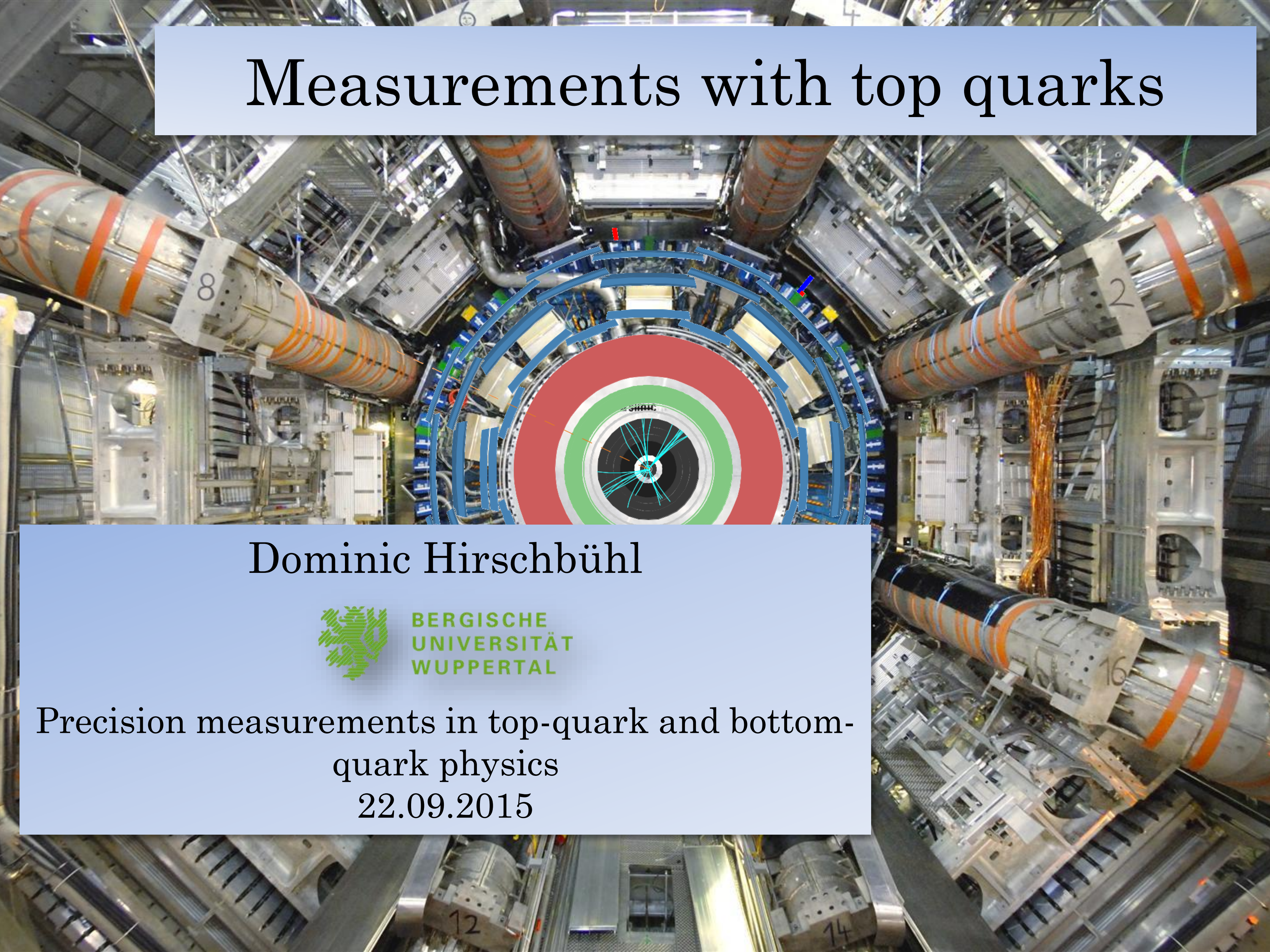


Measurements with top quarks

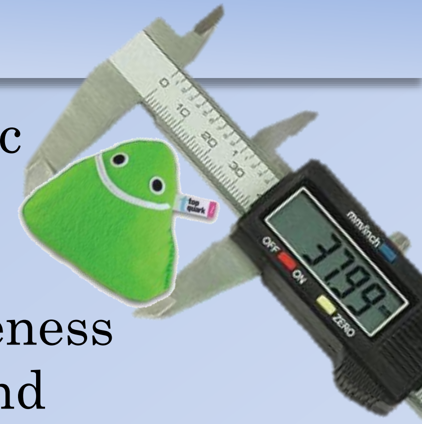
Dominic Hirschbühl

BERGISCHE UNIVERSITÄT WUPPERTAL

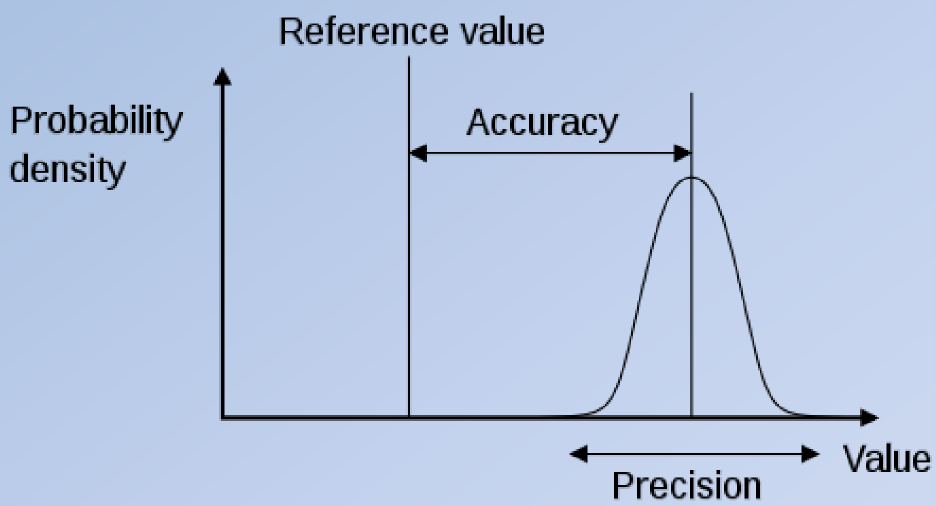
Precision measurements in top-quark and bottom-quark physics

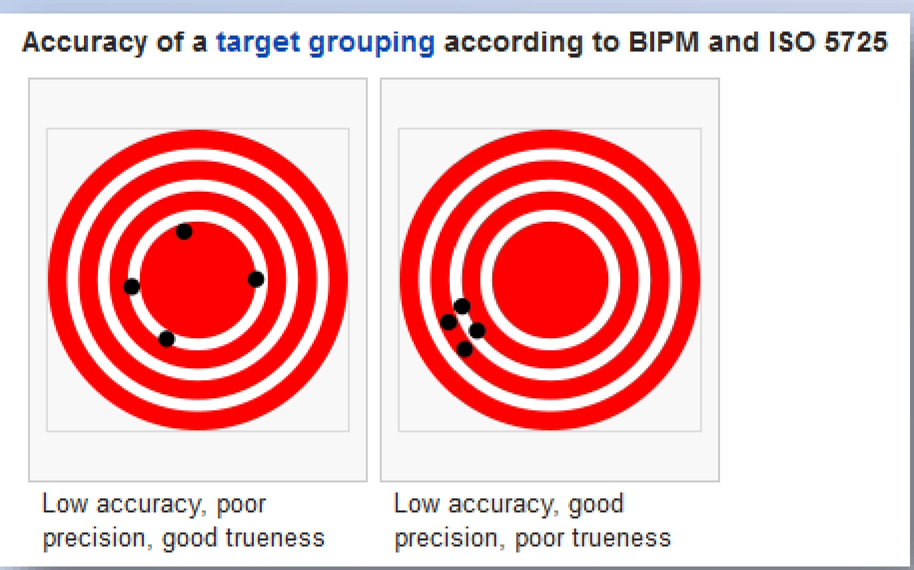
22.09.2015

Precision measurement

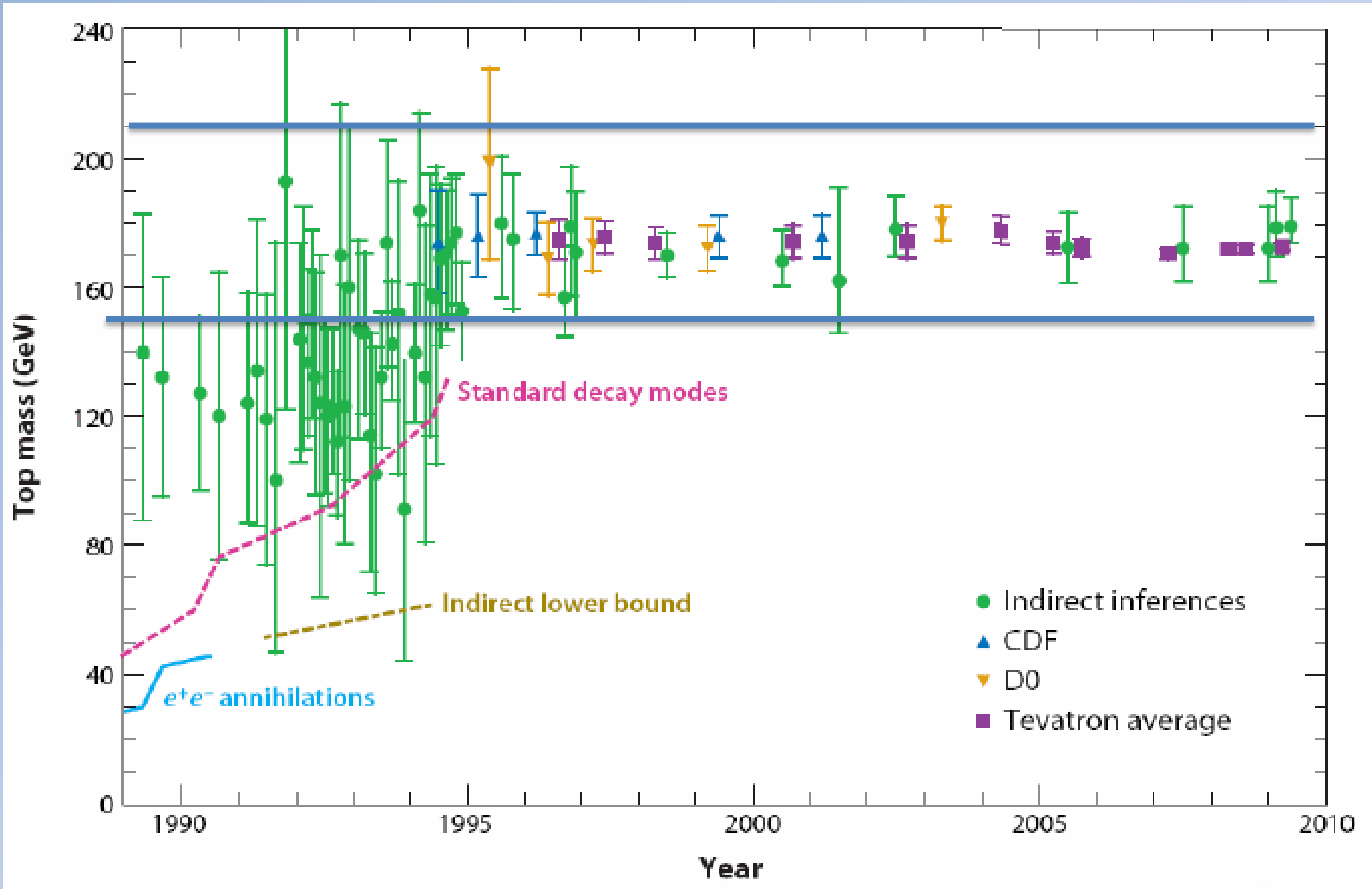


Accuracy and **precision** are defined in terms of systematic and random errors. The more common definition associates accuracy with systematic errors and precision with random errors. Another definition, advanced by ISO, associates trueness with systematic errors and precision with random errors, and defines accuracy as the combination of both trueness and precision.

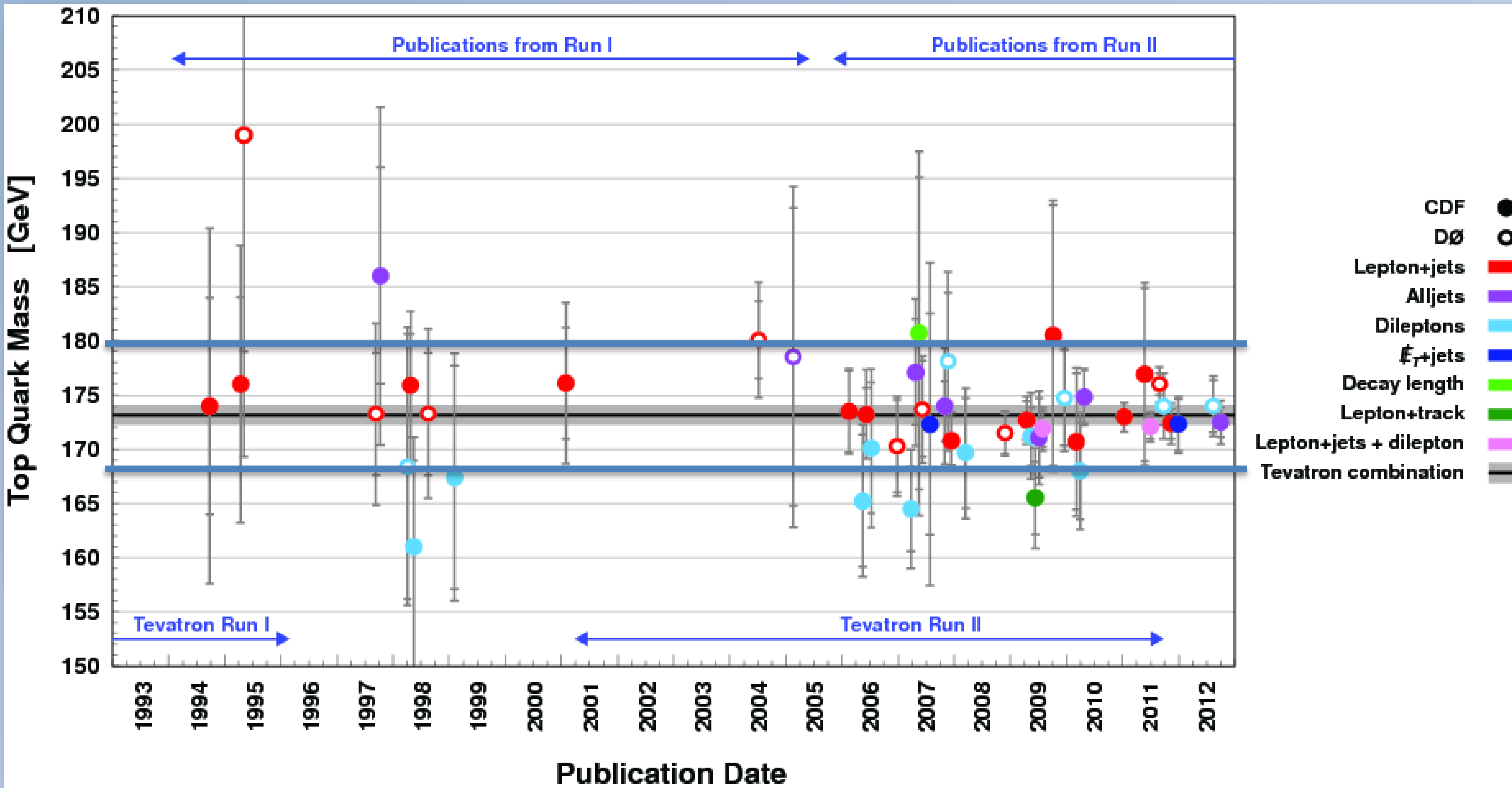




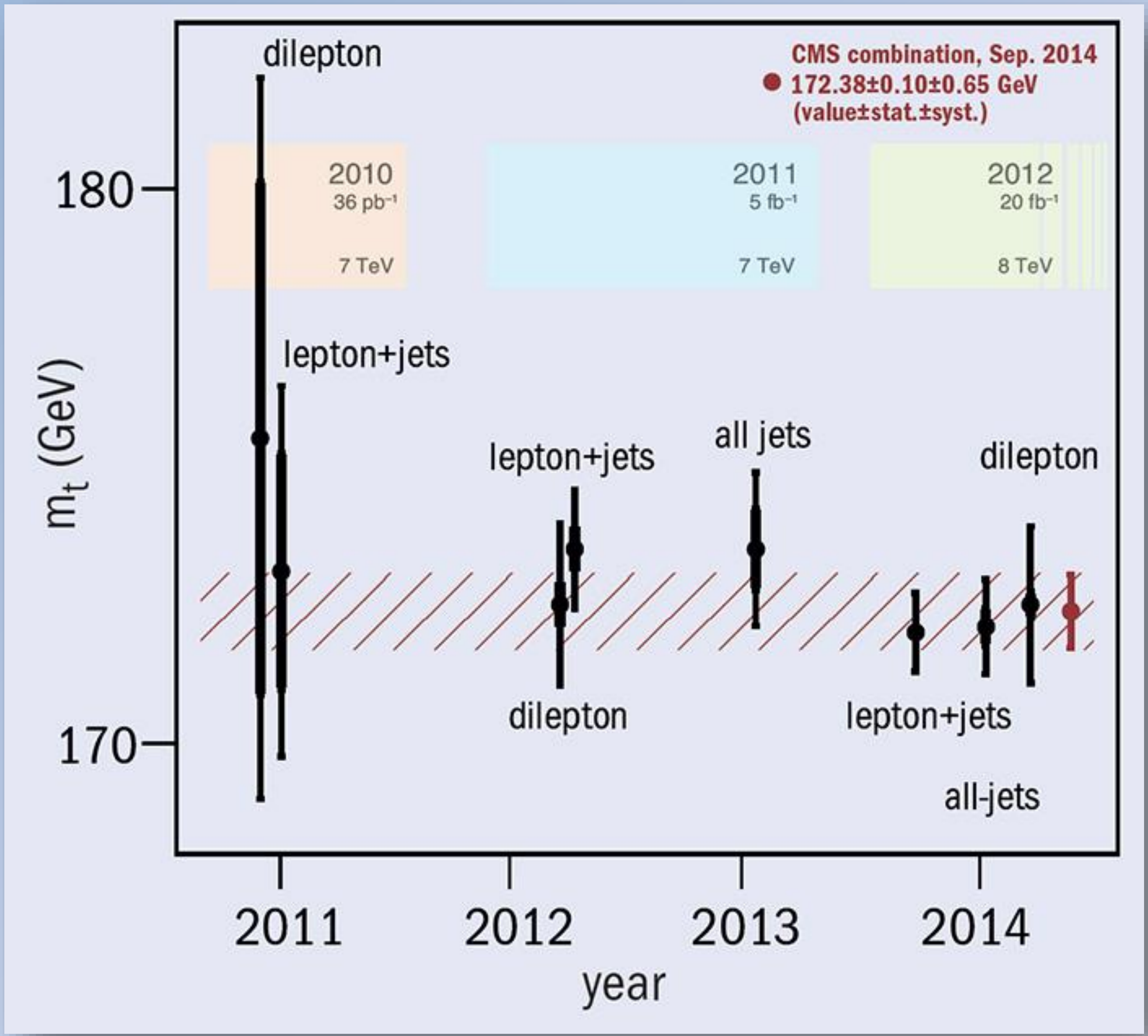
Precision measurement – top quark mass



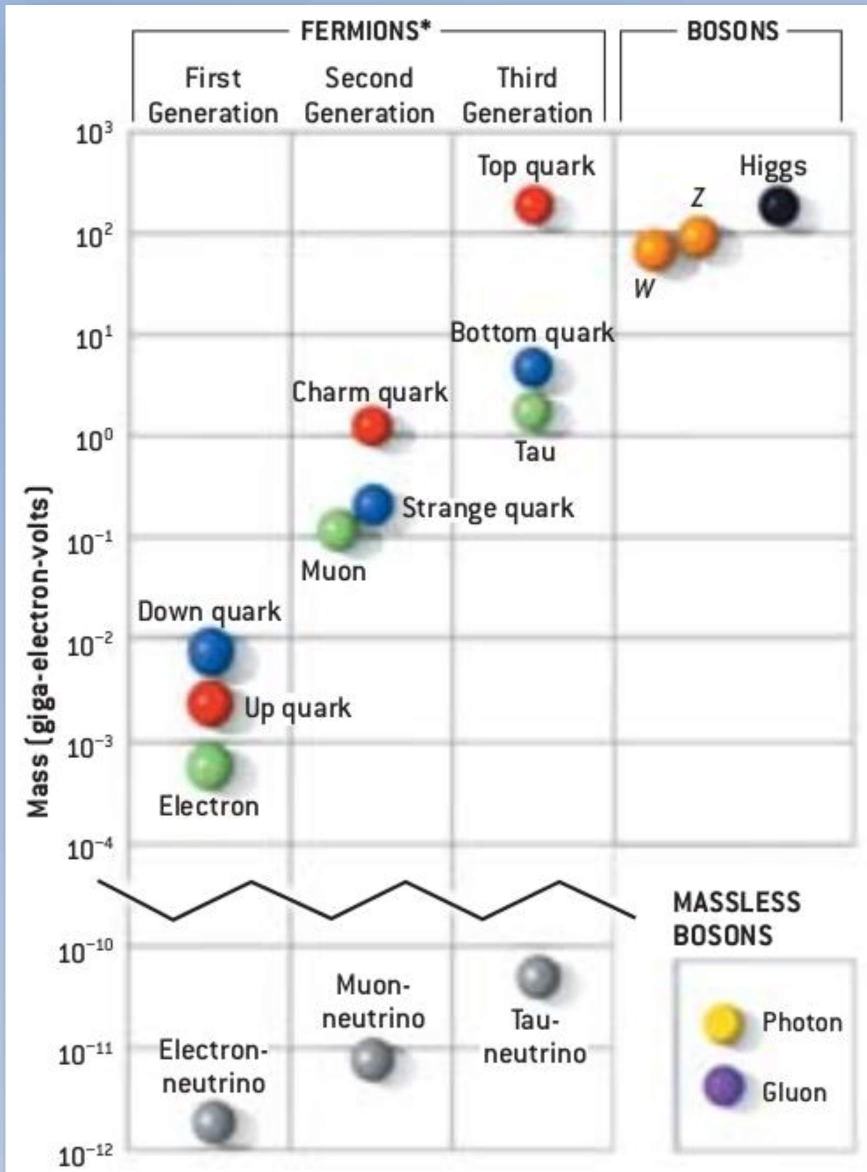
Precision measurement – top quark mass



Precision measurement – top quark mass



The top quark

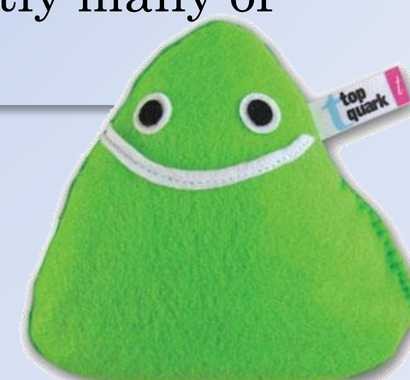


The heaviest know elementary particle.

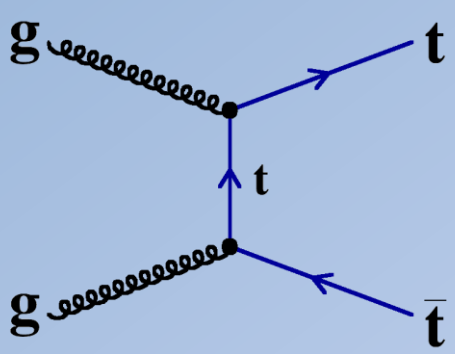
Tight connection to the Higgs-Boson and Electroweak Symmetry Breaking

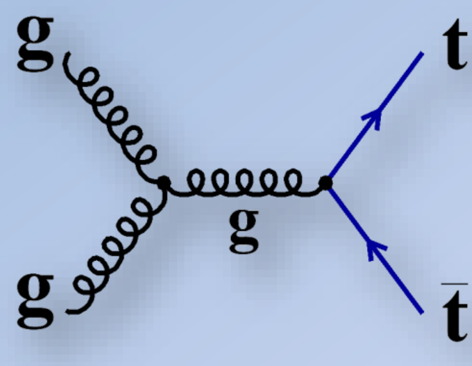
It decays before it hadronies.

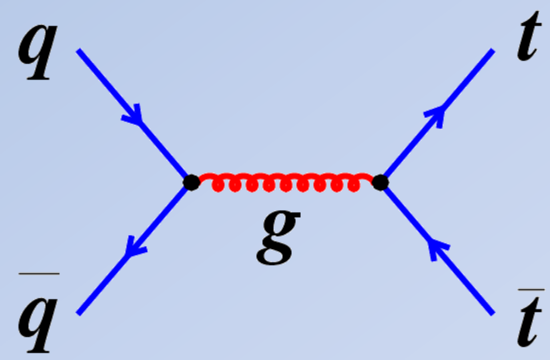
It is still a (old) teenager, discovered in 1995, and we just got recently many of them



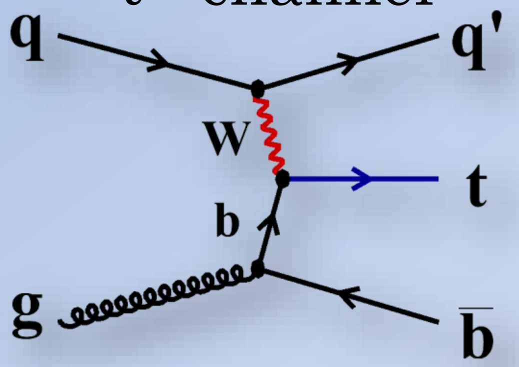
Production modes



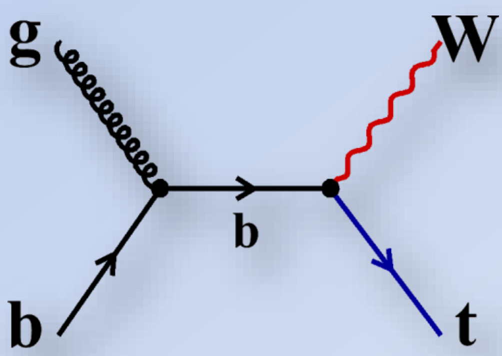




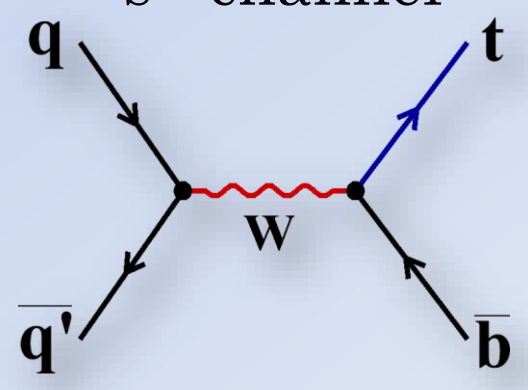
t - channel



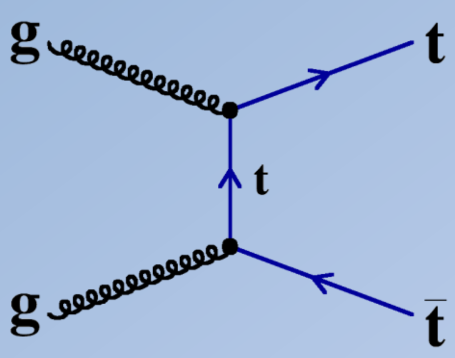
Wt

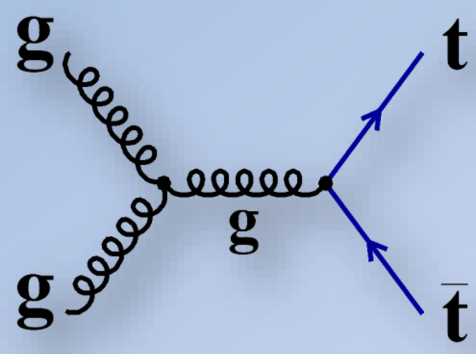


s - channel

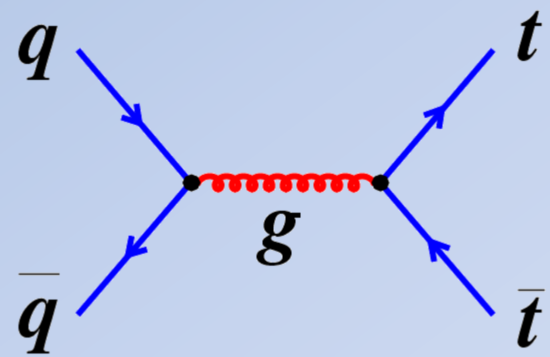


Production modes

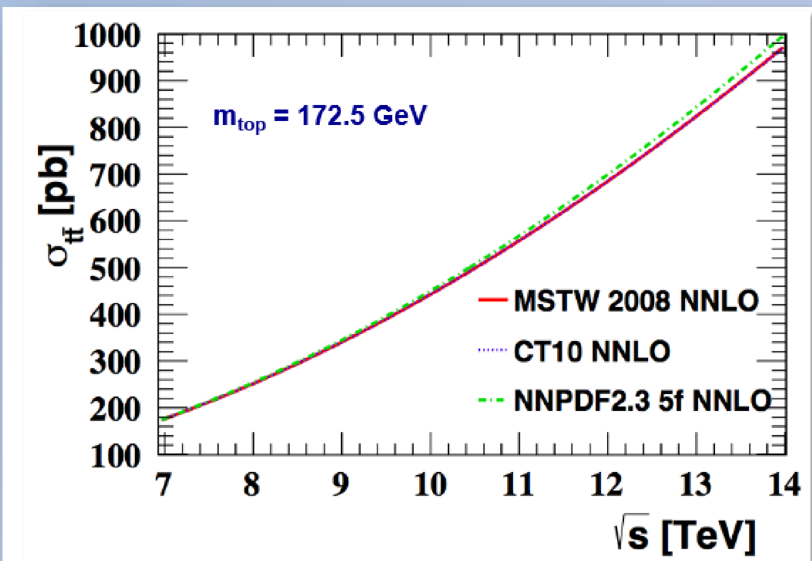




85 % @ LHC



15 % @ LHC

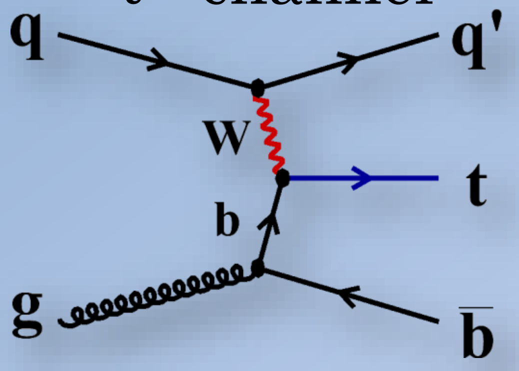


	7 TeV	8 TeV	13 TeV
Cross sections	177 ± 11 pb	252 ± 14 pb	831 ± 46 pb
Produced $t\bar{t}$ events	~ 1 Mio	~ 5 Mio	~25 Mio per year

