CMS

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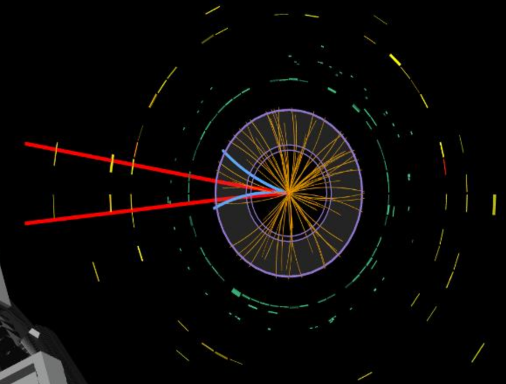


ATLAS and CMS present and future contributions to flavour physics

Umberto De Sanctis
(INFN & Università Roma Tor Vergata)
on behalf of the ATLAS and CMS Collaborations

ATLAS EXPERIMENT

Run: 333181
Event: 1942573294
2017-08-16 07:27:32 CEST

LNF, 10/11/2022

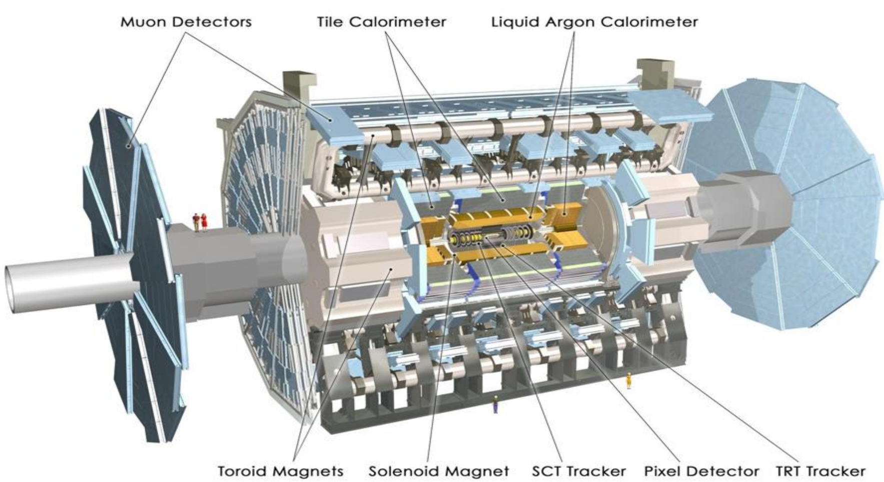
Outline

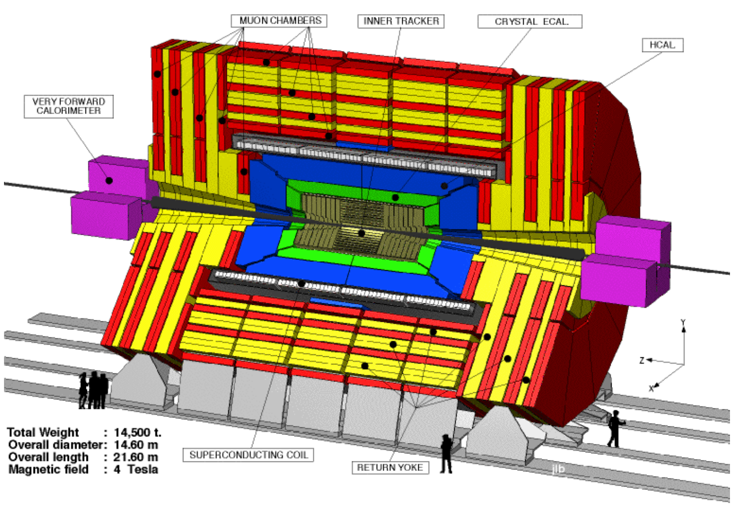
- Both ATLAS and CMS have a wide program in flavour physics
  - Rare Decays (see L. Guzzi's talk yesterday)
  - Spectroscopy (including "exotic states" searches)
  - B-hadrons properties (masses, lifetimes, etc..)
  - Bc physics
  - Quarkonia (single and associated production)

- Focus of this talk is on measurements related to the CKM matrix
  - Measurement of Φs angle in Bs → J/ΨΦ decay
  - Measurement of CKM matrix elements involving the top quark in single top and $t\bar{t}$ events

The ATLAS and CMS Experiments

- ATLAS (**A T**oroidal **L**HC **A**pparatu**S**) and CMS (**C**ompact **M**uon **S**olenoid) are two "general purpose" detectors
  - Optimised for the high-P_T physics (W, Z, top, Higgs, SUSY etc)
  - Can be adapted with great success to measurements in flavour physics in few specific areas
  - Similar overall design but different sub-detectors and technologies employed
    - The main difference for flavour physics is the solenoid magnetic field strength (2T for ATLAS, 3,8T for CMS) → Better resolution for "low-P_T" objects (tracks and muons mainly)





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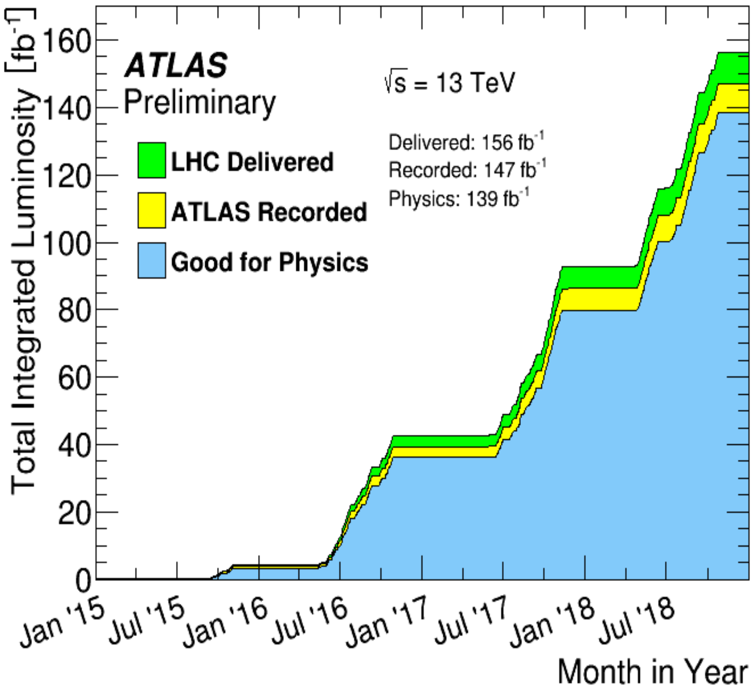
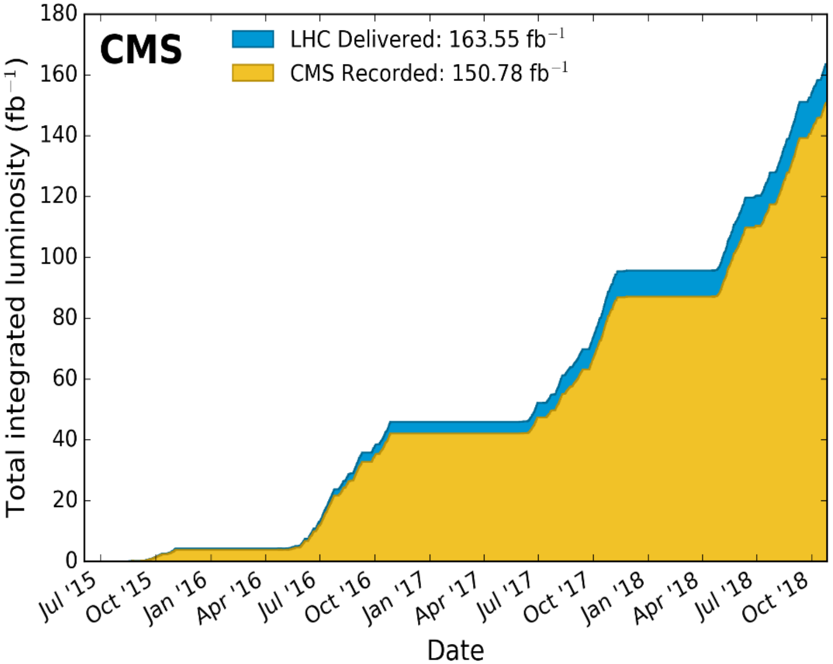
Integrated luminosities

