PHYSICS AND DETECTOR R&D @FCC-EE

PATRIZIA AZZI - INFN-PD/CERN

Fermilab Wine&Cheese

28 October 2022

WHICH TYPE OF COLLIDER?

- Energy: direct access to new resonances
- Precision: indirect evidence of deviations at low and high energy.

More SENSITIVITY, more PRECISION, more ENERGY

- A combination of lepton and hadron colliders provides:
  - Largest luminosity
  - highest parton energy
  - synergies and complementarities between e^+e^- and pp (and more…)
- FCC integrated project offers an appropriate answer to these needs

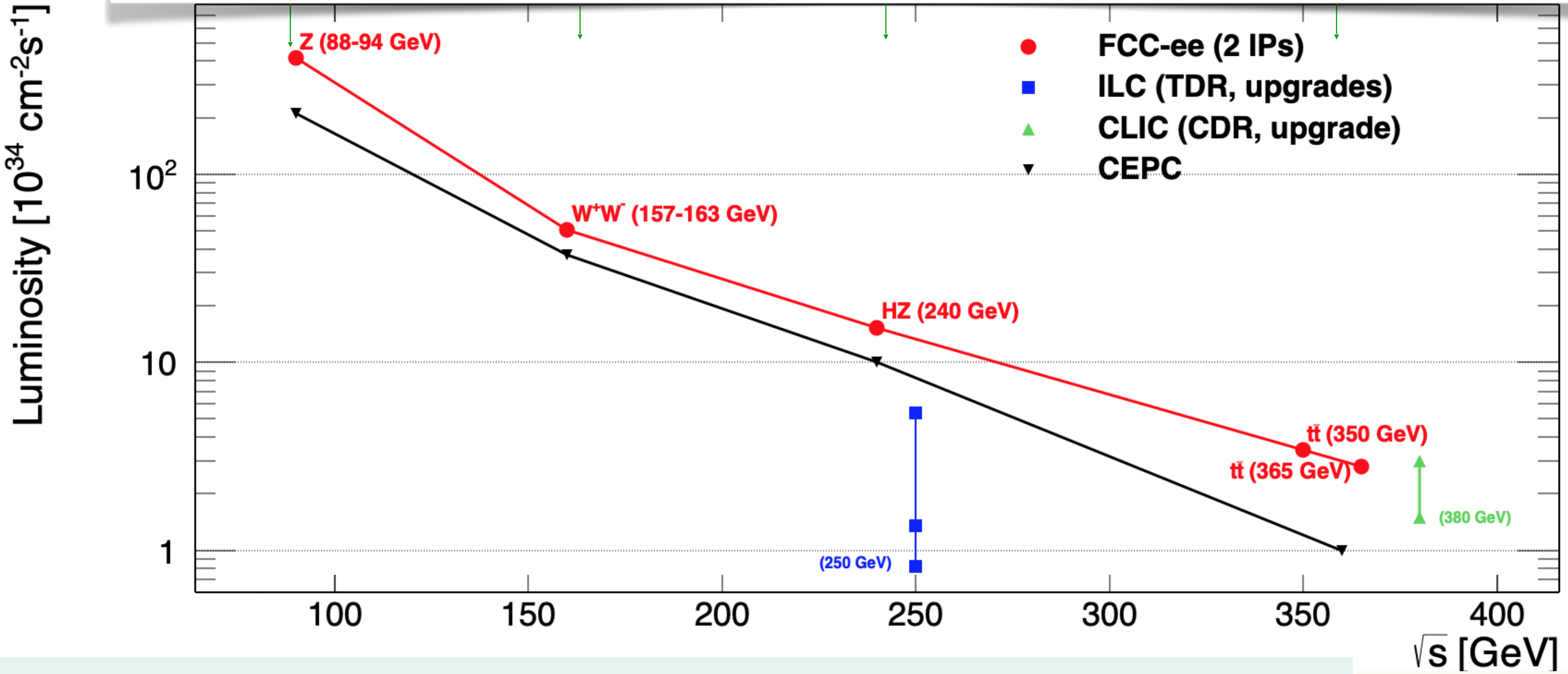
PHYSICS @FCC-ee

- The physics landscape of the FCC-ee program extends in all possible directions:
  - the difference in the physics focus at the different √s
  - the difference in the event kinematic of running from 90GeV (and possibly below) up to 365GeV
  - the challenge of being able to achieve superbe precision on SM processes but also perform unique direct searches for new physics
- *The list of interesting processes and measurement is extensive, and it has not been fully explored yet, even in terms of sensitivity.*
- From this richness, we need to extract concrete benchmark measurements, the « case studies » that will be used to extract requirements on what is missing to achieve our ambitious goals: detector requirements, reconstruction tools, calibration techniques.

ENERGY RANGE & LUMINOSITY

Great energy range for SM heavy particles AND highest luminosities AND $\sqrt{s}$ precision

Can produce all the heaviest particles of the Standard Model



						$\sqrt{s}$ errors
ZH maximum	$\sqrt{s}$ ~ 240 GeV	3 years	10^6	$e^+e^- \rightarrow ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s}$ ~ 350 GeV	5 years	10^6	$e^+e^- \rightarrow t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s}$ ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \rightarrow Z$	LEP x 10^5	< 100 keV
WW threshold+	$\sqrt{s} \geq$ 161 GeV	2 years	$> 10^8$	$e^+e^- \rightarrow W^+W^-$	LEP x 10^3	< 300 keV
s-channel H	$\sqrt{s}$ = 125 GeV	? Years	~5000	$e^+e^- \rightarrow H$	Never done	< 200 keV

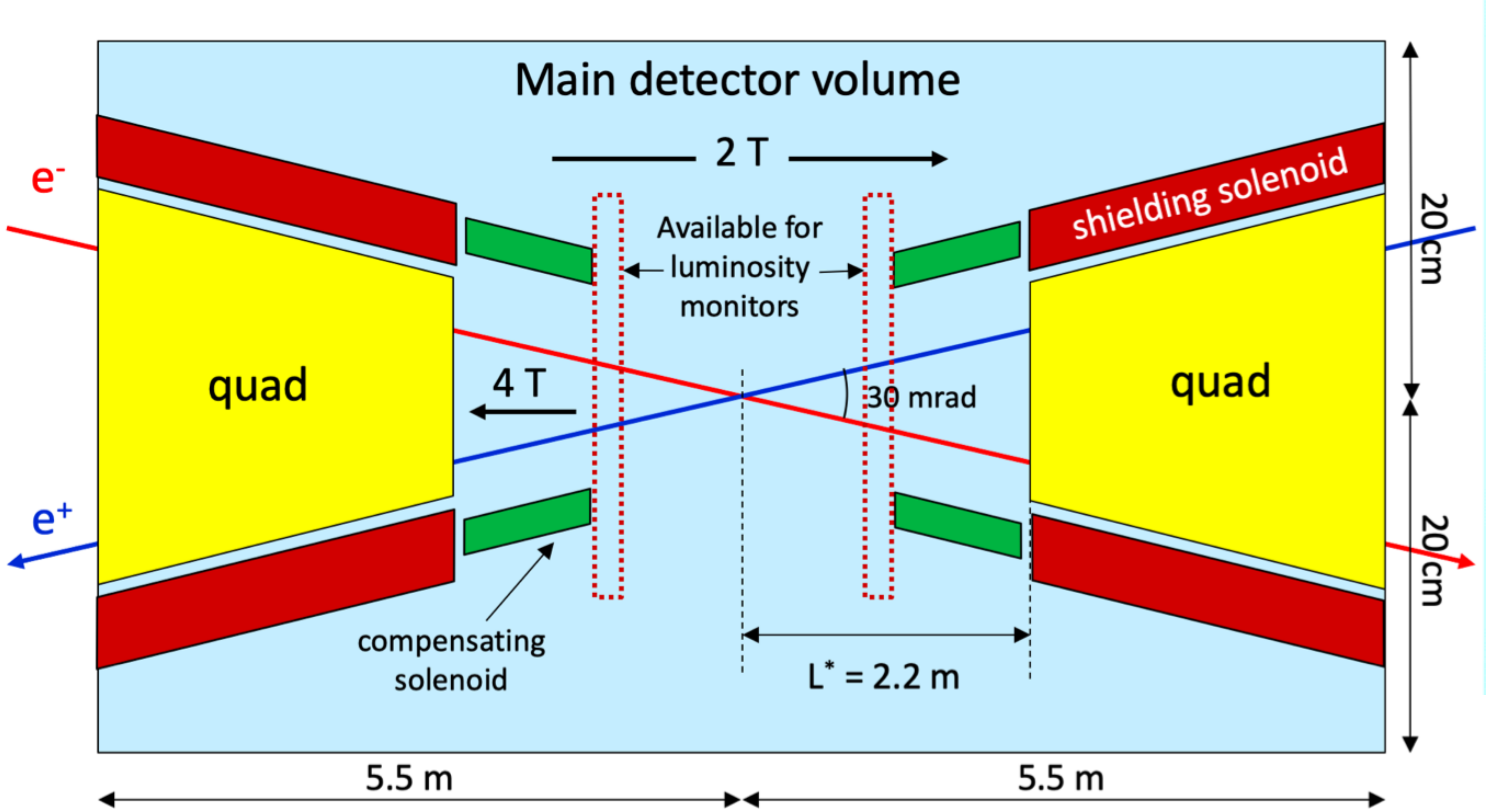
FCC

EXPERIMENTAL CHALLENGES

- ➤ 30 mrad beam crossing angle
  - ➤ Detector B-field limited to 2 Tesla at Z-peak operations
  - ➤ Very complex and tightly packed MDI

- ➤ Bunch spacing down to 20 ns
  - ➤ Power management and cooling (no power pulsing)

- ➤ Extremely high luminosities
  - ➤ High statistical precision – control of systematics down to 10^{-5} level
  - ➤ Online/offline handling of O(1013) events for precision physics



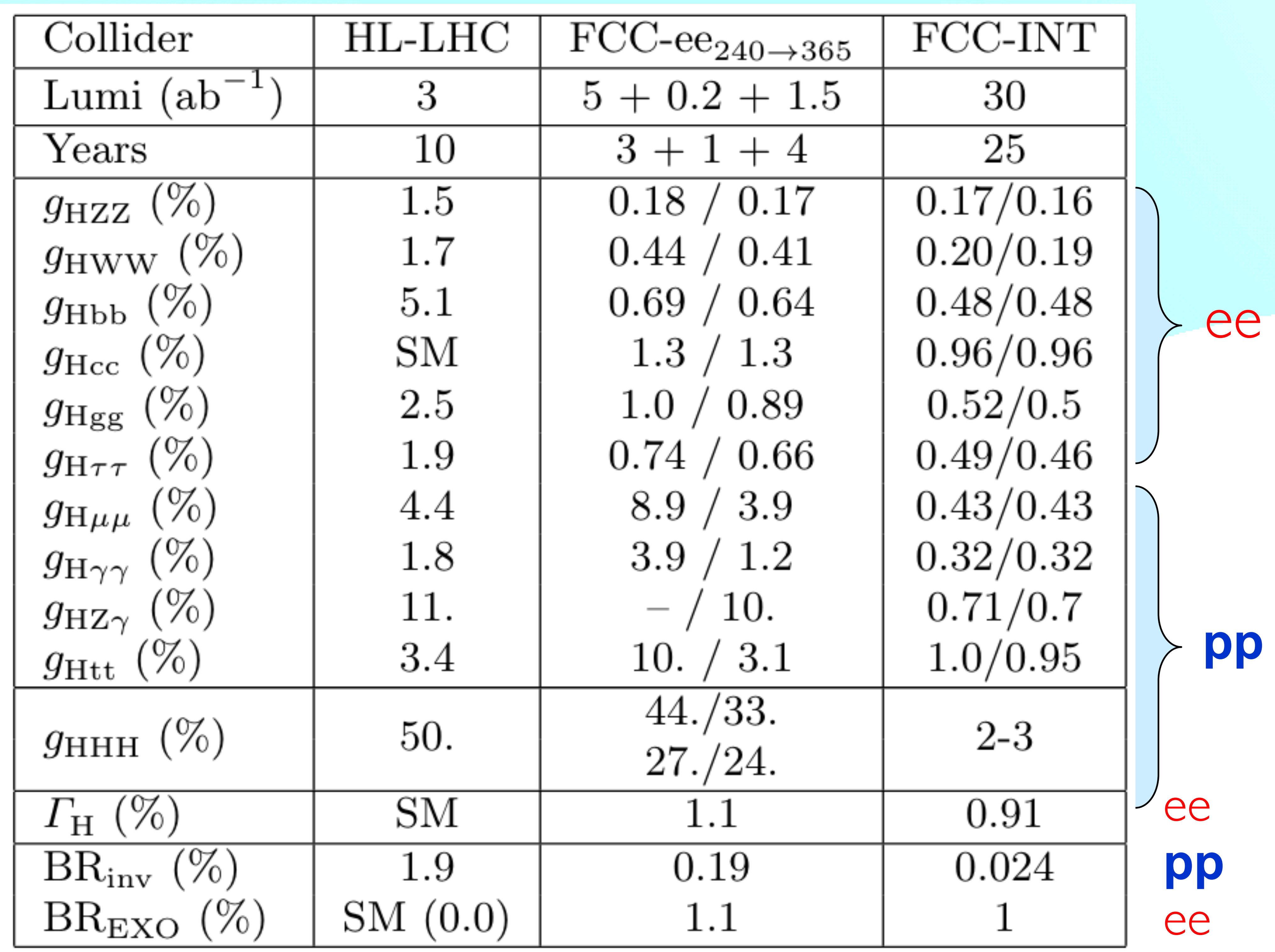
M. Dam

- ➤ Physics events at up to 100 kHz
  - ➤ Fast detector response (≲ 1 μs) to minimise dead-time and event overlaps (pile-up)
  - ➤ Strong requirements on sub-detector front-end electronics and DAQ systems keeping low material budget

FCC-ee AS A HIGGS FACTORY AND BEYOND

Higgs provides a very good reason why we need both e^+e^- AND pp colliders

- FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from σ_{ZH}
  - Γ_H, g_{Hbb}, g_{Hcc}, $g_{H\tau\tau}$, g_{HWW} follow
  - Standard candle fixes all HL-LHC couplings
- FCC-hh produces over 10^{10} Higgs bosons
  - (1^{st} standard candle →) $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}
- FCC-ee measures top EW couplings (e^+e^- → tt)
  - Another standard candle
- FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
  - (2^{nd} standard candle →) g_{Htt} and g_{HHH}



Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95
g_{HHH} (%)	50.	44./33. 27./24.	2-3
Γ_H (%)	SM	1.1	0.91
BR$_{inv}$ (%)	1.9	0.19	0.024
BR$_{EXO}$ (%)	SM (0.0)	1.1	1

- **FCC-ee + FCC-hh is outstanding**
  - All accessible couplings with per-mil precision; self-coupling with per-cent precision

FCC-ee is also the most effective way toward FCC-hh

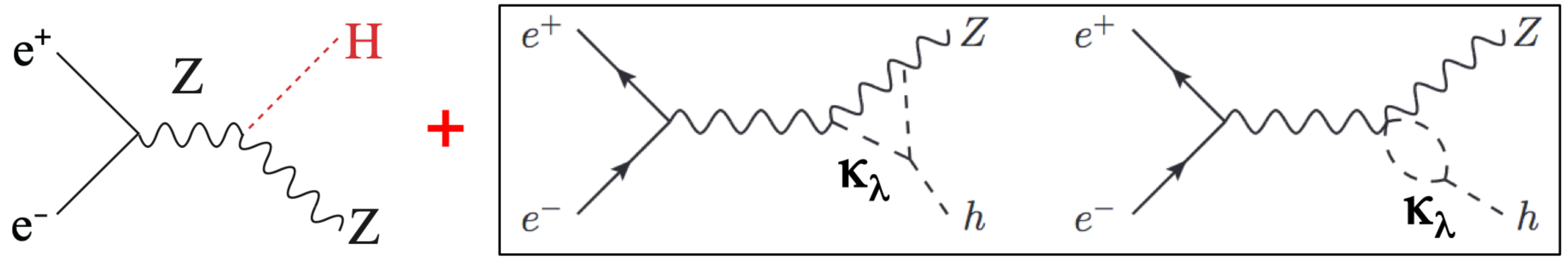
HIGGS SELF-COUPLING WITH SINGLE HIGGS

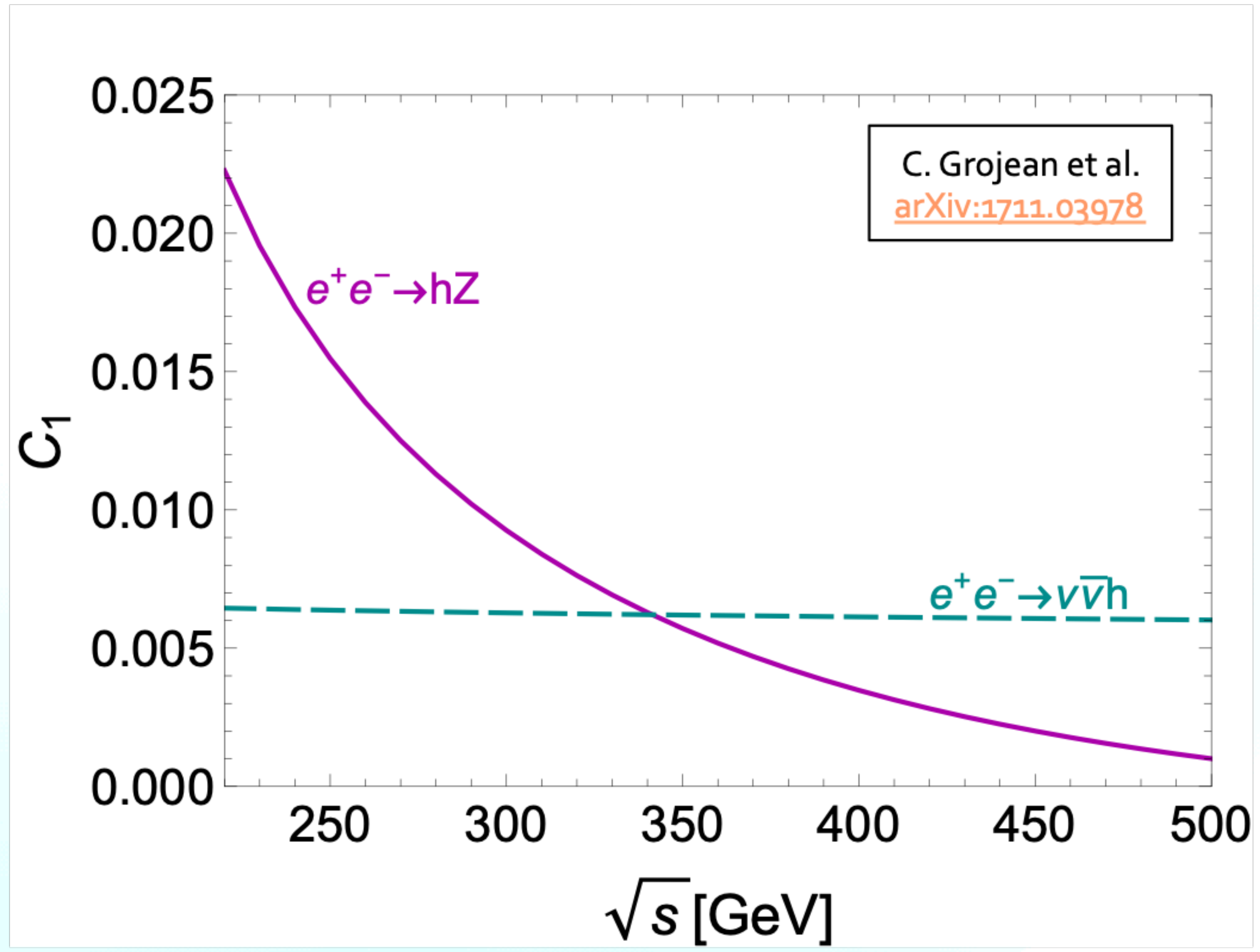
- Traditionally kλ measured in double Higgs production at higher energies. FCC-ee can profit of the significant effect on single Higgs production

Precision on kλ	
FCC-ee	33 %
FCC-ee(4IP)	24 %
FCC(ee+hh)	5 %

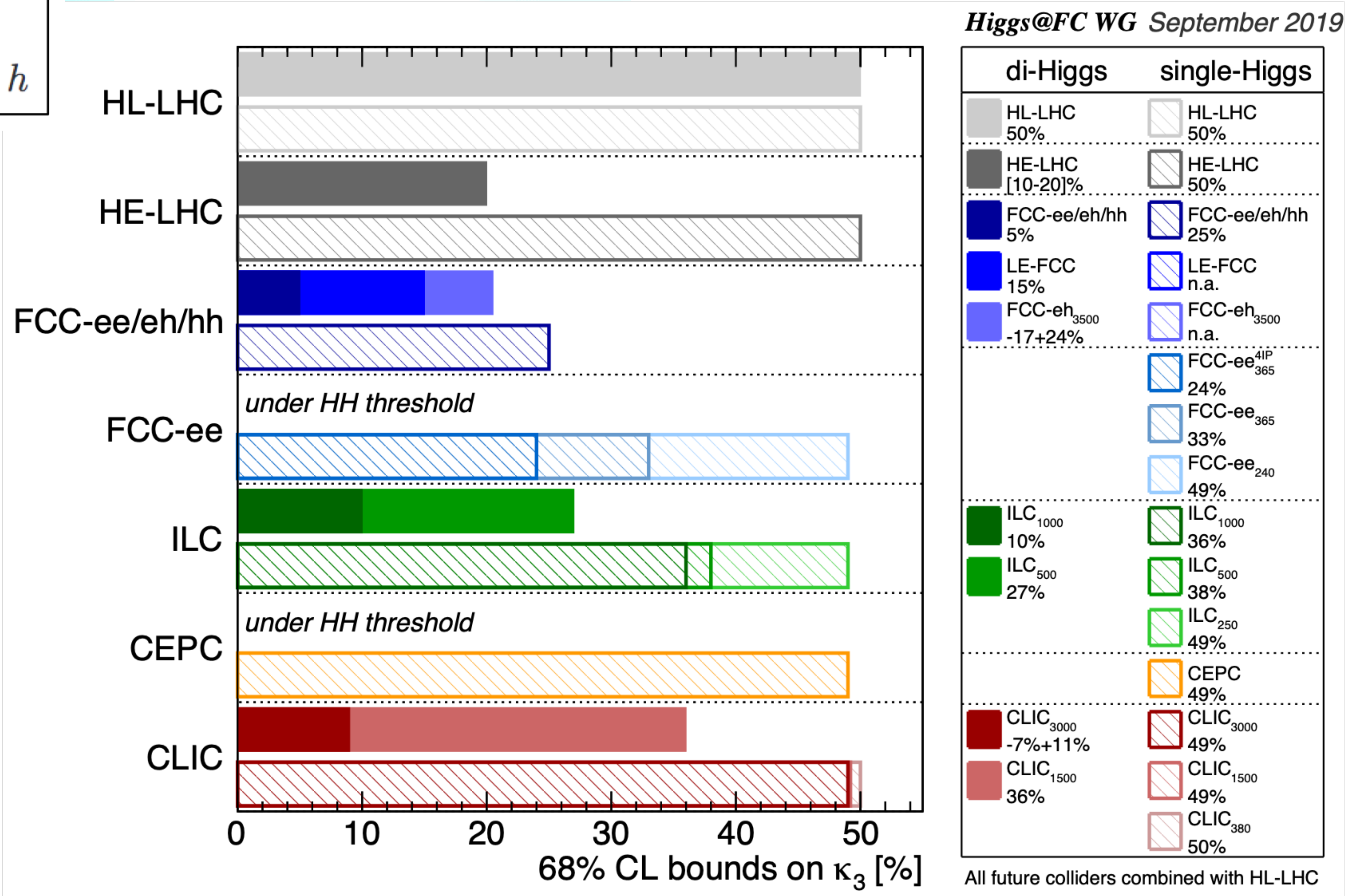
M. McCullough
arXiv:1312.3322

σ_{HZ}




C. Grojean et al.
arXiv:1711.03978

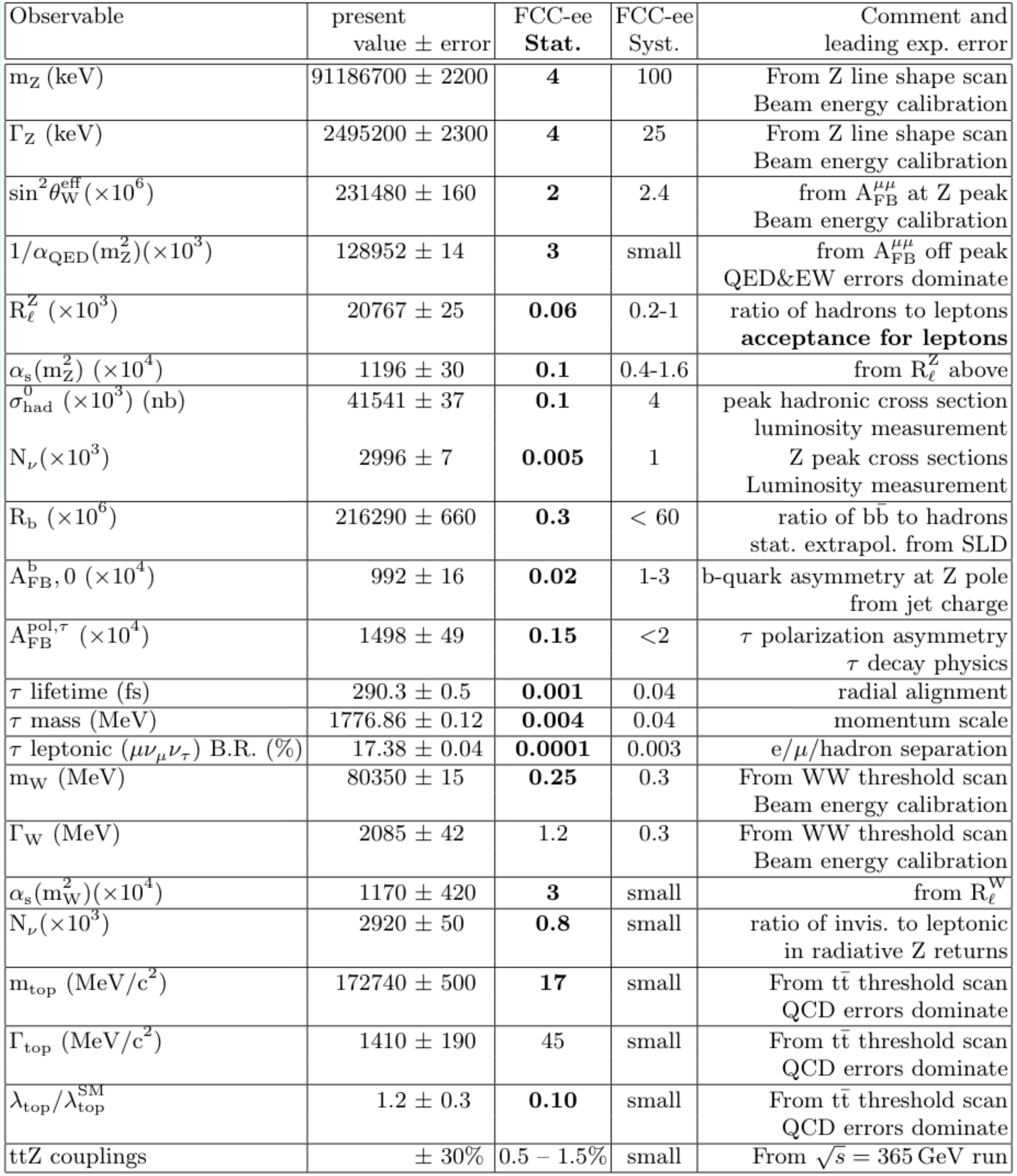
Measurements at different √s also help to lift degeneracy between processes



