Recent results in b-physics with the ATLAS detector

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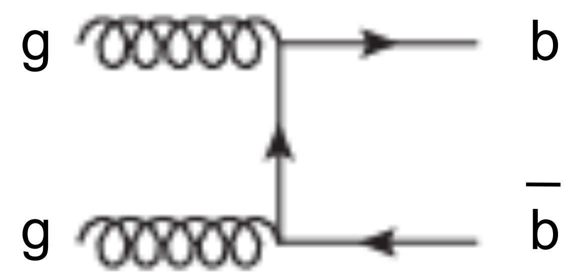
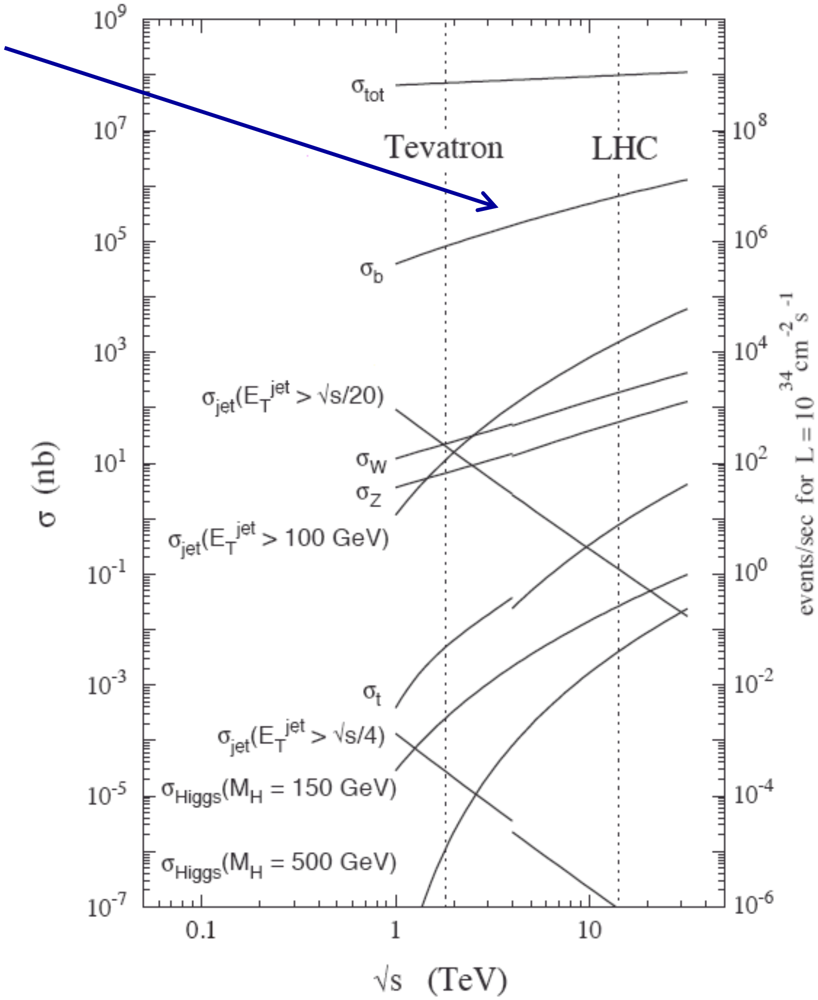
On behalf of the ATLAS Collaboration

b hadron production at the LHC

- *b hadrons (and anti-hadrons) are dominantly produced through strong interaction in pp collisions at the LHC*
  - *Example: gluon-gluon fusion*
  - *Large inclusive $b\bar{b}$ cross-section (~ 0.1 mb)*
  - *All b hadron types including Λ_b and B_s are produced*



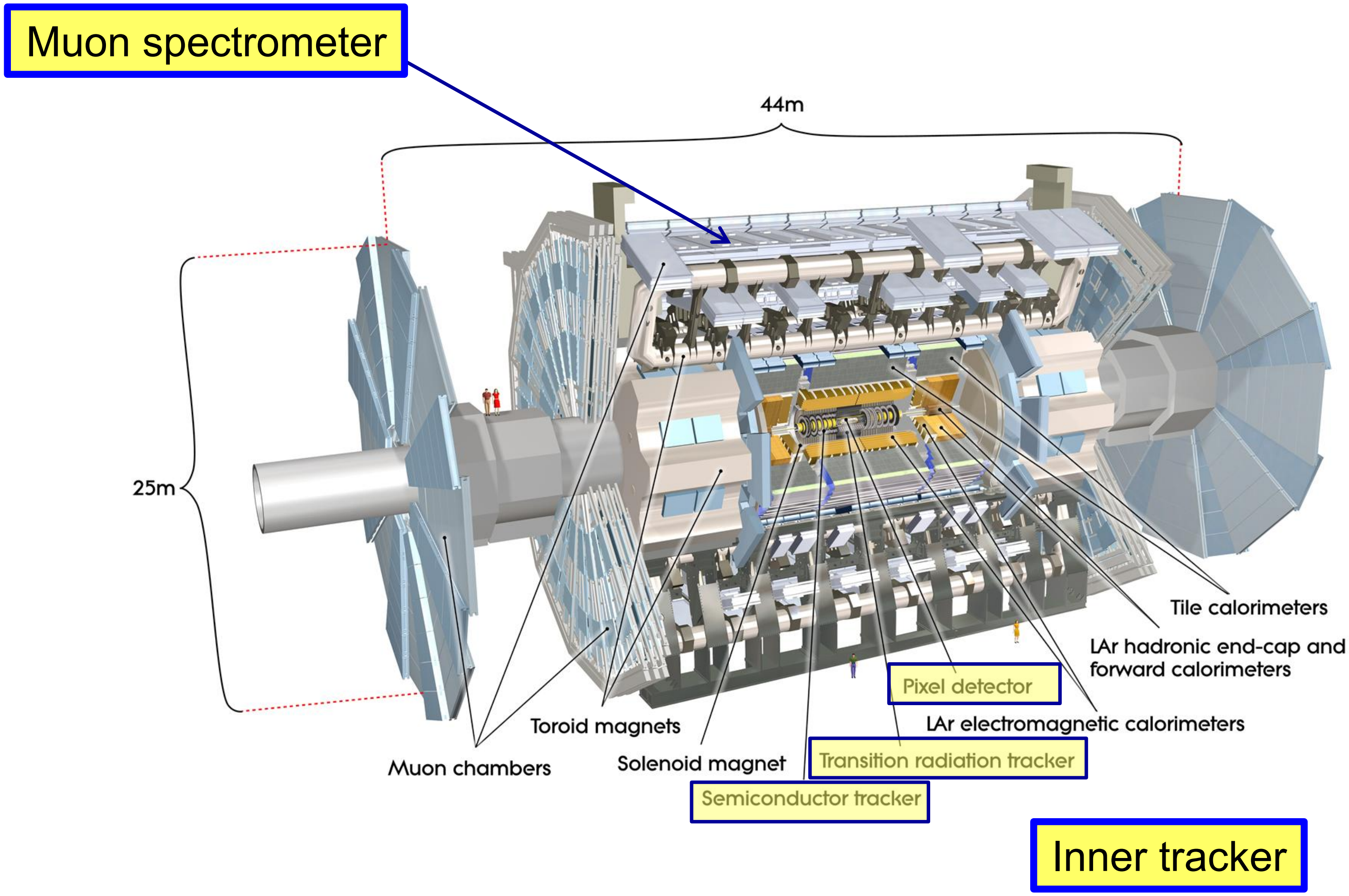


- *Unfortunately, it's hard to efficiently trigger on b hadron decays at the LHC*
  - *b decay products have relatively low p_T*
  - *Rare hadronic final states swamped by light hadron backgrounds*

