Top B Physics at the LHC

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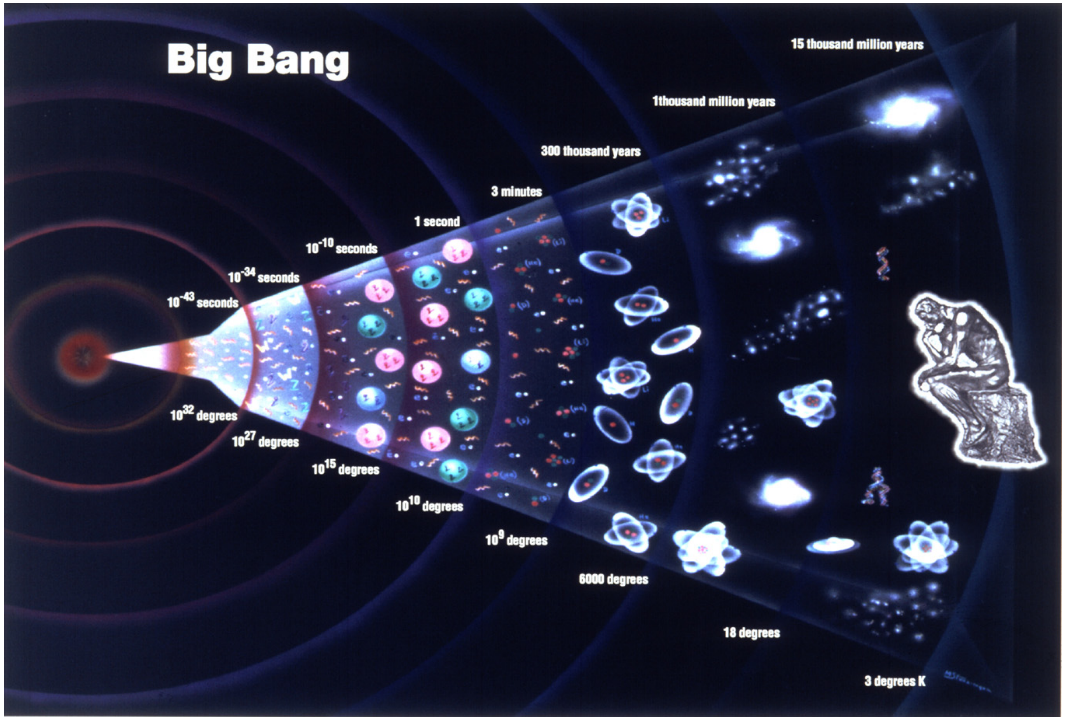
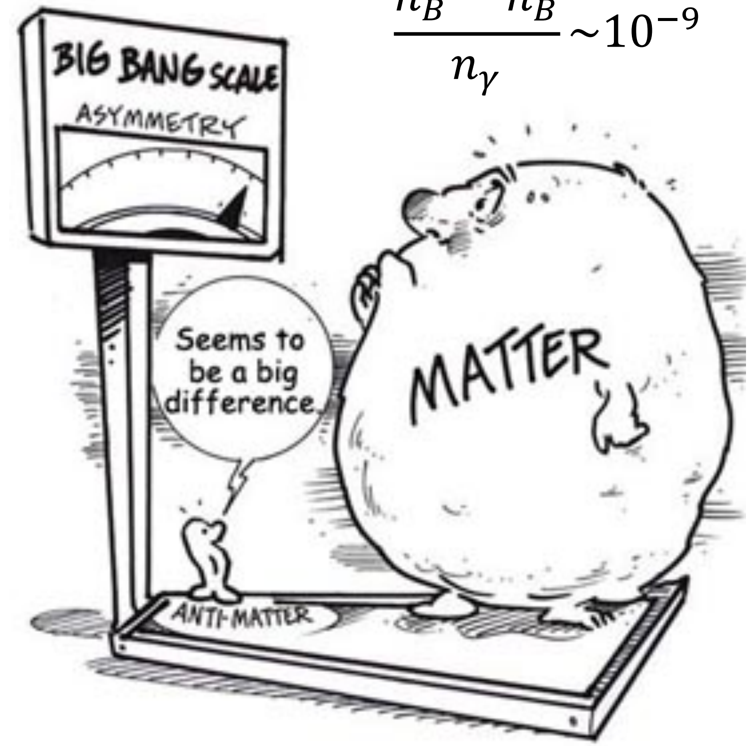
Motivation

What? Where? Why?

Big Bang





$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$

1. *Baryon number violating interactions;*
2. *CP violation;*
3. *Departure from thermal equilibrium;*

Sakharov

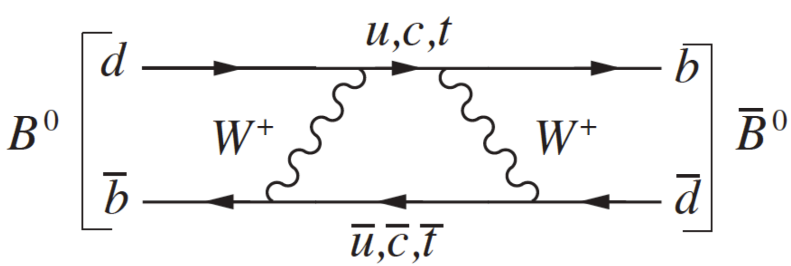
Still not enough! → **Where is the New Physics?**

CP Violation

Particle states have intrinsic charge and parity eigenvalues, conserved through most SM vertices, but violated by the weak interaction. The violation of the combined charge conjugation (C) and parity transformation (P) of particles and antiparticles implies that the laws of physics are not the same for matter and antimatter.

1. Mixing

$$\Gamma\left(B^0 \to \overline{B^0} \to \bar{X}\right) \neq \Gamma\left(\overline{B^0} \to B^0 \to X\right)$$

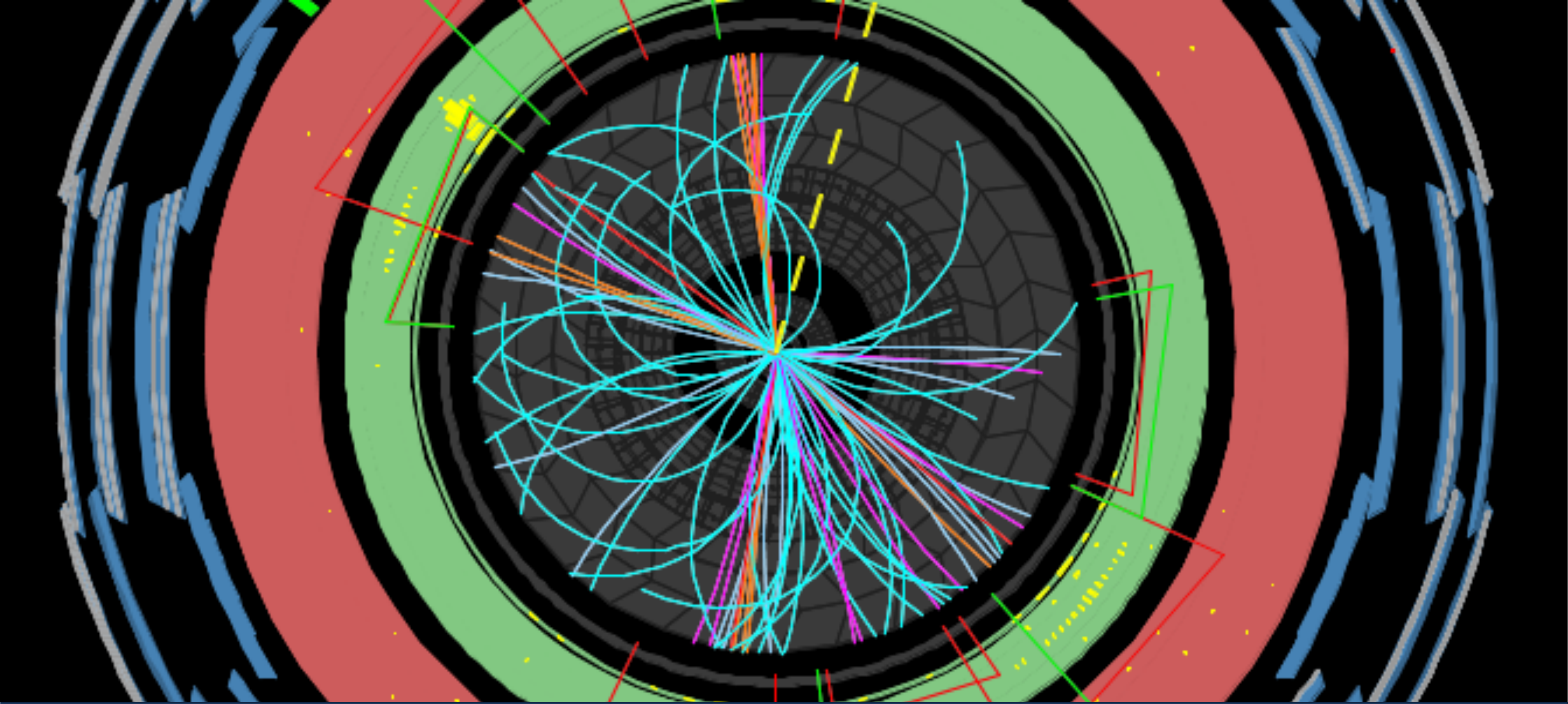


2. Direct

$$\Gamma(B^0 \to X) \neq \Gamma\left(\overline{B^0} \to \bar{X}\right)$$

3. Interference (when mixing and direct share a final state)

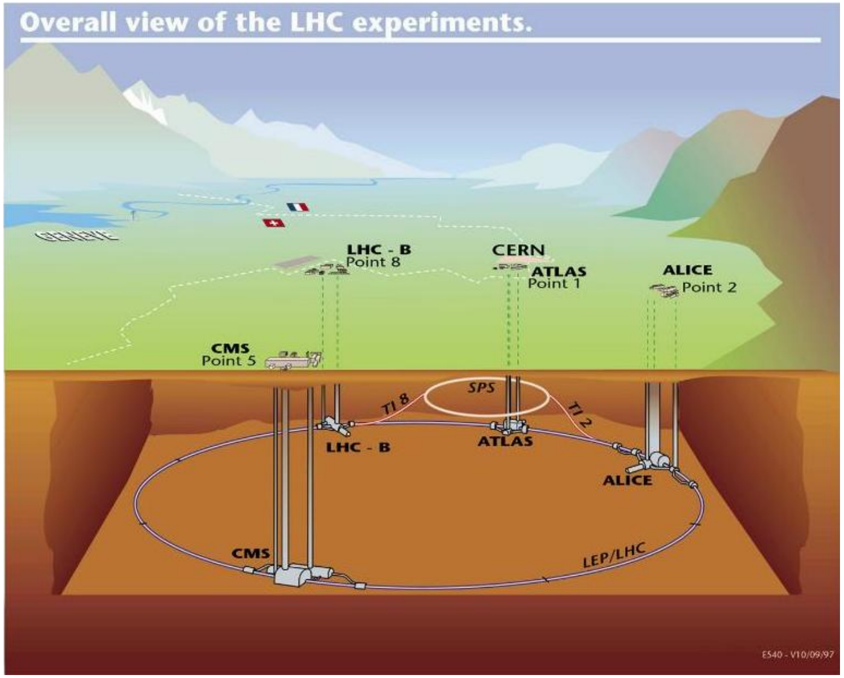
New physics can include additional CP violating processes, which may couple to the *B* sector. Precision measurements of CPV may constrain these models

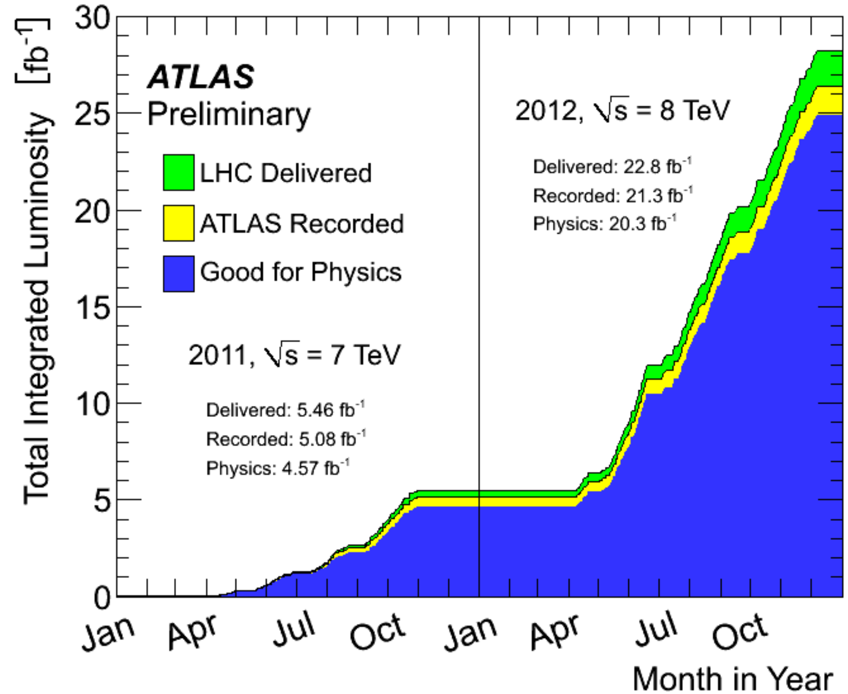


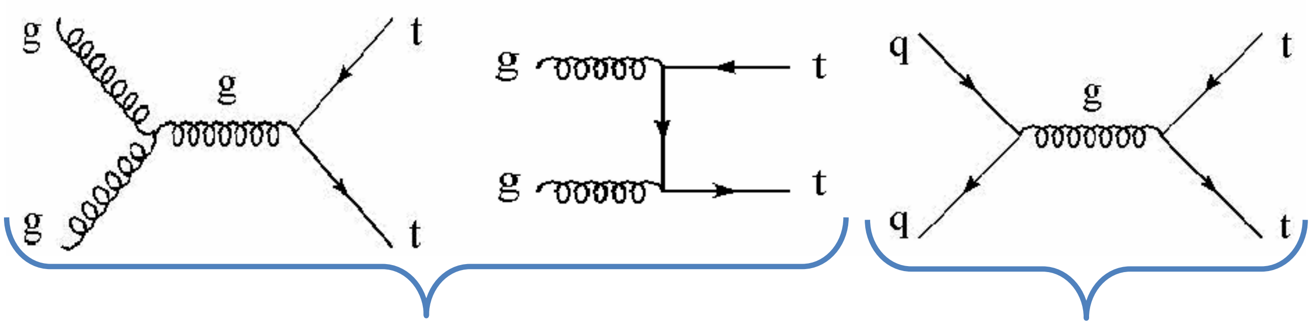
The Top Quark

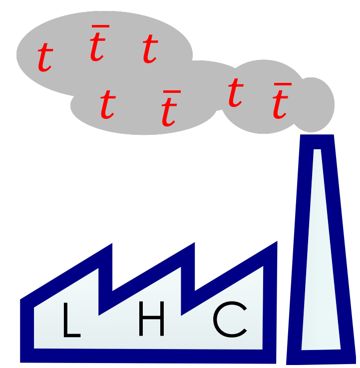
An open window?

Top Physics at the LHC









~88% at $\sqrt{s} = 8$ TeV

~12% at $\sqrt{s} = 8$ TeV

Top Physics at the LHC

Charge $= +\frac{2}{3}$

Spin $= \frac{1}{2}$

Mass $\simeq$ 173 GeV

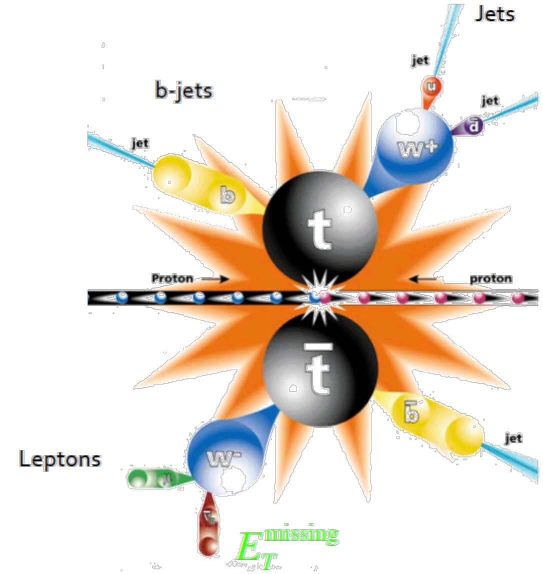
- Cosmic Stability
- Electroweak constraints
- Couplings to new physics

Does not hadronize! (Lifetime shorter than strong interaction requires)

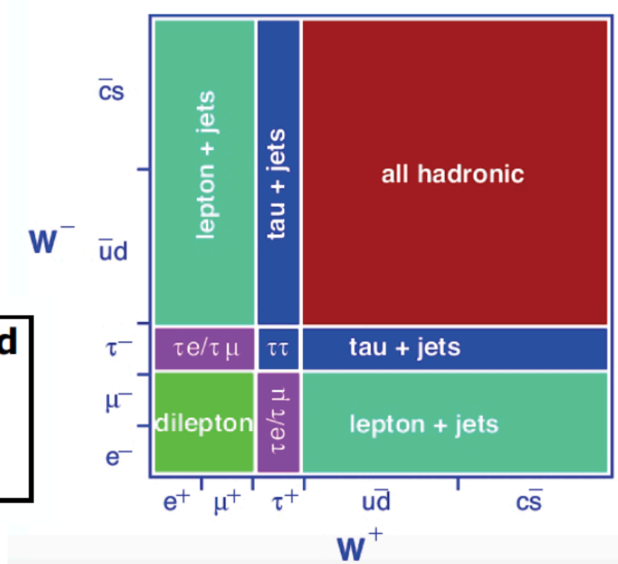
$\mathrm{BR}(t \rightarrow Wb) \simeq 99.8\%$

Opportunities to study a 'bare' quark

- Spin / Polarisation



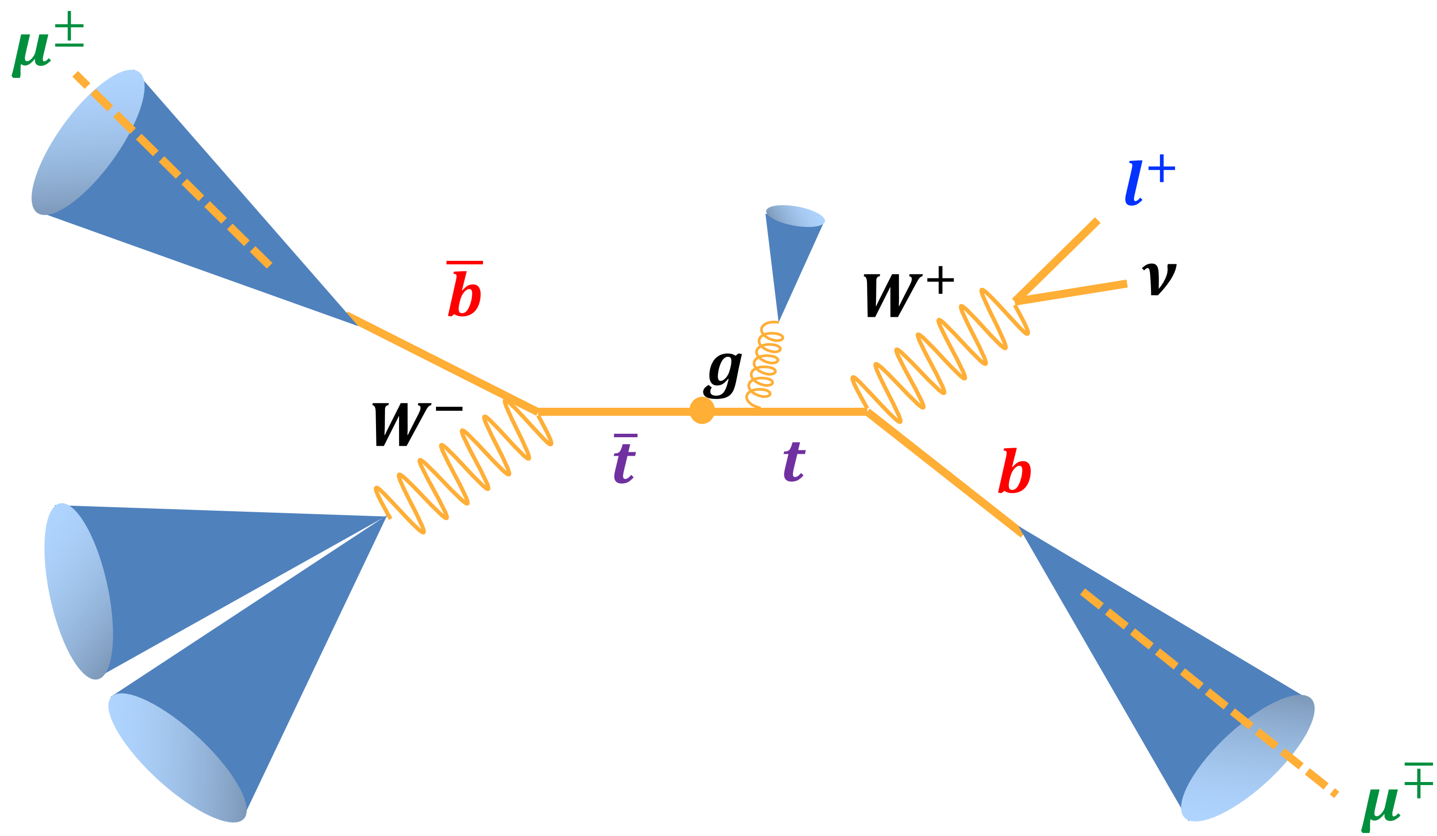
$t\bar{t}$ decay modes



(not inc. τ)	BR	background
dilepton	~5%	low
lepton + jets	~30%	moderate
all hadronic	~44%	high

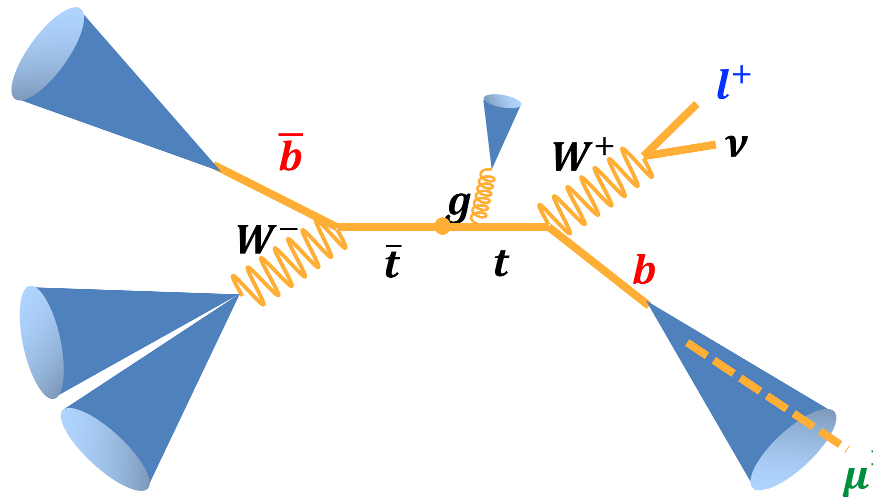
Top B Physics

Lots of tops = lots of b + lots of information



Top B Physics

Unlike $gg \to b\bar{b}$, we know which b we are dealing with!

