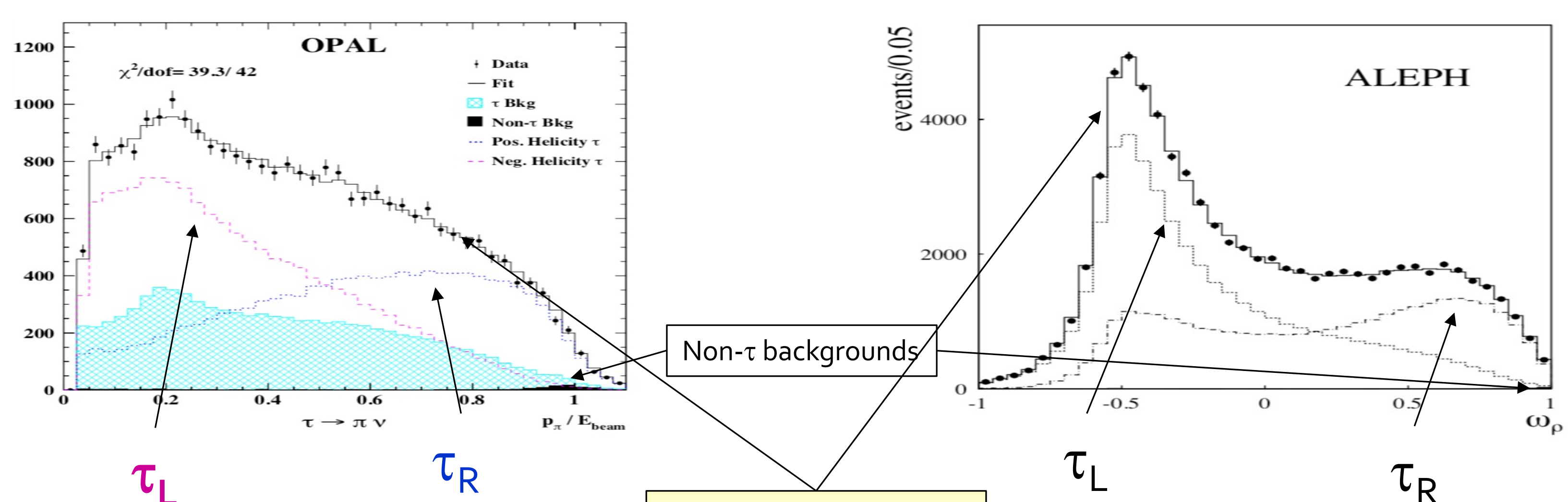
$$\boxed{\langle P_\tau \rangle = \frac{\sigma_{R\tau} - \sigma_{L\tau}}{\sigma_{R\tau} + \sigma_{L\tau}} = -A_\tau}$$

$$\boxed{A_{FB}^{pol\tau} = \frac{\sigma_{RF\tau} - \sigma_{LF\tau} - [\sigma_{RB\tau} - \sigma_{LB\tau}]}{\sigma_{R\tau} + \sigma_{L\tau}} = -\frac{3}{4} A_e}$$

$$\boxed{A_{FB}^{f} = \frac{\sigma_{Ff} - \sigma_{Bf}}{\sigma_{Ff} + \sigma_{Bf}} = \frac{3}{4} A_e A_f}$$

- **$\tau \to \pi\nu_\tau$: pion energy**

$\tau \to \rho\nu_\tau$: optimal observable ω_ρ



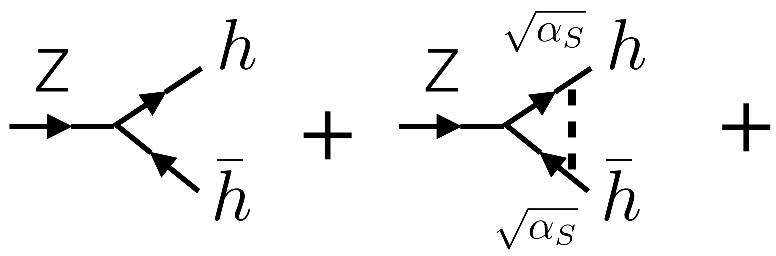
example from LEP

Slide from P. Janot, Precision Calculations for future e+ e- colliders

R_ℓ measurement and α_S

$$R_\ell = \frac{\Gamma_{\rm had}}{\Gamma_\ell}$$

Γ_{had} is sensitive to α_S through QCD loop corrections on final state hadrons: *h*



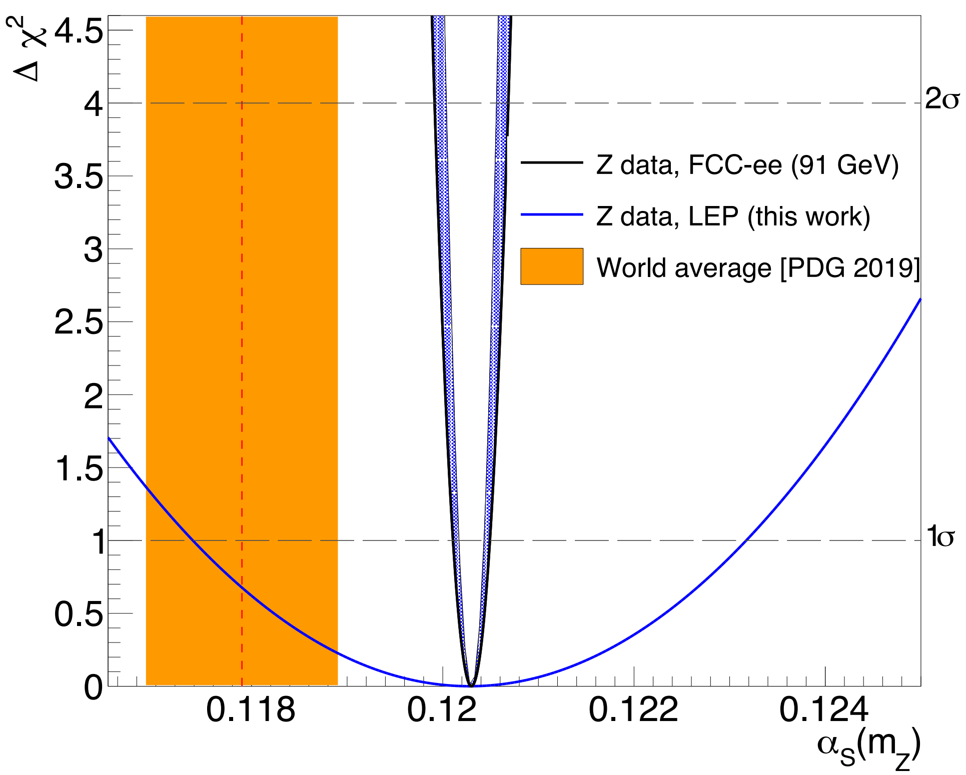
R_ℓ statistical precision at 3×10^{-6} level

- allows a test of lepton universality and quark-lepton universality
- allows the extraction of α_S at m_Z

Main systematics at LEP from detector acceptance

- can be reduced increasing the fiducial volume |cos(θ)| < 0.95 → |cos(θ)| < 0.995;
- providing a clean and simple design of the forward region

Z boson observable	$\alpha_S(m_Z)$ extraction	uncertainties exp.	param.	theor.
Γ_Z^{tot}	0.1192 ± 0.0047	± 0.0046	± 0.0005	± 0.0008
R_Z	0.1207 ± 0.0041	± 0.0041	± 0.0001	± 0.0009
σ_Z^{had}	0.1206 ± 0.0068	± 0.0067	± 0.0004	± 0.0012
All combined	0.1203 ± 0.0029	± 0.0029	± 0.0002	± 0.0008
Global SM fit	0.1202 ± 0.0028	± 0.0028	± 0.0002	± 0.0008
All combined (FCC-ee)	0.12030 ± 0.00026	± 0.00013	± 0.00005	± 0.00022
Global SM fit (FCC-ee)	0.12020 ± 0.00026	± 0.00013	± 0.00005	± 0.00022



α_S from W decays

- QCD coupling extracted from new N^{3}LO fit of combined Γ_W, R_W pseudo-observ.:

W boson observables	$\alpha_S(m_Z)$ extraction	uncertainties exp.	param.	theor.
Γ_W^{tot}, R_W (exp. CKM)	0.044 ± 0.052	± 0.024	± 0.047	(± 0.0014)
Γ_W^{tot}, R_W (CKM unit.)	0.101 ± 0.027	± 0.027	(± 0.0002)	(± 0.0016)
Γ_W^{tot}, R_W (FCC-ee, CKM unit.)	0.11790 ± 0.00023	± 0.00012	± 0.00004	± 0.00019

Slide from D. d'Entreria LFC '21 Trento

- FCC-ee extraction:

– Huge W pole stats. ($\times 10^4$ LEP-2).

– Exquisite syst./parametric precision:

$$\Gamma_W^{tot} = 2088.0 \pm 1.2 \text{ MeV}$$

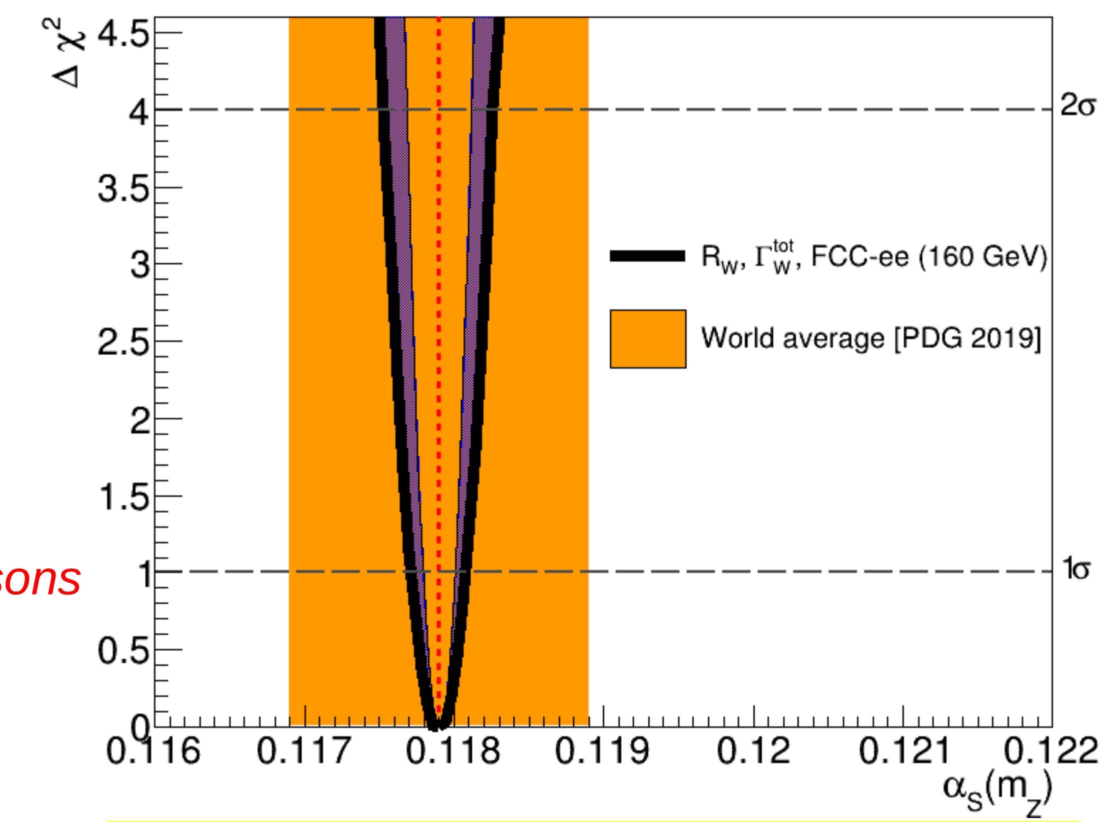
$$R_W = 2.08000 \pm 0.00008$$

$$m_W = 80.3800 \pm 0.0005 \text{ GeV}$$

$$|V_{cs}| = 0.97359 \pm 0.00010$$ ← $O(10^{12})$ D mesons

– TH uncertainty reduced by $\times 10$ after computing missing α_s^5, α^2, α^3, $\alpha\alpha_s^2$, $\alpha\alpha_s^2$, $\alpha^2\alpha_s$ terms

