

# Probing top-quark width using b-jet charge asymmetry

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arXiv:1702.06996, with Pier Paolo Giardino

# The top width

- $\Gamma_t = 1.37$  GeV, but we never measure it well.
  - ▶ Exotic decay channels that cannot be detected in collider still allowed.
- Current limit:  $0.6 < \Gamma_t < 2.5$  GeV, 95% CL at 13 TeV  $13 \text{ fb}^{-1}$ 

*[CMS PAS TOP-16-019]*

  - ▶ Indirect bounds are available but not useful for constraining **new decay channels**
- Already **dominated by systematics**.
- This is not only about the width itself. The more important problem is that **cross sections measurements cannot be accurate**, because only measure

$$\sigma_{tot} \times \text{BR}(t \rightarrow bW) = \sigma_{tot} \frac{\Gamma(t \rightarrow bW)}{\Gamma_t}$$

# Outline

1 Idea

2 Background

3 b-charge tagging

4 Results

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# Idea

Like the Higgs width measurement, we want to

- Measure a resonance (**on-shell**), say  $bW^+ \rightarrow t \rightarrow bW^+$ , scales as  $\Gamma_t^{-1}$ .
- Measure the tail (**off-shell**) of the **same process**, independent of  $\Gamma_t^{-1}$ .
- The ratio of the two is a probe of  $\Gamma_t$ , (roughly) model-independent.

An alternative to the off-shell:

- Measure the same process but **opposite  $b$  charge**, which is a  $t$ -channel process.

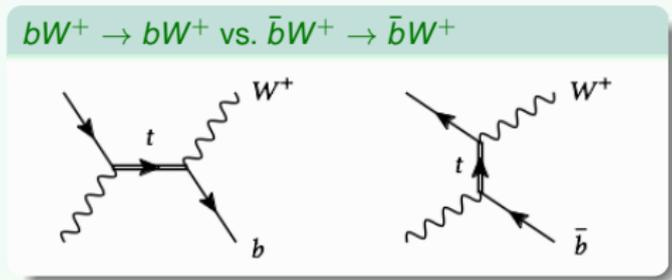
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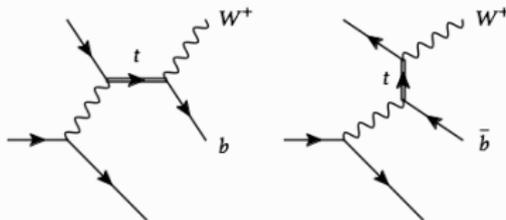
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$bW^+ \rightarrow bW^+$  vs.  $\bar{b}W^+ \rightarrow \bar{b}W^+$



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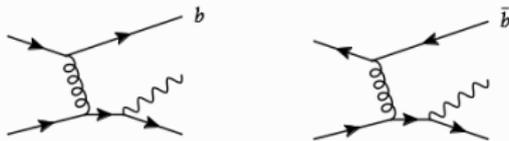
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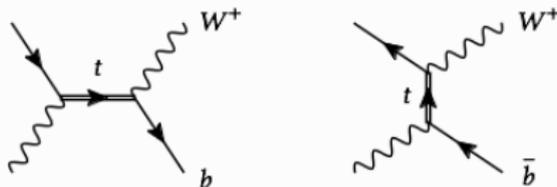
$bW^+ \rightarrow bW^+$  vs.  $\bar{b}W^+ \rightarrow \bar{b}W^+$ : background



The difficulty however is the QCD background.

# Why $b$ charge asymmetry

$bW^+ - \bar{b}W^+ = b$ -charge asymmetry



**Proposal** We measure the **difference** between  $bW$  and  $\bar{b}W$  scattering, which corresponds to a  **$b$ -charge asymmetry**.

**Reason** It removes almost **all background**, because:

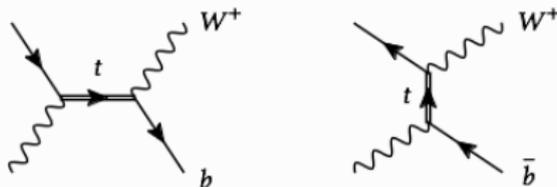
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- In a background process,  $b$  and  $\bar{b}$  remain symmetric.

