Direct $|V_{tq}|$ Determination At The Large Hadron Collider

Monalisa Patra

Jožef Stefan Institute
Ljubljana, Slovenija

Work done in collaboration with D. Faroughy, J. Kamenik, J. Zupan

The CKM Matrix

The Lagrangian for the mass term of the quark fields after EWSB in the Standard Model is

$$\mathcal{L} = (M_d)_{ij} \bar{D}'_{Li} D'_{Rj} + (M_u)_{ij} \bar{U}'_{Li} U'_{Rj},$$

with U'=(u',c',t'), D'=(d',s',b') and $M_q = vY^q/\sqrt{2}$

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$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} \overline{U}_i \gamma^\mu \frac{1-\gamma^5}{2} \left(V_{\text{CKM}}\right)_{ij} D_j W_\mu^+ + \text{h.c.},$$

$V_{\text{CKM}} = V_{uL}^\dagger V_{dL}$ is the unitary CKM matrix:

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

$\lvert V_{ud}\rvert$: Nuclear β decays	$\lvert V_{us}\rvert$: Kaon Decays	$\lvert V_{ub}\rvert$: B decays
$\lvert V_{cd}\rvert$: D decays + ν scatter	$\lvert V_{cs}\rvert$: D Decays	$\lvert V_{cb}\rvert$: B decays

$\lvert V_{ud}\rvert$: 0.97417 ± 0.00021	$\lvert V_{us}\rvert$: 0.2248 ± 0.0006	$\lvert V_{ub}\rvert$: $(4.09 \pm 0.39) \times 10^{-3}$
$\lvert V_{cd}\rvert$: 0.220 ± 0.005	$\lvert V_{cs}\rvert$: 0.995 ± 0.016	$\lvert V_{cb}\rvert$: $(40.5 \pm 1.5) \times 10^{-3}$

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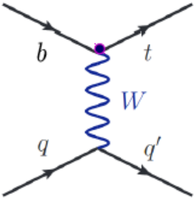
Directly measuring V_{tb} at the LHC

Direct determination without assuming unitarity possible from single top quark production.



t-channel Single top production, $pp \to tj$, $\sigma^{SM} \propto |V_{tb}|^2$

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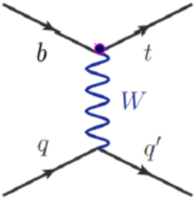
$$|V_{tb}| = \sqrt{\frac{\sigma_{exp}}{\sigma^{SM}_{theory}}}$$

assuming $|V_{tb}| >> |V_{ts}|, |V_{td}|$

$|V_{tb}| = 0.97 \pm 0.01$ @ 8TeV LHC



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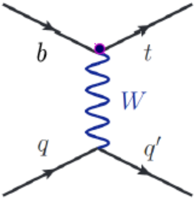

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Indirect measurements

- Weak constraint on $|V_{tb}|$ can be obtained from precision electroweak data, $\Gamma(Z \to b\bar{b})$, $|V_{tb}| = 0.77^{+0.18}_{-0.24}$
- $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq) = |V_{tb}|^2/(\sum_q |V_{tq}|^2)$

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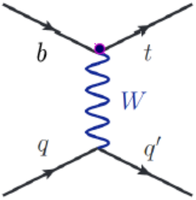

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What about V_{td}, V_{ts} ?

12.2.7. $|V_{td}|$ ***and*** $|V_{ts}|$:   CKM section PDG 2016

The CKM elements $|V_{td}|$ and $|V_{ts}|$ are not likely to be precisely measurable in tree-level processes involving top quarks, so one has to rely on determinations from B–$\overline{B}$ oscillations mediated by box diagrams with top quarks, or loop-mediated rare K and B

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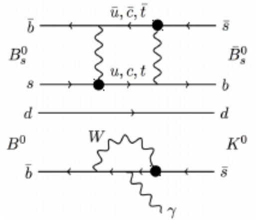
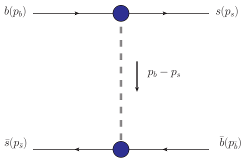
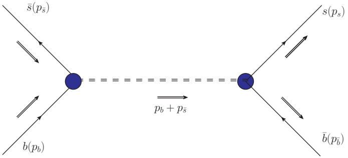


- Indirect determination (loop level) and model dependent
- Theoretical uncertainties in hadronic effects limit the accuracy
- $|V_{td}| = (8.2 \pm 0.6) \times 10^{-3}$, $|V_{ts}| = (40.0 \pm 2.7) \times 10^{-3}$

✶ LHC Limit from R, $\sqrt{|V_{td}|^2 + |V_{ts}|^2} \leq 0.217|V_{tb}|$

- Loop mediated processes are sensitive to new physics effects
- Heavy new particles may contribute to the loop S. Fajfer, B. Melic, MP, arXiv:1801.07115





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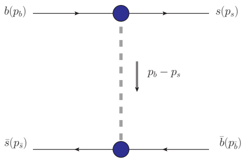
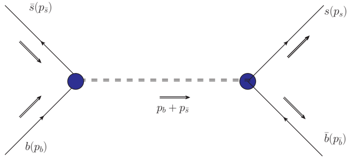