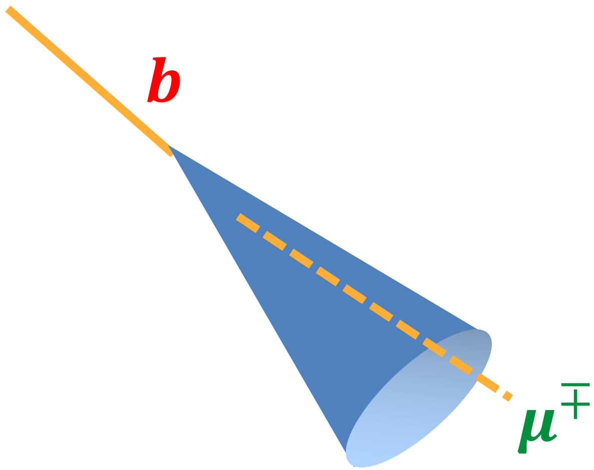


The charge of the W, tagged with a lepton, tells you the charge of the associated b-quark at **production** (providing you know which b you have – see later)

$$l^+ \Rightarrow b \qquad\qquad \Gamma\left(\overline{B^0} \to \bar{X}\right)$$

$$l^- \Rightarrow \bar{b} \qquad\qquad \Gamma\left(B^0 \to X\right)$$

Semileptonic b decay



$$\mathbf{BR}(b \rightarrow (\ldots) \rightarrow \mu) \sim \mathbf{20\%}$$

The charge of the soft muon*, tells you the charge of the associated b-quark at **decay** (providing you know which b you have – see later)

So if we know the charge of a b-quark at production, and the charge at decay, we can build up a picture of the full process

* Semileptonic decays to electrons also exist, but are difficult to detect at ATLAS

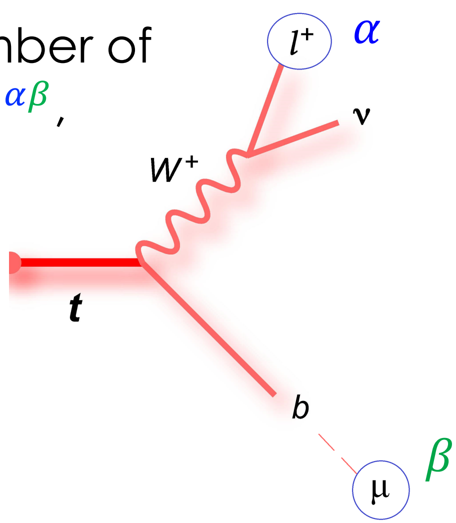
Decay modes

- **Opposite Sign (OS)**
- $t \to l^+\nu\, b \to l^+ l^- X$ ~55%
- $t \to l^+\nu\, (b \to \bar{b} \to \bar{c}) \to l^+ l^- X$ ~4%
- $t \to l^+\nu\, (b \to c\bar{c}) \to l^+ l^- X$ ~3%

- **Same Sign (SS)**
- $t \to l^+\nu\, (b \to \bar{b}) \to l^+ l^+ X$ ~7%
- $t \to l^+\nu\, (b \to c) \to l^+ l^+ X$ ~28%
- $t \to l^+\nu\, (b \to \bar{b} \to c\bar{c}) \to l^+ l^+ X$ ~3%

Comparing these processes with their charge conjugates allows for building of inclusive asymmetries sensitive to CP violation:

- Consider number of soft muons, $N^{\alpha\beta}$, where:



$$P(b \to l^-) = \frac{N(b \to l^-)}{N(b \to l^-) + N(b \to l^+)} = \frac{N^{+-}}{N^{+-} + N^{++}} = \frac{N^{+-}}{N^{+}}$$

$$P(\bar{b} \to l^+) = \frac{N(\bar{b} \to l^+)}{N(\bar{b} \to l^-) + N(\bar{b} \to l^+)} = \frac{N^{-+}}{N^{--} + N^{-+}} = \frac{N^{-+}}{N^{-}}$$

$$P(b \to l^+) = \frac{N(b \to l^+)}{N(b \to l^-) + N(b \to l^+)} = \frac{N^{++}}{N^{+-} + N^{++}} = \frac{N^{++}}{N^{+}}$$

$$P(\bar{b} \to l^-) = \frac{N(\bar{b} \to l^-)}{N(\bar{b} \to l^-) + N(\bar{b} \to l^+)} = \frac{N^{--}}{N^{--} + N^{-+}} = \frac{N^{--}}{N^{-}}$$

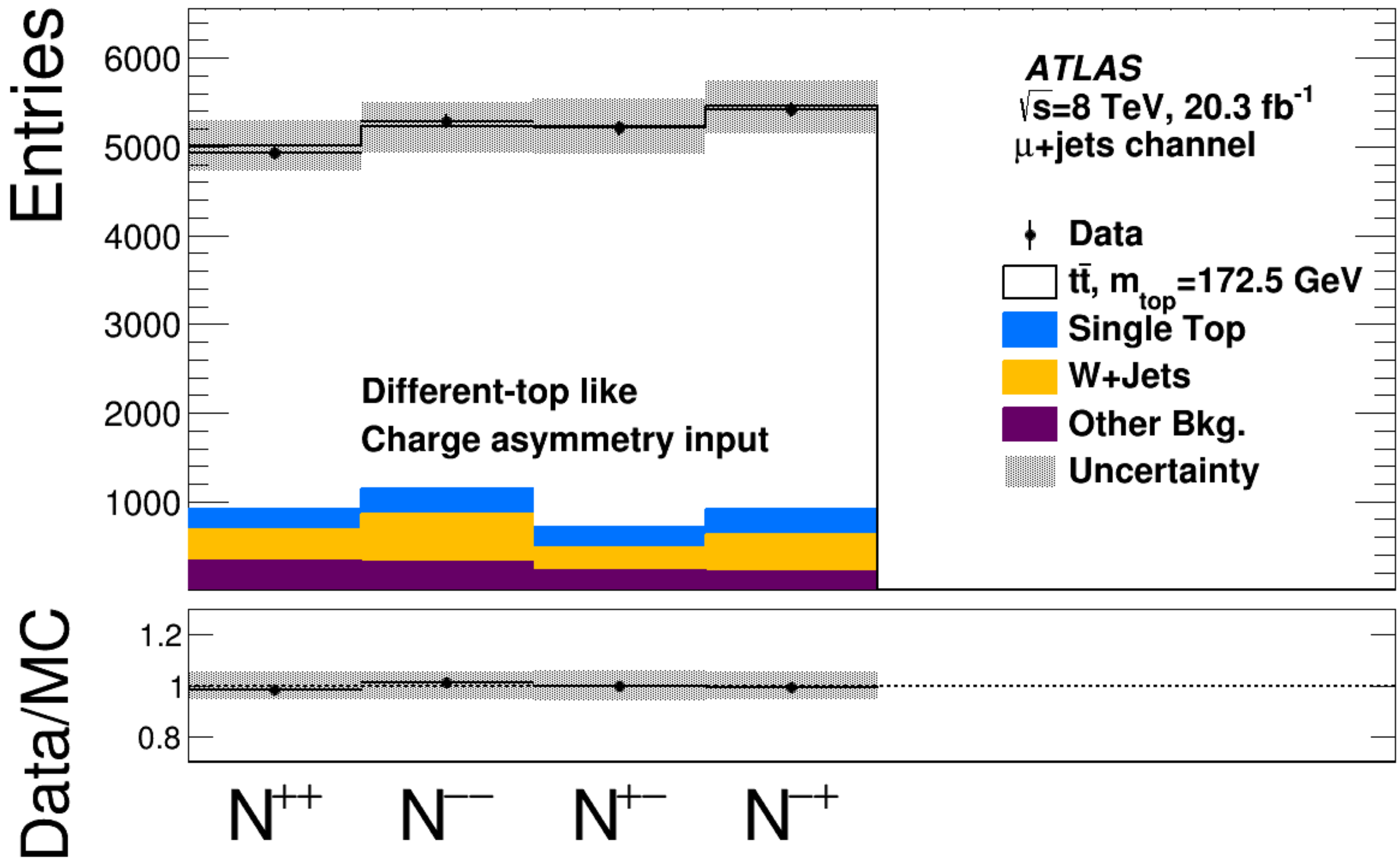
PRL 110,232002 (2013)

Charge Asymmetries

$$A^{ss} = \frac{P(b \to l^+) - P(\bar{b} \to l^-)}{P(b \to l^+) + P(\bar{b} \to l^-)} = \frac{\left(\frac{N^{++}}{N^+}\right) - \left(\frac{N^{--}}{N^-}\right)}{\left(\frac{N^{++}}{N^+}\right) + \left(\frac{N^{--}}{N^-}\right)}$$

$$A^{os} = \frac{P(b \to l^-) - P(\bar{b} \to l^+)}{P(b \to l^-) + P(\bar{b} \to l^+)} = \frac{\left(\frac{N^{+-}}{N^+}\right) - \left(\frac{N^{-+}}{N^-}\right)}{\left(\frac{N^{+-}}{N^+}\right) + \left(\frac{N^{-+}}{N^-}\right)}$$

Charge Asymmetry



CP Asymmetries

- CP asymmetries can be extracted from A^{ss}, A^{os}
- As defined in **PRL 110,232002 (2013)**:

$$A^{ss} = r_b A^{bl}_{\text{mix}} + r_{c\bar{c}} A^{bc}_{\text{mix}} + r_c A^{bc}_{\text{dir}} - (r_c + r_{c\bar{c}}) A^{cl}_{\text{dir}}$$

$$A^{os} = \tilde{r}_c A^{bc}_{\text{mix}} + \tilde{r}_b A^{bl}_{\text{dir}} + (\tilde{r}_c + \tilde{r}_{c\bar{c}}) A^{cl}_{\text{dir}}$$

$$A^{bl}_{\text{mix}} = \frac{\Gamma(b\to\bar{b}\to l^+X)-\Gamma(\bar{b}\to b\to l^-X)}{\Gamma(b\to\bar{b}\to l^+X)+\Gamma(\bar{b}\to\bar{b}\to l^-X)} \quad \xleftrightarrow{A^{b}_{\text{mix}}} \quad A^{bc}_{\text{mix}} = \frac{\Gamma(b\to\bar{b}\to\bar{c}X)-\Gamma(\bar{b}\to b\to cX)}{\Gamma(b\to\bar{b}\to cX)+\Gamma(\bar{b}\to\bar{b}\to cX)}$$

$$A^{bl}_{\text{dir}} = \frac{\Gamma(b\to l^-X)-\Gamma(\bar{b}\to l^+X)}{\Gamma(b\to l^-X)+\Gamma(\bar{b}\to l^+X)}$$

$$A^{cl}_{\text{dir}} = \frac{\Gamma(\bar{c}\to l^-X_L)-\Gamma(c\to l^+X_L)}{\Gamma(\bar{c}\to l^-X_L)+\Gamma(c\to l^+X_L)}$$

$$A^{bc}_{\text{dir}} = \frac{\Gamma(b\to cX_L)-\Gamma(\bar{b}\to\bar{c}X_L)}{\Gamma(b\to cX_L)+\Gamma(\bar{b}\to\bar{c}X_L)}$$

Existing limits

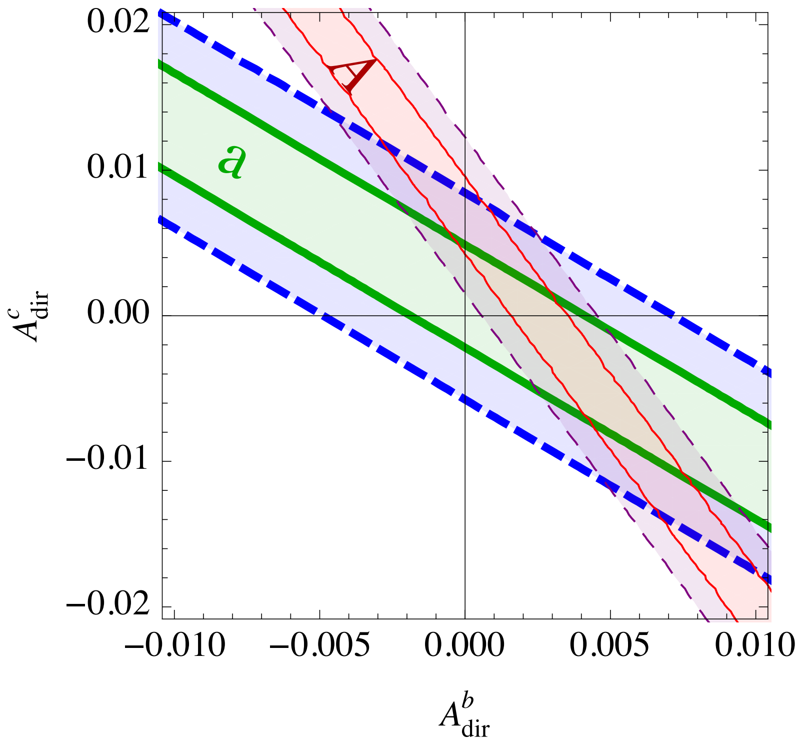
	Existing limits (2σ) (10^{-2})	SM (10^{-2})
A^{ss}	$-$	$< 10^{-2}$ [1]
A^{os}	$-$	$< 10^{-2}$ [1]
A^{b}_{mix}	< 0.1 [3]	$< 10^{-3}$ [2,3]
A^{bl}_{dir}	< 1.2 [4]	$< 10^{-5}$ [1]
A^{cl}_{dir}	< 6.0 [4]	$< 10^{-9}$ [1]
A^{bc}_{dir}	$-$	$< 10^{-7}$ [5]

[1] PRL 110, 232002 (2013) [2] arXiv:1511.09466v1 [3] arXiv:1412.7515v1 (HFAG) [4] PRD 87, 074036 (2015) [5] PLB 694, 374 (2011)

Inclusive like-sign dimuon asymmetry

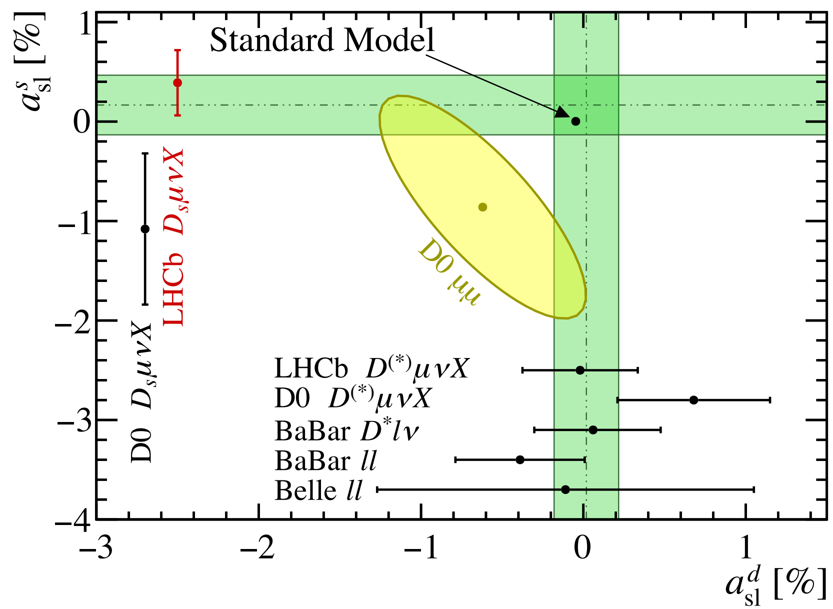
PRD 89, (2014) 012002

$$A_{dir}^{bl} \sim (0.3 \pm 0.1)\%$$
$$A_{dir}^{cl} \sim (0.9 \pm 0.3)\%$$



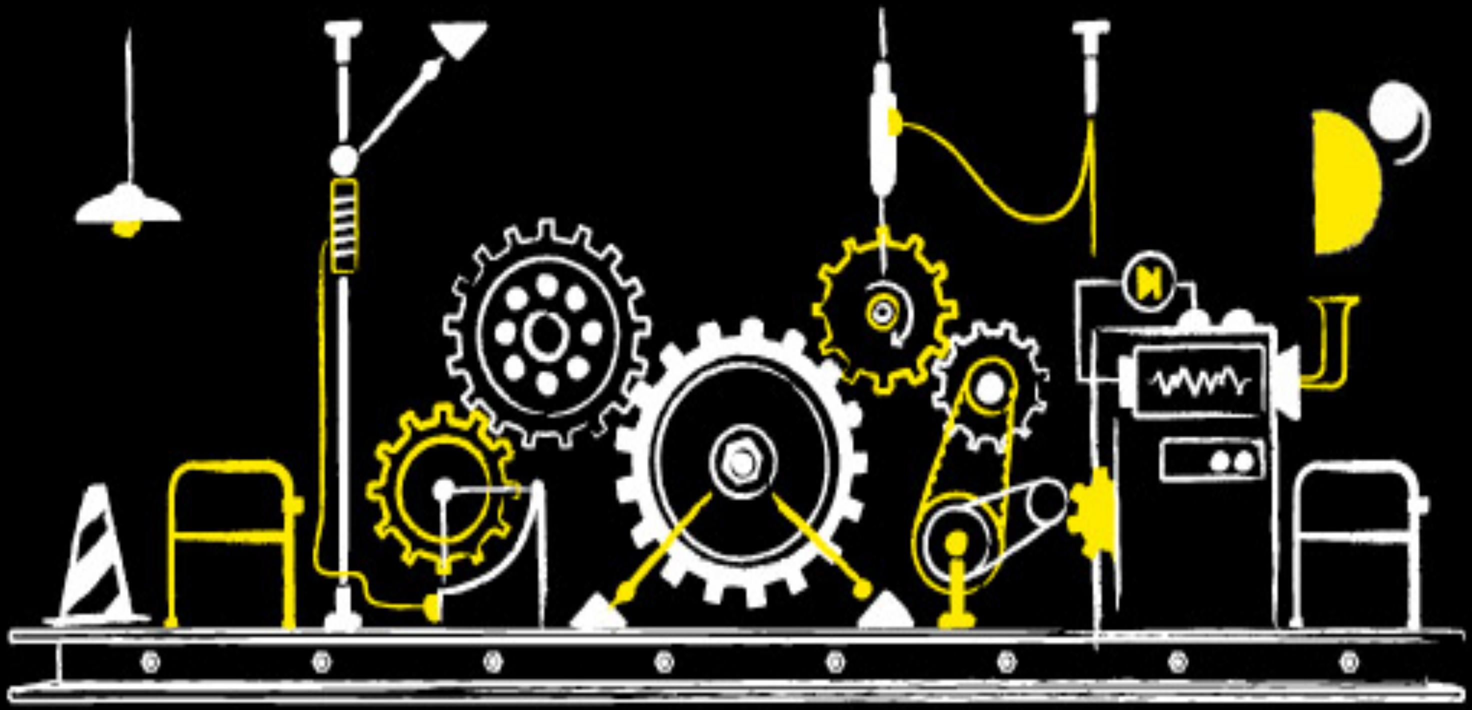
PRD 87, 074036 (2015)

$$A_{\rm mix}^{b}(a_{\rm sl}^{b}) = (-0.496 \pm 0.168)\%$$



$$A_{mix}^{b} = f_s a_{\rm sl}^{s} + f_d a_{sl}^{d}$$

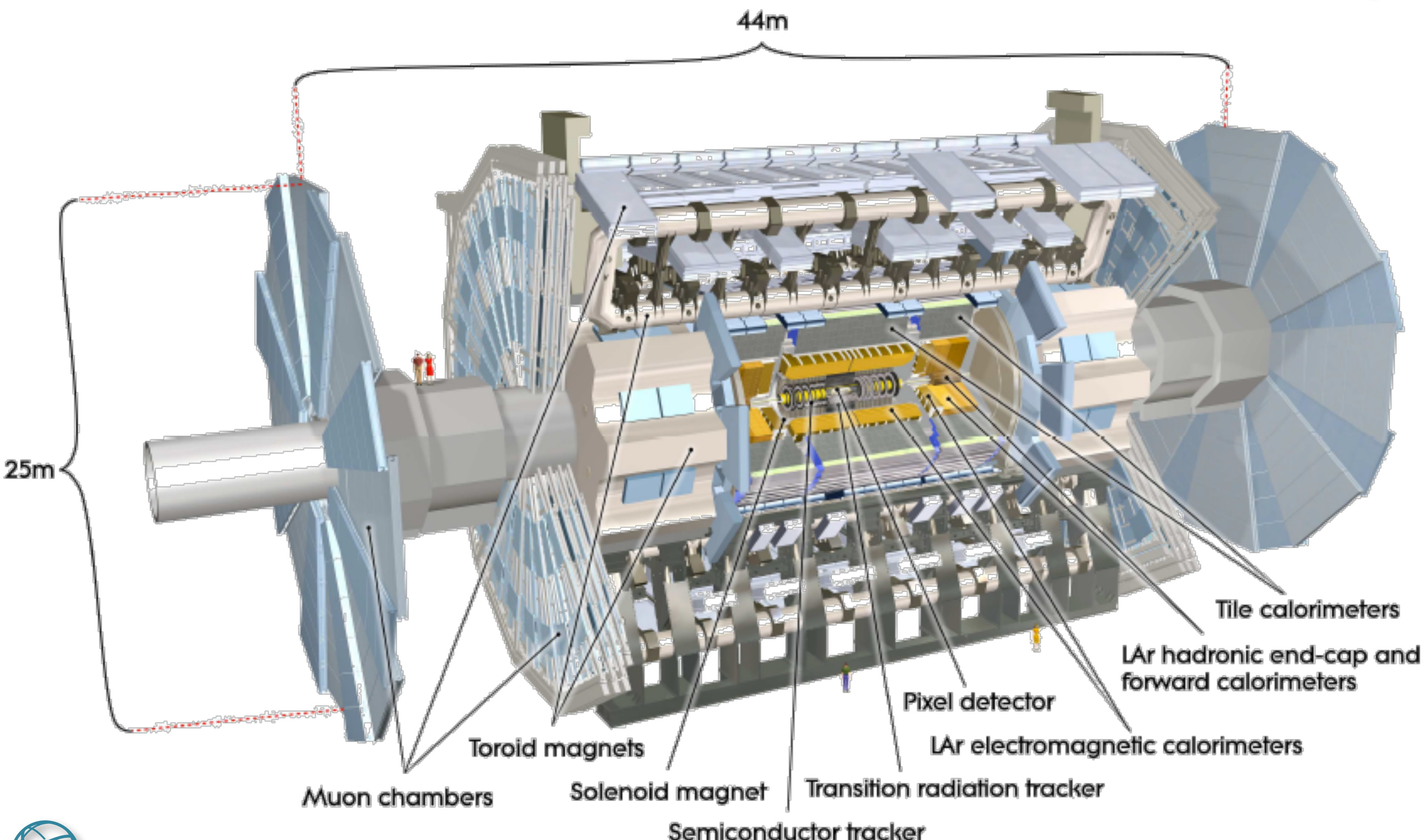
LHCb-PAPER-2016-013



Technique

All about the machinery

ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Event Selection

Electrons

- $p_T \geq$ 25 GeV
- $|\eta^{cl}|$ < 2.47 with crack veto
- Etcone20 @ 90% && Ptcone30 @ 90%
  - Energy and momentum isolation
- Exactly 1 electron and 0 muons

