Top quark physics at FCC-ee

with a focus on new studies on the tt threshold scan

FCC Physics Workshop

13-17 January 2025, CERN

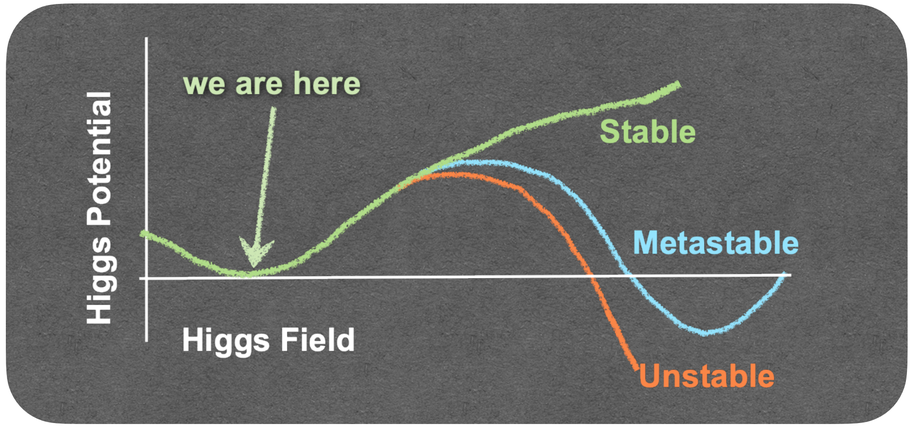
Matteo Defranchis (CERN)

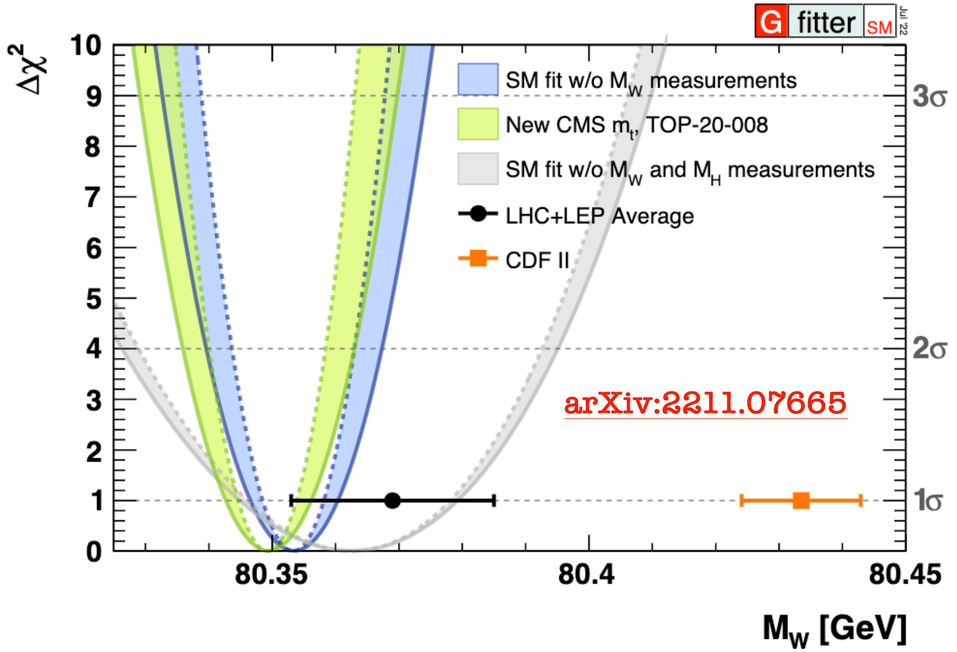
with the precious input from many colleagues

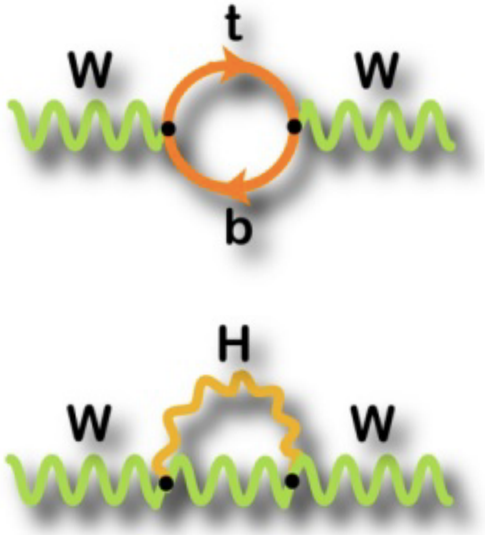
The role of the top quark mass in the (B)SM

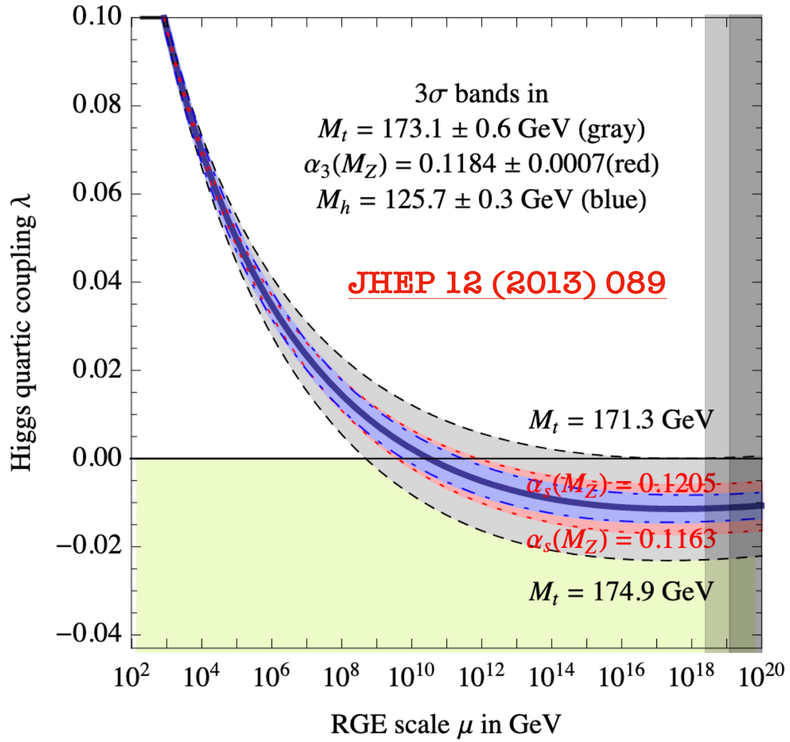
- In the SM, m_t can be related to m_W and m_H thanks to loop corrections -> **internal consistency of SM**
- **Stability of EW potential** at the Planck scale depends on value of m_t, m_H, and α_s via RGE for λ

