Top Future

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on behalf of the ECFA Focus Group on Higgs / Top / EW factories

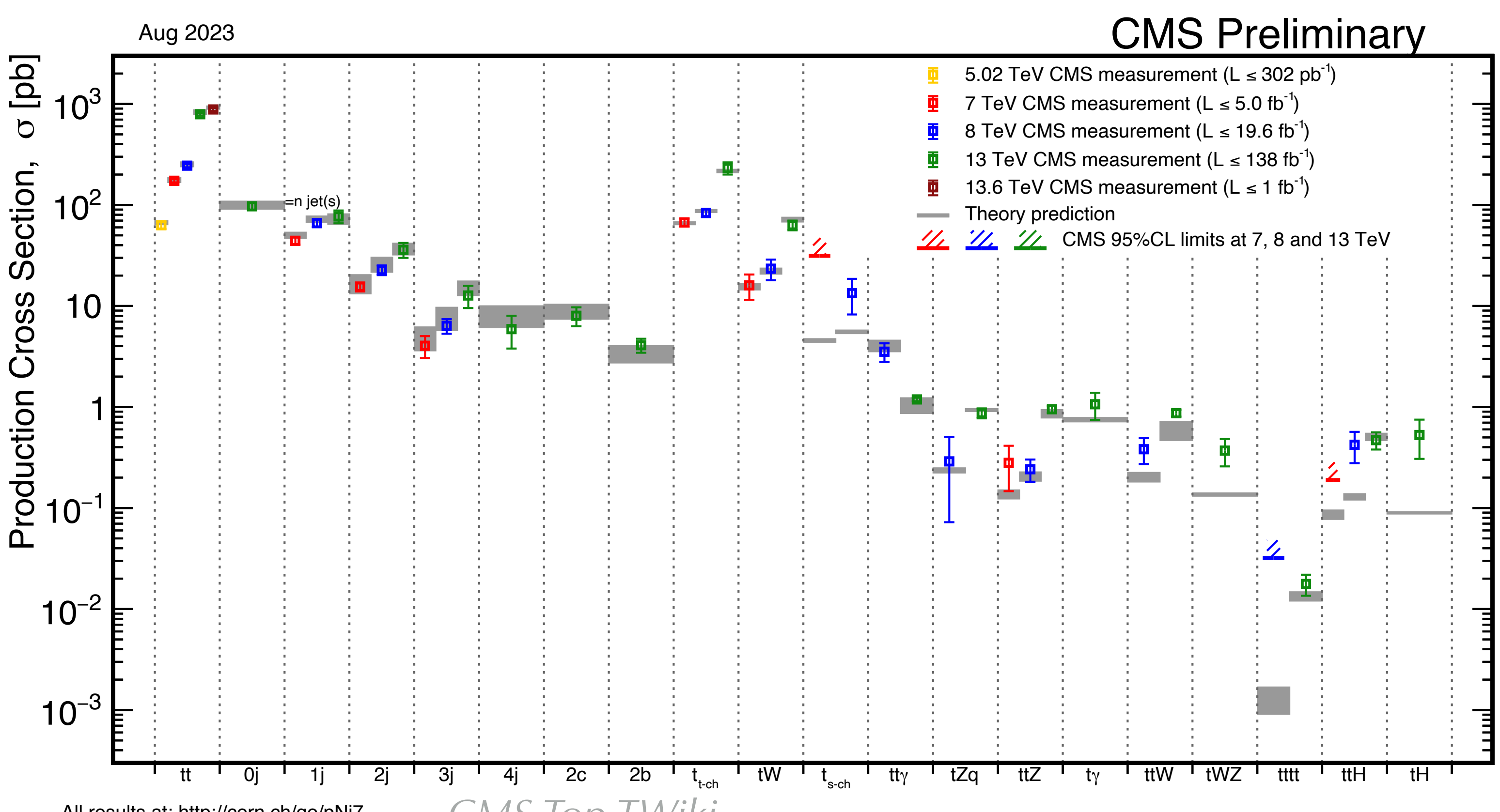
Fundamental Interactions at Future Colliders
Lepton Future Collider (LFC24) workshop

Trieste, Italy
September 16-20, 2024

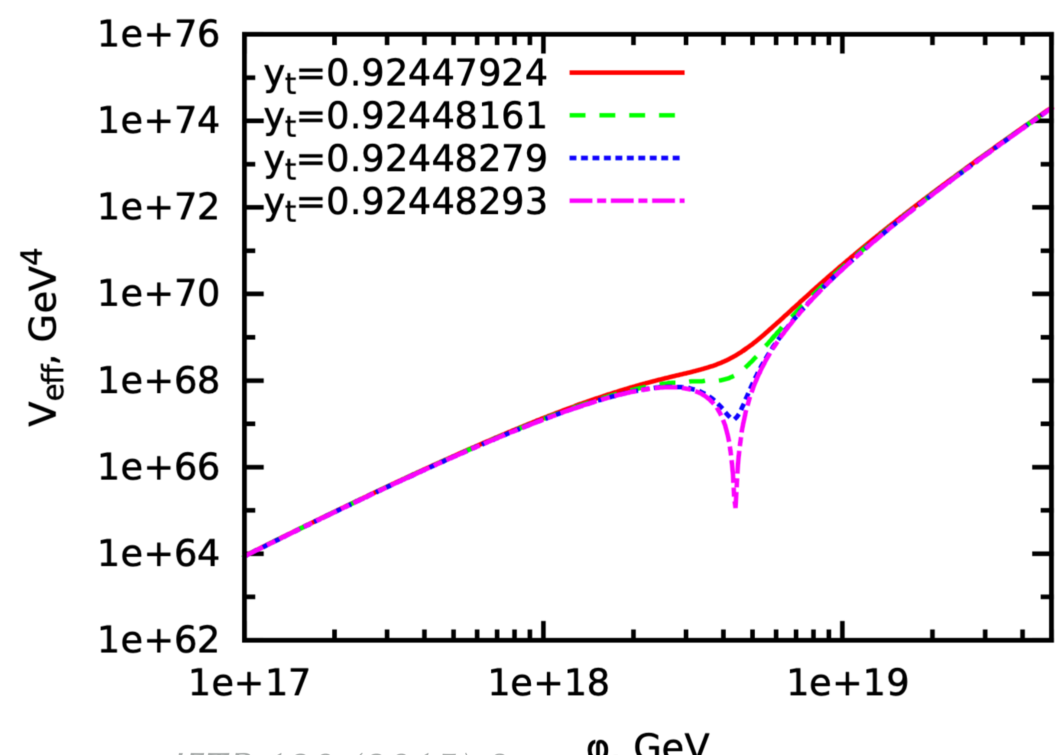
UNIVERSITEIT GENT

The top case

- **First appearance** at Tevatron in 1995
- **Always in the LHC headlines** with new measurements appearing every year
- The **heaviest** authority and fastest decay
- A special agent of the SM - in close relation with the **Higgs boson**



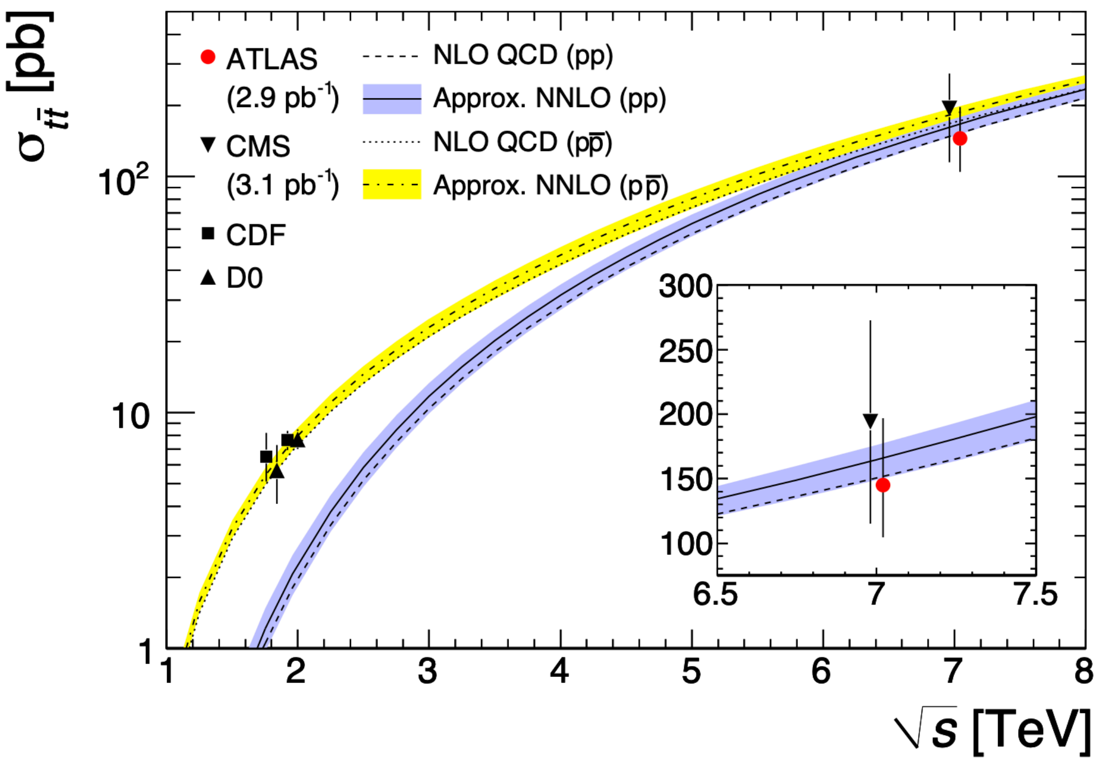
CMS Top TWiki



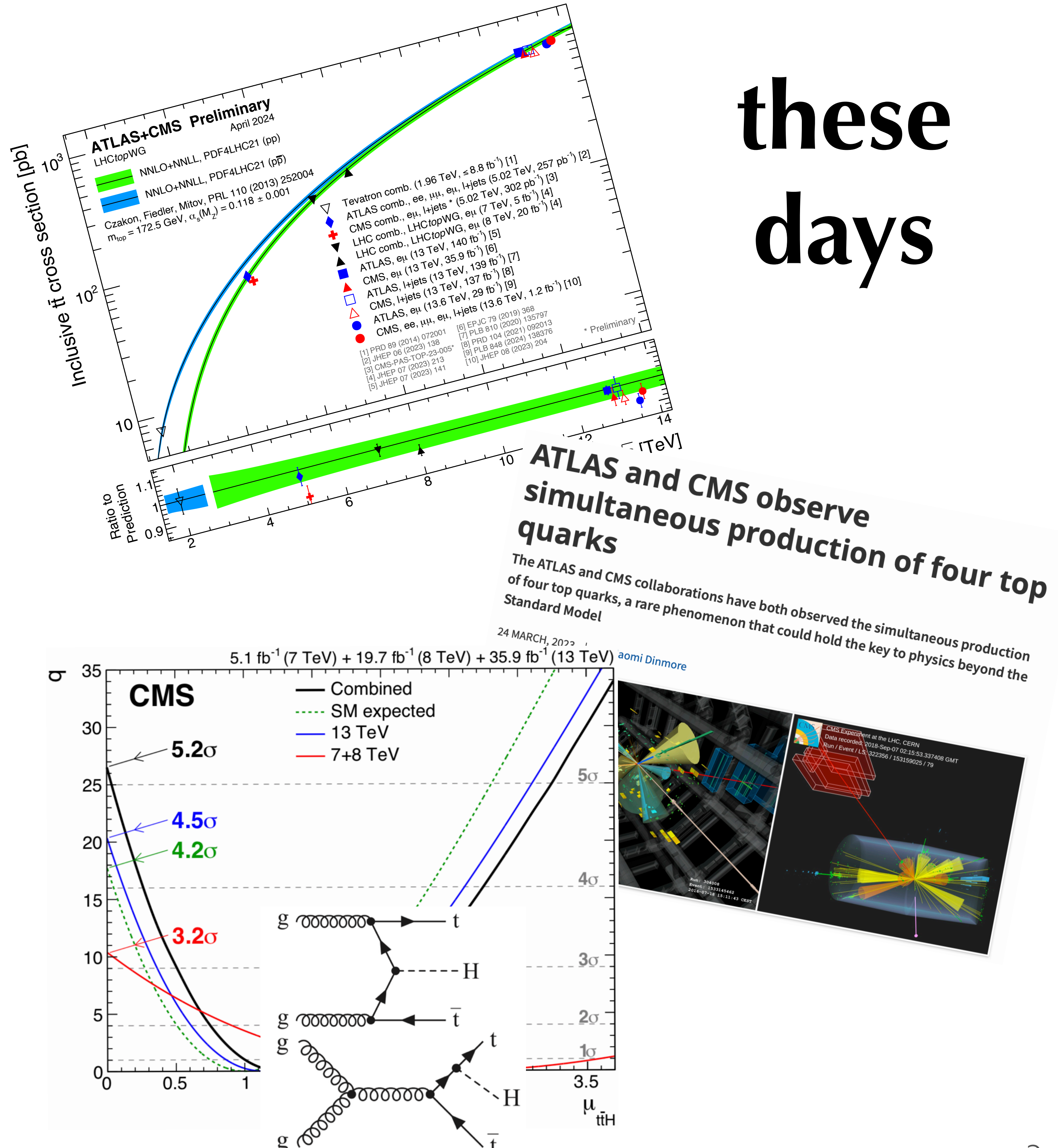
JETP 120 (2015) 3

Time flies ...

