Single-Top Production in ATLAS
– Reconstruction by Kinematic Fitting –

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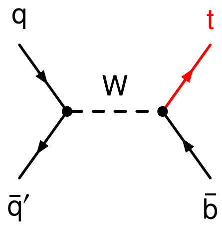
GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Contents

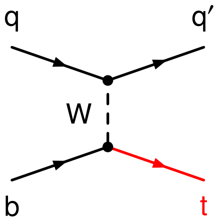
Single-Top Production: 3 Channels

s-Channel

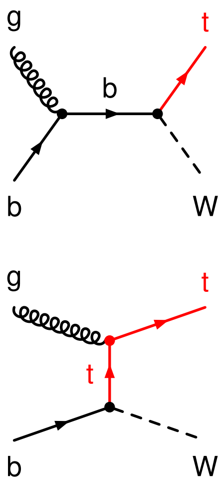


t-Channel

dominant at LHC



Wt-Channel



$q \in \{u, d, c, s\}$

Time t ⟶

Electro-weak production
(in contrast to $t\bar{t}$ production
by strong interaction)

Motivation: Why Single-Top?

Probe **electro-weak interaction** of top-quark:

- $\sigma_{\text{single-top}} \sim |V_{tb}|^2$

  $\Rightarrow$ Direct measurement of CKM-matrix element $|V_{tb}|$

  $\rightarrow$ **More than 3** quark generations?
  CKM-matrix **unitary**?

- $\tau_t \ll \tau_{\text{had}}$

  $\Rightarrow$ Spin information preserved in decay products

  $\rightarrow$ Measure W-helicities!

  $\rightarrow$ Combination with $\sigma_{\text{single-top}}$ allows for determination of **anomalous couplings** at Wtb -vertex

  $\Rightarrow$ Distinction of different models
  of electro-weak symmetry breaking

- Top is **heaviest quark**, strongest coupling to Higgs

  $\Rightarrow$ Possible **modification** of $\sigma_{\text{single-top}}$ by processes beyond the SM (new particles, FCNC)

Expected Backgrounds and Systematics

Background processes

- **$t\bar{t}$ - production** $\left(\sigma_{t\bar{t}} \approx 3 \cdot \sigma^{\text{t-chan}}_{\text{single-top}}\right)$ similar if
  - in semi-leptonic channel ($t\bar{t} \rightarrow \ell\, \nu\, b\, jj\, b$),
  - in dilepton. channel (one lepton Mis-ID) ($t\bar{t} \rightarrow \ell\, \nu\, b\, \ell\, \nu\, b$),
  - if at least one W decays to τ
- **W + jets** $\left(\sigma_{W+\text{jets}} \approx 300 \cdot \sigma^{\text{t-chan}}_{\text{single-top}}\right)$ similar if
  - in leptonic mode: $W \rightarrow \ell\, \nu_\ell$ (Mis-ID due to wrong B-tag)
- **QCD** $\left(\sigma_{\text{QCD}} \gg \sigma^{\text{t-chan}}_{\text{single-top}}\right)$ similar if
  - multi-jet processes (Mis-ID due to lepton fakes)

Systematics $\Delta\sigma/\sigma$ (Statistics $\approx$ 19 %)

(cut-based ATLAS CSC pre-study at 10 TeV)

- **b-tagging** (30 %)
- **Luminosity** (12 %), **jet-energy scale** (16 %)
- **Background-norm.** (19 - 29 %), **PDFs** (18 %)

Why Kinematic Fitting?

Single-top signal is buried under heaps of background!

Advantages of kinematic fitting:

- Simple and robust method
- Transparent – not a black box!
- Little dependence on shapes of MC distributions
- Relaxed event selection possible

➔ Higher acceptance

  - No upper limit on number of jets
  - Loosened b-tag weight cuts (large systematics!)
  - Loosened p_t requirements for jets and leptons

Kinematic Fitter – Description

Use **KinFitter** package

developed by Sundermann and Goepfert (TU Dresden)

- Basic idea:

  Minimize $\chi^2 = (\vec{\xi} - \vec{x})^T C_x^{-1} (\vec{\xi} - \vec{x})$

  while fulfilling constraints $\vec{f}(\vec{\alpha}, \vec{\xi}) = 0$

  x : measurement,
  ξ : estimate,
  α : unmeasured parameter,
  $\vec{f}$: constraints (momentum conservation, inv. mass, ...)
  C_x^{-1}: covariance matrix of measurements