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

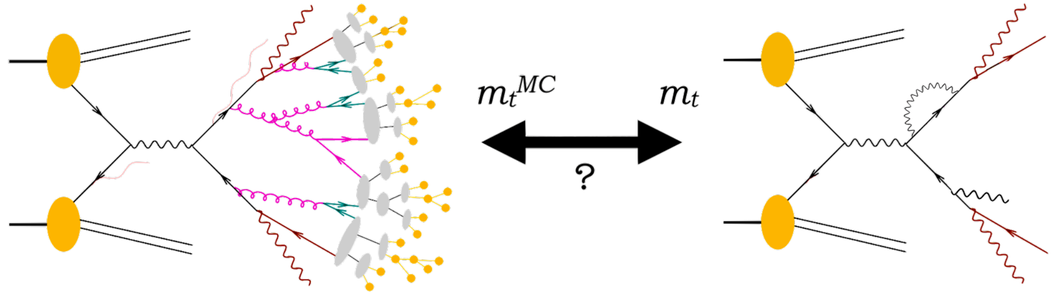








Top quark mass at the LHC



Direct measurements

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

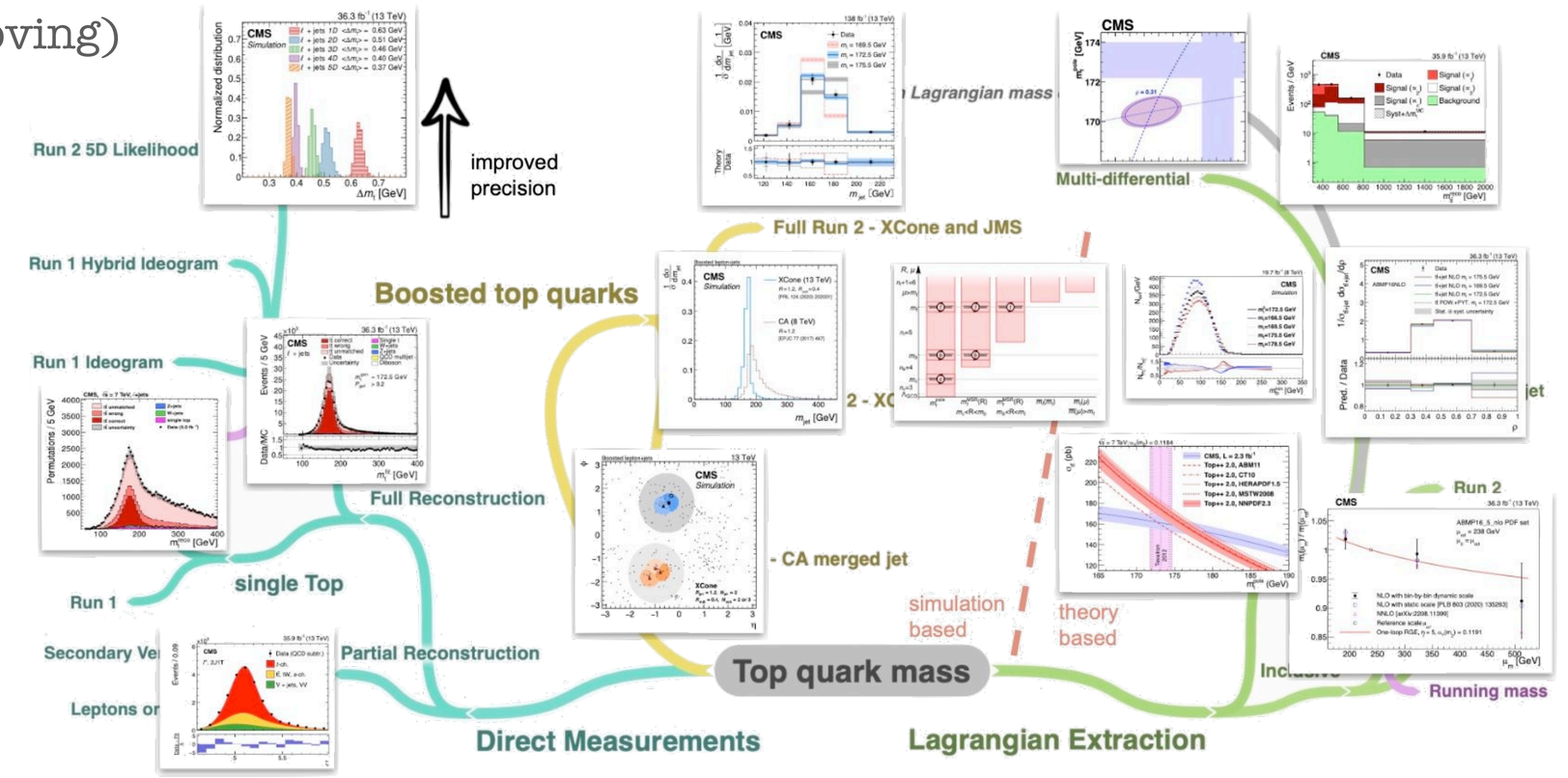
Indirect measurements

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

Boosted measurements

- May help with clarifying the picture, but still exploratory

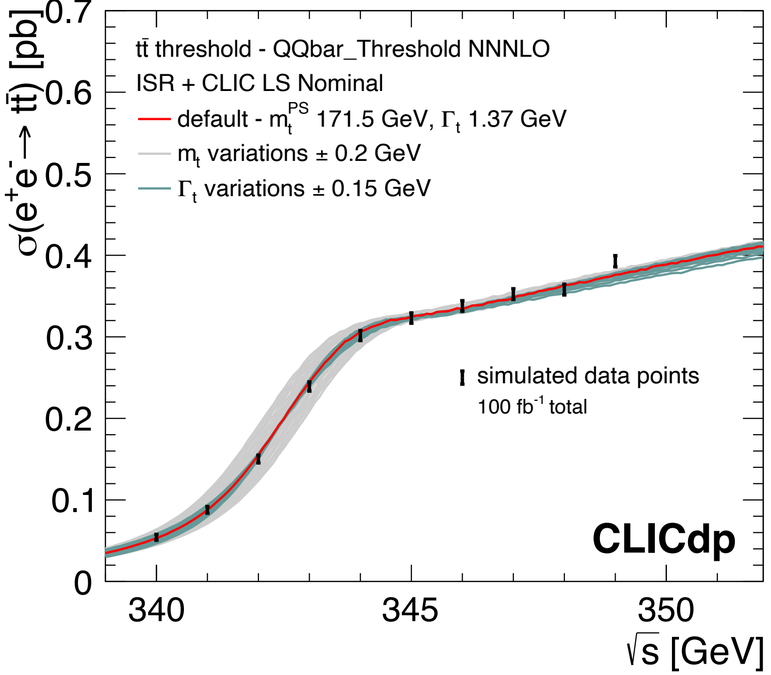
Only lepton collider can provide unambiguous measurement of m_t at the desired precision (few tens of MeV)



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
- Parametric dependence on α_S and top Yukawa

JHEP 11 (2019) 003



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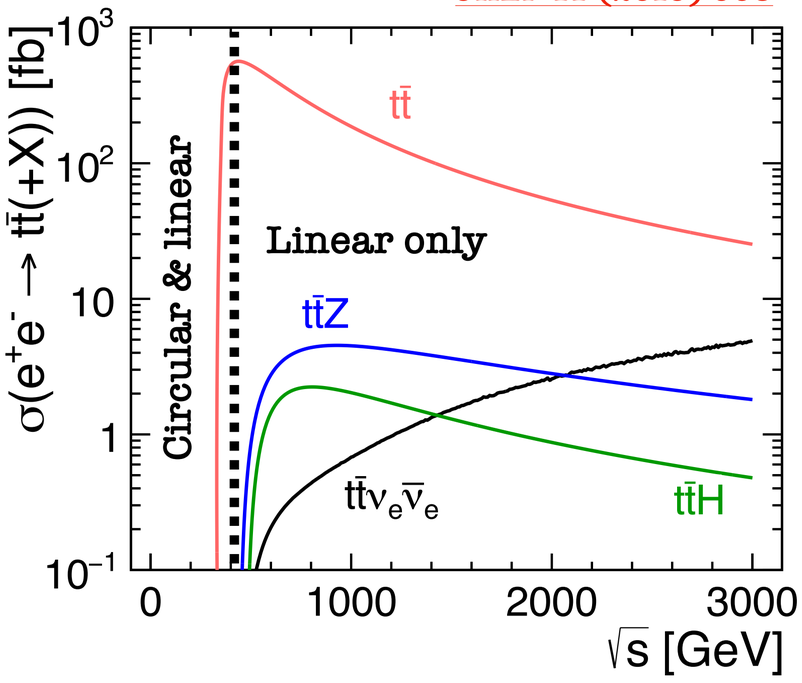
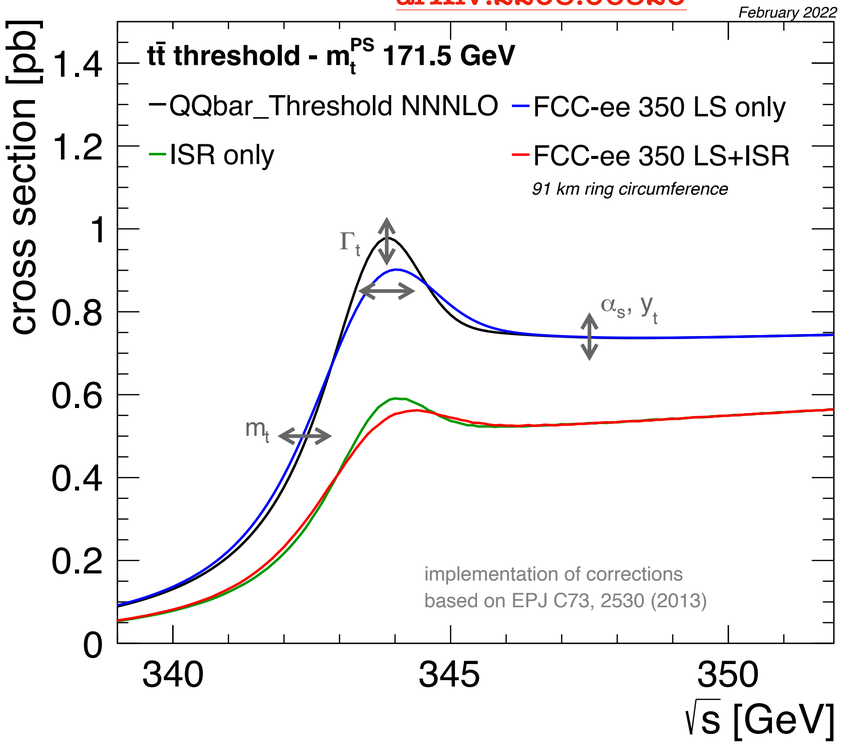
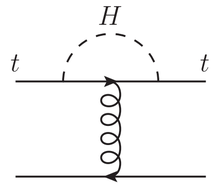
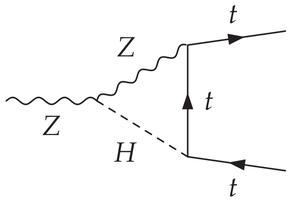
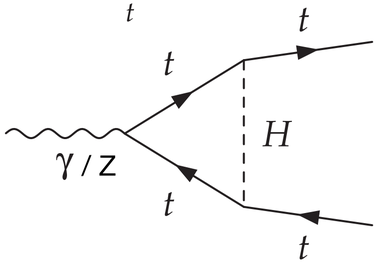


