Precision Physics at Colliders

HOW TO CHOOSE WISELY, MEASURE CAREFULLY, AND EXPLOIT RUTHLESSLY

Precision Physics at Colliders 3:

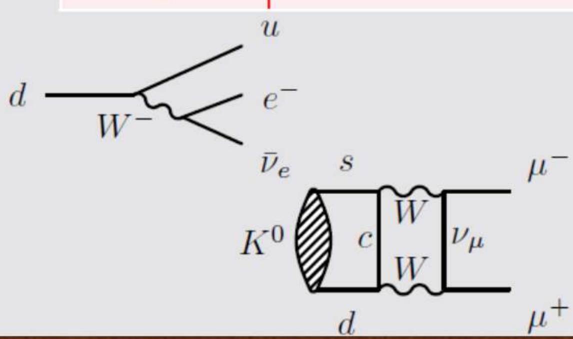
THE MYSTERY OF FLAVOR

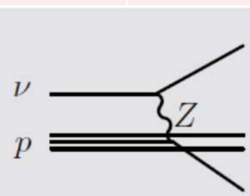
Most major direct discoveries have been heralded by a lower energy measurement!

Heavy Flavour = Precision search for NP

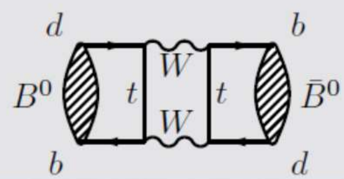
- Direct discoveries rightfully higher valued:

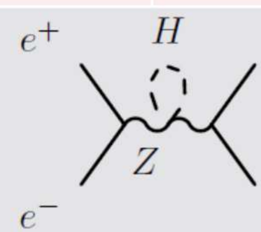
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?





N. Tuning, ICHEP 2018

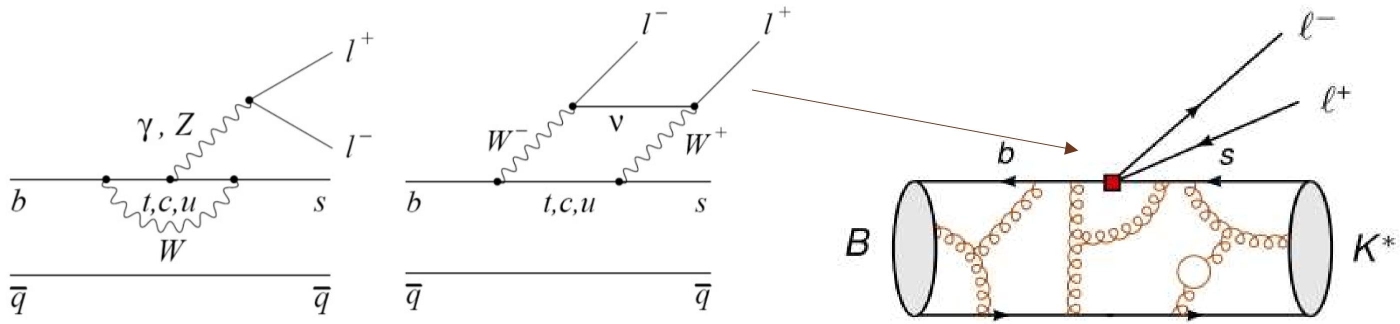




Probing electroweak scale physics with hadron decays

- Use the effective field theory approach:
- Compute short distance matrix element at the electroweak scale for fermion initial and final states of interest
  - b → s l+ l-
  - b → c l ν
  - bs → μμ

  Etc.



- WLOG, the short distance calculations can be characterized by a **general operator product expansion over all allowed combinations of lowest-dimension fermion operators weighted by Wilson coefficients**

- Wilson coefficients can be evolved down to the mhad scale and convolved with **long-distance form factors** which connect quarks to initial and final state hadrons (this part is difficult!)

- Wilson coefficients can be measured experimentally from decay rates and kinematics of hadron decays, and then interpreted with your favorite UV-complete theory (SM, SUSY, leptoquarks, Z', etc.).
- Can also extract CKM matrix elements and CP violating phases as a precision SM test

b-hadron basics

Lowest mass mesons are B^0 ($d\bar{b}$) and B^+ ($u\bar{b}$), with a mass of 5.28 GeV and a lifetime of ~1.5 ps (~100 μm)

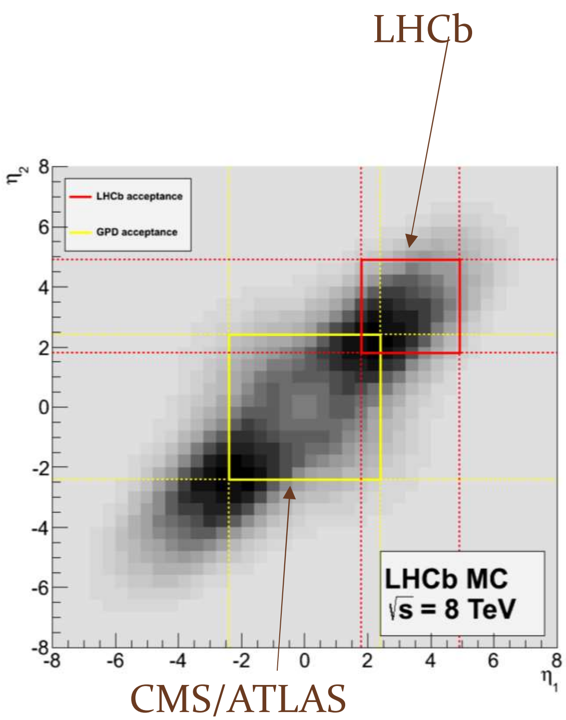
At hadron colliders, produced along with B_s ($s\bar{b}$), B_c ($c\bar{b}$) and Λ_b (udb).

Distinguished from light quarks by a displaced decay vertex (>100 μm), and reconstructed mass close to MB.

Produced with a large cross section at hadron colliders (100s of μb) peaking at forward rapidities

For general purpose experiments (ATLAS/CMS), these can easily overwhelm their trigger/DAQ unless there is high purity selection (decays to single or di-muons)

LHCb geometry, detectors, computing model, and trigger/DAQ optimized to identify and collect b-hadrons



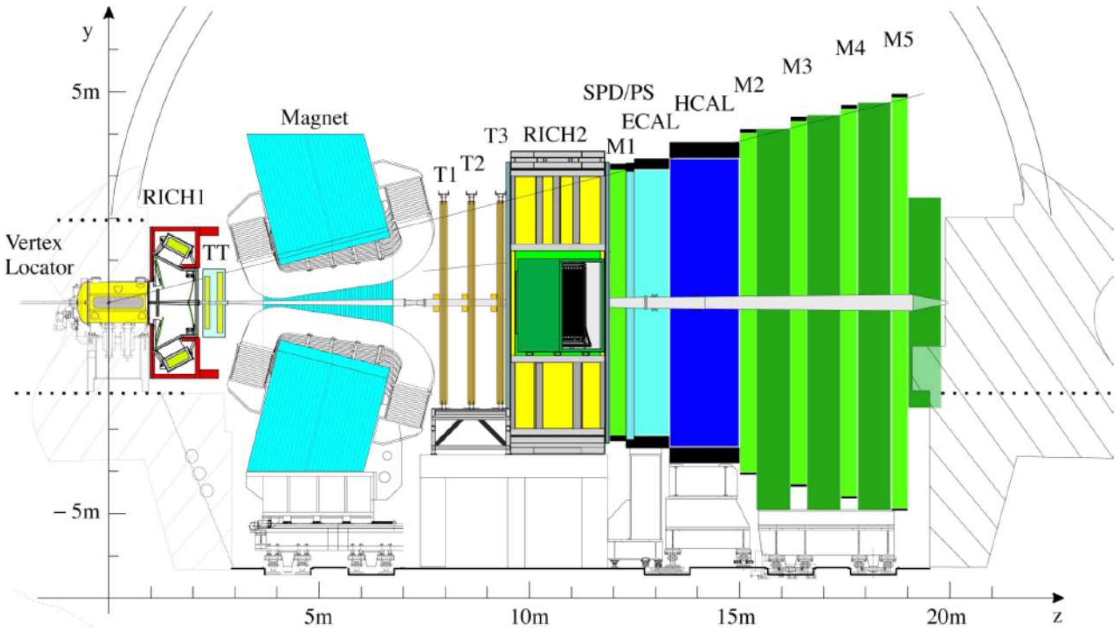
LHCb

Rapidity coverage from η = 2 to 5 (one side only)

Luminosity levelling to keep pileup low (~ 10x less lumi than CMS/ATLAS), but trigger/DAQ to read out a much larger fraction of accepted b hadrons.

Tracking, calorimetry, muons comparable to CMS/ATLAS (can do precision electroweak!)

Ring-imaging Cherenkov detectors to provide π/K particle ID (95% K ID at 5% pion fake rate)



Strange Penguins: The Case of $B^0 \rightarrow K^{*0}\, l^+ l^-$

b→ s Operator Product Expansion

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum [C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)]$$

general Hamiltonian
of b→s transitions

C7 "photon penguin"
C8 "gluon penguin"
C9 "Z penguin"
C10 "W box". etc.

$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O_7' = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

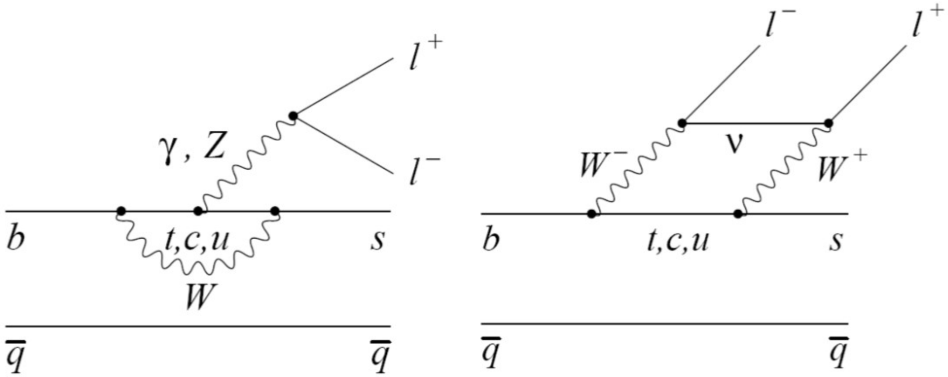
C7', C9', C10' = opposite helicity projection of C7, C9, C10

Plus:
CS, CP = scalar and pseudoscalar FCNCs (e.g. Higgs-like penguin)

In SM, "top-penguins" dominate b→s; u- and c-penguins non-negligible for b→d

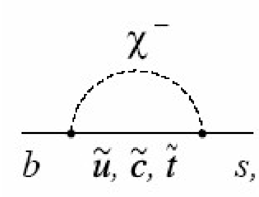
b→s, b→d, s→d, etc. could all have different C_i from new physics

B →K *ll*, B →K* *ll*



Photon penguin (C7)
Vector EW (C9)
Axial-vector EW (C10)

Exclusive decays from three b→ s*ll* penguin diagrams



New physics possible for each diagram, and also new operators (scalar penguins, right-handed currents)

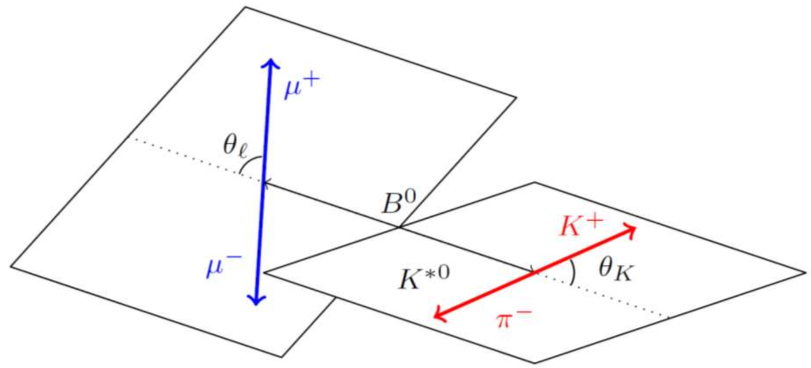
For K*ll, four-body kinematic distributions, angular distributions, and decay rates to measure all three (complex) penguin amplitudes

Rare process with BF ~ 10^{-6}

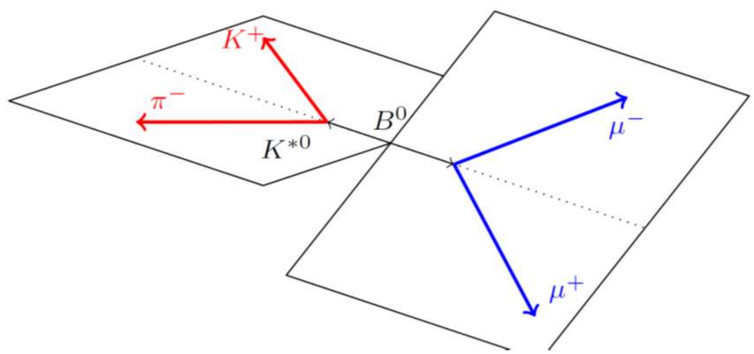
Measuring decay angles

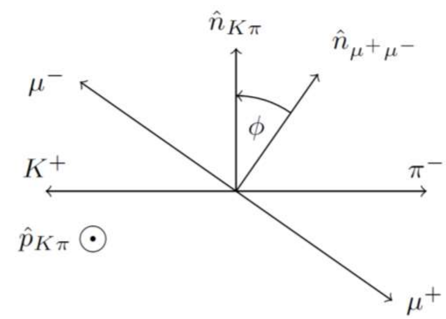
- For B^o, θ_l is the angle between the μ+ in the dimuon rest frame and the dimuon momentum in the B^o rest frame.

- θ_K is the angle between the K+ in the K* rest frame and the K* momentum in the B^o rest frame.



- ϕ is the angle between the two decay planes in the B^o rest frame





B → K* ll observables of interest

- A general angular decomposition can be performed for the CP-summed normalized decay rate as a function of dilepton q²

- Each of the 8 independent coefficients probes a different bilinear dependence on amplitudes encoding K* transversity and lepton chirality $\mathcal{A}_{0,\|,\perp}^{\mathrm{L,R}}$ which in turn have different C_i dependence.