circa 2011

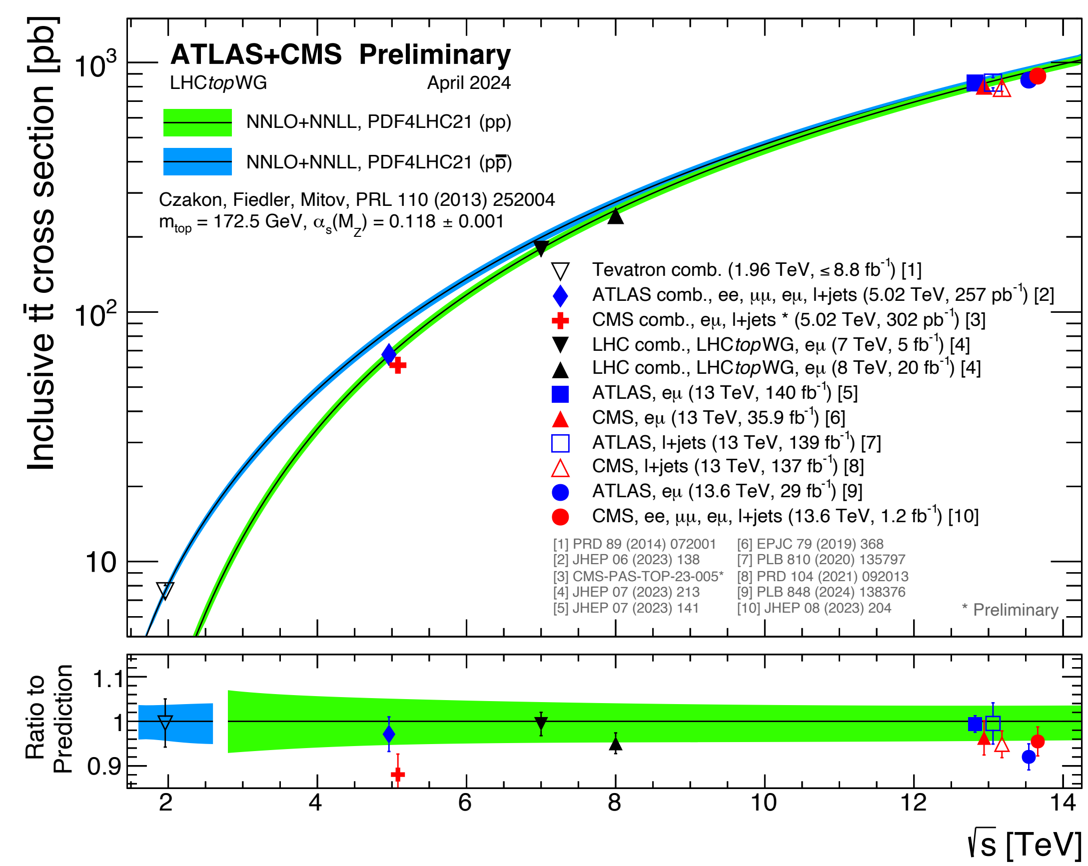


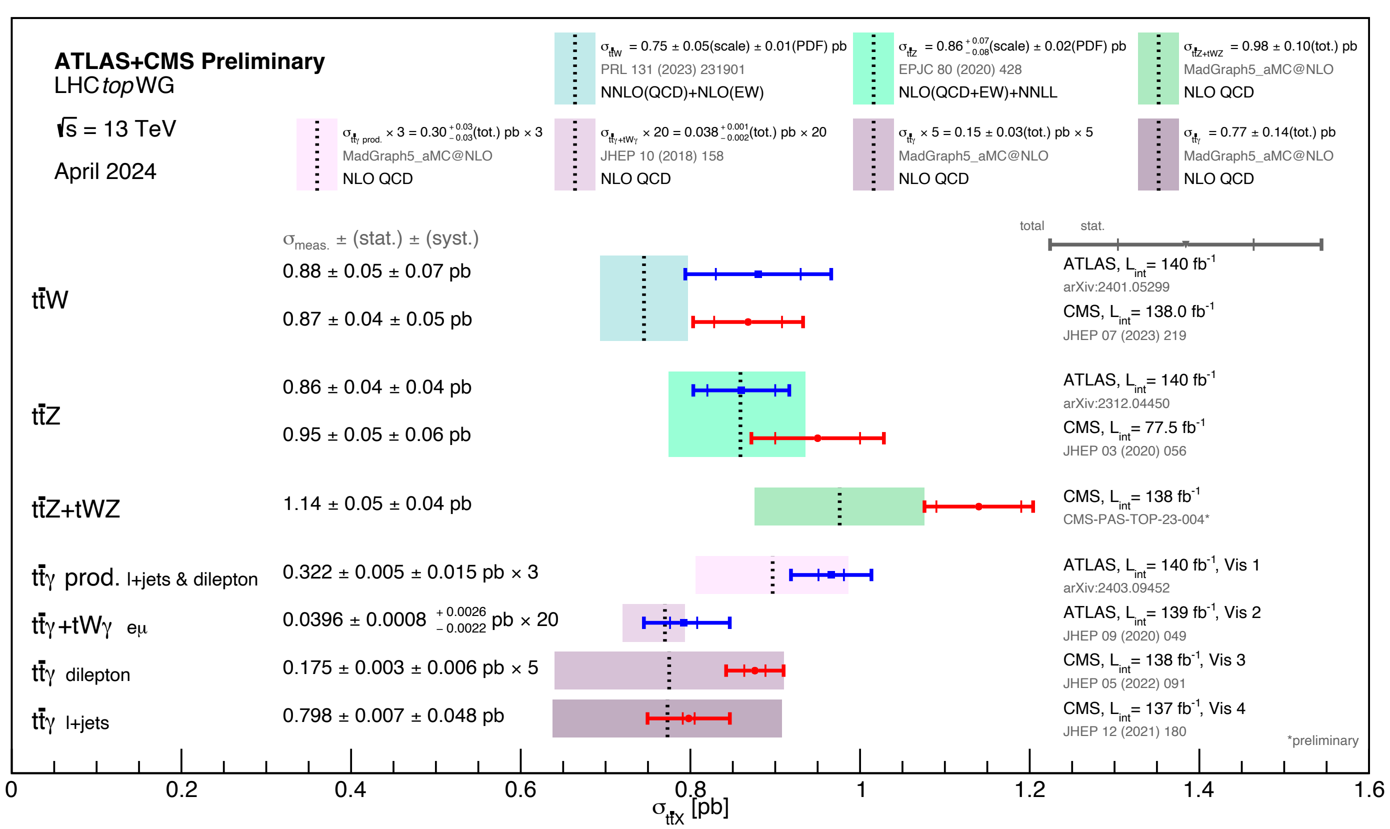
these days

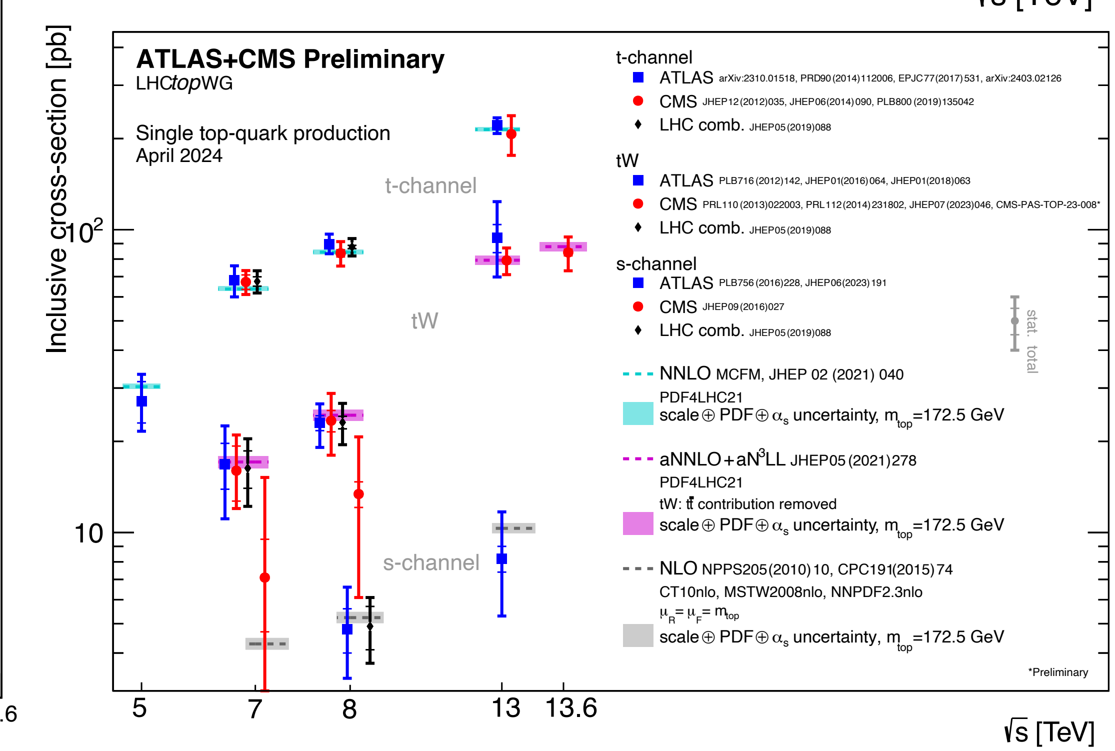


The LHC top portrait

- **Access** to high energies
- **Predominantly produced** via QCD (≈ 300M top pairs at LHC @300fb-1)
- **Significant** electroweak production (≈ 30M single top events at LHC @300fb-1)
- **Distinctive** decay topology helps in busy environment of hadron collisions
- **Cross section** grows with energy

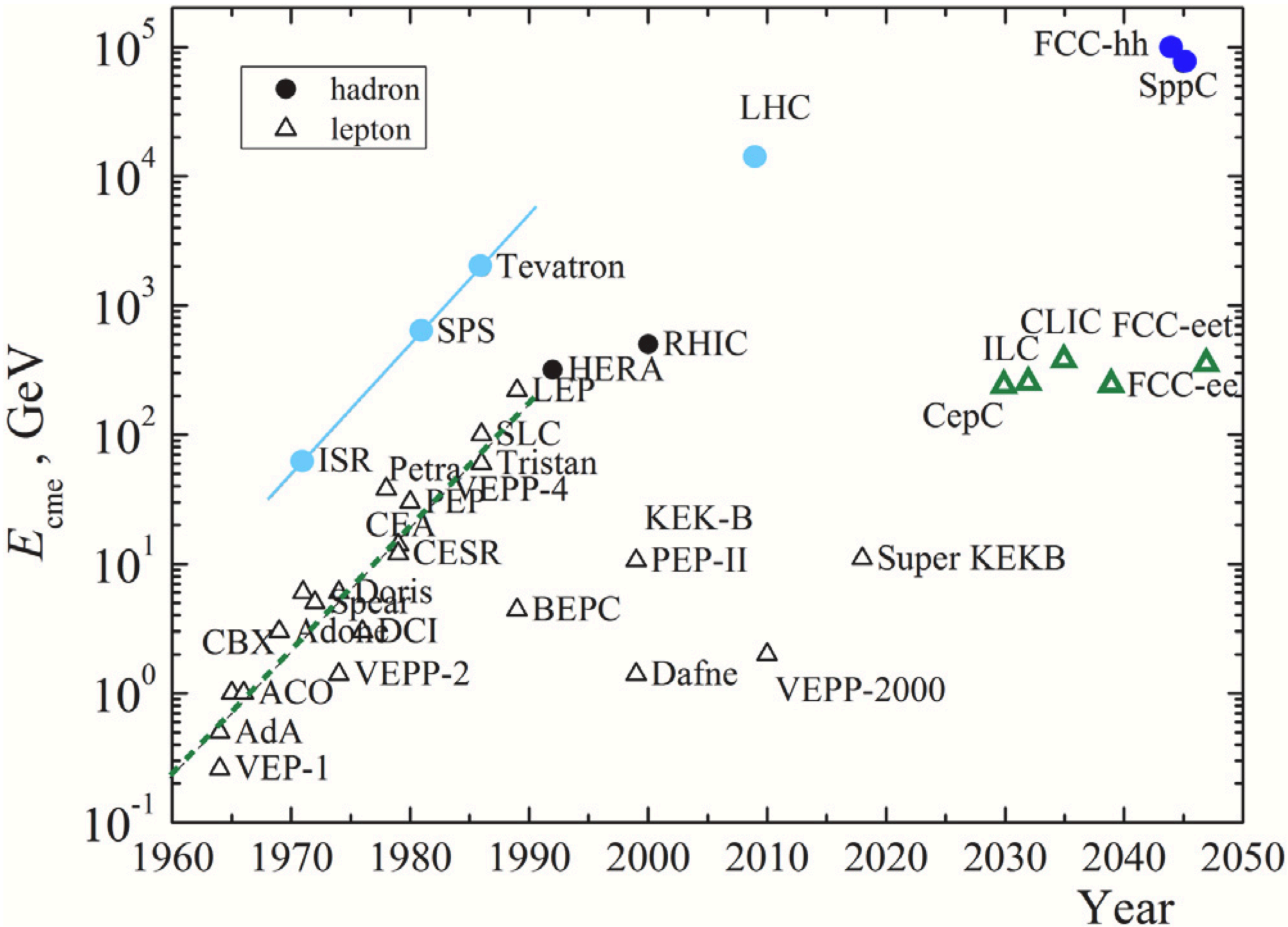






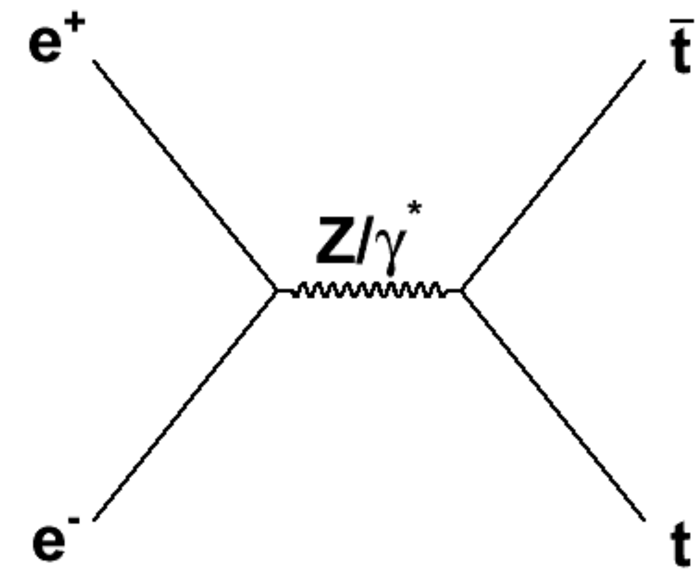
LHCtopWG Summary Plots

Future colliders

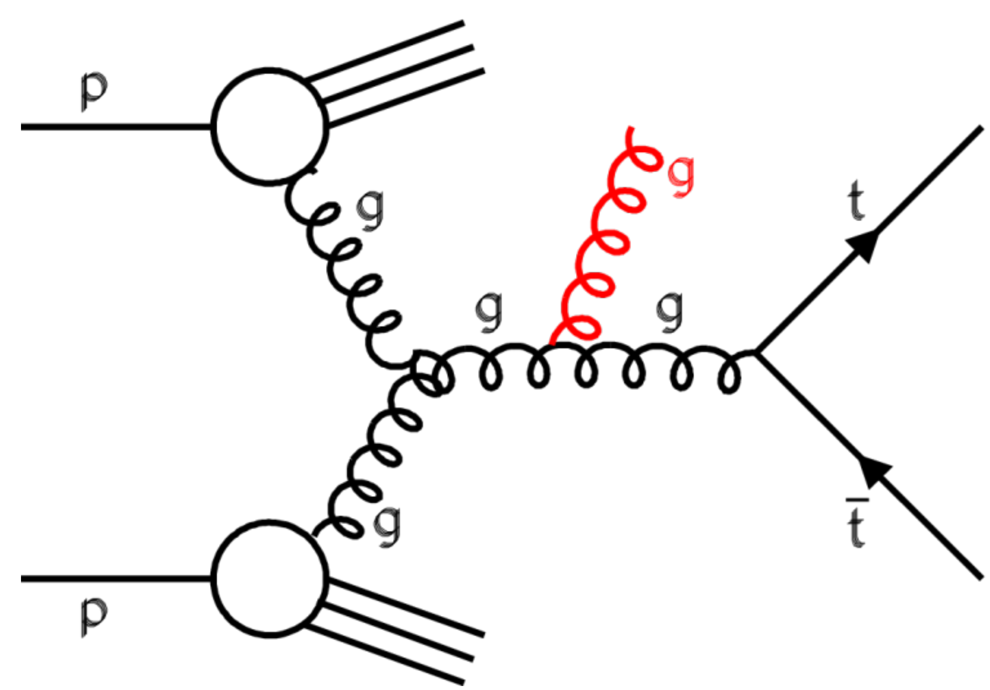


Top pairs

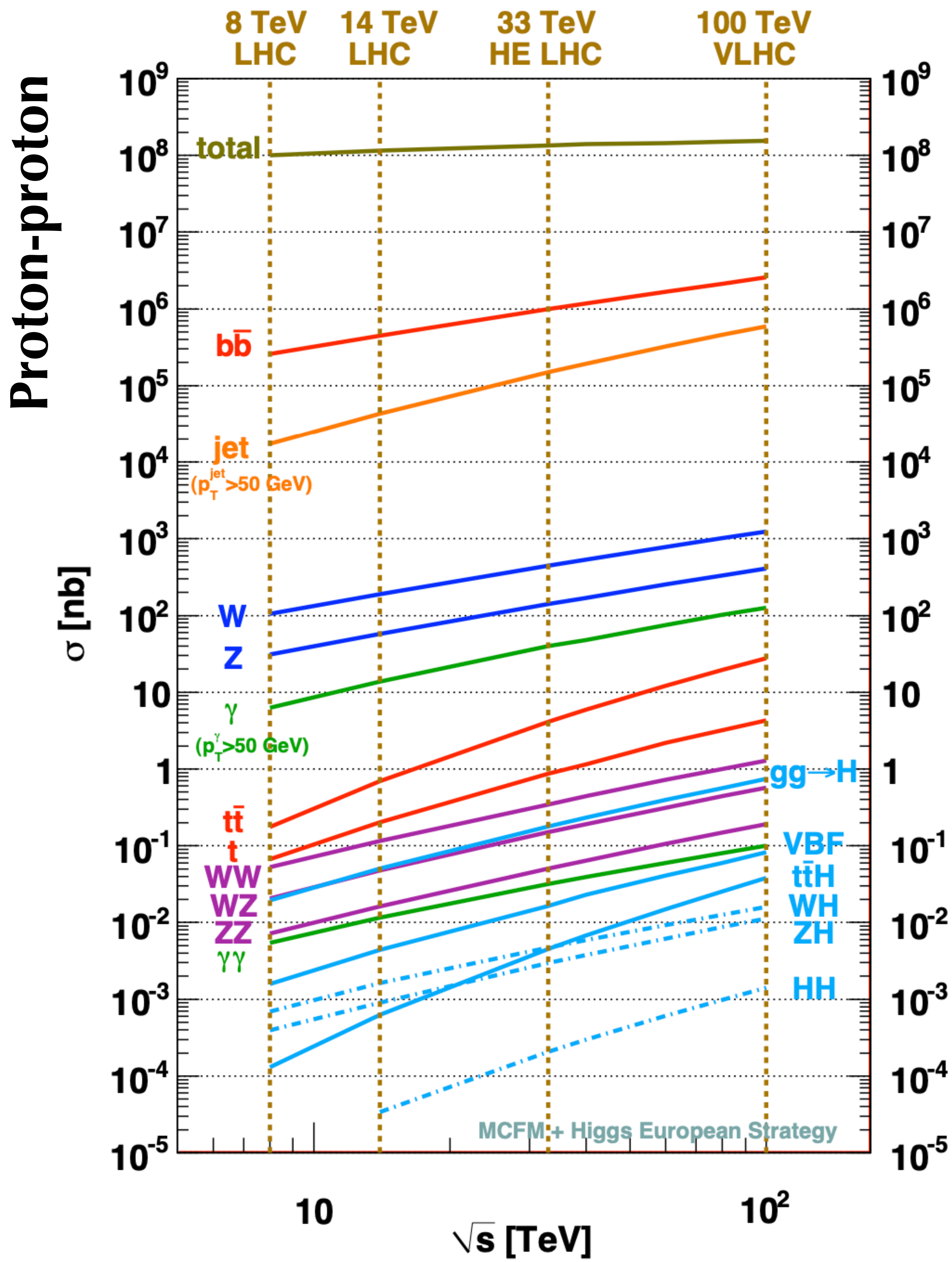
- **Lepton** colliders:
  - Electroweak production via Z/γ^*
  - Initial state well defined
  - Beam polarization to distinguish between Z/γ^* couplings
  - Clean experimental environment

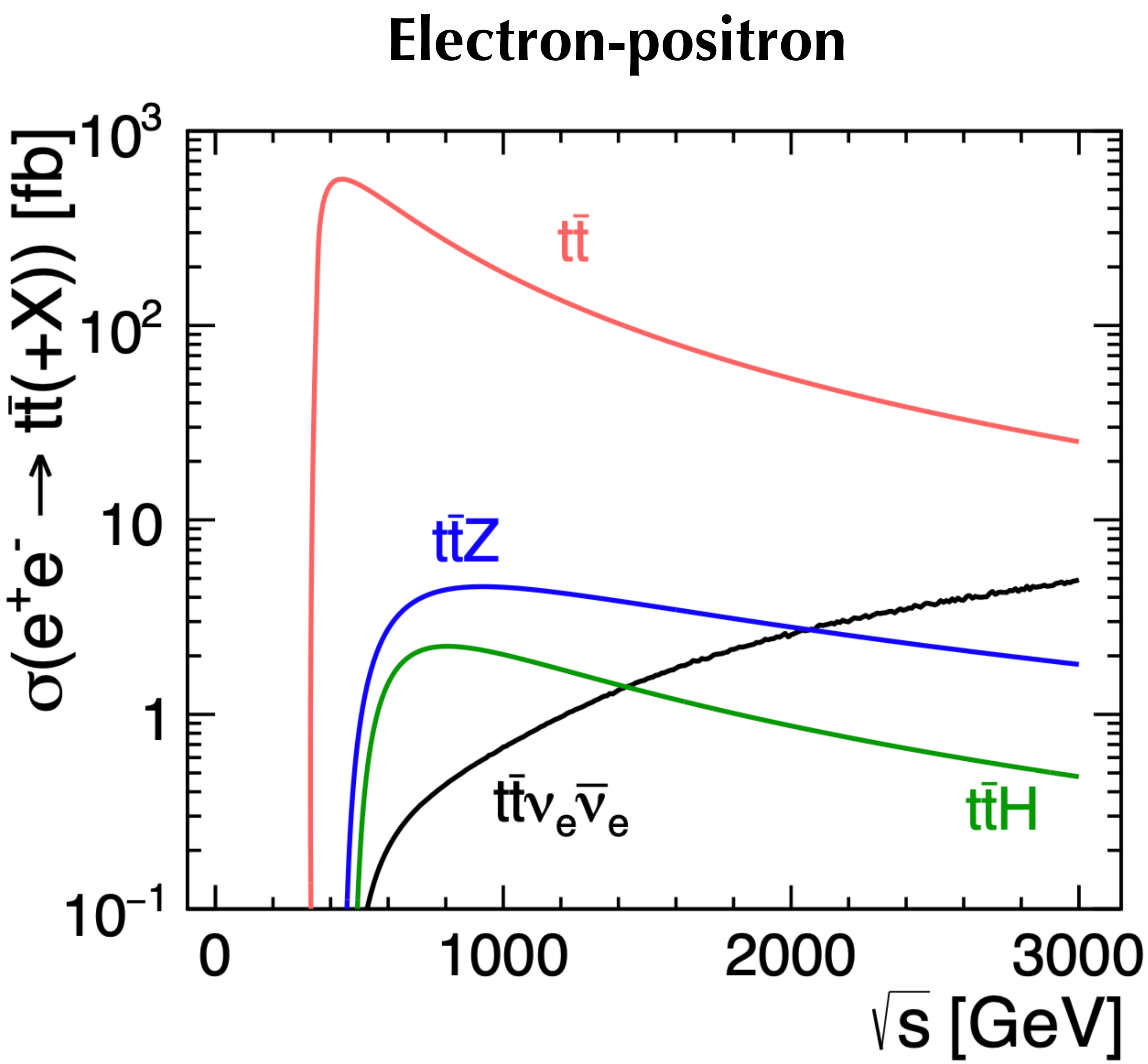


- **Hadron** colliders:
  - Production via strong interactions ($q\bar{q}/gg$)
  - Initial state unknown
  - Larger production cross section at higher energies
  - Large backgrounds