arXiv:2203.06520









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

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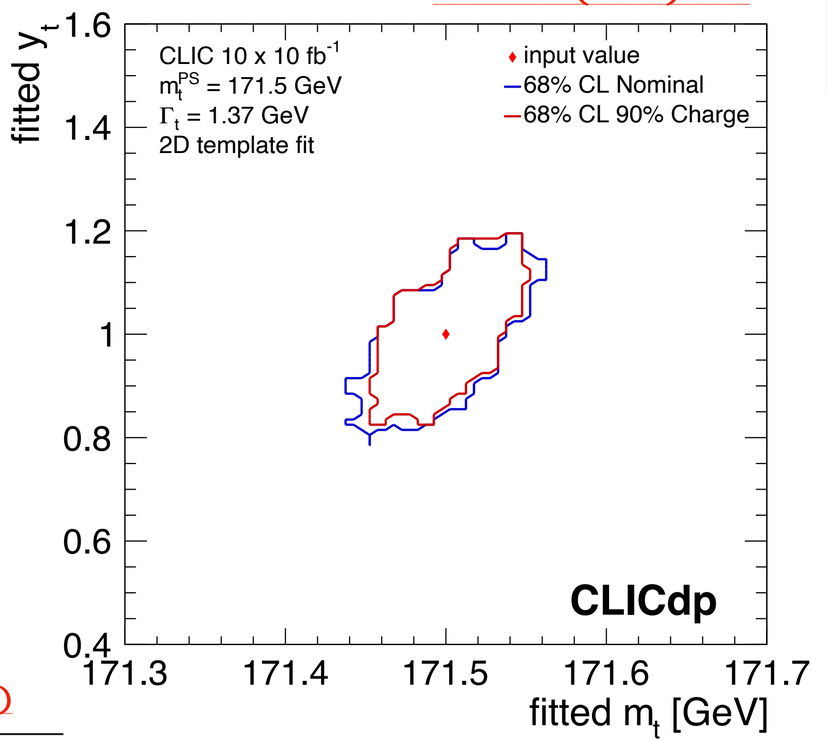


CLIC, 100 fb^{-1}

- 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)**
  - 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

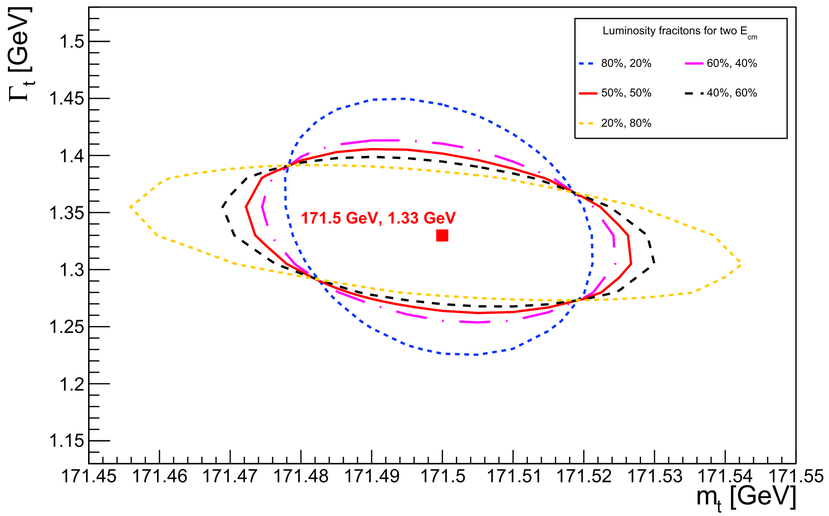
CEPC, 100 fb^{-1}

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

EPJC 83 (2023)

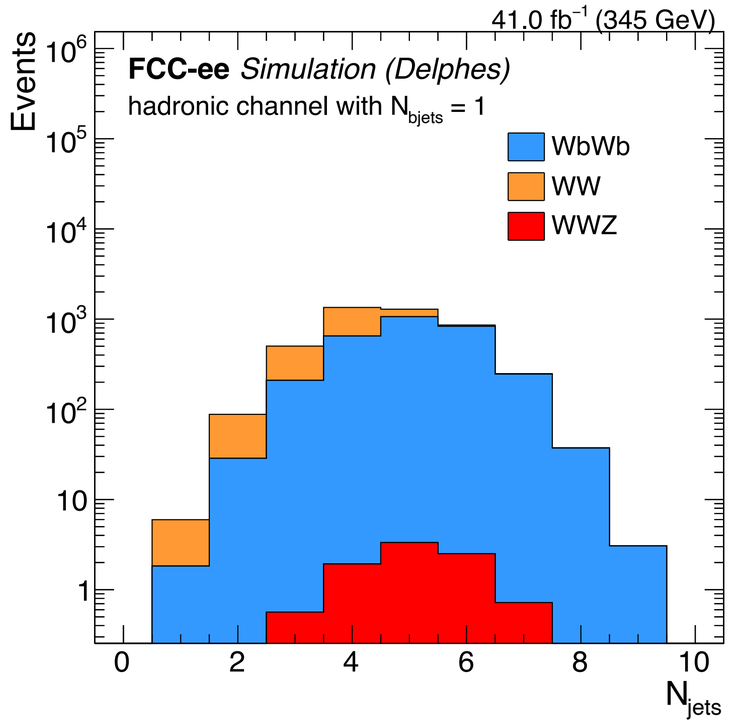
Source	m_{top} precision (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	9	26
Quick scan	3	3
α_S	17	17
Top width	10	10
Experimental efficiency	5	45
Background	4	18
Beam energy	2	2
Luminosity spectrum	3	5
Total	25	59

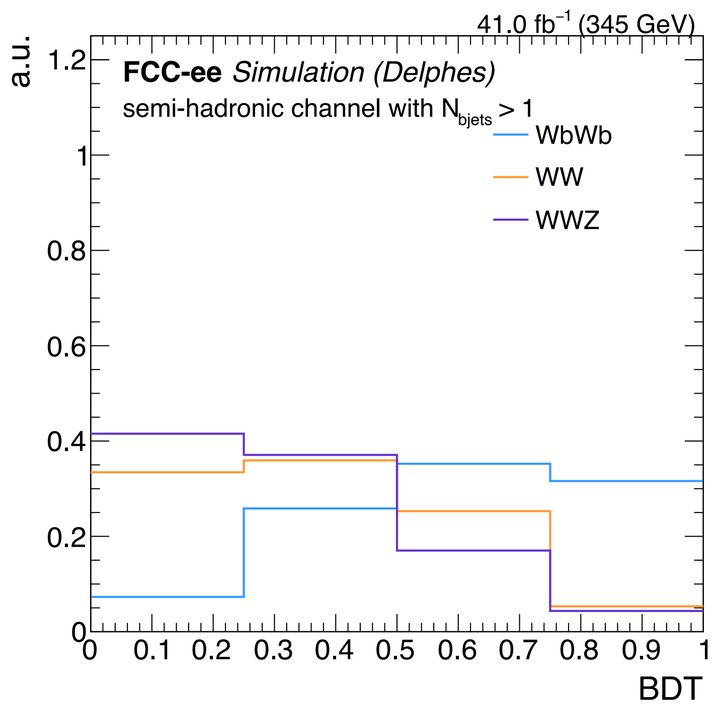
EPJC 83 (2023)

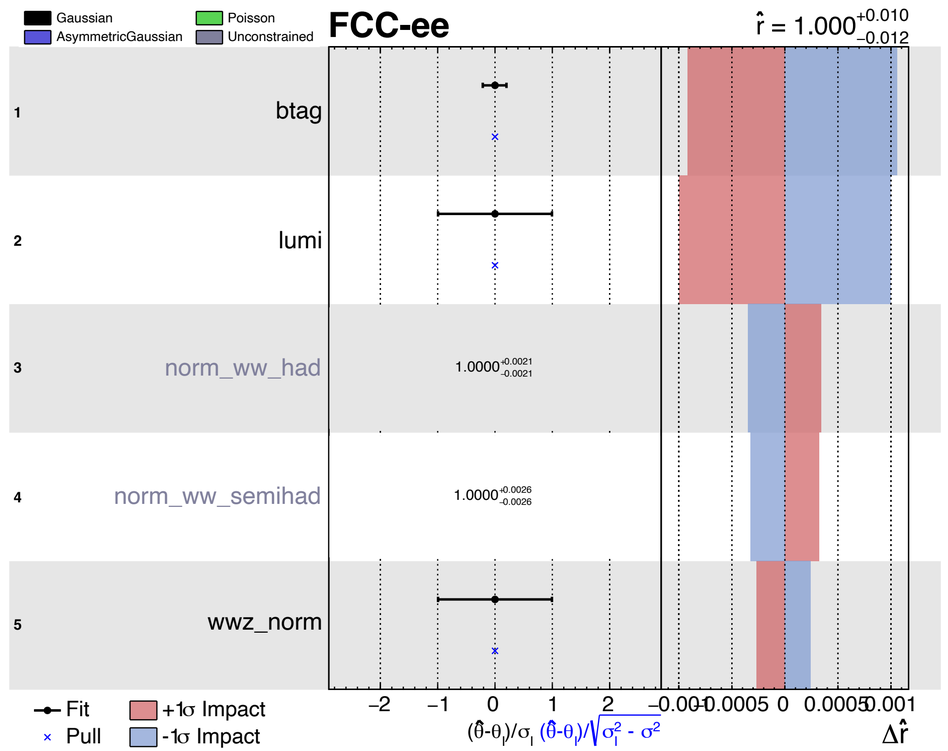


FCC-ee detector-level studies

See talk by A. Mehta at ECFA workshop [link]







