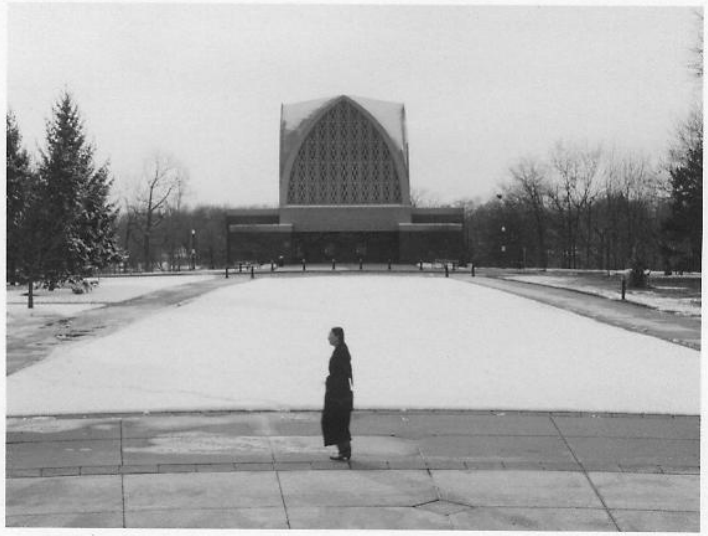
# Lessons from top quark production studies

R. Demina

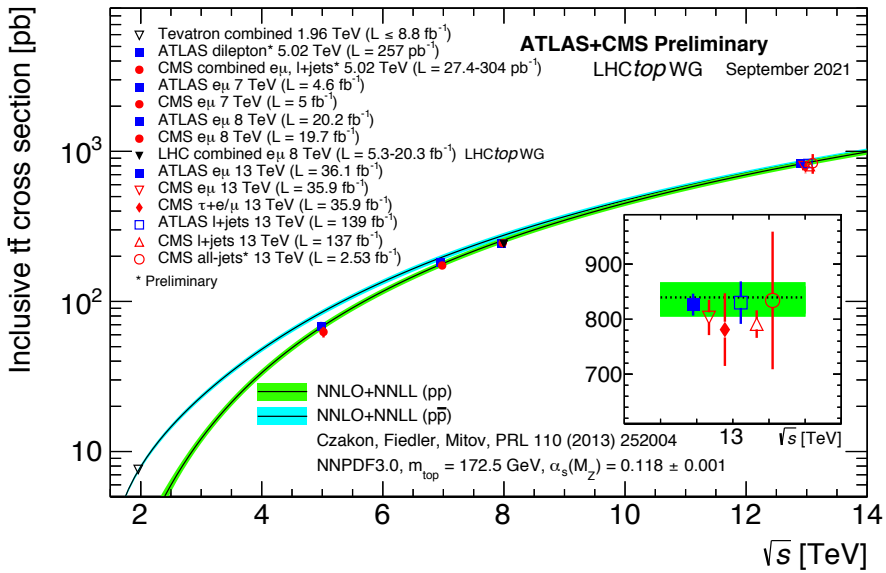
University of Rochester

07/20/2022



# Top pair production at hadron machines

- Many reasons to study top pair production in hadron machines
  - It is the leading source of top quarks
  - Background to virtually any new physics search
  - Could include decay of heavier particles to tt, e.g. H/A, Z'…
  - Test of perturbative QCD and EW corrections




Top pair production cross section was measured

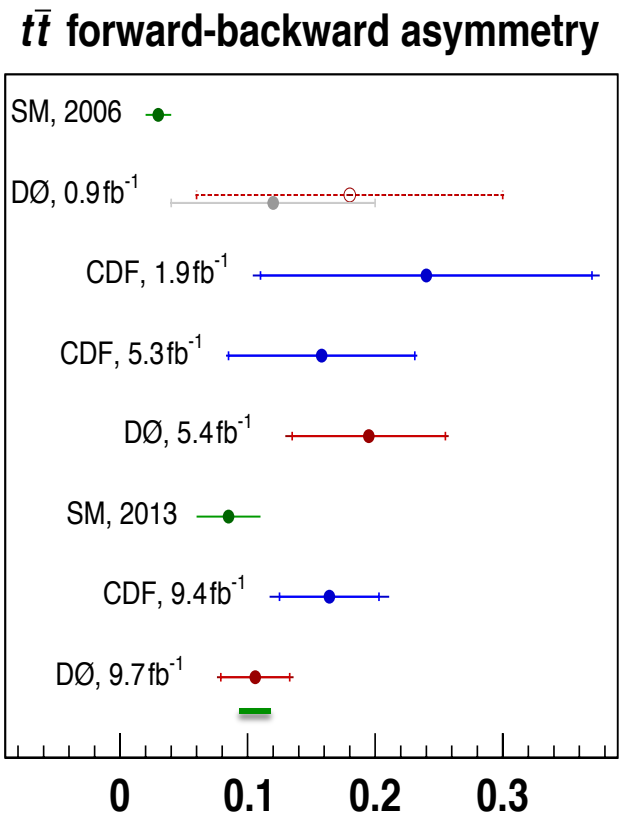
- To 5% precision at the Tevatron
- 2.5% at 8 TeV LHC
- Expected <1% at HL-LHC

