Physics case for a tt threshold scan at FCC-ee

+ opportunities and challenges for top physics at FCC-hh

CEPC Week 2025, Barcelona

with a focus on tt threshold studies from arXiv:2503.18713

FUTURE CIRCULAR COLLIDER

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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

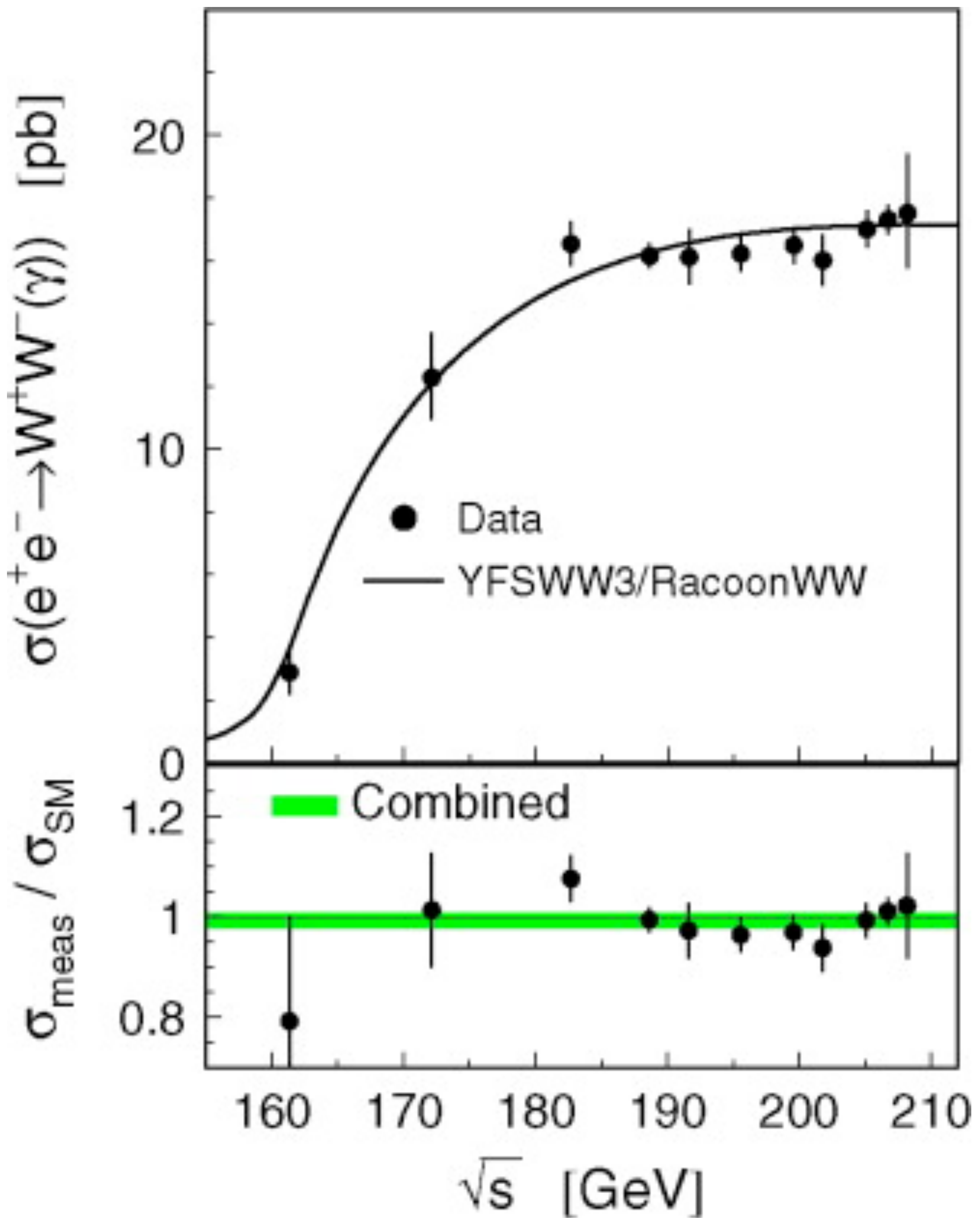
- Measure total production cross section as a function of √s

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

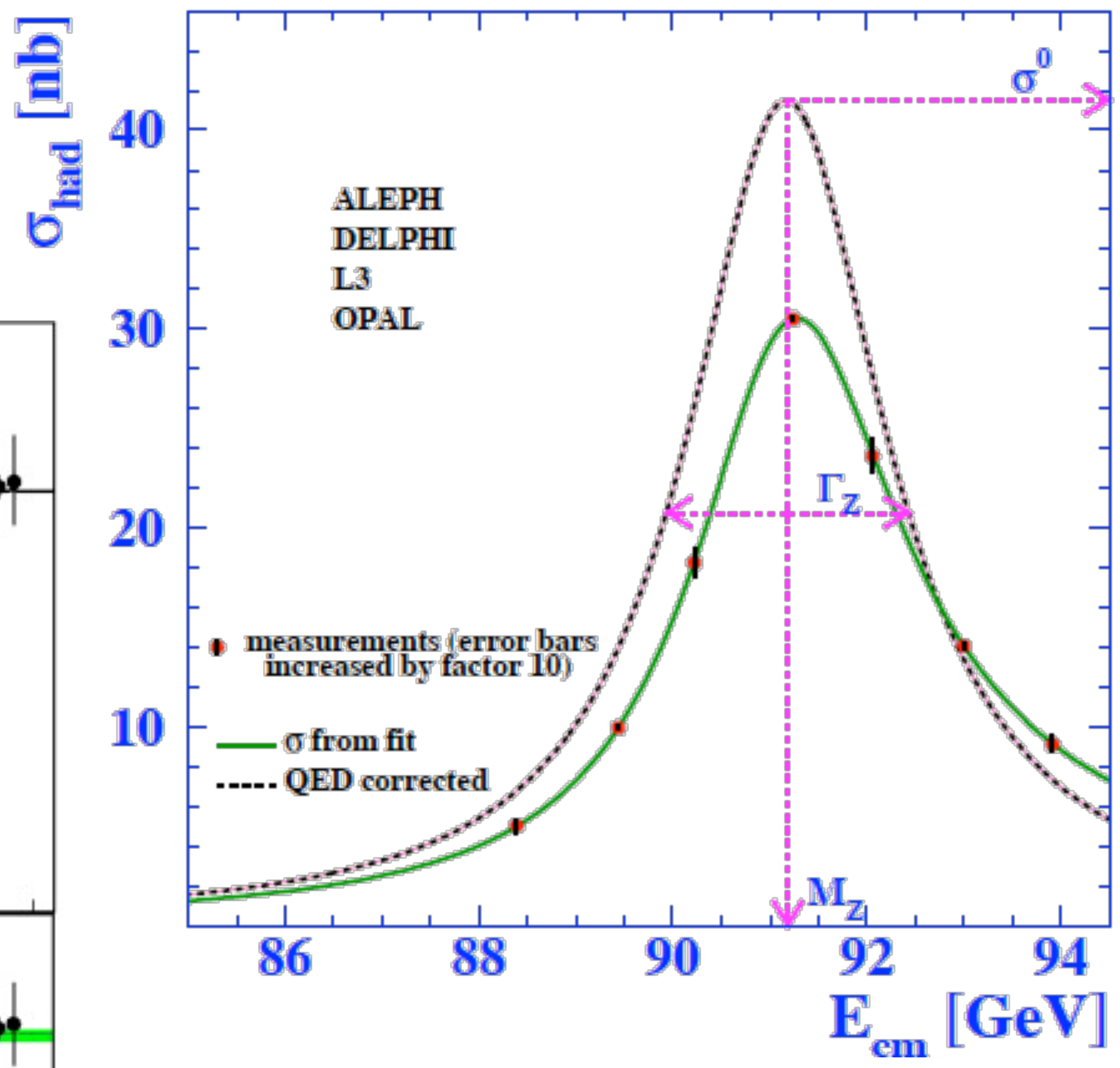
Requires excellent control over beam and luminosity calibration

- Correlations between points also play a crucial role

WW threshold



Z pole



tt threshold scan at e+e- colliders

- Measurement of WbWb total rate around the **tt production threshold -> pseudo bound state**
- Sensitive to top mass, width, Yukawa, and strong coupling

