Constrains on the top quark width from cross section and branching ratio measurements using EFTfitter

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- The Standard Model
- Top quark measurements at LHC
- Inference of model parameters in Bayesian analysis
- Implementation of Bayesian analysis in EFTfitter
- Combination of measurements with the BLUE method and the EFTfitter
- Constraining the top quark width using EFTfitter
- Conclusion and Outlook

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The Standard Model

Fermions (Spin 1/2)		Bosons	
Leptons	$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$	Vector bosons (spin 1)	$\mathrm{W}^{\pm}\ \mathrm{Z}^{0}\ \gamma\ \mathrm{g}$
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	Scalar bosons (spin 0)	H

- Vector bosons as mediators of fundamental forces
- Fermion mass increases per generation
- Gravitation is not included

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The Top Quark

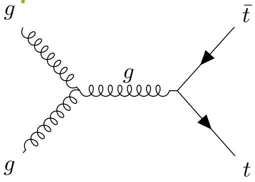

Figure: Example process for $t\bar{t}$ production at the LHC.

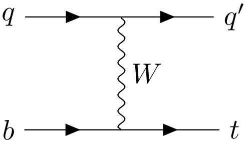

Figure: Example process for single top production at the LHC.

- Up-type quark of third generation
- Charge of $Q = 2/3\,\mathrm{e}$
- Lager mass then every other particle
- Decays before hadronization
- Can either be produced in pairs (strong interaction) or single (weak interaction)

Inference of model parameters

- A function $g(\vec{x}|\vec{\lambda}, M)$ describes physical quantity $\vec{x}$ with parameters $\vec{\lambda}$ in a model M
- Based on Bayes Theorem

$$P(\vec{\lambda}, M|\vec{D}) = \frac{P(\vec{D}|\vec{\lambda}, M)\, P(\vec{\lambda}, M)}{\int g(\vec{x} = \vec{D}|\vec{\lambda}, M) P_i(\vec{\lambda}, M) d\vec{\lambda}}\,.$$

- $P(\vec{\lambda}, M)$ prior probability distribution
- Distribution of single parameter $\vec{\lambda}_i$ with

$$P(\lambda_i|\vec{D}) = \int \prod_{i \neq j} P(\vec{\lambda}|\vec{D})\, d\lambda_j\,.$$

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The EFTfitter

- Based on BAT (Bayesian Analysis Toolkit) [1]
- Individual model implementation
- Generic tool for interpretation of measurements in context of EFT
- Combines measurements comparable to BLUE method

BAYESIAN ANALYSIS TOOLKIT

Combination of measurements

- Observables $\vec{y}$ = Parameters $\vec{\lambda}$
- N number of measurements, n number of observables, $\vec{D}_i$ single measurement
- U_{ik} unity if measurement matches with observable

$$-2\ln\left(P(\vec{D}|\vec{\lambda})\right) = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{N}\sum_{l=1}^{N}\left[D_i - U_{ik}\lambda_k\right] M_{ij}^{-1}\left[D_j - U_{jl}\lambda_l\right],$$

[1] Caldwell, Kollár, Kröninger 2009

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Combination of measurements

- BLUE = Best Linear Unbiassed Estimator Method (Lyons, Gibaut, Clifford 1988)
- Build linear combination of single measurements y_i
- Minimize variance by minimizing weighted sum S

$$\hat{y} = \sum_i \alpha_i y_i \qquad S = \sum_i \sum_j (y' - y_i) E_{ij}^{-1} (y' - y_j)$$

- E_{ij} = Error matrix, S follows χ^2 distribution

- In case of no correlation (E_{ij} is diagonal)

$$\hat{y} = \left(\sum_i \frac{y_i}{\sigma_i^2} \right) / \left(\sum_i \frac{1}{\sigma_i^2} \right) \qquad \frac{1}{\sigma^2} = \sum_i \frac{1}{\sigma_i^2}$$

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The example: Single top + W boson cross section

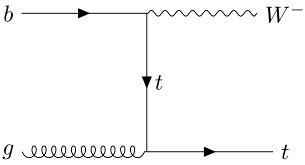

Figure: Example process for single top + W boson production.