- New physics scenarios with Vector-like top quarks, destroys the unitarity of the SM CKM matrix, $\sum_{x=d,s,b} |V_{tx}|^2 < 1$ A. Girdhar, B. Mukhopadhyaya, MP, arXiv:1404.3374
- The left and right handed component of the vector-like quarks have the same quantum number under $SU(3) \times SU(2)_L \times U(1)_Y$

I) $t'_L, t'_R = (3, 1, 4/3)$ with electric charge $+2/3$, and mixes with t

II) $b'_L, b'_R = (3, 1, -2/3)$ with electric charge $-1/3$, and mixes with b

Vector-Like Quarks

$$\begin{pmatrix} d_w \\ s_w \\ b_w \\ b'_w \end{pmatrix} = U \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix}$$

where

$$U_{4\times4} = \begin{pmatrix} V_{3\times4} \\ X_{1\times4} \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ X_{4d} & X_{4s} & X_{4b} & X_{4b'} \end{pmatrix}$$

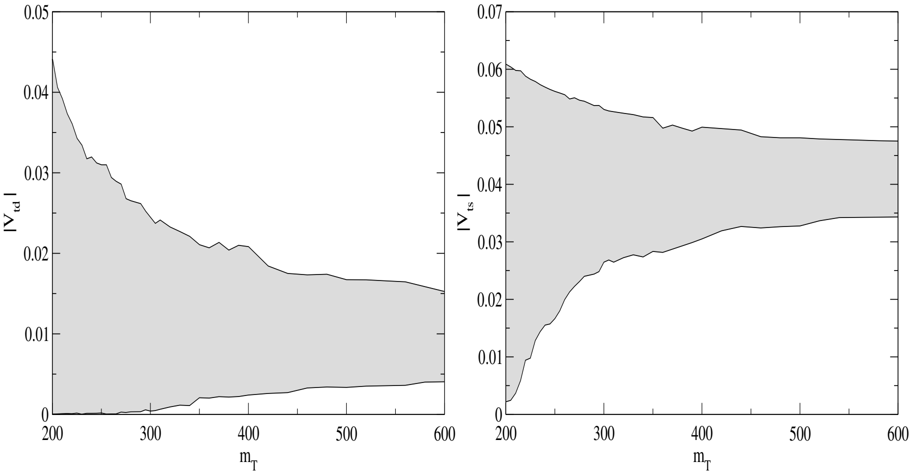
$$\mathcal{L}_{f\bar{f}Z} = \frac{e\gamma_\mu}{6\sin 2\theta_W}\bar{f}(3(1-\gamma_5)|U_{33}|^2 - 4\sin^2\theta_W(|U_{33}|^2 + |U_{43}|^2))fZ^\mu$$

$$\mathcal{L}_{F\bar{F}Z} = \frac{e\gamma_\mu}{6\sin 2\theta_W}\bar{F}(3(1-\gamma_5)|U_{34}|^2 - 4\sin^2\theta_W(|U_{34}|^2 + |U_{44}|^2))FZ^\mu$$

$$\mathcal{L}_{fFZ} = \frac{e\gamma_\mu}{6\sin 2\theta_W}\bar{f}(3(1-\gamma_5)(U^*_{33}U_{34}) - 4\sin^2\theta_W(U^*_{33}U_{34} + U^*_{43}U_{44}))FZ^\mu + h.c.$$

Vector-Like Quarks

A.Saavedra, arXiv: 0210112



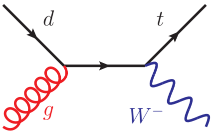
Compare with indirect measurements :

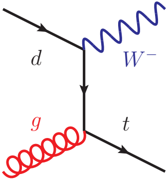
$|V_{td}| = (8.2 \pm 0.6) \times 10^{-3}, |V_{ts}| = (40.0 \pm 2.7) \times 10^{-3}$

Directly measuring V_{td} at the LHC

♣ Proposal : tW associated production at the LHC, $dg \to tW^-, \bar{d}g \to \bar{t}W^+ \quad \propto |V_{td}|^2$

Alvarez, Da Rold, Estevez, Kamenik [1709.07887]





@ 13 TeV LHC
$\sigma(dg \to tW^-) \approx 20$ fb,
$\sigma(\bar{d}g \to \bar{t}W^+) \approx 6$ fb

♣ Special Features :

– Charge asymmetry from (valence) d-quark vs (sea) anti-d quark
– W^- is more forward then W^+

♣ Dominant backgrounds are charge symmetric :

- $bg \to tW^-, \bar{b}g \to \bar{t}W^+, \quad \sigma^{\rm SM}_{tW} \approx 28$ pb
- $gg \to t\bar{t}, \quad \sigma^{\rm SM}_{t\bar{t}} \approx 680$ pb

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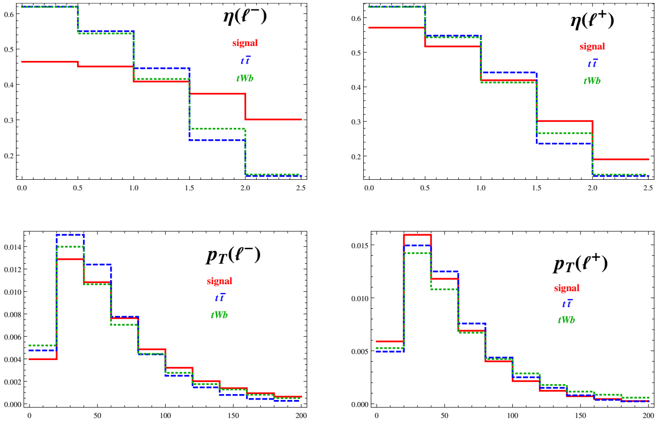