# Top pair production at hadron machines

*Theory and experiment go hand-in-hand*

Large asymmetry in top pair production observed at the Tevatron was explained via inclusion of EW corrections and full NNLO calculations

Same is true for the original discrepancy observed in top $p_T$ spectrum at LHC




O. Astunado, J. Kuhn, G. Rodrigo PRD77(2008) 014003, 256 cit's

D0, PRL100(2008)142002, 227 cit's

CDF, PRL101(2008)202001, 222 cit's

CDF, PRD83(2011)112003,409 cit's

D0, PRD84(2011)112005, 292 cit's

W. Bernreuther, Z.-G. Si, PRD 86, 034026 (2012), 214 cit's

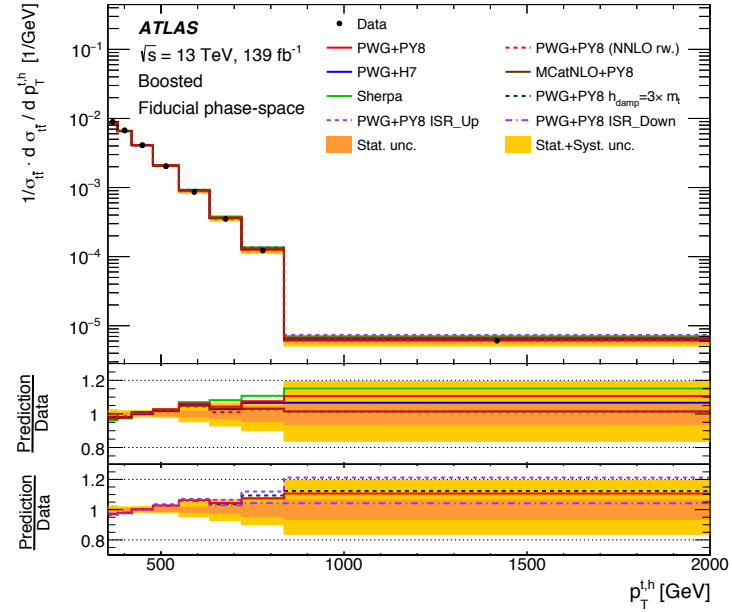
CDF, PRD87(2013)092002, 203 cit's

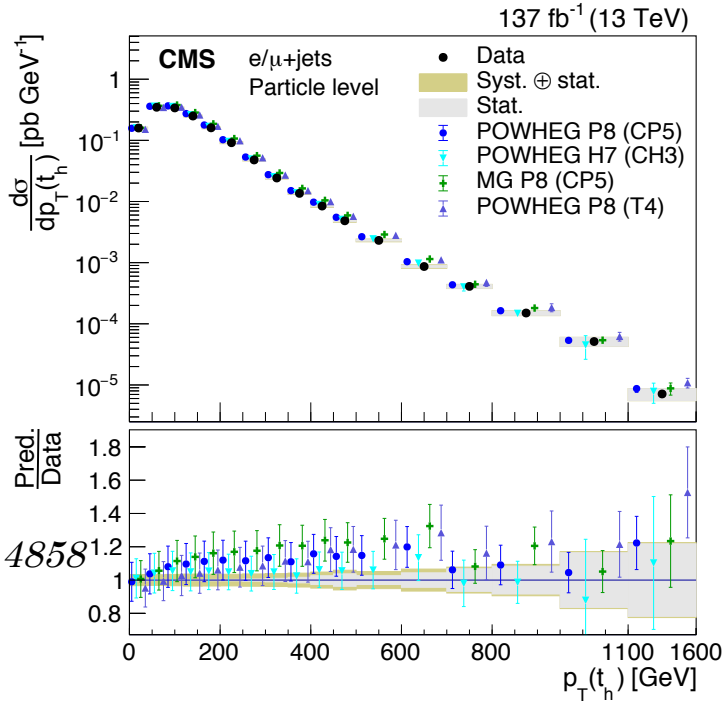
D0, PRD90(2014)072011, 125 cit's