Production cross sections

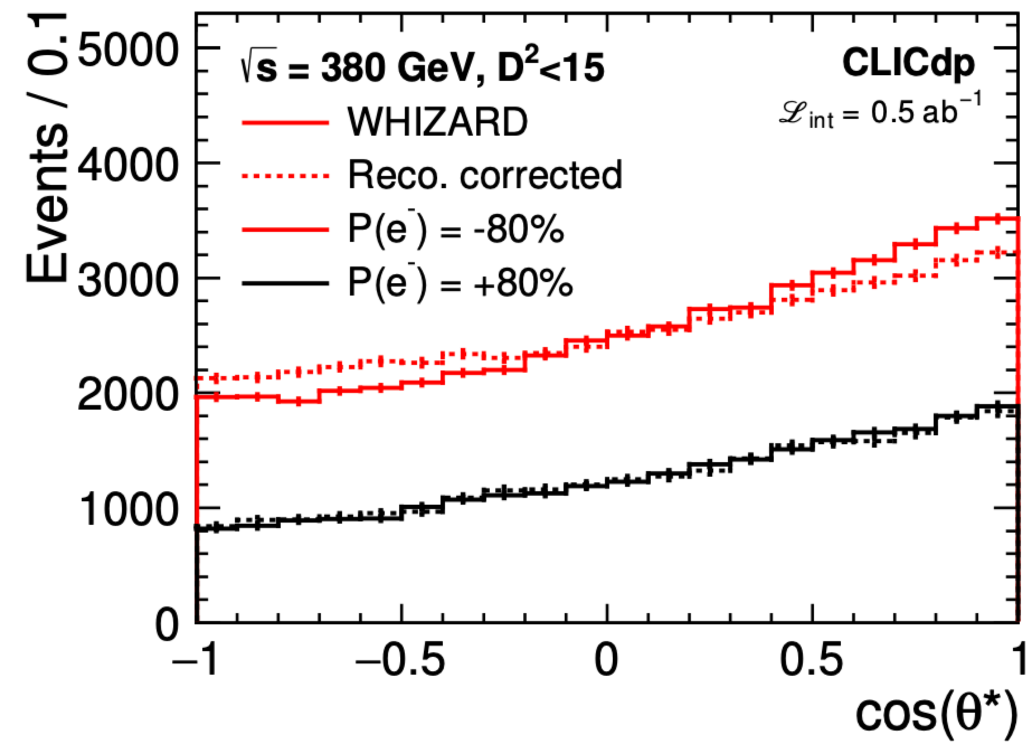




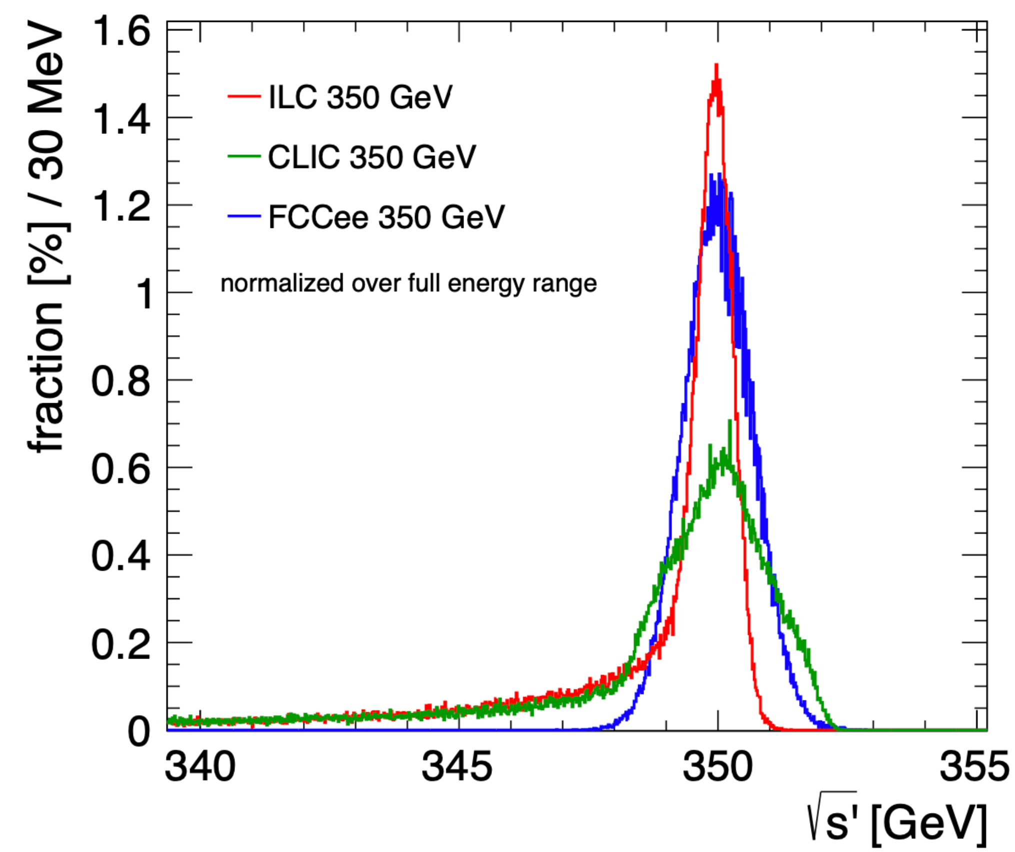
Lepton beams

- Control **polarization states** of top quark pairs with polarized lepton beams (80% e^-, 30% e^+)
- Maximum energy of polarized beams is limited by **beam energy spread**
- Low-energy tail due to significant **beamstrahlung** at ILC/CLIC
- **Synchrotron radiation** limits the maximum energy achievable at FCC-ee
- **No energy limit** at MuC

Int. J. Mod. Phys. A 34 (2019) 1950067



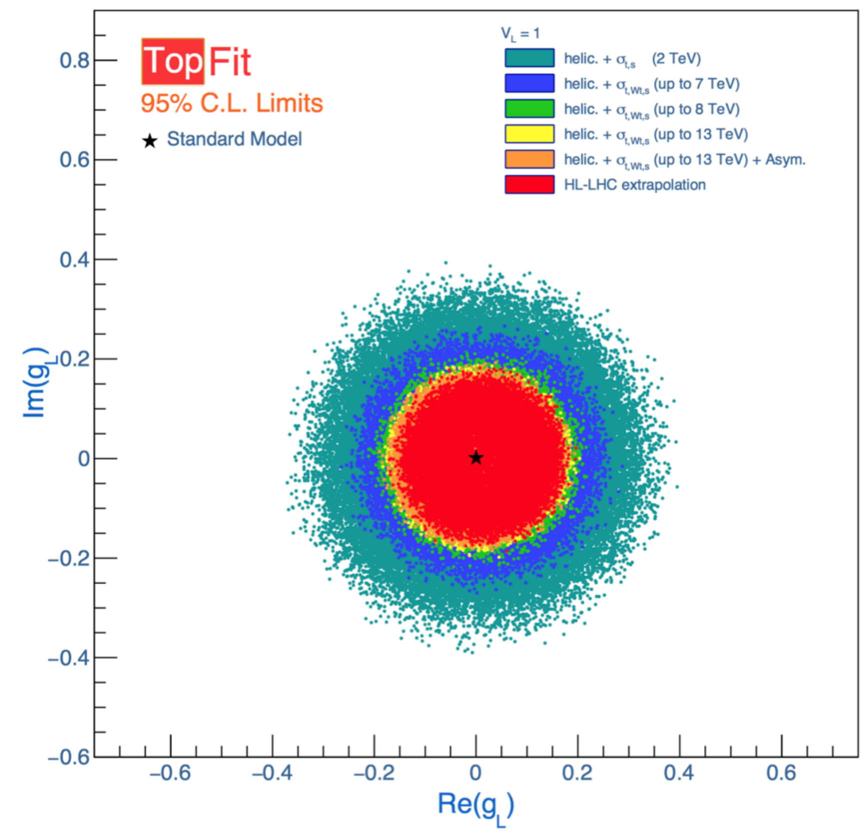
JHEP 11 (2019) 003



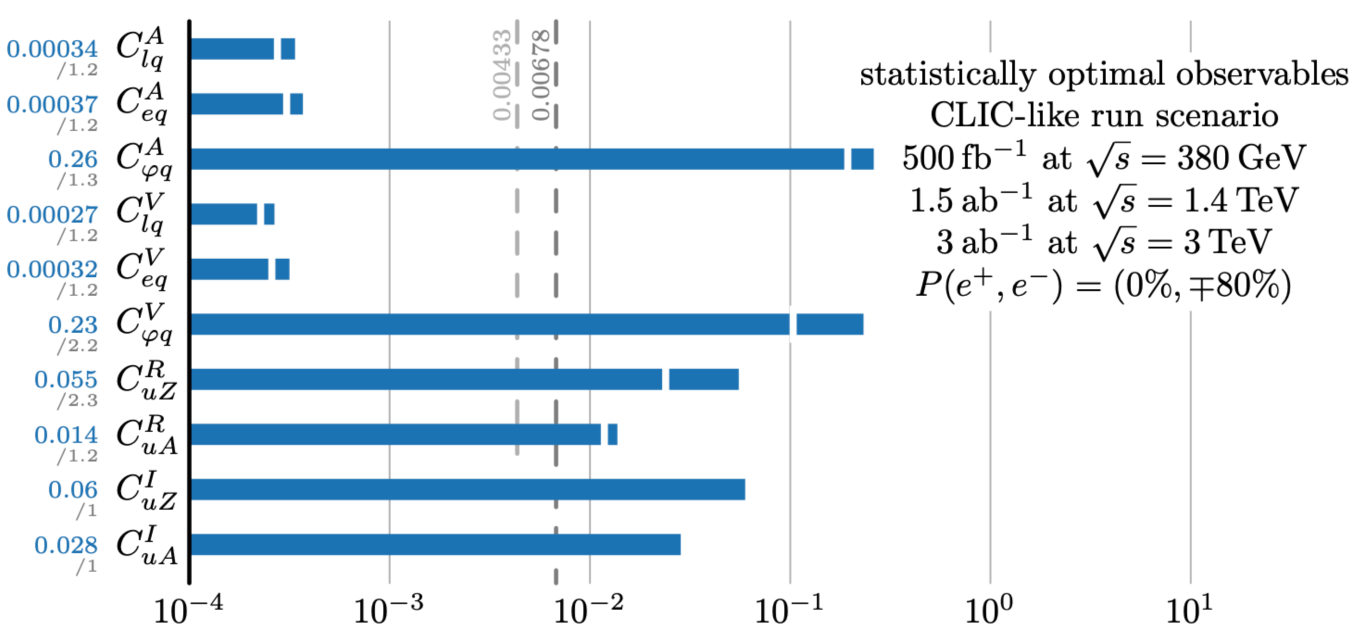
arXiv:1611.03399

Electroweak couplings

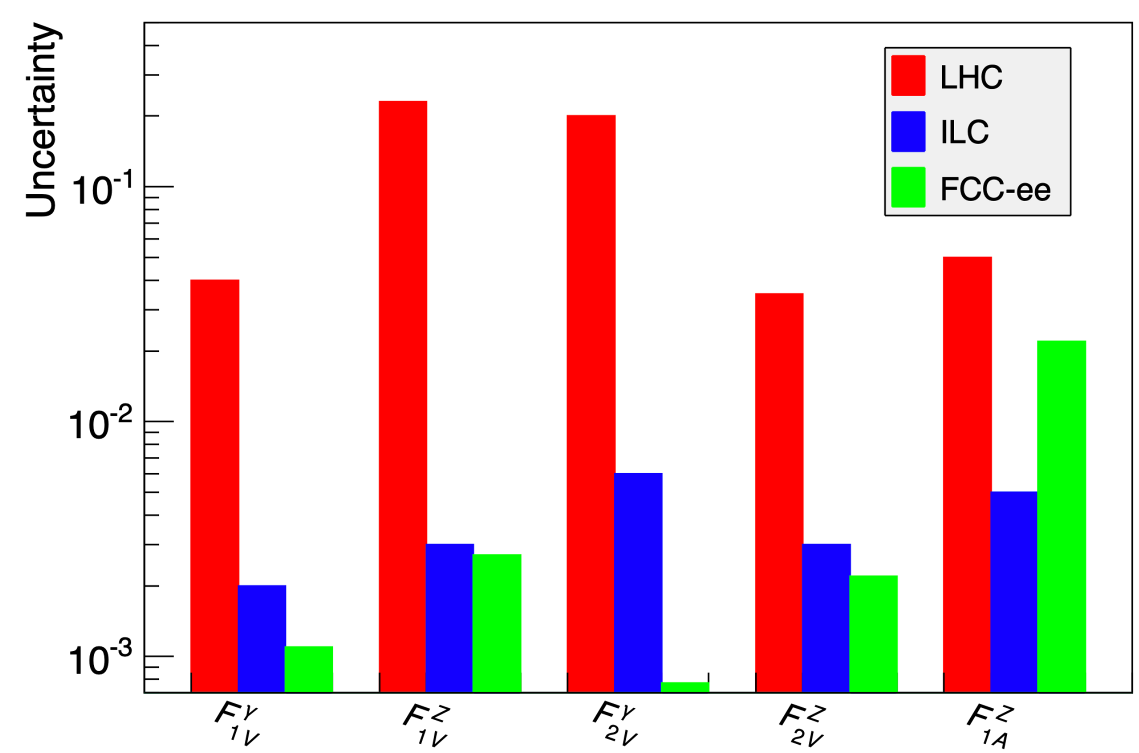
- **Extensively studied** at hadron colliders, though, not easy
- About 10% improvement in **Wtb coupling** determination at HL-LHC with respect to LHC
- Possible to construct **clean optimal observables** with $t\bar{t}$ events in electron-positron collisions
- **Significantly improve** constraints on electroweak EFT couplings with statistically optimal observables (enhanced sensitivity to linear contributions) at lepton colliders