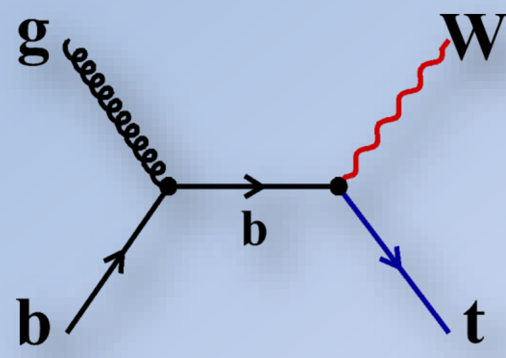
Calculations using Top++2.0 @ NNLO + NNLL
Czakon, Mitov, Comput.Phys.Commun. 185 (2014) 2930

Production cross section

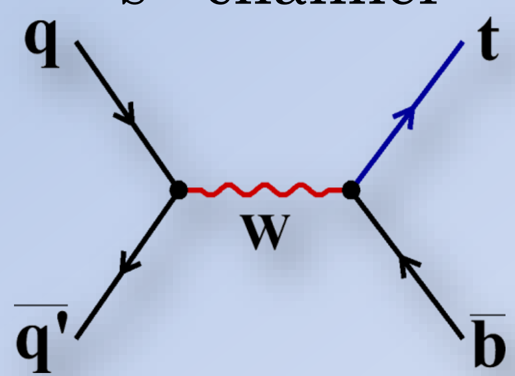
t - channel

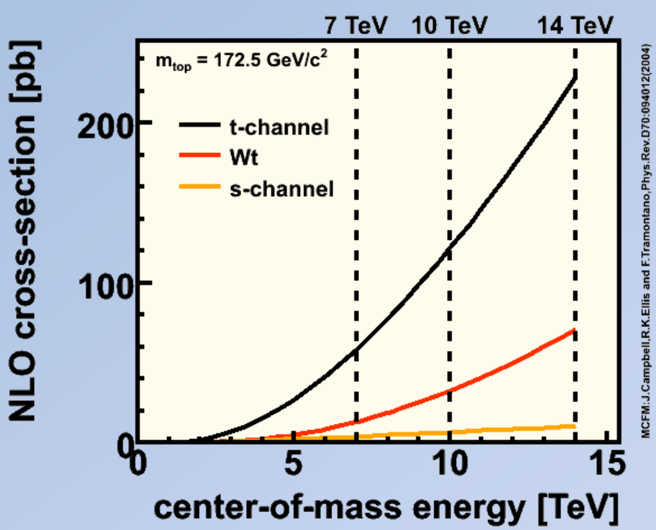


Wt



s - channel



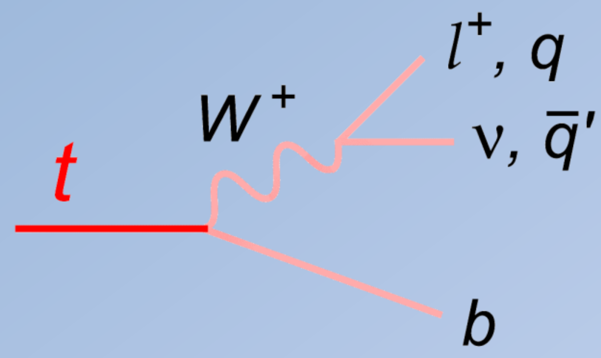


Cross section	7 TeV	8 TeV	13 TeV
t – channel	63.9 ± 2.9 pb	84.7 ± 3.8 pb	217 ± 9 pb
Wt	15.7 ± 1.1 pb	22.4 ± 1.5 pb	71.7 ± 3.8 pb
s - channel	4.3 ± 0.2 pb	5.2 ± 0.2 pb	10.3 ± 0.4 pb

Single-top-quark and antiquark cross sections are different for t- and s-channel at the LHC!

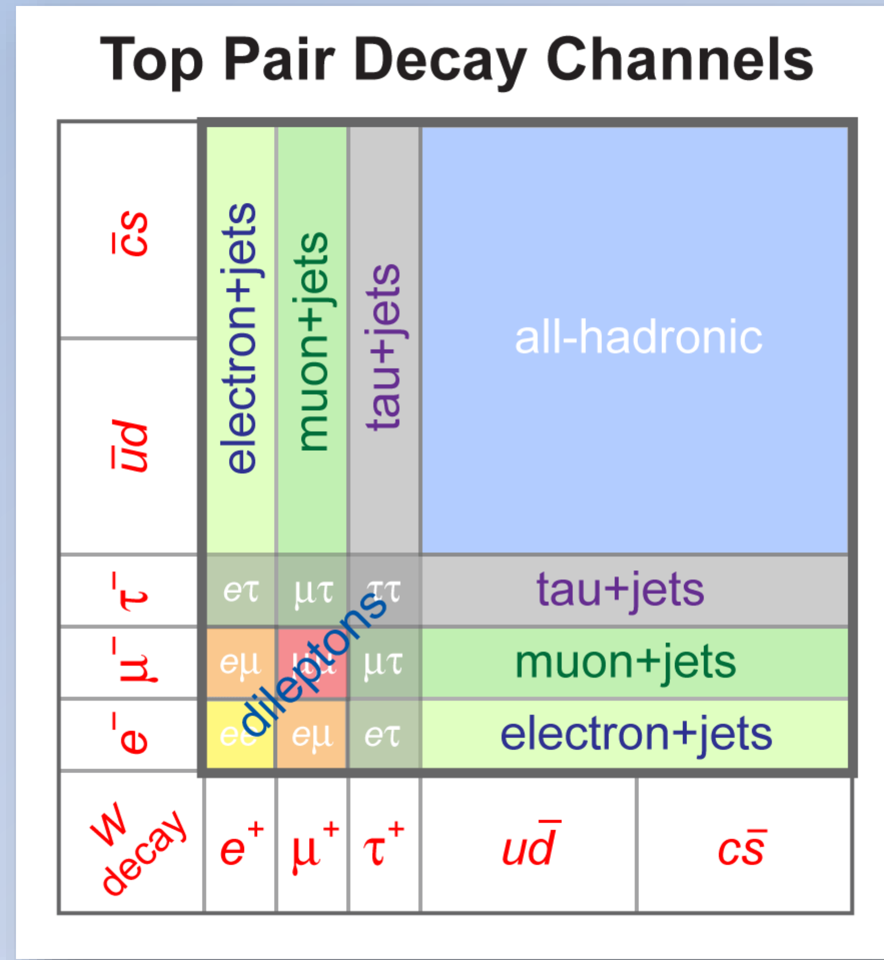
Calculations using MCFM/Hathor @ NLO for t- and s-channel
Calculations by N. Kidonakis for Wt: Phys.Rev.D82 (2010) 054018,2010 @ NLO + NNLL

Decay of the top quark



$$(|V_{ij}|) = \begin{bmatrix} 0{,}97427 & 0{,}22534 & 0{,}00351 \\ 0{,}22520 & 0{,}97344 & 0{,}0412 \\ 0{,}00867 & 0{,}0404 & 0{,}999146 \end{bmatrix}$$

V_{td} V_{ts} V_{tb}



Top quark decays almost in 100% of the time into W boson and a b quark

$t\bar{t}$ production channels

Di-lepton channel ($t\bar{t} \rightarrow l\nu_l l\nu_l b\bar{b}, l = e, \mu$)

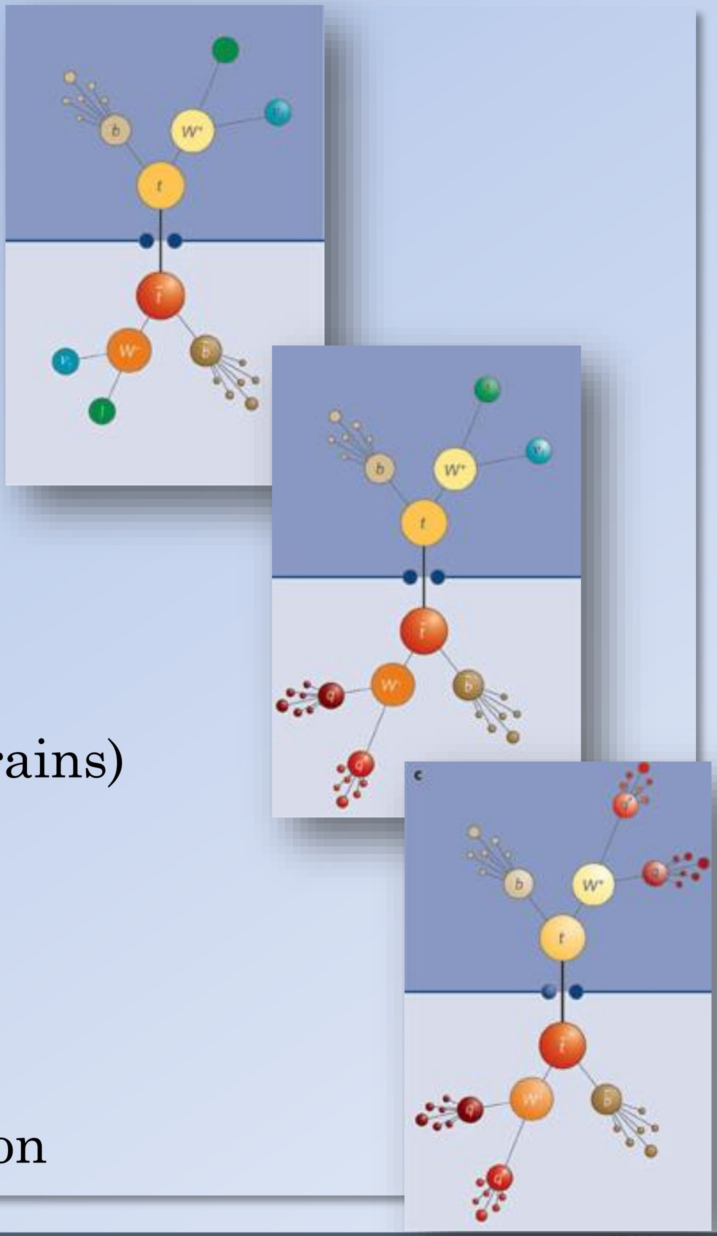
- Branching ratio ~5%
- Low event yield
- High purity / low background rate
- No complete event reconstruction

Lepton + jets channel ($t\bar{t} \rightarrow l\nu_l q\bar{q}' b\bar{b}, l = e, \mu$)

- Branching ratio ~30%
- Good event yield
- Good signal / background ratio
- Golden channel
- Event reconstruction possible (with constrains)

All hadronic channel ($t\bar{t} \rightarrow q\bar{q}' q\bar{q}' b\bar{b}, l = e, \mu$)

- Branching ratio ~45%
- Highest event yield
- Large background
- High combinatorics for event reconstruction



Top quark pair production

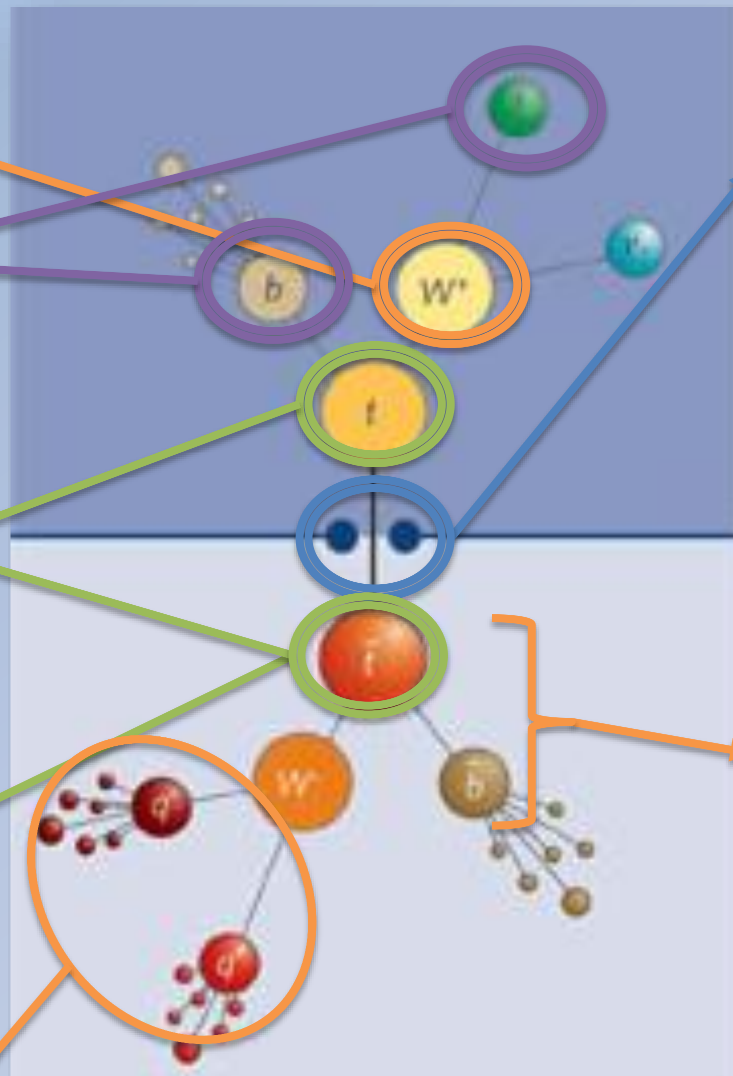
W helicity

Top charge

Mass difference
Spin correlation
Charge asymmetry

Top mass
Top width

Color flow



Production cross section
Production mechanism
New physics contribution

$|V_{tb}|$
Branching rations
Rare decays
Anomalous couplings

Building blocks of a measurement

- Take collision data
- **Object identification**
- **Event selection**
- **Reconstruction of signal process ($t\bar{t}, t\bar{t} + X, t + X, etc.$)**
- **Background estimation / Signal to background optimization**
- Statistical analysis → Lecture by Michael Schmelling
- Evaluating systematic uncertainties → Lecture by Matthew Kenzie
- Result

Example measurements:
$t\bar{t}$ production cross section
t-channel single top quark production cross section
Top quark mass measurment

Building blocks of a measurement

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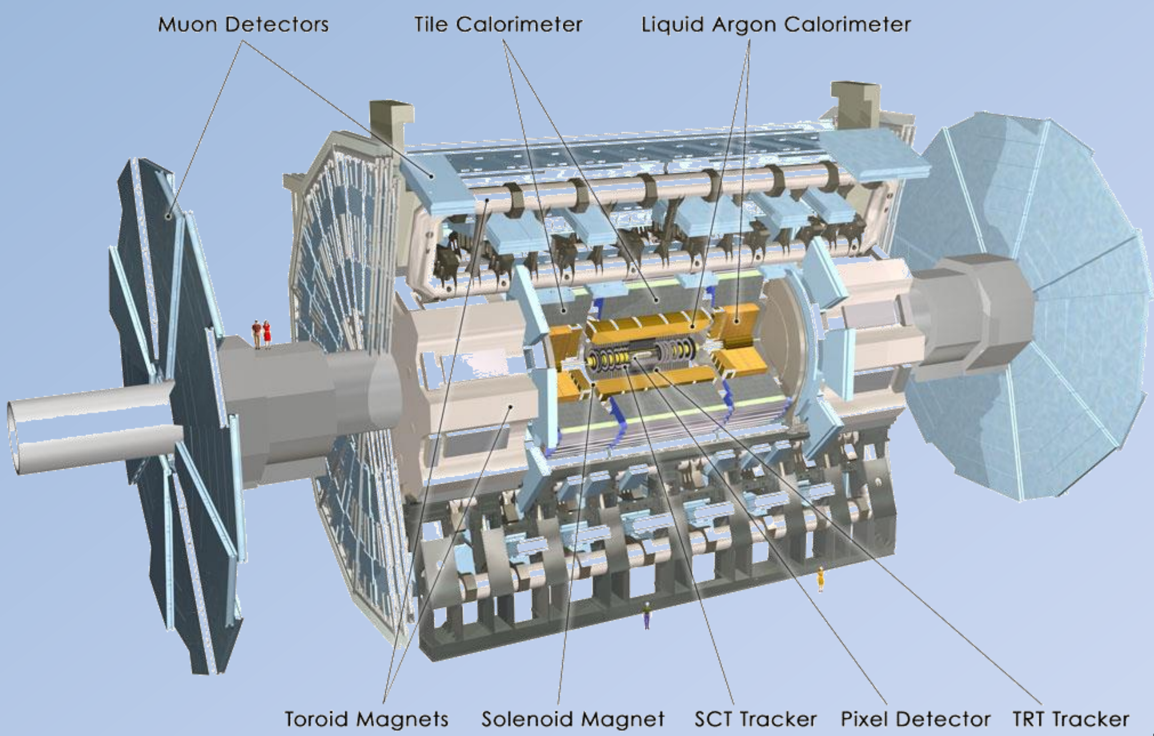
- Evaluating systematic uncertainties → Lecture by Matthew Kenzie
- Result

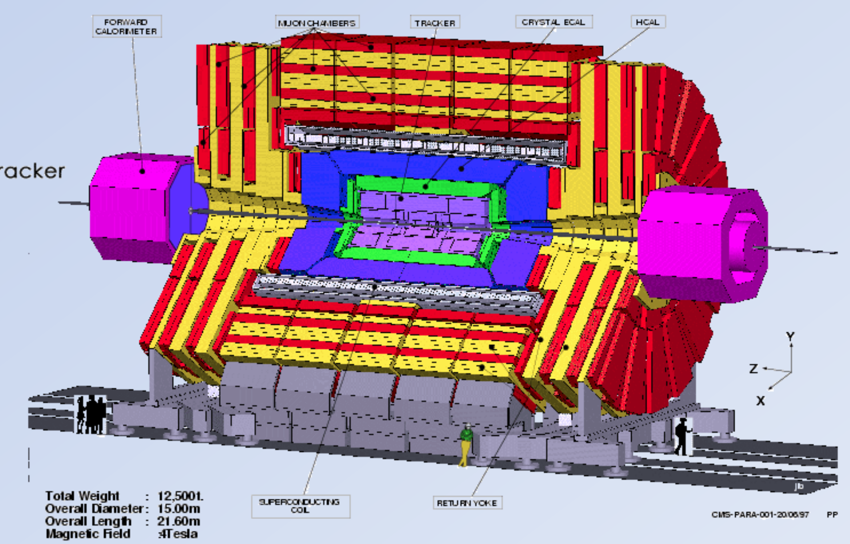
Choose one method you like and understand it as good as possible. (Keeping the application in mind) There is right or perfect method

Example measurements:
$t\bar{t}$ production cross section
t-channel single top quark production cross section
Top quark mass measurement

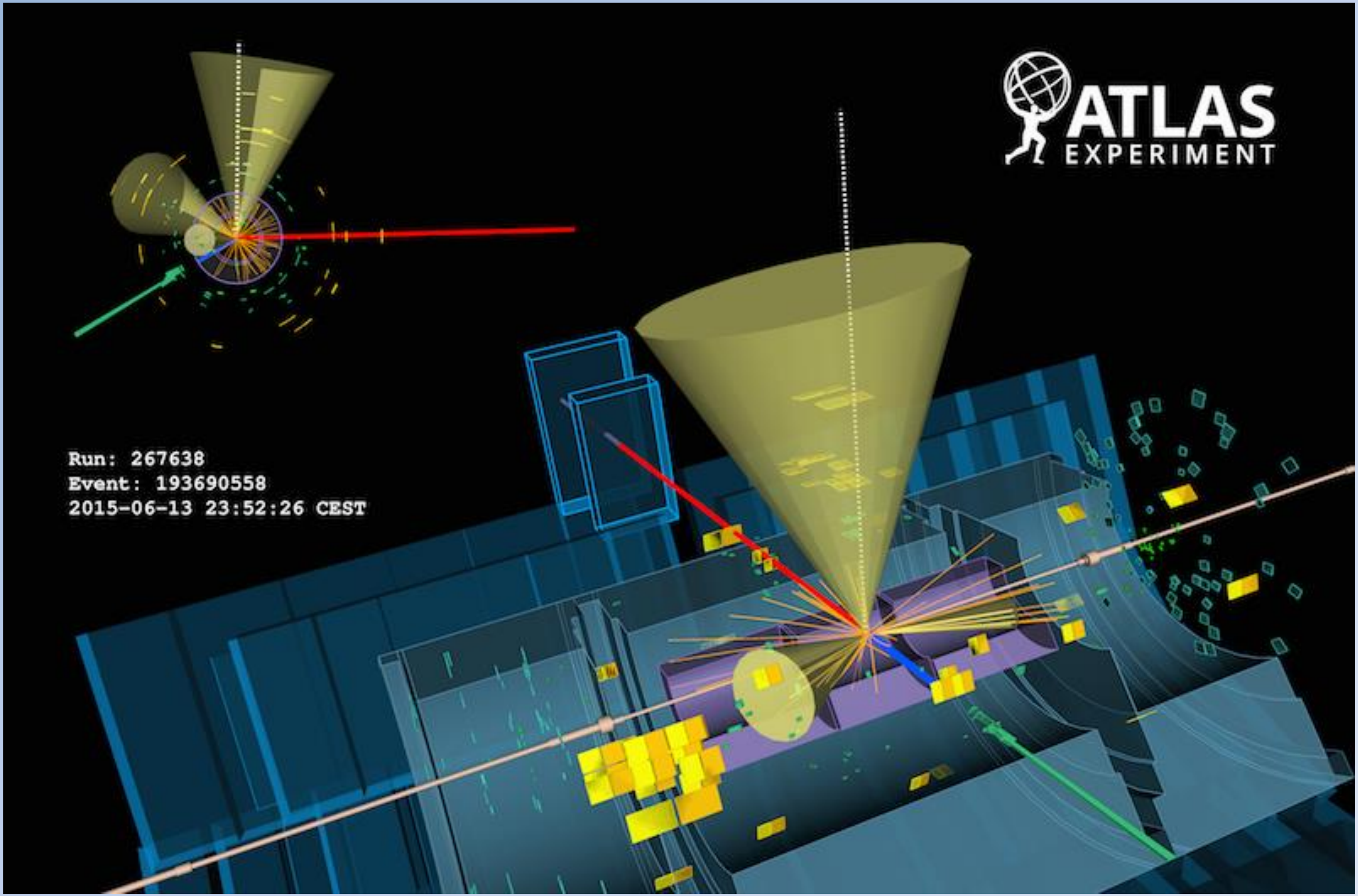
The experiments

Focus on ATLAS





Object reconstruction



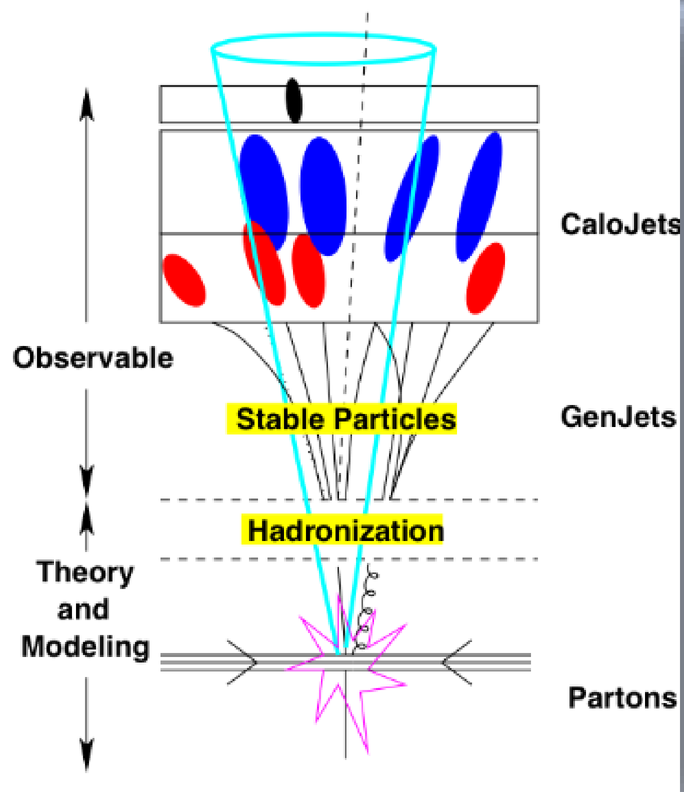
Jet and MET reconstruction

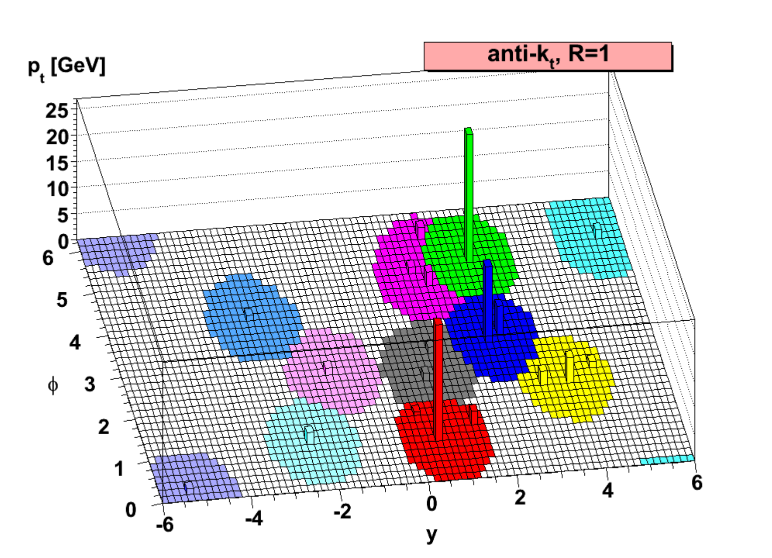
ATLAS

- anti-k_t jets with radius parameter $R = 0.4$
- Input: topological calorimeter clusters

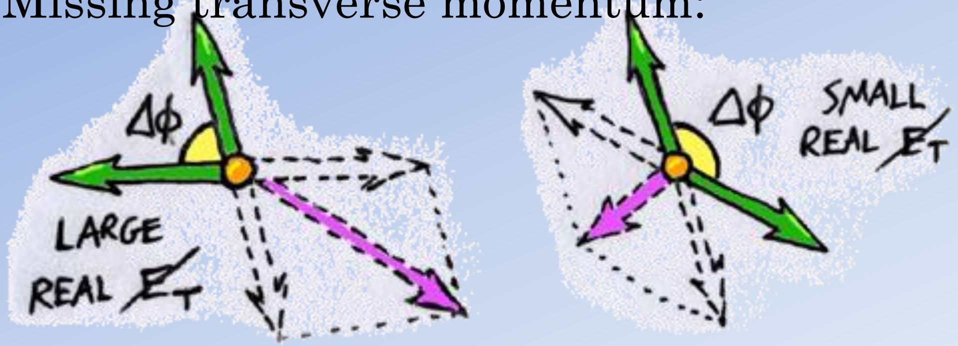
CMS

- anti-k_t jets with radius parameter $R = 0.5$
- Input: particle flow candidates





Missing transverse momentum:



b-tagging

Identify b quark jets through dedicated algorithms which combine information from:

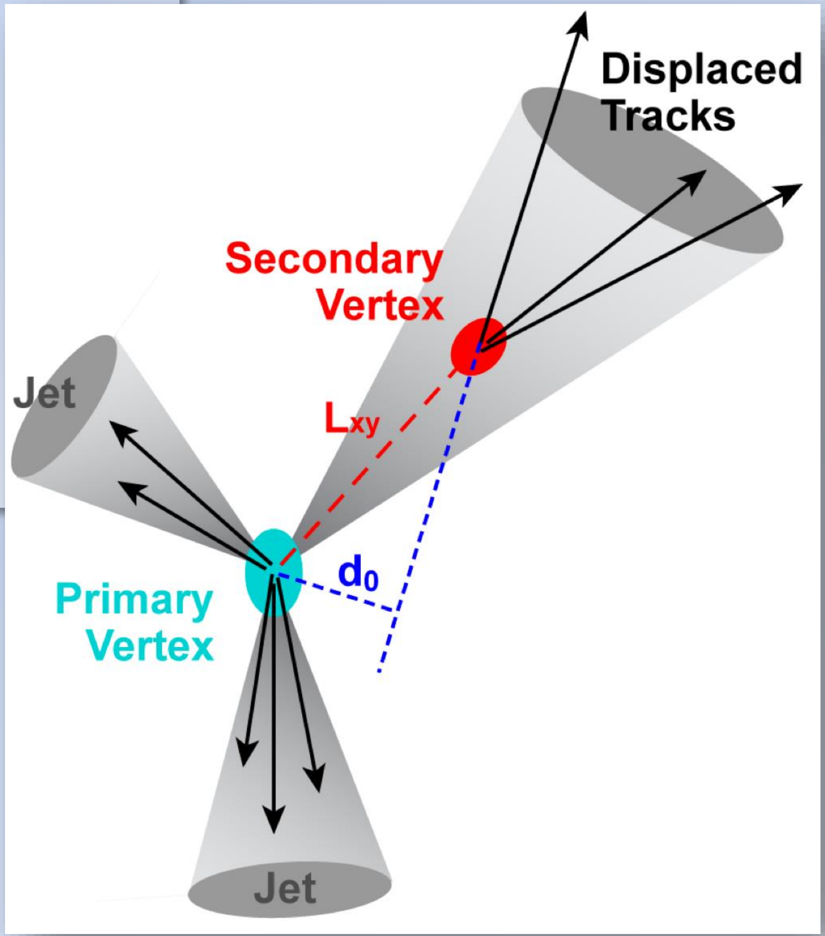
- Existence of a displaced secondary vertex
- Impact parameters of tracks associated with the secondary vertex
- Mass of the secondary vertex
- Etc.