**Bottom line** Only signal generates  **$b$ -charge asymmetry**.

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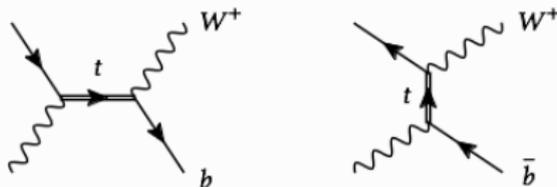
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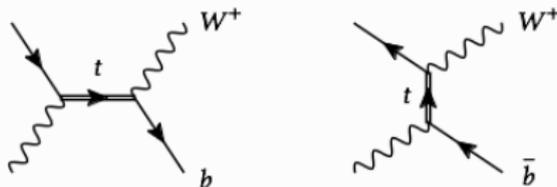
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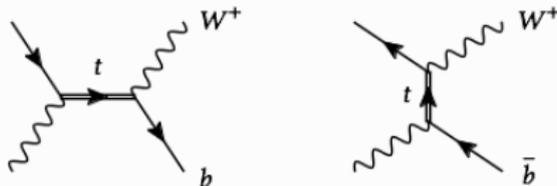
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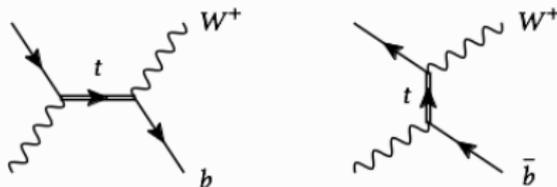
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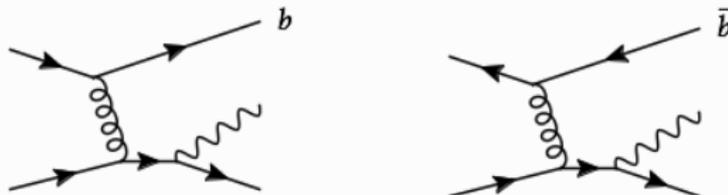
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# E.g. $Wbj$ through QCD



- $bW^{\pm}j$  and  $\bar{b}W^{\pm}j$  are equal at LO.
  - ▶ Charge conjugation on  $b$ -current:  $T \rightarrow -T^*$ ,  $\delta^{AB}$  is invariant.
- Partonic cross section are the same; PDF of  $b$  and  $\bar{b}$  are the same.
- NLO asymmetry is negligible.
- Other backgrounds:
  - ▶  $t\bar{t}$ ,  $tW$ : use CP symmetry.
  - ▶ EW: small and suppressed by kinematic cuts.

# SM cross sections: total rate vs. asymmetry

- Total cross section  $\sigma$ , and  $b$ -charge asymmetry  $\sigma^A = \sigma(b) - \sigma(\bar{b})$ , under the SM assumption.
- On-/off-shell regions are defined by a mass window cut  $m_t \pm 20$  GeV.
  - ▶ A 10 GeV smearing is added to  $bW$  mass.

		Signal+EW	EW only	QCD	$t\bar{t}$	$tW$
Off-shell	$\sigma$	5.08(2)	0.512(2)	4.68(3)	4.39(4)	1.04(1)
	$\sigma^A$	1.40(1)	0.009(1)	-0.04(3)	0.02(3)	-0.005(6)
On-shell	$\sigma$	32.61(5)	0.135(1)	1.32(2)	12.47(9)	1.56(1)
	$\sigma^A$	10.21(3)	0.002(1)	-0.02(1)	-0.07(8)	0.01(1)

**Table:** Total cross sections ( $\sigma$ ) and  $b$ -charge asymmetry ( $\sigma^A$ ) at the LHC 13 TeV, in pb, from signal and background processes. The first column includes both signal and EW background, and their interference.

## *b*-charge asymmetry

Define the asymmetric cross section:

$$\sigma^A = \sigma(bW^\pm j) - \sigma(\bar{b}W^\pm j)$$

and the on-/off-shell ratio:

$$\mathcal{R} = \sigma_{\text{off}}^A / \sigma_{\text{on}}^A$$

$\mathcal{R}$  is a good probe of  $\Gamma_t$ :

- Free of background, **no systematics from background modeling**.
- Other systematic effects, such as luminosity and tagging efficiency (including the *b*-charge tagging) are expected to **cancel in the ratio**.
- Theoretical uncertainties for the signal, due to radiative corrections should partly cancel:  **$\sim 6\% \Rightarrow 1.5\%$ , central value stable**.
- Model-dependence (i.e.  $g_{tbW}$ ) should cancel in the ratio (thus a **direct probe**).