DdE, Jacobsen: arXiv:2005.04545 [hep-ph]

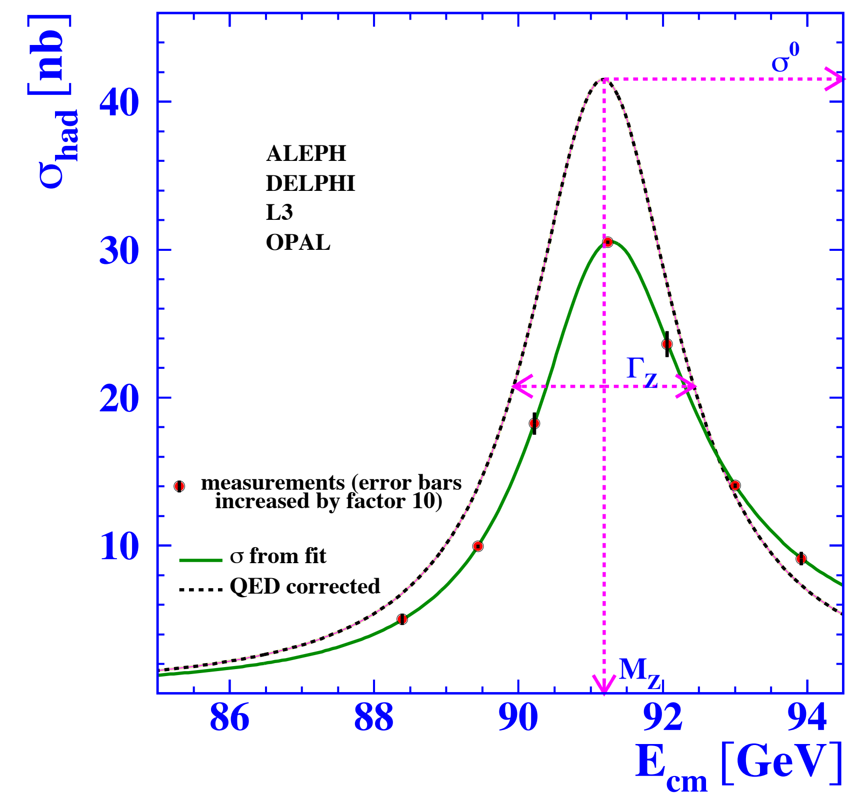


$\alpha_s(m_z) = 0.11790 \pm 0.00023$ ($\pm 0.2\%$)

Measurement of the Z mass and width

10^{12} expected Z bosons

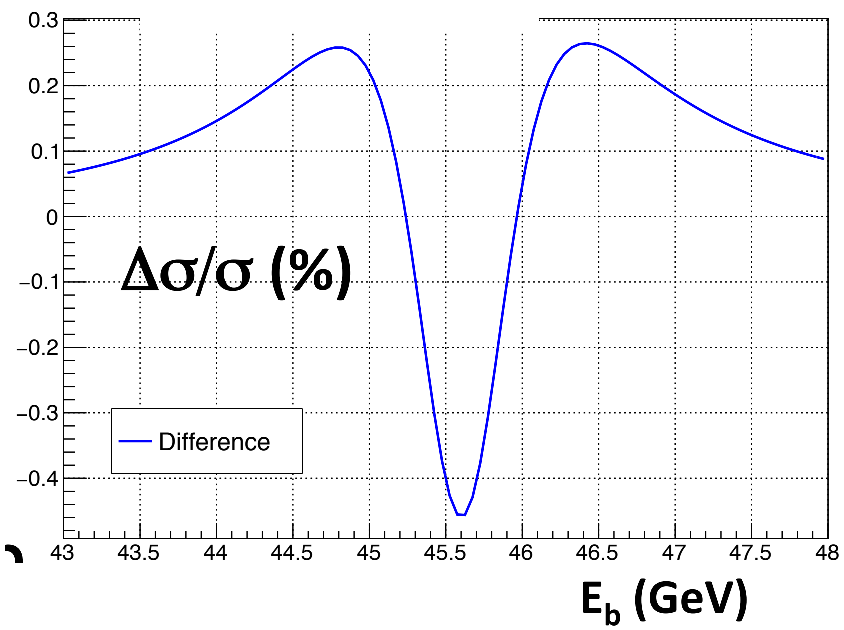
- mass and width are measured using the hadronic cross section as a function of E_{cm}
- statistics error is negligible, main systematics from beam energy calibration ΔE_{cm} = 10 keV (stat.) + 100 keV (syst)
- beam energy calibration from resonant depolarisation technique



Γ_Z measurement

- dominant uncertainty from the beam energy spread

$$\delta\sigma \simeq 0.5\frac{d^2\sigma}{dE^2}\epsilon^2_{CMS}$$

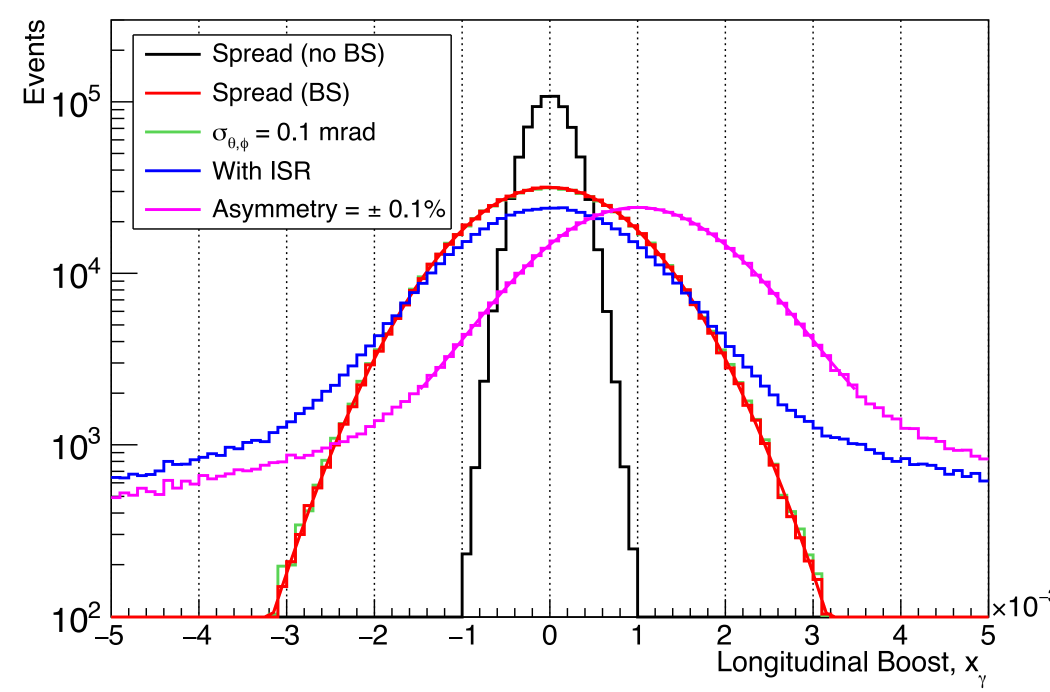


- the beam energy spread is measured using e+e-→$\mu^+\mu^-(\gamma)$

$$x_\gamma = -\frac{x_+\cos\theta^+ + x_-\cos\theta^-}{\cos(\alpha/2) + |x_+\cos\theta^+ + x_-\cos\theta^-|}$$

- 4 min 10^6 muons, energy spread measured at 0.1%
- $\Delta\Gamma_Z$ < 30 keV

One million dimuon events



B

Electroweak observables

Table 3 Measurement of selected precision measurements at FCC-ee, compared with present precision. Statistical errors are indicated in boed phase. The systematic uncertainties are initial estimates, aim is to improve down to statistical errors. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in specific new physics (non-decoupling) models

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 above
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

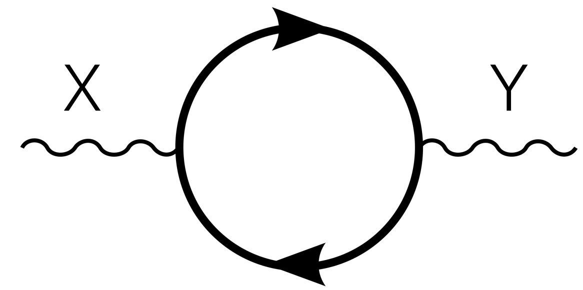
Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and leading exp. error
A_{FB}^b, 0 $(\times 10^4)$	992 ± 16	**0.02**	1–3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 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
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**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/c^2)	172740 ± 500	**17**	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	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

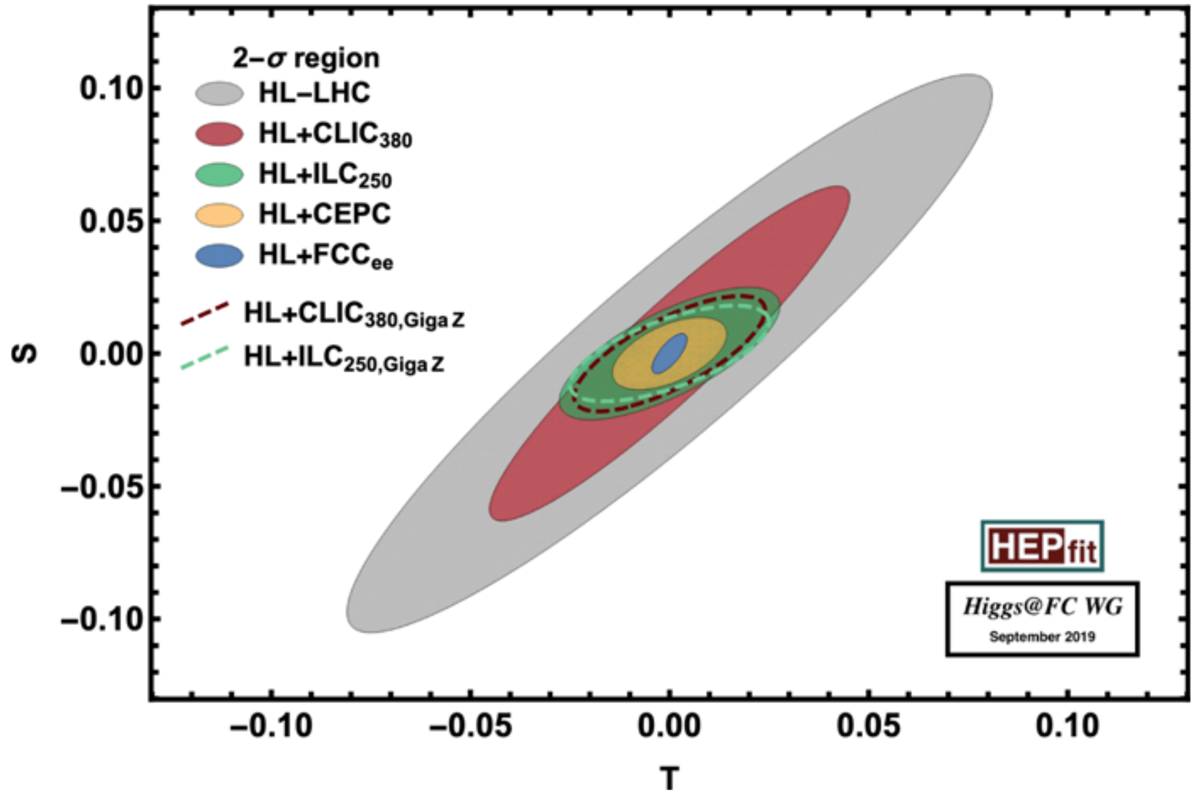
S,T relations

$$\widehat{\alpha}(M_Z)T \equiv \frac{\Pi^{\rm new}_{WW}(0)}{M_W^2} - \frac{\Pi^{\rm new}_{ZZ}(0)}{M_Z^2} \,,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}^2_Z\widehat{c}^2_Z}S \equiv \frac{\Pi^{\rm new}_{ZZ}(M_Z^2) - \Pi^{\rm new}_{ZZ}(0)}{M_Z^2} - \frac{\widehat{c}^2_Z - \widehat{s}^2_Z}{\widehat{c}_Z\widehat{s}_Z}\frac{\Pi^{\rm new}_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi^{\rm new}_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$

