$R_{K^{*0}}$ measurement at LHCb

Physics at the Terascale

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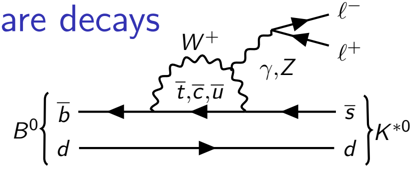
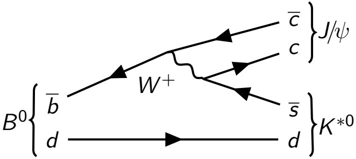
Lepton flavour universality in rare decays



$B^0 \to K^{*0}\ell\ell$ Feynman diagram

- In SM flavour-changing neutral current (FCNC) processes only allowed in loop diagrams
- Their small branching ratios $\mathcal{B}$ make them sensitive to New Physics

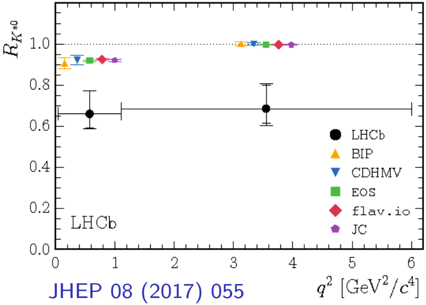


control channel Feynman diagram

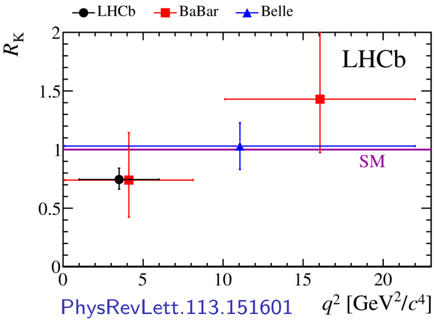
- This analysis measures the ratio of $R_{K^{*0}} = \mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathcal{B}(B^0 \to K^{*0}e^+e^-)$, which is unity in SM due to lepton flavour universality
- The K^{*0} decays further into $K^+\pi^-$
- Use $B^0 \to K^{*0}J/\psi(\to\ell^+\ell^-)$ tree-level decay as control channel $\to$ develop and optimise analysis method

LHCb Run 1 result

- LHCb result with Run 1 data published in JHEP 08 (2017) 055
- $R_{K^{*0}}$ shows a $2.4-2.5\sigma$ deviation from SM in two bins of q^2
- A related measurement of the R_K ratio also lies under SM expectations