- Example for BLUE for a combination of measurements
- Combination of measurements for the production of a top quark and a W boson in pp collisions at $\sqrt{s} = 8\,\text{TeV}$
- Features two measurements, one from ATLAS and one from CMS
- Combines roughly 20 uncertainties
- From ATLAS-CONF-2014-052

The measured cross sections

- ATLAS : $\sigma_{tW} = (27.20 \pm 6.35)\,\text{pb}$
- CMS : $\sigma_{tW} = (23.40 \pm 5.07)\,\text{pb}$
- First comparison only statistical uncertainties
- Tables with uncertainties (values in pb):

Category	ATLAS [pb]	CMS [pb]	Cor.
Data statistics	1.93	1.90	0
Simulation statistics	0.76	0.56	0
Luminosity	1.00	0.70	0.31
ISR/FSR	1.60	2.90	0.95
tW generator	3.00	0.00	0
$t\bar{t}$ generator	2.04	3.30	1
PDF	0.68	0.40	1
tW / $t\bar{t}$ overlap mod.	0.38	0.49	1
Top p_t reweighting	0.00	0.09	0
Background mod.	0.98	0.40	0

Category	ATLAS [pb]	CMS [pb]	Cor.
Z + jets backgound norm.	0.00	0.60	0
JES common	2.72	0.89	0
JES flavour	1.36	0.00	0
Jet identification	0.05	0.00	0
Jet resolution	0.19	0.21	0
Lepton modeling	0.65	0.42	0
MET scale	1.12	0.09	0
MET resolution	1.22	0.00	0
b-tagging	2.28	0.21	0.5
Pileup	0.00	0.09	0

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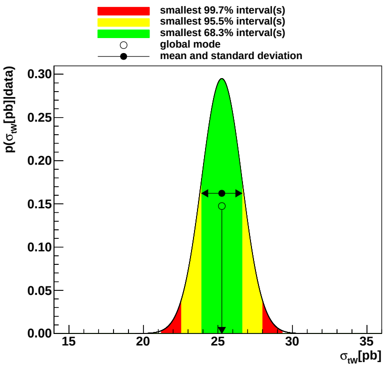

Figure: Combined measurement using EFTfitter. Corresponding value: $\sigma_{tW} = (25.26 \pm 1.35)\,\mathrm{pb}$

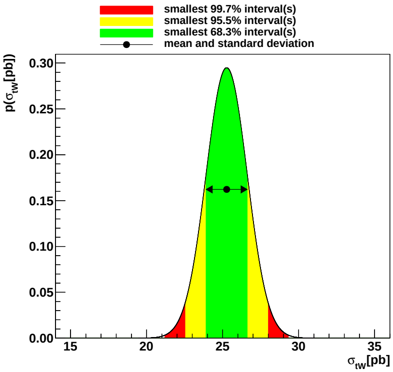

Figure: Combined measurement using BLUE. Corresponding value: $\sigma_{tW} = (25.26 \pm 1.35)\,\mathrm{pb}$

- No correlation between statistical uncertainties
- Same result for both methods

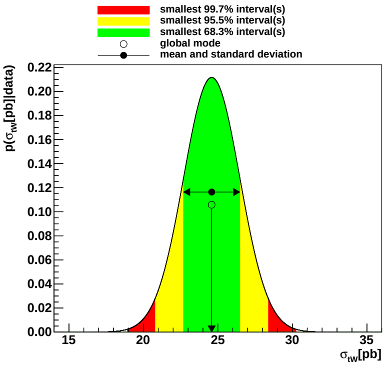

Figure: Combined measurement using EFTfitter. Corresponding value: $\sigma_{tW} = (24.59 \pm 1.89)\,\text{pb}$

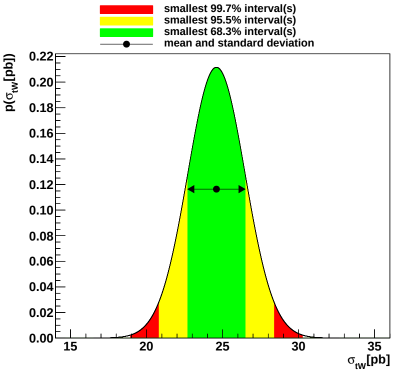

Figure: Combined measurement using BLUE. Corresponding value: $\sigma_{tW} = (24.59 \pm 1.89)\,\text{pb}$