- Detector-level Delphes simulation (IDEA detector)
- **Hadronic** and **semi-hadronic** final states (>80% branching ratio in total)
- Profile-likelihood fit in jet and b-tag multiplicity to extract total rates (maximize acceptance)

- Relevant systematic effects controlled well below stat. uncertainty (permille level)
- Modelling uncertainties in MC simulation (e.g. parton shower) or affecting signal acceptance (e.g. top mass) found to have negligible effect on measured cross section

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

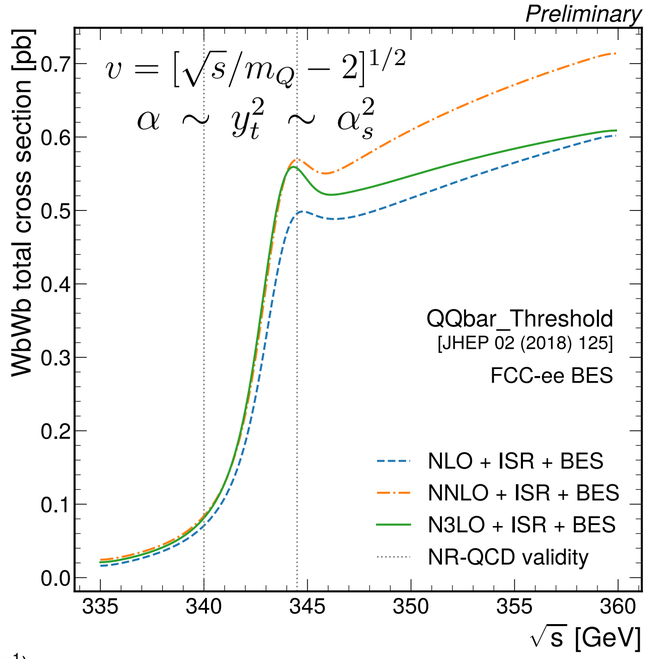
- Folded with FCC-ee beam energy spectrum (BES): 0.23 % / beam
- **2-dimensional fit of m_t and Γ_t, with profiled α_s and y_t**

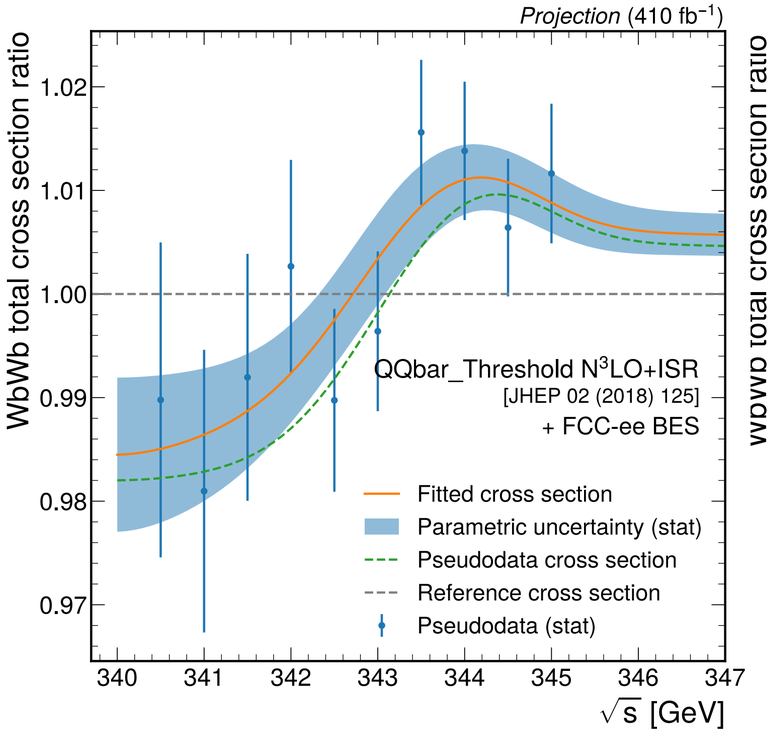
Baseline scenario: 10 equally-spaced (0.5 GeV) equal lumi (41 fb^{-1}) points

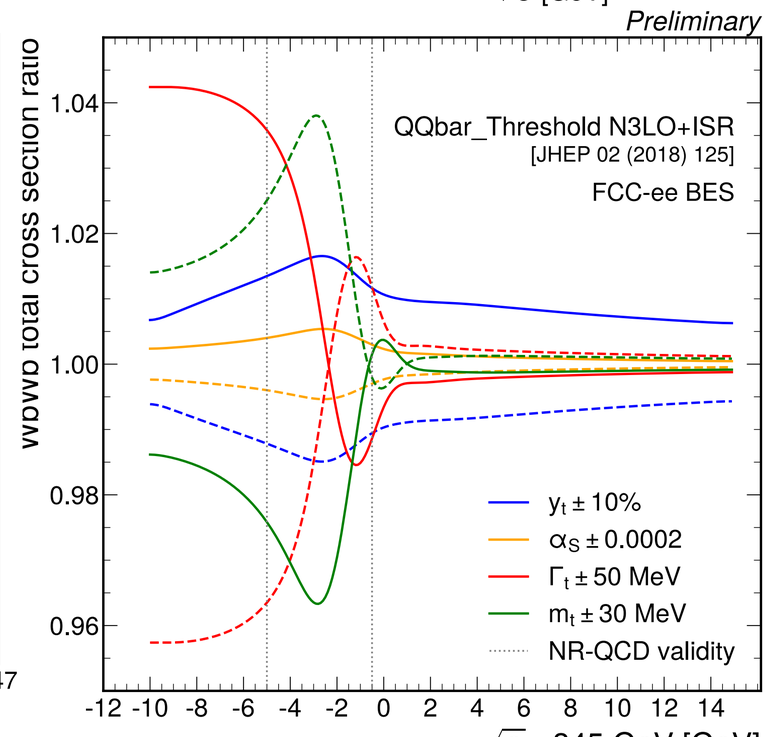
E_{cm} [GeV]	Integrated lumi
340-345	410 fb^{-1}
365	2.65 ab^{-1}

- **4 (10) MeV** statistical uncertainty **in m_t (Γ_t)** in 2D fit (410 fb^{-1})
- **y_t** can be determined to **1.7% (stat)** using 365 GeV run (2.65 ab^{-1}), assuming only effect on Z-tt vertex

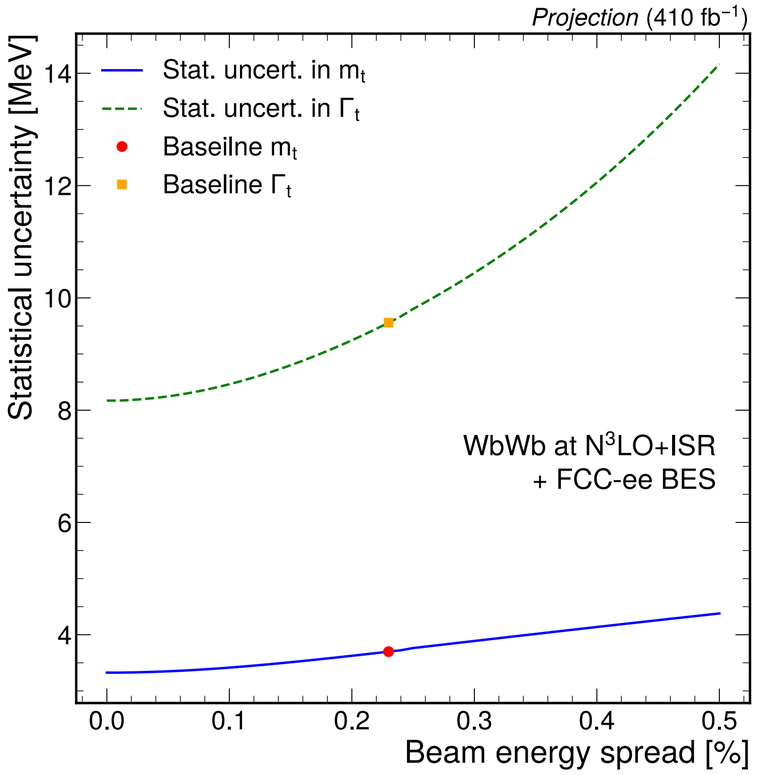
cf. CLIC: 2.7% (stat) in y_t with 2.5 ab^{-1} of ttH

