FCC-ee physics summary

September 19, 2024
LFC24, Trieste

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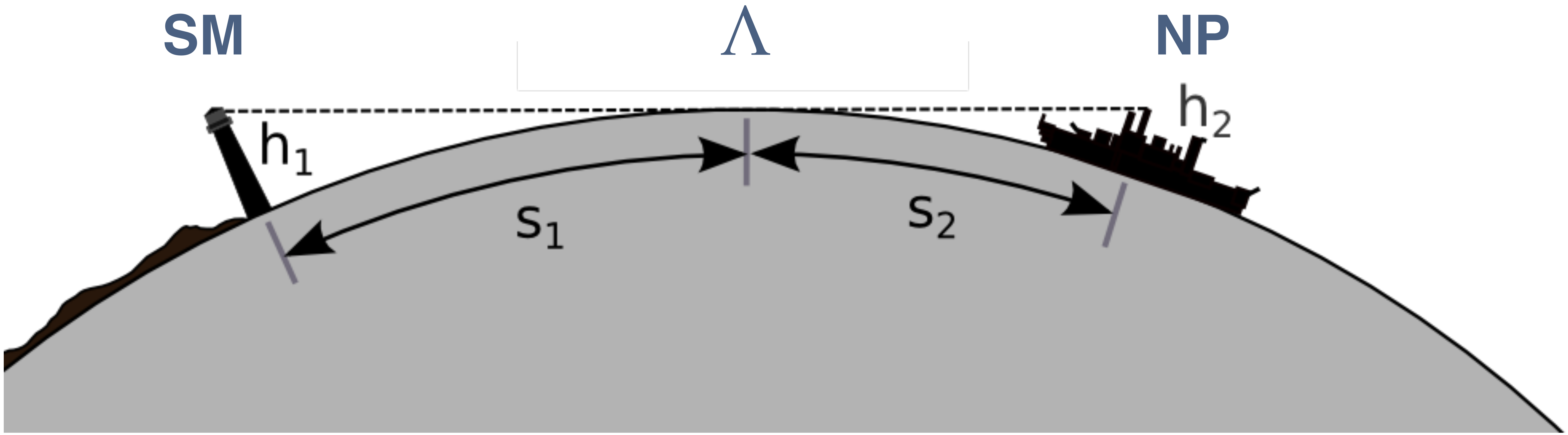
Karlsruhe Institute of Technology

A loose analogue



Could be a vast ocean before the new physics continent…

Update of European Strategy for Particle Physics

3

High-priority future initiatives

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

- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

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FCC project

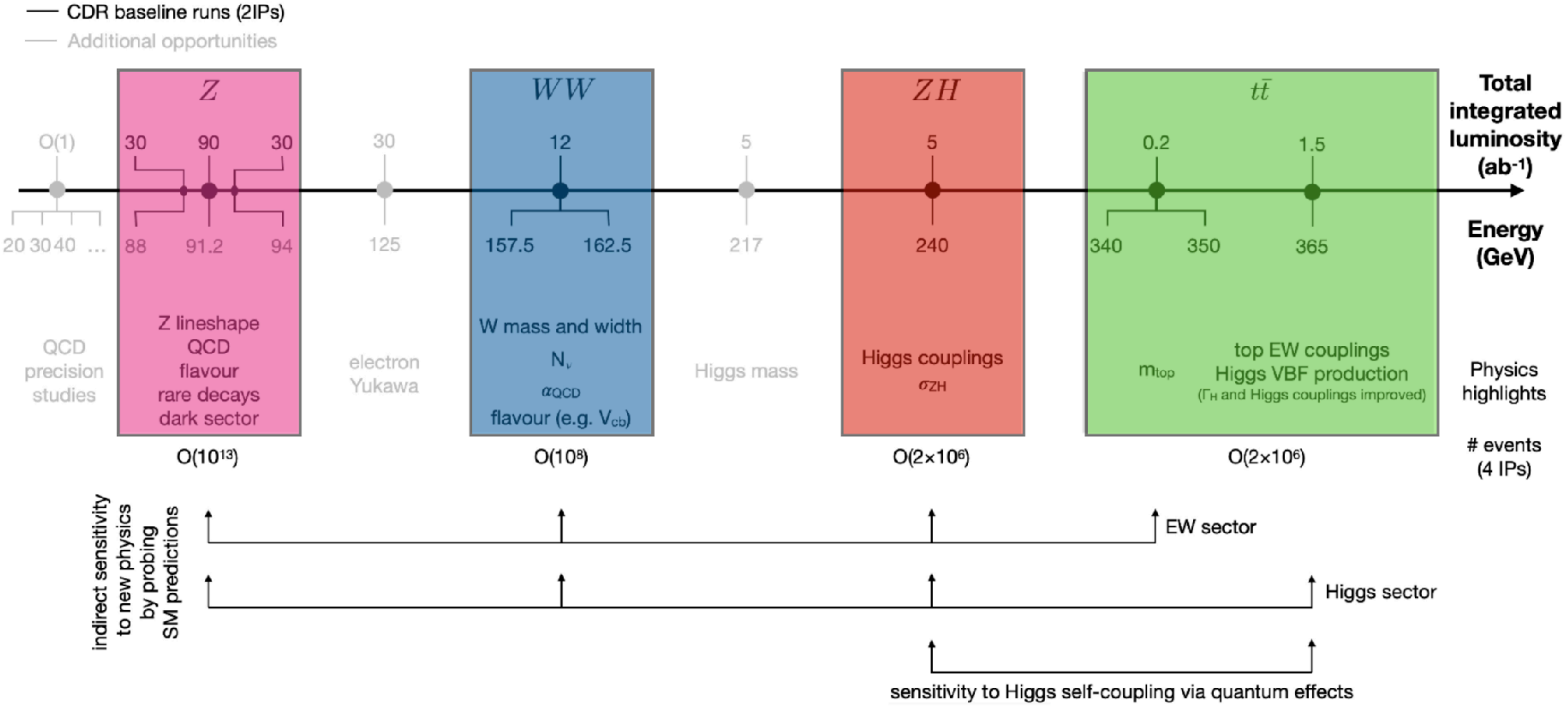
New infrastructure

- 90.7 km tunnel
- 8 surface points
- 4 experimental sites
- Deepest shaft 400 m, average 240 m

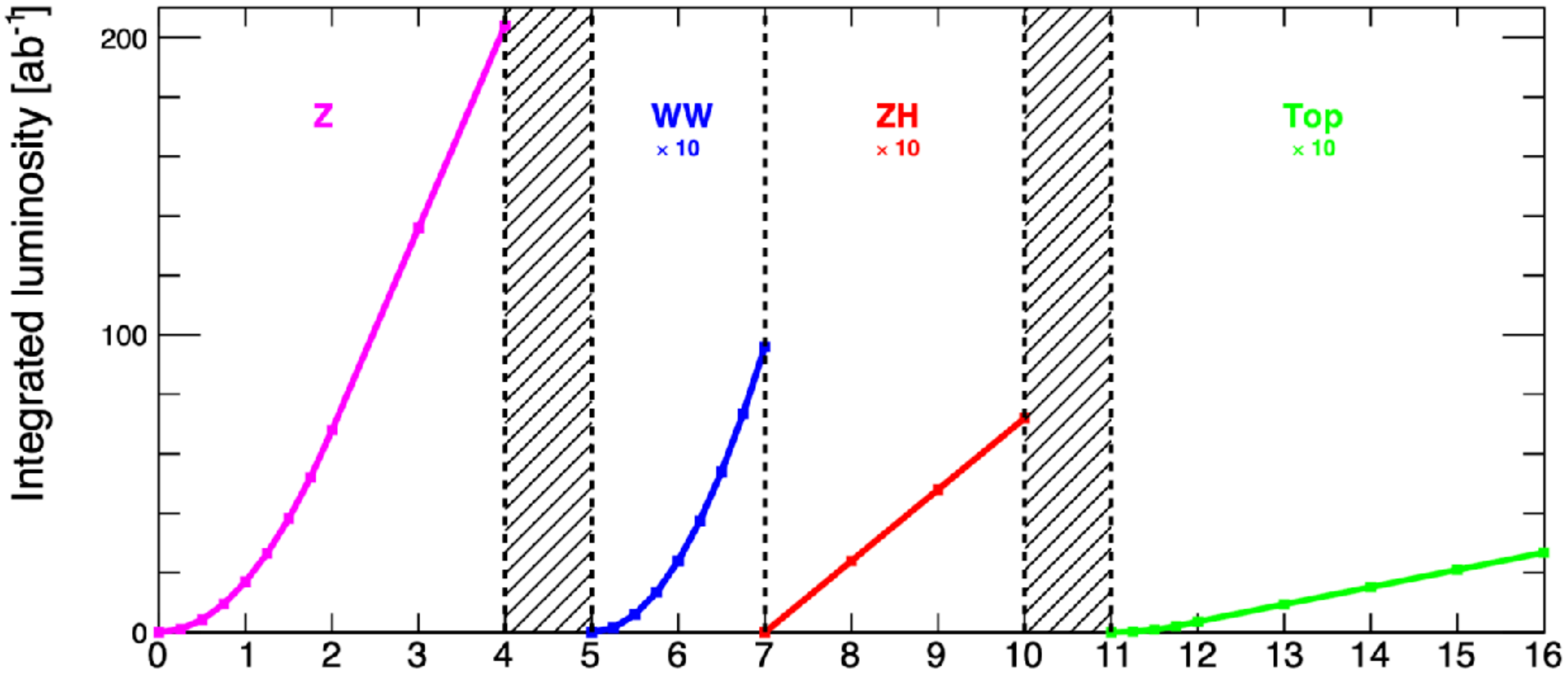
Two stages

- FCC-ee (~15 years)
- FCC-hh (>20 years)

FCC-ee program



FCC-ee dataset



Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW → H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW → H	

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Outline

- **Higgs factory**
  - Complementary to hadron colliders
- **EW+QCD factory**
  - Huge leap (10^5) from LEP
- **Flavor factory**
  - > 10 times more data than Belle II
- **Discovery machine**
  - Direct and indirect probes for BSM

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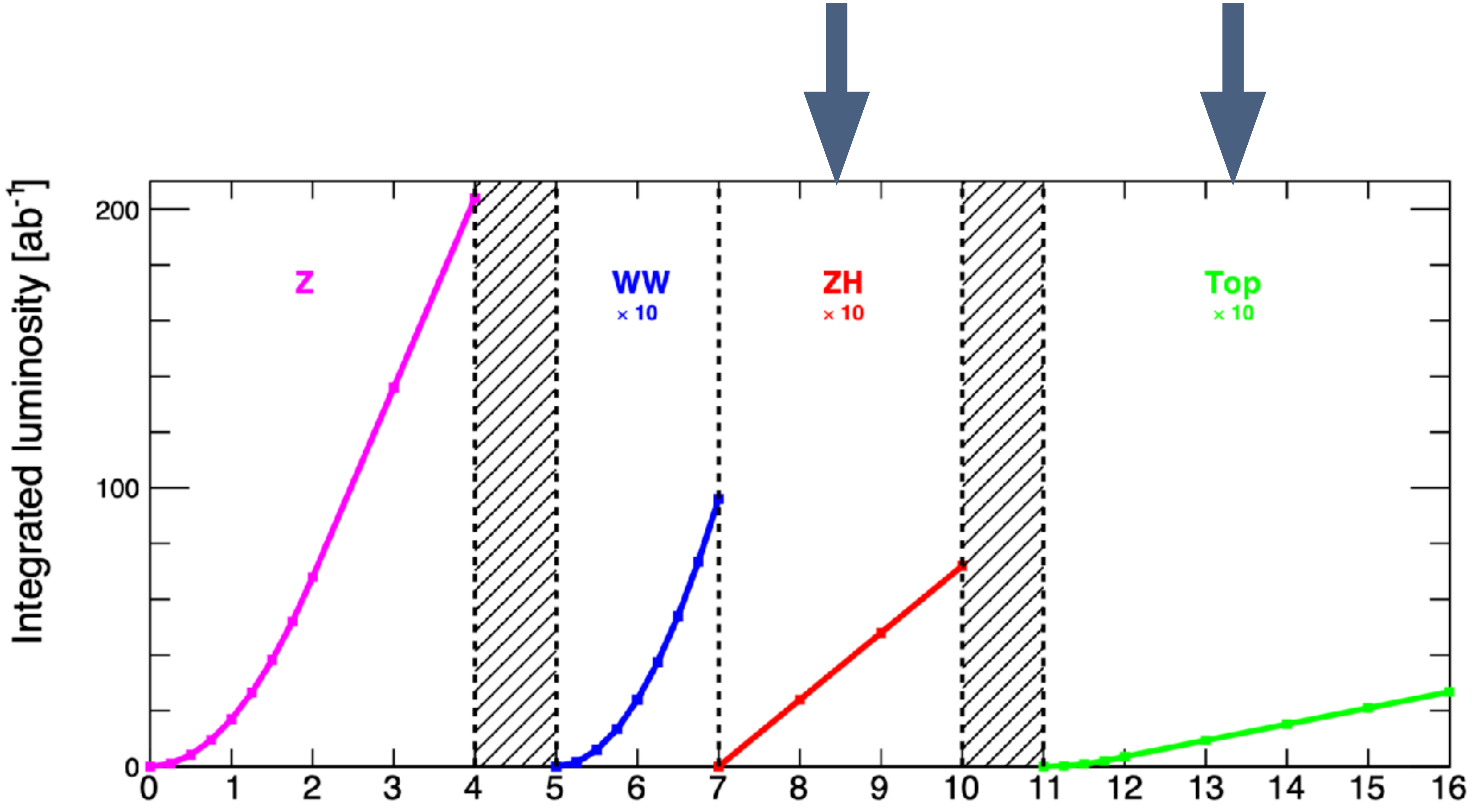
Higgs factory

- couplings overview
- cross section, mass, width
- $H \rightarrow gg, cc, ss$
- self-coupling
- electron Yukawa

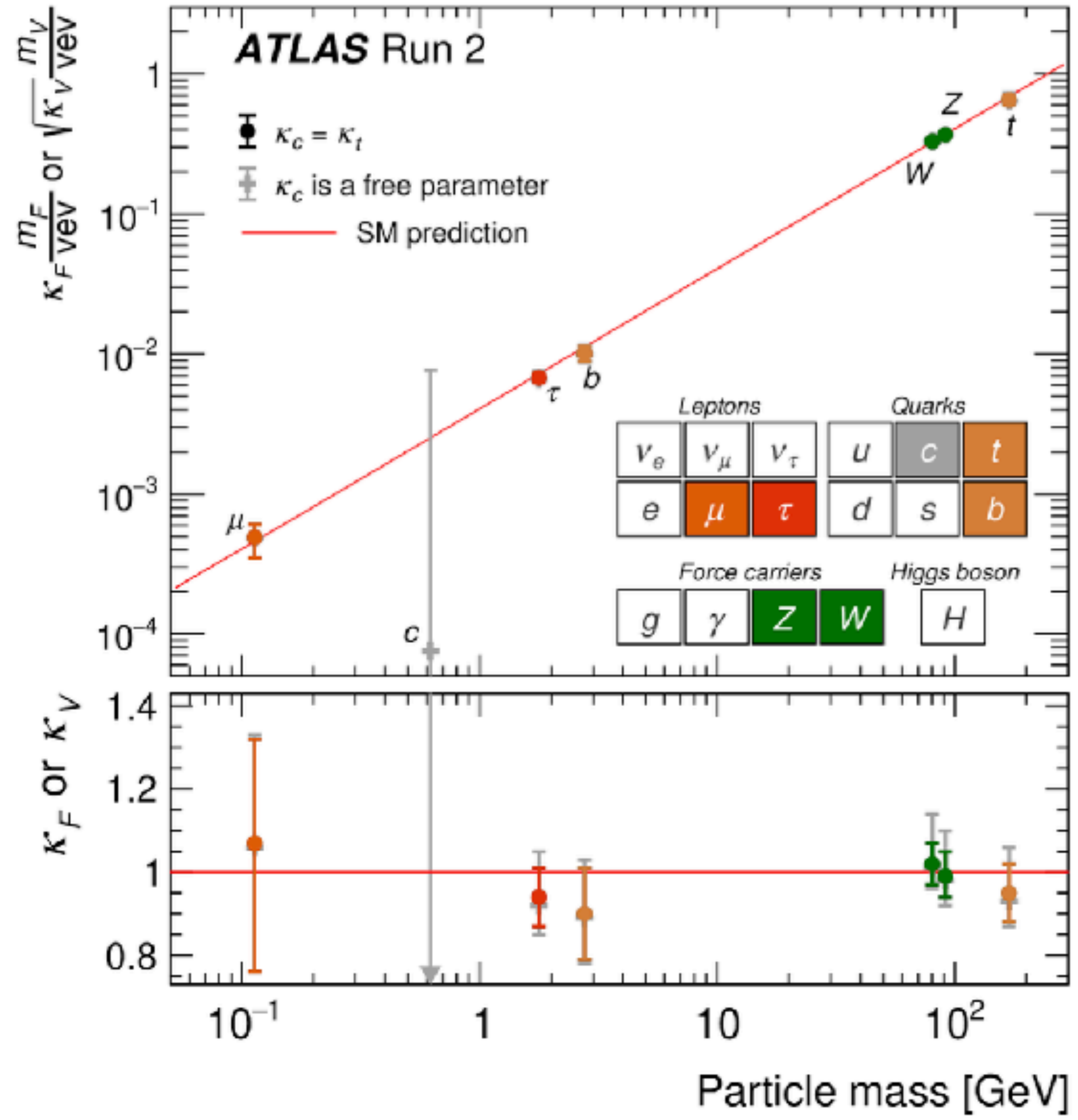
More discussed in talk of G. Panico



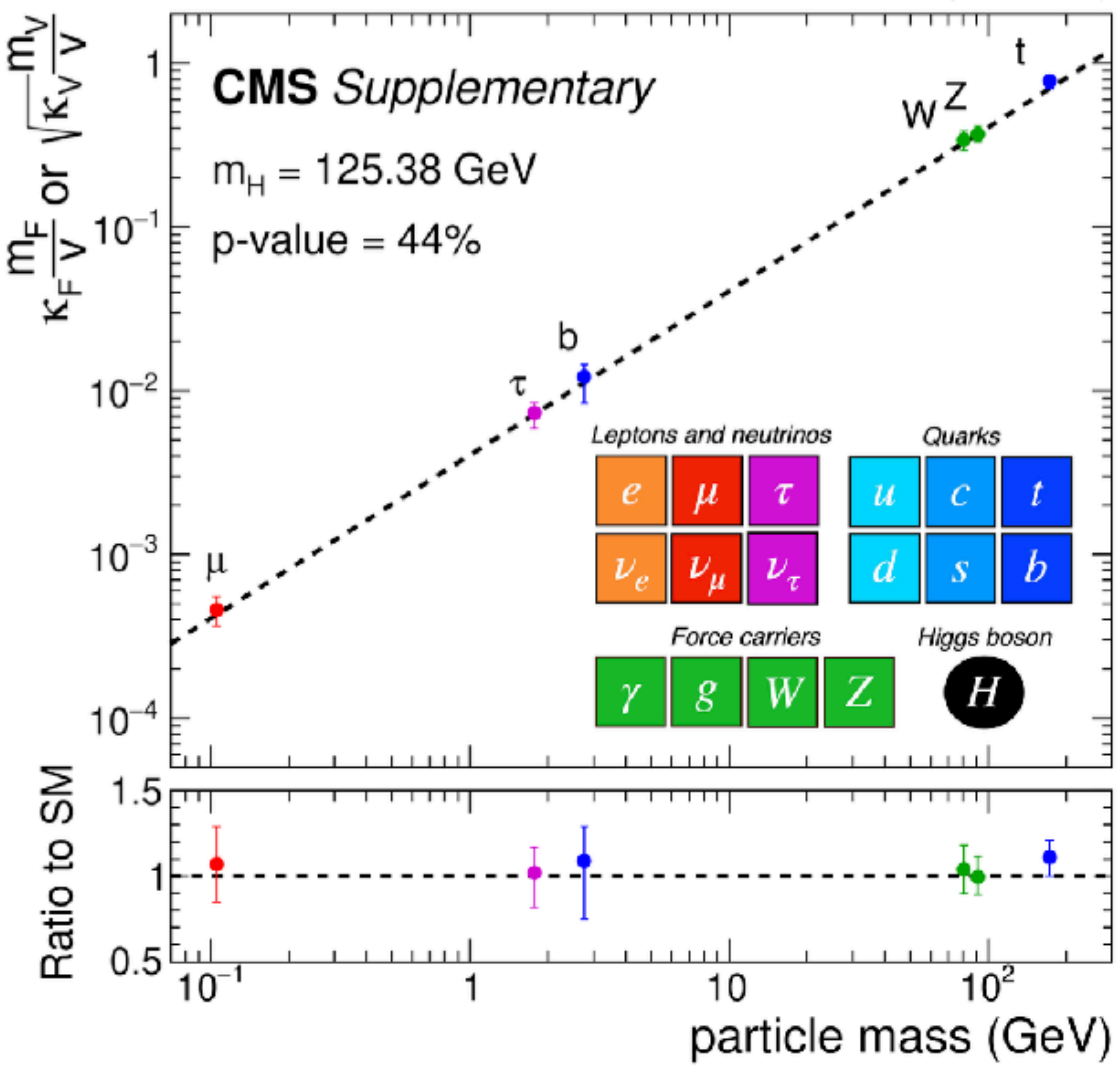
$6 \times 10^{12}\ Z$ $2 \times 10^{8}\ WW$ $2 \times 10^{6}\ ZH$ $2 \times 10^{6}\ t\bar{t}$

