The Future Circular Colliders
CDR and cost review for the next ESU (2018)

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:*** **~16 T magnets**
  ***100 TeV pp*-collider (*FCC-hh*)**

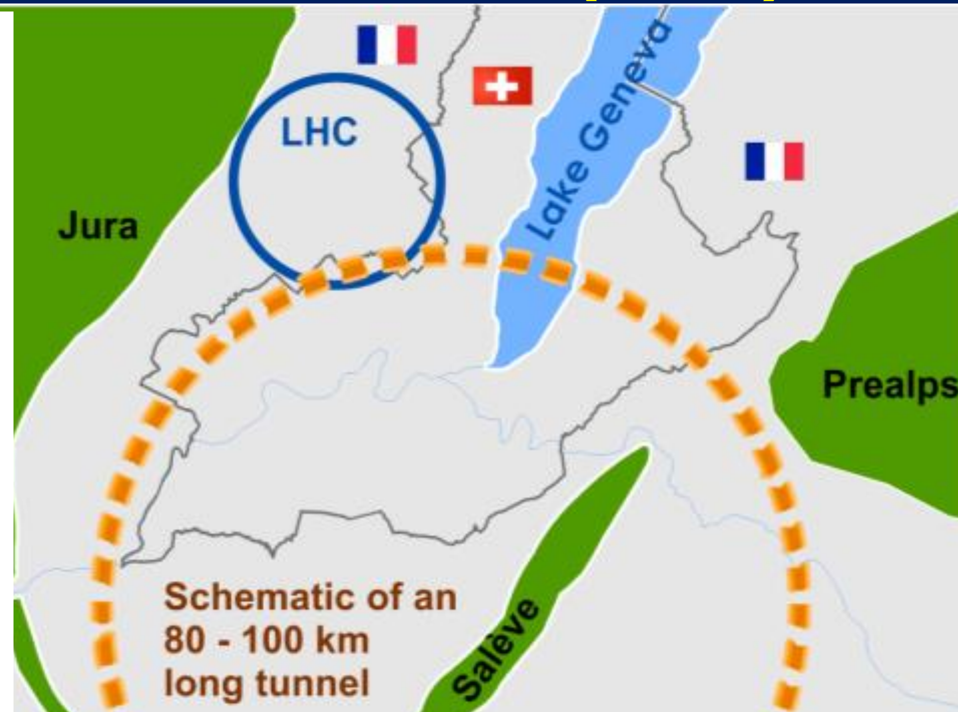
→ defining infrastructure requirements

Two possible first steps:

- **e^+e^- collider (*FCC-ee*)**
  High Lumi, E_{CM} =90-400 GeV
- ***HE-LHC* 16T ⇒ 28 TeV**
  in LEP/LHC tunnel

Possible add-on:

- ***p-e* (*FCC-he*) option**

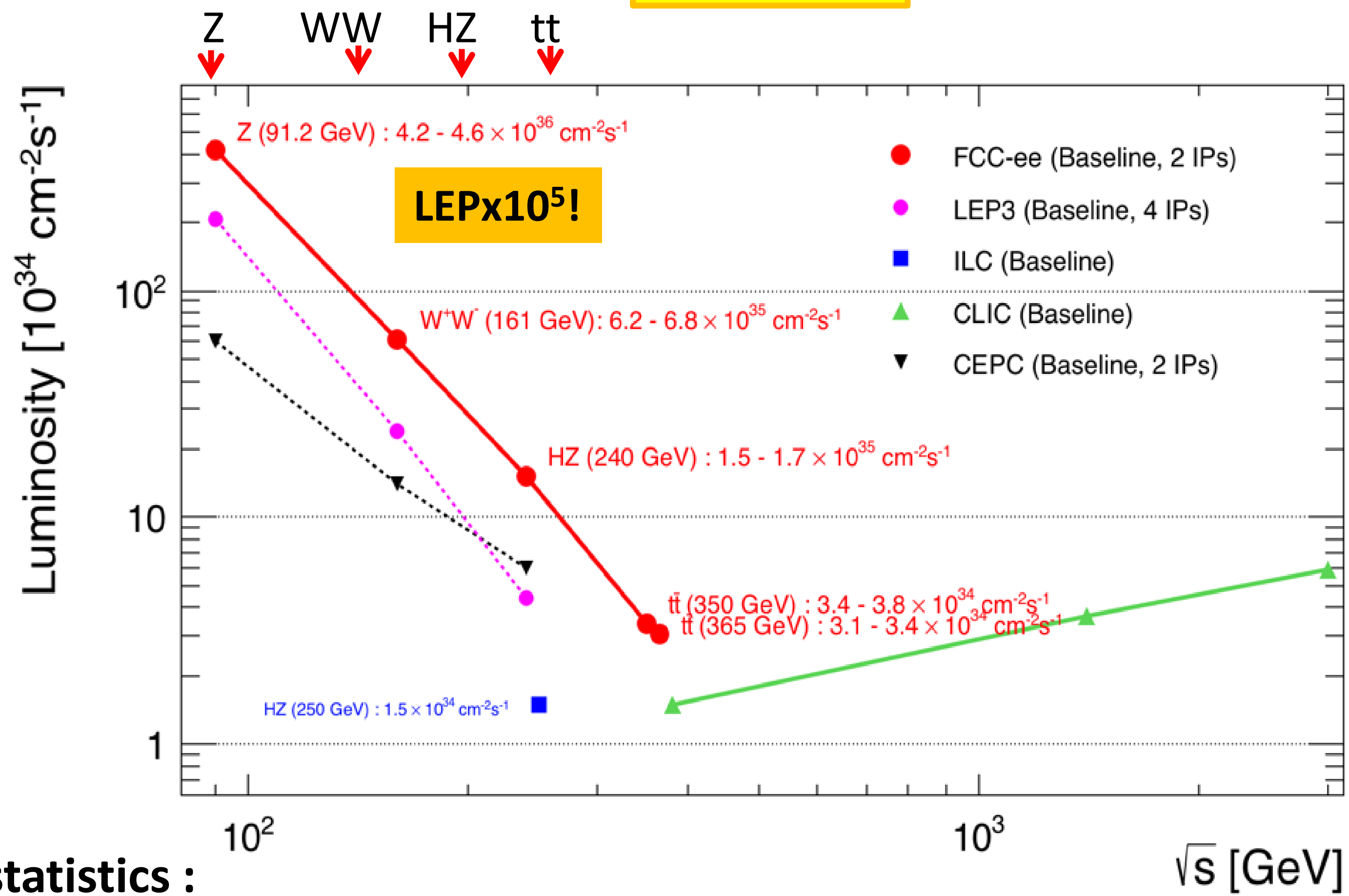


From what we know today :
the way by FCC-ee is the probably fastest and cheapest way to 100 TeV.
That combination also produces the most physics. It is the assumption in the following.

also a good start for μC!

From European Strategy in 2013: "ambitious post-LHC accelerator project"
Study kicked-off in Geneva Feb 2014

FCC-ee



Event statistics :

E_{CM} errors:

Z peak	**E_{cm} : 91 GeV**	**$5\ 10^{12}$ e+e- → Z**	**LEP x 10^5**	100 keV
WW threshold	**E_{cm} : 161 GeV**	**10^8 e+e- → WW**	**LEP x 2.10^3**	300 keV
ZH threshold	**E_{cm} : 240 GeV**	**10^6 e+e- → ZH**	**Never done**	5 MeV
$\bar{t}t$ threshold	**E_{cm} : 350 GeV**	**10^6 e+e- → $\bar{t}t$**	**Never done**	10 MeV

IMPLEMENTATION AND RUN PLAN

"Ampere-class" machine

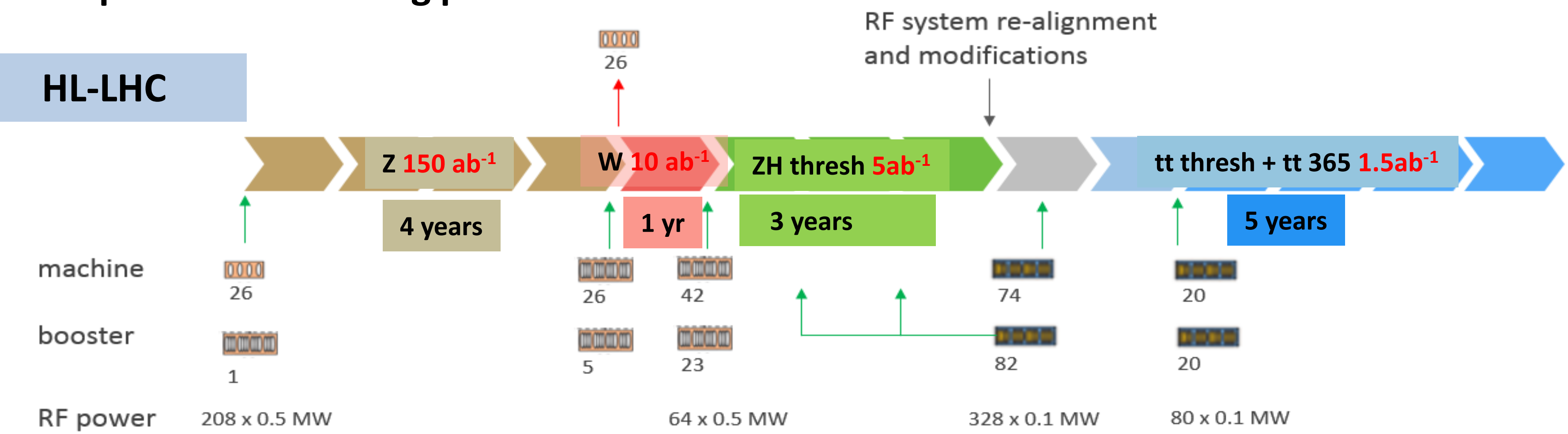
	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

Three sets of RF cavities for FCCee & Booster:

- **Installation as LEP (≈30 CM/winter)**
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source**
- **high energy (W, H, t): 400 MHz four-cell cavities, also for W machine**
- **booster and t machine complement: 800 MHz four-cell cavities**
- **Adaptable 100MW, 400MHz RF power distribution system +High effciency**

➔ Spreads the funding profile



indicative: total ~15 years

O(1/3) of the machine cost comes O(10) years after start

FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
m_Z, m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\ m_W\ m_\tau)$, Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ BR in 2 10^{11} Z→ $\tau\ \tau$
+ flavour physics (10^{12} bb events) (B→s $\tau\ \tau$ etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

+ an enormous amount of clean, unambiguous work on QCD (H→ gg) etc….

NB the «Z factory» as well as the «top» play an important role in the 'discovery potential'

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164

«First look of the physics case of TLEP» (original name of FCC-ee): 398 quotes today

HEP 398 records found 1 - 25 jump to record: 1

1. **Probing TeV scale origin of neutrino mass at lepton colliders**
   P.S. Bhupal Dev, Rabindra N. Mohapatra, Yongchao Zhang. Mar 29, 2018. 48 pp.
   e-Print: **arXiv:1803.11167 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

2. **Review of top and EW physics at future colliders**
   Marcel Vos (Valencia U., IFIC). 2017. 10 pp.
   Published in **PoS EPS-HEP2017 (2017) 471**
   Conference: C17-07-05 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Link to PoS server; Link to Fulltext
   Detailed record

3. **Electroweak Physics at Future e^+e^- Colliders**
   Elizabeth Locci (Saclay), On Behalf Of The Fcc Design Study Group. 2018. 10 pp.
   Published in **PoS EPS-HEP2017 (2018) 449**
   Conference: C17-07-05 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Link to PoS server; Link to Fulltext
   Detailed record

4. **Muon g-2 and dark matter in models with vector-like fermions**
   Enrico Maria Sessolo (NCBJ, Warsaw), Kamila Kowalska (Tech. U., Dortmund (main)). 2017. 6 pp.
   Published in **PoS EPS-HEP2017 (2017) 338**
   Conference: C17-07-05 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Link to PoS server; Link to Fulltext
   Detailed record

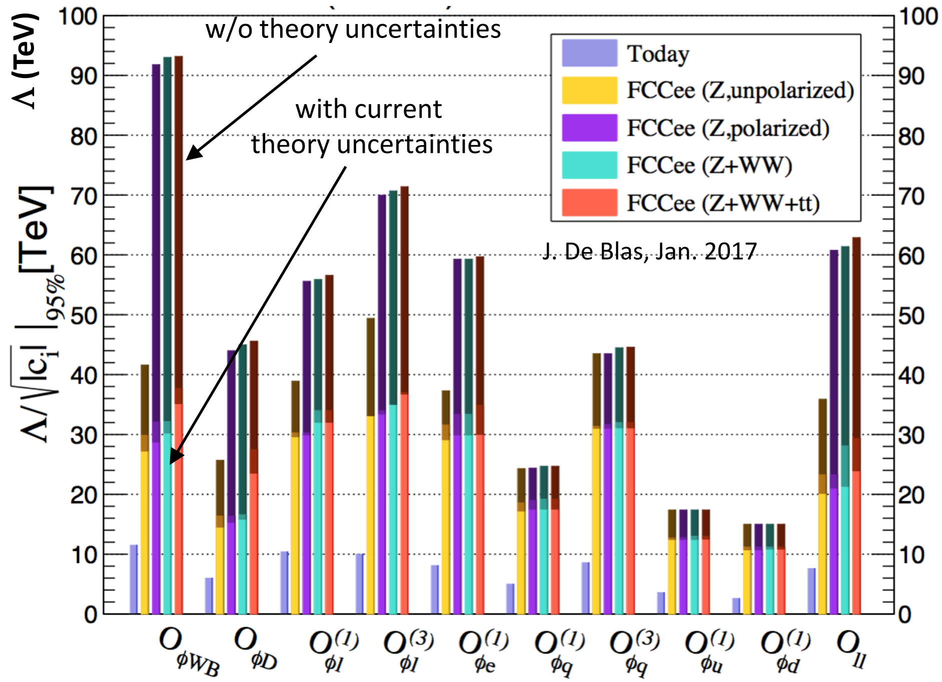
Much more than a Higgs factory!

A sample of observables (more coming)

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	**0.005**	**< 0.1**	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	**0.008**	**< 0.1** *	QED / EW
R_l	Peak	20.767 ± 0.025	**0.001**	**< 0.001**	Statistics
R_b	Peak	0.21629 ± 0.00066	**0.000003**	**< 0.00006**	g → bb
N_ν	Peak	2.984 ± 0.008	**0.00004**	**< 0.004**	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	**0.000003**	**<0.000005** *	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	**0.004**	**< 0.004**	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 ± 0.0030	**0.00001**	**<0.0002**	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	**0.6**	**< 0.6**	EW Corr.
Γ_W (MeV)	Threshold scan	2085 ± 42	**1.5**	**<1.5**	EW Corr.
N_ν	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$	2.92 ± 0.05	**0.001**	**< 0.001**	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	**0.00018**	**< 0.0001**	CKM Matrix
m_{top} (MeV)	Threshold scan	173340 ± 760 ± 500	**20**	**<40**	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	**40**	**<40**	QCD corr.
λ_{top}	Threshold scan	μ = 1.2 ± 0.3	**0.08**	**< 0.05**	QCD corr.
ttZ couplings	√s = 365 GeV	~30%	**~2%**	**<2%**	QCD corr

* work to do: check if we cant improve

many EFTs are accessible



Conclusion from Precision Calculations Mini-Workshop in January 2018:
The necessary theoretical work is doable in 5-10 years perspective, due to steady progress in methods and tools, including the recent completion of NNLO SM corrections to EWPOS. This statement is conditional to a strong support by the funding agencies and the overall community. Appropriate financial support and training programs for these precision calculations are mandatory.

