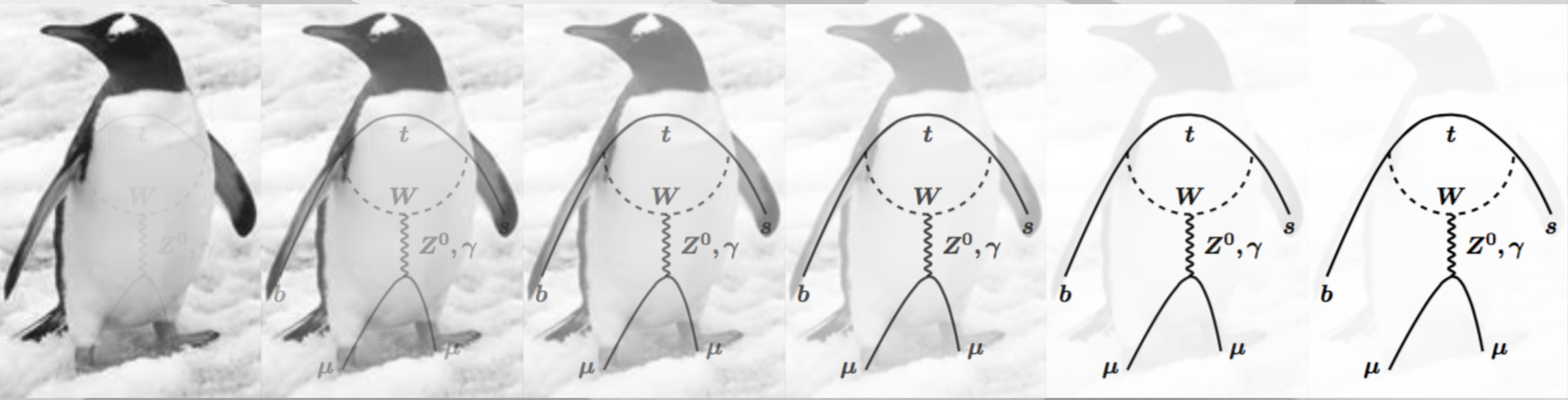
Search for Beyond the SM Physics in B decays to $K^{(*)}ll$ at Belle

Jared Yamaoka | PNNL

19 Aug 2016



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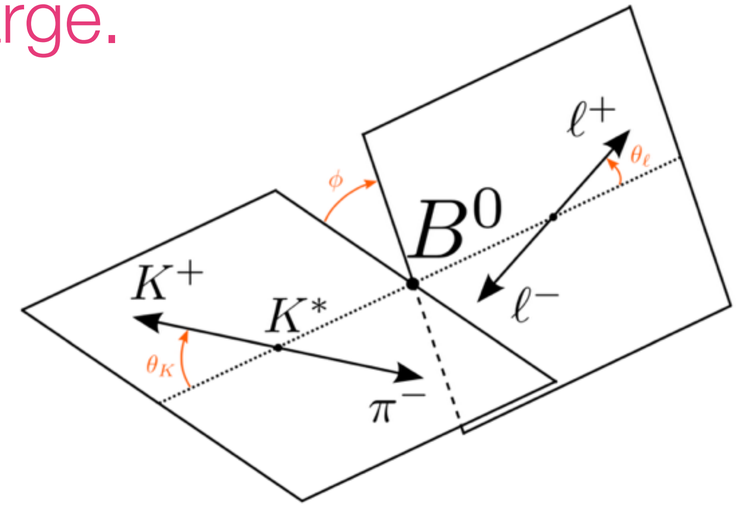
OUTLINE

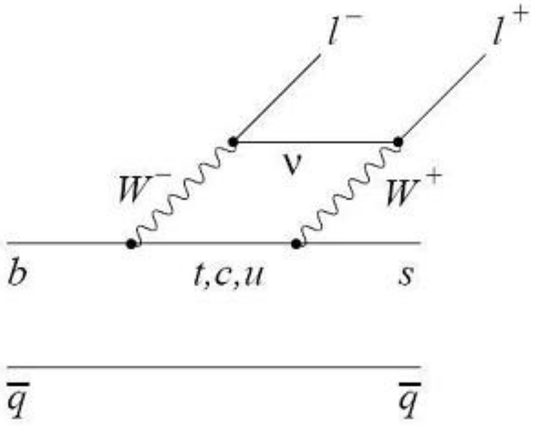
- Motivation
  - …with Theoretical and Experimental Status
- Analyses
- Belle2
- Summary

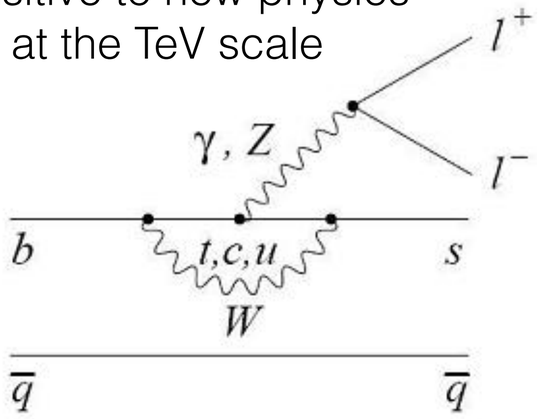
Motivation: $B \to K^{(*)}ll$

- $b \to sll$ transition: flavor-changing neutral current
- Interference: Penguin and box diagrams
  - Lepton (e,μ) forward-backward asymmetry (A_{FB}).
- Beyond the SM contributions can be large.



Sensitive to new physics at the TeV scale





Partial Angular Analysis

f_L vs. q^2 : (f_L= longitudinal polarization fraction for K*)

$$\frac{3}{2}\boxed{f_L}\cos^2\theta_{K^*} + \frac{3}{4}(1-\boxed{f_L})(1-\cos^2\theta_{K^*})$$

A_{FB} vs. q^2:

$$\frac{3}{4}f_L(1-\cos^2\theta_{Bl}) + \frac{3}{8}(1-f_L)(1+\cos^2\theta_{Bl}) + \boxed{A_{FB}}\cos\theta_{Bl}$$

Manifest in the energy spectrum: $q^2 = m_{ll}^2$

Fuller Angular Analysis

Felicias Breiback ICHEP 2016

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

- F_L and S_i functions of q^2
- eight free parameters

$$P'_5, S_5 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

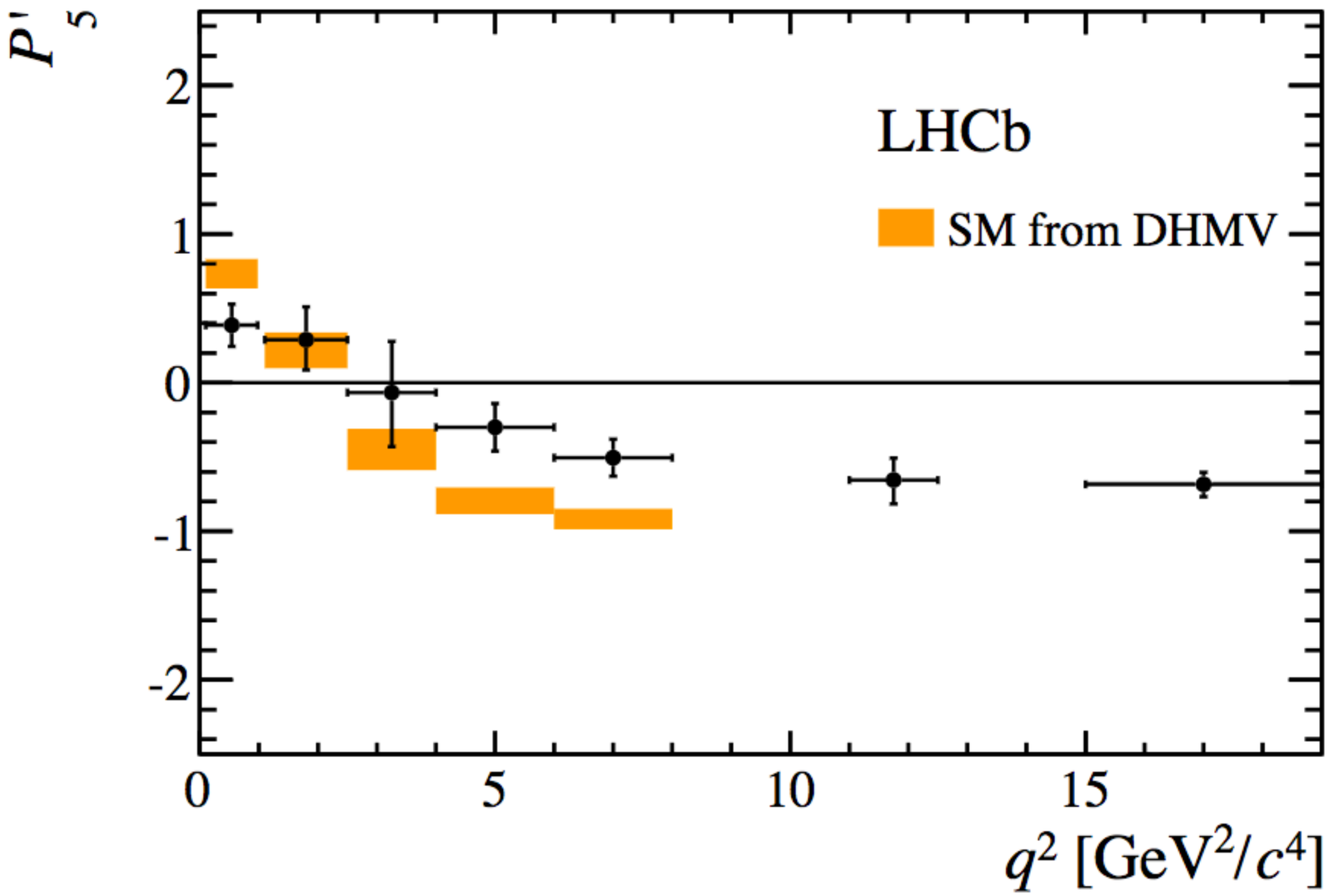
Folding technique:

- not enough statistics to perform eight-dimensional fit
- use symmetries of *sin* and *cos* to cancel terms
- reduce number of free paramters to 3: F_L, S_3 and S_i or P'_i

JHEP 01, 019 (2009) / JHEP 1305, 137 (2013) / Phys. Rev. Lett.111, 191801 (2013) / Cian, Track Reconstruction Efficiency and Analysis of $B^0 \to K^{*0}\mu^+\mu^-$ at the LHCb Experiment, Ph.D. thesis, University of Zurich (2013)