Mod. Phys. Lett. A 34 (2019) 195014

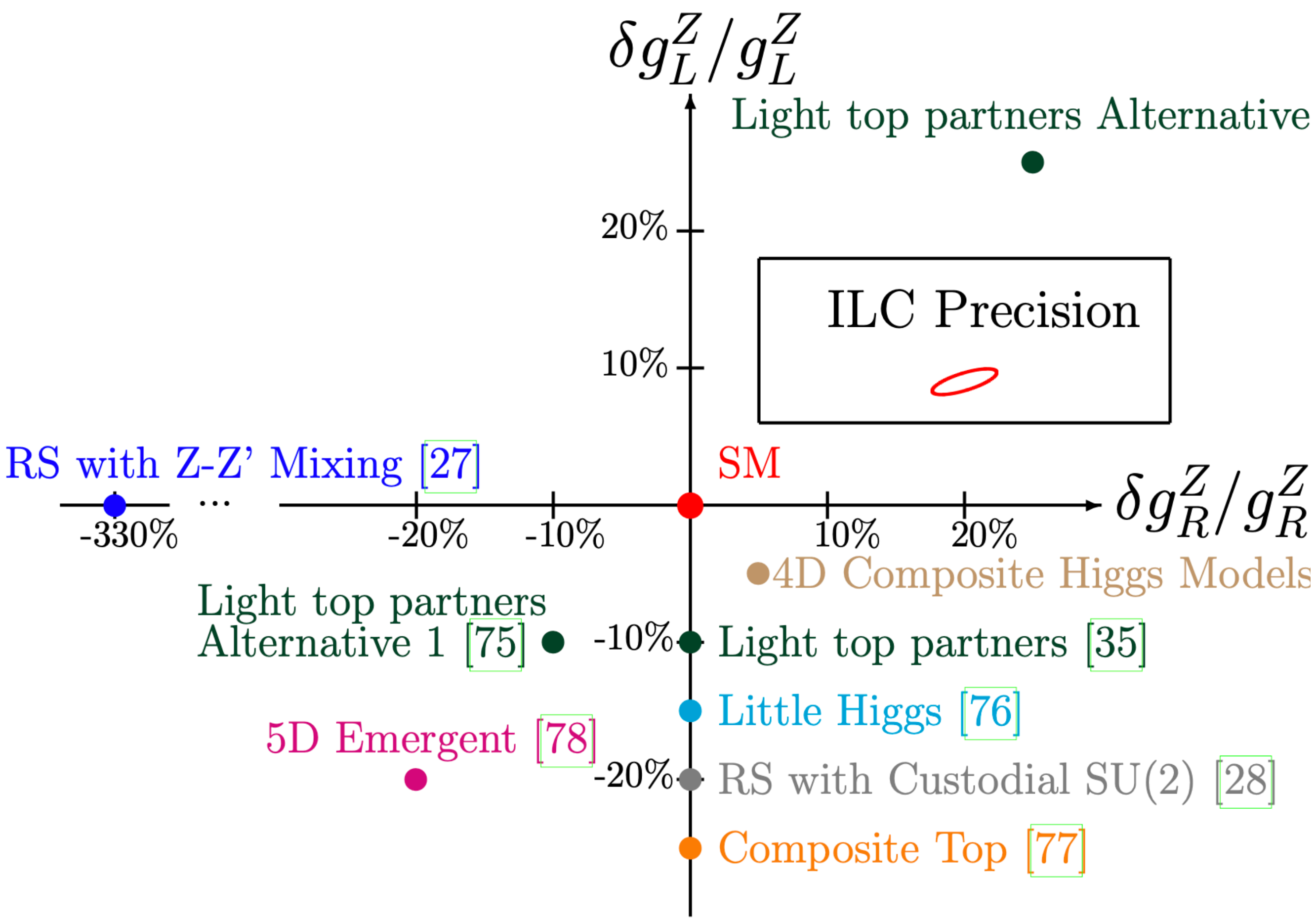


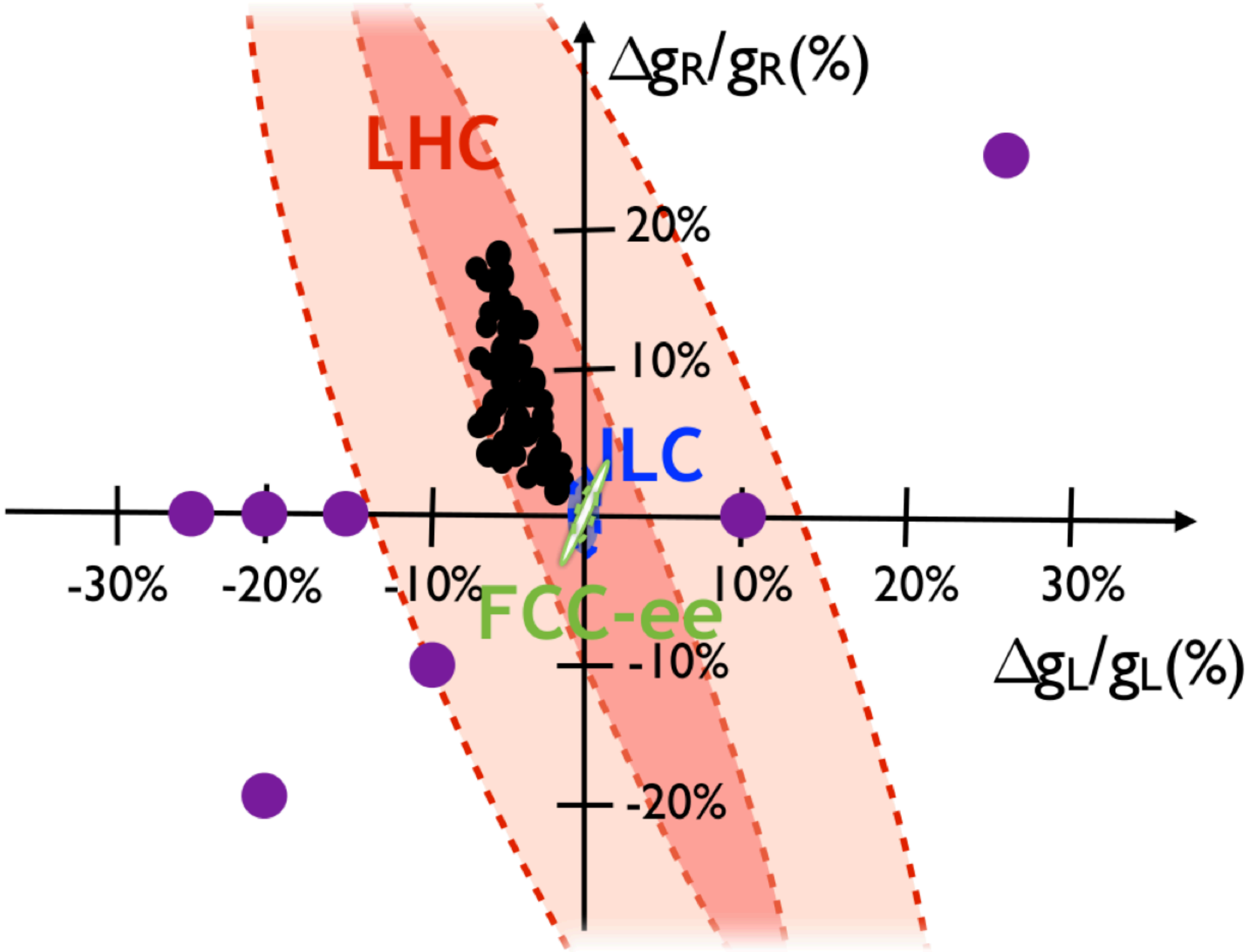
JHEP 10 (2018) 168



JHEP 04 (2015) 182

Electroweak couplings



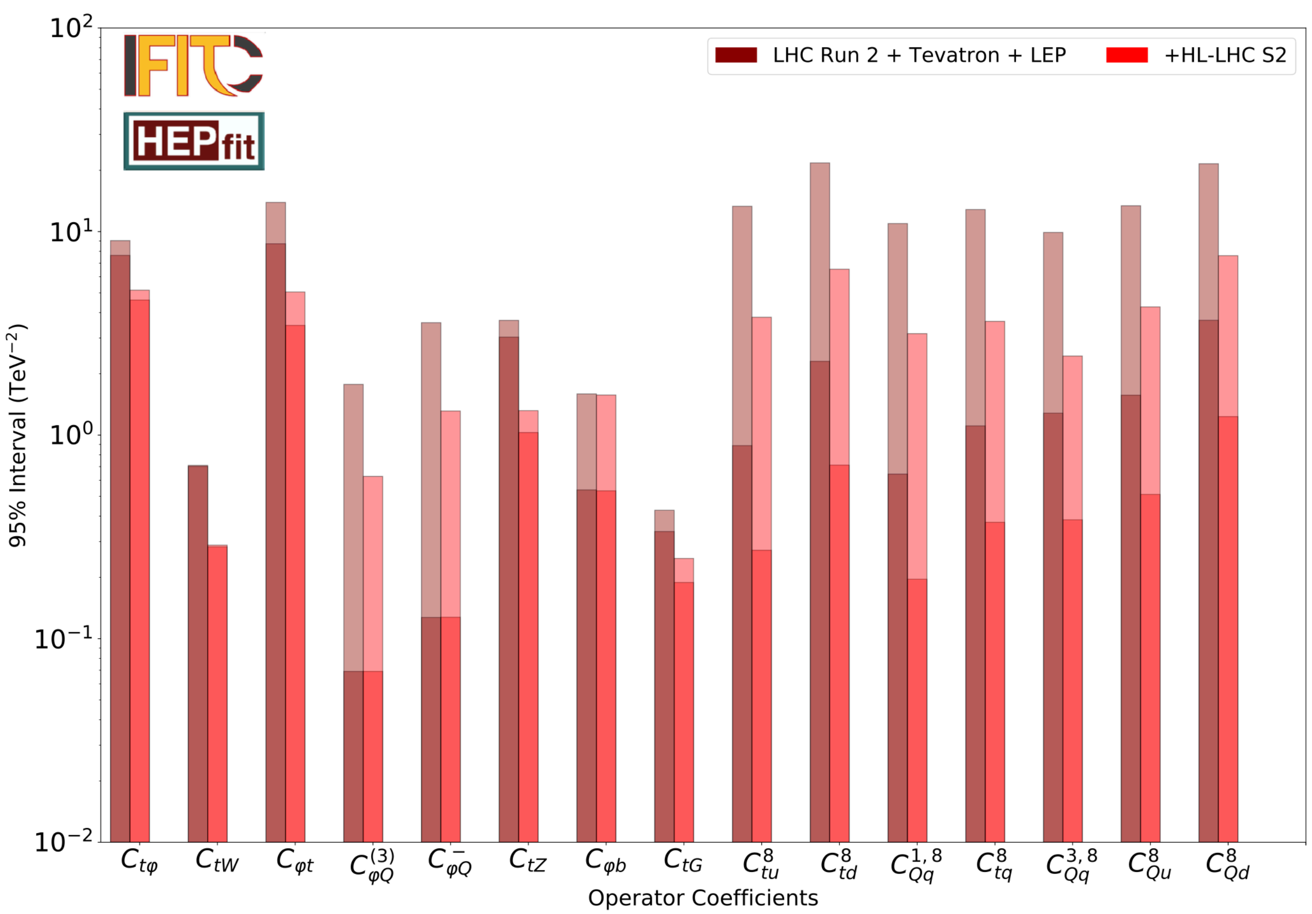


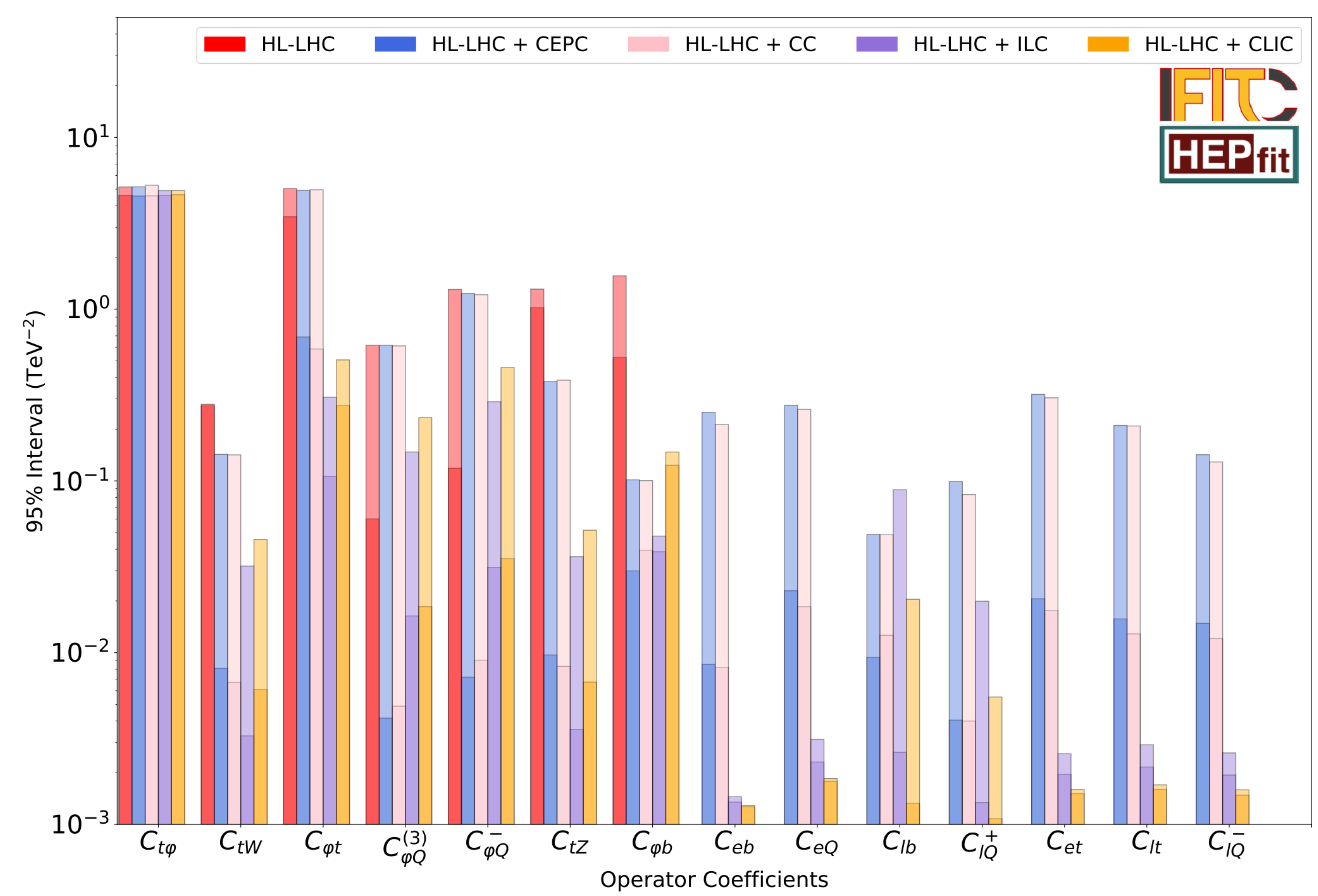
arXiv:1702.05333

JHEP 08 (2015) 127

Global EFT sensitivity

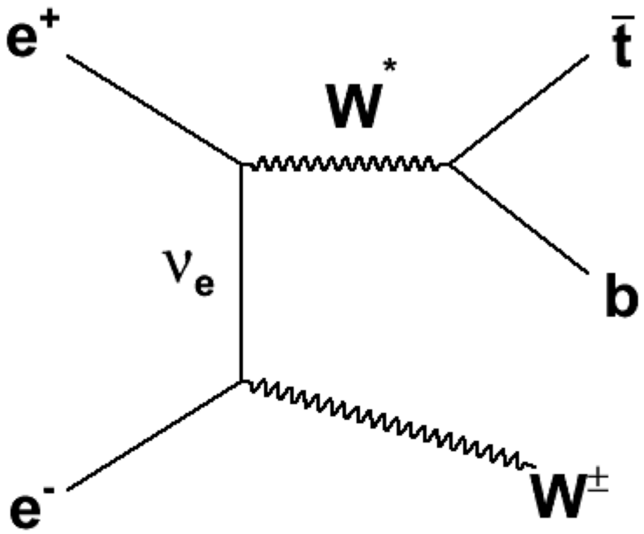
- Improve constraints x2-4 on many operators at **HL-LHC**
- Significant improvement for two-fermion electroweak operators at **FCC-ee**
- Further improvements for various two-fermion operators at higher energies at **ILC/CLIC**
- Entering a highly boosted regime at **FCC-hh** with an order of magnitude improvement for $q\bar{q}t\bar{t}$ with respect to HL-LHC

