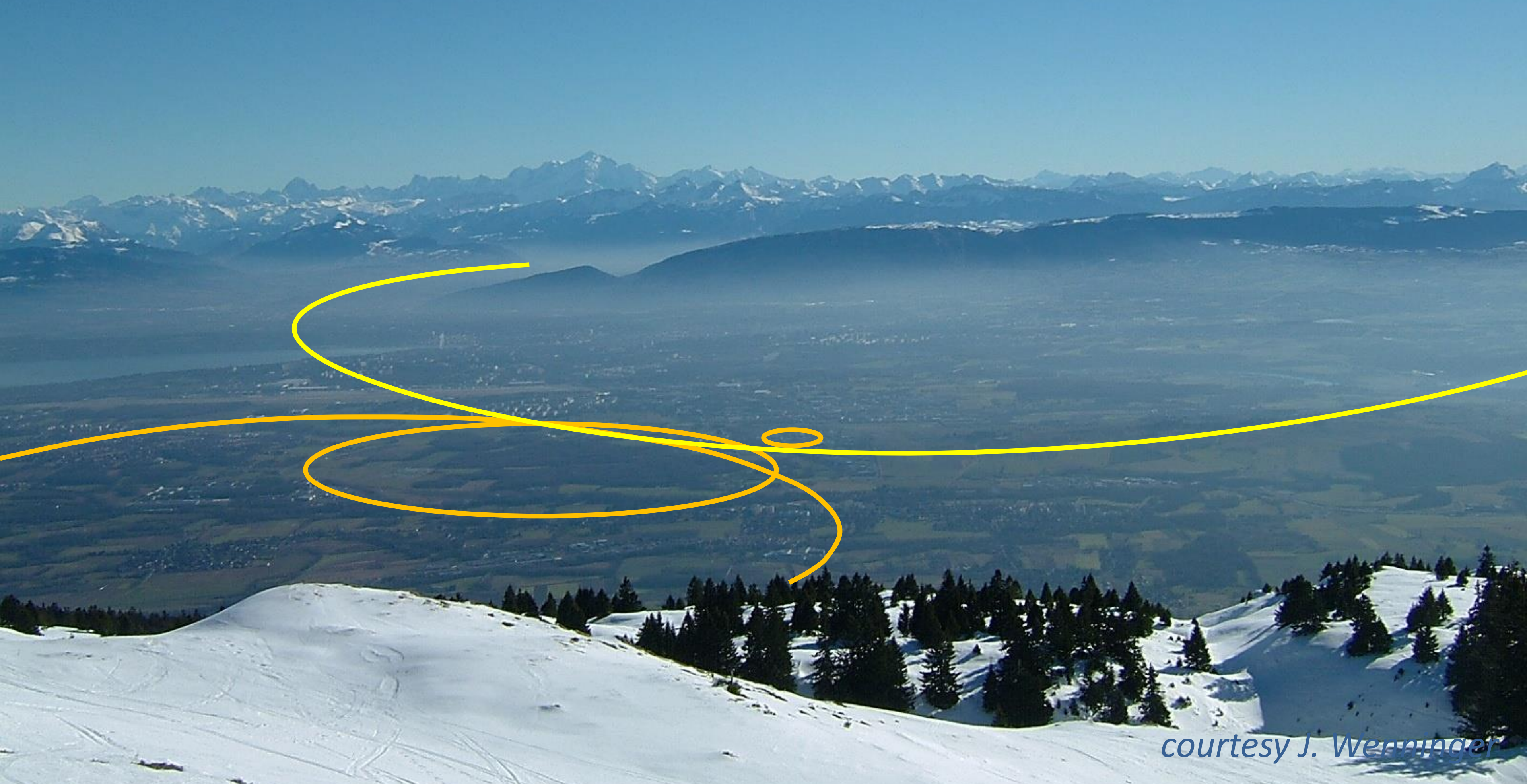
Physics at the FCCs

a story of synergy and complementarity



courtesy J. Wenninger

The same home…

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

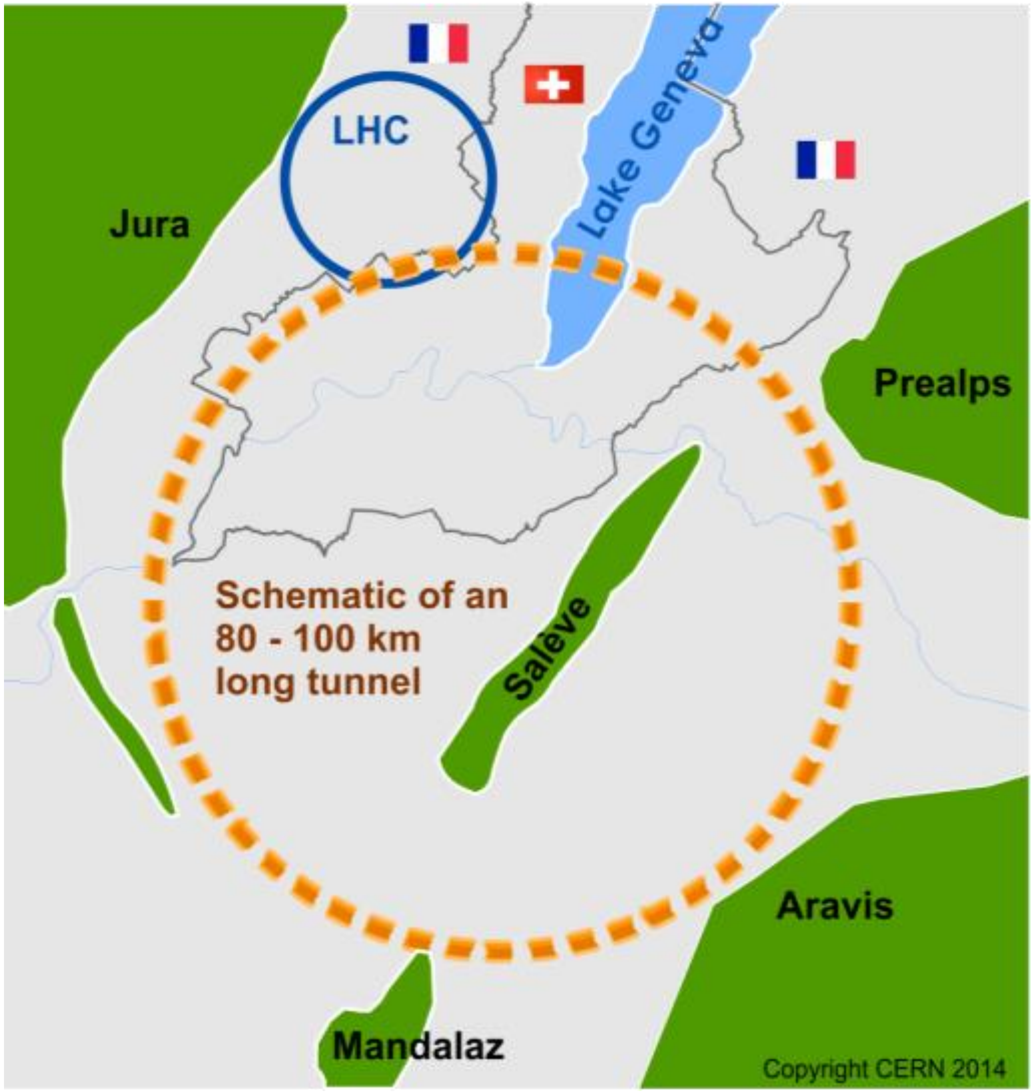
Forming an international collaboration to study:

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

~16 T ⇒ 100 TeV *pp* in 100 km

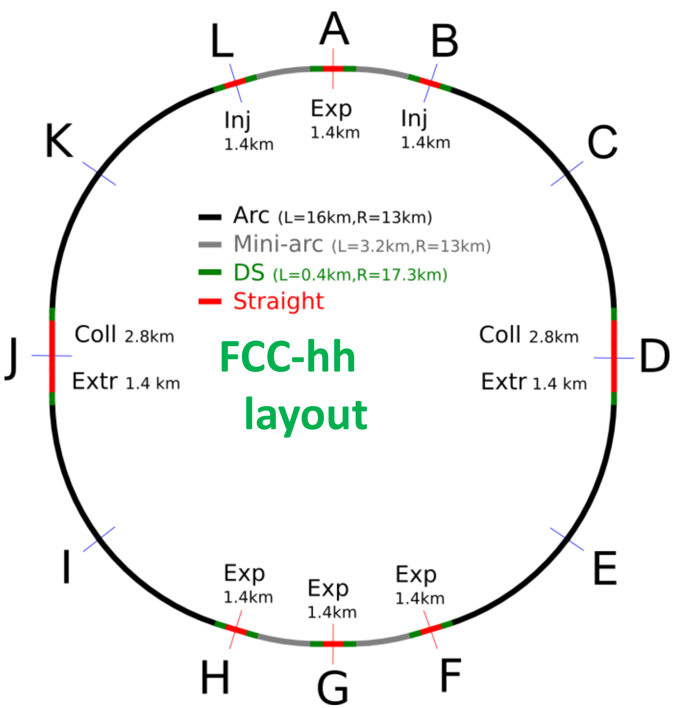
→ ultimate goal defining infrastructure requirements