- *Exceptions*
  - *Dedicated displaced vertex triggers (for example, LHCb)*
  - *Specific final states, e.g. including di-muons*

ATLAS detector and data sample

- *Results based on 20 fb^{-1} of 8 TeV CM pp collisions taken in 2012*
- *Di-muon triggers with varying thresholds depending on instantaneous luminosity*



2 new ATLAS b physics analyses

Angular analysis of $B_d \rightarrow K^* \mu \mu$

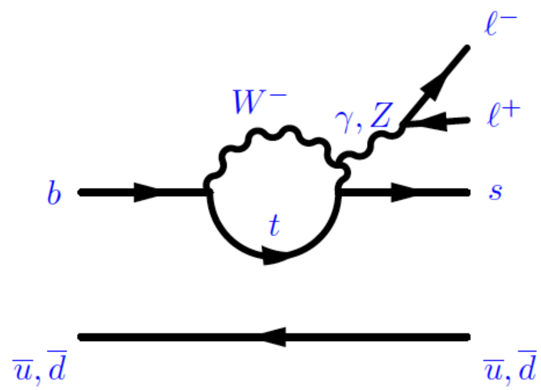
(ATLAS-CONF-2017-023)

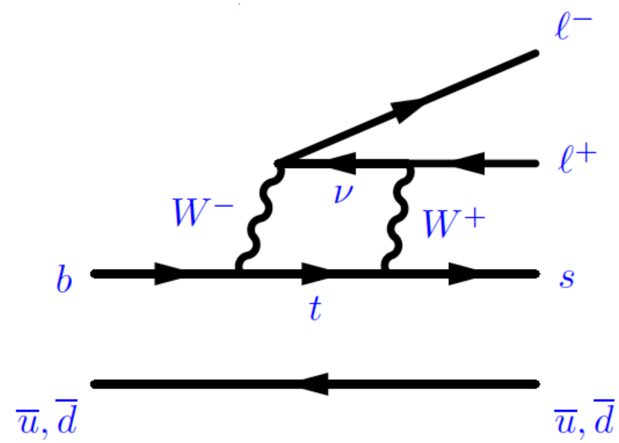
CP asymmetries in b decays using top quark pairs

(JHEP 02 (2017) 071)

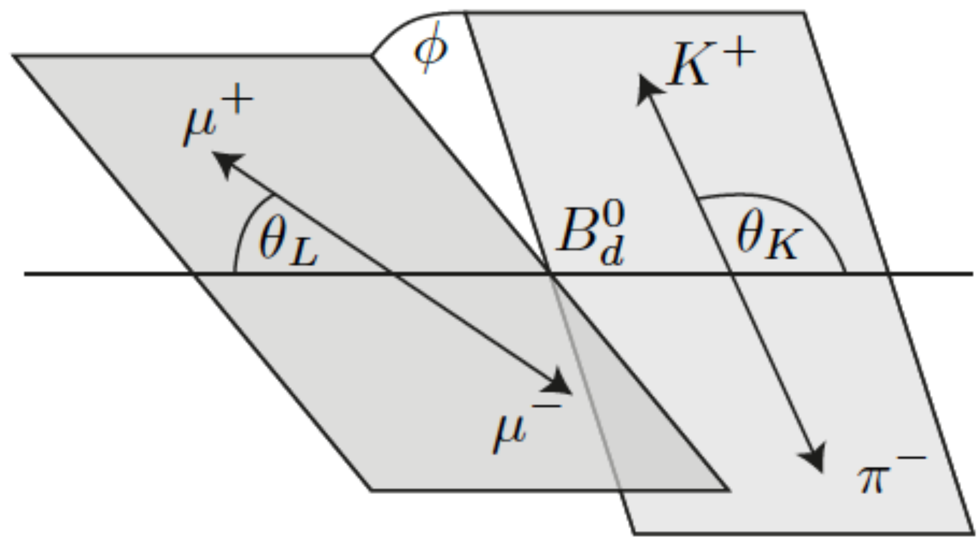
Angular analysis of $B_d \rightarrow K^* \mu\, \mu$

- *Rare flavor-changing neutral current decay*
  - *Loop/box diagram is sensitive to new physics*
  - *$BR(B_d \rightarrow K^* \mu\, \mu) = (1.02 \pm 0.09) \times 10^{-6}$*





- *Angular distributions (θ_L, θ_K, and ϕ) are analyzed in 2 GeV^2 bins of the di-muon invariant mass squared (q^2)*



- *LHCb have reported a 3.4 σ deviation from the Standard Model [JHEP 02 (2016) 104]*

Angular analysis of $B_d \to K^* \mu\mu$

- *The decay angular distribution is given by*

$$
\begin{aligned}
\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Bigg[& \frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L \\
& -F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi \\
& +S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi \\
& +S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi \\
& +S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Bigg]. \qquad (1)
\end{aligned}
$$

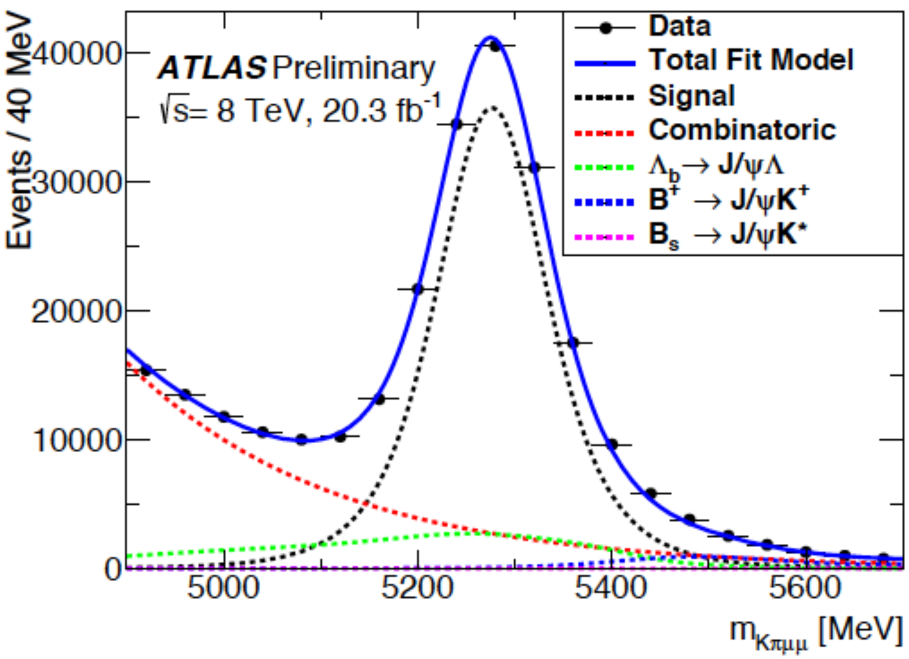
- *ATLAS use trigonometric identities to determine F_L, S_3 and S_i (i = 4,5,7,8) in 4 separate fits for each q^2 bin*
- *S_i parameters are translated into the theoretically cleaner $P^{(')}_i$ parameters*

$$P_1 = \frac{2S_3}{1-F_L} \qquad P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

