Rare decays and search for New Physics

- **Introduction**
- $b \to s$ **transitions:**
  - $b \to s\gamma$
  - $B_s^0 \to \mu^+\mu^-$
  - **The** $B \to \mu\mu K^*$ **decay and the** P_5' **anomaly**
  - **What does the** $b \to s\ell\ell$ **family tell us?**

On behalf of the LHCb collaboration
Including CMS, Atlas, Belle and Babar results

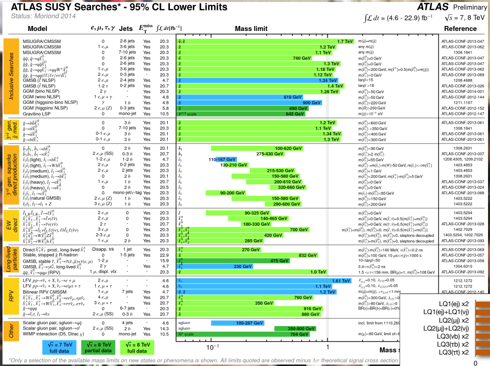
22/05/2014
Rencontres de Blois

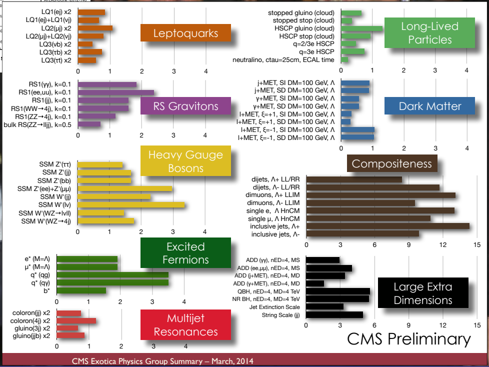
Patrick Koppenburg

NIKHEF CERN

21/05/2014 - www.koppenburg.org

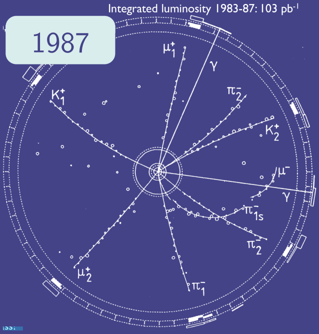
Direct Searches


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: Moriond 2014
ATLAS Preliminary
$\int \mathcal{L}\,dt$ = (4.6 - 22.9) fb^{-1}
$\sqrt{s}$ = 7, 8 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
$\int \mathcal{L}\,dt$[fb^{-1}]
Mass limit
Reference
Inclusive Searches
3rd gen. $\tilde{g}$ med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
$\sqrt{s}$ = 7 TeV full data
$\sqrt{s}$ = 8 TeV partial data
$\sqrt{s}$ = 8 TeV full data
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

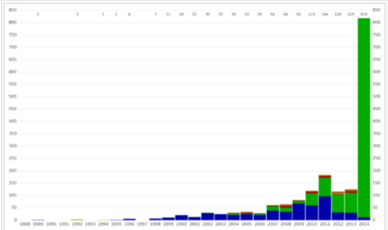

LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(ττ) x2
Leptoquarks
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
Long-Lived Particles
RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
RS1(ZZ→4j), k=0.1
bulk RS(ZZ→llјj), k=0.5
RS Gravitons
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
Dark Matter
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Heavy Gauge Bosons
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Excited Fermions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Large Extra Dimensions
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
0 1 2 3 4
0 3 6 9 12 15
CMS Preliminary
CMS Exotica Physics Group Summary – March, 2014

Precision Measurements

- Sensitive to "New" Physics effects indirectly
  - When was the Z discovered?
    - 1973 from $\nu N \to \nu N$
    - 1983 at SpS collider?
  - c quark needed to explain $K^0_L \to \mu^+\mu^-$ (GIM)
  - Third family (b,t) to explain CP violation (Kobayashi & Maskawa)
- ✔ Estimate masses
  - t quark from $B\overline{B}$ mixing
  - ✔ Much larger mass coverage than $\sqrt{s}$
- ✔ Get phases of couplings
  - Half of new parameters
  - Needed for a full understanding
- Look in lepton and **flavour** sectors
  - ➜ *CP* asymmetry in the Universe



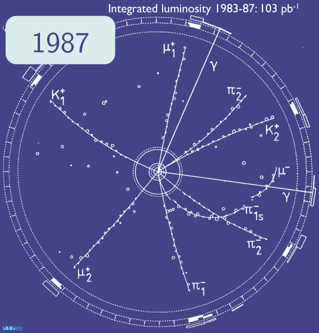
Precision Measurements



Number of extrasolar planet discoveries per year through February 2014, with colors indicating method of detection:

- radial velocity
- transit
- timing
- direct imaging
- microlensing

Hardly any exoplanets have been observed directly. . . but that's the next talk.

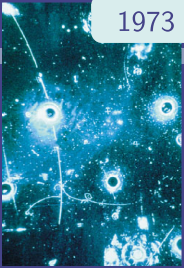


Precision Measurements

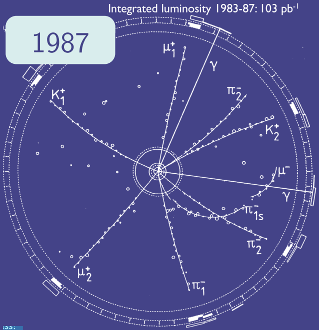
Where to look?

Need three ingredients:

1. Precise SM prediction
2. (desirable) Precise beyond-SM predictions
3. Good experimental precision



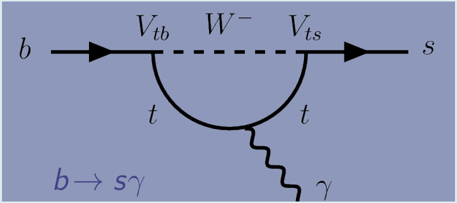
1973



1987

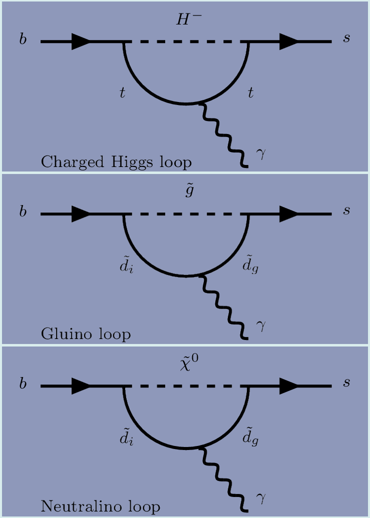
Setting the Scene

$b \to s\gamma$

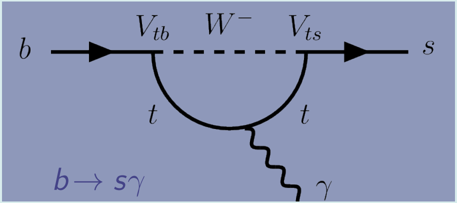


- No tree diagram ➜ suppressed
- First penguin ever observed (93)
- Experiment (WA):
  $\mathcal{B} = (3.40 \pm 0.21) \cdot 10^{-4}$
- SM: $\mathcal{B} = (3.15 \pm 0.23) \cdot 10^{-4}$
  [Misiak et al., hep-ph/0609232]

➜ Strong constraint on New Physics



$b \to s\gamma$ Polarisation



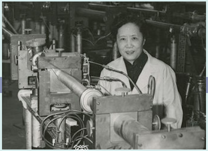
The photon polarisation is not measured.

- Naively $r = \frac{C'_{7\gamma}}{C_{7\gamma}} \overset{\text{SM}}{\simeq} \frac{m_s}{m_b}$
- Gluons contribute a few percent [Ball & Zwicky PLB642:478,2006]
- Right-handed operators could contribute

Ways to measure:

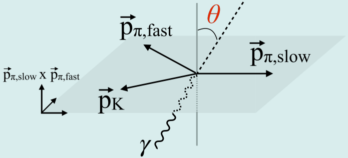
- Mixing-induced *CP* violation
  [Atwood et al., PRL79:185, 1997]
- Λ_b^0 baryons
  [Hiller & Kagan, PRD65:074038, 2002]
- ➜ $B \to \gamma K^{**}(K\pi\pi)$
  [Gronau & Pirjol, PRD66 054008, 2002] [Gronau et al., PRL88:051802, 2002]
- Virtual photons ($b \to \ell\ell s$)
  [Melikhov et al., PLB442:381-389,1998]
- Converted photons
  [Grossman et al., JHEP06:29,2000]

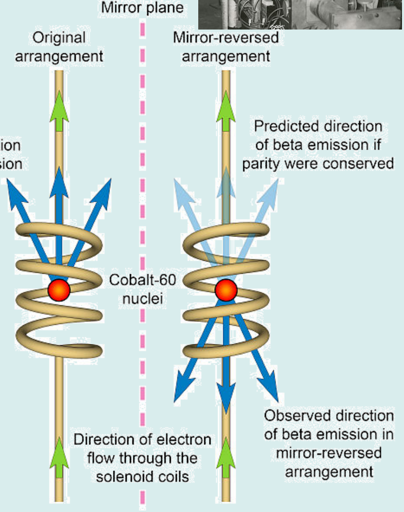
Wu experiment (1956)



- The first measurement of C-parity violation was performed in 1956 with ^{60}Co decays
- The left-handedness of the weak interaction is probed by measuring the direction of beta-rays

➜ Let's measure the handedness of the $b \to s\gamma$ transition

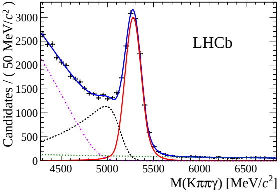


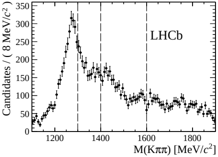


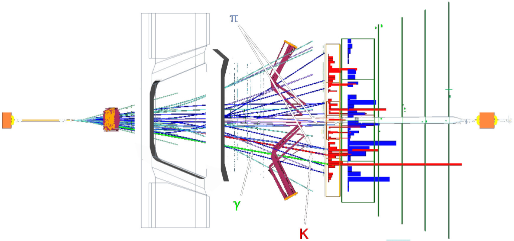
[Phys.Rev.Lett. 112, 161801, arXiv:1402.6852]

Photon polarisation in $b \to s\gamma$

- The SM predicts the photon in $b \to s\gamma$ is left-handed. Corrections $\mathcal{O}(\frac{m_b^2}{m_s^2})$. Polarisation so far unobserved.
- Looking for $B^+ \to K^+\pi^+\pi^-\gamma$ with calorimeter photons. Very clean selection, essentially only part.reco. background left. 13 000 signal candidates in $3\,\text{fb}^{-1}$.
- $m_{K\pi\pi}$ distribution shows many resonances. No attempt to disentangle them. $K_1(1270)$ dominates. Bin in 4 regions.