Muons

- $p_T \geq$ 25 GeV
- $|\eta|$ < 2.5
- Etcone20 $\leq$ 4 GeV && Ptcone30 $\leq$ 2.5 GeV
  - Energy and momentum isolation
- Exactly 1 muon and 0 electrons

Jets

- ≥ 4 anti-$k_t 4$ jets
- $p_T \geq$ 25 GeV and $|\eta|$ < 2.5
- For jets with $p_T < 50$ GeV
  - $|\text{Jet Vertex Fraction}| > 0.5$

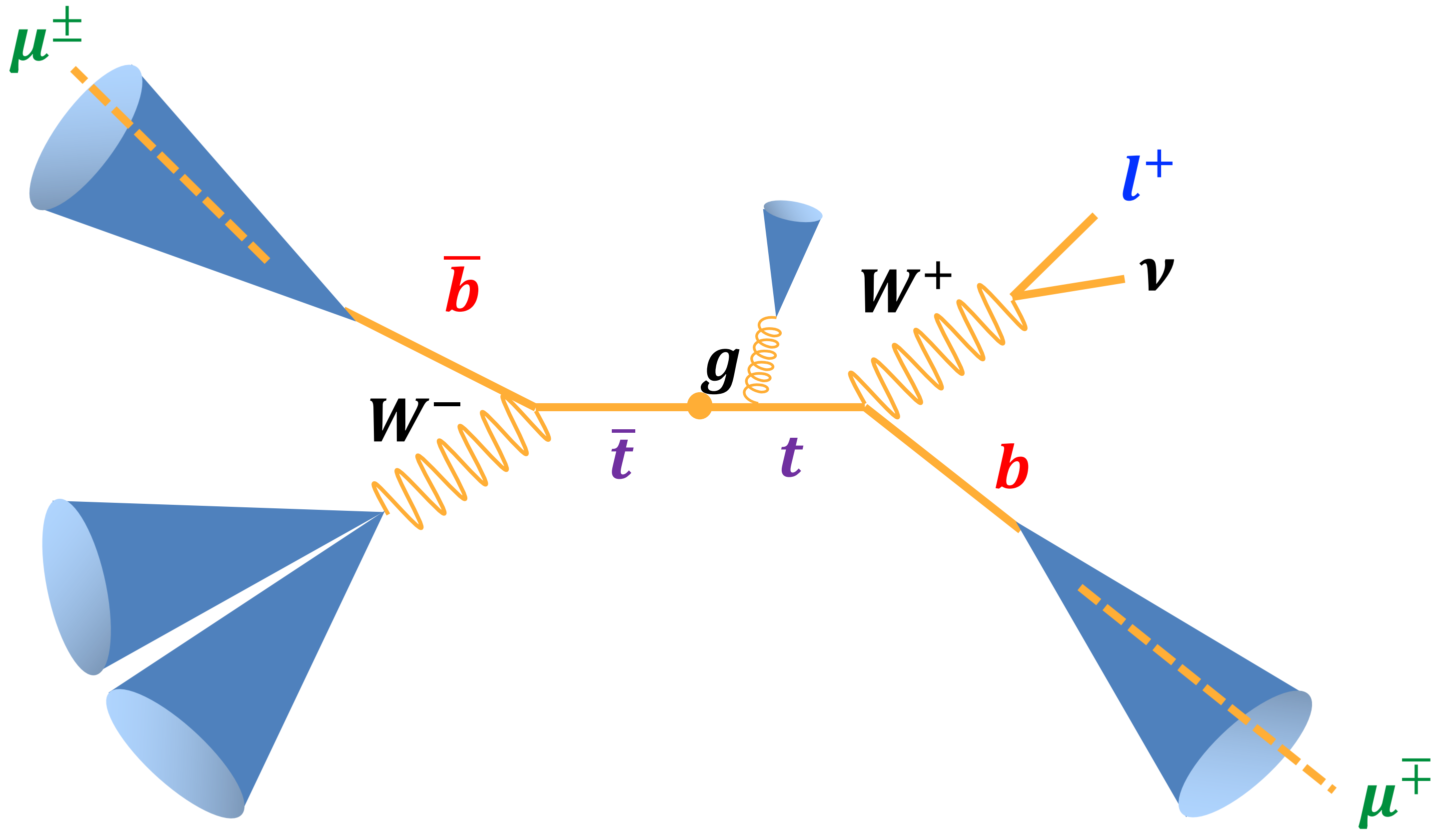
Overlap removal

- Remove jet if $\Delta R(j,e) < 0.2$
- Remove electron if $\Delta R(j,e) < 0.4$
- Remove muon if $\Delta R(j,e) < 0.2$

b-tagging

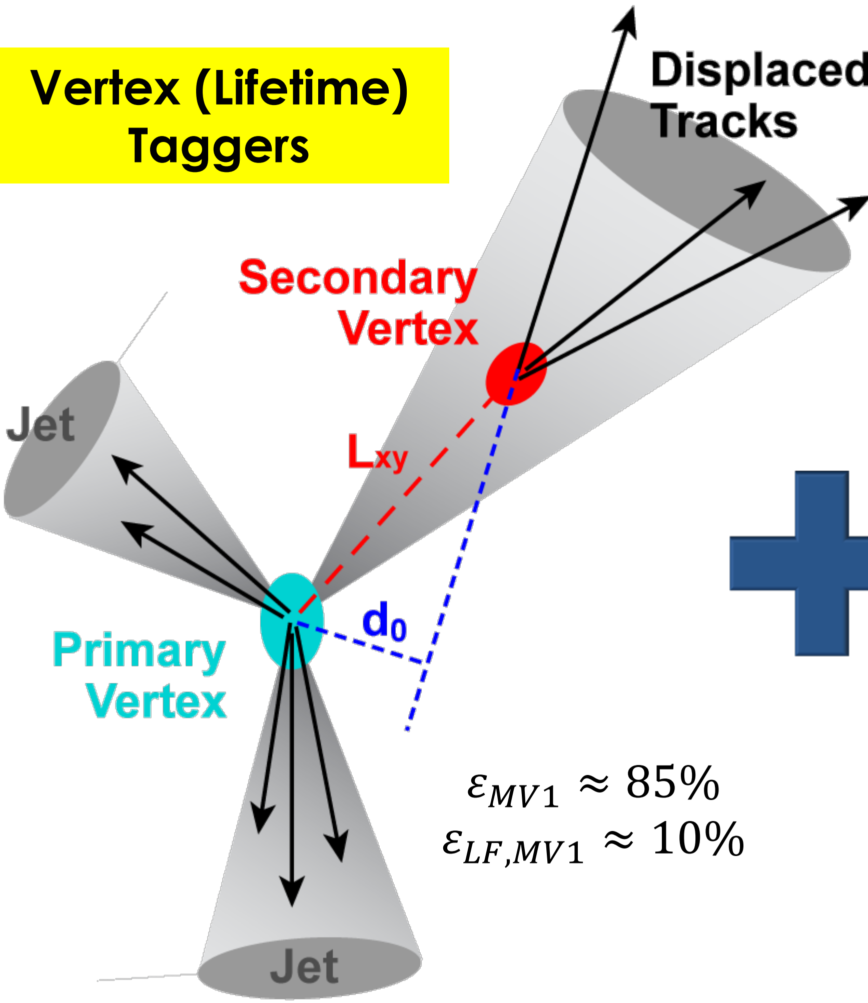
- No missing E_T or W transverse mass cuts are applied
- b-tagging performed with MV1 at 85% working point
- SMT algorithm is applied to MV1@85% b-jets

Event Signature



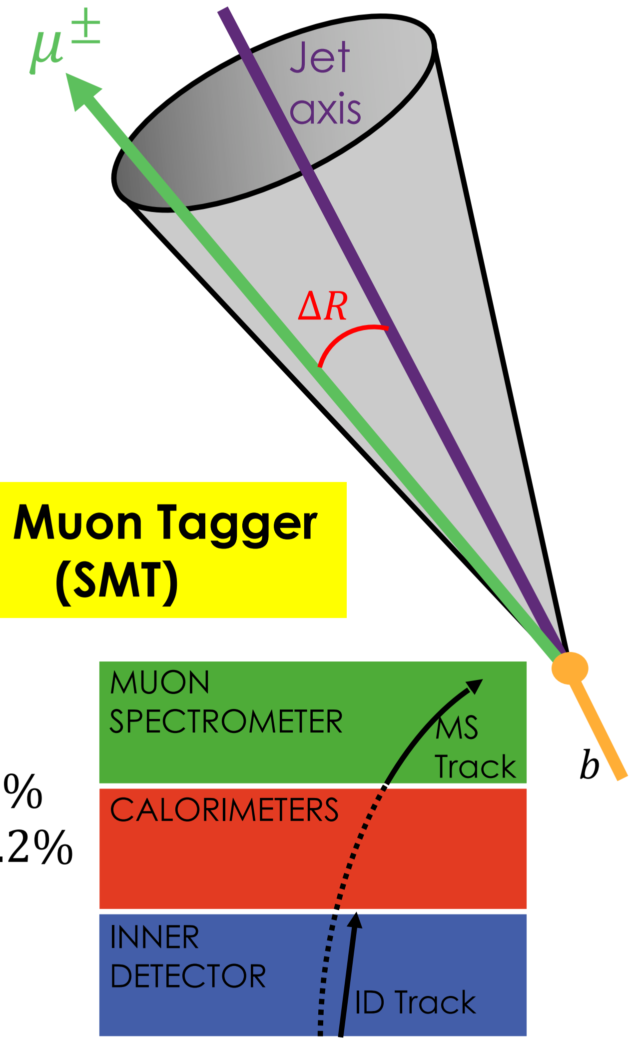
B-Tagging

Vertex (Lifetime) Taggers



$\varepsilon_{MV1} \approx 85\%$
$\varepsilon_{LF,MV1} \approx 10\%$

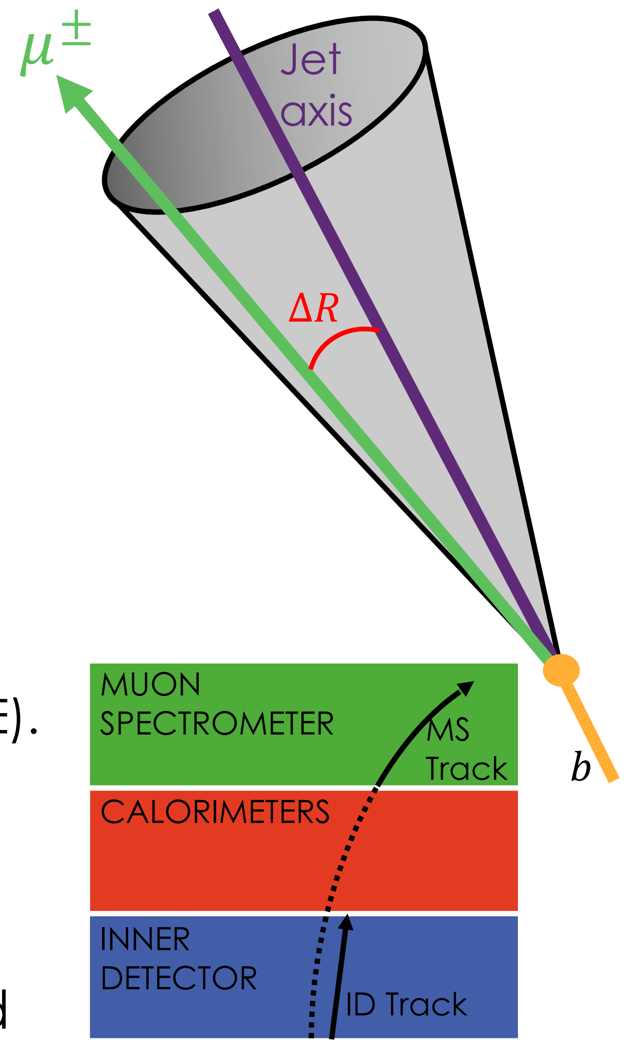
Soft Muon Tagger (SMT)



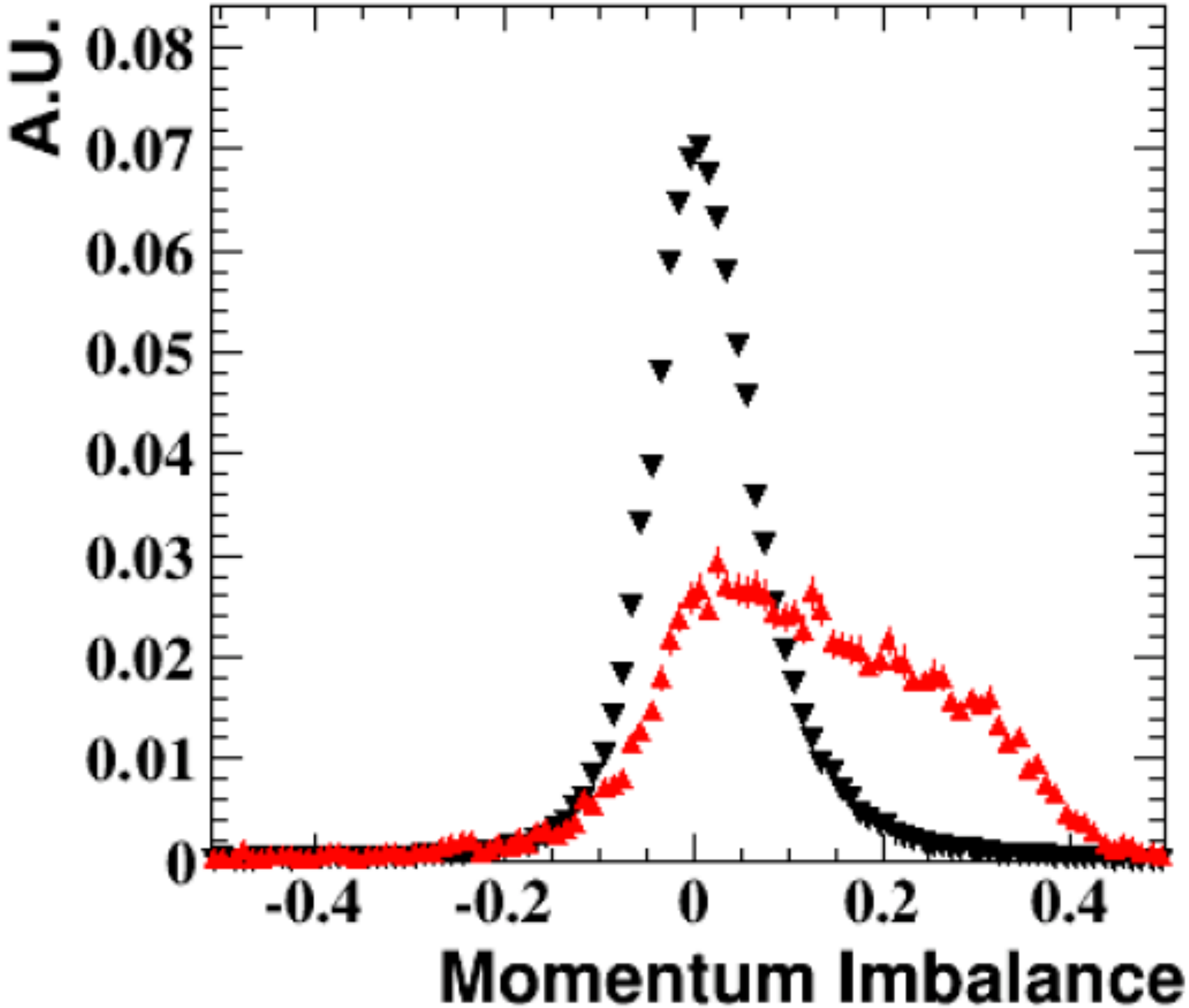
$\varepsilon_{SMT} \approx 90\%$
$\varepsilon_{LF,SMT} \approx 0.2\%$

Soft Muon Tagger

- SMT Muon is a combined track between the Muon Spectrometer (MS) and Inner Detector (ID)
- (Selected) SMT Muon Requirements:
  - Standard quality cuts (Pixel hits, holes….)
  - ΔR (jet, μ) < 0.5
  - p_T > 4 GeV
- Momentum Imbalance $MI = \frac{p^{ID} - p^{ME}}{p^{ID}} < 0.1$
  - Significance of difference between momentum measurements, from the ID track and an extrapolation of the MS track back to the ID (ME).
- Calibrated using Tag and Probe in $J/\psi \rightarrow \mu\mu$ decays
  - Main fakes:
    - Decay-in-flight of charged pions and kaons
    - Punch-through of charged hadrons



Momentum Imbalance

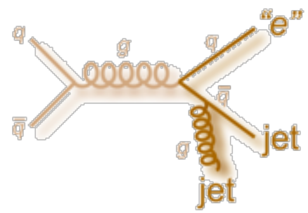


Efficiency from Tag and Probe on $J/\psi \to \mu\mu$ and $Z \to \mu\mu$

Backgrounds

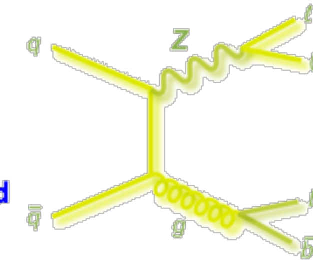
Multijet

Production Charge **Symmetric**
Lepton and SMT charge **uncorrelated**



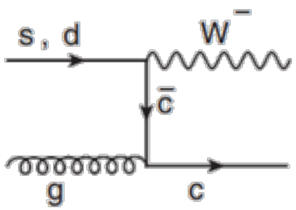
Z+Jets

Production Charge **Symmetric**
Lepton and SMT charge **uncorrelated**

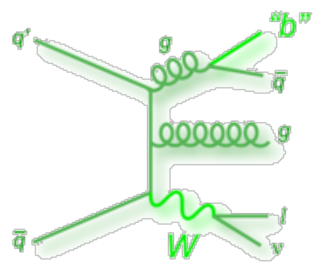


W+Jets

Production Charge **Asymmetric**



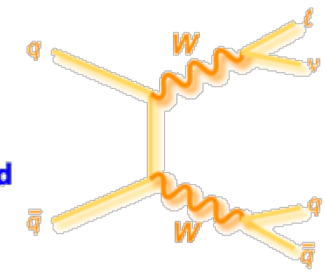
Lepton and SMT **correlated**



Lepton and SMT **uncorrelated**

Diboson

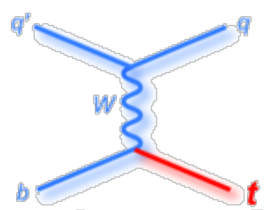
Production Charge **Asymmetric**
Lepton and SMT charge **uncorrelated**

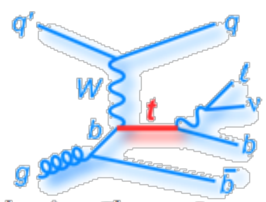


Single Top

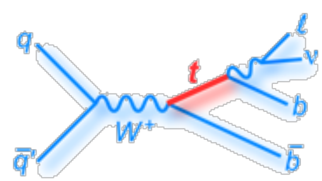
Mixed

t-channel

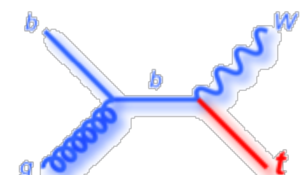




s-channel



Wt-channel



Production Charge **Asymmetric** (t-channel and s-channel)

Production Charge **Symmetric** (Wt-channel)

Lepton and SMT **correlated** (t-channel)

Lepton and SMT **uncorrelated** (s-channel)

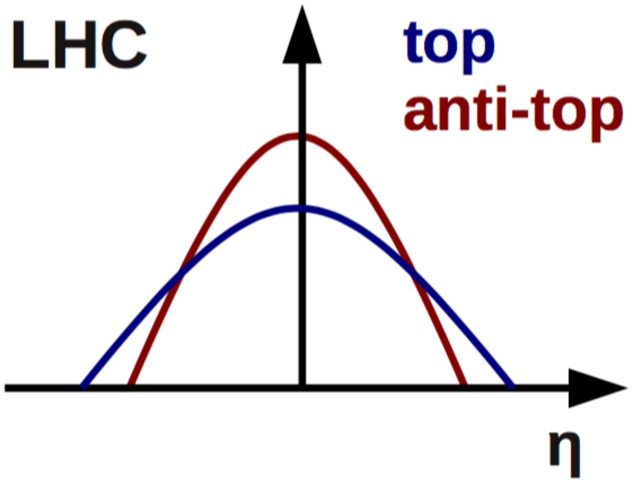
Lepton and SMT **correlated** (Wt-channel)

Detector / Physical asymmetries

There are **many** sources of asymmetries which must be considered:

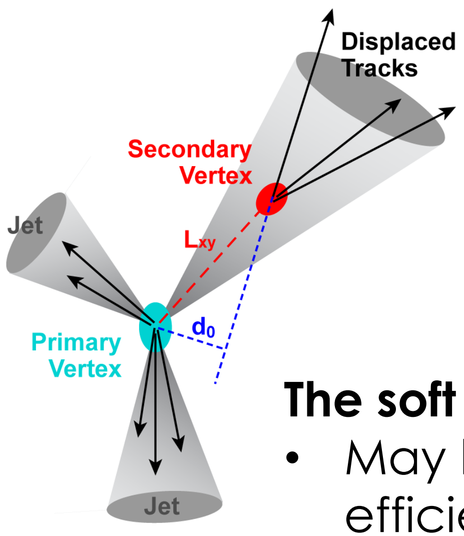
$t\bar{t}$ "charge asymmetry"

- From interference of NLO diagrams in $q\bar{q} \rightarrow t\bar{t}$
- Small effect at LHC (dominated by $gg \rightarrow t\bar{t}$),
  - $A_c = (0.9 \pm 0.5)\%$ **[Eur. Phys. J. C (2016) 76: 87]**
- Cutting on pseudorapidity (including detector acceptance) leads to unequal numbers of tops and anti-tops
  - Leads to unequal numbers of **initial** b and $\bar{b}$



Detector / Physical asymmetries

There are **many** sources of asymmetries which must be considered:

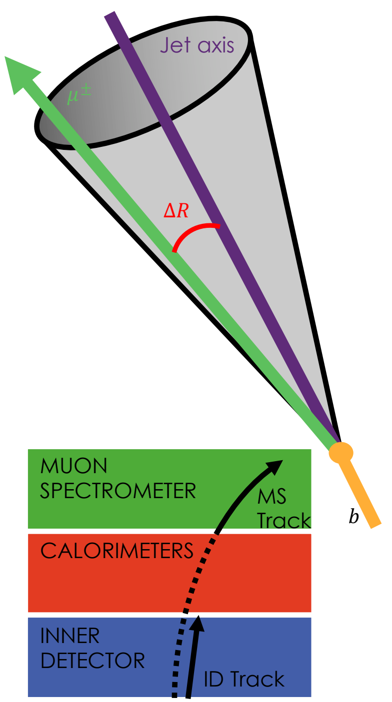


The multivariate tagger

- May have charge-dependent tagging efficiencies or fake rates
  - Would lead to unequal numbers of **initial** b and $\bar{b}$

The soft muon tagger

- May have charge-dependent tagging efficiencies or fake rates
  - Would lead to unequal numbers of **final** μ^+ and μ^-



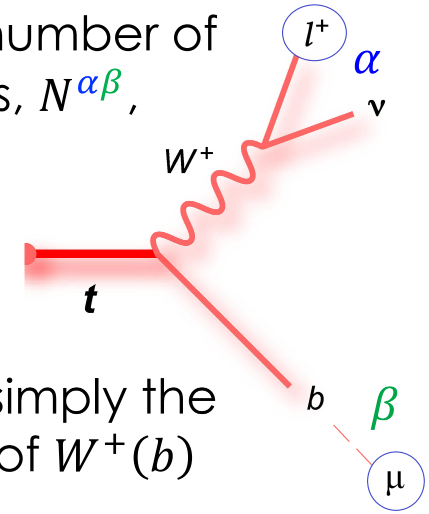
Lepton reconstruction

- Lepton charge-dependent tagging efficiencies or fake rates?
  - Would lead to unequal numbers of **initial** b and $\bar{b}$

Detector / Physical asymmetries

$$A^{ss} = \frac{P(b \to l^+) - P(\bar{b} \to l^-)}{P(b \to l^+) + P(\bar{b} \to l^-)} = \frac{\left(\frac{N^{++}}{N^+}\right) - \left(\frac{N^{--}}{N^-}\right)}{\left(\frac{N^{++}}{N^+}\right) + \left(\frac{N^{--}}{N^-}\right)}$$

- Consider number of SMT muons, $N^{\alpha\beta}$, where:

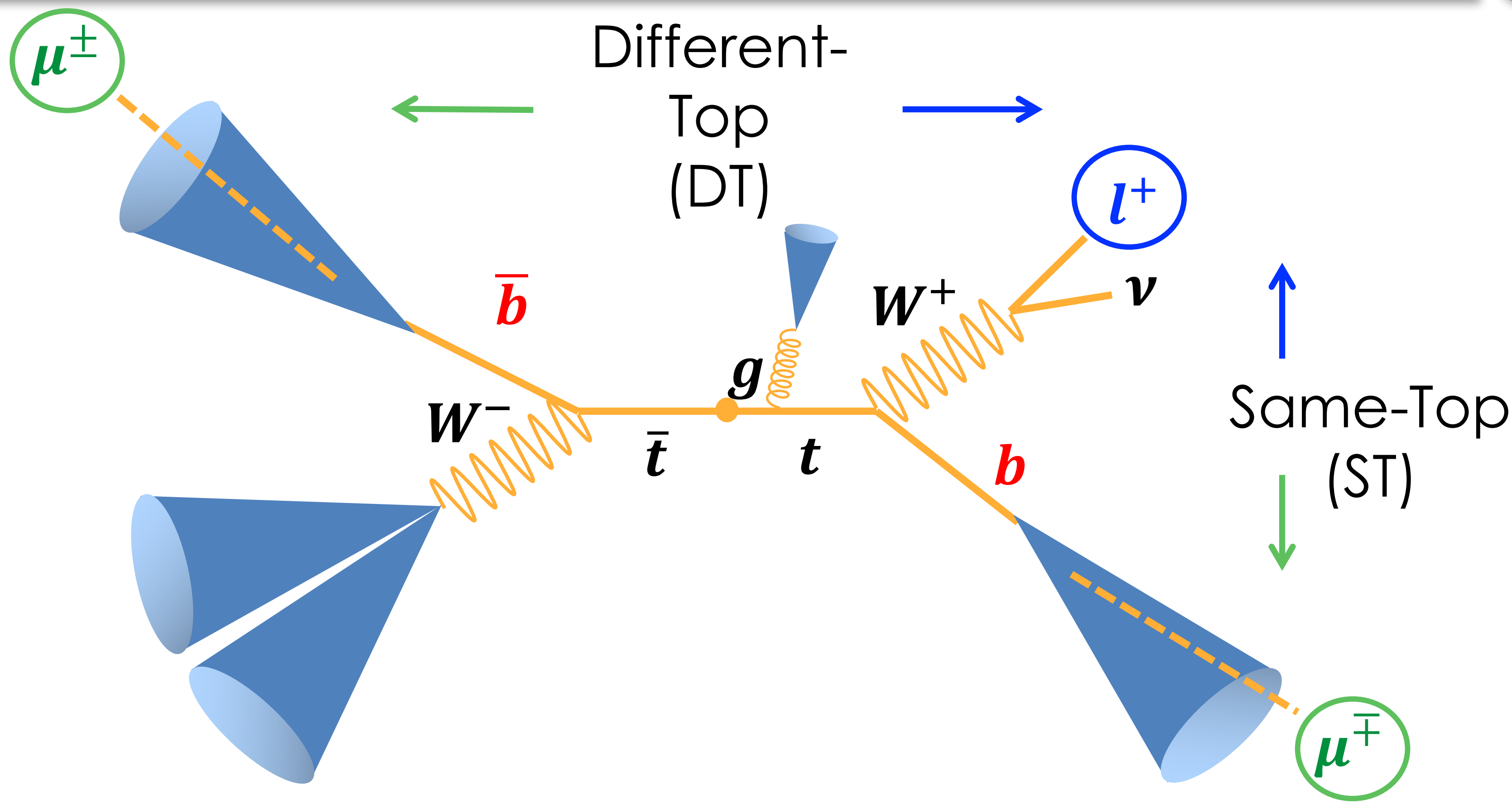


So N^{α} is simply the number of $W^+(b)$ or $W^-(\bar{b})$

Dealing with probabilities makes asymmetries independent of numbers of **initial** b and $\bar{b}$:
$\mathcal{O}(\leq 1\%)$
- $t\bar{t}$ charge asymmetry ✓
- Multivariate tagger charge-characteristics ✓
- Lepton reconstruction charge-characteristics ✓

Still vulnerable to the SMT affecting numbers of **final** $\boldsymbol{\mu}^+$ and $\boldsymbol{\mu}^-$:
$\mathcal{O}(\leq 1\%)$
- ε_{SMT} is charge-dependent, scale factors are provided separately ✓
- Fake rate is not charge-dependent ✓

Which top?



Same-Top:	$l^+ \Rightarrow b$	All good!	$N^{+-} \Rightarrow N^{+-}$
Different-Top:	$l^+ \Rightarrow \bar{b}$	Flip lepton charge	$N^{+-} \Rightarrow N^{--}$

Kinematic Likelihood Fitter (KLFitter)

KLFitter permutes reconstructed jets (label i) between four possible positions in l+jets decay. Fits kinematics of all objects to minimise likelihood.

Transfer functions – account for measurement resolutions of energies and angular information

$$L = \left(\prod_{i=1}^{4} W(\tilde{E}_i|E_i)\right) \cdot W(\tilde{E}_l|E_l) \cdot W(E_x^{miss}|p_x^{\nu}) \cdot W(E_y^{miss}|p_y^{\nu}) \cdot \left(\prod_{i=1}^{4} W(\tilde{\Omega}_i|\Omega_i)\right) \cdot$$
$$BW(m_{jj}|M_W) \cdot BW(m_{l\nu}|M_W) \cdot BW(m_{jjj}|M_t) \cdot BW(m_{l\nu j}|M_t)$$

Breit-Wigner functions– provide constraints on mass reconstruction

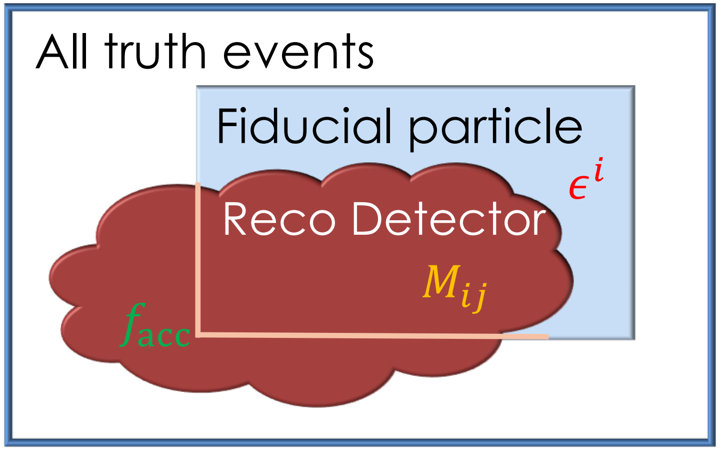
NIMA 748 (2014)

Unfolding

$$N^{i}_{\text{fid}} = \frac{1}{\epsilon^{i}} \cdot \sum_{j} M^{-1}_{ij} \cdot f^{j}_{\text{acc}} \left(N^{j}_{\text{data}} - N^{j}_{\text{bkg}}\right)$$

$$f^{j}_{\text{acc}} \equiv \left(\frac{N_{\text{reco}\wedge\text{part}}}{N_{\text{reco}}}\right)^{j} \qquad \epsilon^{i} \equiv \left(\frac{N_{\text{reco}\wedge\text{part}}}{N_{\text{part}}}\right)^{j}$$

- f^{i}_{acc}= Applied bin-by-bin to correct for SMT muons that are present at the reconstruction level, but not at the fiducial level.
- M_{ij}= Discrete 4x4 Response Matrix. Corrects for migrations between 4 CA bins, these are caused by mistakes in ST/DT identification due to KLF performance or due to charge mis-ID on the triggered leptons (extremely small effect)
- $\frac{1}{\epsilon^{i}}$ = Applied bin-by-bin to the unfolded data to correct for SMT muons that are present at the particle-level, but not at the reconstruction level.



	$N^{++}{}_j$	$N^{--}{}_j$	$N^{+-}{}_j$	$N^{-+}{}_j$
$N^{++}{}_i$	0.79	0.00	0.00	0.21
$N^{--}{}_i$	0.00	0.79	0.21	0.00
$N^{+-}{}_i$	0.00	0.21	0.79	0.00
$N^{-+}{}_i$	0.21	0.00	0.00	0.79

Measure and extract

$$A^{ss} = \frac{\left(\frac{N^{++}}{N^{+}}\right) - \left(\frac{N^{--}}{N^{-}}\right)}{\left(\frac{N^{++}}{N^{+}}\right) + \left(\frac{N^{--}}{N^{-}}\right)}$$

$$A^{os} = \frac{\left(\frac{N^{+-}}{N^{+}}\right) - \left(\frac{N^{-+}}{N^{-}}\right)}{\left(\frac{N^{+-}}{N^{+}}\right) + \left(\frac{N^{-+}}{N^{-}}\right)}$$

Extracting four CP parameters from two variables is a nightmare in fitting – massively under-constrained.

However since all are individually expected to be zero, it is reasonable to consider each one by itself to set simple limits:

$$A^{b}_{\text{mix}} = \frac{A^{ss}}{r_b + r_{c\bar{c}}}$$

$$A^{bl}_{\text{dir}} = \frac{A^{os}}{\tilde{r}_b}$$

$$A^{cl}_{\text{dir}} = \frac{-A^{ss}}{r_c + r_{c\bar{c}}}$$

$$A^{bc}_{\text{dir}} = \frac{A^{ss}}{r_c}$$

When a CP asymmetry may be extracted from either A^{ss} or A^{os}, the tighter constraint is selected

Systematics

Experimental

Leptons
- Lepton charge mis-identification
- Lepton energy resolution
- Lepton trigger, reco, ID

Jets
- Jet energy scale
- Jet energy resolution
- Jet reco efficiency
- Jet vertex fraction

Backgrounds
- Multijet estimate
- Background normalization
- W+Jets estimate (statistical)
- Single top production asymmetry

MV1 tagging
- b-tagging efficiency
- c-jet mistag rate
- Light-jet mistag rate

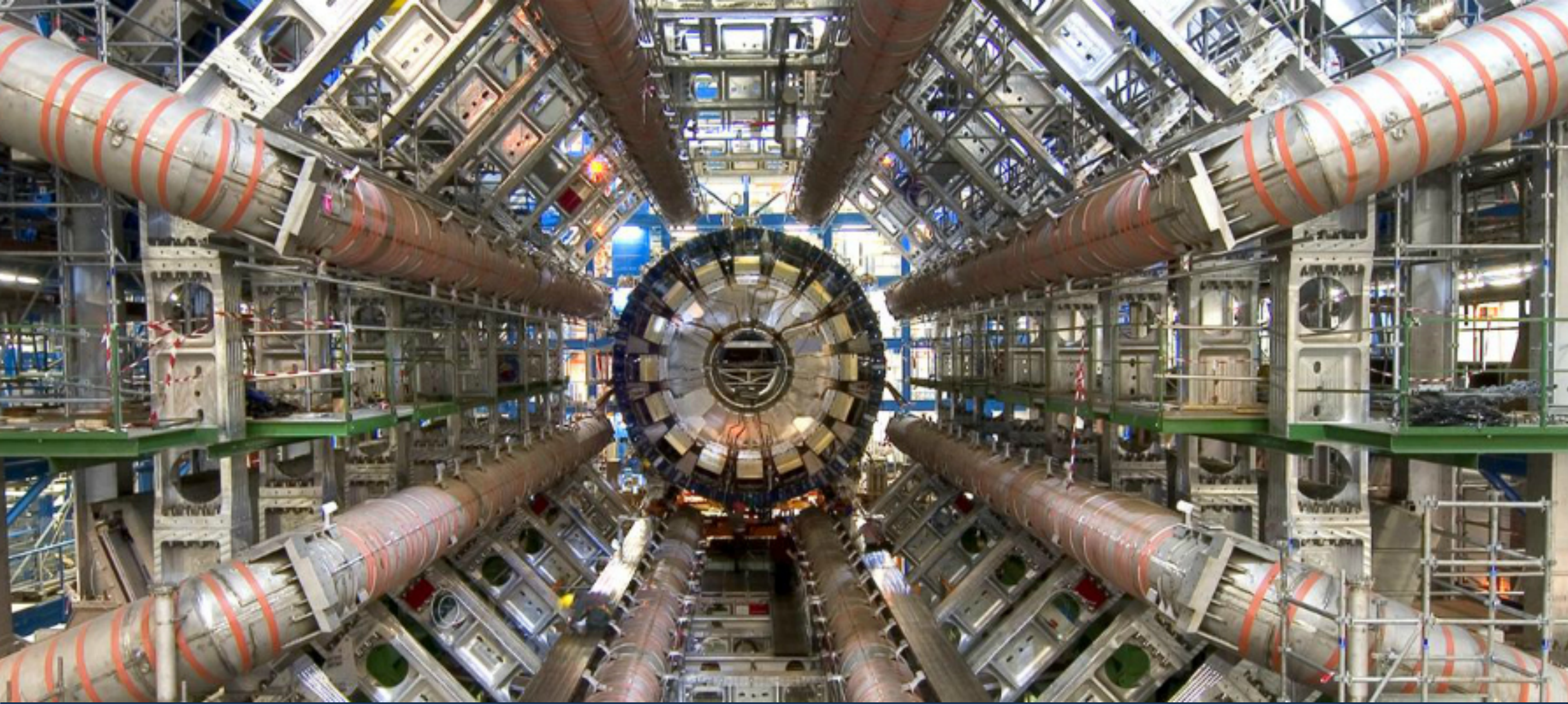
SMT tagging
- SMT reco ID
- SMT momentum imbalance
- SMT light-jet mistag rate

Modelling

- Hadron-to-muon branching ratio
- B-Hadron production
- Additional radiation
- MC generator
- Parton shower
- Parton density function

PDG Corrections (Re-weighting) — Hadron-to-muon branching ratio, B-Hadron production

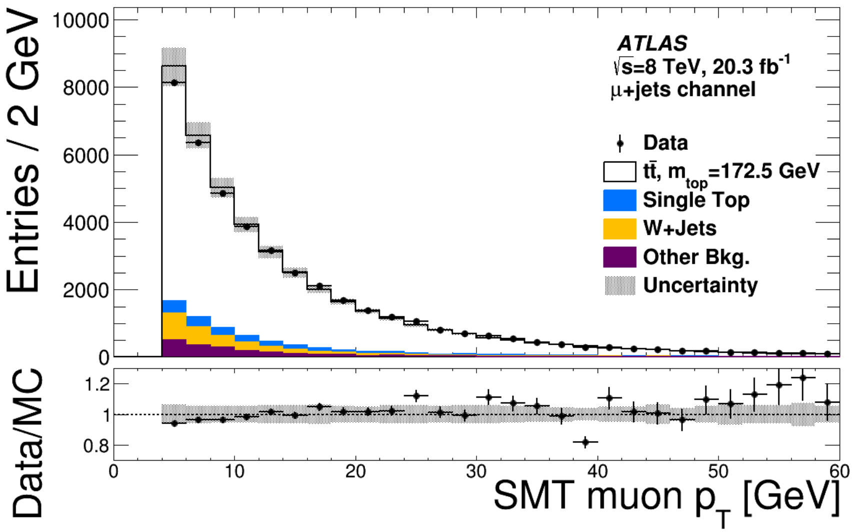
Additional radiation: Largest systematic
Affects the KLFitter performance
(Largest change to response matrix)