✷ Motivates the kinematical variables :

$$\Delta|\eta(\ell)| = |\eta(\ell^+)| - |\eta(\ell^-)|\,, \qquad \Sigma|\eta(\ell)| = |\eta(\ell^+)| + |\eta(\ell^-)|\,,$$

$$\Delta p_T(\ell) = p_T(\ell^+) - p_T(\ell^-)\,, \qquad \Sigma p_T(\ell) = p_T(\ell^+) + p_T(\ell^-)$$

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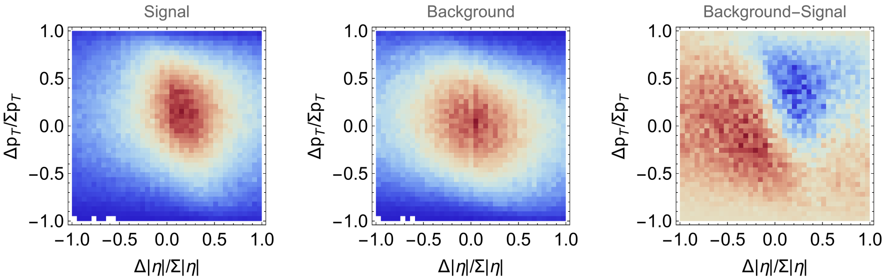

✷ Signal Region : 1st quadrant, Background Region : Symmetric

✷ The following asymmetry is proposed

$$A(\eta, p_T) = \frac{N^+ - N^-}{N^+ + N^-}, \quad \text{where} \quad N^{\pm} = N\left(\Delta|\eta(\ell)| \gtrless 0 \;\&\; \Delta p_T(\ell) \gtrless 0\right),$$

Directly measuring V_{td} at the LHC

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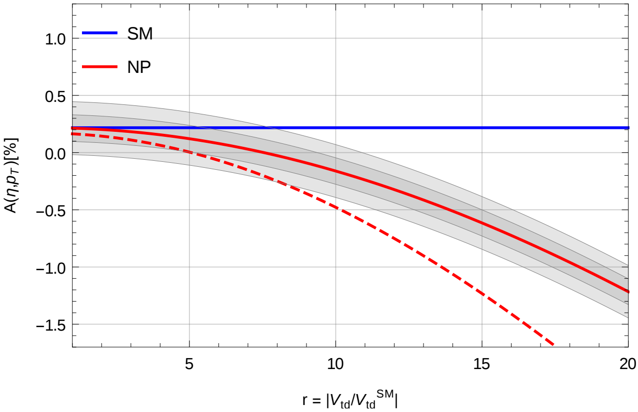

$@L = 3000\ \text{fb}^{-1}$.

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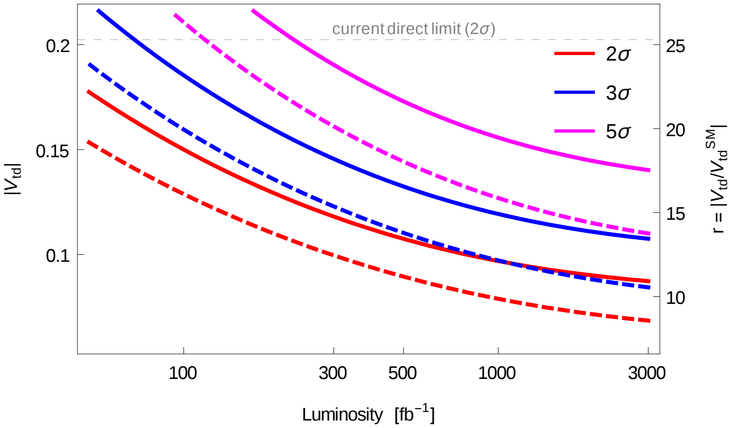

Directly measuring V_{ts} at the LHC

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Why not ?

- Top dominantly decays via $t \to bW^+$, with
  $\mathrm{BR}(t \to sW^+) \approx |V_{ts}|^2 \approx 1.6 \times 10^{-3}$
- No charge asymmetry possible as V_{td}
- Strange and Down quark jets are indistinguishable at Atlas/CMS
  $K^\pm \sim \pi^\pm$ since no particle ID

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Required conditions

- plenty of top quarks
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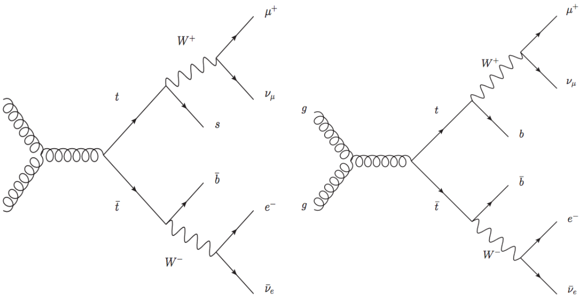
Required conditions

- plenty of top quarks : *at the LHC, with $\sqrt{s}$ = 13 TeV and $\mathcal{L}$ = 30 fb^{-1}, $\mathcal{O}(2 \times 10^7)$ tops will be produced*
- need a light-quark jet tagger, "*s*-tagger" : *Jet tagging technology : b-jets, quark/gluon jets, jet substructure techniques etc*