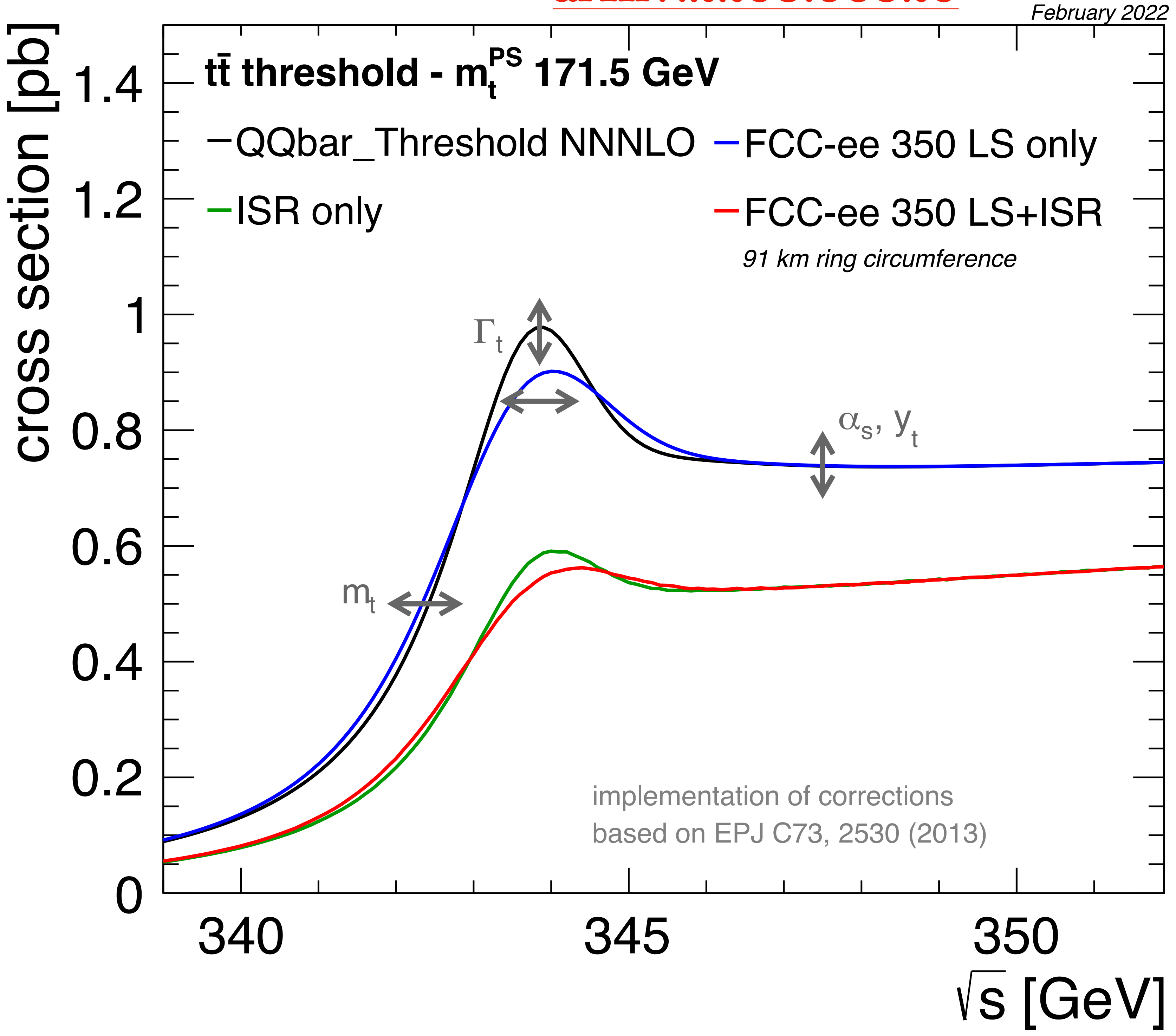
Circular collider advantages

- 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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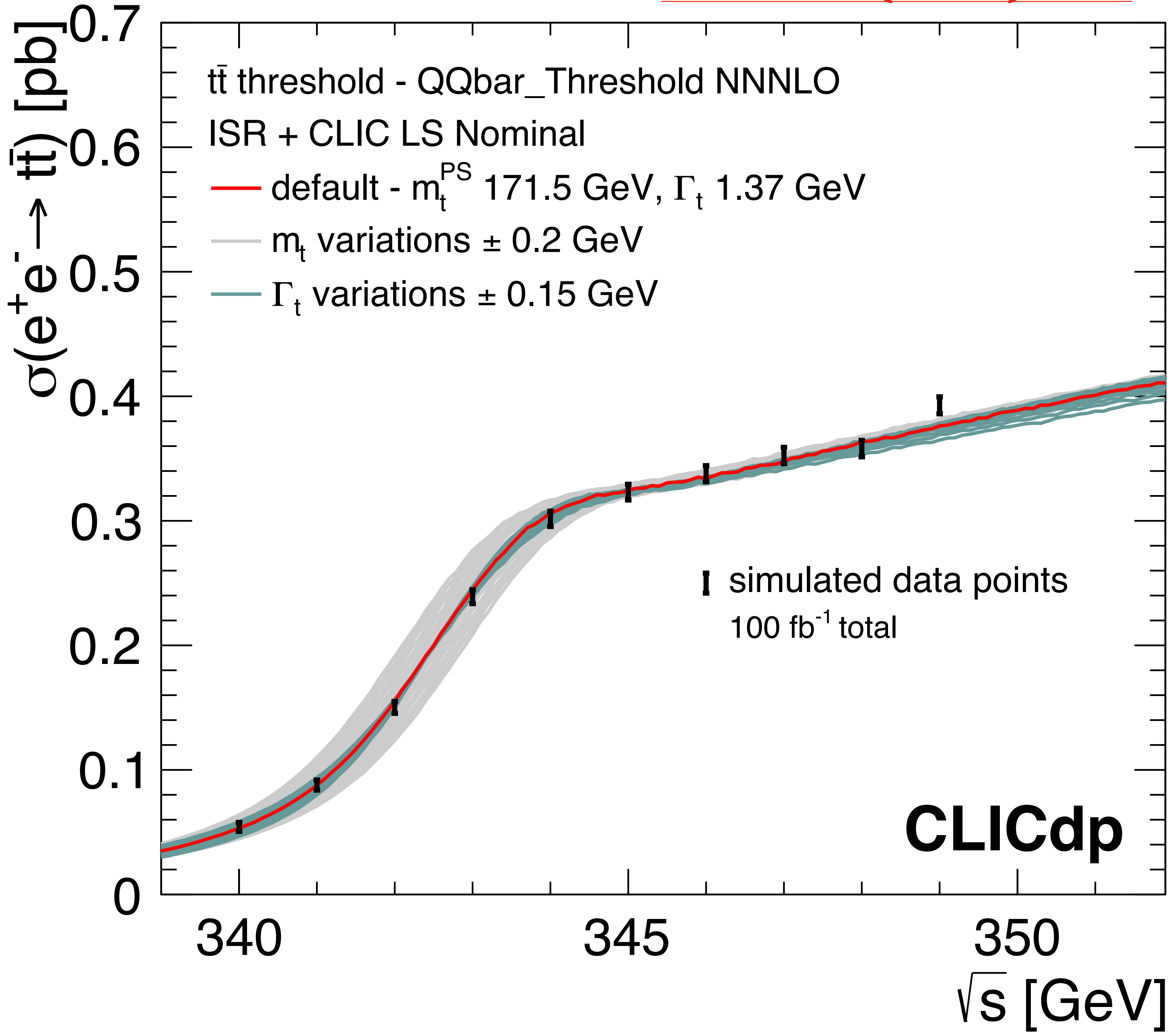
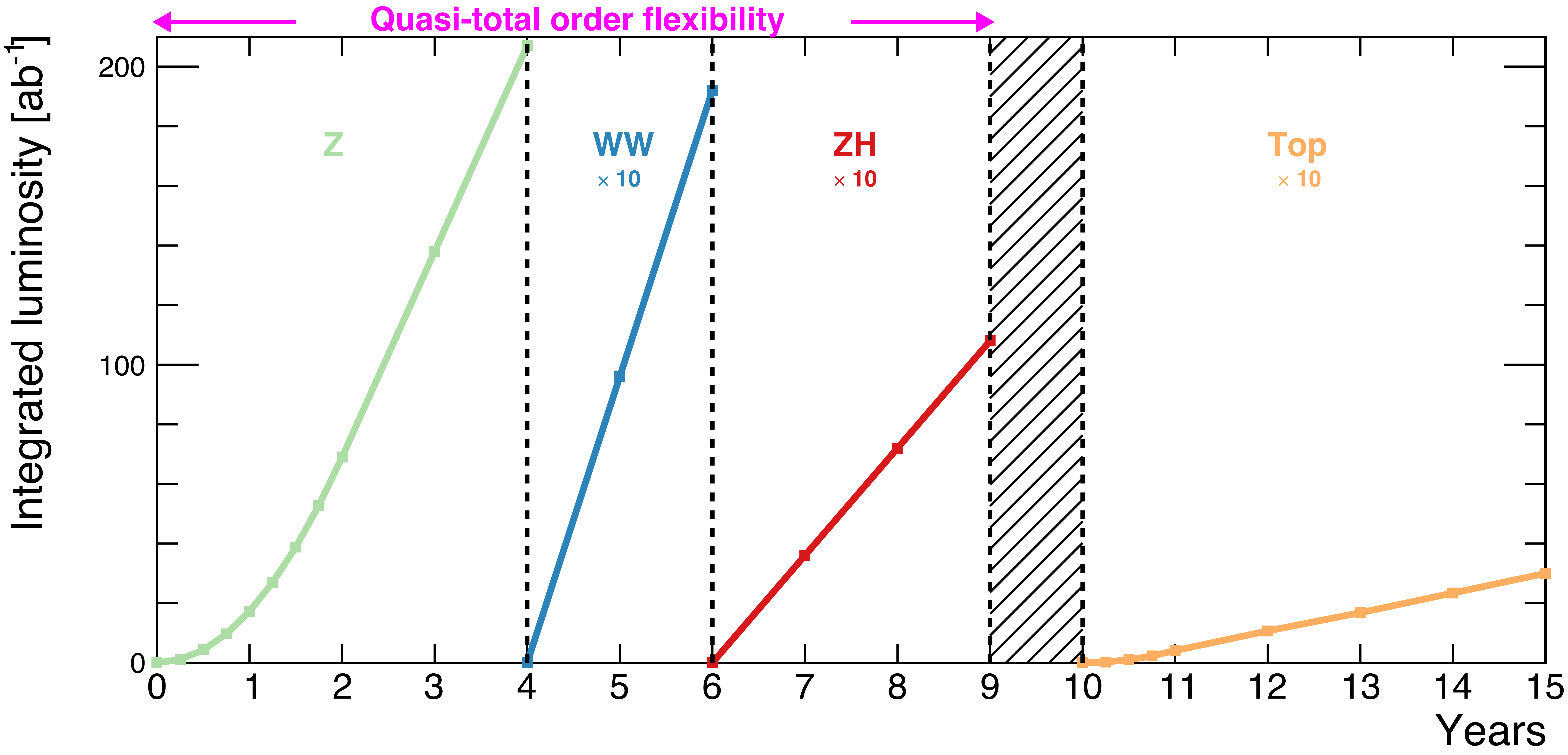


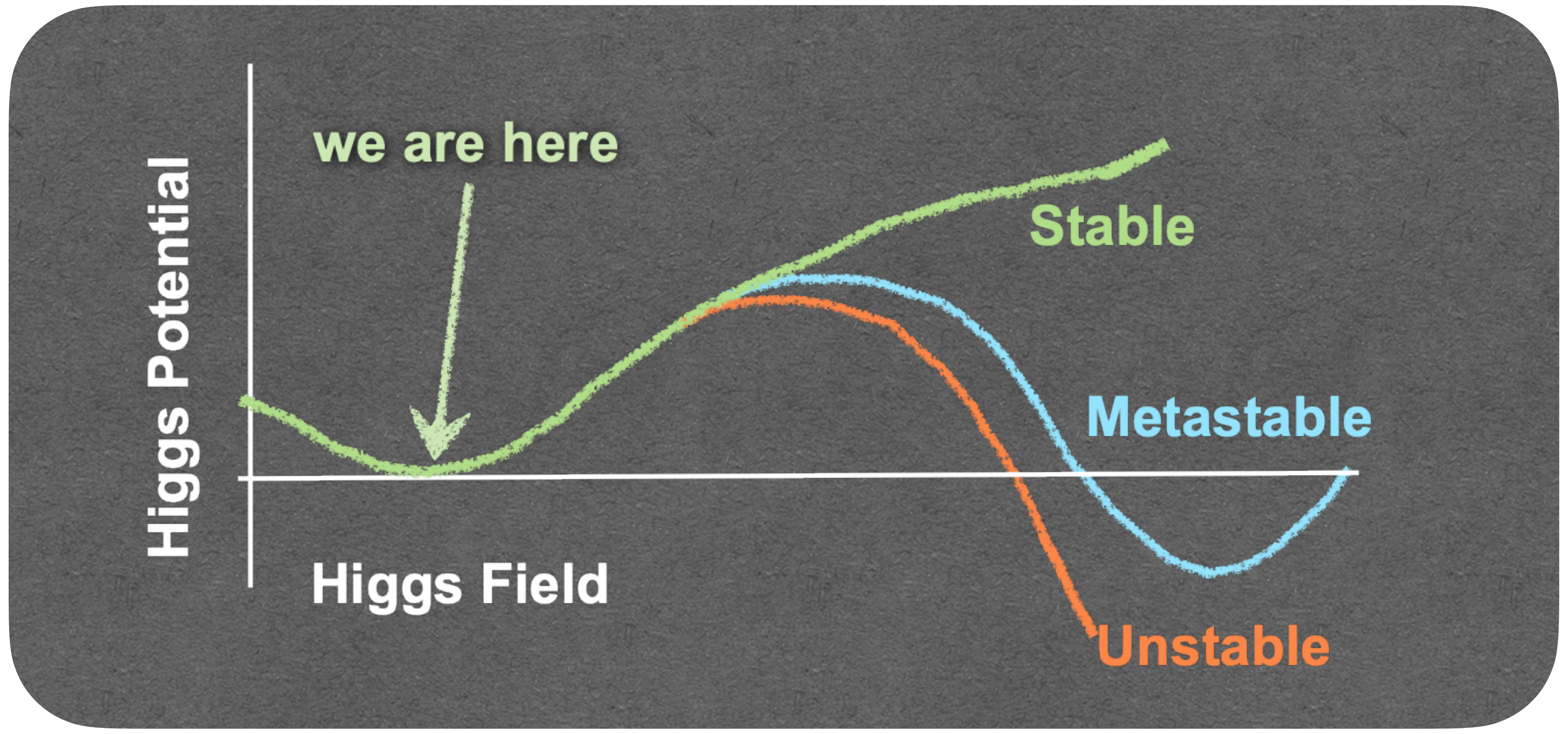
Top run at FCC-ee



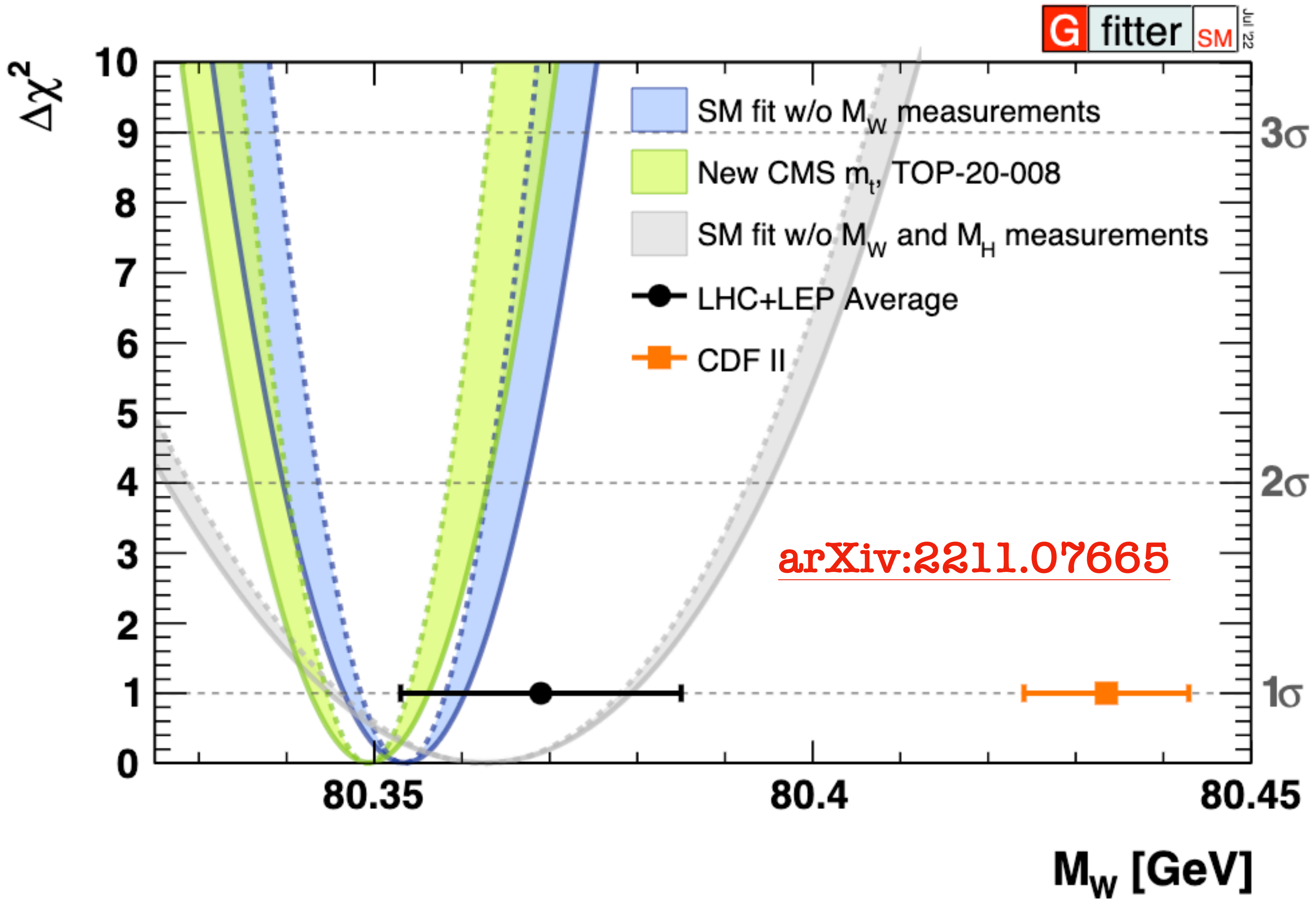
- Top physics run foreseen as an upgrade after the Z, WW, ZH runs
- Important to build **strong physics case for top physics run**

