Measurement of the t-channel single top-quark production cross section at $\sqrt{s}$ =13TeV with the ATLAS detector and interpretations of the measurement

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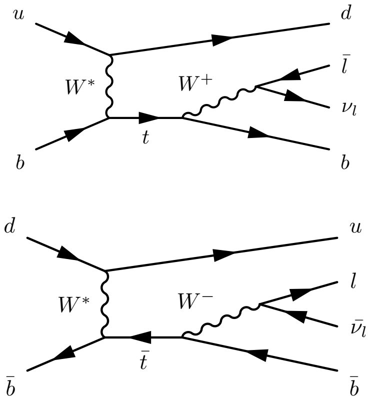
Measurement overview

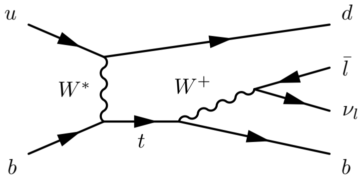
Measurement of the inclusive t-channel top and anti-top cross section and their ratio $R_t = \sigma_t/\sigma_{\bar{t}}$:

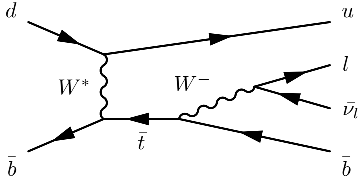
- Precision measurement of the largest single top-quark production channel using the full Run 2 ($140\,\text{fb}^{-1}$, $\sqrt{s}$ =13 TeV) dataset
- R_t sensitive to different PDF predictions
- Interpretations of the measurement:
  - Constrain impact of EFT operator $O^{3,1}_{Qq}$
  - Directly constrain CKM matrix elements $|V_{tx}|$
- Paper: JHEP 05 2024 305



Event selection

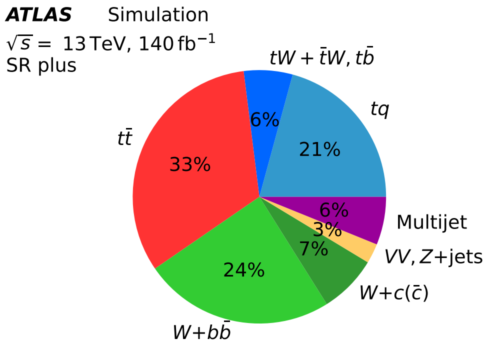
- exactly **one charged lepton** with $p_\mathrm{T}(\ell) > 28$ GeV
- exactly **two jets** with $p_\mathrm{T}(j) > 30$ GeV and $|\eta(j)| < 4.5$
- exactly **one b-tag** (60% WP, DL1r)
- $E_\mathrm{T}^{miss} > 30$ GeV
- $m_\mathrm{T}(W) > 50$ GeV
- $p_\mathrm{T}(\ell) > 40\ \mathrm{GeV} \cdot \frac{|\Delta\Phi(j_1,\ell)|}{\pi}$
- $M(\ell b) < 160$ GeV
- Two different signal regions **separated by lepton charge**





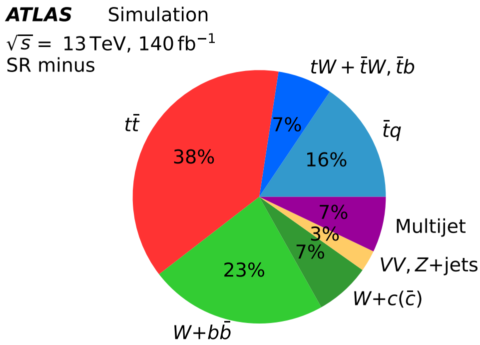
Signal region composition

ℓ^+ signal region



$S/B = 0.27$

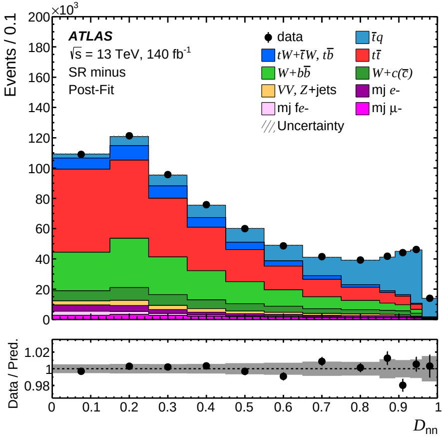
ℓ^- signal region



$S/B = 0.19$

Total cross-section analysis overview

- Neural Network (NN) is trained to separate signal and background events
- Feed-forward NN, trained on 17 variables
- Very good discriminating power
- Cross section determined via binned maximum likelihood fit to the NN output distribution



