Measurement of the W-boson helicity in t decays, from $t\bar{t}$ production, in ℓ+jets events from $p-p$ collisions at $\sqrt{s} = 13$ TeV with the CMS detector

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on behalf of the CMS Collaboration

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Available on CMS information server

CMS AN -2019/066

The Compact Muon Solenoid Experiment

Analysis Note

The content of this note is intended for CMS internal use and distribution only

29 March 2019 (v5, 05 June 2021)

Measurement of the W-boson helicity in top decays from ttbar production in lepton+jets events with the CMS detector at $\sqrt{s}$ =13 TeV

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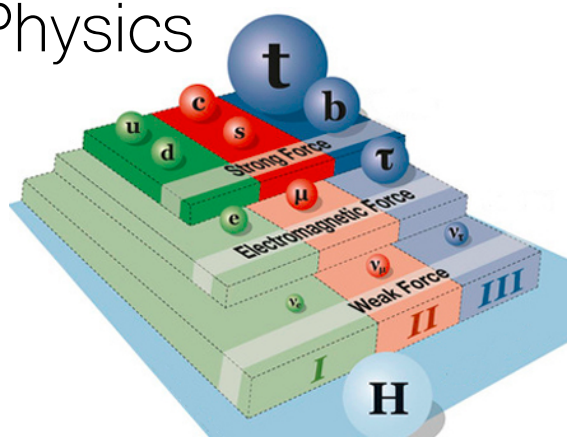
Abstract

We report a measurement of the W-boson helicity fractions from top quark decays, based on a data sample corresponding to an integrated luminosity of 137 fb^{-1} of proton-proton collisions at a centre-of-mass energy of 13 TeV, collected in 2016-2018 by the CMS experiment at the LHC. The measurement uses the semileptonic decays of the $t\bar{t}$ pairs and the single top production (tW and t-channel). The results are consistent with standard model expectations.

Physics Analysis: Top quark & New Physics



Top quark

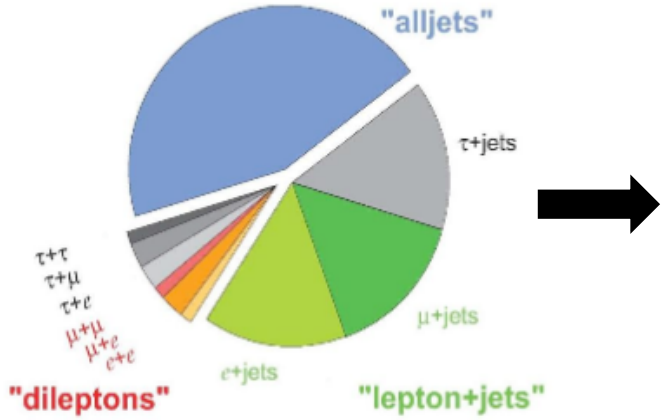
- **Large mass**: Heaviest known elementary particle; $m_t \cong 173\ \mathrm{GeV}$ [Fermilab, 1995]

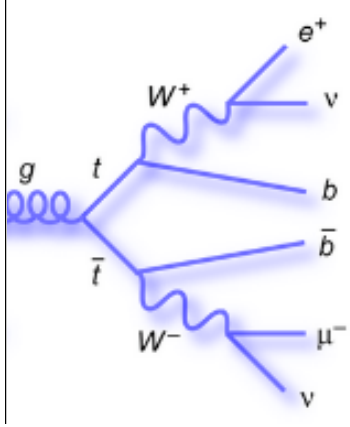
  ⇓

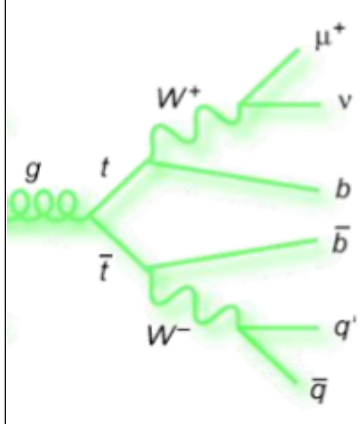
- **Short lifetime:** < strong interactions' timescale; decay time < typical hadronization time ⟹
  - **no jets** (special quark behaviour)
  - passes its info (e.g. spin) to the decay products ⟹ unique opportunity to study the bare quark properties preserved in the decay chain, by measuring observables' **distributions in the products**

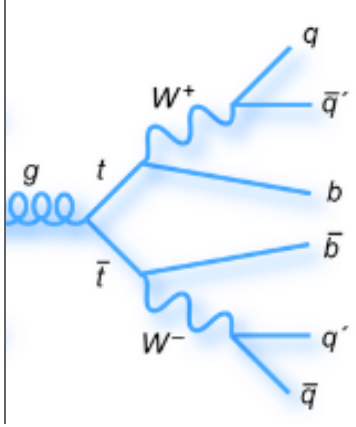
- **Important role** in nature & study of fundamental interactions

- top **couplings may exhibit signs of BSM Physics** ⟹ unique environment for NP searches, beyond SM tests
  - $t \xrightarrow{\text{SM: } Pr\cong 1\ (|V_{tb}|\cong 1)} W + b \rightarrow (\ell + \nu_\ell + b)$ or $(q + \bar{q}' + b)$ [Subsequent W decays define final states of $t\bar{t}$]
  - Anomalous Wtb vertex couplings ⟹ sensitivity to NP processes, extra to the precision measurement









Motivation: W helicity fractions

-Anomalous Wtb couplings ⇐ **Altered W helicity fractions** in t decays (measurement sensitive to the vertex structure)

- **W helicity fractions** in $t \to Wb$: $F_{O,L,R} = \frac{\Gamma_{O,L,R}}{\Gamma}$, where $\Gamma_{(O,L,R)}$: (partial) decay rate

- [SM, NNLO]* $\begin{cases} F_O = 0.687 \pm 0.005 \\ F_L = 0.311 \pm 0.005 \\ F_R = 0.0017 \pm 0.0001 \end{cases}$ O : longitudinal, L : left-handed, R : right-handed

$[m_t = 172.8 \pm 1.3\ \text{GeV},\ m_W = 80.401 \pm 0.043\ \text{GeV}]$

CMS PAPER TOP-19-004 (cds.cern.ch/record/2717564)
Combined result on W helicity measurement by ATLAS & CMS at $\sqrt{s} = 8\ \text{TeV}$

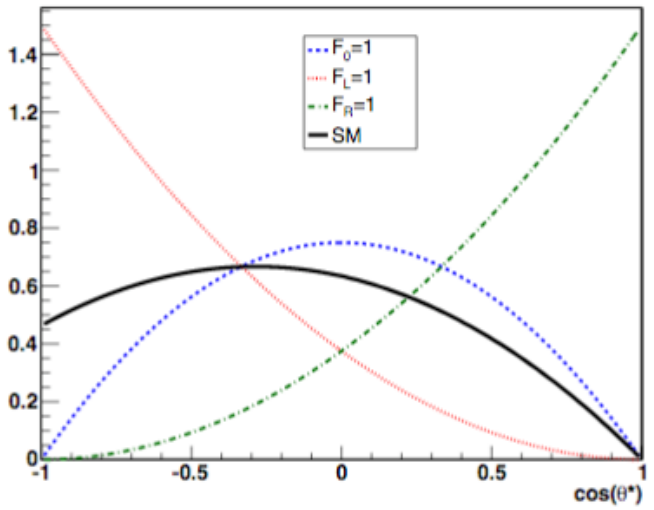
- Experimentally, $F_{O,L,R}$ can be extracted from measurements of **angular distributions of t decay products**, i.e. $\cos\theta^*$

- helicity angle θ^*
  (direction of down-type fermion (lepton) momentum in the the W rest frame and the W momentum in the top quark rest frame)

- $\cos\theta^* \leftrightarrow F_{O,L,R}$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{4}(\sin\theta^*)^2 F_0$$

