DIRECT |Vtq| DETERMINATION AT THE LHC

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MOTIVATION

- Why so strong interest in the direct measurements of |Vts| and |Vtd| in addition to |Vtb|?
- The absolute values of these CKM matrix elements can be modified by approximately a factor 2 from their SM values
  - $|V_{ts}| = 0.0407 \pm 0.001$, $|V_{td}| = (8.74^{+0.26}_{-0.37}) \times 10^{-3}$
  - Taking the example of a four-generation extension of the SM
- Why big prospects of measuring the matrix elements |Vtq| at the LHC?
  - Very large top quark statistics will be available at the LHC@14 TeV from $t\bar{t}$ and single top processes.

INTRODUCTION

- Concentrate here on direct |Vts| determination at the LHC@14 TeV.
- Lacking of a good tagging for the t → d transition, and also because of the small size of the CKM-matrix element, $|Vtd| = O(10^{-2})$, my talk will be mainly about the direct measurements of |Vts| at the LHC from the experimentalist point of view.
- Based on our paper of A. Ali, F.Barreiro and Th. Lagouri, (PLB 693(2010) 44-51).
- Alternative methods for direct |Vtq| determination at LHC are also reported.

HIGHLIGHTS OF TEVATRON AND LHC TOP RESULTS

- A lot of precise top measurements
- Top mass at less than 1% precision.
- Top pair cross section at ~ 5.5% precision.
- Direct CDF and D0 measurements of |Vtb| using $\sigma(p\bar{p}\rightarrow t/\bar{t}X)$=3.14 (3.46) pb
  - |Vtb| = 0.91 (0.88) ± 0.08 (0.07) with |Vtb|> 0.79 (0.77) at 95% C.L.
- Direct determination of |Vtb| with the experiments at the LHC is expected to reach an accuracy of a few per cent.
- The determination of |Vtb| with such an accuracy will be also very valuable to constrain beyond-the-SM physics models.

WHAT IS NEEDED TO MEASURE |Vts| DIRECTLY ? (1)

- To develop efficient discriminants to suppress the dominant decay t → W b
  - First we tag only those events in which the $W^{\pm}$ decay leptonically to reduce the jet activity in top quark decays
- The emerging s-quark from the top quark decay t → W s, and the collinear gluons which are present in the fragmentation process will form a hadron jet
- We suggest tagging on the V0 (K0 and Λ) in this jet, and measure their energy and transverse momentum distributions.

WHAT IS NEEDED TO MEASURE |Vts| DIRECTLY ? (2)

- For the decay $t \rightarrow W\, b$
  - Energetic V0 are present in the b-quark jets and the subsequent weak decays $b \rightarrow c \rightarrow s$.
  - V0 will be softer, will have displaced vertexes (from the interaction point) and they will be often accompanied with energetic charged leptons due to the decays $b \rightarrow l^{\pm}X$.
- For the decay $t \rightarrow W\, s$
  - Absence of a secondary vertex and of the energetic charged leptons in the s-jets provide a strong discrimination on the decays $t \rightarrow Wb$.

WHAT IS NEEDED TO MEASURE |Vts| DIRECTLY ? (3)

- Quantities of principal interest:
  - the scaled energy and transverse momentum distributions of the K0, Λ and $l^{\pm}$
  - the secondary decay vertex distributions (dN/dr).

EXPERIMENTAL ASSUMPTIONS

- Assumed two representative secondary vertex resolution values:
  - σ (vertex) =1 mm and 2 mm, (2 mm is more realistic).
- Experimentally, b-tagging algorithms are based on measurements of the impact parameter from the B meson charged tracks.

MVA BOOSTED DECISION TREE (BDT)

- MVA technique called the Boosted Decision Tree with De-correlated variables (BDTD) a classification model used widely in data mining.
- BDTD used to discriminate the signal events $t \rightarrow Ws$ from the $t \rightarrow W b$ backgrounds.
- The discriminating variables used to develop the splitting criteria to determine the best partitions of the data into signal and background to build up a decision tree (DT).
- The Toolkit for Multivariate Data Analysis in ROOT (TMVA) is used for the BDTD responses.

MONTE CARLO GENERATOR

- The generated input for MVA used for the purpose of training and testing the samples obtained with the help of a Monte Carlo generator PYTHIA.
- PYTHIA model the production processes, gluon radiation, fragmentation and decay chains, and the underlying events.
- 1M events generated with PYTHIA 6.4 with $|V_{ts}| = |V_{tb}| = 0.5$

$pp \rightarrow t\bar{t}X$ AND $t \rightarrow Wb$, Ws DECAYS (1)

- NNLO estimate of the top quark production at LHC: $\sigma(pp \rightarrow t\bar{t}X) = 874(^{+14}{}_{-33})$pb for $m_t = 173$ GeV and $\sqrt{s} = 14$ TeV.
- Compared to the $t\bar{t}$ cross section at the Tevatron $(\sqrt{s}) = 1.96$ TeV),

  $\sigma(p\bar{p} \rightarrow t\bar{t}X) = 7.34(^{+0.23}{}_{-0.38})$ pb *
- Expecting a rise in the $t\bar{t}$ cross section by more than two orders of magnitude between the Tevatron and the LHC@14 TeV.