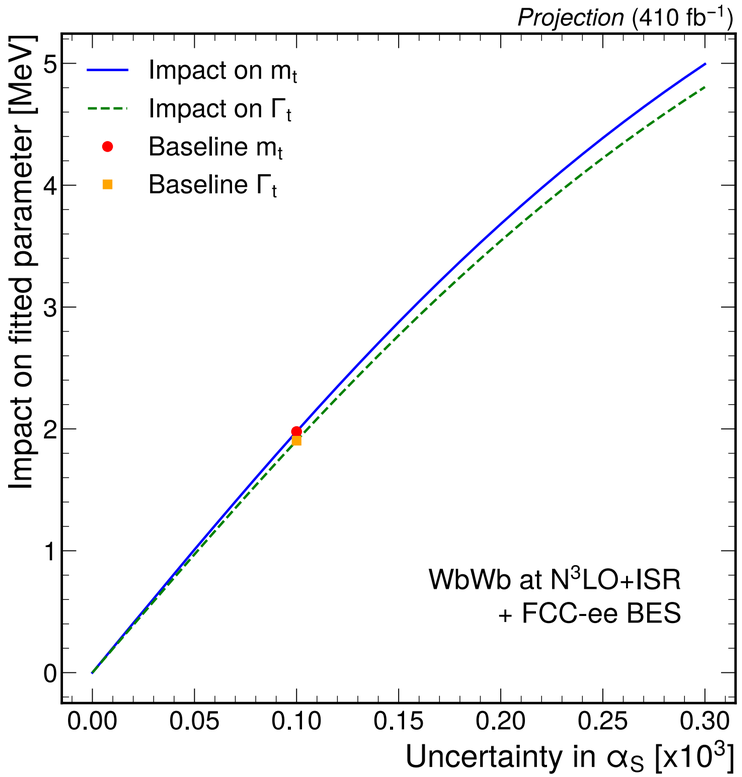


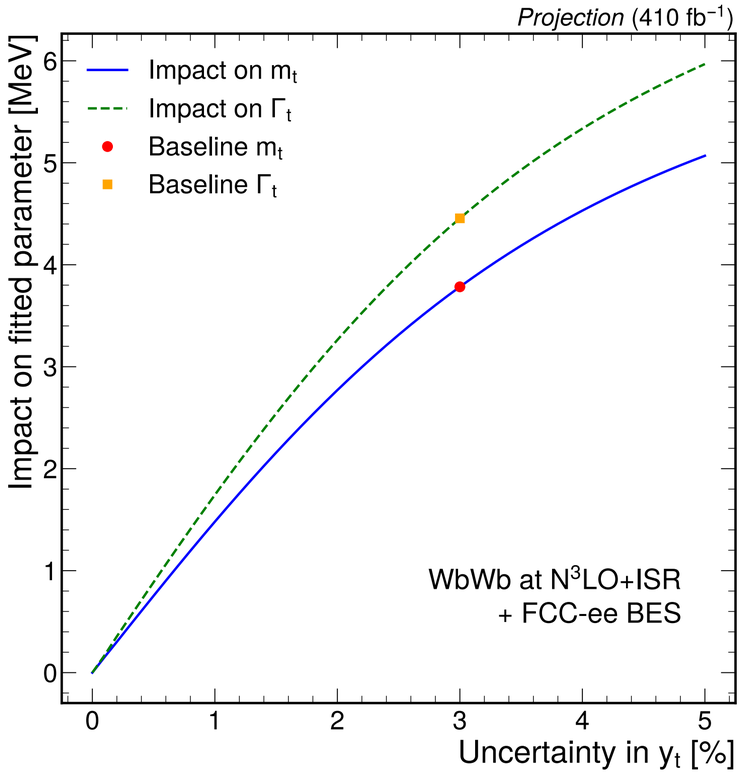




Parametric dependences and uncertainties

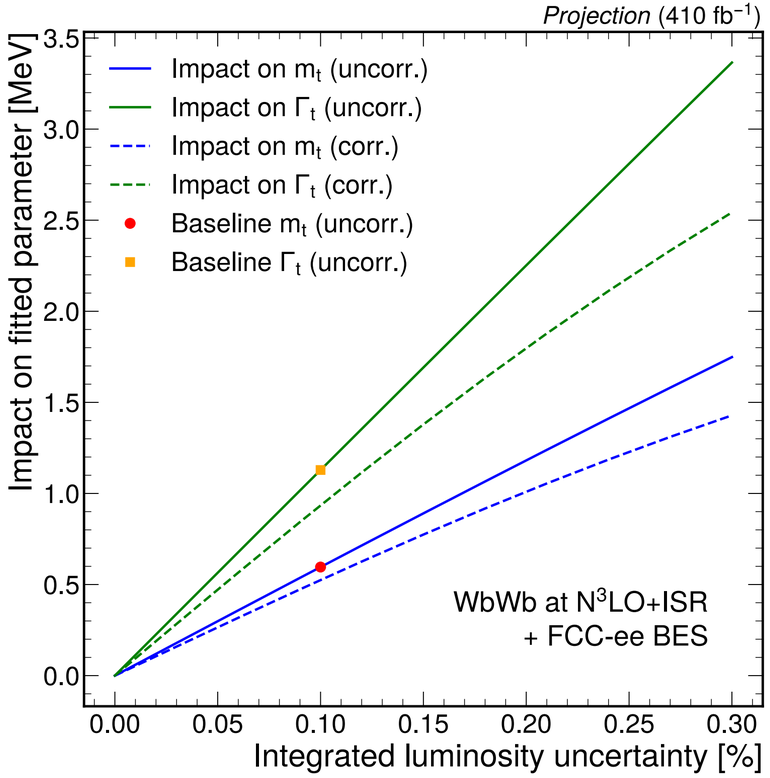


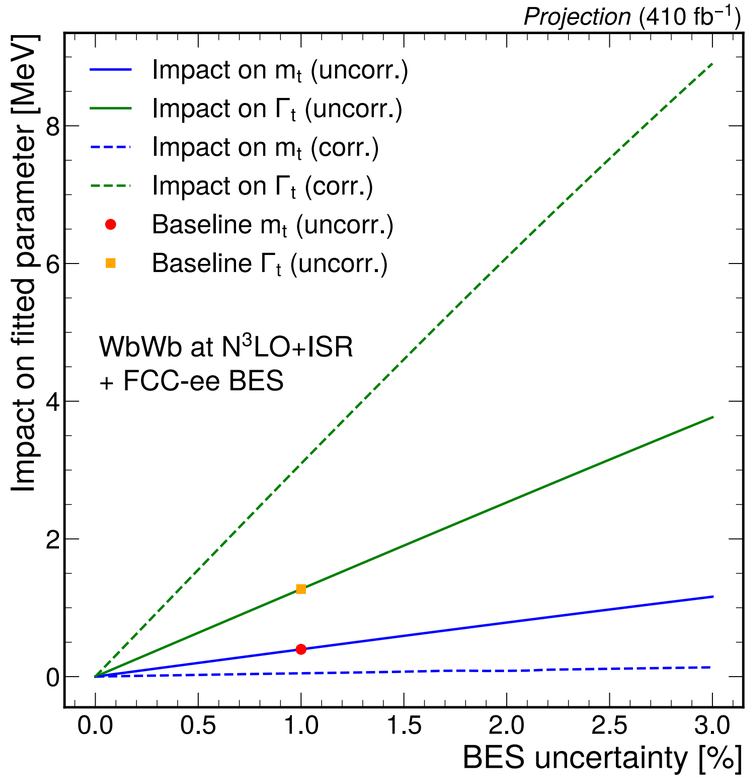


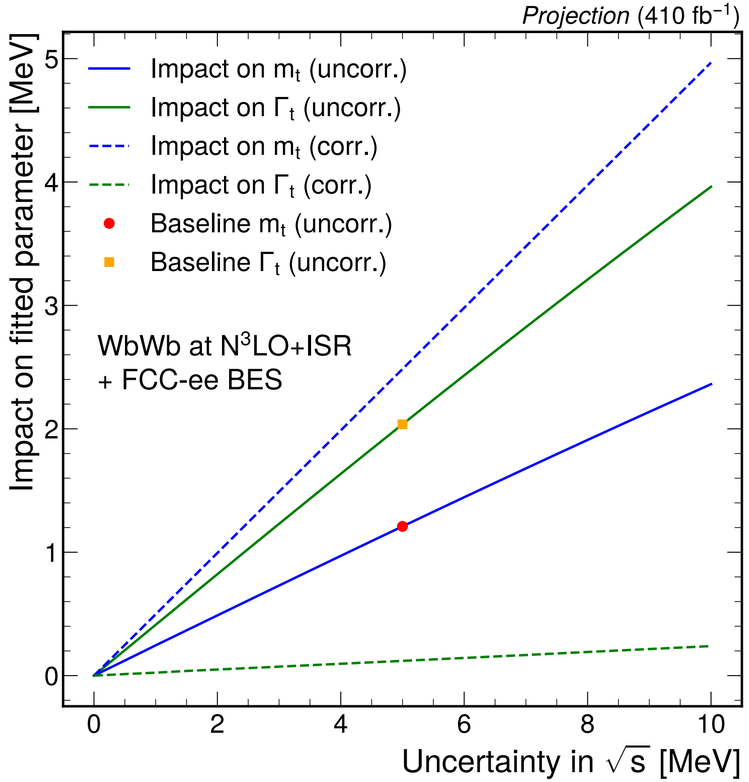


- Studies **parametric dependence** on beam energy spread (BES), strong coupling, and top Yukawa
- Central values from current best estimates (HL-LHC / FCC-ee)
- 3% uncertainty on y_t (HL-LHC) has significant impact on both mass and width