- ATLAS/CMS collected data from 2010 to 2018 at a centre-of-mass energy $\sqrt{s}$ = 7, 8 and 13 TeV
  - Run 1 (2010-2013) → ~ 5 fb^{-1} @ 7 TeV + ~ 20 fb^{-1} @ 8 TeV
  - Run 2 (2015-2018) → ~ 140 fb^{-1} @ 13 TeV
  - "Good for physics"

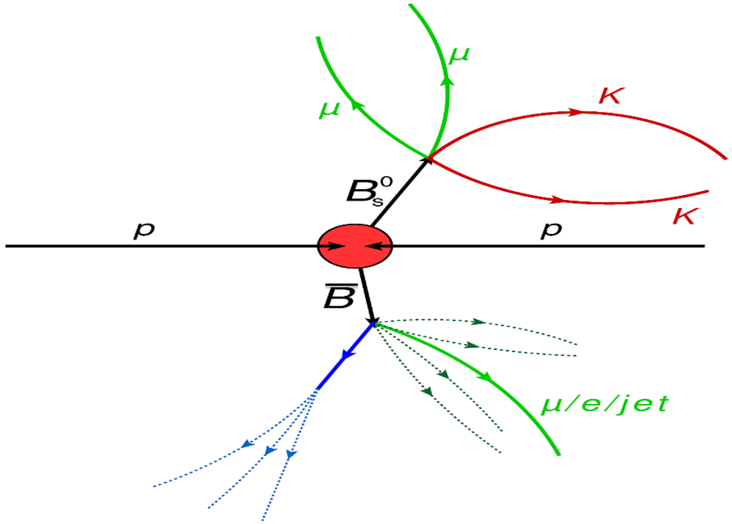




- About 30 fb^{-1} already collected by the two experiments in Run 3…

Typical B-physics signatures

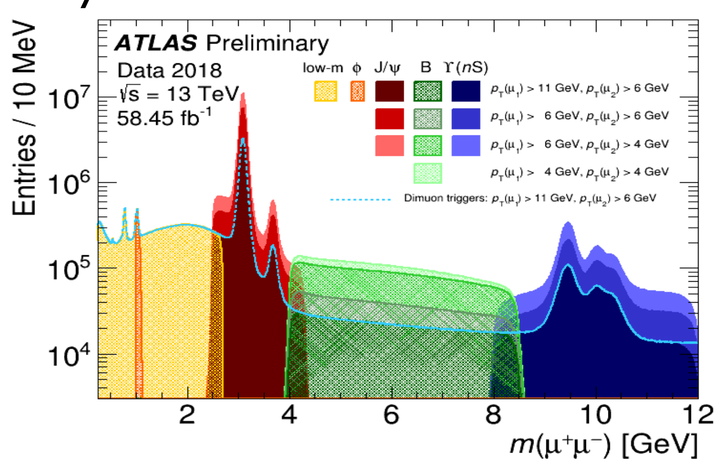
- B-physics signatures at hadron colliders are mainly made by:
  - Low transverse momentum (P_T) muons → Tracking system + muon system
  - Tracks in the Inner detector → Tracking system
  - Rarely photons/electrons → Electromagnetic calorimeter
- Trigger these events is complicated due to low thresholds in muon P_T → Incompatible with bandwidth constraints at high lumin.
- In addition both ATLAS and CMS do not have specific detectors for particle identification → Kaons, pions, protons are all "just" tracks



Triggering events at ATLAS and CMS

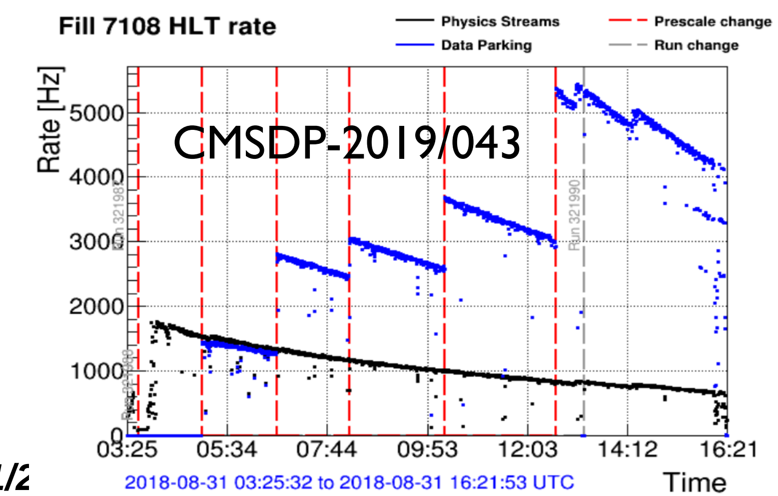
ATLAS

- Regional readout → Define a Region of Interest (RoI) around the L1 muons
  - Lower rate but less efficient for low-P_T
  - Primary trigger in most of Run1
- Run2 : Topological trigger! Use info on PT, η and φ of the muon ROIs to build topological di-μ quantities (inv.mass, ΔR):
  - Gain up to a **factor of 3** in di-muon background rejection!
  - Baseline for 2017-2018 data (with MU4_MU6 and 2MU6 thresholds
- Possibility to have more bandwidth at the end of the fills
- Delayed reconstruction at Tier-0

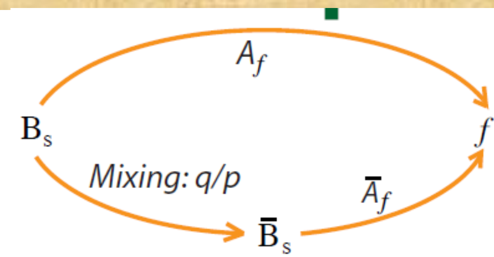


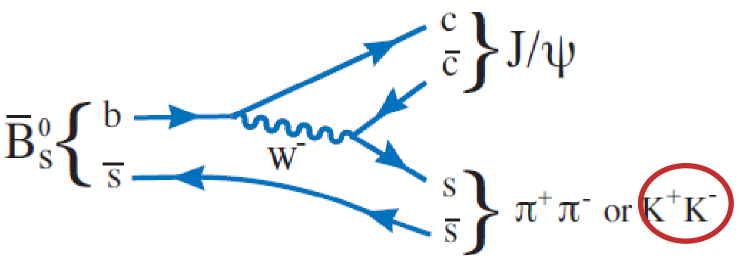
CMS

- 2 level trigger as ATLAS
- L1 hardware; HLT software
- From 2018 a "data-parking" strategy has been applied→ Save more data on disk for a subsequent reconstruction
  - Requiring at L1+HLT a displaced μ
- 10 billions b-hadrons pairs saved on disk
  - Procedure validated by the reconstruction of a subset of them using the B →D*μν →



- Interference between mixing and decay



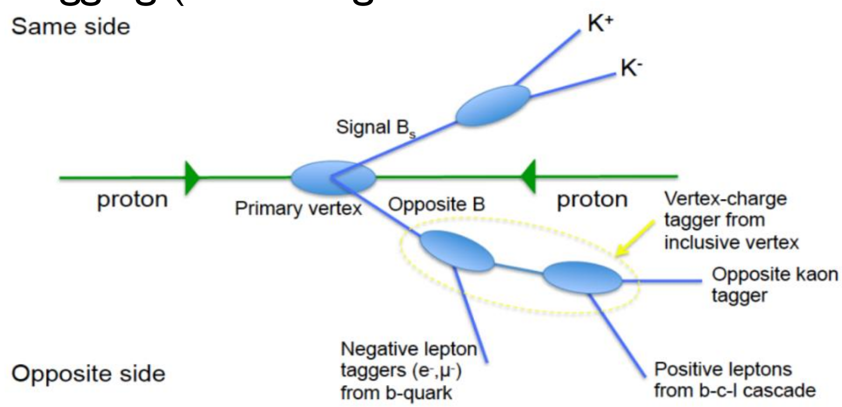


$$\phi_s \simeq 2\arg[-(V_{ts}V^*_{tb})/(V_{cs}V^*_{cb})]$$

Small CPV phase in SM → Ideal place for New-Physics!