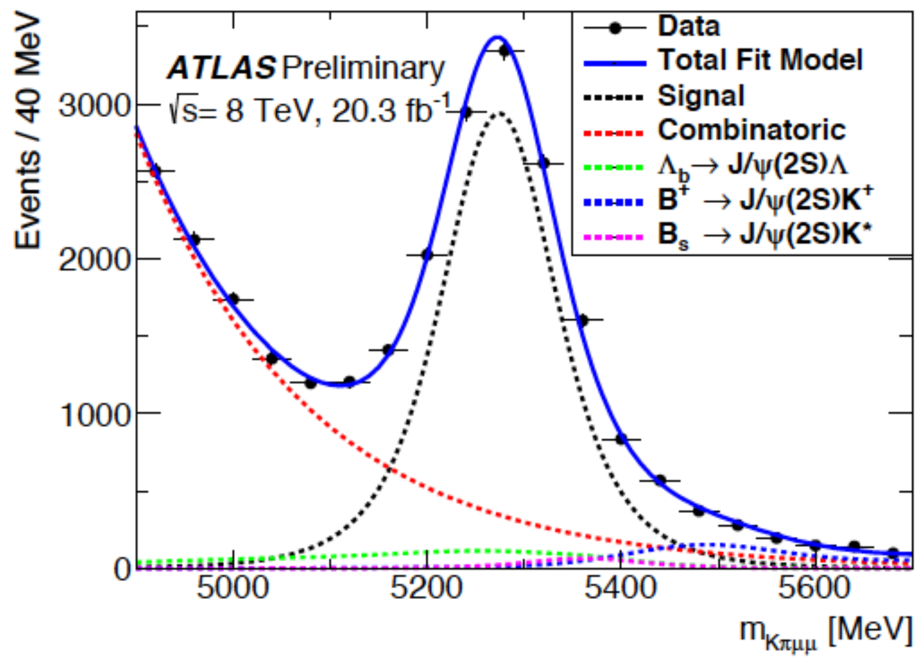
Angular analysis of $B_d \to K^* \mu \mu$

- *Low-background, high-statistics K^* J/ψ and K^* $\psi(2S)$ control samples*
  - *q^2 from 8-11 and from 12-15 GeV^2*
  - *used to extract nuisance parameters (m_B, σ_0) of the signal probability density function (p.d.f.) from data*

B → K J/ψ control sample*

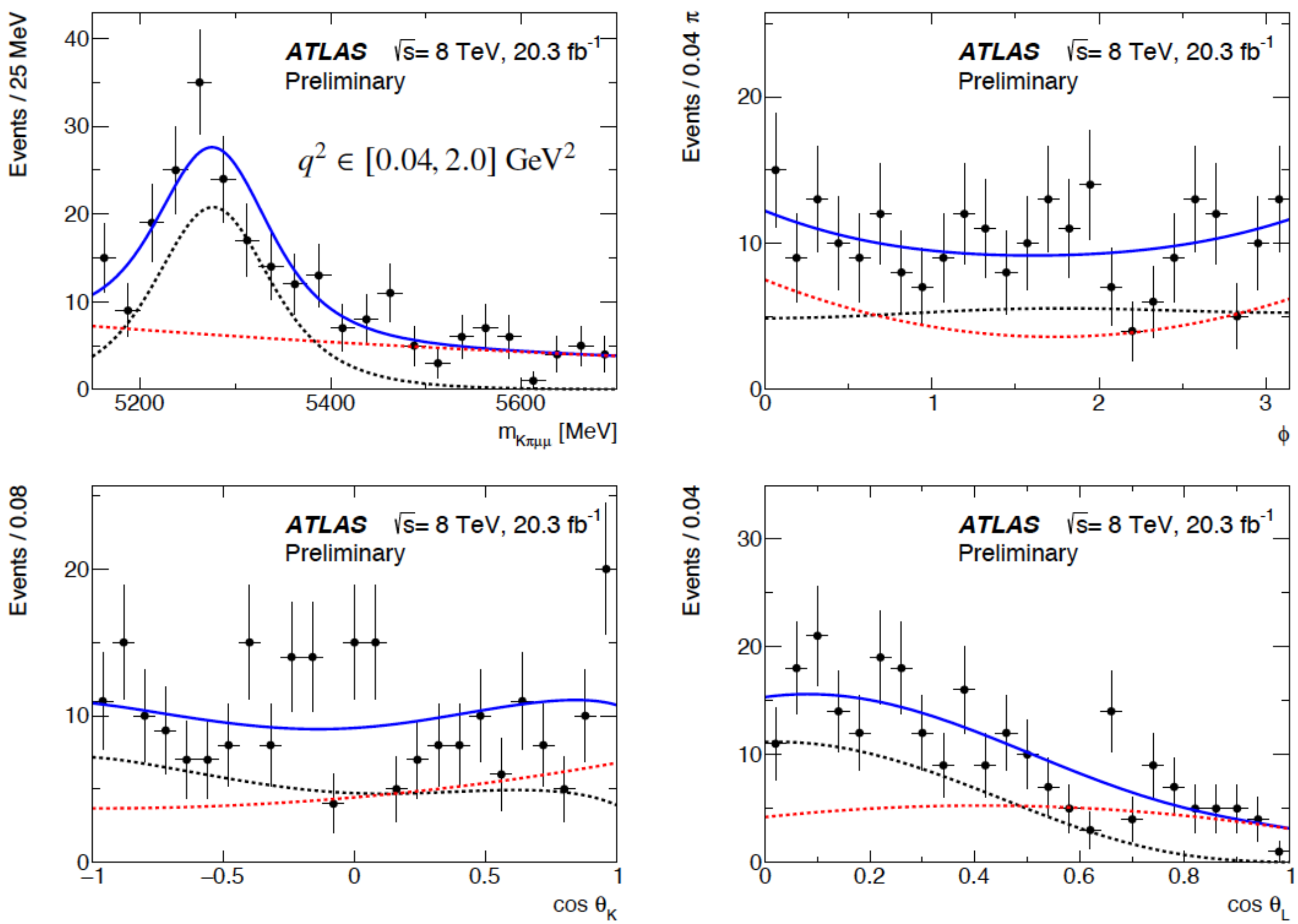


B → K ψ(2S) control sample*



Angular analysis of $B_d \rightarrow K^* \mu\mu$

- *Simultaneous fit to $\cos\theta_L$, $\cos\theta_K$ and φ distributions to isolate signal and extract parameters of interest*
  - *Mass p.d.f. parameters fixed to control region values*



Total p.d.f (blue), signal (black) and background (red) contributions

- *20.3 fb^{-1} of 8 TeV pp collision data*
- *Analyze data in three q^2 bins from 0.04 to 6.0 GeV^2*
  - *Data shown here for $0.04 < q^2 < 2$ GeV^2 overlaid with projections of signal and background p.d.f.s from the S_5 fit*
  - *128 ± 22 signal events in this q^2 bin*
  - *Similar results are obtained for the other q^2 bins and fits*

Angular analysis of $B_d \rightarrow K^* \mu\mu$

- *Results are statistically limited*
  - *Fit values of F_L, S_3, and P_1 from the 4 fits are consistent with each other; reported is the result with the smallest systematic uncertainty*

