The Future Circular Colliders

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Caveat

Cannot possibly cover all the aspects!
A personal selection applied…

The big questions

- What is the origin of Dark Matter / Energy ?
- What is the origin of matter/anti-matter asymmetry ?
- What is the origin of neutrino masses ?
- What is the origin of the Electro-weak symmetry breaking ?
- What is the solution to the hierarchy problem ?

The Standard Model does not provide answers to these questions

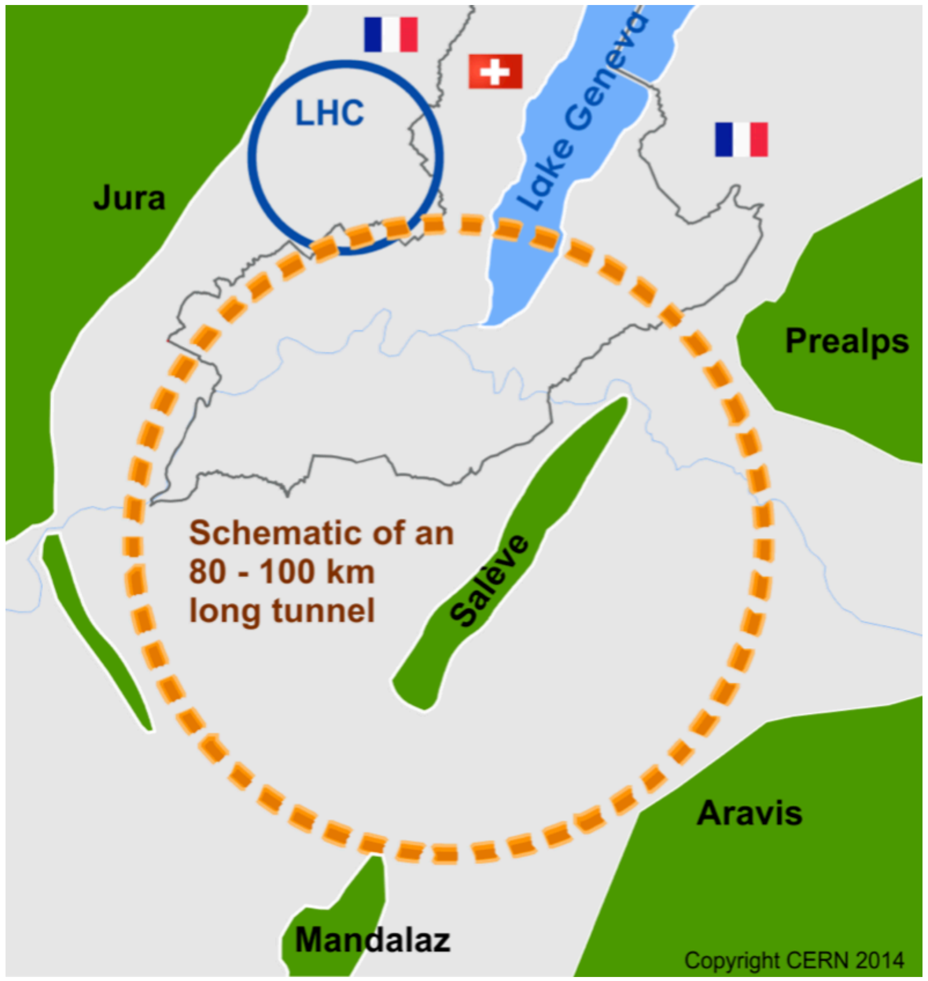
There is new physics out there (beyond the Standard Model)

The big questions

- Keep in mind that no single experiment can:
  - explore all directions at once
  - guarantee discovery
- The only possible approach is to design projects that can deliver:
  - precision
  - sensitivity to as many as possible scenarios of new physics
  - clear yes/no answers to concrete scenarios
- HL-LHC will collect data until 2036, and big physics projects take ~20 years time to plan and build, now is the right time top start defining the future of HEP.

HEP needs a future large collider program

The FCC project



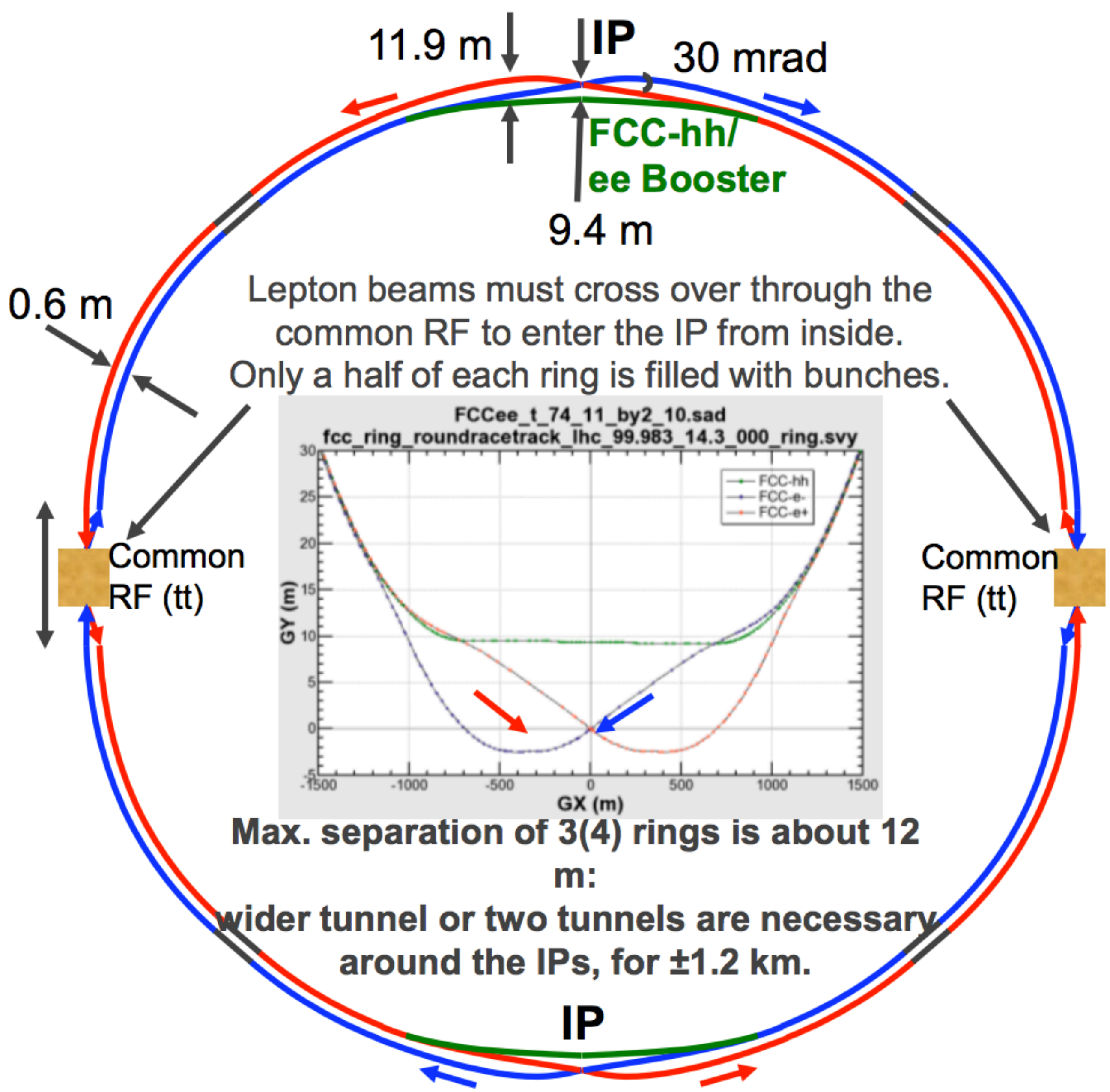
Within the FCC collaboration (CERN as host lab), 4 main accelerator facilities have been studied:

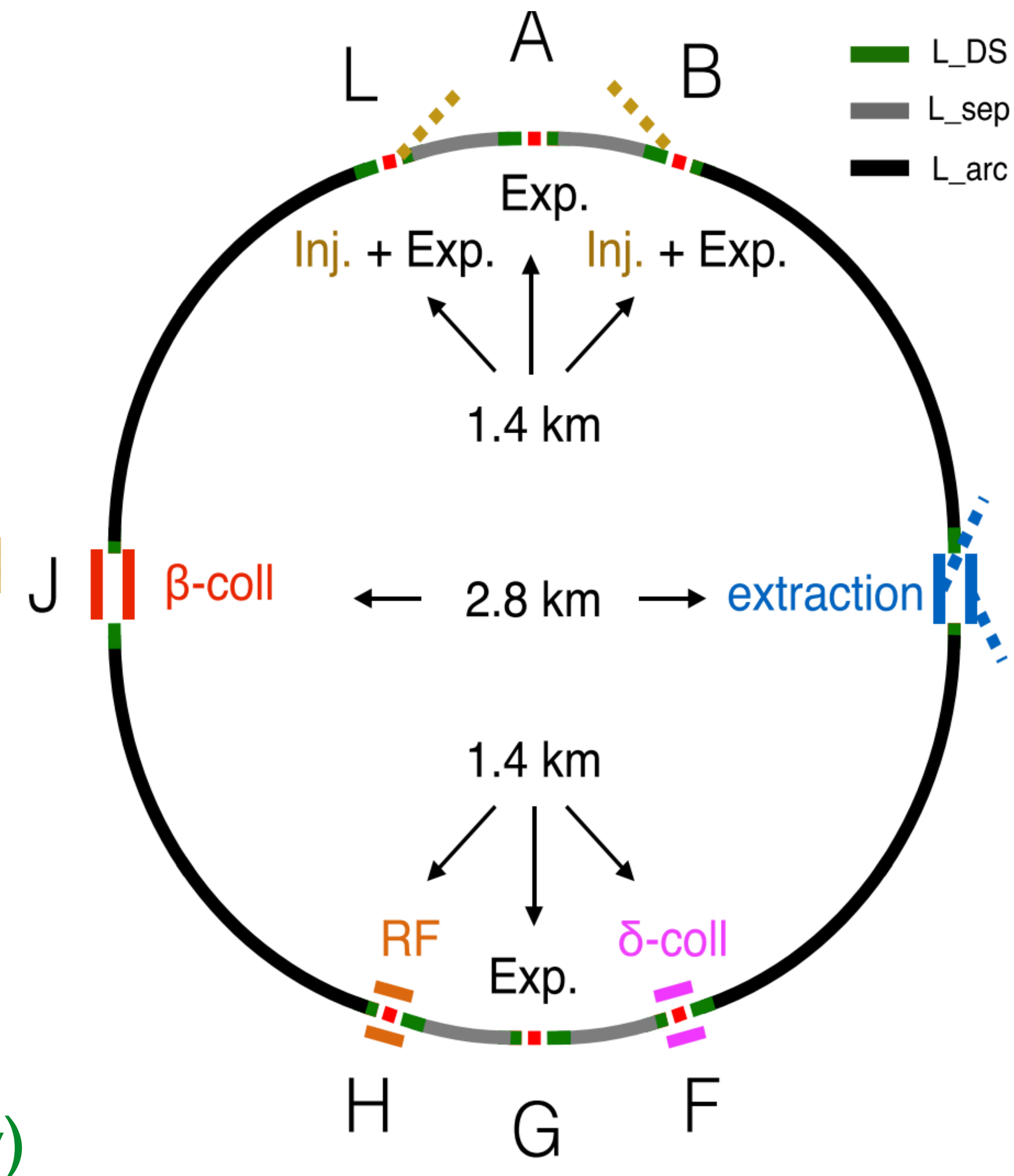
- pp-collider (FCC-hh)
  - defines infrastructure requirements
  - 16 T → 100 TeV in 100 km tunnel
- ee-collider (FCC-ee):
  - as a (potential) first step
- ep collider (FCC-eh)
- HE-LHC :
  - 27 TeV (16T magnets in LHC tunnel)

CDRs and European Strategy documents have been made public in Jan. 2019

https://fcc-cdr.web.cern.ch/

A common layout for FCC-ee/hh





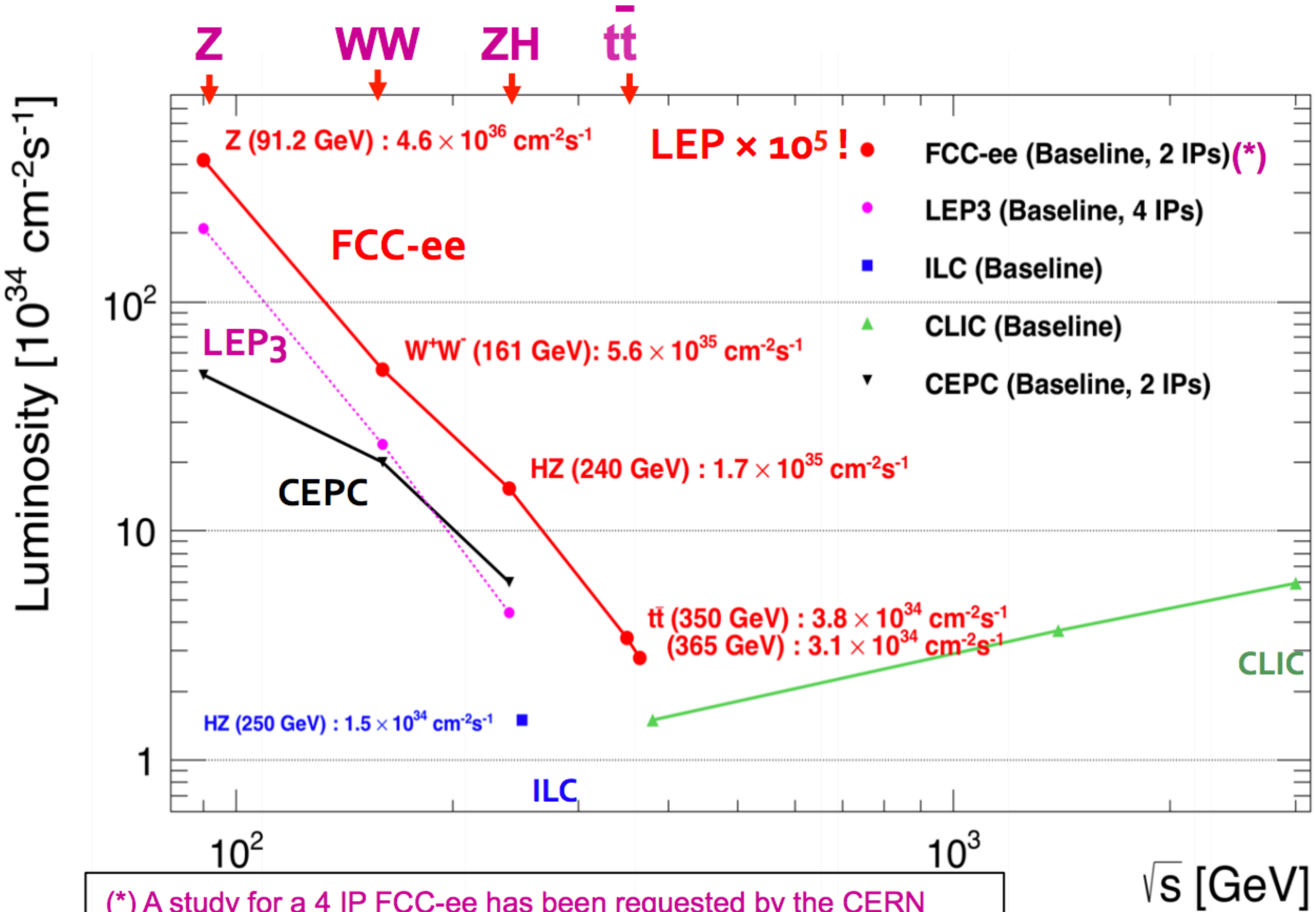
2 IPs for FCC-ee (4 IPs under study)

- Large horizontal crossing angle 30 mrad
- Beams only mildly bent before IP to minimize synchrotron radiation into detector volumes
  - Bend beams after IP

2 IPs (General Exp.) + 2 IPs @ injectors

FCC-ee

Energies and Luminosities



(*) A study for a 4 IP FCC-ee has been requested by the CERN management and is foreseen to be conducted this year (2019)

- Ultimate precision:
  - 100 000 Z / second (!)
    - 1 Z / second at LEP
  - 10 000 W / hour
    - 20 000 W at LEP
  - 1 500 Higgs bosons / day
    - 10 times ILC
  - 1 500 top quarks / day
    - in each detector

… in a clean environment:

- No pileup
- Beam backgrounds under control
- E,p constraints

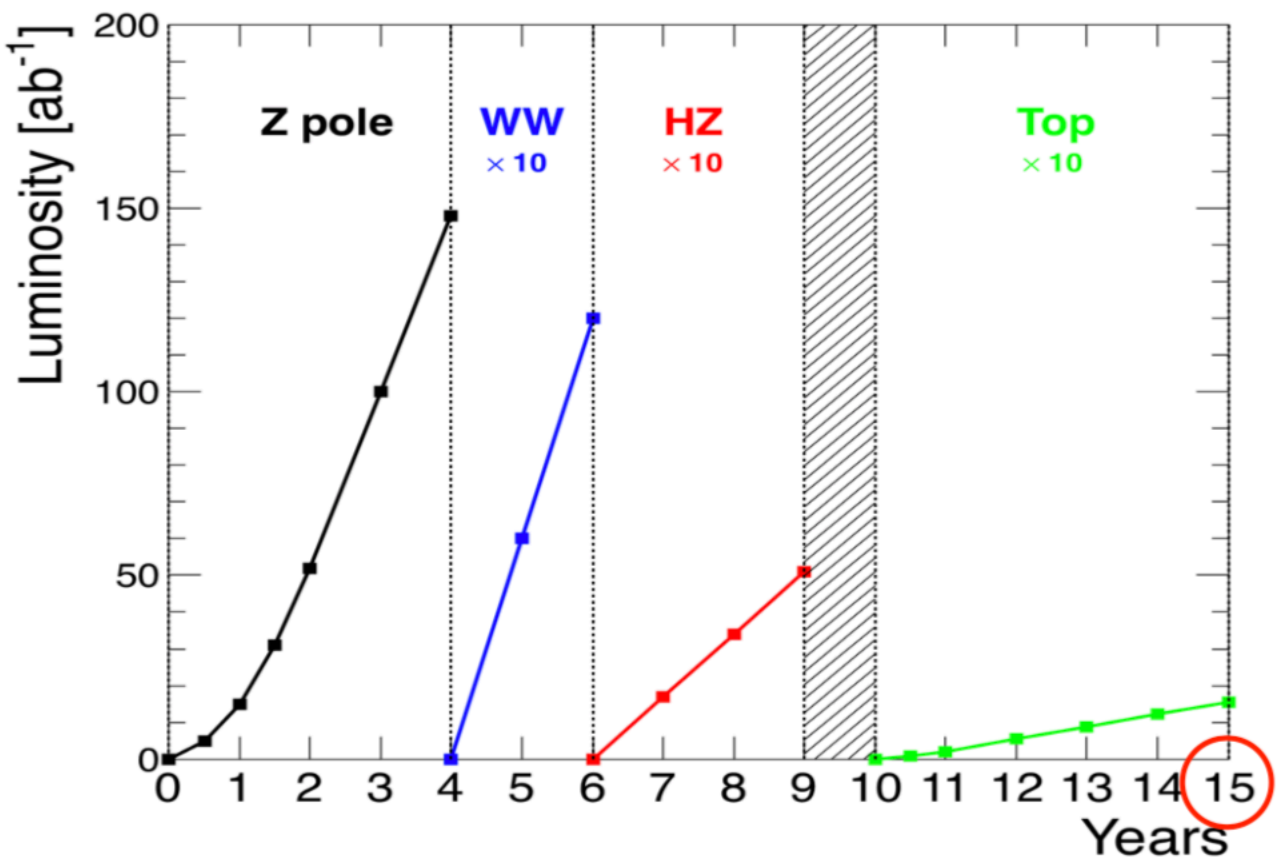
PRECISION and SENSITIVITY to rare or elusive phenomena

The FCC-ee offers the largest luminosities in the 88 → 365 GeV √s range

FCC-ee operations

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

Total : 15 years



Event statistics

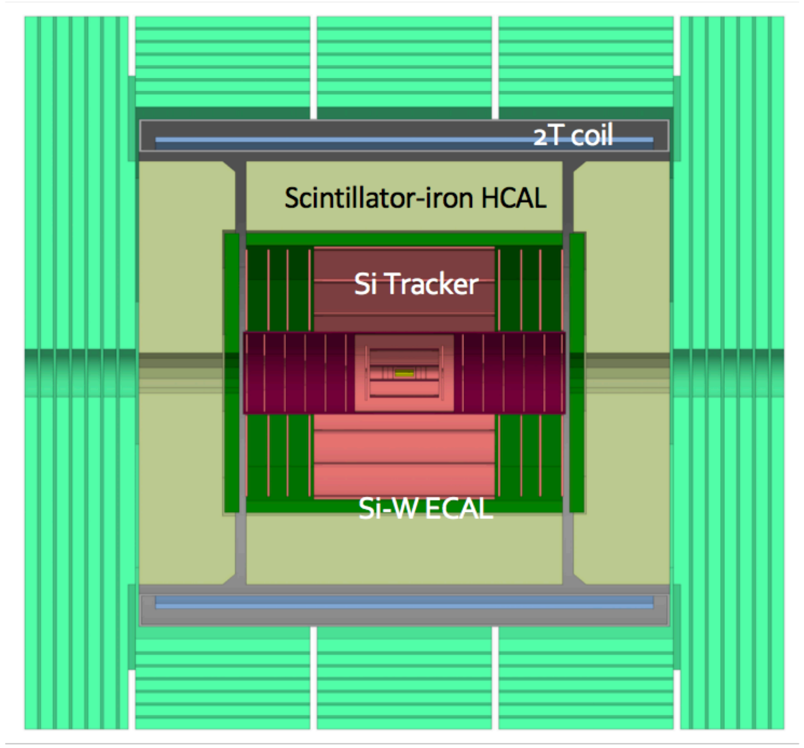
- 5×10^{12} $e^+e^- \to Z$
- 10^8 $e^+e^- \to W^+W^-$
- 10^6 $e^+e^- \to HZ$
- 10^6 $e^+e^- \to t\bar{t}$

$\sqrt{s}$ precision

- 100 keV
- 300 keV
- 2 MeV
- 5 MeV

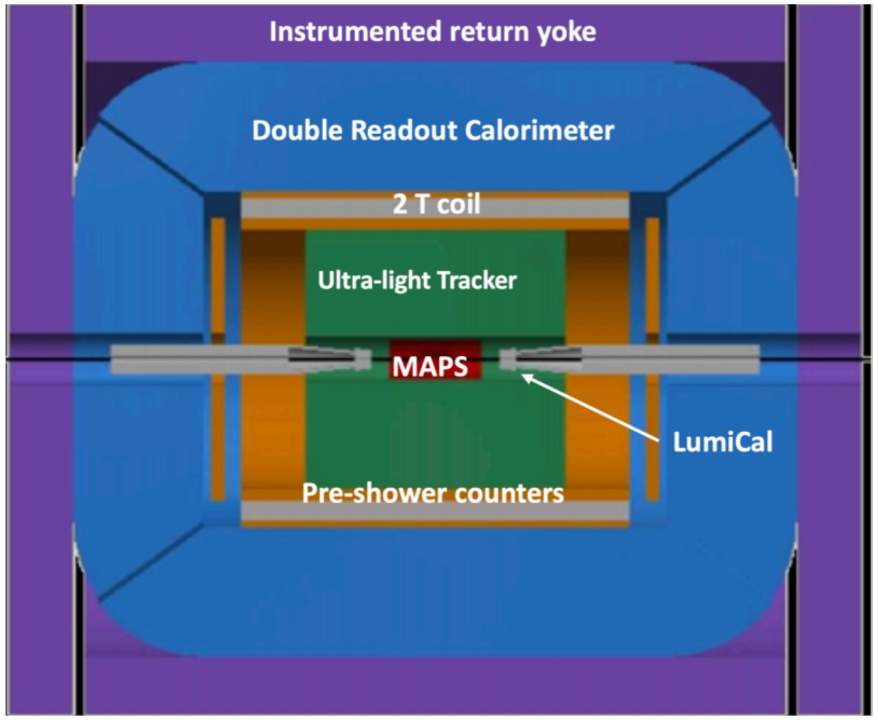
Transverse polarization for $\sqrt{s}$,
no longitudinal polarization.

FCC-ee experiments



CLD

- Consolidated option based on the detector design developed for CLIC
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil outside calorimeter system
- Proven concept, understood performance



IDEA

- New, innovative, possibly more cost-effective design
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Dual-readout calorimeter
  - Thin and light solenoid coil inside calorimeter system

Physics potential of FCC-ee

- **EXPLORE the 10-100 TeV energy scale**
  - With precision measurements of the properties of the Z, W, Higgs, and top particles
    - 20-50 fold improved precision on ALL electroweak observables (EWPO)
      - ➔ m_Z, Γ_Z, m_W, m_{top}, $\sin^2\theta_W^{eff}$, R_b, $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z)$, top EW couplings …
    - 10 fold more precise Higgs couplings measurements
      - ➔ Break model dependence with Γ_H accurate measurement
- **DISCOVER that the Standard Model does not fit**
  - Then extra weakly-coupled and Higgs-coupled particles exist
  - Understand the underlying physics through effects via loops
- **DISCOVER a violation of flavour conservation / universality**
  - e.g., with $B^0 \to K^{*0}\tau^+\tau^-$ or $B_S \to \tau^+\tau^-$ in 10^{12} bb events
- **DISCOVER dark matter as invisible decays of Higgs or Z**
- **DISCOVER very weakly coupled particles in the 5-100 GeV mass range**
  - Such as right-handed neutrinos, dark photons, …
    - May help understand dark matter, universe baryon asymmetry, neutrino masses

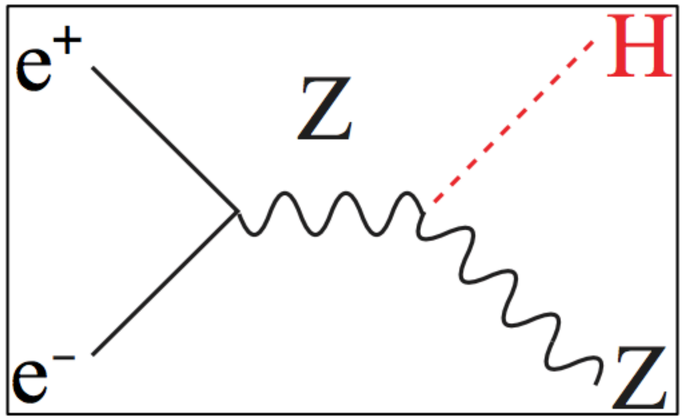
Electro-Weak observables

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	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, 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

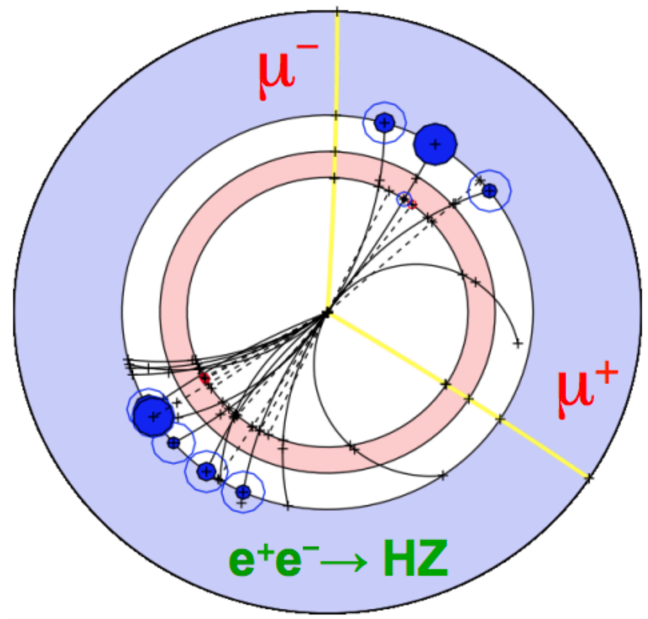
Astounding level of precision achievable of Electro-Weak observables at the FCC-ee

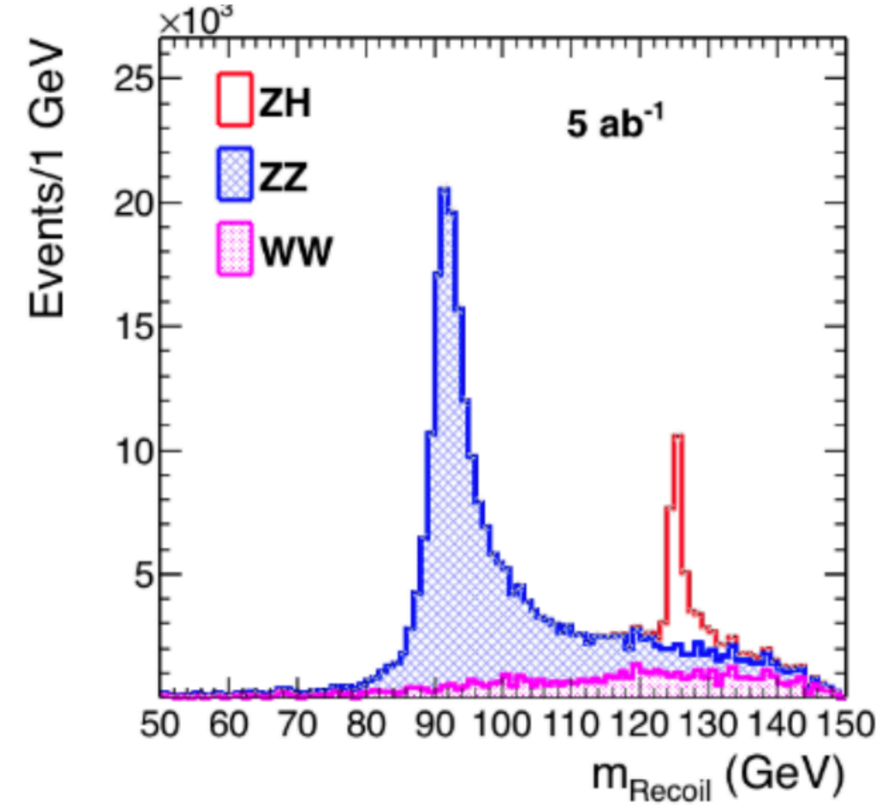
Higgs @ FCC-ee

- Higgs tagged by a Z, Higgs mass from Z recoil



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





- 10^6 Higgs produced @ FCC-ee
- rate ~ $g_{HZZ}^{\ 2}$ → $\delta g_{HZZ}/g_{HZZ}$ ~ 0.1 %

- Then measure ZH → ZZZ
- rate ~ $g_{HZZ}^{\ 4} / \Gamma_H$ → $\delta\Gamma_H / \Gamma_H$ ~ 1 %

- Then measure ZH → ZXX
- rate ~ $g_{HZZ}^{\ 2}\, g_{HXX}^{\ 2} / \Gamma_H$ → $\delta\, g_{HXX}/g_{HXX}$ ~ 1 %

Direct measurement of Higgs width removes model dependence !!

