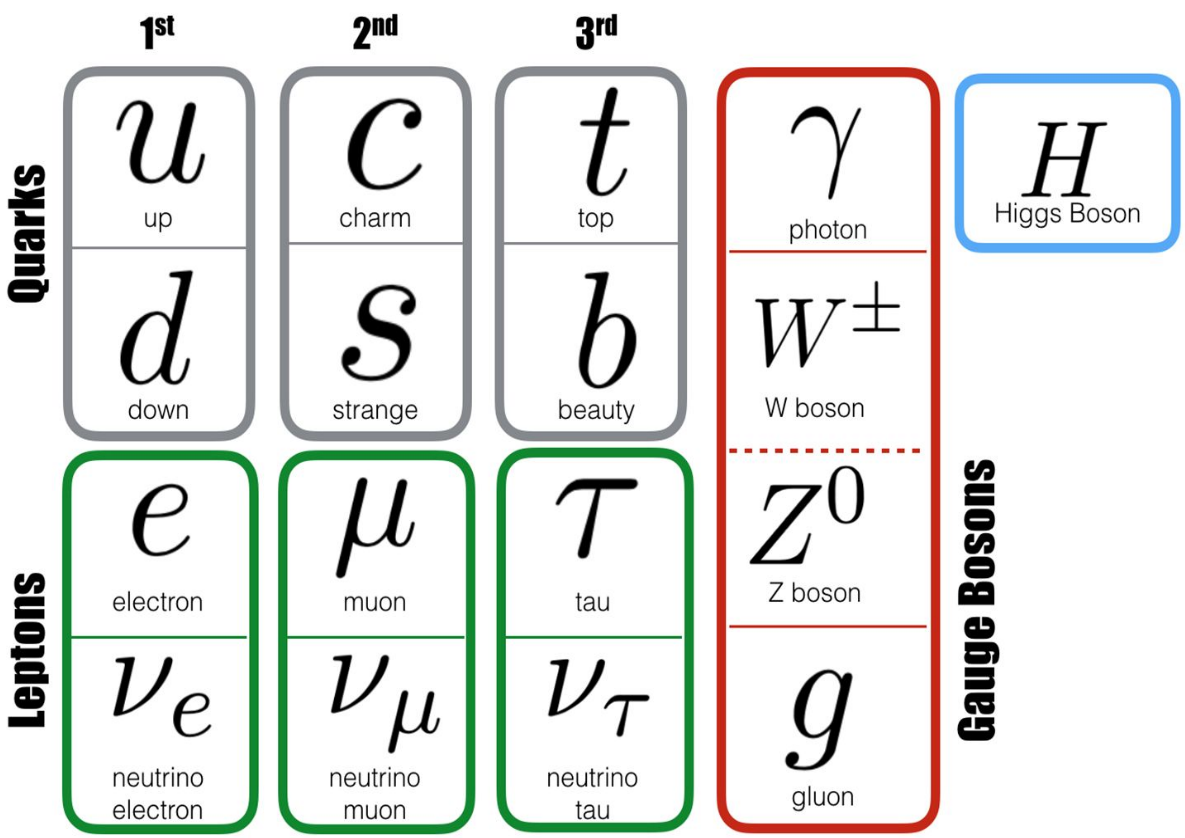
Extraction of CKM matrix elements in single top quark events

9/06/2020

A.O.M. Iorio

- 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 Standard Model of particle physics



The Standard Model is a relativistic quantum field theory:

→ 12 particle fields: "fermions"

→ Electromagnetic, weak, and strong interactions derived from a **Gauge principle**

→ Gauge **bosons** mediate interactions

→ Particles acquire mass with the higgs mechanism

SM fundamental parameters:

→ High number (>18) of fundamental parameters that must be measured from data.

→ Those include, for example, the fermion masses, the interaction strengths, the higgs mass...

The CKM matrix and the top quark

The CKM matrix

Matrix of fundamental parameters regulating the "mixing" between quark families

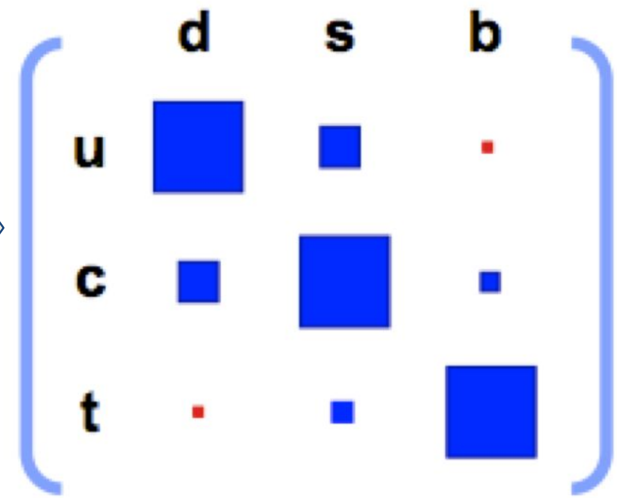
→ Transformation between the **free particle** vs **EW interacting lagrangian** eigenstates

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

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

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

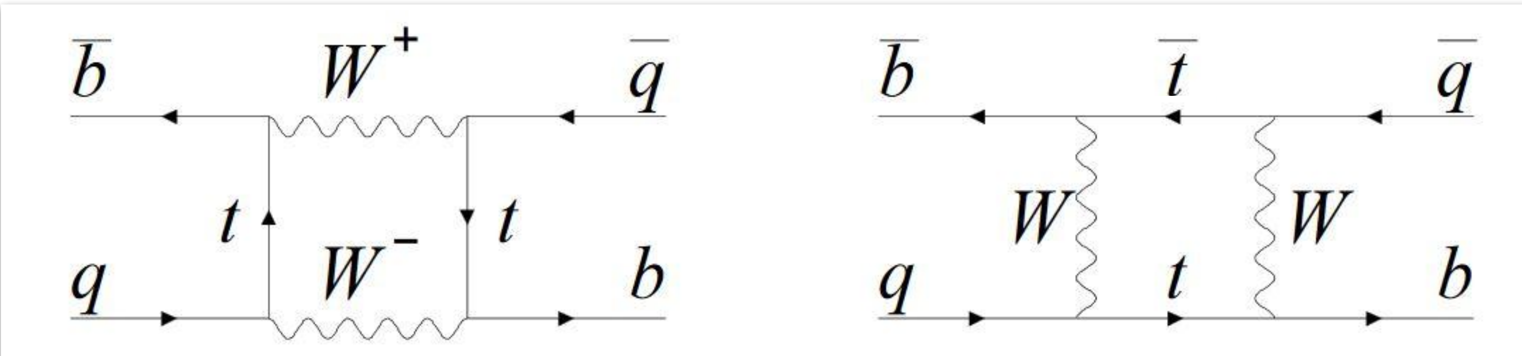
Pictorically representing the couplings



CKM: the third row w/o top quark measurements

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

- Mixing between neutral B-$\bar{B}$ 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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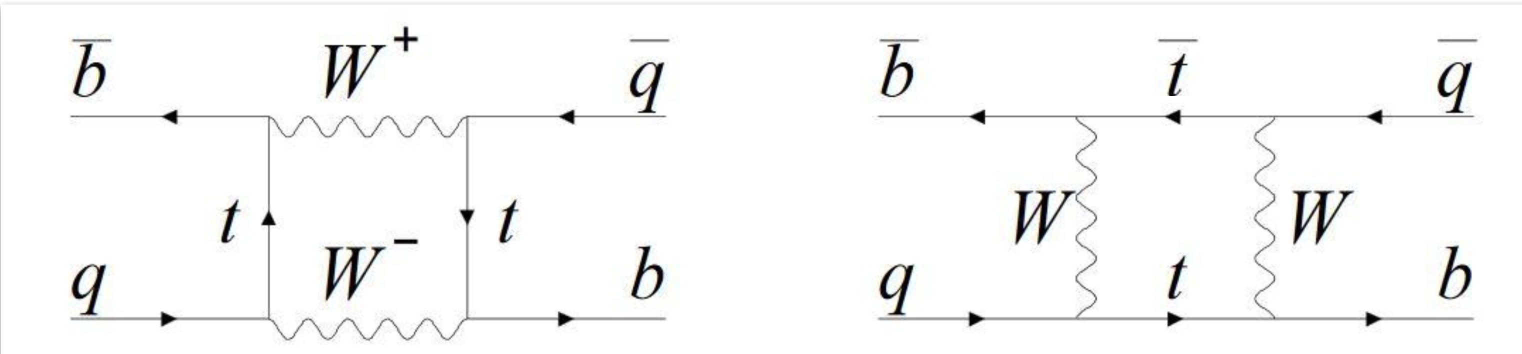

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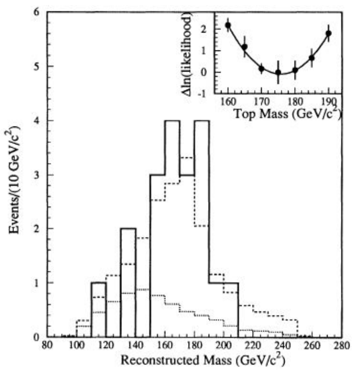
Questions to be answered from top quark measurements:
Is Vtb ≅ 1? If not, what's its value?
Can we **measure** |Vtd| and |Vts| at **tree level?**

The top quark: a story of 25 years

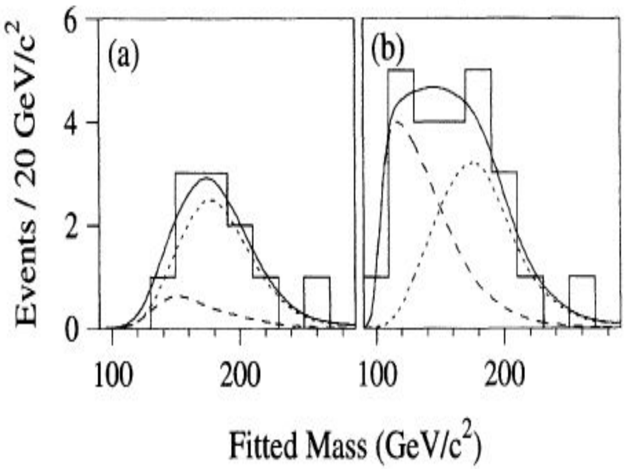
1995 Observation at TeVatron
via strong pair production (tt)

2009 Observation of electroweak
single top production @TeVatron

PRL 74 (1995) 2626



PRL 74 (1995) 2632



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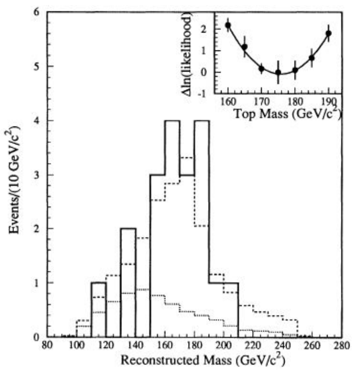