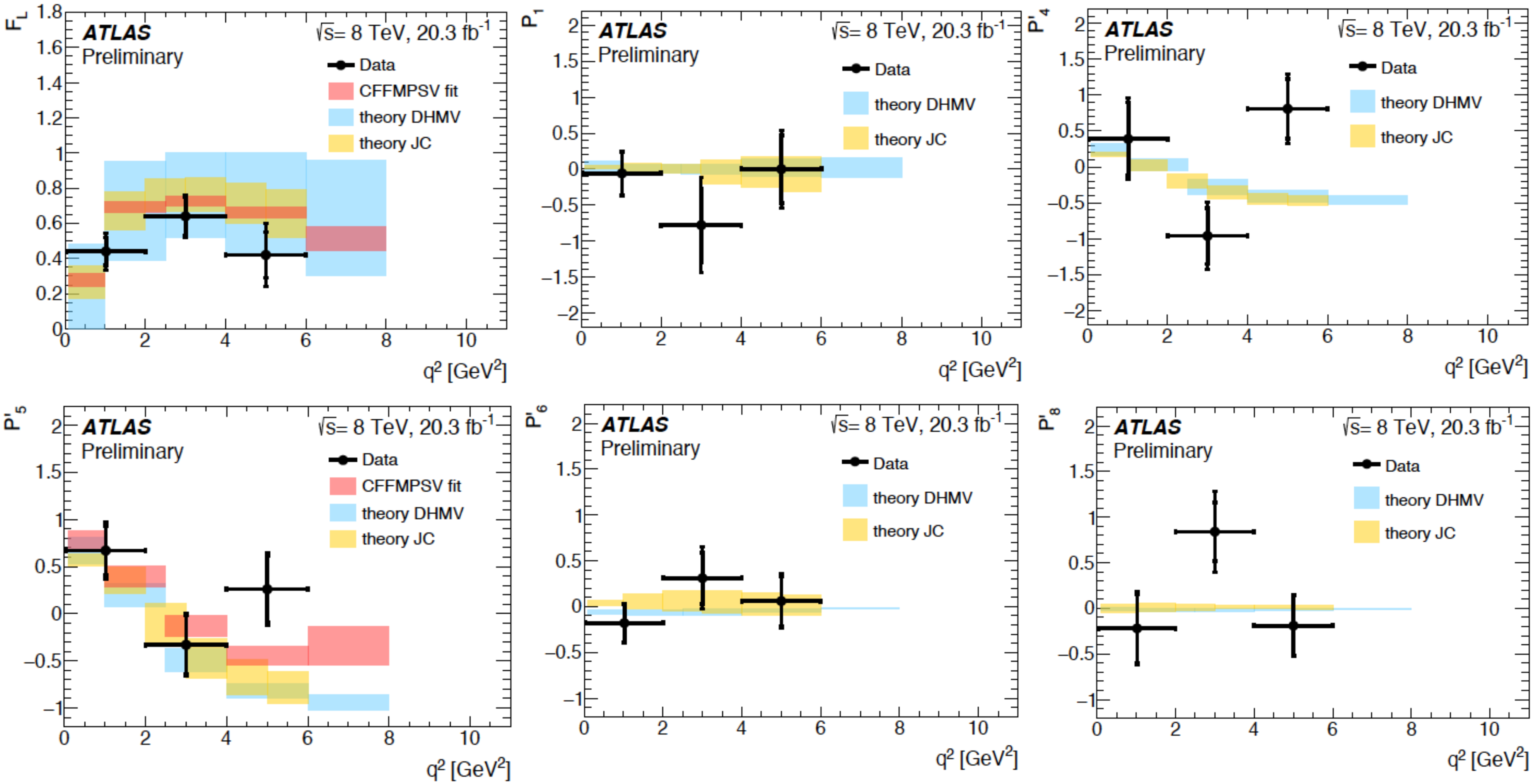
q^2 [GeV^2]	F_L	S_3	S_4	S_5	S_7	S_8
[0.04, 2.0]	$0.44 \pm 0.08 \pm 0.07$	$-0.02 \pm 0.09 \pm 0.02$	$0.19 \pm 0.25 \pm 0.10$	$0.33 \pm 0.13 \pm 0.06$	$-0.09 \pm 0.10 \pm 0.02$	$-0.11 \pm 0.19 \pm 0.07$
[2.0, 4.0]	$0.64 \pm 0.11 \pm 0.05$	$-0.15 \pm 0.10 \pm 0.07$	$-0.47 \pm 0.19 \pm 0.10$	$-0.16 \pm 0.15 \pm 0.05$	$0.15 \pm 0.14 \pm 0.09$	$0.41 \pm 0.16 \pm 0.15$
[4.0, 6.0]	$0.42 \pm 0.13 \pm 0.12$	$0.00 \pm 0.12 \pm 0.07$	$0.40 \pm 0.21 \pm 0.09$	$0.13 \pm 0.18 \pm 0.07$	$0.03 \pm 0.13 \pm 0.07$	$-0.09 \pm 0.16 \pm 0.04$
[0.04, 4.0]	$0.52 \pm 0.07 \pm 0.06$	$-0.05 \pm 0.06 \pm 0.04$	$-0.19 \pm 0.16 \pm 0.09$	$0.16 \pm 0.10 \pm 0.04$	$0.01 \pm 0.08 \pm 0.05$	$0.15 \pm 0.13 \pm 0.10$
[1.1, 6.0]	$0.56 \pm 0.07 \pm 0.06$	$-0.04 \pm 0.07 \pm 0.03$	$0.03 \pm 0.14 \pm 0.07$	$0.00 \pm 0.10 \pm 0.03$	$0.02 \pm 0.08 \pm 0.06$	$0.09 \pm 0.11 \pm 0.08$
[0.04, 6.0]	$0.50 \pm 0.06 \pm 0.04$	$-0.04 \pm 0.06 \pm 0.03$	$0.03 \pm 0.13 \pm 0.07$	$0.14 \pm 0.09 \pm 0.03$	$0.02 \pm 0.07 \pm 0.05$	$0.05 \pm 0.10 \pm 0.07$

q^2 [GeV^2]	P_1	P'_4	P'_5	P'_6	P'_8
[0.04, 2.0]	$-0.06 \pm 0.30 \pm 0.10$	$0.39 \pm 0.51 \pm 0.25$	$0.67 \pm 0.26 \pm 0.16$	$-0.18 \pm 0.21 \pm 0.04$	$-0.22 \pm 0.38 \pm 0.14$
[2.0, 4.0]	$-0.78 \pm 0.51 \pm 0.42$	$-0.96 \pm 0.39 \pm 0.26$	$-0.33 \pm 0.31 \pm 0.13$	$0.31 \pm 0.28 \pm 0.19$	$0.84 \pm 0.32 \pm 0.31$
[4.0, 6.0]	$0.00 \pm 0.47 \pm 0.26$	$0.81 \pm 0.42 \pm 0.24$	$0.26 \pm 0.35 \pm 0.17$	$0.06 \pm 0.27 \pm 0.13$	$-0.19 \pm 0.33 \pm 0.07$
[0.04, 4.0]	$-0.22 \pm 0.26 \pm 0.16$	$-0.38 \pm 0.31 \pm 0.22$	$0.32 \pm 0.21 \pm 0.10$	$0.01 \pm 0.17 \pm 0.10$	$0.30 \pm 0.26 \pm 0.19$
[1.1, 6.0]	$-0.17 \pm 0.31 \pm 0.14$	$0.07 \pm 0.28 \pm 0.18$	$0.01 \pm 0.21 \pm 0.07$	$0.03 \pm 0.17 \pm 0.11$	$0.18 \pm 0.22 \pm 0.16$
[0.04, 6.0]	$-0.15 \pm 0.23 \pm 0.10$	$0.07 \pm 0.26 \pm 0.18$	$0.27 \pm 0.19 \pm 0.07$	$0.03 \pm 0.15 \pm 0.10$	$0.11 \pm 0.21 \pm 0.14$

- *Dominant systematics come from uncertainties in the background*
  - *partially reconstructed decays with open charm and incorrect $K\pi$ combinations (fake K^*)*
  - *$K\pi$ S-wave contributions results only in small systematic uncertainty*

