Top quark properties and couplings at (and above) the $t\bar{t}$ threshold

with a focus on new results for FCC-ee

3rd ECFA workshop on e^+e^- Higgs, Top, & Electroweak Factories

9-11 October 2024, Paris

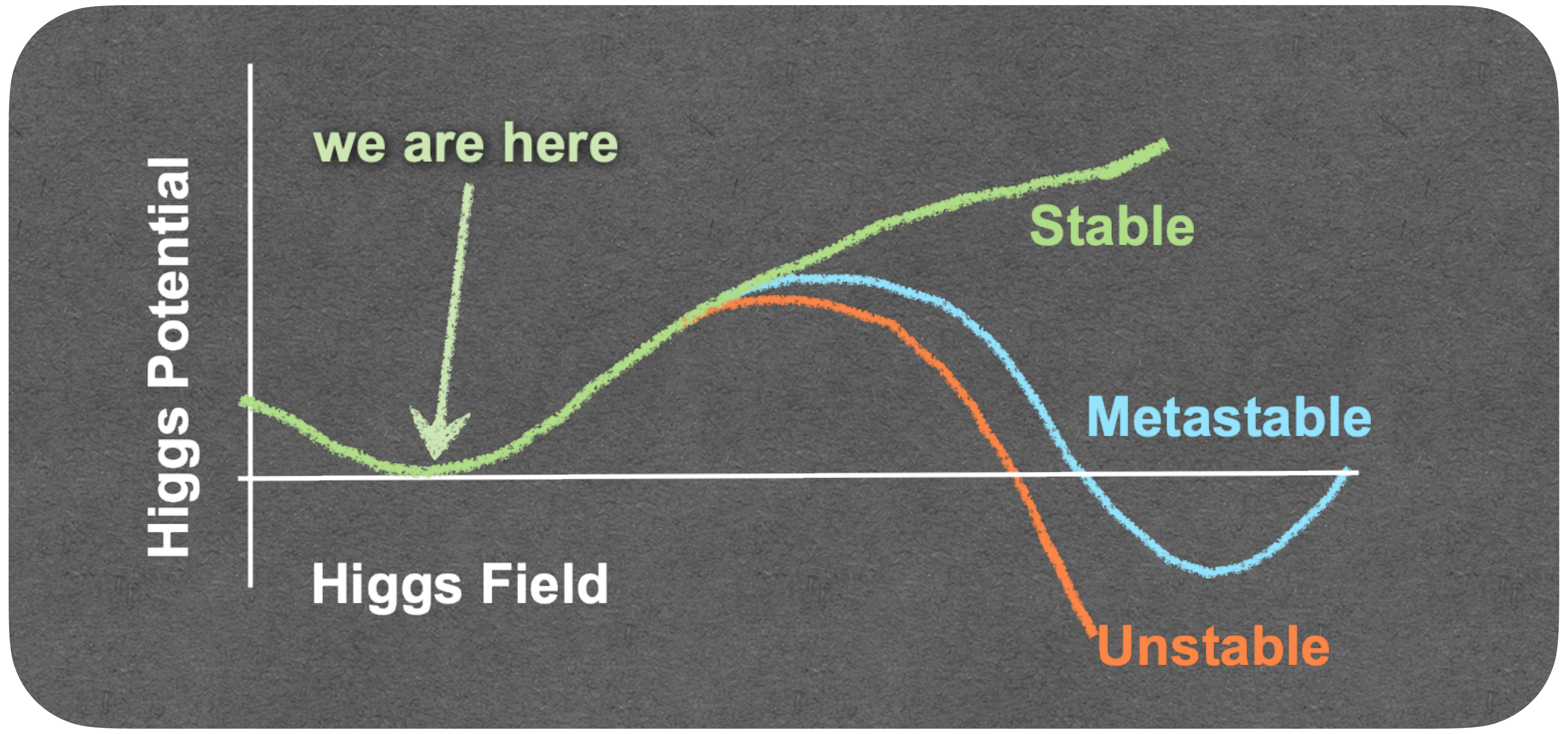
Matteo Defranchis (CERN)

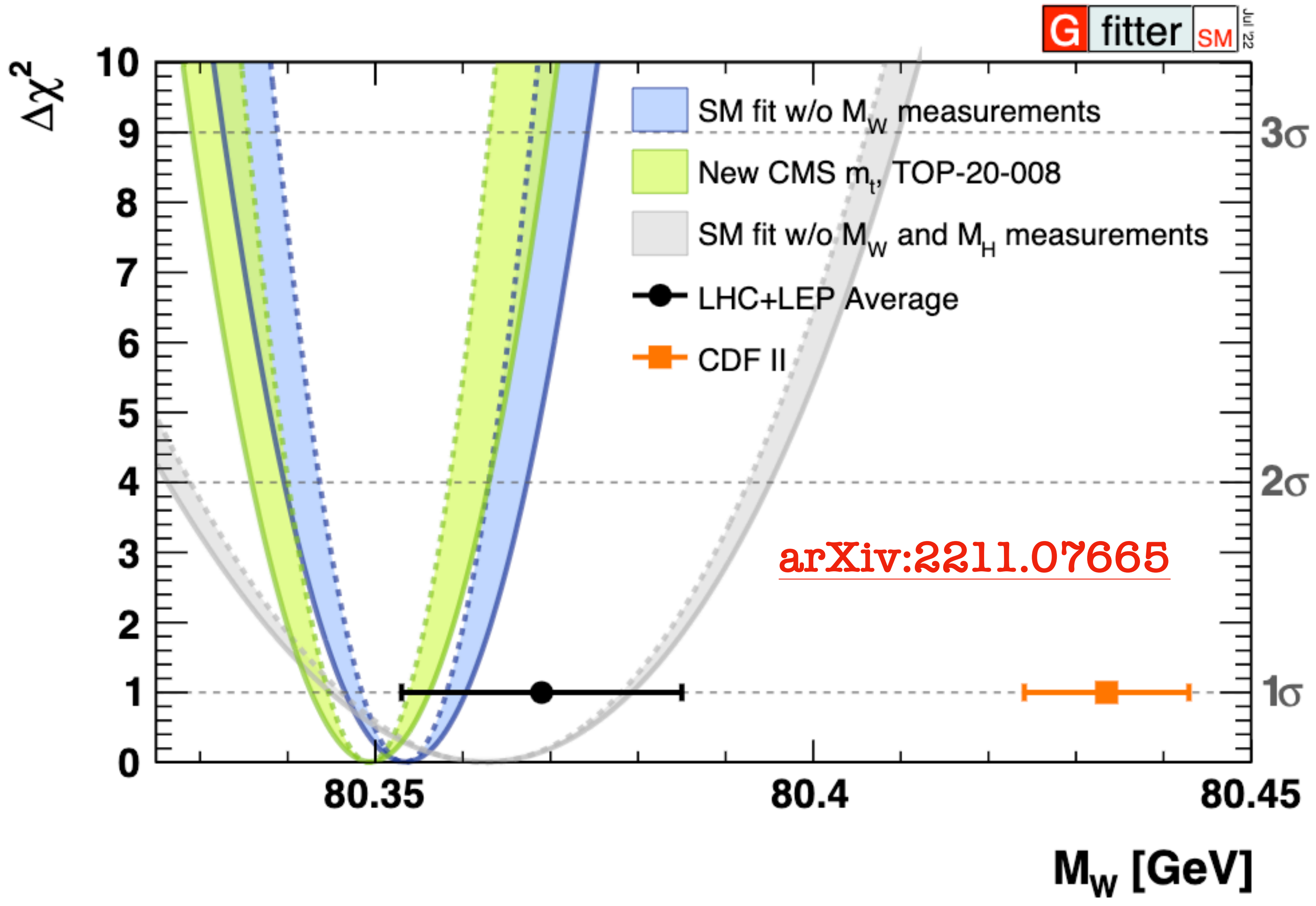
with precious input from Marcel Vos, Michele Selvaggi, Patrick Janot, Frank Simon, Martin Beneke, and many other colleagues

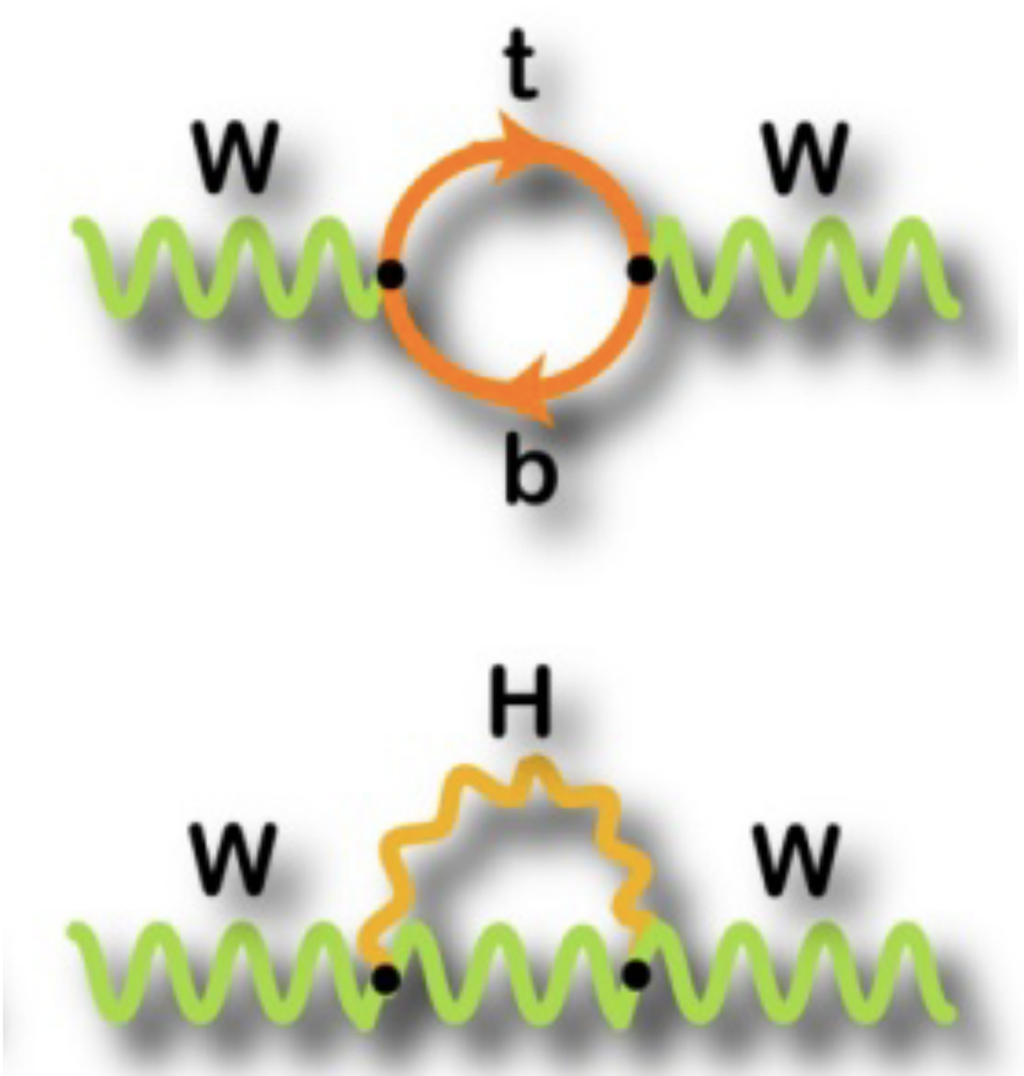
The role of the top quark mass in the (B)SM

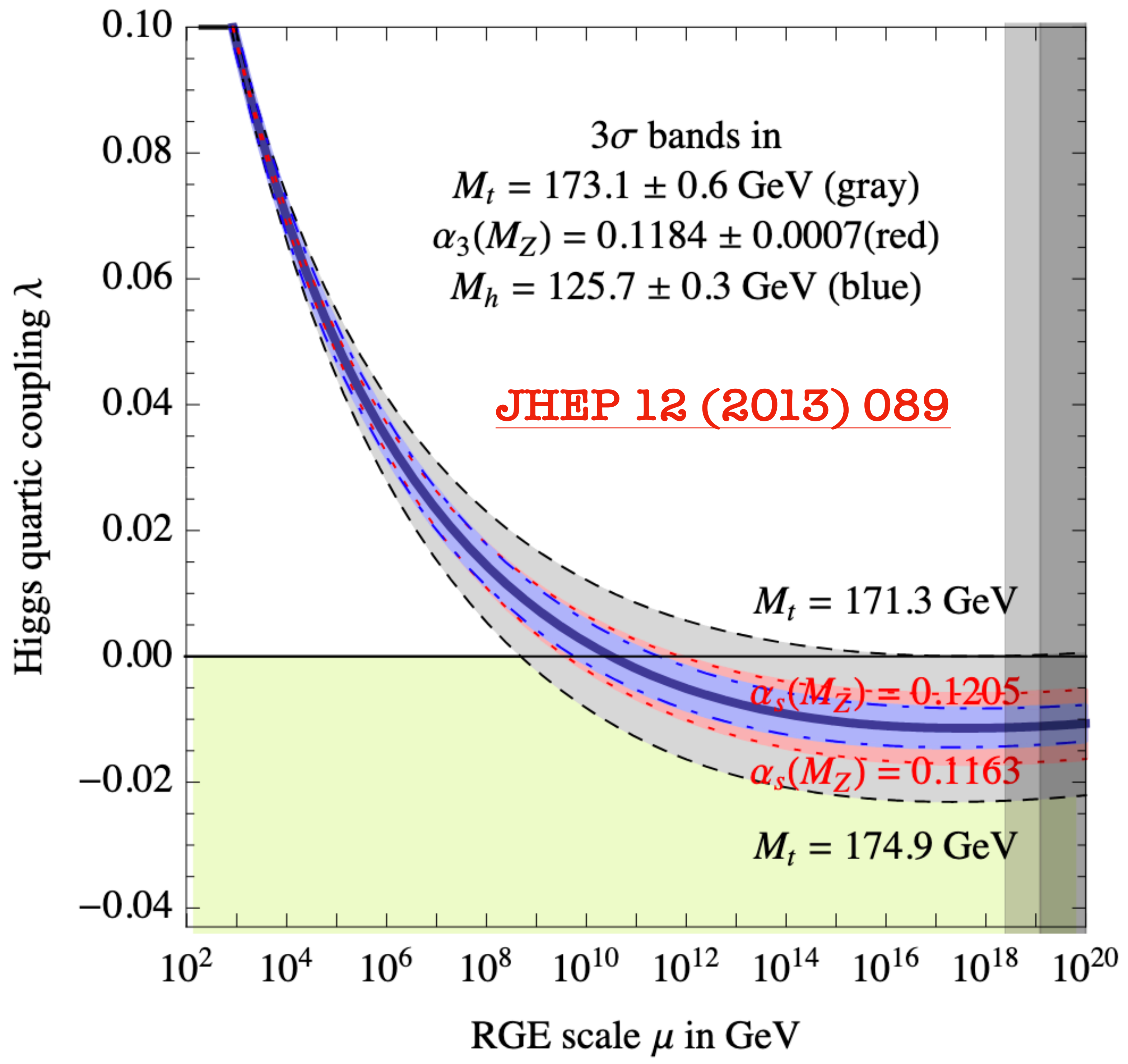
- In the SM, m_t can be related to m_W and m_H thanks to loop corrections -> **internal consistency of SM**
- **Stability of EW potential** at the Planck scale depends on value of m_t, m_H, and α_s via RGE for λ