Full Angular Analysis

- "Famous" P5′ Discrepancy
- 3.4σ
- 8D Fit

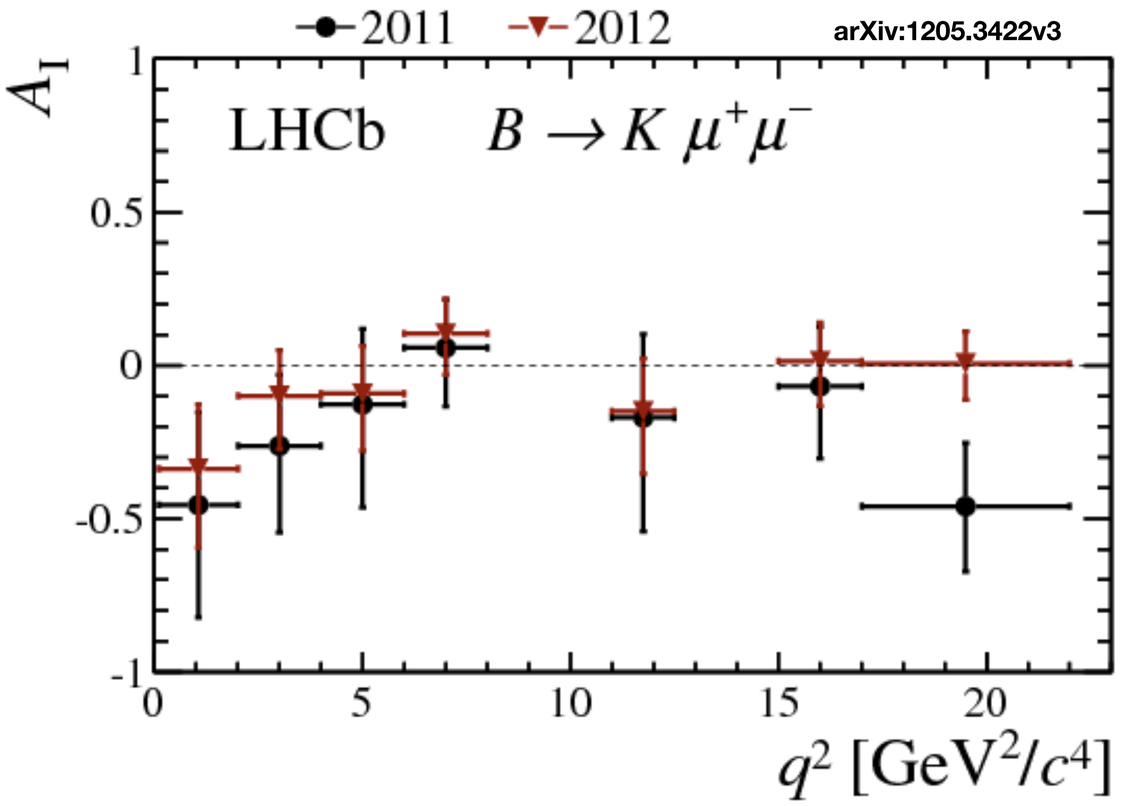


More Motivation: $B \to K^{(*)}ll$

CP Averaged Isospin Asymmetry (A_I)

$$A_I \equiv \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(K^{(*)0}ll) - \mathcal{B}(K^{(*)\pm}ll)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(K^{(*)0}ll) + \mathcal{B}(K^{(*)\pm}ll)}$$

- $B \to K^*ll$: Predicted $A_I \sim -1\%$ in SM.
- $B \to Kll$: No precise prediction A_I SM.
- LHCb shows a A_I below zero in some q^2 regions.



Branching fractions ($\mathcal{B}$) in these flavor-changing decays are not well measured.

Even More Motivation: $B \to K^{(*)}ll$

Lepton Universality

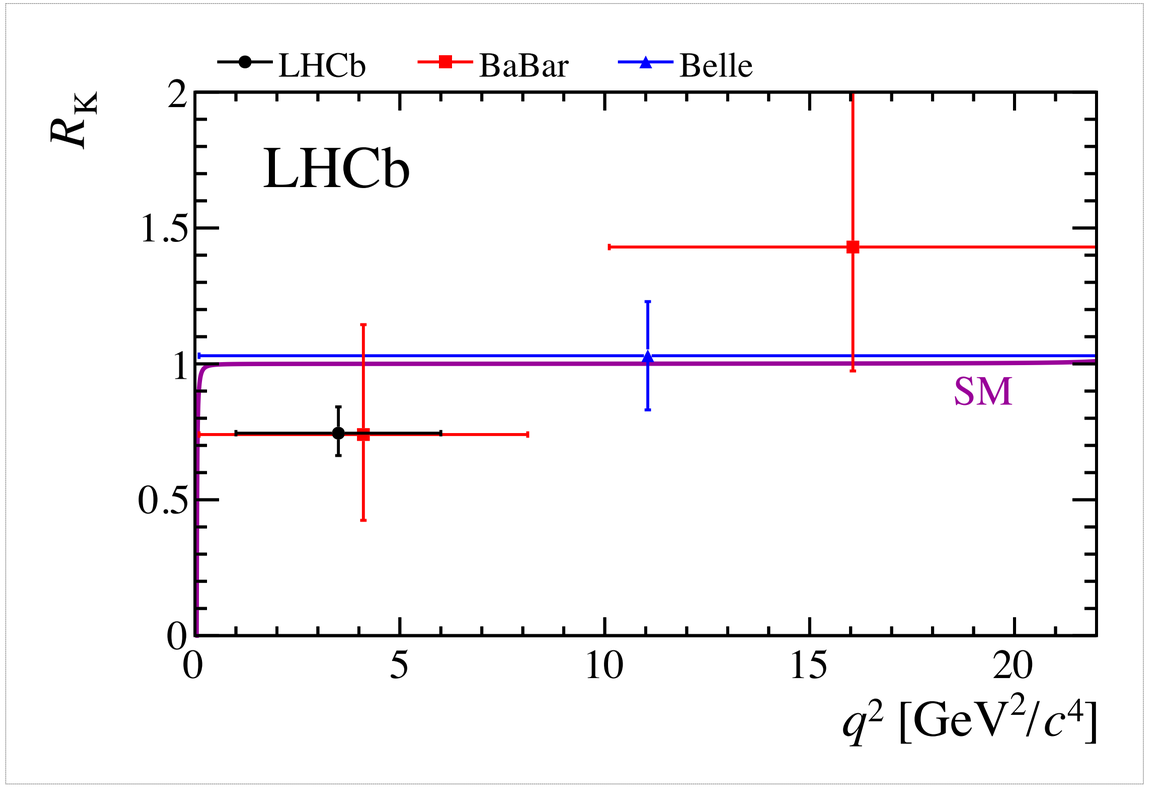
$$R_{K^{(*)}} \equiv \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}$$

- SM Predictes: $R_K^{SM} = 1 + \mathcal{O}(\frac{m_\mu^2}{m_b^2})$

  With a small correction due to higgs penguin diagrams

- New Particles: For example an extended higgs sector, can give ~10% deviation from SM

Advantage of e^+e^- vs LHC:
Better e reconstruction



Analysis Method

- Event Selection
- Fit signal and background in q^2 bin
  - M_{bc}...
    and $M_{K\pi}$ (for K^*)
  - Fix: N_{sig} N_{bkg}
- Calculate **Diff. $\mathcal{B}$, A_I,** and **$R_{K(*)}$**

$$M_{bc} = \sqrt{E_{beam}^2 - (\sum_i \vec{p_i})^2}$$

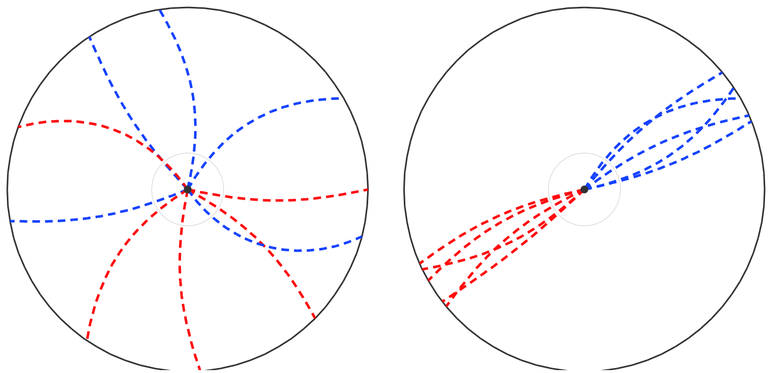
$B \to K^{*0} e^+ e^- \to (K^+\pi^-) e^+ e^-$	$B \to K^{*0} \mu^+ \mu^- \to (K^+\pi^-) \mu^+ \mu^-$
$B \to K^{*0} e^+ e^- \to (K_S^0\pi^0) e^+ e^-$	$B \to K^{*0} \mu^+ \mu^- \to (K_S^0\pi^0) \mu^+ \mu^-$
$B \to \overline{K}^{*0} e^+ e^- \to (K^-\pi^+) e^+ e^-$	$B \to \overline{K}^{*0} \mu^+ \mu^- \to (K^-\pi^+) \mu^+ \mu^-$
$B \to K^{*+} e^+ e^- \to (K_S^0\pi^+) e^+ e^-$	$B \to K^{*+} \mu^+ \mu^- \to (K_S^0\pi^+) \mu^+ \mu^-$
$B \to K^{*+} e^+ e^- \to (K^+\pi^0) e^+ e^-$	$B \to K^{*+} \mu^+ \mu^- \to (K^+\pi^0) \mu^+ \mu^-$
$B \to K^{*-} e^+ e^- \to (K_S^0\pi^-) e^+ e^-$	$B \to K^{*-} \mu^+ \mu^- \to (K_S^0\pi^-) \mu^+ \mu^-$
$B \to K^{*-} e^+ e^- \to (K^-\pi^0) e^+ e^-$	$B \to K^{*-} \mu^+ \mu^- \to (K^-\pi^0) \mu^+ \mu^-$
$B \to K^+ e^+ e^-$	$B \to K^+ \mu^+ \mu^-$
$B \to K_S^0 e^+ e^-$	$B \to K_S^0 \mu^+ \mu^-$
$B \to K^- e^+ e^-$	$B \to K^- \mu^+ \mu^-$

Event Selection

We apply cuts to **insure well measured charged tracks and gamma**, then **veto peaking background.**

- I then developed two multivariate discriminates to an compared their effectiveness
  - Likelihood
  - Neural Network

$e^+e^- \rightarrow BB$ $e^+e^- \rightarrow qq$



Kakuno-Super-Fox-Wolfram (KSFW) utilize event shape in order to suppress continuum background

Likelihood Method

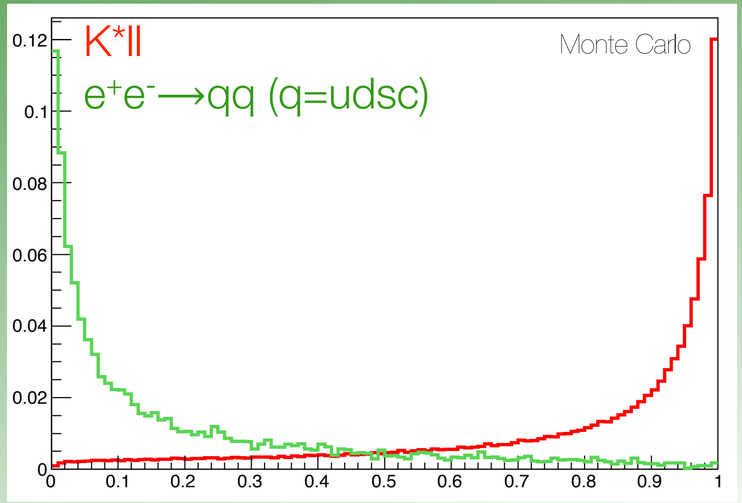
Construct likelihood ratio (LR) from fitted MC distributions

$$L_{S,B(qq)} = P(KSFW) \times P(\Delta Z_{BB}) \times P(\cos\theta_B)$$

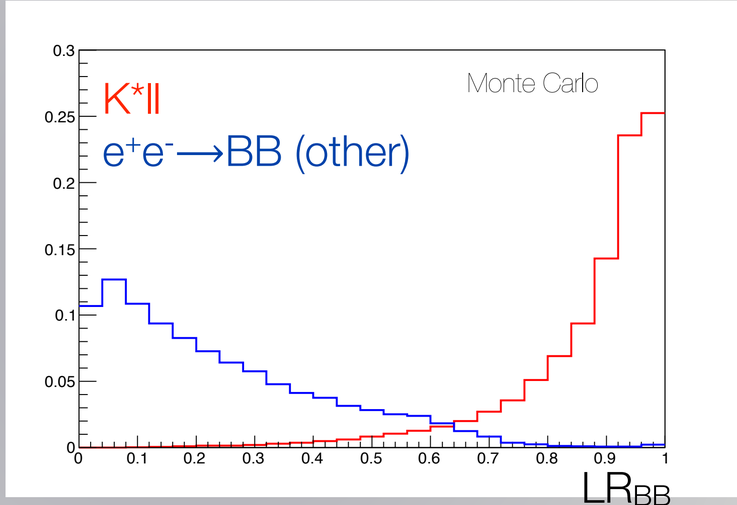
$$LR_{BB,qq} = \frac{L_{S(BB,qq)}}{L_{S(BB,qq)} + L_{B(BB,qq)}}$$

