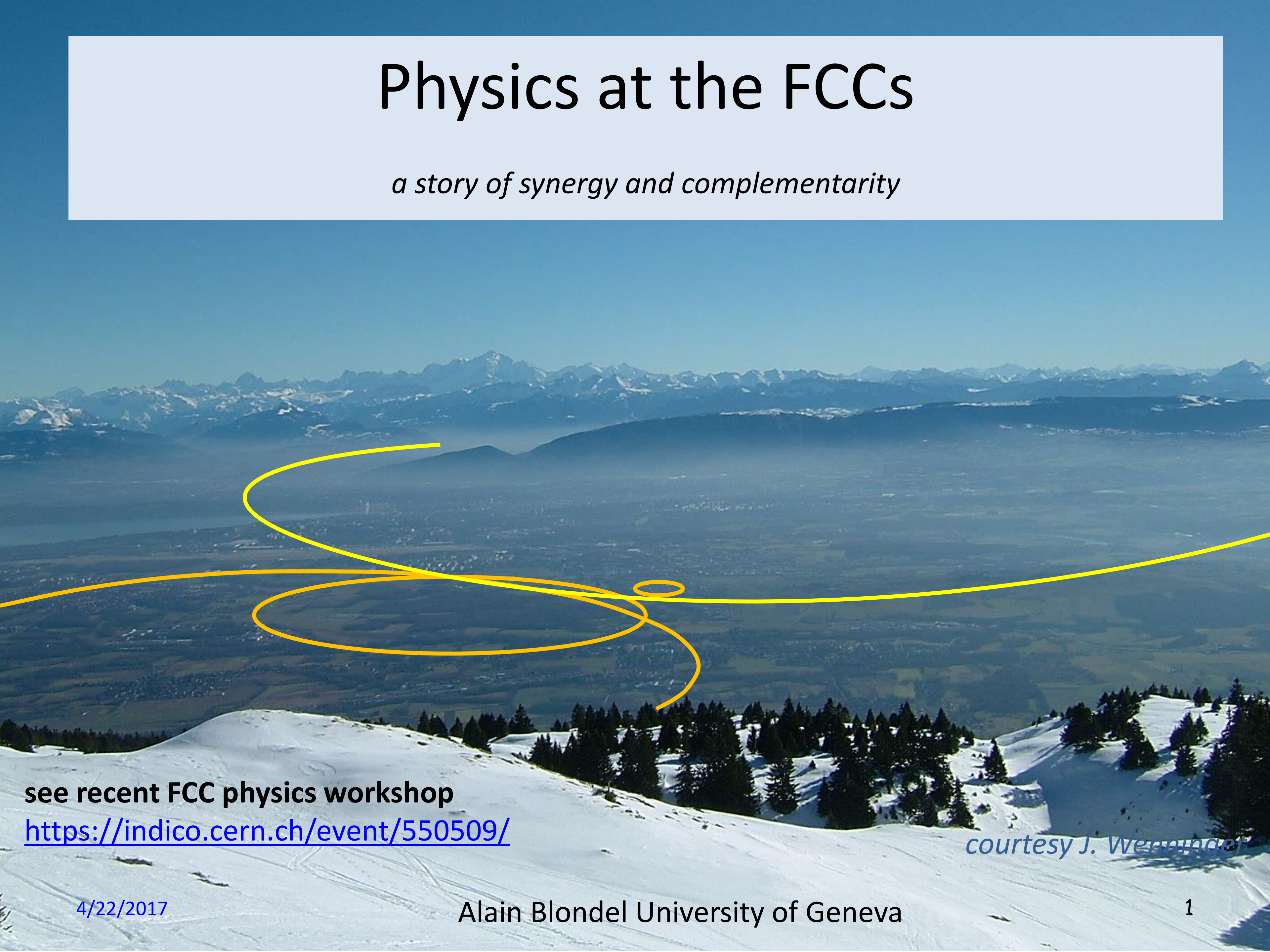
Physics at the FCCs

a story of synergy and complementarity



see recent FCC physics workshop
https://indico.cern.ch/event/550509/

courtesy J. Wenninger

Alain Blondel University of Geneva

Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

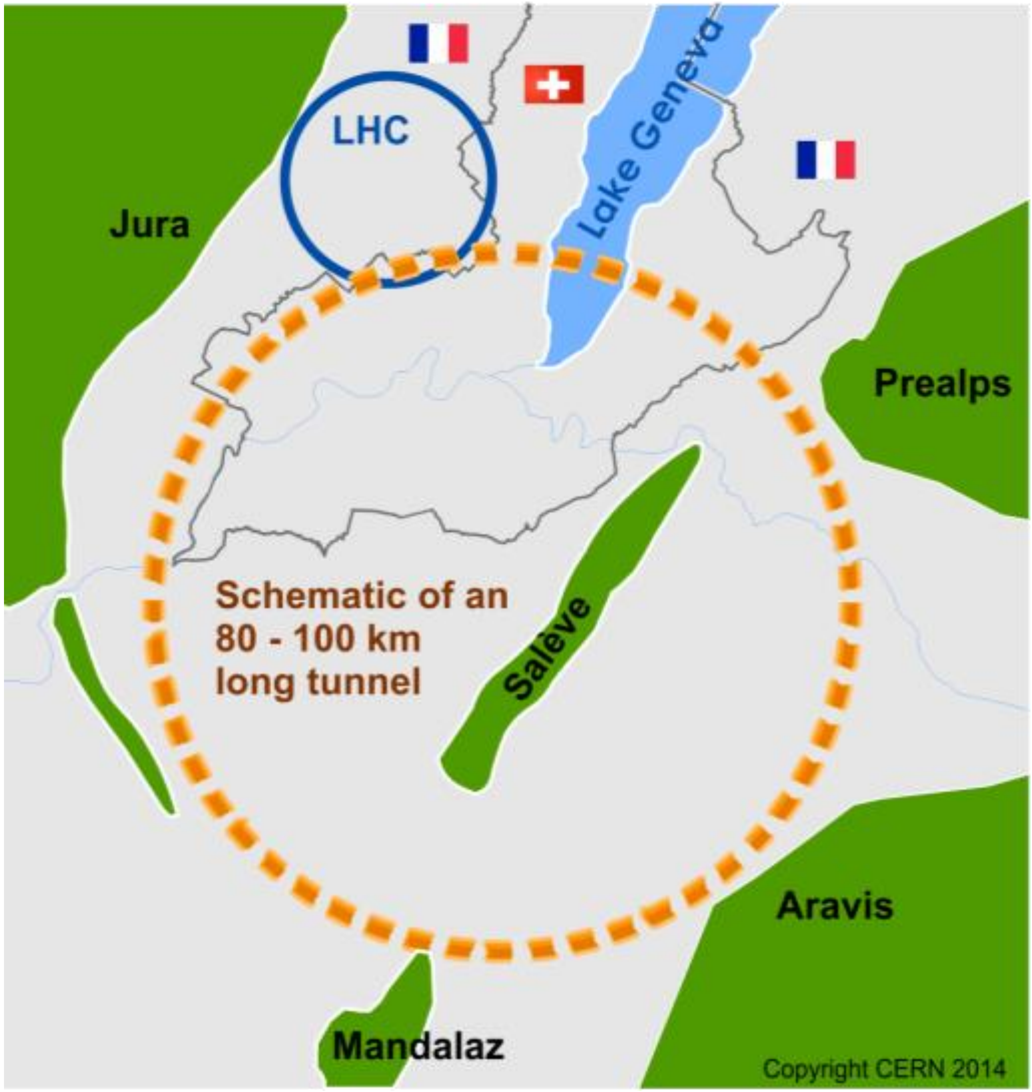
Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**

~16 T ⇒ 100 TeV *pp* in 100 km

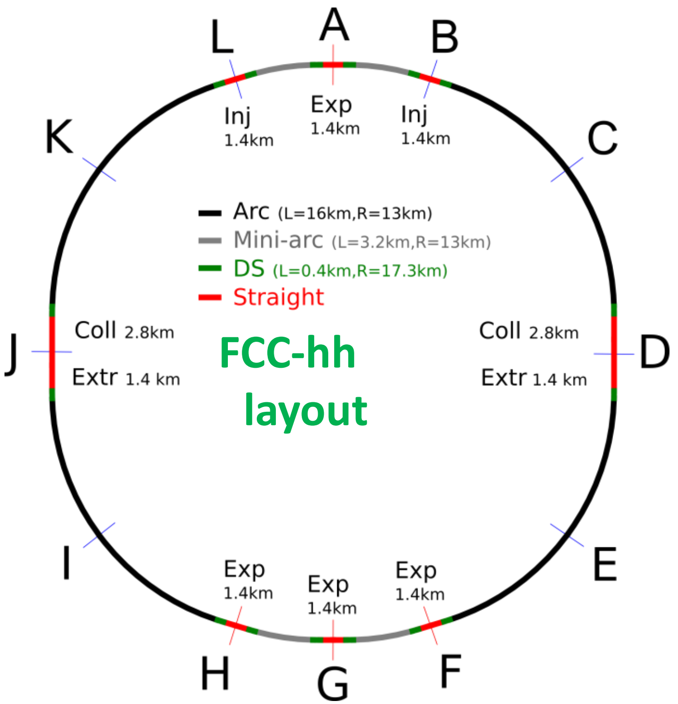
→ ultimate goal defining infrastructure requirements