$t\bar{t}$ production



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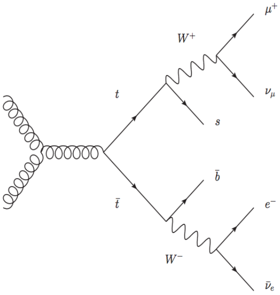
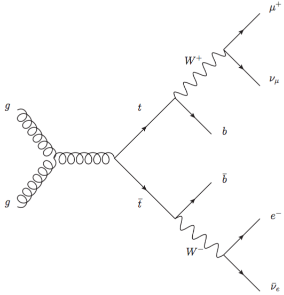
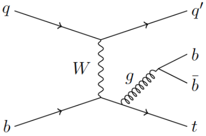
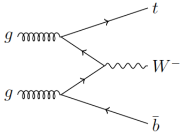
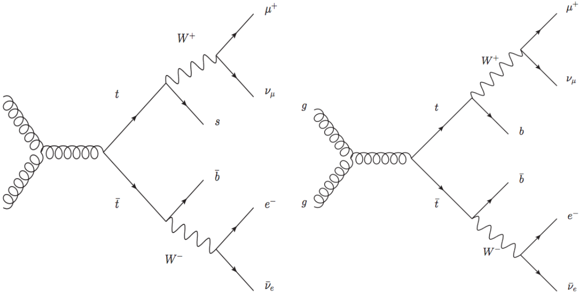


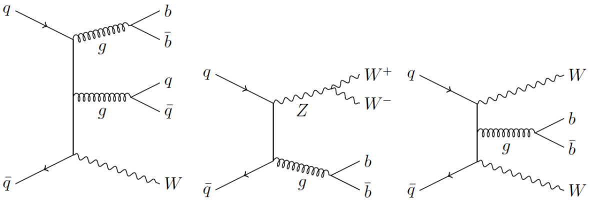






two possible single top processes

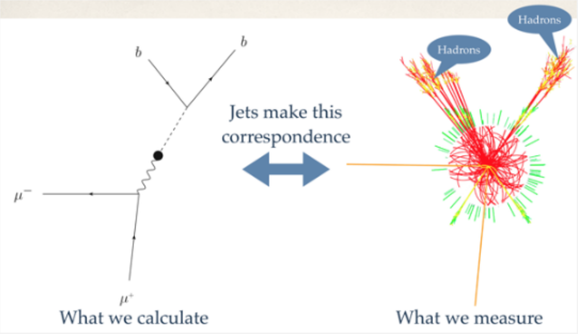




$W+$ jets, Z+jets and Diboson process

Jets

- Jets are the most common objects arising in high energy collisions and heavy particle decays. The LHC is a very jetty place with the **Signal**, **Background** all containing jet
- They are a collimated bunch of energetic hadrons flying roughly in the same direction leaving tracks and energy deposits in the detectors



Simulated event from ATLAS Experiment © 2011 CERN

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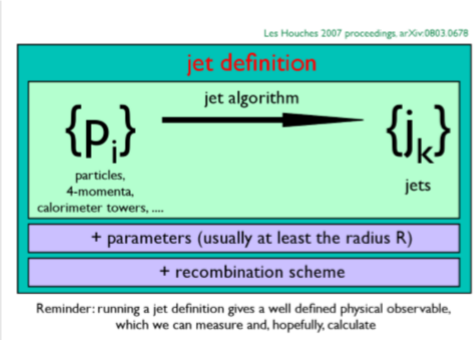

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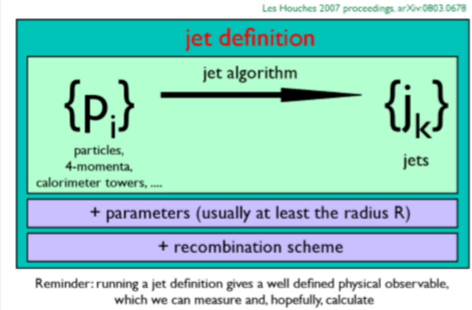

Capability to discriminate light-quark jets (u, d, s) from heavy quark jets (b, c) & g-jets

b-tagging

b-tagging relies on

- long life time, high mass and large momentum of *b* Hadrons

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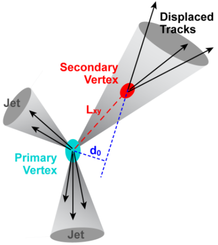

Illustration of a possible hadronically decaying top quark. From D0 collaboration

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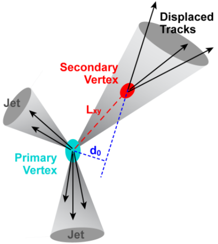

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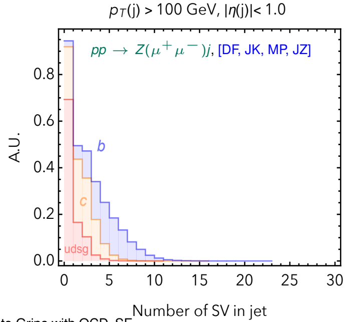

Cuts	ϵ_q	ϵ_b	ϵ_c	ϵ_g
$N_{SV} > 3$	0.0091	0.636	0.094	0.016

Tagging and mis-tagging efficiencies for b-taggers, from the process $pp \to Z(\mu^+\mu^-)j$.

