19TH INTERNATIONAL SYMPOSIUM ON PARTICLES, STRINGS AND COSMOLOGY

STUDY OF RARE AND SUPPRESSED PROCESSES IN B MESON DECAYS WITH ATLAS

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Tapei, Taiwan | 20 – 26 November 2013

OUTLINE

- ATLAS AT LHC
- SEARCH FOR $B_s \rightarrow \mu^+\mu^-$
- ANGULAR ANALYSIS OF $B_D \rightarrow K^*(\rightarrow K^+\pi^-)\,\mu^+\mu^-$
- CONCLUSIONS

ATLAS DETECTOR

INNER DETECTOR ($|\eta| < 2.4$)

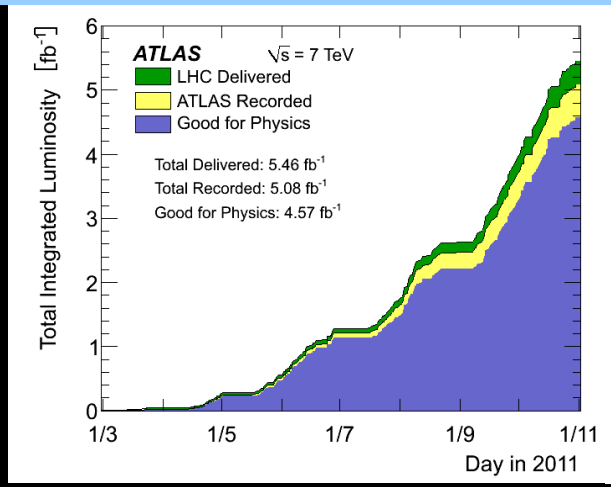
- silicon pixel, strip and transition radiation tracker
- 2T solenoidal field

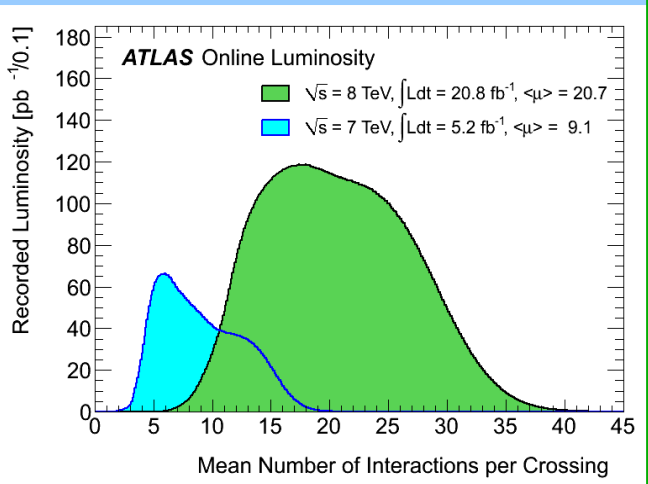
MUON SPECTROMETER ($|\eta| < 2.7$)

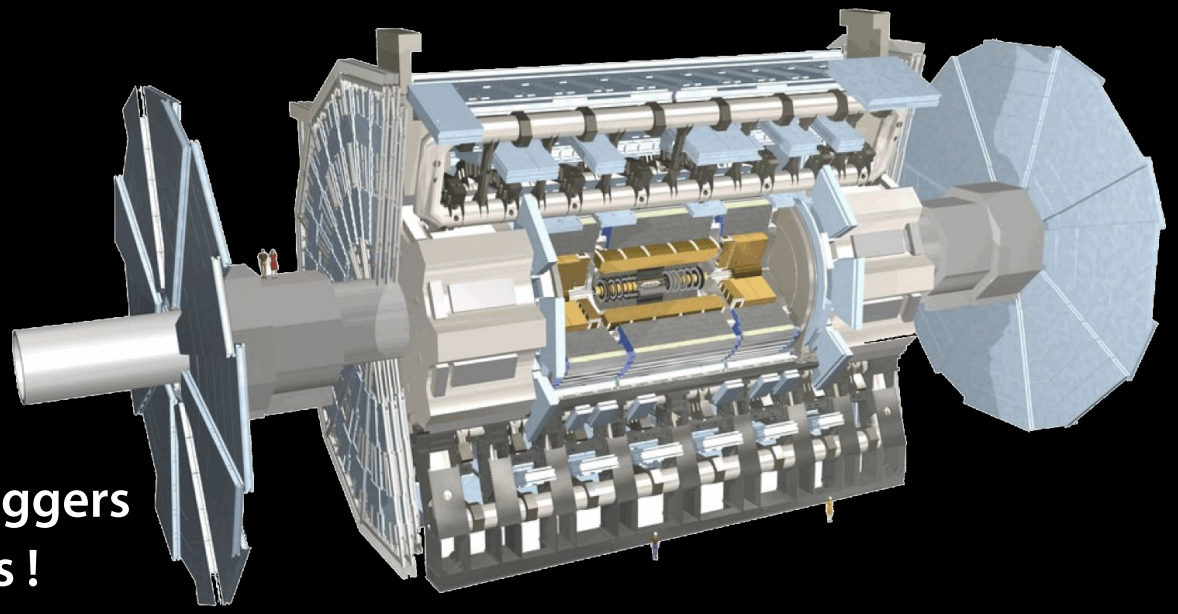
- trigger chambers (RPC, TGC), tracking chambers (MDT, CSC)
- 0.5-2 T toroidal field

DATA TAKING

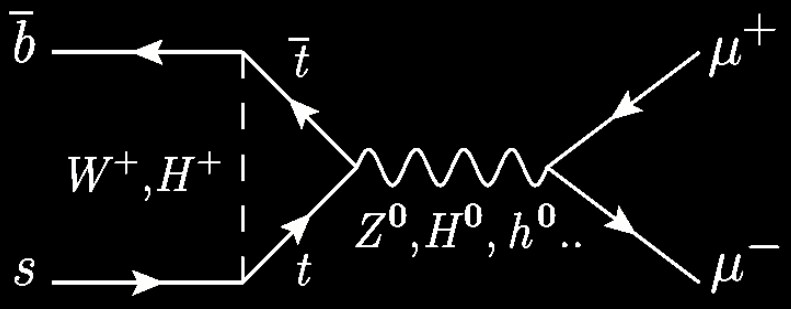
- events selected by dimuon triggers
- challenging pile-up conditions !
- 2011 > 5 fb^{-1} recorded (~ 150G B^0–pairs)
- 2012 ~ 23fb^{-1} recorded

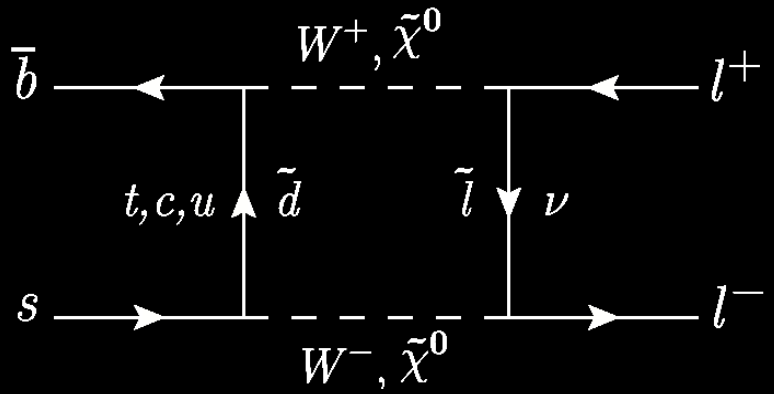






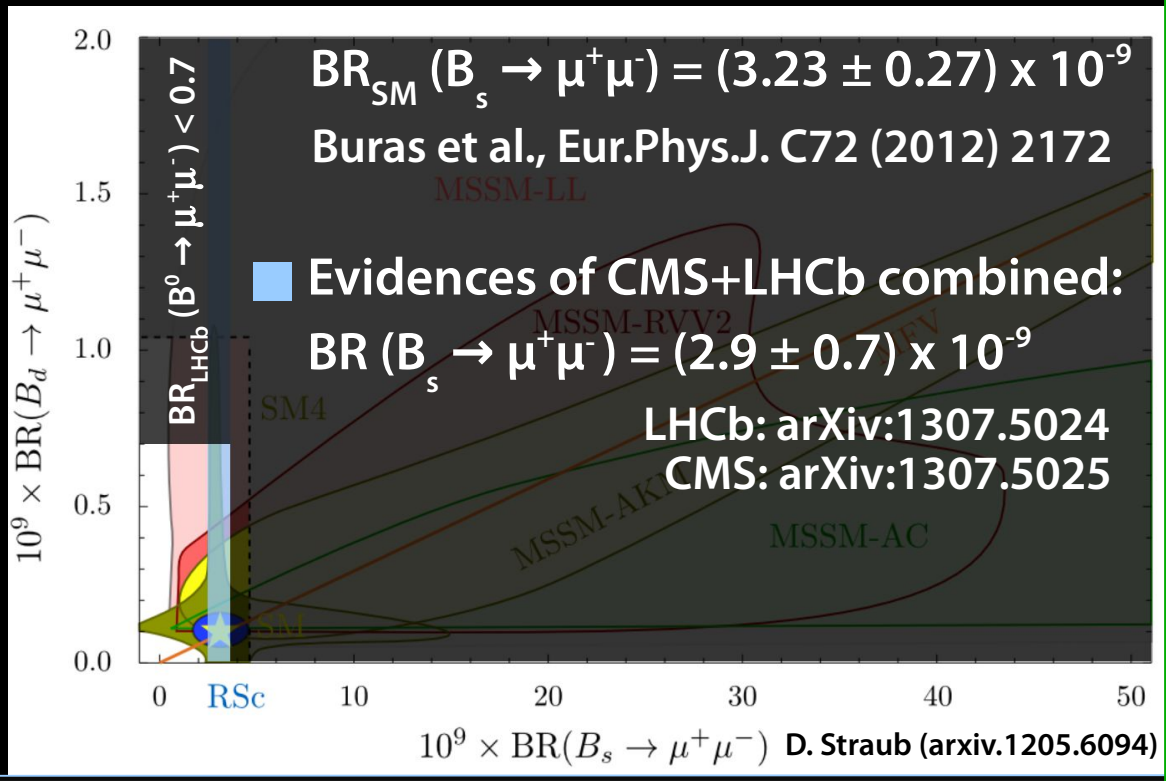
SEARCH FOR $B_s \to \mu^+\mu^-$: RECENT RESULTS





MOTIVATION

- NP (pseudo-)scalar op. can lift strong SM helicity suppression of this FCNC
- strong QCD-free constraint
- genuine probe of Yukawa interactions
- EW precision test (wrt. Z penguin)



SEARCH FOR $B_s \rightarrow \mu^+\mu^-$: ATLAS ANALYSIS STRATEGY

BRANCHING RATIO

- 2011 data used - 4.9fb^{-1}
  - signal region (± 300 MeV around B_s) blinded
  - sideband events – 1/2 background interpolation, 1/2 selection optimization
- high statistics reference signal $B^{\pm} \rightarrow J/\psi\,(\rightarrow \mu^+\mu^-)\,K^{\pm}$ minimizes syst. uncertainty

$$BR(B_s \rightarrow \mu^+\mu^-) = \underbrace{N_{Bs \rightarrow \mu+\mu-} \times (1/N_{ref})}_{\text{DATA}} \times \underbrace{BR(ref) \times (f_u/f_s)}_{\text{PDG, LHC}_B} \times \underbrace{(\varepsilon_{tot} \times A_{tot})_{ref} / (\varepsilon_{tot} \times A_{tot})_{Bs \rightarrow \mu+\mu-}}_{\text{MONTE CARLO}}$$

$$\varepsilon_{TOT} \times A_{TOT} = (N_{\substack{\text{RECONSTRUCTED} \\ \text{AND SELECTED}}} / N_{GENERATED})$$

- derived from simulation ("calibrated" on data)
- systematics taken from data-MC discrepancies in signal distributions

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SEARCH FOR $B_s \rightarrow \mu^+\mu^-$: ATLAS ANALYSIS STRATEGY

$$BR(B_s \rightarrow \mu^+\mu^-) = \underbrace{N_{Bs \rightarrow \mu+\mu-} \times (1/N_{ref})}_{\text{DATA}} \times \underbrace{BR(ref) \times (f_u/f_s)}_{\text{PDG, LHC}_B} \times \underbrace{(\varepsilon_{tot} \times A_{tot})_{ref} / (\varepsilon_{tot} \times A_{tot})_{Bs \rightarrow \mu+\mu-}}_{\text{MONTE CARLO}}$$

SIGNAL EXTRACTION

- N_{Bs} – is a CLs limit derived from:
  - candidate count in the signal region
  - background estimation in the signal region
- N_{ref} - unbinned maximum likelihood fit (same selection as for the signal)

BACKGROUND COMPOSITION

- resonant: $B \rightarrow hh'$ (K/π), fake-muon rates (MC) $\pi\pm$/ K+ /K- ~ 2.1/4.1/3.3 ‰
  - 0.3 $B \rightarrow hh'$ events expected in the signal region
- continuum: non resonant $\bar{b}b \rightarrow \mu^+\mu^- X$
  - smooth in dimuon mass
  - sideband interpolation (even-numbered events)