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

FL : longitudinal polarization of the K*

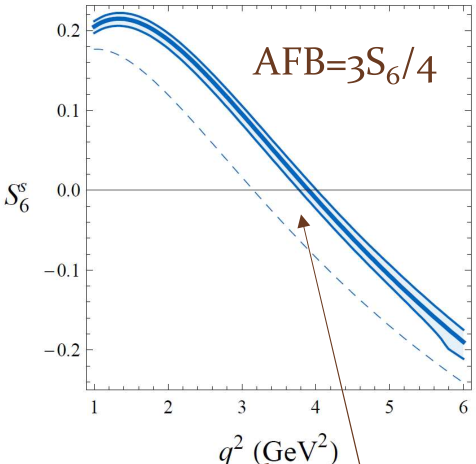
AFB: forward-backward asymmetry of the lepton decay angle

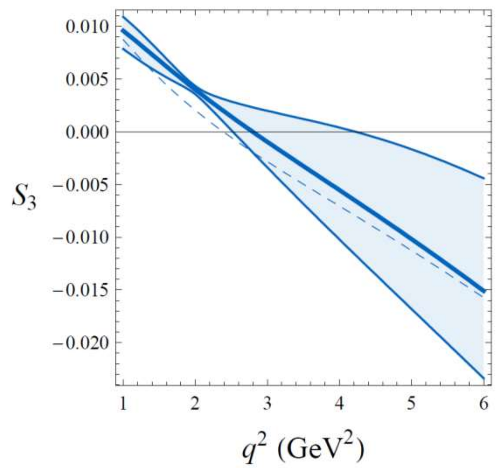
S_i ϕ-dependent angular coefficients

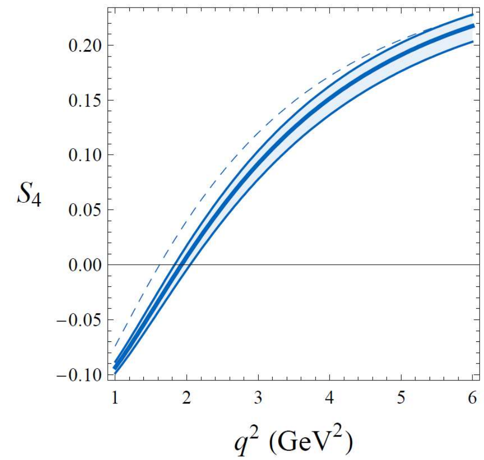
S6 = 4/3*AFB

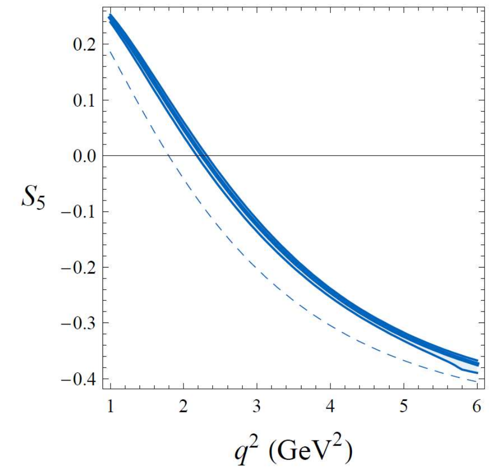
B → K* ll observables of interest

NLO QCD-factorization predictions arxiv:0811.1214

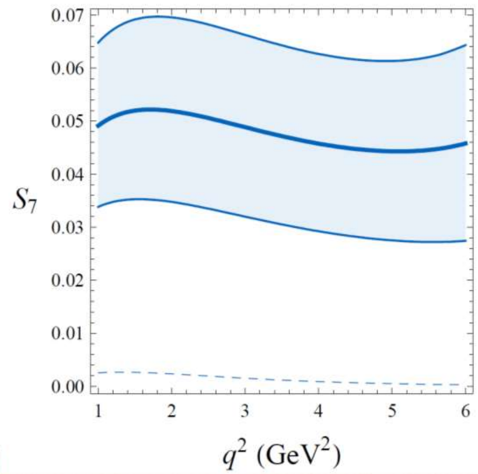


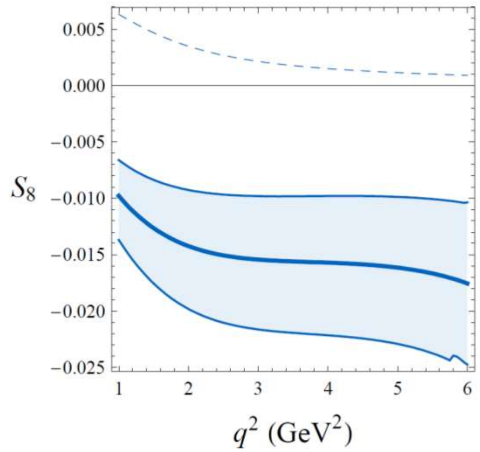


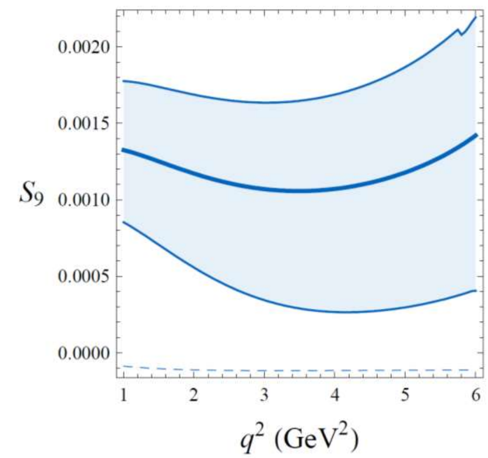




- AFB precisely predicted, as well as a precise 0-point
- Some are more and less precisely predicted, mostly due to form factor uncertainty
- S4-S6 observably large







B → K* ll observables of interest

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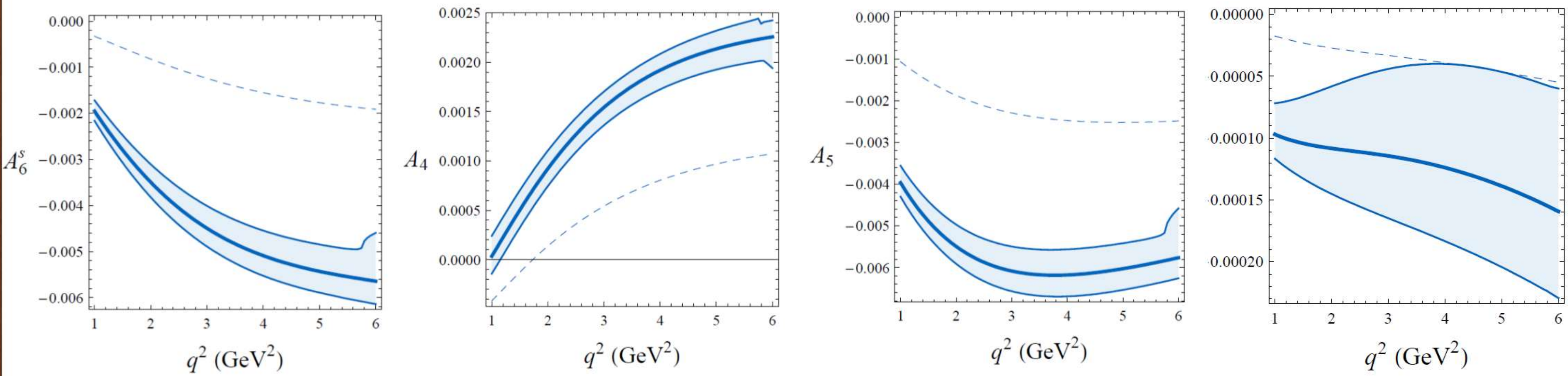
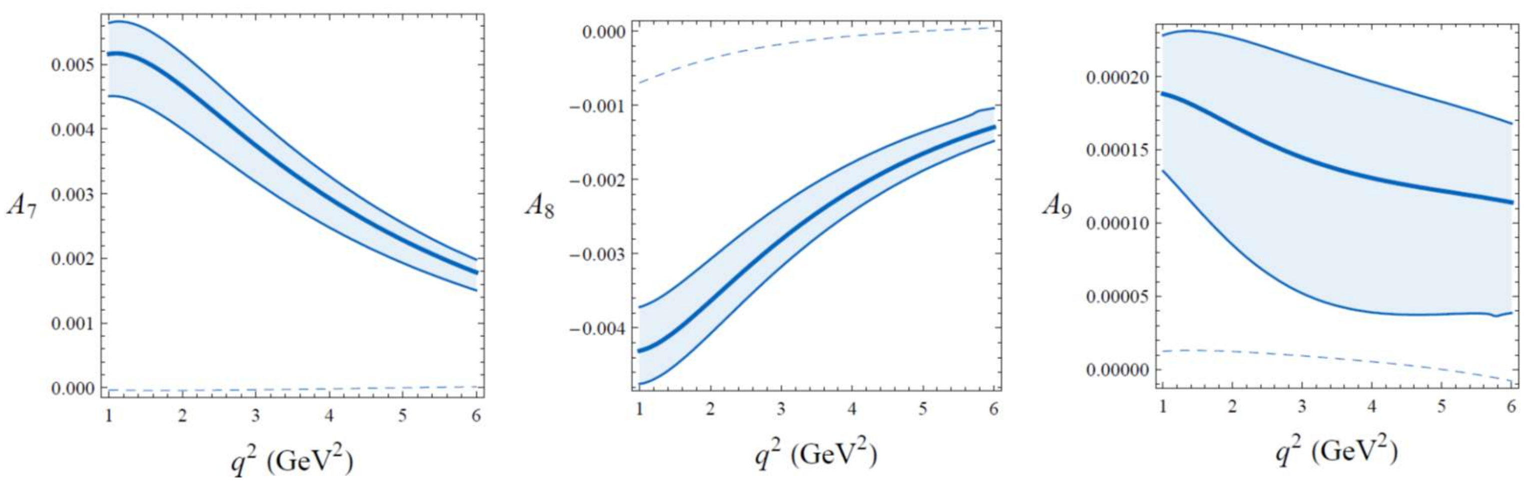


- Each Si can be CP-subtracted (B – $\bar{\text{B}}$) to provide CP-asymmetries
- Ai = Si – $\bar{\text{S}}$i, all tiny in SM



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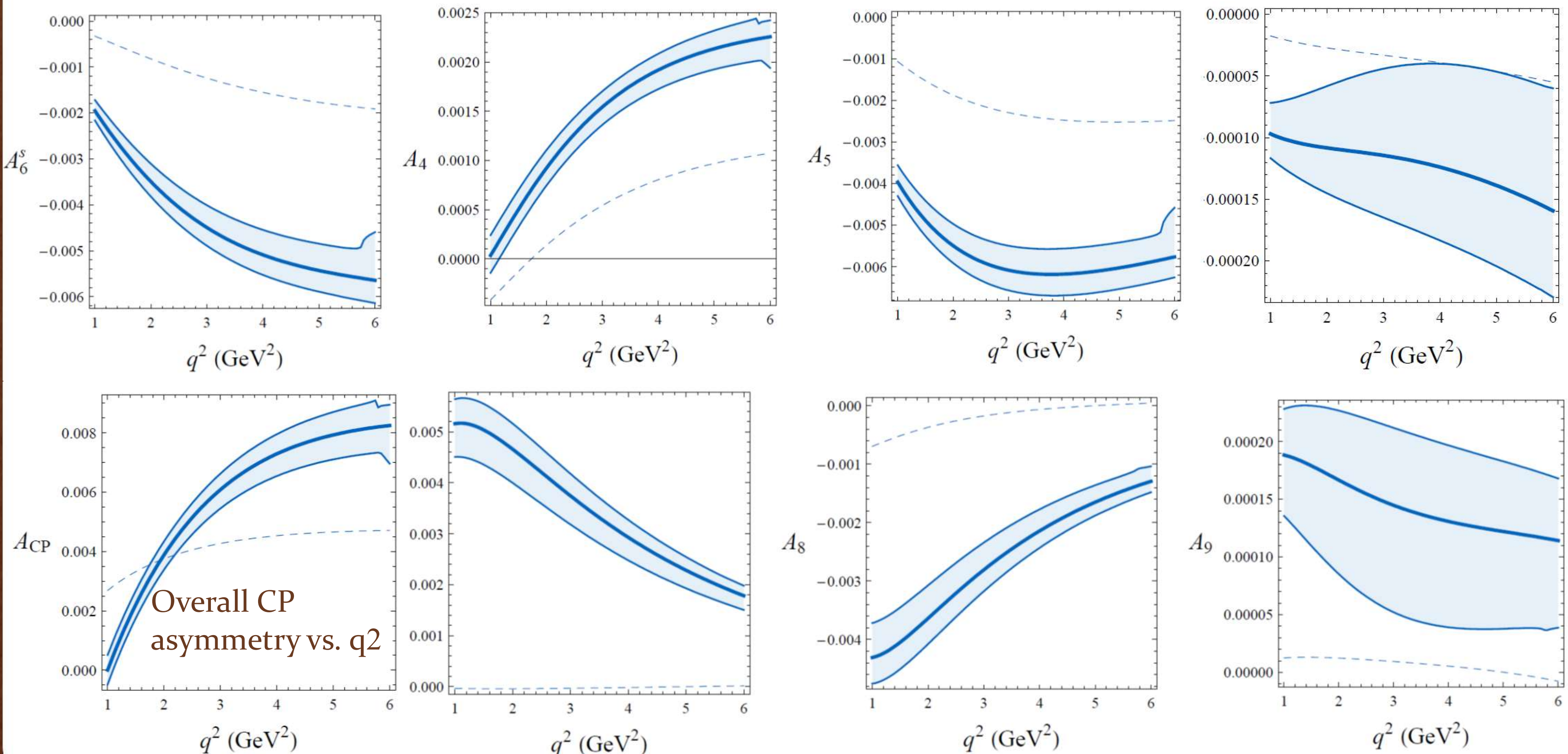


B → K* ll observables of interest

Si, FL and AFB can have significant form factor dependence as well.