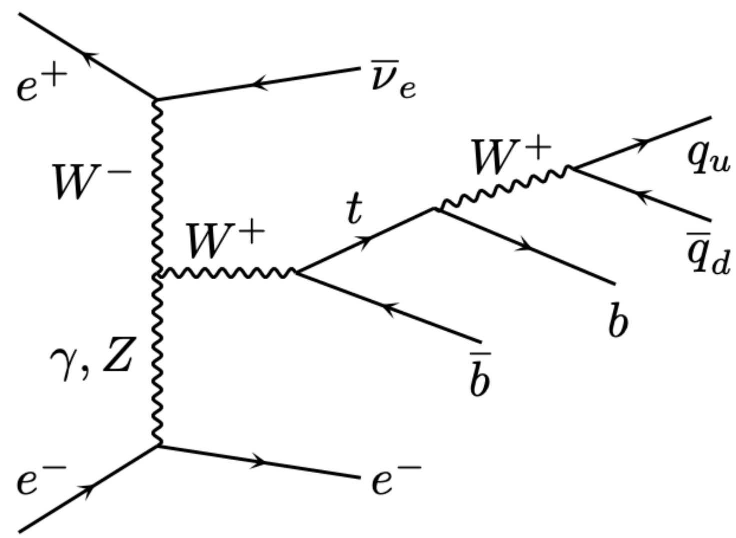




arXiv:2205.02140

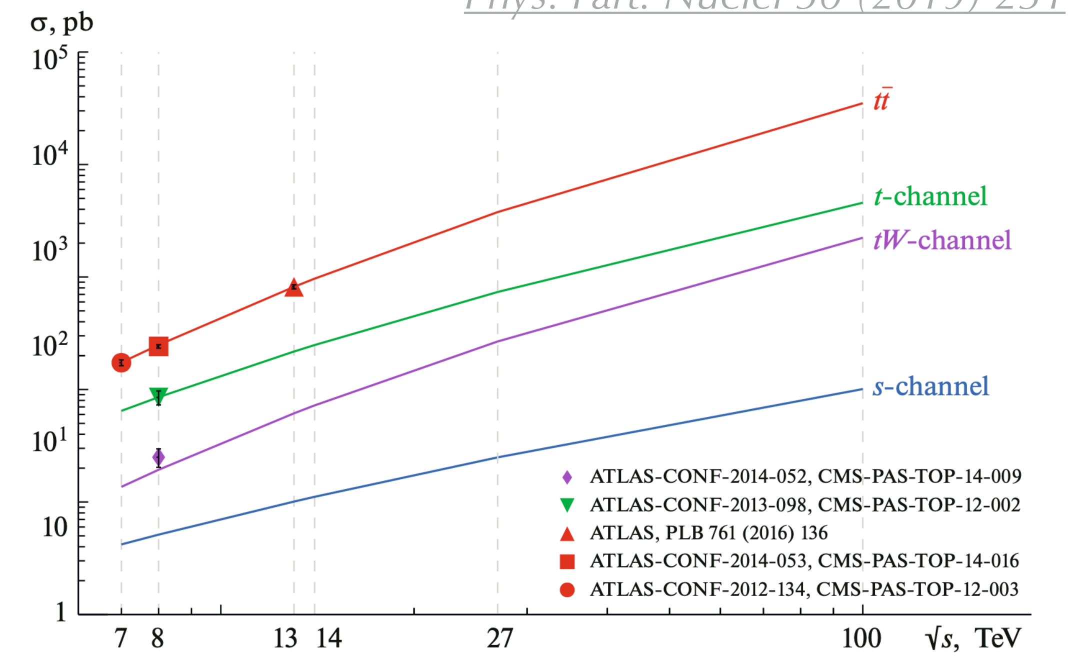
Single top



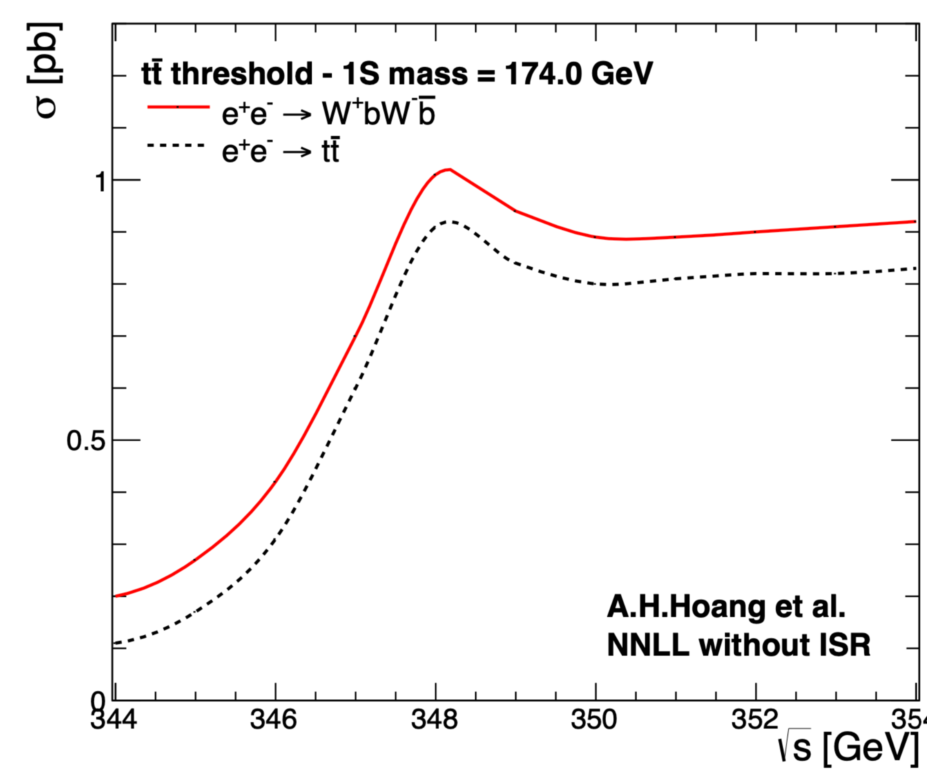


PRD 97 (2018) 033004

Phys. Part. Nuclei 50 (2019) 231



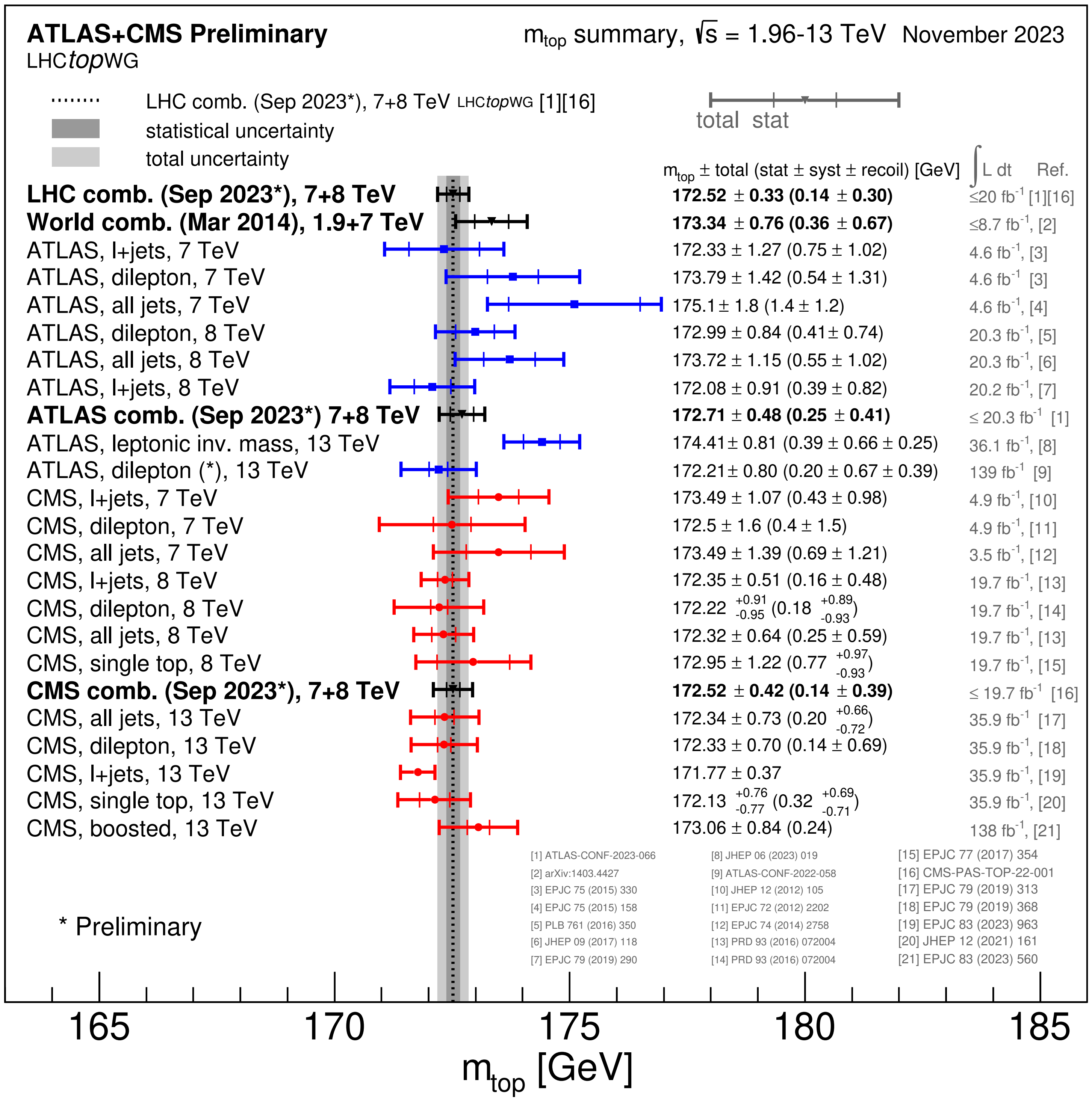
- Always produced through **electroweak couplings**
- **Direct** measurement of $|V_{tb}|$
- Intrinsic **interference** with top quark pair production
- Sensitive to **polarization** of electron and positron beams (possible reduction of uncertainties)
- Inclusively study $W^+bW^-\bar{b}$ final states at lepton colliders to **distinguish** $t\bar{t}$ from single top (a few % of $t\bar{t}$)



EPJC 75 (2015) 223

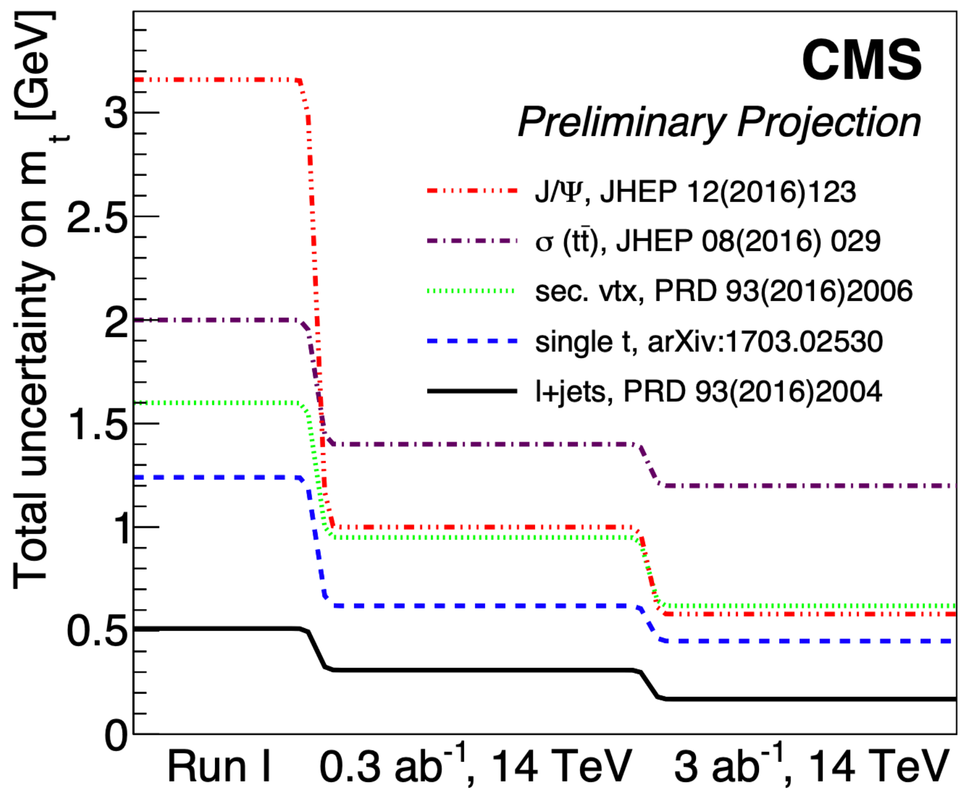
Mass

LHCtopWG Summary Plots

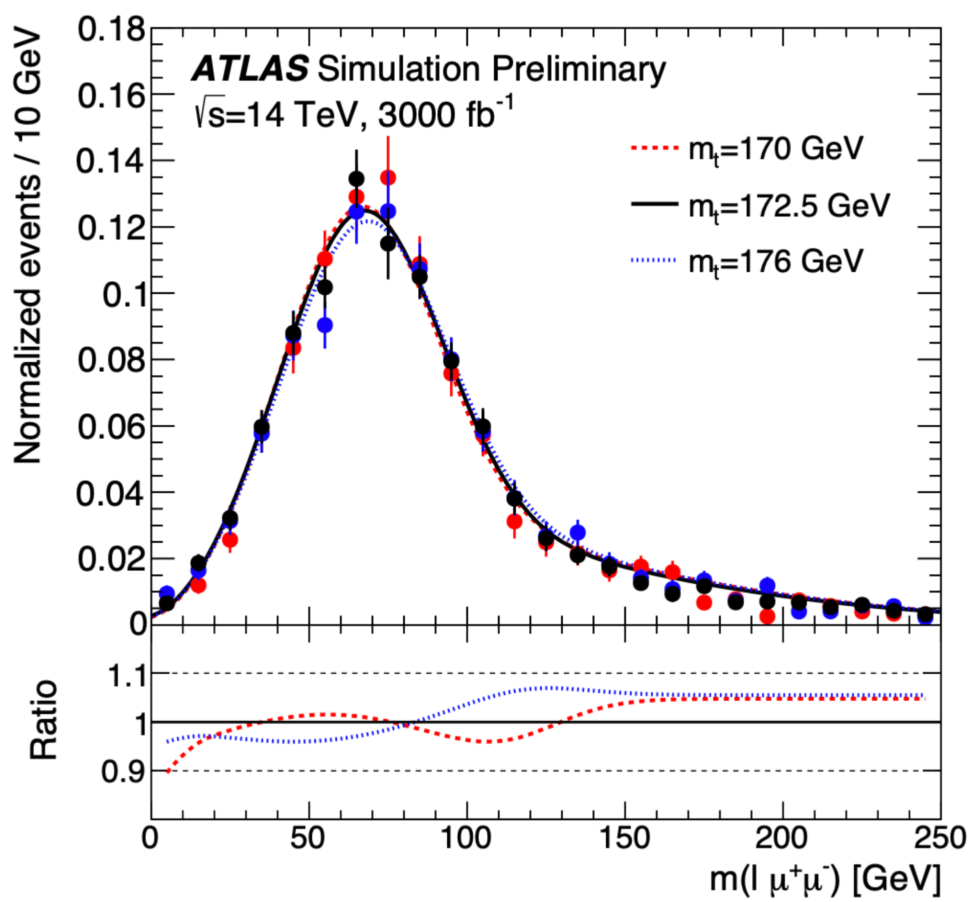


- Measured at 172.52 GeV with **0.2%** (330 MeV) uncertainty
- **Experimental precision** is comparable to the expected differences between pole and MC masses
- Studies done using **$t\bar{t}$ events** in various final states
- **Dominant uncertainties** arise from jet energy calibrations, parton shower modeling, etc.
- **Important ingredient** to global electroweak fits, vacuum stability, etc.

Mass

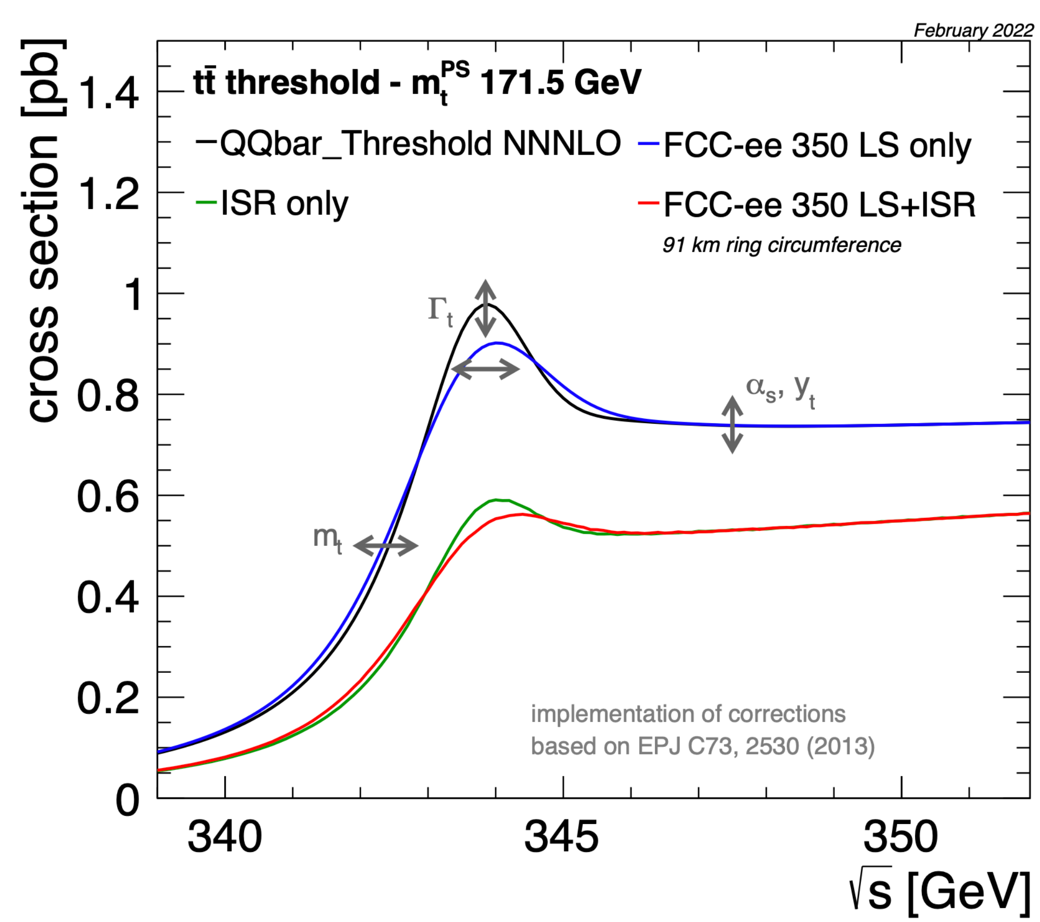


CMS-PAS-FTR-16-006



ATL-PHYS-PUB-2018-042

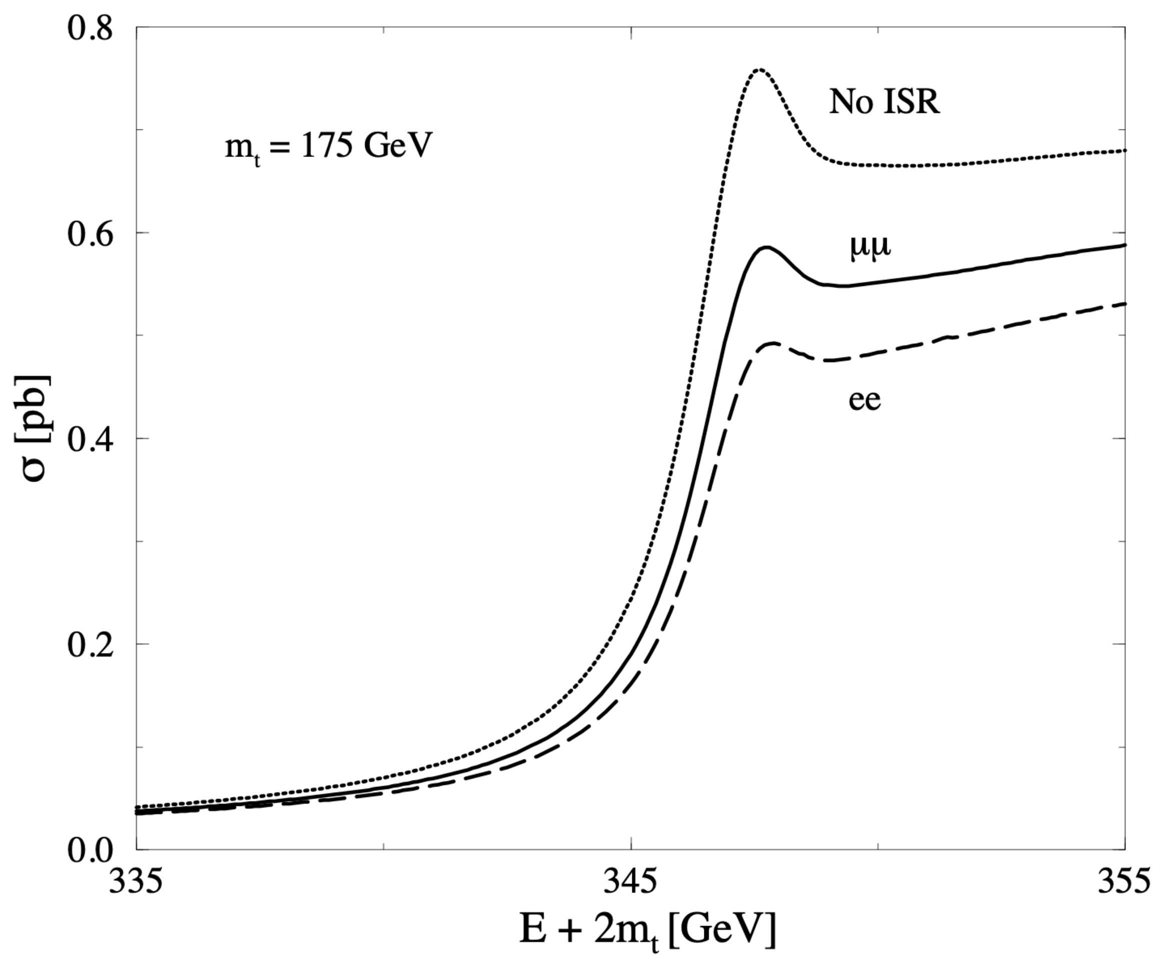
- Projections for **HL-LHC** indicate ≈ 200 MeV uncertainty - limited by large systematics
- Extract top mass from a $t\bar{t}$ production **threshold scan** at lepton colliders:
  - Precisely measure the **cross section shape** at the threshold
  - **Simultaneous measurement** of the top quark mass (≈ 20 MeV) and width, top quark Yukawa coupling, and the strong coupling constant



arXiv:2203.06520

Mass

- The top mass resonance smearing mitigated by **reduced ISR** at MuC
- Less dependence on the **beam profile** if narrow beams are obtained
- Projected sensitivity for the uncertainty can reach **a few tens of MeV**



	LEP2		Tevatron		LHC	NLC	$\mu^+\mu^-$	
$\mathcal{L}$ (fb^{-1})	0.1	2	2	10	10	50	10	100
ΔM_W (MeV)	144	34	35	20	15	20	20	6
Δm_t (GeV)	–	–	4	2	2	0.2	0.2	0.07

