Physics case for a $t\bar{t}$ threshold scan at FCC-ee

+ comparison between circular and linear colliders performance

2025 IFIC-DESY-CERN top mass workshop, Valencia

results from JHEP 11 (2025) 020

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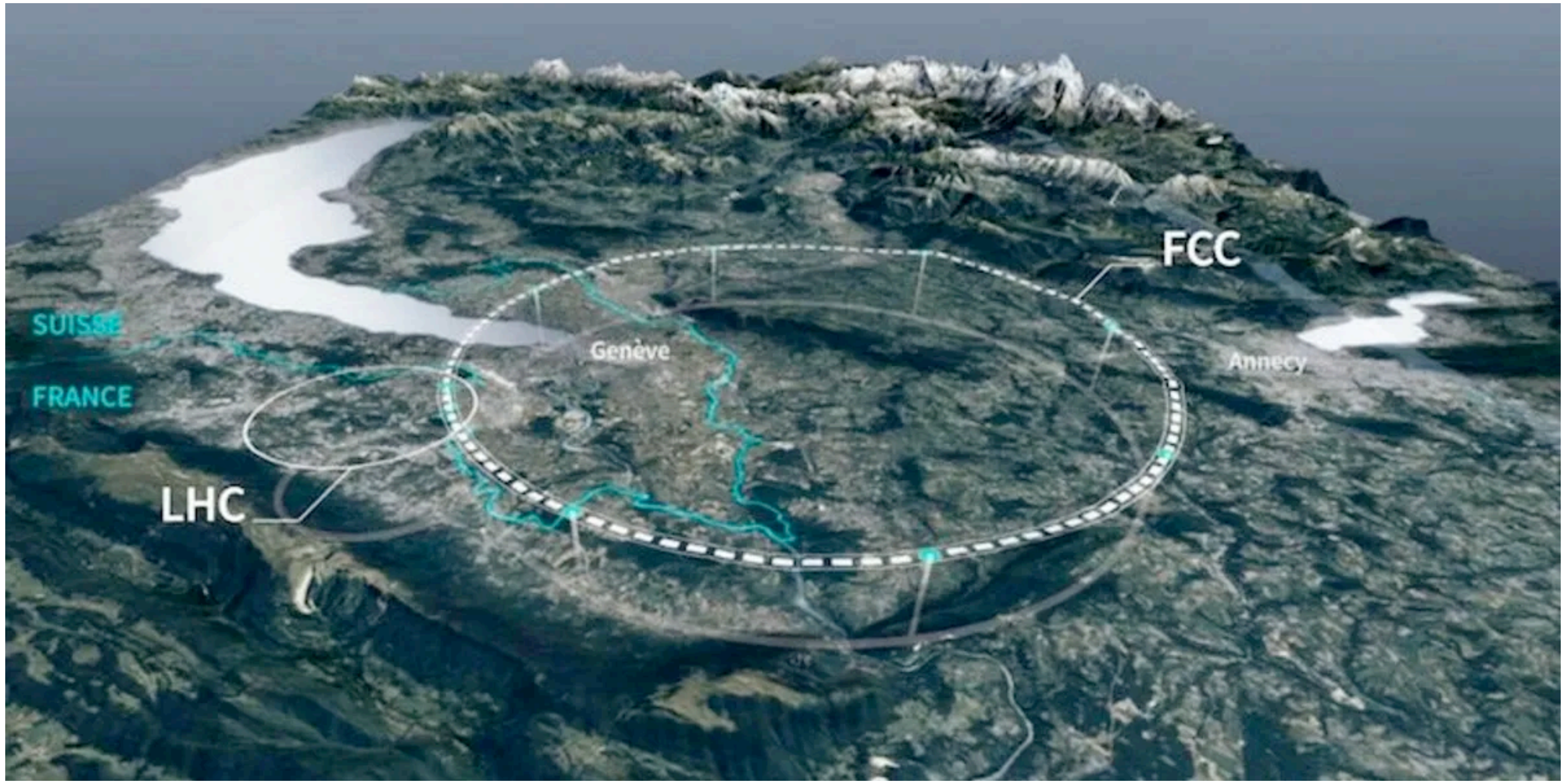
European Strategy update: 2020->2026

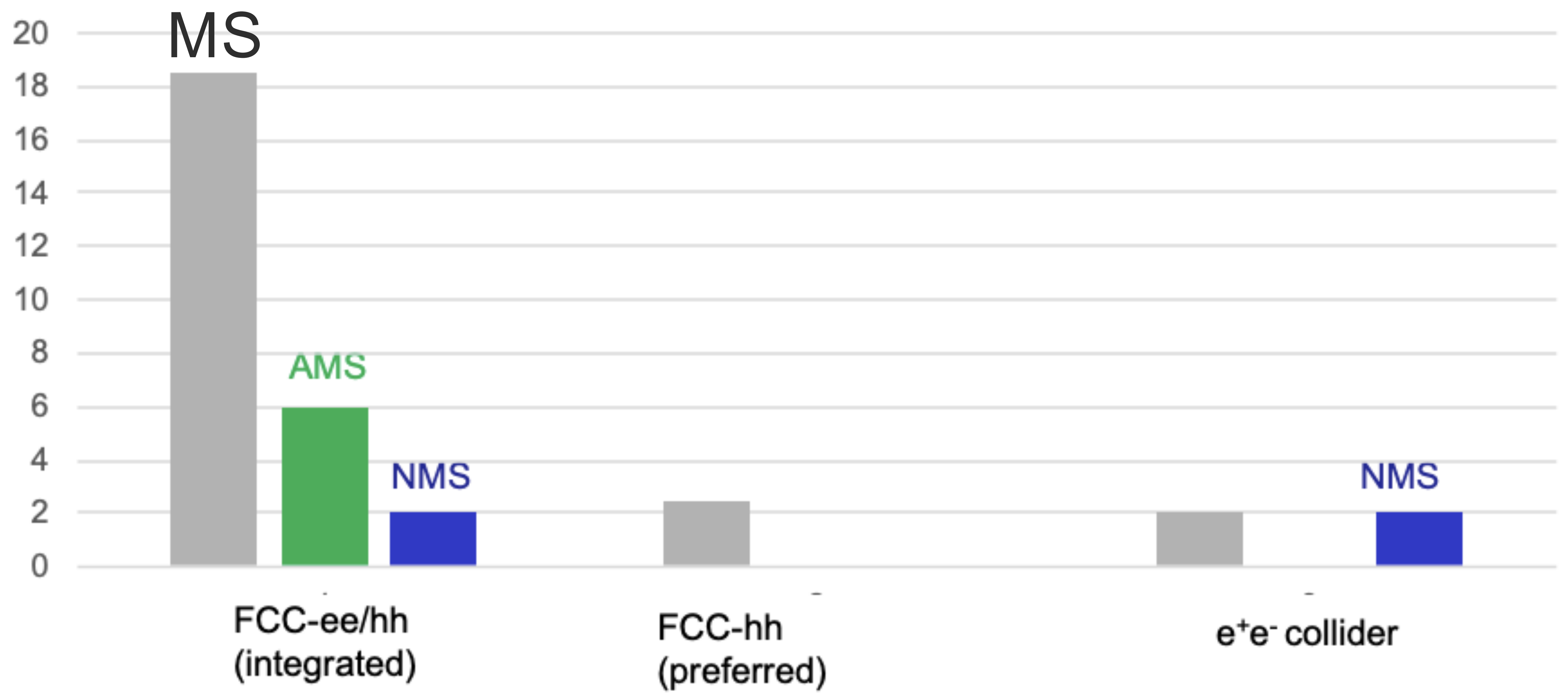
2020 Update of the European Strategy for Particle Physics

"**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**."

- **2021-2025: FCC feasibility study**
  - Various technical / legal aspects
  - Consolidation of physics case and detector concepts
- **2026: European Strategy Update**
  - Including comparison between different proposed colliders



National input to European strategy



Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	**14,020**
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	**15,320**

FCC-ee/hh (integrated)	MS: Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Israel, Italy, Norway, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden, Switzerland, (United Kingdom) AMS: Brazil, Croatia, Lithuania, Pakistan, Slovenia, Ukraine NMS: Canada, USA
FCC-hh preferred (but accept ee first)	Czech Republic, Serbia, (United Kingdom)
e^+e^- collider	MS: Austria, Bulgaria NMS: Australia, Japan

Aiming for CERN Council approval in 2028

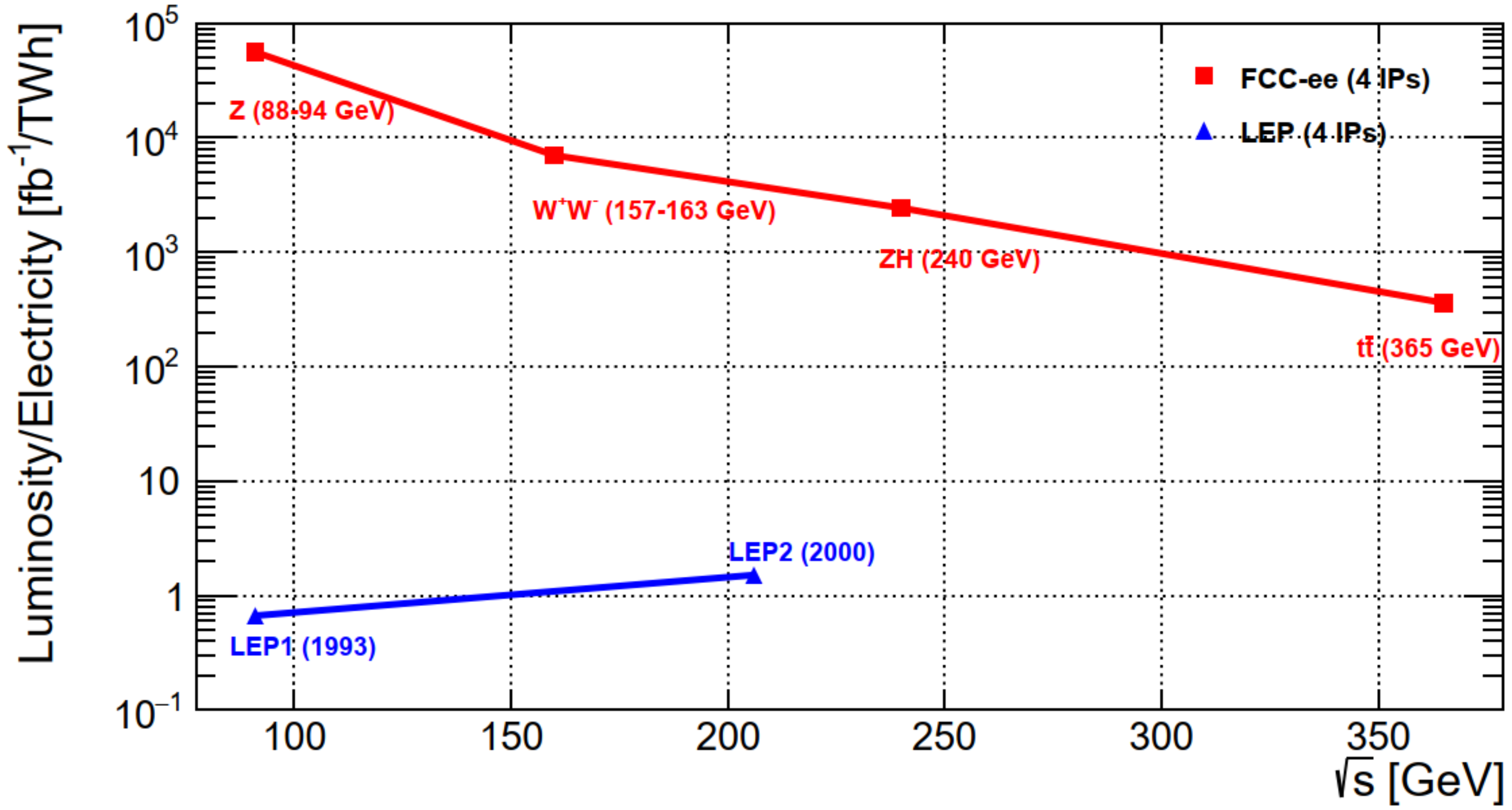
Growing support within the international community (US, Canada, ...)