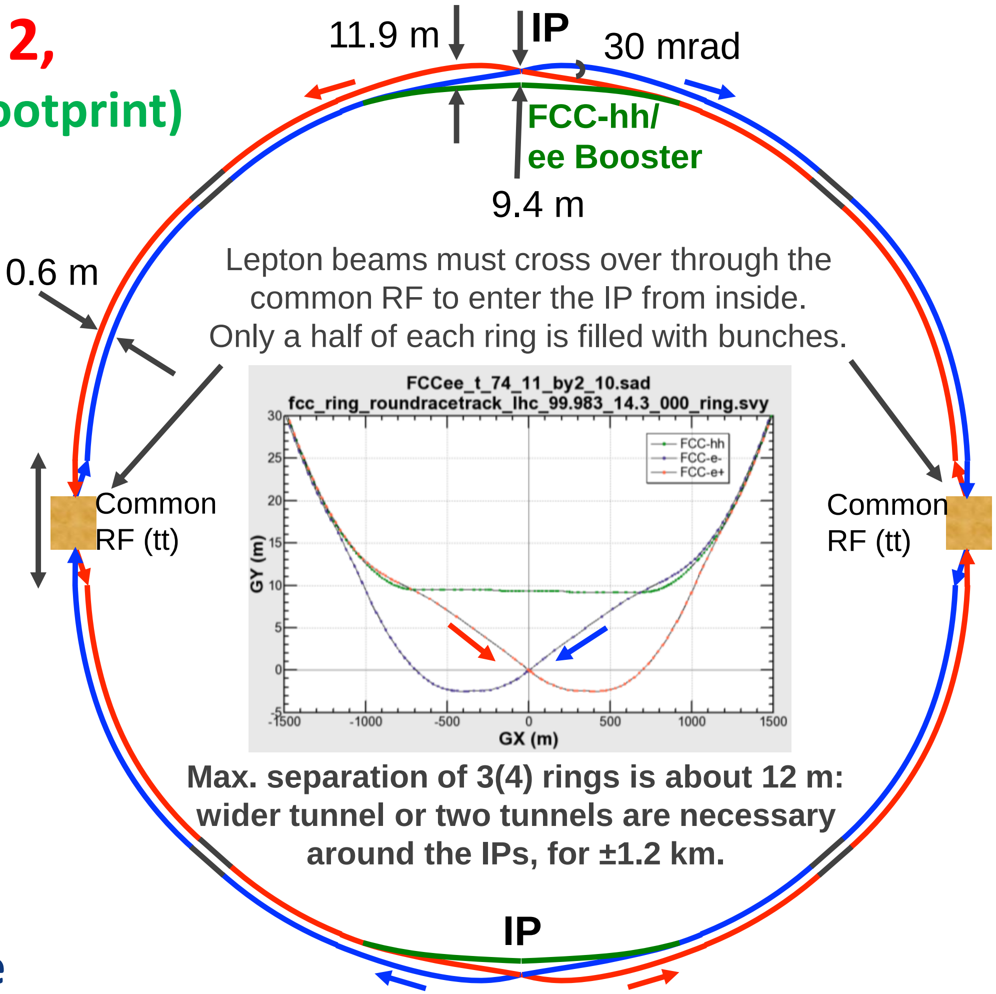
- ***e^+e^-* collider (*FCC-ee*)**
  as potential first step
  ECM=90-400 GeV
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



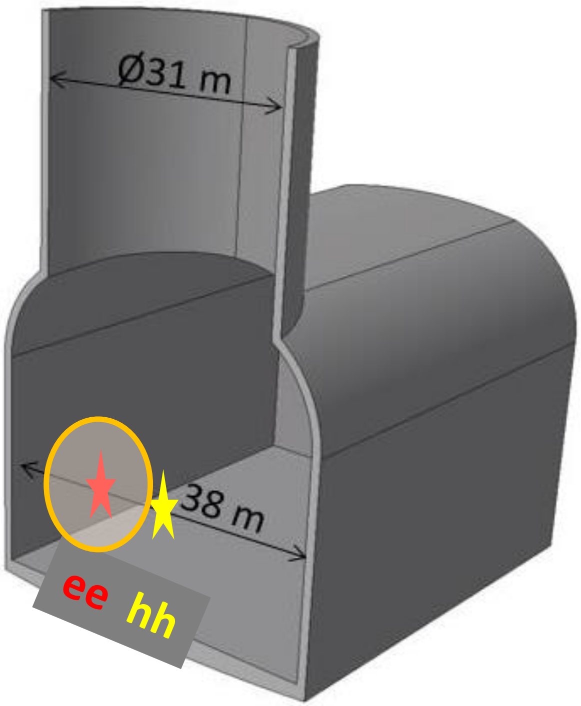
common layouts for hh & ee

FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC-hh footprint)



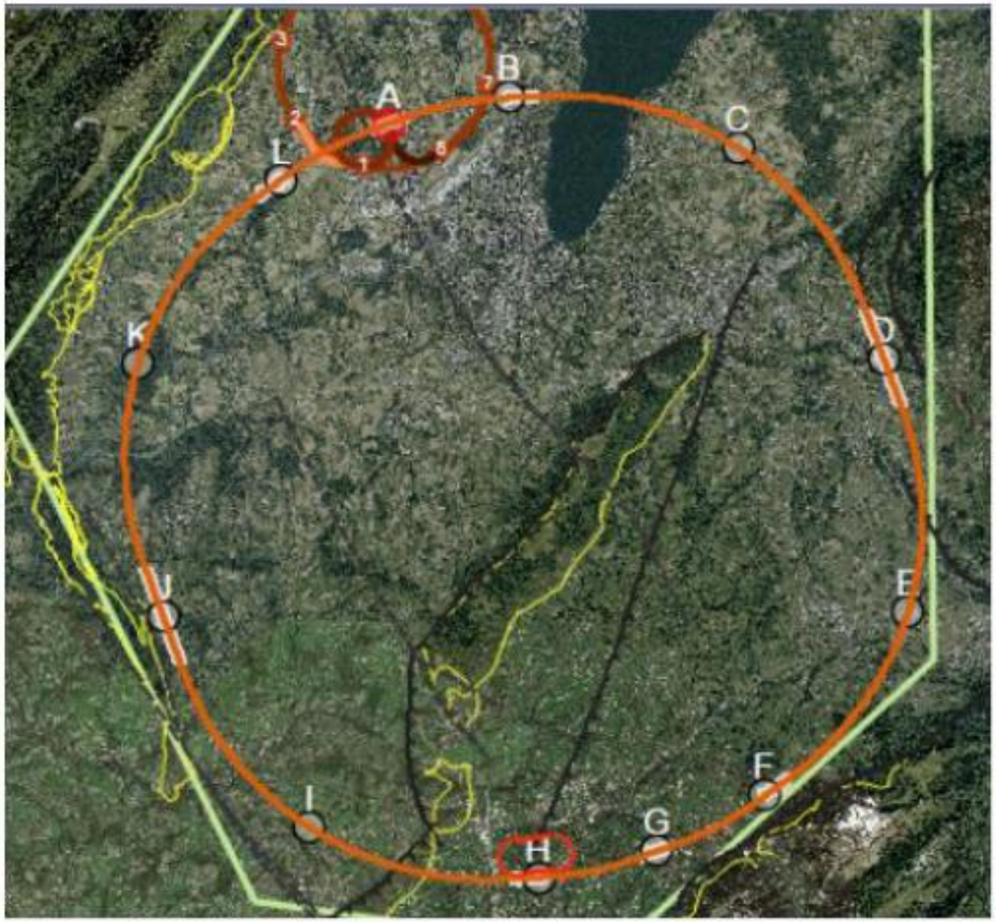


- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**



Sharing the FCC experimental caverns
(Prelim. layout as of FCC-Rome meeting)

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



FCC-eh

FCC-eh requires an additional ERL
but profits from the -- then existing -- FCC-hh,
and, perhaps,
from considerable RF of the
-- then dismantled -- FCC-ee

12 CDR Volumes (9 + 3 Annex)

Preliminary layout of CDR (work in progress)

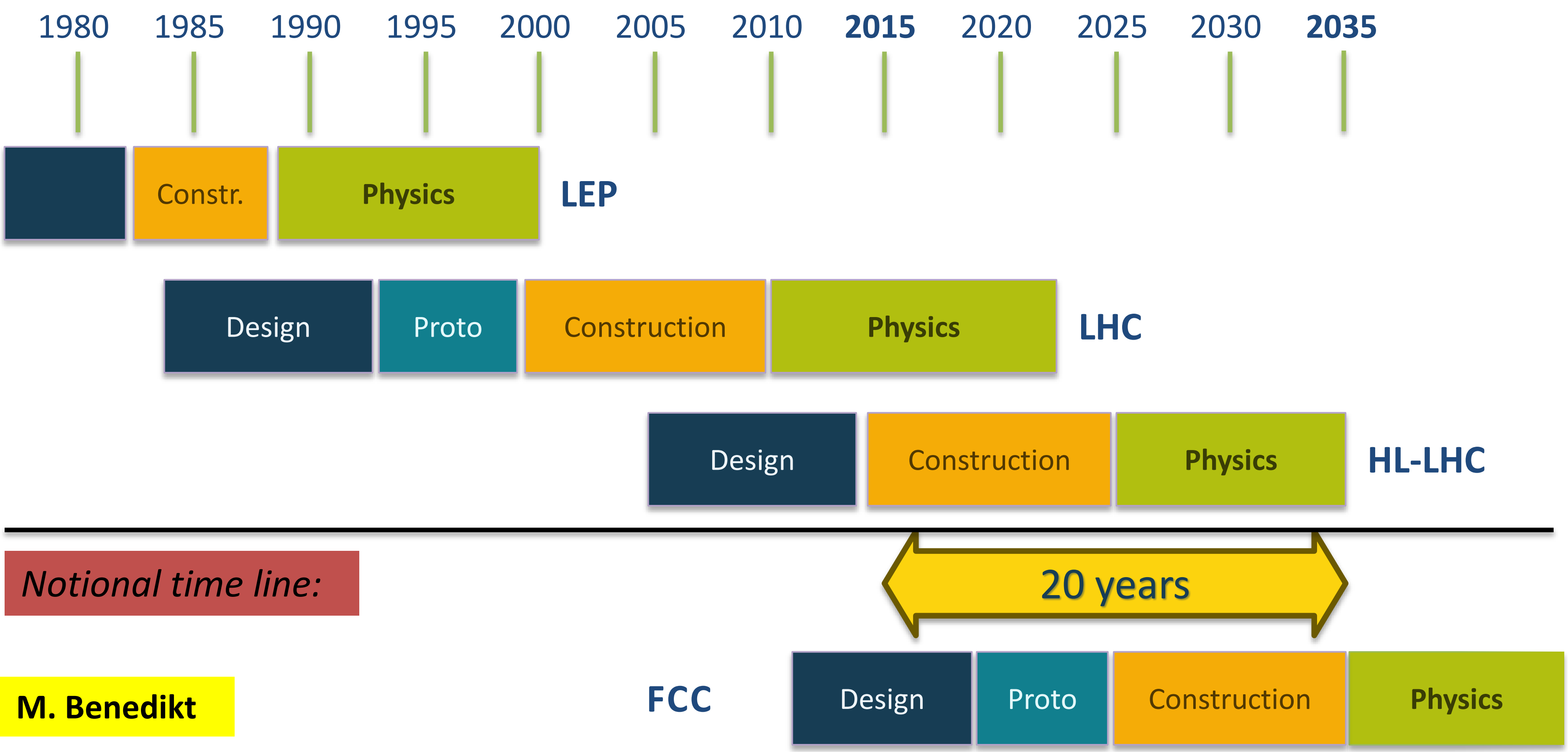
all to be printer-ready by end 2018!