Typical working points

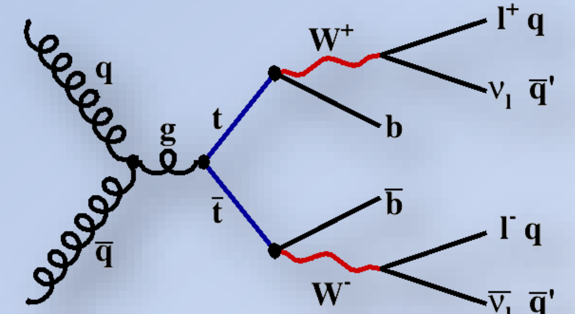
$\varepsilon_{b\ quark}$ = 70%

$\varepsilon_{c\ quark}$ ~10%

$\varepsilon_{light\ quark}$ ~ 1%



Typical event selection

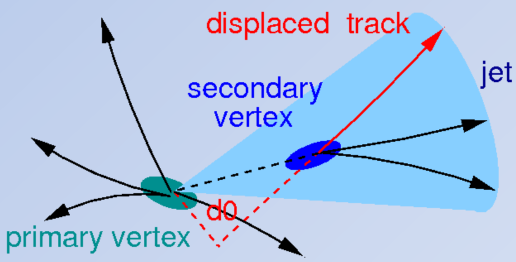


Lepton selection:

- Isolated
- $p_T > 25$ GeV

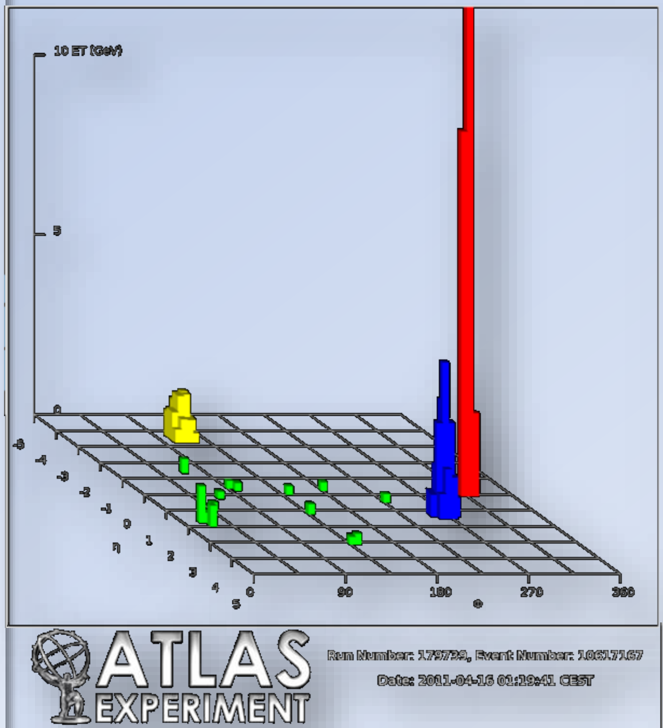
Jets

- Anti-k_T algorithm ($\Delta R = 0.4, 0.5$)
- $p_T > 25/30$ GeV
- For t-channel single top
  Including forward calorimeters (|η|<4.5)
- Identification of b-quark jets

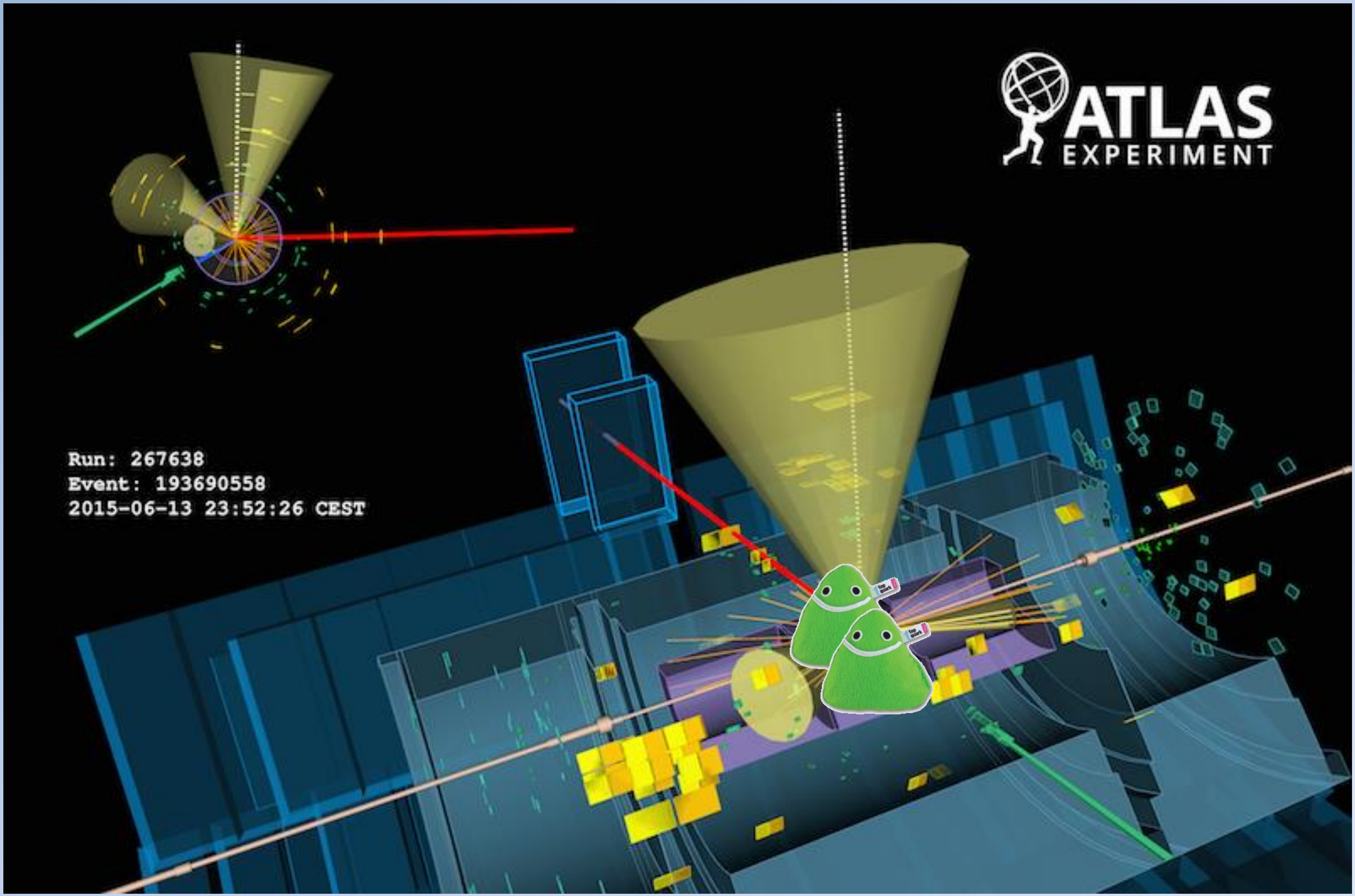


- Number of jets: ≥ 2

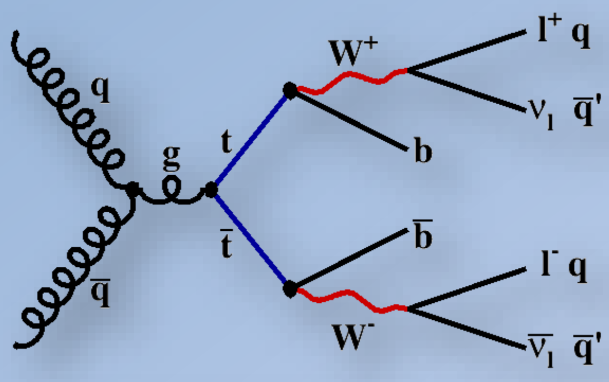
Missing transverse energy

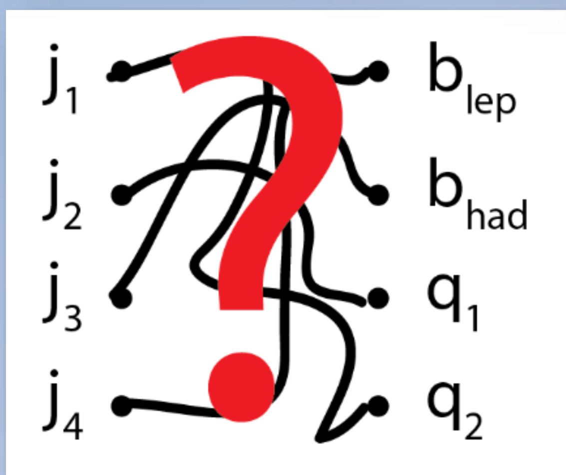


Kinematic reconstruction



Kinematic reconstruction





Leptonically W-boson:

Using know mass to calculate missing p_Z component of neutrino: $P_l^2 + P_\nu^2 = m_W^2$

Leads to quadratic equation for $p_Z(\nu)$

→ 0,1, or 2 solutions

Assignment of jets:

Statistically: N! possible permutations for N jets. But indistinguishable light quarks and indistinguishable hadronic tops is reduced to:

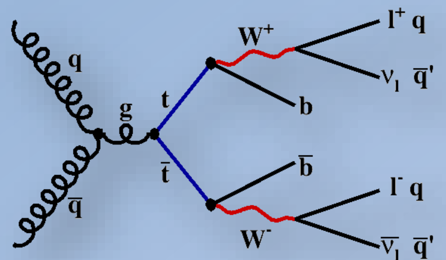
- 12 permutations for semileptonic events
- 90 permutations for fully hadronic events

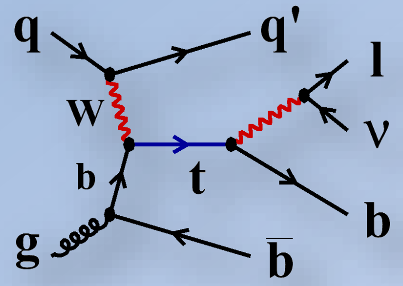
Different methods to resolve ambiguites, e.g.:

χ^2 – method: Find best permutation with minimum χ^2

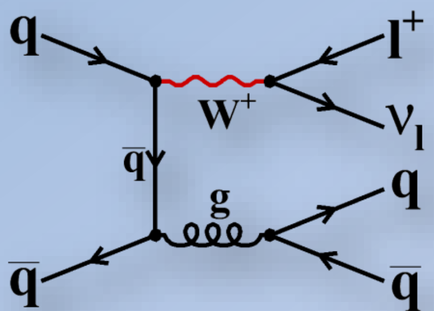
$$\chi^2 = \frac{(m_{j_1 j_2 j_3} - m_{top})^2}{\sigma_{top}^2} + \frac{(m_{j_1 j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_4 j_5 j_6} - m_{top})^2}{\sigma_{top}^2} + \frac{(m_{j_4 j_5} - m_W)^2}{\sigma_W^2}$$

Background processes

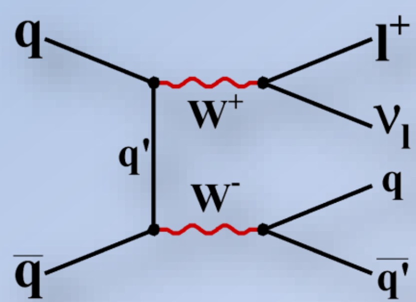


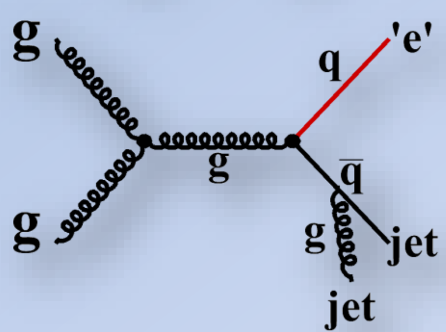


W/Z + jets

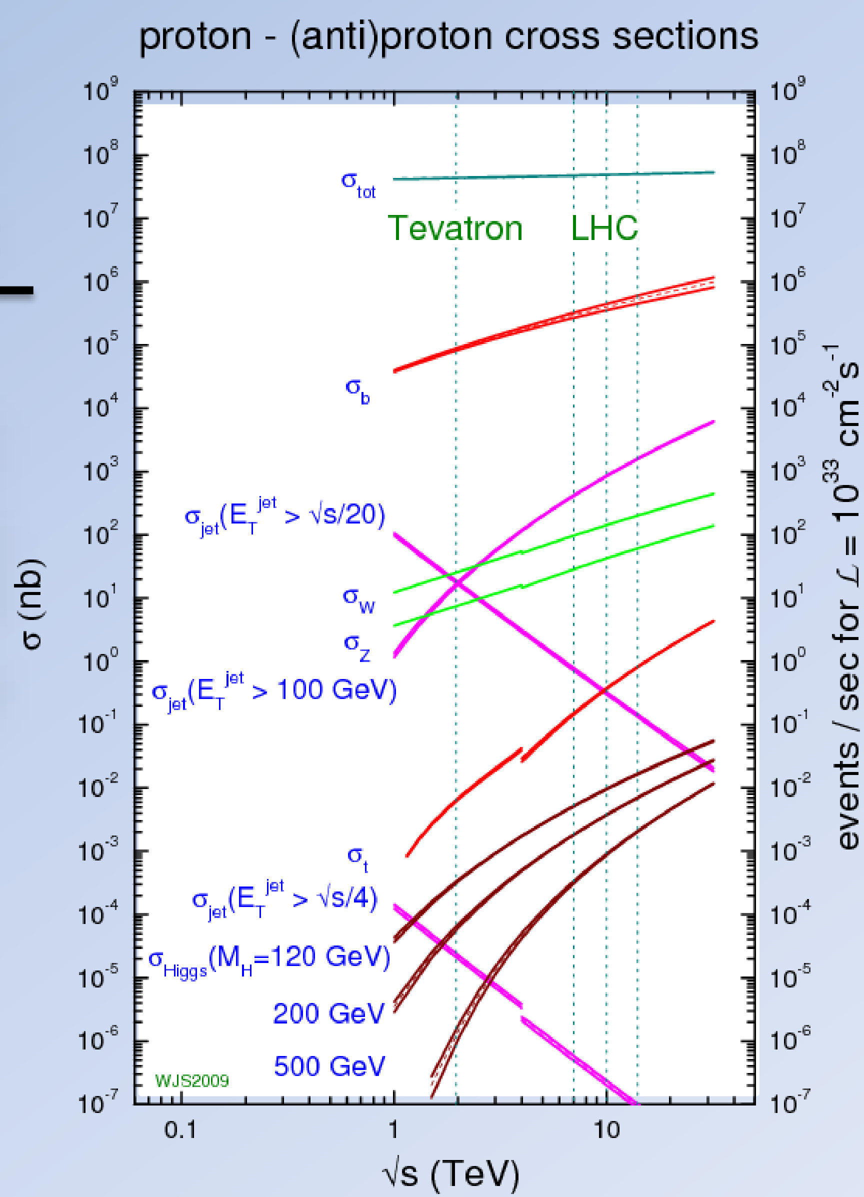


WW/WZ/ZZ





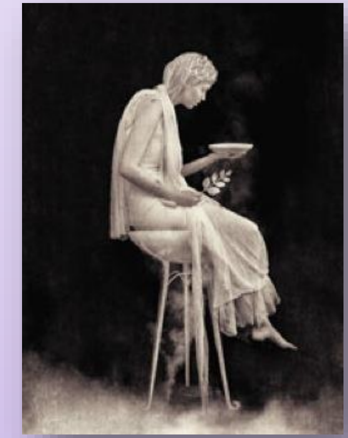
QCD-multijet production
("fake" leptons)



Background estimation

Using MC acceptance and modeling

$N = \sigma \cdot \varepsilon \cdot \mathcal{L}$



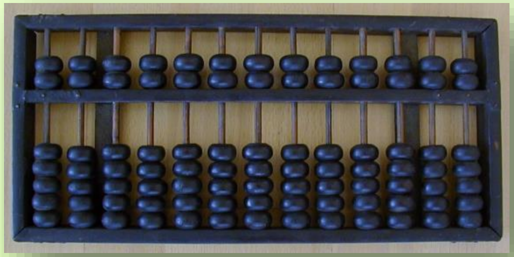
Uncertainty on σ and ε!

Using MC modeling but normalization from data

$$N_{W+jets}^{pretag} = N_{data}^{pretag} - N_{qcd}^{pretag} - N_{MC}^{pretag}$$

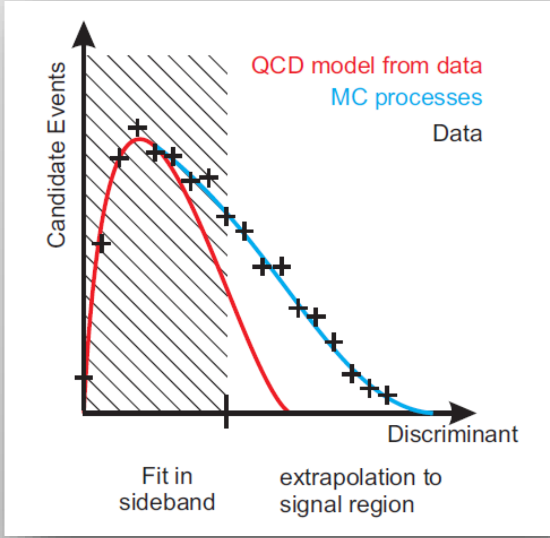
$$N_{\Phi,n}^{tag} = N^{pretag} F_{\Phi,n}^{pretag} P_{\Phi,n}^{tag} .$$

$$N_{data-bkg,2}^{tag} = N_{data-bkg,2}^{pretag} \cdot (F_{bb,2}^{pretag} \cdot P_{bb,2}^{tag} + k_{cctobb}^{pretag} \cdot F_{bb,2}^{pretag} \cdot P_{cc,2}^{tag} + F_{c,2}^{pretag} \cdot P_{c,2}^{tag} + F_{l,2}^{pretag} \cdot P_{l,2}^{tag}) = N_{data-bkg,2}^{pretag} \cdot (k_{bb1to2}^{pretag} \cdot F_{bb,1}^{pretag} \cdot P_{bb,2}^{tag} + k_{cctobb}^{pretag} \cdot k_{bb1to2}^{pretag} \cdot F_{bb,1}^{pretag} \cdot P_{cc,2}^{tag} + k_{c1to2}^{pretag} \cdot F_{c,1}^{pretag} \cdot P_{c,2}^{tag} + k_{l1to2}^{pretag} \cdot F_{l,1}^{pretag} \cdot P_{l,2}^{tag}).$$



Uncertainty:
Only uncertainty on kinematic distributions!

Using modeling and normalization from data (Mostly „fake“ backgrounds)



Uncertainty on model and/or extrapolation

Systematic uncertainties

Theory

Prediction cross section
→ uncertainties given by theorists

MC Modelling:

- Shower / Hadronisation
  → comparing Pythia vs. Herwig
- NLO matching
  → comparing Powheg vs. Herwig
- Renormalization / Factorization / Shower scale
  → vary scales
- Underlying event / color reconnection

Parton distribution functions
→ reweight to different PDFs

Statistical

Data statistics

Limited MC sample size

Systematic uncertainties

Experimental

Lepton trigger efficiency

Lepton identification efficiency

Energy scales
- Lepton / Jets

Energy resolutions
- Lepton / Jets

Missing Et

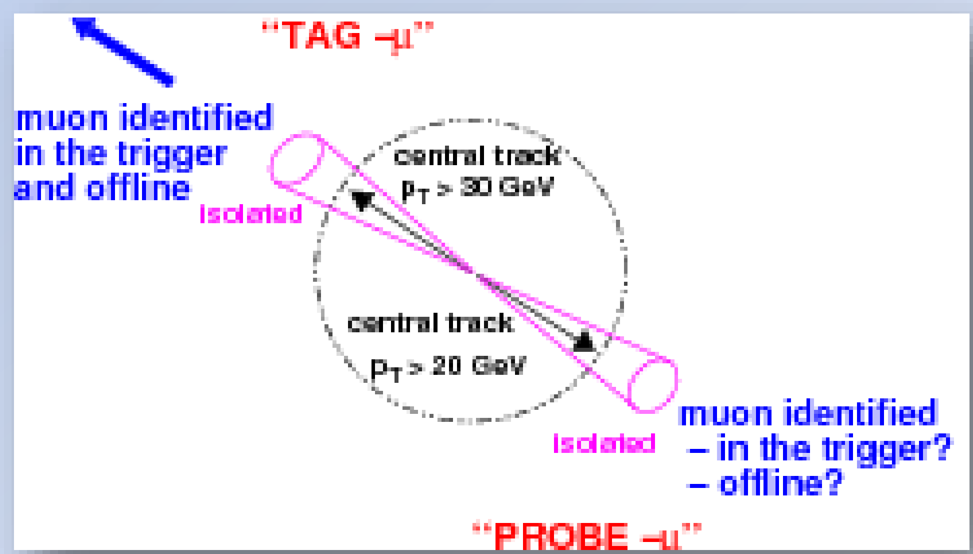
B-tagging

Background estimations

Luminosity

Uncertainties are typically estimated using special datasets or in-situ with the real measurement

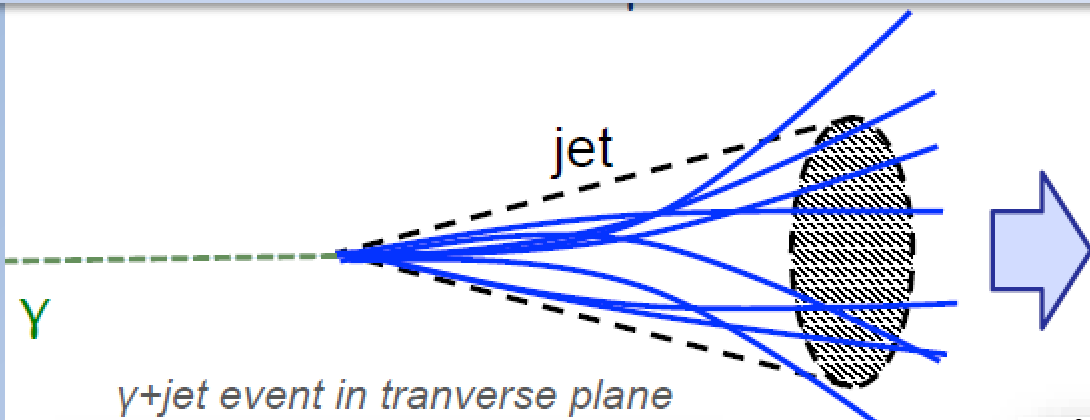
Basic idea: Determine scale factors for differences between simulation and data → estimate uncertainties on these scale factors



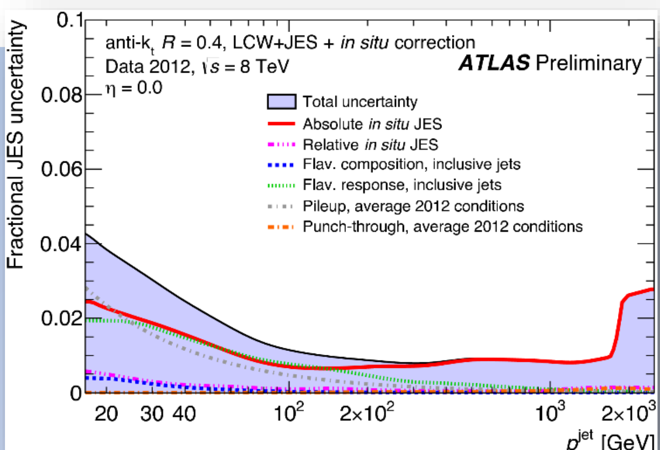
Jet energy scale

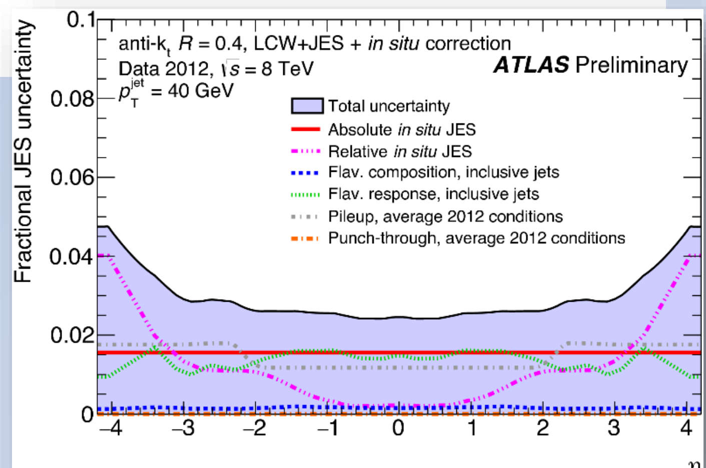
Procedure to calibrate jet energies:

- Calibrate EM energy scale with SM candels, i.e $Z \rightarrow e^+e^-$
- Central (well instrumented) region for absolute calibration
- Correct energy scale for electrons to that of photons
- Use γ + jet events to calibrate major components of JES

