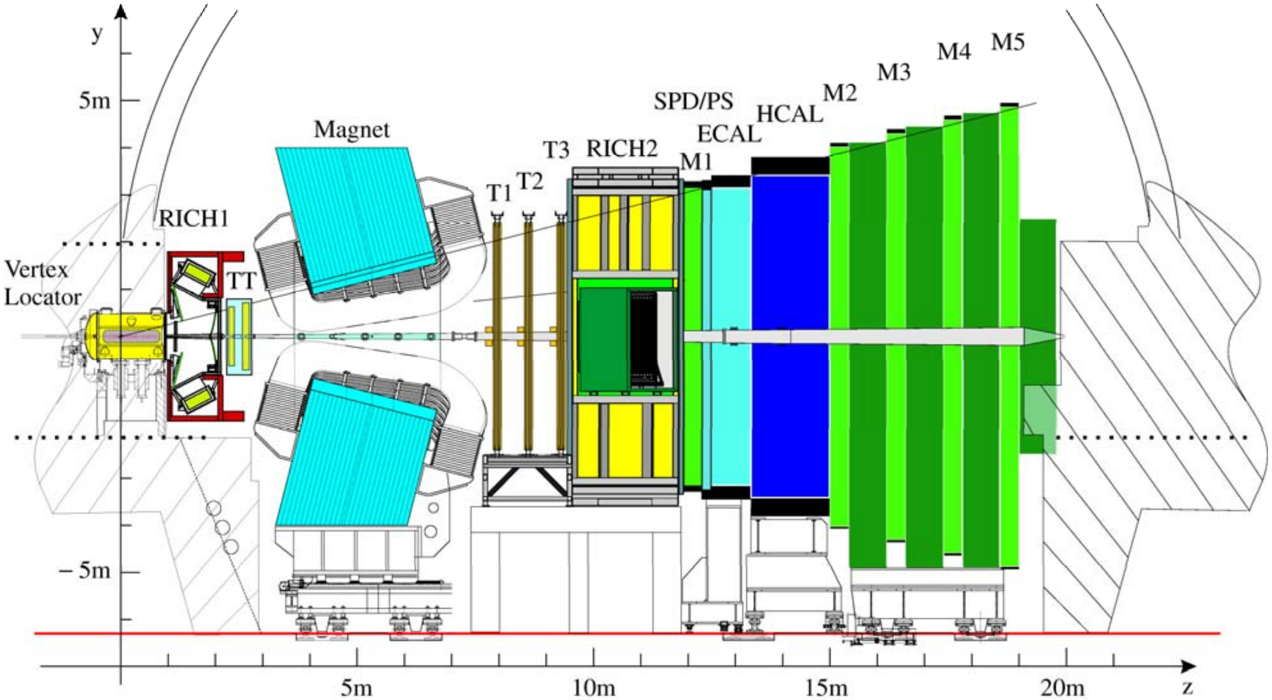
Illuminating new physics with a_{fs} at LHCb

LHCb

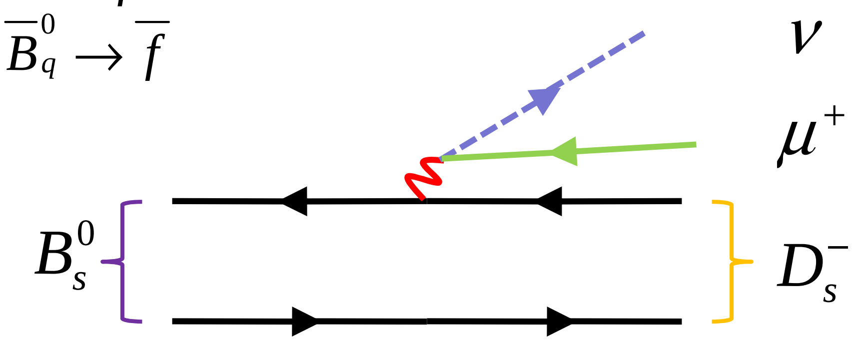
- LHCb is precision experiment targeting *b*-physics
  - 2 fb^{-1} per nominal year : 10^{12} $b\bar{b}$-events
  - *b*-hadrons produced at small angles ∴ forward-arm spectrometer
  - Focus: rare decays and CP-violation parameters



Flavour-specific asym.