- ***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

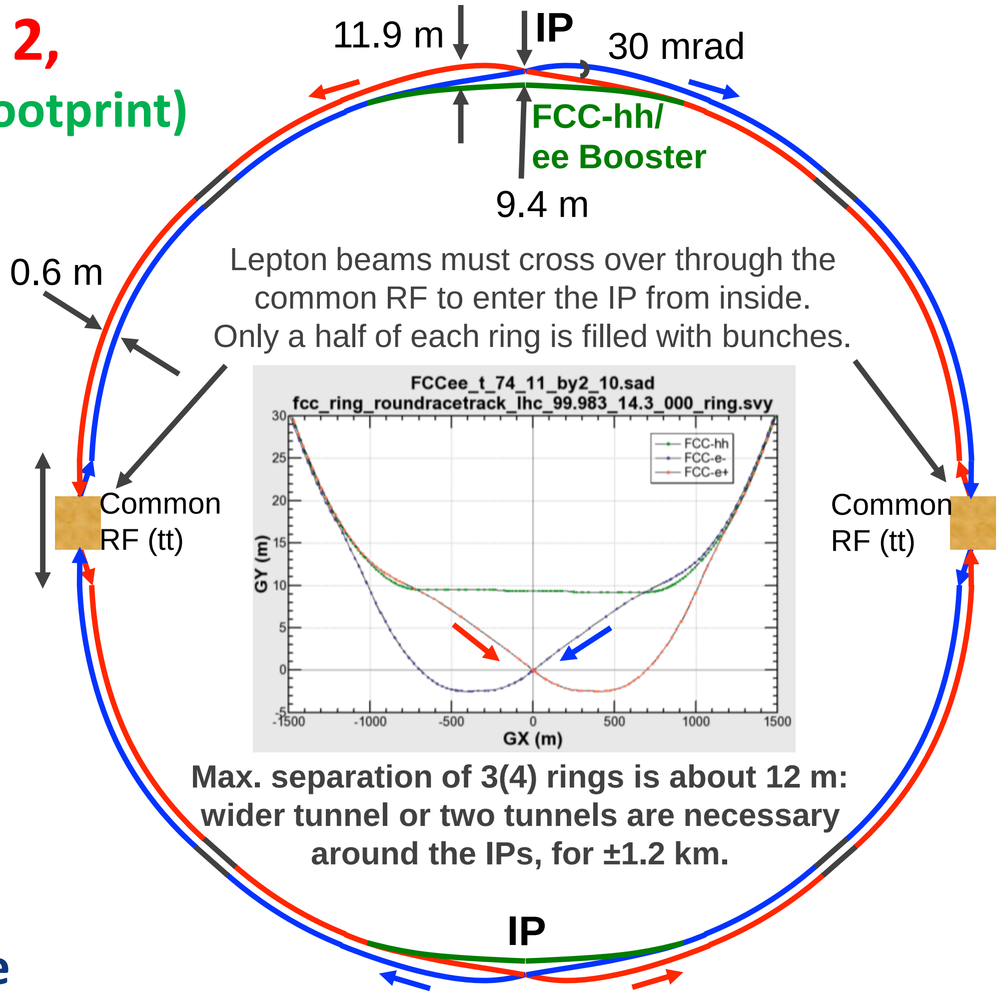


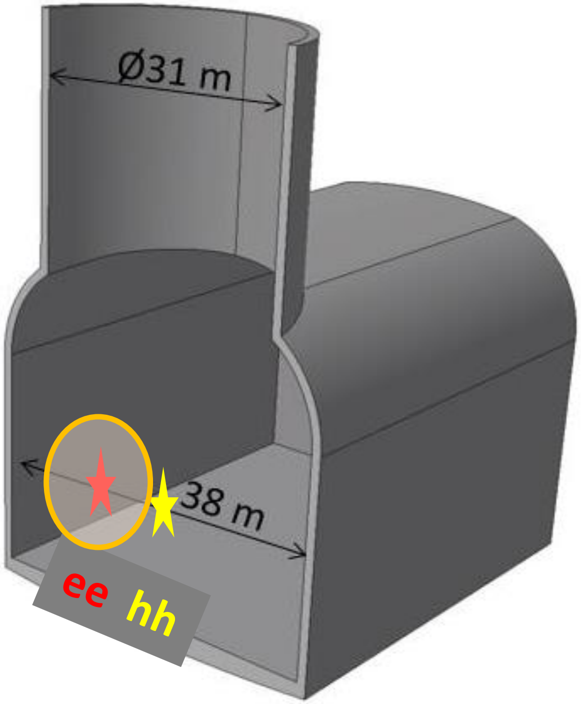
common layouts for hh & ee

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



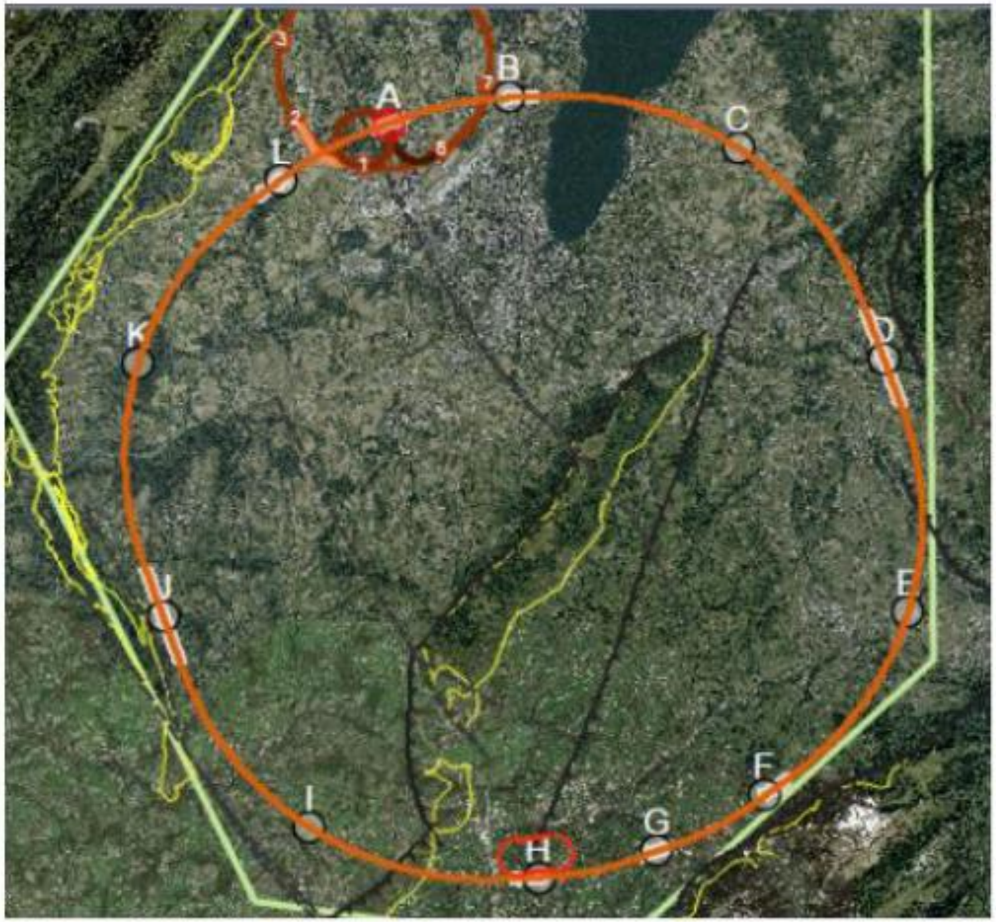
- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**





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, time, 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)

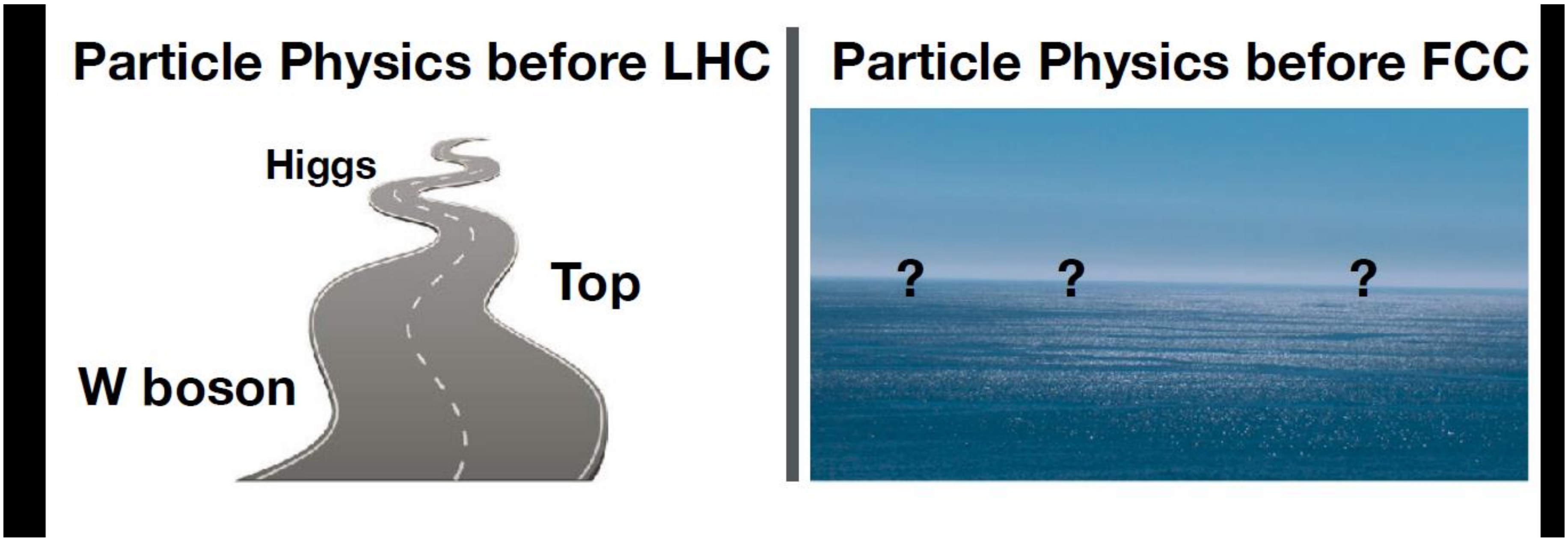
all to be printer-ready by end 2018!

