Looking for beauty using truth: top and bottom quark results from ATLAS

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The Standard Model

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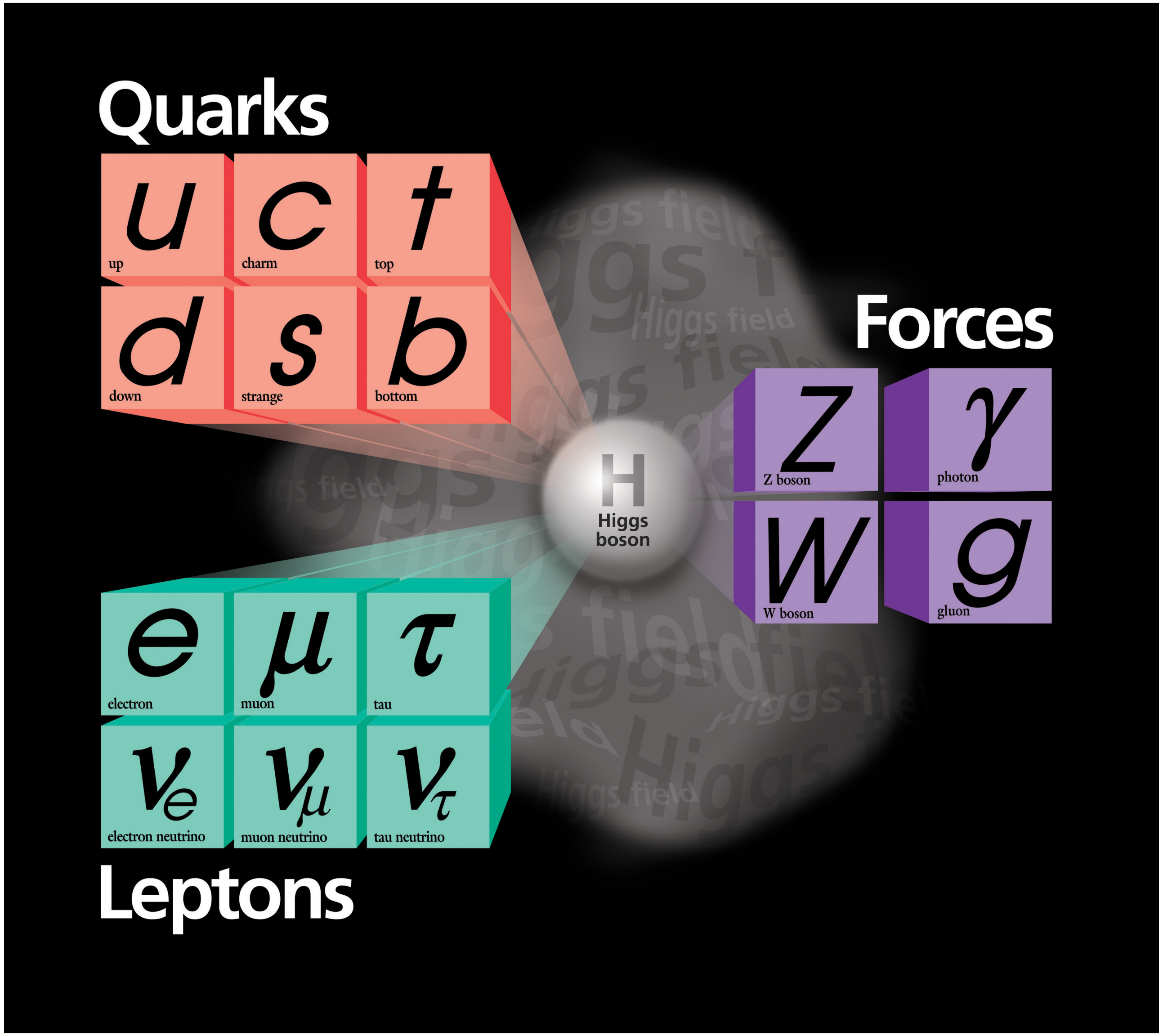
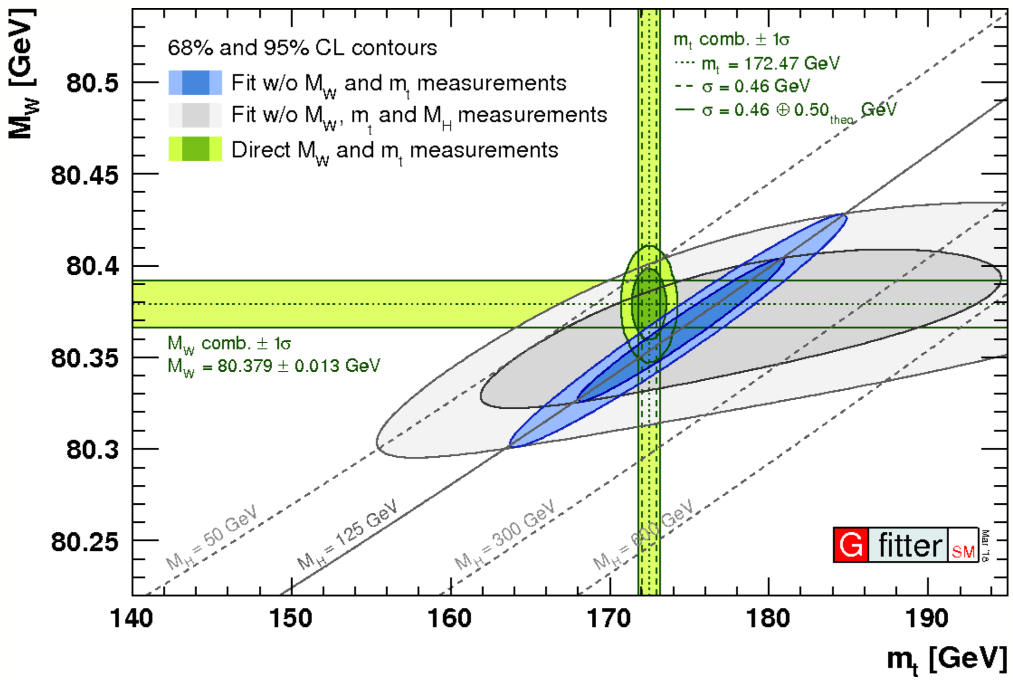


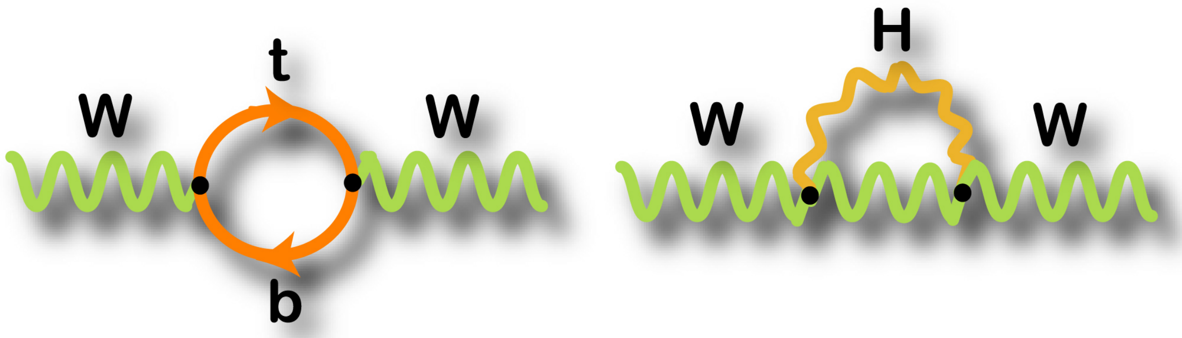
What we don't know…

- Incorporate neutrino mass in the SM in a natural way
- More matter than anti-matter
- Strong CP problem: Why QCD does not break CP?
  - Electric dipole of the neutron: dN~5x10^{-16} θ_{QCD} e cm
  - dN< 3.0x10^{-26} e cm so $\theta_{QCD} < 10^{-10}$
  - naturalness: θ_{QCD} O(1) so fine tuning
- Hierarchy Problem:
  - Higgs mass should be 10^{16} GeV not O(100GeV)
  - Planck scale so different from the Electroweak scale
- Origin of Dark Matter & Dark Energy

Higgs Mass

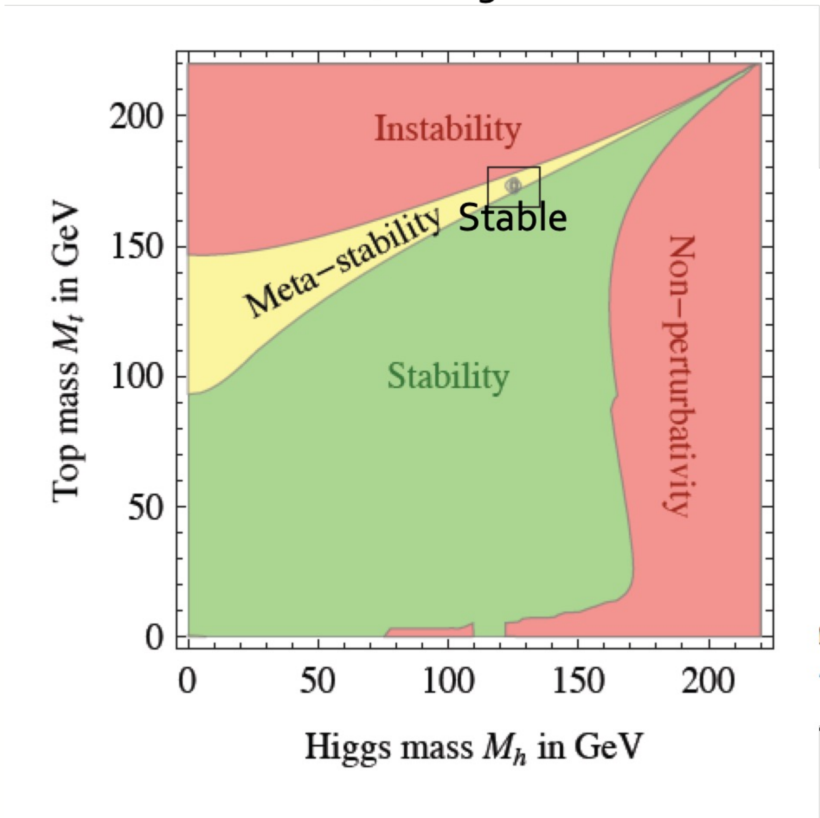
- Electroweak observables put strong constraints on the Higgs mass
- Higgs enters into radiative corrections of EW boson
  - Only logarithmically
  - Top mass enters quadratically…
- Higgs largest coupling is to the top quark

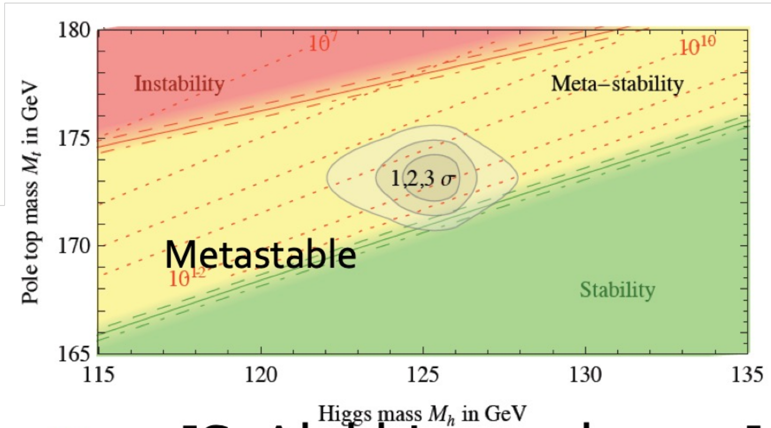




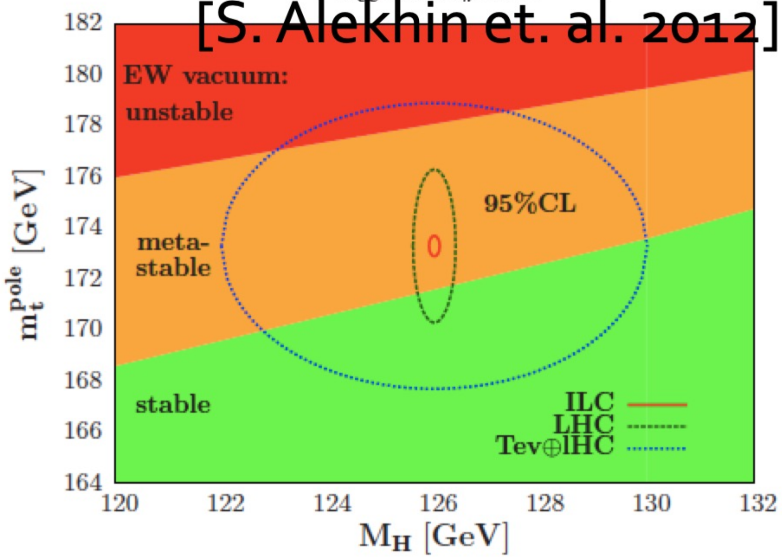
Top is so heavy!

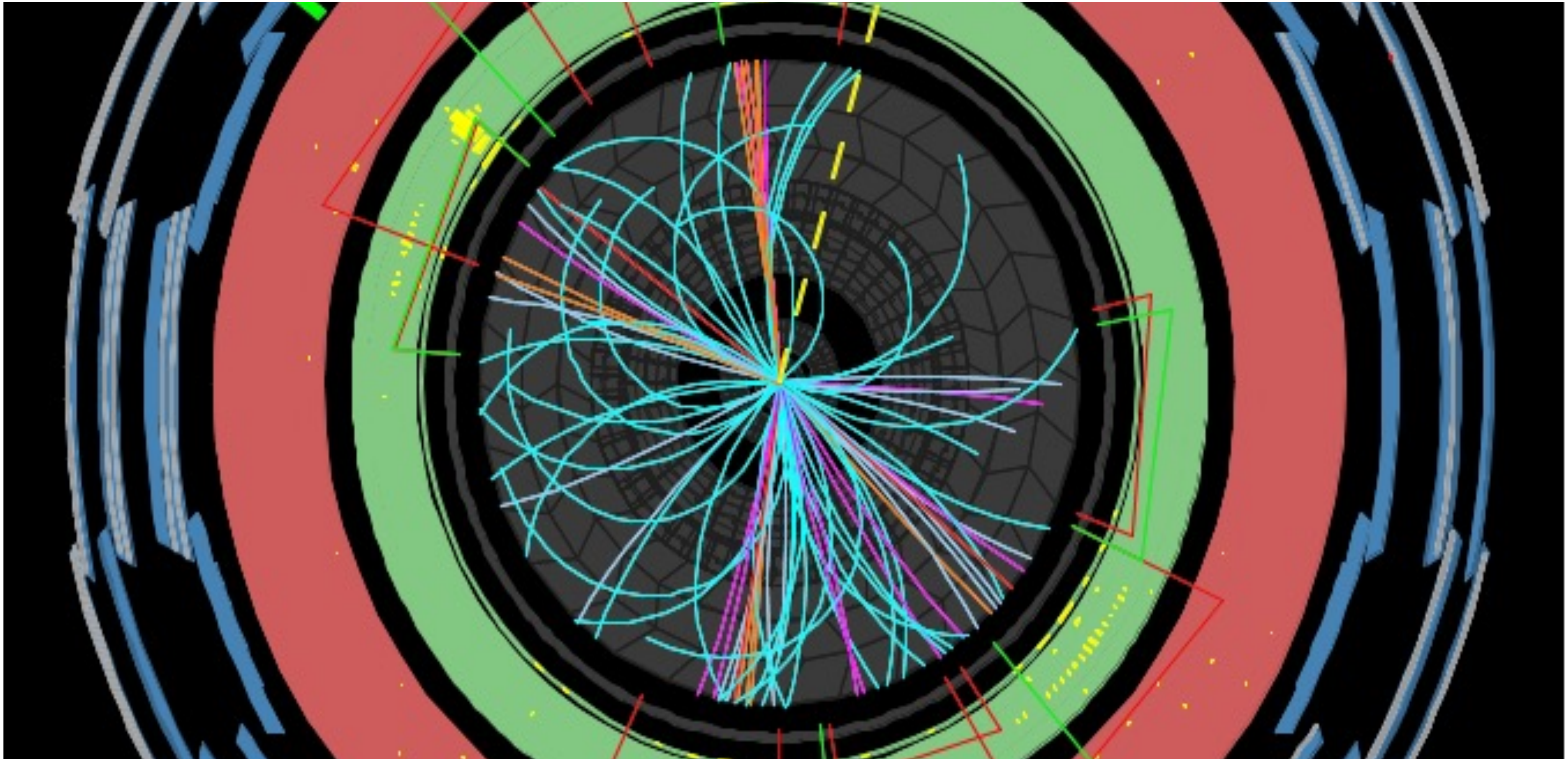
[G. Degrassi et. al. 2012]





[S. Alekhin et. al. 2012]





Producing top quarks

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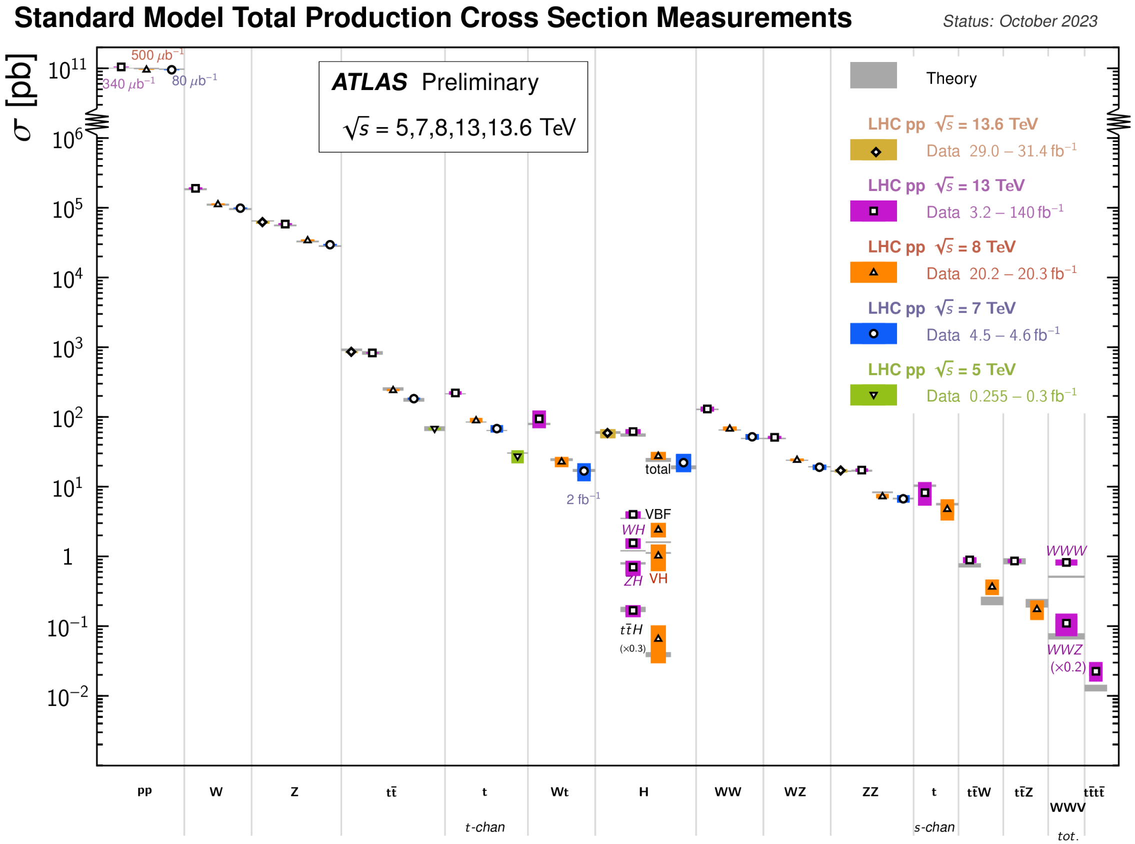
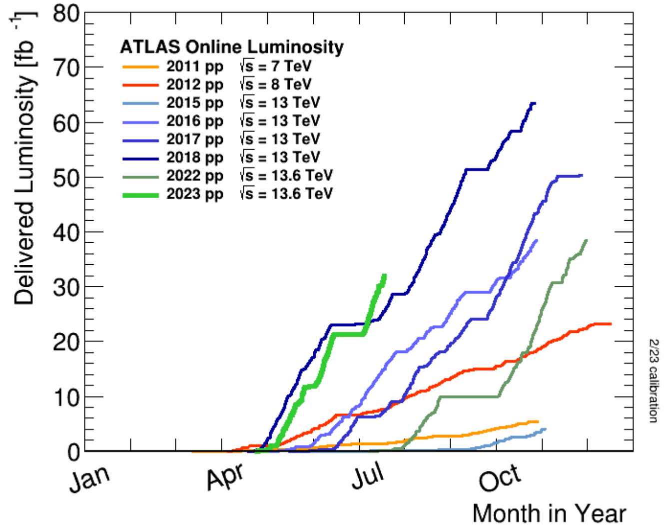
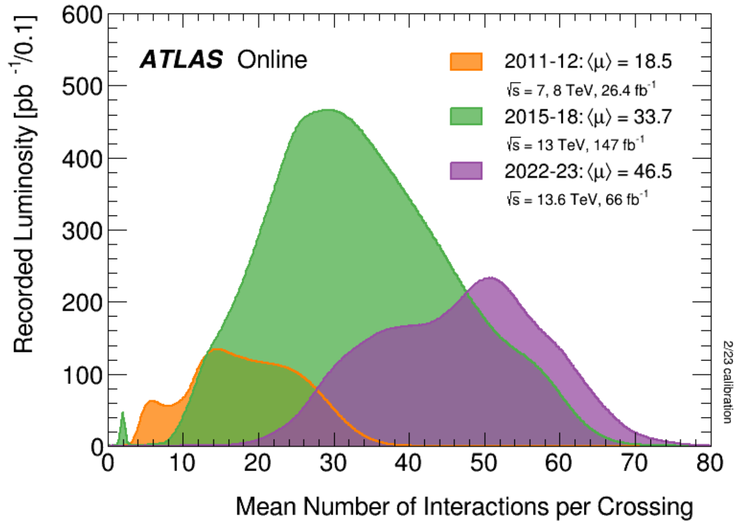
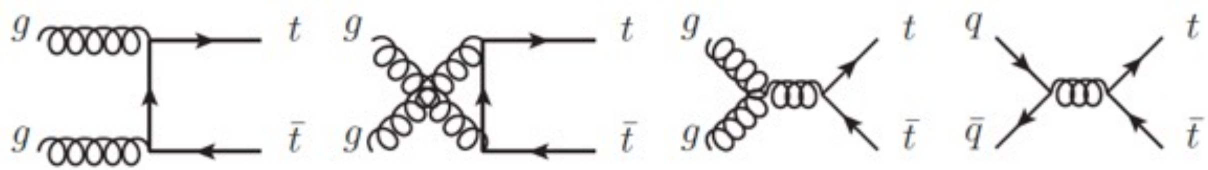
The LHC: a top quark factory