Dependence on luminosity and beam calibrations







- 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

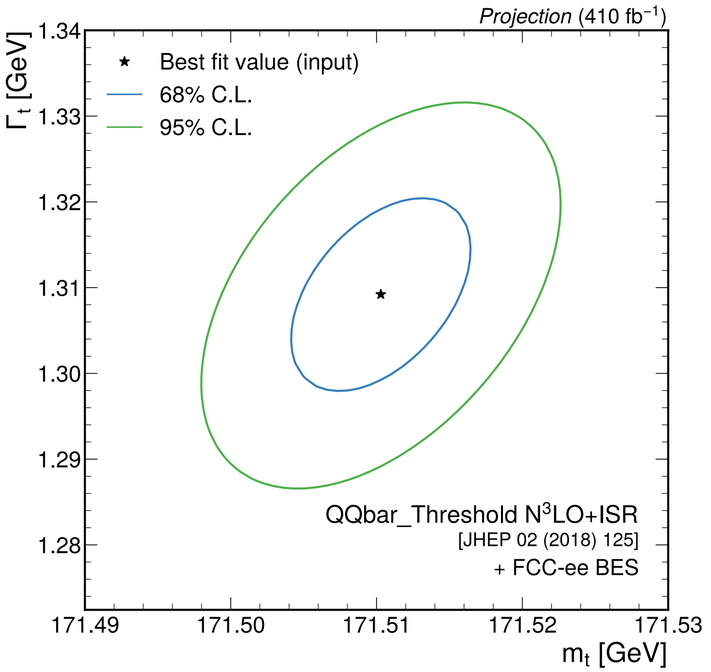
Uncorrelated = of statistical nature

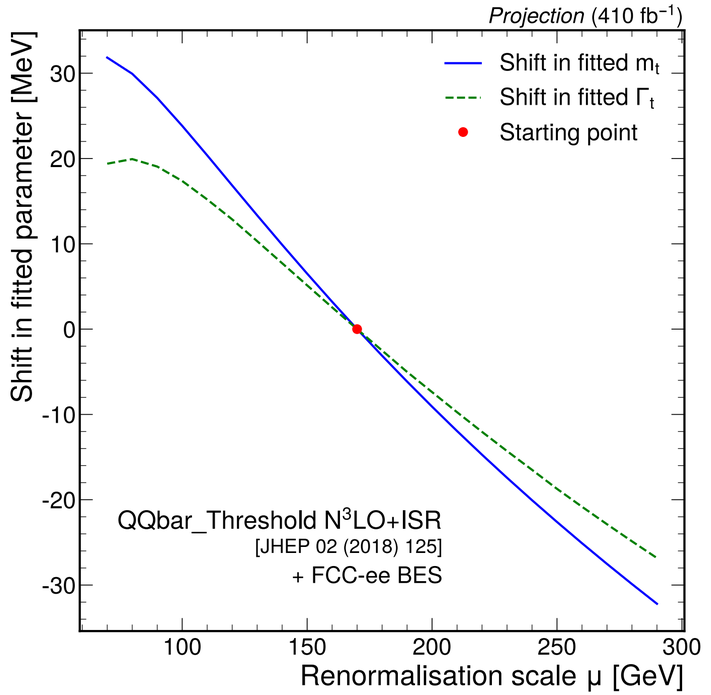
Correlated = residual correlated component between different E_{cm} (e.g. W mass constraint)

Total uncertainty

MD, A. Mehta, M. Selvaggi, M. Vos
(paper in preparation)

uncertainty	m_t^{PS} [MeV]	Γ_t [MeV]	comment
statistical	3.7	9.6	FCC-ee, 410 fb^{-1}
luminosity calibration (uncorr.)	0.6	1.1	$\delta L/L = 1 \times 10^{-3}$
luminosity calibration (corr.)	0.3	0.5	$\delta L/L = 0.5 \times 10^{-3}$
beam energy calibration (uncorr.)	1.2	2.0	$\delta\sqrt{s} = 5$ MeV [16, 17]
beam energy calibration (corr.)	1.2	0.1	$\delta\sqrt{s} = 2.5$ MeV
beam energy spread (uncorr.)	0.6	1.1	$\delta\Delta E = 1\%$ [16]
beam energy spread (corr.)	< 0.1	1.5	$\delta\Delta E = 0.5\%$
parametric (α_s)	2.0	1.9	$\delta\alpha_s = 1 \times 10^{-4}$
parametric (y_t)	3.8	4.5	$\delta y_t = 3\%$
total profiled	6.2	11.3	
b-tagging, background	0.2 – 0.5	0.6 – 1.2	controlled in-situ
theory, unprofiled (scale)	35	25	N^{3}LO NRQCD [7]





- **Arbitrary assumption for illustration**: residual correlated components assumed to be half of the uncorrelated ones
- Simplistic approach, but effect neglected in the past
- Planning more studies to better assess systematic effects

Largely limited by current uncertainty in N^{3}LO NR-QCD calculation

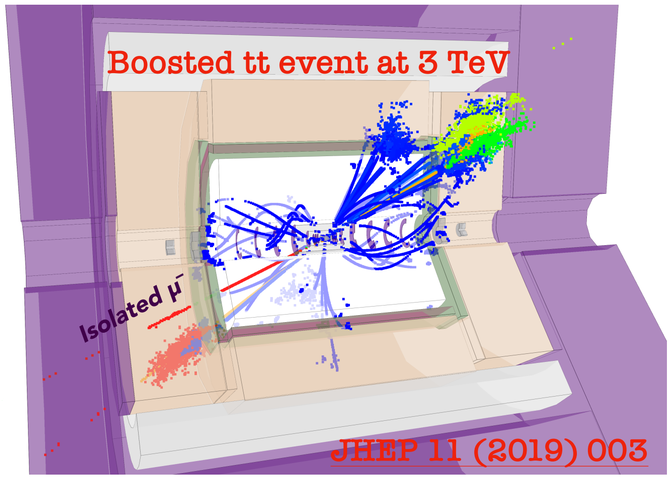
m_t above the tt production threshold

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 ?



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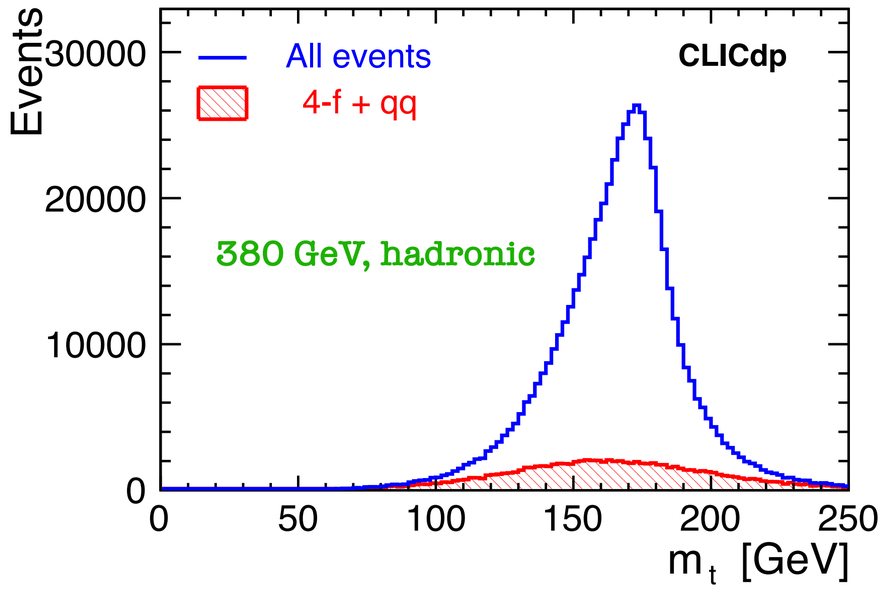
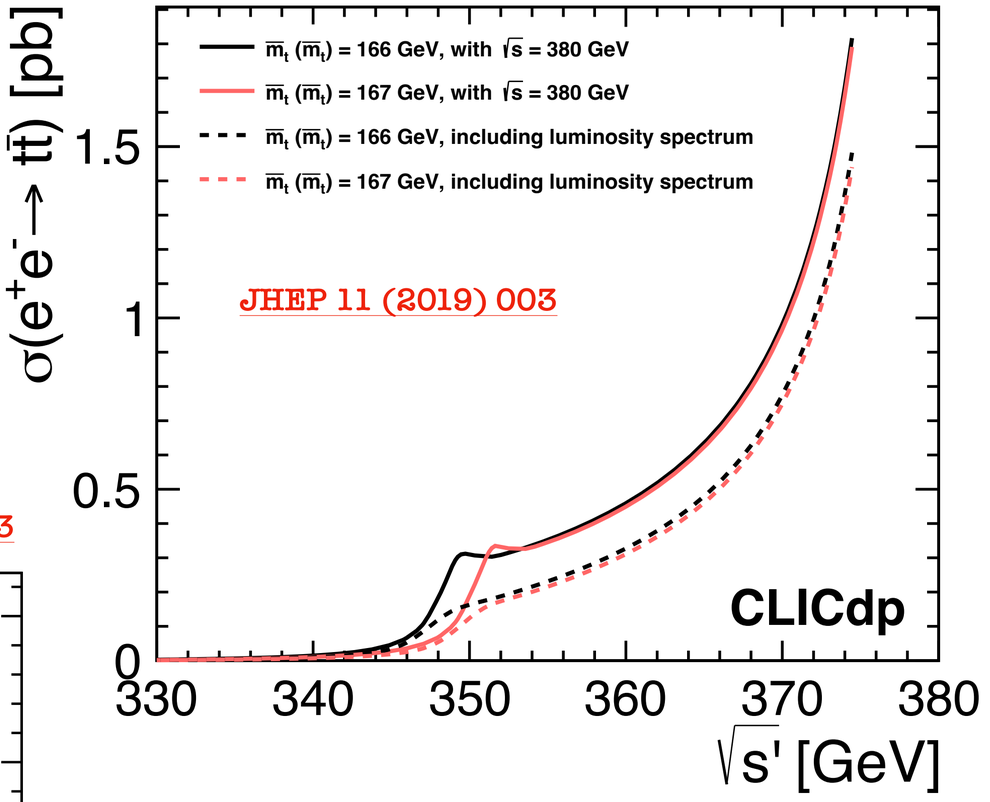
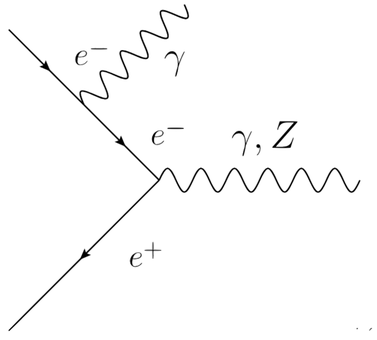