Higgs as we know today

Nature 607, 52–59 (2022)



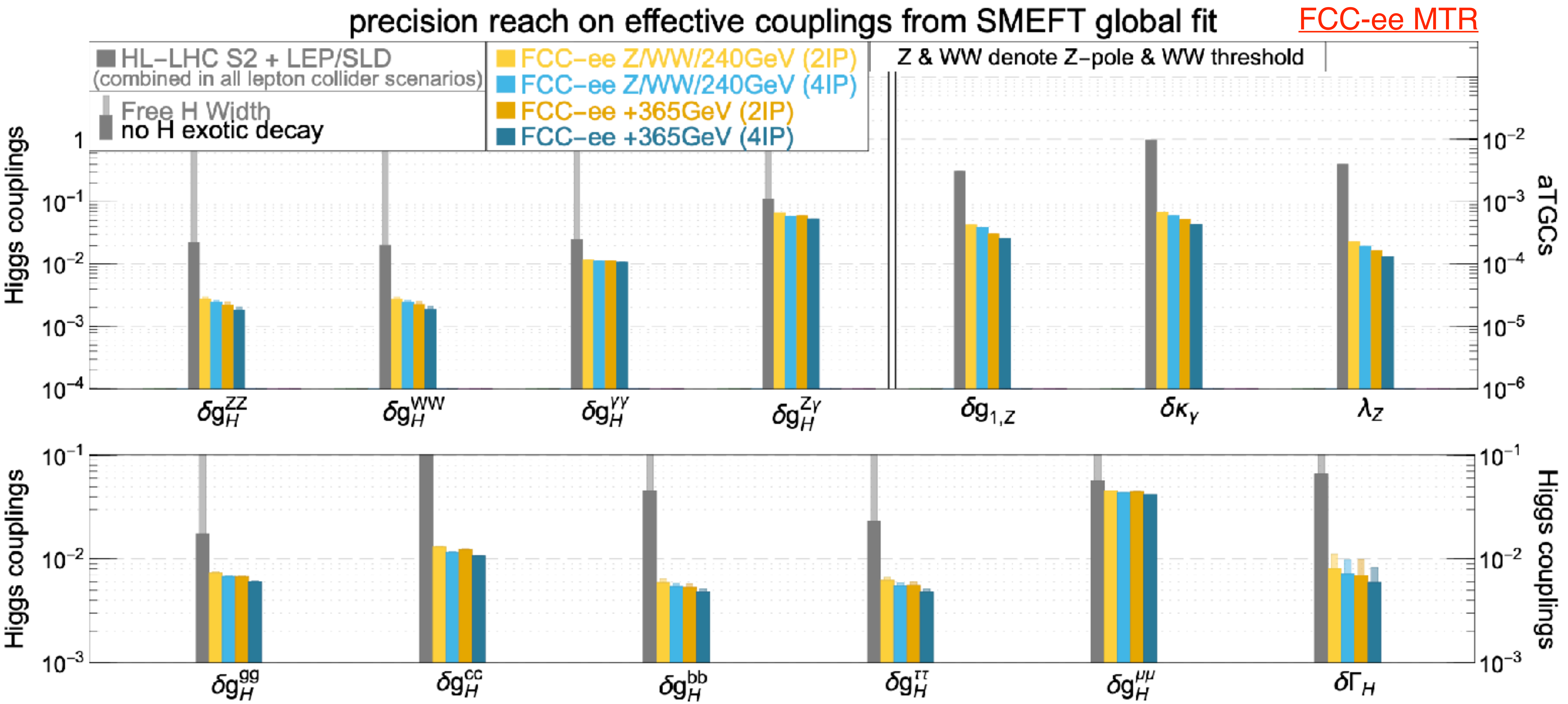
Nature 607, 60–68 (2022)



Great success, albeit

- Certain modes are difficult to probe (light fermions, hadronic final states)
- No direct access to total width (measurements not model-independent)

Higgs coupling at FCC-ee



FCC-ee MTR

- Model-independent Γ_H from $\sigma(ZH)$ and $BR(H \rightarrow ZZ)$
- High precision in modes complementary to HL-LHC

More discussed in talk of J. de Blas

$\sigma(ZH)$, m_H, Γ_H

FCC WIP

Using recoil mass, $m^2_{recoil} = s + m^2_Z - 2E_{ll}\sqrt{s}$

✓ Very precise m_H measurement

✓ Model-independent $\sigma(e^+e^- \to ZH)$ determination

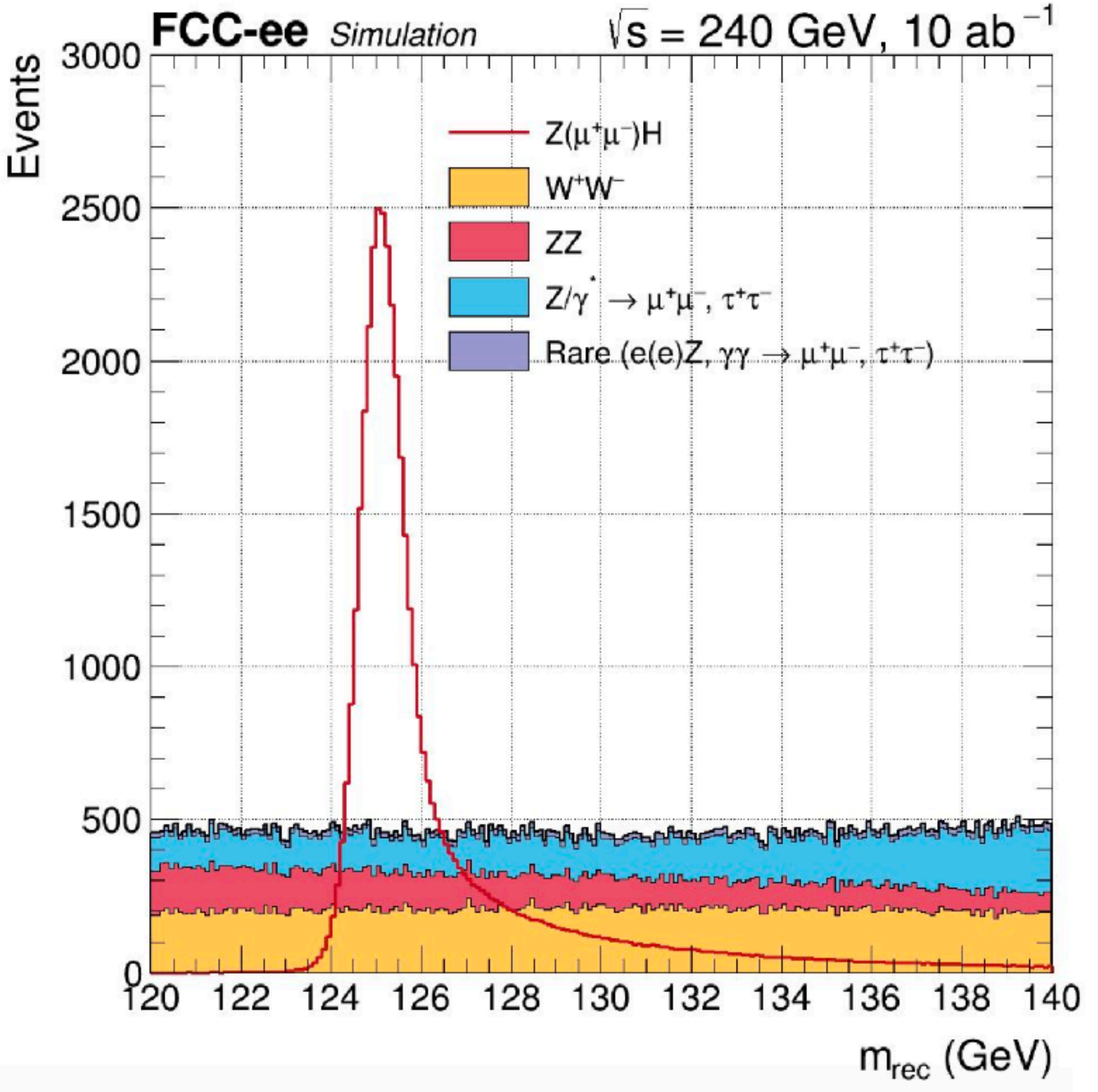
With the $\sigma(e^+e^- \to ZH)$

- $\sigma(ZH) \times \mathscr{B}(H \to XX) \propto g^2_{HZZ} \times \dfrac{g^2_{HXX}}{\Gamma_H}$
- $\Gamma_H \propto \dfrac{\sigma(ZH)^2}{\sigma(ZH, H \to ZZ)}$

✓ Model-independent total Γ_H

✓ Determine other g_{HXX}

measurement	m_H	$\sigma(ZH)$	Γ_H
precision	4 MeV	0.6%	1%



Higgs to hadrons

Major aspect of Higgs properties

- Only $H \to b\bar{b}$ observed so far

Require exquisite understanding of jets

- Nature of hadronization, QCD modeling
- Jet clustering and flavor tagging algos

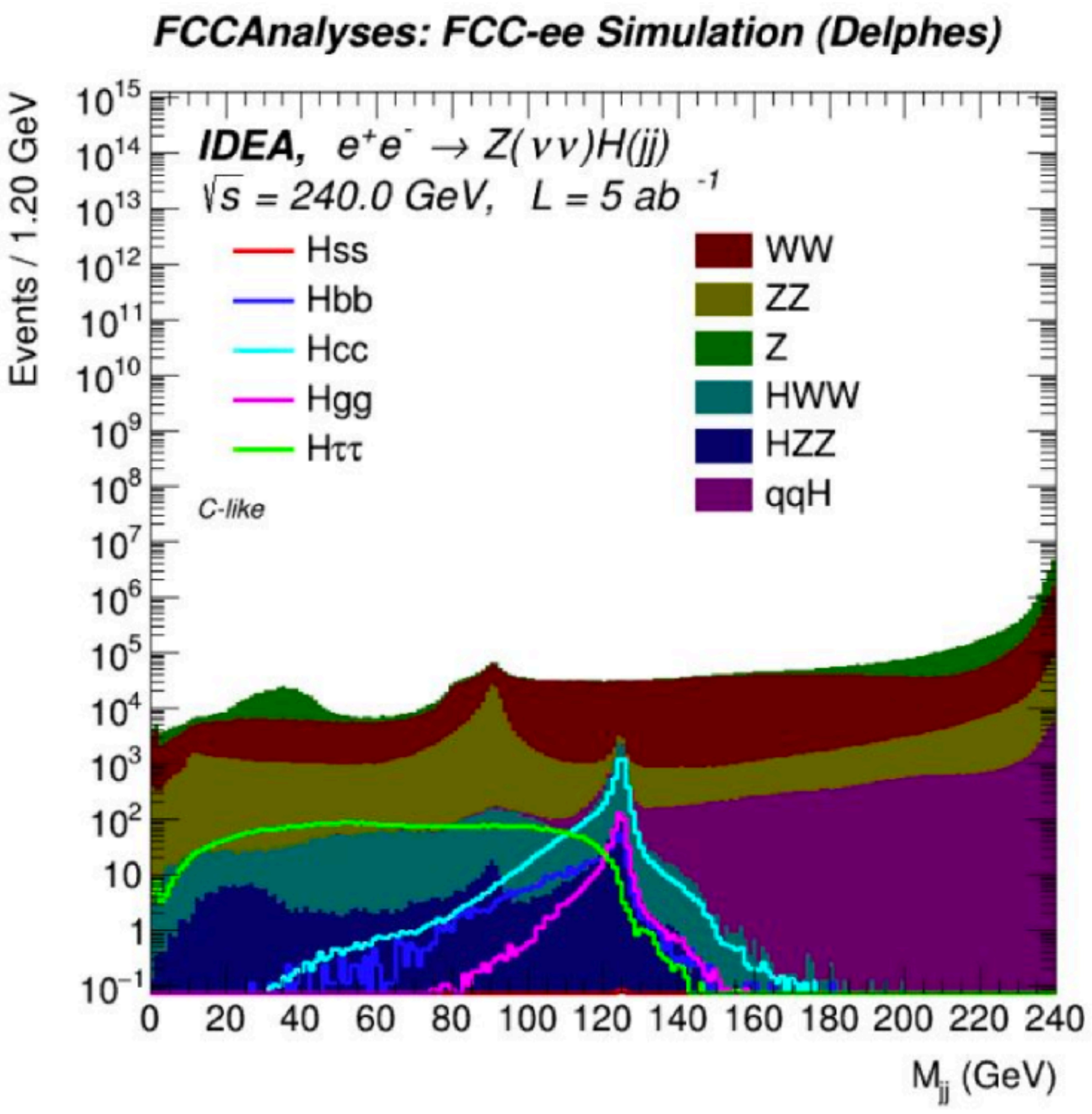
An ensemble of final states

- $(Z \to \ell\ell, \nu\nu, jj) \otimes (H \to bb, cc, ss, gg)$

mode	Hbb	Hcc	Hss	Hgg
SM BR	58%	2.9%	0.024%	8.6%
rel prec.	0.22%	1.7%	120%	0.9%

- Also upper limits on $H \to uu, dd$, and FCNC $H \to bs, bd, sd, cu$

FCC WIP



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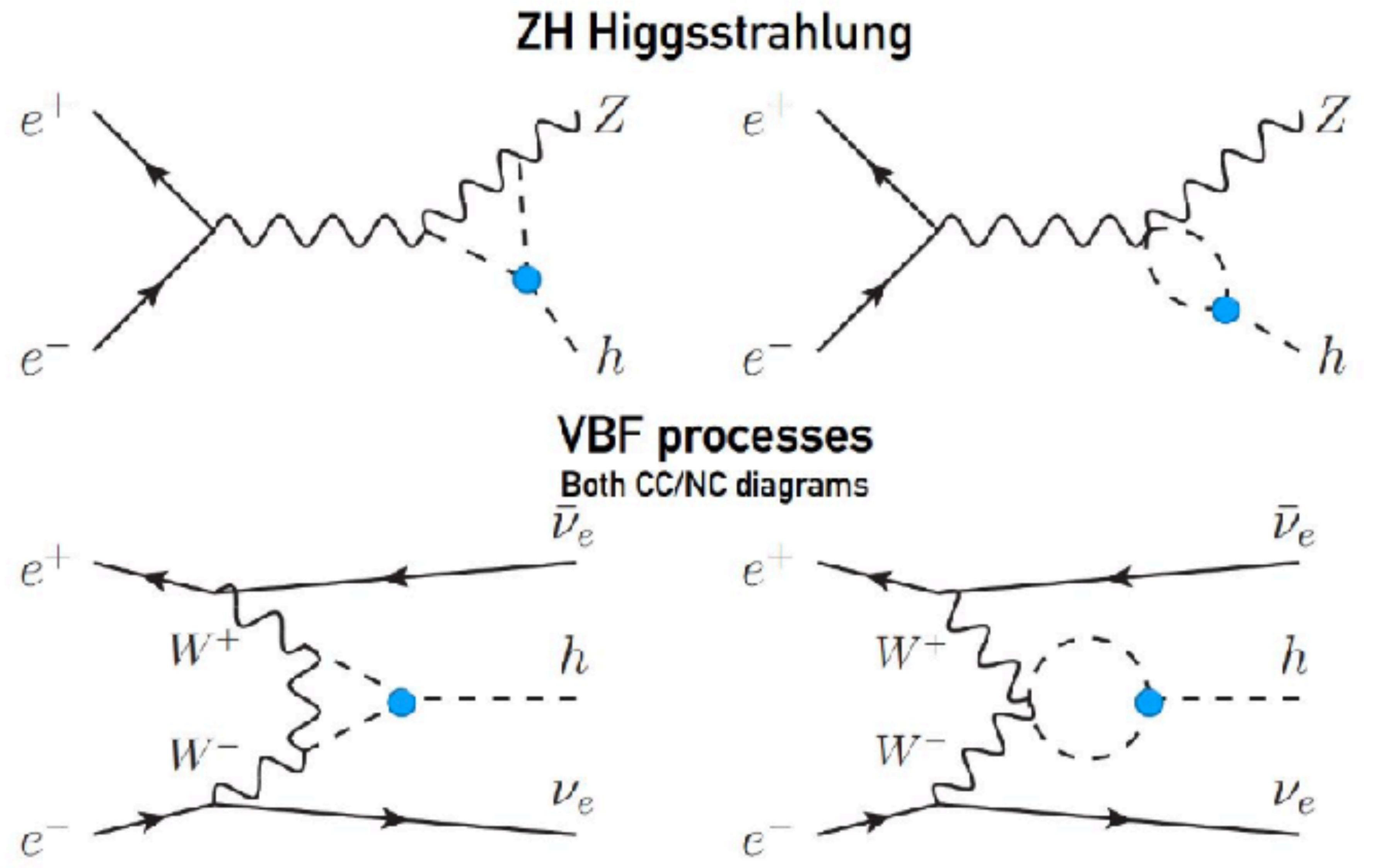
Higgs self-coupling