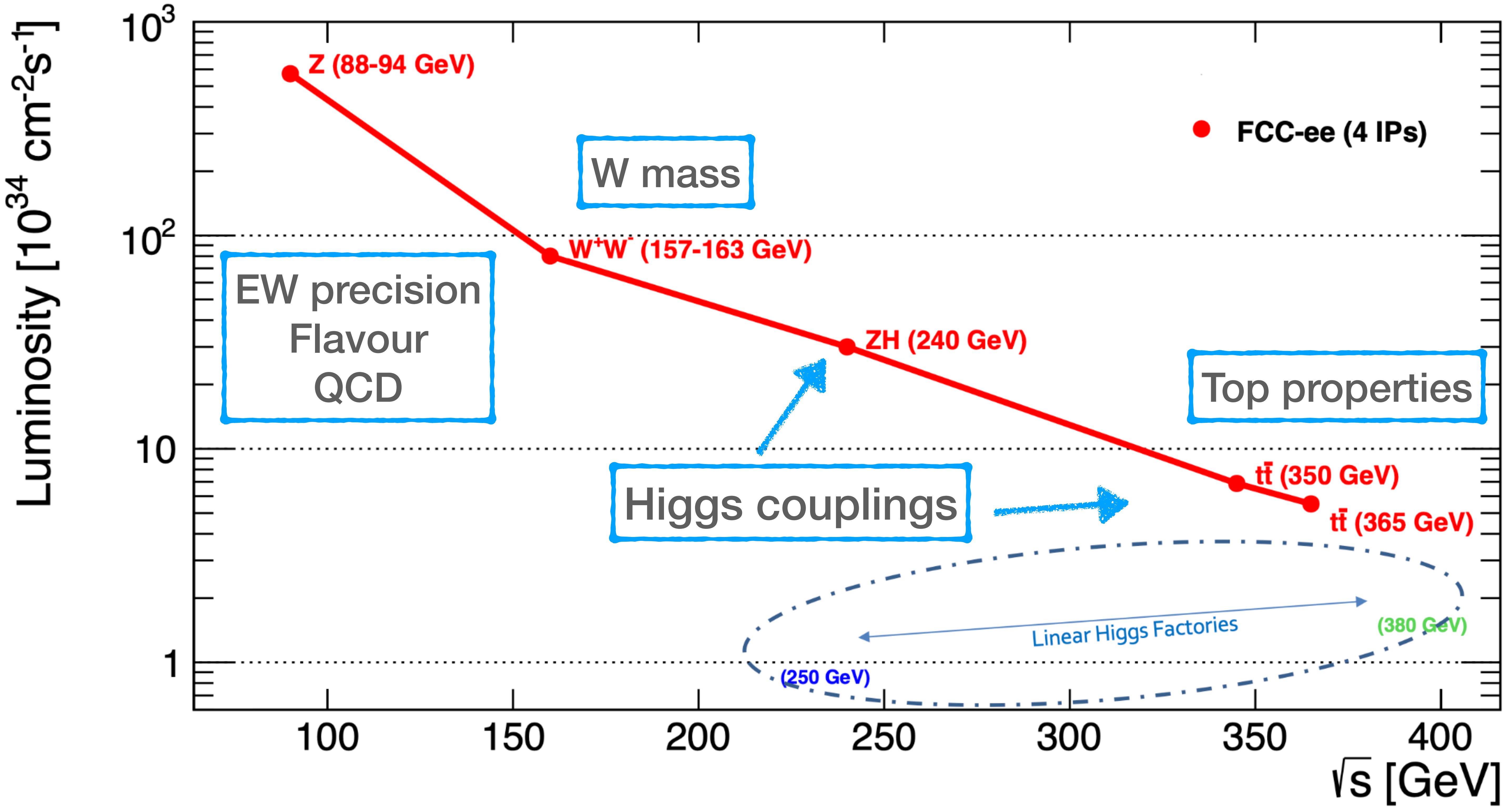
Up to 20% of FCC cost can be financed via EU Multiannual Financial Framework 2028-2034 (moonshot projects)

FCC-ee: an EW/Higgs/top factory

- **Flavour factory** at Z pole
- WW threshold -> W mass
- ZH: **(sub)percent-level** precision on **Higgs couplings** in only a few years of operation
- tt threshold: **top properties** + improved Higgs coupling

Entire LEP program at Z pole can be repeated every 30 seconds at FCC-ee





Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH + 65k WW → H	2×10^{6} $t\bar{t}$ + 370k ZH + 92k WW → H	

Matteo Defranchis (CERN)

Requirements for a threshold scans

- Mass and width of Z and W boson can be accessed via scan in centre-of mass energy at Z pole and WW threshold

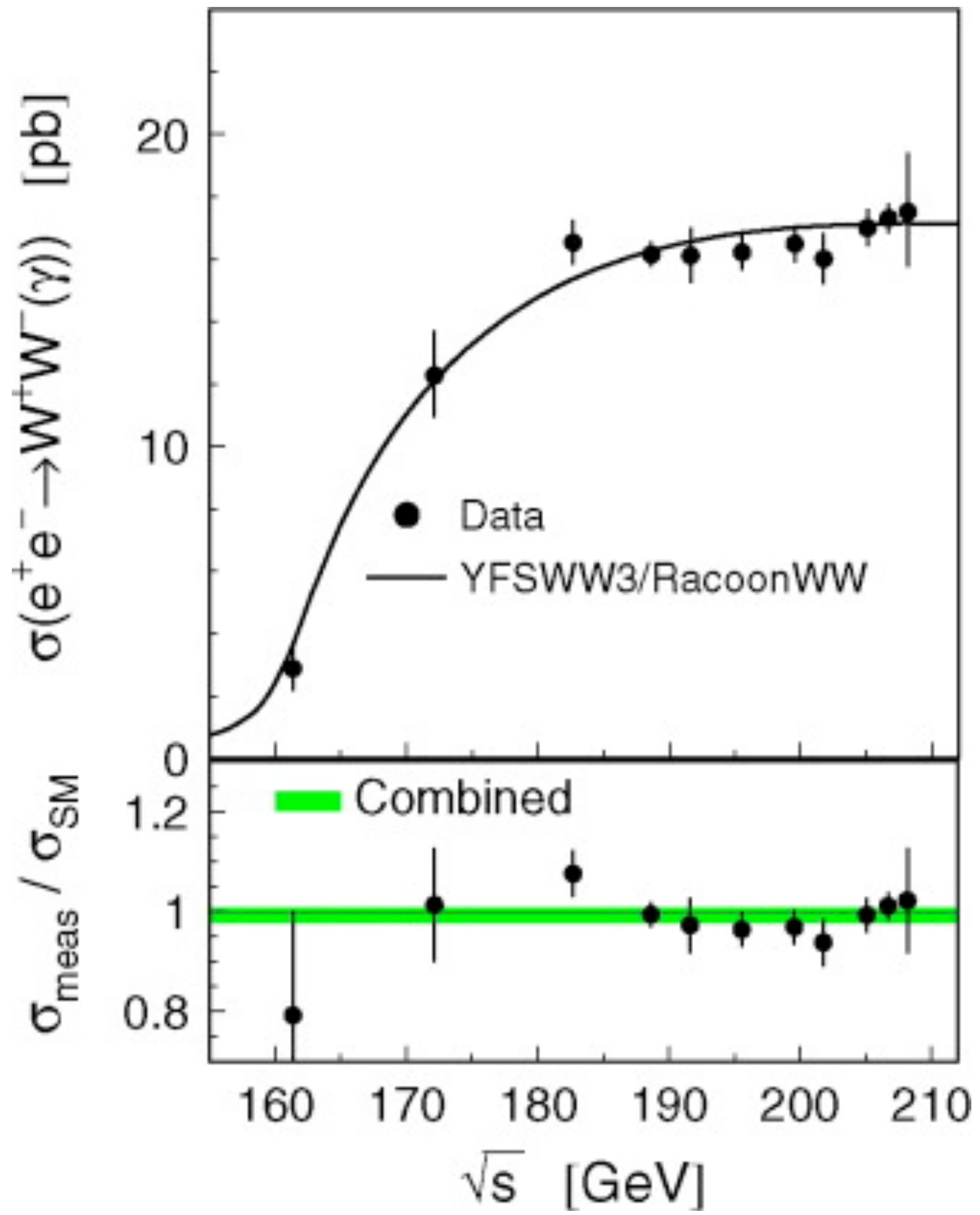
- Measure total production cross section as a function of √s

- Compare to standalone theory prediction to extract physical parameters (mass, total width…)

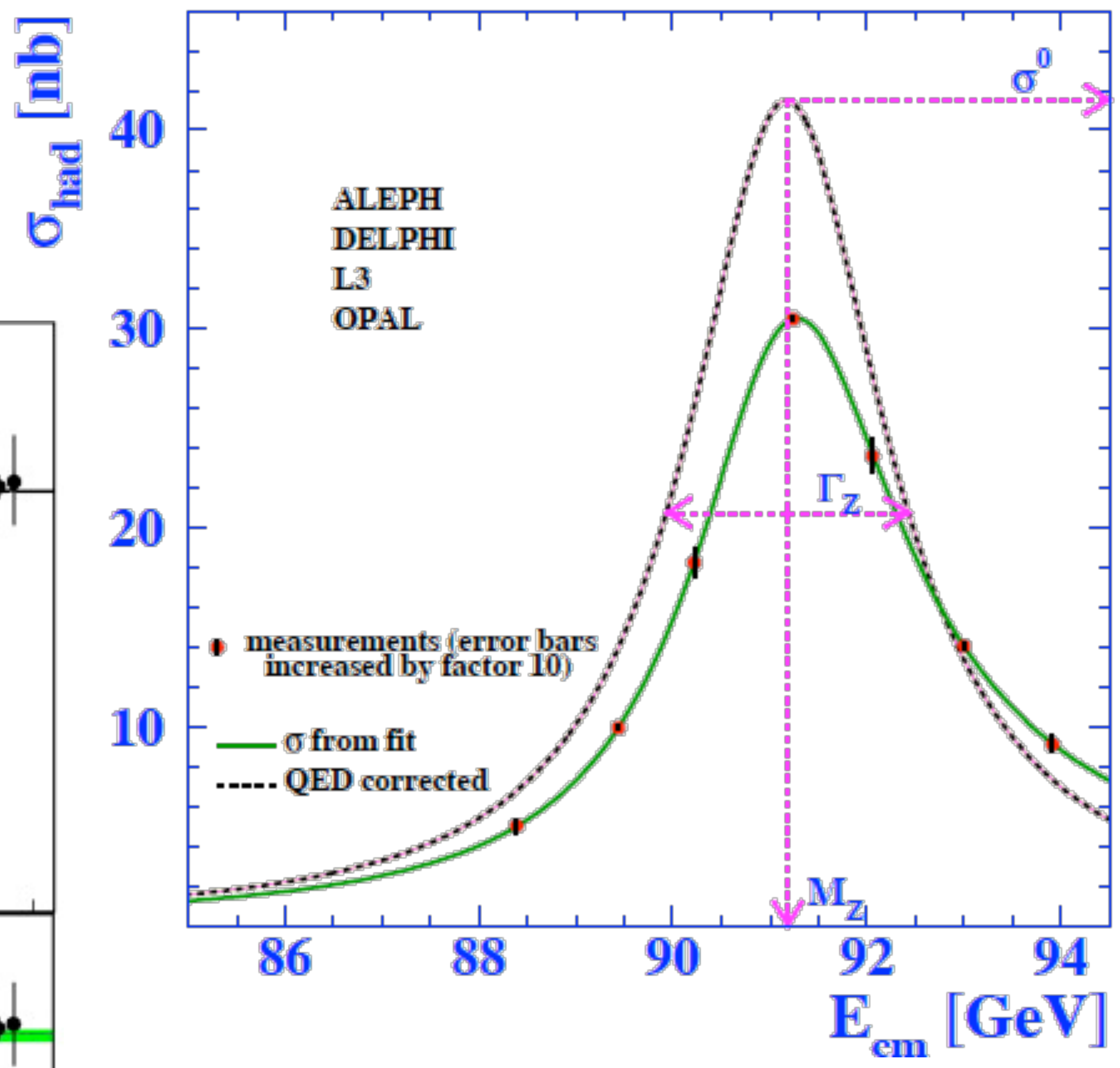
Requires excellent control over beam and luminosity calibration

- Correlations between points also play a crucial role

WW threshold



Z pole



$t\bar{t}$ threshold scan at e^+e^- colliders

- Measurement of WbWb total rate around the **$t\bar{t}$ production threshold -> pseudo bound state**
- Sensitive to top mass, width, Yukawa, and strong coupling