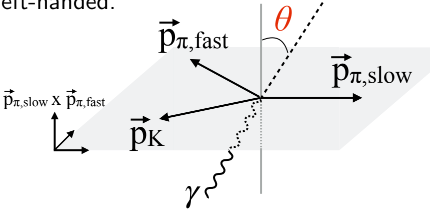
[Phys.Rev.Lett. 112, 161801, arXiv:1402.6852]

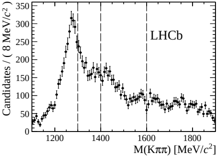
Photon polarisation in $b \to s\gamma$

- The SM predicts the photon in $b \to s\gamma$ is left-handed.
- Compute up-down asymmetry

$$\mathcal{A}_{\text{ud}} = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}}$$

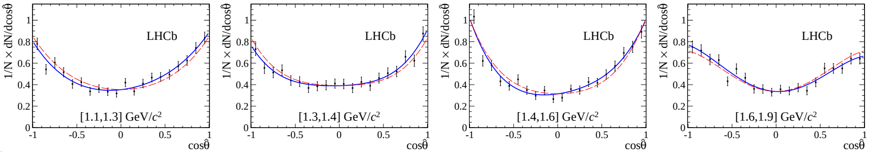
$$= 6.9 \pm 1.7,\ 4.9 \pm 2.0,\ 5.6 \pm 1.8,\ -4.5 \pm 1.9\%$$





➜ 5.2σ first observation of photon polarisation

- Need theory input to determine photon polarisation

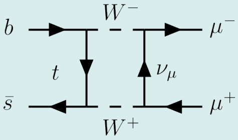


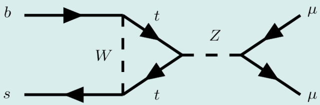
$B_s^0 \to \mu^+\mu^-$

- Very rare decay, well described in the SM

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{SM}} = (3.65 \pm 0.23) \cdot 10^{-9}$$

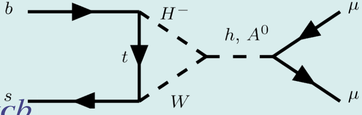
[Bobeth, Gorbahn, ermann, Misiak, Stamou, Steinhauser, Phys. Rev. Lett. 112, 101801 (2014), arXiv:1311.0903], [De Bruyn, Fleischer, Knegjens, PK, Merk, Pellegrino, Tuning, PRL 109, 041801 (2012), arXiv:1204.1737], [Buras, Acta Phys.Polon.B41:2487-2561,2010, arXiv:1012.1447] ...



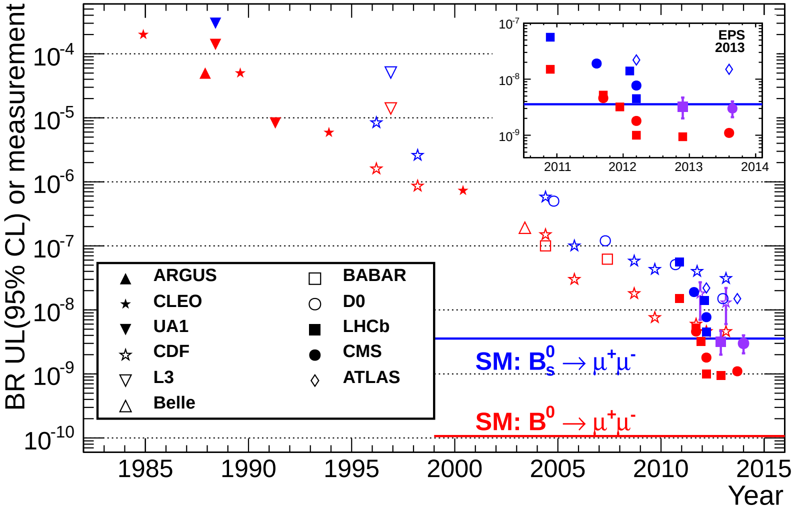


- Very sensitive to NP, e.g. Minimal Susy Models:

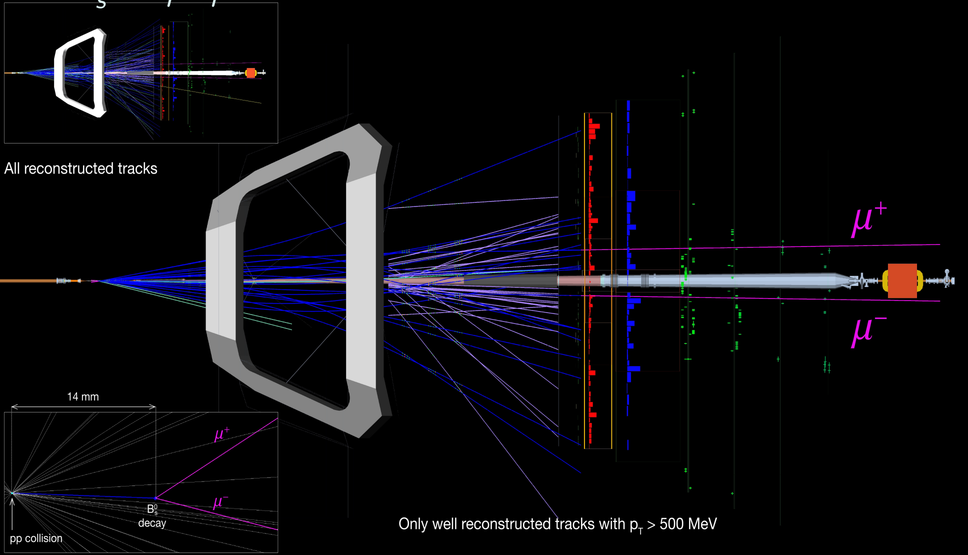
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{MSSM}} \propto \frac{m_b^2 m_\ell^2 \tan^6\beta}{m_A^4}$$



$B_s^0 \to \mu^+\mu^-$ Limits History

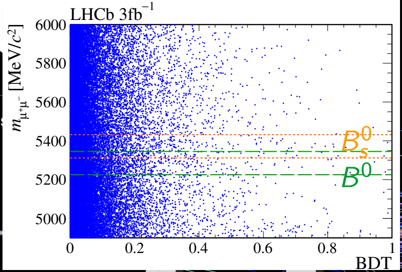


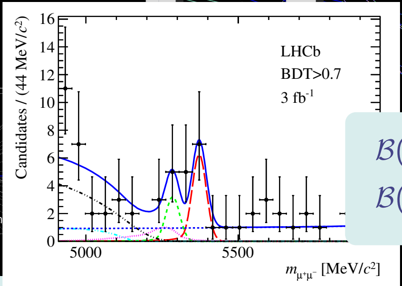
$B_s^0 \to \mu^+\mu^-$ at LHCb



$B_s^0 \to \mu^+\mu^-$ at LHCb

[Phys. Rev. Lett. 111 (2013) 101805, arXiv:1307.5024]



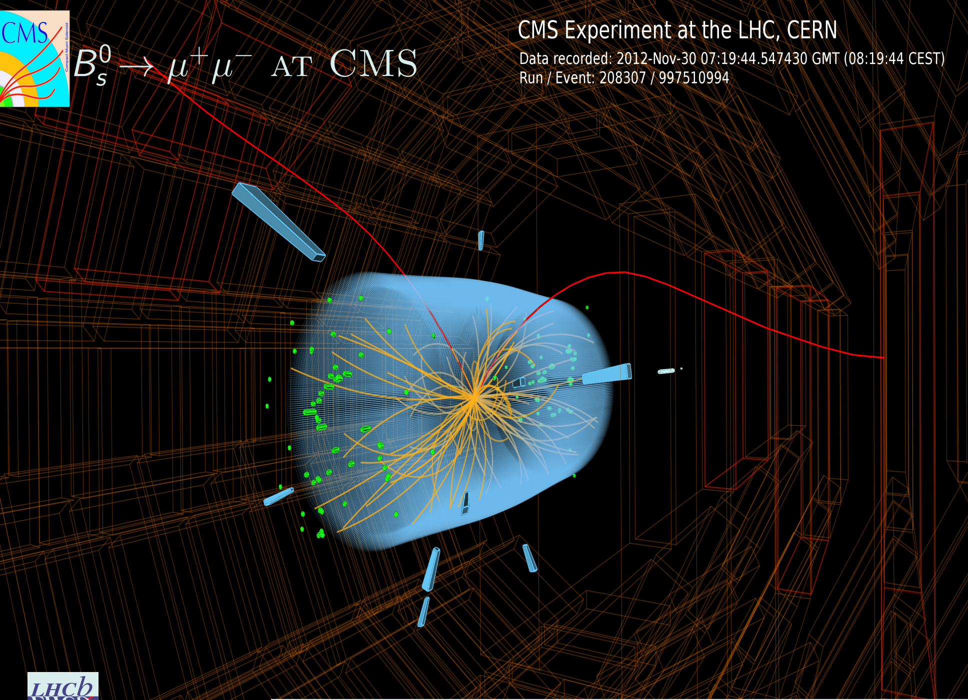


- Classify events with a BDT calibrated on $B \to hh$ and the $\mu^+\mu^-$ mass
- All points in mass window are used in result, but only BDT > 0.7 shown below
- Normalise to $B_s^0 \to J/\psi\,\phi$, $B^+ \to J/\psi\,K$, $B^0 \to K\pi$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.9\,^{+1.1}_{-1.0}\,^{+0.3}_{-0.1} \times 10^{-9}$$

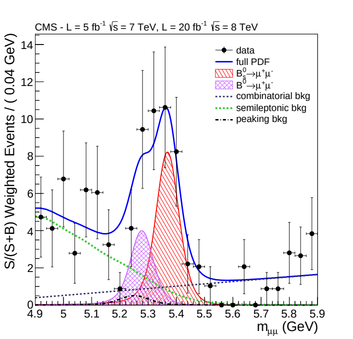
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.7\,^{+2.4}_{-2.1}\,^{+0.6}_{-0.4} \times 10^{-10}$$

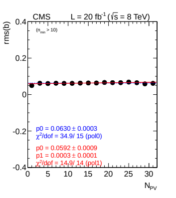
$B_s^0 \to \mu^+\mu^-$ AT CMS



$B_s^0 \to \mu^+\mu^-$ at CMS

CMS Experiment at the LHC, CERN
Data recorded: 2012-Nov-30 07:19:44.547430 GMT (08:19:44 CEST)
Run / Event: 208307 / 997510994