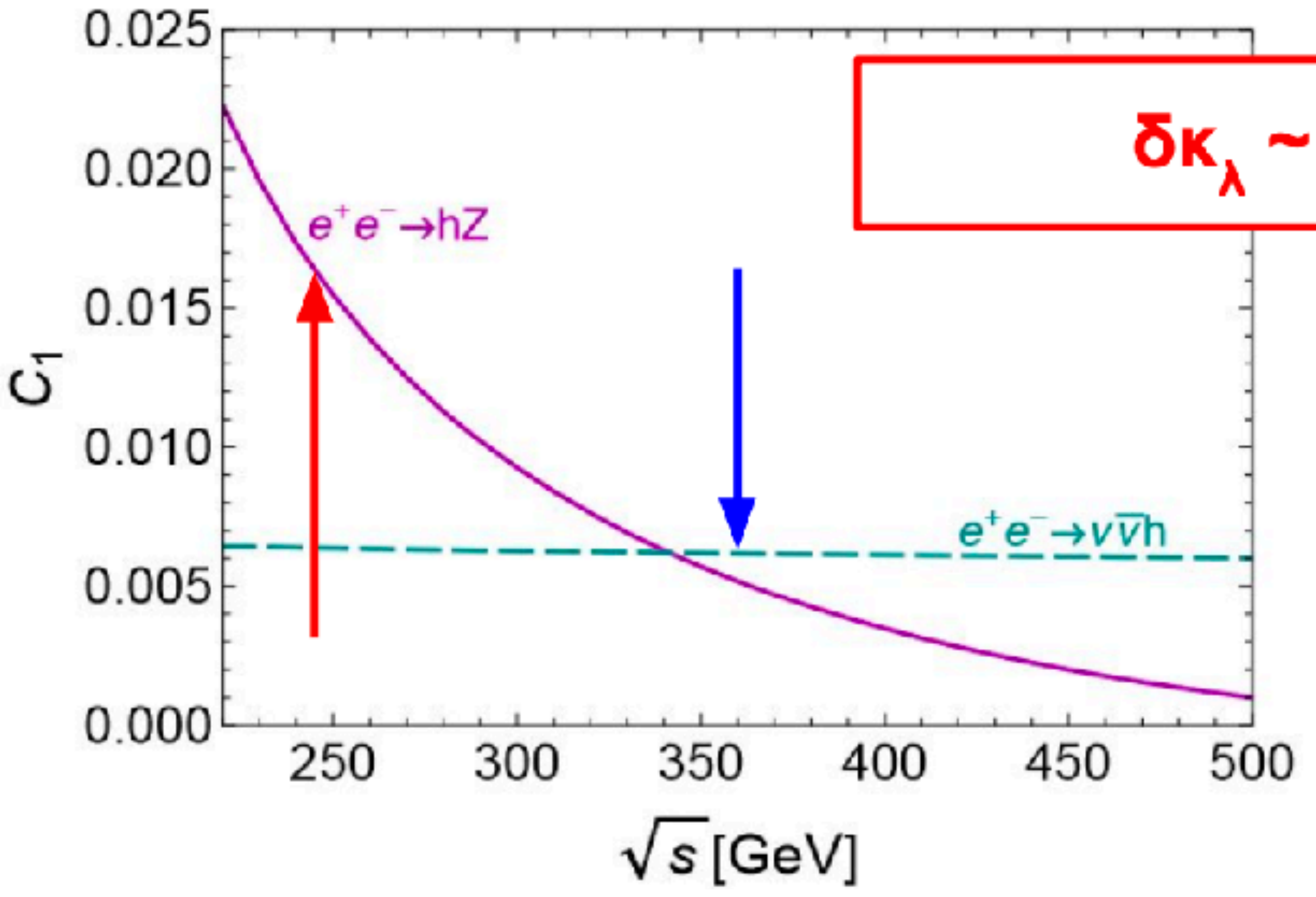
Indirect probe of λ_3 through NLO contributions

- $\sigma_{NLO} = Z_H \sigma_{LO}(1 + \kappa_\lambda C_1)$
- O(1%) level modification

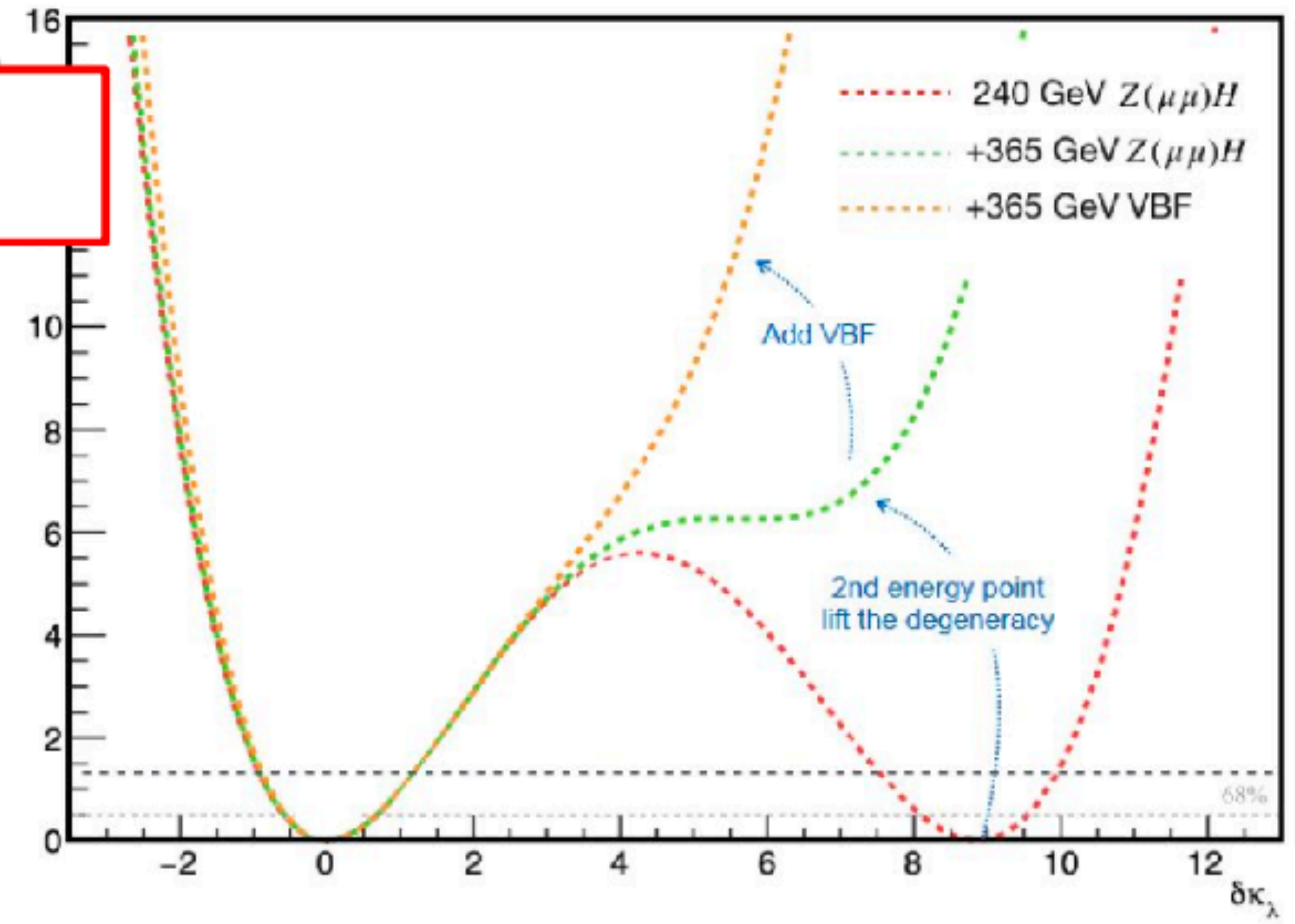
C_1 is energy-dependent

- Use both 240 GeV and 365 GeV to life degeneracy





$\delta\kappa_\lambda$ ~ 24%



More discussed in talk of G. Panico

Electron Yukawa

Resonant Higgs production at 125 GeV

- Only possibility to probe electron Yukawa, $\mathscr{B}(H \to ee) \sim O(10^{-9})$
- Beam monochromotization is crucial

Very rare counting experiment

- $\sigma(e^+e^- \to H) \sim$ O(1) fb
- $\sigma(e^+e^- \to Z) \sim$ O(10^5) fb

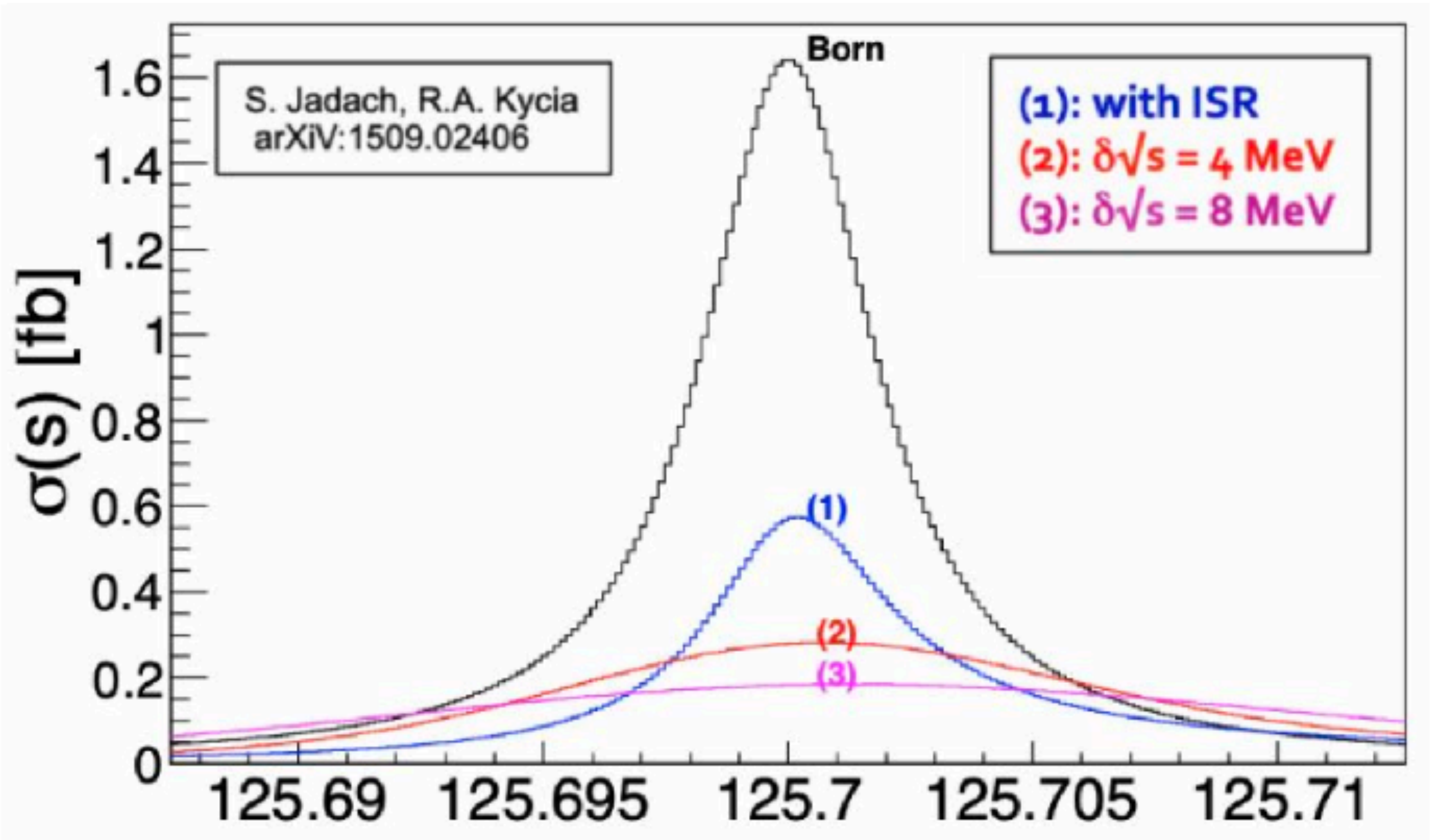
$e^+e^- \to gg$ is golden channel

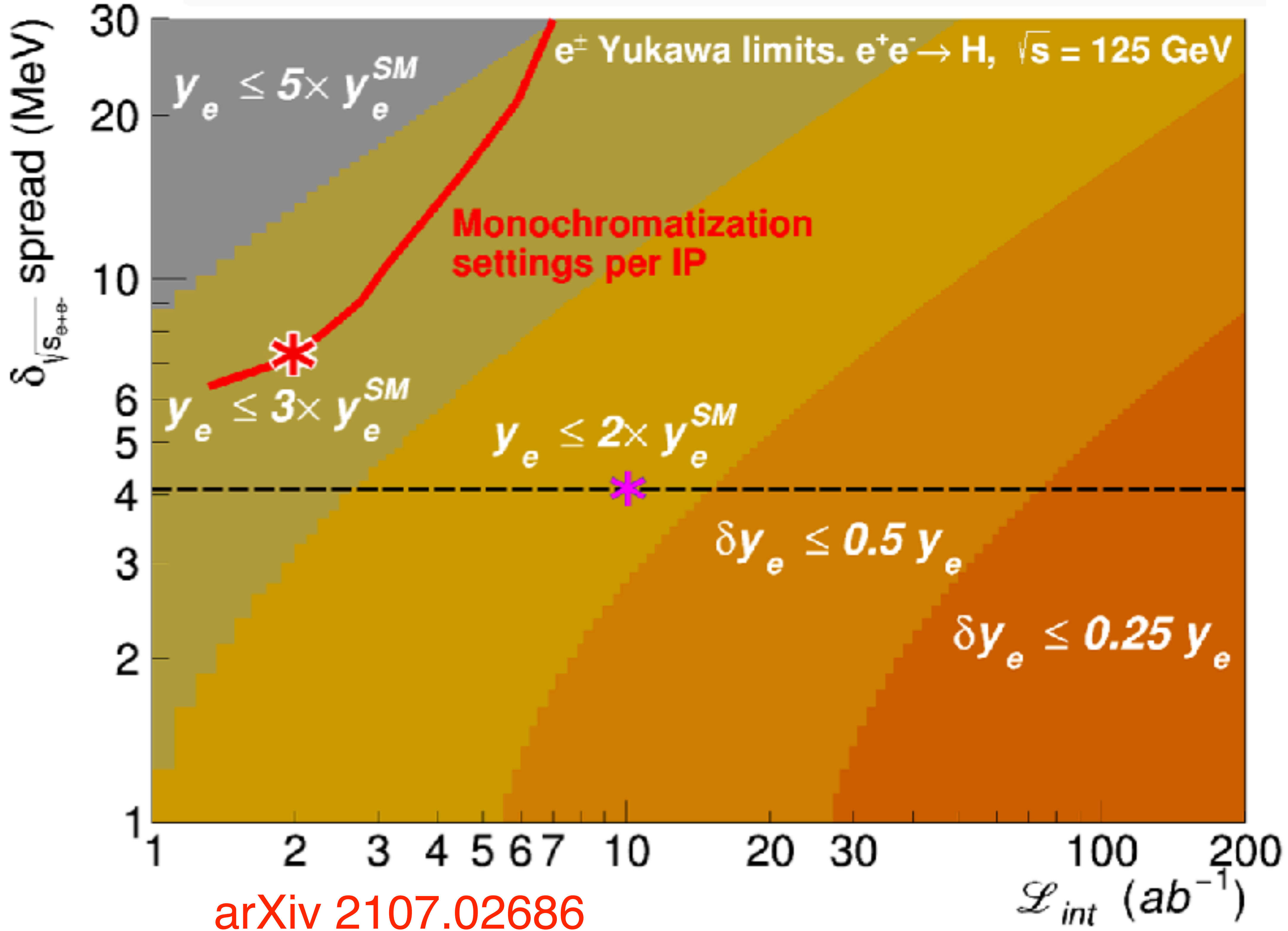
- Only mediated by Higgs, no real background

Expectations

- 20 ab^{-1}/y ~ 6k eeH events/y
- Potential to probe y_e at SM level

More discussed in talk of G. Panico

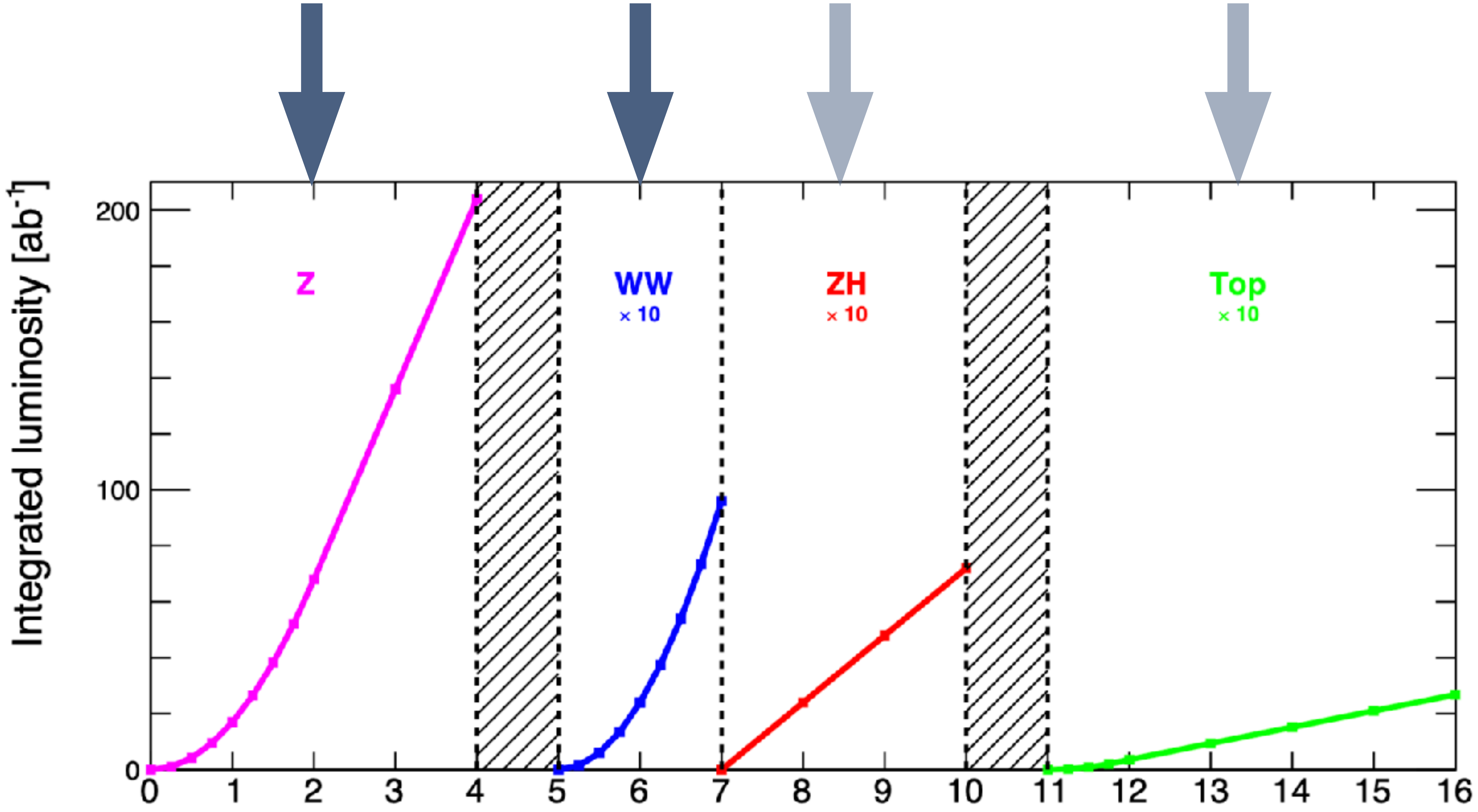




arXiv 2107.02686

EW+QCD factory

- Precision landscape
- m_t scan
- QCD precision



$6 \times 10^{12}\ Z$ $2 \times 10^{8}\ WW$ $2 \times 10^{6}\ ZH$ $2 \times 10^{6}\ t\bar{t}$