- Linearize $\vec{f}(\vec{\alpha}, \vec{\xi})$ and build Lagrange function

  $\mathcal{L} = \chi^2 + 2\,\vec{\lambda}^T \cdot \vec{f}$ ($\vec{\lambda}$: Lagrange multipliers)

- Numerical minimization of χ^2 obeying given constraints

Applying KinFitter to Single-Top

Input to KinFitter for single-top reconstruction:

- 4-vectors of leptons (e/μ), jets and $\not{E}_T$
- Covariance matrices of tracks, jets and $\not{E}_T$

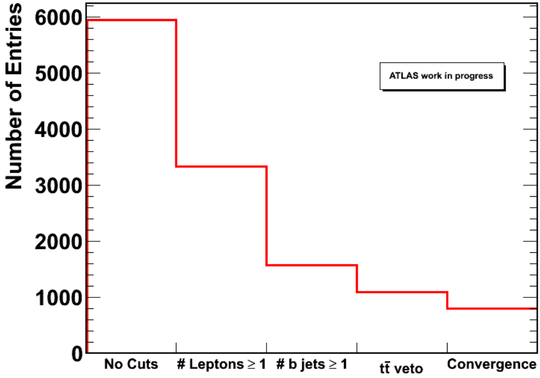
In each event the kinematic fit

- tests every possible combination of a b-jet, a lepton and $\not{E}_T$ assuming the top-quark hypothesis, i.e. respecting the mass constraints for m_W, m_{top}
- assigns a χ^2 value to each outcome
- keeps the best combination (lowest χ^2) as the top quark candidate

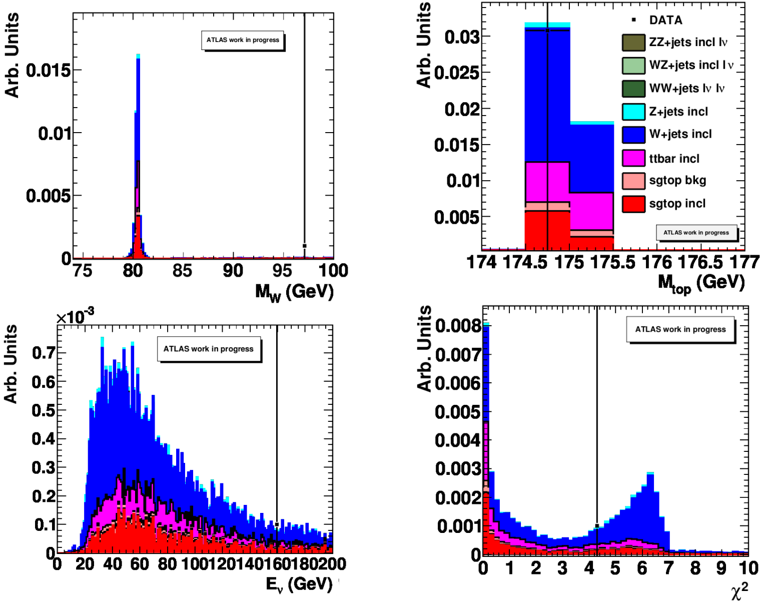
Results of Kinematic Fitting – Event Selection

- **Aim**: Reconstruction of *t*-channel and semi-leptonic Wt-channel single-top production for $W \to e\,\nu_e\,/\mu\nu_\mu$
- **Here:** Restriction to t-channel
- **Event selection:** At least 2 jets, 1 b-tagged | p_T (e/μ, jet) $\geq$ 10 GeV

Cut-flow of t-channel finder ($W \to e\,\nu_e$, 7 TeV MC)

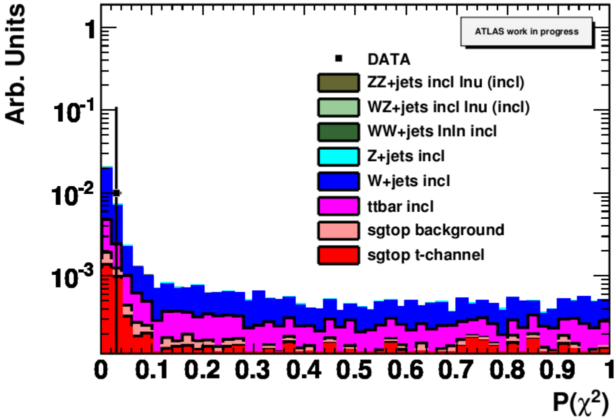


Sig and Bkg (1) (area normalized, no QCD yet)