- High positive correlation between statistical uncertainties
- Both methods behave the same/intended way, uncertainty grows with higher positive correlation

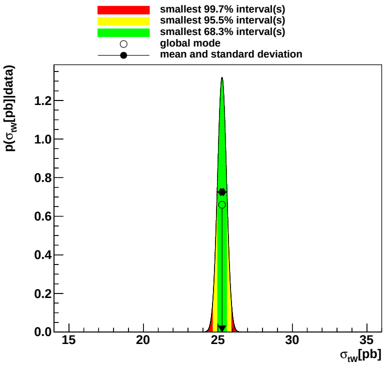

Figure: Combined measurement using EFTfitter. Corresponding value: $\sigma_{tW} = (25.28 \pm 0.30)\,\text{pb}$

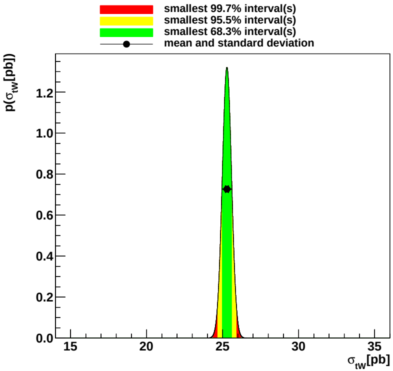

Figure: Combined measurement using BLUE. Corresponding value: $\sigma_{tW} = (25.28 \pm 0.30)\,\text{pb}$

- High negative correlation between statistical uncertainties
- Both methods behave the same/intended way, uncertainty lowers with higher negative correlation

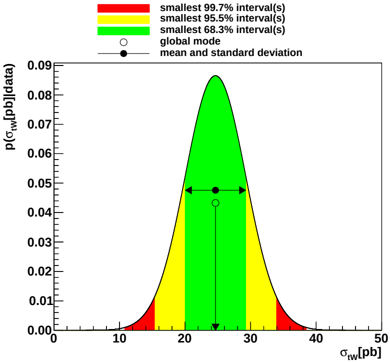

Figure: Combined measurement using EFTfitter. Corresponding value: $\sigma_{tW} = (24.64 \pm 4.61)\,\mathrm{pb}$

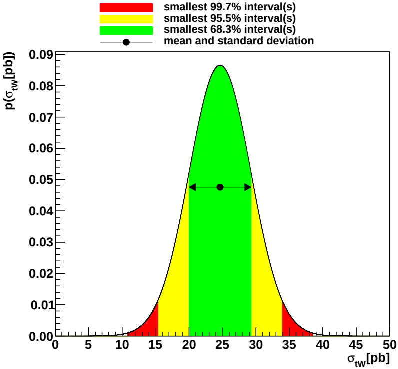

Figure: Combined measurement using BLUE. Corresponding value: $\sigma_{tW} = (24.64 \pm 4.61)\,\mathrm{pb}$

- All 20 uncertainties included with according correlations
- Equal result for both methods even with multiple uncertainties
- High confidence in the EFTfitter as tool for combination of measurements

Procedure for constraining the top quark width

- Main objective: calculate a pdf for the top quark width
- Build a model with observables, measurements and parameters
- Implement dependencies of the observables from the parameters
- Include measurements
- EFTfitter is used in order to implement that model and perform the calculation

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The observables

- Cross section of $t\bar{t}$ production $\sigma_{t\bar{t}}$
- Cross section of single top production in the t channel σ_{st}
- Branching ratio $BR(t \to W + b)$

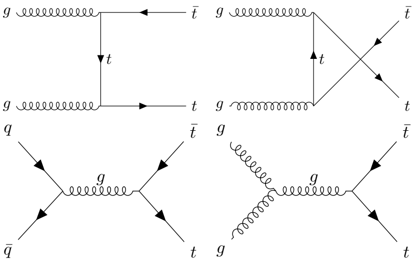

Figure: Example processes for $t\bar{t}$ production.