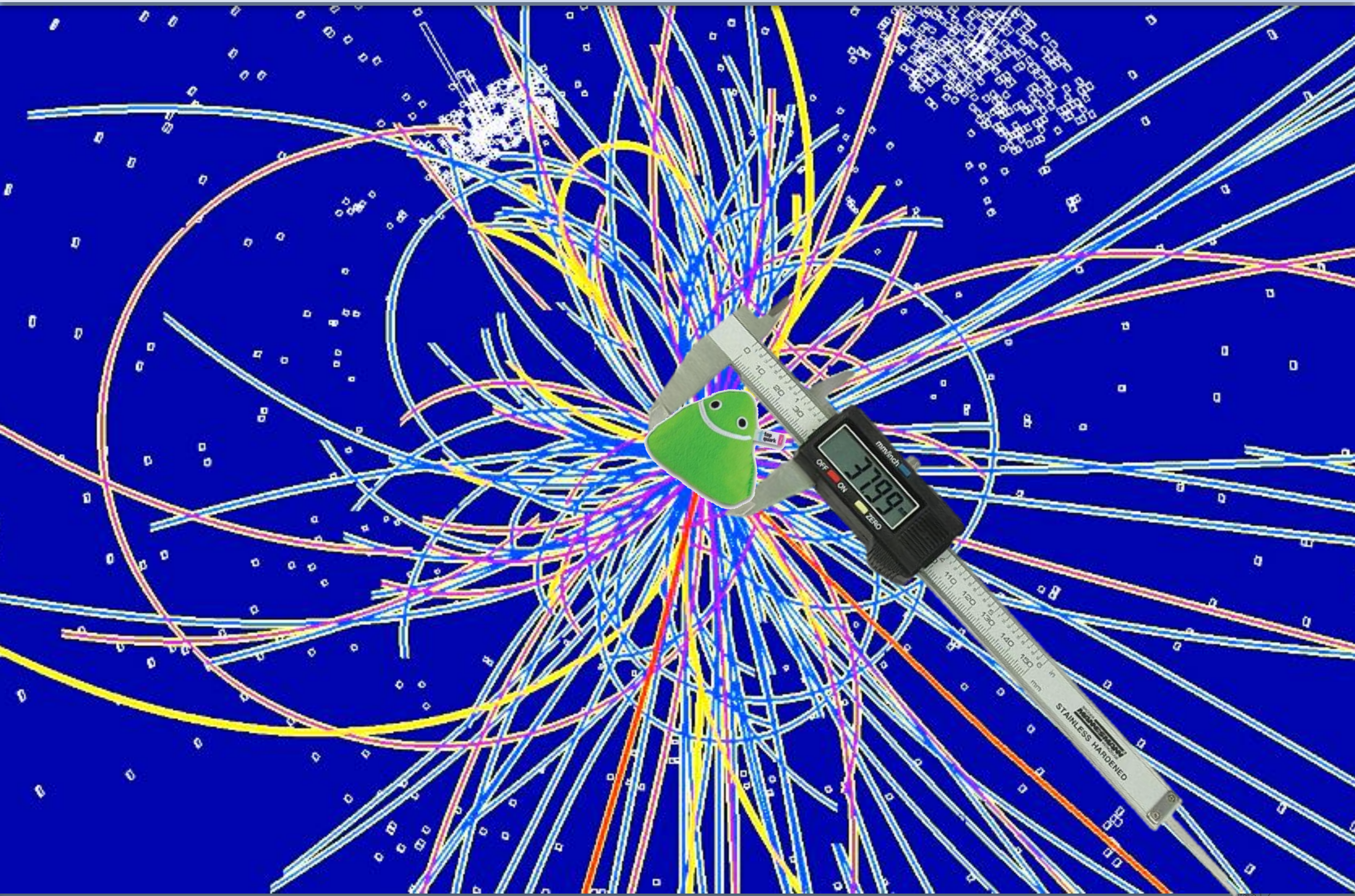


$$E^{\mathrm{ptcl}} = \frac{E^{\mathrm{meas}} - E_{\mathrm{O}}}{R \cdot S}$$

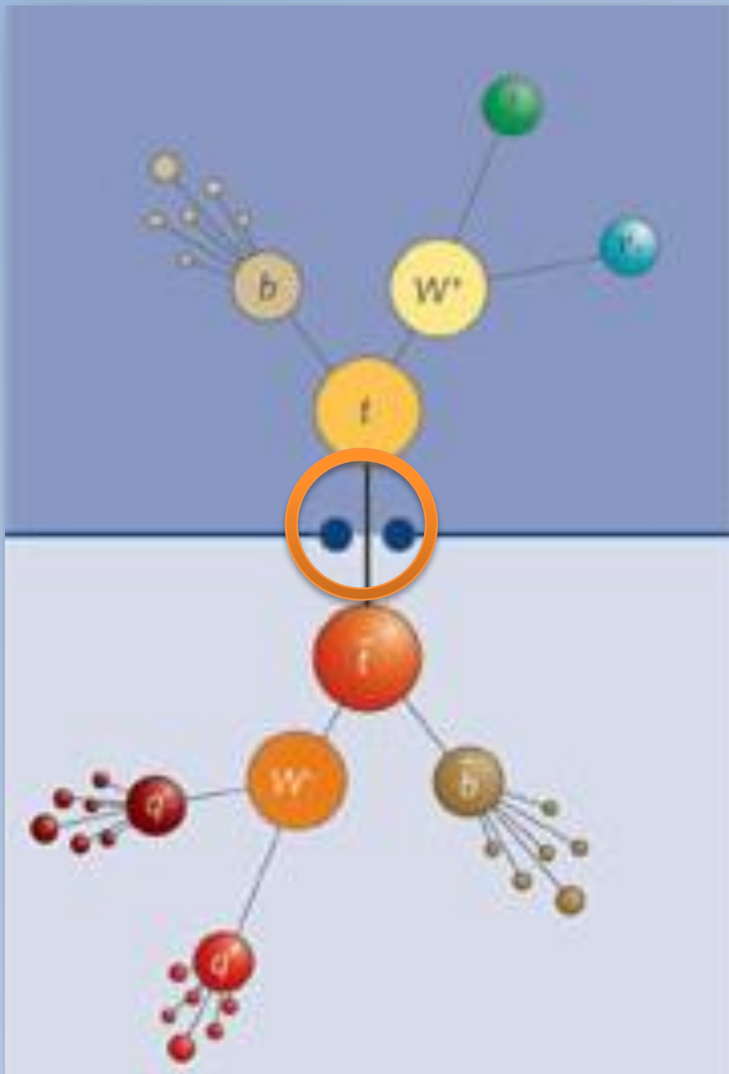




Measurements



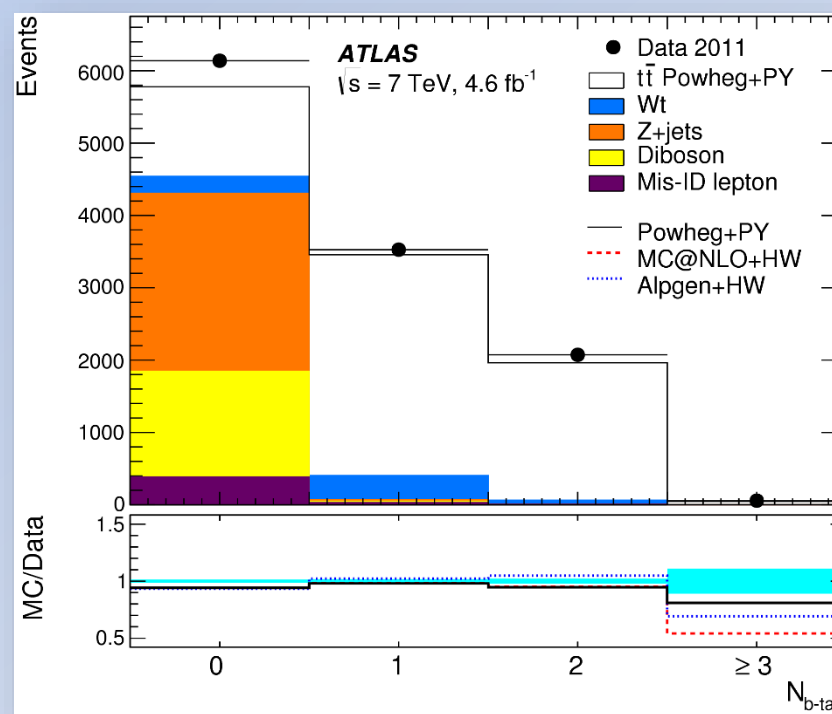
Top quark pair production



Production cross section

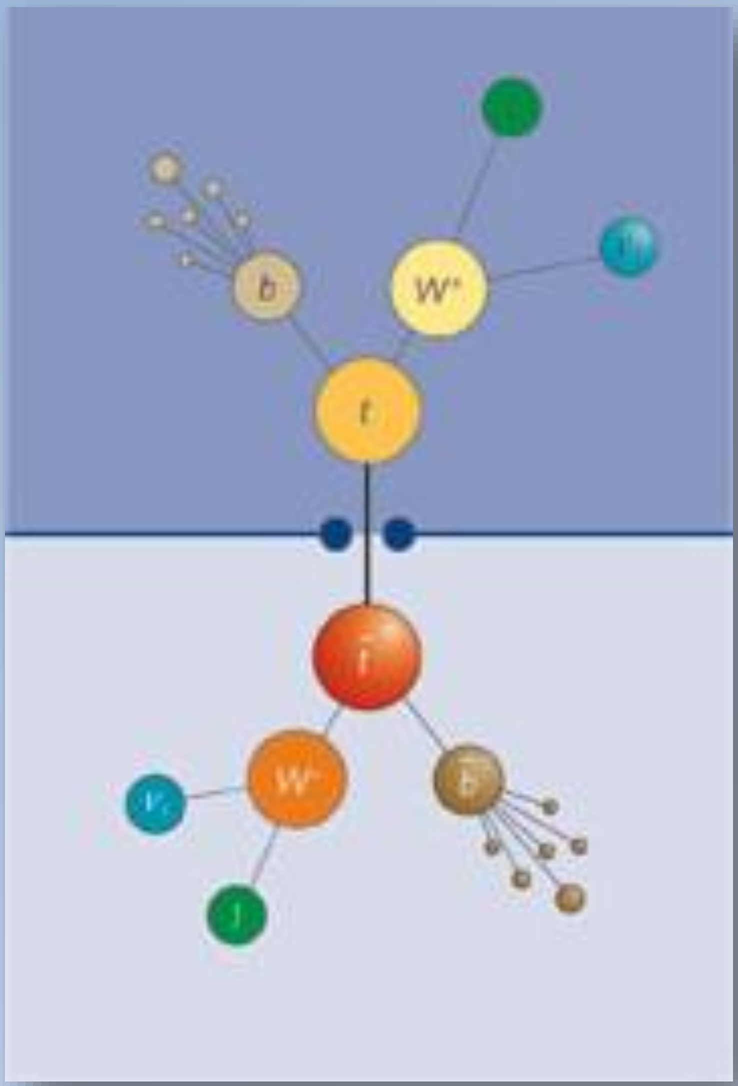
$$N = \epsilon \cdot \sigma \cdot L$$

$$\rightarrow \sigma_{meas} = \frac{N_{meas} - N_{bkg}}{\epsilon \cdot L}, \epsilon = \frac{N_{sel}}{N_{total}}$$



Production cross section measurement

Dilepton - channel



$$\sigma_{meas} = \frac{N_{meas} - \boldsymbol{N_{bkg}}}{\epsilon \cdot L}, \quad \epsilon = \frac{\boldsymbol{N_{sel}}}{N_{total}}$$

Most precise channel: *eμ*-dilepton

- Selection depends only on lepton identification
- Very low background rate
- For cross section no kinematic reconstruction of $t\bar{t}$ system is needed!

Select **opposite-sign eμ-pair**

- b-tagging using multivariate Discriminator – 70% efficiency

Background estimation

Using MC acceptance and modeling

$N = \sigma \cdot \varepsilon \cdot \mathcal{L}$

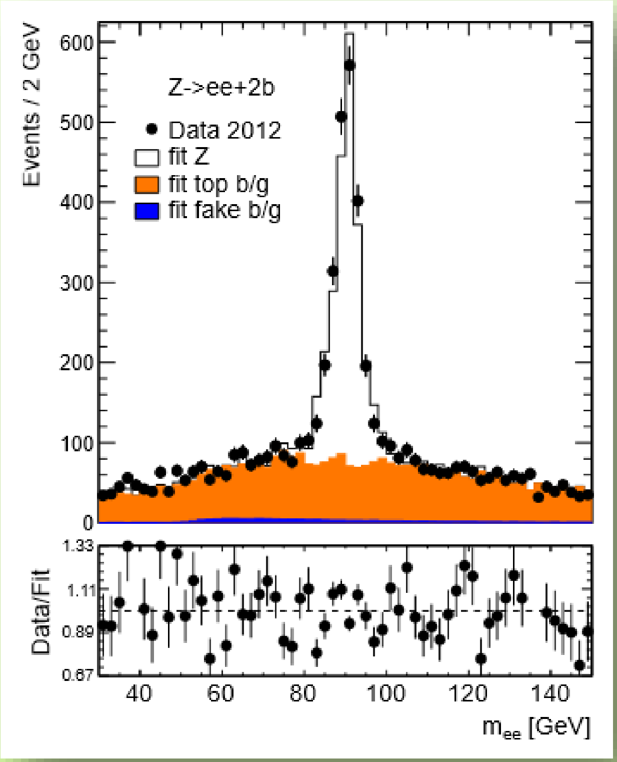
Single top (mainly Wt)

Diboson production (WW / WZ / ZZ)

Using MC modeling but normalization from data

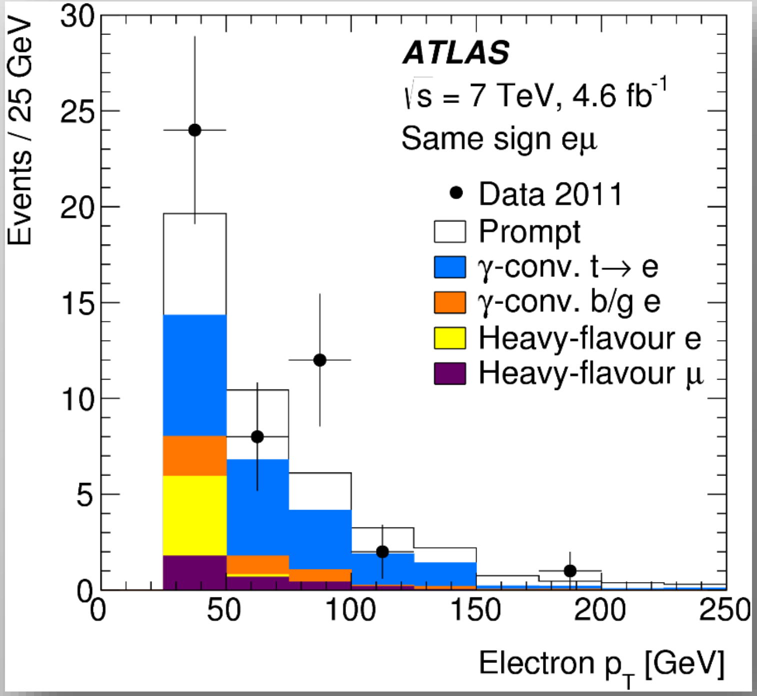
Z+jets

Fit to the Z-mass peak



Background estimation

Using modeling and normalization from data



Use same sign di-lepton events to estimate and model fake background

Final event yield

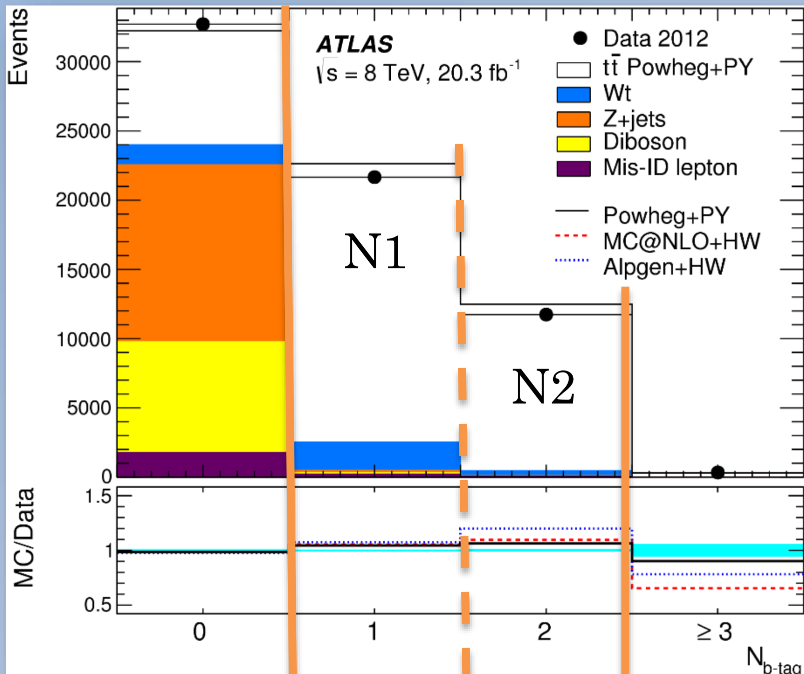
Event counts	$\sqrt{s} = 7$ TeV N_1	N_2	$\sqrt{s} = 8$ TeV N_1	N_2
Data	3527	2073	21666	11739
Wt single top	326 ± 36	53 ± 14	2050 ± 210	360 ± 120
Dibosons	19 ± 5	0.5 ± 0.1	120 ± 30	3 ± 1
$Z(\to \tau\tau \to e\mu)$+jets	28 ± 2	1.8 ± 0.5	210 ± 5	7 ± 1
Misidentified leptons	27 ± 13	15 ± 8	210 ± 66	95 ± 29
Total background	400 ± 40	70 ± 16	2590 ± 230	460 ± 130

Purity:

N1 - exactly 1 b-tagged jet: S/B = 8

N2 - exactly 2 b-tagged jet: S/B = 25

Production cross section measurement



$$\sigma_{meas} = \frac{N_{meas} - \boldsymbol{N_{bkg}}}{\epsilon \cdot L}, \quad \epsilon = \frac{\boldsymbol{N_{sel}}}{N_{total}}$$

- Lepton isolation was directly measured in $t\bar{t}$ like events
- High b-tagging uncertainties
  → determine efficiency from data

$$N_1 = L\boldsymbol{\sigma}_{\mathbf{t\bar{t}}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{bkg}$$

$$N_2 = L\boldsymbol{\sigma}_{\mathbf{t\bar{t}}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{bkg}$$

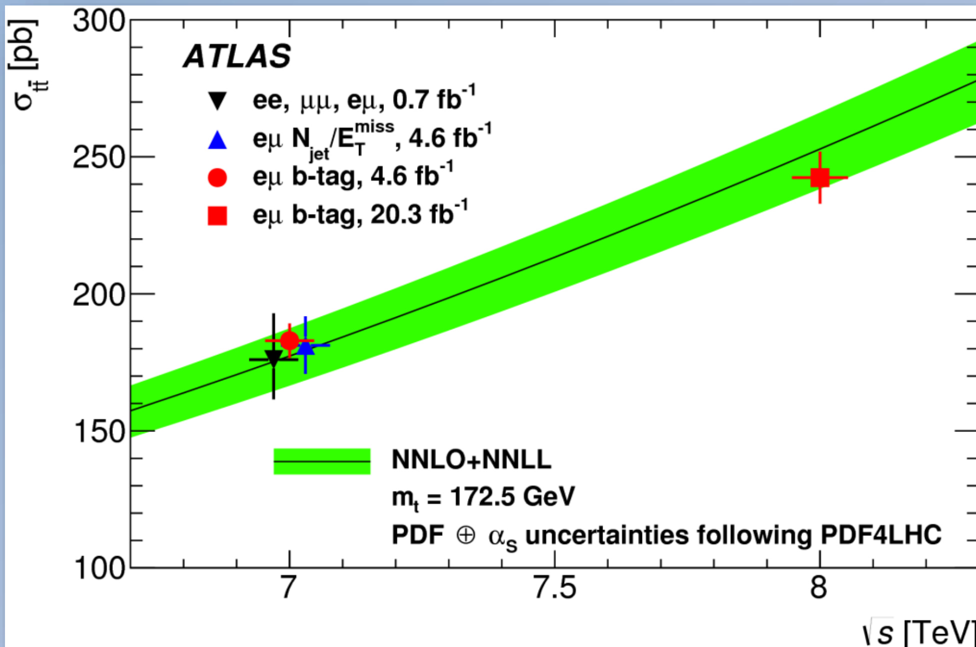
- $\epsilon_{e\mu}$: preselection efficiency
- ϵ_b : b-jet acceptance and tagging efficiency
- C_b : 1 / 2-btag correlation (=1.005)

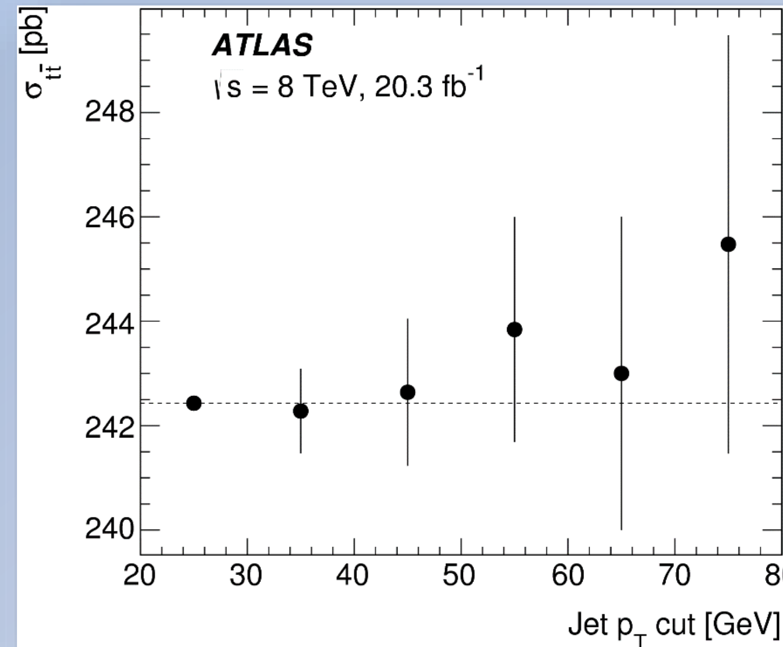
→ Solve equations for $\boldsymbol{\sigma_{t\bar{t}}}$

Systematic uncertaintie

$\sqrt{s}$ Uncertainty (inclusive $\sigma_{t\bar{t}}$)	7 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	7 TeV $\Delta C_b/C_b$ (%)	7 TeV $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	8 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	8 TeV $\Delta C_b/C_b$ (%)	8 TeV $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			1.69			0.71
$t\bar{t}$ modelling	0.71	−0.72	1.43	0.65	−0.57	1.22
Parton distribution functions	1.03	-	1.04	1.12	-	1.13
QCD scale choice	0.30	-	0.30	0.30	-	0.30
Single-top modelling	-	-	0.34	-	-	0.42
Single-top/$t\bar{t}$ interference	-	-	0.22	-	-	0.15
Single-top Wt cross-section	-	-	0.72	-	-	0.69
Diboson modelling	-	-	0.12	-	-	0.13
Diboson cross-sections	-	-	0.03	-	-	0.03
Z+jets extrapolation	-	-	0.05	-	-	0.02
Electron energy scale/resolution	0.19	−0.00	0.22	0.46	0.02	0.51
Electron identification	0.12	0.00	0.13	0.36	0.00	0.41
Muon momentum scale/resolution	0.12	0.00	0.14	0.01	0.01	0.02
Muon identification	0.27	0.00	0.30	0.38	0.00	0.42
Lepton isolation	0.74	-	0.74	0.37	-	0.37
Lepton trigger	0.15	−0.02	0.19	0.15	0.00	0.16
Jet energy scale	0.22	0.06	0.27	0.47	0.07	0.52
Jet energy resolution	−0.16	0.08	0.30	−0.36	0.05	0.51
Jet reconstruction/vertex fraction	0.00	0.00	0.06	0.01	0.01	0.03
b-tagging	-	0.18	0.41	-	0.14	0.40
Misidentified leptons	-	-	0.41	-	-	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	1.56	0.75	2.27	1.66	0.59	2.26
Integrated luminosity	-	-	1.98	-	-	3.10
LHC beam energy	-	-	1.79	-	-	1.72
Total uncertainty ($\sigma_{t\bar{t}}$)	1.56	0.75	3.89	1.66	0.59	4.27

Production cross section measurement





Precision Measurement

stat | syst | lumi | beam

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\mathrm{pb}\ (\sqrt{s} = 7\,\mathrm{TeV})$$ 3.9%

$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\mathrm{pb}\ (\sqrt{s} = 8\,\mathrm{TeV})$$ 4.3%

2%/1% | 2%/2% | 2%/3% | 2%/2%

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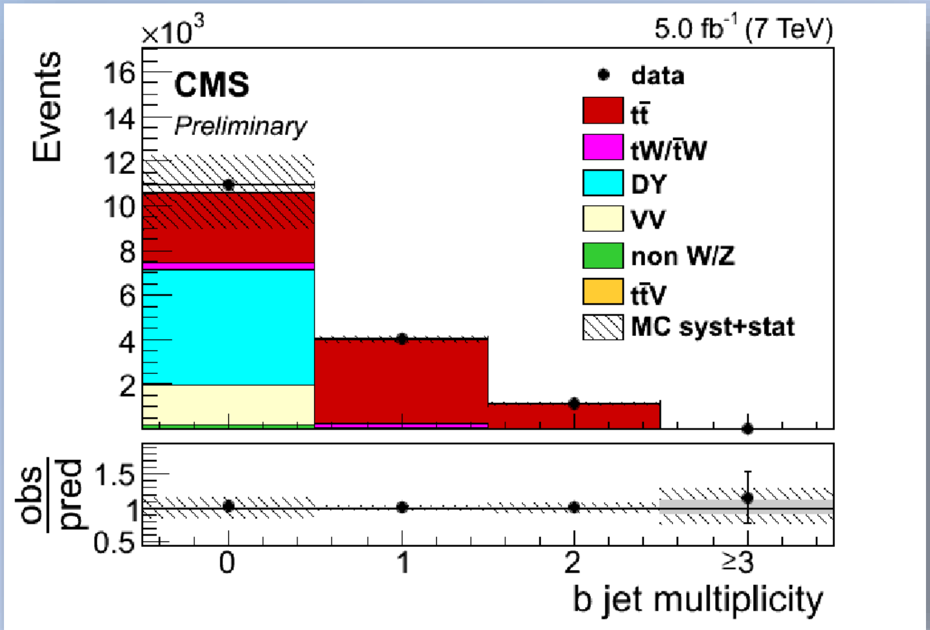
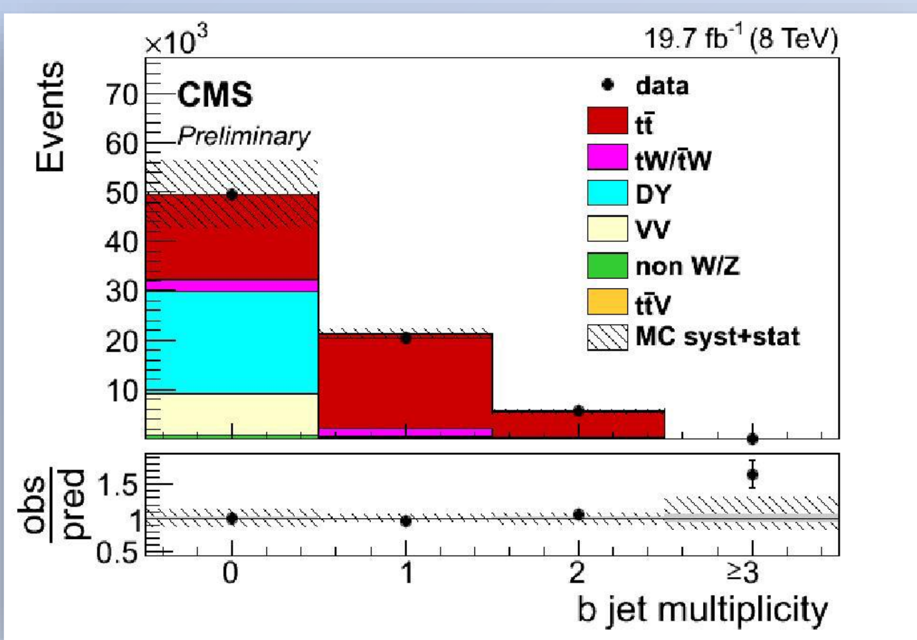
Production cross section measurement

CMS uses an similar approach:

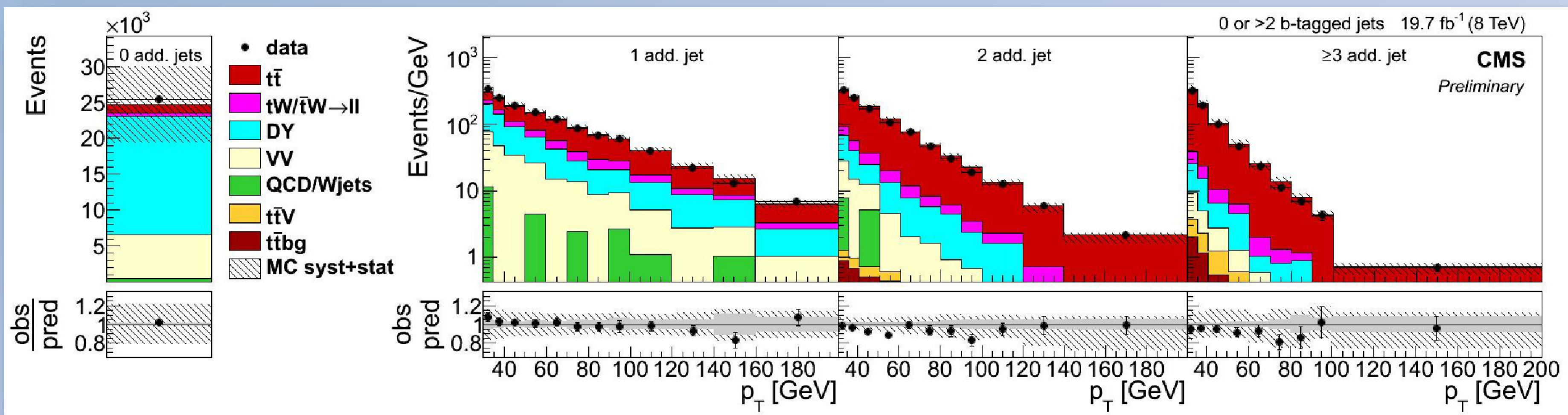
$$s_1 = \mathcal{L}\sigma_{t\bar{t}}^{vis}\epsilon_{e\mu} \cdot 2\epsilon_b(1 - C_b\epsilon_b)$$
$$s_2 = \mathcal{L}\sigma_{t\bar{t}}^{vis}\epsilon_{e\mu} \cdot \epsilon_b^2 C_b$$
$$s_0 = \mathcal{L}\sigma_{t\bar{t}}^{vis}\epsilon_{e\mu} \cdot (1 - 2\epsilon_b(1 - C_b\epsilon_b) - C_b\epsilon_b^2)$$





Production cross section measurement

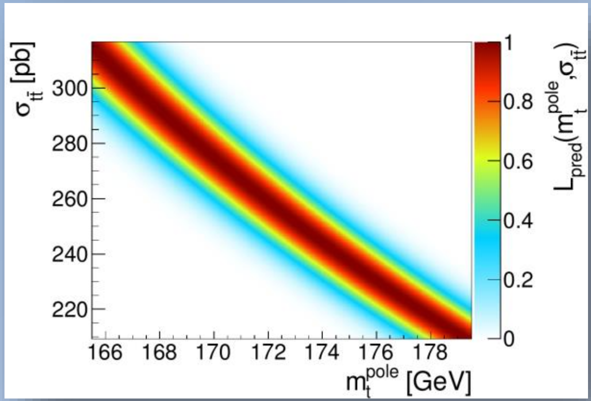
Jet p_T allow fit to constrain systematics related to gluon radiation, jet energy scale, etc.
→ no counting experiment anymore!