... only if we can measure the *b*-charge.

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# b-charge tagging



## ATLAS NOTE

ATL-PHYS-PUB-2015-040

31st August 2015

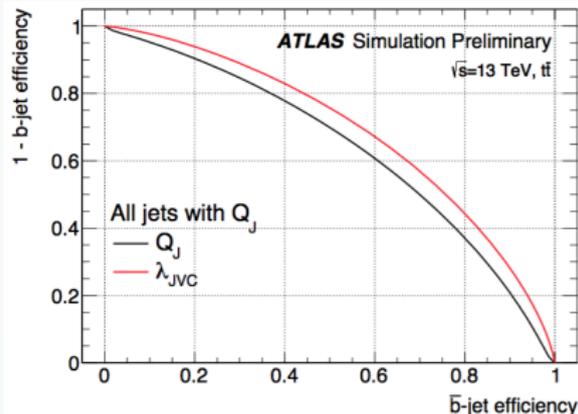
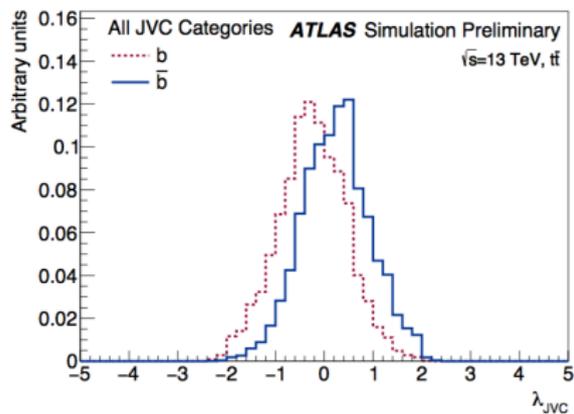


### A new tagger for the charge identification of $b$ -jets

#### Abstract

A newly developed algorithm called the jet vertex charge tagger, aimed at identifying the sign of the charge of jets containing  $b$ -hadrons, referred to as  $b$ -jets, is presented in this note. In addition to the well established track-based jet charge determination, this algorithm introduces the so-called *jet vertex charge* reconstruction, which exploits the charge information associated to the displaced vertices within the jet. Furthermore, the charge of a soft muon contained in the jet is taken into account when available. All available information is combined into a multivariate discriminator produced using an artificial neural network method. The algorithm has been developed on jets matched to truth level  $b$ -hadrons provided by  $t\bar{t}$  events simulated at  $\sqrt{s}=13$  TeV using the full ATLAS detector simulation and reconstruction.

# b-charge tagging



Tag configuration	$\lambda_{JVC} > -0.3$		$\lambda_{JVC} > -0.1$		$\lambda_{JVC} > 0$		$\lambda_{JVC} > 0.1$		$\lambda_{JVC} > 0.3$	
	$\bar{b}$ eff.	$b$ rej.	$\bar{b}$ eff.	$b$ rej.	$\bar{b}$ eff.	$b$ rej.	$\bar{b}$ eff.	$b$ rej.	$\bar{b}$ eff.	$b$ rej.
Untagged	78.1%	46.7%	68.4%	58.4%	63.3%	63.8%	59.6%	68.2%	47.1%	77.8%
MV2c20 at 85%	78.1%	47.8%	68.7%	59.3%	63.9%	64.3%	59.4%	68.6%	48.1%	77.8%
MV2c20 at 77%	78.2%	48.3%	68.9%	59.6%	64.2%	64.5%	59.8%	68.8%	48.6%	77.9%
MV2c20 at 70%	78.2%	48.7%	69.1%	59.9%	64.5%	64.8%	60.1%	68.9%	49.1%	78.0%
MV2c20 at 60%	78.3%	49.5%	69.3%	60.4%	64.8%	65.2%	60.5%	69.2%	49.7%	78.1%

Table 5: Signal efficiencies and background rejection for representative requirements on the  $\lambda_{JVC}$  discriminant obtained using the untagged truth  $b$ -jets, as well as those tagged at various working points of the MV2c20  $b$ -tagging algorithm.