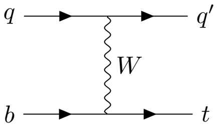

Figure: Single top production in the t-channel.

Overview of the model

Parameter	Observables	Parameters of the observables	Measurement
m_t	$\sigma_{t\bar{t}}$	m_t	available
	σ_{st}	m_t, V_{tb}	available
V_{tb}	$BR(t \to \mathrm{W+b})$	V_{tb}	available
	Γ_t	m_t	not available

- Γ_t is added as observable even though no direct measurement will be included
- Relation of Γ_t and the top quark pole mass m_t:

$$\Gamma = \frac{G_F\, m_t^3}{8\,\pi\,\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\,\alpha_s}{3\,\pi}\left(\frac{2\,\pi^2}{3} - \frac{5}{2}\right)\right]$$

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The measurements

- Measurement for $\sigma_{t\bar{t}}$ from an ATLAS measurement at $\sqrt{s} = 8\,\text{TeV}$:

$$\sigma_{t\bar{t}} = 242.4 \pm 1.7\,(\text{stat}) \pm 10.2\,(\text{syst})\,\text{pb}$$

- The measurement of the inclusive single top quark production cross section in the t-channel from a CMS measurement:

$$\sigma_{st} = 83.6 \pm 2.3\,(\text{stat}) \pm 7.4\,(\text{syst})\,\text{pb}$$

- The measurement of BR ($t \rightarrow$ W+b) from a CMS measurement:

$$BR(t \rightarrow \text{W+b}) = 1.014 \pm 0.003\,(\text{stat}) \pm 0.032\,(\text{syst})$$

- Due to $|V_{tb}| < 1$ an upper limit from that measurement is used:

$$BR(t \rightarrow \text{W+b}) = 1.0 + 0.0 - 0.025$$

Implementation to EFTfitter

- Calculation of $BR(t \to \mathrm{W{+}b})$ straightforward:

$$BR(t \to \mathrm{W{+}b}) = \frac{\Gamma(t \to \mathrm{W{+}b})}{\Gamma(t \to \mathrm{W{+}q})} = |V_{tb}|^2$$

- Calculation of the cross sections with HATHOR (tool to calculate cross section of top quark processes)
- HATHOR used with CT10NLO PDF and $\sqrt{s} = 8\,\mathrm{TeV}$
- Parameters set to

$$150\,\mathrm{GeV} < m_t < 200\,\mathrm{GeV} \quad \text{and} \quad |V_{tb}| = 0.55, 0.77, 0.99$$

- Extract dependency of $|V_{tb}|$ from σ_{st} by analyzing σ_{st} for the three $|V_{tb}|$ values

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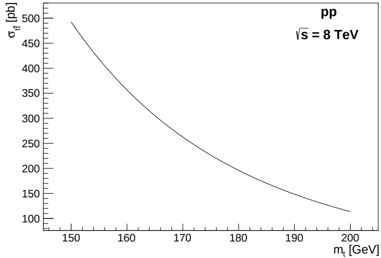
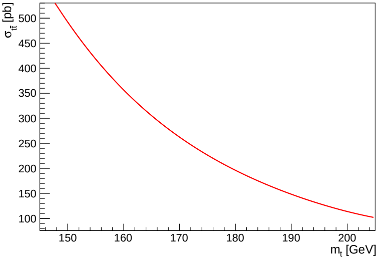
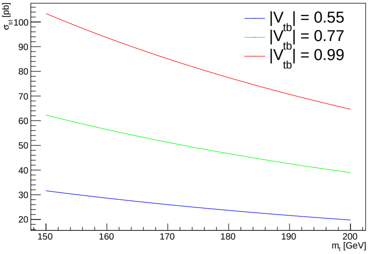
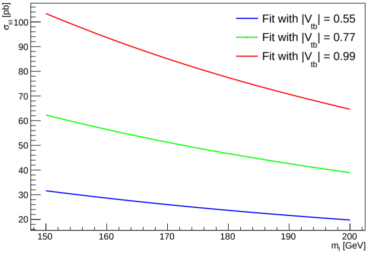
HATHOR implementation