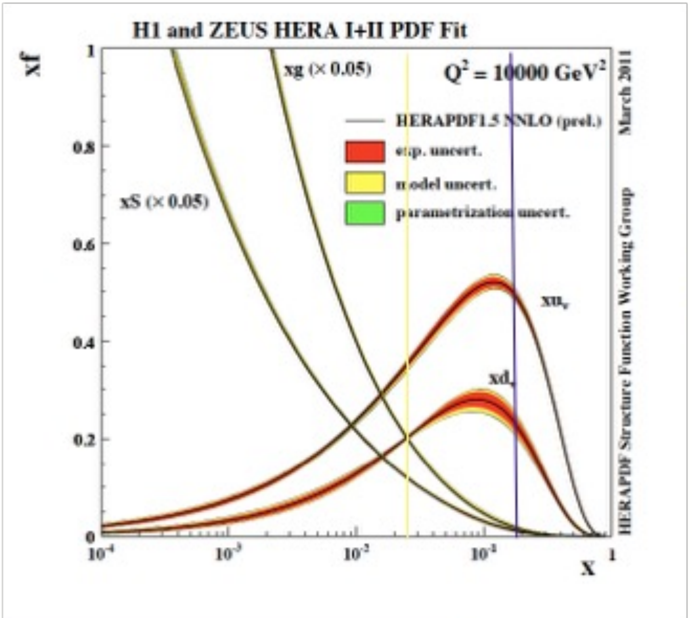


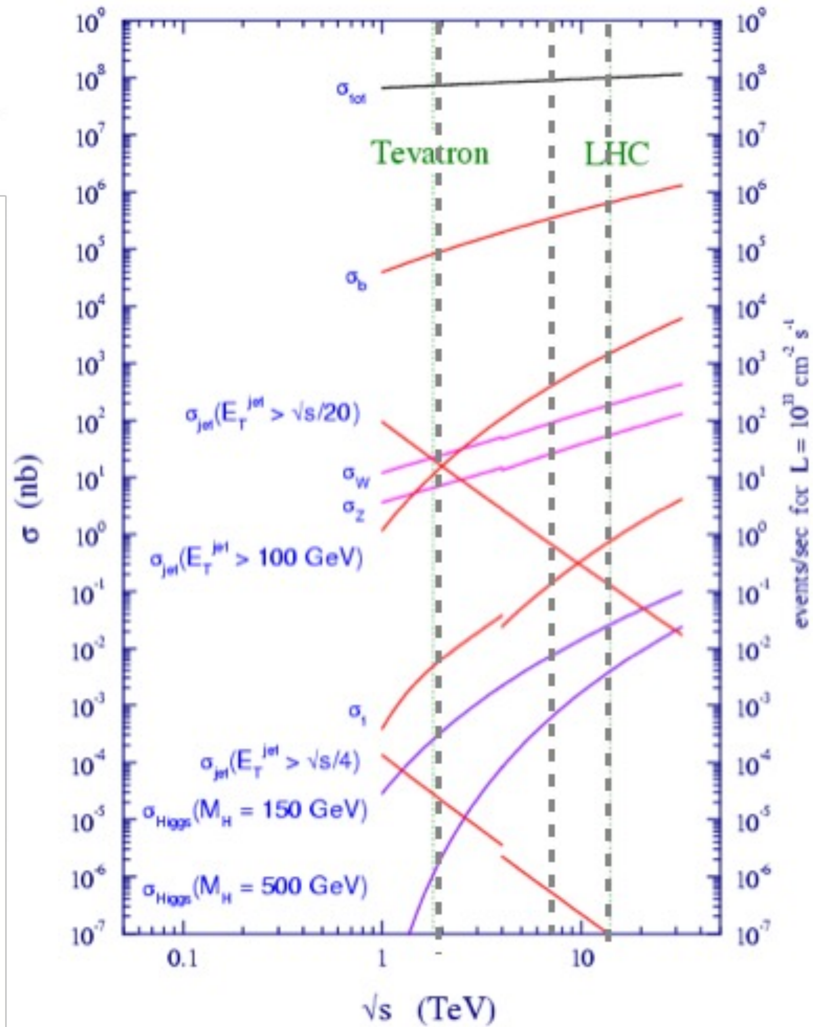
Top –Antitop production



$$\hat{s} = x_i\sqrt{s}\cdot x_j\sqrt{s} \geq (2m_t)^2$$

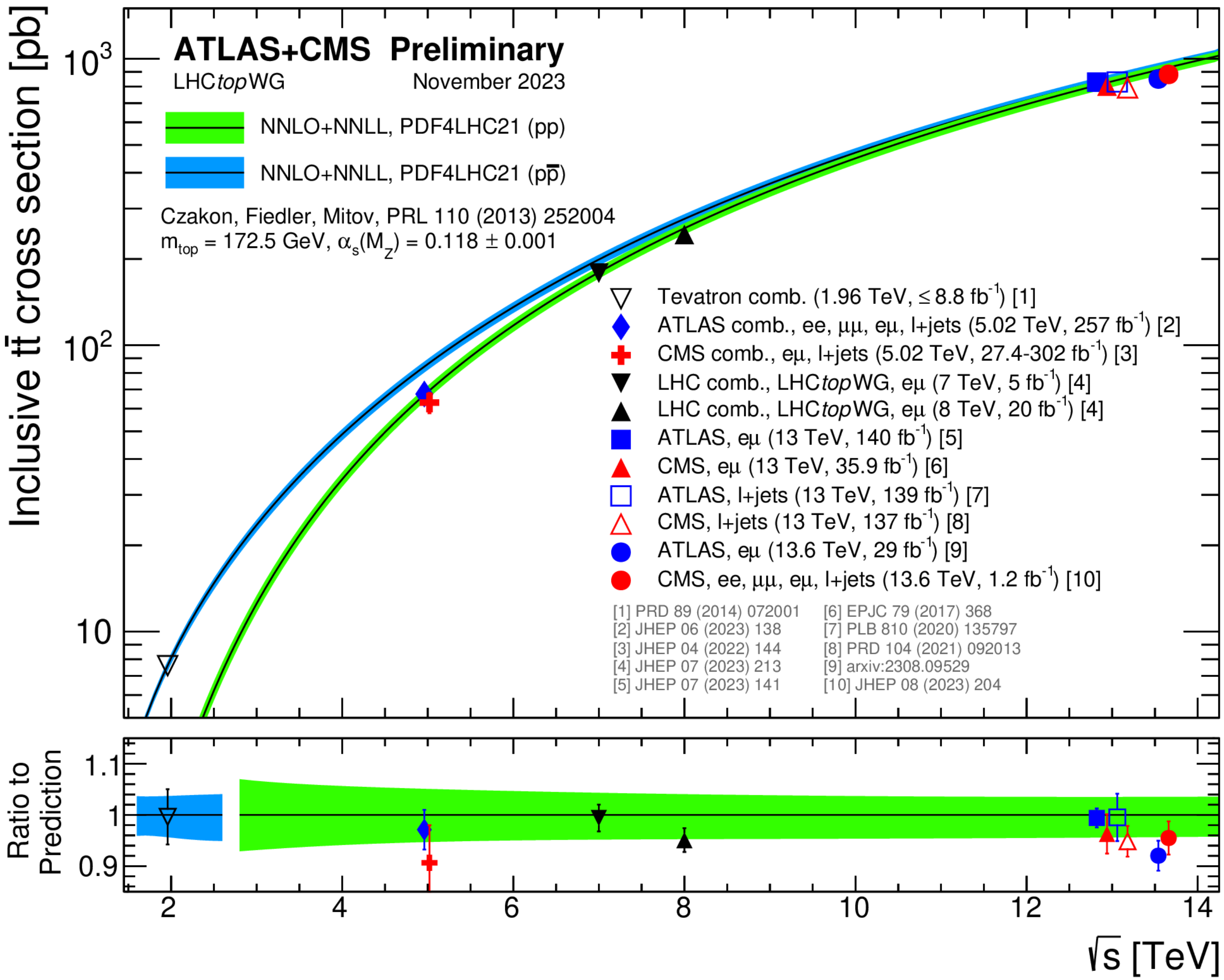
$$x_i \approx \frac{2m_t}{\sqrt{s}}$$

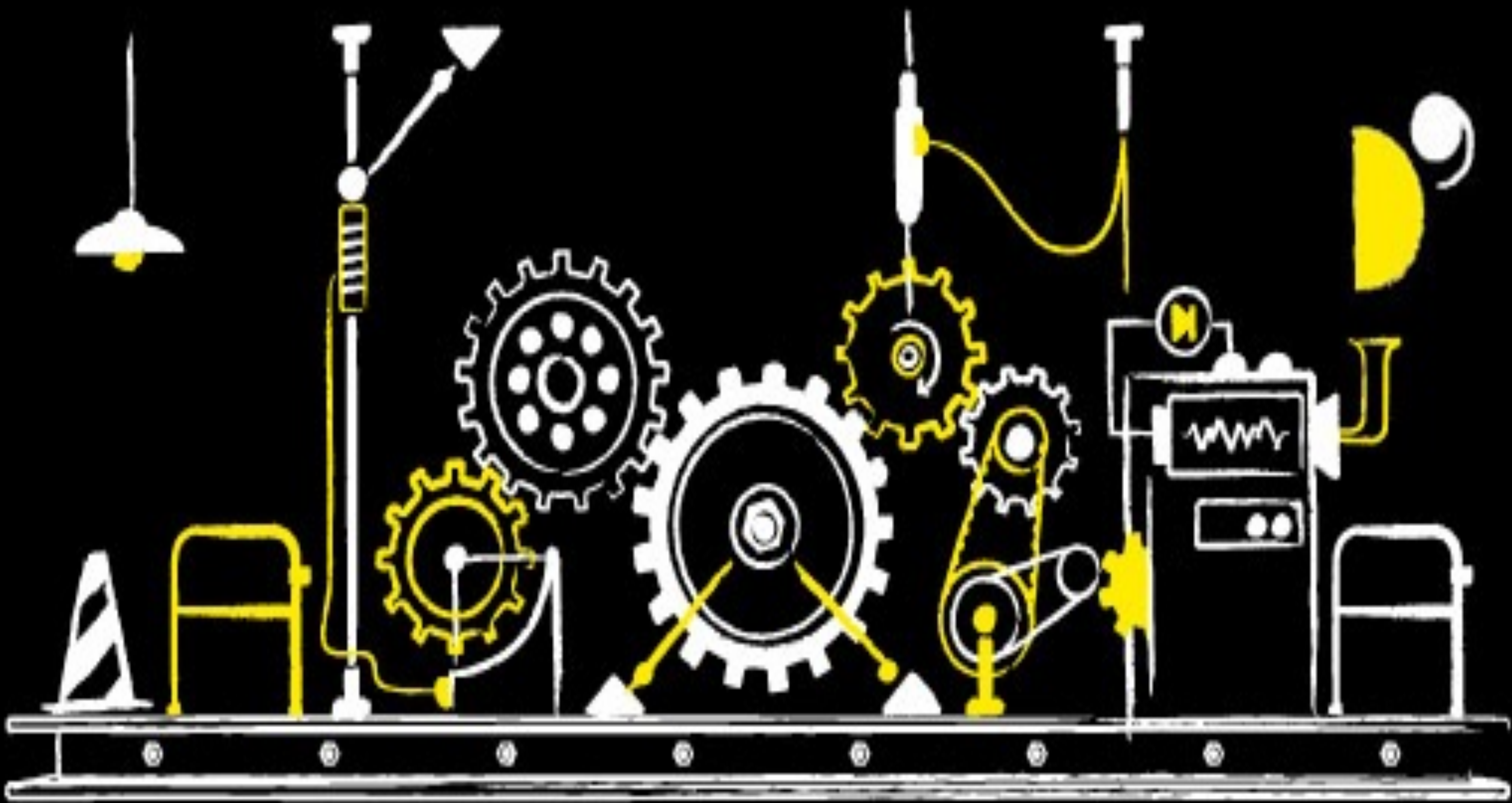




	x	qq vs gg	σ
Tev 1.96 TeV	0.18	90% vs 10%	~ 7 pb
LHC 7 TeV	0.048	15% vs 85%	~ 165 pb
LHC 8 TeV	0.043	12% vs 88%	~ 230 pb
LHC 14 TeV	0.025	10% vs 90%	~ 900 pb

Top –Antitop production





Experimental methods

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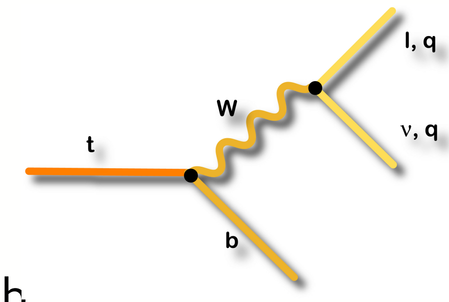
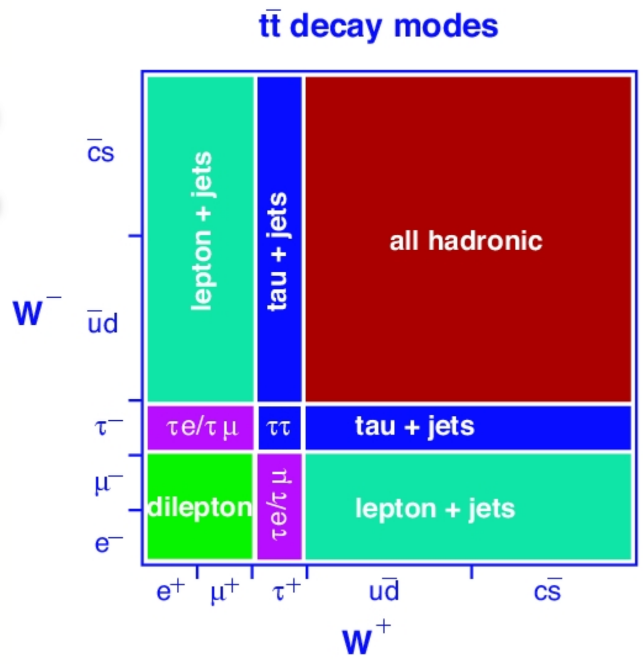
The SM top quark

- Top quark is isospin partner of b quark:
  - Charge = +2/3
  - Spin = 1/2
  - Mass = ???
- $m_t > m_W + m_b$ so dominant decay $t \rightarrow Wb$
- If assume unitarity: $B(t \rightarrow Wb) \sim 100\%$

$$\Gamma(t \rightarrow bW) = \frac{G_F m_t^3}{8\pi\sqrt{2}} |V_{tb}|^2 \approx 1.74 \text{ GeV}$$

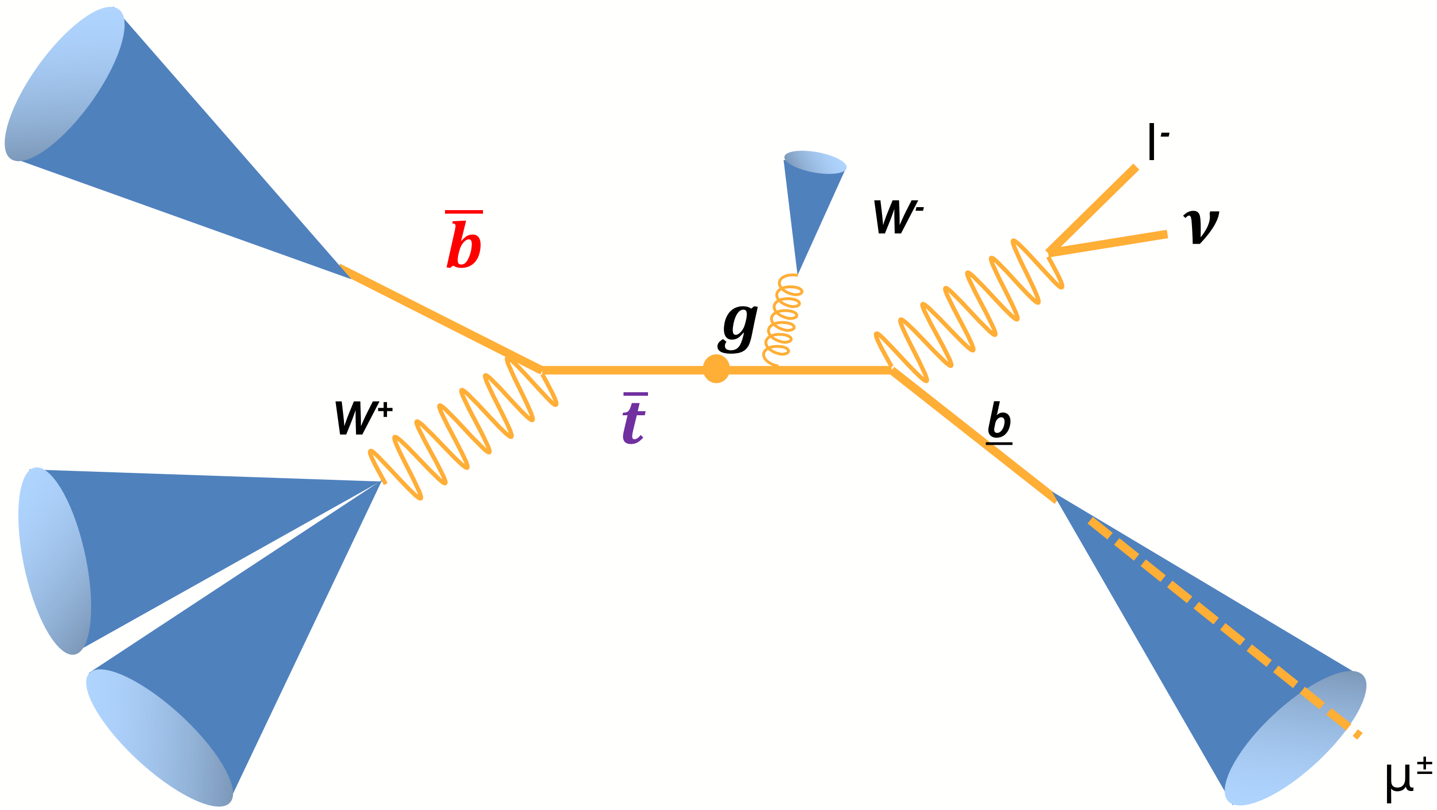




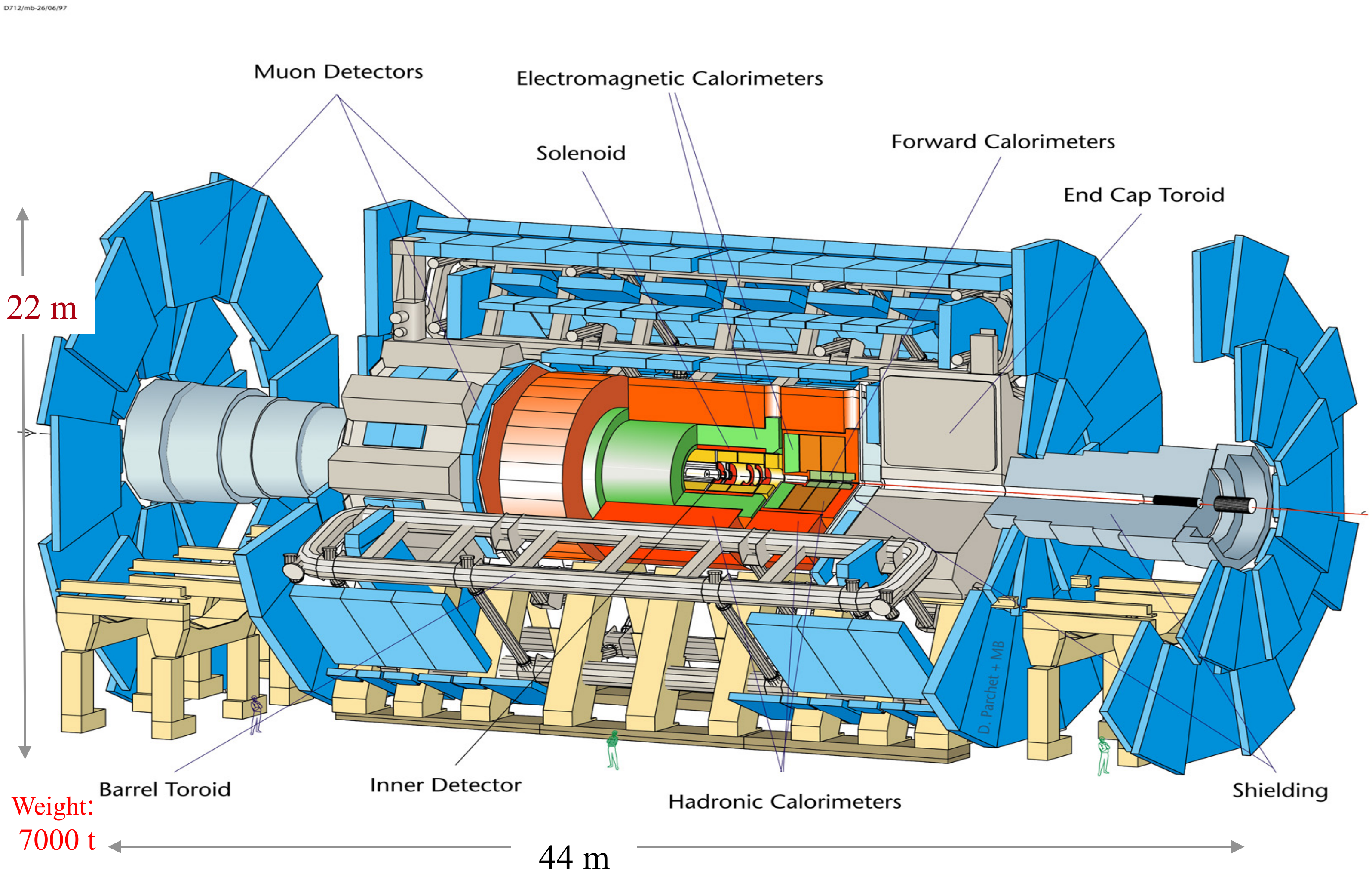
- Top decays before it feels non-perturbative strong interaction
  - Can study the bare quark (eg spin)
  - No top-hadrons or tt-quarkonium
  - Top spin transferred to decay products