FCC overview

Overview of the project.
The big physics questions and how FCC will address them.
ee,hh, AA, eh,HE physics capabilities and complementarities

M. Benedikt

CERN Circular Colliders and FCC



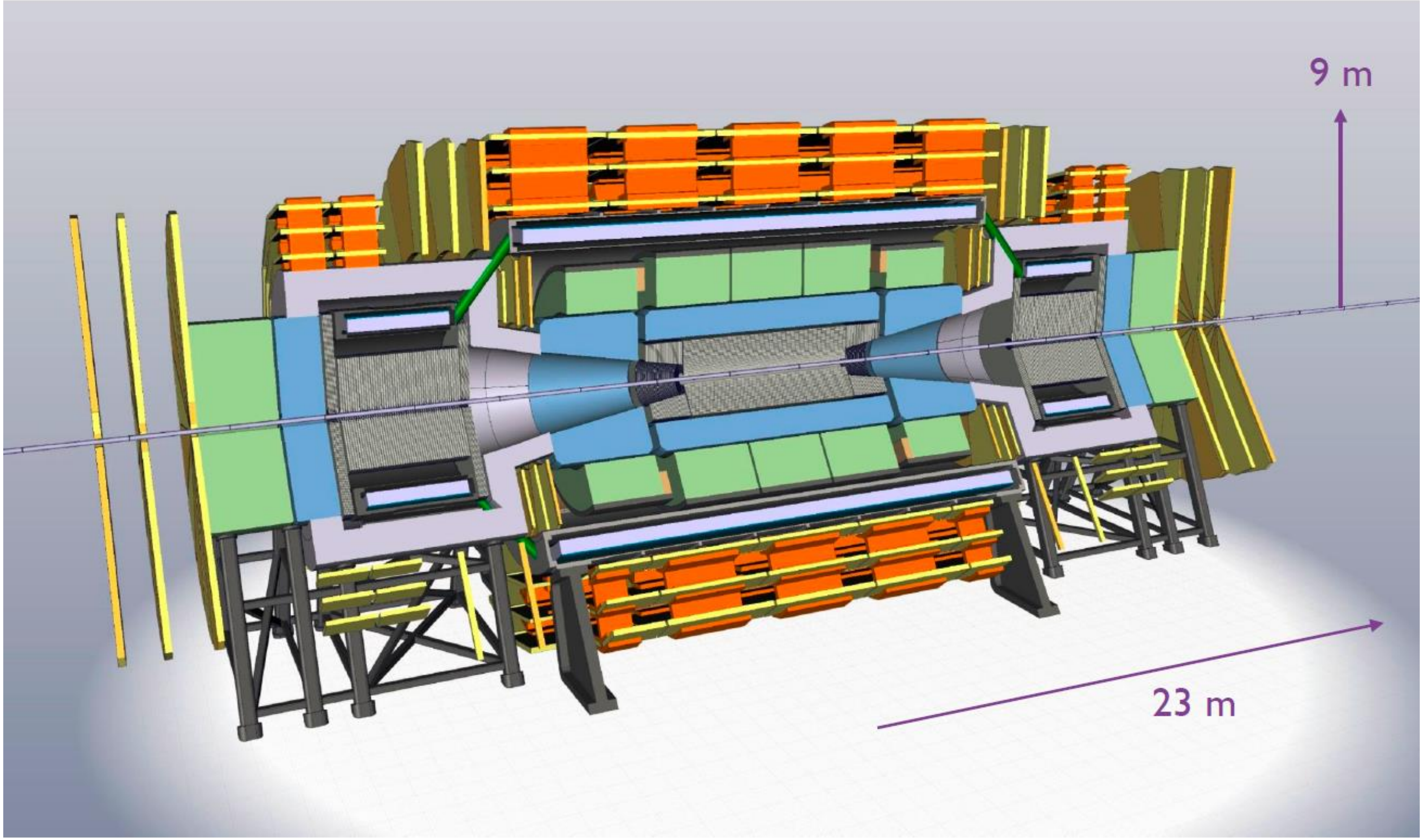
(FCC-ee)

Now is the right time to plan for the period 2035 – 2040
Goal of phase 1: CDR by end 2018 for next update of European Strategy

Hadron collider parameters

parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		3.6	(0.35) 0.18

FCC-hh reference detector



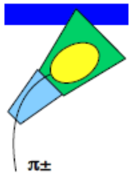
Object reconstruction and performances

✦ Particle Flow Reconstruction

- Using charged hadrons, muons, electrons and calorimeter towers to build particle-flow objects
- Tracks from pile-up are rejected if $|Z_0 - Z_{\rm PV}| > \sqrt{\sigma^2(Z_0) + \sigma^2(Z_{\rm PV})}$

✦ Jets

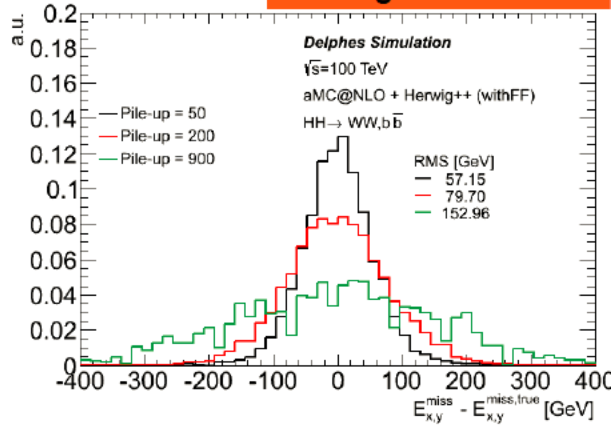
- Anti-Kt (Fast Jet) algorithm
- particle-flow objects as inputs
- R = 0.4
- Jet Area pile-up correction:
- private calibration to particle level $p_T^{\rm corrected} = p_T^{\rm raw} - \rho \cdot {\rm JetArea}$
- $p_T^{jet} > 20$ GeV



✦ Missing Transverse Energy

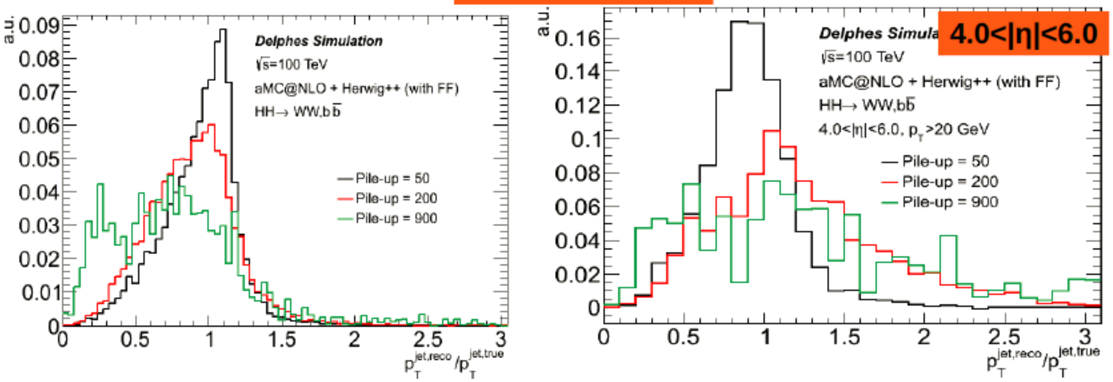
- Anti-Kt (Fast Jet) algorithm
- negative vector sum of Jets, after pile-up correction and calibration

Missing ET resolution

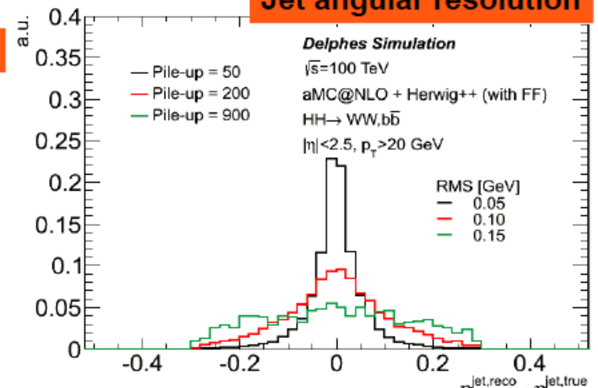


Jet pT response

4.0<|η|<6.0



Jet angular resolution



lepton collider parameters

parameter	FCC-ee (400 MHz)					LEP2
Physics working point	**Z**		**WW**	**ZH**	**tt_{bar}**	
energy/beam [GeV]	**45.6**		**80**	**120**	**175**	105
bunches/beam	30180	**91500**	**5260**	**780**	**81**	4
bunch spacing [ns]	7.5	**2.5**	**50**	**400**	**4000**	22000
bunch population [10^{11}]	1.0	**0.33**	**0.6**	**0.8**	**1.7**	4.2
beam current [mA]	1450	**1450**	**152**	**30**	**6.6**	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	**90**	**19**	**5.1**	**1.3**	0.0012
energy loss/turn [GeV]	0.03	**0.03**	**0.33**	**1.67**	**7.55**	3.34
synchrotron power [MW]	**100**					22
RF voltage [GV]	0.4	**0.2**	**0.8**	**3.0**	**10**	3.5