Can attempt to minimize form factor role by defining quotients of coefficients, Pi which are less model-dependent.

$$P_1 = \frac{2\,S_3}{(1-F_{\rm L})} = A_{\rm T}^{(2)}\,, \qquad P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,,$$

$$P_2 = \frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})}\,, \qquad P'_6 = \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,.$$

$$P_3 = \frac{-S_9}{(1-F_{\rm L})}\,,$$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\rm S+P} = (1-F_{\rm S})\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\rm P}$$
$$+\frac{3}{16\pi}F_{\rm S}\sin^2\theta_l$$
$$+\frac{9}{32\pi}(S_{11}+S_{13}\cos 2\theta_l)\cos\theta_K$$
$$+\frac{9}{32\pi}(S_{14}\sin 2\theta_l+S_{15}\sin\theta_l)\sin\theta_K\cos\phi$$
$$+\frac{9}{32\pi}(S_{16}\sin\theta_l+S_{17}\sin 2\theta_l)\sin\theta_K\sin\phi$$

A scalar, S-wave component to the Kπ system (~5% expected) can modify the angular distributions further

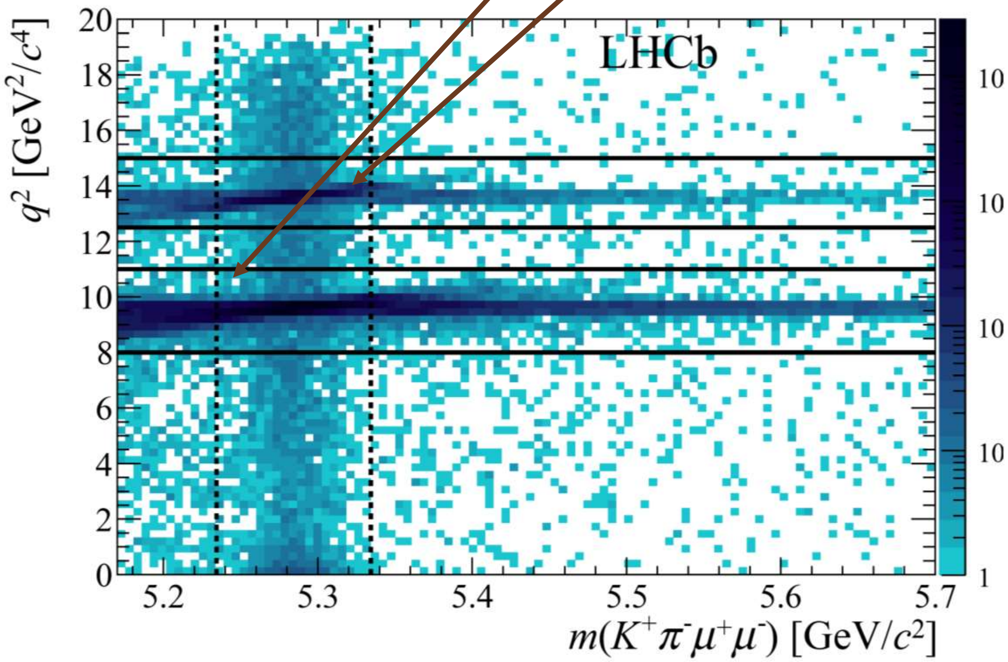
FS fraction of S-wave Kπ
S11-S17: angular coefficients of S-wave/P-wave interference

Event selection

- Use 3/fb collected during Run 1 (~1/fb @7 TeV, ~2/fb at 8 TeV)
- Trigger selects events with a single muon PT > 1.46 (1.78) GeV , at least one of the four candidate tracks with do > 100 μm, two tracks with a good SV
- Offline B candidate reconstruction:
  - Two oppositely charged muons + a Kπ opposite sign pair, with particle ID applied to all
  - Good common vertex for the 4-track system, with significant d_o to PV
  - Angle θ_{DIRA} between B-momentum and vector connecting PV and SV is small
  - **B mass cut** 5170 MeV < mB < 5700 MeV (detected mass resolution ~50 MeV, big sidebands for fitting)
  - **K* mass cut** 796 MeV < mK* < 996 MeV (K* natural width = 50 MeV, so mK*0 +/- 2 widths)

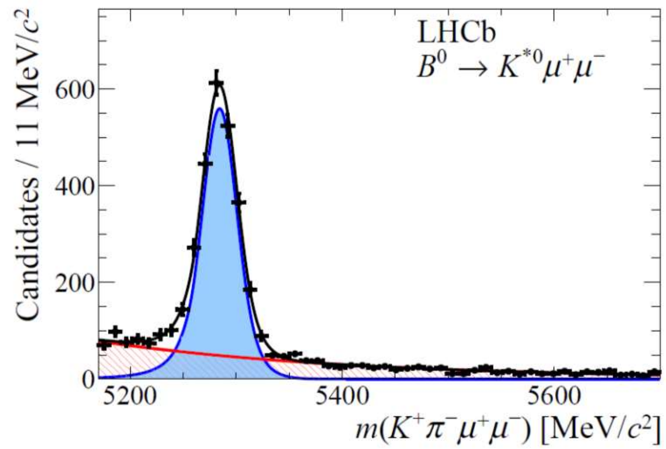
B-meson mass peak

Dilepton mass peaks from b→c$\bar{c}$s, ψ → l+l-
B → J/ψ K*
B → ψ(2S) K*



Event selection

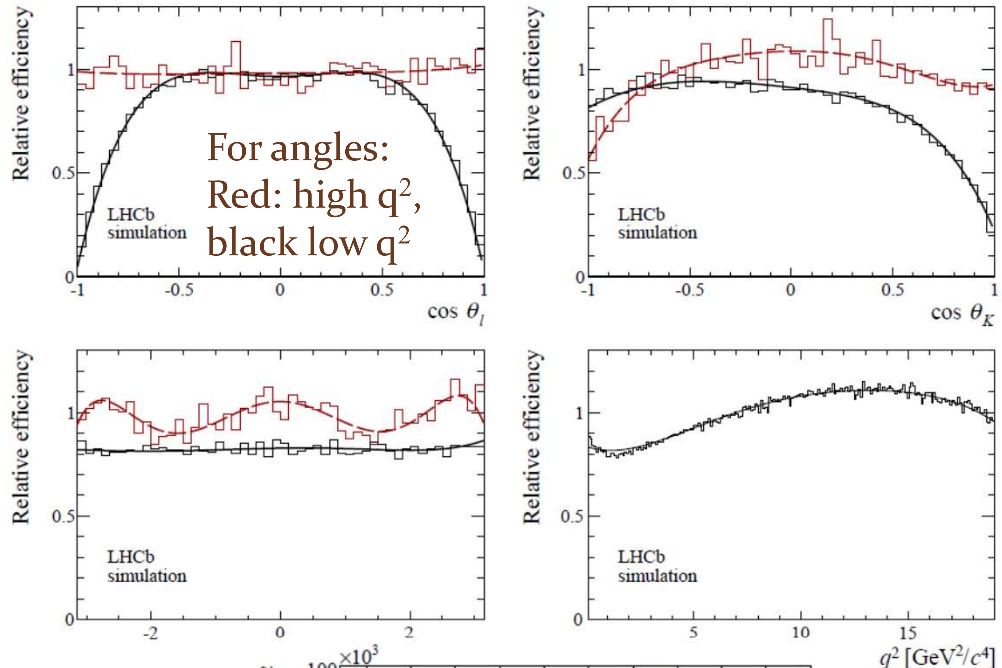
- **Combinatorial background rejection**
  - Most important background is **random combinations of tracks** from B meson decays (esp. B → Dμν + pions, D → Kμν) and from other nearby b/c/light hadrons, creating a 4-track background flat in mB and a poor vertex fit
  - **BDT** trained on B → J/ψ K* data and mB sideband background data
    - B vertex fit quality, B lifetime, B P and PT, cos θDIRA, PID data, signal tracks' isolation
    - Reject 97% background at 85% efficiency, flat in MB and MK*
- **Peaking background rejection**
  - **Veto charmonium J/ψ and ψ(2S)** with dilepton mass vetoes q^2 = 8-11 GeV² and 12.5-15 GeV²
  - And also veto "double-swap" possibility of J/ψK* or ψ(2S)K* where muon and a hadron are misid'd
  - Veto Bs → K* ϕ, ϕ→μμ with ϕ veto on dilepton mass 0.98-1.10 GeV2
  - Veto Λb → pKμμ if a poor ID pion is in range of Λb mass when assigned proton mass
  - Veto Bs → ϕ μμ if a misid'd pion hits the Bs and ϕ mass windows
  - "Feed-up" veto B+ → K+ μμ is Kμμ mass is close to mB
  - Residual peaking background is at ~2% level (Λb, signal swap, Bs), **not explicitly subtracted**



2398 +/- 57 signal candidates

Likelihood fit and validation

- **Fit signal+bkg to MB, MK*, cosθ_l, cosθ_K, ϕ in seven bins in q^2**
  - 5 below J/ψ mass (probes zero of AFB)
  - one between J/ψ and ψ(2S)
  - one above ψ(2S)

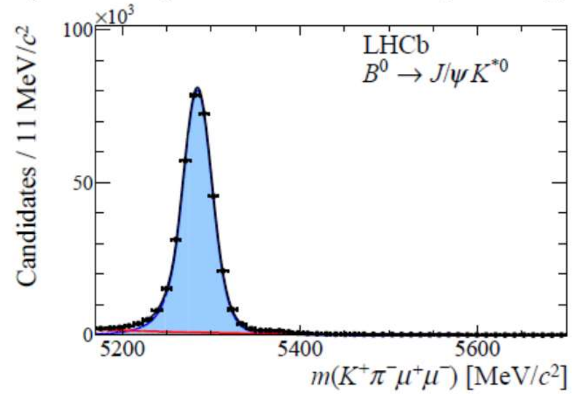


- Angular acceptance will vary significantly in the 4-dimensional space of (q^2, cosθ_l, cosθ_K, ϕ) due to lifetime and momentum cuts suppressing softer tracks.

- 4D acceptance function needed from high-stats simulation

$$\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2) = \sum_{ijmn} c_{ijmn} L_i(\cos\theta_l) L_j(\cos\theta_K) L_m(\phi) L_n(q^2)$$

- Can be validated by measuring angular coefficients in **150x larger B → J/ψ K* sample** and comparing with other experiments (BaBar, Belle, etc.)
- MB, MK* line shapes also validated with J/ψ K*



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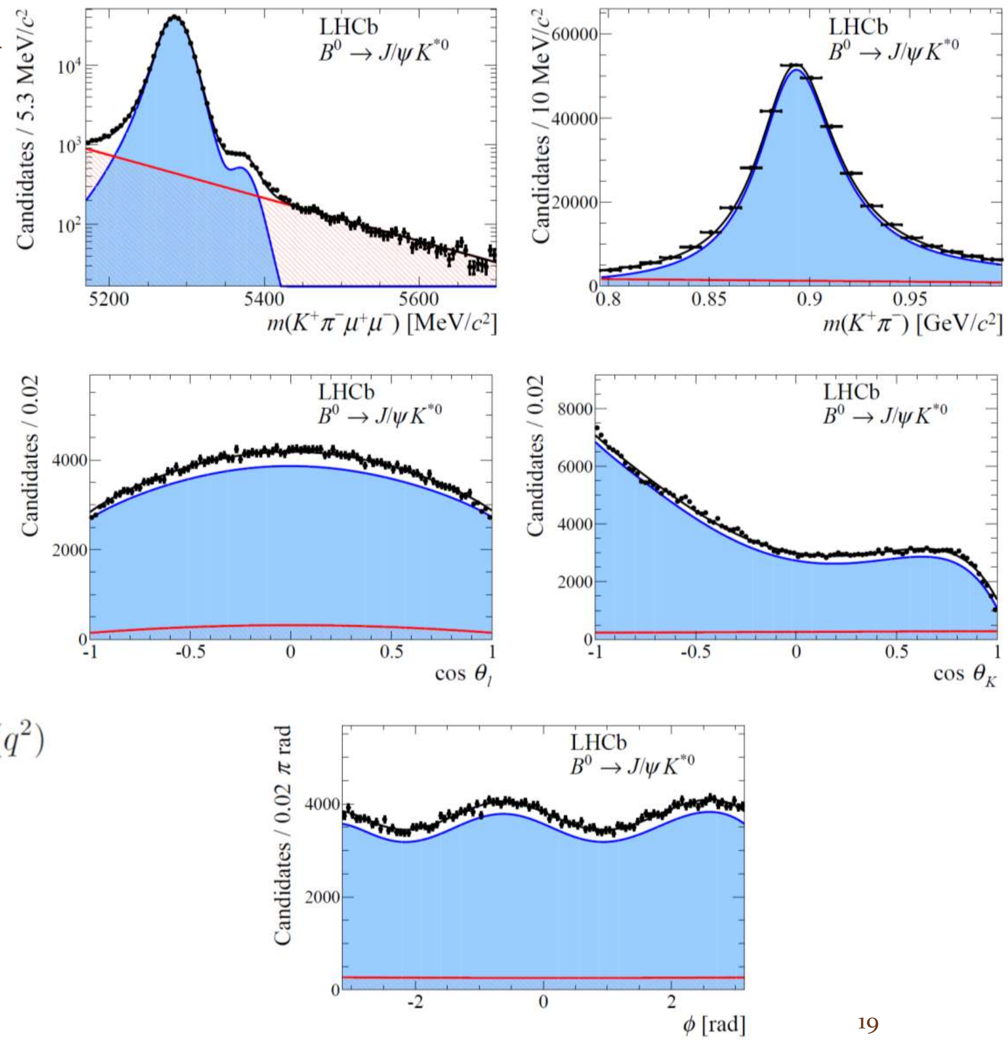
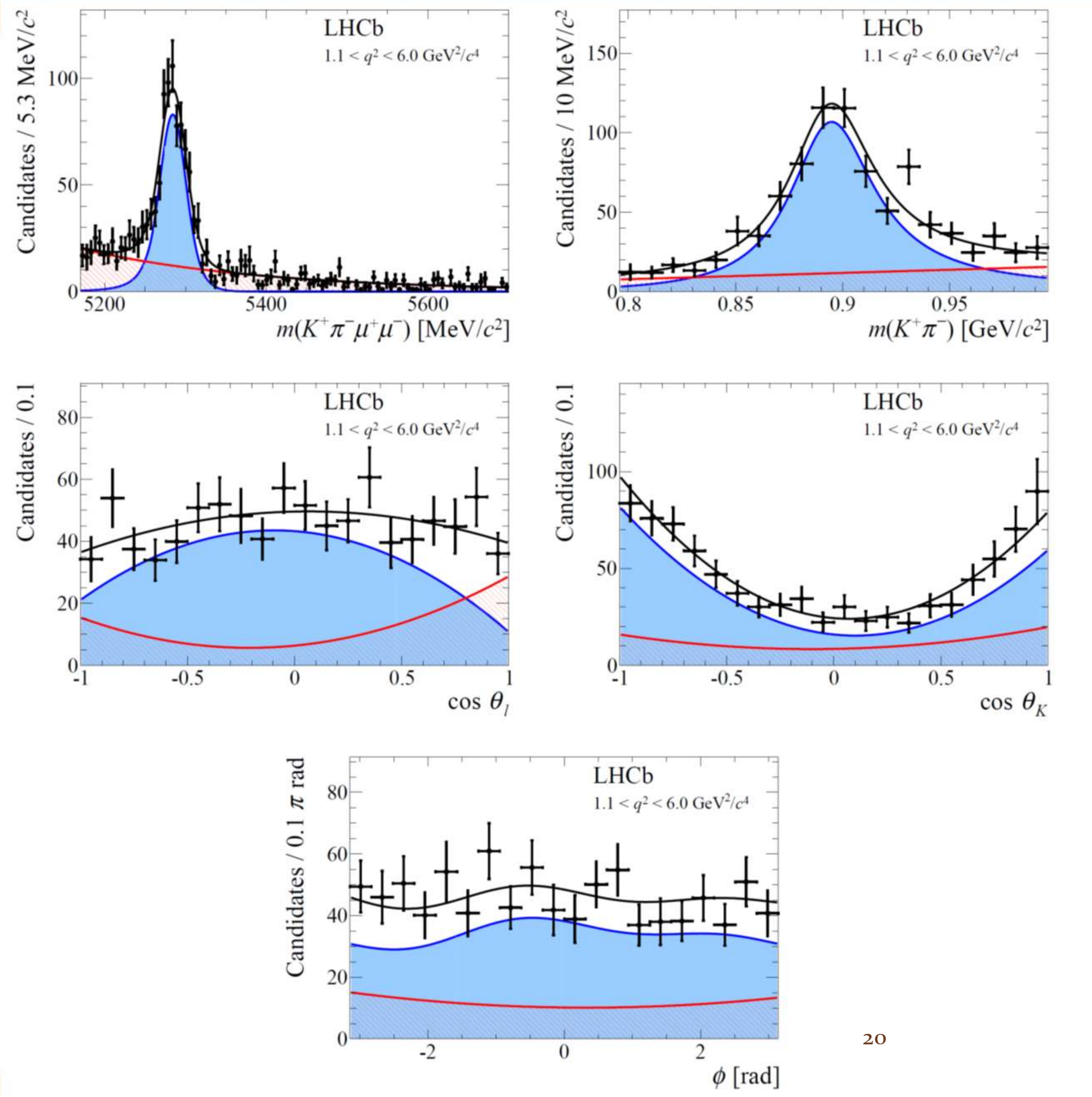


