TOP quark physics

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Outline

- Top quark. Why it is special? What is a role of the Top quark?
- Cross sections, mass, width… Recent progress
- Searches for "New Physics" below and above threshold (few examples)

Top Quark in SM

$Q^t_{em} = +\,\frac{2}{3}\,|\,e\,|$

Weak isospin partner of b quark: $T^t_3 = \frac{1}{2}$

Color triplet

spin-$\frac{1}{2}$

$$\begin{array}{lcccccc} & & & & \underline{SU(3)} & \underline{SU(2)} & \underline{U(1)_Y} \\ Q^i_L = & \begin{pmatrix} u_L \\ d_L \end{pmatrix} & \begin{pmatrix} c_L \\ s_L \end{pmatrix} & \begin{pmatrix} t_L \\ b_L \end{pmatrix} & 3 & 2 & \frac{1}{6} \\ u^i_R = & u_R & c_R & t_R & 3 & 1 & \frac{2}{3} \\ d^i_R = & d_R & s_R & b_R & 3 & 1 & -\frac{1}{3} \end{array}$$

In the Standard Model top quark couplings are uniquely fixed by the principle of gauge invariance, the structure of the quark generations, and a requirement of including the lowest dimension interaction operators.

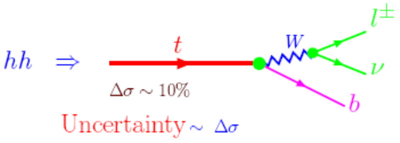
What is a difference with u- and c-quarks?

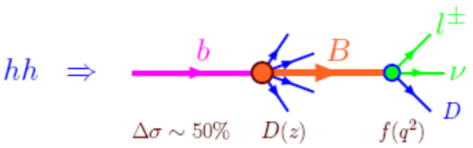
Top quark is the heaviest elementary particle found so far with a mass slightly less than the mass of the gold nucleus

(Mass of 186 gold nucleus isotop is 173.2 GeV,
its life time is about 10 min)

- Top is so heavy and point like at the same time.

- Top decays ($\tau_t \sim 5 \times 10^{-25}\ sec$) much faster than a typical time-scale for a formation of the strong bound states ($\tau_{QCD} \sim 3 \times 10^{-24}\ sec$).
No top hadrons. A very clean source for a fundamental information.





- Top Yukawa coupling ($y_t = \frac{\sqrt{2}M_{top}}{v}$) is very close to unity. Studies of top may shed a light on an origin of the mechanism of the EW symmetry breaking.

- Mixing with 2 first generations is small

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda = 0.2257^{+0.0009}_{-0.0010}, \qquad A = 0.814^{+0.021}_{-0.022}$$

$$\bar\rho = 0.135^{+0.031}_{-0.016}, \qquad \bar\eta = 0.349^{+0.015}_{-0.017}$$

What is a role of the Top quark in SM and BSM?

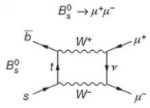
- Cancellation of chiral anomalies in SM with 3 generations

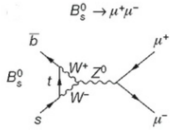
$(Q_{top}+Q_b)\times N_c+Q_{tau}=0$

- GIM mechanism and suppression flavor changing neutral current (FCNC)

FCNC appear from two bosons (W^+ and W^-) emission by the quark currents

$V^\dagger_{su}V_{ub}+V^\dagger_{sc}V_{cb}+V^\dagger_{st}V_{tb}=0$ $\qquad$ $V^\dagger_{su}V_{ub}\ \ S(p,M_u)+V^\dagger_{sc}V_{cb}\ \ S(p,M_c)+V^\dagger_{st}V_{tb}\ \ S(p,M_{top})\neq 0$

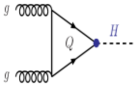


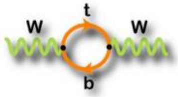


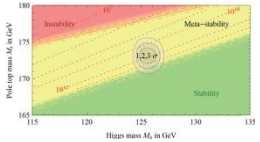
SM: Br($B^0_s\to\mu^+\mu^-$)$_{theory}$ = $(3.66 \pm 0.23)\times 10^{-9}$ Bobeth et al ., PRD (2014) 101801

LHCb&CMS: Br($B^0_s\to\mu^+\mu^-$)$_{exp}$ = $(2.8\,^{+0.7}_{-0.8})\times 10^{-9}$ Nature 522 (2015) 68

- Large Top quark Yukawa coupling







- Key particle in various SM extensions, in particular, in MSSM

MSSM is alive because of heavy Top (light Higgs mass < 135-140 GeV)

$$M_h^{\max}=\sqrt{M_Z^2+\epsilon}$$

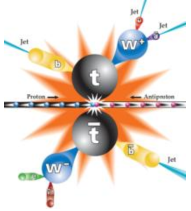
$$\epsilon=\frac{3G_F\overline{m}_t^4}{\sqrt{2}\pi^2\sin^2\beta}\left[f(t)\right]$$

$$t=\log\left(\frac{M_S^2}{m_t^2}\right)$$

- «Laboratory» for many BSM searches

(various signal and background processes)

Top-quark production at hadron colliders

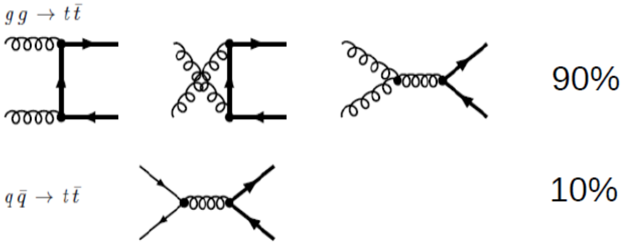


$t\bar{t}$ pair production (QCD)

Tevatron, 1.96 TeV:
$\sigma \approx 7.01$ pb

LHC, 8 TeV: $\sigma \approx 220$ pb
13 TeV: $\sigma \approx 826$ pb
14 TeV: $\sigma \approx 975$ pb

NNLO+NNLL accuracy
Beneke , Falgari ,Klein ,Schwinn'12
Cacciari, Czakon, Mangano, Mitov ,Nason'12
Czakon,Mitov '12,13
Bruncherseifer, Caola, Melnikov'13
Kidonakis' 11-16
…..

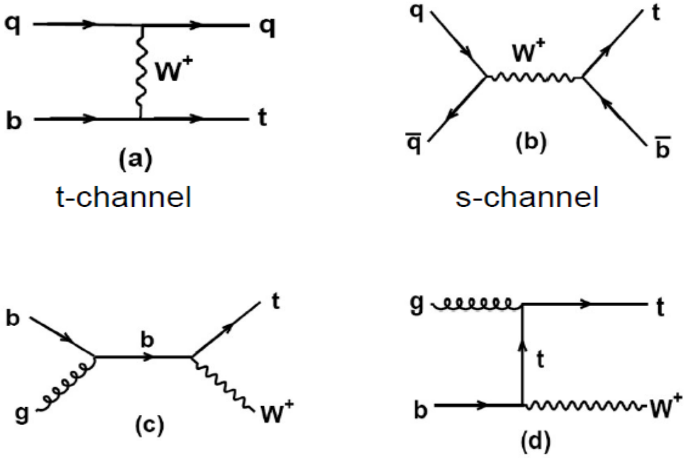


$t(\bar{t})$ single production (electroweak)

NNLO+NNLL accuracy Kidonakis' 14-15

		t-channel pb	s-channel pb	tW-channel pb
	Tevatron, 1.96 TeV	2.26	1.04	0.14
LHC	7 TeV	64	4.6	15.6
	8 TeV	87	5.6	21.1
	13 TeV	221	11.3	72.6
	14 TeV	252	12.4	85.6

The single top rate is about 40% of the top pair rate

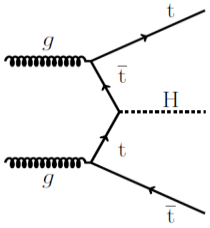


t-channel

s-channel

associated tW production

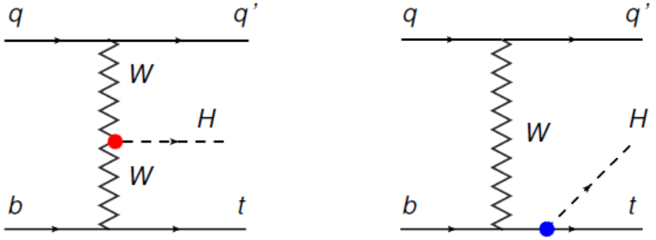
$t\bar{t}$H (W,Z) production



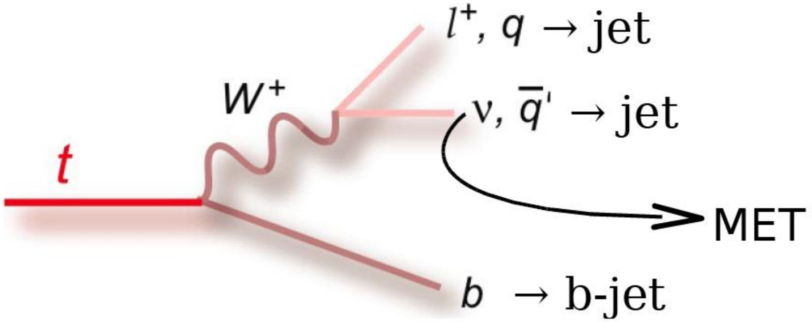
LHC Higgs WG (ttH)
~ 0.13 pb at 8TeV
~ 0.61 pb at 14TeV

tHq production

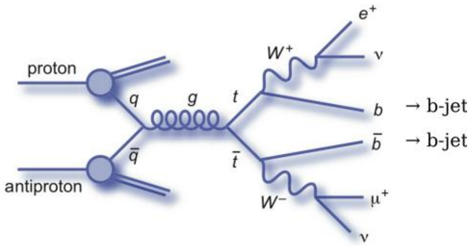
Birwas, Gabrielli, Mele' 12
~ 0.015 pb at 8TeV
~ 0.072 pb at 14TeV

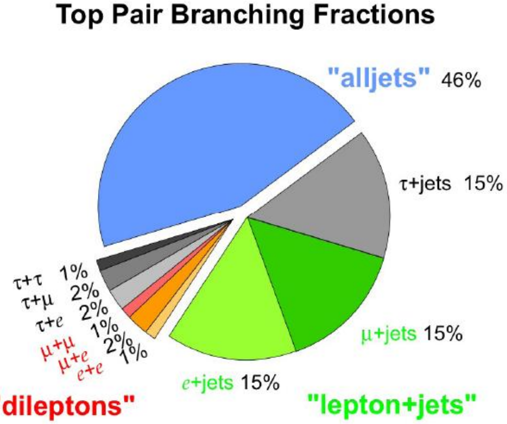


- Top decays:

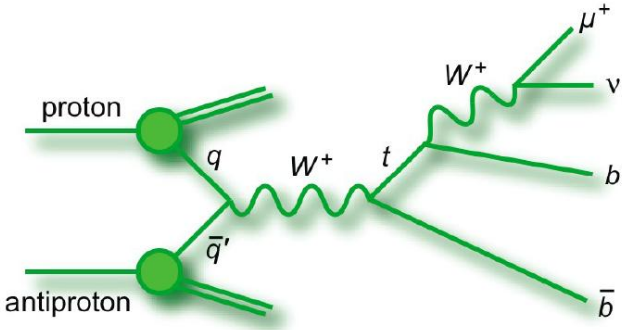


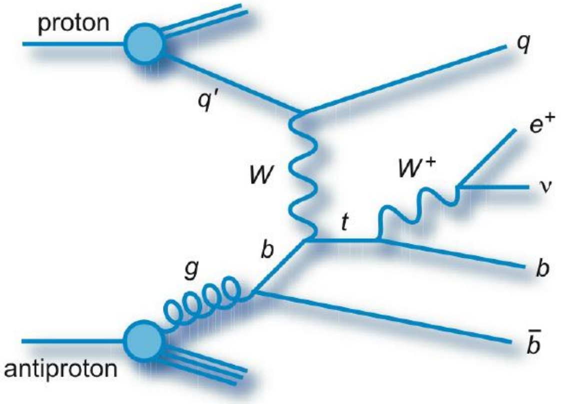
- Top pair signatures:
  - lepton + jets
  - dilepton
  - all jets





- Single Top Signatures:





Recent progress in top cross section measurements

Top pair production

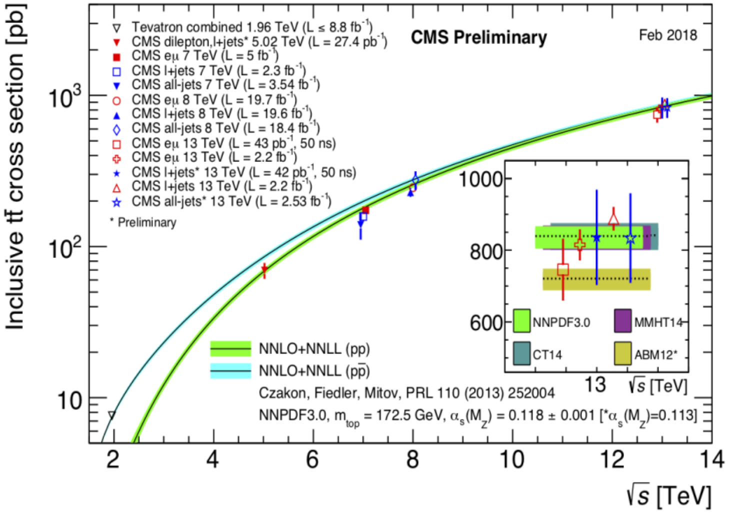
LHCTopWG

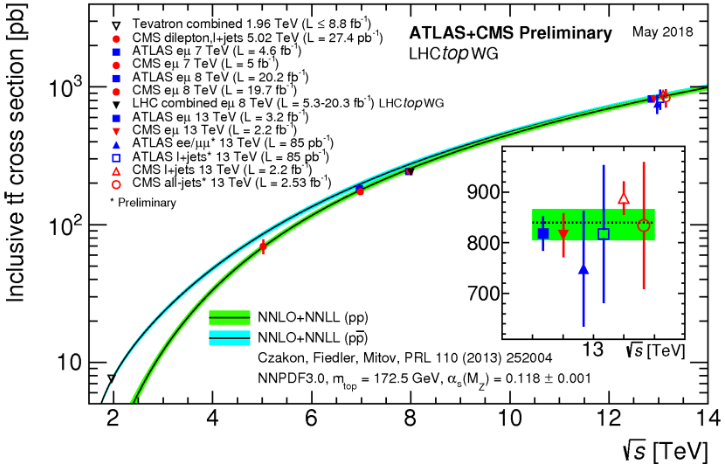
CMS Top WG

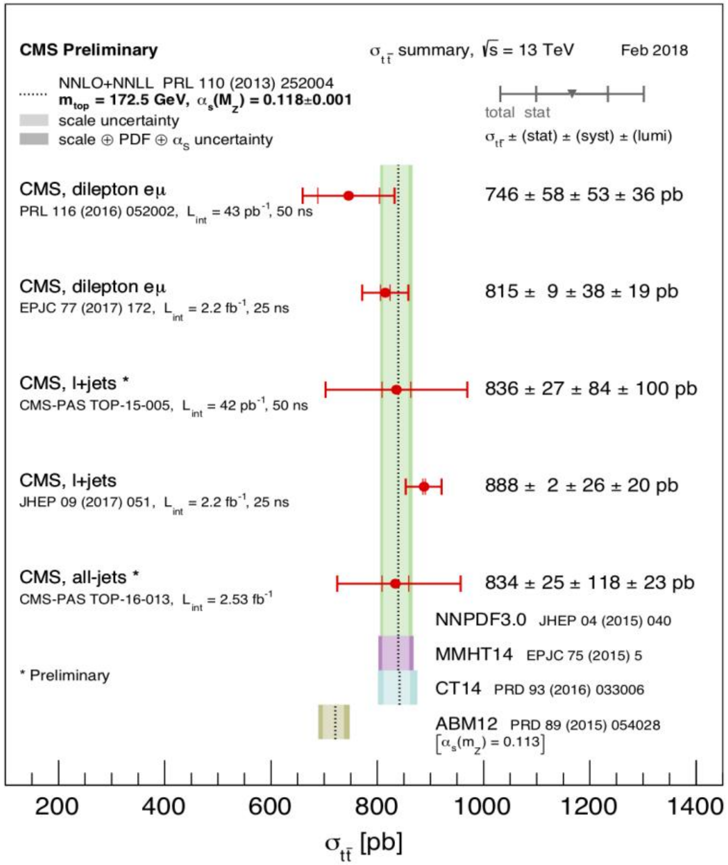
Top quark pair cross section summary in comparison with the theory calculation at NNLO+NNLL accuracy.

Top quark pair cross section summary (13 TeV) in comparison with theoretical NNLO+NNLL computations

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP



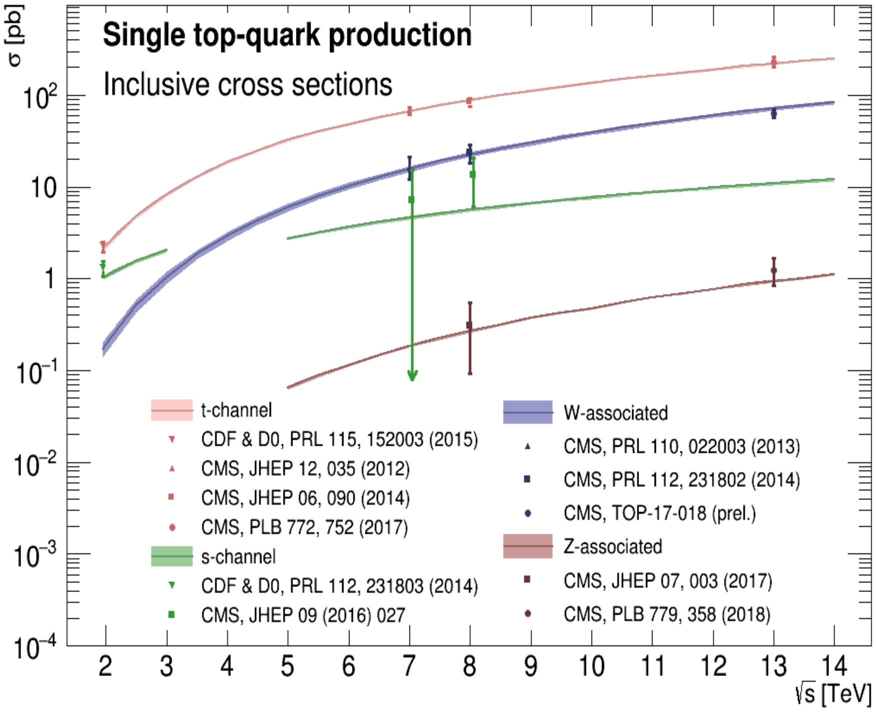




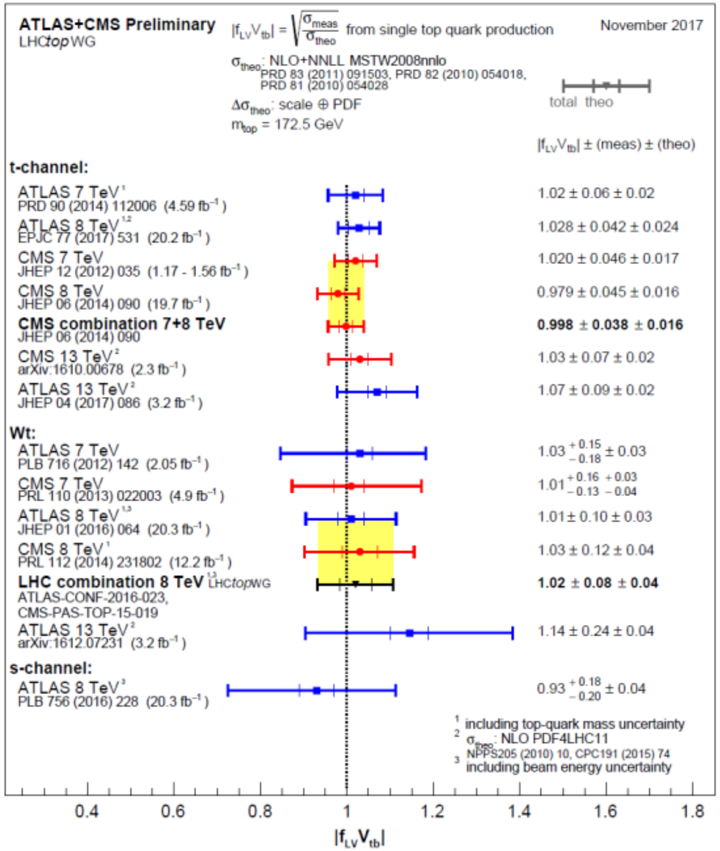
Single top production cross section

LHCTopWG
CMS Top WG

Summary of single top cross section measurements by CMS, as a function of centre-of-mass energy



Direct $|f_{LV}V_{tb}|$ measurement



NNLO

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

$m_{ref} = 173.3$ GeV		$\sigma(m_{ref})$ [pb]	a_1	a_2
Tevatron	Central	7.1642	−1.46191	0.945791
	Scales +	7.27388	−1.46574	0.957037
	Scales −	6.96423	−1.4528	0.921248
	PDFs +	7.33358	−1.4439	0.930127
	PDFs −	7.04268	−1.4702	0.936027
LHC 7 TeV	Central	172.025	−1.24243	0.890776
	Scales +	176.474	−1.24799	0.903768
	Scales −	166.193	−1.22516	0.858273
	PDFs +	176.732	−1.22501	0.861216
	PDFs −	167.227	−1.2586	0.918304
LHC 8 TeV	Central	245.794	−1.1125	0.70778
	Scales +	252.034	−1.11826	0.719951
	Scales −	237.375	−1.09562	0.677798
	PDFs +	251.968	−1.09584	0.682769
	PDFs −	239.441	−1.12779	0.731019

Czakon, Fiedler, Mitov' 13

$$\sigma(m) = \sigma(m_{ref}) \left(\frac{m_{ref}}{m}\right)^4 \times \left(1 + a_1 \frac{m - m_{ref}}{m_{ref}} + a_2 \left(\frac{m - m_{ref}}{m_{ref}}\right)^2\right)$$

CMS EPJ C77 (2017)

LHC 13 TeV $\sigma_{t\bar{t}} = 792 \pm 8\,(\text{stat}) \pm 37\,(\text{syst}) \pm 21\,(\text{lumi})$ pb

Czakon, Mitov Top++ code

$$\sigma_{t\bar{t}} = 832^{+40}_{-46}\ \text{pb}$$

Dynamical scales

$$\mu_{F,R} \in (\mu_0/2, 2\mu_0) \quad \text{with} \quad 0.5 \le \mu_R/\mu_F \le 2$$

$$\mu_0 \sim m_t\,,$$

$$\mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2}\,,$$

$$\mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2}\,,$$

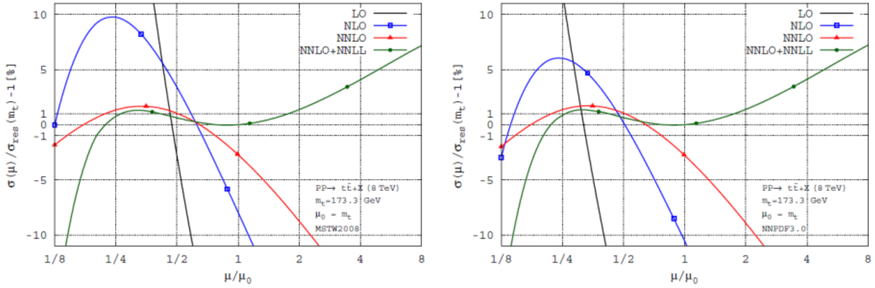
$$\mu_0 \sim H'_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + \sum_i p_{T,i}\,,$$

$$\mu_0 \sim E_T = \sqrt{\sqrt{m_t^2 + p_{T,t}^2}\sqrt{m_t^2 + p_{T,\bar{t}}^2}}\,,$$

$$\mu_0 \sim H_{T,\text{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2}\,,$$

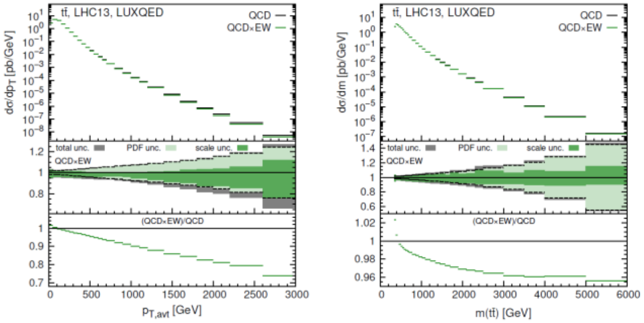
$$\mu_0 \sim m_{t\bar{t}}\,,$$

Czakon, Heymesb, Mitov' 16



QCD and EW

Czakon,Heymes,Mitov,Davide, Pagani,Tsinikosc,Zaroe'17



Top-quark pair-production and decay at high precision

Gao, Papanastasiou 1705.08903
Papanastasiou 1801.01020

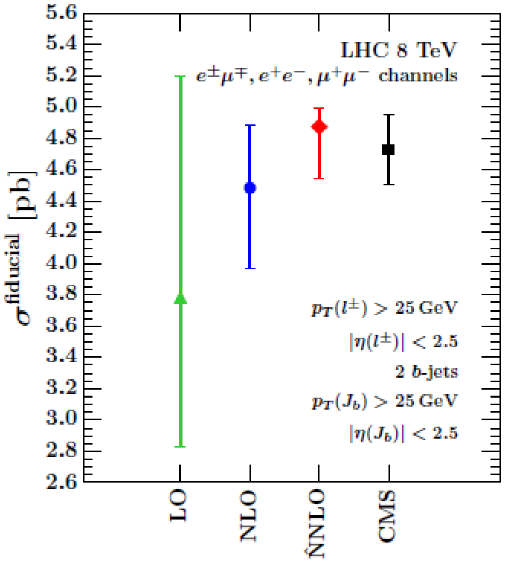
In NWA

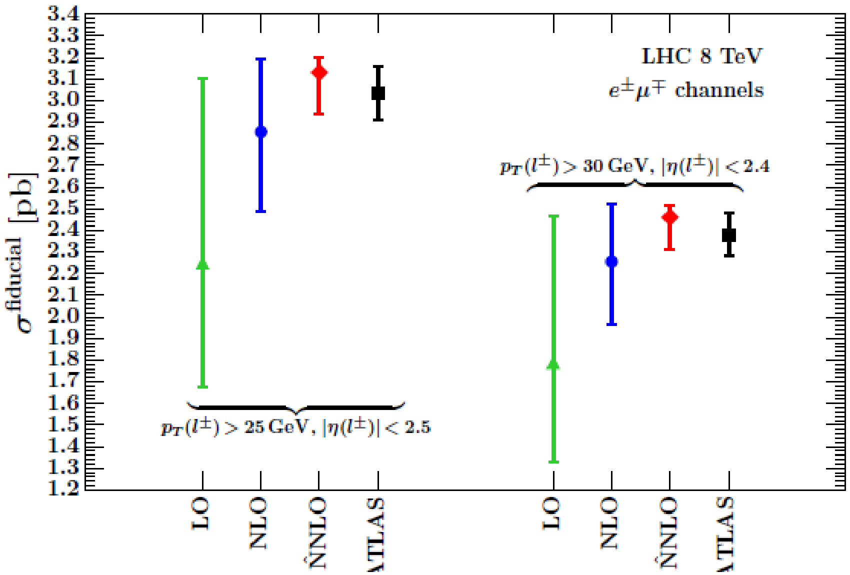
$$d\sigma = d\sigma_{t\bar{t}} \times \frac{d\Gamma_{t\to bl^+\nu_l}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\to\bar{b}l'^-\bar{\nu}_{l'}}}{\Gamma_t}$$

$$d\sigma_{t\bar{t}} = \alpha_s^2 \sum_{i=0}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^i d\sigma_{t\bar{t}}^{(i)},$$

$$d\Gamma_{t\,(\bar{t})} = \sum_{i=0}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^i d\Gamma_{t\,(\bar{t})}^{(i)}, \quad \Gamma_t = \sum_{i=0}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^i \Gamma_t^{(i)}$$