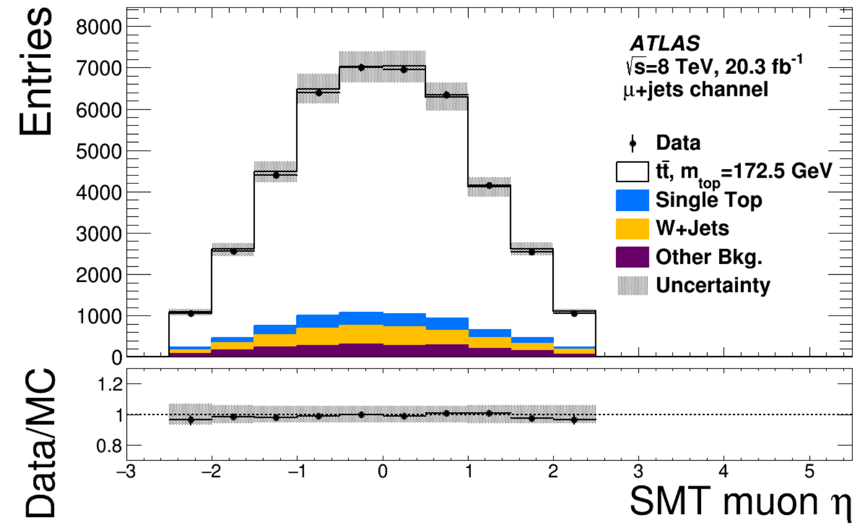


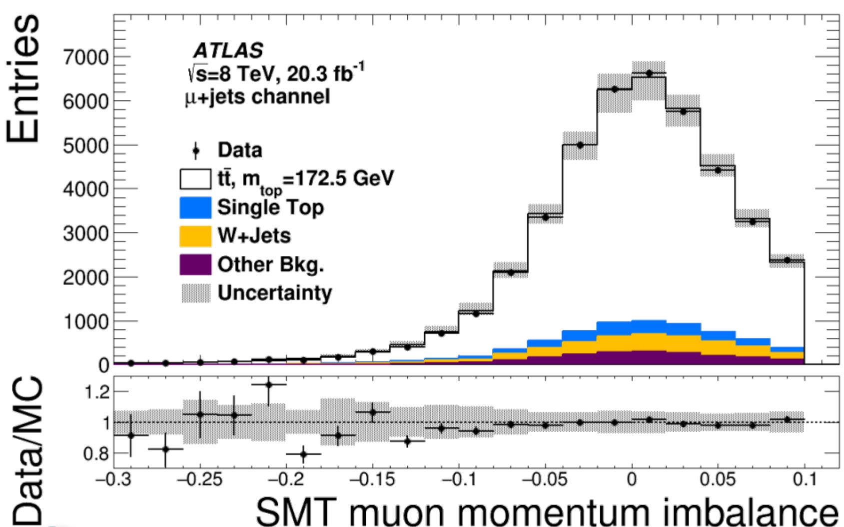
Results

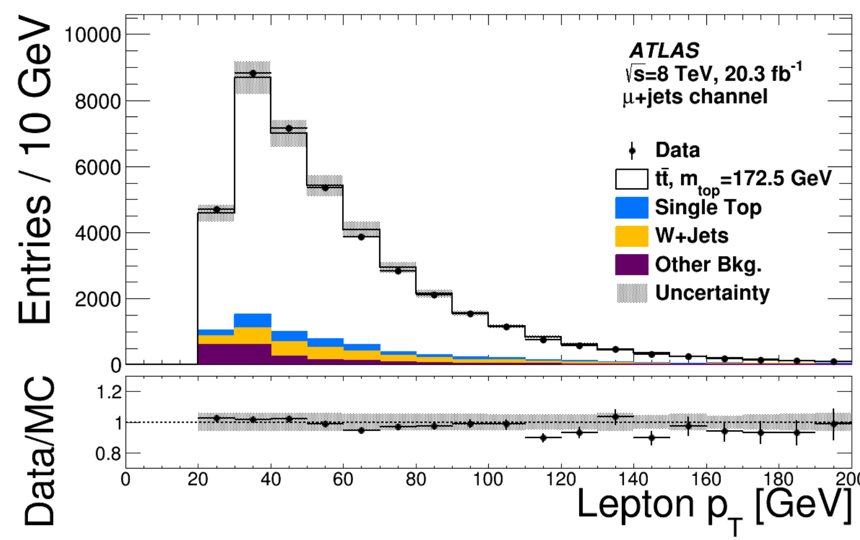
Less talking, more doing

Kinematic Distributions

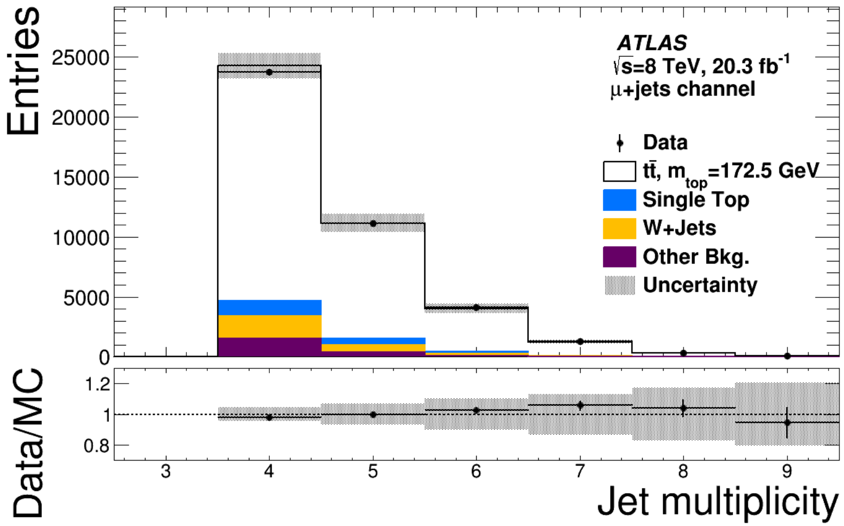


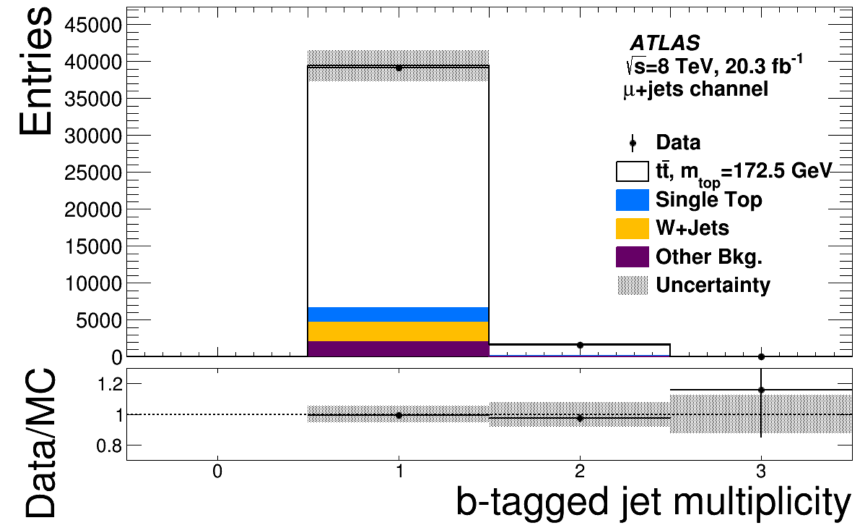


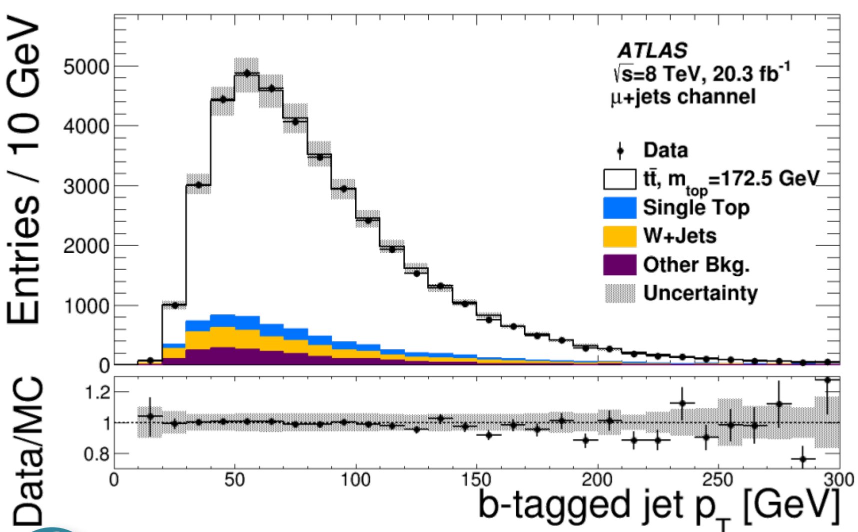


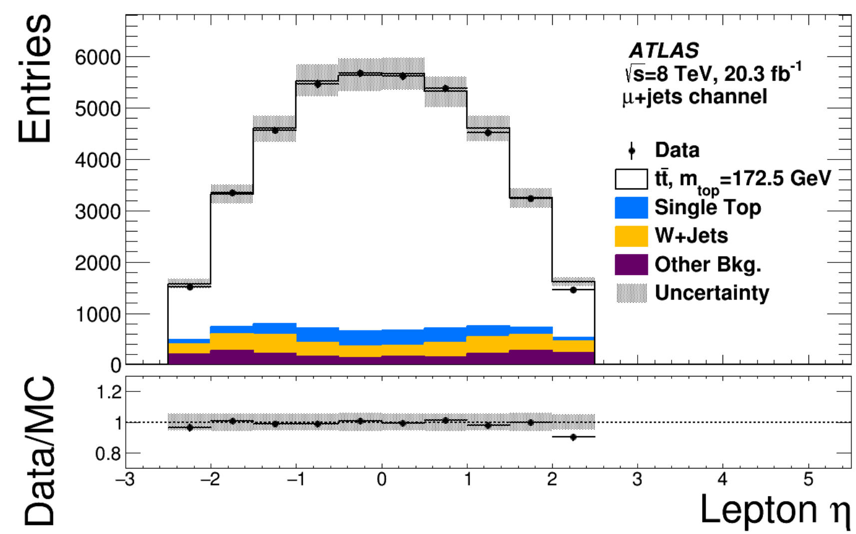


Kinematic Distributions

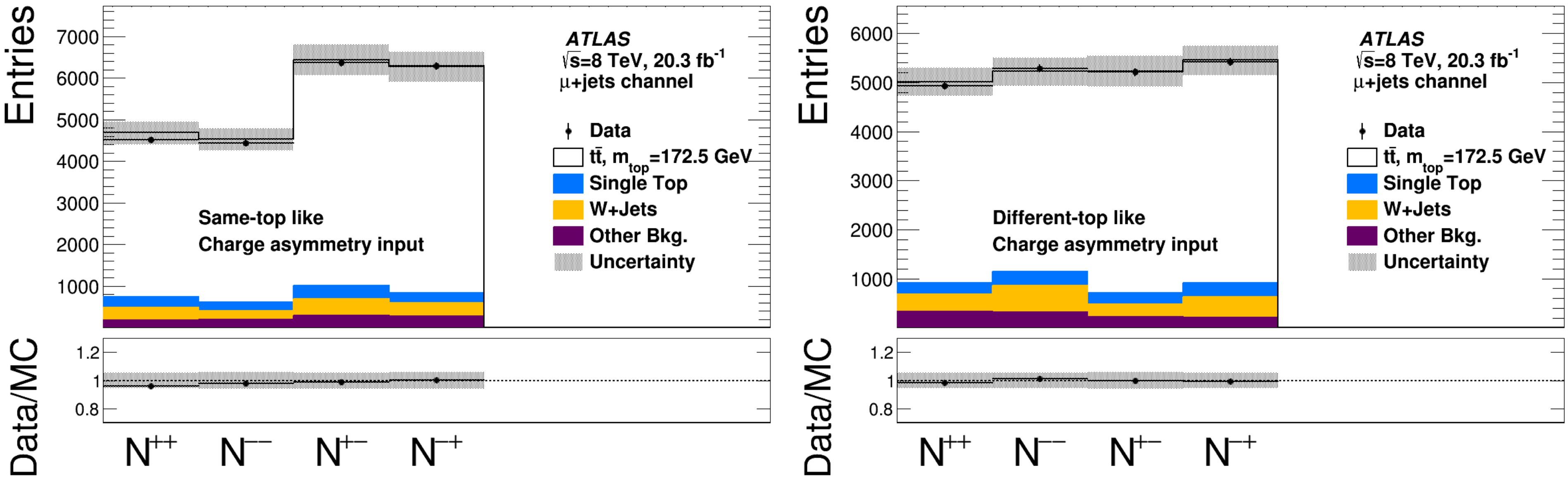








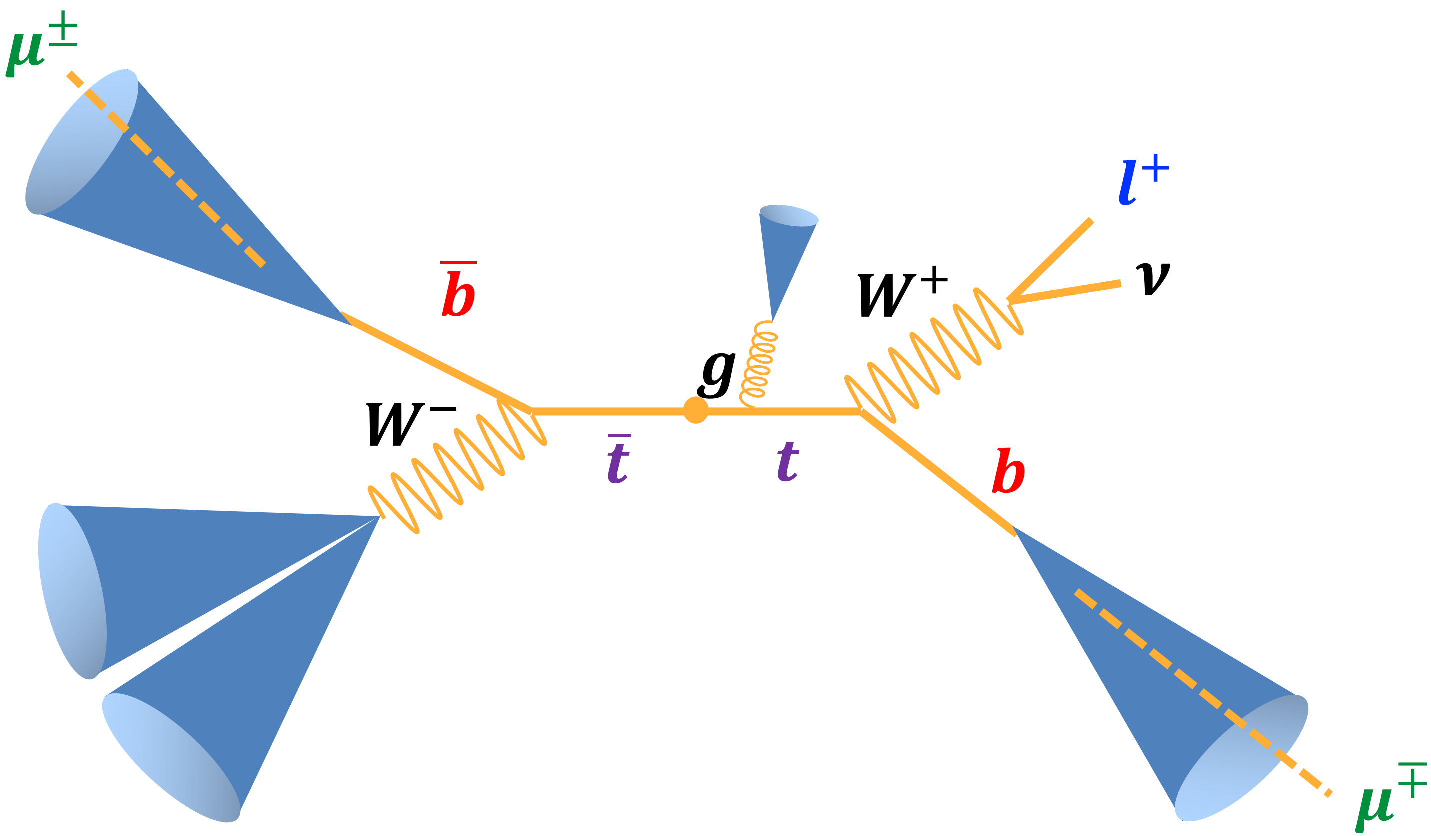
Charge Asymmetry



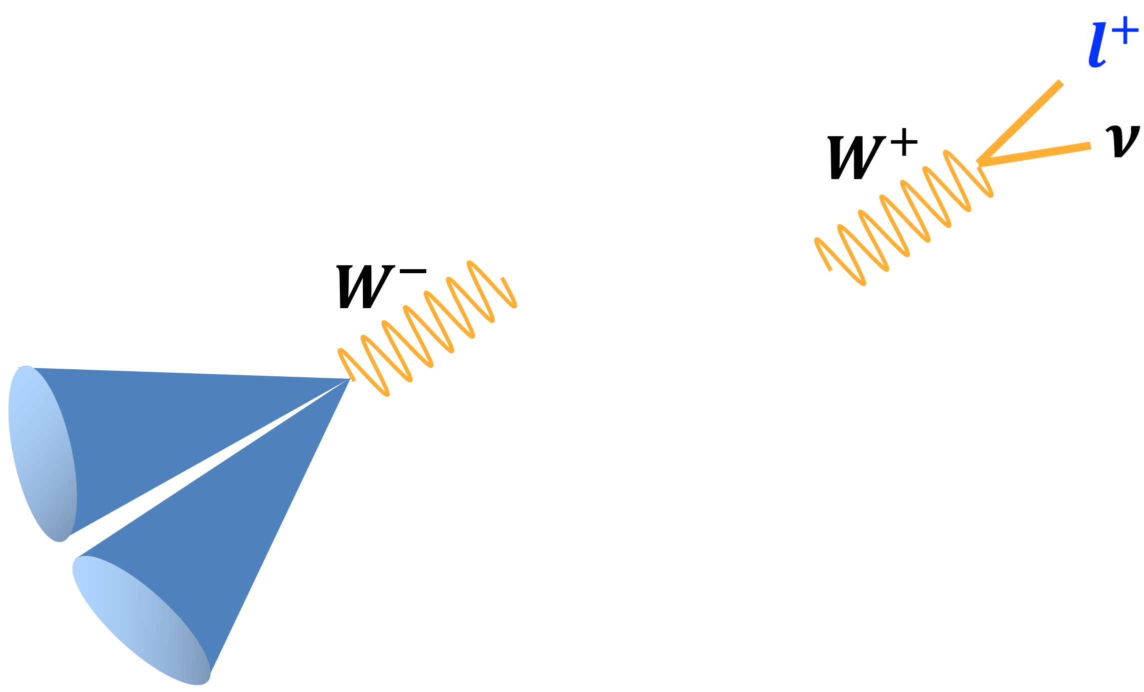
$$A^{ss} = \frac{\left(\frac{N^{++}}{N^{+}}\right) - \left(\frac{N^{--}}{N^{-}}\right)}{\left(\frac{N^{++}}{N^{+}}\right) + \left(\frac{N^{--}}{N^{-}}\right)}$$

$$A^{os} = \frac{\left(\frac{N^{+-}}{N^{+}}\right) - \left(\frac{N^{-+}}{N^{-}}\right)}{\left(\frac{N^{+-}}{N^{+}}\right) + \left(\frac{N^{-+}}{N^{-}}\right)}$$