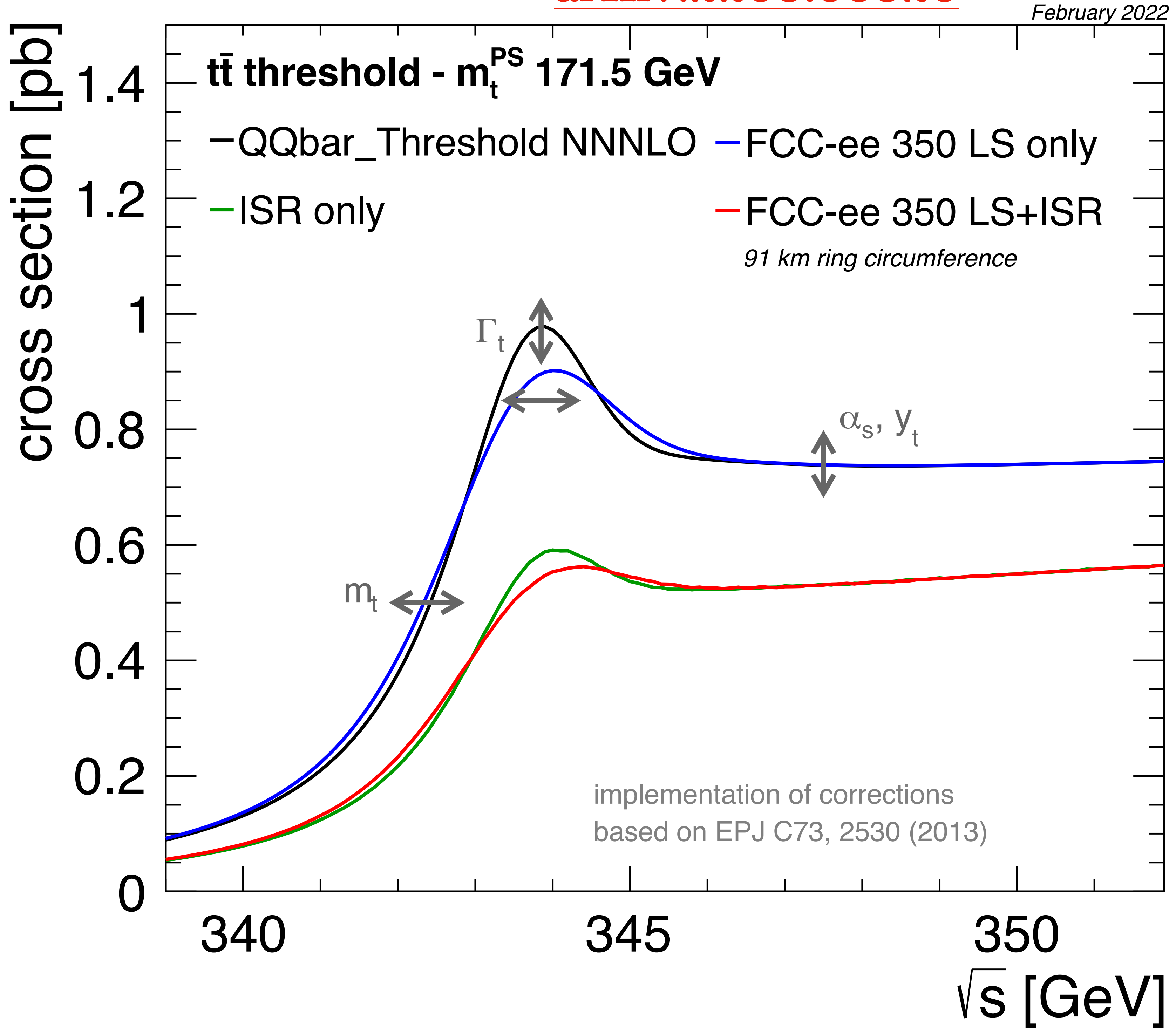
Circular collider advantages

- Better control over **beam spectrum** -> beneficial for m_t and Γ_t
- Access to precise direct determination of **α_S from Z pole run**

LC advantages (not directly related to threshold scan)

- Beam **polarisation** -> interesting for top quark couplings
- Access to **higher energies** (ttH)

arXiv:2203.06520



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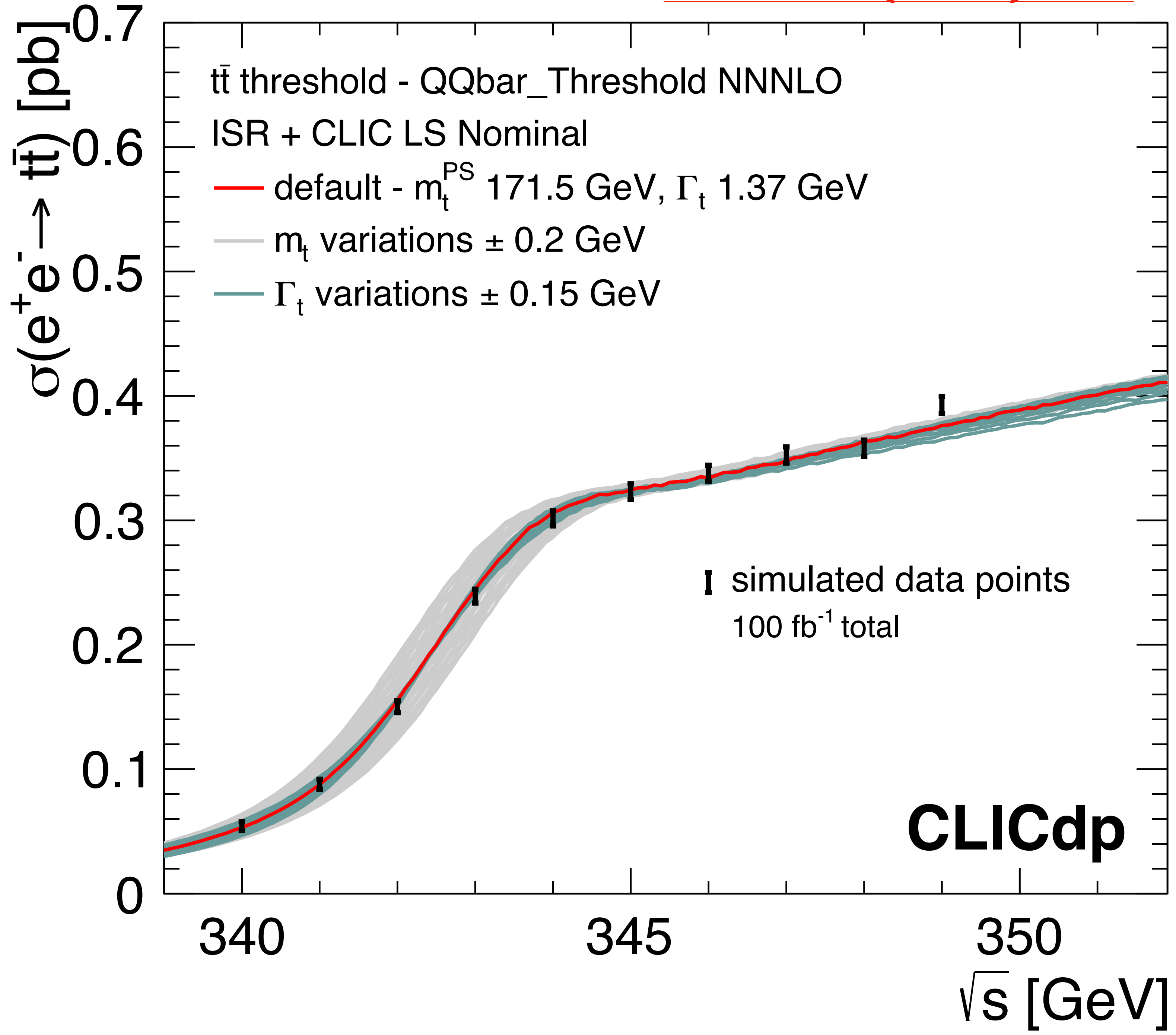
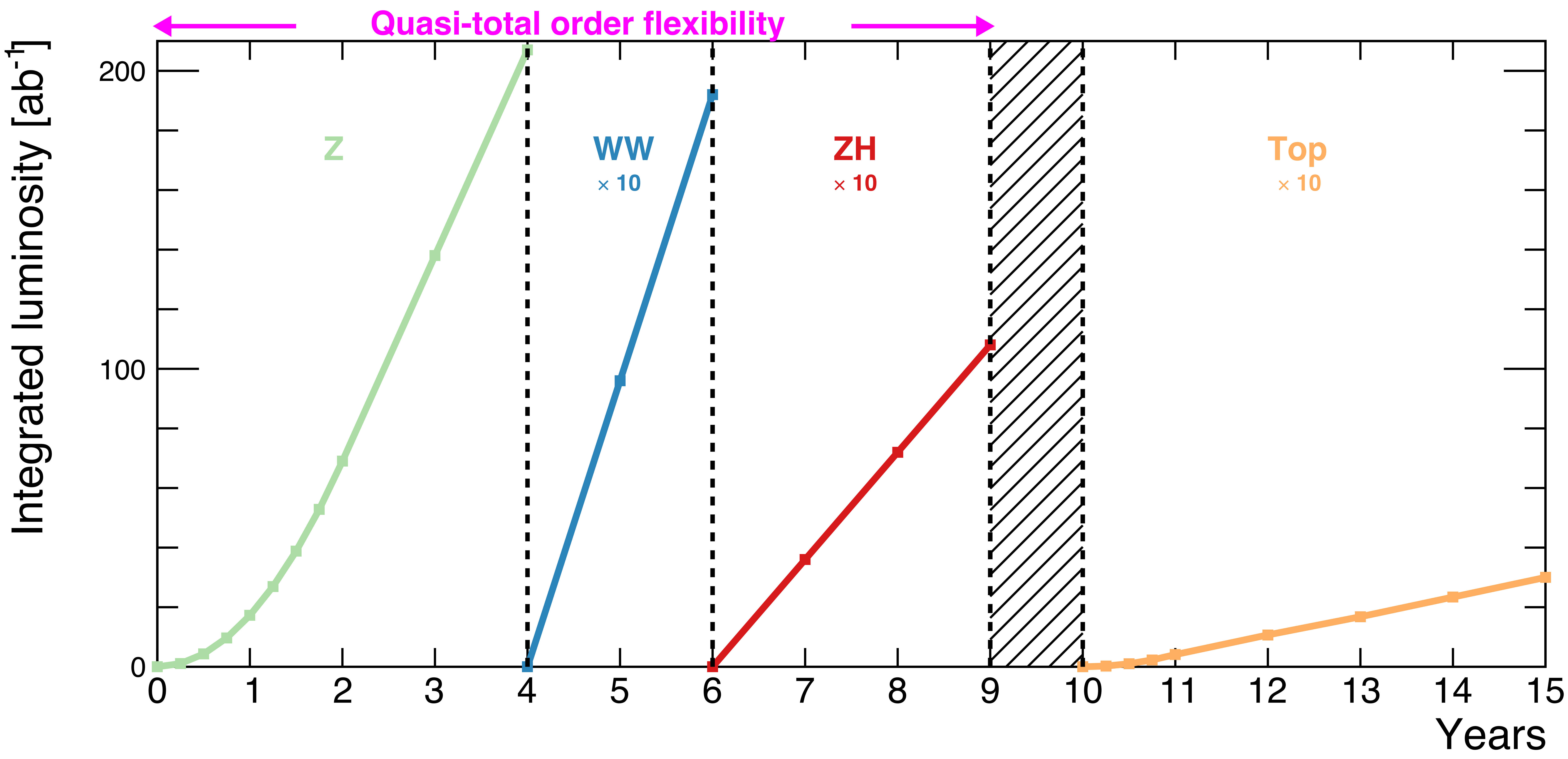
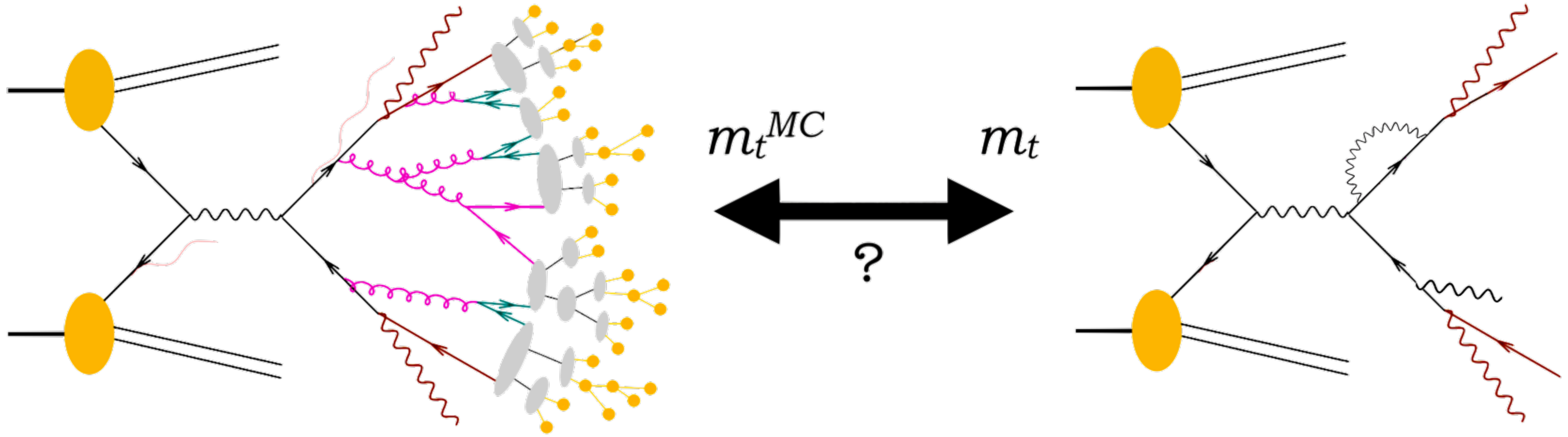