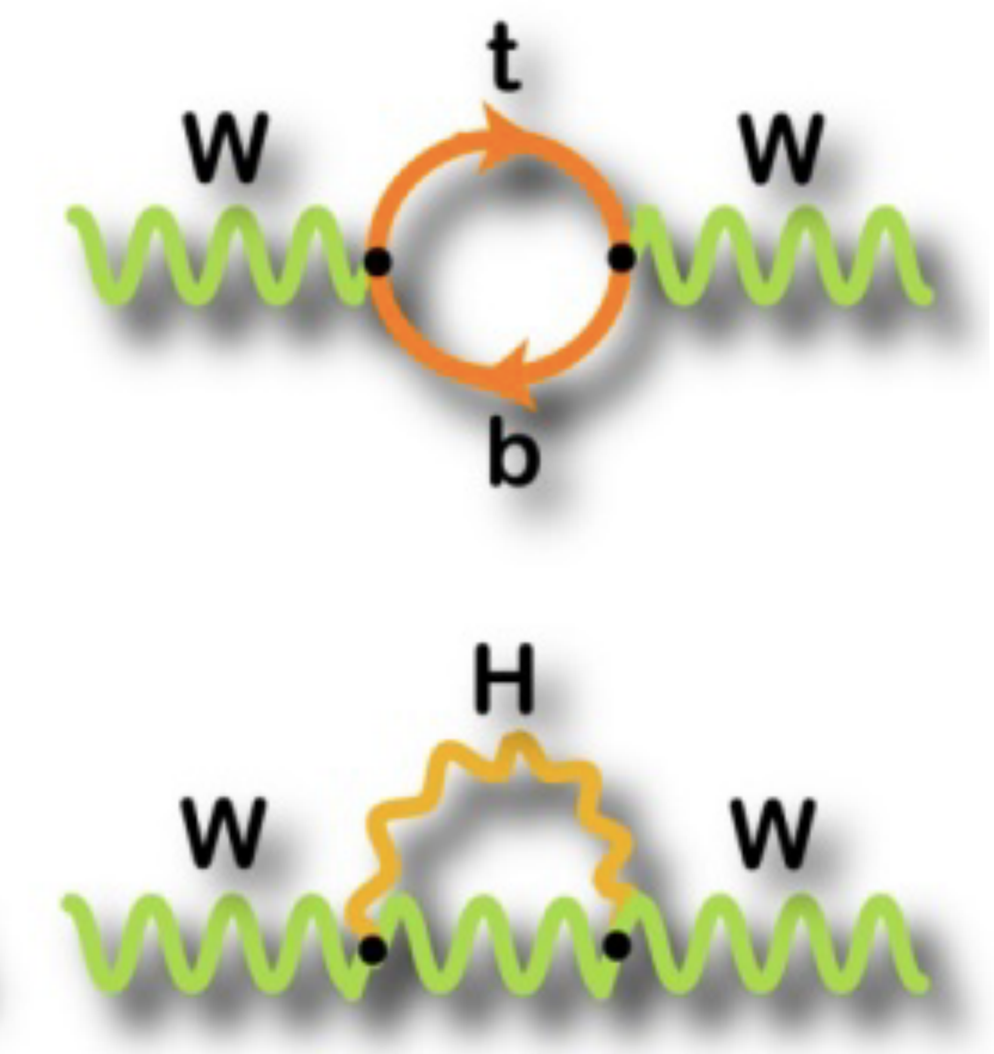
The role of the top quark mass in the (B)SM

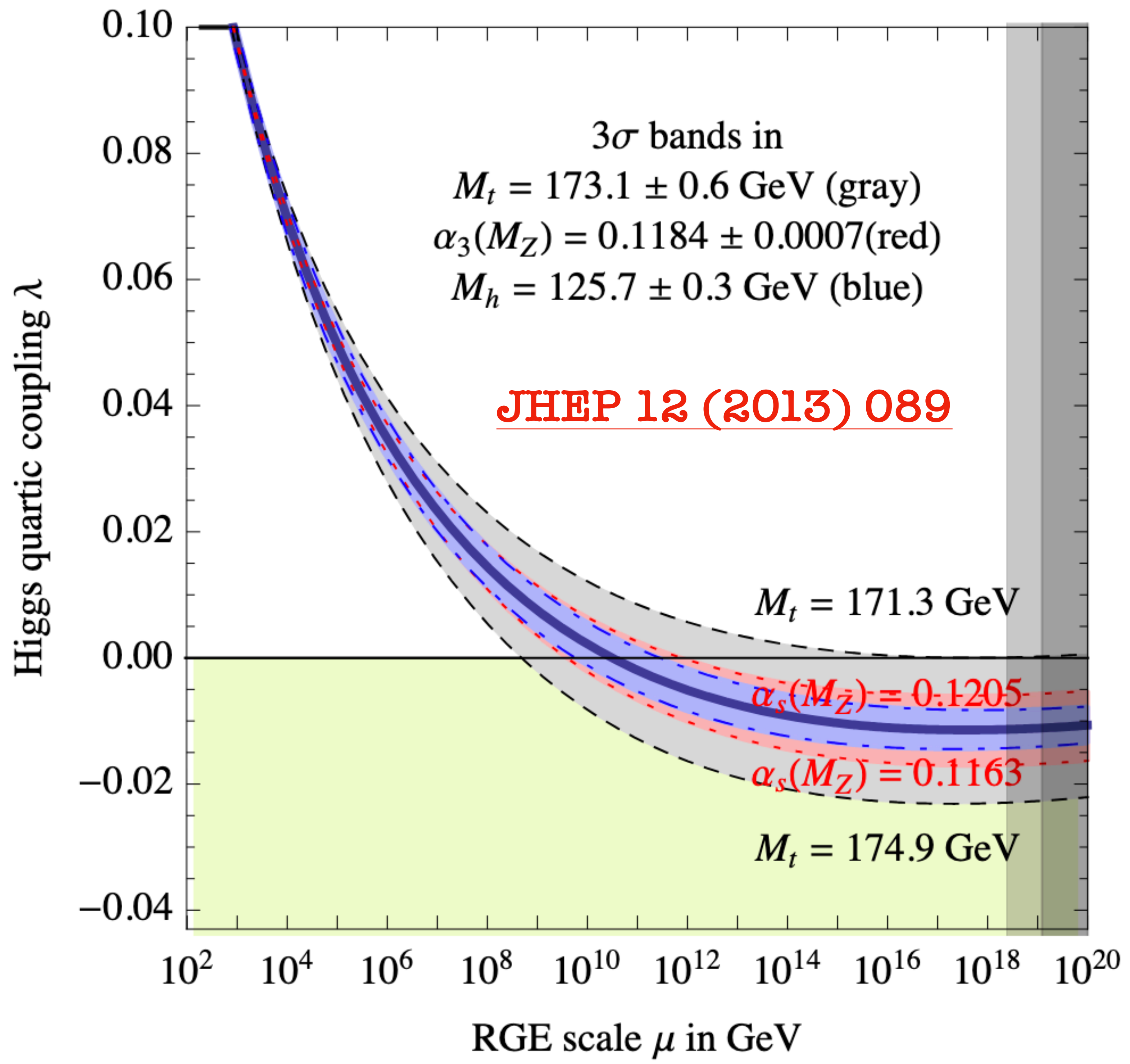
- In the SM, m_t can be related to m_W and m_H thanks to loop corrections -> **internal consistency of SM**
- **Stability of EW potential** at the Planck scale depends on value of m_t, m_H, and α_s via RGE for λ



Imperative to match enormous improvements expected for m_W, m_H, and α_S at e^+e^- colliders



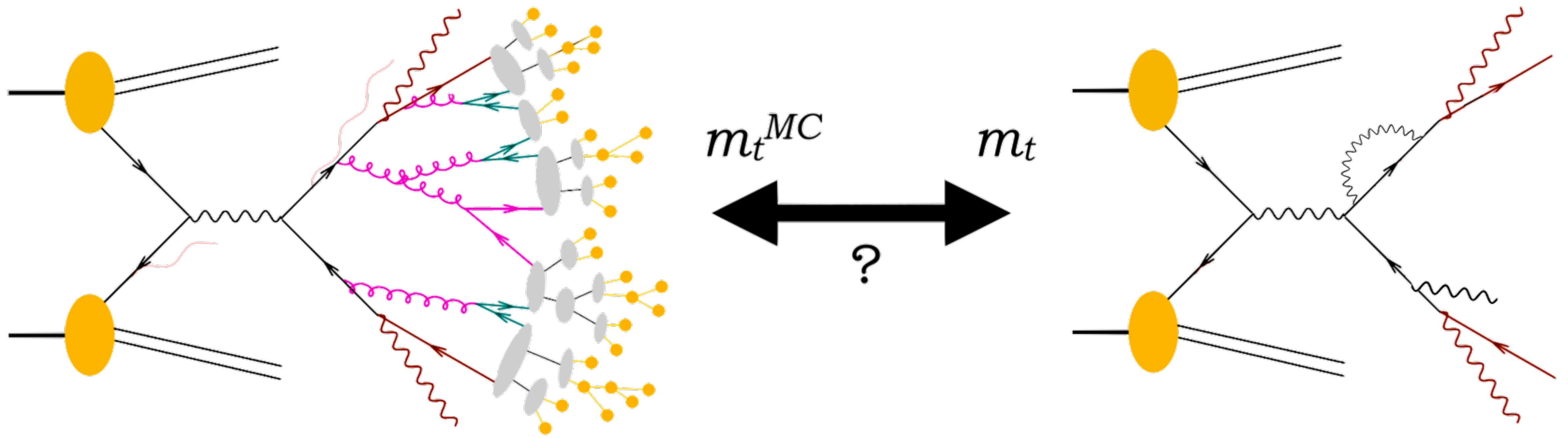




Precision target for m_t

Direct measurements at LHC

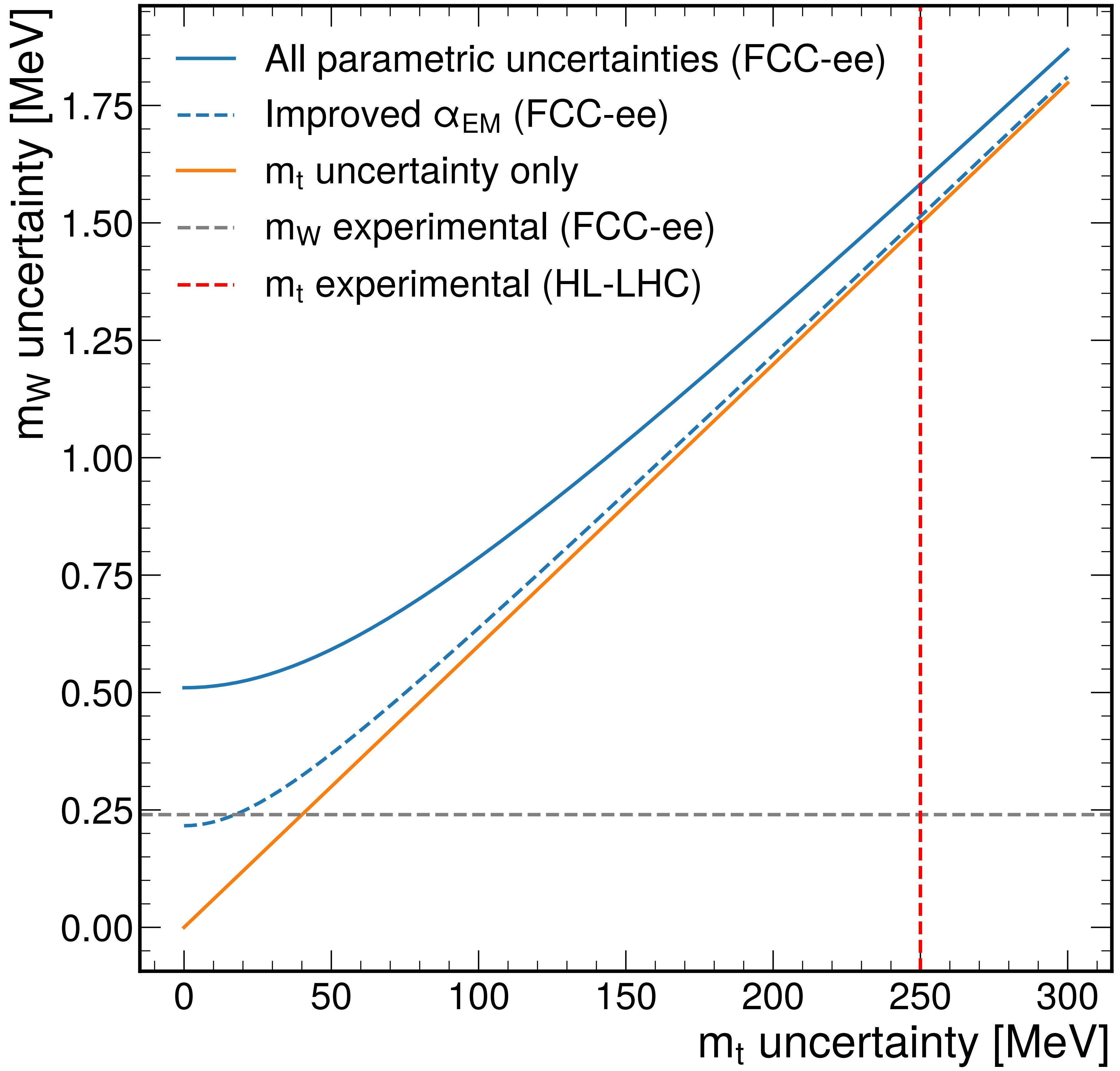
- Most precise measurements: **300 MeV**
- Debated theoretical interpretation