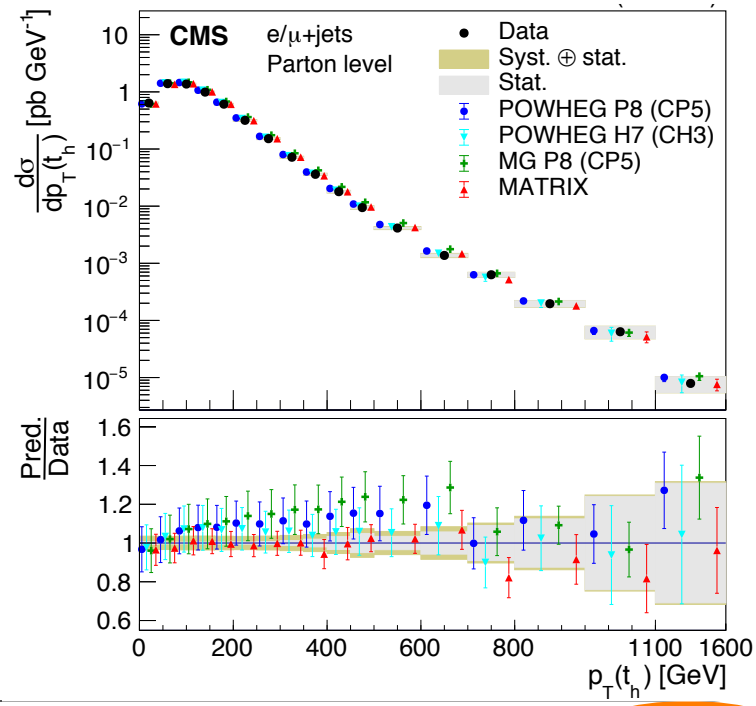
M. Czakon, P. Fiedler, A. Mitov PRL115(2015) 5, 052001, 185 cit's

# Top pair production at LHC

- Matrix (Eur. Phys. J C78 no 7 (2018) 537)– includes NNLO and EW correction – best agreement with data in top $p_T$
- Theoretical uncertainties dominated by parton shower and color reconnection modeling. Compare data to prediction at particle (not parton) level – smaller uncertainties



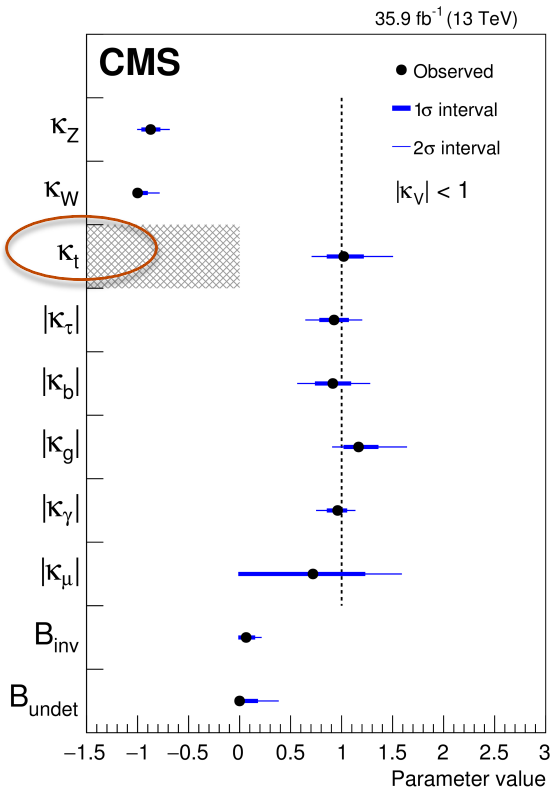




*Atlas: 2202.12134.14858*

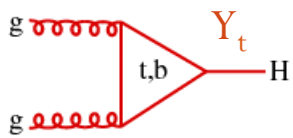
*CMS: 2108.02803*

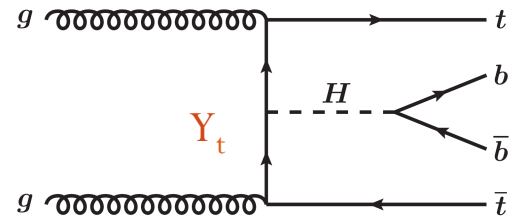
# Top Yukawa coupling from LHC

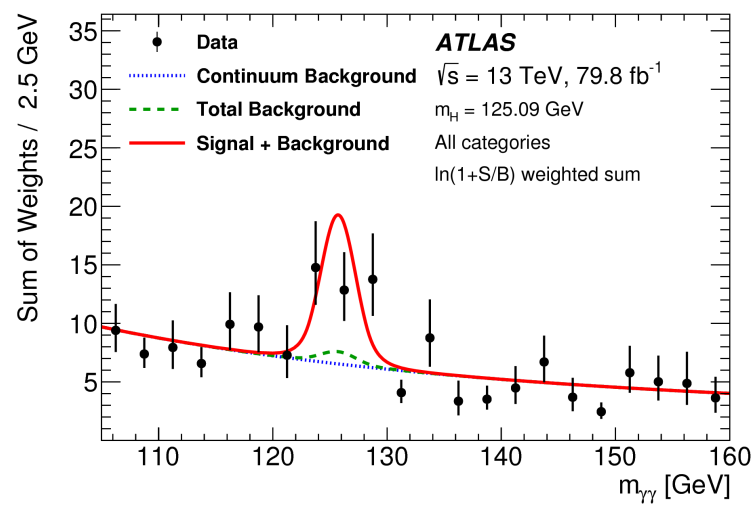
Expected uncertainty on $Y_t$ from HL- LHC 3.4%