Total cross-section results

Results

	σ_t in [pb]	$\sigma_{\bar{t}}$ in [pb]	σ_{tch} in [pb]	R_t
Result	137^{+8}_{-8}	84^{+6}_{-5}	221^{+13}_{-13}	$1.636^{+0.036}_{-0.034}$
NNLO prediction (PDF4LHC21)	$134.2^{+2.6}_{-1.7}$	$80.0^{+1.8}_{-1.4}$	$214^{+4.1}_{-2.6}$	$1.677^{+0.010}_{-0.014}$

Relative uncertainties in %

	μ_t	$\mu_{\bar{t}}$	μ_{tch}	μ_{R_t}
Result	$+5.9$ -5.5	$+6.6$ -6.2	$+6.1$ -5.7	$+2.2$ -2.1
NNLO prediction (PDF4LHC21)	$+1.9$ -0.7	$+2.3$ -1.8	$+1.9$ -0.9	$+0.6$ -0.8

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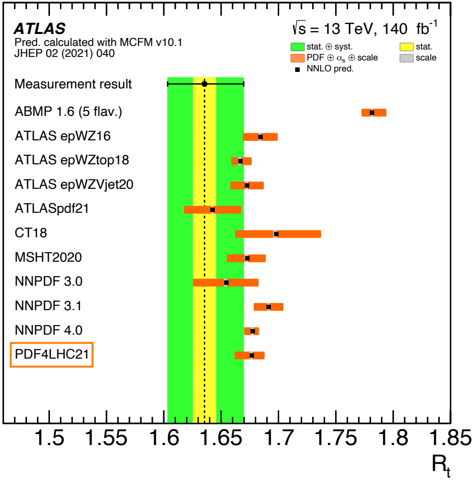
Prediction calculated with MCFM v10.1 JHEP 02 (2021) 040



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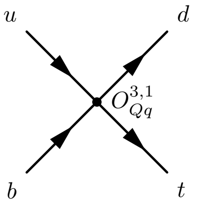
EFT interpretation overview

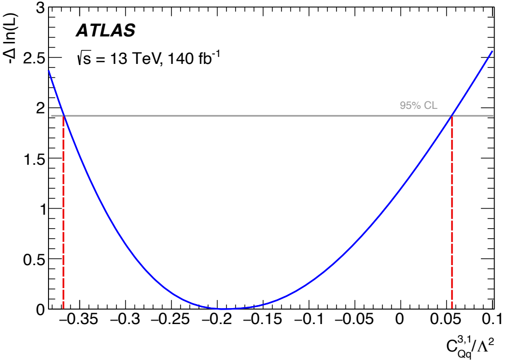
- EFT parameterizes new physics contribution at energy scale Λ via new dimension-6 operators in the Lagrangian: $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i + h.c.$
- Study the four-fermion operator $O_{Qq}^{3,1}$
- $O_{Qq}^{3,1}$ affects the top-quark production angle

  $\Rightarrow$ Fiducial acceptance A of t-channel events changes with $\frac{C_{Qq}^{3,1}}{\Lambda^2}$
- **Quadratic dependence** of $A \cdot \sigma$ on $\frac{C_{Qq}^{3,1}}{\Lambda^2}$ (arXiv:1909.13632)



Stragtegy and result

- Produced dedicated signal MC samples for different values of $\frac{C_{Qq}^{3,1}}{\Lambda^2}$
- Parameterize expected relative change of event yield as a function of $\frac{C_{Qq}^{3,1}}{\Lambda^2}$
- Use the parameterisation to perform a profile likelihood fit with $\frac{C_{Qq}^{3,1}}{\Lambda^2}$ as parameter of interest
- Extract 95% CL from a likelihood scan