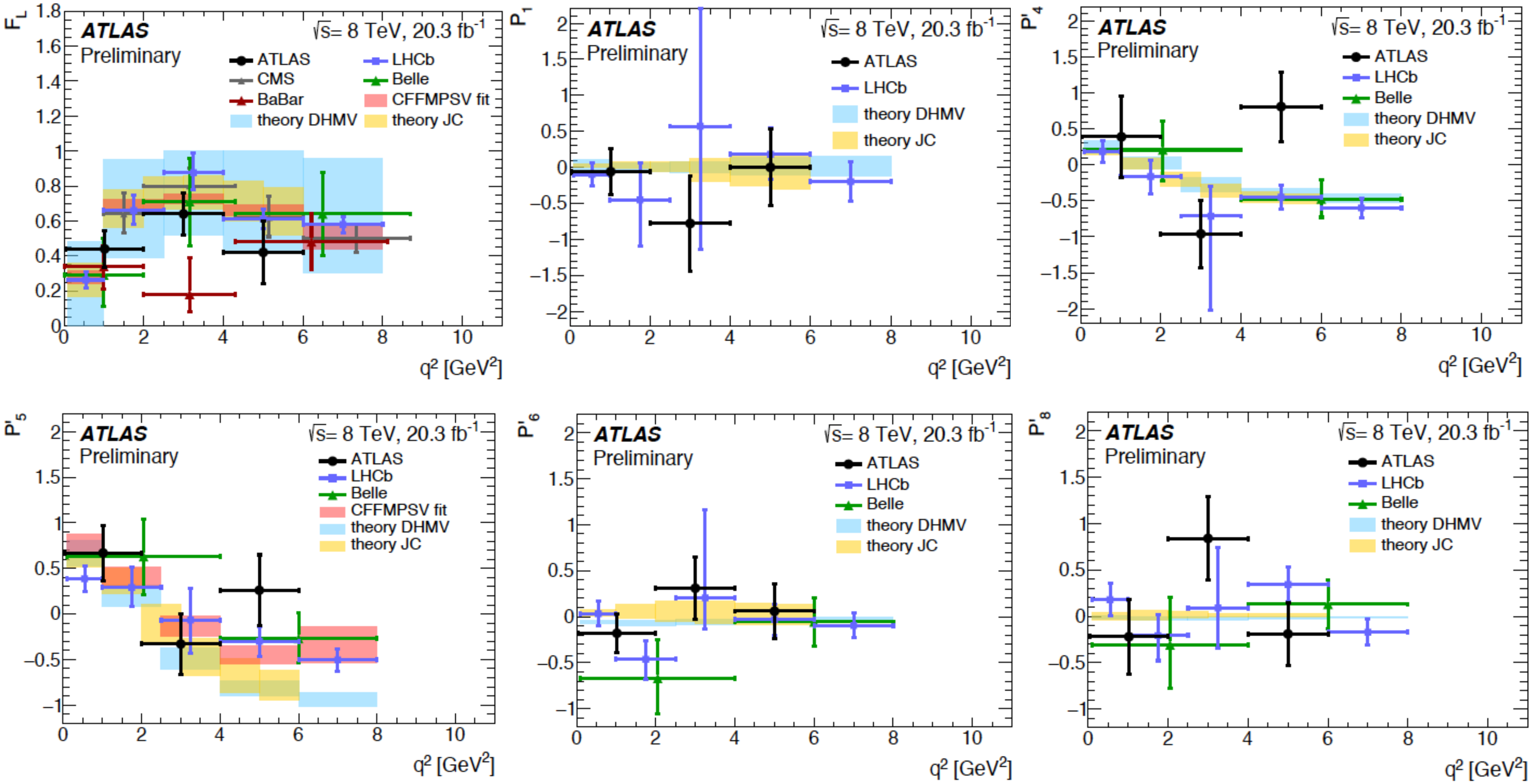
Angular analysis of $B_d \to K^* \mu\,\mu$

- *ATLAS results are compatible with theoretical calculations and fits*



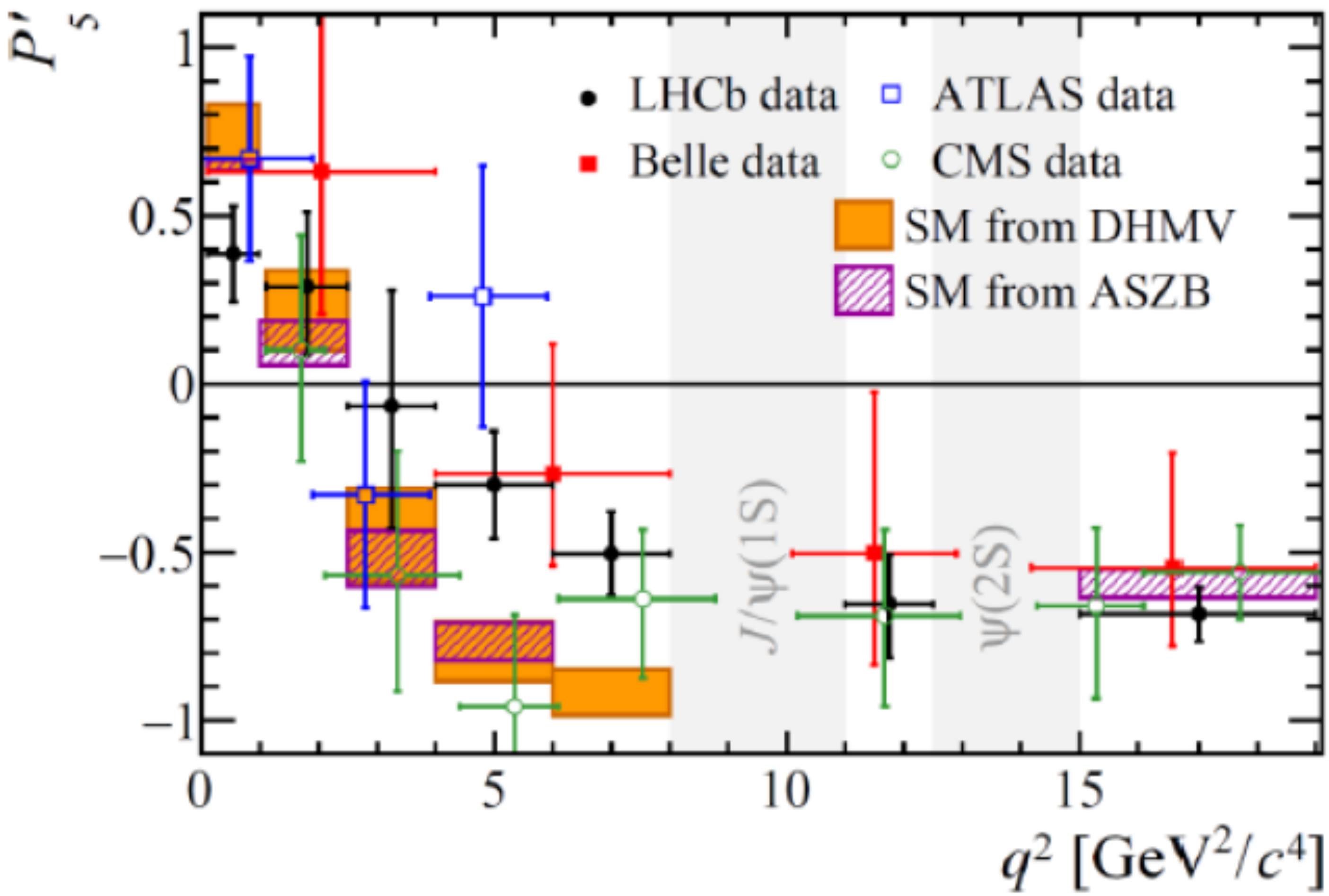
Angular analysis of $B_d \rightarrow K^* \mu\mu$