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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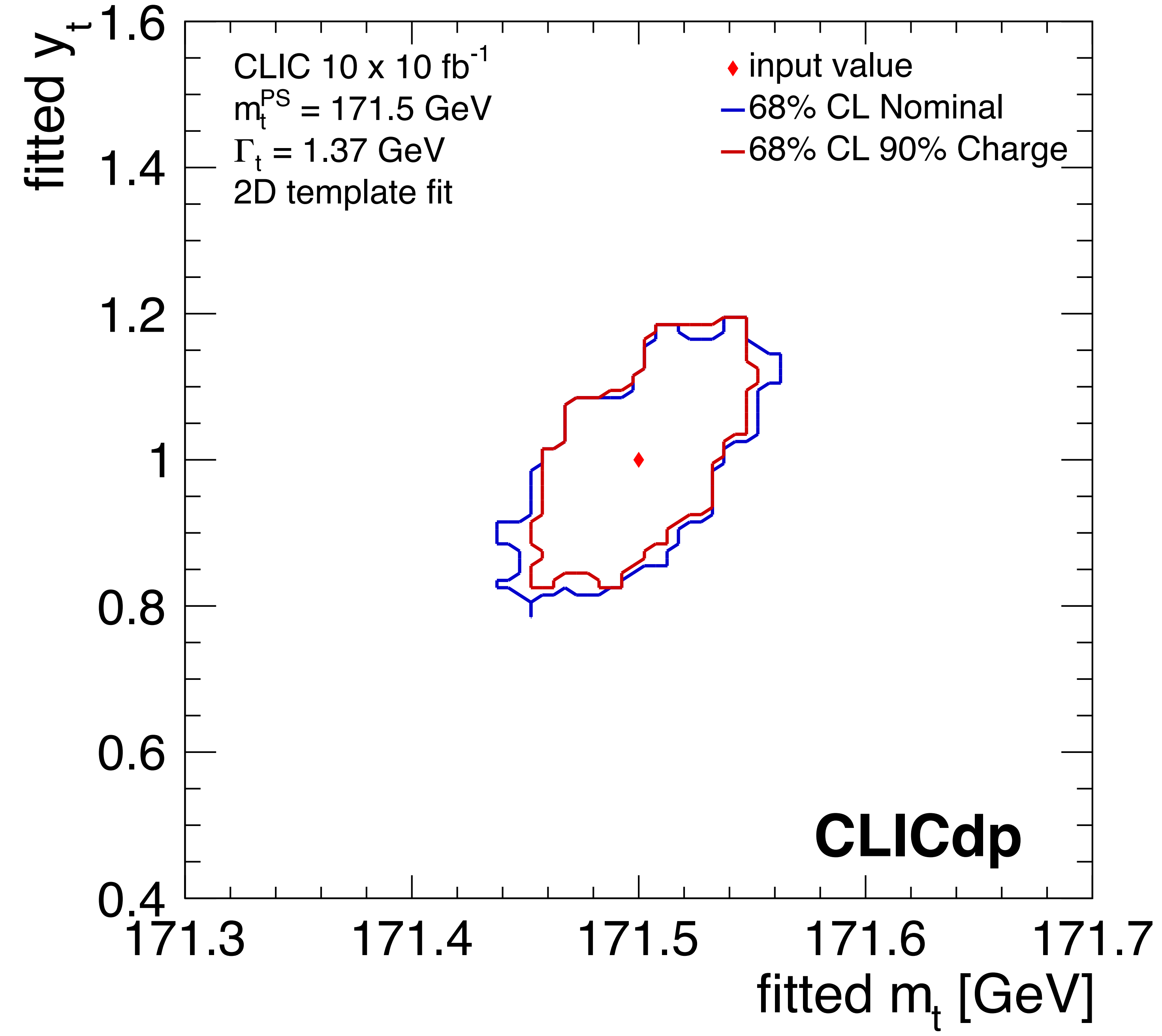
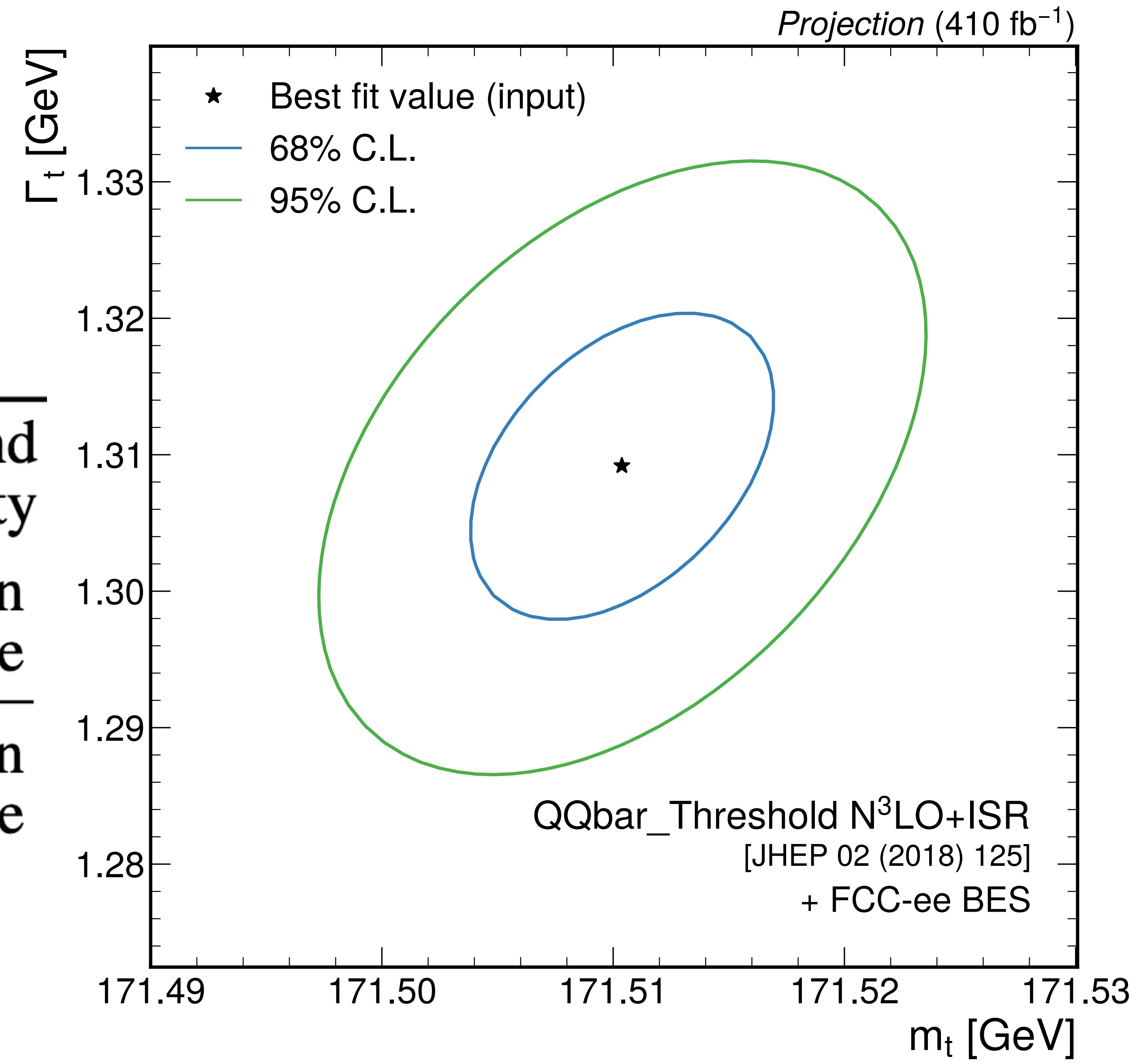
CLIC, 100 fb^{-1}

- 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 $m_t + \Gamma_t + y_t$ 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