Π_{XY}





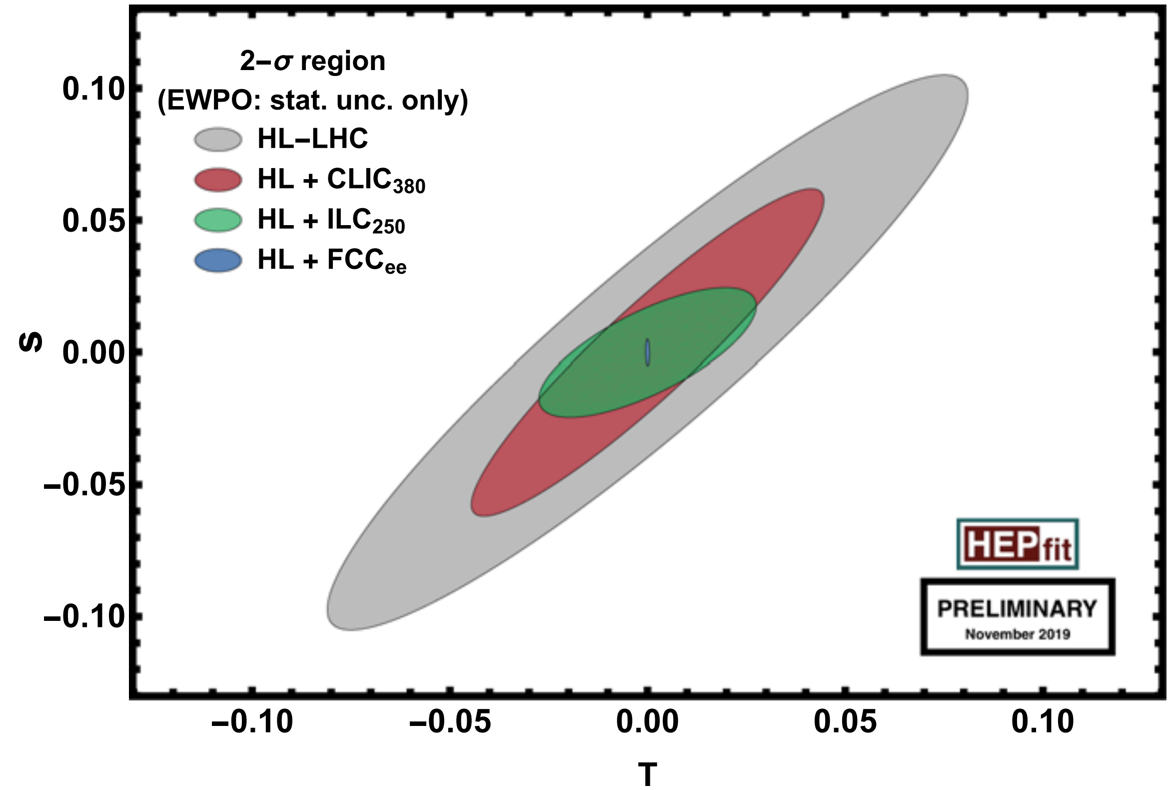
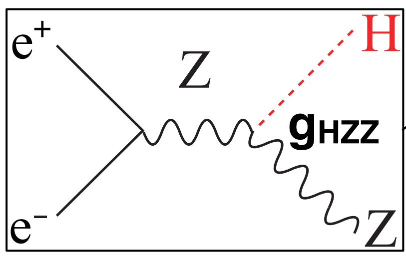
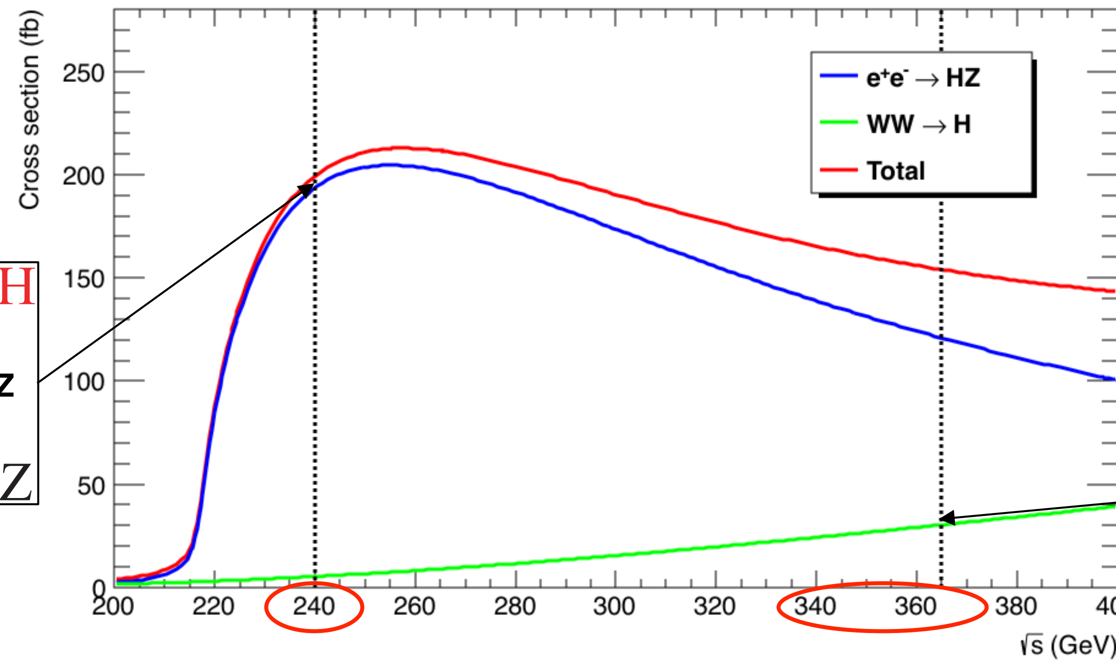
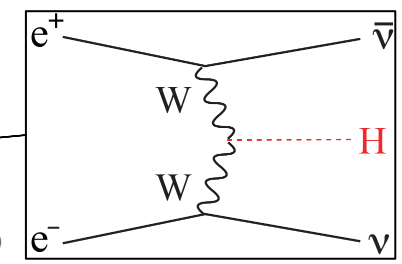


Fig. 4 Expected uncertainty contour for the S and T parameters for various colliders in their first energy stage. For ILC and CLIC, the projections are shown with and without dedicated running at the Z pole, with the current (somewhat arbitrary) estimate of future experimental and theoretical systematic uncertainty (left, from Ref. [36]); and with only statistical and parametric uncertainties (right, from Ref. [48])

Higgs physics

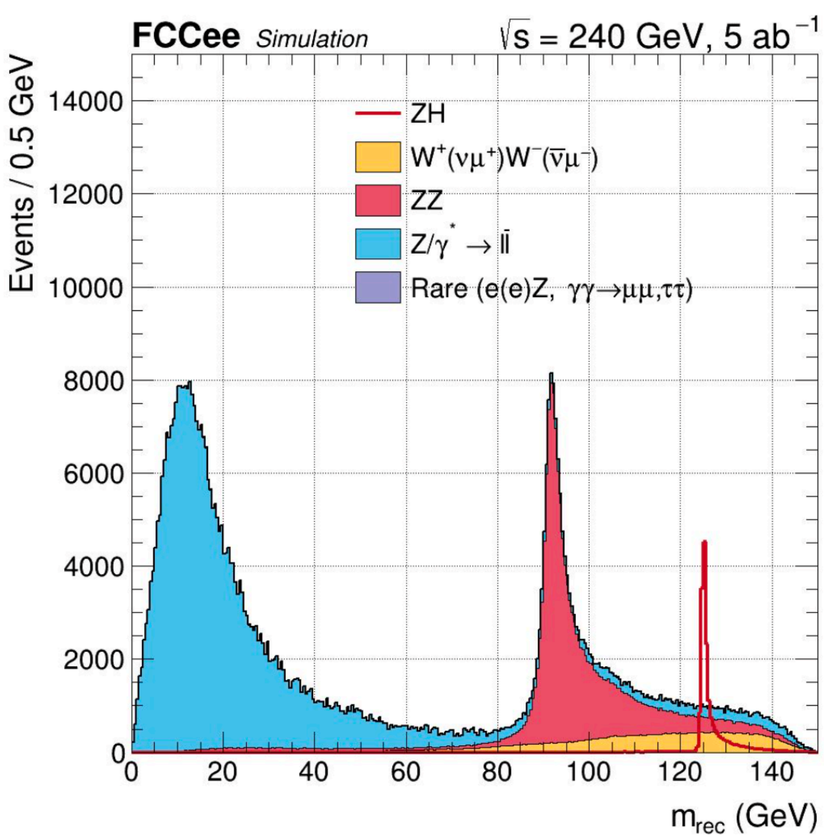






- maximum cross section √s = 250 GeV, luminosity decreases with √s: maximum event production at √s = 240 GeV
- Higgs mass from lepton missing mass