- Flavour-specific decays
  - Favoured/Allowed $B_q^0 \longrightarrow f$
  - Not allowed at tree $B_q^0 \longrightarrow \overline{f}$
  - Through mixing $B_q^0 \rightarrow \overline{B}_q^0 \rightarrow \overline{f}$

$$B_s^0 \rightarrow D_s^- \mu^+ \nu$$
$$B_s^0 \rightarrow D_s^- \pi^+$$
$$B_d^0 \rightarrow D^- \mu^+ \nu$$



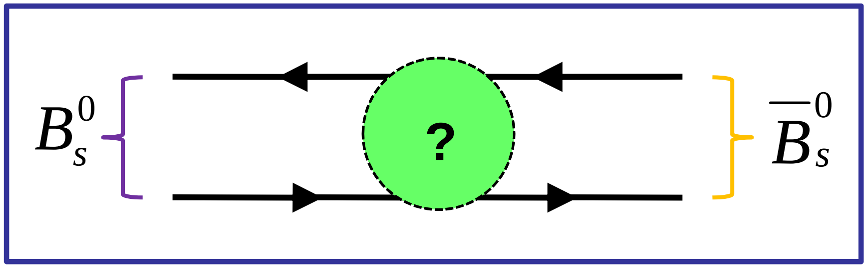
- Flavour specific asymmetry, a_{fs}, parameterises CPV in mixing [1]

$$a_{fs}^q \propto A_{fs}^q(t) = \frac{\Gamma\left(B_q^0 \text{ or } \overline{B}_q^0 \rightarrow \overline{f}\right) - \Gamma\left(B_q^0 \text{ or } \overline{B}_q^0 \rightarrow f\right)}{\Gamma\left(B_q^0 \text{ or } \overline{B}_q^0 \rightarrow \overline{f}\right) + \Gamma\left(B_q^0 \text{ or } \overline{B}_q^0 \rightarrow f\right)}$$

Discovery Potential

- a_{fs} is sensitive to new physics (NP): [1]
  - Very small in the standard model
  - Sensitive to loop contributions
  - Sensitive to new CPV phases

$$\left(a_{fs}^{d}\right)^{SM} = -(5.0 \pm 1.1) \times 10^{-4}$$
$$\left(a_{fs}^{s}\right)^{SM} = (2.1 \pm 0.4) \times 10^{-5}$$



- Up to 200-times the SM prediction, $O(10^{-3})$ [2]
- Current world best: DØ – direct measurement [3]

$$A_{fs}^{s} = \left(2.45 \pm 1.93(\mathrm{st}) \pm 0.35(\mathrm{sy})\right) \times 10^{-2}$$

- LHCb can measure down to 0.22% (stat) in $2 fb^{-1}$ [4]

Analysis Method

- Untagged, time-dependent measurement
  - High statistics, ~1M selected events in $2fb^{-1}$

$$A_{fs}^{q}(t) = \frac{a_{fs}^{q}}{2} \qquad - \left(\frac{a_{fs}^{q}}{2} \qquad \right) \frac{\cos\left(\Delta m_q t\right)}{\cosh\left(\Delta\Gamma_q t / 2\right)}$$

Analysis Method

- Untagged, time-dependent measurement
  - High statistics, ~1M selected events in $2fb^{-1}$

$$A^q_{fs}(t) = \frac{a^q_{fs}}{2} - \frac{\delta^q_c}{2} - \left(\frac{a^q_{fs}}{2} + \frac{\delta^q_p}{2}\right)\frac{\cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2)} + \frac{\delta^q_b}{2}\left(\frac{B}{S}\right)^q$$

- Extra constant and time-dependent terms

Analysis Method

- Untagged, time-dependent measurement
  - High statistics, ~1M selected events in $2fb^{-1}$

$$A_{fs}^{q}(t) = \frac{a_{fs}^{q}}{2} - \frac{\delta_c^q}{2} - \left(\frac{a_{fs}^{q}}{2} + \frac{\delta_p^q}{2}\right)\frac{\cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2)} + \frac{\delta_b^q}{2}\left(\frac{B}{S}\right)^q$$

- Extra constant and time-dependent terms
  - Detector asymmetry δ_c
  - Production asymmetry δ_p
  - Background asymmetry δ_b