  - * Top 2012, updated experimental Tevatron result:

$\sigma(p\bar{p} \rightarrow t\bar{t}X) = (7.65 \pm 0.42)$ pb (rel.5.5%, m_t=172.5 GeV)

$pp \to t\bar{t}X$ AND $t \to Wb$, Ws DECAYS (2)

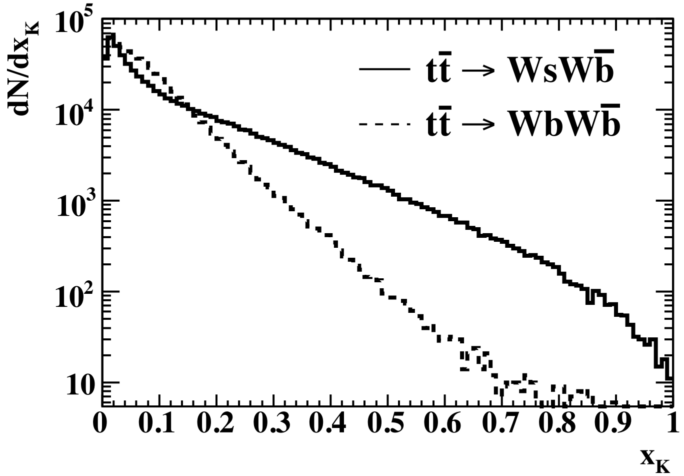
- PYTHIA Monte Carlo 10^6 events $pp \to t\bar{t}X$, followed by the decay chains $t \to W^+ b$, $W^+ s$, $\bar{t} \to W^- \bar{b}$, $W^- \bar{s}$.
- $W^\pm$ are forced to decay only leptonically $W^\pm \to l^\pm \nu$ ($l = e, \mu, \tau$).
- For an estimated (s-tagging) efficiency of 5% at 10^3 b-jet background rejection, and $|V_{ts}|^2 \simeq 1.7\times10^{-3}$ (SM), taking $\sigma(t\bar{t}) \sim 1$nb, for an integrated luminosity of 10 fb^{-1} at 14 TeV, we expect:
  - Signal events of 170.
  - Background events of 10^3.
  - Giving a significance of $\sim 6\sigma$.

V0 PRODUCTION

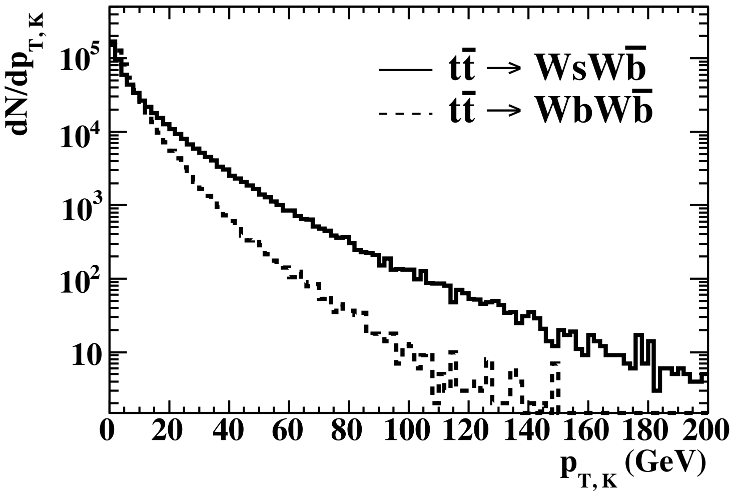
- V0 production => V0 = K^0_S or V0 = Λ, for the experimental conditions of the two main LHC detectors ATLAS and CMS.
- Both K^0_S and Λ can be detected by ATLAS and CMS and their energy and momentum measured with reasonably good precision.
- V0 and soft leptons reconstructed in the rapidity range $|\eta| \leq 2.5$.
- In addition, V0 decay radius required to be in the range 20 to 600 mm.
- The above acceptance cuts are acceptable for both multipurpose LHC detectors.

$t\bar{t}$ ANALYSIS AT LHC @14 TeV

K^0s



Scaled energy $X_K = E_K/E_{jet}$ distributions
dN/dx_K :
$t \to W\, s(\to K^0X)$ (solid histogram)
$t \to W\, b \to K^0\, X$ (dashed histogram).

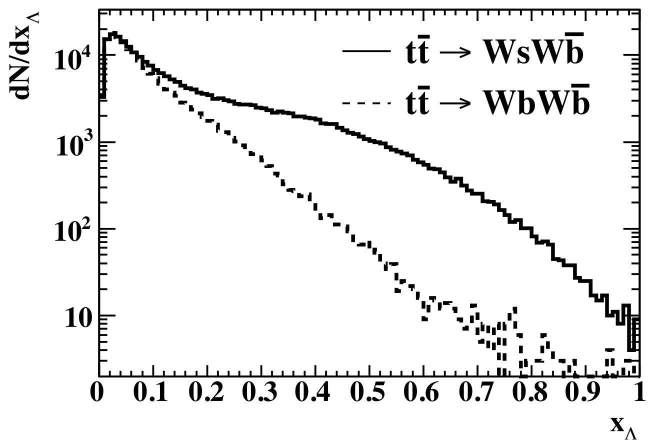


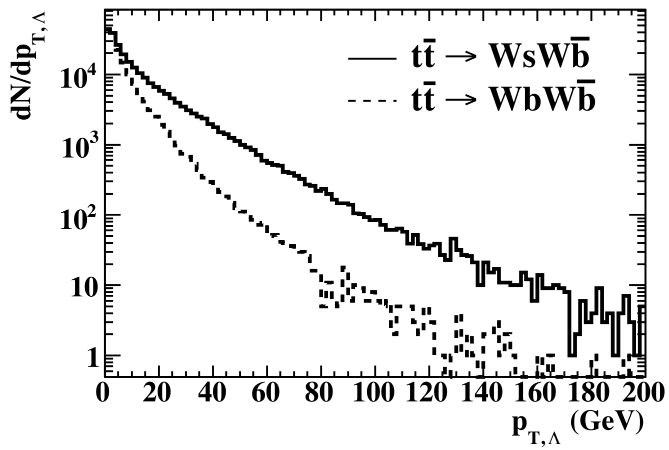
Transverse momentum $p_T(K^0)$ (GeV) distributions dN/dp_{TK} :
$t \to W\, s(\to K^0X)$ (solid histogram)
$t \to W\, b \to K^0\, X$ (dashed histogram)