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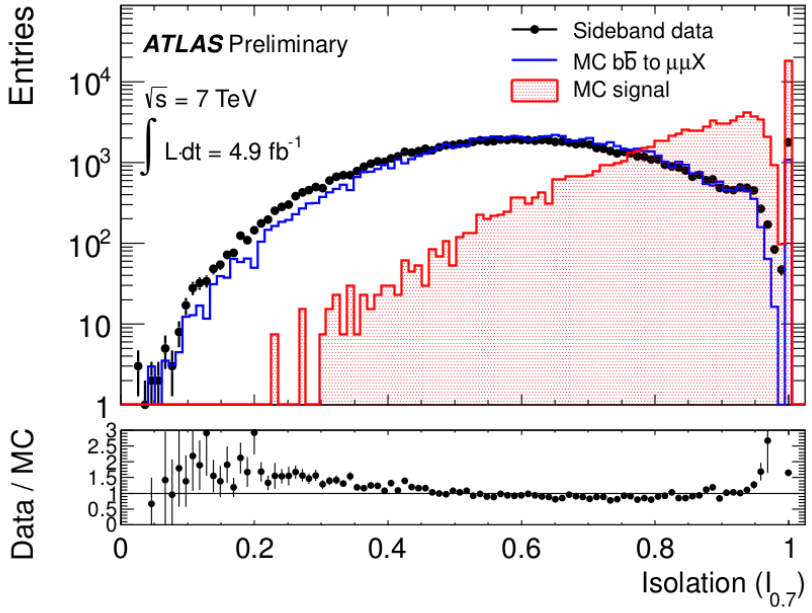
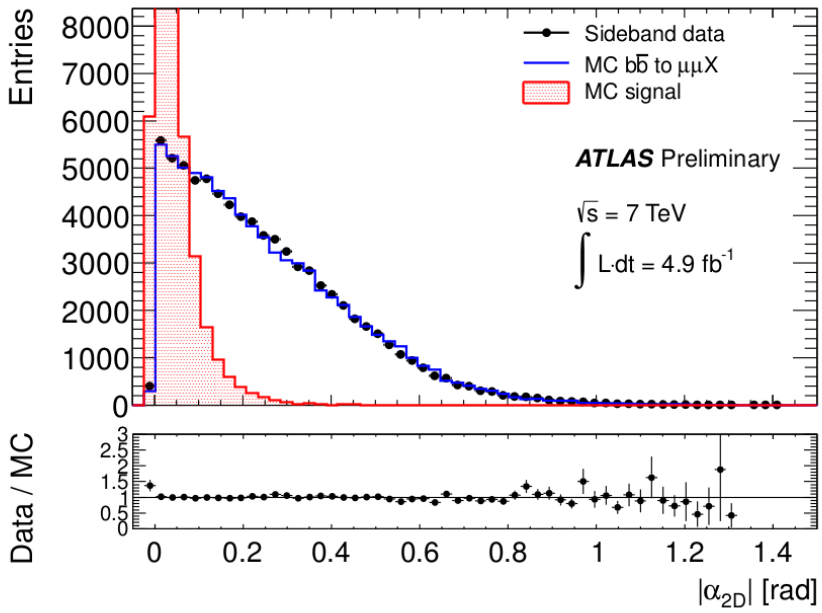
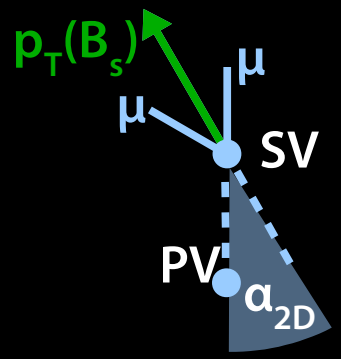
SEARCH FOR $B_s \rightarrow \mu^+\mu^-$: BACKGROUND DISCRIMINATION





CONTINUUM BACKGROUND DISCRIMINATION



- 13 best performing discriminating variables chosen by MVA
- BDT proven as the most powerful event classifier
  - trained on MC events
- plots show Data/MC agreement of pointing angle α_{2D} and isolation variable $I_{0.7}$

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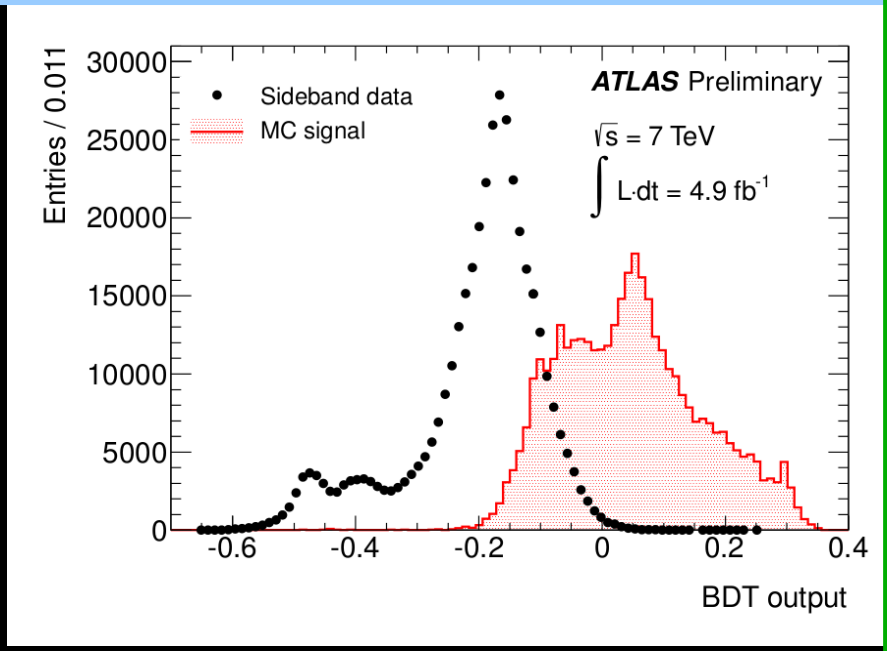
SEARCH FOR $B_s \rightarrow \mu^+\mu^-$: SELECTION OPTIMIZATION



OPTIMIZATION

- for selection on:
  - Δm = signal mass window width
  - q = BDT output (event classifier)
  - odd-numbered sideband events and signal MC used
- optimum = maximum of the Punzi estimator :

$$P(\Delta m, q) = \varepsilon_{sig} / (1+N_{bkg}) \text{ (@95\% CL)}$$

  - ε_{sig} calculated directly on simulated signal events
  - N_{bkg} in sig. region estimated by interpolation from sideband data

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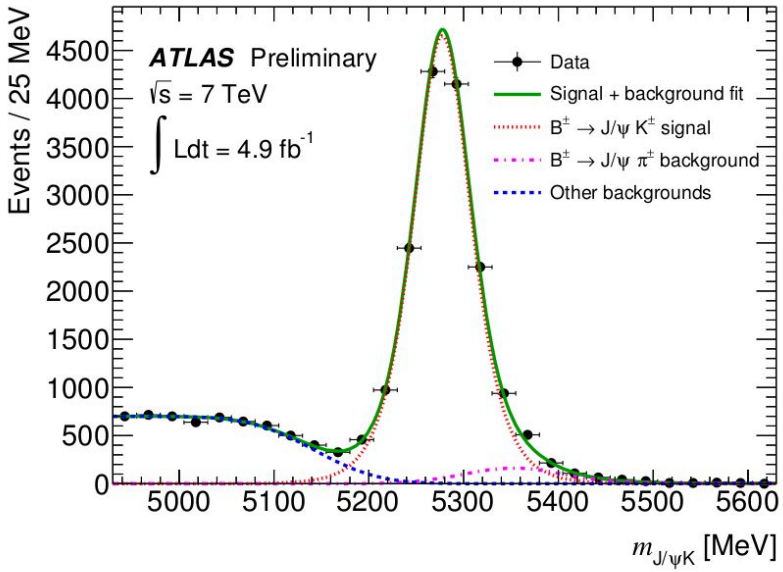
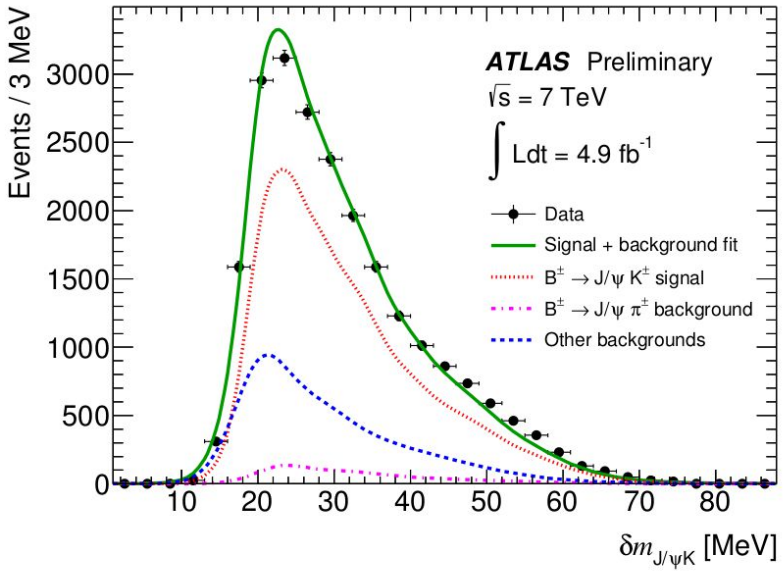
SEARCH FOR $B_s \to \mu^+\mu^-$: REFERENCE CHANNEL YIELD





$B^\pm \to J/\psi(\to \mu^+\mu^-)K^\pm$ YIELD → $N_{J/\psi K+} = 15214 \pm 1.1\%(\text{stat}) \pm 2.4\%(\text{syst})$

- N_{ref} yield extracted by unbinned maximum likelihood fit
- inclusion of per-event mass resolution δm in the fit
- selection kept as close as possible to B_s
- the same B_s-trained BDT used to minimize systematics
- main systematics from varying continuum background fit models

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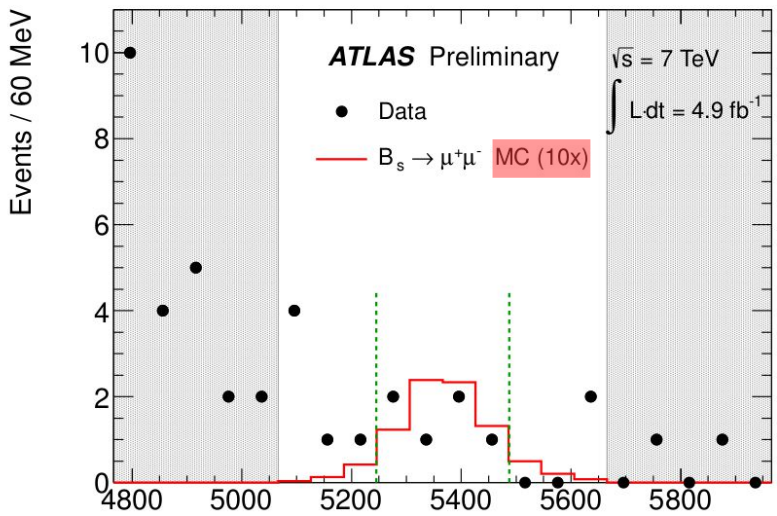
SEARCH FOR $B_s \rightarrow \mu^+\mu^-$: ATLAS RESULT ON 2011 DATA SAMPLE



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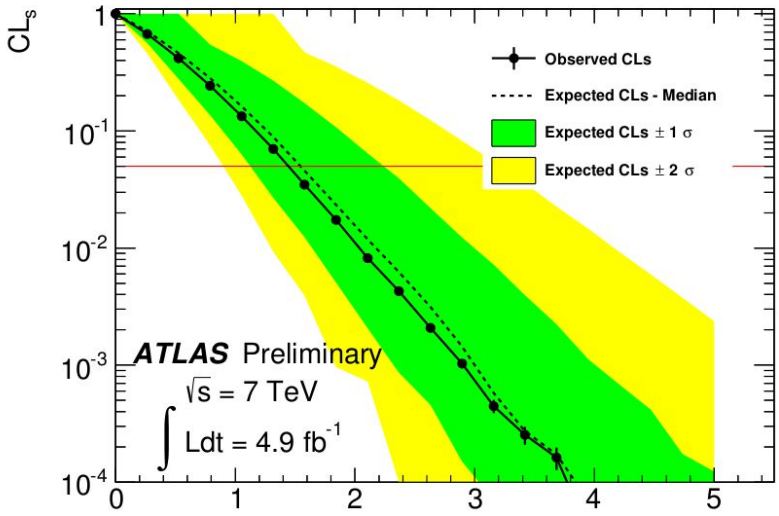


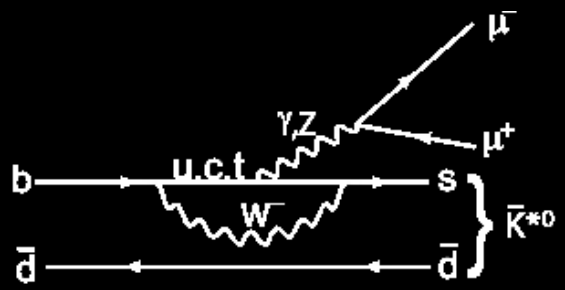
SIGNAL EXTRACTION

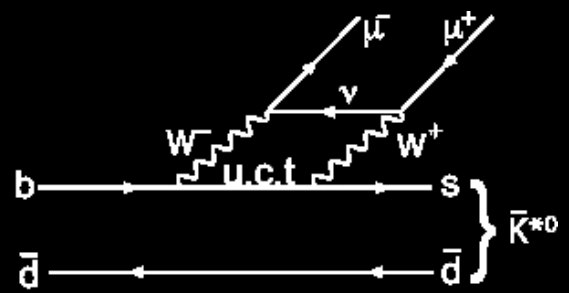
- Single Event Sensitivity
  SES = (2.07 ± 2.1%(stat) ± 12.5%(syst)) x 10^{-9}
- systematic uncertainty dominated by
  - reference channel BR contribution
  - acceptance x efficiency ratio
- N_{bkg} expected in the signal window = 6.75 → $BR(B_s \rightarrow \mu^+\mu^-) < 1.6 \times 10^{-9}$ @ 95% CL
- N_{obs} in the signal window = 6 → $BR(B_s \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-9}$ @ 95% CL

new ATLAS result
on 2012 data on the way !