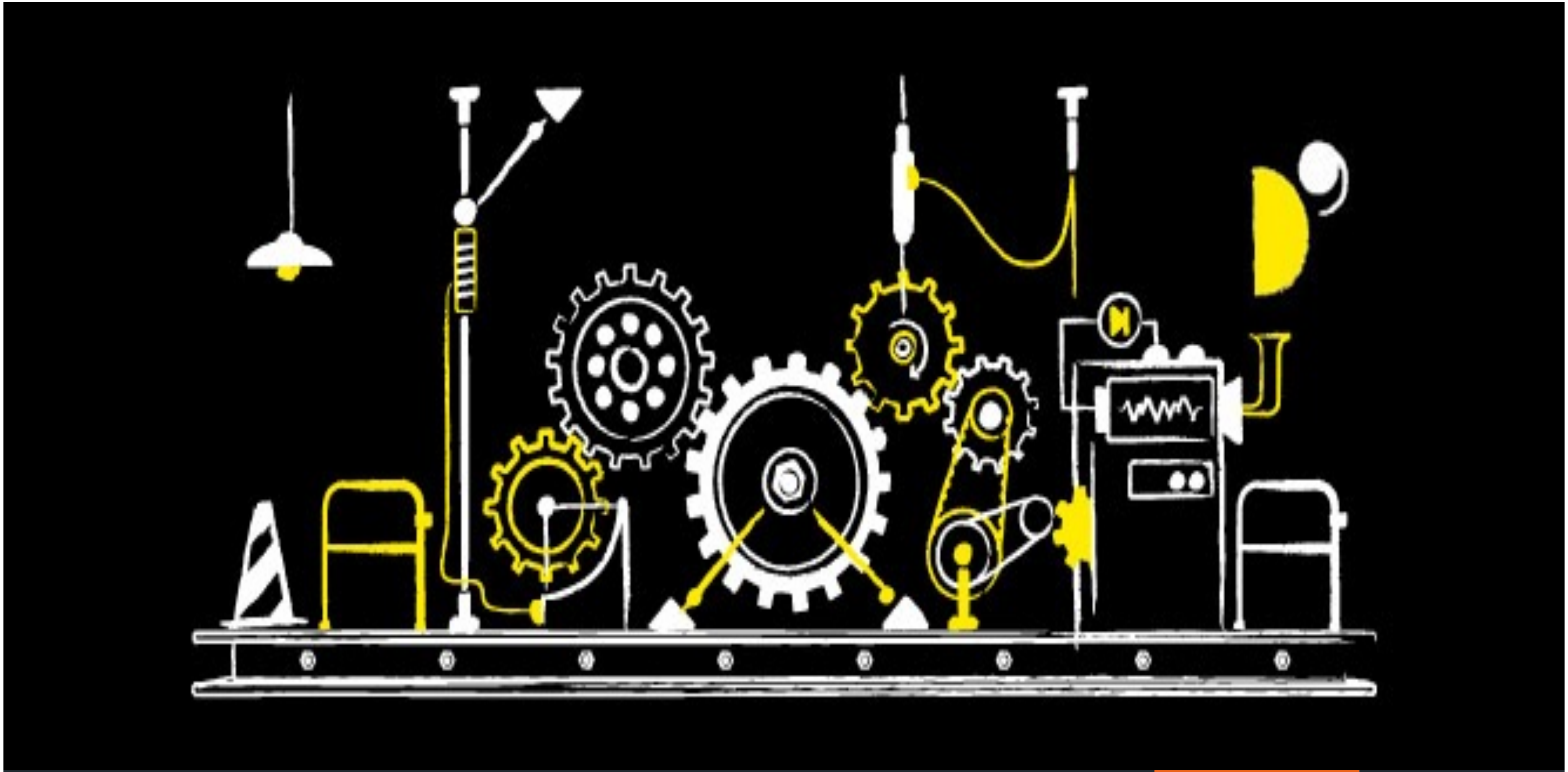
(not inc. τ)	**BR**	**background**
dilepton	~5%	low
lepton + jets	~30%	moderate
all hadronic	~44%	high

Example: Lepton+jets $t\underline{t}$ events



ATLAS


D712/mb-26/06/97
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
22 m
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
Weight: 7000 t
44 m
D. Parchet + MB



Top mass measurements

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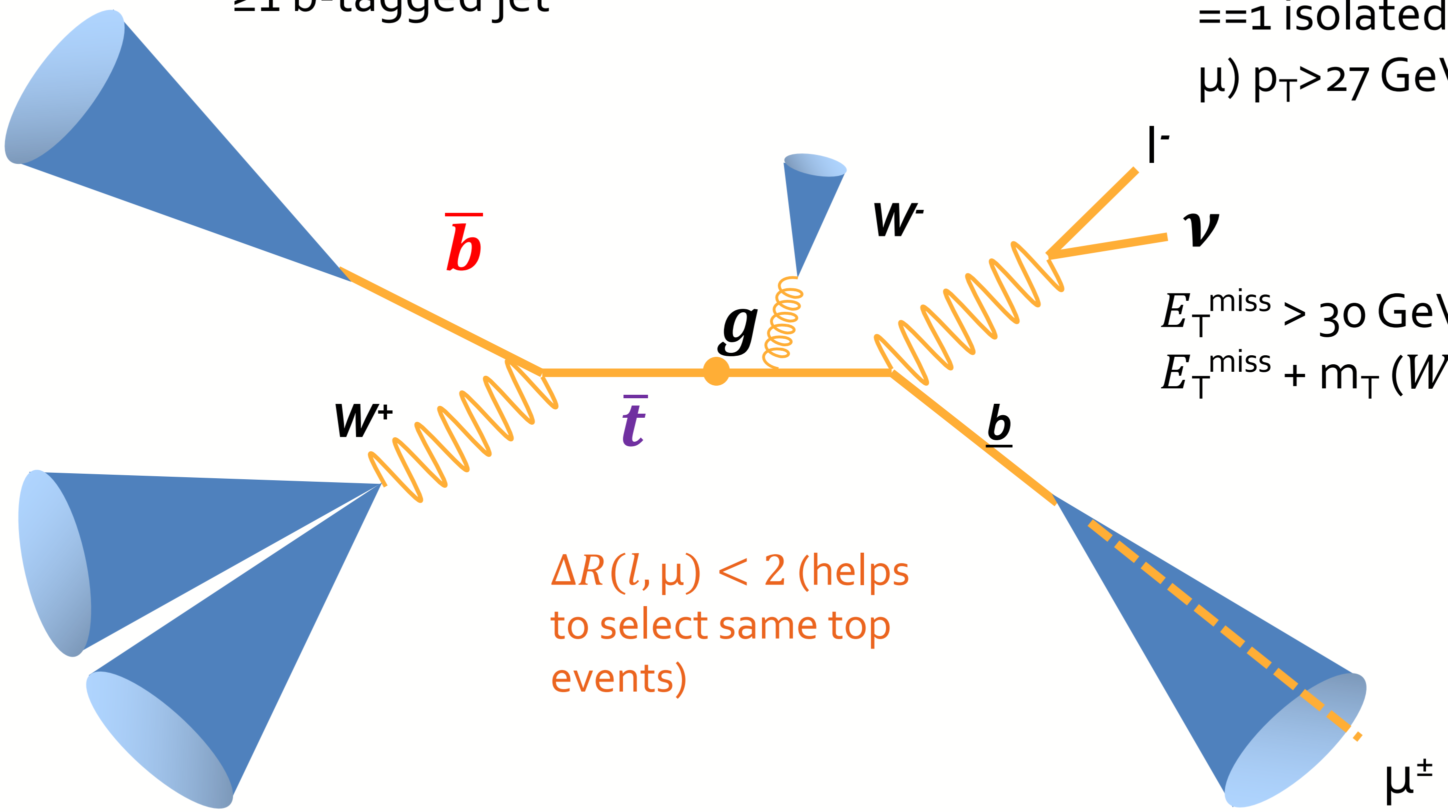
1. Using leptonic invariant mass at 13 TeV using 36 fb^{-1}: JHEP 06 (2023) 019
2. ATLAS+CMS Run 1 combination: submitted to PRL

Object & Event selection

≥1 b-tagged jet

==1 isolated lepton (e or μ) p_T>27 GeV |η|<2.5



E_T^{miss} > 30 GeV
E_T^{miss} + m_T (W) > 60 GeV

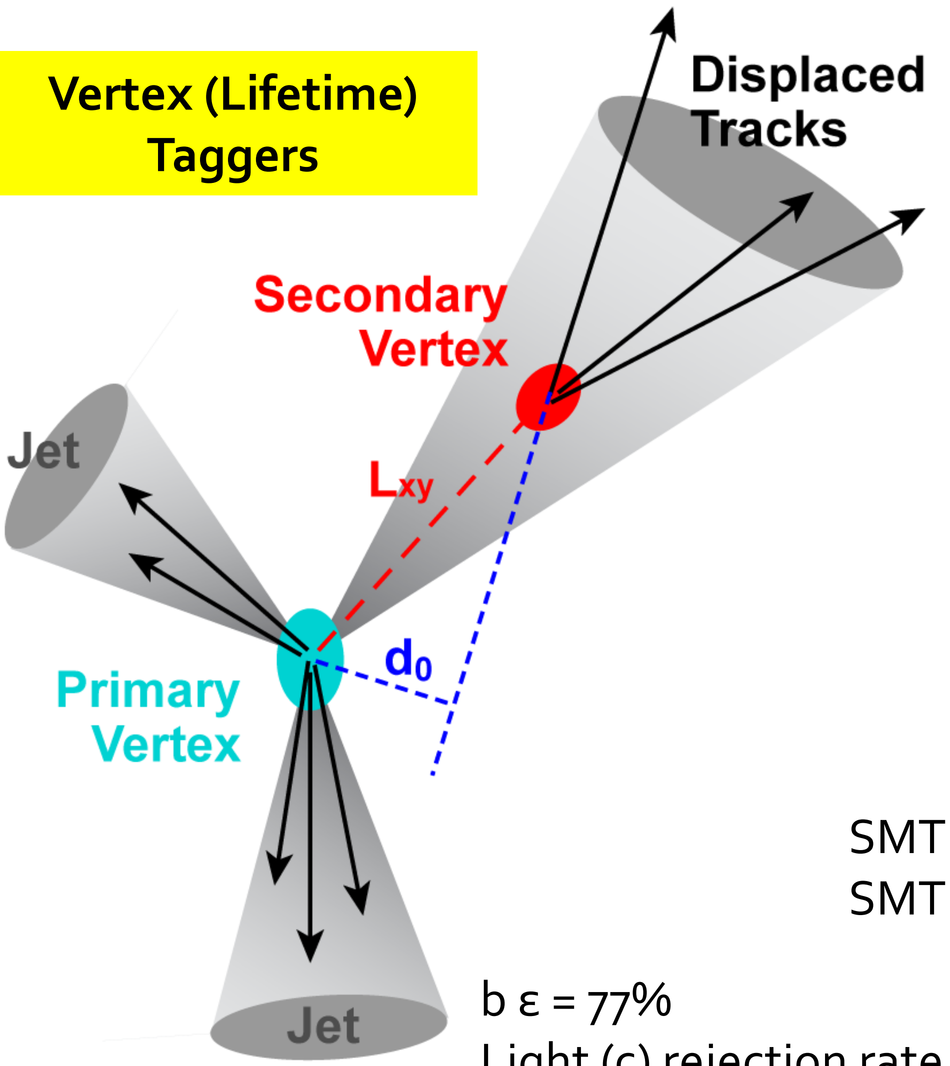
$\Delta R(l, \mu) < 2$ (helps to select same top events)

≥ 4 jets (anti-kt R=0.4) p_T>30 GeV |η|<2.5

≥ SMT tagged jet p_T>25 GeV |η|<2.5 (can be same as b-tagged jet, if more than 1 SMT, for measurement use the one with highest p_T muon)

B-tagging

Vertex (Lifetime) Taggers

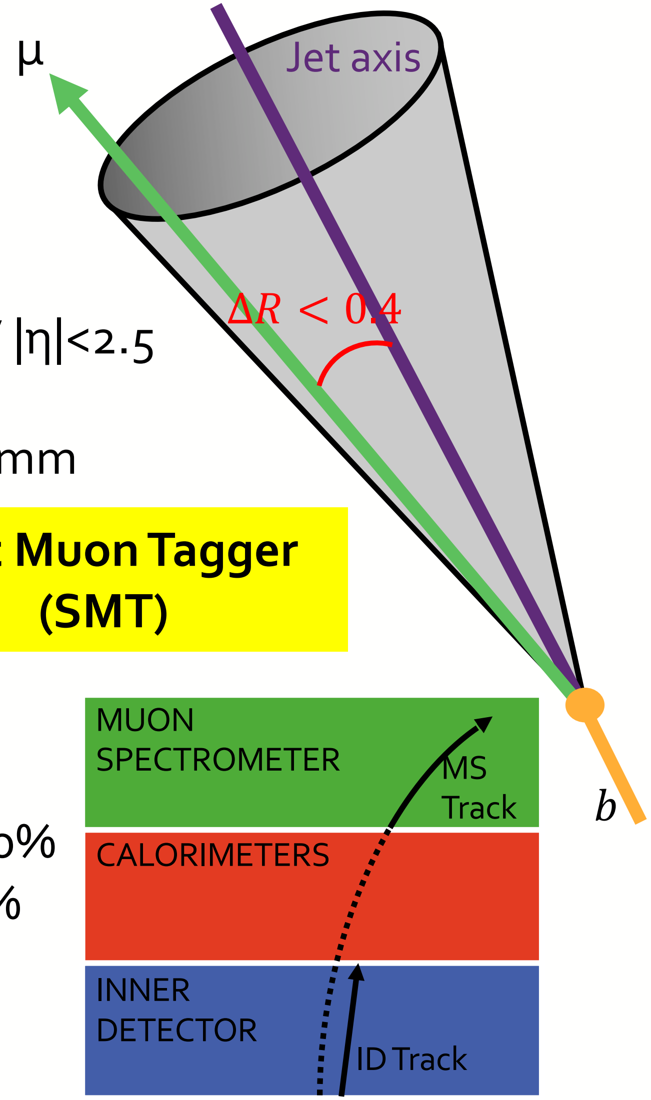


b ε = 77%
Light (c) rejection rate = 100 (7)

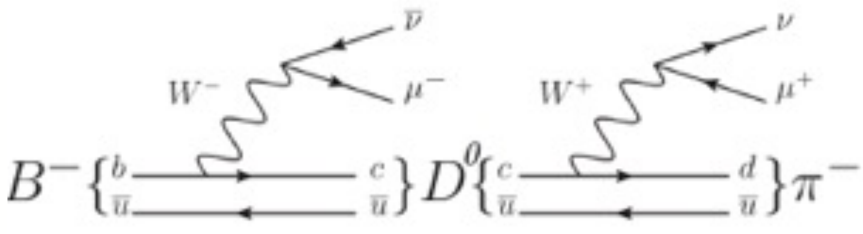
μ p_T>8 GeV |η|<2.5
$|d_0| < 3$ mm
$|Z_0 \sin\theta| < 3$mm

Soft Muon Tagger (SMT)

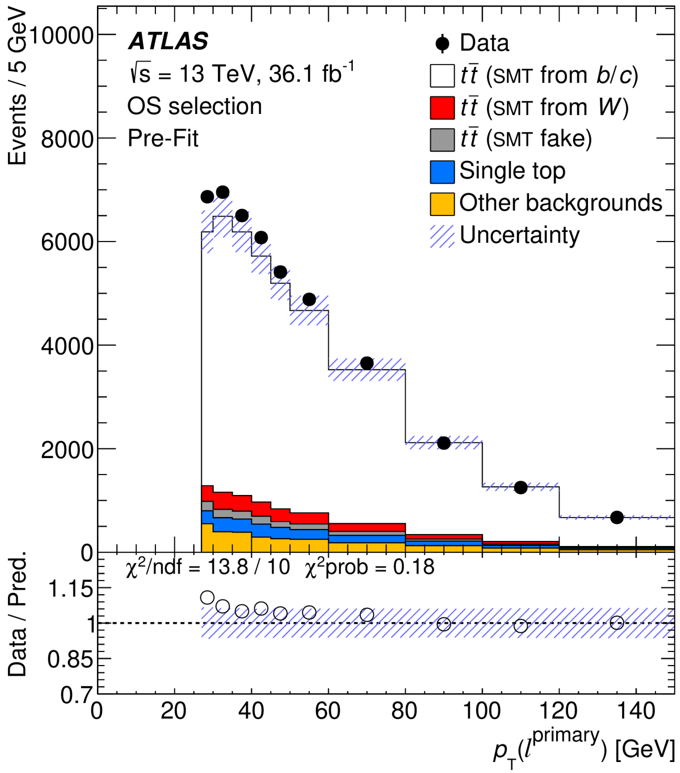
SMT b ε = 50%x20%
SMT light ε = 0.1%



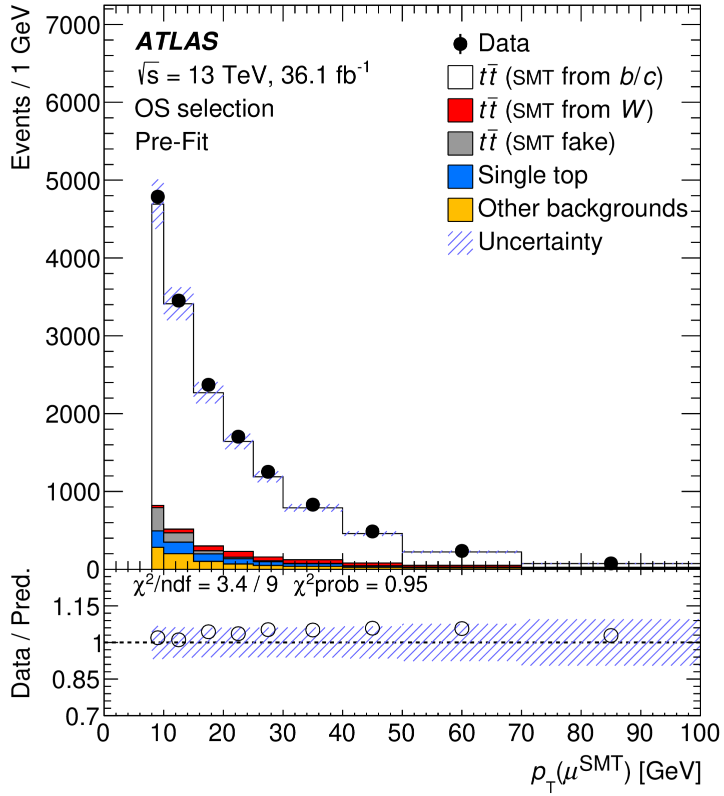
“soft” muons



BR(b→μ)~20%



“Hard-lepton”
“W-lepton”



“Soft Muon”

SMT calibration & Yields

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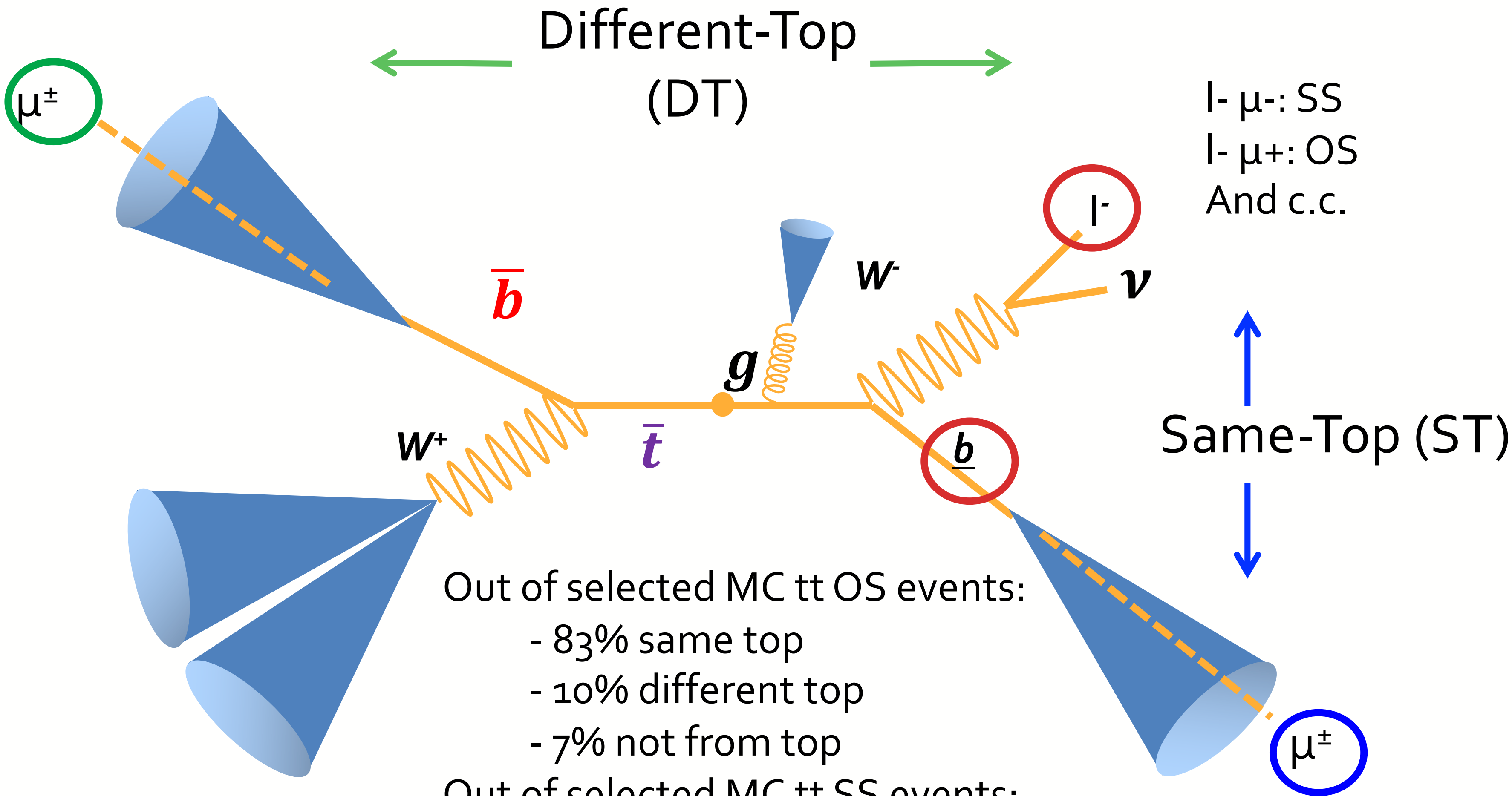
- SMT eff calibration: SF data/MC:
  - Use J/Psi and Z data samples
  - SF vs track and calo activity and vs d_o
  - → no trends and SF close to 1.0
- SMT mistag rate: SF data/MC:
  - Mostly from dif of π/K
  - Light –jet data sample: W+1 jet where jet is SMT-tagged but not b-tagged
  - → SF on normalization: 1.10±0.14
  - → scale p_T of SMT-tagged jet: 0.967±0.024 (using p_T SMT-tagged jet/ p_T non-SMT-tagged jet)