$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$



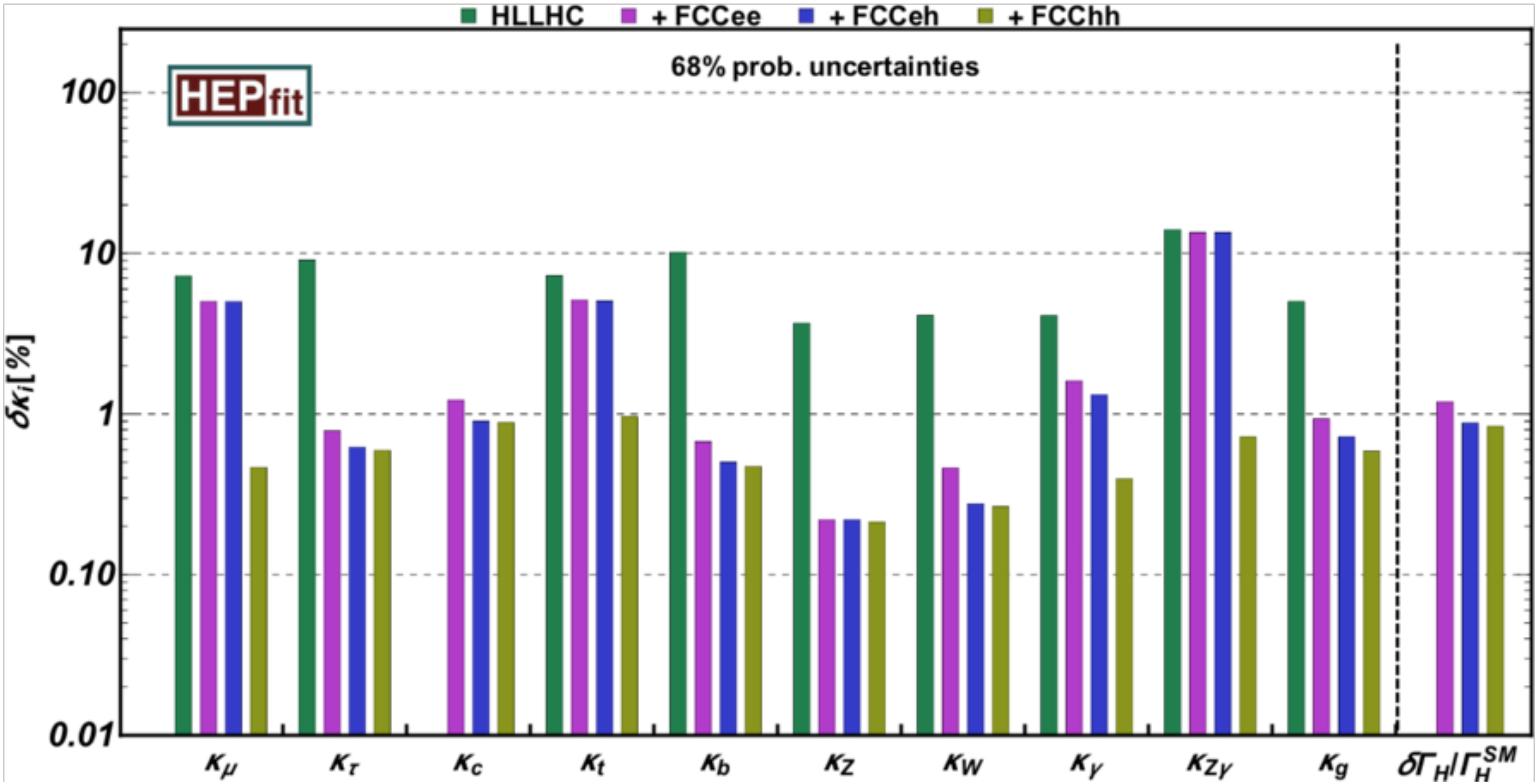
total cross section ~g_{HZZ}^2, g_{HZZ} ~ 0.2%

- ZH → ZZZ ~g_{HZZ}^2Br(H→ZZ) = g_{HZZ}^4/Γ_H, Γ_H ~ 2%
- ZH → ZXX ~g_{HZZ}^2Br(H→XX) = $g_{HZZ}^2 g_{HXX}^2/\Gamma_H$, g_{HXX} ~ 2%
- invisible decays (h → DM), unexpected decays (BSM9

adding e^+e^- → Hνν

- σ(Hνν,H→bb)/[σ(ZH,H→bb)σ(ZH,H→WW)] ~ Γ_H/g_{HZZ}^4, Γ_H ~ 1%
- σ(Hνν,H→WW)/[σ(ZH,H→bb)σ(ZH,H→WW) ~ g_{HWW}^4/Γ_H, g_{HWW} ~0.3%

Higgs boson couplings



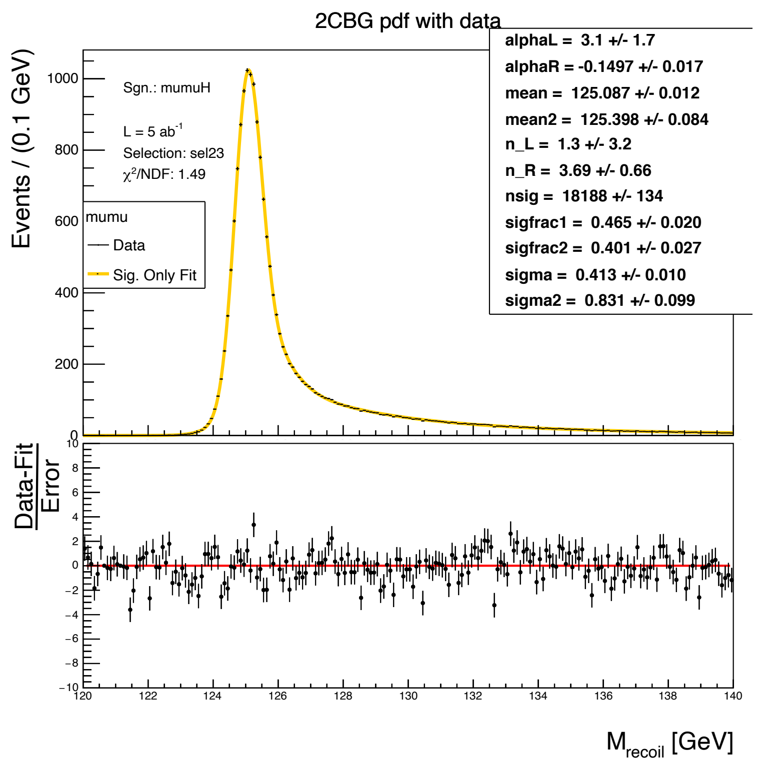
Higgs mass measurement

Higgs mass from the lepton recoil mass distribution

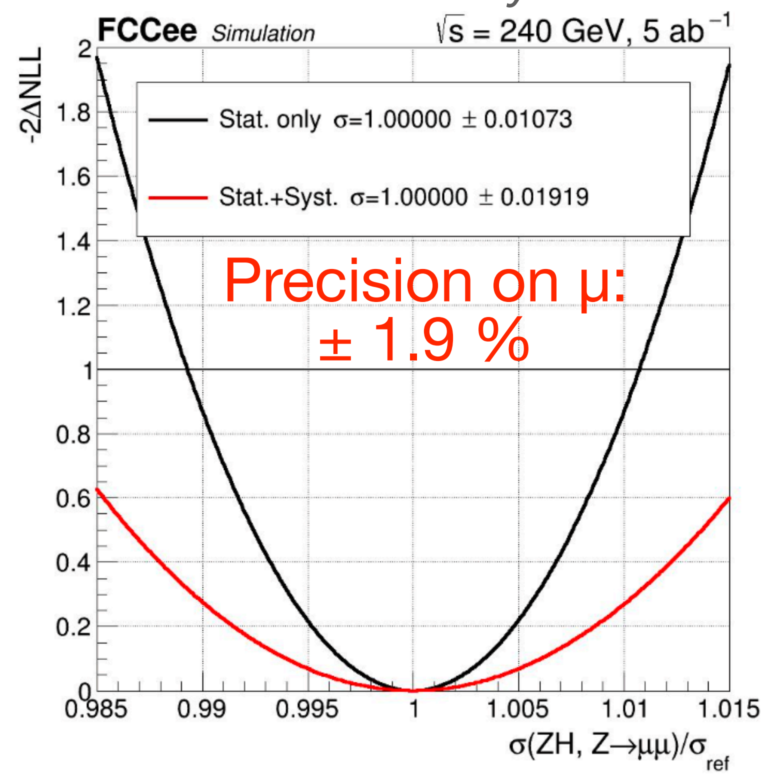
$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