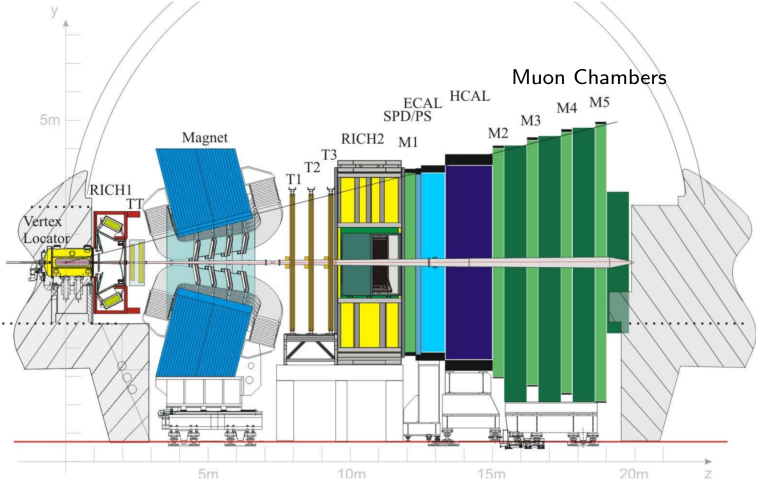
JHEP 08 (2017) 055



PhysRevLett.113.151601

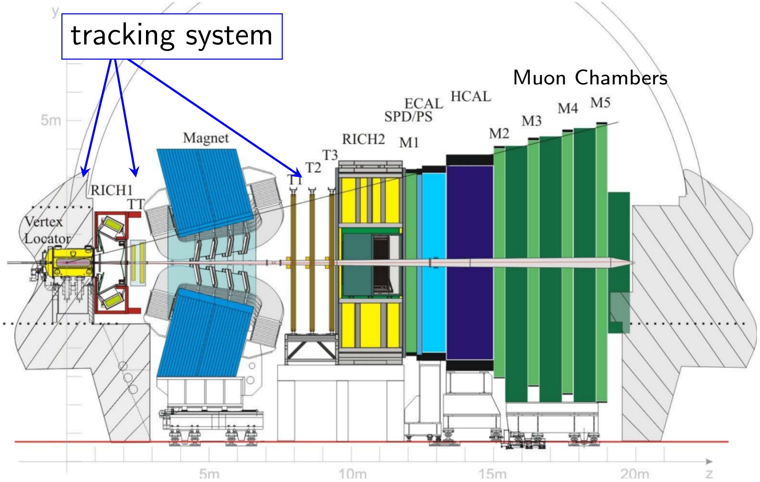
- Goal: update analysis with Run 2 data

LHCb detector



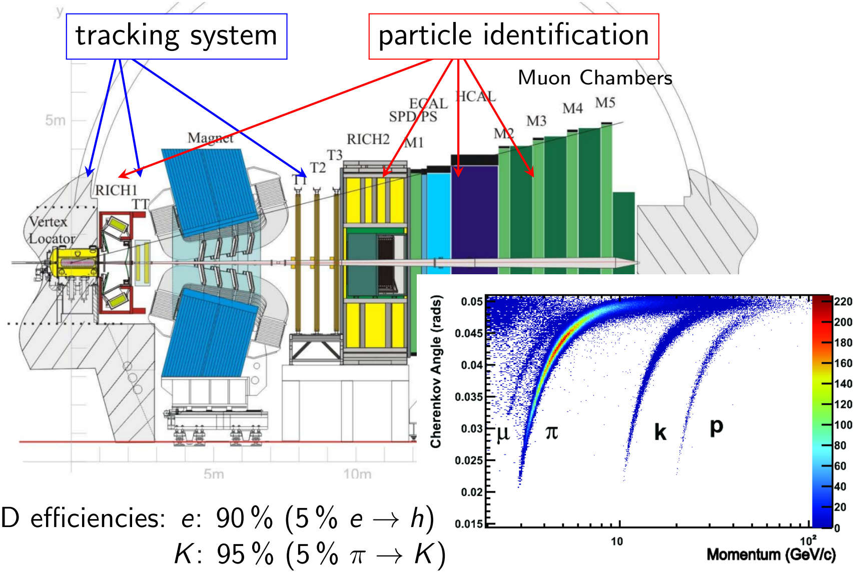
- Designed for heavy flavour decays
- Single arm forward spectrometer covering $2 < \eta < 5$

LHCb detector



- Momentum resolution $\frac{\Delta p}{p} = (0.5 - 1)\%$

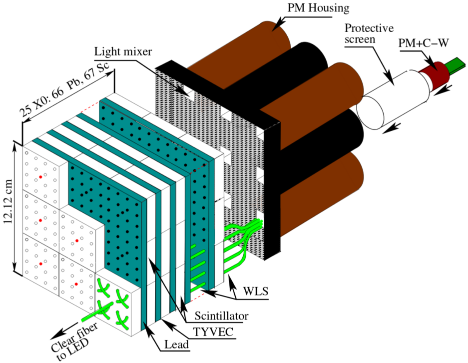
LHCb detector



- PID efficiencies: e: $90\,\%$ ($5\,\%$ $e \to h$)
  K: $95\,\%$ ($5\,\%$ $\pi \to K$)
  μ: $97\,\%$ ($1-3\,\%$ $\pi \to \mu$)

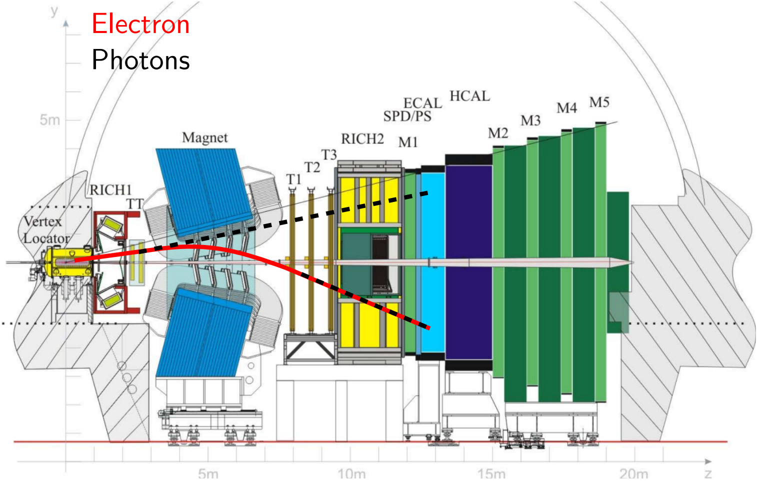
Electromagnetic calorimeter

- Design: alternating scintillator planes and lead plates
- Energy resolution: $\frac{\sigma_E}{E} \approx 1\% + \frac{9\%}{\sqrt{E(\mathrm{GeV})}}$



- Provides high p_{T} electron, photon or π^0 candidates for L0 trigger
- Crucial subdetector for bremsstrahlung recovery

