Bottom-Quark Forward-Central Asymmetry at LHCb

Christopher W. Murphy

Pisa, Scuola Normale Superiore

Implications of LHCb measurements and future prospects – 13/10/2016
Outline

This talk:

(1) Introduction

(2) Theoretical Predictions

(3) Current Experimental Results

Next talk by Rhorry Gauld:

(4) Future Prospects


Million dollar question:
- What lies Beyond the Standard Model (BSM)?

Measuring asymmetries (forward-backward, $CP$, forward-central, production, forward-backward of decay products, ... ) helps to answer this question.

\[ A(x) \equiv \frac{N(x > 0) - N(x < 0)}{N(x > 0) + N(x < 0)} \]

precision predictions / small SM values $\rightarrow$ excellent probe of BSM
Million dollar question:
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\]

- precision predictions / small SM values → excellent probe of BSM
Forward-Backward Asymmetries

Collider w/ asymmetric initial state \((e^+e^-, p\bar{p})\):

\[
A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
\]

Example:
- \(e^-e^+ \rightarrow Q\bar{Q}\)
- \(\Delta y = y_Q - y_{\bar{Q}}\)
**Forward-Backward Asymmetries**

**LEP 1** – $A_{FB}^{(0,b)}$ (Z-pole) – 2.3σ

### CDF – $A_{FB}^{t\bar{t}}$ ($M_{tt} > 450$ GeV) – 3.4σ

<table>
<thead>
<tr>
<th>Quantity</th>
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<td>$M_Z$ [GeV]</td>
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**PDG**

CDF arXiv:1101.0034
Forward-Backward Asymmetries

LEP 1 – $A_{FB}^{(0,b)} (Z$-pole) – $2.3\sigma$

- No significant excess w.r.t. SM
- Agreement not perfect

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What is the Source of $A_{FB}$?

Quark asymmetries hint at physics beyond the Standard Model

3 years ago by davidreiss666
21 comments  share

All 21 Comments

sorted by: best (suggested)

[-] hikaruzero  1  7 points 3 years ago*

Why should there be any asymmetry at all, even in the Standard Model? Anybody who's up on their science care to elaborate?

Edit: I realize I worded the above question pretty vaguely, so for anyone else who wants to take a stab, please see a revised question below:

What is the source of the forwards-backwards asymmetry that is predicted by the Standard Model? For example, is this due to neutral particle oscillation in briefly-existing B+B-bar systems, or due to the CP-violating phase in the CKM matrix, etc.?

2nd Edit: I was given the answer by one of the paper's authors! Check it out!

permalink  embed
What is the Source of $A_{FB}$?

Quark asymmetries hint at physics beyond the Standard Model

Christopher W. Murphy (SNS) LHCb Implications 9 / 29

All 21 Comments

sorted by: best (suggested)

[-] hikaruzero 7 points 3 years ago*

Why should there be any asymmetry at all, even in the SM? I will need to elaborate.

Edit: I realize I worded the above question pretty vague; how about this revised question below:

What is the source of the forwards-backwards asymmetry? Is this due to neutral particle oscillation in briefly-existing $b$-$\bar{b}$ states, $CPT$ matrix, etc.?

2nd Edit: I was given the answer by one of the paper authors.

[-] bgrinstein 2 points 3 years ago

I can explain:"why" there is a FB asymmetry. (I should, I am one of the authors of the paper being reported here). But it takes more than a couple of lines. So I prepared a web page for this. Visit:

http://leewick.ucsd.edu/~ben/FBAsymmetry/Blank.html

Christopher W. Murphy (SNS) A$^{b\bar{b}}_{FC}$ at LHCb
What is the Source of $A_{FB}$?

(1) Kinematics – need odd powers of $\cos \theta$ in $d\sigma$

- Spin-0: $P_0(\cos \theta)$
- Spin-1: $P_{0,1,2}(\cos \theta)$
- $t$-channel: $P_{\text{all}}(\cos \theta)$

Interference between 1- and 2-photon/gluon exchange

$d\sigma$ odd in $\cos \theta$ by $C$-conjugation invariance

Fig. from Kühn, Rodrigo hep-ph/9807420

Fig. from CDF Conf. Note 10974
What is the Source of $A_{FB}$?