$$\sigma^A(\text{tagged}) \approx (2\epsilon - 1)\sigma^A = 30\%\sigma^A$$

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# LHC reach

We estimate the following uncertainty:

- 0% from background.
- 1.5% from TH prediction on  $\mathcal{R}$ , 2% for uncancelled systematic effects.
- Statistics (on  $\sigma^A$ ):  $\sqrt{\sigma\mathcal{L}}/(2\epsilon - 1)\sigma^A\mathcal{L}$

## Expected $1 - \sigma$ exclusion limits at LHC13

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

- At low luminosity, worse than current limit from CMS.
- At high luminosity, can reach good precision ( $\sim$  few hundred MeV), while the CMS limit is unlikely to improve.
- This is because by using  $\sigma^A$  the uncertainties are dominated by statistics, unlike the current method.

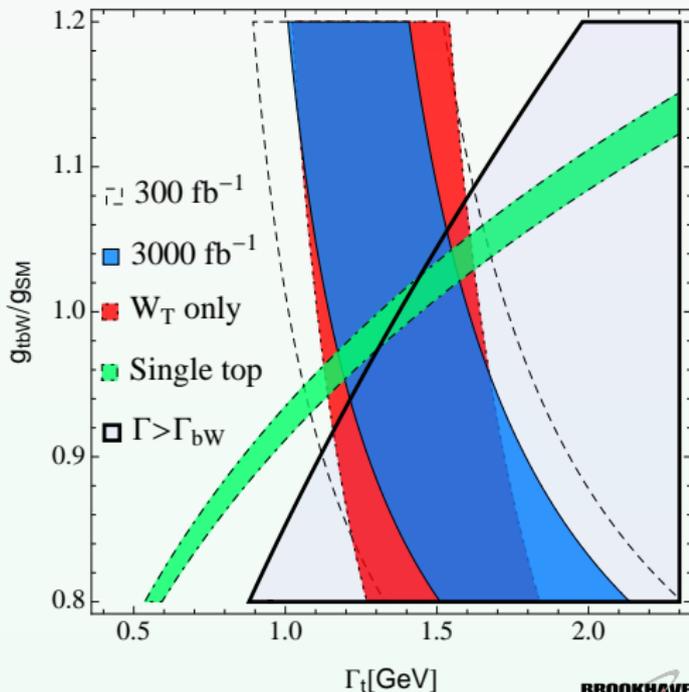
# Model-independence

Assuming:

- $g_{tbW}$  deviates from  $g_w$ .
- $\Gamma_t = \Gamma_{t \rightarrow bW} + \Gamma_{exotic}$

From the plot:

- Blue is the limit from HL-LHC.
- Has a small dependence on  $g_{tbW}$ , from signal-EW interference
  - ▶ Signal  $\sim g_{tbW}^4$ , int.  $\sim g_{tbW}^2$ .
- Red uses only transverse  $W$  to reduce interference.
- Green shows that single top ( $g_{tbW}^4/\Gamma_t$ ) and width measurements are complementary, giving  $1.31 < \Gamma_t < 1.57$ .



# Possible improvements

- Precision  $\propto (2\epsilon - 1)^{-1} \Rightarrow$  improvements on  $b$ -charge tagging algorithm will significantly improve this measurement.
- Defining  $\sigma^A$  with a definite charge of  $W$  will remove the QCD background, while  $t\bar{t}$  and  $tW$  background are not removed but may be measured in the semi-leptonic channel.
- Background suppression can be done by MVA based approach rather than cutting the phase space.
- Instead of on-/off-shell ratio, the full  $m(bW)$  distribution of the asymmetry provides more information.

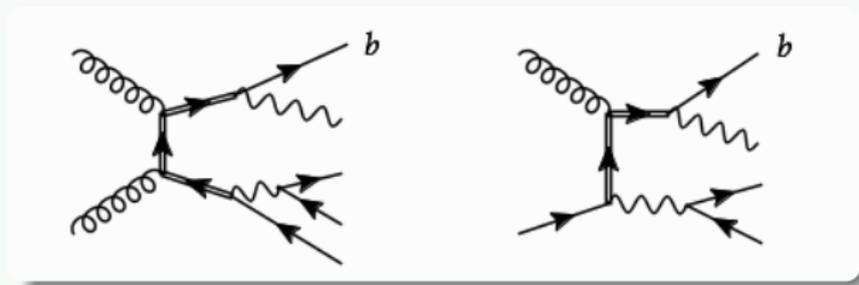
# Summary

- We propose to measure  $\Gamma_t$  in  $pp \rightarrow Wbj$  at the LHC, by using the *b-charge asymmetry to remove backgrounds*.
- Unlike the current approach, the new approach is limited mainly by statistics. Precision goes up with luminosity.
- We estimate that it can reach (*~ a few hundred MeV*) at HL-LHC.
  
