Progress in top quark physics

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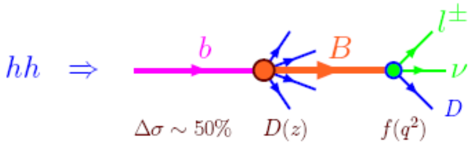
Outline

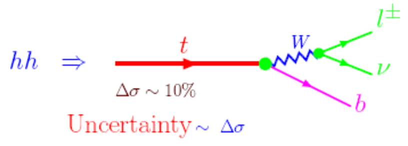
- Top quark in the Standard Model
- Progress in measurements and in perturbative computations
- Searches for "New Physics" in processes involving the top quark (few examples)

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 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 is so heavy and point like at the same time.**

• **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.**

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

Cancellation of chiral anomalies in SM with 3 generations

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

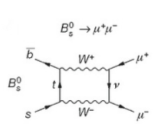
ATLAS: Q_{top} = 0.64±0.02(stat.) ±0.08(syst.) (from charge correlations of $W^\pm$ и b-jets in top and anti-top decays)

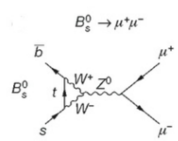
- GIM mechanism and flavor changing neutral current (FCNC) suppression

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

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

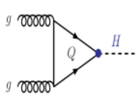


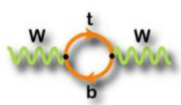


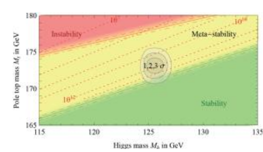
SM: Br($B^0_s \to \mu^+\mu^-$)$_{theory}$ = $(3.66 \pm 0.23)\times 10^{-9}$ Bobeth et al ., PRD (2014) 101801

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







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

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

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

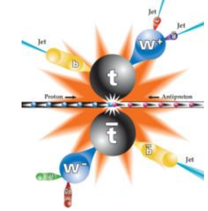
- Key particle in various SM extensions, in particular, in MSSM

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

- «Laboratory» for many BSM searches

(various signal and background processes)

Top-quark production at hadron colliders

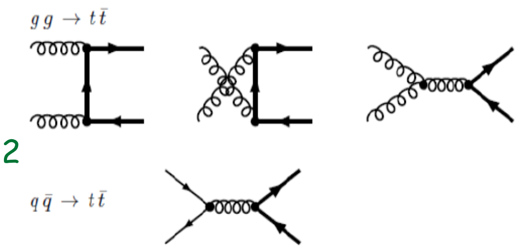


$t\bar{t}$ pair production (QCD)

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
…..



90%

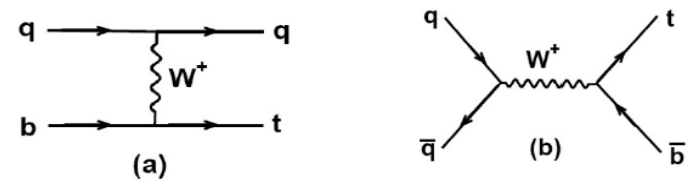
10%

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

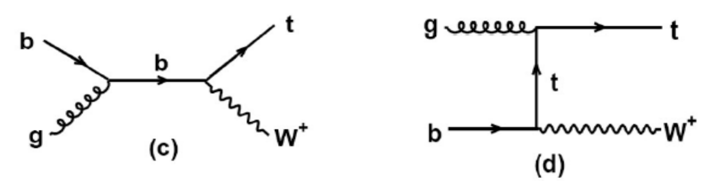
NNLO+NNLL accuracy Kidonakis' 14-15

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

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

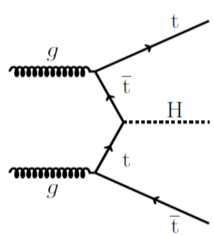


pb t-channel s-channel



associated tW production

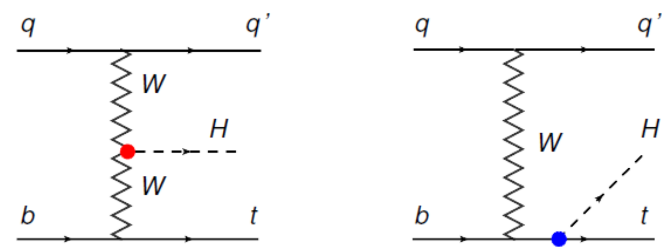
$t\bar{t}$H (W,Z) production



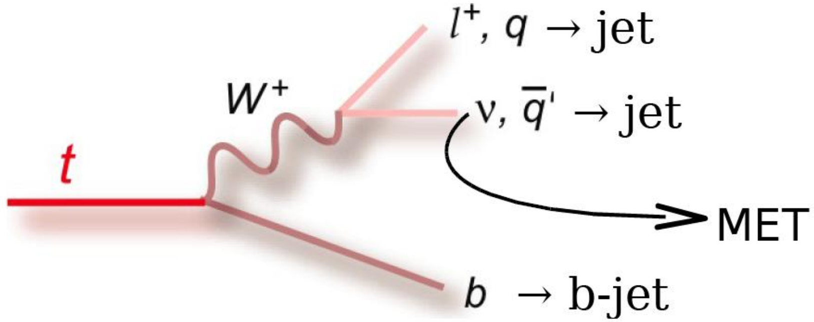
LHC Higgs WG (ttH)
~ 0.13 pb at 8TeV
~ 0.61 pb at 14TeV

tHq production

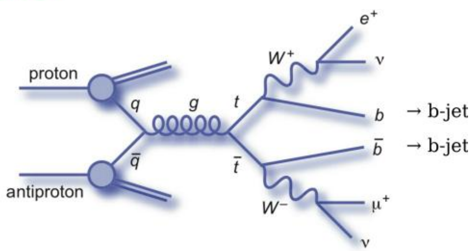
Birwas, Gabrielli, Mele' 12
~ 0.015 pb at 8TeV
~ 0.072 pb at 14TeV



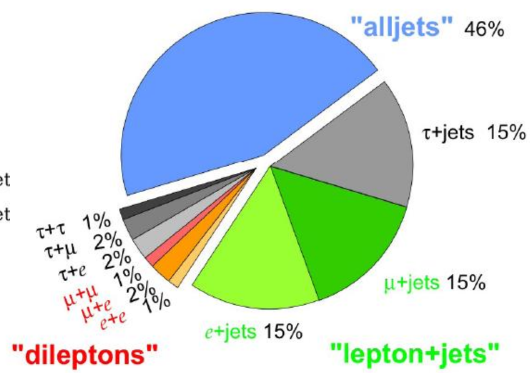
- Top decays:



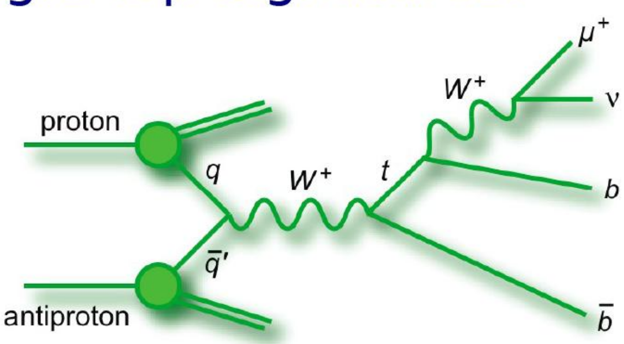
- Top pair signatures:
  - lepton + jets
  - dilepton
  - all jets

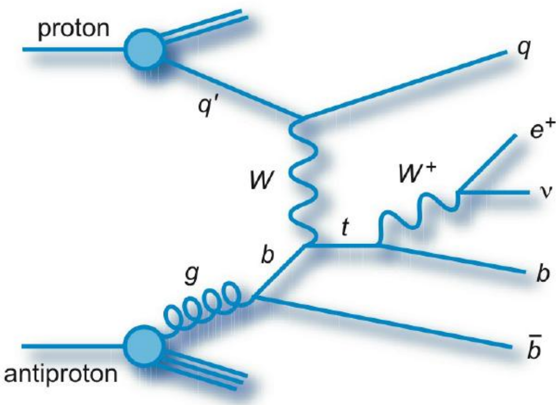


Top Pair Branching Fractions



- Single Top Signatures:

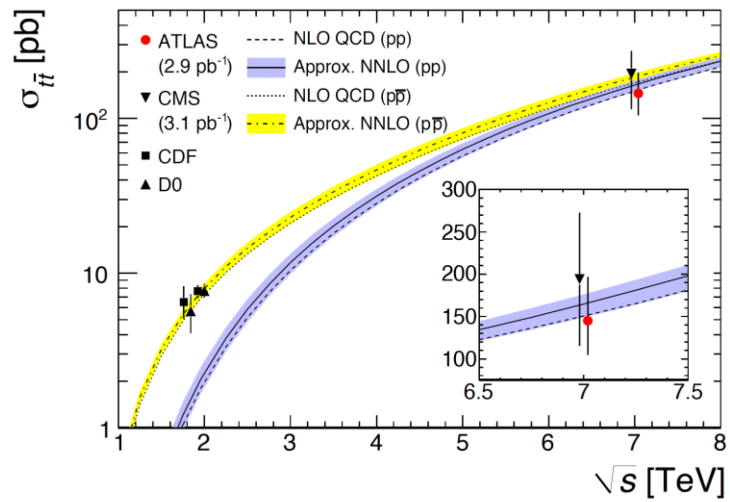


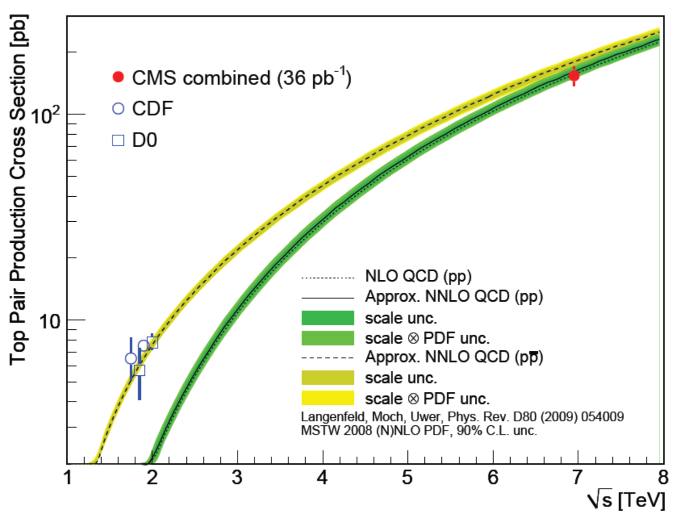


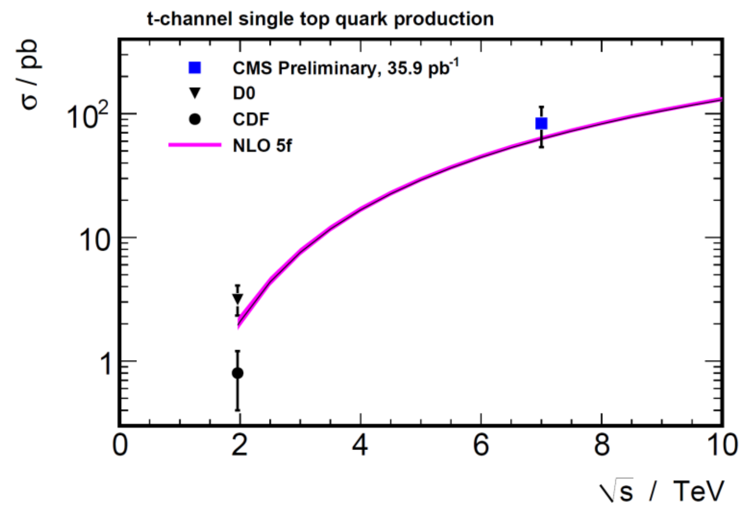
Pair and single top production cross sections at the LHC energy 7 TeV

Phys. Lett. B695, 424 (2010) (CMS)

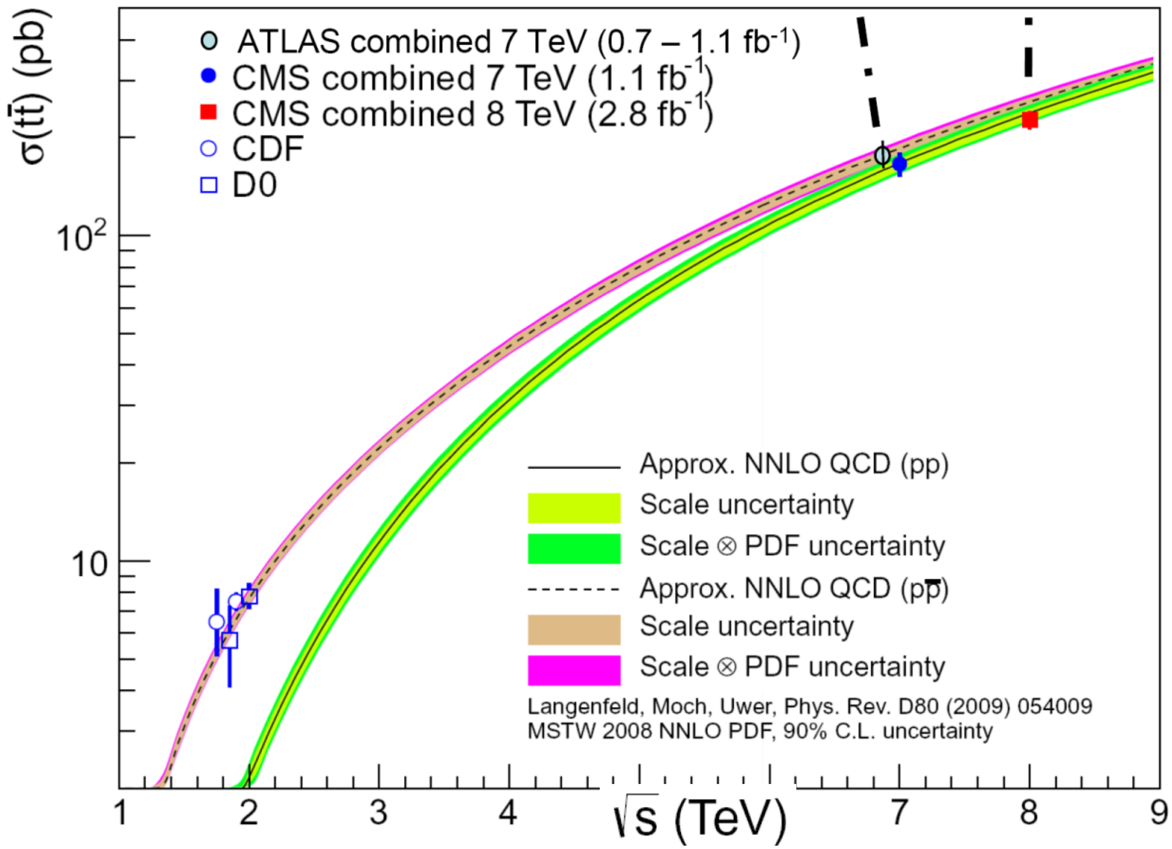
Eur.Phys.J. C71, 1577 (2011) (ATLAS)