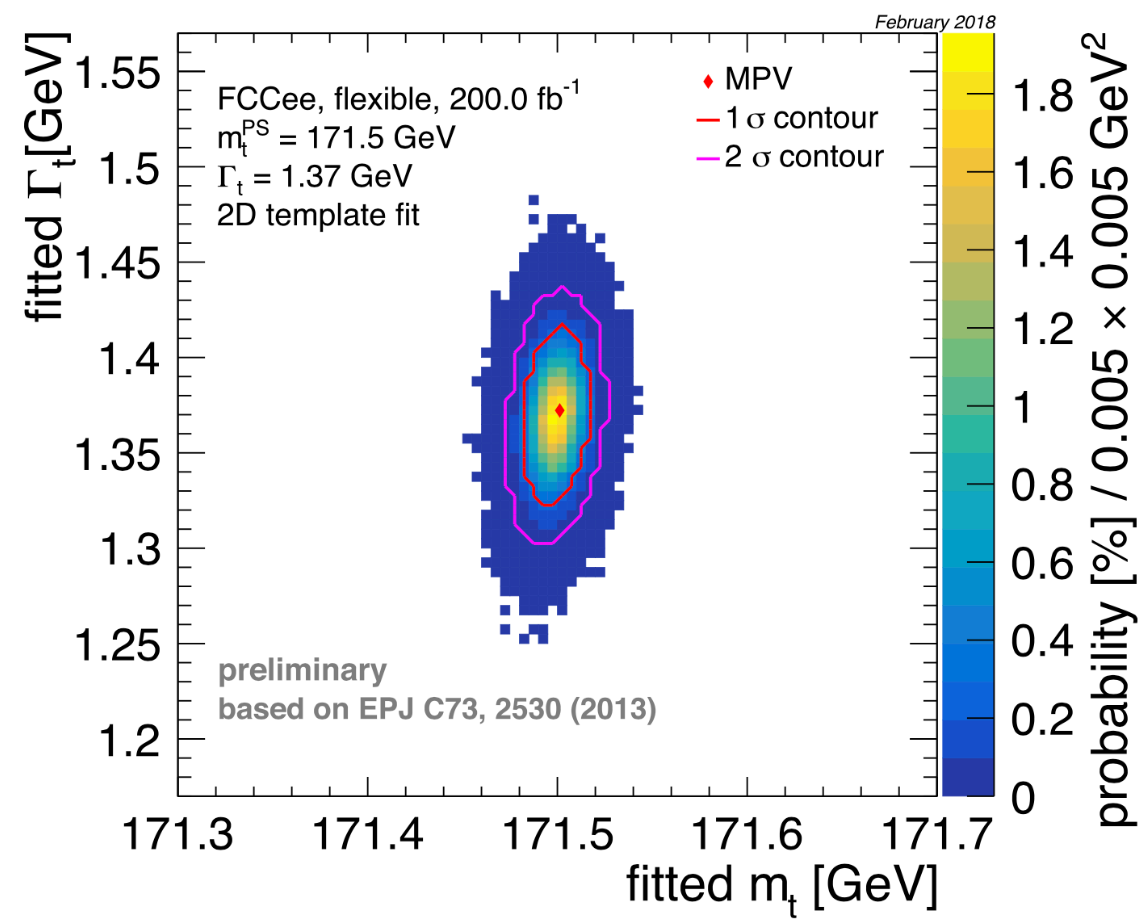
AIP Conf. Proc. 435 (1998) 227

Phys. Rev. D 56 (1997) 1714

Width

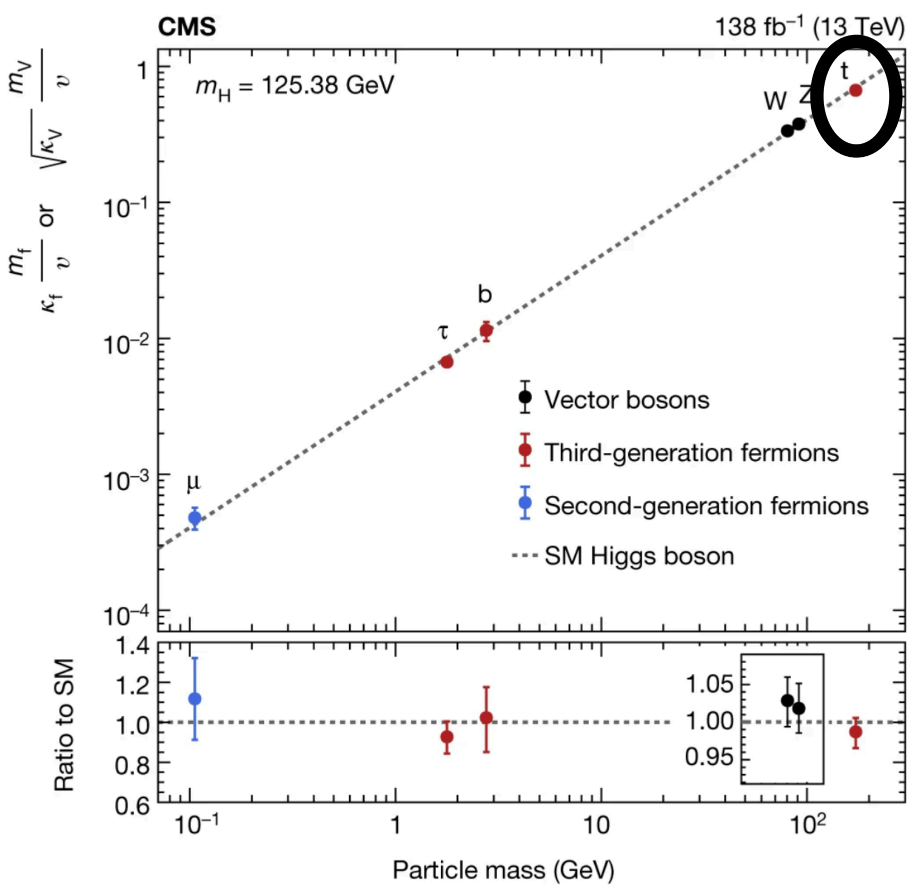
EPJC 79 (2019) 474

- Top width **strongly depends** on the top quark mass ($\sim m_t^3$)
- **Most precise** indirect measurement of 1.36 ± 0.14 GeV
- N.B.: parton shower models treat top quarks in a **narrow width approximation**
- Towards a **simultaneous measurement** of top quark mass and width
- Expect the measurement of the width at ≈ **50 MeV** precision at FCC-ee

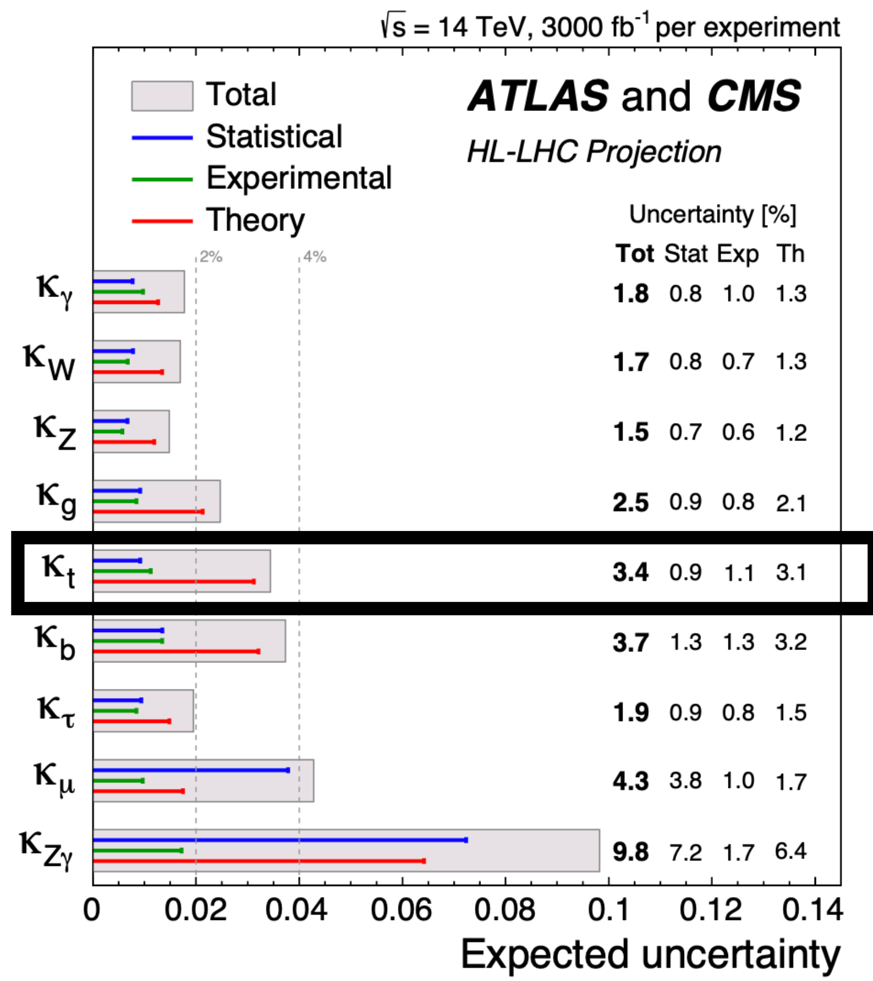


Top Yukawa

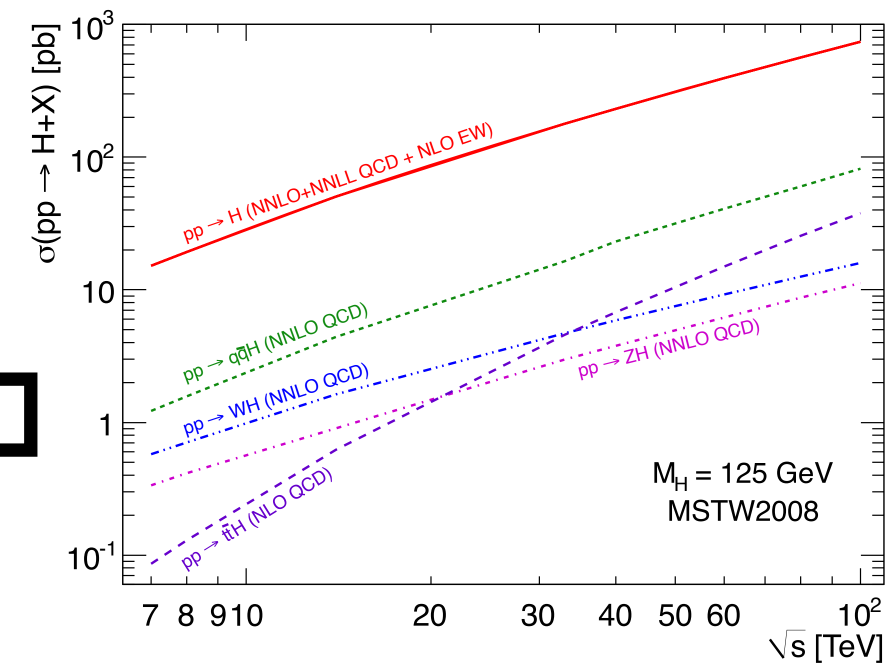
Nature 607 (2022) 60



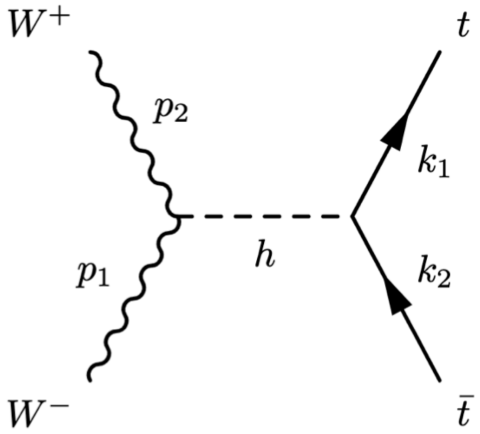
CERN-LPCC-2018-04



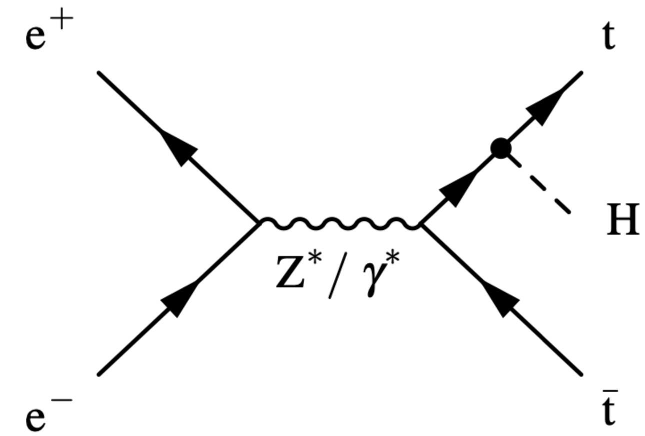
Higgs European Strategy



- Probed directly in $t\bar{t}H$ at the **LHC**, also measured in $H \to \gamma\gamma$, ggH, etc.
- The top Yukawa (y_t) is currently known at ≈ **10%**, with ≈ **4%** expected at HL-LHC
- Observation of the $t(\bar{t})Hq$ process (if not already in Run 3) and first hunt for $\mathbf{t\bar{t}HH}$ at HL-LHC
- The FCC-hh will go below **1%** with a significant increase in the production cross section (≈ 60x)
- A boosted analysis and $t\bar{t}H/t\bar{t}Z$ ($H/Z \to b\bar{b}$) ratio-based extraction

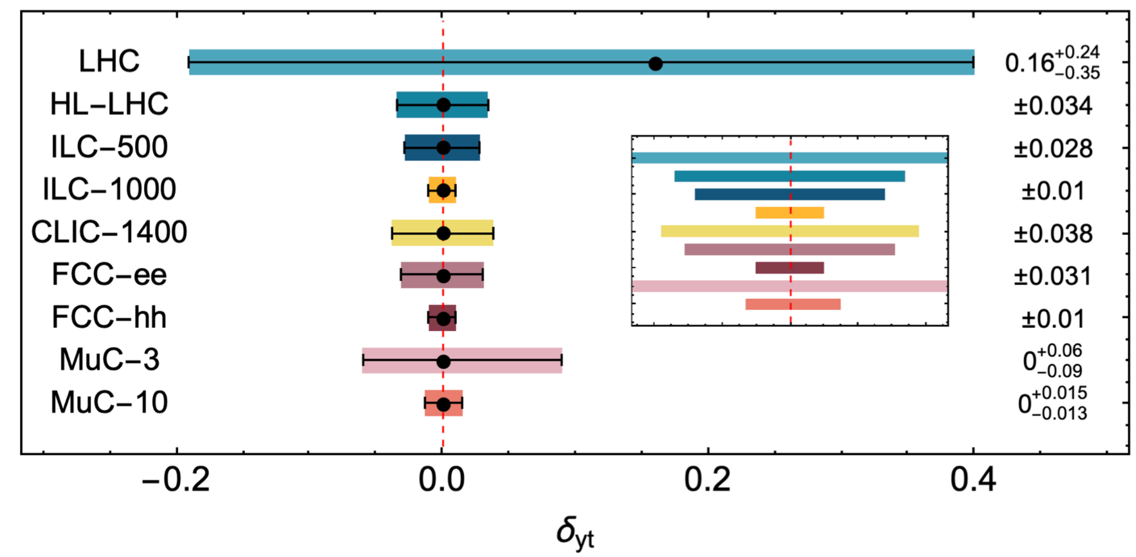


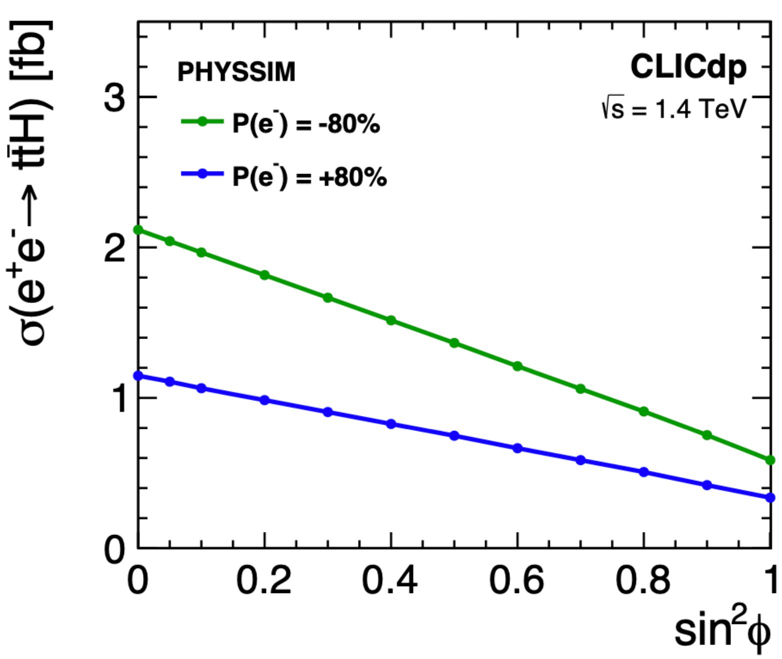
Top Yukawa



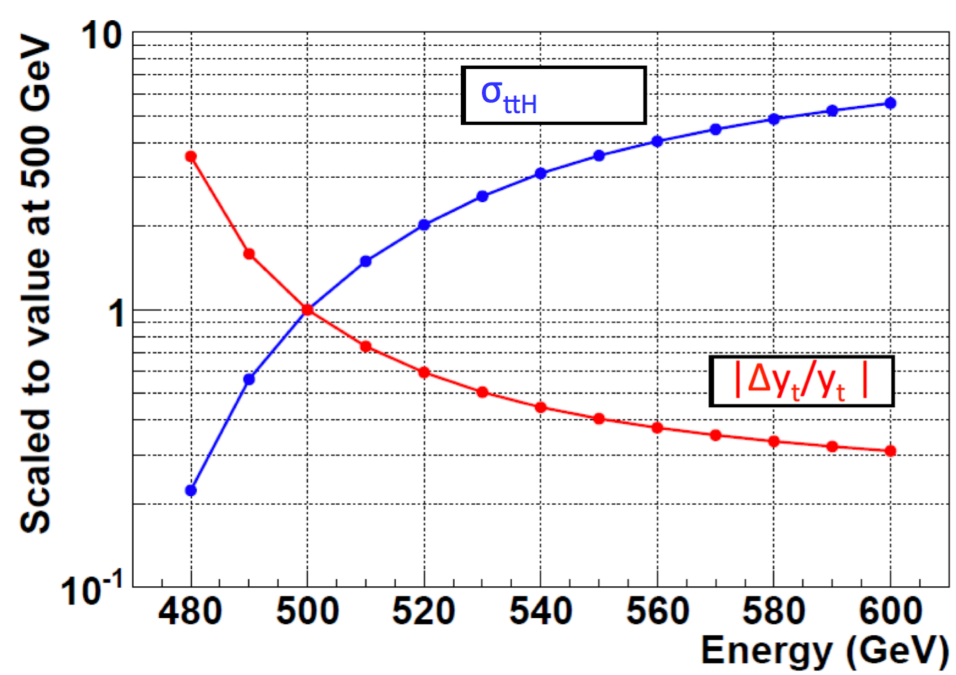
PRD 109 (2024) 035021 JHEP 05 (2024) 176