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Precision landscape

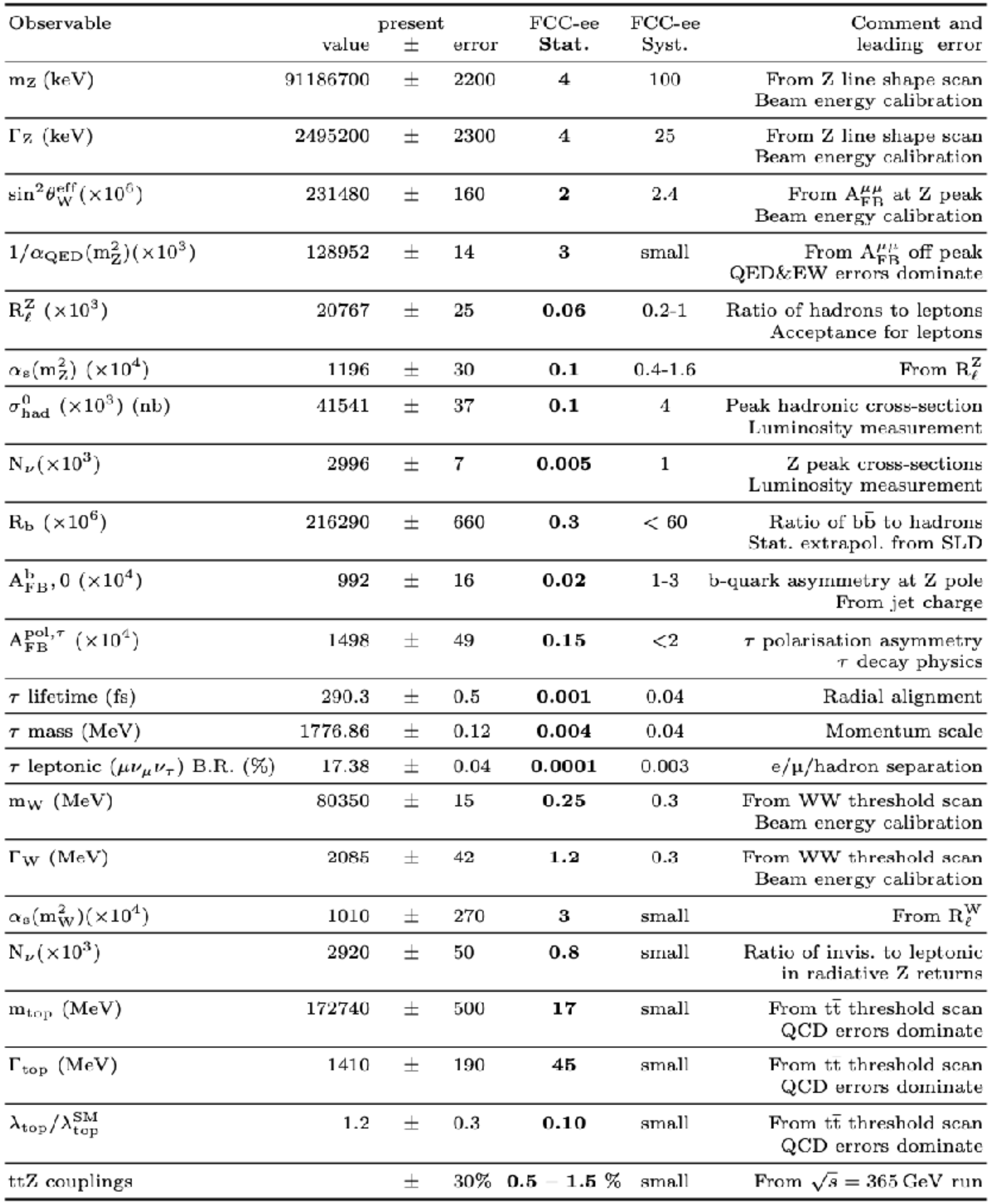
10^5 times luminosity of LEP

- "LEP in a minute"

Sensitive to heavier NP in loops

- (mass scale) $\propto$ (unc)$^{-1/2}$ $\propto$ (stat)$^{-1/4}$

Combining EWK and Higgs measurements, constrain NP up to $\Lambda \sim 70$ TeV in dim-6 EFT



Observable	present value	±	error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

FCC-ee MTR

top mass scan

m_t from template fit

- Also Γ_t, α_s, y_t

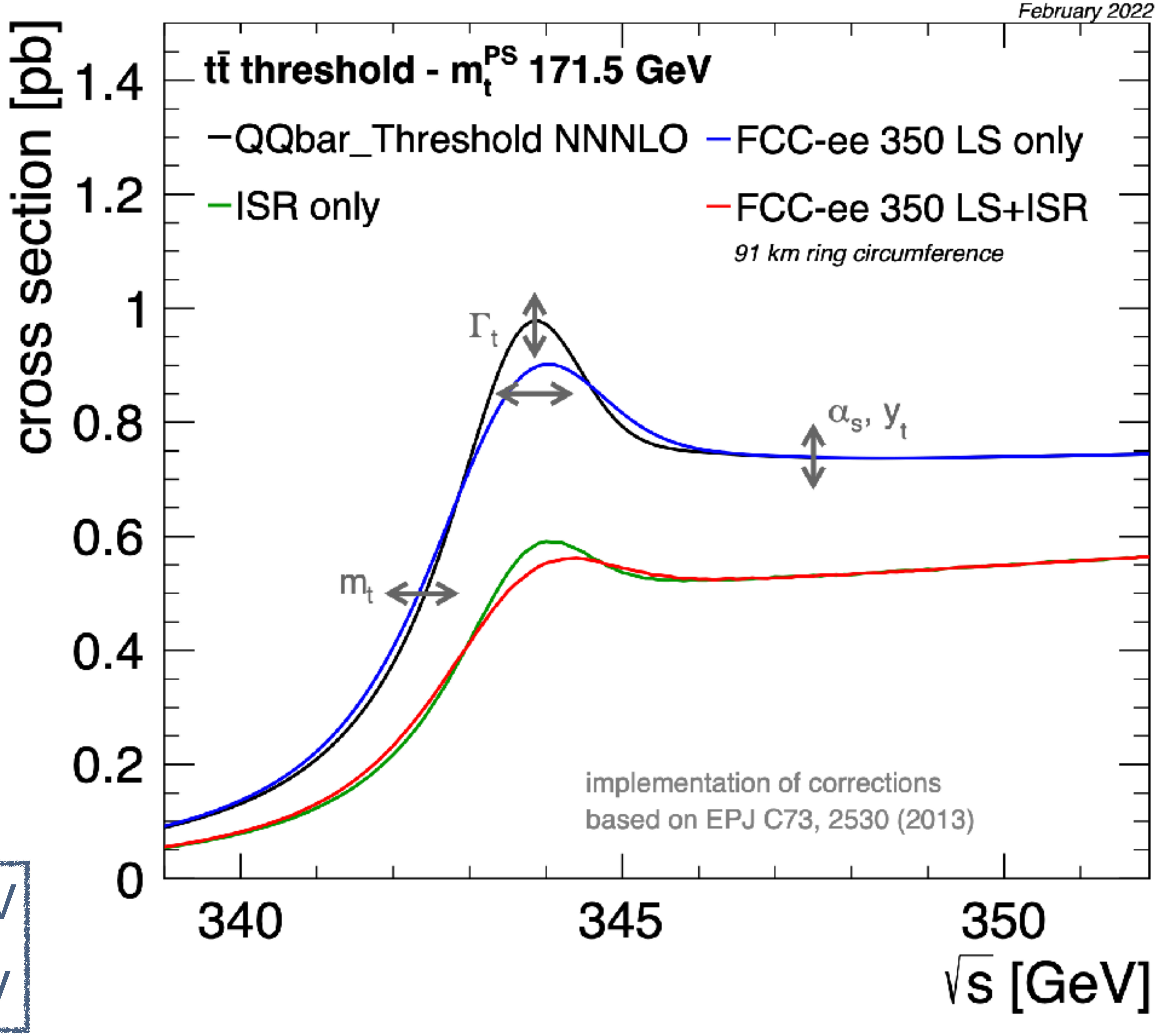
Line shape depends on ISR and beamstrahlung

- ~30% loss of xsec
- Very precise templates needed

High requirement on theory

- High order calculations
- QCD scale uncertainty

$\sigma(m_t)_{\text{stat}} \sim 17$ MeV
$\sigma(\Gamma_t)_{\text{stat}} \sim 45$ MeV



QCD precision

Measure $\alpha_s(m_Z)$ to permille level

- Through τ, Z, W decays, and $e^+e^- \to t\bar{t}$ production

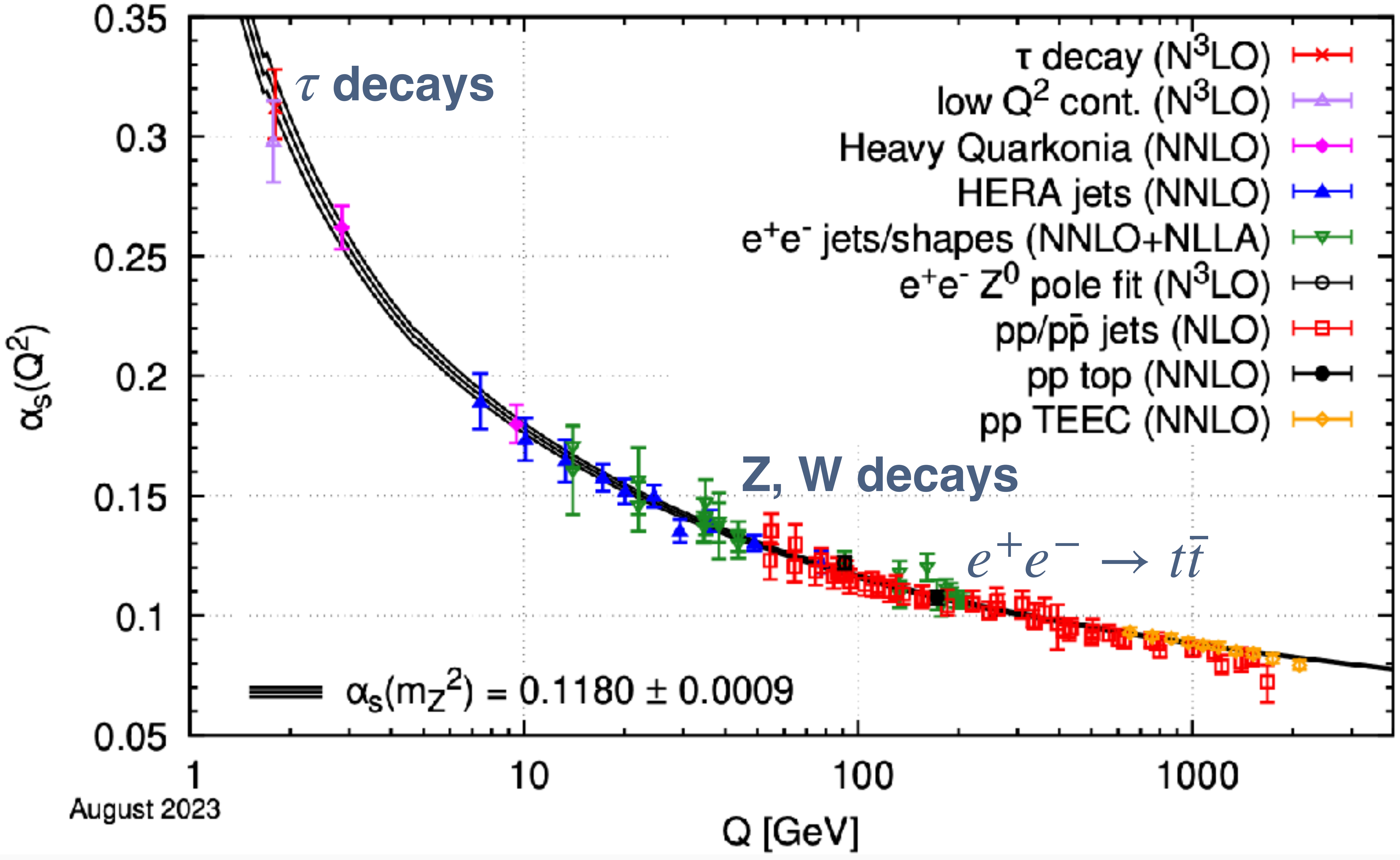
Clean dataset to study jet substructure, parton shower, and hadronization.

- In particular, gluon vs quark discrimination

High demands theory modeling

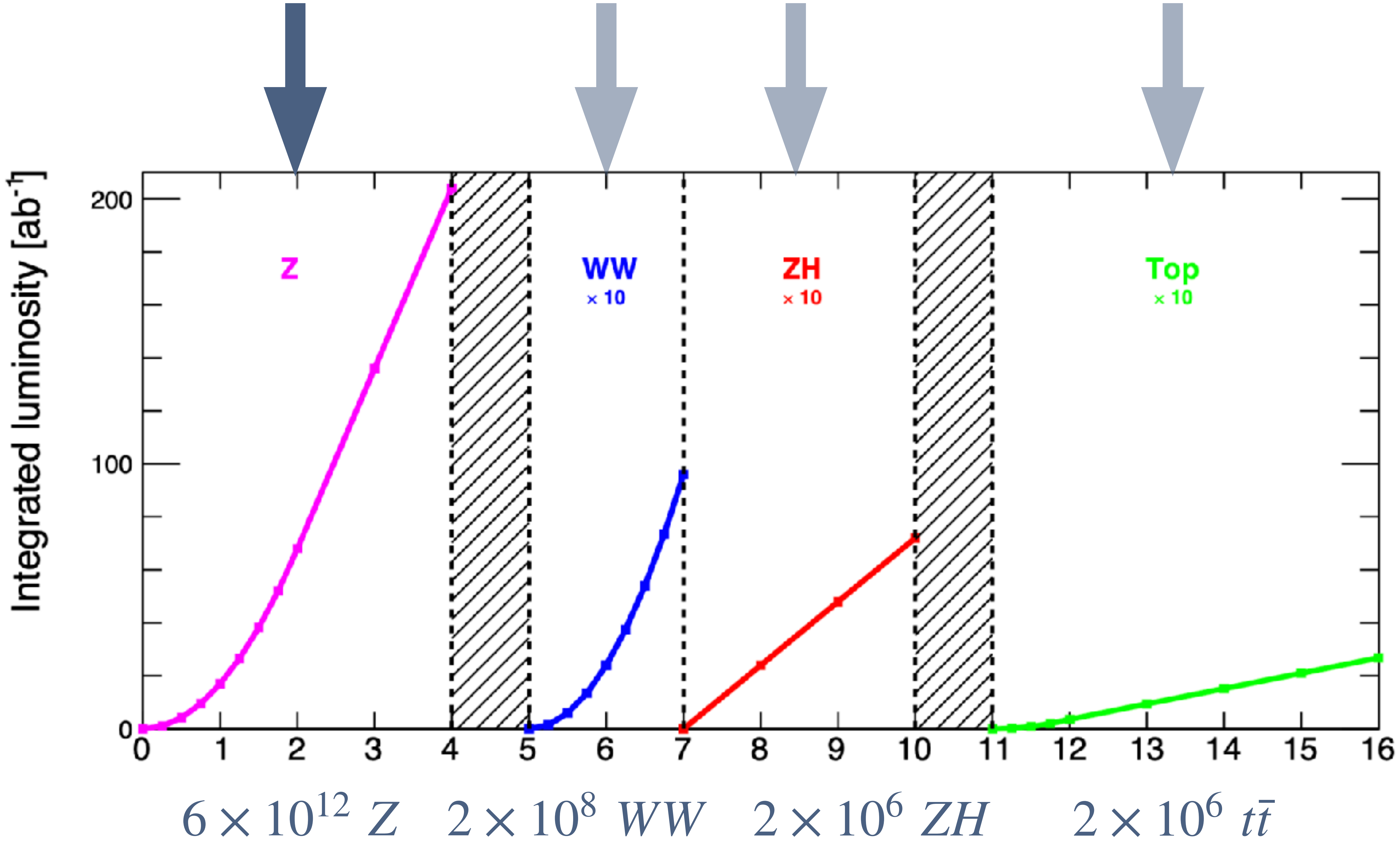
- N^{n}LO + N^{n}LL calculation
- Precise non-pQCD studies

PDG



Flavor factory

- Rare b decays
- $|V_{cs}|, |V_{ts}|$ measurements
- τ physics



More discussed in talk of M. Fedele

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FCC-ee as flavor factory

A Z factory is the best next-generation flavor factory

6×10^{12} Z bosons expected at Z-pole run

- About 14x as many B^0/B^+ as at Belle II (50 ab^{-1})
- About 9x as many τ as Super tau-charm factory
- All species of b-hadrons are produced
- Decay products significantly boosted

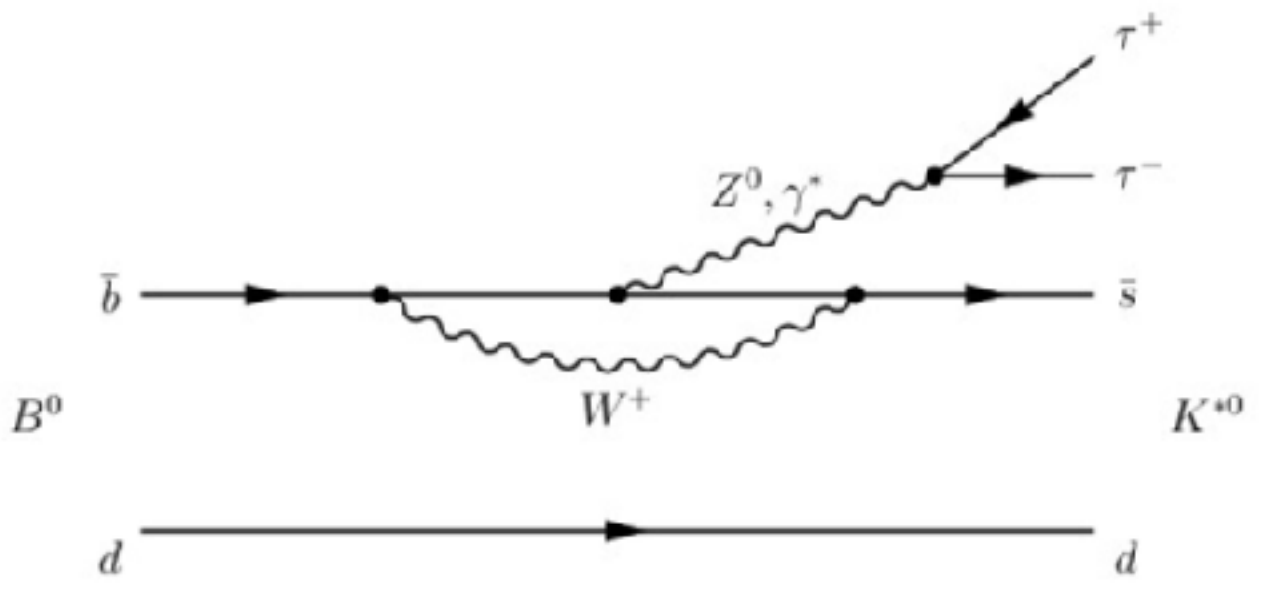
Beyond the Z pole, WW, ZH, and $t\bar{t}$ events

- Direct measurement of CKM matrix
- LFU test with W decays
- FCNC in Z, H, top decays

particle count $(\times 10^9)$	$B^0\ (\bar{B}^0)$	$B^\pm$	$B_s\ (\bar{B}_s)$	$B_c^\pm$	$\Lambda_b\ (\bar{\Lambda}_b)$	$c\ (\bar{c})$	$\tau^\pm$
Belle II	55	55	0.6	N.A.	N.A.	130	90
FCC-ee	770	770	170	7	150	1400	400