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





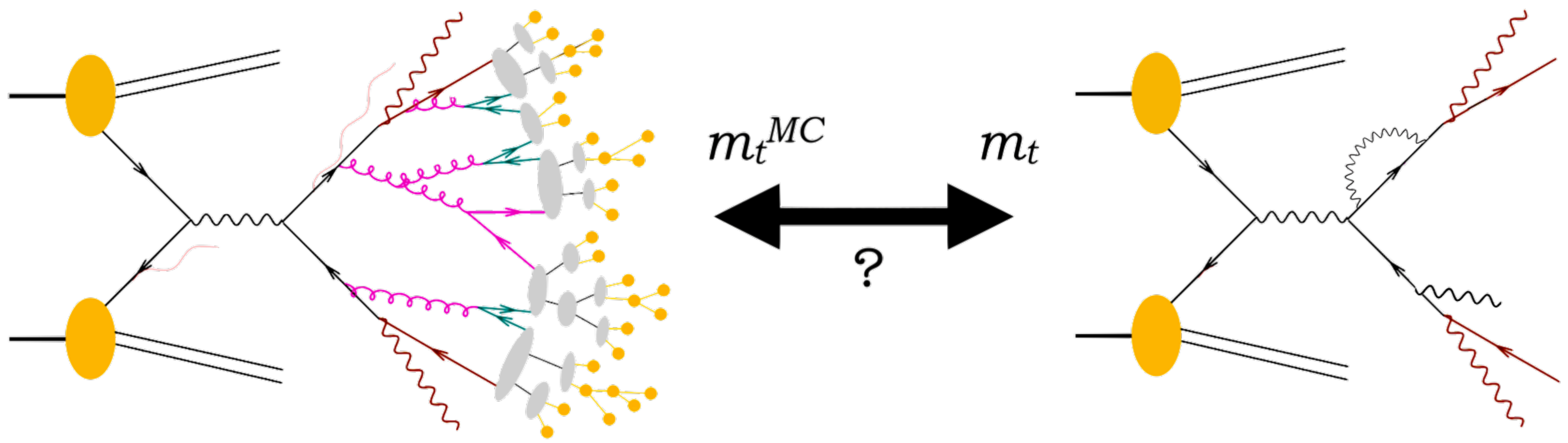




Top quark mass at the LHC

Direct measurements

- Most precise (**300 MeV**)
- Debated theoretical interpretation



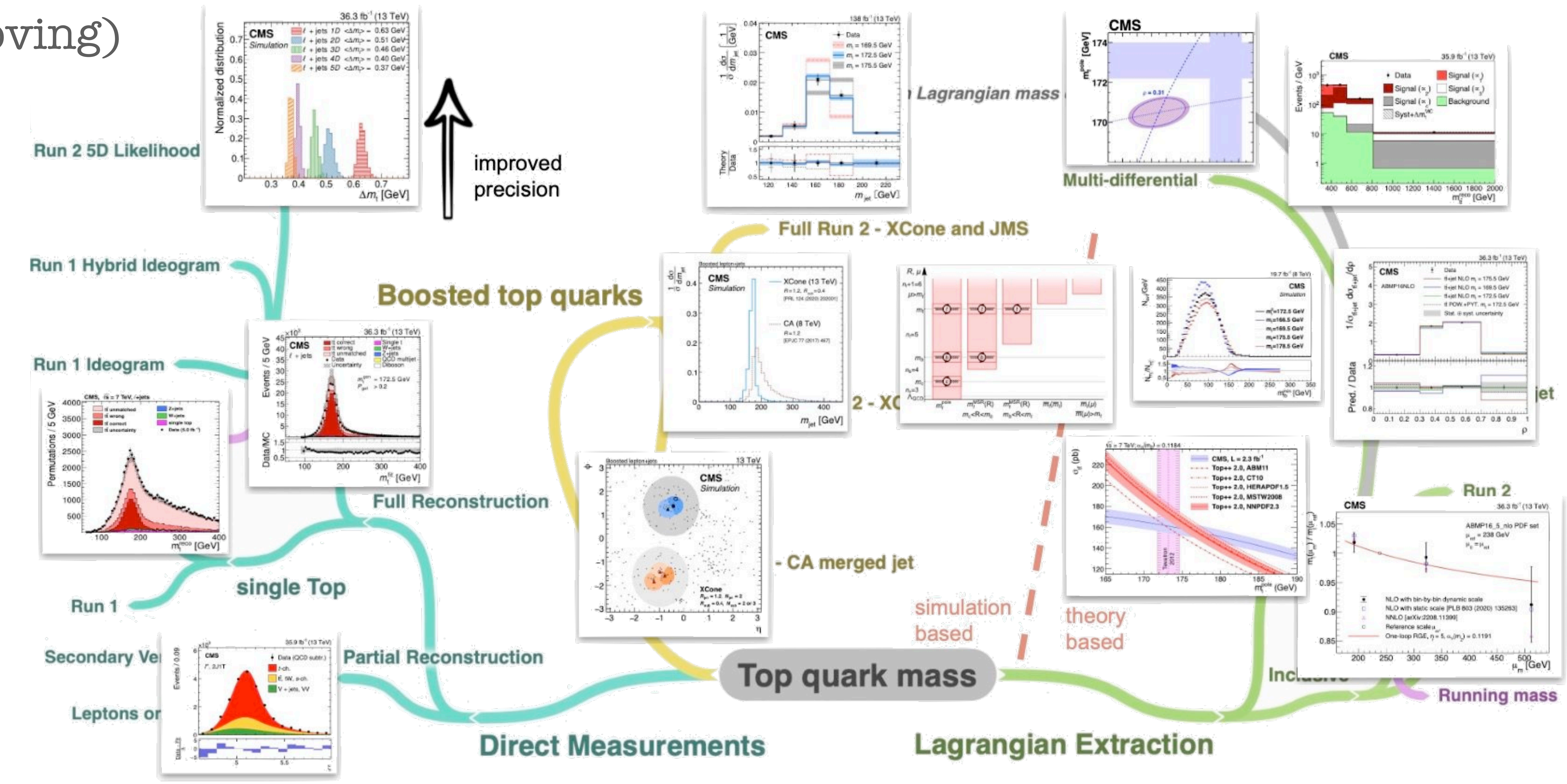
Indirect measurements

- Lower precision (order 1 GeV, improving)
- Need improved theory predictions

Boosted measurements

- May help with clarifying the picture, but still exploratory

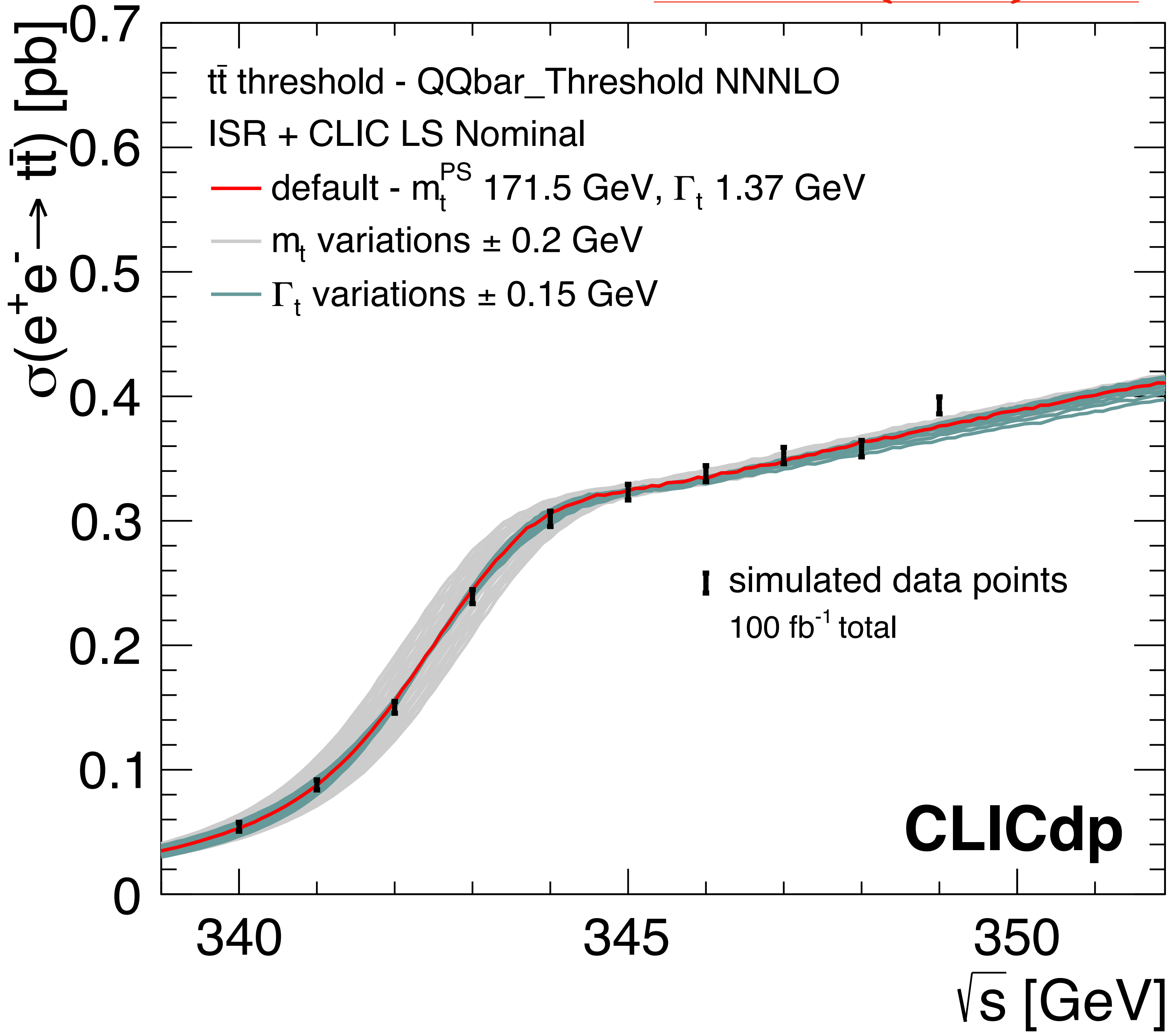
Only lepton collider can provide unambiguous measurement of m_t at the desired precision (few tens of MeV)



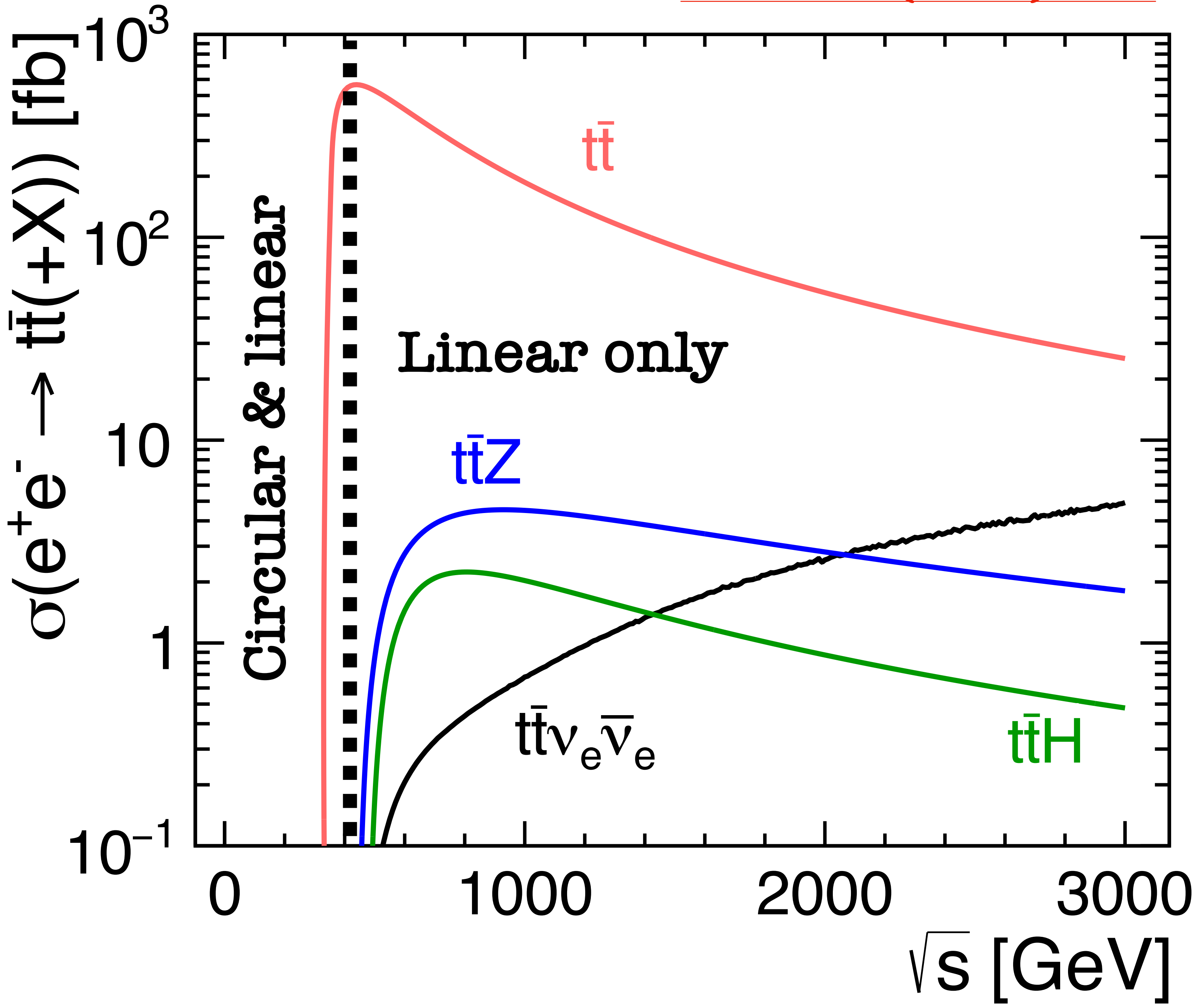
tt threshold scan at e+e- colliders

- Measurement of WbWb total rate around the **tt production threshold**
- Simultaneous measurement of top quark mass and width, without assuming SM relation between the two
- Additional dependence on α_S and top Yukawa