Fiducial cross sections computed using approximate NNLO for production and exact NNLO for decay





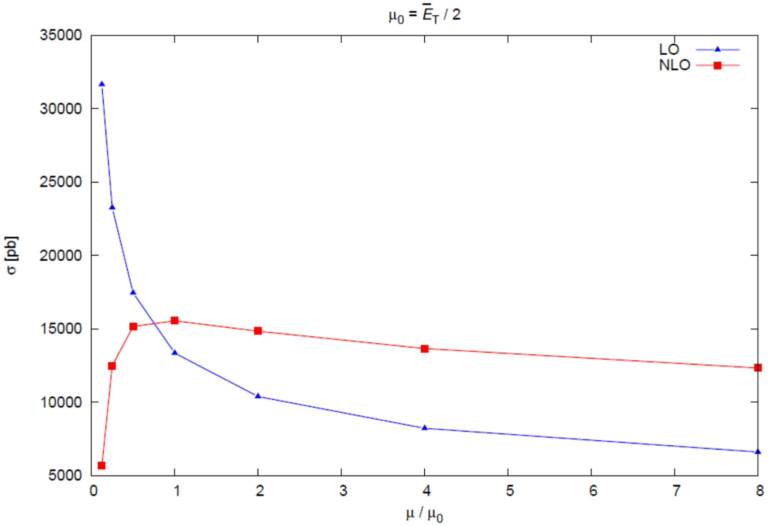
NNLO top width 1.322 GeV for 172.5 GeV top mass

Gao, Li, Zhu 1210.2808

Denner, Pellen 1711.10359

First complete NLO QCD computation for the process

$$\mathrm{pp} \;\rightarrow\; \mu^- \bar{\nu}_\mu \mathrm{b}\bar{\mathrm{b}}\mathrm{jj}$$



$$\mu_0 = \overline{E_\mathrm{T}}/2 = \frac{1}{2}\sqrt{\sqrt{m_\mathrm{t}^2 + p_{\mathrm{T,t}}^2}\sqrt{m_\mathrm{t}^2 + p_{\mathrm{T},\bar{\mathrm{t}}}^2}}$$

light/bottom jets:	$p_{\mathrm{T,j/b}} > 25\,\mathrm{GeV}$,	$\lvert y_{\mathrm{j/b}}\rvert < 2.5$
charged lepton:	$p_{\mathrm{T},\ell} > 25\,\mathrm{GeV}$,	$\lvert y_\ell\rvert < 2.5$

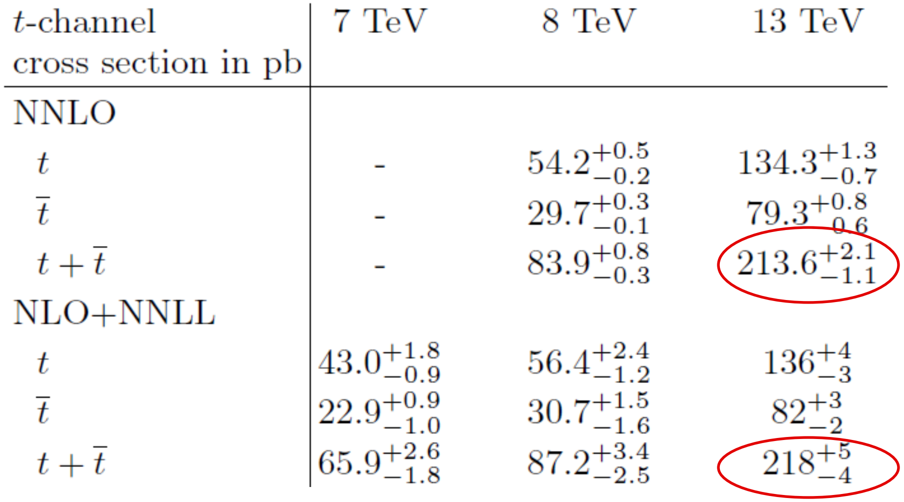
Fiducial cross section

$$\sqrt{s} = 13\,\mathrm{TeV}$$

Ch.	σ_{LO} [pb]	σ_{NLO} [pb]	K-factor
gg	12.0257(5)	13.02(7)	1.08
$q\bar{q}$	1.3308(3)	0.942(7)	0.71
$gq(/\bar{q})$		1.604(5)	
pp	13.3565(6)	15.56(7)	1.16

Single top theory cross sections

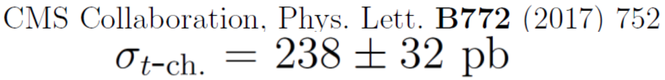
Tables from: Giammanco, Schwienhorst (2017)1710.10699



t-channel cross section in pb	7 TeV	8 TeV	13 TeV
NNLO			
t	-	$54.2^{+0.5}_{-0.2}$	$134.3^{+1.3}_{-0.7}$
$\bar{t}$	-	$29.7^{+0.3}_{-0.1}$	$79.3^{+0.8}_{-0.6}$
$t+\bar{t}$	-	$83.9^{+0.8}_{-0.3}$	$213.6^{+2.1}_{-1.1}$
NLO+NNLL			
t	$43.0^{+1.8}_{-0.9}$	$56.4^{+2.4}_{-1.2}$	136^{+4}_{-3}
$\bar{t}$	$22.9^{+0.9}_{-1.0}$	$30.7^{+1.5}_{-1.6}$	82^{+3}_{-2}
$t+\bar{t}$	$65.9^{+2.6}_{-1.8}$	$87.2^{+3.4}_{-2.5}$	218^{+5}_{-4}

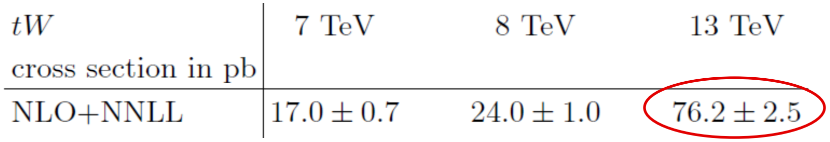
Brucherseifer, Caola, Melnikov (2014), 1404.7116
Berger, Gao, Yuan, Zhu (2016)1606.08463

Kidonakis (2011) 1103.2792, (2016)1607.08892



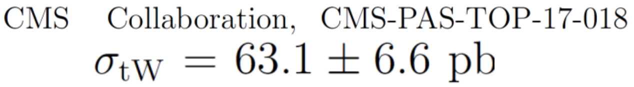
CMS Collaboration, Phys. Lett. **B772** (2017) 752

$$\sigma_{t\text{-ch.}} = 238 \pm 32 \text{ pb}$$



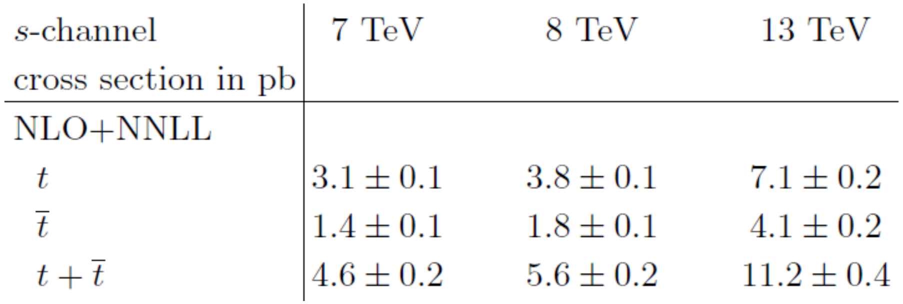
tW cross section in pb	7 TeV	8 TeV	13 TeV
NLO+NNLL	17.0 ± 0.7	24.0 ± 1.0	76.2 ± 2.5

Kidonakis (2016) 1612.06426



CMS Collaboration, CMS-PAS-TOP-17-018

$$\sigma_{\text{tW}} = 63.1 \pm 6.6 \text{ pb}$$

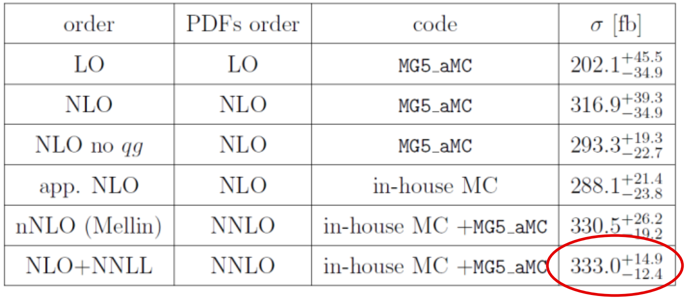


s-channel cross section in pb	7 TeV	8 TeV	13 TeV
NLO+NNLL			
t	3.1 ± 0.1	3.8 ± 0.1	7.1 ± 0.2
$\bar{t}$	1.4 ± 0.1	1.8 ± 0.1	4.1 ± 0.2
$t+\bar{t}$	4.6 ± 0.2	5.6 ± 0.2	11.2 ± 0.4

Kidonakis (2010) 1001.5034

Rare processes

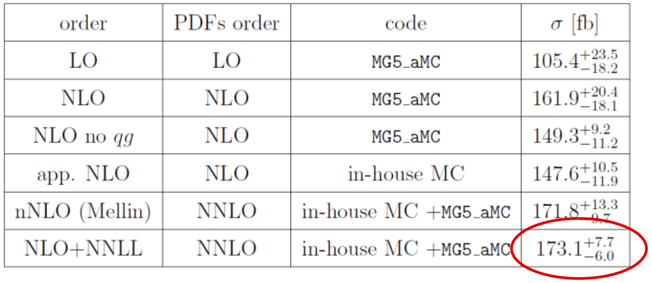
$t\bar{t}W^+$



order	PDFs order	code	σ [fb]
LO	LO	`MG5_aMC`	$202.1^{+45.5}_{-34.9}$
NLO	NLO	`MG5_aMC`	$316.9^{+39.3}_{-34.9}$
NLO no qg	NLO	`MG5_aMC`	$293.3^{+19.3}_{-22.7}$
app. NLO	NLO	in-house MC	$288.1^{+21.4}_{-23.8}$
nNLO (Mellin)	NNLO	in-house MC +`MG5_aMC`	$330.5^{+26.2}_{-19.2}$
NLO+NNLL	NNLO	in-house MC +`MG5_aMC`	$333.0^{+14.9}_{-12.4}$

$t\bar{t}W^-$

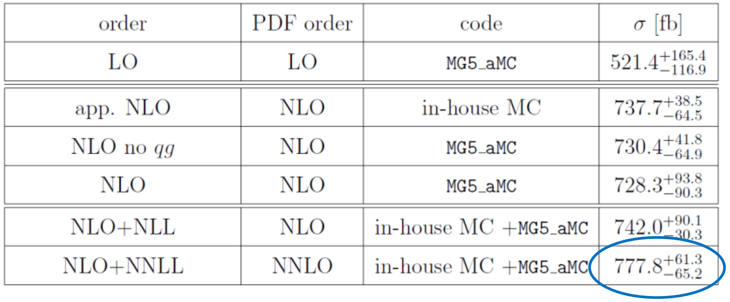
Broggio, Ferroglia,Ossola, Pecjakd 1607.05303



order	PDFs order	code	σ [fb]
LO	LO	`MG5_aMC`	$105.4^{+23.5}_{-18.2}$
NLO	NLO	`MG5_aMC`	$161.9^{+20.4}_{-18.1}$
NLO no qg	NLO	`MG5_aMC`	$149.3^{+9.2}_{-11.2}$
app. NLO	NLO	in-house MC	$147.6^{+10.5}_{-11.9}$
nNLO (Mellin)	NNLO	in-house MC +`MG5_aMC`	$171.8^{+13.3}_{-9.7}$
NLO+NNLL	NNLO	in-house MC +`MG5_aMC`	$173.1^{+7.7}_{-6.0}$