- High energy reach of **linear lepton colliders** (> 500 GeV) provides direct access to $t\bar{t}H$
- Possible to reach ≈ 4% precision in y_t at **ILC/CLIC**
- Indirect probe of y_t at **FCC-ee** at $t\bar{t}$ threshold with ≈ 10% uncertainty
- Expected uncertainty of ≈ 1.5% at **MuC**

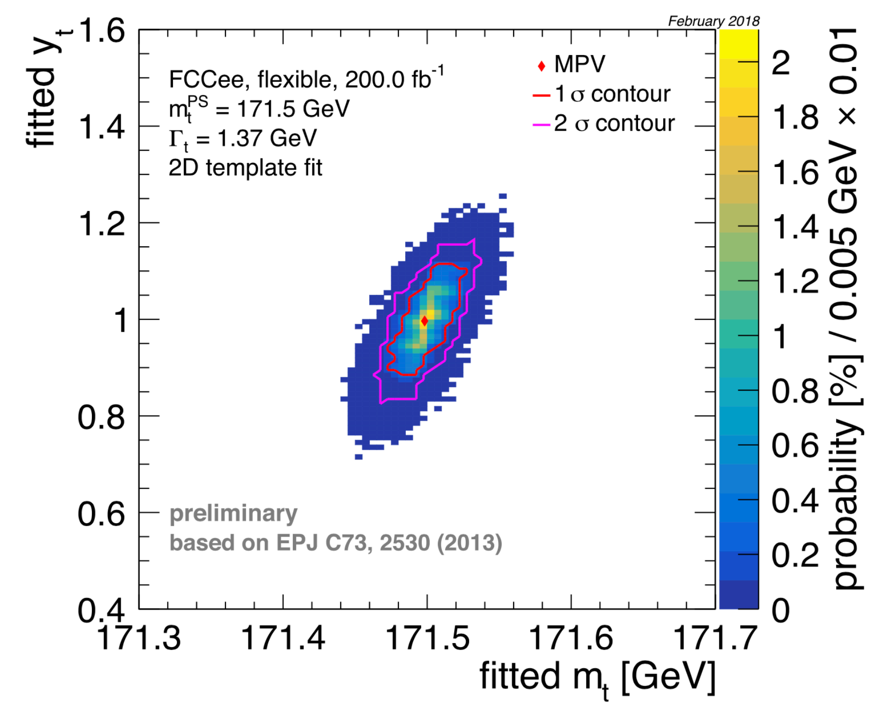




JHEP 11 (2019) 003



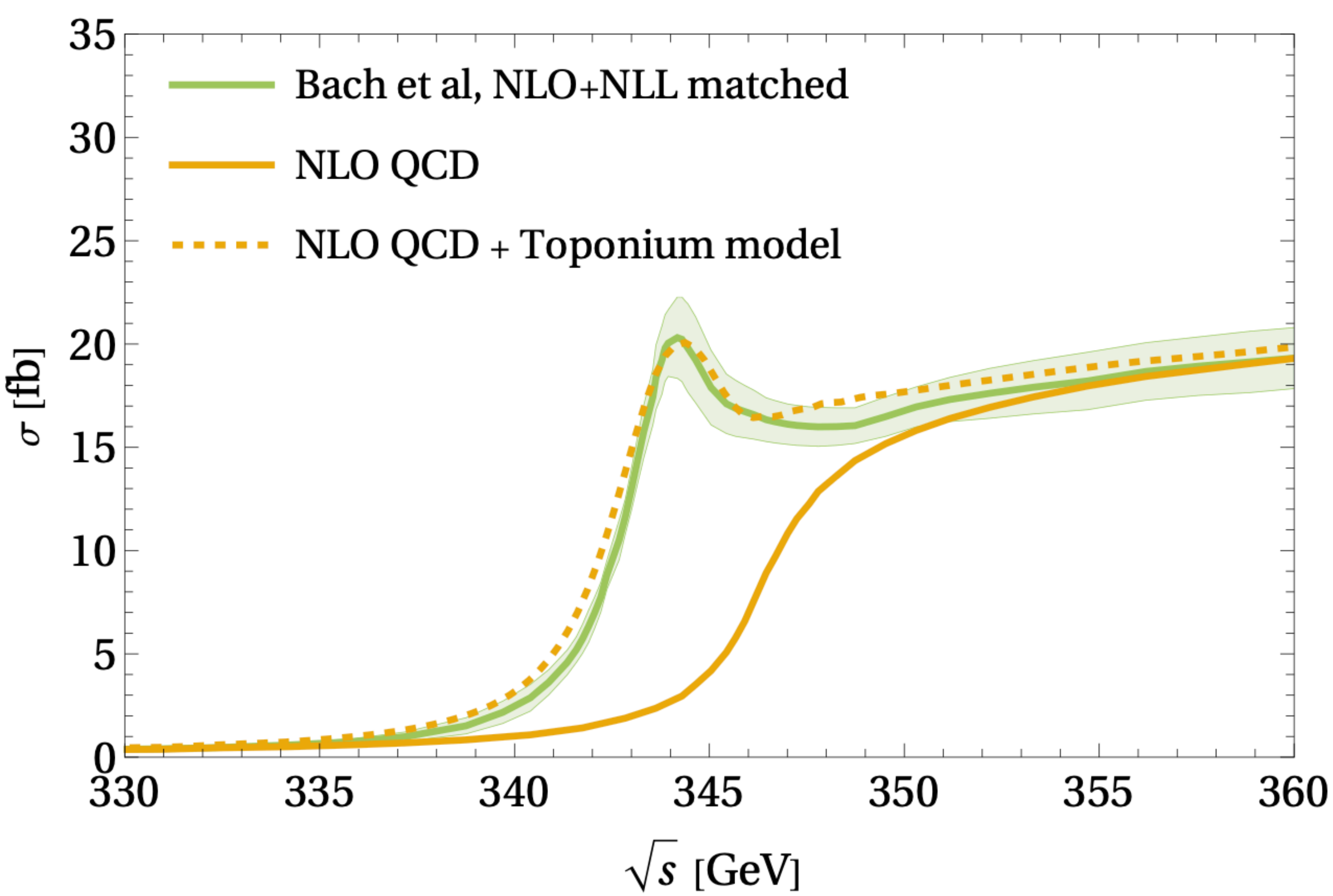
ILC-NOTE-2015-068

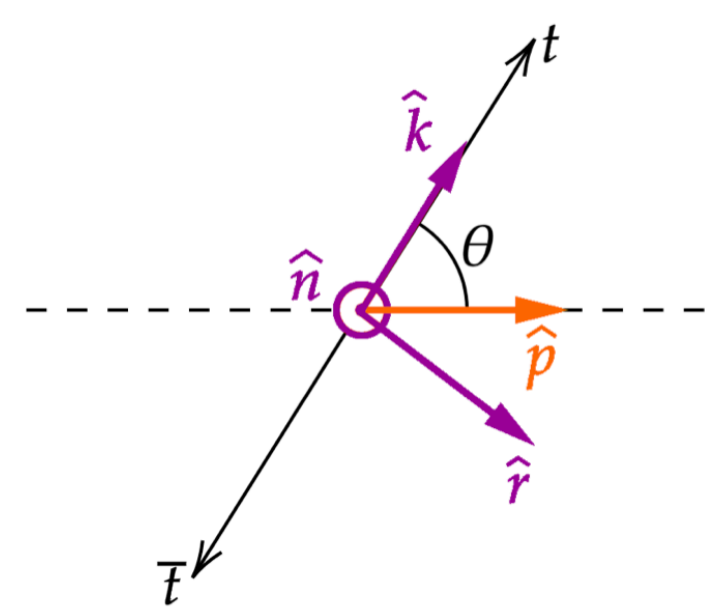


EPJC 79 (2019) 474

Quantum effects

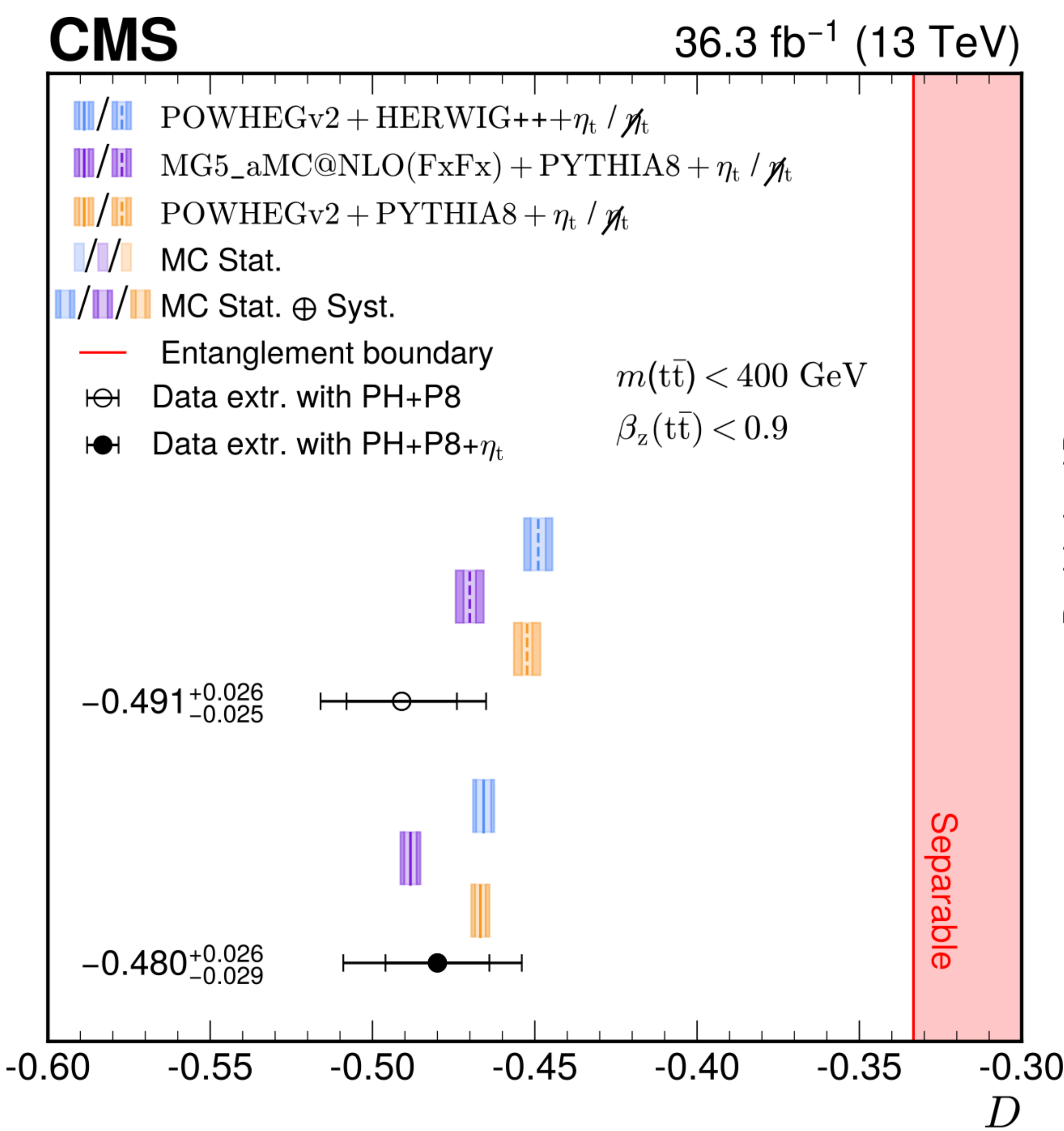
- Top quarks **feel each other** at the threshold as pseudoscalar and vector bound states (toponium)
- Recent **observation** of the top quark entanglement in $t\bar{t}$ events at the LHC
- Introduce an **observable D** (angles of charged leptons)
- Top quarks are entangled if **D < -1/3**
- Confirmation of the **existence of the toponium** requires a high experimental precision and more theory developments for future lepton collider studies