$K^0{}_S$, Λ DISTRIBUTIONS

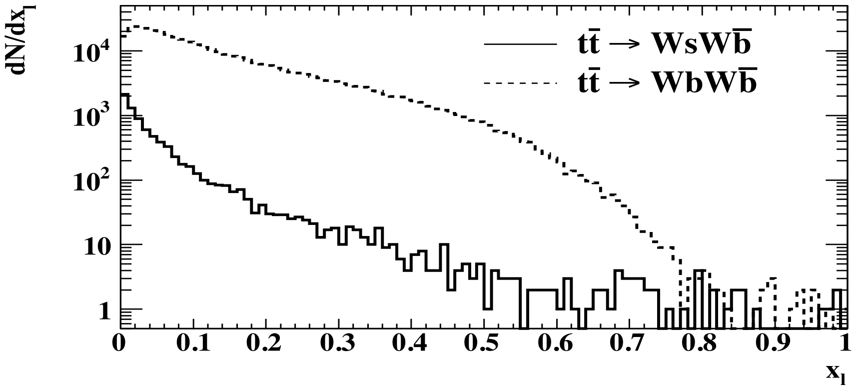
- The decay chain $t \rightarrow Ws(\rightarrow K^0{}_s)$ has a much stiffer distribution both in X_K and $p_T(K^0)$,
  - $K^0{}_s$ descending from the decay chain $t \rightarrow W\ b(\rightarrow c \rightarrow s)$ are rapidly degraded in these variables due to the subsequent weak decays.
- The corresponding distributions for the Λ are qualitatively very similar to those of the $K^0{}_s$.

Λ





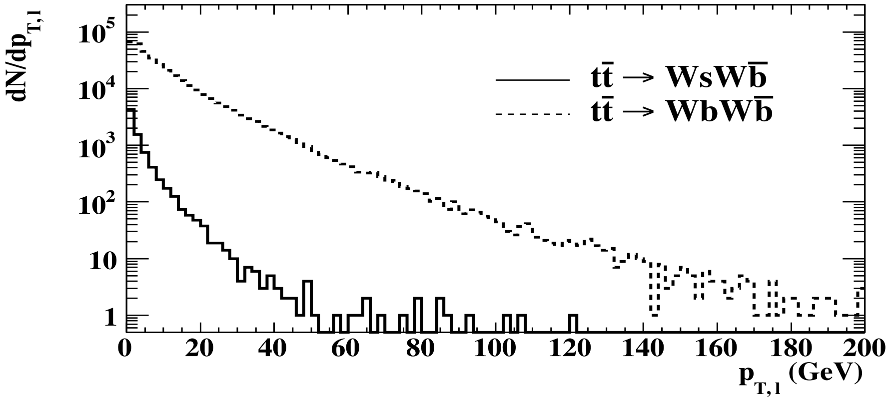
CHARGED LEPTON ENERGY FROM $t \to b \to l^{\pm}X$ AND $t \to s \to l^{\pm}X$ (1)



Scaled $l^{(\pm)}$ energy $X_l = E_l/E_{jet}$ distributions dN/dx_l :

$t \to W\,s \to l^{\pm}X$ (solid histogram)

$t \to W\,b \to l^{\pm}X$ (dashed histogram).



Transverse momentum p^{l}_{T} (GeV) distributions of the $l^{\pm}$, dN/dpT_l :

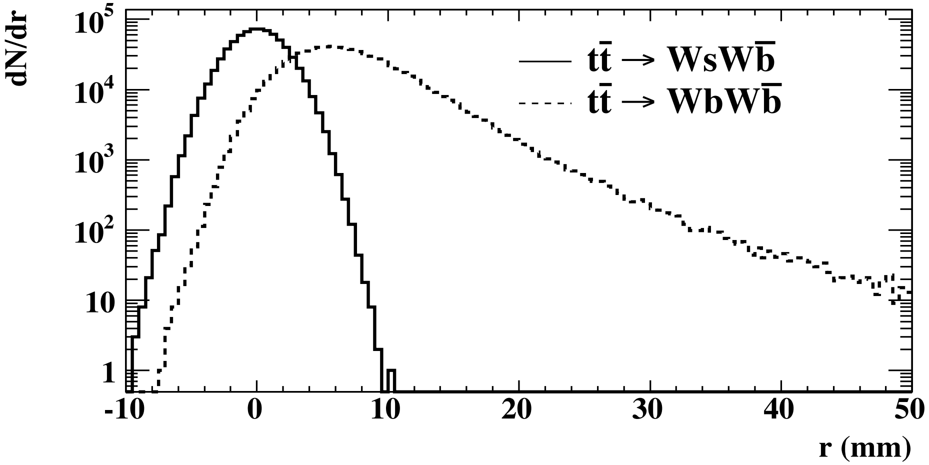
$t \to W\,s \to l^{\pm}X$ (solid histo)

$t \to W\,b \to l^{\pm}X$ (dashed histogram).

CHARGED LEPTON ENERGY FROM $t \rightarrow b \rightarrow l^{\pm}X$ AND $t \rightarrow s \rightarrow l^{\pm}X$ (2)

- Richness of the b-jets in charged leptons and stiff character of the energy/transverse momentum distributions due to the weak decays.
- Leptons from $s \rightarrow l^{\pm}X$, are soft coming from the leptonic decays of the various resonances produced in the fragmentation of the s-quark.
- Absence of energetic charged leptons in the s-quark jet in the decay $t \rightarrow W\, s$ is a powerful tool in reducing the background from $t \rightarrow W\, b$.

