Top quark physics

Slabospitsky Sergey

NRC “Kurchatov Institute” - IHEP, Protvino, Russia

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Why we like the t-quark ?

The top-quark is an extraordinary Standard Model (SM) object

- the most heavy SM object, $m_t \approx 172.5$ GeV and $|V_{tb}| \lesssim 1$
- $\Rightarrow$ top decays before hadronization $\Rightarrow$ there are no “top” hadrons
- connection with other generations is very small: $|V_{td}| \simeq 0.008$, $|V_{ts}| \simeq 0.04$
- extraordinary accuracy of the theoretical predictions $(\sigma, \Gamma, \mathrm{Br}, \ldots, \sim \mathcal{O}(1\,\%))$
- all properties are described within the SM without additional phenomenological parameters
- provides the direct information about spin and polarization
- the largest Yukawa coupling: $y_t = \sqrt{2}m_t/v \approx 1$

t-quark is an excellent laboratory to search for New Physics

- new interactions and particles
- new anomalous interactions: tWb; tHq; $t\,g/\gamma/Z\,q$
- new heavy objects $R(t\bar{t})$, $Q \to tX, \ldots$
- ...

Top-quark interactions within the Standard Model

The Lagrangian

$$\mathcal{L}_{\rm SM} \quad = \quad -\frac{y_t}{\sqrt{2}}\bar{t}\; t\, H - g_s\bar{t}\gamma^{\mu} t^a\; t\; G^a_{\mu} - \frac{g}{\sqrt{2}}\sum_{q=d,s,b}\frac{V_{tq}}{2}\bar{t}\gamma^{\mu}\,(1-\gamma_5)\; q\; W^+_{\mu}$$
$$-Q_t e\bar{t}\gamma^{\mu}\; t\, A_{\mu} - \frac{g}{2\cos\vartheta_W}\bar{t}\gamma^{\mu}\left[\left(\frac{1}{2} - 2Q_t\sin^2\vartheta_W\right) - \frac{1}{2}\gamma_5\right]\; t\, Z_{\mu} + \text{h.c.}$$

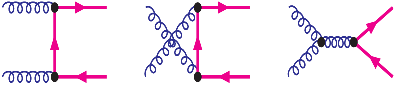
$$y_t = \sqrt{2}\frac{m_t}{v_{ew}} \approx 1, \quad v_{ew} \approx 246 \text{ GeV}$$

v_{ew} - electroweak scale - vacuum expectation value

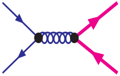
Top-quark production processes in the SM

- QCD t-quarks production

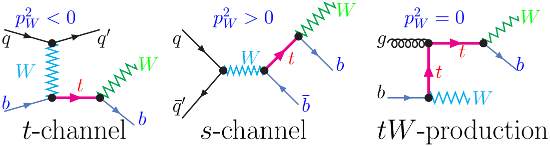
$g\,g \to t\,\bar{t}$



$q\,\bar{q} \to t\,\bar{t}$



- t-quarks production due to electroweak interactions



Top-quark decays within the SM

dominant decay channel $t \to b\, W^+;\ W^+ \to q\, \bar{q}', \ell\, \nu$
decay width (neglecting m_b^2/m_t^2)

$$\Gamma_{tot} = \Gamma_t = \frac{G_F\, m_t^3}{8\sqrt{2}\pi} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$

$$G_F = 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2},\ m_t = 172.5\,\mathrm{GeV},\ \alpha_s(m_t) = 0.118$$

$$\Rightarrow\ \Gamma_t \simeq 1.39\ \mathrm{GeV}\ \gg \Lambda_{QCD} \simeq 200\ \mathrm{MeV}$$

t-quark decays before hadronization. There are no "top"-hadrons $(t\bar{t}), (t\bar{q}), (tqq')$

$$BR(t \to b\,\ell^+(e, \mu, \tau)\,\nu) \simeq 33\,\%;\ BR(t \to b\,q\,q') \simeq 67\,\%$$

decay probabilities for $t\bar{t}$ pair

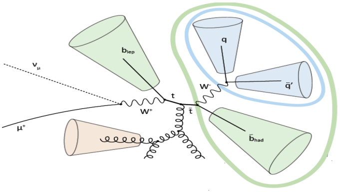
$$t\bar{t} \to b\,\bar{b}q\,\bar{q}'\, q''\, \bar{q}''' \simeq 46.2\,\%$$
$$t\bar{t} \to b\,\bar{b}q\,\bar{q}'\, \ell^+\,\nu\ +\ b\,\bar{b}q\,\bar{q}'\,\ell^-\,\bar{\nu} \simeq 43.5\,\%$$
$$t\bar{t} \to b\,\bar{b}\ell^+\,\ell^-\,\nu\,\bar{n}u \simeq 10.3\,\%$$

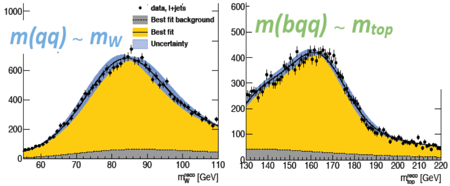
the final states have two b-jets; 0, 1, 2 "isolated" charged leptons; "missing" energy (neutrino) and several hadronic jets from light quarks