Two **LR** for each channel (K*ee, $K_S$ee, Kee, K*μμ, K_Sμμ and Kμμ) **12 total**

- KSFW
- ΔZ_{BB}
- cos θ_B



- KSFW
- ΔZ_{ll}
- cos θ_B



NeuroBayes Method

- Use the NeuroBayes package from KIT
- Equal size signal and background samples used for training
- 8 NN trained NN_{kee} ($K^{\pm}/K_S$), NN_{k^*ee}, $NN_{k\mu\mu}$ ($K^{\pm}/K_S$), and $NN_{k^*\mu\mu}$
- Continuum training fails if I separate K and K_S

	K*ee	Kee	Ksee	K*mm	Kmm	Ksmm
Continuum (5 stream)	9297	1866	466	11712	2374	547
Other BB (10 streams)	136750	8220	2392	109998	6734	1880
Signal	83617	219222	137864	121765	269755	167654

```
// TODO: Adding all variables to the network
// nb->SetIndividualPreproFlag(index,preproflag,varname);
nb->SetIndividualPreproFlag(0, 35, "cosb");
nb->SetIndividualPreproFlag(1, 14, "abs(q)");
nb->SetIndividualPreproFlag(2, 14, "k0mm2");
nb->SetIndividualPreproFlag(3, 14, "k0et");
nb->SetIndividualPreproFlag(4, 34, "k0hso00");
nb->SetIndividualPreproFlag(5, 34, "k0hso02");
nb->SetIndividualPreproFlag(6, 34, "k0hso04");
nb->SetIndividualPreproFlag(7, 34, "k0hso10");
nb->SetIndividualPreproFlag(8, 34, "k0hso12");
nb->SetIndividualPreproFlag(9, 34, "k0hso14");
nb->SetIndividualPreproFlag(10, 34, "k0hso20");
nb->SetIndividualPreproFlag(11, 34, "k0hso22");
nb->SetIndividualPreproFlag(12, 34, "k0hso24");
nb->SetIndividualPreproFlag(13, 34, "k0hoo0");
nb->SetIndividualPreproFlag(14, 34, "k0hoo1");
nb->SetIndividualPreproFlag(15, 34, "k0hoo2");
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nb->SetIndividualPreproFlag(17, 34, "k0hoo4");
nb->SetIndividualPreproFlag(18, 12, "abs(q)");
nb->SetIndividualPreproFlag(19, 12, "k0mm2");
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nb->SetIndividualPreproFlag(22, 92, "k0hso02");
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nb->SetIndividualPreproFlag(37, 14, "deltaz");
nb->SetIndividualPreproFlag(38, 18, "binF");
```
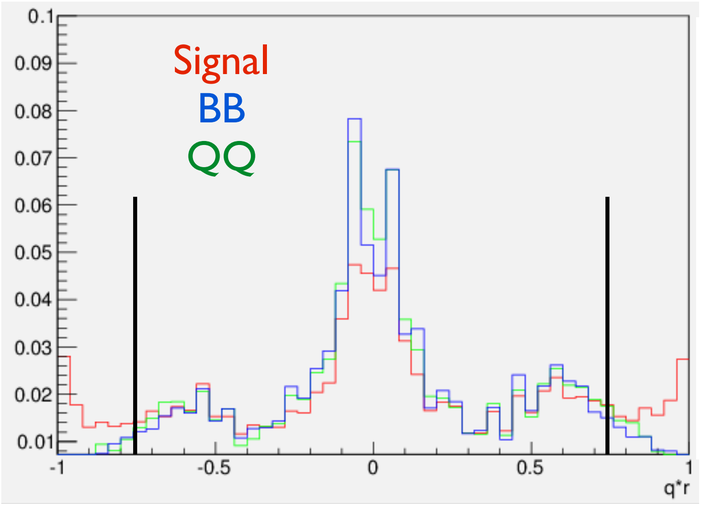
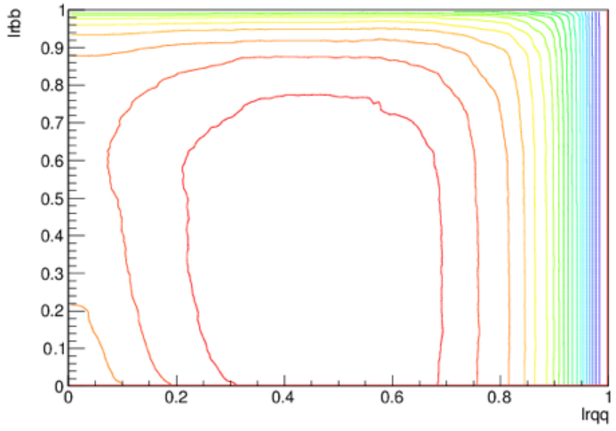

OPTIMIZE



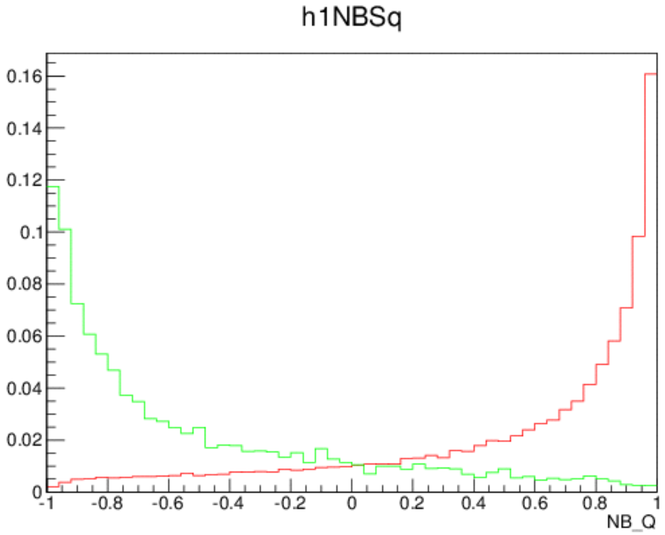


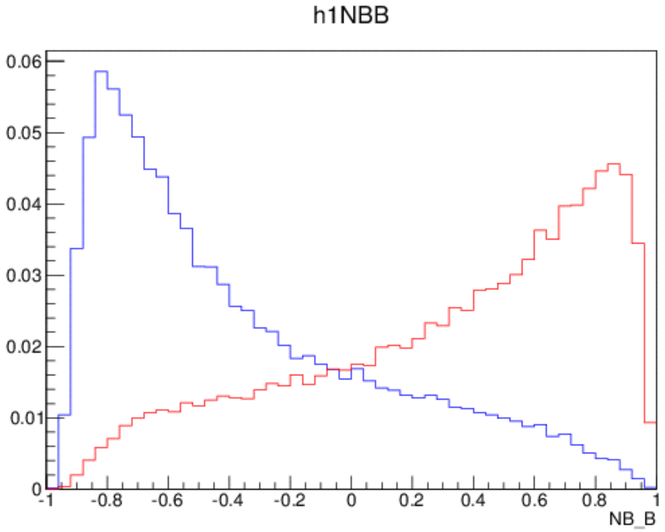
Likelihood

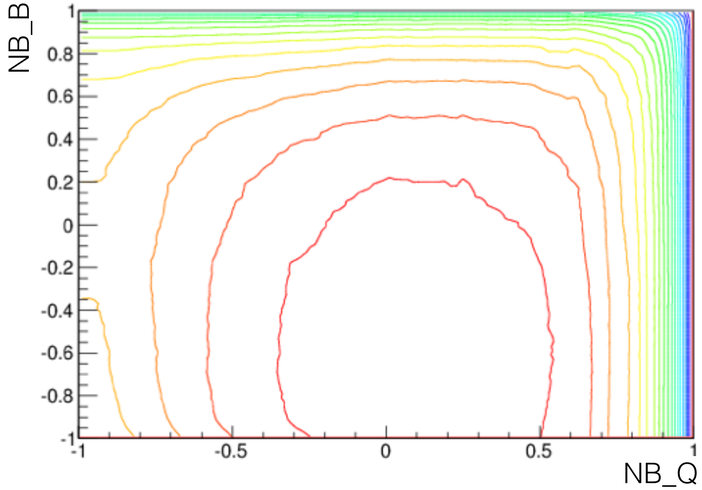
$$Signif. = \frac{NSignal}{\sqrt{NSignal + NBackgrd}}$$

- Perform a 2D optimization of the significance
- Likelihood the optimized in q*r: |q*r| < 0.75 and |q*r| > 0.75

NeuroBayes







Significance and Efficiency

Calculate expected significance and signal efficiency for each channel

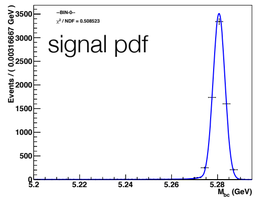
LR	K*ee	Kee	Ksee	K*mm	Kmm	Ksmm
Signif.	5.35946	4.90234	3.5892	9.79904	7.25788	4.75724
Eff.	0.938199	0.957814	0.97269	0.856836	0.9888	0.963318

NN	K*ee	Kee	Ksee	K*mm	Kmm	Ksmm
Signif.	5.6632	4.85164	3.51039	9.63919	6.97751	4.70041
Eff.	0.729199	0.834178	0.918757	0.729888	0.852004	0.938353

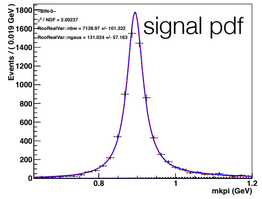
PERFORMANCE IS THE SAME, but still an unresolved issue