Higgs couplings

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

- The FCC-ee precision better than HL-LHC by large factors (for the copious modes)
  - The FCC-ee is best on the e^+e^- Higgs factory market
- It is important to have two energy points (240 and 365 GeV), as at the FCC-ee
  - Combination better by a factor up to 2 (4) than 240/250 (365/380) GeV alone

The FCC-ee provides the most precise measurement of Higgs couplings among all proposed future e^+e^- families

FCC-hh

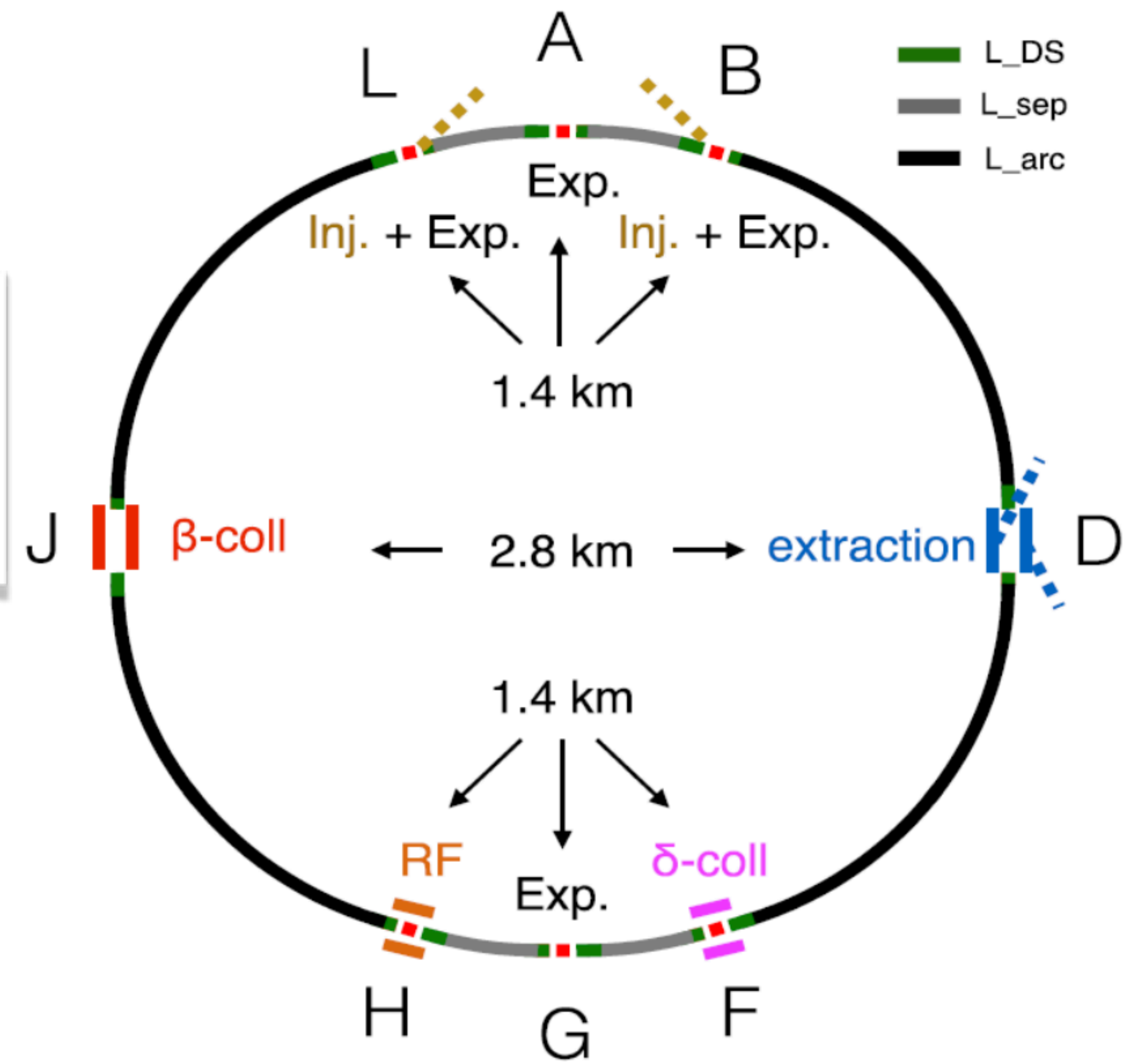
The FCC-hh

- Circumference = 100 km
- Need dipoles that generate B = 16 T (Need R&D)

$\sqrt{s}$ = 100 TeV

8 GJ kinetic energy per beam
- Airbus A380 at 720 km/h
- 2000 kg TNT
- O(20) times LHC

	FCC-hh Initial	FCC-hh Ultimate
Luminosity L [$10^{34}cm^{-2}s^{-1}$]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4



In its high luminosity phase, FCC-hh produces **1000 PU interactions** per bunch crossing

Int. luminosity 30 ab^{-1}

FCC-hh in a nutshell

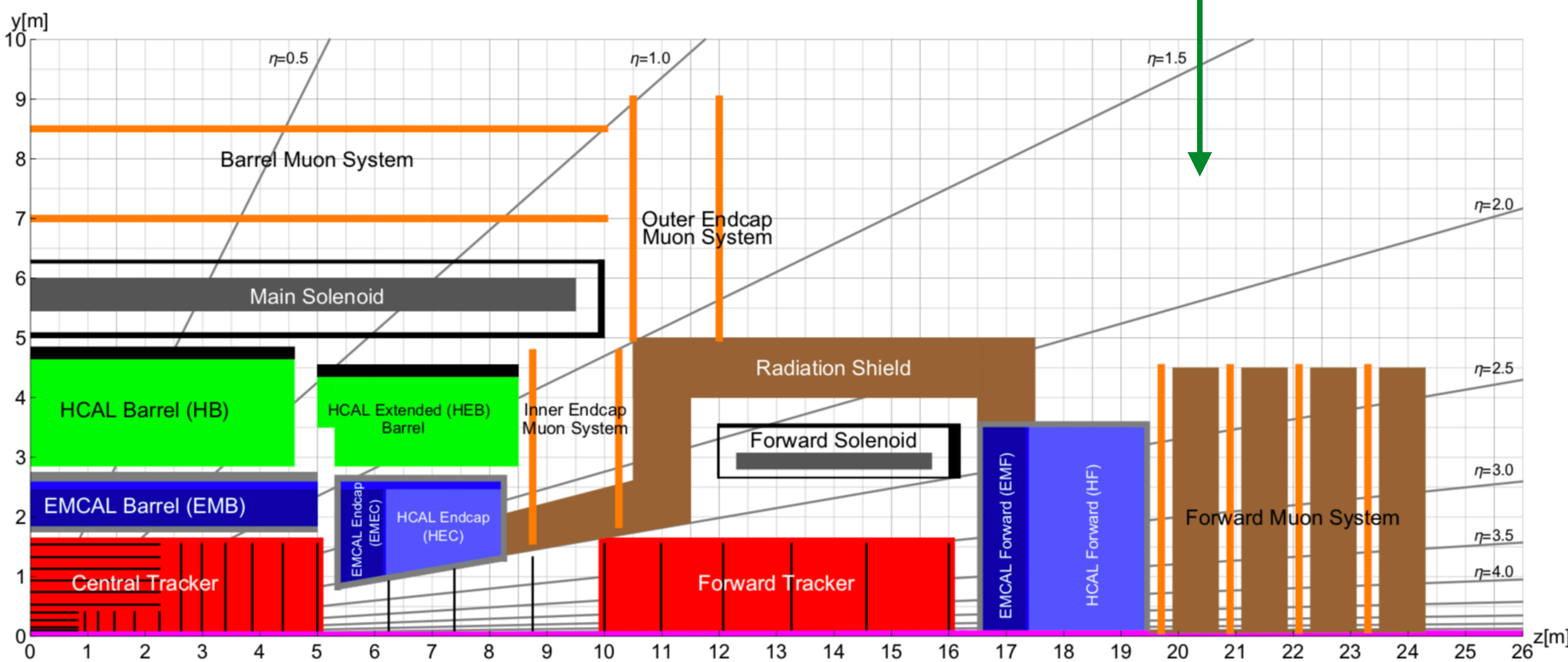
- **Ultimate discovery machine**
  - **directly** probe new physics up to **unprecedented** scale
  - discover/exclude:
    - heavy resonances "strong" m(q*) ≈ 50 TeV,
      "weak" m(Z') ≈ 40TeV,
    - SUSY m(gluino) ≈ 15 TeV,
      m(stop). ≈ 10 TeV
- **Precision machine**
  - probe Higgs **self-coupling** to few % level, and %-level precision for top Yukawa and 2nd generation.
  - measure **SM parameters** with high precision
  - exploit **complementarity with e^+e^-** by probing **high dim.operators** (EFT) in **extreme kinematic** regimes (boosted)

Physics program spans over very wide range of energy scales !

An FCC-hh detector

- Must be able to cope with:
  - very large dynamic range of signatures (E = 20 GeV -20 TeV)
  - hostile environment (1k pile-up and up to 10^{18} cm^{-2} MeV neq fluence)

- Characteristics:
  - large acceptance (for low p_T physics)
  - extreme granularity (for high p_T and pile-up rejection)
  - timing capabilities
  - radiation hardness

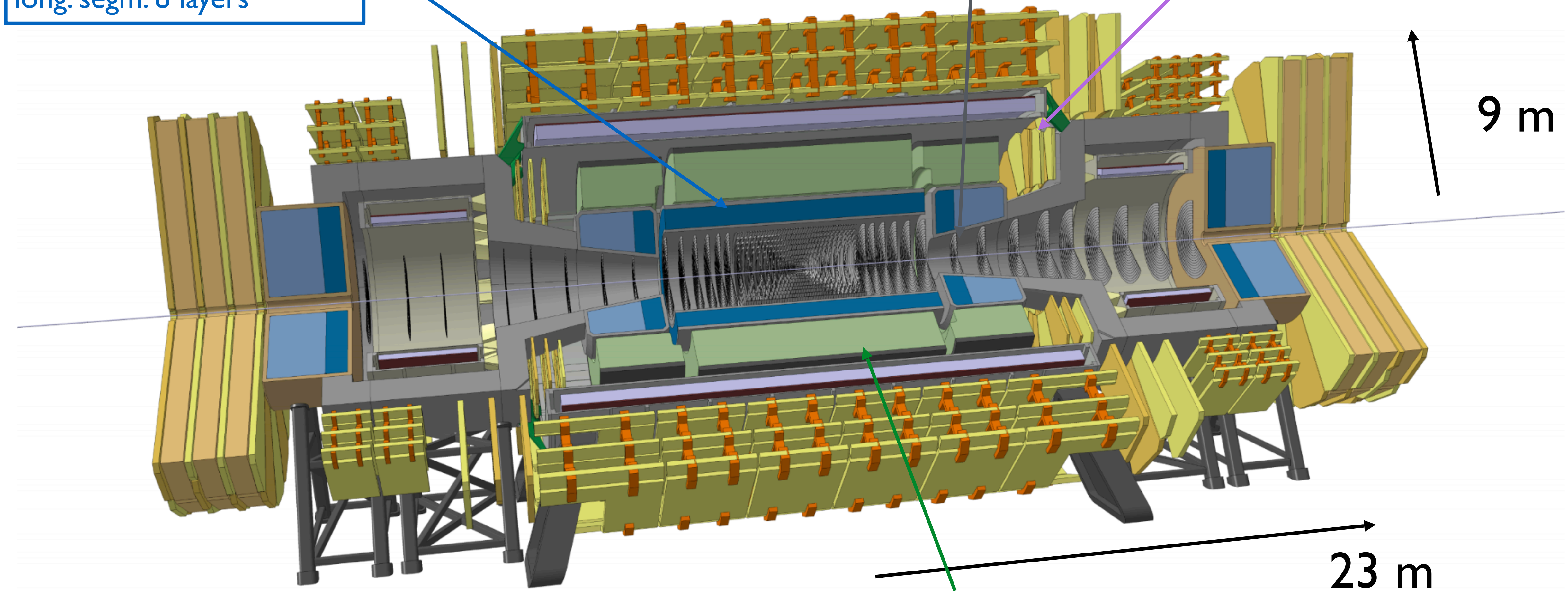


The FCC-hh detector

Tracker: σ_{p_T}/p_T ~ 20% at 10 TeV (1.5m radius)

Central Magnet + Fwd solenoids 4T

Barrel ECAL: LAr/Pb
σ_E/E ~10%/$\sqrt{E}$ ⊕ 0.7 %
30 X_0
lat. segm: $\Delta\eta\Delta\phi \approx$ 0.01
long. segm: 8 layers



Fwd ECAL: LAr/Cu
σ_E/E ~30%/$\sqrt{E}$ ⊕ 1 %
lat. segm: $\Delta\eta\Delta\phi \approx$ 0.01
long. segm: 6 layers

Fwd HCAL: LAr/Cu
σ_E/E ~100%/$\sqrt{E}$ ⊕ 10 %
lat. segm: $\Delta\eta\Delta\phi \approx$ 0.05
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
σ_E/E ~50-60%/$\sqrt{E}$ ⊕ 3 %
11 λ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx$ 0.025
long. segm: 10 layers

Higgs at the FCC-hh

- FCC-hh provides **unique and complementary measurements** to FCC-ee:
  - Higgs **self-coupling**
  - top Yukawa
  - **rare decays** (BR(μμ), BR(Zɣ), ratios, ..) measurements will be **statistically limited** at FCC-ee

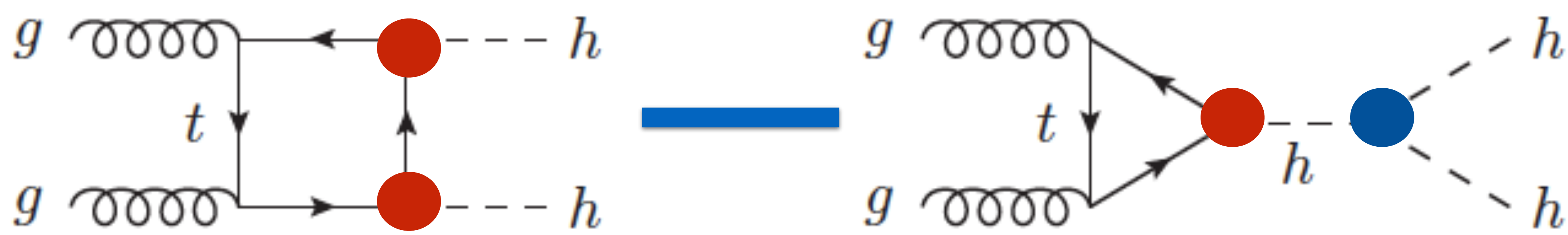
- Assuming, we know production xsec and luminosity, at pp colliders we **measure** $\mathbf{BR(i) = \Gamma_i / \Gamma_H}$

$$N = \sigma \mathcal{L} = \mathcal{L} * \sigma_{prod} * BR(i)$$

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	1.3	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	0.17	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	0.43	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	0.61	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	1.21	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	1.01	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	0.74	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	0.65 (*)
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	0.4 (*)
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–	0.95 (**)
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	0.91 (*)
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	7
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%	$BR_{inv} < 0.025\%$

- By performing measurements of ratios of BRs, FCC-ee allows to "convert" **relative measurements into absolute** via **HZZ (standard candle)**

Higgs at the FCC-hh



$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

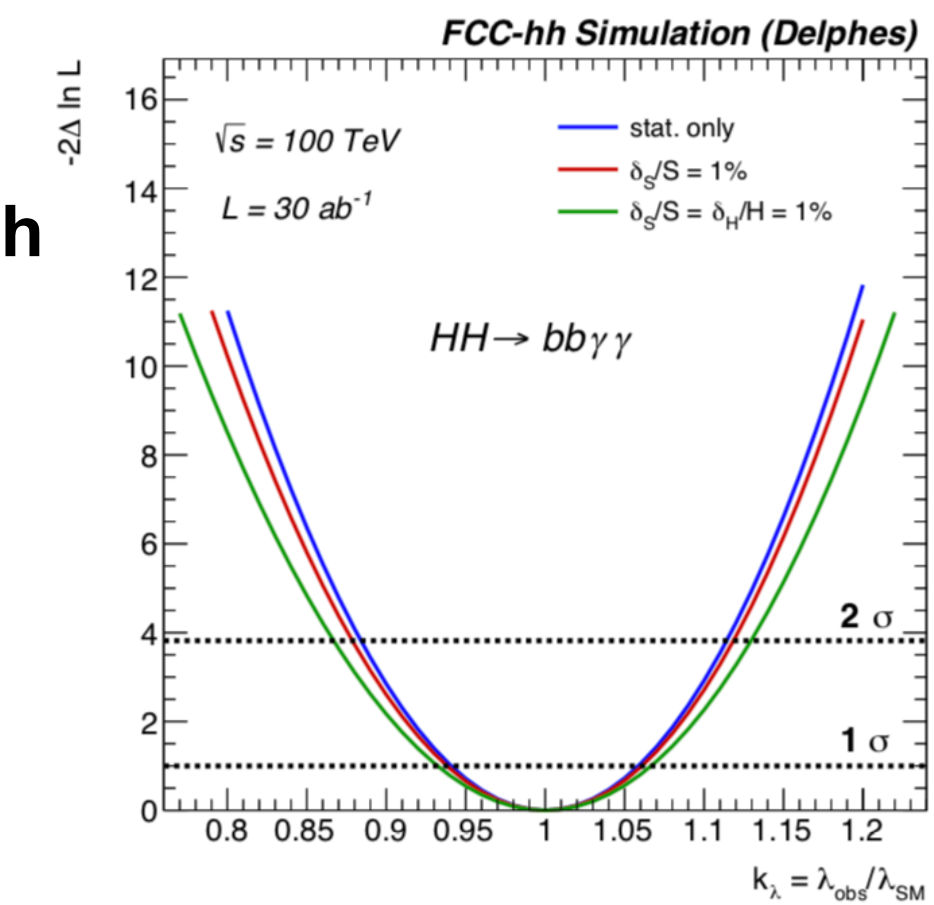
EFT Lagrangian

➡ **Enormous di-Higgs samples produced at FCC-hh**

- σ(100 TeV) / σ(14 TeV) ≅ 40
- L (SPPC) / L (HL-LHC) ≅ 10
- Naively, factor 20 smaller statistical uncertainty

➡ **Can study a number of final states**

- bbγγ most sensitive channel



$\delta k_\lambda / k_\lambda$ = 5 %

combining all channels

Summary Higgs measurements

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
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$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.91 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**7**
BR_{exo} (95%CL)	BR_{inv} < 2.5%	**< 1%**	**BR_{inv} < 0.025%**

Perfect complementarity between FCC-ee and FCC-hh !!!

What can the FCC-hh say about BSM physics

Exploration potential:

- New machines are built to make discoveries!
- Mass reach enhanced by factor $\sqrt{s}$/14TeV (5-7 at 100TeV)
- Statistics enhanced by several orders of magnitude for possible BSM seen at HL-LHC
- Benefit from both direct (large Q^2) and indirect precision probes

Could provide answers to questions such as:

- Is the SM dynamics all there at the TeV scale?
- Is there a TeV-Scale solution the hierarchy problem?
- Is Dark Matter a thermal WIMP?
- Was the cosmological EW phase transition 1st order? Cross-over?
- Could baryogenesis have taken place during EW phase transition?

Conclusions - I

HEP Landscape

G. Giudice

- Particle accelerators are built to answer some of the most fundamental questions about the natural world
- Physics priorities are likely to shift swiftly, as we advance in our exploration, both experimentally and theoretically
- There are many unknowns ahead of us that may reshuffle the cards (e.g. any discoveries of HL-LHC)

→ We need a broad and bold program capable of adapting to the swift changes in the physics landscape that are likely to happen

→ 100TeV hadron collider – In times of uncertainty, bold exploration is the way to go

Complementary and synergetic with a high luminosity e+e- machine such as the FCC-ee

Conclusions - 2

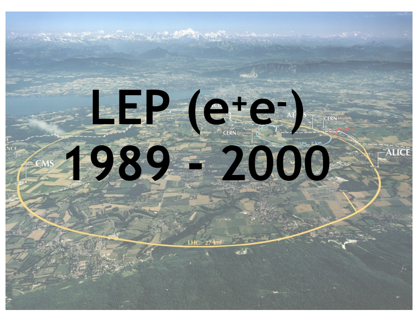
Future of HEP

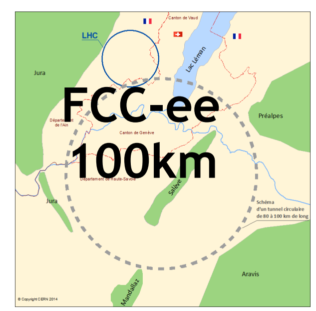
Tevatron 2TeV → (x 7) → **LHC 14TeV** → (x 7) → **FCC-hh 100TeV**

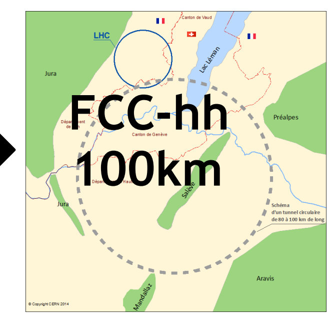
M. Aleksa pECFA

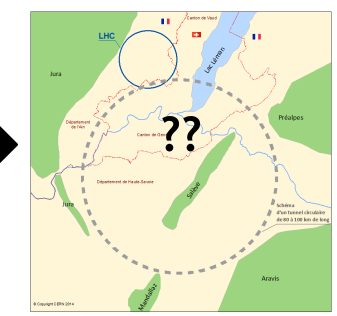
27km tunnel

The next step: 100km tunnel









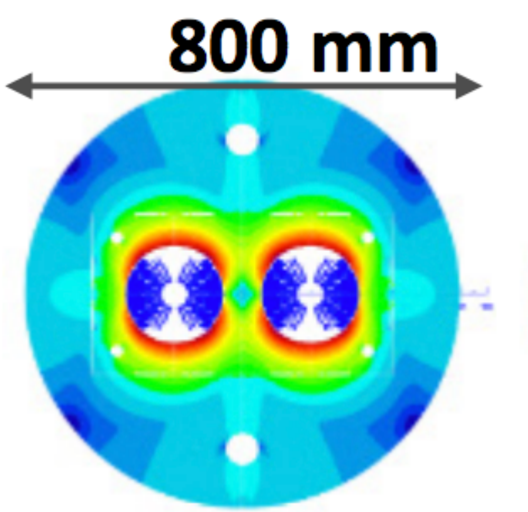
The FCC design study has established the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology

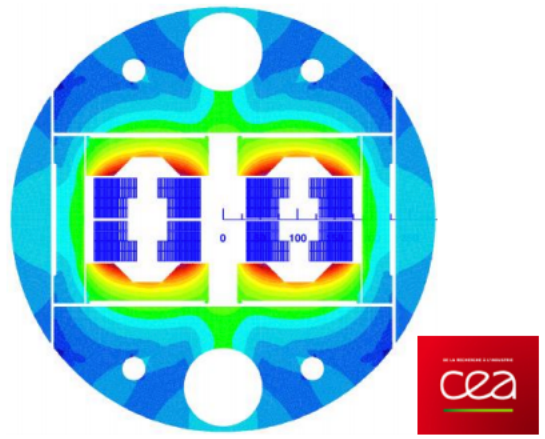
Let's make this happen !

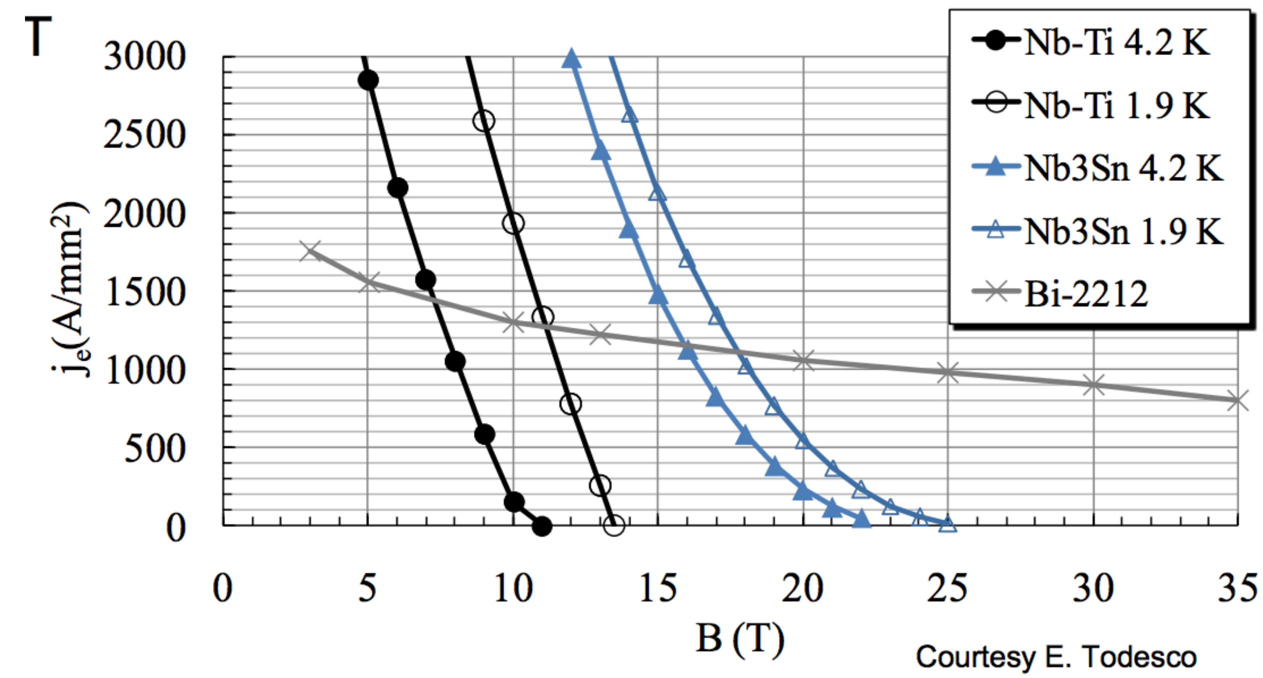
Backup

High Field Dipoles Magnets (16T)

- Nb-Ti not suited anymore (4-10T)
- Focus on Nb3Sn (also HLLHC)







Courtesy E. Todesco

Goal: Jc = 1500 A/mm² @ 4.2 K

- High Temperature Superconductors (Bi-2212) are promising, but stress sensitive, also low current density (but constant)

Many challenges:

- Need margin B ~ 20 T
- Conductor instabilities
- NbSn3 stress sensitivity …
- Cost?

How long? Manageable in ~ 15-20 yrs?

The FCC project (rationale)

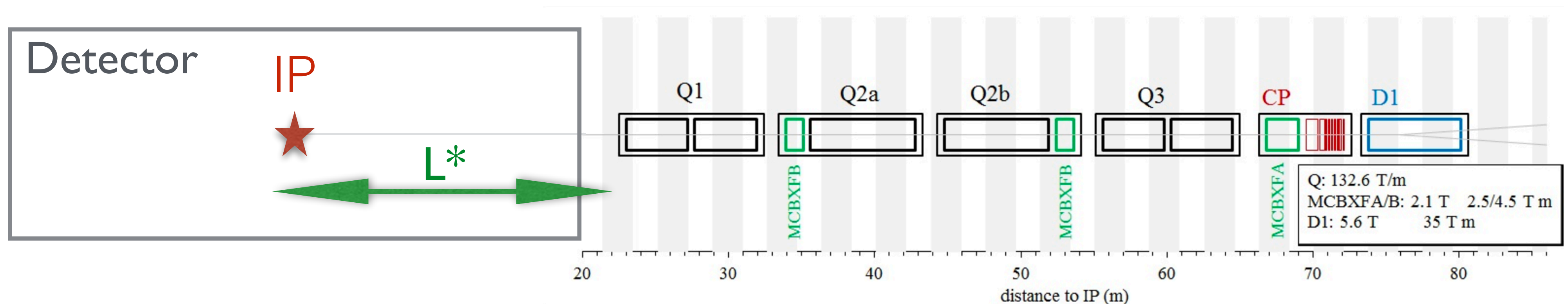
- HL-LHC data-taking ends in 2035
- Build a 100 km tunnel
- If magnets are ready by ~ 2040 go for FCC-hh
- If not FCC-ee ~20 yrs
- then FCC-hh ~20 yrs

Domain	**Cost in MCHF**
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**

~1 espresso/year/person

- 100 km tunnel ensures HEP field activities for ~ 60 yrs
- FCC-ee → FCC-hh → FCC-xx (x=μ)
- Long term accelerator complex easier to fund on flat budget

Constraints from the machine



- L* = 45 m
  - Distance between **triplet and IP**
  - determines overall **longitudinal size** of detector

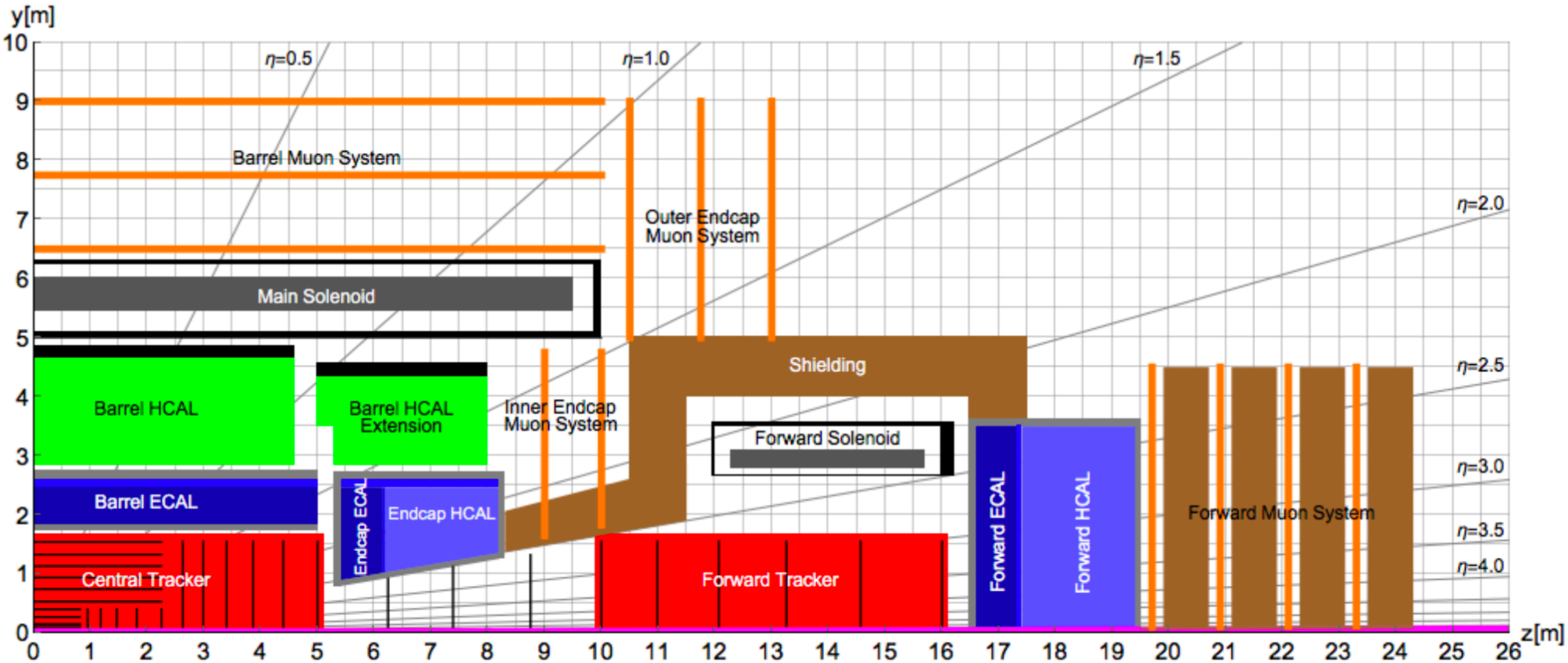
- Luminosity = [5×10^{34} - 30×10^{34}] $cm^{2}s^{-1}$
  - low lumi , N_{PU} = 170 (25ns)
  - high lumi , N_{PU} = **1020** (25ns) - 204 (5ns)

radiation

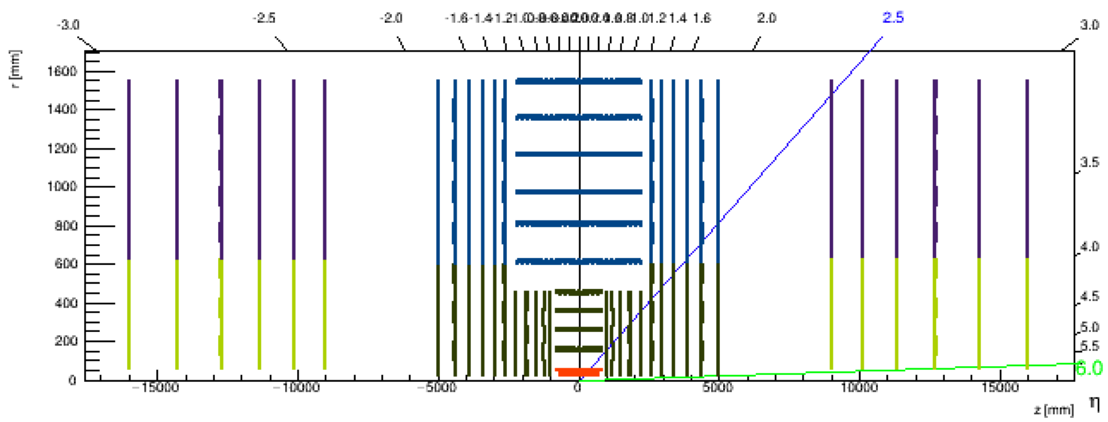
z_{vtx} resolution
CPU time
timing detector?