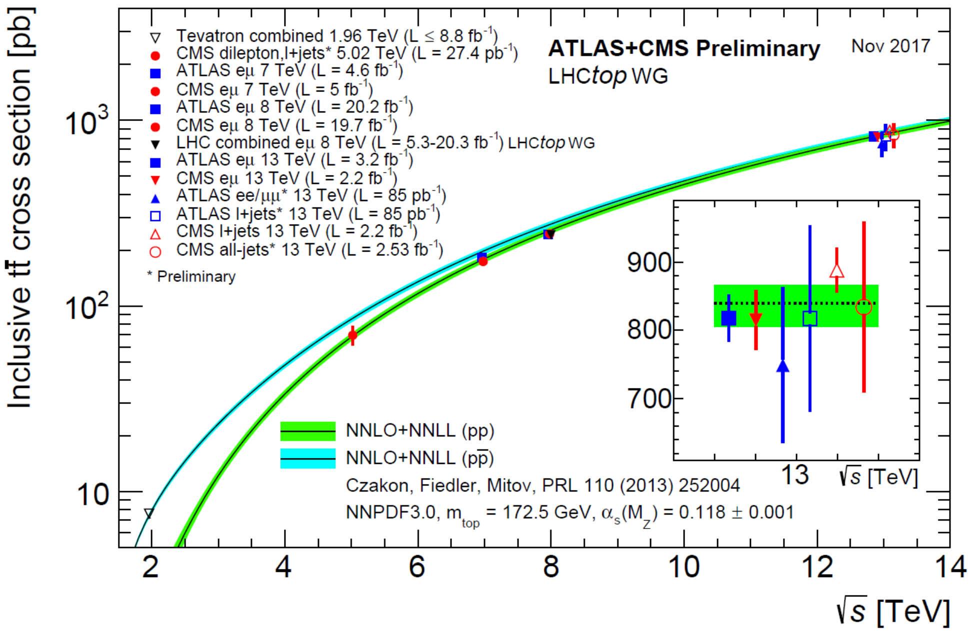
$$|V_{tb}| = \sqrt{\frac{\sigma^{exp}}{\sigma^{th}}} = 1.16 \pm 0.22(exp) \pm 0.02(th)$$



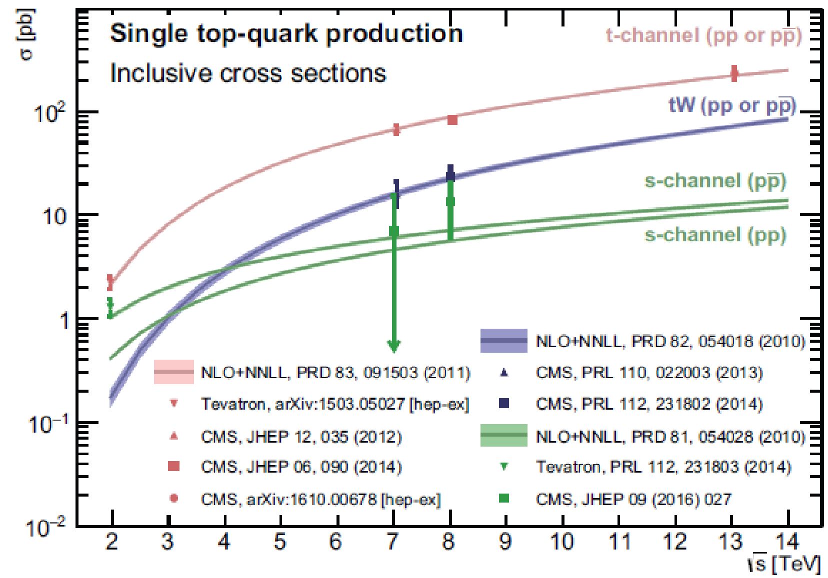
$$\sigma(8\text{TeV})/\sigma(7\text{TeV}) = 1.41 \pm 0.11$$

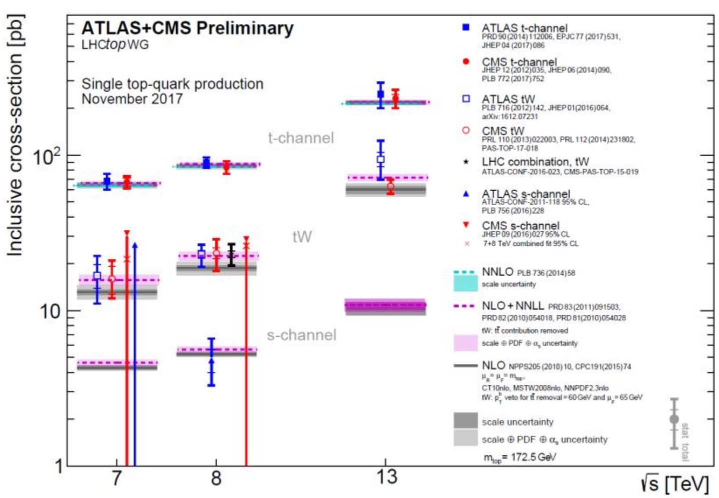
Further progress in top cross section measurements

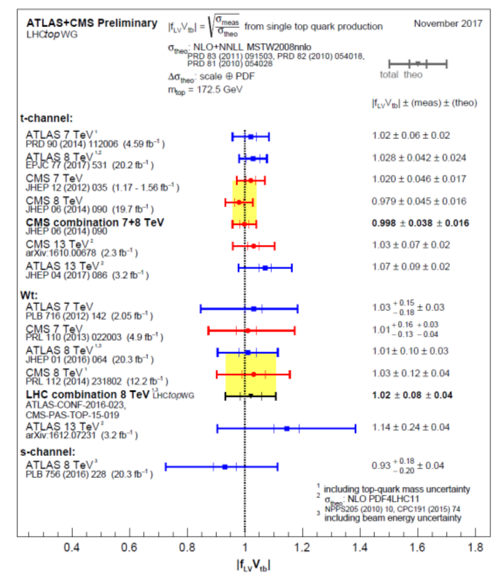
Top pair production



Single top production







NNLO

Collider	$\sigma_{\rm tot}$ [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

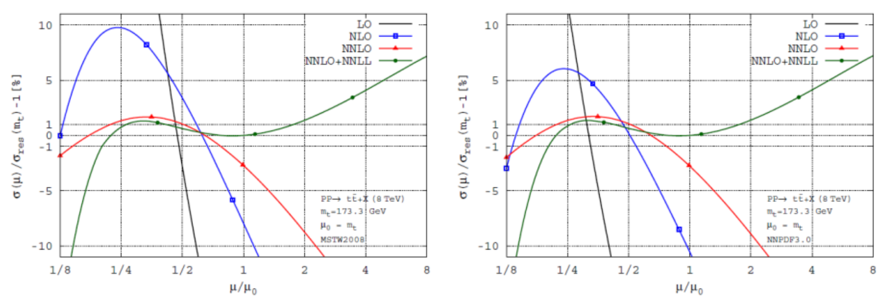
$\sigma_{t\bar{t}} = 832^{+40}_{-46}$ pb

Dynamical scales

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

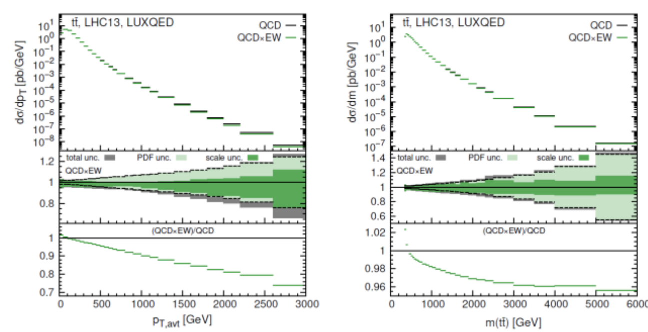
$$\mu_0 \sim m_t\,,$$
$$\mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2}\,,$$
$$\mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2}\,,$$
$$\mu_0 \sim H_T' = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + \sum_i p_{T,i}\,,$$
$$\mu_0 \sim E_T = \sqrt{\sqrt{m_t^2 + p_{T,t}^2}\sqrt{m_t^2 + p_{T,\bar{t}}^2}}\,,$$
$$\mu_0 \sim H_{T,\text{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2}\,,$$
$$\mu_0 \sim m_{t\bar{t}}\,,$$

Czakon, Heymesb, Mitov' 16



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

QCD and EW



Top-quark pair-production and decay at high precision

Gao, Papanastasiou 1705.08903
Papanastasiou 1801.01020

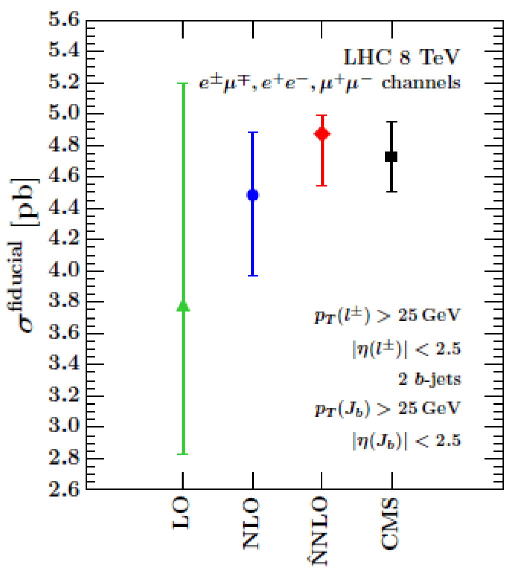
In NWA

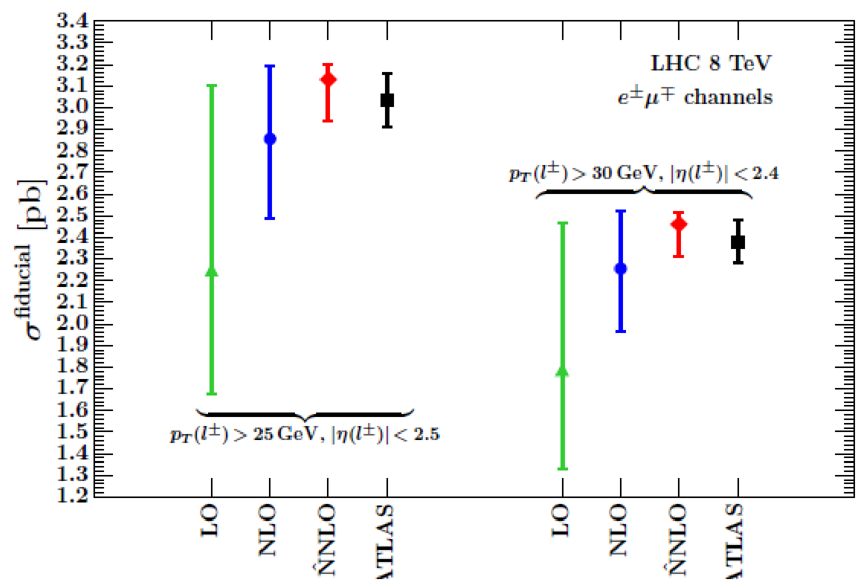
$$d\sigma = d\sigma_{t\bar{t}} \times \frac{d\Gamma_{t\to bl^+\nu_l}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\to \bar{b}l'^- \bar{\nu}_{l'}}}{\Gamma_t}$$

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

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

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





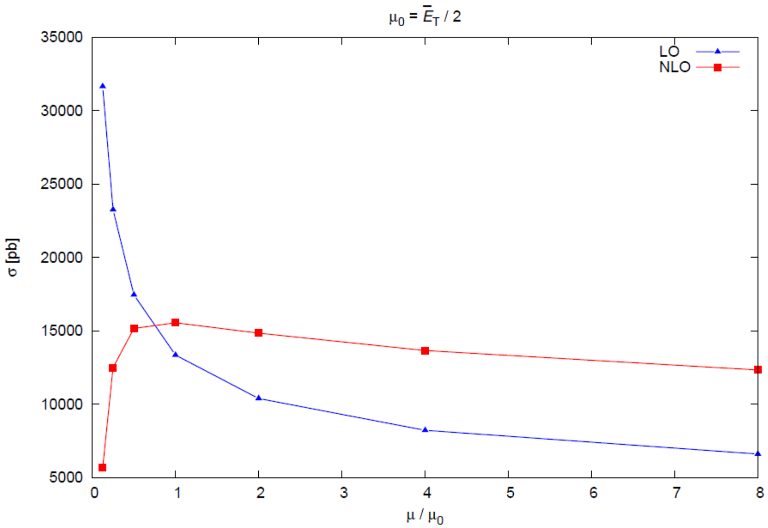
NNLO top width 1.322 GeV for 172.5 GeV top mass

Gao, Li, Zhu 1210.2808

Denner, Pellen 1711.10359 Jan 2018

First complete NLO QCD computation for the process

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



$$\mu_0 = \overline{E_T}/2 = \frac{1}{2}\sqrt{\sqrt{m_t^2 + p_{T,t}^2}\sqrt{m_t^2 + p_{T,\bar{t}}^2}}$$