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings, LEP: single beam pipe

Detectors similar to ILC/CLIC

smaller beam pipe and B field

FCC–ee physics plan

- **physics programs / energies:**

  Z (45.5 GeV) Z pole, *'TeraZ' and high precision M_Z & Γ_Z*

  W (80 GeV) W pair production *threshold, high precision M_W*

  H (120 GeV) ZH production *(maximum rate of H's)*

  t (175 GeV): $t\bar{t}$ threshold*, H studies*

- **beam energy range from 40 GeV to ≈ 190 GeV**
- **highest possible luminosities** *at all working points*
- *possibly* ***H*** **(126 GeV) direct *s*-channel** production with

  monochromatization

  (**c.m. energy spread <6 MeV**, presentation at IPAC'16)
- **beam polarization up to ≥80 GeV - 100keV E_{beam} calibration**

PHYSICS COMPLEMENTARITY

Some examples

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

Search for Heavy Physics
-- ee gives precision measurements (m_Z m_W to < 0.5 MeV, m_{top} 10 MeV, etc…)
sensitive to heavy physics up to … 100 TeV
-- FCC-hh gives access to direct observation

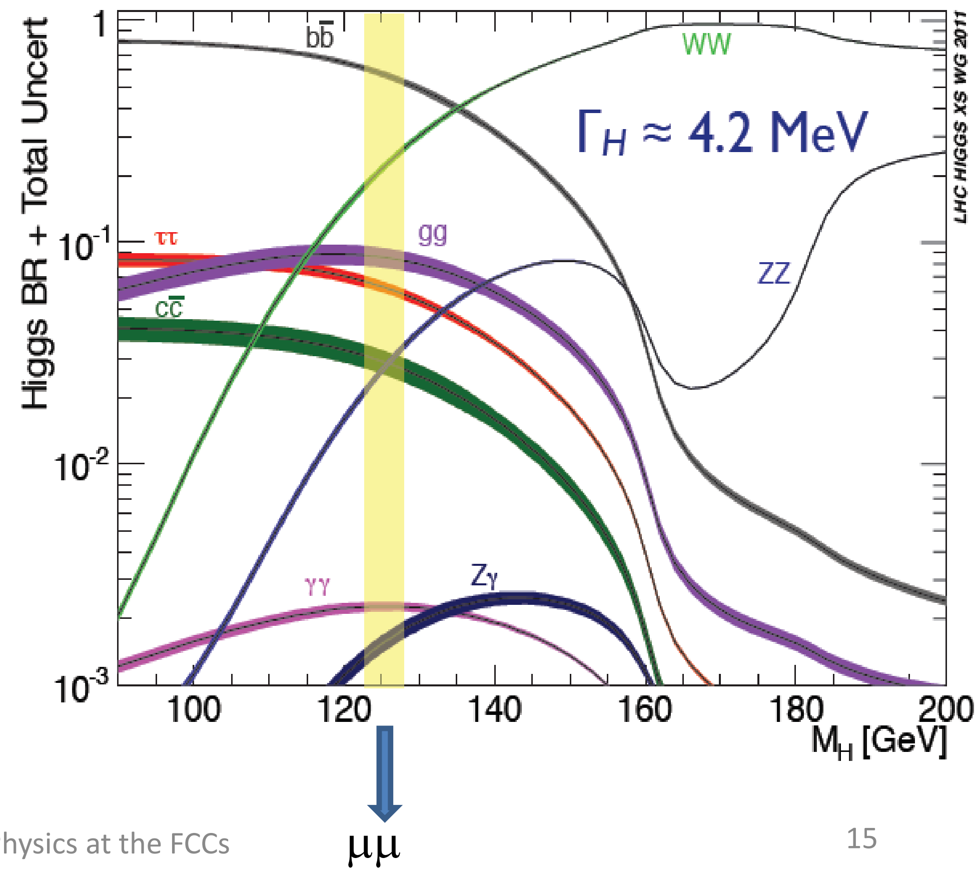
QCD -- ee gives $\alpha_s \pm 0.0002$ (R_{had})
also H→gg events (gluon fragmentation!)
-- ep provides tructure functions and $\alpha_s \pm 0.0003$
-- all this improves the signal and background predictions
for new physics signals at FCC-hh

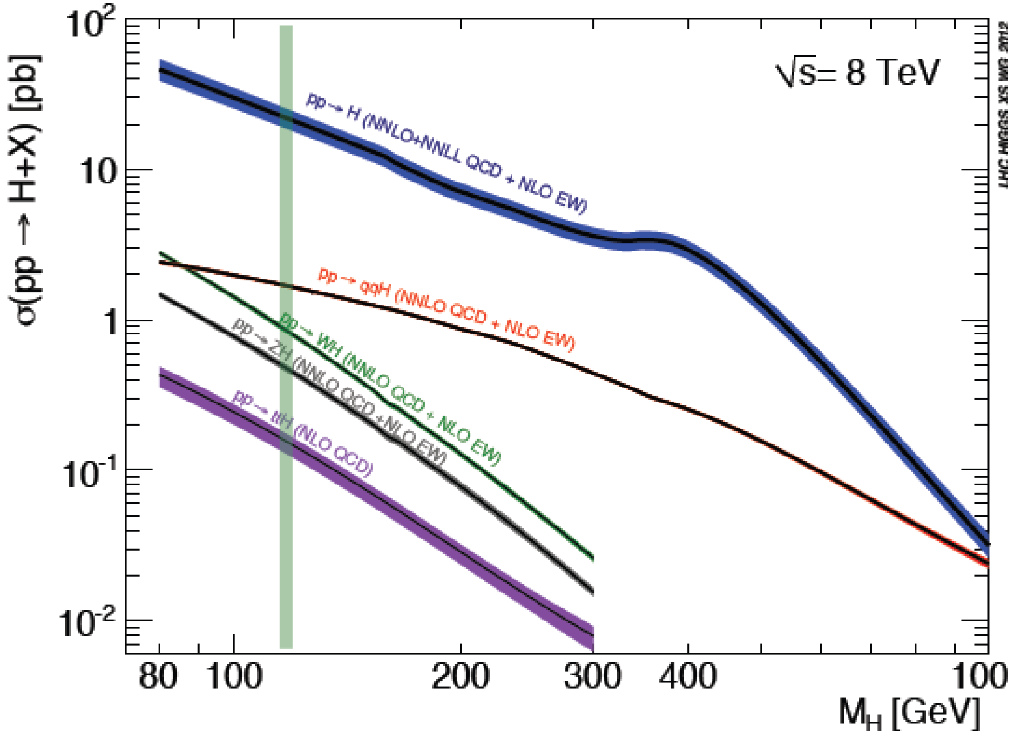
Heavy Neutrinos -- ee: powerful and clean, but flavour-blind
-- hh and eh more difficult, but potentially flavour sensitive
NB this is very much work in progress!!

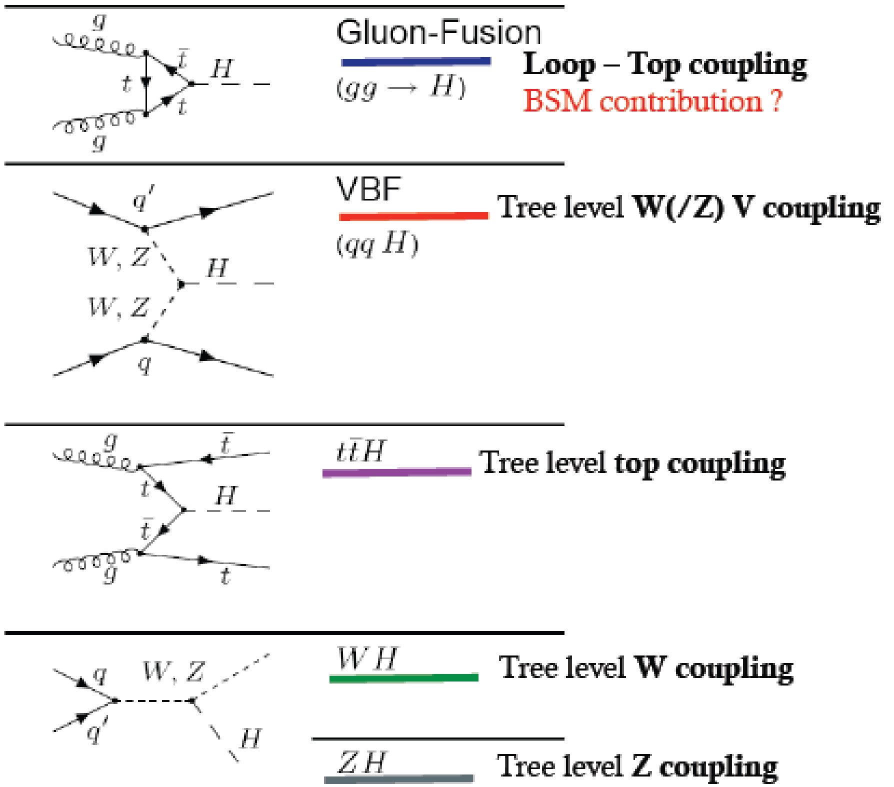
Higgs Physics

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





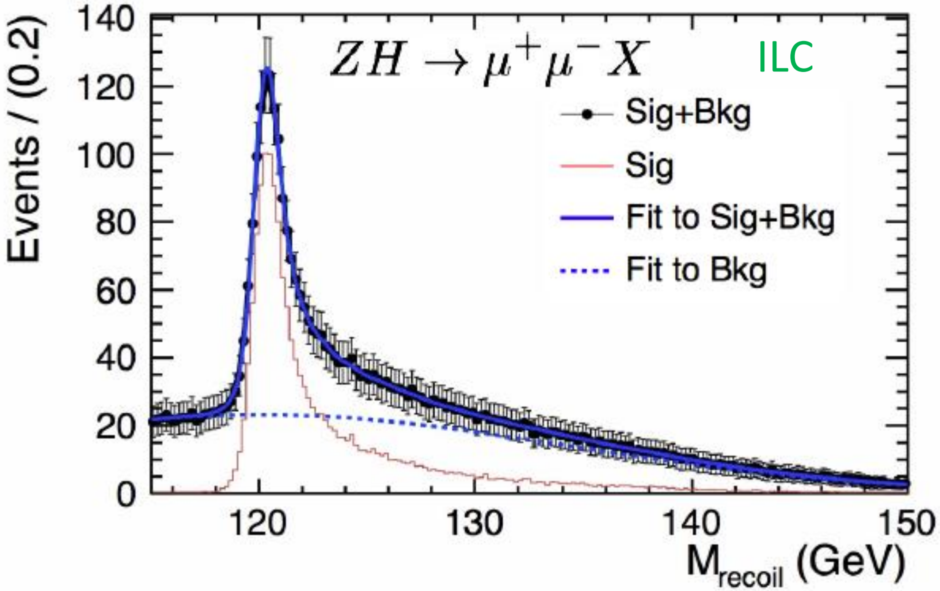


The LHC is a Higgs Factory !