SECONDARY VERTEX DISTRIBUTIONS



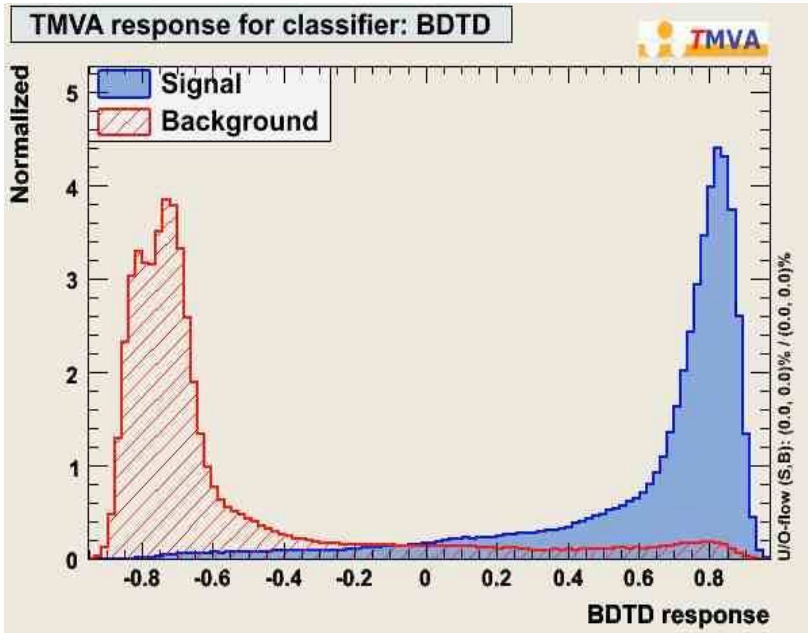
Secondary decay vertex r (mm) distributions:
t → W s (solid histogram)
t → W b (dashed histogram)
obtained by smearing the decay length with a Gaussian with σ of 2 mm.

- Reflects the long lifetime of the b-quark (of the B and Λ_b hadrons), as opposed to the lack of a secondary vertex from the s-quark fragmentation process.
- Also it gives a very powerful discrimination of t → W b vs. t → W s decays.

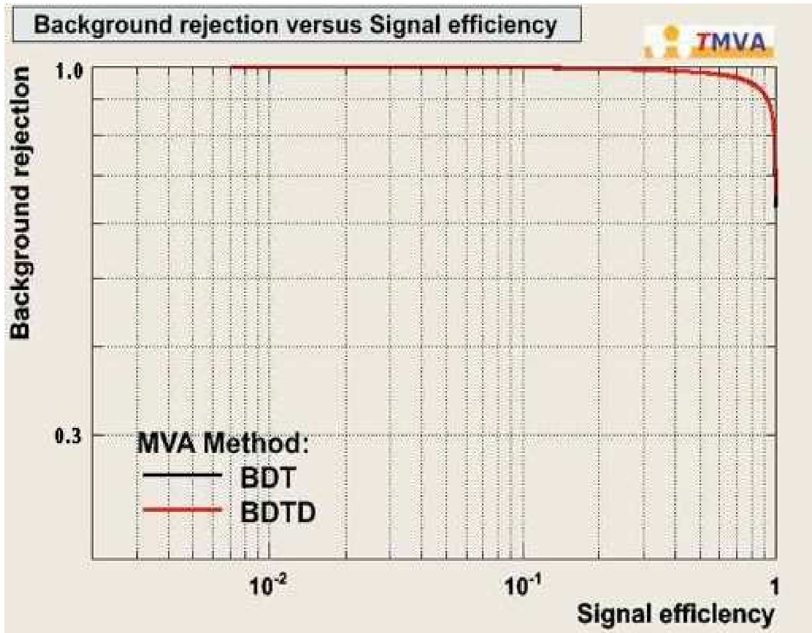
EFFICIENCY VS BACKGROUND REJECTION FOR $t\bar{t}$

- BDTD trained in the TMVA framework with the previous shown variables.

Normalised BDTD response.



Background rejection vs. signal efficiency



The signal (blue shaded) from the decay $t \to W\,s$ and the background (red shaded) from the decay $t \to W\,b$ are clearly separated.

RESULTS FOR $t\bar{t}$

Tagging efficiencies (in %) for the process $pp \rightarrow t\bar{t}X$, followed by the decay $t \rightarrow Ws$ (signal) and $t \rightarrow Wb$ (background), calculated for an acceptance of 0.1% for the background at LHC@14 TeV. Two Gaussian vertex smearing (σ of 2 mm and 1 mm) are assumed for calculating the displaced vertex distributions dN/dr.

Table I (LHC@14 TeV)

Vertex smearing σ (mm)	Tag Eff. (%) bb/bs	Tag Eff. (%) bs/ss
2	5.0	12.3
1	15.5	34.2

SINGLE TOP (ANTI-TOP) ANALYSIS AT LHC @14 TeV

- Three basic processes at the LO which contribute to $\sigma(pp \rightarrow t/\bar{t}X)$
- Single top (anti-top) NLO cross section $\sigma \simeq 1.8$ pb at the Tevatron.