- $\cos\theta^*$: strong discrimination power →



* doi:10.1103/PhysRevD.81.111503

Measurement: W helicity (fractions $F_{O,L,R}$) in t decays from $t\bar{t}$ production in 1ℓ+jets events

- *Goal*

  Extraction by means of a template fit, using a strong discriminating variable

- Signal
  - $t\bar{t}$
  - t (added as well)

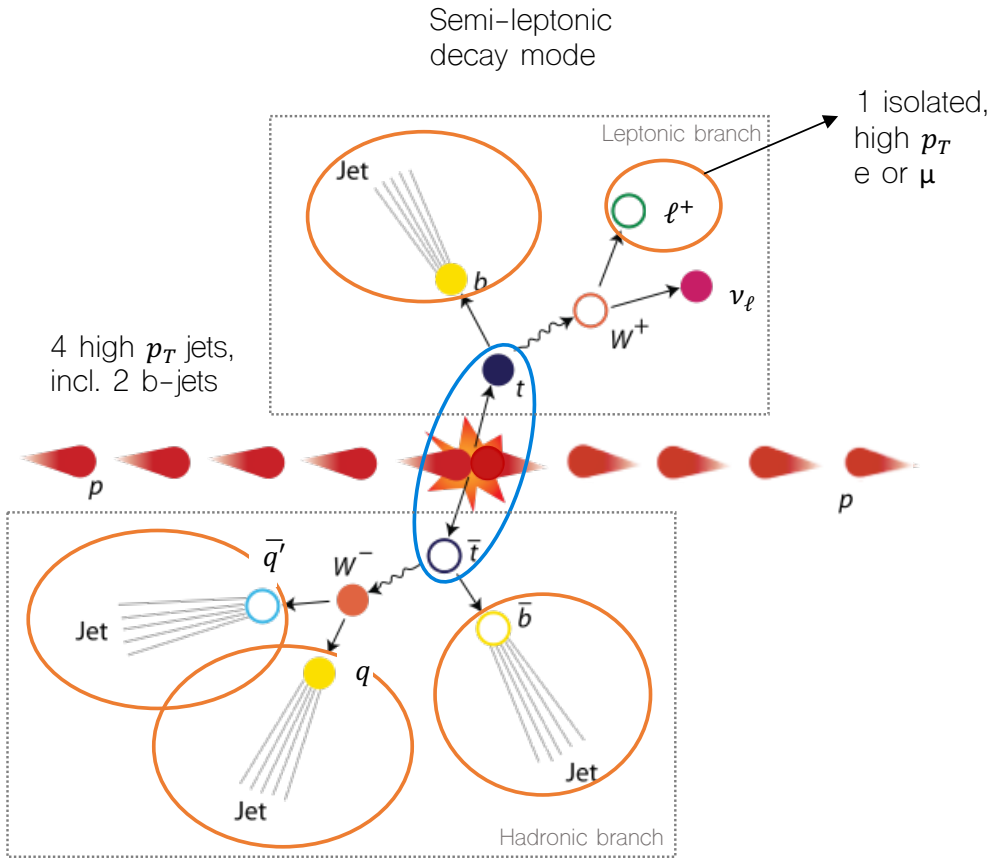
- Background
  - W+jets
  - QCD
  - Z+jets
  - VV

- Data

  Full RunII $p-p$ collision data at $\mathbf{13\ TeV}$: 2016, 2017, 2018

  $\Longrightarrow$ high $t\bar{t}$ production rate

  $\Longrightarrow$ high precision in measurement of t production & decay properties



$\Longrightarrow$ Significant opportunity to check validity of SM -consistent with results so far- and/or provide NP hint if deviations found

MC & Data samples: Production

MC (central)	Signal		tt	(semileptonic)	
				(inclusive)	
			st	tW	
				t-channel	
				s-channel	
	BKG	tt BKG	tt	toHadronic	
				to2L2Nu	
		other BKG	ttV	ttW	
				ttZ	
			V+jets	W+jets	
				DY+jets	
			QCD	MuEnriched	diff pt ranges
				EMEnriched	diff pt ranges
Data	Single lepton	SingleMuon			
		SingleElectron			
MC (systematics)	Signal		tt / st	mtop	diff mass ranges
				Tune	up
					down
				DS	
				erdON	
				scale	up
					down
				hdamp	up
					down
				ISR	up
					down
				FSR	up
					down
				colourFlip	
				CR1	
				CR2	

basic in the analysis	diff generators(signal)
	diff extensions
for more statistics	Psweights/-
	new_pmx/-

~170 samples for 2016

version	v5
	v6
	v7
Tune	CUETP8M1/M2T4
	CP5
Year	2016
	2017
	2018
necessary code adaptations	

A very large amount of samples "produced" for the needs of this analysis

W helicity fractions extraction: Discriminating variables

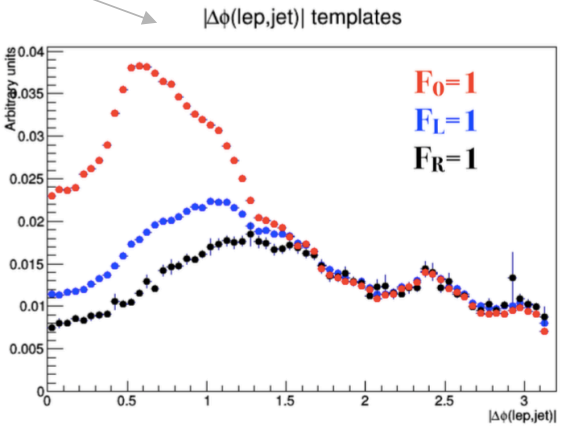
		Strong discrimination power among F_0 , F_L , F_R :	Requires the reconstruction of :
Approaches towards W-helicity extraction	$\cos\theta^*$	Yes	full $t\bar{t}$ system (~complex)
	$m_{\ell b}$ [1]	Yes	correct lepton-jet pair (more direct)
	$\Delta\varphi(\ell, \mathrm{b})$ [1]	Yes (low values of $\Delta\varphi(\ell, \mathrm{jet})$)	correct lepton-jet pair (more direct)

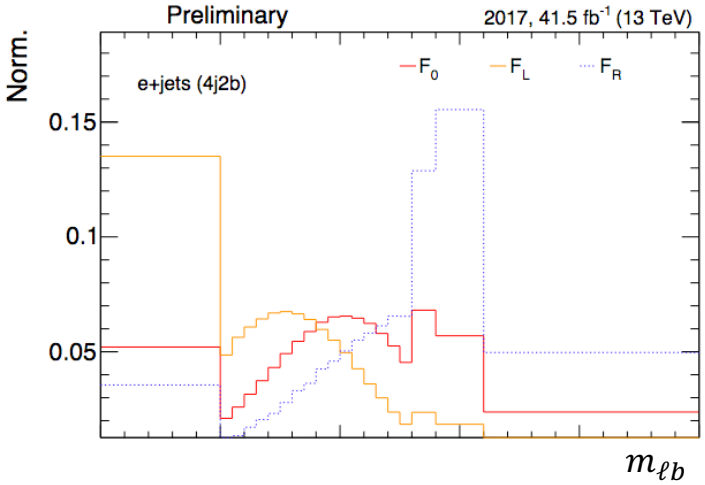
Solutions:
- diff. reconstruction method or
- diff. discriminating variable