CL_s EXTRACTION

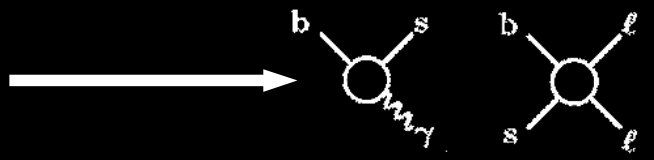
ANGULAR ANALYSIS OF $B_0 \to K^{*}(\to K^{+}\pi^{-})\,\mu^{+}\mu^{-}$: MOTIVATION





MOTIVATION

- relatively small SM BR ≈ $1.1*10^{-6}$
- loop-mediated FCNC,
  $b \to s + \mu^{+}\mu^{-}$ transition sensitive to NP
  via interference of the 4- fermion operators

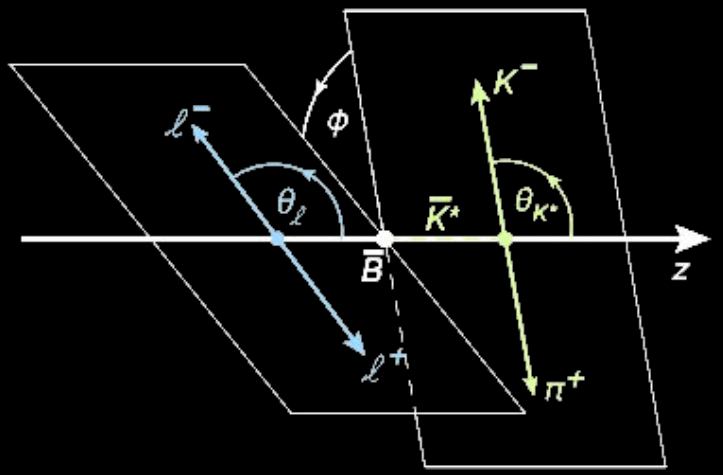


- the hadronic uncertainties cancel out (to some order) for:
  - lepton forward-backward asymmetry – A_{FB}
  - K^{*0} longitudinal polarization fraction - F_L
- differential angular distributions of the 4-body final state are measured
  (as function of dimuon mass q^2)

ANGULAR ANALYSIS OF $B_D \to K^*(\to K^+\pi^-)\mu^+\mu^-$: DECAY DESCRIPTION

KINEMATIC OBSERVABLES

- 3 angles (θ_L, θ_K, Φ) and dimuon mass q^2 ($K^{*0}_{\text{on shell}}$)
- differential decay rate: $\dfrac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi}$



MEASURED QUANTITIES

- due to insufficient statistics 2 out of 3 angles integrated out from the 4 differential decay rate – studied 2D rates:

$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_K} = \frac{3}{2}F_L(q^2)\cos^2\theta_K + \frac{3}{4}\left(1-F_L(q^2)\right)\left(1-\cos^2\theta_K\right)$$

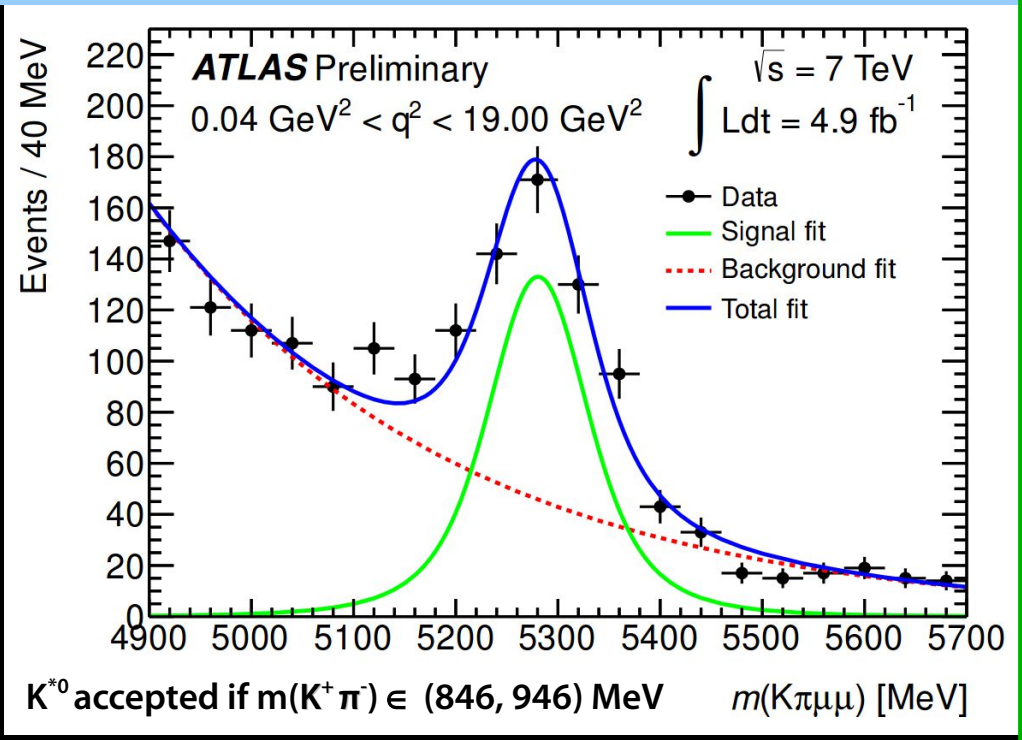
$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_L} = \frac{3}{4}F_L(q^2)\left(1-\cos^2\theta_L\right) + \frac{3}{8}\left(1-F_L(q^2)\right)\left(1+\cos^2\theta_L\right) + A_{FB}(q^2)\cos\theta_L$$

- measured $\langle A_{FB}\rangle$ and $\langle F_L\rangle$ with unbinned maximum likelihood fit in q^2 bins

ANGULAR ANALYSIS OF $B_D \to K^{*}(\to K^{+}\pi^{-})\,\mu^{+}\mu^{-}$: SIGNAL

B_D MASS LIKELIHOOD FIT :

- cut-based selection optimized on MC
- gaussian for signal (with per-event errors) exponential for the background.
  - $N_{sig} = 466 \pm 34$
  - $N_{bkg} = 1132 \pm 43$

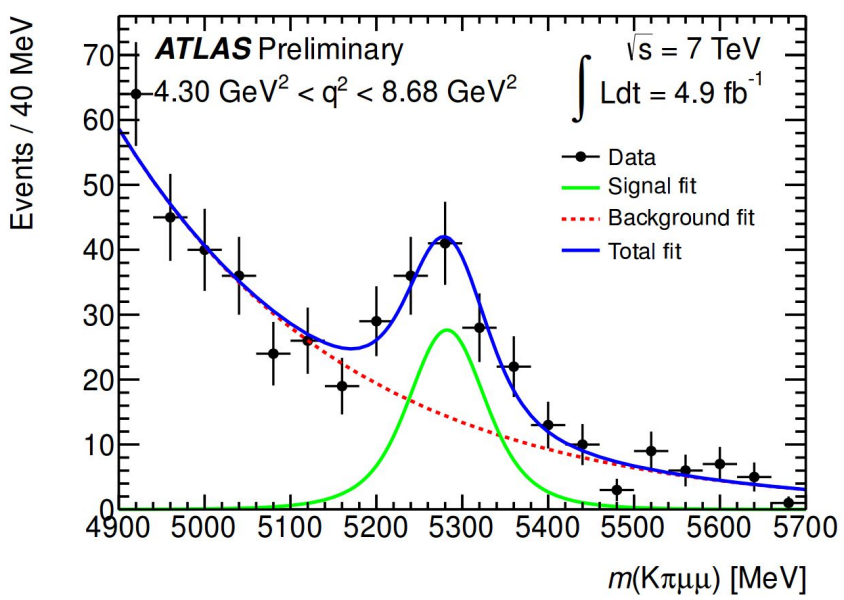


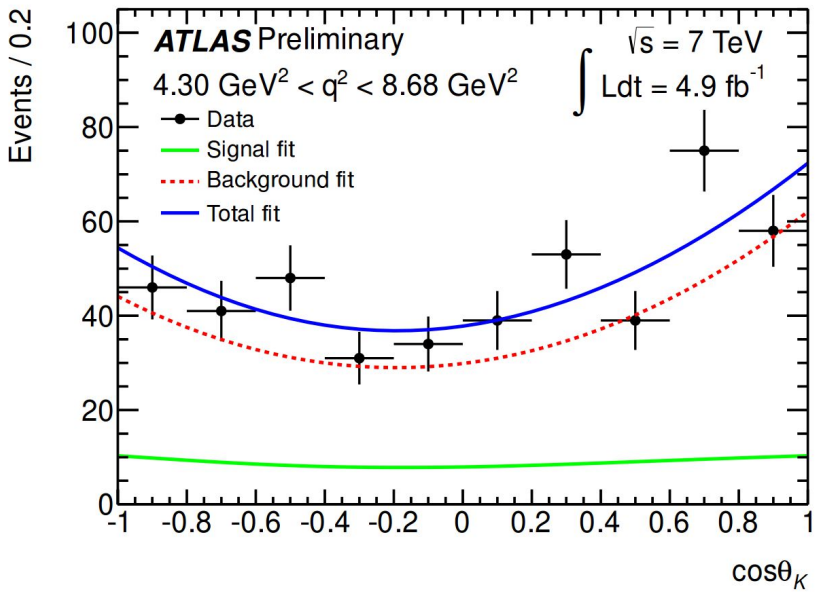
NO MEASUREMENT ON:

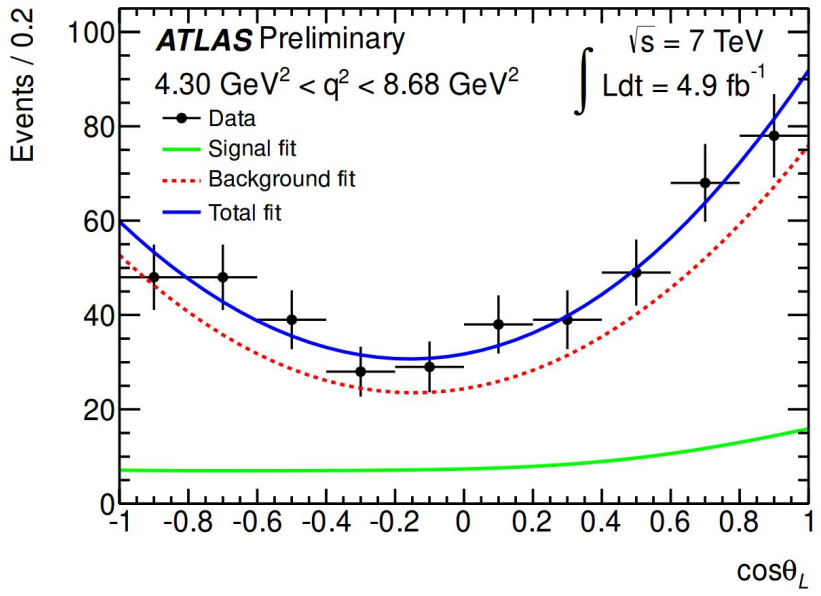
- $q^2 < 2$ GeV^2, limited statistics due to trigger acceptance
- experimental veto on J/ψ and ψ(2S) regions :
  - $8.68 < q^2 < 10.09$ - J/ψ region
  - $12.86 < q^2 < 14.18$ - ψ(2S) region
  - cut $\big|\,|m(B_d)_{REC} - m(B_d)_{PDG}| - |m(\mu^+\mu^-)_{REC} - m(J/\psi)_{PDG}|\,\big| < \Delta m$ with Δm = 130 MeV is applied