Fitting For Signal Yield

M_{bc} ($K^{(*)}ll$)
- ArgusBG
- Crystal Ball



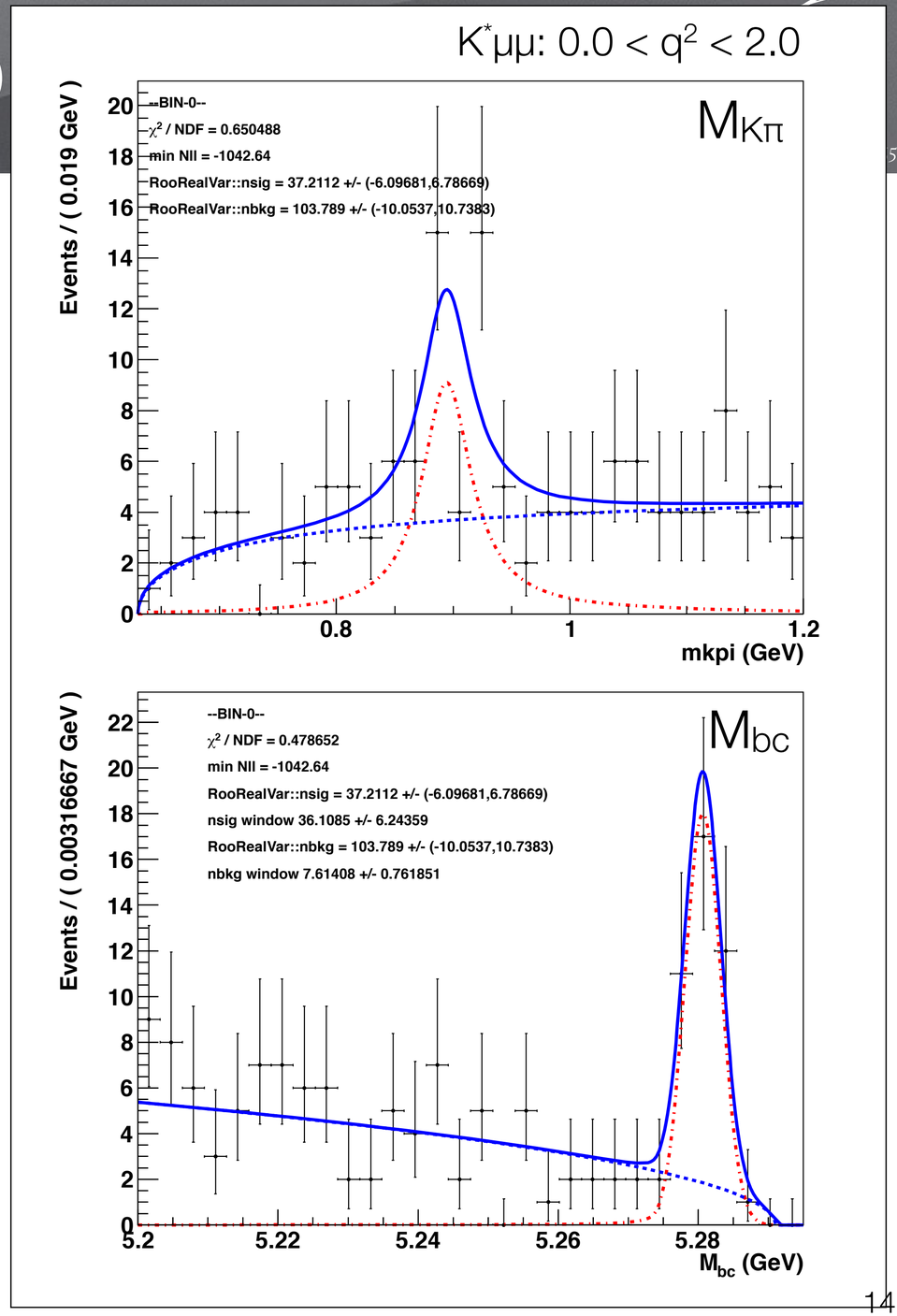
$M_{K\pi}$ ($K^{*}ll$)
- Threshold function
- Relativistic Breit-Wigner + Gaussian



- Signal PDF from MC
- Bkg. PDF free
- Simultaneous unbinned fit

Pseudo-experiment

q2 (GeV^2/c^4)	$K^{*+-}ll$ Fit Yield	$K^{*0}ll$ Fit Yield
0.0 - 2.0	24±8	45±7
2.0 - 4.3	15±4	32±6
4.3 - 8.69	21±5	31±6
10.09 - 12.86	7±3	11±3
14.18 - 16.0	9±3	12±4
> 16	13±3	14±4



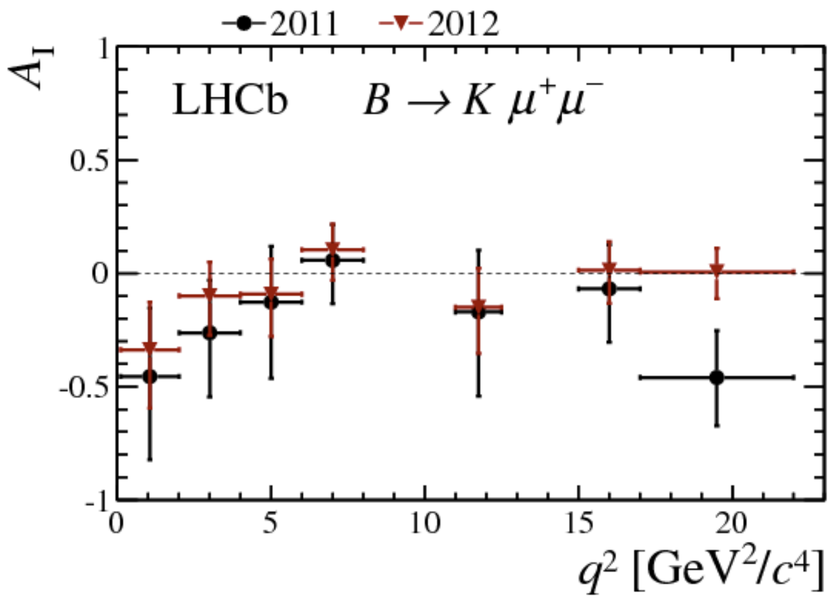
Isospin Asymmetry

CP averaged isospin asymmetry (A_I)

$$A_I \equiv \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(K^{(*)0}ll) - \mathcal{B}(K^{(*)\pm}ll)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(K^{(*)0}ll) + \mathcal{B}(K^{(*)\pm}ll)}$$

Derived directly for the efficiency corrected fit yields (previous slide) and number of BB.
Expected to be small, but LHCb sees a large negative A_I at in Kμμ [arXiv:1205.3422v3].
Below we calculate our expected sensitivity using MC, taking into account the uncertainty on the fit yields.

Advantages of e^+e^- vs LHC:
- Include e in final state
- Good K^0_s reconstruction
- Good π_0 reconstruction

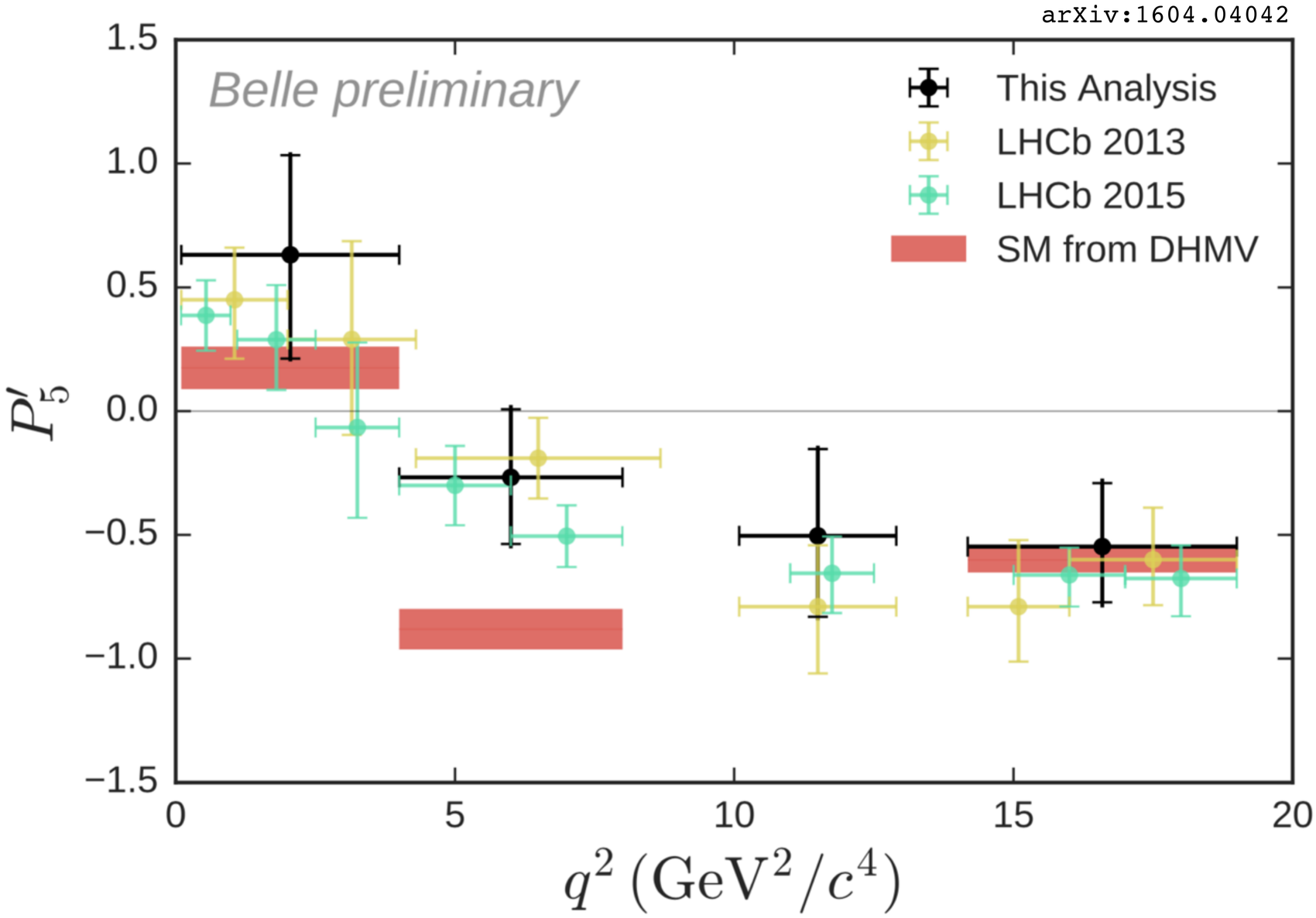


Expected Error

q2 (GeV^2/c^4)	K*ll Error	Kll Error
0.0 - 2.0	0.12	0.11
2.0 - 4.3	0.14	0.07
4.3 - 8.69	0.12	0.07
10.9 - 12.86	0.14	0.1
14.18 - 16.0	0.18	0.11
> 16	0.23	0.09

Full Angular Analysis

- Simon Wehle (KIT)
- $B^0 \to K^{*0} ll$
- NN PID
- 3D Fit
- Compatible with LHCb



Belle Inclusive Analysis

- Y. Sato (Tohoku)
- Inclusive has less theoretical uncertainty than $B \to K^{(*)} l^+ l^-$
- Semi-inclusive (sum of exclusive) method, with 36 modes of which 20 are used for A_{fb}
- The fraction of all X_s decays covered by 20 final states is ~50 %

Currently Being Updated by E Kato (Tohoku)