Reconstruction of electrons

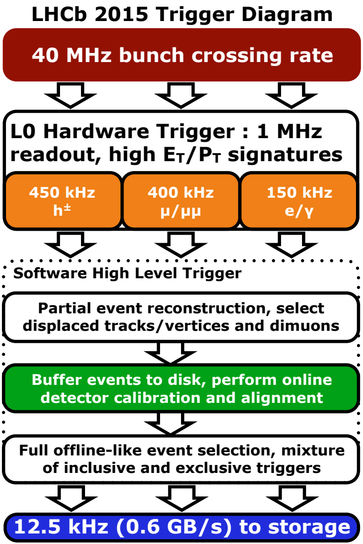


- Electrons produce bremsstrahlung in large amounts
- Reconstruction of brem. photons limited by calorimeter resolution

Trigger system

L0 hardware trigger used:

- For muonic decays:
  L0muon: $p_{\mathrm{T}} > 1.76\,\mathrm{GeV}$ track in muon chamber
- For electronic decays:
  L0electron: $E_{\mathrm{T}} > 3\,\mathrm{GeV}$ hit in ECAL
  L0tis: events triggered on non signal particles

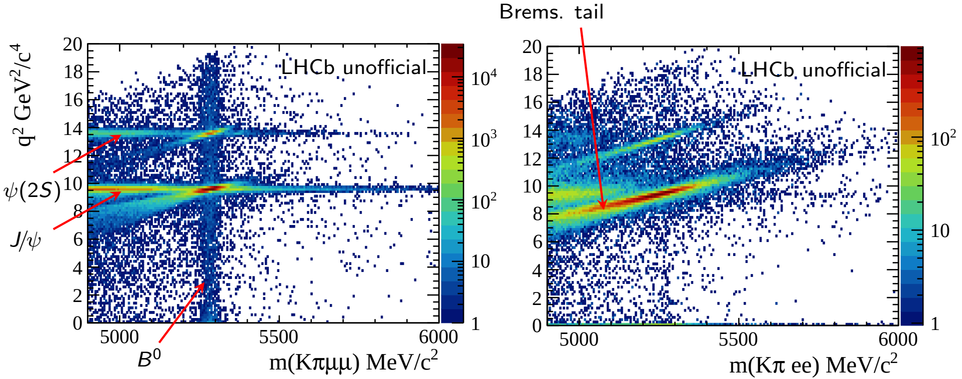


HLT trigger

- First reconstruction of tracks and vertices
- Selects events with > 1 high p_{T} track(s)
- Performs a topological selection of $(2-4)$-body decays

Electrons experimentally challenging

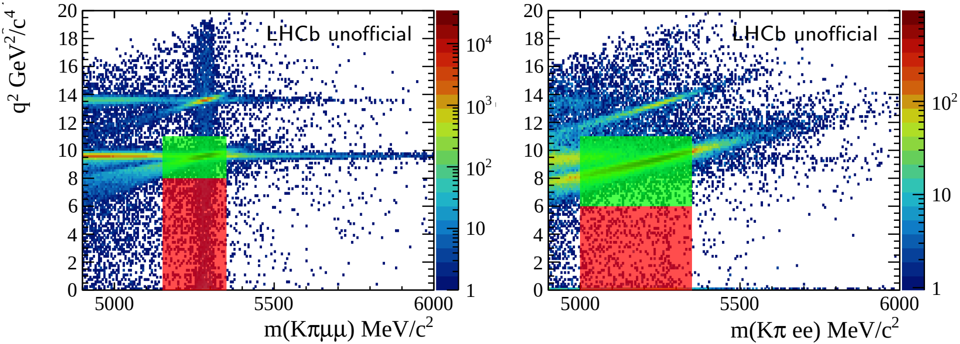
Plot of the di-lepton mass squared (q^2) vs. the reconstructed B^0 mass on Run 1 data after full selection



Electron decay shows a lower yield ← lower trigger and reco. efficiency
and a much worse resolution ← high Bremsstrahlung

Electrons experimentally challenging

Plot of the di-lepton mass squared (q^2) vs. the reconstructed B^0 mass on Run 1 data after full selection



$B^0 \to K^{*0} J/\psi(\to \ell^+\ell^-)$ control channel region

$B^0 \to K^{*0}\ell^+\ell^-$ signal region

Analysis strategy

- Starting with Run 1 analysis strategy
- Study possible improvements (background vetos, MC corrections, MVA...)
- Perform blinded analysis with Run 2 data

- Measure double ratio, where the tree-level decays $B^0 \to K^{*0} J/\psi(\to \ell^+ \ell^-)$ are used as normalisation channels