FCC-ee AS AN ELECTROWEAK FACTORY

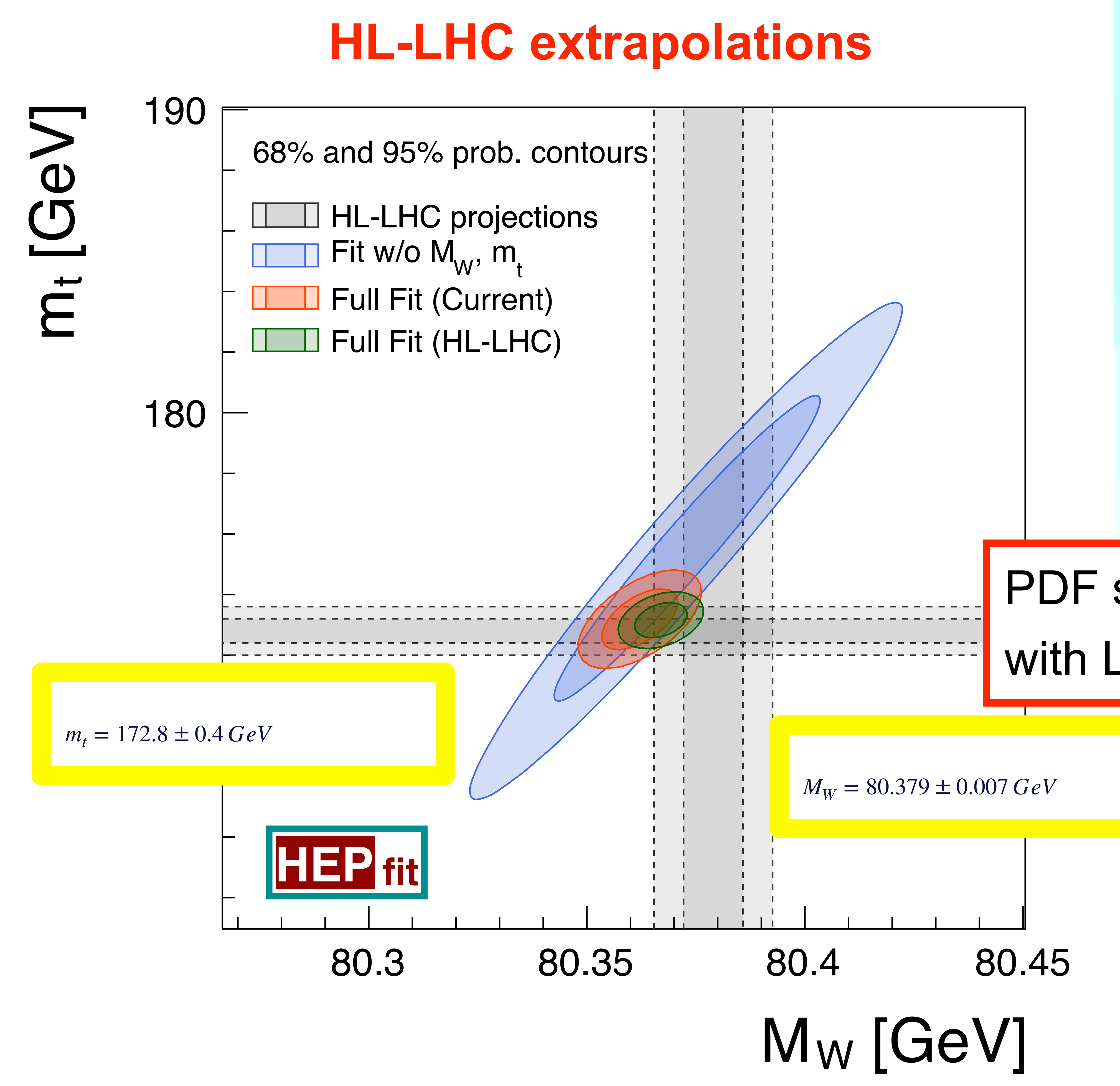
- **Complete set of EW observables can be precisely measured:**
  - Precision 10^{-3} today → few 10^{-6} !!!
  - Precision unique to FCC-ee, with *smallest parametric errors*
- **Challenge: match systematic uncertainties to the statistical precision: need theory as well!**

PRECISION = DISCOVERY



Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. 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
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	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 above
σ_{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
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization 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
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**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_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	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

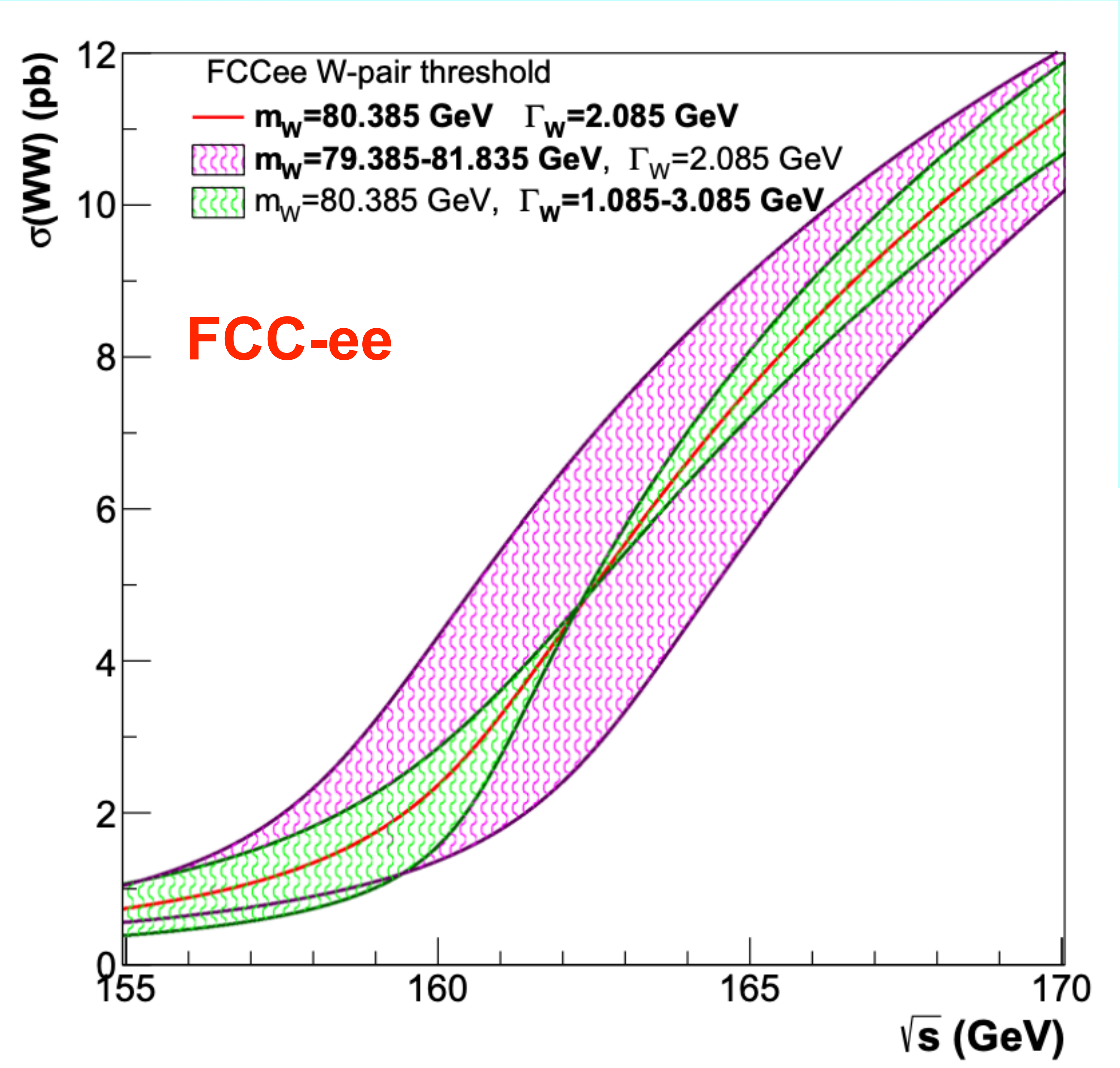
M(W) FROM HL-LHC TO FCC-ee



$m_t = 172.8 \pm 0.4\,GeV$

$M_W = 80.379 \pm 0.007\,GeV$

PDF syst on M_W ~2MeV with LHeC PDF set



From threshold measurement:
L_{int}=12ab^{-1} E1=157, E2=163

$\Delta M(W) = 0.5MeV$ & $\Delta\Gamma(W) = 1.2MeV$

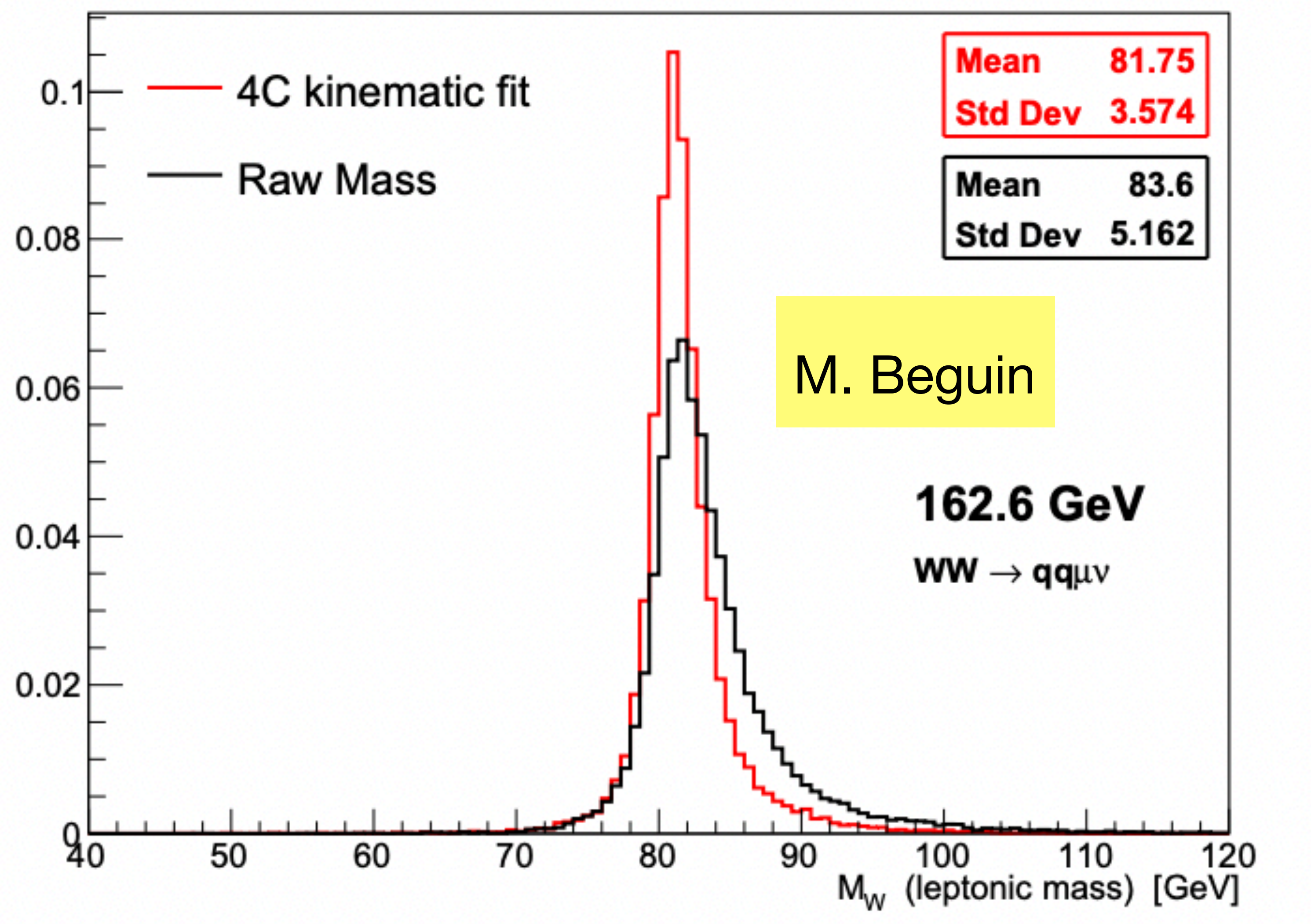
Direct reconstruction of M(W) at other energies (240, 365) similar stat. uncertainty. Different syst.

New CMS top mass 171.77 ± 0.38 GeV
New CDF W mass 80433.5 ± 6.4 (stat) ± 6.9 (syst) MeV.

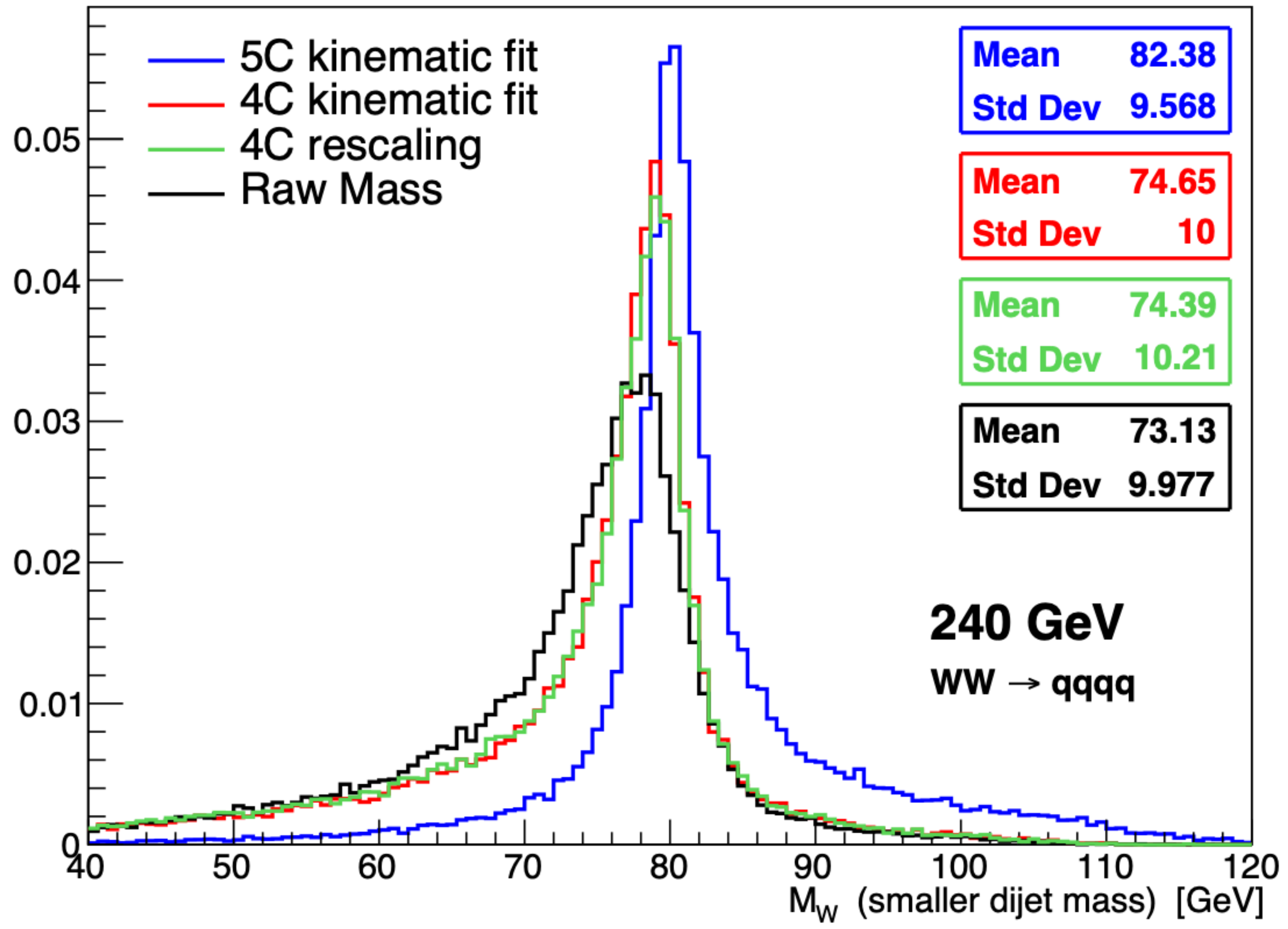
W MASS DIRECT RECONSTRUCTION

- **M(W) direct reconstruction from decay products necessary at any energy**
- Competitive as statistical uncertainty & setting requirements on:
    - Event reconstruction, choice of jet algorithms
    - Lepton momentum scale and resolution
    - Kinematical fitting

Semi-leptonic channel



Fully hadronic channel



Definition of W mass estimators and study and optimisation of:

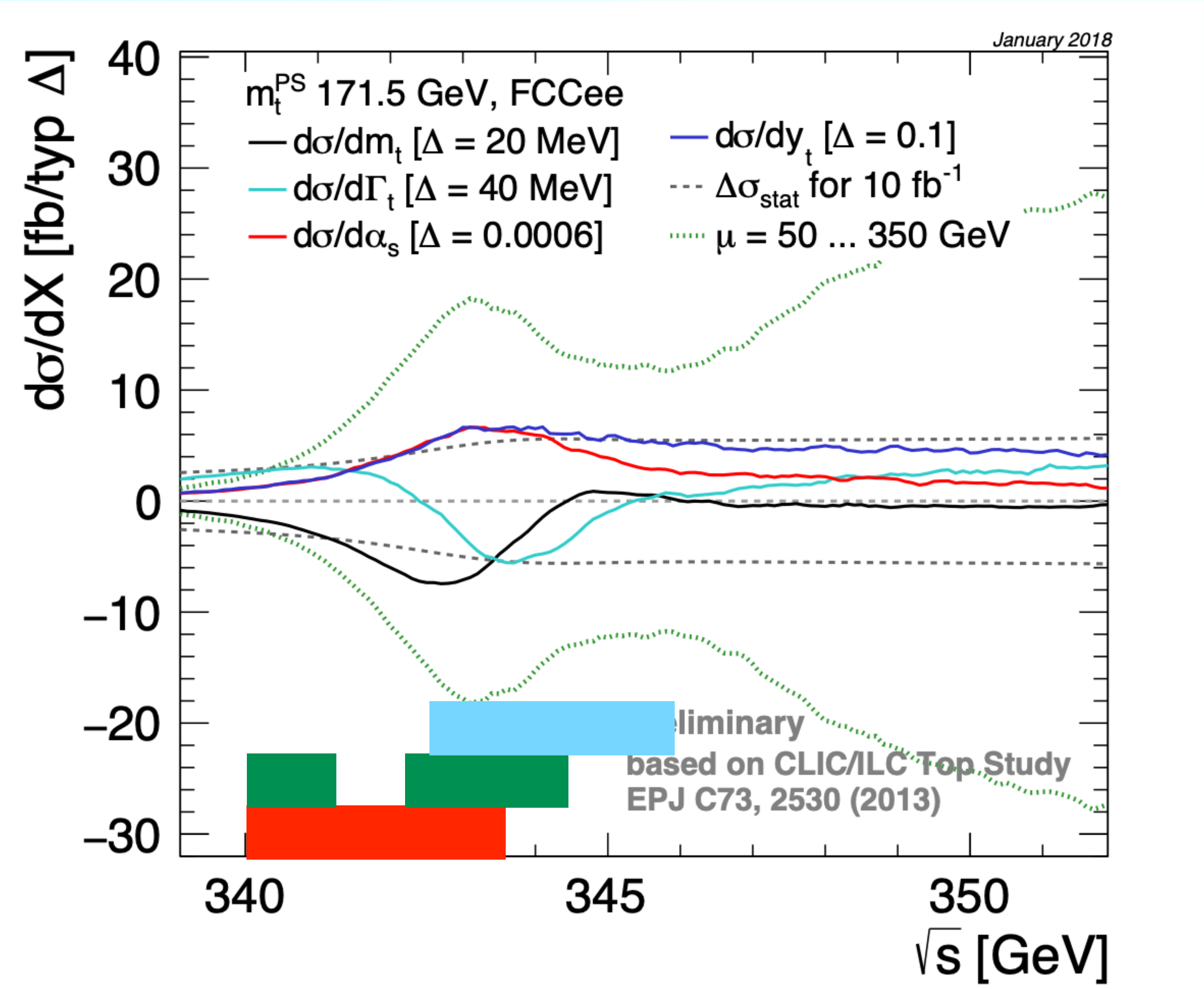
- Statistical and systematic uncertainties with templates fit
- W hadronic decay modelling systematics
- Exploiting also ZZ and Zγ events for constraints and calibration

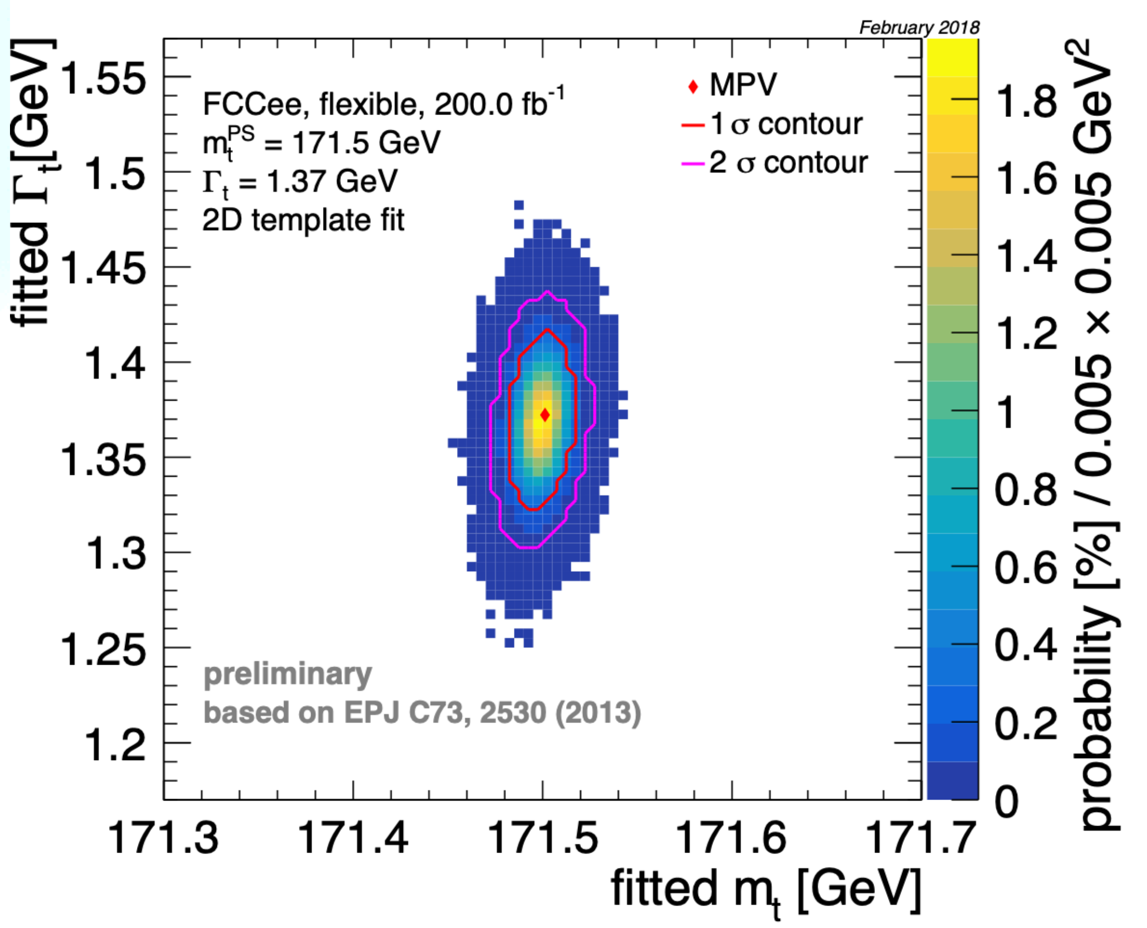
TOP PHYSICS AT FCC-ee

- **Threshold region allows most precise measurements of top mass, width**
  - **Top Yukawa from combination with HL-LHC result of 3.1% (with FCC-ee Higgs measurements removing the model dependence)** while from the measurements at thresholds only about 10% precision

