Rare decays at LHC*b*

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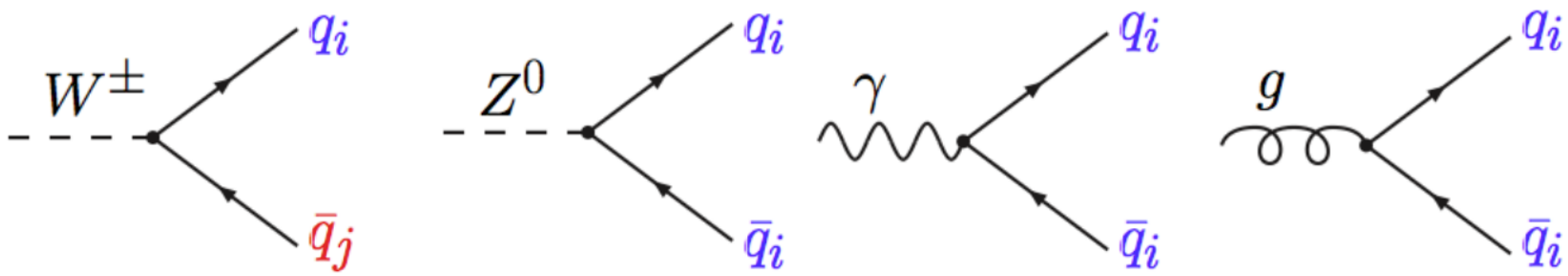
On behalf of the LHC*b* collaboration.

August 28, 2014

Rare decays

- Will talk about decays involving $b \to s$ quark transitions (also $c \to u$)
- Within the Standard Model (SM) only the *charged current* mediates flavour changing transitions at tree level



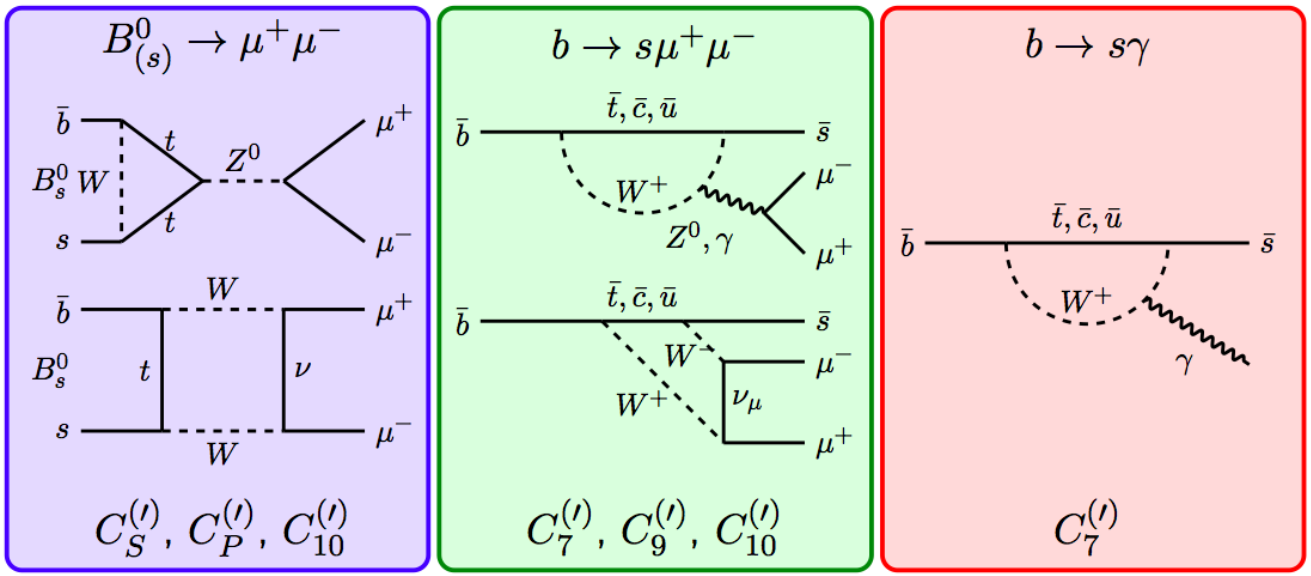
- Flavour changing neutral currents (FCNC) are **only** allowed via loop diagrams
  ⇒ Contribution in SM suppressed
  ⇒ Sensitive to NP particles contributing to the loop

Observables in $b \to s$ loop decays

Rare decays are parametrized in terms of operators and *Wilson coefficients*

$$\mathrm{H_{eff}} = -\frac{4\mathrm{G_F}}{\sqrt{2}}\mathrm{V_{tb}V_{ts}^*}\sum_i \Big[\underbrace{\mathrm{C_i(\mu)O_i(\mu)}}_{\text{left-handed part}} + \underbrace{\mathrm{C_i'(\mu)O_i'(\mu)}}_{\substack{\text{right-handed part}\\ \text{suppressed in SM}}}\Big]$$