- Due to computation time HATHOR included as polynomial fit







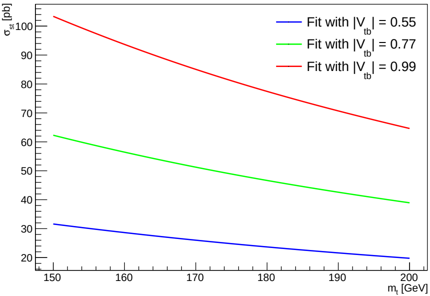


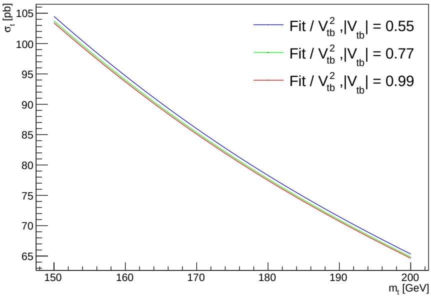
$|V_{tb}|$ extraction

- Assuming the dependency of $|V_{tb}|$ is quadratic the following extraction is useful

$$\sigma_{st}(m_t, |V_{tb}|) = |V_{tb}|^2 \, \sigma_{st}(m_t)$$

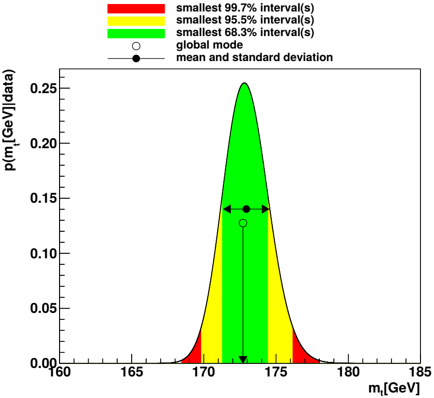
- $\sigma_{st}(m_t)$ follows from mean of "nomalized" distributions (normalized to $|V_{tb}| = 1$)

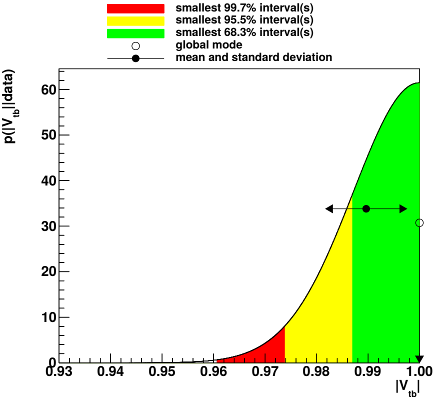




The results

- Providing the model and measurements to the EFTfitter it provides the posterior probabilities



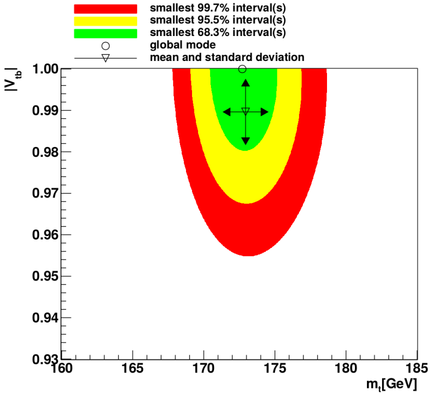


- Comparison between global mode (GM) and world combination (WC) values of the top quark width

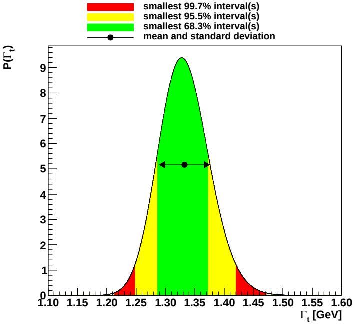
$$\Gamma_t^{GM} = (1.335 \pm 0.040)\,\text{GeV} \quad \text{with} \quad m_t^{GM} = (172.707 \pm 1.554)\,\text{GeV}$$