- $\phi_s = -0.03696^{+0.00072}_{-0.00082}$ rad by CKMFitter group PhysRevD.91.073007
- $\phi_s = -0.03700 \pm 0.00104$ rad according to UTfit Collaboration arXiv: hep-ph/0606167 [hep-ph].

- Essential ingredients at hadron colliders:
  - Good time (spatial) resolution to measure the oscillation accurately
  - Flavour tagging (i.e. distinguish the "Bs side" of the event)



ATLAS: μ, e and jet charge used as taggers
CMS: only μ (adding other taggers for full Run 2 analysis)

Bs → J/ΨΦ measurement

- Flavour tagging calibration done using **$B^{\pm}$ → J/Ψ$K^{\pm}$**
- Information on $B^{\pm}$ flavour extracted from the kaon charge
- Flavour tagging probability affects significantly the precision on the extraction of the parameters
- Total tagging power: 1.65% (ATLAS); ~10% (CMS)
- Angular analysis with 10 amplitude functions is done (J/ΨΦ is a superposition of CP eigenstates!!)

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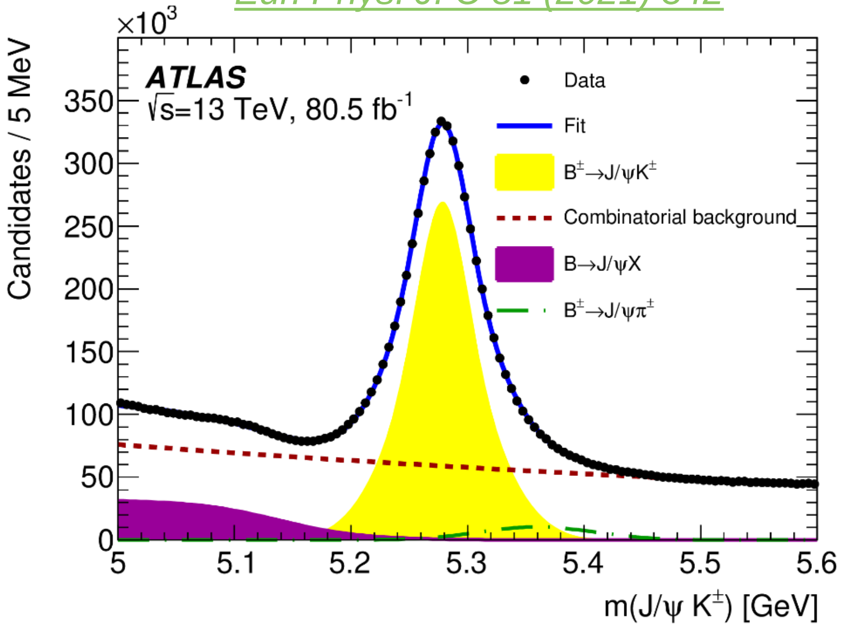

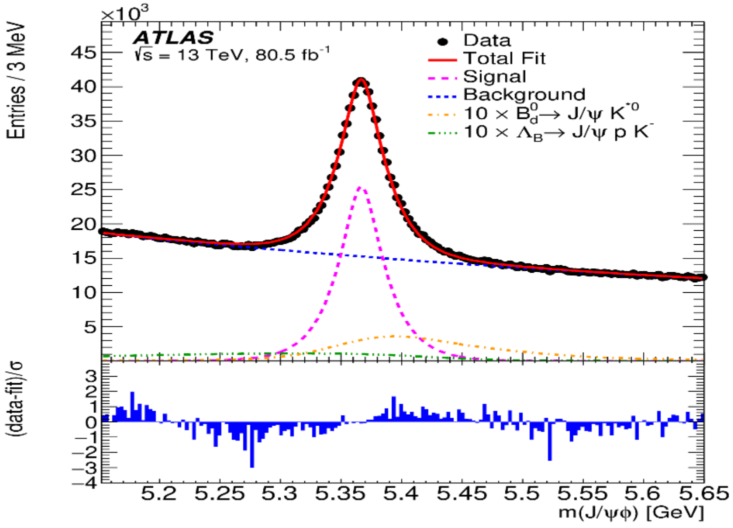

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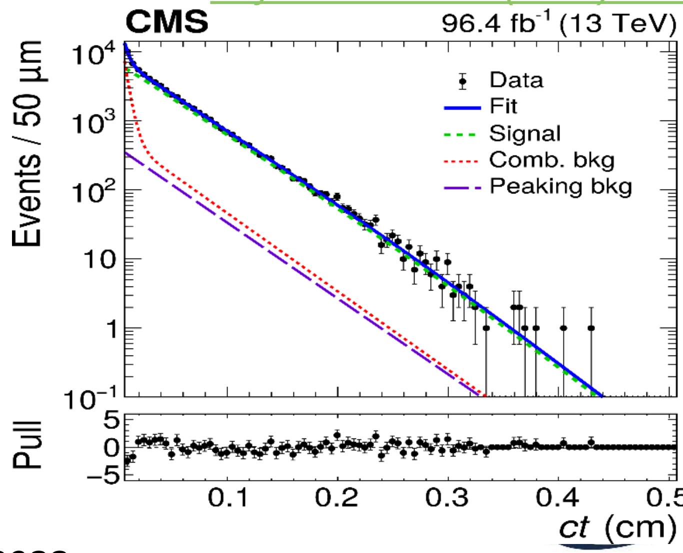
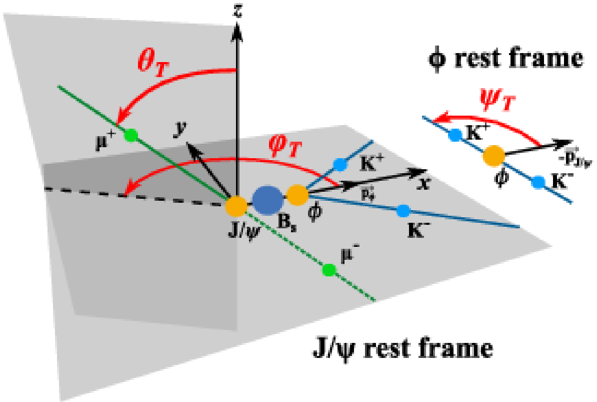
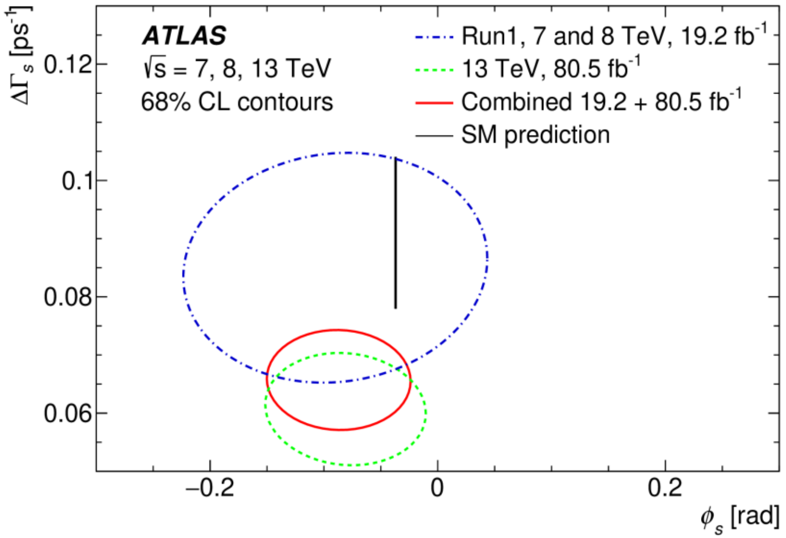
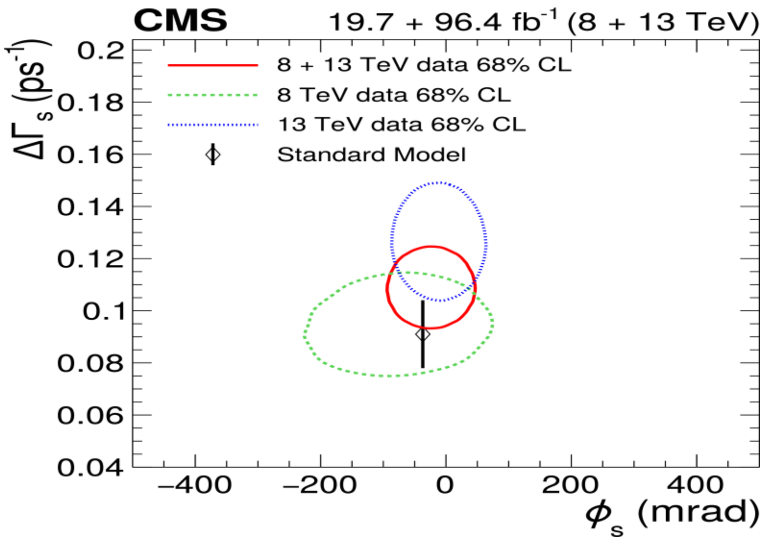