$pp \rightarrow t/\bar{t}X$	σ (pb) Tevatron	σ (pb) LHC@14 TeV
t-channel	1.14±0.06	149±6
s-channel	0.53±0.02	7.7(+0.6-0.7)
tW associated	0.14±0.03	43±5

- Expected LHC@14 TeV:
- $\sigma(pp \rightarrow tX) \simeq 200$ pb and about half this number for $\sigma(pp \rightarrow \bar{t}X)$
- Summed single top and anti-top cross sections at ~300 pb
- Approximately two orders of magnitude larger than those at the Tevatron.
- With a luminosity of 10 fb^{-1}, one anticipates $O(3 \times 10^6)$ single top (or anti-top) events, $O(10^6)$ events in the leptonic channel.
- Monte Carlo generator PYTHIA, models so far only the s-channel single top production process $pp \rightarrow W \rightarrow t\, b$.

RESULTS FOR SINGLE TOP (ANTI-TOP)

Tagging efficiencies (in %) for the process pp → t/$\bar{t}$ X, followed by the decay t → Ws (signal) and t → Wb (background), calculated for an acceptance of 0.1% for the background at LHC@14 TeV. Two Gaussian vertex smearing (σ values of 2 mm and 1 mm) are assumed for calculating the displaced vertex distributions dN/dr.

Table II (LHC@14 TeV)

Vertex smearing σ (mm)	Tag Eff. (%) b/s
2	5.3
1	19.9

- Also in single top production process a background rejection of 10^3 can be achieved at a signal efficiency of about 5% to reach the SM-sensitivity of the CKM matrix element |Vts|.
- Thus we would expect 90 signal events with a background of 10^3 events giving a significance of ~ 3 σ .

SUMMARY OF $|V_{ts}|$ DETERMINATION (1)

- Matrix element $|V_{ts}|$ measurement from the top quark decays $t \to W^+ s$ and its charge conjugate $\bar{t} \to W^- \bar{s}$, making use of the characteristic differences in the b- and s-jet profiles.
- Concentrated on the V0 (K^0 and Λ) energy-momentum profiles emanating from the signal ($t \to W s$) and the dominant background ($t \to Wb$).
- Combined with the secondary vertex distributions, anticipated from the decays ($b \to c \to s$), and the absence of energetic charged leptons in s-quark jets.
- Important parameter is the vertex resolution,
  - used two values, σ(vertex) = 1 mm and 2 mm, assuming a Gaussian distribution.

Summary of $|V_{ts}|$ determination (2)

- Boosted decision tree (BDTD) classifiers used
  - BDTD-response functions for the signal ($t \to W s$) and background ($t \to W b$) events.
- Study the background rejection versus the signal efficiency
  - would enable to achieve typically 10% signal efficiency and a background rejection of 10^3.
- Studies done at three representative values of the LHC centre-of-mass energies, $\sqrt{s}$ = 7 TeV, 10 TeV and 14 TeV.
  - As the principal results (BDTD) response functions and background rejection versus signal efficiencies are very similar for all three energies, presented detailed results only for $\sqrt{s}$ = 14 TeV.

FURTHER IMPROVEMENTS FOR $|V_{ts}|$ DETERMINATION (1)

- The cross sections for the top pair ($pp \rightarrow t\bar{t}X$) and single top production ($pp \rightarrow t/\bar{t}X$) in PYTHIA can be adjusted to correspond to the theoretical precision currently available.
- The distributions and topologies, in particular for the single top (anti-top) production processes, will have to be correctly incorporated in a realistic simulation.
- No attempt to define the s- and b-quark jets using a modern jet algorithm.
- No attempt has been made at improving the training process by adding some more variables, like the b-jet shapes, which are known to have some discriminating power.

FURTHER IMPROVEMENTS FOR $|V_{ts}|$ DETERMINATION (2)

- We recall some of the important sources of uncertainties in our analysis:
  - (i) predicted rates of the top quark production,
  - (ii) histogram shapes,
  - (iii) integrated luminosities,
  - (iv) efficiencies of the b- and s-quark tagging, reflecting in our study the relative efficiencies given in Tables I and II, and
  - the uncertainty in top mass (m_t)
- All these experimental and theoretical refinements will have to be incorporated in the analysis of the LHC data to draw quantitative conclusions. In particular, background processes, most notably W + jets, Z + jets will have to be considered.

Alternative methods determining the matrix elements $|V_{td}|$, $|V_{ts}|$, $|V_{tb}|$

USING SINGLE TOP (ANTI-TOP) PRODUCTION TO DETERMINE THE MATRIX ELEMENTS (1)

From the cross section measurement by a simultaneous fit:

- $\sigma(pp \to t/X) = A_d |Vtd|^2 + A_s |Vts|^2 + A_b |Vtb|^2$ (and $\sigma(pp \to \bar{t}\bar{t}X)$)
- One then solves the cross-section for the CKM matrix elements, given the dynamical quantities A_d, A_s and A_b.
- Depend on estimates of the various electroweak processes in the single-top (or anti-top) production and on the parton distribution functions (PDFs)
- Typical estimates at LHC ($\sqrt{s}$ = 14 TeV)
  - A_d = 766(253) pb,
  - A_s = 277(172) pb
  - A_t = 150(87) pb

  where the numbers in the parenthesis refer to the production of anti-top.
- Based on these estimates, at the LHC: A_s/A_b ~ 2 and A_d/A_b ~ 5.

USING SINGLE TOP (ANTI-TOP) PRODUCTION TO DETERMINE THE MATRIX ELEMENTS (2)

- In the SM, one expects
  - $|Vts|^2/|Vtb|^2 \sim 1.6 \times 10^{-3}$ and
  - $|Vtd|^2/|Vtb|^2 \sim 6 \times 10^{-5}$.
- In the example of realistic beyond-the SM physics that we are using to motivate these studies, these CKM matrix element ratios could be larger by a factor 4.
- Both in the SM, and in the four generation extension of it, the cross sections $\sigma(pp \to tX)$ and $\sigma(pp \to \bar{t}X)$ are completely dominated by the $A_b\,|Vtb|^2$ term.
- This proposal does not have the desired sensitivity to measure the matrix elements $|Vtd|$ and $|Vts|$ at the level of theoretical interest.