Rare b decays

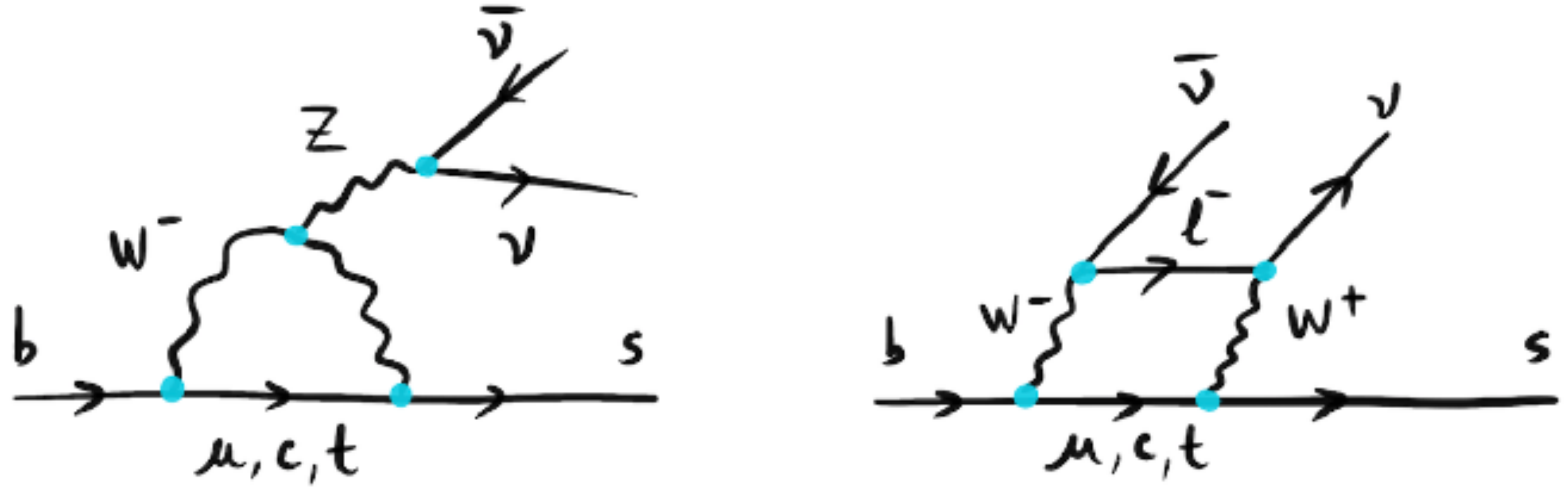
$b \to s\ell\ell$ transition



Case: $B^0 \to K^{*0}\tau^+\tau^-$

- SM BR ~ $O(10^{-7})$
- Current limit at 10^{-3}
- Complex final state, but fully reconstructable

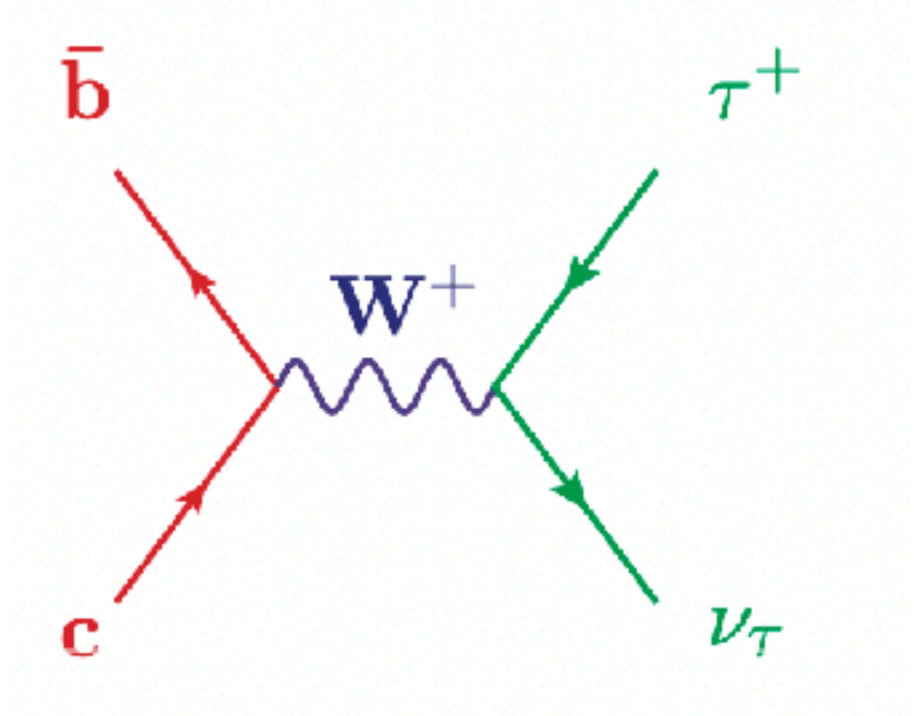
$b \to s\nu\nu$ transition



Case: $H_b \to H_s\nu\nu$

- SM BR ~ $O(10^{-7})$
- Belle II expects 10% precision
- $B_s \to \phi\nu\nu,\ \Lambda_b \to \Lambda\nu\nu$ unique at Z factories

$b \to q\ell\nu$ transition



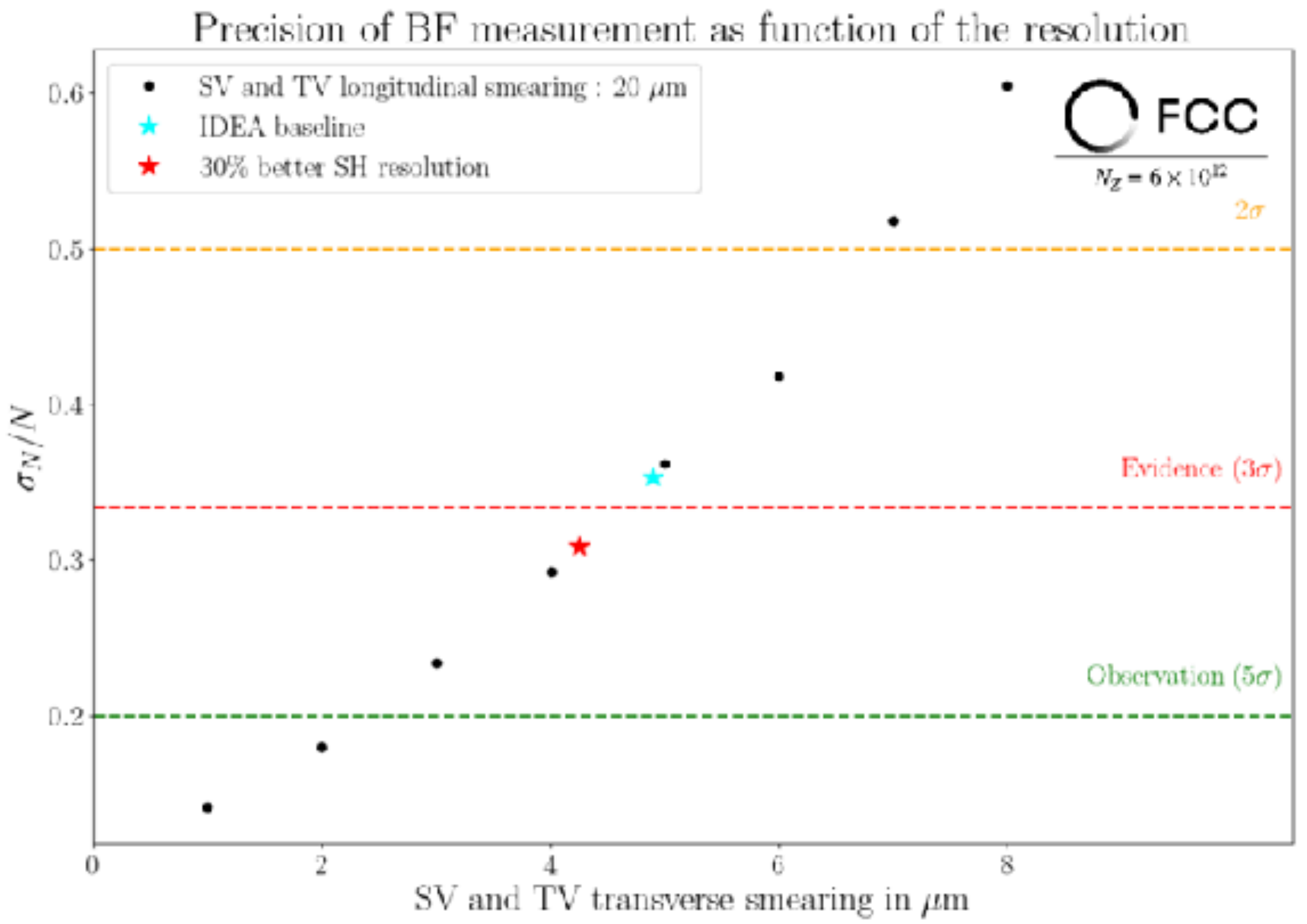
Case: $B^+/B_c^+ \to \tau^+\nu_\tau$

- Unresolved incl. vs excl. tension in $|V_{ub}|, |V_{cb}|$
- Unresolved $R(D)$ and $R(D^*)$ deviation
- $B_c^+ \to \tau^+\nu_\tau$ unique at Z factories

Rare b decays

$b \to s\ell\ell$ transition

FCC-ee MTR

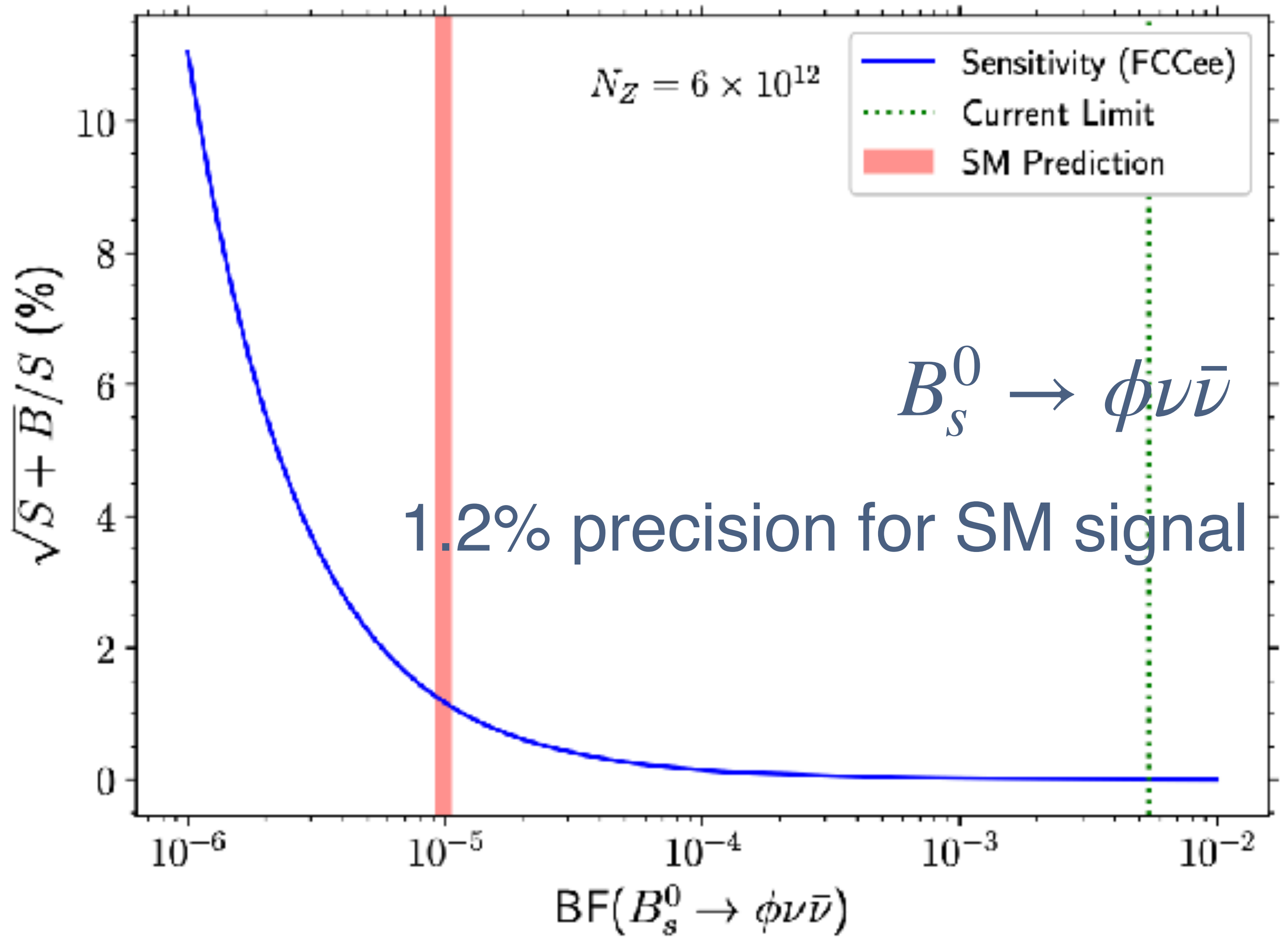


Case: $B^0 \to K^{*0}\tau^+\tau^-$

- Potential to see this mode
- High demand for vertex resolution

$b \to s\nu\nu$ transition

JHEP 2024, 144 (2024)



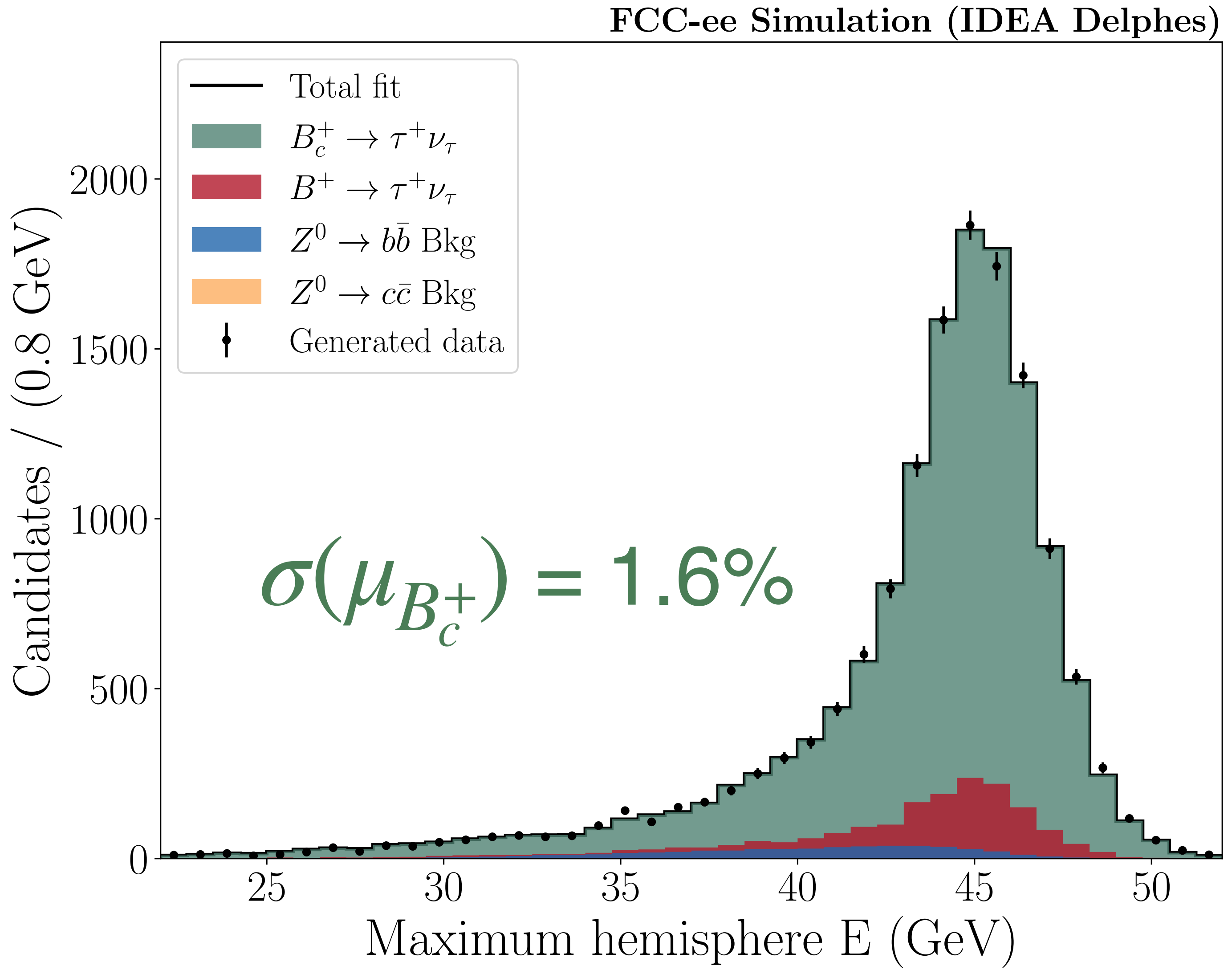
1.2% precision for SM signal

Case: $H_b \to H_s\nu\nu$

- (sub)percent precision with several modes
- Pinpoint many EFT operators

$b \to q\ell\nu$ transition

EPJC 84, 87 (2024)



$\sigma(\mu_{B_c^+}) = 1.6\%$

Case: $B^+/B_c^+ \to \tau^+\nu_\tau$

- Independent determination of $|V_{ub}|$
- Pinpoint EFT operators

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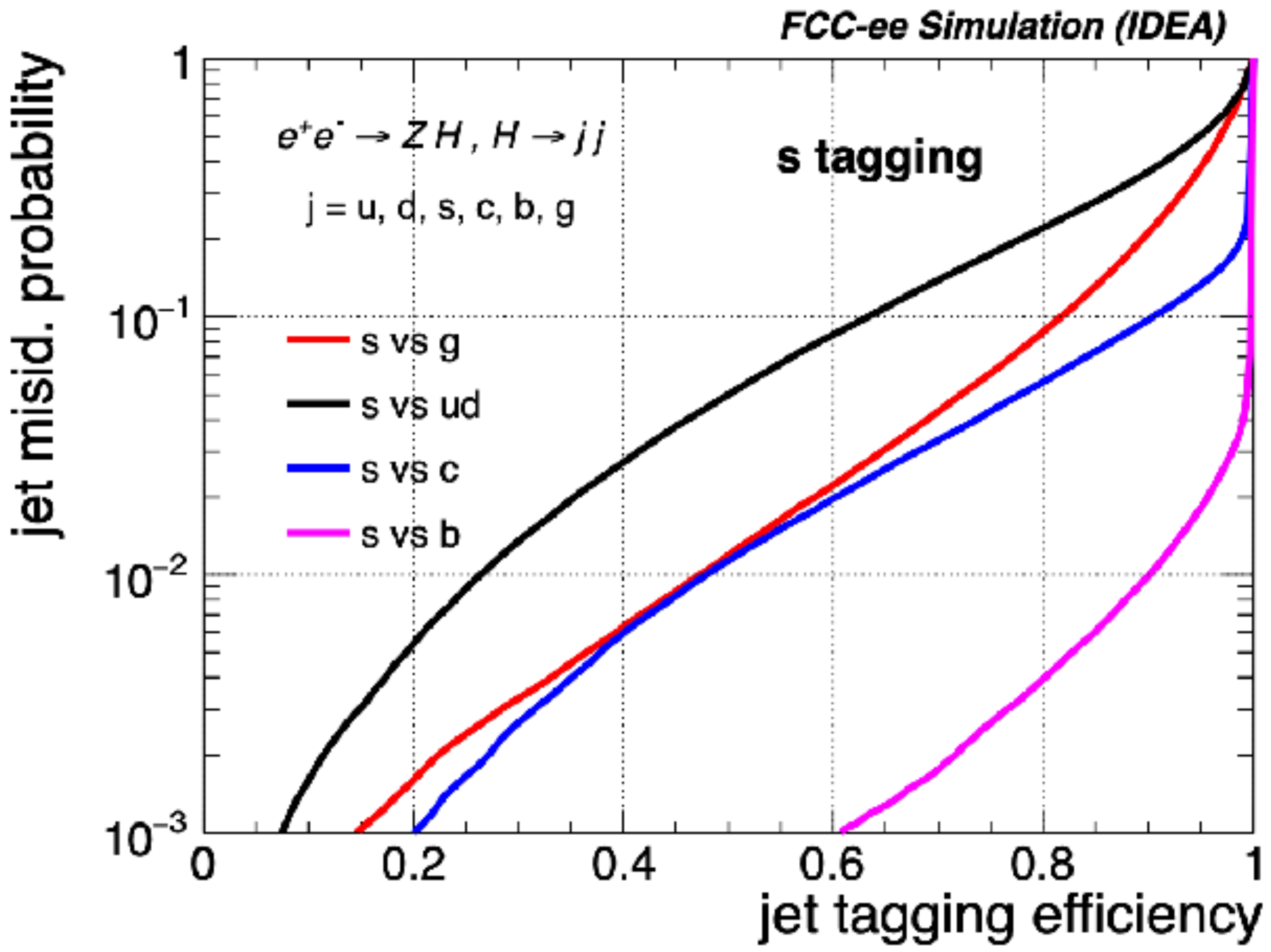
$|V_{cs}|, |V_{cb}|$ and $|V_{ts}|$ measurements