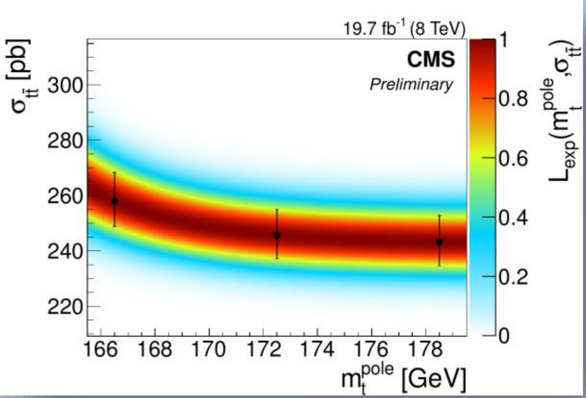


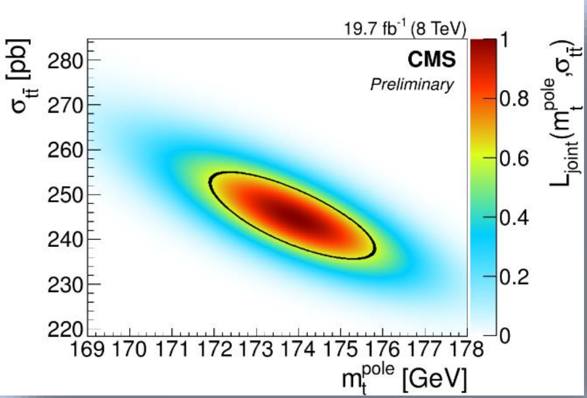
$$\sigma_{t\bar{t}} = 174.5 \pm 2.1\,(\text{stat}) \pm^{4.5}_{4.0}\,(\text{syst}) \pm 3.8\,(\text{lumi})\,\text{pb} \quad \text{at } \sqrt{s} = 7\,\text{TeV}$$
$$\sigma_{t\bar{t}} = 245.6 \pm 1.3\,(\text{stat}) \pm^{6.6}_{5.5}\,(\text{syst}) \pm 6.5\,(\text{lumi})\,\text{pb} \quad \text{at } \sqrt{s} = 8\,\text{TeV}.$$

Application of cross section measurement

These applications are only possible with a high precision cross section

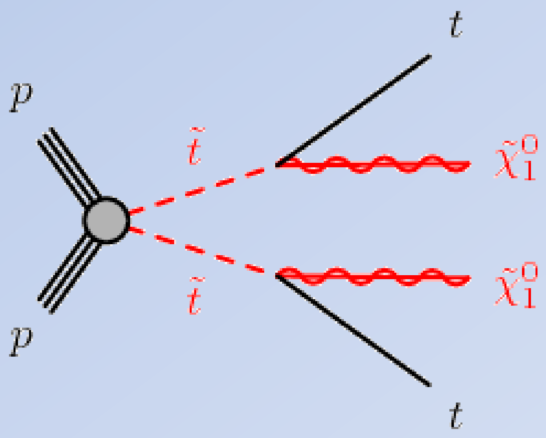


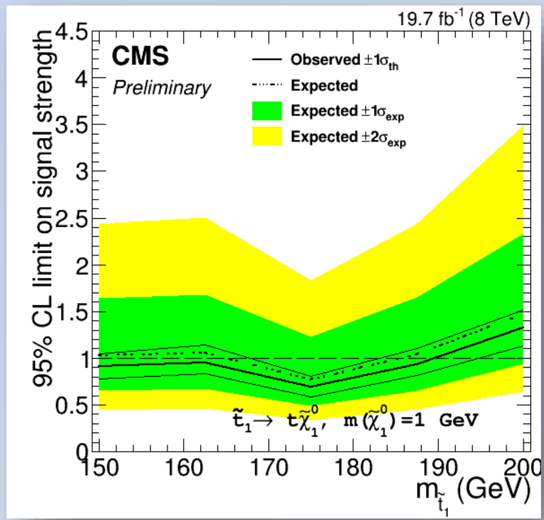




$\rightarrow m_{top} = 173.6^{+1.7}_{-1.8}$ GeV

Search for SUSY particles with mass close to the top quark





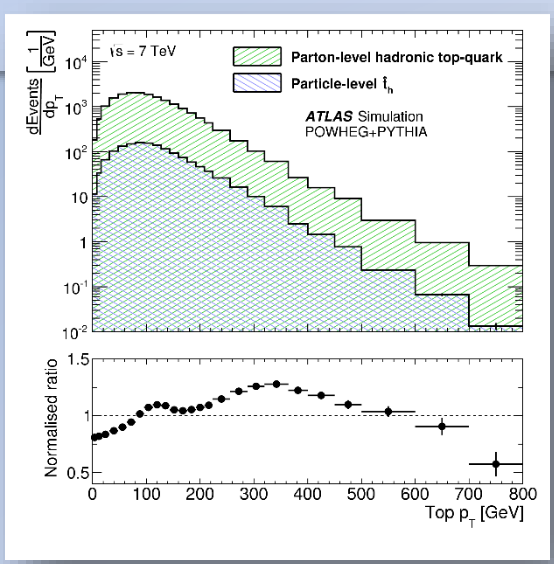
Differential cross sections

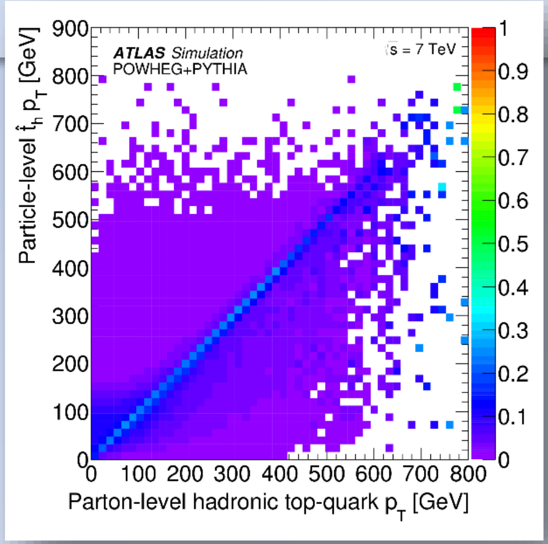
Idea: Measure cross section with respect of a kinematic distribution

Two different conventions:

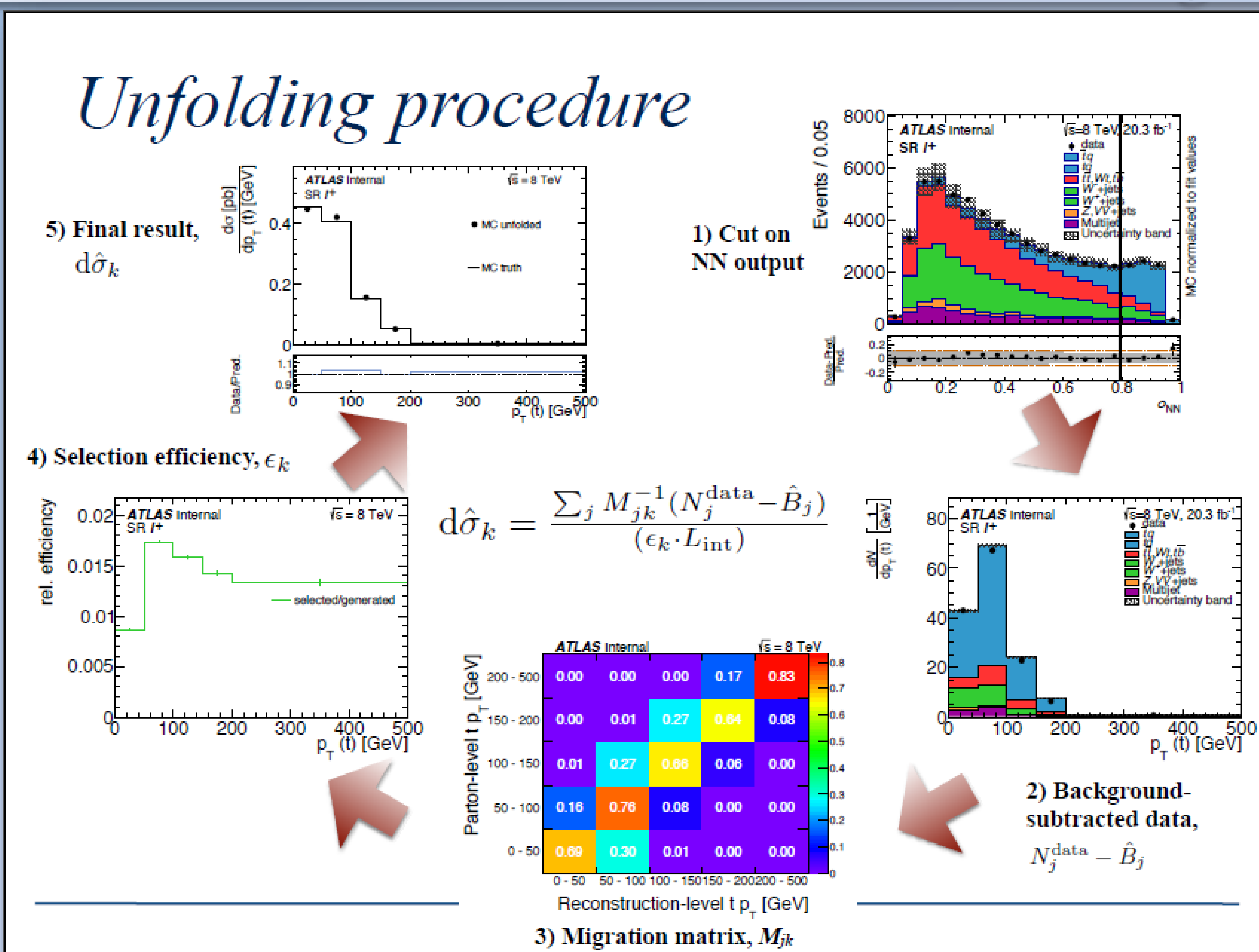
- **Parton level**:
  Select the last top quark after radiation from the MC event record

- **Particle level**:
  Reconstruct "pseudo"-top from stable particles
  → consistent with measurable quantities, no extrapolation into full phase space

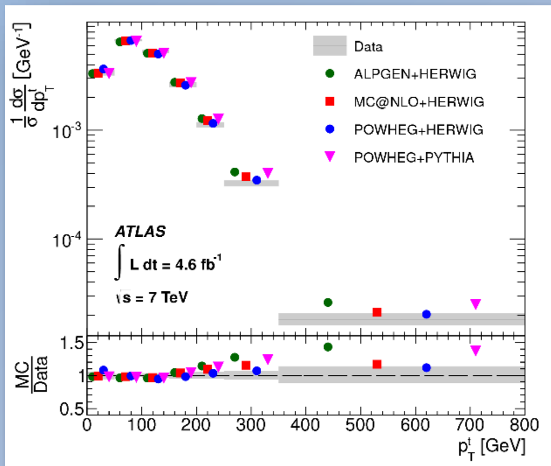


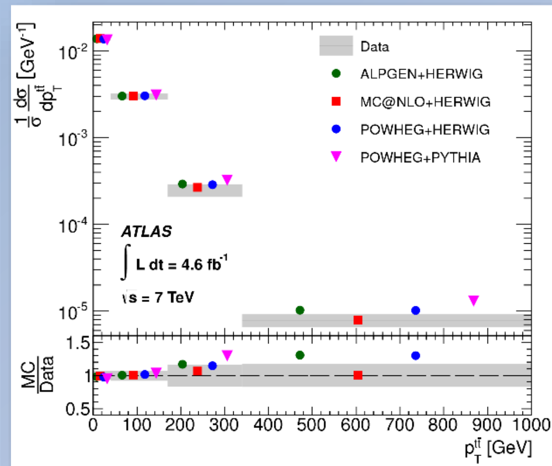


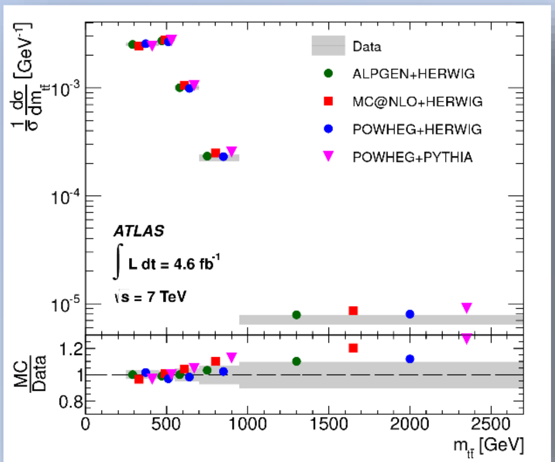
Differential cross sections - Unfolding

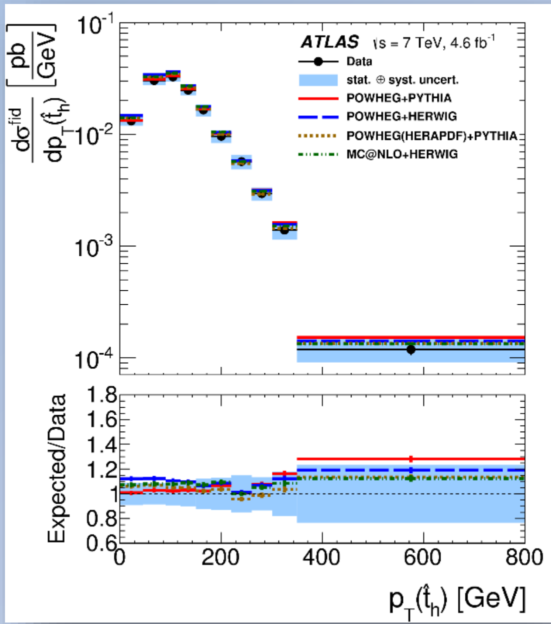


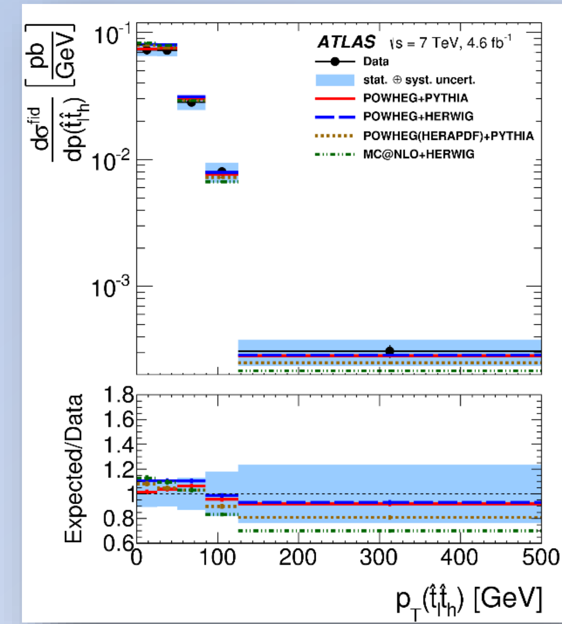
Differential cross sections

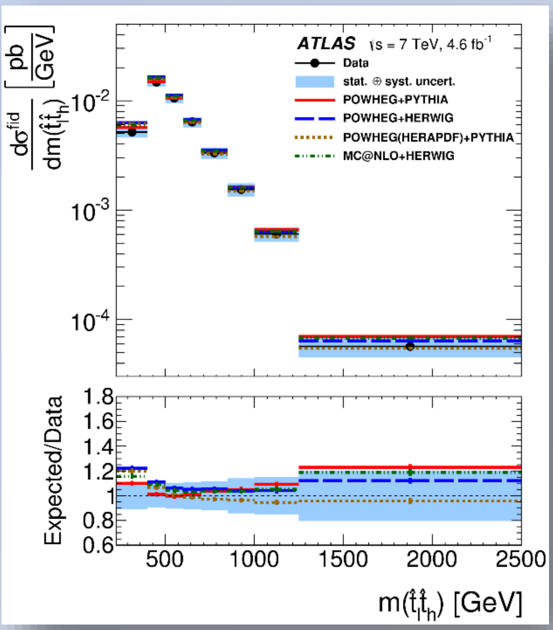




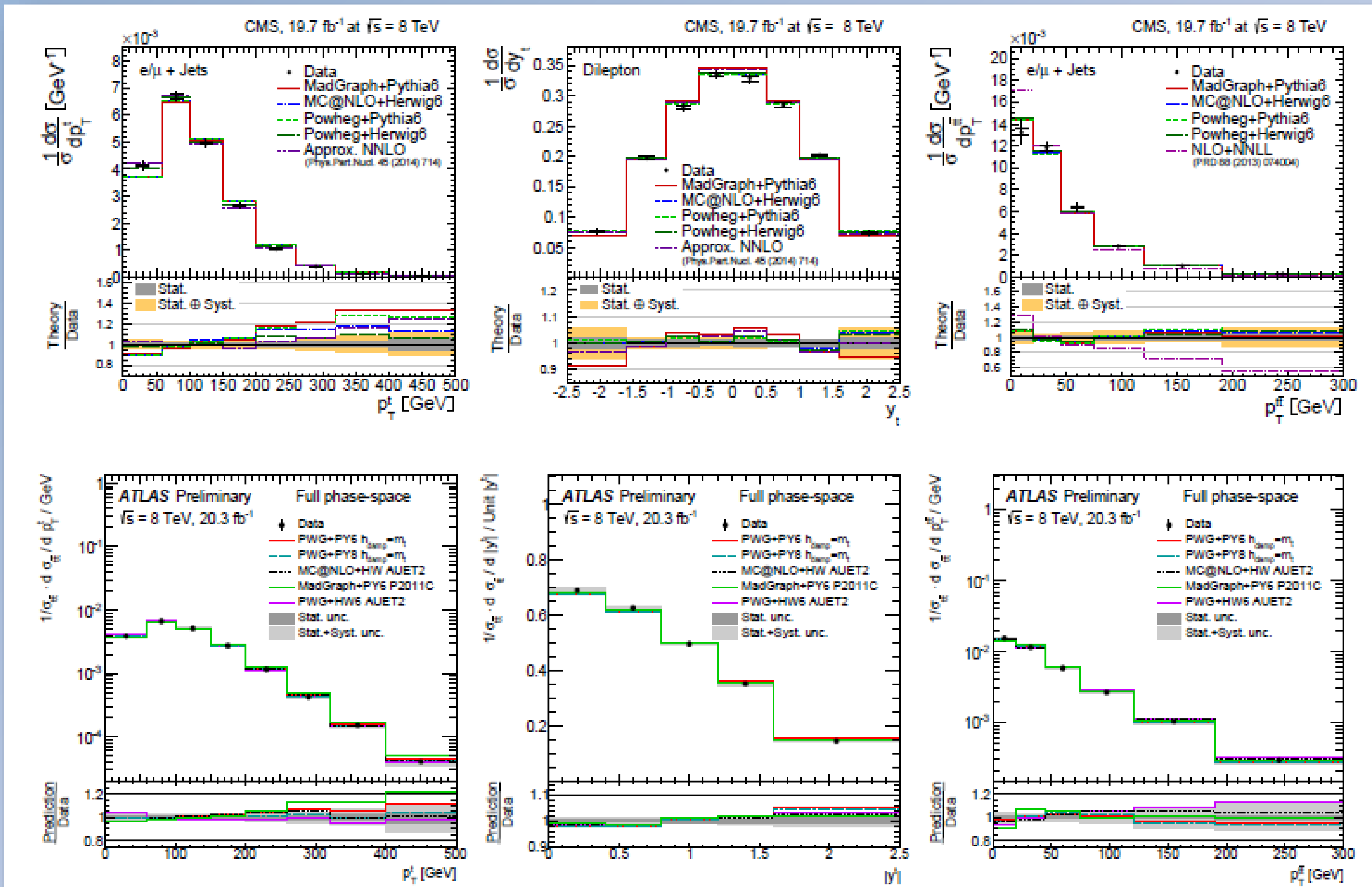




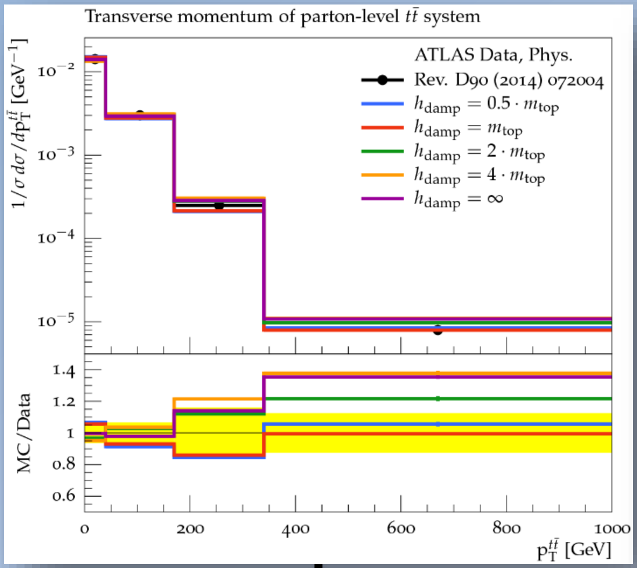


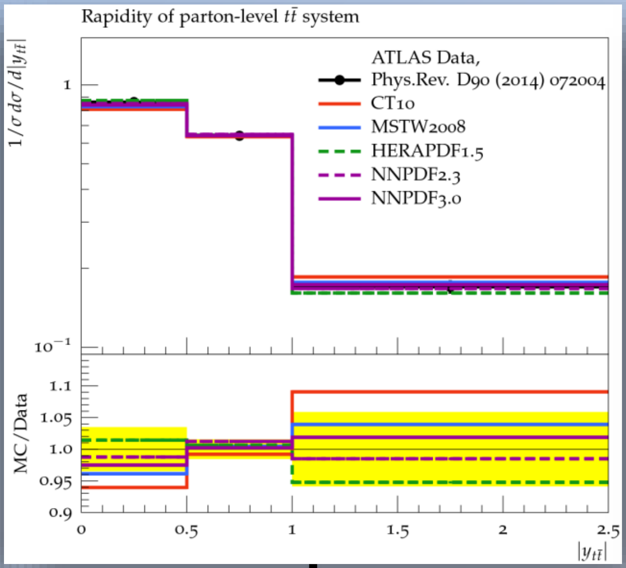


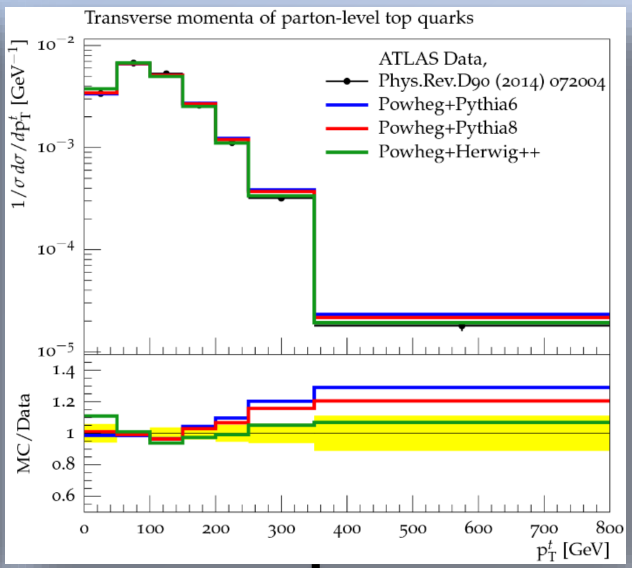
Differential cross sections



Tuning of MC parameters







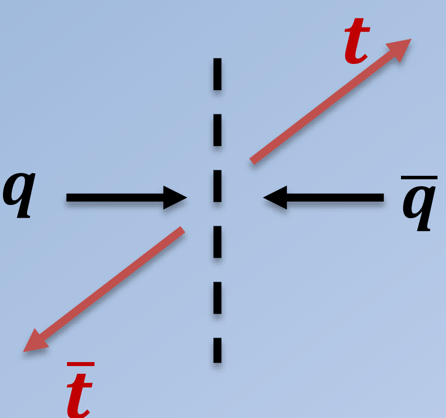
Tuning matching parameter between matrix element calculation and parton shower

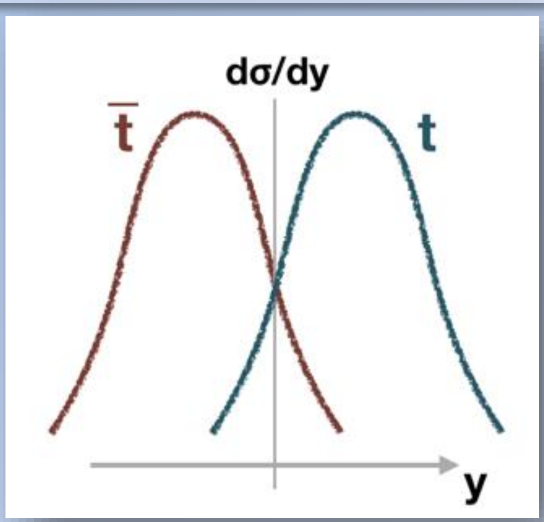
„Tune“ choice of PDF

Soft top p_T not fully understood yet!

