Extraction of CKM matrix elements in single top quark events

19/05/2020

A.O.M. Iorio, for the CMS Collaboration

- The two actors: top quark and CKM
- CKM Measurements in the top sector
- Analysis of single top quark production and decays
- Results and interpretation

The CKM matrix and the top quark

The CKM matrix

Matrix of fundamental parameters regulating the “mixing” between quark families

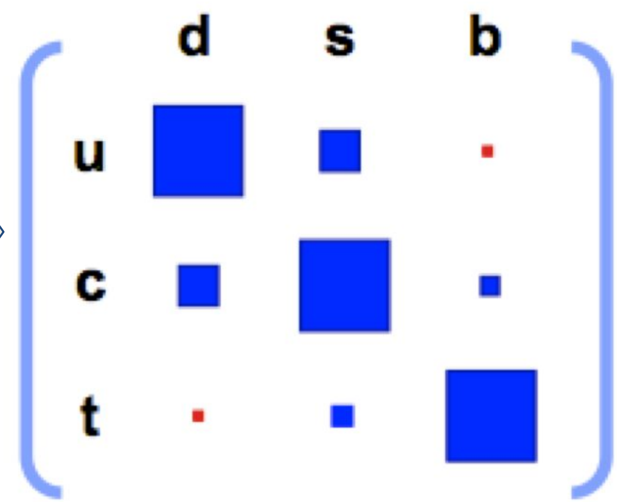
→ Transformation between the **free particle** vs **EW interacting lagrangian** eigenstates

→ **Strong diagonal trend:** disfavours cross-family couplings

→ This trend is **the most evident** in the third family

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \overbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}^{V_{\mathrm{CKM}}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

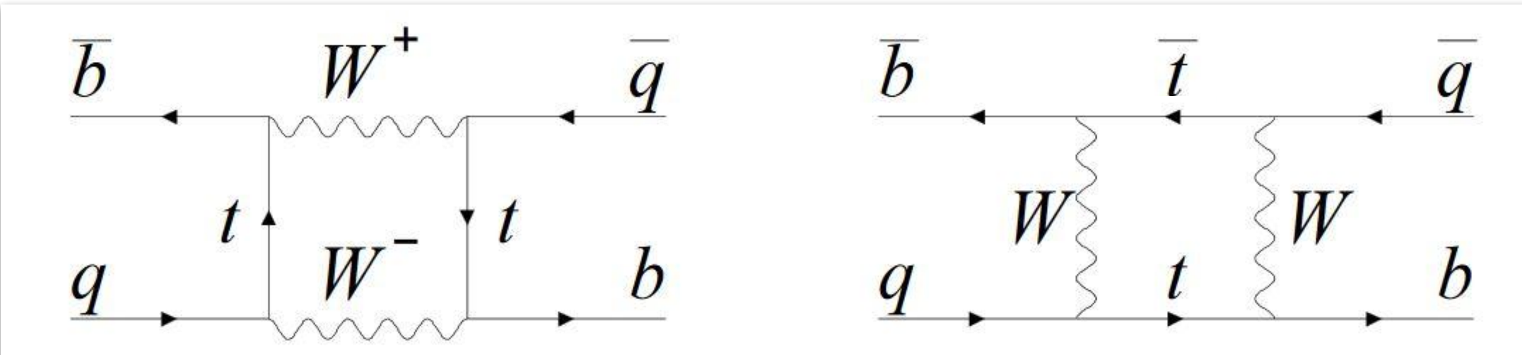
Pictorically representing the couplings



CKM: the third row w/o top quark measurements

Components in the third row: observations from B-meson physics

- Mixing between neutral B-$\overline{\text{B}}$ mesons, for either B^0 or B^0_s the box diagram is:



→ Oscillation term Δm_d (Δm_s) depending on $|V_{td}|$, $|V_{ts}|$ [see also pdg]

→ From lattice QCD, neglecting terms in $|V_{tb}|$ - 1:

$$|V_{td}| = (8.1 \pm 0.5) \times 10^{-3}, \qquad |V_{ts}| = (39.4 \pm 2.3) \times 10^{-3}$$

Ratio more robust theoretically, giving: $$|V_{td}/V_{ts}| = 0.210 \pm 0.001 \pm 0.008$$

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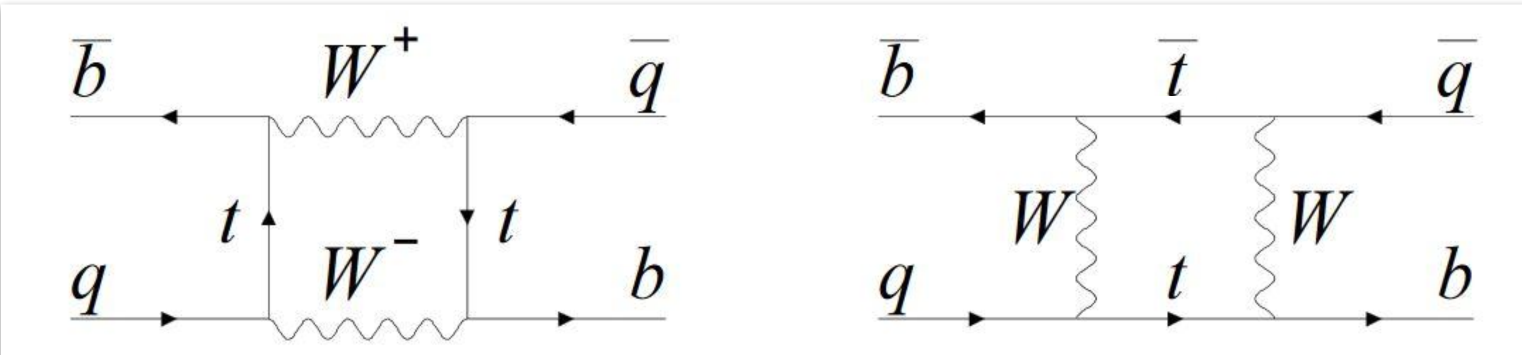

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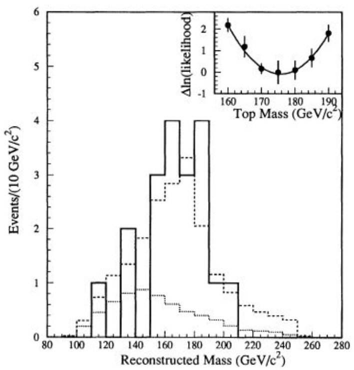
Questions to be answered from top quark measurements:
Is Vtb ≅ 1? If not, what's its value?
Can we **measure** |Vtd| and |Vts| at **tree level?**

The top quark: a story of 25 years

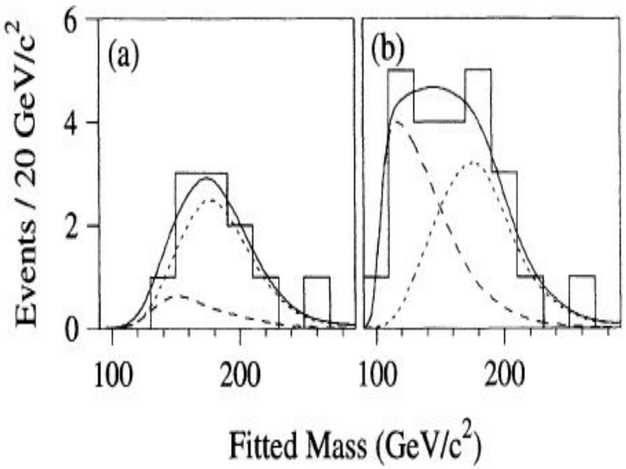
1995 Observation at TeVatron
via strong pair production (tt)

2009 Observation of electroweak
single top production @TeVatron

PRL 74 (1995) 2626



PRL 74 (1995) 2632



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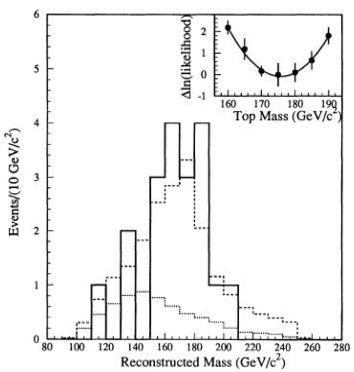

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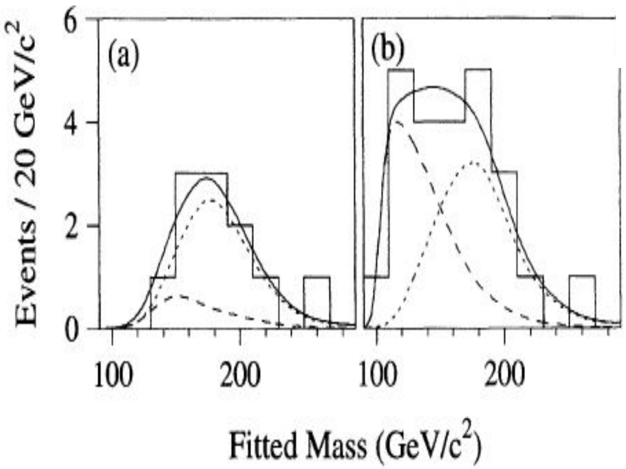
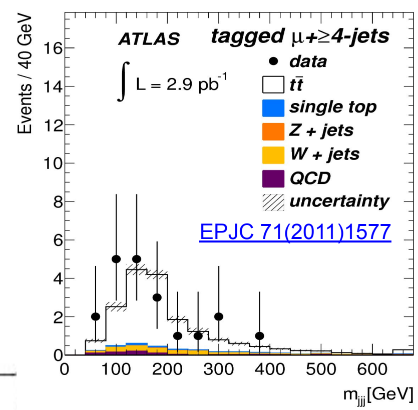
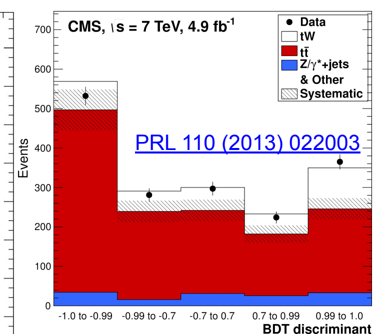




EPJC 71(2011)1577



PRL 110 (2013) 022003

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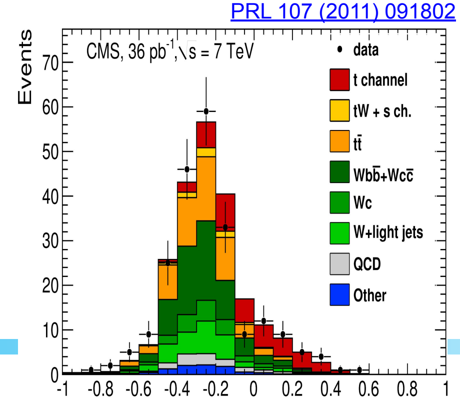

The top quark: a story of 25 years

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2010-11 Rediscovery @LHC:
tt, single top

2016-18
New channels @LHC:
tZq, tγq, ttZ, ttW

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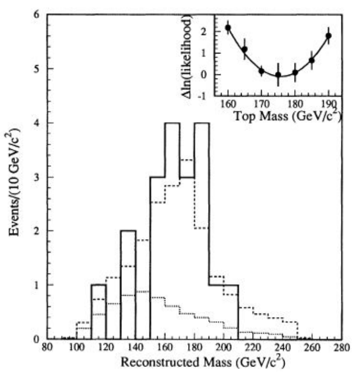