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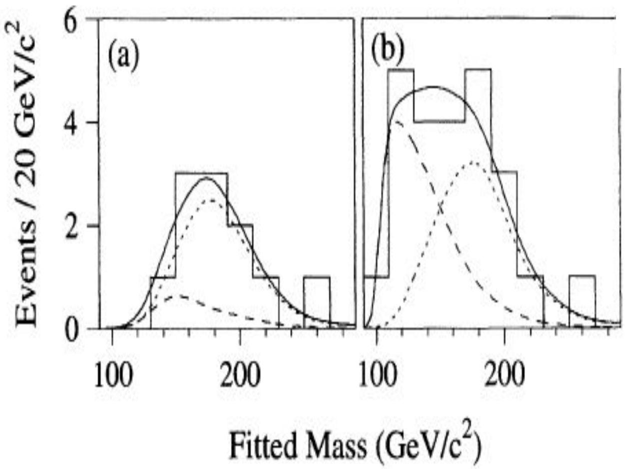
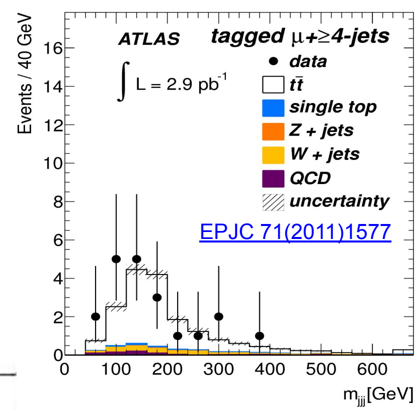
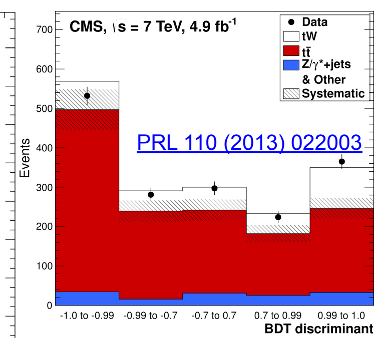


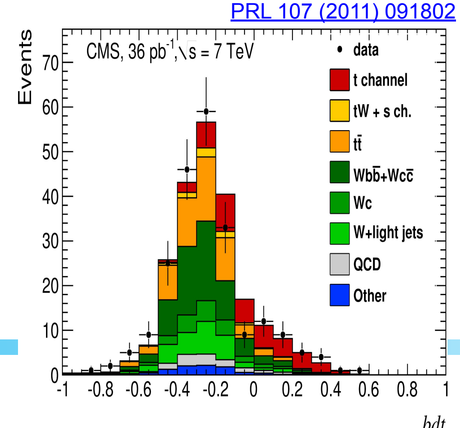


EPJC 71(2011)1577



PRL 110 (2013) 022003

PRL 107 (2011) 091802



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2010-11 Rediscovery @LHC:
tt, single top

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

2009 Observation of electroweak
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2012 first entirely new
mode @LHC : t+W

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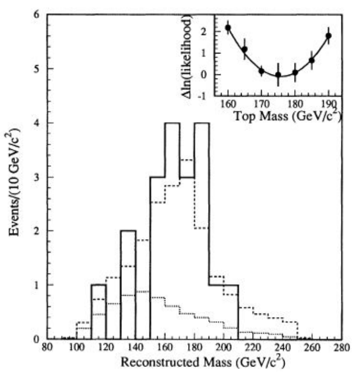

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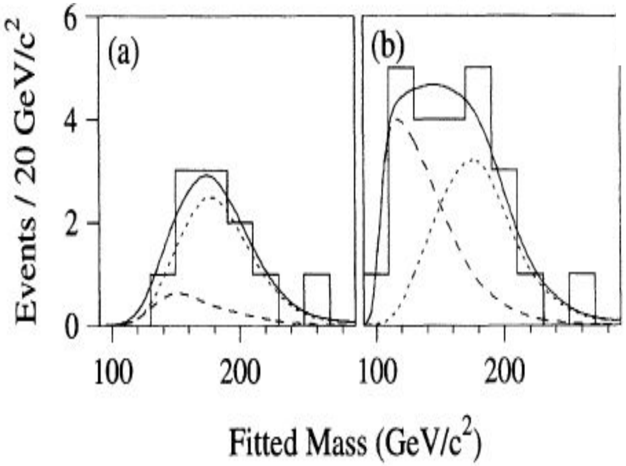

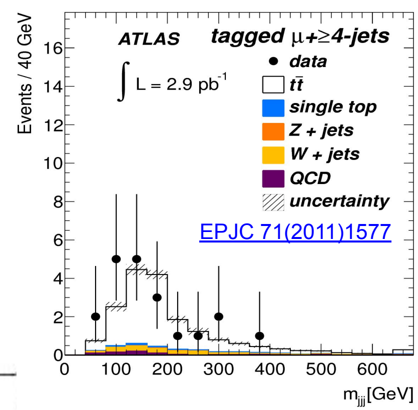

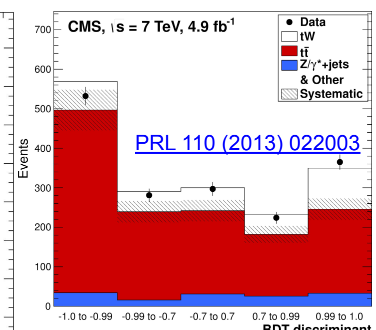

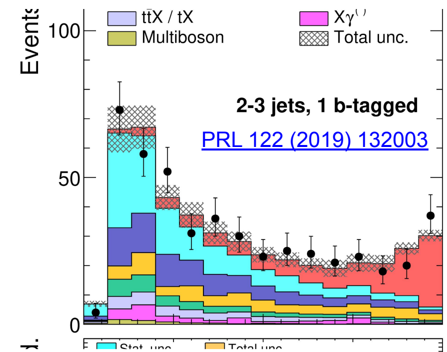

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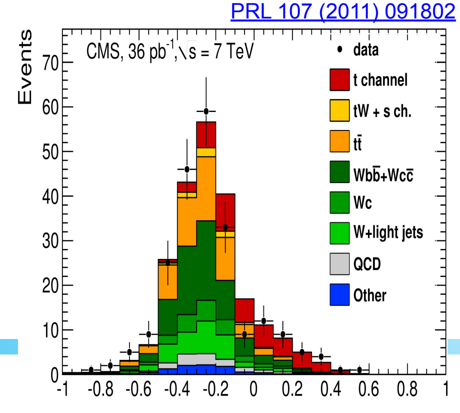
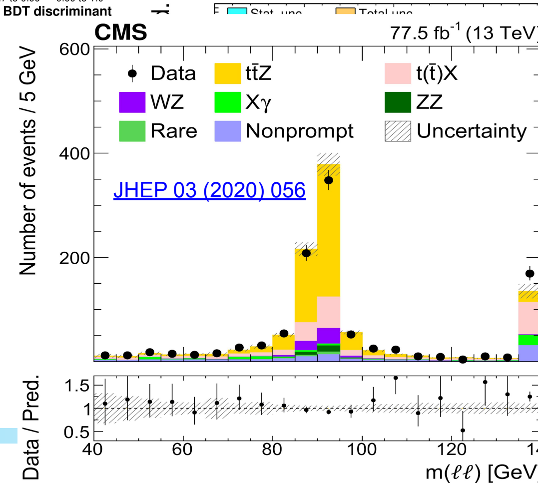
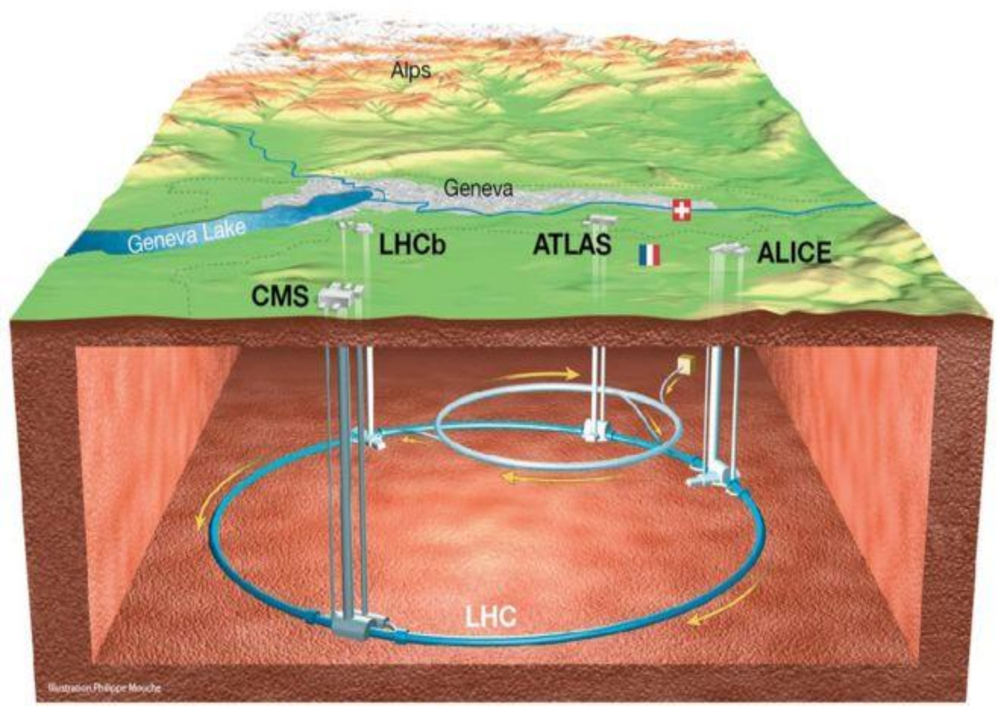




Top-CKM measurements at LHC so far

The Large Hadron Collider



Most powerful hadronic collider to date

- 27 Km accelerating complex below the French-Swiss border close to Geneva
- proton-proton collision energy up to **13 TeV**
- Luminosity up to ~10^{34} cm^{-2} s^{-1}
  → 1 billion interactions/s

4 experiments at the interaction points: CMS, Atlas, Alice, LHCb, and LHCb

Proton-proton collision data taking:

Period	Year	CM Energy (TeV)	Collected luminosity (fb^{-1})
Run I	2010-2011	7	6.1
Run I	2012-2013	8	23.3
Run II	2015-2018	13	158 6

The Compact Muon Solenoid experiment

One of the four large experiments

◦ "General purpose" detector:

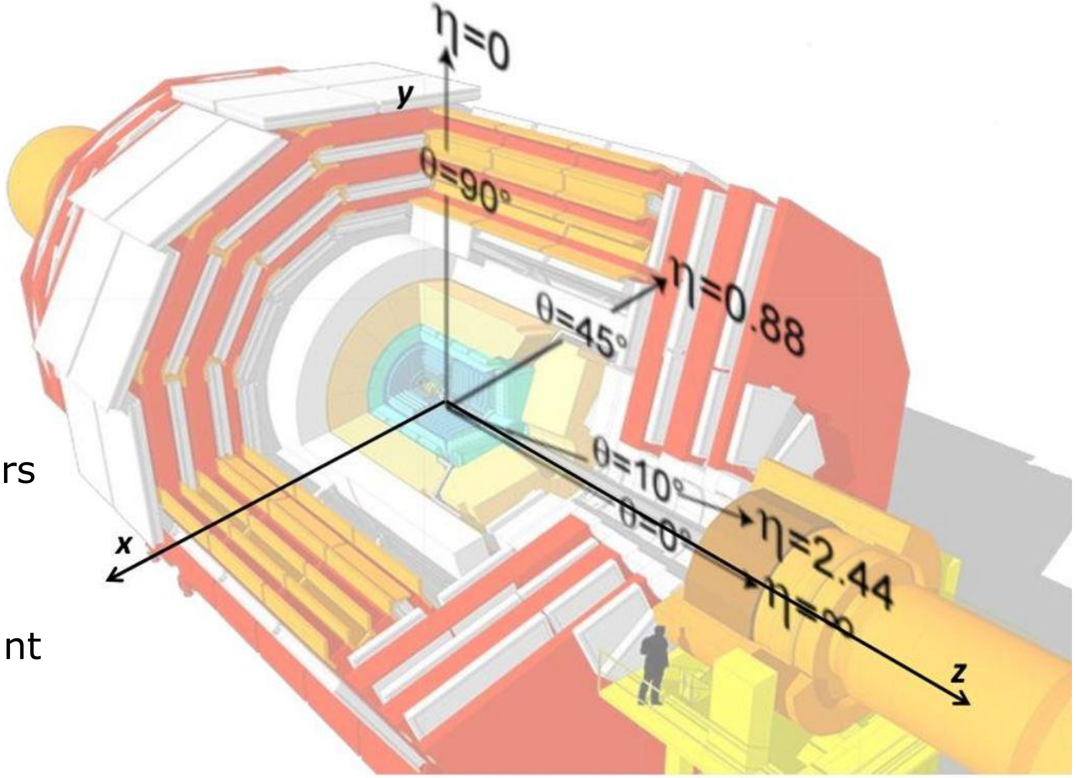
→ SM measurements and BSM searches

◦ Structure of layered sub-detectors:

→ Silicon detectors for charged particles
→ Electromagnetic and hadronic calorimeters
→ Superconducting coil
→ Muon gas detectors

◦ Centered around the beam interaction point

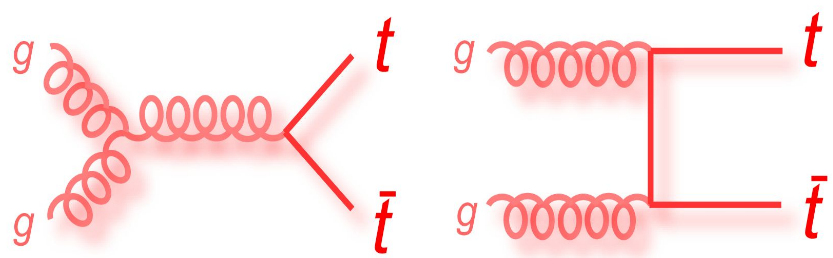
→ Polar coordinate system
→ Using pseudorapidity "η" = -ln (tan θ/2)

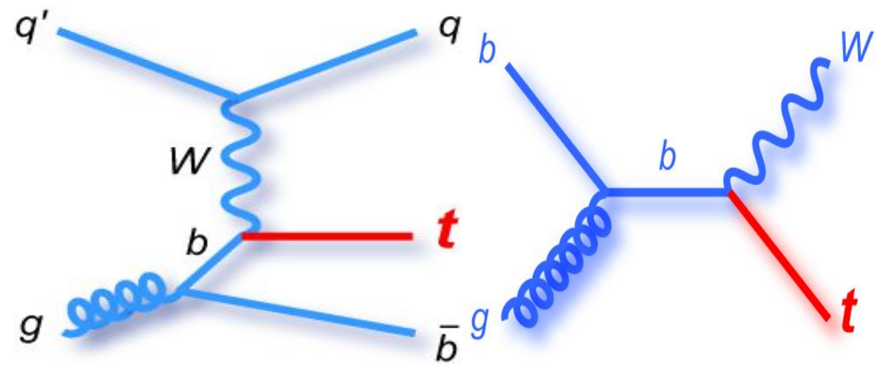


Top quark at LHC:
main production modes

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 ∝ $(\alpha_s/m_{top})^2$**

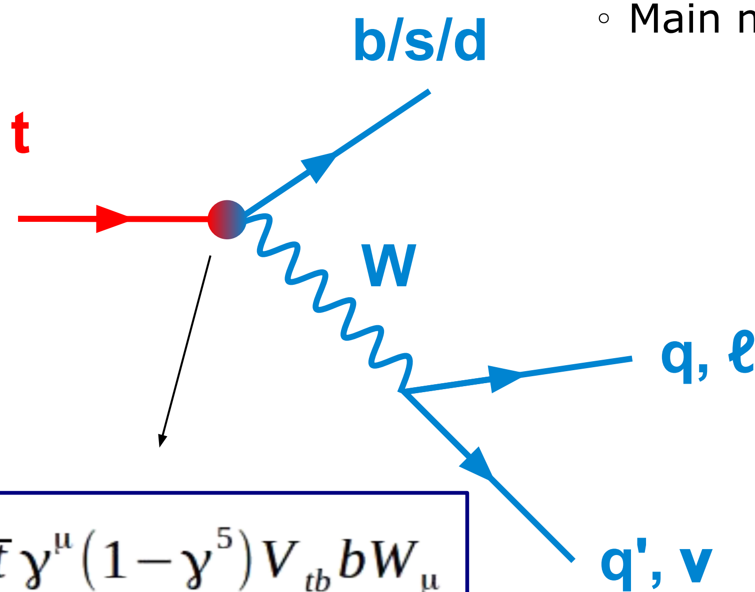
- **single-top quarks:**

  - 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



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

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

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

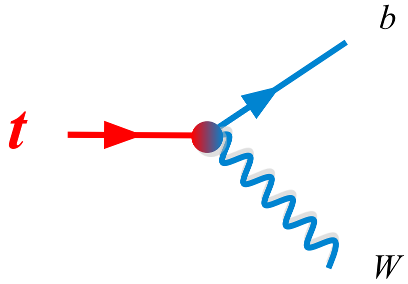
- Electroweak **tWb vertex:**
  - V-A: **polarization** of the products and defined **W-helicity**
  - CKM matrix element enters the decay → usually one considers

$|V_{tb}|$ $\sim 1 \rightarrow \Gamma(t \rightarrow b) >> \Gamma(t \rightarrow s,d)$ for most measurements

CKM measurements in the top quark sector

1) **Decays** of top quark pairs

BR (t→ Wb)∝ 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

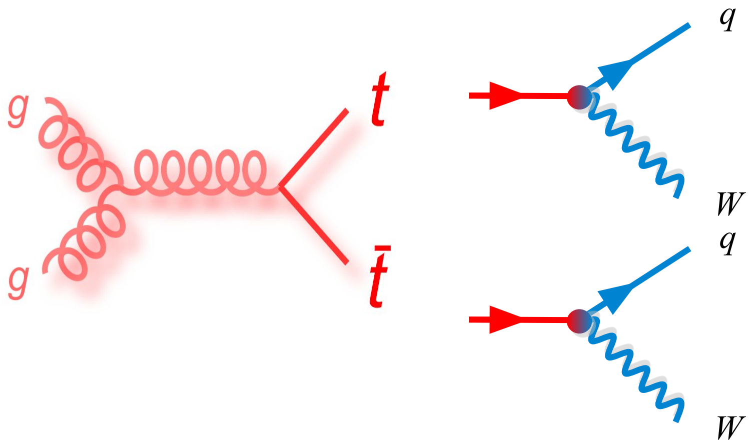
1.2 Unitarity gives $|V_{tb}|^2+|V_{td}|^2+|V_{ts}|^2=1$

→ allows to "translate" to $|V_{tb}|$

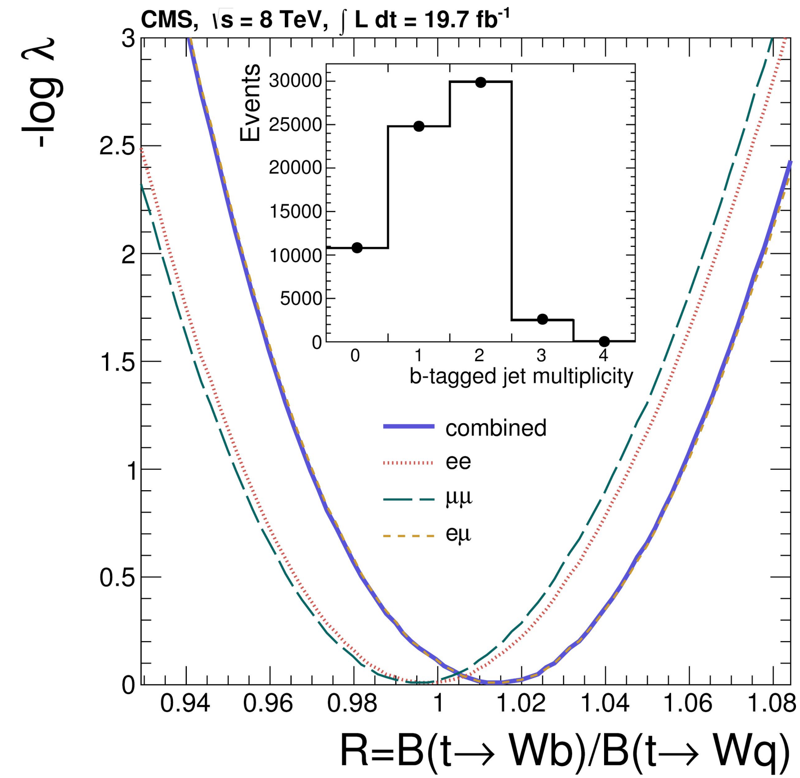
tt events: measurement of *R*

High precision measurement through tt pairs:

- Count the number of tt events to ℓℓvvjj



- Fit b-tagged jets multiplicity



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

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

CKM measurements in the top quark sector

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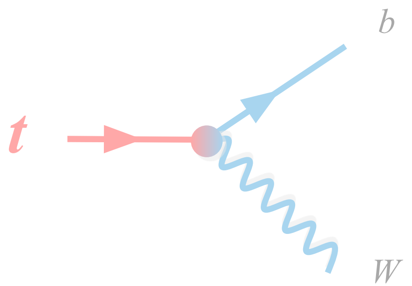

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1.2 Unitarity gives $|V_{tb}|^2+|V_{td}|^2+|V_{ts}|^2 = 1$