$t\bar{t}Z$

Broggio,Ferroglia, Ossola, Pecjak,Sameshimab 1702.00800



order	PDF order	code	σ [fb]
LO	LO	`MG5_aMC`	$521.4^{+165.4}_{-116.9}$
app. NLO	NLO	in-house MC	$737.7^{+38.5}_{-64.5}$
NLO no qg	NLO	`MG5_aMC`	$730.4^{+41.8}_{-64.9}$
NLO	NLO	`MG5_aMC`	$728.3^{+93.8}_{-90.3}$
NLO+NLL	NLO	in-house MC +`MG5_aMC`	$742.0^{+90.1}_{-30.3}$
NLO+NNLL	NNLO	in-house MC +`MG5_aMC`	$777.8^{+61.3}_{-65.2}$

CMS Collaboration, CMS-PAS-TOP-16-017 (2017)

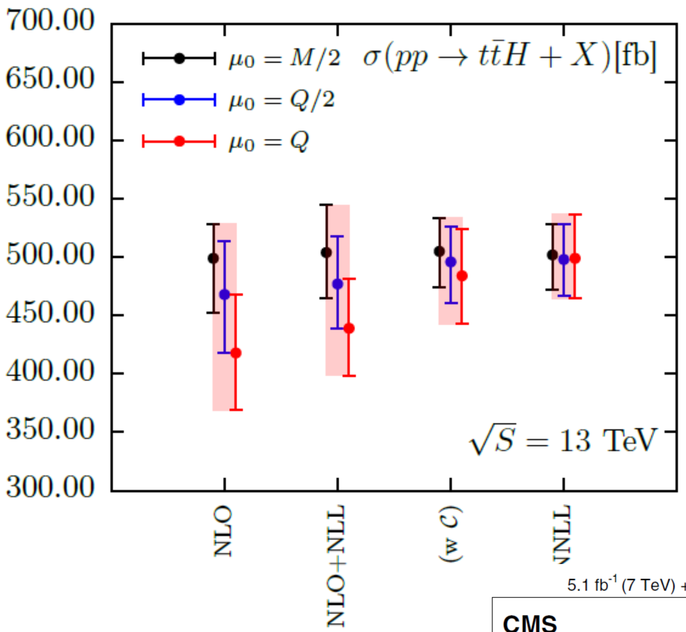
$$\sigma(t\bar{t}W) = 0.98^{+0.23}_{-0.22}\ (\text{stat.})^{+0.22}_{-0.18}\ (\text{sys.})\ \text{pb}$$

$$\sigma(t\bar{t}Z) = 0.70^{+0.16}_{-0.15}\ (\text{stat.})^{+0.14}_{-0.12}\ (\text{sys.})\ \text{pb}$$

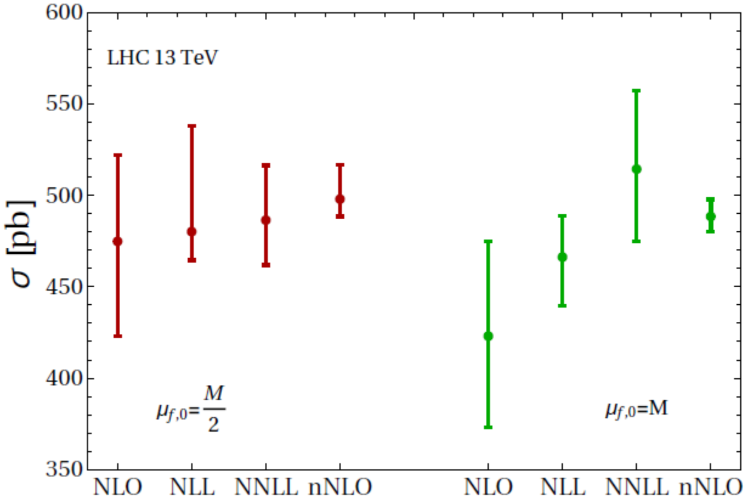
⇨ **Better precision is needed**

ttH at 13 TeV

Kulesza, Motyka, Stebel, Theeuwes 1704.03363



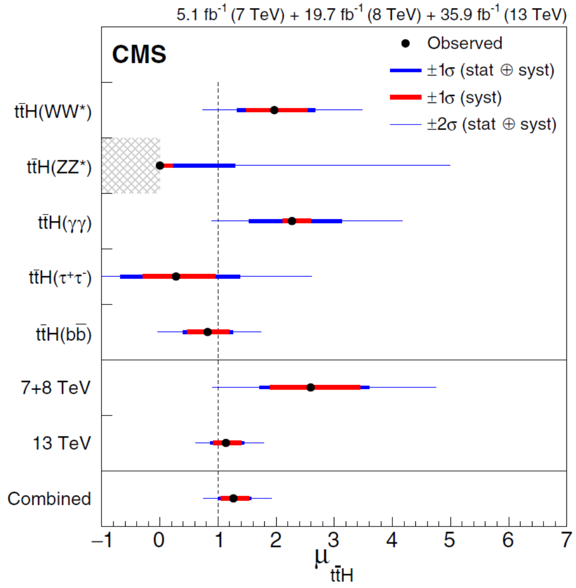
Broggio, Ferroglia, Pecjak, Yang 1611.00049



CMS

PRL 120, 231801 (2018)

$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26}$$



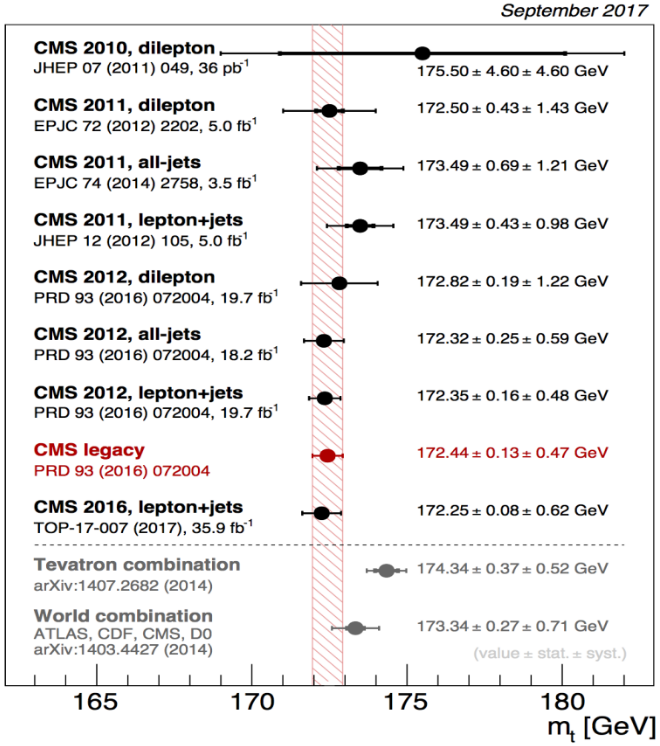
ATLAS 1712.0889

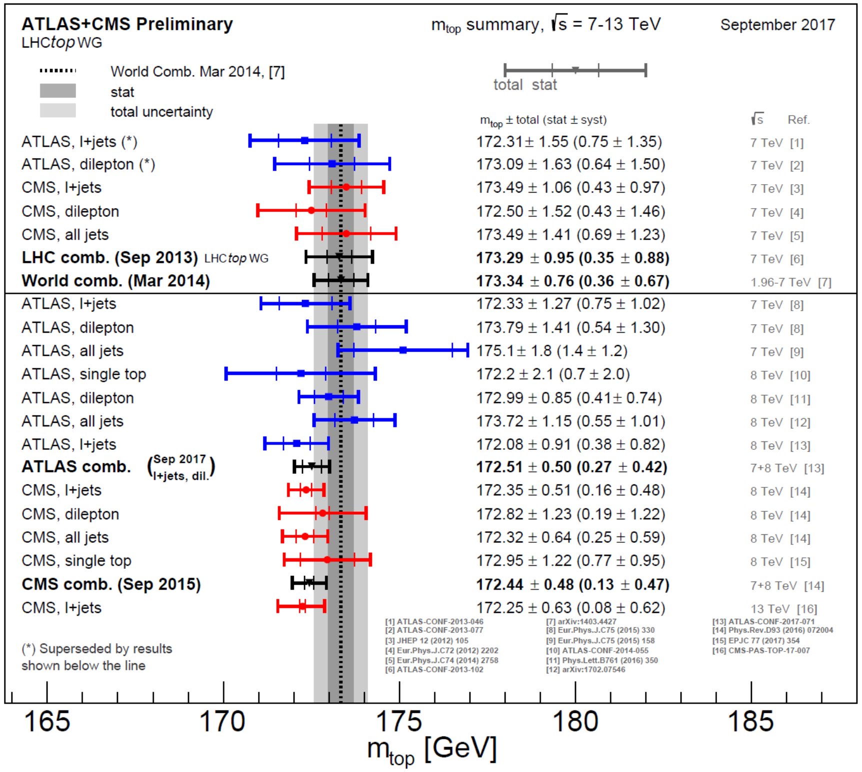
$$\sigma(t\bar{t}H) = 790^{+230}_{-210}\ \text{fb}$$

Top quark mass

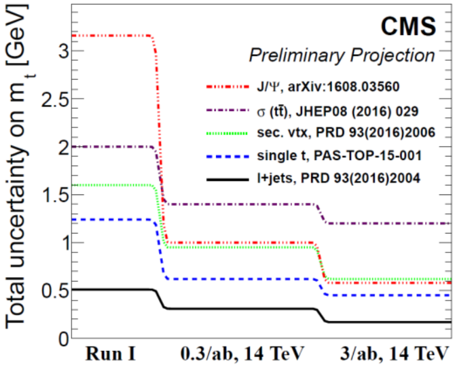
LHCTopWG

CMS Top WG





Estimated improvement



Top quark mass

Most precisely known quark mass !

Three top quark masses in PDG

K.Melnikov

t-Quark Mass (Direct Measurements).

t-Quark Mass from Cross-Section Measurements (MS-bar mass)

t-Quark Pole Mass from Cross-Section Measurements

$$m_{\mathrm{MC}} = m_{\mathrm{Pole}}\left(1 \pm \Delta\right)$$

$$\Delta \overset{?}{=} \begin{cases} \frac{\Lambda}{m} \approx 0.13\% \\ \frac{\Gamma}{m} \approx 0.8\% \\ \frac{\alpha_s}{\pi} \approx 3.7\% \end{cases}$$

P. Uwer
K.Melnikov
P.Nason
G. Corcella...

Main question is whether or not all sources of systematic uncertainties, including non-perturbative effects, are properly accounted for…

Top quark width

K. G. Chetyrkin, R. Harlander, T. Seidensticker and M. Steinhauser,
Second order QCD corrections to $\Gamma(t \to Wb)$,
Phys. Rev. D 60 (1999) 114015, arXiv: hep-ph/9906273.

A.Czarnecki and K. Melnikov,
Two loop QCD corrections to top quark width,
Nucl. Phys. B 544 (1999) 520, arXiv: hep-ph/9806244.

J. Gao, C. S. Li and H. X. Zhu,
Top Quark Decay at Next-to-Next-to Leading Order in QCD,
Phys. Rev. Lett. 110 (2013) 042001, arXiv: 1210.2808 [hep-ph].

NNLO top quark width 1.322 GeV for 172.5 GeV top quark mass

Top quark width measurements in most cases are done under assumption of the SM top

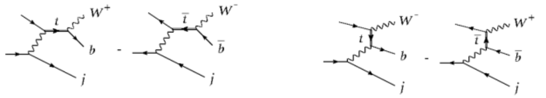
Errors of measurements in more model independent way are still very large

$\Gamma_t = 2.0^{+0.47}_{-0.43}$ GeV	D0 Collaboration (2012, 1201.4151)
$0.6 < \Gamma_t < 2.5$ GeV	CMS Collaboration (CMS-PAS-TOP-16-019)
$\Gamma_t = 1.76 \pm 0.33\,(\text{stat.})\,^{+0.79}_{-0.68}\,(\text{syst.})$ GeV	ATLAS Collaboration (2017, 1709.04207)

Top quark width

Giardino, Zhang 1702.06996
Zhang 1711.09592

New proposal – ratio of resonant and non-resonant asymmetries



One-sigma exclusion limits at 13 TeV

Luminosity [fb^{-1}]	30	300	3000
Limits [GeV]	[0.40,2.30]	[1.01,1.73]	[1.14,1.60]

Double, Single and non-resonant fiducial cross sections

Baskakov, Boos, Dudko 1807.11193

In paper by F. Caola, K. Melnikov (1307.4935) the new method for deriving model-independent upper bound on the Higgs boson width was proposed by comparing pp->ZZ* rate close the Higgs pole with pp->ZZ above ZZ threshold.

In case of the top quark there are two valuable differences:

1) Higgs width / Higgs mass << Top width / Top mass

2) One can calculate separately amplitudes for pole, non pole, and the interference parts in case of pp->H->ZZ* and pp->ZZ in gauge invariant way.
But one can not separate contributions in gauge invariant way for the top pair and the single top quark production.