Top-quark reconstruction

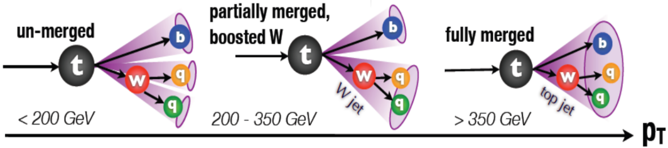
- two ways for the reconstruction: $t \to bW^+(\to \ell^+\nu)$ and $t \to bW^+(\to q\bar{q}')$

reconstruction of the $W(m(jj) \sim M_W)$, then $m(J_b\text{“}W'') = m(j_b jj)$





- "boosted" t-quark

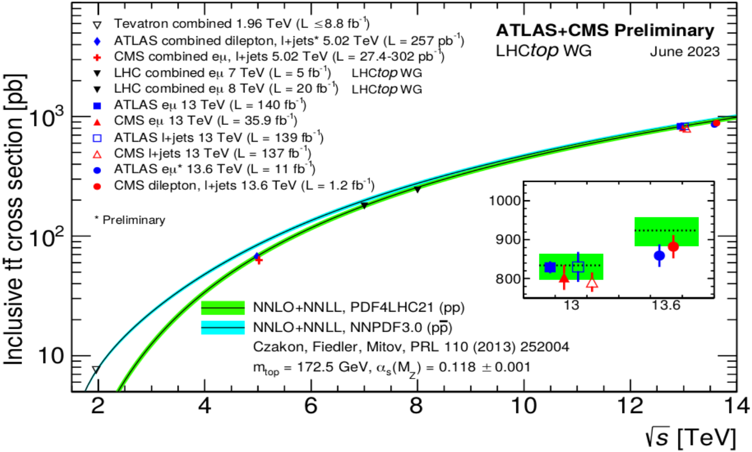


Total cross sections production of $t\,\bar{t}$ at the LHC

Great progress has been made in describing the production of $t\bar{t}$ taking into account higher orders of perturbation theory (NNLO and NNLL). The main theoretical uncertainty comes from PDF

The cross sections for the production of the pair $t\,\bar{t}$ are measured in various final states:

ee, $\mu\mu$, $e\mu$, $\ell\tau_h$, $e/\mu+$jets, all jets



Total cross sections production of $t\,\bar{t}$ at the LHC

joint analysis of two experiments ("LHC Top Physics Working Group"):

$\sqrt{s}$, TeV	σ(pb) (experiment)	σ(pb) (theory)
7	$69.5 \pm 6.1(stat) \pm 5.6(syst) \pm 1.6(lumi)$	70 ± 10 (scale + PDF+α_s)
7	$173 \pm 3(stat) \pm 8(syst) \pm 6(lumi)$	$177.3^{+4.7}_{-6.8}(scale) \pm 9$ (PDF+α_s)
8	$240.6 \pm 1.4(stat) \pm 5.7(syst) \pm 6.2(lumi)$	$252.9^{+6.4}_{-8.6}(scale) \pm 11.7$ (PDF+α_s)
13.0	$836 \pm 27(stat) \pm 81(syst) \pm 100(lumi)$	$832.0^{+20}_{-28}(scale) \pm 35$ (PDF+α_s)

• there are two measurements of the top pair production in *pp*-collisions at $\sqrt{s} = 13.6$ TeV

CMS: JHEP 08, p. 204 (2023), arXiv:2303.10680, $\mathcal{L}_{int} = 1.21$ fb^{-1}
ATLAS: arXiv:2308.09529, $\mathcal{L}_{int} = 29$ fb^{-1}

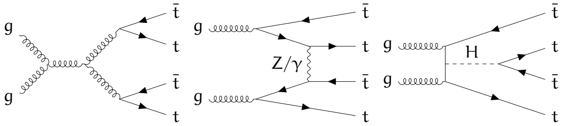
ATLAS $\sigma(t\bar{t}) = 850 \pm 3(\text{stat}) \pm 18(\text{syst}) \pm 20(\text{lumi})$ pb

CMS $\sigma(t\bar{t}) = 881 \pm 23(\text{stat+syst}) \pm 20(\text{lumi})$ pb

theory $\sigma(t\bar{t}) = 924^{+32}_{-40}(\text{scale} + \text{PDF} + \alpha_s)$ pb

Four-top-quark production

Four top quark production in *pp*-collisions is among the rarest SM processes currently accessible at hadron colliders



The SM cross section is calculated at NLO in QCD and EW theory *JHEP 02 (2018) 031, arXiv:1711.02116 [hep-ph] and arXiv:2212.03259 (2022)*

$$\sigma^{theory} = 12.0 \pm 2.4\,\text{fb} \;\text{ and }\; = 13.4^{+1.0}_{-1.8}\;\text{fb}\;\; \sqrt{s} = 13\;\text{TeV}$$

there two measurements of the four-top-quark production in *pp*-collisions at $\sqrt{s} = 13$ TeV

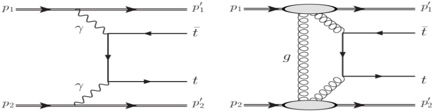
ATLAS: Eur. Phys. J. C 83 (2023) 496, arXiv:2303.15061
$\mathcal{L}_{int} = 140\ \text{fb}^{-1}$, $\sigma(t\bar{t}t\bar{t}) = 22.5^{+4.7}_{-4.3}(\text{stat})^{+4.6}_{-3.4}\text{syst})$ pb $= 22.5^{+6.6}_{-5.5}$ fb
top-quark Yukawa coupling $|\kappa_t| < 2.2(1.8)$
CMS: Phys.Lett.**B** 847 (2023) 138290, arXiv:2305.13439 [hep-ex]
$\mathcal{L}_{int} = 138\ \text{fb}^{-1}$, $\sigma(t\bar{t}t\bar{t}) = 17.7^{+3.7}_{-3.5}(\text{stat})^{+2.3}_{-1.9}\text{syst})$ pb $= 17.4^{+4.4}_{-4.0}$ fb

$$\sigma(t\bar{t}W) = 990 \pm 98\ \text{fb},\ \sigma^{theor} = 722 \pm 74\ \text{fb}$$
$$\sigma(t\bar{t}Z) = 945 \pm 81\ \text{fb},\ \sigma^{theor} = 859 \pm 80\ \text{fb}$$

top-quark Yukawa coupling $|\kappa_t| < 1.7$

$pp \to pt\bar{t}p$ and $PbPb \to t\bar{t}$

- CMS+TOTEM Collaborations, arXiv:2310.11231. Central exclusive production of $t\bar{t}$ pairs ...