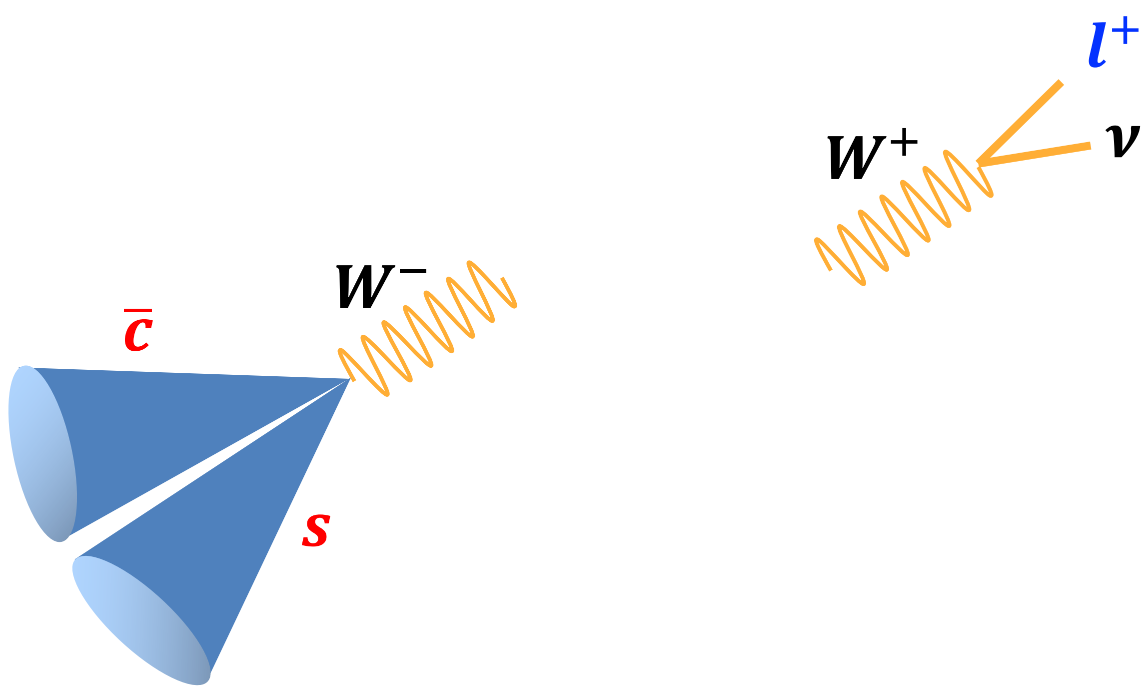
$W \to cs \to \mu$



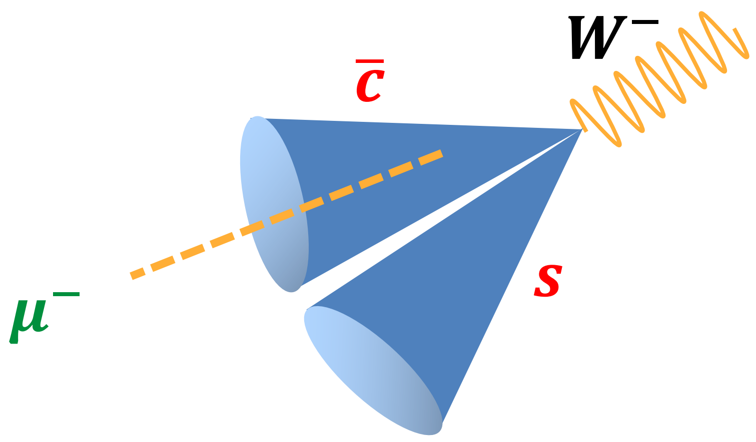
$W \rightarrow cs \rightarrow \mu$

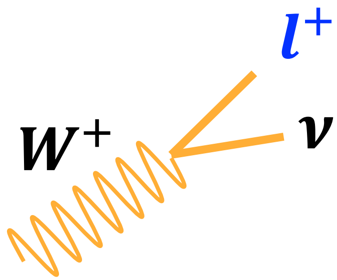


$W \to cs \to \mu$



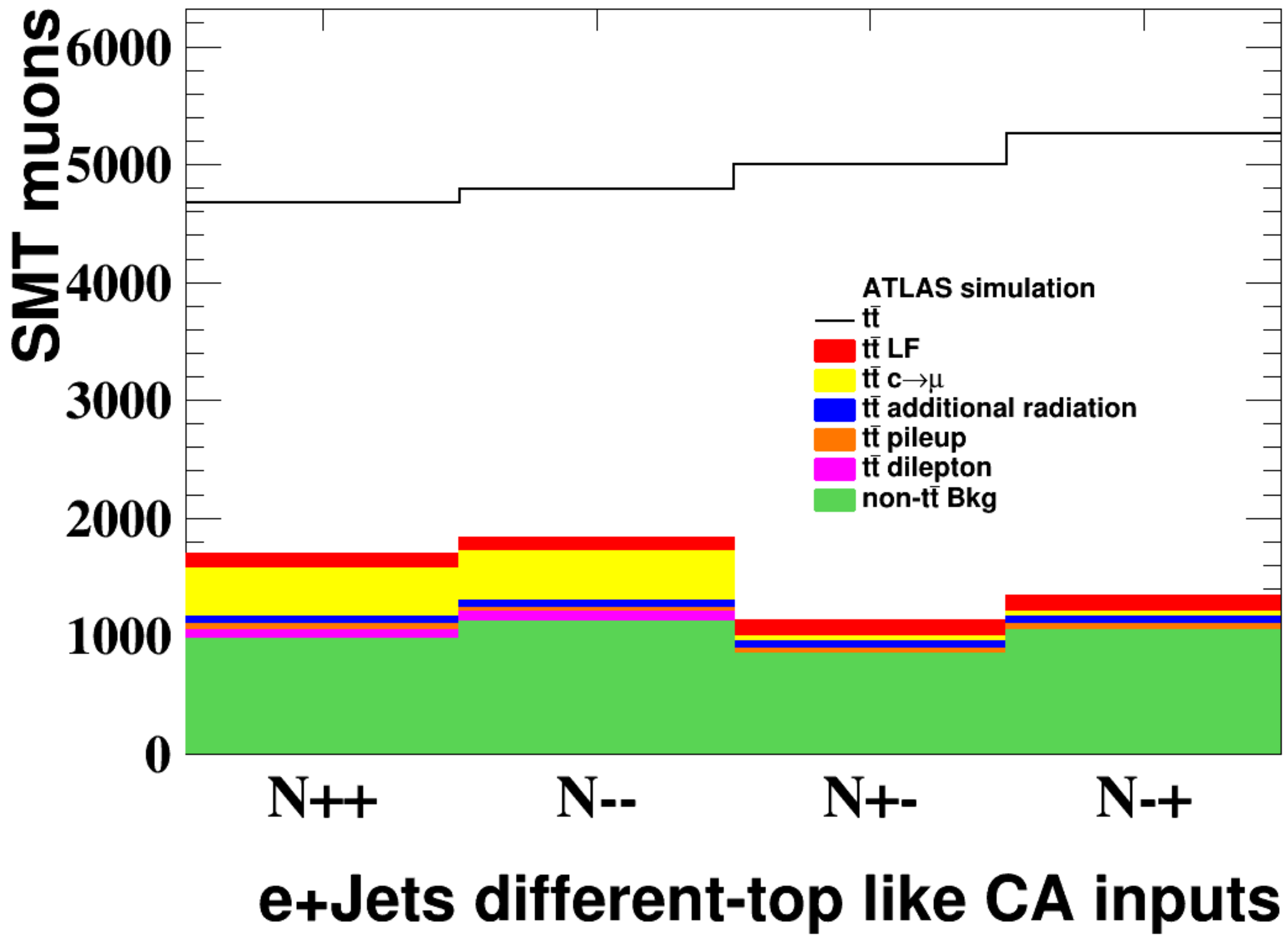
$W \to cs \to \mu$





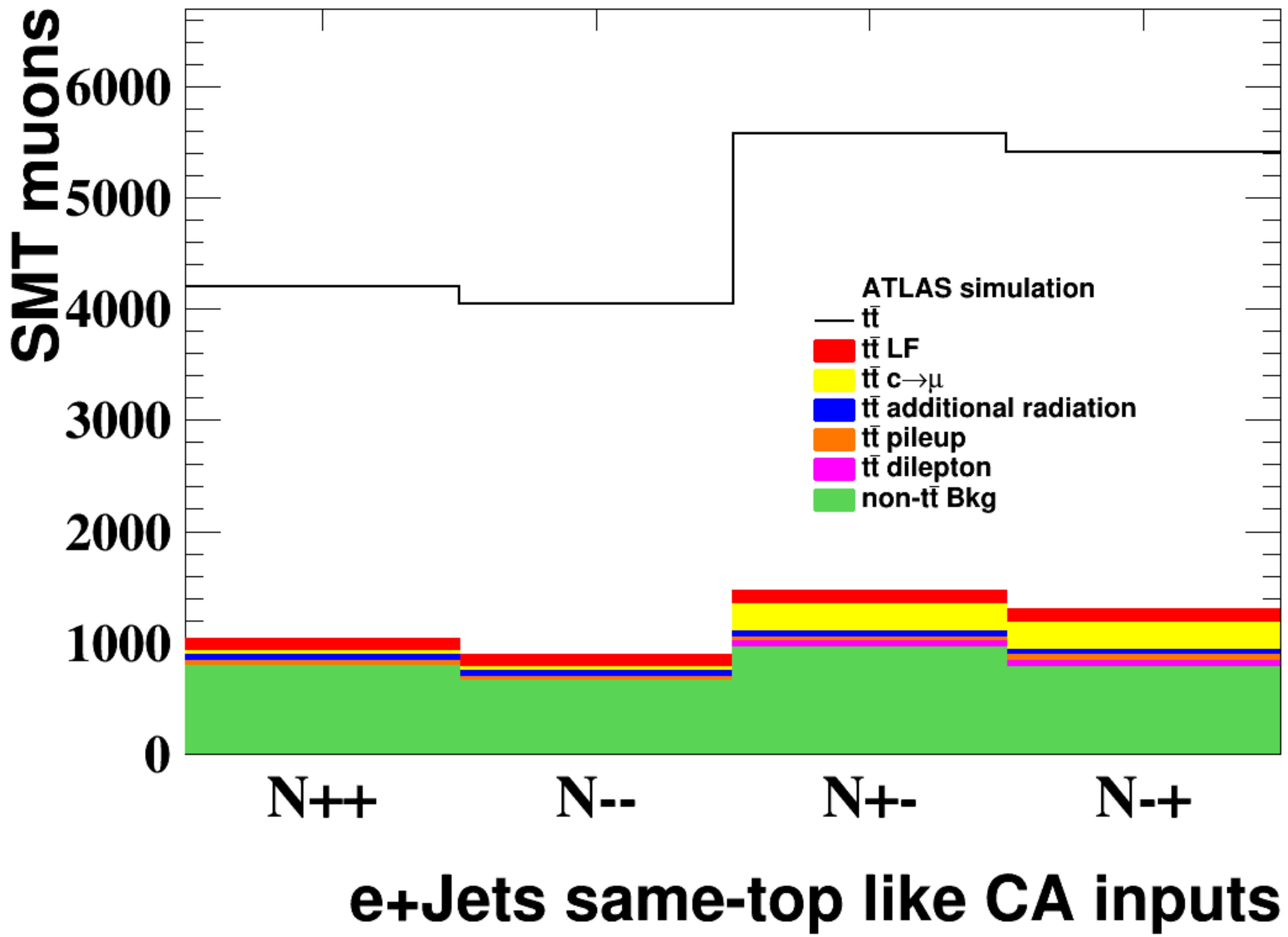
- Opposite Sign
- Different Top
  - But we charge flip-different top events
  - “Same-Sign”

$W \to cs \to \mu$



SMT muons
6000
5000
4000
3000
2000
1000
0
ATLAS simulation
tt̄
tt̄ LF
tt̄ c→μ
tt̄ additional radiation
tt̄ pileup
tt̄ dilepton
non-tt̄ Bkg
N++
N--
N+-
N-+
e+Jets different-top like CA inputs

$W \rightarrow cs \rightarrow \mu$



Charge Asymmetry

Results	Data (10^{-2})	Existing limits (2σ) (10^{-2})	SM (10^{-2})
A^{ss}	-0.7 ± 0.8	$-$	$< 10^{-2}$ [1]
A^{os}	0.4 ± 0.5	$-$	$< 10^{-2}$ [1]
A^{b}_{mix}	-2.5 ± 2.8	< 0.1 [3]	$< 10^{-3}$ [2,3]
A^{bl}_{dir}	0.5 ± 0.5	< 1.2 [4]	$< 10^{-5}$ [1]
A^{cl}_{dir}	1.0 ± 1.0	< 6.0 [4]	$< 10^{-9}$ [1]
A^{bc}_{dir}	-1.0 ± 1.1	$-$	$< 10^{-7}$ [5]

At 2σ the constraints made by this analysis are stronger than the existing limit on A^{cl}_{dir}
This the first direct experimental constraint on A^{bc}_{dir}.

[1] PRL 110, 232002 (2013) [2] arXiv:1511.09466v1 [3] arXiv:1412.7515v1 (HFAG) [4] PRD 87, 074036 (2015) [5] PLB 694, 374 (2011)

Charge Asymmetry results

	A^{ss} (10^{-2})		A^{os} (10^{-2})	
Measured value	−0.7		0.41	
Statistical uncertainty	±0.6		±0.35	
Sources of experimental uncertainty				
Leptons	+0.09	−0.11	+0.07	−0.06
Jets	+0.14	−0.17	+0.09	−0.08
Backgrounds	±0.05		±0.03	
MV1 tagging	±0.03		±0.018	
SMT tagging	±0.06		±0.04	
Sources of modelling uncertainty				
PDG corrections	+0.04	−0.05	+0.026	−0.023
Additional radiation	±0.4		±0.23	
MC generator	±0.05		±0.025	
Parton shower	±0.04		±0.017	
Parton distribution function	±0.22		±0.13	
Total experimental uncertainty	+0.19	−0.22	+0.13	−0.11
Total modelling uncertainty	+0.5	−0.5	+0.27	−0.27
Total systematic uncertainty	+0.5	−0.5	+0.30	−0.29

Summary

- CP-sensitive same- and opposite-sign charge asymmetries have been measured.
- The **first analysis to use this technique** to measure CPV in b- and c-quark decays

- The charge asymmetries and CP asymmetries presented are **consistent with the Standard Model** expectations.

- This analysis produced the first experimental constraint of A_{dir}^{bc}, strengthened the existing 2σ on A_{dir}^{cl} and provided an equivalent constraint on A_{dir}^{bl}.

- The largest uncertainty on all asymmetry measurements reported is statistical.
- The largest systematic uncertainty is additional radiation.

(JHEP 02 (2017) 071)

Outlook

- A repeat analysis at 13 TeV (e.g. $100\ \text{fb}^{-1}$) has the potential to reduce the statistical uncertainty by a factor of 4

Uncertainties	Observed at 8 TeV, 20.3 fb^{-1}, (10^{-2})			Predicted at 13 TeV, 100 fb^{-1}, (10^{-2})		
	Statistical	Systematic	Total	Statistical	Systematic	Total
A^{ss}	0.6	0.5	0.8	0.2	0.5	0.5
A^{os}	0.5	0.4	0.5	0.1	0.3	0.3
A^{b}_{mix}	2.1	1.8	2.8	0.5	1.8	1.9
$A^{b\ell}_{\text{dir}}$	0.4	0.3	0.5	0.1	0.3	0.4
$A^{c\ell}_{\text{dir}}$	0.7	0.7	1.0	0.2	0.7	0.7
A^{bc}_{dir}	0.8	0.7	1.1	0.2	0.7	0.7

Table 13.1: Predictions for the uncertainties on a repeated analysis using 100 fb^{-1} of Run 2 LHC data at a collision energy of $\sqrt{s} = 13$ TeV.

- If you focused on the systematics (e.g reduce IFSR by 1/3)
  - **Total uncertainties could be reduced by a factor 2.5!**
- Additional statistics would potentially allow for a time-dependent analysis
  - Secondary vertex tagger provides b-decay time