Top run at FCC-ee



- Top physics run foreseen as an upgrade after the Z, WW, ZH runs
- Important to build **strong physics case for top physics run**

Precision target for m_t



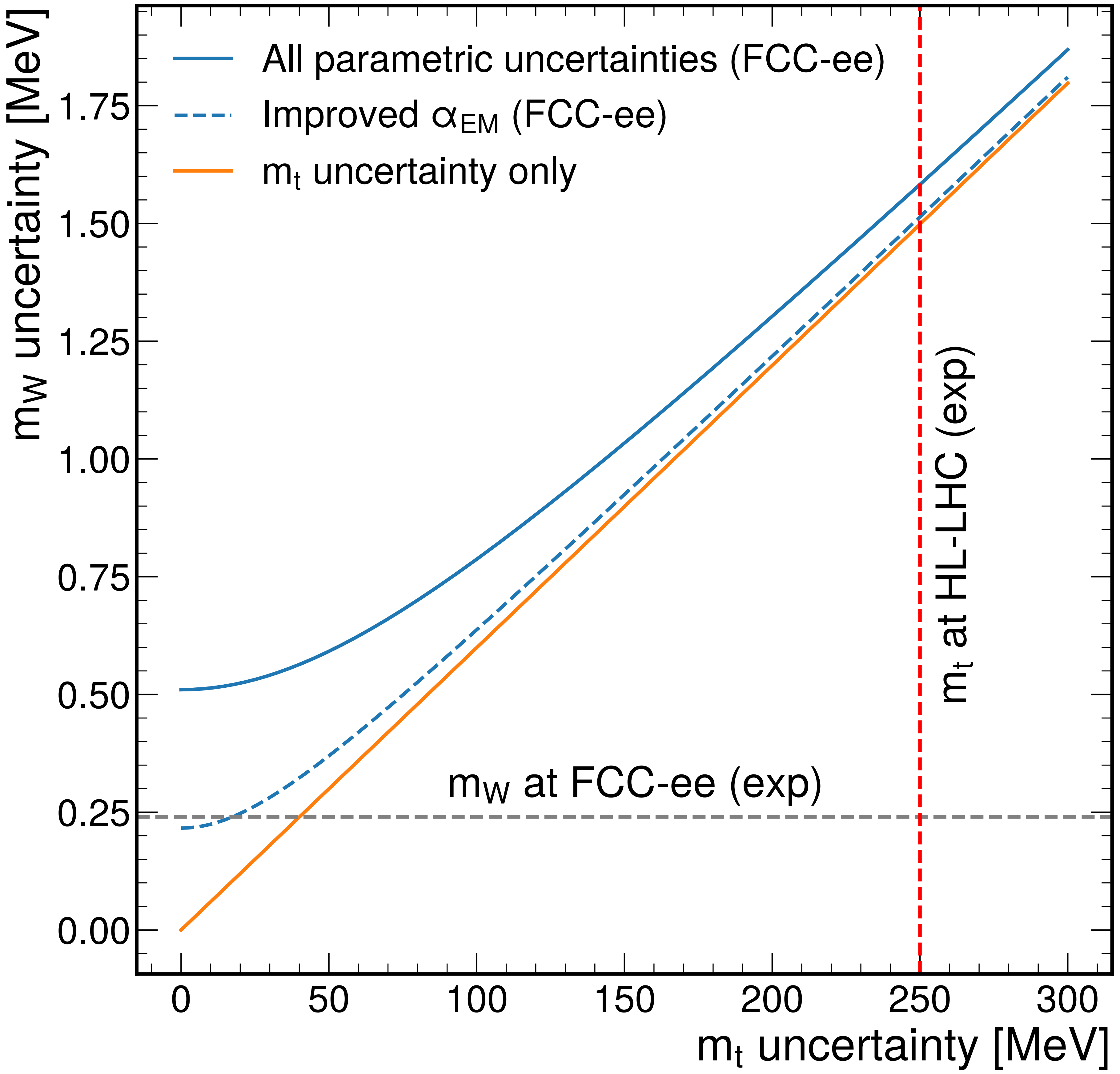
Direct measurements at LHC

- Most precise measurements: **300 MeV**
- Debated theoretical interpretation

Indirect measurements at LHC

- Lower precision (order 1 GeV, improving)
- Need improved theory predictions
- **Can reach order 250 MeV at HL-LHC (optimistically)**

m_W measurements at FCC-ee: 0.24 MeV
-> need to measure **m_t with < 20 MeV precision**



Unambiguous measurement of m_t with required precision can only be reached at a lepton collider

CLIC vs FCC expected precision

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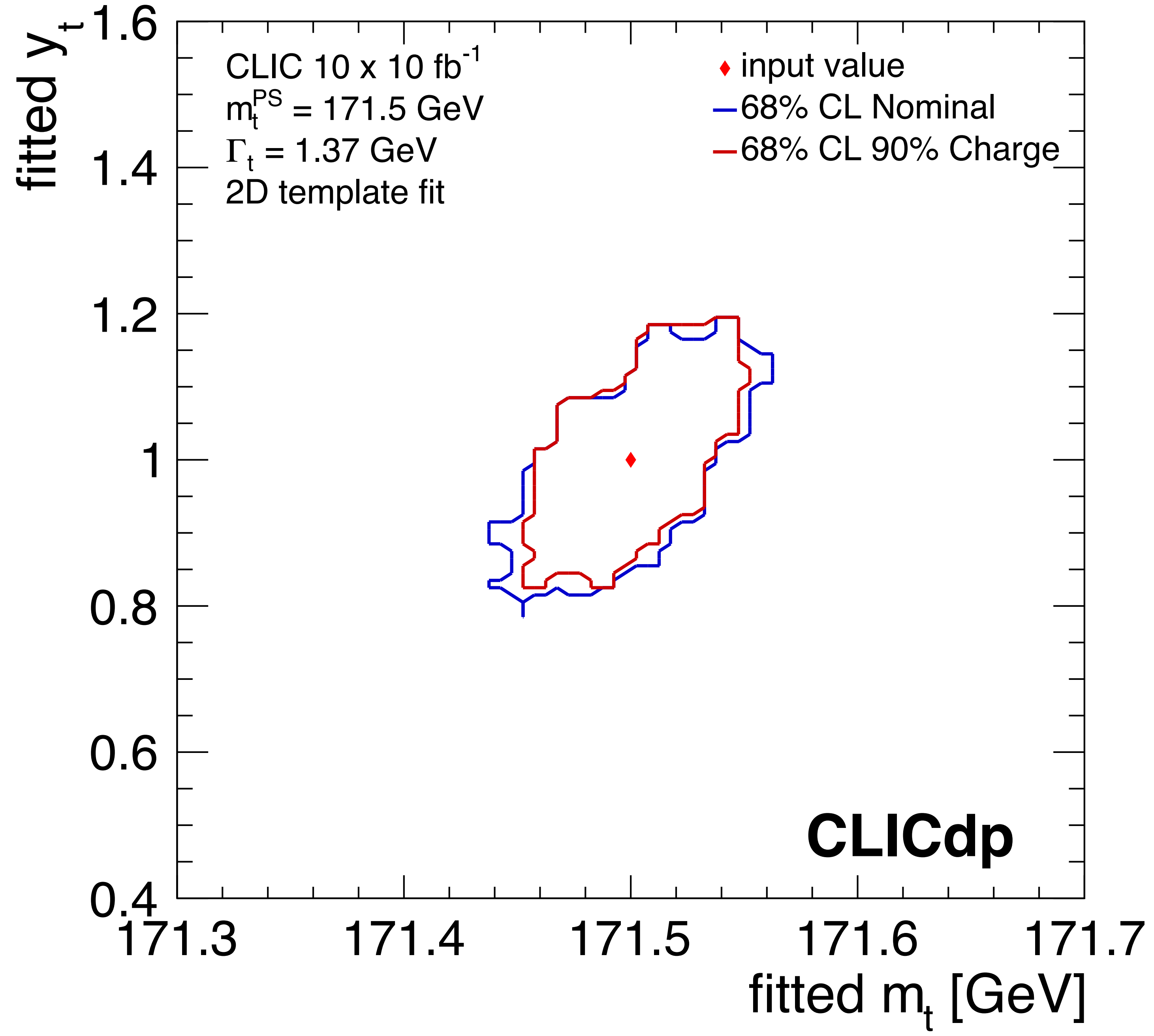
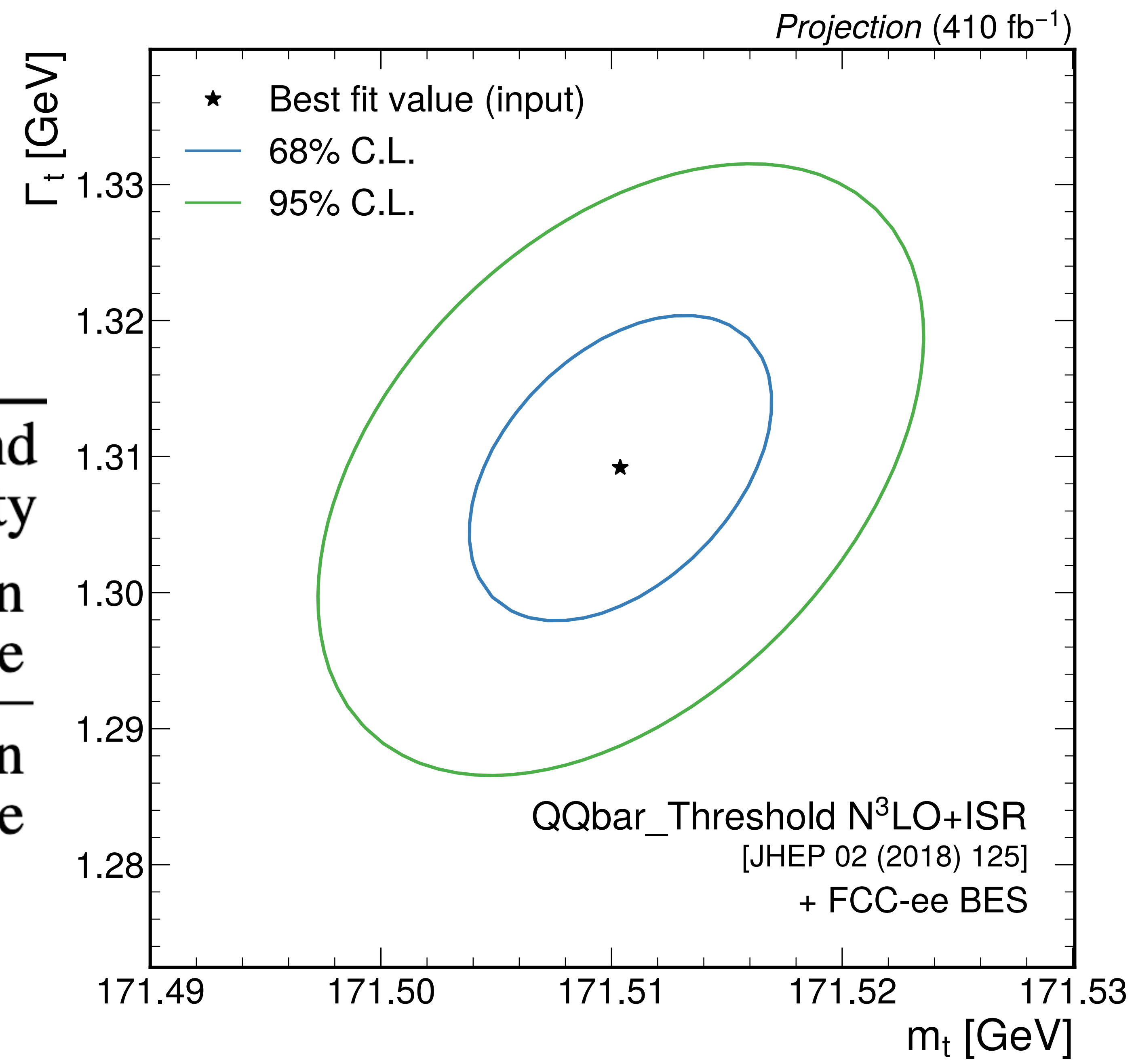
CLIC, 100 fb^{-1}