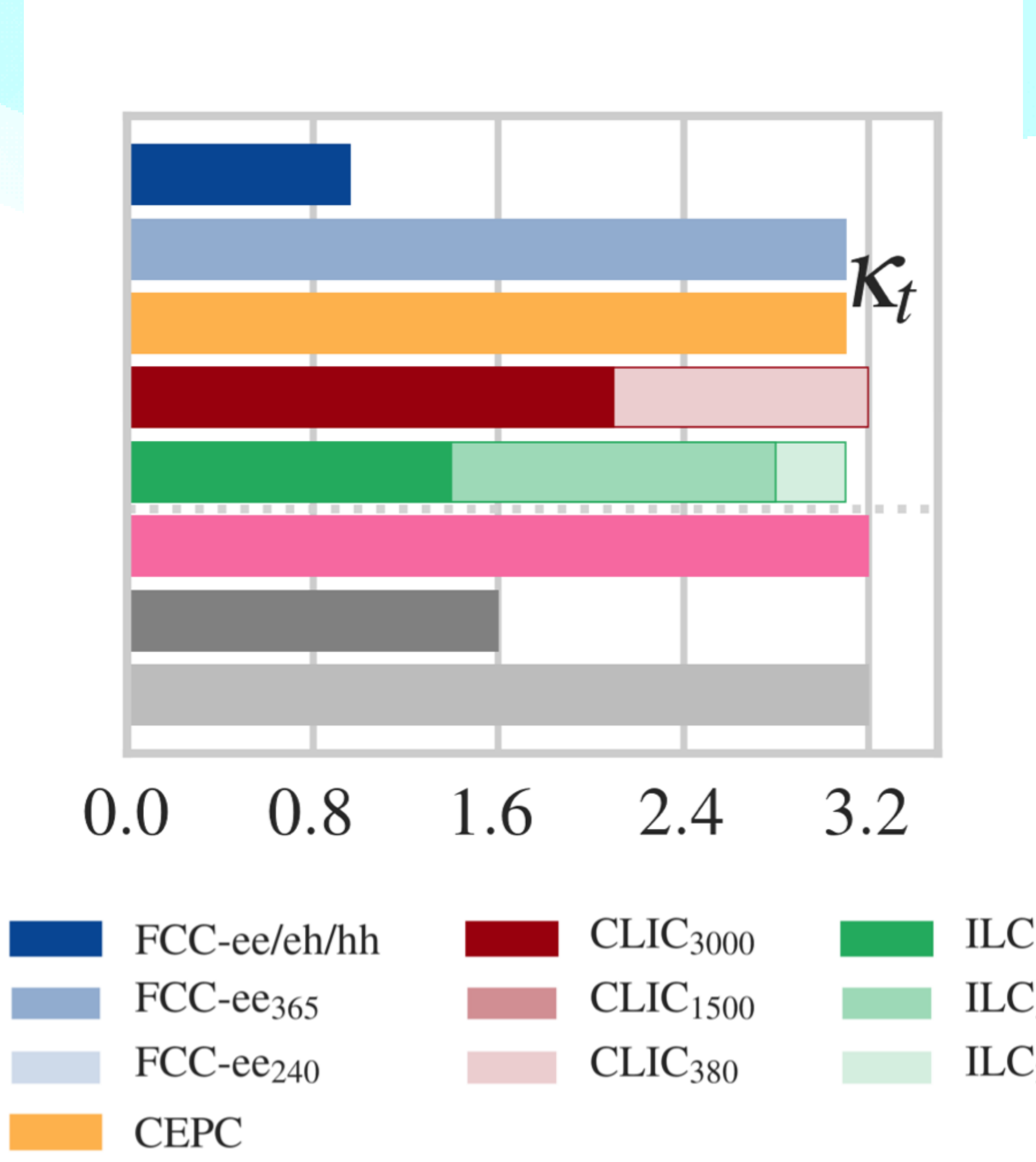
sensitivity to:

🟥 mass
🟩 width
🟦 Yukawa





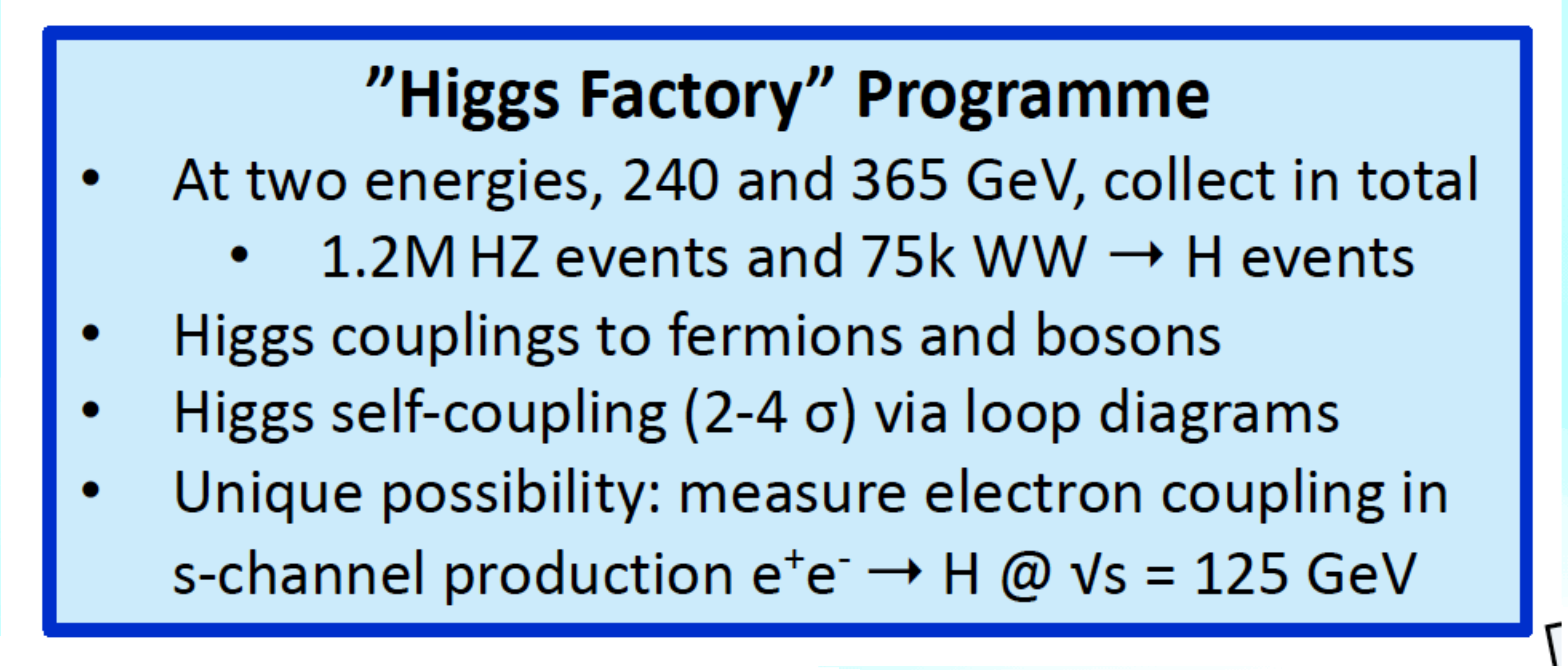
Mass only: 8.8 MeV (stat), 5.4 MeV (αs [2 x 10-4]),   44 MeV (theo)



➤ **Run at 365 GeV used also for measurements of top EWK couplings (at the level of 10^{-2}-10^{-3}) and FCNC in the top sector.**

PHYSICS & DETECTOR REQUIREMENTS HIGGS/EW/TOP

M. Dam



”Higgs Factory” Programme

- At two energies, 240 and 365 GeV, collect in total
    - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s} = 125$ GeV

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DETECTOR REQUIREMENTS

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of $30\%/\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

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Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale

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- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. Γ_{had}/Γ_ℓ) to 10^{-5}
- Momentum resolution ”as good as we can get it”
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6}: stability of $\sqrt{s}$ meast.

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…are these requirements enough to design our best detector?

FCC-ee AT THE INTENSITY FRONTIER

➤ TeraZ offers four additional pillars to the FCC-ee Higgs/EW/Top physics programme

Flavour physics programme

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., $b \to s\tau\tau$

QCD programme

- Enormous statistics with $Z \to \ell\ell$, qq(g)
- Complemented by 100,000 $H \to gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Often statistics-limited
$5 . 10^{12}$ Z is a minimum

Tau physics programme

- Enormous statistics: $1.7\ 10^{11}$ $\tau\tau$ events
- Clean environment, boost, vertexing
- Much improved measurement of mass, lifetime, BR's

1. τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
2. Lepton universality violation tests
3. PMNS matrix unitarity
4. Light-heavy neutrino mixing

Rare/BSM processes, e.g. Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m_Z

- Signature: long lifetimes (LLP's)
- Other ultra-rare Z (and W) decays

1. Axion-like particles
2. Dark photons
3. Heavy Neutral Leptons

Slide by P. Janot Ecfa meeting 19 Nov 2021

FCC-ee AT THE INTENSITY FRONTIER

➤ … which in turn provide specific detector requirements

Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z resonance

QCD + EW programme

- Particle-Flow reconstruction
- Lepton and jet angular and energy resolution ; Lepton ID

More case studies will lead to more detector requirements

Tau physics programme

- Momentum resolution
  Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  Lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation
  BR measurements, EWPOs, spectral functions

Rare/BSM processes, e.g. Feebly Coupled Particles

- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

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If all these constraints are met, Higgs and top programme probably OK (tbc)

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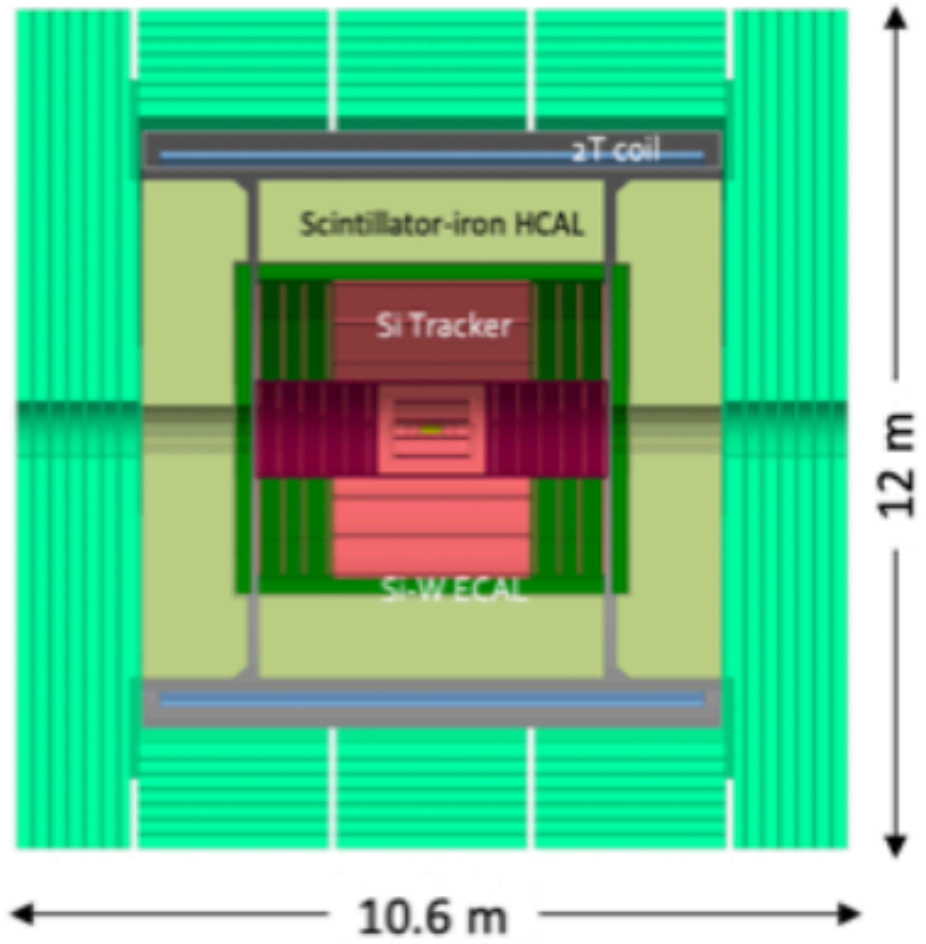
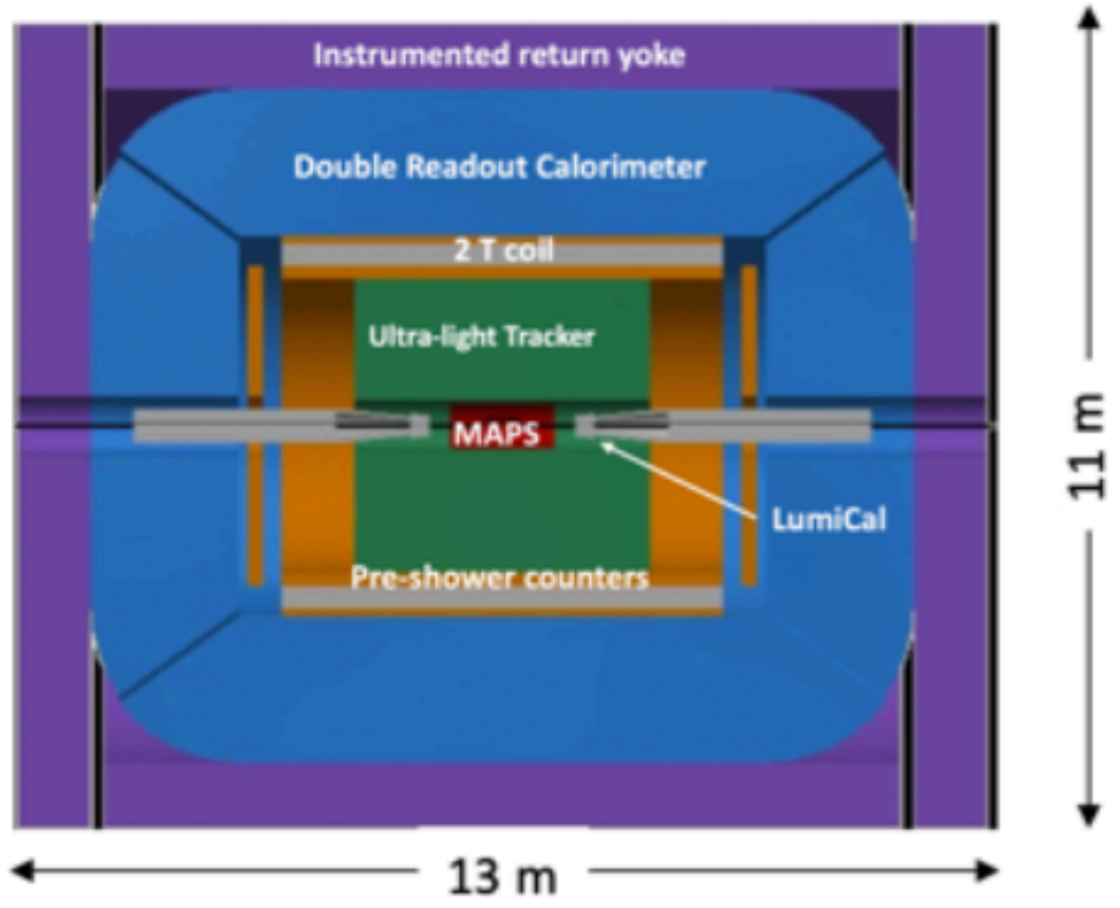
CURRENT DETECTOR CONCEPTS

CLD

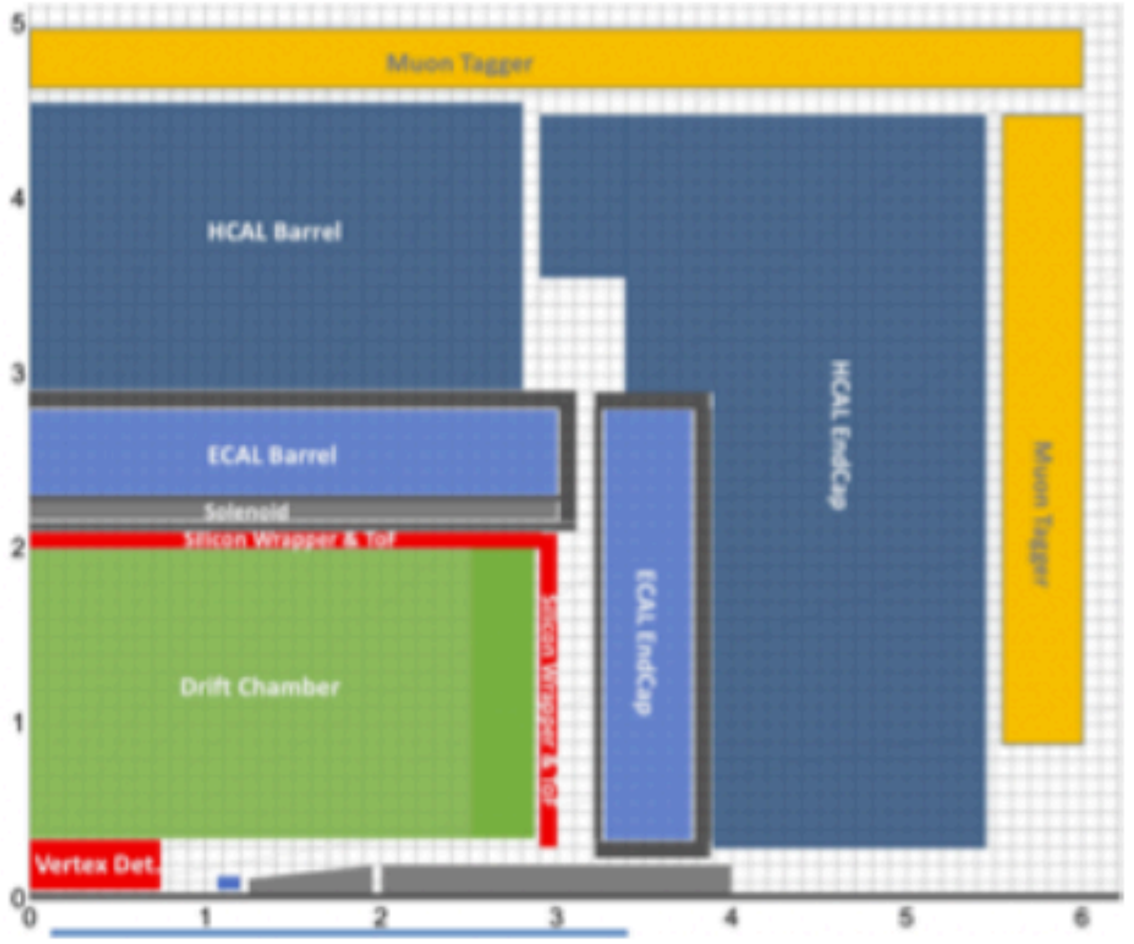


CDR

IDEA



Noble Liquid ECAL based



new

- CLIC detector -> CLD
- 2T solenoid outside Calo
- Full Si vtx + tracker
- CALICE-like calo
- RPC muon system

1911.12230, 1905.02520

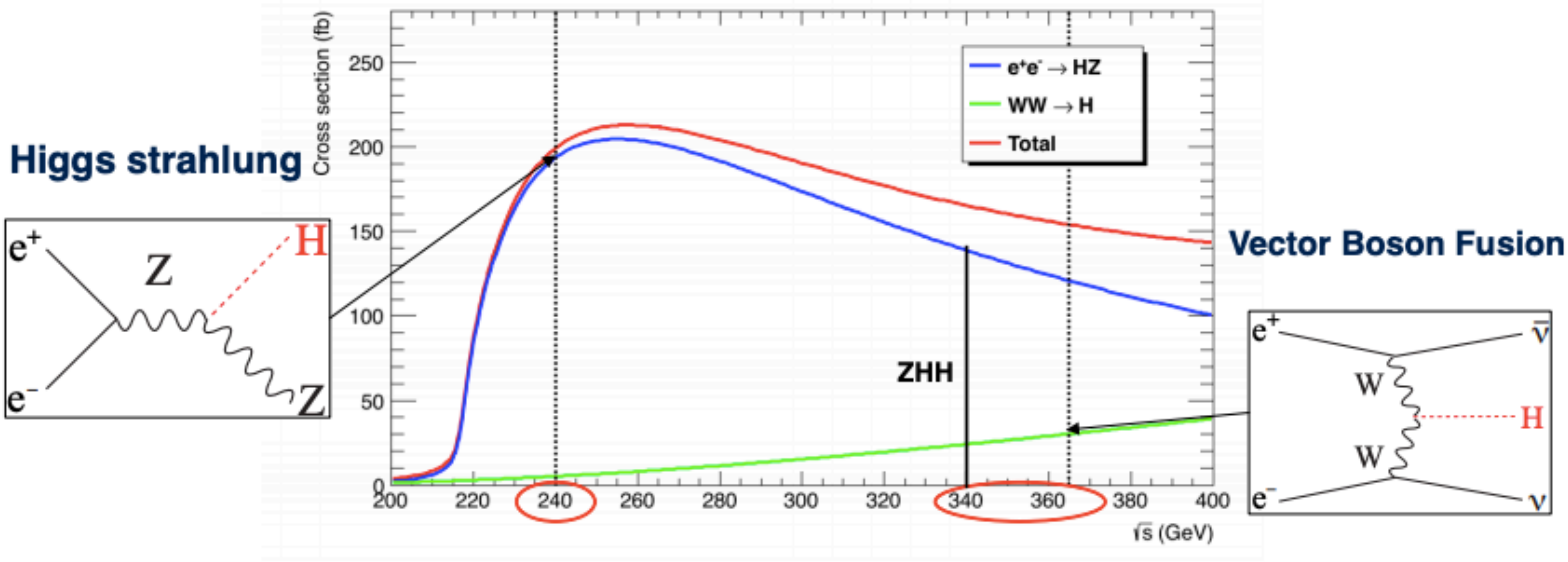
- 2T thin solenoid within Calo
- Si vtx detector
- Ultra light drift chamber
- Dual Readout calo+preshower
- Possible crystal ECAL
- MPGD (μ-rwell) muon system

CERN-ACC-2018-0057

- High granularity ECAL
  - Pb+Lar (or W+LKr)
- Drift chamber (or Si) tracker; CALICE-like HCAL; muon sys.
- Coil in same cryostat as LAr

HIGGS PRODUCTION AT FCC-ee

Higgs boson production through Higgs strahlung and VBF



- maximum ZH cross section value at √s = 255 GeV
- luminosity drops with √s at constant ISR dissipation power

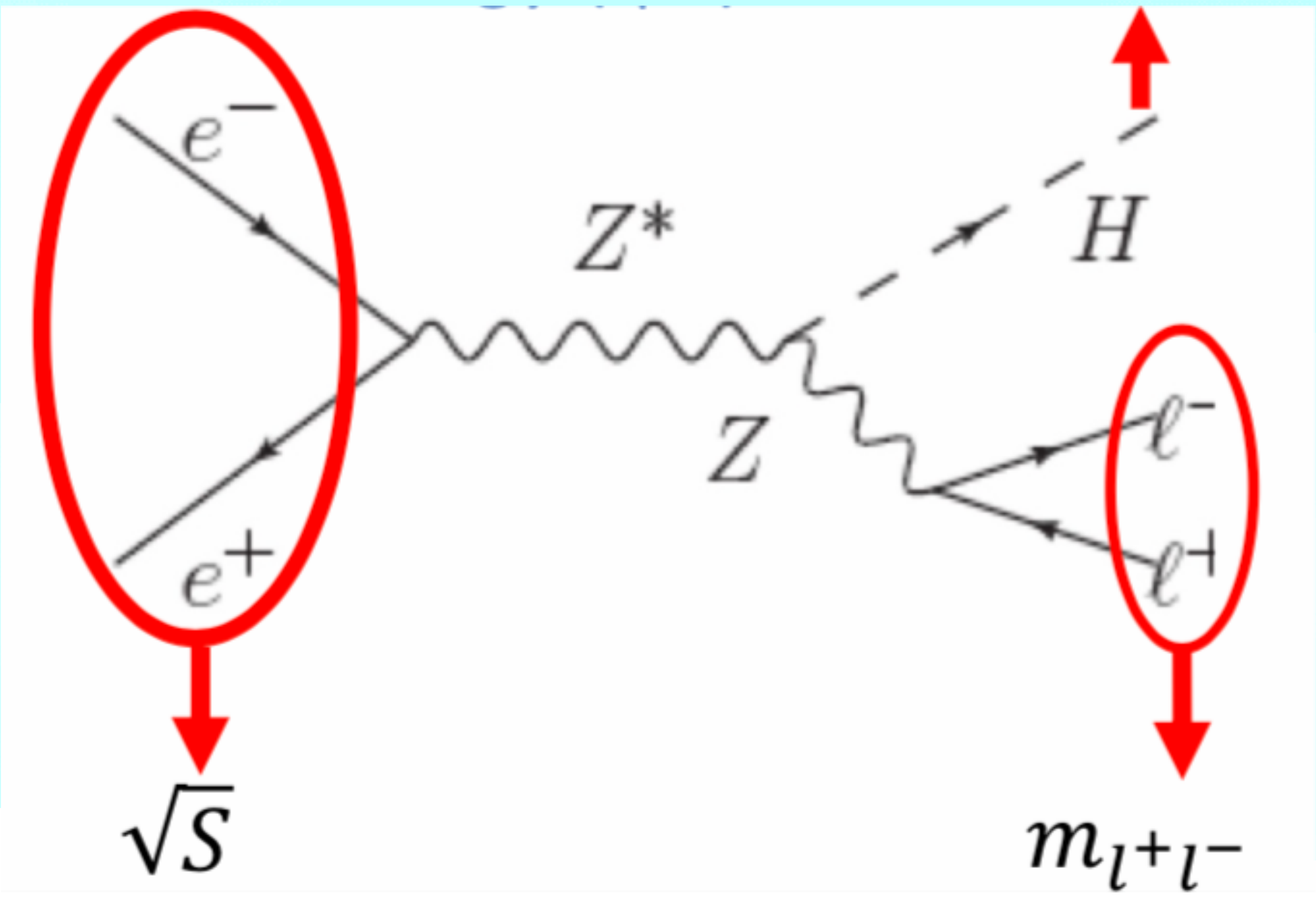
maximum event production at √s = 240 GeV