Process	Yield (OS)	Yield (SS)
$t\bar{t}$ (SMT from b- or c-hadron)	55 700 ± 3400	34 800 ± 2300
$t\bar{t}$ (SMT from $W \to \mu\nu$)	2190 ± 310	4.9 ± 3.6
$t\bar{t}$ (SMT fake)	1490 ± 210	1240 ± 170
Single top t-channel	770 ± 70	490 ± 40
Single top s-channel	63 ± 6	49 ± 4
Single top Wt channel	1840 ± 140	1260 ± 100
W+jets	1600 ± 400	1080 ± 240
Z+light jets	210 ± 80	15 ± 6
Z+HF jets	550 ± 180	310 ± 100
Diboson	17.2 ± 2.9	6.3 ± 1.4
Multijet	530 ± 140	480 ± 130
Total Expected	65 000 ± 4000	39 700 ± 2500
Data	66 891	42 087

86% signal 88% signal

- Background estimations:
  - MC for single top, Z+jets, Diboson
  - Data-driven for: W+jets (using "Charge Asymmetry method") and Multijet (using "Matrix Method")

Opposite Sign vs Same Sign



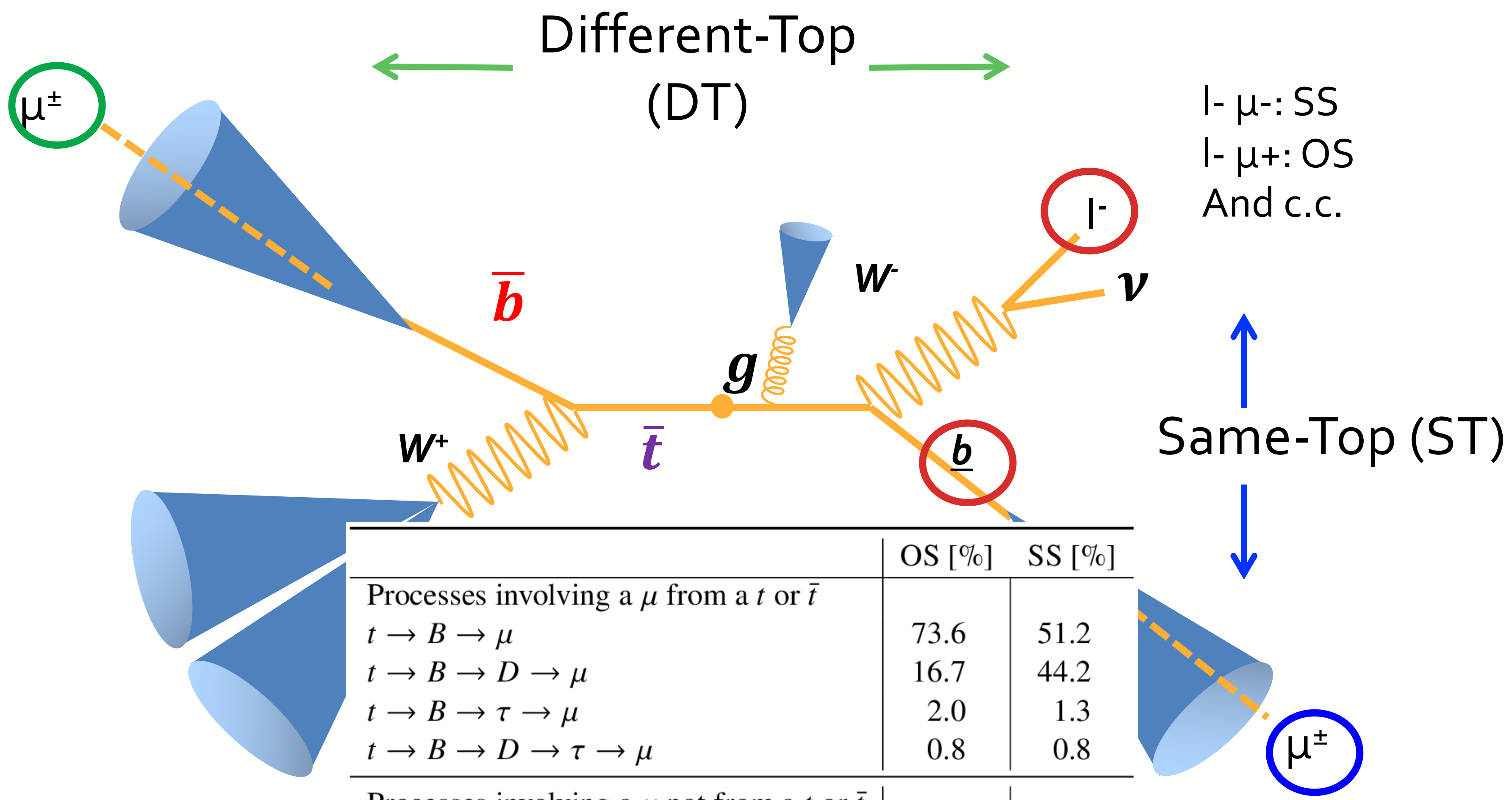
l- μ-: SS
l- μ+: OS
And c.c.

Out of selected MC tt OS events:
- 83% same top
- 10% different top
- 7% not from top

Out of selected MC tt SS events:
- 57% same top
- 41% different top
- 2% not from top

$\Delta R(l, \mu) < 2$ helps to select same top events

Opposite Sign vs Same Sign



l- μ-: SS
l- μ+: OS
And c.c.

	OS [%]	SS [%]
Processes involving a μ from a t or $\bar{t}$		
$t \to B \to \mu$	73.6	51.2
$t \to B \to D \to \mu$	16.7	44.2
$t \to B \to \tau \to \mu$	2.0	1.3
$t \to B \to D \to \tau \to \mu$	0.8	0.8
Processes involving a μ not from a t or $\bar{t}$		
$B \to \mu$	0.6	0.9
$D \to \mu$	5.8	1.4
Other ($\tau \to \mu$)	0.5	0.1

$\Delta R(l, \mu) < 2$ (helps to select same top events)

Observable: $m_{inv}(l, \mu)$

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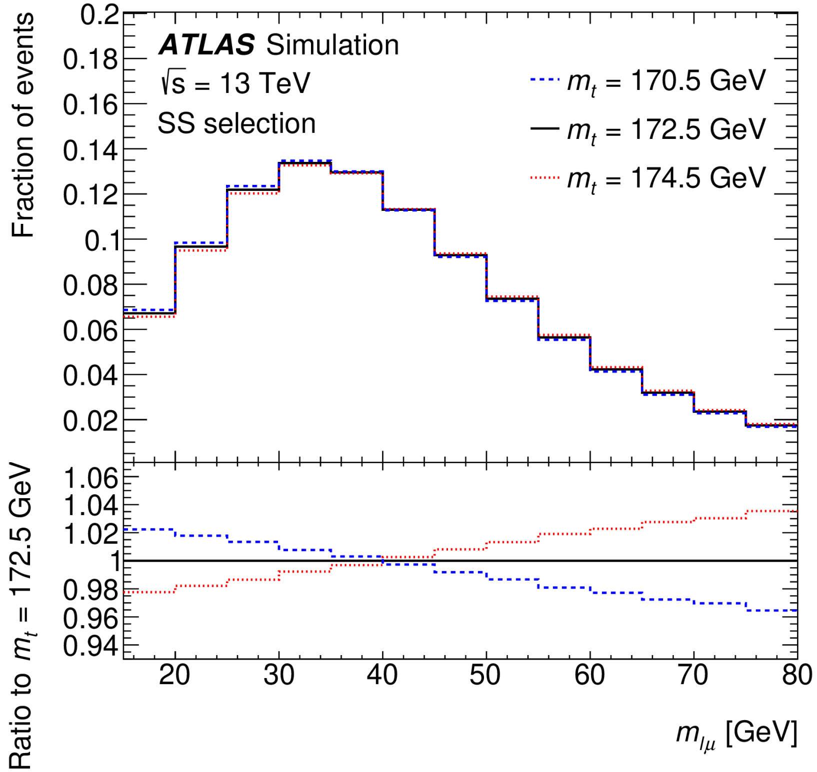
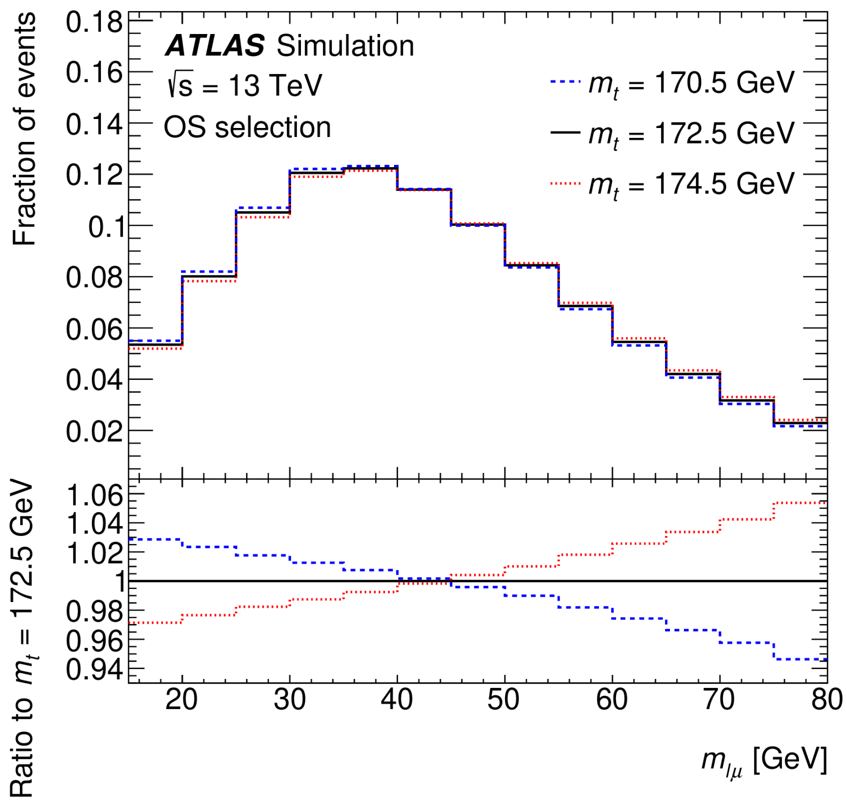
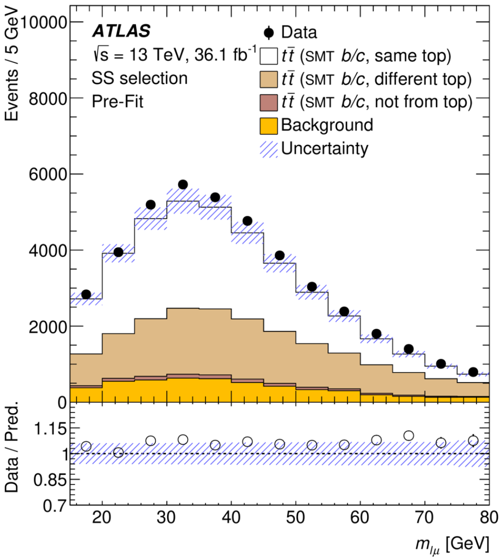
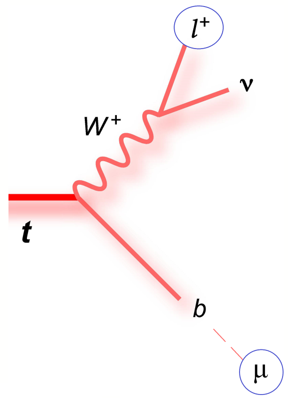
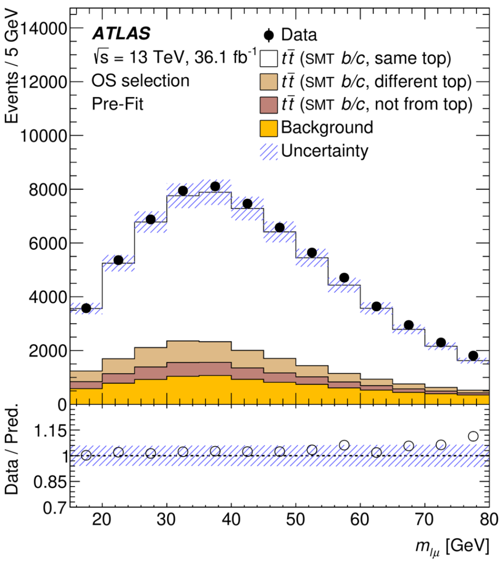


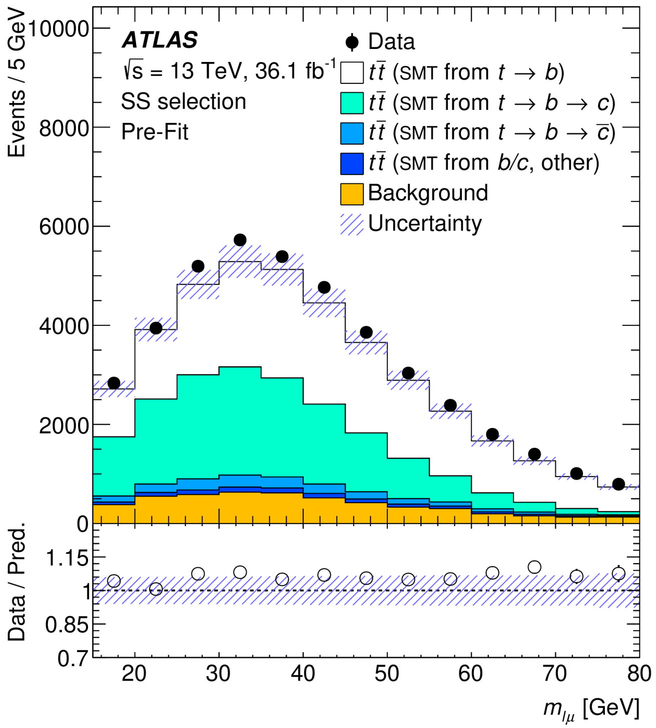


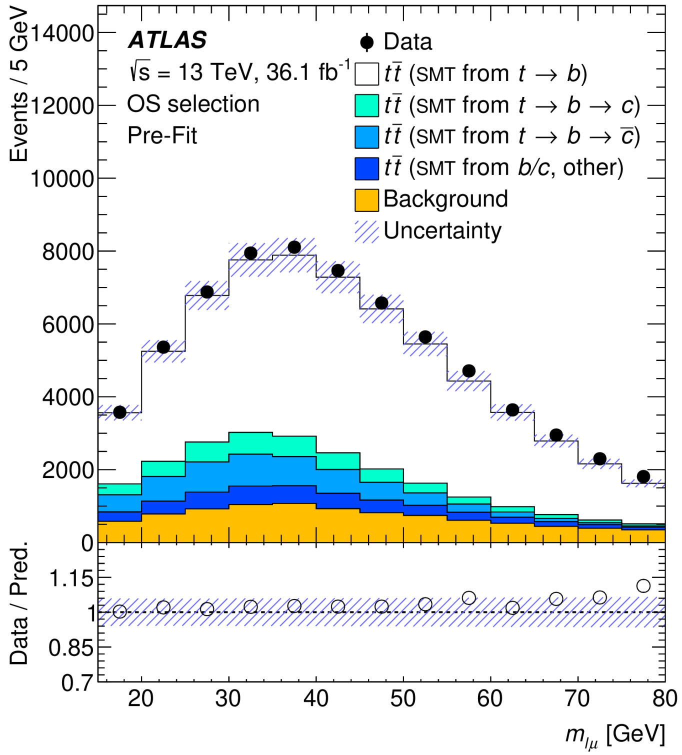
Observable: $m_{inv}(l, \mu)$











Tt MC simulation

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- Hvq program in Powheg-Box v2 using NNPDF3.0NLO
- PS and hadronisation: Pythia 8.2 using A 14-rb setting based on A 14 ATLAS tune
- Bottom and charm mixing and decays: EvtGen v1.2.0
- Modelling of momentum transfer between b-quark and b-hadron:
  - Pythia8 uses parametric functions to describe b fragmentation
  - Fit to e+e- data (applies to pp)
- Pythia Lund-Bowler fragmentation function:

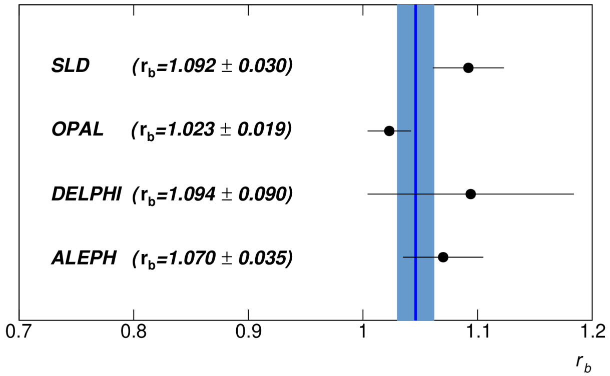
$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-bm_T^2/z)$$

  - a,b: data-fitted parameters, universal between light and heavy quarks
  - r_b: specific to b quark fragmentation
  - m_T: b-hadron transverse mass
  - z: E_z (b-had)/E_z (b) in light-cone reference frame
  - Controlled by both α_S and r_b, since α_S=0.127 in A14, r_b needs to be tuned (r_b = 0.855)
  - Fit uses A14 tune with e+e- → Z → bb data from ALEPH, OPEAL, DELPHI and SLD
  - Use RIVET v3.1.0 and :

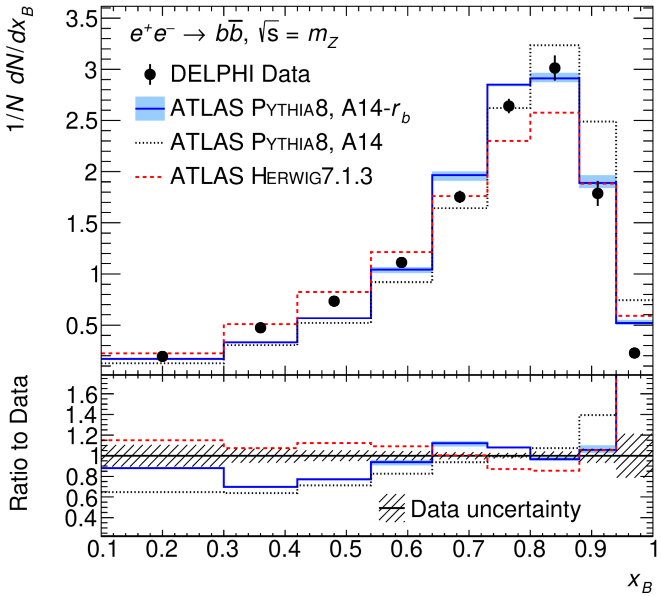
$$x_B = 2p_B \cdot p_Z/m_Z^2 = 2E_B/m_Z$$

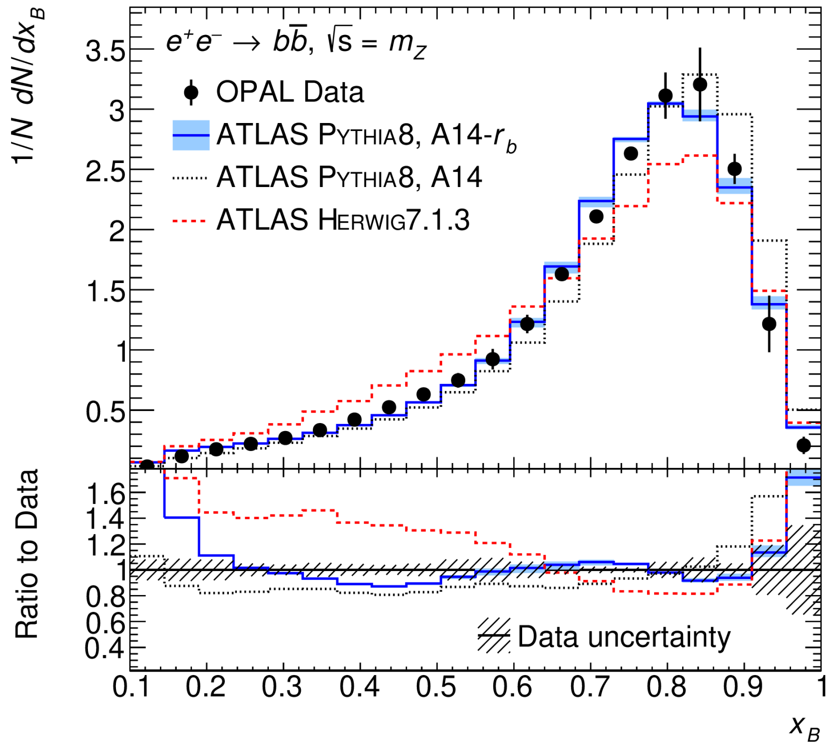
Tt MC simulation

- Result of the fit: r_b =1.05 ± 0.02



Experiment	r_b	χ^2/ndf
ALEPH	1.070 ± 0.035	21/18
DELPHI	1.094 ± 0.030	73/8
OPAL	1.023 ± 0.019	18/19
SLD	1.092 ± 0.018	58/21