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

Fiducial cross section

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

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

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

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

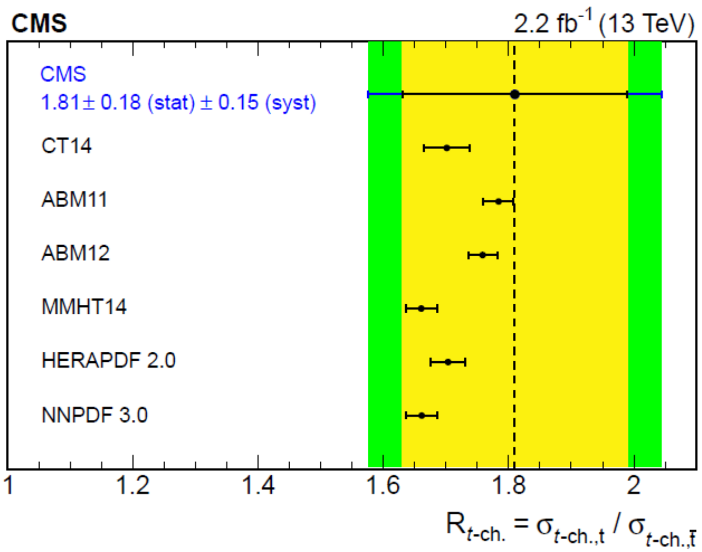
Kidonakis (2010) 1001.5034

Theory results in a reasonable agreement with LHC at 13 TeV

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

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

NNLO 213 pb



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

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

NLO+NNLL 76 pb

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)

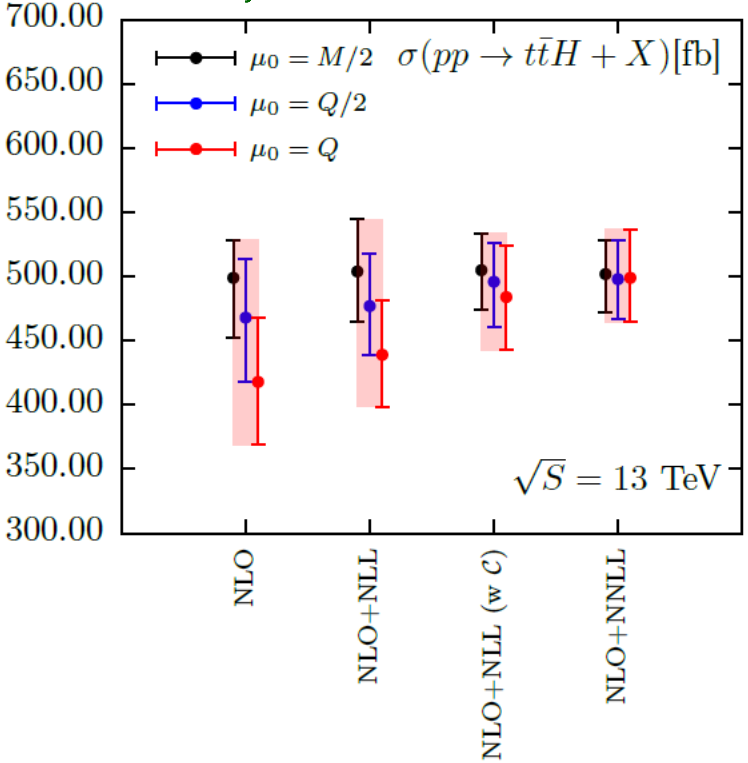
$$\sigma(t\bar{t}W) = 0.98^{+0.23}_{-0.22}\ (\text{stat.})^{+0.22}_{-0.18}\ (\text{sys.})\ \text{pb}$$

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

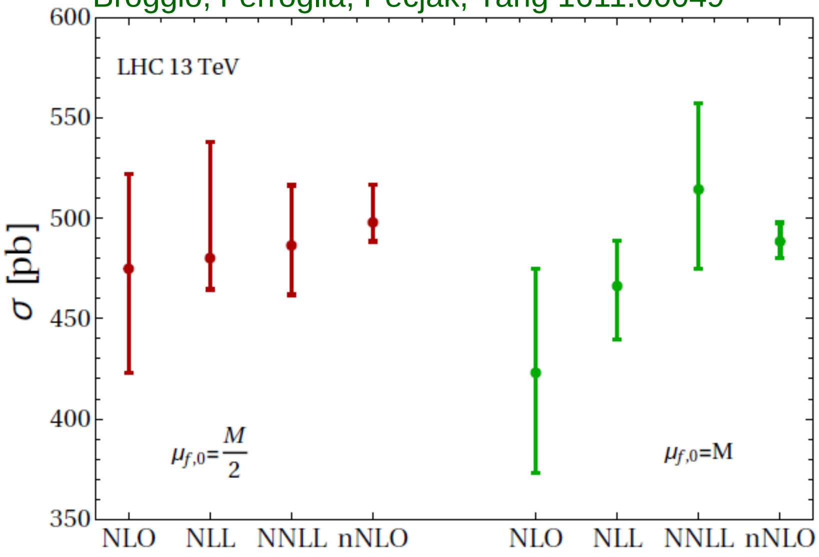
ttH at 13 TeV

Vryonidou 1712.0993

Kulesza, Motyka, Stebel, Theeuwes 1704.03363



Broggio, Ferroglia, Pecjak, Yang 1611.00049



ATLAS 1712.0889 $\sigma(t\bar{t}H) = 790^{+230}_{-210}$ fb

Top quark mass

Most precisely known quark mass !

Three top quark masses in PDG

K.Melnikov

t-Quark Mass (Direct Measurements). PDG average **173.1 ± 0.6 GeV**

t-Quark Mass from Cross-Section Measurements (MS-bar mass) **160.0 ± 4.8 GeV**

t-Quark Pole Mass from Cross-Section Measurements.
PDG average **173.5±1.1 GeV**

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

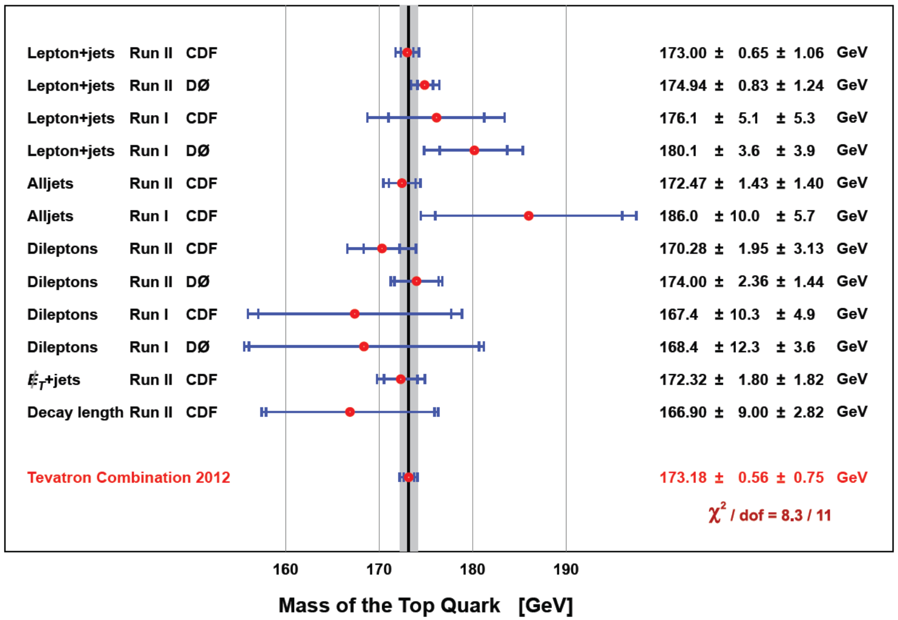
$$\Delta \overset{?}{=} \begin{cases} \frac{\Delta}{m} \approx 0.13\% \\ \frac{\Gamma}{m} \approx 0.8\% \\ \frac{\alpha_s}{\pi} \approx 3.7\% \end{cases}$$

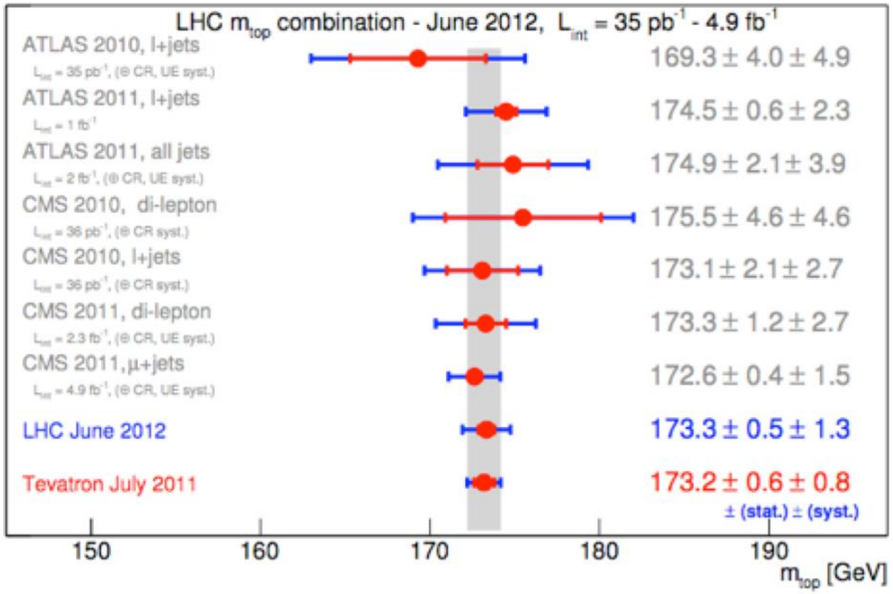
P. Uwer
K.Melnikov
P.Nason
G. Corcella...

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

Latest LHC values: CMS 172.44 ± 0.48 GeV, ATLAS 172.51 ± 0.50 GeV

Top quark mass

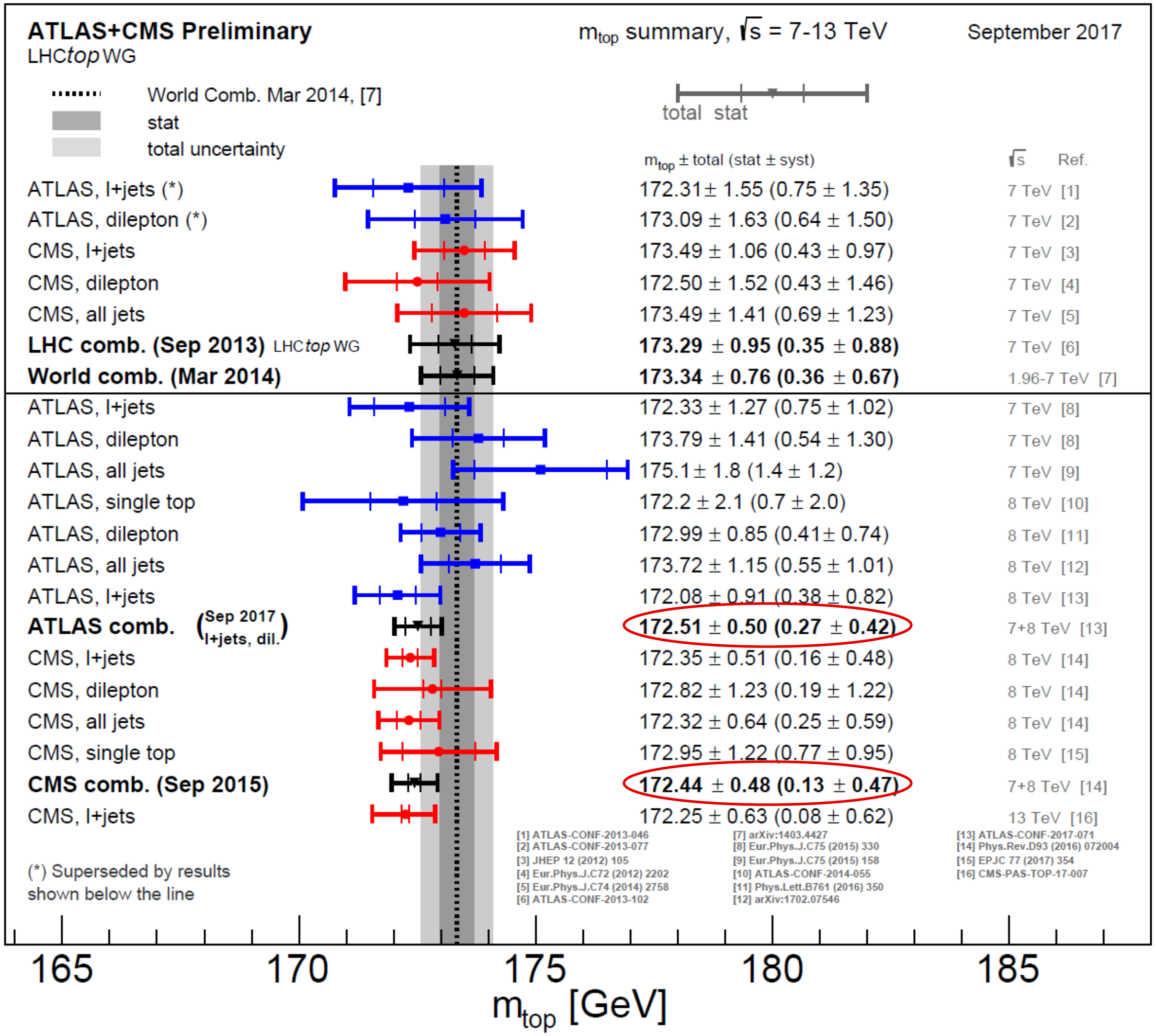




$$m_t^{\rm comb} = 173.18 \pm 0.56\,({\rm stat}) \pm 0.75\,({\rm syst})\ \ {\rm GeV}$$
$$= 173.18 \pm 0.94\ {\rm GeV}$$

LHC: $$m_{\rm top} = 173.3 \pm 0.5\ ({\rm stat}) \pm 1.3\ ({\rm syst})\ \ {\rm GeV}$$
$$= 173.3 \pm 1.4\ {\rm GeV}$$

Top quark mass



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

Top quark width measurement in most cases is done under assumption of the SM top

$$\Gamma_t = 2.0^{+0.47}_{-0.43}\ \mathrm{GeV}$$ D0 Collaboration (2012, 1201.4151)

$$\Gamma_t = 1.36^{+0.14}_{-0.11}\ \mathrm{GeV}$$ CMS Collaboration (2014, 1404.2292)

$$\Gamma_t = 1.76 \pm 0.33\ (\mathrm{stat.})\ ^{+0.79}_{-0.68}\ (\mathrm{syst.})\ \mathrm{GeV}$$ ATLAS Collaboration (2017, 1709.04207)

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.