Thanks for your attention

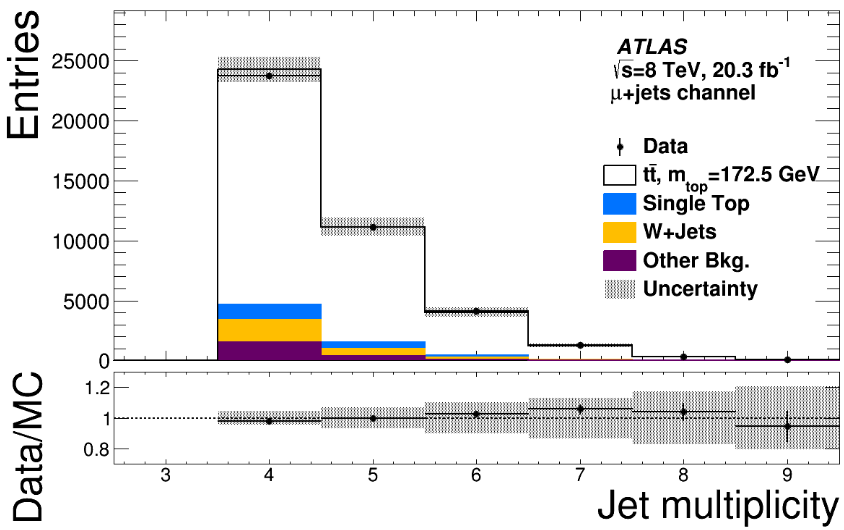
Jacob Kempster

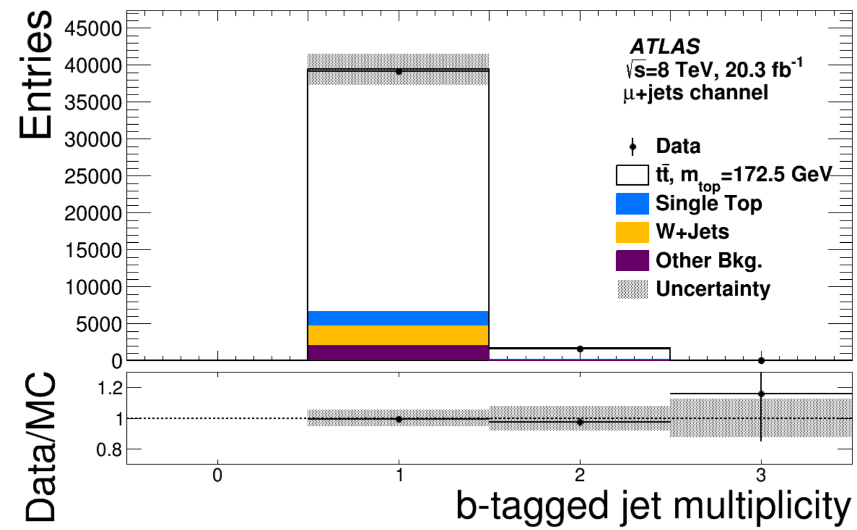
27 September 2017

Backup

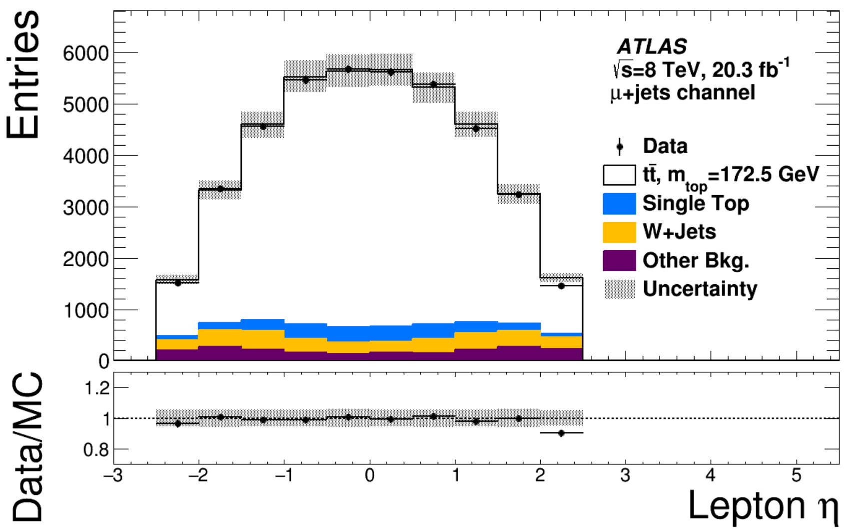
The bonus stuff

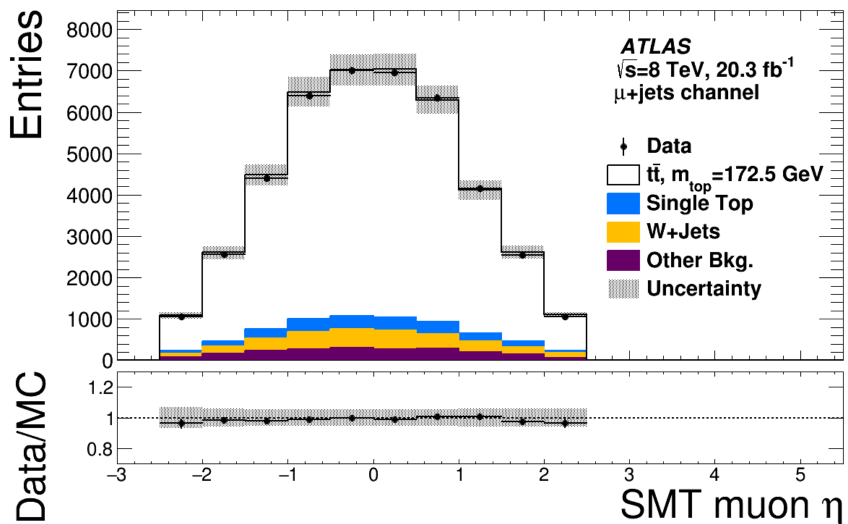
Kinematic Distributions



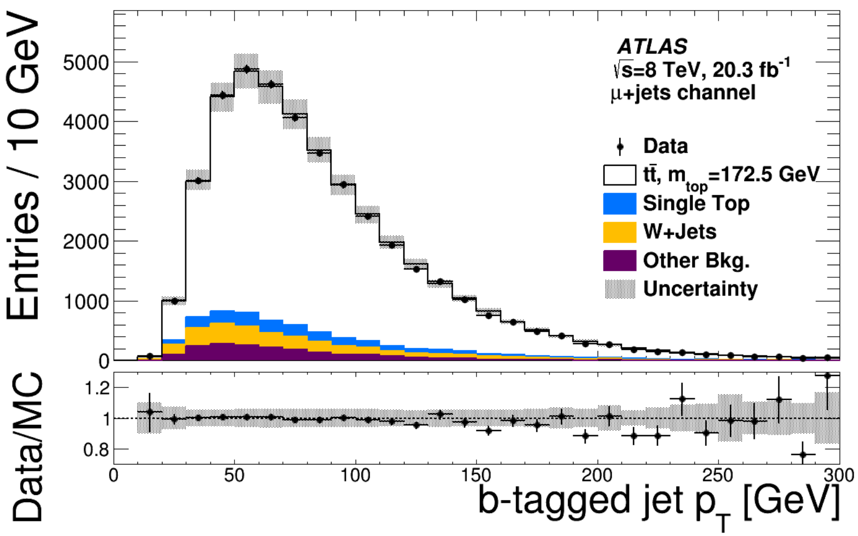


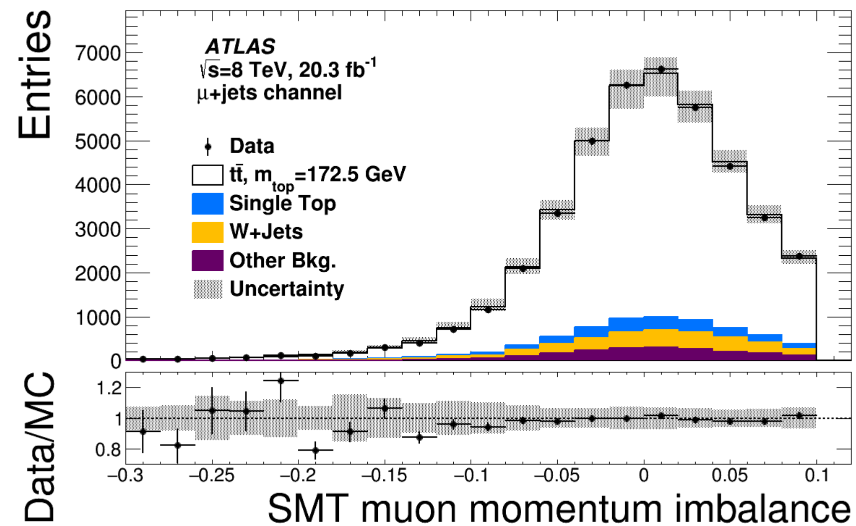
Kinematic Distributions



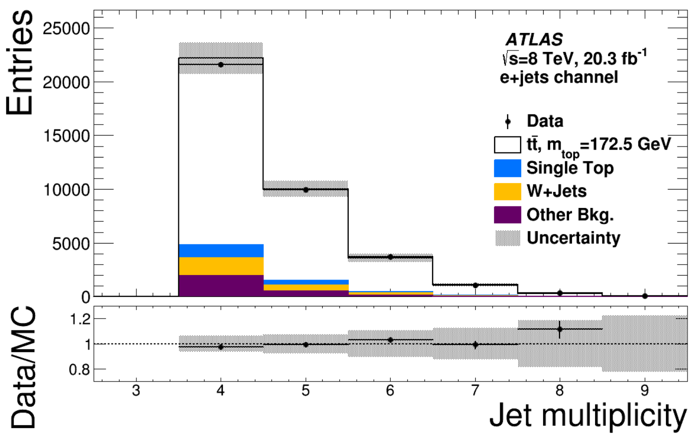


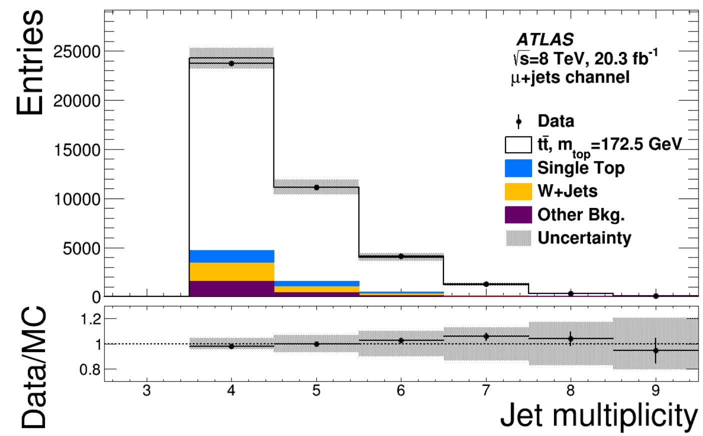
Kinematic Distributions

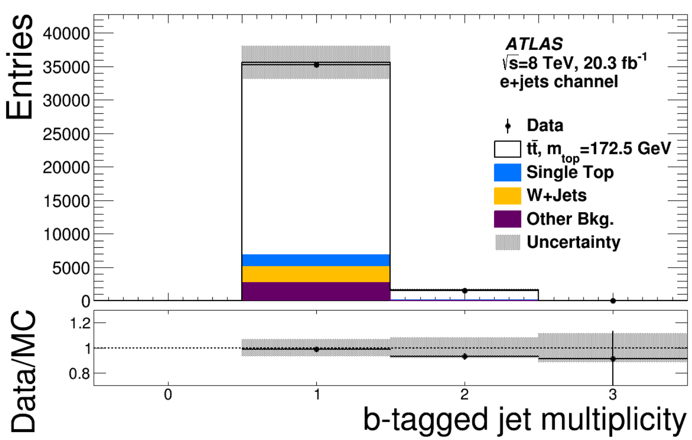


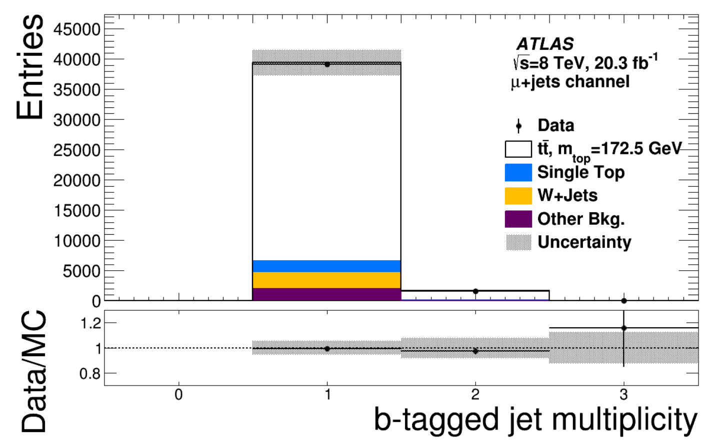


Kinematic Distributions

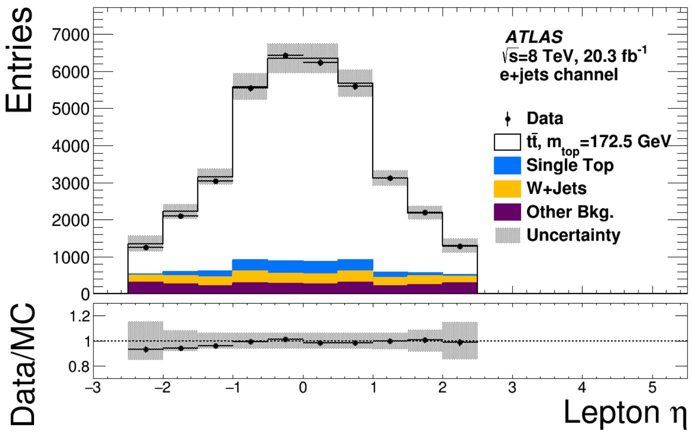


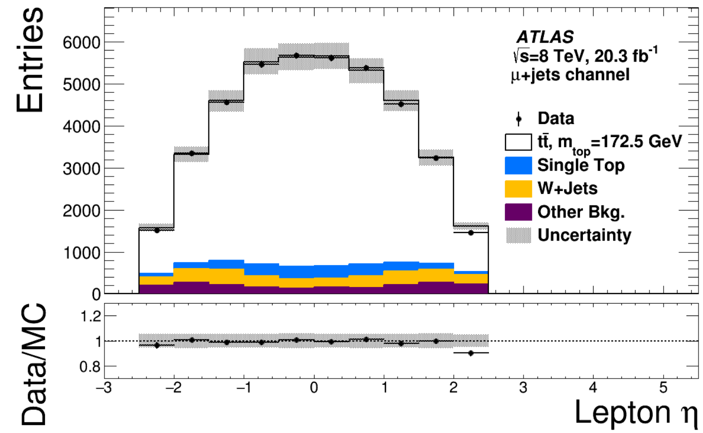


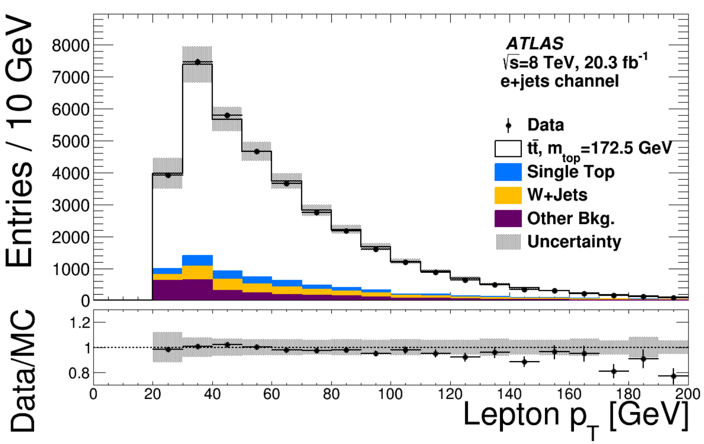


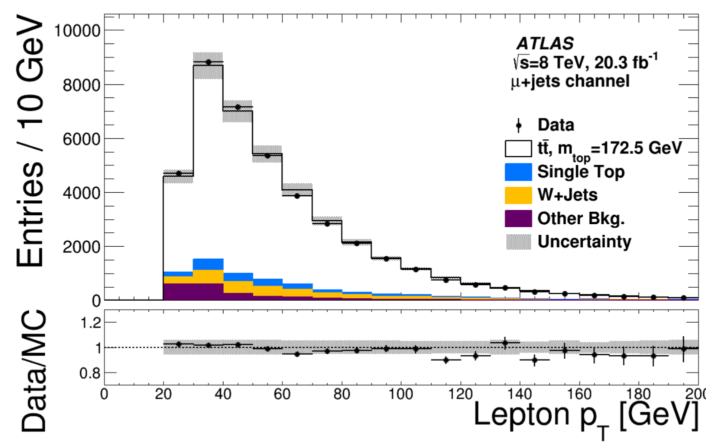


Kinematic Distributions

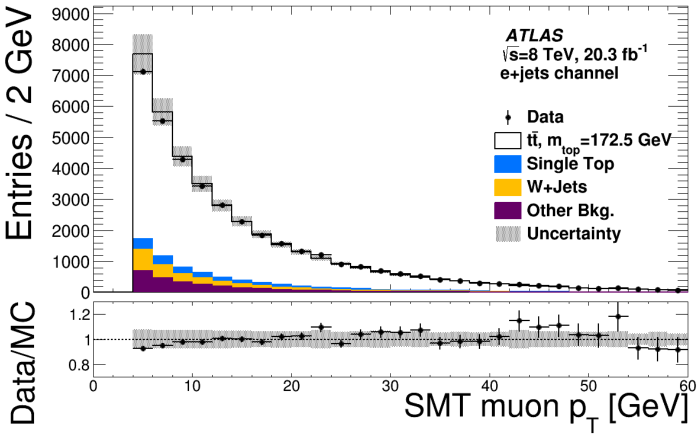


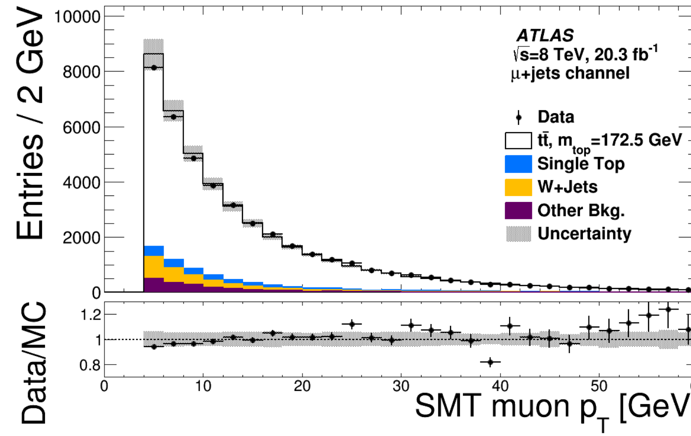


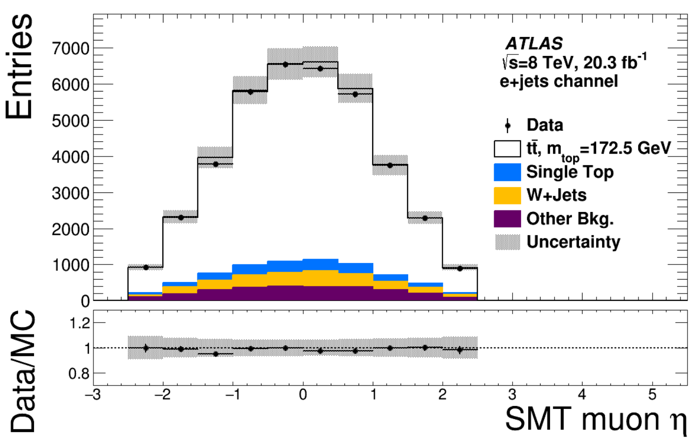


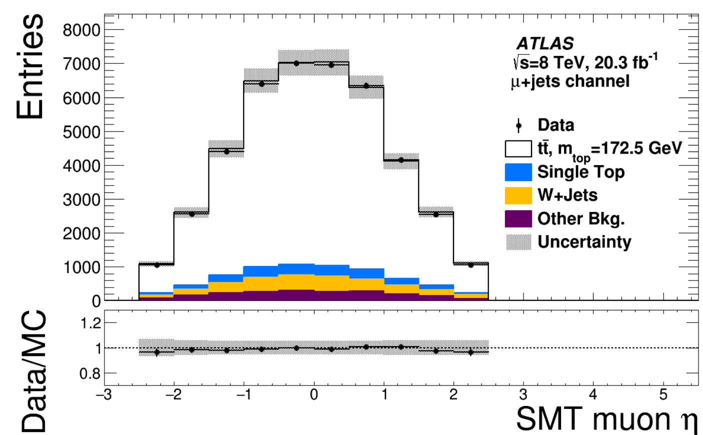


Kinematic Distributions

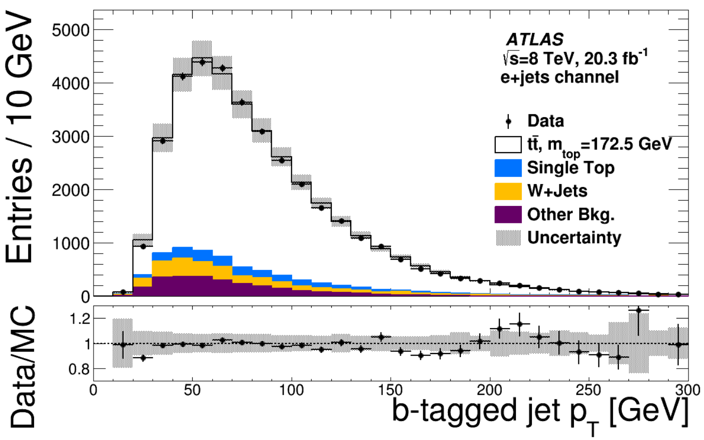


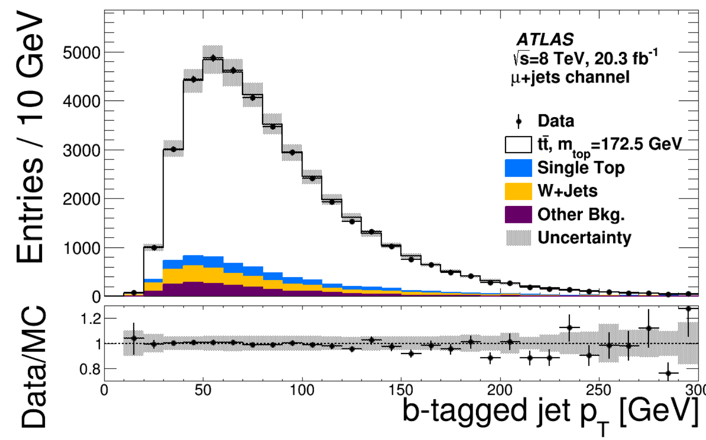


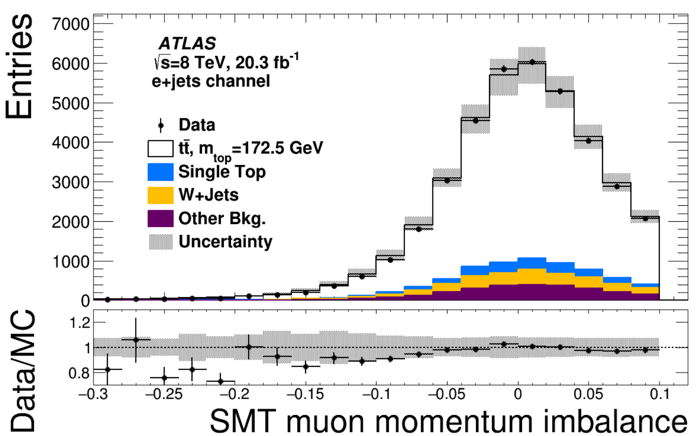


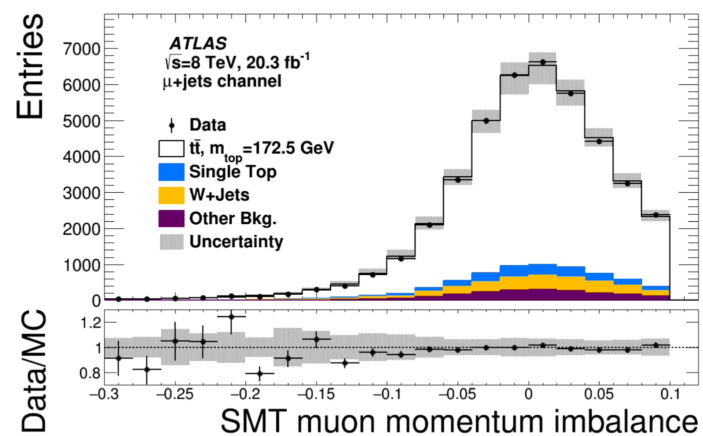


Kinematic Distributions

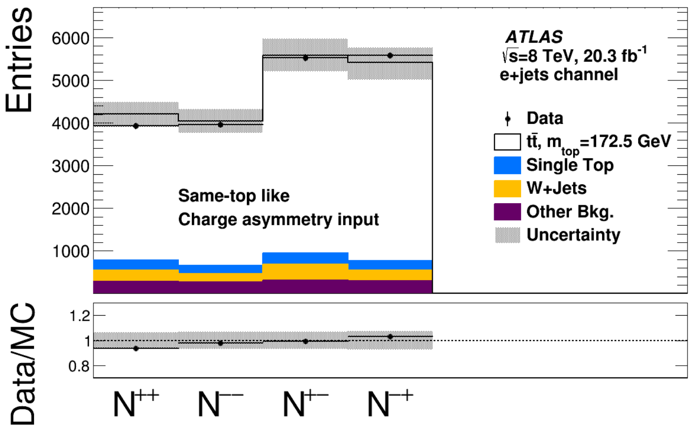


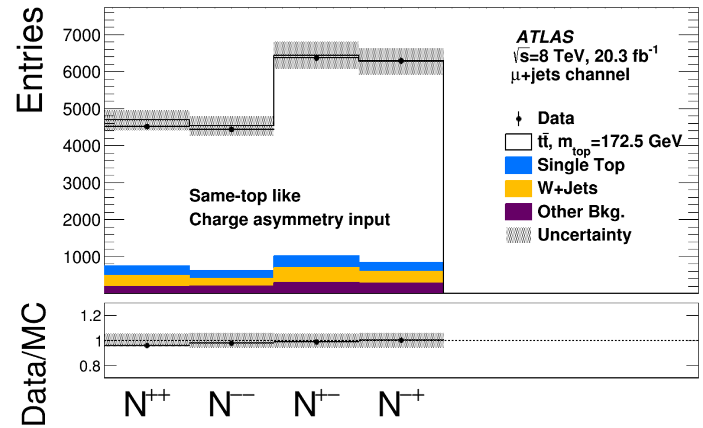


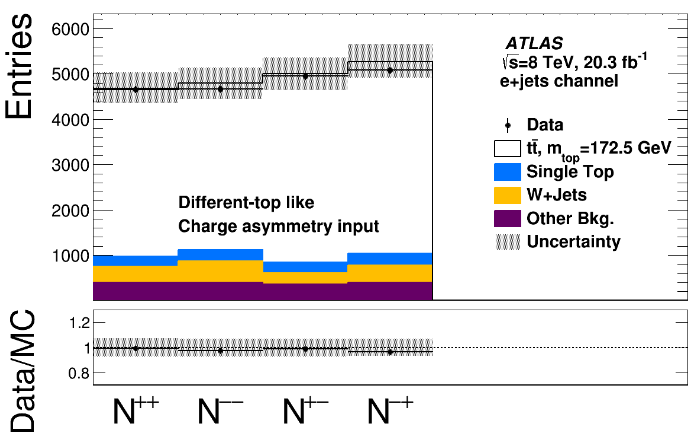


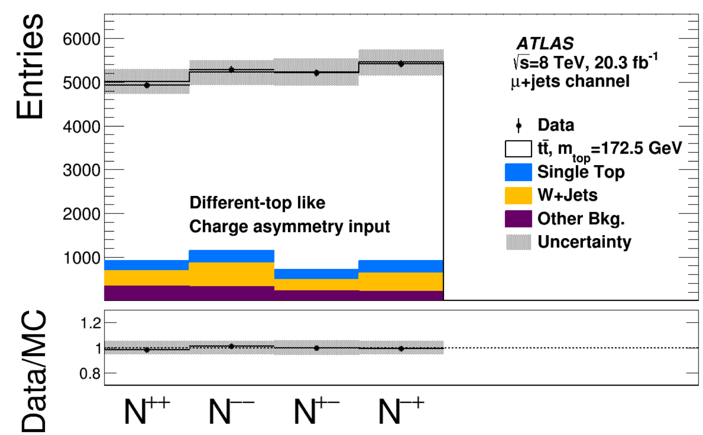


Charge asymmetry









Data and Software

Data & Software

- p1562 NTUP_COMMON data. AnalysisTop-1.8.1
- p1575 NTUP_COMMON MC. AnalysisTop-1.8.0
  - Use a custom MiniBase algorithm : MiniSMT
  - MiniSMT = MiniSL + run the SMT algorithm
- Using full 2012 8 TeV dataset $\mathcal{L} = 20.3 fb^{-1}$

Signal samples

- $t\bar{t}$: Powheg+Pythia $h_{\mathrm{damp}} = m_{\mathrm{top}}$ 110404
- Radiation syst : Powheg+Pythia $h_{\mathrm{damp}} = m_{\mathrm{top}}$ 11040{7, 8}

Background samples

- Single top : Powheg+Pythia 110{090, 091, 119, 140}
- W+Jets and Z+Jets : Alpgen+Pythia
- Di-boson : Herwig
- Multijet using FakesMacros-00-01-03
- Fully profiled W+Jets estimate

Sakharov

1. *Baryon number violating interactions*; Processes must exist which allow for the production or destruction of baryons and antibaryons in unequal numbers.

2. *CP violation*; A baryon number violating process is not enough to produce an asymmetry if the *CP* conjugate generates the exact opposite process, as this would re-balance the total number of baryons and antibaryons present.

3. *Departure from thermal equilibrium*; In thermal equilibrium, even with the first two conditions satisfied every process would occur at an equal rate to its inverse process and again the baryon numbers would be balanced.

Still not enough! → **Where is the New Physics?**

Background determination - *W*+Jets

- *W*+jets is charge asymmetric – very important to this analysis
- Data driven *W*+jets estimate
  - Scaling factors determined in 2-jet exclusive region
  - Flavour fractions, CA normalisation and scale factors extrapolated into a 4-jet inclusive region
- Full profiled *W*+jets:
  - Scale factor determined for each and every systematic
  - Approx. 350 SF per channel (195 SF for the PDF)
  - Any *W*+jets variation absorbed into all other systematics
- *W*+jets performed for 3 tagging combinations
  - MV1@85%, SMT, MV1@85%+SMT
  - Monitor interplay between different taggers
  - Overall systematic effects are reduced by combination

W+Jets methodology

- Determine charge asymmetry and flavor fractions from data
- Use 2 jet exclusive bin and extrapolate to 4 jet inclusive
- Solve the following matrix via iteration:

$$\begin{bmatrix} CA\cdot\left(N^{bb}_{MC,W-}+N^{cc}_{MC,W-}\right) & CA\cdot N^{c}_{MC,W-} & CA\cdot N^{lf}_{MC,W-} \\ (f_{bb}+f_{cc}) & f_c & f_{LF} \\ CA\cdot\left(N^{bb}_{MC,W+}+N^{cc}_{MC,W+}\right) & CA\cdot N^{c}_{MC,W+} & CA\cdot N^{lf}_{MC,W+} \end{bmatrix}\cdot\begin{bmatrix} K_{bb,cc} \\ K_c \\ K_{LF} \end{bmatrix}=\begin{bmatrix} D_{W-} \\ 1.0 \\ D_{W+} \end{bmatrix}$$

- CA = charge asymmetry, K_i = scaling factors
- f_i = flavor fractions, $D_{W\pm}$ = Tagged Data - Bkg
- Fix scaling $K_{bb} = K_{cc} = K_{bb,cc}$
  - $\Rightarrow$ 3 equations and 3 unknowns

Iterate until stable ($\sim$ 10 times)

1. Start with $K_{bb,cc} = K_c = K_{LF} = 1.0$
2. Apply scaling factors K_i to MC pretag yields
3. Re-calculate charge asymmetry normalization
4. Build matrix above, invert, extract scaling factors K_i
5. If K_i are stable, end iterations. If not, go back to step 2

Systematic uncertainties

- We apply the standard top group systematics:
  - 4-momenta smearing
  - Scale factors
  - Signal modelling
- We considered additional systematic uncertainties:
  - Electron charge mis-ID
    - Official e/γ tool used, up-to-date calibration
  - Muon charge mis-ID is negligible and not considered
  - Production of $B^0_{d,s}$, B^+, and B-baryons in MC does not match PDG
    - ➔ Re-weighting for PYTHIA and HERWIG
  - $b \to \mu$ branching fractions in MC does not match PDG
    - ➔ Re-weighting for PYTHIA and HERWIG
  - Single top production asymmetry
    - More tops producted than anti-tops
    - Uncertainty on theoretical cross-section
    - ➔ Varying t or $\bar{t}$ rate within theoretical uncertainties

Scale factors applied

- Standard reconstruction scale factors:
- jvfsf_up , jvfsf_down , lep_trigSF_up , lep_trigSF_down
- lep_idSF_up , lep_idSF_down , lep_recoSF_up , lep_recoSF_down

- MV1 *b*-tagging scale factors:
- BTAGSFUP_BREAK[0-5] , BTAGSFDOWN_BREAK[0-5]
- CTAUTAGSFUP_BREAK[0-3] , CTAUTAGSFDOWN_BREAK[0-3]
- MISTAGSFUP_BREAK[0-11] , MISTAGSFDOWN_BREAK[0-11]

- SMT specific scale factors:
- SMT_RECO_SFUP , SMT_RECO_SFDOWN , SMT_MISTAG_SFUP
- SMT_ID_SFUP , SMT_ID_SFDOWN , SMT_MISTAG_SFDOWN
- SMT_MOMENTUMIMBALANCE_SFUP , SMT_MOMENTUMIMBALANCE_SFDOWN

- $b \rightarrow \mu$ branching ratio re-weighting (driven by PDG values):
- B_TO_MU_UP , B_TO_MU_DOWN , B_TO_TAU_TO_MU_UP , B_TO_TAU_TO_MU_DOWN
- B_TO_C_TO_MU_UP , B_TO_C_TO_MU_DOWN , B_TO_BARC_TO_MU_UP
- B_TO_BARC_TO_MU_DOWN , C_TO_MU_UP , C_TO_MU_DOWN

- *B*-hadron production fractions (driven by PDG values):
- BHADPROD_511521_UP , BHADPROD_511521_DOWN , BHADPROD_531_UP
- BHADPROD_531_DOWN , BHADPROD_BARYON_UP , BHADPROD_BARYON_DOWN

- Single top production asymmetry:
- TCHAN_TOP_UP , TCHAN_TOP_DOWN , TCHAN_ANTITOP_UP , TCHAN_ANTITOP_DOWN
- SCHAN_TOP_UP , SCHAN_TOP_DOWN , SCHAN_ANTITOP_UP , SCHAN_ANTITOP_DOWN