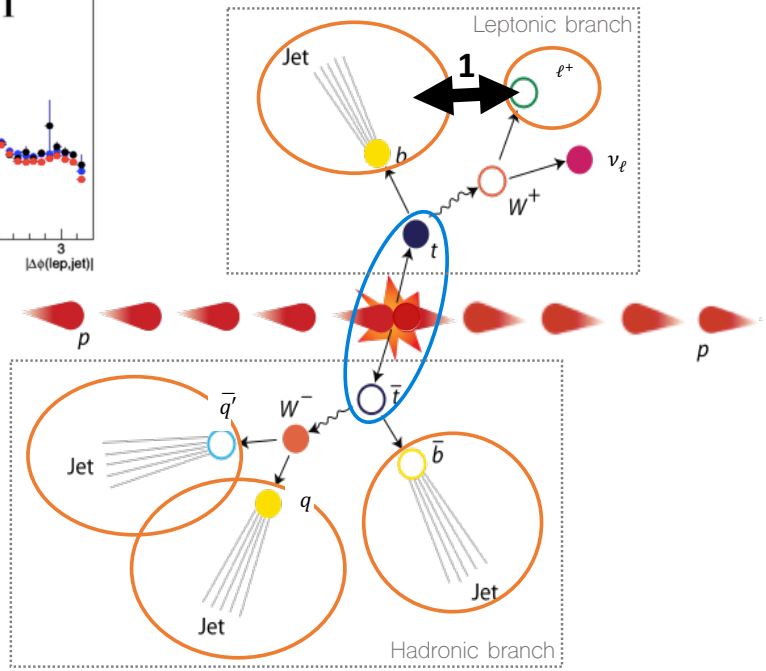
Currently focusing on this variable.

Already tested this variable.
Issues in:
- Sensitivity on the fractions
- Data/MC agreement

$$\cos\theta^* = 2\frac{m_{\ell b}^2}{m_t^2 - m_W^2} - 1$$







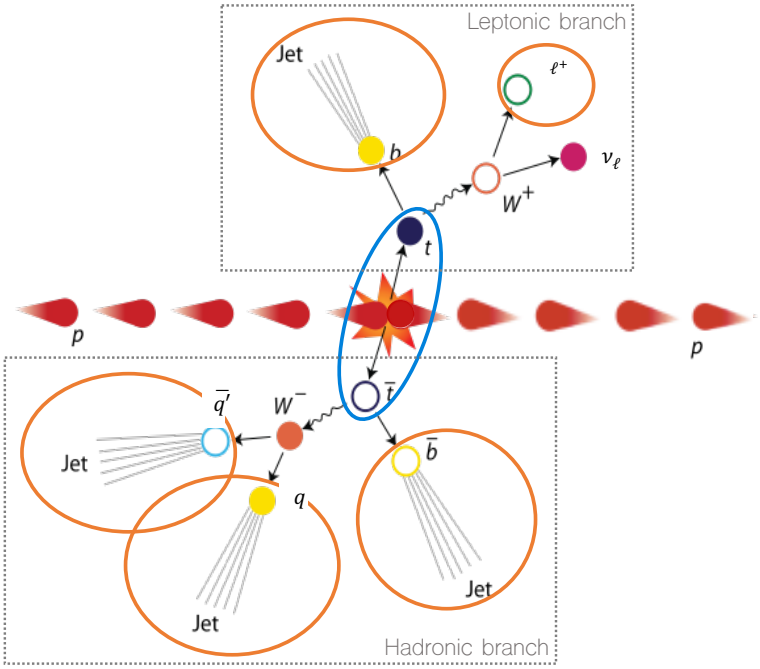
Object reconstruction and Event selection

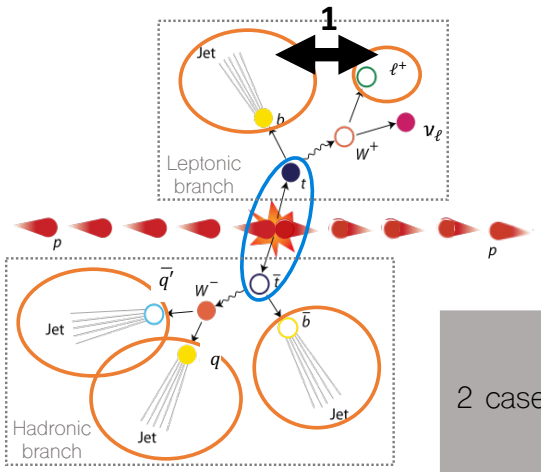
- **Selection**
  - Single lepton channels
    - Triggers used: [2016, 2018] IsoMu24, Ele32_WPTight_Gsf
      [2017] IsoMu27, Ele35_WPTight_Gsf
    - p_T cuts: [2016, 2018] μ (e) : $p_T > 25\ (34)\ GeV$
      [2017] μ (e) : $p_T > 28\ (36)\ GeV$
    - Vetoed ≥ 1 additional iso μ or e ⟹ dileptonic ($t\bar{t}$ or DY+jets) rejected
  - ≥ 2 jets: $p_T > 40, 30\ GeV$, additional jets: $p_T > 20\ GeV$
  - ≥ 1 b-jet ⟹ W+jets and QCD suppressed

- **Objects**
  - Cut based leptons (tight for both, e and μ)
  - Jet cleaning from selected leptons
  - DeepCSV tagging algorithm, Medium W.P.

- **Scale factors**
  - Lepton ID/ISO/Trigger

- **6 different regions** for the $m_{\ell b}$ distribution (under testing)
  - (2j, 2b), (3j, 2b), (3j, 3b), (4j, 2b), (4j, ≥3b), (≥5j ,≥2b)