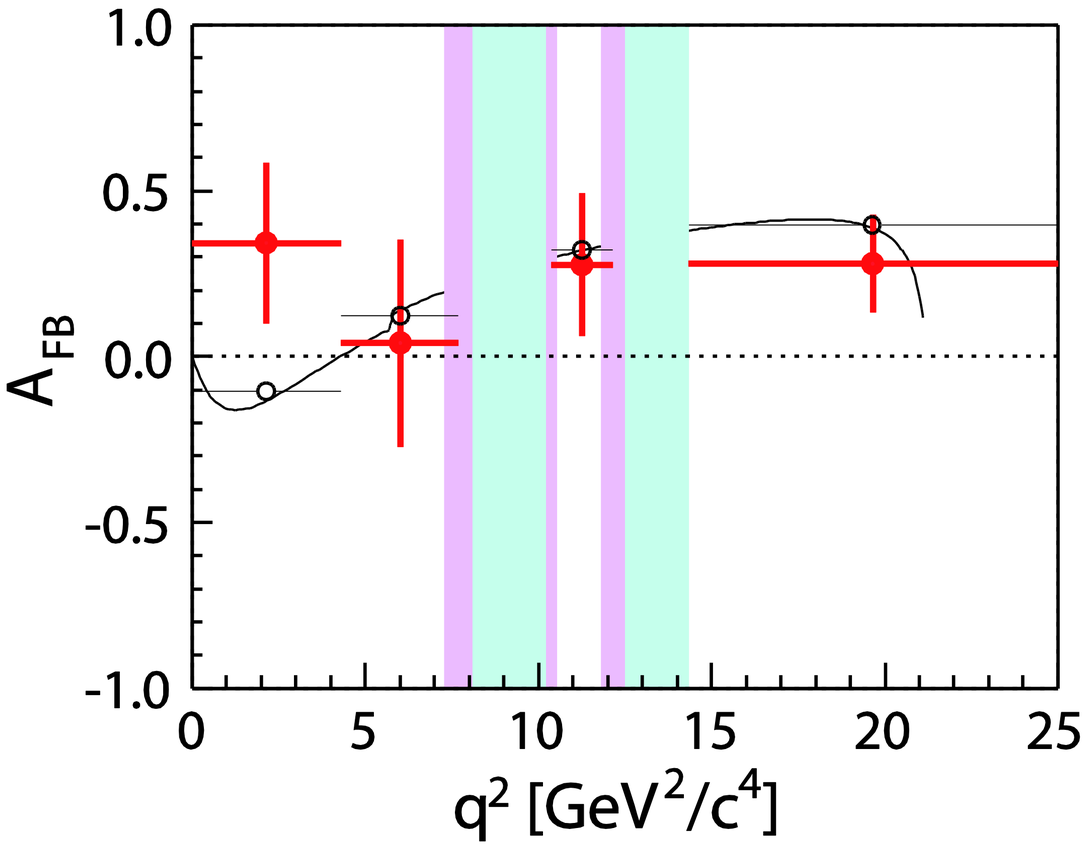
- Neural network is employed for backgrounds suppression
  - ✦ Semi-leptonic B decays
  - ✦ Continuum (u,d,s,c)

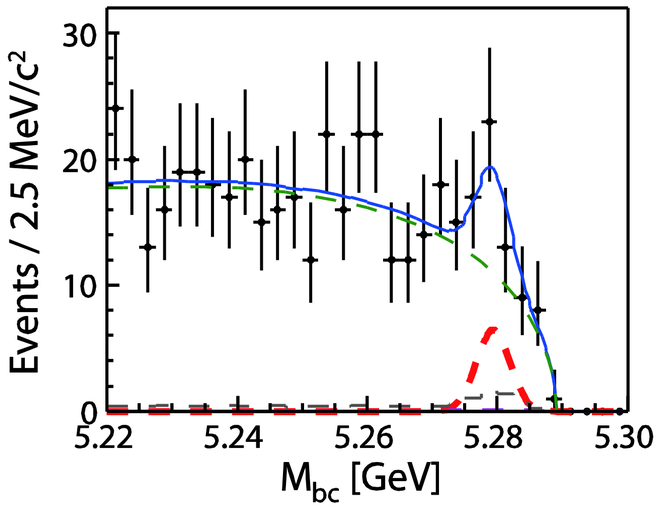
TABLE I. The 18 hadronic final states used to reconstruct X_s. The 8 final states enclosed in parentheses are not used for the measurement of $\mathcal{A}_{FB}$.

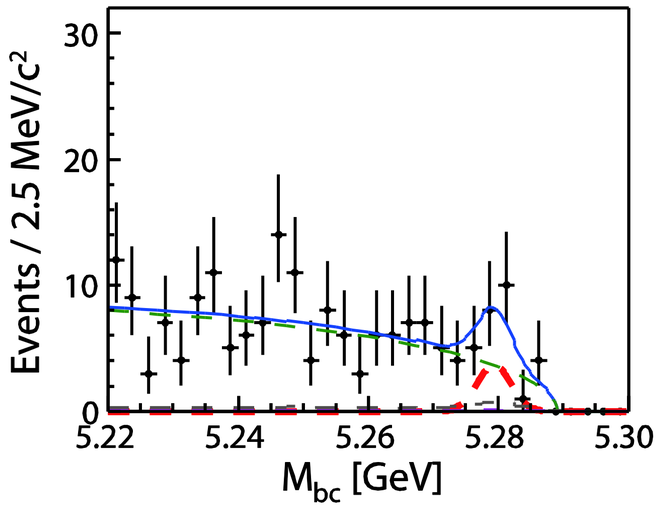
$\bar{B}^0$ decays		B^- decays	
	(K_S^0)	K^-	
$K^-\pi^+$	$(K_S^0\pi^0)$	$K^-\pi^0$	$K_S^0\pi^-$
$K^-\pi^+\pi^0$	$(K_S^0\pi^-\pi^+)$	$K^-\pi^+\pi^-$	$K_S^0\pi^-\pi^0$
$K^-\pi^+\pi^-\pi^+$	$(K_S^0\pi^-\pi^+\pi^0)$	$K^-\pi^+\pi^-\pi^0$	$K_S^0\pi^-\pi^+\pi^-$
$(K^-\pi^+\pi^-\pi^+\pi^0)$	$(K_S^0\pi^-\pi^+\pi^-\pi^+)$	$(K^-\pi^+\pi^-\pi^+\pi^-)$	$(K_S^0\pi^-\pi^+\pi^-\pi^0)$

Phys. Rev. D 93, 032008 (2016)

Belle Inclusive Analysis







Fit $X_s\mu\mu$ 2nd q^2 bin: N_{sig} = 23.9±10.5 (stat)

- Consistent with SM
- Total Signal Yields
  - N_{sig}^{ee} = 139.9 ± 18.6 (stat)
  - $N_{sig}^{\mu\mu}$ = 160.8 ± 20.0 (stat)

Bin 1: **Consistent with SM at 1.8σ** (6.6% C.L.)
Bin 3/4: **Exclude C_{10}*C_9 > 0 with 2.3σ** (97.9% C.L.)

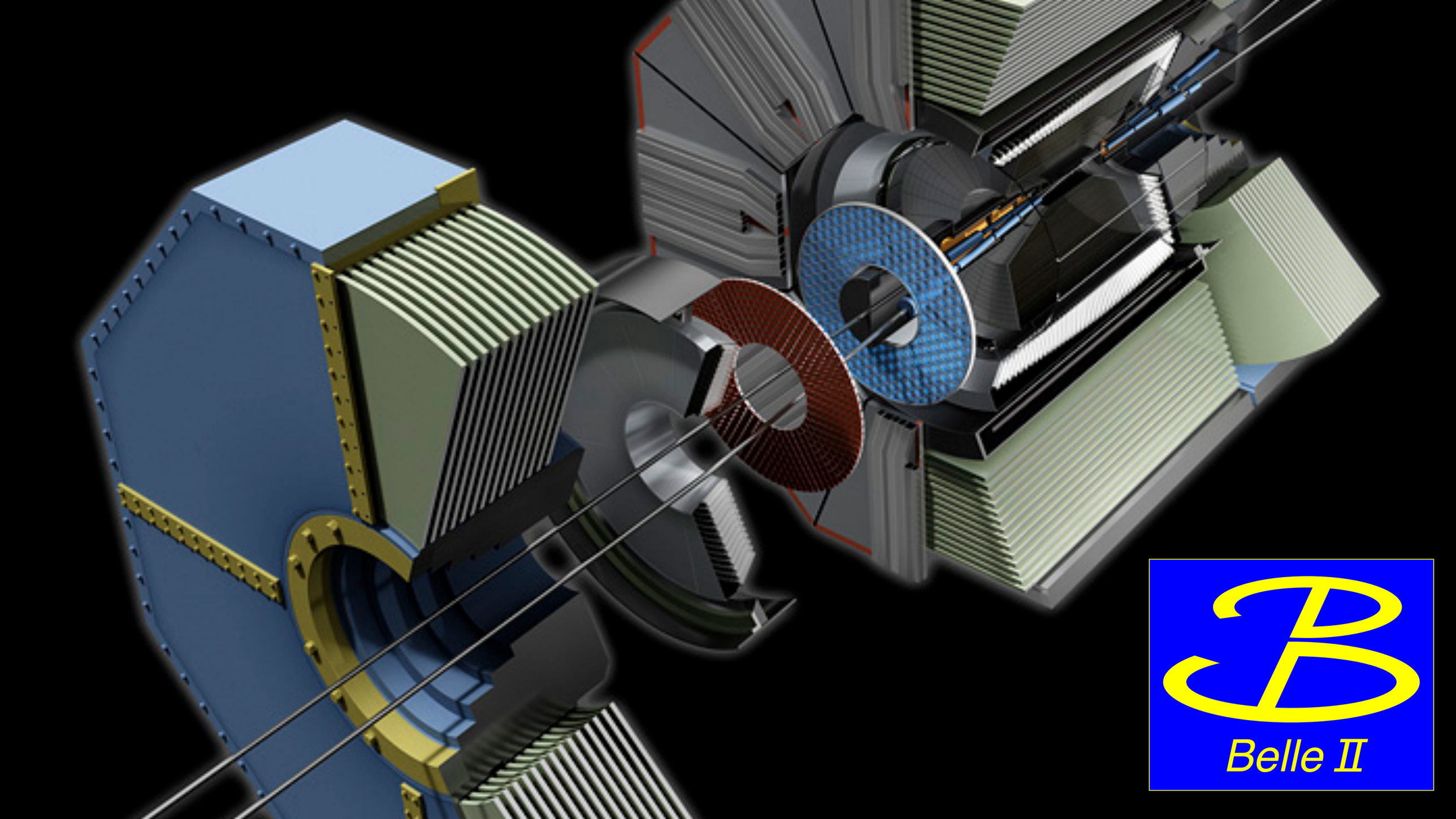
INCLUSIVE $X_s ll$

- Important for all cases not just inclusive
- What is possible experimentally?
  - ✦ Inclusive analysis are supposed to be a Belle2 strong suit

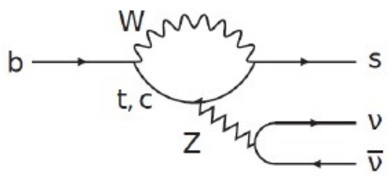
Conclusion

Tobias Huber
Universität Siegen

- Inclusive $\bar{B} \to X_s \ell^+\ell^-$ is an unsung hero
  - Complementarity to $\bar{B} \to X_s \gamma$ and $\bar{B} \to K^{(*)} \mu^+\mu^-$ can help in the search for NP
  - 5 selected modes of WG2 should contain inclusive $\bar{B} \to X_s \ell^+\ell^-$
- Complete phenomenological analysis to NNLO QCD + NLO QED for all angular observables
  - Careful investigation of treatment of energetic collinear photons
  - Most observables have parametric + perturbative errors of $\mathcal{O}(5-10\%)$
- Questions to experimenters
  - Fully inclusive analysis with recoil technique possible at Belle II, or sum of exclusive modes?
  - Optimal choice for QED-sensitive observables, if any?
  - Envisaged precision with final Belle II data set?