$$\delta_c = \frac{\varepsilon(\bar{f}_i)}{\varepsilon(f_i)} - 1$$

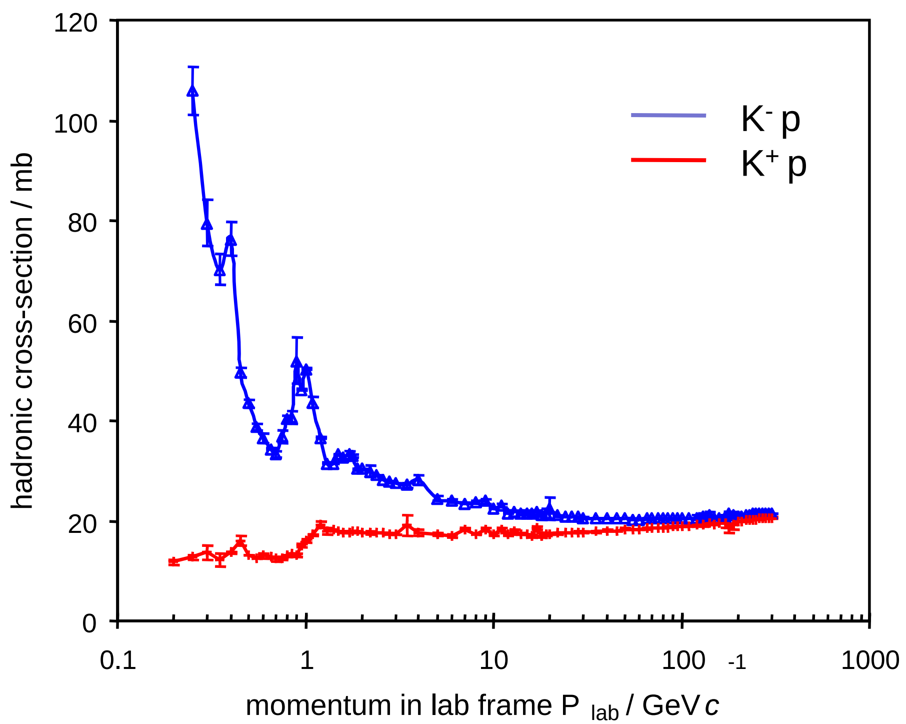
$$\delta_p = \frac{N(\overline{B}_q^0)}{N(B_q^0)} - 1$$

$$\delta_b = \frac{\overline{B}/\overline{S}}{B/S} - 1$$

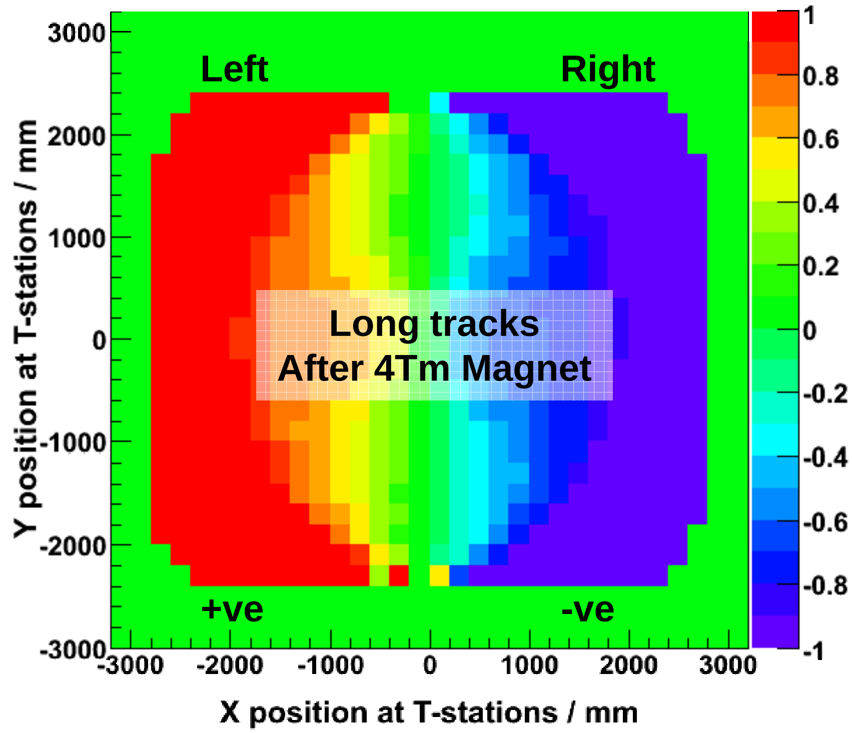
Detector Asymmetry, δ_c

- Matter detector → hadronic interactions are asymmetric
- Magnet divides +/- charge, allowing +/- asymmetry

Kaon interaction cross-section [5]