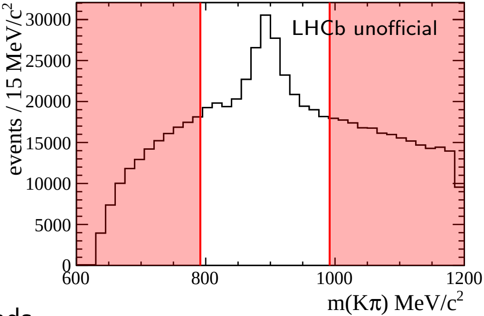
$$R_{K^{*0}} = \underbrace{\frac{\mathcal{N}_{B^0 \to K^{*0} \mu^+ \mu^-}}{\mathcal{N}_{B^0 \to K^{*0} J/\psi(\to \mu^+ \mu^-)}} \cdot \frac{\mathcal{N}_{B^0 \to K^{*0} J/\psi(\to e^+ e^-)}}{\mathcal{N}_{B^0 \to K^{*0} e^+ e^-}}}_{\text{determined by fits}} \cdot \underbrace{\frac{\mathcal{E}_{B^0 \to K^{*0} J/\psi(\to \mu^+ \mu^-)}}{\mathcal{E}_{B^0 \to K^{*0} \mu^+ \mu^-}} \cdot \frac{\mathcal{E}_{B^0 \to K^{*0} e^+ e^-}}{\mathcal{E}_{B^0 \to K^{*0} J/\psi(\to e^+ e^-)}}}_{\text{determined via corrected MC samples}}$$

- Single ratio of resonant channels is unity (powerful cross-check)
- This way, many systematic uncertainties cancel

Offline selection

Offline selection introduces many requirements on the events:

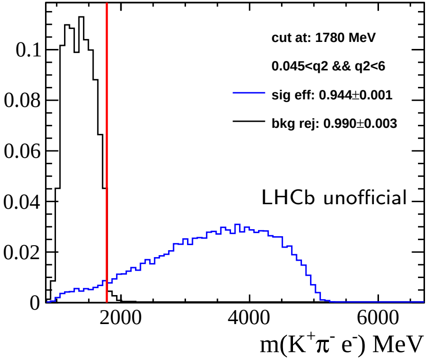
- Good track quality of all final state particles
- Cut around nominal K^{*0} mass
- Transverse momentum threshold on all final states particles
- Positively identify all final state particles: K, π, μ, e



- Vetos against physical backgrounds
- Multivariate classifier to further reduce combinatorial background

Semi-leptonic cascade background

- The decay $B^0 \to (D^- \to K^{*0} e^- \overline{\nu_e}) e^+ \nu_e$ can be reconstructed as signal if ν's have low momenta

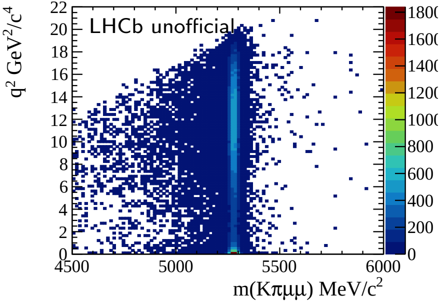


- This veto has an improved background rejection and signal efficiency

Multivariate classifier (preliminary version)

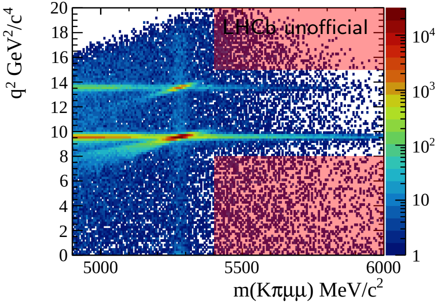
- Boosted Decision Trees (BDT) are trained to reduce combinatorial bkg
- Trained 4 BDTs for μ, e in Run 1 and Run 2 separately
- Signal: fully reconstructed and pre-selected signal MC
- Background: pre-selected data obtained from upper mass sideband

Simulation



Signal proxy for Run 1 muons

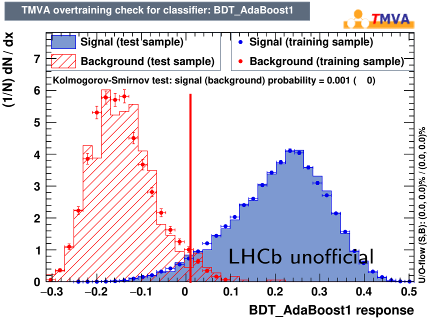
Run 1 data

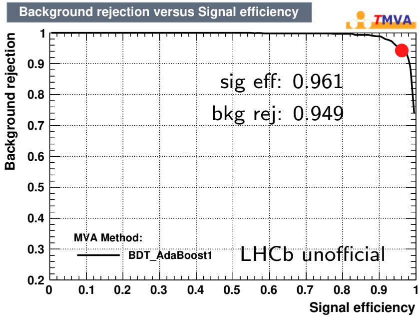


Bkg proxy for Run 1 muons (red boxes)