fractional momentum loss of the intact protons $\zeta = (|\vec{p}_i| - |\vec{p}_0|)/|\vec{p}_i|$, $\vec{p}_i$ and $\vec{p}_0$ are the momenta of the incoming and outgoing protons: $0.02 < \zeta < 0.20$

$$pp \to pt\bar{t}p \quad : \quad \sigma(t\bar{t}) < 0.59 \text{ pb at } 95\%, \quad \sqrt{s} = 13 \text{ TeV}$$
$$pp \to p\gamma\gamma p \to pt\bar{t}p \quad : \quad \sigma(t\bar{t})^{theor} = 0.22 \pm 0.05 \text{ fb}$$

- CMS Collaboration "Evidence for top quark production in nucleus-nucleus collisions", PRL 125 (2020) 22, 222001, arXiv:2006.11110

$$Pb\,Pb \to t\bar{t}X, \quad \sqrt{s_{NN}} = 5.02 \text{ TeV}$$
$$\sigma_{t\bar{t}} = 2.54^{+0.84}_{-0.74}\ (\ell\ell') \quad = 2.03^{+0.71}_{-0.64}\ (+b)\ \mu\text{b}$$

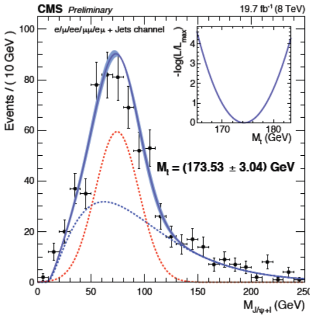
it is compatible with previous CMS result times $A(Pb)^2$

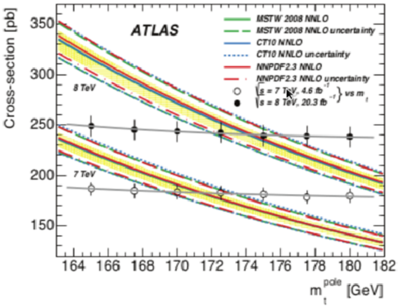
$$pp \to t\bar{t}X, \ \sqrt{s} = 5.02 \text{ TeV}, \quad \sigma_{t\bar{t}} = 69.5 \pm 8.43 \text{ pb}$$

Top-quark mass

m_t is the fundamental parameter of theory

- ◇ related to other EW parameters – stringent tests of SM
- ◇ vacuum stability depends on exact value of m_t
- ◇ important for m_W, $\mathrm{Br}(B_s \to \mu\mu)$, ...
- $m_t \Leftarrow M_{inv}(j_b\, {''}W{''}(jj))$
- $m_t \Leftarrow M_{inv}(j_b\, M_T(\ell E_T^{miss}))$
- $m_t \Leftarrow M_{inv}(j_b\, \ell^\pm),\, M_{inv}(\ell^+\ell^-)$
- $m_t \Leftarrow M_{inv}(\ell^\pm\; J/\psi)$
- $m_t \Leftarrow \sigma(pp \to t\bar{t}) = f(m_t)$





t-quark mass

CMS: $\sqrt{s} = 13$ TeV, five observables: $m_W, m_{\ell b}, m_t, m_{\ell b}/m_t, R_{\ell b}$,
ATLAS+CMS (15 measurements), $\sqrt{s} = 7$, 8 TeV

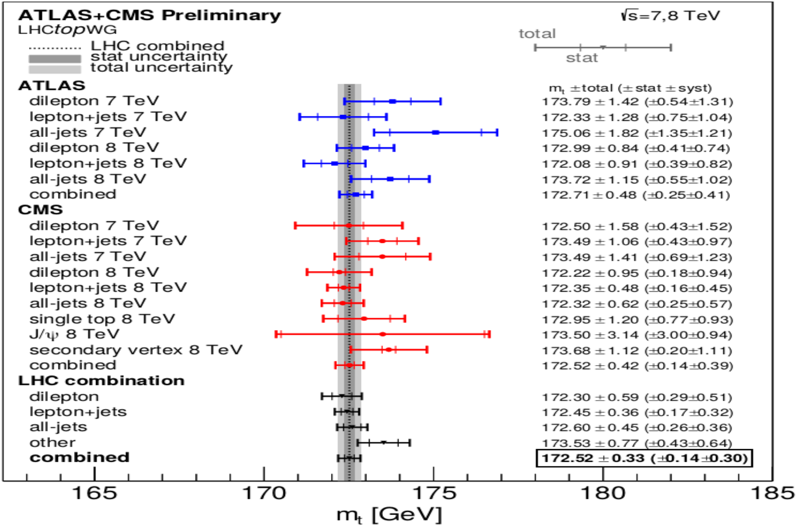
$$
\begin{aligned}
m_{\text{top}}(\text{CMS}) &= 171.37 \pm 0.37 \text{ GeV}, \text{ arXiv:2302.01967 (2023)} \\
m_{\text{top}}(\text{ATLAS+CMS}) &= 172.52 \pm 0.33 \text{ GeV}, \text{ ATLAS-CONF-2023-066} \\
\text{CMS} \Rightarrow \Delta m_{\rm t} &= m_{\rm t} - m_{\bar{\rm t}} = -0.15 \pm 0.19(\text{stat}) \pm 0.09(\text{syst})
\end{aligned}
$$

RPP: *R.L. Workmanet al.(Particle Data Group),*
Prog.Theor.Exp.Phys.2022, 083C01 (2022) and 2023 update