J. Eysermans - talk at the FCC week - June 2021

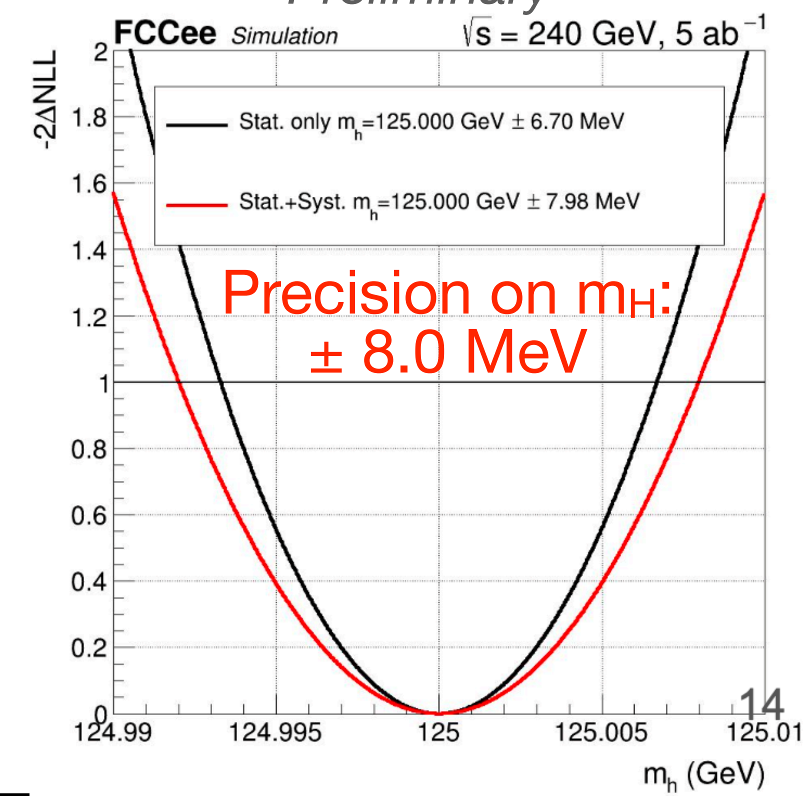
Preliminary



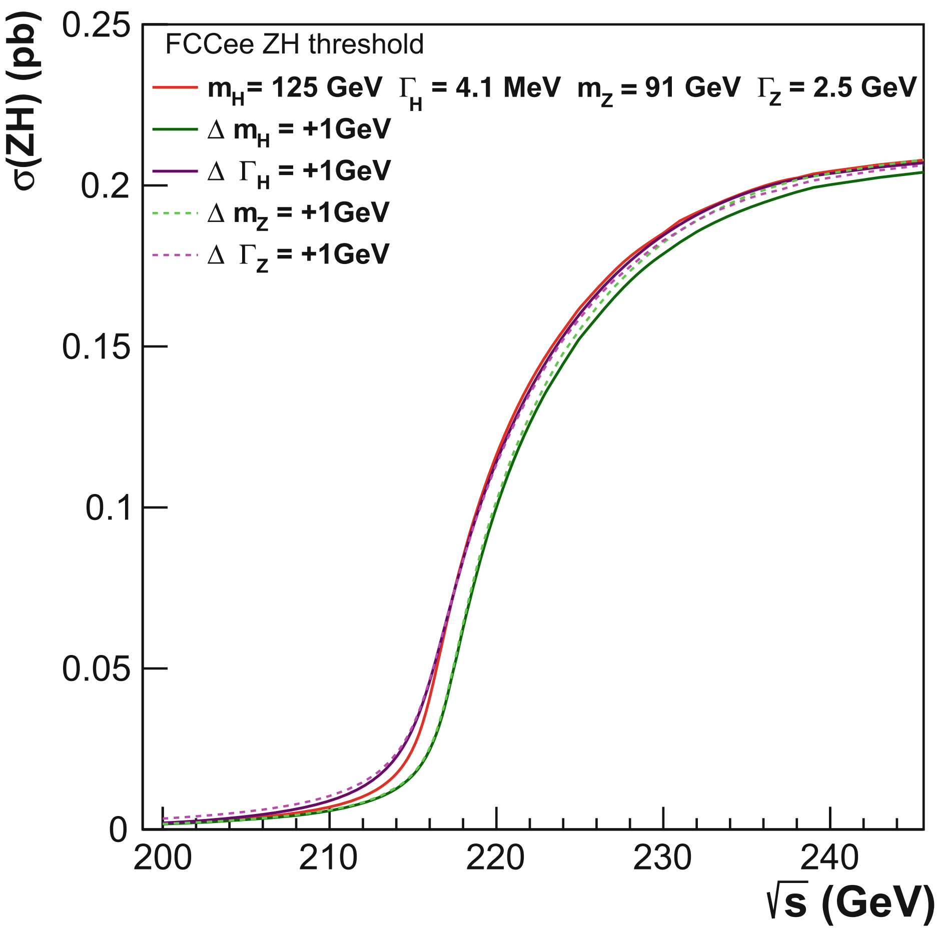
Preliminary



Preliminary



Higgs mass from ZH threshold scan



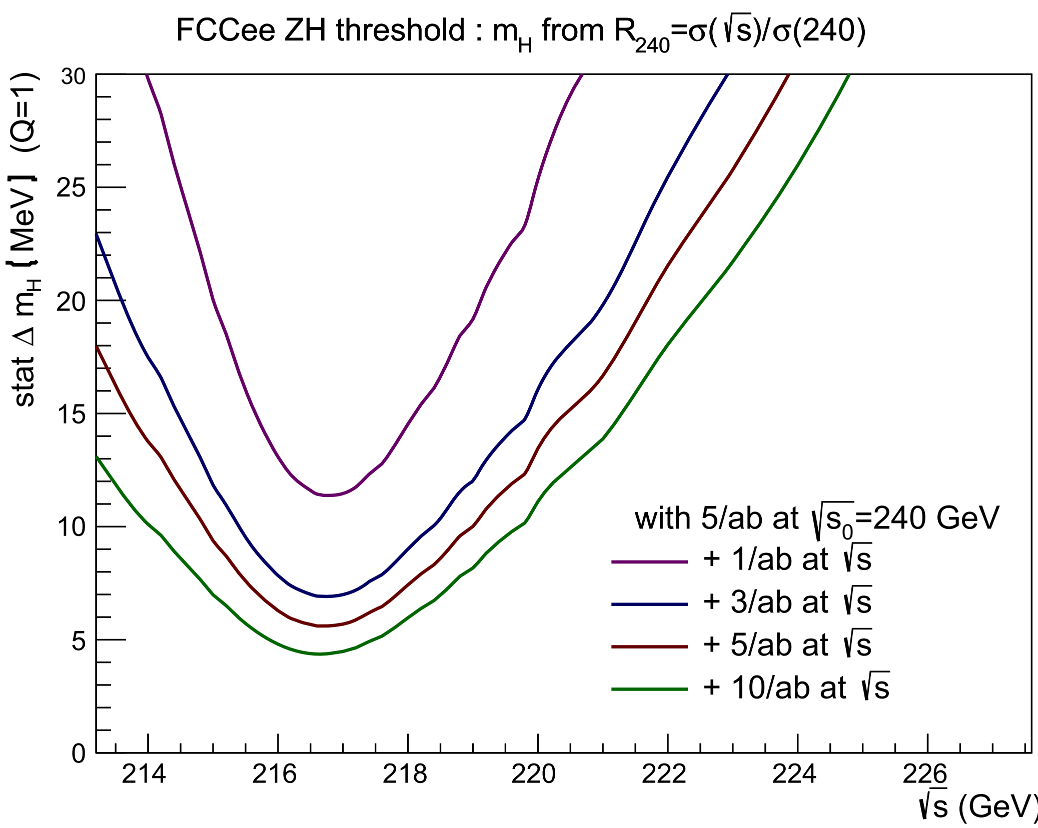
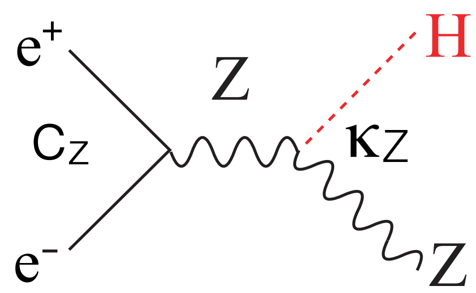


Fig. 6 Expected ideal statistical uncertainties on the Higgs boson mass from the threshold cross section ratio R (Eq. 4) assuming an integrated luminosity of $5\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 240\,\mathrm{GeV}$ and different integrated luminosities accumulated at lower centre-of-mass energies around the ZH production threshold

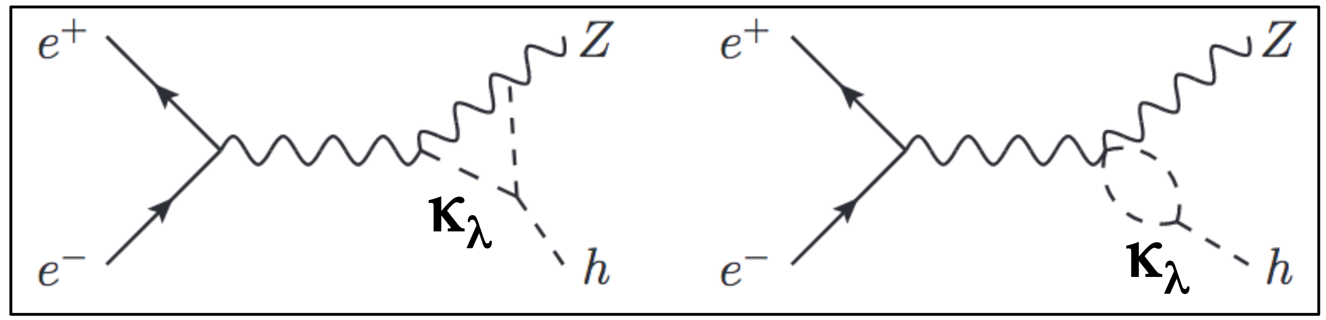
Uncertainties on the Higgs mass of 6 MeV (stat.) can be obtained with 3 ab^{-1} at $\sqrt{s}$ = 217 GeV

Higgs boson self-coupling determination

σ_{HZ}

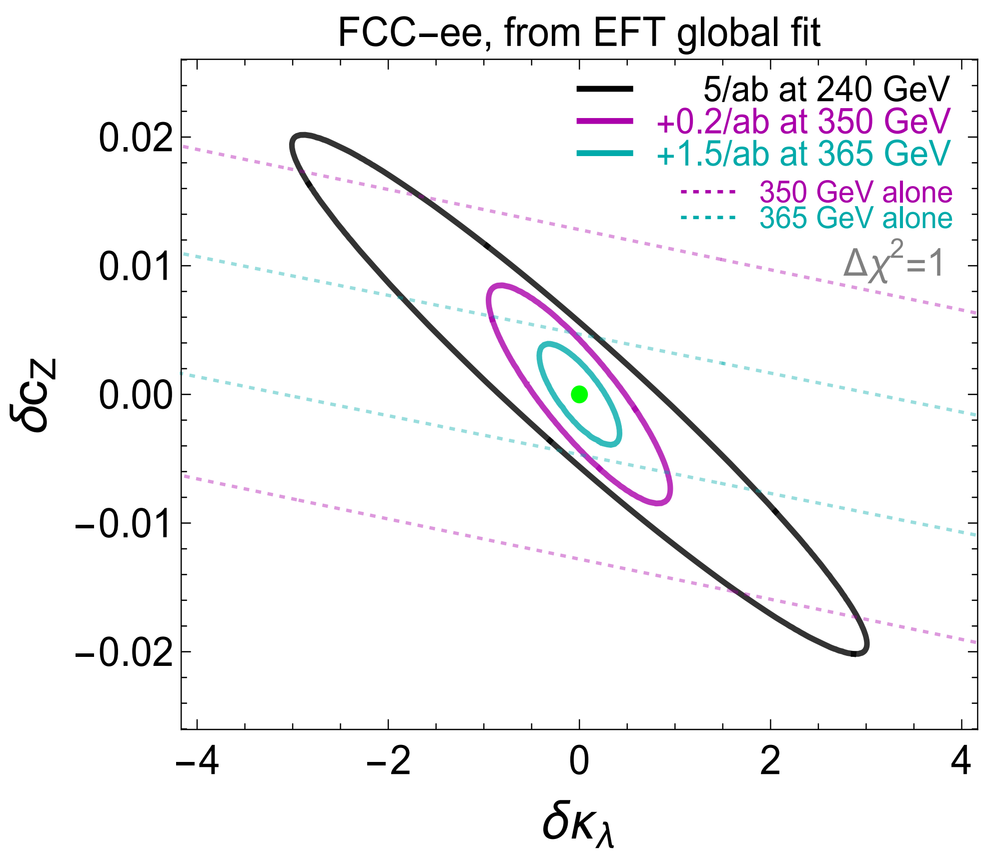


+



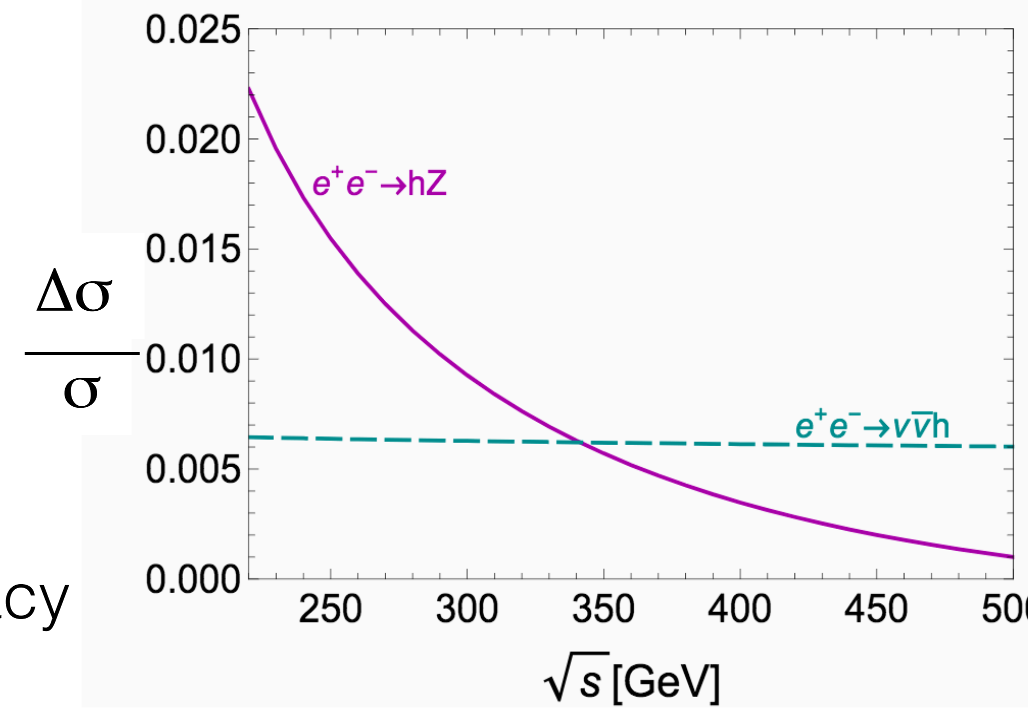
$\kappa = g/g_{SM}$

M. McCullough
arXiv:1312.3322



- setting all other SM paramters to the SM, $\Delta\kappa_\lambda/\kappa_\lambda \sim 9\%$
- using a global EFT fit $\Delta\kappa_\lambda/\kappa_\lambda \sim 25\%$ with 4 IP.