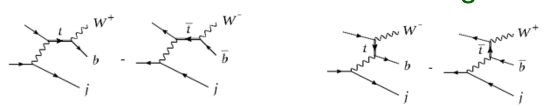
In case of the top quark there are two valuable differences:

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.

Giardino, Zhang 1702.06996
Zhang 1711.09592

New proposal – ratio on resonant and non-resonant asymmetries



One-sigma exclusion limits at 13 TeV

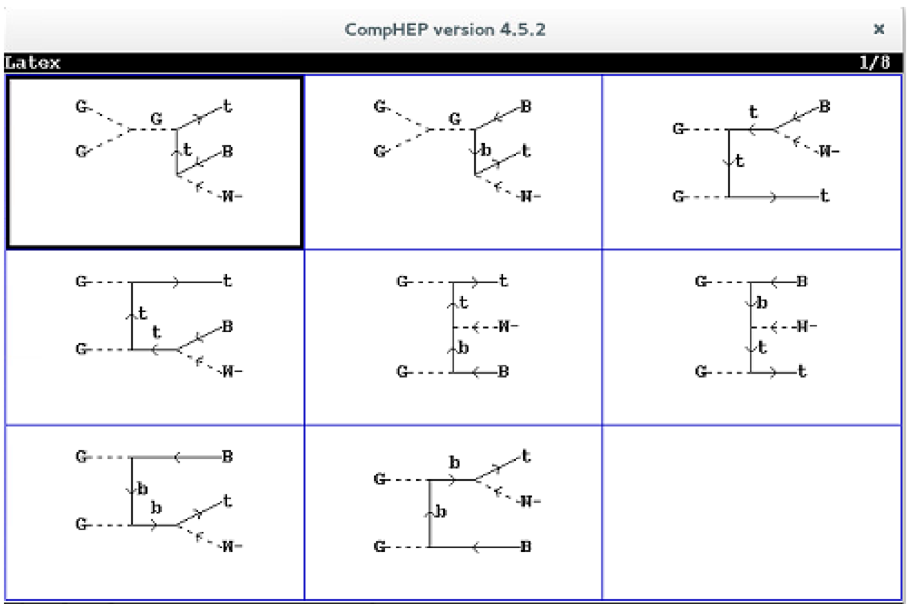
Luminosity [fb^{-1}]	30	300	3000
Limits [GeV]	[0.40,2.30]	[1.01,1.73]	[1.14,1.60]

Baskakov, Boos, Dudko' 2017, 2018

We propose to compute complete gauge invariant set of diagrams and investigate sensitivity in measuring deviations from the SM top quark width coming from different kinematical regions

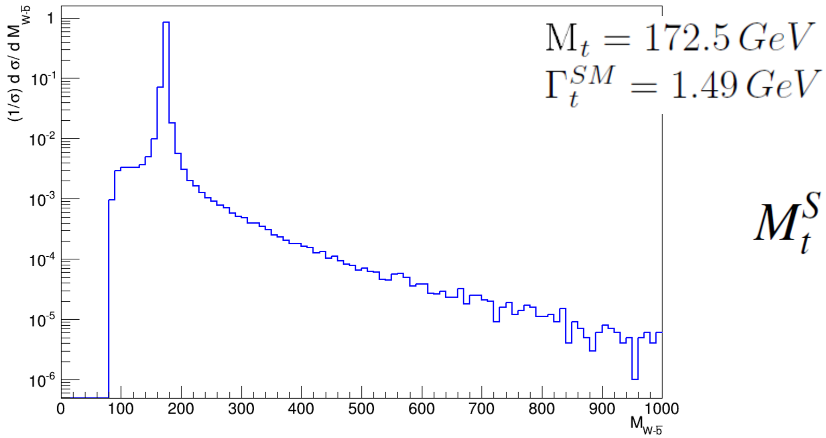
To demonstrate the main idea we consider first the process

$$gg \to tW^-\bar{b}$$



Complete gauge invariant set of diagrams include top pair and single top

Definitions



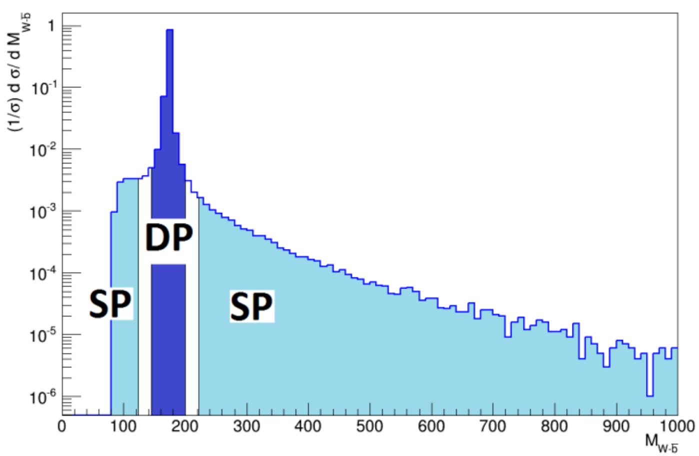
We define 2 kinematic regions.

Double pole (DP):

$$M_t^{SM} - n \cdot \Gamma_t^{SM} \leq M_{W-\bar{b}} \leq M_t^{SM} + n \cdot \Gamma_t^{SM}$$

Single pole (SP):

$$M_{W-\bar{b}} \leq M_t^{SM} - k \cdot \Gamma_t^{SM} \quad or \quad M_t^{SM} + k \cdot \Gamma_t^{SM} \leq M_{W-\bar{b}}$$



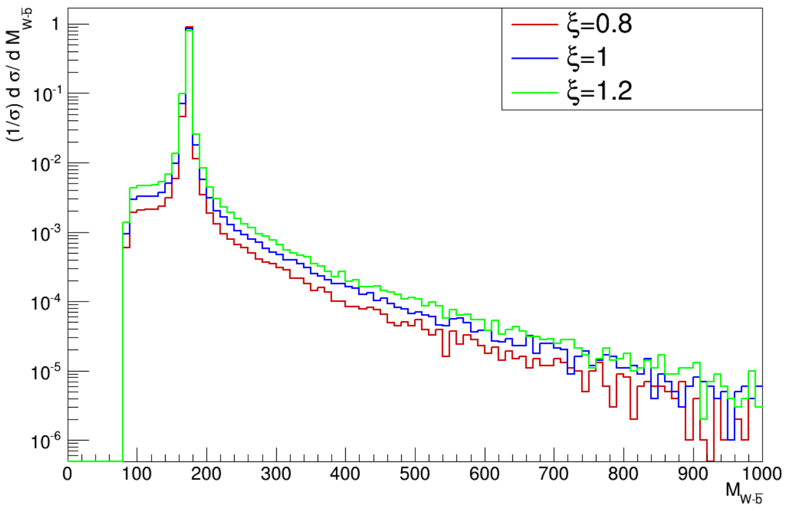
n, k are integer numbers and define boundary position

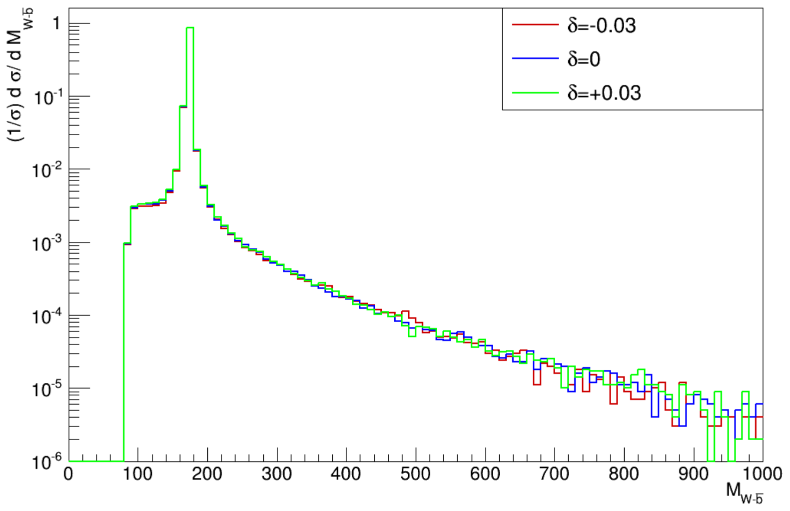
Top quark width parametrization

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

ξ - coupling rescaling

$\Delta = \delta \cdot \Gamma_t^{SM}$ - additional contributions, decay modes

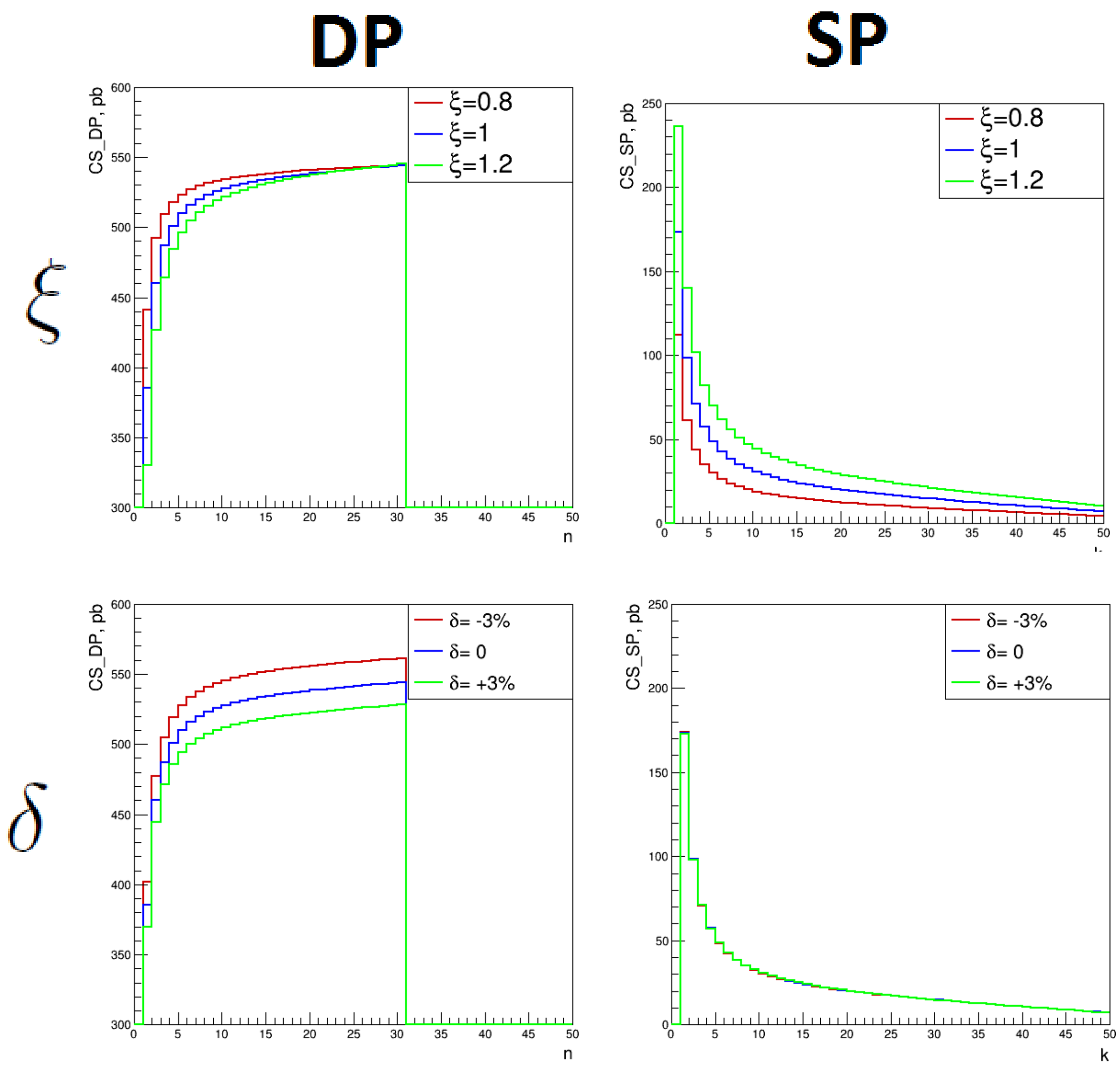




as expected ξ changes shape of the distribution mostly in SP region

Δ affects mostly the distribution in DP region

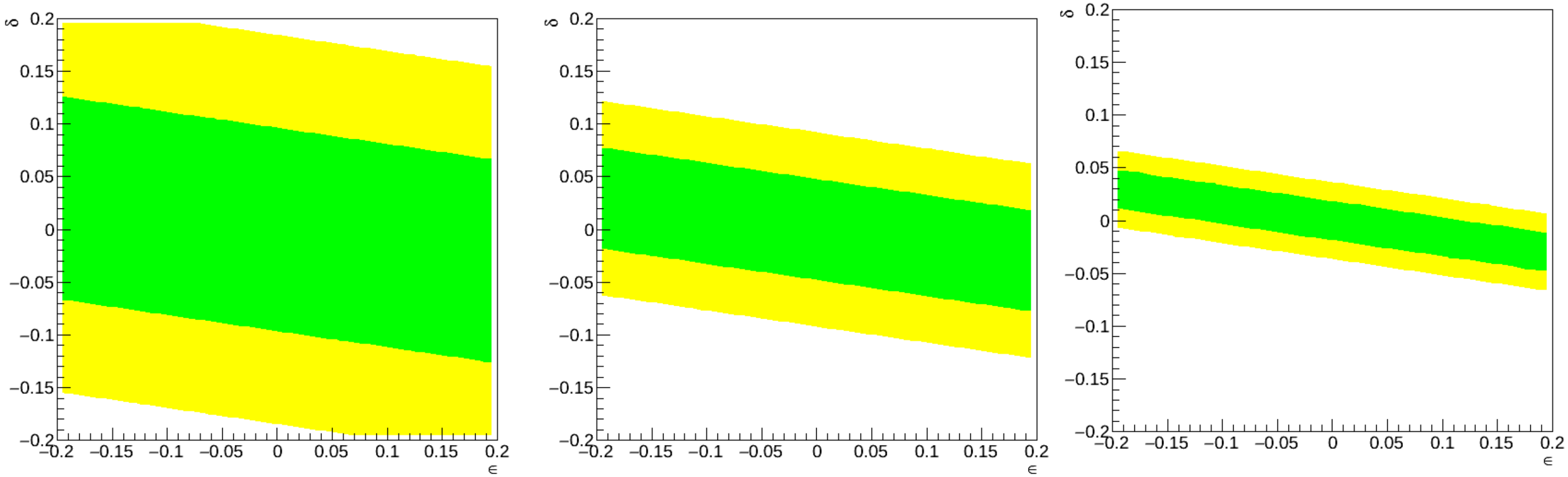
Cross sections in the DP and SP regions depending on parameters