$m_t(\text{RPP}) = 172.69 \pm 0.30$ GeV — direct measurements

$m_t(\text{RPP}) = 172.5 \pm 0.7$ GeV — from $\sigma_{t\bar{t}}$

t-quark mass

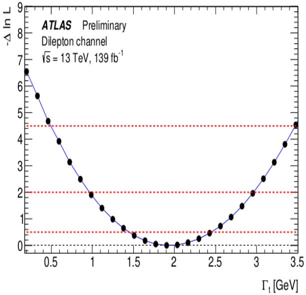

ATLAS+CMS Preliminary
LHCtopWG
√s=7,8 TeV
LHC combined
stat uncertainty
total uncertainty
total
stat
ATLAS
dilepton 7 TeV
lepton+jets 7 TeV
all-jets 7 TeV
dilepton 8 TeV
lepton+jets 8 TeV
all-jets 8 TeV
combined
CMS
dilepton 7 TeV
lepton+jets 7 TeV
all-jets 7 TeV
dilepton 8 TeV
lepton+jets 8 TeV
all-jets 8 TeV
single top 8 TeV
J/ψ 8 TeV
secondary vertex 8 TeV
combined
LHC combination
dilepton
lepton+jets
all-jets
other
combined
m_t ±total (±stat ±syst)
173.79 ± 1.42 (±0.54±1.31)
172.33 ± 1.28 (±0.75±1.04)
175.06 ± 1.82 (±1.35±1.21)
172.99 ± 0.84 (±0.41±0.74)
172.08 ± 0.91 (±0.39±0.82)
173.72 ± 1.15 (±0.55±1.02)
172.71 ± 0.48 (±0.25±0.41)
172.50 ± 1.58 (±0.43±1.52)
173.49 ± 1.06 (±0.43±0.97)
173.49 ± 1.41 (±0.69±1.23)
172.22 ± 0.95 (±0.18±0.94)
172.35 ± 0.48 (±0.16±0.45)
172.32 ± 0.62 (±0.25±0.57)
172.95 ± 1.20 (±0.77±0.93)
173.50 ± 3.14 (±3.00±0.94)
173.68 ± 1.12 (±0.20±1.11)
172.52 ± 0.42 (±0.14±0.39)
172.30 ± 0.59 (±0.29±0.51)
172.45 ± 0.36 (±0.17±0.32)
172.60 ± 0.45 (±0.26±0.36)
173.53 ± 0.77 (±0.43±0.64)
172.52 ± 0.33 (±0.14±0.30)
165
170
175
180
185
m_t [GeV]

Measurements of the total decay width Γ_t

- conventional methods (peak value in $M_{inv}(bW)$) do not provide acceptable accuracy

- ATLAS - $M_{inv}^{exp}(j_b\,\ell^{\pm})$ comparison with modeling events for different Γ_t
$\Gamma_t = 0.1, 0.2, 0.3, ...5.0$ GeV, $\Delta\Gamma = 0.1$ GeV
ATLAS Collaboration, ATLAS-CONF-2019-038

- CMS - indirect measurement
CMS Collaboration, *Phys.Lett. B 736 (2014), 33; arXiv:1404.2292 [hep-ex]*
$\Gamma_t = \frac{\sigma^{exp}_{t-channel}}{\mathcal{B}(t\to Wb)} \times \frac{\Gamma^{th}(t\to bW)}{\sigma^{th}_{t-ch}}$



collaboration	Γ_t^{exp}, GeV	Γ_t^{SM}
ATLAS	$\Gamma_t = 1.94^{+0.52}_{-0.49}$	1.39 GeV
CMS	$\Gamma_t = 1.36 \pm 0.02(stat.)^{+0.14}_{-0.11}$ (syst.)	

Measurements of t-quark parameters

Measurements of events with $t\bar{t}$-pair production with subsequent decays into different final states:
dileptons: ee, $e\mu$, $\mu\mu$, $\ell + jets$: $e + jets$, $\mu + jets$ and $\ell + \tau$ allow ones to measure decay probabilities through various channels (Br, %)

channel	Br, %	SM	$W^{\pm}$ (LEP)
$t \to b\,j\,j$	66.5 ± 0.4 (stat) ± 1.3 (syst)	67.51 ± 0.007	67.48 ± 0.28
$t \to b\,e\,\nu$	13.3 ± 0.4 (stat) ± 0.5 (syst)	12.72 ± 0.01	67.48 ± 0.20
$t \to b\,\mu\,\nu$	13.4 ± 0.3 (stat) ± 0.5 (syst)	12.72 ± 0.01	12.60 ± 0.18
$t \to b\,\tau\,\nu$	7.0 ± 0.3 (stat) ± 0.5 (syst)	7.05 ± 0.01	7.2 ± 0.12

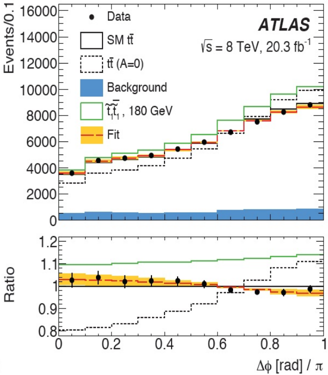
- CMS

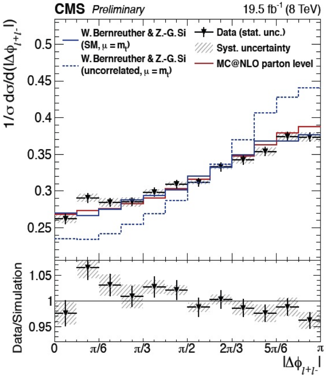
$$pp \to t\bar{t}X, \quad t(\bar{t}) \to \ell^{\pm} j_b$$

$$R = \frac{\mathcal{B}(t \to b\,W)}{\sum_{q=s,d,s,b} \mathcal{B}(t \to q\,W)} = 1.014 \pm 0.003(stat) \pm 0.032(syst)$$

Measurements of t-quark parameters

- polarized t-quark transits the information about the spin to the decay products (angular distributions)
- “at the threshold” pair of $t\bar{t}$ quarks is produced mainly with identical helicities, and for large $\sqrt{S_{t\bar{t}}}$ - with opposite ones
- $pp \to t\bar{t}X, \quad t \to \ell^+ X, \ \bar{t} \to \ell^- X$: $\Delta\phi_{l^+l^-}$ sensitive to the presence of quark polarization