Charge asymmetry - Tevatron

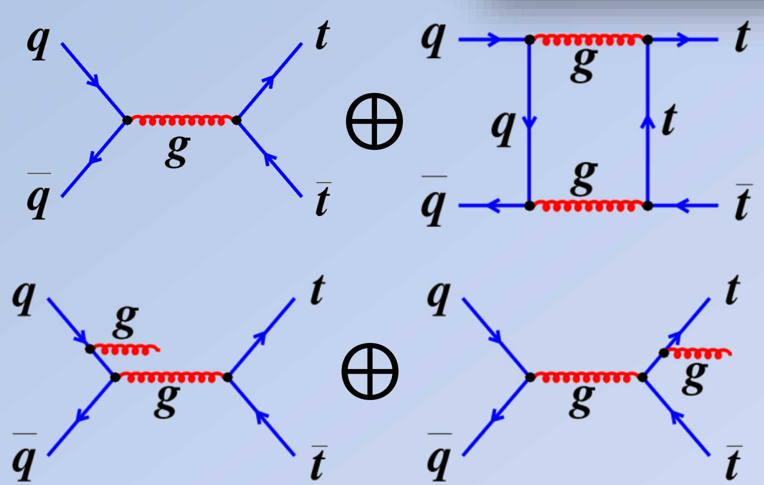
What is charge asymmetry?
An asymmetry in the differential rate of top quark and anti-top quark production with respect to some direction

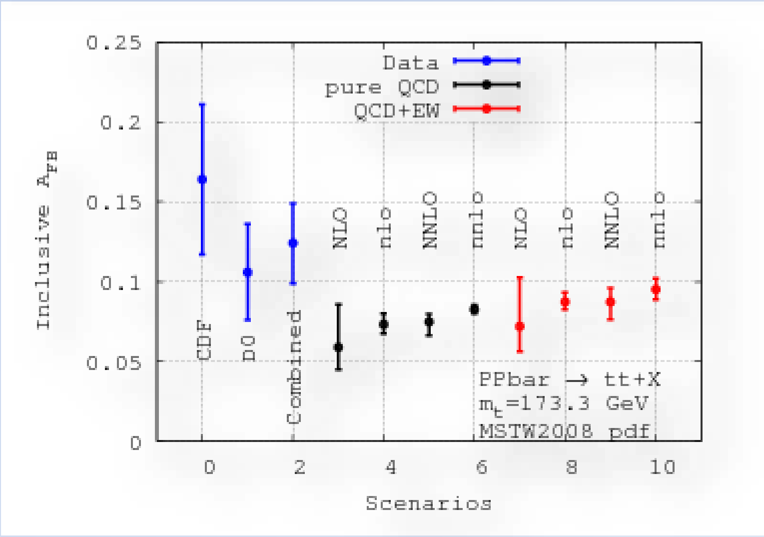




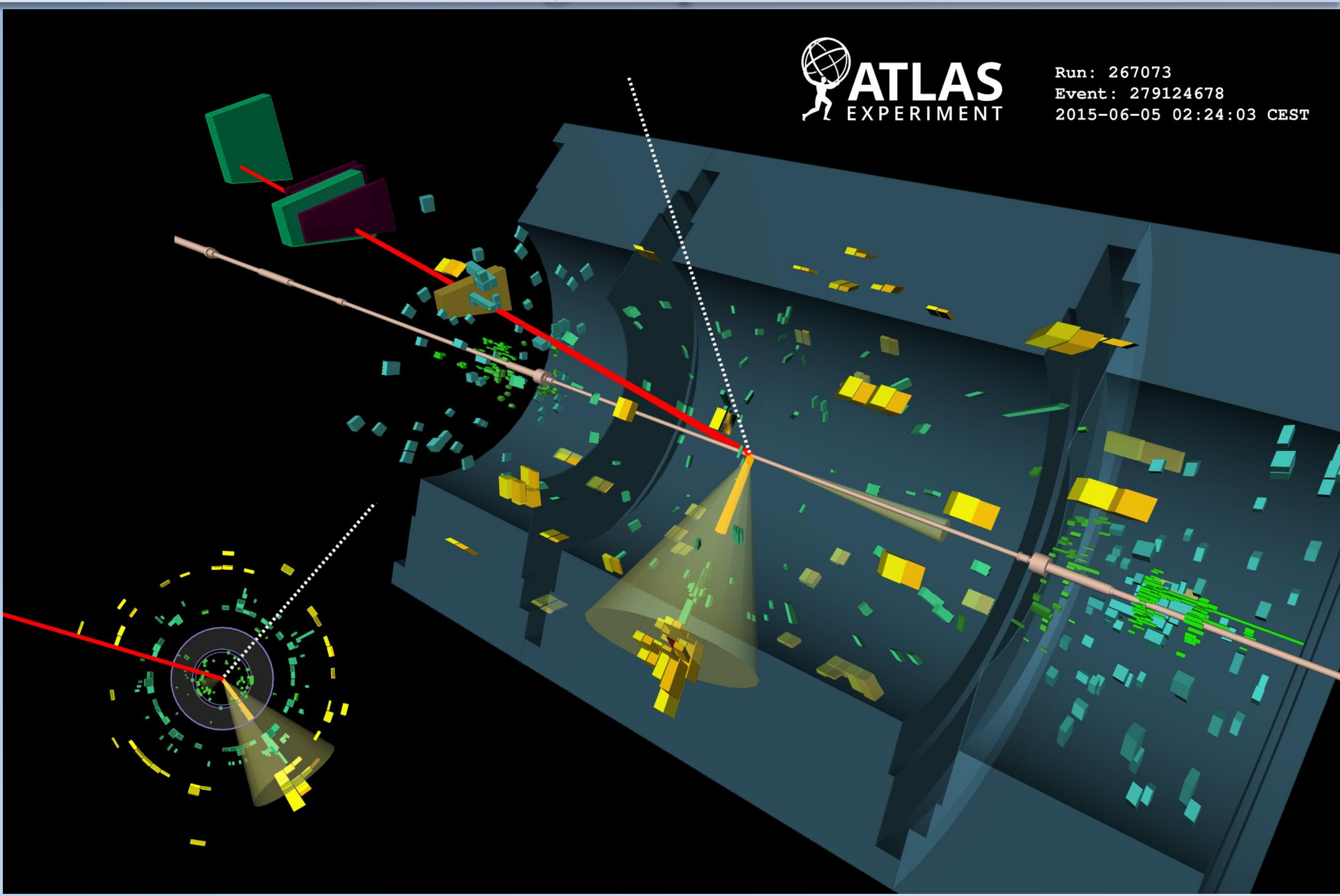
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

with $\Delta y = y_{top} - y_{anti\text{-}top}$

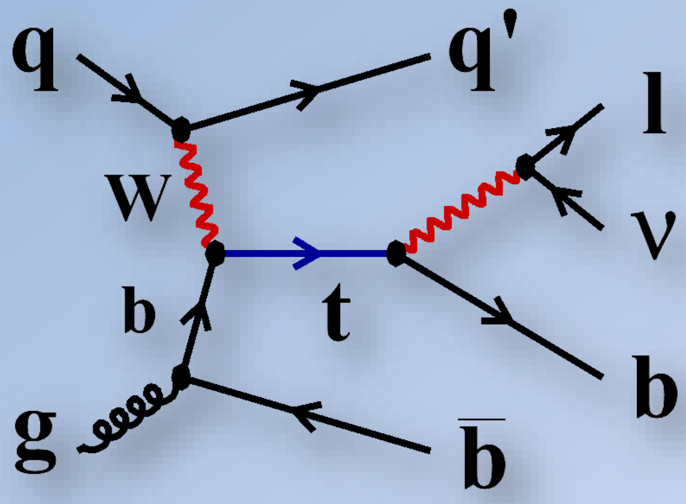




t-channel singe top measurements

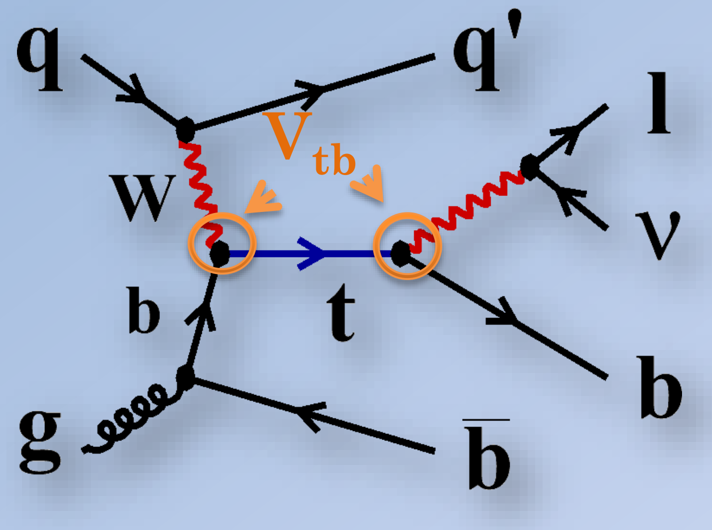


t-channel single top quark production



Why study t-channel single top?

Cross section ∝ $|V_{tb}|^2$
→ test of the unitarity of the CKM Matrix



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Cross section ∝ $|V_{tb}|2$
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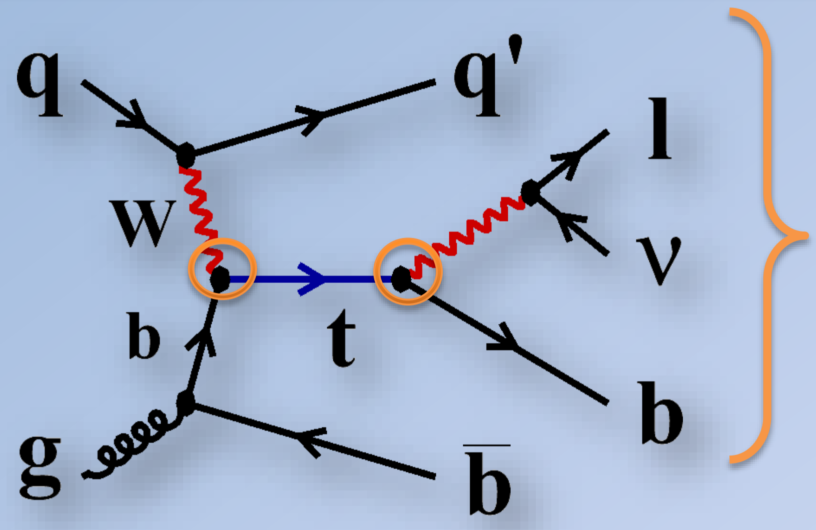

Test of the V-A structure of the Wtb vertex, e.g. using the top polarisation or W helicity

Why study t-channel single top?

Cross section ∝ $|V_{tb}|2$
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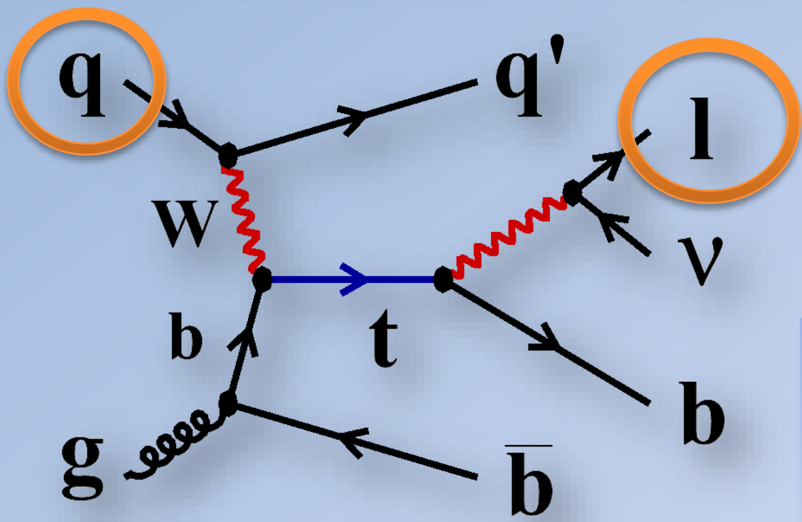
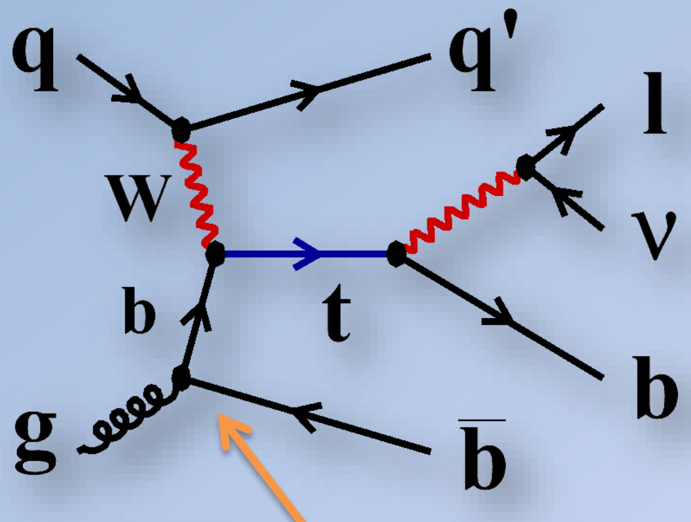


Test of the V-A structure of the Wtb vertex, e.g. using the top polarisation or W helicity

The cross-section ratio top-quark/top-antiquark production is sensitive to the u/d-quark ratio in the PDF sets.

Why study t-channel single top?

Cross section ∝ $|V_{tb}|2$
→ test of the unitarity of the CKM Matrix



Test of the b-quark PDF

Test of the V-A structure of the Wtb vertex, e.g. using the top polarisation or W helicity

The cross-section ratio top-quark/top-antiquark production is sensitive to the u/d-quark ratio in the PDF sets.

Why study t-channel single top?

Cross section ∝ $|V_{tb}|^2$
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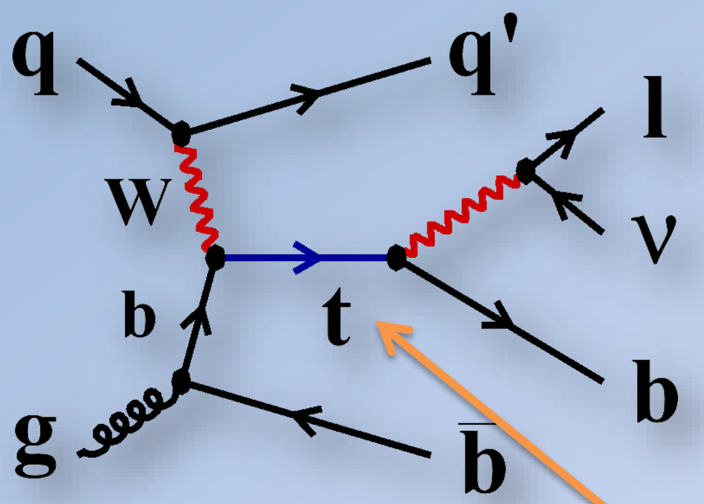


Test of the V-A structure of the Wtb vertex, e.g. using the top polarisation or W helicity

The cross-section ratio top-quark/top-antiquark production is sensitive to the u/d-quark ratio in the PDF sets.

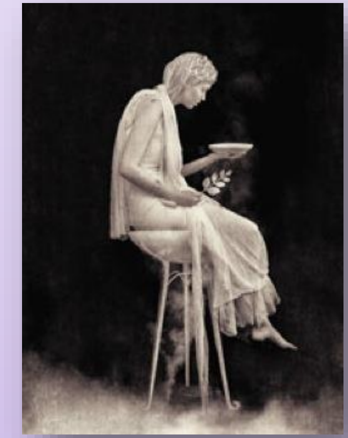
Test of the b-quark PDF

Top quark mass

Background estimation

Using MC acceptance and modeling

$N = \sigma \cdot \varepsilon \cdot \mathcal{L}$



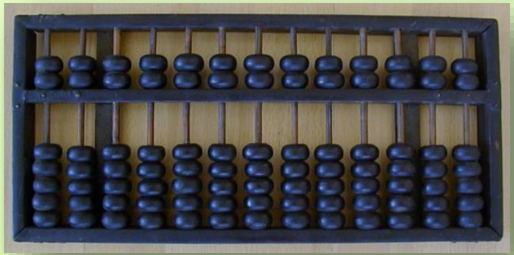
Diboson, Z+jets, s-channel, Wt

Using MC modeling but normalization from data

$$N^{pretag}_{W+jets} = N^{pretag}_{data} - N^{pretag}_{qcd} - N^{pretag}_{MC}$$

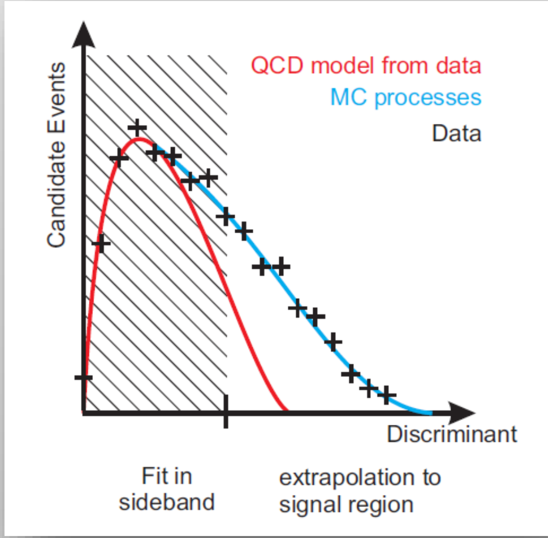
$$N^{tag}_{\Phi,n} = N^{pretag} F^{pretag}_{\Phi,n} P^{tag}_{\Phi,n} \, .$$

$$N^{tag}_{data-bkg,2} = N^{pretag}_{data-bkg,2} \cdot (F^{pretag}_{bb,2} \cdot P^{tag}_{bb,2} + k^{pretag}_{cctobb} \cdot F^{pretag}_{bb,2} \cdot P^{tag}_{cc,2} + F^{pretag}_{c,2} \cdot P^{tag}_{c,2} + F^{pretag}_{l,2} \cdot P^{tag}_{l,2}) = N^{pretag}_{data-bkg,2} \cdot (k^{pretag}_{bb1to2} \cdot F^{pretag}_{bb,1} \cdot P^{tag}_{bb,2} + k^{pretag}_{cctobb} \cdot k^{pretag}_{bb1to2} \cdot F^{pretag}_{bb,1} \cdot P^{tag}_{cc,2} + k^{pretag}_{c1to2} \cdot F^{pretag}_{c,1} \cdot P^{tag}_{c,2} + k^{pretag}_{l1to2} \cdot F^{pretag}_{l,1} \cdot P^{tag}_{l,2}).$$



W+jets , $t\bar{t}$

Using modeling and normalization from data (Mostly „fake“ backgrounds)



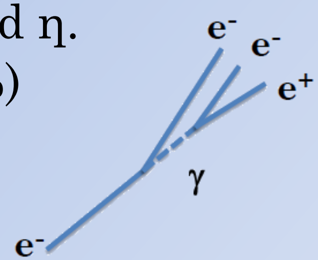
QCD multijets
W+jets
(CMS in some analyses)

Models for QCD-multijet background

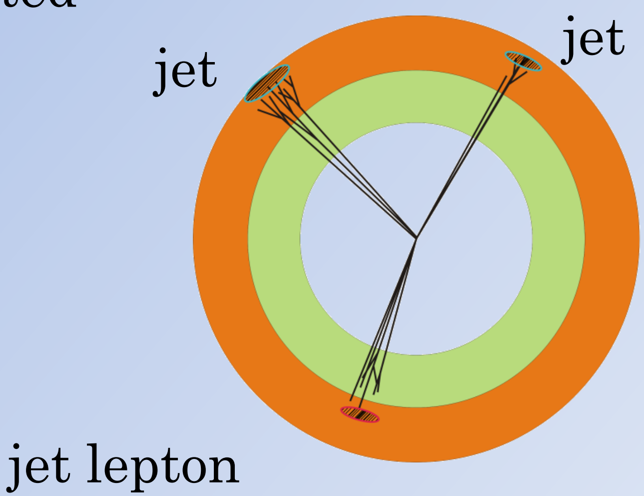
Jet lepton model:
Use jet triggered data or di-jet MC

Identification of a jet as a "fake" lepton:

- Use same acceptance as real electrons / muons in p_T und η.
- High em fraction (80% - 95%)
- At least 3 tracks



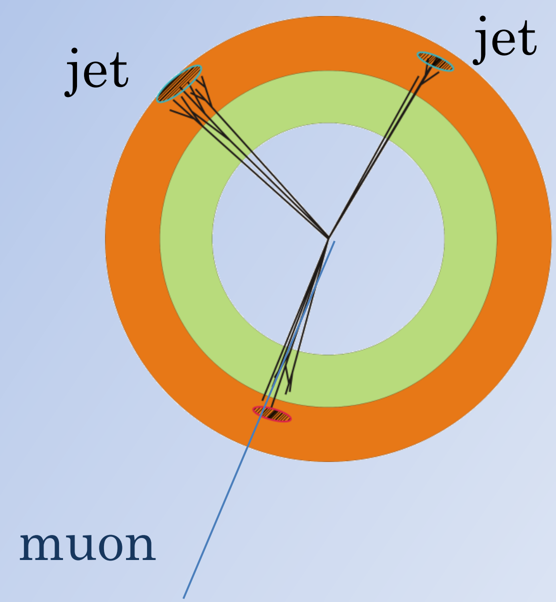
- Events with real (signal) leptons are rejected



Anti-muon / Anti-electron:
Use lepton triggered data

Revert some ID cuts, e.g.:

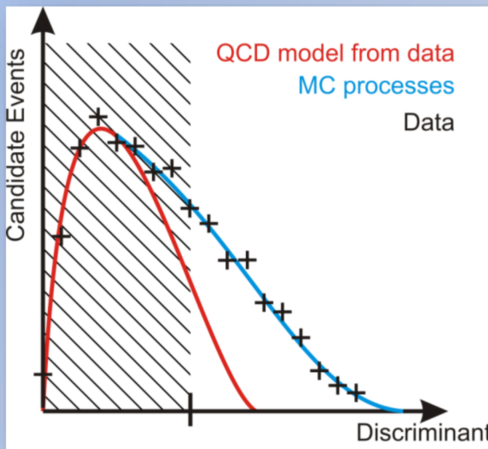
- Impact parameter
- Isolation
- Energy loss type

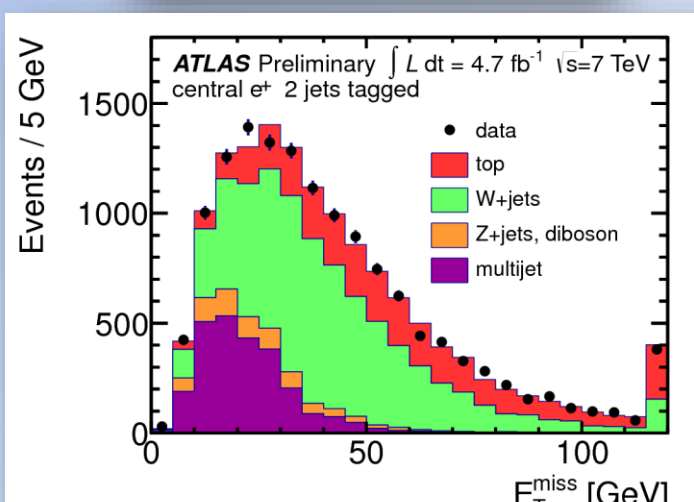


Determination of the QCD-multijet background

ATLAS:

Binned Likelihood fit to the E_T^{miss} distribution





CMS:

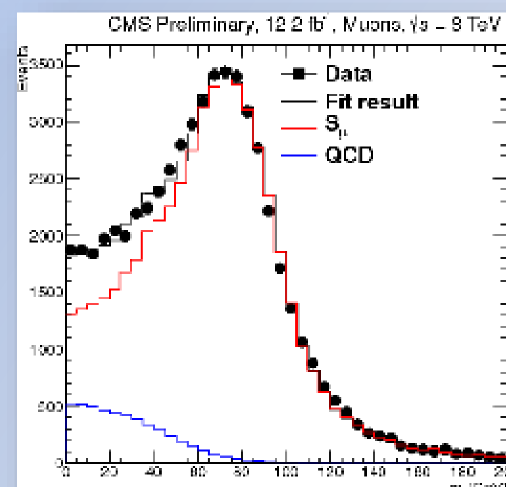
Likelihood fit to the E_T^{miss} (electrons) or $m_T(W)$ (muons) distribution

Parameterisation:

$$F(x) = a \cdot S(x) + b \cdot B(x)$$

W-Boson processes (from MC)

QCD model



Typical event yields

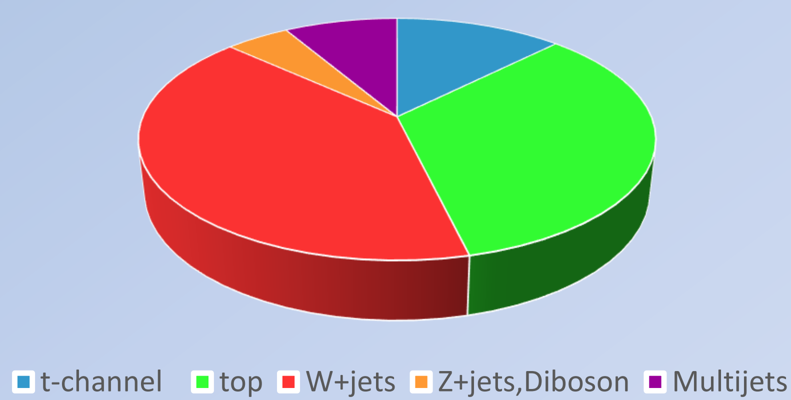
Numbers are for 20 fb^{-1} @ 8 TeV

Process	W CR	$t\bar{t}$ CR	SR
t-channel	9580 ± 960	647 ± 65	18100 ± 1800
$t\bar{t}$, Wt, s-channel	25500 ± 2000	9560 ± 770	54200 ± 4300
W+jets	285000 ± 156000	2000 ± 1100	51000 ± 28000
Z+jets, diboson	25000 ± 6000	328 ± 79	6900 ± 1700
Multijet	44000 ± 22000	650 ± 320	11800 ± 5900
Total expectation	390000 ± 158000	13000 ± 1400	142000 ± 29000
Data	389919	13041	143332

Purity:
2 jet channel: S/B = 13%
3 jet channel: S/B = 9%

→ Usage of neural networks to further enhance the signal, but cut-based is also possible

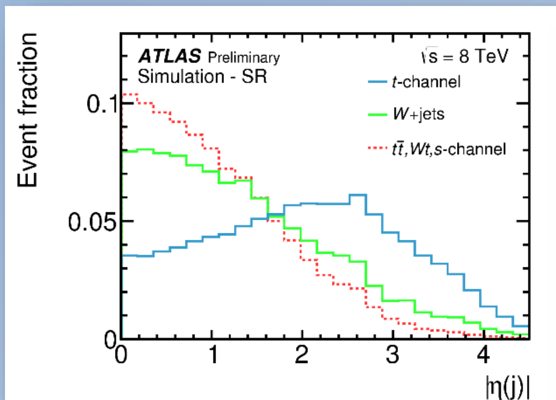
Event Fractions

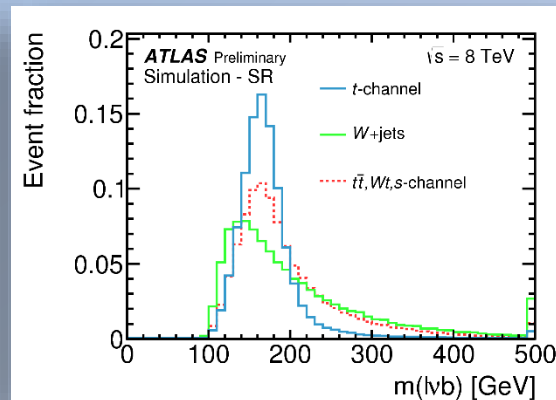


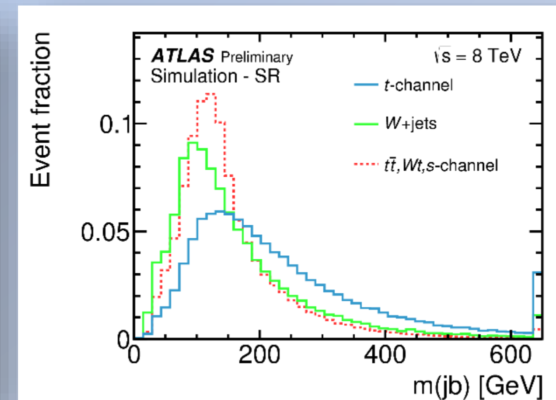
Process	Fraction
t-channel	13%
s-channel, Wt, tt	38%
W+jets	36%
Z+jets,Diboson	5%
Multijet	8%

Multivariate Analyses

Idea: Combine many variables including correlations in one discriminate







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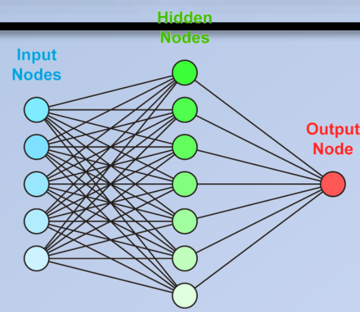
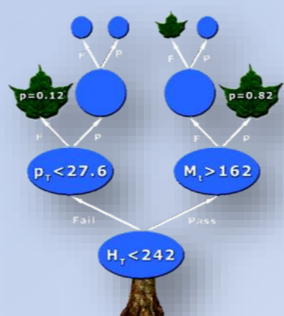
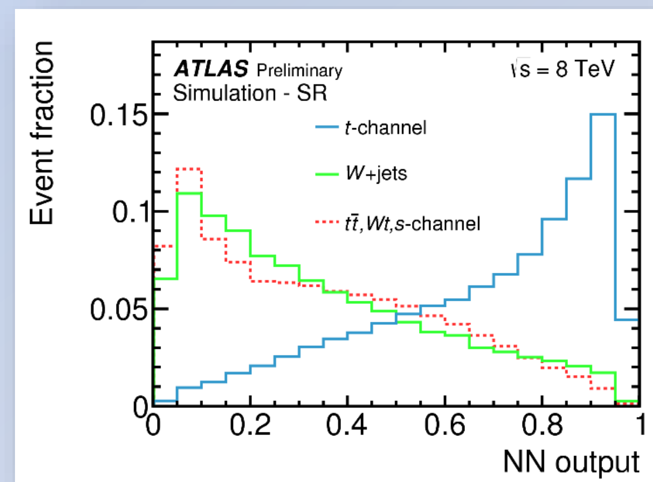
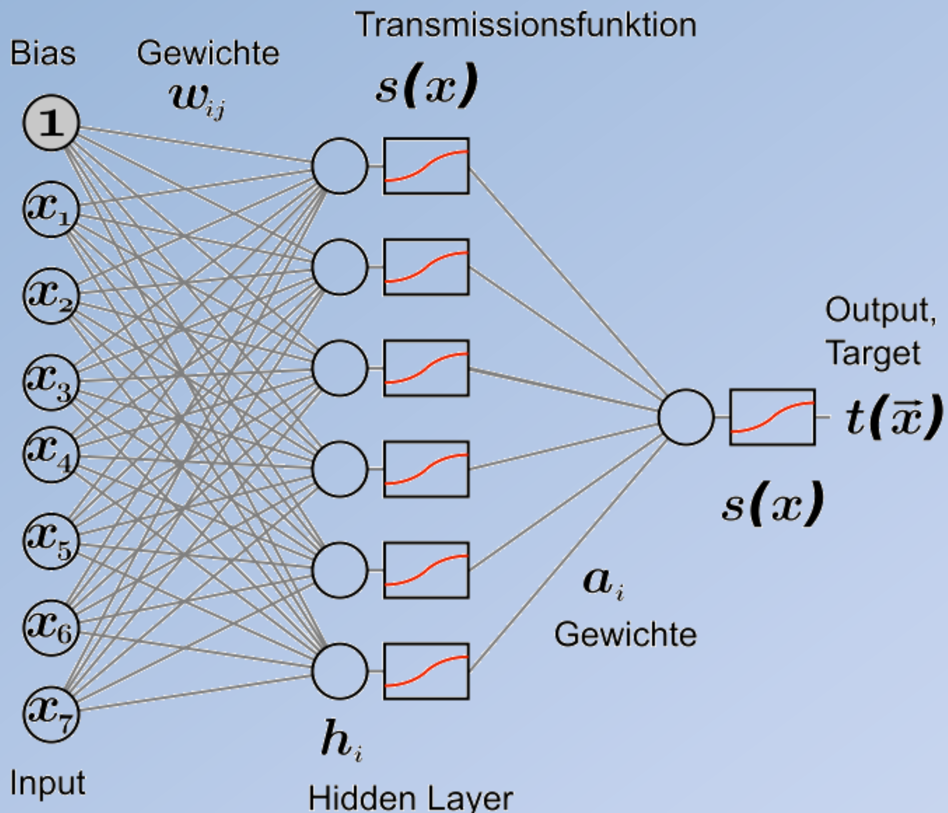


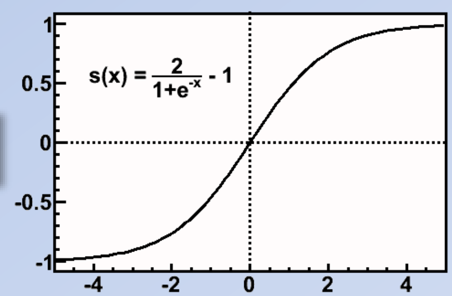




Analysis technique – neural networks



$$(-\infty, +\infty) \xrightarrow{s(x)} [-1, +1]$$



Implementation in NeuroBayes

Construction of a continuous discriminate from several variables using a neural network

Training with simulated events:

- Training target:
  signal = 1, background = 0.
- Modification of the weights between different nodes for a optimal separation.