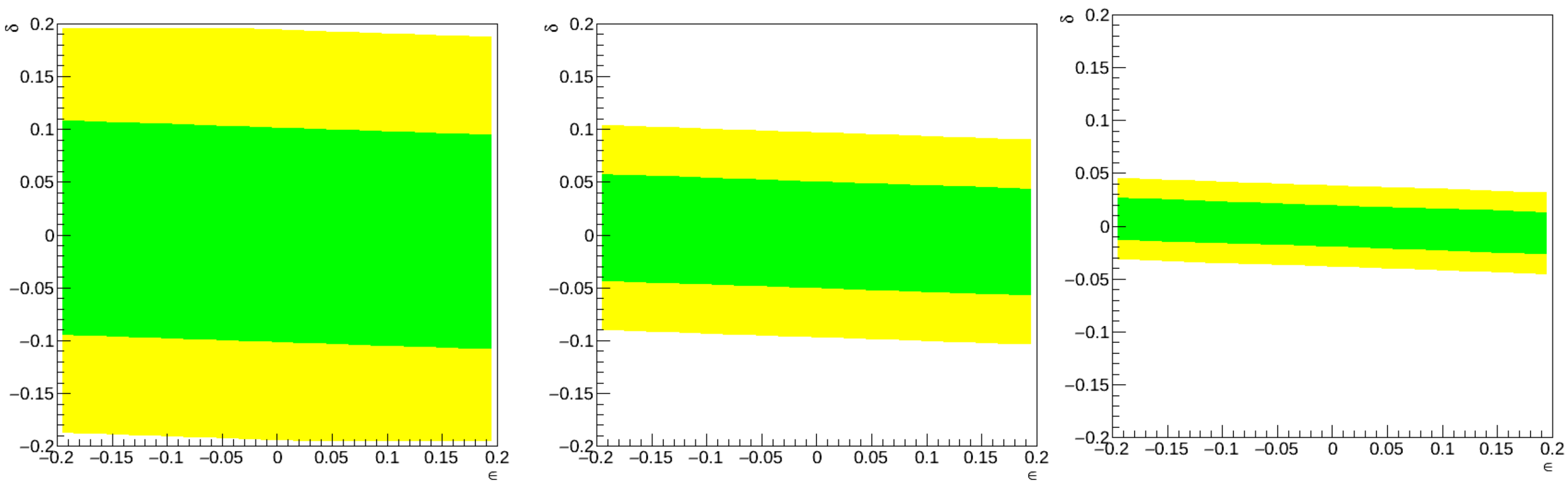
DP and SP depend differently on ξ and δ

DP fit, uncertainty of 10, 5, 2 %

DP, n = 5

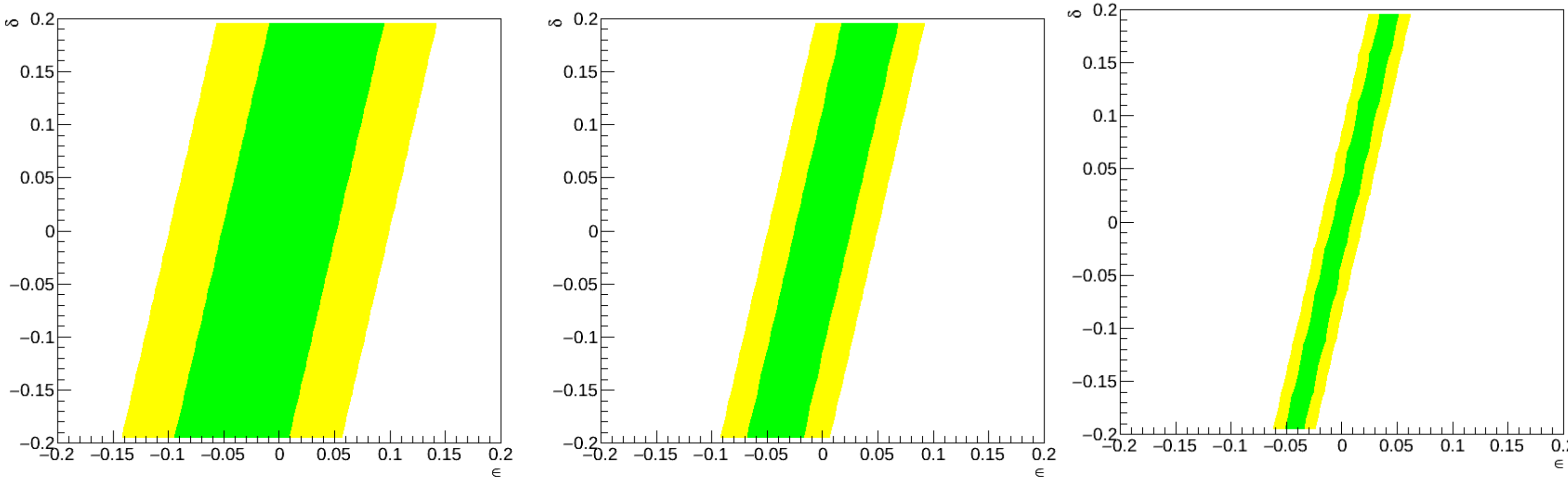


DP, n = 15

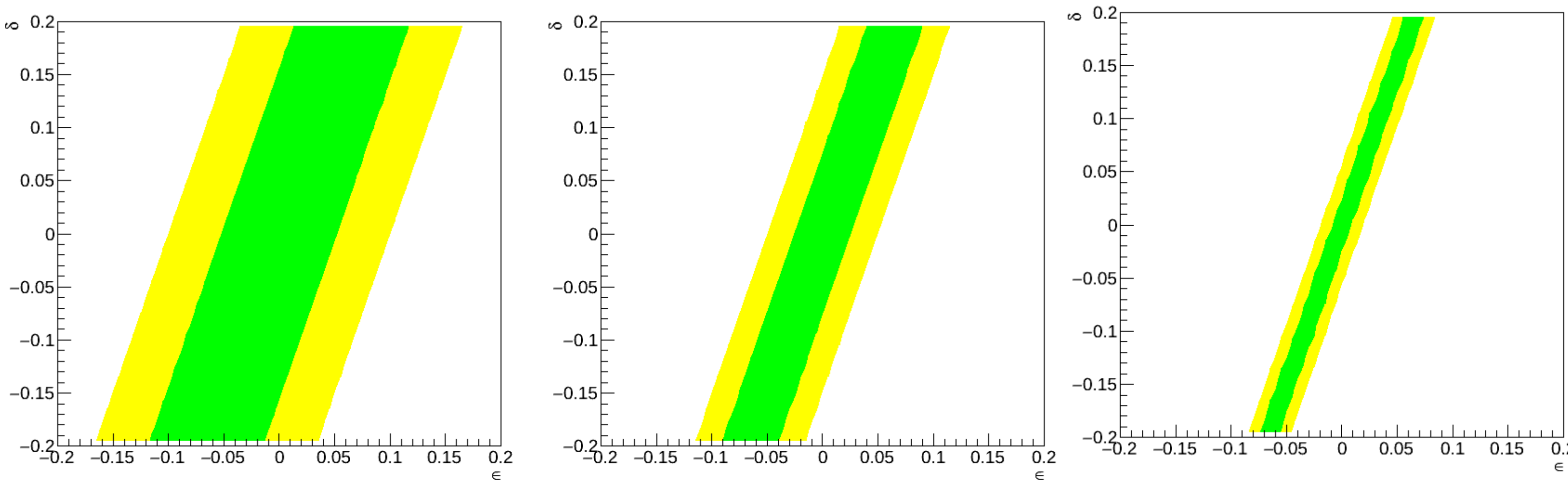


SP fit, uncertainty of 10, 5, 2 %

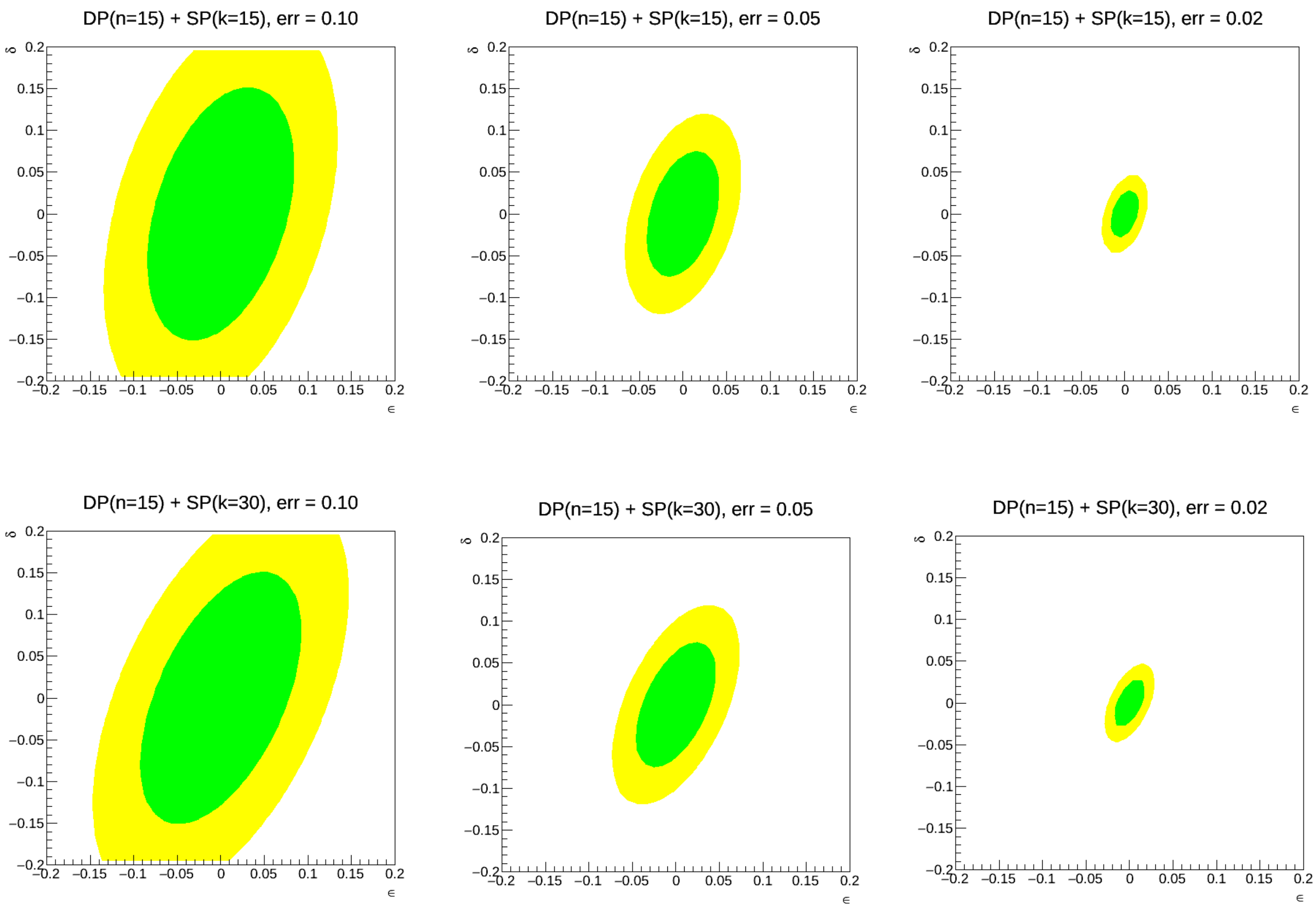
SP, k = 15



SP, k = 30



Combined fit, assuming an uncertainty of 10, 5, 2 %



29 % 14% 6% for Γ_t

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

DP - Double pole region

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

SP - Single pole region

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

$$or$$

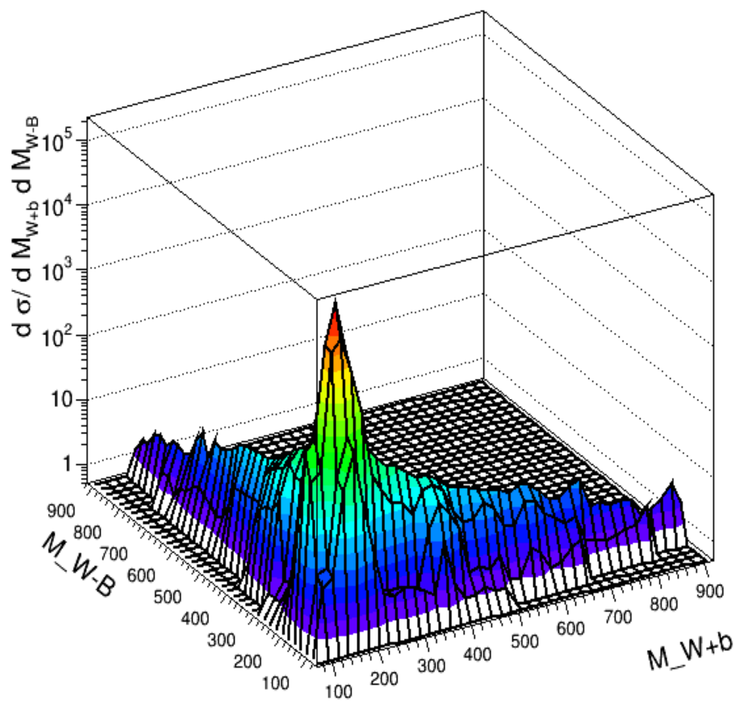
$$\left(M_t^{SM} - n\cdot\Gamma_t^{SM} \le M_{W^+b} \le M_t^{SM} + n\cdot\Gamma_t^{SM}\right) and \left(M_{W^-\bar{b}} \le M_t^{SM} - k\cdot\Gamma_t^{SM} \; or \; M_t^{SM} + k\cdot\Gamma_t^{SM} \le M_{W^-\bar{b}}\right)$$