Several EFTs will achieve sensitivity exceeding 50 TeV (decoupling physics!)
junction with FCC-hh EFTs under progress by Jorge de Blas

Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^{*}_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

FCC-hh discovery potential
Highlights

FCC-hh is a HUGE discovery machine (if nature …), but not only.

FCC-hh physics is dominated by three features:

-- **Highest center of mass energy** –> a big step in high mass reach!
- ex: strongly coupled new particle up to >30 TeV
  - Excited quarks, Z', W', up to ~tens of TeV
  - Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV
  - Sensitivity to high energy phenomena in e.g. WW scattering

-- **HUGE production rates** for single and multiple production of SM bosons (H,W,Z) and quarks
- -- Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau$/ZZ, ttH/ttZ @<% level
- -- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling
- -- detection of rare decays $H \rightarrow V\gamma$ ($V = \rho, \varphi, J/\psi, \Upsilon, Z$…)
- -- search for invisibles (DM searches, RH neutrinos in W decays)
- -- renewed interest for long lived (very weakly coupled) particles.
- -- rich top and HF physics program

-- **Cleaner signals for high Pt physics**
- -- allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)

FCC-hh discovery potential

Physics at a 100 TeV pp collider: CERN Yellow Report (2017) no.3

1) Standard Model processes: https://arxiv.org/pdf/1607.01831v1.pdf
2) Higgs and EW symmetry breaking studies: https://arxiv.org/pdf/1606.09408v1.pdf
3) Beyond the Standard Model phenomena: https://arxiv.org/abs/1606.00947
4) Heavy ions at the Future Circular Collider: https://arxiv.org/abs/1605.01389

Now proceeding to ascertain these cross-section calculations with real detector and simulations…

PHYSICS COMPLEMENTARITY

Some examples

Higgs Physics -- ee → ZH fixes Higgs width and HZZ coupling , (and many others)
-- FCC-hh gives huge statistics of HH events for Higgs self-coupling and ttH

Search for Heavy Physics
-- ee gives precision measurements (m_Z m_W to < 0.6 MeV, m_{top} 10 MeV, etc…) sensitive to heavy physics up to … 100 TeV
-- FCC-hh gives access to direct observation at unprecedented energies
Also huge statistics of Z,W H and top → rare decays

QCD -- ee gives $\alpha_s \pm 0.0002$ (R_{had})
also H→gg events (gluon fragmentation!)
-- ep provides tructure functions and $\alpha_s \pm 0.0002$
-- all this improves the signal and background predictions
for new physics signals at FCC-hh

Heavy Neutrinos -- ee: very powerful and clean, but flavour-blind
-- hh and eh more difficult, but potentially flavour sensitive
NB this is very much work in progress!!

HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

hh, eh precisions assume SM or ee measurements

FCC-hh to ZZ to serve as cross-normalization

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.15 %**	**< 1%** *	
WW	**0.20%**		
Γ_H	**1%**		
$\gamma\gamma$	1.5%	**<1%**	
$Z\gamma$	--	**1%**	
tt	13%	**1%**	
bb	**0.4%**		0.5%
$\tau\tau$	**0.5%**		
cc	**0.7%**		1.8%
$\mu\mu$	6.2%	**2%**	
uu,dd	$H \rightarrow \rho\gamma$?	$H \rightarrow \rho\gamma$?	
ss	$H \rightarrow \phi\gamma$?	$H \rightarrow \phi\gamma$?	
ee	**ee → H**		
HH	30%	**~3%**	20%
inv, exo	<0.45%	**10^{-3}**	5%

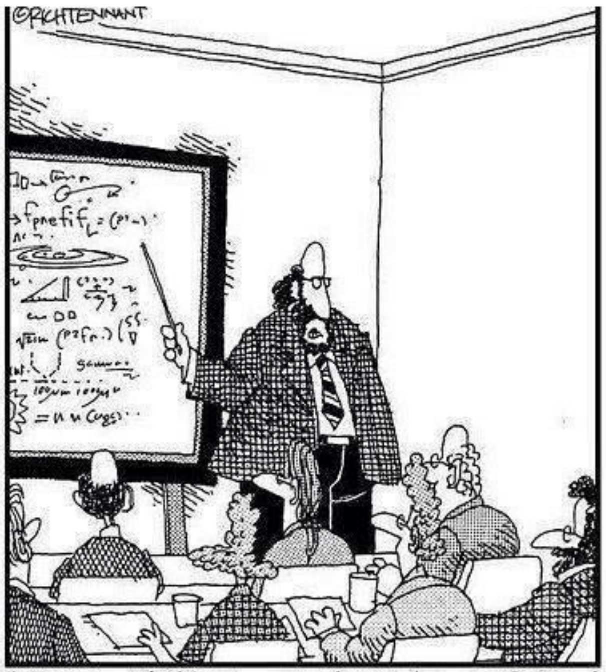
The Hunt for right-Handed Neutrinos at the FCC

Alain Blondel University of Geneva
with many thanks to
S. Antusch, E. Graverini, P. Mermod, N. Serra, M. Shaposhnikov, O. Fischer, E. Cazzatto
P. Hernandez, and many others

4/4/2018

Electroweak eigenstates

I = 1/2	I = 0	
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Right handed neutrinos are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –

Also called 'sterile'

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\ \bar{N}_R^c)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0+M_R) - \sqrt{(0-M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0+M_R) + \sqrt{(0-M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m

	ν_L	ν_R	$\bar{\nu}_L$	$\bar{\nu}_R$
I_{weak}=	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m

	ν_L	$\bar{\nu}_R$
I_{weak}=	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ — see-saw

Dirac + Majorana

m

dominantly:

	ν	N	$\bar{\nu}$	$\bar{N}$
I_{weak}=	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu = \nu_L \cos\theta - N^c_R \sin\theta$$

$$N = N_R \cos\theta + \nu_L{}^c \sin\theta$$

what is produced in W, Z decays is:

$$\nu_L = \nu \cos\theta + N \sin\theta$$

ν = light mass eigenstate
N = heavy mass eigenstate
$\neq \nu_L$, active neutrino
which couples to weak inter.
and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences
- -- if very light (eV) , possible effect on neutrino oscillations
- -- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$

-- possibly measurable effects at High Energy

If N is heavy it will decay in the detector (not invisible)

➔ PMNS matrix unitarity violation and deficit in Z «invisible» width

➔ Higgs, Z, W visible exotic decays $H \rightarrow \nu_i \bar{N}_i$ and $Z \rightarrow \nu_i \bar{N}_i$, $W \rightarrow l_i \bar{N}_i$

➔ also in K, charm and b decays via $W^* \rightarrow l_i^{\pm} \bar{N}$, $N \rightarrow l_j^{\pm}$
with any of six sign and lepton flavour combination

➔ violation of unitarity and lepton universality in Z, W or τ decays

-- etc... etc...

-- Couplings are very small (m_ν / m_N) *(but who knows?)* **and generally seem out of reach at high energy colliders.**

(indirect) Effect of right handed neutrinos on EW precision observables

The relationship $|U|^2 \propto \theta^2 \approx \boldsymbol{m_\nu} / m_N$ is valid for one family see-saw.
For two or three families the mixing can be larger (*Shaposhnikov*)
Antush and Fisher have shown that a slight # in Majorana mass can generate larger mixing between the left- and right-handed neutrinos. ***Worth exploring.***

«$\boldsymbol{v_L} = \boldsymbol{v} \cos\theta + \boldsymbol{N} \sin\theta$» → $(\cos\theta)^2$ becomes parametrized as 1+ $\varepsilon_{\alpha\beta}$ ($\varepsilon_{\alpha\alpha}$ is negative)
the coupling to light 'normal' neutrinos is typically reduced.
In the G_F, M_Z α_{QED} scheme, G_F (extracted from $\mu \to e \nu_e \nu_\mu$) and *g* should be increased
This leads to *correlated* variations of all predictions upon e or mu neutrino mixing.
Only the 'number of neutrinos' (R_{inv} and σ_{had}^{peak}) is sensitive to the tau-neutrino mixing.

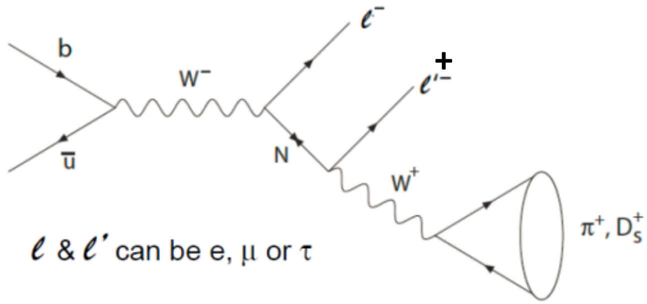
Prediction in MUV	Prediction in the SM	Experiment
$[R_\ell]_{\text{SM}}\,(1-0.15(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\text{SM}}\,(1+0.03(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\text{SM}}\,(1-0.06(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$[\sigma^0_{had}]_{\text{SM}}\,(1-0.25(\varepsilon_{ee}+\varepsilon_{\mu\mu})-0.27\varepsilon_\tau)$	41.470(15) nb	41.541(37) nb
$[R_{inv}]_{\text{SM}}\,(1+0.75(\varepsilon_{ee}+\varepsilon_{\mu\mu})+0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\text{SM}}(1-0.11(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	80.359(11) GeV	80.385(15) GeV
$[\Gamma_{\text{lept}}]_{\text{SM}}(1-0.59(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	83.966(12) MeV	83.984(86) MeV
$[(s^{\ell,\text{lep}}_{W,\text{eff}})^2]_{\text{SM}}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s^{\ell,\text{had}}_{W,\text{eff}})^2]_{\text{SM}}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.23150(1)	0.23222(27)

Table 1: Experimental results and SM predictions for the EWPO, and the modification in the MUV scheme, to first order in the parameters $\varepsilon_{\alpha\beta}$. The theoretical predictions and experimental values are taken from Ref. [16]. The values of $(s^{\ell,\text{lep}}_{W,\text{eff}})^2$ and $(s^{\ell,\text{had}}_{W,\text{eff}})^2$ are taken from Ref. [17].

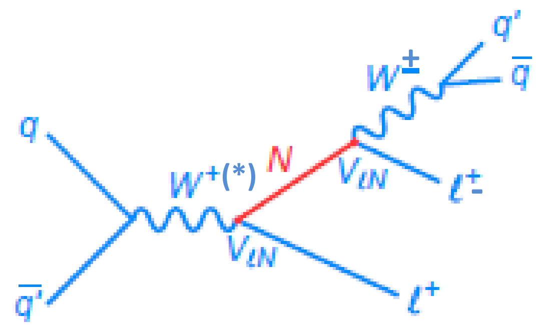
NB this is not decoupling

Detection of heavy right-handed neutrinos in collider experiments.

B factories



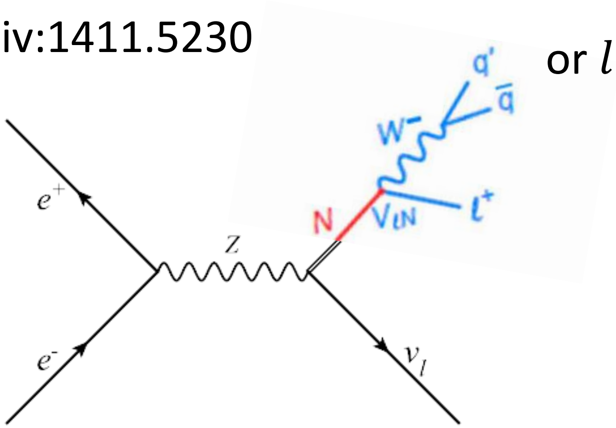
Hadron colliders



or $l^{\pm}\nu$

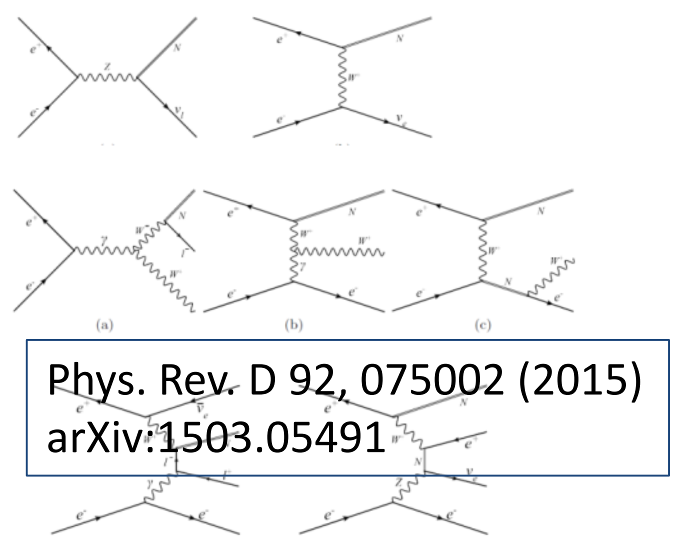
Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230

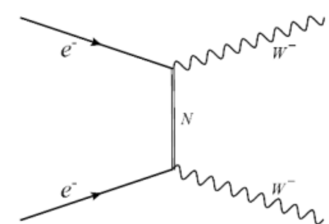


or $l - \nu$

HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)



E. $e^-e^- \rightarrow W^-W^-$



Phys. Rev. D 92, 075002 (2015)
arXiv:1503.05491

RH neutrino production in Z decays

Production:

$$BR\left(Z^0 \to \nu_m \overline{\nu}\right) = BR\left(Z^0 \to \nu\overline{\nu}\right)\left|U\right|^2\left(1-\frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)^2\left(1+\frac{1}{2}\frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)$$

multiply by 2 for antineutrino and add contributions of 3 neutrino species (with different $|U|^2$)