- *ATLAS results are compatible with measurements from other experiments*



Angular analysis of $B_d \rightarrow K^* \mu \mu$

- *ATLAS results are compatible with measurements from other experiments*

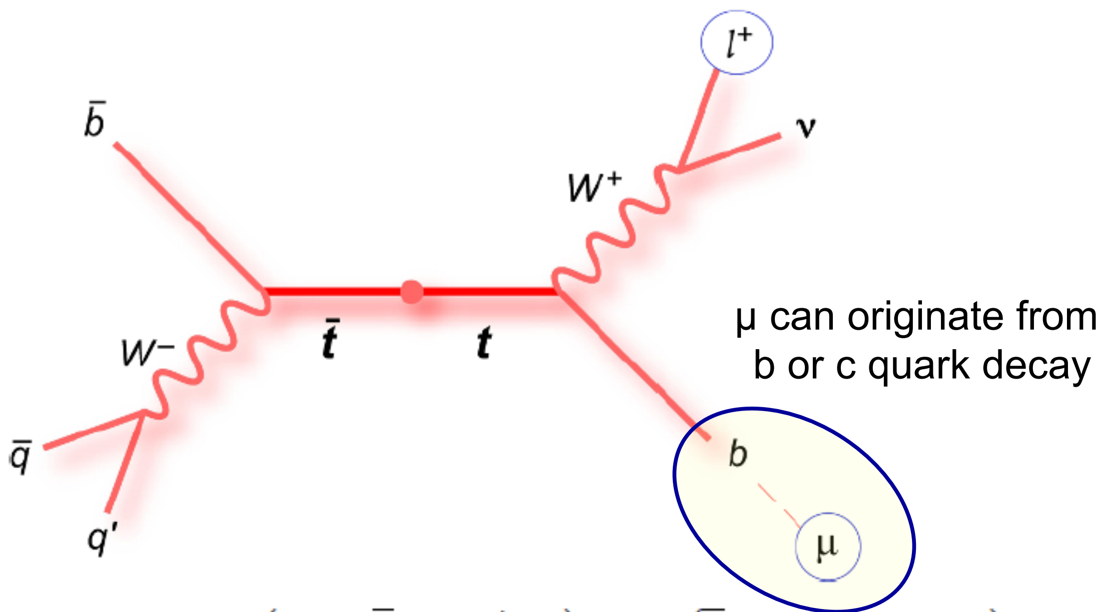


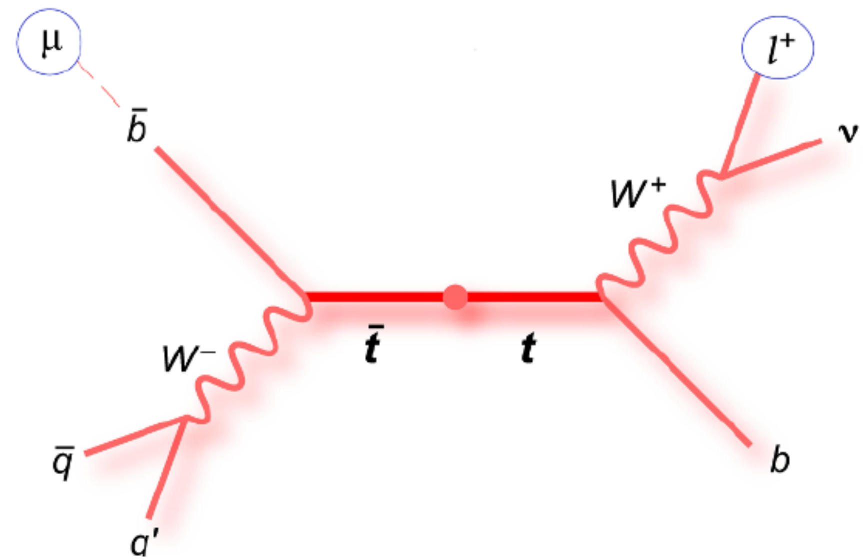
Uwer, Lenz
Pheno 2017

Recent CMS results for P_1 and P'_5 also agree with SM predictions (CMS PAS BPH-15-008)

CP violation in b decays using top quark pairs

- *Measure same sign (SS) and opposite sign (OS) lepton pairs in top quark pair events to determine mixing and direct CP asymmetries from observed N^{++}, N^{--}, N^{+-} and N^{-+} rates ($N^{q(l(W))q'(l(b))}$)*





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

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

Based on idea by Gedalia et al.,
Phys. Rev. Lett. 110, 232002 (2013)

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

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

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

CP violation in b decays using top quark pairs

- *Standard top reconstruction for semi-leptonic $t\bar{t}$ events*
- *Require 2 leptons in an event*
  - *Hard lepton from W tags the b flavor at production through $t \to bW^+ \to b\, l^+\, \nu$*
  - *Soft muon tagger (SMT[1]) constrains the b decay chain*

Same sign leptons

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

Opposite sign leptons

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

  - *Fully reconstruct $t\bar{t}$ candidate with KLFitter[2]*

$$P\left(b \to \ell^+\right) = \frac{N\left(b \to \ell^+\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell^+\right)} = \frac{N^{++}}{N^{+-} + N^{++}} = \frac{N^{++}}{N^{+}},$$
$$P\left(\bar{b} \to \ell^-\right) = \frac{N\left(\bar{b} \to \ell^-\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{--}}{N^{--} + N^{-+}} = \frac{N^{--}}{N^{-}},$$
$$P\left(b \to \ell^-\right) = \frac{N\left(b \to \ell^-\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell^+\right)} = \frac{N^{+-}}{N^{+-} + N^{++}} = \frac{N^{+-}}{N^{+}},$$
$$P\left(\bar{b} \to \ell^+\right) = \frac{N\left(\bar{b} \to \ell^+\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{-+}}{N^{--} + N^{-+}} = \frac{N^{-+}}{N^{-}},$$

$$A^{\rm ss} = \frac{P\left(b \to \ell^+\right) - P\left(\bar{b} \to \ell^-\right)}{P\left(b \to \ell^+\right) + P\left(\bar{b} \to \ell^-\right)},$$
$$A^{\rm os} = \frac{P\left(b \to \ell^-\right) - P\left(\bar{b} \to \ell^+\right)}{P\left(b \to \ell^-\right) + P\left(\bar{b} \to \ell^+\right)},$$

Relate charge asymmetries to mixing and direct CP asymmetries

$$A^{\rm ss} = r_b A^{b\ell}_{\rm mix} + r_c \left(A^{bc}_{\rm dir} - A^{c\ell}_{\rm dir}\right) + r_{c\bar{c}} \left(A^{bc}_{\rm mix} - A^{c\ell}_{\rm dir}\right)$$
$$A^{\rm os} = \tilde{r}_b A^{b\ell}_{\rm dir} + \tilde{r}_c \left(A^{bc}_{\rm mix} + A^{c\ell}_{\rm dir}\right) + \tilde{r}_{c\bar{c}} A^{c\ell}_{\rm dir}$$

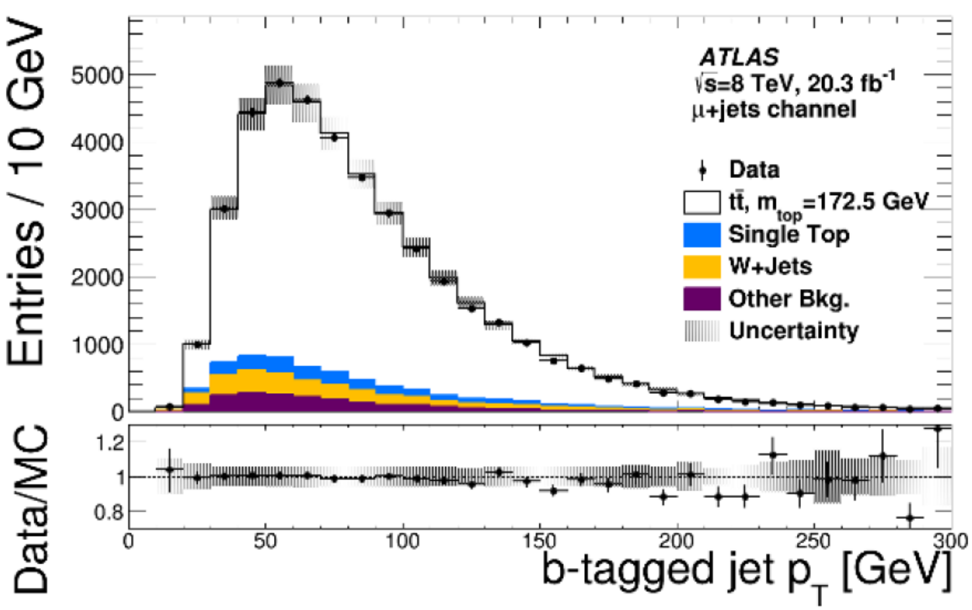
r's are decay rate fractions in the fiducial volume