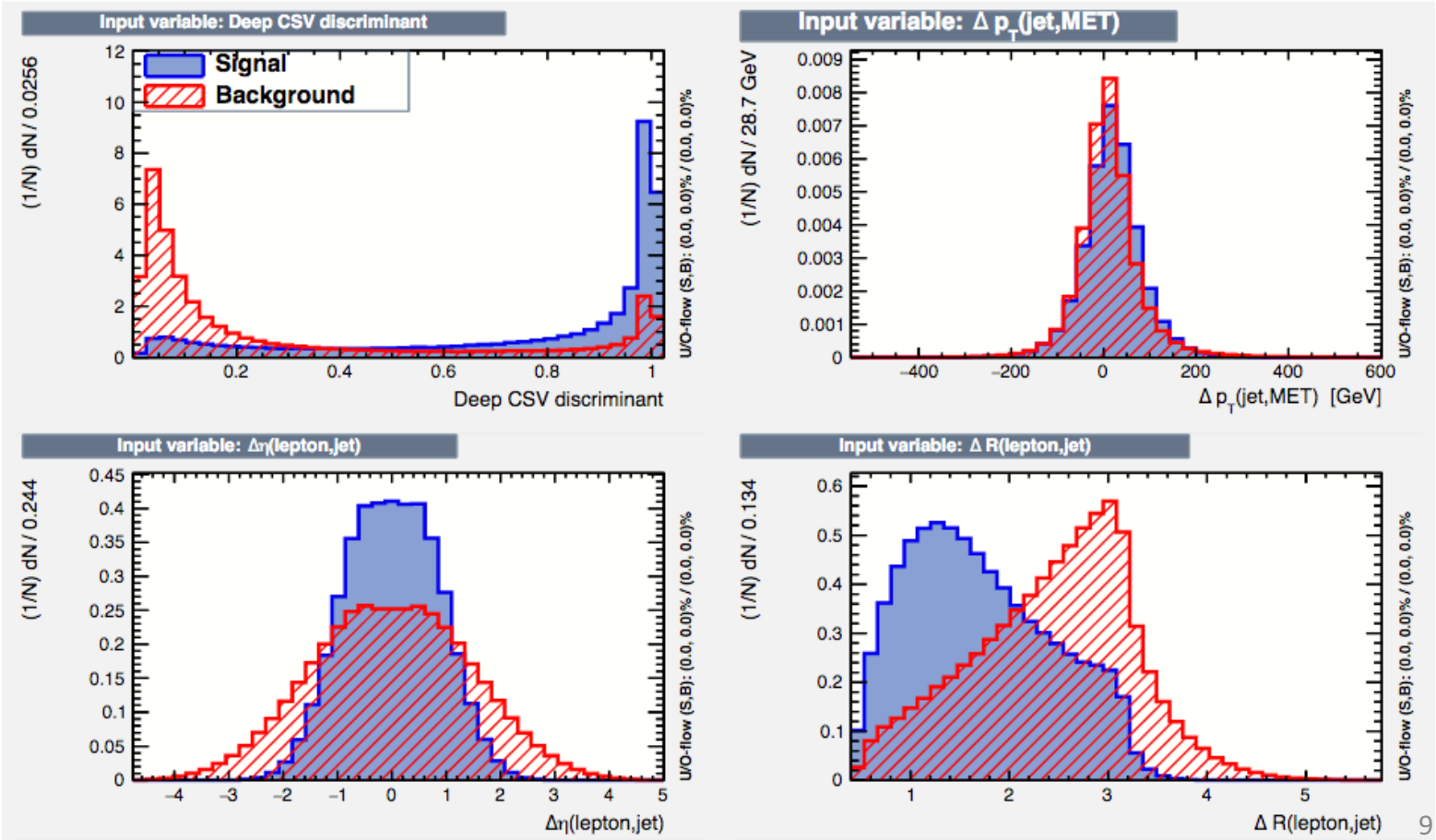


b-jet from the leptonic t decay ⇐ BDT for the correct pair (ℓ, jet)

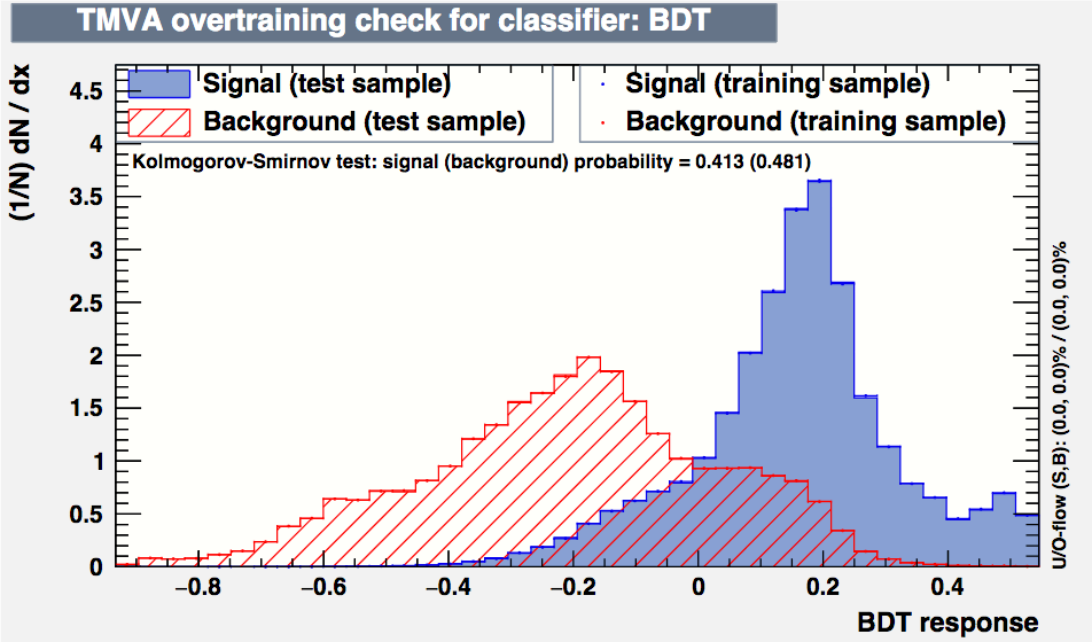
		Reco-level b- jet :	Training on pairs
2 cases	Matched	Identified, matched to gen-level b-quark	& ℓ-jet from the same top decay ⟹ correct
	Not possible	Not matched or not identified (e.g. outside event selection acceptance)	& whatever ℓ-jet combination ⟹ wrong

Input variables:

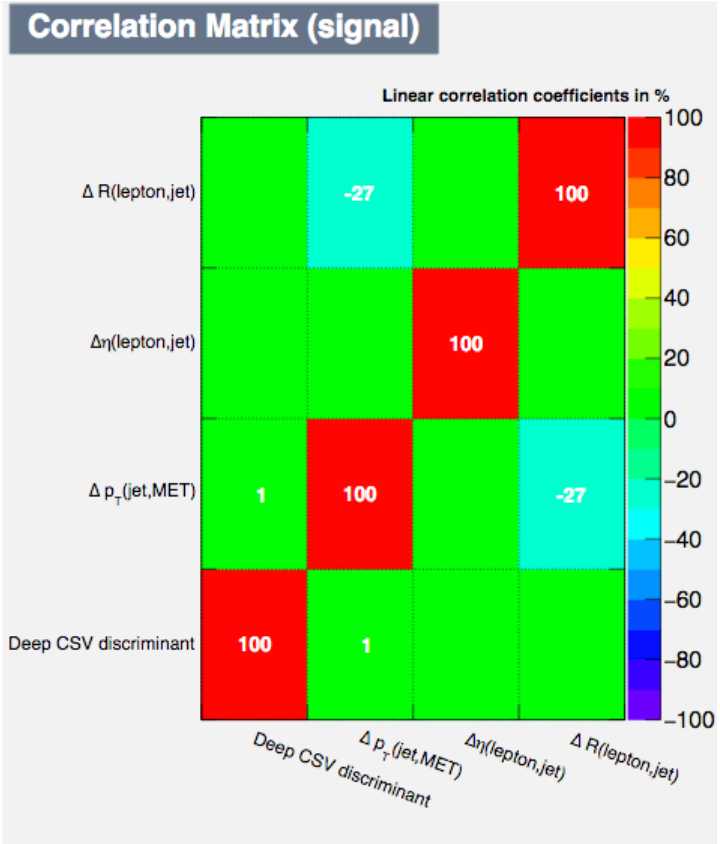
1. DeepCSV response
2. $\Delta R(\ell, \text{jet})$
3. $\Delta\eta(\ell, \text{jet})$
4. $\Delta p_T\ (\text{MET}, \text{jet})$



BDT: response, correlation matrix & results



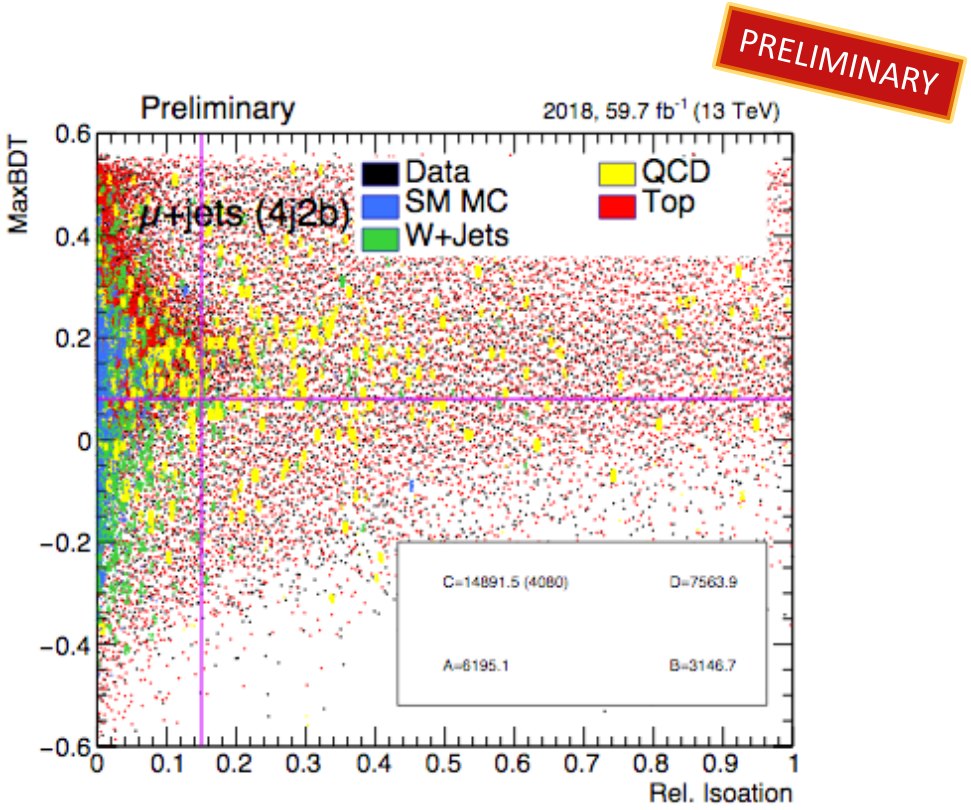
Additional (loose) cut imposed to improve purity of selected events