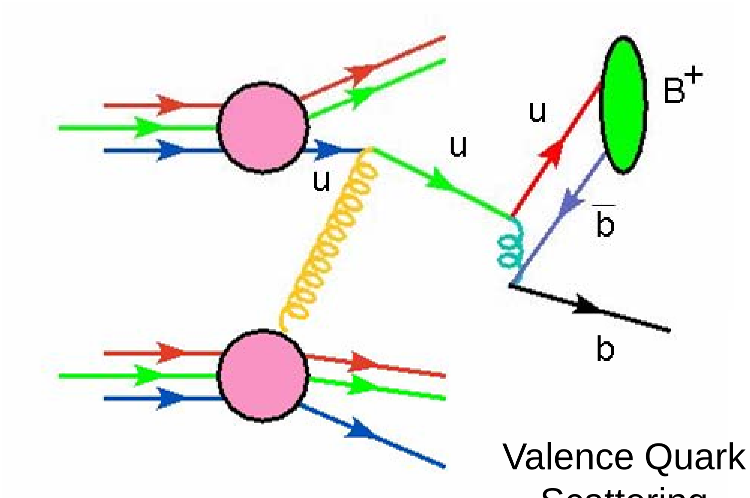
Charge distribution from MC



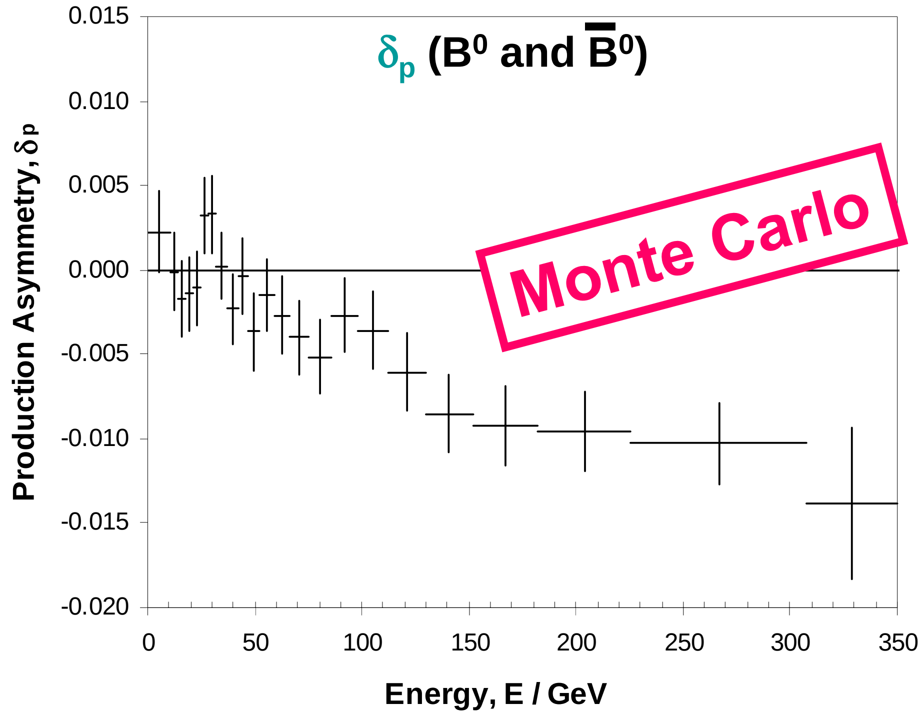
Production Asymmetry, δ_p

➢ LHC is a proton-proton collider: not CP-symmetric [6,7]

Explicitly asymmetric at LHC



Valence Quark Scattering



➢ LHCb is at high rapidity where production asymmetries are largest

Complications

$$A_{fs}^{q}(t) = \frac{a_{fs}^{q}}{2} - \frac{\delta_c^q}{2} - \left(\frac{a_{fs}^{q}}{2} + \frac{\delta_p^q}{2}\right)\frac{\cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2)} + \frac{\delta_b^q}{2}\left(\frac{B}{S}\right)^q$$

10^{-4} **10^{-2}** **10^{-2}** **10^{-3}**

- Polluting asymmetries are much larger than a_{fs}
  - Detector asymmetry δ_c ~(10^{-2})
  - Production asymmetry δ_p ~(10^{-2})
  - Background asymmetry δ_b ~(10^{-3})
- Should be reduced as much as possible
  - δ_c Reverse magnet
  - δ_p Separate out using time dependence
  - δ_b Eliminate specific backgrounds

$$\delta_c = \frac{\varepsilon(\bar{f}_i)}{\varepsilon(f_i)} - 1$$

$$\delta_p = \frac{N(\bar{I}_0)}{N(I_0)} - 1$$

$$\delta_b = \frac{\overline{B}/\overline{S}}{B/S} - 1$$

Handling systematics

$$A_{fs}^{q}(t) = \frac{a_{fs}^{q}}{2} - \frac{\delta_{c}^{q}}{2} - \left(\frac{a_{fs}^{q}}{2} + \frac{\delta_{p}^{q}}{2} \right) \frac{\cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2)} + \frac{\delta_{b}^{q}}{2} \left(\frac{B}{S} \right)^{q}$$