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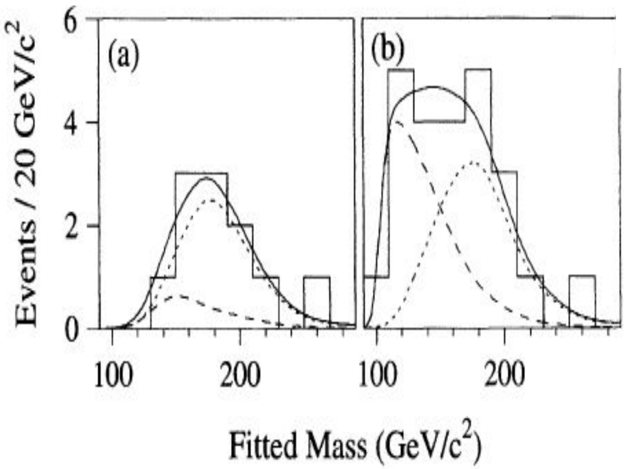

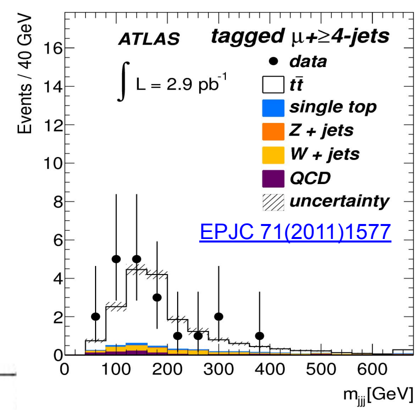

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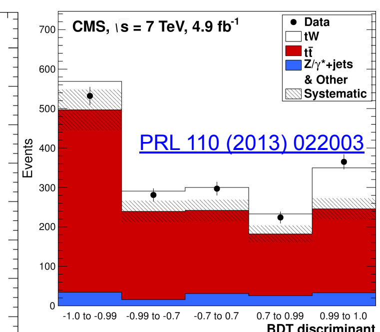

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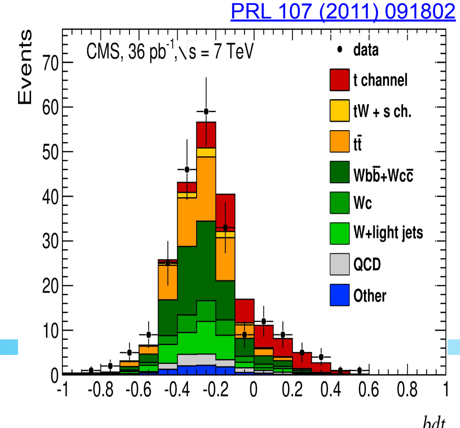
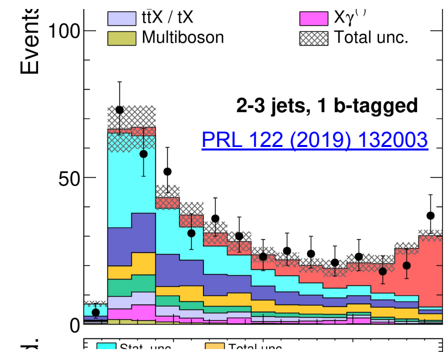
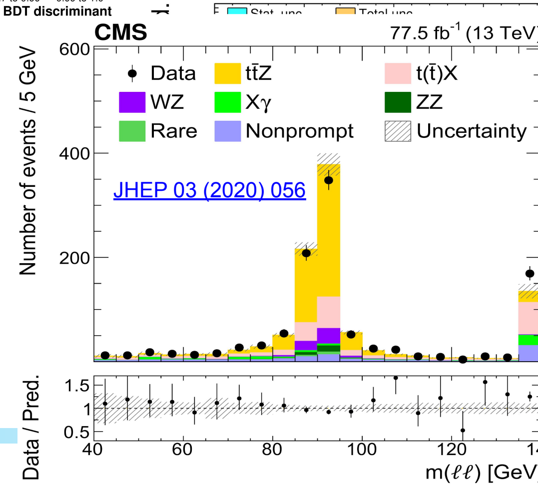




PRL 122 (2019) 132003



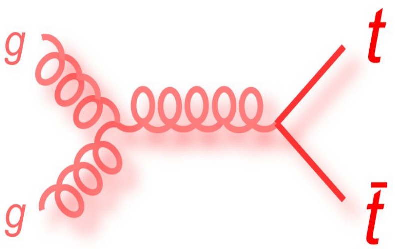
JHEP 03 (2020) 056

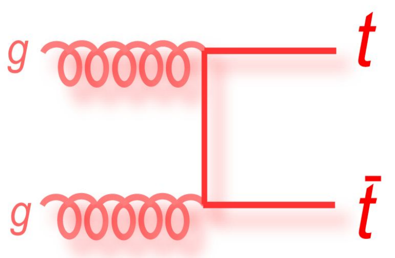
Top-CKM measurements at LHC so far

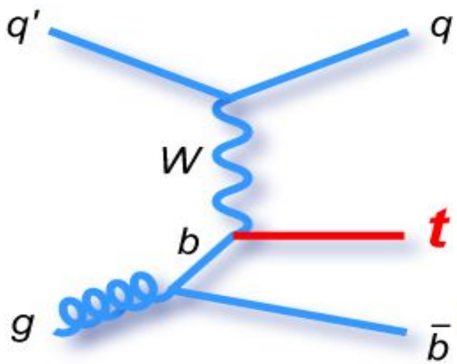
Top quark at LHC: main production modes

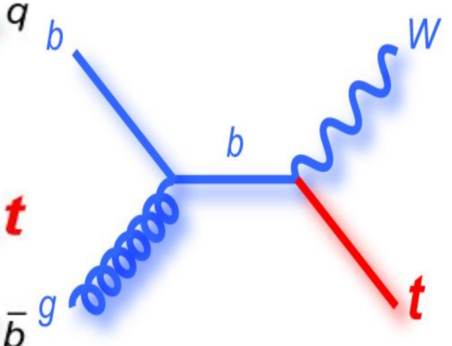
Most abundant processes, ideal for:

- **Coupling properties:** inclusive and differential cross sections
- Top quark-related **parameters:** mass, width, CKM elements etc.
- **Modeling of QCD** (perturbative and non-pert.) and **PDF**









- **tt pairs** via strong interaction:

  - dominant at the LHC and Tevatron
  - depends on α_s
  - sensitive to pdf

- **σ at LO ∝ $(\alpha_s/m_{top})^2$**

- **single-top quarks:**

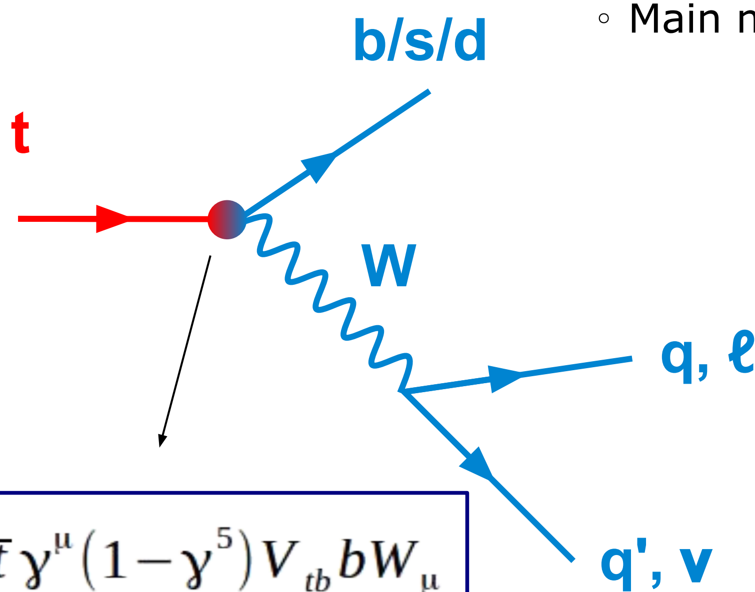
  - weak charged current interactions
    - *t*-, *s*-channel and W-associated
    - tWb vertex in production
    - Sensitive to Vtb

- **σ at LO ∝ $(\alpha \cdot |V_{tb}|)^2$**

NB: Several other associated production modes are studied, not yet used for CKM measurements

Top quark decays vademecum

◦ Main mechanism is **electroweak: no hadronisation**



W decay:	Branching Ratio
$W \to \ell\nu$ (any)	0.32
$W \to qq'$ (any)	0.68

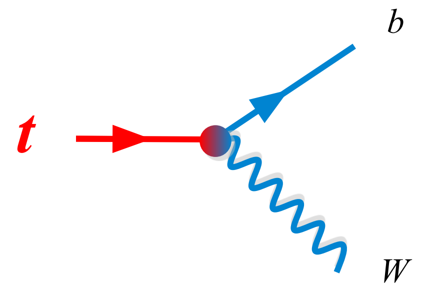
$$\boxed{\frac{-ig}{2\sqrt{2}}\bar{t}\,\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}\,b\,W_{\mu}}$$

◦ Electroweak **tWb vertex:**
- V-A: **polarization** of the products and defined **W-helicity**
- CKM matrix element enters the decay → usually one considers $|V_{tb}| \sim 1 \to \Gamma(t \to b) >> \Gamma(t \to s,d)$ for most measurements

CKM measurements in the top quark sector

1) **Decays** of top quark pairs

BR ($t \rightarrow Wb$) $\propto$ R = $|V_{tb}|^2/(|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2)$



Assumptions:

1.1 Kinematic part of the decays: same for d,s,b

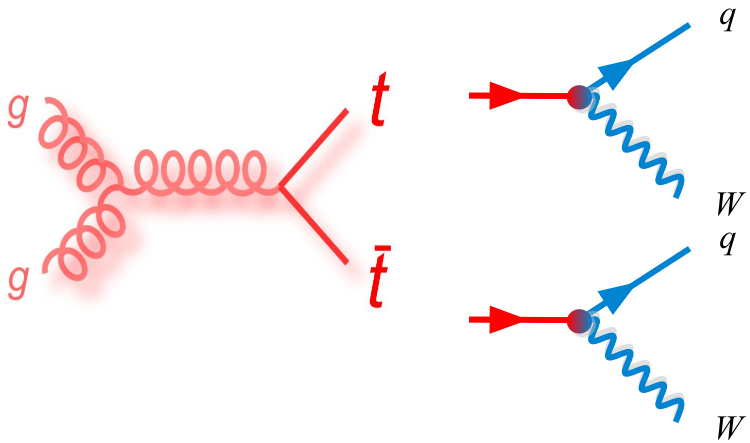
1.2 Unitarity gives $|V_{tb}|^2+|V_{td}|^2+|V_{ts}|^2 = 1$