Top quark width parametrization

$$\Gamma_t = \xi^2 \cdot \Gamma_t^{SM} + \Delta$$

ξ - coupling rescaling

$$\epsilon = \xi^2 - 1$$

$$\Delta = \delta \cdot \Gamma_t^{SM}$$

- additional contributions,
  decay modes

$pp \rightarrow W^+W^-bb$

Double-resonant region (DR)

$$\left(M_t^{SM} - n\cdot\Gamma_t^{SM} \le M_{W^-\bar{b}} \le M_t^{SM} + n\cdot\Gamma_t^{SM}\right) \quad and \quad \left(M_t^{SM} - n\cdot\Gamma_t^{SM} \le M_{W^+b} \le M_t^{SM} + n\cdot\Gamma_t^{SM}\right) \;(1)$$

Single-resonant region (SR)

$$\left(M_t^{SM} - n\cdot\Gamma_t^{SM} \le M_{W^-\bar{b}} \le M_t^{SM} + n\cdot\Gamma_t^{SM}\right) and \left(M_{W^+b} \le M_t^{SM} - k\cdot\Gamma_t^{SM} \; or \; M_t^{SM} + k\cdot\Gamma_t^{SM} \le M_{W^+b}\right)$$

$$or$$

$$\left(M_t^{SM} - n\cdot\Gamma_t^{SM} \le M_{W^+b} \le M_t^{SM} + n\cdot\Gamma_t^{SM}\right) and \left(M_{W^-\bar{b}} \le M_t^{SM} - k\cdot\Gamma_t^{SM} \; or \; M_t^{SM} + k\cdot\Gamma_t^{SM} \le M_{W^-\bar{b}}\right)$$

Non-resonant region (NR)

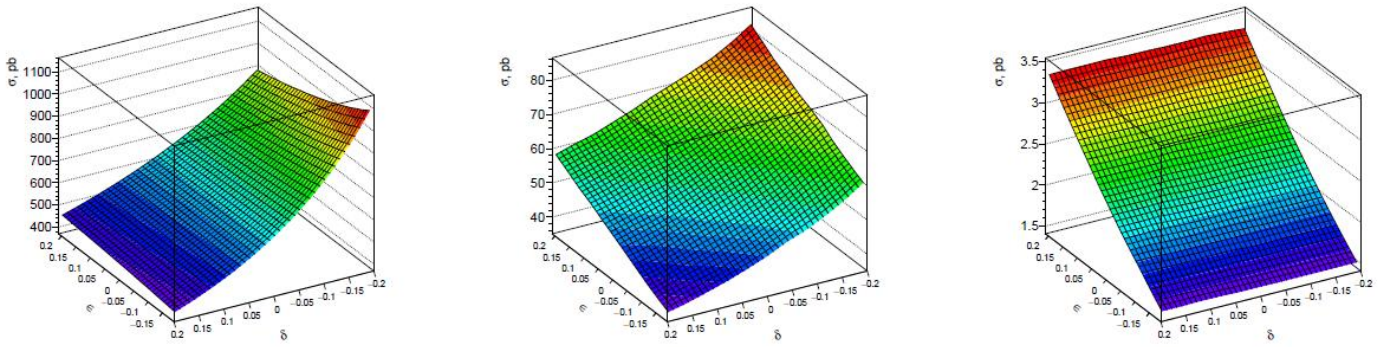
$$\left(M_{W^-\bar{b}} \le M_t^{SM} - k\cdot\Gamma_t^{SM} \quad or \quad M_t^{SM} + k\cdot\Gamma_t^{SM} \le M_{W^-\bar{b}}\right)$$

$$and$$

$$\left(M_{W^+b} \le M_t^{SM} - k\cdot\Gamma_t^{SM} \quad or \quad M_t^{SM} + k\cdot\Gamma_t^{SM} \le M_{W^+b}\right)$$

Fiducial cross section dependencies on parameters ε and δ

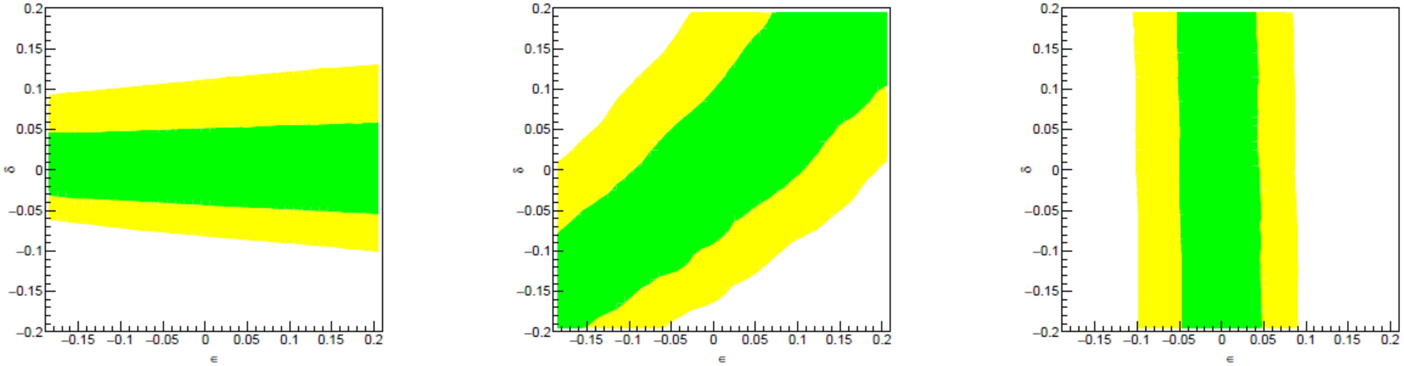
(14 TeV collision energy, n = k = 15)



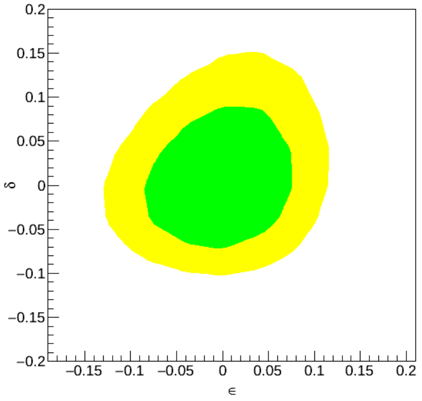
(a) DR region (b) SR region (c) NR region

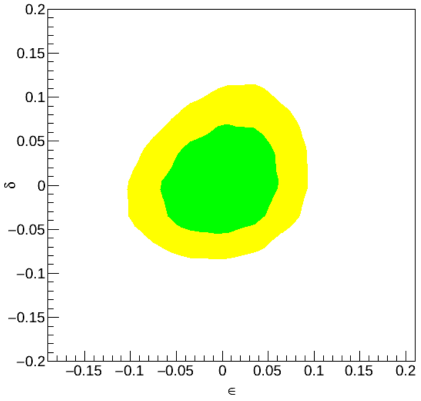
Constraints on parameters ε and for DR, SR and NR regions

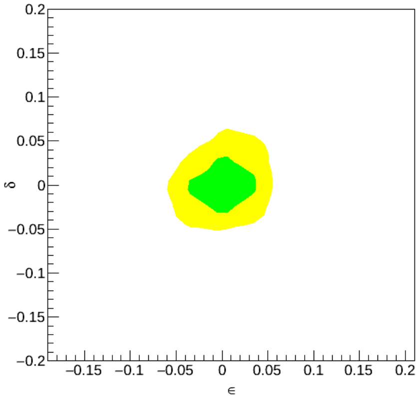
Green and yellow arias correspond to exclusion limits
at 68% and 95% CL assuming 10% systematical uncertainty



(a) DR region (b) SR region (c) NR region


14 TeV


28 TeV


100 TeV

Statistical uncertainty is estimated to be less than 1%.

Systematic uncertainty is assumed to be
10%, 8% and 5% for 14, 28 and 100 TeV respectively.

Under these assumptions allow one obtains model independent and gauge invariant constrains of the top quark width from

20% for 14 TeV up to **8% for 100 TeV**.

Two possibilities to search for BSM

Collision energy E > production thresholds

⇒New resonances decaying to tops
⇒New states produced in association with the top

Z', W', π_T, ρ_T , KK states
top partners such as stop, sbottom, vector like quarks, t* …

Collision energy E < production thresholds

⇒New effective anomalous interactions of the top with other SM particles

⇒New particle contributions via quantum loops

(modification of top decay and production properties)

Searches below threshold

Effective field theory approach or SM Effective Field Theory (SMEFT)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i + \cdots$$

c_i - dimensionless coefficients
O_i – operators constructed from SM fields preserving
SM gauge invariance

1802.07237
1807.02121

Several issues

- choice of operator basis,
-validity of computation for a particular observable,
- simultaneous analysisof different signatures (processes),
- NLO corrections,
- proper modeling and strategy to get limits from exp. data
  etc.

Anomalous Wtb couplings

Operators contributing to tWb interactions

Aguilar-Saavedra 0811.3842

$$O_{\phi q}^{(3,3+3)} = \frac{i}{2}\left[\phi^\dagger(\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I)\phi\right](\bar{q}_{L3}\gamma^\mu \tau^I q_{L3}), \qquad O_{\phi\phi}^{33} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{t}_R \gamma^\mu b_R),$$

$$O_{dW}^{33} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I b_R)\phi\, W_{\mu\nu}^I, \qquad O_{uW}^{33} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I t_R)\tilde{\phi}\, W_{\mu\nu}^I,$$

Kane, Ladinski, Yaun

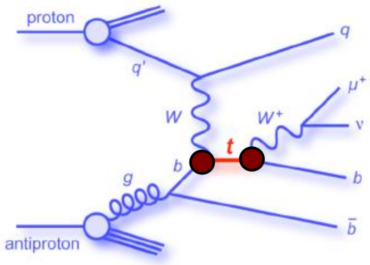
$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\gamma^\mu\left(f_{\mathrm{V}}^{\mathrm{L}}P_{\mathrm{L}} + f_{\mathrm{V}}^{\mathrm{R}}P_{\mathrm{R}}\right)\mathrm{t}\mathrm{W}_\mu^- - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\frac{\sigma^{\mu\nu}\partial_\nu \mathrm{W}_\mu^-}{M_{\mathrm{W}}}\left(f_{\mathrm{T}}^{\mathrm{L}}P_{\mathrm{L}} + f_{\mathrm{T}}^{\mathrm{R}}P_{\mathrm{R}}\right)\mathrm{t} + \mathrm{h.c.}$$

where $f_{LV} = V_{tb} + C_{\phi q}^{(3,3+3)*}\frac{v^2}{\Lambda^2}, \quad f_{RV} = \frac{1}{2}C_{\phi\phi}^{33*}\frac{v^2}{\Lambda^2}, \quad f_{LT} = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}, \quad f_{RT} = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}$

CM: f_1^L = Vtb, f_1^R = 0, $f_2^{L,R}$ = 0

Natural size $|1-f_L^V|$, $f_R^V \sim v^2/\Lambda^2$

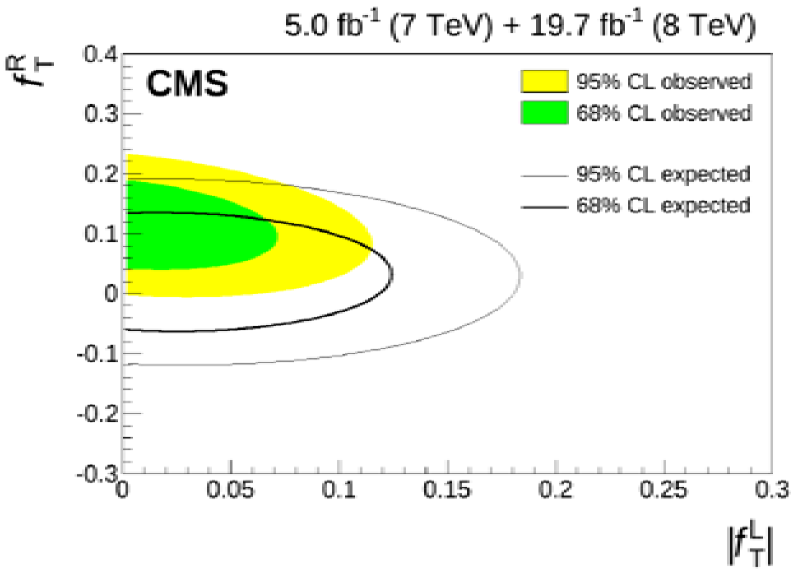
Natural size f_L^T, $f_R^T \sim v^2/\Lambda^2$

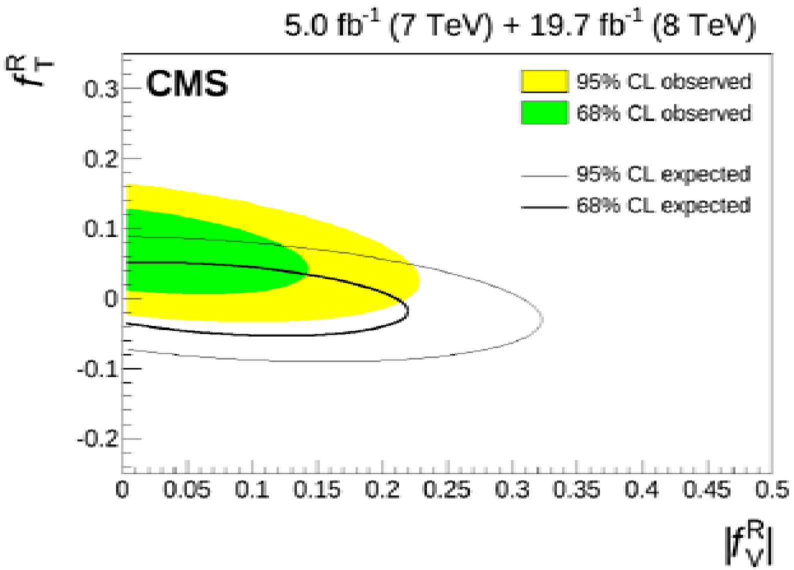


Anomalous Wtb couplings

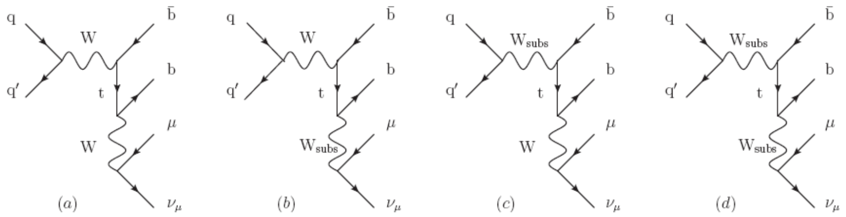
CMS limits

JHEP 02 (2017) 028





Method of modeling with subsidiary gauge fields corresponding to each anomalous coupling