$\Delta\sigma = \sigma(\kappa_\lambda=1) - \sigma(\kappa_\lambda=0)$



varying $\sqrt{s}$ removes partially cZ, κ_λ degeneracy

V_{us} from KLOE

- Combination of the previous result from KLOE based on an independent data sample ($L=0.41\ fb^{-1}$) $BR(K_{Se3})=(7.046 \pm 0.078 \pm 0.049)\times 10^{-4}$ [KLOE PLB636 (2006)] gives:

$$\boxed{BR(K_S \rightarrow \pi e \nu)=\left(7.153 \pm 0.037_{stat} \pm 0.043_{syst}\right)\times 10^{-4}}$$

KLOE-2 combined result (2022)
arXiv :2208.04872v2 [hep-ex] (submitted to JHEP)

- From

$$\mathcal{B}(K_S \to \pi \ell \nu) = \frac{G^2 (f_+(0)|V_{us}|)^2}{192\pi^3} \tau_S m_K^5 I_K^\ell S_{\rm EW}(1+\delta_{\rm EM}^{K\ell})$$

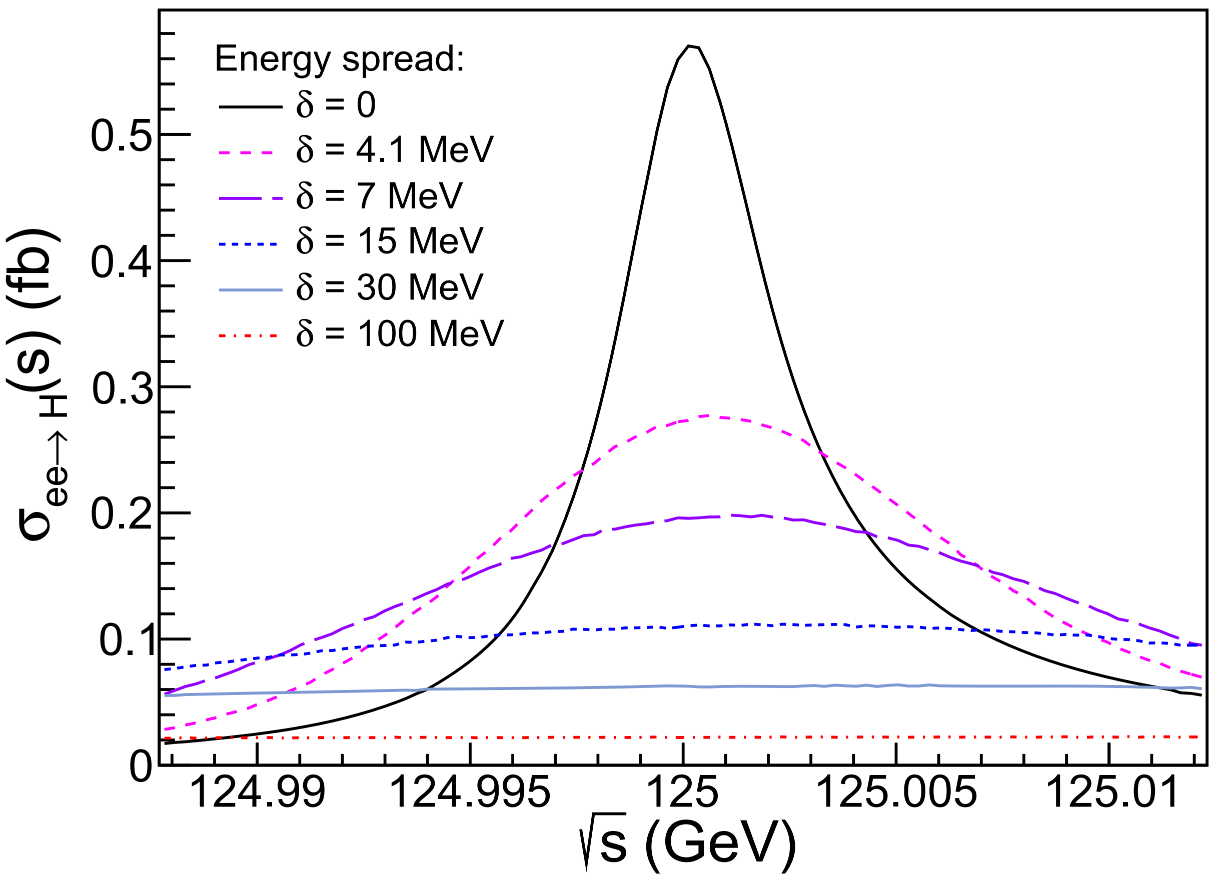
using the values $S_{EW} = 1.0232 \pm 0.0003$ [Marciano, Sirlin PRL 71 (1993) 3629] and $I_K^e = 0.15470 \pm 0.00015$ and $\delta_{EM}^{Ke} = (1.16 \pm 0.03)\times 10^{-2}$ [Seng, Galviz, Marciano, Meissner, PRD 105, (2022) 013005] we derive:

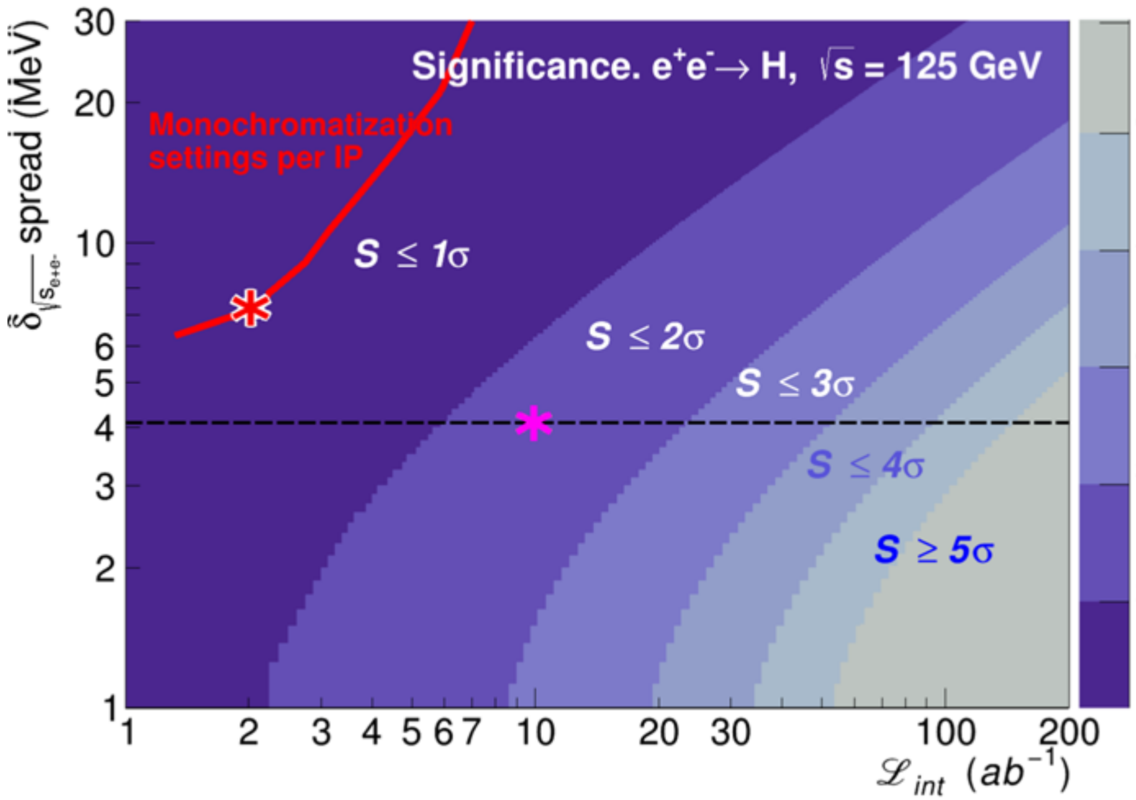
$$\boxed{f_+(0)\,|V_{us}| = 0.2170 \pm 0.0009}$$

Electron Yukawa coupling

- Electron Yukawa coupling can be measured using $e^+e^- \to H \to$ all, Γ_H = 4.1 MeV, knowledge of Higgs mass at MeV level is needed before starting the run;
- Event yield extremely low due to the low value of the electron coupling; $\sigma_{\mathrm{ee}\to\mathrm{H}} = 4\pi\mathcal{B}(\mathrm{H}\to\mathrm{e}^+\mathrm{e}^-)/m_{\mathrm{H}}^2 = 1.64$ fb
- the beam energy spread strongly affects the cross section peak value
- initial state radiation increases the line-shape width and reduces the peak value to 0.57 fb, the beam energy spread further reduces the xs value

Target Higgs decay	Final state definition	Signal presel. efficiency (%)
$\mathrm{H}\to b\bar{b}$	2 (excl.) jets, 1 b-tagged jet, no τ_{had}	80
$\mathrm{H}\to gg$	2 (excl.) gluon-tagged jets, 0 isolated $\ell^\pm$	50
$\mathrm{H}\to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$	Exactly 2 τ_{had}, 0 isolated $\ell^\pm$	65
$\mathrm{H}\to c\bar{c}$	2 (excl.) jets, 1 c-tagged jet, no τ_{had}	70
$\mathrm{H}\to \mathrm{WW}^*\to \ell\nu 2j$	1 isolated $\ell^\pm$, $E_{\mathrm{miss}} > 2$ GeV, 2 (excl.) jets	~100
$\mathrm{H}\to \mathrm{WW}^*\to 2\ell 2\nu$	2 isolated opp.-charge $\ell^\pm$, $E_{\mathrm{miss}} > 2$ GeV, 0 non-isol. $\ell^\pm$, 0 charged hadrons	~100
$\mathrm{H}\to \mathrm{WW}^*\to 4j$	4 (excl.) jets, ≥ 1 c-tag jets, 0 b-,g-tag jets; jets with $m_{j1j2}\approx m_{\mathrm{W}}$ not both c-tagged, 0 τ_{had}, 0 isolated $\ell^\pm$	70
$\mathrm{H}\to \mathrm{ZZ}^*\to 2j2\nu$	2 (excl.) jets, $E_{\mathrm{miss}} > 30$ GeV, 0 isolated $\ell^\pm$, 0 τ_{had}	~100
$\mathrm{H}\to \mathrm{ZZ}^*\to 2\ell 2j$	2 isolated opposite-charge $\ell^\pm$, 2 (excl.) jets, 0 τ_{had}	~100
$\mathrm{H}\to \mathrm{ZZ}^*\to 2\ell 2\nu$	2 isolated opp.-charge $\ell^\pm$, $E_{\mathrm{miss}} > 2$ GeV, 0 non-isol. $\ell^\pm$, 0 charged hadrons	~100
$\mathrm{H}\to \gamma\gamma$	2 (excl.) isolated photons	~100