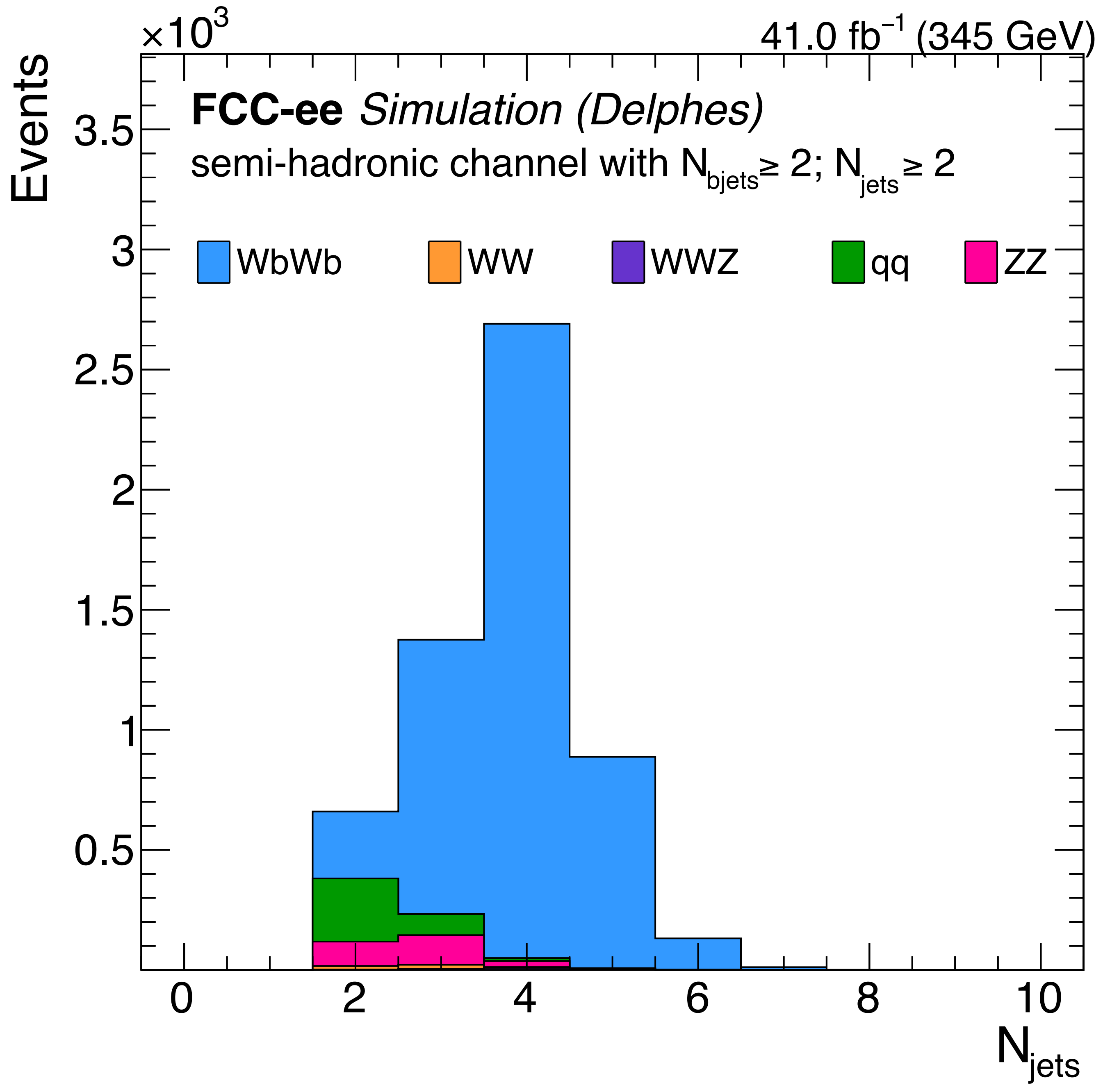


Factor 2 better than (rescaled) LC @ 400 fb^{-1}

FCC-ee detector-level studies

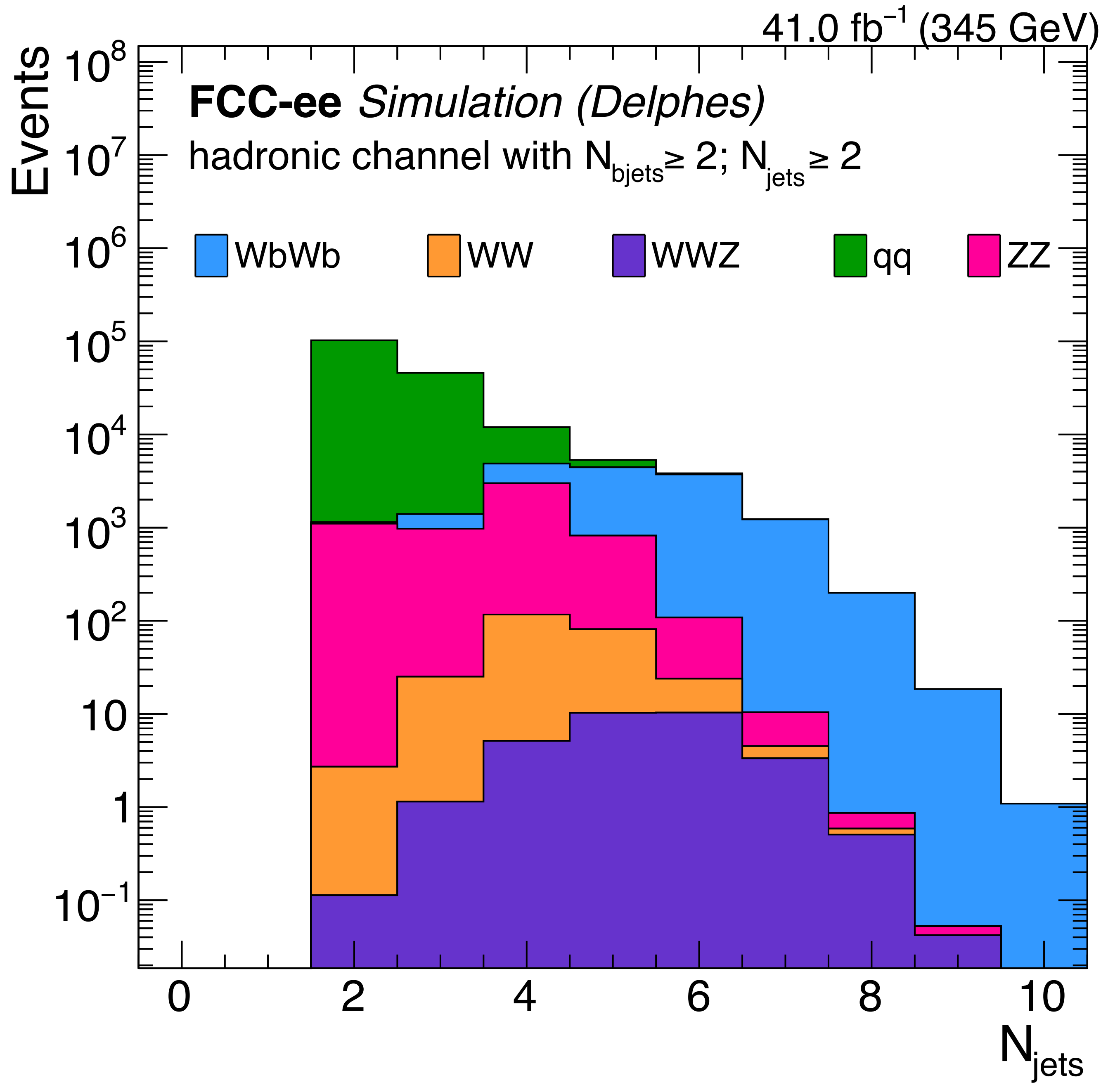
- **Hadronic** and **semi-hadronic** final states of WbWb decays (>80% branching ratio in total)

- Profile-likelihood fit in **jet and b-tag multiplicity** to extract total rates -> determine b-tagging efficiency in-situ

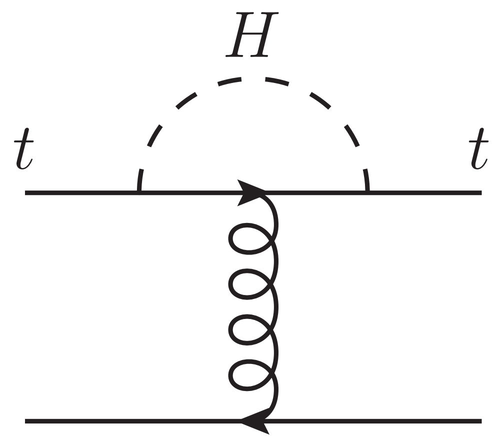


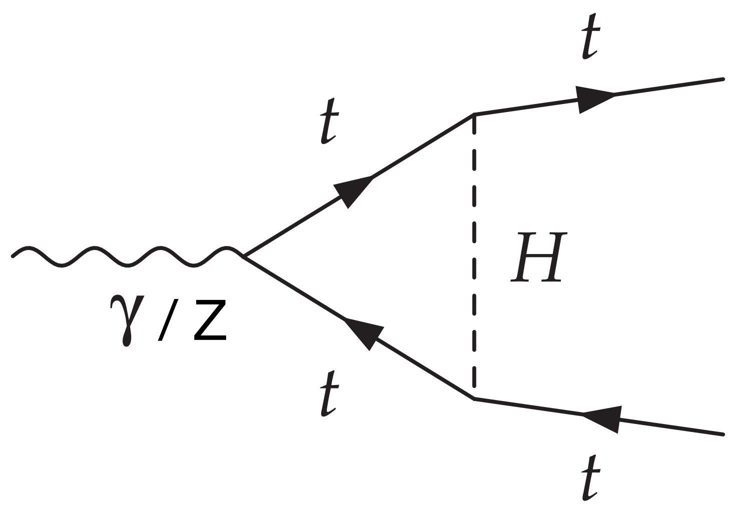
- Highly pure and almost fully efficient signal selection can be achieved in all channels
- Relevant systematic effects controlled well below statistical uncertainty

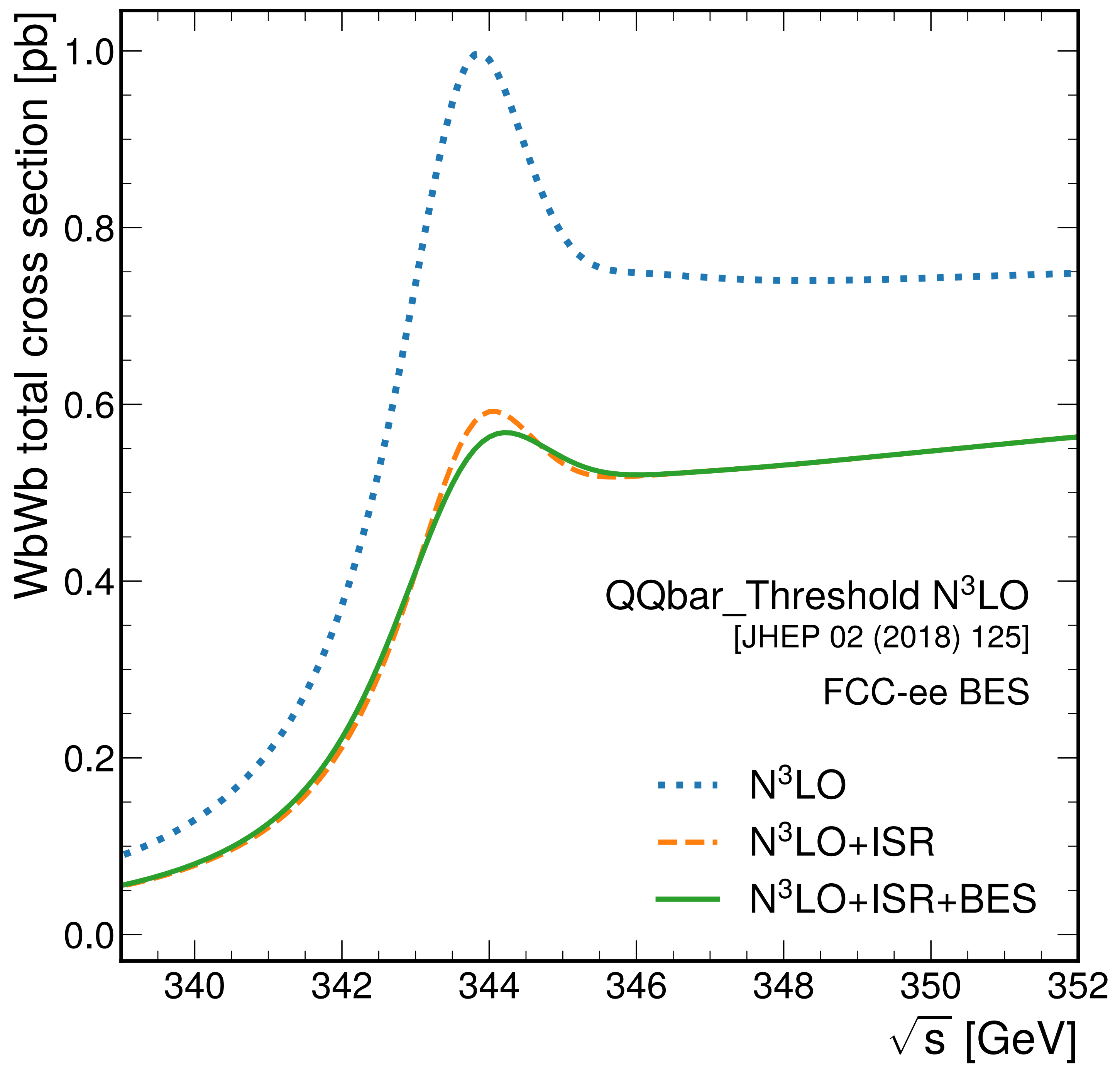
Uncertainty source	Impact on σ_{WbWb} [%]		
	340 GeV	345 GeV	365 GeV
Integrated luminosity	0.12	0.11	0.02
b tagging	0.11	0.06	0.01
ZZ had. norm.	0.46	0.19	0.04
ZZ semihad. norm.	0.23	0.07	0.03
WW had. norm.	0.17	0.09	0.02
WW semihad. norm.	0.06	0.04	0.03
$q\bar{q}$ had. norm.	0.12	0.09	0.02
$q\bar{q}$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