Background shape and fits

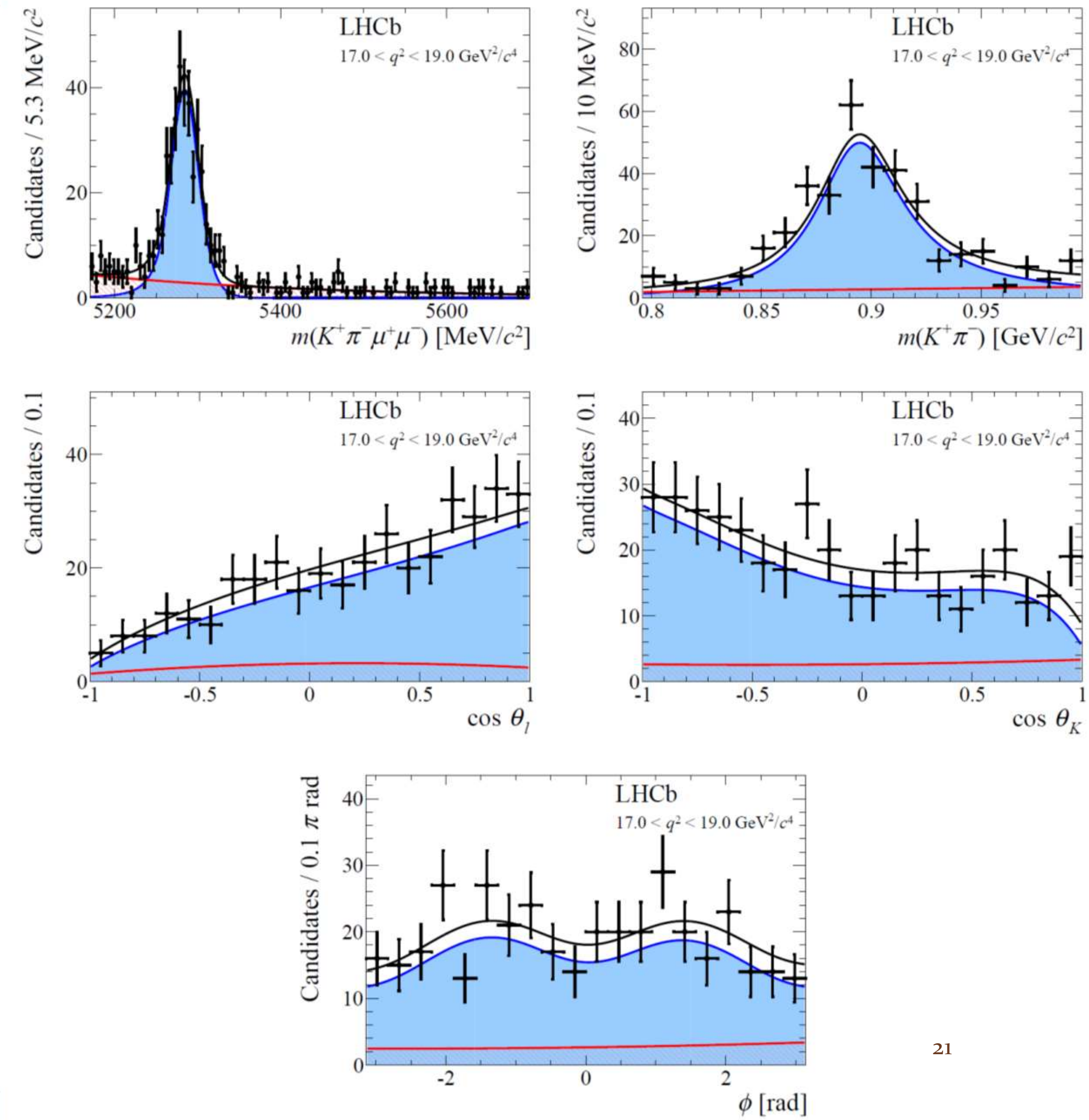
- Background MB shape is exponential
- Background angular shape is an uncorrelated product of free-floating 2[nd]-order polynomials
- Background angular shape validated in MB upper-sideband
- Background K* shape is linear

- S-wave component to MKπ allowed for signal, with scalar fraction F_S floating

- Projections of 5-d fit with +/- 50 MeV MB cut describe the data well!



High Q^2 fit result



Systematic uncertainties

- Generally subleading to the statistical uncertainties.

- Fit model is modified in various ways due to hypothetical biases, and a pseudoexperiment method determines the mean bias associated with not having quite the right model.

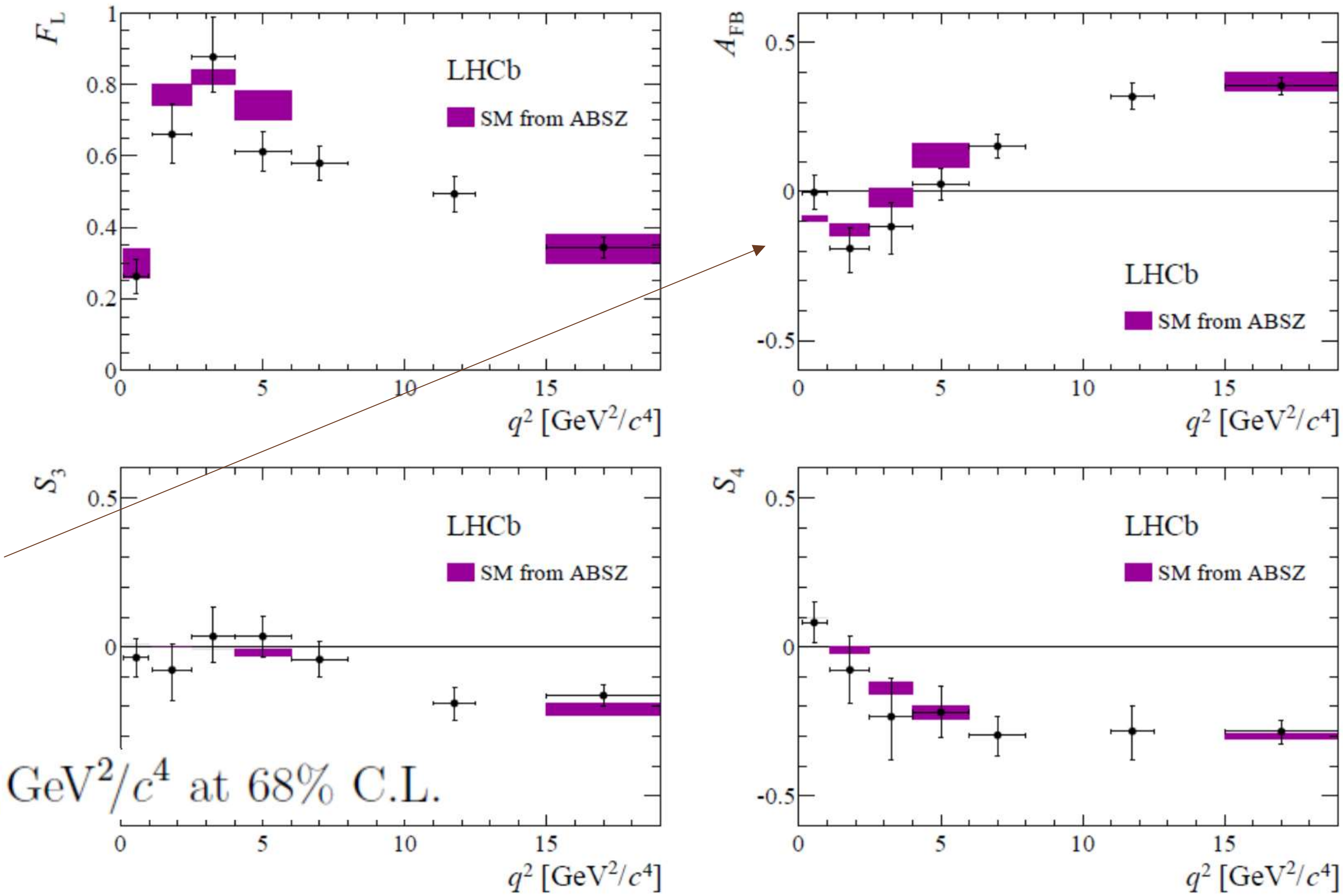
- Effect of neglecting peaking backgrounds
- Different control samples for background shape determination
- Observed differences in data/MC agreement (low PT pion efficiency, e.g.)
- Different polynomial order for free-floating shapes
- Variations in S-wave shape
- Detector CP-asymmetries in efficiency

Source	F_L	S_3–S_9	A_3–A_9	P_1–P'_8	q_0^2 GeV^2/c^4
Acceptance stat. uncertainty	< 0.01	< 0.01	< 0.01	< 0.01	0.01
Acceptance polynomial order	< 0.01	< 0.02	< 0.02	< 0.04	0.01–0.03
Data-simulation differences	0.01–0.02	< 0.01	< 0.01	< 0.01	< 0.02
Acceptance variation with q^2	< 0.01	< 0.01	< 0.01	< 0.01	–
$m(K^+\pi^-)$ model	< 0.01	< 0.01	< 0.01	< 0.03	< 0.01
Background model	< 0.01	< 0.01	< 0.01	< 0.02	0.01–0.05
Peaking backgrounds	< 0.01	< 0.01	< 0.01	< 0.01	0.01–0.04
$m(K^+\pi^-\mu^+\mu^-)$ model	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
Det. and prod. asymmetries	–	–	< 0.01	< 0.02	–

Results

- Predictions with form-factor uncertainties combining lattice and LCSR
- 5th and 6th bins near charmonium are unreliable due to contamination from long-distance/ccs effects.

- AFB crossing zero is clearly seen and measured!



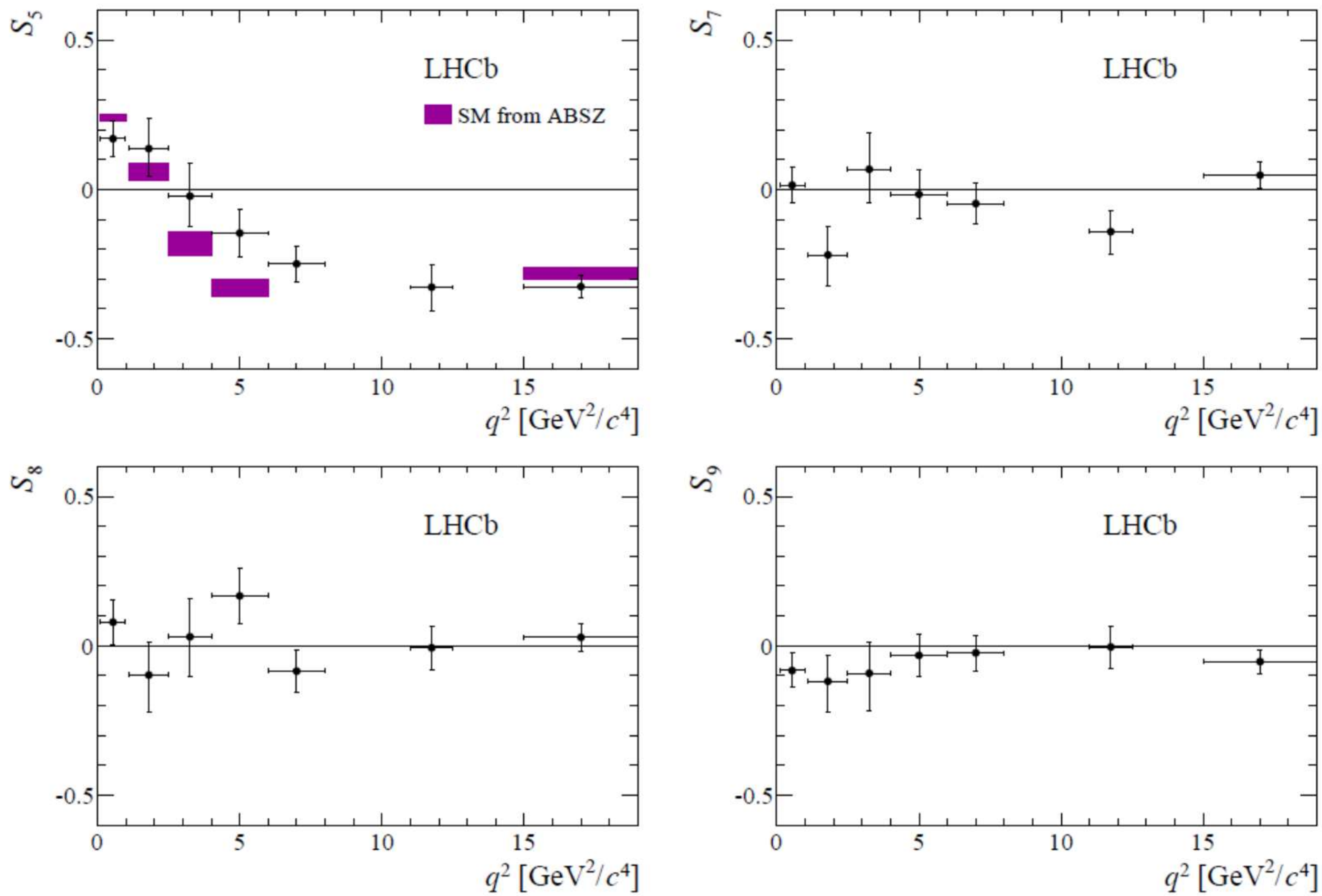
$$q_0^2(A_{\rm FB}) \in [3.40, 4.87]\ \mathrm{GeV}^2/c^4 \text{ at } 68\%\ \text{C.L.}$$