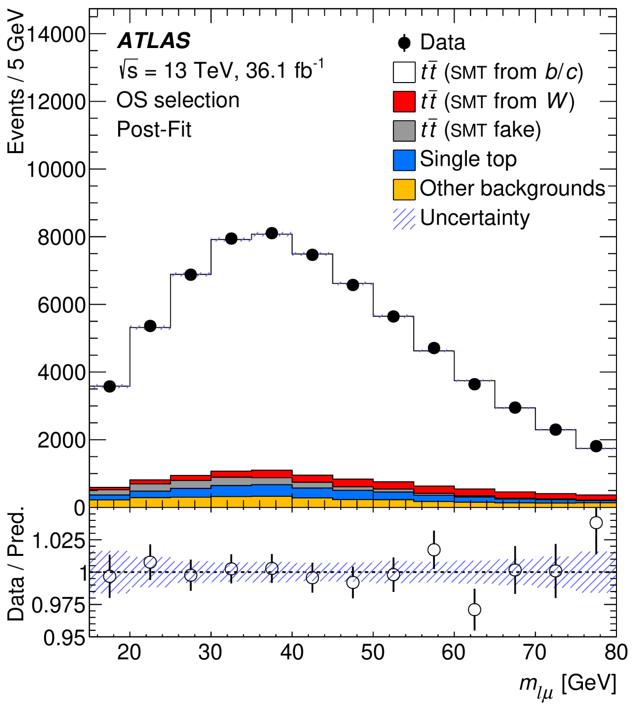


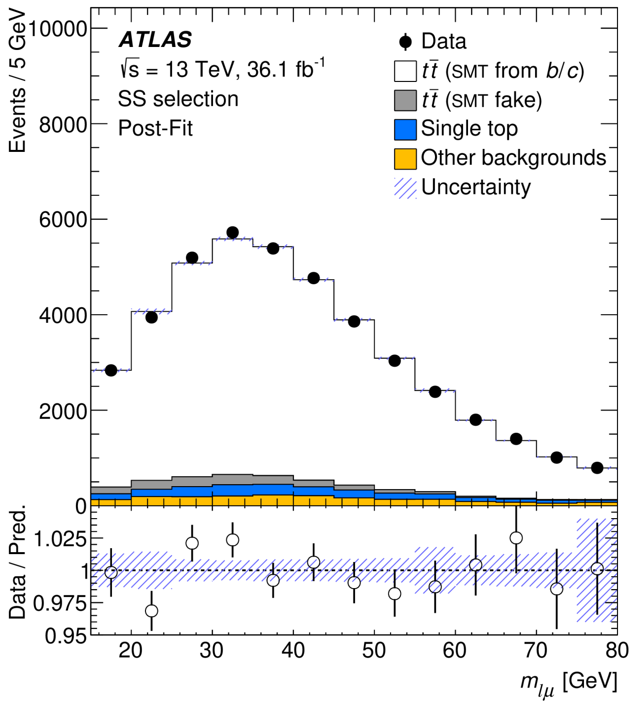


Fit to extract top mass

- Binned-template (smoothed) profile likelihood fit
  - Poisson likelihood model
  - Gaussian-constrained nuisance parameters (pruned)
- OS and SS simultaneously
  - SS less sensitivity to top mass

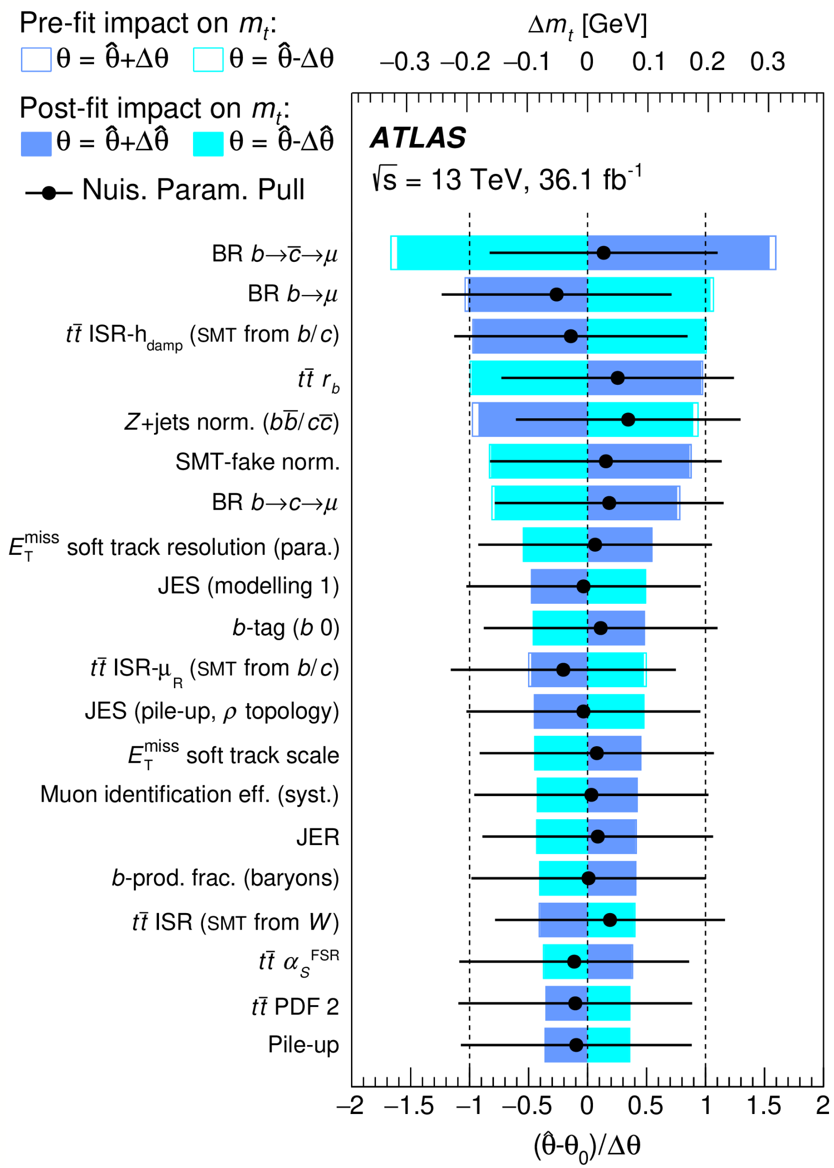
- 3 fit parameters:
  - Top mass
  - N tt in OS and SS
- Pseudo-experiments: fit is linear, unbiased and correct stat unc.
- Slight trend in lepton p_T: from boost of ttbar, various checks done





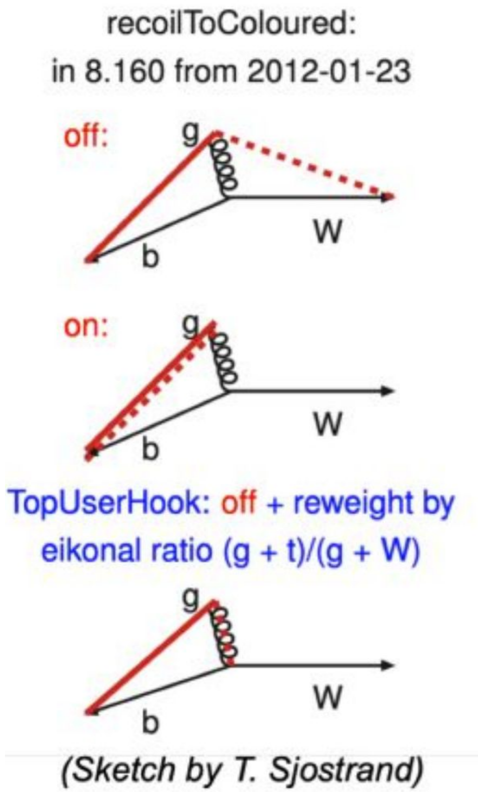
Profiled Systematic uncertainties

- Detector systematics (JES, lepton ID, b-tagging SF, etc.)
- Modelling systematics:
  - Generator: compare with Madgraph5_aMC@NLO+Pythia8 (with pT(tt) reweighted to the Powheg+P8 one)
  - PS and hadronization:
    - Compare with Herwig 7.1.3 (angle-ordered shower alg)
    - r_b unc.
    - Final State Radiation: renormalization and factorization scales with rb fitted for each (called α_S^{FSR})
  - Initial State Radiation
  - PDF
  - B production fraction and decay BR
- Background modelling/normalizations



Recoil uncertainty: New!

- In Pythia: setting to model the 2nd+n gluon radiation from b in t→Wb
  - RecoilToColoured=off, on or userHook
- Tune will influence the impact of setting
- RTW and RTT: wider-angle gluon radiation and lower gluon emissions: change b p_T, W p_T and angle between W and b
- Top mass extracted from RTT and RTB leads to a 0.25 GeV shift: added as extra uncertainty outside of the profile likelihood fit

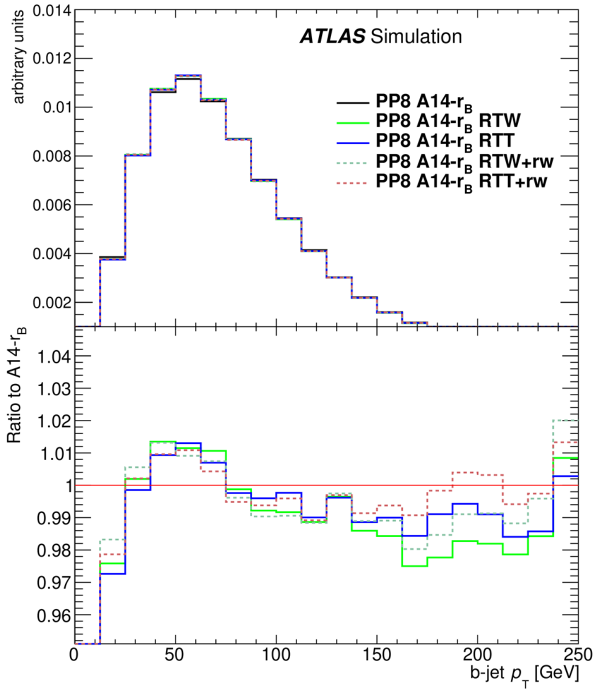


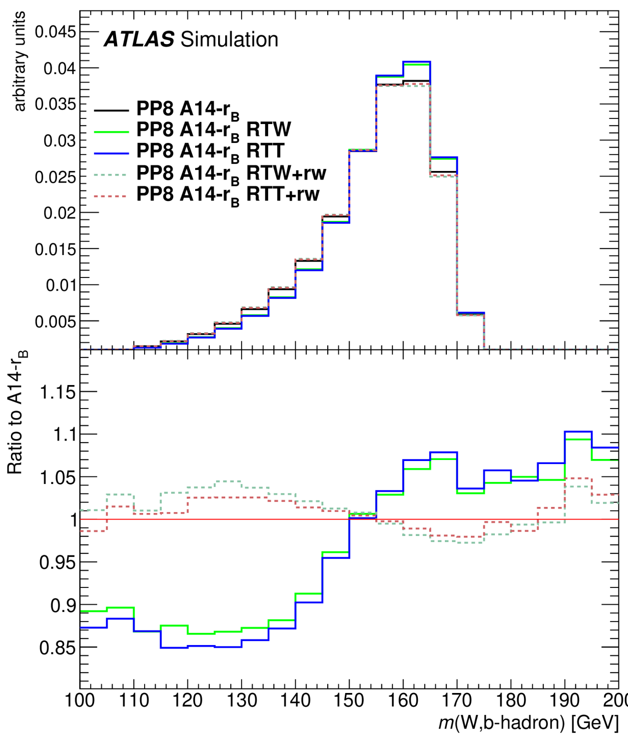
RTW (obsolete)

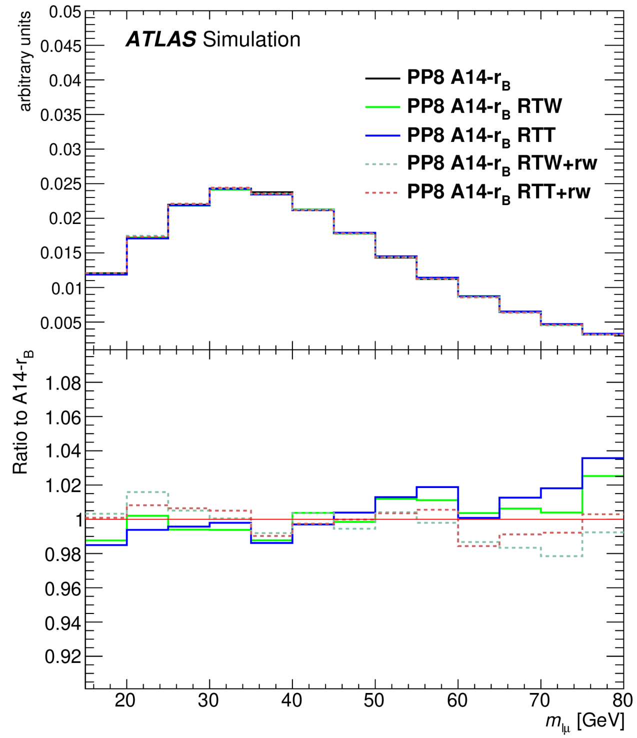
RTB (used in A14)

RTT (new)

Recoil Uncertainty





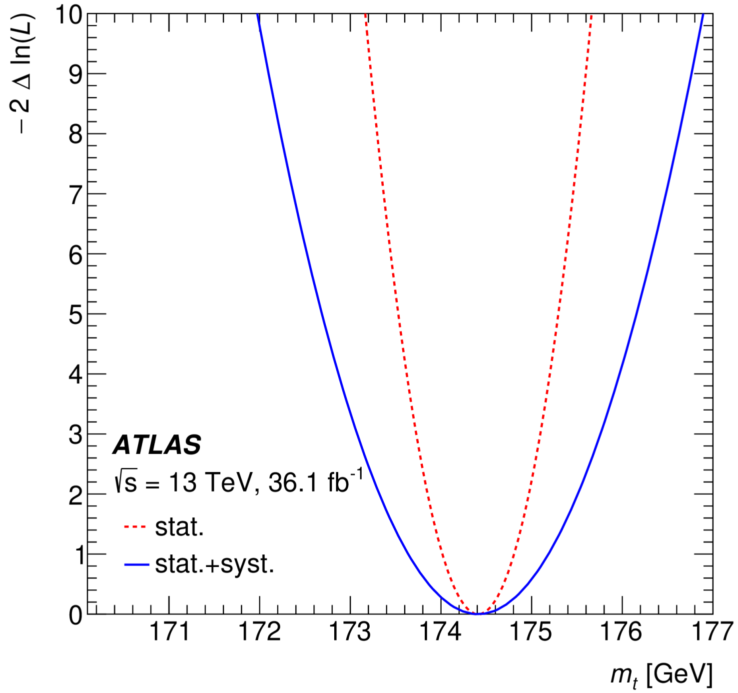


Result!

$$m_t = 174.41 \pm 0.39\ (\text{stat.}) \pm 0.66\ (\text{syst.}) \pm 0.25\ (\text{recoil})\ \text{GeV}$$

0.22% 0.38% 0.14%

m_t = 174.41 ± 0.81 (0.46%)



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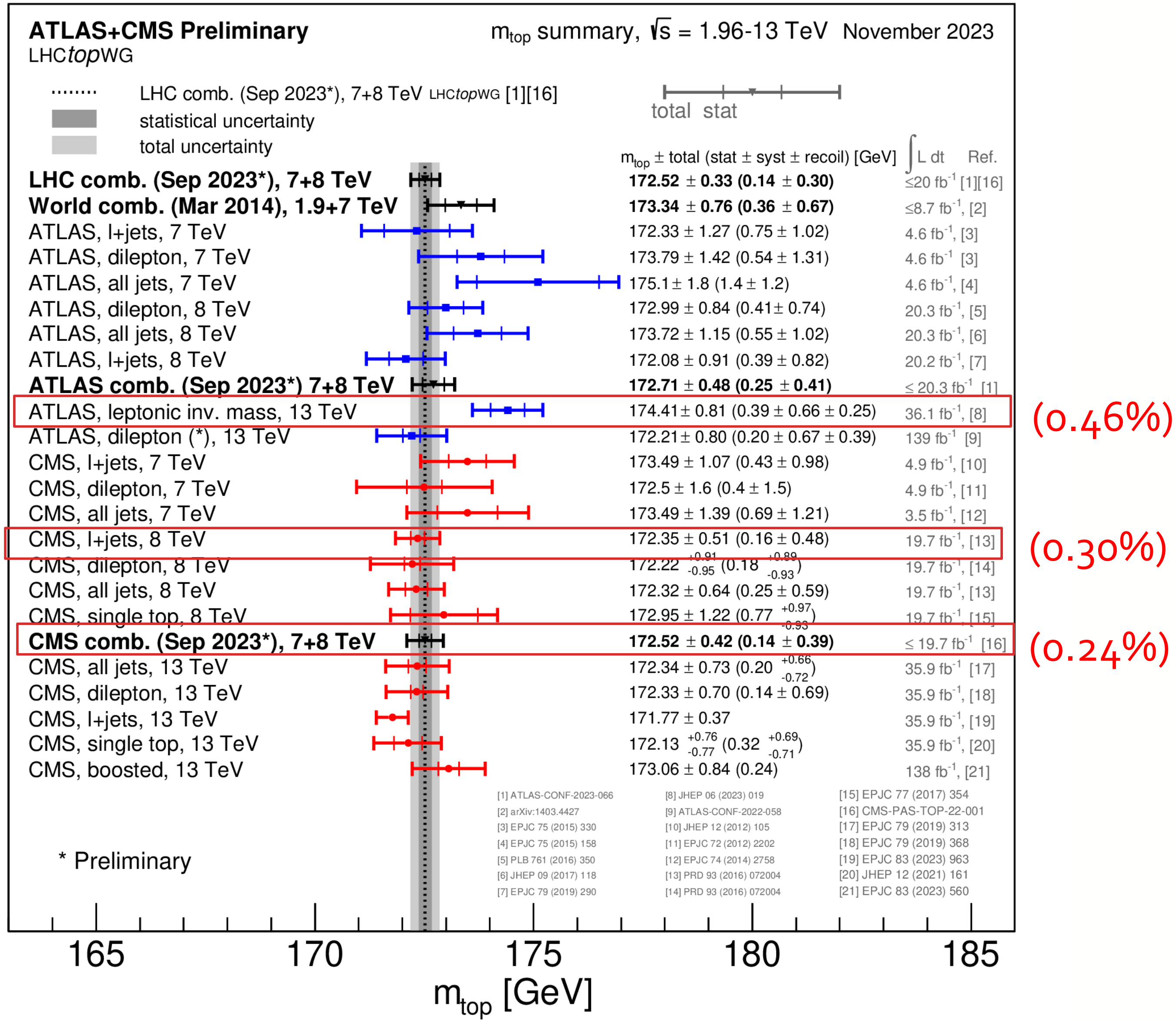
ATLAS and CMS measurements



Run 1 ATLAS+CMS Mass combination

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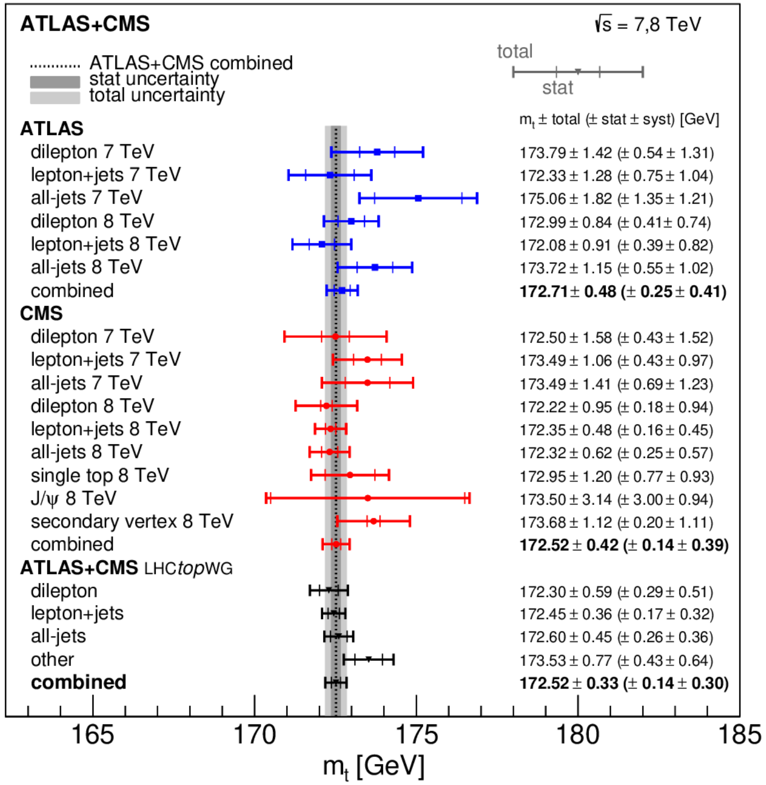
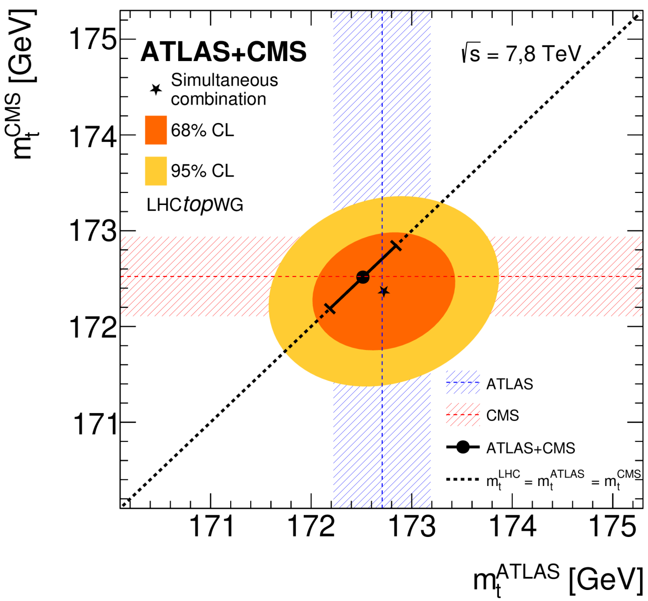
submitted to PRL