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

A particular view of the big picture



Andrea Wulzer

Complementarity

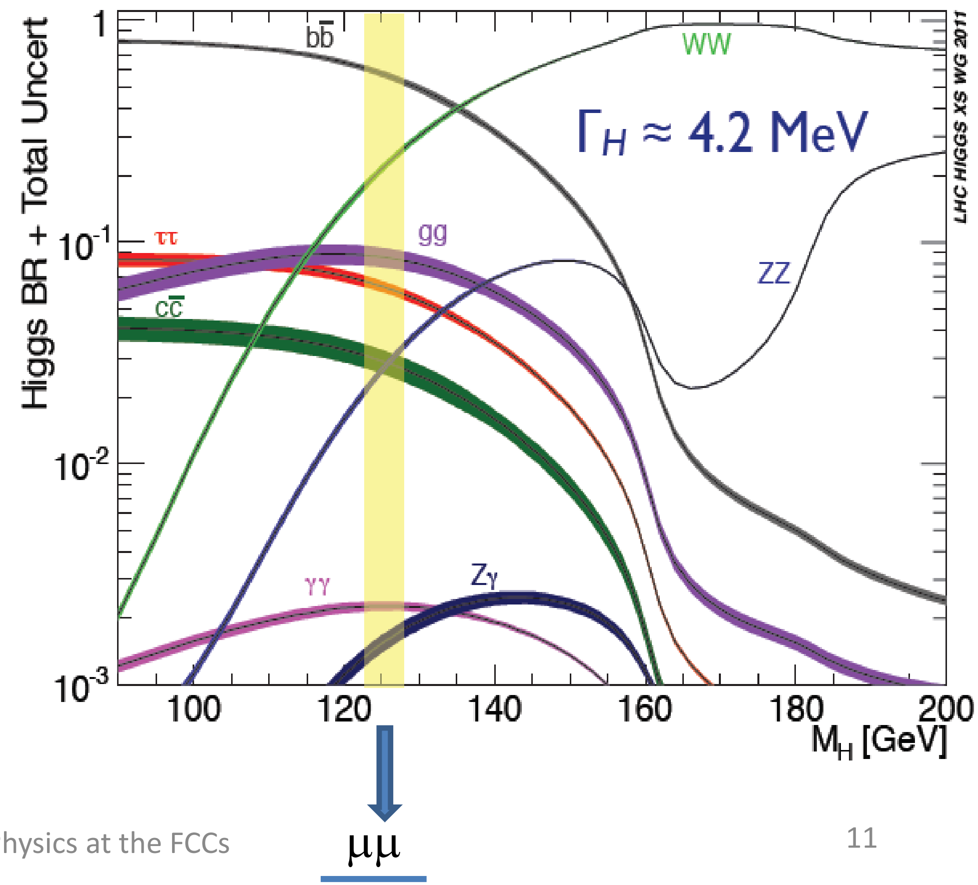
Proposed physics topics to be used in the study of **synergy/complementarity** among experiments **at FCC-hh/ee/eh**

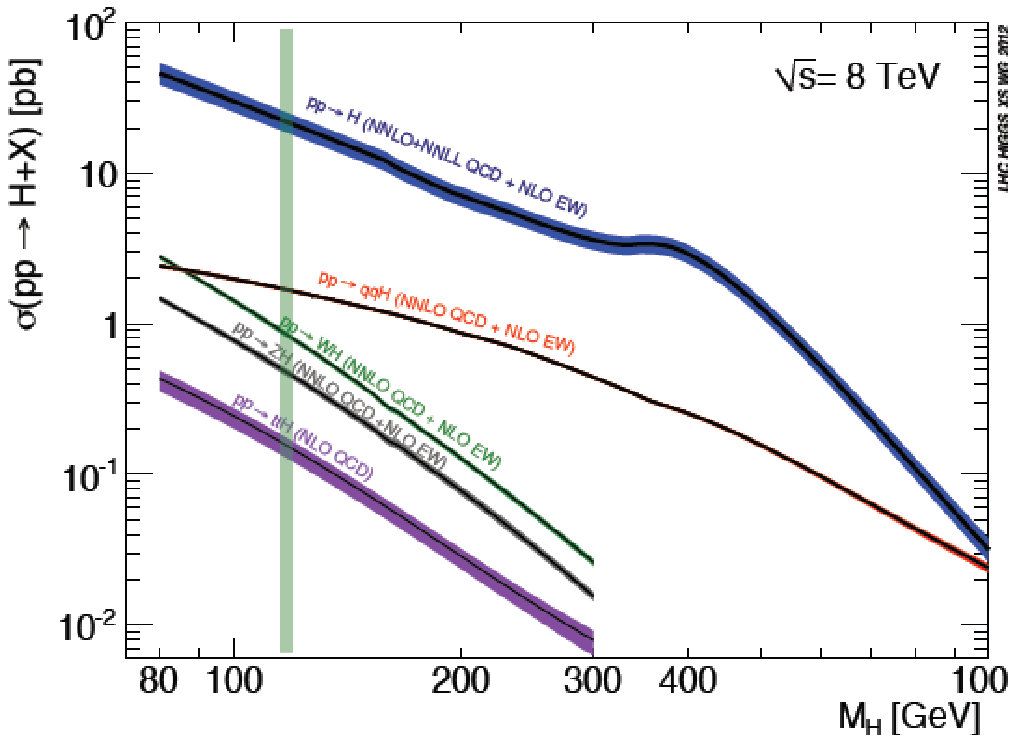
Subject		ee	hh	he
Higgs Physics	precision studies higher dimension operators composite Higgs rare and exotic decays multiple Higgs production extra Higgs bosons			
Interface with Cosmology	Dark matter baryogenesis right-handed/(almost) sterile neutrinos			
Electroweak Sym. Breaking	WW scattering supersymmetry extra dimensions composite models			
Flavour Changing	rare H,Z,W,top decays lepton flavor violation			
Extensions of the SM	extra vector-like fermions $SU(2)_R$ models leptoquarks			
QCD	Perturbation theory, structure functions Modelling final states			
EW/SM precision issues	precision measts (m_Z,m_W,m_t,α,$\alpha_s(m_Z)$,$\sin^2\theta_W$.R_b... higher-order EW corrections W,Z triple and quadruple couplings top (anomalous) couplings charm/bottom flavor studies			