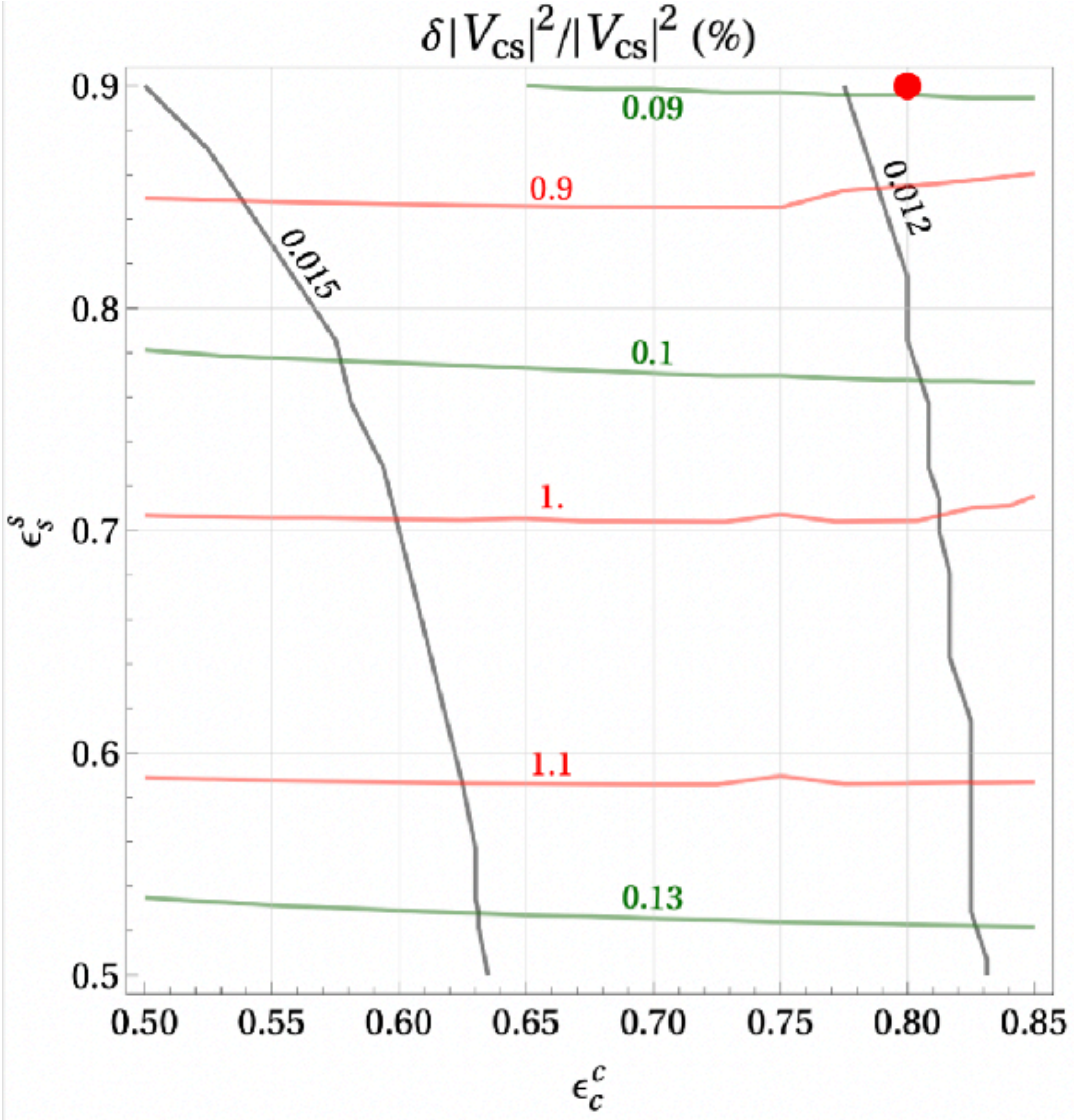
$|V_{cs}|, |V_{cb}|$ from $W \to cs, cb$

- PDG current precision $\sigma_{|V_{cs}|}$ = 0.6%, $\sigma_{|V_{cb}|}$ = 3.4%
- subpercent precision at Z factories, free from theory input
- Rely on excellent jet tagging
- $\sigma_{|V_{cs}|}, \sigma_{|V_{cb}|}$ at 0.1% - 1%

EPJC 82, 646 (2022)



arXiv 2405.08880



$|V_{ts}|$ from $t \to Ws$ decay

- PDG current precision 2%
- Sensitive to BSM (4-th gen fermions)
- Expect to observe $t \to Ws$, precision limited by stats

More discussed in talk of M. Tammaro

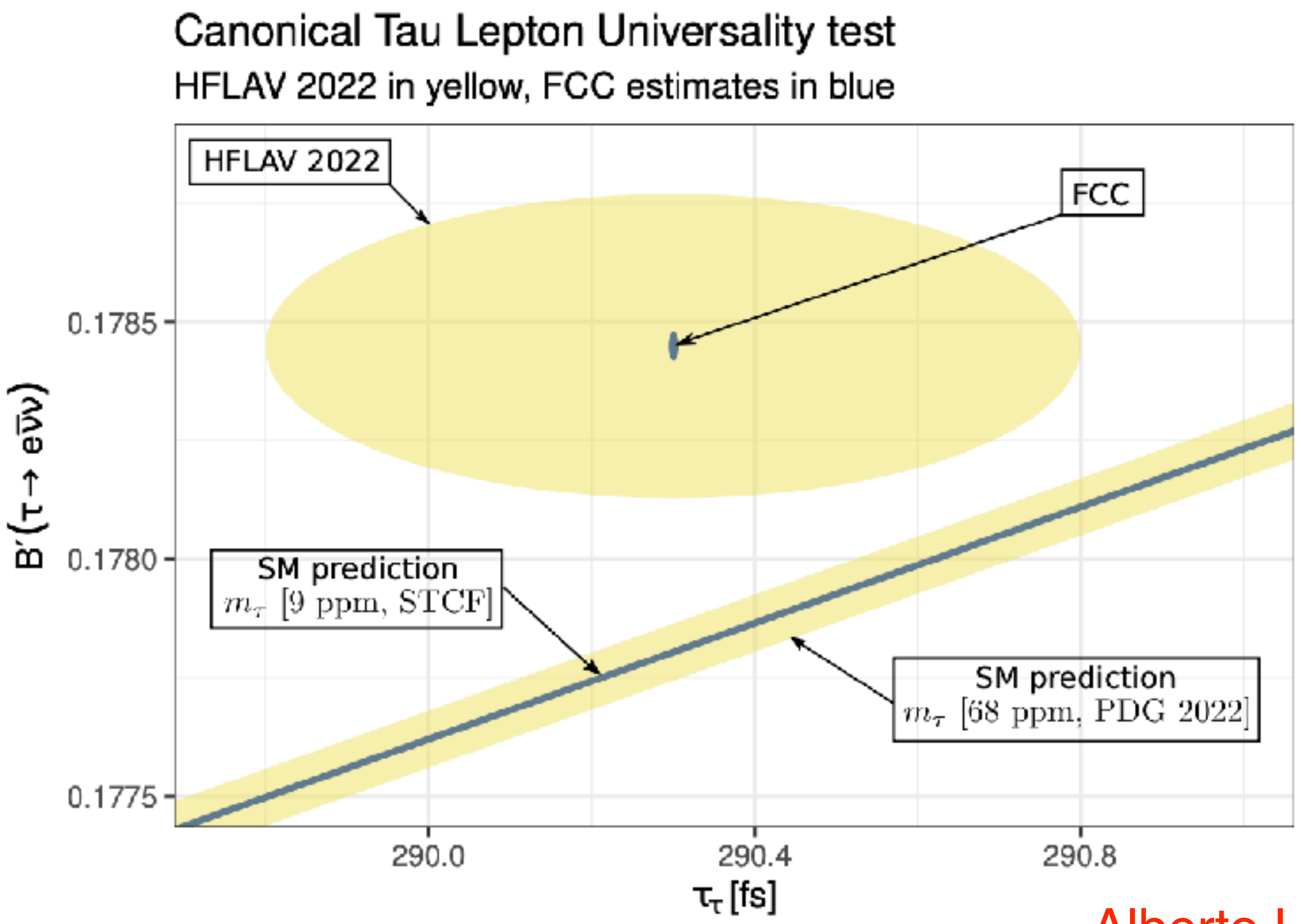
tau properties

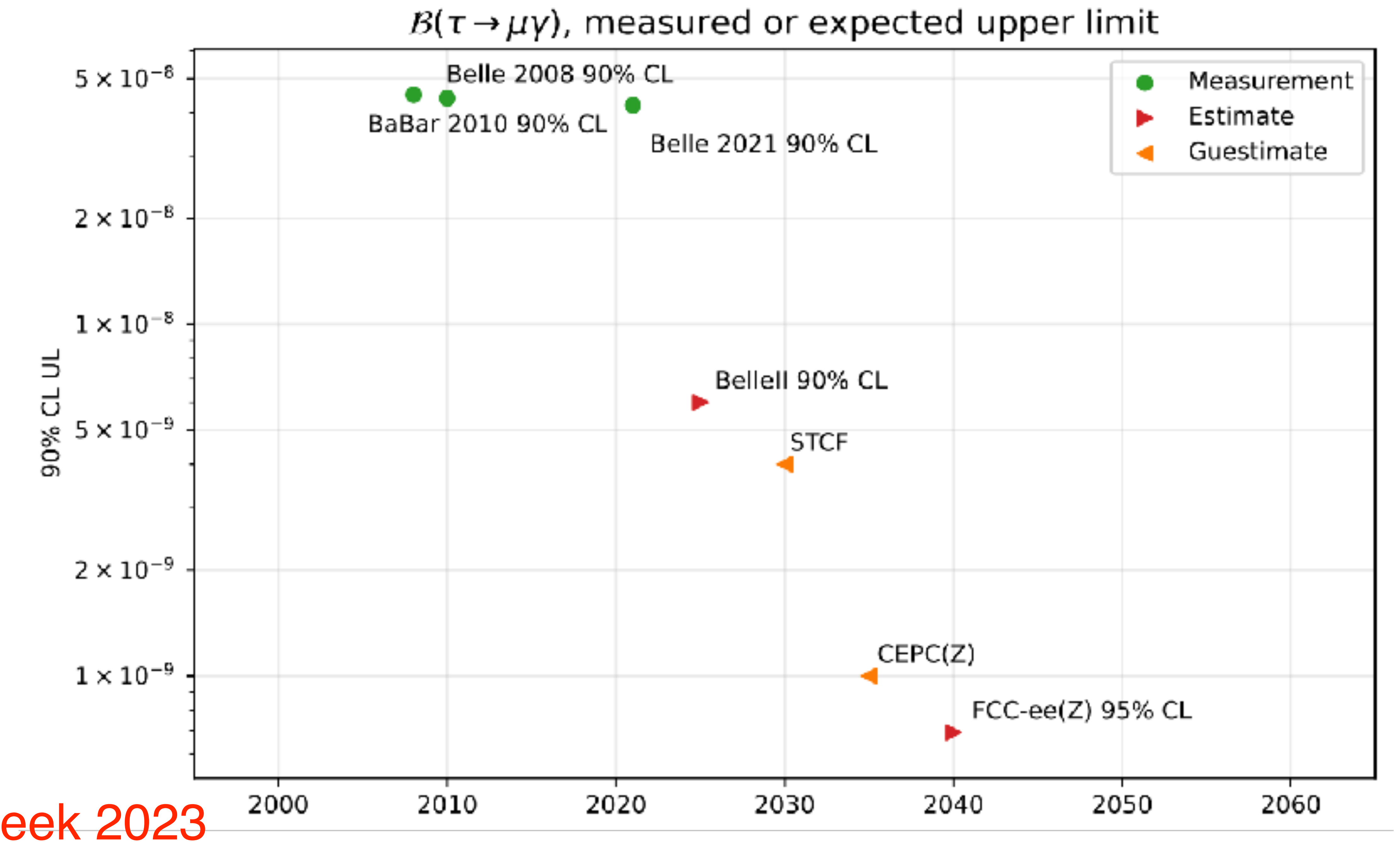
High precision measurements

- Lifetime at 10 ppm, benefiting from high boost
- m_τ at 14 ppm, depending on track momentum calibration
- LFU test of $\mathscr{B}(\tau \to e\nu\nu)/\mathscr{B}(\tau \to \mu\nu\nu)$, 190 ppm

BSM probes

- $\tau \to \mu\gamma$ at 10^{-9} level
- $\tau \to 3\mu$ at 10^{-10} level

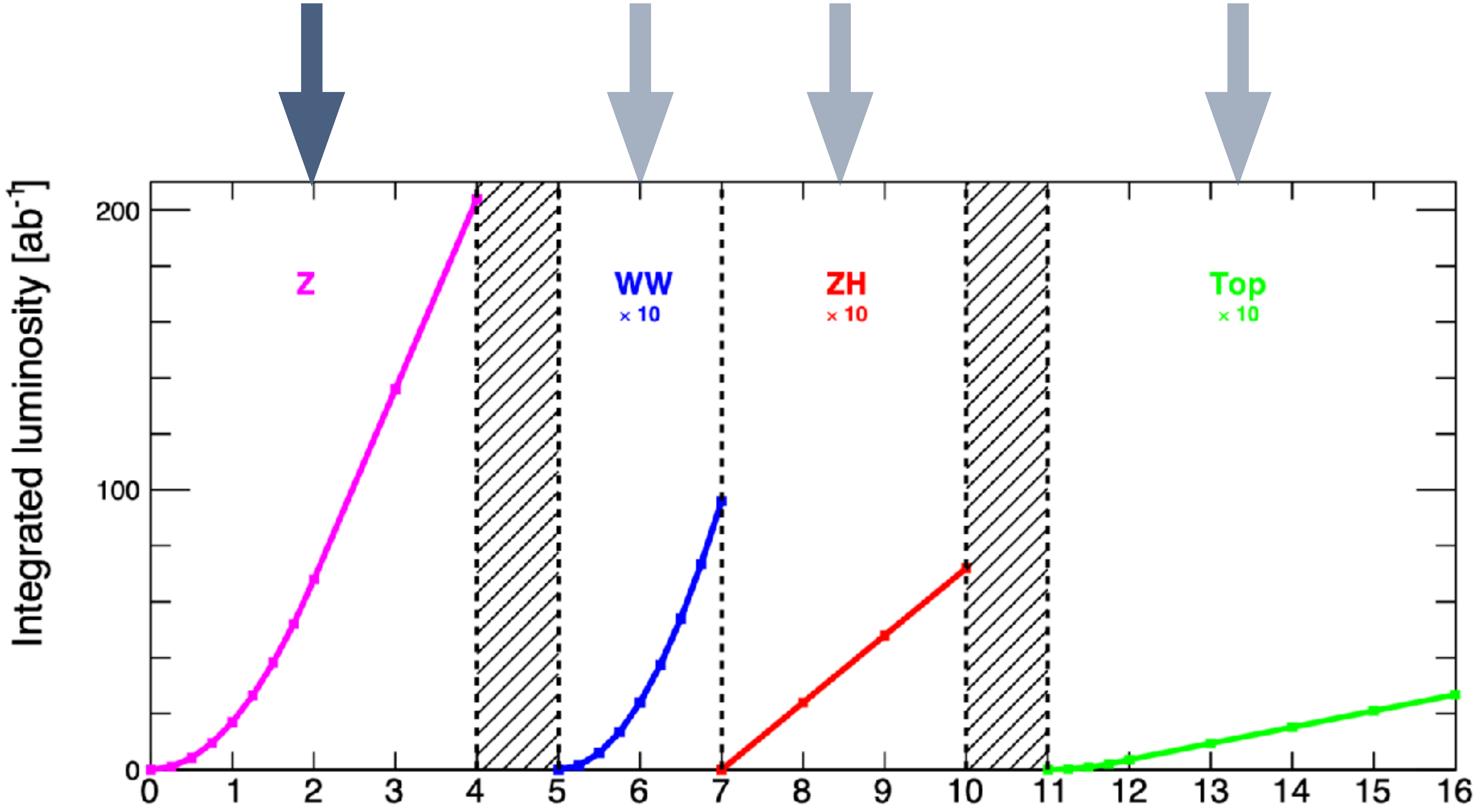




Alberto Lusiani at FCC Week 2023

Discovery machine

- Indirect BSM probes
- Direct BSM searches



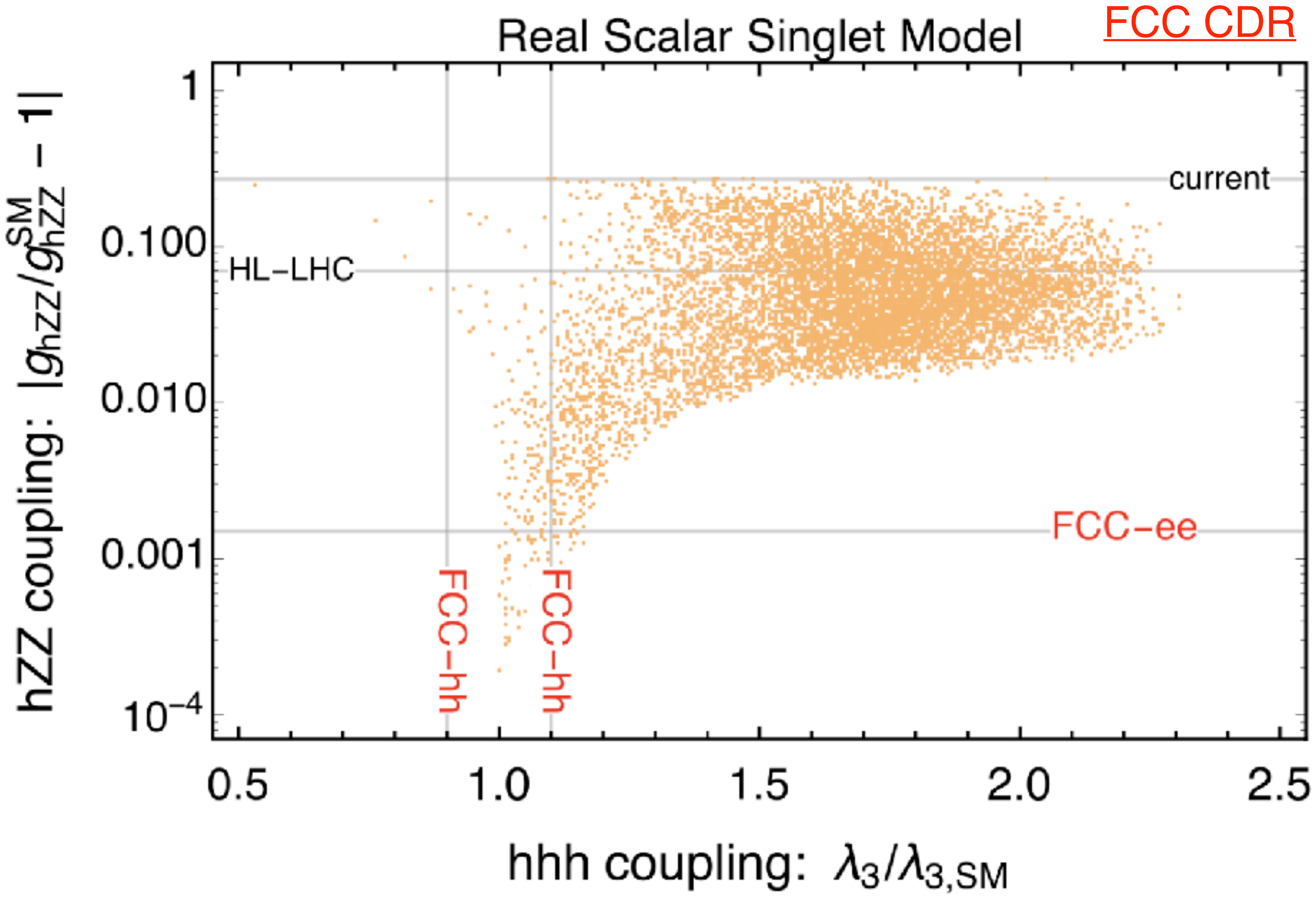
$6 \times 10^{12}\ Z$ $2 \times 10^{8}\ WW$ $2 \times 10^{6}\ ZH$ $2 \times 10^{6}\ t\bar{t}$