Bs → J/ΨΦ measurement

- Extract the 10 parameters from a global simultaneous fit to the various distributions (mass, angles, etc)
- CMS applies a cut on Lxy to J/Ψ triggers → better S/B but MC efficiency param. more difficult to treat
- CMS uses DNNs to improve tagging power
- Focus on three parameters:
  - Γ_s (decay width)
  - $\Delta\Gamma_s$ (difference of the widths)
  - Φ_s (the CPV weak-phase)







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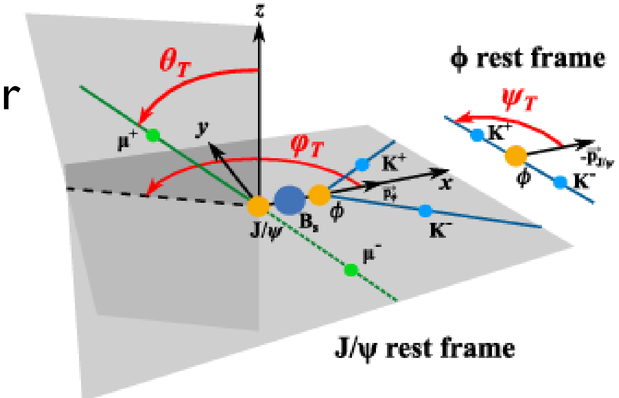

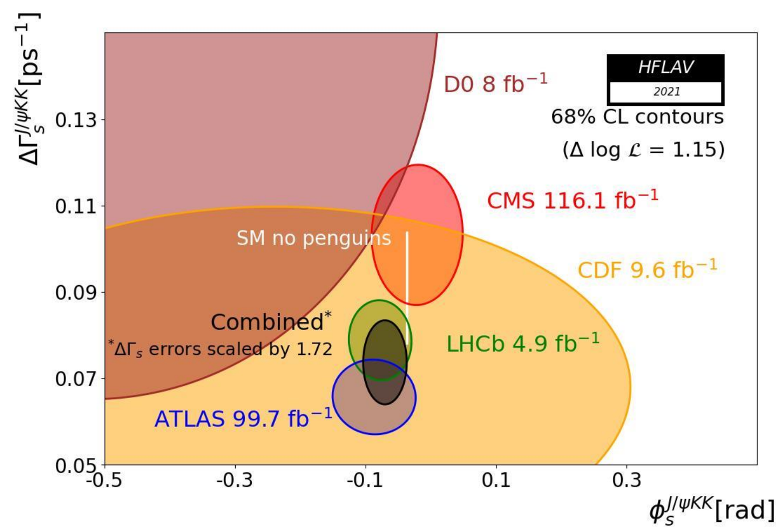

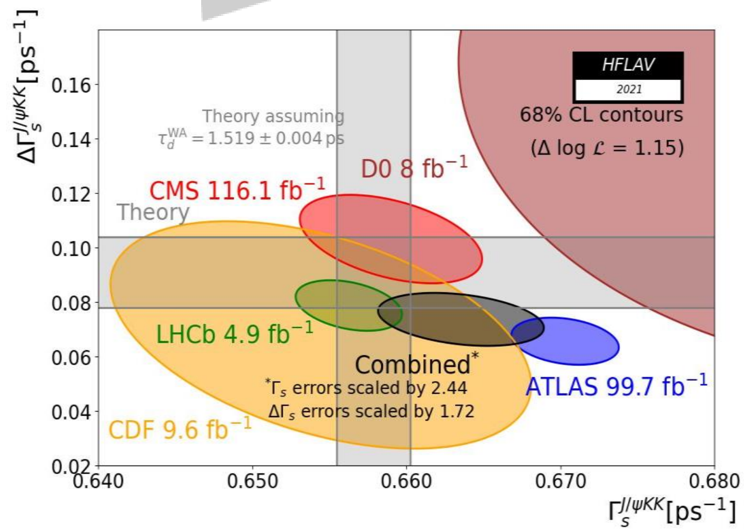

- Γ_s «tension» between ATLAS and CMS/LHCb
- Supporting measurements ongoing to clarify this discrepancy

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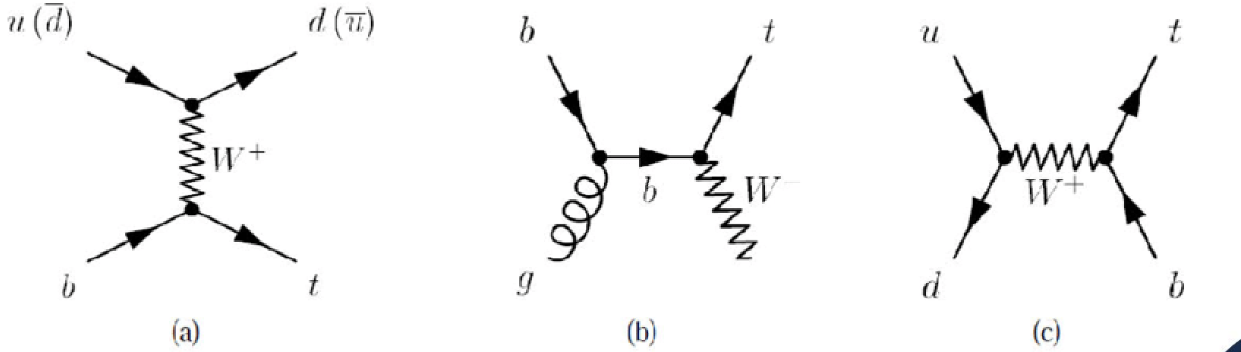
CKM elements from top events

- LHC is a real top factory: why don't we use these events to measure CKM elements involving the top quark?
- The process that best suits for these measurements is the single top events production
- 3 channels (ordered by production x-sec)
  - t-channel
  - Wt channel
  - s-channel
- Leptonic decay of the top quark: t → Wb → blν
  - Only electrons and muons are used
- High-PT single lepton triggers used
  - Thresholds around 20-27 GeV (depends on inst. lumin.)