(2) (non-)symmetries (gauge, discrete) of theory

\[ \frac{d\sigma}{d\Omega}(q_{L\bar{q}_R} \rightarrow V_\mu \rightarrow Q_L \bar{Q}_R) \sim g_{Lq}^2 g_{LQ}^2 (1 + \cos \theta)^2 \]

Parity violation $\rightarrow$ tree level $A_{FC}$

$U(1), SU(N \geq 3) \rightarrow A_{FC}$ at NLO

Fig. from Kühn, Rodrigo hep-ph/9807420
Heavy Quark $A_{FB}$ at Hadron Colliders

Contributions to asymmetry:
- LEP – directly sensitive to asymmetry from matrix elements
- Tevatron – matrix elements and PDFs must be asymmetric

Extracting a heavy quark asymmetry:
- $tt$: decay products preserve info about $A_{FB}^{tt}$
- $b\bar{b}, c\bar{c}$: hadronize before decaying
  - Hadron based: $p\bar{p} \rightarrow B^\pm X$ w/ $q_{FB} = -Q_B \text{sign}(\eta_B)$
  \[
  A_{FB}(B^\pm) = \frac{N(q_{FB} > 0) - N(q_{FB} < 0)}{N(q_{FB} > 0) + N(q_{FB} < 0)}
  \]
  - Jet based: $p\bar{p} \rightarrow b\bar{b}X$ w/ $\Delta y = y_b - y_{\bar{b}}$
  \[
  A_{FB}^{b\bar{b}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
  \]
What about at LHCb?

- LHC: symmetric initial state
  - \( A_{FB} = 0 \) by construction
  - underlying matrix elements still asymmetric
  - exploit asymmetry between PDFs of \( q \) and \( \bar{q} \)

- Hadron based: \( pp \to B^\pm X \) – production asymmetry
  \[
  A_P(B^\pm) = \frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)}
  \]

- Jet based: \( pp \to b\bar{b}X \) – forward-central asymmetry
  \[
  A_{b\bar{b}}^{FC} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}
  \]
  now with \( \Delta|y| = |y_b| - |y_{\bar{b}}| \)
\( A_{FC} \) in the Standard Model

\[
A_{FC} \sim \frac{\alpha^2 \tilde{N}_0 + \alpha_3^3 N_1 + \alpha_3^2 \alpha \tilde{N}_1 + \alpha_4^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_2^2 D_0 + \alpha_3^3 D_1 + \alpha_2^2 \alpha \tilde{D}_1 + \cdots}
\]

- NLO QCD dominant contribution to \( A^{\bar{t}t}_{FB} \) at hadron colliders
  \((\sim \alpha_s N_1/D_0 + \cdots)\)

- Grinstein, CM 1302.6995 showed previously neglected tree level \( Z \) exchange dominates \( A^{b\bar{b}}_{\bar{F}B,FC} \) for \( M_{b\bar{b}} \sim M_Z \)

- \( Z \) can decay to \( b\bar{b}, c\bar{c} \) (but not \( t\bar{t} \)) → resonant enhancement
  \((Z - \gamma \) interference not enhanced)\)

- Gauld et al. 1505.02429: \( Z \) contribution to \( \tilde{N}_1 \) (not enhanced),
  \( O(\alpha^2 \alpha_s) \) corrections, \( qg \) initiated asymmetry \((\sim 10\% \text{ of } N_1, \text{ unlike } t\bar{t} \text{ case})\)
$A_{FC}$ in the Standard Model

$$A_{FC} \sim \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots}$$

- NLO QCD dominant contribution to $A_{FB}^{t\bar{t}}$ at hadron colliders ($\sim \alpha_s N_1 / D_0 + \cdots$)
- Grinstein, CM 1302.6995 showed previously neglected tree level $Z$ exchange dominates $A_{FB}^{b\bar{b}}$ for $M_{b\bar{b}} \sim M_Z$
- $Z$ can decay to $b\bar{b}$, $c\bar{c}$ (but not $t\bar{t}$) → resonant enhancement ($Z - \gamma$ interference not enhanced)
- Gauld et al. 1505.02429: $Z$ contribution to $\tilde{N}_1$ (not enhanced), $O(\alpha^2 \alpha_s)$ corrections, $qg$ initiated asymmetry ($\sim 10\%$ of $N_1$, unlike $t\bar{t}$ case)
CDF $A_{FB}^{b\bar{b}}$ Results