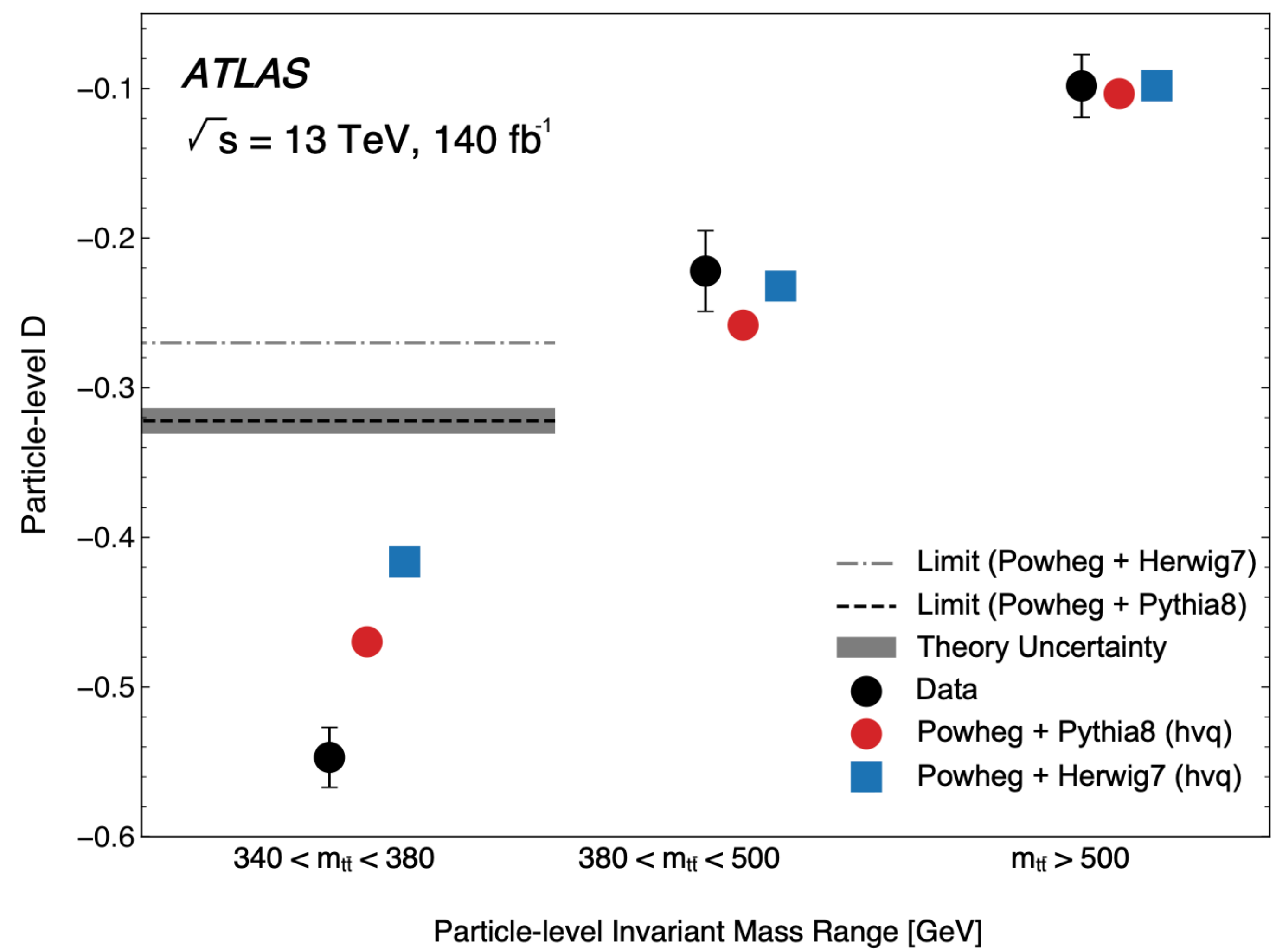


arXiv:2404.08049

Quantum effects

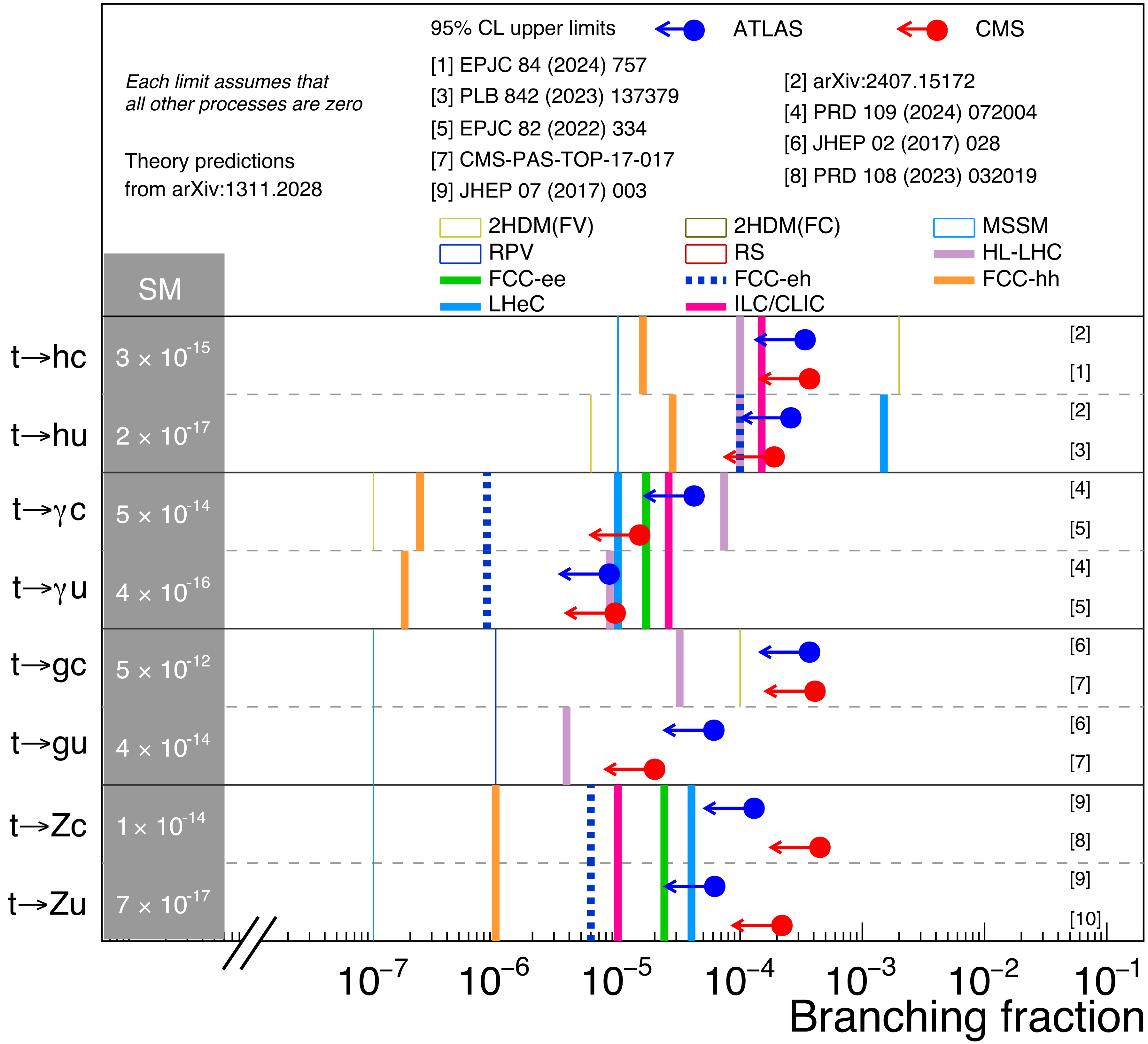


arXiv:2406.03976



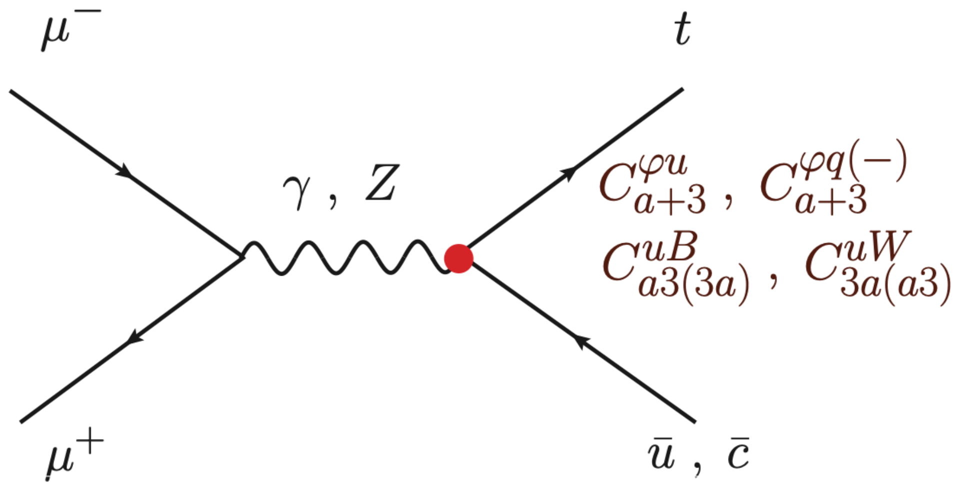
arXiv:2311.07288

Top FCNC

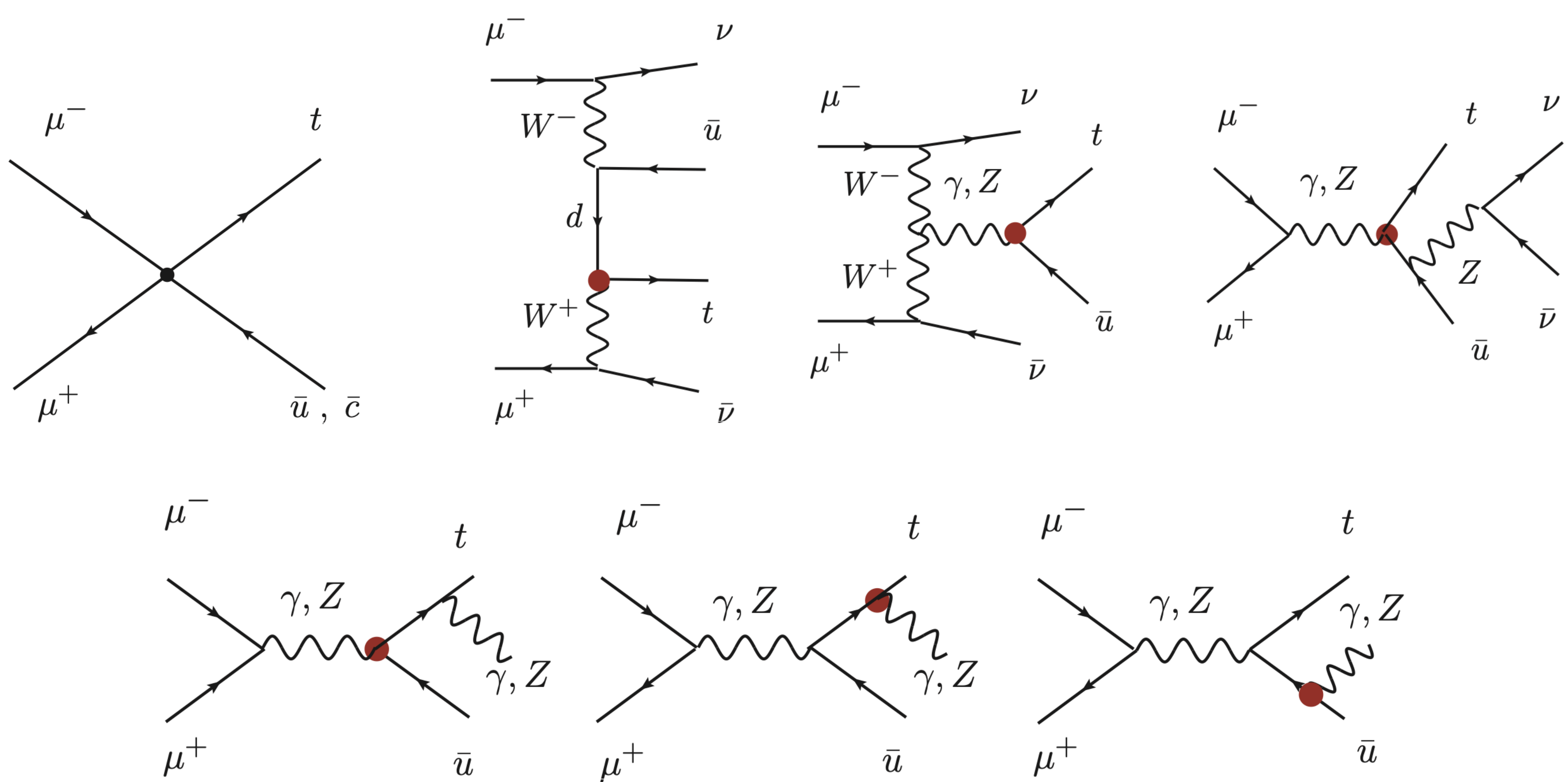


- The **latest LHC constraints** come very stringent thanks to improved reconstruction techniques and analysis optimizations
- The previous **HL-LHC projections** most likely conservative
- Several orders of magnitude improvement at **FCC-hh**
- Moderate improvement at **FCC-ee** and **ILC/CLIC** for electroweak couplings
- Benefit from **single top** quark production at 240 GeV at FCC-ee
- Hard times for **BSM**

Top FCNC at MuC



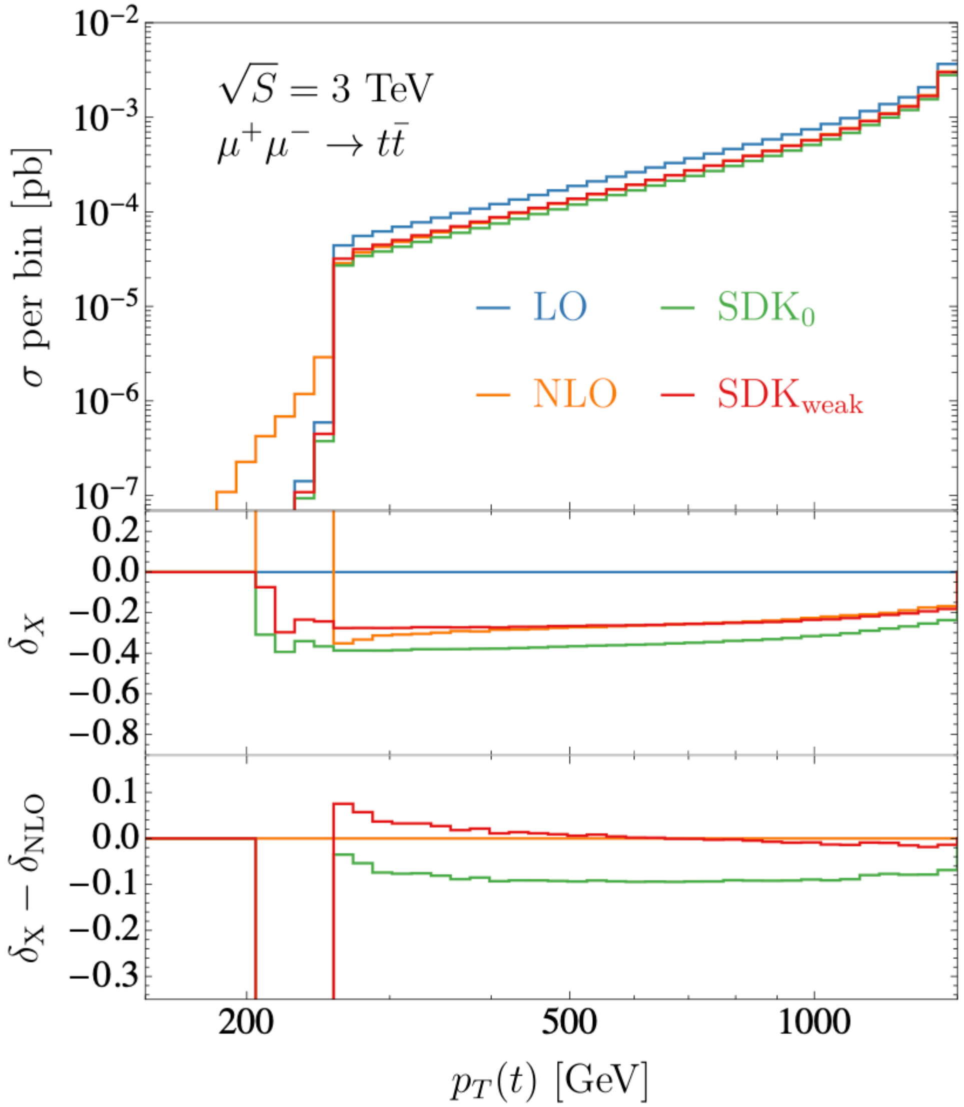
- Probe **electroweak** (Z/γ) anomalous FCNC couplings of the top quark
- **Competitive or weaker constraints** when compared to the latest LHC results (C_{uB} and C_{uW})



Adv. High Energy Phys. 2024 (2024) 2038180

Top quarks at MuC

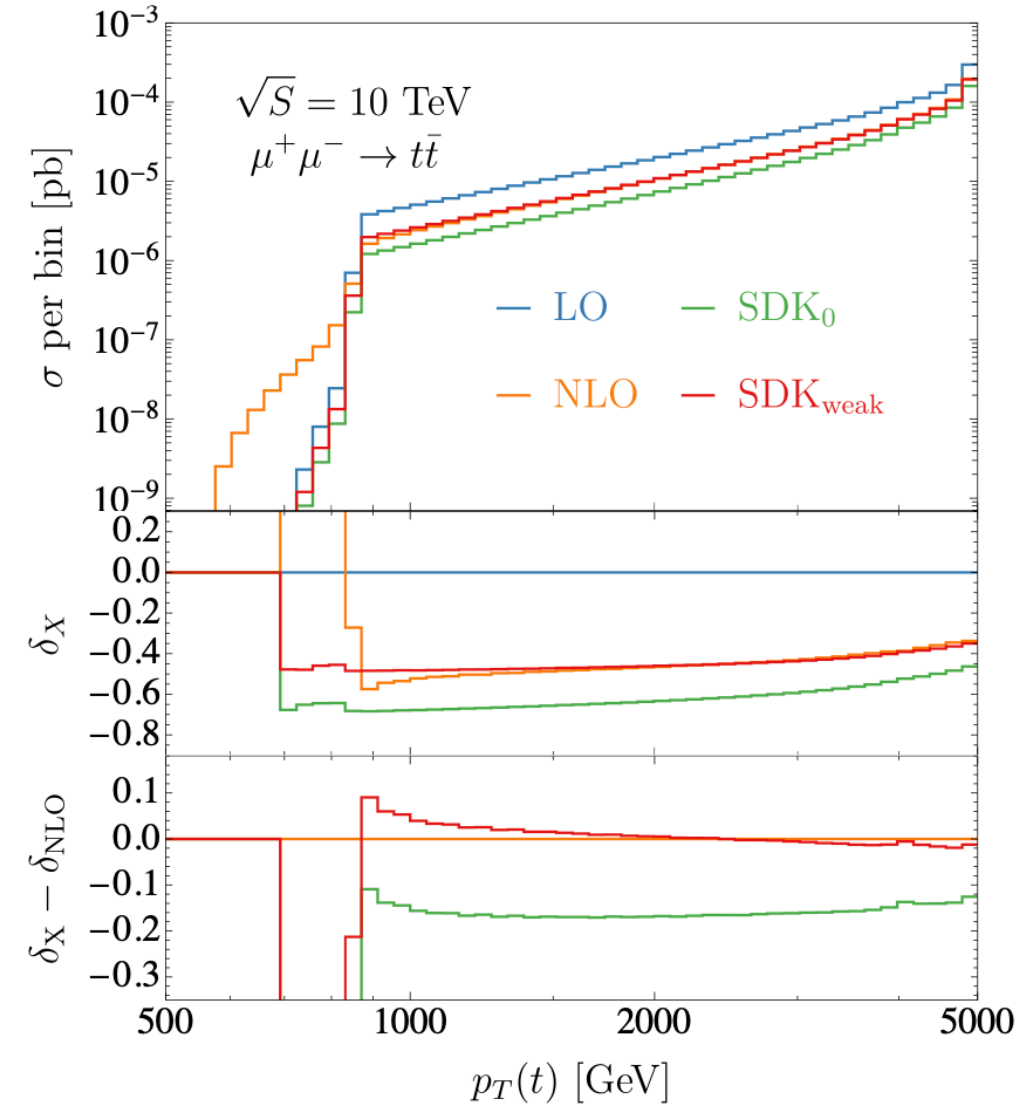
from D. Pagani's talk



For smaller p_T, larger corrections.

Sudakov (in the $\mathbf{SDK_{weak}}$ scheme) **capture NLO EW corrections** up to the % level.

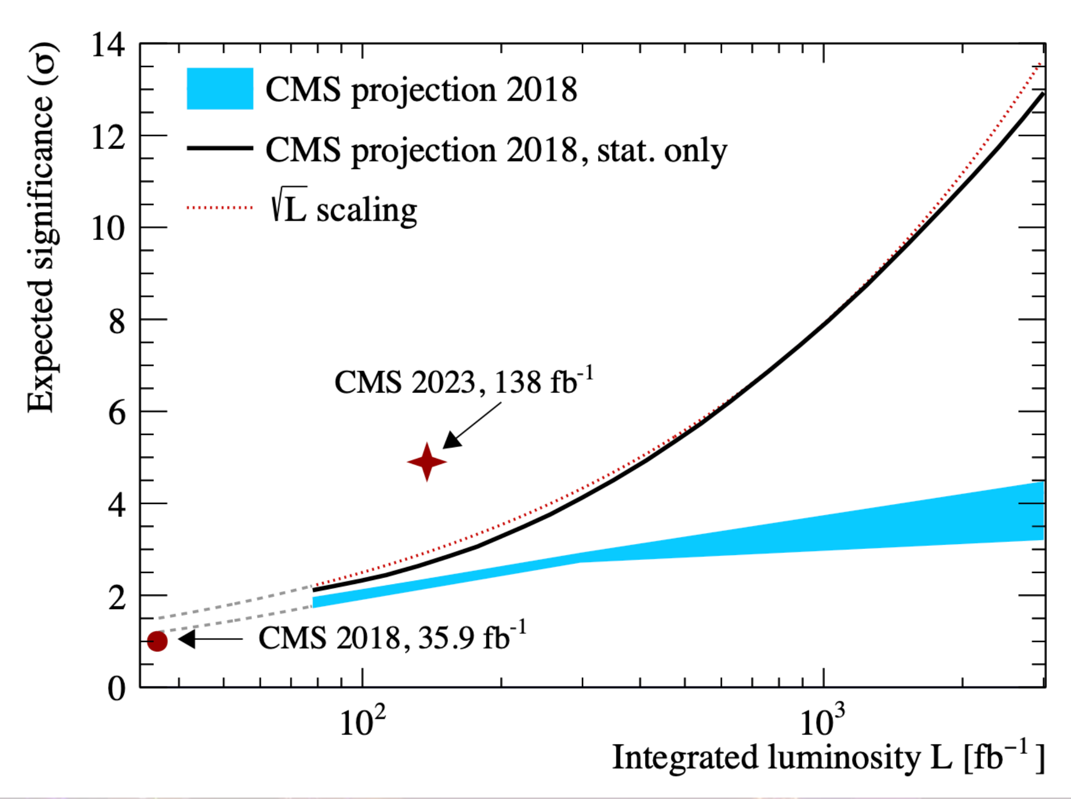
If double logs are written in the form $\log^2(s/m_W^2)$, the shapes observed here are all arising from **single logs**.



arXiv:2409.09129

Summary

- The **HL-LHC** is our imminent bright future for important unfinished top quark business from the LHC
- The **post-HL-LHC** scenarios will provide a highly complementary way to study top quark properties
- From **lepton threshold scans** to **high-energy frontier** of hadron collisions
- The top quark will remain a **key portal to BSM** in future collider projects
- Modern experimental particle physics is highly driven by **machine-learning developments** - anticipate sensitivity improvements
- The show **must** go on



Eur. Phys. J. C 84 (2024) 715