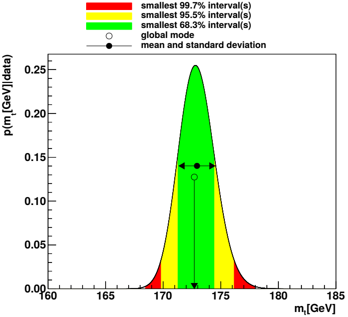
$$\Gamma_t^{WC} = (1.352 \pm 0.020)\,\text{GeV} \quad \text{with} \quad m_t^{WC} = (173.34 \pm 0.76)\,\text{GeV}$$

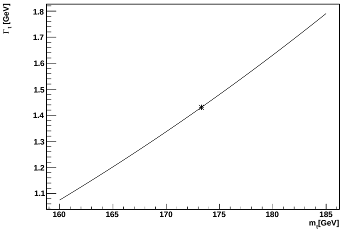
- 2D distribution of the parameters
- Top quark width PDF can be calculated from m_t PDF



- Similarity in shape of m_t and Γ_t PDF
- Follows from linear dependency visible in plot below







Conclusions

- Combination of measurements works reliably
- Global mode values agree within one standard deviation
- Resulting plots fit expectations
- Possible next steps
  - Expand the model with more observables
  - Add more (also multiple of the same) measurements
  - Create a "global fit" on physical quantities that cannot be measured directly
- Thanks for your attention

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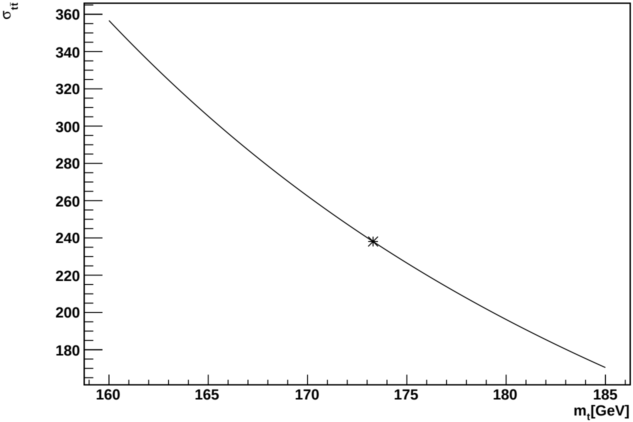
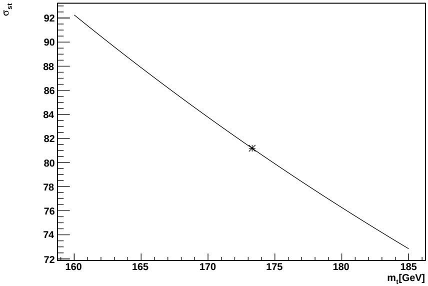
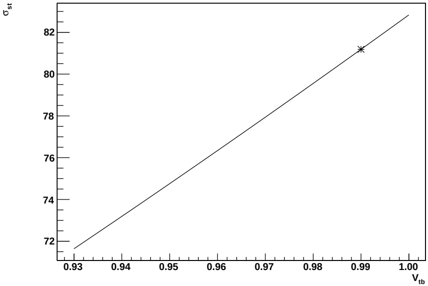
Observables

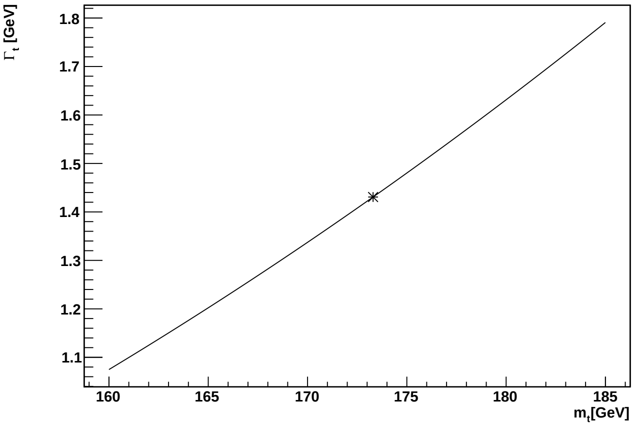


Observables





Observables



Single top measurement correlation