Low Mass Analysis 1601.06526

High Mass Analysis 1504.06888

SM predictions from CM 1504.02493

Christopher W. Murphy (SNS)
LHCb 7 TeV $A^{b\bar{b}}_{FC}$ Results

Shape of SM prediction drastically different w/o EW terms

Fig. & SM predictions from Gauld, Haisch, Pecjak, Re 1505.02429; LHCb results from 1406.4789

Christopher W. Murphy (SNS)
LHCb $A_{\bar{b}b}^{FC}$ Results & Future Prospects

SM Future Prospects

- $A_{\bar{b}b}^{FC}$ becomes systematically limited around $\sim 10 \text{ fb}^{-1}$
- Central value smaller at 13/14 TeV than 7/8 TeV (even smaller for 100 TeV)
- $A_{\bar{b}b}^{FC}(Z\text{-pole})$ currently non-zero at 1.8σ
  - 3.0σ w/ 10 fb$^{-1}$ & same central value
  - 1.7σ w/ 10 fb$^{-1}$ & 13 TeV SM central value

Fig. & SM predictions from Gauld et al. 1505.02429; LHCb results from 1406.4789
BSM Future Prospects

- Lighter mass BSM ($M \lesssim 250$ GeV) already constrained by Tevatron + LHC7
- More data useful for constraining heavier BSM scenarios
- Distinguish flavor structure of competing BSM models

Grinstein, CM 1302.6995; CM 1504.02493
Modified $Zb\bar{b}$ Couplings

- Current hadron collider results not competitive w/ LEP
- See next talk by Rhorry for future prospects

![Graph showing modified couplings](image)

CM 1504.02493
Production asymmetry can mimic $CP$ violation

\[ A(t) \approx A_{CP} + A_D + A_P \frac{\cos(\Delta m t)}{\cosh(\Delta \Gamma t / 2)} \]

\[ A_{CP} = \frac{\Gamma(\overline{B}_0^0 \to \bar{f}) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}_0^0 \to \bar{f}) + \Gamma(B^0 \to f)}, \quad A_D = \frac{\epsilon_{\bar{f}} - \epsilon_f}{\epsilon_{\bar{f}} + \epsilon_f}, \quad A_P = \frac{N(\overline{B}_0^0) - N(B^0)}{N(\overline{B}_0^0) + N(B^0)} \]

- $A_P(D_{s}^{\pm}) = (-0.33 \pm 0.22 \pm 0.10)\%$ 1205.0897
- $A_P(D^{\pm}) = (-0.96 \pm 0.26 \pm 0.18)\%$ 1210.4112
- $A_P(B_{0}^0) = (-0.35 \pm 0.76 \pm 0.28)\%$ 1408.0275
- $A_P(B_{s}^0) = (1.09 \pm 2.61 \pm 0.66)\%$ 1408.0275
Production Asymmetries at LHCb

Production asymmetry can mimic $CP$ violation

$$A(t) \approx A_{CP} + A_D + A_P \frac{\cos(\Delta m t)}{\cosh(\Delta \Gamma t/2)}$$

$$A_{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{f}) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to \bar{f}) + \Gamma(B^0 \to f)}, \quad A_D = \frac{\epsilon_{\bar{f}} - \epsilon_f}{\epsilon_{\bar{f}} + \epsilon_f}, \quad A_P = \frac{N(\bar{B}^0) - N(B^0)}{N(\bar{B}^0) + N(B^0)}$$

LHCb-CONF-2012-031

- Reports $\sigma(pp \to \Lambda^0_b X)$ and $\sigma(pp \to \bar{\Lambda}^0_b X)$
- $A_P(\Lambda^0_b) = (-0.23 \pm 0.13)\%$ w/ 36.4 pb$^{-1}$
- $A_P(\Lambda^0_b) = (-0.23 \pm 0.06)\%$ (naïvely) w/ full Run-1 dataset, non-zero at 3.4$\sigma$
Measuring a more significant non-zero asymmetry at 13/14 TeV (w.r.t. 7 TeV) naïvely requires improved systematics or undiscovered BSM.

More data useful for constraining BSM scenarios with $M \gtrsim 250$ GeV (provided there is some motivation for such models).