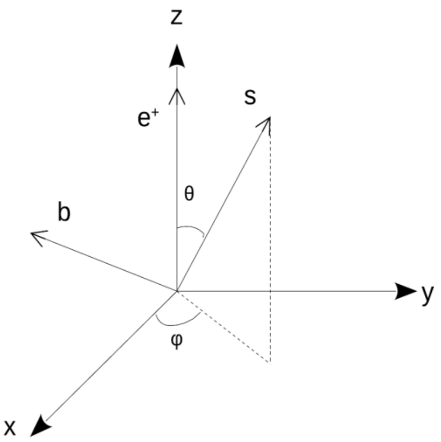


Boos, Bunichev, Dudko, Perfilov
Int. J. Mod. Phys. A 32, 1750008 (2016)

Polarized top quark differential decay width

Most general case with complex anomalous parameters

Boos, Bunichev 2018



Integrating over b-quark and neutrino 4-momenta:

$$\frac{d\Gamma_{t\to b\nu e^+}}{dE_{e^+}\cdot d\cos\theta\cdot d\phi} = \frac{g^4}{256\cdot\pi^3\cdot\Gamma_W\cdot m_W}\cdot[$$

$$+|f_{LV}|^2 \cdot (E_{max}-E_{e^+})\cdot E_{e^+}\cdot(1+\cos\theta)$$

$$+|f_{LT}|^2 \cdot (E_{e^+}-E_{min})\cdot E_{e^+}\cdot(1+\cos\theta)$$

$$+|f_{RT}|^2 \cdot (E_{max}-E_{e^+})\cdot\left(E_{min}+E_{max}-E_{e^+}+\frac{m_W}{E_{e^+}}\cdot c_{e^+}\cdot\sin\theta\cos\phi+\left(\frac{m_W^2}{2E_{e^+}}+E_{e^+}-E_{min}-E_{max}\right)\cdot\cos\theta\right)$$

$$+|f_{RV}|^2 \cdot (E_{e^+}-E_{min})\cdot\left(E_{min}+E_{max}-E_{e^+}+\frac{m_W}{E_{e^+}}\cdot c_{e^+}\cdot\sin\theta\cos\phi+\left(\frac{m_W^2}{2E_{e^+}}+E_{e^+}-E_{min}-E_{max}\right)\cdot\cos\theta\right)$$

$$+(Ref_{LV}\cdot Ref_{RT}+Imf_{LV}\cdot Imf_{RT}) \cdot (E_{max}-E_{e^+})\cdot(-2c_{e^+}\cdot\sin\theta\cos\phi-m_W\cdot(1+\cos\theta))$$

$$+(Ref_{LT}\cdot Ref_{RV}+Imf_{LT}\cdot Imf_{RV}) \cdot (E_{e^+}-E_{min})\cdot(-2c_{e^+}\cdot\sin\theta\cos\phi-m_W\cdot(1+\cos\theta))$$

$$+(Ref_{LV}\cdot Imf_{RT}-Imf_{LV}\cdot Ref_{RT}) \cdot (E_{max}-E_{e^+})\cdot(-2c_{e^+}\cdot\sin\theta\sin\phi)$$

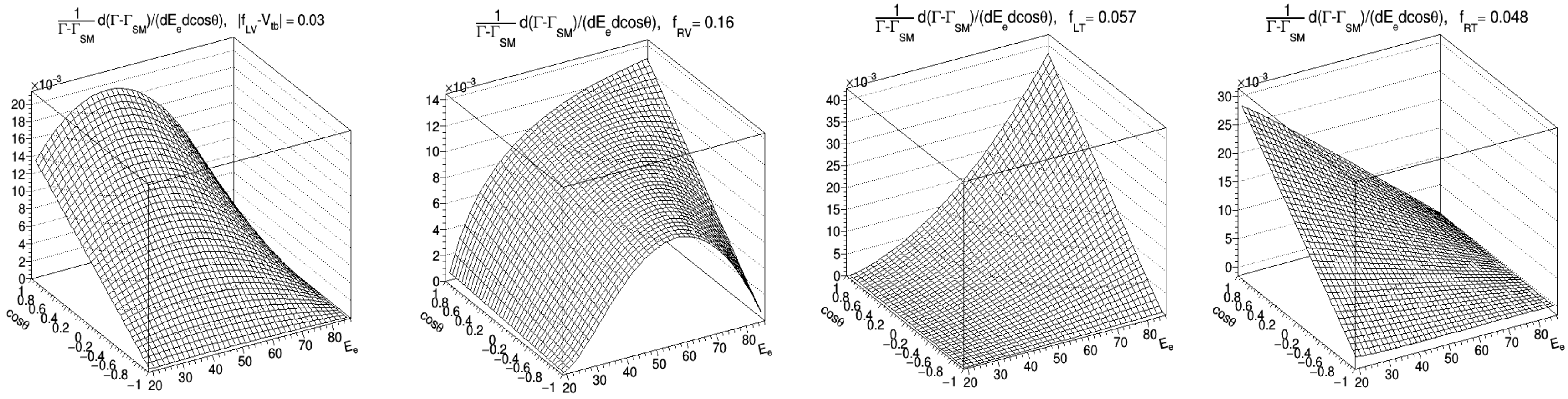
$$+(Ref_{LT}\cdot Imf_{RV}-Imf_{LT}\cdot Ref_{RV}) \cdot (E_e-E_{min})\cdot(-2c_{e^+}\cdot\sin\theta\sin\phi)\quad]$$

where:

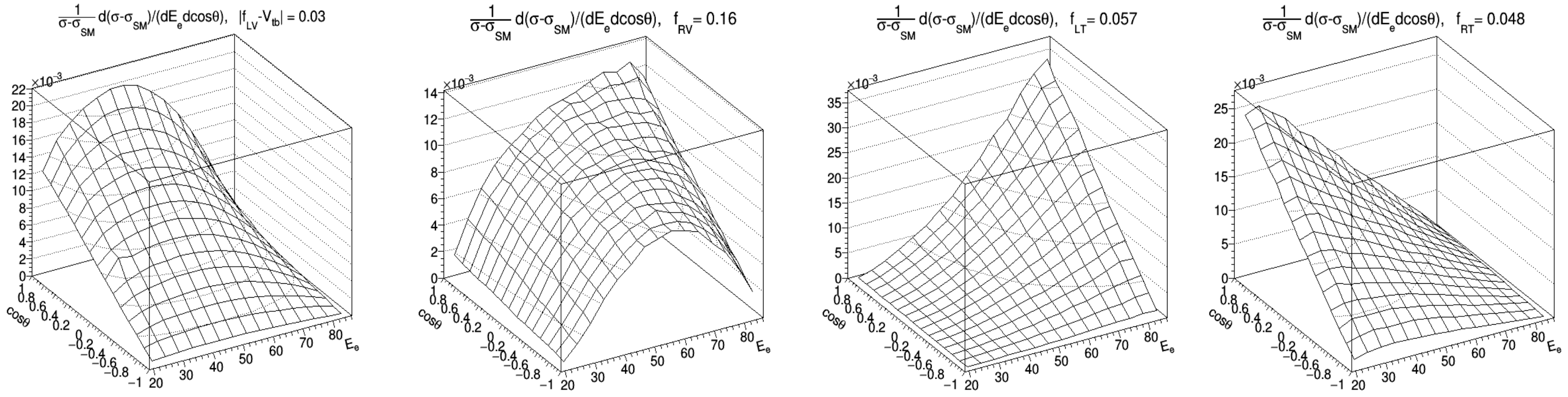
$$c_{e^+} = \sqrt{(E_{max}-E_{e^+})\cdot(E_{e^+}-E_{min})},\quad E_{max}=m_t/2,\quad E_{min}=m_W^2/(2m_t)$$

8 different kinematical expressions as functions of E_e, θ, φ

Distributions predicted by the analytic formula



Monte-Carlo simulation of the complete t-quark production and decay process
(it contains all t-channal subprocesses and also contains anomalous couplings both in production and in decay)



Two dimensional distribution shapes are significantly different for different anom. coupling scenarios

Fitting in the 2D coordinate space (E_e, cosθ)

The accuracy of measuring the two anomalous parameters by fitting in the 2D coordinate space (E_e, cosθ), sqrt(s) = 14TeV:

L, fb^{-1}	$\Delta\, Re\, f_{LV}$, $\Delta\, Re\, f_{RV}$	$\Delta\, Re\, f_{LV}$, $\Delta\, Re\, f_{LT}$	$\Delta\, Re\, f_{LV}$, $\Delta\, Re\, f_{RT}$
10	0.0025 0.02	0.002 0.01	0.003 0.003
300	0.0005 0.003	0.0004 0.0015	0.001 0.001
3000	0.0001 0.0005	0.0001 0.0004	0.0003 0.0003

The accuracy of measuring the three anomalous parameters by fitting in the 2D coordinate space (E_e, cosθ), sqrt(s) = 14TeV:

L, fb^{-1}	$\Delta\, Re\, f_{LV}$ $\Delta\, Im\, f_{LV}$, $\Delta\, Im\, f_{RT}$	$\Delta\, Re\, f_{LV}$ $\Delta\, Im\, f_{RV}$, $\Delta\, Im\, f_{LT}$
10	0.002 0.025 0.025	0.002 0.04 0.05
300	0.0004 0.005 0.005	0.0004 0.01 0.01
3000	0.0002 0.001 0.001	0.0002 0.002 0.002

FCNC. CMS searches

- Couplings: $tqg,\ tq\gamma,\ tqZ$, where $q = u, c$

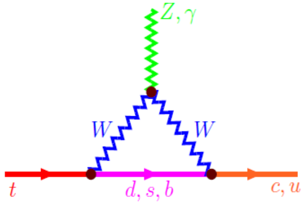
$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda}\left[\kappa_{tq}^{\gamma,Z} e\bar{t}\sigma_{\mu\nu} q F^{\mu\nu}_{\gamma,Z} + \kappa_{tq}^{g} g_s \bar{t}\sigma_{\mu\nu}\frac{\lambda^i}{2} q G^{i\mu\nu}\right] + h.c.$$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

$$\Gamma(t\to qg) = \left(\frac{\kappa_{tq}^{g}}{\Lambda}\right)^2 \frac{8}{3}\alpha_s m_t^3 \quad , \quad \Gamma(t\to q\gamma) = \left(\frac{\kappa_{tq}^{\gamma}}{\Lambda}\right)^2 2\alpha m_t^3,$$

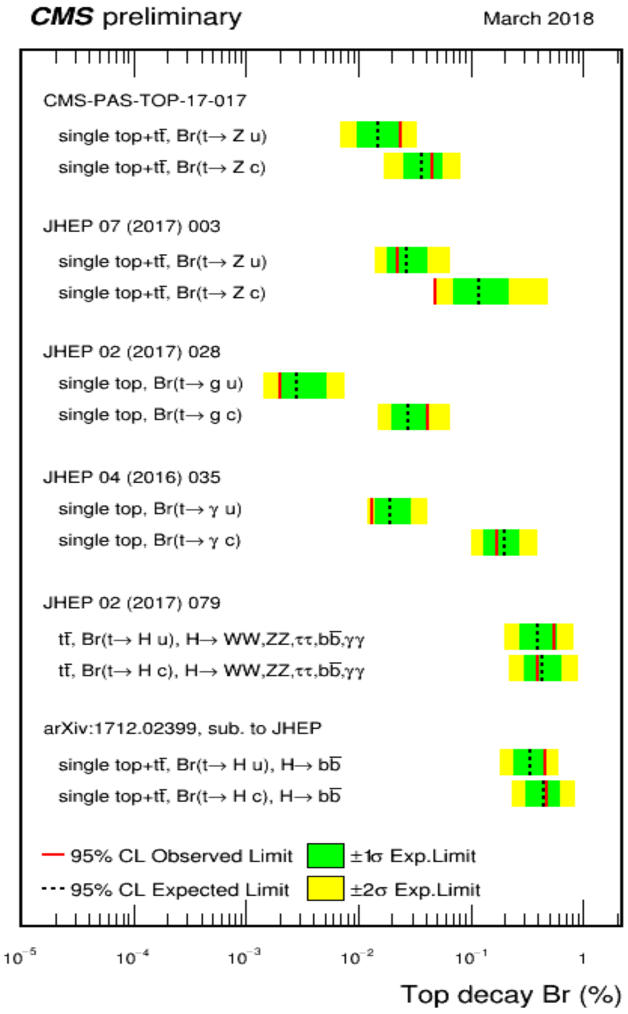
$$\Gamma(t\to qZ)_\sigma = \left(\frac{\kappa_{tq}^{Z}}{\Lambda}\right)^2 \alpha\, m_t^3 \frac{1}{\sin^2 2\theta_W}\left(1-\frac{M_Z^2}{m_t^2}\right)^2\left(2+\frac{M_Z^2}{m_t^2}\right)$$