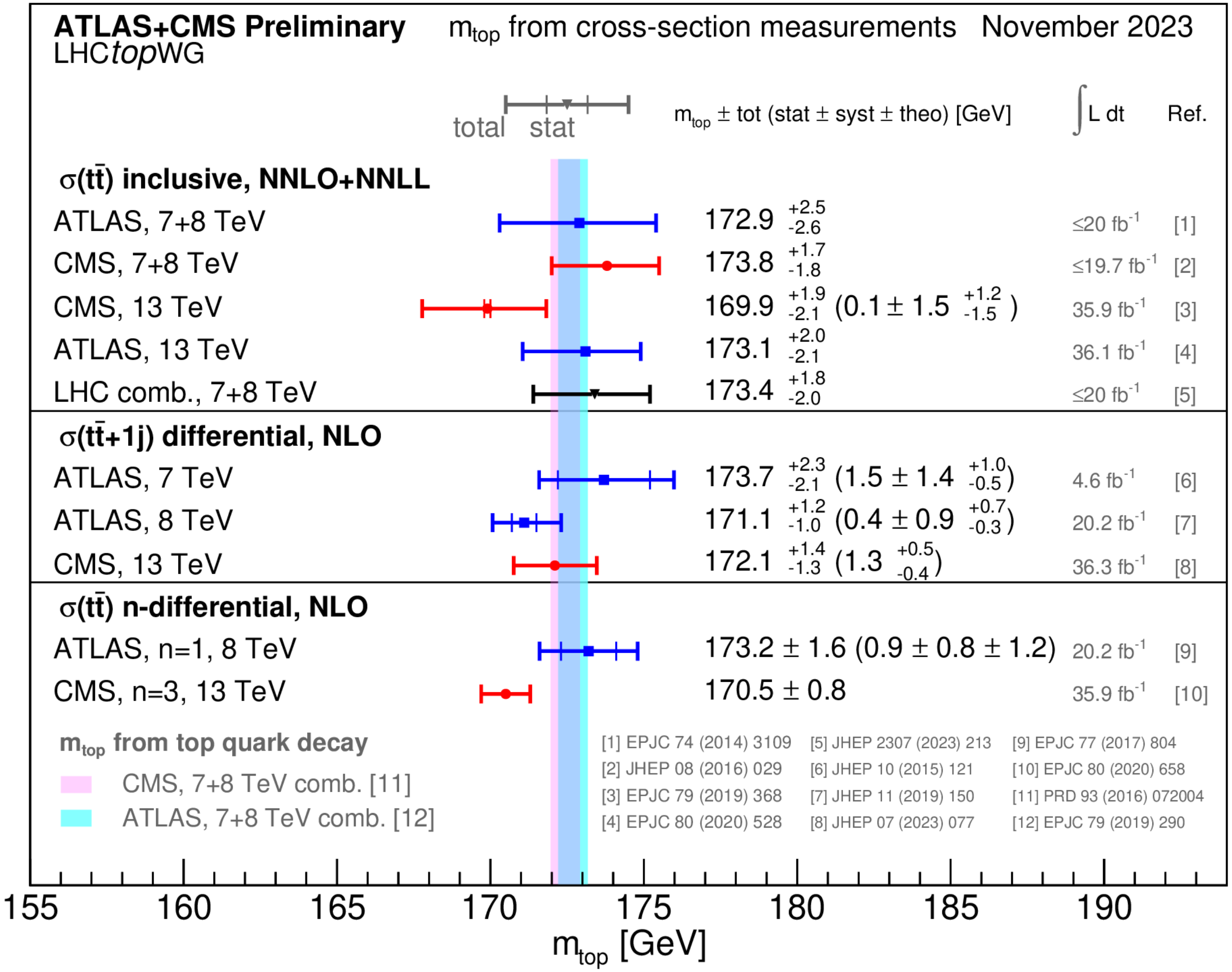




Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

Indirect top mass measurements

- Can unfold the $m_{inv}(l, \mu)$ distribution to get differential distribution, which is then sensitive to top pole mass
- Alex Mitov et al now obtained the NNLO calculations needed for this:
- [2210.06078] NNLO B-fragmentation fits and their application to $t\bar t$ production and decay at the LHC (arxiv.org)



CP violation in b decays using top events

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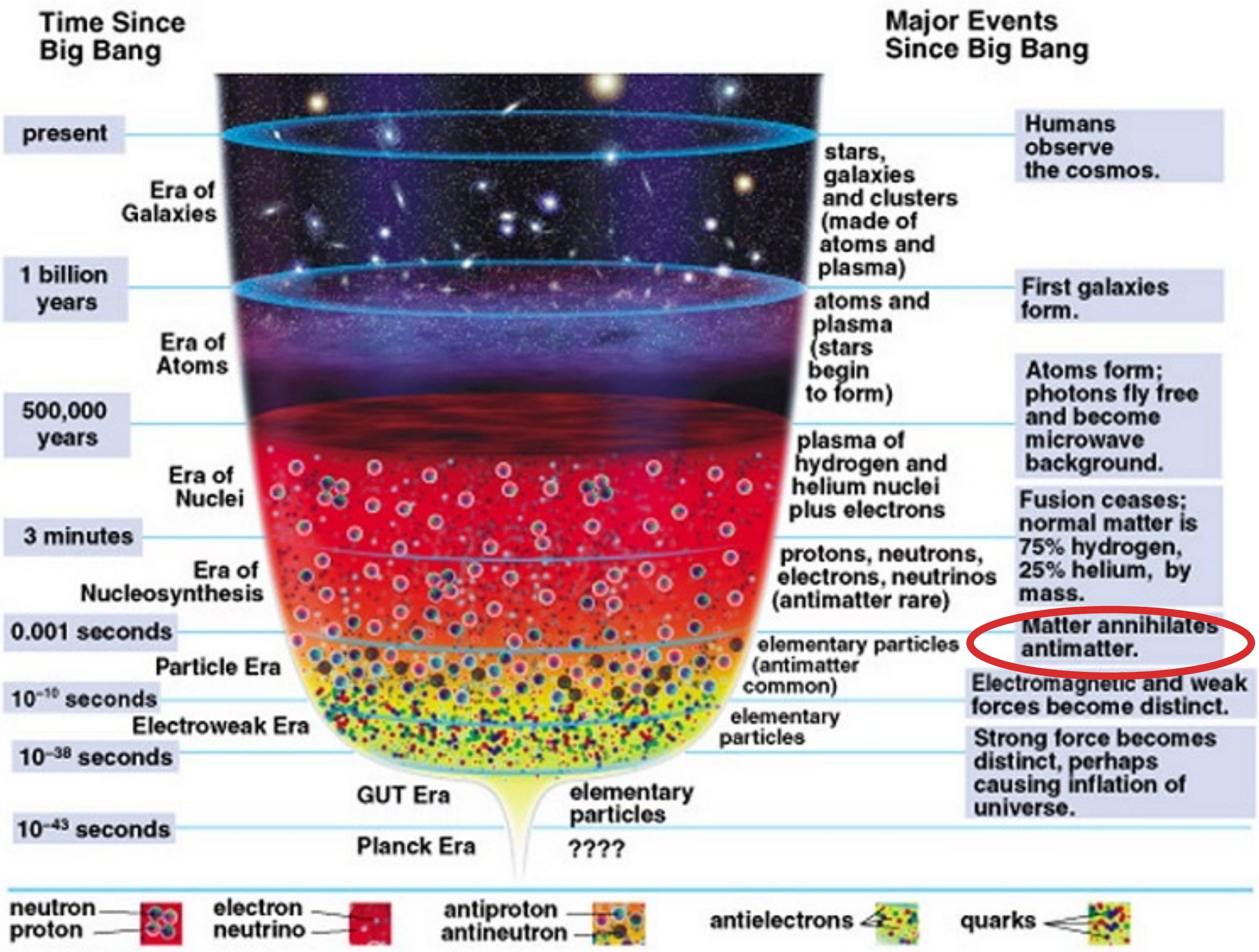
1. 8 TeV measurement: JHEP02 (2017) 071
2. 13 TeV update ongoing

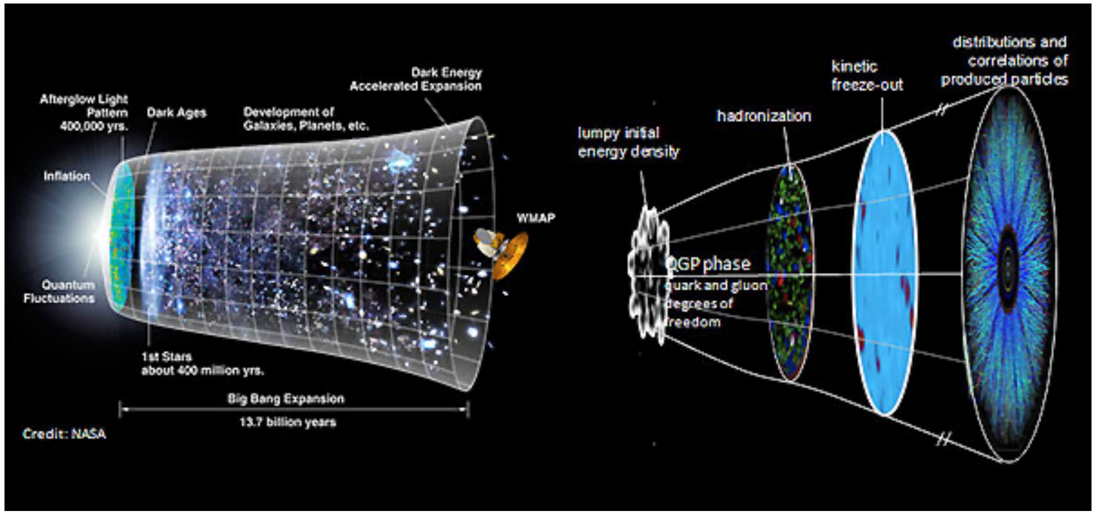
The Big Bang



Time Since Big Bang
Major Events Since Big Bang
present
Era of Galaxies
1 billion years
Era of Atoms
500,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 seconds
Particle Era
10⁻¹⁰ seconds
Electroweak Era
10⁻³⁸ seconds
GUT Era
10⁻⁴³ seconds
Planck Era
stars, galaxies and clusters (made of atoms and plasma)
atoms and plasma (stars begin to form)
plasma of hydrogen and helium nuclei plus electrons
protons, neutrons, electrons, neutrinos (antimatter rare)
elementary particles (antimatter common)
elementary particles
elementary particles
????
Humans observe the cosmos.
First galaxies form.
Atoms form; photons fly free and become microwave background.
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Matter annihilates antimatter.
Electromagnetic and weak forces become distinct.
Strong force becomes distinct, perhaps causing inflation of universe.
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks

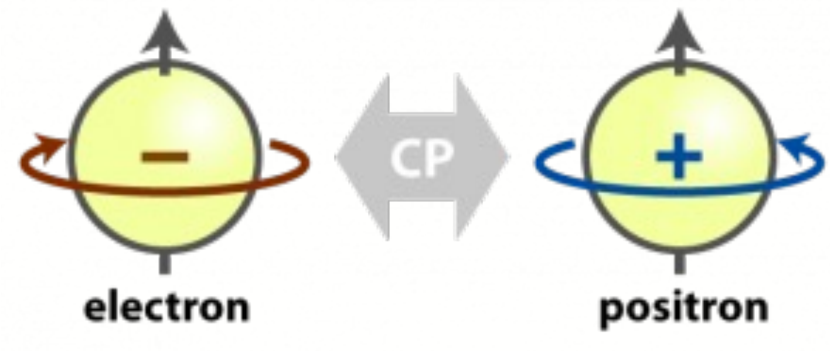
Baryogenesis & CP violation

- Baryogenesis: n(baryons) = n(antibaryons) ~ 10^{-18} n (photons)
- But actually in the early universe: for every 10^9 antibaryons: 10^9 + 1 baryons, giving 10^9 photons + 1 baryon!
- Sakharov conditions:
  - 1) baryon number violation
  - 2) C and CP violation
  - 3) departure from thermal equilibrium



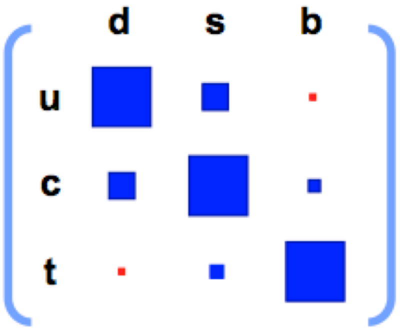
CP violation and the CKM matrix

- Parity is conserved in QED and QCD but violated in weak interactions
- CP violated in weak interactions
- Need 3rd generation of quarks



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates



$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\eta \neq 0$ ➔ CP violation

CKM elements not predicted by the SM, need to measure them

CP violation and the CKM unitarity triangle

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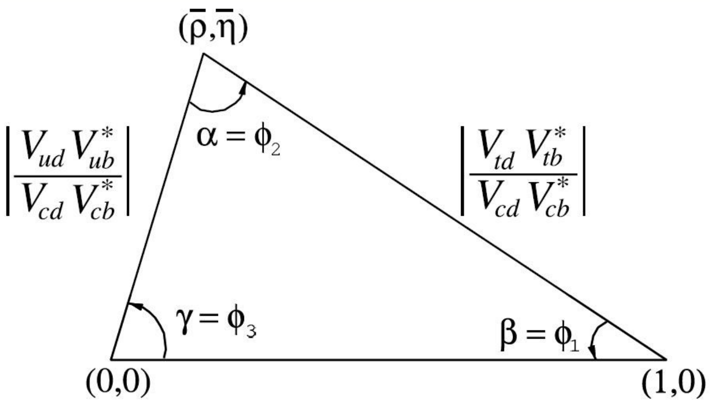
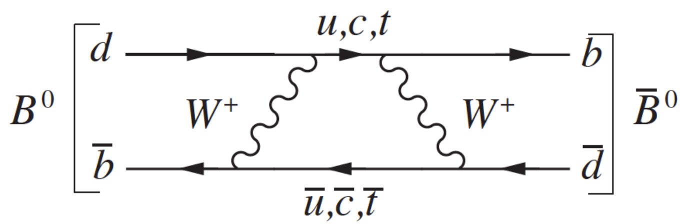
- In SM CKM is unitary: $V^{\dagger}V=1$
- 3 types of CPV:
  - Direct CP violation: $\Gamma(B \to X) \neq \Gamma(\underline{B} \to \underline{X})$
    - SM: smallest
  - CP violation in mixing (indirect): : $\Gamma(B^0 \to \underline{B}^0 \to X) \neq \Gamma(\underline{B}^0 \to B^0 \to \underline{X})$
    - SM: small
  - CP violation in interference between decays to a common final state with and without mixing: $\Gamma(B^0 \to X) \neq \Gamma(B^0 \to \underline{B}^0 \to X)$
    - SM: larger





- Lots of BSM models predict large CP violation effects: fertile group to make precise measurements!

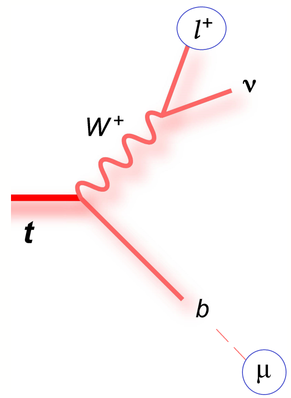
b→μ decay modes

- Opposite Sign (OS):

$$t \to \ell^+ \nu b \to \ell^+ \ell^- X$$ 55%

$$t \to \ell^+ \nu \left(b \to \bar{b} \to \bar{c}\right) \to \ell^+ \ell^- X$$ 4%

$$t \to \ell^+ \nu \left(b \to c\bar{c}\right) \to \ell^+ \ell^- X$$ 3%

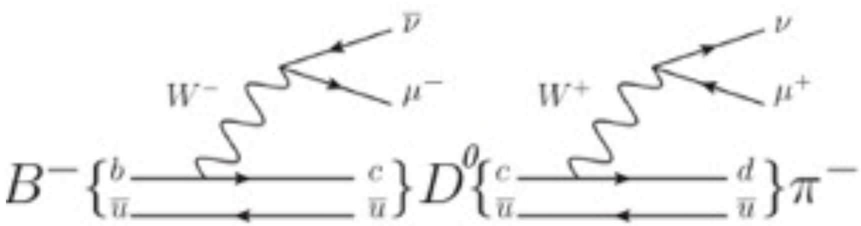


- Same Sign (SS):

$$t \to \ell^+ \nu \left(b \to \bar{b}\right) \to \ell^+ \ell^+ X$$ 7%

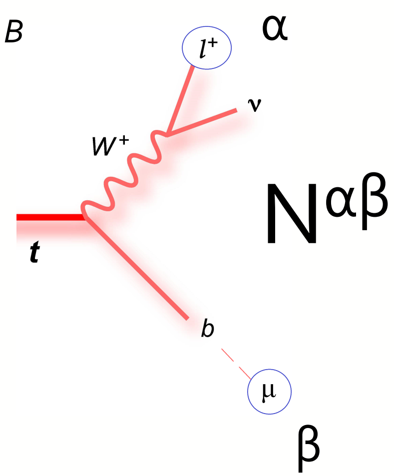
$$t \to \ell^+ \nu \left(b \to c\right) \to \ell^+ \ell^+ X$$ 28%

$$t \to \ell^+ \nu \left(b \to \bar{b} \to c\bar{c}\right) \to \ell^+ \ell^+ X$$ 3%



Charge Asymmetries

Gedalia, Isidori, Maltoni, Perez,Selvaggi, Soreq, *Top B physics at the LHC*, PRL 110 232002 (2013)



$$A^{\rm OS} = \frac{P(b \to \ell^-) - P(\bar{b} \to \ell^+)}{P(b \to \ell^-) + P(\bar{b} \to \ell^+)}$$

$$A^{\rm SS} = \frac{P(b \to \ell^+) - P(\bar{b} \to \ell^-)}{P(b \to \ell^+) + P(\bar{b} \to \ell^-)}$$

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

$$N^+ \equiv N^{++} + N^{+-}$$

$$N^- \equiv N^{-+} + N^{--}$$

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

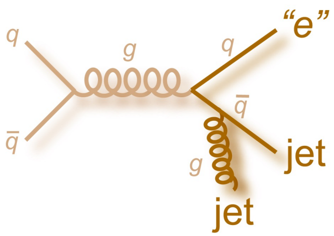
Those charge asymmetries are functions of asymmetries associated with CP Violation in decay and mixing

Measurements are unfolded to particle-level in a fiducial phase-space to minimize the uncertainties

Backgrounds ($t\bar{t}$ lepton+jets and SMT)

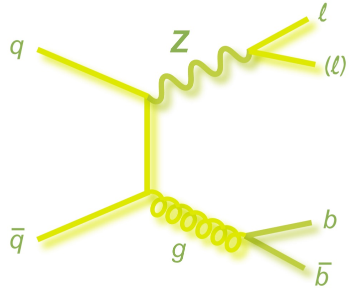
Multijet

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



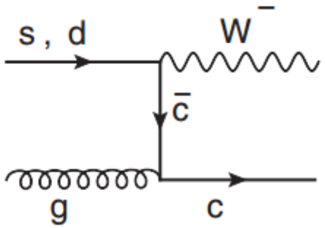
Z+Jets

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

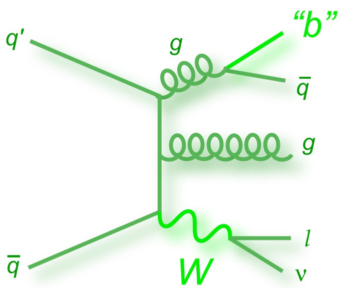


W+Jets

Production Charge **Asymmetric**



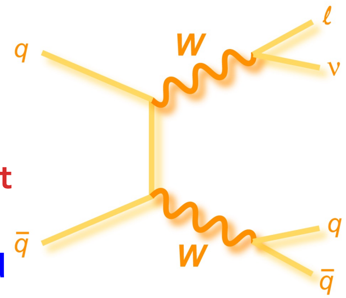
Lepton and SMT **correlated**



Lepton and SMT **uncorrelated**

Diboson

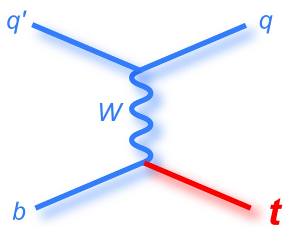
Production Charge **Symmetric (except for WZ production)**
Lepton and SMT charge **uncorrelated**

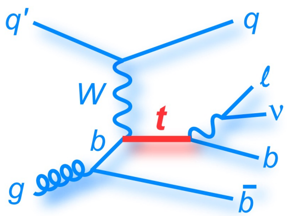


Single Top

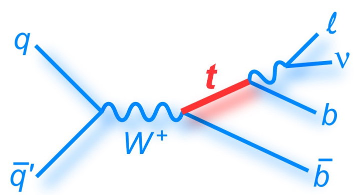
Mixed

t-channel

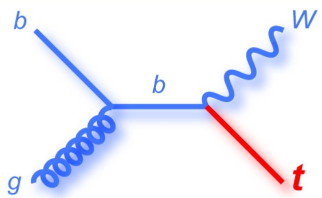




s-channel



Wt-channel



t-channel and s-channel: Production Charge **Asymmetric**
Wt-channel: Production Charge **Symmetric**

Lepton and SMT **correlated** (t-channel) | Lepton and SMT **uncorrelated** (t-channel, s-channel) | Lepton and SMT **correlated** (Wt-channel)