ATLAS-CONF-2013-038

ANGULAR ANALYSIS OF $B_0 \to K^{*}(\to K^{+}\pi^{-})\mu^{+}\mu^{-}$: A_{FB} & F_L MEASUREMENTS





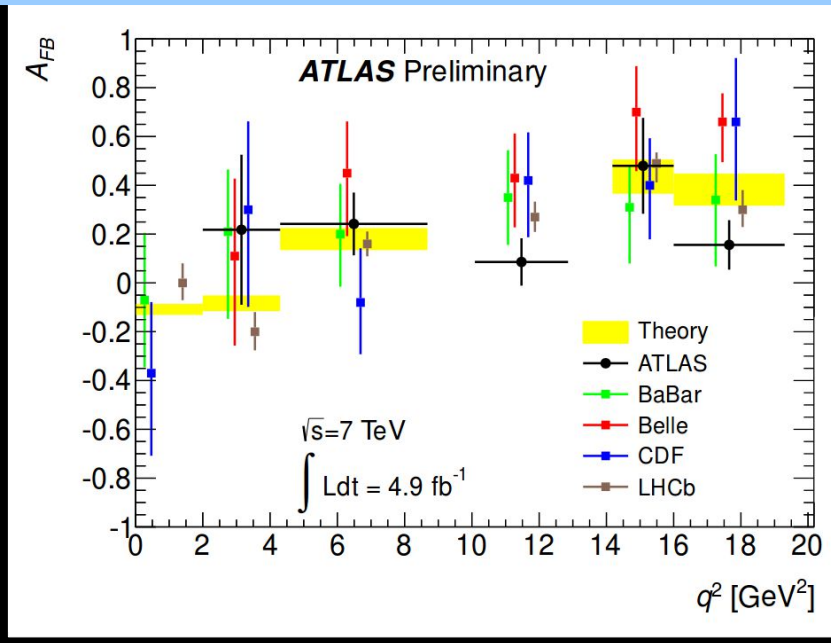


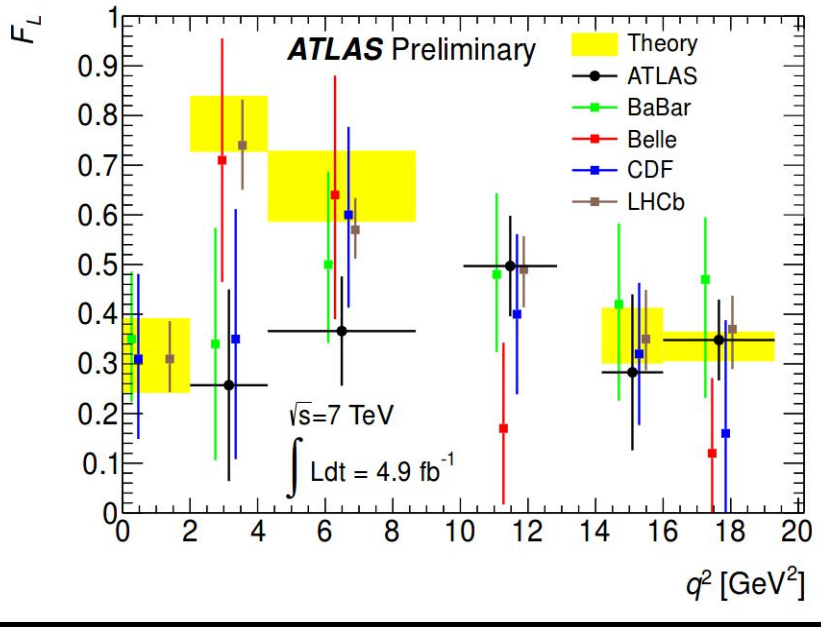
FIT STRATEGY

- extended unbinned maximum likelihood fit (performed sequentially):
  - 1) mass distribution fitted to separate signal and background yields
  - 2) simultaneous mass-angular fit performed on the events
    (the mass PDF parameters and signal fraction kept fixed from the previous fit)
  - done separately for each of the 6 q^2 bins

ATLAS-CONF-2013-038

ANGULAR ANALYSIS OF $B_0 \to K^{*}(\to K^{+}\pi^{-})\,\mu^{+}\mu^{-}$: A_{FB} & F_L FIT RESULTS





Theory: C. Bobeth, G. Hiller and D. van Dyk, arXiv:1105.2659

q^2 range (GeV^2)	N_{sig}	A_{FB}	F_L
$2.00 < q^2 < 4.30$	19 ± 8	$0.22 \pm 0.28 \pm 0.14$	$0.26 \pm 0.18 \pm 0.06$
$4.30 < q^2 < 8.68$	88 ± 17	$0.24 \pm 0.13 \pm 0.01$	$0.37 \pm 0.11 \pm 0.02$
$10.09 < q^2 < 12.86$	138 ± 31	$0.09 \pm 0.09 \pm 0.03$	$0.50 \pm 0.09 \pm 0.04$
$14.18 < q^2 < 16.00$	32 ± 14	$0.48 \pm 0.19 \pm 0.05$	$0.28 \pm 0.16 \pm 0.03$
$16.00 < q^2 < 19.00$	149 ± 24	$0.16 \pm 0.10 \pm 0.03$	$0.35 \pm 0.08 \pm 0.02$
$1.00 < q^2 < 6.00$	42 ± 11	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

ATLAS-CONF-2013-038

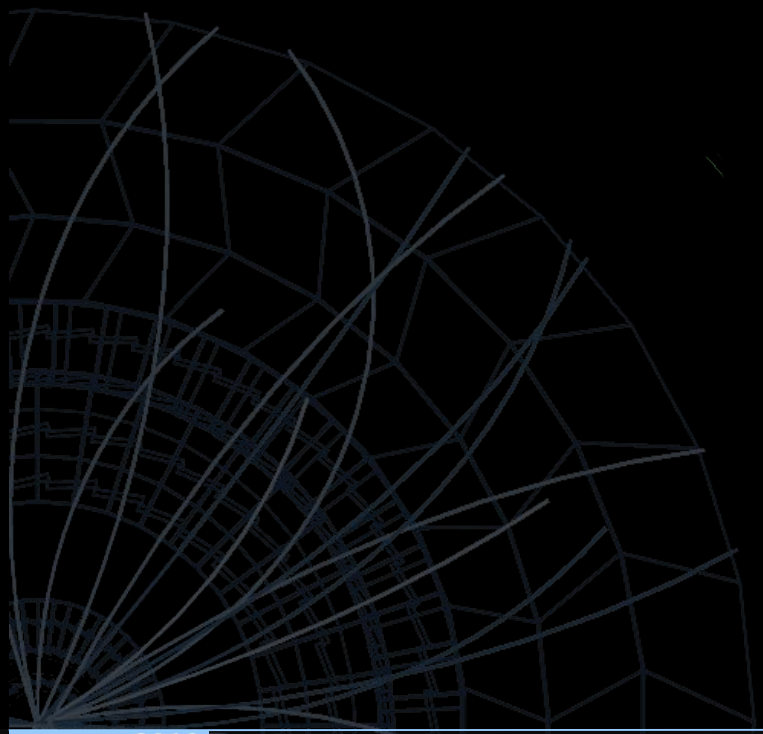
FIT RESULTS

- statistical uncertainty dominates
- ATLAS measurement in agreement with SM

CONCLUSIONS

- **ATLAS HAS HIGH QUALITY B PHYSICS PROGRAM**
  - search for the rare decay $B_s \rightarrow \mu^+\mu^-$
    ATLAS-CONF-2013-076
  - angular analysis of the decay $B_d \rightarrow K^*(\rightarrow K^+\pi^-)\,\mu^+\mu^-$
    ATLAS-CONF-2013-038
- **NO SIGNIFICANT DEVIATION FROM SM PREDICTIONS (NO NP SIGNS)**
- **UPDATED RESULTS WITH THE FULL 2011 DATASET**
- **> 20 FB^{-1} OF THE FULL 2012 DATASET IS BEING ANALYZED**
- **IMPROVED ANALYSIS TECHNIQUES ON THE WAY – STAY TUNED**

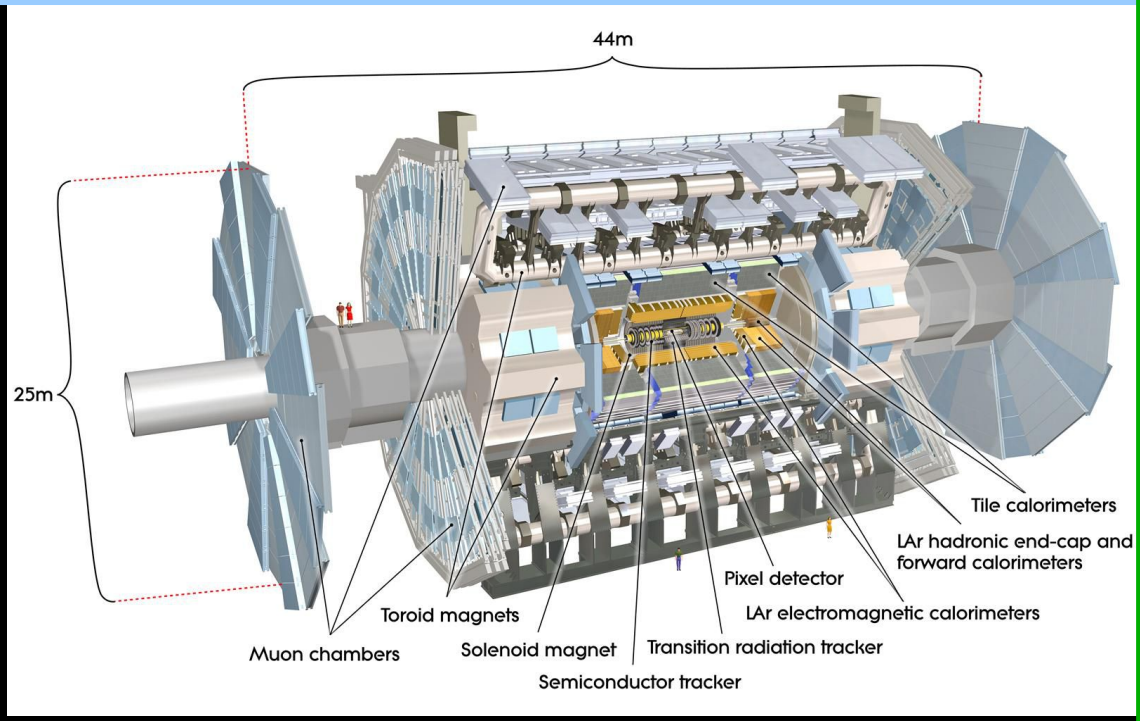
BACKUP



ATLAS DETECTOR

INNER DETECTOR ($|\eta| < 2.4$)

- silicon pixel, strip and transition radiation tracker
  - impact parameter resolution
    ≈ 10 μm
- 2T solenoidal field



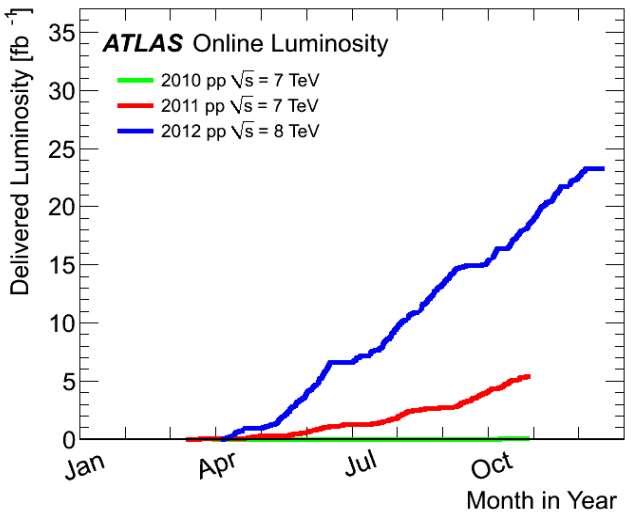
MUON SPECTROMETER ($|\eta| < 2.7$)

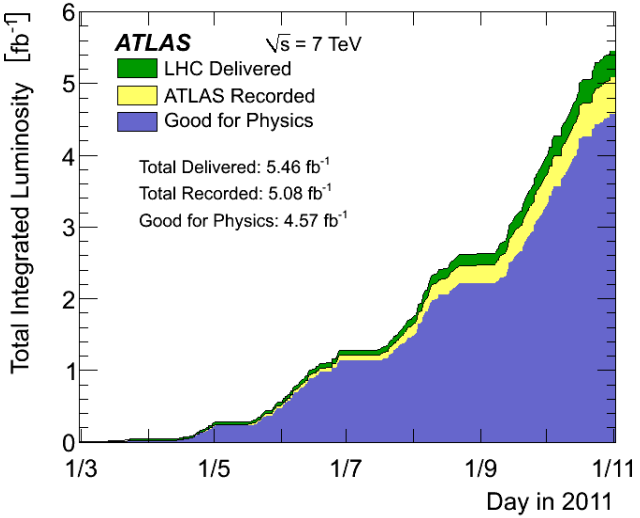
- trigger chambers (RPC, TGC), tracking chambers (MDT, CSC)
- 0.5-2 T toroidal field