BSM sensitivity

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

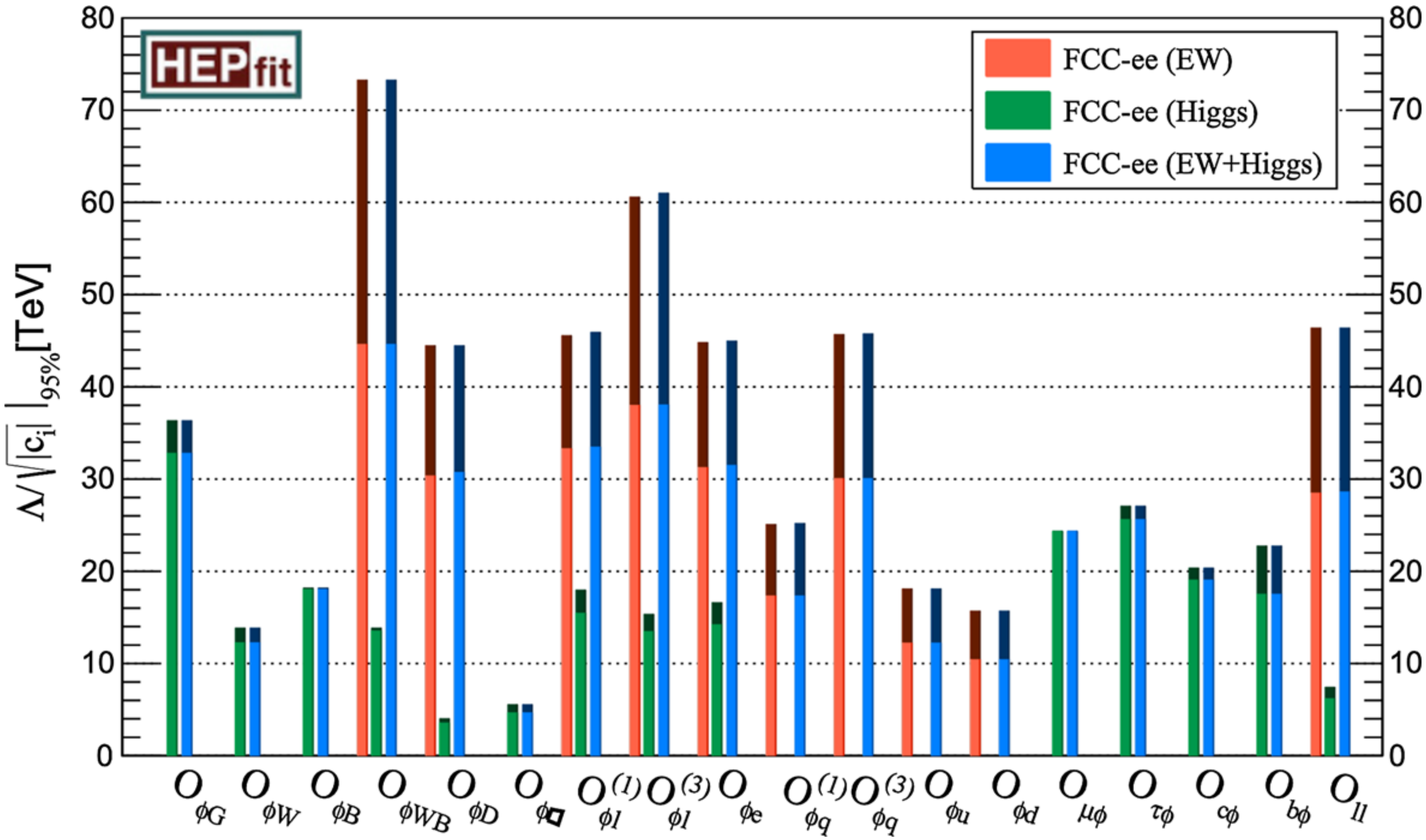


Fig. 5 Electroweak (red) and Higgs (green) constraints from FCC-ee, and their combination (blue) in a global EFT fit. The constraints are presented as the 95% probability bounds on the interaction scale, $\Lambda/\sqrt{c_i}$, associated to each EFT operator. Darker shades of each colour indicate the results when neglecting all SM theory uncertainties

Flavour physics at FCC-ee

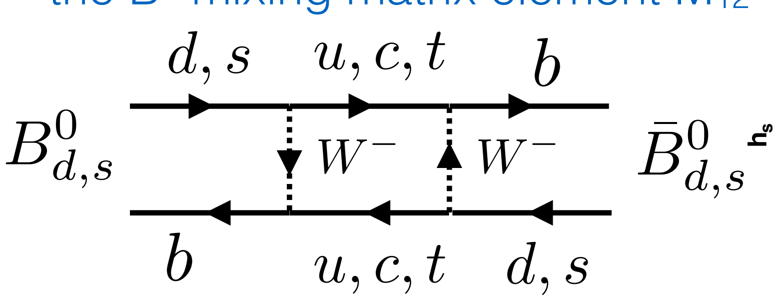
- FCC-ee is a Z^0 factories, a huge number of C, B mesons and τ mesons are produced through the decay of 10^{12} Z^0 bosons

- FCC-ee provides the richness and the statistics of hadronic final states of LHCb and the clean environment of e^+e^- colliders as Belle-2

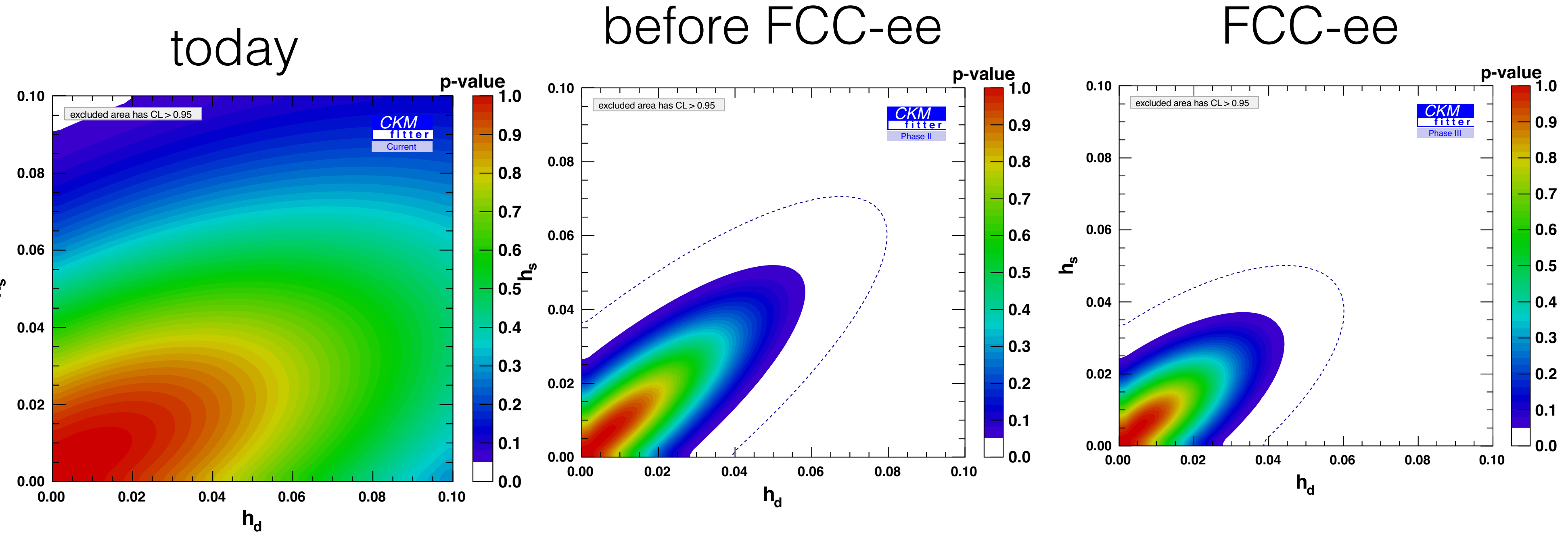
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

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

- New physics can be parametrised as contribution to the B^0 mixing matrix element M_{12}

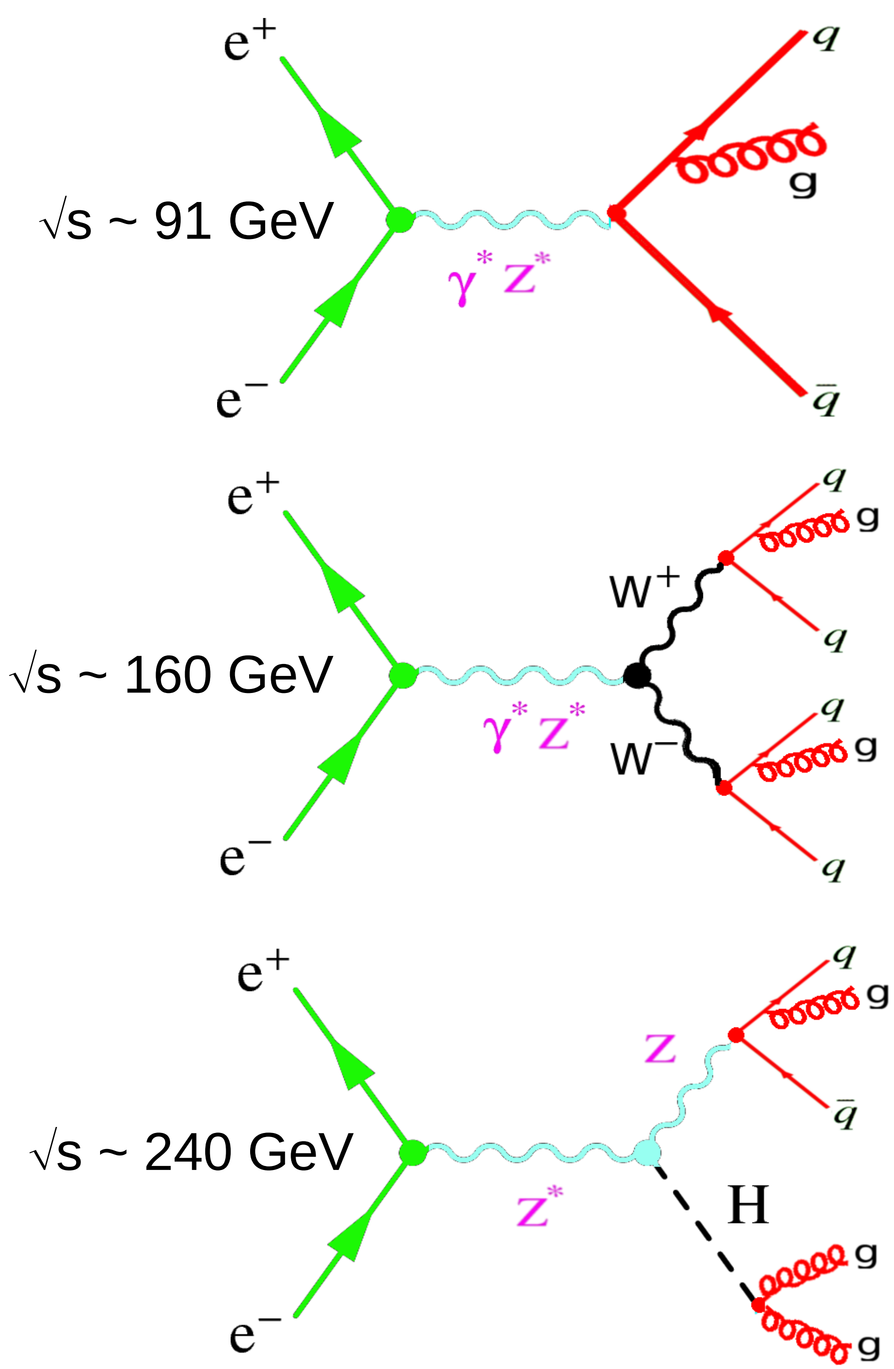


$$M_{12} = (M_{12})_{\mathrm{SM}} \times (1 + he^{2i\sigma})$$



QCD physics at e+e-

e+e- collisions provide a clean environment also for QCD measurements



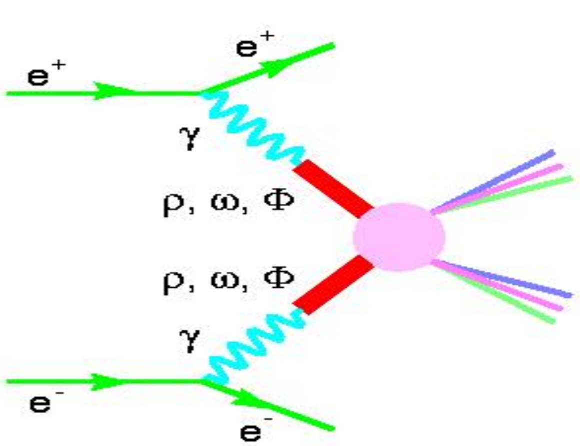
Advantages compared to p-p collisions:

- QED initial-state with known kinematics
- Controlled QCD radiation (only in final-state)
- Well-defined heavy-Q, quark, gluon jets
- Smaller non-pQCD uncertainties:

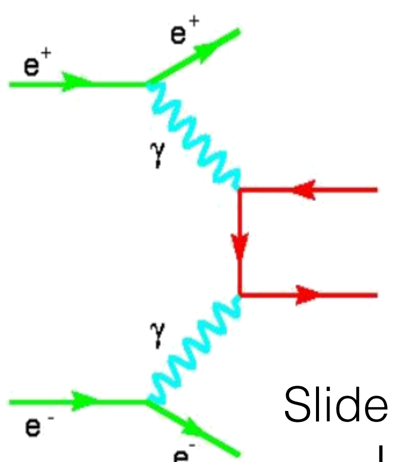
  no PDFs, no QCD "underlying event",…

  Direct clean parton fragmentation & hadroniz.