*Top Yukawa coupling (Eur. Phys. J. C79(2019) 421) based on H production cross sections and decays, effective loops*



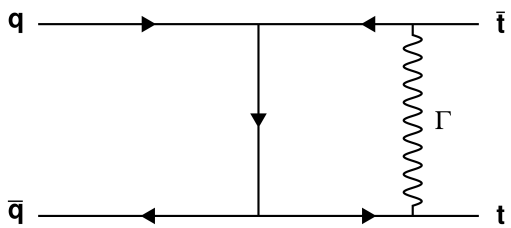



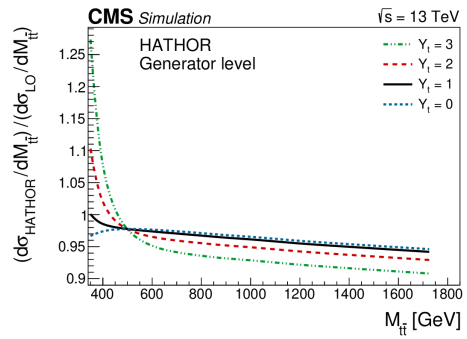



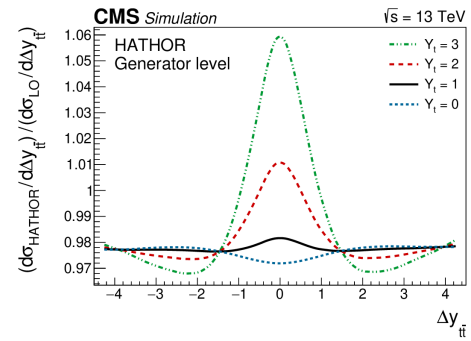

*Top Yukawa coupling from ttH production (Eur. Phys. J. C80(2020) 957)*

# Top Yukawa coupling from tt production

Top pair production cross section near threshold is sensitive to virtual Higgs boson exchange.



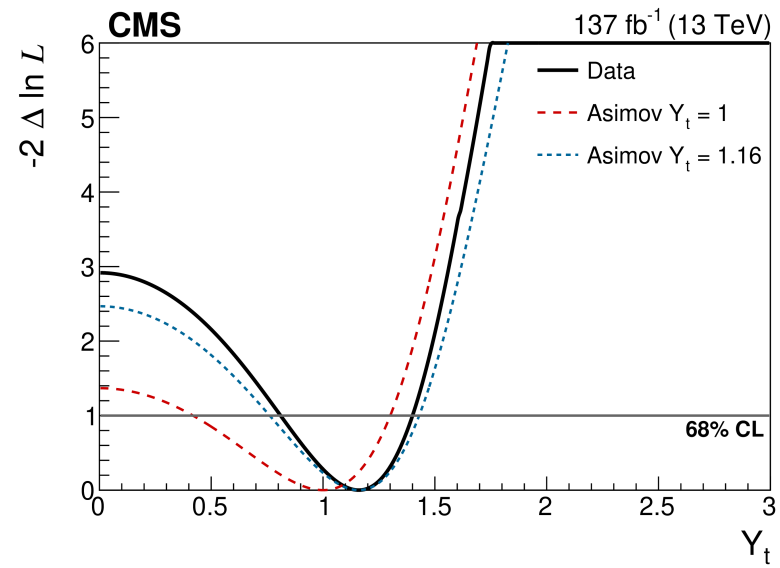

P. Uwer et al.
[arxiv: 1305.5773, Phys. Rev. D 91, 014020 (Feb 2015)]

Realization that EW correction are important in top pair production in hadronic collisions led to a new method to measure the top Yukawa coupling

Diagrams including the exchange of a virtual Higgs boson interfere with the tree level top pair production, hence proportional to $Y_t^2$

Leads to distortion of top kinematics near the production threshold

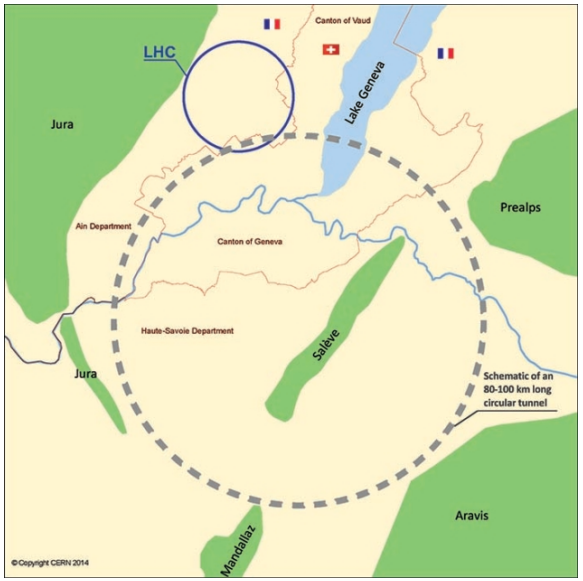
Theoretical limitations due to modeling of parton shower and color reconnection.