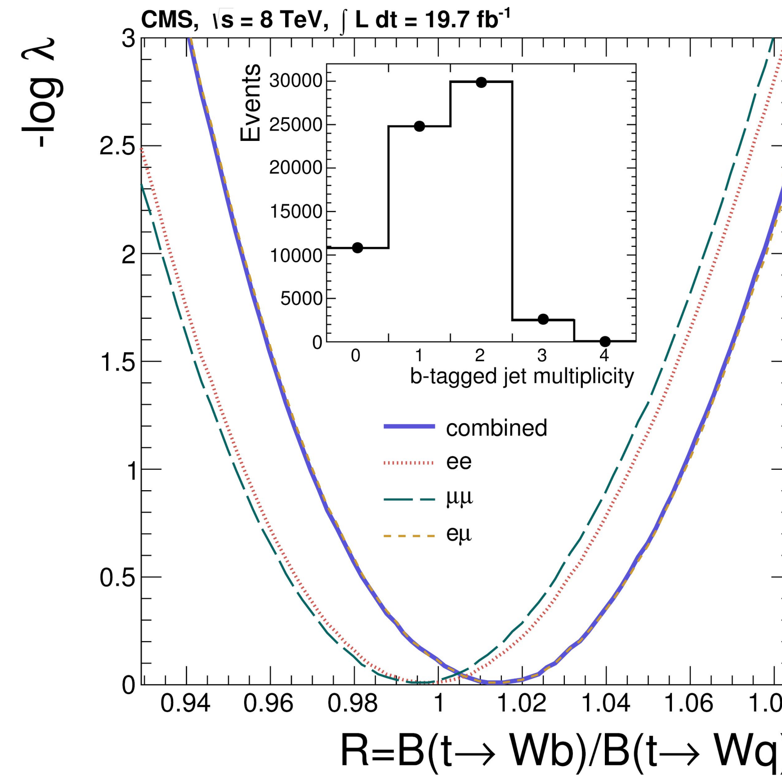
$\rightarrow$ allows to "translate" to $|V_{tb}|$

tt events: measurement of R

High precision measurement through tt pairs:

- Count the number of tt events to ℓℓνν jj





- Fit b-tagged jets multiplicity

→ allows to translate to $|V_{tb}|$ in the unitarity assumption

$$\mathcal{R} = |V_{tb}|^2 \qquad |V_{tb}| > 0.975 \text{ at the 95\% CL}$$

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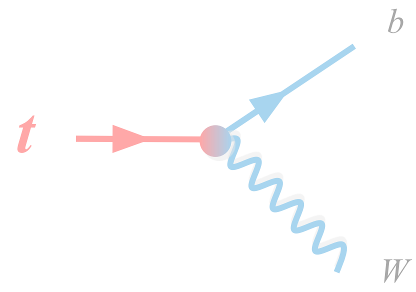

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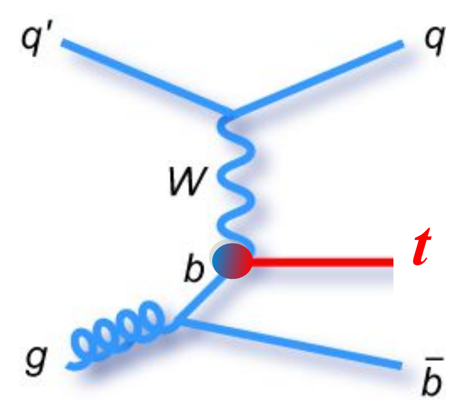
2) **Single top quark** production cross section

$\sigma \propto |V_{tb}|^2$



Assumptions:

2.1 dependence in the decay is neglected - only effects affecting production!

2.2 No enhancement from $|V_{td}|$ or $|V_{ts}|$ initiated processes is considered.

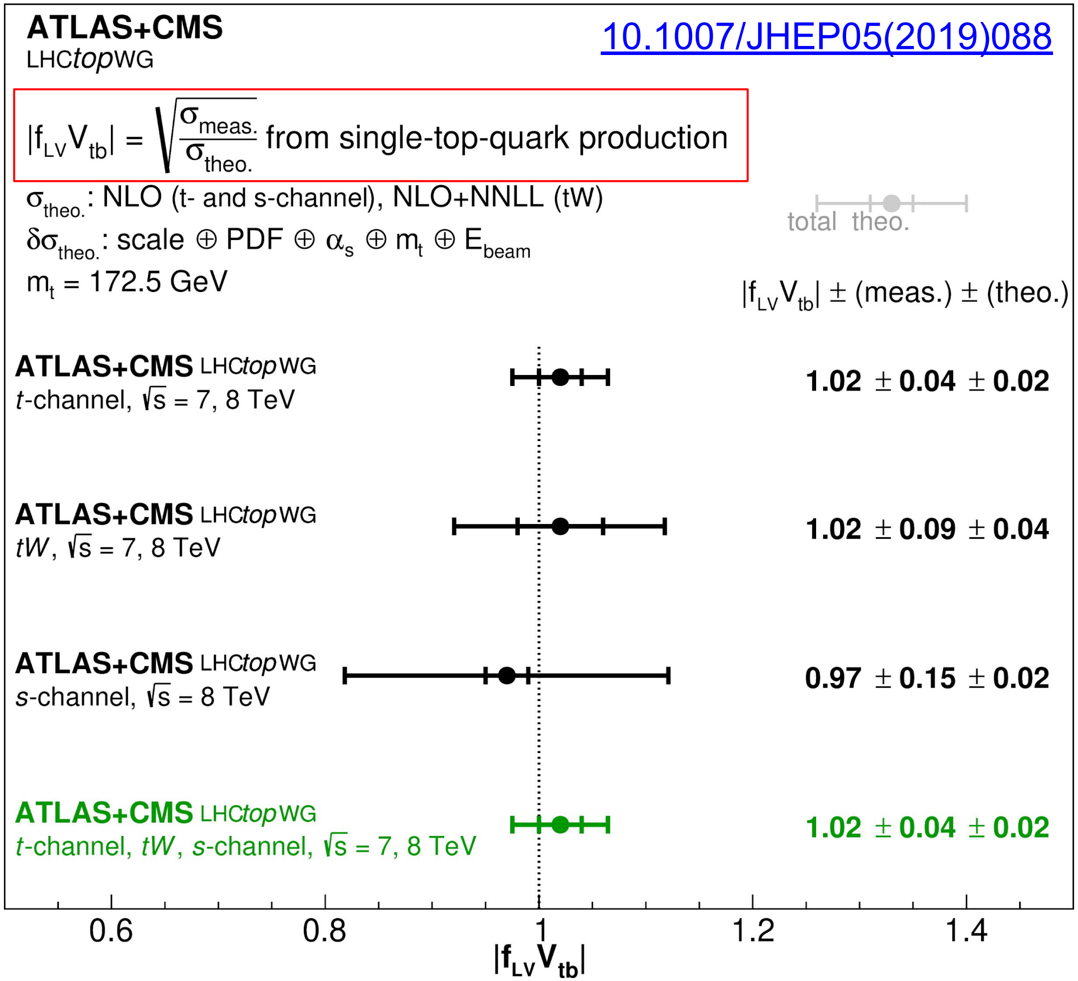
- Often referred to as $|f_{lv} V_{tb}|$: probing an “altered” coupling

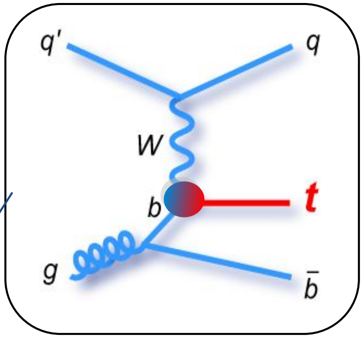
$|V_{tb}|$ in single t processes

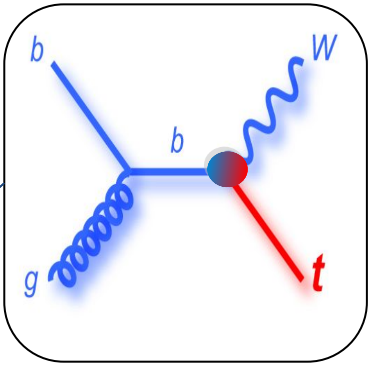
Huge success in LHC combination of Run-I analyses:

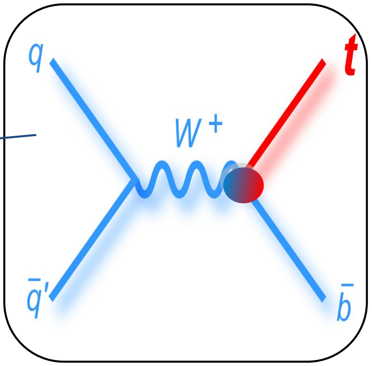
- Leading process: single top quarks in the *t*-channel,

- Sub-leading effects: single t + W associated production







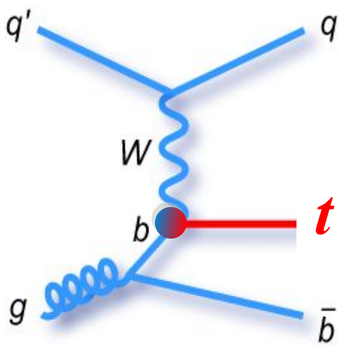


New idea for CKM extraction in the *t*-channel

Paper TOP-17-012: described in this talk!
→ submitted to PLB: https://arxiv.org/abs/2004.12181
The idea is to get "the best of both worlds" and probe at the same time:

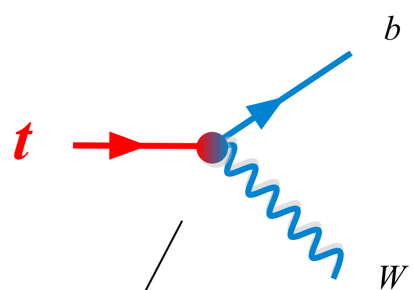
Production mechanism:

$\sigma \propto |V_{tb}|^2$



Decay mechanism:

$BR(t \to Wb) \propto |V_{tb}|^2 / (|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2)$



$$\boxed{\frac{-ig}{2\sqrt{2}} \bar{t} \gamma^{\mu} (1 - \gamma^{5}) V_{tb} b W_{\mu}}$$

Advantages with this approach

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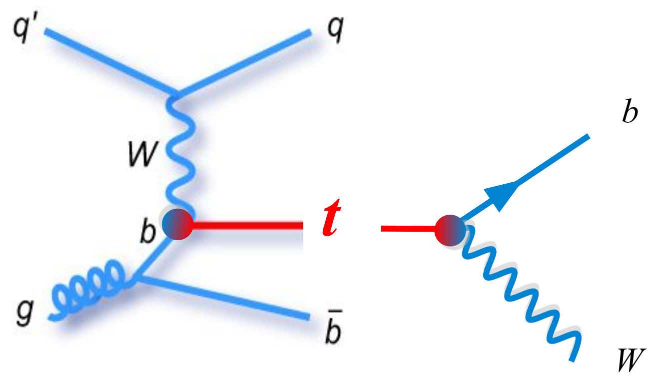
Production + decay:

σ x BR (t→ Wb) $\propto |V_{tb}|^2 \times |V_{tb}|^2/(|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2)$



SM measurement:

→ More precise $|V_{tb}|$ determination exploiting stronger dependence from $|V_{tb}|^4$

→ Possibility to probe $|V_{td}|$,$|V_{ts}|$ at tree level

Possible other fit interpretations:

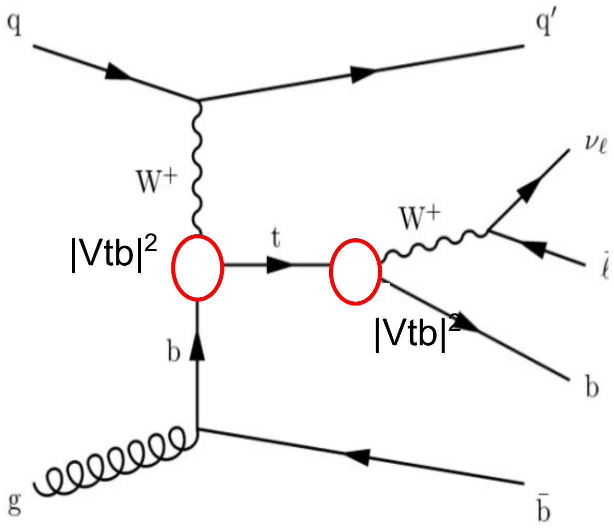
→ gradually releasing assumptions where new physics might affect the process