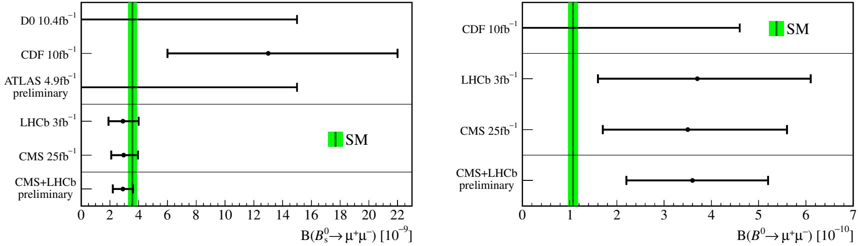


- Classify events with a BDT calibrated on $B_s^0 \to J/\psi\,\phi$ and the $\mu^+\mu^-$ mass
  - Different classification of barrel and endcap events
  - ✔ BDT stable versus event multiplicity
- Normalise to $B^+ \to J/\psi\,K$
- In the figure the events are weighted by $S/\sqrt{S+B}$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.0\,^{+1.0}_{-0.9} \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.5\,^{+2.1}_{-1.8} \times 10^{-10}$$

[Phys. Rev. Lett. 111 (2013) 101804, arXiv:1307.5024]

$B_s^0 \to \mu^+\mu^-$ Combined

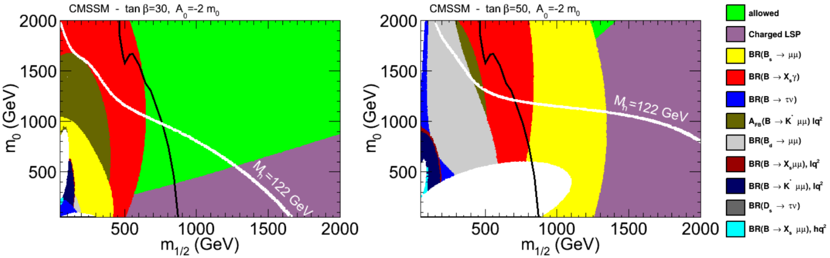


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10}$$

First observation of $B_s^0 \to \mu^+\mu^-$!

ATLAS: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8}$ [ATLAS-CONF-2013-076]

Constraints



- There are as many exclusion plots as models.
- In this CMSSM (MSSM with universality assumptions at the GUT scale) flavour physics excludes everything at large $\tan\beta$ (remember $\mathcal{B} \sim \tan^6\beta$), while at $\tan\beta \sim 30$ direct searches (black line) compete with flavour physics
- White line: above the Higgs can have a mass larger than $122\ \mathrm{GeV}/c^2$

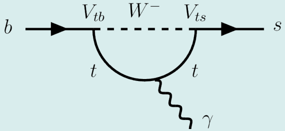
Is there any space for new physics left?

"The **success** *of the LHCb experiment has so far been a* **nightmare** *for all flavour physicists that were hoping to see signs of new physics popping up in B_s^0–$\overline{B}_s^0$ mixing and the rare $B_s^0 \to \mu^+\mu^-$ decay. This situation might have* **changed** *with the latest measurements [1,2]"*

[Gauld, Goertz, Haisch, arXiv:1310.1082]

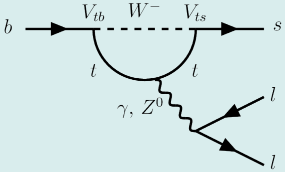
[1,2] are discussed in the next slides.

$b \to \ell\ell s$



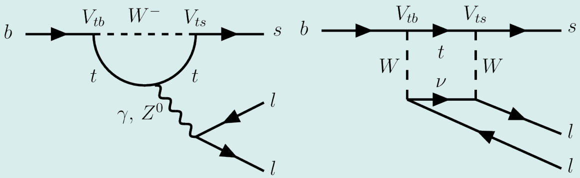
- Start with $b \to s\gamma$

$b \to \ell\ell s$



- Start with $b \to s\gamma$, pay a factor $\alpha_{\rm EM}$
  - ➜ Decay the γ into 2 leptons

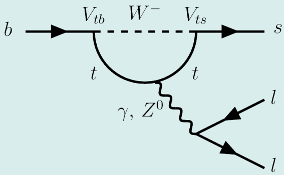
$b \to \ell\ell s$

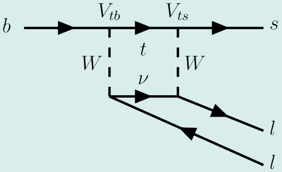


- Start with $b \to s\gamma$, pay a factor α_{EM}
  - ➜ Decay the γ into 2 leptons
  - Add an interfering box diagram
  - ➜ $b \to \ell\ell s$, very rare in the SM
    $\mathcal{B}(B \to \ell\ell K^*) = (1.8 \pm 0.2) \cdot 10^{-6}$

    [Huber et al., Nucl.Phys.B802:40-62,2008]

$b \to \ell\ell s$





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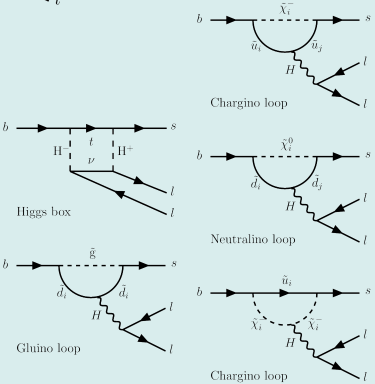
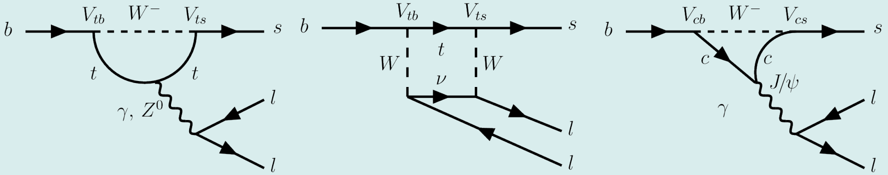
    [Huber et al., Nucl.Phys.B802:40-62,2008]
- Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions ...



✔ Ideal place to look for new physics

$b \to \ell\ell s$



- Start with $b \to s\gamma$, pay a factor α_{EM}
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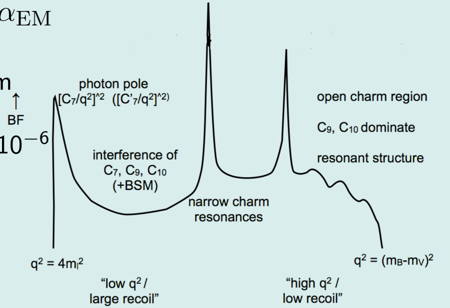
    $\mathcal{B}(B \to \ell\ell K^*) = (1.8 \pm 0.2) \cdot 10^{-6}$

    [Huber et al., Nucl.Phys.B802:40-62,2008]

✗ But beware of LD effects:

- Tree $b \to c\bar{c}s$, $(c\bar{c}) \to \ell\ell$
- ✔ Can be removed by mass cuts
- ✗ ✔ Interferes elsewhere

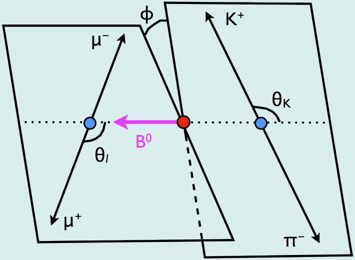


(c) Jaeger

$B \to \ell\ell K^*$ Angular Distributions

A lot of information in the full θ_ℓ, θ_K and ϕ distributions

$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{16\pi}\Bigg[F_\mathrm{L}\cos^2\theta_K + \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) + F_\mathrm{L}\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K)(2\cos^2\theta_\ell-1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_\mathrm{FB}(1-\cos^2\theta_K)\cos\theta_\ell + S_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Bigg]$$



➜ Many observables depending on $q^2 = m^2_{\mu\mu}c^4$

[Altmannshofer et al., JHEP 0901:019,2009]
[Krüger & Matias, Phys.Rev.D71:094009]
[Egede et al., JHEP 0811:032,2008]
[Ali et al., Phys.Rev.D61:074024]

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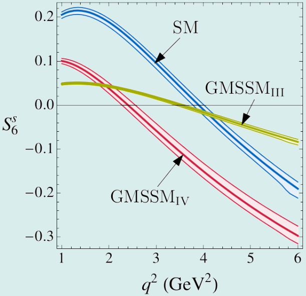

→ **Forward-backward asymmetry $S_6 = \frac{4}{3}A_\mathrm{FB}$**

[Altmannshofer et al., JHEP 0901:019,2009]
[Krüger & Matias, Phys.Rev.D71:094009]
[Egede et al., JHEP 0811:032,2008]
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$B \to \ell\ell K^*$ Angular Distributions

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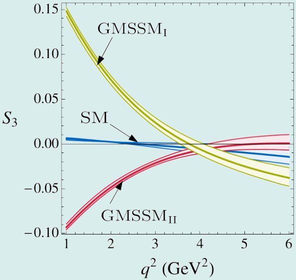
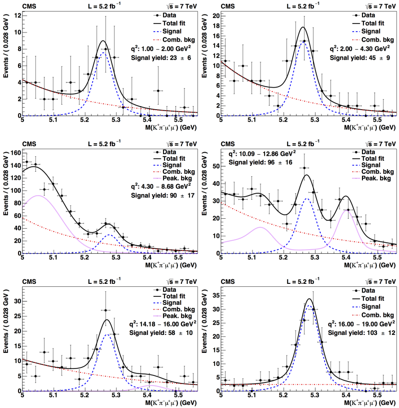


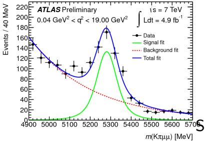
➜ **Transverse asym.** $S_3 = (1-F_{\mathrm{L}})A_T^{(2)}$ **(RH)**

[Altmannshofer et al., JHEP 0901:019,2009]
[Krüger & Matias, Phys.Rev.D71:094009]
[Egede et al., JHEP 0811:032,2008]
[Ali et al., Phys.Rev.D61:074024]

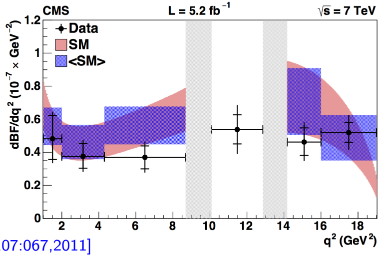
[PLB 727 (2013) 77, arXiv:1308.3409] [ATLAS-CONF-2013-038]