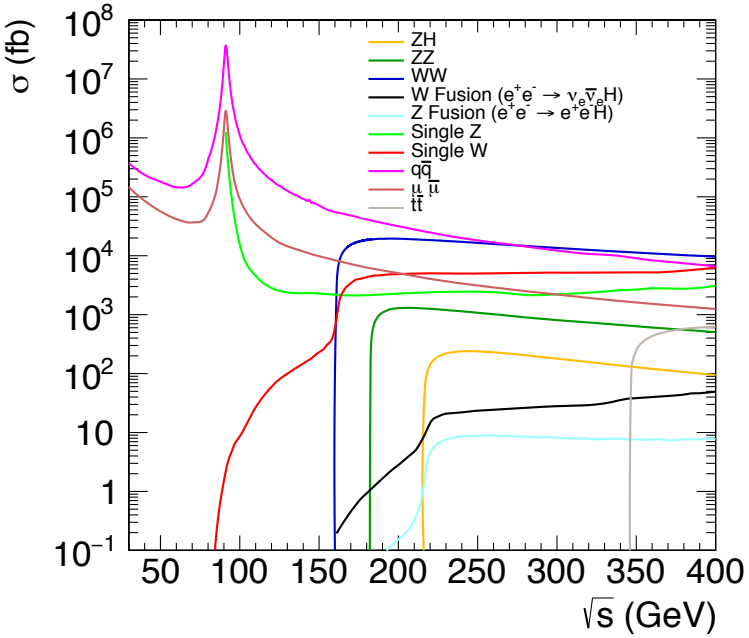



Phys. Rev. D. 102 (2020) 092013
Yt=1.16+0.24-0.35

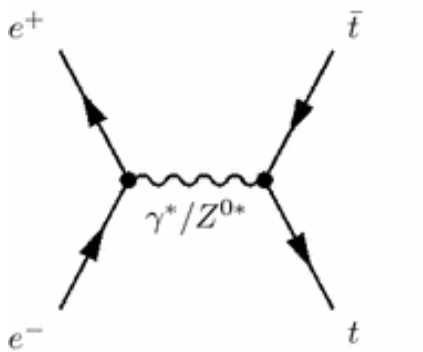
# Future circular collider

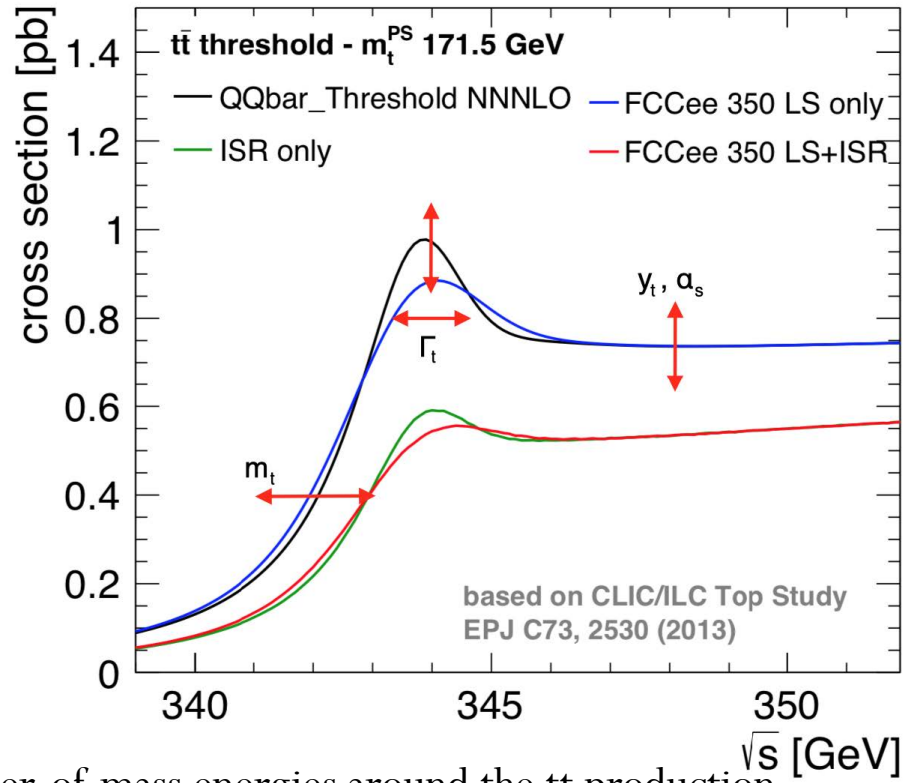
- About 1 M ttbar events are expected to be produced at FCC-ee near and above the production threshold
  - clean environment,
  - the precise knowledge of the collision energy and total momentum,
  - the ability to scan the center-of-mass energy
- Ultimate precision in top quark mass as well as other properties
  - Together with W and H boson masses over constrain the standard model
- The tunnel is planned to be used for FCC--hh at 100TeV center of mass energ



# Top production threshold scan at FCC-ee




Top quark parameters are evaluated by comparison of the production rates to the theoretical prediction, which exists at the $N^3LO$ QCD precision[1] and NNLL resummation[2] level level.