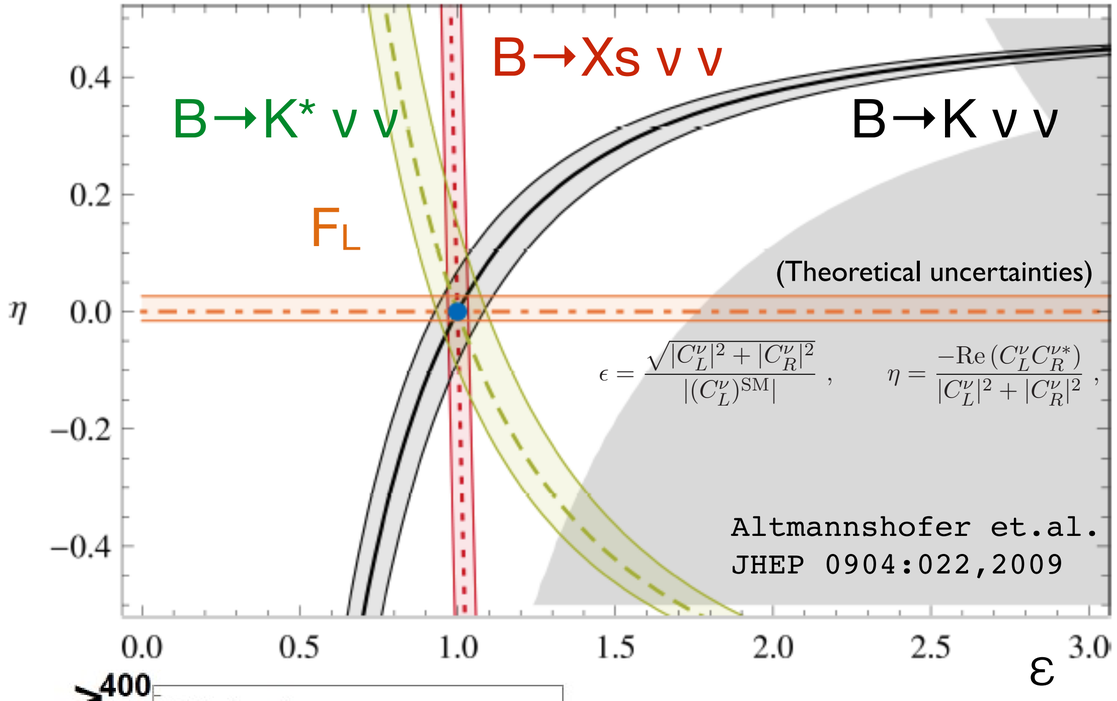

Belle II

Other Leptons: K*νν

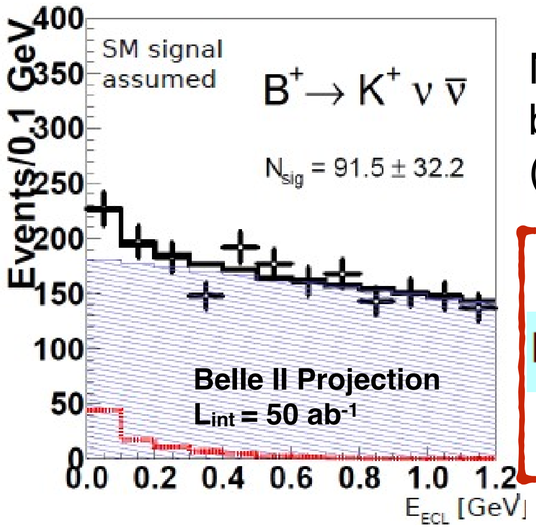


Ultimate test of Belle II

Further improvements to consider: tag efficiency, calorimeter timing, better K_L ID



- $BF(B^+ \to K^+ \nu \nu) = (4.4 \pm 0.7) 10^{-6}$
  [Buchalla, NPPS 209, 137]
- $BF(B^+ \to K^{*+} \nu \nu) = (6.8^{+1.0}_{-1.1}) 10^{-6}$
  [Altmannshofer, JHEP 0904, 022]



N_{sig} at Belle II ~90±30 based on Belle 2013 (hadronic tag only)

Better tag now!

Resent Result

$$Br(B^0 \to K^{*0} \nu\bar{\nu})_{SM} = (9.19 \pm 0.86 \pm 0.50) \cdot 10^{-6}$$

Buras et al 1409.4557

Lots of interest

Elisa Manoni	Perugia	Staff	B -> K(*) nu nu tagged
Johannes Grygier	Karlsruhe	PhD	B -> K(*) nu nu tagged
James Kahn	LMU	PhD	B -> K(*) nu nu tagged
Sasha Glazov	DESY	Staff and students	B -> K(*) nu nu tagged

K*νν: THEORY

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Straub B2TiP (Oct 2014)

$B \to K^{(*)}\nu\bar{\nu}$ decays in the Standard Model and beyond

based on arXiv:1409.4557 with A. Buras, J. Girrbach-Noe, C. Niehoff

Presented by David M. Straub

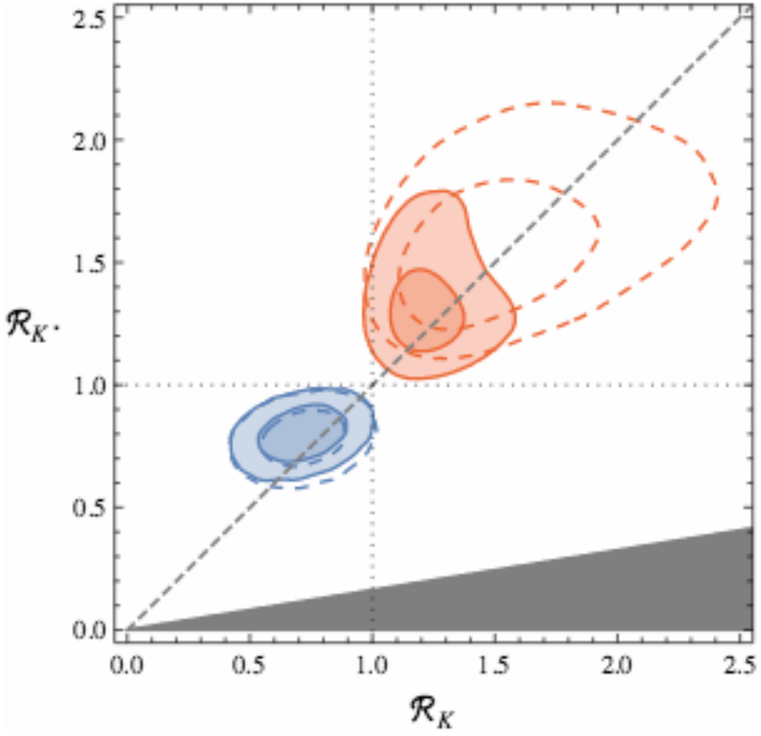
News on $b \to s\nu\bar{\nu}$

1. Better control of form factor uncertainties thanks to lattice
   - More precise & reliable SM predictions **10%**
2. Many new results on $b \to s\ell^+\ell^-$ transitions from LHC
   - How large can NP effects in $b \to s\nu\bar{\nu}$ still be?
   - If there is NP in $b \to s\ell^+\ell^-$, can $b \to s\nu\bar{\nu}$ help?

- Prediction for $\mathrm{BR}(B \to K^*\nu\bar{\nu}) \sim 40\%$ higher than before
  - (EW corrections, form factor normalization, cf. [Altmannshofer et al. 0902.0160])

Standard Model update | New physics analysis | $B \to K^{(*)}\nu\bar{\nu}$ in the SM and beyond

Allowed ranges for $B \to K^{(*)}\nu\bar{\nu}$ in Z, Z' scenarios



solid: real Wilson coeff.; dashed: complex

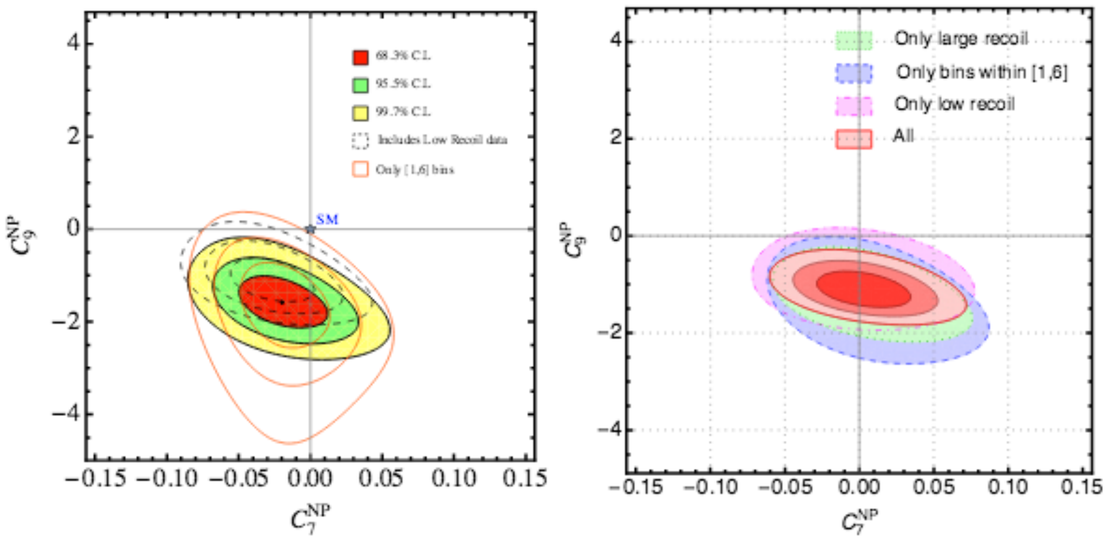
- Current data favour suppression in Z scenario and enhancement in Z' scenario
- even if tensions are not due to NP, plot shows that
  - overall effects quite limited, barring cancellations
  - $b \to s\nu\bar{\nu}$ can help distinguish models looking similar in $b \to s\ell^+\ell^-$

David Straub (Universe Cluster)

SUMMARY

- The FCNC process B to $K^{(*)}ll$ is a rich topic than can be used to explore beyond the Standard Model
- Tantalizing hints of new physics from other experiment
- Angular analysis is compatible with current measurement.
- Isospin asymmetry (A_I) sensitivity is very competitive in the low q^2 region
- Belle2 will have an important role in looking at **inclusive and missing energy modes**

From 2013 to 2015



[SDG, J. Matias, Virto] (2013) [SDG, L. Hofer J. Matias, Virto] (2015)