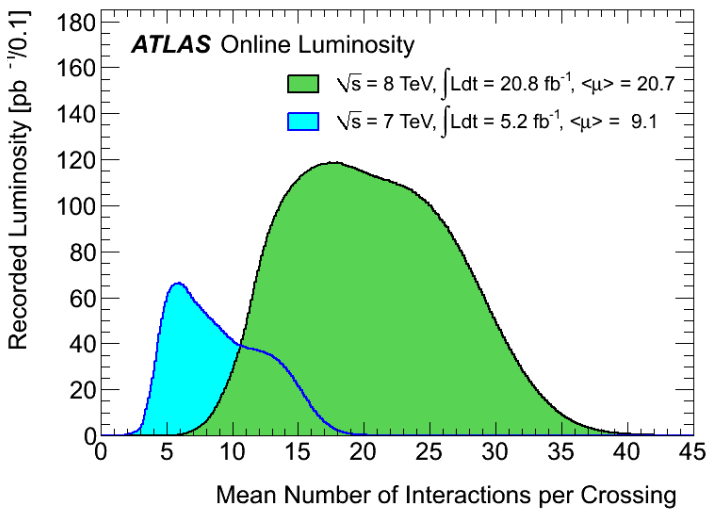
TRACKING

- $\sigma_{pT}/p_T \sim 0.05\%\ p_T \oplus 1.5\%$
  (for $p_T < 100$ GeV is ID dominated)
- $\sigma_m(J/\psi\text{-}\Upsilon) \sim 60\text{-}120$ MeV
  (ID dominated)

ATLAS DATA TAKING





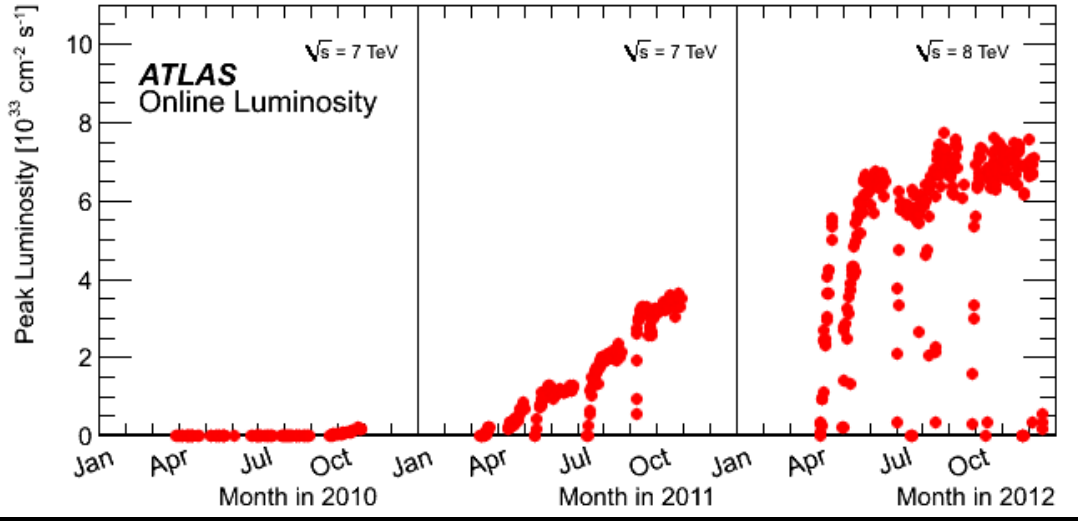


2011

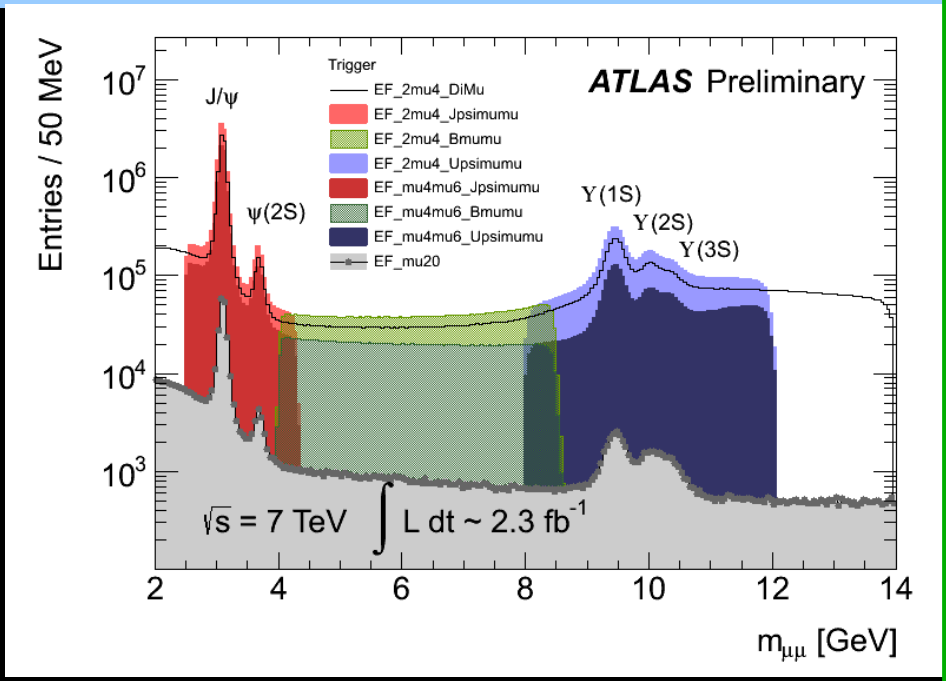
- > 5 fb^{-1} recorded
- instantaneous luminosity and pile-up steadily increasing

2012

- ~ 23fb^{-1} recorded
- Flatter instantaneous luminosity profile
- Challenging pile-up conditions !



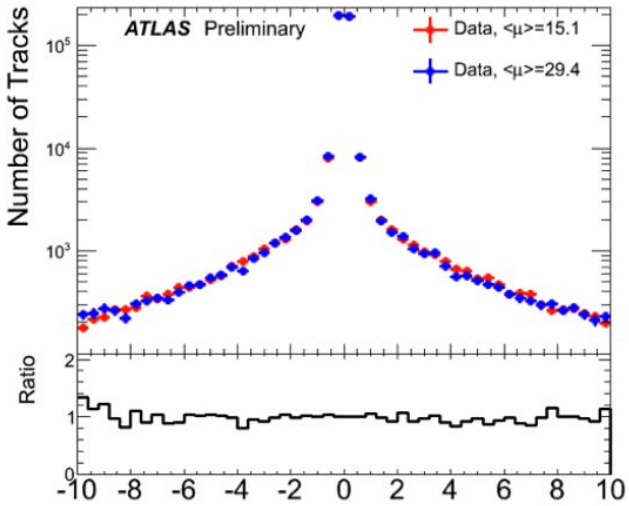
ATLAS B-EVENT SELECTION @ 2011 DATA



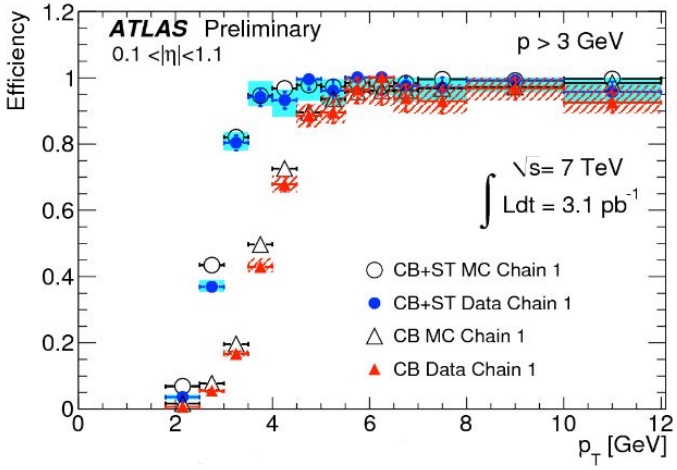
ATLAS DI-MUON TRIGGER

- 5 fb^{-1} ~ 150G B^0–pairs, ~ 30M $B_s \rightarrow J/\psi\,\Phi$
- events are selected by dimuon triggers
- specific dimuon selections with Barrel/Endcap logic introduced in 2012
- new dedicated $\mu^+\mu^-X$ trigger introduced in 2012
- B-physics trigger (mu4mu4) thresholds kept unprescaled during 2011 despite the increasing instantaneous luminosity

ATLAS TRACKING IN PILE-UP



ATLAS-COM-PHYS-2011-1312



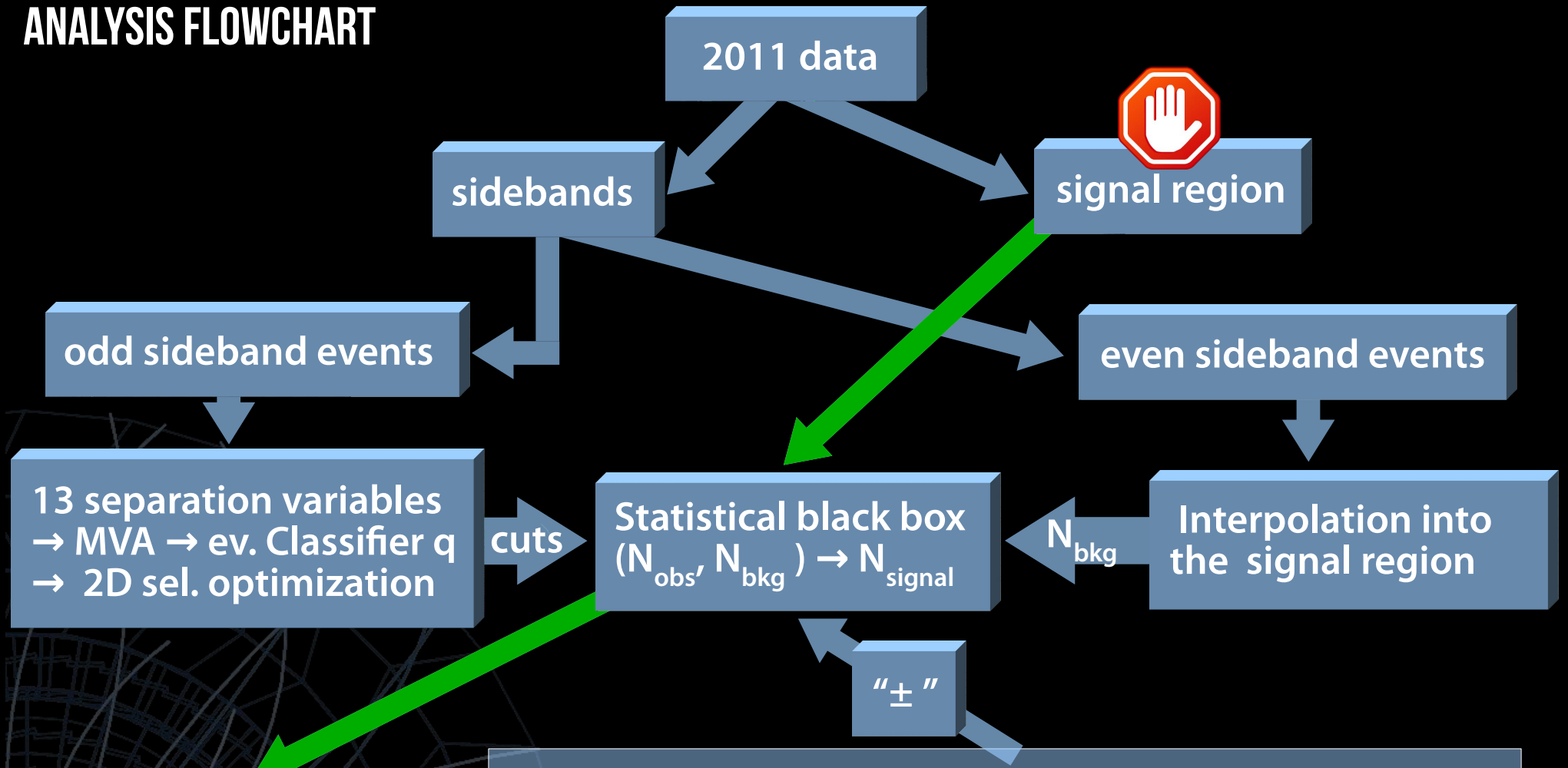
ATLAS-CONF-2011-021

MUON RECONSTRUCTION

- plots show:
  - transverse impact parameter at two different pile-up conditions
    (tails sensitive to rate of secondaries and muon fake rate - no increase observed)
  - muon reconstruction efficiency using J/ψ decays
    (CB=ID+MS tracks matched, ST = ID track +MS segment matched)