Update $A_P(\Lambda_b^0)$ measurement with at least full Run-1 dataset (currently stat. limited).

Charm-Quark Asymmetry?
Charm-Quark Asymmetry

$Z$-pole asymmetry about half as big as $b\bar{b}$ case:

$$\frac{\tilde{N}_{0,c\bar{c}}}{\tilde{N}_{0,b\bar{b}}} \sim \frac{3 - 8s^2_W}{3 - 4s^2_W} \approx 0.55$$

$t$-channel $W$ exchange – less CKM suppression than $b\bar{b}$, $t\bar{t}$:

$$\frac{d\sigma_{A}^{\alpha_s \alpha}}{d \cos \theta} = -\frac{\alpha_s \alpha |V_{cd}|^2}{s^2_W} \frac{\pi C_F}{N_C} \frac{\beta \cos \theta}{8\hat{s}} f(\cos^2 \theta, m^2_c, M^2_W, \hat{s})$$

$\sim -6\%$ of NLO QCD contribution to $A_{F_C}^{c\bar{c}}$ at large $M_{c\bar{c}}$ CM 1504.02493
BSM Future Prospects

- Lighter mass BSM ($M \lesssim 250$GeV) already constrained by Tevatron + LHC7
- More data useful for constraining heavier mass scenarios
- Distinguish flavor structure of competing BSM scenarios

CM 1504.02493
Hadron Asymmetry Measurements

- Perturbative calculation not always relevant
- MC generators not always accurate (worse for $A_{FB}(Λ^0_b)$)

$$A_{FB}(B^±) \quad A_P(Λ^0_b)$$

D0 1411.3021; CM 1504.02493

MC seems fine here
LHCb-CONF-2012-031

Christopher W. Murphy (SNS)
Production and $CP$ Asymmetries at LHCb

Production asymmetry can mimic $CP$ violation

$$A(t) \approx A_{CP} + A_D + A_P \frac{\cos(\Delta m t)}{\cosh(\Delta \Gamma t/2)}$$

$$A_{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{f}) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to \bar{f}) + \Gamma(B^0 \to f)}, \quad A_D = \frac{\epsilon_{\bar{f}} - \epsilon_f}{\epsilon_{\bar{f}} + \epsilon_f}, \quad A_P = \frac{N(\bar{B}^0) - N(B^0)}{N(\bar{B}^0) + N(B^0)}$$

Measure instead $\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$; $A_D, A_P$ cancel

1112.0938 See also talks by Petridis, de Boer, Davis, ...
Lepton $A_{FB}$ in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ at LHCb

Forward-Backward Asymmetry of Decay Products

$$\frac{1}{d\Gamma/dq^2 dq^2 d\cos \theta_\ell d\cos \theta_K d\phi} = \frac{9}{16\pi} \left[ F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_K) - F_L \cos^2 \theta_K (2 \cos^2 \theta_\ell - 1) + \frac{1}{4} (1 - F_L)(1 - \cos^2 \theta_K)(2 \cos^2 \theta_\ell - 1) + S_3 (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_\ell) \cos 2\phi + \frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_\ell + A_9 (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_\ell) \sin 2\phi \right] .$$

$$R_K = \frac{\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\Gamma(B^+ \rightarrow K^+ e^+ e^-)}$$

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.035$$

$$M_{\ell^+ \ell^-}^2 \in [1, 6] \text{ GeV}^2$$

2.6σ deviation from SM

1304.6325 (left)
1406.6482 (right)

See also talks by Martin Camalich, Petridis, Mahmoudi, ...
**Lepton $A_{FB}$ in $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ at LHCb**

- Take ratio of $A_{FB}(\mu^+\mu^-)$ vs. $A_{FB}(e^+e^-)$
- Distinguish between competing explanations of $R_K$

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<td>$C_9' = 0$</td>
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<td>$10^7 \frac{dBR}{dq^2} (\bar{B}^0 \rightarrow \bar{K}^{*0} \ell^+ \ell^-)_{[1,6]}$</td>
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<td>$A_{FB}(\bar{B}^0 \rightarrow \bar{K}^{*0} \ell^+ \ell^-)_{[15,19]}$</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**Altmannshofer, Straub 1411.3161**

See also talks by Martin Camalich, Petridis, Mahmoudi, . . .