Single top quark *t*-channel analysis

t-channel analysis: signals considered

Considering contributions from different combinations of **tWb, tWd, tWs vertices:**

Signal 1 ***ST*(b,b)**



This is the mode considered for **single t** inclusive **cross sections and properties measurements**

→ Usually **only CKM vertex in production** is considered when looking for deviations

t-channel analysis: signals considered

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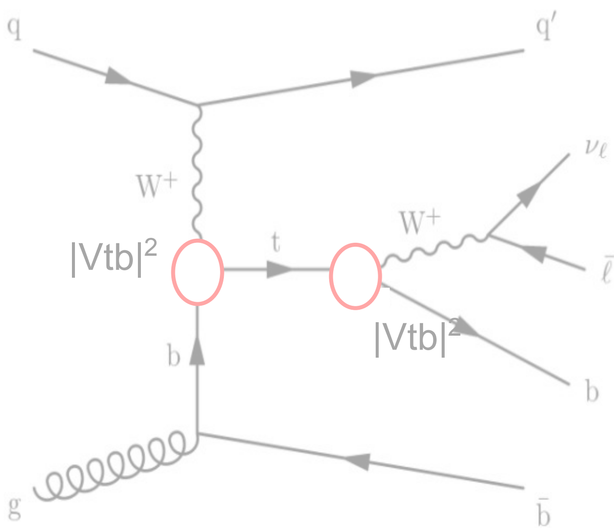
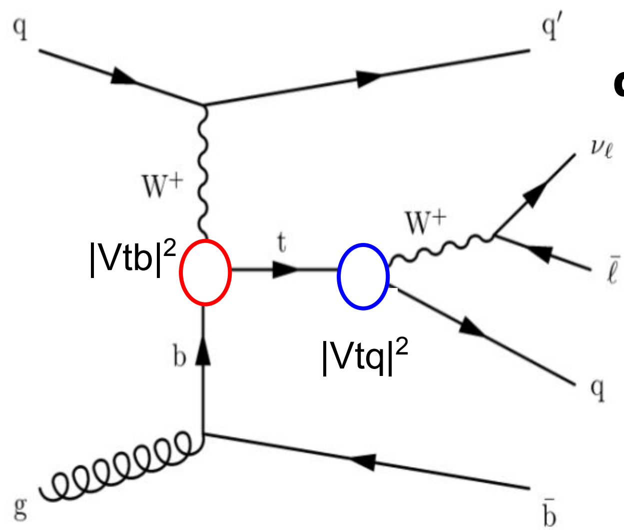


Signal 2 ***ST*(b,q)**



decays through tWs/d vertex

t-channel analysis: signals considered

Considering contributions from different combinations of **tWb, tWd, tWs vertices:**

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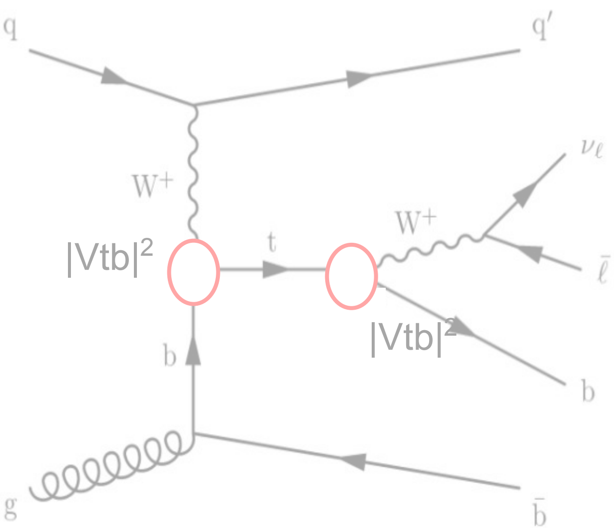
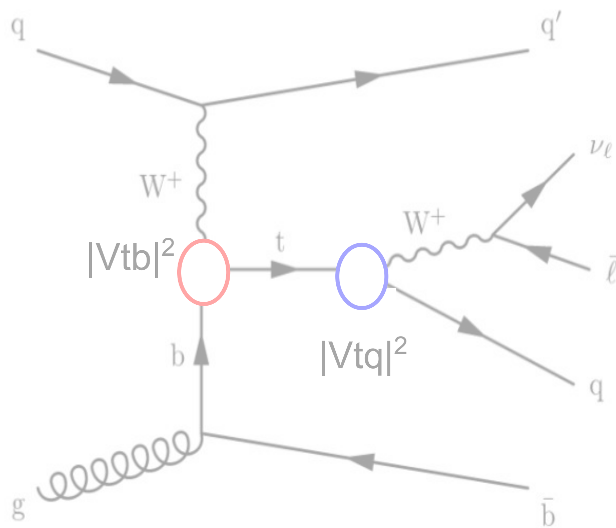
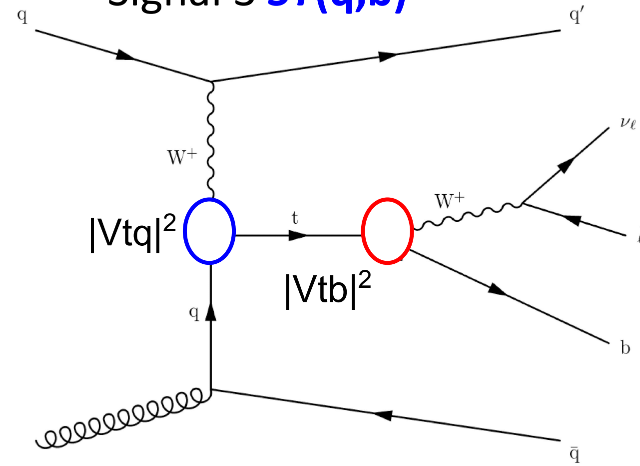
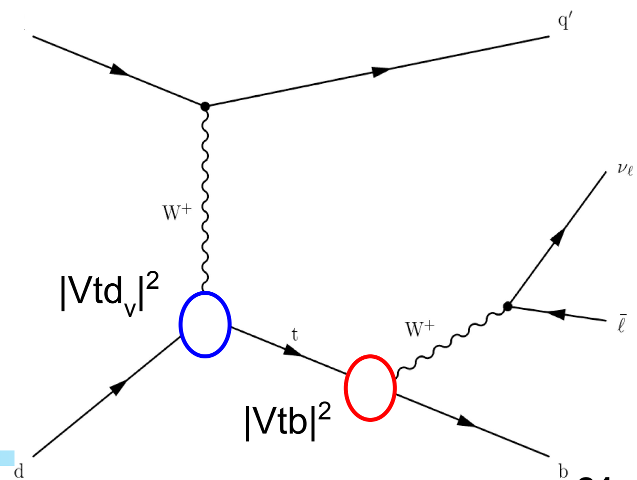


Signal 2 ***ST*(b,q)**



Signal 3 ***ST*(q,b)**





tWd or tWs in production, includes valence quarks d_v

Note: we consider contributions with **two tWs/d** vertices **negligible**

Analysis setup: data samples and simulation

Analysis is based on **proton-proton collision data** at 13 TeV collected in **2016.**
→ **Integrated luminosity = 35.9 fb^{-1}**
→ **Triggers:** 1 muon OR 1 electron

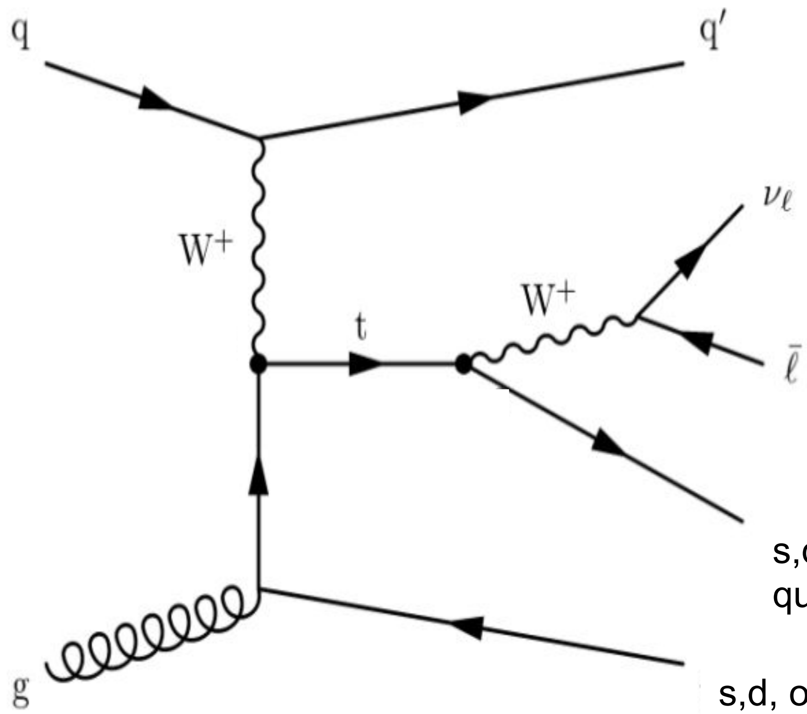
Initial values of CKM elements taken from low energy measurements:

	Production	Decay	Cross section × branching fraction (pb)
Signal 1 ***ST*(b,b)**	tWb	tWb	217.0 ± 8.4
Signal 2 ***ST*(b,q)**	tWb	(tWs + tWd)	0.41 ± 0.05
Signal 3 ***ST*(q,b)**	tWd	tWb	0.102 ± 0.015
	tWs	tWb	0.92 ± 0.11

In the analysis, $|V_{td}/V_{ts}|$ is kept constant → the relative normalization of the Signal 3 processes is fixed, only variations due to systematic effects.

The baseline selection for all signals

Final state | **@Reconstruction level**



1 high-η "forward" jet* jet called ***j'***

Missing transverse momentum $p_{T,miss}$

Well reconstructed muon or electron **
- veto additional leptons

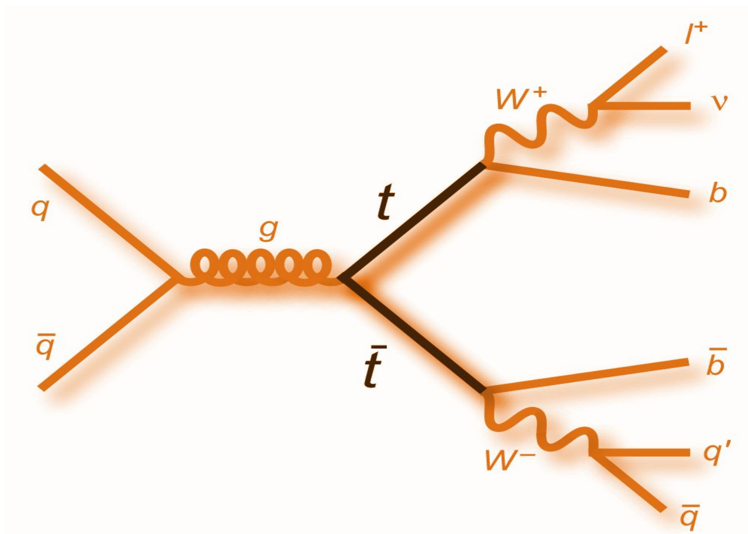
s,d, or b quark → jet, potentially reconstructed as b

s,d, or b quark → low-p_T jet, potentially reconstructed as b

All three processes should have:
- at least 2 jets
- at least 1 b-jet

* η is the pseudorapidity in the CMS frame
** tau leptonic decays are part of the signal