- We show that the *b-charge tagging algorithm*, even though with only 65% efficiency, *is already a powerful tool*.

# Backups



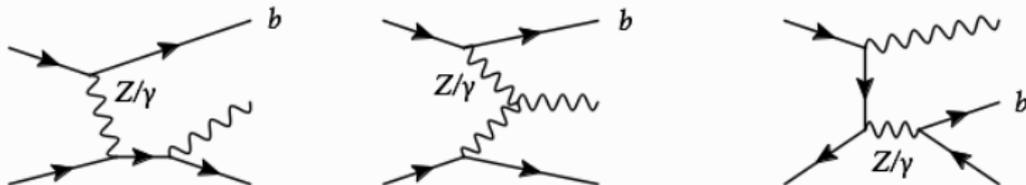
## Background 2: $t\bar{t}$ and $tW$



- Partonic cross sections are invariant under CP.
  - ▶ PDF for  $gg \rightarrow t\bar{t}$ ,  $gb \rightarrow tW$  are the same.
  - ▶ PDF for  $q\bar{q}$  is not; it leads to  $t\bar{t}$  charge asymmetry, and potentially  $b$ -charge asymmetry, which is an NLO effect, and is known to be tiny.

Conclusion:  $bW^+$  cancels  $\bar{b}W^-$ ,  $bW^-$  cancels  $\bar{b}W^+$

## “Background 3”: $Wbj$ through EW, without top



- EW  $pp \rightarrow Wbj$  are strictly speaking **part of the signal**, as they can be in the same gauge group.
- We consider them as background, because they don't probe the wanted amplitude  $bW \rightarrow t \rightarrow bW$ .
- $g_{tbW}$  couplings won't cancel when taking the ratio. . . small BSM-dependence remains.
- $b$ -charge asymmetry is generated only through the  $V - A$  interference, and after imposing kinematic cuts they are small ( $\sim$  a few percent.)

# Cuts

$$\begin{aligned} \eta(j_1) &> 2.3, \quad \eta(j_{b_1}) < 2.5, \\ p_T(j_{b_1}) &> 25 \text{ GeV}, \quad p_T(j_2) < 50 \text{ GeV}, \quad p_T(j_{b_2}) < 50 \text{ GeV}, \\ \eta(W) &< 4.0, \quad p_T(W) < 120 \text{ GeV}, \quad m(Wj_1) > 140 \text{ GeV}. \end{aligned}$$

Here  $j_{1,2}$  ( $j_{b_{1,2}}$ ) represent the non- $b$  ( $b$ ) jets with the largest and the second largest  $p_T$ . We consider events with at least one  $b$  and one non- $b$  jet, and at most two  $b$  and two non- $b$  jets. Cuts on the first  $b$ -jet are to be consistent with the  $b$ -jet charge tagger simulation in Ref. [21]. On-/off-shell events are defined by a mass window cut of  $m_t \pm 20 \text{ GeV}$ . If either  $m(Wj_{b_1})$  or  $m(Wj_{b_2})$  falls into the window, we consider the event as an on-shell event. We further smear  $m(Wj_{b_{1,2}})$  by a Gaussian with a 10 GeV width to account for possible errors in reconstructing the

# $b$ -charge asymmetry

- Define jet charge variables  $Q_{jet}$

$$Q_{jet} = \frac{\sum_{i \in \text{Trk}} q_i \cdot p_{Ti}^{\kappa}}{\sum_{j \in \text{Trk}} p_{Tj}^{\kappa}}$$

where depending on tracks used, three jet charges are defined:

- ▶ Jet charge  $Q_j^{\text{all tracks}}$ ,  $Q_j$  (selected tracks). ( $\kappa \approx 1.1$ )
  - ▶ Secondary vertex charge  $Q_{SV}$ , tracks associated to SV. ( $\kappa \approx 0.7$ )
  - ▶ Tertiary vertex charge  $Q_{TV}$ , tracks associated to TV. ( $\kappa \approx 0.7$ )
- Charge of the  $\mu$  from the decay of  $b$ - or  $c$ -hadrons.
  - A multivariate analysis (MLP) is employed, using  $Q_j$ ,  $Q_{SV}$ ,  $Q_{TV}$ ,  $Q_{\mu}$ , and a set of auxiliary variables.