better for Tracking

Detector layout



Subdetectors

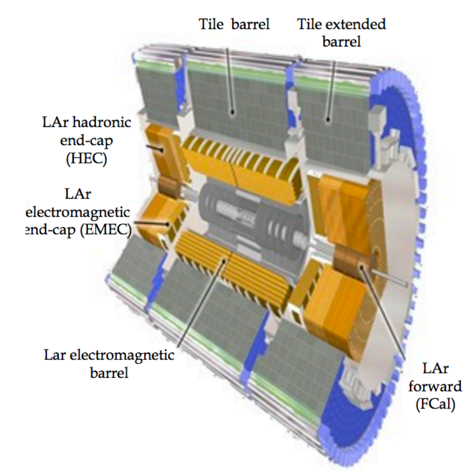


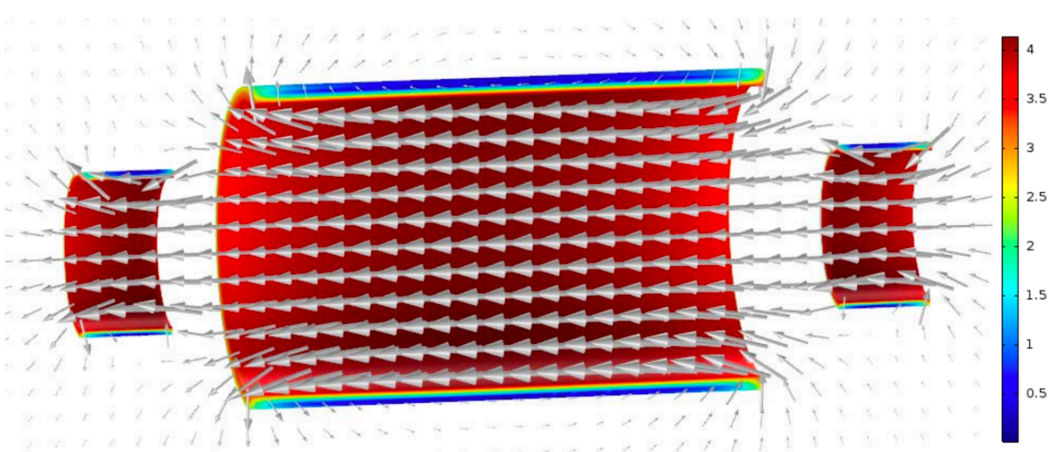
Tracker

- $-6 < \eta < 6$ coverage
- pixel : $\sigma_{r\phi} \sim 10\mu m$, $\sigma_Z \sim 15\text{-}30\mu m$, $X/X_0(\text{layer}) \sim 0.5\text{-}1.5\%$
- outer : $\sigma_{r\phi} \sim 10\mu m$, $\sigma_Z \sim 30\text{-}100\mu m$, $X/X_0(\text{layer}) \sim 1.5\text{-}3\%$

Calorimeters

- ECAL: LArg , $30X_0$, 1.6 λ, r = 1.7-2.7 m (barrel)
- HCAL: Fe/Sci , 9 λ, r = 2.8 - 4.8 m (barrel)
- endcaps and fwd to be defined (investigating HGCAL …)



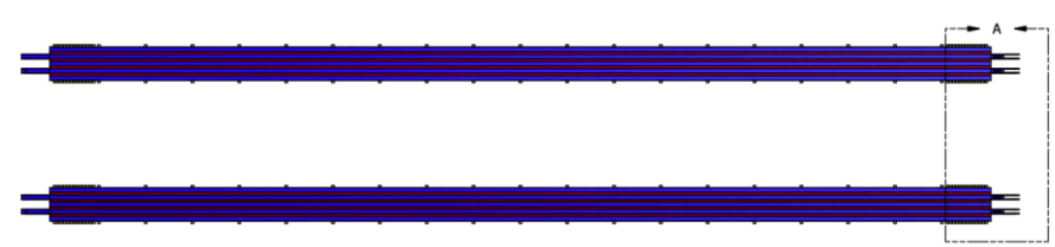


Magnet

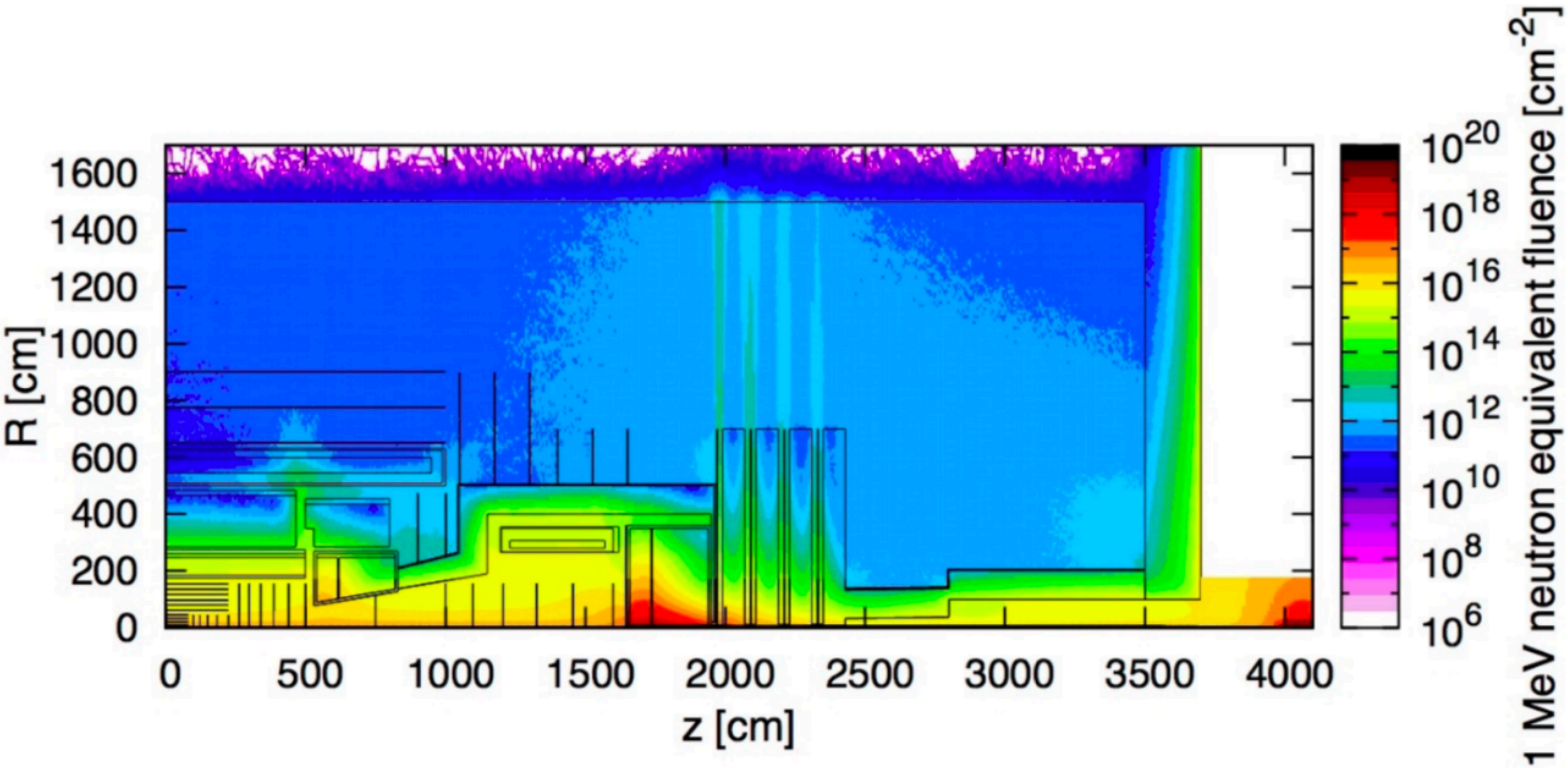
- central R = 5, L = 10 m, B = 4T
- forward R = 3m , L = 3m , B = 4T

Muon spectrometer

- Two stations separated by 1-2 m
- 50 µm pos., 70µrad angular



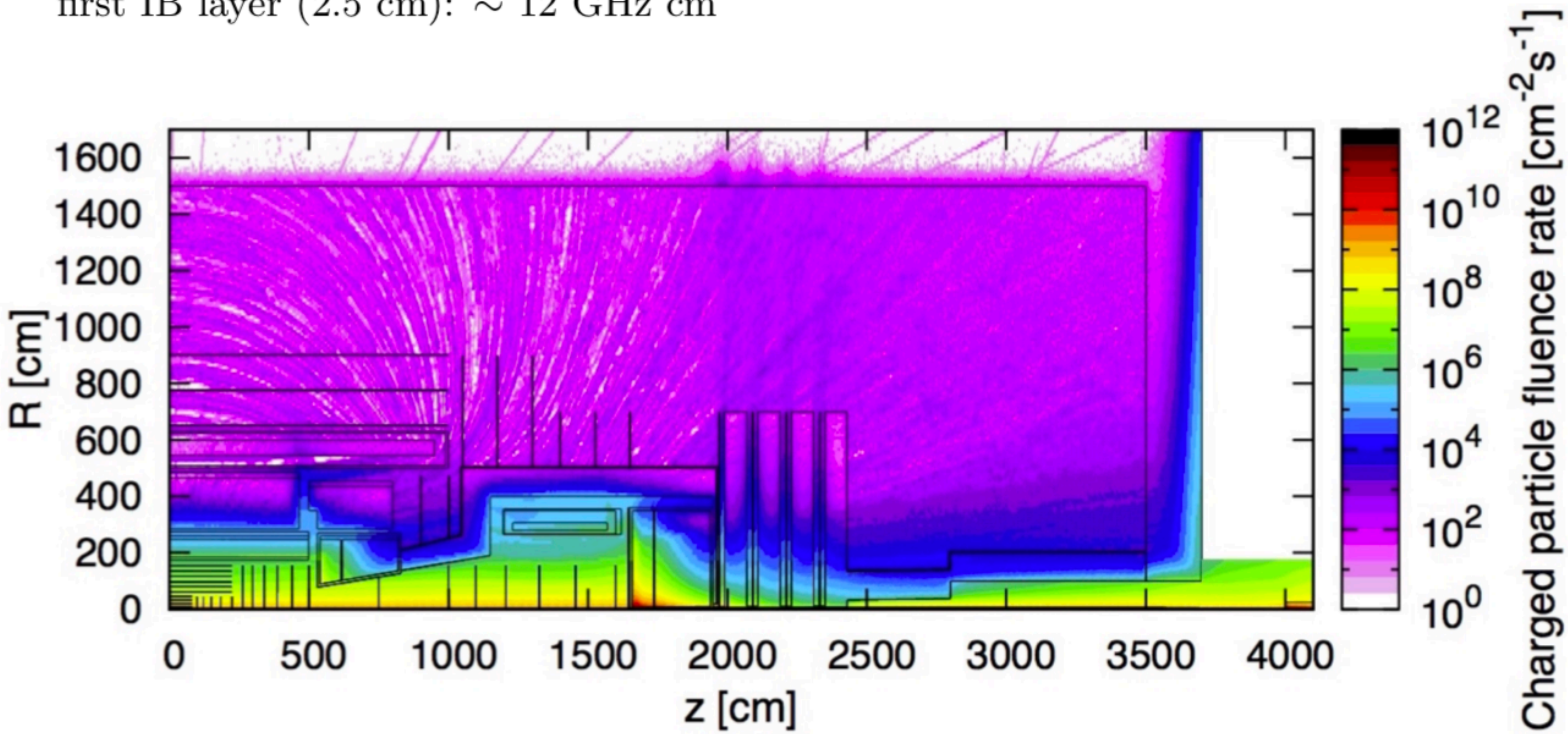
1 MeV neutron equivalent fluence for 30 ab^{-1}



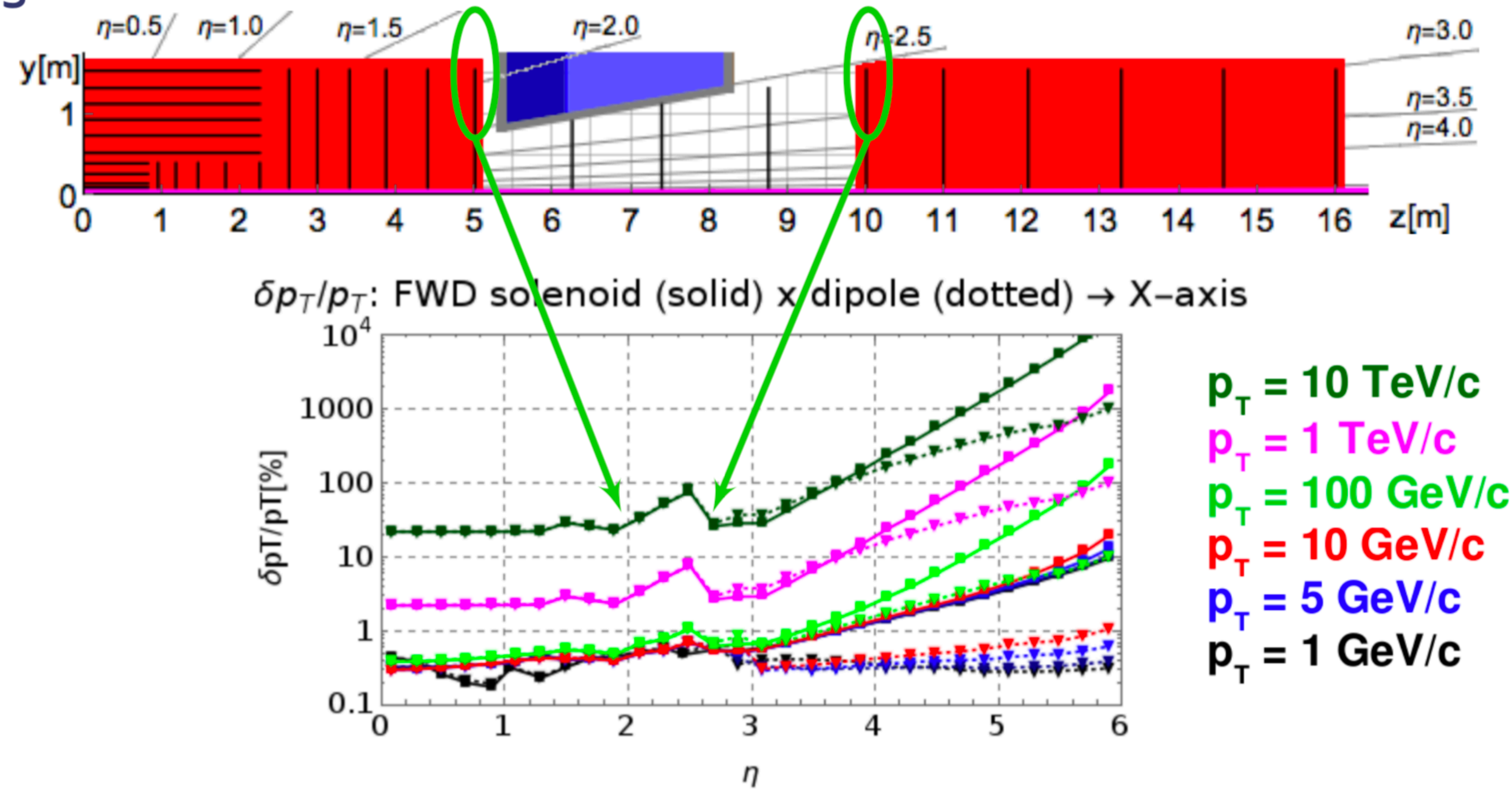
Forward calorimetry:
maximum at $\sim 10^{18}$ cm^{-2}

Charged particle fluence rate for $\mathrm{L} = 30 \cdot 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

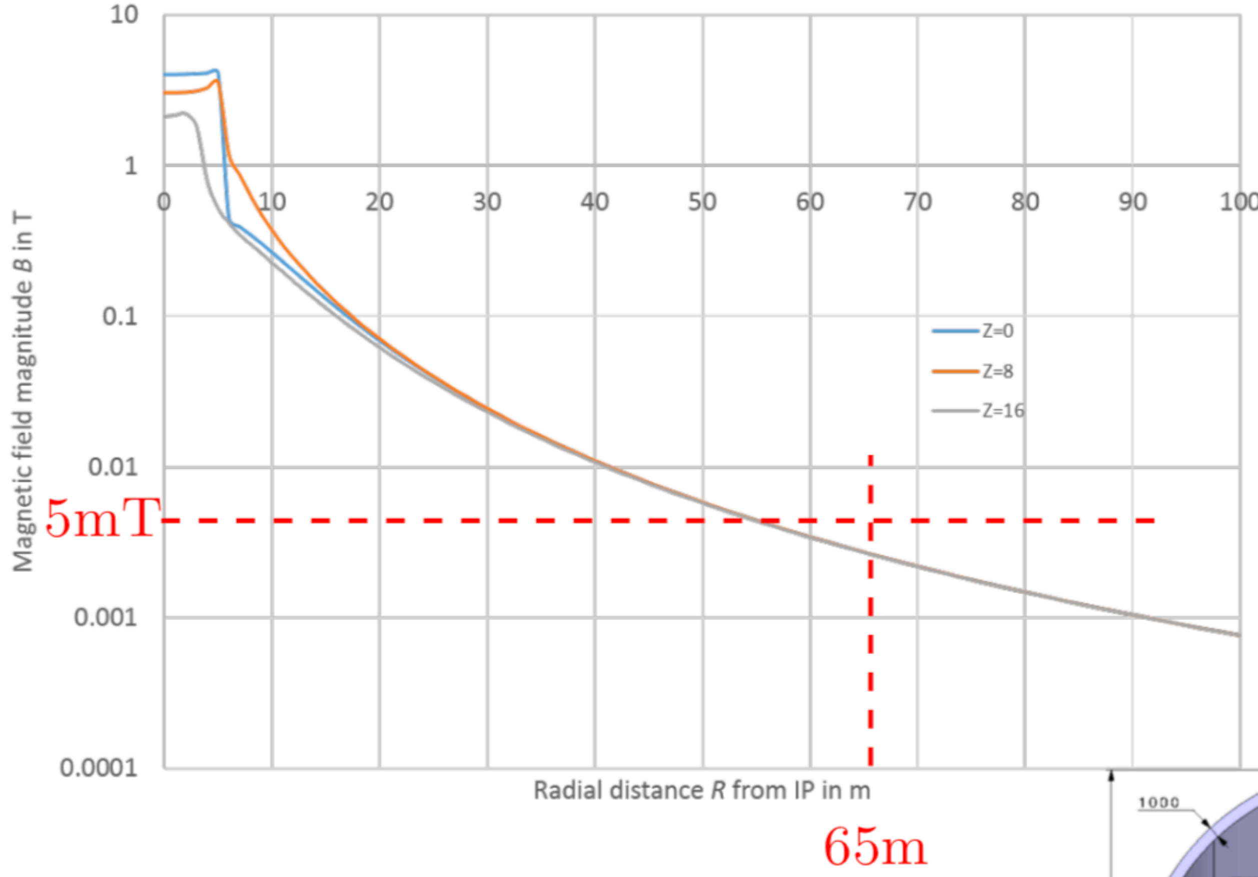
Tracker:
first IB layer (2.5 cm): ~ 12 GHz cm^{-2}

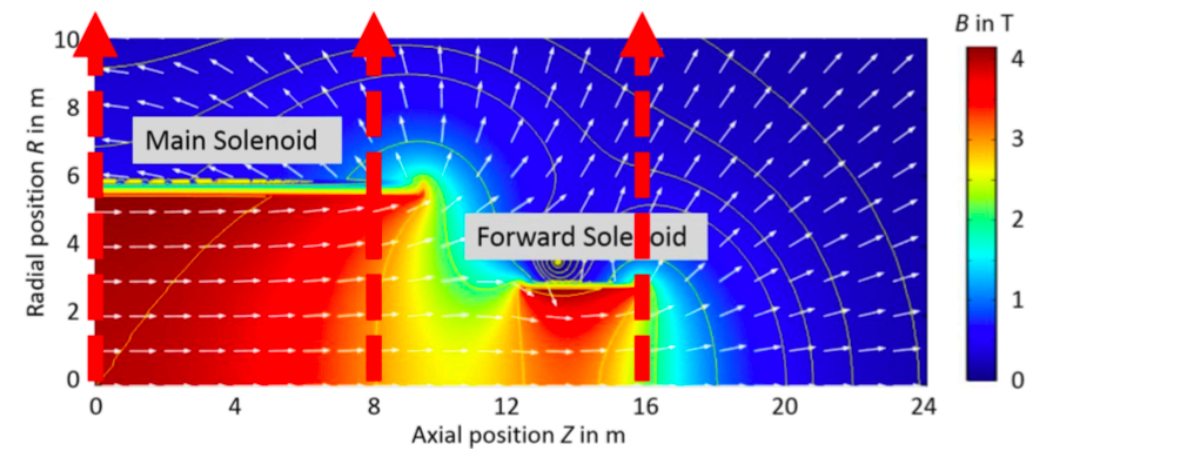


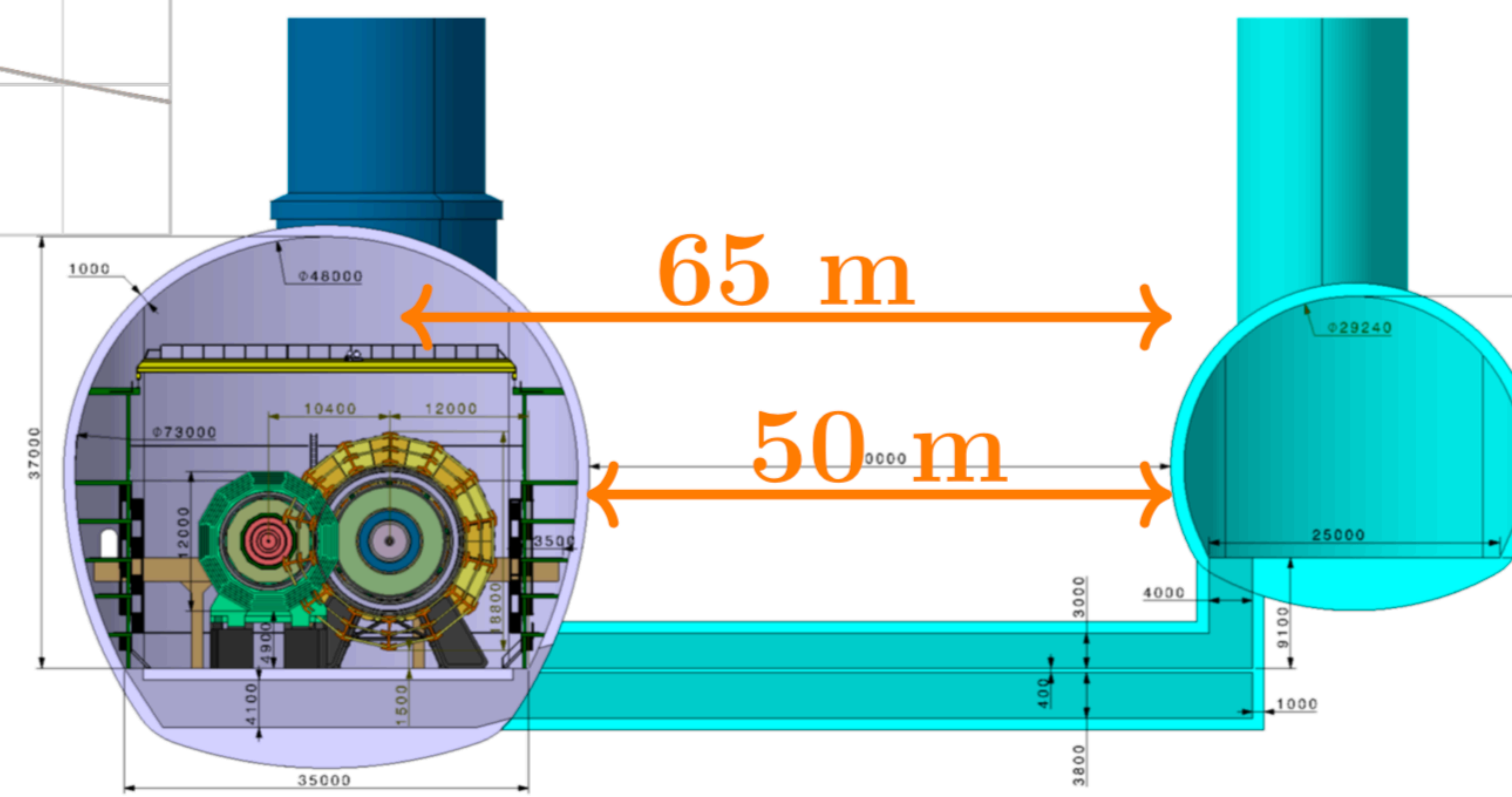
Magnet: momentum resolution



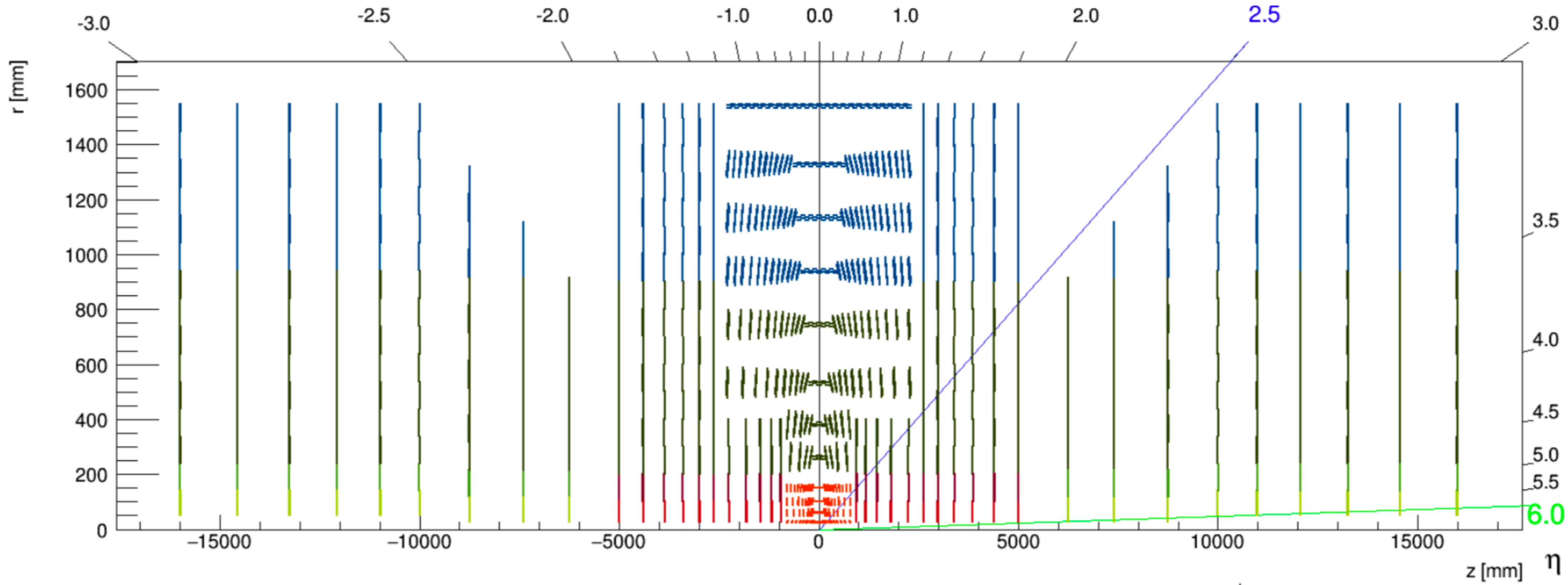
Stray field and service cavern





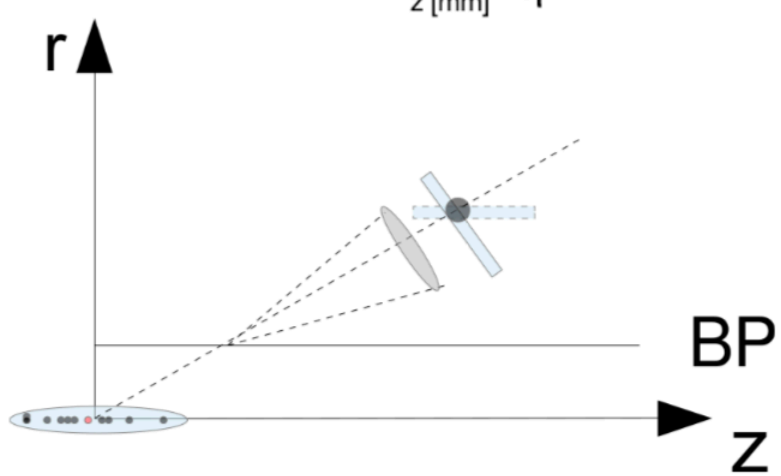


Subdetectors

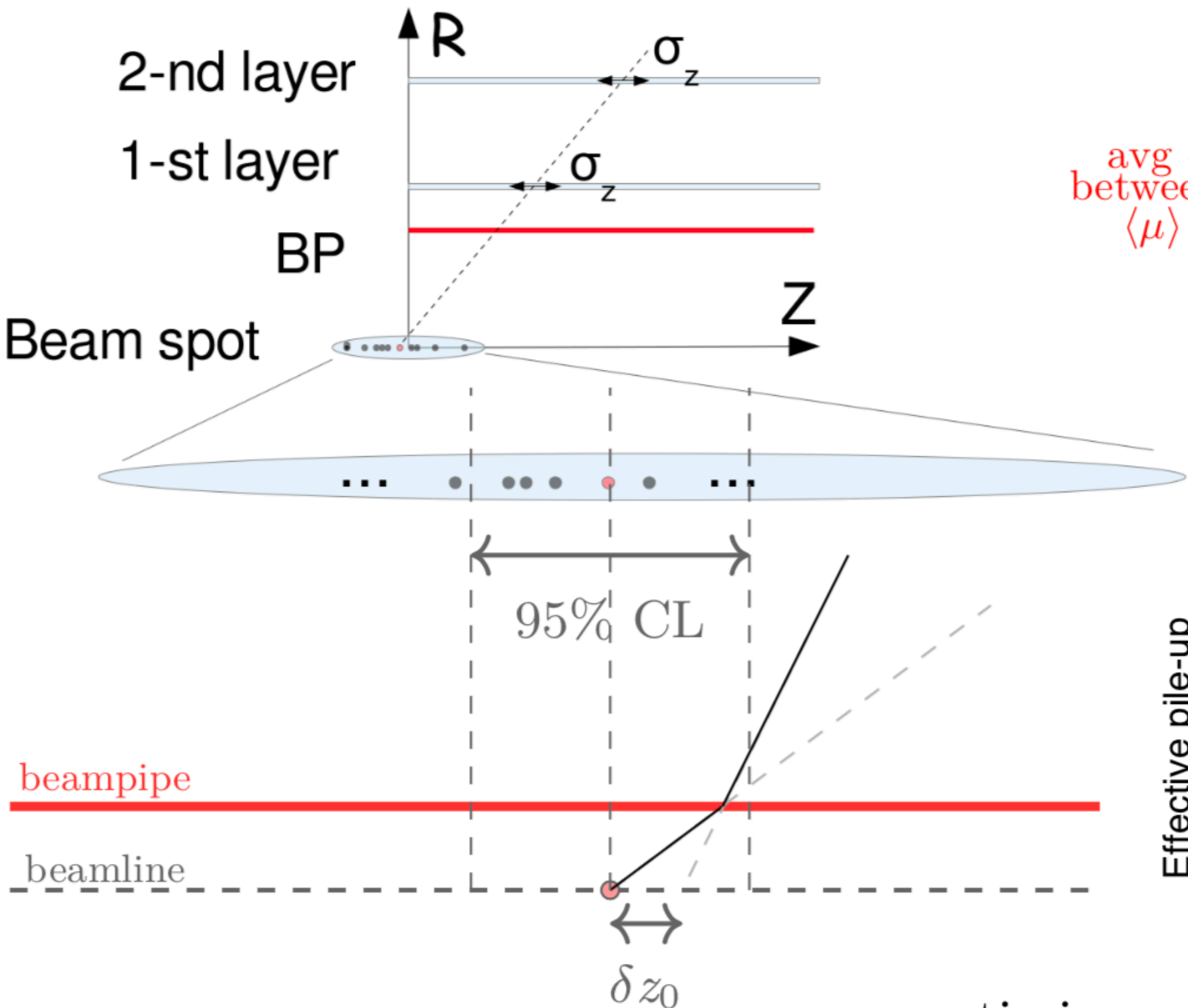


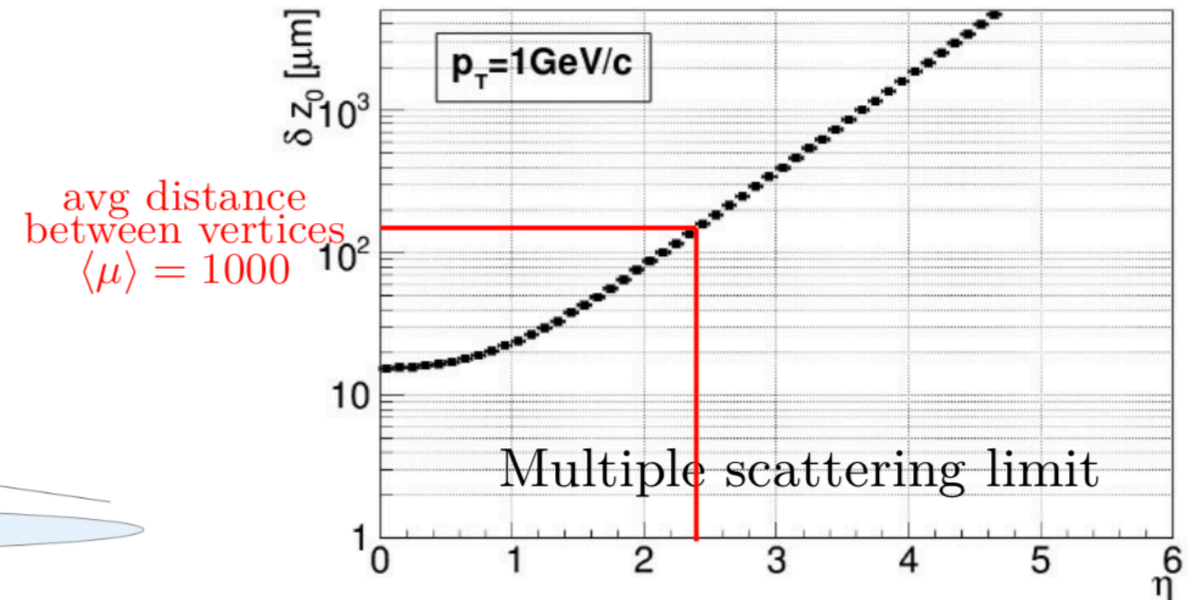
- Minimization of the effect of multiple scattering (material budget).
- Optimised by the pattern recognition and vertexing.