Sig and Bkg (2) (area normalized, no QCD yet)

$P(\chi^2)$ for L1_Calo DATA (Run 155112 with $\mathcal{L} = 3260\,\mu b^{-1}$) and MC (sig + bkg)



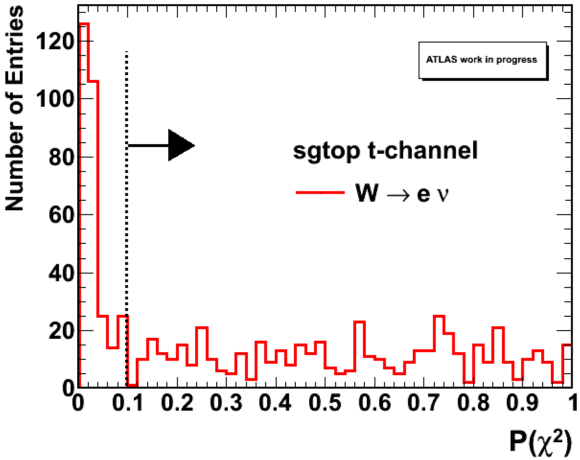
- $P(\chi^2)$ reasonably flat for all samples
- **S/B ratio** for $P(\chi^2) \geq 10$ acceptable ($\approx$ **1/3**)

Single-top reconstruction by kinematic fitting works!

Results of Kinematic Fitting – Finder Performance

- Require $P(\chi^2)$ to be reasonably flat, i.e. $P(\chi^2) \geq 10\%$

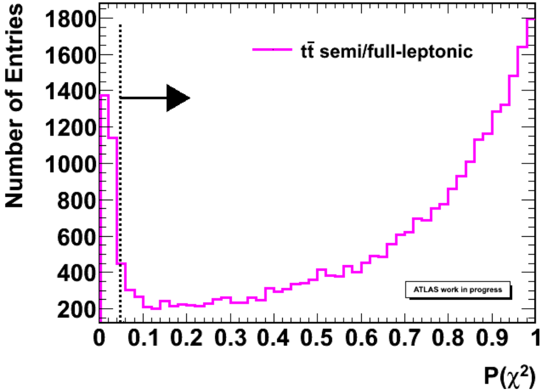
  $\Rightarrow$ Efficiency of t-ch. finder ($W \rightarrow e\nu_e / \mu\nu_\mu$): $\epsilon_{\text{t-ch}} = 11\%$



Results of Kinematic Fitting – $t\bar{t}$-Veto

- **Veto** semi-leptonic $t\bar{t}$ by excluding events with an additional hadronically decaying W which is successfully reconstructed for $P(\chi^2) \geq 5\%$

$P(\chi^2)$ for reconstruction of hadronic W



- $P(\chi^2)$ distribution not flat $\Rightarrow$ jet cov. matrices flawed
- Jet cov. matrices preliminary so far, detailed determination ongoing

Conclusion

- Measurement of single-top **t-channel** cross-section offers possibility to measure anomalous couplings at Wtb -vertex
- First kinematic fit of t-channel and bkg MC-events **works fine**
- Kinematic fit allows for relaxed event selection
- t-channel finder efficiency $\approx 11\%$ and $\frac{S}{B} \approx \frac{1}{3}$ with current $t\bar{t}$-veto
- Efficiency calculation (truth matching) is currently being improved

Outlook

- Extension of t-channel finder with kinematic fit to explicitly exploit **t-channel** properties
- (p_T,η)-map of **jet** / p_T-map of $\not{E}_\mathbf{T}$ **covariance matrices**
- Further improvement of $t\bar{t}$-veto
- Set-up of analogous finder for single-top Wt-production

Waiting for sufficient statistics in data to be able to

- Measure differential t-channel cross-sections

$$\frac{d\sigma_{\text{t-chan}}}{d\theta} \quad \text{and} \quad \frac{d\sigma_{\text{t-chan}}}{dp_\mathrm{T}}$$