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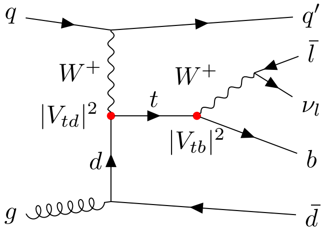
Obtained 95% confidence interval: $-0.37 < \frac{C_{Qq}^{3,1}}{\Lambda^2} < 0.06$

CKM interpretation

- Goal: Measurement of CKM matrix elements V_{tb}, V_{td}, V_{ts}
- Directly accessible in top-quark production and decay
- Dedicated MC samples for t-channel and $t\bar{t}$ used
- $t\bar{t}$ treated as signal
- Number of expected signal events:

$$N_{\mathrm{sig}} = \sum_{i=1}^{3}\sum_{j=1}^{3} N_{\mathrm{sig},ij}, \text{ with } N_{\mathrm{sig},ij} = \mathcal{L} \cdot \underbrace{\sigma_i^t |V_{ti}|^2}_{\text{prod.}} \cdot \underbrace{\mathcal{B}(t \to jW)}_{\text{decay}}$$

  with production cross-section $\sigma_i^t = \sigma^t(V_{ti} = 1)$,
  Flavour indices $i, j = b, d, s$
- Limits on CKM matrix elements set via 2D likelihood scans



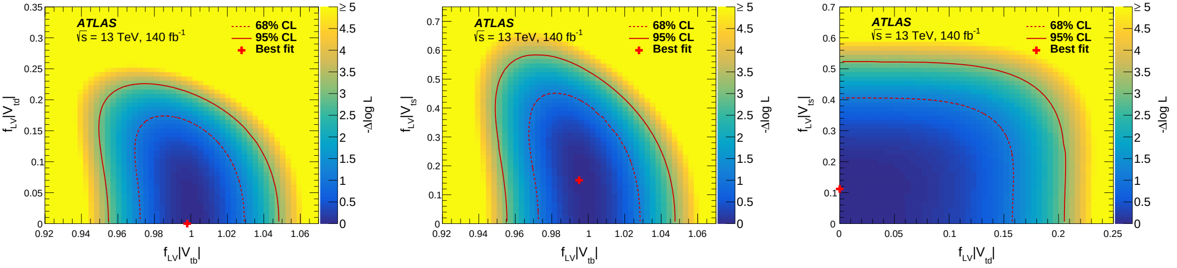
2D Fit Results

3 different scan scenarios:

$$\text{Scenario 1} \ |V_{tb}| \neq 0, \ |V_{td}| \neq 0 \text{ and } |V_{ts}| = 0 \text{ fixed}$$

$$\text{Scenario 3} \ |V_{tb}| \neq 0, \ |V_{ts}| \neq 0 \text{ and } |V_{td}| = 0 \text{ fixed}$$

$$\text{Scenario 2} \ |V_{td}| \neq 0, \ |V_{ts}| \neq 0 \text{ and } f_{LV}|V_{tb}| = 1 \text{ fixed}$$



Conclusion

- Measured the t-channel single top-quark production cross section at $\sqrt{s}$ =13TeV, with signal modeling uncertainties as leading uncertainties
- Set constrains on EFT parameter $\frac{C_{Qq}^{3,1}}{\Lambda^2}$ as an interpretation of the measurement, obtained confidence interval: [-0.37, 0.06]
- Set constrains on CKM matrix elements V_{tb}, V_{td}, V_{ts} via 2D-likelihood scans

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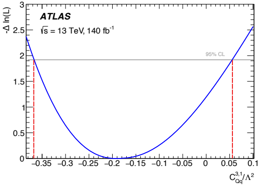
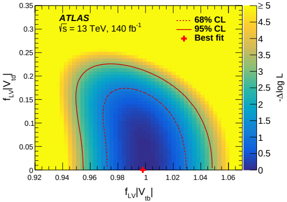
σ_t in [pb]	$\sigma_{\bar{t}}$ in [pb]	σ_{tch} in [pb]	R_t
137^{+8}_{-8}	84^{+6}_{-5}	221^{+13}_{-13}	$1.636^{+0.036}_{-0.034}$