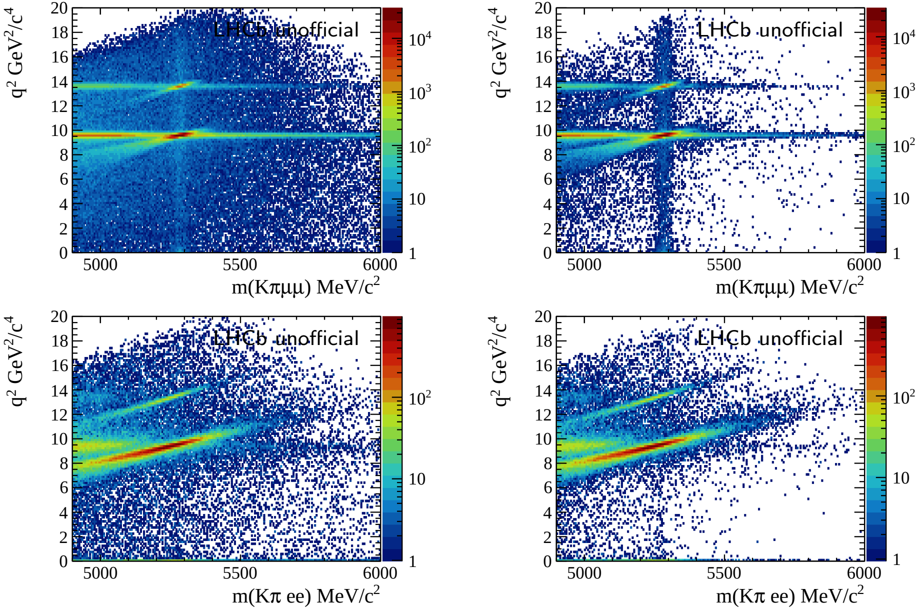
Multivariate classifier (preliminary version)

- Boosted Decision Trees (BDT) are trained to reduce combinatorial bkg
- Trained 4 BDTs for μ, e in Run 1 and Run 2 separately
- Signal: fully reconstructed and pre-selected signal MC
- Background: pre-selected data obtained from upper mass sideband





Run 1 data (left before BDT, right after BDT)

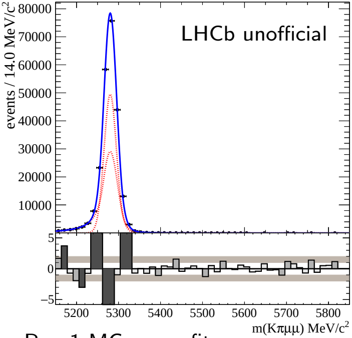


Control channel yields

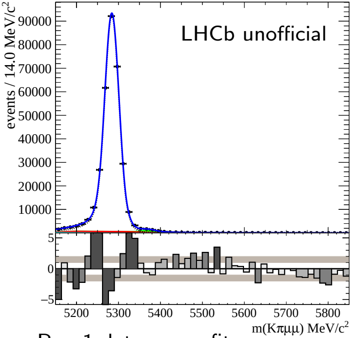
$$R_{K^{*0}} = \overbrace{\frac{\mathcal{N}_{B^0 \to K^{*0} \mu^+ \mu^-}}{\mathcal{N}_{B^0 \to K^{*0} J/\psi(\to \mu^+ \mu^-)}} \cdot \frac{\mathcal{N}_{B^0 \to K^{*0} J/\psi(\to e^+ e^-)}}{\mathcal{N}_{B^0 \to K^{*0} e^+ e^-}}} \cdot \frac{\mathcal{E}_{B^0 \to K^{*0} J/\psi(\to \mu^+ \mu^-)}}{\mathcal{E}_{B^0 \to K^{*0} \mu^+ \mu^-}} \cdot \frac{\mathcal{E}_{B^0 \to K^{*0} e^+ e^-}}{\mathcal{E}_{B^0 \to K^{*0} J/\psi(\to e^+ e^-)}}$$

$B^0 \to K^{*0} J/\psi$ control channel yields

- Tails of signal PDF fixed from fit to simulation
- Residual backgrounds from $\Lambda_b \to pKJ/\psi$, $B_s \to K^{*0} J/\psi$ and combinatorial are also modelled in the fit (more details in backup)
- Fit to data in $J/\psi - q^2$ region after full selection (right plot)