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.

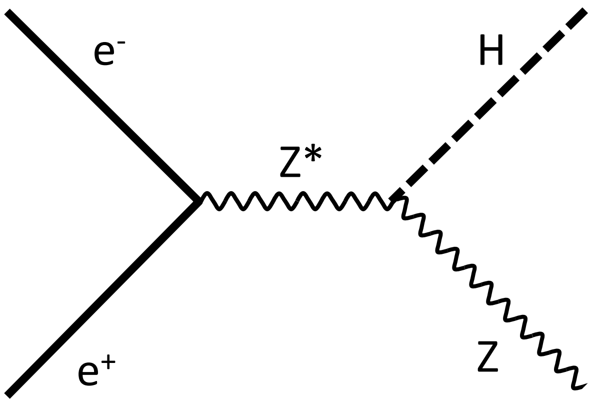
$$\sigma_{i\to f}^{\;observed} \propto \sigma_{prod} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

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

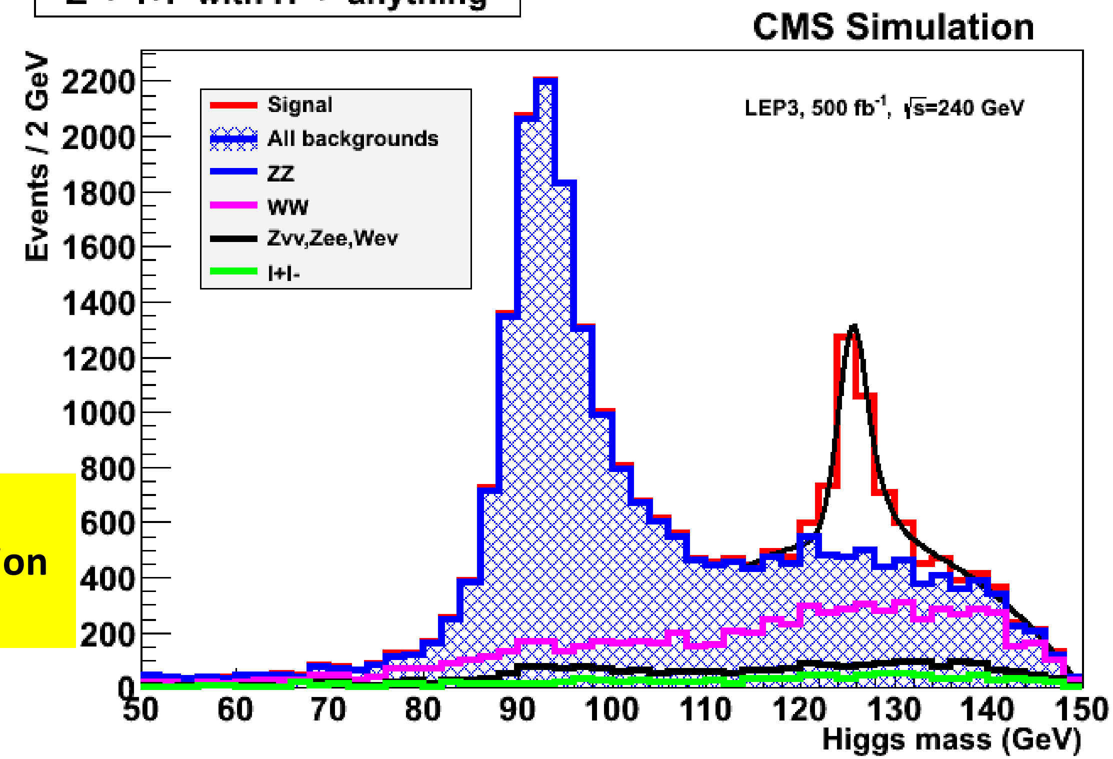


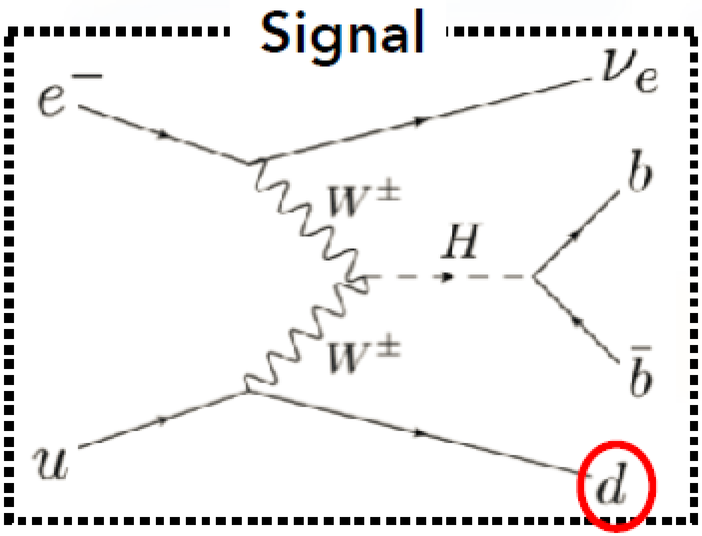
FCC-ee
H signal in missing mass

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

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

because $\Gamma_{H\to bb}$ ~ 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

similarly 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

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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

$N_{100} = \sigma_{100\,\text{TeV}} \times 20\ \text{ab}^{-1}$

$N_8 = \sigma_{8\,\text{TeV}} \times 20\ \text{fb}^{-1}$

$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

- 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

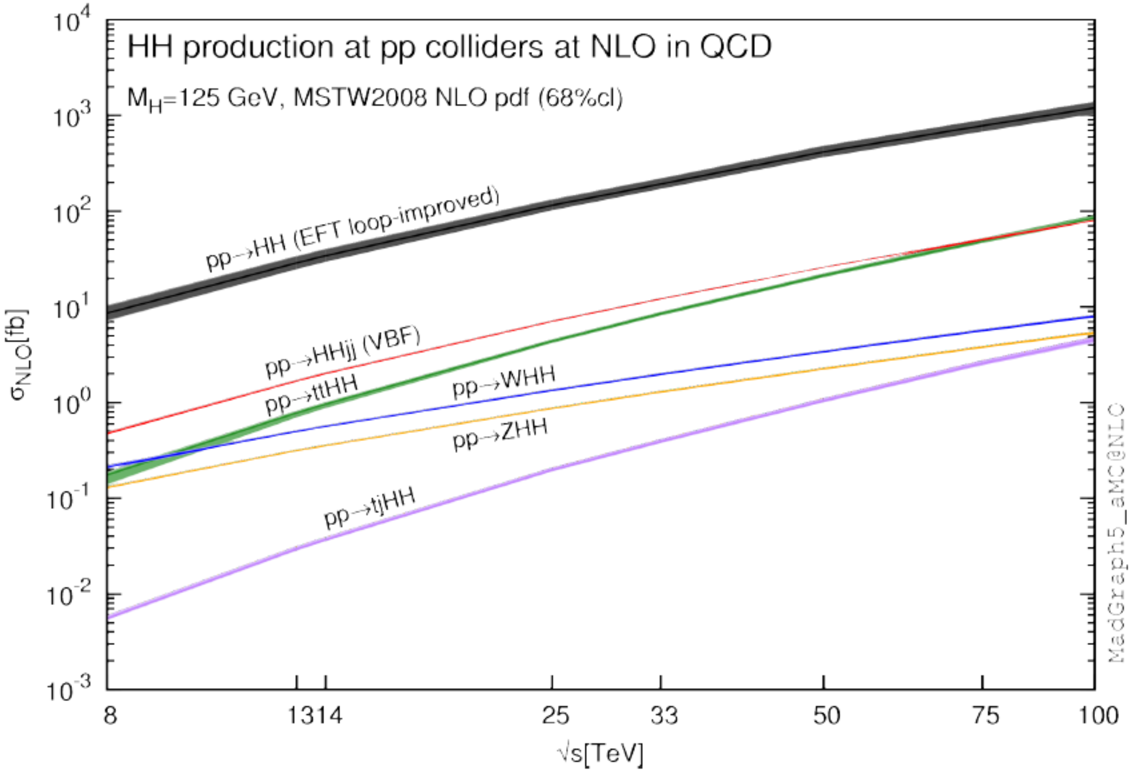
$>10^9$ H produced

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 rat

t:

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

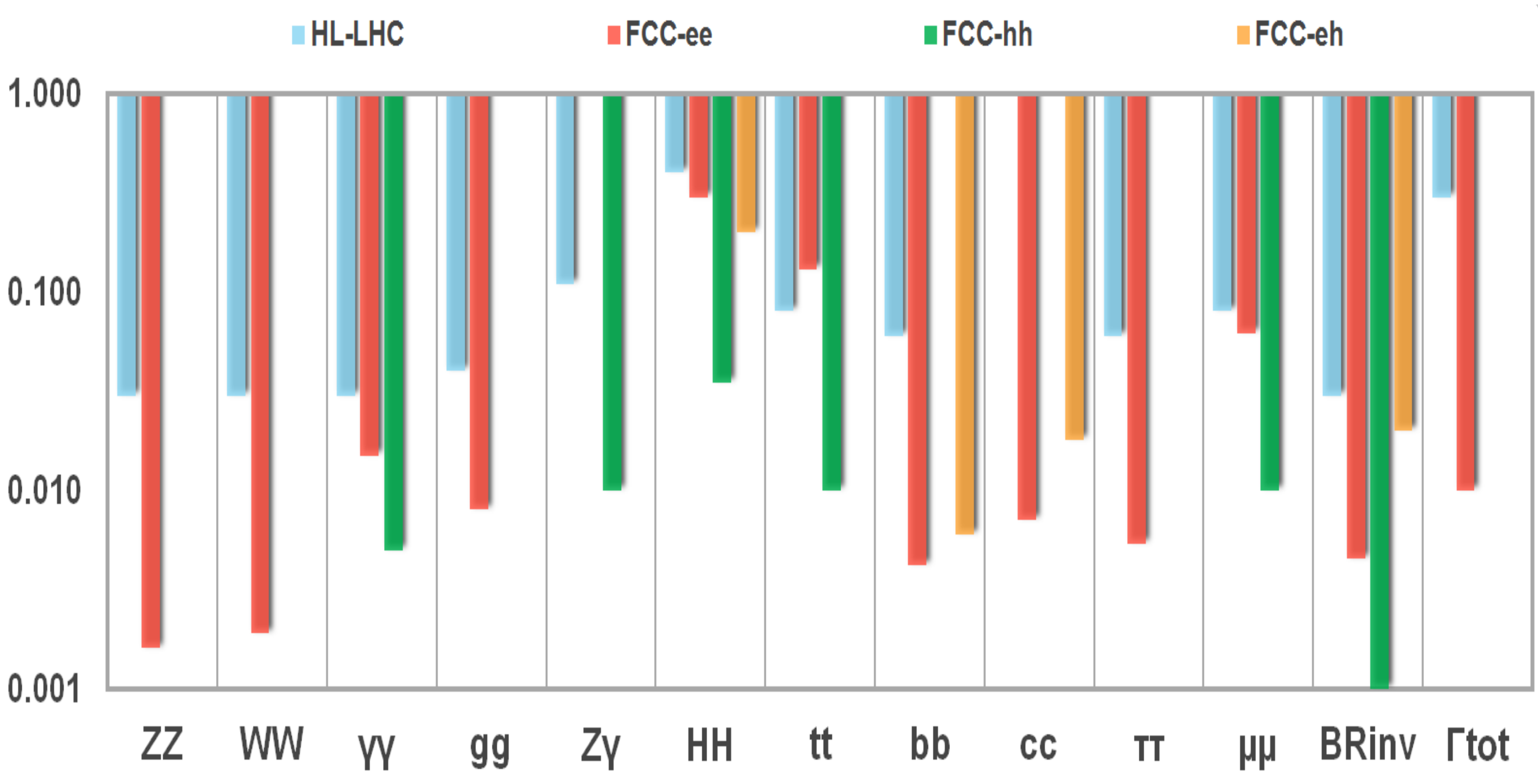
be

predicted with great precision

HIGGS PHYSICS

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%

hh, eh precisions assume ee measurements!


HL-LHC
FCC-ee
FCC-hh
FCC-eh
1.000
0.100
0.010
0.001
ZZ
WW
γγ
gg
Zγ
HH
tt
bb
cc
ττ
μμ
BRinv
Γtot

A Sample of Essential Quantities:

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	**Input**	91187.5 $\pm$2.1	Z Line shape scan	**0.005 MeV** **<$\pm$0.1 MeV**	E_cal	QED corrections
Γ_Z MeV/c2	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495.2 $\pm$2.3	Z Line shape scan	**0.008 MeV** **<$\pm$0.1 MeV**	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 $\pm$ 0.025	Z Peak	**0.0001** **$\pm$ 0.0002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 $\pm$0.008	Z Peak Z+γ(161 GeV)	**0.00008** **$\pm$0.004** **0.0004-0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 $\pm$0.00066	Z Peak	**0.000003** **$\pm$0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)	0.1514 $\pm$0.0022	Z peak, polarized	**$\pm$0.000015**	4 bunch scheme	Design experiment
M_W MeV/c2	$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$ (T, S, U)	80385 $\pm$ 15	Threshold (161 GeV)	**0.3 MeV** **<0.5 MeV**	E_cal & Statistics	Backgrounds, QED/EW
m_{top} MeV/c2	**Input**	173340 $\pm$ 760	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 50 MeV?

Theoretical limitations

FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

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

0.0005

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

0.00001

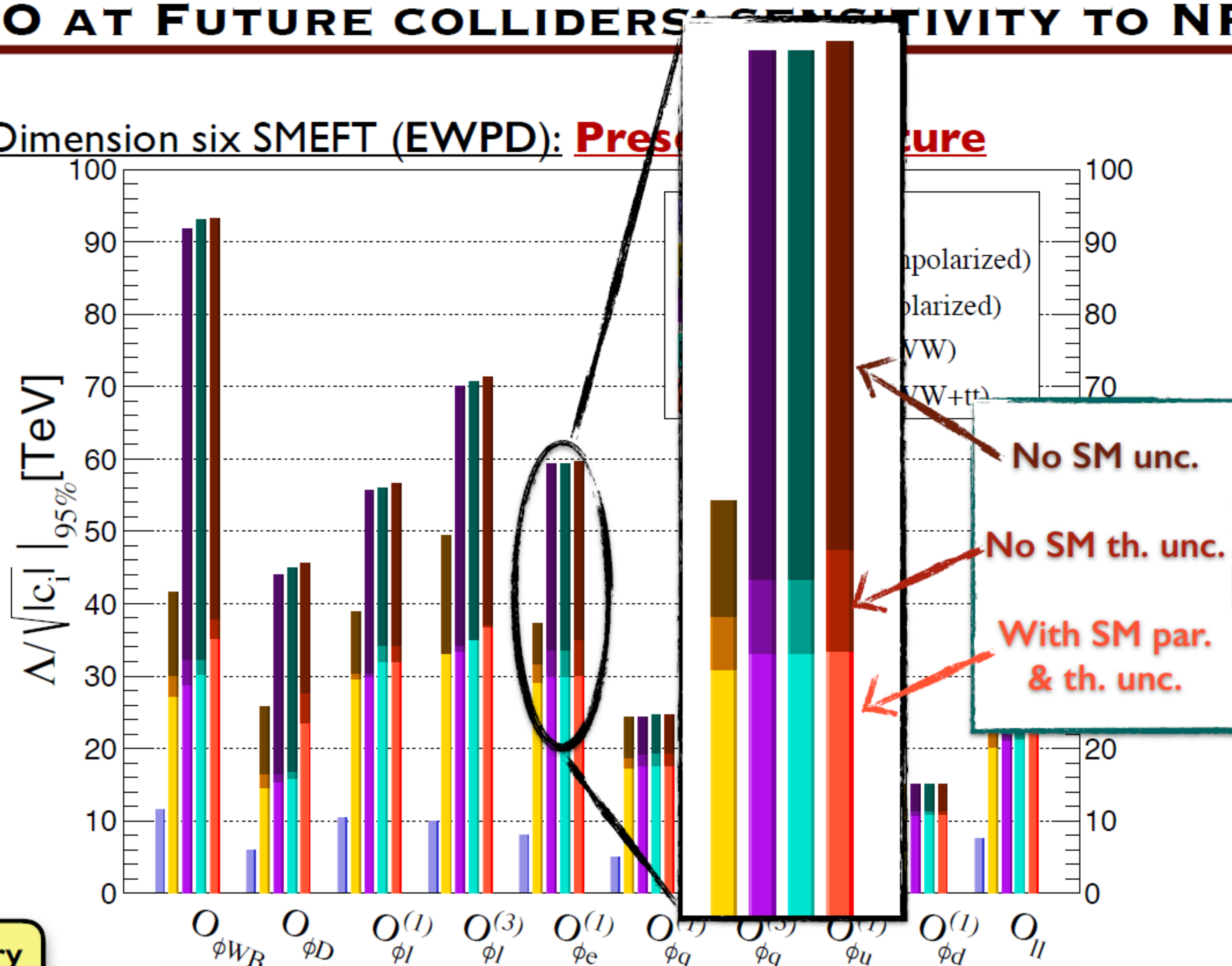
Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.
BUT can be typically 10 -30 times smaller than present level of theory errors
Will require significant theoretical effort and additional measurements!

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): **Pres** **ture**

1 operator at a time. Flavor universal.



Preliminary

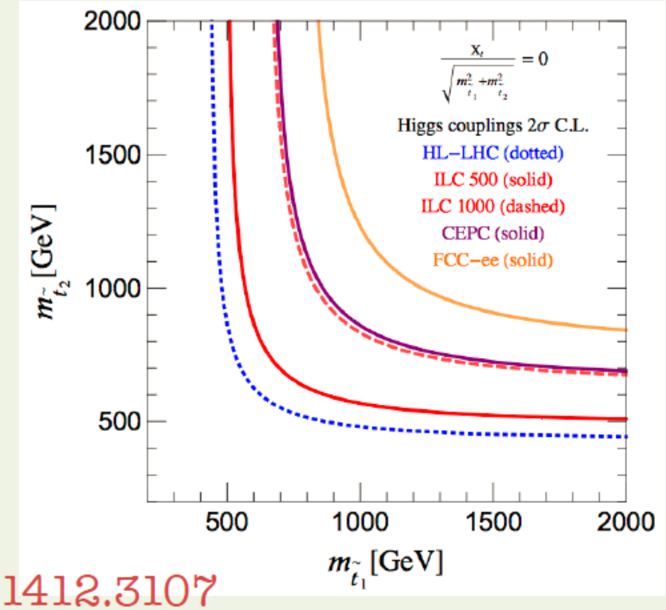
LARGE impact of SM uncertainties

Comprehensive Complementarity

In supersymmetry this is the "stop squark".