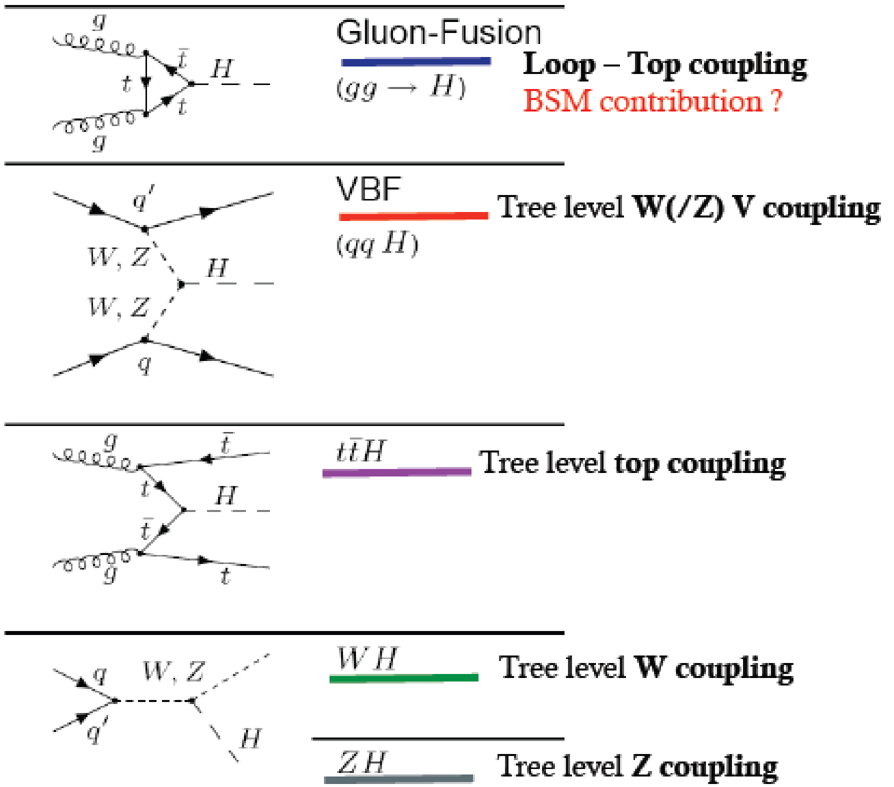
Higgs Physics

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





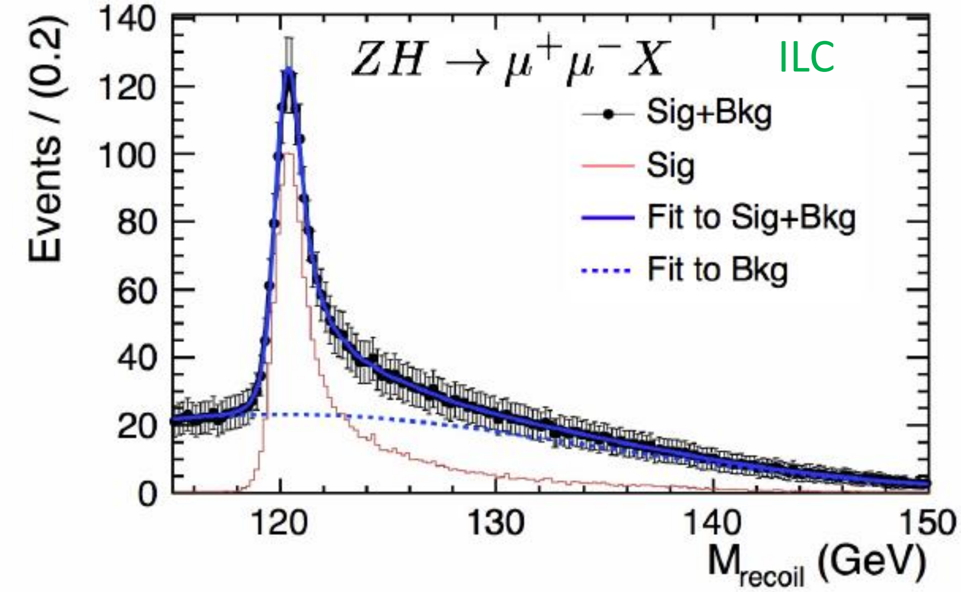


The LHC is a Higgs Factory !

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.

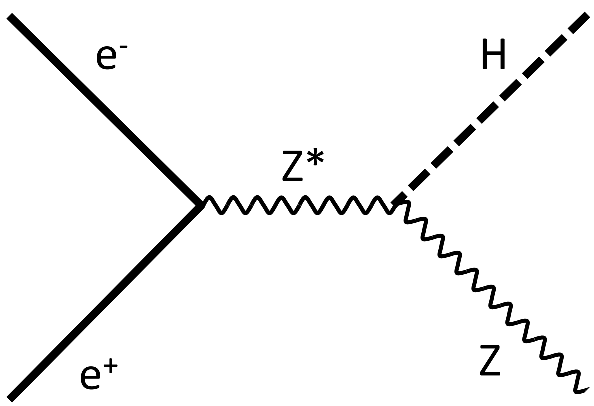
$$\sigma_{i\to f}^{\ observed} \propto \sigma_{prod} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

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

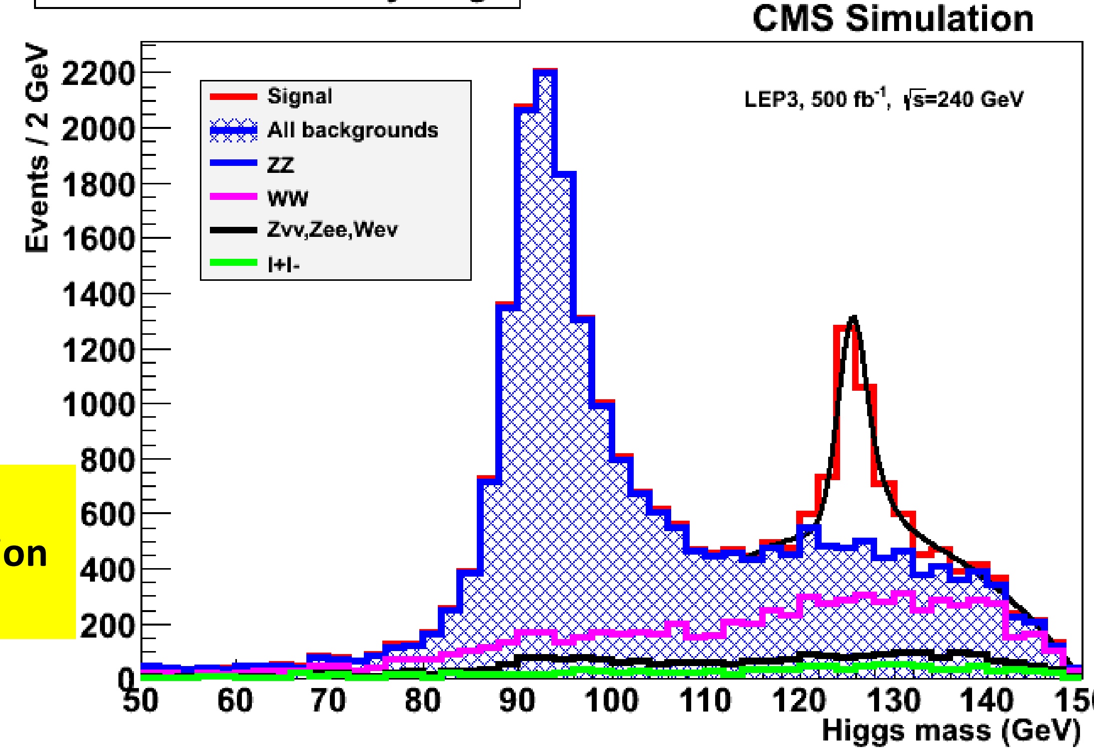


FCC-ee
H signal in missing mass

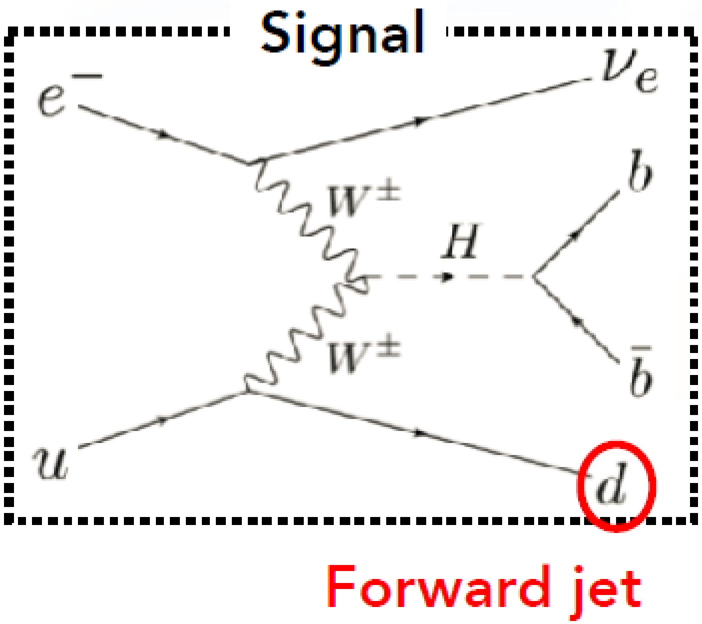
total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
➔ measure total width Γ_H and g_{HZZ}
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold



Z -> l+l- with H -> anything



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



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

because $\Gamma_{H\to bb} \sim 0.6\ \Gamma_H$ 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

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

g_{HXY}	FCC-ee	FCC-hh	FCC-ep?
ZZ	0.15%		
WW	0.2%		
γ γ	1.5%	<1% ?	
Zγ		1% ?	
tt	13%*)	1% ?	
bb	0.4%		(0.5%)
τ τ	0.5%		
cc	0.7%		1.8%
ss	H→ φγ ?		
μμ	6.2%	2% ?	
uu,dd	H→ ργ?		
ee	ee->H 100%?		
HH	30%**)	5% ?	some
BR_{exo}	<0.45% inv	$< 10^{-6}$?	
Γ_H	1%		

*) from tt threshold loop
**) from ZH threshold loop

NB 1. for γγ or μμ FCC-hh can normalize to H-> ZZ which is very well measured at FCC-ee
NB 2. for tth normalize to ttZ and use top couplings to γ,Z measured at FCC-ee
For FCC-hh need to ascertain the effect of pile-up of 200/1000 events.