■ Plus QCD physics in γγ (EPA) collisions:



(soft, VDM)

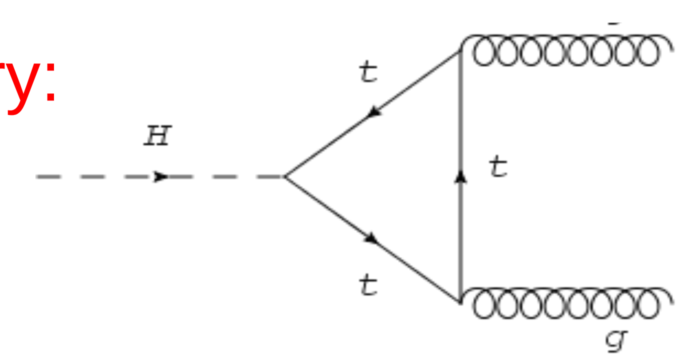


(direct)

Slide from D. d'Enterria
LFC '21 Trento

High precision gluon and jet studies

- Exploit FCC-ee H(gg) as a "pure gluon" factory: H→gg (BR~8% accurately known) provides O(100.000) extra-clean digluon events.

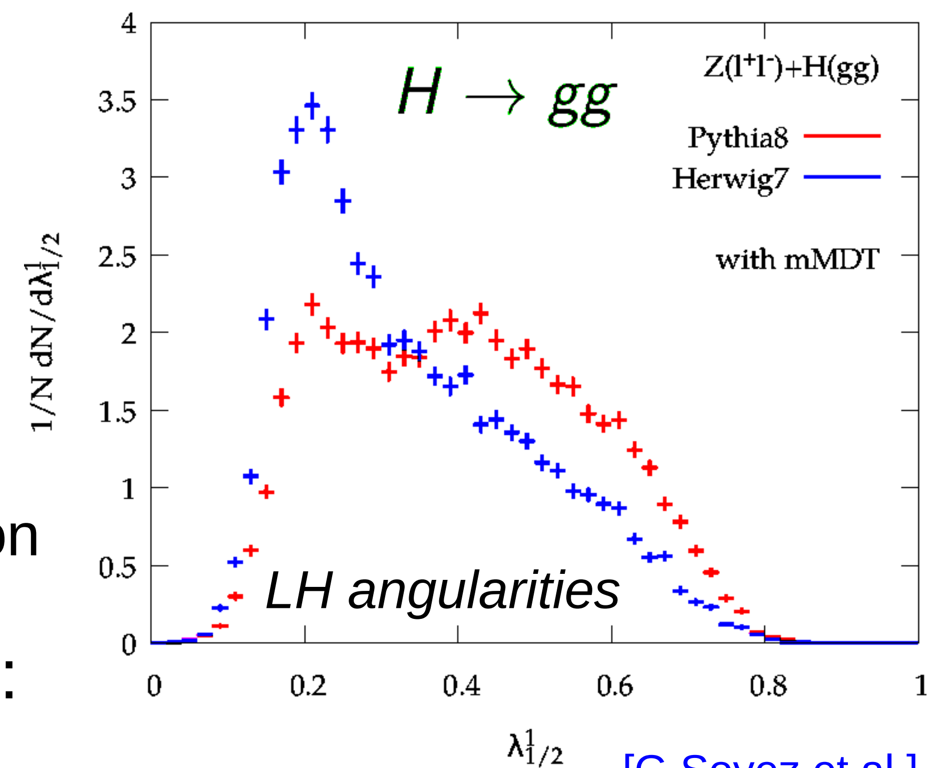


jet substructure

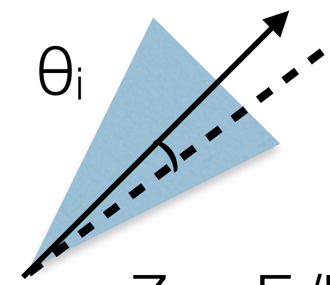
$$\lambda^{\kappa}_{\beta} = \sum_{i \in \mathrm{jet}} z_i^{\kappa} \theta_i^{\beta},$$

(normalized $E^n \times \theta^n$ products)

- Multiple handles to study gluon radiation & g-jet properties:
  - Gluon vs. quark via H→gg vs. Z→qq (Profit from excellent g,b separation)
  - Gluon vs. quark via Z→bbg vs. Z→qq(g) (g in one hemisphere recoiling against 2-b-jets in the other).
  - Vary E_{jet} range via ISR: $e^+e^- \to Z^*,\gamma^* \to jj(\gamma)$
  - Vary jet radius: small-R down to calo resolution



[G.Soyez et al.]



$Z_i = E_i/E_{jet}$

- Multiple high-precision analyses at hand:
  - BSM: Improve q/g/Q discrimination tools
  - pQCD: Check N^nLO antenna functions. High-precision QCD coupling.
  - non-pQCD: Gluon fragmentation: Octet neutralization? (zero-charge gluon jet with rap gaps). Colour reconnection? Glueballs ? Leading η's,baryons?

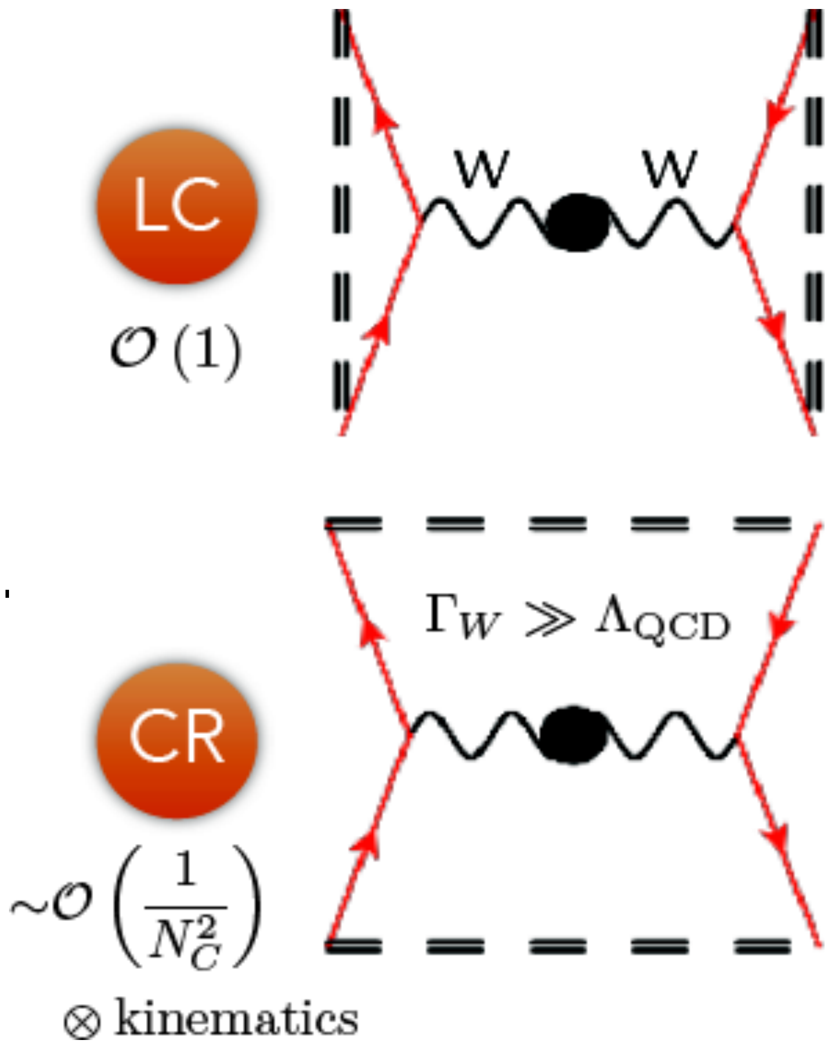
Slide from D. d'Entreria
LFC '21 Trento

Color reconnection

- Colour reconnection among partons is source of uncertainty in m_W, m_{top}, aGC extractions in multijet final-states. Especially in pp (MPI cross-talk).

  - CR impacts all FCC-ee multi-jet final-states (potentially shifted angular correlations):
    – $e^+e^- \rightarrow$ WW(4j), Z(4j), ttbar,
    – H(2j,4j) CP studies,…
    – String-drag effect on W mass
    (Hinted at LEP: No-CR excluded at 99% CL).

  - Exploit huge W stats ($\times 10^4$ LEP) to "turn the m_W measurement around": Determine m_W leptonically and constrain CR in hadronic WW: Colour reconnection controlled to <1%



Slide from D. d'Entreria
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Conclusions

- FCC-ee has a rich and striking physics goal
- improving accuracy of EWK measurement by factors 10-100
- constraints Higgs potential related parameters m_H, m_t, m_W, κ_λ
- providing the best measurement of the Higgs boson potential (check validity of the Higgs boson as inflation field, probe the vacuum instabilities, probe the nature of the Higgs boson)
- if you think that a 27 km muon collider could be a valuable option after HL-LHC, think what could be a 100 km muon collider if a working muon cooling mechanism will be available at the end of the FCC-ee running

Higgs boson couplings

Table 2 Precision on the Higgs boson couplings from Ref. [37], in the κ framework without (first numbers) and with (second numbers) HL-LHC projections, for the FCC-ee and the complete FCC integrated programme (including both the FCC-hh and the FCC-ep option) [38]

Collider	HL-LHC	$\text{FCC-ee}_{240\to 365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18/0.17	0.17/0.16
g_{HWW} (%)	1.7	0.44/0.41	0.20/0.19
g_{Hbb} (%)	5.1	0.69/0.64	0.48/0.48
g_{Hcc} (%)	SM	1.3/1.3	0.96/0.96
g_{Hgg} (%)	2.5	1.0/0.89	0.52/0.5
$g_{H\tau\tau}$ (%)	1.9	0.74/0.66	0.49/0.46
$g_{H\mu\mu}$ (%)	4.4	8.9/3.9	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9/1.2	0.32/0.32
$g_{HZ\gamma}$ (%)	11	–/10	0.71/0.7
g_{Htt} (%)	3.4	10./3.1	1.0/0.95
g_{HHH} (%)	50	44/33	3–4
		27/24	
Γ_H (%)	SM	1.1	0.91
BR_{inv} (%)	1.9	0.19	0.024
BR_{EXO} (%)	SM (0.0)	1.1	1