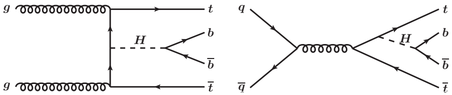


Top-quark and Higgs boson

◇ all Higgs boson couplings are evaluated within SM ($g, v, m_t, m_{W/Z}$)

$$f\bar{f}H \Leftrightarrow y_f = \sqrt{2}\frac{m_f}{v}; \quad y_t(m_t = 172.5 \text{ GeV}) = 0.99,\ y_b(m_b = 4.5 \text{ GeV}) = 0.02$$

◇ $t\bar{t}$-pair and Higgs production provides the direct measurement of y_t



• Higgs decay channels

channel	$H \to b\bar{b}$	$H \to WW/ZZ$	$H \to gg$	$H \to \gamma\gamma$
Br	~ 58 %	~ 24 %	~ 8 %	~ 0.2 %

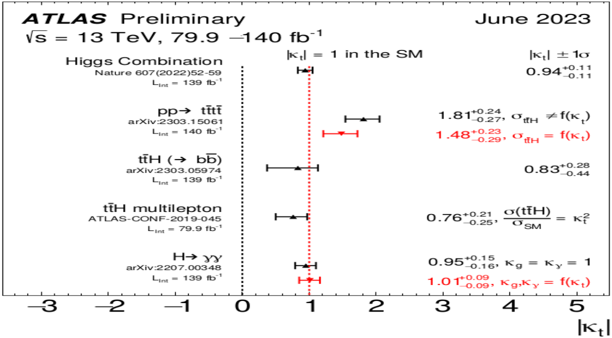
the main contribution to the Higgs inclusive cross section production comes from gluon annihilation $gg \to H$ (loop contribution)

Higgs boson and t-quark

y_t parameter can be measured both in pair and single production of t-quarks

$$pp \to t\,\bar{t}\,HX,\; pp \to t\,HX, \quad H \to b\bar{b},\, WW^*,\, ZZ^*,\, \tau^+\tau^-, \gamma\gamma$$

$\kappa_t = y_t^{mes}/y_t^{SM} \approx 1.01 \pm 0.1$



• there were obtained the limits on on the anomalous interaction of the Higgs boson with the t-quark

$$\mathcal{L} = -\frac{y_t}{\sqrt{2}}\bar{\psi}_t\left(c_\alpha\kappa_{Htt} + is_\alpha\kappa_{Att}\gamma_5\right)\psi_t X_0$$

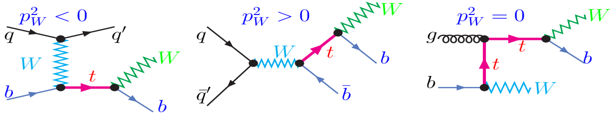
Electroweak t-quark production - "single" top

- The cross section production up to 50% to QCD

There are three processes of the single top production

$$\sigma_{t-chan}(t+\bar{t}) \simeq 218 \text{ pb}, \quad \sigma_{tW-chan}(t+\bar{t}) \simeq 70 \text{ pb}, \quad \sigma_{s-chan}(t+\bar{t}) \simeq 11 \text{ pb}$$

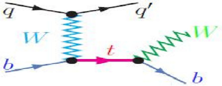
- production mechanisms depend on W-boson virtuality

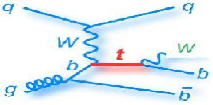


t-канал s-канал tW-канал

- cross sections are calculated with NNLO accuracy, in this case, NNLO makes a small correction (mutual cancellation of QCD and EW)

- calculations can be done in 4F (without taking into account the contribution of the initial b-quarks) and 5F



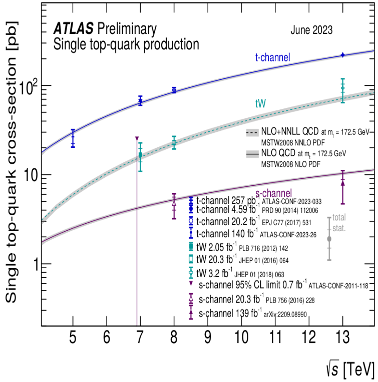


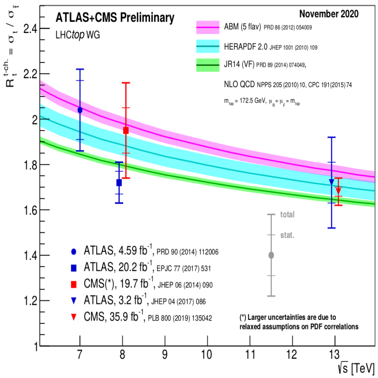
$$\sqrt{s} = 13 \text{ TeV}, \quad \sigma_{t-chan}(5Fs) = 134.0^{+0.7}_{-0.6} \text{ pb}, \quad \sigma_{t-chan}(4Fs) = 127.0^{+2.0}_{-0.6} \text{ pb}$$

Electroweak t-quark production

s-channel

$$\begin{aligned}
ATLAS \quad & \sigma = 8.2 \pm 0.6(stat)^{+3.4}_{-2.8}(syst) = 8.2^{+3.5}_{-2.9}\text{ pb}, \quad \sigma^{theor} = 10.32^{0.40}_{-0.36}\text{ pb} \\
theory(tW) \quad & \sigma = 71.7 \pm 1.8(scale) \pm 3.4(PDF)\text{ pb} \\
ATLAS(tW) \quad & \sigma = 94 \pm 109(stat)^{+28}_{-22}(syst) \pm 2(lumi)\text{ pb} \\
CMS(tW) \quad & \sigma = 79.2 \pm 0.9(stat)^{+2.7}_{-8.0}(syst) \pm 1.2(lumi)\text{ pb}
\end{aligned}$$