QCD Estimation: Shape & Normalisation

- QCD – shape & normalisation – is estimated from data
  - **Shape** ← from anti-isolation region
  - **#Events** ← via ABCD method
    1. Isolation
    2. BDT response

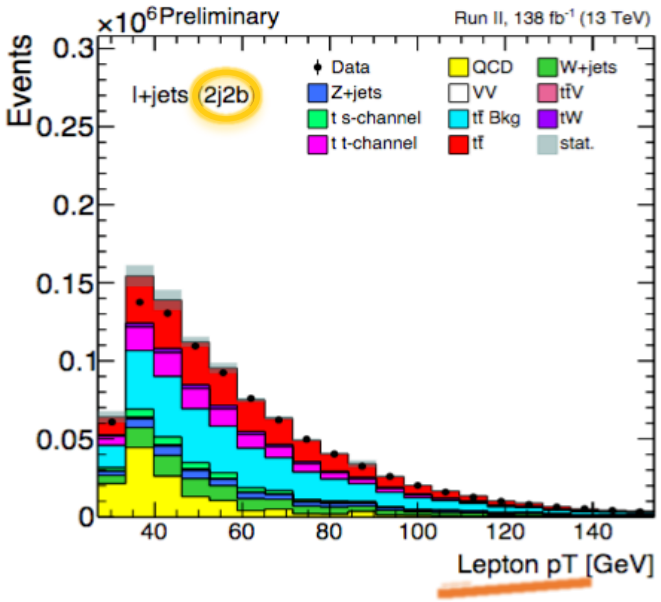
Example
for the 4j2b region
for μ+jets , 2018

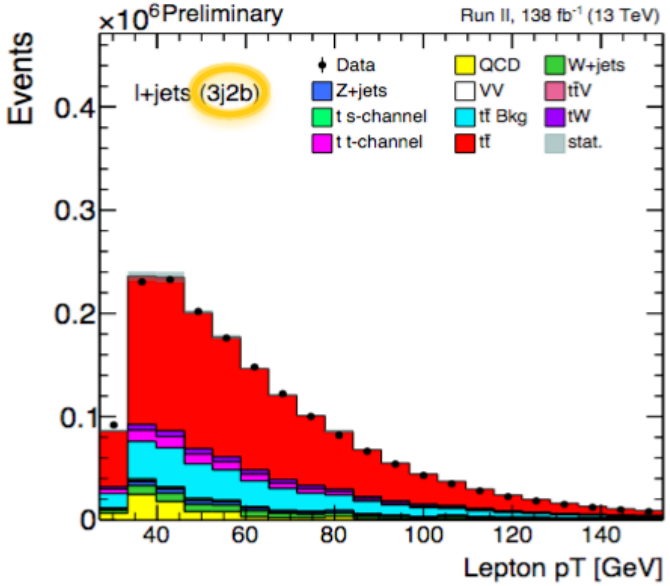


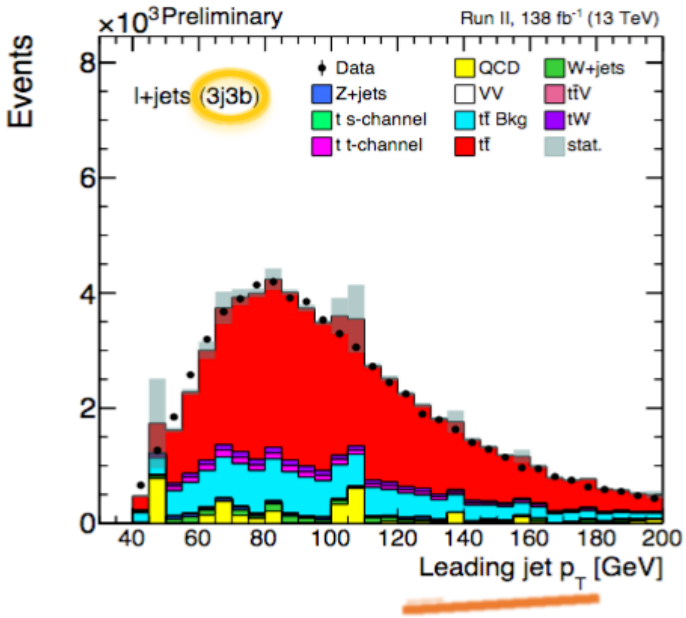
Distributions: Various variables [RunII]