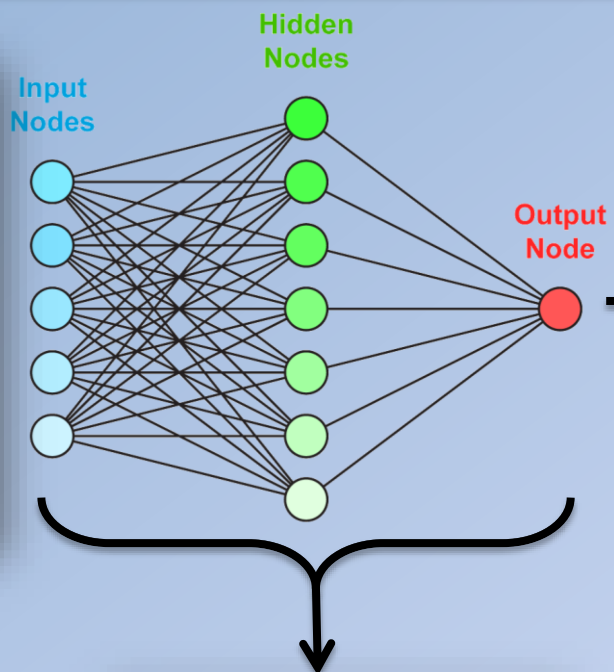
- Minimizing the „quadratic loss-function “:

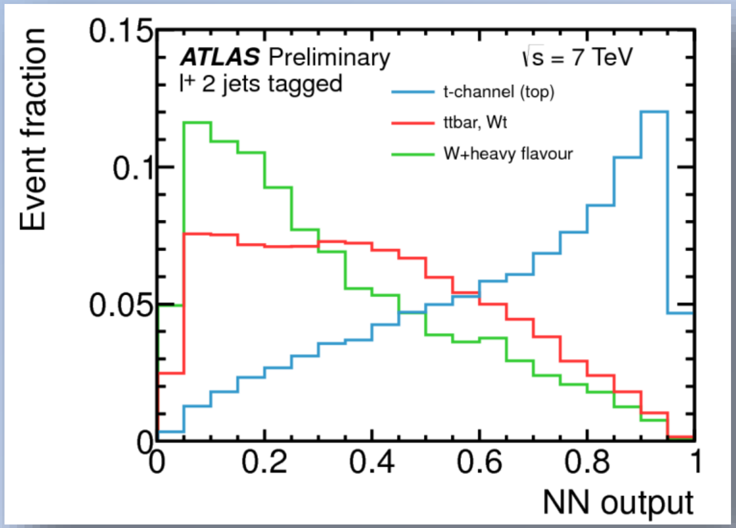
$$E = \frac{1}{2} \sum_i (t(\vec{x}_i) - T_i)^2$$

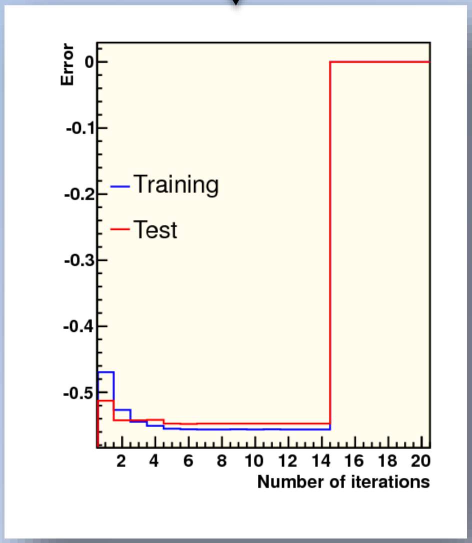
Known target

Training / validation of neural networks

Variable
$m(jb)$
$m(\ell b)$
$\lvert\eta(j)\rvert$
$m(\ell\nu b)$
$\cos\theta(\nu, W)$
H_T
polarization
$\lvert\Delta\eta(b,\ell)\rvert$
$m(b)$
sphericity
$E_T(j)$
$\lvert\Delta\eta(j,\ell)\rvert$
$m(jt)$
$\lvert\Delta\eta(\nu,b)\rvert$
$\lvert\Delta\eta(j,b)\rvert$







Choice of the variables:

- Good data/MC agreement
- Good separation power

Typical training parameters

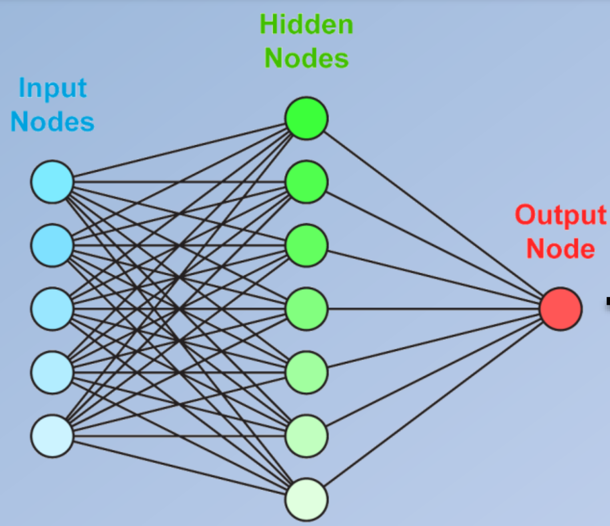
- 50% signal / 50% background
- 10-15 nodes in the hidden layer
- 50k – 150k trainig events

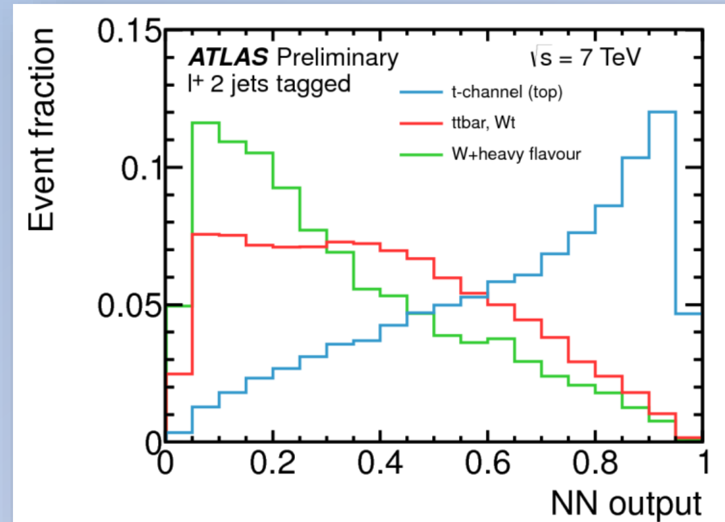
Validation of the networks

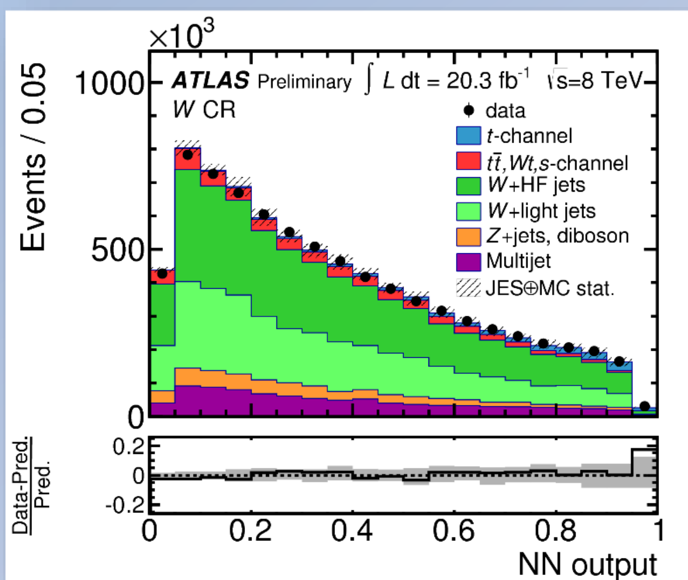
- Overtraining test

Training / Validierung von Neuronalen Netzen

Variable
$m(jb)$
$m(\ell b)$
$\|\eta(j)\|$
$m(\ell\nu b)$
$\cos\theta(\nu, W)$
H_T
polarization
$\|\Delta\eta(b,\ell)\|$
$m(b)$
sphericity
$E_T(j)$
$\|\Delta\eta(j,\ell)\|$
$m(jt)$
$\|\Delta\eta(\nu,b)\|$
$\|\Delta\eta(j,b)\|$







Choice of the variables:

- Good data/MC agreement
- Good separation power

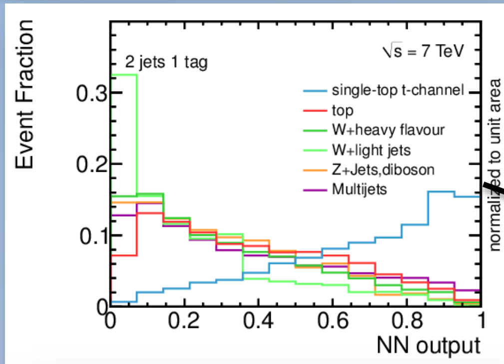
Typical training parameters

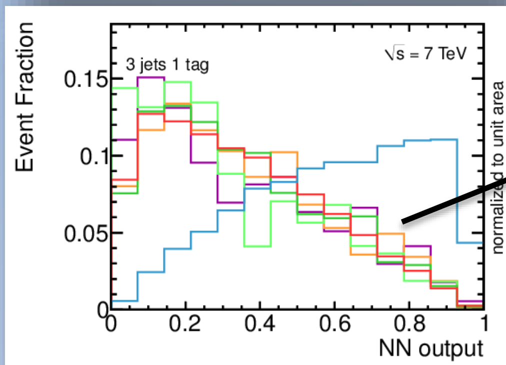
- 50% signal / 50% background
- 10-15 nodes in the hidden layer
- 50k – 150k trainig events

Validation of the networks

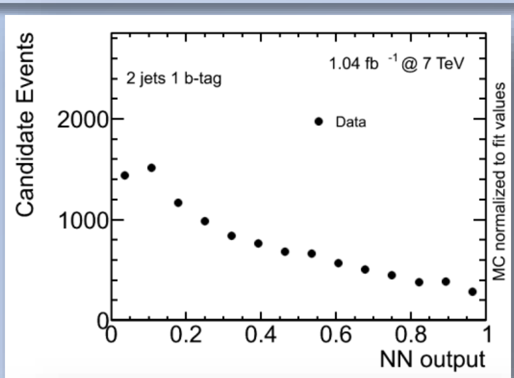
- Overtraining test
- Application in control regions

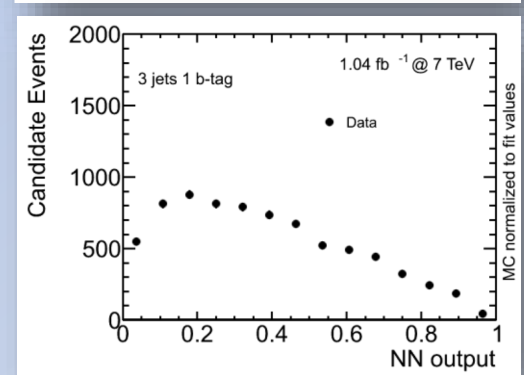
Measurement of the cross section





$$L(\beta^s; \beta_1^b, \ldots, \beta_B^b)$$



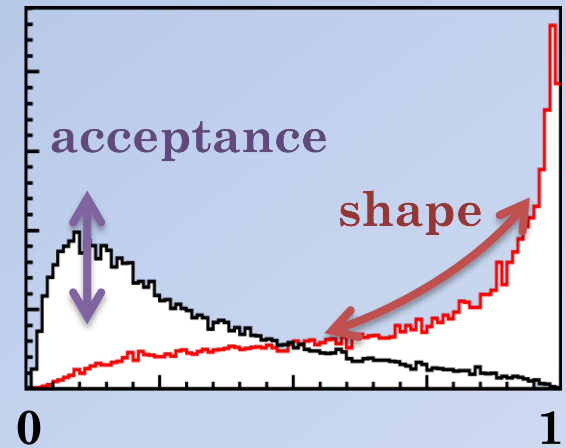


- Simultanious fit of all analysis channels to extract the signal events
- Free parameter in the likelihood function $\beta = \frac{n_{obs}}{n_{exp}}$.

$$L(\beta^s; \beta_1^b, \ldots, \beta_B^b) = \prod_{k=1}^{M} P(n_k; \mu_k) \cdot \prod_{j=1}^{B} G(\beta_j^b; 1.0, \Delta_j).$$

$$P(n_k; \mu_k) = \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!} \qquad G(\beta_j^b; 1.0, \Delta_j) = \frac{1}{\sqrt{2\pi\Delta_j^2}} \cdot \exp\frac{-\left(\beta_j^b - 1\right)^2}{2\Delta_j^2}$$

Treatment of systematic uncertainties

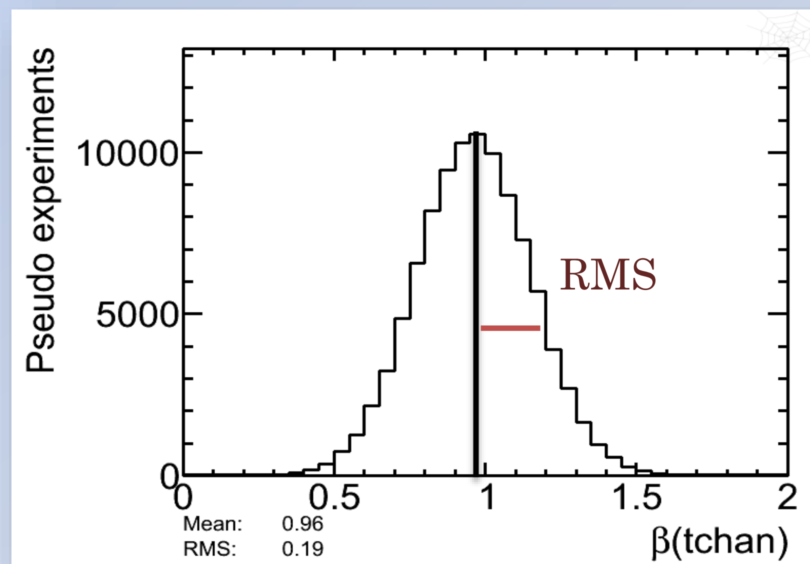


Effect of systematic uncertainties

- Acceptance
- Shape of the network distribution

Ensemble tests

- Construction of pseudo data from template distributions
- Variation of systematic effect in acceptance and shape
- RMS of the β-distribution is a measure of the size of the systematic effect.

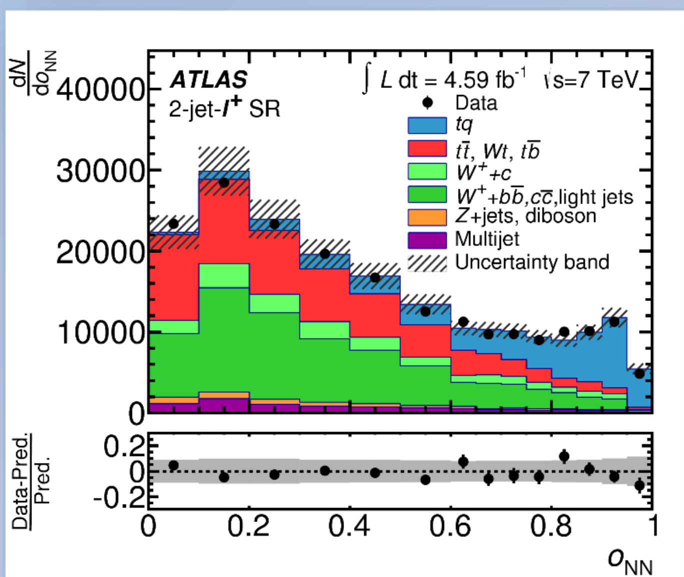


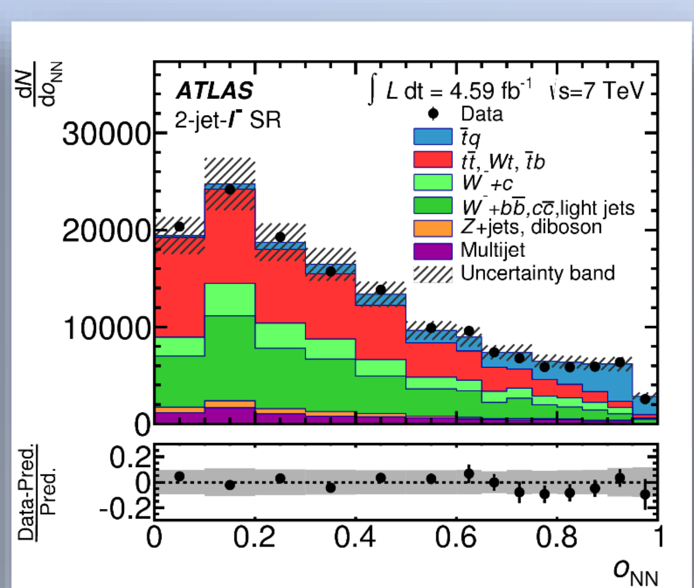
Sources of systematic uncertainties

- Reconstruction / calibration
- Event simulation
- Background estimation

Measurement using 7 TeV

Analysis channels:

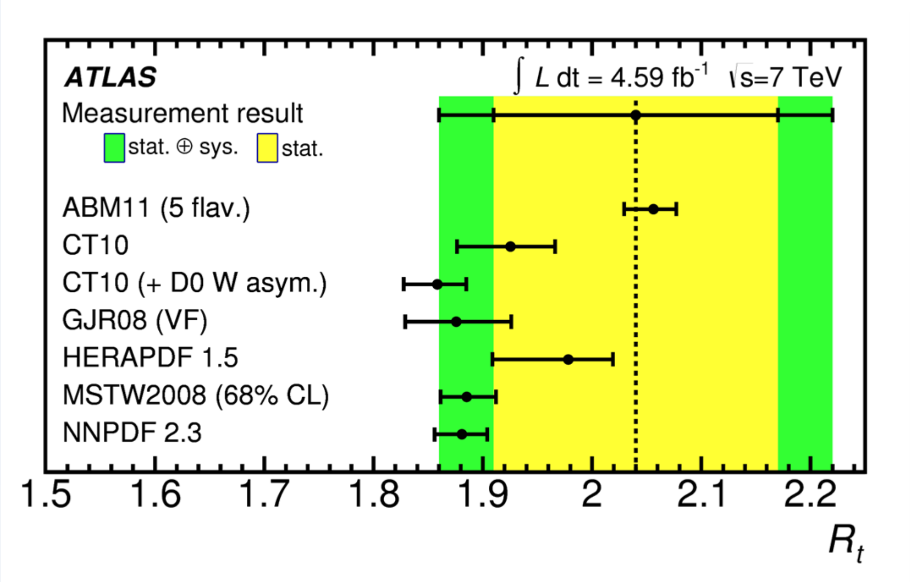




To constrain the b-tagging efficiency

Measurement using 7 TeV

Measured cross sections
$\sigma(tq)$=46±6 pb
$\sigma(\bar{t}q)$=23±4 pb

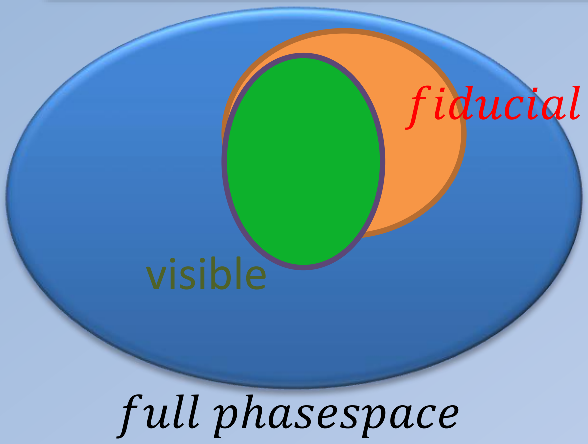


Measured cross section ratio
$R_t = 2.04 \pm 0.18$

Source	$\Delta\sigma(tq)/\sigma(tq)$[%]	$\Delta\sigma(\bar{t}q)/\sigma(\bar{t}q)$[%]
Data statistics	±3.1	±5.4
MC statistics	±1.9	±3.2
Mulitjet normlization	±1.1	±2.0
Other bkg norm.	±1.1	±2.8
JES detector	±1.6	±1.4
JES h intercalibration	±6.9	±8.4
JES flavour comp.	±1.4	±1.4
Jet energy resolution	±2.1	±1.6
b-tagging efficiency	±3.8	±4.1
E_T^{miss} modeling	±2.3	±3.4
Lepton uncertainties	±2.8	±3.0
PDF	±3.2	±5.8
tq generator + parton shower	±1.9	±1.6
tq scale variations	±2.6	±3.0
Total	**± 12.4**	**±15.9**

Fiducial cross section

Idea: Measure cross section only in visible phase space, don't add theoretical uncertainties from the extrapolation to the measurement.



Traditionally: $\boldsymbol{\sigma} = \frac{N_{signal}}{\epsilon \mathcal{L}}$

This can be re-written: $\boldsymbol{\sigma} = \frac{1}{\epsilon_{fid}} \cdot \frac{\epsilon_{corr}}{\epsilon_{corr}} \cdot \frac{N_{signal}}{\mathcal{L}}$

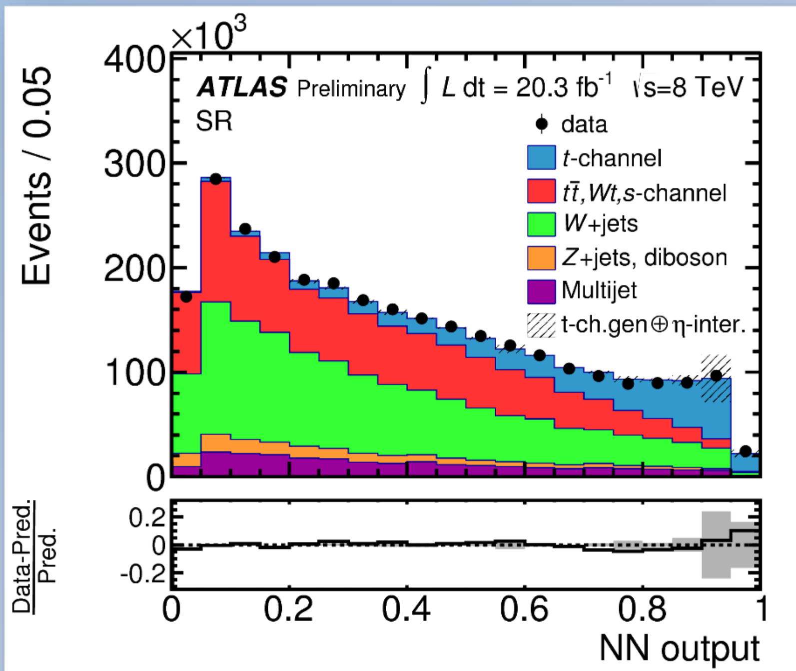
Fiducial cross section

Fiducial phase space defined close to the phase space of the selected data events

Object	Cut
Electrons	$p_T > 25$ GeV and $\|\eta\| < 2.5$
Muons	$p_T > 25$ GeV and $\|\eta\| < 2.5$
Jets	$p_T > 30$ GeV and $\|\eta\| < 4.5$
	$p_T > 35$ GeV, if $2.75 < \|\eta\| < 3.5$
Lepton (ℓ), Jets (j_i)	$\Delta R(\ell, j_i) > 0.4$
E_T^{miss}	$E_T^{miss} > 30$ GeV
Transverse W-boson mass	$m_T(W) > 50$ GeV
Lepton (ℓ), jet with the highest p_T (j_1)	$p_T(\ell) > 40\ \text{GeV}\left(1 - \frac{\pi - \|\Delta\phi(j_1,\ell)\|}{\pi - 1}\right)$

Fiducial cross section measurment

Used 20.3 fb^{-1} of the 2012 data set
One neural network in the 2 jet channel, 14 variables



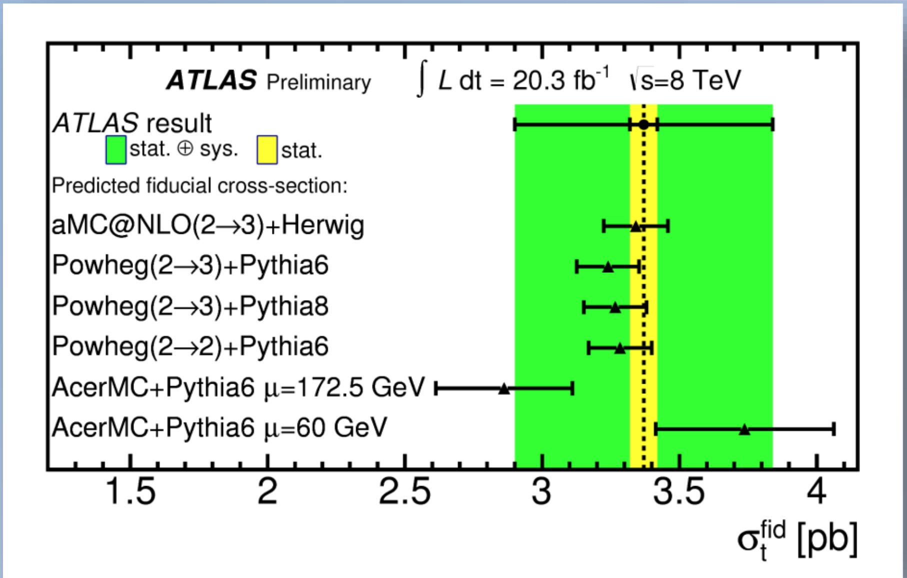
Measured fiducial cross section:

$$\sigma_{\text{fid}} = 3.37 \pm 0.05\ (stat.) \pm 0.47\ (\text{syst.}) \pm 0.09\ (\text{lumi.})\ \text{pb}$$

Source	$\Delta\sigma_{\text{fid}}/\sigma_{\text{fid}}$ [%]
Data statistics	±1.5
MC statistics	±1.1
Multijet normalisation	+2.3 -1.4
Other background normalization	±0.8
JES η intercalibration	±7.9
JES physics modelling	±3.0
JES detector	< 0.5
JES statistical	< 0.5
JES mixed detector and modelling	< 0.5
JES single particle	< 0.5
JES pile-up	< 0.5
JES flavor composition	±0.8
JES flavor response	±0.5
b-JES	< 0.5
Lepton uncertainties	±2.9
E_T^{miss} modelling	±3.0
b-tagging efficiency	±3.5
c-tagging efficiency	< 0.5
Mistag efficiency	< 0.5
Jet energy resolution	±1.7
Jet reconstruction eff.	< 0.5
Jet vertex fraction	< 0.5
t-channel generator	±7.9
W+jets generator	±1.4
PDF	±1.1
$t\bar{t}$,Wt and s-channel generator	< 0.5
ISR / FSR ($t\bar{t}$)	< 0.5
Total Systematic	±14
Total	±14

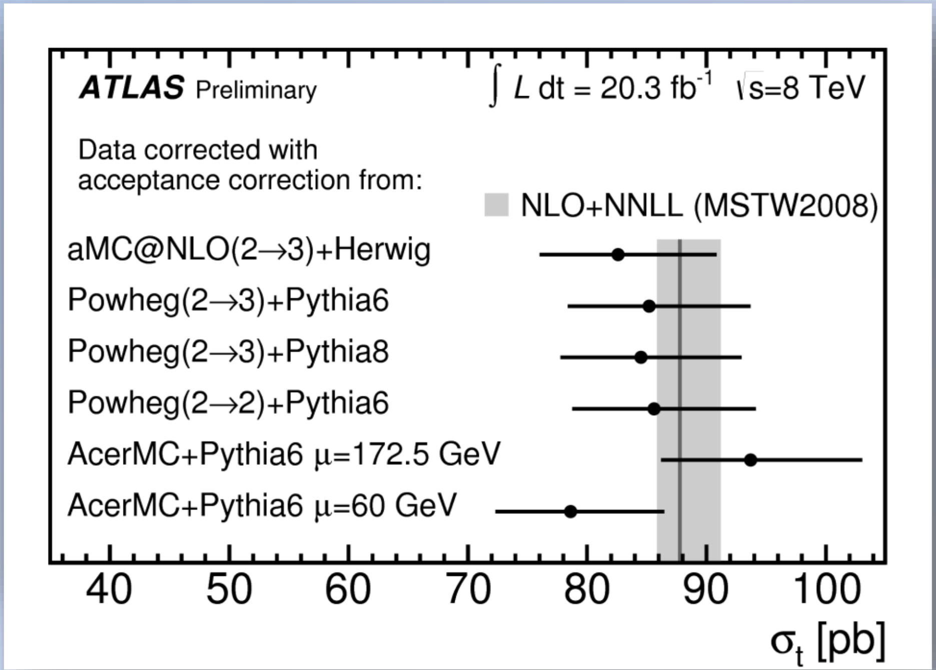
Fiducial and extrapolated cross section

Comparison of different of generator predictions



- Inclusive cross section for each generator calculated accordingly
- Uncertainy includes scale variations and PDF uncertainty (PDF4LHC description)