I. PROSPECTS FOR DETERMINATION OF $|V_{tb}|$ AT LHC

- Through the measurement of single top cross sections, directly proportional to $|Vtb|^2$
- Single top production mechanism t-channel is the most promising
- Relative uncertainty in cross section of t-channel estimated at 10 fb^{-1}

$$\frac{\Delta\sigma}{\sigma} = \pm 3\%(\text{stat.}) \pm 7\%(\text{syst.}) \pm 5\%(\text{lum.}).$$

- Vtb could be determined at 5% precision level with 10 fb^{-1} .

J. Alwall et al., Eur. Phys. J. C 49, 791–801 (2007), arXiv:0607115 [hep-ph]

II. USING THE SINGLE TOP QUARK RAPIDITY DISTRIBUTIONS AT LHC TO IMPROVE THE SENSITIVITY TO $|V_{td}|$

- In t-channel and tW production from initial s, b sea quarks, the events more central than those resulting from initial d quarks.
  - more pronounced for final state t quarks than for antiquarks.
- At LHC@14 TeV with 10 fb^{-1}
  - Limits on Vtd may be reduced by a factor of ~2
  - Limits on Vtb can be reduced by 15%
  - Limits $|Vtd| \leq 0.12$, $|Vts| \leq 0.27$, $0.94 \leq |Vtb| \leq 1.05$ could be achieved.
- Sensitivity of this method is far from the expected value of $|Vtd|$ by an order of magnitude.
- The top quark rapidity distributions do not provide an improved determination of $|Vts|$ from the single top production process
  - as the s-quark and the b-quark are both sea-quarks in the proton.
- Our method based on the top quark decay characteristics to determine $|Vts|$ complements the existing proposal.

J. A. Aguilar-Saavedra and A. Onofre, (2011), arXiv:1002.4718 [hep-ph]

|Vtq| DETERMINATION AT TEVATRON

I. RATIO OF THE CKM MATRIX ELEMENTS $(|V_{td}|^2 + |V_{ts}|^2)/|V_{tb}|^2$ BY MEASURING THE RATIO R

$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2$$

through the number of events with zero-, one-, and two b-tags in the process $p\bar{p} \to t\bar{t}X$

- Can be combined with the determination of the ratio $|Vts|^2/|Vtb|^2$ discussed here, to constrain (or measure) the quantity $|Vtd|^2/|Vtb|^2$

CDF (2005),arXiv:0505091v2 [hep-ex]
D0 (2008),arXiv:0801.1326v1 [hep-ex]

|Vtq| DETERMINATION AT TEVATRON

II. MODEL-INDEPENDENT EXTRACTION OF $|V_{tq}|$ MATRIX ELEMENTS FROM TOP-QUARK MEASUREMENTS

Triggered by a recent (D0)* measurement of the ratio R=0.90

- Strategy that allows to extract in a model-independent way the quark mixing matrix elements |Vtd|, |Vts|, and |Vtb| from the measurement of R and from single-top measured event yields.
- Method applied to the Tevatron data using a CDF analysis of the measured single-top event yield with two jets in the final state one of which is identified as a b-quark jet.
- This method provides information that can be directly used to put constraints on 4SM and other scenarios with new heavy quarks and to extract the top-quark width within these scenarios.
- Can also be applied to single top-quark measurements at the LHC.

H. Lacker, A. Menzel, F. Spettel (CKMfitter group), D. Hirschbühl, J. Lück, F. Maltoni, W. Wagner, M. Zaro, (2012) arXiv:1202.4694 [hep-ph].

* V. M. Abazov et al. (D0 collaboration), arXiv:1106.5436 [hep-ex], Phys.Rev.Lett. 107,121802 (2011).

CONCLUSIONS

- First study of its kind show that a direct measurement of |Vts| in top quark decays is feasible at the LHC.
- The simulations presented here for 14 TeV correspond to an integrated luminosity of 10 fb^{-1}.
- TMVA results in 5% efficiency for s-tagging with 10^3 b-jet rejection.
- Oversimplified exercise for an integrated luminosity of 10 fb^{-1} at $\sqrt{s}$ = 14 TeV taking $\sigma(t\bar{t})$ ~ 1nb:
  - ✓ Expected significance S ~6 σ.
- Similar exercise for single top
  - ✓ Expected significance S ~3 σ.
- Few alternative methods to measure directly |Vtq| matrix elements exist.
- Our method can complement these methods or directly be combined with them.

FUTURE PLANS

- **Future plans:**

Need to do a more realistic analysis with full detector ATLAS/ CMS simulation events.