Background processes: “prompt” leptons

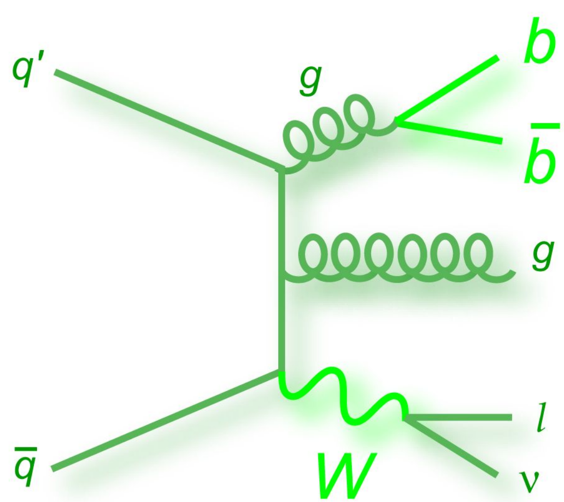


Top quark pair production

- 1 top quark decays leptonically to Wb

- 1 top decays either leptonically or hadronically

Typical features:
high jet multiplicity, top quark decay features
“central” jets in the detector



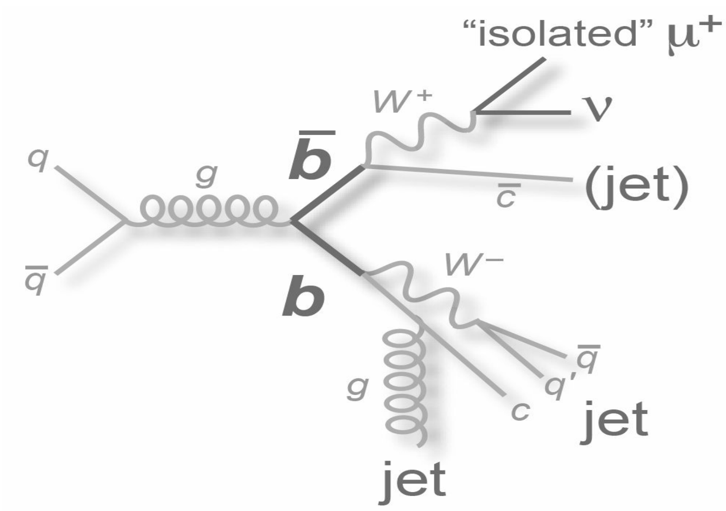
W+jets production

- b- or c- associated production

- W decaying leptonically

Typical features:
low jet multiplicity, no top quark decay features,
“central” jets in the detector

Background process: QCD multijet



QCD multijet

- bb pair with one b not tagged

- lepton from B meson decay chain

- additional radiation can mimic forward jet

Typical features:

low $p_{T,lepton}$ and $p_{T,miss}$

leptons and $p_{,miss}$ co-linear with jets

Shapes estimated from data

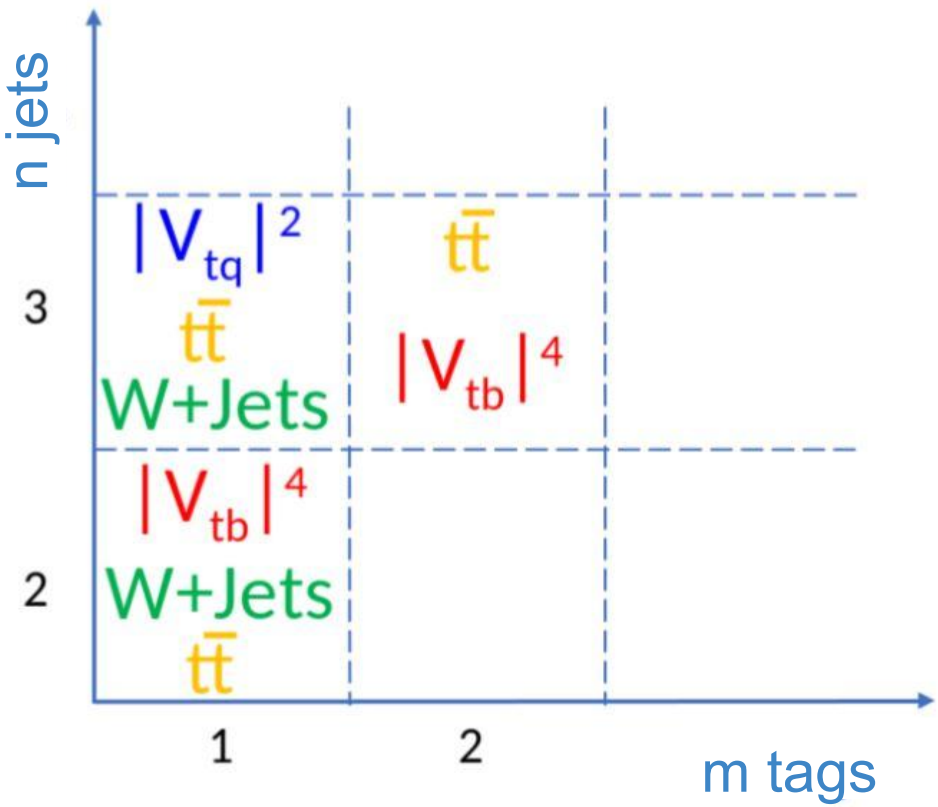
1) QCD enriched sideband defined inverting lepton identification criteria

2) All non-QCD are subtracted in sideband according to simulation

Selected categories

Categorisation as n-jets m-tags:

2-jets 1-tag: allows ***ST*(b,b)** discrimination from **W+jets** and **tt**
3-jets 1-tag: allows ***ST*(b,b)** vs ***ST*(b,q)** discrimination
3-jets 2-tag: helps with ***ST*(b,b)** extraction and **tt** background control



- Differently populated by signal or backgrounds processes
- QCD estimated in situ
- All signals are considered in all categories

W boson and top quark reconstruction

W transverse mass M_{TW} : from one lepton and $p_{x,miss}$,$p_{y,miss}$(proxy for $p_{x,\nu}$,$p_{y,\nu}$)

$$m_{\mathrm{T}}^{\mathrm{W}} = \sqrt{\left(p_{\mathrm{T},\ell} + p_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(p_{x,\ell} + p_{x}^{\mathrm{miss}}\right)^2 - \left(p_{y,\ell} + p_{y}^{\mathrm{miss}}\right)^2}.$$

Top quark 4 momentum: from one lepton, one jet, and $p_{x,miss}$,$p_{y,miss}$

→ To obtain $p_{z,\nu}$ we impose constraint on the W mass, which is set to its central value from PDG.

In summary:

For each ***event*** → **one W** candidate → m_{TW}

For each ***jet in the event*** → **one top** quark candidate → top quark 4-momentum

QCD estimation and reduction

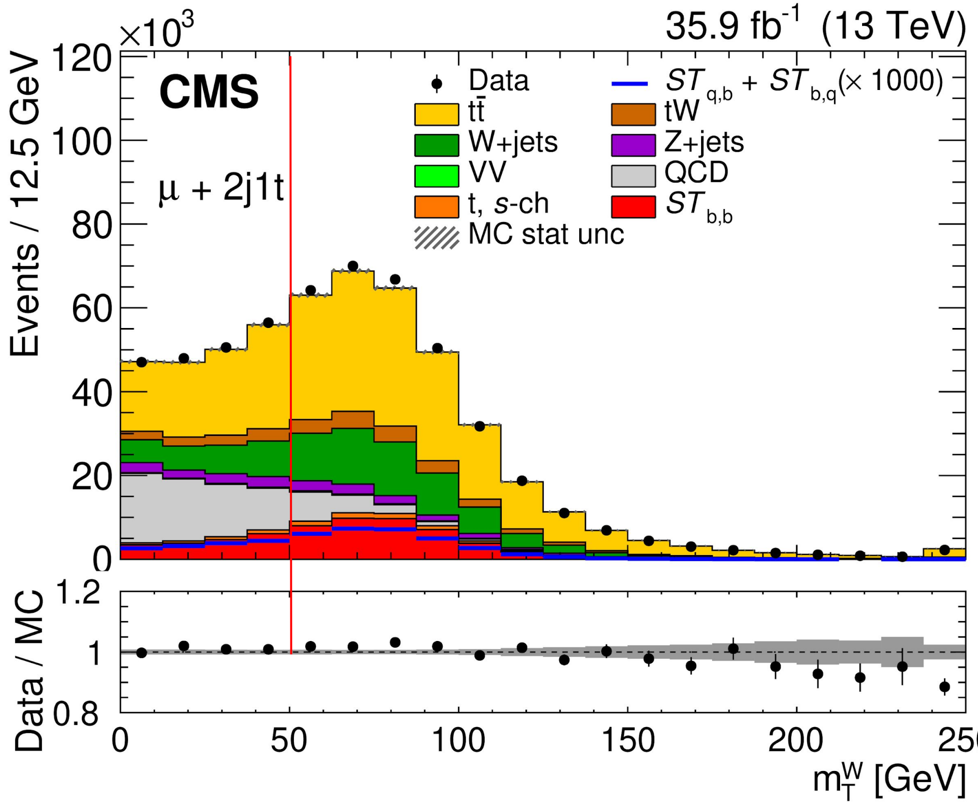
QCD extraction procedure

1 extract M_{TW} shape from QCD-enriched region

2 Maximum Likelihood fit to data M_{TW} distribution. Two components: **QCD** vs **Non-QCD**

3 Require on M_{TW} > 50 GeV to reduce QCD contamination

QCD negligible in 3-jets 2-tag



Uncertainties:

- All systematic uncertainties are propagated through the procedure

- 50% uncertainty on the QCD yield from the fit

Definition of discriminating variables

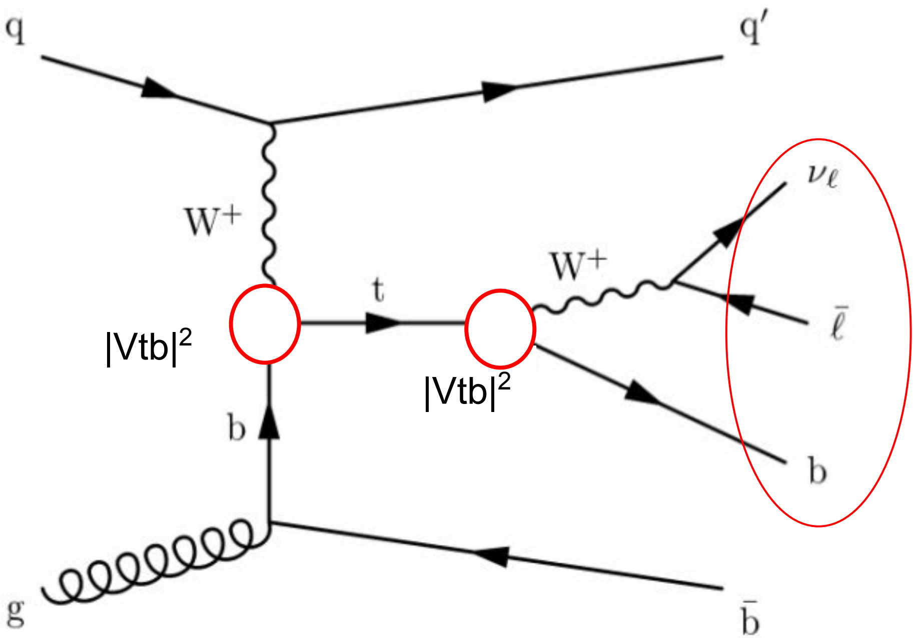
Dedicated selection in the three regions:
→ define a forward jet ***j'*** in each region
→ reconstruct top quark candidates with all other jets