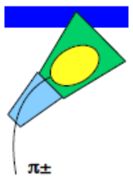
Object reconstruction and performances

✦ Particle Flow Reconstruction

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

✦ Jets

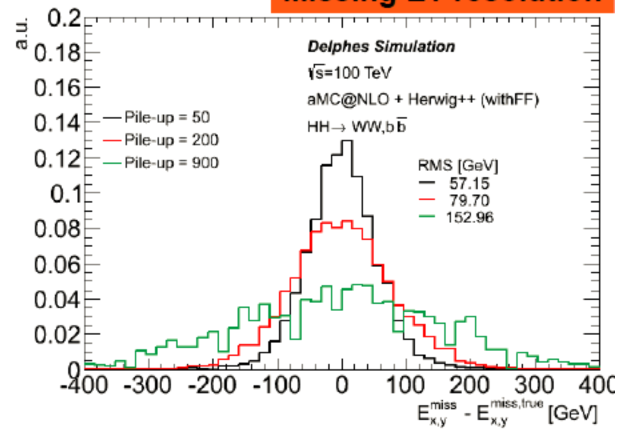
- Anti-Kt (Fast Jet) algorithm
- particle-flow objects as inputs
- R = 0.4
- Jet Area pile-up correction:
- private calibration to particle level $p_T^{\mathrm{corrected}} = p_T^{\mathrm{raw}} - \rho \cdot \mathrm{JetArea}$
- $p_T^{\mathrm{jet}} > 20$ GeV



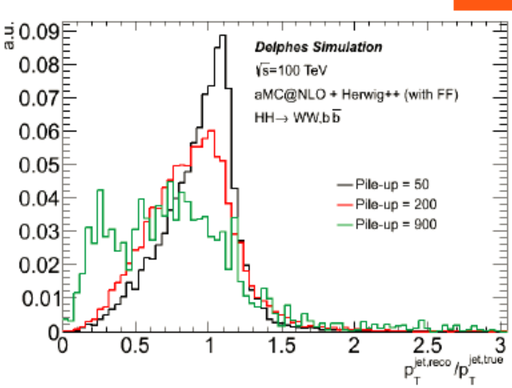
✦ Missing Transverse Energy

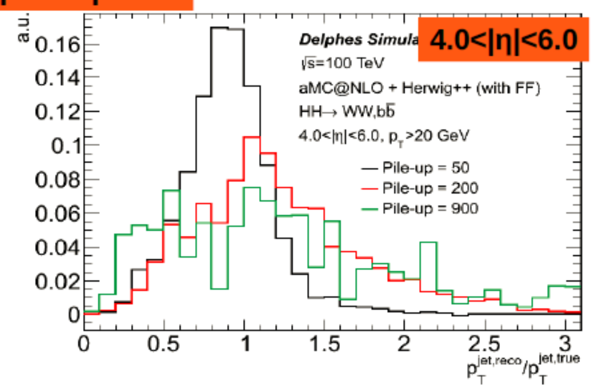
- Anti-Kt (Fast Jet) algorithm
- negative vector sum of Jets, after pile-up correction and calibration

Missing ET resolution

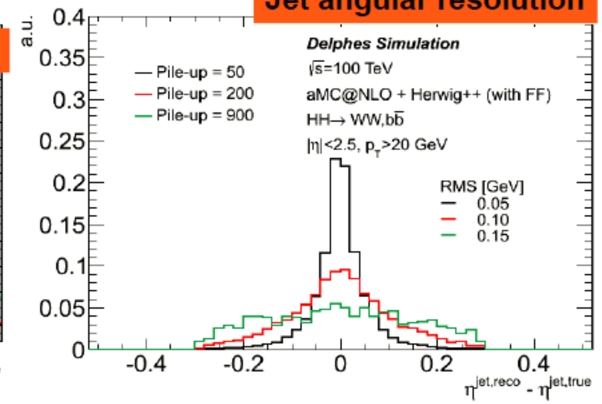


Jet pT response





Jet angular resolution



- Complementarity breaks degeneracy in EFT space (e.g., ttH vs ggH vs ttZ)
- How to fit rare Higgs channels on a map? Light weakly-coupled new physics?
- PDF measurements @ ep useful to control PDF uncertainty for Higgs precision program and new physics tests?
- Independent alpha_S(Mz) measurement @ ep improves EW precision tests @ ee?
- LHC/ILC Higgs complementarity [Peskin 1312.4974] : BR(γγ)/BR(ZZ) @LHC plus Kv @ILC => Kγ. Something similar @FCC?

W.i.Progress

to be ascertained

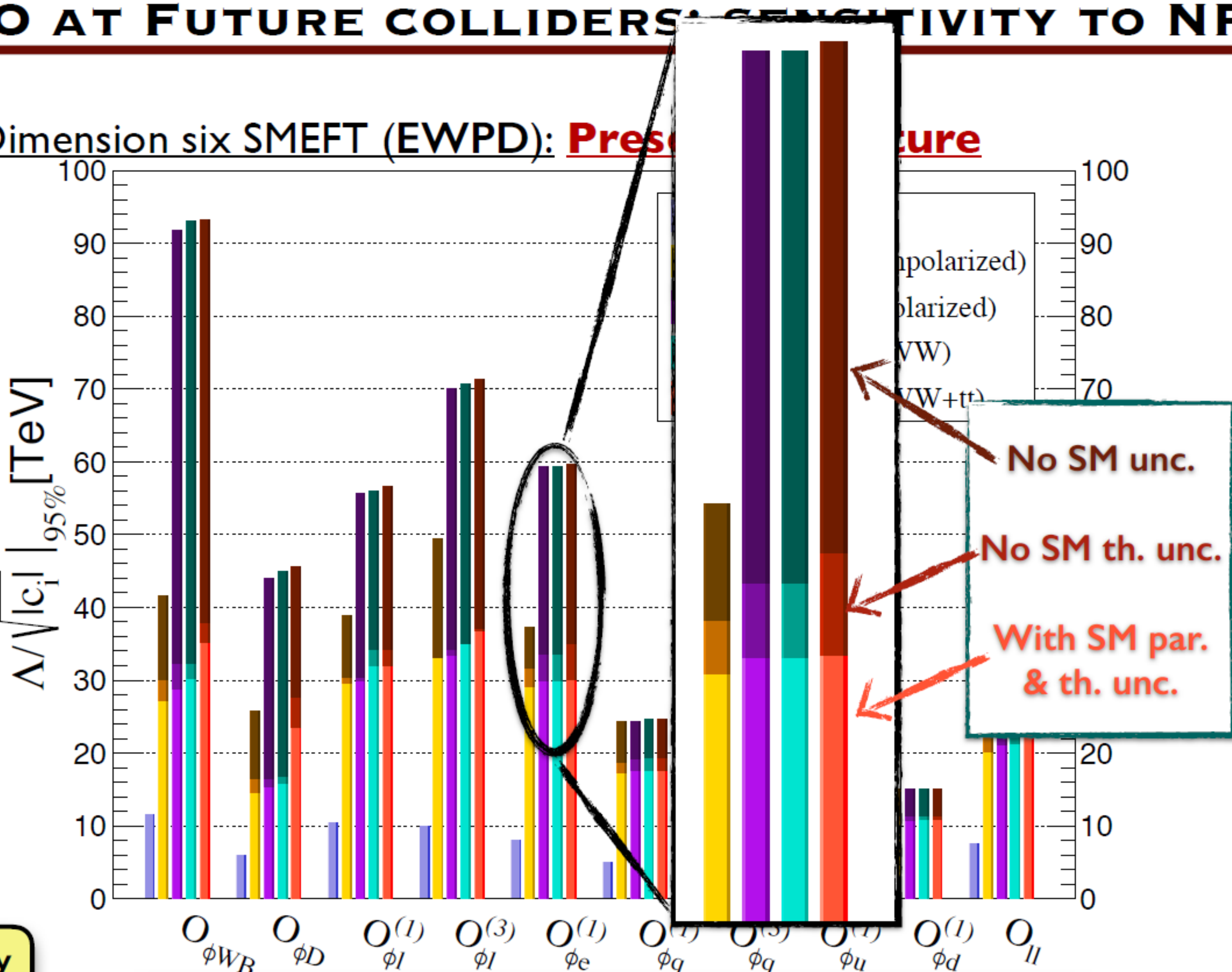
to be ascertained

YES!

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

Message

Michelangelo

- Theoretical progress proceeds at astounding pace, thanks to the current and future needs of the LHC

can we expect the same once FCC_{ee} will have its needs?

- As we approach the few-% level in systematics, several relevant effects appear:
  - finite m_{top} corrections
  - higher-order EW corrections
  - PDF
- While these will require the development of new techniques, input from data (eg for PDFs, validation of HO calculations, ...), and a lot of sweat and blood, it is reasonable to assume that the TH systematics will have reached by the start of FCC-pp the level of
  - % for absolute rates
  - sub-% (per mille?) for shapes and ratios (eg ttH/ttZ vs pt(H,Z))

Remarks

- Being optimistic in the assumptions about TH syst's when exploring the potential of FCC to perform precise Higgs measurements, will expose much more clearly the value of theoretical progress, and will be a very strong motivation and incentive to work hard on this progress!
- This will also set higher standards for the detector performance

Michelangelo

This is the right attitude!
can we synergize?

EW precision measurements will need full three loop (exponentiated) to match 10^{-5} precision on $\sin^2\theta^{eff}_{w}$, 0.5 MeV on m_W, 0.1 MeV on m_Z, Γ_Z etc…

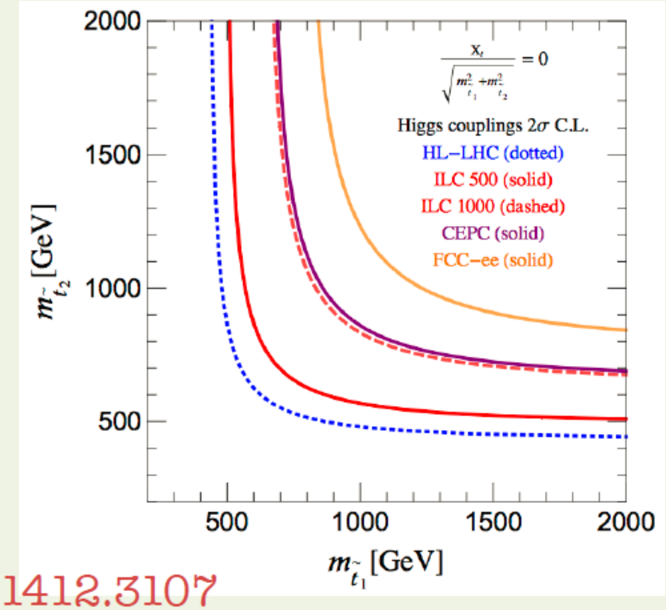
Synergy between theory and experiment and accelerator

Comprehensive Complementarity

In supersymmetry this is the "stop squark".