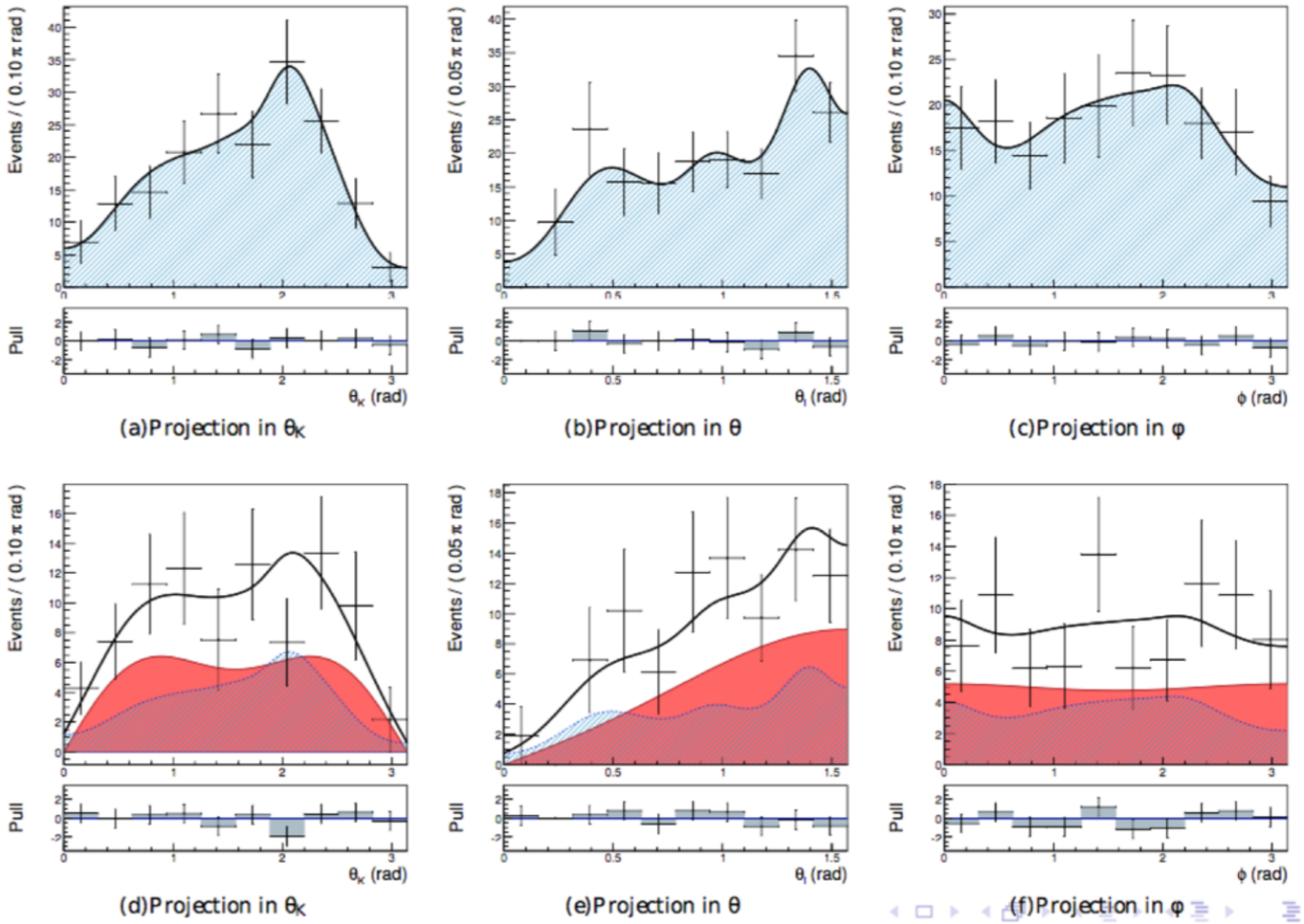
S. Descotes-Genon (LPT-Orsay) $B \to K^* \mu\mu$ theory 25/10/15 21

♓: *Back Up* :♓

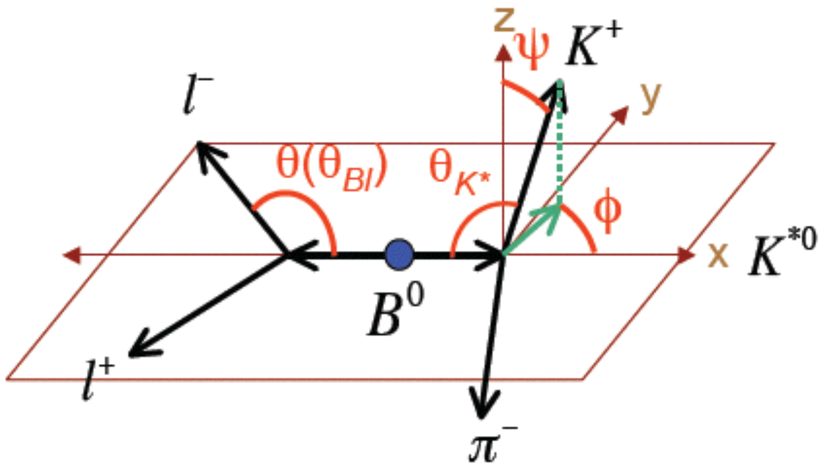
Fit Projections

HEPHY Institute of High Energy Physics
ÖAW
BELLE

$B^0 \to K^*(892)^0 \ell^+\ell^-$: Fit projections



COS Θ_{K^*} / COS Θ_{BL} FITS



RECALL: Fix N_{sig} and N_{bkg}, then **TWO Step Fit**.

f_L vs. q^2 :

Step 1: $$\frac{3}{2}\boxed{f_L}\cos^2\theta_{K^*} + \frac{3}{4}(1-\boxed{f_L})(1-\cos^2\theta_{K^*})$$

A_{FB} vs. q^2:

Step 2: $$\frac{3}{4}f_L(1-\cos^2\theta_{Bl}) + \frac{3}{8}(1-f_L)(1+\cos^2\theta_{Bl}) + \boxed{A_{FB}}\cos\theta_{Bl}$$

Procedure:

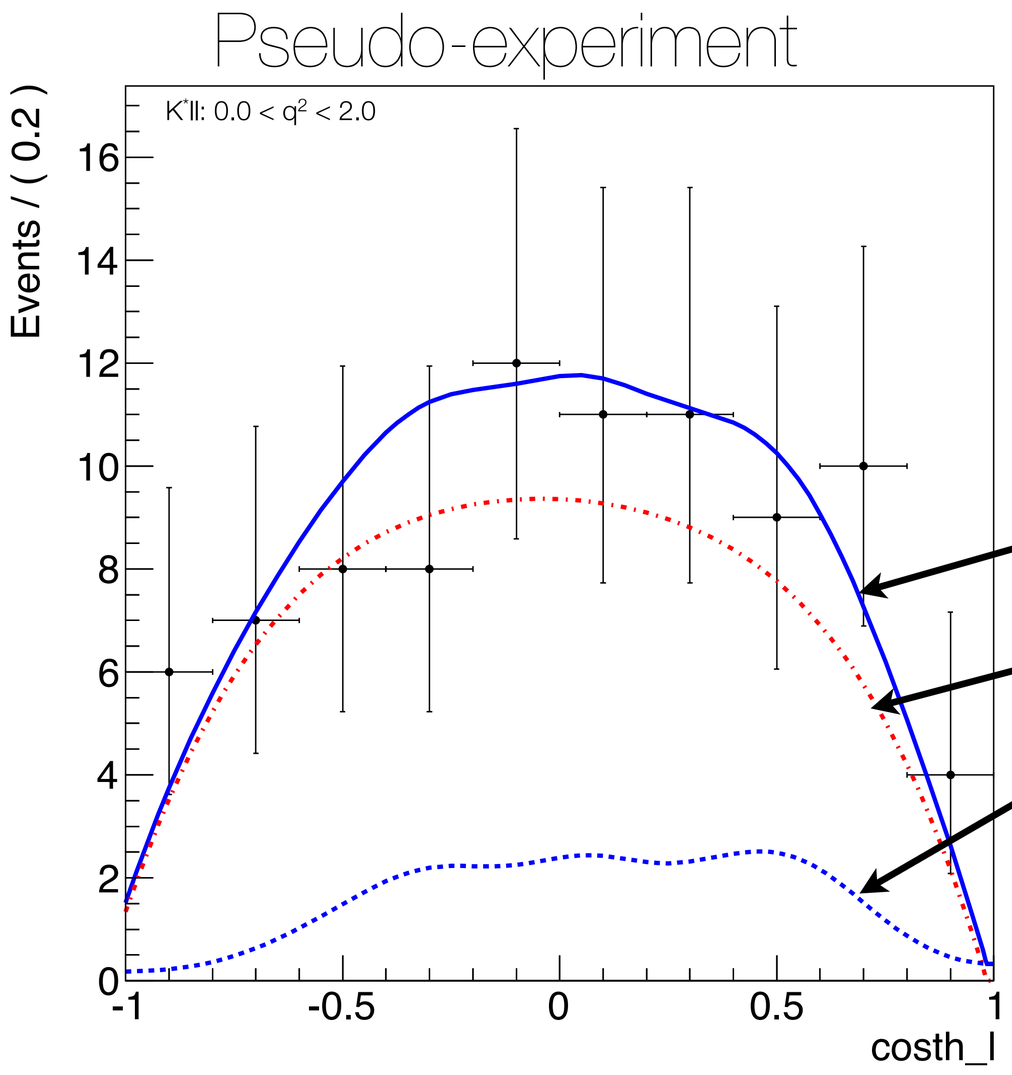
SigPDF = eff (Smoothed MC Hist) * Func (f_L (A_{FB})| cos θ_{K^*} (θ_{Bl}))

BkgPDF = Smoothed MC Hist

Final PDF = N_{sig}*SigPDF + N_{bkg}*BkgPDF

UNBINNED FITS

Example A_{FB} Fit



$$\frac{3}{4} f_L (1-\cos^2\theta_{Bl}) + \frac{3}{8}(1-f_L)(1+\cos^2\theta_{Bl}) + \boxed{A_{FB}} \cos\theta_{Bl}$$