$B \to \mu\mu K^*$ at CMS and ATLAS





- Select $B^0 \to K^* \mu^+ \mu^-$
  - Take the K-π hypo that gets closest to the K^* mass
  - Cut out J/ψ and $\psi(2S)$
  - CMS observe 415 ± 30 events in 5.2 fb^{-1} (2011)
  - ATLAS 466 ± 34 in 4.9 fb^{-1}
- Bin in $q^2 = m^2_{\mu^+\mu^-}$ ➜ $\mathrm{d}\Gamma/\mathrm{d}q^2$



SM: [Bobeth et al., JHEP 1107:067,2011]

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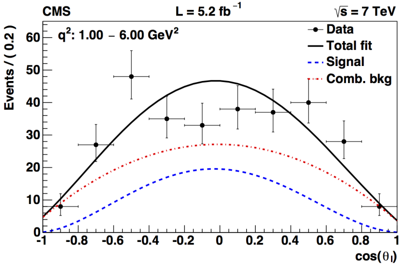

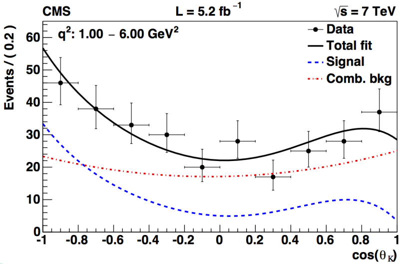

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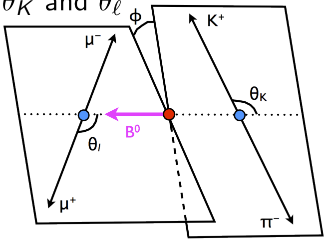

[PLB 727 (2013) 77, arXiv:1308.3409] [ATLAS-CONF-2013-038]

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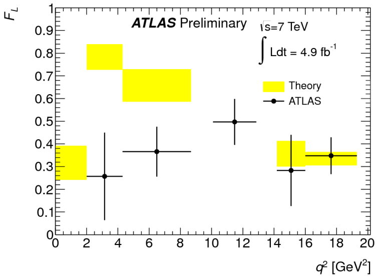

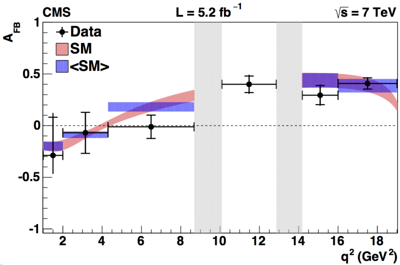

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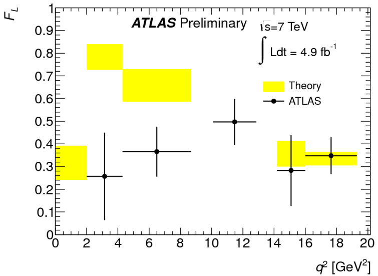
  - ATLAS 466 ± 34 in 4.9 fb^{-1}
- Bin in $q^2 = m^2_{\mu^+\mu^-}$ ➜ $\mathrm{d}\Gamma/\mathrm{d}q^2$
- Fit for θ_K and θ_ℓ

➜ F_L and A_FB

- All compatible with SM

SM: [Bobeth et al., JHEP 1107:067,2011]

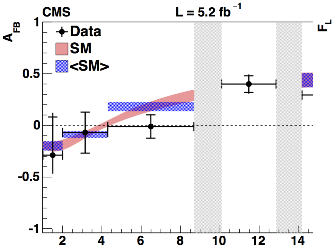
$B \to \mu\mu K^*$ at CMS and ATLAS

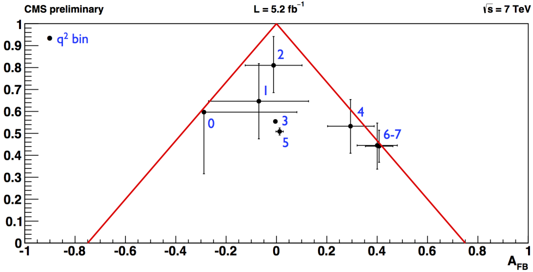


- Select $B^0 \to K^* \mu^+ \mu^-$
- Bin in $q^2 = m^2_{\mu^+\mu^-}$ ➜ $\mathrm{d}\Gamma/\mathrm{d}q^2$
- Fit for θ_K and θ_ℓ

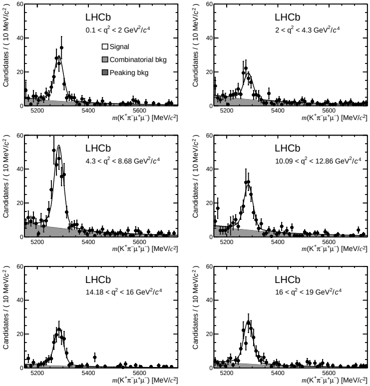
➜ F_L and A_FB

- Note the physical boundary limiting the values of F_L and A_FB

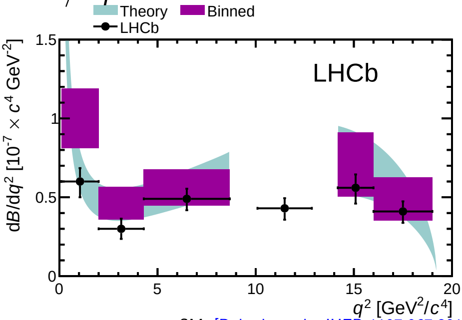




$B \to \mu\mu K^*$ at LHCb ($1\ \mathrm{fb}^{-1}$)



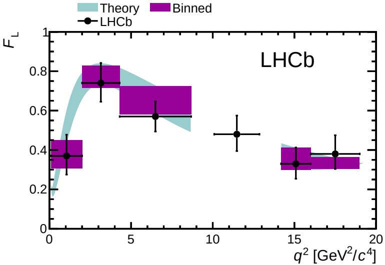
- Select $B^0 \to K^* \mu^+ \mu^-$ using a boosted decision tree
  - Cut out J/ψ and $\psi(2S)$
  - Observe 883 ± 34 events in $1\ \mathrm{fb}^{-1}$
- Bin in $q^2 = m^2_{\mu^+\mu^-}$ and extract $\mathrm{d}\Gamma/\mathrm{d}q^2$

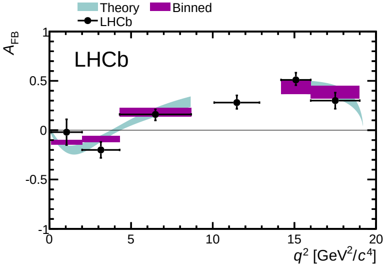


SM: [Bobeth et al., JHEP 1107:067,2011]

[JHEP 08 (2013) 131, arXiv:1304.6325]

$B \to \mu\mu K^*$ at LHCb (1 fb^{-1})





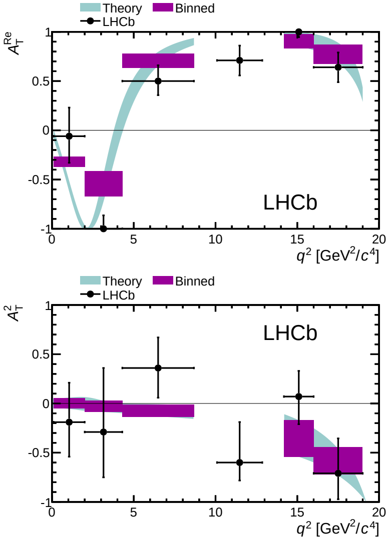
- Select $B^0 \to K^* \mu^+ \mu^-$
- Bin in $q^2 = m^2_{\mu^+\mu^-}$
- Fit for θ_K and θ_ℓ
  - ➜ F_L and A_{FB}
  - ➜ Extract zero crossing point (4.9 ± 0.9) GeV$^2/c^4$

- All compatible with SM

SM: [Bobeth et al., JHEP 1107:067,2011]

[JHEP 08 (2013) 131, arXiv:1304.6325]

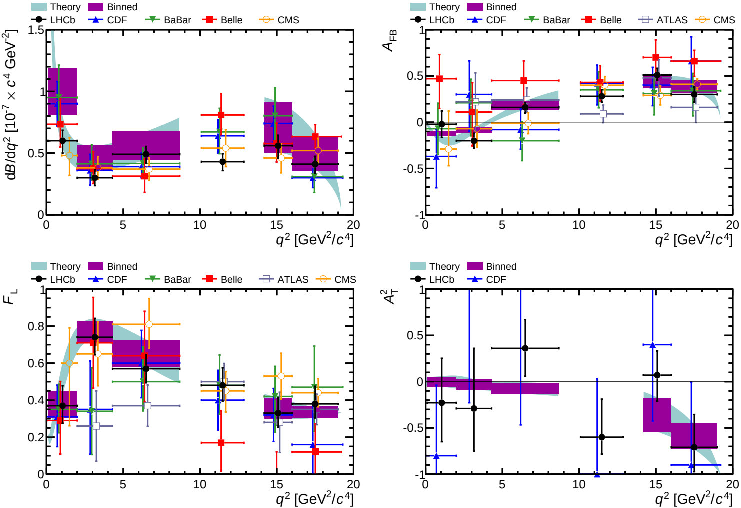
$B \to \mu\mu K^*$ at LHCb ($1\,\mathrm{fb}^{-1}$)



- Select $B^0 \to K^* \mu^+ \mu^-$
- Bin in $q^2 = m^2_{\mu^+\mu^-}$
- Fit for θ_K and θ_ℓ
  - ➜ F_L and A_{FB}
  - ➜ Extract zero crossing point $(4.9 \pm 0.9)\ \mathrm{GeV}^2/c^4$
  - ➜ Extract T-odd S_9. And S_3, sensitive to right handed currents
  - ➜ And A_T^{Re}, and A_T^2 (also right-handed)...
- All compatible with SM

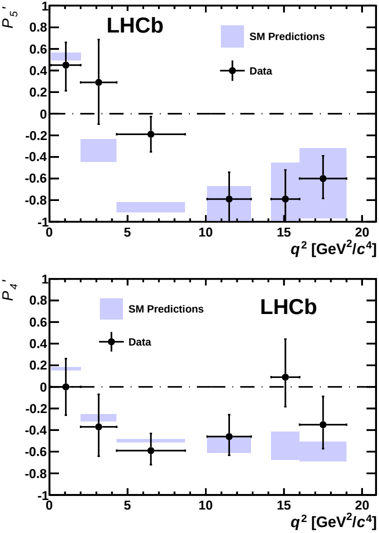
SM: [Bobeth et al., JHEP 1107:067,2011]

Comparison of all Experiments



LHCb [JHEP 08 (2013) 131] CMS [PLB 727 (2013) 77], ATLAS [ATLAS-CONF-2013-038], Belle [Phys. Rev. Lett. 103 (2009) 171801], Babar [Phys. Rev. D. 73. 092001], CDF [Phys. Rev. Lett. 108 081807]