$$q_0^2(A_{\rm FB}) = 4.36\,^{+0.33}_{-0.31}\ \mathrm{GeV}^2/c^4$$

arxiv:hep-ph/0412400

Results

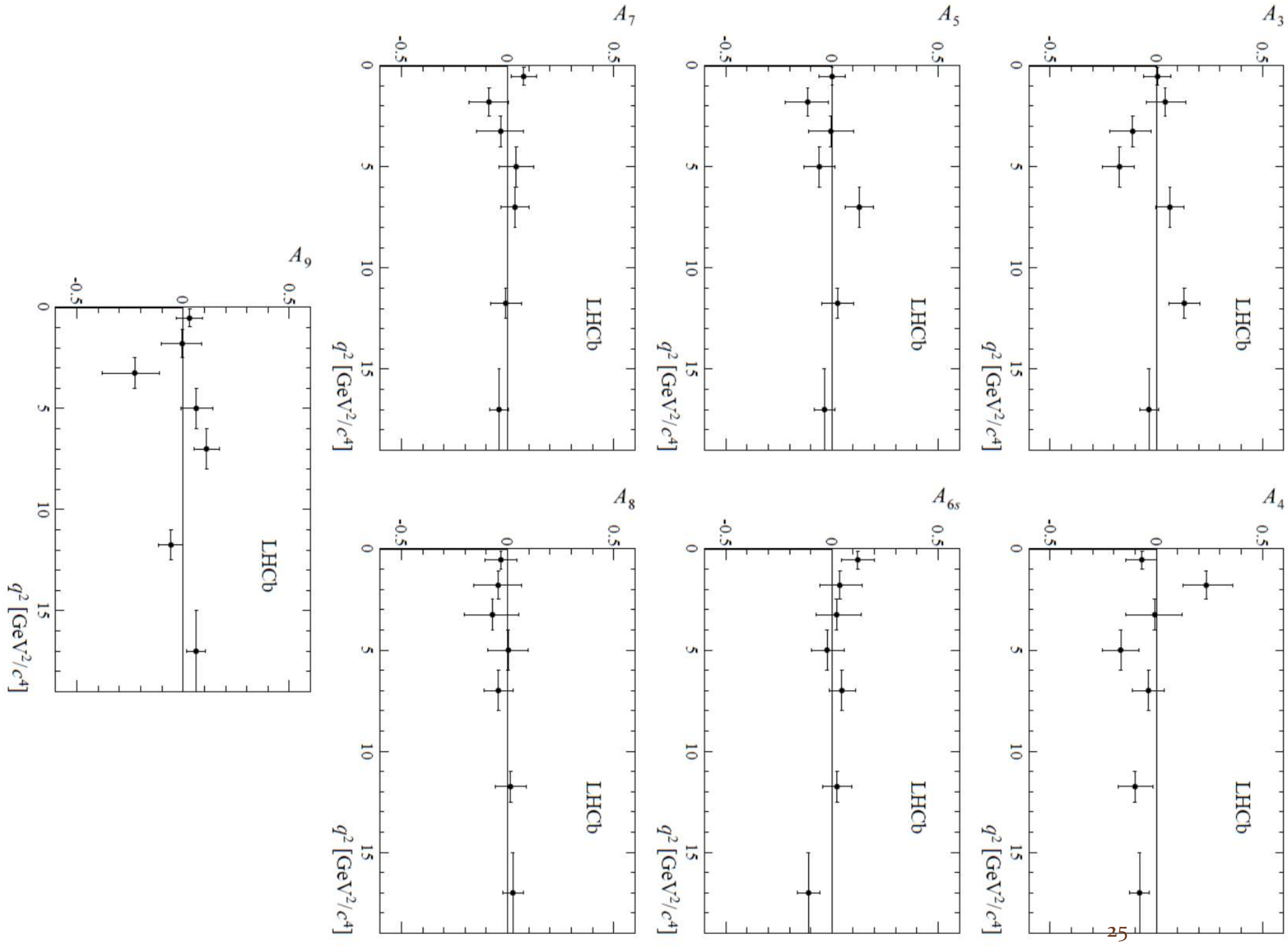
- Predictions with form-factor uncertainties combining lattice and LCSR
- 5th and 6th bins near charmonium are unreliable due to contamination from long-distance/ccs effects.
- S7-9 are predicted to be ~0
- S5 starting to see a problem?



Results

- Predictions with form-factor uncertainties combining lattice and LCSR
- 5th and 6th bins near charmonium are unreliable due to contamination from long-distance/ccs effects.

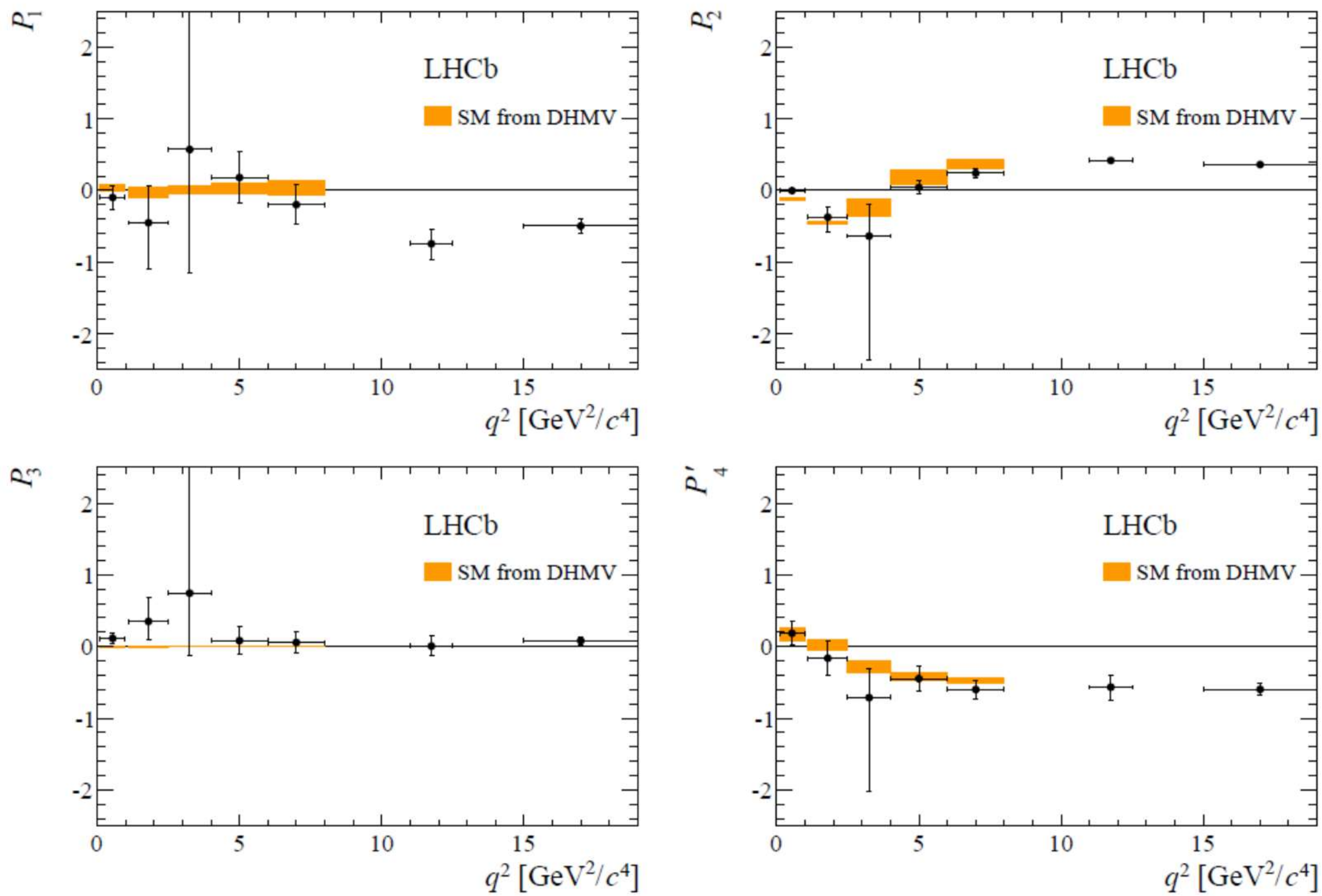
- Ai are predicted to be ~0
- No significant Ai or ACP seen



Results

arxiv:1407.8526

- Predictions with partially cancelling form factor uncertainties for low q2
- Good agreement for the P1-P4!

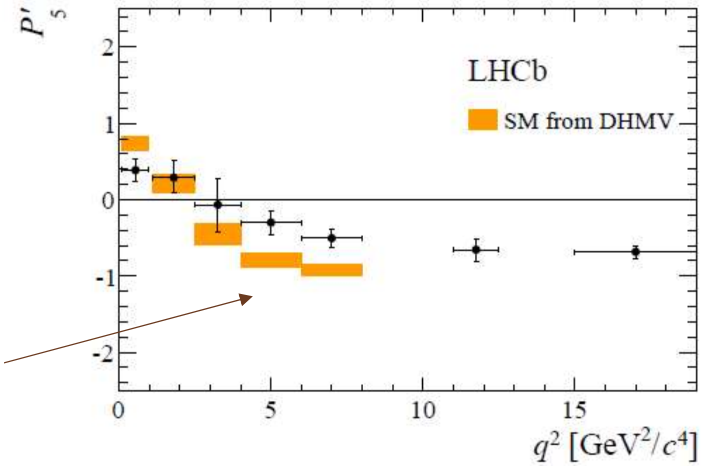


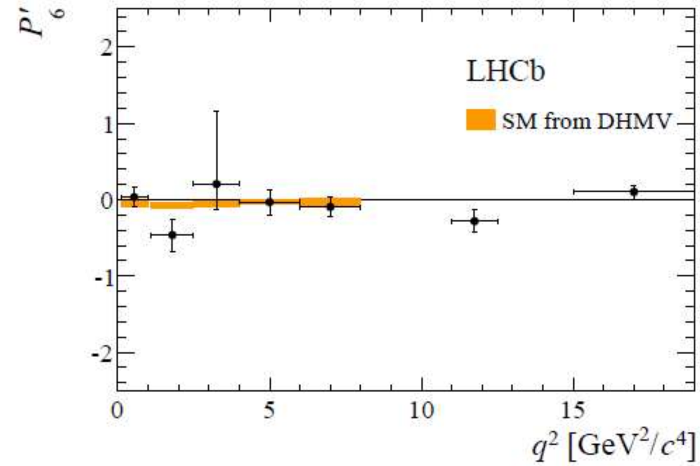
Results

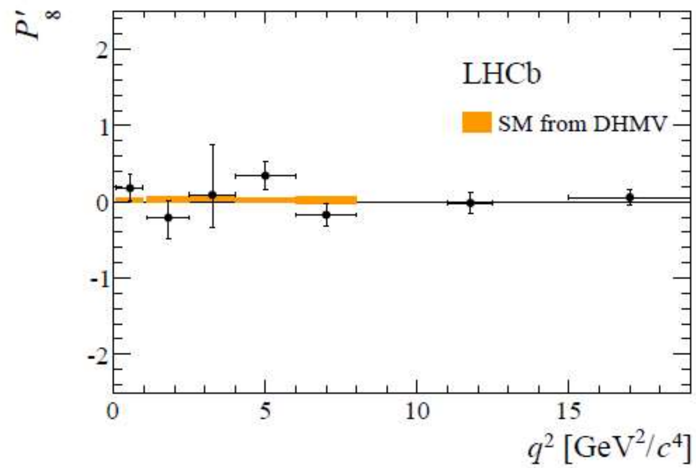
arxiv:1407.8526

- Predictions with partially cancelling form factor uncertainties

- P5’ deviation in 4th and 5th bins are 2.8σ and 3.0σ, resp.







Interpretations as Wilson coefficients

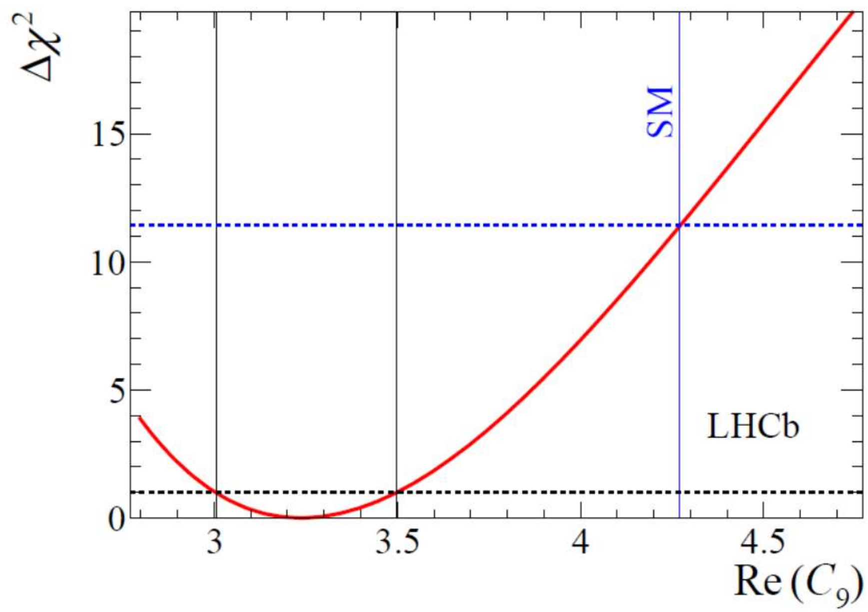
- A global analysis of C7, C9, and C10 with b → sll and b→sγ data suggest there is mostly room for new physics in Re(C9). C7 and C10 are constrained by b→sγ and Bs → μμ decay rates, resp.