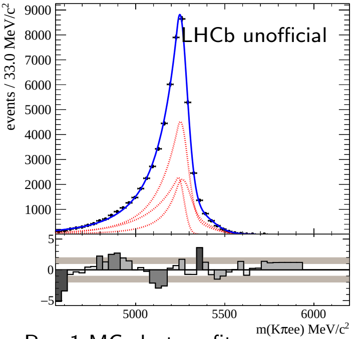
Run 1 MC muon fit



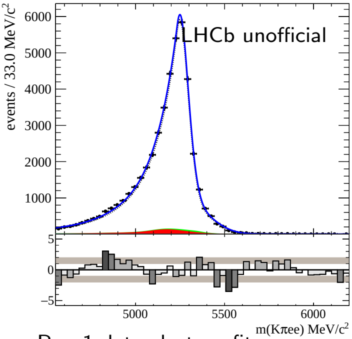
Run 1 data muon fit

$B^0 \to K^{*0} J/\psi$ control channel yields

- Tails of signal PDF fixed from fit to simulation
- Residual backgrounds from $\Lambda_b \to pKJ/\psi$, $B_s \to K^{*0} J/\psi$ and combinatorial are also modelled in the fit (more details in backup)
- Fit to data in $J/\psi - q^2$ region after full selection (right plot)



Run 1 MC electron fit



Run 1 data electron fit

- Run 2 control channel fits show increased electron yield due to improved selection

Efficiencies

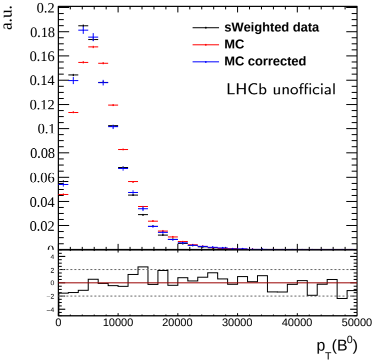
$$R_{K^{*0}} = \frac{\mathcal{N}_{B^0\to K^{*0}\mu^+\mu^-}}{\mathcal{N}_{B^0\to K^{*0}J/\psi(\to\mu^+\mu^-)}} \cdot \frac{\mathcal{N}_{B^0\to K^{*0}J/\psi(\to e^+e^-)}}{\mathcal{N}_{B^0\to K^{*0}e^+e^-}} \cdot \overbrace{\frac{\mathcal{E}_{B^0\to K^{*0}J/\psi(\to\mu^+\mu^-)}}{\mathcal{E}_{B^0\to K^{*0}\mu^+\mu^-}} \cdot \frac{\mathcal{E}_{B^0\to K^{*0}e^+e^-}}{\mathcal{E}_{B^0\to K^{*0}J/\psi(\to e^+e^-)}}}$$

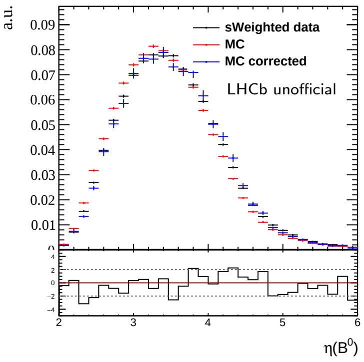
MC corrections

- Good data $\leftrightarrow$ MC agreement required to calculate efficiencies
- Effects like low momentum photons challenging to simulate
  $\rightarrow$ MC deviates from data in several observables
- MC corrections in three categories:
  1) Particle identification variables
  2) B^0 kinematics and track multiplicity
  3) Trigger (not included in this talk)

B^0 kinematics and track multiplicity

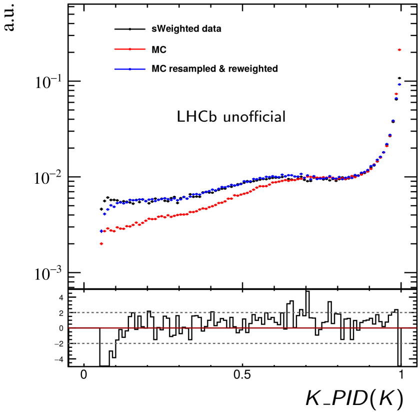
- Reweighting of $p_T(B^0)$, $\eta(B^0)$ and $N_{\text{SPD hits}}$, $N_{\text{Velo tracks}}$
- Determine weights on muon mode $B^0 \to K^{*0} J/\psi(\to \mu\mu)$ between data and MC
- Weights calculated with iso-populated binned histograms
- Apply weights on both $\mu\mu$ and ee MC samples





Correction of particle identification variables

- Correct PID variables with clean data calibration samples
- Example: Probability that the kaon was a kaon



- Residual differences will be covered by systematic uncertainty

Conclusion

- Run 1 analysis successfully reproduced
- Many improvements already made: trigger, bkg. vetos, MVA, ...
- Electron yield significantly increased
- Analysis is already in a good shape