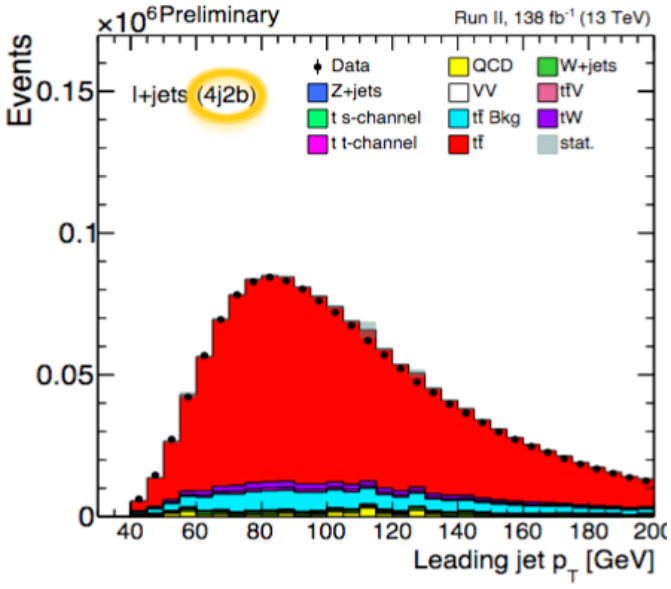
PRELIMINARY

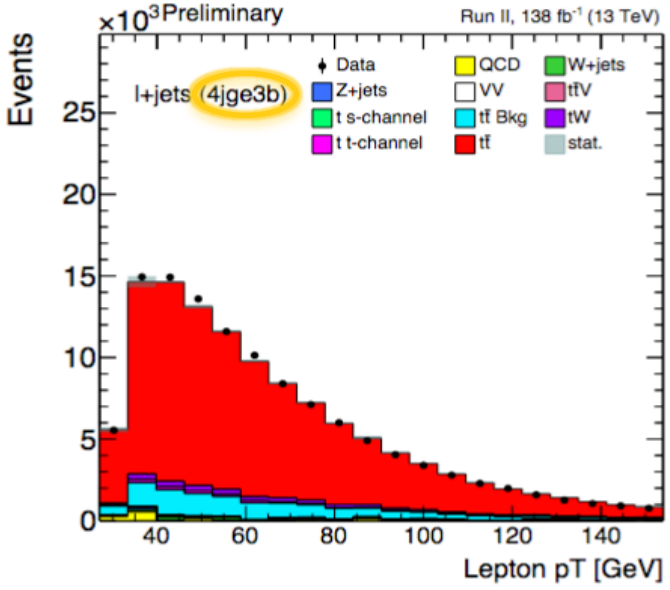
QCD from MC

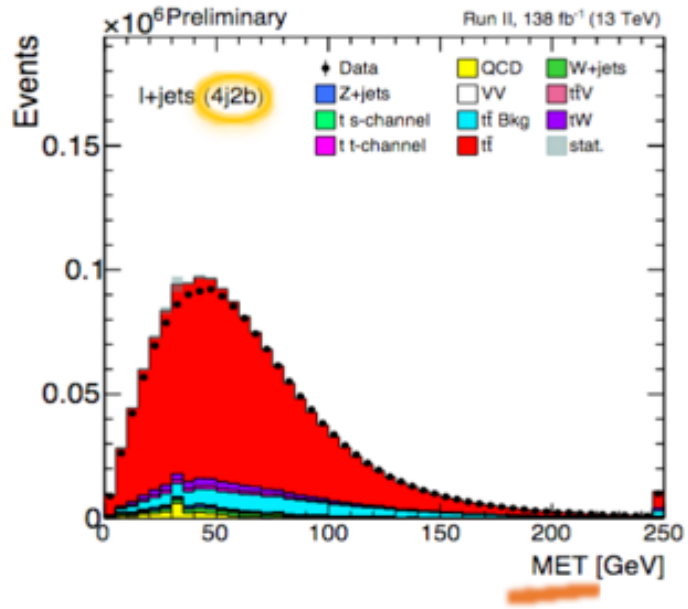












Fit performance: Template fit

- Performed with COMBINE tool

- The templates fitted correspond to the (5) regions 2j2b, 3j2b, 4j2b, [3j3b and (4j, ≥3b)], (≥5j ,≥2b) /channel/year

- Fit performed simultaneously over all 5 regions and both decay modes

- Binning selected based on the available statistics, stability in the uncertainties & discrimination power among fractions

- Fit Model: 3 POIs: $\sigma_{t\bar{t}}$ associated to the normalisation of the $t\bar{t}$ events, F_0 and F_L

F_R comes from unitarity: $F_0 + F_L + F_R = 1.0$

$$\text{Data} = \left(\frac{\sigma_{t\bar{t}}^{Fit}}{\sigma_{t\bar{t}}^{MC}}\right) \times \left[\frac{F_0{}^{Fit}}{F_0{}^{SM}}\,\text{PDF}(t\bar{t}_{F_0}) + \frac{F_L{}^{Fit}}{F_L{}^{SM}}\,\text{PDF}(t\bar{t}_{F_L}) + \frac{1 - F_0{}^{Fit} - F_L{}^{Fit}}{F_R{}^{SM}}\,\text{PDF}(t\bar{t}_{F_R})\right]$$
$$+ \left(\frac{\sigma_{t\bar{t}}^{Fit}}{\sigma_{t\bar{t}}^{MC}}\right) \times \text{PDF}(t\bar{t}_{\text{Bkg}}) + \text{Bkg}$$

- Systematic uncertainties implemented as nuisance parameters. Almost all systematic uncertainties included (≅ 60)

- Multiple pseudo-experiments run to check the fit performance (based on the same Fit Model/ templates ($m_{\ell b}$))

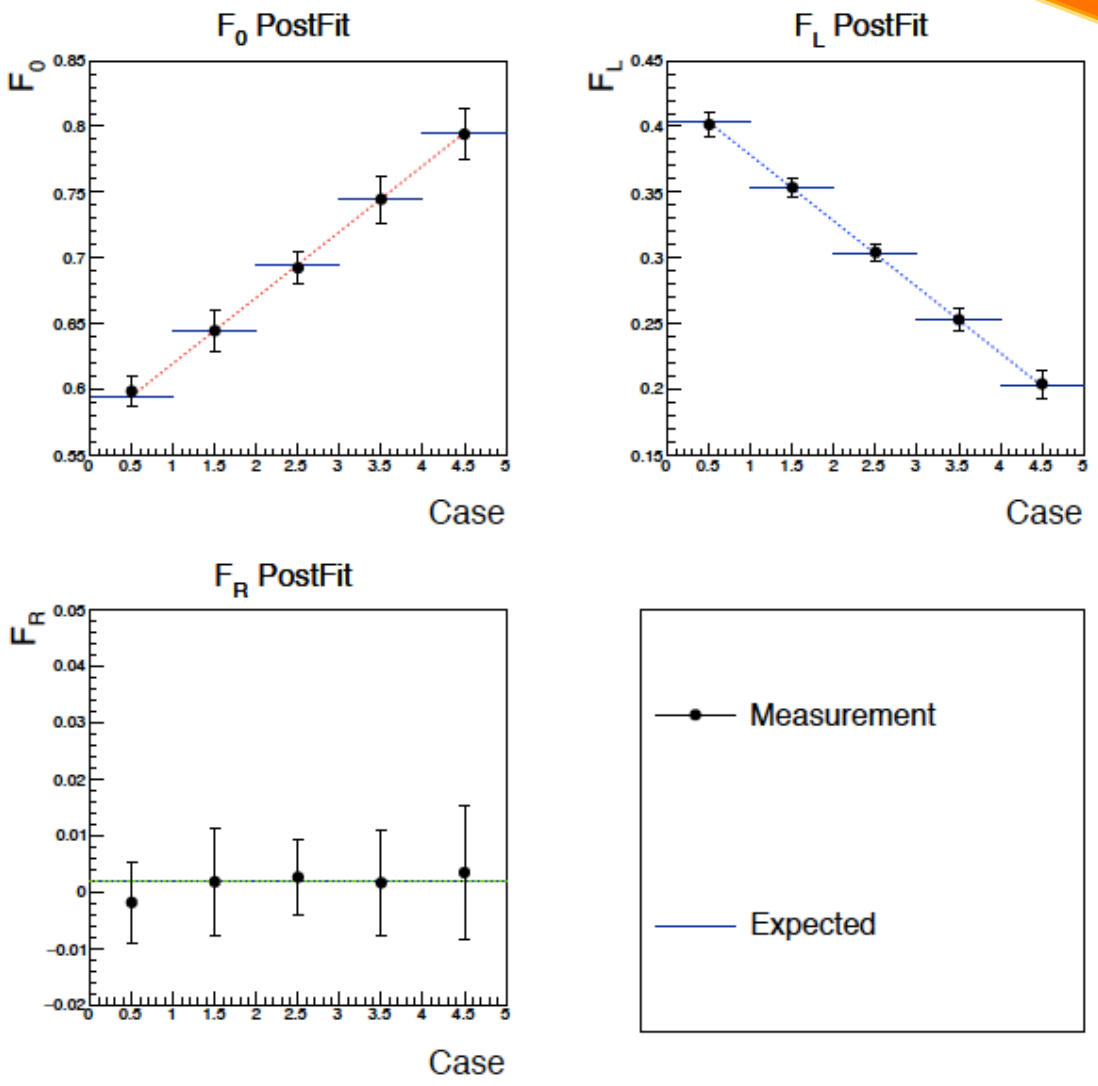
Fit performance: Validation via pseudo-experiments

- BSM fractions: Pseudo-data created modifying the W-helicity fractions. E.g. (5 points):
  - F_0 from 0.5952 to 0.7952
  - F_L from 0.4030 to 0.2030
  - $F_R = 0.0018$ (constant)

- 60 Pseudo-experiments:
  bin-by-bin Gaussian smearing
  (10x expected statistical uncertainty)

- SM fractions:
  - $F_0 = 0.6952$
  - $F_L = 0.3030$
  - $F_R = 0.0018$

EXAMPLE



Fit performance: Systematic Uncertainties

- **Detector** uncertainties are implemented as Shape uncertainties (shapeN2), comprising:
  - Lepton Scale Factors
  - PileUp reweighting
  - JER
  - JES
  - b-tagging for c, heavy, light flavour. 8 variations in total

- **Theoretical** uncertainties ('dedicated' samples), comprising:
  - Q^2 scale (Renormal. & Factor. scales at ME, PS)
  - ISR/FSR
  - ME-PS matching scale (hdamp)
  - Underlying event
  - Diagram Subtractions (DS)
  - Colour Reconnection:
    - erdON
    - QCDbasedCRTune
    - GluonMoveCRTune
    - colourFlip