# *b*-charge asymmetry

Variable	Description
$Q_j$	See Sec. 4.1 for a detailed explanation
$Q_j^{\text{all tracks}}$	See Sec. 4.1 for a detailed explanation
$Q_{SV}$	See Sec. 4.1 for a detailed explanation
$Q_{TV}$	See Sec. 4.1 for a detailed explanation
$Q_\mu$	Charge of the muon associated to the jet
$N_{\text{trk}}(Q_j)$	Number of tracks used to compute $Q_j$
$p_T^{\text{trk}}(Q_j)$	$p_T$ of the hardest track used to compute $Q_j$
$N_{\text{trk}}(\text{SV})$	Number of tracks in the SV
$p_T^{\text{trk}}(\text{SV})$	$p_T$ of the hardest track used to compute $Q_{SV}$
$L_{3D}(\text{SV})$	Distance between the SV and the PV along the jet-axis
$\Delta L_{3D}(\text{SV})$	Error on the fitted SV position
$m(\text{SV})$	Invariant mass of the SV computed under the hypothesis that all the particles are pions
$N_{\text{trk}}(\text{TV})$	Number of tracks used to compute $Q_{TV}$
$L_{3D}(\text{TV})$	Distance between the TV and the PV along the jet-axis
$\Delta L_{3D}(\text{TV})$	Error on the fitted TV position
$m(\text{TV})$	Invariant mass of the TV, computed under the hypothesis that the most energetic particle is a kaon and the remaining particles are pions
$p_T^{\text{Rel}}(\mu)$	Muon momentum component orthogonal to the jet plus muon axis
$p_T^{\text{Long}}(\mu)$	Muon momentum component parallel to the jet plus muon axis
$\Delta R(\mu, j)$	$\Delta R$ angle between the muon and the jet axes
$I_{40}^{\text{var Pr}}(\mu)$	Track momentum sum contained in the $p_T$ -dependent cone of the maximal size of $\Delta R = 0.4$ around the muon

- We simulate **background at NLO** and **signal at LO**.
- MADGRAPH5\_AMC@NLO+PYTHIA8
- MADSPIN is used for NLO background.
- Kinematic cuts are imposed to reduce background.
  - ▶ Background has no contribution to the central value asymmetry, but **does contribute to statistical error**.
- On-/off-shell regions are defined by a mass window cut  $m_t \pm 20$  GeV.
  - ▶ A 10 GeV smearing is added to  $bW$  mass.
- Signal:
  - ▶ Different values of  $\Gamma_t$  and  $g_{tbW}$  are scanned at LO.
  - ▶ **SM case is simulated also at NLO to check that the approach is stable under QCD correction.**

# SM cross sections: QCD corrections

QCD corrections to  $\sigma^A = \sigma(b) - \sigma(\bar{b})$  and  $\mathcal{R} = \sigma_{\text{off}}^A / \sigma_{\text{on}}^A$  are main source of TH uncertainty.

- QCD corrections to single top production and decay is significant, in particular changes  $m(bW)$  shape.
- However, the effect is mostly captured by PS.
  - ▶ Confirmed by full off-shell+NLO+PY8 calculation.

*[Frederix, Frixione, Papanastasiou, Prestel, Torrielli]*

- Our simulation:
  - ▶ MADSPIN used for  $bW^+$  and  $\bar{b}W^-$  production (with potential top resonance).
  - ▶  $bW^-$  and  $\bar{b}W^+$  is calculated fully at NLO.

# SM cross sections: QCD corrections

$\mathcal{R} = \sigma_{\text{off}}^A / \sigma_{\text{on}}^A$  is stable under QCD correction.