Charge asymmetries ingredients

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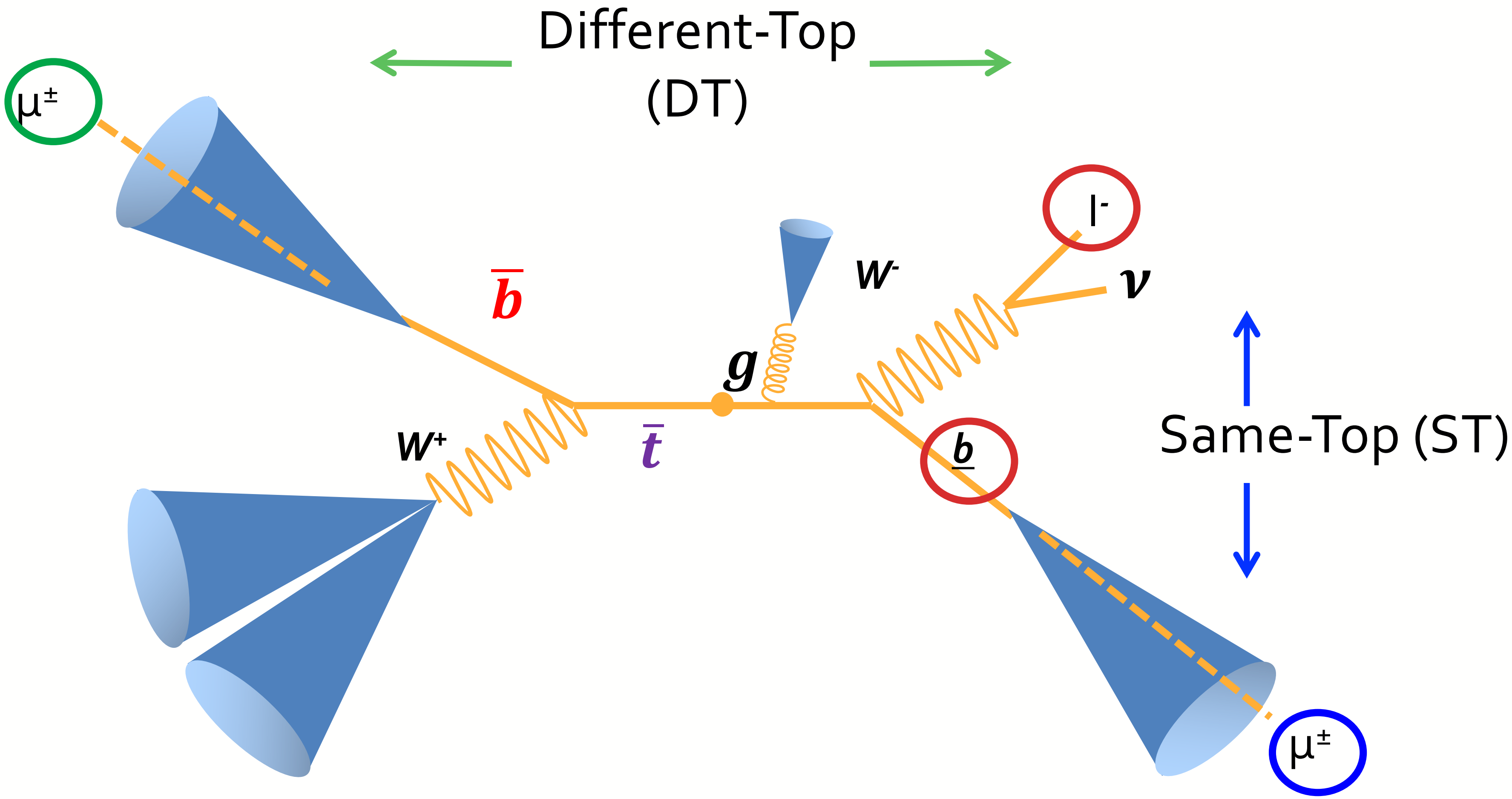

If event is DT: flip charge of W-lepton

ST/DT Assignment

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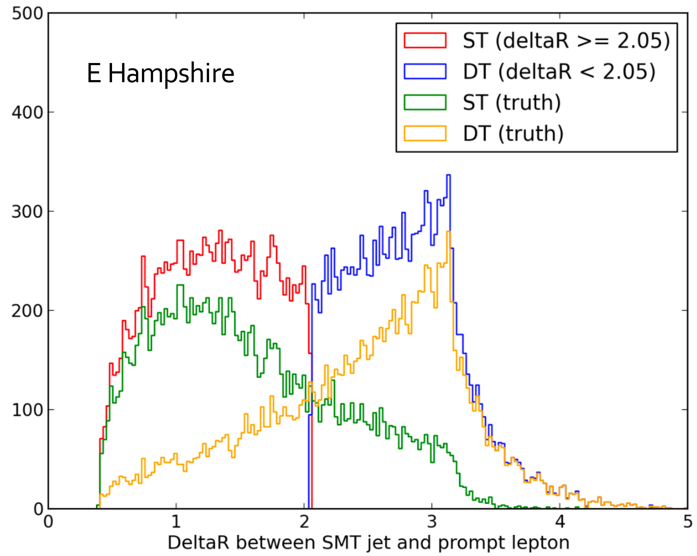
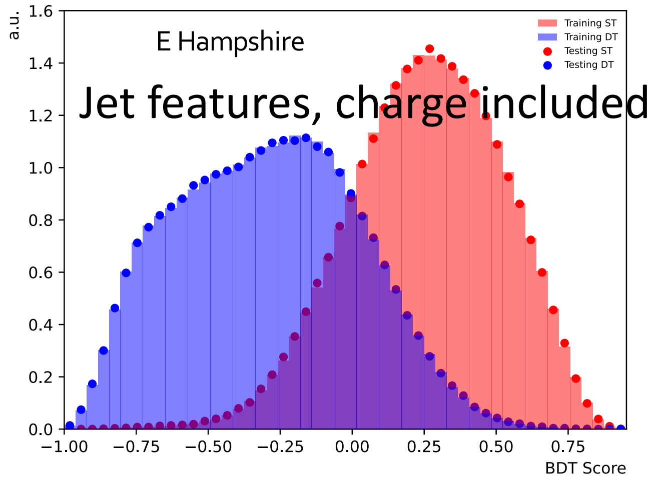
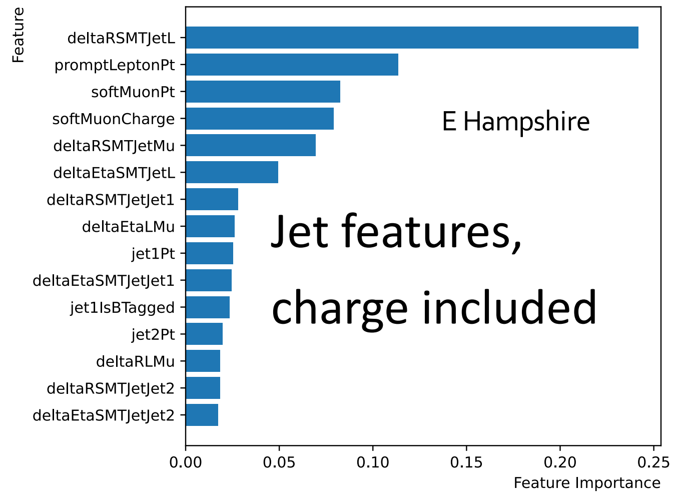
- 8 TeV: Kinematic Likelihood fitter, purity: 79%
- 13 TeV: 3 methods to compare:
  - Simple DR(l, μ), purity: 73%
  - Simple kinematic method: 68%
  - BDT:
    - Including jet features: 82%
    - Not including jet features: 76%
- Final choice based on total uncertainty of measurements





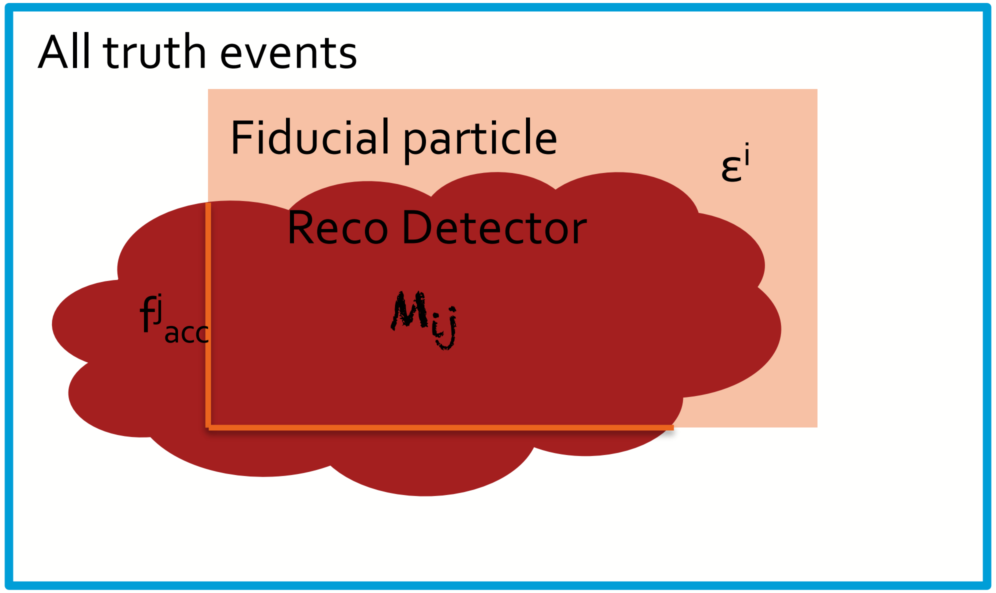


Unfolding from reconstruction to particle

particle → N^i ; reconstructed → N^j_{bkg}

$$N^i = \frac{1}{\epsilon^i} \cdot \sum_j \mathcal{M}^{-1}_{ij} \cdot f^j_{\text{acc}} \cdot (N^j_{\text{data}} - N^j_{\text{bkg}})$$

$$i, j = \{\mathrm{N}^{++}, \mathrm{N}^{--}, \mathrm{N}^{+-}, \mathrm{N}^{-+}\}$$



8 TeV: Unfolding done using unregularized matrix inversion

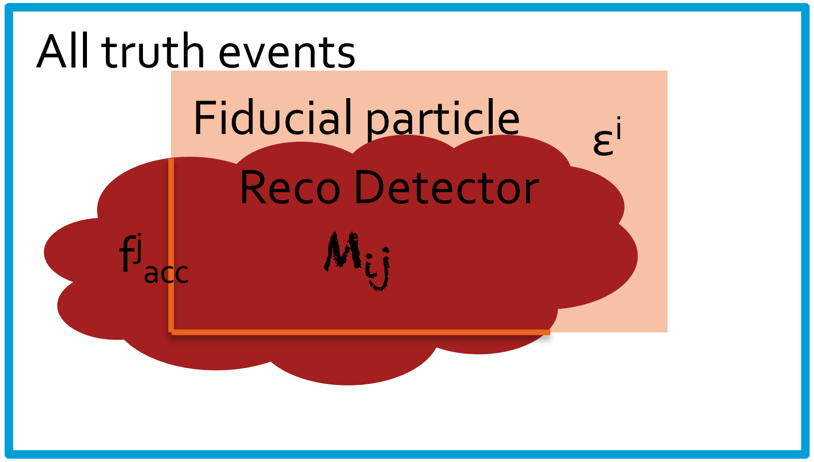
13 TeV: Profile Likelihood unfolding

Unfolding from reconstruction to particle

particle → N^i ; reconstructed → $N^j_{\rm bkg}$

$$N^i = \frac{1}{\epsilon^i} \cdot \sum_j \mathcal{M}^{-1}_{ij} \cdot f^j_{\rm acc} \cdot (N^j_{\rm data} - N^j_{\rm bkg})$$

$$i, j = \{N^{++}, N^{--}, N^{+-}, N^{-+}\}$$



	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

Diagonal = KLFitter performance

Off-Diagonal = Charge mis-ID (negligible)

ε is about 28%
f_{acc} is about 64% for SS
69% for OS
(because of tt background)

Systematic Uncertainties 8 TeV

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- Experimental ones:
  - Leptons, jets, backgrounds, MV1 and SMT tagging, etc.
- Modelling:
  - Usual tt signal modelling:
    - PDF
    - Initial/Final State Radiation
    - Generators (Powheg vs MC@NLO)
    - Parton shower & hadronization (Pythia vs Herwig)
  - Specific ones:
    - b-hadron production rates (scale to RPP and reweight according to uncertainty)
    - b-hadron to mu decay fractions (scale to RPP and reweight according to uncertainty)

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

JHEP02 (2017) 071

Systematic Uncertainties on the asymmetries 8 TeV

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- Statistical uncertainties largest
- Since asymmetries are ratios, most cancel out, remaining ones:
  - IFSR: affects the KLFitter performance, modifies the response matrix, so large effect on asymmetries
  - PDF

	$A^{ss}\,(10^{-2})$		$A^{os}\,(10^{-2})$	
Measured value	[redacted]		[redacted]	
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

Charge Asymmetries: consistent with 0!

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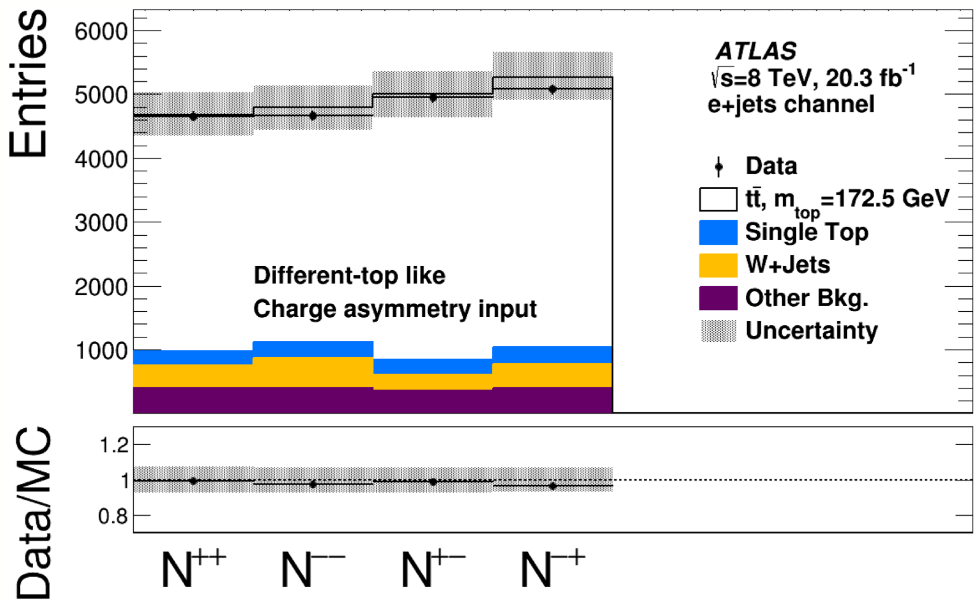
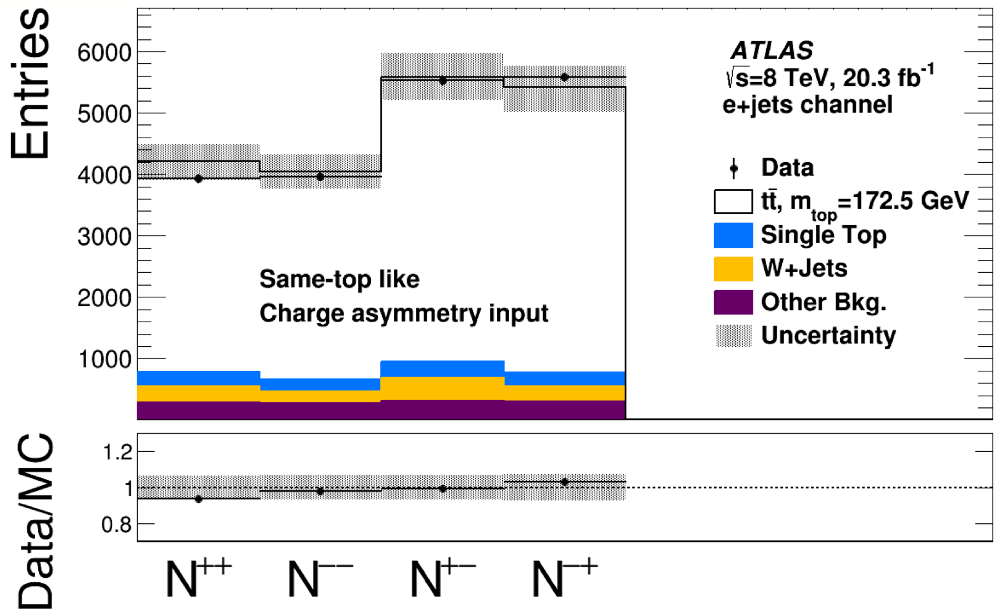
$$A^{os} = \frac{\left(\frac{N^{+-}}{N^{+}} - \frac{N^{-+}}{N^{-}}\right)}{\left(\frac{N^{+-}}{N^{+}} + \frac{N^{-+}}{N^{-}}\right)}$$

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





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

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

X (X_L): final state with no leptons and contain both light and charm quarks (only light quarks)

PRL 110 232002 (2013)

Connecting charge asymmetries with CP ones

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$$A_{\rm mix}^{b\ell} = \frac{\Gamma\left(b\to\bar{b}\to\ell^+X\right)-\Gamma\left(\bar{b}\to b\to\ell^-X\right)}{\Gamma\left(b\to\bar{b}\to\ell^+X\right)+\Gamma\left(\bar{b}\to b\to\ell^-X\right)},$$

$$A_{\rm mix}^{bc} = \frac{\Gamma\left(b\to\bar{b}\to\bar{c}X\right)-\Gamma\left(\bar{b}\to b\to cX\right)}{\Gamma\left(b\to\bar{b}\to\bar{c}X\right)+\Gamma\left(\bar{b}\to b\to cX\right)},$$

Probes CPV in mixing

$$A_{\rm dir}^{b\ell} = \frac{\Gamma\left(b\to\ell^-X\right)-\Gamma\left(\bar{b}\to\ell^+X\right)}{\Gamma\left(b\to\ell^-X\right)+\Gamma\left(\bar{b}\to\ell^+X\right)},$$

$$A_{\rm dir}^{c\ell} = \frac{\Gamma\left(\bar{c}\to\ell^-X_L\right)-\Gamma\left(c\to\ell^+X_L\right)}{\Gamma\left(\bar{c}\to\ell^-X_L\right)+\Gamma\left(c\to\ell^+X_L\right)},$$

$$A_{\rm dir}^{bc} = \frac{\Gamma\left(b\to cX_L\right)-\Gamma\left(\bar{b}\to\bar{c}X_L\right)}{\Gamma\left(b\to cX_L\right)+\Gamma\left(\bar{b}\to\bar{c}X_L\right)},$$

Probes direct CPV

OS — $\tilde{r}$

Process	$\tilde{r}$
$t\to\ell^+\nu b\to\ell^+\ell^-X$	89%
$t\to\ell^+\nu\left(b\to\bar{b}\to\bar{c}\right)\to\ell^+\ell^-X$	6%
$t\to\ell^+\nu\left(b\to c\bar{c}\right)\to\ell^+\ell^-X$	5%

SS — r

Process	r
$t\to\ell^+\nu\left(b\to\bar{b}\right)\to\ell^+\ell^+X$	20%
$t\to\ell^+\nu\left(b\to c\right)\to\ell^+\ell^+X$	72%
$t\to\ell^+\nu\left(b\to\bar{b}\to c\bar{c}\right)\to\ell^+\ell^+X$	8%

$$A^{\rm SS} = r_b A_{\rm mix}^{b\ell} + r_c\left(A_{\rm dir}^{bc} - A_{\rm dir}^{c\ell}\right) + r_{c\bar{c}}\left(A_{\rm mix}^{bc} - A_{\rm dir}^{c\ell}\right)$$

$$A^{\rm OS} = \tilde{r}_b A_{\rm dir}^{b\ell} + \tilde{r}_c\left(A_{\rm mix}^{bc} + A_{\rm dir}^{c\ell}\right) + \tilde{r}_{c\bar{c}} A_{\rm dir}^{c\ell}$$

5 parameters, 2 (correlated) equations...

CP Asymmetries

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- Measure one CP asymmetry assuming all other 4 are 0
- Also, if no direct CPV, then

$$A_{\text{mix}}^{b\ell} = A_{\text{mix}}^{bc} \equiv A_{\text{mix}}^{b} = f_d a_{\text{SL}}^{d} + f_s a_{\text{SL}}^{s} = f_d \frac{1-|q_{B_d}/p_{B_d}|^4}{1+|q_{B_d}/p_{B_d}|^4} + f_s \frac{1-|q_{B_s}/p_{B_s}|^4}{1+|q_{B_s}/p_{B_s}|^4}$$

$$a_{\text{sl}}^{q} = \frac{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) - \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) + \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)} \qquad |B_L\rangle = p\,|B^0\rangle + q\,|\bar{B}^0\rangle\,, \qquad |B_H\rangle = p\,|B^0\rangle - q\,|\bar{B}^0\rangle\,,$$

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

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

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

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

CP Asymmetries

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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]

More competitive result for $A^{cl}{}_{dir}$!

First **direct** measurements of $A^{bl}{}_{dir}$, $A^{cl}{}_{dir}$, $A^{bc}{}_{dir}$!