Backup

List of NN variables

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No.	Symbol	Description
1.	$m(jb)$	Invariant mass of the untagged jet (j) and the b-tagged jet (b)
2.	$\|\eta(j)\|$	Absolute value of the pseudorapidity of the untagged jet
3.	$\|\Delta p_{\mathrm{T}}(W, jb)\|$	Absolute value of the difference in transverse momentum between the reconstructed W boson and the jet pair
4.	$\|\Delta\phi(W, jb)\|$	Absolute value of the difference in azimuthal angle between the reconstructed W boson and the jet pair
5.	$m(t)$	Invariant mass of the reconstructed top quark
6.	$\|\Delta\eta(\ell, j)\|$	Absolute value of the difference in pseudorapidity between the charged lepton (ℓ) and the untagged jet
7.	$\Delta R(\ell, j)$	Angular distance of the charged lepton and the untagged jet
8.	$\|\Delta\eta(b, \ell)\|$	Absolute value of the difference in pseudorapidity between the b-tagged jet and the charged lepton
9.	$m_{\mathrm{T}}(W)$	Transverse mass of the W boson
10.	$m(\ell b)$	Invariant mass of the charged lepton and the b-tagged jet
11.	$H_{\mathrm{T}}(\ell, \text{jets}, E_{\mathrm{T}}^{\mathrm{miss}})$	Scalar sum of the transverse momenta of the charged lepton and the jets and $E_{\mathrm{T}}^{\mathrm{miss}}$
12.	$\|\Delta\eta(b, j)\|$	Absolute value of the difference in the pseudorapidity of the two jets
13.	$\|\Delta\phi(j, t)\|$	Absolute value of the difference in the azimuthal angle between the untagged jet and the reconstructed top quark
14.	$\cos\theta^{*}(\ell, j)$	Cosine of the angle θ^{*} between the charged lepton and the untagged jet in the rest frame of the reconstructed top quark
15.	$\|\eta(\ell)\|$	Absolute value of the pseudorapidity of the charged lepton
16.	S	Sphericity defined as the sum of the 2nd and 3rd largest eigenvalues of the sphericity tensor multiplied by $3/2$
17.	$\|\Delta p_{\mathrm{T}}(\ell, j)\|$	Absolute value of the difference in transverse momentum of the charged lepton and the untagged jet

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Post-fit event yields

ATLAS

Process	SR plus	SR minus
tq	169 000 ± 6000	150 ± 150
$\bar{t}q$	90 ± 90	109 000 ± 4000
$tW + \bar{t}W, t\bar{b} + \bar{t}b$	51 000 ± 4000	49 000 ± 4000
$t\bar{t}$	265 000 ± 14 000	265 000 ± 14 000
W+$b\bar{b}$	198 000 ± 21 000	159 000 ± 17 000
W+$c(\bar{c})$	60 000 ± 13 000	49 000 ± 11 000
Z+jets, diboson	21 000 ± 4000	19 000 ± 4000
Multijet	50 000 ± 10 000	50 000 ± 10 000
Total	814 000 ± 2100	698 800 ± 2000
Observed	814 185	698 845

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Impact of systematic uncertainties