Decay

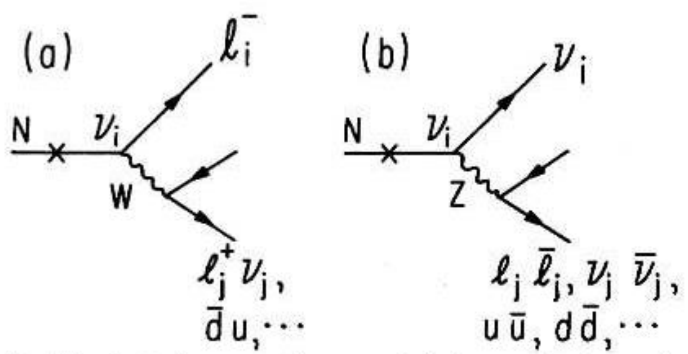


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

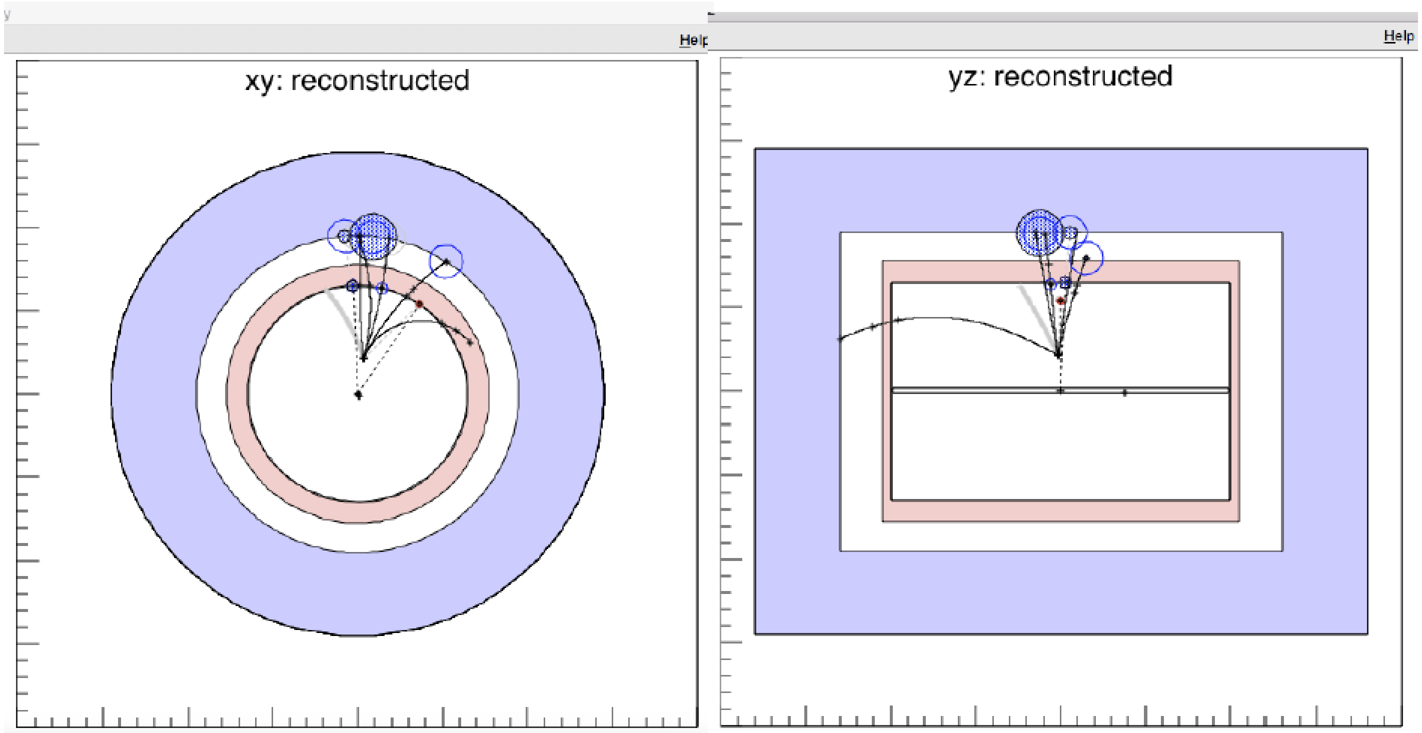
$$L \approx \frac{3 \text{ cm}}{|U|^2\left(m_{\nu_m}(\mathrm{GeV}/c^2)\right)^6}$$

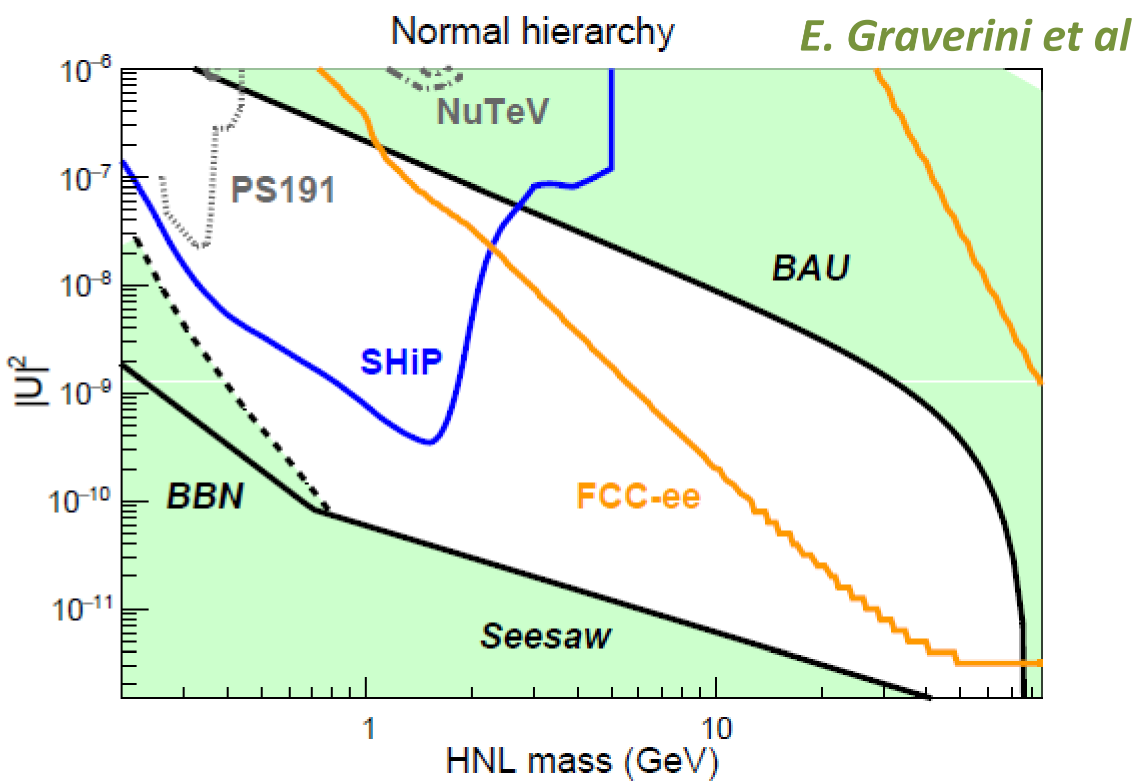
NB CC decay always leads to $\geq$ 2 charged tracks

Backgrounds : four fermion: e+e- → $W^{*+} W^{*-}$ e+e- → $Z^*(\nu\nu)$ + $(Z/\gamma)^*$

Long life time → detached vertex for ~<M_Z

Simulation of heavy neutrino decay in a FCC-ee detector



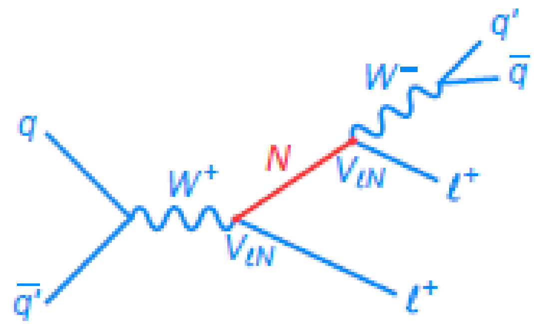


(a) Decay length 500 μm to 2 m

with 5 10^{12} Z

Outlook for FCC-hh

We have seen that the Z factory offers a clean method
for detection of Heavy Right-Handed neutrinos
Ws are less abundant at the lepton colliders



At the 100 TeV pp W is the dominant particle,
Expect 10^{13} real W's.

There is a lot of /pile-up/backgrounds/lifetime/trigger issues which need to be investigated.
BUT.... in the regime of long lived HNLs the simultaneous presence of
-- the initial lepton from W decays
-- the detached vertex with kinematically constrained decay
allows for a significant background reduction.

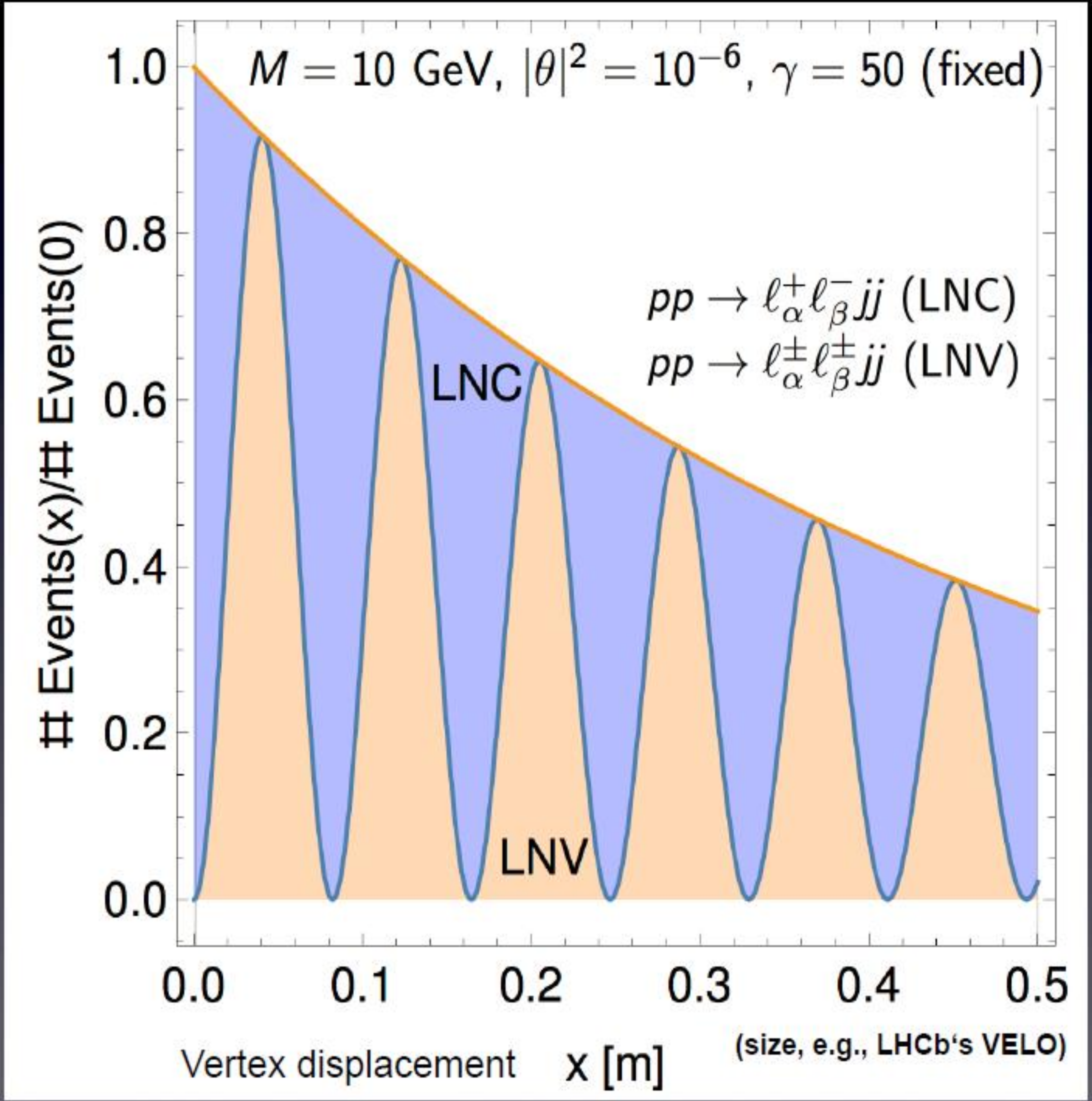
But it allows also a characterization both in flavour and charge of the produced neutrino, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate (Majorana) particle.

VERY interesting...

Recent result: Heavy neutrino-antineutrino oscillations at colliders can be resolvable

Example:
Linear seesaw (inverse mass ordering)

(using the prediction for ΔM in the minimal linear seesaw model for inverse neutrino mass ordering)



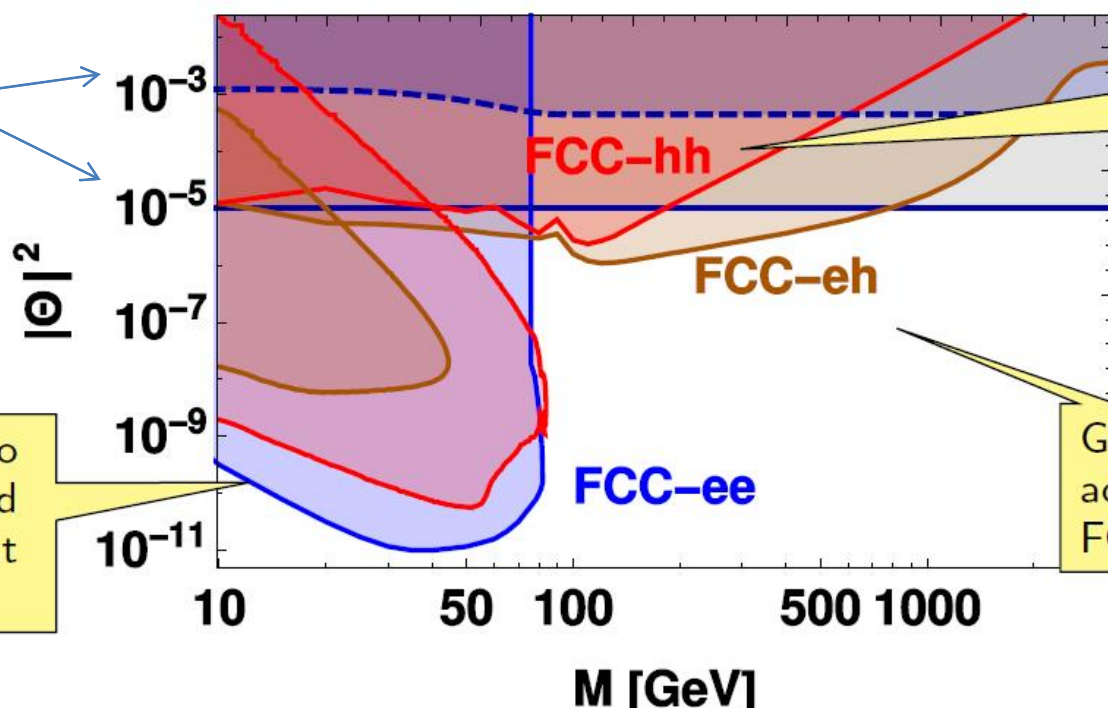
S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

Summary

Another example of Synergy
while ee covers a large part of space very cleanly ,
its either 'white' in lepton flavour or the result of EWPOs etc
Observation at FCC –hh or eh would test flavour mixing matrix!

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search

EWPO



FCC-hh able to test all flavour combinations.

Good sensitivity reach from FCC-hh & FCC-eh.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

CONCLUSIONS

-- The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology.

-- The right-handed neutrino search and study is a very interesting example of complementarity between the various avatars of the FCC.

-- Both FCC-ee and FCC-hh have outstanding physics cases
 -- each in their own right
 -- the sequential implementation of FCC-ee, FCC-hh, FCC-eh would maximise the physics reach

-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities.


FCC WEEK 2018
Future Circular Collider Conference
AMSTERDAM, Netherlands
09 - 13 APRIL
fccw2018.web.cern.ch

A successful model!

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

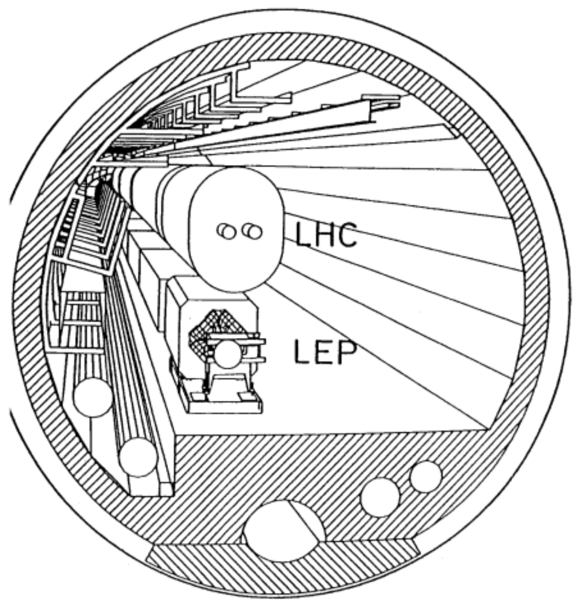
ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel >60 years later?

ECFA 84/85
CERN 84-10
5 September 1984

e+e- 1989-2000



p p 2009-2039

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

Let's not be SHY!

Back up slides

FCC : the important strategic equations

I cannot reveal costs BUT I can give you relationships between them

$C_{(FCC\text{-}ee)} << C_{(HE\text{-}LHC)}$ (machine only) ➔ **this is the strategy defining equation**

$\mathbf{C_{(tunnel)} \lessapprox C_{(HE\text{-}LHC)}}$ this is important also.