→ allows to translate to $|V_{tb}|$

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

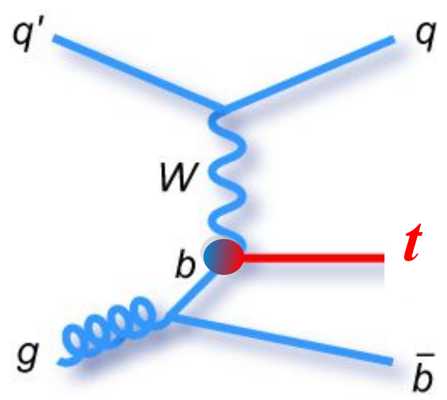
$\sigma \propto |V_{tb}|^2$

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

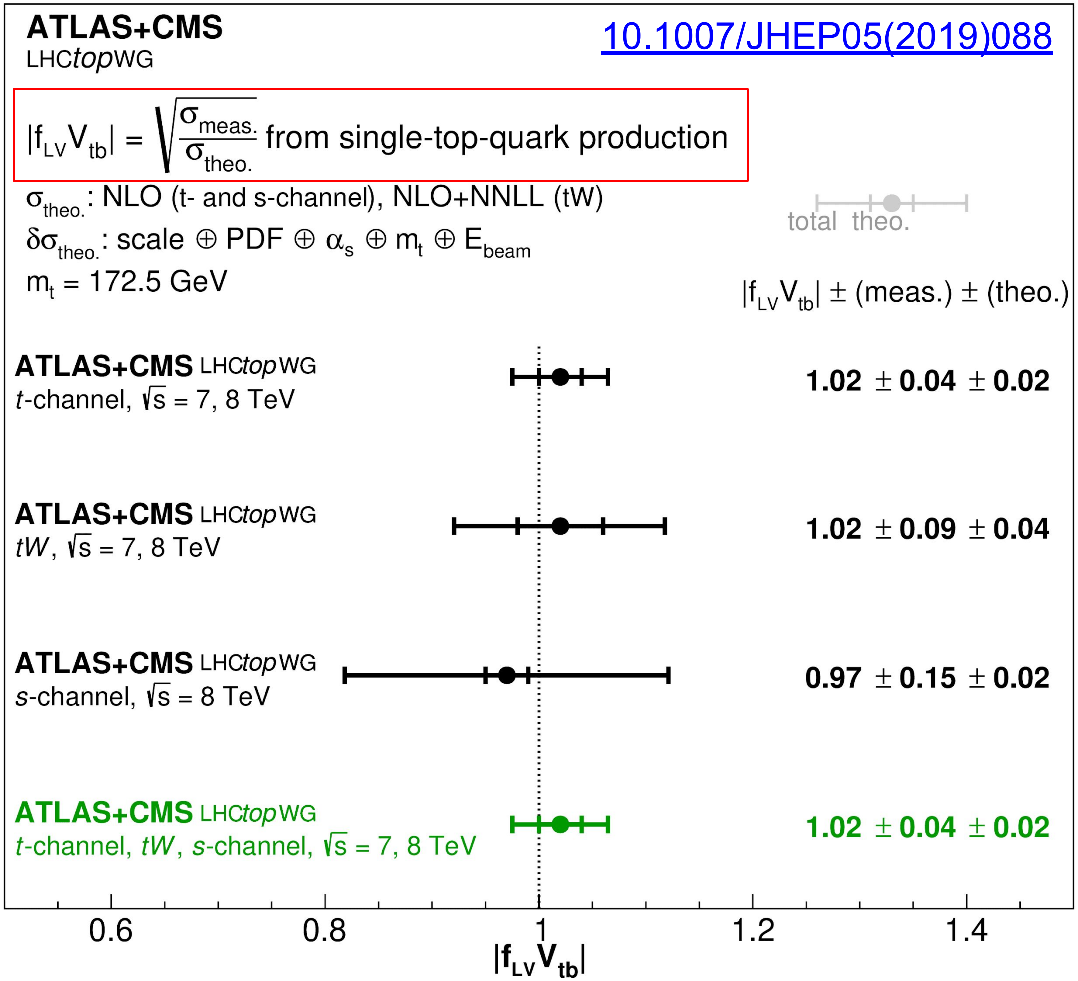


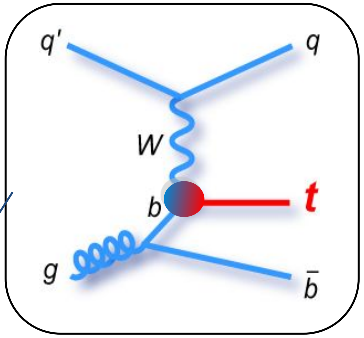
$|V_{tb}|$ in single t processes

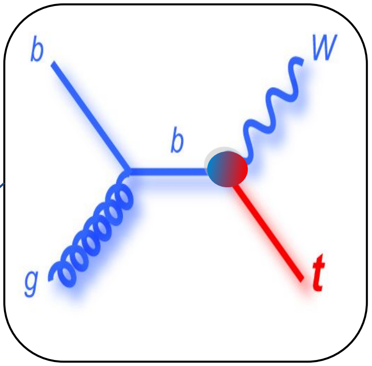
Huge success in LHC combination of Run-I analyses:

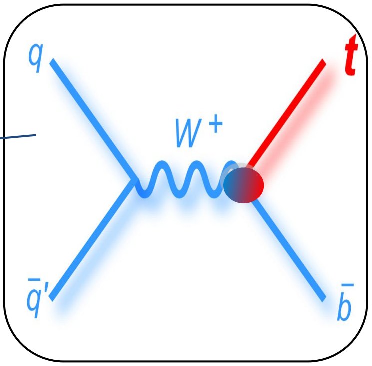
- Leading process: single top quarks in the *t*-channel,

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







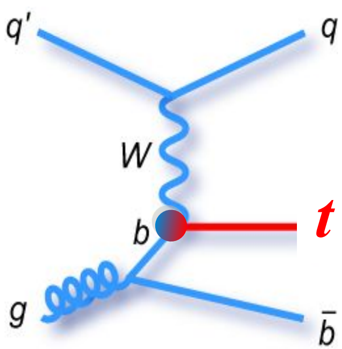


New idea for CKM extraction in the *t*-channel

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:

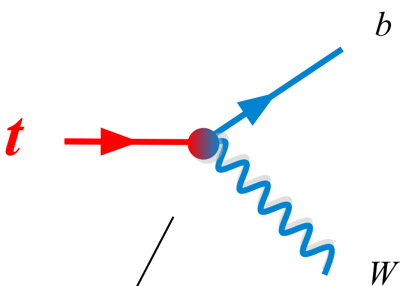
Production mechanism:

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



Decay mechanism:

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



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

Advantages with this approach

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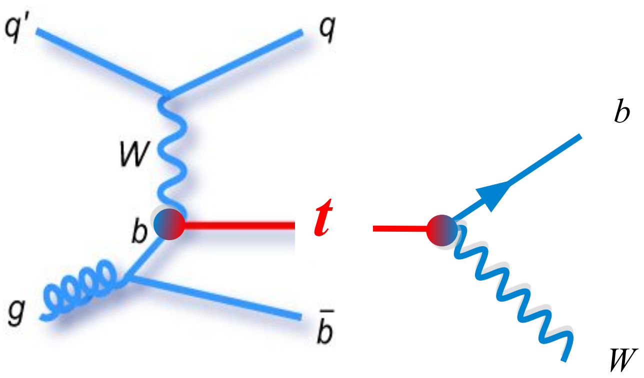
The idea is to get "the best of both worlds" and probe at the same time:

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:

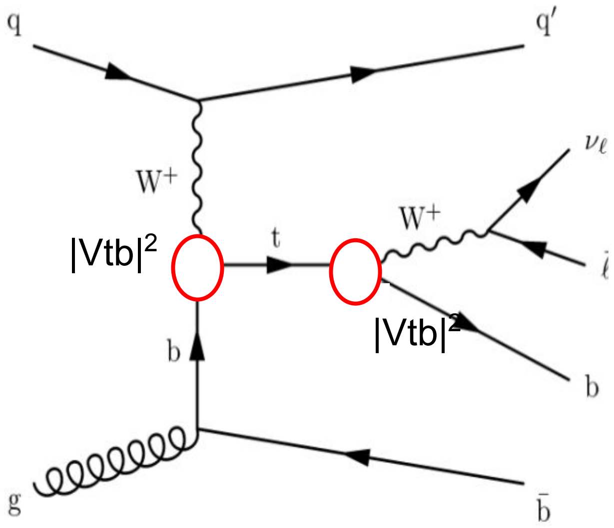
→ gradually releasing assumptions where new physics might affect the process

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

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

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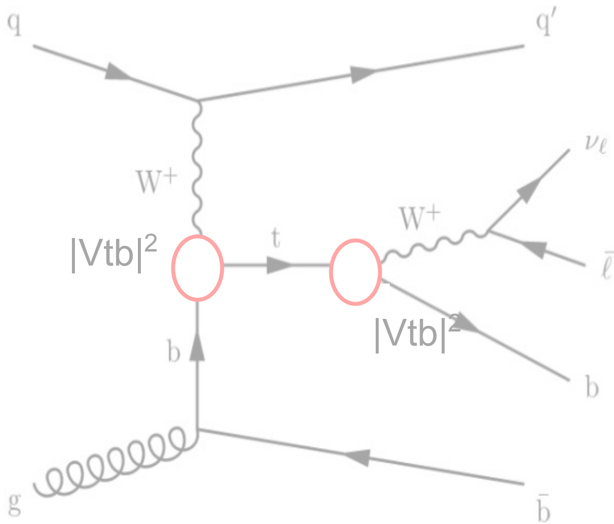
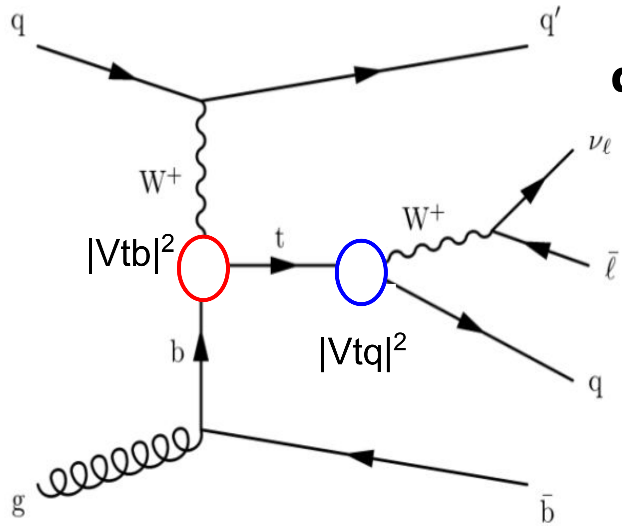


Signal 2 ***ST*(b,q)**



decays through tWs/d vertex

t-channel analysis: signals considered

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

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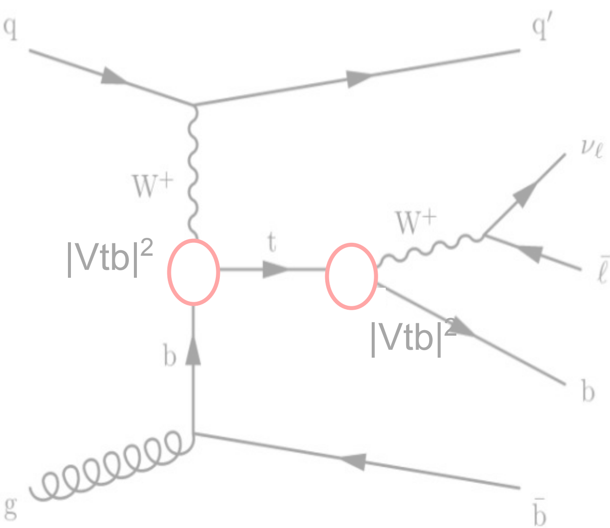