FCC-ee

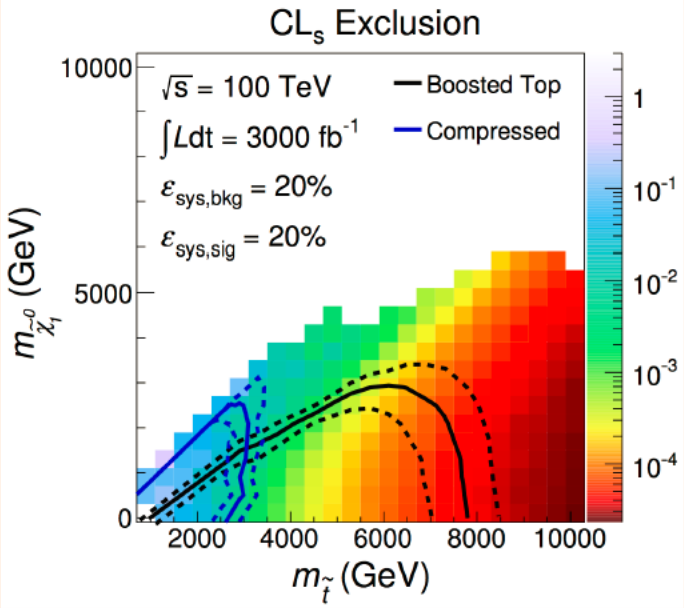
Coloured and charged, stops modify Higgs couplings:



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).

-- need to understand how measurement of R_b would reduce model dependence of extraction of α_s from R_{had} -- also meast from Ws.

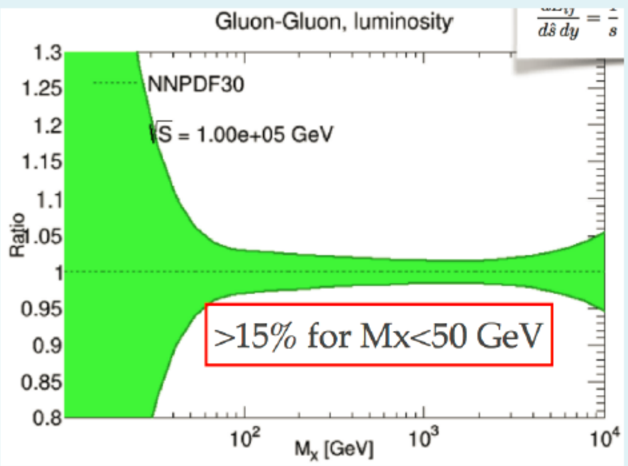
-- FCC-ep can also contribute at level of $3\ 10^{-4}$

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



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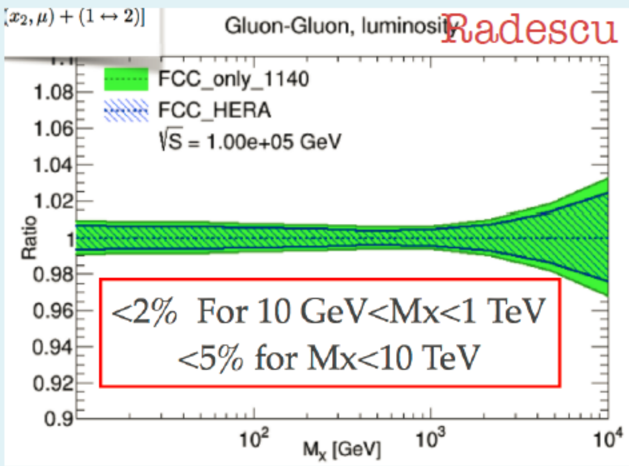


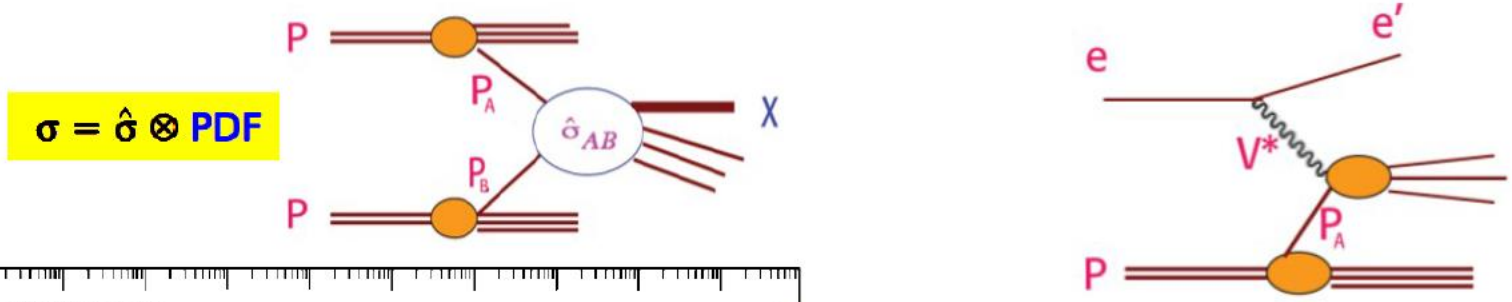
Improvement in low-x predictions for FCC-hh.

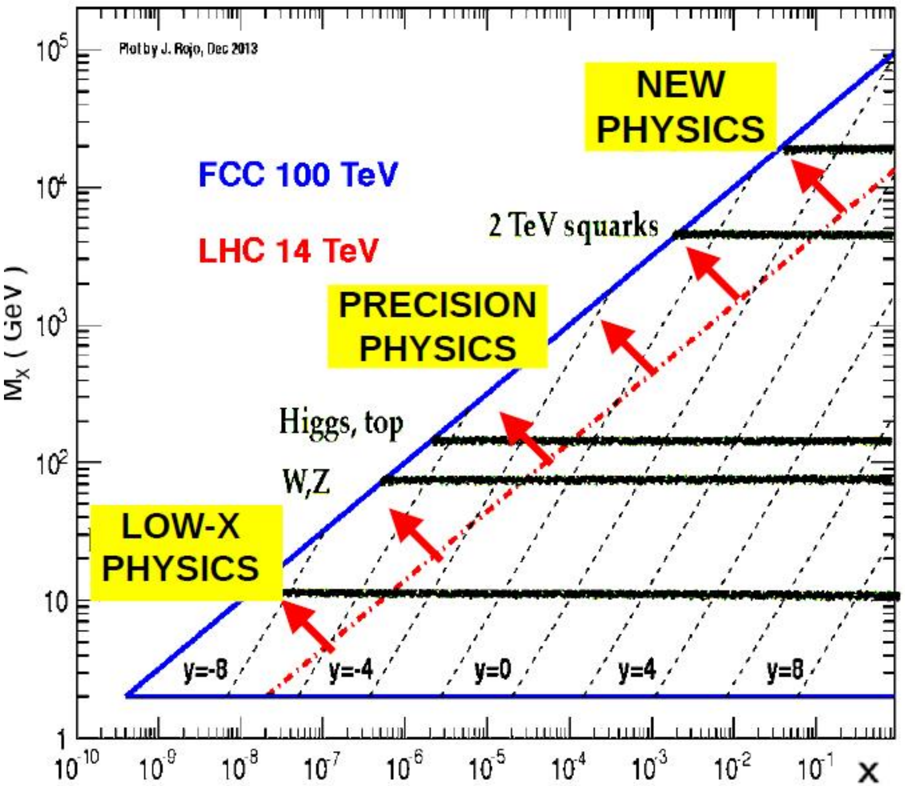
→ **comprehensive assessment of impact**

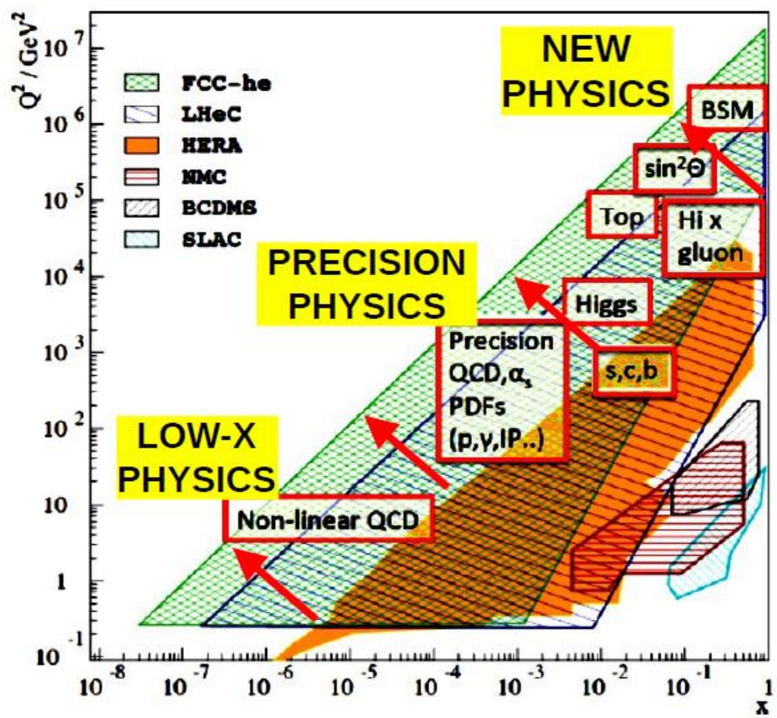
McCullough

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

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



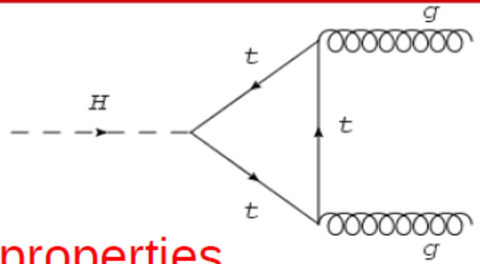




Higgs as a source of pure gluons (FCC-ee)