Single top & $|V_{tb}|$

- $|V_{tb}|$ can be extracted from the cross-section measurements of the three processes (t-, Wt- and s- channels)
  - Direct cross-section measurement to be compared with theoretical predictions (which assumes $|V_{tb}| = 1$)
  - Sensitive also to modifications of the LH coupling tWb in the SM $\mathbf{f_{LV}}$

$$|f_{\rm LV} V_{tb}| = \sqrt{\frac{\sigma_{\rm meas.}}{\sigma_{\rm theo.\ (V_{tb}=1)}}}.$$

  - $\mathbf{f_{LV}}$ assumed to be real
- Some assumption is needed:
  - $|V_{tb}| >> |V_{ts}| + |V_{td}|$
    - Well motivated by global CKM fits of B-physics measurements (but assumes CKM matrix unitarity)
  - tWb coupling is LH
- The determination of $| f_{LV} V_{tb} |$ is independent from assumptions of:
  - CKM unitarity
  - Number of quark generations

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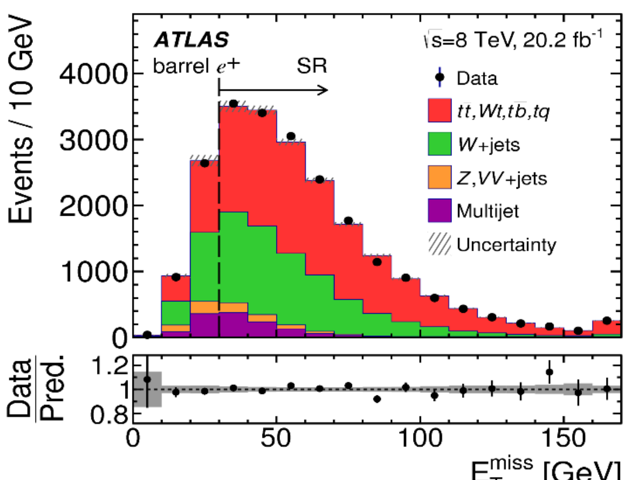
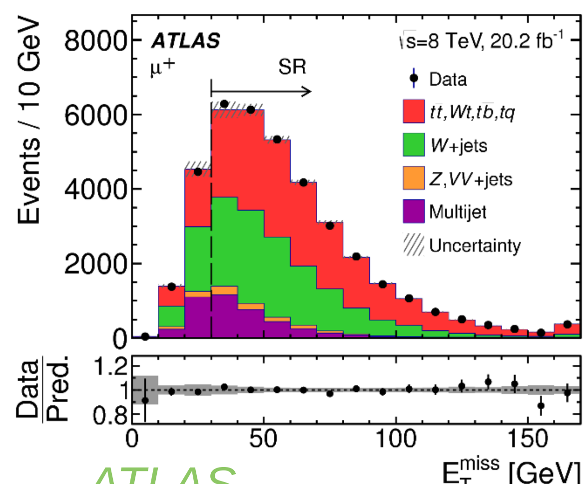
Measuring single-top x-sec in t-channel

- Both experiments use a similar strategy. Events with
  - One isolated prompt lepton (e/μ) with PT > 25-30 GeV
  - At least one high-PT jet
  - Missing transverse energy > 30 GeV
  - One jet must be b-tagged
  - m(lb) < 160 GeV (the kinematic limit for t →Wb decay)
- Main backgrounds:
  - $t\bar{t}$, W + jets, multijet events
  - Estimated in specific control regions and extrapolated through validation regions
  - Mixed approach: MC simulation (with normalisation fitted in data) and data-driven techniques.





ATLAS

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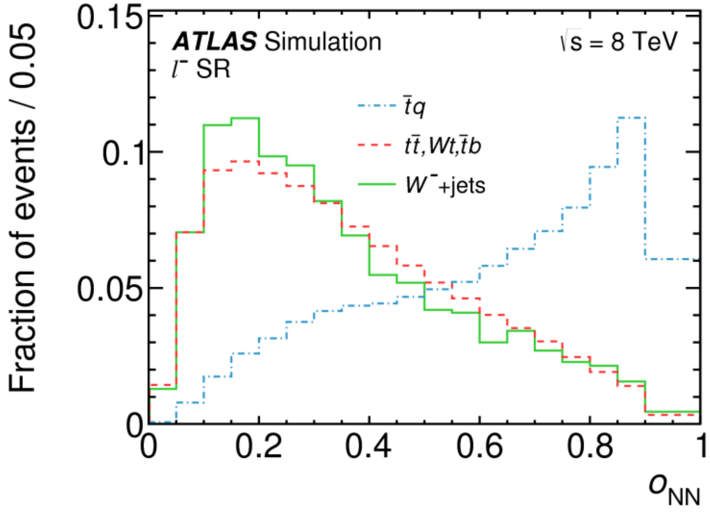
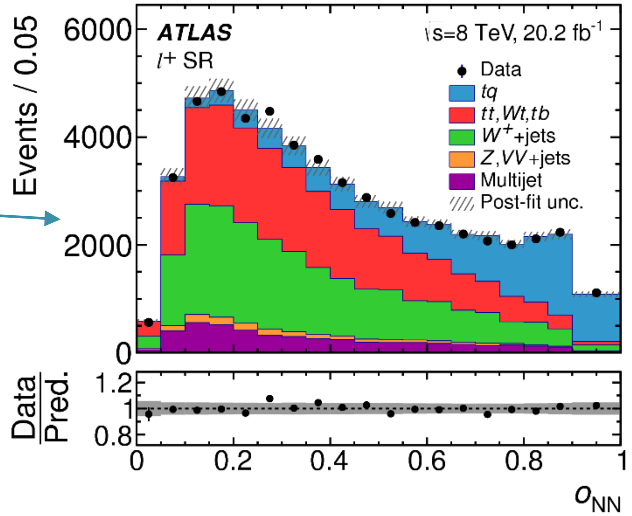
Measuring single-top x-sec in t-channel

- Neural Networks are used to further reduce the $t\bar{t}$ and W + jets backgrounds
  - based on kinematic variables describing production and decay



- Two SR depending on the charge of the lepton
- Cross-section extracted through a binned ML fit to the NN output
- Main systematics:
  - Lepton reconstruction, JES and NLO corrections
- Overall precision ~ 5%



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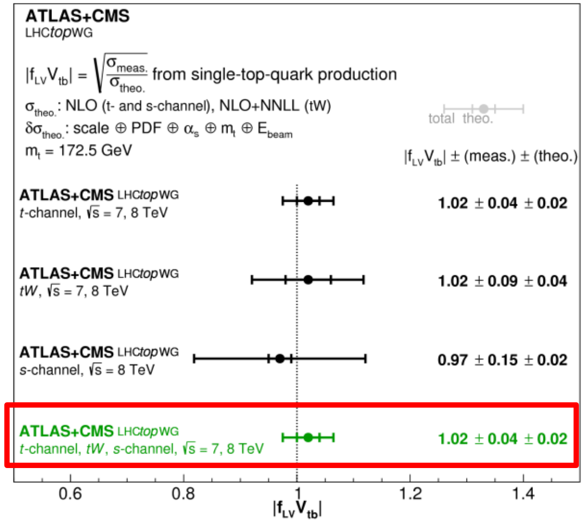
Extracting $|V_{tb}|$

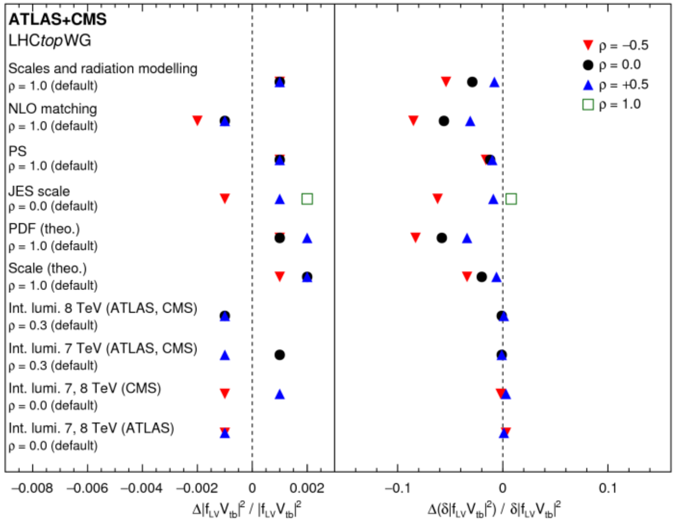
Combination

- Combination of the x-sec measured by ATLAS and CMS at 7 and 8 TeV in the three channels

		ATLAS		CMS	
$\sqrt{s}$	Process	σ [pb]	Lumi. [fb^{-1}]	σ [pb]	Lumi. [fb^{-1}]
7 TeV	t-channel	68 ± 8	4.59	67.2 ± 6.1	1.17–1.56
	tW	16.8 ± 5.7	2.05	16^{+5}_{-4}	4.9
	s-channel	—	—	7.1 ± 8.1	5.1
8 TeV	t-channel	$89.6^{+7.1}_{-6.3}$	20.2	83.6 ± 7.8	19.7
	tW	$23.0^{+3.6}_{-3.9}$	20.3	23.4 ± 5.4	12.2
	s-channel	$4.8^{+1.8}_{-1.5}$	20.3	13.4 ± 7.3	19.7