- LHCb exercise: Fit all of the measurements, float Re(C9), and nuisance parameters for form factors and other theory parameters within errors

  - Re(C9) is found to be **shifted downward by 3.4σ relative to the SM**

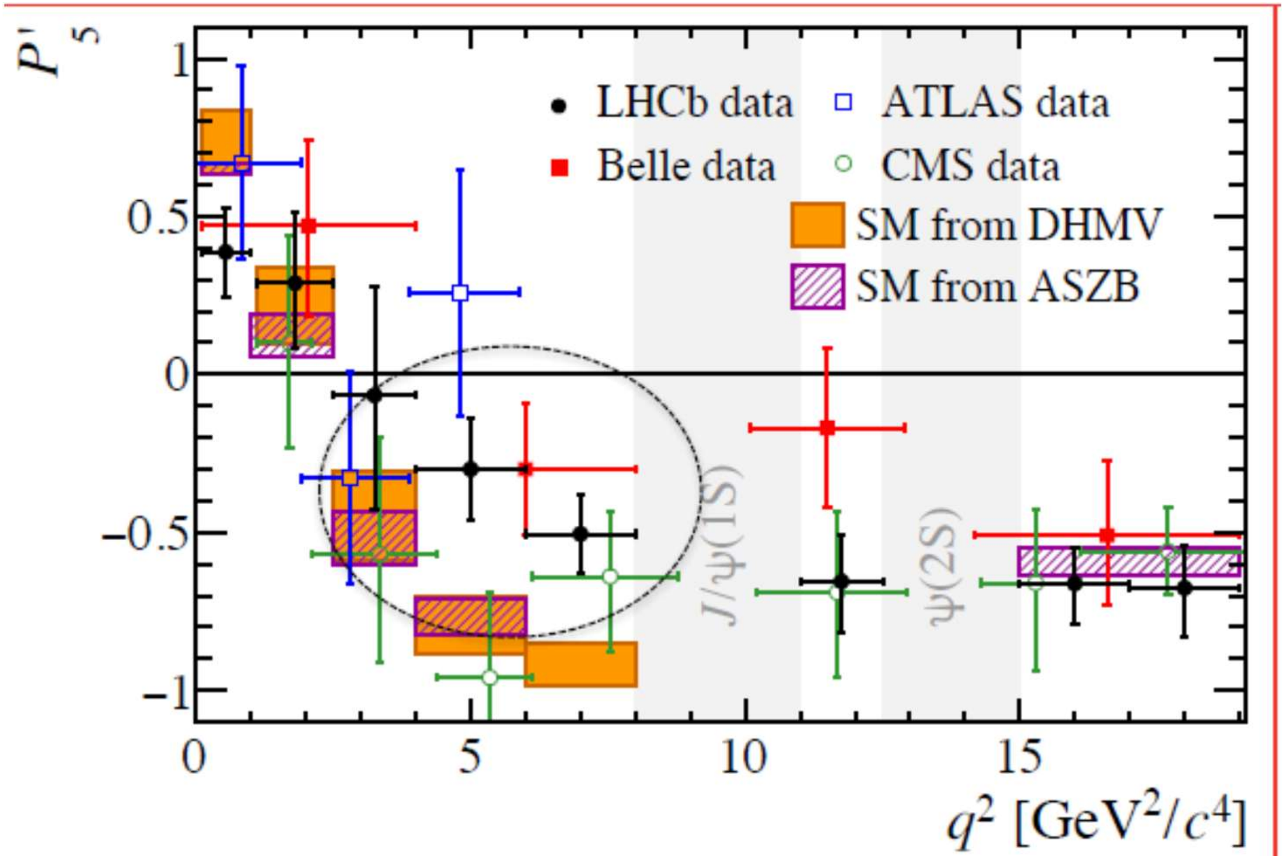
  - Appropriately coupled Z' or leptoquarks could satisfy this and other constraints

  - Or "an unexpectedly large hadronic effect"



Interpretations as Wilson coefficients

- ATLAS, CMS, Belle can all weigh in as well
- CMS data is more SM-like, but not as precise
- CMS will have a competitive K*ll trigger capability with Run 2 data; Belle2 will be competitive in ~2 years. LHCb Run 2 results are coming. Stay tuned!

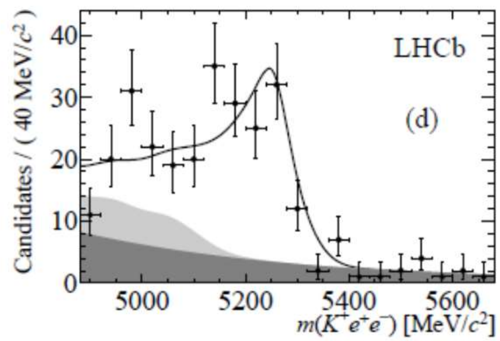


K*ll*, K**ll* and lepton universality

arxiv:1406.6482

- LHCb has the capability to measure K^+ll, $K^{*0}ll$ in both electron and muon final states. **Test lepton universality in b→sll via a ratio $R_{K(*)}$**

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+\mu^+\mu^-]}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+e^+e^-]}{dq^2} dq^2}$$



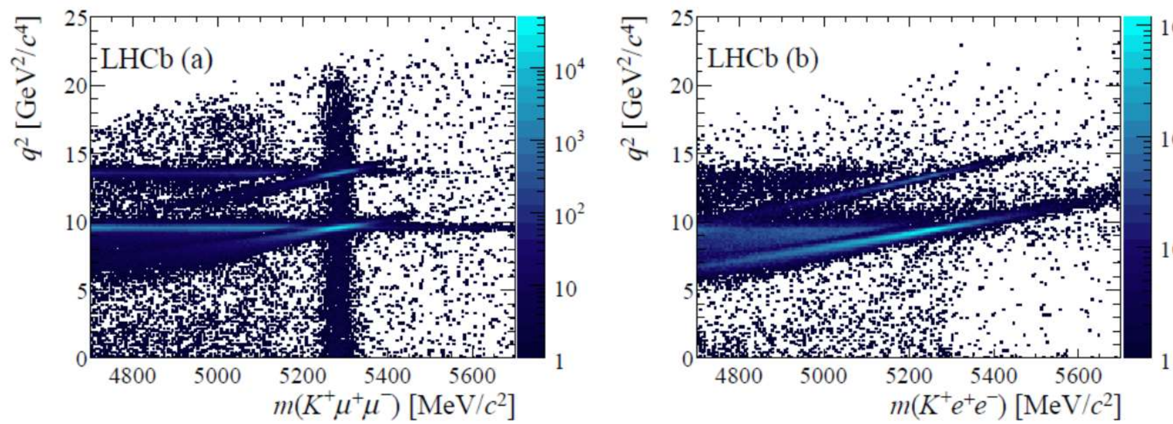
- **Lepton-universal B→J/ψK(*) can be used to normalize** decay rates and relative lepton efficiencies!

$$R_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right)\left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}}\right)$$

  - Main difference for electron channel is understanding of higher electron FSR

$$R_K = 0.745^{+0.090}_{-0.074}\,({\rm stat}) \pm 0.036\,({\rm syst})$$

  - **2.6σ deficit of mu vs. e for K^+ll!**
  - Main systematics are J/ψK model and trigger efficiency



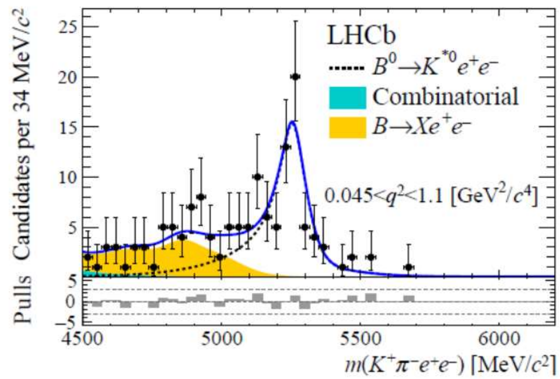
arxiv:1705.05802

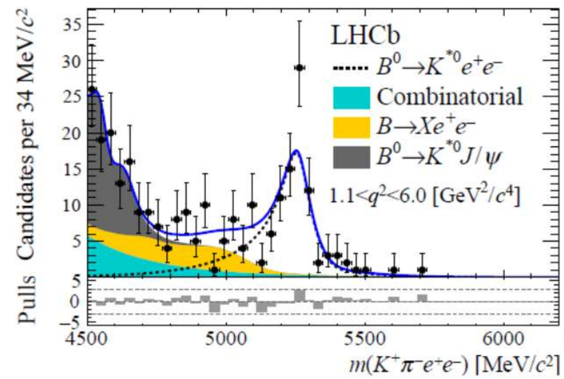
K*ll and lepton universality

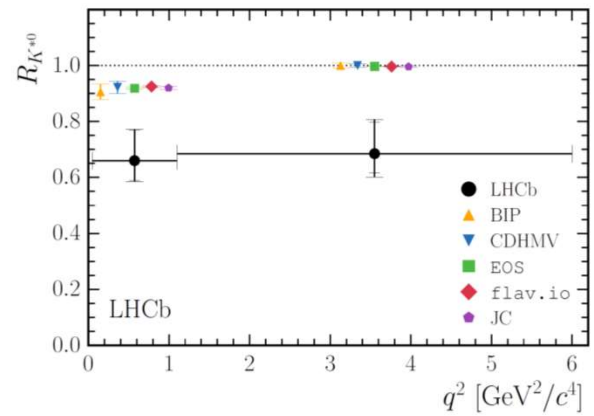
- LHCb has the capability to measure K^{+}ll, K$^{*0}ll$ in both electron and muon final states. **Test lepton universality in b→sll via a ratio R$_{K(*)}$**

- **Lepton-universal B→J/ψK(*) can be used to normalize** decay rates and relative lepton efficiencies!

- K*ee channel is also larger than K*μμ in two different bins in q²! Statistics limited.







$$R_{K^{*0}} = \begin{cases} 0.66 \,{}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \ \text{GeV}^2/c^4 \\ 0.69 \,{}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0 \ \text{GeV}^2/c^4 \end{cases}$$

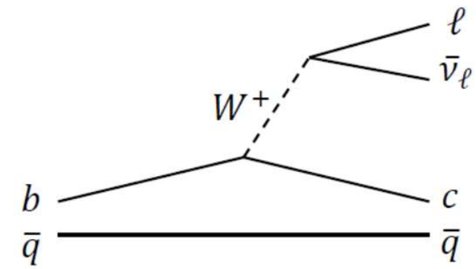
2.1σ muon deficit

2.4σ muon deficit

Leptons out of Balance: Semi-leptonic B decays

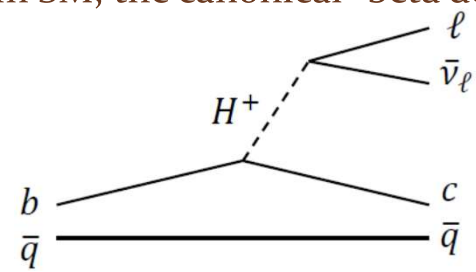
b → c semi-leptonic B decays

- One of the most common ways a b-hadron decays is through a semi-leptonic "beta decay" b → clν, proportional to CKM |Vcb|^2.
- Decays to light leptons are well-studied and accurately predicted. BF($B^0 \rightarrow D^{*-}\mu^+\nu$) = 4.88+/-0.10%
- Decays to taus are not as experimentally accessible and have only come into focus over the past 10 years.



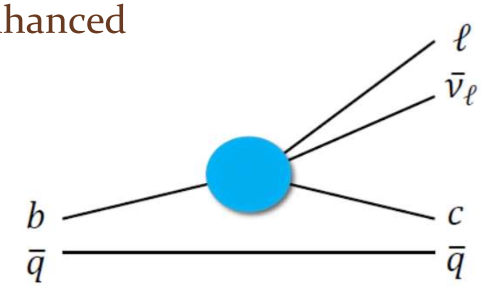
$$\sim \frac{G_F}{\sqrt{2}} m_B^2$$

In SM, the canonical "beta decay" of the b quark



$$\sim \frac{G_F}{\sqrt{2}} m_\ell m_B \frac{\tan^2\beta}{m_{H^+}^2}$$

Type II 2-Higgs doublet model is 3-gen and tan^{2}β enhanced



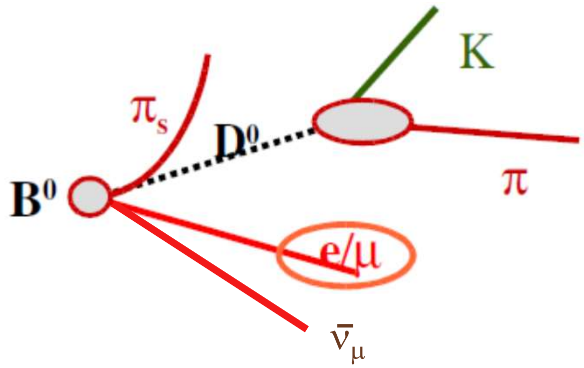
Leptoquark, W', etc., w/3-gen enhancement

$B^o \rightarrow D^{-*}l\nu$

- D*- hadronic final state is popular due to the simple 3-hadron final state $D^{*-} \rightarrow \bar{D}^o \pi^-$, $\bar{D}^o \rightarrow K^+\pi^-$ with narrow mass peaks in mD (8 MeV) and mD*-mD (0.8 MeV!)

$$\frac{d\Gamma}{dw}(\bar{B} \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2 m_B^5}{48\pi^3}|V_{cb}|^2(w^2-1)^{1/2}P(w)(\eta_{\mathrm{ew}}\mathcal{F}(w))$$

$$P(w) = r^3(1-r)^2(w+1)^2\left(1+\frac{4w}{w+1}\frac{1-2rw+r^2}{(1-r)^2}\right) \qquad \begin{array}{l} r = m_{D^*}/m_B \\ w \equiv v \cdot v' \end{array}$$

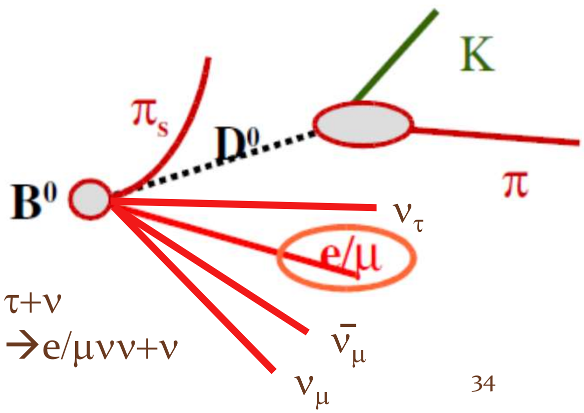


- HQET simplifies form factor F(B→D*) in terms of four-velocity product w.
- Lattice estimation of F(1) allows experimental measurement of |Vcb|
- BF for tau is ~¼ that of mu due to smaller phase space P

$$\mathcal{R}_{D^{(*)}} \equiv \mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell)$$

$$\mathcal{R}_{D^*}^{\mathrm{SM}} = 0.252 \pm 0.003$$

Unc. from form factor sampling different w



τ+ν
→e/μνν+ν

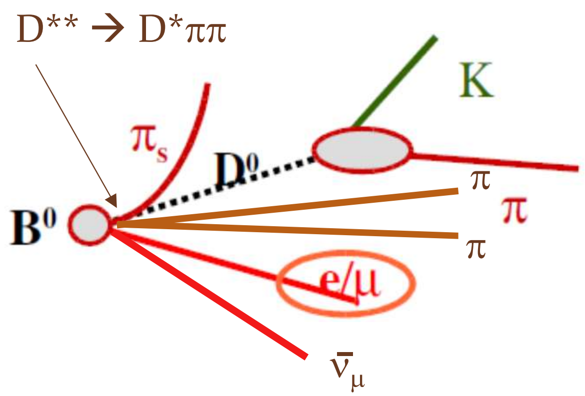
Event selection

- Hardware trigger selects charm mesons or unrelated high PT tracks. NO muon trigger to ensure low PT acceptance.
- D^0 software trigger accepts $K\pi$ pairs with D meson PT > 2 GeV.

- D candidate daughters pass PID requirements, have a common SV, and mD within 3xresolution (24 MeV)
- Add a slow pion, perform kinematic fit to get a D* candidate within 2 MeV of mD*-mD.
- Select muon > 3 GeV with common SV with D*, and a combined mu-D* mass < mB.