SEARCH FOR $B_s \rightarrow \mu^+\mu^-$: ATLAS ANALYSIS STRATEGY

ANALYSIS FLOWCHART



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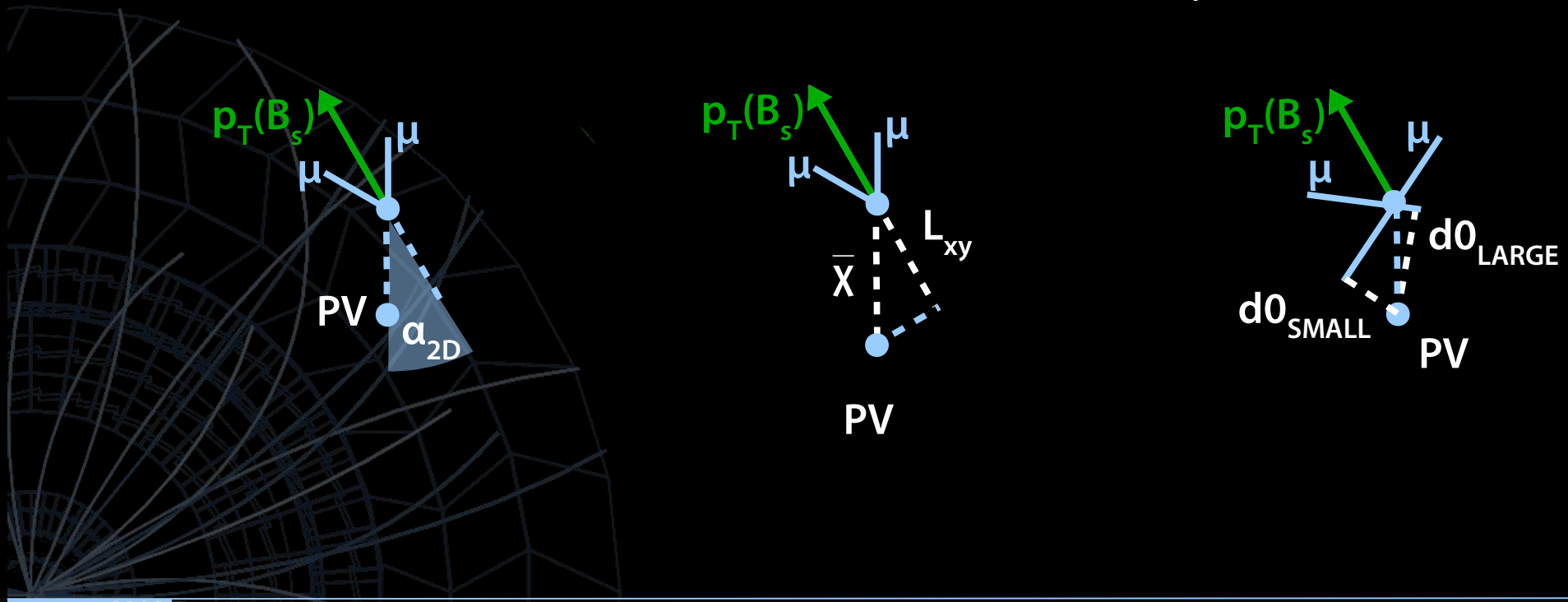
BACKUP: SEARCH FOR $B_s \rightarrow \mu^+\mu^-$, EVENT RECONSTRUCTION

SIGNAL CANDIDATE SELECTION

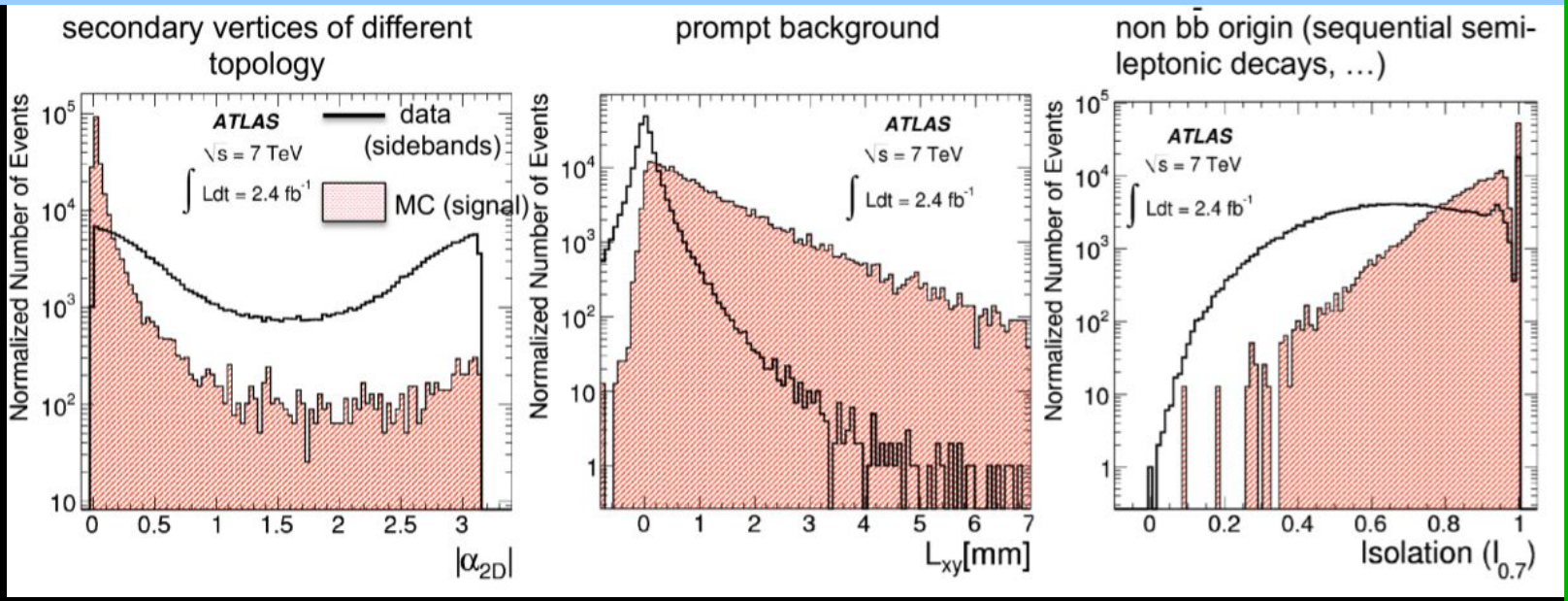
- 2, 3 or 4 prong vertex constraint depending on decay topology
- primary vertex selection:
  - closest in z to the B candidate
  - re-fit excluding B daughters
- tracks:
  - at least 1 pixel, 6 SCT and 9 TRT hits (good tracks)
  - $|\eta| < 2.5$ and $p_T > 4$ (2.5) GeV for muons (kaons)
  - tracks from the tracking systems matched to muon spectrometer tracks
- B candidates $p_T > 8$ GeV and $|\eta| < 2.5$
  - events selected based on their decay topology using many discriminating variables

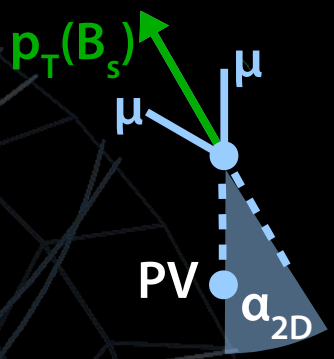
BACKUP: SEARCH FOR $B_s \to \mu^+\mu^-$, DISCRIMINATING VARIABLES

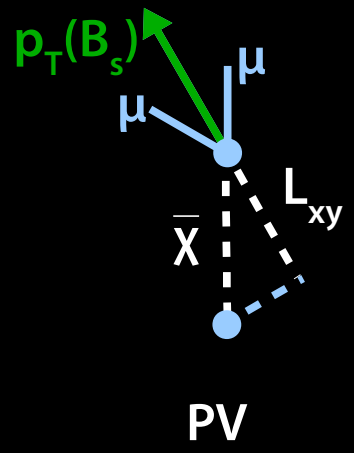
- discriminating variables:
  - distinguish B and continuum events
  - highest discriminating power
  - exclusion of highly correlated variables
  - only variables not correlated with invariant mass were taken
  - exploit PV-SV separation (L_{xy}), symmetry of the final state (d_0), pointing angle, b-hadronisation features (isolation, p_T of the B)



BACKUP: SEARCH FOR $B_s \to \mu^+\mu^-$, DISCRIMINATING VARIABLES







$$I^{\Delta R} = \frac{P_T^B}{P_T^B + \sum_i^{\Delta R} p_T^i}$$

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BACKUP: SEARCH FOR $B_s \to \mu^+\mu^-$, DISCRIMINATING VARIABLES

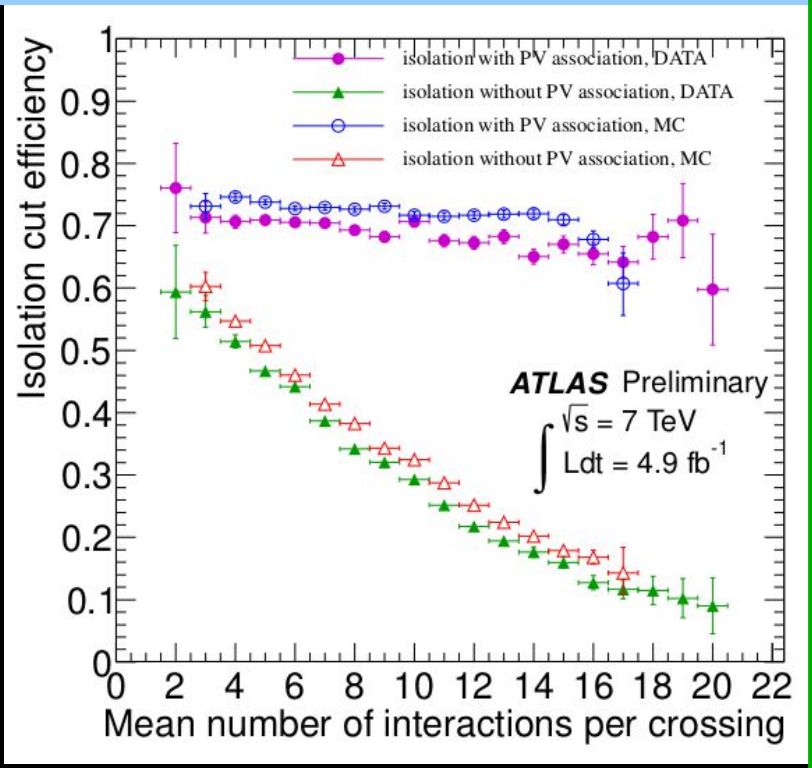
Variable	Description	Ranking
L_{xy}	Scalar product in the transverse plane of $(\Delta\vec{x} \cdot \vec{p}^B)/\lvert\vec{p}^B_T\rvert$	1
$I_{0.7}$ isolation	Ratio of $\lvert\vec{p}^B_T\rvert$ to the sum of $\lvert\vec{p}^B_T\rvert$ and the transverse momenta of all tracks with $p_T > 0.5$ GeV within a cone $\Delta R < 0.7$ from the B direction, excluding B decay products	2
$\lvert\alpha_{2D}\rvert$	Absolute value of the angle in the transverse plane between $\Delta\vec{x}$ and $\vec{p}^B$	3
p_L^{min}	Minimum momentum of the two muon candidates along the B direction	4
p_T^B	B transverse momentum	5
ct significance	Proper decay length $ct = L_{xy} \times m_B/p_T^B$ divided by its uncertainty	6
χ^2_z, χ^2_{xy}	Significance of the separation between production (PV) and decay vertex (SV) $\Delta\vec{x}^T \cdot \left(\sigma^2_{\Delta\vec{x}}\right)^{-1} \cdot \Delta\vec{x}$, in z and (x, y), respectively	7, 13
$\lvert D_{xy}\rvert^{min}, \lvert D_z\rvert^{min}$	Absolute values of the minimum distance of closest approach in the xy plane or along z of tracks in the event to the B vertex	8, 11
ΔR	Angle $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ between $\Delta\vec{x}$ and $\vec{p}^B$	9
$\lvert d_0\rvert^{max}, \lvert d_0\rvert^{min}$	Absolute values of the maximum and minimum impact parameter in the transverse plane of the B decay products relative to the primary vertex	10, 12

BACKUP: SEARCH FOR $B_s \to \mu^+\mu^-$, ISOLATION

- isolation variable:

$$I^{\Delta R} = \frac{P_T^B}{P_T^B + \sum_i^{\Delta R} p_T^i}$$

  - tracks with pT > 0.5 GeV excluding B daughters in cone $\Delta R < 0.7$, where $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\Phi^2)}$
  - only tracks associated with the corresponding PV are taken to avoid isolation cut efficiency to depend on pile-up



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BACKUP: SEARCH FOR $B_s \to \mu^+\mu^-$, ACCEPTACE X EFFICIENCY RATIO

$$BR(B_s \to \mu^+\mu^-) = N_{Bs \to \mu+\mu-}(1/N_{ref}) \times BR(ref) \times (f_u/f_s) \times (\varepsilon_{tot} \times A_{tot})_{ref} / (\varepsilon_{tot} \times A_{tot})_{Bs \to \mu+\mu-}$$