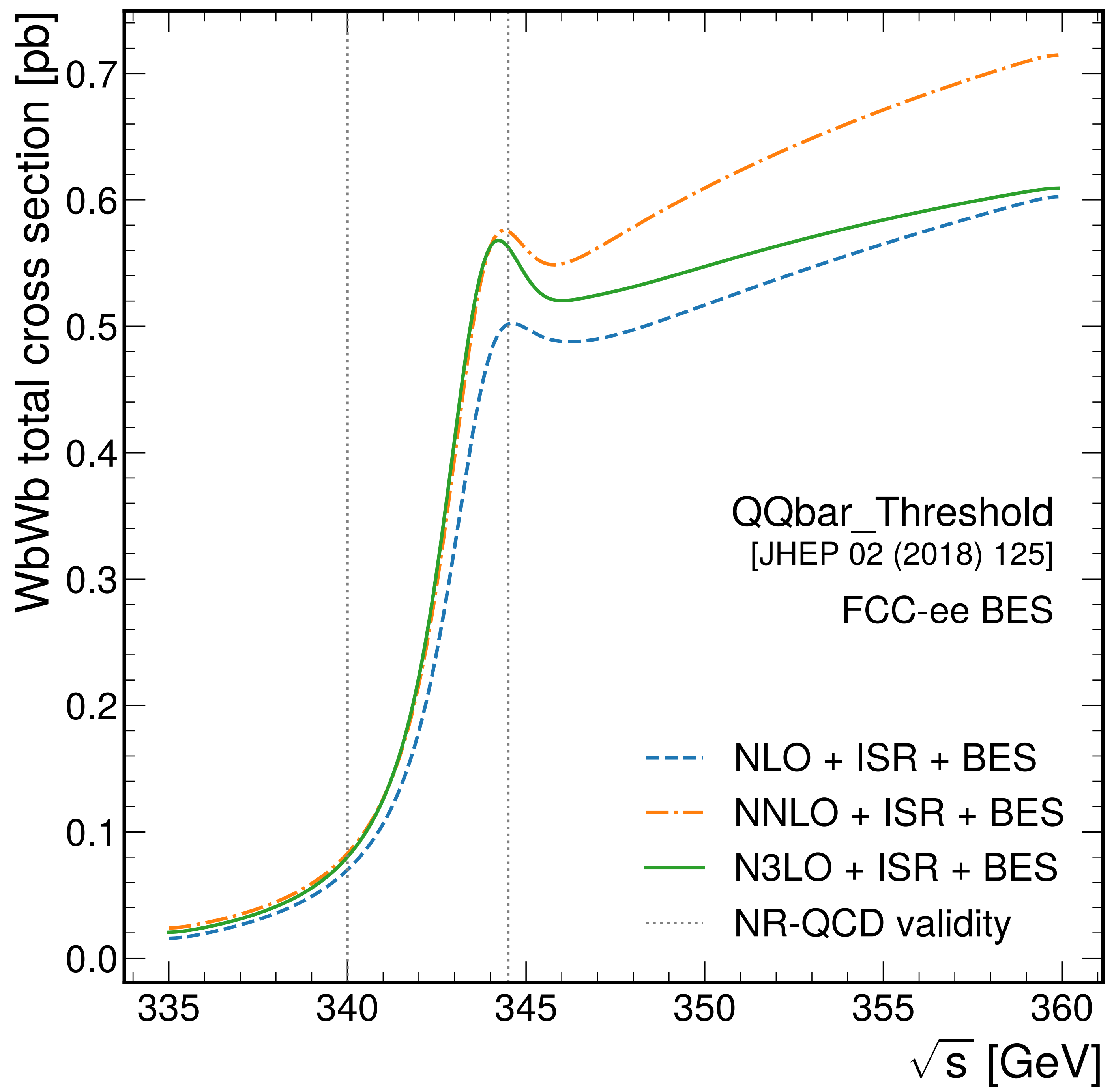


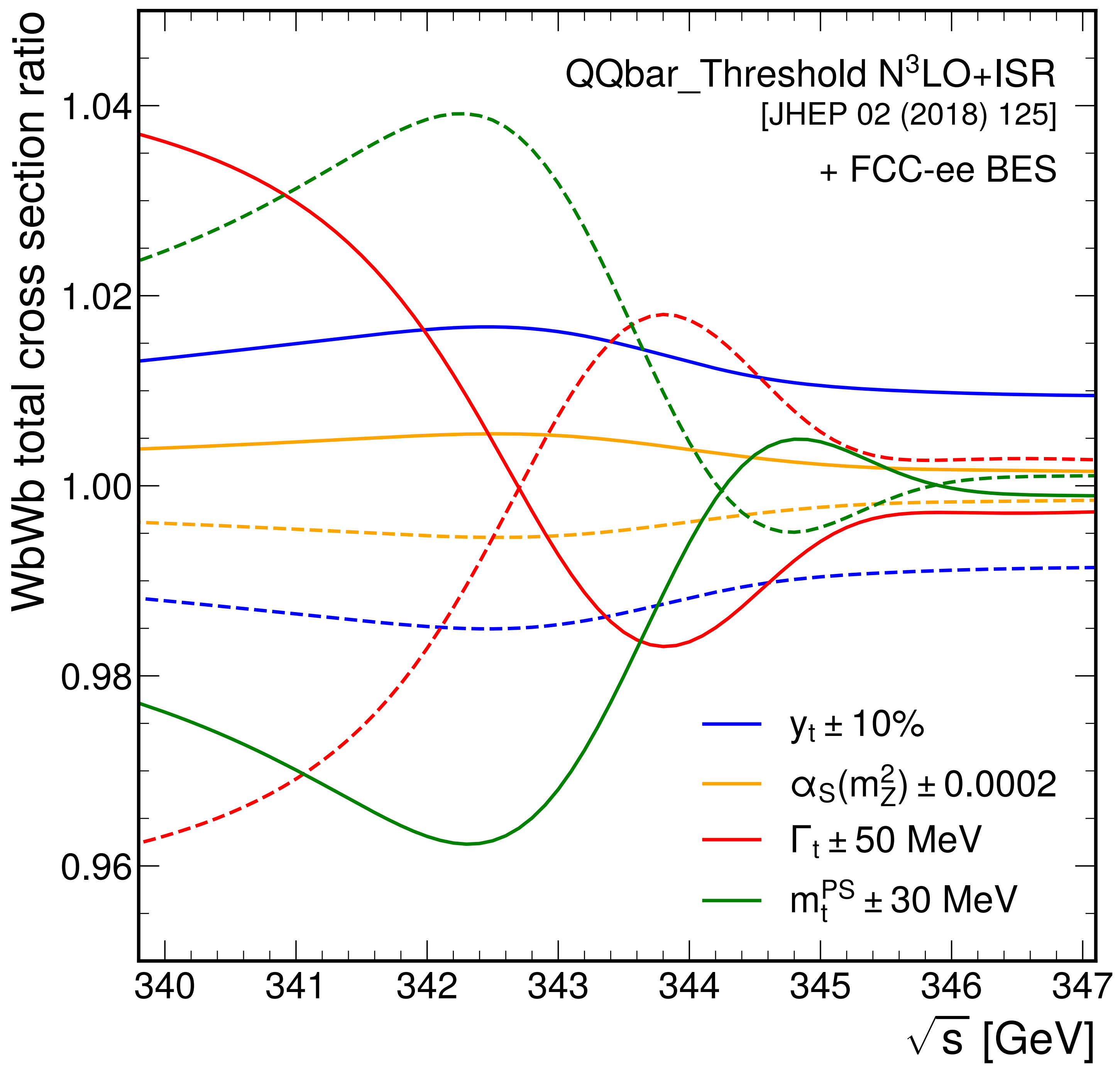
Theoretical calculation











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

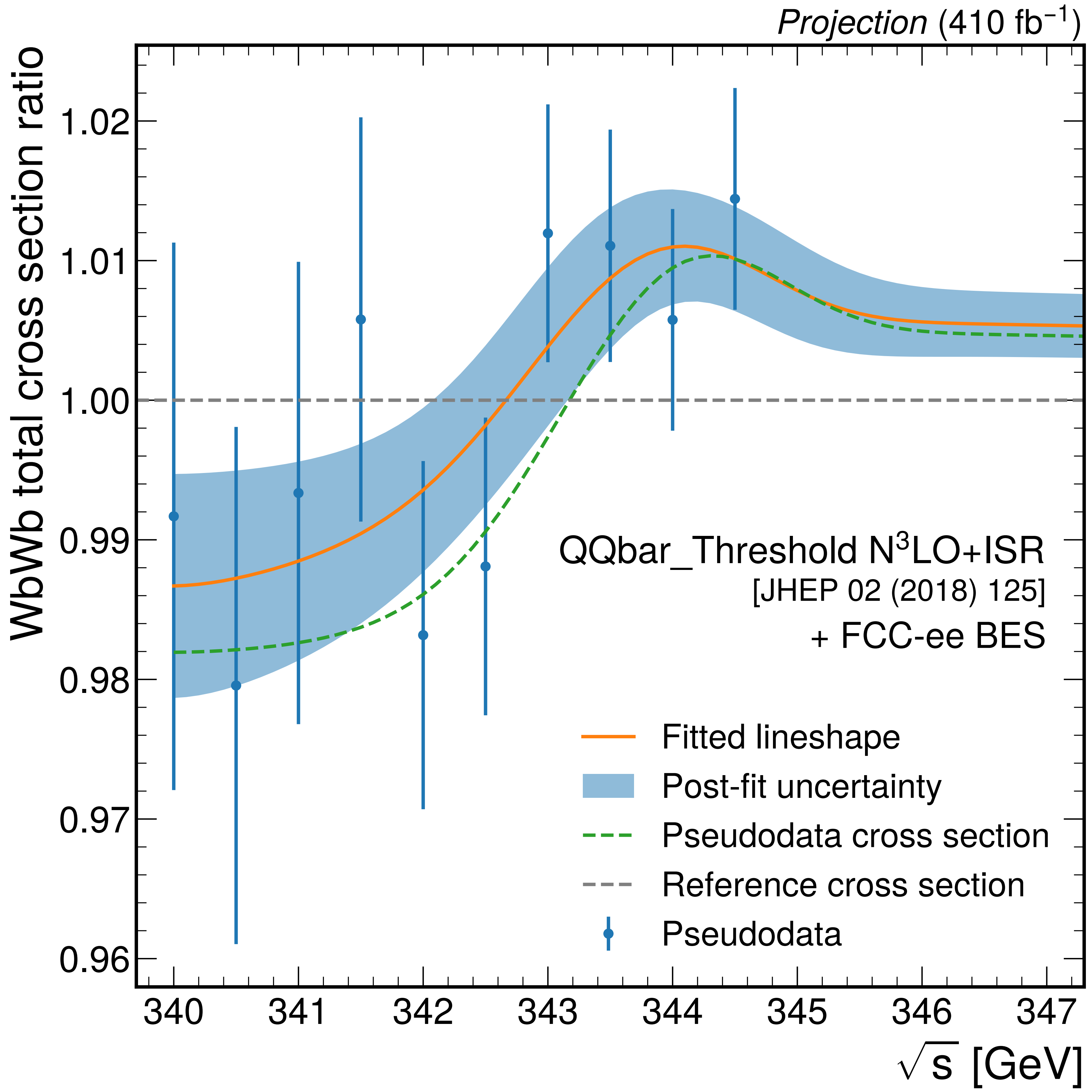
- Calculation only valid in the vicinity of threshold, where the sensitivity to the parameters lies

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}

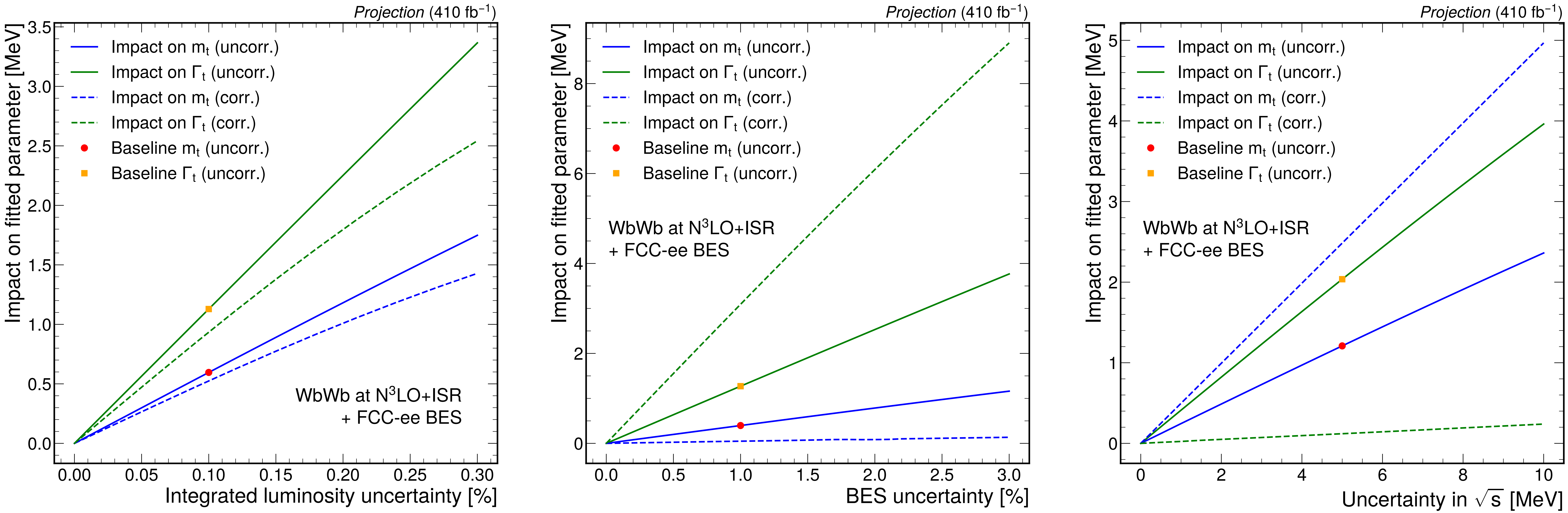
Uncertainty source	m_t^{PS} [MeV]	Γ_t [MeV]	y_t [%]
Experimental (stat. ×1.2)	4.2	10.0	1.5
Parametric m_t	–	5.3	1.2
Parametric Γ_t	3.0	–	0.8
Parametric y_t	3.8	4.8	–
Parametric α_S	2.2	1.6	0.2
Luminosity calibration (uncorr.)	0.6	1.1	0.2
Luminosity calibration (corr.)	1.0	0.7	0.9
Beam energy calibration (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