- 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→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)

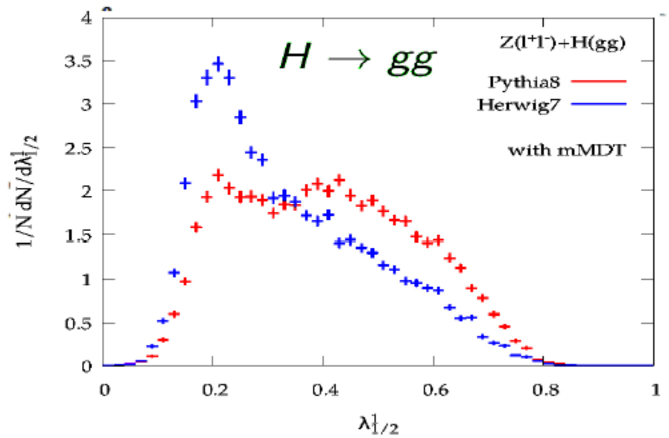
g in one hemisphere recoils against two b-jets in other hemisphere: **b tagging**

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

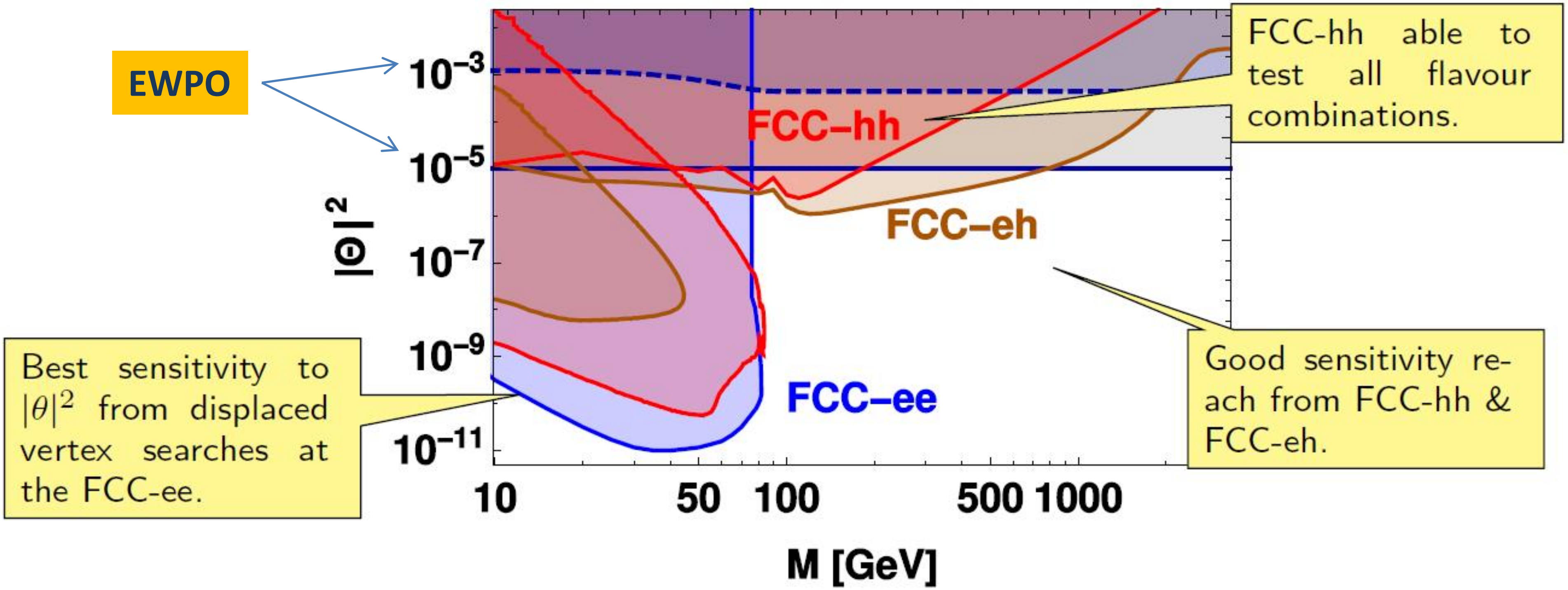


– Check N^nLO antenna functions
– Improve q/Q/g discrim. tools
– Octet neutralization? (zero-charge gluon jet w/ rap-gaps)
– Colour reconnection? Glueballs ?
– Leading η's,baryons in g jets?

Summary

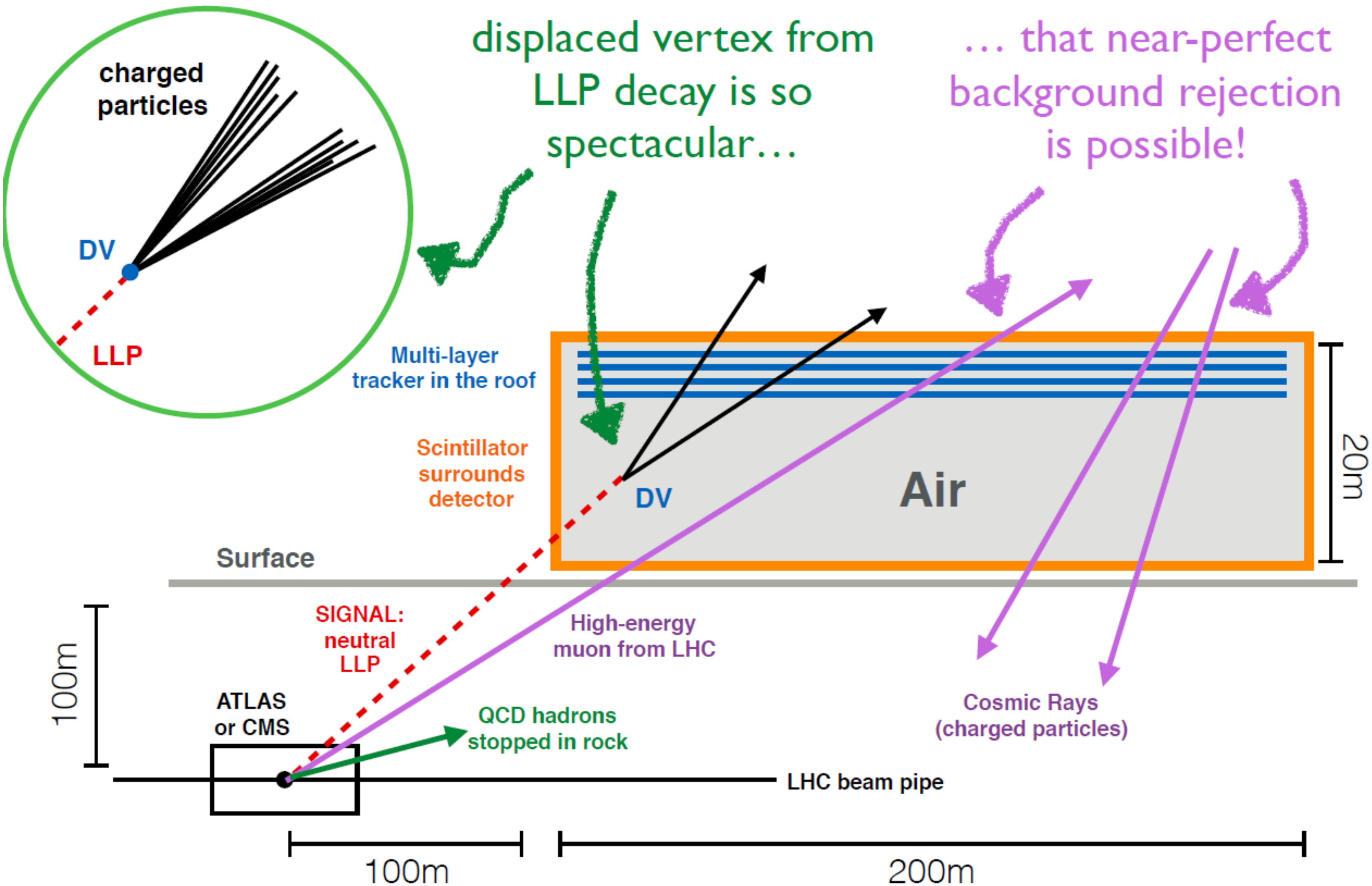
Another example of Synergy
while ee covers a large part of space very cleanly ,
its either 'white' in lepton flavour or the result of EWPOs etc
Observation at FCC –hh or eh would test flavour mixing matrix!