Also: $C_{ILC\text{-}EU} + C_{HE\text{-}LHC} \approx C_{tunnel} + C_{FCC\text{-}ee}$

➔ $C_{(tunnel+FCC\text{-}ee+FCC\text{-}hh)} < C_{(HE\text{-}LHC + tunnel + FCC\text{-}hh)}$ (1)

Practical arguments lead to the timing discussion:

$[T_{(HL\text{-}LHC \rightarrow HE\text{-}LHC)} + T_{(HE\text{-}LHC \rightarrow FCC\ injector)}] > T_{(FCC\text{-}ee \rightarrow FCC\text{-}hh)}$

The time it takes to des-install HL-LHC, install HE-LHC
des-install HE-LHC, install the FCC injector
is longer than the time it takes to intall the FCC-hh at the end of FCC-ee

➔ $T_{(tunnel+FCC\text{-}ee+FCC\text{-}hh)} < T_{(HE\text{-}LHC + tunnel + FCC\text{-}hh)}$ (2)

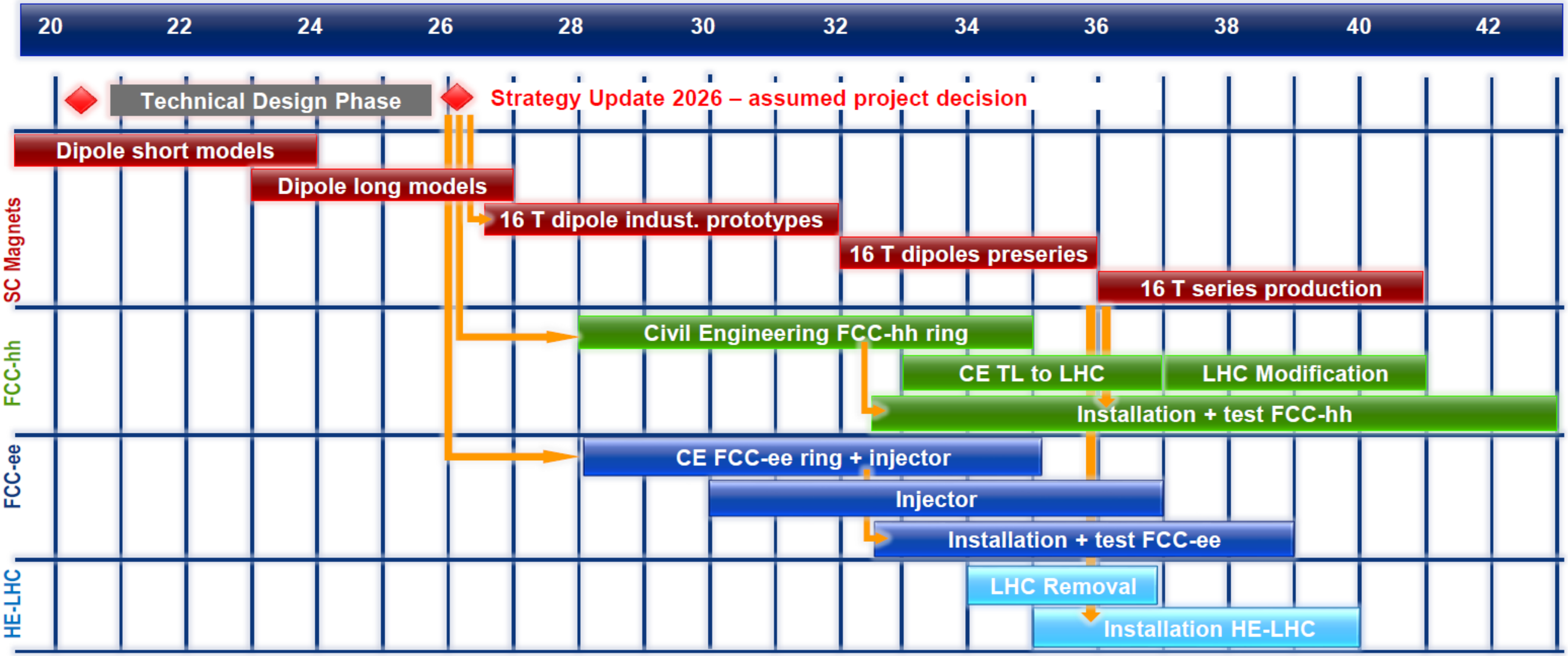
then trivially the physics Φ

➔ $\Phi_{FCC\text{-}ee+FCC\text{-}hh} > \Phi_{HE\text{-}LHC+FCC\text{-}hh}$ (3)

➔ the way by FCC-ee is the cheapest and fastest way to get to 100 TeV and the along the way physics is (much) superior.

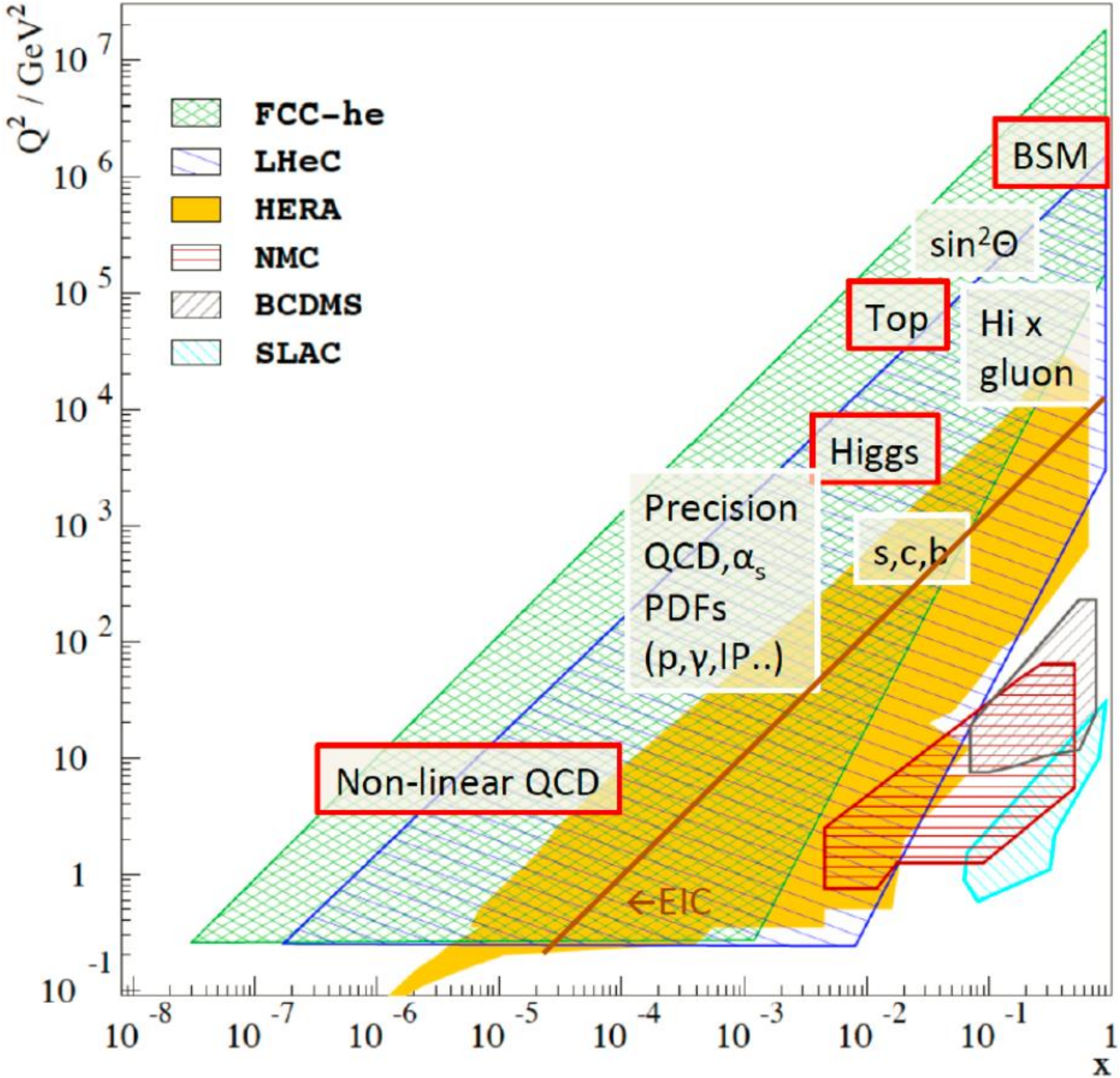
and we can also dream of a >5 TeV muon collider using the tunnels of CERN

Draft Schedule Considerations



FCC Study Status and Plans
Michael Benedikt
3rd FCC Week, Berlin, 29 May 2017

25



Q^2 / GeV^2
FCC-he
LHeC
HERA
NMC
BCDMS
SLAC
BSM
sin$^2\Theta$
Top
Hi x gluon
Higgs
Precision QCD,α_s PDFs (p,γ,IP..)
s,c,b
Non-linear QCD
←EIC
x

Physics references

FCC-ee

-- First look at the physics case of TLEP JHEP 1401 (2014) 164 arXiv:1308.6176

-- "Precision Observables and Radiative Corrections", https://indico.cern.ch/event/387296/

-- "Higgs at FCC-ee", https://indico.cern.ch/event/401590/

-- "High-precision α_S measurements: from LHC to FCC-ee", https://indico.cern.ch/event/392530/

serie ongoing: FCC-ee physics Indico: https://indico.cern.ch/category/5259/

Physics at a 100 TeV pp collider: CERN Yellow Report (2017) no.3

1) Standard Model processes: https://arxiv.org/pdf/1607.01831v1.pdf
2) Higgs and EW symmetry breaking studies: https://arxiv.org/pdf/1606.09408v1.pdf
3) Beyond the Standard Model phenomena: https://arxiv.org/abs/1606.00947
4) Heavy ions at the Future Circular Collider: https://arxiv.org/abs/1605.01389

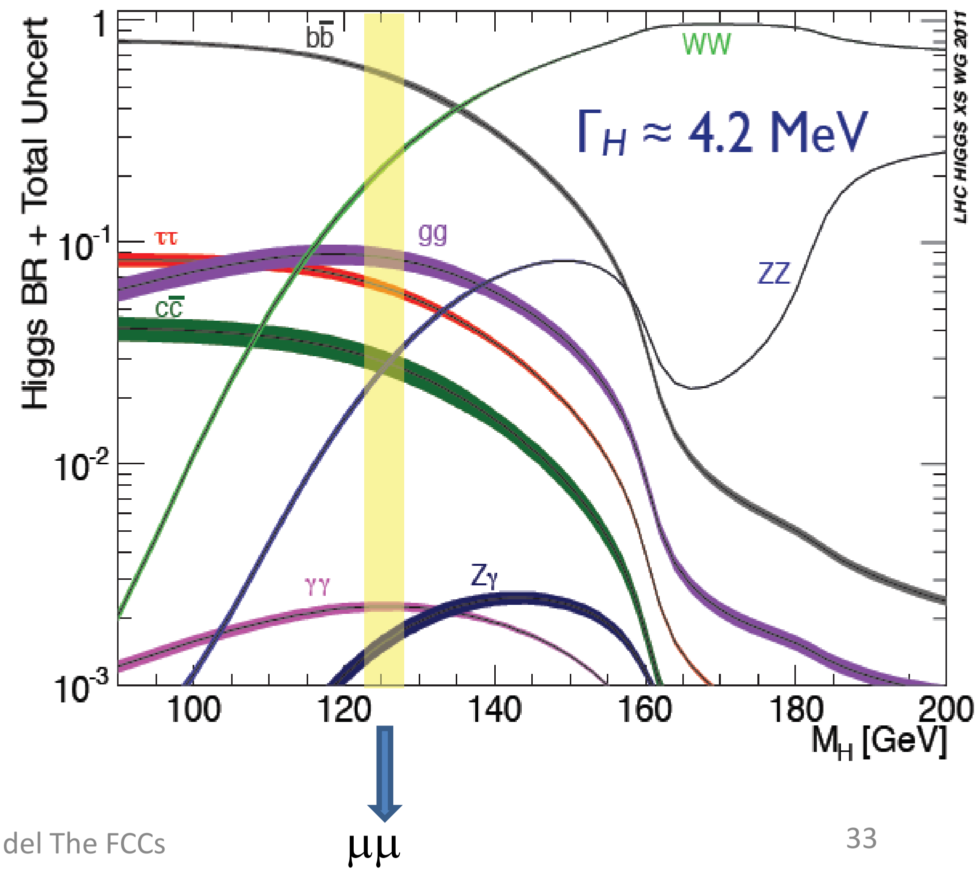
LHeC and FCC-eh

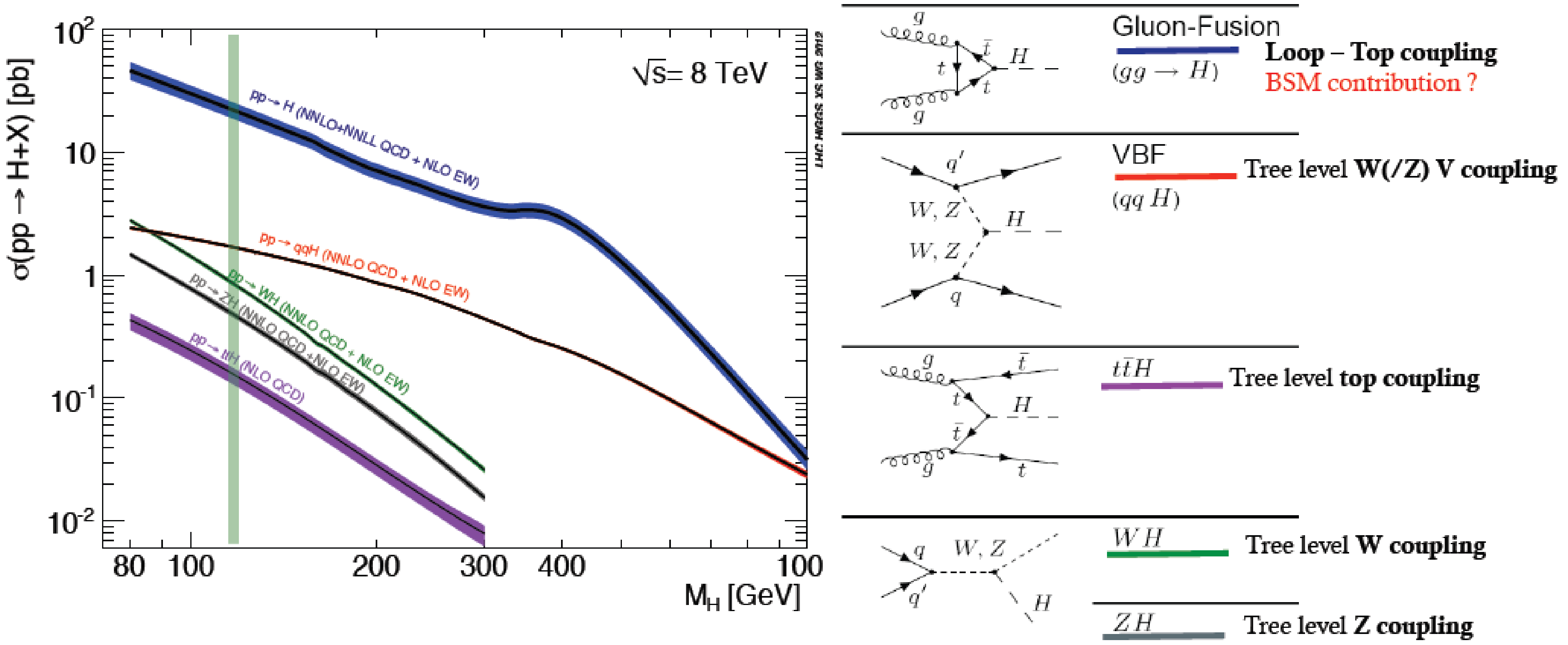
- "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J.Phys. G39 (2012) 075001
- LHeC Workshop (24-26 June 2015) https://indico.cern.ch/event/356714/
- Higgs at LHeC/FCC-eh: WG mtgs at https://indico.cern.ch/category/1874/

Higgs Physics

The only known spin = 0 elementary particle
We must study it as well and thoroughly as we can

Aram Apyan
Michelangelo Mangano
Biagio Di Micco
Fady Bishara
Ennio Salvioni
Masahiro Tanaka
Gilad Perez





The LHC is a Higgs Factory !