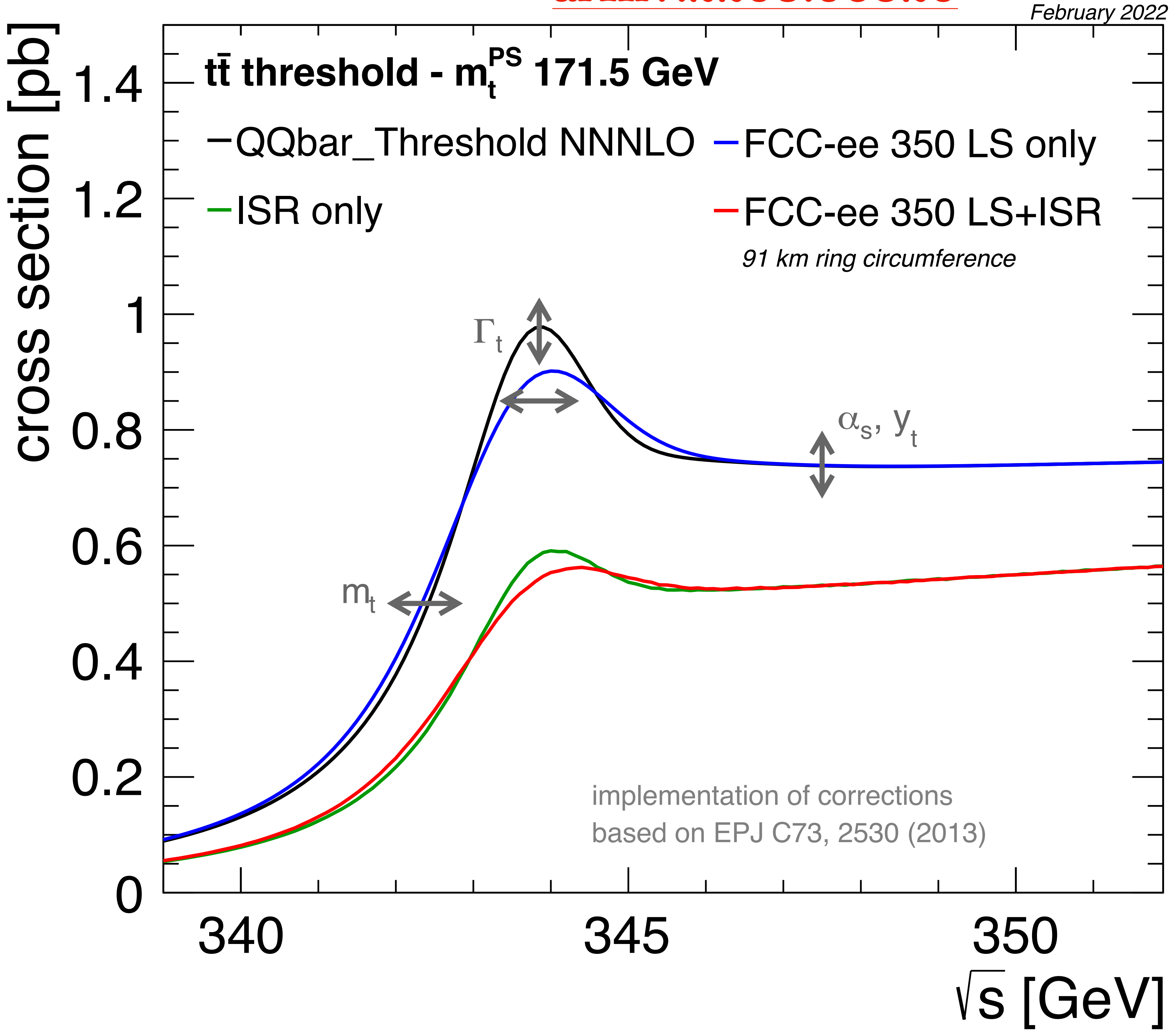
JHEP 11 (2019) 003

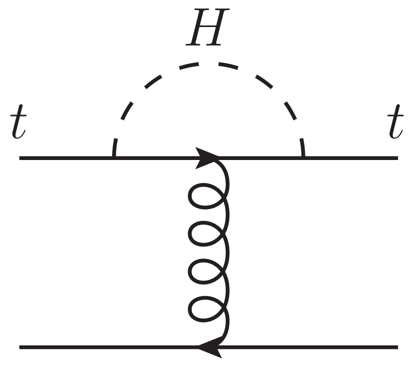


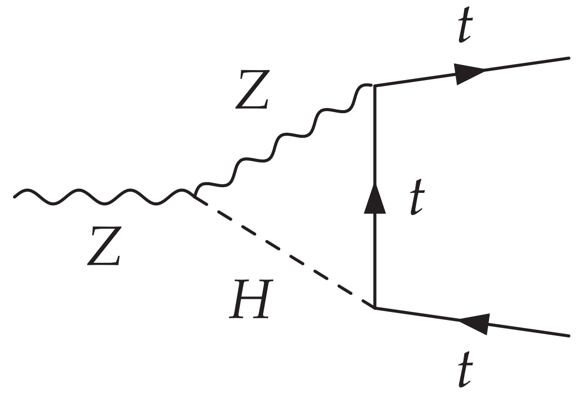
JHEP 11 (2019) 003

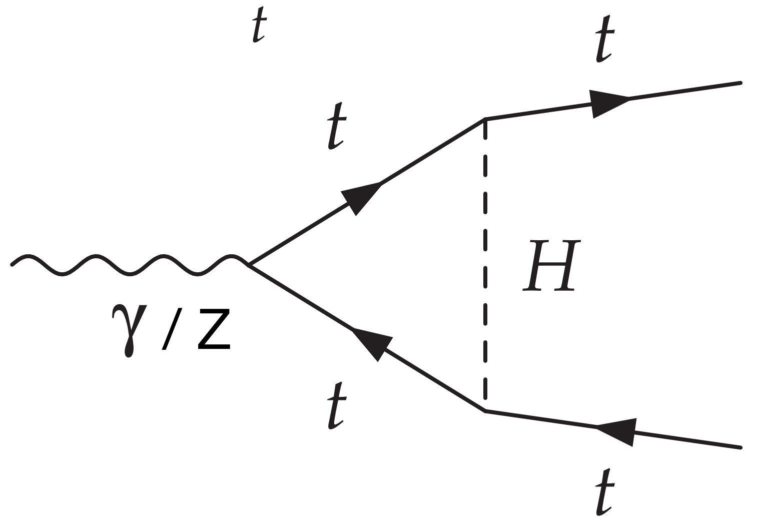


arXiv:2203.06520









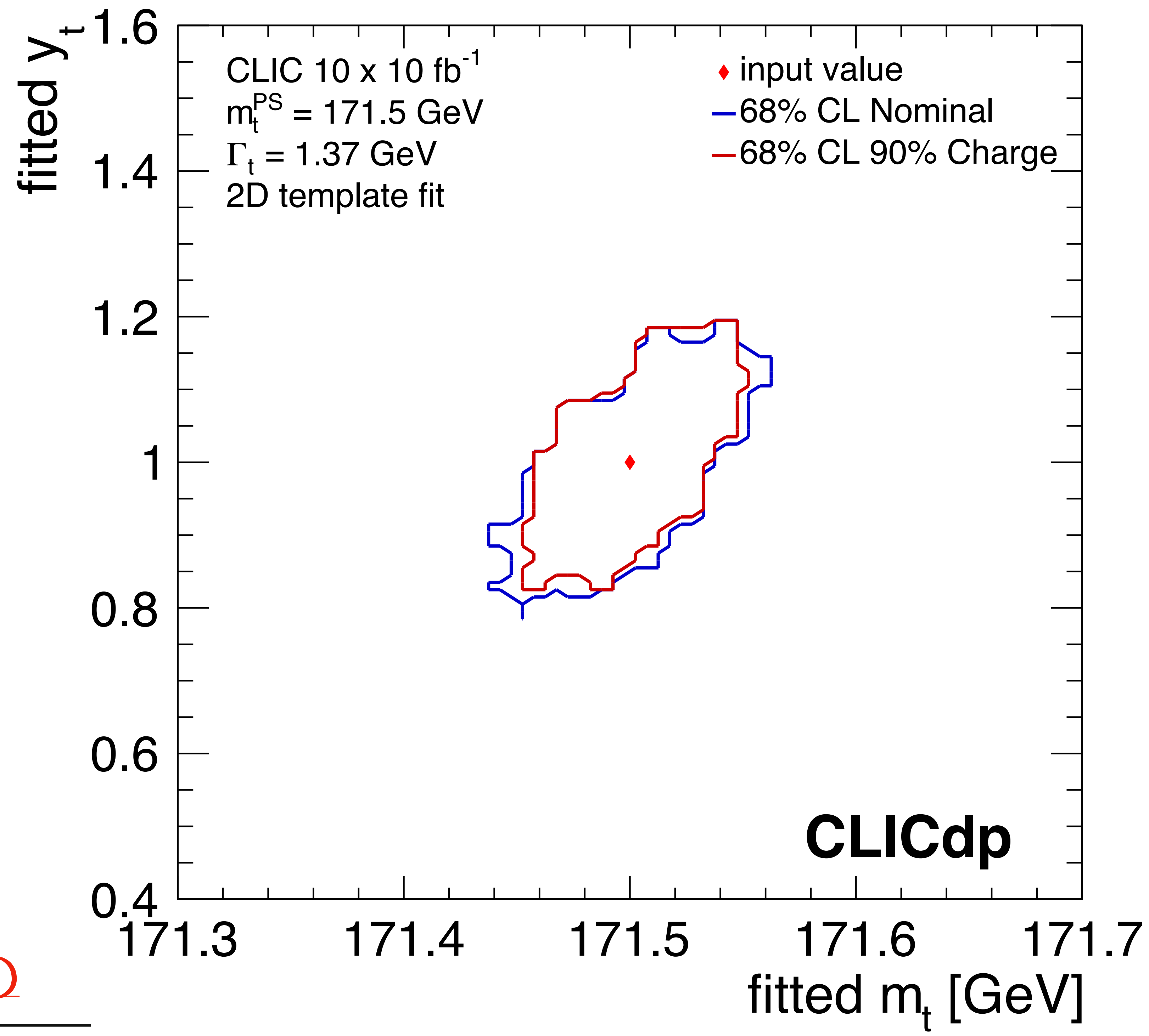
Linear collider: direct access to y_t via ttH production
Circular collider: indirect access to y_t via loop diagrams

CLIC and CEPC threshold studies

JHEP 11 (2019) 003

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)**
    - Γ_t measurement penalised by broad luminosity spectrum
    - **40 MeV** theoretical uncertainty (N3LO NR-QCD)



Recall: uncertainty in top mass and width ~300 MeV at LHC

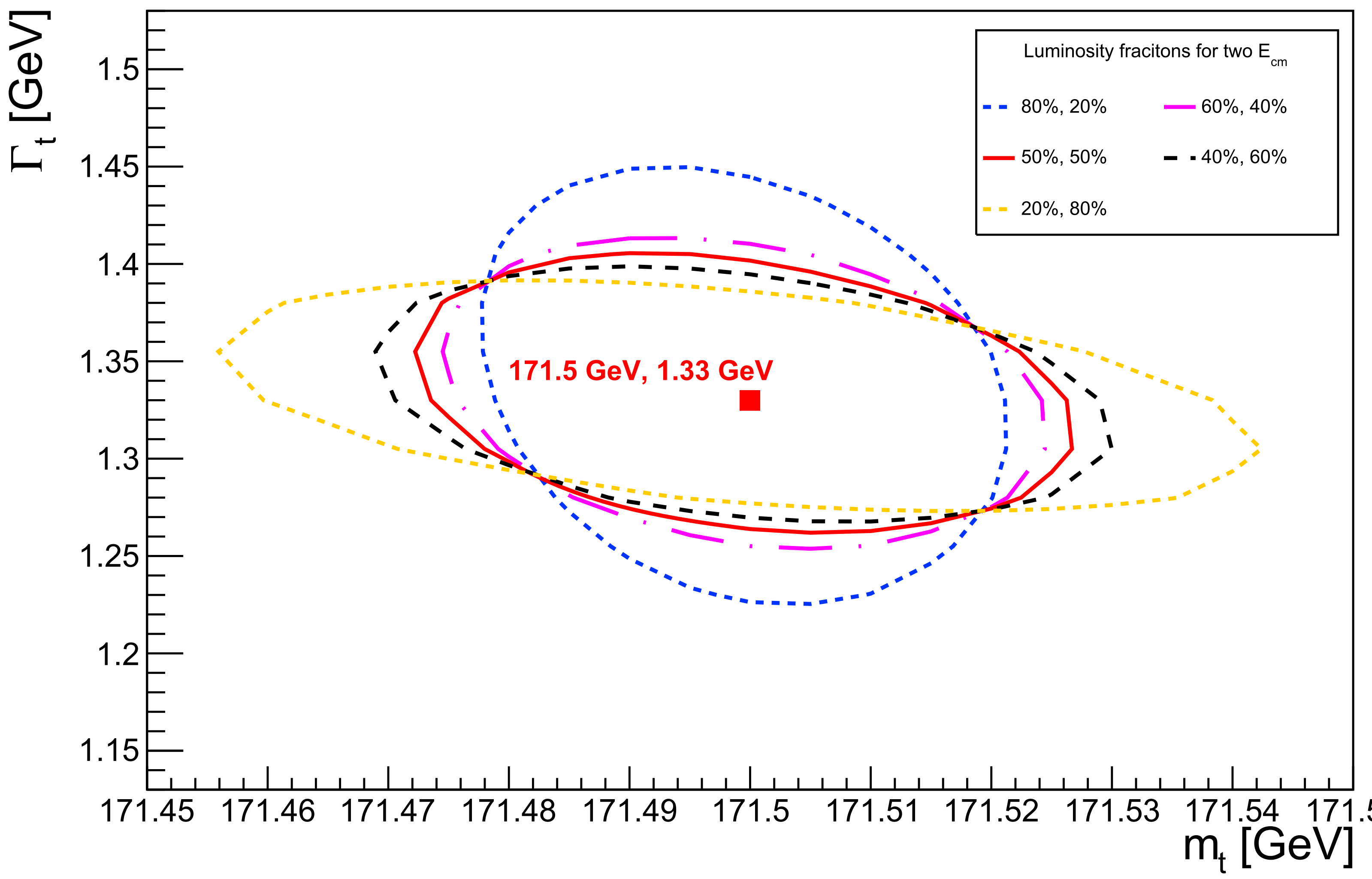
CEPC, 100 fb^{-1}

- Optimised **2-points scan** (maximises precision, but reduces testability of theory)
- Reduced **correlation** between measured parameters

EPJC 83 (2023)

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

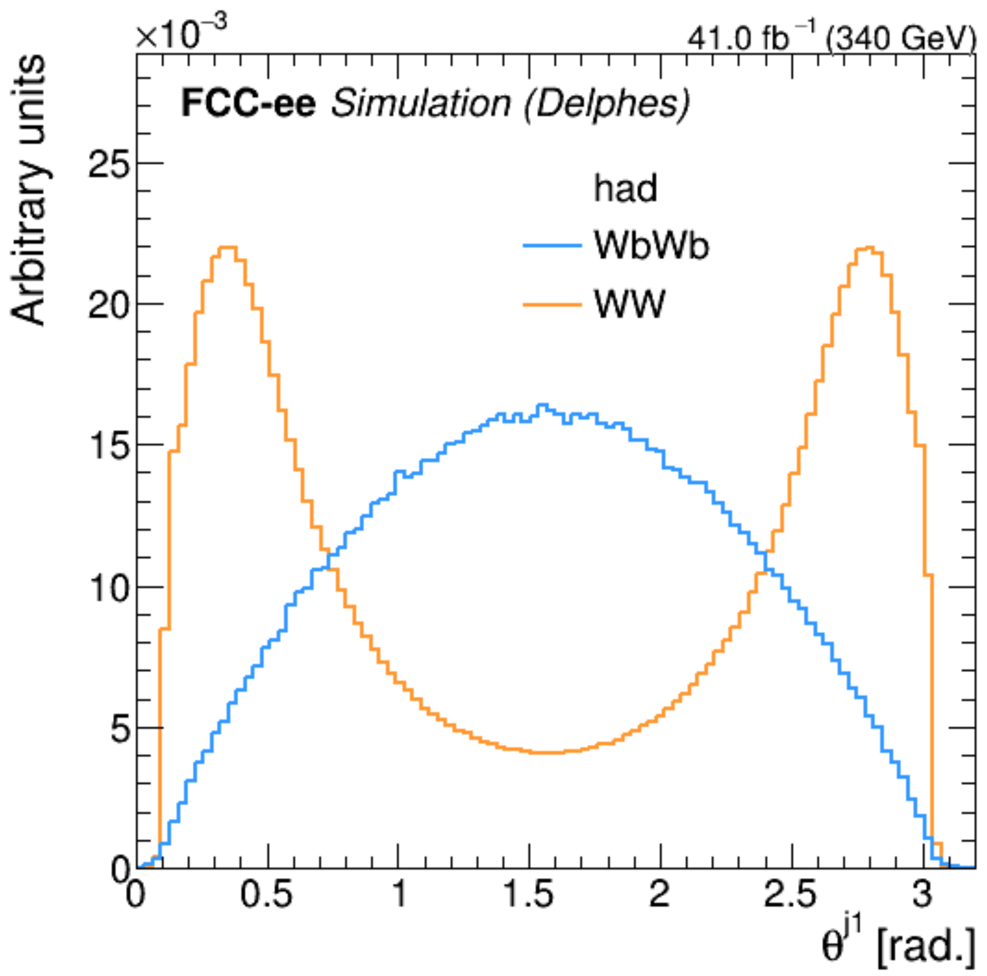
EPJC 83 (2023)

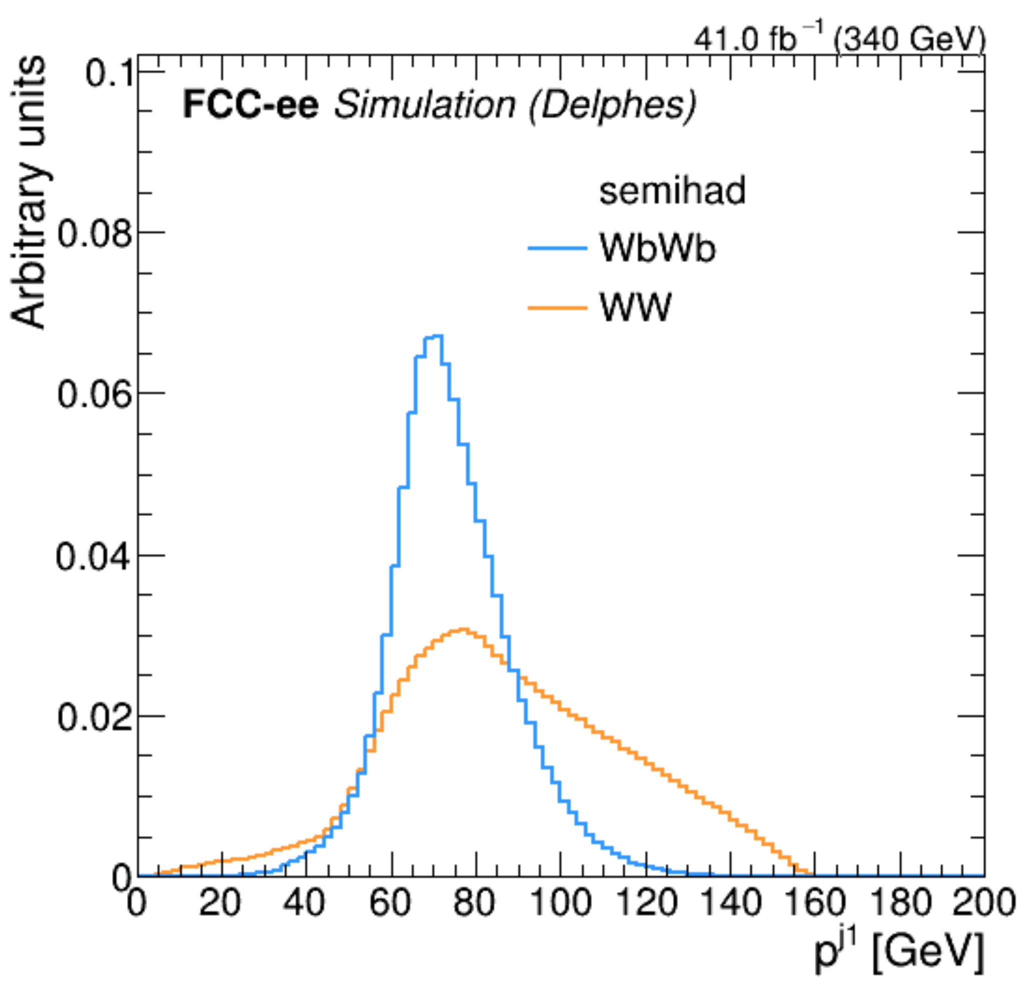


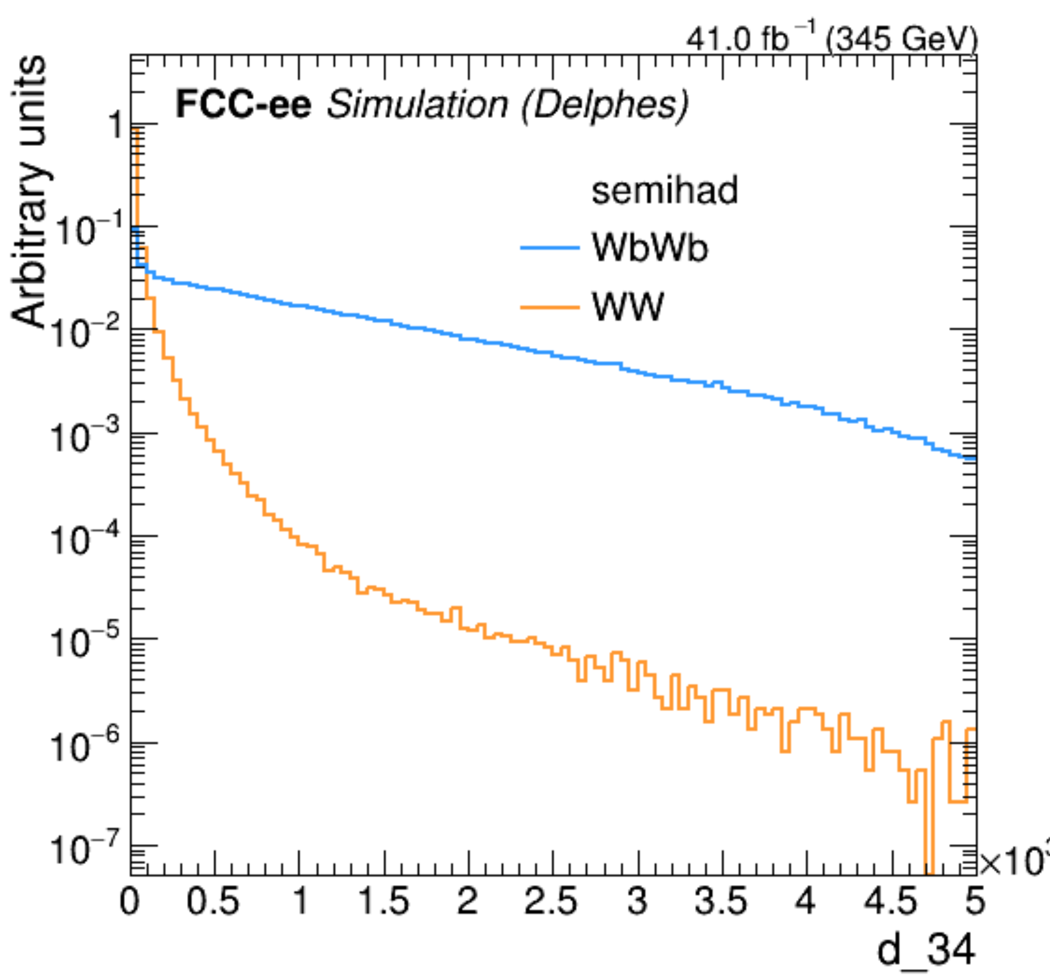
FCC-ee detector-level studies: signal selection