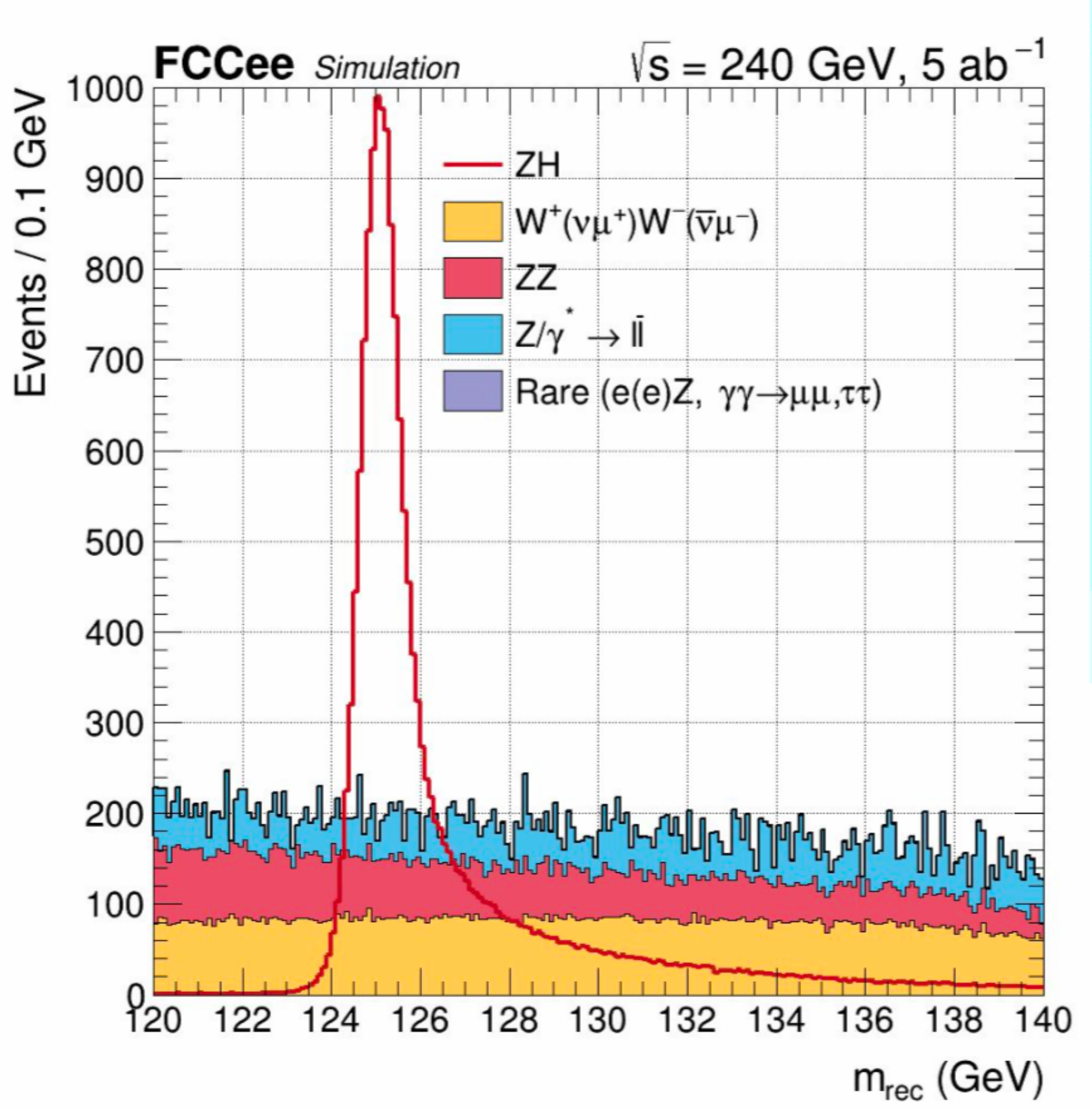
- higher energy points available for other physics targets (top physics), but they can be used to improve Higgs measurements (in particular Γ_H and Higgs self-coupling)

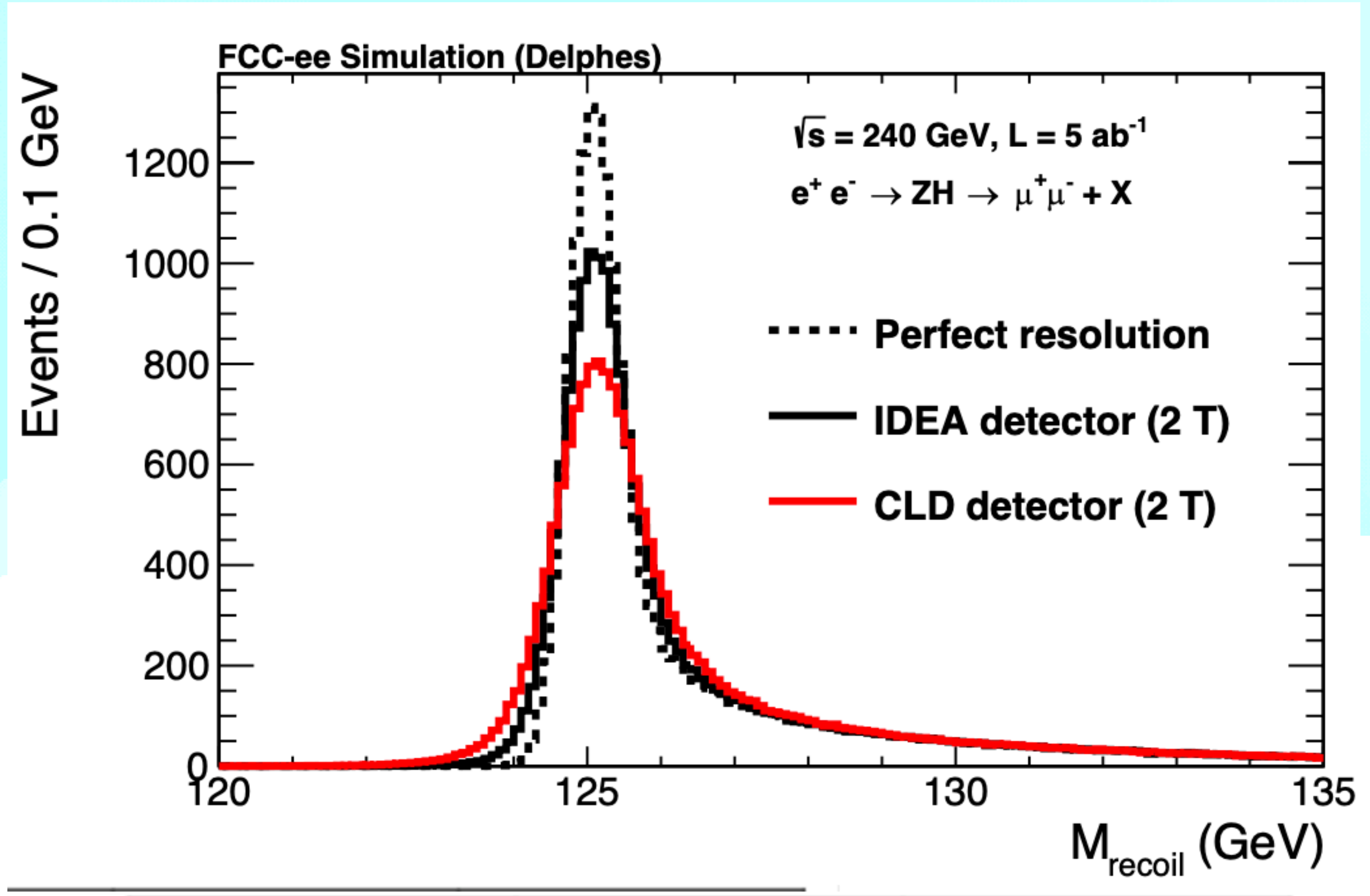
HIGGS MASS AND CROSS SECTION “CASE STUDY”

$e^+e^- \rightarrow ZH, Z \rightarrow \mu\mu$

2107.04509







Main TK	Δm_H (MeV)	$\Delta\sigma$ (%)
IDEA 2T	**6.70**	**1.07**
CLD 2T	**9.01**	**1.12**
IDEA 3T	**5.78**	**1.06**
Perfect resol	**4.75**	**1.04**

$$m^2_{\text{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

Recoil mass affected by :
- The beam energy spread
- The momentum resolution (and the ISRs for the tail)

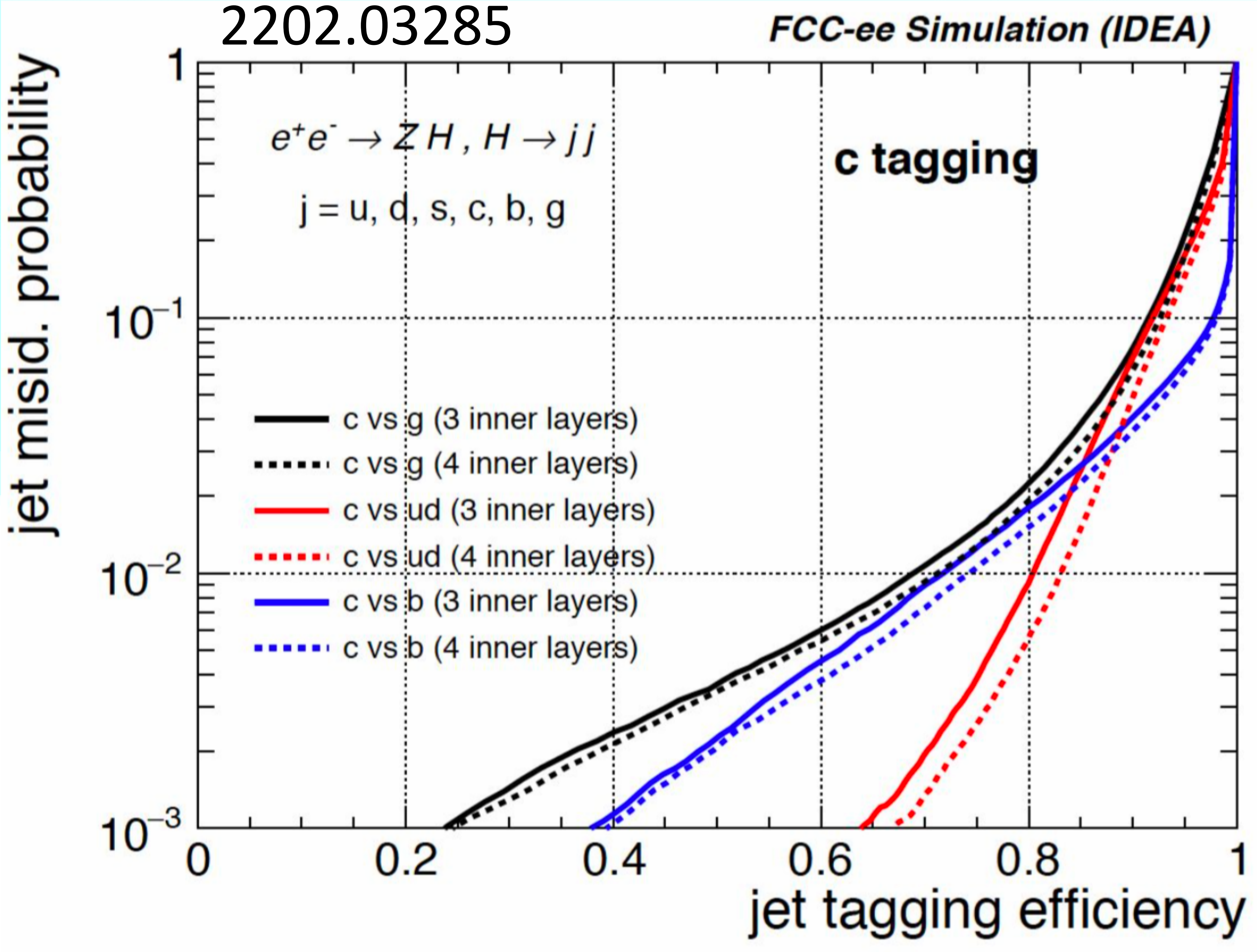
Higgs mass measurement:

$\Delta(m_H) < O(\Gamma_H)$ i.e. 4 MeV desirable in view of $e^+e^- \rightarrow H$

HIGGS COUPLINGS TO b/c-QUARKS AND GLUONS

- ➤A must for any Higgs factory
  - ➤Precise measurement of all Higgs couplings to ff, VV
  - ➤H(cc), H(gg) won't be measured at HL-LHC

- ➤Flavour tagging is the key
  - ➤Main motivation for developing state-of-the-art tagging algorithms
  - ➤Algorithms based on advanced Neural Networks:
    - ➤several proposals in progress (see e.g. arXiv:2202.03285)


2202.03285

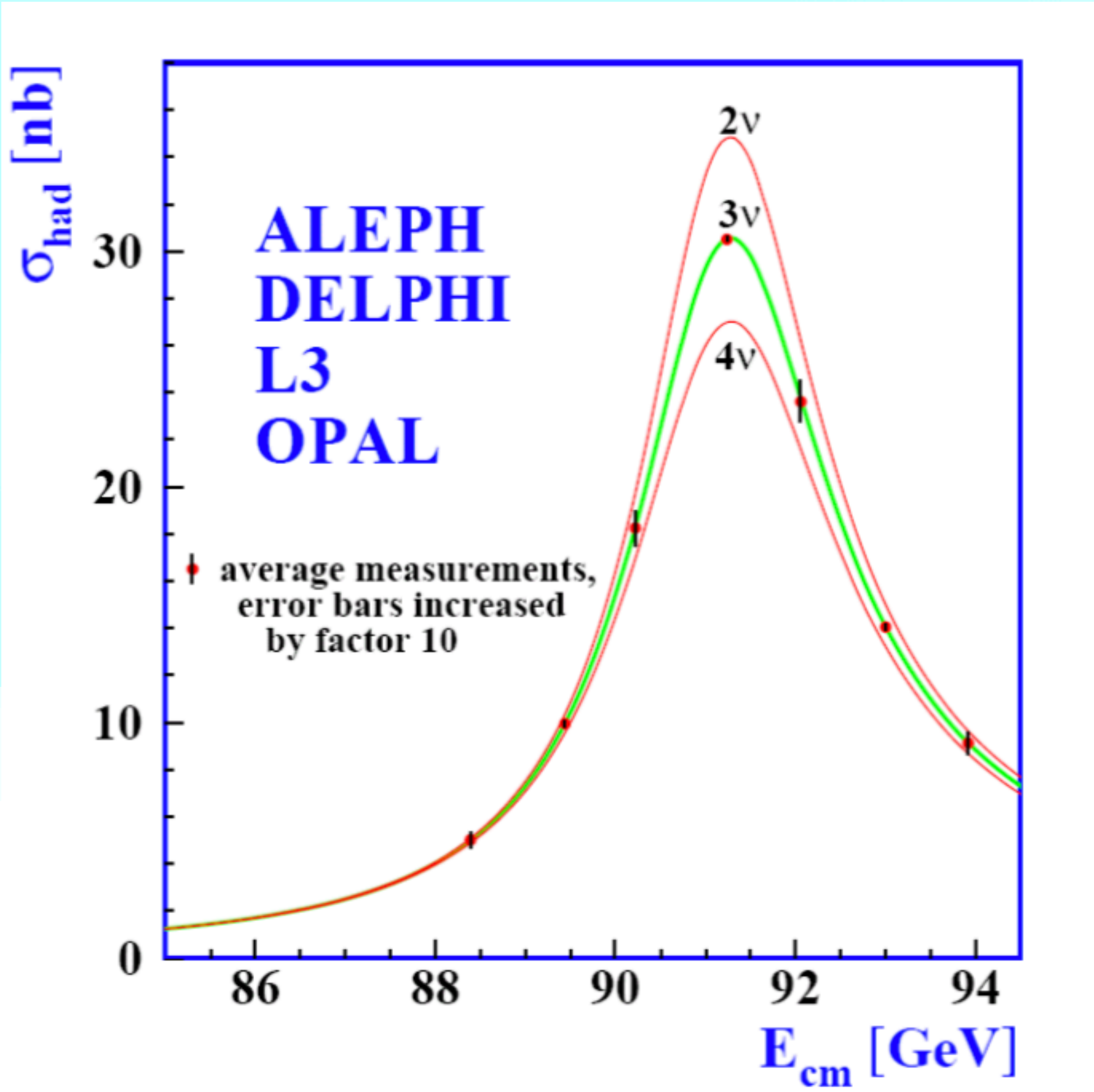
Position of innermost layer of VXD: smaller BP reduces by x2 the mistag rate for c-tagging.

Benchmarks for flavour tags

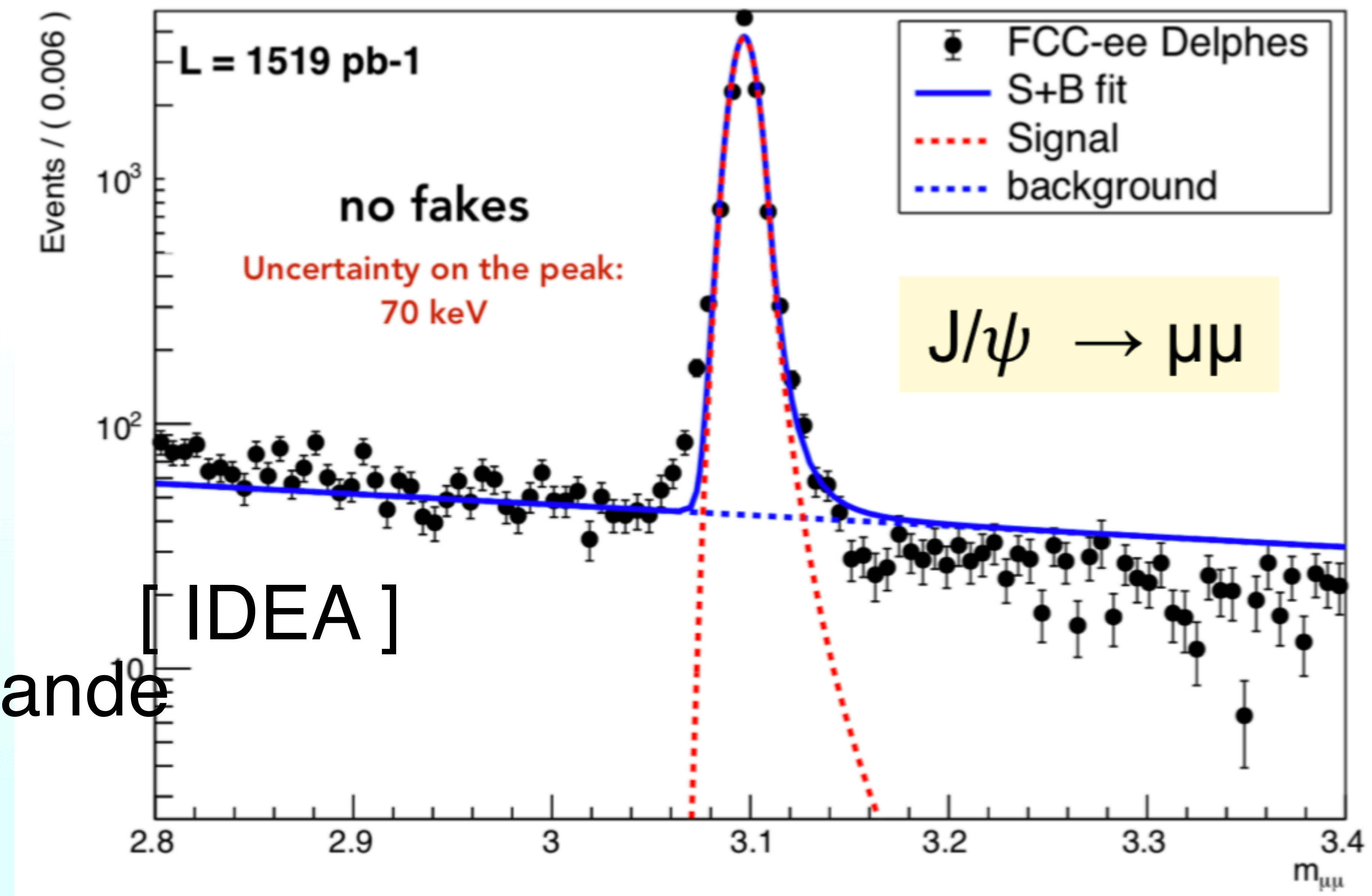
- Final states:
  - Z(ll) H(qq) : clean, use the recoil mass again
  - Z(vv) H(qq) : probably drives the sensitivity
  - Z(qq) H(qq) : performance depends in addition on jet pairing, see later

“CASE STUDY” DETERMINATION OF THE Z WIDTH

Key = Relative uncertainty of √s between the different energy points of the lineshape scan.



Can be controlled via the direct measurement of M(μμ) in di-muon events : compare the peak positions at the different √s points.
σ(Mμμ) : statistical potential to control relative δ(√s) to O(40 keV)
Requires the stability of the momentum scale, esp. of B, to that level, i.e. 40 keV / 90 GeV < 10-6



[IDEA]

E. Leogrande

E. Perez

In-situ, using the large statistics of well-known resonances, e.g. J/ψ → μμ

First studies: Target seems within reach with an IDEA-like resolution (drift chamber as tracker)

FCC

THE INTENSITY FRONTIER - FLAVOR PHYSICS

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., b → s$\tau\tau$

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

~15 times Belle's stat

Boost at the Z!

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	~ 2 000	~ 10	n/a (5)
LHCb Run I	150	-	~ 15 (–)
LHCb Upgrade	~ 5000	-	~ 500 (50)
FCC-ee	~ 200000	~ 1000	~1000 (100)

Yelds for flavor anomalies studies:

b→sll yelds and $B^0 \to K^{*0}\tau^+\tau^-$ 👍

Full reconstruction possible

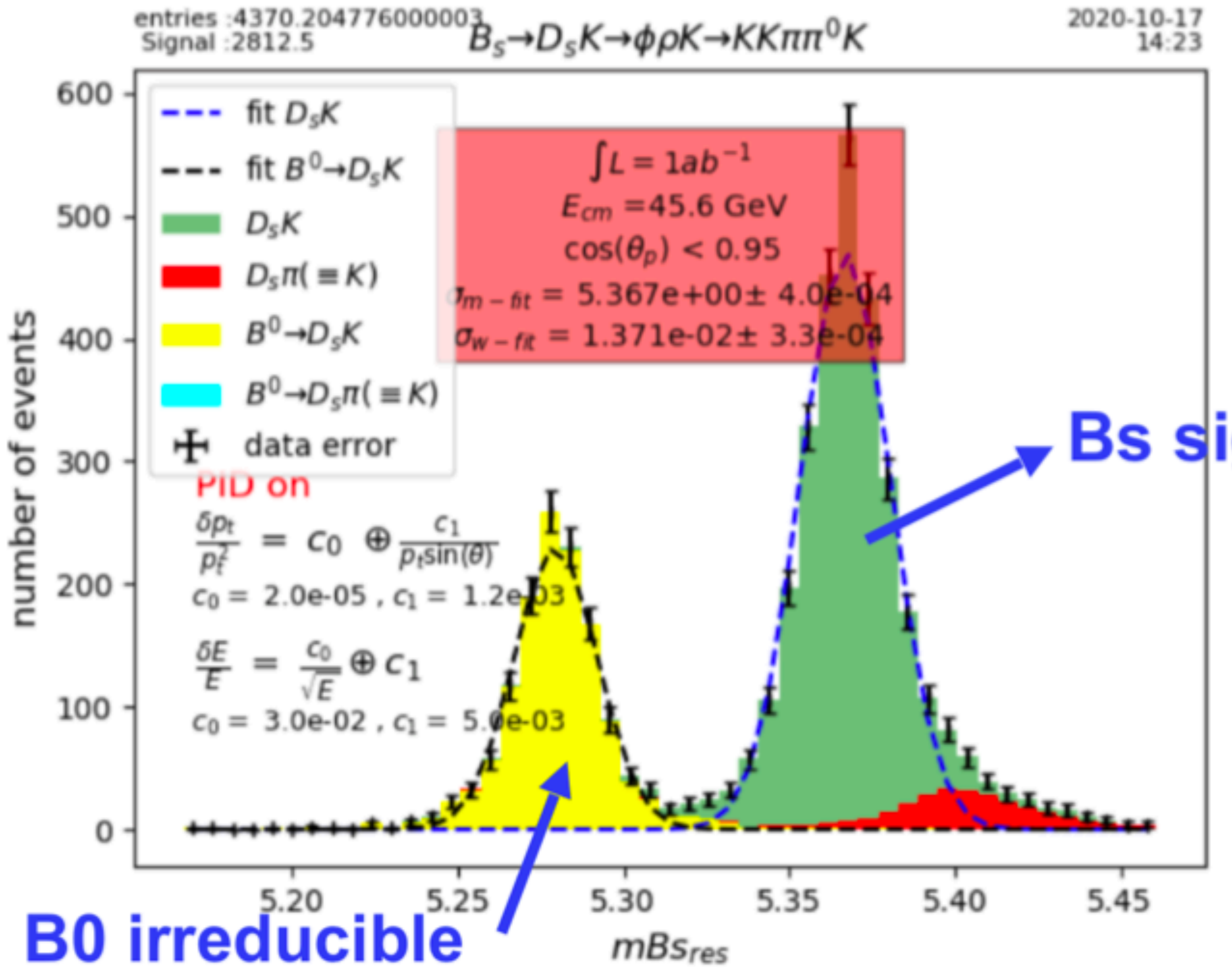
BENCHMARK ECAL ENERGY RESOLUTION: $B_s \to D_s K$