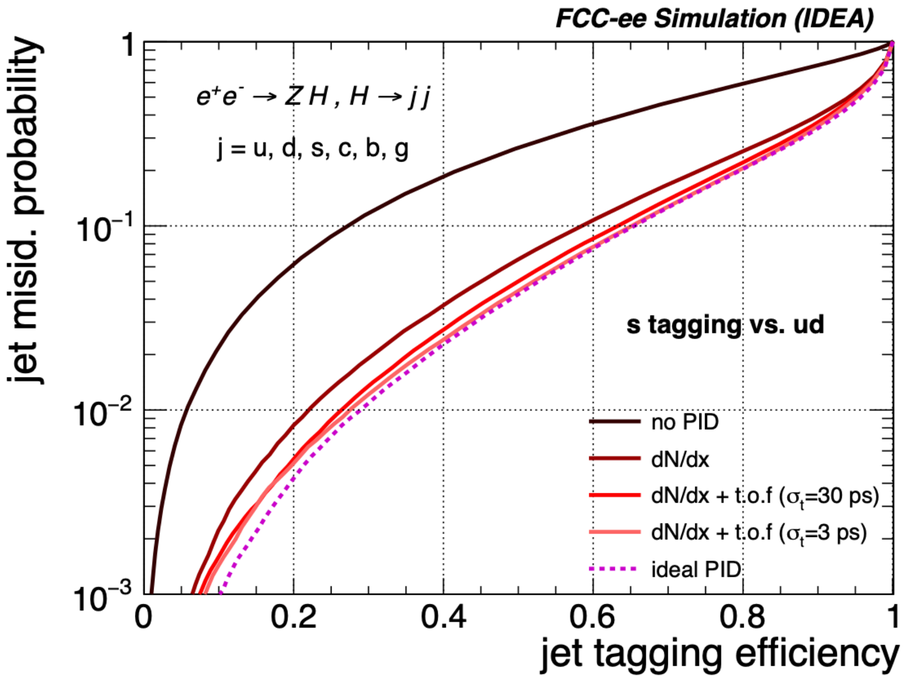
$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

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

More details in Xunwu's talk at ECFA workshop [link]

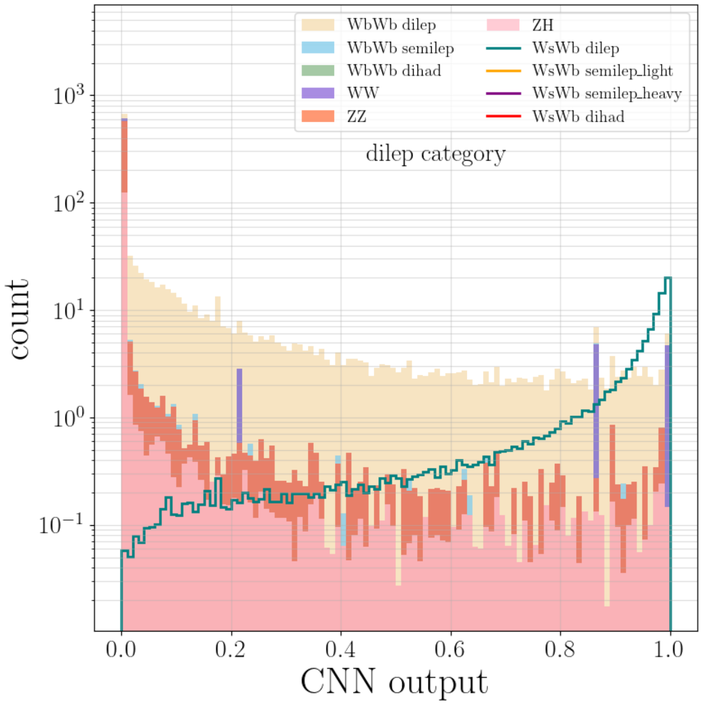
Current measurements on $|V_{ts}|$

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



Significance ~10 sigma (stat) using multivariate approach
-> 15% precision in $|V_{ts}|$

Couplings to photon and Z boson

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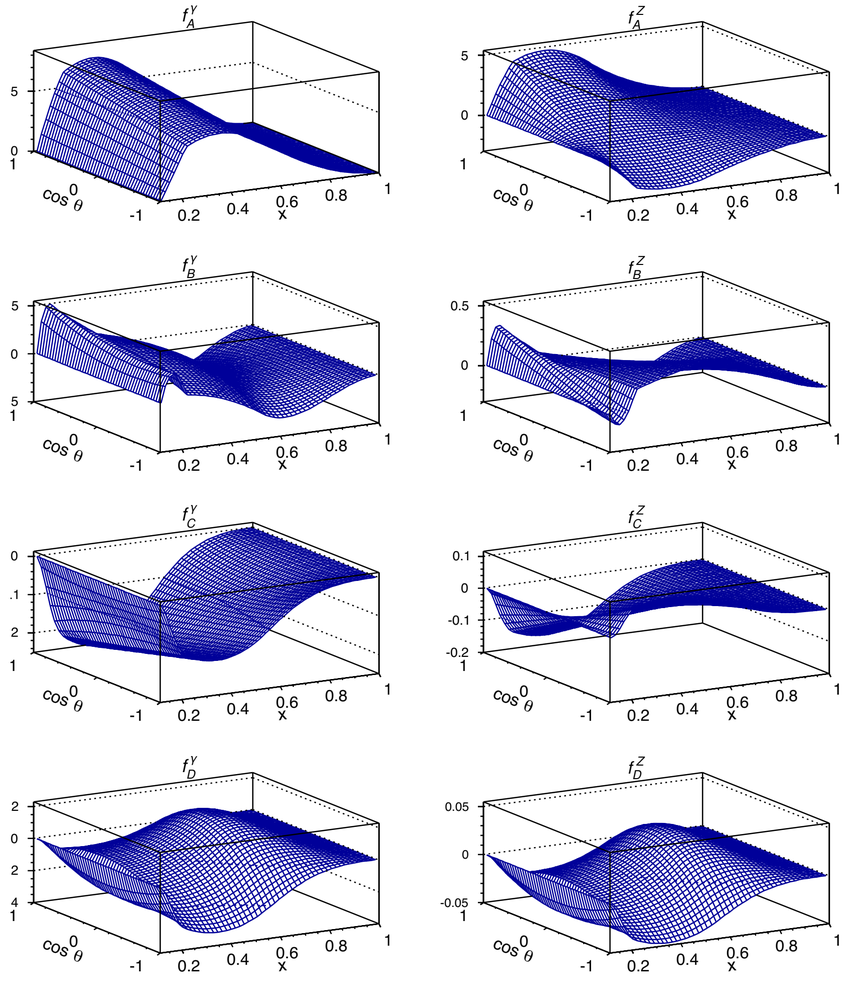
- Can be **simultaneously constrained** at FCC-ee via lepton kinematics in semi-leptonic decay channel
- Requires differential measurement in lepton azimuthal angle and (reduced) energy (x)
- This method does not require beam polarisation, which however remains very beneficial for this measurement

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



See talk from X. Zuo at ECFA workshop [link]