NP - No pole region

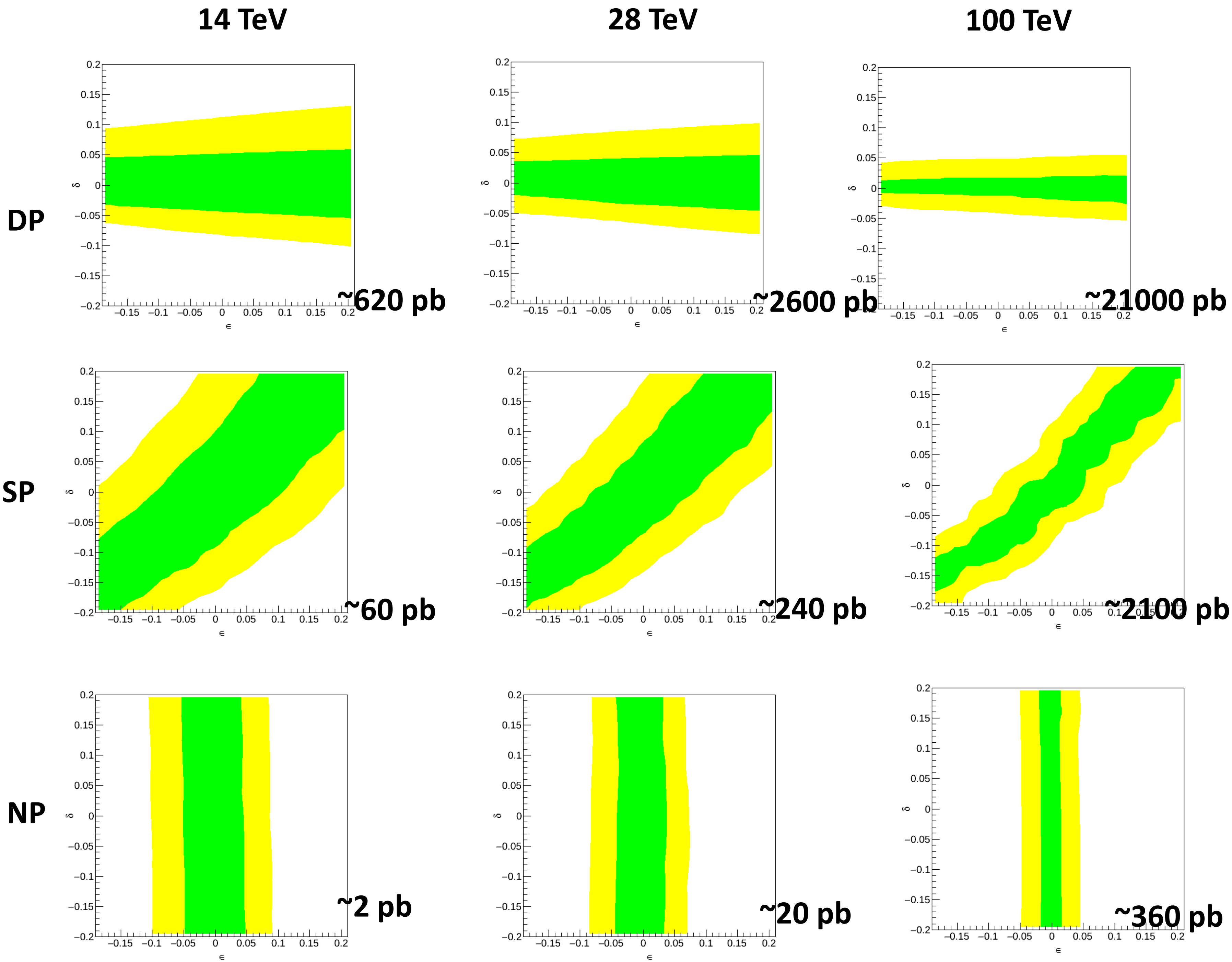
$$\left(M_{W^-\bar{b}} \le M_t^{SM} - k\cdot\Gamma_t^{SM} \quad or \quad M_t^{SM} + k\cdot\Gamma_t^{SM} \le M_{W^-\bar{b}}\right)$$

$$and$$

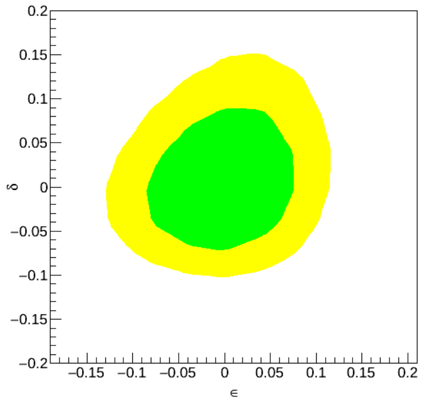
$$\left(M_{W^+b} \le M_t^{SM} - k\cdot\Gamma_t^{SM} \quad or \quad M_t^{SM} + k\cdot\Gamma_t^{SM} \le M_{W^+b}\right)$$



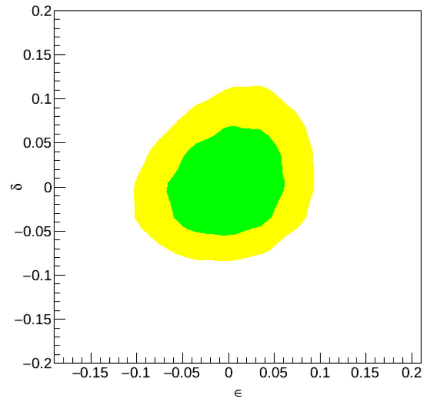
On next slides results for n=k=15


14 TeV
28 TeV
100 TeV
DP
SP
NP
~620 pb
~2600 pb
~21000 pb
~60 pb
~240 pb
~2100 pb
~2 pb
~20 pb
~360 pb
δ
ϵ

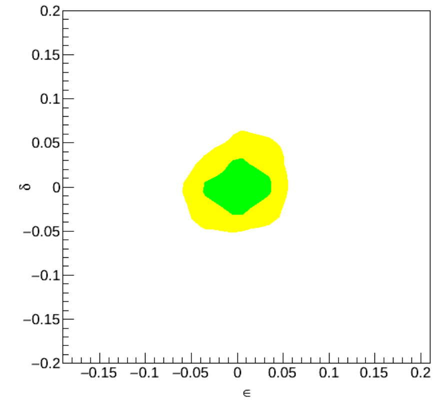
14 TeV



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

Several issues – choice of operator basis, validity of computation for a particular observable, simultaneous analysis of 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

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

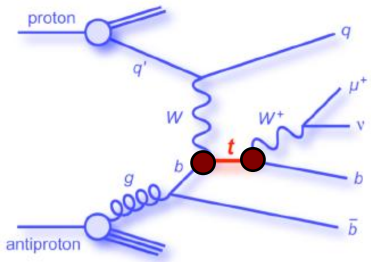
where $f_{LV} = V_{tb} + C_{\phi q}^{(3,3+3)*}\frac{v^2}{\Lambda^2}, \quad f_{RV} = \frac{1}{2}C_{\phi\phi}^{33*}\frac{v^2}{\Lambda^2}, \quad f_{LT} = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}, \quad f_{RT} = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}$

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

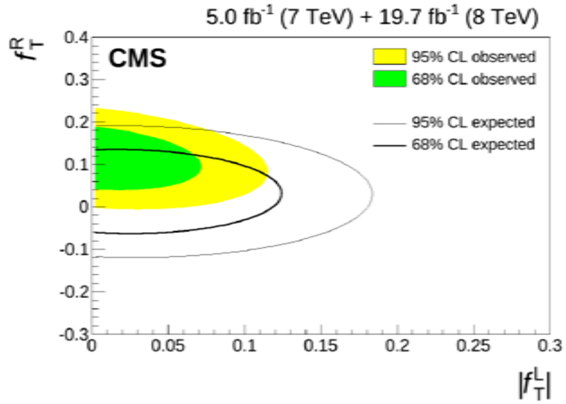
Natural size $|1-f_L^V|$, $f_R^V \sim v^2/\Lambda^2$

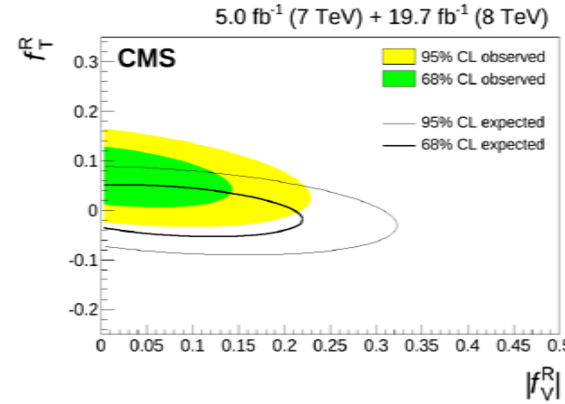
Natural size f_L^T, $f_R^T \sim v^2/\Lambda^2$

Anomalous Wtb couplings

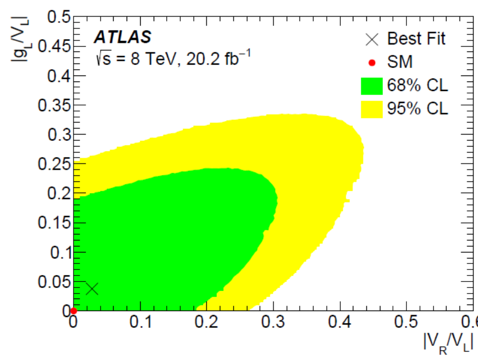


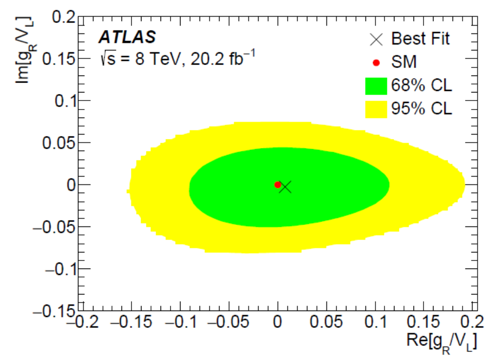
CMS limits



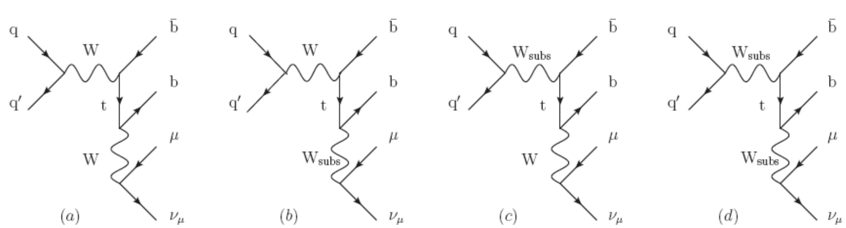


ATLAS limits





New method of modeling with subsidiary gauge fields corresponding to each anomalous coupling

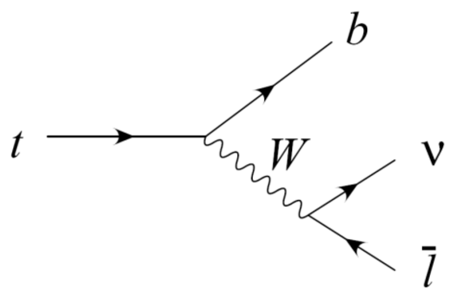


Boos, Bunichev, Dudko, Perfilov
Int. J. Mod. Phys. A 32, 1750008 (2016)

Spin correlations in single top

Yadzabek, Kuhn

V-A vertex structure in SM



$$d\Gamma \sim |\mathcal{M}|^2 \sim (t + ms)\cdot \ell b \cdot \nu$$

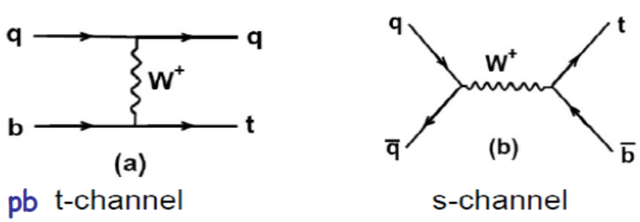
where in the top-quark rest frame, the spin four-vector $s = (0, \hat{s})$ $\hat{s}$ - a unity vector that defines the spin quantization axis of the top quark. In the top quark rest frame:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \cos\theta_\ell)$$

Hence the charged lepton tends to point along the direction of top spin

Single top production as top decay back in time

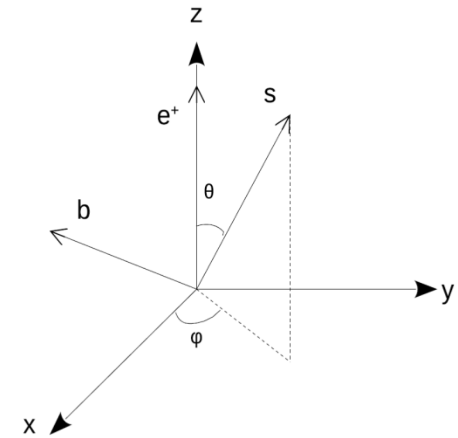
Mahlon, Parke;
Boos, Sherstnev



Down-type component of weak isospin doublet - d-quark in production plays a role of lepton in decay

Polarized top quark differential decay width.
Most general case with complex anomalous parameters.