Including the neutral decays in the reconstruction drives the ECAL resolution

$D_s^+ K^-$	$D_s^+ \to \phi\pi$	$K^+K^-\pi^+K^-$	$\sim 5.2\ 10^5$
$D_s^+ K^-$	$D_s^+ \to \phi\rho$	$K^+K^-\pi^+K^-\pi^0$	$\sim 9.8\ 10^5$

Assuming **state-of-the-art** calorimeter with

$$\frac{\delta E}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005$$

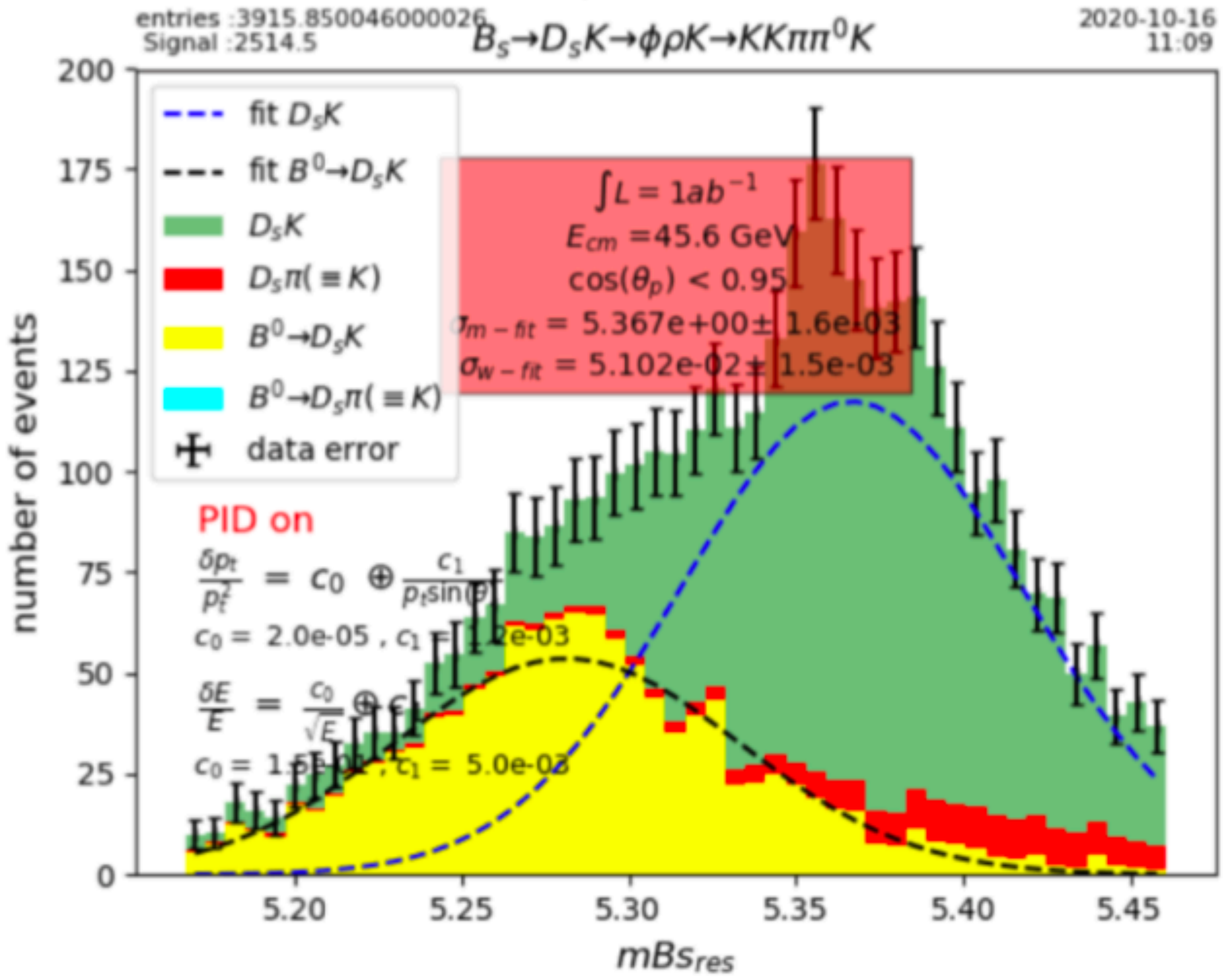


Bs signal

B0 irreducible bckgd

Assuming **HGCal like** calorimeter with

$$\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} \oplus 0.005$$



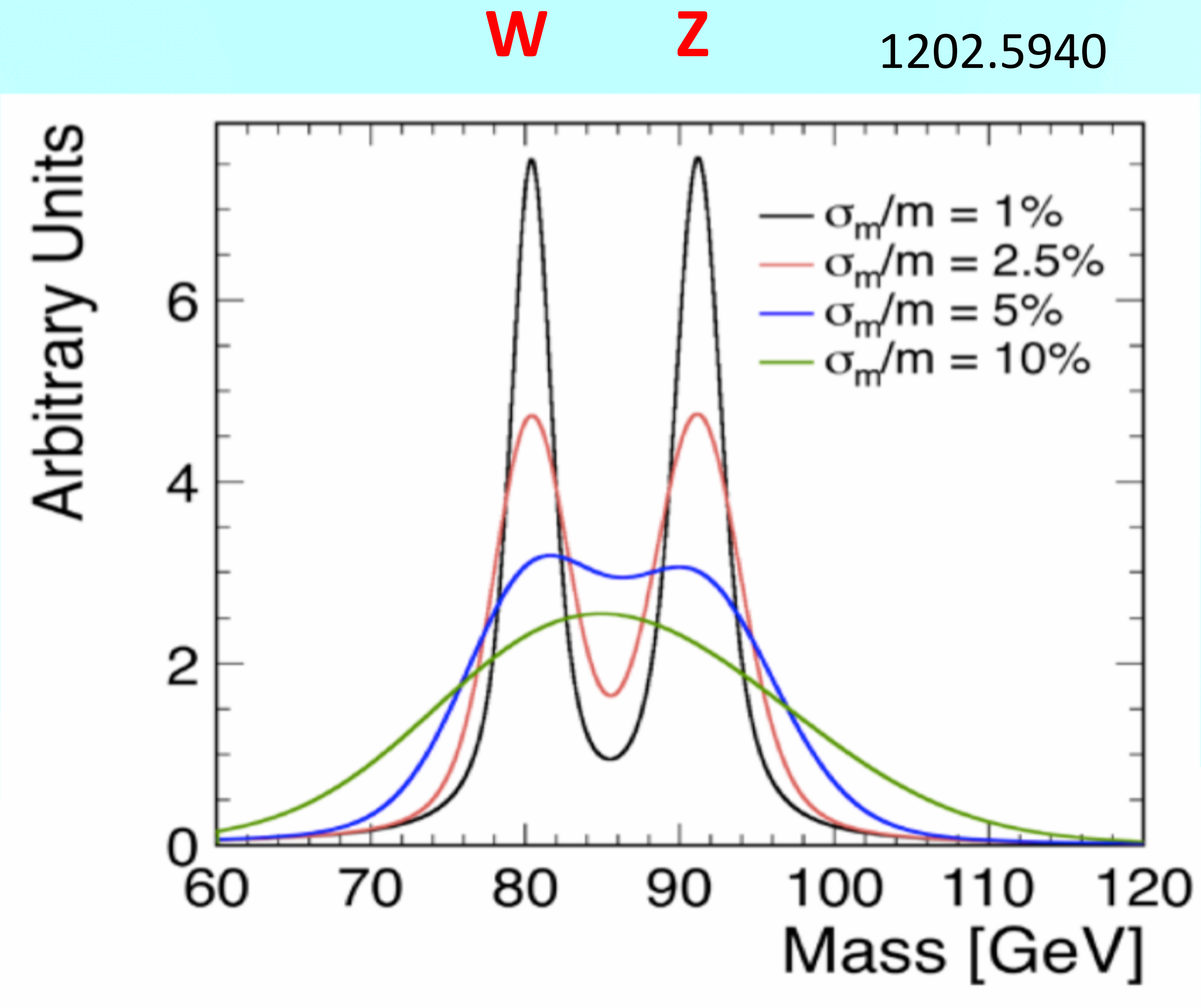
R. Aleksan

2107.02002

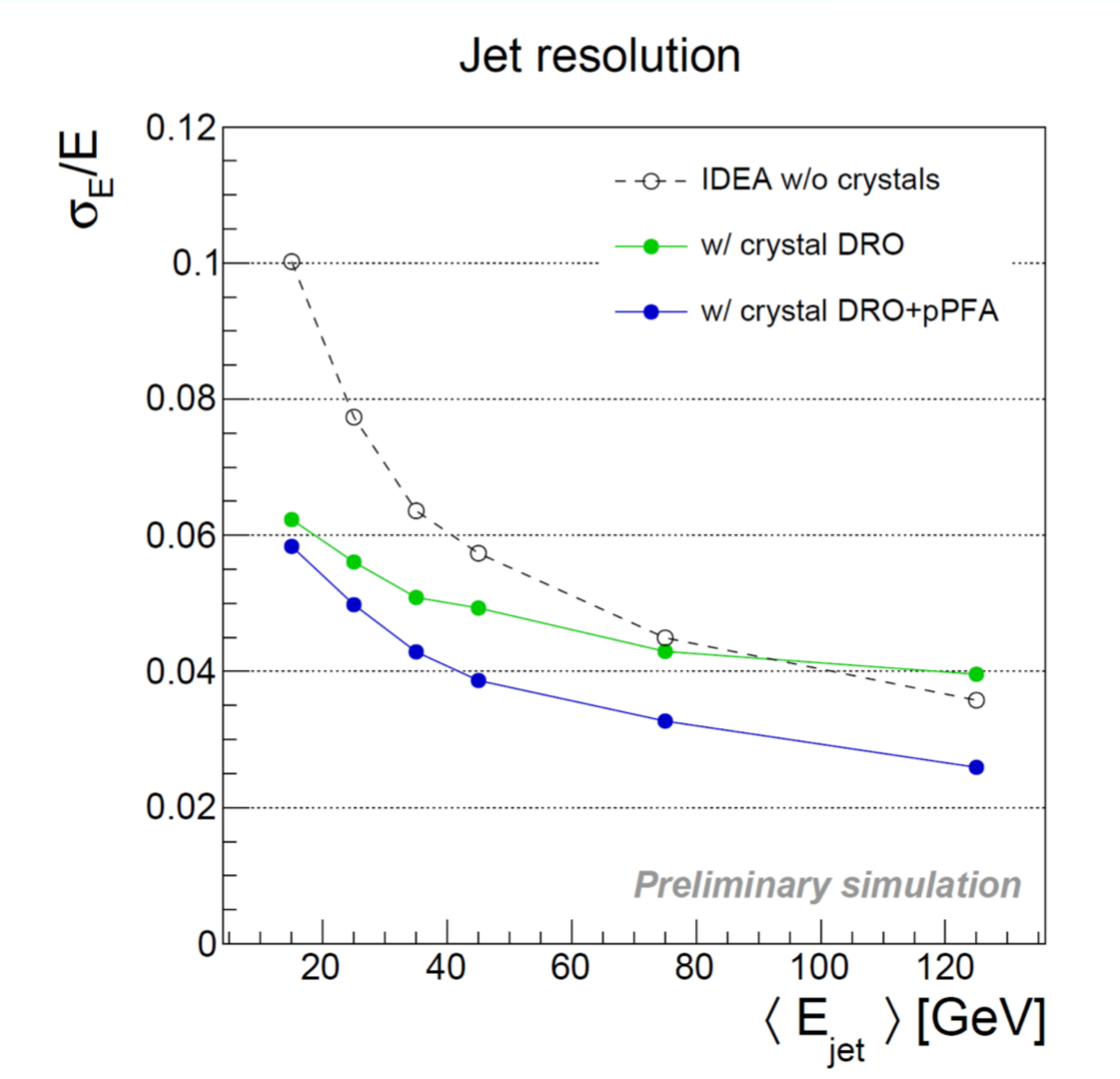
State-of-the-art Xtal-type to HGCal-type : $\sigma\left(D_s^{\pm}(\phi\rho^{\pm})K^{\mp}\right) \approx 14MeV \to 51MeV$

CALORIMETRY SUMMARY

- Jet energy resolution 30-40%/$\sqrt{E}$
  - Fine segmentation for PF algorithm and powerful γ/π0 separation and measurement
  - Exploit resolution of color singlet



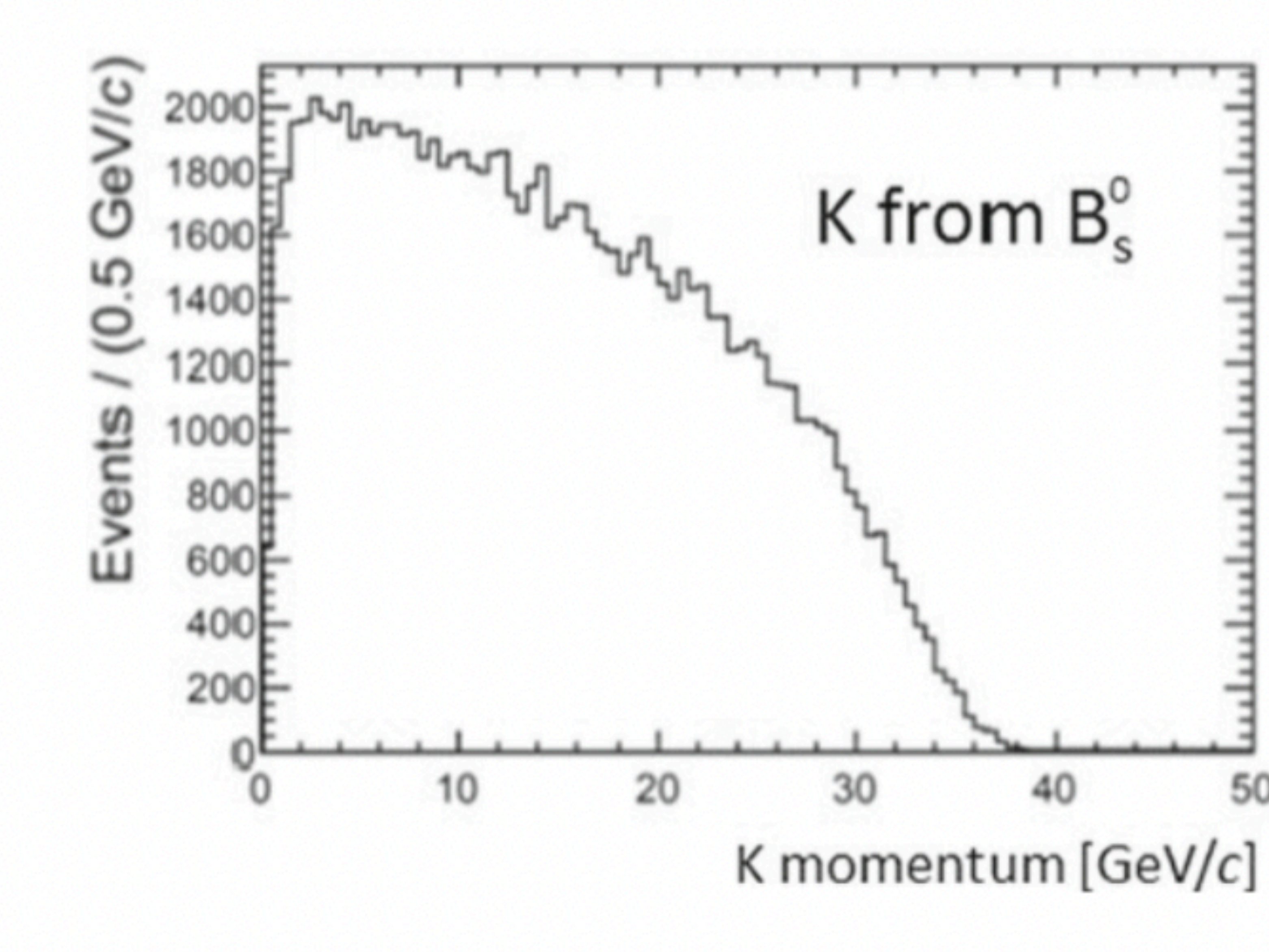
At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution comparable to Γ_W and Γ_Z



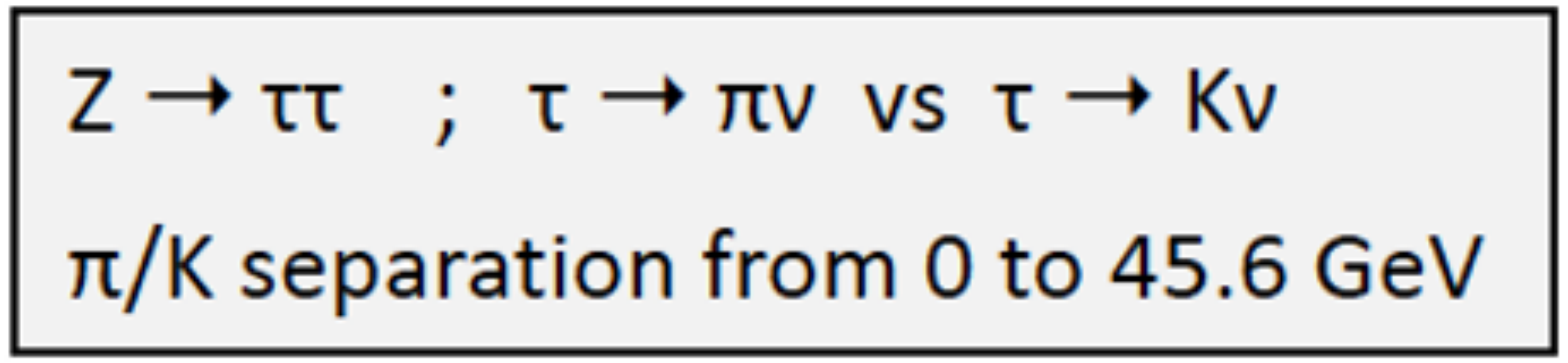
- ~ 10-15%/$\sqrt{E}$ ECAL res, sufficient for Higgs physics, 15%/√E → 8%/√E → 3%/√E for HF physics!
- ECAL Transverse granularity < 1 cm for π0 from τ and H

PARTICLE ID

G. Wilkinson



- Essential for flavour physics / spectroscopy
  - Suppress backgrounds: e.g. $B_s \to D_s K$, p(K) extends up to 30 Gev
- Important for tau physics


$Z \to \tau\tau$; $\tau \to \pi\nu$ vs $\tau \to K\nu$

π/K separation from 0 to 45.6 GeV

- Higgs Physics
  - Allows to develop a strange tagger
  - Improves sensitivity to Higgs strange Yukawa coupling H $\to s\bar{s}$, or H → c$\bar{s}$ and more…

dN/dx=Cluster counting in the IDEA drift chamber

PARTICLE ID

G. Wilkinson

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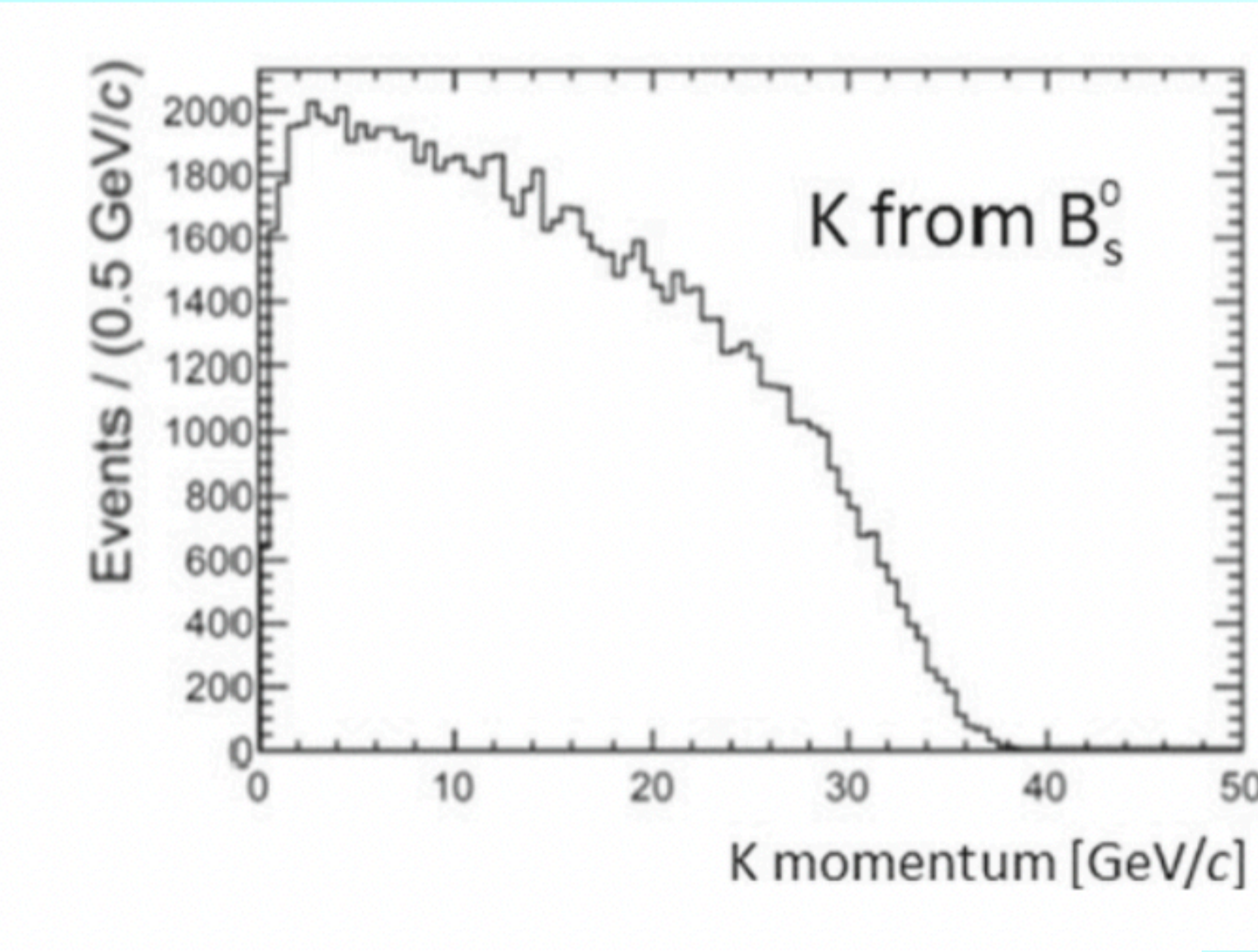
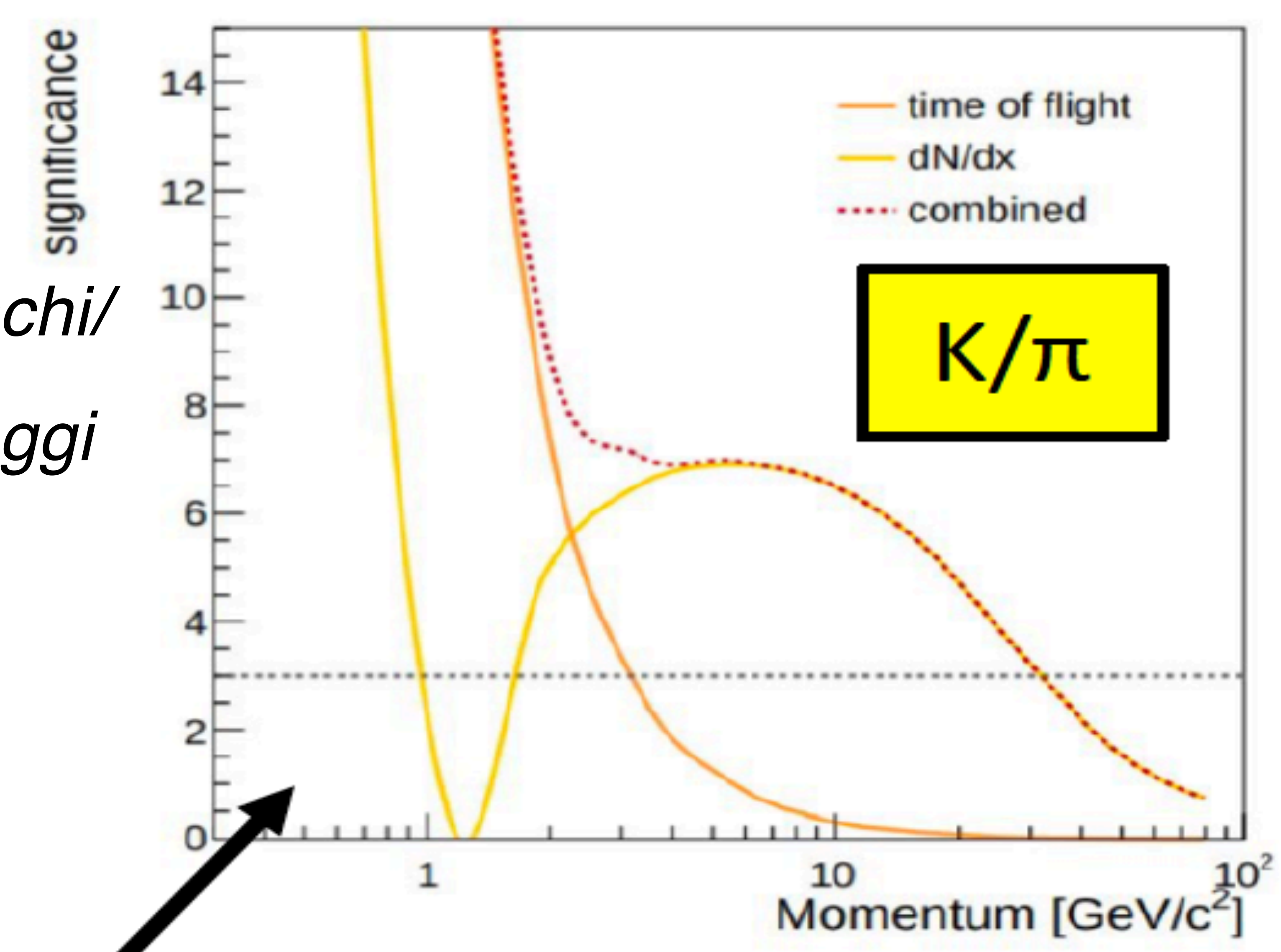