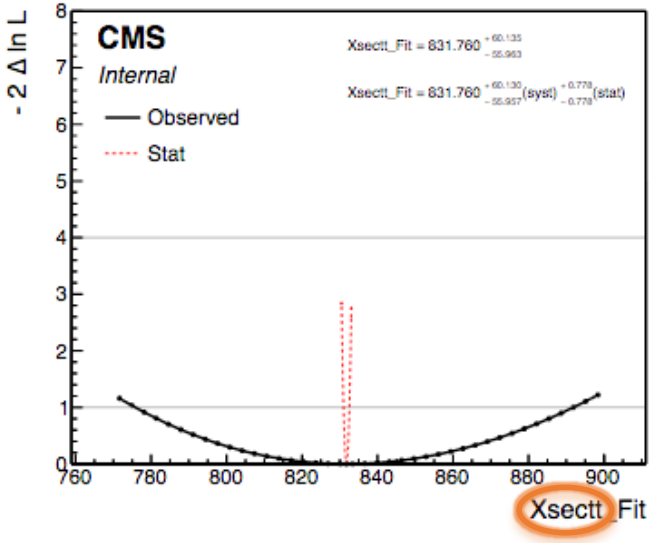
Due to low statistics, we applied transformation (smooth+symmetrization) to improve the fit

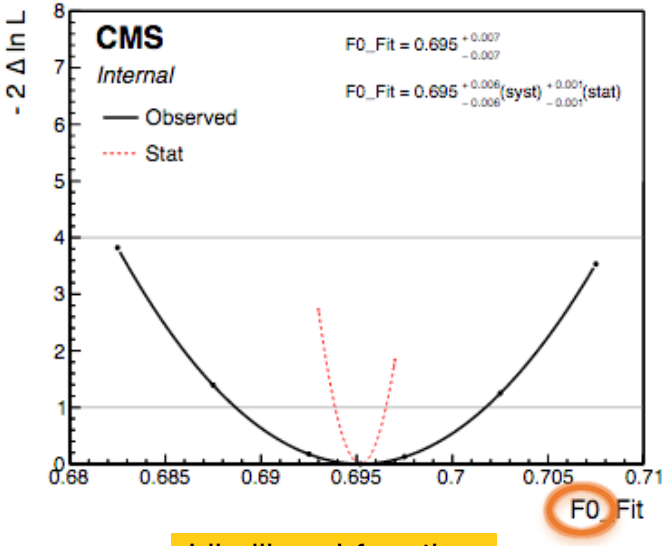
- **Background** uncertainties (lnN) included for:
  - Single top (10%)
  - W+jets (10%)
  - DY+jets (15%)
  - QCD (20%)
  - VV (20%)
  - $t\bar{t}$V (30%)

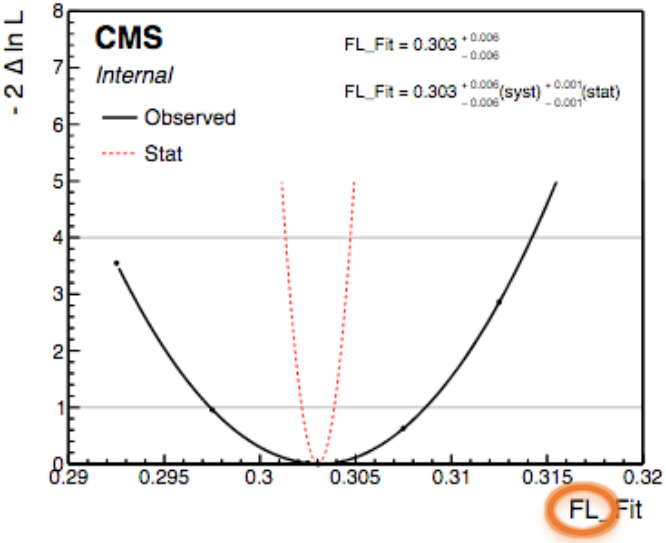
- **PDF** uncertainties to be included

Fit results: Expected [2017] (I)