Boos, Bunichev 2018



Integrating over b and v 4-momenta we have:

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

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

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

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

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

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

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

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

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

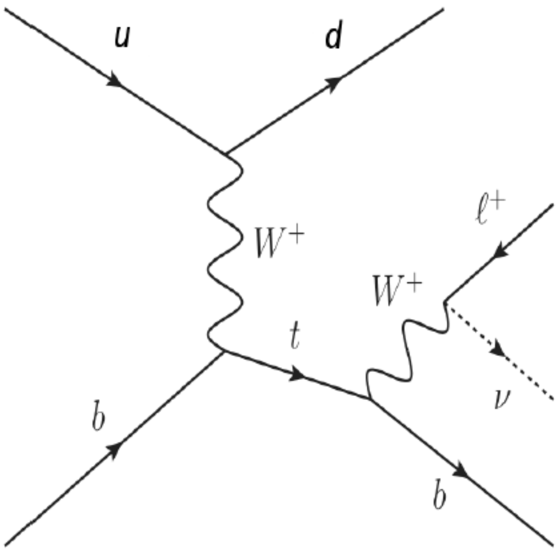
where:

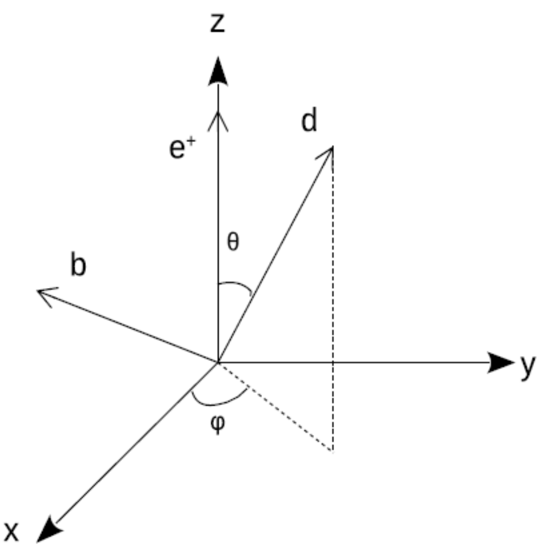
$$c_{e^+} = \sqrt{(E_{max}-E_{e^+})\cdot(E_{e^+}-E_{min})},\quad E_{max}=m_t/2,\quad E_{min}=m_W^2/(2m_t)$$

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

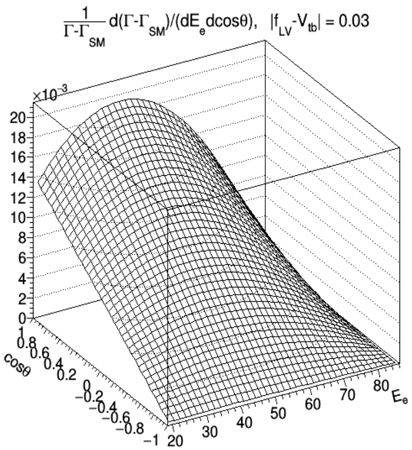
In the single top quark production (t-channel) top is produced in the SM highly polarized in the direction the d-quark (light out going jet). It should remain true for the case of small anomalous contributions.

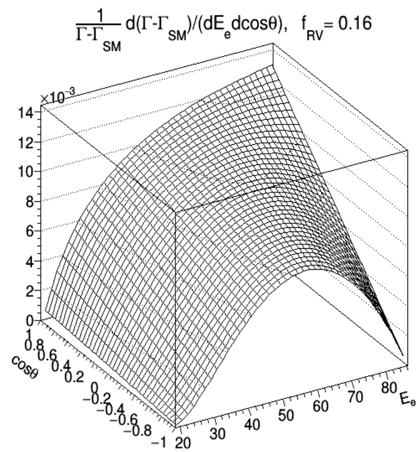
So, one expects the same (similar) forms of surfaces for 2->4 complete process if one takes the same angular variables chosen d-quark direction instead of s.

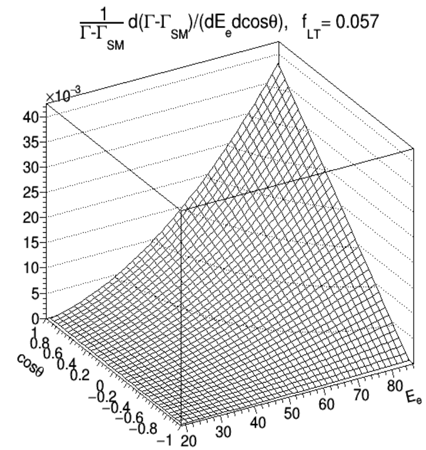


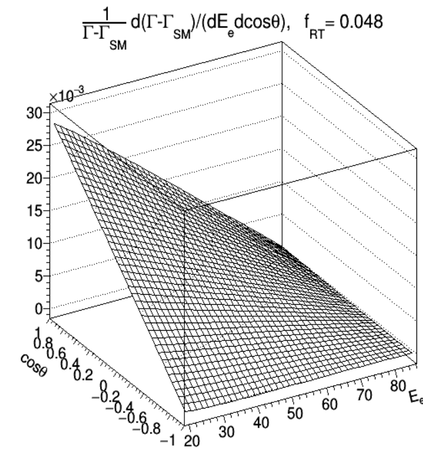


Distributions predicted by the analytic formula

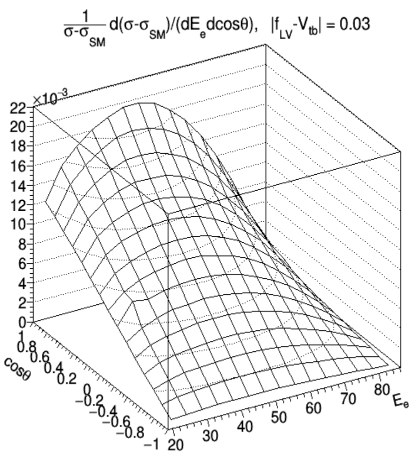


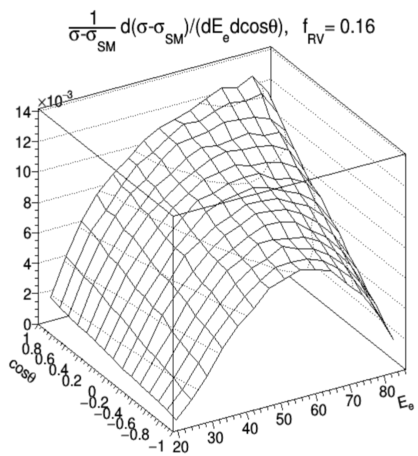


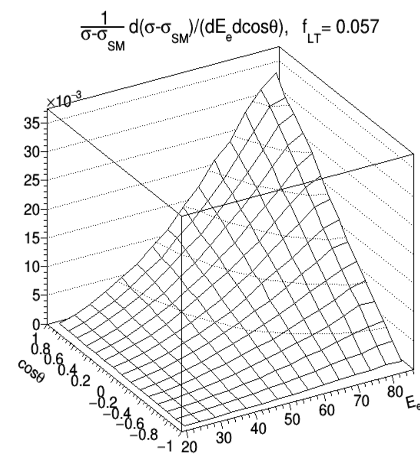


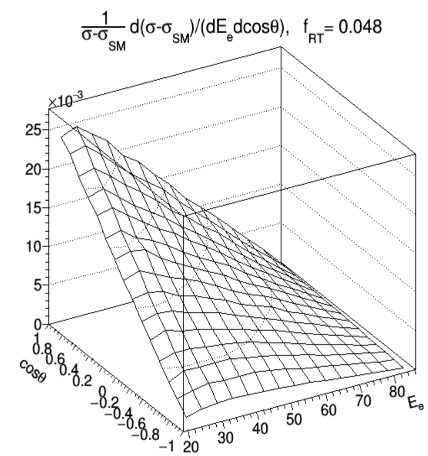


Monte-Carlo simulation of the complete t-quark production and decay process
(it contains all t-channal subprocesses and also contains anomalous couplings both in production and in decay)









Two dimensional distribution shapes are significantly different for different anom. couplings

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:

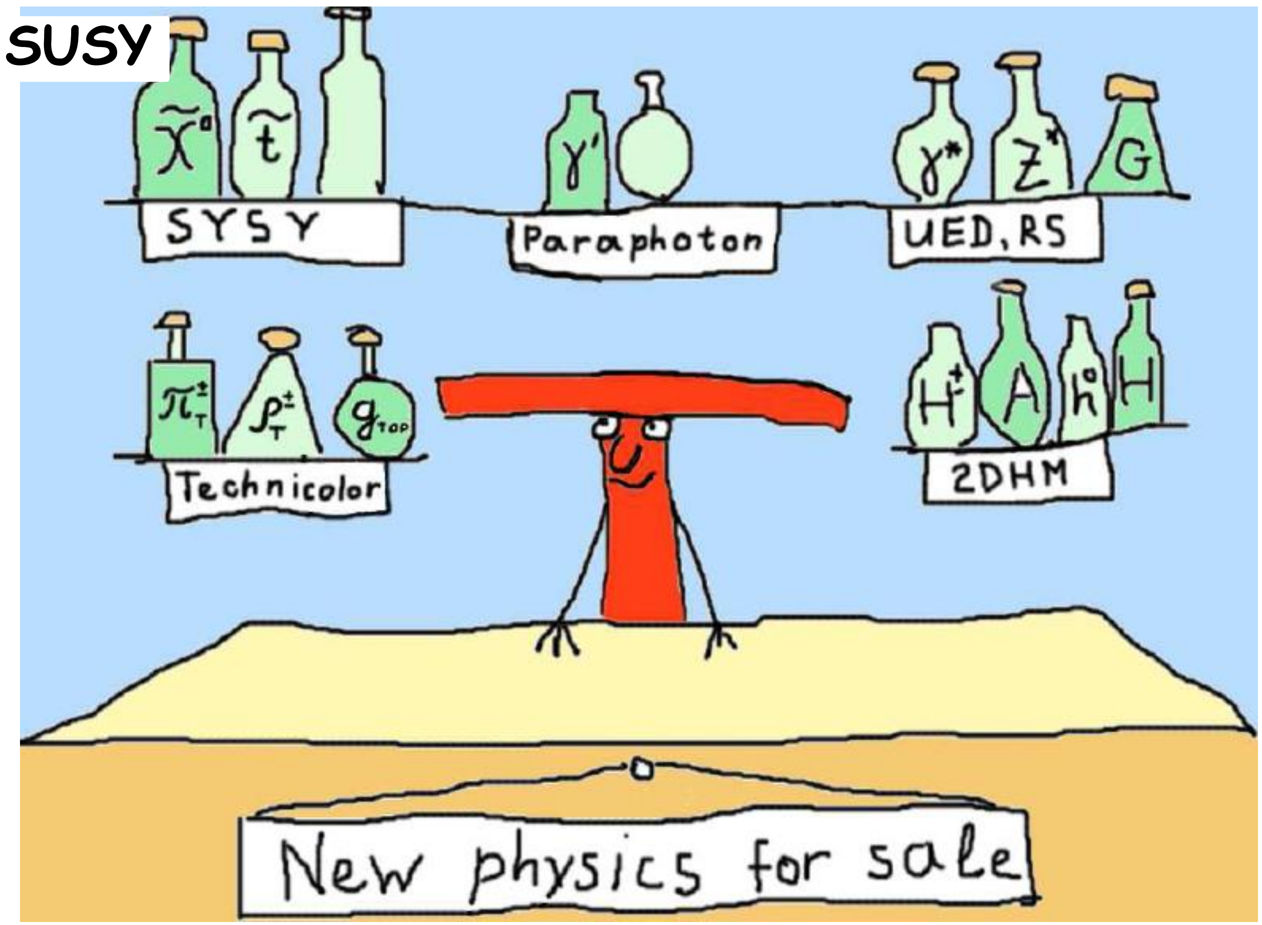
L, fb^{-1}	$\Delta\, Re\, f_{LV}$, $\Delta\, Re\, f_{RV}$	$\Delta\, Re\, f_{LV}$, $\Delta\, Re\, f_{LT}$	$\Delta\, Re\, f_{LV}$, $\Delta\, Re\, f_{RT}$
10	0.0025 0.02	0.002 0.01	0.003 0.003
300	0.0005 0.003	0.0004 0.0015	0.001 0.001
3000	0.0001 0.0005	0.0001 0.0004	0.0003 0.0003

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

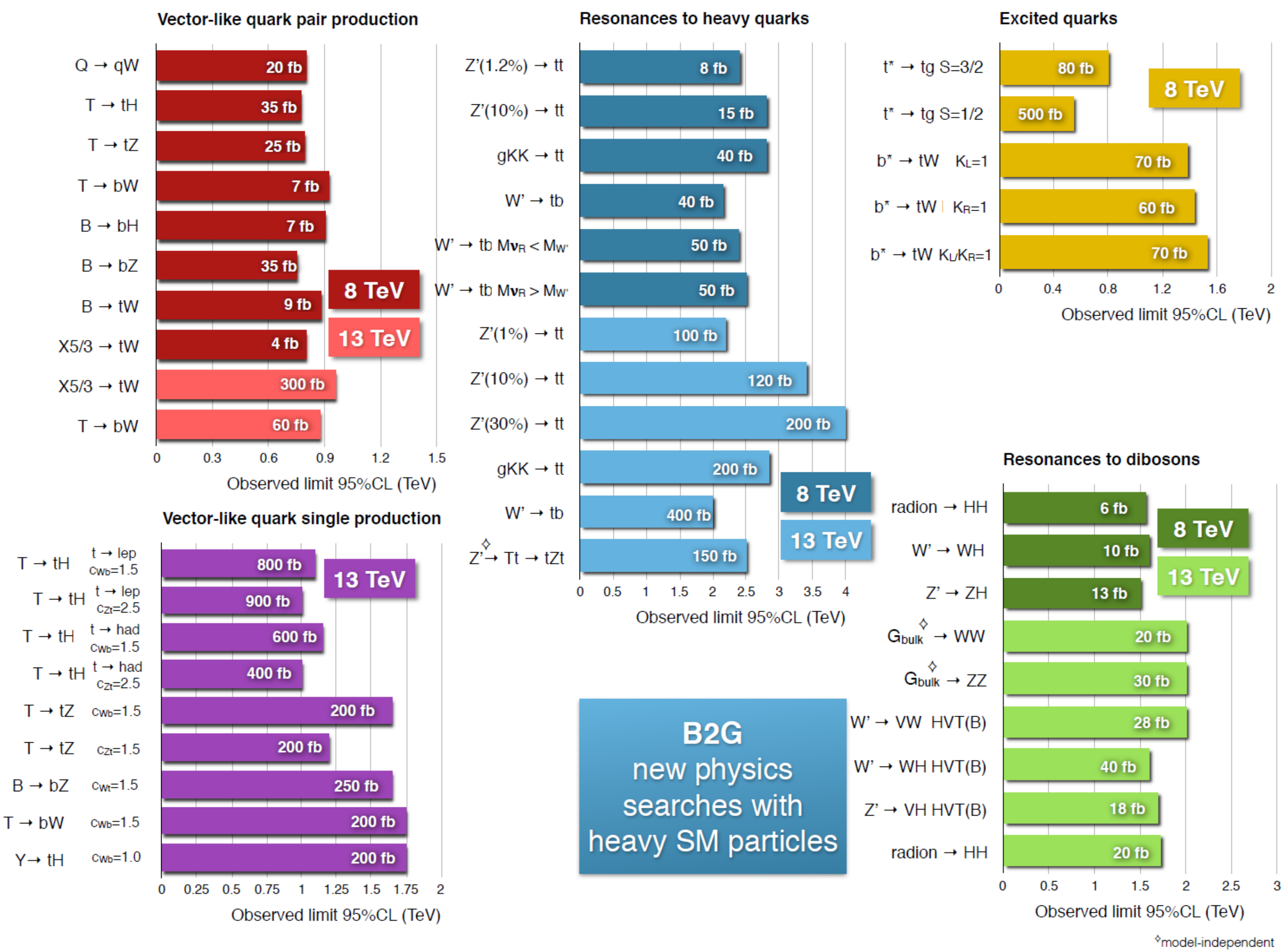
L, fb^{-1}	$\Delta\, Re\, f_{LV}$ $\Delta\, Im\, f_{LV}$, $\Delta\, Im\, f_{RT}$	$\Delta\, Re\, f_{LV}$ $\Delta\, Im\, f_{RV}$, $\Delta\, Im\, f_{LT}$
10	0.002 0.025 0.025	0.002 0.04 0.05
300	0.0004 0.005 0.005	0.0004 0.01 0.01
3000	0.0002 0.001 0.001	0.0002 0.002 0.002