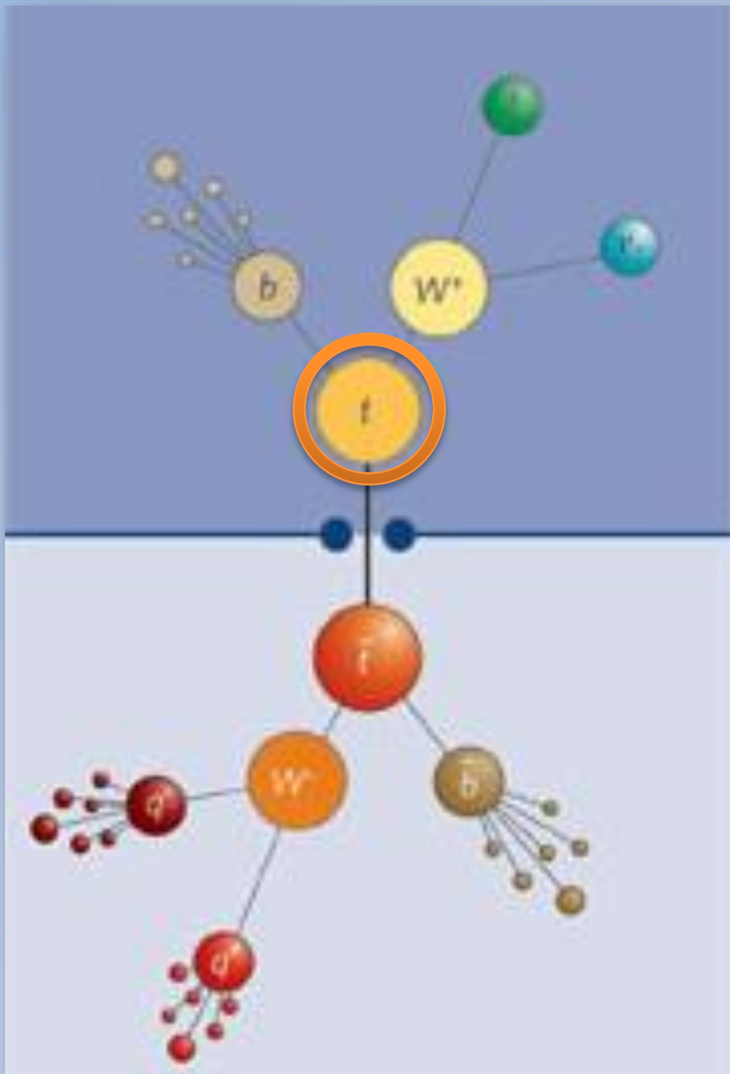
Extrapolated inclusive cross section

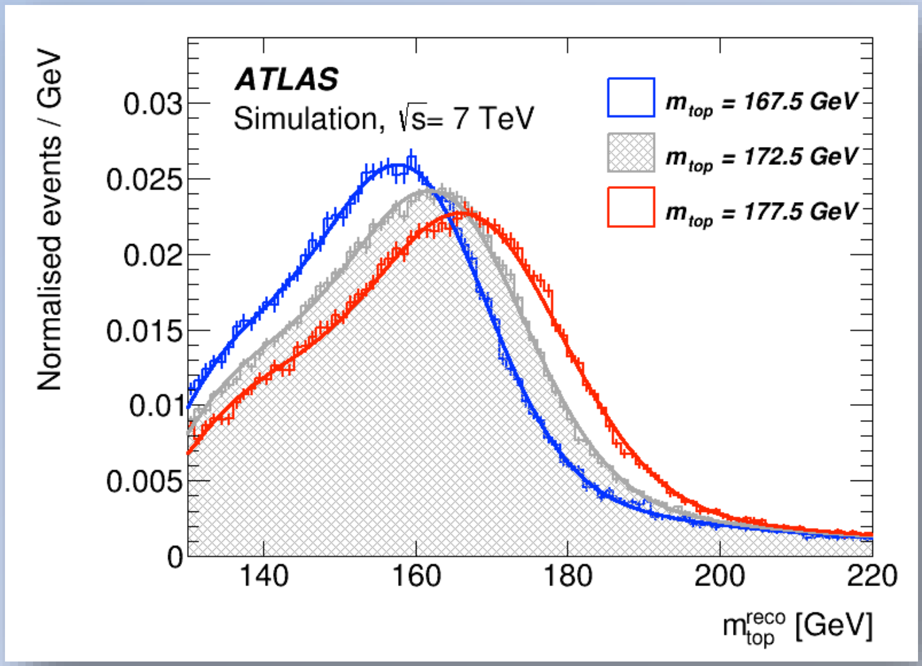


Uncertainty includes measured uncertainty plus PDF uncertainty of the extrapolation

First time, that signal modelling can be studied in data!

Top quark mass measurement

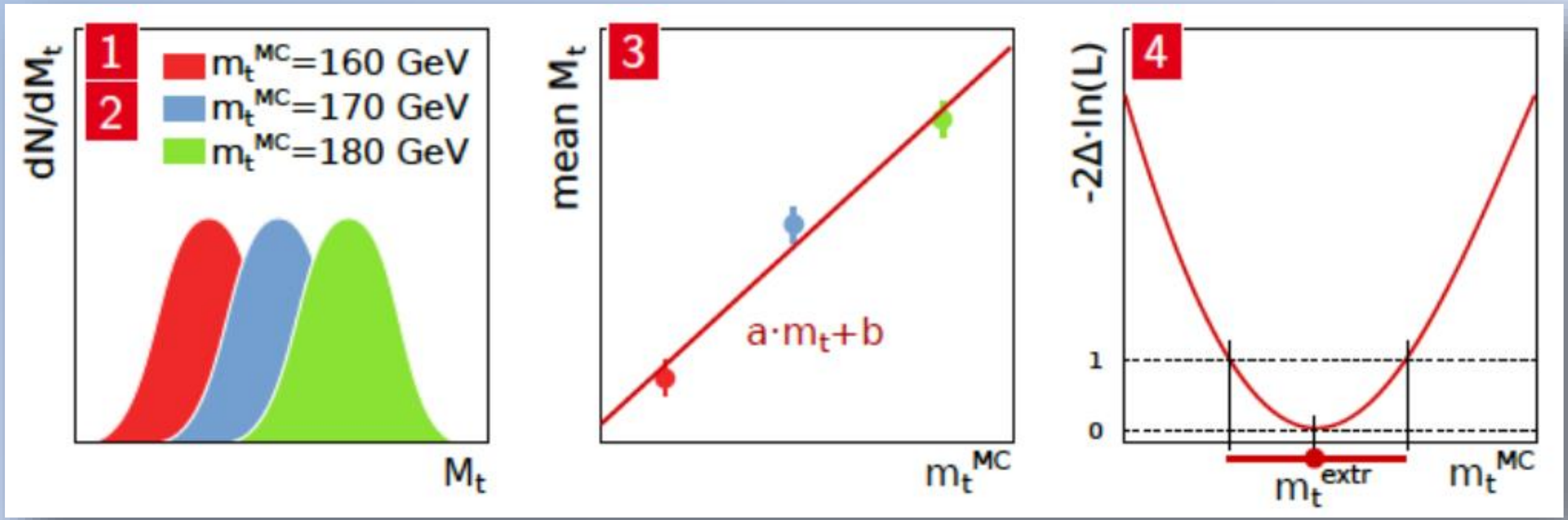




Top quark mass measurements

Basic steps:

1. Select $t\bar{t}$ candidate events
   - high integrated luminosity, efficient b-tag algorithms
2. Construct estimator M_t for top quark mass
3. Parametrize dN/dM_t in terms of m_t MC
   - e.g. l+jets, alljets, template and ideogram methods used at LHC
4. Perform maximum likelihood fit
5. Calibrate on MC, evaluate on data, $t\bar{t}$ modeling very important



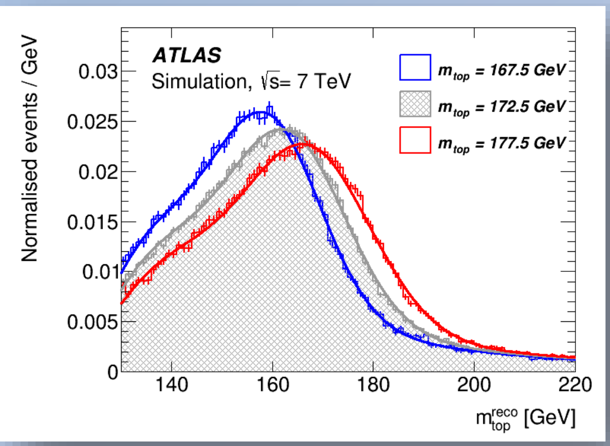
Top quark mass measurements

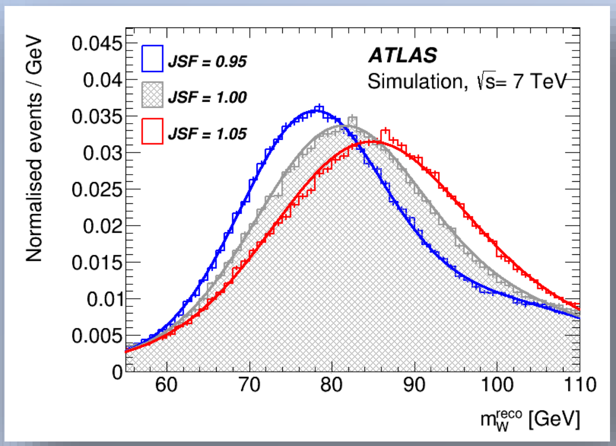
Template method:

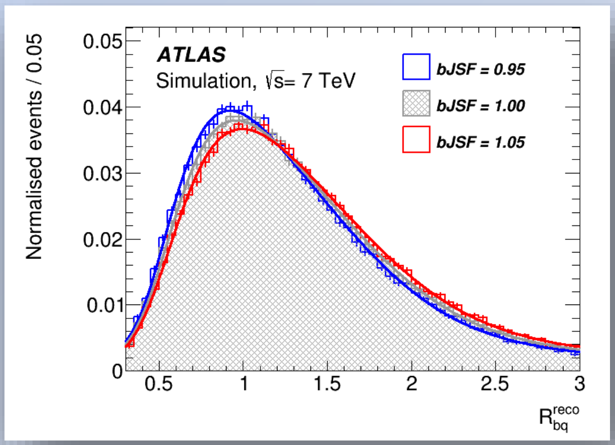
Distributions of sensitive variables

- M_t template from reconstructed M_t^{reco} from χ^2 to WbWb
- M_W templates for in-situ calibration of JES
- Possible to add constraints on b-jet JES

→ Relatively simple, fast, but non optimal statistical uncertainty







$$R_{bq}^{\mathrm{reco,1b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{tag}}}}{(p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}})/2}$$

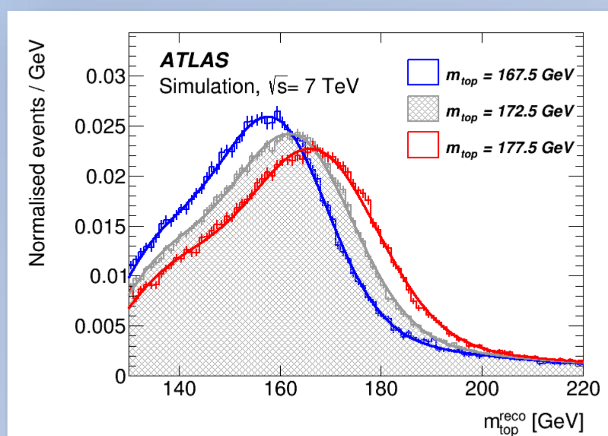
Top quark mass measurements

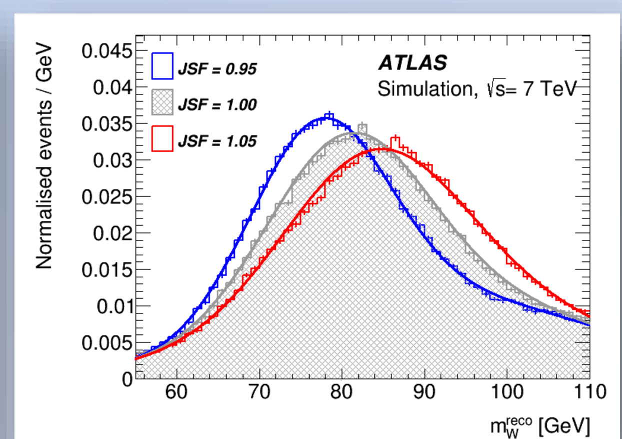
Template method:

Distributions of sensitive variables

- M_t template from reconstructed M_t^{reco} from χ^2 to WbWb
- M_W templates for in-situ calibration of JES

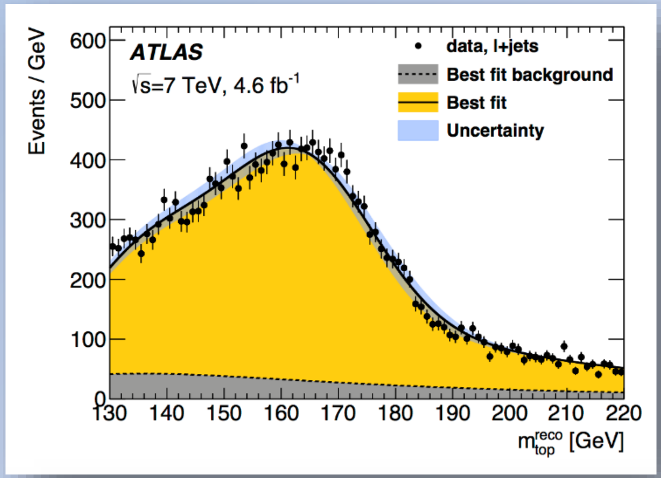
→ Relatively simple, fast, but non optimal statistical uncertainty

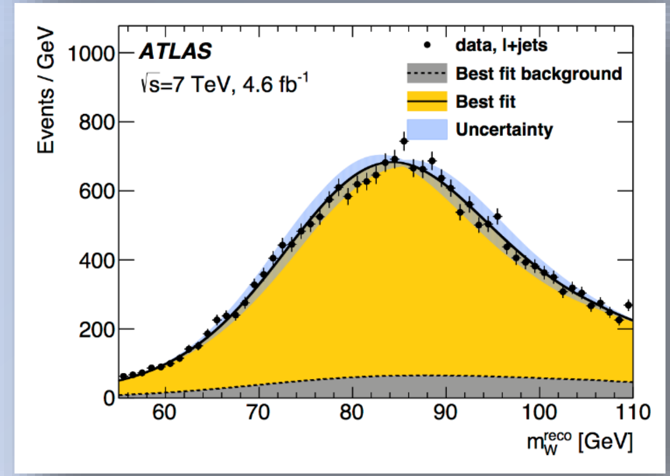




Top quark mass measurements

	$t\bar{t} \to$ lepton+jets		
	$m_{\text{top}}^{\ell+\text{jets}}$ [GeV]	JSF	bJSF
Results	172.33	1.019	1.003
Statistics	0.75	0.003	0.008
– *Stat. comp.* (m_{top})	*0.23*	*n/a*	*n/a*
– *Stat. comp. (JSF)*	*0.25*	*0.003*	*n/a*
– *Stat. comp. (bJSF)*	*0.67*	*0.000*	*0.008*
Method	0.11 ± 0.10	0.001	0.001
Signal MC	0.22 ± 0.21	0.004	0.002
Hadronisation	0.18 ± 0.12	0.007	0.013
ISR/FSR	0.32 ± 0.06	0.017	0.007
Underlying event	0.15 ± 0.07	0.001	0.003
Colour reconnection	0.11 ± 0.07	0.001	0.002
PDF	0.25 ± 0.00	0.001	0.002
W/Z+jets norm	0.02 ± 0.00	0.000	0.000
W/Z+jets shape	0.29 ± 0.00	0.000	0.004
NP/fake-lepton norm.	0.10 ± 0.00	0.000	0.001
NP/fake-lepton shape	0.05 ± 0.00	0.000	0.001
Jet energy scale	0.58 ± 0.11	0.018	0.009
b-Jet energy scale	0.06 ± 0.03	0.000	0.010
Jet resolution	0.22 ± 0.11	0.007	0.001
Jet efficiency	0.12 ± 0.00	0.000	0.002
Jet vertex fraction	0.01 ± 0.00	0.000	0.000
b-Tagging	0.50 ± 0.00	0.001	0.007
$E_{\text{T}}^{\text{miss}}$	0.15 ± 0.04	0.000	0.001
Leptons	0.04 ± 0.00	0.001	0.001
Pile-up	0.02 ± 0.01	0.000	0.000
Total	1.27 ± 0.33	0.027	0.024





$M_t = 172.33 \pm 0.75 (\text{stat}) \pm 1.02 (\text{syst})$ GeV

$M_t = 172.33 \pm 1.27$ GeV (±0.73%)

Top quark mass measurements

Ideogram method:

- Modification of template method using multiple permutations with different weights
- Starts from kinematical reconstruction, then computes event likelihood as a function of M_t
- Different pdf's used for different jet-quark assignments
- Event likelihoods (ideograms) are given by

$$\mathcal{L}\left(\text{sample}|m_{\text{t}}, \text{JSF}\right) = \prod_{\text{events}} \mathcal{L}\left(\text{event}|m_{\text{t}}, \text{JSF}\right)^{w_{\text{event}}}$$

$$w_{\text{event}} = c \sum_{i=1}^{n} P_{\text{gof}}(i)$$

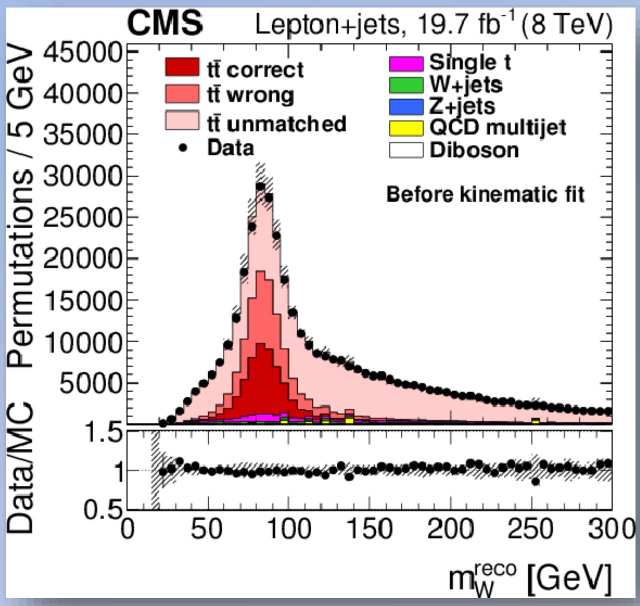
$$P_{gof} = e^{-\frac{\chi^2}{2}}$$

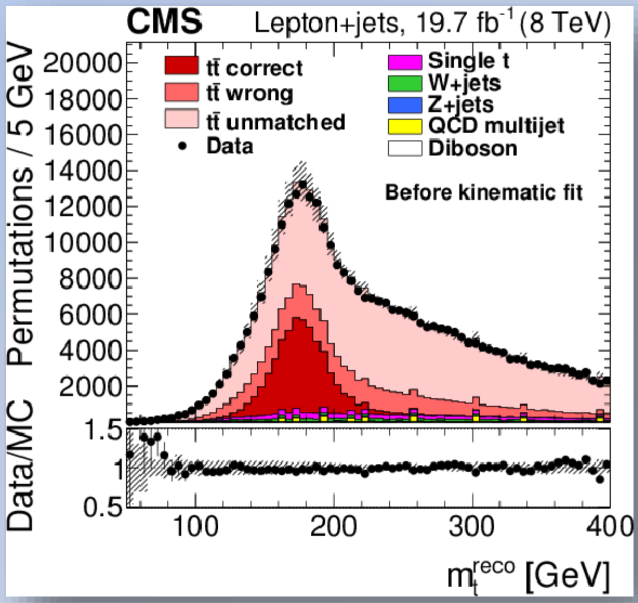
$$\mathcal{L}\left(\text{event}|m_{\text{t}}, \text{JSF}\right) = \sum_{i=1}^{n} P_{\text{gof}}(i) \left\{ f_{\text{sig}} P_{\text{sig}}\left(m_{\text{t},i}^{\text{fit}}, m_{\text{W},i}^{\text{reco}} | m_{\text{t}}, \text{JSF}\right) + (1 - f_{\text{sig}})\, P_{\text{bkg}}\left(m_{\text{t},i}^{\text{fit}}, m_{\text{W},i}^{\text{reco}}\right) \right\},$$

Top quark mass measurements

Possible combinations treated separately:

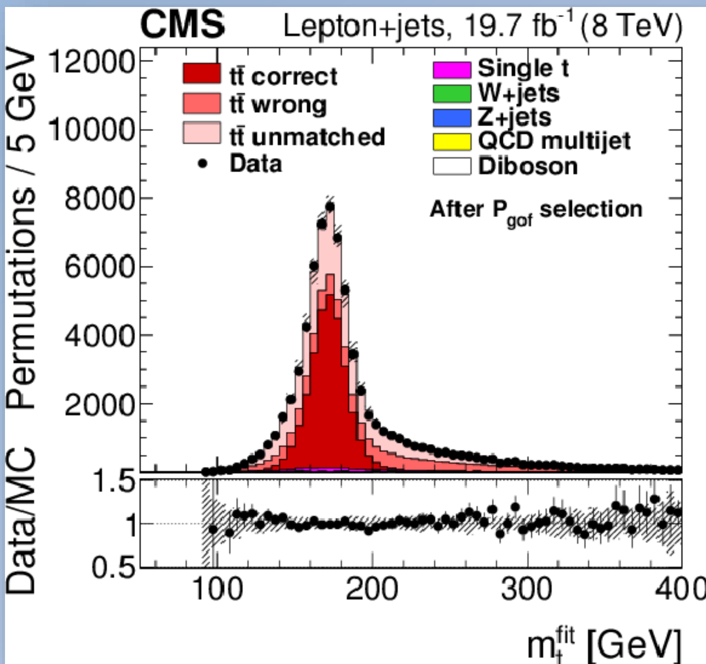
- correct: 4 jets match the 4 quarks correctly
- wrong: wrong permutation
- unmatched: at least one quark does not match any jet

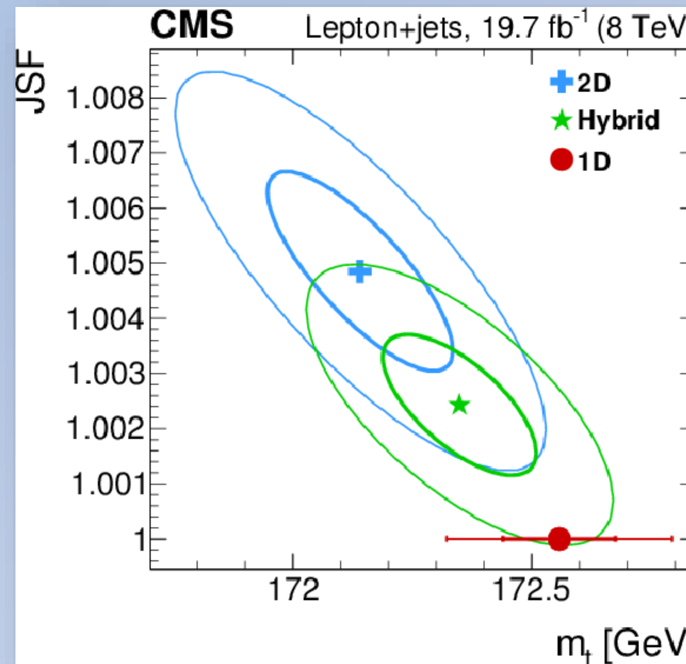




- **2D or 1D fit**: w. or w/o JSF calibration
- **Hybrid fit**: JSF with Gaussian constraint incorporating JES prior knowledge

Top quark mass measurements





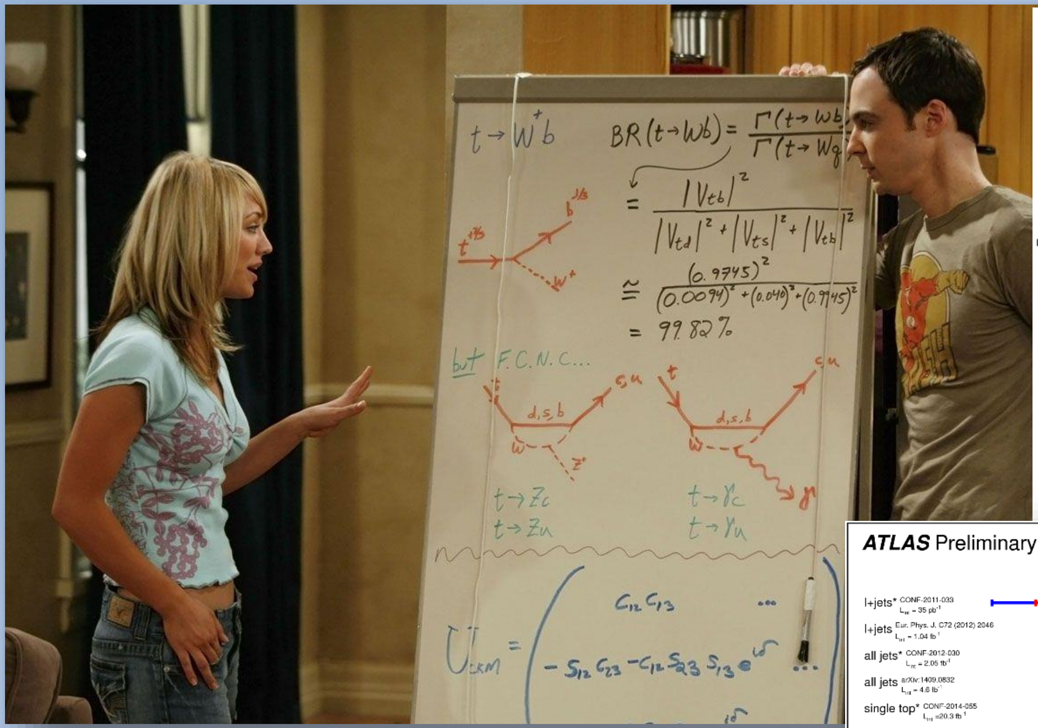
Hybrid fit

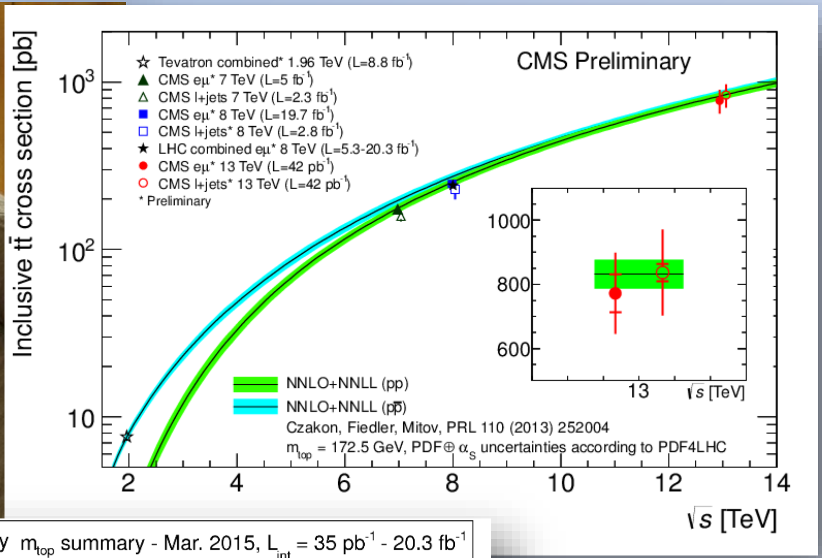
M_t=172.35±0.16(stat+JSF)±0.48(syst) GeV

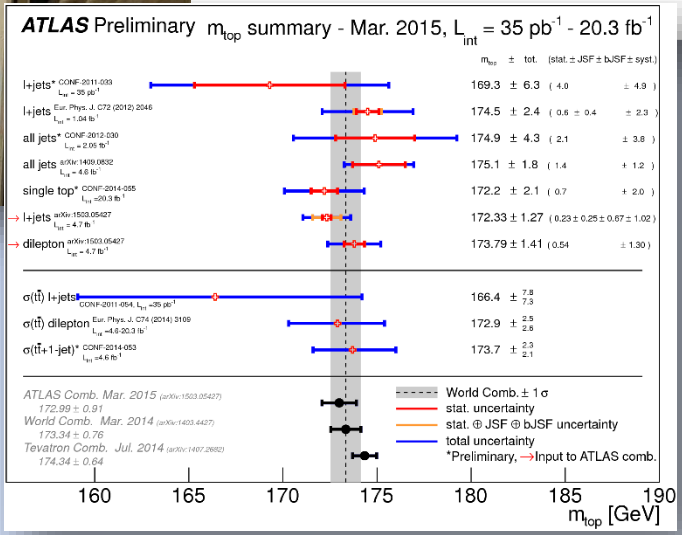
M_t=172.35±0.51 GeV (±0.29%)

syst	GeV
bJES	0.32
ME generator	0.12
underlying evt	0.11

Summary







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