Flavor Changing Neutral Currents (FCNC) $t\to qg,\ \ t\to q\gamma,\ \ t\to qZ$



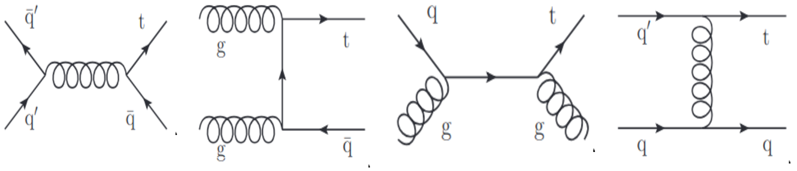
	SM	two-Higgs	SUSY
$B(t\to cg)$	$5\cdot 10^{-11}$	10^{-6}	10^{-3}
$B(t\to c\gamma)$	$5\cdot 10^{-13}$	10^{-6}	10^{-5}
$B(t\to cZ)$	$\sim 10^{-13}$	10^{-9}	10^{-4}

Br	LHC	HL-LHC
$t\to uH$	49×10^{-4}	2.1×10^{-4}
$t\to cH$	16×10^{-4}	1.1×10^{-4}
$t\to u\gamma$	130×10^{-5}	0.9×10^{-5}
$t\to c\gamma$	170×10^{-5}	7.4×10^{-5}
$t\to uZ$	17×10^{-5}	13×10^{-5}
$t\to cZ$	24×10^{-5}	23×10^{-5}

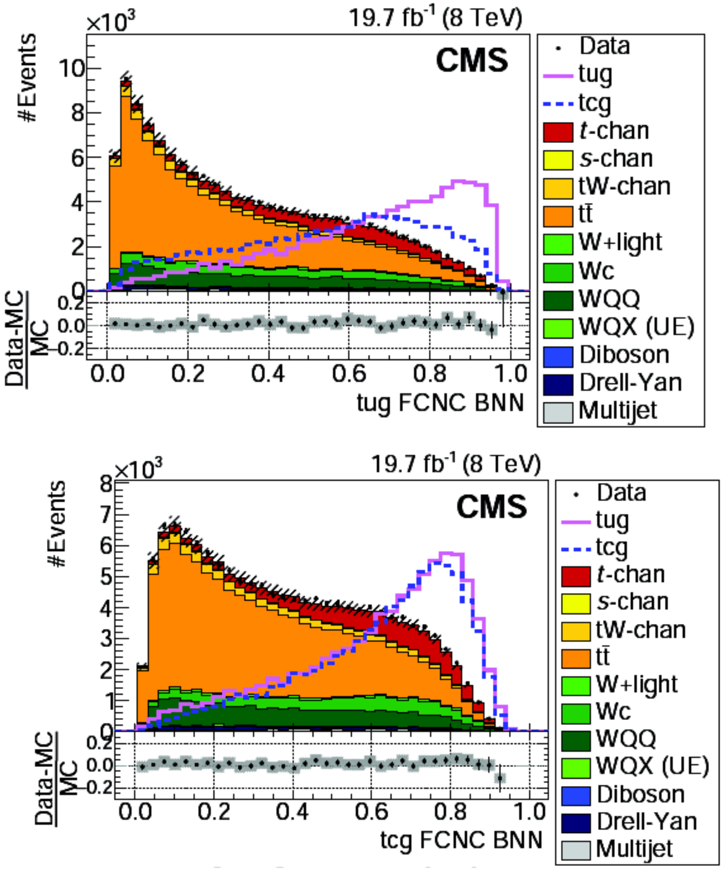


FCNC. CMS searches

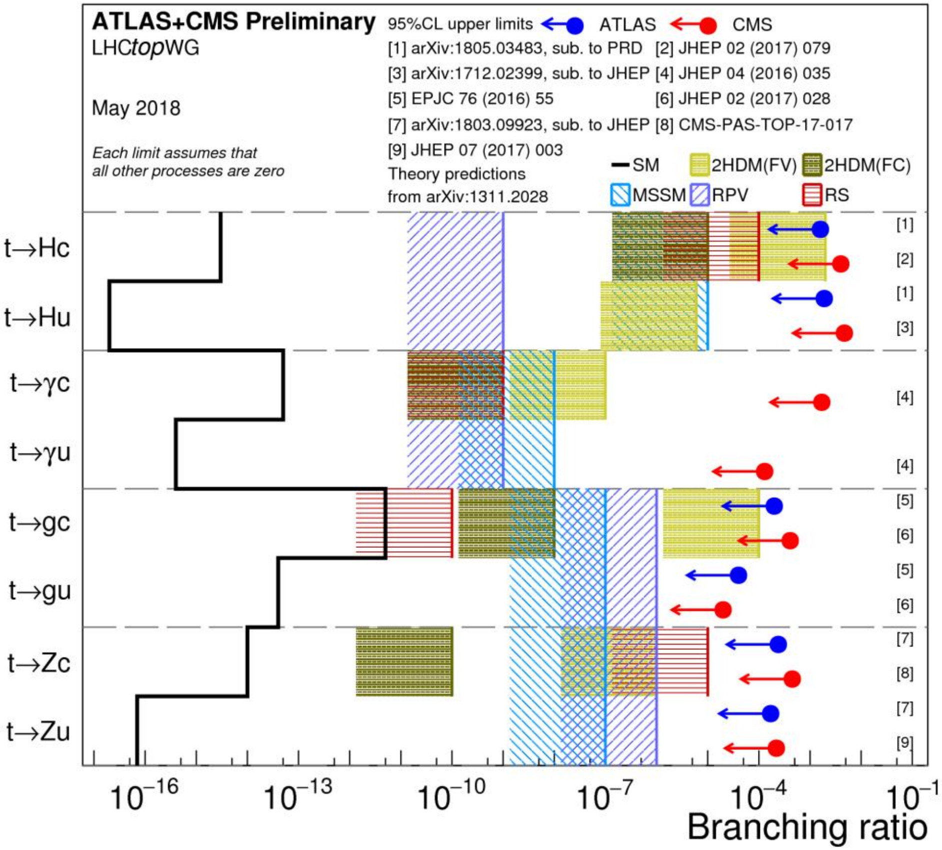
$$g_s \frac{\kappa_{tug}}{\Lambda}\,\bar{u}\,\sigma^{\mu\nu}\frac{\lambda^a}{2}t\,G^a_{\mu\nu} + g_s\frac{\kappa_{tcg}}{\Lambda}\,\bar{c}\,\sigma^{\mu\nu}\frac{\lambda^a}{2}t\,G^a_{\mu\nu} + h.c.$$



JHEP 02 (2017) 028

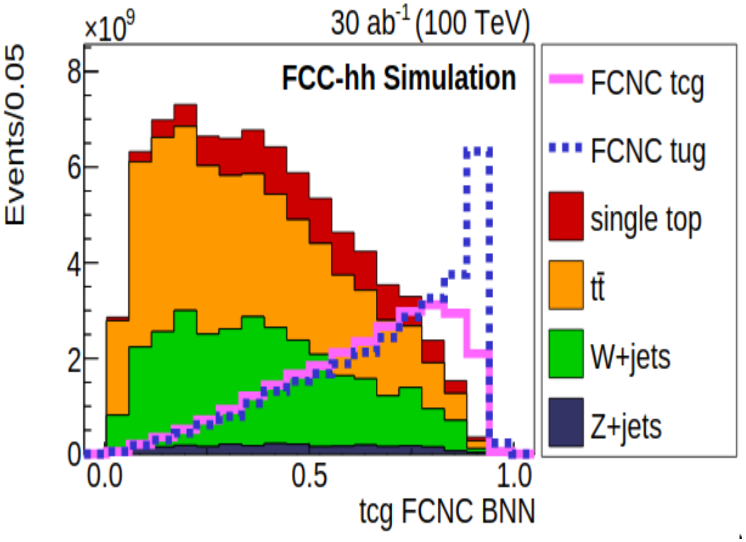


The FCNC BNN discriminant distribution to distinguish FCNC from the SM contribution



tqg FCNC at FCC

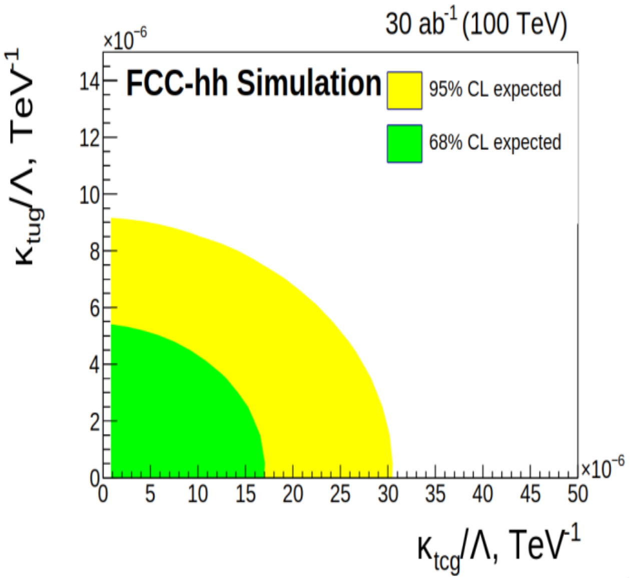
FCC-hh Conceptual Design Report



- **BNN analysis**

The FCNC BNN discriminant distribution to distinguish FCNC from the SM contribution

- **2D limits:**



- **1D limits:**

$$\mathcal{B}(t \to ug) < 7.1 \cdot 10^{-11}$$

$$\mathcal{B}(t \to cg) < 8.5 \cdot 10^{-10}$$

current CMS constraints:

Br(t→ug) < $2.0*10^{-5}$, Br(t→cg) < $4.1*10^{-4}$

SM prediction Br(t→qg) ~ $5.0*10^{-11}$

tqγ FCNC at FCC

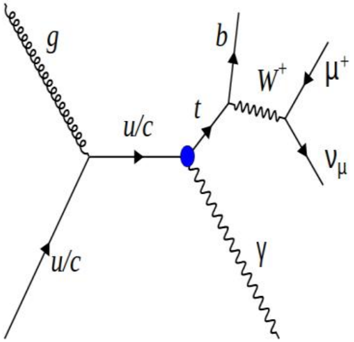
FCC-hh Conceptual Design Report

- **FCNC *tqγ* couplings at FCC**

- SM: Br(t→uγ) and Br(t→cγ) ~ 10^{-14}

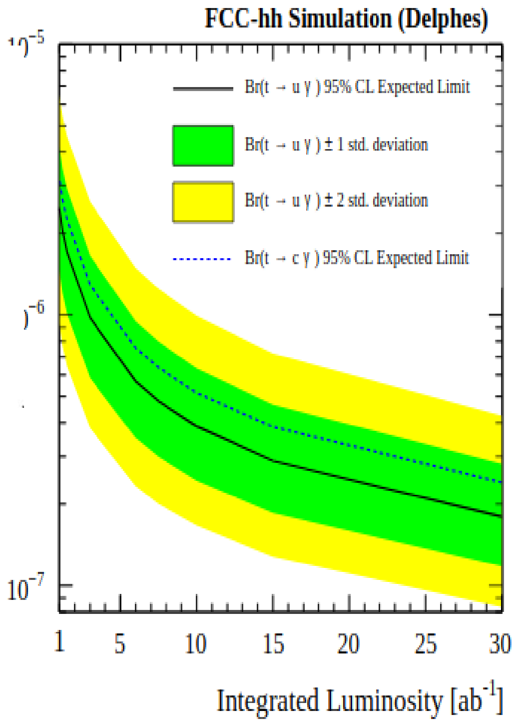
- existed CMS constraints:

Br(t→uγ) < $1.6*10^{-4}$, Br(t→cγ) < $1.8*10^{-3}$

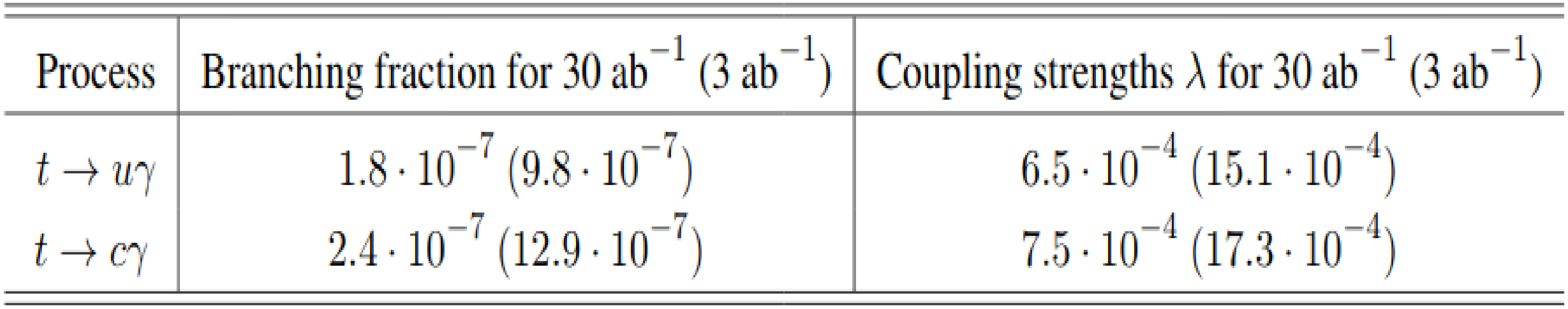


- **BDT multivariate analysis**

- **FCC prospects would improve the existing experimental limits by about three-four orders of magnitude**