- 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

Long Lived Particles will be hunted actively!



NB this is recent – there was no mention of this at the kick-off meeting in Geneva!

Curtin

Dark matter searches

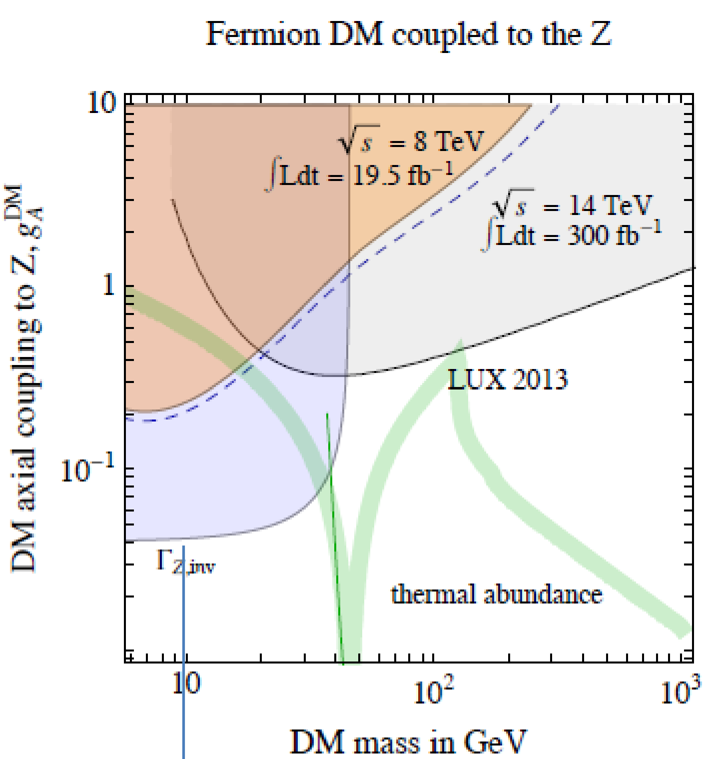
‘sterile neutrinos’

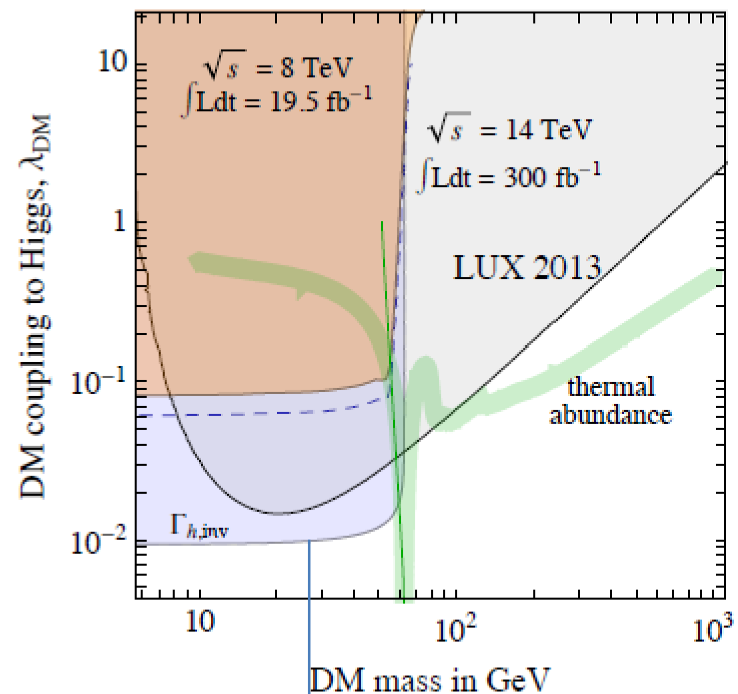
’invisible Higgs’ decay   work in progress: what systematics are needed at FCC-hh to match the e+e- measurement. Can one improve on either (tag ZH with Z-> light quarks + inv)

‘LSP searches etc…’ FCC-ee unbeatable for SUSY like couplings
– do we understand the gaps etc…?

Γ_Z and Γ_h invisible are the most efficient way to explore SM-mediated DM at colliders

(Giudice)



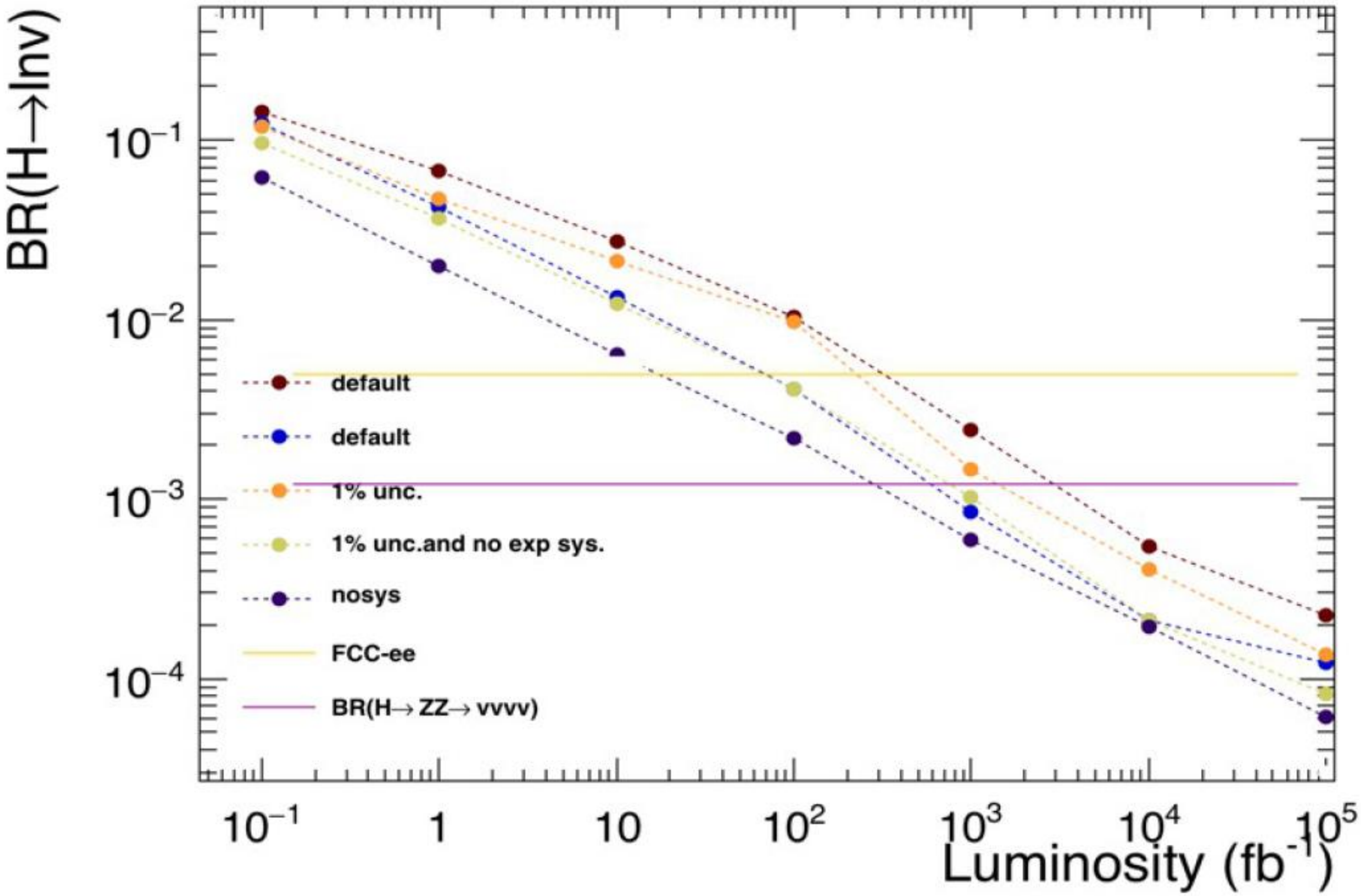


Will improve these by large factors!

ΔN_ν = 0.0004?
from e+e-→Zγ

$\Delta\Gamma_{h,inv} / \Gamma_{tot}$ <0.19%

How do things scale?



Cross the SM neutrino wall at FCC with < 1 ab^{-1}

Complementarity

table to be completed and revised!

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Flavour Changing	rare H,Z,W,top decays lepton flavor violation			
Extensions of the SM	extra vector-like fermions $SU(2)_R$ models leptoquarks			
QCD	Perturbation theory, structure functions Modelling final states			
EW/SM precision issues	precision measts (m_Z,m_W,m_t,α,$\alpha_s(m_Z)$,$\sin^2\theta_W$.R_b... higher-order EW corrections W,Z triple and quadruple couplings top (anomalous) couplings charm/bottom flavor studies			

We are making significant progress towards a **demonstration that**

The combination of the FCC machines offers outstanding discovery potential by exploration of new domains of

-- both **direct search**,

and

-- **precision**

-- at high energy and

-- at very small couplings

Synergy and Complementarity

On wednesday we had this rather inspired exchange:

Complementarity is like «you have the bread and I have the ham» MMcC

Or rather « you have the steak and I have the barbecue» MLM

But Synergy is when we take the bus together to go eat at the same place! AB

Conclusion:

Complementarity can be very painful without synergy!

LETS WORK TOGETHER TOWARDS THE CDR!