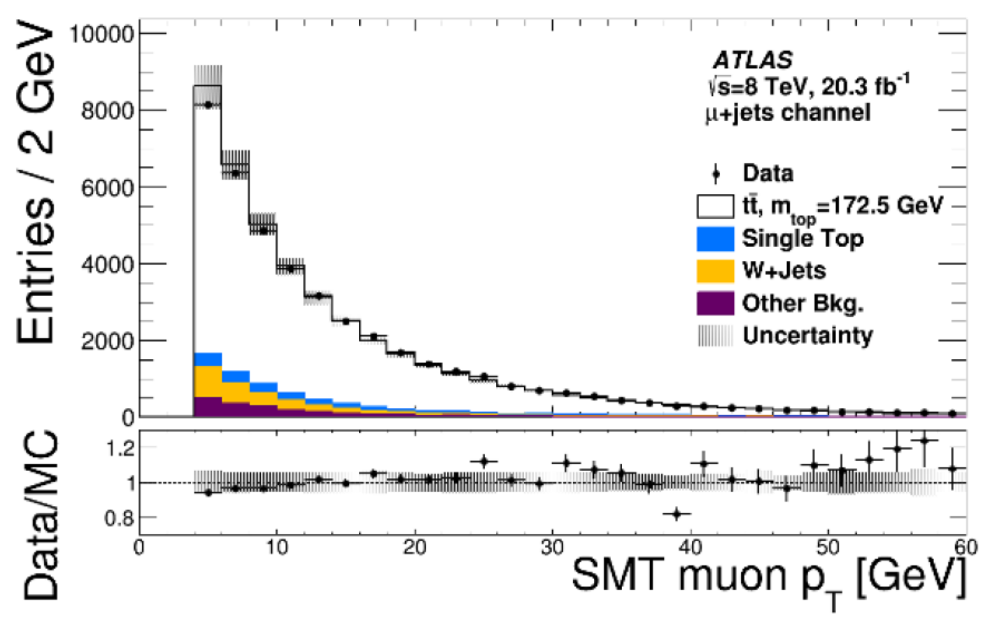
[1] Soft Muon Tagger, ATLAS Collaboration, JINST 11(2016) P04008
[2] Kinematic Likelihood fitter, Erdmann et al., NIM A 748 (2014) 18

CP violation in b decays using top quark pairs

- *Good agreement between expected and measured event yields*
- *~ 80 % signal purity in selected sample of $t\bar{t}$ candidates*

	e+jets		μ+jets	
WW, WZ, WW	50	± 7	45	± 5
Z+jets	800	± 80	450	± 60
Multijet	1 800	± 1 400	1 500	± 330
Single top	1 800	± 150	2 000	± 150
W+jets	2 500	± 160	2 800	± 150
$t\bar{t}$	30 000	± 1 900	34 000	± 2 000
Expected	37 000	± 2 600	41 000	± 2 300
Data	36 796		40 807	





CP violation in b decays using top quark pairs

- *Measured charge and CP asymmetries are*
  - *Determined with %-level uncertainties*
  - *Consistent with zero and SM predictions*

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

[19] Gedalia et al. Phys. Rev. Lett. 110 (2013) 232002

[94] Decotes-Genon et al., Phys. Rev D87 (2015)

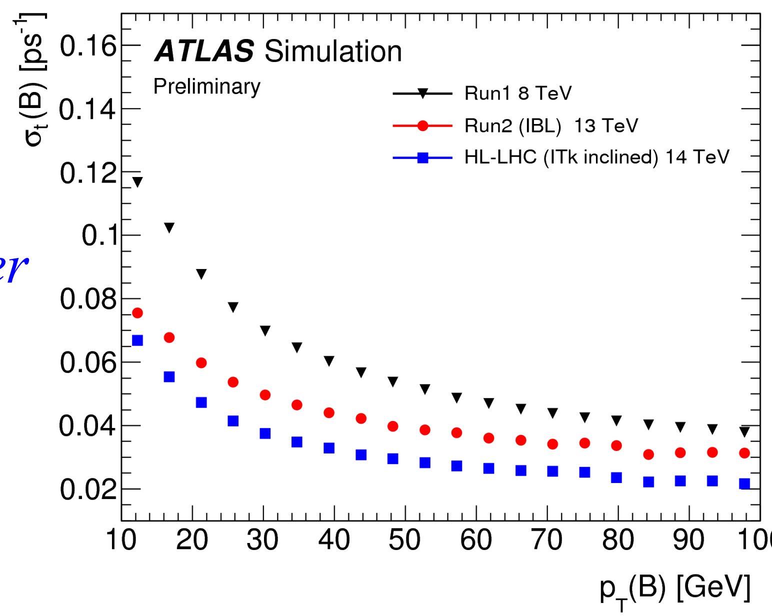
[95] HFAG, arXiv:1412.7515

[97] Bar-Shalom et al., Phys. Lett B694 (2011) 374

Conclusions

- *Presented two recent ATLAS results in b physics*
  - *Results of angular analysis of rare decay $B_d \rightarrow K^* \mu\, \mu$ are consistent with the SM and show no evidence of new physics (ATLAS-CONF-2017-023)*
  - *Measurements of direct and mixing CP asymmetries in b decays from $t\bar{t}$ pairs are consistent with zero and the SM (JHEP 02 (2017) 071)*

- *Since 2015 ATLAS is taking data at 13 TeV (Run 2), expect more heavy flavor results in the near future*
  - *Higher b pair cross-section*
  - *Improved decay time and vertex resolution from new Insertable B Layer (IBL)*
  - *Commissioning topological di-muon trigger (p_T and opening angle)*
  - *Expect about 100 fb^{-1} by end of 2018*