Light quark tagging

Discriminate from the *b*, *c* jets

Light quark tagging opposite to *b*-tagging

- Absence of secondary vertex and energetic charged leptons

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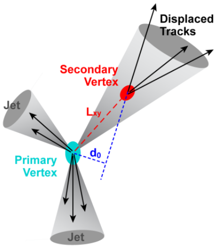
  $d_0 \rightarrow$ transverse impact parameter



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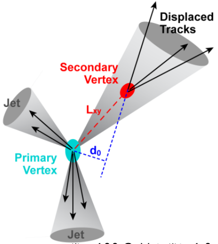


Discriminate from the gluon jets

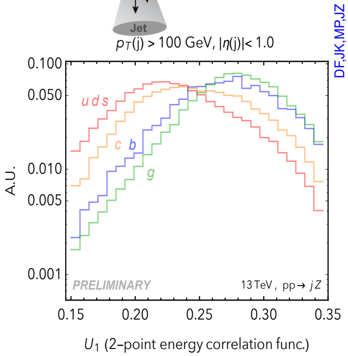
– multiplicity of (charged) particles in jet

– mass and width of the jet

– 2-point energy correlation function :

$$U_1 = \sum_{i<j\epsilon J} z_T^i z_T^j \, (R_{ij})^\beta, \;\; z_T^i \equiv p_T^i / p_T^{jet}$$

$$R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$



Light quark tagging : contd.

QCD factorization theorem : High p_T hadron production cross section in hadron-hadron collisions can be written

$$d\sigma^{\text{hard}}_{AB\to h} = \underbrace{f_{a/A}(x_1, Q^2) \otimes f_{b/B}(x_1, Q^2)}_{PDF's} \otimes \underset{\text{Parton-Parton c.s.}}{\underset{\downarrow}{d\sigma^{\text{hard}}_{ab\to c}(x_1, x_2, Q^2)}} \otimes \underset{\text{Fragmentation Function}}{\underset{\downarrow}{D_{c\to h}(z, Q^2)}}$$

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Fragmentation functions encode the probability of a parton to fragment into a hadron with a momentum fraction , $\frac{p^{hadron}}{p^{parton}}$

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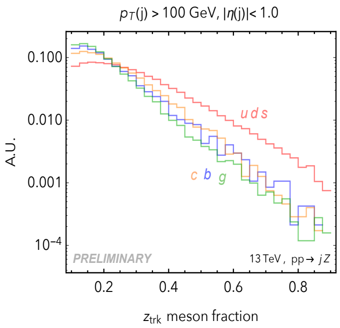
Fragmentation functions encode the probability of a parton to fragment into a hadron with a momentum fraction , $\frac{p^{hadron}}{p^{parton}}$

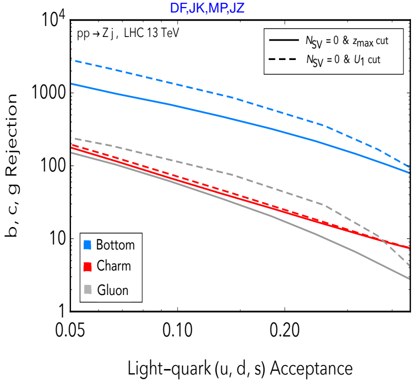
– Consider $z_x = \frac{\vec{p}_{jet}\cdot\vec{p}_x}{|\vec{p}_{jet}|^2}$, related to the jet-fragmentation function

– Fraction of the jet momentum carried by the hardest charged track, $z_{max} \equiv \max\{z_x\}_{x\epsilon jet}$

– Observable has been studied at **ATLAS** and **CMS**. Good agreement with Montecarlo generator, Pythia

DF,JK,MP,JZ





ROC curves for the two q-taggers

(t) type	Cuts	ϵ_q^t	ϵ_b^t	ϵ_c^t	ϵ_g^t
q-tagger	$N_{SV} = 0$ & $z_{max} > 0.3$	0.18	0.0031	0.038	0.049
q-tagger	$N_{SV} = 0$ & $U_1 < 0.21$	0.19	0.0017	0.036	0.019

Tagging and mis-tagging efficiencies for $q-$ taggers

Leptonic Final State

❂ Events with 2 isolated leptons [mini-isolation criteria]

❂ $e\mu$ final state, to reduce Drell-Yan Z boson production

❂ Select 2 jet candidates :

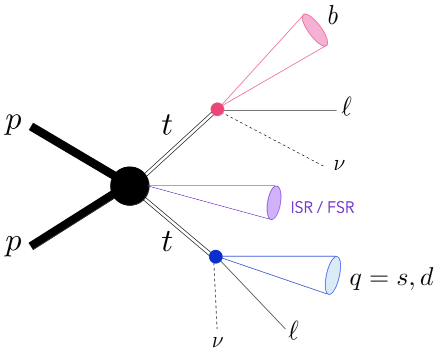
leading & sub-leading jets

$p_T(j_1, j_2) > p_T^{cut}$, $|\eta(j_1, j_2)| < 1.1$

❂ Tag j_1 and j_2 with light-quark and bottom tagger

Signal Region : $j_1 j_2$ tagged as qb

Background Region : $j_1 j_2$ tagged as qq, bb, $q\jmath$, $b\jmath$, $\jmath\jmath$