- A lot of work not shown today/still on-going

backup

Stripping line

- Run 1 data
- 2012 MC
- Stripping line *ee*: Bu2LLKeeLine2, version 21r1p1
- Stripping line $\mu\mu$: Bu2LLKmumuLine, version 21r0p1

type	requirement
B^0	$\lvert m - m_{B^0}^{\mathrm{PDG}} \rvert < 1000\ \mathrm{MeV/c^2}$ DIRA > 0.9995 $\chi^2_{\mathrm{IP}}(\mathrm{primary}) < 25$ end vertex $\chi^2/\mathrm{ndf} < 9$ $\chi^2_{B_{\mathrm{flight}}} > 100$
K^{*0}	$\lvert m - m_{B^0}^{\mathrm{PDG}} \rvert < 300\ \mathrm{MeV/c^2}$ $p_T > 500\ \mathrm{MeV/c}$ $\chi^2_{\mathrm{IP}}(\mathrm{primary}) > 9$ origin vertex $\chi^2/\mathrm{ndf} < 25$
K	$\mathrm{DLL}_{K\pi} > -5$ $\chi^2_{\mathrm{IP}}(\mathrm{primary}) > 9$
π	$\chi^2_{\mathrm{IP}}(\mathrm{primary}) > 9$
ll	$m < 55\,000\ \mathrm{MeV/c^2}$ end vertex $\chi^2/\mathrm{ndf} < 9$ $\chi^2_{\mathrm{DiLep_{flight}}} > 16$
e, μ	$p_T > 300\ \mathrm{MeV/c}$ $\chi^2_{\mathrm{IP}}(\mathrm{primary}) > 9$
μ	isMuon
e	$\mathrm{DLL}_{e\pi} > 0$

Preselection

type	requirement	sample
all tracks	$\chi^2/\text{ndof} < 3$ $\text{GhostProb} < 0.4$	all
K, π e	$\text{region}_{\text{HCAL}}^{\text{L0CaloTool}} \geq 0$ $\text{region}_{\text{ECAL}}^{\text{L0CaloTool}} \geq 0$	all all *ee*
e	$!(\lvert\text{xProjection}_{\text{ECAL}}^{\text{L0CaloTool}}\rvert 363.6\,\text{mm}$ $\&\&\lvert\text{yProjection}_{\text{ECAL}}^{\text{L0CaloTool}}\rvert < 282.6\,\text{mm})$	all *ee*
K^{*0}	$\lvert m(K\pi) - m_{K^{*0}}^{\text{PDG}}\rvert < 100\,\text{MeV}$ $p_T > 4000\,\text{MeV/c}^2$	all all (only L0H)
all μ e	hasRich hasMuon hasCalo	all all $\mu\mu$ all *ee*
K, π μ e	$p_T > 250\,\text{MeV/c}$ $p_T > 800\,\text{MeV/c}$ $p_T > 500\,\text{MeV/c}$	all all $\mu\mu$ all *ee*
K π e	$\text{ProbNNk} \cdot (1 - \text{ProbNNp}) > 0.05$ $\text{ProbNNpi} \cdot (1 - \text{ProbNNk}) \cdot (1 - \text{ProbNNp}) > 0.1$ $\text{ProbNNe} > 0.2$	all all all *ee*

Vetos against physical background

- Several B decays can be misidentified as signal decay
- These processes peak in some variable $\rightarrow$ can be vetoed

Used in Run 1 paper:

type	reconstructed as signal if
$B^+ \rightarrow K^+(J/\psi \rightarrow \ell\ell)$	combined with a random π
$B_s^0 \rightarrow (\phi \rightarrow KK)(J/\psi \rightarrow \ell\ell)$	$K \rightarrow \pi$ mis-identification
partially reconstructed	$>= 1$ final state not reconstructed

Improved vetos:

type	reconstructed as signal if
$B^0 \rightarrow K^{*0}(J/\psi \rightarrow \ell\ell)$	$H \leftrightarrow \ell$ double swap
$B^0 \rightarrow (D^- \rightarrow K^{*0}\ell^-\overline{\nu_\ell})\ell^+\nu_\ell$	ν carry low momenta

New vetos:

type	reconstructed as signal if
$B^0 \rightarrow D^+(\rightarrow K\pi\pi)\ell^-\nu$	$\pi \rightarrow \ell$ mis-identification
$B^0 \rightarrow D^0(\rightarrow K\pi)\pi\ell\nu$	$\pi \rightarrow \ell$ mis-identification

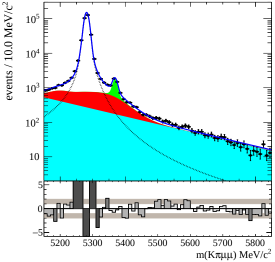
BDT input variables

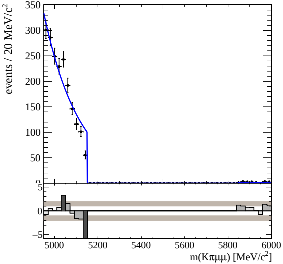
- first a BDT is run with 24 input variables to test their separation power