See Ankita's talk [link]

- Detector-level Delphes simulation
- **Hadronic** and **semi-hadronic** final states (>80% branching ratio in total)
- Exclusive jet clustering with (4) 6 jets in (semi-) hadronic channel

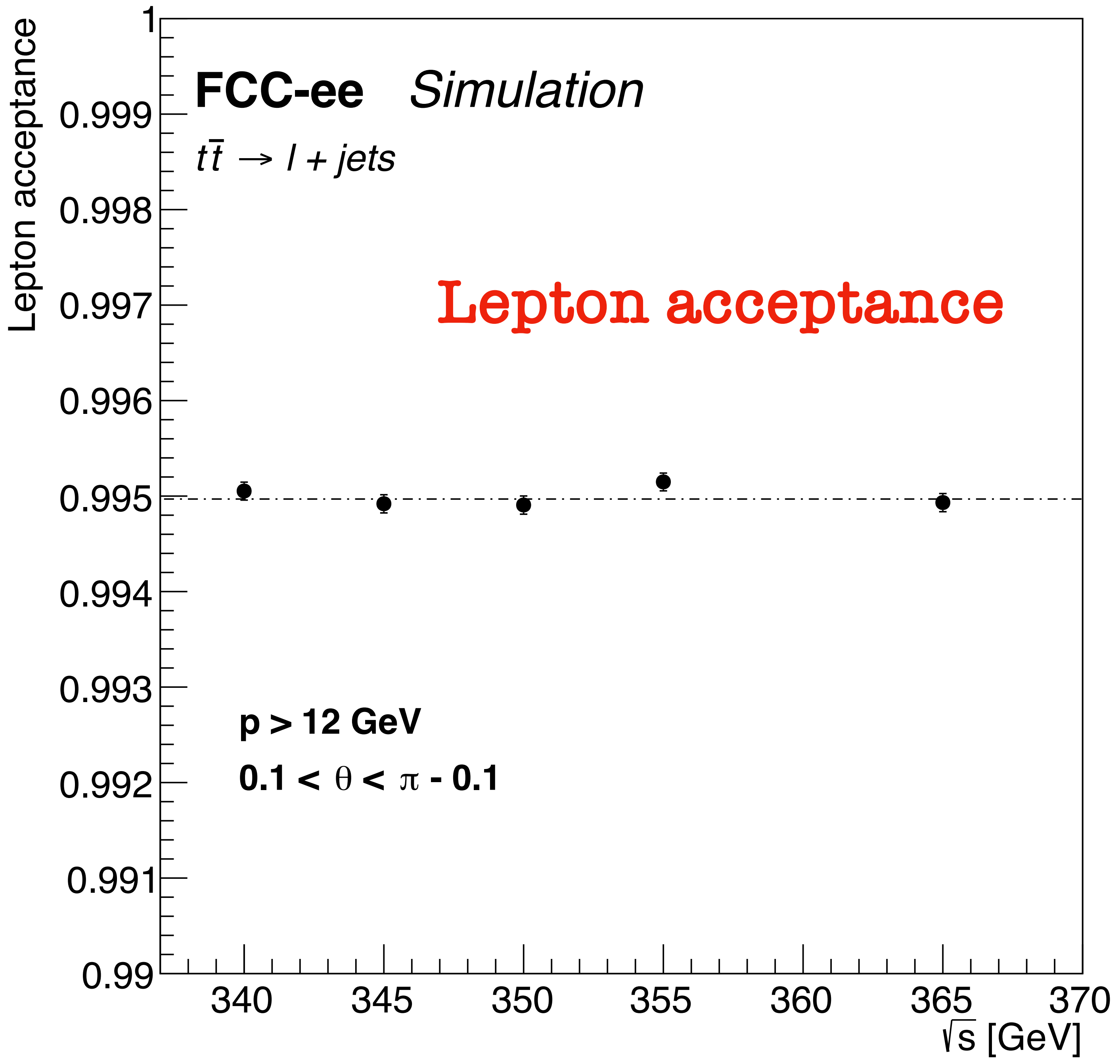




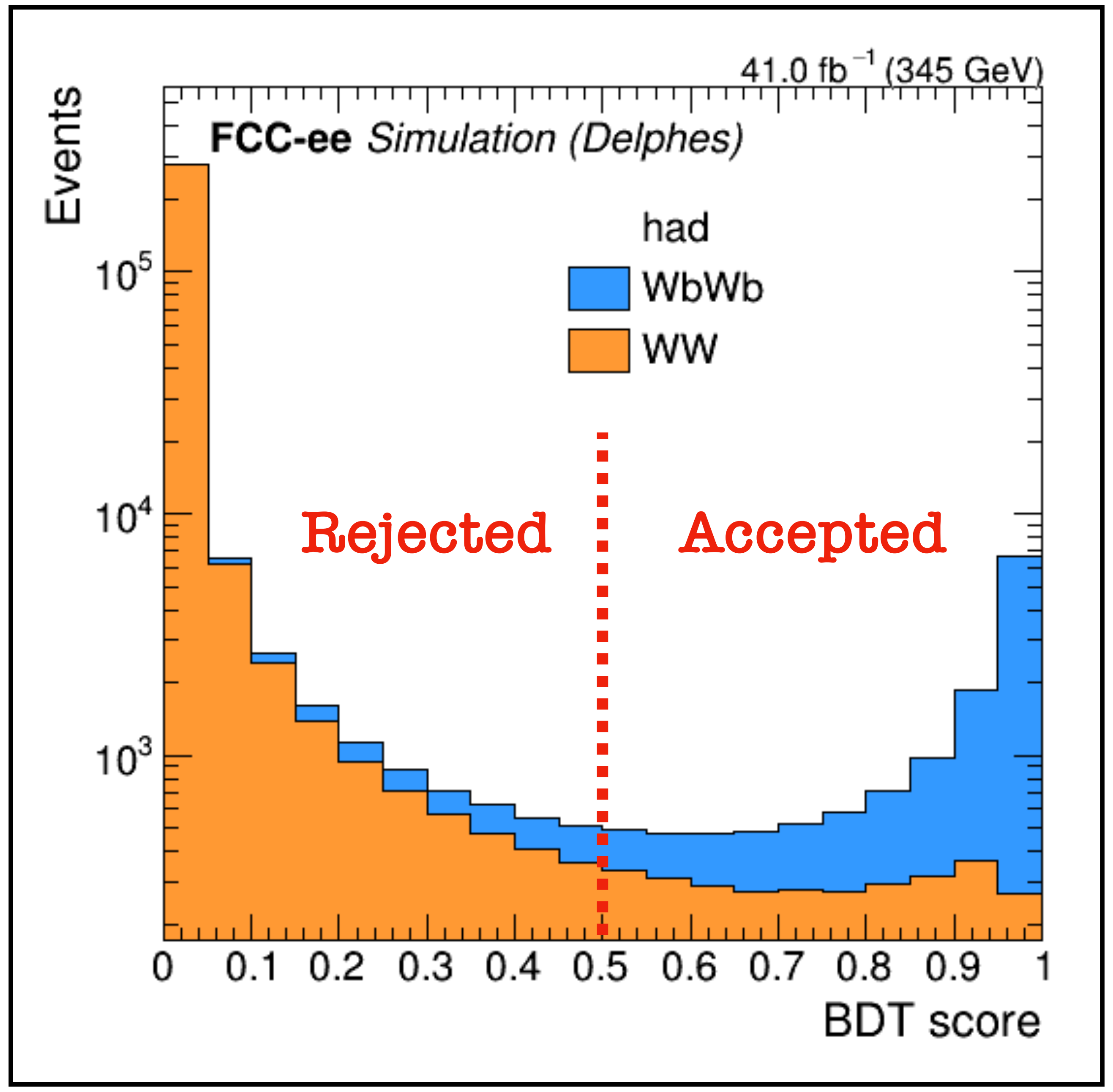


- Semi-hadronic: select events based on reconstructed lepton (**99.5% acceptance**)
- Hadronic: no selection (**100% acceptance**)

Stable acceptance over the entire range relevant for FCC-ee

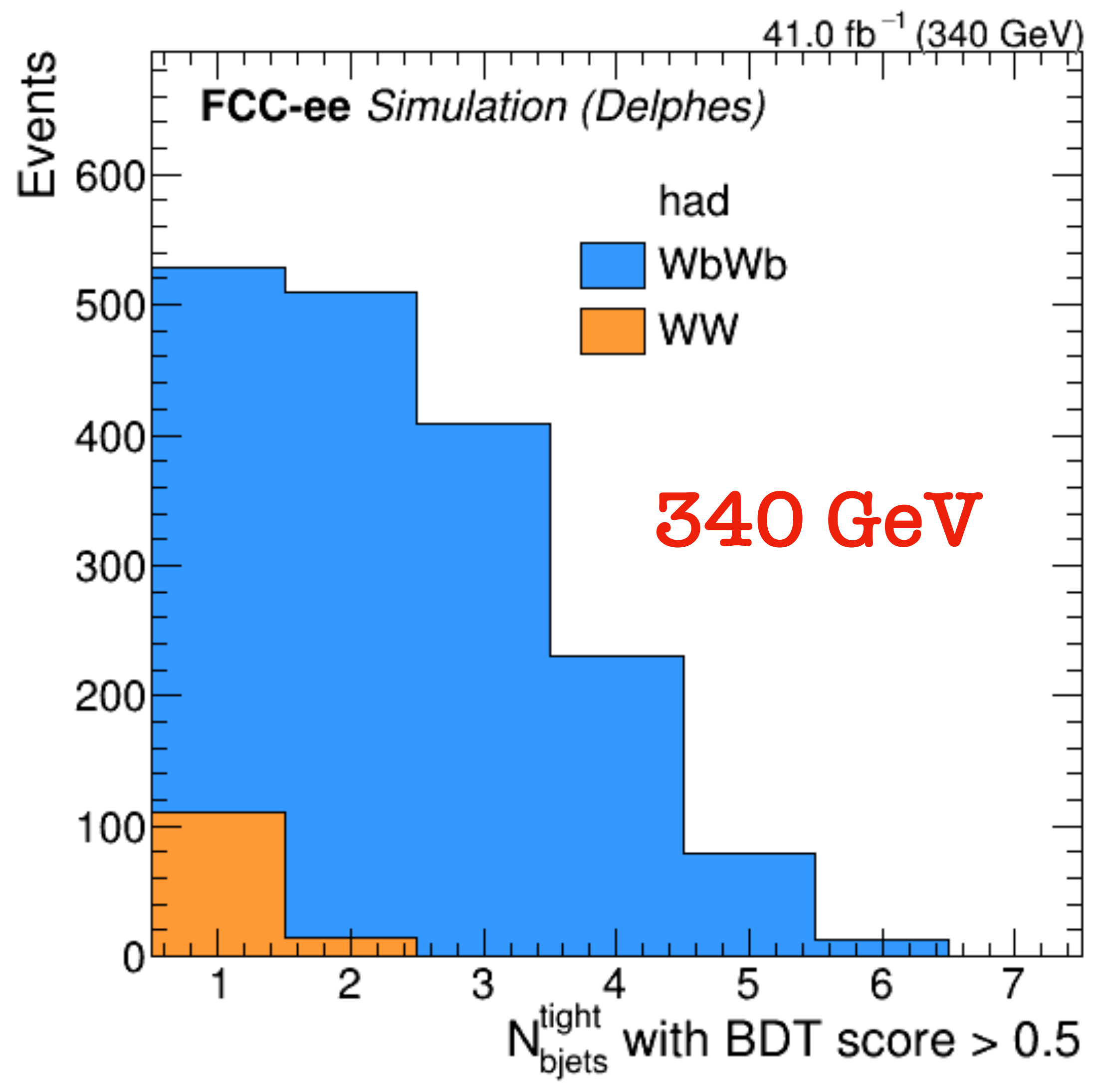


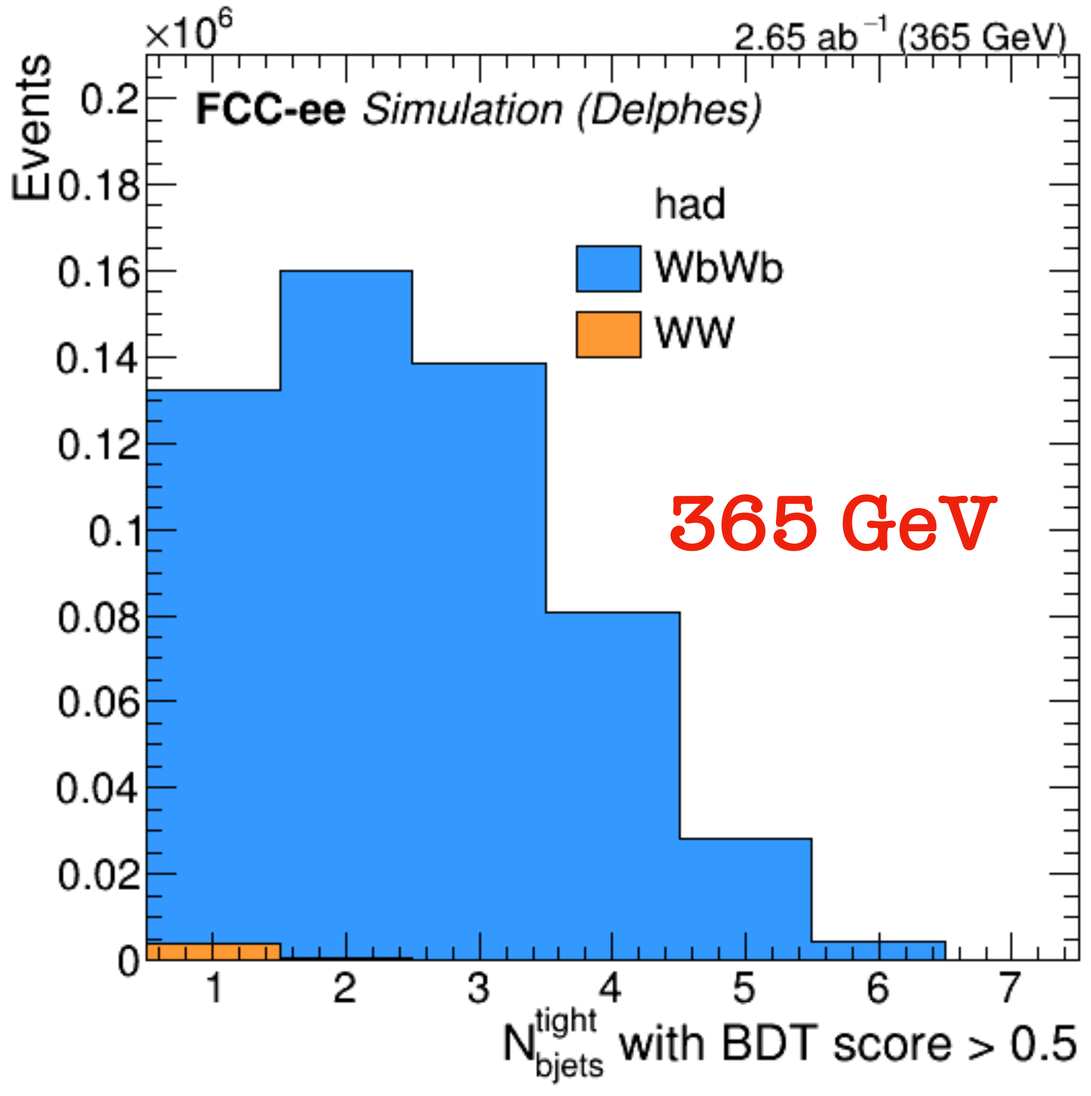
- BDT trained without flavour information (kinematic observables only)
- Flavour information used at later stage