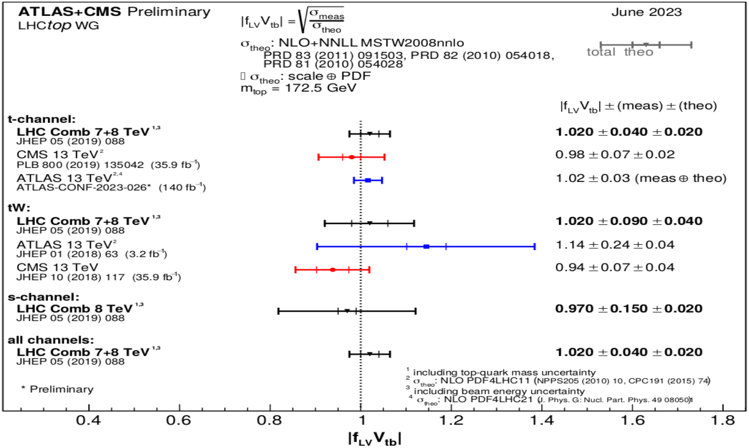




$|V_{tb}|$ *measurements*

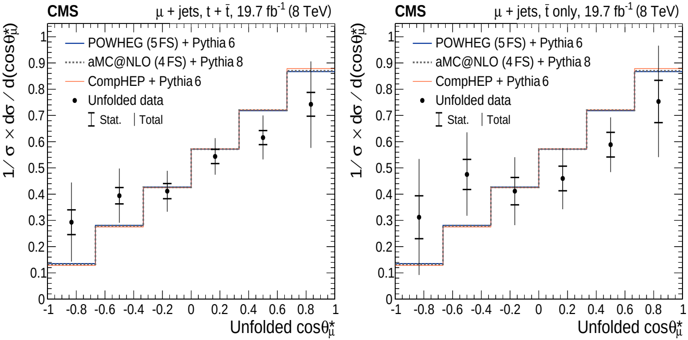
- cross-section of the electroweak t-quark production $\sigma_{EW}(tX) \propto |V_{tb}|^2$

$$\Rightarrow |V_{tb}|_{EW\ top} = 1.019 \pm 0.028$$



Measuring t-quark polarization

- CMS: t-quark polarization in processes single top production: $bu \to d\, t\, (\to \ell^+ X)$
- distributions over $\cos\vartheta^*_\mu$ - between $\ell^\pm$ from decay t-quark and light quark
- correlations of the spin states in the production and decay of the t-quark

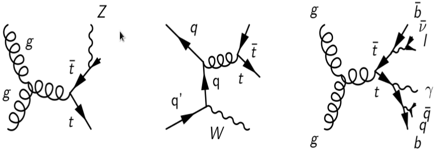


Top-quarks and W/Z-bosons associated production

vector bosons and t-quark associated production processes:

$$pp \to t\bar{t} + Z,\ t\bar{t} + W^{\pm},\ t\bar{t} + \gamma, \quad \text{CDF}:\ \sigma(p\bar{p} \to t\bar{t}\gamma)_{\sqrt{S}=2\ \text{TeV}} = 180 \pm 80\ \text{fb}$$

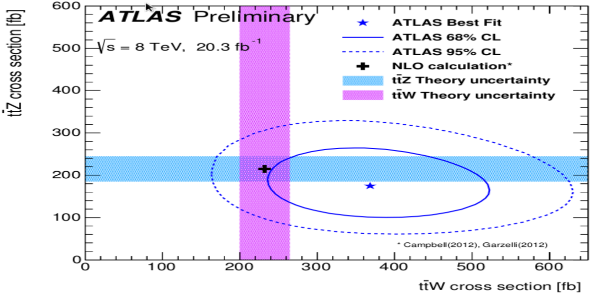
are sensitive to physics beyond SM



$\sigma(t\bar{t}V)$	ATLAS (fb)	CMS (fb)
$\sigma_{t\bar{t}\gamma}$(7 TeV)	$2000 \pm 500(stat) \pm 700(syst)$	
$\sigma_{t\bar{t}\gamma}$(8 TeV)		$2400 \pm 200(stat) \pm 600(syst)$
$\sigma_{t\bar{t}Z/\gamma^*}$(7 TeV)	< 700	$280^{+140}_{-110}(stat)^{+60}_{-30}(syst)$
$\sigma_{t\bar{t}Z/\gamma^*}$(8 TeV)	$150^{+55}_{-50}(stat) \pm 21(syst)$	$200 \pm 90(total)$
$\sigma_{t\bar{t}W}$(8 TeV)	$300^{+120}_{-100}(stat)^{+70}_{-40}(syst)$	$170^{+110}_{-100}(total)$

Top-quarks and W/Z-bosons associated production

$\sqrt{S} = 8$ TeV	σ(SM), fb	ATLAS (fb)	CMS (fb)
$t\bar{t} + \gamma$	1880 ± 500		
$t\bar{t}Z/\gamma^*$	215 ± 30	$176^{+52}_{-48}(stat) \pm 24(syst)$	242^{+65}_{-55}
$t\bar{t}W$	232 ± 32	$369^{+86}_{-79}(stat) \pm 44(syst)$	382^{+117}_{-102}



Search for the New physics beyond the Standard Model

In the top quark sector, New physics may manifest itself in the following
◇ rare (within the SM) decays of t-quarks;
◇ deviations in t-quark production cross sections (within the SM framework);
◇ production of t-quarks due to very rare reactions in the SM;
◇ decays of t-quarks through channels absent in the SM;
◇ new particles decaying into final states containing t and/or $\bar{t}$-quark and possibly other particles and resonances

• Numerous SM extensions $\Longrightarrow$ various predictions in the t-quark sector with their a specific set of interaction types and parameters (coupling constants, masses of new objects)
• different scenarios $\Longrightarrow$ processes with identical final states

• Effective field theory formalism - effective (phenomenological) Lagrangian $\mathcal{L}_{\mathcal{EFT}}$ gauge-invariant with respect to to calibration group SM

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \kappa_4 \bar{\psi}_q \hat{O}^{(4)} \psi_t + \frac{\kappa_6}{\Lambda^2} \bar{\psi}_q \hat{O}^{(6)} \psi_t + \cdots$$

• Experimental results are presented in the form restrictions
◇ κ/Λ - values of anomalous constants interaction
◇ in the form of limits on probability rare decays of the t-quark

Anomalous $gt\bar{t}$ and tWb interactions

• $gt\bar{t}$: deviations from the SM can manifest themselves in energy and angle distributions phenomenological Lagrangian (with anomalous chromomagnetic moment):