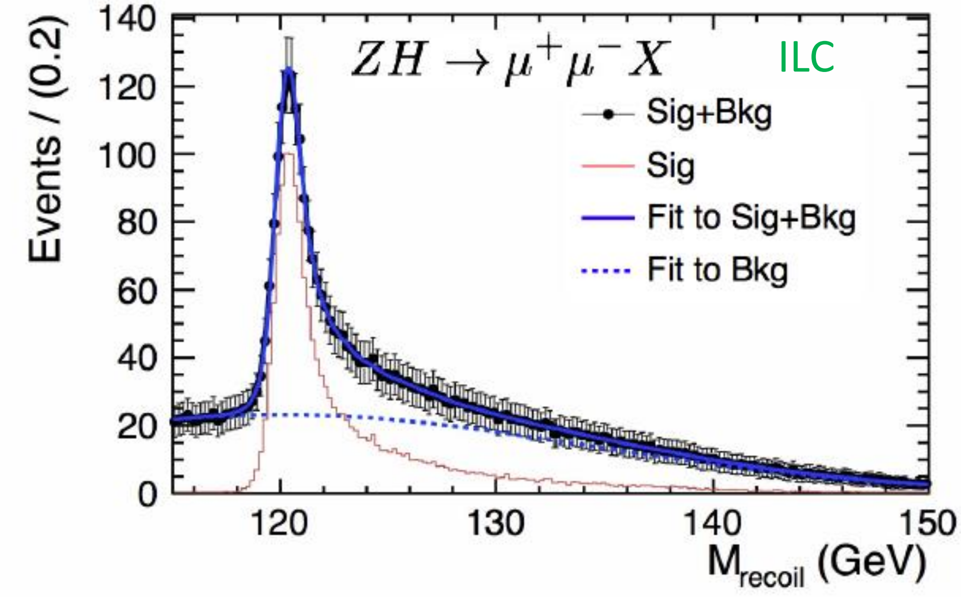
Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections σ_{prod} .
Challenge will be to reduce systematics by measuring related processes.

$$\sigma_{i \to f}^{\ observed} \propto \sigma_{prod} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

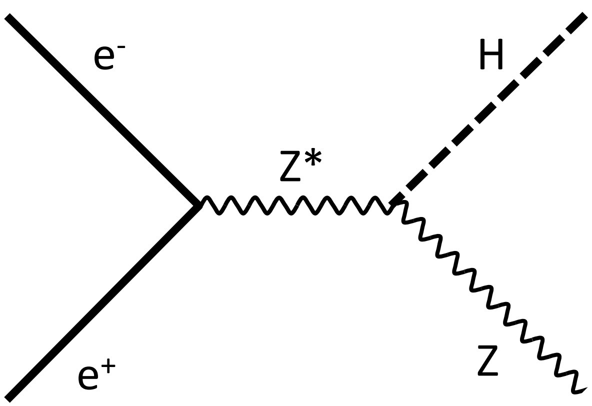
overall normalization by Γ_H required
this is also true for FCC-hh and FCC-ep

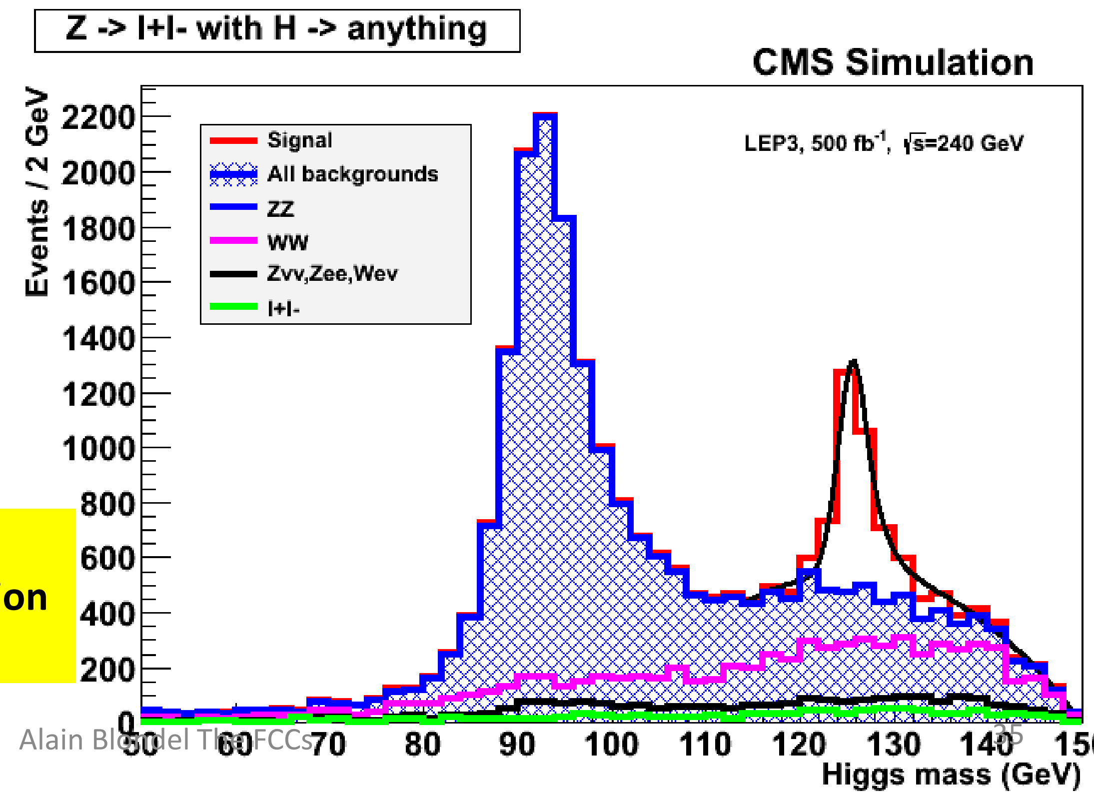
FCC-ee

H signal in missing mass

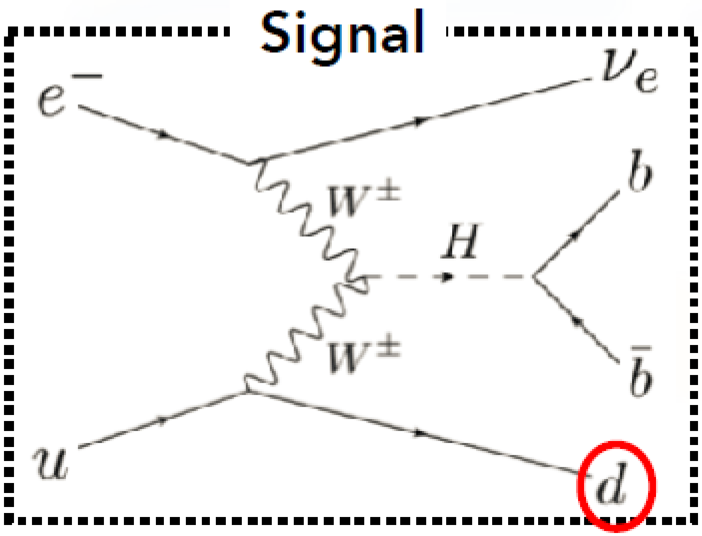


total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
➔ measure total width Γ_H and g_{HZZ}
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold





UNIQUE!
The ability to measure the Higgs cross-section without seeing the Higgs is crucial for this.



Forward jet

$$\sigma_{ep\rightarrow H\text{->}bb}{}^{\text{observed}} \propto \sigma_{prod} \frac{(g_{Hww})^2 (g_{Hbb})^2}{\Gamma_H}$$

because $\Gamma_{H\rightarrow bb}$ ~ **0.6** Γ_H sensitivity to g_{Hbb} is reduced by factor 1/(1-0.6) =2.5
0.4% meast of x-section→ 0.5 % on g_{Hbb} coupling

➔ for complementarity study,
suggest to include bb, cc in global fit with ee results

simillarly for HH result

Higgs chapter of FCC physics report

arXiv:1606.09408

CERN-TH-2016-113

Physics at a 100 TeV *pp* collider: Higgs and EW symmetry breaking studies

Editors:
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SM Higgs rates at 100 TeV

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$
$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$
$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

- Huge production rates imply:
    - can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
    - can explore new dynamical regimes, where new tests of the SM and EWSB can be done

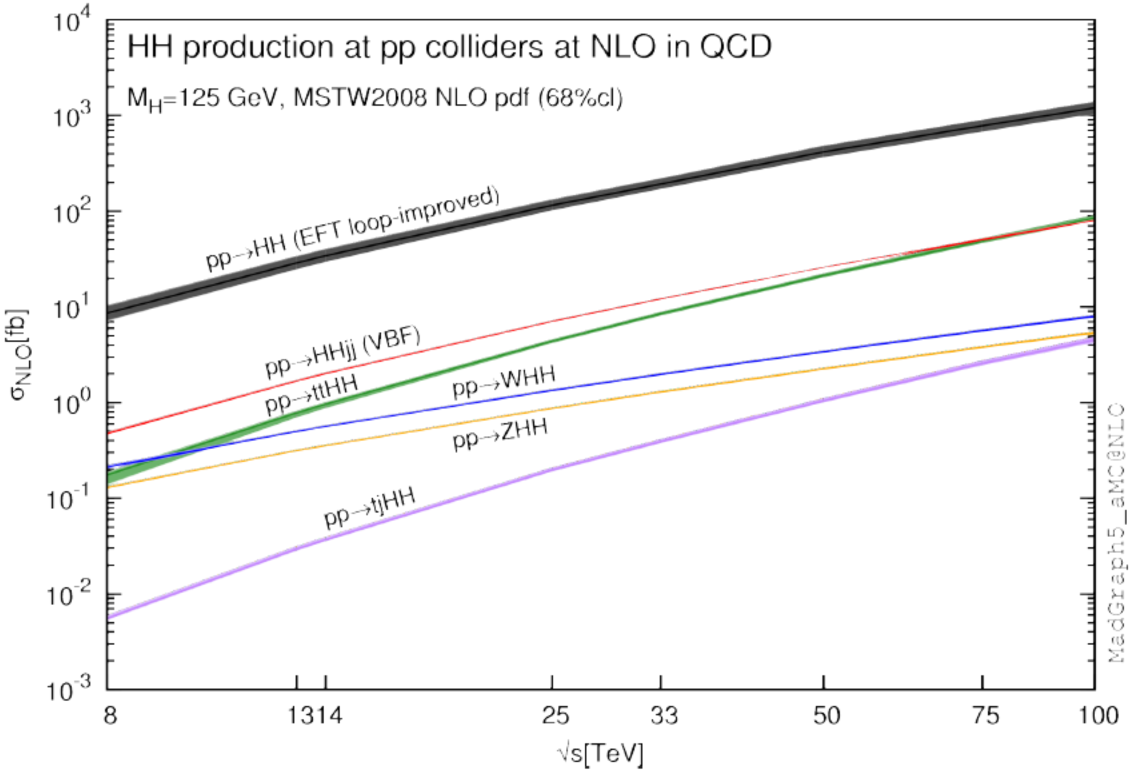
$>10^9$ H produced

HH production at pp colliders

)8169

- VBF cross-section at the LHC is small ~ 2 [fb] w/o $\mathcal{BR}$s (100[fb] at the FCC)

- But, is a unique probe of the EWSB mechanism



for L= 2 $10^{35}/cm^2$

This is 200 times the LHC rate.

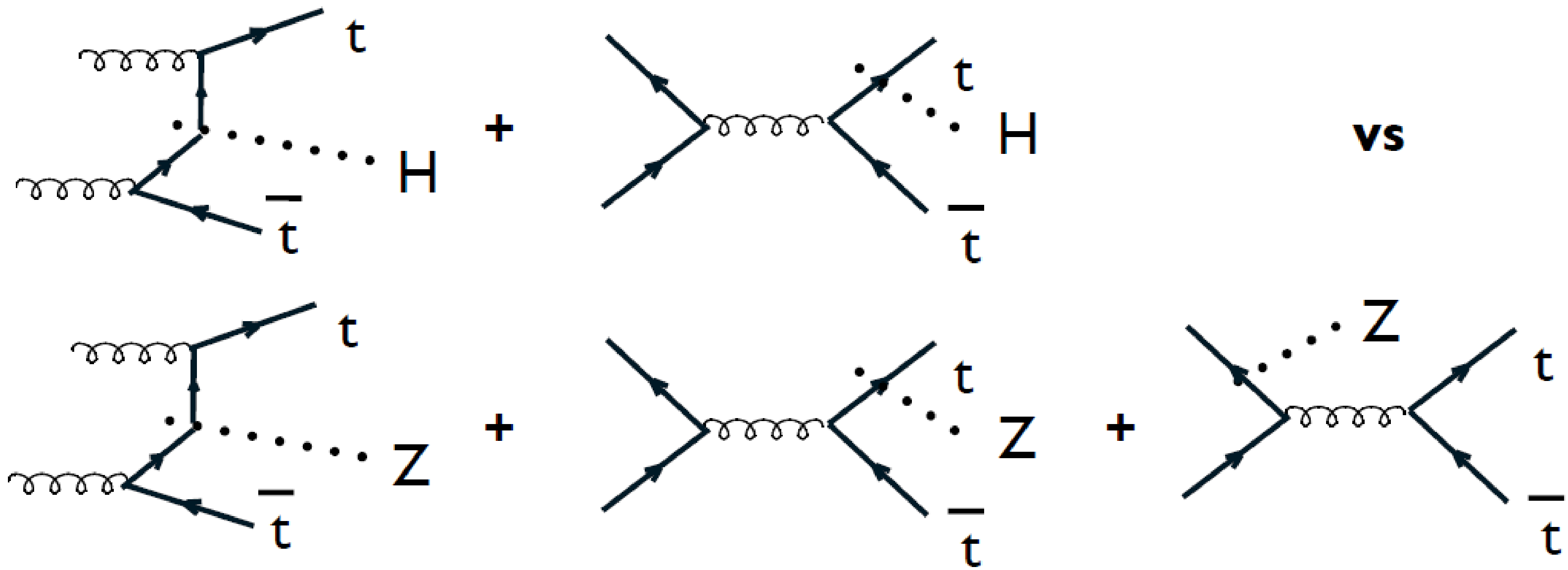
t:

Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro: 1401.7340

be

predicted with great precision

Top Yukawa coupling from σ(ttH)/σ(ttZ)



To the extent that the qqbar → tt Z/H contributions are subdominant:

- Identical production dynamics:
  - o correlated QCD corrections, correlated scale dependence
  - o correlated α_S systematics
- $m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:
  - o correlated PDF systematics
  - o correlated m_{top} systematics