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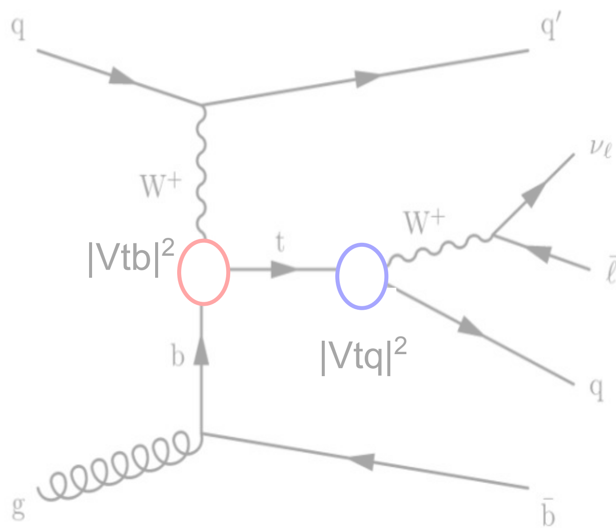
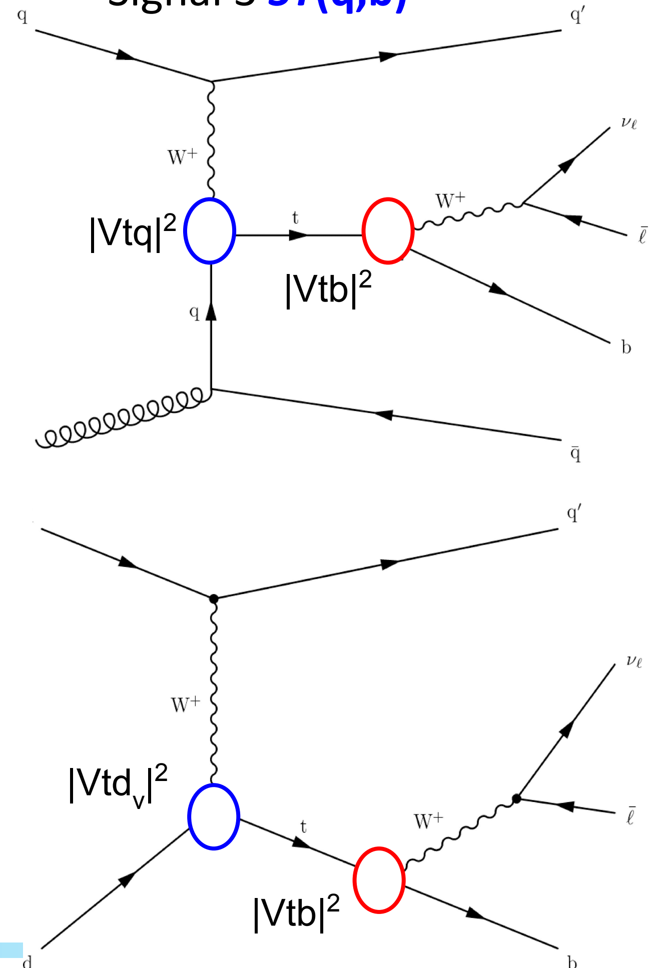


Signal 3 ***ST*(q,b)**



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

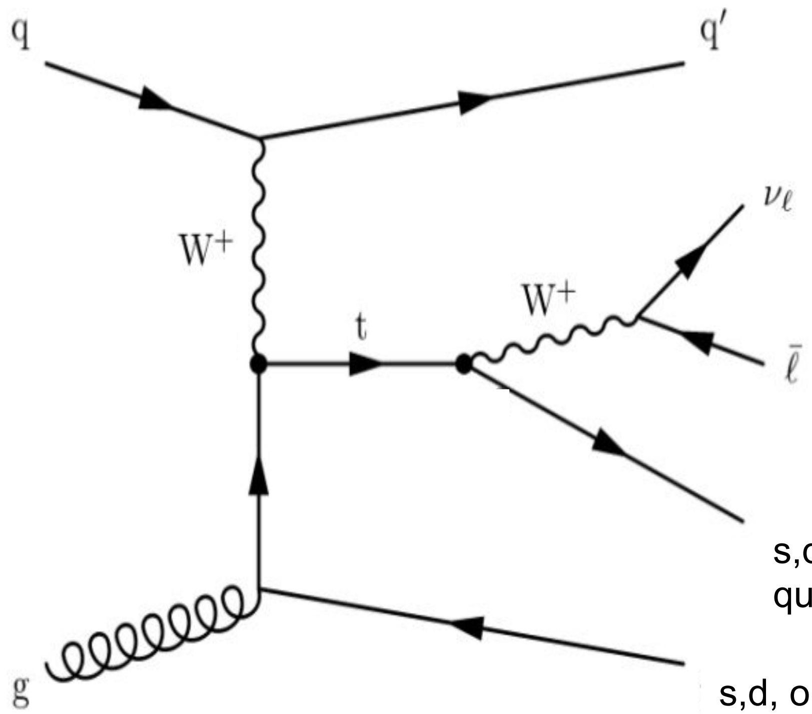
Initial values of CKM elements taken from low energy measurements:

	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

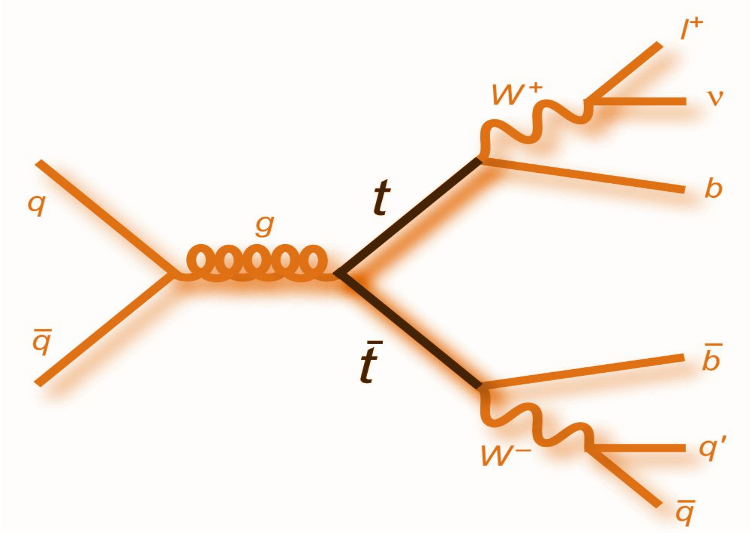
s,d, or b quark → jet, potentially reconstructed as b

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

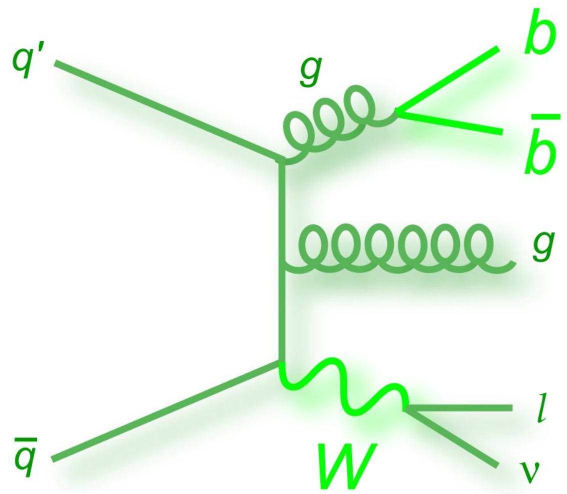


Top quark pair production

- 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



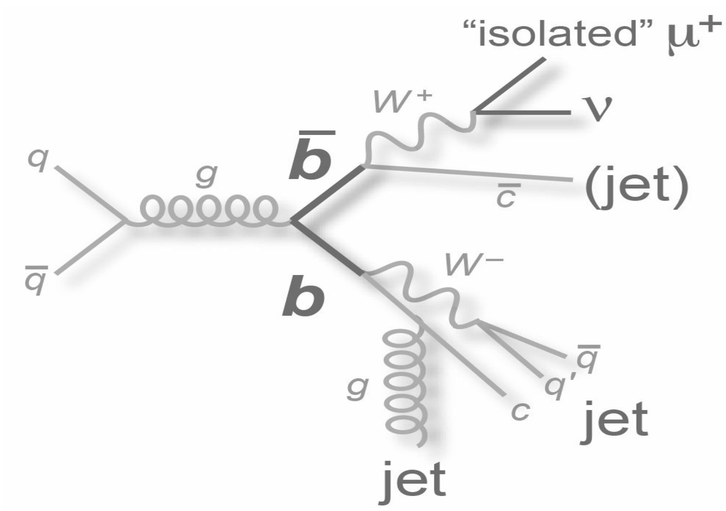
W+jets production

- 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

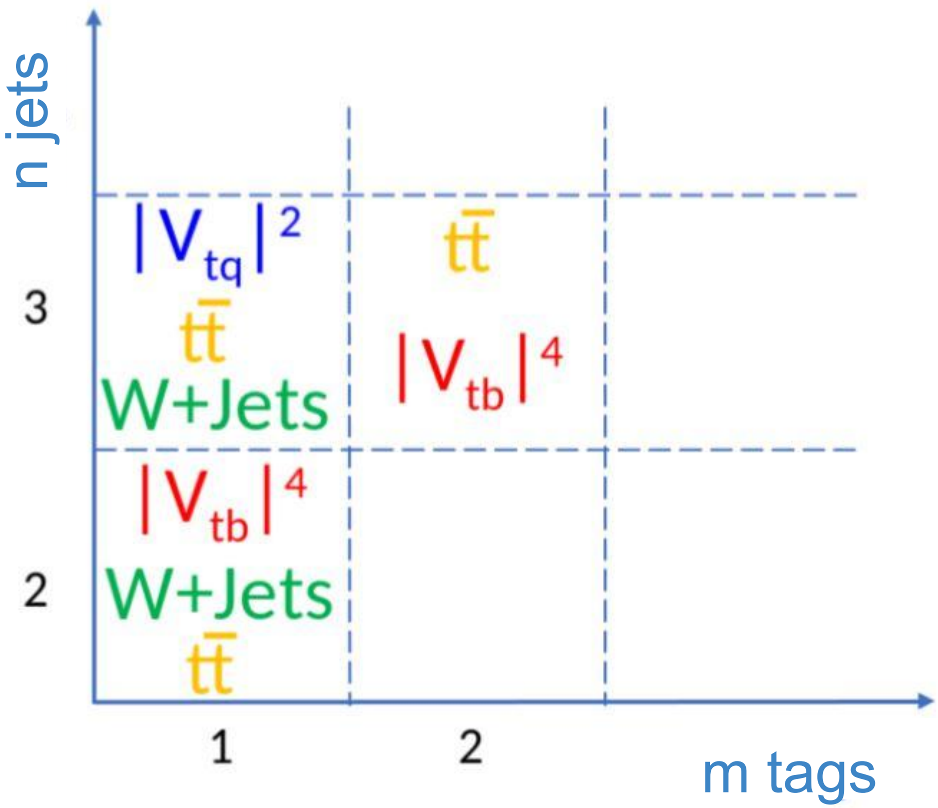
1) QCD enriched sideband defined inverting lepton identification criteria