$\epsilon A\sigma$ [fb]	$\jmath\jmath$	$\jmath q$	$\jmath b$	qb	qq	bb
$t\bar{t} \to b\bar{b}$	459	26	1156	35	0.27	665
$t\bar{t} \to q\bar{b}$	3.3	0.79	3.4	0.65	0.033	0.054
$tW \to bq$	41	3.7	77	4.6	0.046	27

Computed fiducial cross-sections for each tagged di-jet bin in the jj + $e\mu$ channel at the 13 TeV LHC, assuming the SM values for V_{tx}

✷ Select pair of high p_T jets from the top-decays $t\bar{t} \rightarrow j_1 j_2 W^+ W^-$

1. no jet from the top decays selected (background-dominated [ISR/FSR]) [α_0]
2. only one jet correctly assigned to a top decay (combination of signal and background) [α_1]
3. two jets correctly assigned to the top decays (signal-dominated) [α_2]

Relative contributions of the above three classes of events expressed by weights α_i, with $\sum_i \alpha_i = 1$

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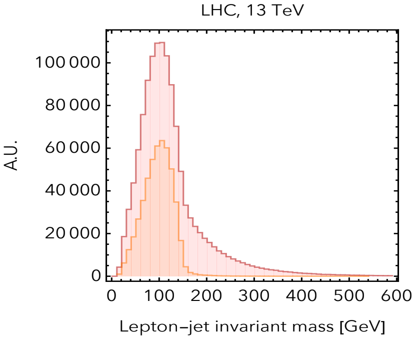
❂ **The α_i's can be estimated directly from data using the kinematic properties of the events**

Extraction of the $\alpha_i's$

❂ The lepton-jet pairs originating from the same top quark decay are kinematically correlated with a kinematical end-point at $M_{\ell,b}^{max} \equiv \sqrt{m_t^2 - m_W^2} \approx 156$ GeV



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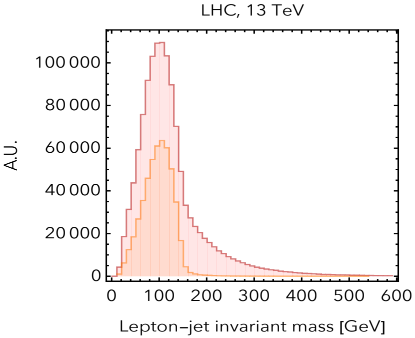
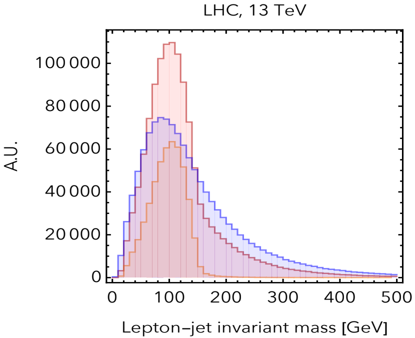


❂ "**random rotation**" of the momentum of the selected leptons in the $(\cos\theta, \phi)$ phase space & recomputation of $M_{\ell j}$



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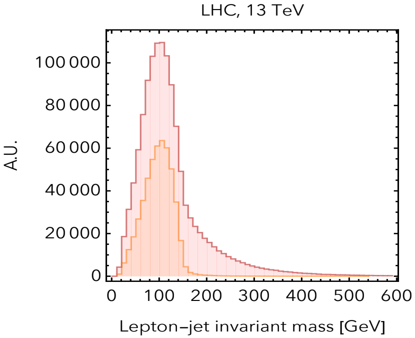

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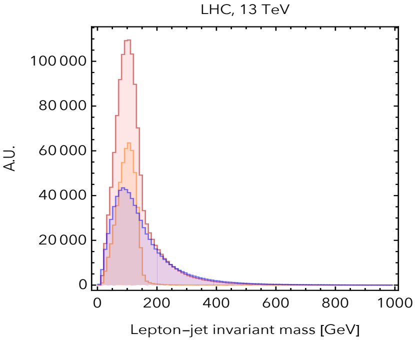
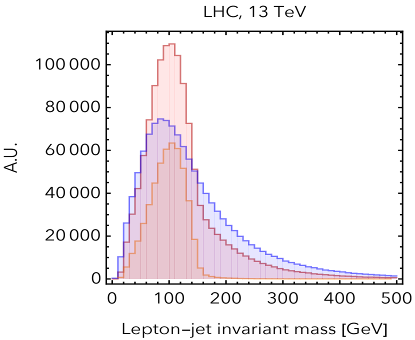
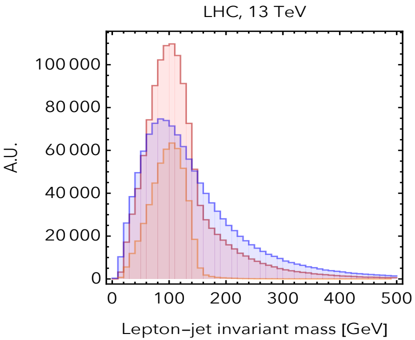


Extraction of the α_i's



- N : All lepton-jet pairs (Red)
- N_{model} : All randomly rotated lepton-jet pairs (Blue)
- N_{mis} : All mis-assigned lepton-jet pairs (Red-Orange)