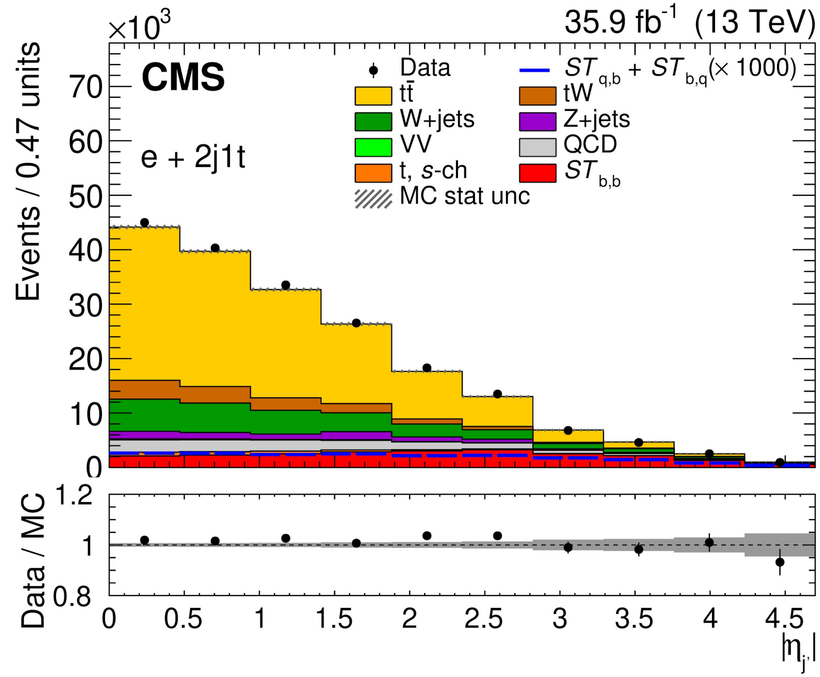
2-jets 1-tag
- ***j'*** defined as the non b-tagged jet
- Multivariate discriminant to separate ***ST*(b,b)** from **W+jets** and **tt**

3-jets 1-tag
- ***j'*** defined as non b-tagged jet with the highest $|\eta|$;
- W+jets and tt depletion requirement : j' $|\eta| > 2.5$
- Multivariate discriminant to separate ***ST*(b,b)** vs ***ST*(b,q) and *ST*(q,b)**

3-jets 2-tag
- ***j'*** defined as the non b-tagged jet
- Multivariate discriminant to separate ***ST*(b,b)** vs **tt**

Features of signal 1 *ST*(b,b)





b-jet comes from top quark:

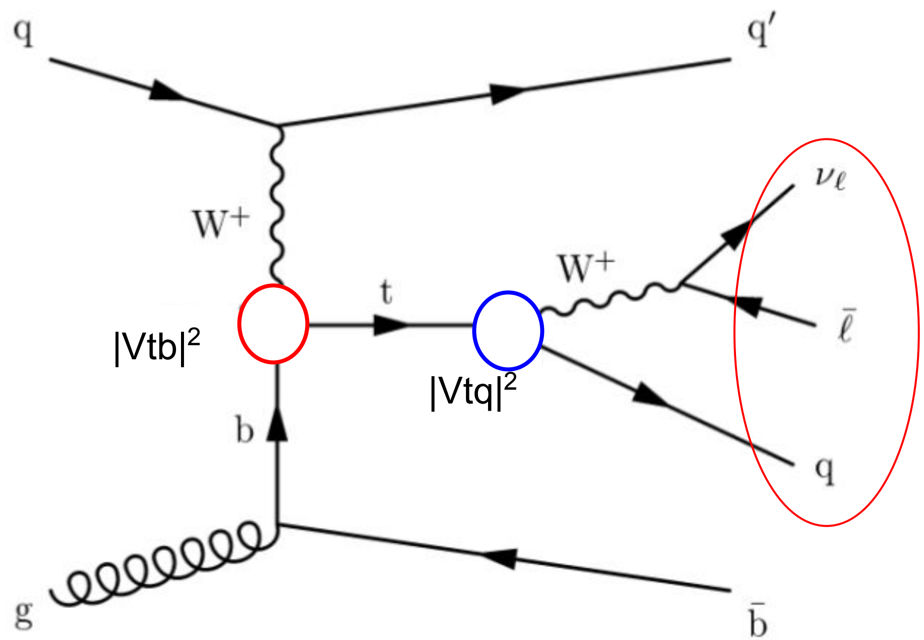
- the correct permutation is **ℓν**+ b jet

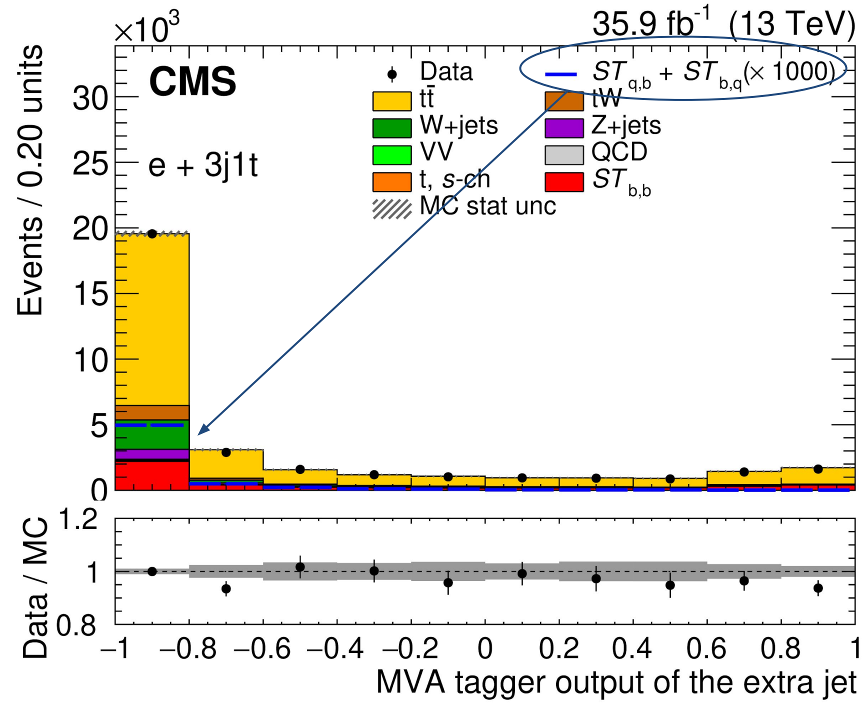
2nd b at low pt from gluon splitting:

- When not passing selection: 2-jets 1-tag
- When not passing b-tagging: 3-jets 1-tag
- When selected: 3-jets 2-tags

Discrimination from tt and W+jets: $|\eta|_{j'}$, top quark features

Features of signal 2 *ST*(b,q)





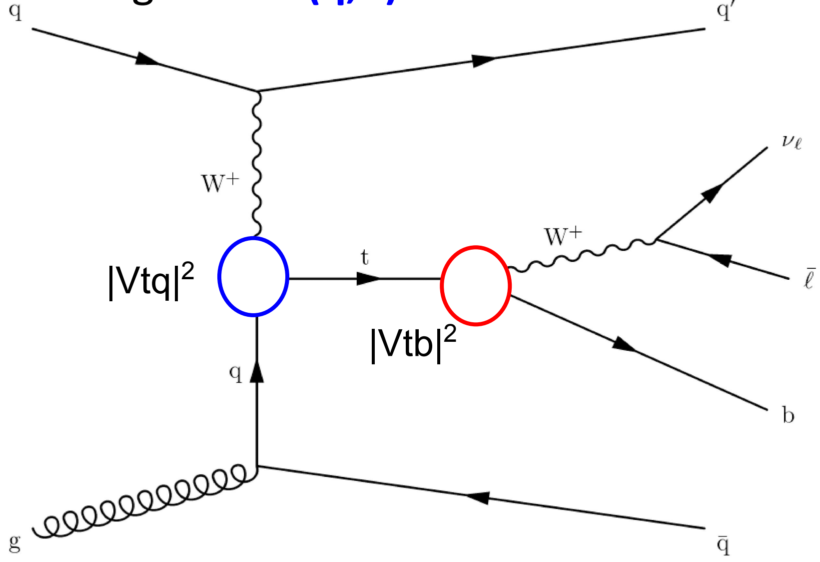
top quark decays to light quark:
- the correct permutation is **ℓv** + non-b jet
- reconstructing the top quark with the b-jet gives you the wrong permutation

Main region: 3-jets 1-tag

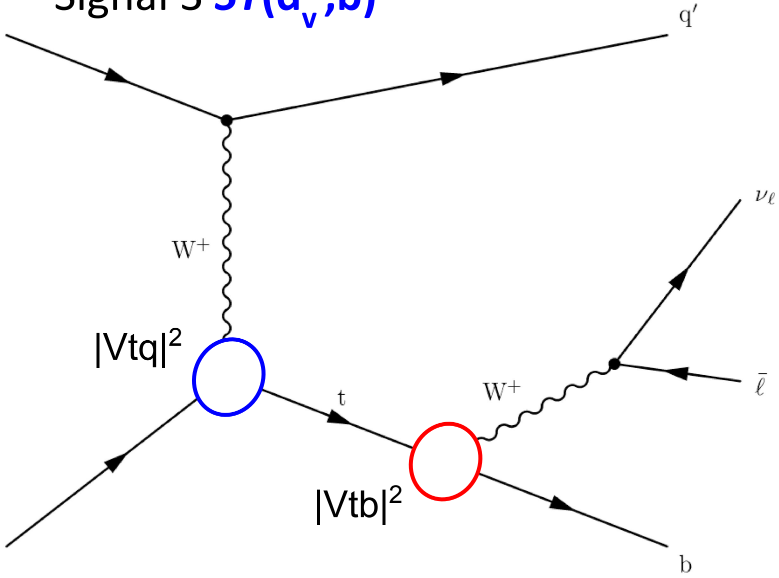
Discriminating variables against *ST*(b,b): b-discriminator of secondary top, kinematics of top quark candidates

Features of signal 3 *ST*(q,b)

Signal 3 ***ST*(q,b)**



Signal 3 ***ST*(d_v ,b)**



top quark decays to b quarks:

- the correct permutation is **ℓν** + b jet

Main region: 3-jets 1-tag for *ST*(q,b) or 2-jets 1-tag for *ST*(d_v b)

Discriminating variables against *ST*(b,b):