- Methodology:
  - Best Linear Unbiased Estimator (BLUE) (i.e. minimisation of a global χ^2 including correlations among measurements)





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To be compared with indirect measurement from CKM fit

$|V_{tb}| = 0.999105 \pm 0.000032$

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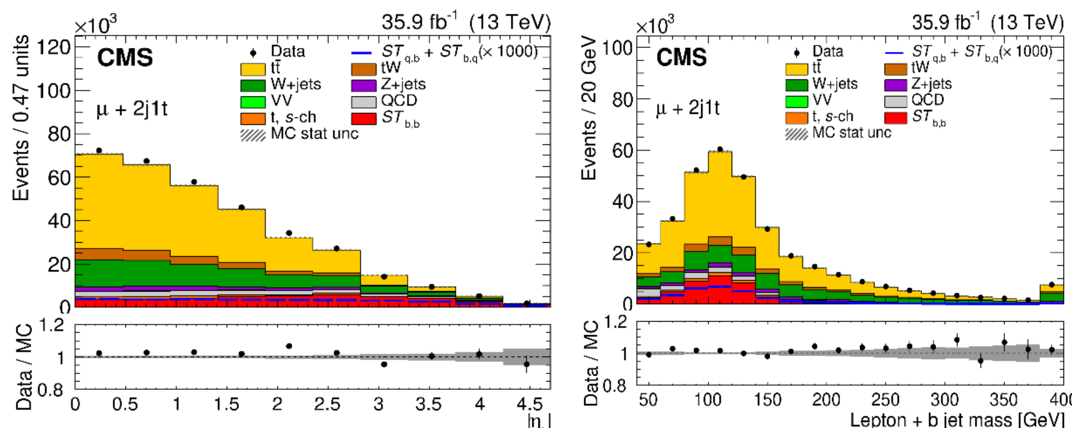
$|V_{tb}|$ & $|V_{ts}|+|V_{td}|$

- First measurement at 13 TeV by CMS in t-channel CMS
- Aim to extract from single top events $|V_{tb}|$, $|V_{ts}|$, $|V_{td}|$ simultaneously
- Idea: look at all top decays and categorise them into the 3 possible decays: t→Wb, t→Ws, t→Wd to measure the overall BR(t → Wq) and the single BRs
  - Differences arise from:
    - Jet flavour
    - Jet composition
    - Kinematic of the event depending on the quark involved in production
- Different categories based on these properties to disentangle the following contributions in production and decay

Production	Decay	Cross section × branching fraction (pb)
tWb	tWb	217.0 ± 8.4
tWb	(tWs + tWd)	0.41 ± 0.05
tWd	tWb	0.102 ± 0.015
tWs	tWb	0.92 ± 0.11

- 3 BDTs are used to discriminate between categories



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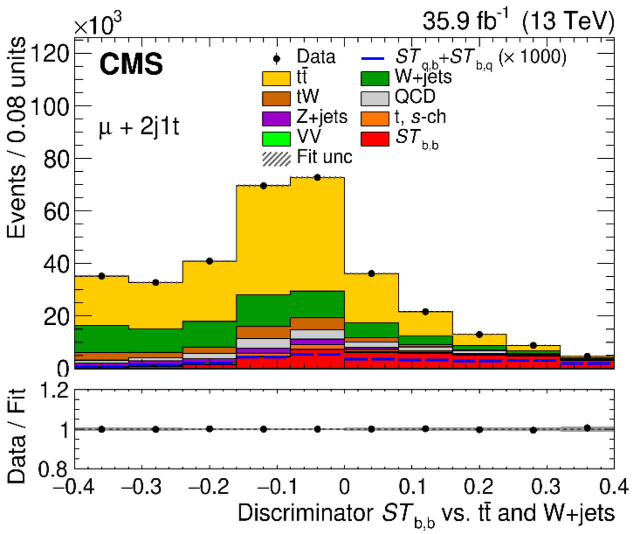
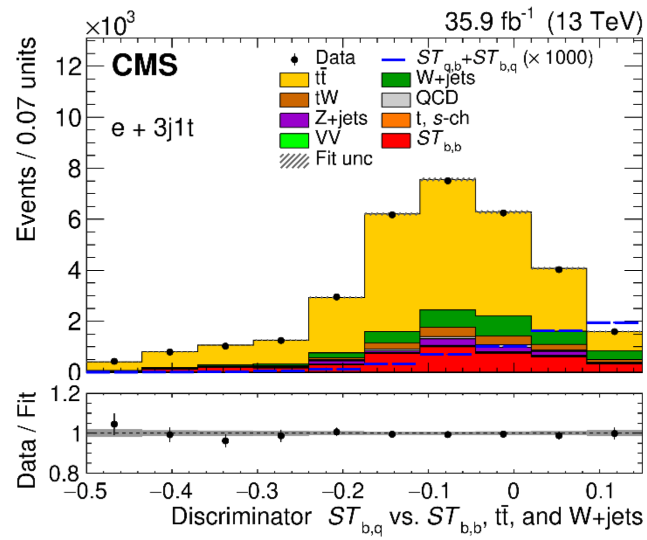
$|V_{tb}|$ & $|V_{ts}|+|V_{td}|$

- The 3 CKM elements are extracted from a simultaneous ML fit to M_T (W) first (to fix the QCD normalis.) and then to the discriminator variable distribution for the various event categories





- From the observed x-sec one can extract 2 signal strenght parameters:

$$\mu_b = \frac{\sigma^{obs}_{t\text{-ch,b}} \mathcal{B}(t \to Wb)^{obs}}{\sigma_{t\text{-ch,b}} \mathcal{B}(t \to Wb)}$$

$$\mu_{sd} = \frac{\sigma^{obs}_{t\text{-ch,b}} \mathcal{B}(t \to Ws,d)^{obs} + \sigma^{obs}_{t\text{-ch,s,d}} \mathcal{B}(t \to Wb)^{obs}}{\sigma_{t\text{-ch,b}} \mathcal{B}(t \to Ws,d) + \sigma_{t\text{-ch,s,d}} \mathcal{B}(t \to Wb)},$$

$$|V_{tb}| > 0.970$$
$$|V_{td}|^2 + |V_{ts}|^2 < 0.057.$$

Assuming SM and CKM unitarity

$$|V_{tb}| = 0.988 \pm 0.051$$
$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06,$$

Sensitive to BSM modifications

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Compatible with indirect determinations

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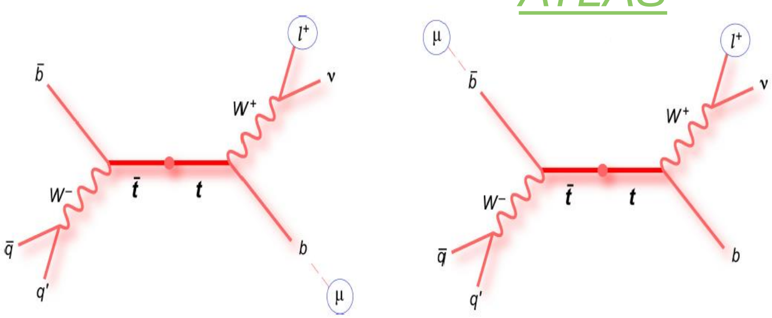
CP-violation in b-decays

- Look for **CP violation** in b-semileptonic decays @ 8 TeV
- 2 muons: one from the W, one from the b-cascade
- Count the number of same-charge/opposite-charge muons N^{++}, N^{--}, N^{+-}, N^{-+}
- Build inclusive asymmetries sensitive to CP violation both in $B^0 - \bar{B}^0$ mixing and direct b/c semileptonic decays

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

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

ATLAS



(a) Same-top SMT muon (b) Different-top SMT muon

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

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

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

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

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

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CP-violation in b-decays

- Standard semileptonic tt selection + a muon inside a jet
- Kinematic reconstruction of the event → Associate the muon to top/antitop decay