FCC-ee

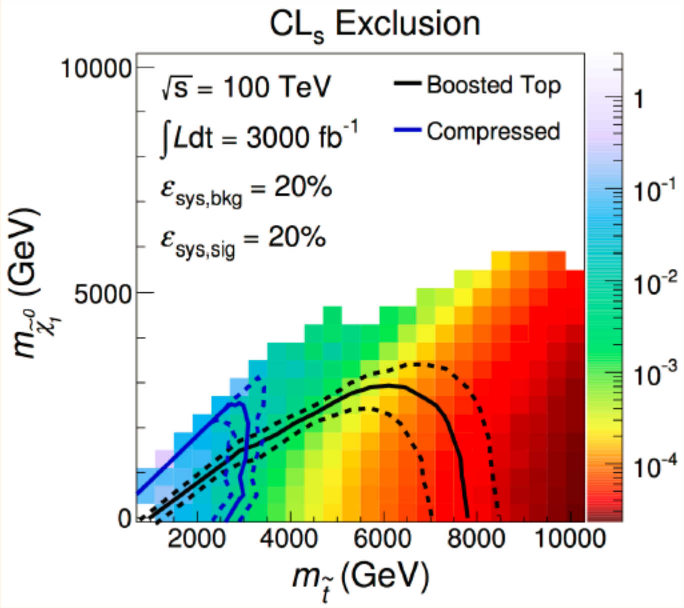
Coloured and charged, stops modify Higgs couplings:



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

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

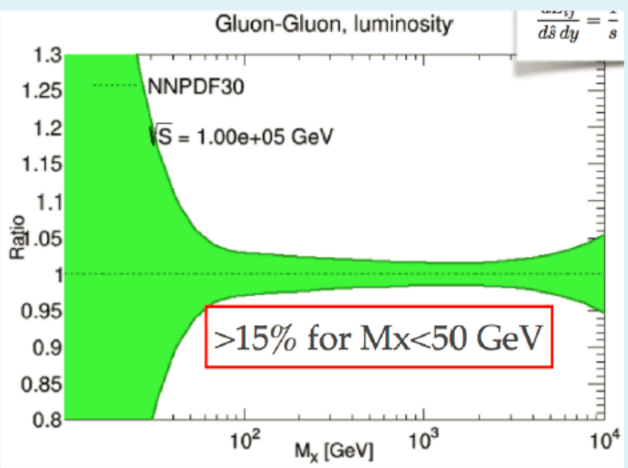
Would reduce systematic uncertainties in BSM searches at FCC-hh, both direct (e.g. extra dimensions) and indirect (e.g. Higgs couplings).

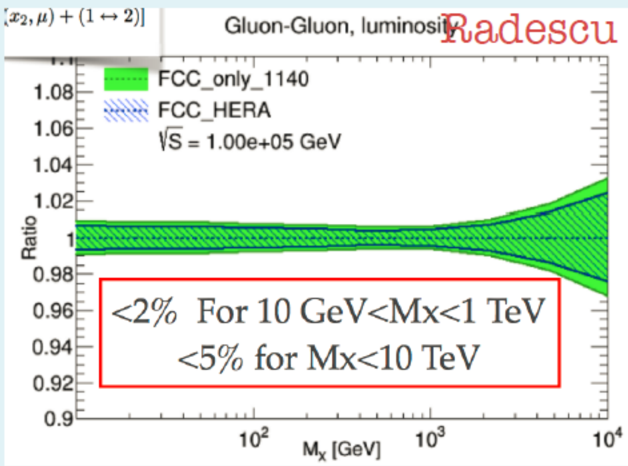
Systematic Complementarity

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





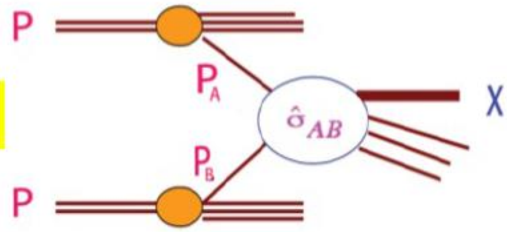
Improvement in low-x predictions for FCC-hh.

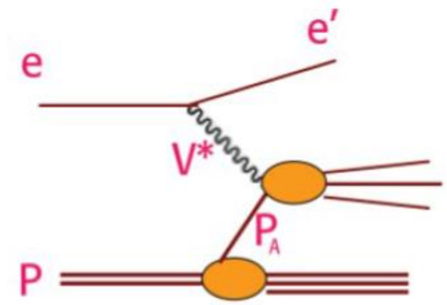
McCullough

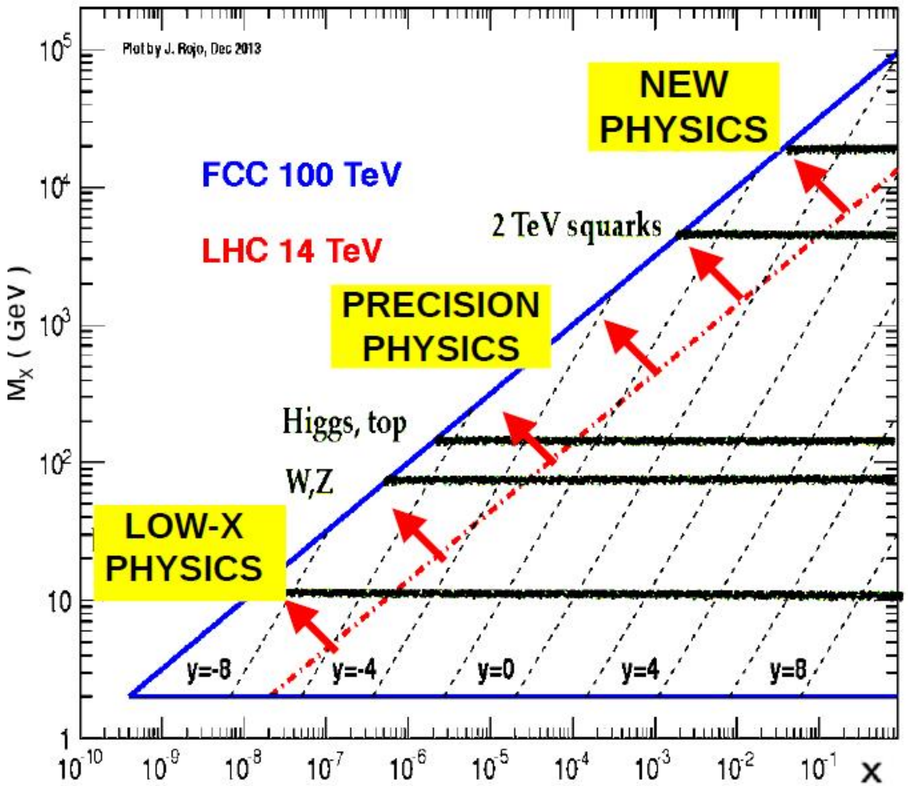
FCC-ep “comes to the rescue” of FCC-pp

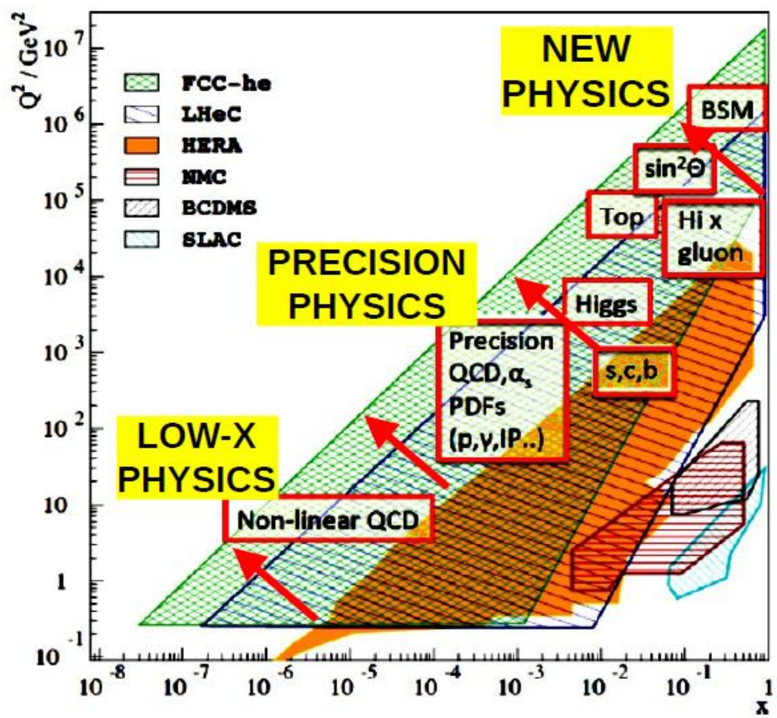
- FCC-ep: Fully complementary with FCC-pp to improve parton densities.

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





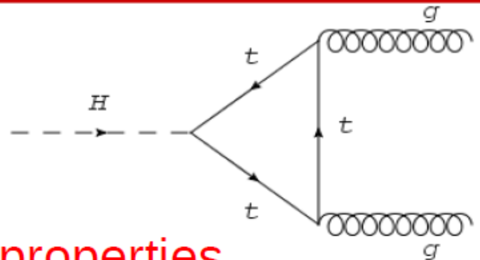




Higgs as a source of pure gluons (FCC-ee)

- FCC-ee H(gg) is a "pure gluon" factory:
  H → 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→gg vs Z→qq

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

Z→bbg vs Z→qq(g)

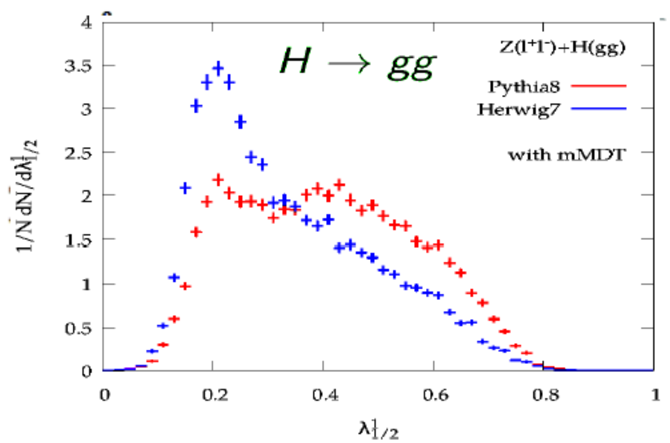
g in one hemisphere recoils against two b-jets in other hemisphere: **b tagging**

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?