ATLAS

Uncertainty group	$\Delta\sigma(tq)/\sigma(tq)$	$\Delta\sigma(\bar{t}q)/\sigma(\bar{t}q)$	$\Delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)$	$\Delta R_t/R_t$
Data statistics	+0.4 / −0.4	+0.5 / −0.5	+0.3 / −0.3	+0.6 / −0.6
Signal modelling	+4.9 / −4.5	+5.2 / −4.8	+5.0 / −4.6	+0.9 / −0.9
Background modelling	+1.8 / −1.6	+2.1 / −1.9	+1.8 / −1.6	+1.5 / −1.4
MC statistics	+1.0 / −1.0	+1.4 / −1.3	+1.1 / −1.0	+0.8 / −0.8
PDFs	+0.4 / −0.4	+1.2 / −1.0	+0.6 / −0.6	+0.9 / −0.8
Jets	+2.2 / −2.0	+3.0 / −2.7	+2.5 / −2.2	+1.0 / −0.9
b-tagging	+1.6 / −1.5	+1.7 / −1.5	+1.6 / −1.5	+0.2 / −0.1
Leptons	+1.1 / −1.0	+1.1 / −1.0	+1.1 / −1.0	+0.1 / −0.1
Luminosity	+0.9 / −0.8	+0.9 / −0.9	+0.9 / −0.8	< 0.1
Total	+5.9 / −5.5	+6.6 / −6.2	+6.1 / −5.7	+2.2 / −2.1

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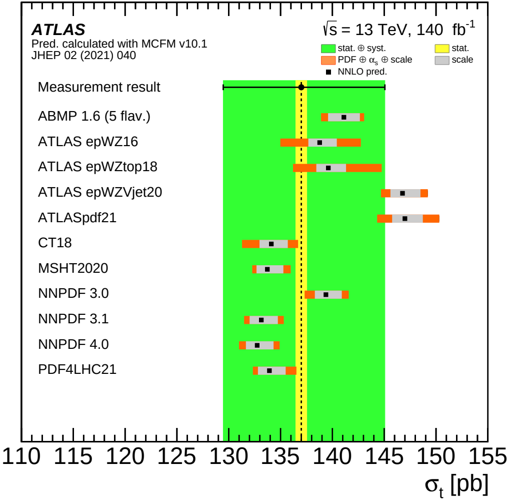
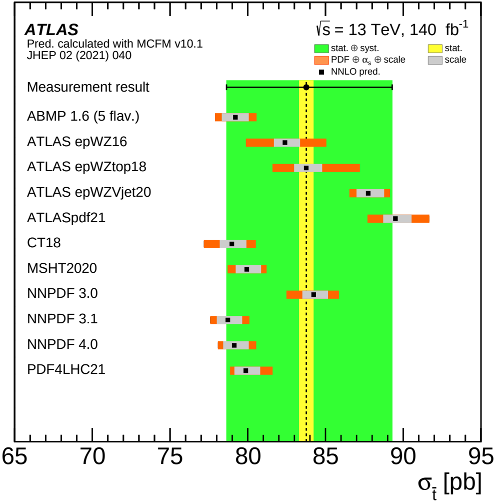
Comparison with PDF sets





EFT interpreation: Strategy

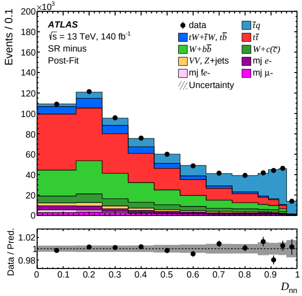
- $A \cdot \sigma$ depends on $\frac{C_{Qq}^{3,1}}{\Lambda^2}$ (arXiv:1909.13632):

  $A \cdot \sigma = A^{\mathrm{SM}}\sigma^{\mathrm{SM}} + A^{\mathrm{Interf}}\sigma^{\mathrm{Interf}}\frac{C_{Qq}^{3,1}}{\Lambda^2} + A^{\mathrm{BSM}}\sigma^{\mathrm{BSM}}\frac{(C_{Qq}^{3,1})^2}{\Lambda^4}$

  ⇒ $\mathrm{Yield_{total}}$ of the EFT samples can be written as:

  $\mathrm{Yield_{total}} = \mathrm{Yield_{SM}} + \mathrm{Yield_{Interf}} + \mathrm{Yield_{BSM}}$

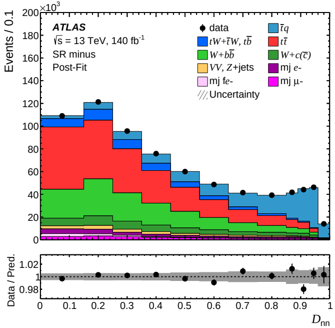
  with $\mathrm{Yield_{Interf}} \propto \frac{C_{Qq}^{3,1}}{\Lambda^2}$ and $\mathrm{Yield_{BSM}} \propto (\frac{C_{Qq}^{3,1}}{\Lambda^2})^2$