- Measure remaining asymmetry:
  - Measure δ_c using partial reconstruction in control channels
  - Measure δ_b in sidebands
- Error/uncertainty in measurement will produce residual asymmetry
- Try to eliminate the contribution entirely
  - Subtraction between channels

$$\Delta A_{fs}^{s,d} = A_{fs}^{s} - A_{fs}^{d}$$

Subtraction method

- Examine decays in different channels to the same final state:

$$B_s^0 \to D_s^- \mu^+ \nu$$
$$D_s^- \to K^+ K^- \pi^-$$
$$A_{fs}^s \approx \frac{a_{fs}^s}{2} - \frac{\delta_c^s}{2}$$

$$B_d^0 \to D^- \mu^+ \nu$$
$$D^- \to K^+ K^- \pi^-$$
$$A_{fs}^d \approx \frac{a_{fs}^d}{2} - \frac{\delta_c^d}{2}$$

- The detector asymmetries should be equal
  - subtraction will remove detector asymmetry

$$\Delta A_{fs}^{s,d} = A_{fs}^s - A_{fs}^d \approx \frac{a_{fs}^s}{2} - \frac{a_{fs}^d}{2}$$

  - Can use precise *B*-factory results for a_{fs}^d to determine a_{fs}^s

Conclusions

- a_{fs} is a sensitive probe of new physics
- Precision measurement of a_{fs} can constrain many NP models
- LHCb measurement polluted by other asymmetries
  - Magnet needs to be reversed
  - All asymmetries will be measured in data
  - Subtraction method promises to eliminate many terms
- LHCb can measure a_{fs} to 0.22 % (stat) with 2 fb^{-1} of data
  - Possible world-leading measurement with 1 nominal year of data
  - Constraining or measuring the NP regime

References

1. Nierste, hep-ph/0406300, 2006
2. Georgi, hep-ph/0703260
3. V. M. Abazov *et al.*, D0, PRL **98** (2007) pp. 151801
4. N. Brook *et al.,* LHCb-note CERN-LHCb-2007-054
5. Y.-M. Yao *et al.*, the Particle Data Group, Review 2006, http://pdg.lbl.gov/
6. M. Botlo et. al, SLAC-PUB-5795 SSCL-538 (1992) pp. 1-56
7. E. Norrbin and T. Sjostrand, Eur. Phys. J. C. **17** (2000) pp. 137-161

Backup

- Additional slides hereafter

Tagged vs. Untagged

- Decay rates

$$\Gamma^{RS} = \Gamma\left(B_q^0 \to f\right) \qquad \overline{\Gamma}^{RS} = \Gamma\left(\overline{B}_q^0 \to \overline{f}\right)$$

$$\Gamma^{WS} = \Gamma\left(B_q^0 \to \overline{f}\right) \qquad \overline{\Gamma}^{WS} = \Gamma\left(\overline{B}_q^0 \to \overline{f}\right)$$

- No direct CP-violation

$$\Gamma^{RS} = \overline{\Gamma}^{RS}$$

Tagged vs. Untagged

- Tagged

$$A_{fs}^{q}=\frac{\Gamma\left(B_q^0\to\overline{f}\right)-\Gamma\left(\overline{B}_q^0\to f\right)}{\Gamma\left(B_q^0\to\overline{f}\right)+\Gamma\left(\overline{B}_q^0\to f\right)}=\frac{\Gamma^{WS}-\overline{\Gamma}^{WS}}{\Gamma^{WS}+\overline{\Gamma}^{WS}}$$

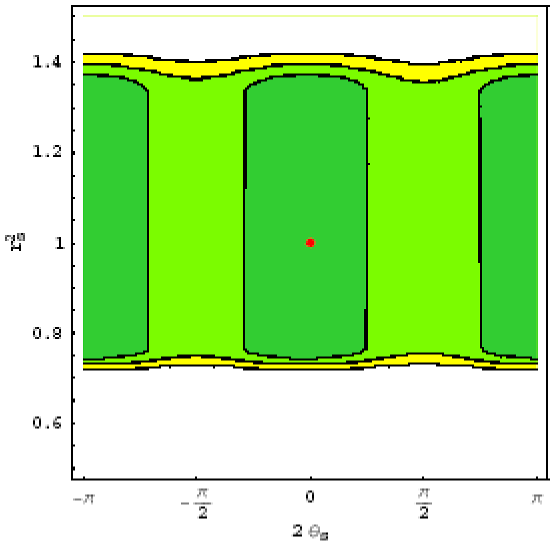
- Untagged

$$A_{fs}^{q}=\frac{\Gamma\left(B_q^0\text{ or }\overline{B}_q^0\to\overline{f}\right)-\Gamma\left(B_q^0\text{ or }\overline{B}_q^0\to f\right)}{\Gamma\left(B_q^0\text{ or }\overline{B}_q^0\to\overline{f}\right)+\Gamma\left(B_q^0\text{ or }\overline{B}_q^0\to f\right)}$$

$$=\frac{\Gamma^{WS}+\overline{\Gamma}^{RS}-\Gamma^{RS}-\overline{\Gamma}^{WS}}{\Gamma^{WS}+\overline{\Gamma}^{RS}+\Gamma^{RS}+\overline{\Gamma}^{WS}}\propto\Gamma^{WS}-\overline{\Gamma}^{WS}$$

a_{fs} and NP

- Constrains NP even if
  - No new flavour structure
  - Unitary CKM matrix
  - Tree-level SM dominated
  - No new direct/interference CPV
- No New Direct CPV