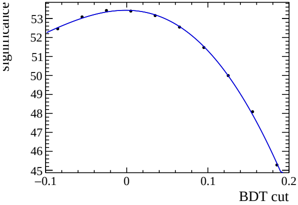
particle	Variables					
B^0	p_T	χ^2_{IP}	χ^2_{FD}	χ^2_{vtx}	DIRA	χ^2_{DTF}
K^{*0}	p_T	χ^2_{IP}	χ^2_{FD}	χ^2_{vtx}	DIRA	
J/ψ	p_T	χ^2_{IP}	χ^2_{FD}	χ^2_{vtx}	DIRA	
K/π	$\min(p_{T,h})$	$\max(p_{T,h})$	$\min(\chi^2_{IP,h})$	$\max(\chi^2_{IP,h})$		
ll	$\min(p_{T,l})$	$\max(p_{T,l})$	$\min(\chi^2_{IP,l})$	$\max(\chi^2_{IP,l})$		

BDT optimisation

- Calculate significance $s = \frac{N_{sig}}{\sqrt{N_{sig}+N_{bkg}}}$
- N_{sig}: fit control channel and estimate signal mode with branching fractions
- $f = \frac{\mathcal{B}(B^0 \to K^{*0}\mu\mu)}{\mathcal{B}(B^0 \to K^{*0}J/\psi)} = 0.0135$
- N_{bkg}: fit in signal q^2-range and interpolate to B^0-signalrange

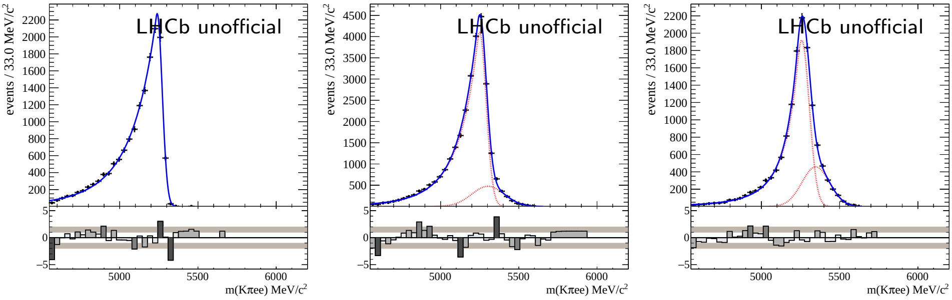






Fit of $B^0 \to K^{*0} J/\psi(\to ee)$ simulation

- Performed to determine signal mass model
- Fit in three different bremstrahlung categories:
  Brem0: no brem. photon added to both e
  Brem1: 1 brem. photon added to one e
  Brem2: $>=$ 2 brem. photons added
- Brem0 fitted with Crystall Ball (CB) function
  Brem1 and Brem2 fitted with sum of CB and Gauss function



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- Fit in three different bremstrahlung categories:
  Brem0: no brem. photon added to both e
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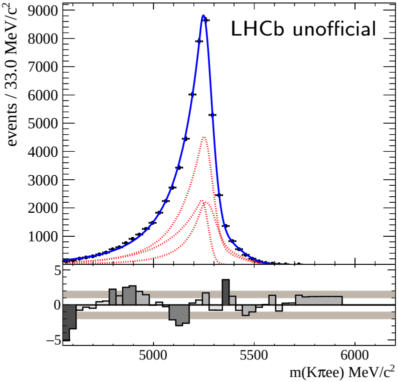
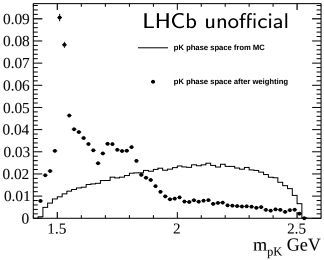
  Brem2: $>=$ 2 brem. photons added
- Combined fit to full MC sample

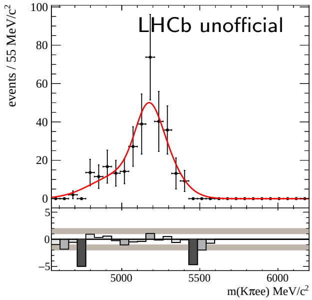


$\Lambda_b \to pK(J/\psi \to ee)$ fit modelling

- Reconstructed as signal if $p \to \pi$ mis-identification occurs
- Using $\Lambda_b \to pK(J/\psi \to ee)$ MC after full selection
- MC corrected for pK phase space distribution
- Using weights determined in penta-quark analysis at LHCb (PhysRevLett.115.072001)
- Model background using superposition of Gaussian kernels



reweighting of pK phase space distribution



fit to dalitz weighted Λ_b bkg