- B candidate momentum must point to a good PV
- "Wrong-sign" combinations mu/D*, D/pi retained for background studies
- D*h sample, >mB sample, mD*-mD sidebands retained for background studies.

- Require isolation of D*mu from other tracks to reduce higher mass D state background

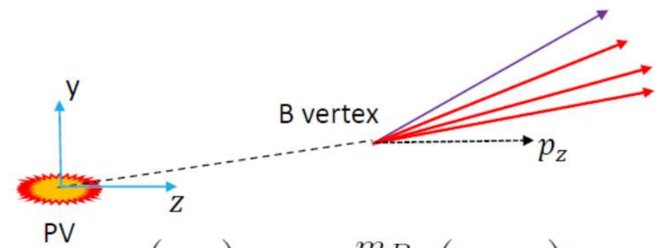


Higher D mass state background
Missed pions fake missing mass!

Track kinematics and geometry used for MVA which classifies events w/0/1/2 extra pions for signal and control samples

Kinematic discrimination of mu and tau

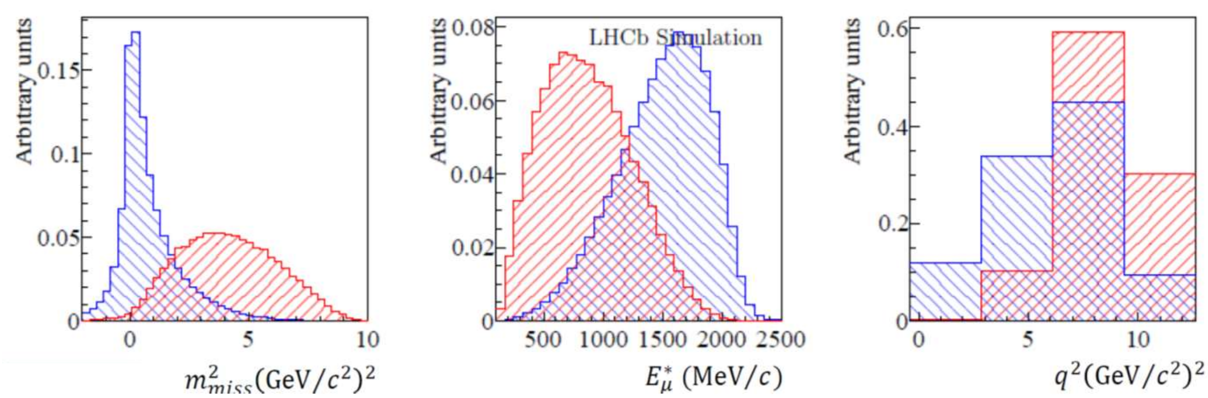
- Tau events have a softer muon energy spectrum in the B rest frame.
- Mu events have one neutrino and hence =0 missing mass in the B rest frame. Taus have 3ν and a broad mass.
- The q^2 of the lepton system $(PB^{\mu} - PD^{*\mu})^2$ is higher for tau.
- Signal is extracted via a 3D likelihood fit to these three variables.

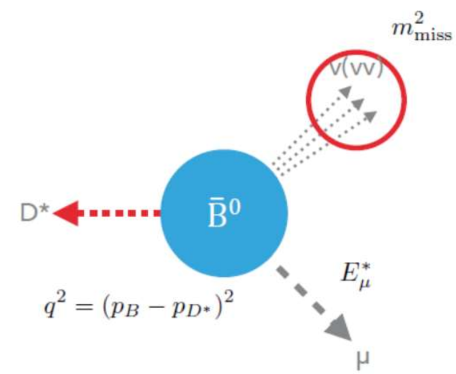


$$(p_B)_z = \frac{m_B}{m_{\text{reco}}}(p_{\text{reco}})_z$$

B momentum is approximated by PV-SV direction and rescaled PB_z

(B boost >> decay boost in B frame)



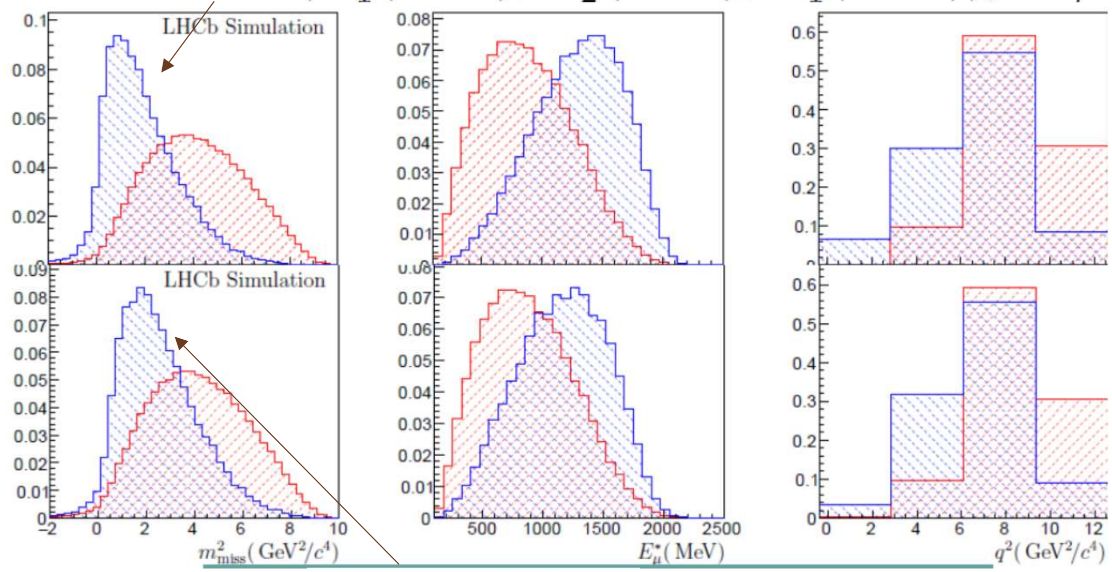


Signal and background models

- $D^*\tau\nu$ and $D^*\mu\nu$ modeled from simulation with HQET form factors
- Known one-pion higher D resonances modeled also from form factors with a floating form factor slope determined from the +1 pion control sample.

- +2 pion backgrounds estimated from form Factors and constrained by +2 pion control sample

$$\overline{B} \to (D_1(2420), D_2^*(2460), D_1'(2430))\mu^-\overline{\nu}_\mu$$



$$D^{**} \to D^{*+}\pi\pi$$

Signal and background models

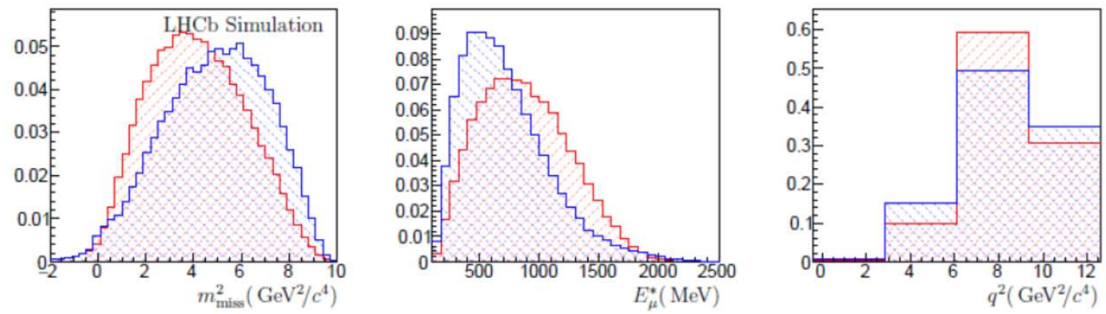
- A D*mu+K sample is used to normalize backgrounds from **B → D*H$_c$X, H$_c$→Xμν**

- D*h sample normalize and shape misid'd muon bkg.

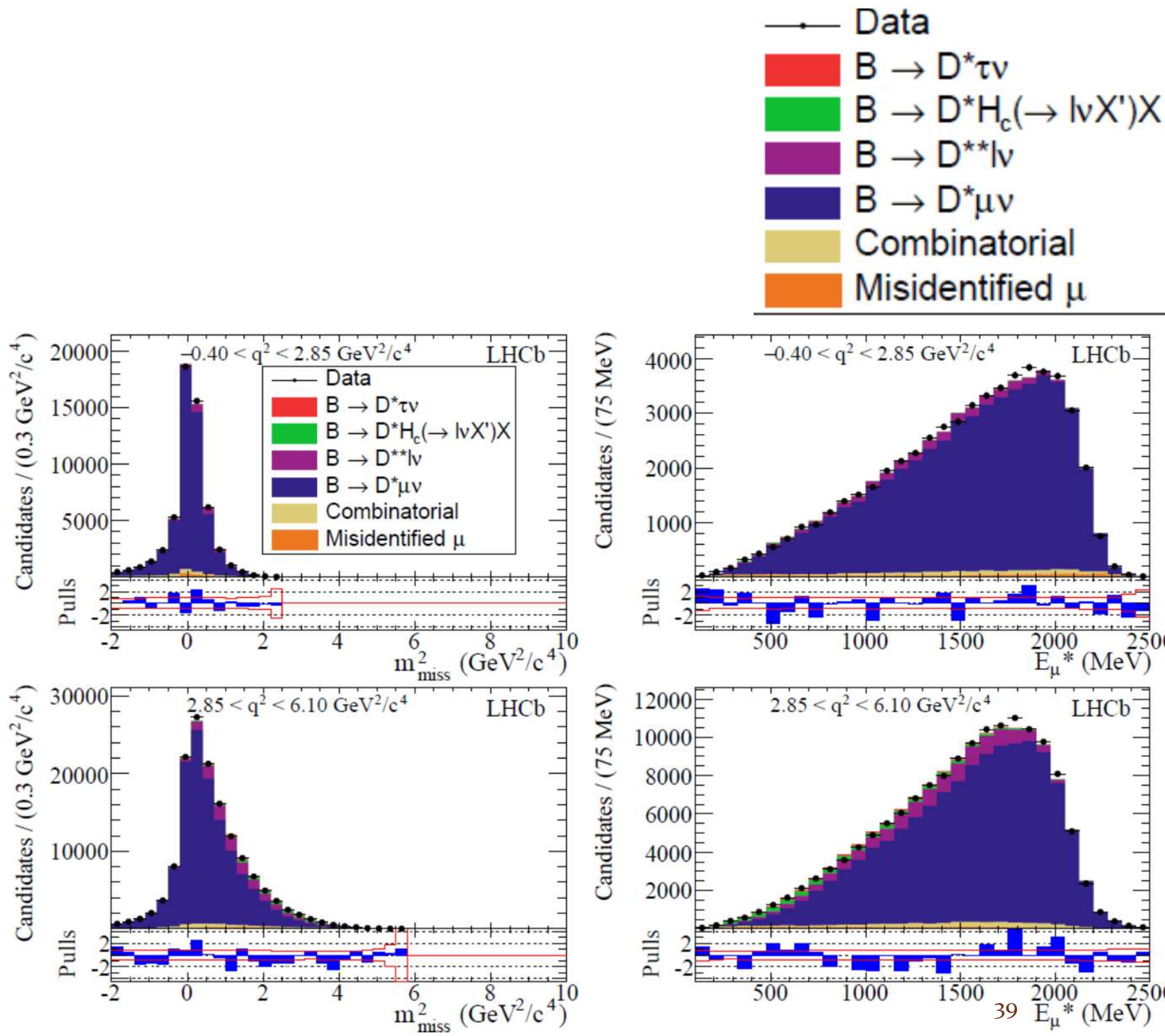
- Wrong-sign combinations normalize and shape combinatorial background.

B → D*D$_S$X, D$_s$ → ϕμν e.g.

$\bar{B}^0 \to D^{*+}H_c(\to \mu\nu X')X$ vs $\bar{B}^0 \to D^{*+}\tau^-\nu_\tau$



Fit Results



1D projections of M^2_{miss} and E_μ* of the 3D fit to signal-like final states in slices of leptonic q^2

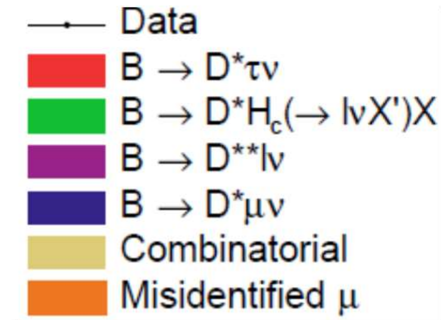
-0.4-2.85 GeV^2
2.85-6.10 GeV^2

Mostly D*μν and D**μν in these slices.

Fit Results

$$\mathcal{R}(D^*) = \mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$$

$$0.336 \pm 0.027\,(\mathrm{stat}) \pm 0.030\,(\mathrm{syst})$$

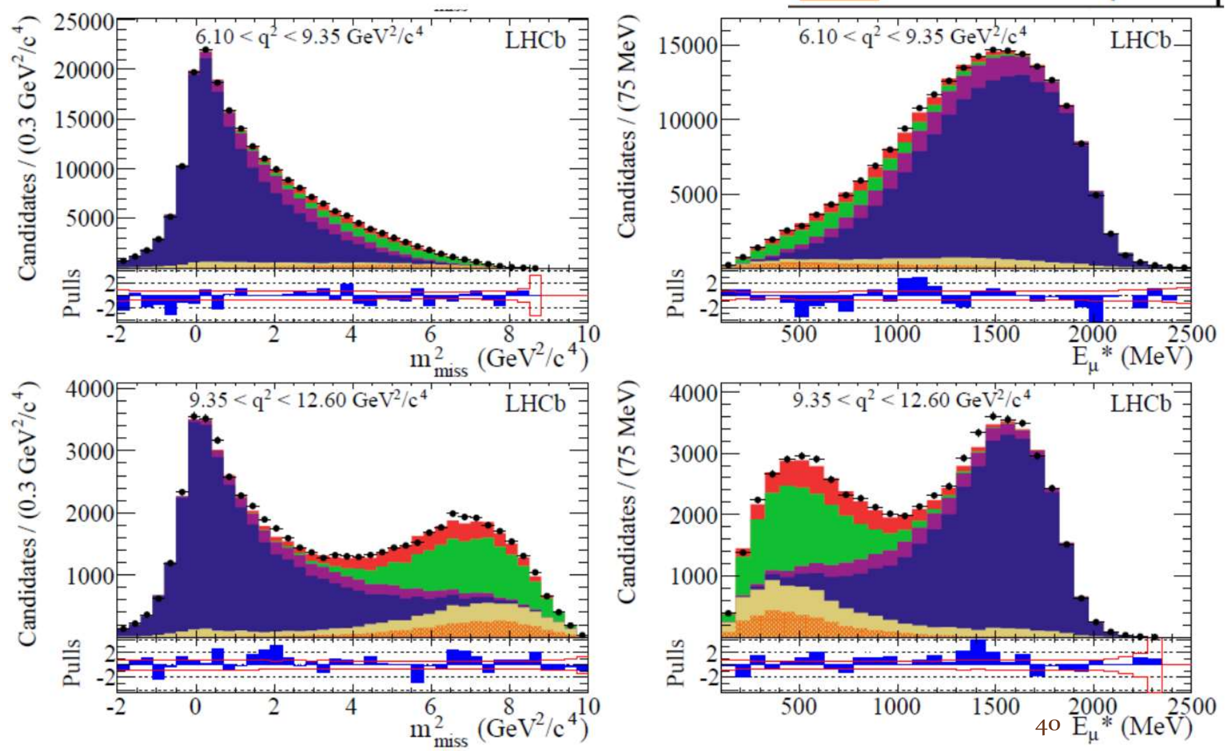


1D projections of M^2_{miss} and E_μ^* of the 3D fit to signal-like final states in slices of leptonic q^2

6.10-9.35 GeV^2
9.35-12.60 GeV^2

Signal is most prominent in these slices. **D^*H_c component (green) is -68% anticorrelated with signal!**

+2.1σ from SM prediction 0.252+/-0.003



Systematic uncertainties

Systematics mostly arising from MC statistics and fake muon template shape, which will improve over time.