Current Constraints On r_s^2 and $2\theta_s$. SM in red

$$\left(\Gamma_{12}^{q}\right)^{NP} = \left(\Gamma_{12}^{q}\right)^{SM}$$

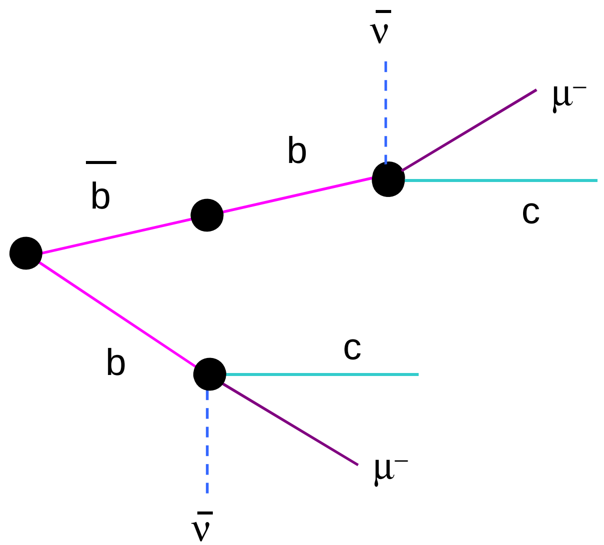
$$\left(M_{12}^{q}\right)^{NP} = r_q^2 e^{2i\theta_q} \left(M_{12}^{q}\right)^{SM}$$

$$\left(\Delta m_q\right)^{NP} = \left(\Delta m_q\right)^{SM} r_q^2$$

$$\left(a_{fs}^{q}\right)^{NP} = -\mathrm{Re}\left\{\frac{\Gamma_{12}^{q}}{M_{12}^{q}}\right\}^{SM} \frac{\sin(2\theta_q)}{r_q^2}$$

Dimuon Measurements

- Babar, Belle, Cleo and D0 all use the di-muon sample
  - Removes dependence on flavour tagging
  - Assume no production asymmetry, correct detector asymmetry
  - Predict branching fraction [$f_{s/d}$ & $Z_{s/d}$] in SM



$$a_{fs}^{q} \propto \frac{\Gamma_q^{WS} - \overline{\Gamma}_q^{WS}}{\Gamma_q^{WS} + \overline{\Gamma}_q^{WS}} = A_{SL}^{q}$$

$$N^{++} = N(b\bar{b} \to Xl^{+}l^{+})$$

$$A_{SL} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \propto f_d^{\,i} Z_d^{i} A_{SL}^{d} + f_s^{\,i} Z_s^{i} A_{SL}^{s}$$

$$\left(A_{SL}^{d}\right)^{b-fact} = -(1.1 \pm 5.5) \times 10^{-3}$$

$$\left(A_{SL}^{s}\right)^{D0+b-fact} = (8 \pm 11) \times 10^{-3}$$

Hadronic Channels

- Semileptonic $\overline{B}_q^0 \longrightarrow D_q^+ l^- \overline{\nu}$
  - Recent result from D0

$$\left(A_{SL}^s\right)^{D0} = (1.23 \pm 0.97(stat) \pm 0.17(syst)) \times 10^{-2}$$

  - Statistically limited
  - LHCb will vastly improve on this
- Hadronic $\overline{B}_q^0 \longrightarrow D_q^+ \pi^-$
  - LHCb will be the first to measure this
  - $D_q^+ \to K^+ K^- \pi^+$ reduces detector asymmetry

Sensitivity to a_{fs}

- DC04 – based study on A_{fs} completed
  - Joint Bristol-Edinburgh LHCb note

Scenario $B_s^0 \to \ldots$	Resolution/ps	$\sigma_{a_{fs}}/1M$	$\sigma_{a_{fs}}/2\,fb^{-1}$	$\sigma_{A_p}/1M$	$\sigma_{A_p}/2\,fb^{-1}$
$D_s^- \mu^+ \nu_\mu$ (< 4.5GeV)	0.270	0.20%	0.22%	None	None
$D_s^- \mu^+ \nu_\mu$ (> 4.5GeV)	0.120	0.20%	0.47%	1.29%	3.01%
$D_s \pi$	0.030	0.20%	0.54%	0.19%	0.51%