Searches above threshold

V.Bunichev



CMS limits



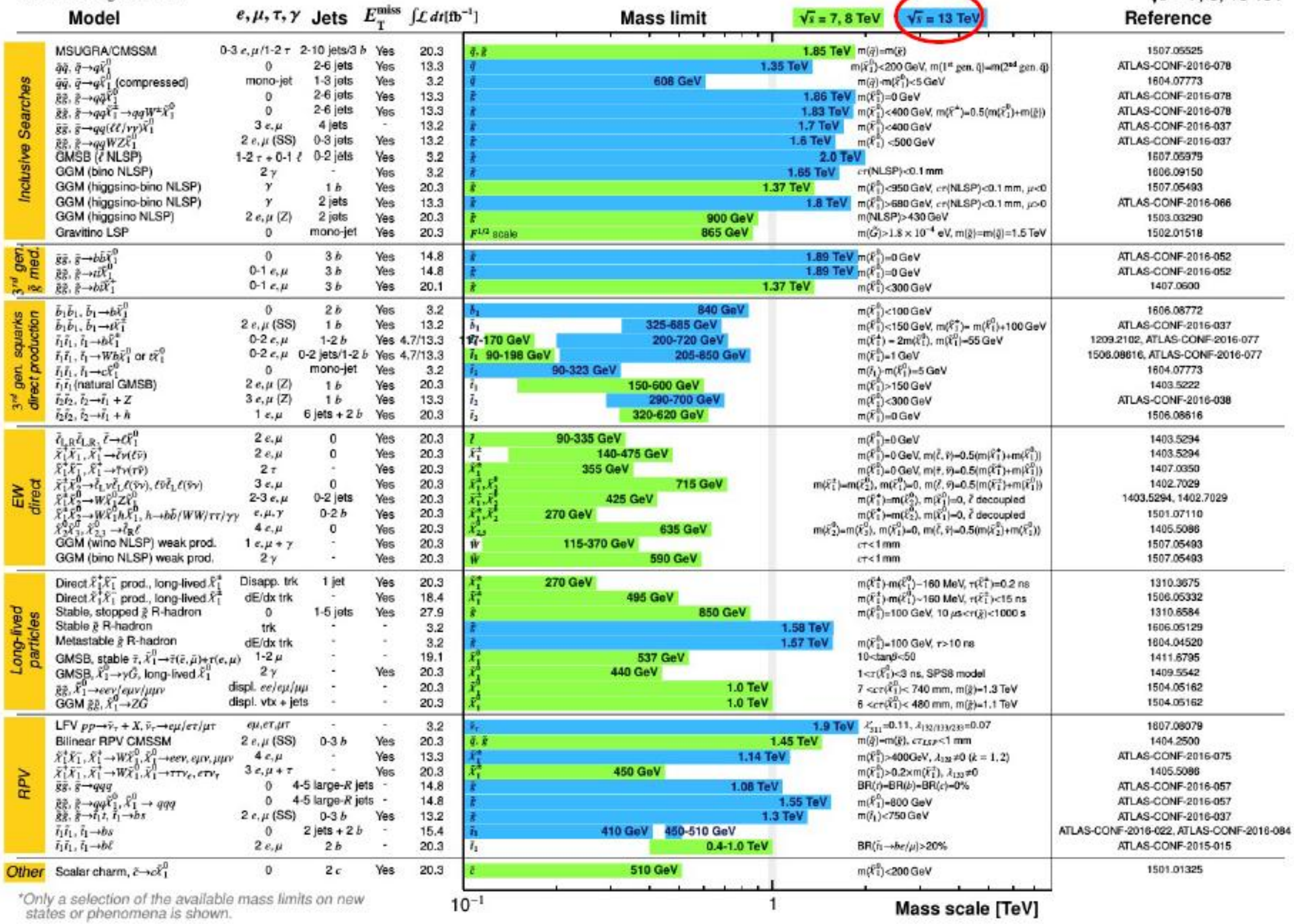
Vector-like quark pair production
Q → qW 20 fb
T → tH 35 fb
T → tZ 25 fb
T → bW 7 fb
B → bH 7 fb
B → bZ 35 fb
B → tW 9 fb
X5/3 → tW 4 fb
X5/3 → tW 300 fb
T → bW 60 fb
8 TeV
13 TeV
Observed limit 95%CL (TeV)
Vector-like quark single production
T → tH t → lep Cwb=1.5 800 fb
T → tH t → lep Czt=2.5 900 fb
T → tH t → had Cwb=1.5 600 fb
T → tH t → had Czt=2.5 400 fb
T → tZ Cwb=1.5 200 fb
T → tZ Czt=1.5 200 fb
B → bZ Cwt=1.5 250 fb
T → bW Cwb=1.5 200 fb
Y→ tH Cwb=1.0 200 fb
13 TeV
Observed limit 95%CL (TeV)
Resonances to heavy quarks
Z'(1.2%) → tt 8 fb
Z'(10%) → tt 15 fb
gKK → tt 40 fb
W' → tb 40 fb
W' → tb MνR < MW' 50 fb
W' → tb MνR > MW' 50 fb
Z'(1%) → tt 100 fb
Z'(10%) → tt 120 fb
Z'(30%) → tt 200 fb
gKK → tt 200 fb
W' → tb 400 fb
Z'→ Tt → tZt 150 fb
8 TeV
13 TeV
Observed limit 95%CL (TeV)
Excited quarks
t* → tg S=3/2 80 fb
t* → tg S=1/2 500 fb
b* → tW KL=1 70 fb
b* → tW KR=1 60 fb
b* → tW KL/KR=1 70 fb
8 TeV
Observed limit 95%CL (TeV)
Resonances to dibosons
radion → HH 6 fb
W' → WH 10 fb
Z' → ZH 13 fb
Gbulk → WW 20 fb
Gbulk → ZZ 30 fb
W' → VW HVT(B) 28 fb
W' → WH HVT(B) 40 fb
Z' → VH HVT(B) 18 fb
radion → HH 20 fb
8 TeV
13 TeV
Observed limit 95%CL (TeV)
model-independent
B2G
new physics
searches with
heavy SM particles

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

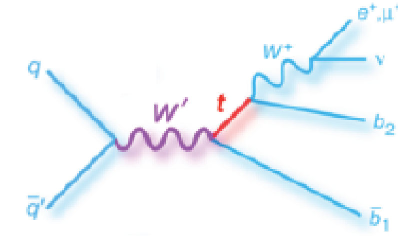
ATLAS Preliminary

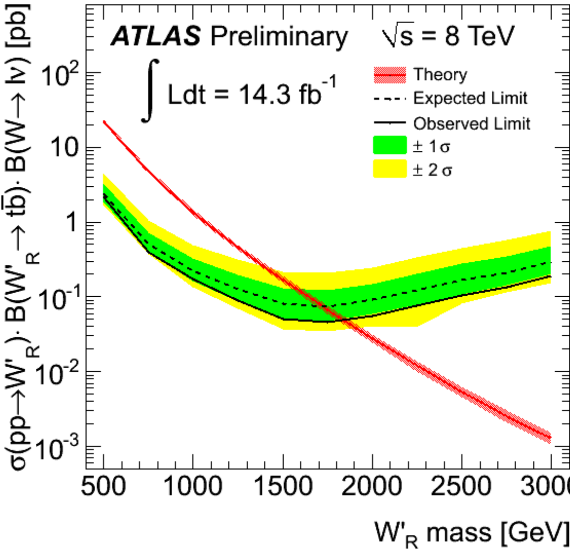
$\sqrt{s}$ = 7, 8, 13 TeV

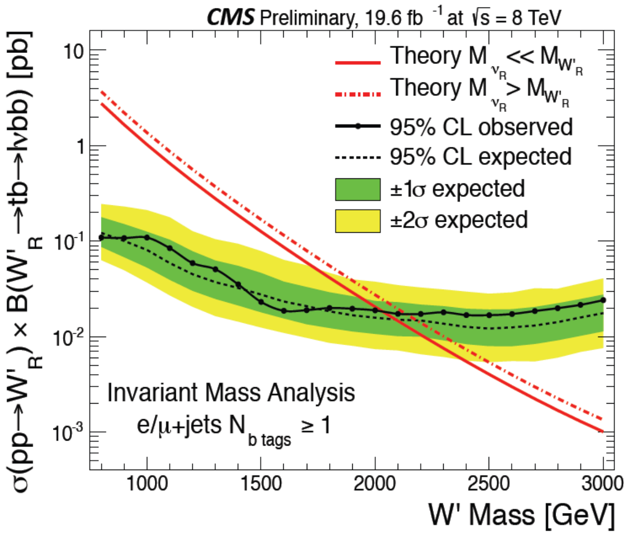


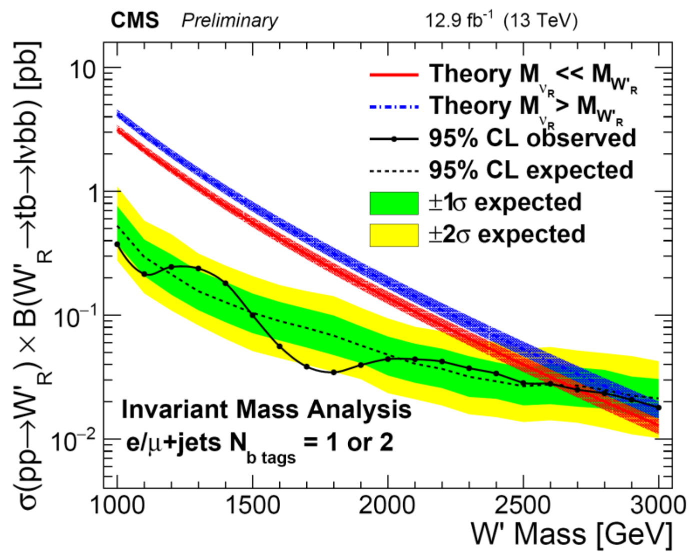
*Only a selection of the available mass limits on new states or phenomena is shown.

Searches for W' in top+b

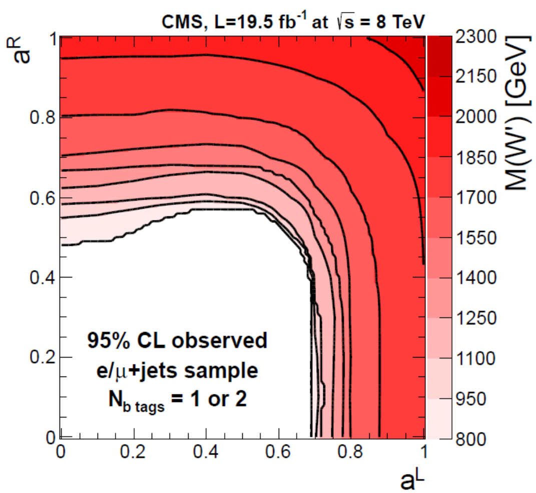


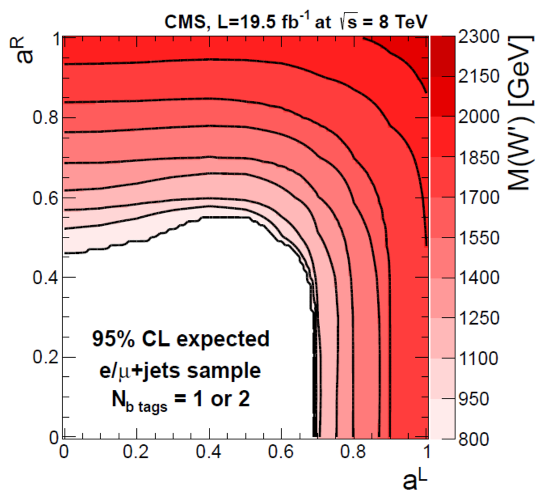






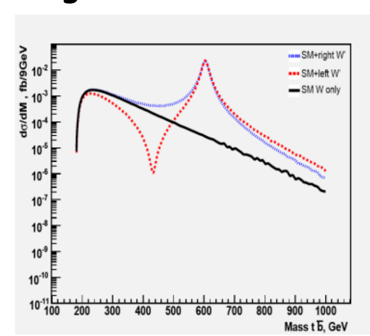
$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \overline{f}_i \gamma_\mu \left(a^{\mathrm{R}}_{f_i f_j} (1 + \gamma^5) + a^{\mathrm{L}}_{f_i f_j} (1 - \gamma^5) \right) W'^\mu f_j + \mathrm{h.c.}$$





E.B., Bunichev, Dudko, Perfilov

Negative interference



Concluding remarks

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

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

Thank you !