After fitting and fixing F_L, fit A_{FB}

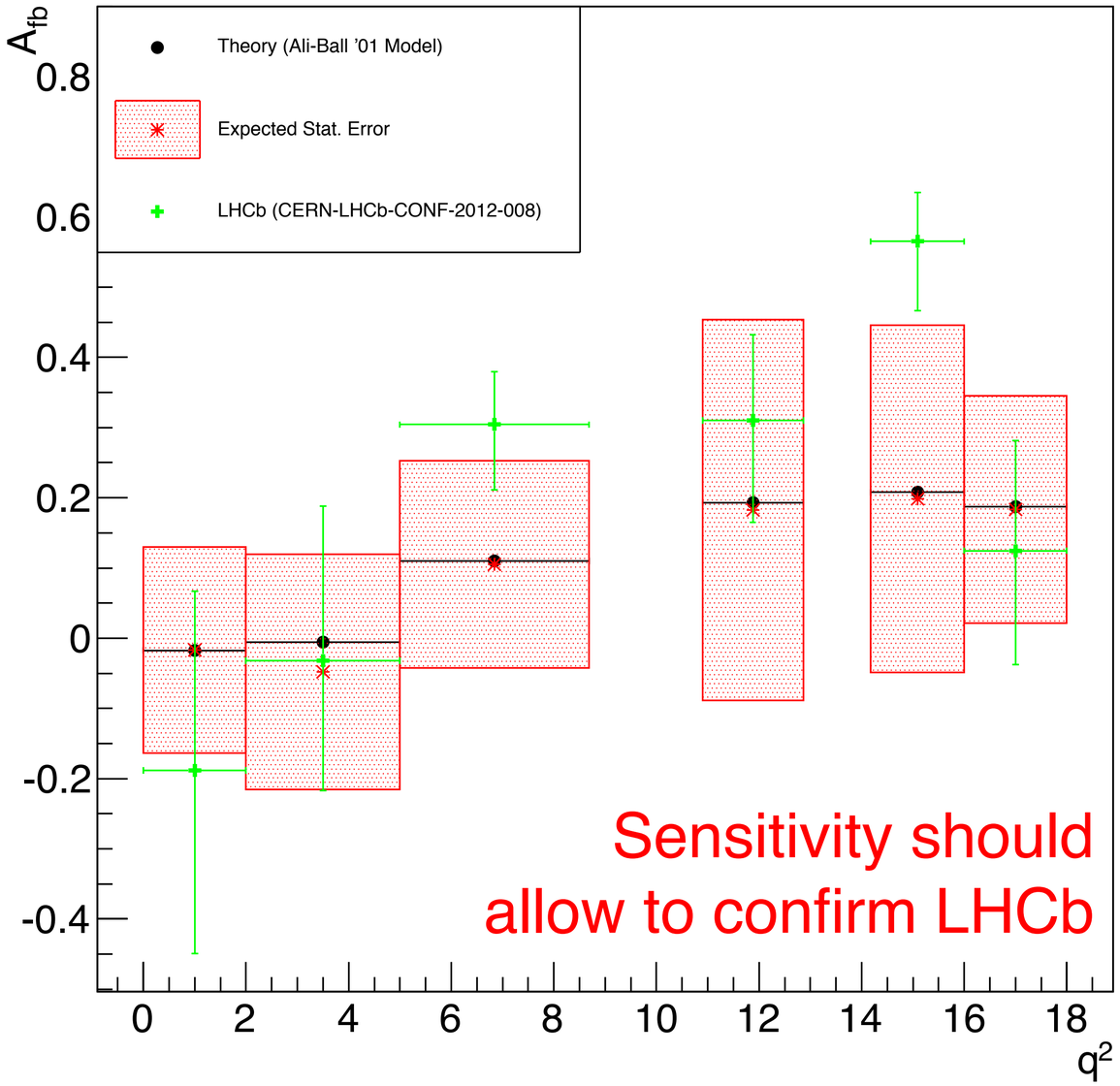
Composite Fit

Signal

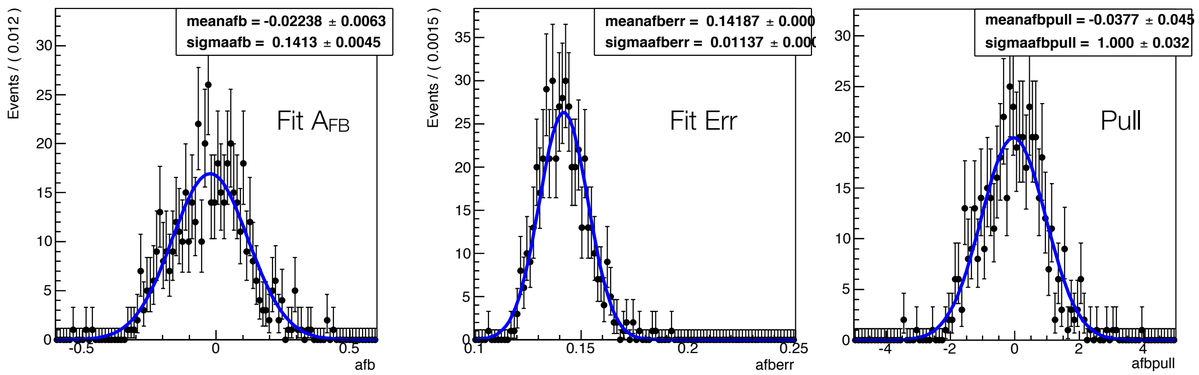
Background

Generate many pseudo-experiments to estimate final sensitivity.

A_{FB} Sensitivity



K*ee PSE: $0.0 < q^2 < 2.0$



- Using pseudo experiments estimate our sensitivity
- Expected error "comparable" in most q^2 bins.

Exclusive $X_s ll$

Presented by David M. Straub

- Are neutrinos the way to go
- Impossible at LHCb?

Conclusions

- $B \to K^{(*)}\nu\bar{\nu}$ are theoretically clean and the BRs are now known to 10%
- LHC measurements of $b \to s\ell^+\ell^-$ decays imply that the BRs are within 50% of SM **unless**
  - $b \to s\ell^+\ell^-$ effects suppressed by cancellations ($\to$ leptoquark model)
  - only τ leptons/neutrinos affected: $b \to s\nu\bar{\nu}$ is most powerful constraint
- Future $B \to K^{(*)}\nu\bar{\nu}$ measurement very useful to
  - disentangle QCD vs. NP or different NP models in $b \to s\ell^+\ell^-$
  - testing lepton flavour universality
  - testing more exotic models (leptoquarks, models with light dark matter ...)
  - measuring form factors (?)

Inclusive $X_s ll$

Tobias Huber
Universität Siegen

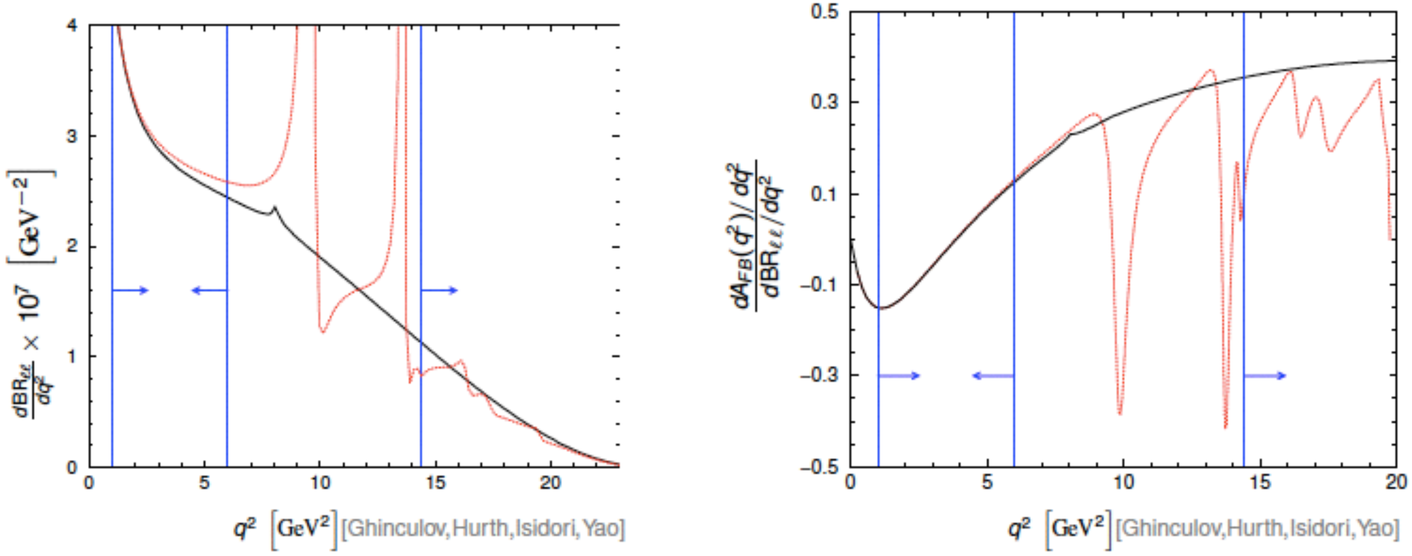
- Probes SM at loop level
- Set of observable for experimentalist

Observables

- Double differential decay width ($z = \cos\theta_\ell$) [Lee, Ligeti, Stewart, Tackmann'06]

$$\frac{d^2\Gamma}{dq^2\,dz} = \frac{3}{8}\left[(1+z^2)\,H_T(q^2) + 2\,z\,H_A(q^2) + 2\,(1-z^2)\,H_L(q^2)\right]$$

Note: $\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2)\,, \qquad \frac{dA_{FB}}{dq^2} = 3/4\,H_A(q^2)$



- Low-q^2 region: $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$
- High-q^2 region: $q^2 > 14.4\,\mathrm{GeV}^2$

Form Factors/Inclusive

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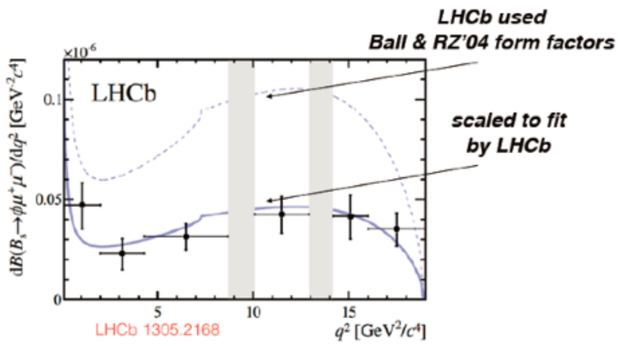
Matthew Wingate Roman Zwicky

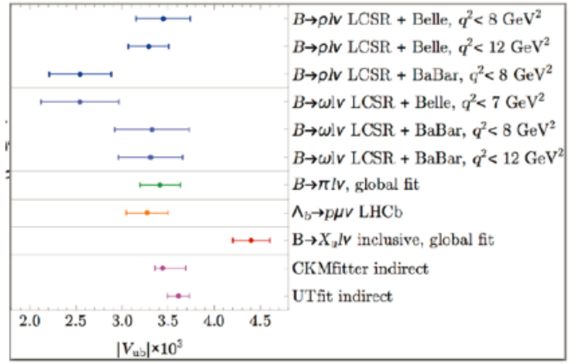
Form Factors in B→Vll

- By Lattice QCD and LCSR



"we're off by factor of 2"

a **problem** with **form factor normalisation?**

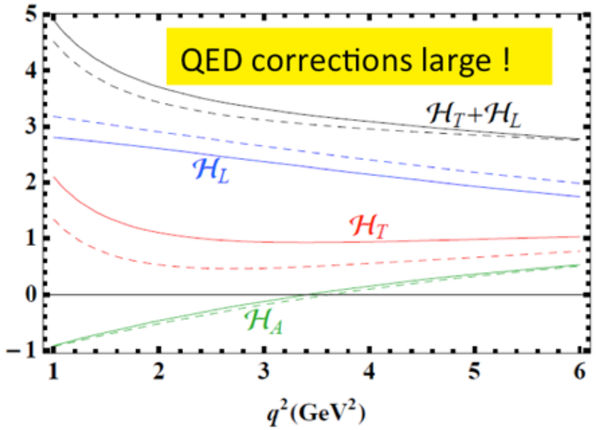


⇒ no sign of (serious) normalisation problems as questioned by $B_s\to\phi\mu\mu$

Tobias Hurth

Complete angular analysis of inclusive b > s l l
and the role of collinear photons

- Exclusive modes are experimentally easier (LHCb), but have larger theoretical uncertainties (issue of unknown power corrections !)
- Inclusive modes require Belle-II for full exploitation (complete angular analysis) but are theoretically very clean



Only 6% uncertainty in low q^2.

Low-q^2 $(1GeV^2 < q^2 < 6GeV^2)$

$BR(B\to X_s ee) = (1.67\pm0.10)\,10^{-6}$

$BR(B\to X_s\mu\mu) = (1.62\pm0.09)\,10^{-6}$

High-q^2, Theory: $q^2 > 14.4GeV^2$,

$BR(B\to X_s ee) = (0.220\pm0.070)\,10^{-6}$

$BR(B\to X_s\mu\mu) = (0.253\pm0.070)\,10^{-6}$

We Belle are updating these now, so please wait for a while.