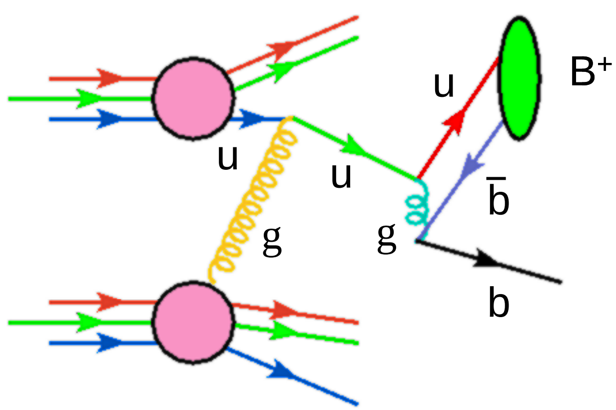
- Assuming:
  - No Background asymmetry
  - Well known Detector asymmetry OR Production asymmetry

What Asymmetry?

- conservation principles: $B\ l_e\ l_\mu\ l_\tau$
- Three main phenomena [2,3,4]

A Valence-Quark Scattering

Enhances production of high energy species containing beam constituents



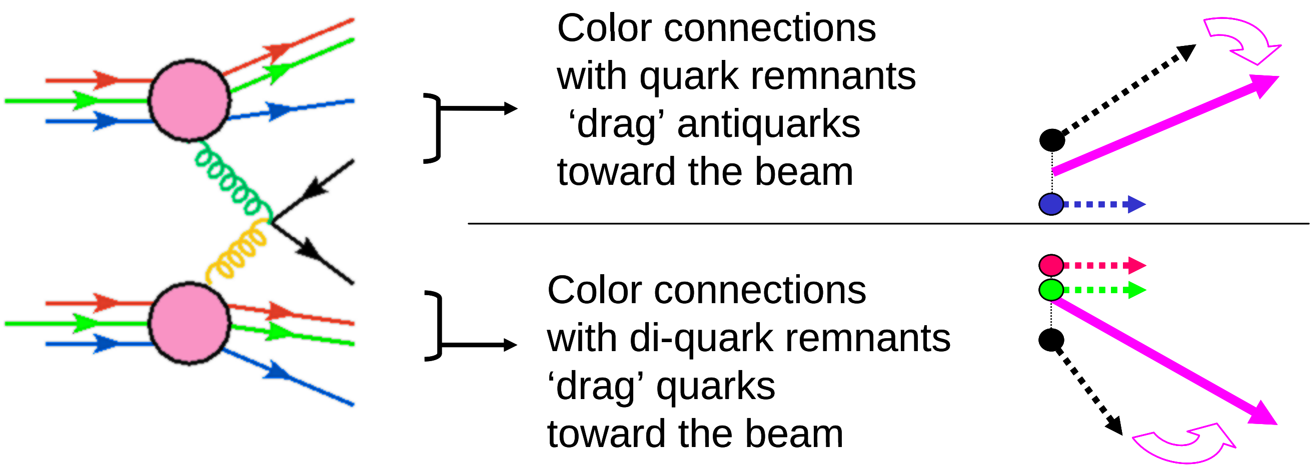
Example production of high-energy B^+-meson by scattering of a u-type valence quark in the initial proton

What Asymmetry?

- conservation principles: $B\ l_e\ l_\mu\ l_\tau$
- Three main phenomena [2,3,4]

(B) Beam Drag

Redistributes particle-antiparticle content as a function of transverse momentum (p_t) and rapidity (direction)

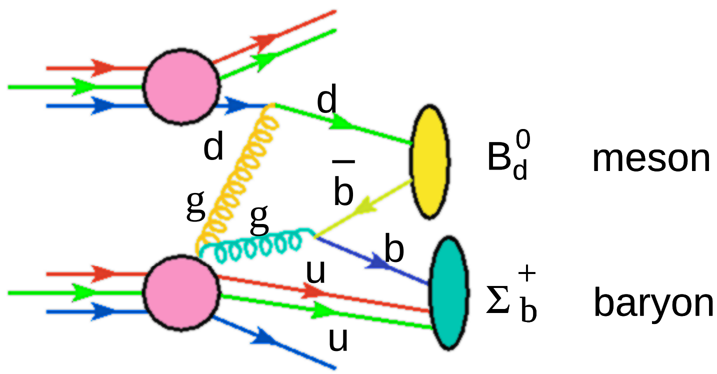


What Asymmetry?