Uncorrelated = of statistical nature

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

First study of this kind for tt threshold scan

Comparison with previous CEPC studies

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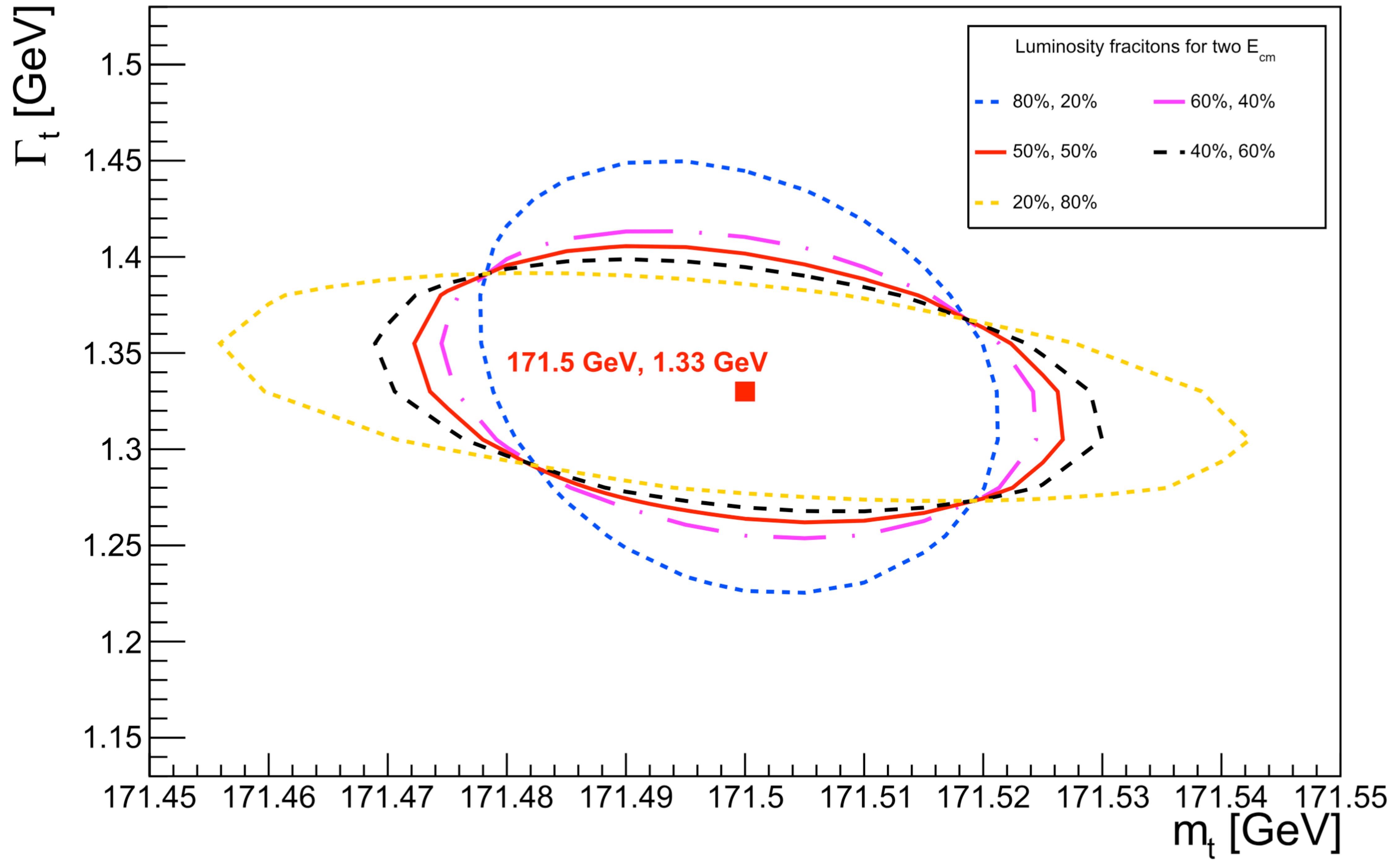


- Strategy: "**quick scan**" with 10% of total lumi and 6 energy points to obtain first determination of parameters
- Select two optimal energy points to maximize precision and minimize correlations
- Disadvantage: choice of optimal points heavily relies on theoretical prediction

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

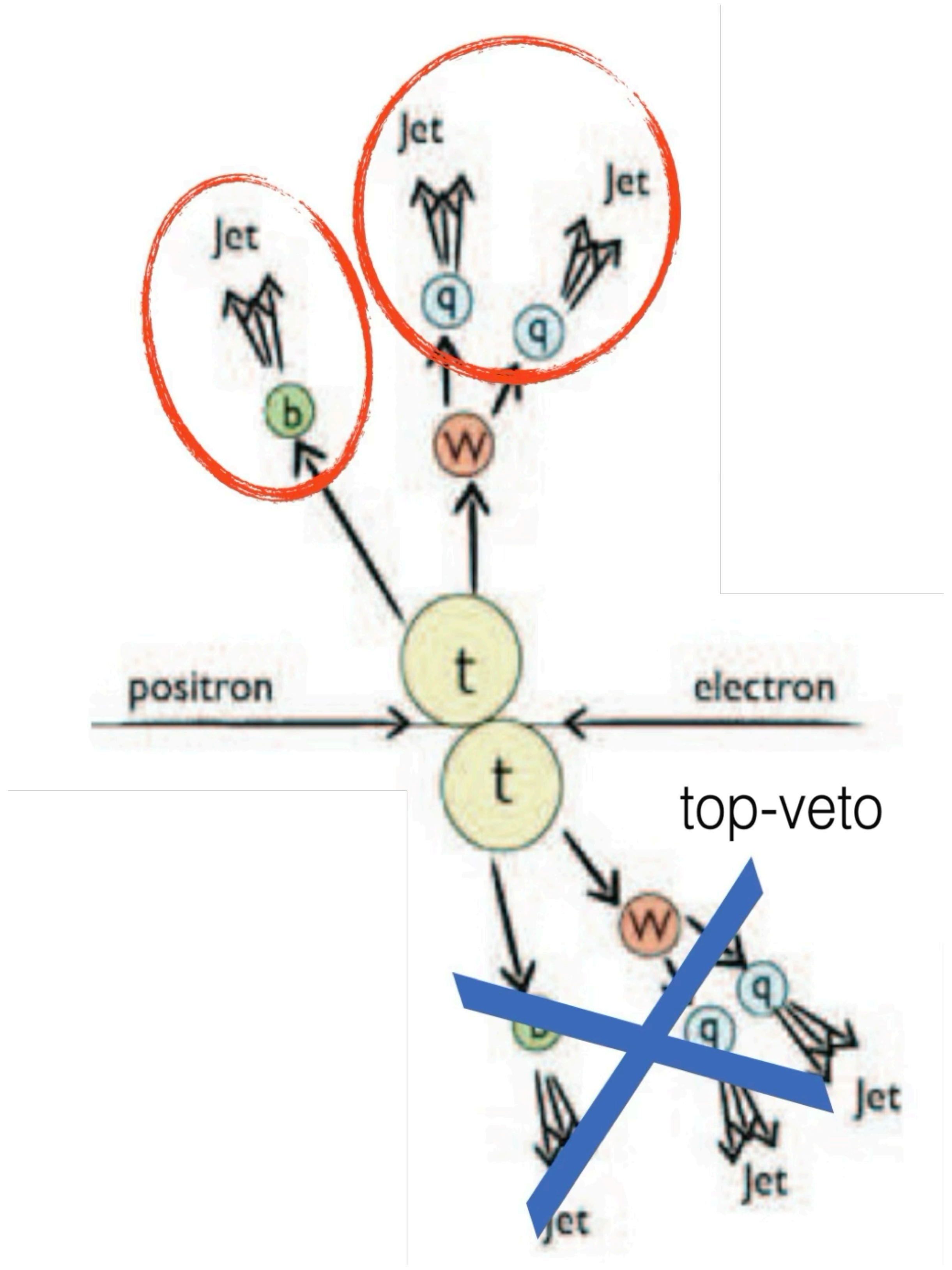
- Same ballpark uncertainty as FCC-ee result, despite very different assumptions and strategies
- Estimate of theoretical uncertainty seems optimistic
- Dependence on top Yukawa coupling to be assessed
- α_S uncertainty can be improved (similarly to FCC-ee)