- **Aim:**

Short and medium term: set limits

Longer term: do a measurement

ADDITIONAL SLIDES

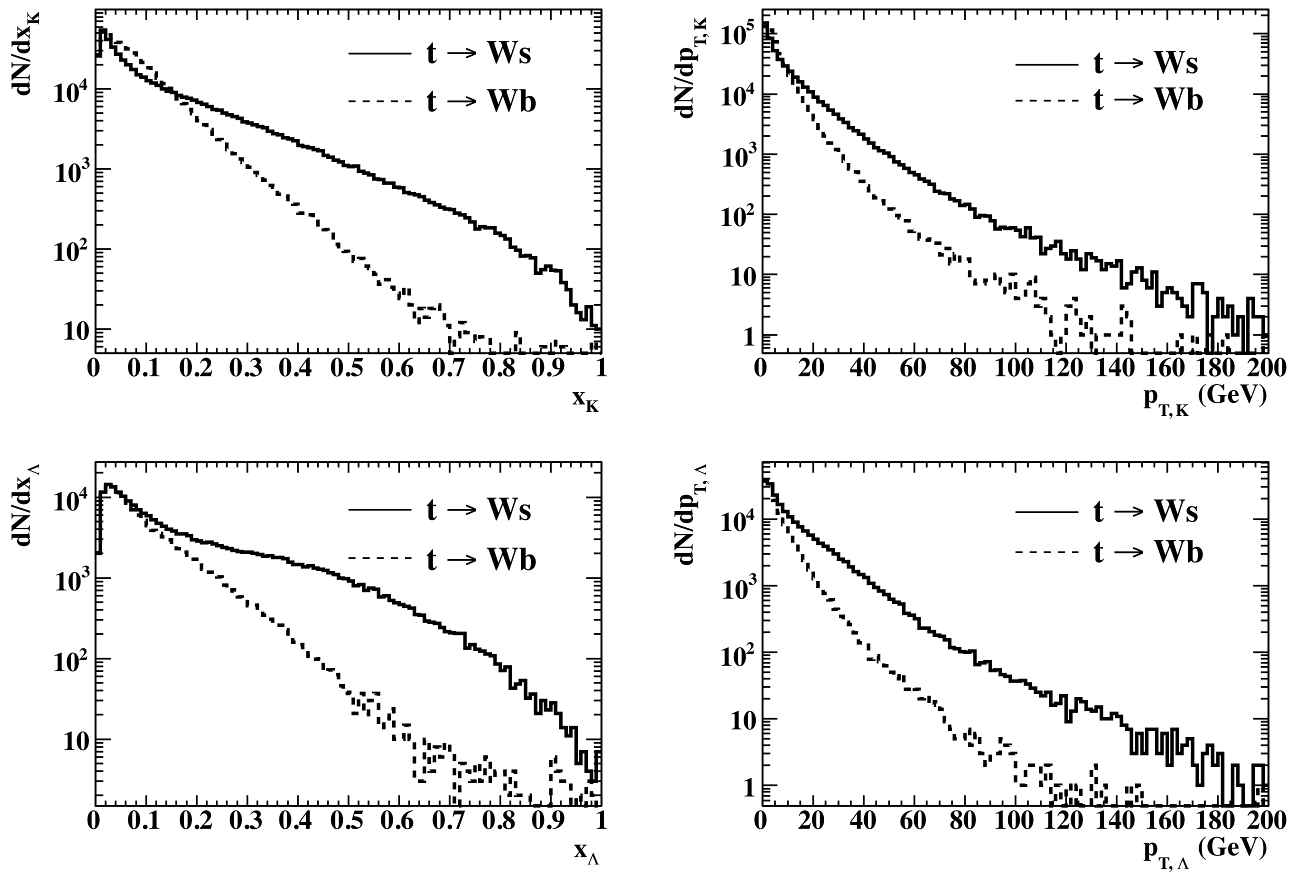
$$V_{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} .$$

In the Wolfenstein Parametrisation, this matrix is expressed as

$$V_{\mathrm{CKM}} \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda(1+iA^2\lambda^4\eta) & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2\left(1+i\lambda^2\eta\right) & 1 \end{pmatrix}$$

where A, λ, ρ and η are the Wolfenstein parameters.
In the SM $|V_{ts}| = 0.041 \pm 0.001$

Single top(anti-top) analysis, LHC @14 TeV (1)

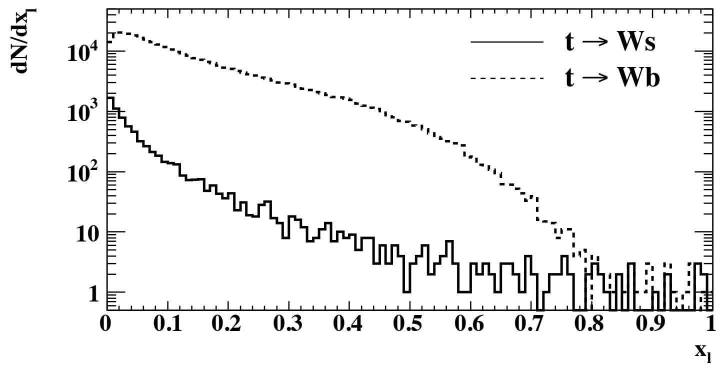


<= K^0s

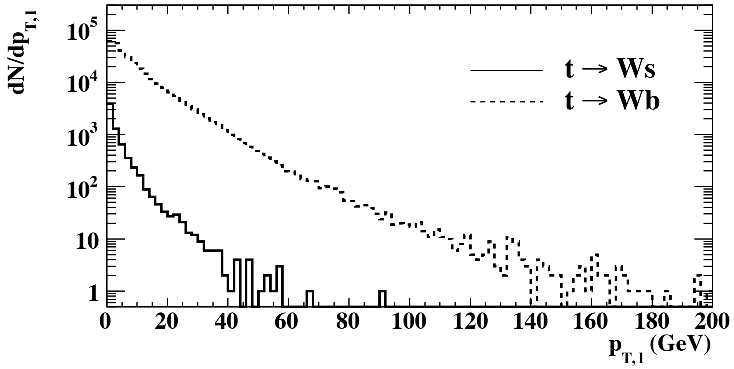
<= Λs

Upper left frame: scaled K^0 energy distributions dN/dx_K from t → W s(→ K^0X) (solid histogram) and t → W b → K^0 X (dashed histogram).
Upper right frame: Transverse momentum distributions of the K^0s measured w.r.t. beam axis dN/dp_{TK} (in GeV).
Lower frames: show the distributions dN/dx_Λ and $dN/dp_{T\Lambda}$ (in GeV) for t → W s → Λ X (solid histogram) and t → W b(→ Λ X) (dashed histogram).