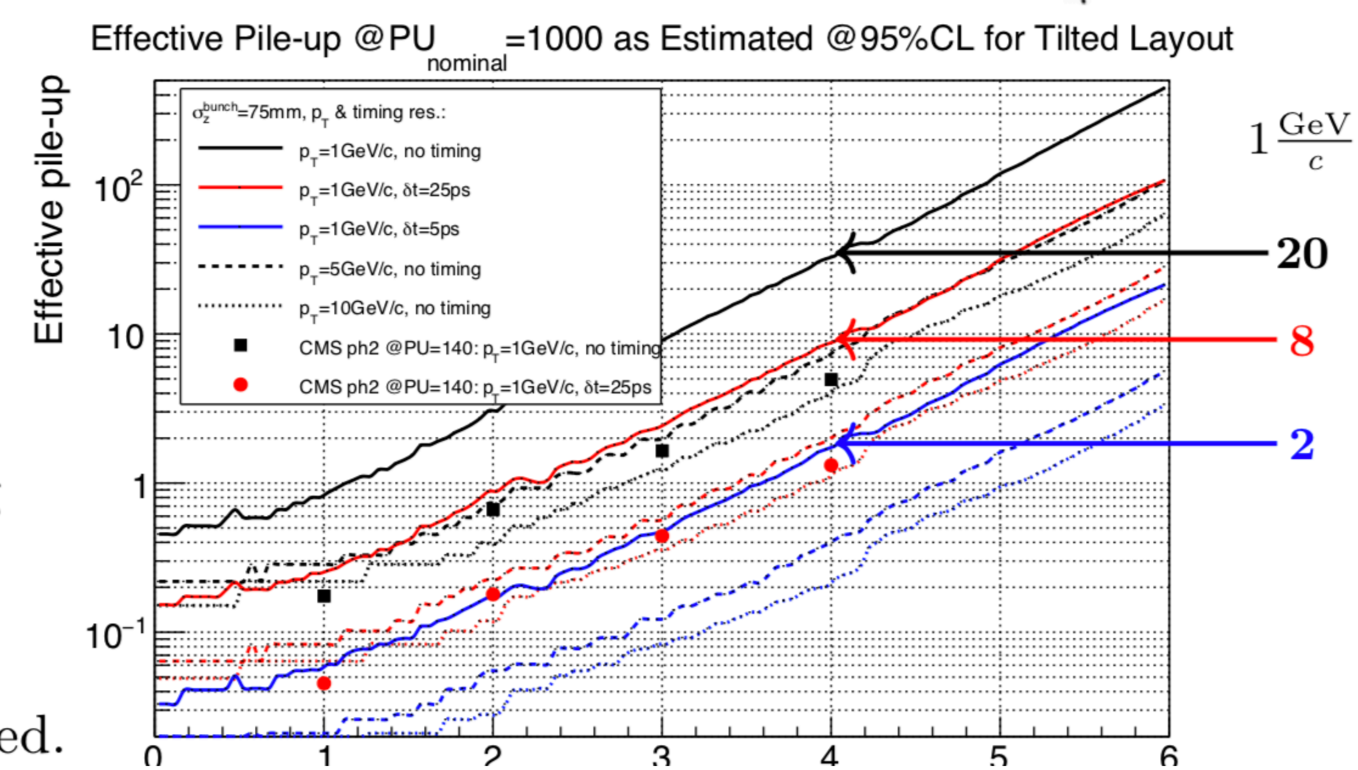
→ Inclined tracker modules.



Tracker



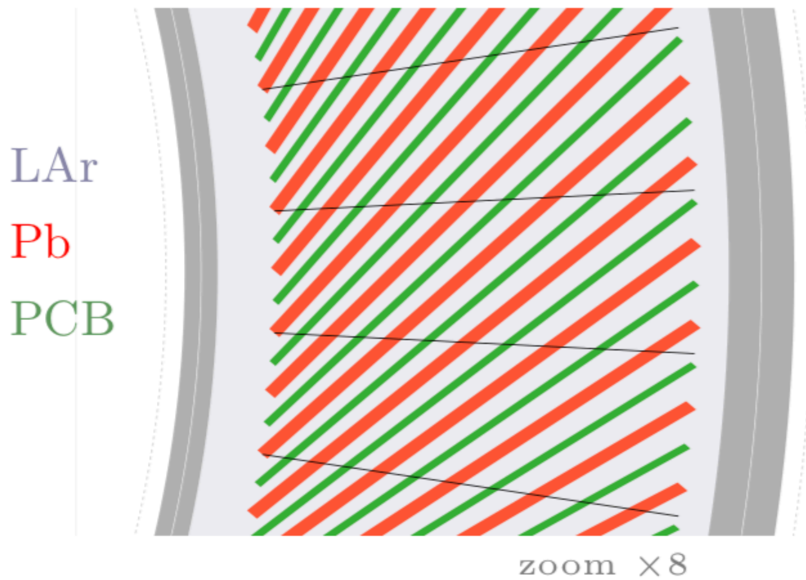




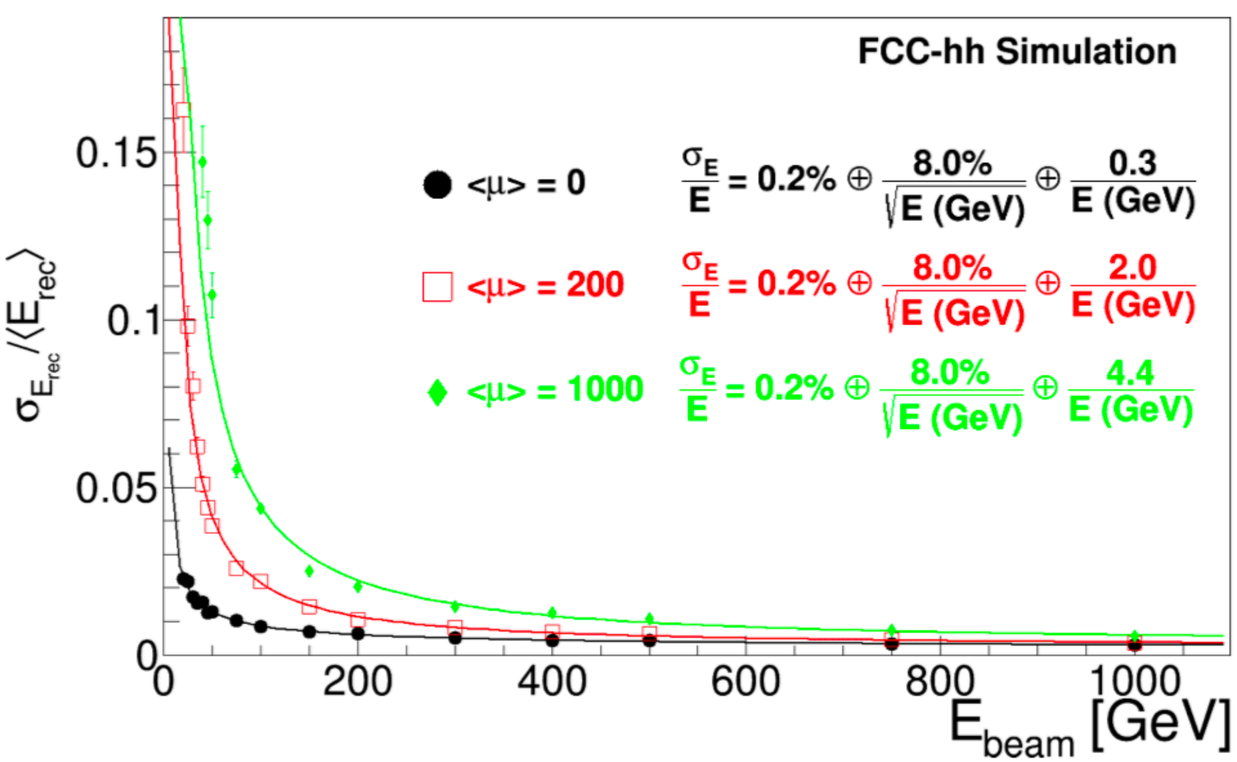
no timing
δt=25 ps
δt=5 ps

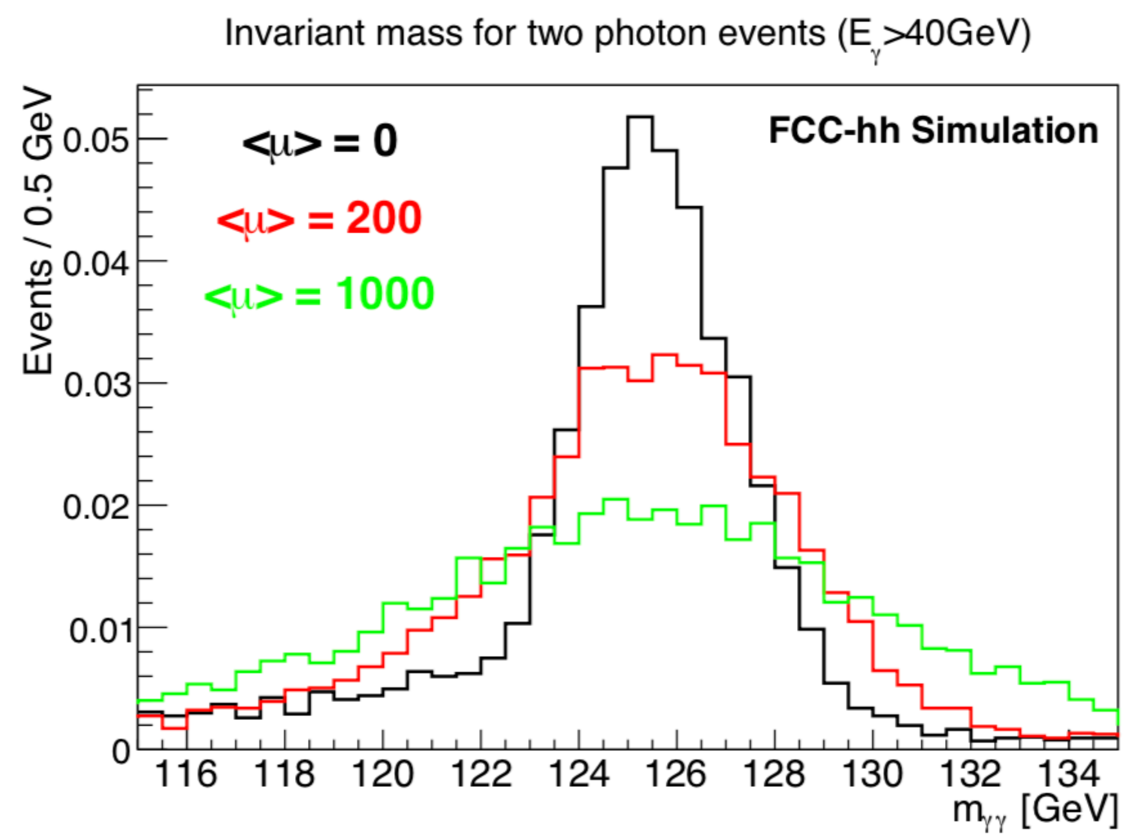
To mitigate the pile-up effect
tracking with precise timing information required.

LAr electromagnetic calorimeter



- Much more granular than ATLAS calorimeter (×10).
- High longitudinal and lateral segmentation possible with straight, multilayer electrodes.
- Huge impact of pile-up in calorimeter standalone measurement
need to subtract pile-up using pile-up track identification.





Trigger

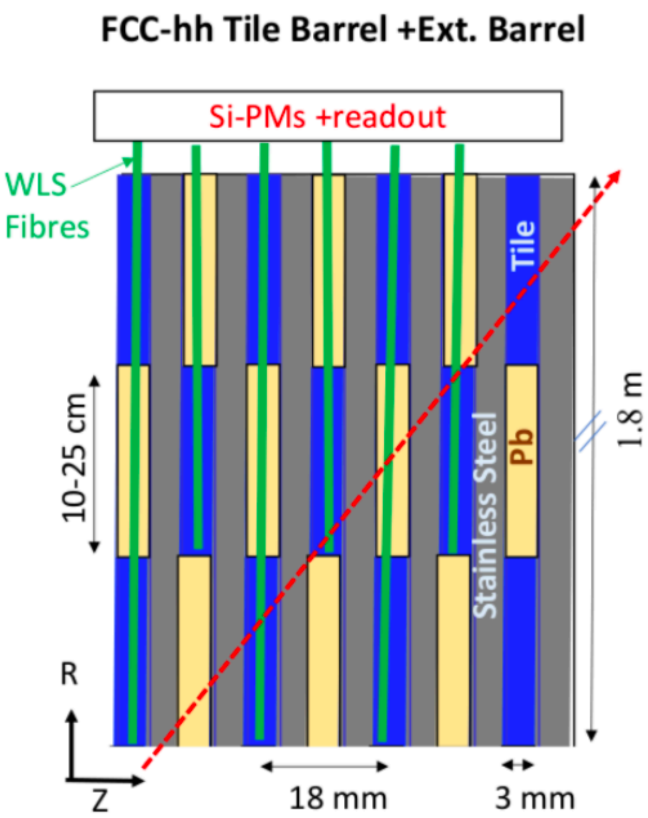
Example: ATLAS Phase-II:

- Calorimetry will be digitized at 40 MHz and sent via optical fibers to L1 electronics outside the cavern at **25 TB/s** to create the L1 Trigger.
- Muon system will also be read out at 40 MHz to produce a L1 Trigger.

FCC-hh detector:

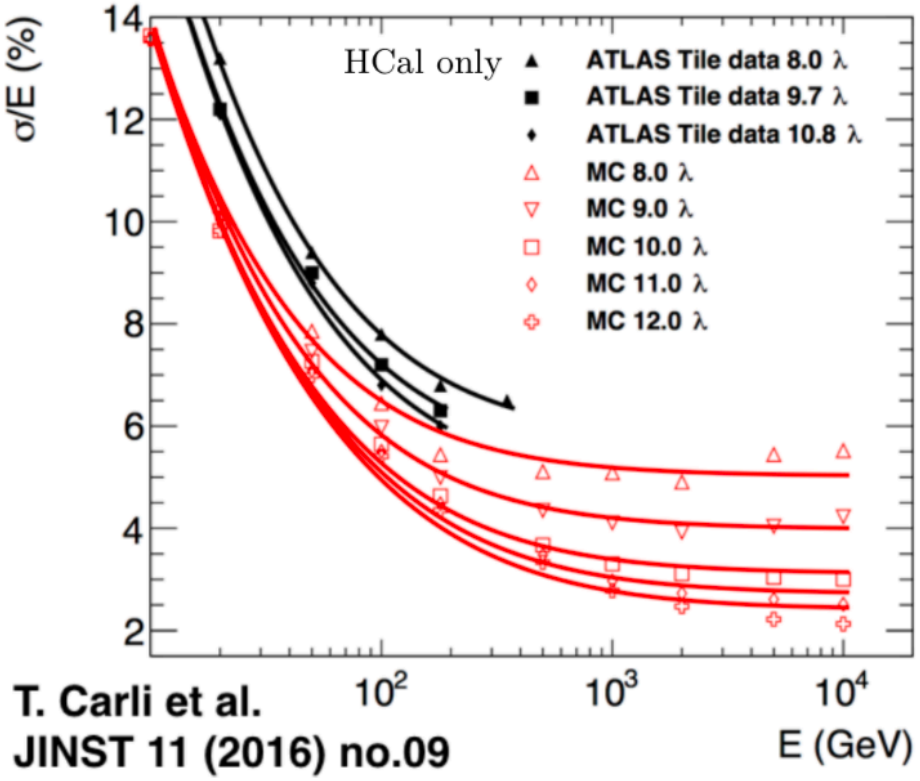
- Reading out the FCC detector calorimetry and muon system at 40 MHz result in **200-300 TB/s**: seems feasible.
- Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1 MHz ?
  - Reading tracker at 40 MHz results in ~**800 TB/s**.
  - Untriggered detector readout at 40 MHz would result in over **1 PB/s** over optical links to the underground service cavern and/or a HLT computing farm on the surface.

Hadronic barrel calorimeter



- ATLAS-like tile calorimeter with scintillating tiles/WLS fibres + stainless steel and lead (1: 3.3:1.3)
- SiPM readout: faster, less noise, less space
- 3-4 times higher granularity in $\Delta\eta\Delta\varphi = 0.025 \times 0.025$ and 10 layers
- For containment of multi-TeV jets (98%): ECAL + HCAL depth $\sim 11\lambda$ at $\eta = 0$.

calorimeter depth



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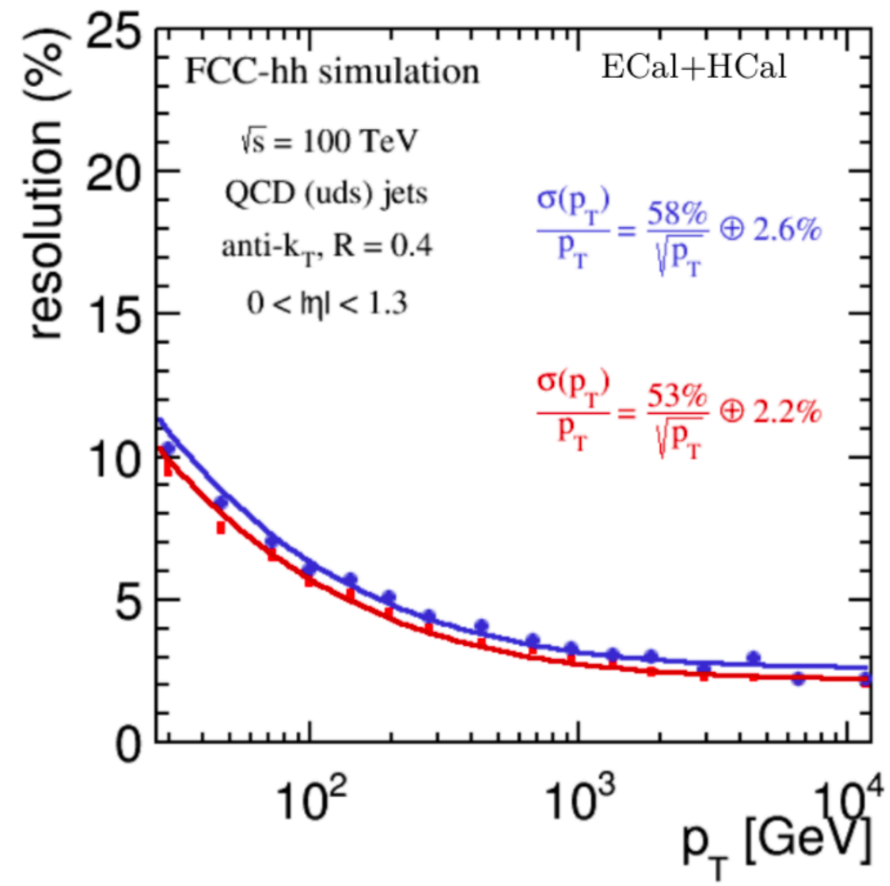
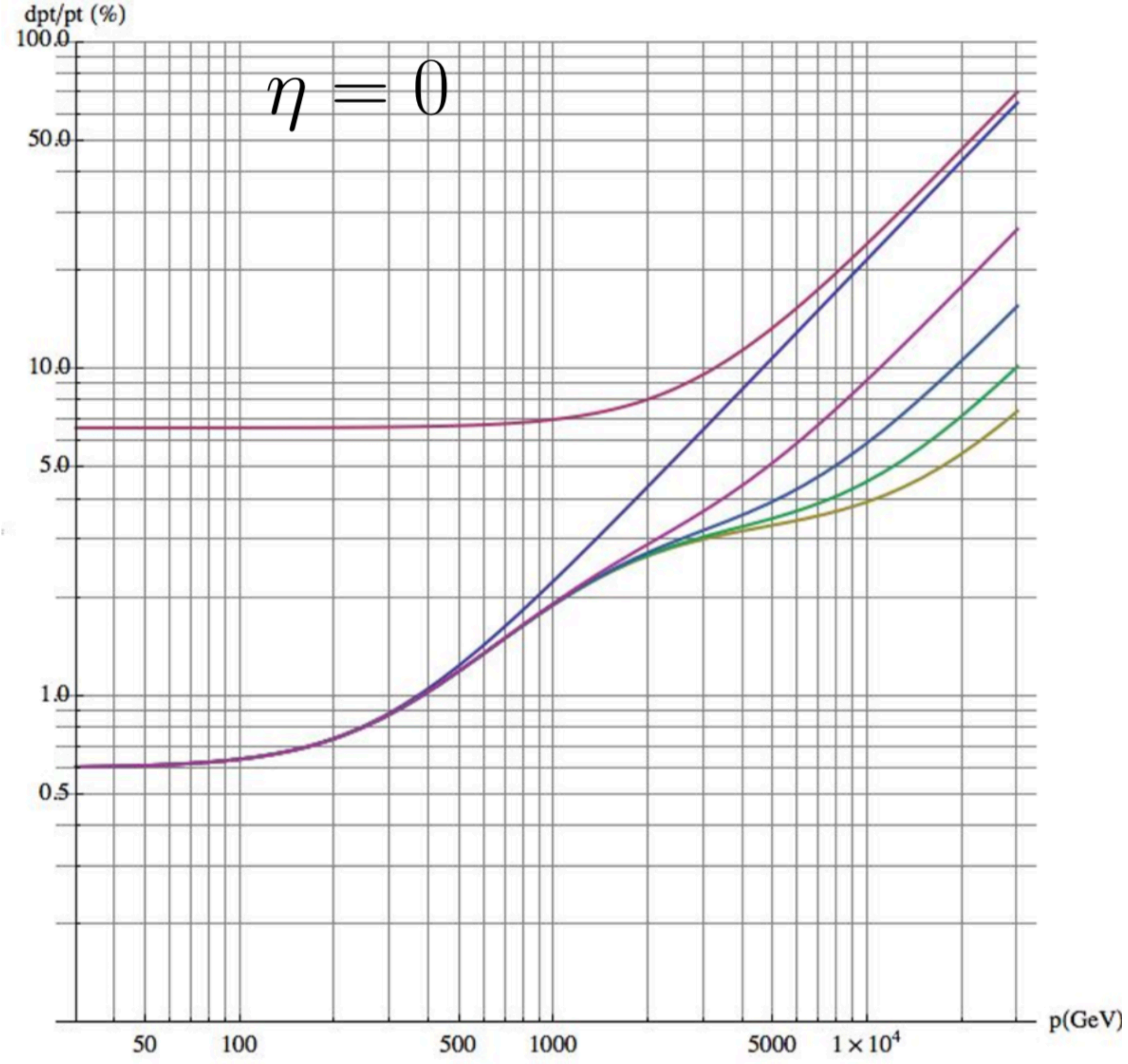
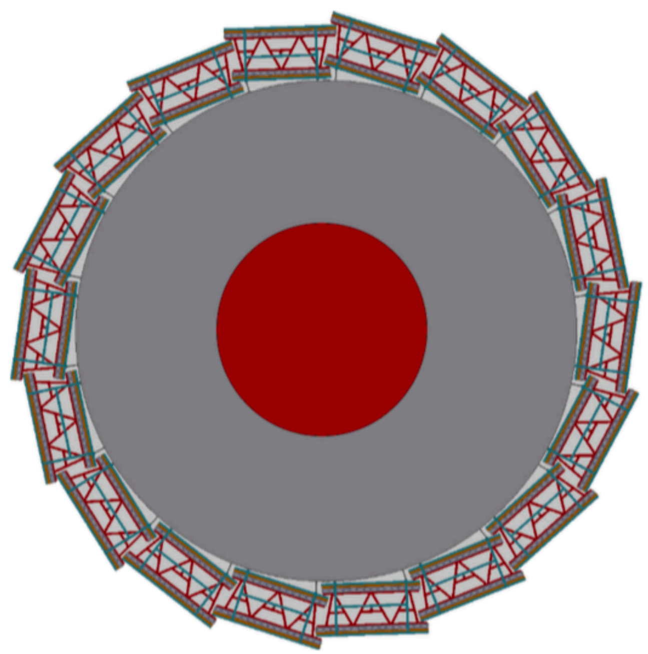
jet resolution



Muon chambers





- FCC Tracker
- FCC Muon standalone 70uRad Angular Resolution
- FCC Combined M.S. Limit
- FCC combined 25um Muon Position Resolution
- FCC combined 50um Muon Position Resolution
- FCC combined 100um Muon Position Resolution

Precision vs. sensitivity

- We often talk about "**precise**" SM measurements. What we actually aim at is "**sensitive**" tests of the Standard Model, where *sensitive* refers to the ability to reveal BSM behaviours.
- **Sensitivity** may not require extreme precision. Going after "sensitivity", rather than *just* precision, opens itself new opportunities .
- For example, in the context of dim. 6 operators in EFT, some operators grow with energy:

BR measurement: $$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$ ⇒ **precision** probes large Λ

e.g. $\delta O = 1\%$ ⇒ $\Lambda \sim 2.5$ TeV

$\sigma(p_T > X)$: $$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$ ⇒ **kinematic reach** probes large Λ

e.g. $\delta O = 15\%$ at Q=1 TeV ⇒ $\Lambda \sim 2.5$ TeV

Reach @100TeV

$\mathcal{L}$ = integrated luminosity

L = parton luminosity

$L \sim 1/\tau^a$, $\tau = x_1 x_2 = M^2 / s$

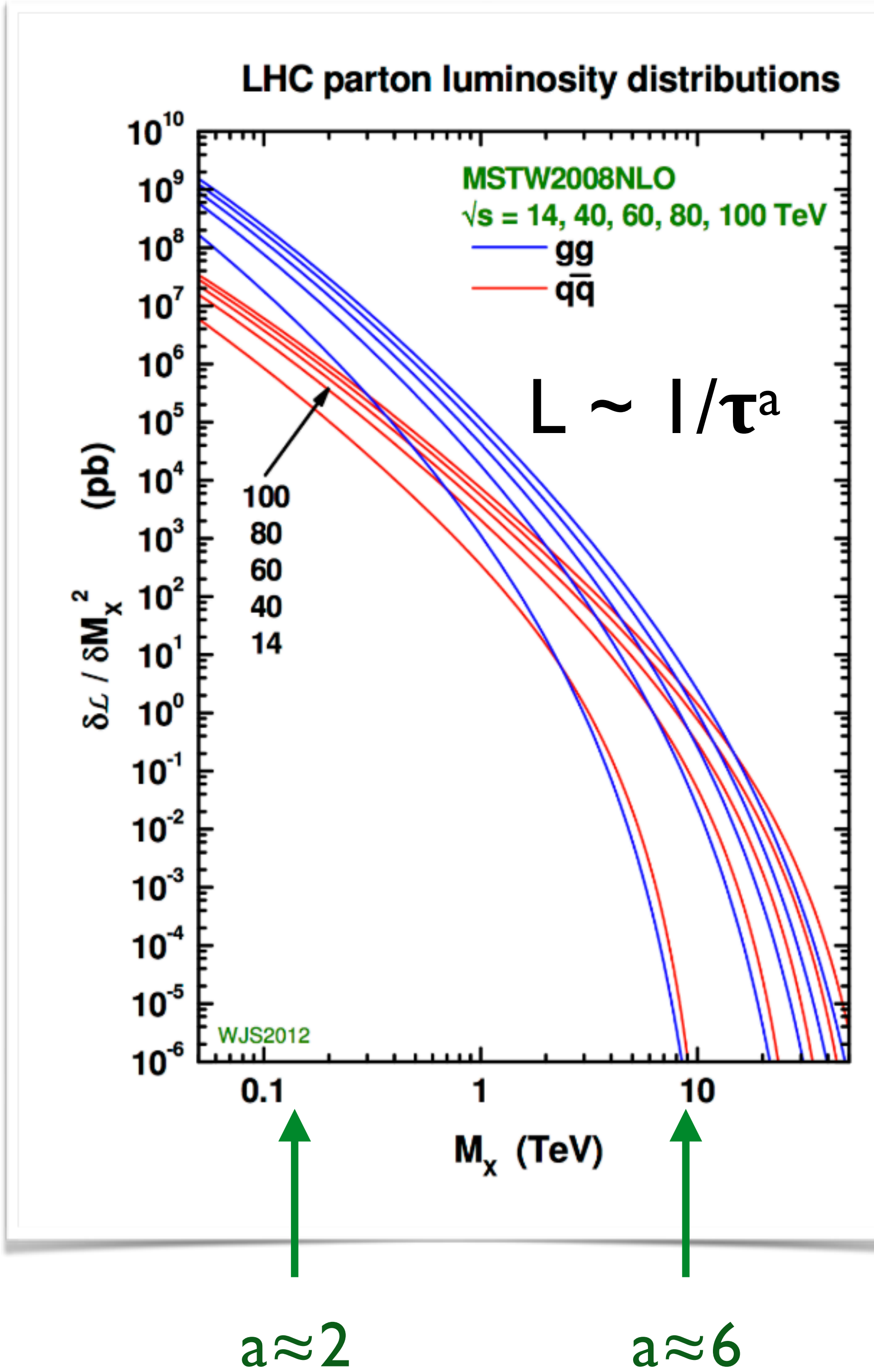
$L \sim (s/M^2)^a$

σ (part) $\sim 1/M^2$

\# events = $\sigma \mathcal{L}$

$\sigma \approx \sigma$ (part) L

$\sigma \approx (s / M^{2+2/a})^a$



Reach of collider at $\sqrt{s_1}$ vs $\sqrt{s_2}$:

$(M_2 / M_1) \sim (s_2 / s_1)^{1/2} \, [(s_1/s_2)(\mathcal{L}_2/\mathcal{L}_1)]^{1/(2a+1)}$

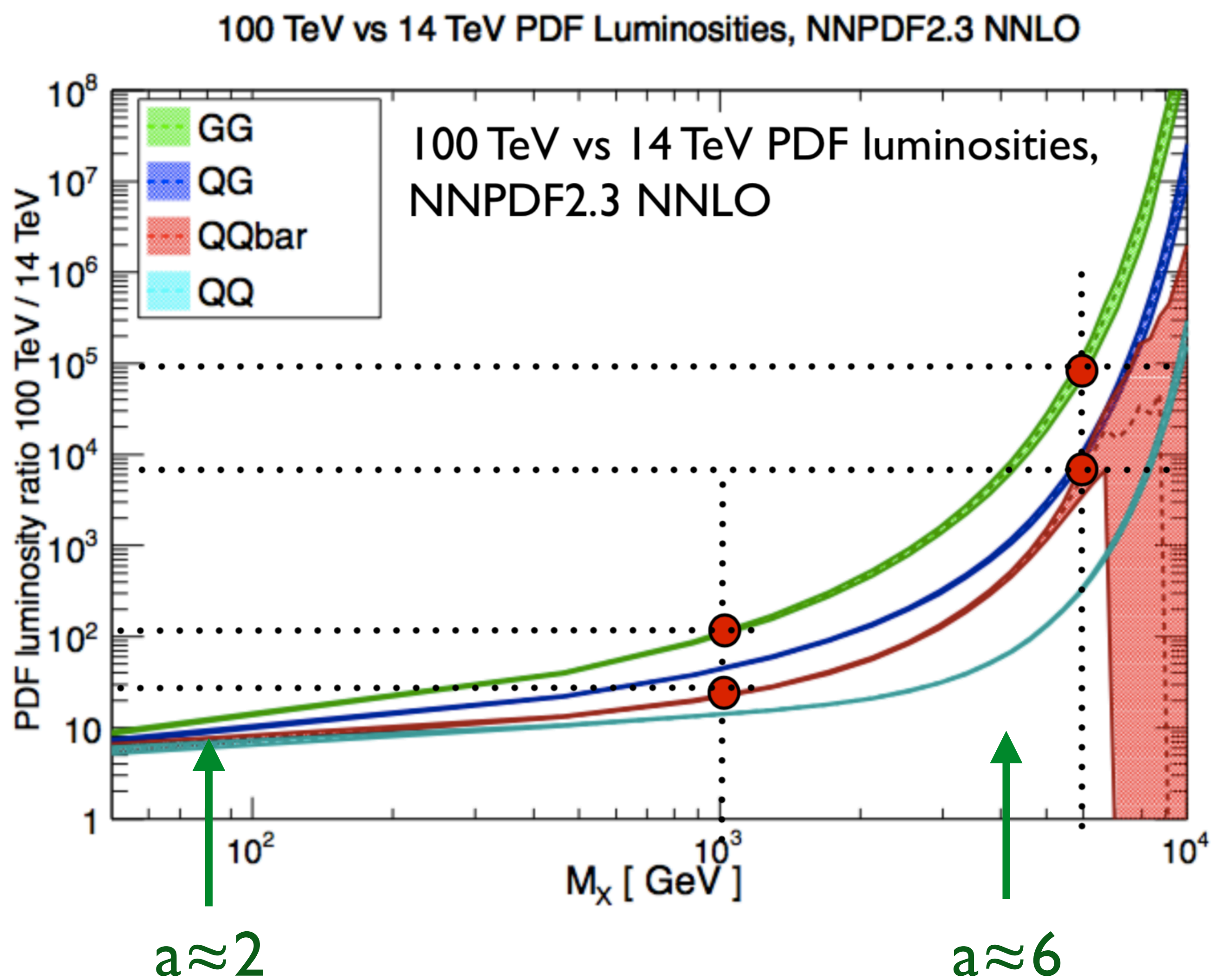
At high mass (high x), a >> 1:

Mass reach goes up by factor 7 (roughly)

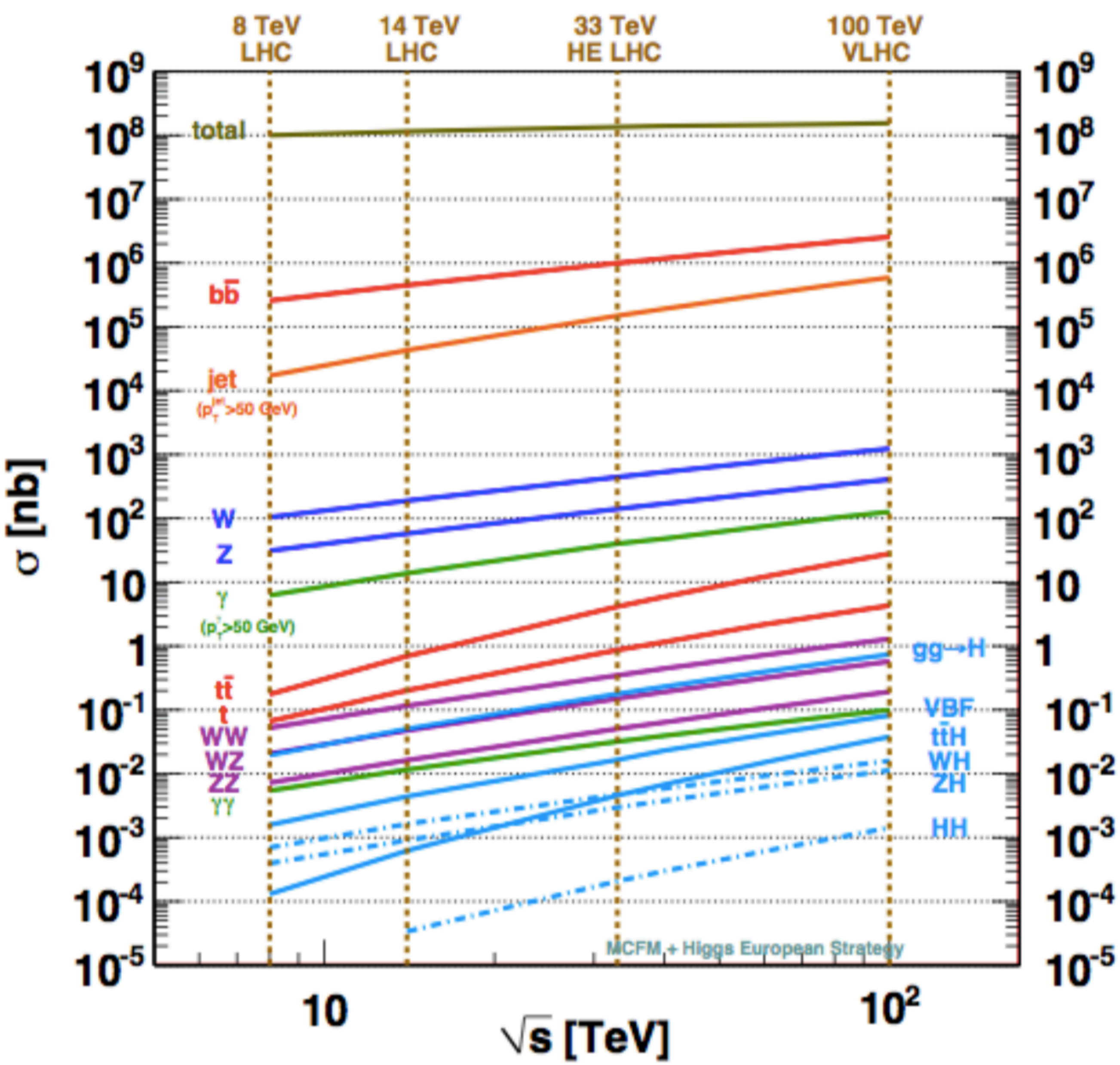
Ratio parton-luminosity

Indicates how rate of **given process** (e.g. single Higgs production) scales from 14 TeV to 100 TeV:

$$\frac{\#\ \text{events}\ (\sqrt{s} = 100\ \text{TeV})}{\#\ \text{events}\ (\sqrt{s} = 14\ \text{TeV})} \approx L_1 / L_2 \approx (s_2/s_1)^a \approx (100/14)^{2a}$$



Rates at 100 TeV



final state	$N_{ev}/10ab^{-1}$
W	10^{13}
t tbar	3×10^{11}
H	10^{10}
HH	10^{6}
jets (p_T>5 TeV)	10^{6}
jets (p_T>10 TeV)	10^{4}

Huge statistics allow for **great potential of further exploration of SM particles** at 100 TeV

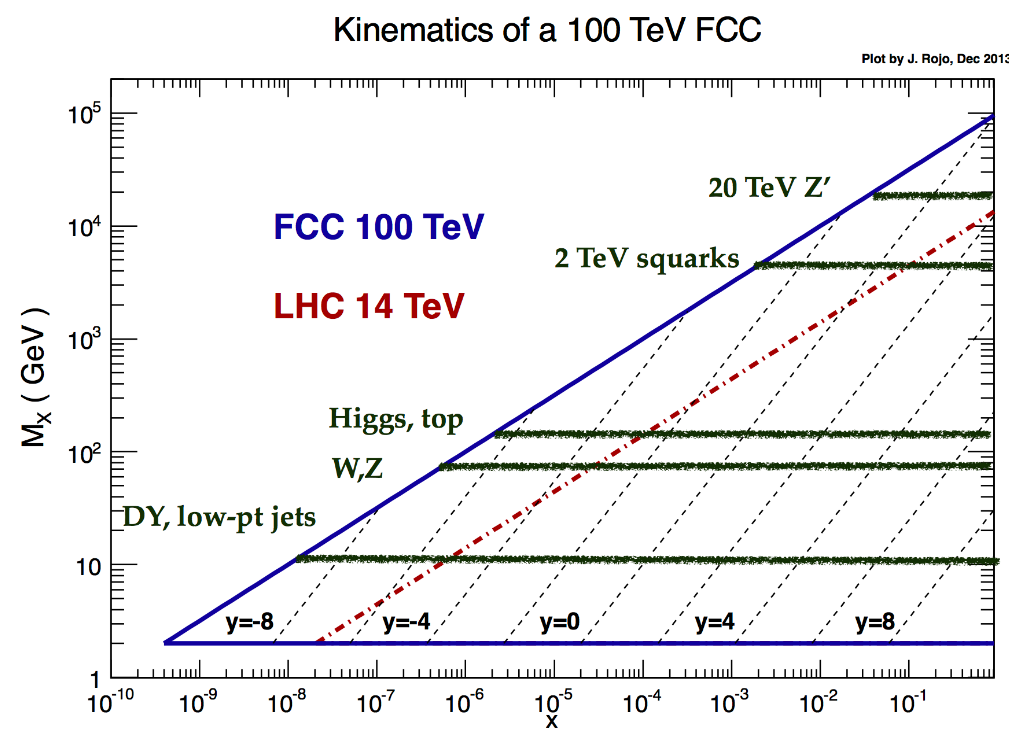
Kinematics @ 100 TeV

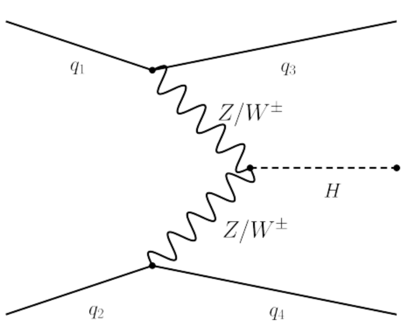
$x_1 * x_2 * s = M^2$

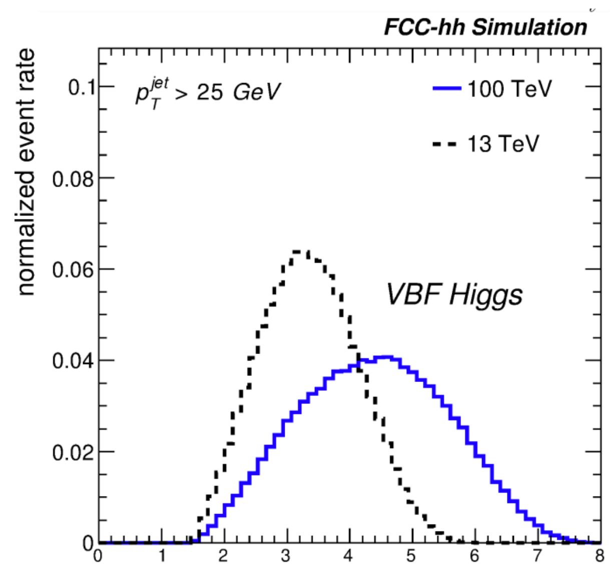
Physics is more forward @100TeV

- less for "high pT" physics
- more for "low pT" physics (W/Z/Higgs, top)
- in order to maintain sensitivity in need **large rapidity** (with tracking) and **low pT** coverage

→ 1k pile-up will certainly be an issue at large rapidities



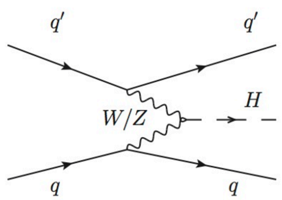


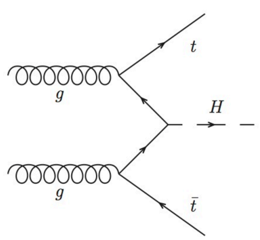


Why Higgs at the FCC-hh?

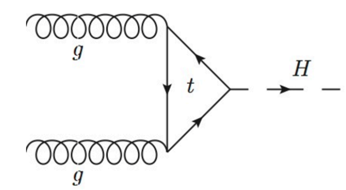
- Huge Higgs production rates:
  - access (very) rare decay modes
  - push to %-level Higgs self-coupling measurement
- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (e.g. *decay BRs*) at $Q \sim m_H$
- High energy reach:
  - direct probes of BSM extensions of Higgs sector (e.g. SUSY)
  - Higgs decays of heavy resonances
  - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)

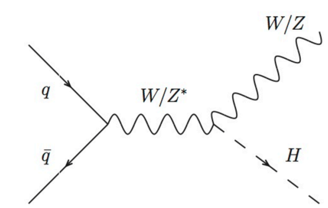
Single Higgs production @FCC-hh





	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N³LO)	49 pb	803 pb	16
VBF (N²LO)	3.8 pb	69 pb	16
VH (N²LO)	2.3 pb	27 pb	11
ttH (N²LO)	0.5 pb	34 pb	55





Expected improvement at FCC-hh:

- **20 billion Higgses** produced at FCC-hh
- **factor 10-50** in cross sections (and Lx10)
- reduction of a **factor 10-20 in statistical** uncertainties

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

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

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

	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

Factor: 1/100 1/10

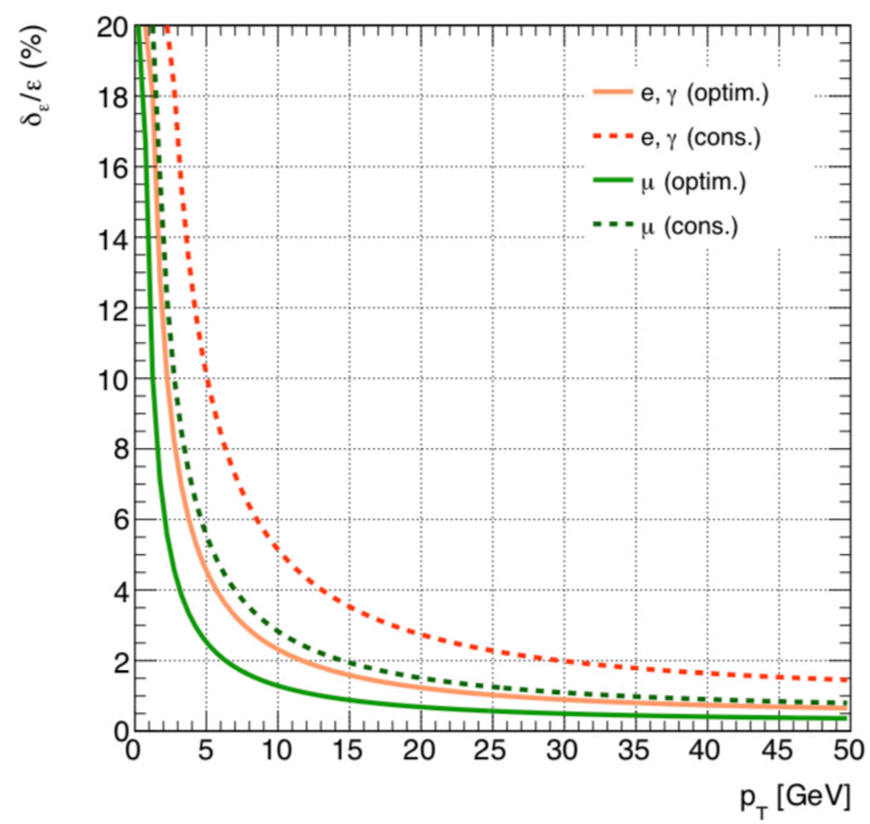
reduction in stat. unc.

Large statistics will allow:

- for % - **level precision in statistically limited** rare channels (μμ, Zɣ)
- in **systematics limited** channel, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

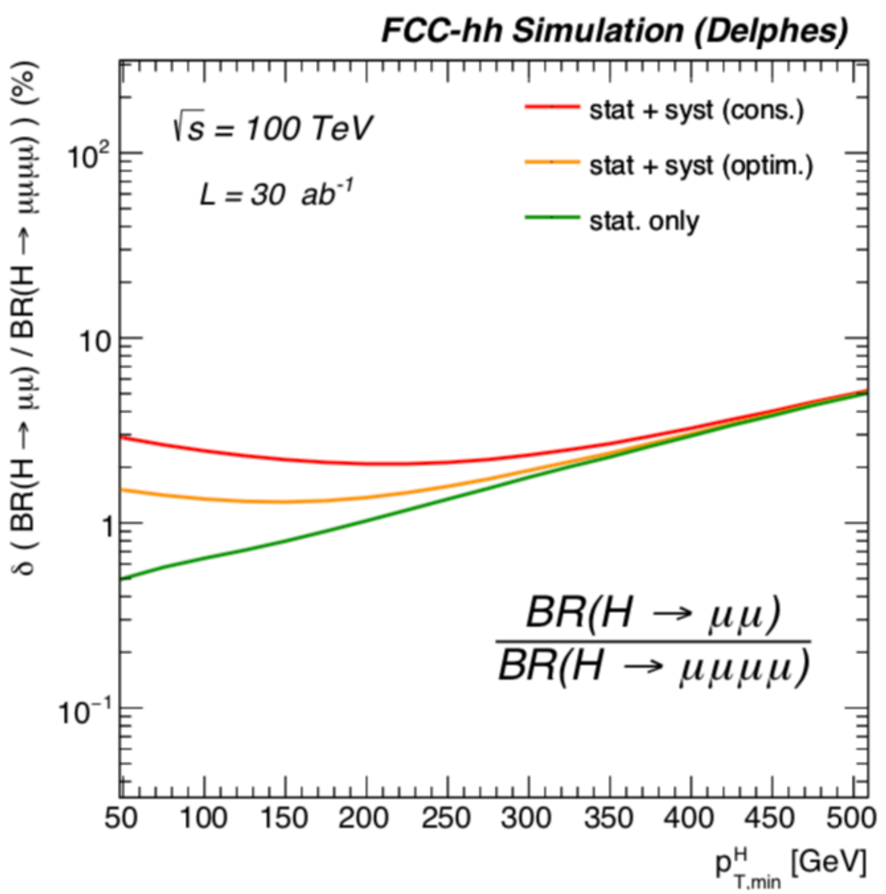
Systematics assumptions on Higgs couplings

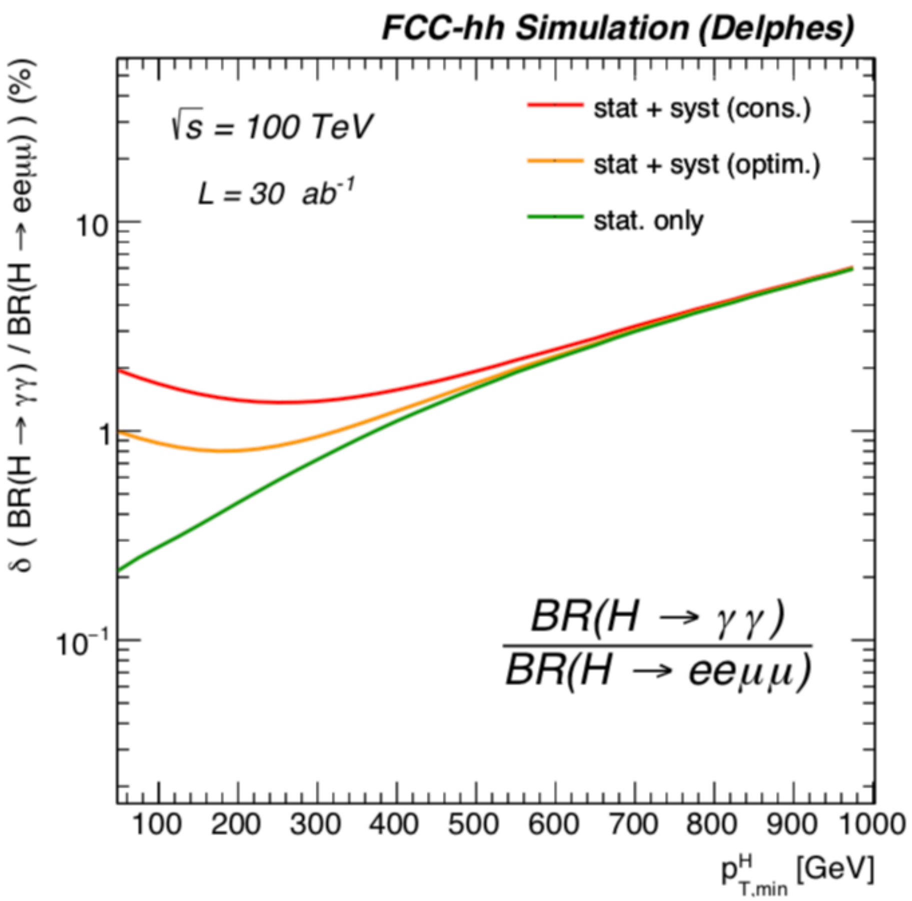
- 1% **systematics on (production x luminosity)**, meant as a reference target. Assumes good theoretical progress over the next years, and **reduction of PDF+α_S uncertainties with HL-LHC + FCC-ee**.
- **e/μ/γ efficiency systematics** shown on the right. Conservative ~ today. In situ calibration, with the immense available statistics in possibly new clean channels ($Z\rightarrow\mu\mu\gamma$), will most likely reduce the uncertainties.
- All final states considered here rely on reconstruction of m_H to within few GeV. **Backgrounds** (physics and instrumental) to be **determined with great precision from sidebands** (~ infinite statistics)
- **Impact of pile-up**: hard to estimate with today's analyses. **Focus on high-p_T objects** will help to decrease relative impact of pile-up
- Assume **(un-)correlated uncertainties** for **(different) same** final state objects
- Following **scenarios** are considered:
    - δ_{stat} → stat. only (I) (signal + bkg)
    - δ_{stat} , δ_{eff} → stat. + eff. unc. (II)
    - δ_{stat} , δ_{eff} , δ_{prod} = 1% → stat. + eff. unc. + prod (III)



Ratios of BRs

- measure **ratios of BRs** to cancel correlated sources of systematics:
  - luminosity
  - object efficiencies
  - production cross-section (theory)
- Becomes **absolute precision** measurement in particular if combined with **H→ZZ** measurement from e^+e^- (at 0.2%)

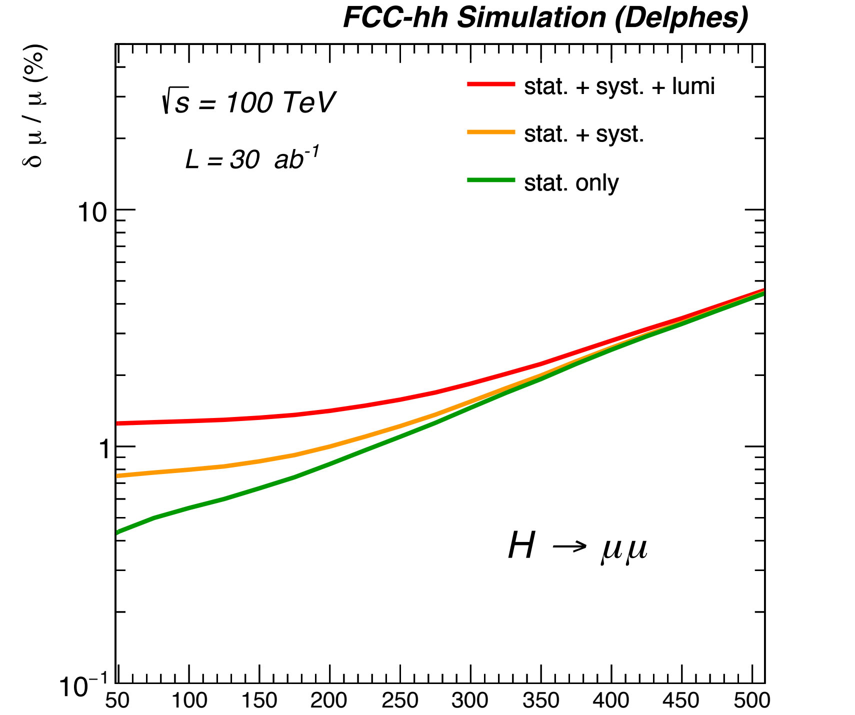


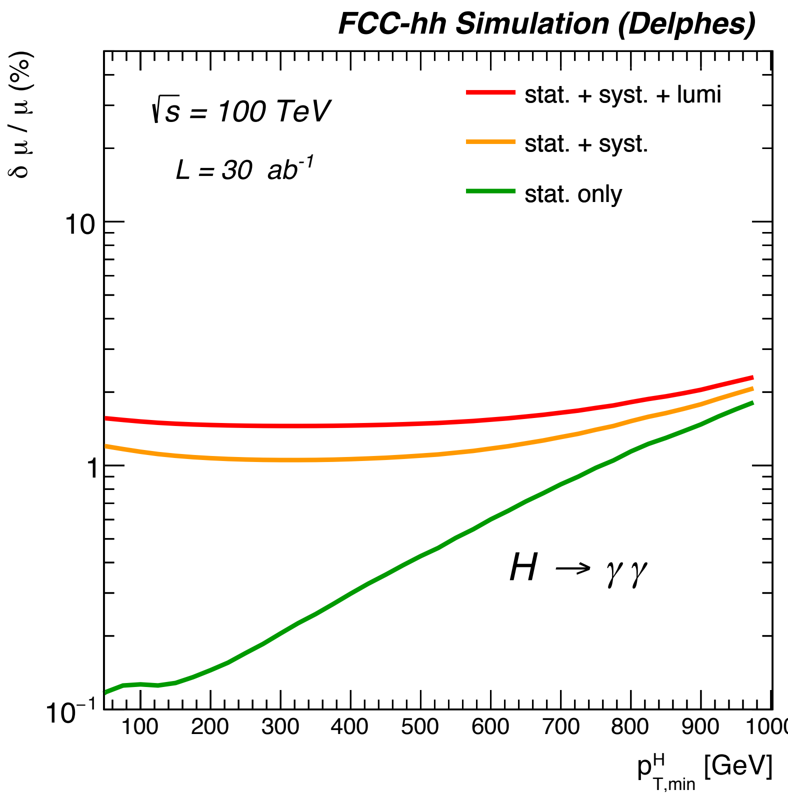


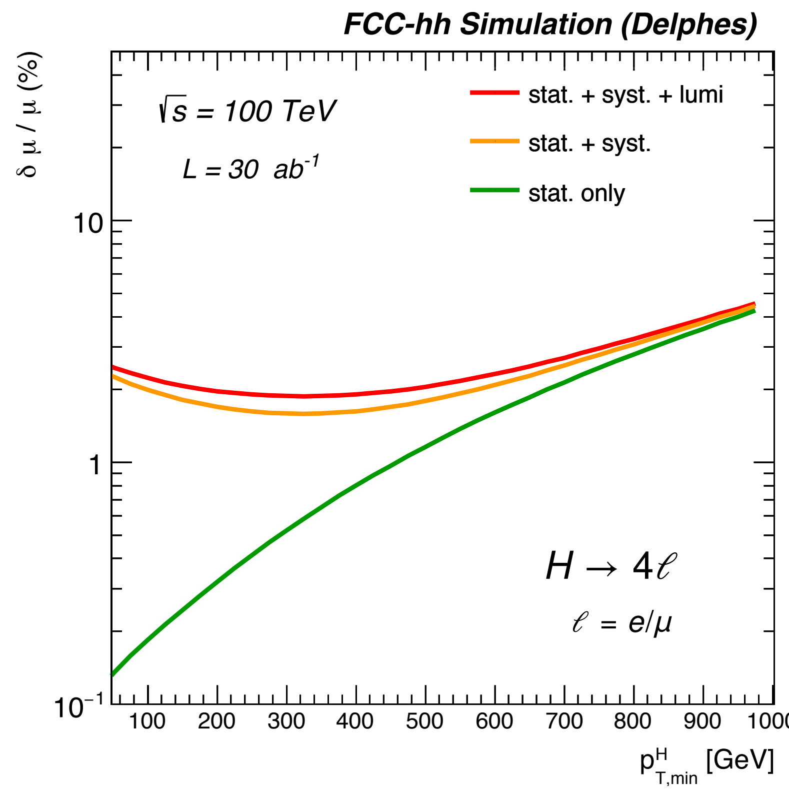
Higgs decays (μμ and Z(ll)γ)

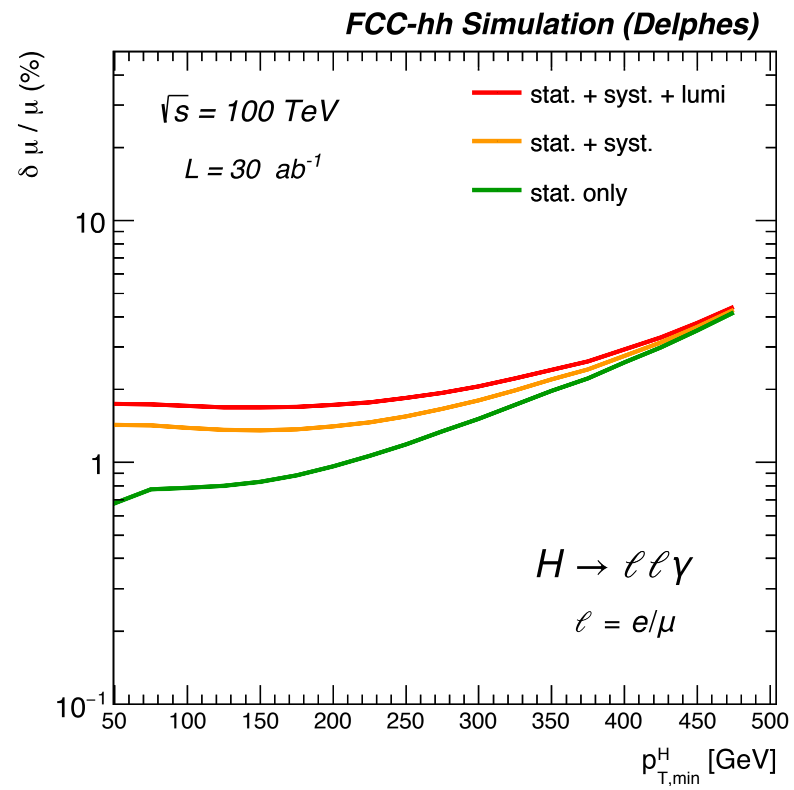
- 1% lumi + theory uncertainty
- p_T dependent object efficiency:
  - $\delta\varepsilon(e/\gamma)$ = 0.5 (1)% at $p_T \to \infty$
  - $\delta\varepsilon(\mu)$ = 0.25 (0.5)% at $p_T \to \infty$

- study sensitivity as a function of **minimum p_T(H)** requirement in the **γγ, ZZ(4l), μμ and Z(ll)γ** channels
- **low** p_T(H): **small stat**. and **high syst**. unc.
- **large** p_T(H): **high stat**. and **small syst**. unc.
- **O(1-2%) precision on BR** achievable up to very high p_T (means 0.5-1% on the couplings)