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

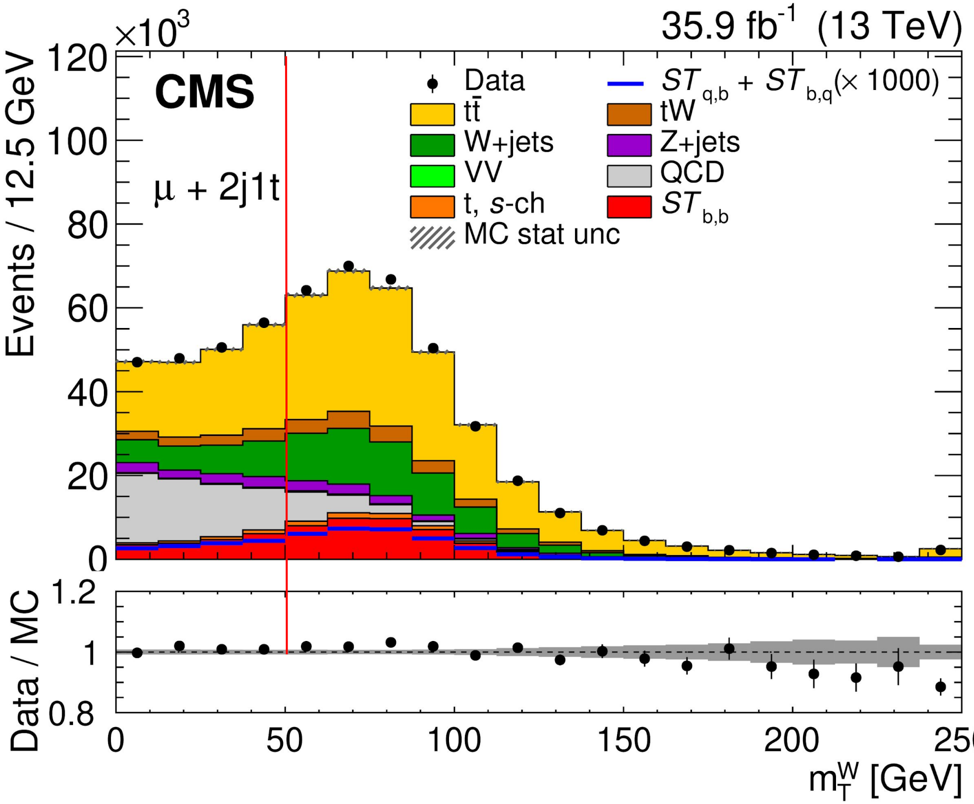
QCD extraction procedure

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

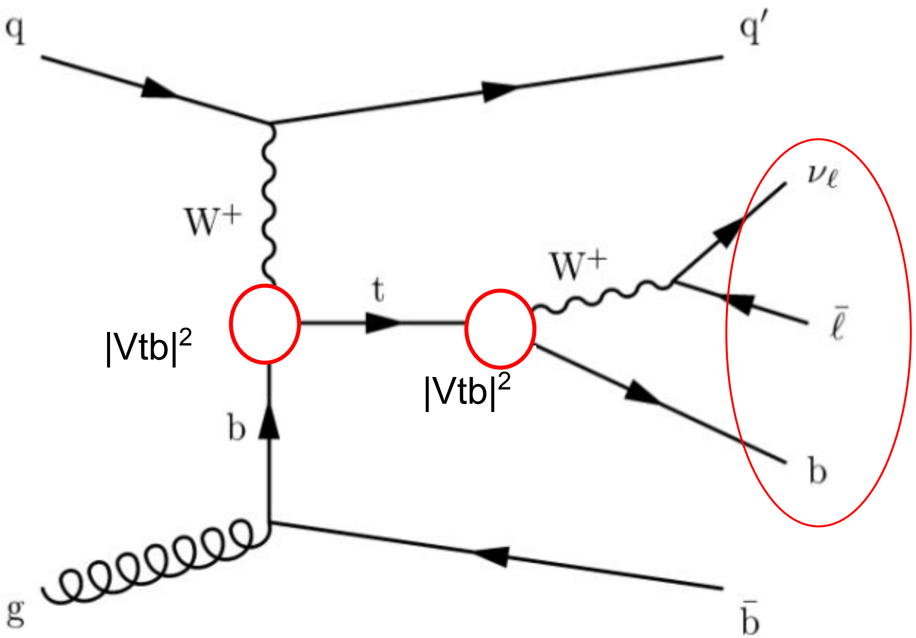
Dedicated selection in the three regions:
→ define a forward jet ***j'*** in each region
→ reconstruct top quark candidates with all other jets

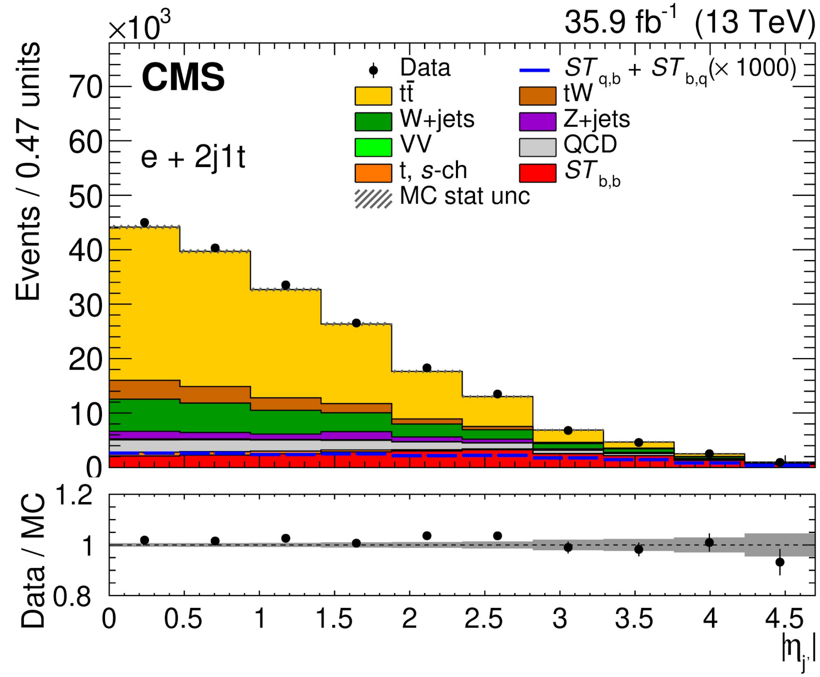
2-jets 1-tag
- ***j'*** defined as the non b-tagged jet
- Multivariate discriminant to separate ***ST*(b,b)** from **W+jets** and **tt**

3-jets 1-tag
- ***j'*** defined as non b-tagged jet with the highest |η|;
- W+jets and tt depletion requirement : *j'* |η| > 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:

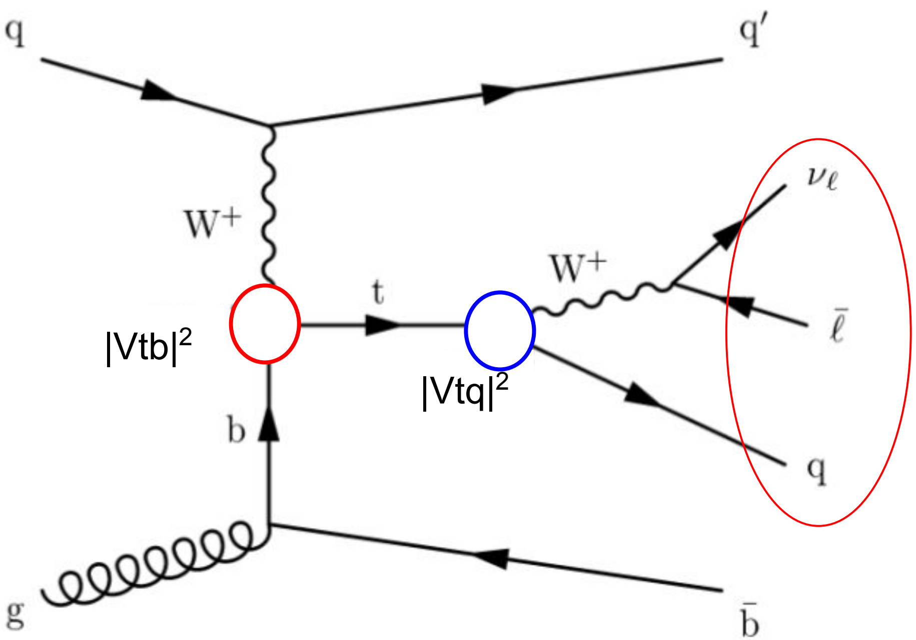
- the correct permutation is **ℓν**+ b jet

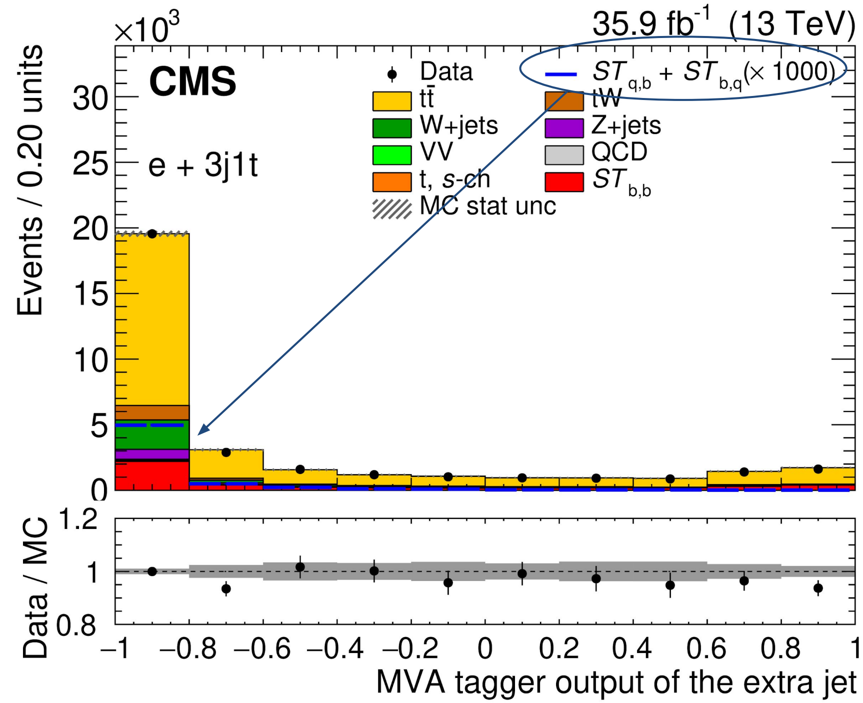
2nd b at low pt from gluon splitting:

- 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)