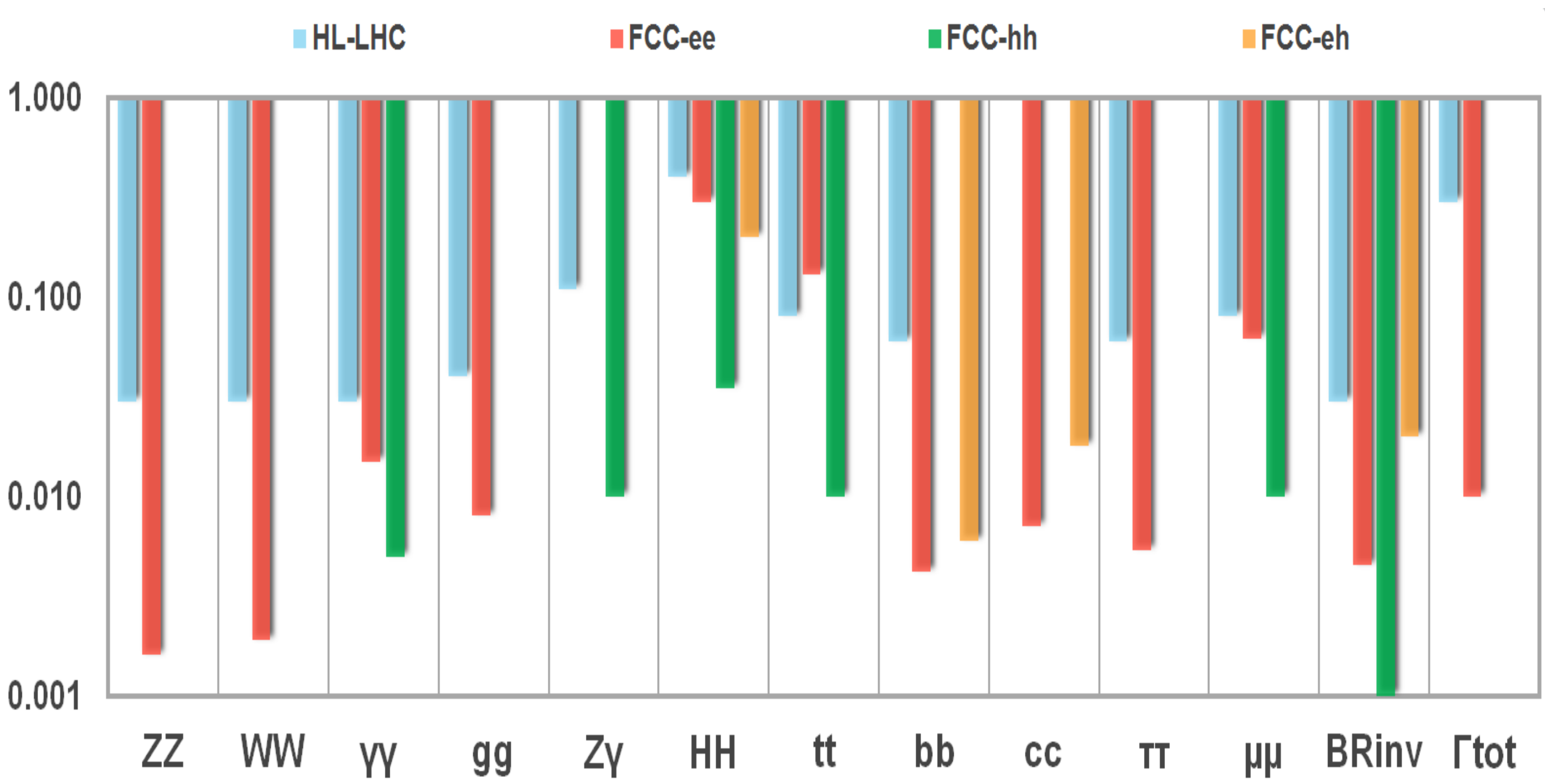
	$\sigma(t\bar{t}H)[\mathrm{pb}]$	$\sigma(t\bar{t}Z)[\mathrm{pb}]$	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$ (± scale ± PDF)
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

HIGGS PHYSICS
more to come

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.15 %**		
WW	**0.20%**		
Γ_H	**1%**		
$\gamma\gamma$	1.5%	**<1%**	
$Z\gamma$	--	**1%**	
tt	13%	**1%**	
bb	**0.4%**		0.5%
$\tau\tau$	**0.5%**		
cc	**0.7%**		1.8%
$\mu\mu$	6.2%	**2%**	
uu,dd	$H\rightarrow \rho\gamma$?	$H\rightarrow \rho\gamma$?	
ss	$H\rightarrow \phi\gamma$?	$H\rightarrow \phi\gamma$?	
ee	**ee → H**		
HH	30%	**<5%**	20%
inv, exo	<0.45%	**10^{-3}**	5%

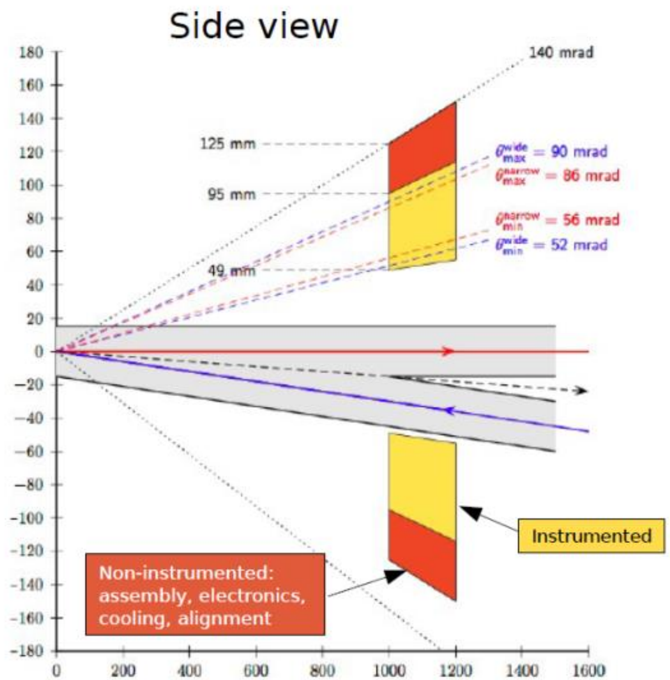
NB precisions on g_{Hxx}

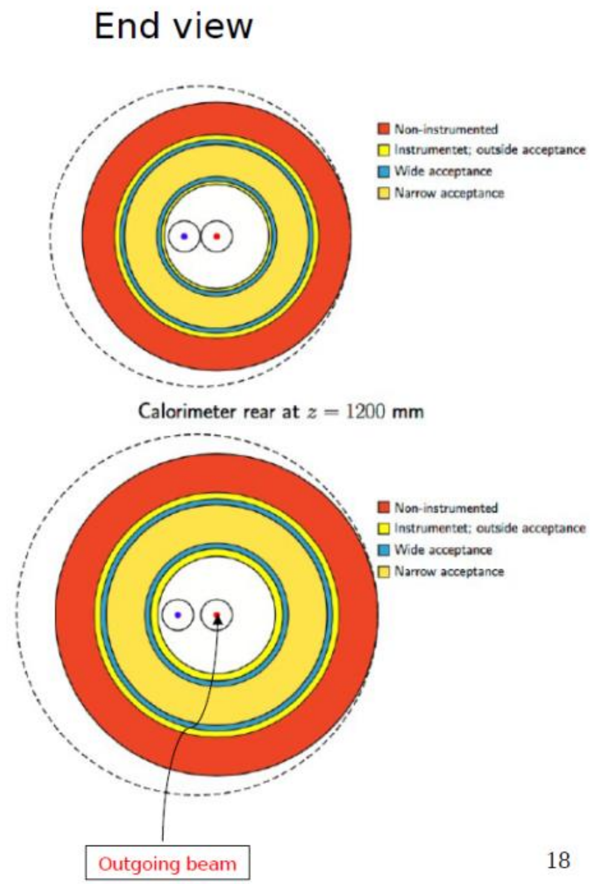
hh, eh precisions assume ee measurements



NB this is an ‘impression plot’ not the consistent result of a Higgs coupling fit!

LumiCal geometry





Cross section: σ = 23 nb
Geometric precision needed for absolute normalization to 10^{-4}

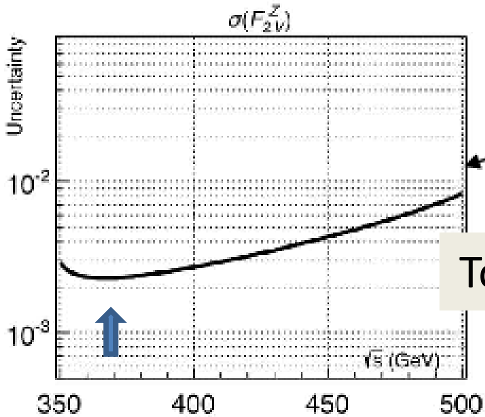
- $\delta z = 50\ \mu m$
- $\boxed{\delta r_{min} = 1.6\ \mu m}$
- $\delta r_{max} = 5.8\ \mu m$

Luminosity measurement challenging: L* is small.
Use mainly for Z line shape and fast lumi.

For absolute measurements can use large angle e+e- $\rightarrow \gamma\gamma$

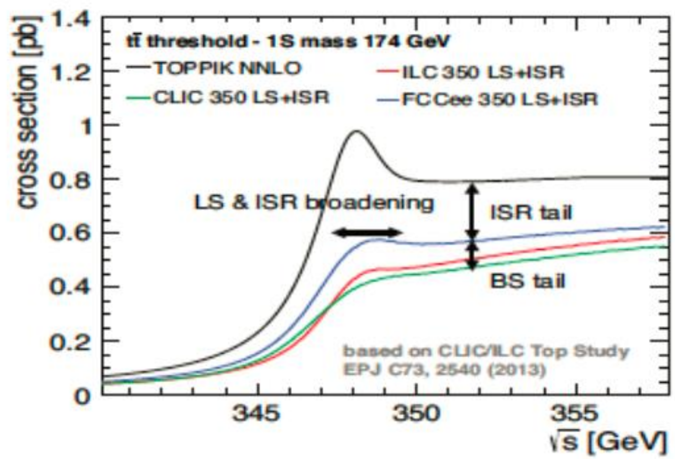
Top physics

Determination of top-quark EW couplings via measurement of top-quark polarization.
In semileptonic decays, fit to lepton momentum vs scattering angle



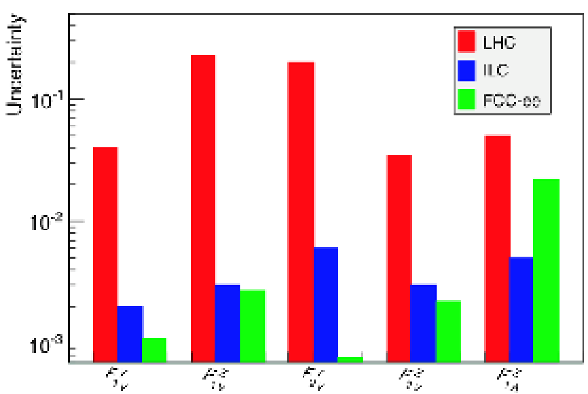
Typically best sensitivity just above production threshold

Top beam energy is 185 GeV



Top mas can be measured to O(10 MeV)
Beam energy calibration from WW, γZ, ZZ
Reduce th. errors due α_S meast @FCC-ee

Patrick Janot
arXiv:1503.01325v2



Also:
CKM measurements
FCNC decays down to 10^{-6}
All luminosity can be used!

Theoretical limitations

FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

$$M_W = 80.3593 \pm 0.0002_{m_t} \pm 0.0001_{M_Z} \pm 0.0003_{\Delta\alpha_{\mathrm{had}}}$$
$$\pm 0.0001_{\alpha_S} \pm 0.0000_{M_H} \pm 0.0040_{\mathrm{theo}}$$

0.0005

$$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.231496 \pm 0.0000015_{m_t} \pm 0.000001_{M_Z} \pm 0.00001_{\Delta\alpha_{\mathrm{had}}}$$
$$\pm 0.0000014_{\alpha_S} \pm 0.000000_{M_H} \pm 0.000047_{\mathrm{theo}}$$

0.00001

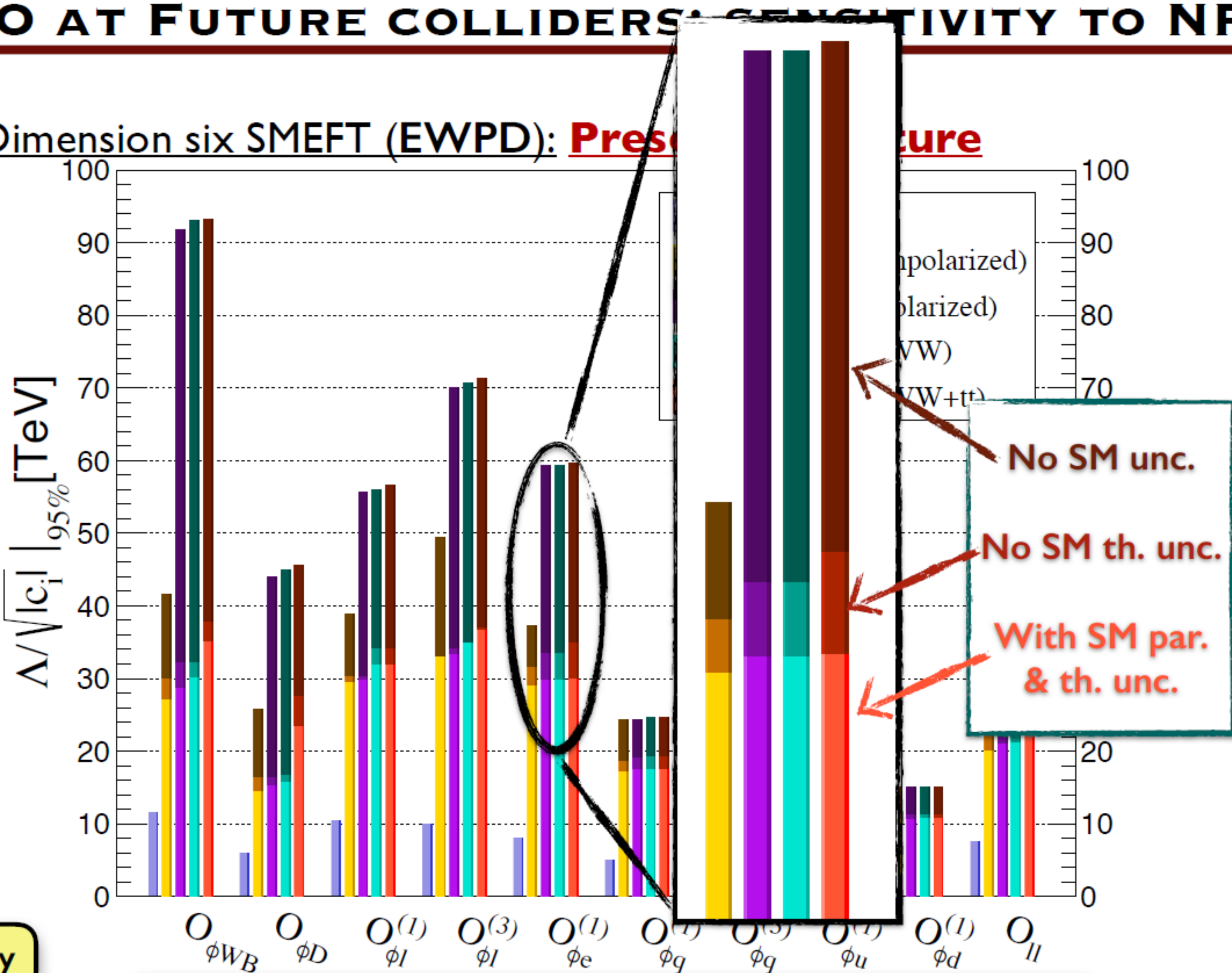
Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.
BUT can be typically 10 -30 times smaller than present level of theory errors
Will require significant theoretical effort and additional measurements!