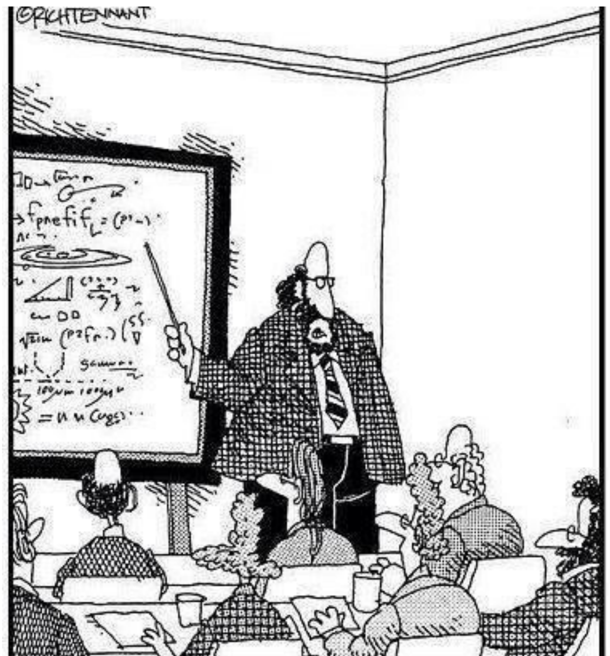
Electroweak eigenstates

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

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'



"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."

Mass eigenstates

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

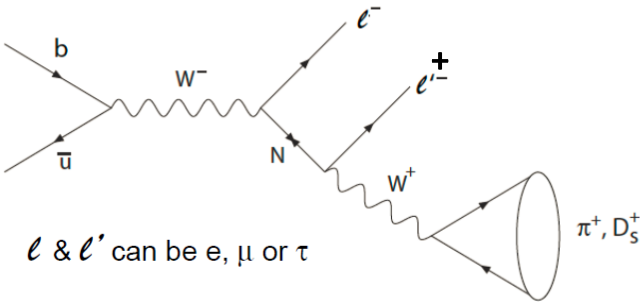
➔ violation of unitarity and lepton universality in Z, W or τ decays

-- etc... etc...

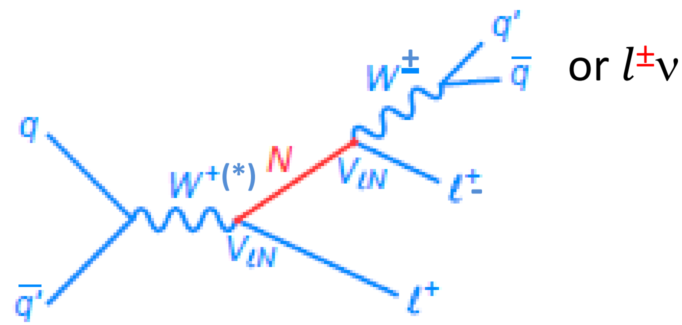
-- Couplings are very small (m_ν / m_N) *(but who knows?)* **and generally seem out of reach at high energy colliders.**

Search for heavy right-handed neutrinos in collider experiments.

B factories

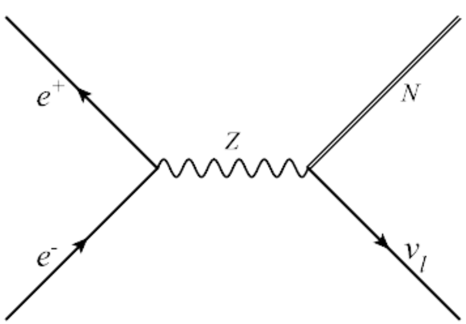


Hadron colliders

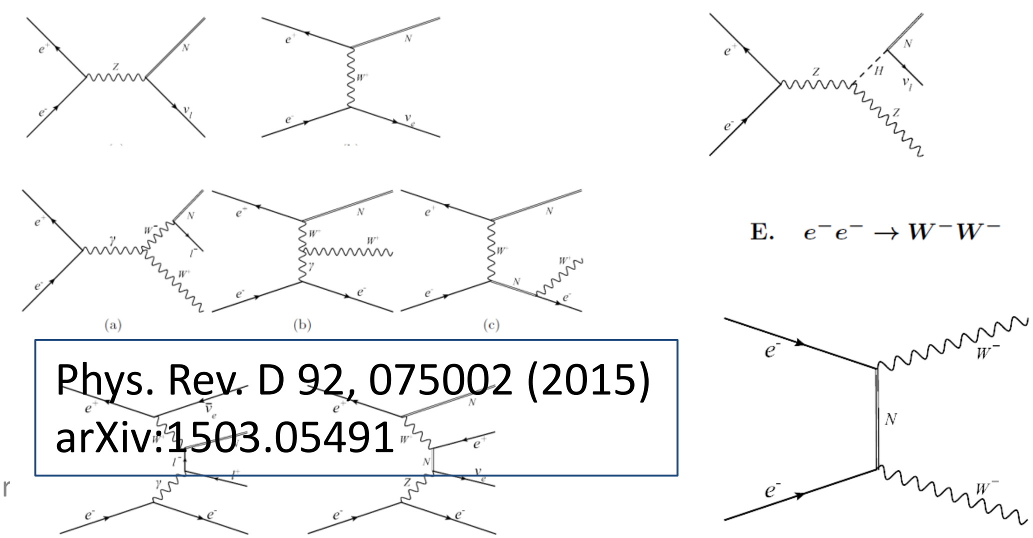


Z factory (FCC-ee, Tera-Z)

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:

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

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

Decay

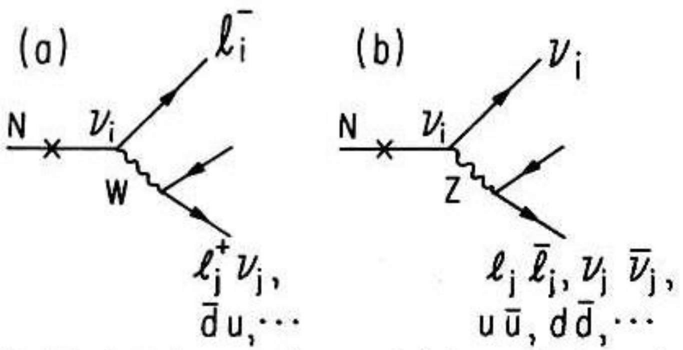


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

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- → $Z^*(\nu\nu) + (Z/\gamma)^*$

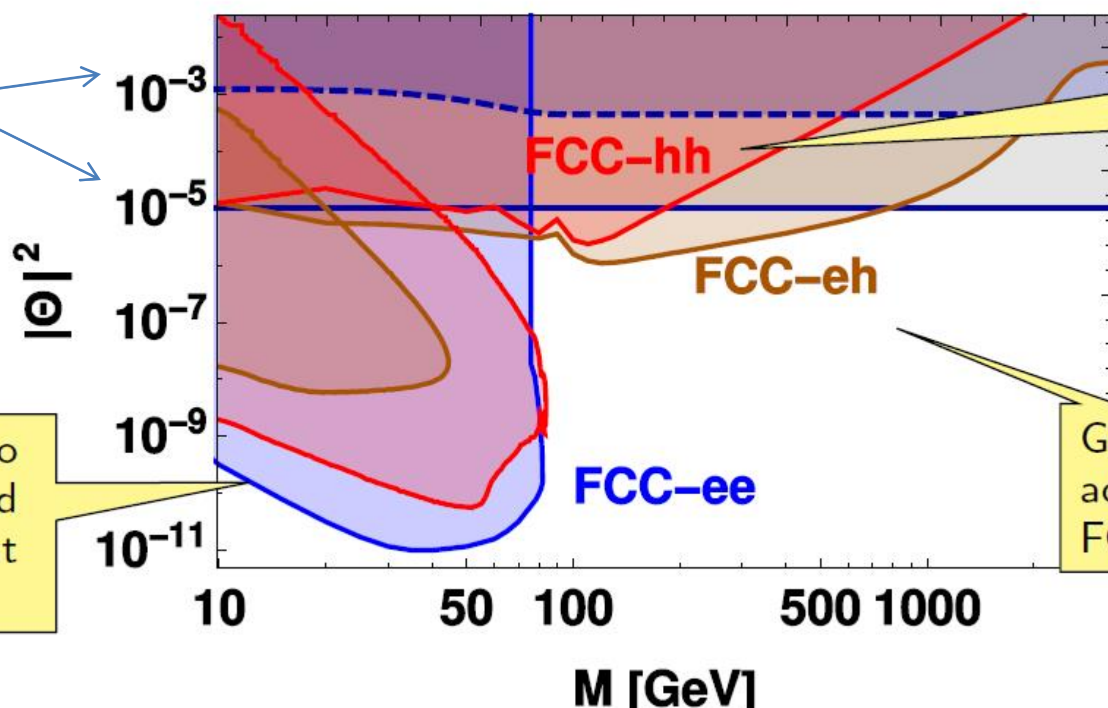
Long life time → deta ched vertex for ~<M_Z

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

EWPO



FCC-hh able to test all flavour combinations.

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

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

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

CONCLUSIONS

The FCC machines offers the broadest discovery potential, by exploration of new domains of

-- both **direct search**,

-- at high energy and/or

-- at very small couplings

and

-- **precision**

The synergy is crucial in making the project feasible