FCC-ee provides an advantage over linear colliders due to the absence of a pronounced beamstrahlung tail in the luminosity spectrum (LS).

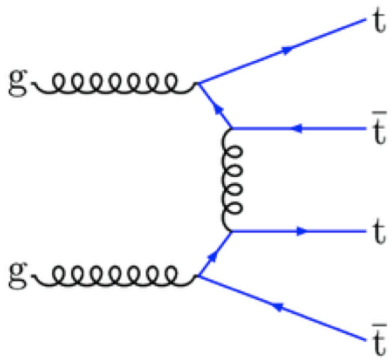
For L=200 $fb^{-1}$ evenly split across eight different center-of-mass energies around the tt production threshold (340, 341, 341.5, 342, 343, 343.5, 344, and 345~GeV), top mass can be determined with a statistical precision of better than 9 MeV when assuming SM values for $\Gamma_t$ and $Y_t$.

3.1% uncertainty on $Y_t$ from the combination of HL-LHC and FCC-ee.

Simultaneous fit of $m_t$ and $\Gamma_t$ results in a statistical precision of 17 and 45 MeV respectively.


1. M. Beneke, Y. Kiyo, P. Marquard, A. Penin, J. Piclum, M. Steinhauser. Phys. Rev. Lett 115 (2015) 192001
2. A. Hoang, A. Manobar, I. Steward, T. Teubner, Phys. Rev. D 65 (2002) 014014

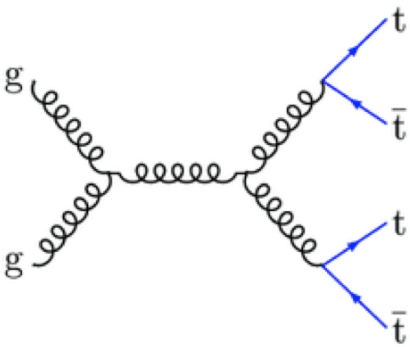
# Four top production at LHC




Four top quark production is sensitive to

- SUSY gluino pair production
- Two Higgs doublet models
- Top-philic Dark Matter
- Composite Higgs