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

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

- r_i are the fractions in MC for the various decay modes
- Asymmetries unfolded at particle level

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

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

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

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

- Results consistent with the SM
  - Need more precision on A^{b}_{mix} (< 10^{-3}); First direct limit on A^{bc}_{dir}

	Data (10^{-2})		MC (10^{-2})		Existing limits (2σ) (10^{-2})		SM prediction (10^{-2})	
A^{ss}	-0.7	$\pm\,0.8$	0.05	$\pm\,0.23$	-		$< 10^{-2}$	[19]
A^{os}	0.4	$\pm\,0.5$	-0.03	$\pm\,0.13$	-		$< 10^{-2}$	[19]
A^{b}_{mix}	-2.5	$\pm\,2.8$	0.2	$\pm\,0.7$	< 0.1	[95]	$< 10^{-3}$	[96] [95]
$A^{b\ell}_{dir}$	0.5	$\pm\,0.5$	-0.03	$\pm\,0.14$	< 1.2	[94]	$< 10^{-5}$	[19] [94]
$A^{c\ell}_{dir}$	1.0	$\pm\,1.0$	-0.06	$\pm\,0.25$	< 6.0	[94]	$< 10^{-9}$	[19] [94]
A^{bc}_{dir}	-1.0	$\pm\,1.1$	0.07	$\pm\,0.29$	-		$< 10^{-7}$	[97]

Conclusions & outlooks

- ATLAS and CMS have a very focused program of measurements related to CKM matrix

- The parameters measured are:
  - The weak-phase Φ_s in Bs → J/ΨΦ decay
  - The three CKM elements involving the top quark in single top events
- All measurements are at the moment compatible with the SM
- Effort started in the LHC HF WG to combine Φ_s measurements from the 3 experiments, now on hold (waiting for full Run 2 results)

- Since several years the two experiments works together within the LHC Top WG to combine single top measurements
  - Most precise direct measurement of $|V_{tb}| = 1.02 \pm 0.04 \pm 0.02$
  - Recent measurement by CMS determining $|V_{tb}|$ and $|V_{ts}|+|V_{td}|$ directly from with no assumptions on CKM unitarity.
- Possible future measurements of CP asymmetries involving inclusive b→μ+X decays

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BACKUP

Unbinned maximum likelihood fit applied simultaneously to B_s^0 mass, decay time and decay angles.

Physics parameters

- CPV phase ϕ_s
- Decay widths: $\Delta\Gamma_s$, Γ_s
- Decay amplitudes: $|A_0(0)|^2$, $|A_\parallel(0)|^2$, $\delta_\parallel$, $\delta_\perp$
- S-wave: $|A_S(0)|^2$, δ_S
- Δm_s fixed to PDG

Observables

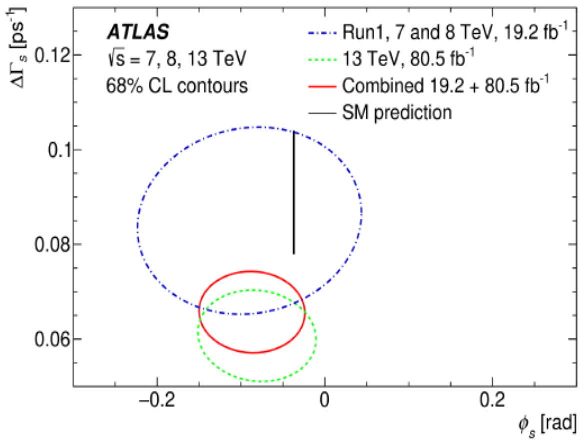
- Basic observables : m_i, t_i, Ω_i
- Conditional observables per-candidate:
  - resolutions: σ_{m_i}, σ_{t_i}
  - tagging probability and method: $P(B|Q)$

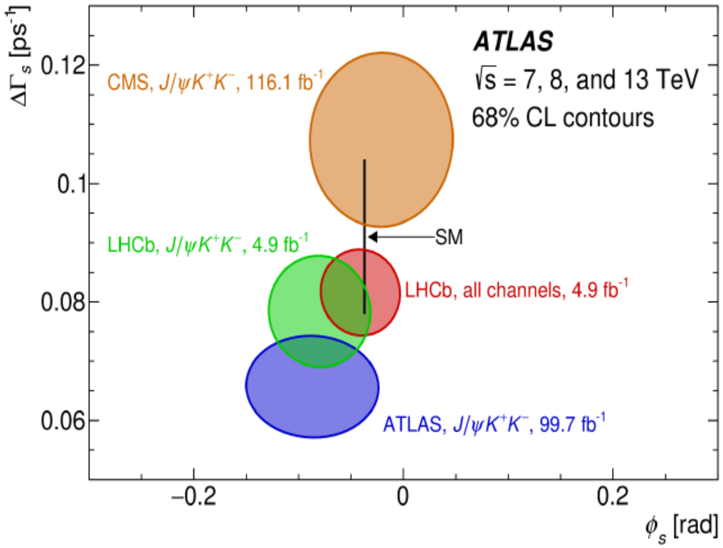
Opposite side Tagging

Tag method	Efficiency [%]	Effective Dilution [%]	Tagging Power [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	5.54 ± 0.01	20.4 ± 0.1	0.231 ± 0.005
Total	14.74 ± 0.02	33.4 ± 0.1	1.65 ± 0.01

ATLAS $B_s^0 \to J/\psi\phi$ Combination Run2 + 1. Comparison with CMS and LHCb

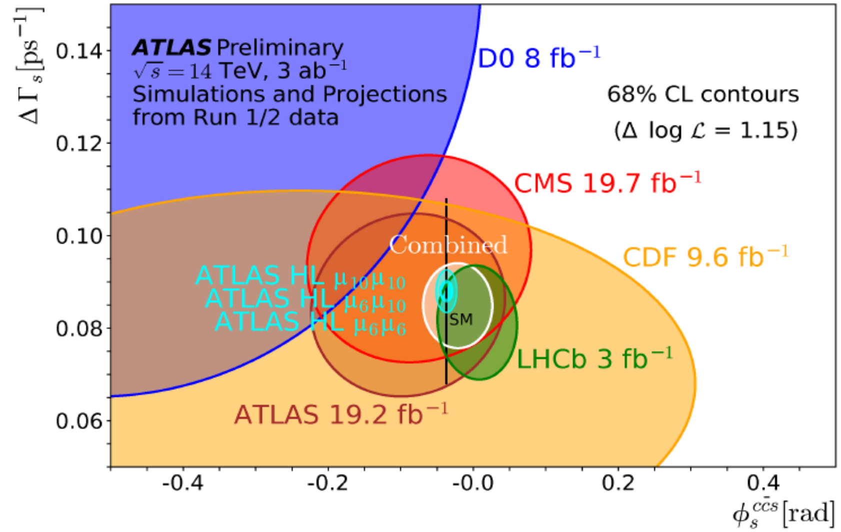
Parameter	Solution (a) Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018
$\lvert A_\parallel(0)\rvert^2$	0.2220	0.0017	0.0021
$\lvert A_0(0)\rvert^2$	0.5152	0.0012	0.0034
$\lvert A_S\rvert^2$	0.0343	0.0031	0.0045
$\delta_\perp$ [rad]	3.22	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.09
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.04