F. Bedeschi/

M. Selvaggi

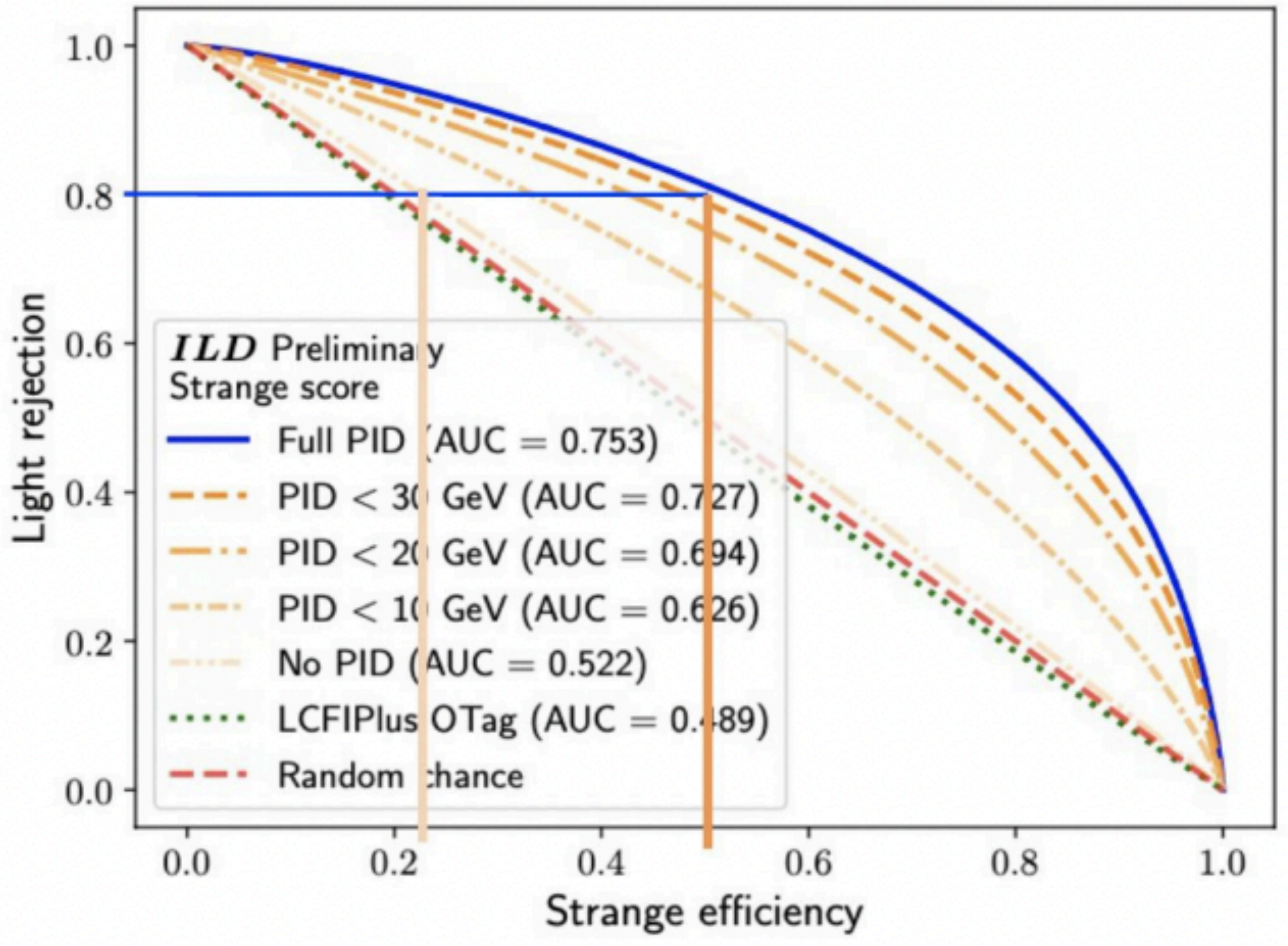


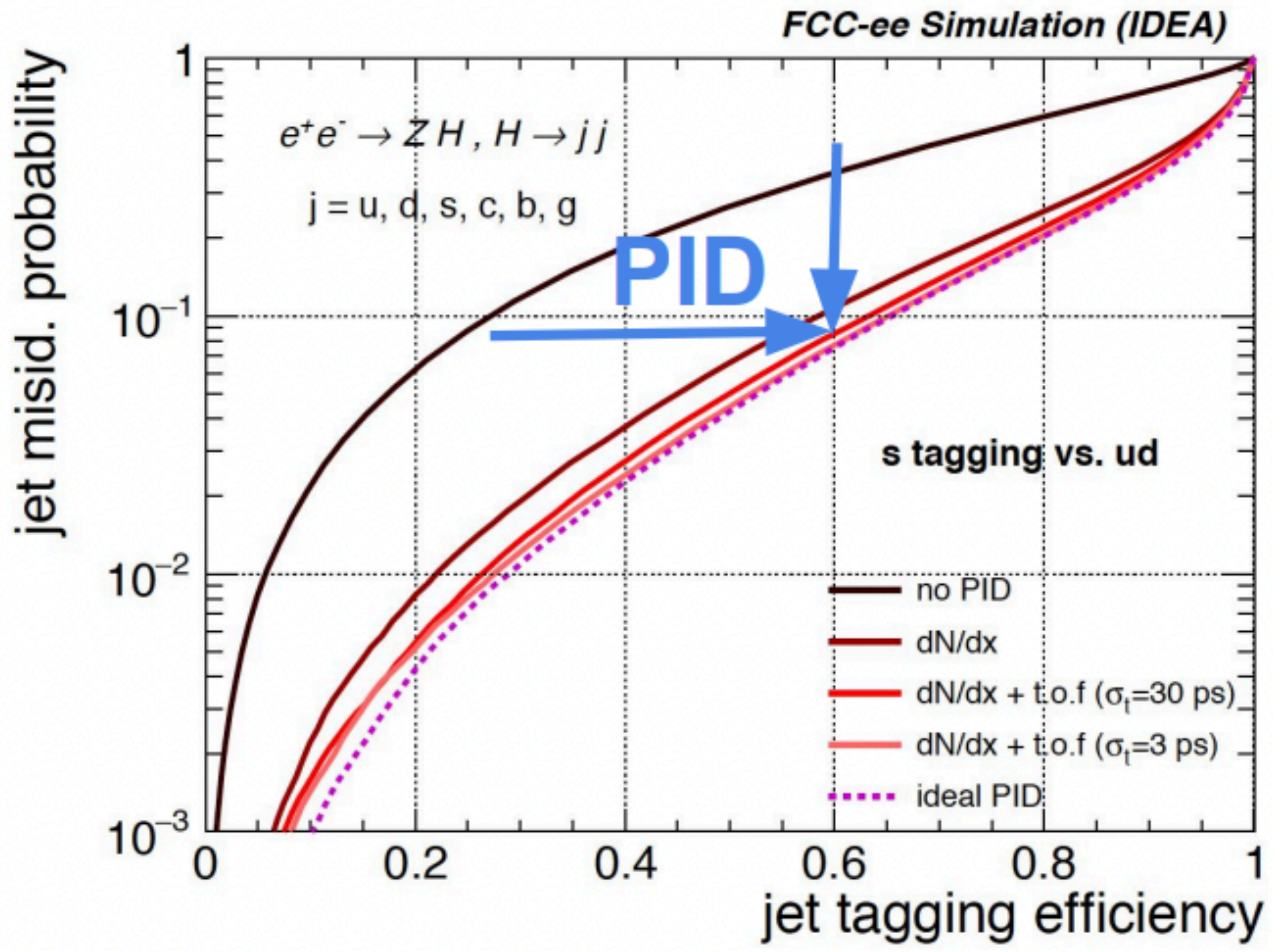
3-sigma separation for tracks with **p < 30GeV**

dN/dx=Cluster counting in the IDEA drift chamber

A NEW PLAYER: STRANGE TAGGING

- ➤ Strange tagging brings in other constraints as well:
  - ➤ 2.5x increase in tagging efficiency with PID
  - ➤ x10 reduction in light mistag rate
- ➤ Timing might help as well: studies in progress both on the physics needs and the technologies.





Detector constraints:

- Excellent PID:
  - Low momentum (p<5 GeV):
    - timing detectors
  - High momentum (p>5 GeV)
    - charged energy loss (gas/silicon)
    - cherenkov

BSM PHYSICS: RARE PROCESSES FIP

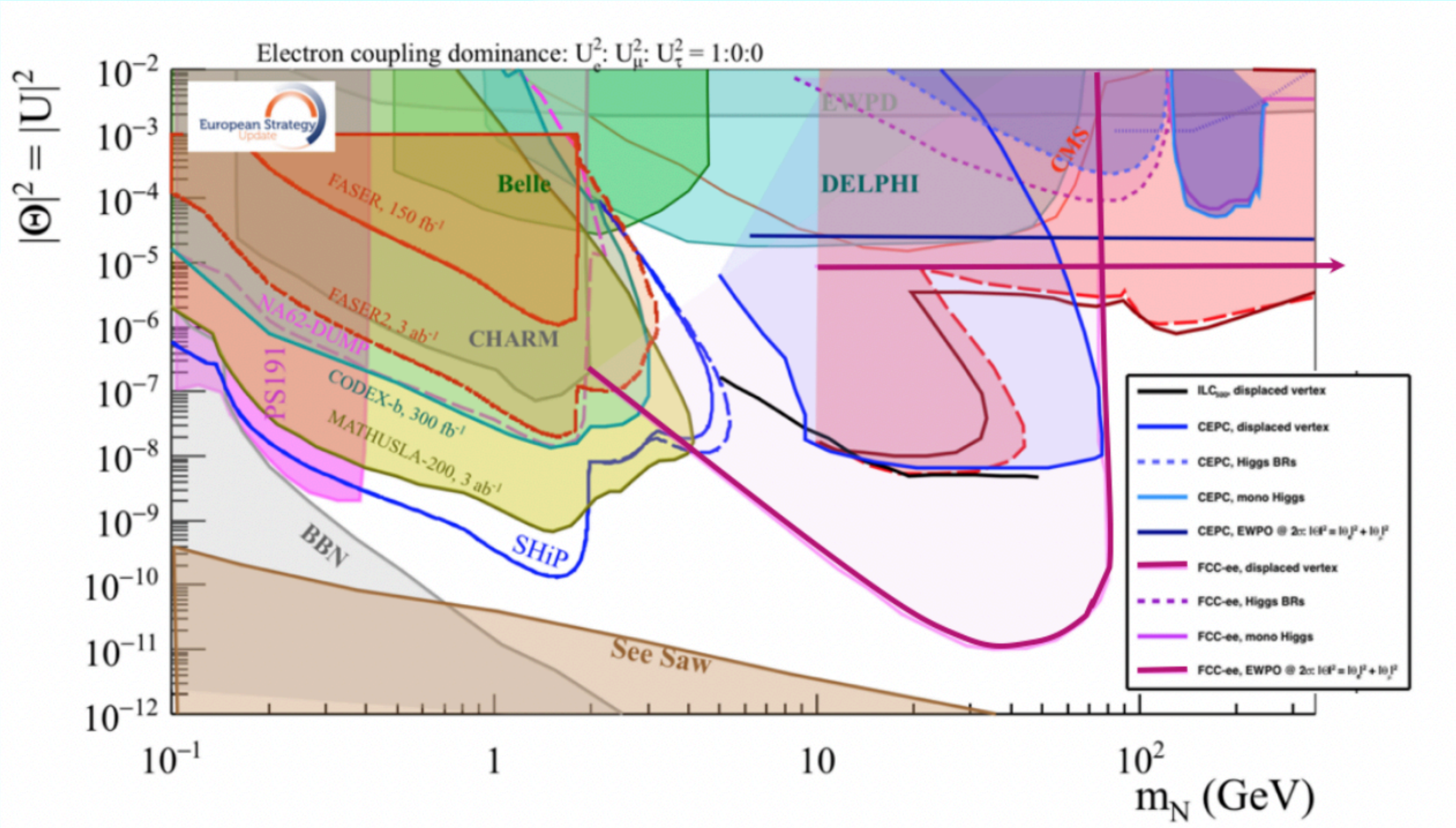
- ➤ Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m(Z)
- ➤ Signature: long lifetimes (LLP's)
  - ➤ Heavy Neutral Leptons
  - ➤ Axion-like particles
  - ➤ Dark photons

Detector Requirements

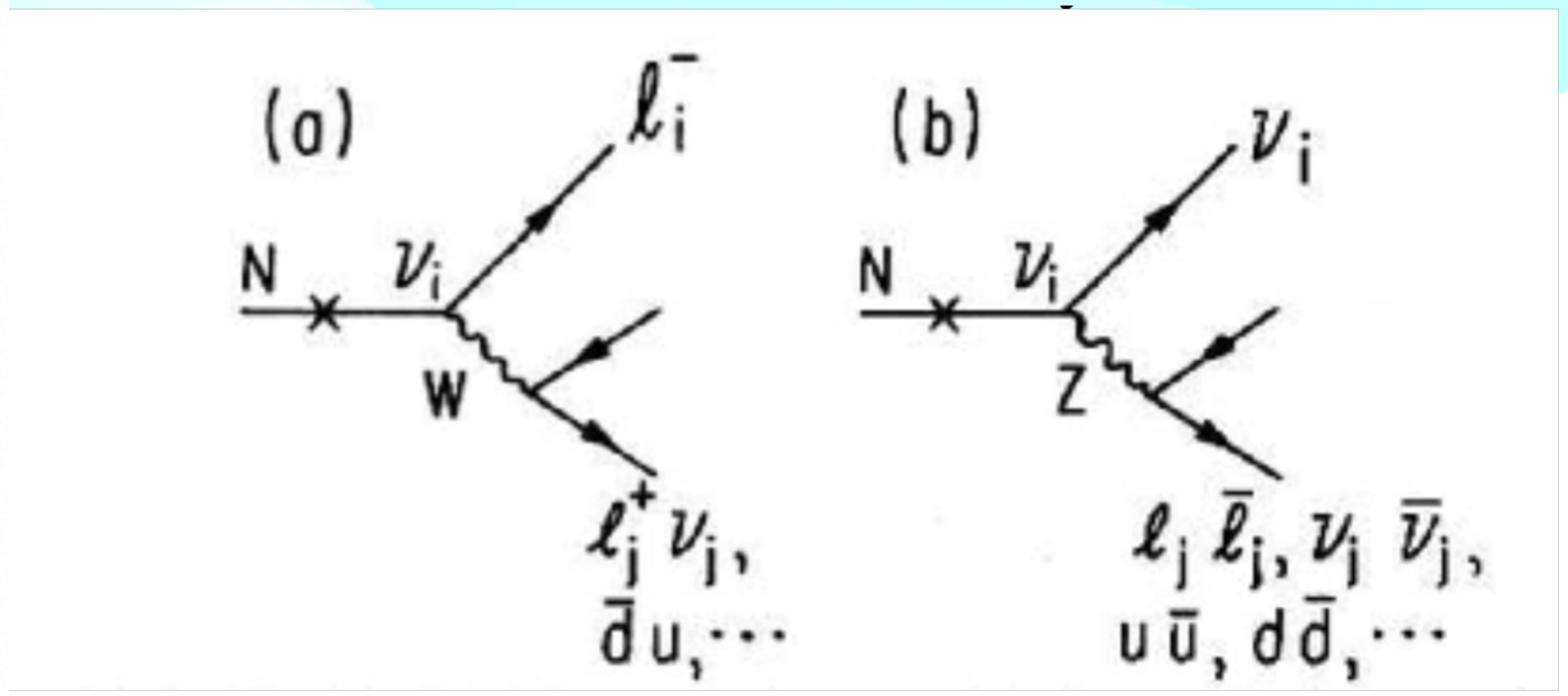
- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

BSM DIRECT SEARCHES - HEAVY NEUTRAL LEPTONS

- Test minimal type I seesaw hypotesis
- Together with ΔM also tests the compatibility with leptogenesis



From EPPSU BriefingBook 2019

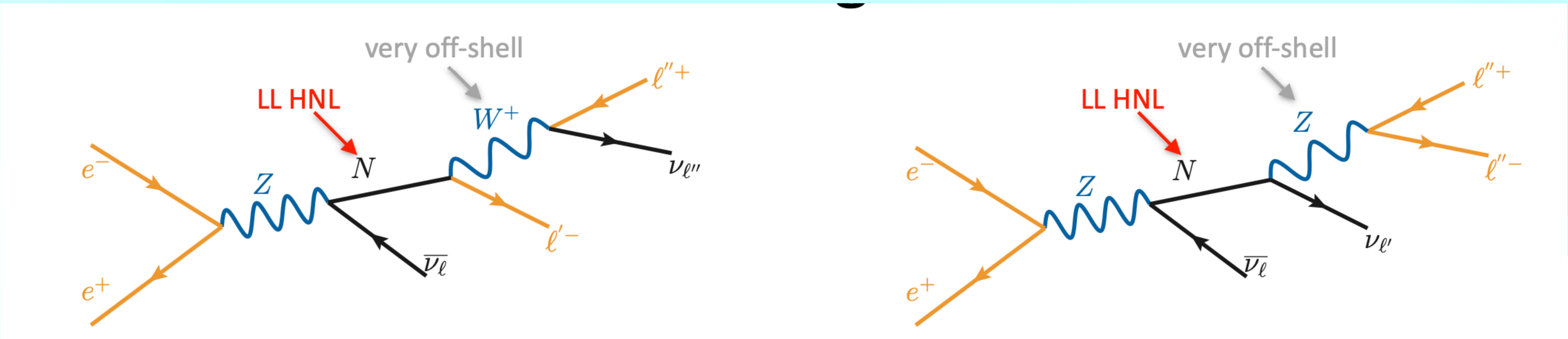


$$L \sim \frac{3\,[cm]}{|U|^2 . (m_N [GeV]\,)^6}$$

L~1m for mN=50GeV and |U|2=10^{-12}

HEAVY NEUTRAL LEPTONS "CASE STUDY"

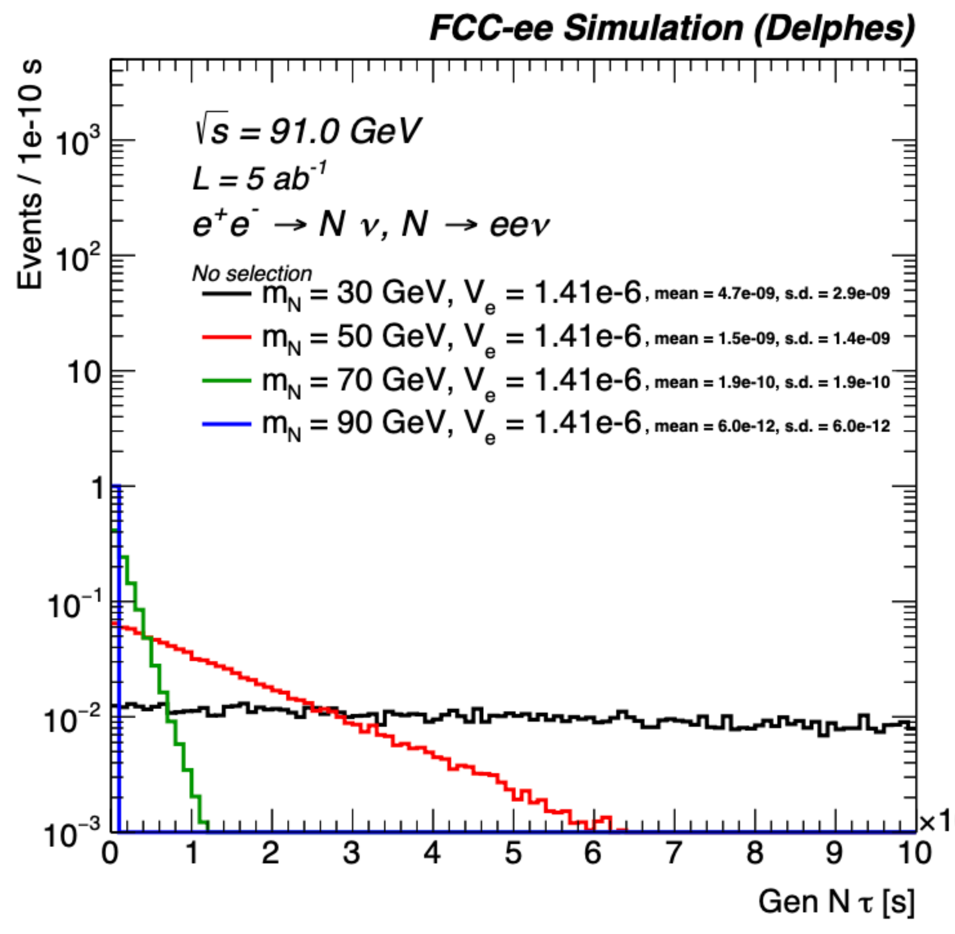
- HNL "case study" in progress
- Upgrading Delphes for LLP

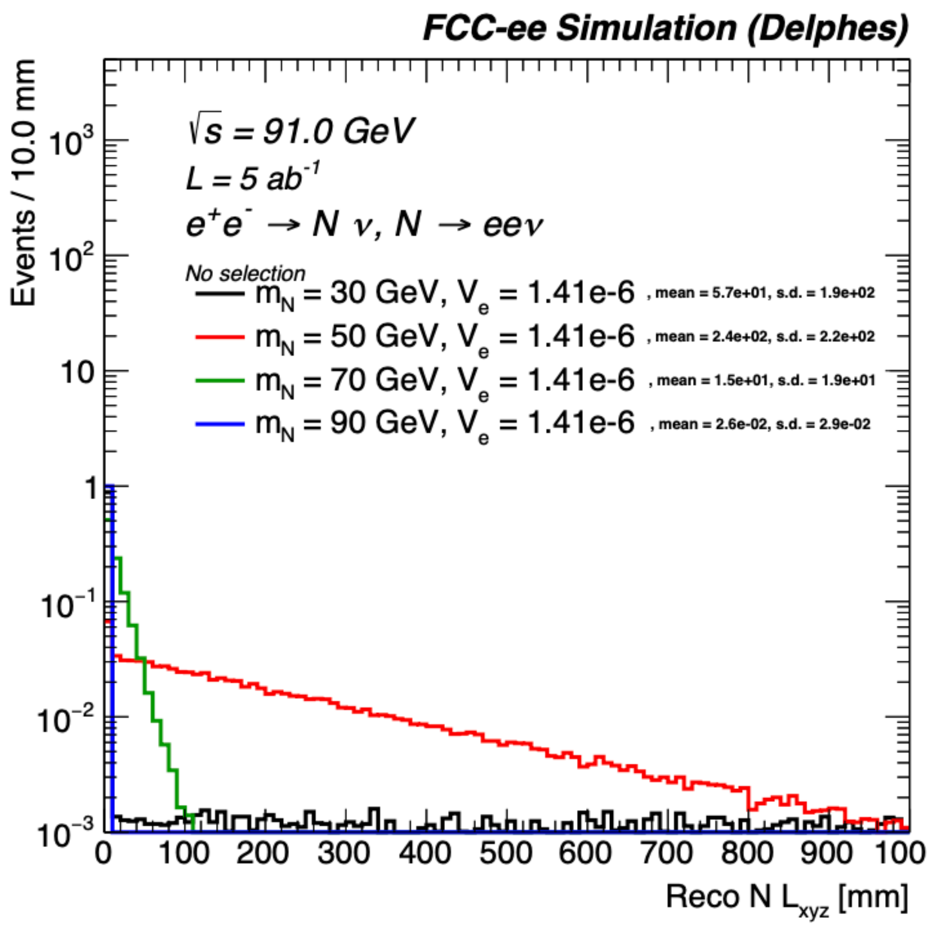


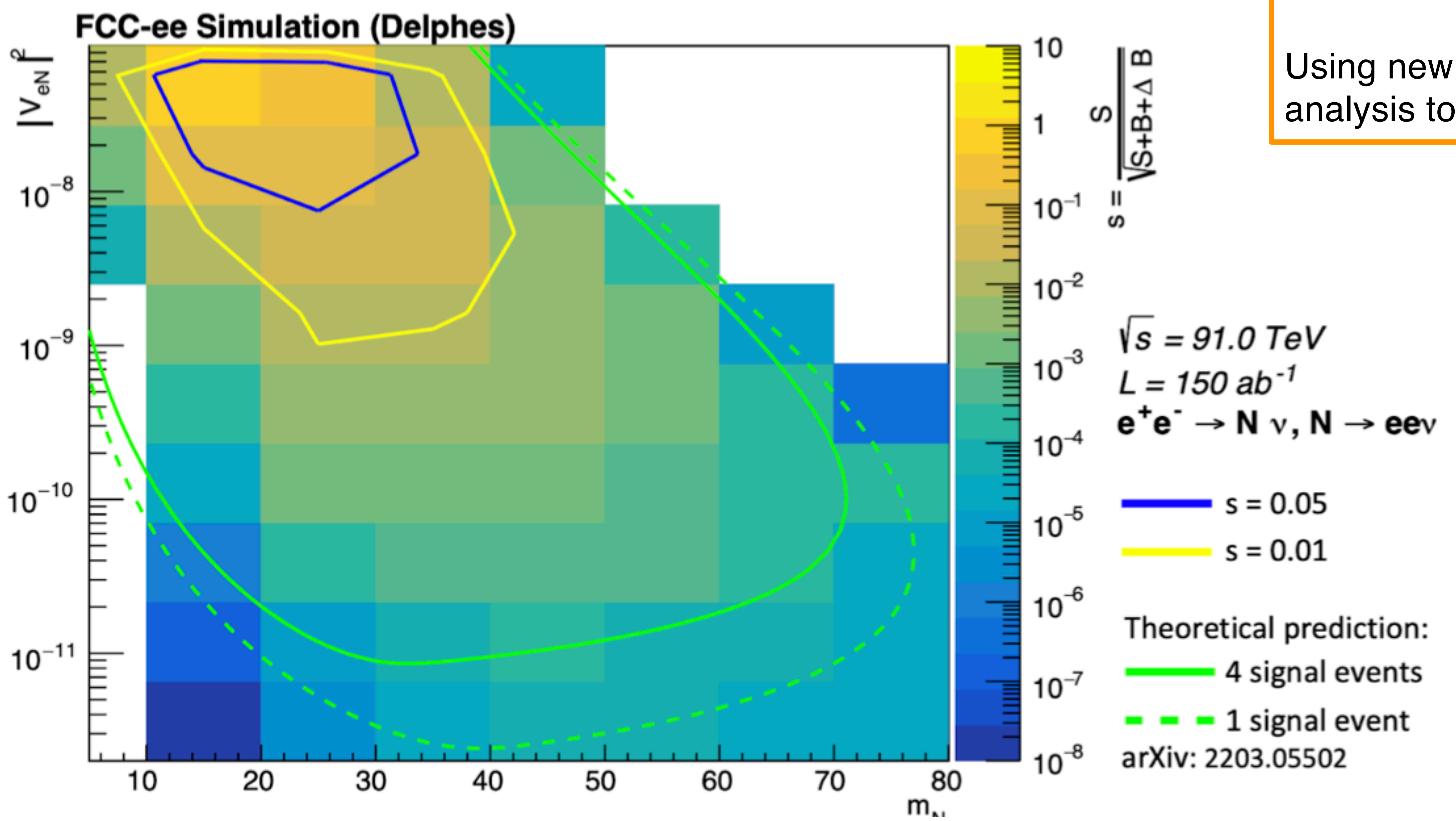
$$L \sim 0.025\text{m}\left(\frac{10^{-6}}{V_l}\right)^2\left(\frac{100\text{ GeV}}{m_N}\right)^5$$