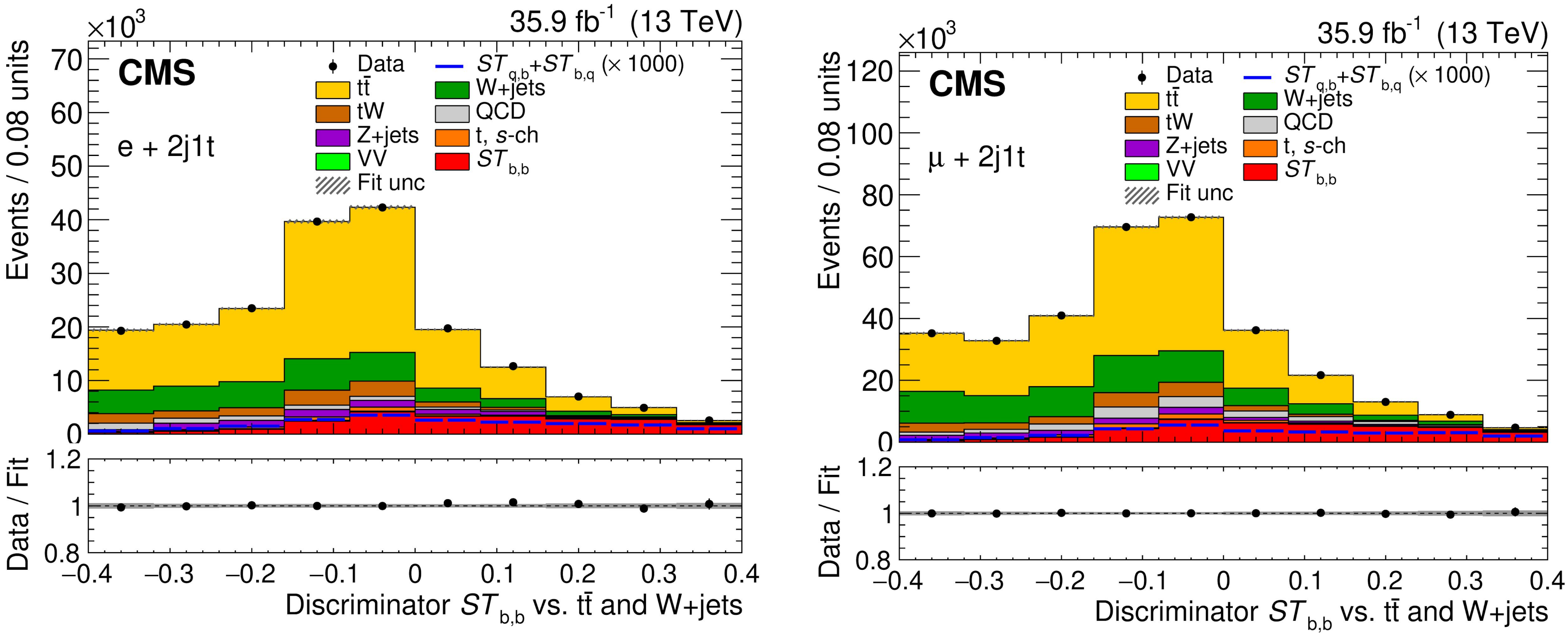
- For non d_v initiated processes, top quark kinematics is the same as *ST*(b,b), additional non b-jets can be present.
- For d_v - initiated process PDF do alter top quark rapidity.

Multivariate discriminants and fit

Separate **Boosted Decision Trees** trained in each category → training performed on muons, features are similar across leptons

Simultaneous **Maximum likelihood fit to data in the 6 categories**

2-jets 1-tag, for *ST*(all) vs **tt** and **W+jets** discrimination:

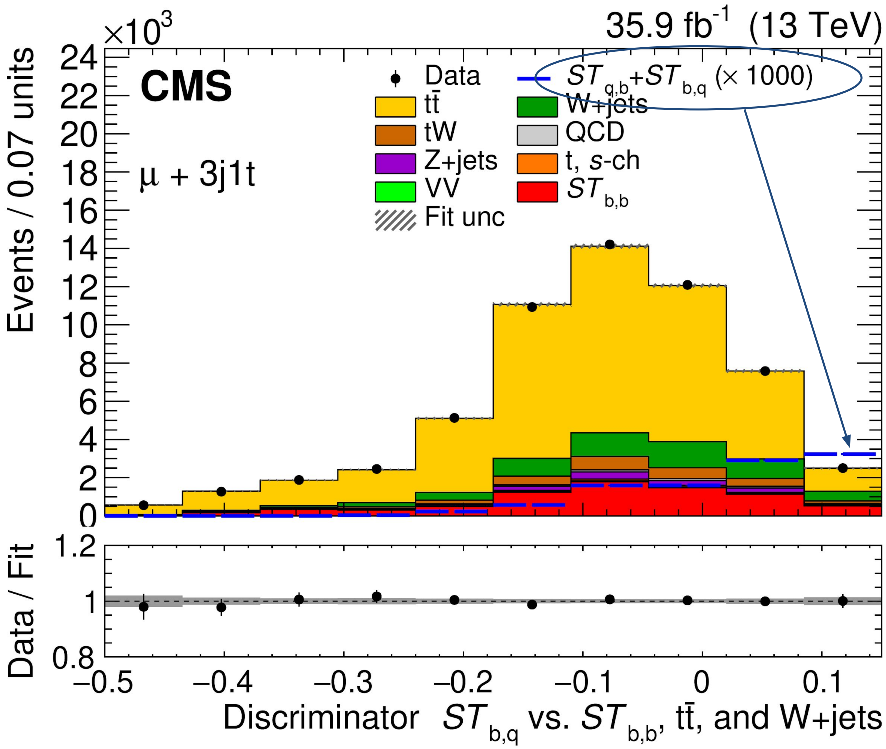


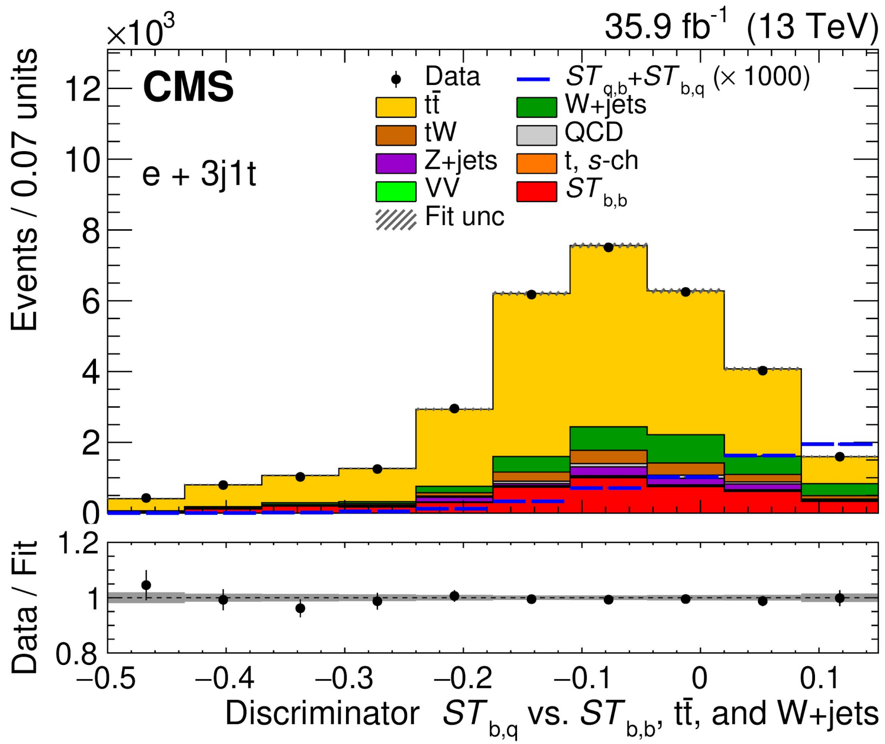
Multivariate discriminants and fit

Separate **Boosted Decision Trees** trained in each category → training performed on muons, features are similar across leptons

Simultaneous **Maximum likelihood fit to data in the 6 categories**

3-jets 1-tag, for **Signal 1** vs **Signal 2,3** discrimination:





Systematic uncertainties

Profiled: treated within the fit as additional nuisance parameters
Non-profiled: repeat fit with varied scenario, uncertainty = difference in the fit results

List of uncertainties and impact on *t*-channel cross section measurement:

Treatment	Uncertainty	$\Delta\sigma_{ST_{b,b}}/\sigma$ (%)
Profiled	Lepton trigger and reconstruction	0.50
	Limited size of simulated event samples	3.13
	$t\bar{t}$ modelling	0.66
	Pileup	0.35
	QCD background normalisation	0.08
	W+jets composition	0.13
	Other backgrounds μ_R/μ_F	0.44
	PDF for background processes	0.42
	b tagging	0.73
	Total profiled	3.4
Nonprofiled	Integrated luminosity	2.5
	JER	2.8
	JES	8.0
	PDF for signal process	3.8
	Signal μ_R/μ_F	2.4
	ME-PS matching	3.7
	Parton shower scale	6.1
	Total nonprofiled	11.5
Total uncertainty		12.0

Criteria to profile:

1) Prior distribution is independent from our observed quantity

→ most instrumental **yes**
→ signal modeling **no**
→ background modeling **yes**

2) No strong correlation with other systematic effects affecting observed quantity

→ jes, jer **no**
→ luminosity **no**

Fit models and interpretation

Fit parametrization: signal strengths

Fit strengths written in terms of measured vs injected cross sections

$$\mu_{\mathrm{b}} = \frac{\sigma^{\mathrm{obs}}_{t\text{-ch,b}} \mathcal{B}(\mathrm{t} \to \mathrm{Wb})^{\mathrm{obs}}}{\sigma_{t\text{-ch,b}} \mathcal{B}(\mathrm{t} \to \mathrm{Wb})}$$

$$\mu_{\mathrm{sd}} = \frac{\sigma^{\mathrm{obs}}_{t\text{-ch,b}} \mathcal{B}(\mathrm{t} \to \mathrm{Ws,d})^{\mathrm{obs}} + \sigma^{\mathrm{obs}}_{t\text{-ch,s,d}} \mathcal{B}(\mathrm{t} \to \mathrm{Wb})^{\mathrm{obs}}}{\sigma_{t\text{-ch,b}} \mathcal{B}(\mathrm{t} \to \mathrm{Ws,d}) + \sigma_{t\text{-ch,s,d}} \mathcal{B}(\mathrm{t} \to \mathrm{Wb})}$$

Where:

μ_{b} = signal strength of ***ST*(b,b)**

μ_{sd} = signal strength of sum of the two ***ST*(q,b) + *ST*(b,q)**

Fit results

μ_{sd} can be written as function of $|V_{td}|^2+|V_{ts}|^2$, and $|V_{td}|/|V_{ts}|$

-$|V_{td}|/|V_{ts}|$ appears in a term contributing by 5% to the total strength.

- This term comes from Signal 3 ***ST*(d$_v$,b)**. The analysis is not sensitive to floating this parameter, due to the similarity with the *ST*(b,b) signature.

→ Performing the fit one finds:

$$\boxed{\begin{aligned} \mu_{\mathrm{b}} &= 0.99 \pm 0.03\,(\text{stat+prof}) \pm 0.12\,(\text{nonprof}) \\ \mu_{\mathrm{sd}} &< 87 \text{ at } 95\% \text{ confidence level (CL),} \end{aligned}}$$

The Standard Model measurement

Imposing unitarity, one finds σ x BR ($t \rightarrow Wb$) $\propto$ $|V_{tb}|^2$ x $|V_{tb}|^2$

$$\mu_{\mathrm{b}} = \frac{|V_{\mathrm{tb}}|^4_{\mathrm{obs}}}{|V_{\mathrm{tb}}|^4}$$

$$\mu_{\mathrm{sd}} = \frac{|V_{\mathrm{tb}}|^2_{\mathrm{obs}}(1 - |V_{\mathrm{tb}}|^2_{\mathrm{obs}})}{|V_{\mathrm{tb}}|^2(1 - |V_{\mathrm{tb}}|^2)}$$

→ Here there is only 1 effective parameter for the signal

→ Uncertainty on $|V_{\mathrm{tb}}|$ is reduced because of the fourth power dependence.