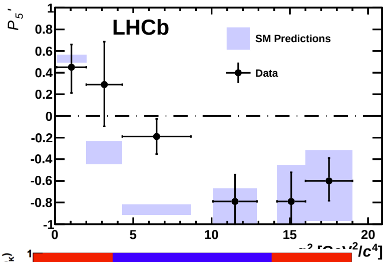
$B \to \mu\mu K^*$ at LHCb ($1\ \mathrm{fb}^{-1}$) — 2^{nd} paper

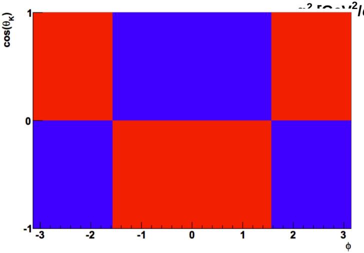


- Select $B^0 \to K^* \mu^+ \mu^-$
- We also measure $P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$, which are largely free from form-factor uncertainties, [Descotes-Genon et al., JHEP, 1305:137, 2013]

SM: [Descotes-Genon et al., JHEP, 1305:137, 2013]

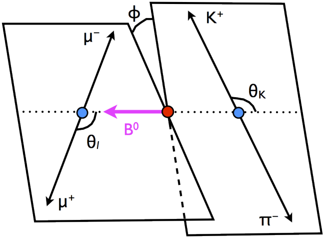
$B \to \mu\mu K^*$ at LHCb ($1\ \mathrm{fb}^{-1}$) — 2^{nd} paper



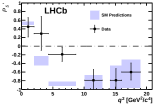


Counting S_5: blue minus red

- Select $B^0 \to K^* \mu^+ \mu^-$
- We also measure $P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$, which are largely free from form-factor uncertainties, [Descotes-Genon et al., JHEP, 1305:137, 2013]
  - ✔ **Local discrepancy in P'_5 at 3.7σ observed.** ($P = 0.5\%$ with look-elsewhere effect)

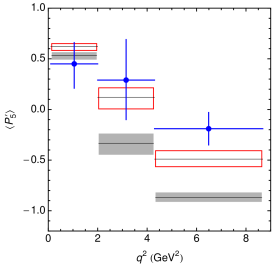


What is it?

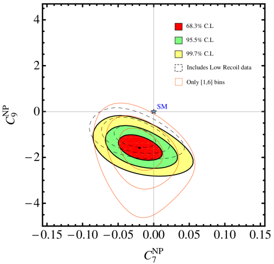


What is it? Can a new physics model explain such a discrepancy while still being compatible with 50 years of HEP measurements?

- ➜ 28 theory papers and still counting. Here are a few:



Descotes-Genon, Matias, Virto fit this and other measurements and get a 4.5σ discrepancy with the SM. Their best fit favours a modified C_9 coefficient ➜ Non-SM vector current. [Phys. Rev. D 88, 074002]



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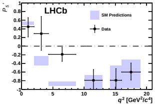

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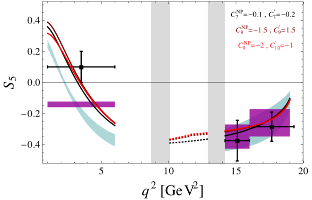
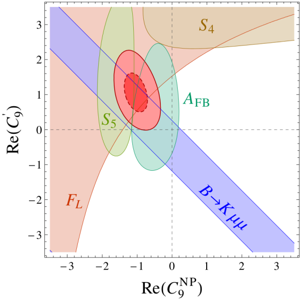
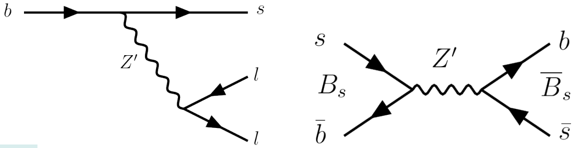


Altmannshofer and Straub find three discrepancies at the 2–3σ level in $B \to \mu\mu K^*$. Modified C_9 and C_9' are needed.
The MSSM cannot do that without breaking B_s^0 mixing. A FCNC Z' of $\mathcal{O}(1)$ TeV would work.

[Eur.Phys.J.C 73:2646]





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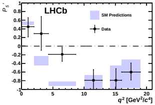

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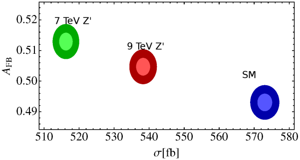
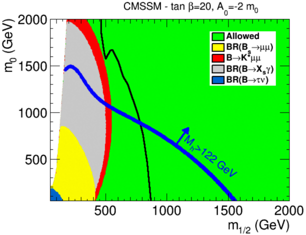
Altmannshofer and Straub find three discrepancies at the 2–3σ level in $B \to \mu\mu K^*$. A FCNC Z' of $\mathcal{O}(1)$ TeV would work. [Eur.Phys.J.C 73:2646]



Gauld, Goertz, Haisch also favour the Z' option, but prefer a mass of $\mathcal{O}(7)$ TeV. They also predict the cross-section to muons at a 500 GeV linear collider. [JHEP 01 (2014) 069]

Mahmoudi et al. show constraints on the MSSM [arXiv:1401.2145]



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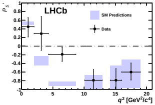

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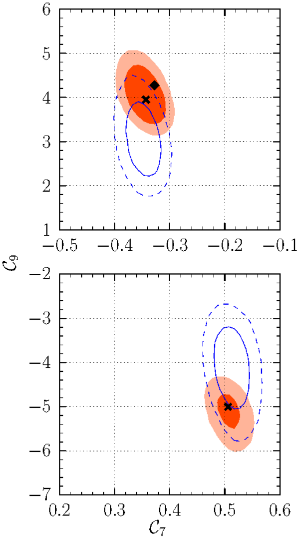
- Beaujean, Bobeth, van Dyk add hadronic form factors as nuisance parameters and find the SM agrees at the 2σ level. [Accepted by EPJC, arXiv:1310.2478]

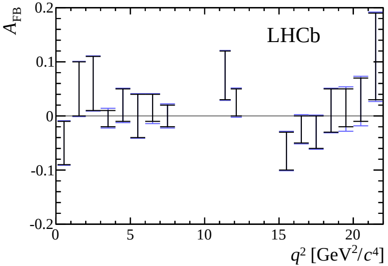


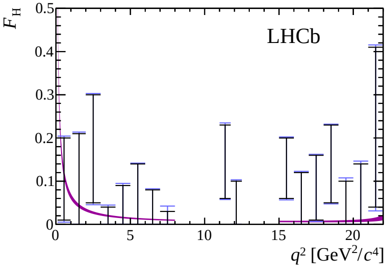
Other players

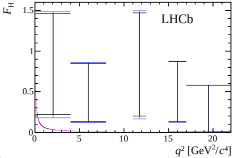
Is there something in other decays?

Angular analysis of $B \to K\mu^+\mu^-$

- What about angular distributions in $B \to K\mu^+\mu^-$? In the SM $A_{\mathrm{FB}} = 0$ because of the scalar K.
- Only one angle in decay ➜ measure A_{FB} and F_H (fraction of scalar and tensor)
- $B^+ \to K^+\mu^+\mu^-$ (right) and $B^0 \to K^0_{\mathrm{S}}\mu^+\mu^-$ (bottom), where only F_{H} can be determined.
- Everything very SM-like





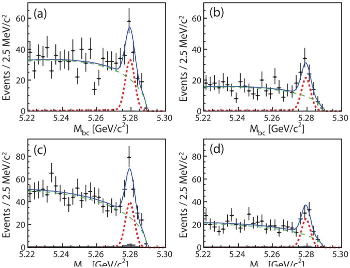


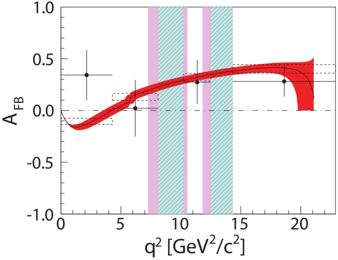
[submitted to PRL, arXiv:1402.7134]

$B \to \ell\ell X_s$ AT BELLE

- Sum ten self-tagging X_s final states ($K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$ ($\bar{B}^0$), K^-, $K^-\pi^0$, $K^-\pi^+\pi^-$, $K^-\pi^+\pi^-\pi^0$, $K^0_S\pi^-$, $K^0_S\pi^-\pi^0$, $K^0_S\pi^-\pi^+\pi^-$ (B^-)) with $m_{X_s} < 2.0\ \mathrm{GeV}/c^2$, combined with $\mu^+\mu^-$ and e^+e^-.
- Build an asymmetry between $\cos\theta_l > 0$ (left) and $\cos\theta_l < 0$ (right) for $X_s e^+e^-$ (top) and $X_s\mu^+\mu^-$ (bottom)

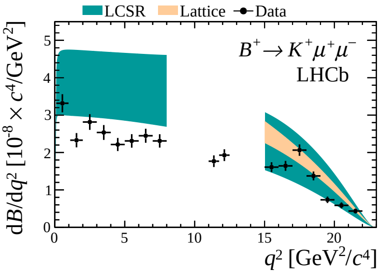
➜ Result consistent with SM prediction, though uncertainties are large

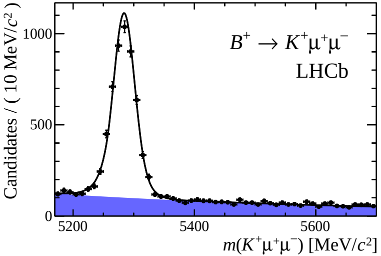




Differential BFs of $B \to K^{(*)}\mu^+\mu^-$

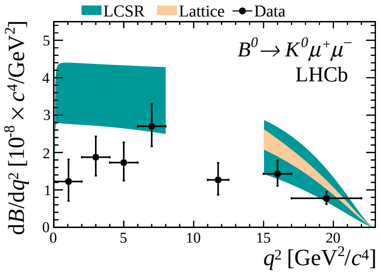
- Reconstruct $B^+ \to K^+\mu^-\mu^+$
  - $B \to J/\psi K$ is taken as normalisation mode.
  - Removing the charmonia, one gets the mass plot below
  - ...and the differential cross-section versus $q^2 = m^2_{\mu^-\mu^+}$