Efficiency systematics and form factor systematics sub-leading due to mostly cancelling in the ratio

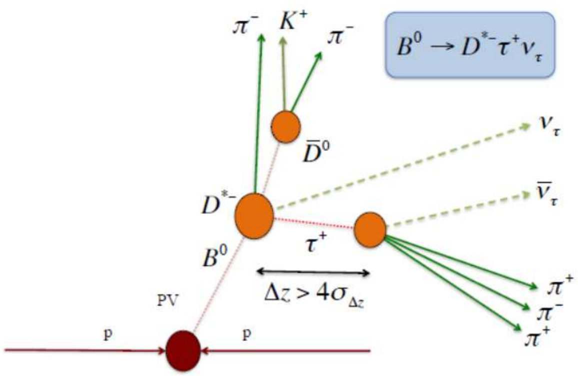
~9% uncertainty total for the ratio of BFs

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Another way: 3-prong tau decays

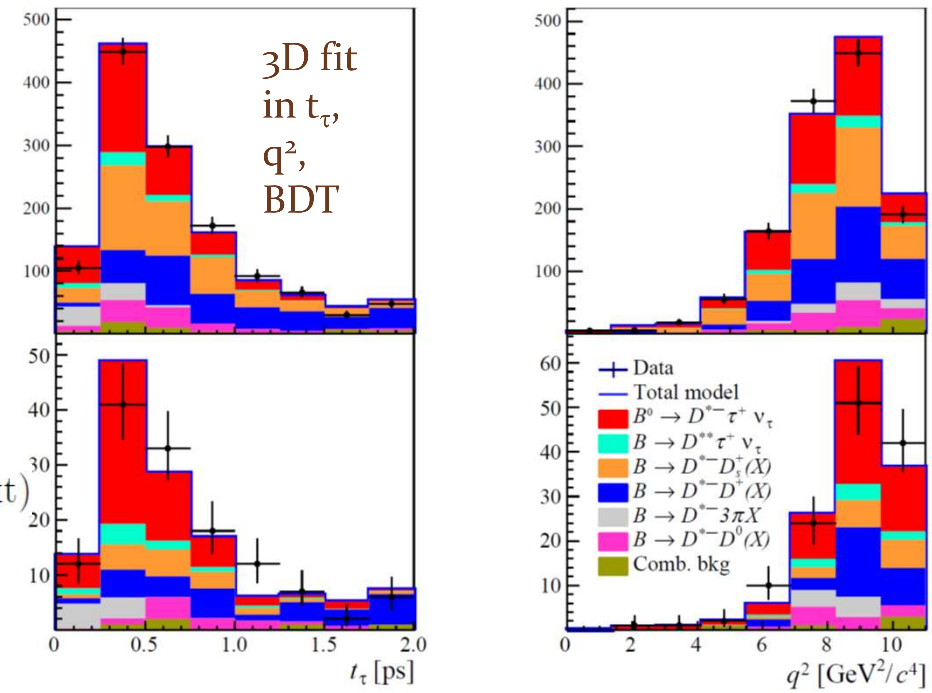
arxiv:1708.08856

- Use hadronic tau decays $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$, $\pi^+\pi^-\pi^+\pi^0\overline{\nu}_\tau$



- Use different normalization mode $\mathcal{K}(D^{*-}) \equiv \dfrac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$

$$\mathcal{R}(D^{*-}) = \mathcal{K}(D^{*-}) \times \mathcal{B}(B^0 \to D^{*-}3\pi)/\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$$



- **Tau vertex and lifetime reconstruction** suppresses B→DD$_x$X backgrounds

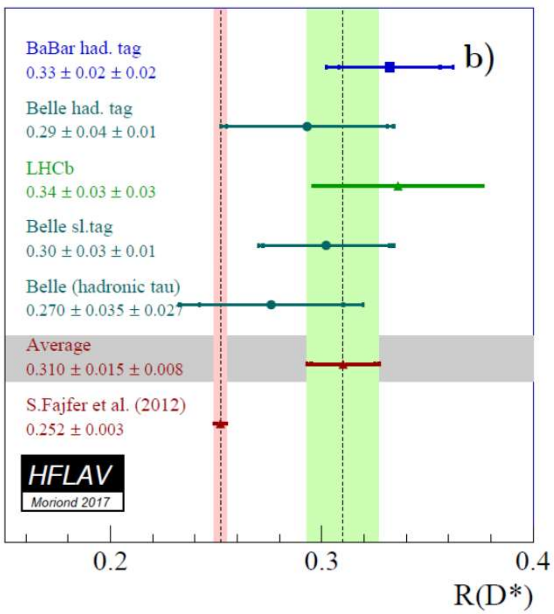
$$\mathcal{R}(D^{*-}) = 0.291 \pm 0.019\,(\mathrm{stat}) \pm 0.026\,(\mathrm{syst}) \pm 0.013\,(\mathrm{ext})$$

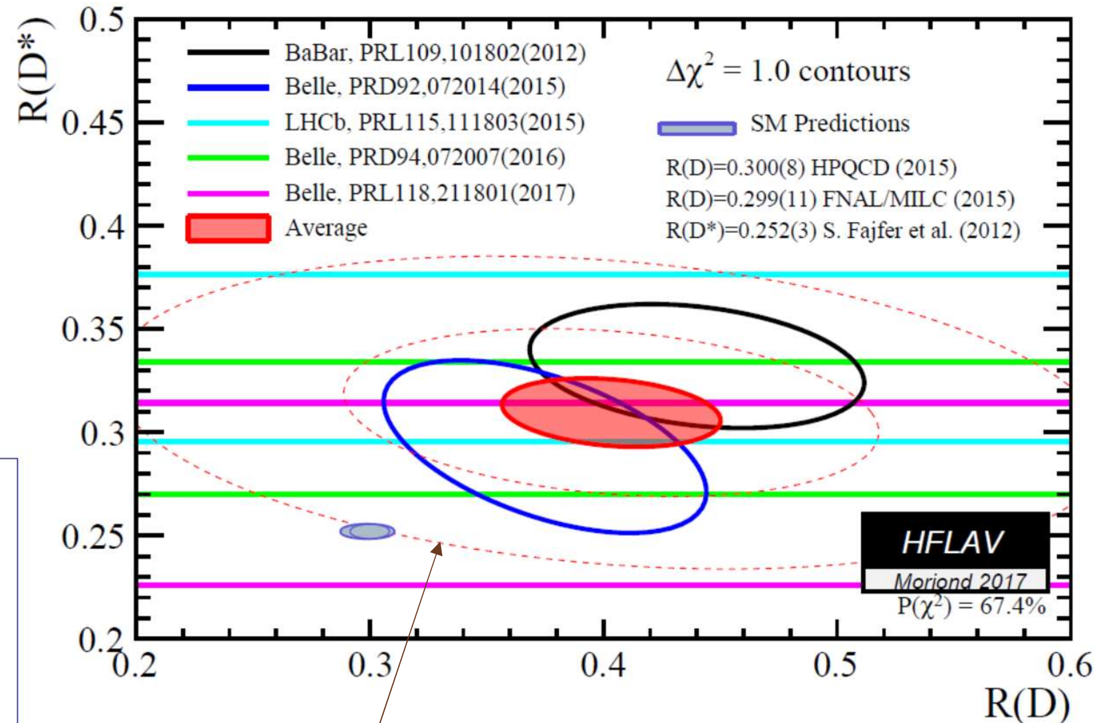
- **+1.1σ from SM prediction**, same precision as leptonic result with very different S/B and systematics (+2.2σ when averaged)

A global τ problem

- BaBar and Belle have also measured tau excesses in both B→Dτν and B→D*τν
- **Global fit to all data results in a 4.1σ discrepancy with the SM.**

arxiv:1612.07233



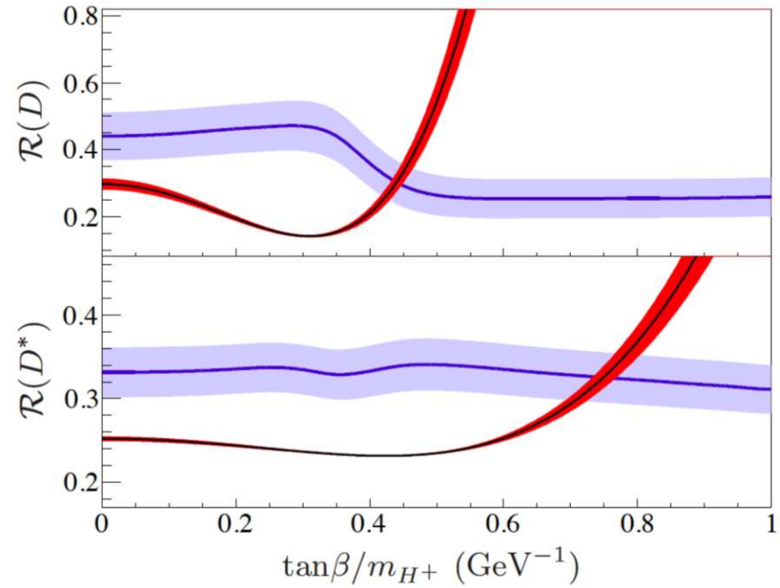


4σ contour!!

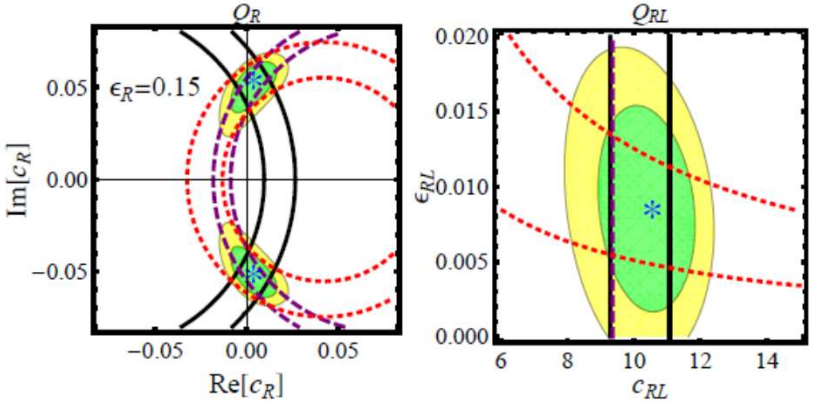
- LHCb, CMS Run 2, Belle II will all have another say soon!

A global τ problem

- Type II two-Higgs doublet interpretation seems to be ruled out due to differing R(D) and R(D*)



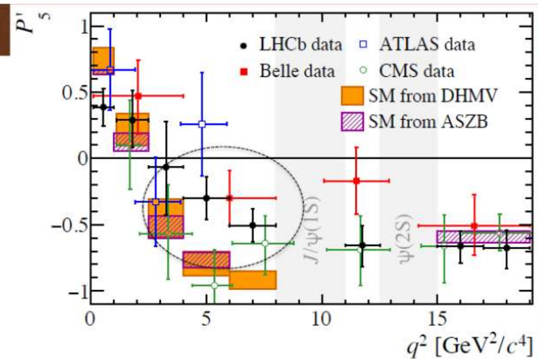
- An EFT analysis can fit the data best with "right-right vector and right-left scalar" operators. i.e., right-handed new physics.

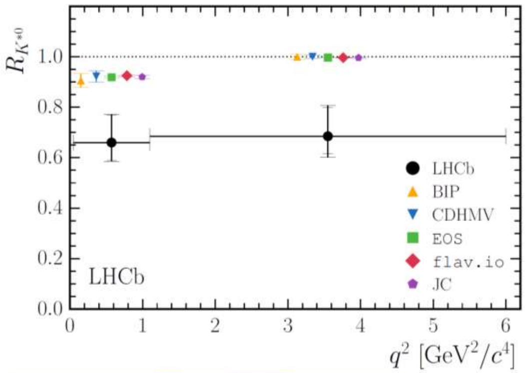


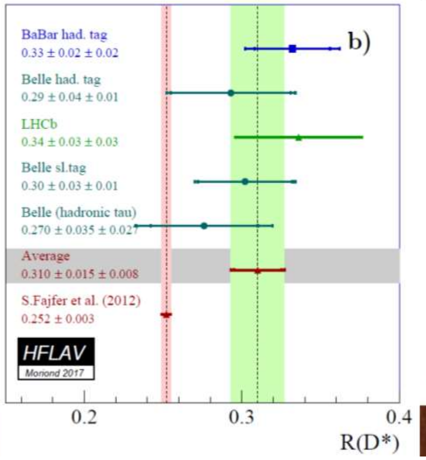
arxiv:1206.1872

Conclusions for Lecture 3

- Theory machinery exists to infer new physics at the electroweak scale (and higher) from exclusive b hadron decays (and s and c…), accessible through multiple decay channels. A comprehensive program is well underway to systematically analyze the EFT operators changing quark flavor.
- The right choice of decay mode and observable is important. Angular coefficients, flavor universality ratios, CP-asymmetries, or near-null tests are attractive experimentally.
- Exploit the hard-won knowledge of similar, higher-rate decay modes as a control for more rare processes.
- Multiple experiments can get in on the game, LHCb does not have a monopoly. There is usually more than one way to do it!
- The sensitivity of these measurements is unique and surprising, and historically herald a new direct discovery!







References

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- K^*ll angular coefficients predictions arxiv:0811.1214 arxiv:1407.8526 arxiv:hep-ph/0412400
- LHCb $B \rightarrow D^* \tau\nu$ analyses arxiv:1506.08614 arxiv:1708.08856 arxiv:1711.02505
- LHCb $K(^*)ll$ lepton universality tests arxiv:1406.6482 arxiv:1705.05802
- PDG review of $b \rightarrow cl\nu$, $ul\nu$ PDG review of semi-leptonic B decays