[Valid when $m_N \lesssim 100$ GeV, arXiv:1905.11889]

Get long-lived HNLs when coupling and mass are small







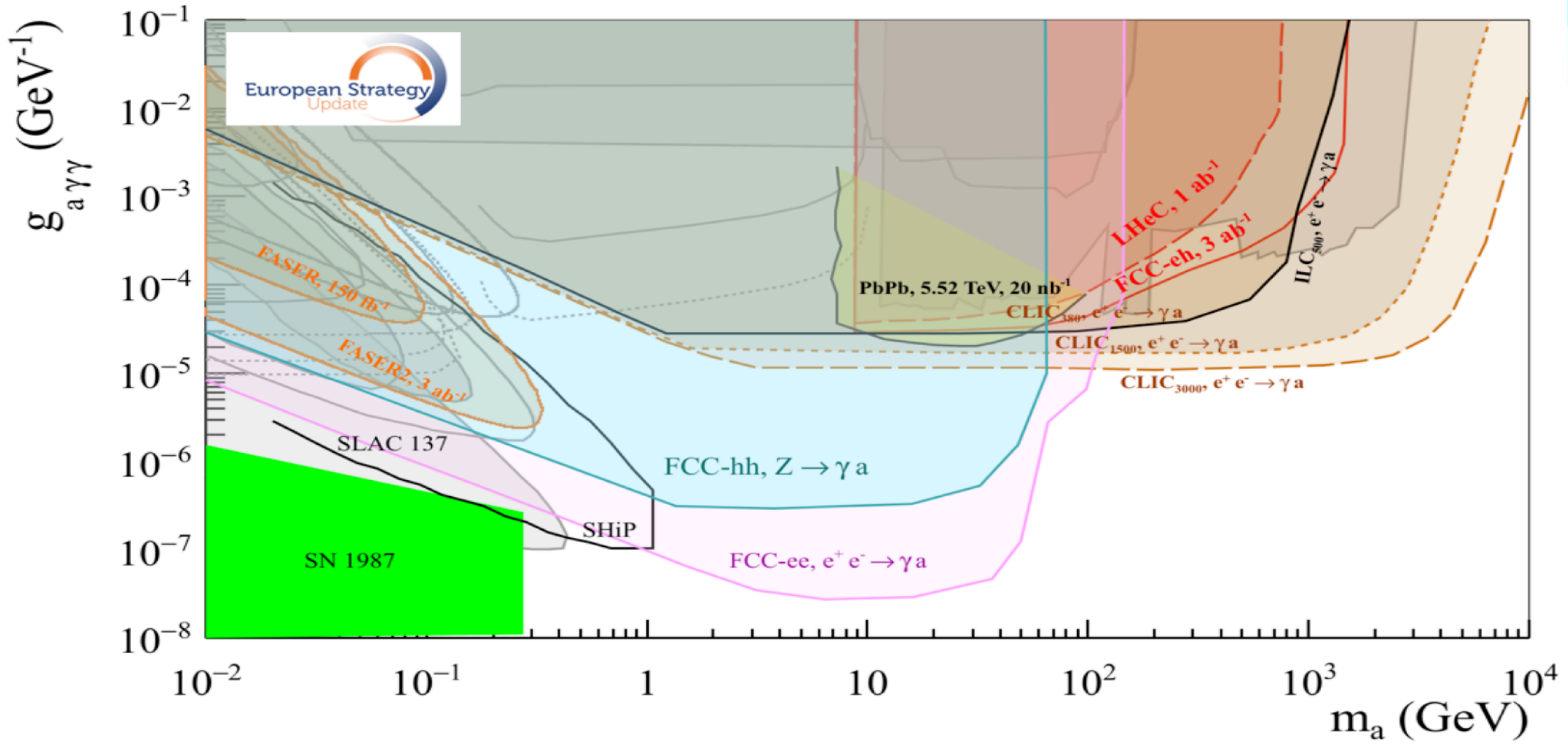
Preliminary

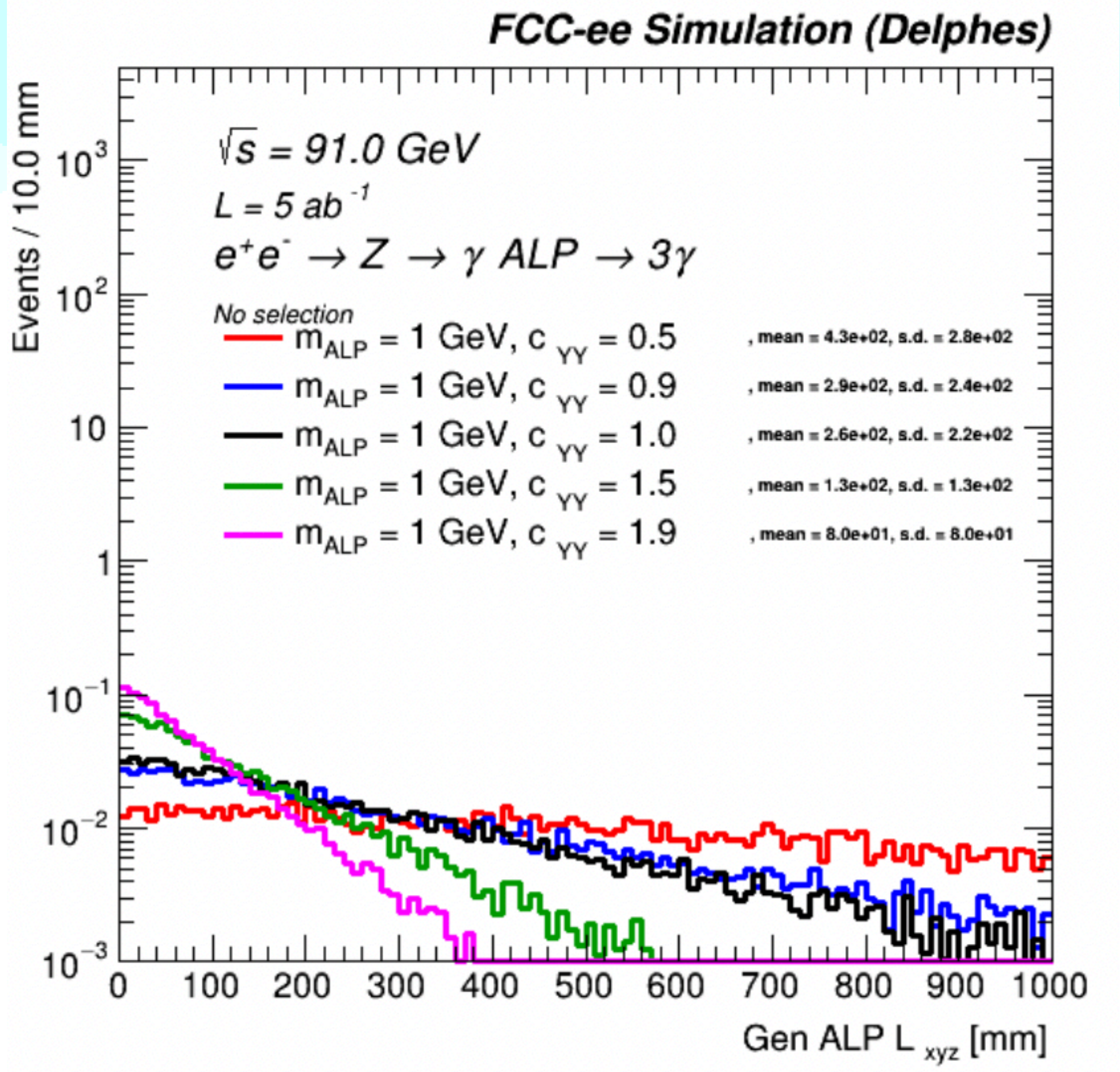
Using new software and analysis tools!

J. Alimena, L.Rygaard

BSM DIRECT SEARCHES - ALPS

- Similar situation for Axion-like-particles: luminosity is key to the game
- Complementarity with high energy lepton collider
- Fertile ground for development of innovative detector ideas: requirements on calorimeter (photon separation) and more…



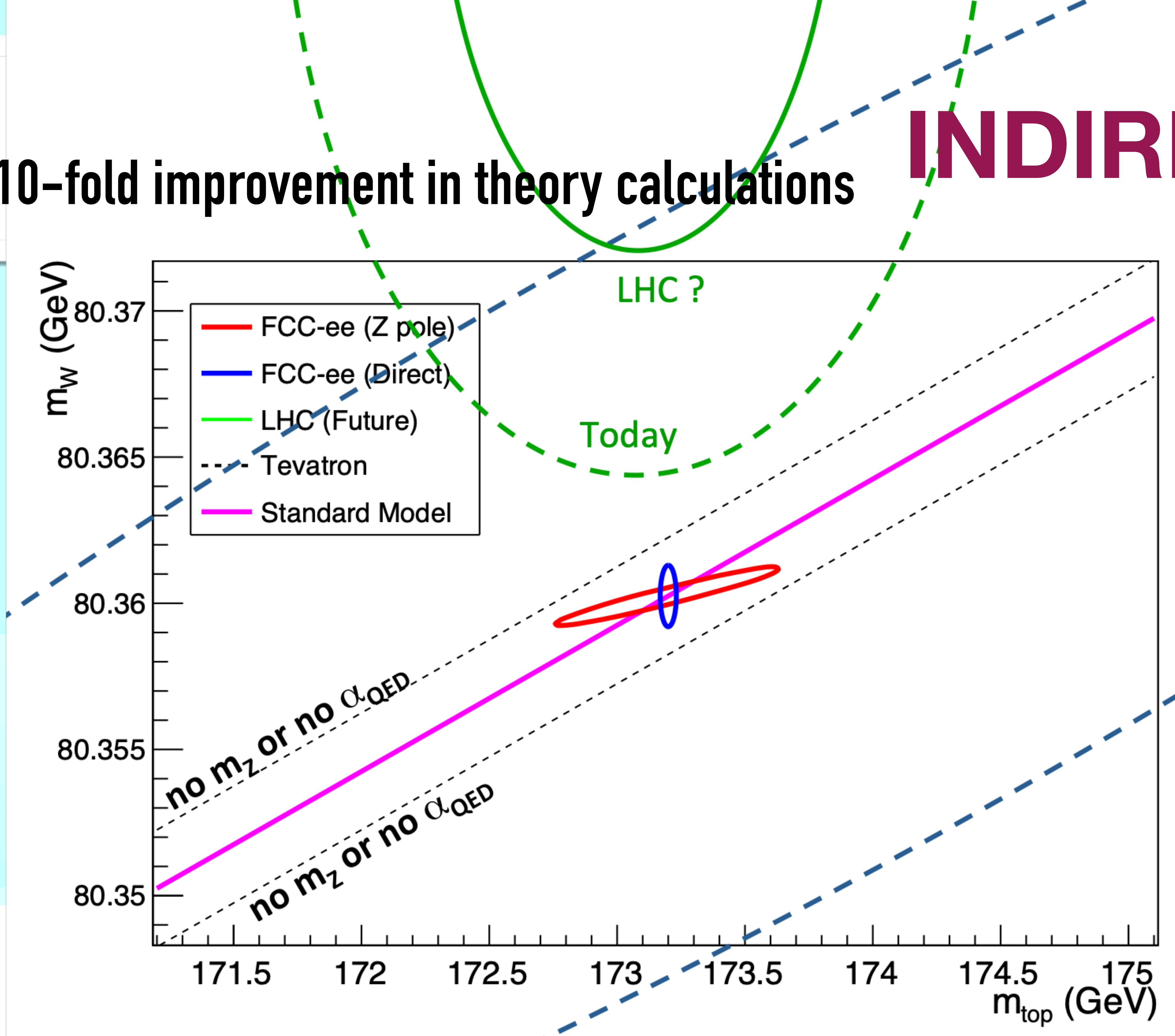


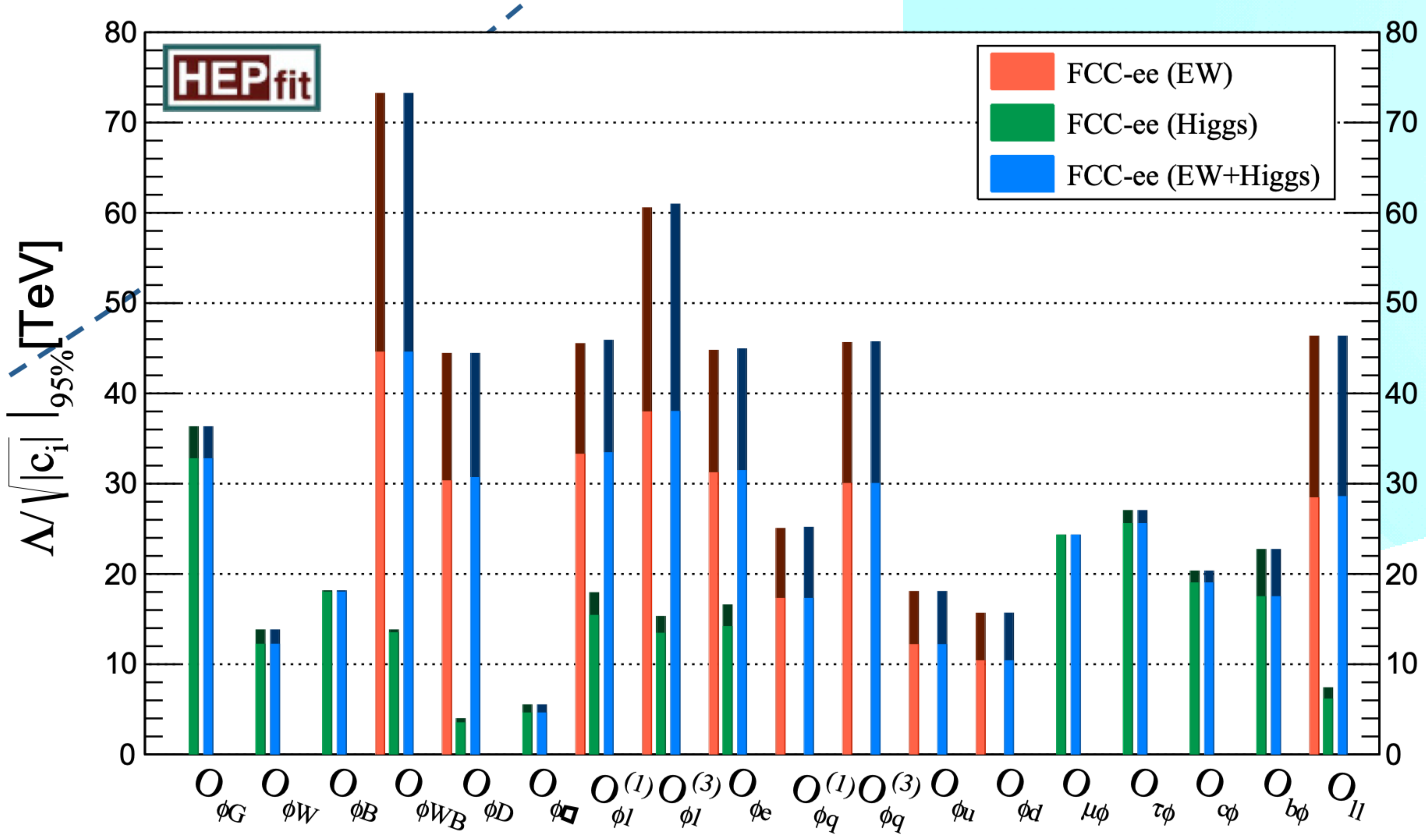
ALPS can be long lived too.

“case study” analysis starting…

INDIRECT NEW PHYSICS SENSITIVITIES

Requires 10-fold improvement in theory calculations





- ➤ Fit to new physics effects parameterized by dim 6 SMEFT operators
- ➤ single operator fit can be informative
- ➤ model independent result only for global fit

What do we mean by "Sensitivity to NP up the scale of N TeV?" e.g.

$$\frac{c}{\Lambda^2} \sim \frac{g_{\mathrm{NP}}^2}{M_{\mathrm{NP}}^2} < 0.01\ \mathrm{TeV}^{-2} \longrightarrow M_{\mathrm{NP}} > 10\, g_{\mathrm{NP}}\ \mathrm{TeV}$$

(**Weakly coupled NP** $M_{\mathrm{NP}} > 10\ \mathrm{TeV}\ \ (g_{\mathrm{NP}} \sim 1)$)

- ➤ ***Points to the physics to be studied with high energy colliders (FCC-hh, muon)***

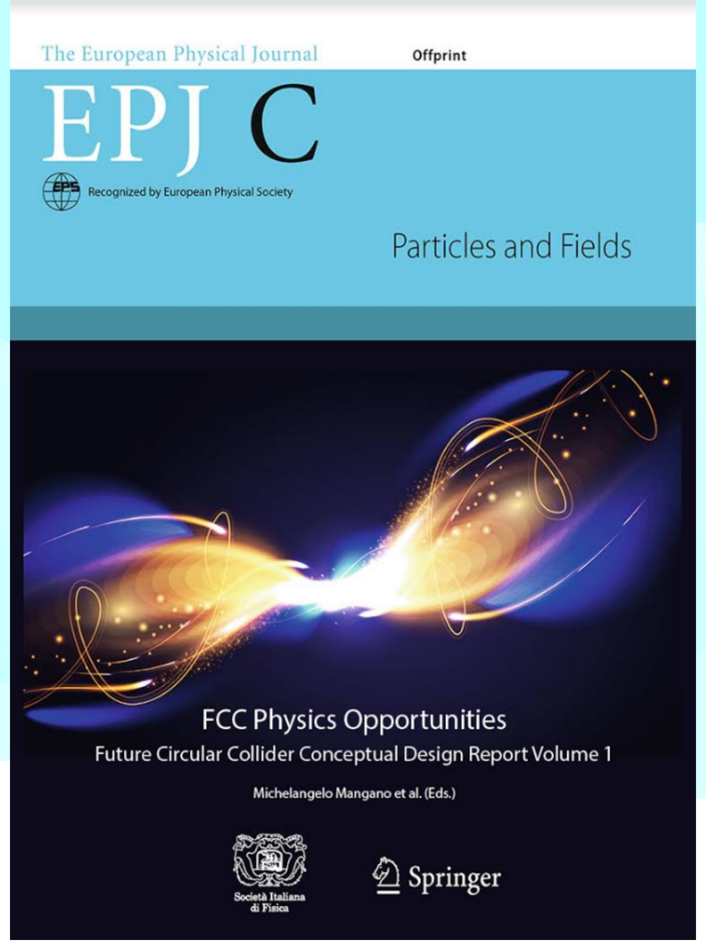
TAKE AWAY MESSAGE

- **A first round of analyses** to frame the impressive physics case of the FCC-ee has been summarized in the CDRs
- **New focus on « case studies » to determine the detector requirements** needed to achieve the desired precision and to inform the technology choices for detector concepts
  - Working in the new software framework (KEY4HEP), common to all future projects
  - Ongoing ECFA workshop focuses on commonality/complementarity of future e+e- projects
- **Mid-Term Report of the FCC Feasibility Study to appear at the end of 2023** with new & updated detector concept proposals to realise the needs of the physics programme

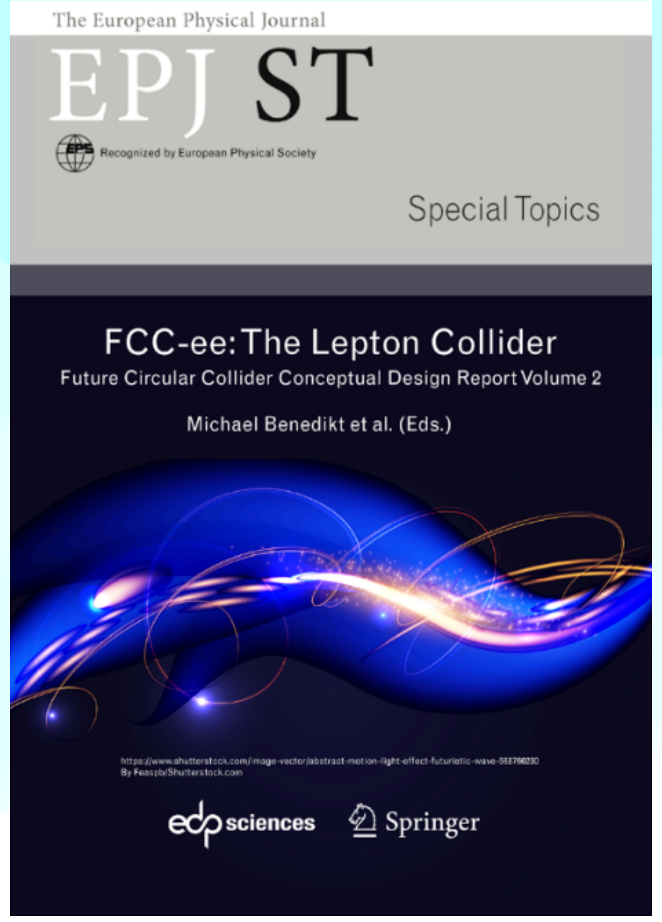
FCC integrated project is based on the goal of guaranteed physics deliverables. FCC-ee is a big player in the choice for next lepton collider and requires a significant R&D in all areas to fully exploit its enormous potential

FIND OUT MORE: SOME FCC DOCUMENTATION

4 CDR volumes published in EPJ


The European Physical Journal
Offprint
EPJ C
Recognized by European Physical Society
Particles and Fields
FCC Physics Opportunities
Future Circular Collider Conceptual Design Report Volume 1
Michelangelo Mangano et al. (Eds.)
Società Italiana di Fisica
Springer

FCC PhysicsOpportunities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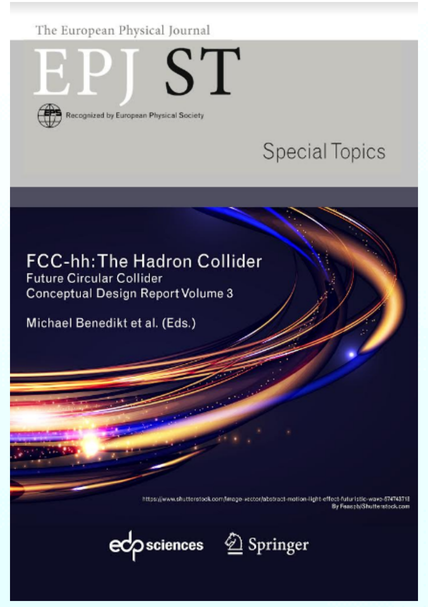
FCC-ee: The Lepton Collider
Future Circular Collider Conceptual Design Report Volume 2
Michael Benedikt et al. (Eds.)
edp sciences
Springer

FCC-ee: The Lepton Collider


The European Physical Journal
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Future Circular Collider
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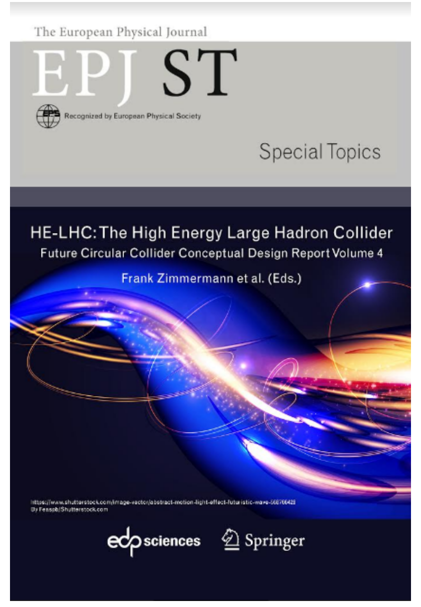
FCC-hh: The Hadron Collider


The European Physical Journal
EPJ ST
Special Topics
HE-LHC: The High Energy Large Hadron Collider
Future Circular Collider Conceptual Design Report Volume 4
Frank Zimmermann et al. (Eds.)
edp sciences
Springer