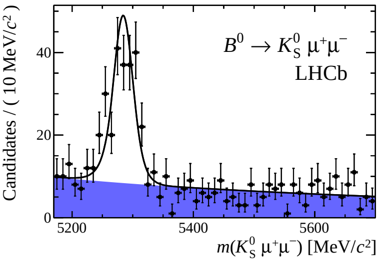




Differential BFs of $B \to K^{(*)}\mu^+\mu^-$

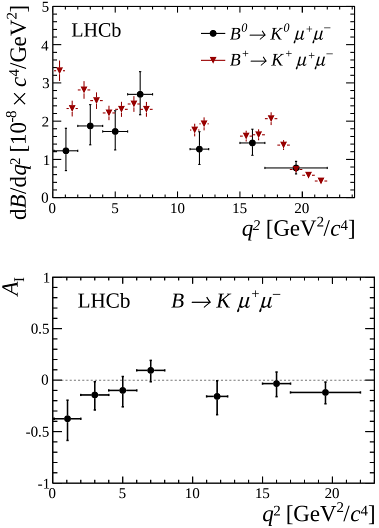
- Reconstruct $B^+ \to K^+\mu^-\mu^+$
- and $B^0 \to K^0\mu^-\mu^+$ (K^0 as $K^0_S \to \pi^-\pi^+$)
  - ✗ Much lower statistics due to high K^0_S lifetime
  - The theoretical expectation of $d\mathcal{B}/dq^2$ is the same up to τ_{B^0}/τ_{B^+}
- The BFs are compatible with the SM expectation, but on the low side





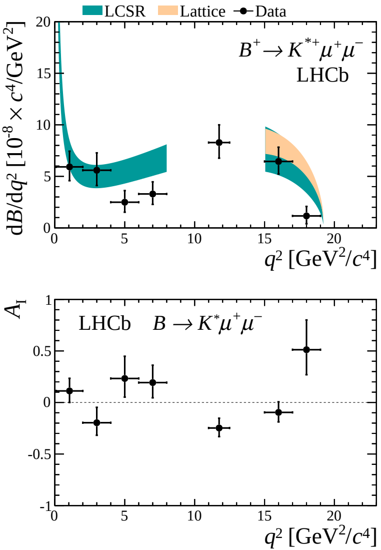
Differential BFs of $B \to K^{(*)}\mu^+\mu^-$

- Reconstruct $B^+ \to K^+\mu^-\mu^+$
- and $B^0 \to K^0\mu^-\mu^+$ (K^0 as $K^0_S \to \pi^-\pi^+$)
- The BFs are compatible with the SM expectation, but on the low side
- The isospin asymmetry is compatible with zero at the 1.5σ level

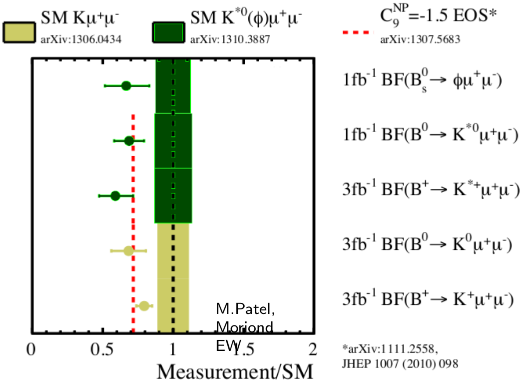


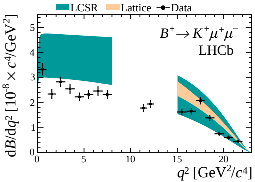
Differential BFs of $B \to K^{(*)}\mu^+\mu^-$

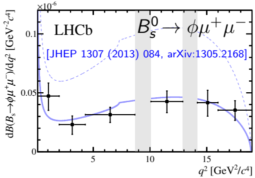
- Reconstruct $B^+ \to K^+\mu^-\mu^+$
- and $B^0 \to K^0\mu^-\mu^+$ (K^0 as $K^0_S \to \pi^-\pi^+$)
- The BFs are compatible with the SM expectation, but on the low side
- The isospin asymmetry is compatible with zero at the 1.5σ level
- Do the same for $B^+ \to K^{*+}\mu^-\mu^+$ ($K^{*+} \to K^0_S\pi^+$) wrt $B^0 \to K^{*0}\mu^-\mu^+$
  - Details on $B^0 \to K^{*0}\mu^-\mu^+$ will come later (needs S-wave)



Too low BFs at high q^2?





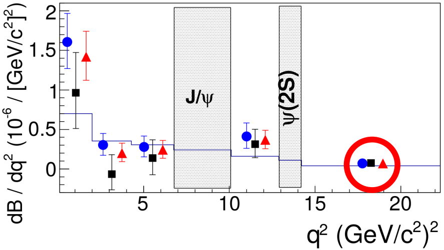


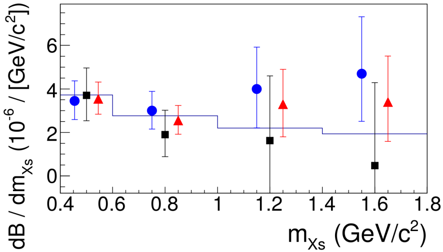
- All LHCb BF measurements are on the low side at high q^2 compared to the SM
- Something wrong with form factors?
- Or $C_9' < 0$, which is also indicated by angular anomalies?

[accepted by PRL, arXiv:1312.5364]

$B \to \ell\ell X_s$ BF at Babar

- Sum ten X_s final states (K^+, $K^+\pi^0$, $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+$, K^0_S, $K^0_S\pi^0$, $K^0_S\pi^+$, $K^0_S\pi^+\pi^0$, $K^0_S\pi^+\pi^-$) with $m_{X_s} < 1.8\ \mathrm{GeV}/c^2$, combined with $\mu^+\mu^-$ and e^+e^-.
- Get dB/dq^2 and dB/m_{X_s} for ● e^+e^-, ■ $\mu^+\mu^-$ and ▲ sum.
- Babar get a (non-significant) enhancement in the last q^2 bin, rather than a suppression.





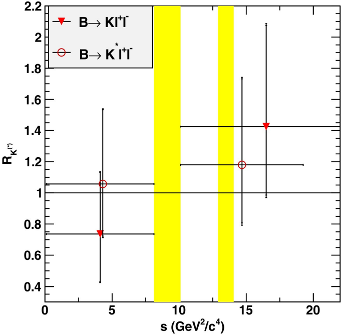
Other asymmetries in $B \to K^{(*)}\ell\ell$

Isospin asymmetries: There were some evidences reported by Belle [Phys.Rev.Lett 103 171801,2009, arXiv:0904.0770], Babar [Phys.Rev.D.86 032012] and LHCb [JHEP 07 (2012) 133]. Now essentially gone [LHCb-PAPER-2014-006]

***CP* asymmetries:** No evidence has even been reported (Most precise: [Phys. Rev. Lett. 110, 031801] by LHCb)

Lepton universality violation: If there's a flavour-changing Z', how does it couple to leptons? All measurements are consistent with no violation. (Belle [Phys.Rev.Lett 103 171801,2009], Babar [Phys.Rev.D.86 032012]).

➜ And I don't mention here $B \to X_d\ell\ell$



Ratio of $B \to K\mu^+\mu^-$ and $B \to Ke^+e^-$ Babar [Phys.Rev.D.86 032012]

Conclusion

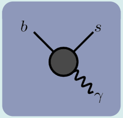
- The LHC is the new b factory
- But the B factories are still producing results
- Exploring $b \to s$ transitions
  - $B_s^0 \to \mu^+\mu^-$ and $b \to s\gamma$ do not highlight large SUSY effects
  - Interesting deviation from the SM in $B \to \mu\mu K^*$
    - ➜ Are we seeing a heavy Z'?
- Many analyses to be updated to 2012 data
- ...and beyond with LHC's Run II and Belle II...
- And I haven't discussed CP violation and charm

Backup

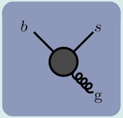
Operators of Interest

Operator

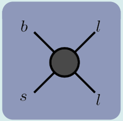
$\mathcal{O}_{7\gamma}$



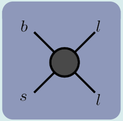
$\mathcal{O}_{8\mathrm{g}}$



$\mathcal{O}_{9\mathrm{V},10\mathrm{A}}$



$\mathcal{O}_{\mathrm{S,P}}$



Effective Hamiltonian $\mathcal{H}$

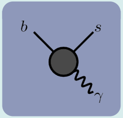
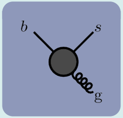
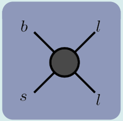
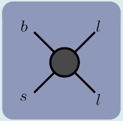
$$A(M \to F) = \langle F \left| \mathcal{H}_{\text{eff}} \right| M \rangle$$

$$\mathcal{H}_{\text{eff}} = -\frac{4 G_F}{\sqrt{2}} V_{ts}{}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu)$$

- Operators $\mathcal{O}_i$: Long-distance effects
- Wilson coefficients C_i: Short-distance effects(masses above μ are integrated out)

New physics can show up in new operators or modified Wilson coefficients

Operators of Interest

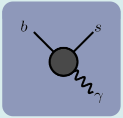
Operator		Magnitude	Phase	Helicity flip $\mathcal{O}'_i$
$\mathcal{O}_{7\gamma}$		$b \to s\gamma$	$A_{CP}(b \to s\gamma)$	$\Lambda_b^0 \to \Lambda\gamma$ $B \to K^{**}\gamma$ $B \to \ell\ell K^*$
$\mathcal{O}_{8g}$		$b \to s\gamma$ $b \to \{s, u, d\}$	$A_{CP}(b \to s\gamma)$ $B \to \phi K$	$\Lambda_b^0 \to \Lambda\phi$ $B \to K^*\phi$
$\mathcal{O}_{9V,10A}$		$b \to \ell\ell s$	$A_{FB}(b \to \ell\ell s)$	$B \to \ell\ell K^*$
$\mathcal{O}_{S,P}$		$B \to \mu\mu$	$B \to \tau^+\tau^-$	$b \to s\tau^+\tau^-$

Adapted from [G.Hiller,hep-ph/0308180]

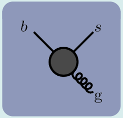
Operators of Interest

Operator

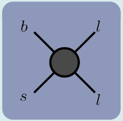
$\mathcal{O}_{7\gamma}$



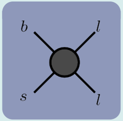
$\mathcal{O}_{8\mathrm{g}}$



$\mathcal{O}_{9\mathrm{V},10\mathrm{A}}$



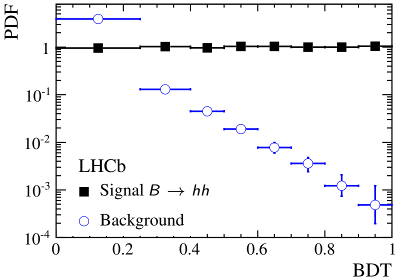
$\mathcal{O}_{\mathrm{S},\mathrm{P}}$



- All C_i calculated at NLO if not NNLO in SM
- We need to measure all coefficients
- Any discrepancy is a sign of New Physics