PRELIMINARY

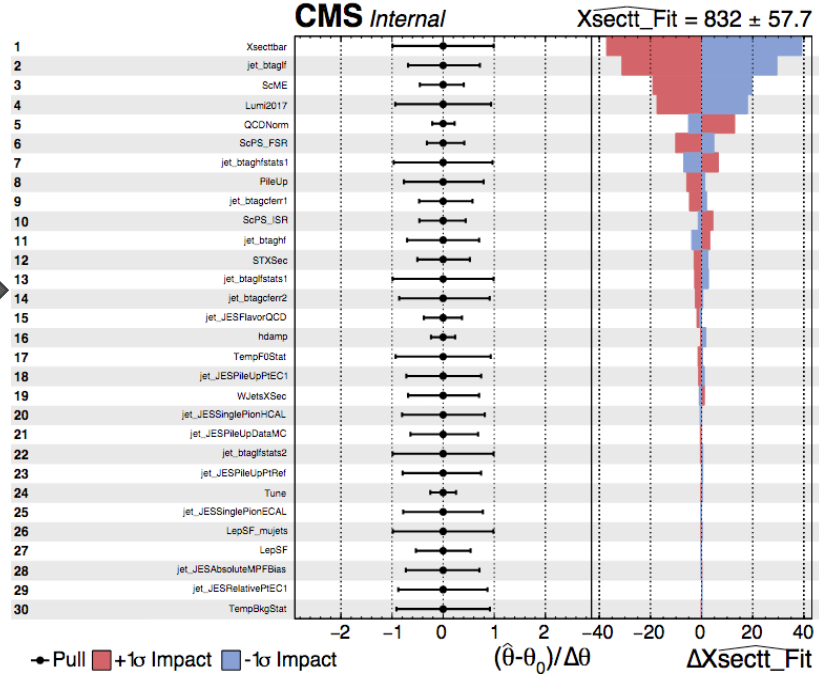


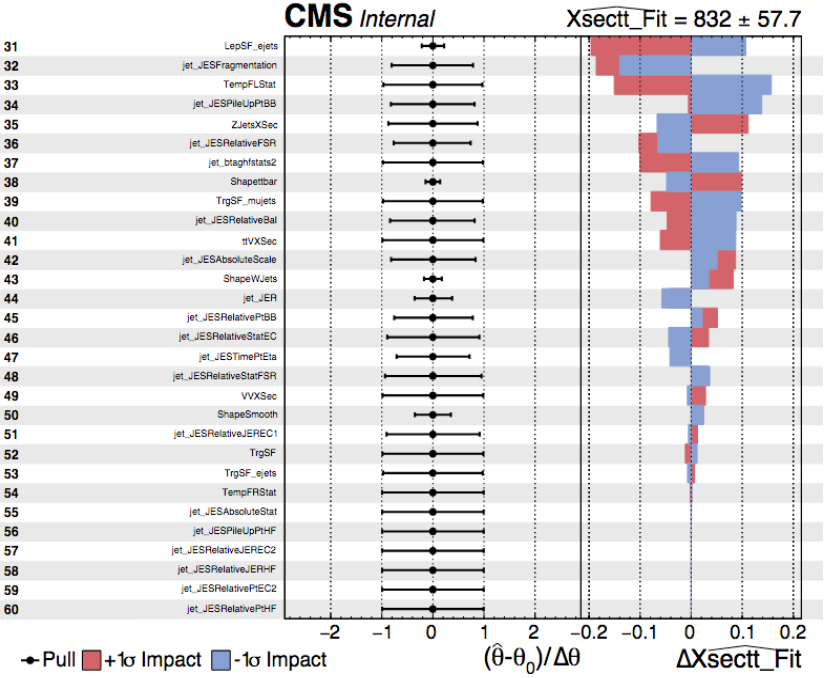




Likelihood function

Impact Plot for $\sigma_{t\bar{t}}$

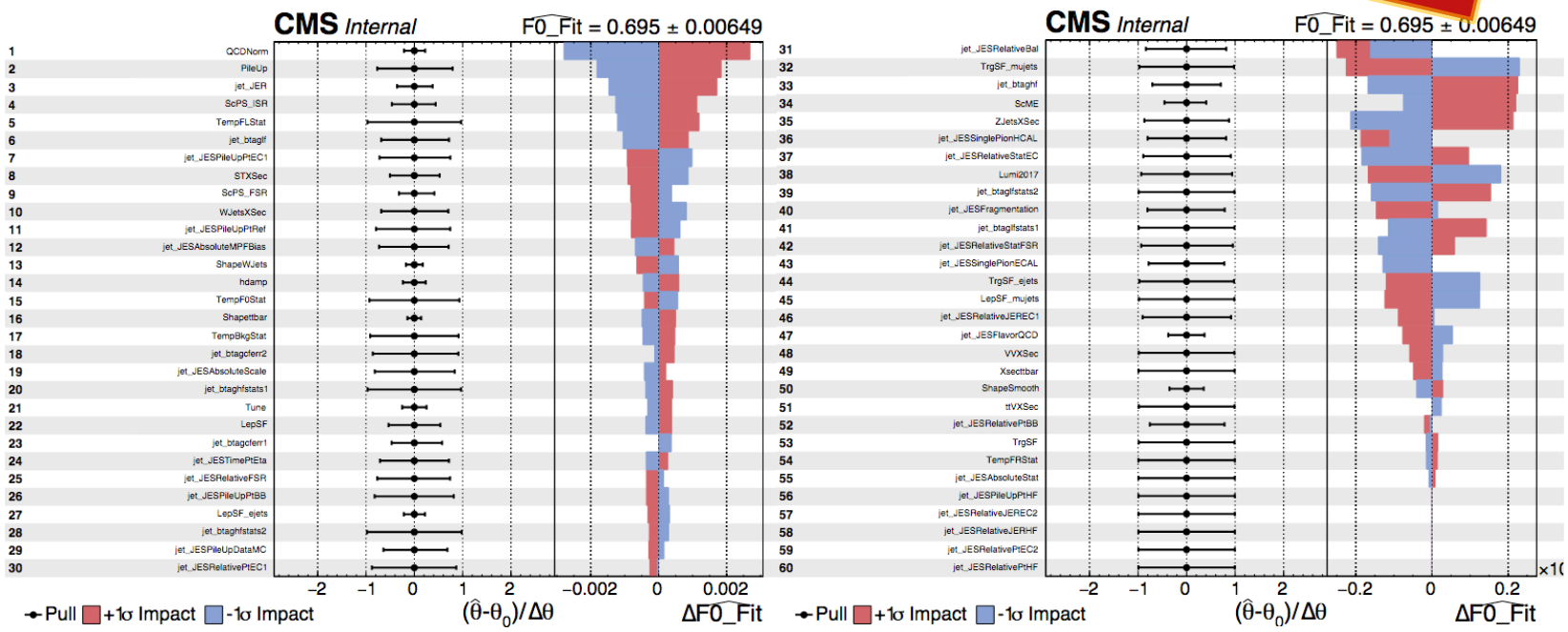




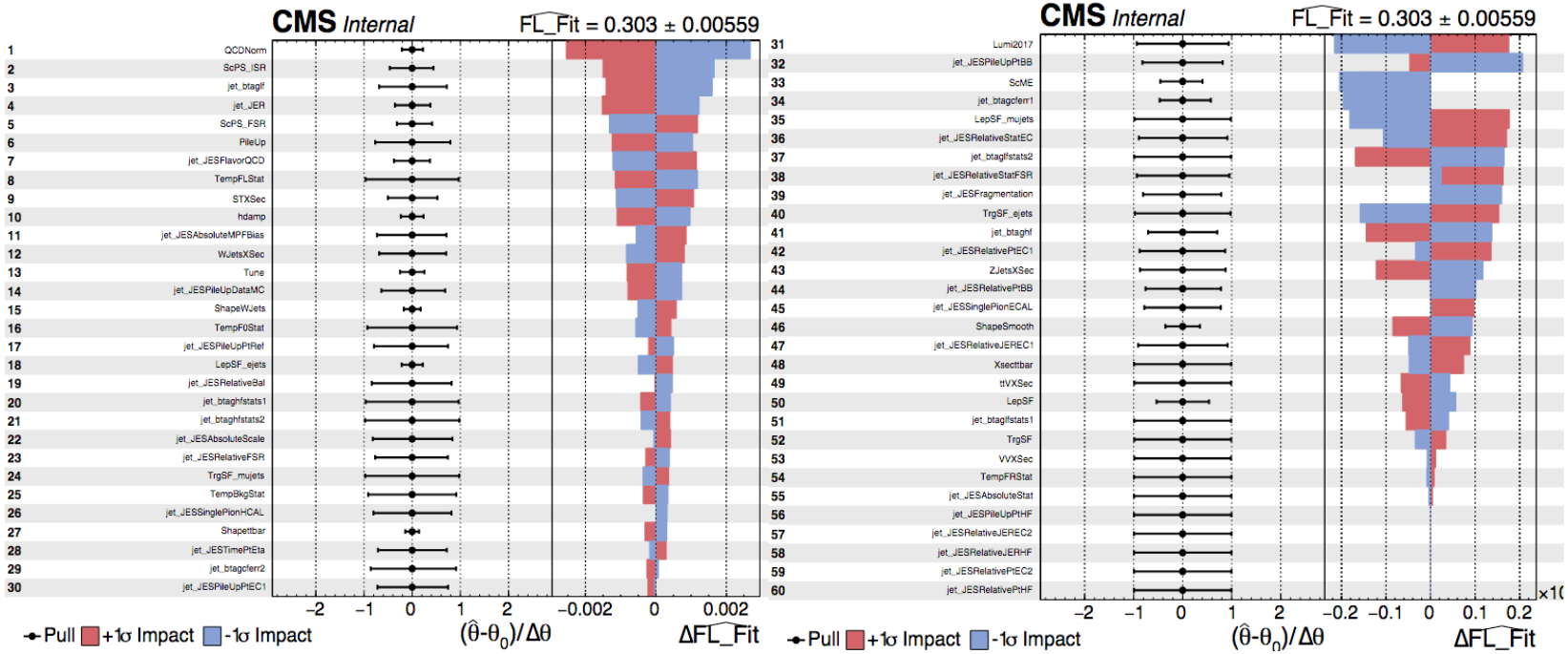
Fit results: Expected [2017] (II)

PRELIMINARY

Impact Plot for F_0



Impact Plot for F_L



Conclusions

All points considered in this presentation constitute part of extensive work being carried out on the Analysis, which is still in progress and towards achieving the best possible sensitivity & precision on the full RunII dataset while using the most performant discriminating variable for this purpose.

- $m_{\ell b}$ **important change** wrt previous options, **performant variable** in the extraction of the W-helicity fractions from top events
- **BDT** and Data-driven method for **QCD estimation** **work properly** with new variable choice
- **Data/MC** **good agreement** for full RunII in the control plots we have examined for various variables used in the Analysis*
- **Systematic uncertainties** **almost all** added into the fit*
- **Fit stability** tested with **multiple pseudodata experiments**. In all cases, **good results; expected fractions obtained***
- **Template fit** using multiple regions **good performance** recovering the expected W-helicity fractions as well as constraining several systematic uncertainties*
- **Combination of 3 years** results from 2016-17-18 combined also **under study**
- **Top p_T reweighting** also **applied** and seems improving Data/MC agreement
- **Other studies** **e.g. binning studies** in parallel for **further fit improvement***

*still under investigation for further possible improvements

Thank you for your attention