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} - \frac{\tilde{\mu}_t}{2}\bar{\psi}_t \sigma^{\mu\nu}\psi_t G^a_{\mu\nu} \quad \text{experiment} \quad \Rightarrow \; -0.50 < Re(\tilde{\mu}_t) < 0.070(95\% CL)$$

• tWb : effective interaction Lagrangian

$$\mathcal{L}_{EFT} = \quad \frac{g}{\sqrt{2}}\bar{b}\gamma^\mu (f_V^L P_L + f_V^R P_R) t W_\mu^- + \frac{g}{\sqrt{2}}\bar{b}\,\frac{\sigma^{\mu\nu}}{2M_W}(f_T^L P_L + f_T^R P_R) t W_{\mu\nu}^- + h.c.$$

where $W_{\mu\nu}^- = \partial_\mu W_\nu^- - \partial_\nu W_\mu^-$, within SM one has: $f_V^L = V_{tb}$; $f_V^R = f_T^L = f_T^R = 0$

$$|f_V^R| < 0.16, \quad |f_T^L| < 0.057, \quad |f_T^R| < 0.048 \quad \text{at} \;\; 95\% \;\; CL$$

Flavor changing neutral currents – FCNC: tVq

FCNC interactions tVq, $V = g, \gamma, Z, H$ strongly suppressed within SM

	SM	two-Higgs	SUSY	“exotic” quarks
$BR(t \to qg)$	5×10^{-11}	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 5 \times 10^{-4}$
$BR(t \to q\gamma)$	5×10^{-13}	$\sim 10^{-7}$	$\sim 10^{-5}$	$\sim 10^{-5}$
$BR(t \to qZ)$	$\sim 10^{-13}$	$\sim 10^{-6}$	$\sim 10^{-4}$	$5\times \sim 10^{-2}$

	SM	SUSY	MSSM	2HDM
$BR(t \to Hc)$	3×10^{-15}	10^{-6}	10^{-5}	10^{-3}
$BR(t \to Hu)$	2×10^{-17}	10^{-6}	8×10^{-5}	10^{-4}

model independent analysis. The phenomenological Lagrangian

$$\mathcal{L}_{FCNC} = -e \sum_{q=u,c} \frac{\kappa_q^\gamma}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_q^\gamma + i h_q^\gamma \gamma_5) q A_{\mu\nu} - g_s \sum_{q=u,c} \frac{\kappa_q^g}{\Lambda} \bar{t} \sigma^{\mu\nu} t^a (f_q^g + i h_q^g \gamma_5) q G^a_{\mu\nu}$$

$$-\frac{g}{2\cos\theta_W} \sum_{q=u,c} \kappa_q^Z \bar{t} \gamma^\mu (f_q^Z - h_q^Z \gamma_5) q Z_\mu - \frac{g}{2\cos\theta_W} \sum_{q=u,c} \frac{\tilde{\kappa}_q^Z}{\Lambda} \bar{t} \sigma^{\mu\nu} (\tilde{f}_q^Z + i \tilde{h}_q^Z \gamma_5) q Z_{\mu\nu}$$

FCNC tgq, $t\gamma q$, tZq, tHq

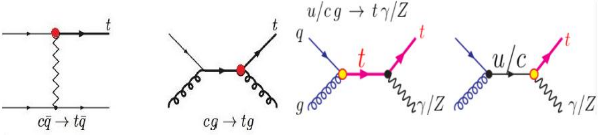
- two scenarios for searching (FCNC/SM $\ll 1$)

◇ $t\bar{t}$-pair production with the subsequent FCNC decay

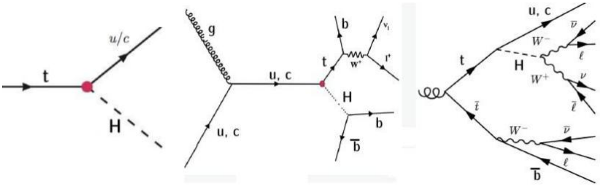
$$pp \to t\,\bar{t}\ :\ t \to q\,g,\ t \to q\,\gamma,\ t \to q\,Z$$

◇ t-quark production due to FCNC with subsequent SM decay

$$g\,u(c)\ \to\ t;\, uu\ \to\ tt;\ cg \to\ t\,g;\, qg\ \to\ t\,\gamma/Z, ... t \to bW$$



◇ tHq : $t\ \to\ H\ u/c\ \ \to$ Higgs + FCNC



Summary for FCNC $t \to q\ H/g/\gamma/Z$

the best constraints on anomalous FCNC interactions in the t-quark sector

	$\mathcal{B}$ (95% CL)			$\mathcal{B}$ (95% CL)	
channel	ATLAS	CMS	mode	ATLAS	CMS
$t \to Hu$	6.9×10^{-4}	1.9×10^{-4}	$t \to Hc$	9.4×10^{-4}	7.3×10^{-4}
$t \to gu$	4.0×10^{-5}	2.0×10^{-5}	$t \to gc$	20.0×10^{-5}	41×10^{-5}
$t \to \gamma u$		0.95×10^{-5}	$t \to \gamma c$		1.51×10^{-5}
$t \to Zu$	6.2×10^{-5}	22×10^{-5}	$t \to Zc$	12×10^{-5}	44×10^{-5}

Lepton-flavor violation (CMS arXiv:22060159)
$t \to e^{\pm}\mu^{\mp}q$ due to vector (V), scalar (S) tensor (T) interactions

	$\mathcal{B}$ (95% CL)		
channel	V	S	T
$t \to e^{\pm}\mu^{\mp}u$	1.3×10^{-7}	0.7×10^{-7}	2.5×10^{-7}
$t \to e^{\pm}\mu^{\mp}c$	13.1×10^{-7}	8.9×10^{-7}	25.9×10^{-7}