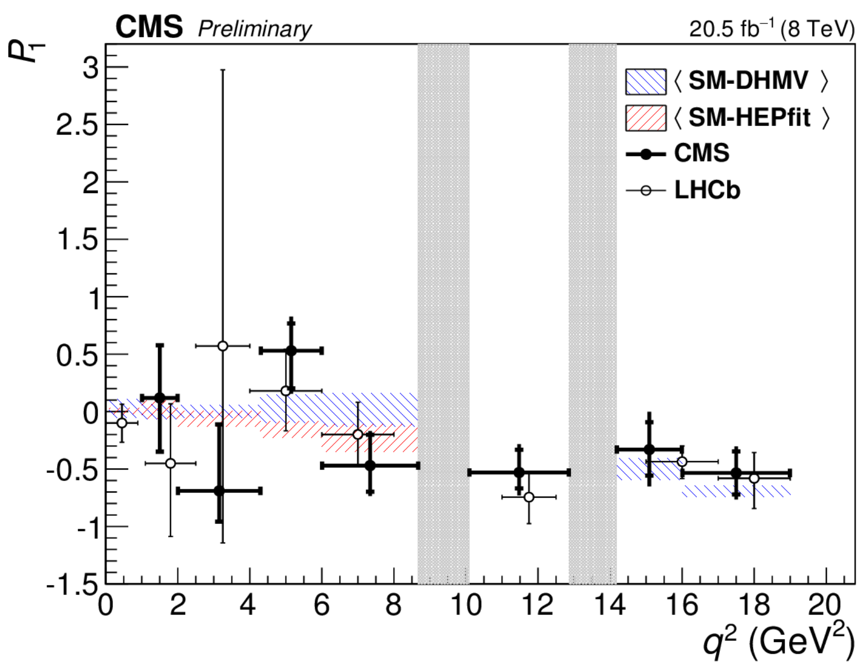


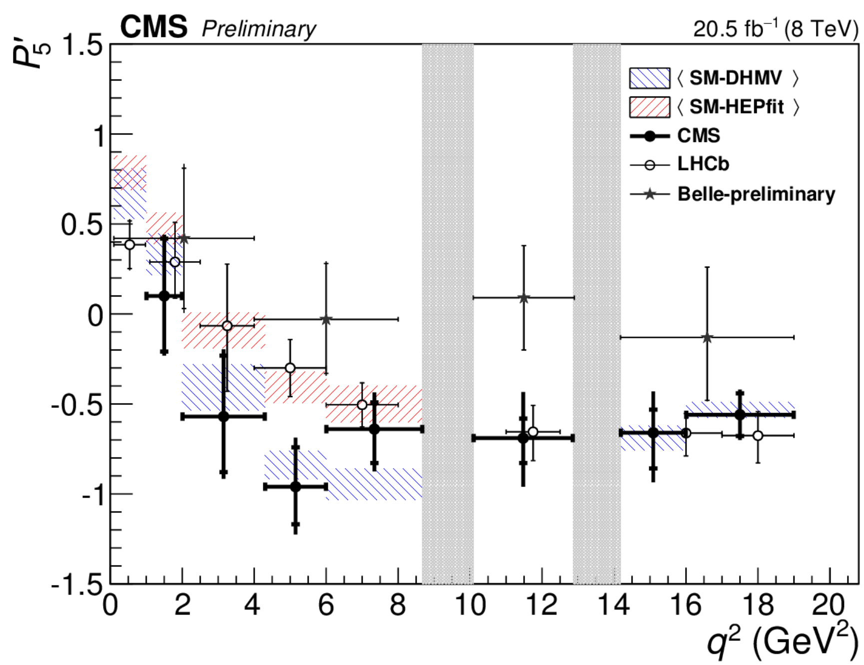
Back-Up Slides

Angular analysis of $B_d \to K^* \mu\, \mu$

- *Recent result from CMS for P_1 and P'_5 agree with SM predictions* *(CMS PAS BPH-15-008)*

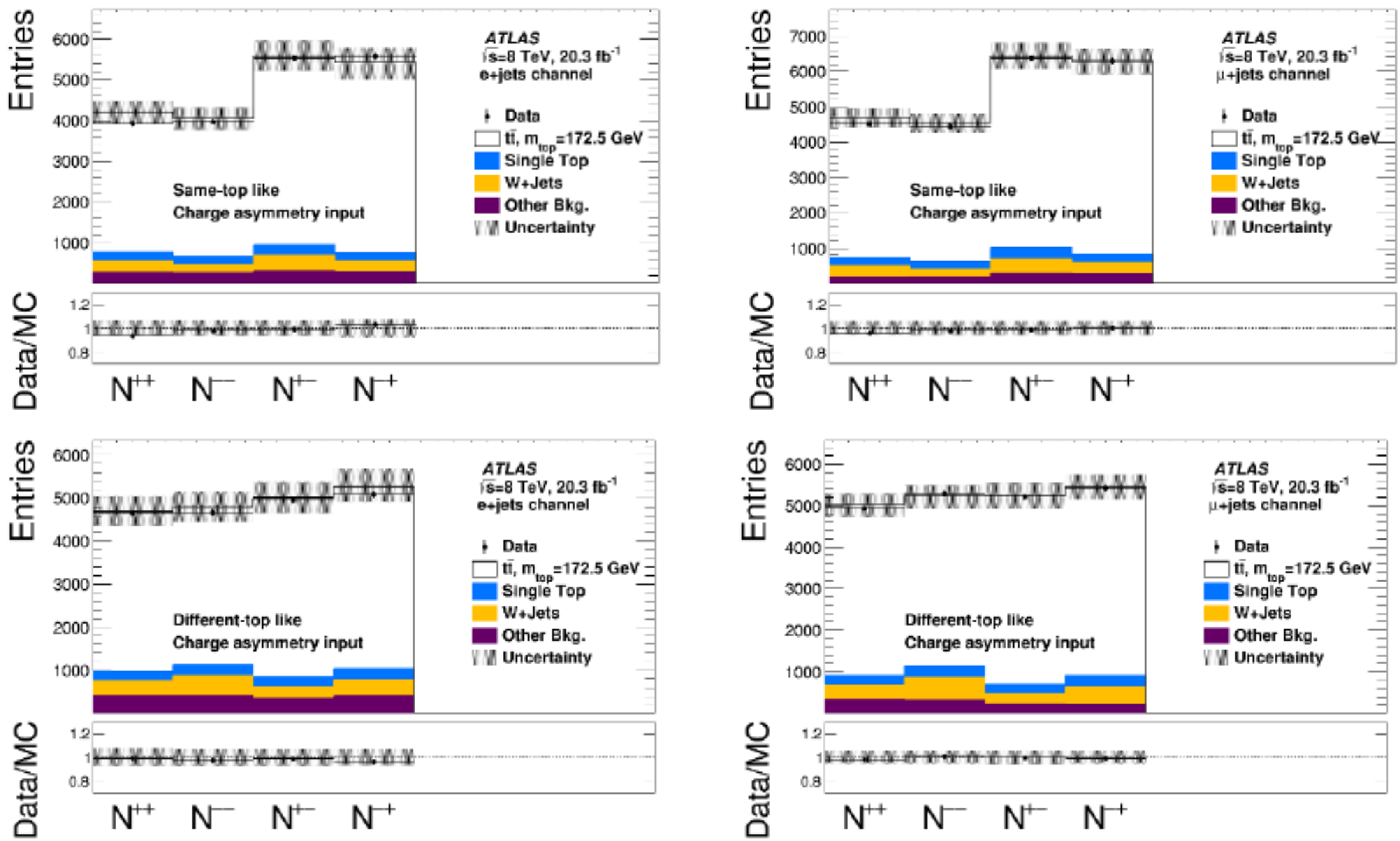
q^2 (GeV^2)	Signal yield	P_1	P'_5
1.00–2.00	80 ± 12	$+0.12^{+0.46}_{-0.47} \pm 0.06$	$+0.10^{+0.32}_{-0.31} \pm 0.12$
2.00–4.30	145 ± 16	$-0.69^{+0.58}_{-0.27} \pm 0.09$	$-0.57^{+0.34}_{-0.31} \pm 0.15$
4.30–6.00	119 ± 14	$+0.53^{+0.24}_{-0.33} \pm 0.18$	$-0.96^{+0.22}_{-0.21} \pm 0.16$
6.00–8.68	247 ± 21	$-0.47^{+0.27}_{-0.23} \pm 0.13$	$-0.64^{+0.15}_{-0.19} \pm 0.14$
10.09–12.86	354 ± 23	$-0.53^{+0.20}_{-0.14} \pm 0.14$	$-0.69^{+0.11}_{-0.14} \pm 0.23$
14.18–16.00	213 ± 17	$-0.33^{+0.24}_{-0.23} \pm 0.22$	$-0.66^{+0.13}_{-0.20} \pm 0.19$
16.00–19.00	239 ± 19	$-0.53^{+0.19}_{-0.19} \pm 0.13$	$-0.56^{+0.12}_{-0.12} \pm 0.07$





CP violation in b decays using top quark pairs

- *Same-top (top) and different-top (bottom) N^{ij} rates*



(a) e+jets channel. (b) μ+jets channel.