4-momentum shifting systematics

- Electrons:
- ees_up , eer_up , ees_down , eer_down

- Muons:
- musc_up , musc_down , mums_res , muid_res

- Jets non-JES:
- jvf_up , jvf_down , jer , jeff

- Jet Energy Scale:
- JesEffectiveStat1_up , JesEffectiveStat2_up , JesEffectiveStat3_up , JesEffectiveStat4_up
- JesEffectiveModel1_up , JesEffectiveModel2_up , JesEffectiveModel3_up , JesEffectiveModel4_up
- JesEffectiveDet1_up , JesEffectiveDet2_up , JesEffectiveDet3_up
- JesEffectiveMix1_up , JesEffectiveMix2_up , JesEffectiveMix3_up , JesEffectiveMix4_up
- EtaIntercalibrationModel_up , EtaIntercalibrationTotalStat_up , SinglePart_up
- Pileup_OffsetMu_up , Pileup_OffsetNPV_up , Pileup_Pt_up , Pileup_Rho_up , sc_soft_up
- flavor_comp_up , flavor_response_up , PunchThrough_up , BJesUnc_up , res_soft_up

- JesEffectiveStat1_down , JesEffectiveStat2_down , JesEffectiveStat3_down , JesEffectiveStat4_down
- JesEffectiveModel1_down , JesEffectiveModel2_down , JesEffectiveModel3_down , JesEffectiveModel4_down
- JesEffectiveDet1_down , JesEffectiveDet2_down , JesEffectiveDet3_down
- JesEffectiveMix1_down , JesEffectiveMix2_down , JesEffectiveMix3_down , JesEffectiveMix4_down
- EtaIntercalibrationModel_down , EtaIntercalibrationTotalStat_down , SinglePart_down
- Pileup_OffsetMu_down , Pileup_OffsetNPV_down , Piledown_Pt_down , Piledown_Rho_down , sc_soft_down
- flavor_comp_down , flavor_response_down , PunchThrough_down , BJesUnc_down , res_soft_down

Cross-section measurement

- Measuring $\sigma_{t\bar{t}}$ demonstrates that we understand the data
- Good agreement with theory and other measurements
  - Only published papers are listed in the comparison table

$$\boldsymbol{\sigma_{t\bar{t}} = 250 \pm 1(\text{Stat.})^{+24}_{-23}(\text{Syst.}) \pm 5(\text{Lumi.}) \pm 4(\text{Beam})\ \text{pb}}$$

Theory prediction	$\sigma_{t\bar{t}} = 252.0 \pm 11.7^{+6.4}_{-8.6}$ pb
ATLAS $e\mu$	$\sigma_{t\bar{t}} = 242.4 \pm 1.7(\text{Stat.}) \pm 5.5(\text{Syst.}) \pm 7.5(\text{Lumi.}) \pm 4.2(\text{Beam})$ pb
ATLAS l + jets	$\sigma_{t\bar{t}} = 260 \pm 1(\text{Stat.})^{+22}_{-23}(\text{Syst.}) \pm 8(\text{Lumi.}) \pm 4(\text{Beam})$ pb
CMS $ee, \mu\mu, e\mu$	$\sigma_{t\bar{t}} = 239 \pm 2(\text{Stat.}) \pm 11(\text{Syst.}) \pm 6(\text{Lumi.})$ pb
CMS $e\tau, \mu\tau$	$\sigma_{t\bar{t}} = 257 \pm 3(\text{Stat.}) \pm 24(\text{Syst.}) \pm 7(\text{Lumi.})$ pb
CMS all hadronic	$\sigma_{t\bar{t}} = 275.6 \pm 6.1(\text{Stat.}) \pm 37.8(\text{Syst.}) \pm 7.2(\text{Lumi.})$ pb

- This is included in the paper
- It demonstrates that:
  - We understand our backgrounds
  - We understand our modelling

$\sigma_{t\bar{t}}$ systematics

$\sigma_{t\bar{t}}$ [pb]	e+jets 248.0	μ+jets 251.4	ℓ+jets 249.6
Statistical uncertainty in %	±0.6	±0.6	±0.4
Sources of experimental uncertainty in %			
Lepton charge misidentification	+0.0 −0.0	+0.0 −0.0	+0.0 −0.0
Lepton energy resolution	+1.1 −1.0	+1.0 −1.0	+1.0 −1.0
Lepton trigger, reco, identification	+2.8 −2.6	+2.1 −2.0	+2.1 −2.0
Jet energy scale	+5.2 −5.2	+4.7 −4.6	+5.0 −4.8
Jet energy resolution	+0.1 −0.1	+0.3 −0.3	+0.1 −0.1
Jet reco efficiency	+0.1 −0.1	+0.1 −0.1	+0.1 −0.1
Jet vertex fraction	+1.0 −1.0	+1.0 −1.0	+1.0 −1.0
Fake lepton estimate	+4.7 −4.7	+1.0 −1.0	+2.7 −2.7
Background normalisation	+0.2 −0.2	+0.1 −0.1	+0.2 −0.2
W+jets estimate (statistical)	+0.0 −0.0	+0.0 −0.0	+0.0 −0.0
Single-top production asymmetry	+0.1 −0.0	+0.1 −0.0	+0.1 −0.0
b-tagging efficiency	+2.2 −2.1	+2.2 −2.1	+2.2 −2.1
c-jet mistag rate	+0.4 −0.4	+0.4 −0.4	+0.4 −0.4
Light-jet mistag rate	+0.1 −0.1	+0.1 −0.1	+0.1 −0.1
SMT reco identification	+1.6 −1.5	+1.5 −1.5	+1.5 −1.5
SMT momentum imbalance	+1.0 −1.0	+1.0 −1.0	+1.0 −1.0
SMT light-jet mistag rate	+0.4 −0.5	+0.4 −0.5	+0.4 −0.5
Sources of modelling uncertainty in %			
Hadron-to-muon branching ratio	+2.8 −2.6	+2.8 −2.5	+2.8 −2.6
b-hadron production fractions	+0.4 −0.3	+0.4 −0.4	+0.4 −0.4
Additional radiation	±5.3	±3.9	±4.5
MC generator	±3.0	±3.1	±3.0
Parton shower	±2.1	±1.7	±1.9
Parton distribution function	±1.1	±0.8	±0.9
Total experimental uncertainty	+8.3 −8.1	+6.2 −6.0	+6.9 −6.7
Total modelling uncertainty	+7.1 −7.0	+6.0 −5.9	+6.5 −6.4
Total systematic uncertainty	+11 −11	+8.6 −8.4	+9.4 −9.3
Luminosity uncertainty	±1.9	±1.9	±1.9
LHC beam energy	±1.7	±1.7	±1.7

Detector / Physical Asymmetries

ATLAS is made of matter

- Kaons (and other hadrons) have different interaction lengths than their antiparticles
- When considering nuclear interactions, the K^- has more hyperon (strange-quark) final states than K^+
- K^+ is therefore more likely to produce a muon final state, or to *punch-through* and fake a muon
  - Leads to unequal numbers of **fake** $\boldsymbol{\mu}^+$ and $\boldsymbol{\mu}^-$

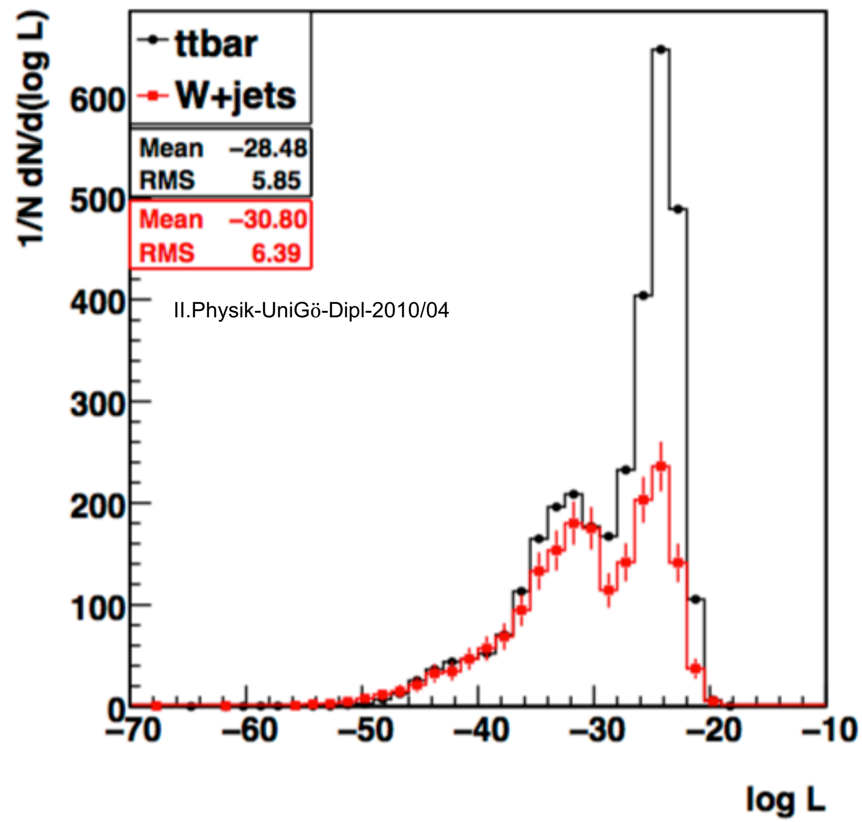
$$\boldsymbol{K^- + n \rightarrow \Lambda^0 + \pi^-}$$

$$\boldsymbol{K^- + p \rightarrow \Sigma^+ + \pi^-}$$

Kinematic Likelihood Fitter (KLFitter)

Optimization:

- Allow for up to 5 reconstructed jets
- Correct b-jet four-momenta for semileptonic decay components (ν)
- Fix top mass (172.5 GeV)
- Veto b-tagged jets in light-flavour positions
- Do not cut on the likelihood
  - No additional ST - DT separation
  - No additional signal – background separation



Achieves approximately 80% correct separation between ST and DT events!

Unfolding

- Fiducial volume: Provides a prescription for extracting CP asymmetries from Charge asymmetries
  - MC determination of the decay chain fractions r_i

$$A^{ss} = r_b A^{bl}_{\mathrm{mix}} + r_{c\bar{c}} A^{bc}_{\mathrm{mix}} + r_c A^{bc}_{\mathrm{dir}} - (r_c + r_{c\bar{c}}) A^{cl}_{\mathrm{dir}}$$

$$A^{os} = \tilde{r}_c A^{bc}_{\mathrm{mix}} + \tilde{r}_b A^{bl}_{\mathrm{dir}} + (\tilde{r}_c + \tilde{r}_{c\bar{c}}) A^{cl}_{\mathrm{dir}}$$

- Minimizes systematic uncertainties by avoiding extrapolating to full phase space
  - Low energy QCD very poorly modelled
- Allows for correction of KLFitter mistakes (ST vs DT) using a response matrix

Fiducial volume

Electrons

- Dressed 4-momenta used
- $p_T \geq 25$ GeV
- $|\eta| < 2.5$
- Exactly 1 electron and 0 muons

Muons

- Dressed 4-momenta used
- $p_T \geq 25$ GeV
- $|\eta| < 2.5$
- Exactly 1 muon and 0 electrons

Jets

- ≥ 4 anti-k_t4 jets formed from all stable MC particles
- $p_T \geq 25$ GeV and $|\eta| < 2.5$

Overlap removal

- Remove jet if $\Delta R(j, e) < 0.2$
- Remove electron if $\Delta R(j, e) < 0.4$
- Remove muon if $\Delta R(j, e) < 0.2$

b-tagging

- No missing E_T or W transverse mass cuts are replied
- ΔR to match *B*-hadron with $p_T \geq 5$ GeV
- SMT muon with *B*-hadron and top quark in ancestral history

Unfolding

	$N^{++}{}_j$	$N^{--}{}_j$	$N^{+-}{}_j$	$N^{-+}{}_j$
$N^{++}{}_i$	0.79	0.00	0.00	0.21
$N^{--}{}_i$	0.00	0.79	0.21	0.00
$N^{+-}{}_i$	0.00	0.21	0.79	0.00
$N^{-+}{}_i$	0.21	0.00	0.00	0.79

i = Fiducial Index

j = Reconstruction Index

Diagonal = KLFitter performance

Off-Diagonal = Charge mis-ID (negligible)

Decay chain fractions (Obtained from simulation)

Same Sign

$$N_{r_b} = N\left[t \to \ell^+\nu\left(b \to \overline{b}\right) \to \ell^+\ell^+X\right],$$

$$N_{r_c} = N\left[t \to \ell^+\nu\,(b \to c) \to \ell^+\ell^+X\right],$$

$$N_{r_{c\overline{c}}} = N\left[t \to \ell^+\nu\left(b \to \overline{b} \to c\overline{c}\right) \to \ell^+\ell^+X\right],$$

$$r_b = \frac{N_{r_b}}{N_{r_b} + N_{r_c} + N_{r_{c\overline{c}}}},$$

$$r_c = \frac{N_{r_c}}{N_{r_b} + N_{r_c} + N_{r_{c\overline{c}}}},$$

$$r_{c\overline{c}} = \frac{N_{r_{c\overline{c}}}}{N_{r_b} + N_{r_c} + N_{r_{c\overline{c}}}},$$

Opposite Sign

$$N_{\widetilde{r}_b} = N\left[t \to \ell^+\nu b \to \ell^+\ell^-X\right],$$

$$N_{\widetilde{r}_c} = N\left[t \to \ell^+\nu\left(b \to \overline{b} \to \overline{c}\right) \to \ell^+\ell^-X\right],$$

$$N_{\widetilde{r}_{c\overline{c}}} = N\left[t \to \ell^+\nu\,(b \to c\overline{c}) \to \ell^+\ell^-X\right].$$

$$\widetilde{r}_b = \frac{\widetilde{N}_{r_b}}{\widetilde{N}_{r_b} + \widetilde{N}_{r_c} + \widetilde{N}_{r_{c\overline{c}}}},$$

$$\widetilde{r}_c = \frac{\widetilde{N}_{r_c}}{\widetilde{N}_{r_b} + \widetilde{N}_{r_c} + \widetilde{N}_{r_{c\overline{c}}}},$$

$$\widetilde{r}_{c\overline{c}} = \frac{\widetilde{N}_{r_{c\overline{c}}}}{\widetilde{N}_{r_b} + \widetilde{N}_{r_c} + \widetilde{N}_{r_{c\overline{c}}}}.$$

(Best measured in a well-defined fiducial volume)

Decay chain fractions

	r_b	r_c	$r_{c\bar{c}}$	$\widetilde{r}_b$	$\widetilde{r}_c$	$\widetilde{r}_{c\bar{c}}$
Nominal	0.200	0.715	0.085	0.882	0.069	0.048
Relative uncertainty in %						
Hadron-to-muon branching ratio	+3.8 −3.2	+2.9 −2.3	+23 −30	+1.6 −1.3	+3.3 −3.3	+25 −31
b-hadron production	+1.8 −1.8	+0.5 −0.5	+0.3 −0.3	+0.2 −0.2	+1.9 −1.9	+0.2 −0.2
Additional radiation	±2.4	±0.6	±0.4	±0.1	±0.9	±1.1
MC generator	±0.2	±0.1	±0.1	±0.1	±0.5	±0.7
Parton shower	±6.8	±2.2	±2.6	±0.6	±12	±6.1
Parton distribution function	±0.1	±0.1	±0.9	±0.0	±0.3	±0.2
Total uncertainty	+8.4 −8.1	+3.7 −3.3	+23 −30	+1.7 −1.4	+13 −13	+25 −31

Charge asymmetry results

$$A^{ss} = -0.007 \pm 0.006 \text{ (stat.)} {}^{+0.002}_{-0.002} \text{ (expt.)} \pm 0.005 \text{ (model)}$$

$$A^{os} = 0.0041 \pm 0.0035 \text{ (stat.)} {}^{+0.0013}_{-0.0011} \text{ (expt.)} \pm 0.0027 \text{ (model)}$$

$$A^{b}_{mix} = \frac{A^{ss}}{r_b + r_{c\bar{c}}} = -0.025 \pm 0.021 \text{ (stat.)} \pm 0.008 \text{ (expt.)} \pm 0.017 \text{ (model)}$$

$$A^{b\ell}_{dir} = \frac{A^{os}}{\widetilde{r}_b} = 0.005 \pm 0.004 \text{ (stat.)} \pm 0.001 \text{ (expt.)} \pm 0.003 \text{ (model)}$$

$$A^{c\ell}_{dir} = \frac{-A^{ss}}{r_c + r_{c\bar{c}}} = 0.009 \pm 0.007 \text{ (stat.)} \pm 0.003 \text{ (expt.)} \pm 0.006 \text{ (model)}$$

$$A^{bc}_{dir} = \frac{A^{ss}}{r_c} = -0.010 \pm 0.008 \text{ (stat.)} \pm 0.003 \text{ (expt.)} \pm 0.007 \text{ (model)}$$

Charge asymmetry results

	$A^{ss}\left(10^{-2}\right)$		$A^{os}\left(10^{-2}\right)$	
Measured value	−0.7		0.41	
Statistical uncertainty	±0.6		±0.35	
Sources of experimental uncertainty				
Lepton charge misidentification	+0.002	−0.002	+0.001	−0.001
Lepton energy resolution	+0.09	−0.11	+0.07	−0.06
Lepton trigger, reco, identification	+0.004	−0.004	+0.002	−0.002
Jet energy scale	+0.10	−0.14	+0.08	−0.06
Jet energy resolution	+0.019	−0.019	+0.009	−0.009
Jet reco efficiency	+0.010	−0.010	+0.006	−0.006
Jet vertex fraction	+0.09	−0.09	+0.05	−0.05
Fake lepton estimate	+0.05	−0.05	+0.025	−0.025
Background normalisation	+0.002	−0.002	+0.001	−0.001
W+jets estimate (statistical)	+0.003	−0.002	+0.001	−0.002
Single-top production asymmetry	+0.016	−0.002	+0.001	−0.009
b-tagging efficiency	+0.008	−0.008	+0.004	−0.004
c-jet mistag rate	+0.020	−0.020	+0.013	−0.013
Light-jet mistag rate	+0.022	−0.023	+0.013	−0.012
SMT reco identification	+0.004	−0.004	+0.004	−0.004
SMT momentum imbalance	+0.06	−0.06	+0.04	−0.035
SMT light-jet mistag rate	+0.010	−0.009	+0.005	−0.005
Sources of modelling uncertainty				
Hadron-to-muon branching ratio	+0.04	−0.05	+0.026	−0.022
b-hadron production	+0.013	−0.008	+0.003	−0.008
Additional radiation	±0.4		±0.23	
MC generator	±0.05		±0.025	
Parton shower	±0.04		±0.017	
Parton distribution function	±0.22		±0.13	
Total experimental uncertainty	+0.19	−0.22	+0.13	−0.11
Total modelling uncertainty	+0.5	−0.5	+0.27	−0.27
Total systematic uncertainty	+0.5	−0.5	+0.30	−0.29

CP asymmetry results

	$A^{b}_{\mathrm{mix}}\,(10^{-2})$		$A^{b\ell}_{\mathrm{dir}}\,(10^{-2})$		$A^{c\ell}_{\mathrm{dir}}\,(10^{-2})$		$A^{bc}_{\mathrm{dir}}\,(10^{-2})$	
Measured value	−2.5		0.5		0.9		−1.0	
Statistical uncertainty	± 2.1		± 0.4		± 0.7		± 0.8	
Sources of experimental uncertainty								
Lepton charge misidentification	+0.008	−0.007	+0.001	−0.002	+0.002	−0.003	+0.003	−0.003
Lepton energy resolution	+0.33	−0.39	+0.07	−0.06	+0.14	−0.12	+0.13	−0.15
Lepton trigger, reco, identification	+0.016	−0.015	+0.003	−0.003	+0.005	−0.006	+0.006	−0.006
Jet energy scale	+0.4	−0.5	+0.09	−0.07	+0.17	−0.13	+0.15	−0.19
Jet energy resolution	+0.07	−0.07	+0.011	−0.011	+0.024	−0.024	+0.027	−0.027
Jet reco efficiency	+0.034	−0.034	+0.006	−0.006	+0.012	−0.012	+0.014	−0.014
Jet vertex fraction	+0.33	−0.33	+0.06	−0.06	+0.12	−0.12	+0.13	−0.13
Fake lepton estimate	+0.18	−0.19	+0.029	−0.029	+0.07	−0.07	+0.07	−0.08
Background normalisation	+0.008	−0.009	+0.001	−0.001	+0.003	−0.003	+0.003	−0.003
W+jets estimate (statistical)	+0.009	−0.008	+0.002	−0.002	+0.003	−0.003	+0.004	−0.003
Single-top production asymmetry	+0.06	−0.01	+0.002	−0.011	+0.002	−0.020	+0.022	−0.003
b-tagging efficiency	+0.028	−0.028	+0.005	−0.005	+0.010	−0.010	+0.011	−0.011
c-jet mistag rate	+0.07	−0.07	+0.015	−0.015	+0.025	−0.026	+0.029	−0.027
Light-jet mistag rate	+0.08	−0.08	+0.014	−0.014	+0.028	−0.028	+0.031	−0.032
SMT reco identification	+0.013	−0.012	+0.004	−0.004	+0.004	−0.005	+0.005	−0.005
SMT momentum imbalance	+0.21	−0.22	+0.04	−0.04	+0.08	−0.08	+0.09	−0.09
SMT light-jet mistag rate	+0.035	−0.031	+0.005	−0.006	+0.011	−0.012	+0.014	−0.012
Sources of modelling uncertainty								
Hadron-to-muon branching ratio	+0.25	−0.36	+0.023	−0.020	+0.06	−0.05	+0.04	−0.04
b-hadron production fractions	+0.031	−0.021	+0.004	−0.010	+0.013	−0.020	+0.022	−0.015
Additional radiation	±1.4		±0.26		±0.6		±0.6	
MC generator	±0.17		±0.029		±0.07		±0.08	
Parton shower	±0.08		±0.021		±0.06		±0.07	
Parton distribution function	±0.8		±0.15		±0.29		±0.32	
Total experimental uncertainty	+0.7	−0.8	+0.14	−0.12	+0.27	−0.24	+0.27	−0.31
Total modelling uncertainty	+1.6	−1.7	+0.30	−0.30	+0.6	−0.6	+0.7	−0.7
Total systematic uncertainty	+1.8	−1.8	+0.34	−0.33	+0.7	−0.6	+0.7	−0.7