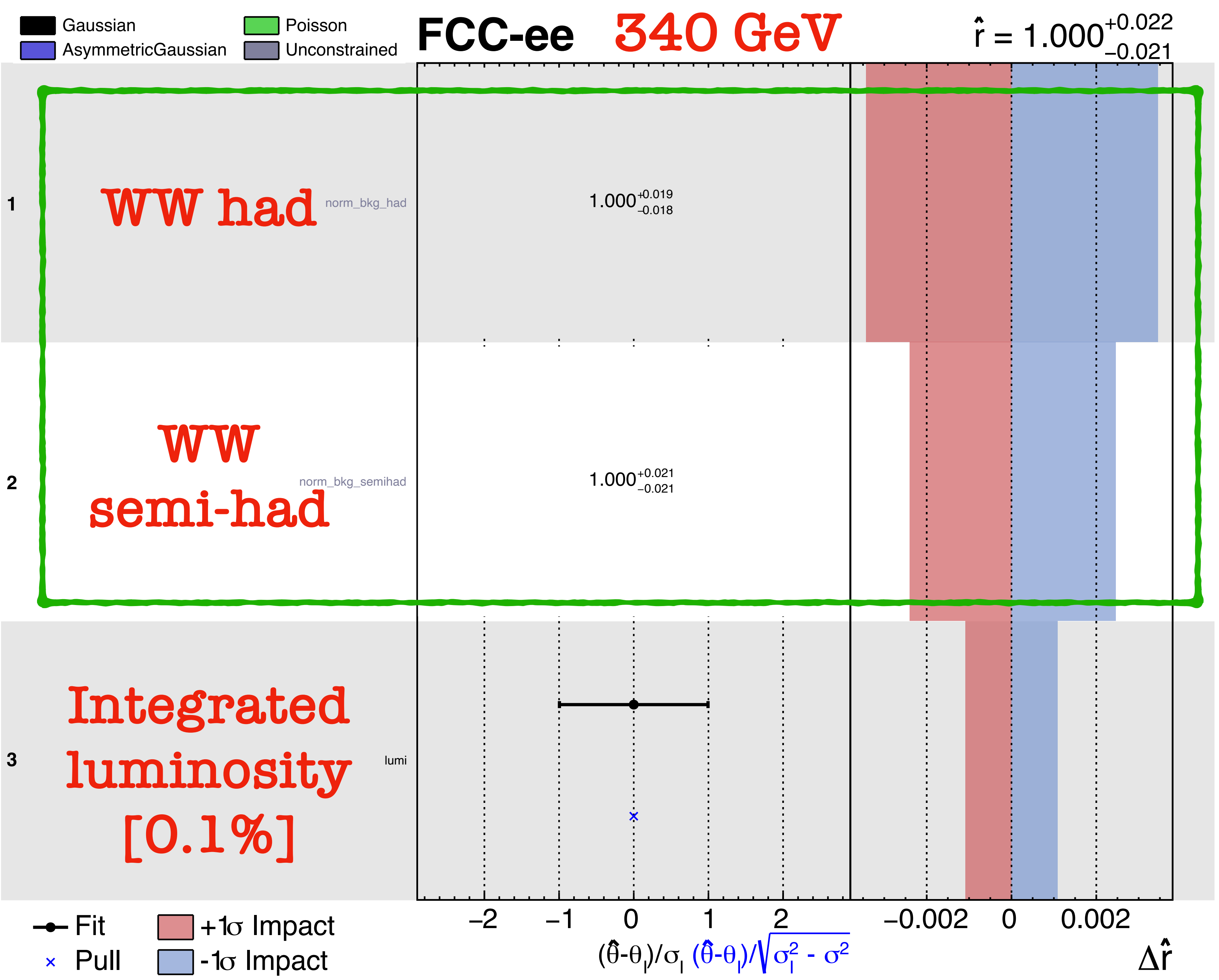
FCC-ee: WbWb x-sec fit

- b-tagged jet multiplicity -> extra handle on WW
- **Simultaneous fit** to WbWb signal region (>1b) and WW control region (0b)
- Simultaneous fit to hadronic and semi-hadronic final states (uncorrelated backgrounds)

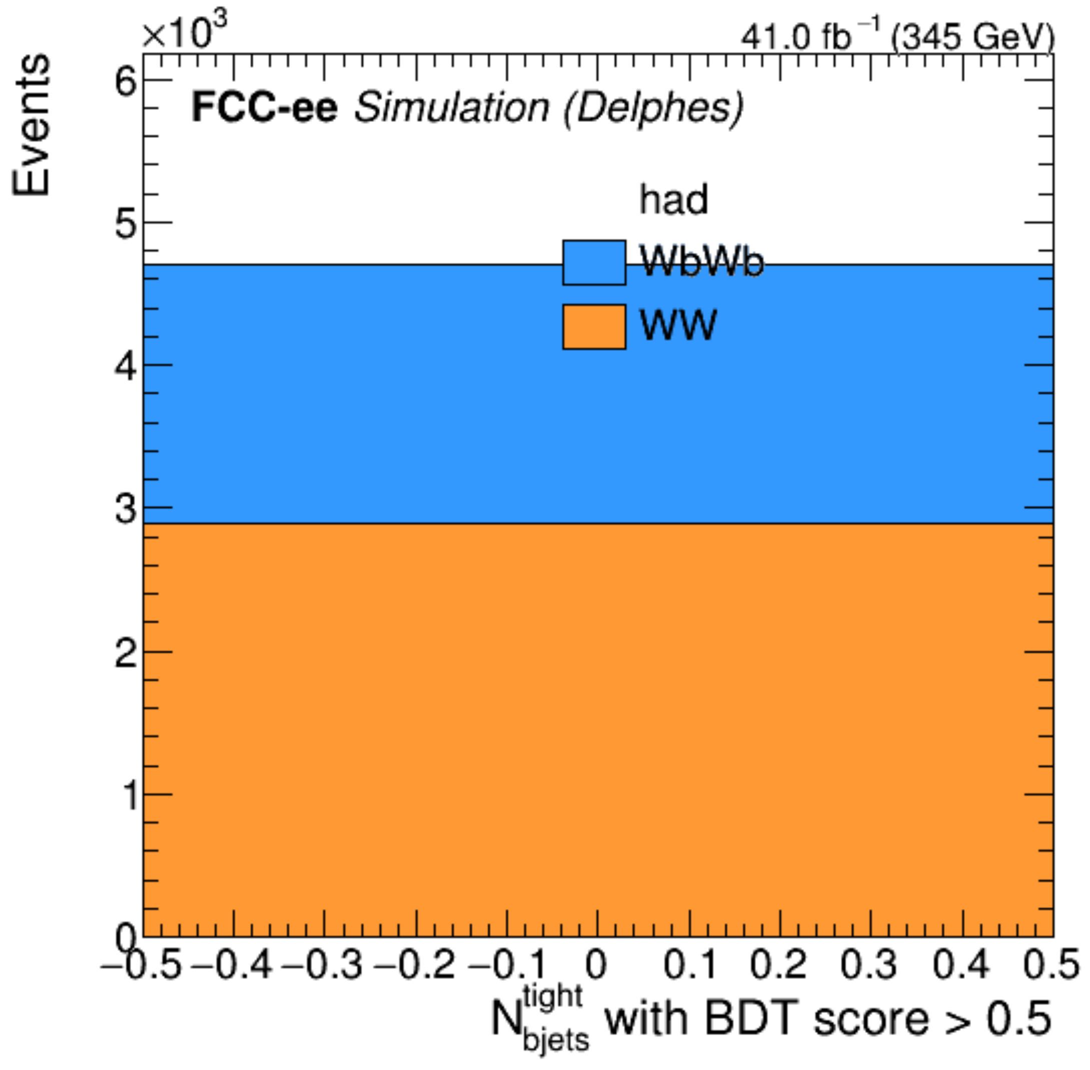




WW background well under control over the entire range relevant for FCC-ee [340-365] GeV



WW control region (0 b-tagged jets)

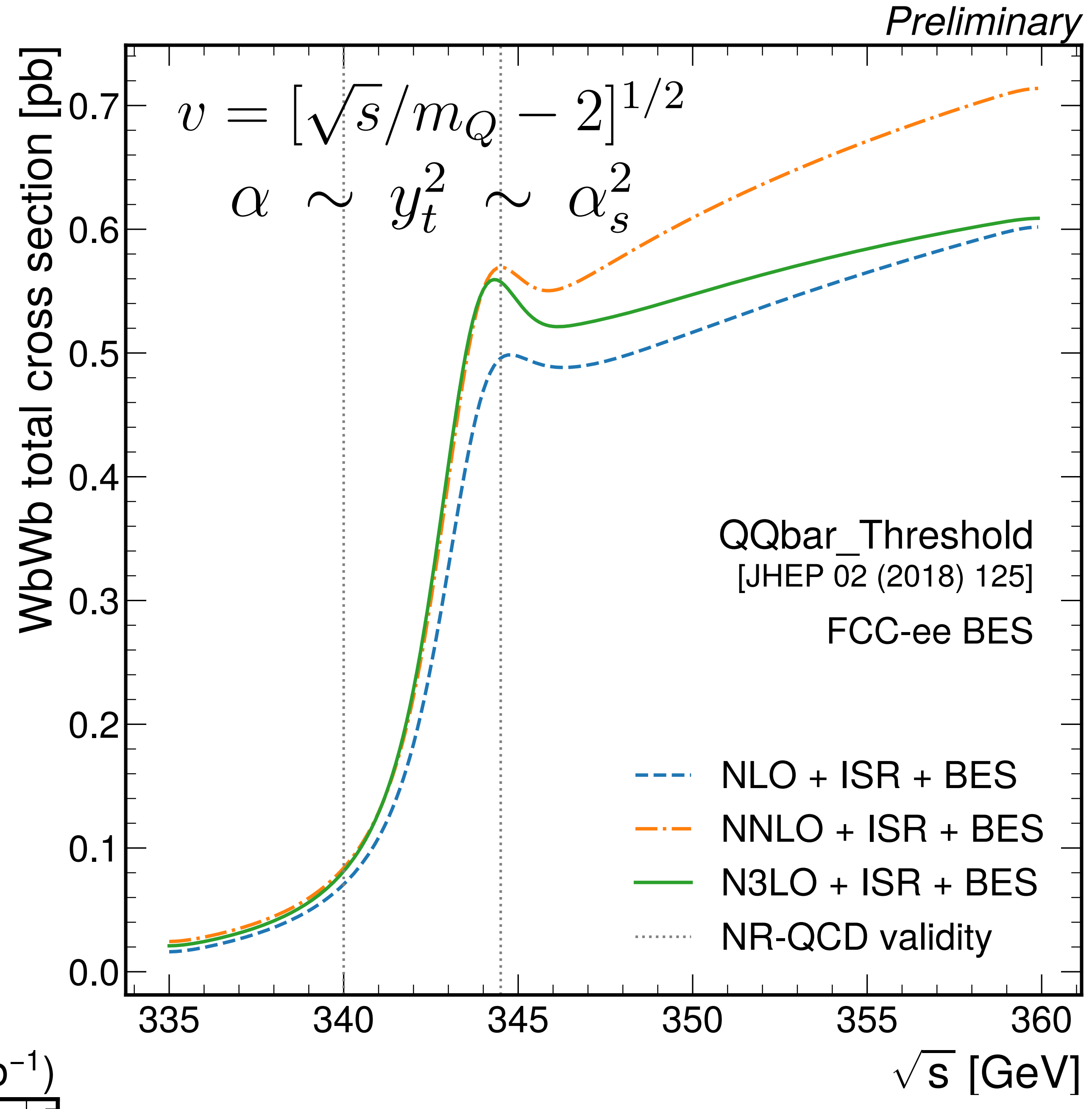


- Impact of b-tagging calibration (and other systematics) to be assessed
- In-situ calibrations can be envisaged

Fit of near-threshold prediction

- **N3LO** calculation (NR-QCD) including EW and Higgs effects + ISR
- Top mass in potential subtracted (PS) scheme, suitable for threshold

- Folded with FCC-ee beam energy spectrum (BES): 0.23 % / beam
- **3-dimensional fit of m_t, Γ_t, y_t, with profiled α_S (uncert. from Z)**

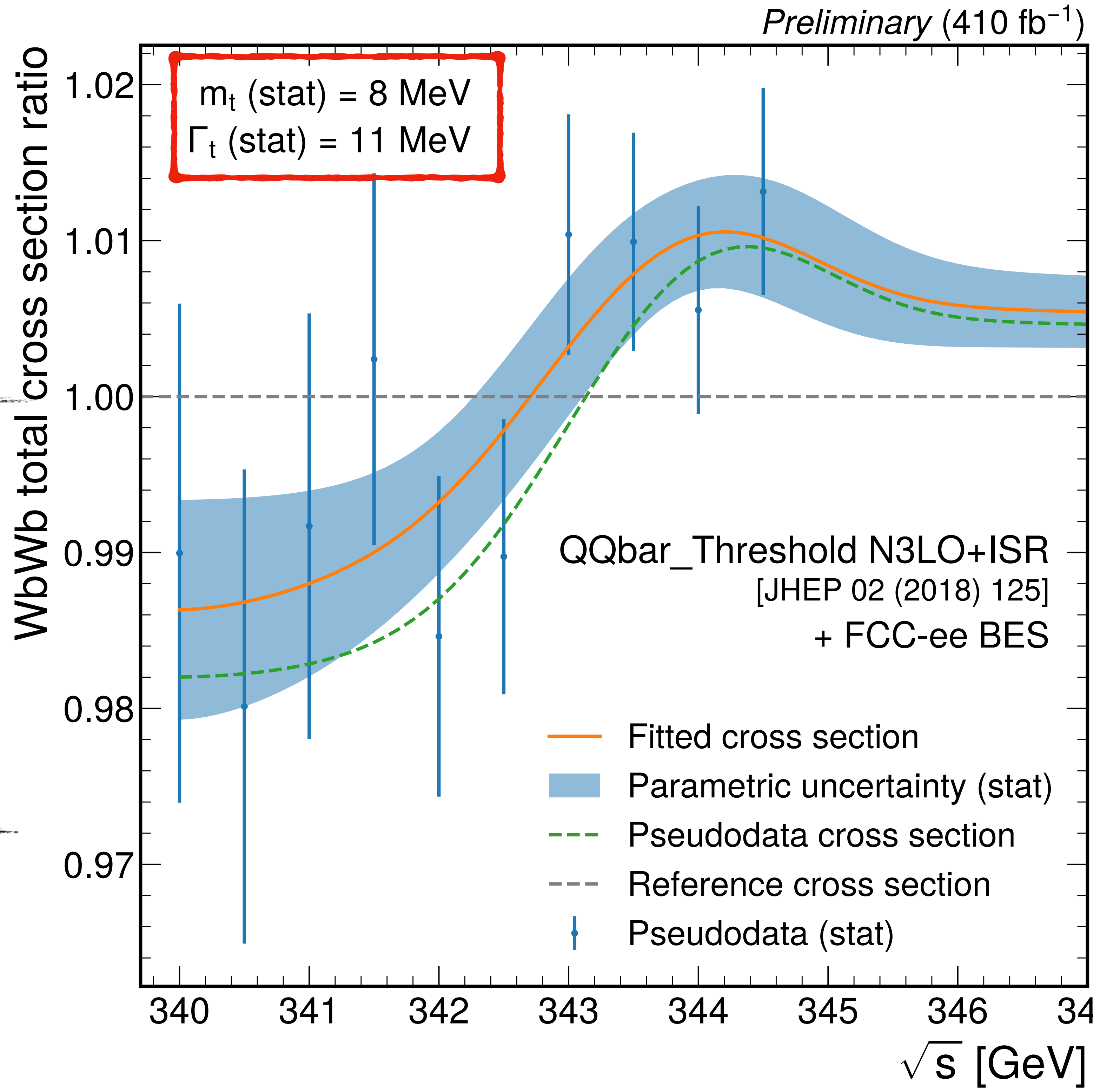


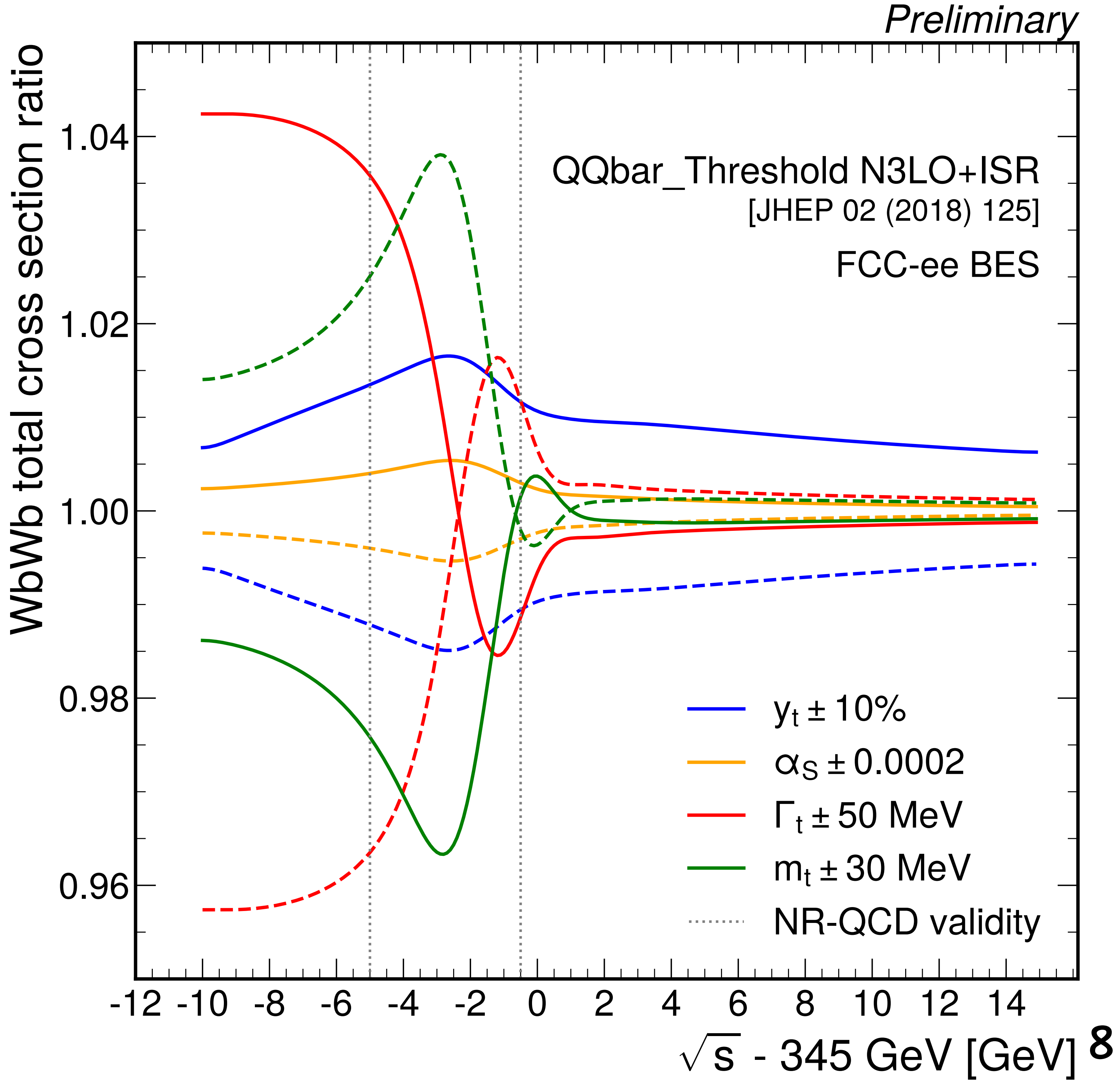
Baseline scenario: 10 equally-spaced (0.5 GeV) equal lumi (41 fb^{-1}) points