- 10 equally-spaced points (1 GeV) with 10 fb^{-1} each
- 2D fits of m_t/Γ_t and m_t/y_t
  - Stat: **20 MeV (m_t), 50 MeV (Γ_t), 8% (y_t)**
  - **40 MeV** theoretical uncertainty (currently), expected to improve over time -> largely collider-independent



- New results for FCC, including experimental and beam-related uncertainties (fist study of this kind)
- Simultaneous m_t + Γ_t + y_t measurement (+ profiled uncertainties)

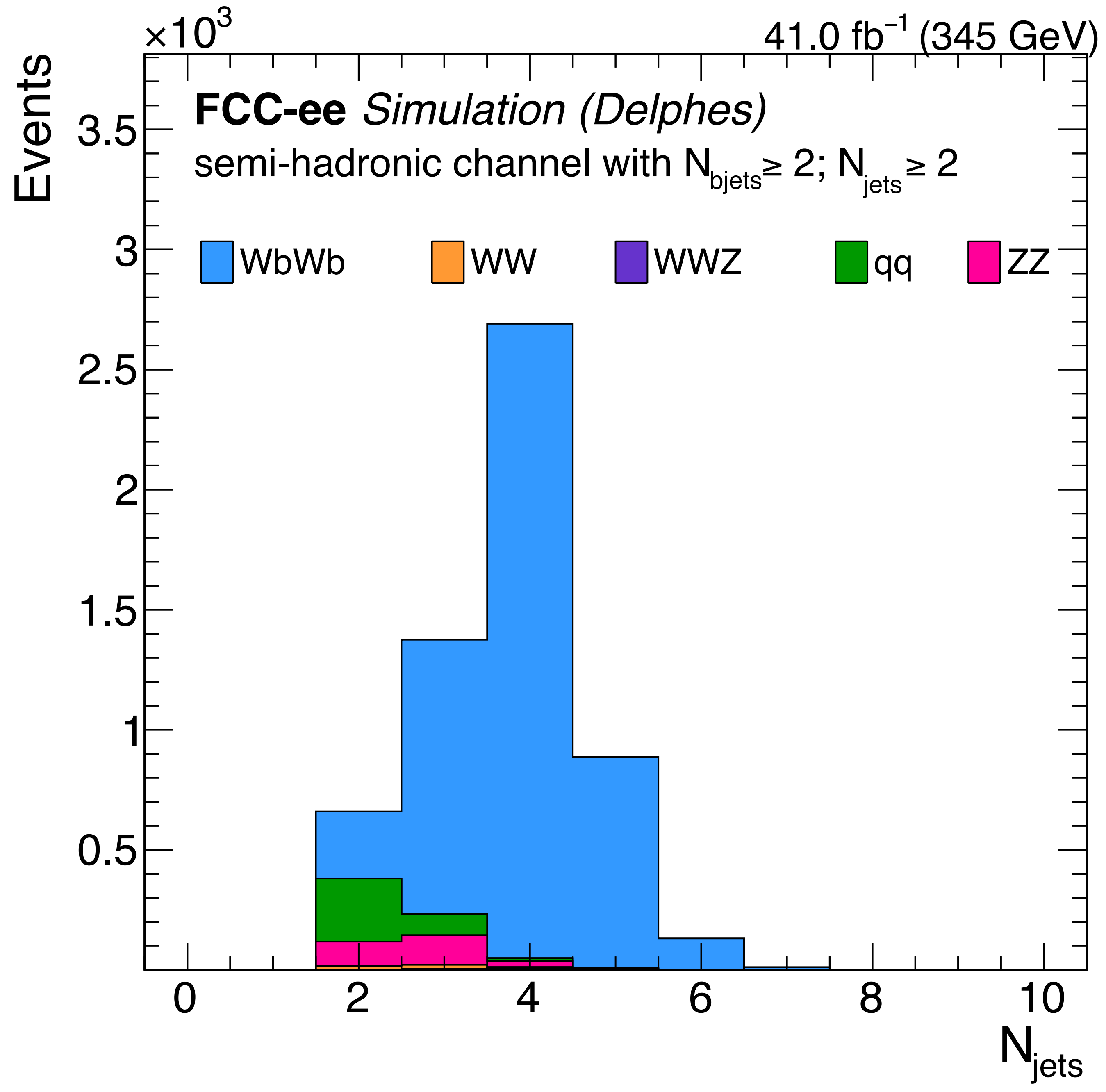
Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate



More detailed comparison later…

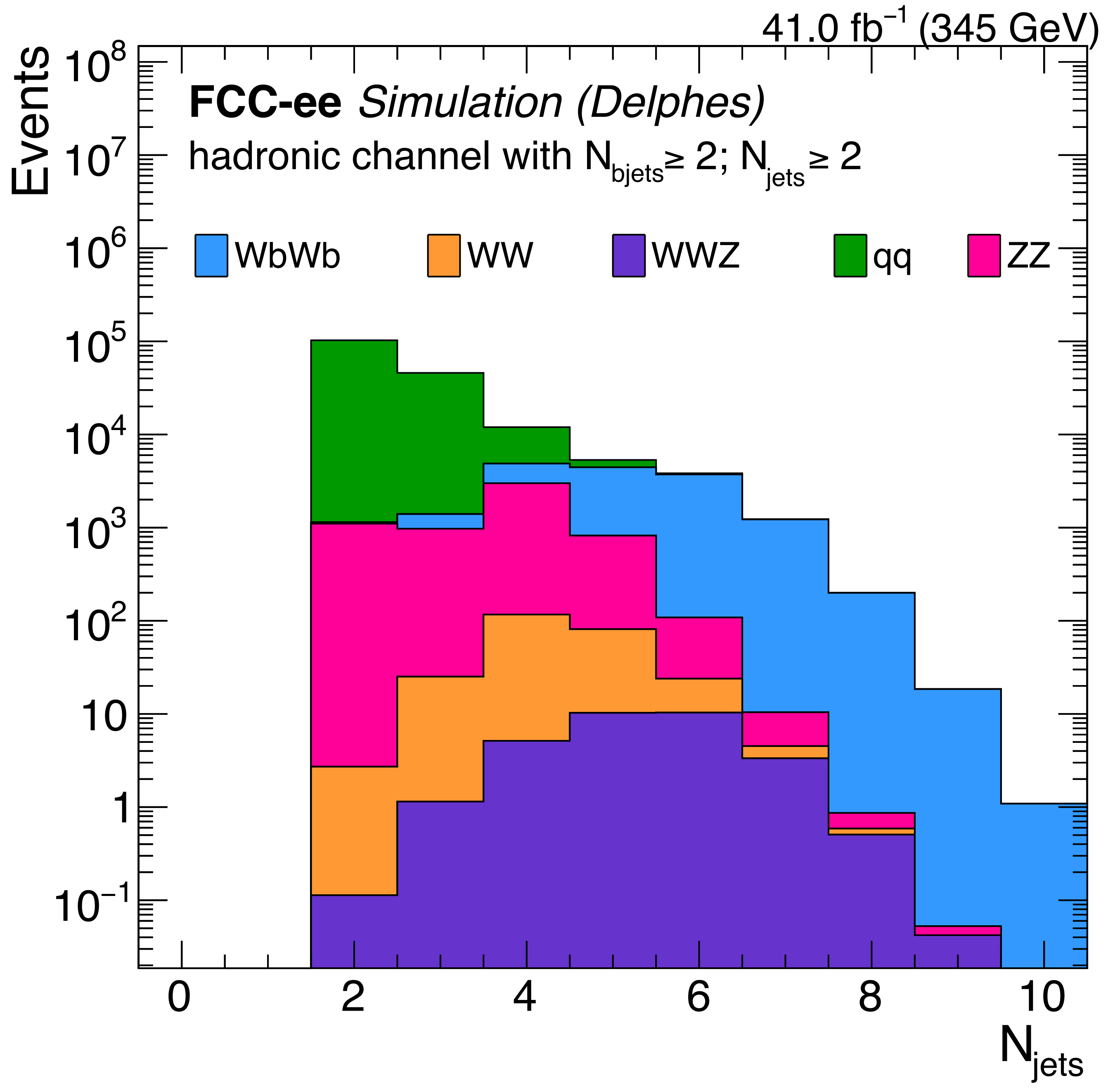
FCC-ee detector-level studies

- **Hadronic** and **semi-hadronic** final states of WbWb decays (>80% branching ratio in total)
- Profile-likelihood fit in **jet and b-tag multiplicity** to extract total rates -> determine b-tagging efficiency in-situ

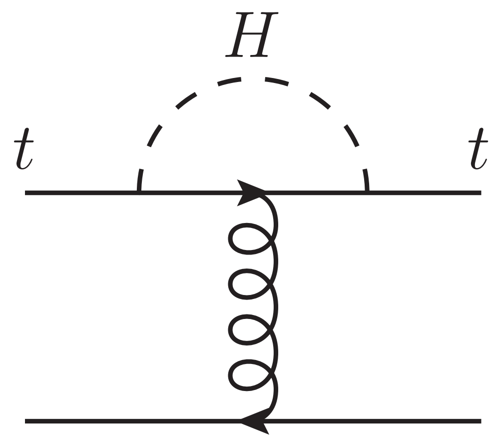


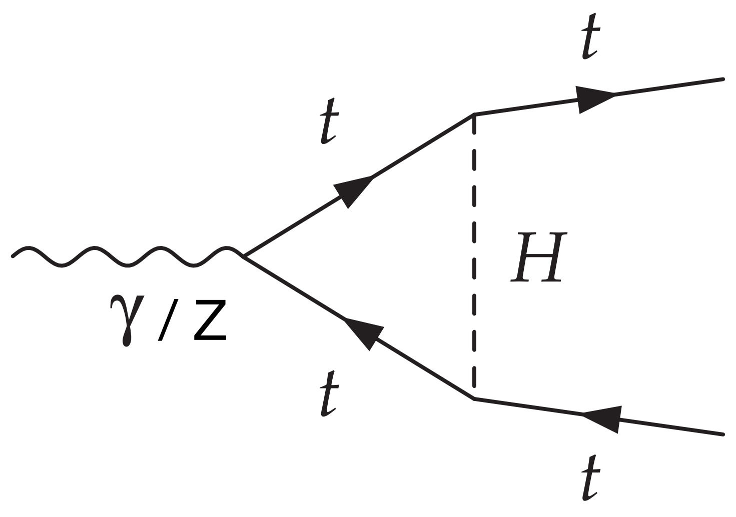
- Highly pure and almost fully efficient signal selection can be achieved in all channels
- Relevant systematic effects controlled well below statistical uncertainty