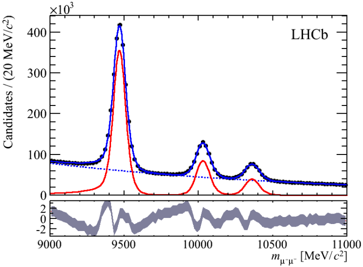
$B_s^0 \to \mu^+\mu^-$ Strategy

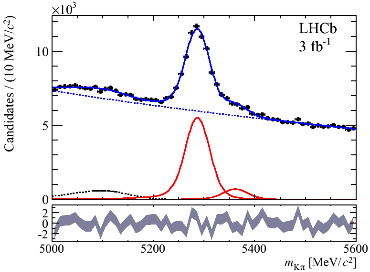
1. Select $B \to \mu^+\mu^-$ using a boosted decision tree (BDT) tuned on MC but calibrated on real data $B \to hh$ signal and background from mass sidebands



$B_s^0 \to \mu^+\mu^-$ Strategy

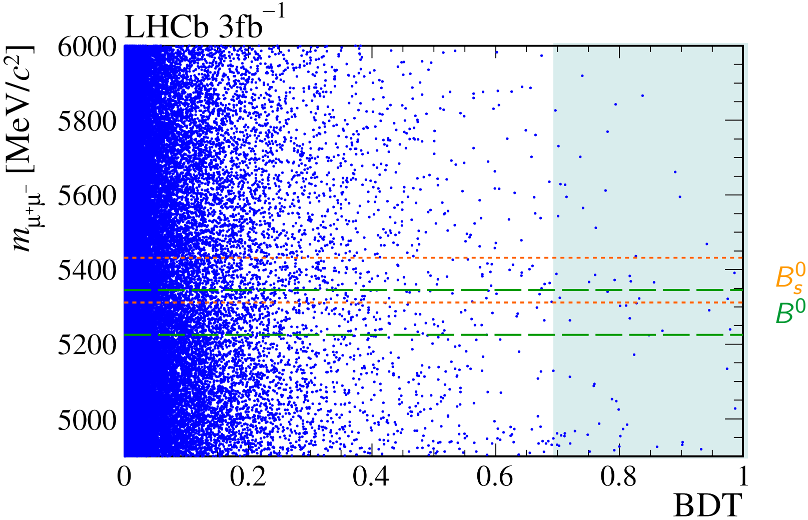
1. Select $B \to \mu^+\mu^-$ using a boosted decision tree (BDT) tuned on MC but calibrated on real data $B \to hh$ signal and background from mass sidebands
2. Mass resolution calibrated on $B \to hh$ and dimuon resonances: $(23.2 \pm 0.4)\ \mathrm{MeV}/c^2$





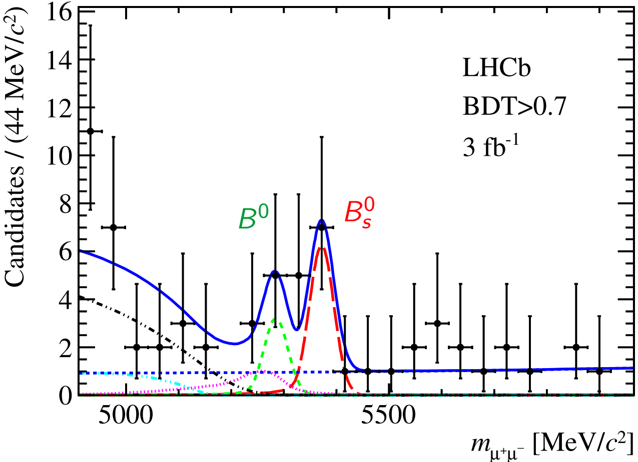
[Phys. Rev. Lett. 111 (2013) 101805, arXiv:1307.5024]

$B_s^0 \to \mu^+\mu^-$ Signal window



All points in mass window are used in result, but only BDT > 0.7 shown in next slide

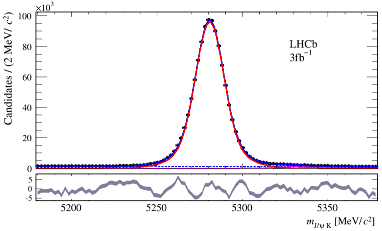
B^0 and $B_s^0 \to \mu^+\mu^-$ Signal peaks

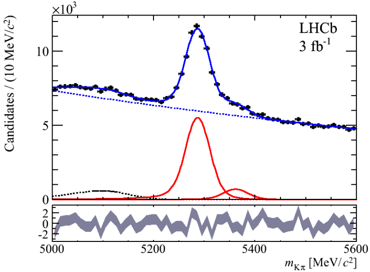


- Data points. Background components: $B \to hh$, $B \to \pi\mu^+\mu^-$, Combinatorial, $B \to h\mu\nu$

$B_s^0 \to \mu^+\mu^-$ Strategy

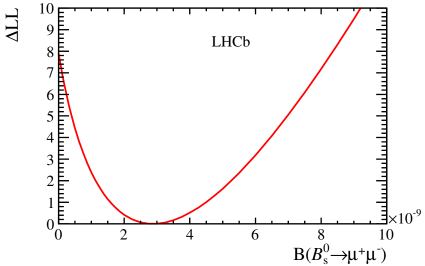
1. Select $B \to \mu^+\mu^-$ using a boosted decision tree (BDT) tuned on MC but calibrated on real data $B \to hh$ signal and background from mass sidebands
2. Mass resolution calibrated on $B \to hh$ and dimuon resonances: $(23.2 \pm 0.4)\ \mathrm{MeV}/c^2$
3. Normalise to $B_s^0 \to J/\psi\,\phi$, $B^+ \to J/\psi\,K$, $B^0 \to K\pi$

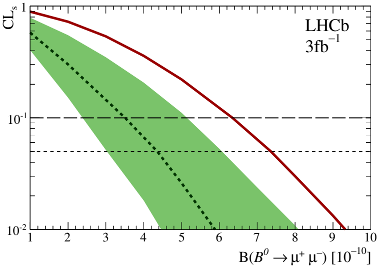




[Phys. Rev. Lett. 111 (2013) 101805, arXiv:1307.5024]

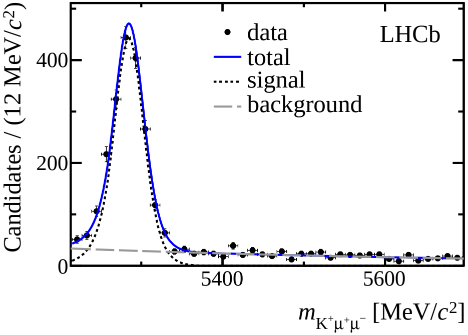
$B \to \mu^+\mu^-$ at LHCb BFs and limits





	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$
Expected Significance (SM)		**5.0σ**
Observed Significance	**2.0σ**	**4.0σ**
Branching fraction	$3.7\,^{+2.4}_{-2.1}\,^{+0.6}_{-0.4} \times 10^{-10}$	$\mathbf{2.9\,^{+1.1}_{-1.0}\,^{+0.3}_{-0.1} \times 10^{-9}}$
Expected limit assuming bkg only (95%)	4.4×10^{-10}	
Expected limit assuming bkg+SM (95%)	5.4×10^{-10}	
Observed limit (95%)	$\mathbf{7.4 \times 10^{-10}}$	

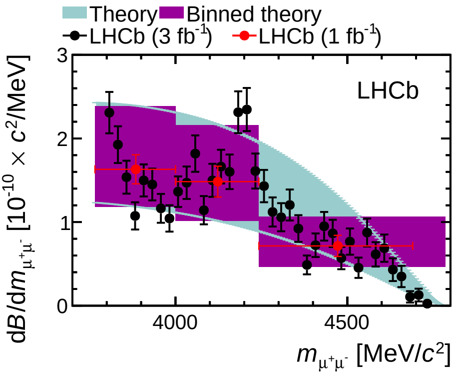
Resonance in $B^+ \to K^+\mu^+\mu^-$ at low recoil



$m_{\mu\mu K}$ with $m_{\mu\mu} > m_{\psi(2S)}$:
1830 candidates with 3 fb^{-1}

- We look at $B^+ \to \mu\mu K$ for $m_{\mu\mu} > m_{\psi(2S)}$

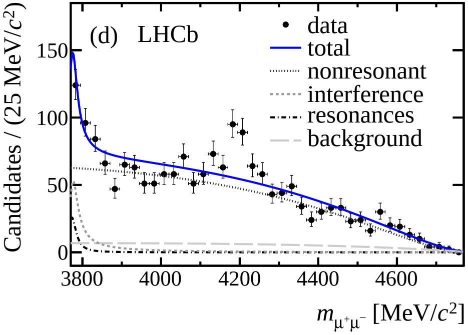
Resonance in $B^+ \to K^+\mu^+\mu^-$ at low recoil



Differential BF

- We look at $B^+ \to \mu\mu K$ for $m_{\mu\mu} > m_{\psi(2S)}$
- ✗ Something odd at 4.2 GeV/c^2

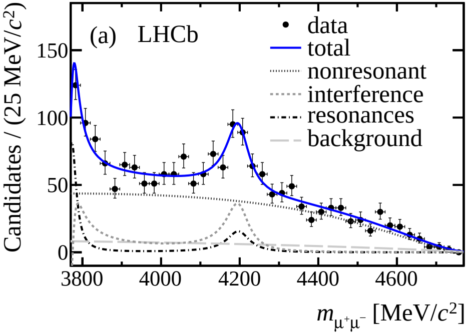
Resonance in $B^+ \to K^+\mu^+\mu^-$ at low recoil



Fit with $\psi(2S)$ included

- We look at $B^+ \to \mu\mu K$ for $m_{\mu\mu} > m_{\psi(2S)}$
- ✗ Something odd at 4.2 GeV/c^2

Resonance in $B^+ \to K^+\mu^+\mu^-$ at low recoil

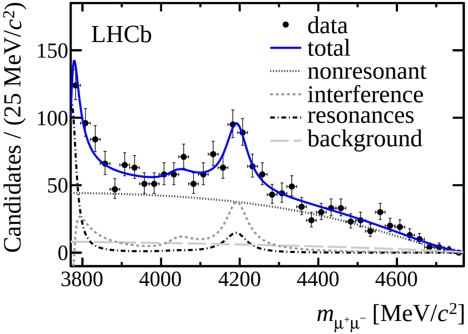


Fit with $\psi(2S)$ and free single extra resonance

- We look at $B^+ \to \mu\mu K$ for $m_{\mu\mu} > m_{\psi(2S)}$
- ✗ Something odd at 4.2 GeV/c^2
- A free fit gives $m = 4191\,^{+9}_{-8}$ and $\Gamma = 65\,^{+22}_{-16}$.