Extraction of the α_i's



- N : All lepton-jet pairs (Red)
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Correctly assigned ℓj pairs $\alpha = \frac{N - N_{\text{mis}}}{2N_{\text{evts}}} = \frac{N}{2N_{\text{evts}}}\left(1 - \frac{N^{M_{\ell j} > z}}{N_{\text{model}}^{M_{\ell j} > z}}\right) = 0.812$ for the "$e\mu$" sample

Agrees well with the experiment, arXiv : 1404.2292

$$\alpha_2 = \alpha^2 = 0.675, \quad \alpha_1 = 2\alpha(1-\alpha) = 0.295, \quad \alpha_0 = (1-\alpha)^2 = 0.030$$

$$N(i\,\mathrm{t}\,k\mathrm{t}'|2\,\mathrm{jets}) = \sum_{l=0}^{2} N^{obs}(2)\cdot\alpha_l\cdot\mathcal{P}^{l|2}_{i\mathrm{t}\,k\mathrm{t}'}\,, \quad \mathrm{t}^{(\prime)} = (q, b, \jmath)$$

✲ $N^{obs}(2)$: total number of observed events with exactly 2 jets prior to tagging

✲ $\mathcal{P}^{l|2}_{i\mathrm{t}\,k\,\mathrm{t}'}$: probability of tagging i t-jets and k t′-jets, ($qb, qq, bb, q\jmath, b\jmath, \jmath\jmath$)

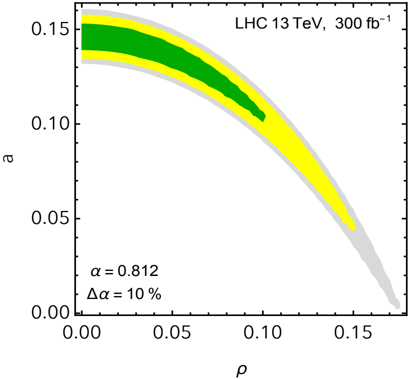
$$\mathcal{P}^{0|2}_{\mathrm{tt}'} = \frac{2\,\varepsilon^{\mathrm{t}}_{q*}\,\varepsilon^{\mathrm{t}'}_{q*}}{1+\delta_{\mathrm{tt}'}}$$

$$\mathcal{P}^{1|2}_{\mathrm{tt}'} = \frac{(\varepsilon^{\mathrm{t}}_{q*}\,\varepsilon^{\mathrm{t}'}_{b} + \varepsilon^{\mathrm{t}'}_{q*}\,\varepsilon^{\mathrm{t}}_{b}) + (\varepsilon^{\mathrm{t}}_{q*}\,\varepsilon^{\mathrm{t}'}_{q} + \varepsilon^{\mathrm{t}'}_{q*}\,\varepsilon^{\mathrm{t}}_{q})\,\rho^2}{(1+\delta_{\mathrm{tt}'})(1+\rho^2)}$$

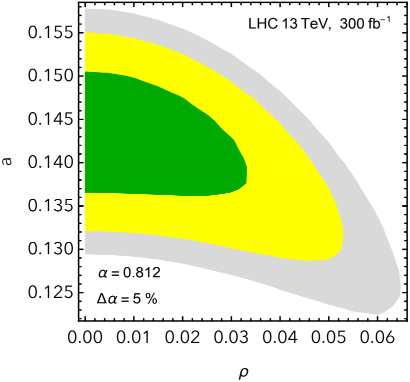
$$\mathcal{P}^{2|2}_{\mathrm{tt}'} = \frac{2\,(\varepsilon^{\mathrm{t}}_{b} + \varepsilon^{\mathrm{t}}_{q}\,\rho^2)(\varepsilon^{\mathrm{t}'}_{b} + \varepsilon^{\mathrm{t}'}_{q}\,\rho^2)}{(1+\delta_{\mathrm{tt}'})(1+\rho^2)^2}$$

$$\varepsilon^{\mathrm{t}}_{q*} = a\,\varepsilon^{\mathrm{t}}_{q} + b\,\varepsilon^{\mathrm{t}}_{b} + c\,\varepsilon^{\mathrm{t}}_{c} + (1-a-b-c)\,\varepsilon^{\mathrm{t}}_{g}$$

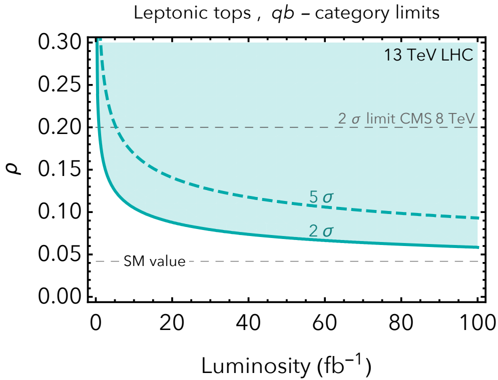
$$\mathcal{R}_q \equiv \frac{\mathcal{B}(t\to sW)+\mathcal{B}(t\to dW)}{\sum_{j=d,s,b}\mathcal{B}(t\to jW)}, \quad \rho^2 \equiv \frac{\mathcal{R}_q}{\mathcal{R}_b} = \frac{\mathcal{B}(t\to sW)+\mathcal{B}(t\to dW)}{\mathcal{B}(t\to bW)}$$



LHC 13 TeV, 300 fb^{-1}
0.15
0.10
0.05
0.00
a
α = 0.812
$\Delta\alpha$ = 10 %
0.00
0.05
0.10
0.15
ρ