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

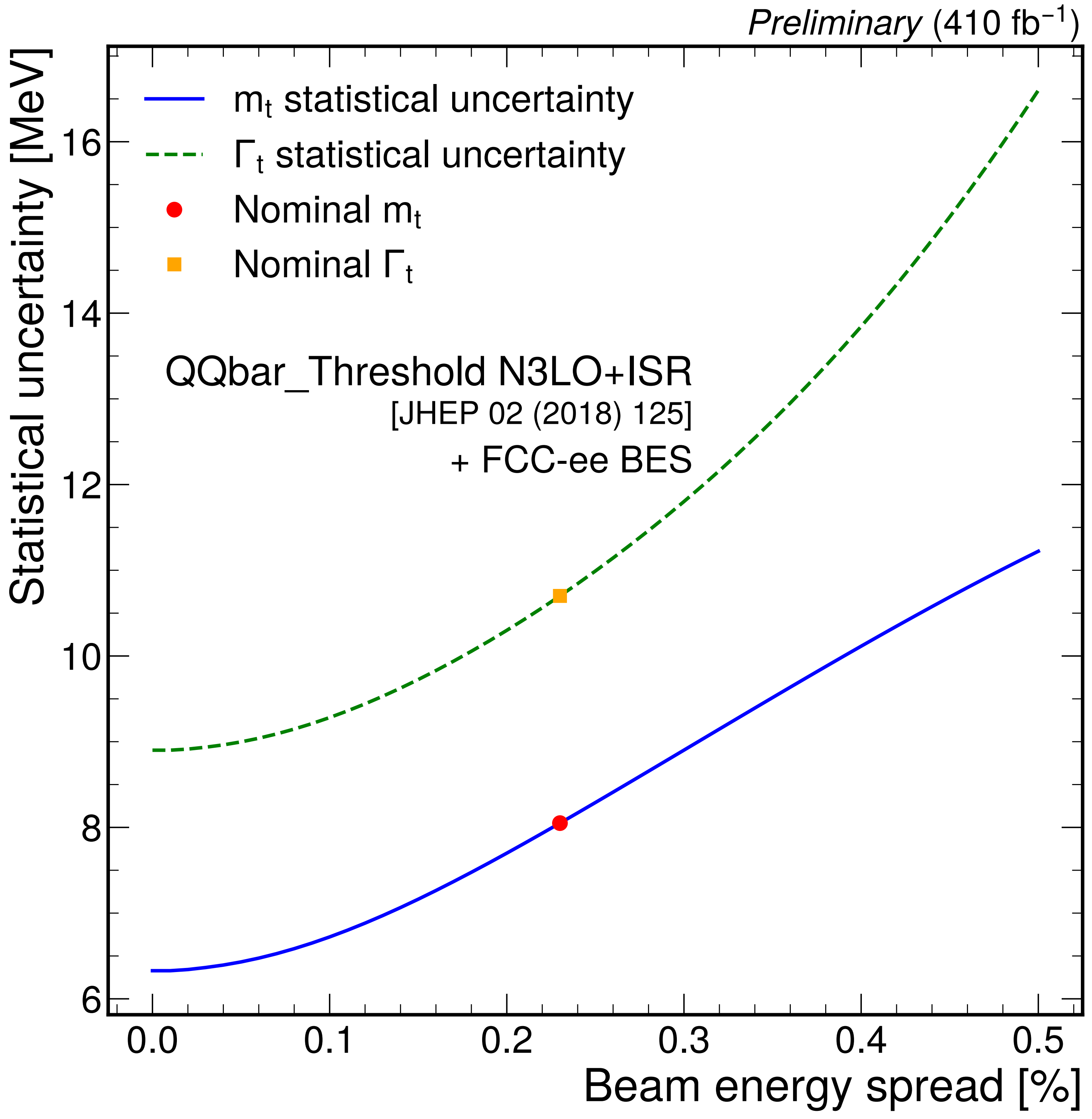
- **8 (11) MeV** statistical uncertainty **in m_t (Γ_t)**, including param. uncert.
- y_t can be determined to **1.7% (stat)**
  - Assuming only effect on Ztt vertex

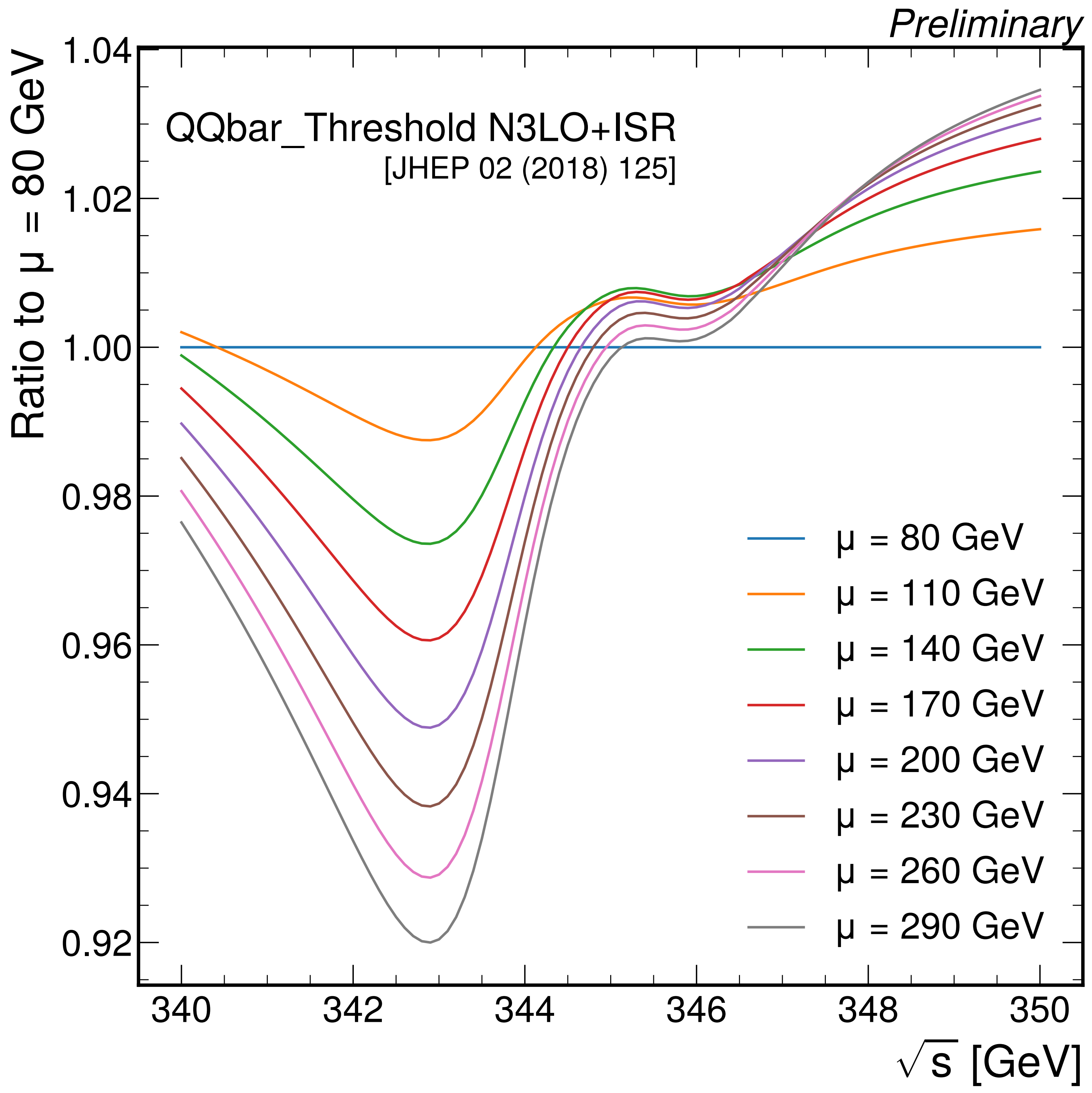
cf. CLIC: 2.7% (stat) in y_t with 2.5 ab^{-1} of ttH

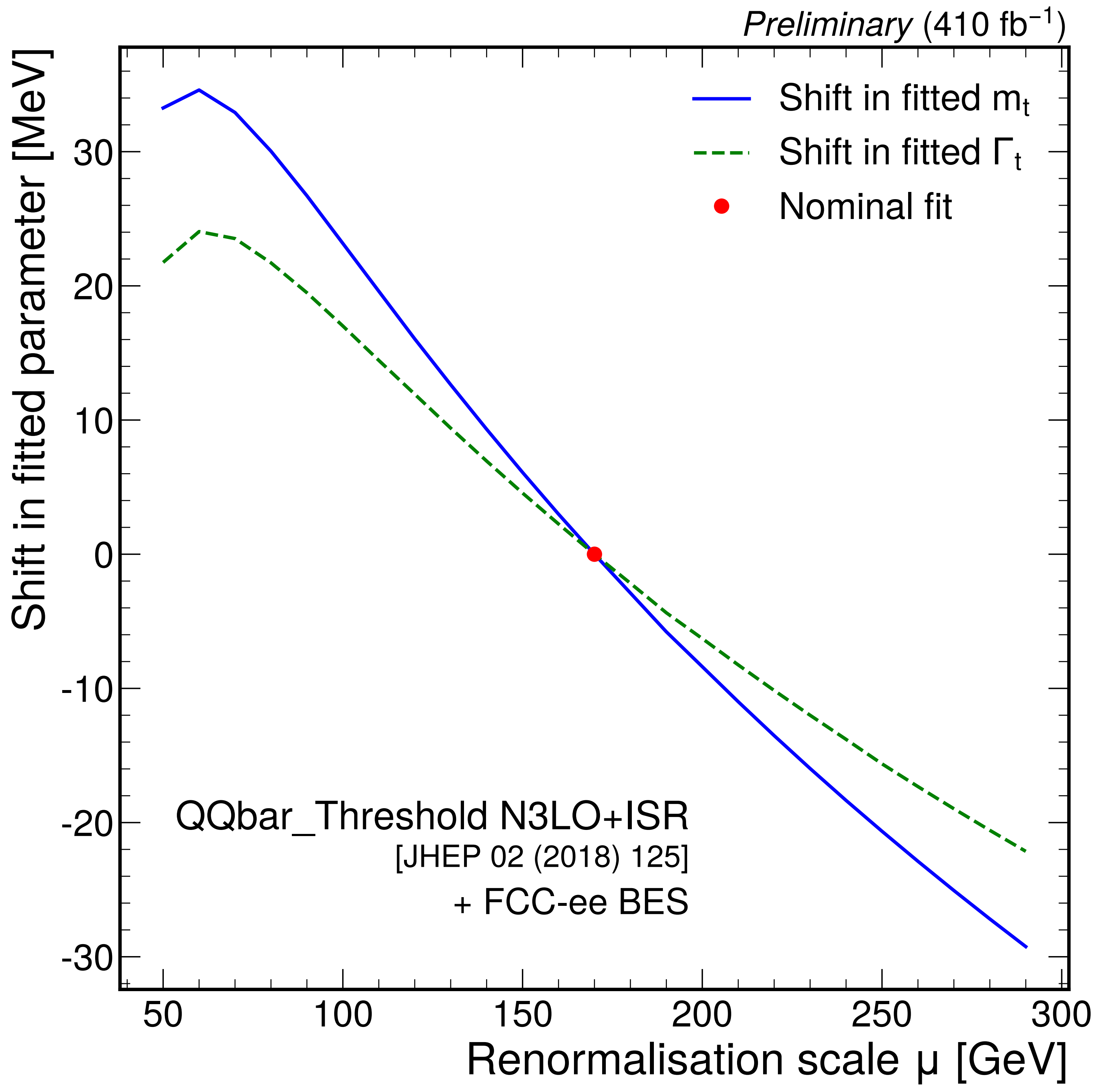




Dependence on theory & beam energy spectrum







- Width depends on beam energy resolution more strongly than mass
- Expect the other way around for beam energy calibration (under study)

- Both mass and width measurements currently **limited by renormalisation scale uncertainties** (30/40 MeV, depending on assumptions)

How much can we expect the theory predictions to be improved?