- determined on reweighted B_s and B^+ MC samples wrt the fiducial volume
- systematic uncertainties:
  - dominant contribution from data-MC discrepancies of separation variables
  - main discrepancies come from : Isolation and L_{xy}
  - isolation is B-flavour dependent
  - L_{xy} is correlated with the vertex reconstruction (→ with other discriminant variables) but it is B-flavour independent

Channel	$A \times \epsilon$	$R_{A\epsilon}$
B^+	1.317 ± 0.008% (stat)	0.267 ± 1.8% (stat) ± 6.9% (syst)
B_s^0	4.929 ± 0.084% (stat)	

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BACKUP: SEARCH FOR $B_s \rightarrow \mu^+\mu^-$, SES

SINGLE EVENT SENSITIVITY

$$BR(B_s \rightarrow \mu^+\mu^-) = N_{Bs \rightarrow \mu+\mu-} (1/ N_{ref}) \times BR(ref) \times (f_u/f_s) \times (\varepsilon_{tot} \times A_{tot})_{ref} / (\varepsilon_{tot} \times A_{tot})_{Bs \rightarrow \mu+\mu-}$$

- Corresponds to signal branching fraction which would yield one observed signal event in the data sample
- From the interpolation of 50% of the sideband events (8 even events) we expect: 6.75 background events in the optimized search window

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BACKUP: SEARCH FOR $B_s \to \mu^+\mu^-$, SYSTEMATICS ON SES

SES SYSTEMATIC UNCERTAINTIES

- Table shows summary of ΔSES/SES uncertainty (due to syst. uncertainty sources) → SES statistical uncertainty of 2.1%

description	contribution
PDG branching fractions and f_s/f_d	8.5%
$K^\pm$ tracking efficiency	5%
vertexing efficiency	2%
$K^\pm$ charge asymmetry. in $B^\pm \to J/\psi K^\pm$	1%
$B^\pm \to J/\psi K^\pm$ yield	2.4%
$R_{A\epsilon}$	6.9%
total (comb. in quadrature)	12.5%

- contributions from backgrounds:
  - background interpolation from sidebands → 4% on R_{bkg}
  - B → hh' negligible
- Mainly contribute: BR_{ref} and f_u/f_s, acc-vs-eff ratio (data-MC discrepancies), K tracking efficiency

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BACKUP: SEARCH FOR $B_s \to \mu^+\mu^-$, UPPER LIMIT EXTRACTION

CL_s METHOD WITH PROFILE LIKELIHOOD FUNCTION:

$$\mathcal{L} = \text{Poisson}(N_{SR}^{obs}|\epsilon\,\mathcal{B} + N_{bkg} + N_{B\to hh})\,\text{Poisson}(N_{bkg,SB}^{obs}|R_{bkg}\,N_{bkg}) \times \text{Gauss}(\epsilon^{obs}|\epsilon,\sigma_\epsilon)\,\text{Gauss}(R_{bkg}^{obs}|R_{bkg},\sigma_{R_{bkg}})$$

$\varepsilon = 1/SES$ $\quad R = \Delta_{SB}/\Delta_{SR}$

- the expected UL is calculated assuming the number of events in the signal region as the number of expected events obtained from the sideband interpolation (6.75 events):

quantity	value
$N_{J/\psi K^\pm}$	$15\,214 \pm 1.10\% \pm 2.39\%$
$R_{A\epsilon}$	$0.267 \pm 1.8\% \pm 6.9\%$
SES	$(2.07 \pm 0.26) \cdot 10^{-9}$
R_{bkg}^{obs}	1.240 ± 0.050
N_{SR}^{exp} | N_{SR}^{obs}	6.75 | 6
$N_{bkg,SB}^{obs}$	8
$N_{B\to hh}$	0.30

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BACKUP: SEARCH FOR $B_s \rightarrow \mu^+\mu^-$

FINAL SELECTION OPTIMIZATION

- signal efficiency calculated directly
- background from sidebands
- The odd sideband event optimization gives a maximum of P estimator = 0.0145
- The corresponding final selection cuts on the mass window and the BDT classifier are:
  - BDT classifier > 0.118 and $|\Delta m| < 121$ MeV

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BACKUP: SEARCH FOR $B_s \rightarrow \mu^+\mu^-$

PEAKING BACKGROUND

- fake rates for π±/ K+ /K- obtained on MC = 2.1/4.1/3.3 ‰ (uncertainty on these fake rates is ~20%)
- 0.3 ev contribution to the signal region
  - $BR_{B \rightarrow hh'}$ x (fake rate) ≈ 10^{-9} ≈ SM BR_{sig}
    → (also accounted for in systematics)
- included in the optimization procedure and in the upper limit calculation.

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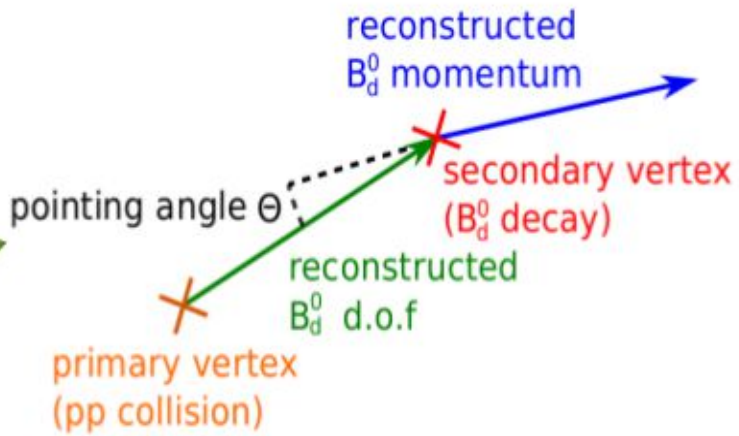
BACKUP: ANGULAR ANALYSIS OF $B_0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$: BASELINE CUTS

- Baseline:
  - $p_T(\mu) > 3.5$ GeV
  - $|\eta| < 2.5$ for all tracks
  - $\chi^2/\text{n.d.f}(\mu\mu) < 10$
  - $846 < M(K^{*0}) < 946$ MeV
  - $p_T(K) > 0.5$ GeV
  - $p_T(\pi) > 0.5$ GeV
- J/ψ, $\Psi'(2S)$ regions are excluded
- Selection (cut values are optimized):
  - $\tau/\Delta\tau(B_d) > 12.75$
  - $\cos(\theta) > 0.999$
  - $\chi^2/\text{n.d.f.}(B_d) < 2.0$
  - $p_T(K^*) > 3$ GeV
  - $|(M(B^0)_{rec} - M(B^0)_{PDG})| - |(M(\mu\mu)_{rec} - M(J/\psi)_{PDG})| > 130$ MeV



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BACKUP: ANGULAR ANALYSIS OF $B_D \to K^*(\to K^+\pi^-)\mu^+\mu^-$: MASS FIT

FIT STRATEGY

- Extended unbinned maximum likelihood fit (performed sequentially):
  - 1) mass (Kπμμ) distribution fitted to separate signal and background yields

$$\mathcal{L} = \prod_{i=1}^{N} \left[N_{\text{sig}} \cdot \mathcal{M}_{\text{sig}}(m_i, \delta_{m_i}) + N_{\text{bckg}} \cdot \mathcal{M}_{\text{bckg}}(m_i) \right],$$

$$\mathcal{M}_{\text{bckg}}(m_i) = e^{-\lambda \cdot m_i}$$

$$\mathcal{M}_{\text{sig}}(m_i, \delta_{m_i}) = \frac{1}{\sqrt{2\pi} s_m \delta_{m_i}} \exp\left(\frac{-(m_i - m_{B_d^0})^2}{2(s_m \delta_{m_i})^2} \right)$$

  - 2) angular fit performed on the signal and background events from the previous fit (fixed mass)
  - Done separately for each of the 6 q^2 bins
- The procedure checked to give the same results as single-step fit except the lowest q^2 bin (included in systematics there).

BACKUP: ANGULAR ANALYSIS OF $B_D \to K^*(\to K^+\pi^-)\mu^+\mu^-$: ANGULAR FIT

- Angular fit (in each q2 bin) :

$$\mathcal{L} = \prod_{i=1}^{N} [N_{\text{sig}}^{\text{fix}} \cdot \mathcal{M}_{\text{sig}}(m_i, \delta_{m_i}|\text{fixed}) \cdot \mathcal{A}_{L,\text{sig}}(\cos\theta_{L,i}) \cdot \alpha_L(\cos\theta_{L,i}) \cdot \mathcal{A}_{K,\text{sig}}(\cos\theta_{K,i}) \cdot \alpha_K(\cos\theta_{K,i}) + N_{\text{bckg}}^{\text{fix}} \cdot \mathcal{M}_{\text{bckg}}(m_i|\text{fixed}) \cdot \mathcal{A}_{L,\text{bckg}}(\cos\theta_{L,i}) \cdot \mathcal{A}_{K,\text{bckg}}(\cos\theta_{K,i})]$$

- Signal PDFd:

$$\mathcal{A}_{L,\text{sig}}(\cos\theta_{L,i}) = \frac{3}{4} F_L(q^2)\left(1-\cos^2\theta_{L,i}\right) + \frac{3}{8}\left(1-F_L(q^2)\right)\left(1+\cos^2\theta_{L,i}\right) + A_{FB}(q^2)\cos\theta_{L,i}$$

$$\mathcal{A}_{K,\text{sig}}(\cos\theta_{K,i}) = \frac{3}{2} F_L(q^2)\cos^2\theta_{K,i} + \frac{3}{4}\left(1-F_L(q^2)\right)\left(1-\cos^2\theta_{K,i}\right)$$

- Background PDF – linear combination of Chebyshev polynomials (to 2nd order)

$$\mathcal{A}_{L(K),\text{bkg}} = 1 + p_{1L(K)}\cos\theta_{L(K),i} + p_{2L(K)}\left(2\cos^2\theta_{L(K),i} - 1\right)$$

- detector and selection effects on the angular shapes taken into account via the acceptance functions $\alpha_L(\cos\theta_{L,i})$, $\alpha_K(\cos\theta_{K,i})$

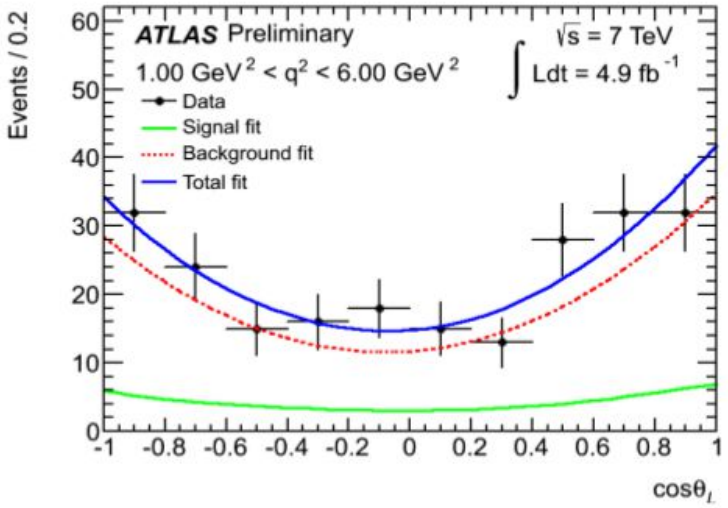
BACKUP: ANGULAR ANALYSIS OF $B_D \to K^*(\to K^+\pi^-)\,\mu^+\mu^-$: SYSTEMATICS