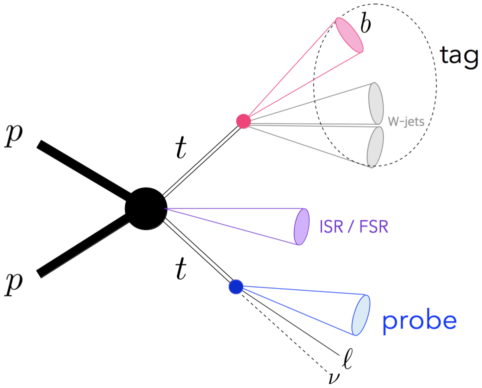


LHC 13 TeV, 300 fb^{-1}
0.155
0.150
0.145
0.140
0.135
0.130
0.125
a
α = 0.812
$\Delta\alpha$ = 5 %
0.00
0.01
0.02
0.03
0.04
0.05
0.06
ρ



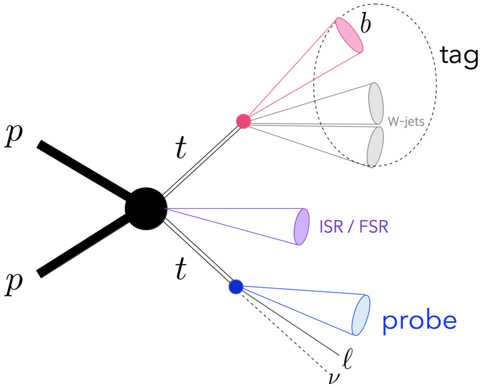
Leptonic tops , qb – category limits
13 TeV LHC
2 σ limit CMS 8 TeV
5 σ
2 σ
SM value
ρ
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
20
40
60
80
100
Luminosity (fb^{-1})

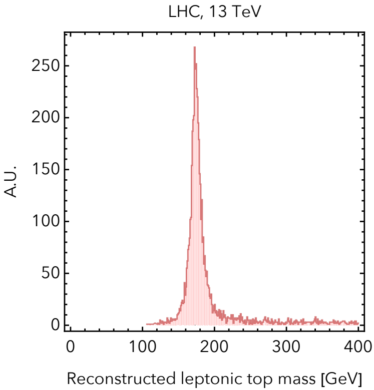
Boosted semi-leptonic $t\bar{t}$ category



- Select events with 1 isolated lepton and a Fat-jet with $R = 1.5$
- The subjet j_1 within the fat jet is tagged as b or q jet
- Remove top-jet from event and re-cluster jets with $R = 0.3$ and $p_T >$ 100 GeV
- Jet j_2 which best reconstructs leptonic top is selected and then tagged as bottom or light-quark jet

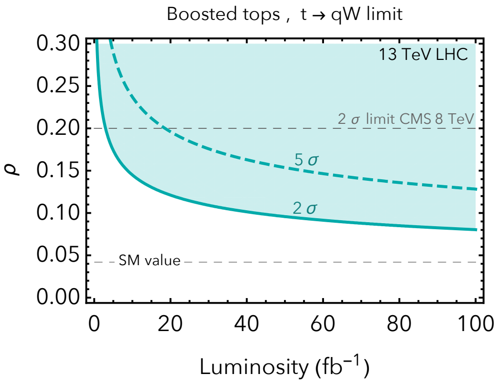
Boosted semi-leptonic $t\bar{t}$ category





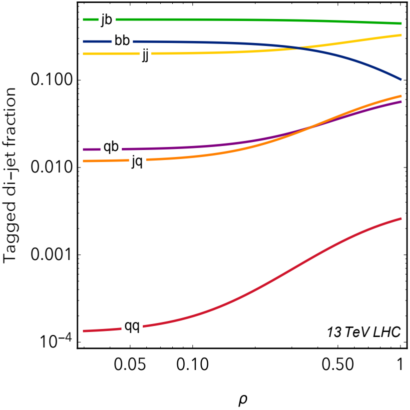
$\epsilon A\sigma$ [fb]	$\jmath$	q	b
$t\bar{t} \to bt_j$	716	18	1232
$t\bar{t} \to qt_j$	3	0.5	0.095
$tW \to bt_j$	11	0.61	4.6

Computed fiducial cross-sections for the tagged probed jet bin in the semi-leptonic boosted $t\bar{t}$ channel at the 13 TeV LHC, assuming the SM values for V_{tx}



Conclusions

- The CKM parameters V_{td} and V_{ts} are fundamental parameters of the SM governing flavor conversion in the top sector
- These elements are constrained indirectly as their determination through direct measurement requires processes with on-shell quarks with a very small branching ratio making it difficult
- We propose a light quark tagger, which discriminates the light quark jets from the gluon and the heavy quark jets
- The fully leptonic and the boosted semi-leptonic scenarios are analysed
- We show that the current bound on the direct determination of $\sqrt{V_{td}^2 + V_{ts}^2}$ can be surpassed with the existing LHC dataset
- It will be possible to exclude $\sqrt{V_{td}^2 + V_{ts}^2} > 0.06$ at the 2σ level with a luminosity of $100\ \text{fb}^{-1}$ at the 13 TeV LHC


jb
bb
jj
qb
jq
qq
0.100
0.010
0.001
10^{-4}
Tagged di-jet fraction
13 TeV LHC
0.05
0.10
0.50
1
ρ