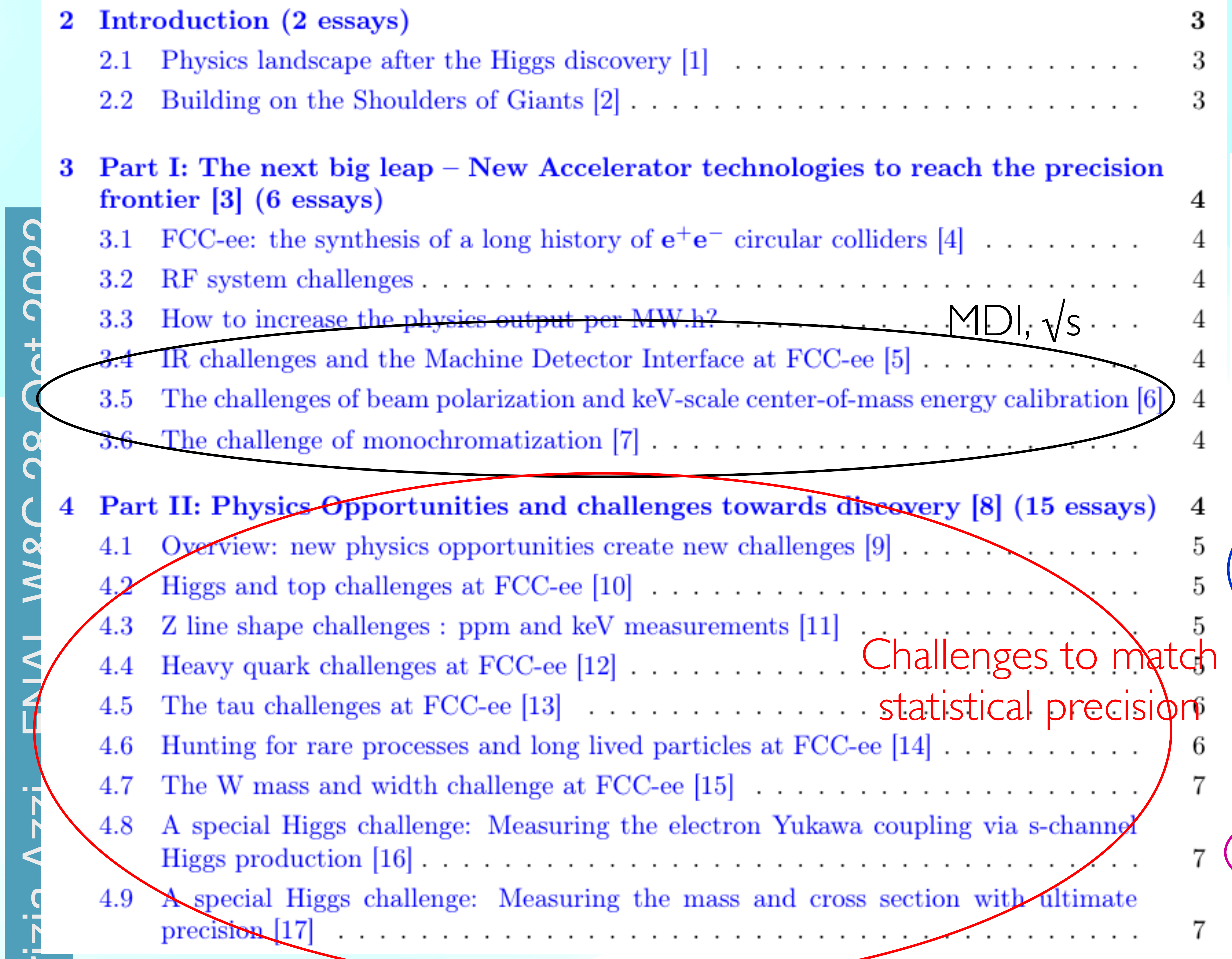
HE-LHC: The High Energy Large Hadron Collider

- Future Circular Collider - European Strategy Update Documents
  - (FCC-ee), (FCC-hh), (FCC-int)
- FCC-ee: Your Questions Answered
  - arXiv:1906.02693
- Circular and Linear e+e- Colliders: Another Story of Complementarity
  - arXiv:1912.11871
- Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders
  - arXiv:1901.02648
- Polarization and Centre-of-mass Energy Calibration at FCC-ee
  - arXiv:1909.12245

NEW OPPORTUNITIES CREATE NEW CHALLENGES

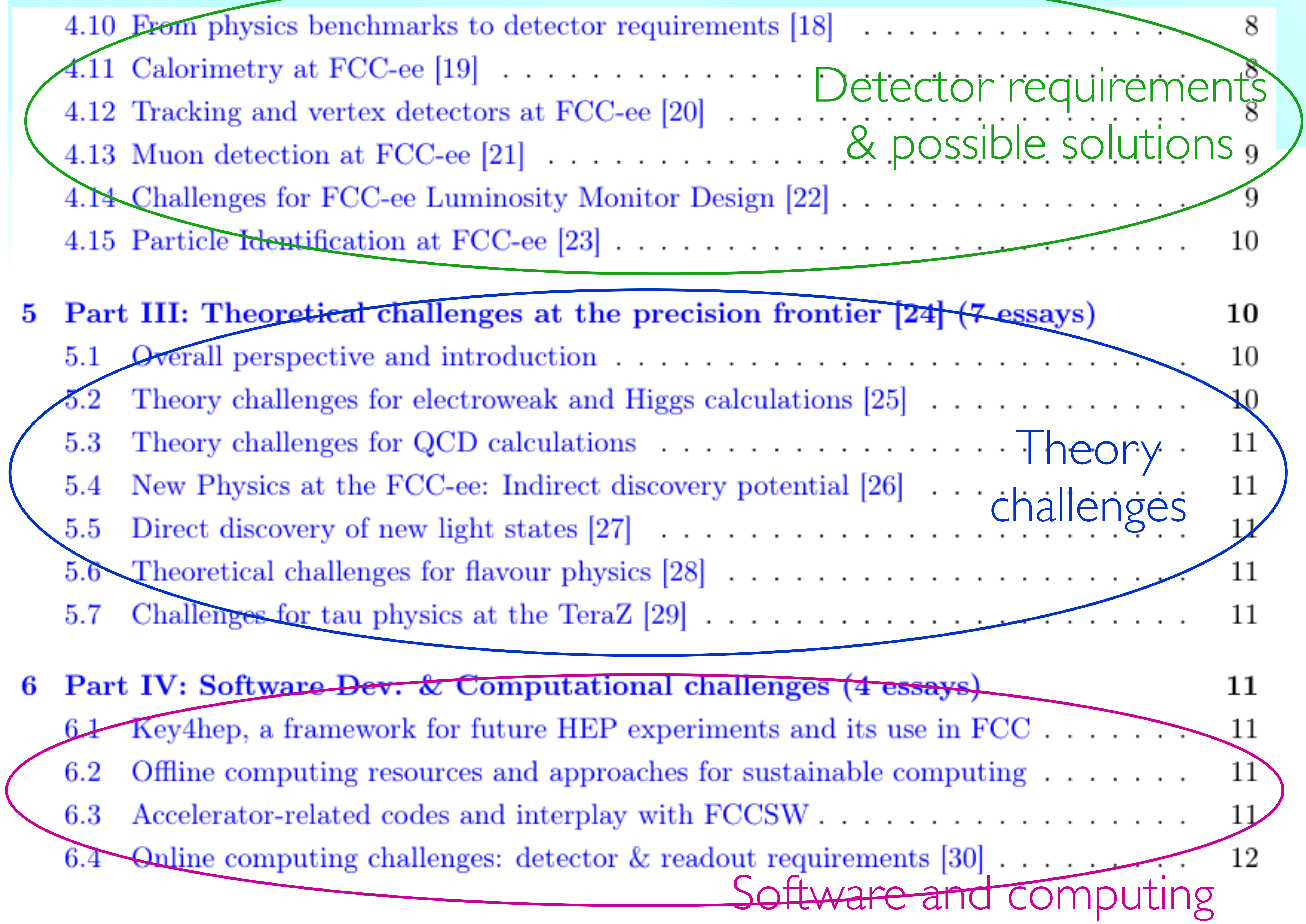
- EPJ+ special issue “A future Higgs and EW Factory: Challenges towards discovery”

All 34 references in this Overleaf document:
https://www.overleaf.com/read/xcssxqyhtrgt



MDI, $\sqrt{s}$

Challenges to match statistical precision



Detector requirements & possible solutions

Theory challenges

Software and computing challenges

BACKUP

FUTURE
CIRCULAR
COLLIDER

Timeline of the FCC integrated programme

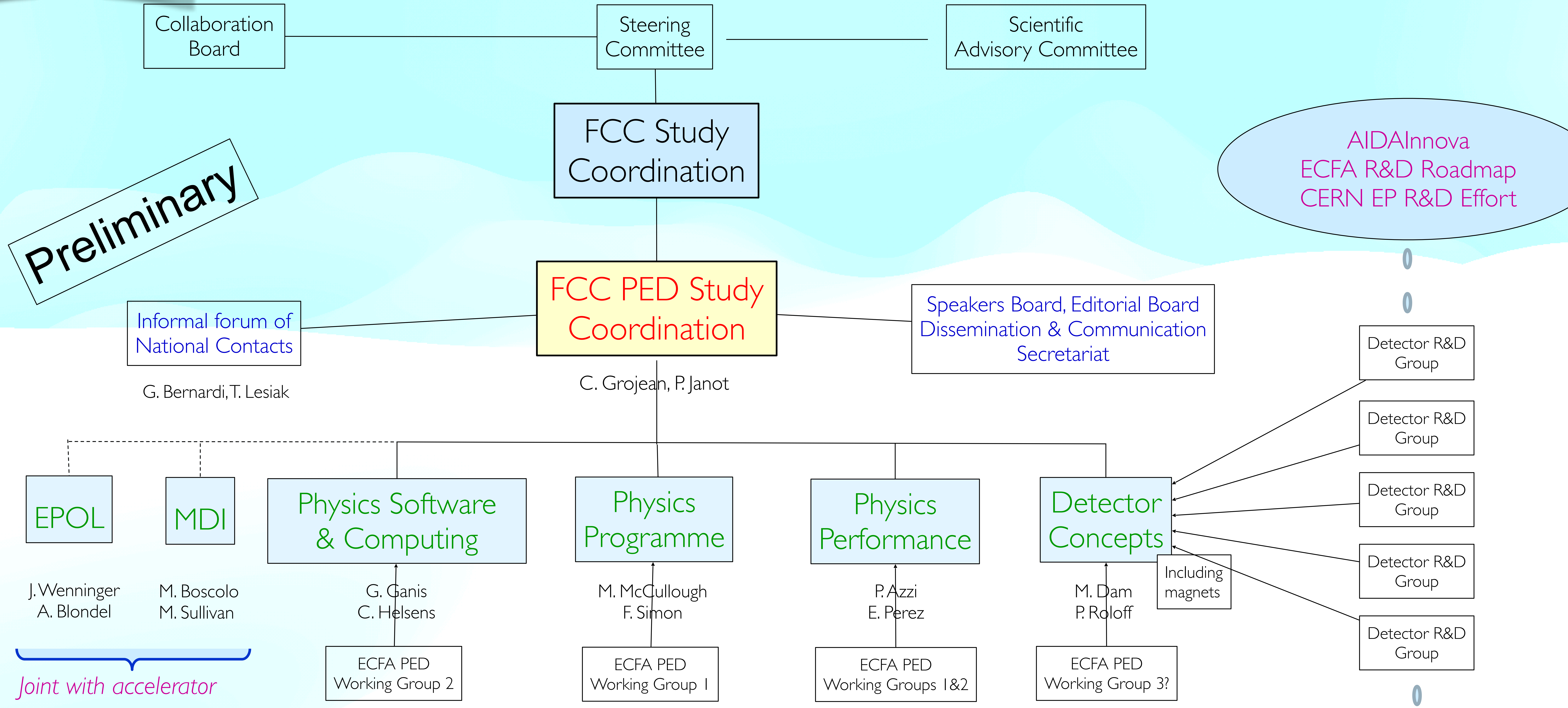
- ❑ Feasibility Study: 2021-2025
- ❑ If project approved before end of decade → construction can start beginning 2030s
- ❑ FCC-ee operation ~2045-2060
- ❑ FCC-hh operation 2070-2090++

F. Gianotti

➤ *The FCC is an ambitious project for the future of particle physics with concrete goals and deliverables to find the answers that we need from Nature.*

Patrizia

PED ORGANISATION TO TACKLE THE CHALLENGES OF THE FCC FEASIBILITY STUDY



Preliminary

Collaboration Board

Steering Committee

Scientific Advisory Committee

FCC Study Coordination

AIDAInnova
ECFA R&D Roadmap
CERN EP R&D Effort

FCC PED Study Coordination

C. Grojean, P. Janot

Informal forum of National Contacts

G. Bernardi, T. Lesiak

Speakers Board, Editorial Board
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EPOL

J. Wenninger
A. Blondel

MDI

M. Boscolo
M. Sullivan

Joint with accelerator

Physics Software & Computing

G. Ganis
C. Helsens

ECFA PED Working Group 2

Physics Programme

M. McCullough
F. Simon

ECFA PED Working Group 1

Physics Performance

P. Azzi
E. Perez

ECFA PED Working Groups 1&2

Detector Concepts

M. Dam
P. Roloff

Including magnets

ECFA PED Working Group 3?

Detector R&D Group

Detector R&D Group

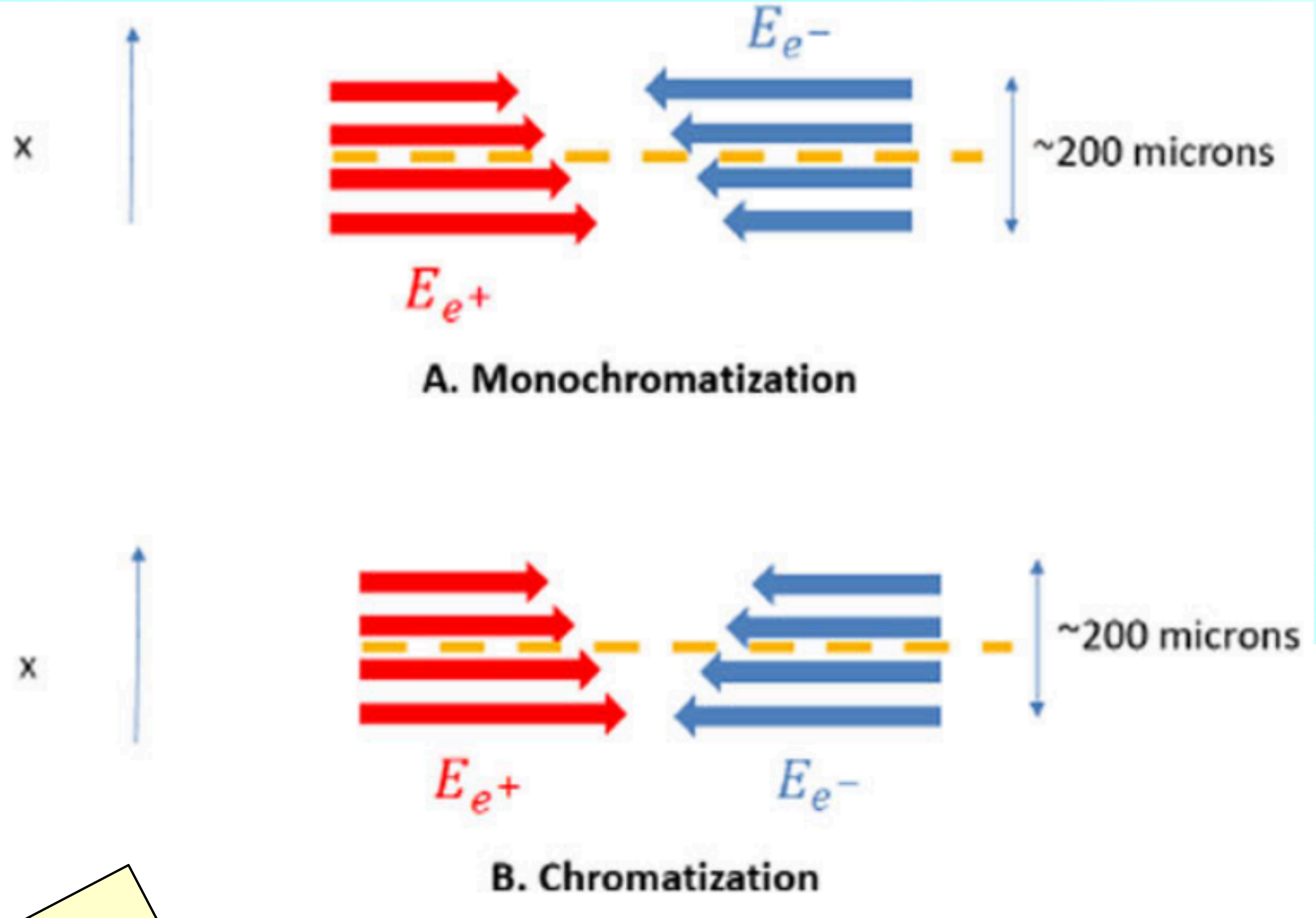
Detector R&D Group

Detector R&D Group

Detector R&D Group

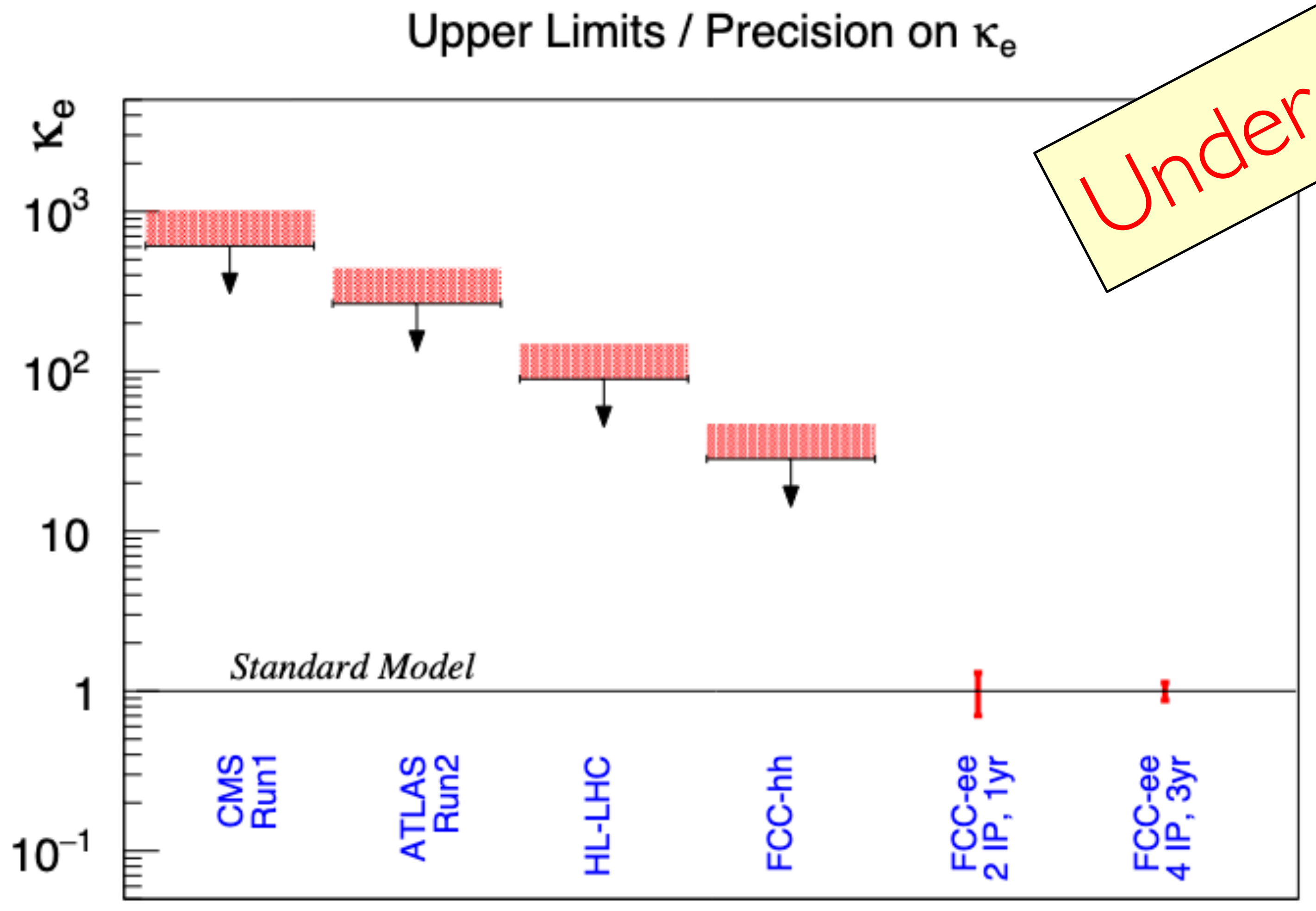
ELECTRON YUKAWA COUPLING

- Something unique: electron Yukawa coupling from $e^+e^- \to H$
  - One of the toughest challenges, which requires:
    - Higgs boson mass prior knowledge to a couple MeV
    - Huge luminosity (i.e., several years with possibly 4 IPs)
    - (Mono)chromatisation: Γ_H (4.2 MeV) ≪ $\delta_{\sqrt{s}}$ (100 MeV)
    - Continuous monitoring and adjustment of $\sqrt{s}$
    - Different e^+ and e^- energies (to avoid integer spin tune)
    - Extremely sensitive event selection against SM backgrounds
      - For all Higgs decay channels

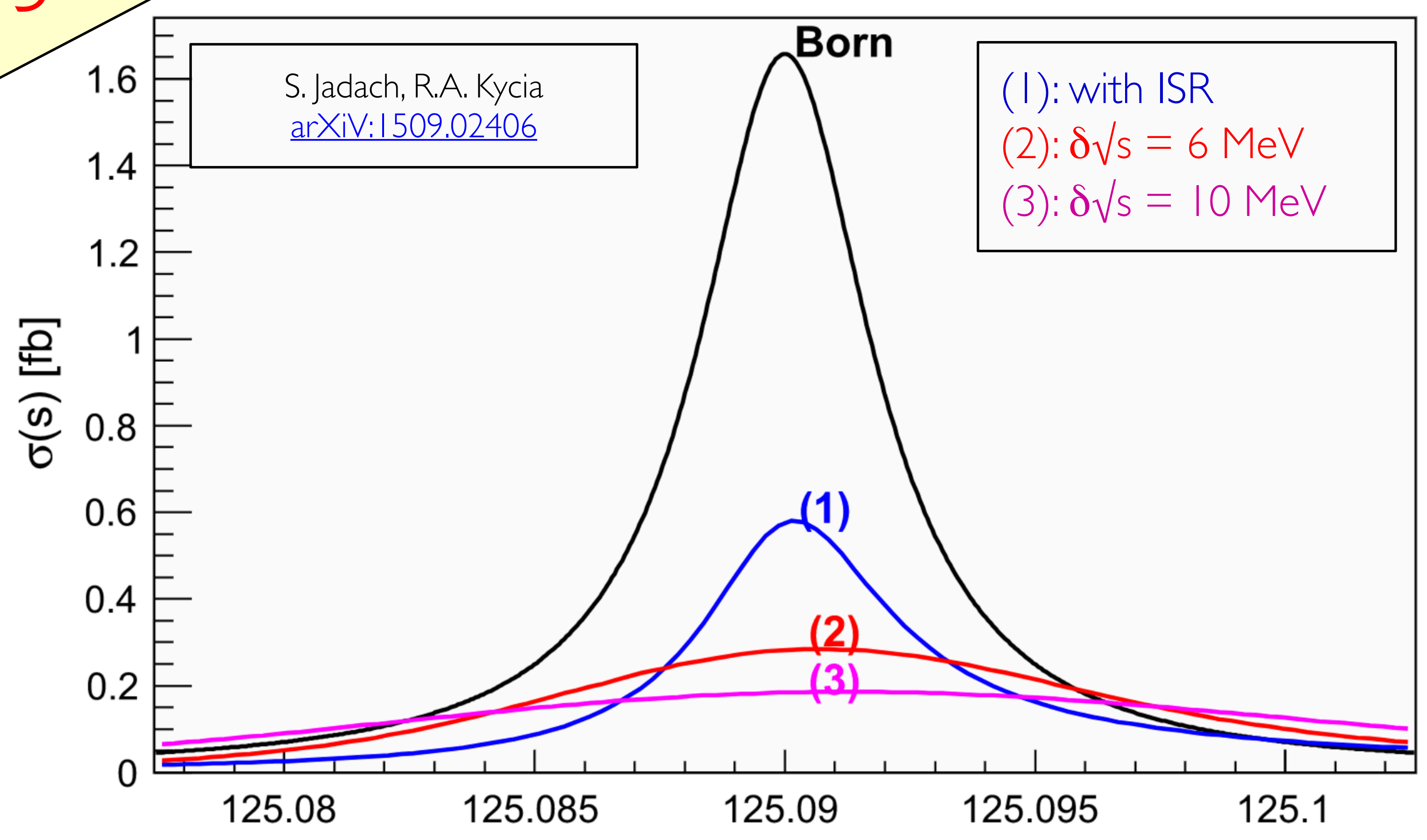


Uncertainty at the SM level
(IFF everything works nominally)

Indicates whether the Higgs boson (also) gives mass to ordinary matter.



Under Study



Benchmark on electron reco

- Precision measurements of Z couplings: R_l, R_b e R_c

$$1 / R_l = \Gamma_l / \Gamma_{had},$$
$$R_{b,c} = \Gamma_{b,c} / \Gamma_{had}$$

- Dominant systematics in R_l from:
  - Identification efficiencies with a few times the LEP statistics (ILC 250)
  - Determination of the acceptance (FCC)

- Example: R_l @ FCC, goal for $\Delta R_l/R_l = 1\text{-}5\text{x}10^{-5}$. The edge of the tracking (and calorimetric) fiducial acceptance should be known to O(10 μm).
  - Forward detector must be carefully designed
  - Will need «asymmetric» selection as done for the luminosity measurement

- Possible impact on design: Innermost radius of ECAL needs to be very precisely known: for instance consider different geometries, simpler to monitor such has two halves instead of petals

COMPARISON OF TRACKER MATERIAL