Way to constrain top Yukawa coupling

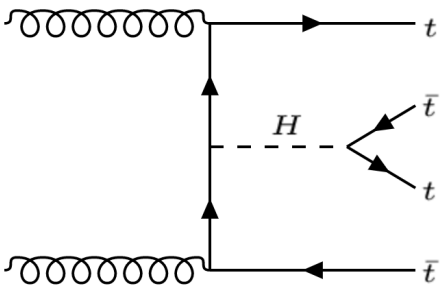


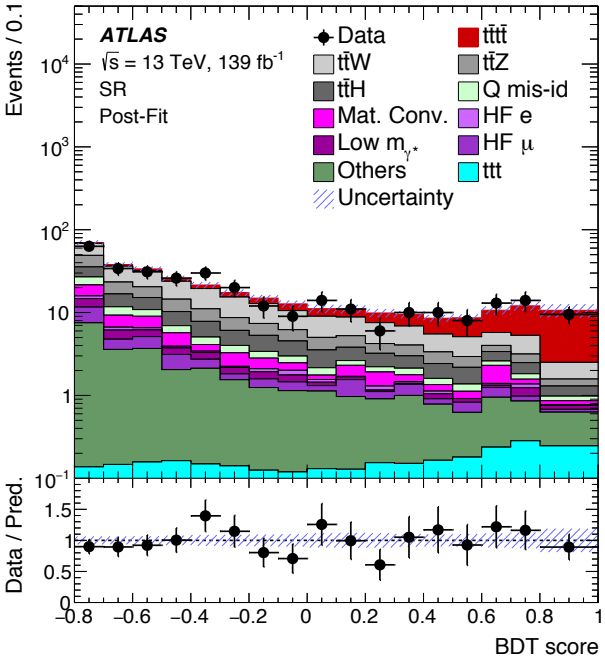

Observed/expected signal significance

Atlas: 4.7/2.6 σ

CMS: 2.6/2.7 σ

CMS: $Y_t$<1.7 at 95%CL



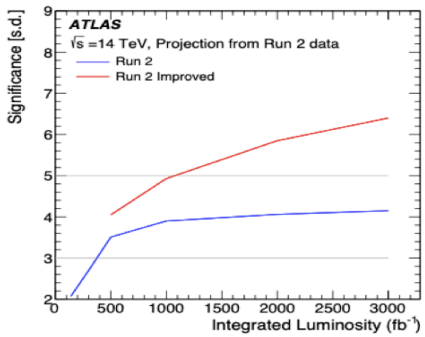



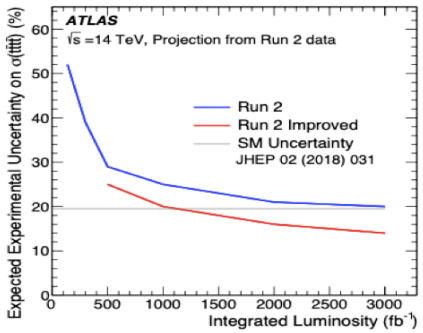

*Atlas: JHEP 11, 118(2021), 2106.11683*

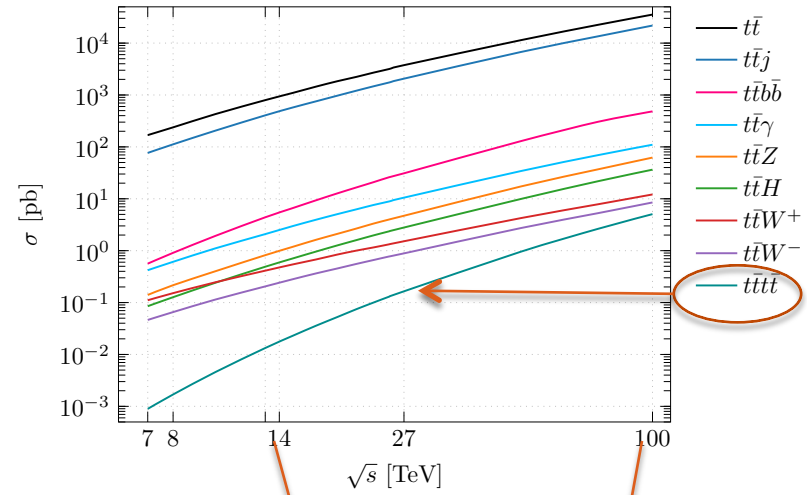
*Eur. Phys. J. C 80, 1085 (2020), 2007.14858*

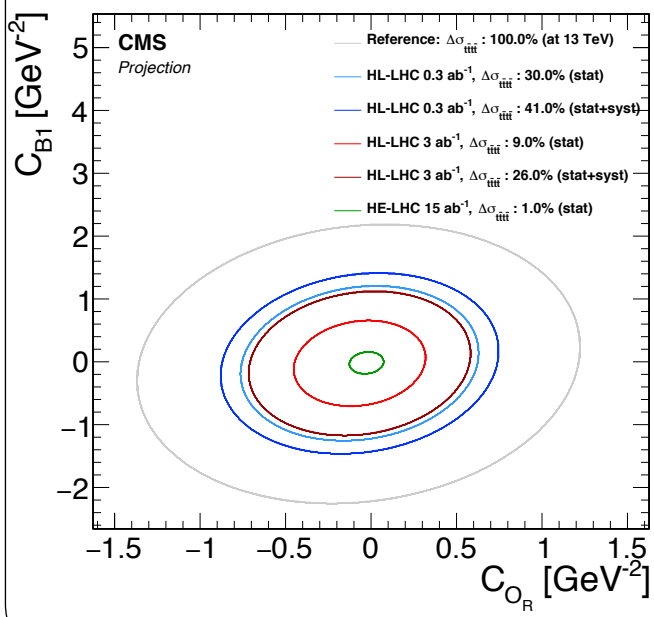
*CMS: Eur. Phys. J. C 80, 75 (2020), 1908.06463*

# Four top production at future machines




- Four top production is enhanced by 2 orders of magnitude at FCC-hh compared to LHC
- It allows to put much more stringent boundaries on 4t EFT operator

| | HL-LHC | FCC-hh |
|---|---|---|
| $\sqrt{s}$, TeV | 14 | 100 |
| L, $ab^{-1}$ | 3 | 30 |
| Limit on $\Lambda/\sqrt{\lvert c_{tt} \rvert}$, TeV | 1.3 | 6.5 |

# Conclusions

- The future of top physics is bright
  - With high statistics of HL-LHC we will be able to perform a number of precision measurements
    - Top Yukawa coupling
    - Top couplings parameterized in EFT
  - Close communication with theory is key to progress on this front
    - Work together to minimize theoretical uncertainties (see N. Kidonakis talk in this meeting)
- FCC-ee is an ideal machine for top quark studies
  - Precision measurements of top mass, width and Yukawa coupling from the production threshold scan
  - $\Delta m_t = 9 \mathrm{MeV}/c^2$

# Backup slides

# Searches for FCNC interactions

- FCNC interactions in top quark sector involve exchange of a neutral boson ($H,\gamma,g,Z$)
  - Highly suppressed in the Standard Model (BR: $10^{-12}$ - $10^{-17}$)
  - Large enhancements possible due to loop contributions from beyond-SM particles - important probe of new physics!