- conservation principles: $B\ l_e\ l_\mu\ l_\tau$
- Three main phenomena [2,3,4]

C Cluster Collapse

Enhances the production of species containing beam remnants at low transverse momentum (p_t)



Example enhancement of low-p_t, high-rapidity B_d and Σ_b - production through hadronisation with beam remnants

Production Asymmetry

- Tuned Pythia samples

δ_p x1000	Min Bias (10M)*	bb – inclusive (10M)*	$B_s^0 B_d^0$ (20M) †
Pions	-(4.23±0.16)	-(2.16±0.09)	-(2.27±0.07)
Kaons	-(17.0±0.5)	-(7.73±0.26)	-(8.2±0.2)
Muons	--	+(2.0±1.2)	+(1.0±0.9)
Ds	--	-(1.6±1.1)	-(1.6±1.1)
Bs	--	-(1.9±1.3)	-(1.5±0.8)
Bd	--	-(3.2±0.7)	-(3.2±0.4)

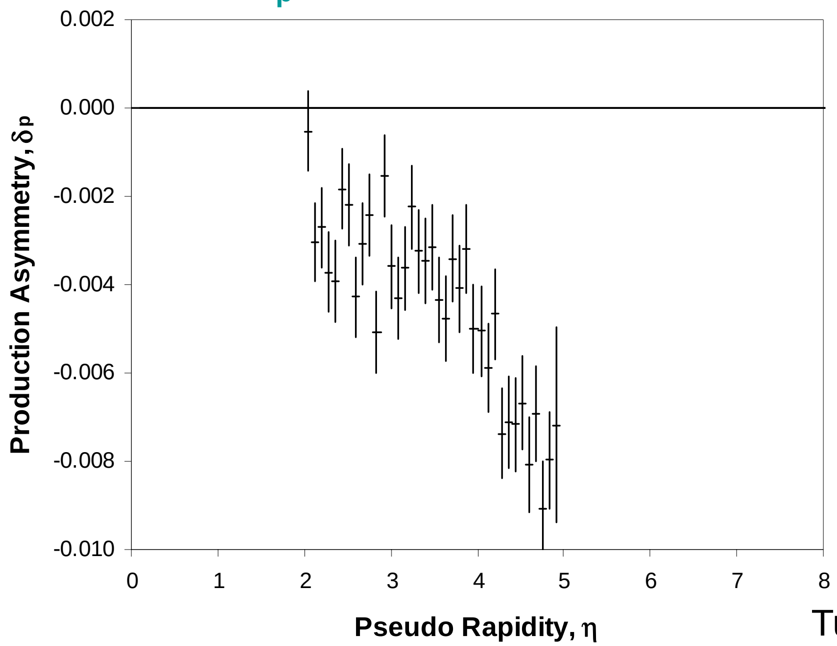
*=standard decays, †=Stable Bd+Bs

- Asymmetries agree with generic bb events

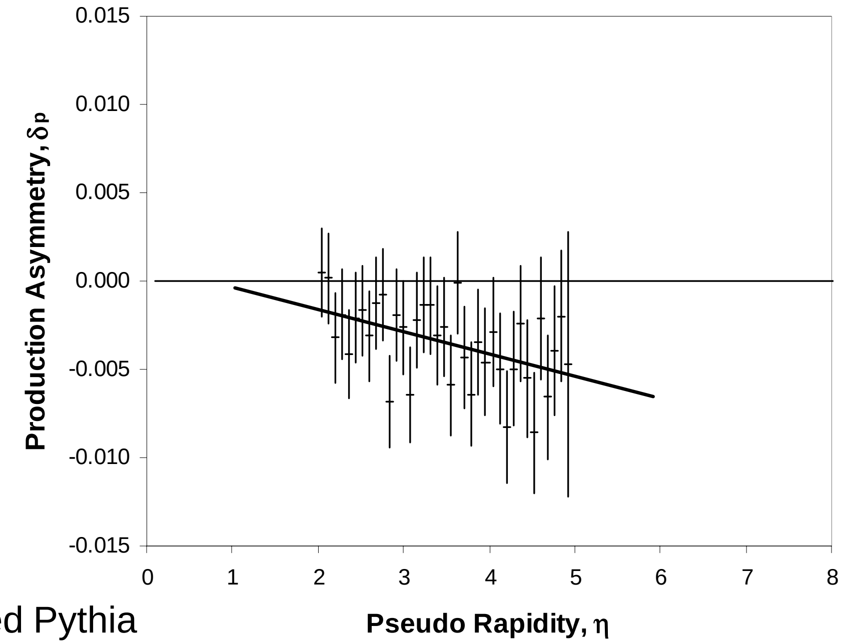
Rapidity Distribution

- [2,3,4] Predicted that δ_p is a fn of Pseudo-Rapidity
  - Low opening angle=high asymmetry
- LHCb Looks at high rapidity ranges

Pion δ_p (π^+ and π^-) (min bias)



B^0 δ_p (B^0 and $\bar{B}^0$) (signal)



Tuned Pythia

Detector Asymmetry

- Interactions asymmetric, tracking symmetric