- Search for anomalous couplings with the help of PROTOS or MadGraph generators

General Case of Least Squares

- Determination of n measurable values η_i, $i = 1, 2, ..., n$ and r unmeasured parameters x_i, $i = 1, 2, ..., r$
- $\vec{\eta} = \vec{y} + \vec{\epsilon}$, $\vec{y}$: measured values, C_y: covariance matrix
- m constraints (non-linear in general):

$$f_k(x,\eta) = 0, \quad k = 1, 2, ..., m$$

- 1^{st} order expansion of f_k about (x_0, η_0), $\eta_0 = y$:

$$\vec{f}(x,\eta) = \underbrace{\vec{f}(x_0,\eta_0)}_{:=\vec{c}} + (\underbrace{\vec{x} - \vec{x}_0}_{:=\vec{\xi}}) \cdot A + (\underbrace{\vec{\eta} - \vec{\eta}_0}_{:=\vec{\delta}}) \cdot B$$

$$\text{with} \quad A_{ij} = \frac{\partial f_i}{\partial x_j}(x_0,\eta_0), \quad B_{ij} = \frac{\partial f_i}{\partial \eta_j}(x_0,\eta_0).$$

Minimum Function with Constraints

- Constraints: $A\vec{\xi} + B\vec{\delta} + \vec{c} = 0$
- Minimum function: S=$\vec{\delta}^T C_y^{-1} \vec{\delta}$
- To minimize S while respecting constraints, build Lagrange function with multipliers $\vec{\mu}$:

$$L = \vec{\delta}^T C_y^{-1} \vec{\delta} + 2\vec{\mu}^T (A\vec{\xi} + B\vec{\delta} + \vec{c})$$

- For given parameters $\vec{x}$: $\nabla_\delta L = 0$ & $\nabla_\mu L = 0$
  $\Rightarrow$ Minimum of S while following constraints
- $\Sigma : \mathbb{R}^r \to \mathbb{R}$,
  $\vec{\xi} \mapsto \Sigma(\vec{\xi})$ = Minimum of S following the constraints $\vec{f} = 0$
  1. find analytical expression of $\Sigma(\vec{\xi})$
  2. minimize Σ

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Iteration procedure (1)

- Step 1:
  - $\nabla_\delta L = 0$ & $\nabla_\mu L = 0 \;\Rightarrow\; \vec{\delta} = \vec{\delta}(\vec{\xi})$
  - $\Sigma(\vec{\xi}) = \vec{\delta}(\vec{\xi})^T C_y^{-1} \vec{\delta}(\vec{\xi})$
- Step 2:
  - $\nabla_\xi \Sigma = 0 \Rightarrow$ optimal values $\tilde{\xi}$
- Go back to the Lagrange function: $\tilde{\delta} = \vec{\delta}(\tilde{\xi}),\ \tilde{\mu} = \vec{\mu}(\tilde{\xi})$
- Solution:

$$
\begin{aligned}
\tilde{\xi} &= -(A^T G_B A)^{-1} A^T G_B \vec{c},\\
\tilde{\delta} &= -C_y B^T G_B (1 - A(A^T G_B A)^{-1} A^T G_B)\vec{c},\\
\tilde{\mu} &= G_B (1 - A(A^T G_B A)^{-1} A^T G_B)\vec{c},
\end{aligned}
$$

$$G_B = (B C_y B^T)^{-1}.$$

Iteration procedure (2)

$\Rightarrow$ Improved parameters $\vec{x}$ and measurements $\vec{\eta}$:

$$\vec{x} = \vec{x}_0 + \tilde{\xi}, \vec{\eta} = \vec{\eta}_0 + \tilde{\delta}.$$

- Computation of covariance matrices via propagation of errors law [1] (assumption of linearity!) and $\partial c_i / \partial y_j = \partial f_i / \partial y_j (x_0, y) = B_{ij}$:

$$C_x = (A^T G_B A)^{-1},$$

$$C_\eta = C_y - C_y B^T G_B B C_y + C_y B^T G_B A (A^T G_B A)^{-1} A^T G_B B C_y.$$

- Repeat algorithm until divergence or convergence, take improved values as new starting point
- Evaluation by minimum function S and constraints
  1. Sum of constraints $\sum_{k=1}^{m} | f_k | < \epsilon_c$,
  2. Change of S small, significance can be tested: assuming gaussian errors and sufficient linearity of constraints S follows a χ^2 distribution of $m - r$ degrees of freedom

[1] $\vec{y} = T\vec{x} + \vec{b} \Rightarrow C_y = T C_x T^T$