Radiative correction : need for 3 loop calculations for the future!
Suggest including manpower for theoretical calculations in the project cost.

EWPO at Future colliders: sensitivity to NP

- Dimension six SMEFT (EWPD): **Present / Future**

1 operator at a time. Flavor universal.



Preliminary

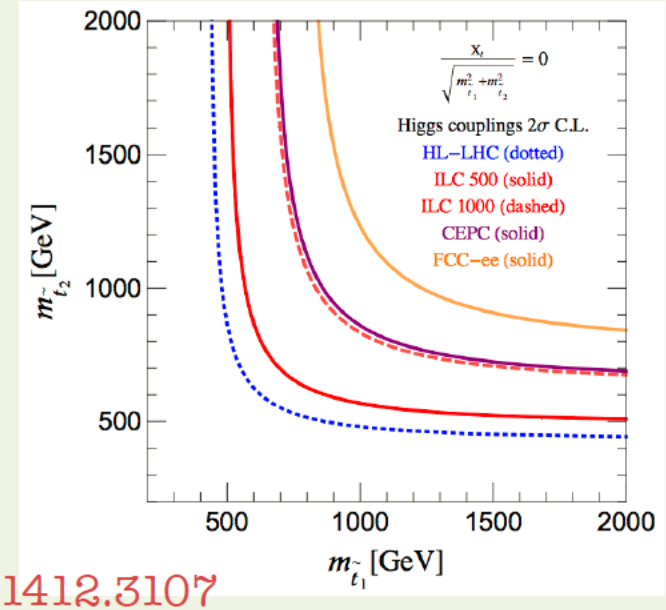
LARGE impact of SM uncertainties

Comprehensive Complementarity

In supersymmetry this is the "stop squark".

FCC-ee

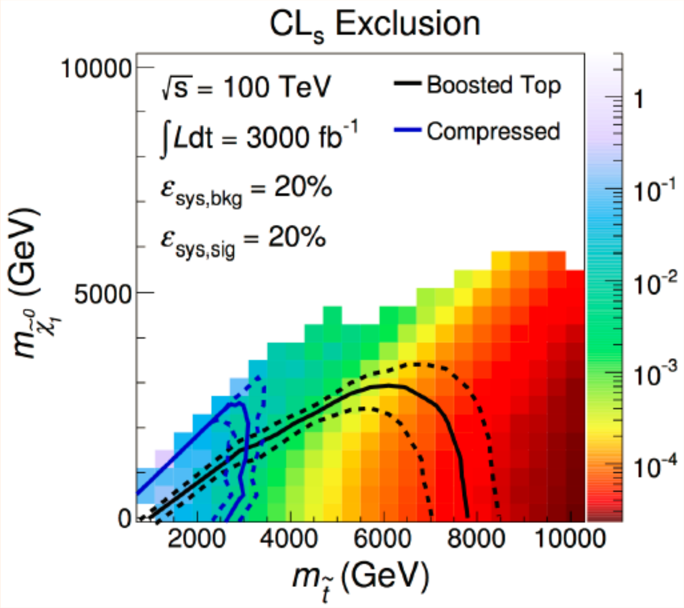
Coloured and charged, stops modify Higgs couplings:



1412.3107

FCC-hh

And show up directly at hadron colliders:



FCC-ee: Indirect, but more "spectrum independent", for a model.
FCC-hh: Direct confirmation, but direct might be hidden.

McCullough

Systematic Complementarity

Thus returning to the third notion of complementarity: "Different FCC Colliders enhance the exploratory power of one another, when a measurement at one reduces a systematic uncertainty in another."

One can see that the estimated FCC-ee determination, from runs at the Z-pole and at higher energies, of

$$\Delta\alpha_S(M_Z^2) \sim \pm 0.0001(0.08\%)$$

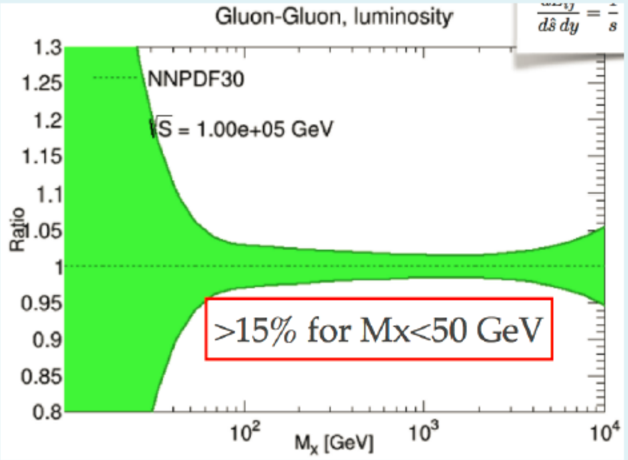
Would reduce systematic uncertainties in BSM searches at FCC-hh, both direct (e.g. extra dimensions) and indirect (e.g. Higgs couplings).

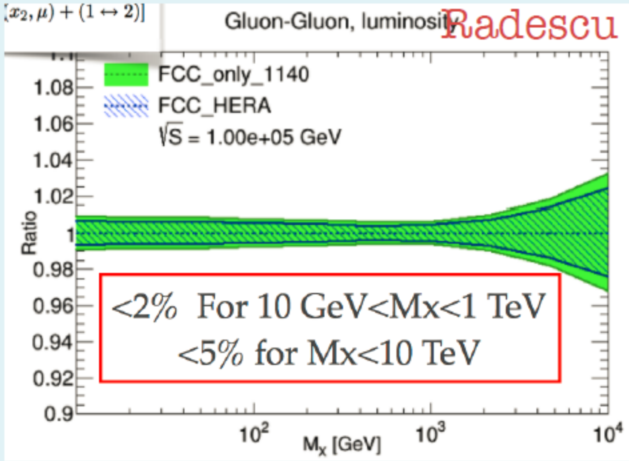
Systematic Complementarity

Thus returning to the third notion of complementarity: "Different FCC Colliders enhance the exploratory power of one another, when a measurement at one reduces a systematic uncertainty in another."

PDFs a similar story at FCC-eh

Camarda Radescu





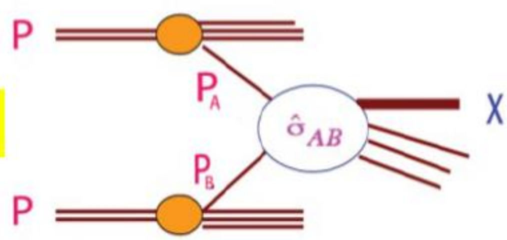
Improvement in low-x predictions for FCC-hh.

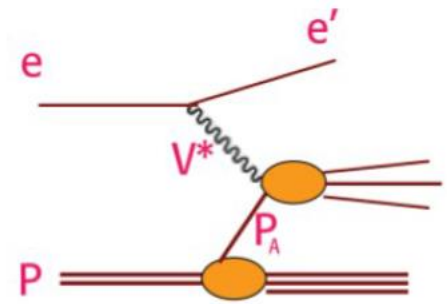
McCullough

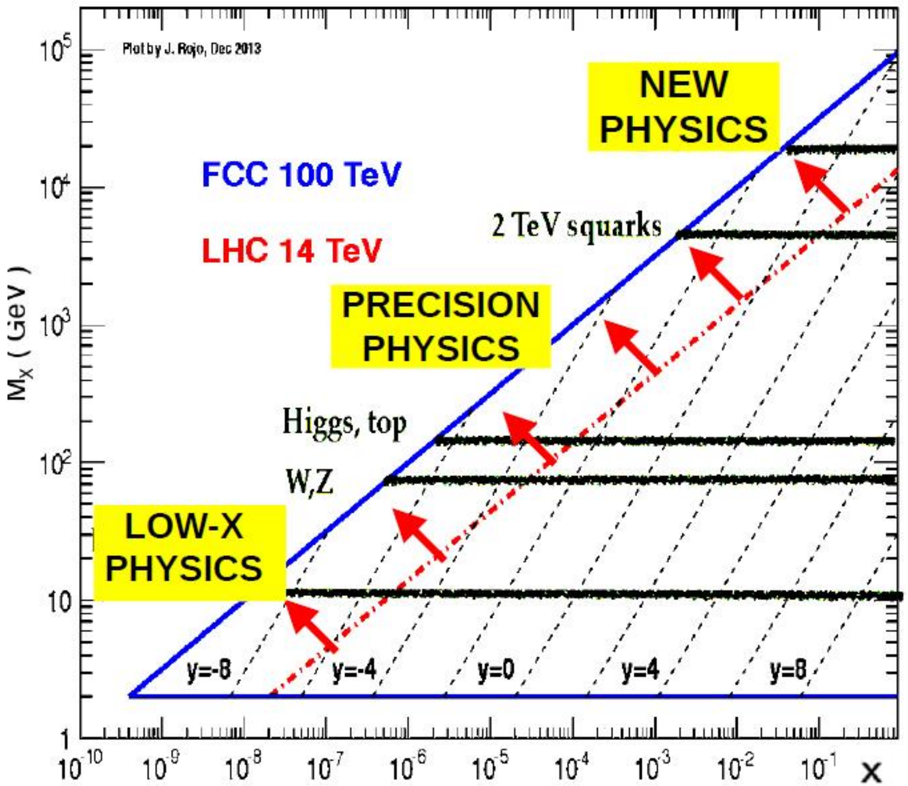
FCC-ep "comes to the rescue" of FCC-pp

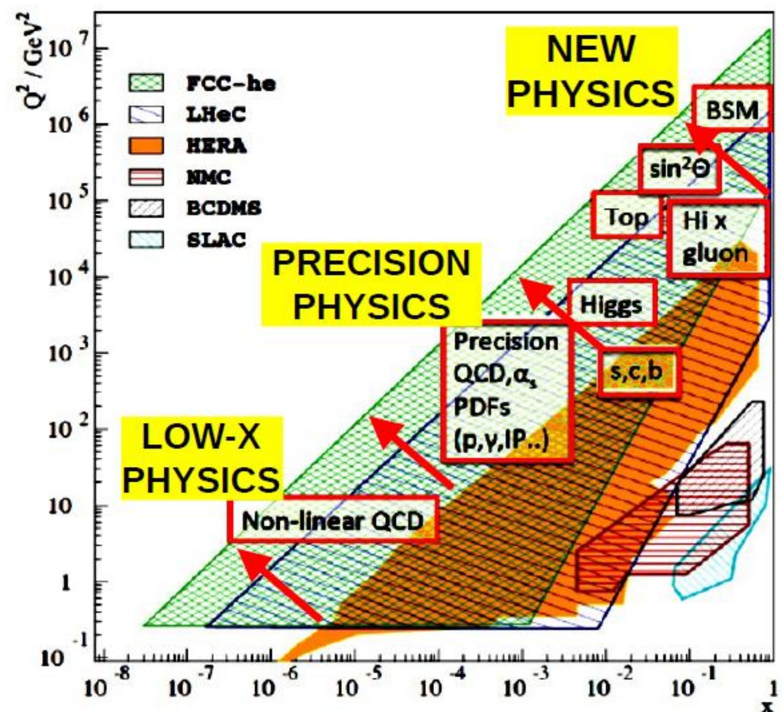
- FCC-ep: Fully complementary with FCC-pp to improve parton densities.

$\sigma = \hat{\sigma} \otimes \text{PDF}$







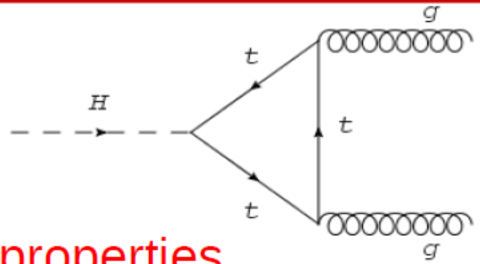


FCC Phys. Workshop, CERN, Jan. 2017 18/31 David d'Enterria (CERN)

Higgs as a source of pure gluons (FCC-ee)

- FCC-ee H(gg) is a "pure gluon" factory:
  $H \rightarrow gg$ (BR~10% accurately know) provides
  O(200.000) extra-clean digluon events:

→ High-precision study of gluon radiation & g-jet properties



Handles to split degeneracies

G. Soyez, K. Hamacher, G. Rauco, S. Tokar, Y. Sakaki

$H \rightarrow gg$ vs $Z \rightarrow qq$

Rely on good **$H \rightarrow gg$ vs $H \rightarrow bb$** separation; mandated by Higgs studies requirements anyway?

$Z \rightarrow bbg$ vs $Z \rightarrow qq(g)$

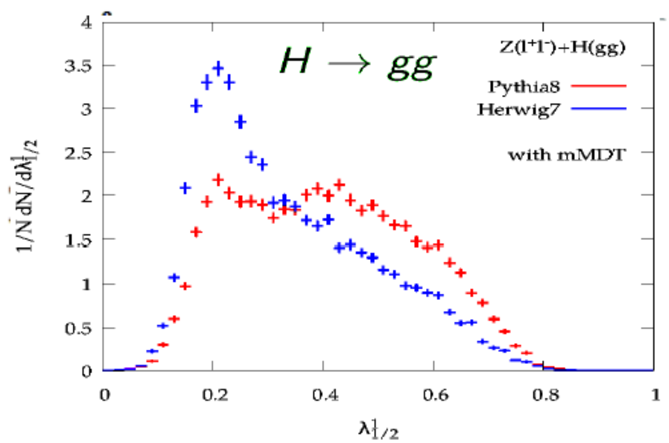
g in one hemisphere recoils against two b-jets in other hemisphere: **b tagging**

Vary jet radius: small-R → calo resolution

(R ~ 0.1 also useful for jet substructure)

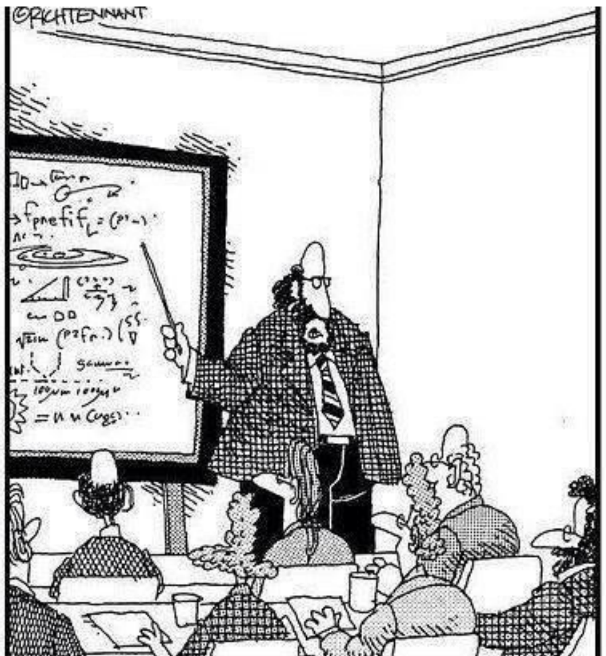
Vary E_{CM} range : below m_Z : radiative events → **forward** boosted

(also useful for FFs & general scaling studies);
Scaling is **slow**, logarithmic → large lever arm



- Check N^nLO antenna functions
- Improve q/Q/g discrim. tools
- Octet neutralization? (zero-charge gluon jet w/ rap-gaps)
- Colour reconnection? Glueballs ?
- Leading η's,baryons in g jets?