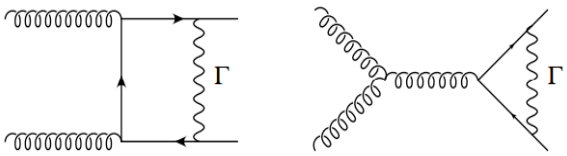
- Searches at FCC-ee can probe FCNCs…
  - (i) in the decay of a top quark from $tt$ production, or
  - (ii) via anomalous single-top quark production

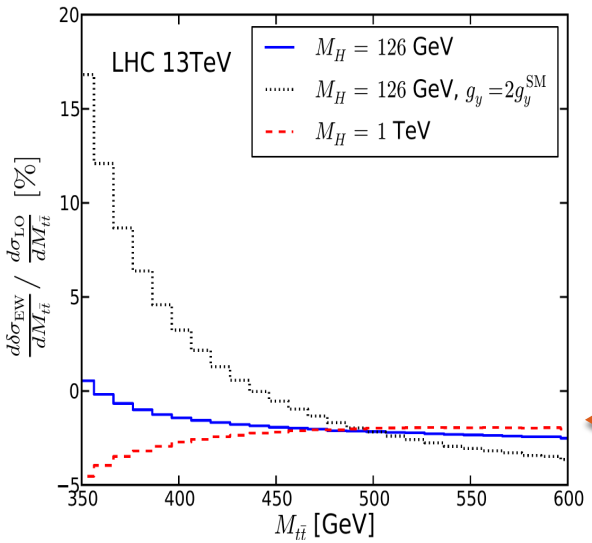
A. Abada, et al. EPJC 79 (2019) 474
H. Khanpour, et al. PLB 775 (2017) 25
P. Azzi, et al. EPJP 137 (2021) 39

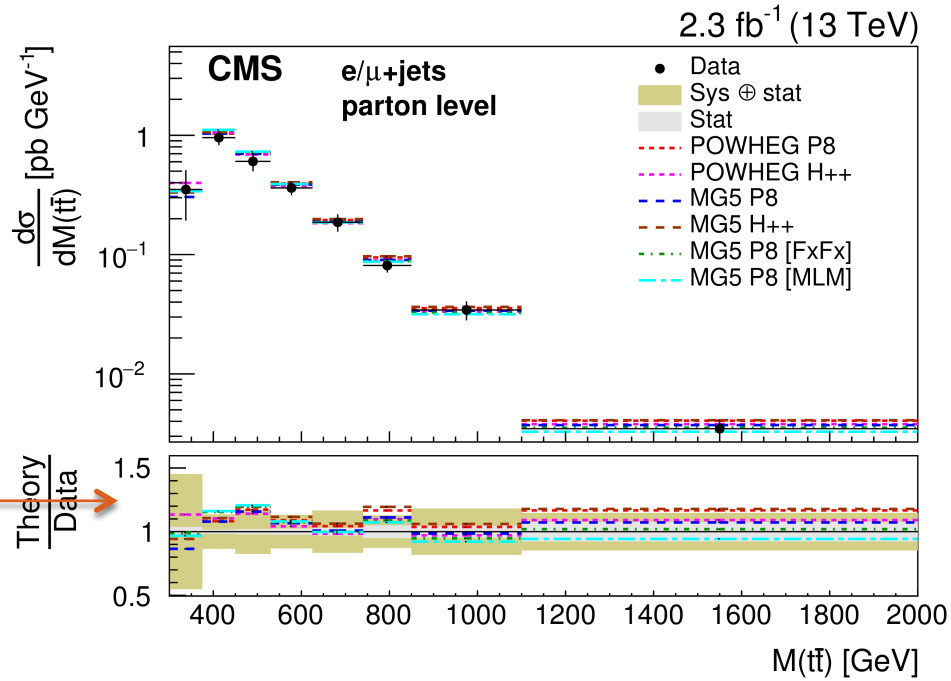
- Preliminary studies performed of $e\uparrow+ e\uparrow- \rightarrow Z/\gamma \rightarrow tq\ (t\ q)$, where the top quark decays as: $t\rightarrow Wb\rightarrow l\nu\downarrow l\ b\ (l=e,\mu)$
  - **Resulting expected sensitivity to FCNC BRs ($t\rightarrow q\gamma$, $t\rightarrow qZ$) of about $10^{-5}$**
  - Further improvements possible from including hadronic decay channel, combining with results from searches of FCNCs in top quark decays, and utilizing more advanced analysis techniques

# Top Yukawa coupling

- Top quark interaction with Higgs affects the ttbar differential cross section
- Problem: systematics at low Mtt – mostly due to parton shower modeling – jets migrating in and out of acceptance
- Use old trick – add l+3-jets – helps constrain the parton shower in situ (nuisance parameter)




P. Uwer et al.
[arxiv: 1305.5773, Phys. Rev. D 91, 014020 (Feb 2015)]