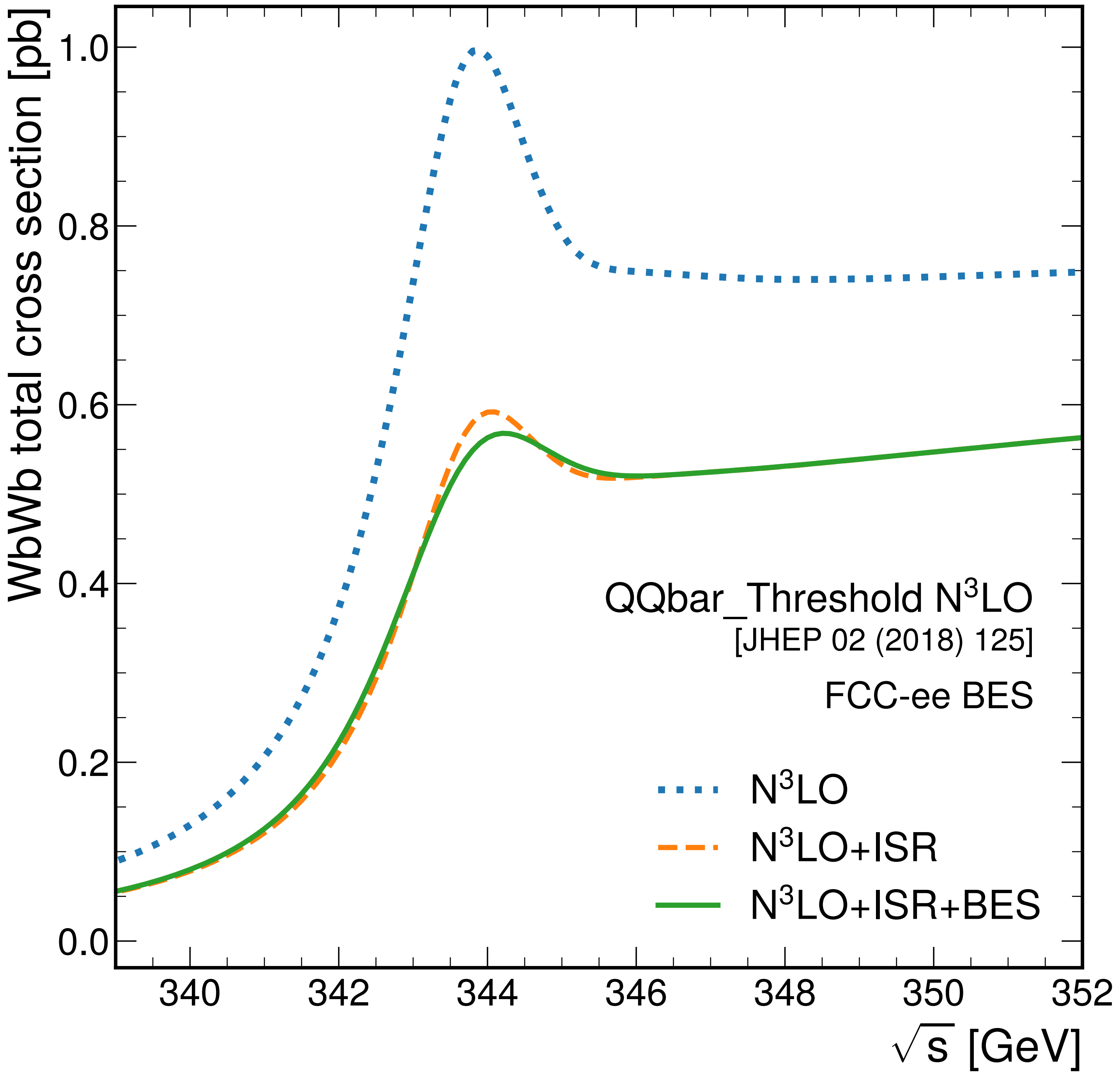
Uncertainty source	Impact on σ_{WbWb} [%]		
	340 GeV	345 GeV	365 GeV
Integrated luminosity	0.12	0.11	0.02
b tagging	0.11	0.06	0.01
ZZ had. norm.	0.46	0.19	0.04
ZZ semihad. norm.	0.23	0.07	0.03
WW had. norm.	0.17	0.09	0.02
WW semihad. norm.	0.06	0.04	0.03
$q\bar{q}$ had. norm.	0.12	0.09	0.02
$q\bar{q}$ semihad. norm.	0.18	0.06	0.01
WWZ norm.	0.03	0.01	0.01
Total (incl. stat)	2.31	0.89	0.12

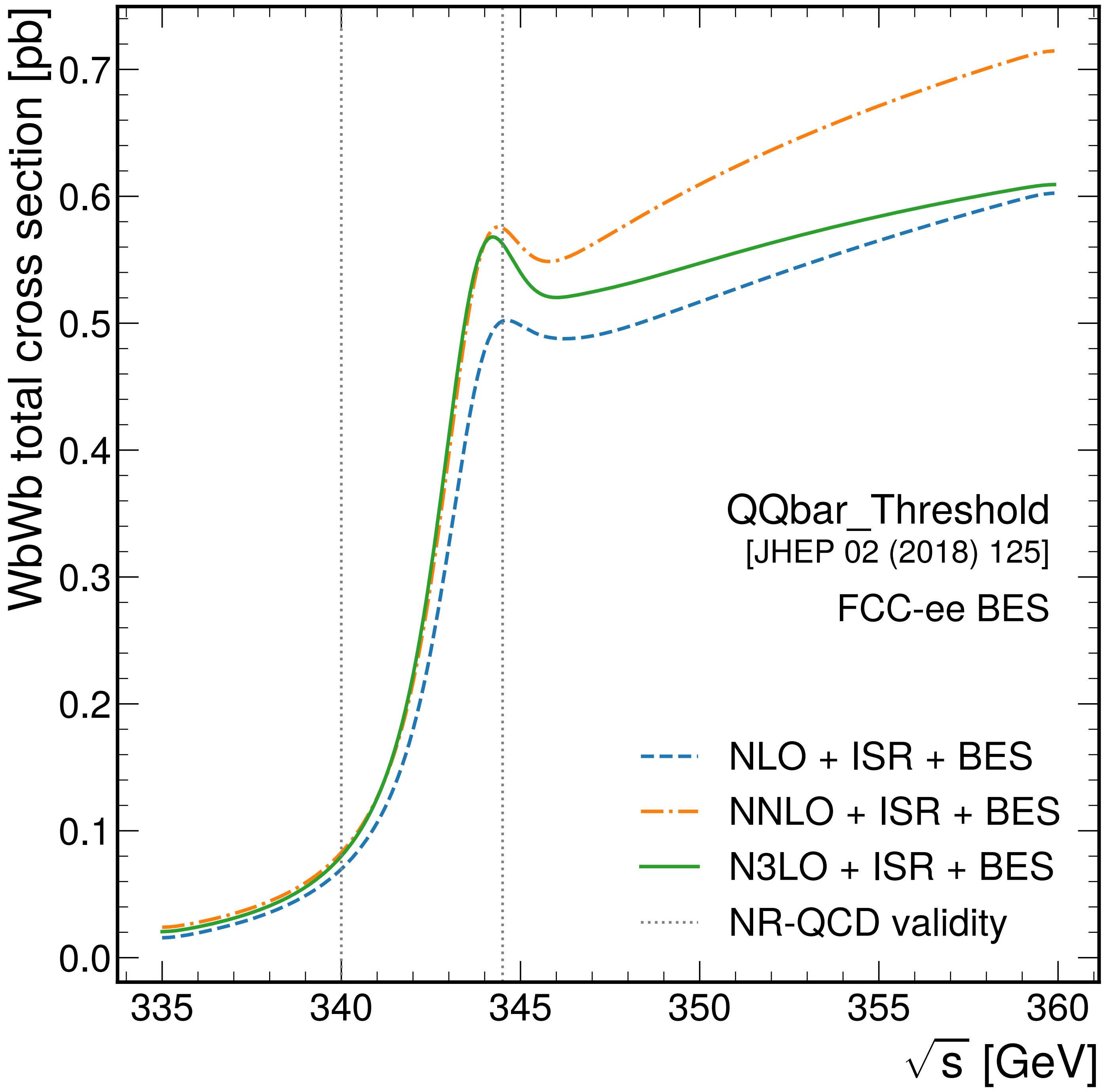


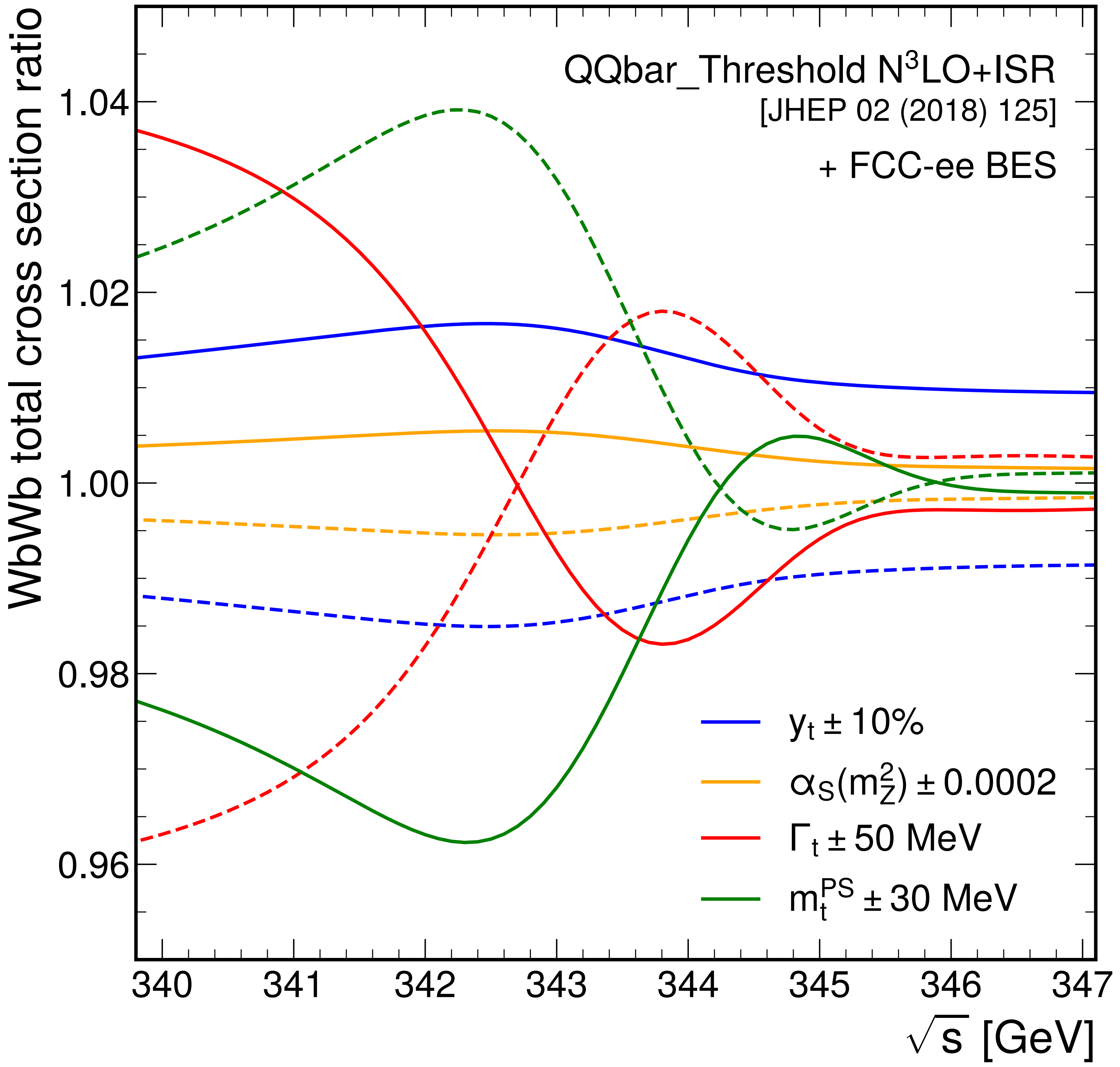
Theoretical calculation











- Top quarks form a **quasi-bound state** -> non-relativistic QCD calculation (NR-QCD) at N^{3}LO
- Initial state radiation (**ISR**) effectively reduces total cross section (LL precision)
- Calculation convoluted with expected FCC beam energy spread (**BES**): 0.18% / beam

- Calculation only valid in the vicinity of threshold, where the sensitivity to the parameters lies