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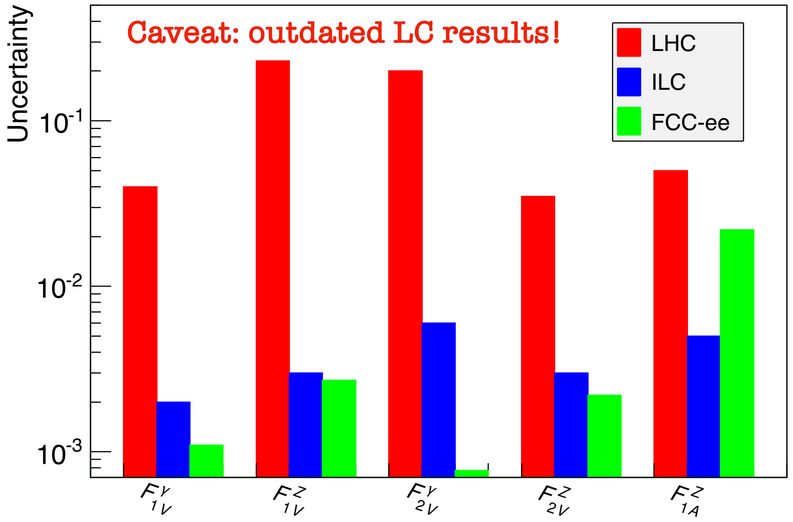
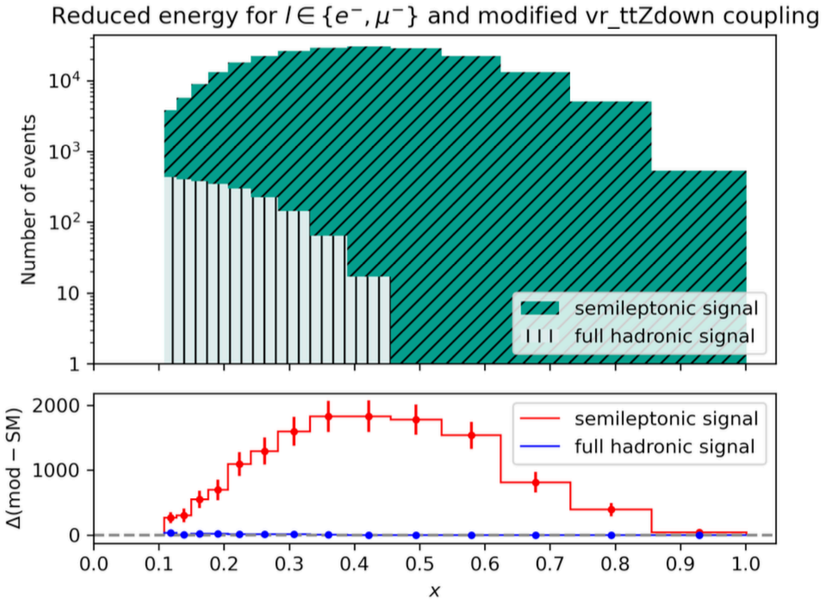




Ongoing detector-level analysis with FCC-ee Delphes simulation

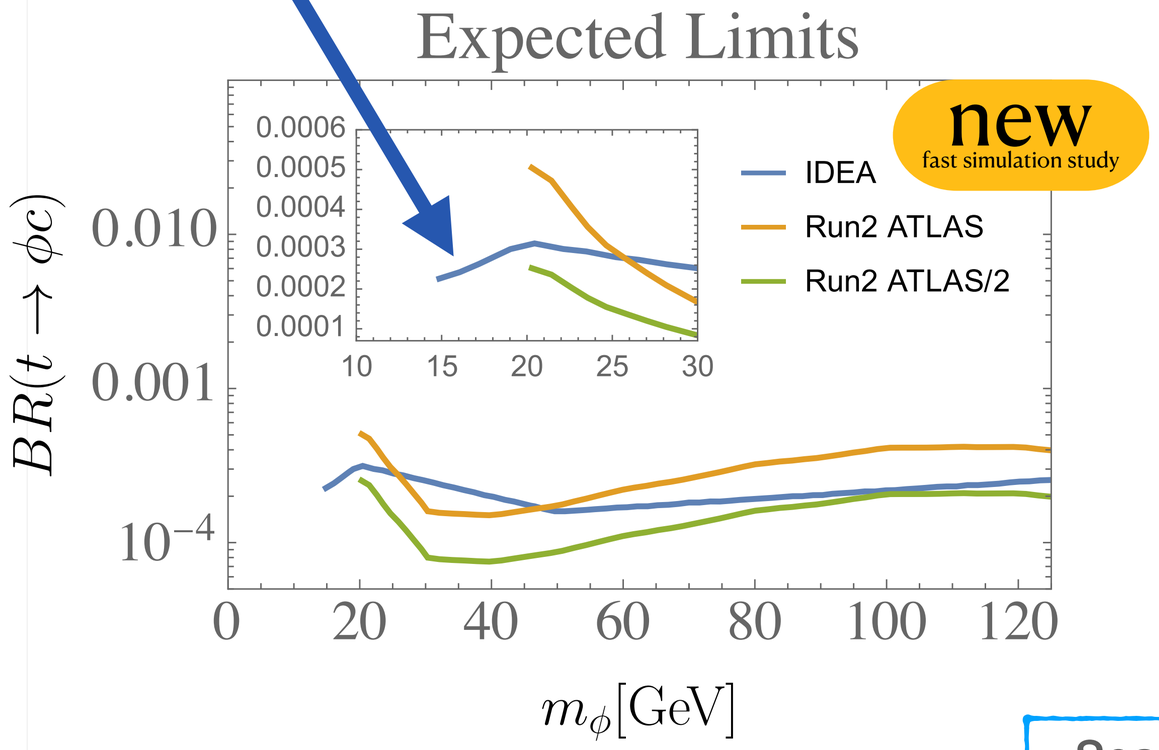
BSM top quark decays

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

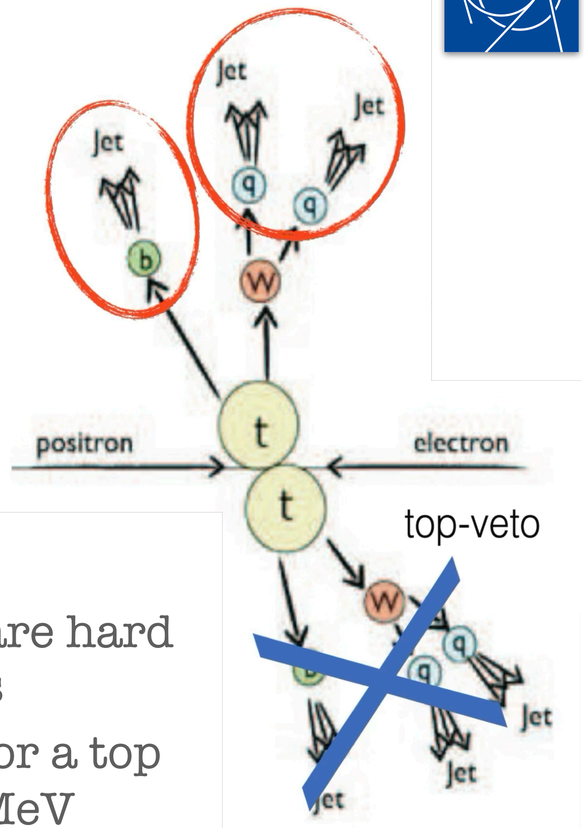
- **New study** $t \to c\phi, \phi \to b\bar{b}$ **with** $\phi \neq h$

Demonstrated sensitivity to light scalar below range probed at LHC

Direct search for FCNC

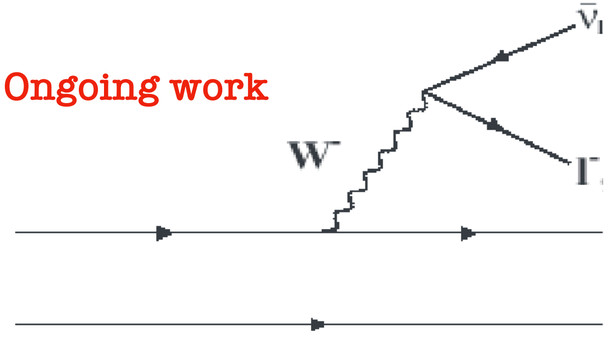


Model-independent search for BSM decays



- Model-independent searches are hard to conceive at hadron colliders
- **Room for a few % exotic BR** for a top with uncertainty of order 30 MeV
- Can be probed with order 10^6 tt events

Ongoing work



Search for top hadrons

Summary and outlook

More details on global fits in dedicated talks this week

- **Complete study of tt threshold** including detector-level, machine-related, and parametric uncertainties
  - Shown that systematic effects are well under control
- Determination of top quark mass and width currently limited by theoretical uncertainties (30/40 MeV)
  - **Calls for advances in theoretical calculations**
- Measurement of top quark Yukawa coupling via loop corrections to tt events can be envisaged
  - More studies needed (planned)
- High potential to constrain top quark **couplings** and **BSM decays** at the 365 GeV FCC-ee run

Thank you