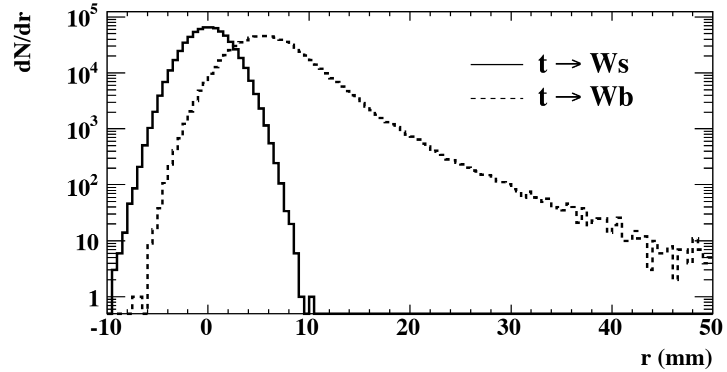
Single top (anti-top) analysis, LHC @14 TeV (2)



Upper frame: scaled $l^{(\pm)}$ energy distributions, dN/dx_l, from $t \rightarrow W\ s \rightarrow l^{\pm}X$ (solid histogram) and $t \rightarrow W\ b \rightarrow l(\pm)X$ (dashed histogram).



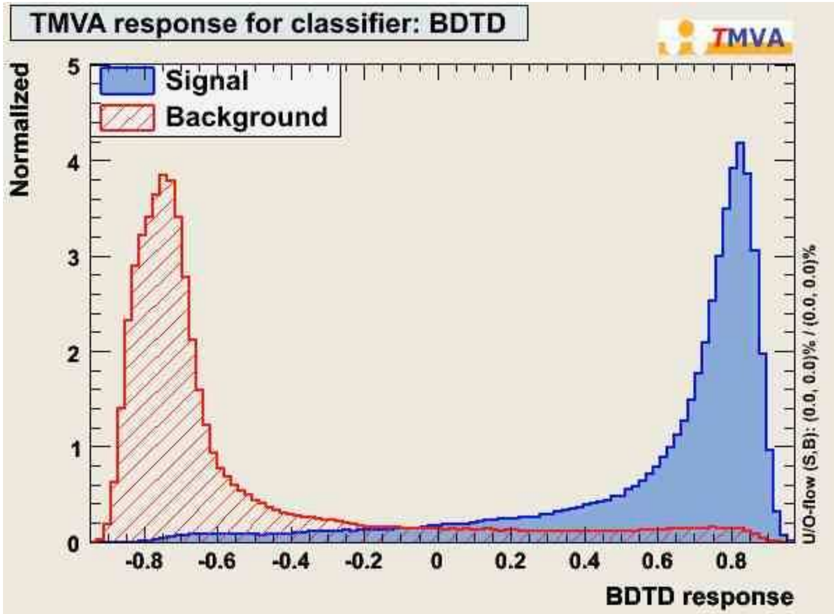
Middle frame: Transverse momentum distributions of the $l^{\pm}$s measured w.r.t. beam axis, dN/dpT_l (in GeV)

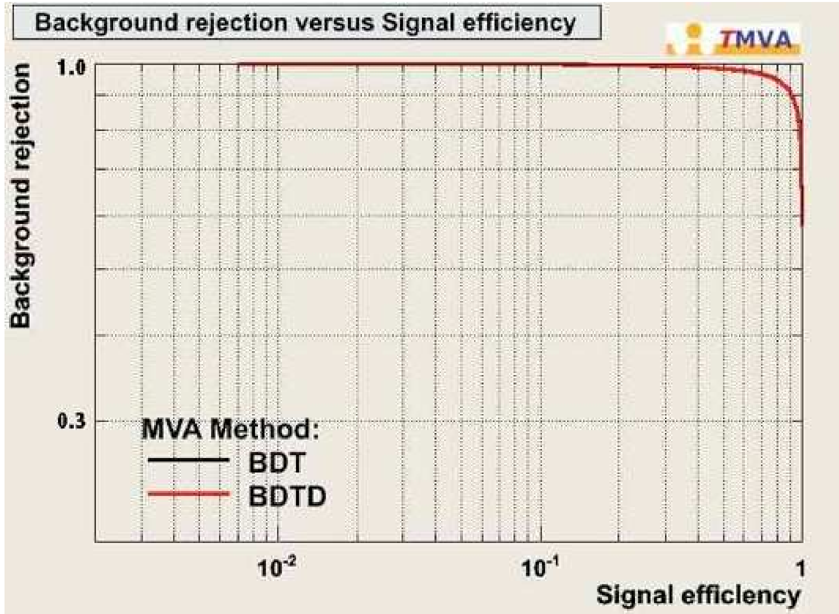


Lower frame: Secondary decay vertex distributions in the variable r (mm) for the two decay chains $t \rightarrow W\ s$ (solid histogram) and $t \rightarrow W\ b$ (dashed histogram), obtained by smearing the decay length with a Gaussian having an r.m.s. value of 2 mm.

EFFICIENCY VS BACKGROUND REJECTION FOR SINGLE TOP (ANTI-TOP)

We have trained a BDTD algorithm in the TMVA framework with the previous shown variables.





Left frame: The normalised BDTD response. The signal (blue shaded) from the decay $t \rightarrow W\,s$ and the background (red shaded) from the decay $t \rightarrow W\,b$ are clearly separated.
Right frame: Background rejection vs. signal efficiency calculated from the BDTD response.