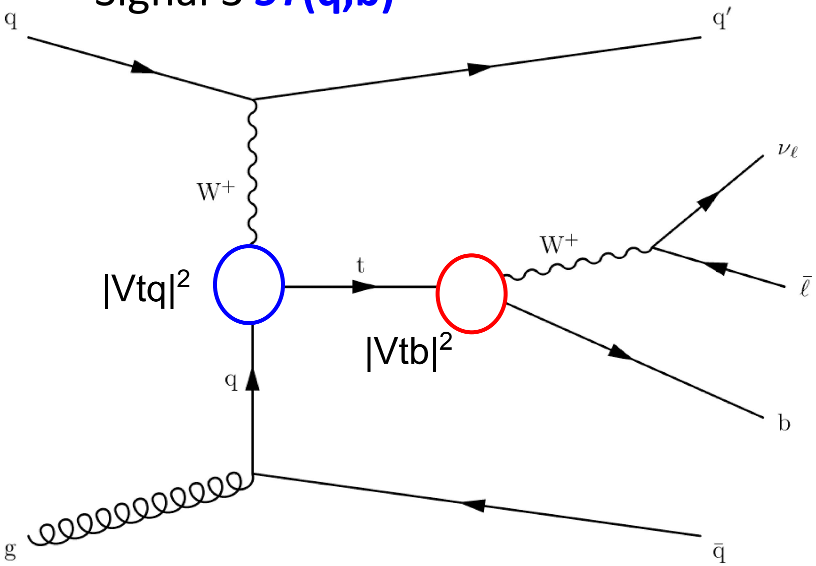
top quark decays to light quark:
- the correct permutation is **ℓν** + non-b jet
- reconstructing the top quark with the b-jet gives you the wrong permutation

Main region: 3-jets 1-tag

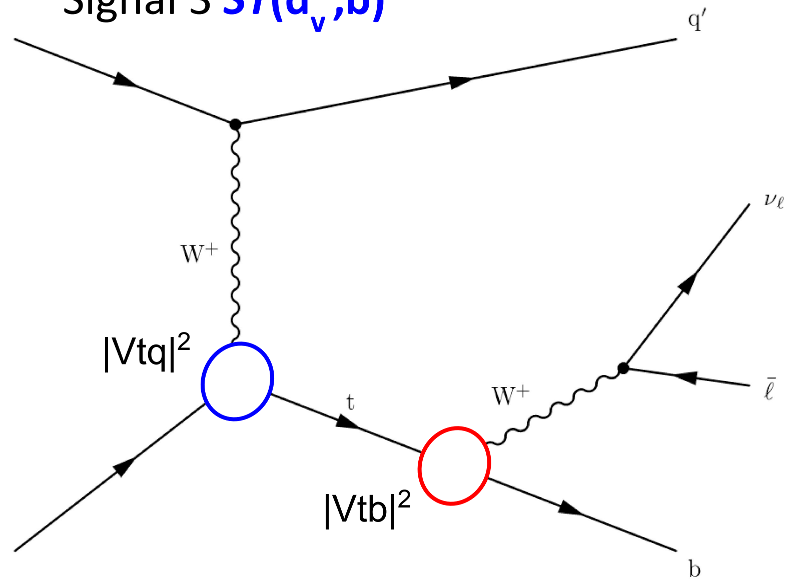
Discriminating variables against *ST*(b,b): b-discriminator of secondary top, kinematics of top quark candidates

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)

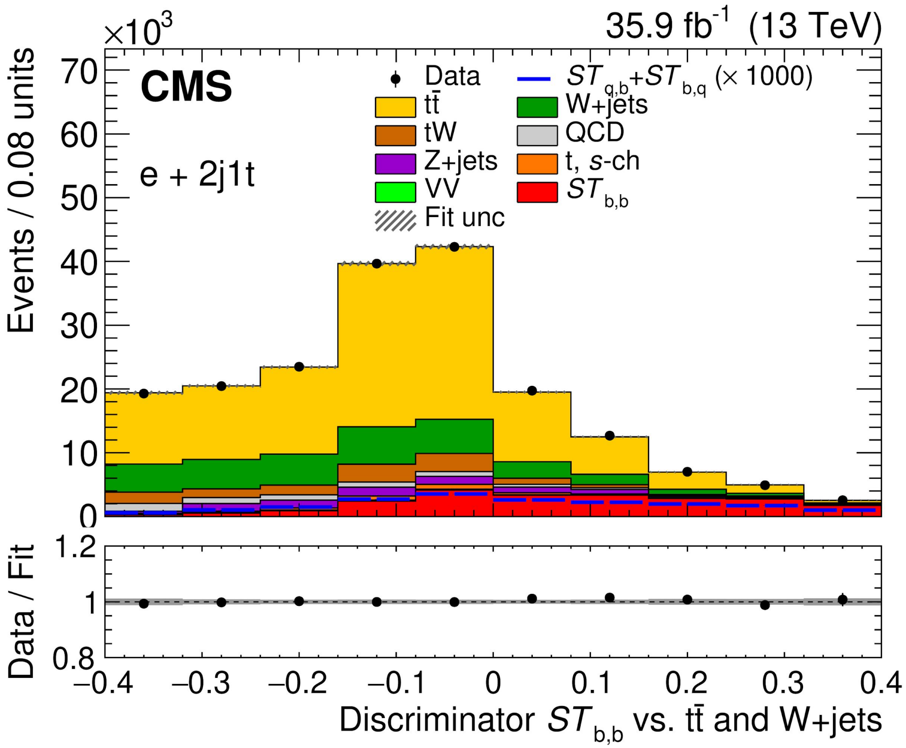
Discriminating variables against *ST*(b,b):
- For non d_v initiated processes, top quark kinematics is the same as *ST*(b,b), additional non b-jets can be present.
- For d_v - initiated process PDF do alter top quark rapidity.

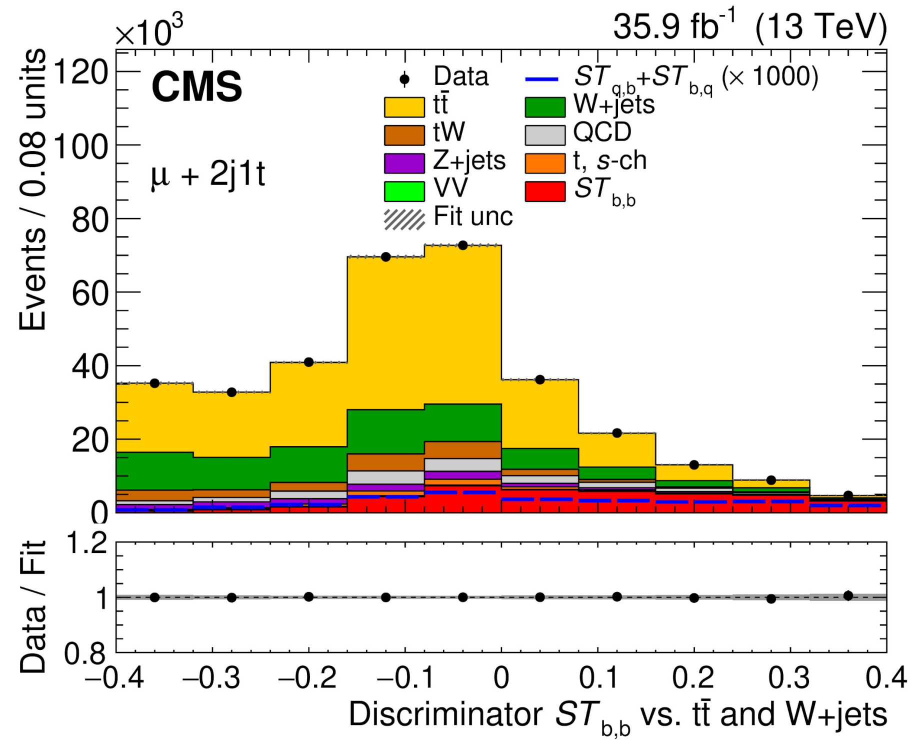
Multivariate discriminants and fit

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:



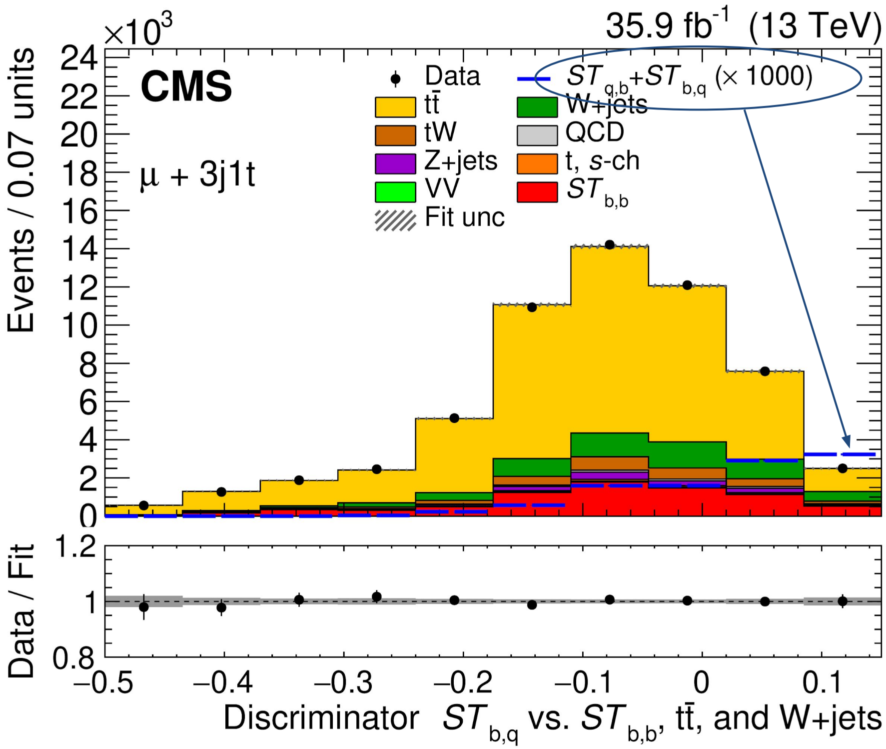


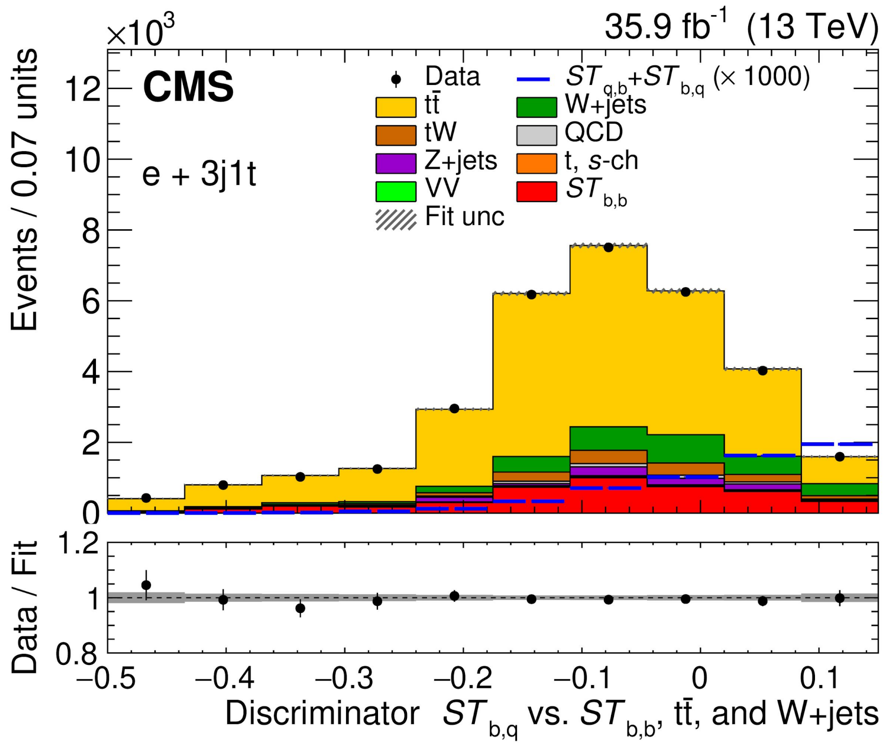
Multivariate discriminants and fit

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:





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:

$$\mu_b = 0.99 \pm 0.03\,(\text{stat+prof}) \pm 0.12\,(\text{nonprof})$$

$$\mu_{sd} < 87 \text{ at } 95\% \text{ confidence level (CL)},$$

The Standard Model measurement

Imposing unitarity, one finds **σ x BR (t→ Wb)∝ $|V_{tb}|^2$ x $|V_{tb}|^2$**

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

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

→ Here there is only 1 effective parameter for the signal

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

Limits at 95% CL:

$$|V_{tb}| > 0.970$$
$$|V_{td}|^2 + |V_{ts}|^2 < 0.057.$$

Releasing unitarity assumption

Parametrizing under different hypotheses on scenarios, widths may vary

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

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

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

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:

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

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:

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

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:

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

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:

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

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

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

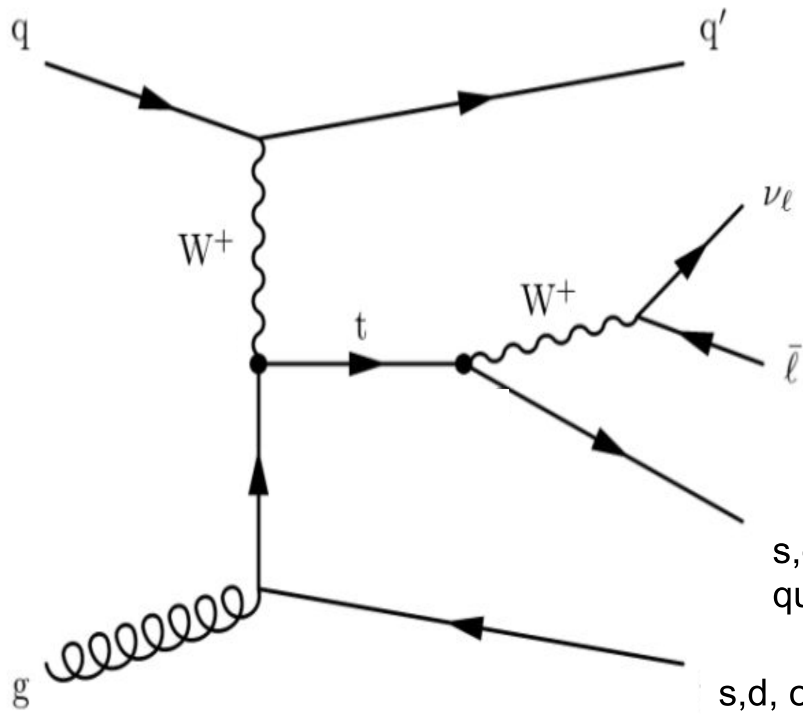
The route undertaken here shows promise for future measurements, that could aim at increasing sensitivity to $|V_{td}|/|V_{ts}|$, and considering other scenarios for the measurement of partial and total widths.

thank you!

Additional material

The baseline selection for all signals

Final state | **@Reconstruction level**



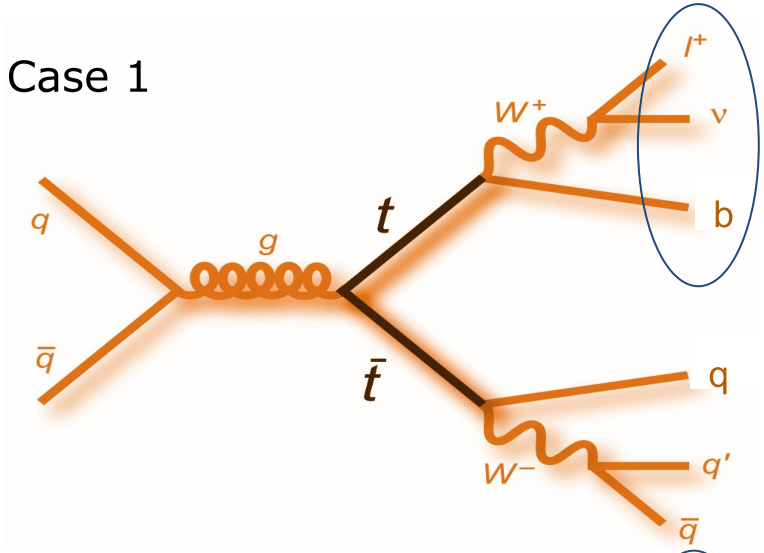
- → 1 high-η "forward" jet* jet called ***j'***
- → Missing transverse momentum $p_{T,miss}$
- → Well reconstructed muon or electron ** - veto additional leptons
- s,d, or b quark → jet, potentially reconstructed as b
- s,d, or b quark → low-p_T jet, potentially reconstructed as b

Required objects

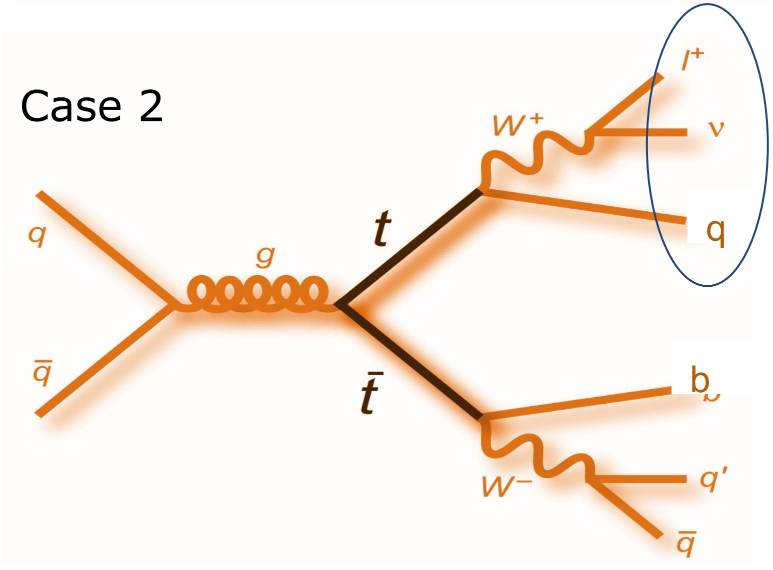
1	Tight muon	$p_T > 26$ GeV/c	$\|\eta\| < 2.4$	$I^{\mu}_{rel} < 0.06$	
0	Loose muon	$p_T > 10$ GeV/c	$\|\eta\| < 2.4$	$I^{\mu}_{rel} < 0.2$	
1	Tight electron	$E_T > 35$ GeV	$\|\eta\| < 2.1$	$I^{e}_{rel} < 0.0588$ (B)	$I^{e}_{rel} < 0.0571$ (E)
0	Veto electron	$E_T > 15$ GeV	$\|\eta\| < 2.5$	$I^{e}_{rel}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

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:

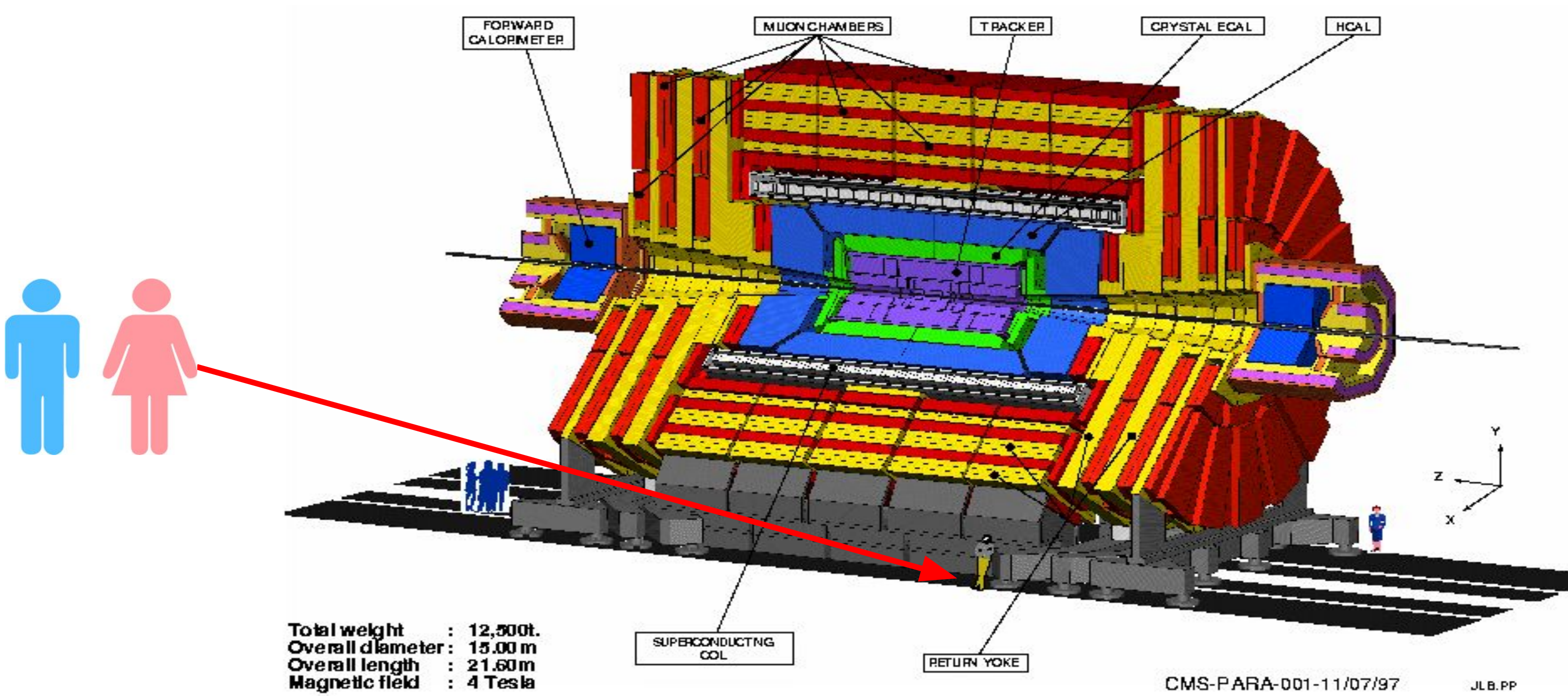
1) Prior distribution is independent from our observed quantity

→ 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**

The CMS detector



Detectors → Onion Structures:

- ❑ Inner Detector
- ❑ E.M. and Hadronic Calorimeters
- ❑ Muon Spectrometers
- ❑ Magnet System: → superconducting solenoid magnet (coils of wire)