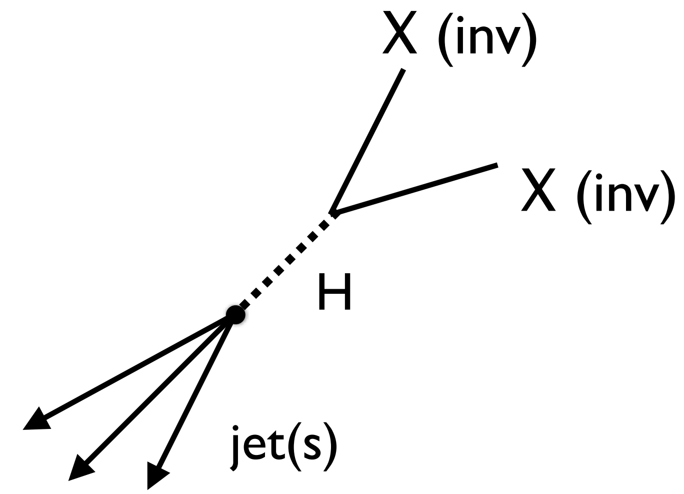




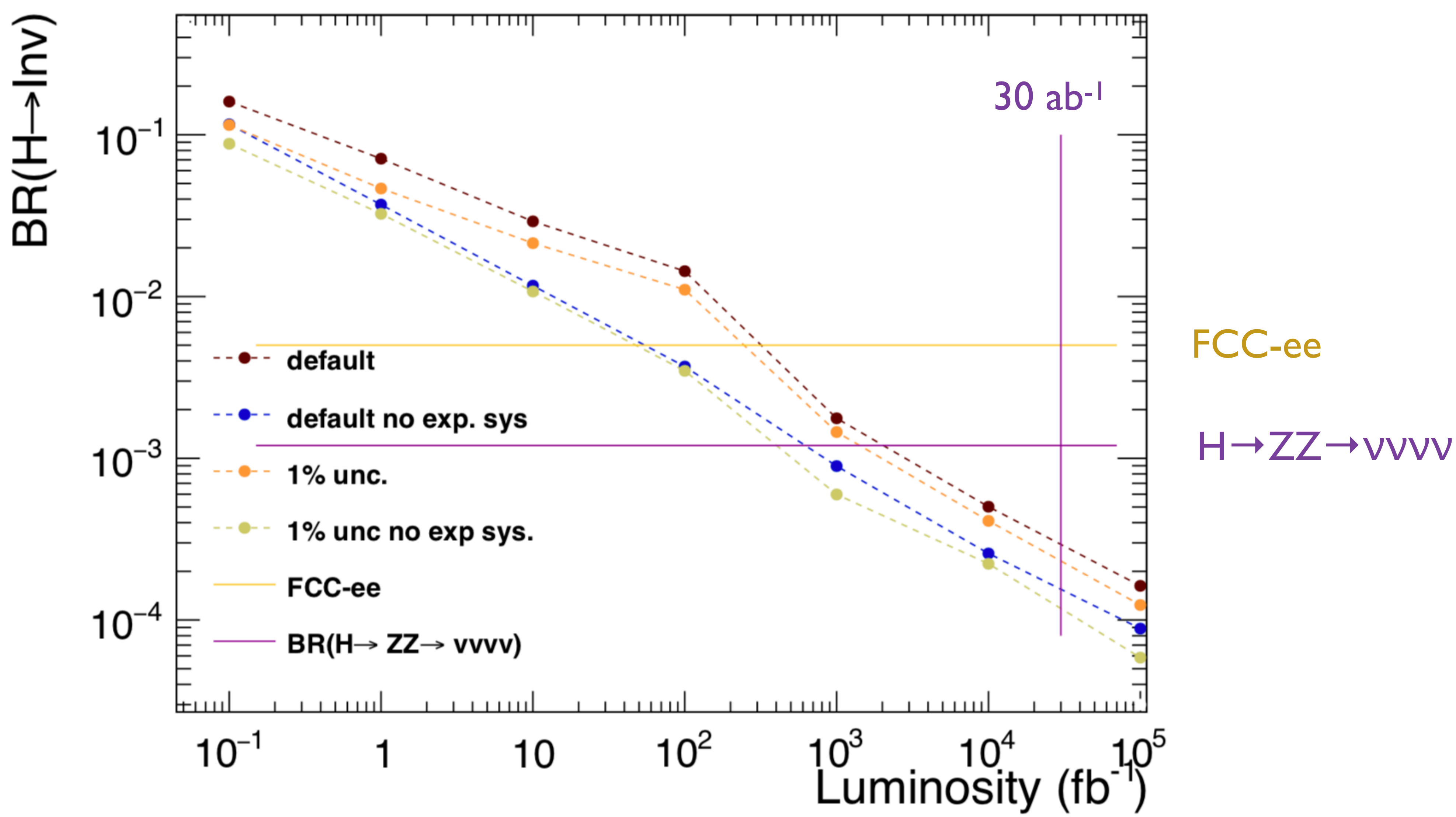




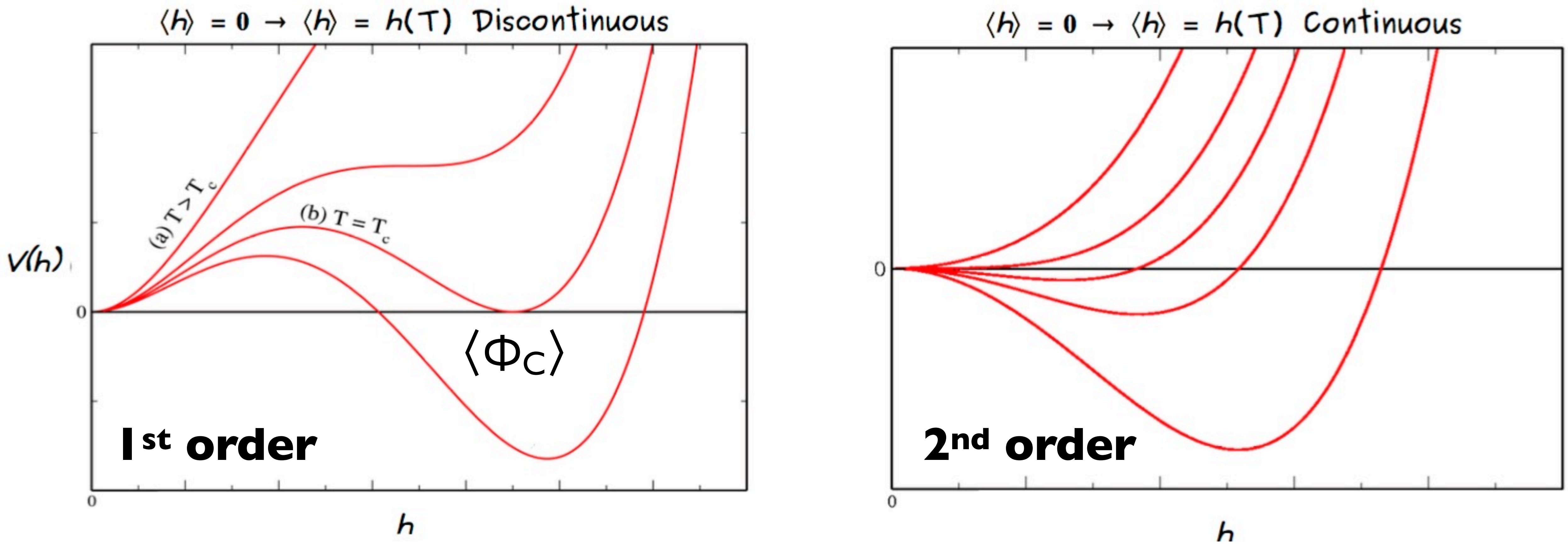
$H \rightarrow$ invisible



- Measure it from H + X at large $p_T(H)$
- Fit the E_T^{miss} spectrum
- Estimate $Z \rightarrow \nu\nu$ from $Z \rightarrow ee/\mu\mu$ control regions.
- Constrain background p_T spectrum from $Z \rightarrow \nu\nu$ to the % level using NNLO QCD/EW to relate to measured Z, W and γ spectra
- $BR(H \rightarrow inv) \lesssim 2.5\ 10^{-4}$



The nature of the EW phase transition



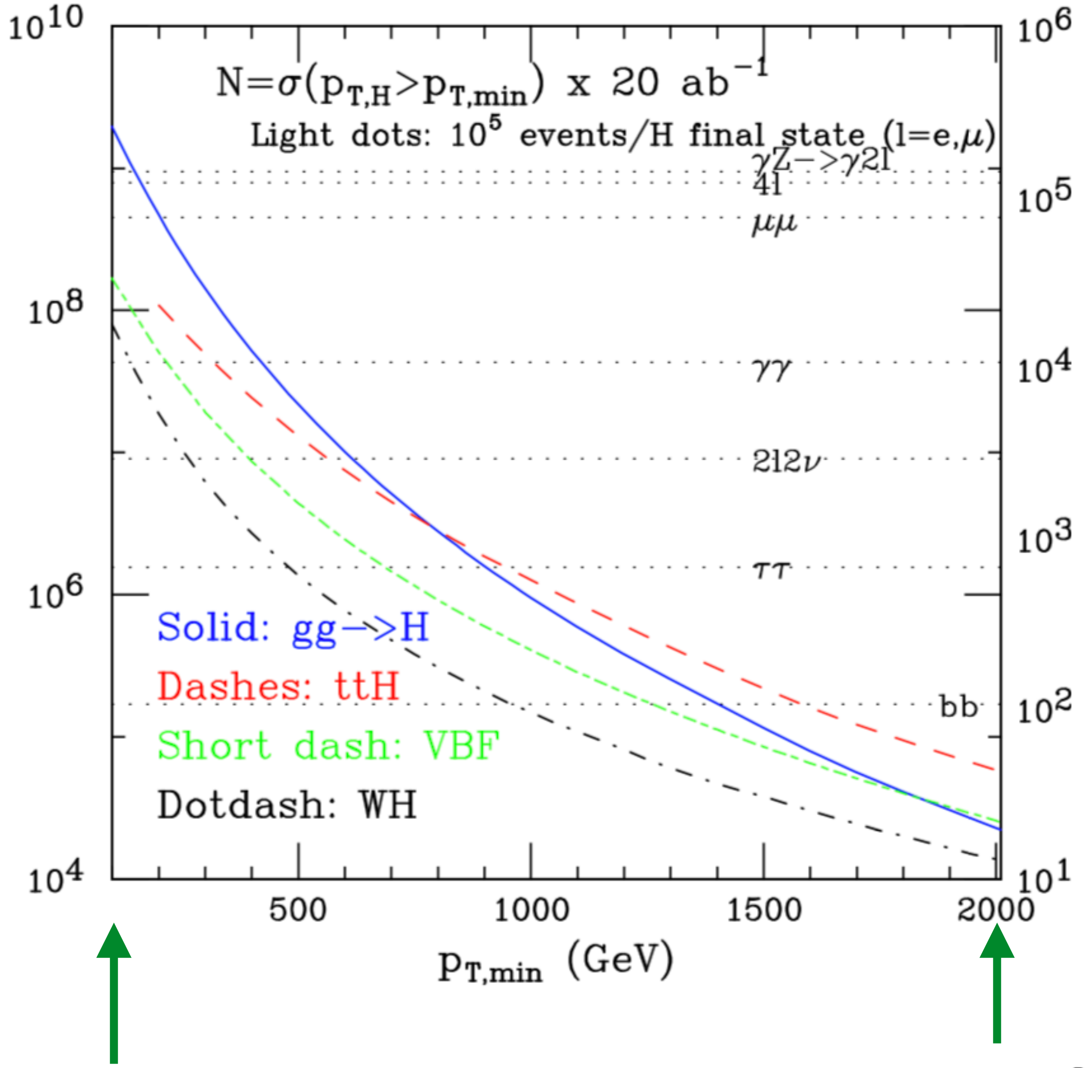
Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

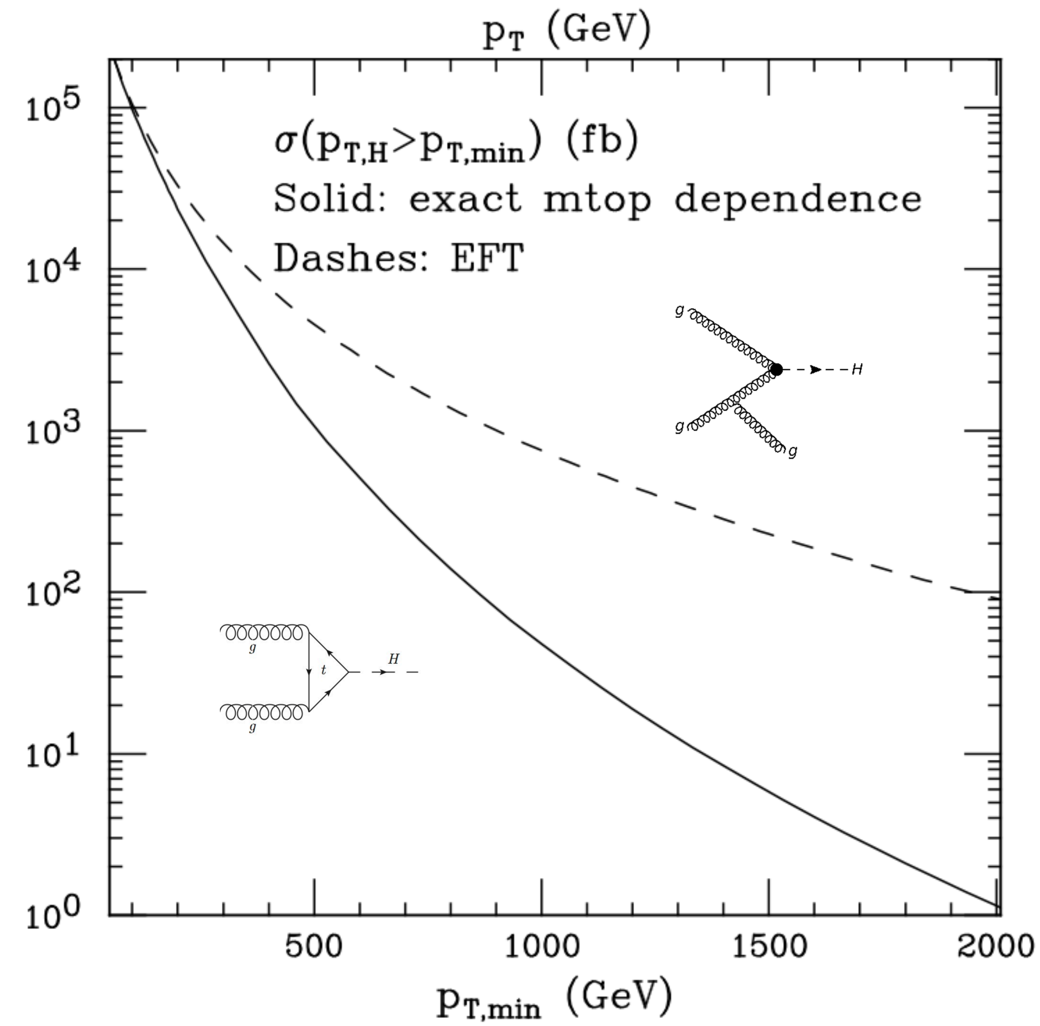
Strong 1st order phase transition $\Rightarrow \langle \Phi_C \rangle > T_C$

This requires O(1) deviations in the 3rd derivative of the Higgs potential w.r.t to value predicted in the SM

- Probe higher-order terms of the Higgs potential (selfcouplings)
- Probe the existence of other particles coupled to the Higgs

Higgs production @ high p_T



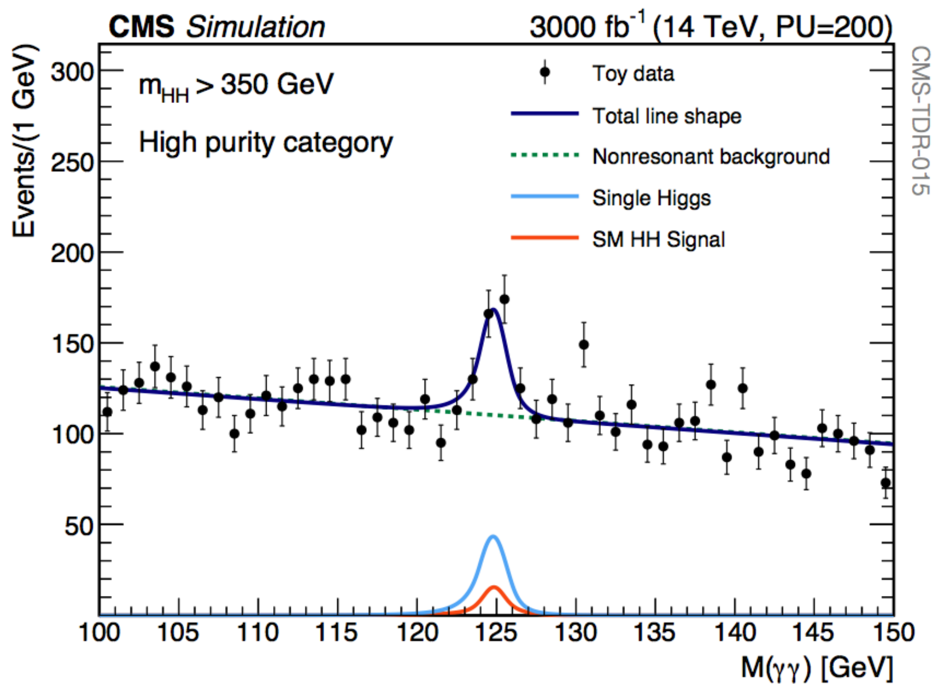


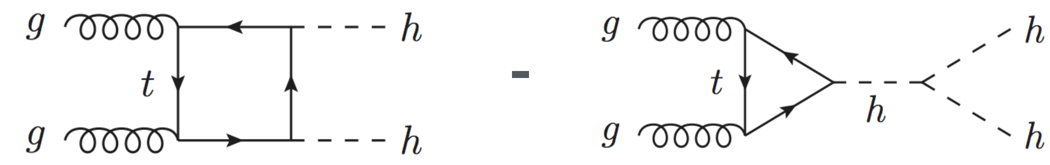
$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \qquad \delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

- will have at disposal, o(10^6) Higgs bosons at p_T(H) > 1 TeV
- **ttH (VBF) overcomes ggH at p_T > 800 (2000) GeV,** distinctive signatures can be used
- Higgs p_T spectrum is an indirect probe for new physics modifying, e.g. ggH coupling
  - heavy states running in the loop
  - complementary to Hgg measurement in e+ e-

Higgs self-coupling at FCC-hh

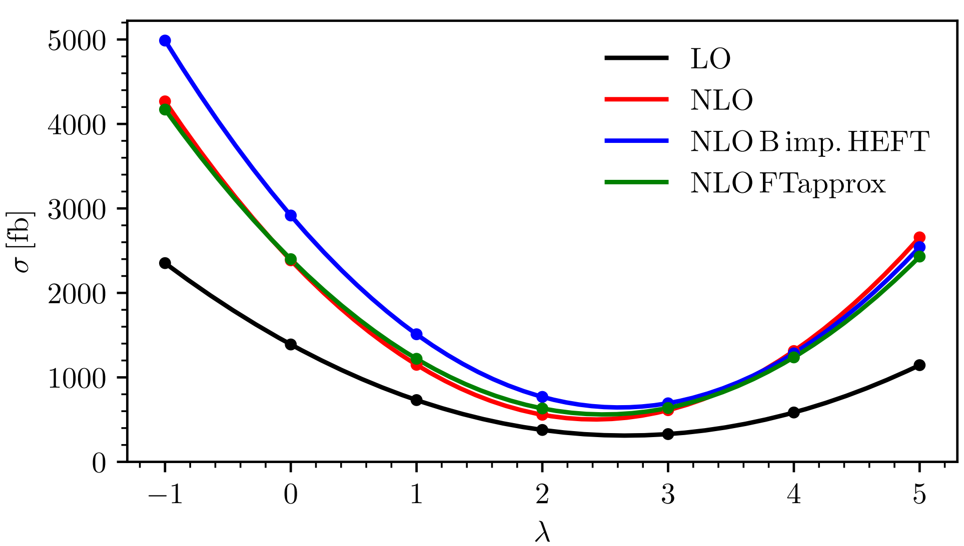
HL-LHC





- Very small cross-section due to negative interference with box diagram
- HL-LHC projections : $\delta k_\lambda / k_\lambda \approx 50\%$
- Expect large improvement at FCC-hh:
  - σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10)
  - x400 in event yields and x20 in precision
- main channels studied:
  - bbγγ (most sensitive - discussed here)
  - bbZZ(4l) (in backup)
  - bbbbj (boosted) (in backup)
- Two very sensitive channels not considered yet:
  - bbττ ($\delta k_\lambda / k_\lambda \approx 8\%$ from [1802.01607])
  - 4b

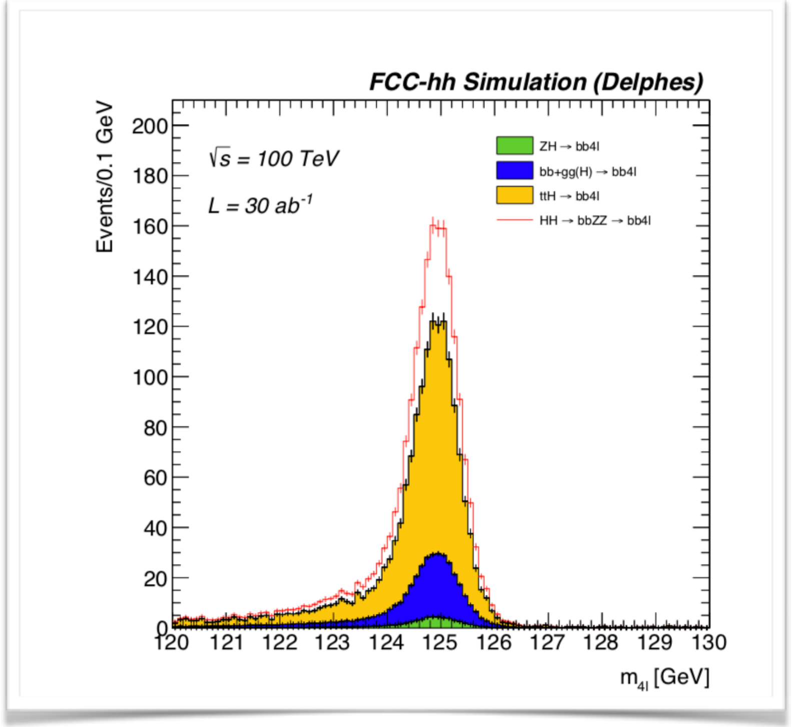
G. Heinrich et.al [1608.04798]

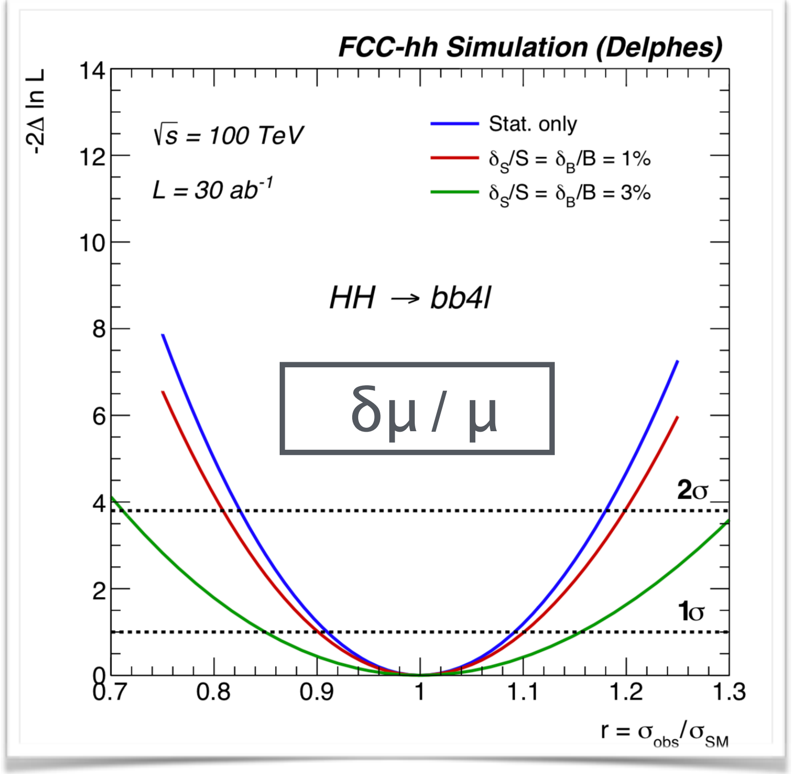


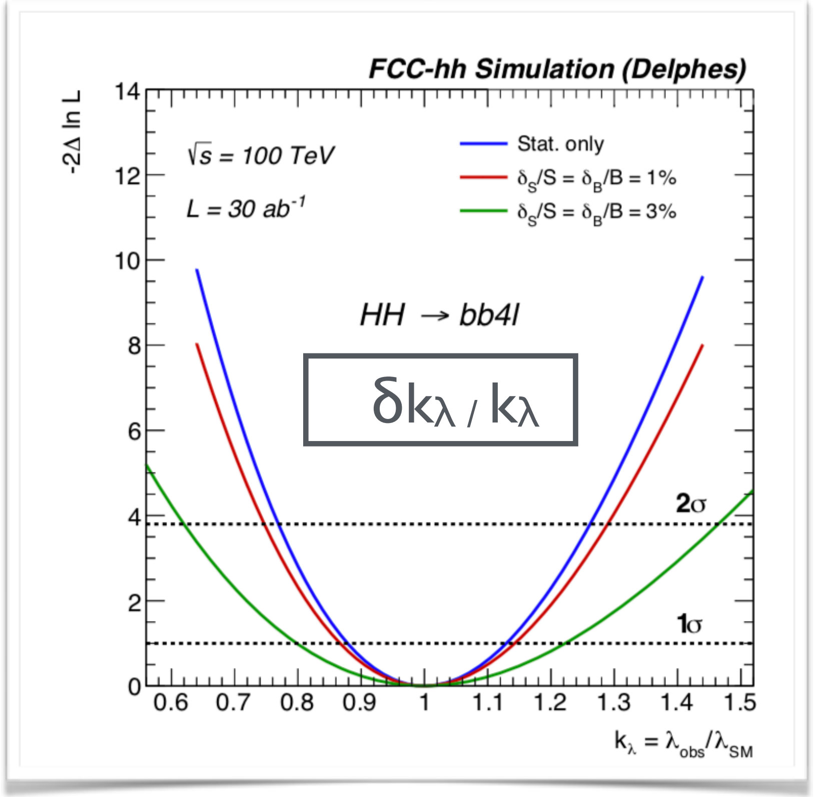
[Borgonovi, Braibant, De Filippis, Fontanesi, Ortona, MS]

HH →bb4l

- **New channel** opening at FCC-hh !!
- clean channel with mostly reducible backgrounds (**single Higgs**)
- Simple cut and count analysis on (4e, 4μ and 2e2μ channels)
- **δkλ / kλ = 15-20%** depending on systematics assumptions







Summary direct measurements

Observable	Parameter	Precision (stat.)	Precision (stat.+syst.+lumi.)
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(H) \times B(H \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)\, B(H \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = B(H \to \mu\mu\gamma)/B(H \to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}H) \times B(H \to b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

- **Percent level precision on σ x BR** in most rare decay channels
- **Percent level precision on BRs** if HZZ coupling known from FCC-ee (to 0.2%)

One should not underestimate the value of FCC-hh standalone precise “ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways:

BR(H→μμ)/BR(H→ZZ*)

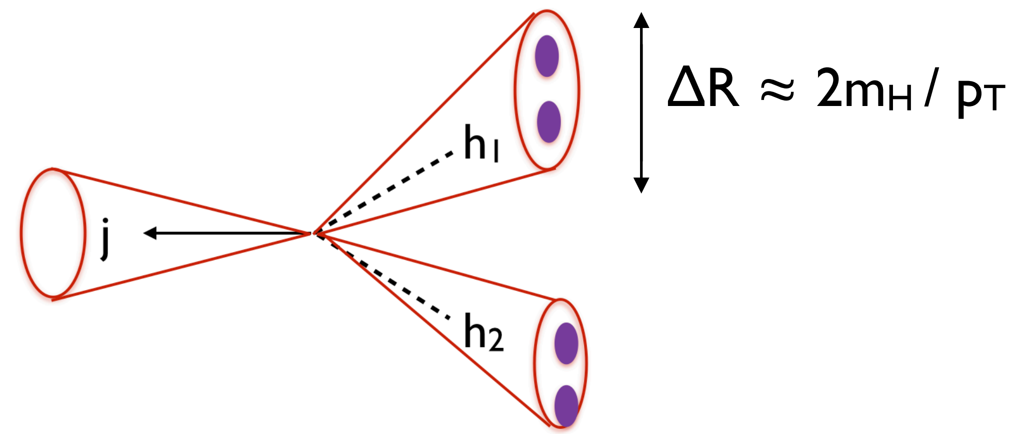
2nd gen. yukawa — gauge coupling

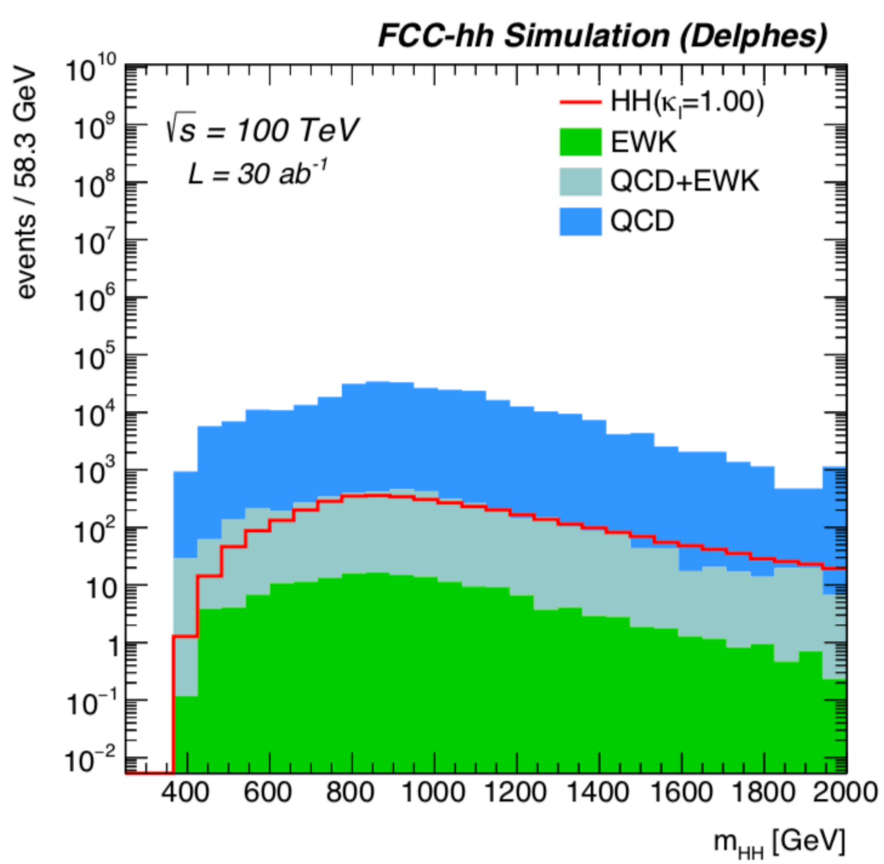
BR(H→γγ)/BR(H→ZZ*)

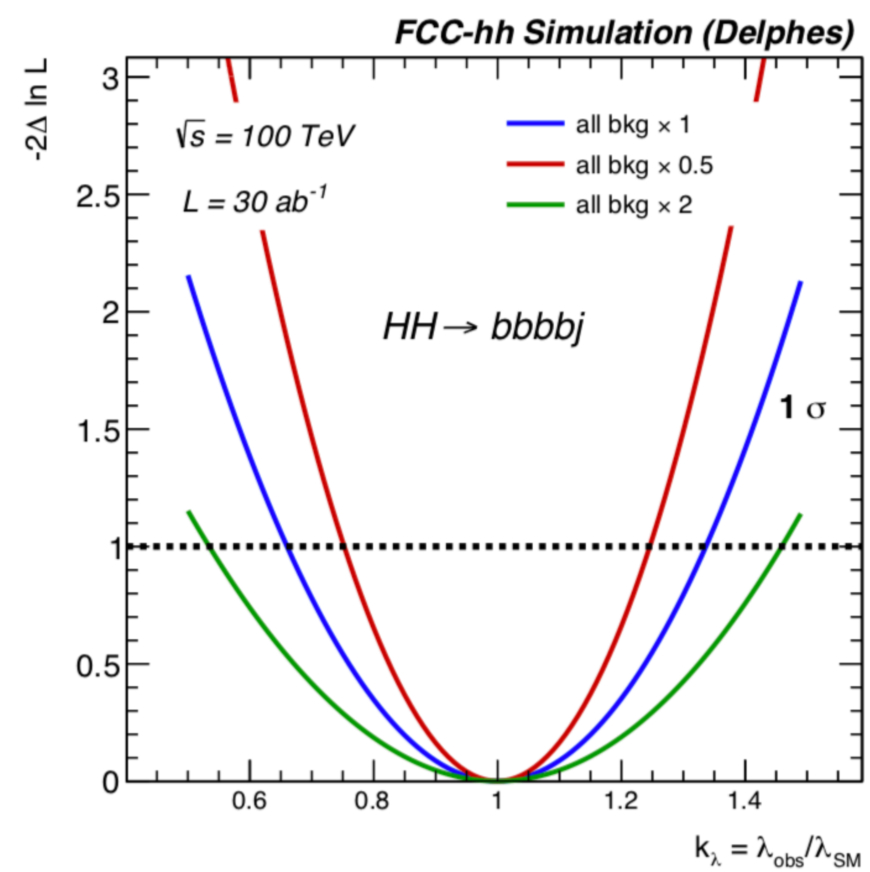
loop level — tree level

HH →4b+j boosted

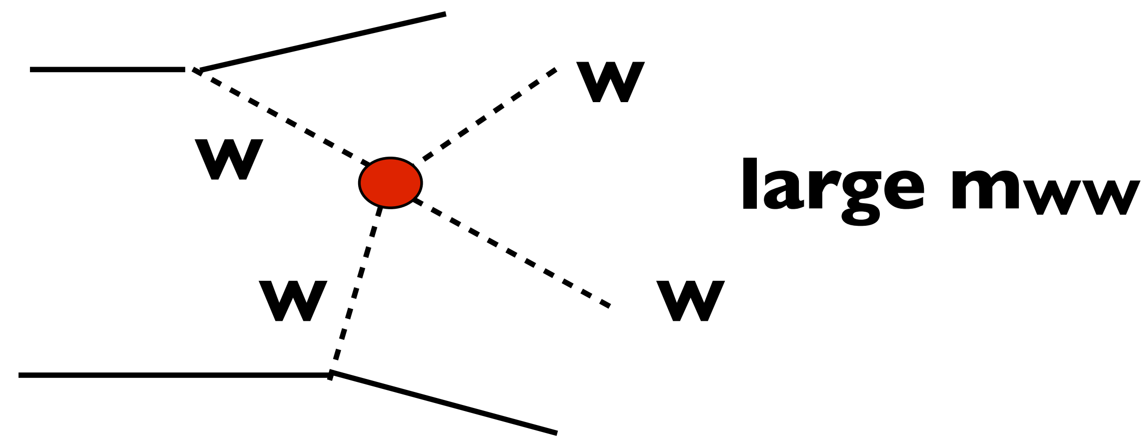
- Large rates allow to look for **boosted HH** recoiling against a jet (**low m_{HH}** drives the sensitivity)
- relies on identification **two boosted Higgs-jets**
- **fit the di-jet mass spectrum** dominated by the large QCD background
- **$\delta k_\lambda / k_\lambda$ = 20-40%** depending on assumed background rate