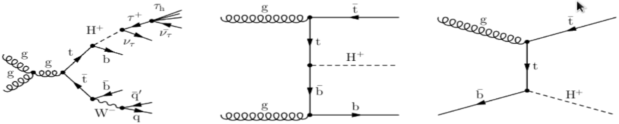
Charged Higgs $H^{\pm}$ and rare processes with t-quarks

- interaction Lagrangian of the charged Higgs $H^{\pm}$ (MSSM)

$$\mathcal{L} = \frac{g}{\sqrt{2}M_W} H^+ \{ V_{ud}\overline{u}(m_u \cot\beta P_L + m_d \tan\beta P_R)d + \overline{\nu}(\tan\beta m_\ell P_R)\ell \}, \quad P_{L/R} = 1/2\left(1 \mp \gamma^5\right)$$

- two regions of the charged Higgs mass

$$m_{H^\pm} = 80 - 160 \text{ GeV} \; : \; t \to H^{\pm}\, b \quad m_{H^\pm} > 180 \text{ GeV} \; : \; pp \to \bar{t}\, H^{\pm}\, b$$



- charged Higgs is excluded in the regions:

$$\tan\beta < \mathcal{O}(1) \qquad m_H < 180 \text{ GeV and } m_H > 180 \text{ GeV}$$
$$\tan\beta \gtrsim 1 \qquad m_H(90 \div 2000) \text{ GeV}$$

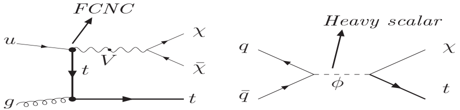
Search for heavy particles decaying into t-quarks

- CMS: arXiv:2310.19893

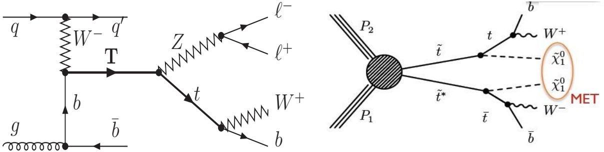
new heavy charged vector boson $W' \to tb$, $\sqrt{s} = 13$ TeV, $\mathcal{L}_{int} = 138$ fb^{-1}
Multiple hypotheses are considered for the new particle mass, width, and chirality

$\Gamma(W')/M(W')$	right-handed	left-handed
1%	< 4.3 TeV	< 3.9 TeV
10%	< 2.7 TeV	< 2.5 TeV

- SUSY predicts a large number of new reactions with t quarks with presence of large "lost" energy carried away by the new neutral particle. For example, single t-quark production with a large "lost" energy ("mono-top") $\Rightarrow$ search for "dark matter"

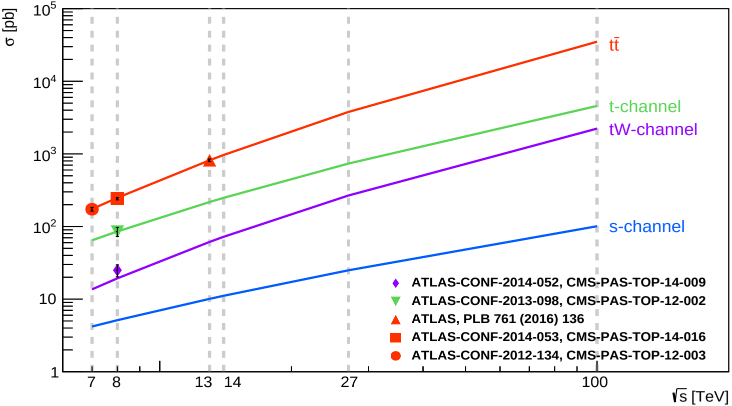


- "vector" T-quarks: $T \to tZ$. SUSY $\Rightarrow$ ($\tilde{t} \to t\,\chi_1^0$, spin($\tilde{t}$) = 0), constraint: $m_t \leq m_{stop} < 195$ GeV



Top-quark physics at future hadronic colliders

collider	$\sqrt{s}$, TeV	$\mathcal{L}$, $cm^{-2} \cdot c^{-1}$	$\int \mathcal{L}$, ab^{-1}	$< \mu >$
LHC	7-13	$\approx 10^{34}$	0.3	10-40
HL-LHC	14	10^{35}	3	140-200
HE-LHC	27	2.5×10^{35}	12	800
FCC-hh	100	3×10^{35}	30	500-1000



Summary of the top-quark properties (RPP)

R.L. Workmanet al.(Particle Data Group), Prog.Theor.Exp.Phys. **2022**, *083C01 and 2023*

$$m_t = 172.69 \pm 0.30 \text{ GeV} \qquad \text{direct measurements}$$
$$m_t = 172.5 \pm 0.7 \text{ GeV} \qquad \text{from } \sigma_{t\bar{t}}$$
$$m_t - m_{\bar{t}} = 0.15 \pm 0.20 \text{ GeV}$$
$$\Gamma_{tot} = 1.42^{+0.19}_{-0.15} \text{ GeV}$$
$$\Gamma(Wb)/\Gamma(Wq(q=b,s,d)) = 0.957 \pm 0.034$$

t-quark decay modes (Br $= \Gamma_j/\Gamma_{tot}$ and CL - confidence level)

decay mode	Br	*CL*
$e\nu_e b$	$(11.10 \pm 0.30)\%$	
$\mu\nu_\mu b$	$(11.40 \pm 0.20)\%$	
$\tau\nu_\tau b$	$(10.7 \pm 0.5)\%$	
$q\bar{q}b$	$(66.5 \pm 1.4)\%$	
$\gamma q(q=u,c)$	$< 1.8 \times 10^{-4}$	95%
$Zq(q=u,c)$	$< 5 \times 10^{-4}$	95%
$Hu(c)$	$< 1.9(7.3) \times 10^{-4}$	95%
$\ell^+ q\bar{q}'(q=d,s,b;\ q'=u,c)$	$< 1.6 \times 10^{-3}$	95%
$e^\pm\mu^\mp c$	$< 8.9 \times 10^{-7}$	
$e^\pm\mu^\mp u$	$< 7 \times 10^{-8}$	

Thank you very much !