Indirect probes

In general, combining EWK and Higgs measurements, constrain NP up to $\Lambda \sim 70$ TeV in dim-6 EFT

In specific models, new particles usually correlated with EWK parameters

- Example: real scalar singlet model
  - EW baryogenesis requires first-order phase transition
  - Phase transition behavior correlated with g_{hZZ} coupling
  - Almost fully constrained by FCC-ee

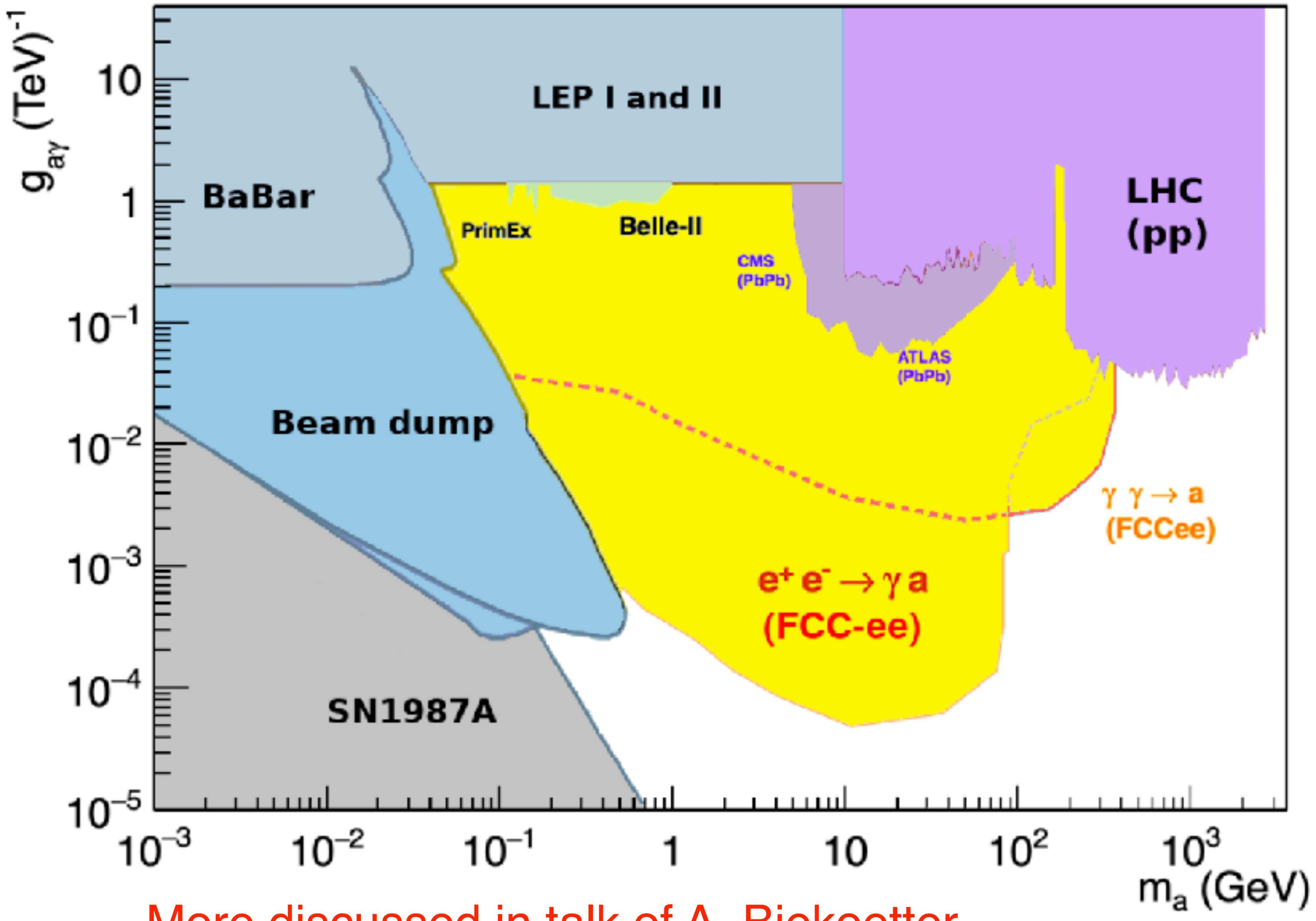


Direct searches

Axion-like particles (ALPs)

- Motivated by multiple BSM scenarios
- Covering large phasespace between beam dump and LHC limits

FCC-ee MTR

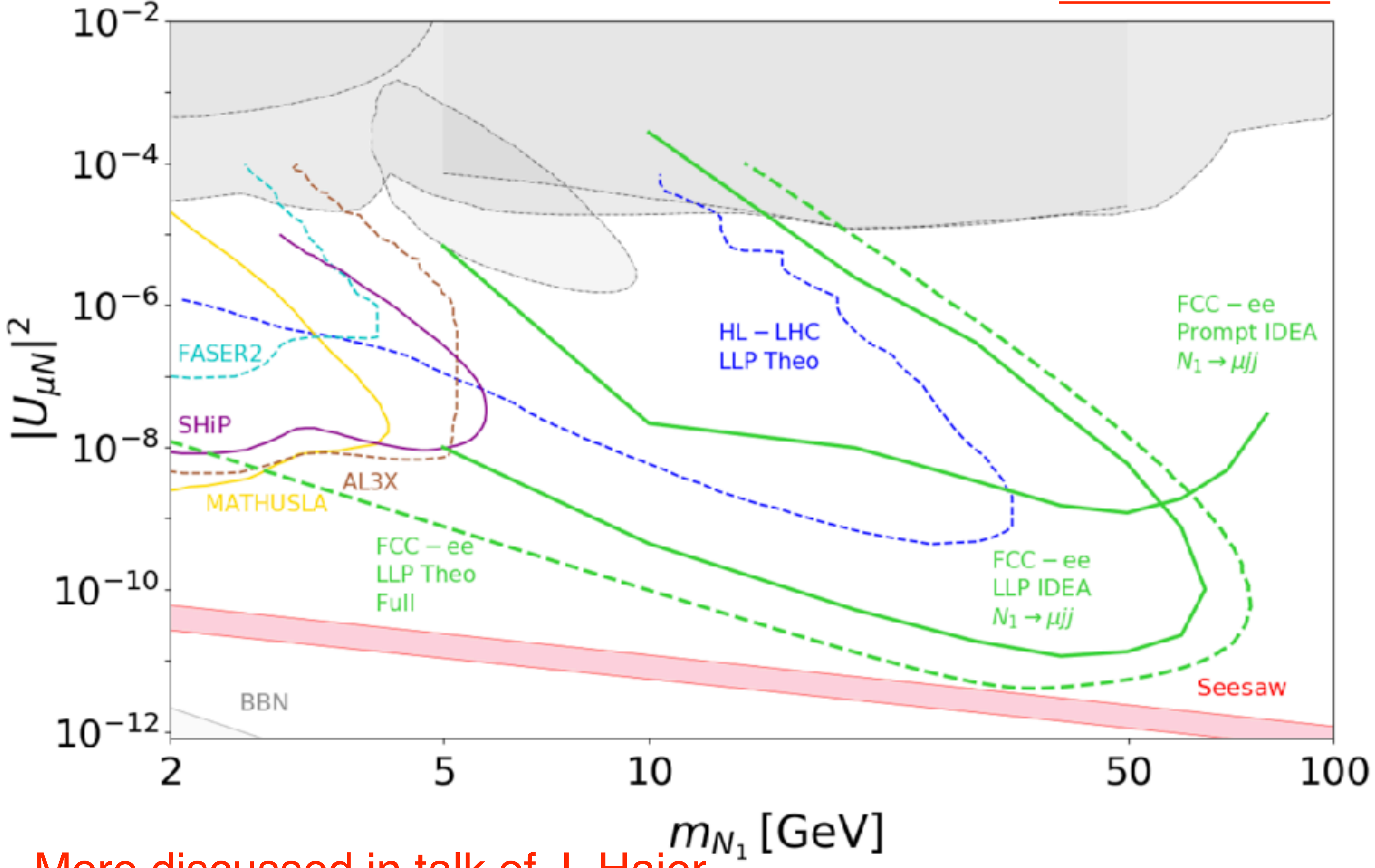


More discussed in talk of A. Biekoetter

Heavy neutral leptons (HNLs)

- Explain nonzero neutrino mass
- Probe phasespace not covered by astrophysics, cosmology, or fixed target exp.

FCC-ee MTR



More discussed in talk of J. Hajer

What is beyond the (current) horizon?

created by DALL-E

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If we search far and look carefully, maybe…

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Summary

An age of exploration ahead…

The
- Higgs factory
- EW+QCD factory
- Flavor factory
- Discovery machine

can be the right vessel for it!

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Backup

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schedule

Karlsruher Institut für Technologie

2021 - 2025

Feasibility Study

(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

~2028

Project approval by CERN Council

(or alternative project selected)

~2030

Construction starts

~2041

HL-LHC ends

2045-2048

Operation of FCC-ee

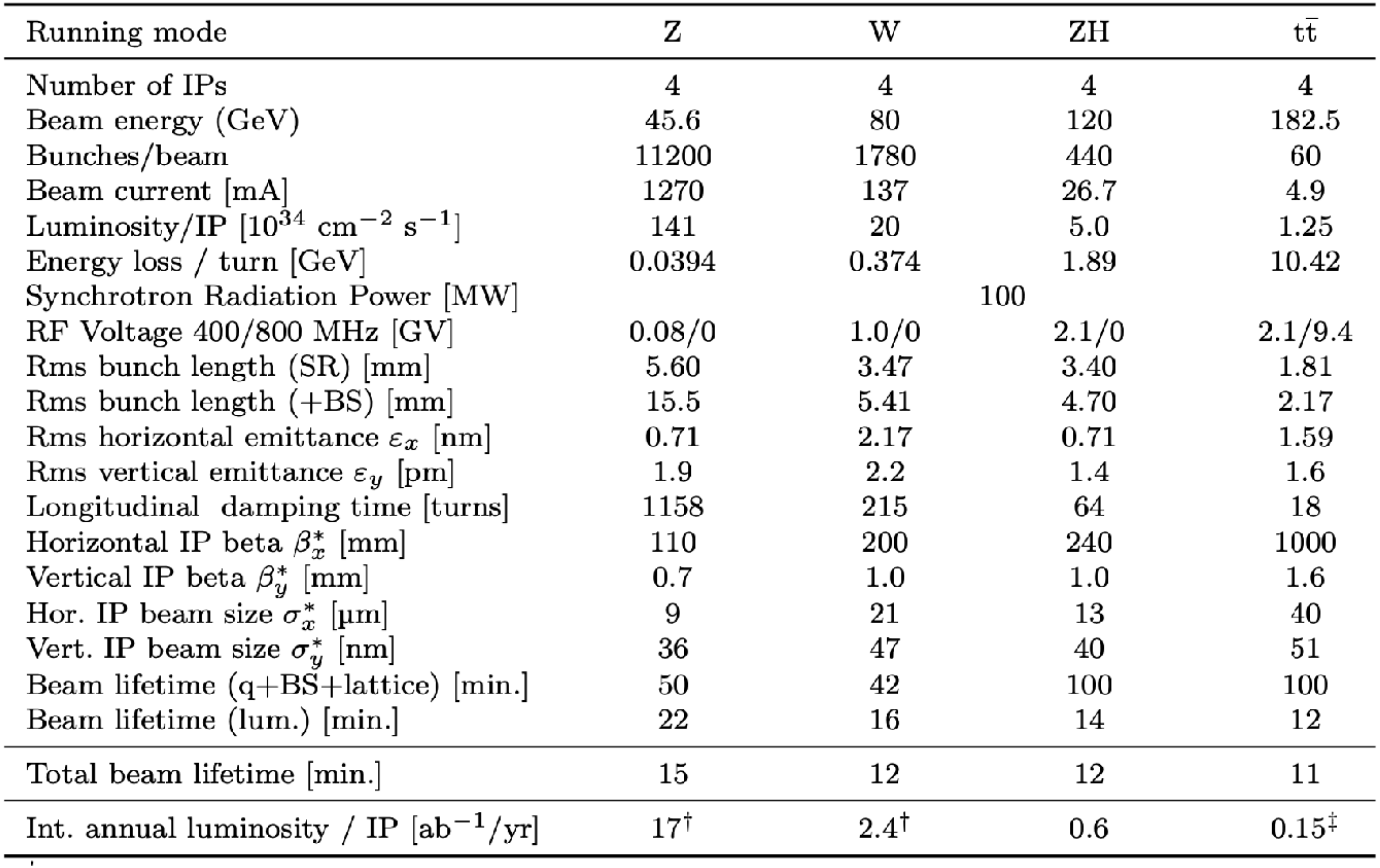
(15 years physics exploitation)

~2070

Operation of FCC-hh

(~ 20 years of physics exploitation)

Beam specs



Running mode	Z	W	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1270	137	26.7	4.9
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	141	20	5.0	1.25
Energy loss / turn [GeV]	0.0394	0.374	1.89	10.42
Synchrotron Radiation Power [MW]	100			
RF Voltage 400/800 MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	3.47	3.40	1.81
Rms bunch length (+BS) [mm]	15.5	5.41	4.70	2.17
Rms horizontal emittance ε_x [nm]	0.71	2.17	0.71	1.59
Rms vertical emittance ε_y [pm]	1.9	2.2	1.4	1.6
Longitudinal damping time [turns]	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	200	240	1000
Vertical IP beta β_y^* [mm]	0.7	1.0	1.0	1.6
Hor. IP beam size σ_x^* [µm]	9	21	13	40
Vert. IP beam size σ_y^* [nm]	36	47	40	51
Beam lifetime (q+BS+lattice) [min.]	50	42	100	100
Beam lifetime (lum.) [min.]	22	16	14	12
Total beam lifetime [min.]	15	12	12	11
Int. annual luminosity / IP [ab^{-1}/yr]	$17^{\dagger}$	$2.4^{\dagger}$	0.6	$0.15^{\ddagger}$

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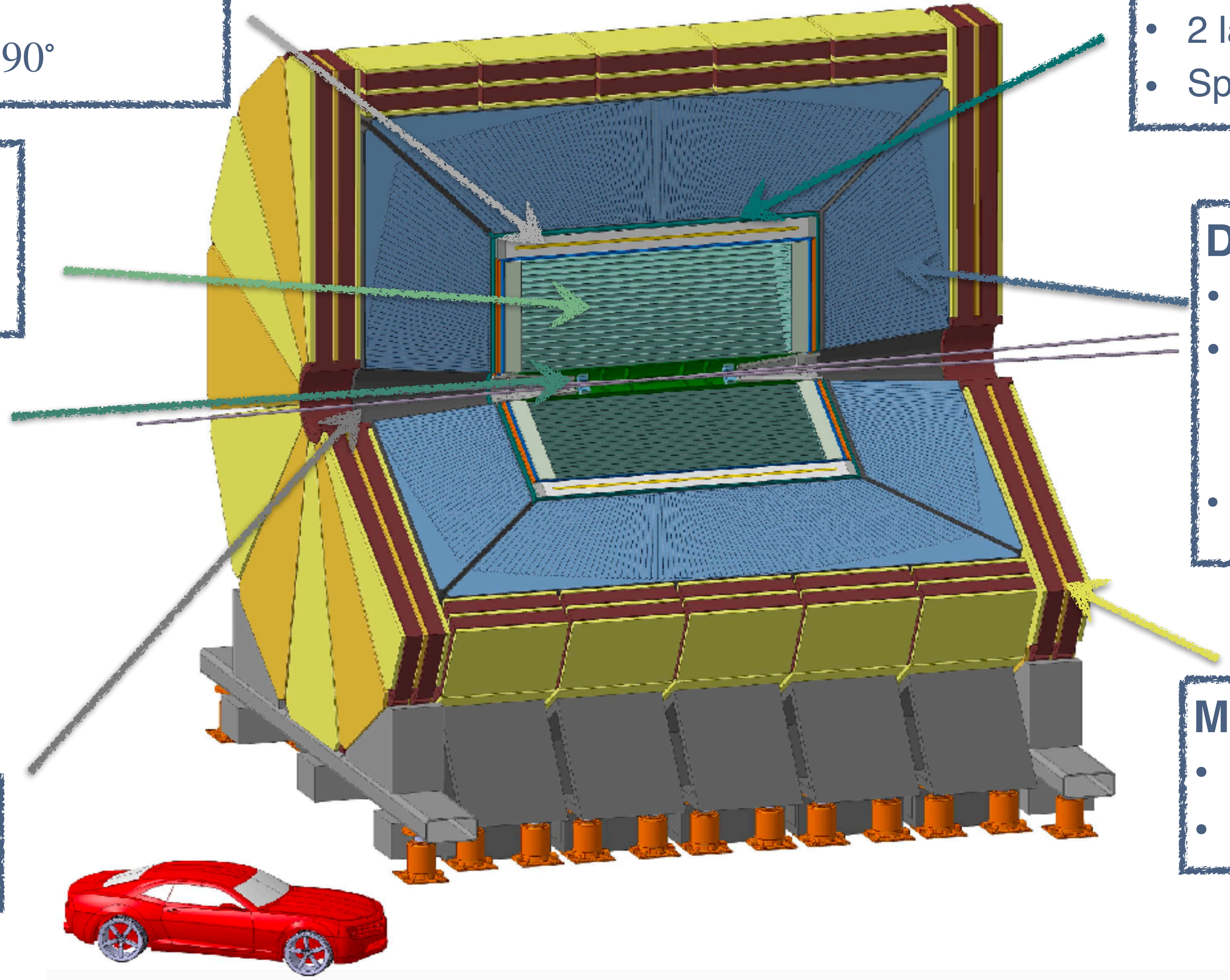
IDEA detector



Superconducting solenoid
- 2 T, R = 2.0 - 2.4 m
- $0.74\ X_0,\ 0.16\ \lambda\ @90^\circ$