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0
I = 1/2	I = 0	



" Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –

Also called 'sterile'

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
<u>Dirac + Majorana mass terms</u>

$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
<u>Dirac only, (like e- vs e+):</u>

m ↑

ν_L ν_R $\bar{\nu}_L$ $\bar{\nu}_R$

I_{weak}= ½ 0 ½ 0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
<u>Majorana only</u>

m ↑

ν_L $\bar{\nu}_R$

I_{weak}= ½ ½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$

see-saw

<u>Dirac + Majorana</u>

m ↑

dominantly: ν N $\bar{\nu}$ $\bar{N}$

I_{weak}= ½ 0 ½ 0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D{}^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu = \nu_L \cos\theta - N^c{}_R \sin\theta$$

$$N = N_R \cos\theta + \nu_L{}^c \sin\theta$$

what is produced in W, Z decays is:

$$\nu_L = \nu \cos\theta + N \sin\theta$$

ν = light mass eigenstate
N = heavy mass eigenstate
$\neq \nu_L$, active neutrino which couples to weak inter.
and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences
- -- if very light (eV) , possible effect on neutrino oscillations
- -- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$

-- possibly measurable effects at High Energy

If N is heavy it will decay in the detector (not invisible)

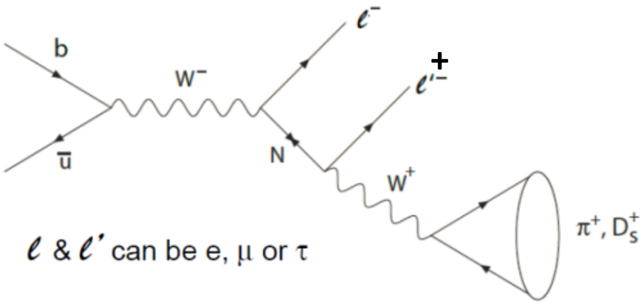
- ➔ PMNS matrix unitarity violation and deficit in Z «invisible» width
- ➔ Higgs, Z, W visible exotic decays $H \rightarrow \nu_i \bar{N}_i$ and $Z \rightarrow \nu_i \bar{N}_i$, $W \rightarrow l_i \bar{N}_i$
- ➔ also in K, charm and b decays via $W^* \rightarrow l_i^\pm \bar{N}$, $N \rightarrow l_j^\pm$
  with any of six sign and lepton flavour combination
- ➔ violation of unitarity and lepton universality in Z, W or τ decays

-- etc... etc...

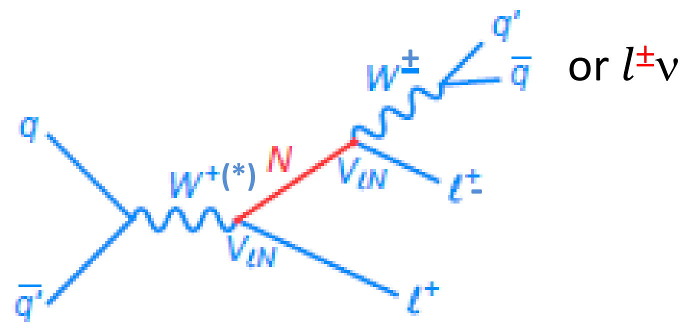
-- Couplings are very small (m_ν / m_N) *(but who knows?)* **and generally seem out of reach at high energy colliders.**

Search for heavy right-handed neutrinos in collider experiments.

B factories

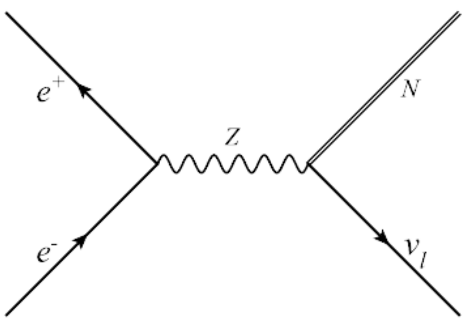


Hadron colliders

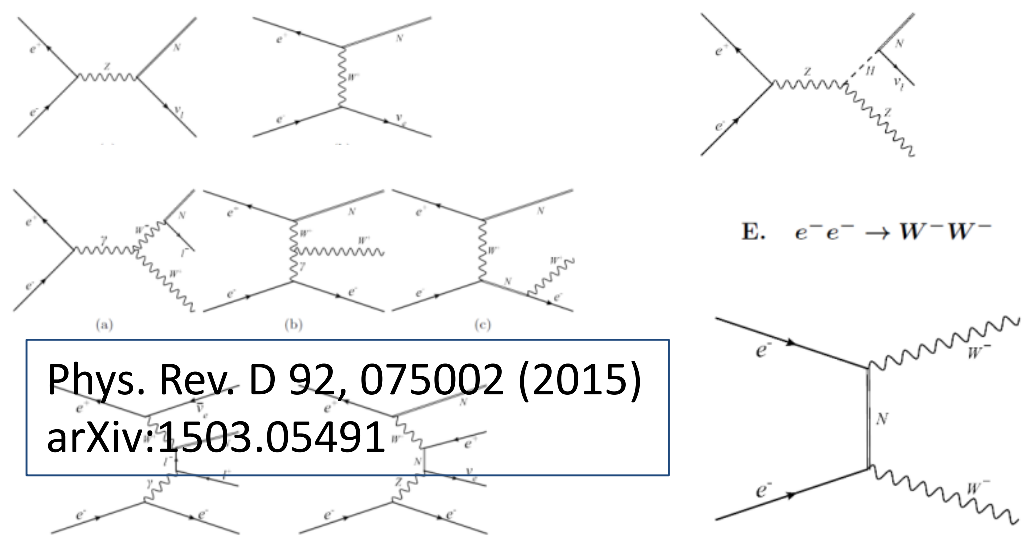


Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230



HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)



Phys. Rev. D 92, 075002 (2015)
arXiv:1503.05491

RH neutrino production in Z decays

Production:

$$BR\left(Z^0 \rightarrow \nu_m \overline{\nu}\right) = BR\left(Z^0 \rightarrow \nu\bar{\nu}\right) \left|U\right|^2 \left(1 - \frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)^2 \left(1 + \frac{1}{2}\frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)$$

multiply by 2 for antineutrino and add contributions of 3 neutrino species (with different $|U|^2$)

Decay

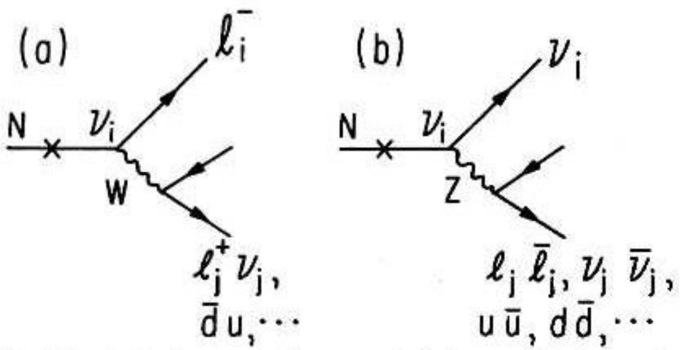


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

$$L \approx \frac{3\ \text{cm}}{|U|^2\ \left(m_{\nu_m}(\mathrm{GeV}/c^2)\right)^6}$$

NB CC decay always leads to ≥ 2 charged tracks

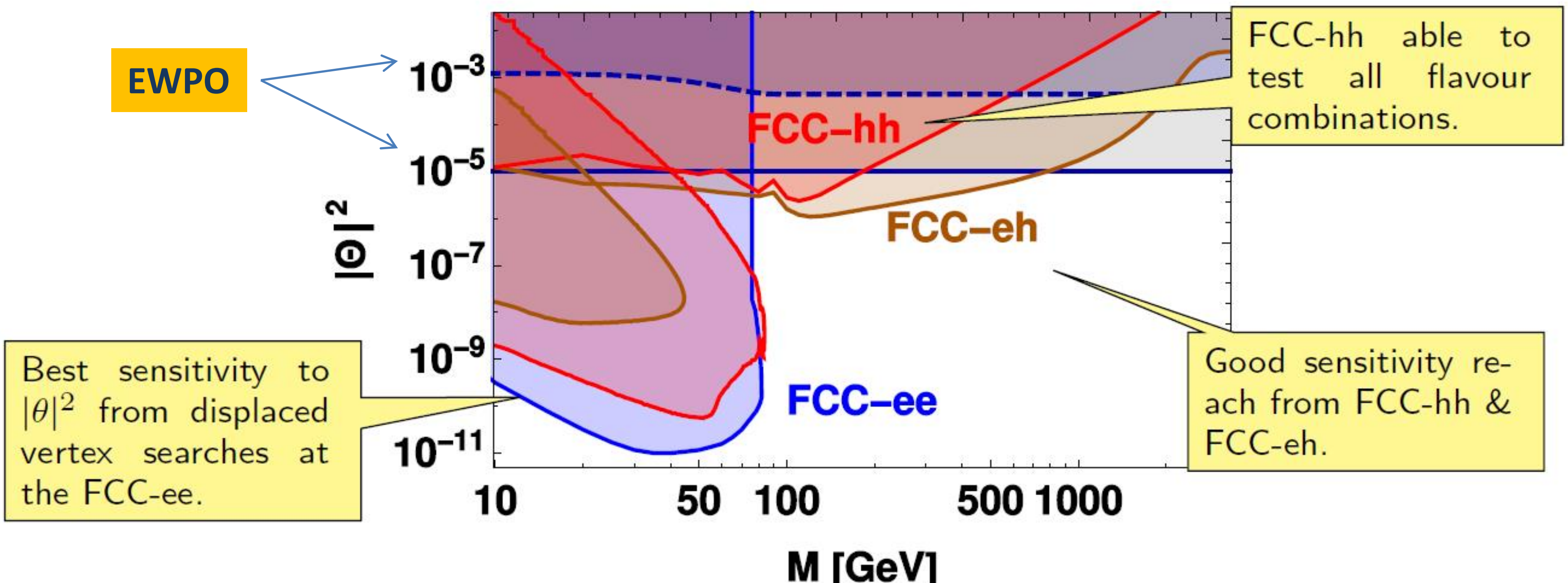
Backgrounds : four fermion: e+e- → W^{*+} W^{*-} e+e- → Z*(νν) + (Z/γ)*

Long life time → deta ched vertex for ~<M_Z

Summary

Another example of Synergy
while ee covers a large part of space very cleanly ,
its either 'white' in lepton flavour or the result of EWPOs etc
Observation at FCC –hh or eh would test flavour mixing matrix!

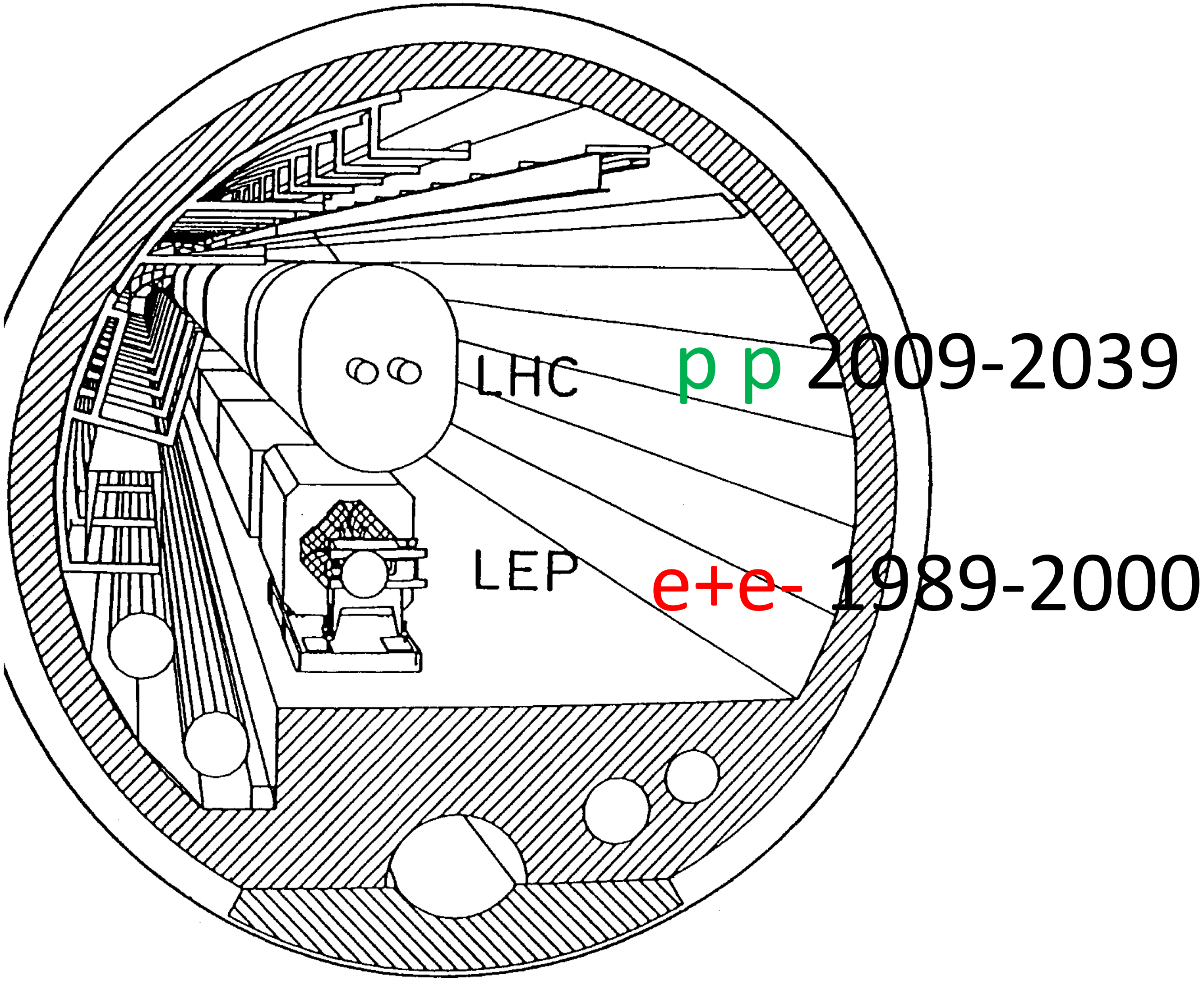
- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search



detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

A successful model!

ECFA 84/85
CERN 84-10
5 September 1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

A successful model!

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

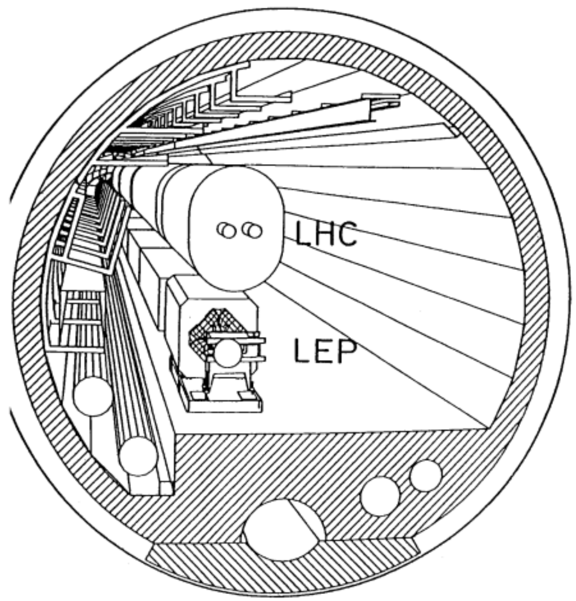
ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

~60 years!

ECFA 84/85
CERN 84-10
5 September 1984

e+e- 1989-2000



p p 2009-2039

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

- FCC-ee may serve as spring board for the FCC-hh 100 TeV pp collider, bringing a large tunnel, infastructure, cryogenics, time, addt‘l physics motivations + performance goals for FCC-hh
  Zimmermann