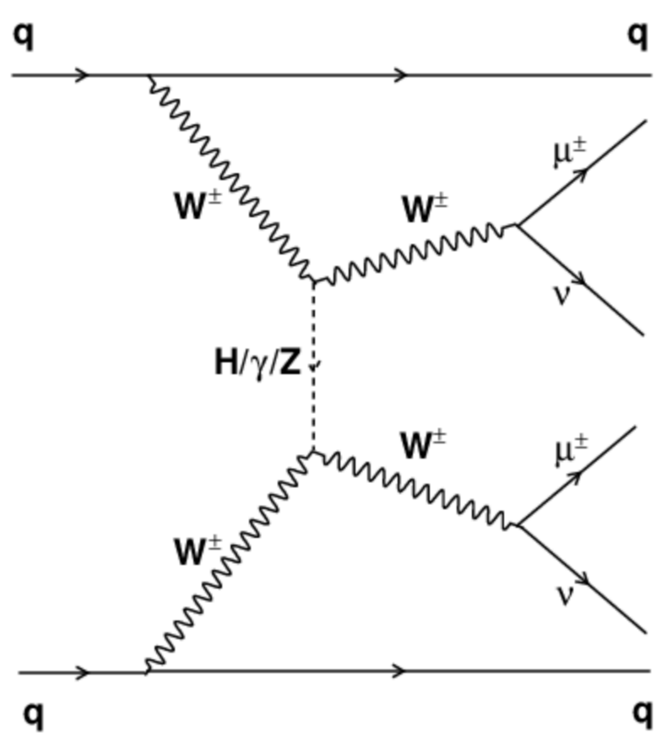


Vector Boson Scattering



- Sets constraints on **detector acceptance** (fwd jets at **η≈4**)
- Study **W+/-W+/- (same-sign)** channel
- **Large WZ** background at FCC-hh
- **3-4% precision on W_LW_L scattering** xsec. achievable with full dataset
- Indirect measurement of HWW coupling possible, **$\delta\kappa_W/\kappa_W \approx 2\%$**

[1002.1011]



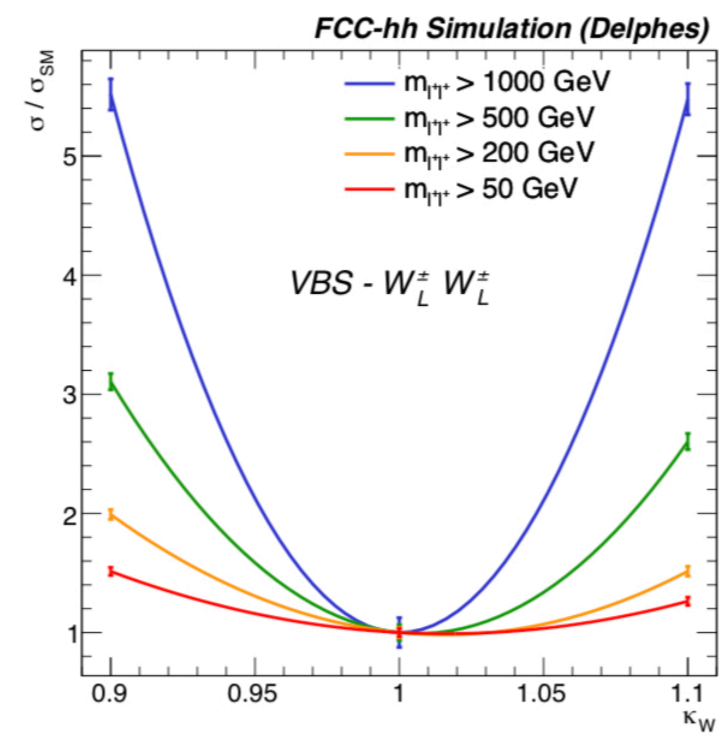
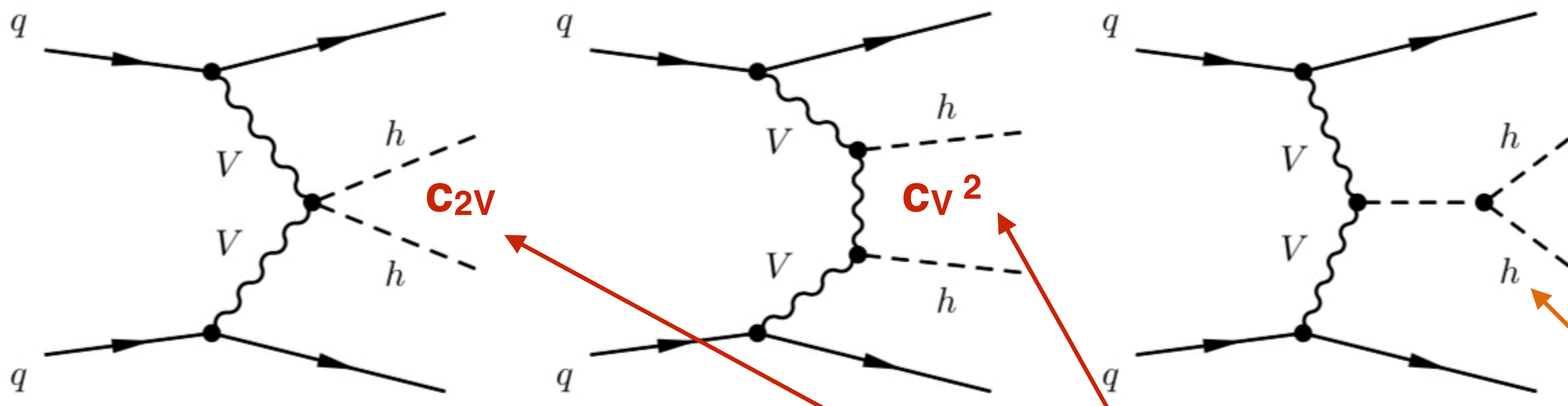


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \to HH$ process.

$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

$W_L W_L \to HH$

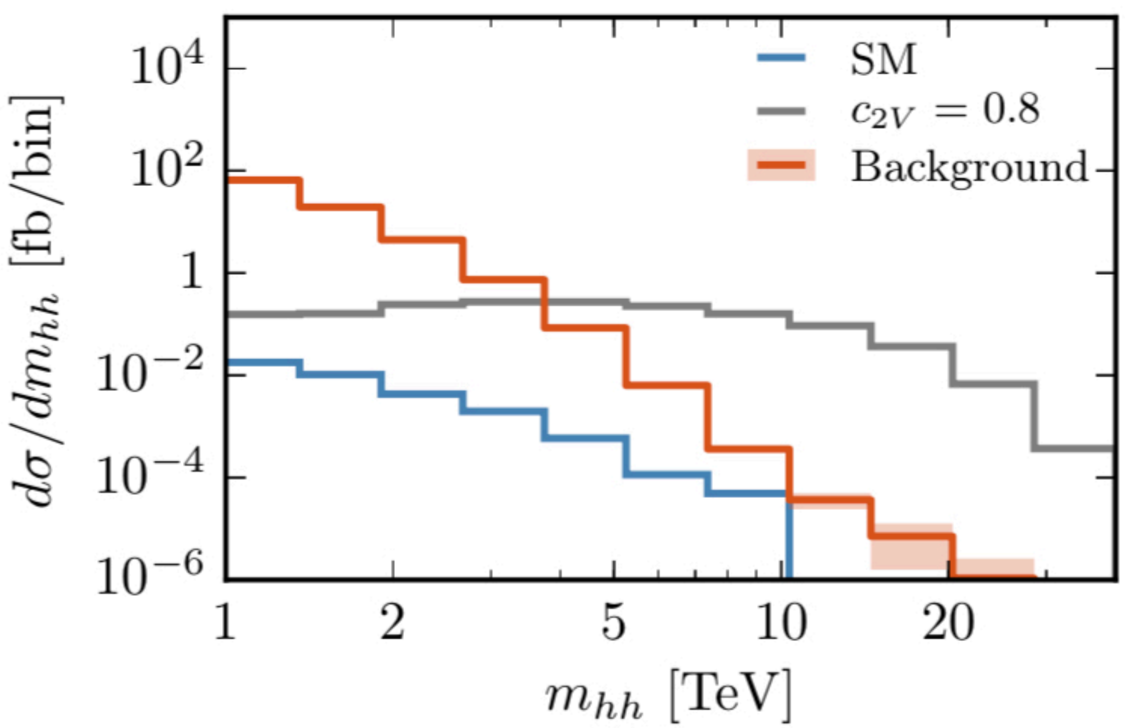
[1611.03860]

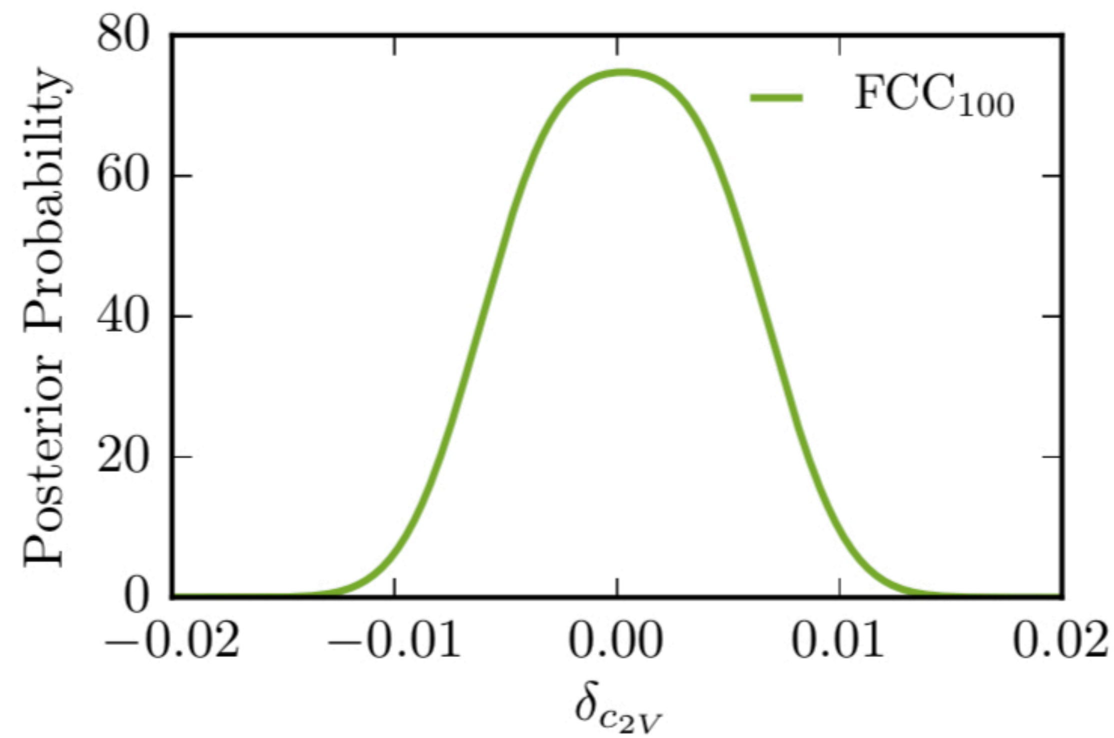


$$A(V_L V_L \to HH) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}),$$

0 in the SM

high energy behaviour driven by C_{2V} and C_V, if $\delta C_{2V} \neq 0$, grows with E



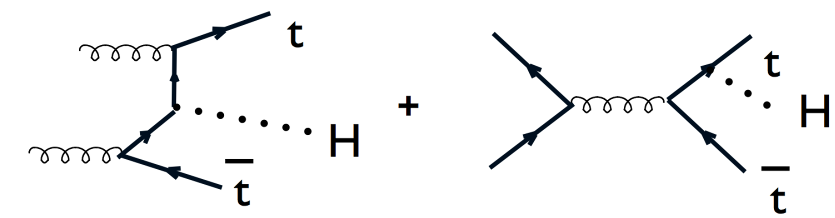


With c_V from FCC-ee, $\delta c_{2V} < 1\%$

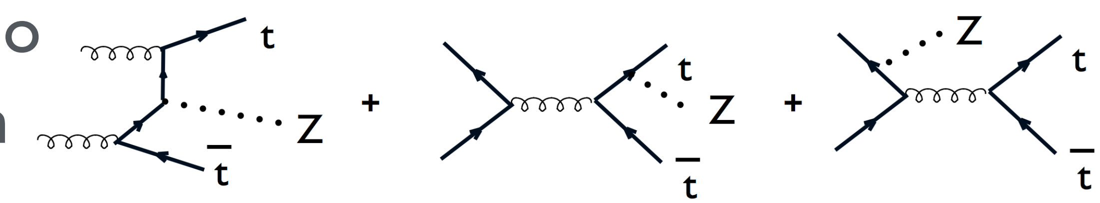
Top Yukawa (production)

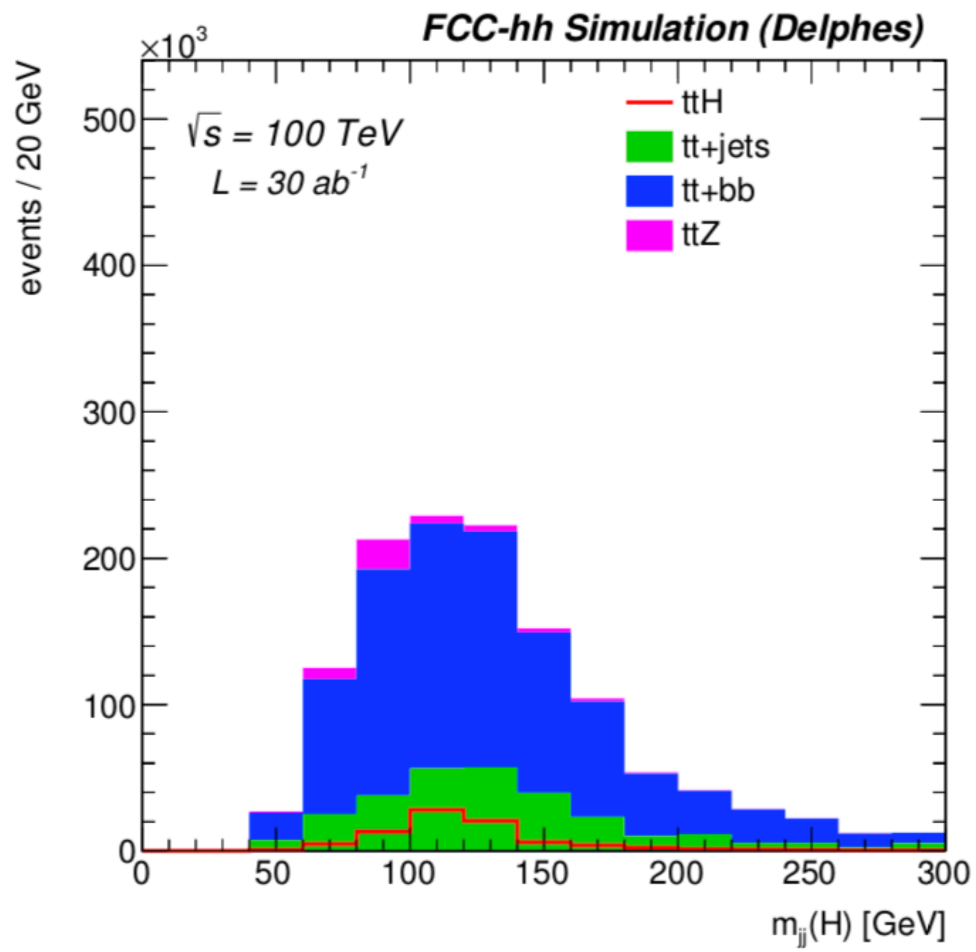
- production ratio **σ(ttH)/σ(ttZ)**
- predicted to **1%** precision [1507.08169]
- measure **σ(ttH)/σ(ttZ)** in **H/Z→bb** mode in the boosted regime, in the **semi-leptonic** channel
- perform **simultaneous fit of double Z and H peak**
- (lumi, pdfs, efficiency) **uncertainties cancel out** in ratio
- assuming g_{ttZ} and κ_b known to 1% (from FCC-ee) , can measure y_t to **1%**

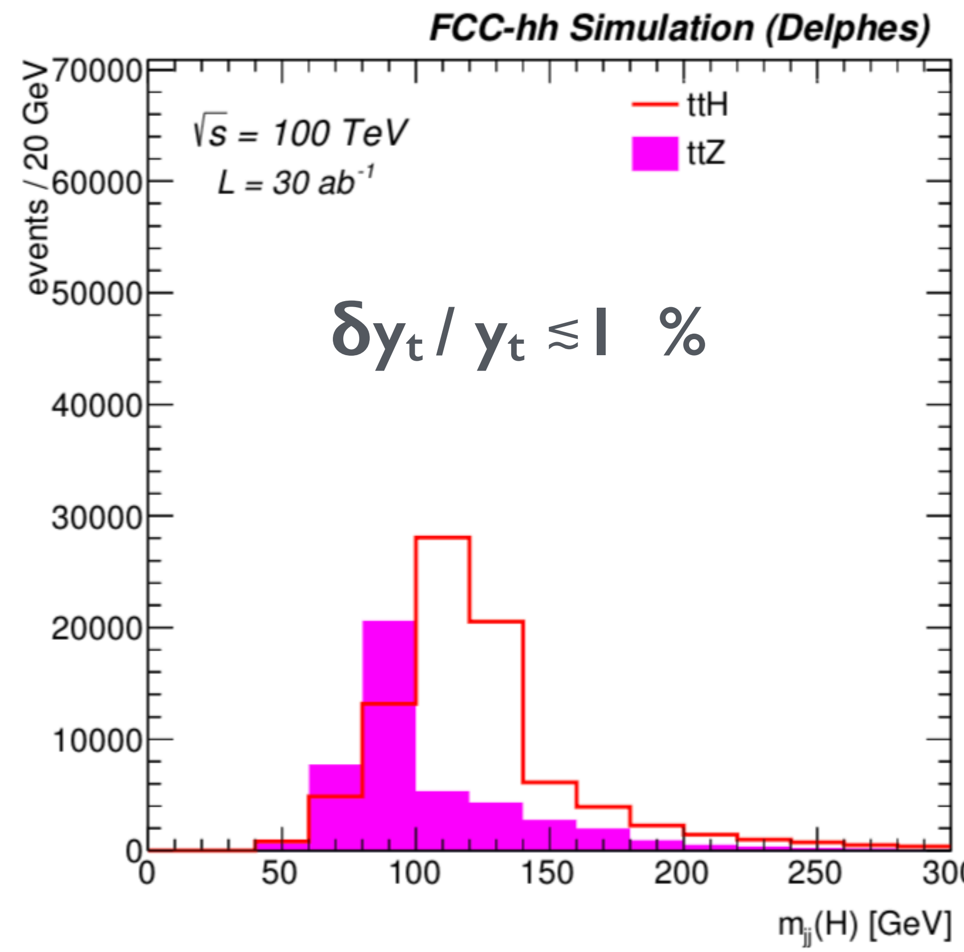
ttH



ttZ

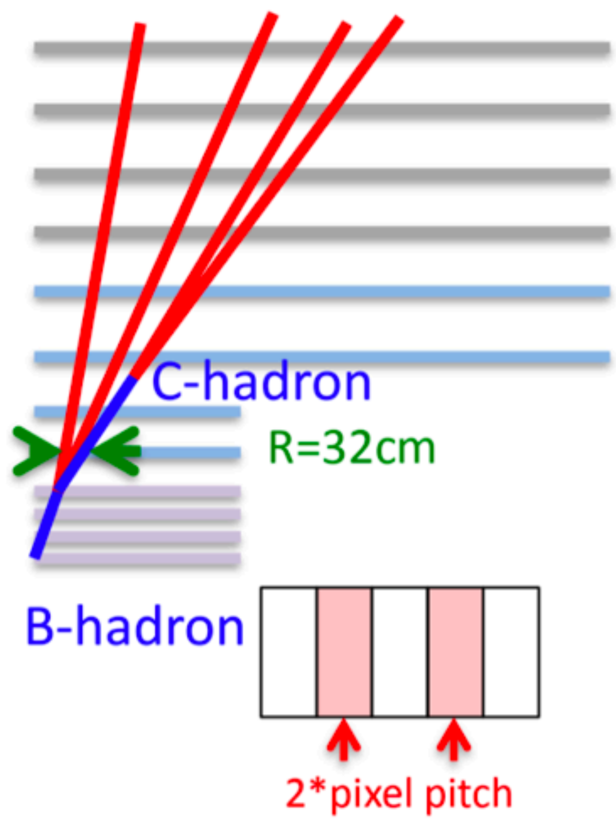






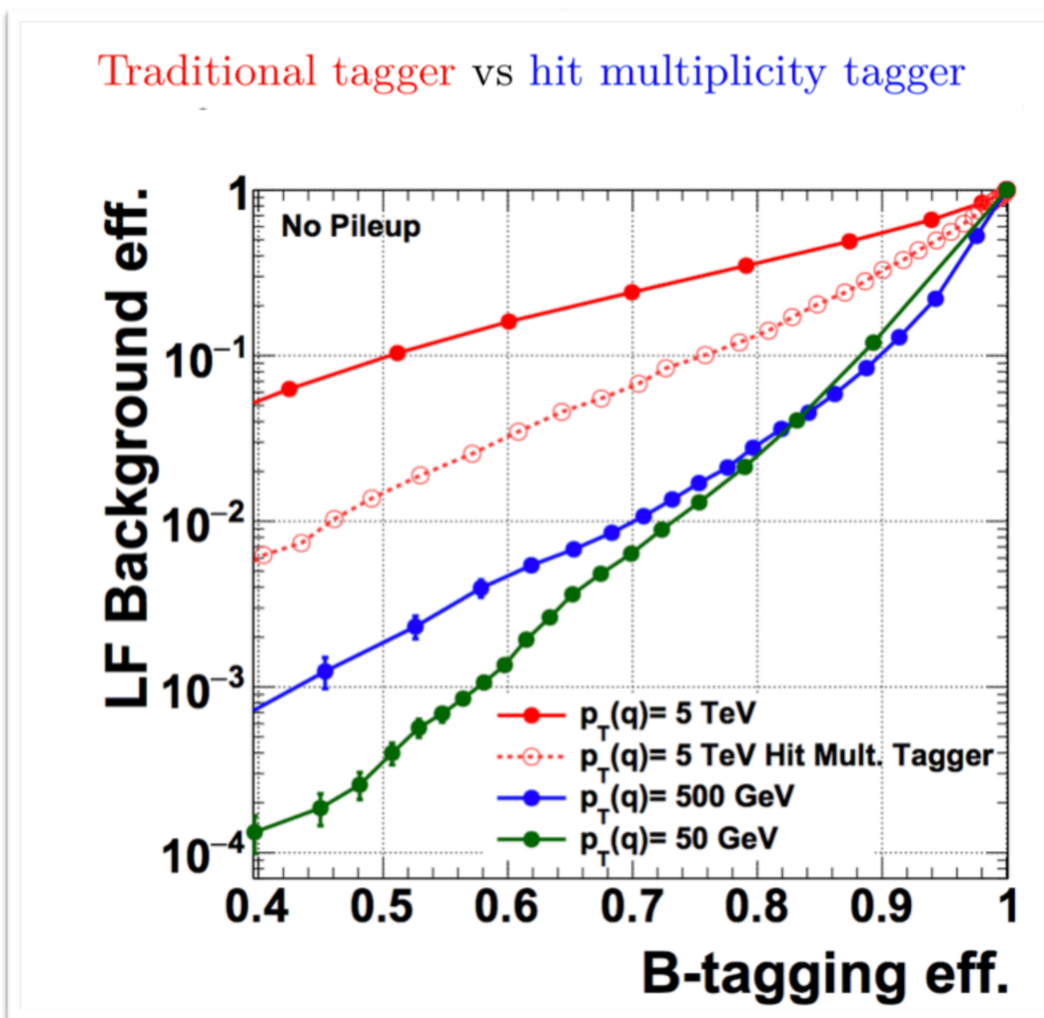
Detector requirements from high p_T searches

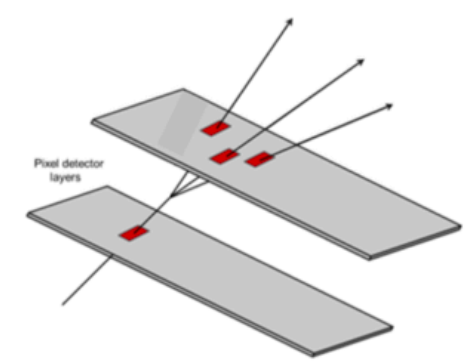
- Change in paradigm: heavy flavour tagging
- multi-TeV b-Hadrons decay outside the pixel volume
- Need to adapt identification algorithms for maintaining sensitivity in in high mass searches .



Only 71% 5 TeV b-hadrons decay < 5th layer.

- displaced vertices

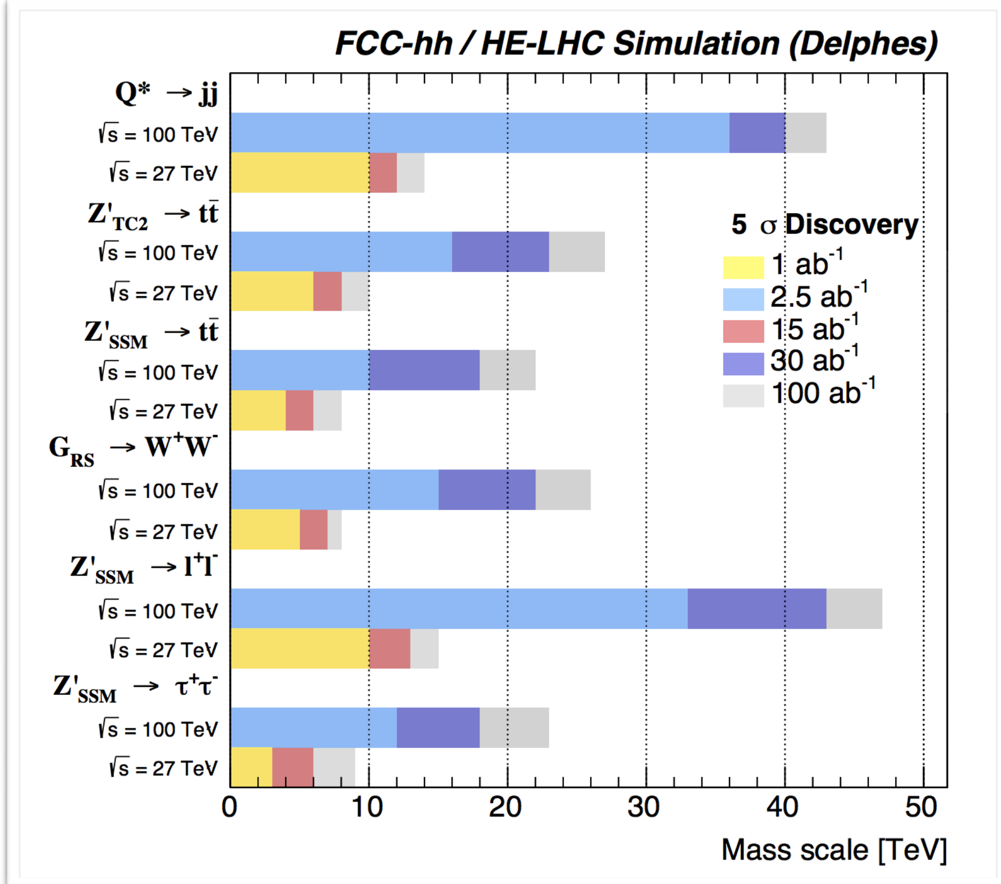




arXiv:1701:06832

To be verified in high pile-up environment.

Heavy resonances @ 100 TeV



Experimental Constraints

Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$ calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

- Tracking target : achieve **σ / p = 10-20% @10 TeV**
- Keep calorimeter **constant term** as small as possible.

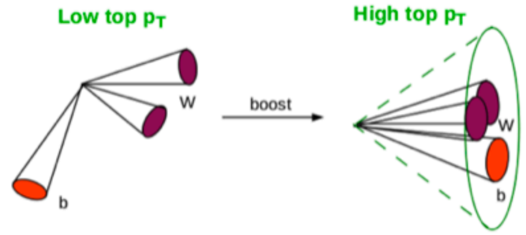
- Long-lived particles live **longer**:

ex: 5 TeV **b-Hadron** travels **50 cm** before decaying
5 TeV **tau lepton** travels **10 cm** before decaying

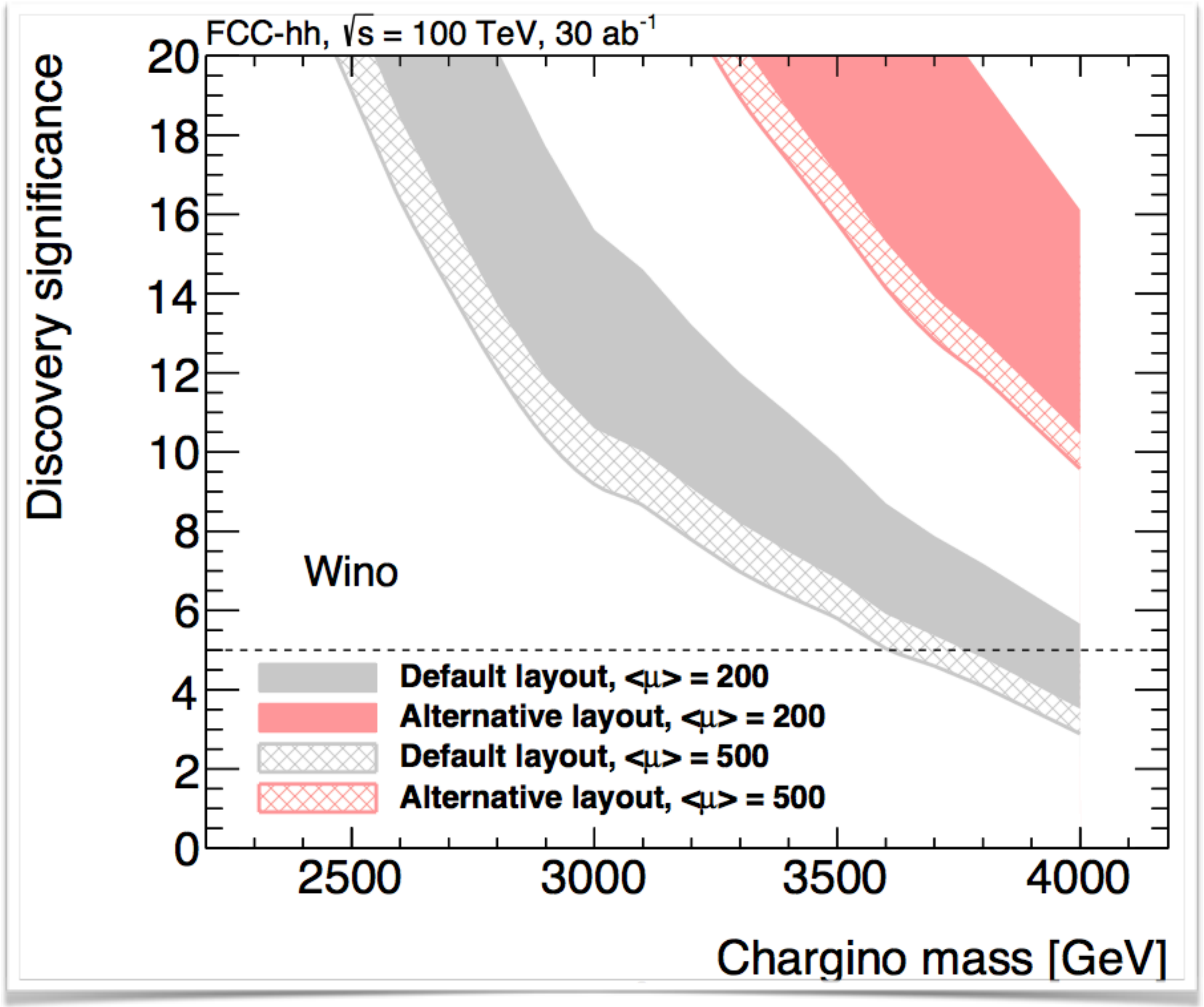
→ re-think reconstruction, include **dE/dx ?**