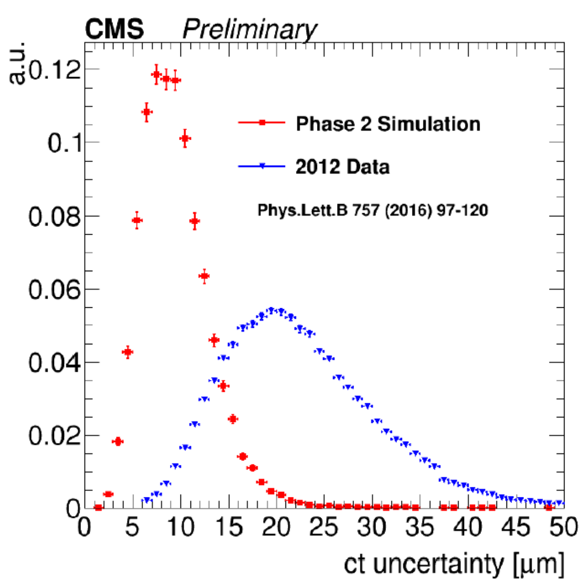


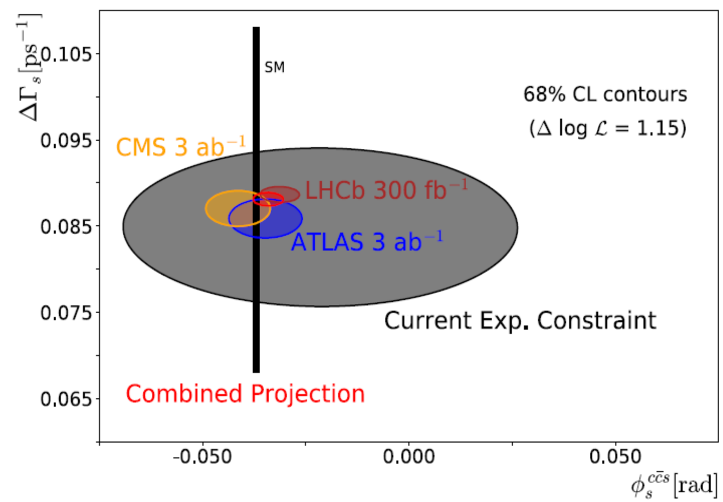


- ϕ_s result consistent with results from CMS, LHCb and SM
- Competitive single measurement of $\Delta\Gamma_s$, Γ_s and helicity parameters
- Still to add 60 fb^{-1} from 2018

- ATL-PHYS-PUB-2018-041
- Inner Detector upgrade: proper decay time resolution improved by 21% w.r.t. Run 2
- Three trigger scenarios for muon momenta thresholds
- ϕ_s precision improves (9 - 20) times w.r.t.Run1, or (4 - 9) times w.r.t. current result combining Run1 and Run2 99.7 fb^{-1}







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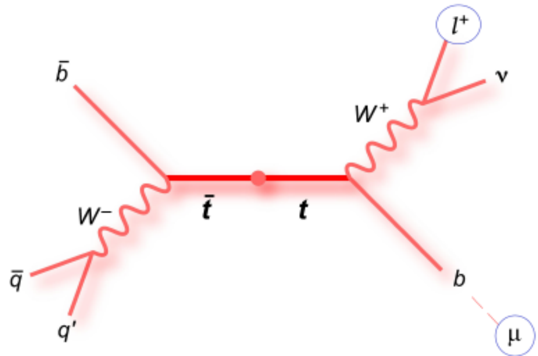
Kinematic Likelihood Fitter

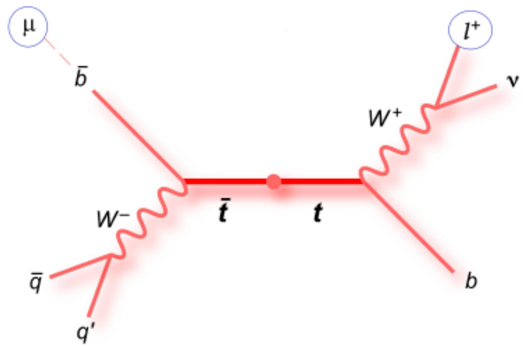
Physics Department

- KLFitter is designed to provide **kinematic fitting using a likelihood approach** (arXiv:1312.5595)
- Used to fully reconstruct the $t\bar{t}$ event topology
- Allows for determination of the initial charge of the b
  - For same-top SMT muons : $W^{\pm} \Rightarrow b^{\mp}$
  - For different-top SMT muons : $W^{\pm} \Rightarrow b^{\pm}$
- Calculates a likelihood (event probability,) for the four reconstructed jets to produce each possible permutation – maximum likelihood permutation is taken as correct jet topology
- **KLFitter performs with around 80% purity after extensive optimisation**

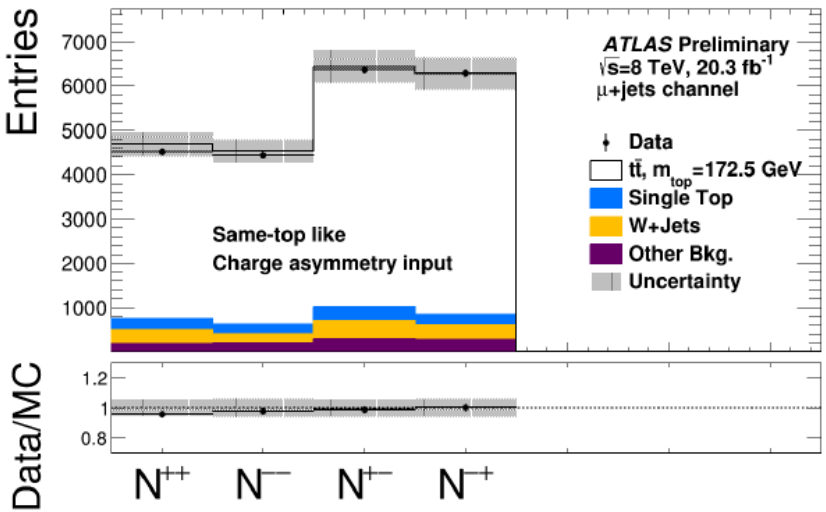
Same Top Events



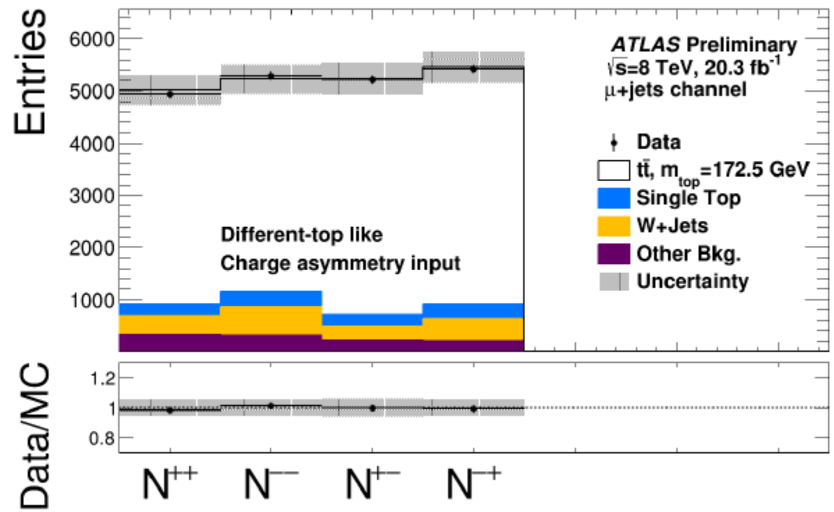
Different Top Events



Lepton charge pairs



Same-Top KLFitter Decision



Different-Top KLFitter Decision

Lepton charge pairing distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties.

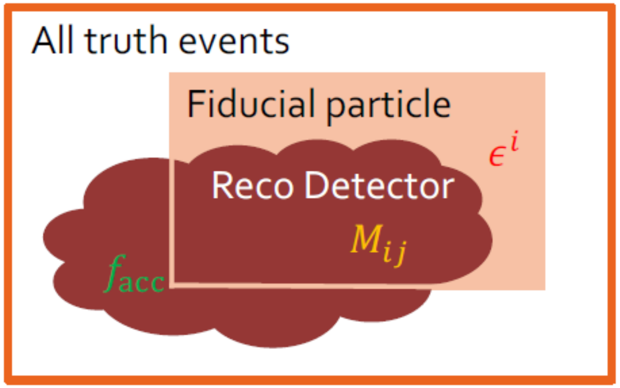
Unfolding

Physics Department

$$N_{\text{fid}}^{i} = \frac{1}{\epsilon^{i}} \cdot \sum_{j} M_{ij}^{-1} \cdot f_{\text{acc}}^{j} \left(N_{\text{data}}^{j} - N_{\text{bkg}}^{j}\right)$$

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

- f_{acc}^{i}= 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