	$\sigma_{\text{off}}^A$ [pb]	$\sigma_{\text{on}}^A$ [pb]	$\mathcal{R}$ ratio
LO	1.32(2) <sup>+9%</sup> <sub>-12%</sub>	9.0(1) <sup>+9%</sup> <sub>-12%</sub>	0.146(3) <sup>+0.1%</sup> <sub>-0.1%</sub>
NLO	1.41(8) <sup>+6.2%</sup> <sub>-6.4%</sub>	9.8(1) <sup>+4.8%</sup> <sub>-5.1%</sub>	0.144(8) <sup>+1.3%</sup> <sub>-1.6%</sub>

**Table:** Approximate LO and NLO asymmetries for on-/off-shell cross sections and their ratio. Uncertainties shown in percentage come from scale variation, while those in the bracket are numeric.

# $\sigma^A(\Gamma_t, g_{tbW}), \mathcal{R}(\Gamma_t, g_{tbW})$

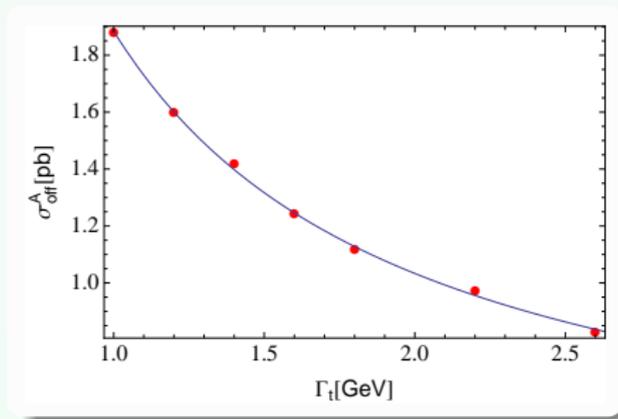
- To extract the dependence of asymmetries on  $\Gamma_t$ , and on  $g_{tbW}$  (to check model-dependence), we redo the simulation for different values of  $\Gamma_t$  and  $g_{tbW}$ .
- Results are fitted to  $\sigma(\Gamma_t, g_{tbW}) = \sigma_0(g_{tbW}) + \sigma_1(g_{tbW})/\Gamma_t$ .
- $\sigma_{0,1}(g_{tbW})$  are quadratic functions of  $g_{tbW}^2$ .
- E.g. for  $g_{tbW} = 1$ :

$$\sigma_{off}^A = 0.18 + 1.70\Gamma_t^{-1}$$

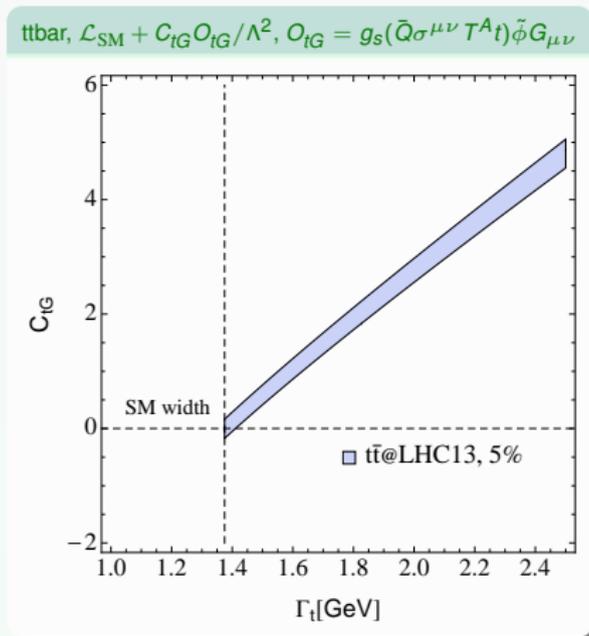
$$\sigma_{on}^A = -0.35 + 14.5\Gamma_t^{-1}$$

$$\mathcal{R}(\Gamma_t) = \frac{\sigma_{off}^A}{\sigma_{on}^A}$$

$$\approx 0.14 (1 + 0.16 \cdot \delta\Gamma_t/\Gamma_{SM})$$



Assuming  $\Gamma_t = \Gamma(t \rightarrow bW) + \Gamma_{exotic} \Rightarrow$  blind directions



Directly measurement of  $\Gamma_t$  is crucial for extracting top couplings.