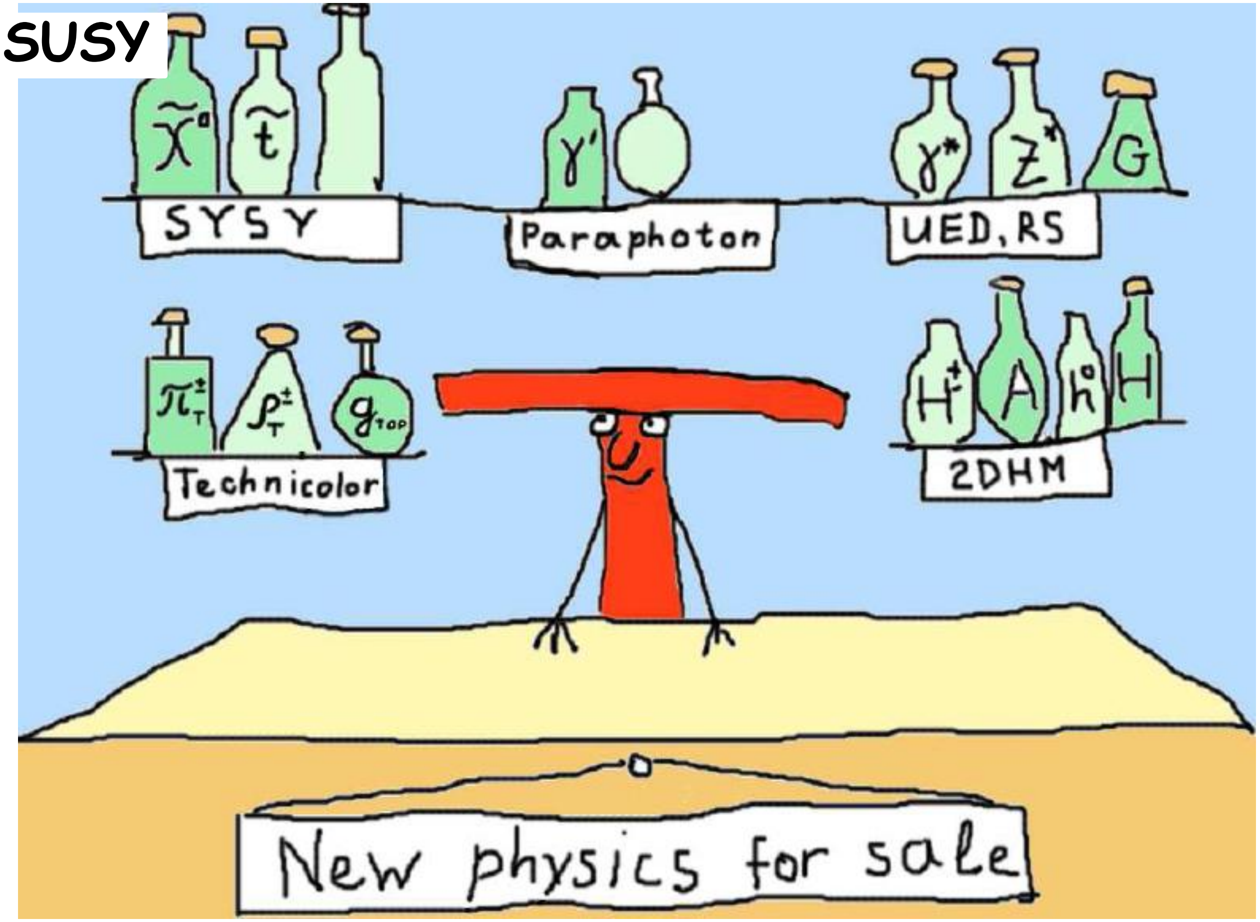
Expected exclusion limits on the FCNC branching fractions as a function of integrated luminosity.



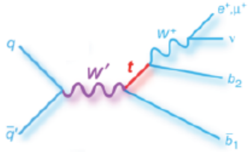
Process	Branching fraction for 30 ab^{-1} (3 ab^{-1})	Coupling strengths λ for 30 ab^{-1} (3 ab^{-1})
$t \to u\gamma$	$1.8 \cdot 10^{-7}$ ($9.8 \cdot 10^{-7}$)	$6.5 \cdot 10^{-4}$ ($15.1 \cdot 10^{-4}$)
$t \to c\gamma$	$2.4 \cdot 10^{-7}$ ($12.9 \cdot 10^{-7}$)	$7.5 \cdot 10^{-4}$ ($17.3 \cdot 10^{-4}$)

Searches above threshold

V.Bunichev


SUSY

Searches for W' in top+b



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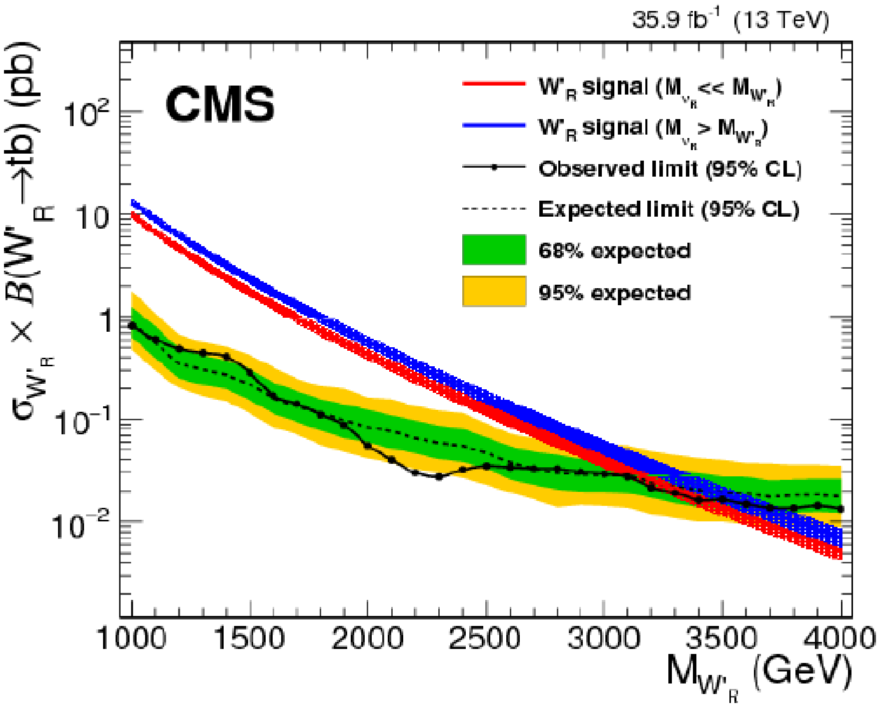
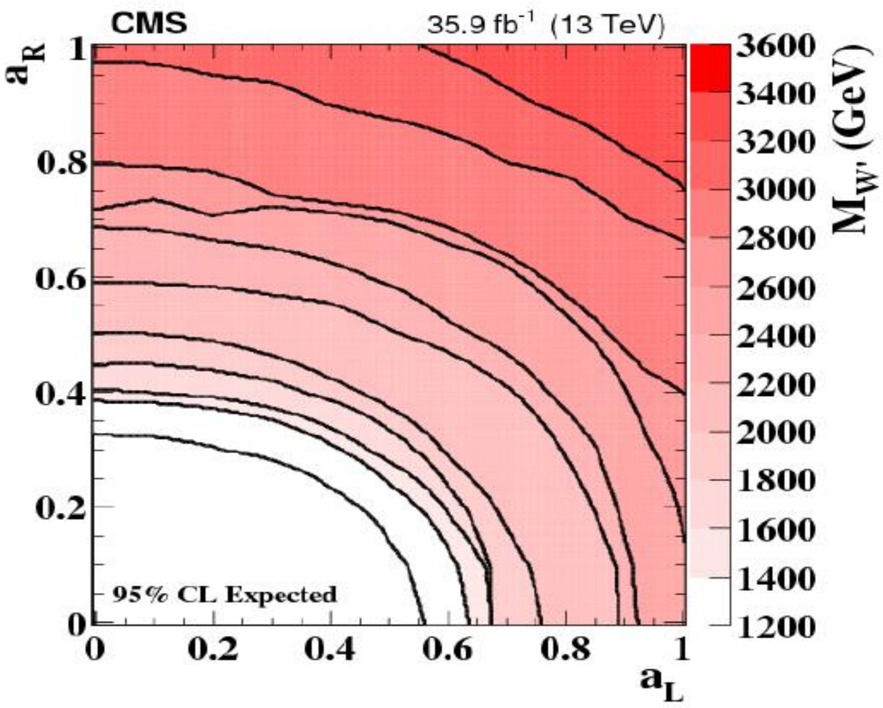
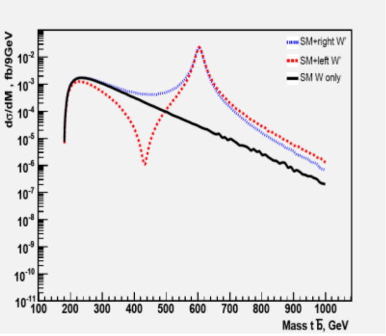




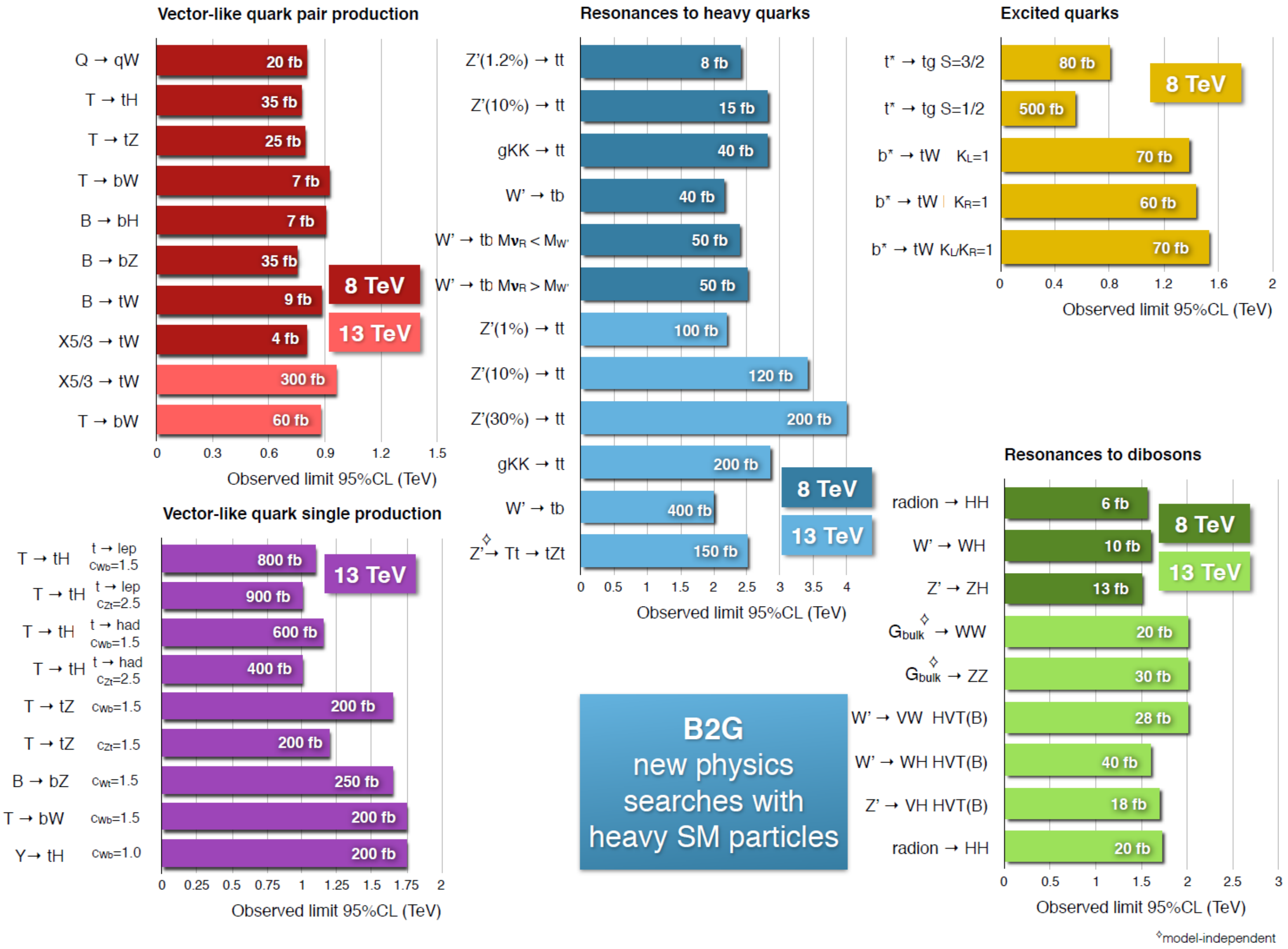
$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \overline{f}_i \gamma_\mu \left(a^{\mathrm{R}}_{f_i f_j} (1+\gamma^5) + a^{\mathrm{L}}_{f_i f_j} (1-\gamma^5) \right) W'^{\mu} f_j + \mathrm{h.c.}$$

E.B., Bunichev, Dudko, Perfilov, PL 2007

Negative interference



CMS limits



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

Concluding remarks

No experimental observation of significant deviation from SM in top quark sector. But many new limits on BSM parameter spaces!

Remarkable progress in precision from both sides
- theoretical computations
- experimental measurements

With more statistics and with higher energies
- one can study phase space regions with smaller rates where New Physics might be better pronounced
- one can study multidimensional distributions
- one can study better rare processes (top production in association with various particles, rare top decays)

However better accuracy in computation and modeling is needed in case of rare processes or in low rate phase space regions including spin correlations, QCD and EW corrections, complete gauge invariant set of diagrams…

Thank you !