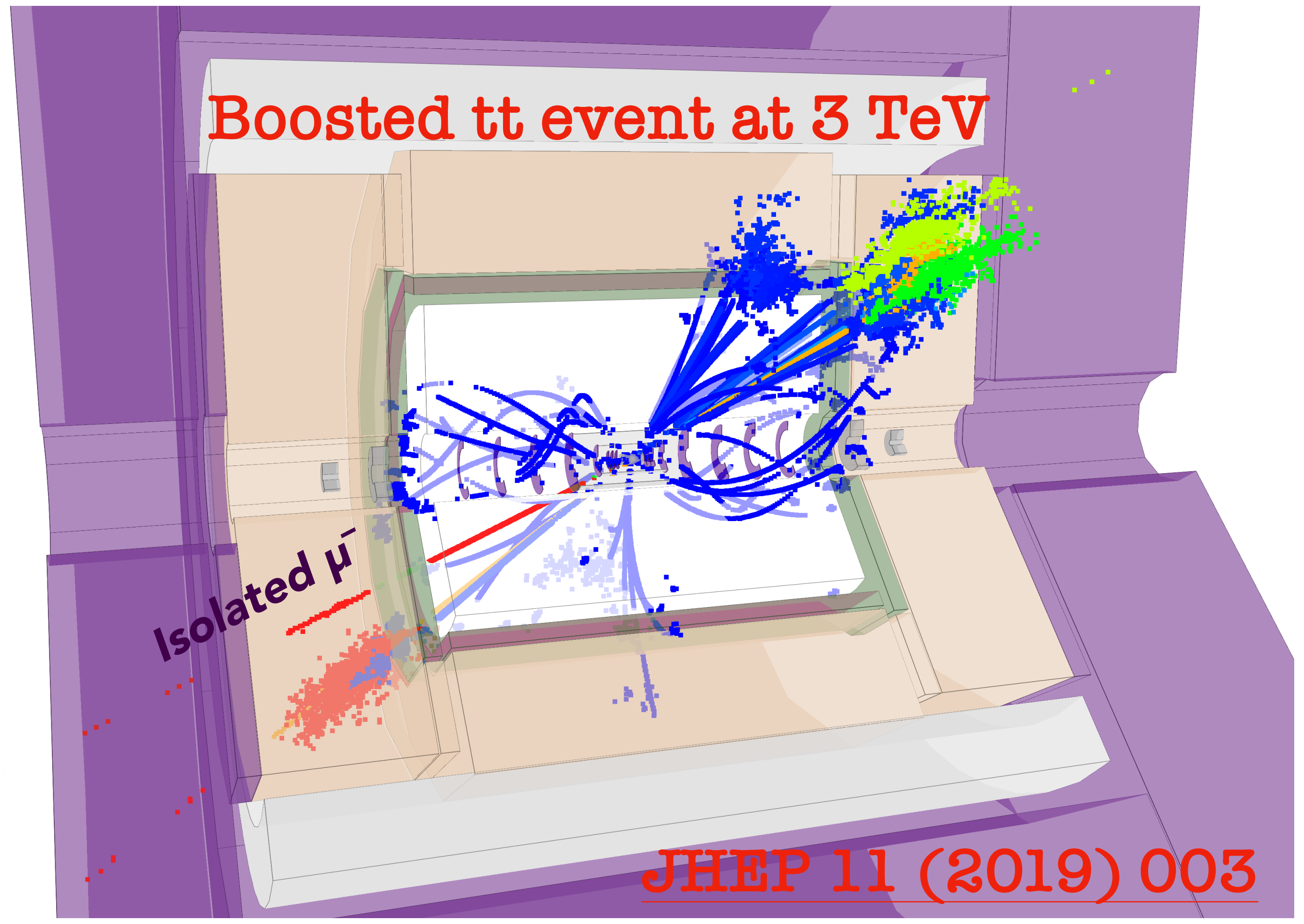
m_t above the tt production threshold

Radiative events at 380 GeV

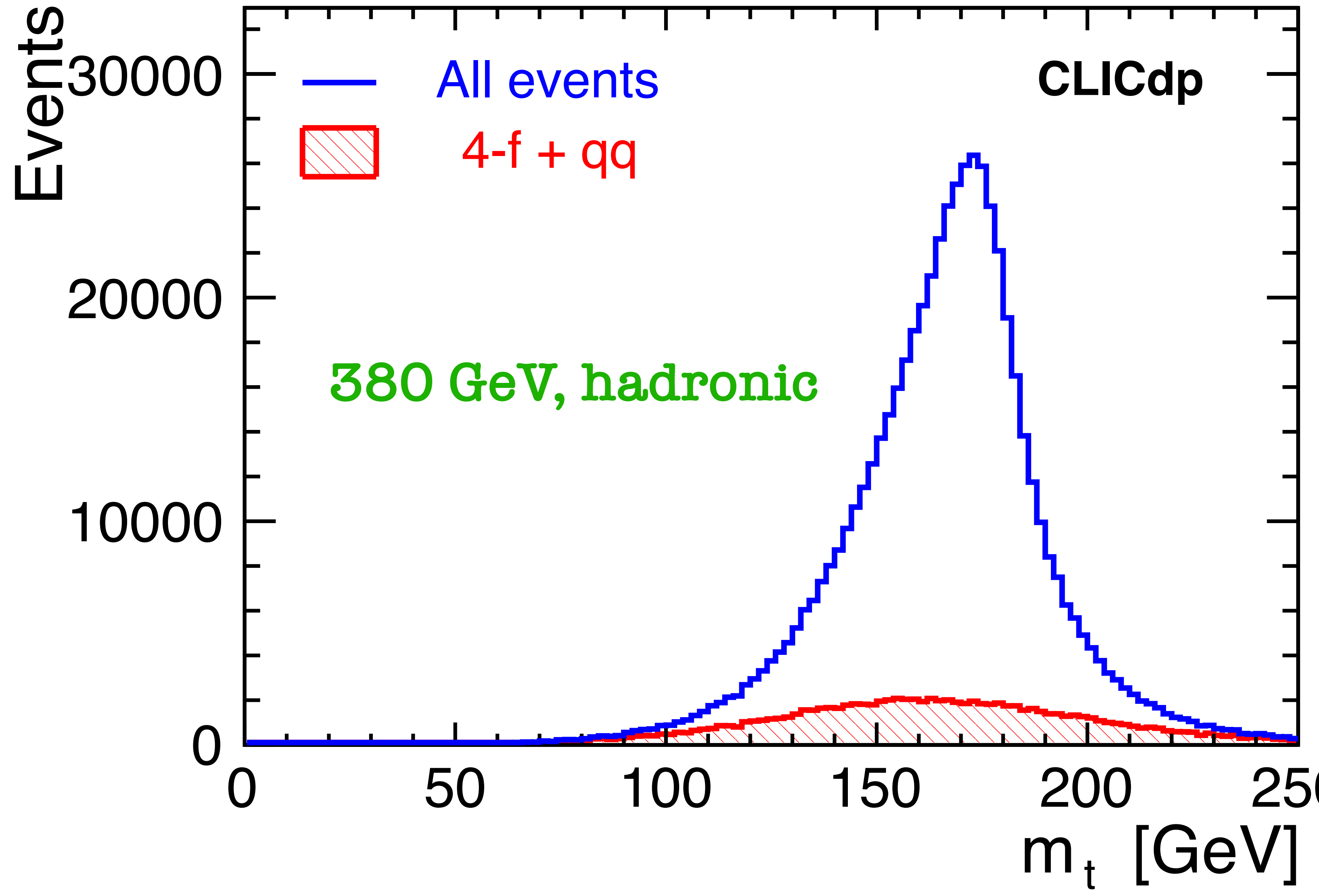
- **Hard ISR photon** can allow production of tt pair at threshold
- Recovers sensitivity to top mass

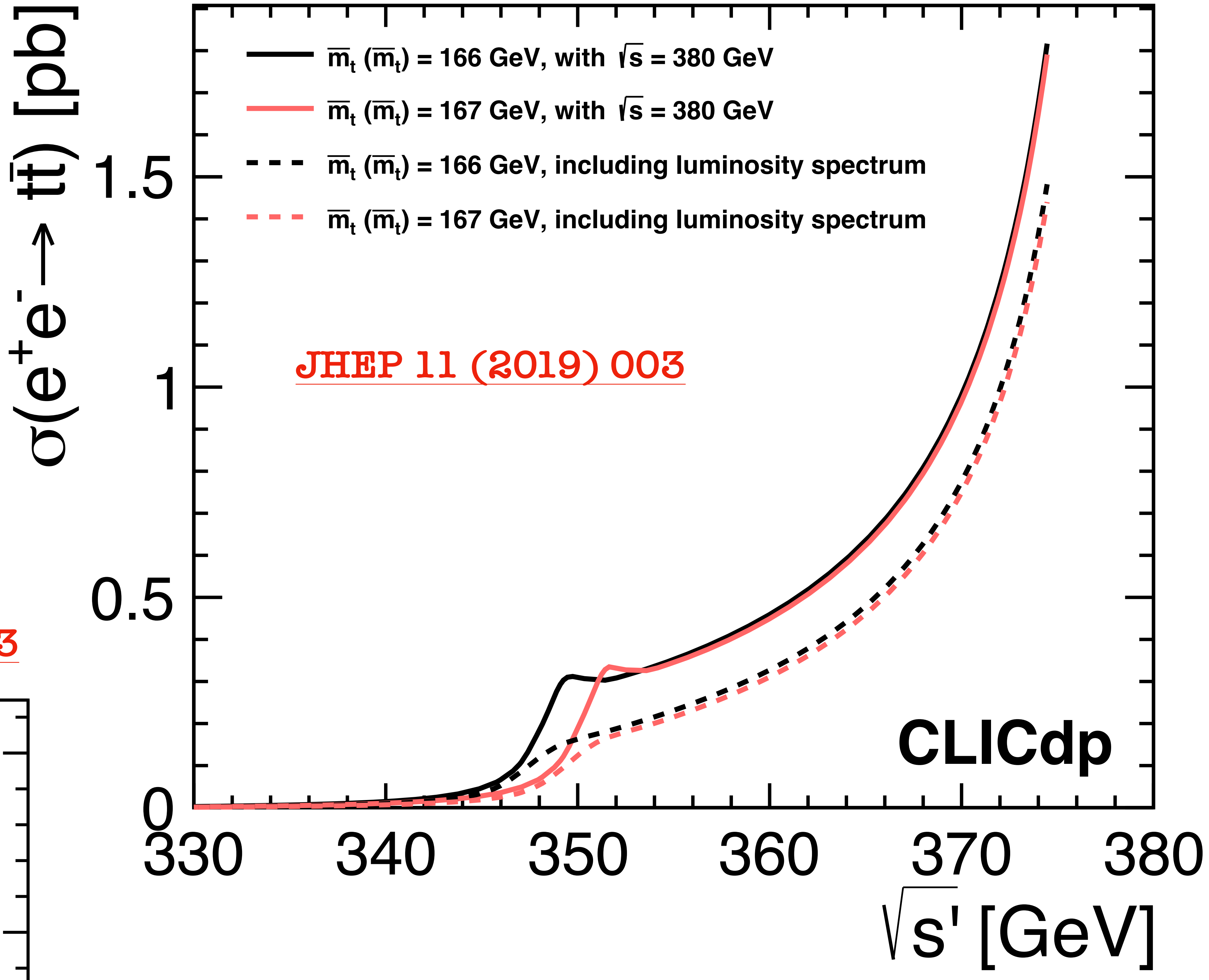
- 100 MeV statistical uncertainty for 1 ab^{-1}
- 100 MeV theoretical uncertainty (NNLO+NNLL)

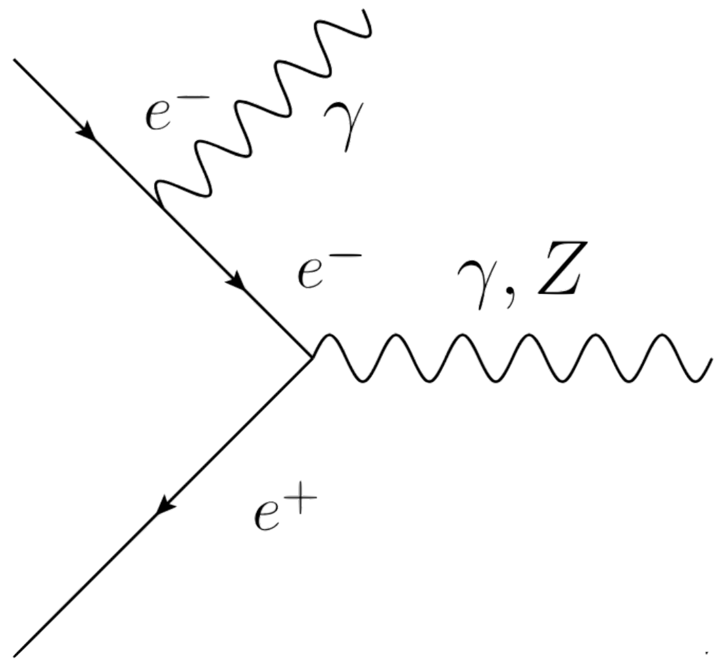
Can this be envisaged at FCC-ee @ 365 GeV ?



JHEP 11 (2019) 003







$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

$|V_{ts}|$ at FCC-ee

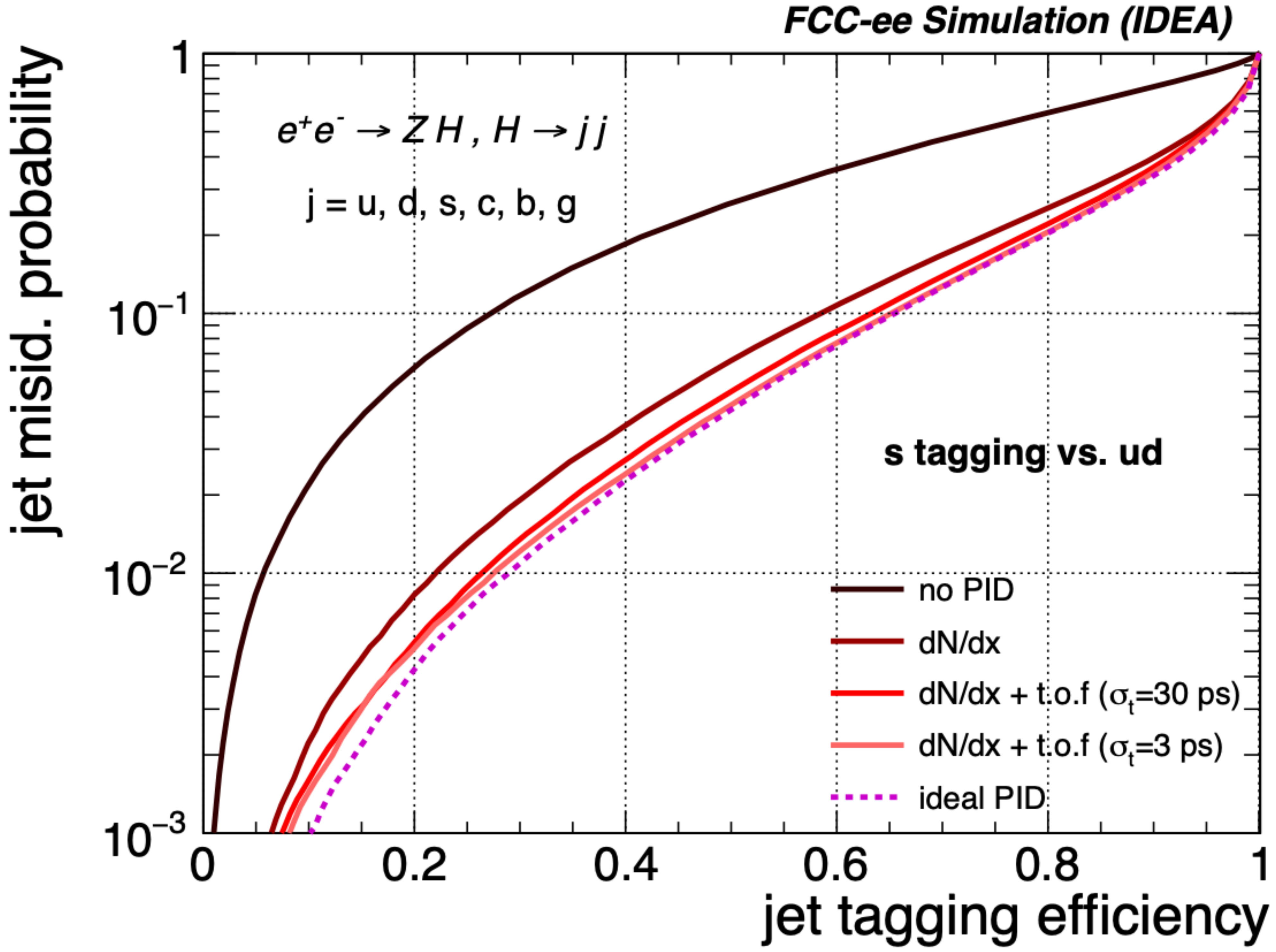
From Xunwu's talk [link]

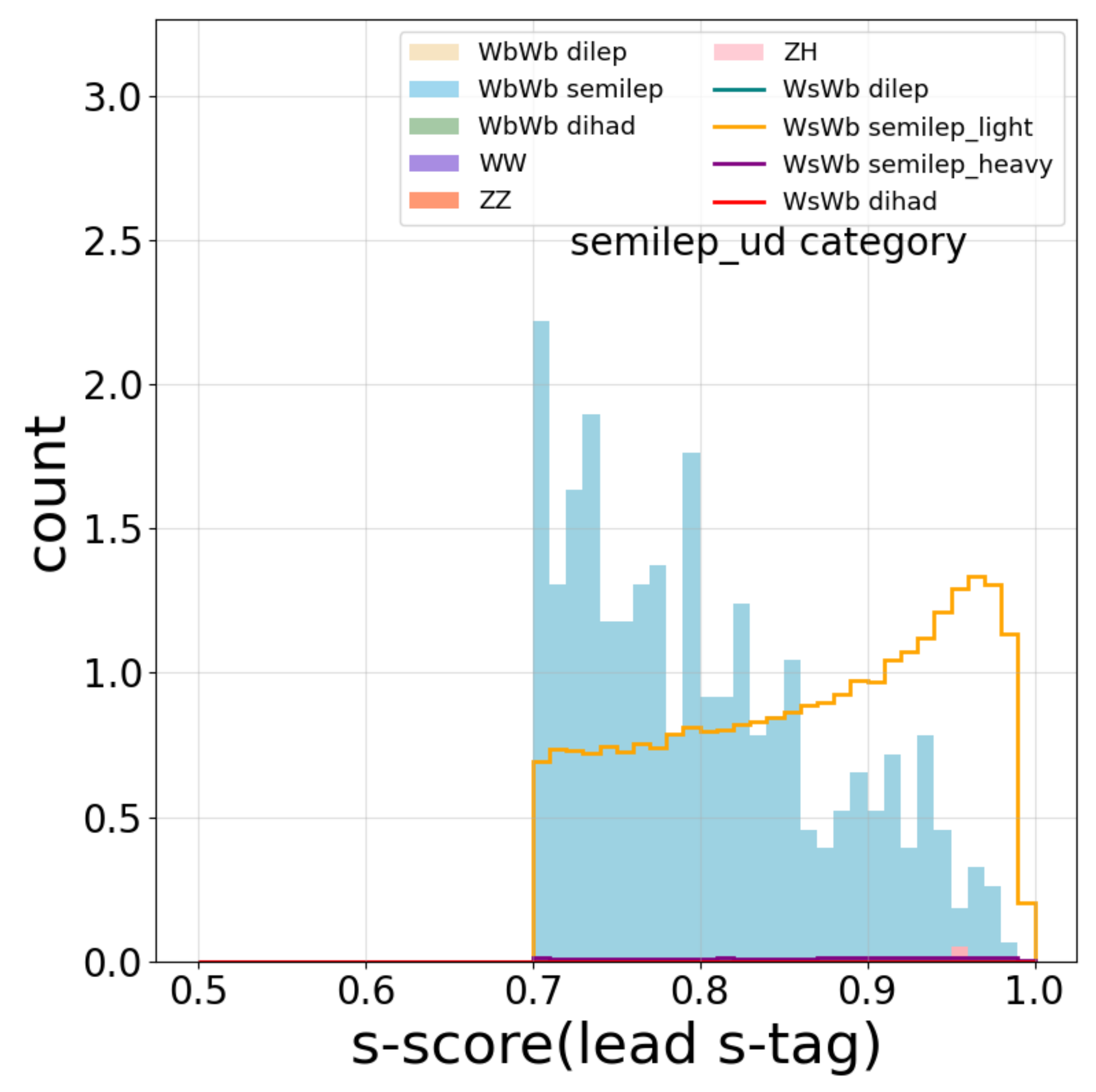
Current measurements on $|V_{ts}|$

- PDG value: $|V_{ts}| = (41.5 \pm 0.9) \times 10^{-3}$
  - From $B_s^0 - \bar{B}_s^0$ mixing, mediated via t-W box diagrams
  - Assume no NP in the loop
  - Dominated by theory uncertainty from lattice QCD