Wire drift chamber
- 112 layers, R = 35 - 200 cm
- 0.016 $X_0 @ 90^\circ$

Silicon vertex detector
- 5 layers, R = 1.7 - 34 cm
- Pixel $20 \times 20\ \mu\text{m}^2$

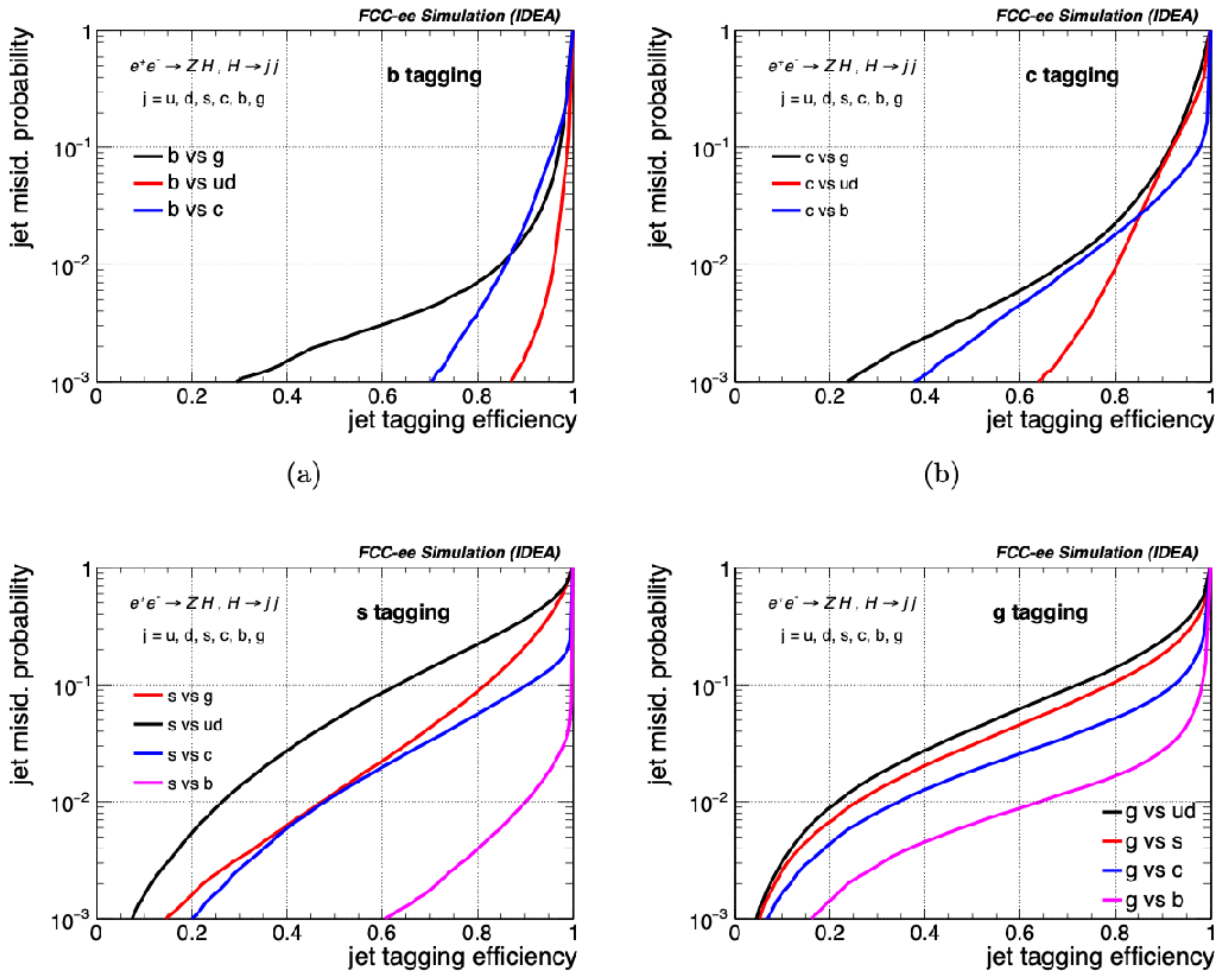
Beam pipe
- R ~ 1.5 cm

Preshower
- 2 layers, gas detector
- Spatial reso < 100 μm

Dual-readout calorimeter
- 2 m capillaries
- Alternate Cherenkov and scintillation fibers
- $\sigma_{EM} \approx \frac{10\,\%}{\sqrt{E}},\ \sigma_{had} \approx \frac{30\,\%}{\sqrt{E}}$

Muon chambers
- 3 layers, gas detector
- Spatial reso < 400 μm

flavor tagging

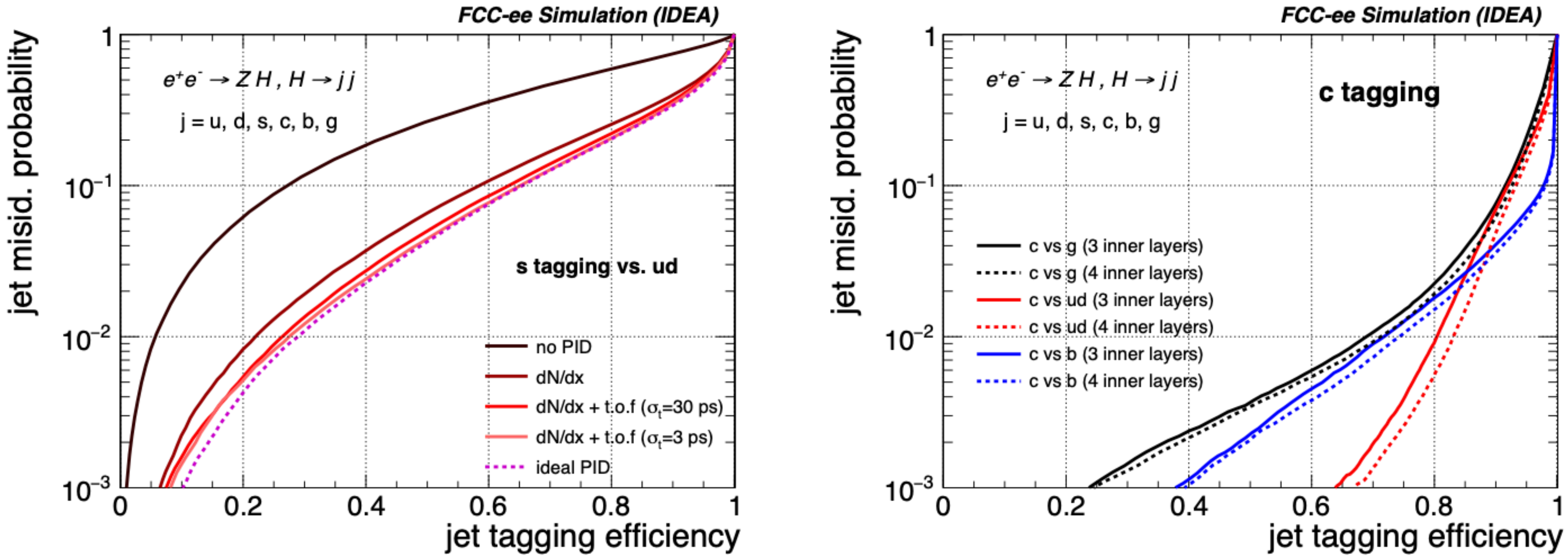


(a) (b)

(c) (d)

EPJC 82, 646 (2022)

flavor tagging



(a)

(b)

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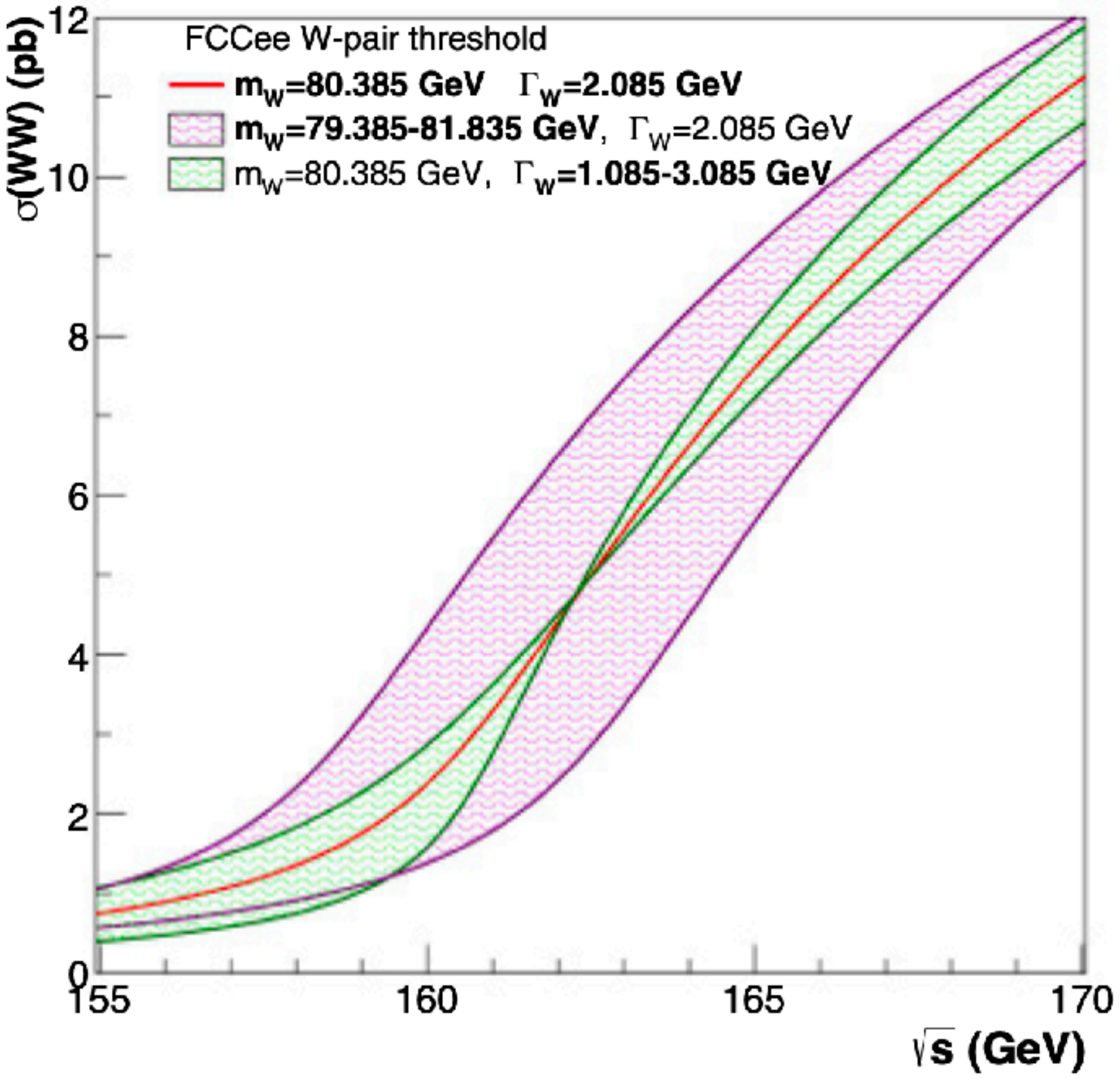
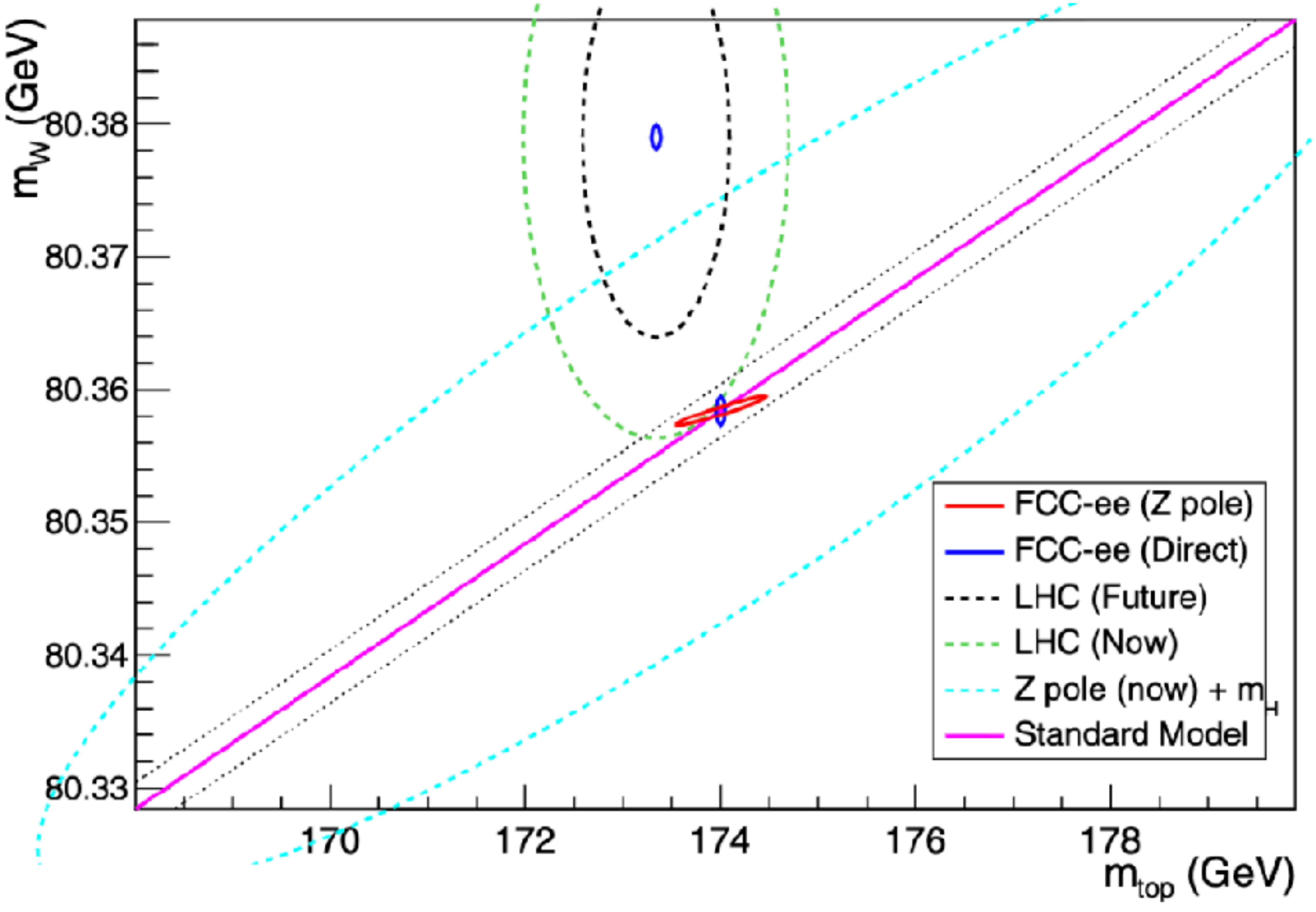
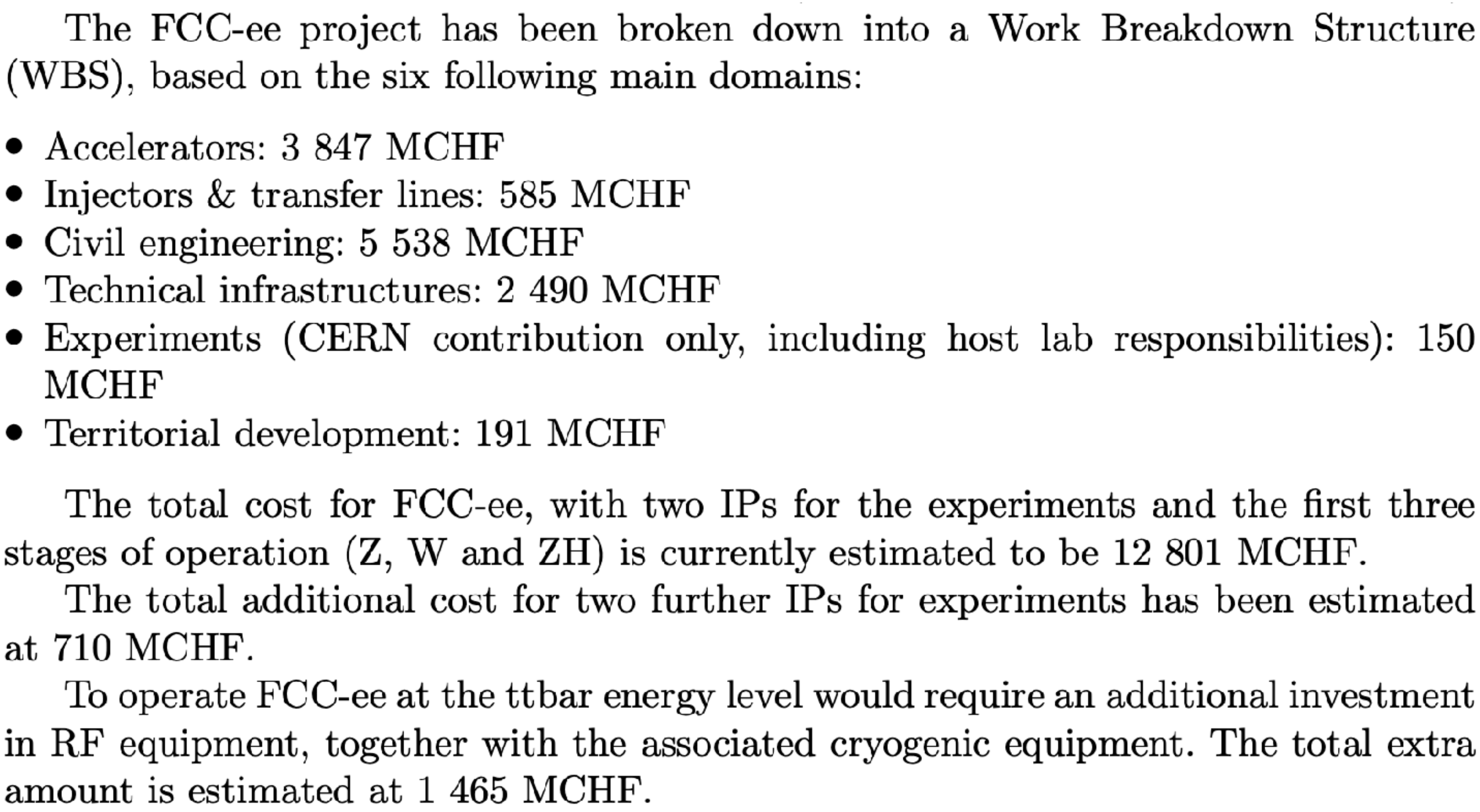
m_W, m_t

- Expect $\sigma(m_W) \sim$ MeV, $\sigma(m_t) \sim$ O(10) MeV
- Challenges in beam energy calibration and theory calculations





cost feasibility



The FCC-ee project has been broken down into a Work Breakdown Structure (WBS), based on the six following main domains:

- Accelerators: 3 847 MCHF
- Injectors & transfer lines: 585 MCHF
- Civil engineering: 5 538 MCHF
- Technical infrastructures: 2 490 MCHF
- Experiments (CERN contribution only, including host lab responsibilities): 150 MCHF
- Territorial development: 191 MCHF

The total cost for FCC-ee, with two IPs for the experiments and the first three stages of operation (Z, W and ZH) is currently estimated to be 12 801 MCHF.

The total additional cost for two further IPs for experiments has been estimated at 710 MCHF.

To operate FCC-ee at the ttbar energy level would require an additional investment in RF equipment, together with the associated cryogenic equipment. The total extra amount is estimated at 1 465 MCHF.

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