[Phys. Rev. Lett. 111, 112003 (2013), arXiv:1307.7595]

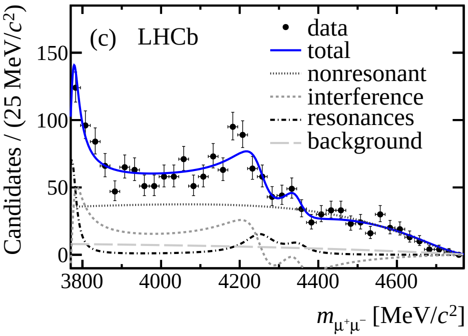
Resonance in $B^+ \to K^+\mu^+\mu^-$ at low recoil



Fit with $\psi(2S)$, $\psi(4040)$ and $\psi(4160)$

- We look at $B^+ \to \mu\mu K$ for $m_{\mu\mu} > m_{\psi(2S)}$
- ✗ Something odd at 4.2 GeV/c^2
- A free fit gives $m = 4191\,^{+\,9}_{-\,8}$ and $\Gamma = 65\,^{+\,22}_{-\,16}$.
- Could be $\psi(4160)$ (note $m = 4192 \pm 7$ from BES)

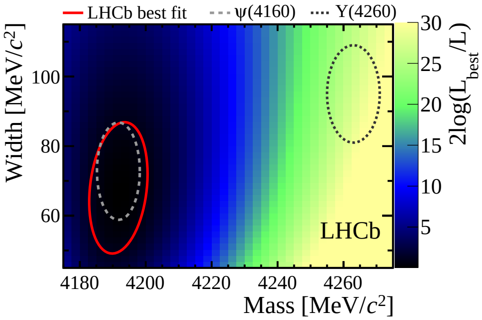
Resonance in $B^+ \to K^+\mu^+\mu^-$ at low recoil



Fit with $\psi(2S)$, $Y(4260)$ and $Y(4350)$

- We look at $B^+ \to \mu\mu K$ for $m_{\mu\mu} > m_{\psi(2S)}$
- ✗ Something odd at 4.2 GeV/c^2
- A free fit gives $m = 4191\,^{+9}_{-8}$ and $\Gamma = 65\,^{+22}_{-16}$.
- Could be $\psi(4160)$ (note $m = 4192 \pm 7$ from BES)
- Fit with $Y(4260)$ is not as good

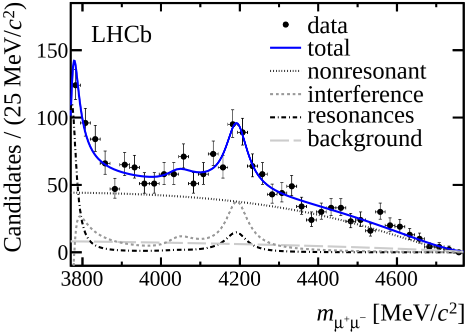
Resonance in $B^+ \to K^+\mu^+\mu^-$ at low recoil



Profile likelihood for mass and width of a single resonance.

- We look at $B^+ \to \mu\mu K$ for $m_{\mu\mu} > m_{\psi(2S)}$
- ✗ Something odd at 4.2 GeV/c^2
- A free fit gives $m = 4191\,^{+9}_{-8}$ and $\Gamma = 65\,^{+22}_{-16}$.
- Could be $\psi(4160)$ (note $m = 4192 \pm 7$ from BES)
- Fit with $Y(4260)$ is not as good
- Good agreement of $\psi(4160)$ hypothesis with free fit

Resonance in $B^+ \to K^+\mu^+\mu^-$ at low recoil



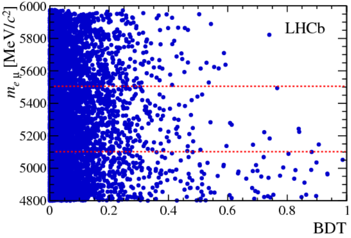
Fit with $\psi(2S)$, $\psi(4040)$ and $\psi(4160)$

This is the first observation of $B^+ \to \psi(4160)K$ and of $\psi(4160) \to \mu\mu$.

20% of the $m_{\mu\mu} > m_{\psi(2S)}$ yield comes from resonant and interference terms
This is much larger than theoretical models.

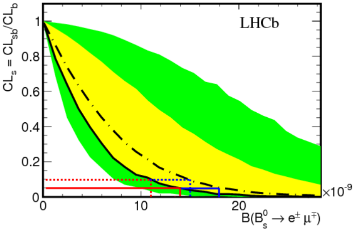
Theorists take $c\bar{c}$ contributions into account, but not their resonant structure

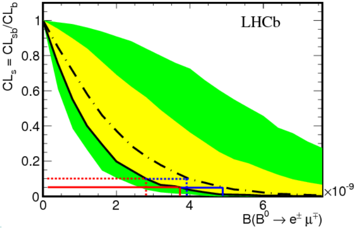
By-product: $B_s^0 \to e\mu$



- Repeat the same analysis with $e\mu$ final states
  - A bit more tricky to get the mass resolution right due to Bremsstrahlung
- "Forbidden" in the SM

By-product: $B_s^0 \to e\mu$





- Repeat the same analysis with $e\mu$ final states
- "Forbidden" in the SM
- Indeed we see nothing and set limits (90%)

$$\mathrm{BR}(B_s^0 \to e^\pm \mu^\mp) < 1.1 \times 10^{-8}$$
$$\mathrm{BR}(B^0 \to e^\pm \mu^\mp) < 2.8 \times 10^{-9}$$

[Phys. Rev. Lett. 111, 141801 (2013), arXiv:1307.4889]

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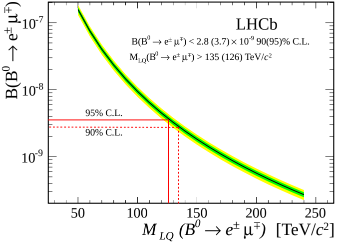

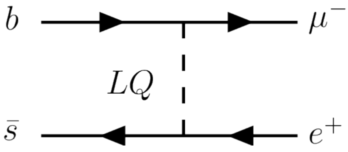

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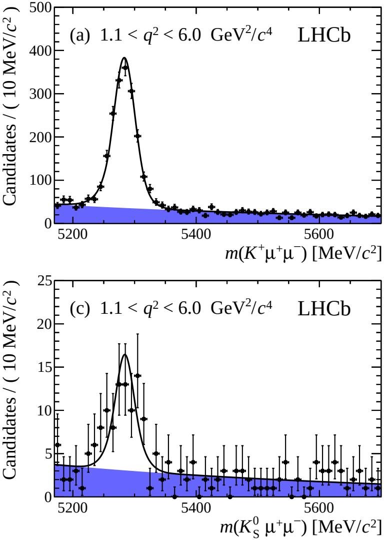
- In the context of the Pati-Salam leptoquark model, this can be converted to a limit on leptoquark masses [Phys.Rev. D10 (1974) 275-289]
  - ➜ Limits of 101 an 135 TeV for LQ coupling to $(bse\mu)$ and $(bde\mu)$, respectively.

ANGULAR ANALYSIS OF $B \to K\mu^+\mu^-$

- Select $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0_S\mu^+\mu^-$ decays with $K^0_S \to \pi^+\pi^-$



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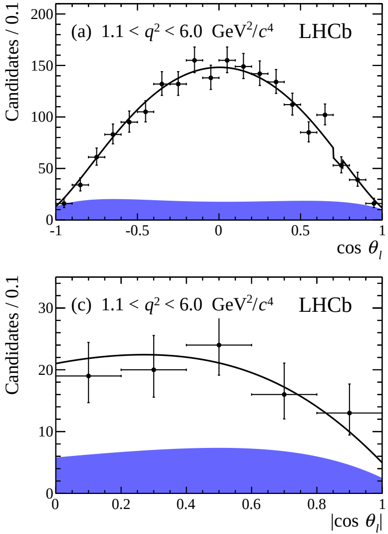
- Select $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0_S\mu^+\mu^-$ decays with $K^0_S \to \pi^+\pi^-$
- Look at angular distribution of θ_l
  - ϕ and θ_K are not defined, as there are only 3 particles

➜ No P'_5



[LHCb-PAPER-2014-007, arXiv:1403.8045]

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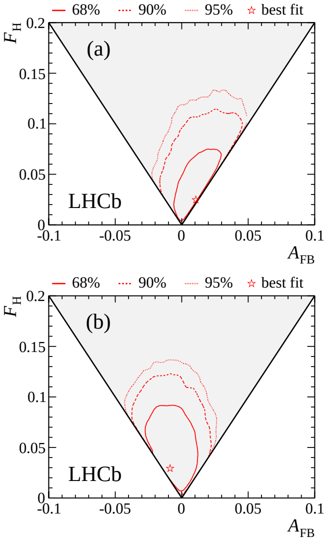
  - ➜ No P'_5
- $B^+ \to K^+\mu^+\mu^-$: fit A_{FB} and F_H (fraction of non-vector amplitudes) in $1.1 < q^2 < 6\ \mathrm{GeV}^2c^{-4}$ (top) and $15 < q^2 < 22\ \mathrm{GeV}^2c^{-4}$ (bottom)



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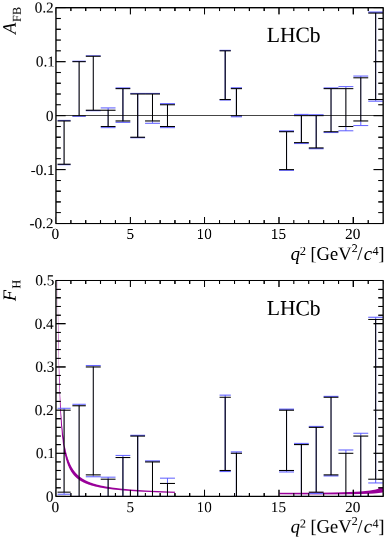
  - ➜ No P'_5
- $B^+ \to K^+\mu^+\mu^-$: fit A_{FB} and F_H
- Get projections versus q^2



Angular analysis of $B \to K\mu^+\mu^-$

- Select $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0_S\mu^+\mu^-$ decays with $K^0_S \to \pi^+\pi^-$
- Look at angular distribution of θ_l
  - ϕ and θ_K are not defined, as there are only 3 particles
  - ➜ No P_5'
- $B^+ \to K^+\mu^+\mu^-$: fit A_{FB} and F_H
- Get projections versus q^2
- Same for $B^0 \to K^0_S\mu^+\mu^-$, except only F_H can be determined.
- Everything very SM-like