- Parameterize relative change of event yield as a function of $\frac{C_{Qq}^{3,1}}{\Lambda^2}$
  - Apply the NN of the main analysis to the EFT samples to create D_{nn} distributions
  - For each bin i of the D_{nn} distributions:
    - Get event yield in bin i for each $\frac{C_{Qq}^{3,1}}{\Lambda^2}$ value
    - Fit quadratic function $f_i(\frac{C_{Qq}^{3,1}}{\Lambda^2}) = p_{\mathrm{SM},i} + p_{\mathrm{Interf},i} \cdot \frac{C_{Qq}^{3,1}}{\Lambda^2} + p_{\mathrm{BSM},i} \cdot (\frac{C_{Qq}^{3,1}}{\Lambda^2})^2$
  - Normalize $f_i(\frac{C_{Qq}^{3,1}}{\Lambda^2})$ to $p_{\mathrm{SM},i}$

EFT interpreation: Profile likelihood fit

- TRExFitter fit setup:
  - Split nominal t-channel MC samples in 12 seperate samples (one per NNout bin)
  - Use respective normalized $\mathrm{f_i}(C_{Qq}^{3,1})$ as NormFactor
    $\Rightarrow \frac{C_{Qq}^{3,1}}{\Lambda^2}$ is not fitted directly, only via the quadratic expressions
  - General fit setup from the main analysis is used (definition of signal regions, systematic uncertainties . . .)
  - Single-top and single-antitop processes are scaled to theory prediction of respective cross section, the theory uncertainties are applied as systematic uncertainties



Literature $\frac{C_{Qq}^{3,1}}{\Lambda^2}$

- Results for $\frac{C_{Qq}^{3,1}}{\Lambda^2}$ obtained in published analyses
  1. Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC (arXiv:2105.00006)
  2. Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory (arXiv:2012.02779)
  3. O new physics, where art thou? A global search in the top sector (arXiv:1910.03606)
  4. Our result

Source	95% CL linear fit		95% CL quadratic fit	
	Individual	Marginalized	Individual	Marginalized
1.	[-0.099, 0.155]	[-0.163, 0.296]	[-0.088, 0.166]	[-0.167, 0.197]
2.	[-0.043, 0.16]	[-0.071, 0.17]	-	-
3.	-	-	[-0.25, 0.05]	[-0.39, 0.11]
4.	-	-	[-0.37,0.06]	-

CKM Branching ratios

Branching ratios can be written as:

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

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

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

CKM signal events

Full parametrisation of the signal events:

$$N_{\text{t-chan}} = \mathcal{L} \cdot R \left[\underbrace{\mu_b \cdot \sigma_b}_{\text{VtbVtb}} + \underbrace{\mu_d \cdot \sigma_d}_{\text{VtdVtb}} + \underbrace{\mu_s \cdot \sigma_s}_{\text{VtsVtb}} + \underbrace{\left(\frac{1 - R - R_d}{R}\right) \cdot \mu_b \cdot \sigma_b}_{\text{VtbVts}} + \underbrace{\left(\frac{1 - R - R_s}{R}\right) \cdot \mu_b \cdot \sigma_b}_{\text{VtbVtd}} \right.$$

$$+ \underbrace{\left(\frac{1 - R - R_s}{R}\right) \cdot \mu_d \cdot \sigma_d}_{\text{VtdVtd}} + \underbrace{\left(\frac{1 - R - R_s}{R}\right) \cdot \mu_s \cdot \sigma_s}_{\text{VtsVtd}} + \underbrace{\left(\frac{1 - R - R_d}{R}\right) \cdot \mu_s \cdot \sigma_s}_{\text{VtsVts}}$$

$$\left. + \underbrace{\left(\frac{1 - R - R_d}{R}\right) \cdot \mu_d \cdot \sigma_d}_{\text{VtdVts}} \right],$$