Potential at e^+e^- colliders

- **Model-independent direct measurement**
- $\sim 6400\ t \to Ws$ decays expected at FCC-ee (2.5 ab^{-1})
  - Crucially depend on s-tagging performance
  - Limited by statistical uncertainty





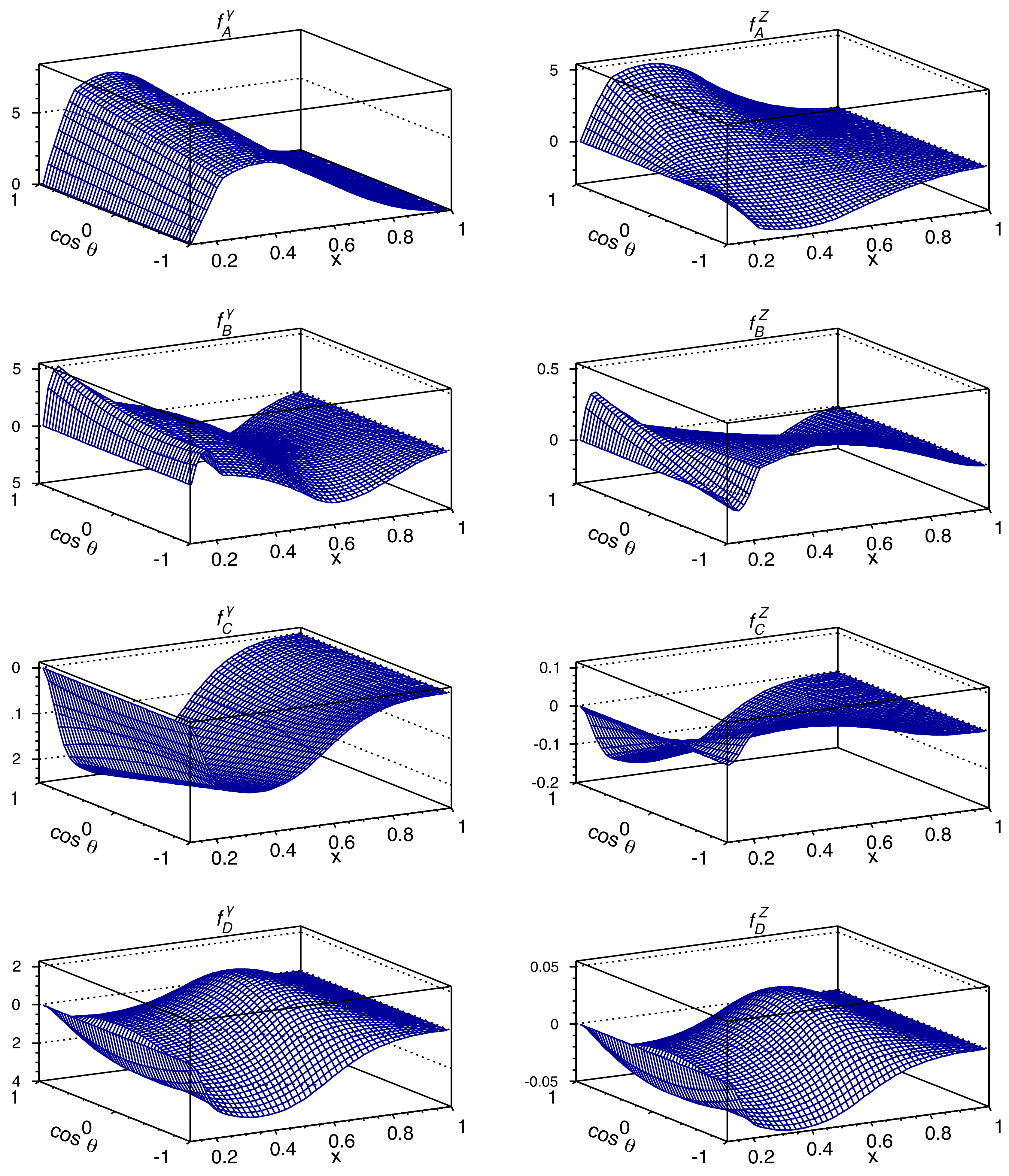
Significance of 7.7 sigma -> |Vts| measurement with statistical precision of 10%

Couplings to photon and Z boson

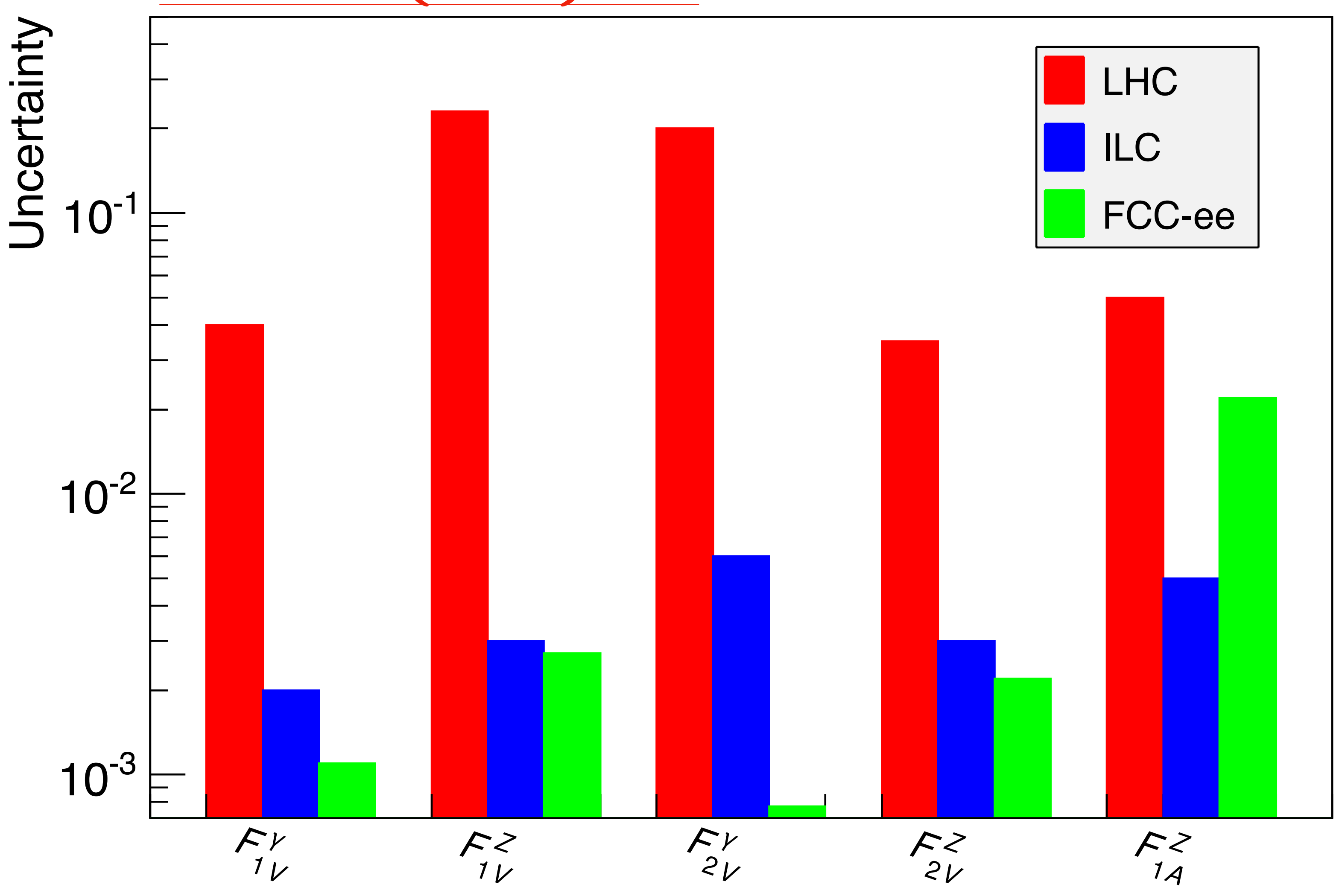
JHEP 04 (2015) 182

- Can be **simultaneously constrained** at FCC-ee via lepton kinematics in semi-leptonic decay channel
- Requires differential measurement in lepton azimuthal angle and (reduced) energy (x)
- **Does not require beam polarisation!**

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



JHEP 04 (2015) 182



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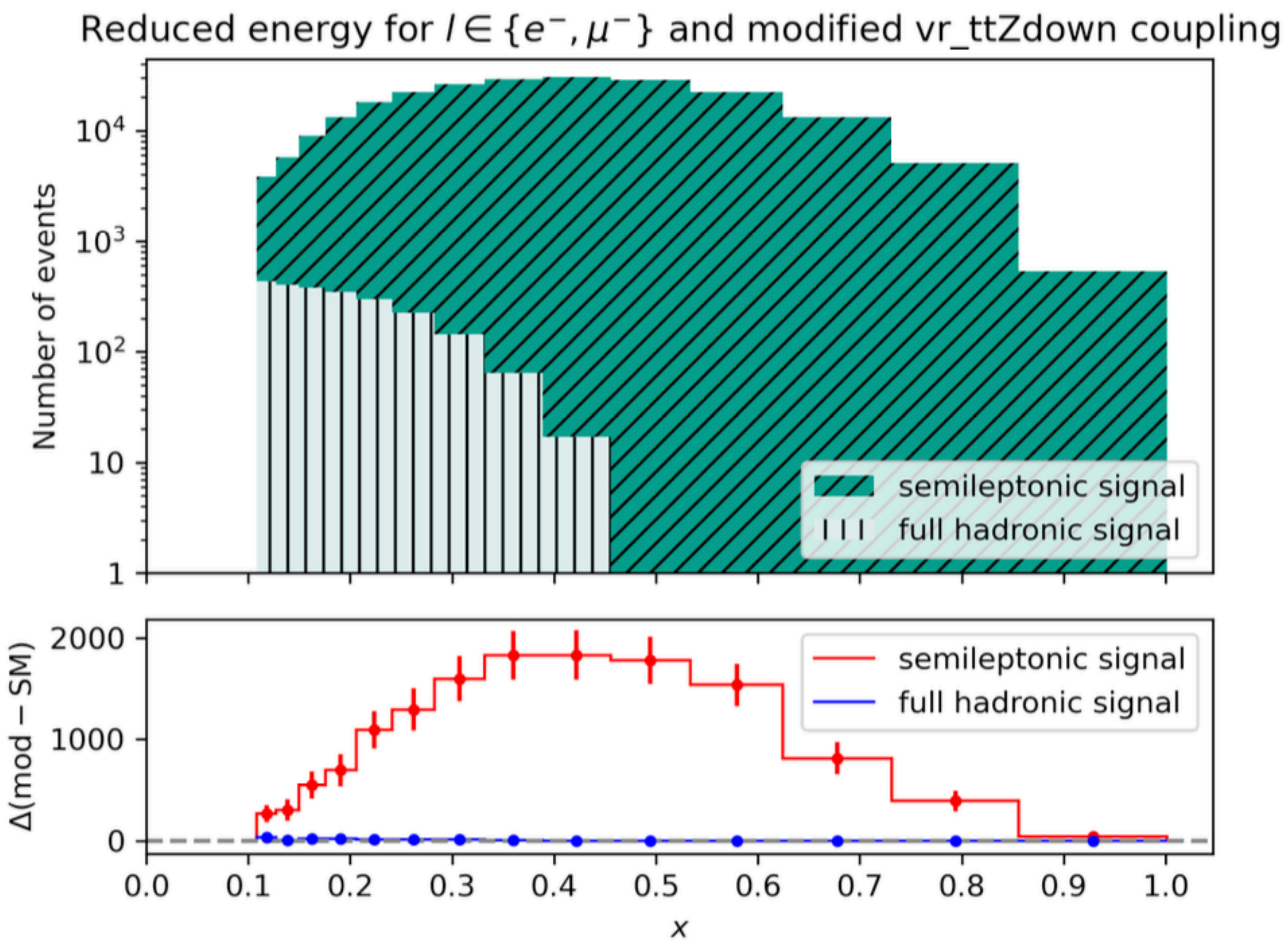


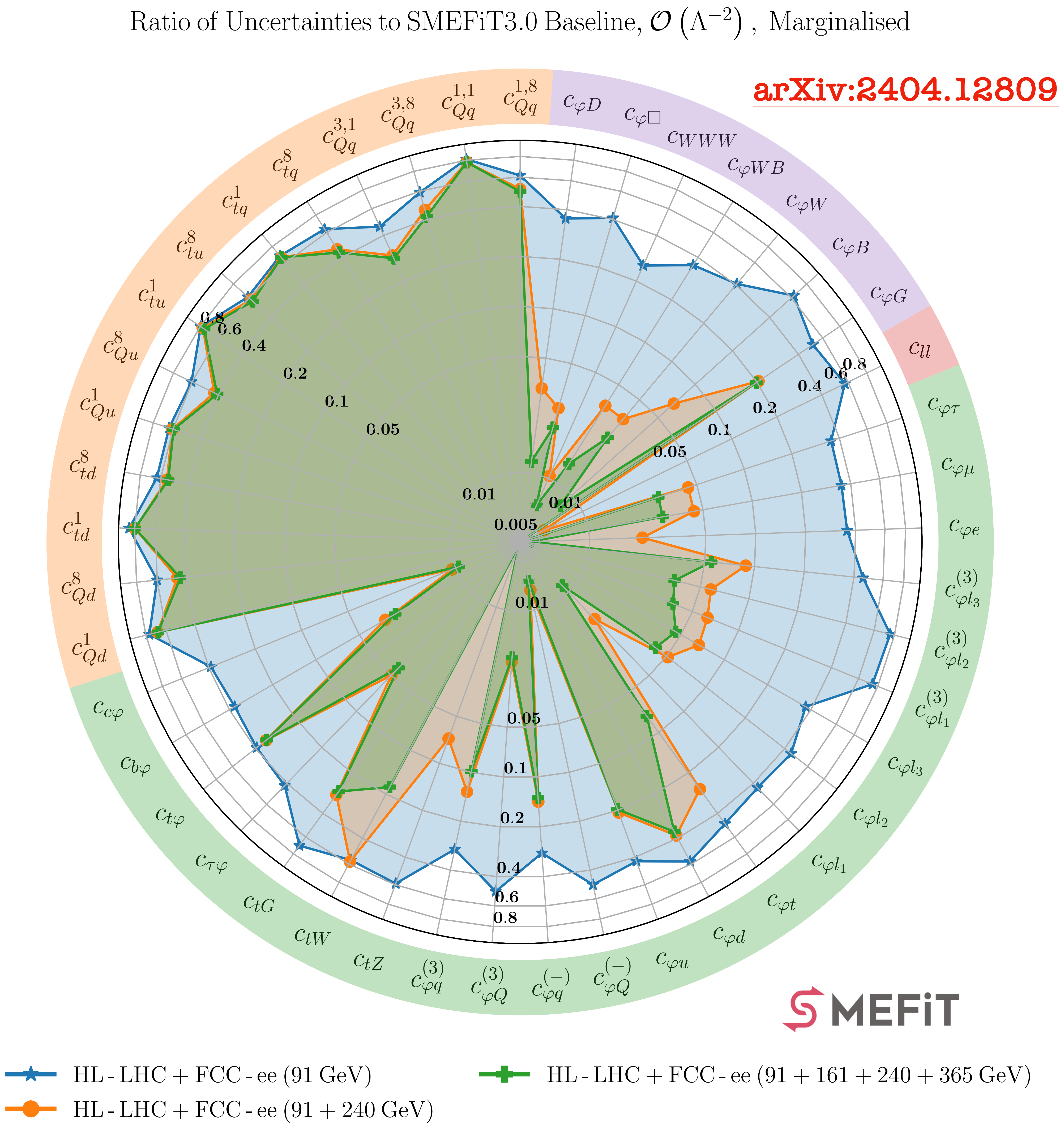
Ongoing detector-level analysis with FCC-ee Delphes simulation

Summary and outlook

See Marcel's talk on global interpretations [link]

- **Plenty of potential** to constrain top quark properties and couplings at (and above) the tt production threshold
- Possibility to determine **top quark Yukawa coupling with competitive precision**
- Determination of top quark mass and width currently limited by theoretical uncertainties (30/40 MeV)
  - **Need improvements on theory predictions**

- Efforts started with FCC-ee simulation for both top properties and couplings, showing promising results
- Aiming at being **included in the input to the strategy**, and at further improvements in the future



Thank you