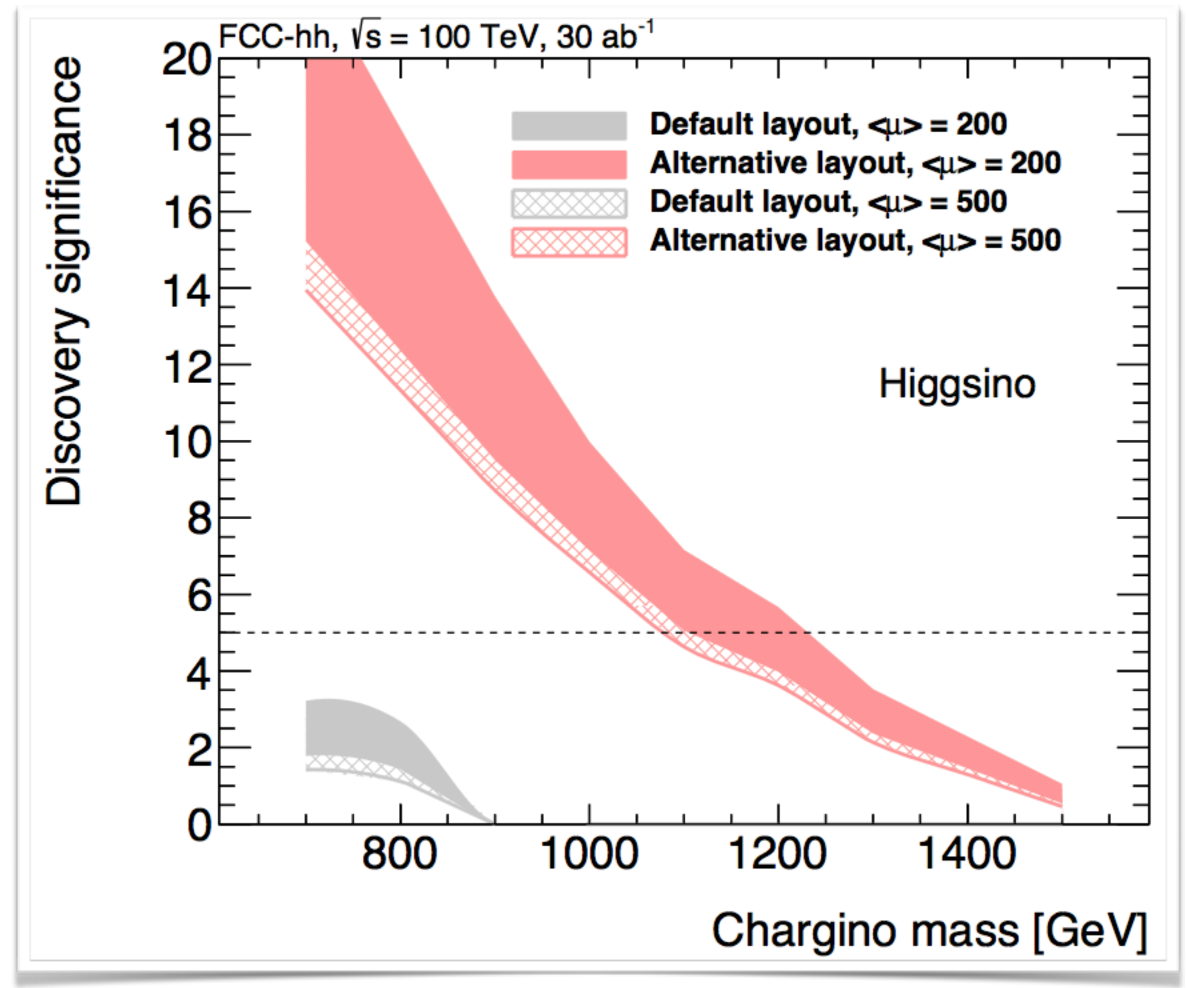
Require **high granularity** (both in tracker and calos):

ex: W(10 TeV) will have decay products separated by DR = 0.01



Heavy resonances @ 100 TeV



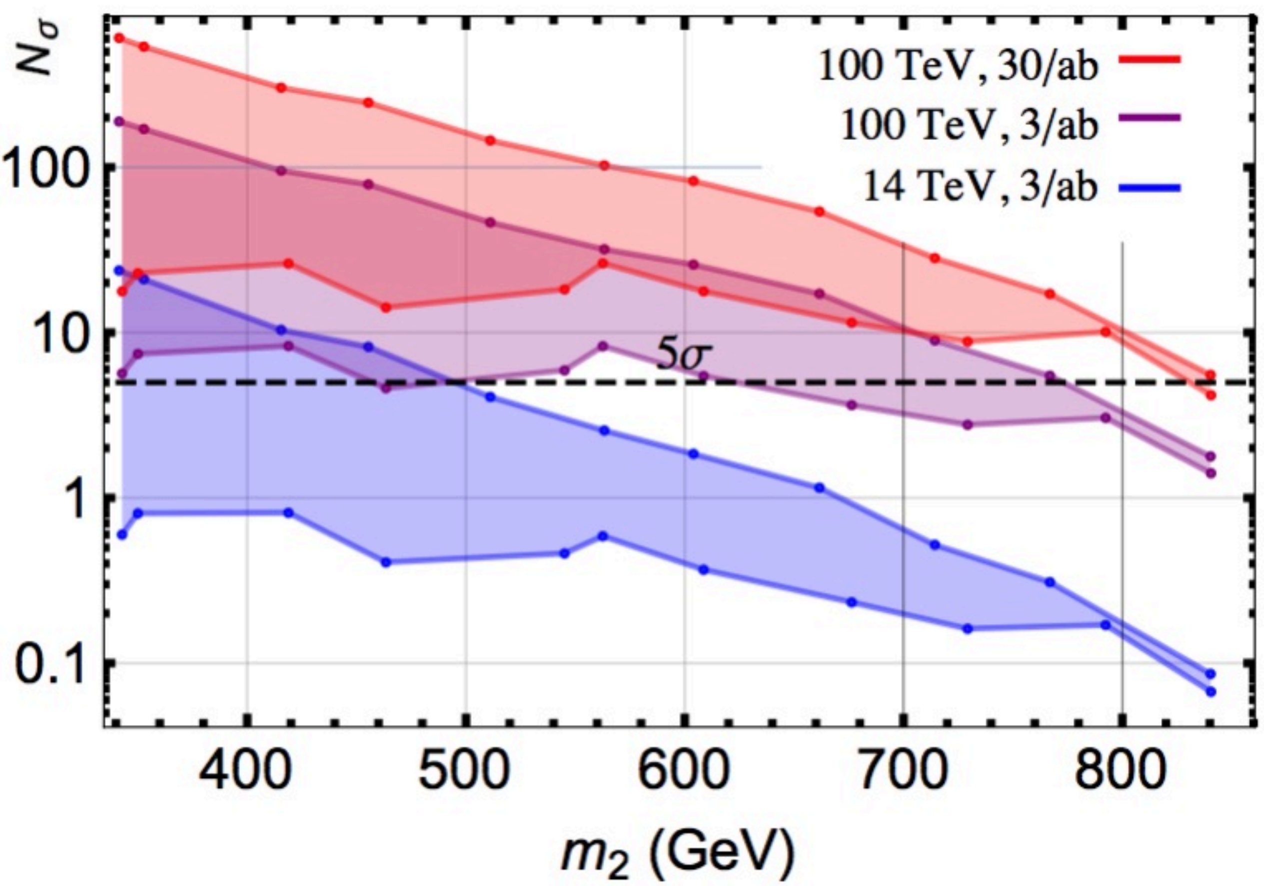


- M = 1 TeV Higgsino can be discovered
- M = 3 TeV Wino can be discovered

Higgs Self-coupling and constraints on models with 1st order EWPT

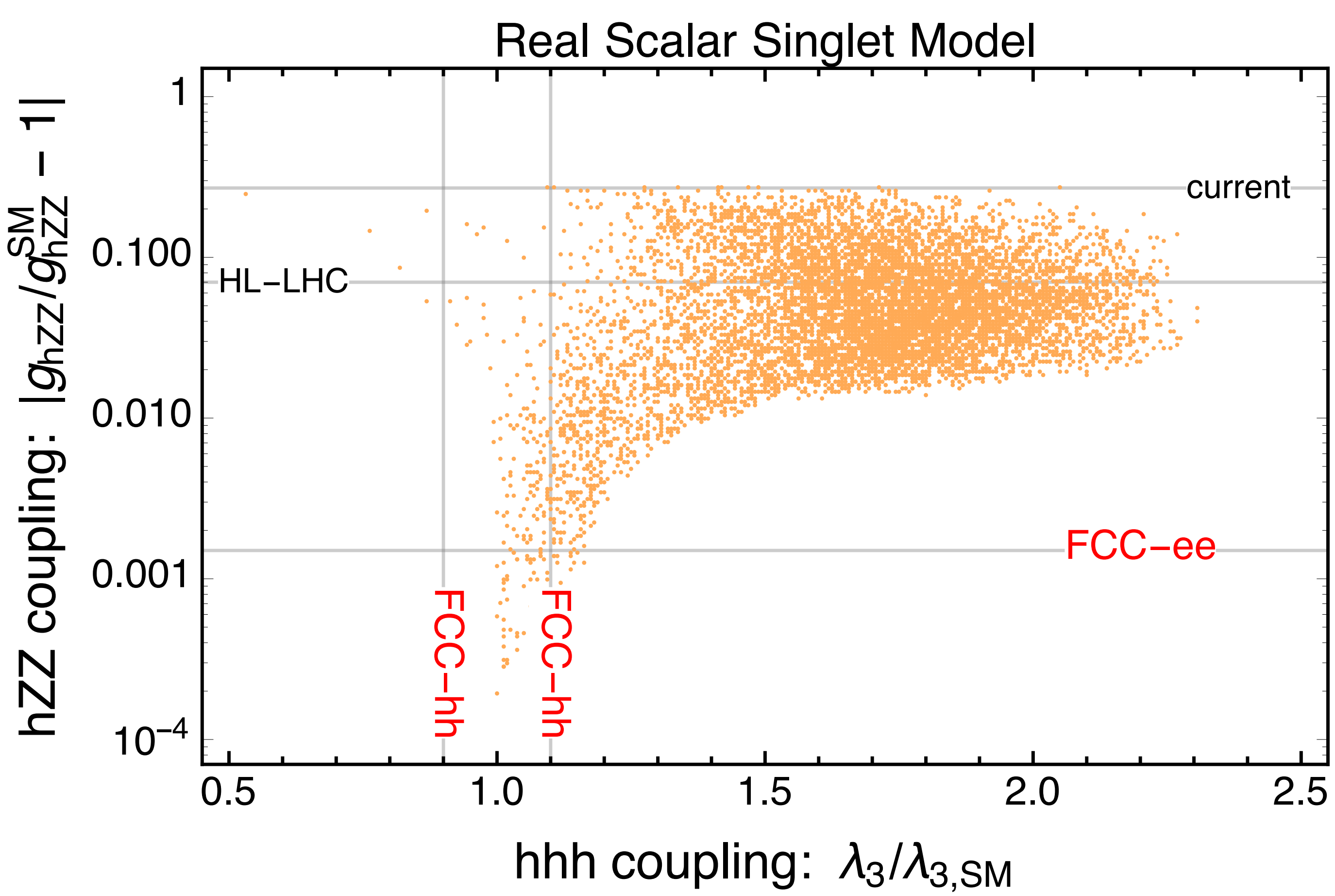
- **Strong 1st order EWPT** needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states



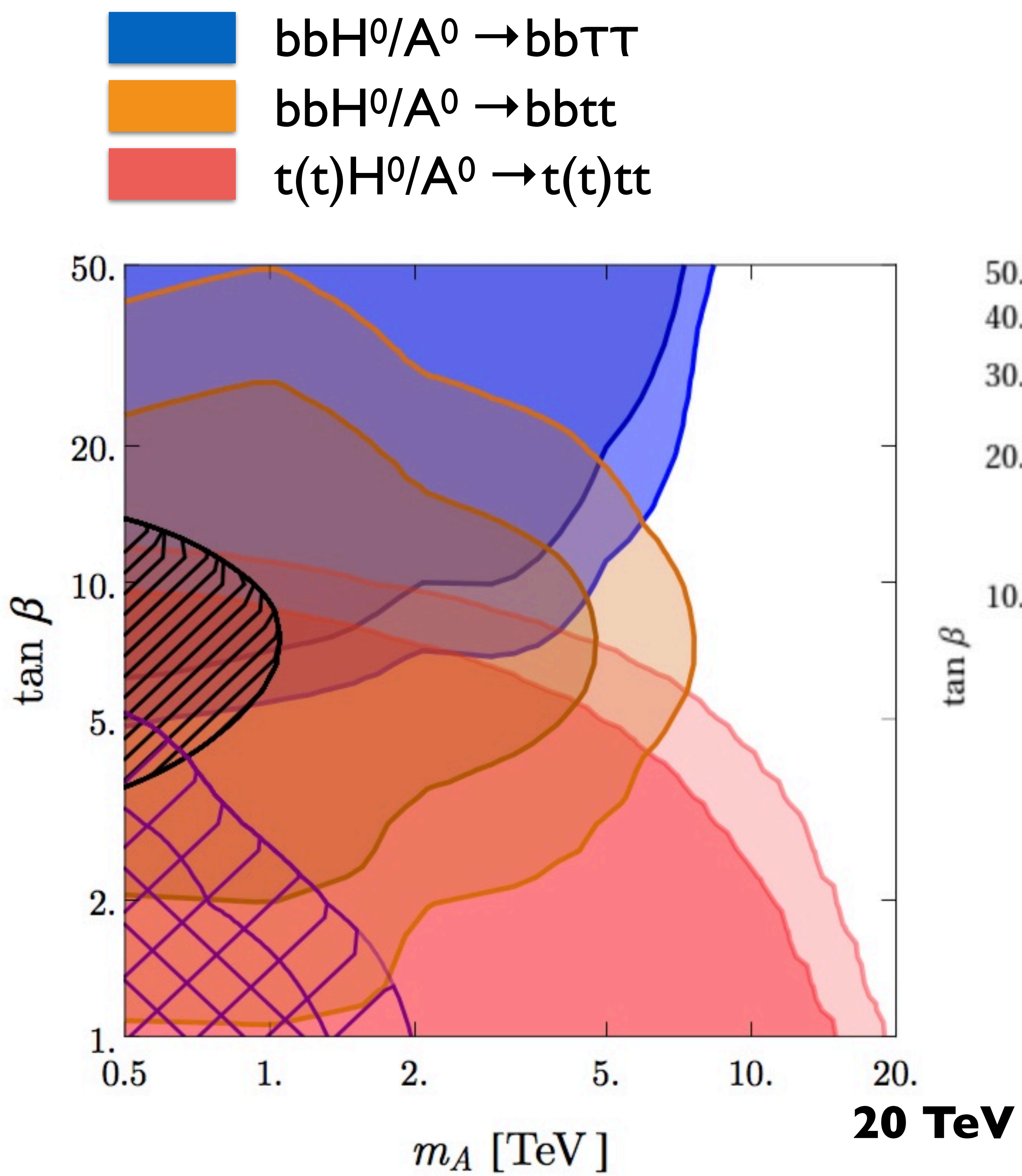
$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

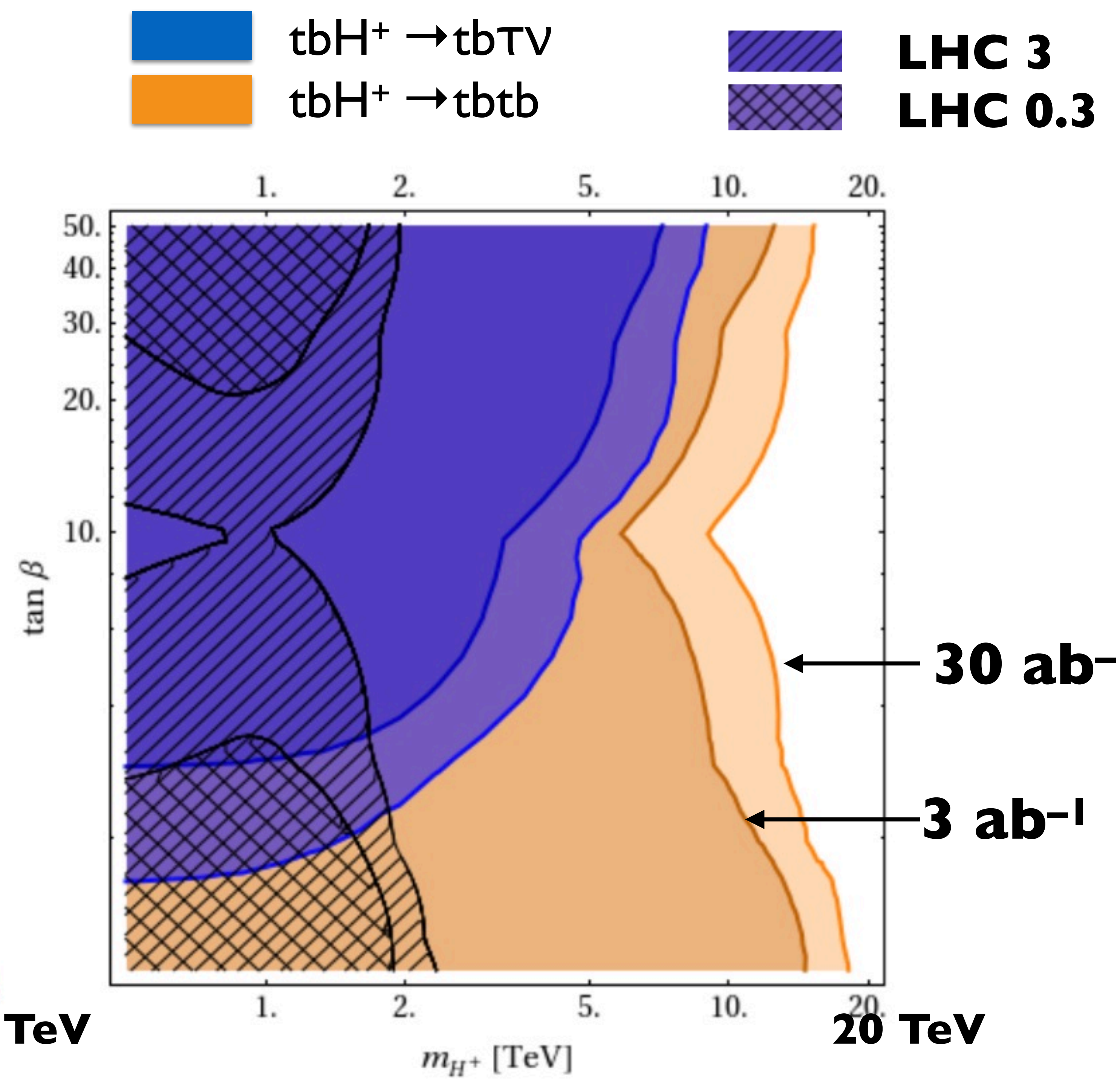
Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

MSSM Higgs





N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

Minimal stealthy model for a strong EW phase transition:
the most challenging scenario for discovery

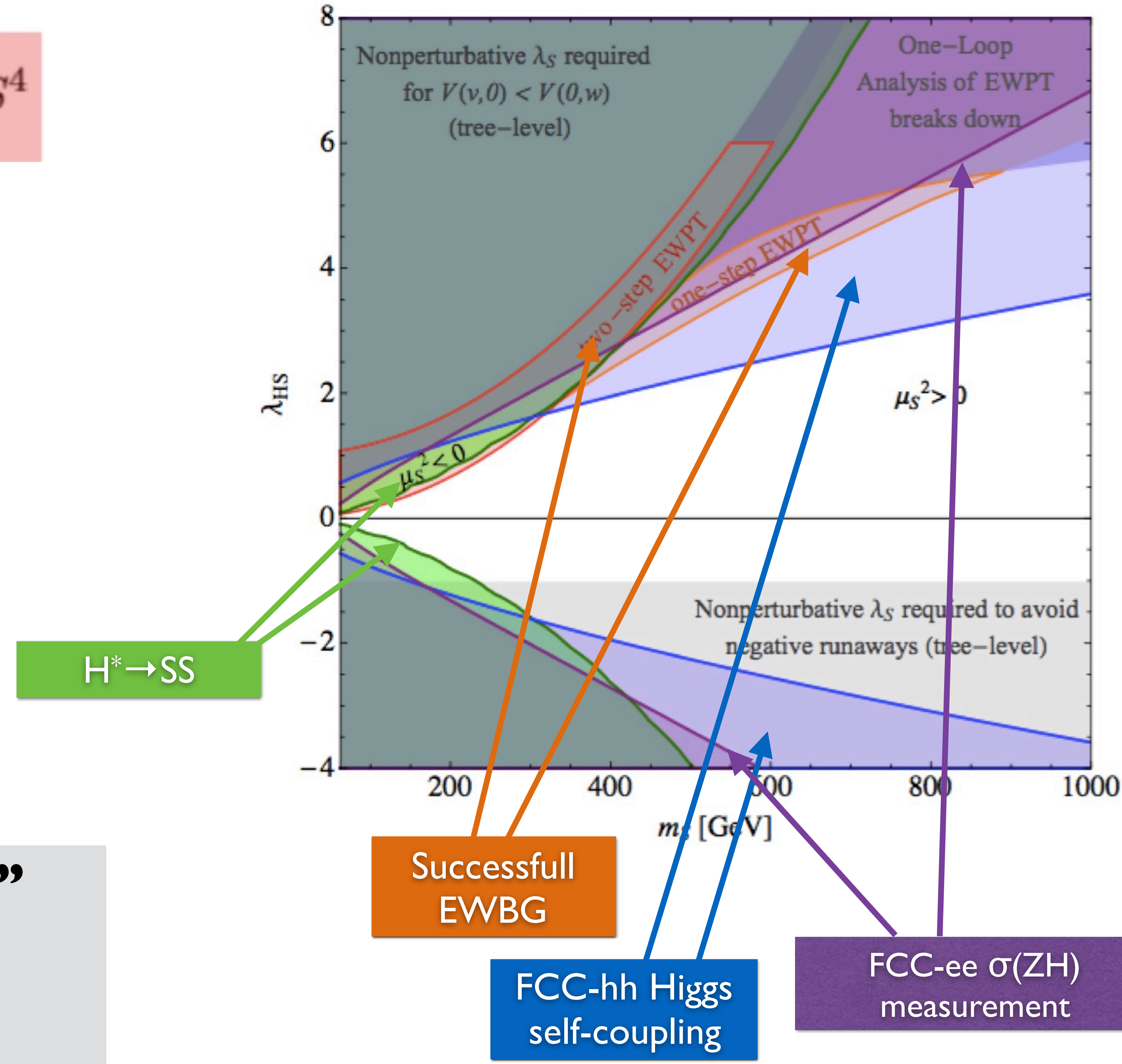
$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

Unmixed SM+Singlet.
No exotic H decay, no H-S mixing, no EWPO, …

Two regions with strong EWPT

Only Higgs Portal signatures:
$h^* \rightarrow SS$ direct production
Higgs cubic coupling
σ(Zh) deviation (> 0.6% @ TLEP)

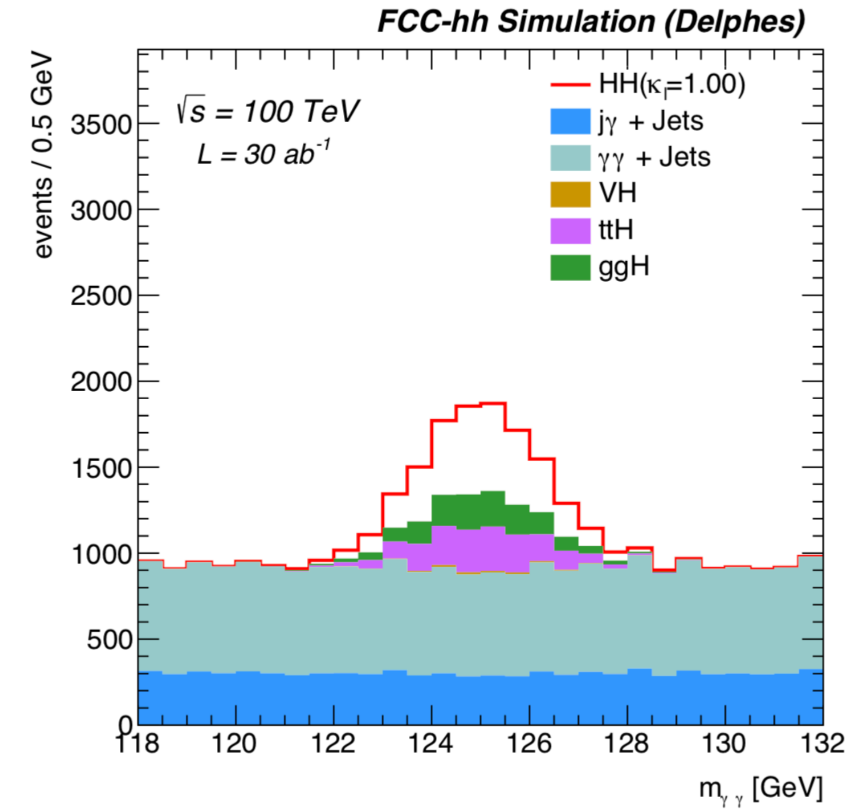
Curtin, Meade, Yu, arXiv:1409.0005

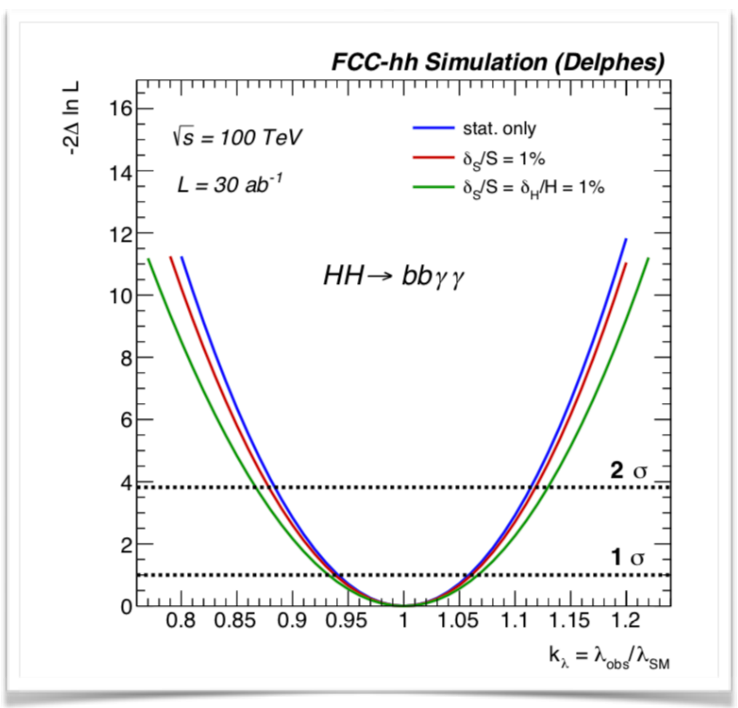


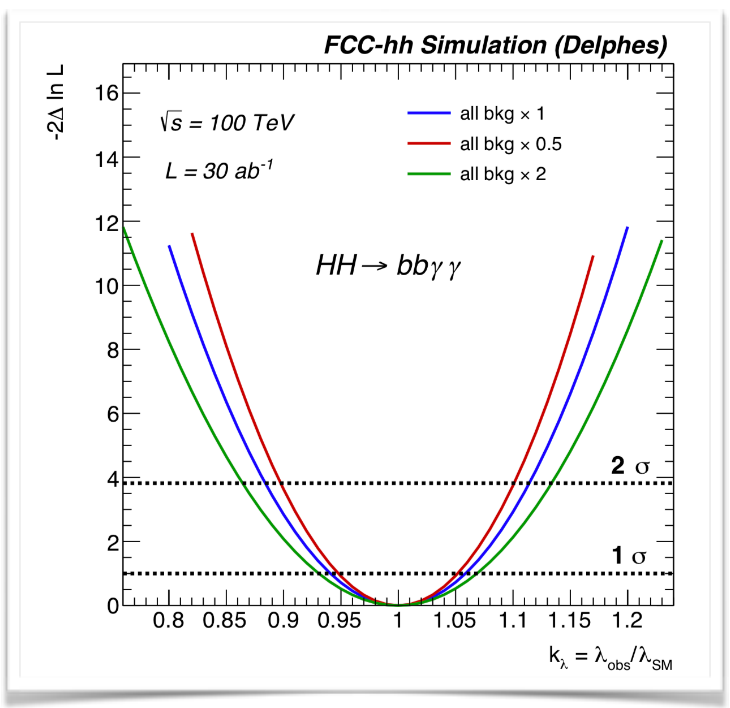
⇒ Appearance of first "no-lose" arguments for classes of compelling scenarios of new physics

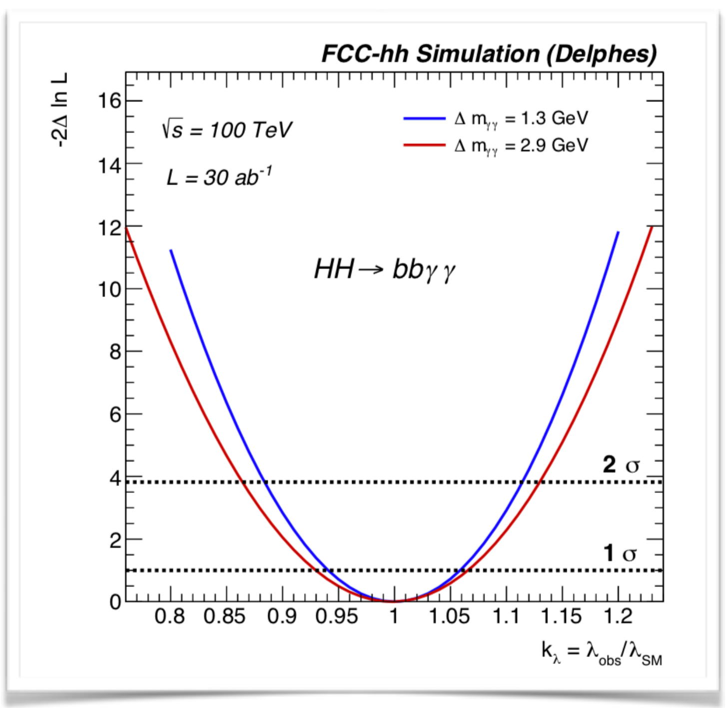
HH →bbγγ

- **Large QCD** backgrounds (jjγγ and γ+jets)
- Main difference w.r.t LHC is the very large **ttH background**
- Strategy:
  - exploit **correlation of means in ($m_{\gamma\gamma}$, m_{hh})** in signal
  - build a **parametric model in 2D**
  - perform a **2D Likelihood fit** on the coupling modifier k_λ
  - **$\delta k_\lambda / k_\lambda$ = 5-7%** (stat - stat+syst.) in this channel alone









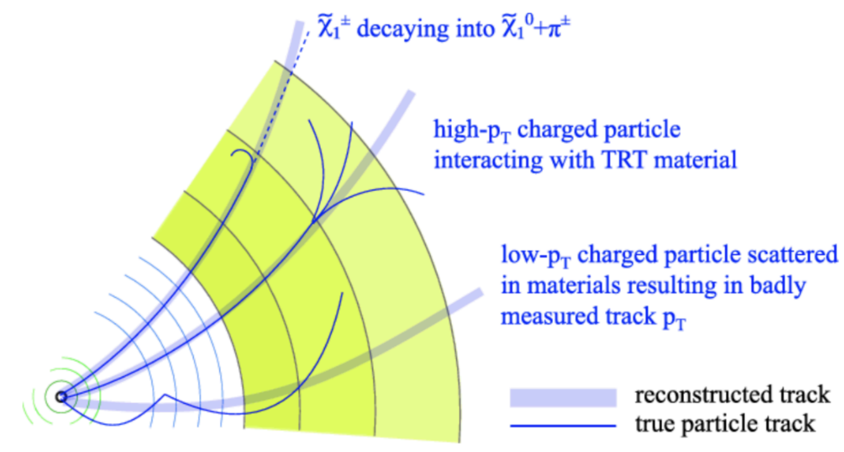
$\delta k_\lambda / k_\lambda$ = 5 % by combining with other channels

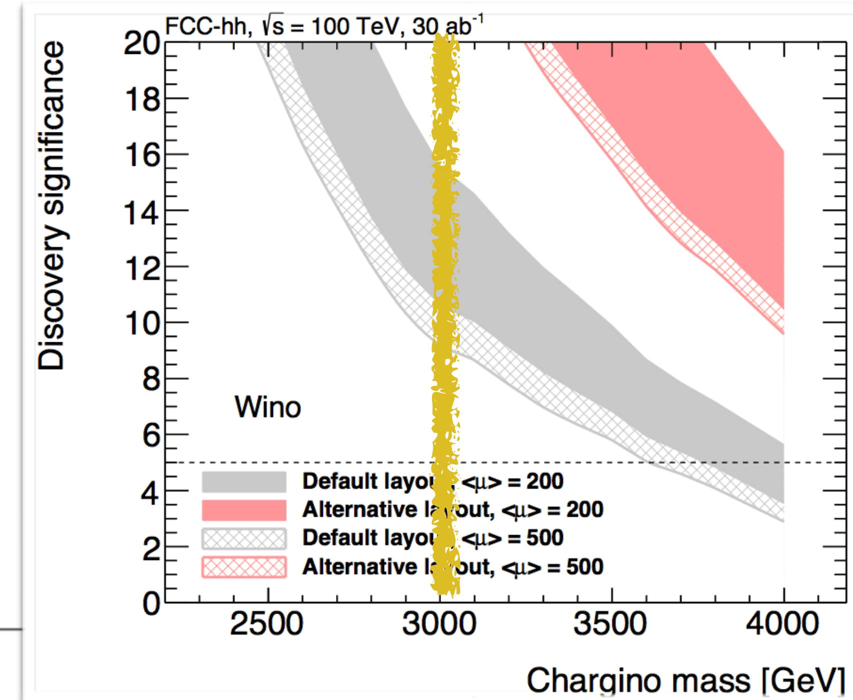
Disappearing Tracks

- Observed relic density of Dark Matter
  - Higgsino-like: 1TeV,
  - Wino-like: 3TeV

- Mass degeneracy: wino 170MeV, Higgsino 350MeV
  - disappearing track signature

FCC-hh can explore conclusively EW charged WIMP models, (low multiplets)





Compatible with observed relic abundance