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

D0 and LHCb

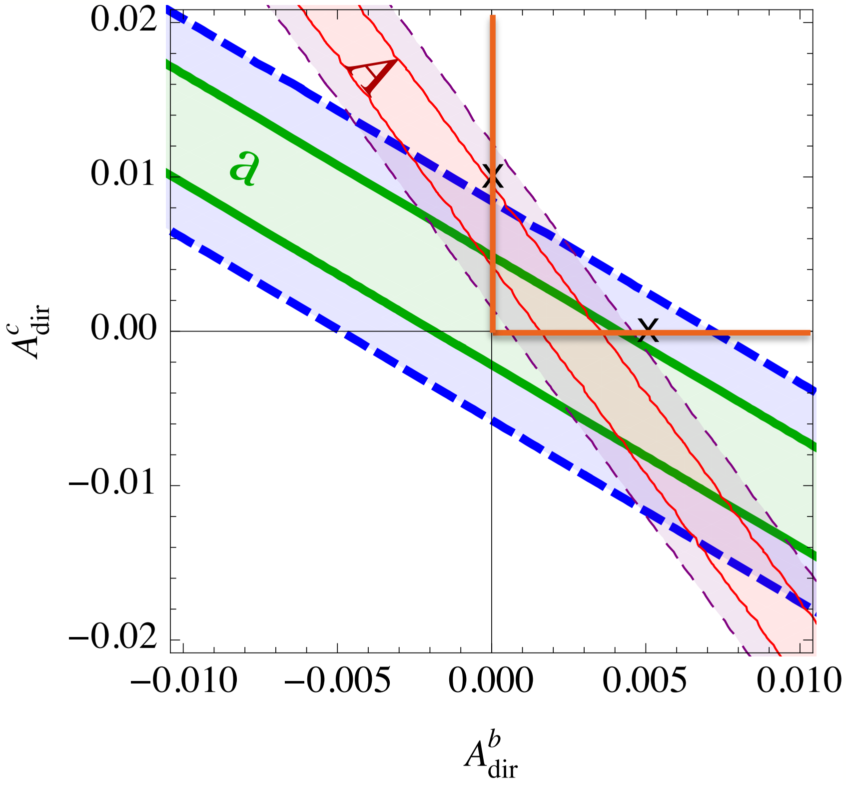
D0: Inclusive single-muon and dimuon CP Asymmetries

PRD 89, (2014) 012002

$$a = \frac{(N^+ - N^-)}{(N^+ + N^-)} \qquad A = \frac{(N^{++} - N^{--})}{(N^{++} + N^{--})}$$

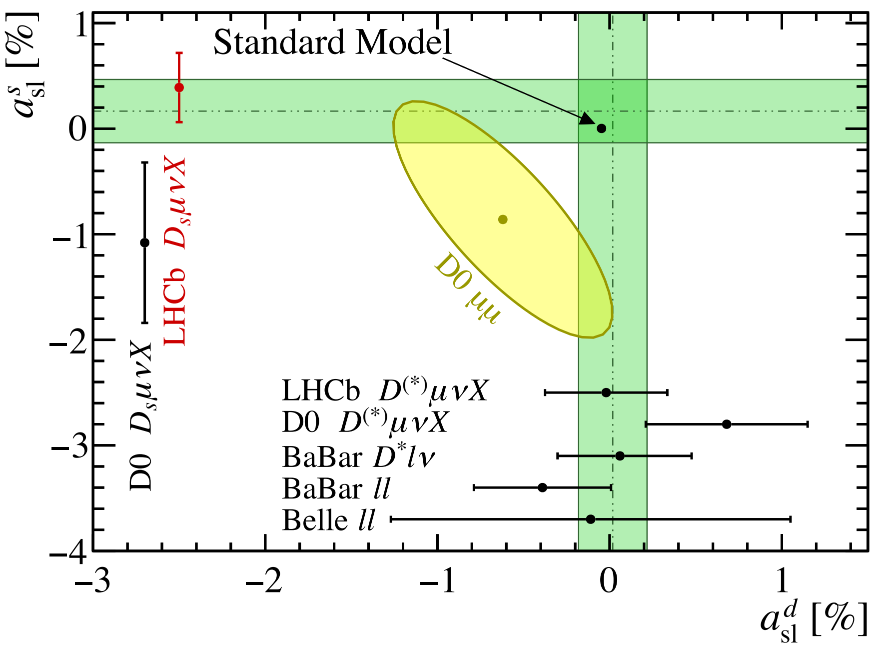
A^{bl}_{dir}~(0.3±0.1)%

A^{cl}_{dir}~(0.9±0.3)%



PRD 87, 074036 (2013)

A^b_{mix}=(-0.496±0.168)%



$$A^b_{mix} = f_d a^d_{\rm SL} + f_s a^s_{\rm SL}$$

LHCb: PRL 117 (2016) 061803

Conclusions and prospects

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- First top mass analysis using novel method not relying on jet measurements, first and most precise published single analysis from ATLAS at 13 TeV
- Fragmentation simulation quite challenging
- Soft Muon Tagging can be used for other novel measurements:
  - CP violation in b-quark sector using $t\bar{t}$ events:
    - first measurement at 8 TeV: stat limited, but makes first direct CP violation measurements
    - Updating for 13 TeV:
      - syst. limited
      - will be able to confirm/refute D0 measurement for direct CP violation
      - Enough data to do time dependent measurement of asymmetry (vs muon production vertex)

Backups

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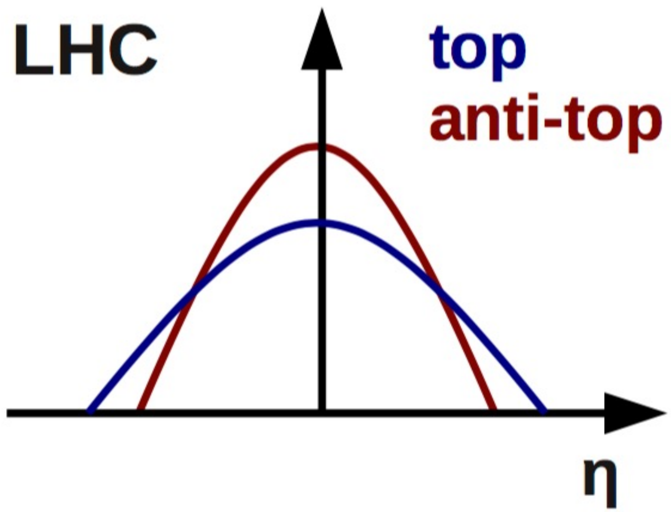
Potential asymmetric worries…

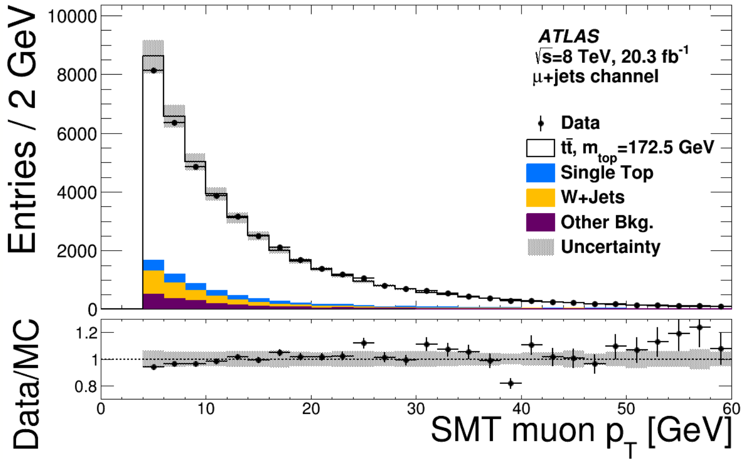
- Theoretical asymmetries:
  - tt has a charge asymmetry coming from NLO interference effects at 1% level
    - Leads to different initial number of b vs b
- Experimental asymmetries:
  - MV1 tagging asymmetries: does it tag in the same rate b vs b?
  - Lepton reconstruction and identification: do we get more l+ vs l-?
  - SMT efficiency and fake rate:
    - Eg K+p vs K-p cross section is different!
- Solutions:
  - SMT efficiency and fake rates are calibrated as a function of charge in the data
  - For all the others: we have a ratio of ratio!

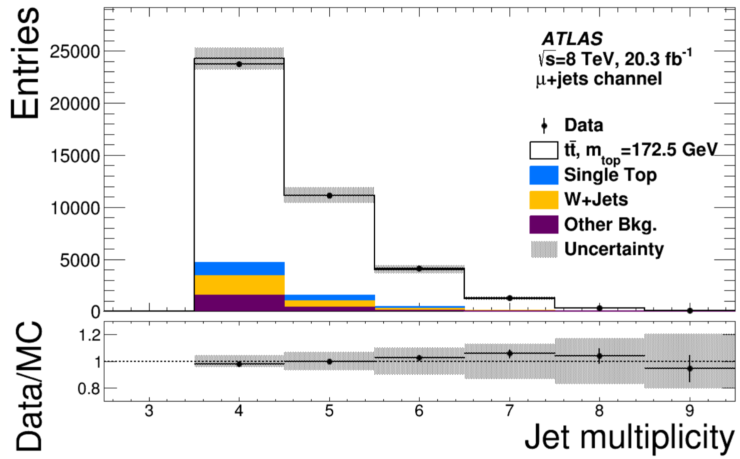


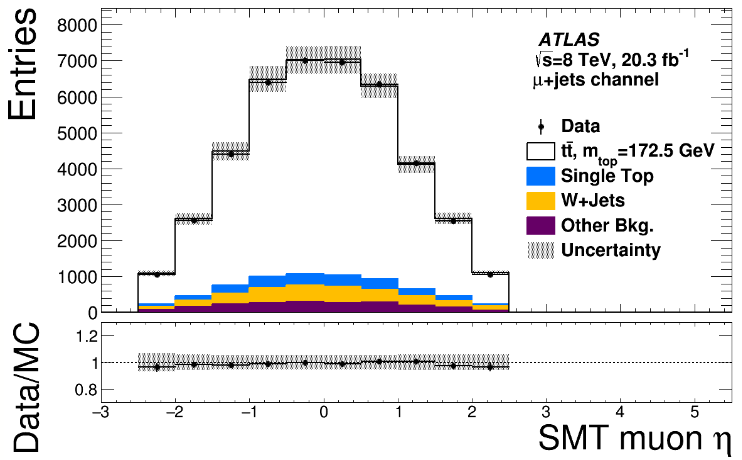
$$A^{os} = \frac{\left(\frac{N^{+-}}{N^{+}} - \frac{N^{-+}}{N^{-}}\right)}{\left(\frac{N^{+-}}{N^{+}} + \frac{N^{-+}}{N^{-}}\right)} \qquad A^{ss} = \frac{\left(\frac{N^{++}}{N^{+}} - \frac{N^{--}}{N^{-}}\right)}{\left(\frac{N^{++}}{N^{+}} + \frac{N^{--}}{N^{-}}\right)}$$

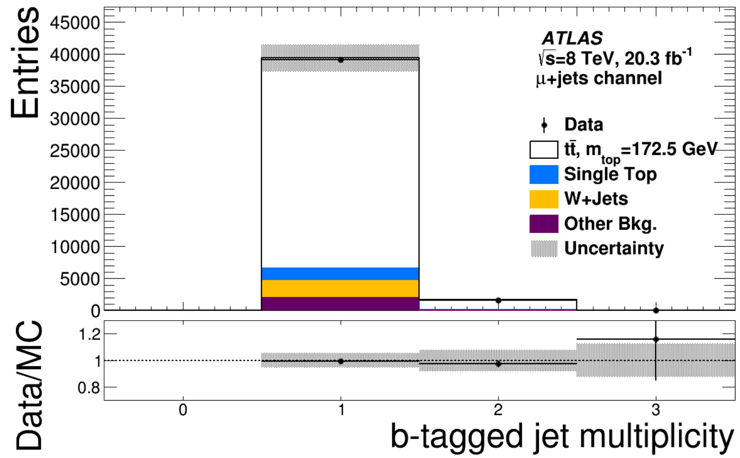
$$N^{+} \equiv N^{++} + N^{+-} \qquad N^{-} \equiv N^{-+} + N^{--}$$

Control plots

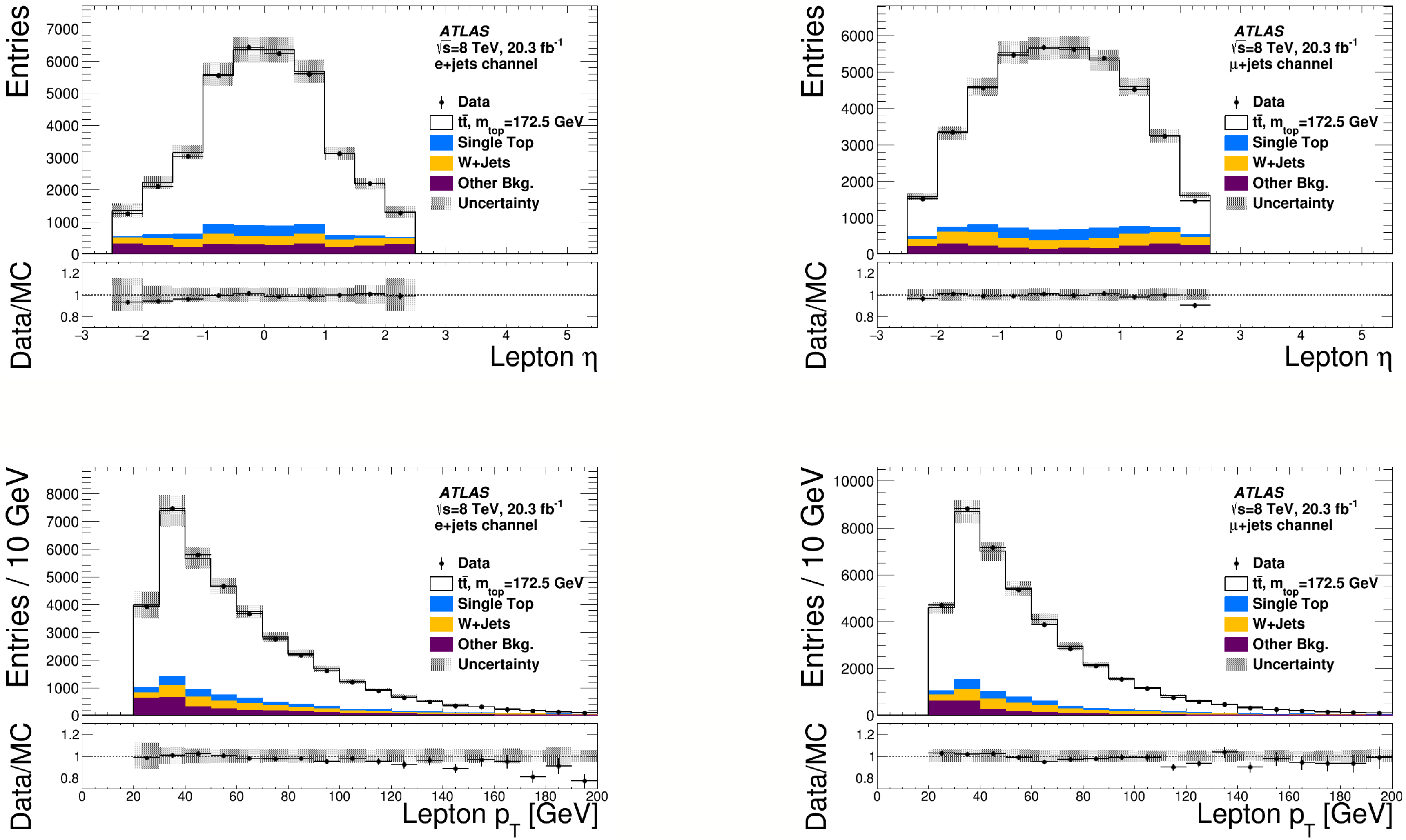








Control plots



W+jets

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- 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

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

CP asymmetries

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	$A^{b}_{\mathrm{mix}}\,(10^{-2})$		$A^{b\ell}_{\mathrm{dir}}\,(10^{-2})$		$A^{c\ell}_{\mathrm{dir}}\,(10^{-2})$		$A^{bc}_{\mathrm{dir}}\,(10^{-2})$	
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

Detector effects

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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 $\boldsymbol{\mu}^-$

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

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

Production rates

- Production fractions of B^0, B^+, B_s^0 and b-baryons in MC differs from PDG
- Latest production fractions and uncertainties driven by CDF & LHCb data

PDG production fractions and uncertainties

Hadron	PDG (%)	$B^{\pm,0}\uparrow$	$B^{\pm,0}\downarrow$	$B_s^0\uparrow$	$B_s^0\downarrow$	b-baryon $\uparrow$	b-baryon $\downarrow$
B^0	0.402 $\pm$ 0.007	0.409	0.395	0.401	0.403	0.395	0.409
B^+	0.402 $\pm$ 0.007	0.409	0.395	0.401	0.403	0.395	0.409
B_s^0	0.104 $\pm$ 0.006	0.103	0.105	0.110	0.098	0.102	0.106
b-baryon	0.092 $\pm$ 0.015	0.078	0.106	0.088	0.096	0.107	0.077

PowhegPythia (110404) production fractions and SF

Hadron	MC	Nominal SF	$B^{\pm,0}\uparrow$ SF	$B^{\pm,0}\downarrow$ SF	$B_s^0\uparrow$ SF	$B_s^0\downarrow$ SF	b-baryon $\uparrow$ SF	b-baryon $\downarrow$ SF
B^0	0.422	0.954	0.971	0.936	0.951	0.956	0.938	0.969
B^+	0.422	0.953	0.971	0.936	0.951	0.956	0.938	0.969
B_s^0	0.082	1.273	1.265	1.280	1.346	1.200	1.252	1.294
b-baryon	0.075	1.231	1.046	1.416	1.175	1.287	1.431	1.031

branching ratio

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- The $b \to \mu$ branching ratios in MC differ from those in MC
- Need to correct for this otherwise we will get the SMT rate wrong
- Even if we used EvtGen, we still need this procedure for the uncertainties it's just that the nominal SF would be 1
- Uncertainties taken from Particle Data Group (PDG) and largely driven by LEP data

Hadron	PDG	PYTHIA		HERWIG	
		MC Observed	SF	MC Observed	SF
$b \to \mu$	$0.1095^{+0.0029}_{-0.0025}$	0.102	$1.078^{+0.029}_{-0.025}$	0.086	$1.266^{+0.034}_{-0.029}$
$b \to \tau \to \mu$	0.004 ± 0.0004	0.007	0.573 ± 0.055	0.007	0.523 ± 0.055
$b \to c \to \mu$	0.0802 ± 0.0019	0.078	1.023 ± 0.024	0.023	3.417 ± 0.081
$b \to c\bar{c} \to \mu$	$0.016^{+0.004}_{-0.005}$	0.029	$0.546^{+0.136}_{-0.170}$	0.008	$1.971^{+0.493}_{-0.616}$
$c \to \mu$	0.082 ± 0.005	0.100	0.823 ± 0.050	0.083	0.982 ± 0.060

Single-top

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- Single top production is charge asymmetric
- Vary relative cross section of t and $\bar{t}$ according to theoretical uncertainties
- Do this for t-channel and s-channel
- Wt is of course charge symmetric

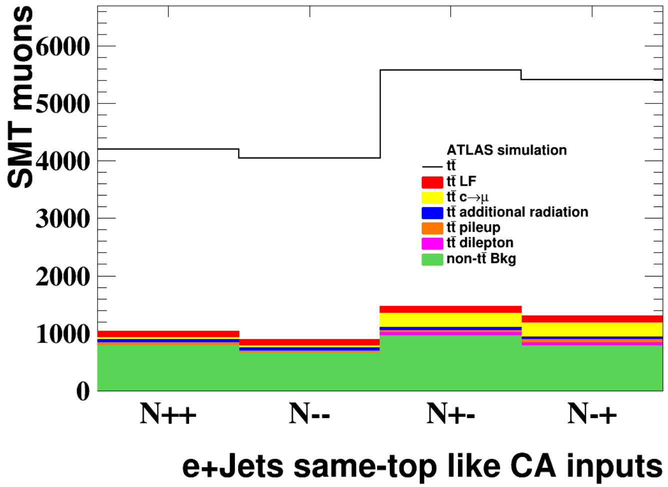
t-channel production asymmetry SF

Systematic	Total Cross Section	Top XS	AntiTop XS	Top %	AntiTop %	Top SF	AntiTop SF
Nominal	87.76	57.66	30.10	65.7	34.3	1.0	1.0
Top ↑	91.20	61.10	30.10	67.0	33.0	1.020	0.962
Top ↓	85.85	55.75	30.10	64.9	35.1	0.988	1.022
AntiTop ↑	91.20	57.66	33.54	63.2	36.8	0.962	1.072
AntiTop ↓	85.85	57.66	28.19	67.2	32.8	1.022	0.957

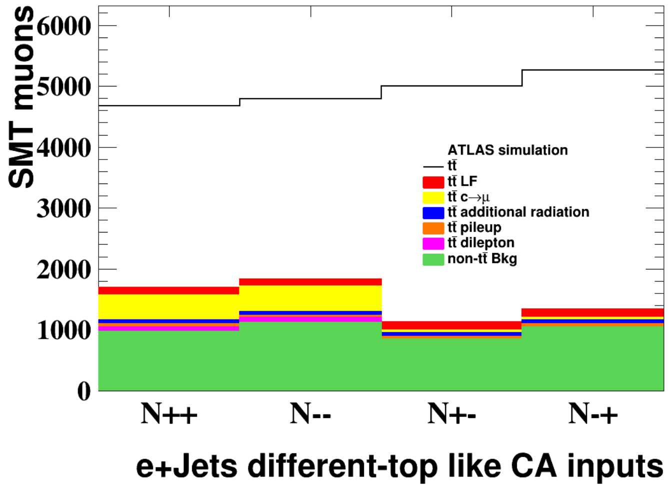
s-channel production asymmetry SF

Systematic	Total Cross Section	Top XS	AntiTop XS	Top %	AntiTop %	Top SF	AntiTop SF
Nominal	5.61	3.64	1.97	64.8	35.2	1.0	1.0
Top ↑	5.83	3.86	1.97	66.1	33.9	1.021	0.962
Top ↓	5.39	3.42	1.97	63.4	36.6	0.978	1.041
AntiTop ↑	5.83	3.64	2.19	62.4	37.6	0.962	1.070
AntiTop ↓	5.39	3.64	1.75	67.4	32.6	1.041	0.925

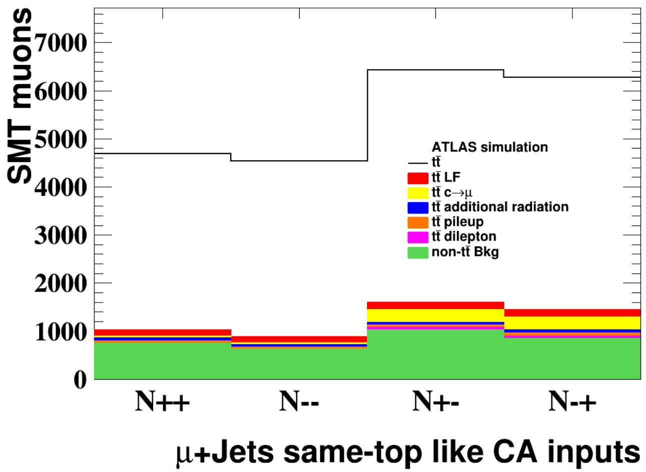
Tt background



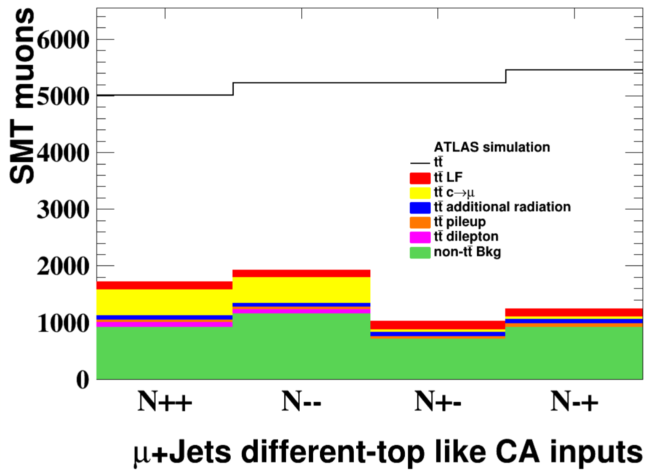
(a) Same-top SMT Muons.



(b) Different-top SMT Muons.



(a) Same-top SMT Muons.



(b) Different-top SMT Muons.