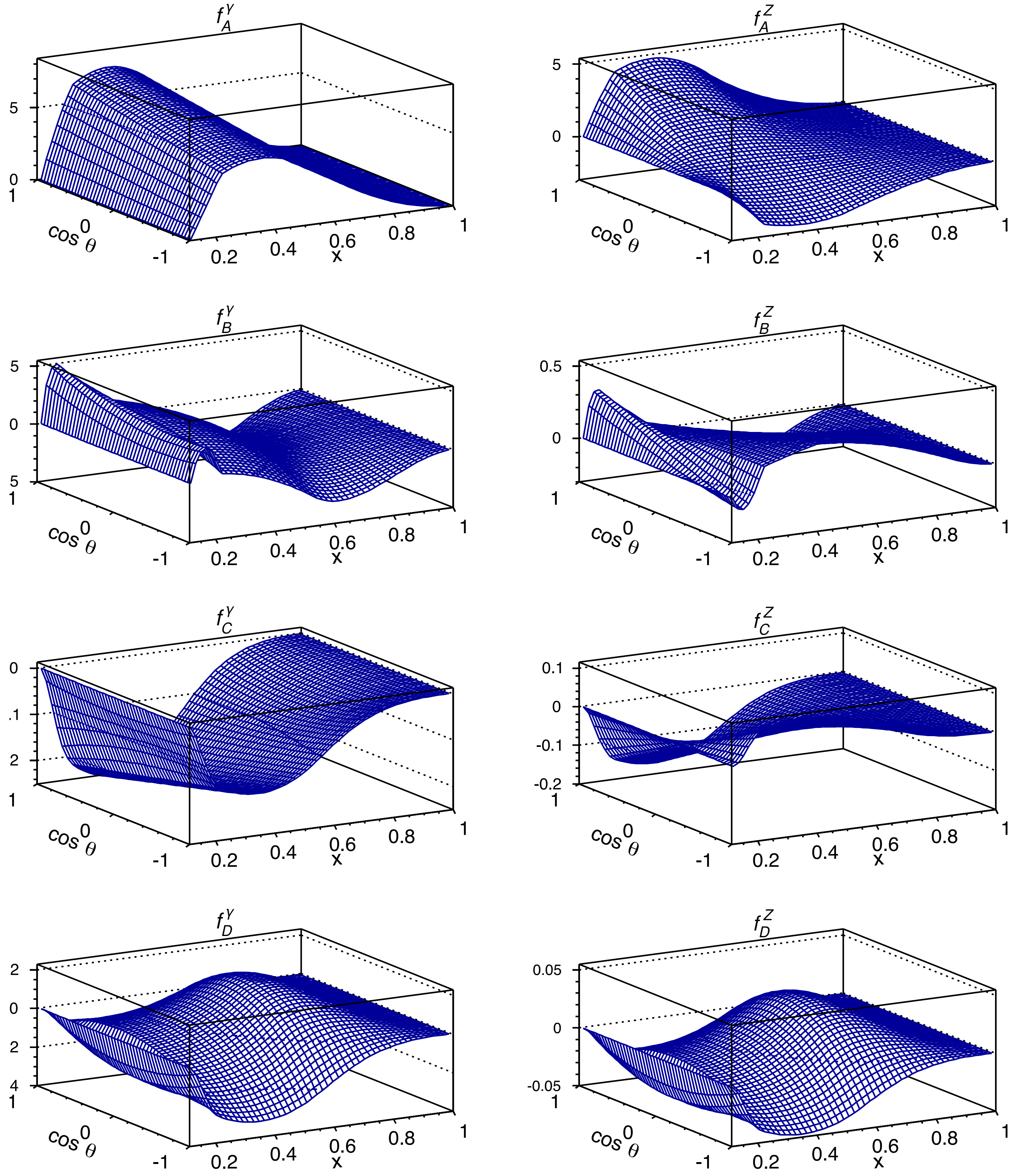
Top physics at 365 GeV

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

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

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



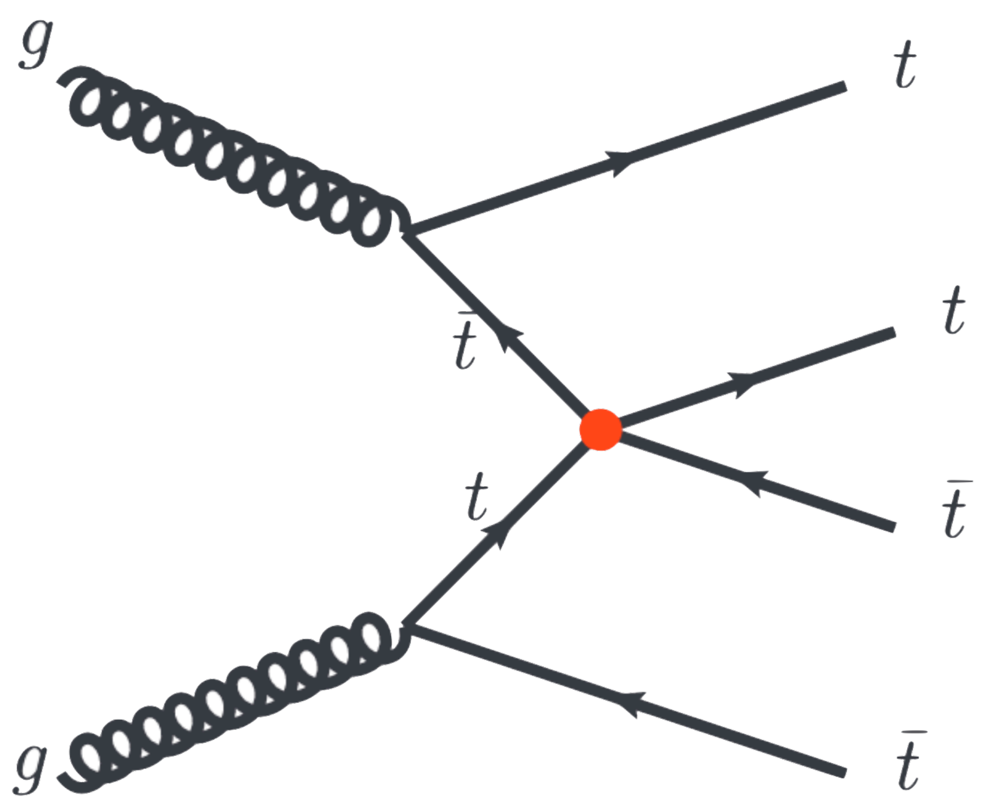


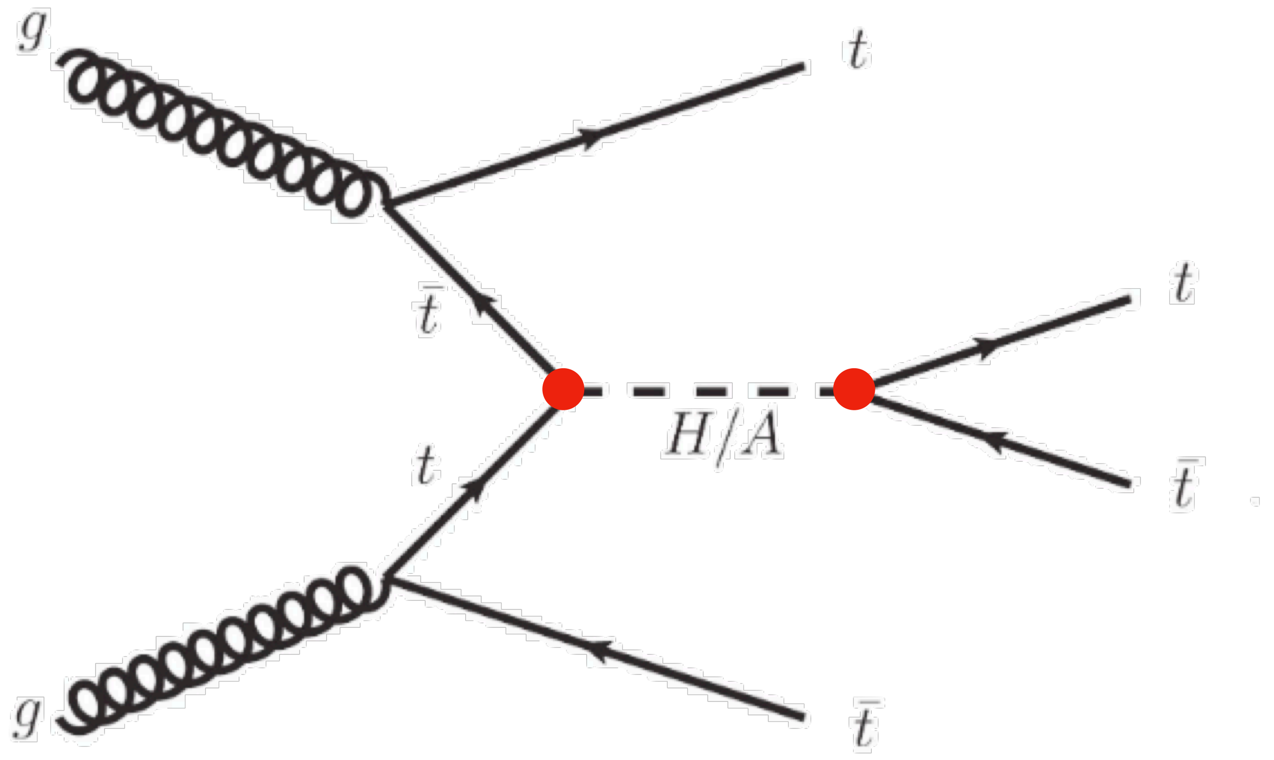
- Model-independent searches for **BSM top decays** are hard to conceive at hadron colliders
- **Room for a few % exotic BR** for a top with uncertainty of order 10 MeV
- Can be probed with order 10^6 tt events

Top physics at FCC-hh: 4t production

Heaviest process observed at LHC
-> more favorable S/B at higher centre-of-mass energies

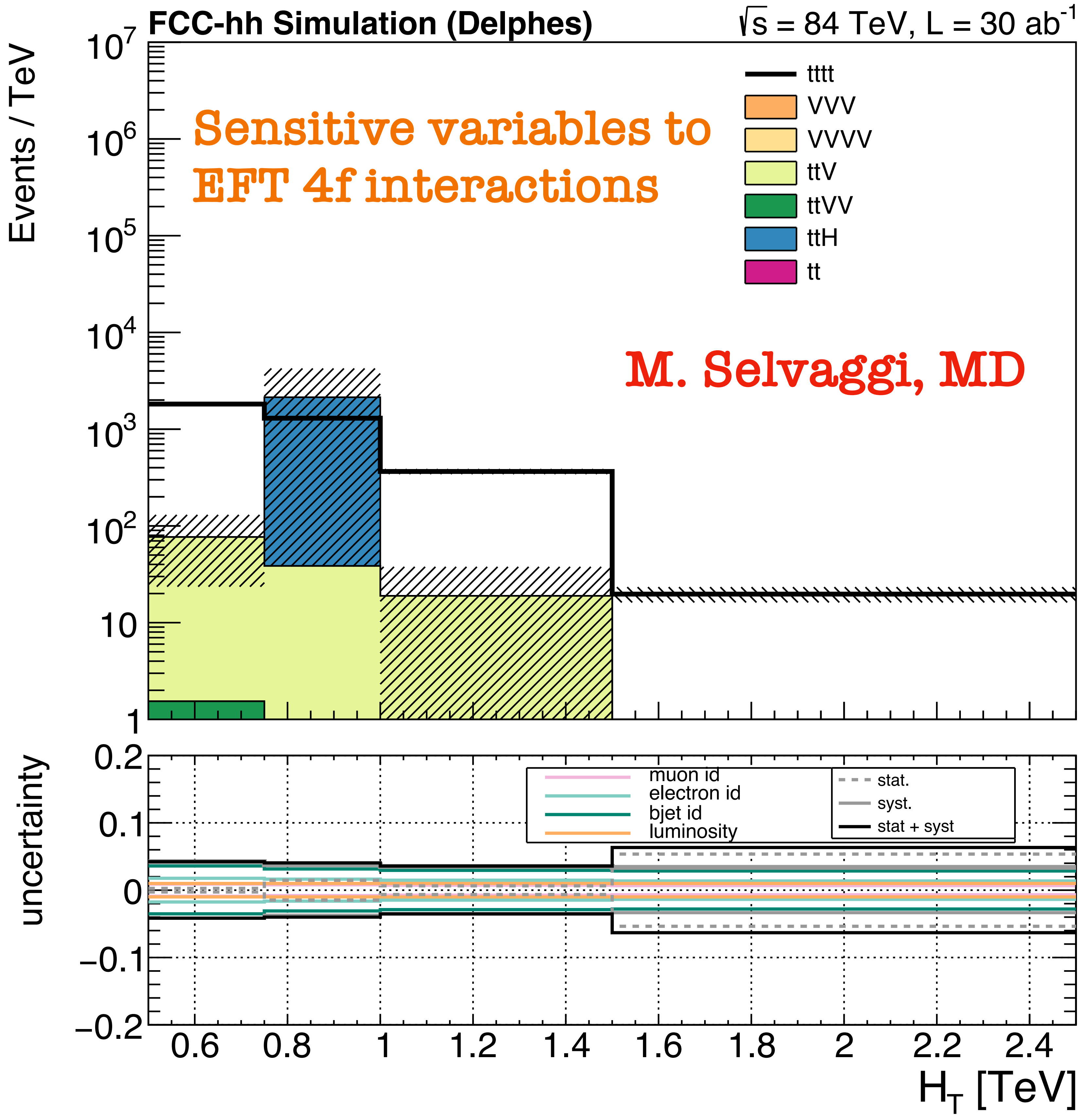
Particularly sensitive to **top self-interaction** (energy-growing effect)





- Additional sensitivity to top Yukawa coupling
  -> complementary to ttH

- Tool to access top-philic BSM physics at the TeV scale



Extremely pure selection can be achieved at FCC-hh by restricting to (very exclusive) $e^\pm e^\pm \mu^\mp \mu^\mp$ channel

- ttZ background strongly suppressed by charge requirement
- Requires good control over lepton charge and non-prompt leptons

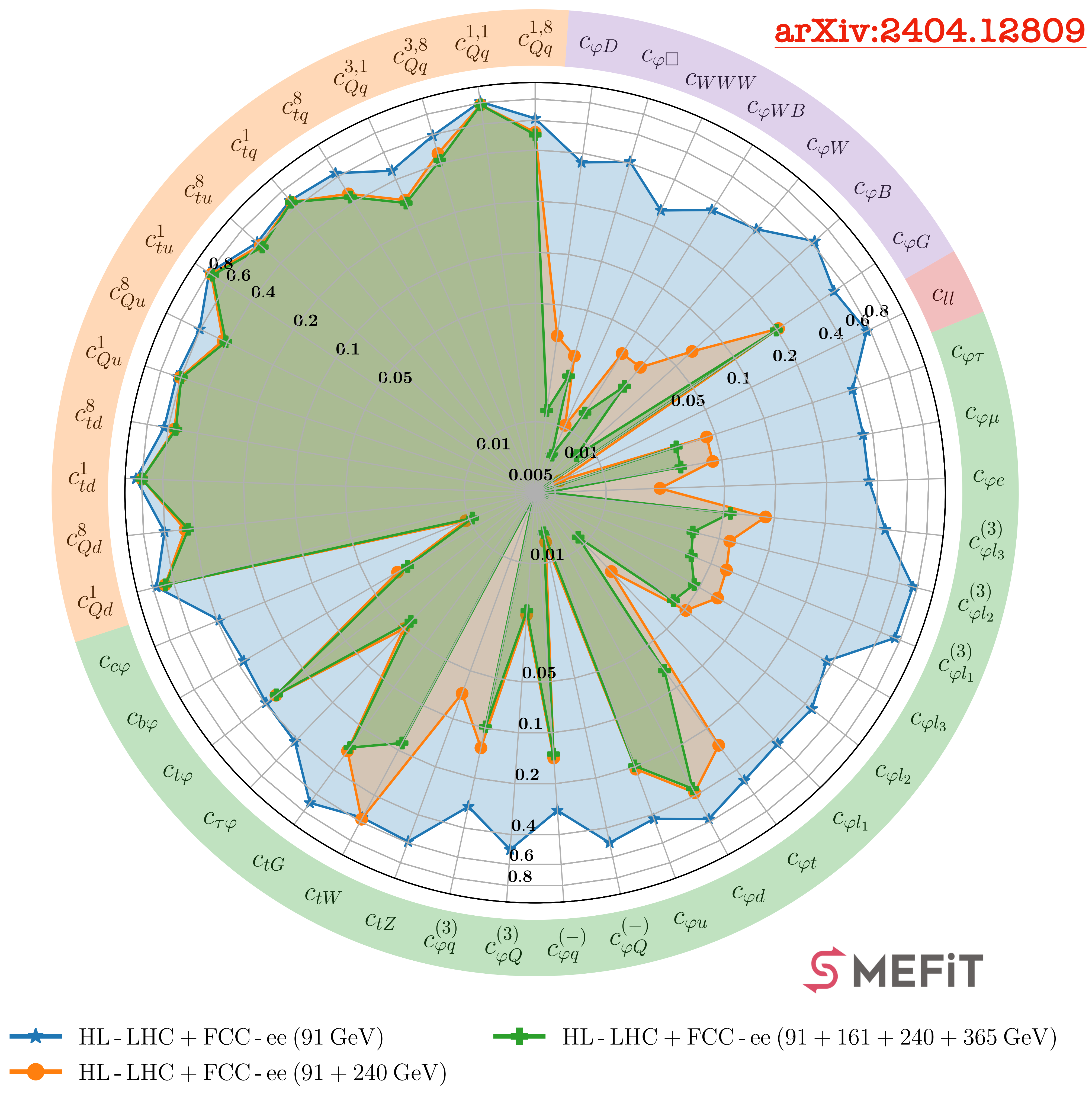
Summary and outlook

FCC-ee top run also has strong impact in global interpretations (not covered in this talk)

- **Outlined physics case for a tt threshold run at FCC-ee**
- **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
- New opportunities (and challenges) for **top physics at FCC-hh** starting to be explored

Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-2}\right)$, Marginalised

arXiv:2404.12809



Thank you