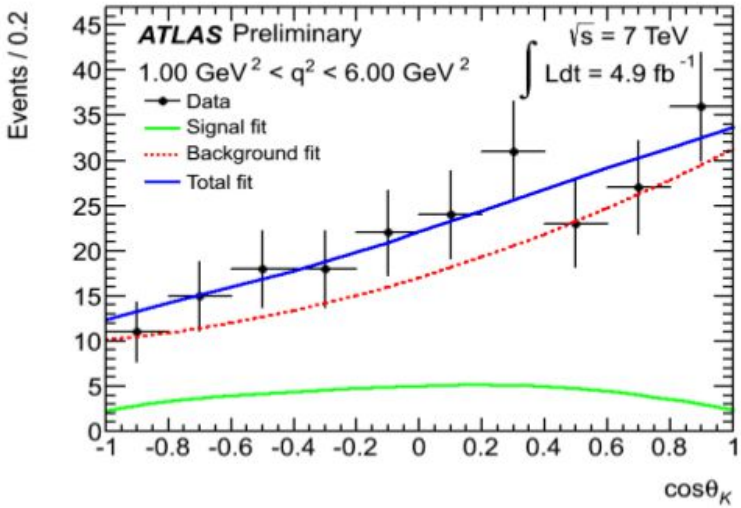
SYSTEMATIC UNCERTAINTIES

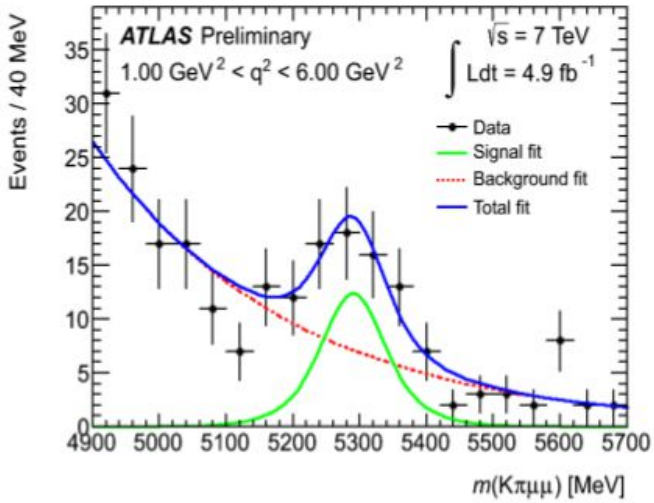
- Ranges of the mass fit region
  - Differ in q^2 bins due to ΔM cut effect
- Angular background shapes
  - Varied between 2nd and 3rd Chebyshev polynomials
- Contribution of $B^\pm \to \mu^+\mu^- K^\pm$ events
  - estimated by removing potential $B^\pm \to \mu^+\mu^- K^\pm$ candidates
- Angular acceptance effects
  - Mainly from limited MC statistics
  - Various signal angular shapes tested
- Sequential fitting approach
  - Non-negligible effect only in $2.00 < q^2 < 4.30\ \mathrm{GeV}^2$ bin due to low statistics
- Negligible sources:
  - Contribution from S-wave ($B_d \to K^+\pi^-\mu^+\mu^-$)
  - Contribution from $B_s \to \Phi(\to K^+K^-)\,\mu^+\mu^-$
  - Background mass shape
  - Possible bias due to angular fit approach (neglecting correlation)

BACKUP: ANGULAR ANALYSIS OF $B_0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$: OTHER BINS

$1.00 < q^2 < 6.00$







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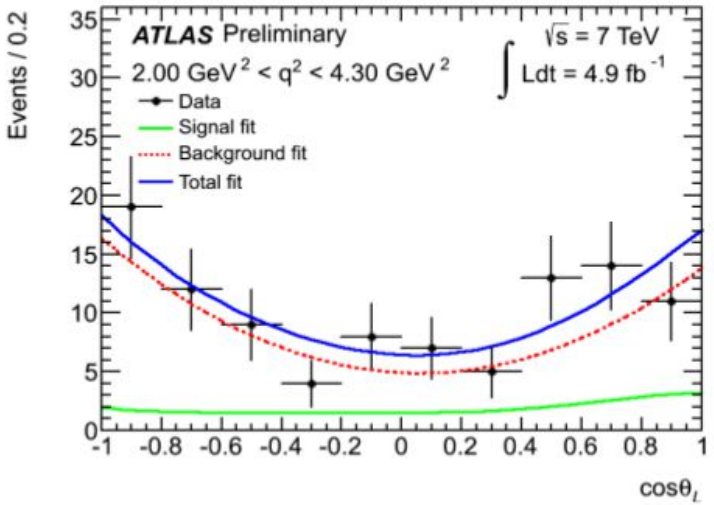
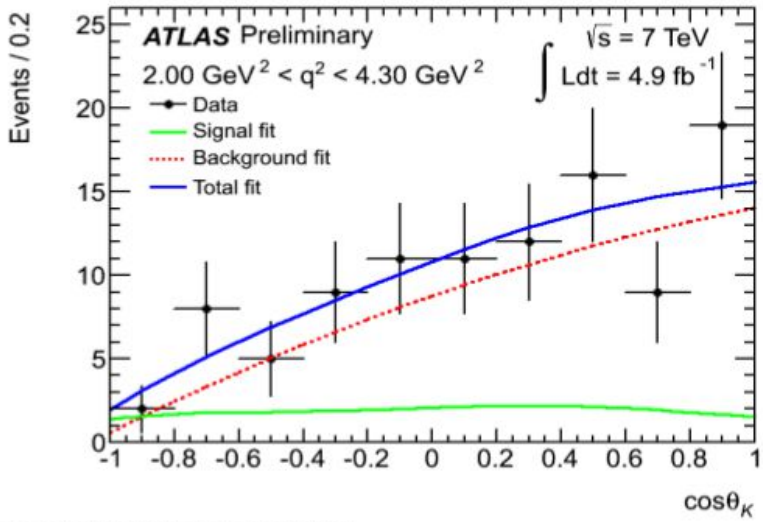
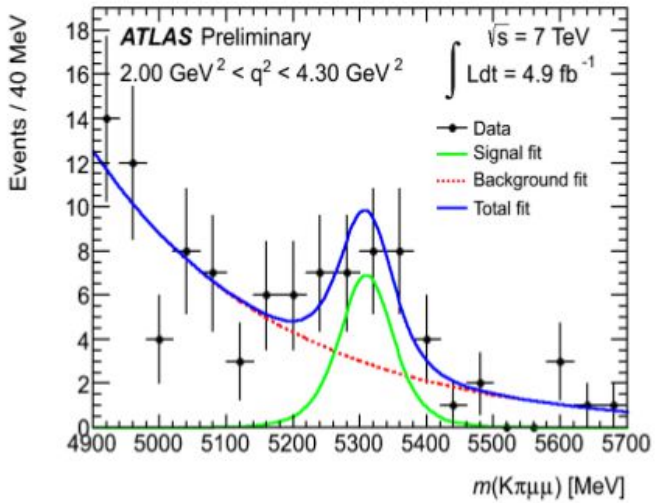
BACKUP: ANGULAR ANALYSIS OF $B_0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$: OTHER BINS

$2.00 < q^2 < 4.30$







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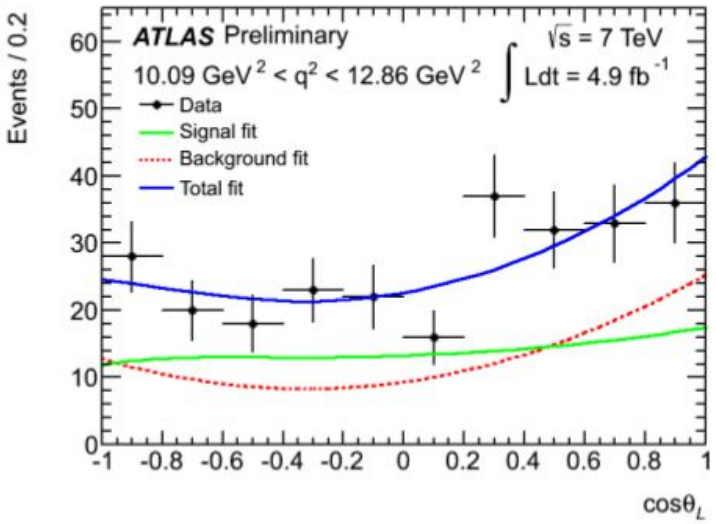
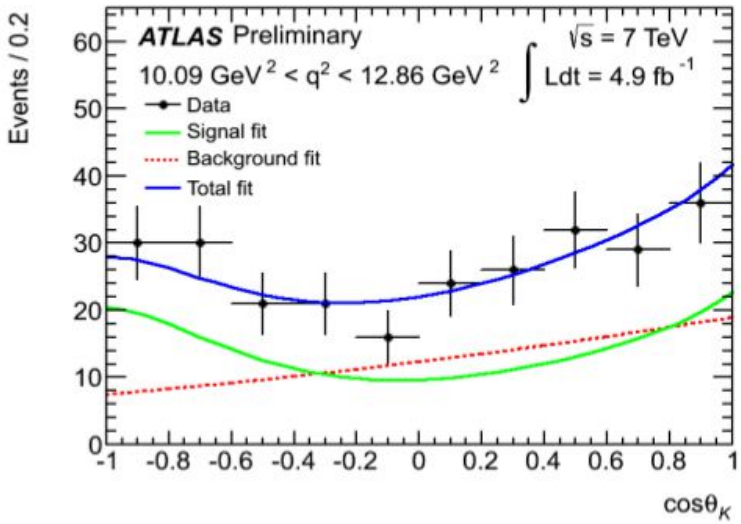
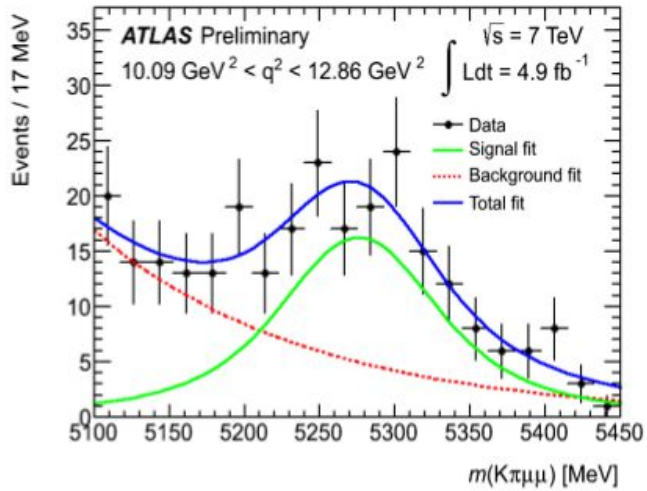
BACKUP: ANGULAR ANALYSIS OF $B_0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$: OTHER BINS

$10.09 < q^2 < 12.86$







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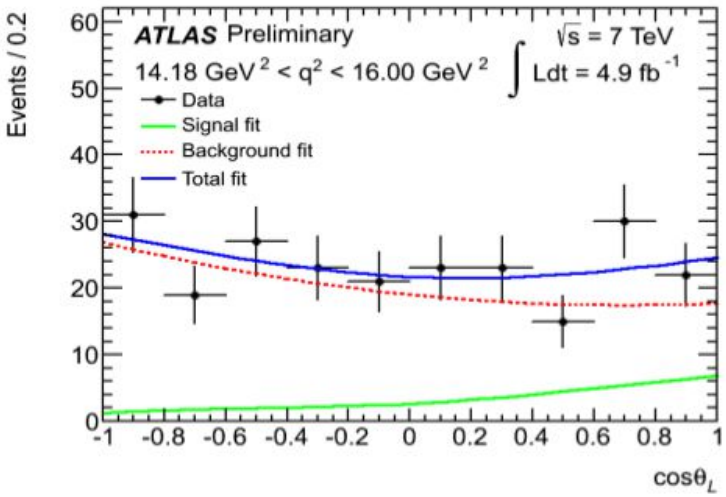
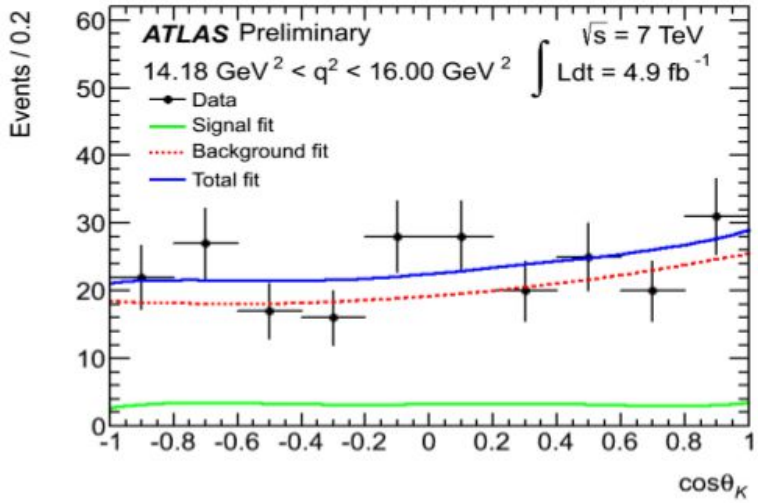
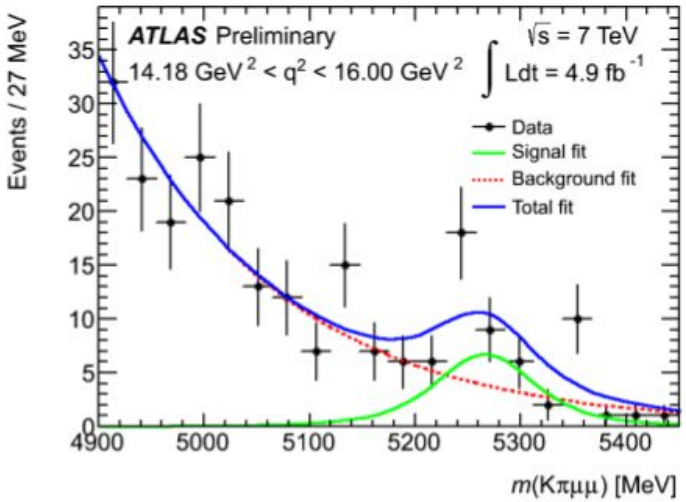
BACKUP: ANGULAR ANALYSIS OF $B_0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$: OTHER BINS

$14.18 < q^2 < 16.00$







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