Limits at 95% CL:

$$\boxed{\begin{aligned} |V_{\mathrm{tb}}| &> 0.970 \\ |V_{\mathrm{td}}|^2 + |V_{\mathrm{ts}}|^2 &< 0.057. \end{aligned}}$$

Releasing unitarity assumption

Parametrizing under different hypotheses on scenarios, widths may vary

Defining a convenient reduced width $\widetilde{\Gamma}_{\mathrm{q}}$ such that $\Gamma_{\mathrm{q}} = \widetilde{\Gamma}_{\mathrm{q}}|V_{\mathrm{tq}}|^2$

$$\mu_{\mathrm{b}} = \frac{|V_{\mathrm{tb}}|^4_{\mathrm{obs}}\widetilde{\Gamma}^{\mathrm{obs}}_{\mathrm{q}}\Gamma_{\mathrm{t}}}{|V_{\mathrm{tb}}|^4\widetilde{\Gamma}_{\mathrm{q}}\Gamma^{\mathrm{obs}}_{\mathrm{t}}}$$

$$\mu_{\mathrm{sd}} = \frac{|V_{\mathrm{tb}}|^2_{\mathrm{obs}}\left(|V_{\mathrm{ts}}|^2_{\mathrm{obs}} + |V_{\mathrm{td}}|^2_{\mathrm{obs}}\right)\widetilde{\Gamma}^{\mathrm{obs}}_{\mathrm{q}}\Gamma_{\mathrm{t}}}{|V_{\mathrm{tb}}|^2\left(|V_{\mathrm{ts}}|^2 + |V_{\mathrm{td}}|^2\right)\widetilde{\Gamma}_{\mathrm{q}}\Gamma^{\mathrm{obs}}_{\mathrm{t}}}$$

Releasing unitarity different assumptions can be made on the way decay and production are affected. We consider two scenarios

→ Γ_{t} and Γ_{q} have the same expression as SM, but $|V_{\mathrm{tq}}|$ can vary freely.

→ Γ_{q} has the same expression as SM, Γ_{t} and $|V_{\mathrm{tq}}|$ can vary freely

Releasing unitarity assumption: case 1

$|V_{tq}|$ varies freely: the CKM matrix comes from effective couplings.

If we consider Γ_t varying only because of the coupling strength, one finds:

$$\mu_b = \frac{|V_{tb}|^4_{obs}}{|V_{tb}|^4\left(|V_{tb}|^2_{obs} + |V_{ts}|^2_{obs} + |V_{td}|^2_{obs}\right)}$$

$$\mu_{sd} = \frac{|V_{tb}|^2_{obs}\left(|V_{ts}|^2_{obs} + |V_{td}|^2_{obs}\right)}{\left(|V_{ts}|^2 + |V_{td}|^2\right)\left(|V_{tb}|^2_{obs} + |V_{ts}|^2_{obs} + |V_{td}|^2_{obs}\right)}$$

The corresponding fit results in:

$$\boxed{\begin{aligned} &|V_{tb}| = 0.988 \pm 0.027\,(\text{stat+prof}) \pm 0.043\,(\text{nonprof}) \\ &|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.05\,(\text{stat+prof})\,^{+0.04}_{-0.03}\,(\text{nonprof}). \end{aligned}}$$

Releasing unitarity assumption: case 2

The width also varies freely: the main width variations come from kinematic effects or new physics decays.

→ The current experimental uncertainty on Γ_t is in fact much greater than the precision we have on $|V_{tb}|$, making this possibly the leading effect

Signal strengths:

$$\mu_b = \frac{|V_{tb}|^4_{obs}\Gamma_t}{|V_{tb}|^4\Gamma_t^{obs}}$$

$$\mu_{sd} = \frac{|V_{tb}|^2_{obs}(|V_{ts}|^2_{obs} + |V_{td}|^2_{obs})\Gamma_t}{|V_{tb}|^2(|V_{ts}|^2 + |V_{td}|^2)\Gamma_t^{obs}}$$

We measure:

$$|V_{tb}| = 0.988 \pm 0.011\,(\text{stat+prof}) \pm 0.021\,(\text{nonprof})$$
$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.05\,(\text{stat+prof}) \pm 0.04\,(\text{nonprof})$$
$$R_\Gamma = 0.99 \pm 0.42\,(\text{stat+prof}) \pm 0.03\,(\text{nonprof}).$$

Summary and outlook

We performed a **first measurement** of CKM matrix elements in single top quark events relieving many of the assumptions done in previous analyses.

This approach allows to significantly improve the precision on $|V_{tb}|$ achievable in single top events without having to rely on any additional assumptions on the decay.

The obtained measurement is comparable with the equivalent in tt events:

$$\boxed{|V_{\mathrm{tb}}| > 0.970}$$

Comparison with previous single top quark measurements is possible by specifying the assumption to be considered on the decay.

By leaving the top quark width fully floating one finds:

$$\boxed{|V_{\mathrm{tb}}| = 0.988 \pm 0.024}$$

Summary and outlook

The analysis for the first time **probes the CKM element modules |V_{td}| and |V_{ts}|** at tree level in single top quark processes, yielding:

$$\boxed{|V_{td}|^2 + |V_{ts}|^2 < 0.057}$$

Under circumstances that allow to violate CKM unitarity, one can extract limits on these new couplings, yielding:

$$\boxed{|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06}$$

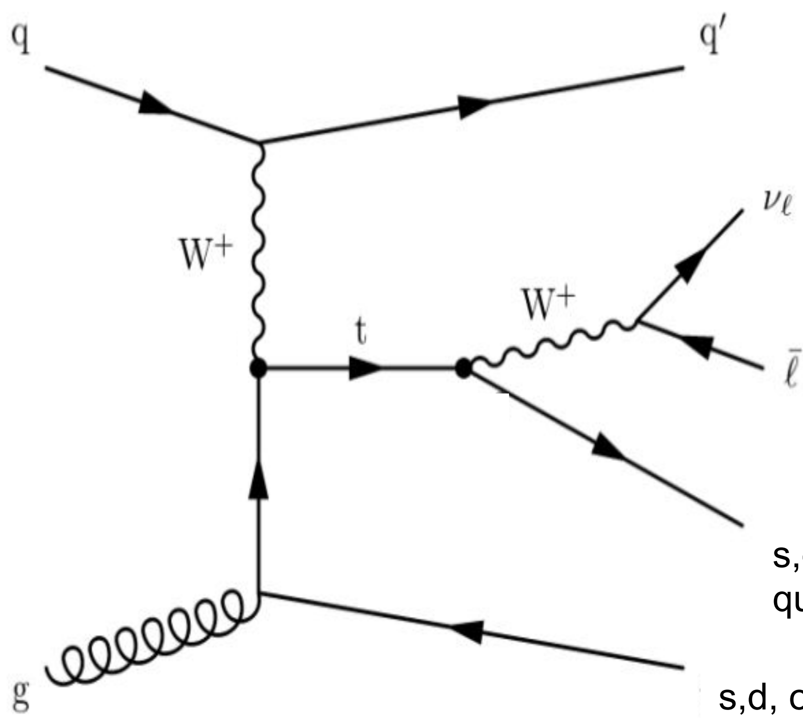
The route undertaken here shows promise for future measurements, that could aim at increasing sensitivity to $|V_{td}|/|V_{ts}|$, and considering other scenarios for the measurement of partial and total widths.

thank you!

Additional material

The baseline selection for all signals

Final state **@Reconstruction level**



1 high-η "forward" jet* jet called ***j'***

Missing transverse momentum $p_{T,miss}$

Well reconstructed muon or electron **
- veto additional leptons

s,d, or b quark → jet, potentially reconstructed as b

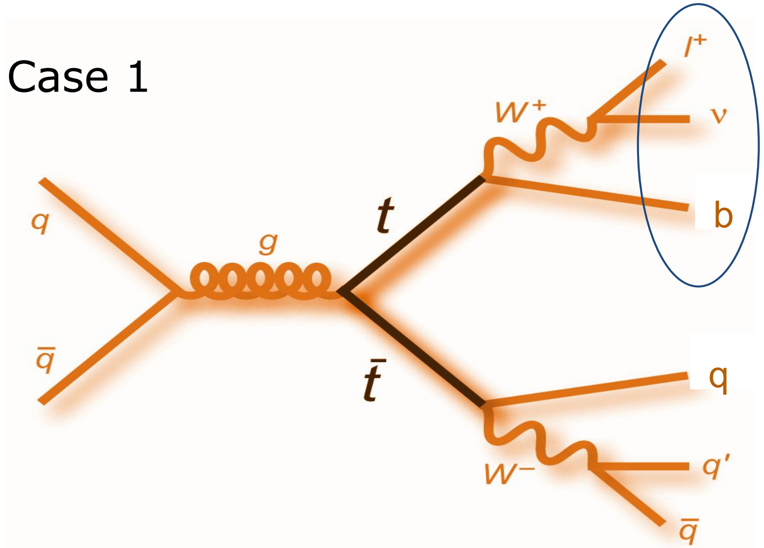
s,d, or b quark → low-p_T jet, potentially reconstructed as b

Required objects

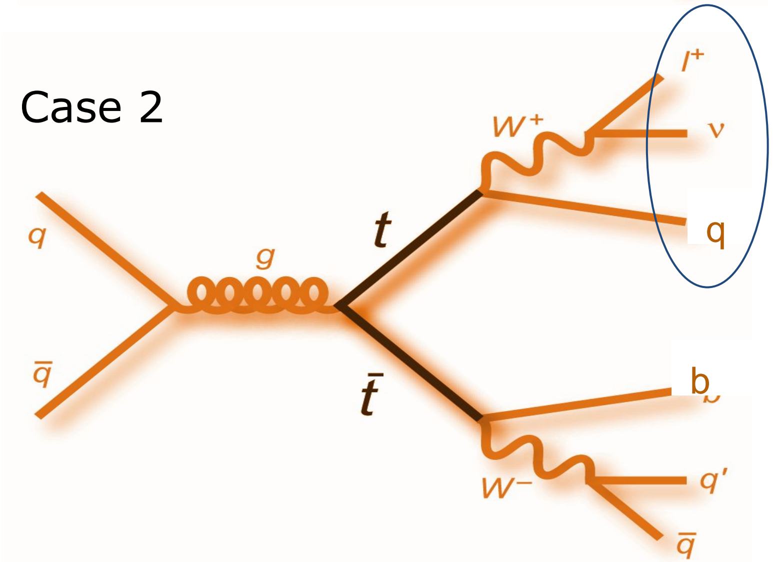
1	Tight muon	$p_T > 26$ GeV/c	$\lvert\eta\rvert < 2.4$	$I^{\mu}_{rel} < 0.06$	
0	Loose muon	$p_T > 10$ GeV/c	$\lvert\eta\rvert < 2.4$	$I^{\mu}_{rel} < 0.2$	
1	Tight electron	$E_T > 35$ GeV	$\lvert\eta\rvert < 2.1$	$I^{e}_{rel} < 0.0588$ (B)	$I^{e}_{rel} < 0.0571$ (E)
0	Veto electron	$E_T > 15$ GeV	$\lvert\eta\rvert < 2.5$	$I^{e}_{rel} < 0.2$	
2(3)	Jet	$E_T > 40$ GeV	$\lvert\eta\rvert < 4.7$		
1(2)	b-Jet	$E_T > 40$ GeV	$\lvert\eta\rvert < 2.4$	CMVA ≥ 0.9432	

TT → lvb lvq

Case 1



Case 2



Top quark pairs with 1 tWq vertex

- Populates 3-jet 1-tag region

- Our analysis exploits the correlation between b-tagging and reconstruction of the correct top quark

- The probability to get the correct b-jet to be the one to reconstruct our top quark is 50% regardless of whether it's a b-jet or non-b jet

Case 1: the b-tagged jet gives the best top

Case 2: the non-b -tagged jet gives the best top

Simply by considering the total yield and the residual power of the b discriminator has proven insufficient to discriminate this channel vs systematic variations