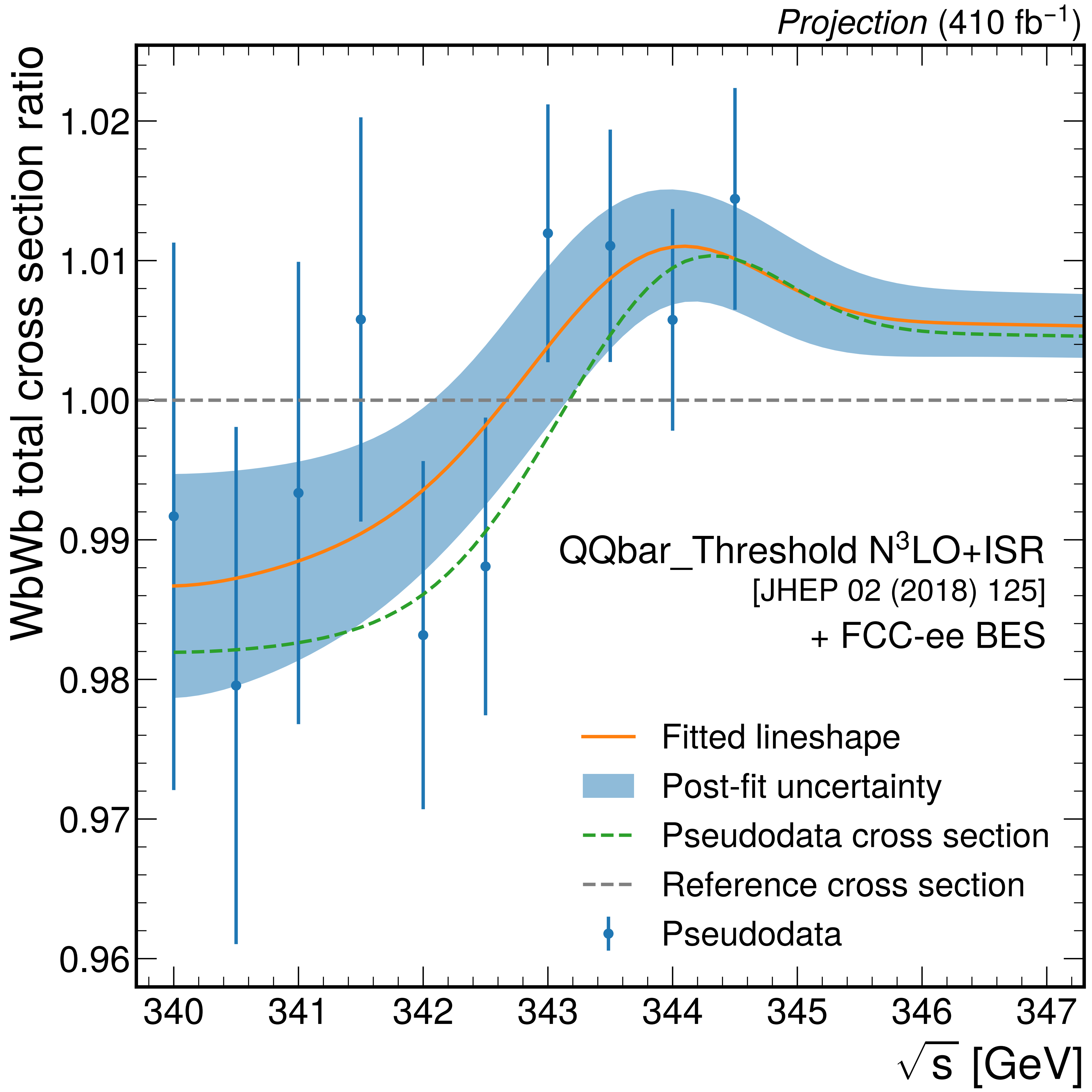
Fit of near-threshold + above threshold

- **3-dimensional fit** of m_t, Γ_t, and y_t, with profiled α_S and calibration parameters
- 10 equally-spaced points (0.5 GeV) with equal luminosity (41 fb^{-1})
- 365 GeV run provides additional sensitivity to **top Yukawa**

√s [GeV]	Integrated lumi
340-345	410 fb^{-1}
365	2.65 ab^{-1}

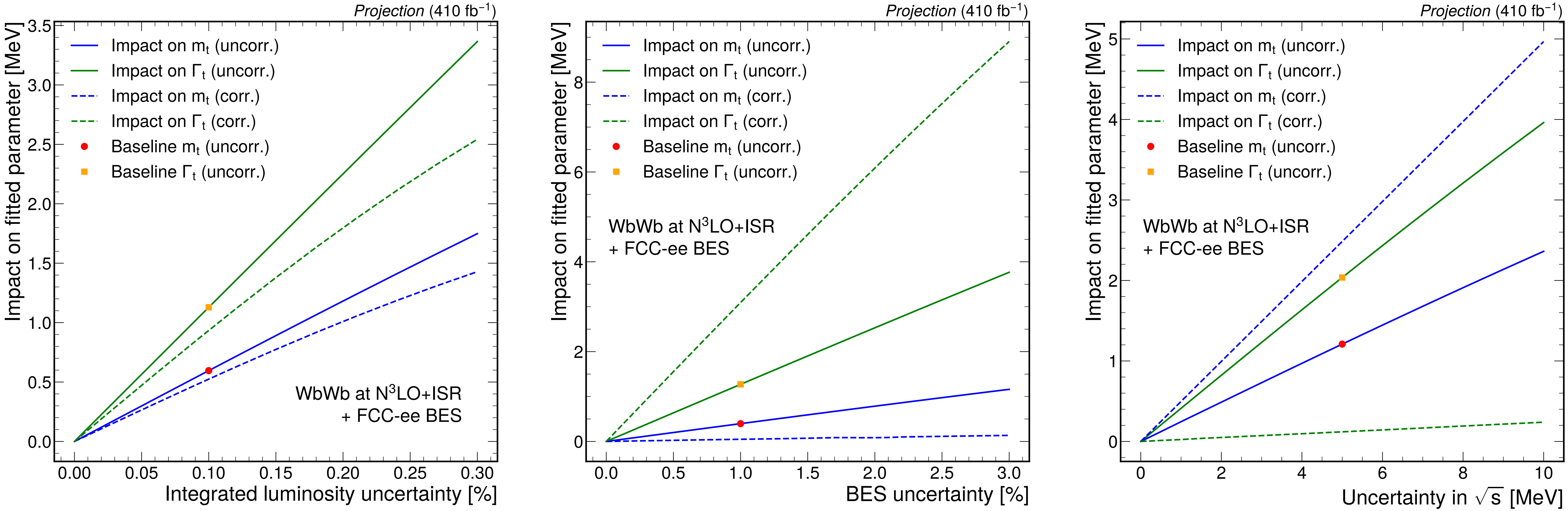
Uncertainty source	m_t^{PS} [MeV]	Γ_t [MeV]	y_t [%]
Experimental (stat. ×1.2)	4.2	10.0	1.5
Parametric m_t	–	5.3	1.2
Parametric Γ_t	3.0	–	0.8
Parametric y_t	3.8	4.8	–
Parametric α_S	2.2	1.6	0.2
Luminosity calibration (uncorr.)	0.6	1.1	0.2
Luminosity calibration (corr.)	1.0	0.7	0.9
Beam energy calibration (uncorr.)	1.3	1.9	0.1
Beam energy calibration (corr.)	1.3	< 0.1	< 0.1
Beam energy spread (uncorr.)	0.3	0.9	< 0.1
Beam energy spread (corr.)	< 0.1	1.1	< 0.1
Total profiled	6.5	11.7	2.1
Theory	**35**	**25**	**?**

N.B. y_t result assumes SM coupling of top quark to Z boson and photon



cf. CLIC: 2.7% (stat) in y_t with 2.5 ab^{-1} of ttH

Dependence on systematic assumptions



- Luminosity: back-of-the-envelope from di-photon events
- Beam energy calibration: estimate from WW assuming m_W constraint
- Beam energy spread (BES): estimate from di-muon events

First study of this kind for tt threshold scan

Uncorrelated = of statistical nature

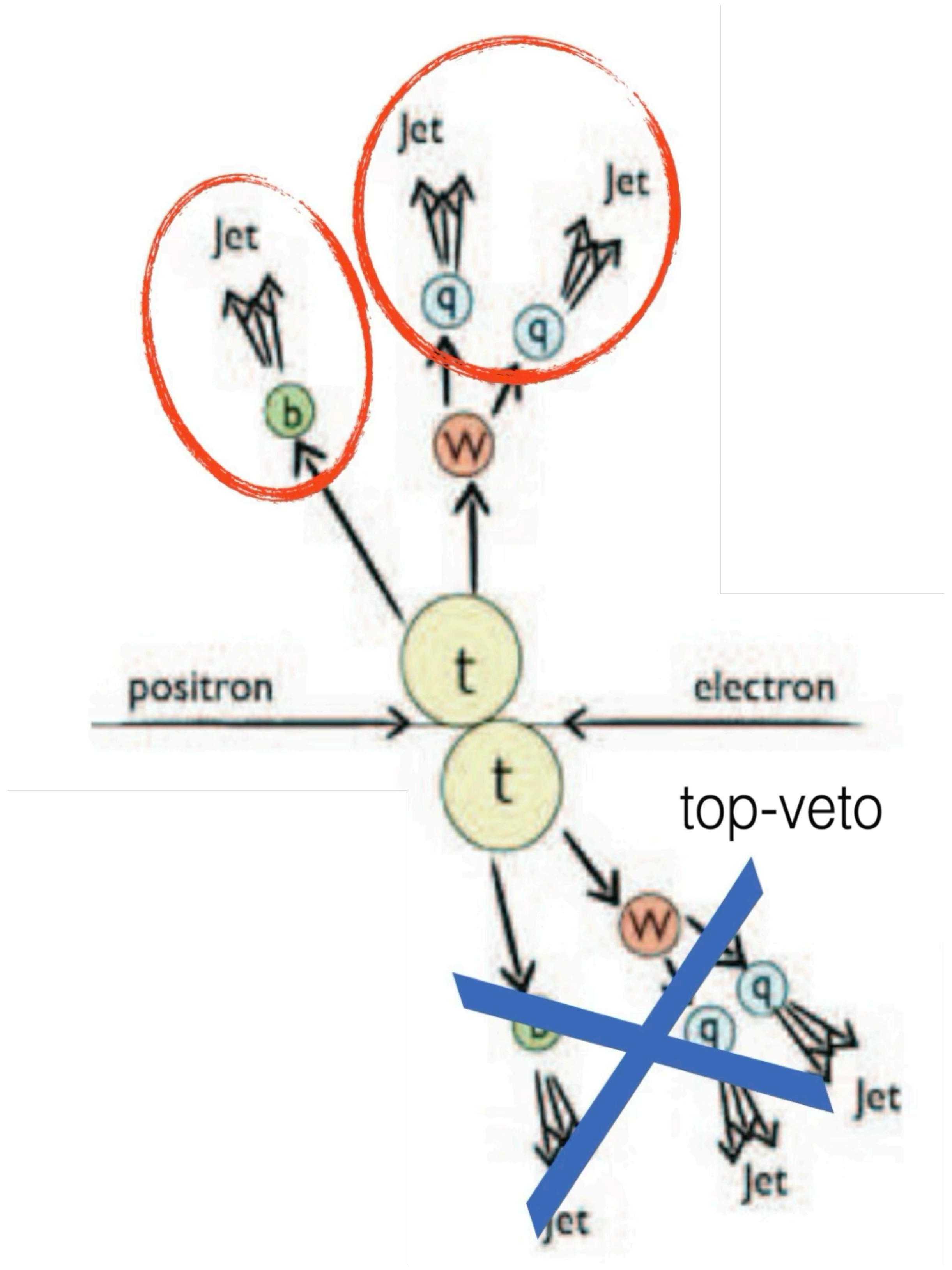
Correlated = residual correlated component between different E_{cm} (e.g. W mass constraint)

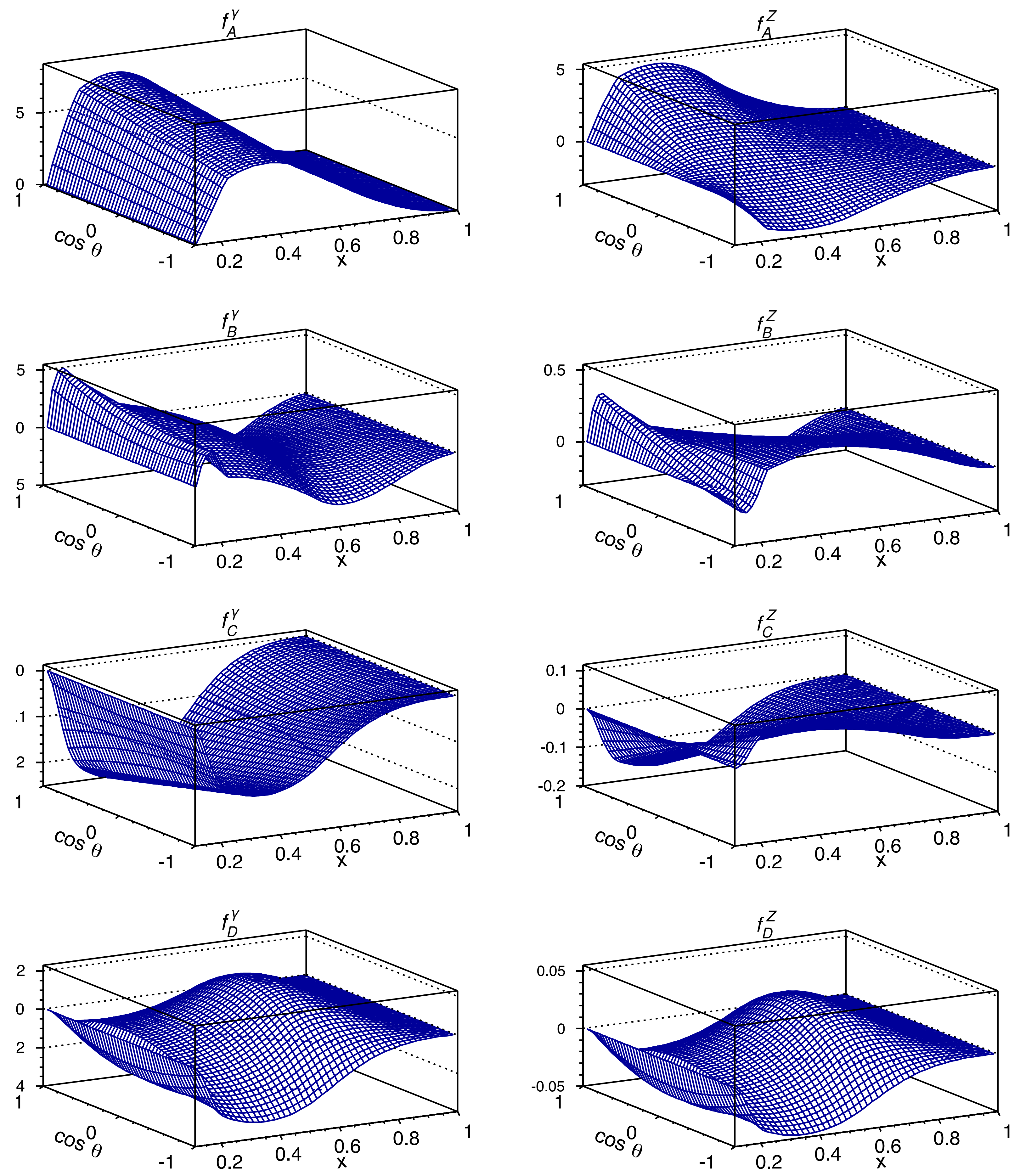
Top physics at 365 GeV

See talks by X. Zuo at ECFA workshop [link] and by B. Mele at FCC Italy & France [link]

$$\Gamma_{\mu}^{ttX} = -ie\left\{\gamma_{\mu}\left(F_{1V}^{X} + \gamma_5 F_{1A}^{X}\right) + \frac{\sigma_{\mu\nu}}{2m_{\mathrm{t}}}(p_t + p_{\bar{t}})^{\nu}\left(iF_{2V}^{X} + \gamma_5 F_{2A}^{X}\right)\right\}$$

- **Top couplings** to Z boson and photon can be simultaneously constrained from **lepton kinematics**
- This method does not require beam polarisation





- Model-independent searches for **BSM top decays** are hard to conceive at hadron colliders
- **Room for a few % exotic BR** for a top with uncertainty of order 10 MeV
- Can be probed with order 10^6 tt events

Comparison between different machines

Goal: factor-out all collider-independent assumptions in the various published studies

- Signal acceptance
- Choice of scan points

Incorporate expected gain from **beam polarization** in LC results (not considered in original studies)

Assume **equal integrated luminosity** (instantaneous luminosity expected to be similar)

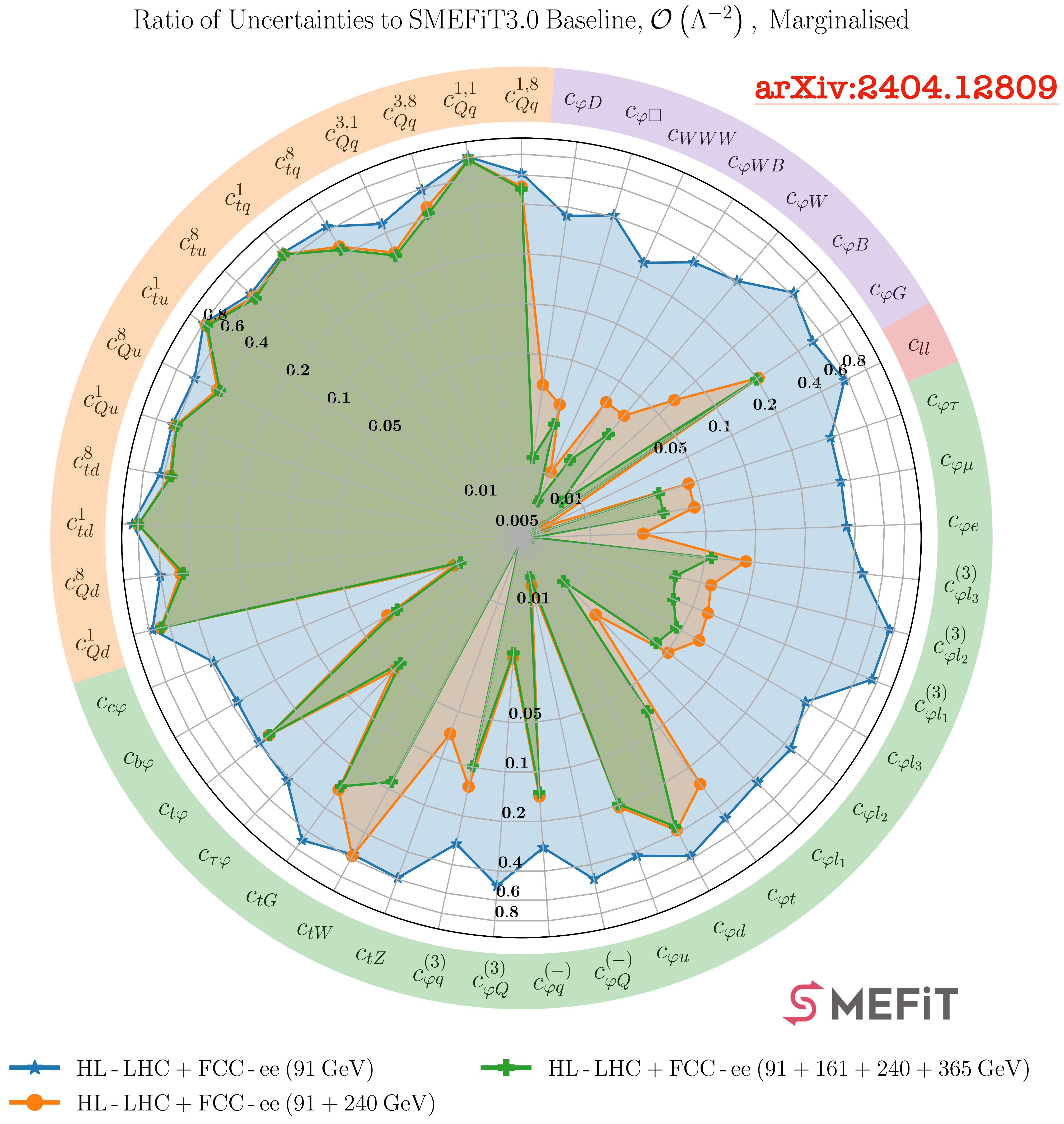
	FCC-ee	ILC [51]	CLIC [18]
m_{t} stat. uncert. [MeV]	4.3	13	21
Γ_{t} stat. uncert. [MeV]	10.4	30	51
Integrated luminosity [fb^{-1}]	410	200	100
Signal acceptance	0.75	0.7	0.7
Beam polarisation: gain on σ_{WbWb} [50]	–	1.43	1.43
FCC scan range: gain on m_{t}	–	1.39	1.39
FCC scan range: gain on Γ_{t}	–	1.34	1.34
Stat. uncert. inflation	1.2	–	–
m_{t} stat. uncert. rescaled [MeV]	4.3	6.3	7.2
Γ_{t} stat. uncert. rescaled [MeV]	10.4	15.1	18.1

Same statistical precision as FCC-ee would require approximately x2 (x3) longer runtime at ILC (CLIC)

Summary and outlook

FCC-ee top run also has strong impact in global interpretations (see Victor's talk today)

- **Outlined physics case for a tt threshold run at FCC-ee** + detailed comparison to LC performance
- **Complete study of tt threshold** including detector-level, machine-related, and parametric uncertainties
  - Shown that systematic effects are well under control
  - Theoretical progress needed to fully profit from physics potential of FCC-ee
- Measurement of top quark Yukawa coupling via loop corrections to tt events can be envisaged
- High potential to constrain top quark **couplings** and **BSM decays** at the 365 GeV FCC-ee run



Thank you

BACKUP

Comparison with previous CEPC studies

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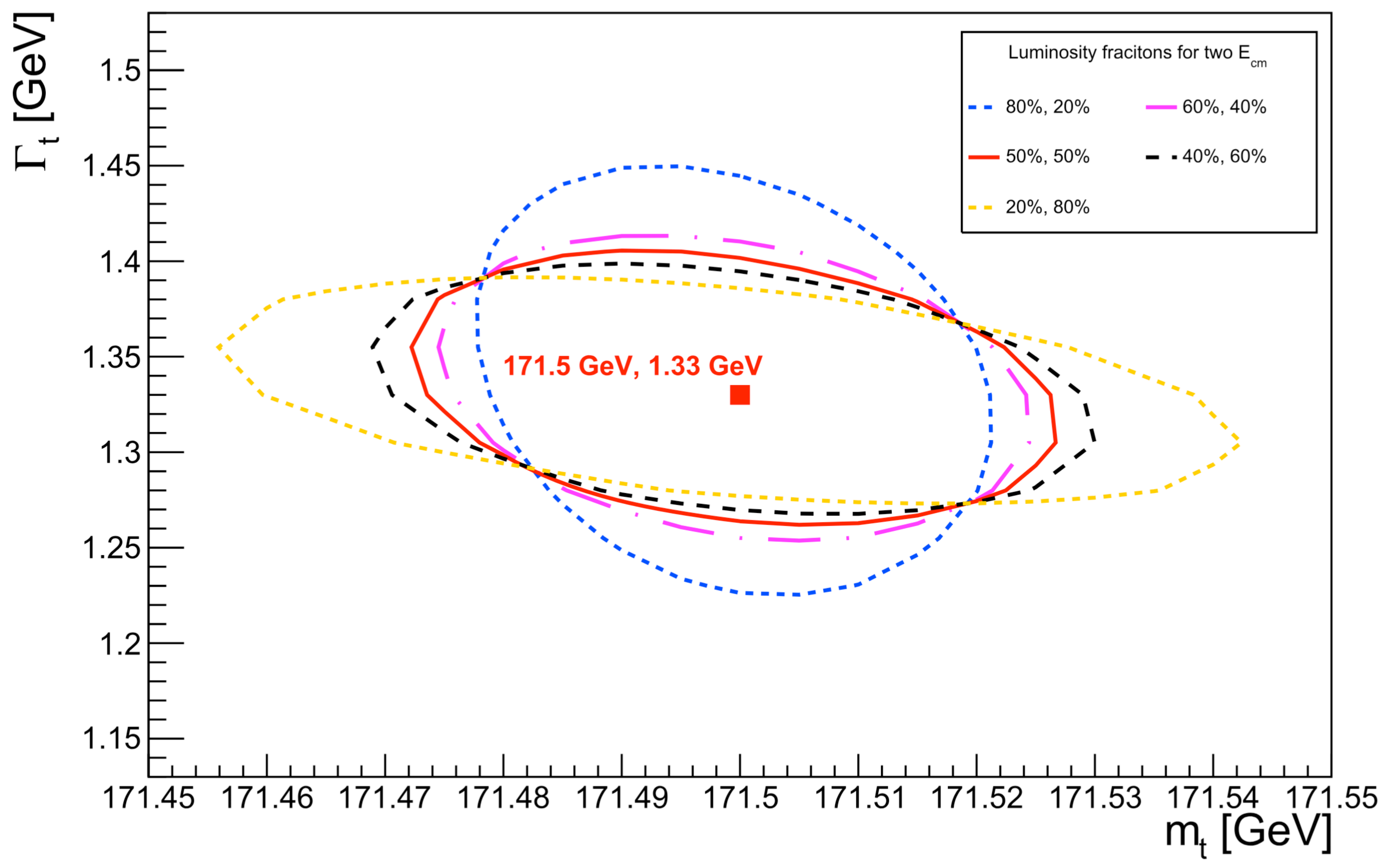

- Same ballpark uncertainty as FCC-ee result, despite very different assumptions and strategies
- Estimate of theoretical uncertainty seems optimistic
- Dependence on top Yukawa coupling to be assessed
- α_S uncertainty can be improved (similarly to FCC-ee)

- Strategy: "**quick scan**" with 10% of total lumi and 6 energy points to obtain first determination of parameters
- Select two optimal energy points to maximize precision and minimize correlations
- Disadvantage: choice of optimal points heavily relies on theoretical prediction

100 fb^{-1}

Source	m_{top} precision (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	9	26
Quick scan	3	3
α_S	17	17
Top width	10	10
Experimental efficiency	5	45
Background	4	18
Beam energy	2	2
Luminosity spectrum	3	5
Total	25	59