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin



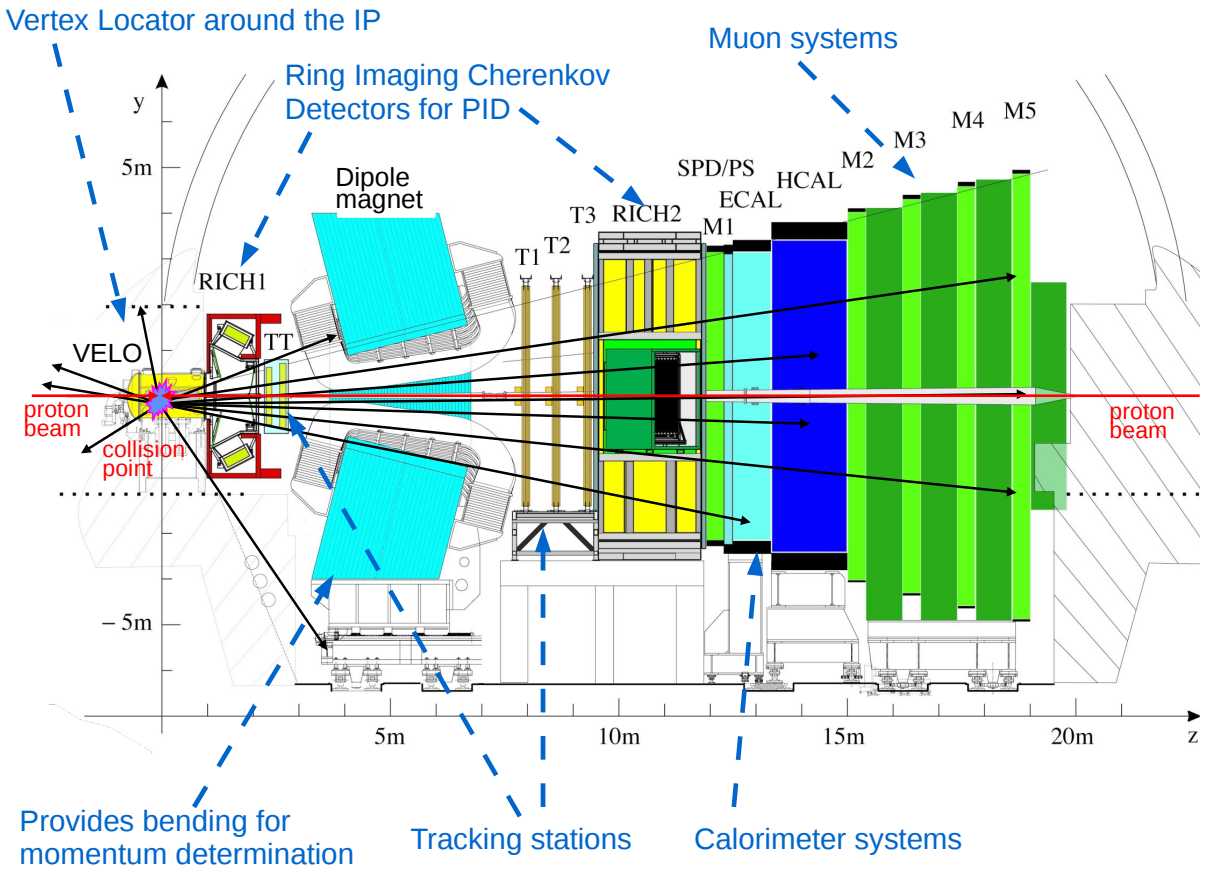
Measure

- Decay rates e.g. in $B^0_{(s)} \to \mu^+\mu^-$, $D^0 \to \mu^+\mu^-$ etc
- Lorentz structure via angular distributions in $B \to \ell^+\ell^- K^{(*)}$ and photon polarization in $B \to X_s\gamma$ decays

The LHC*b* detector

A dedicated flavour physics experiment at the LHC.

Has recorded $3\,\text{fb}^{-1}$ of luminosity from pp collisions at 7 and 8 TeV



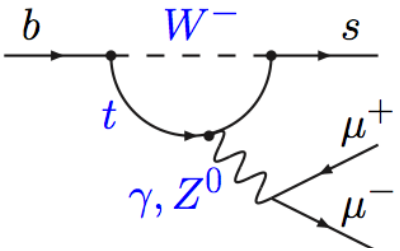
- Precise **vertex reconstruction:** a dedicated silicon detector (VELO) around the pp interaction point
- Excellent **particle identification:** Few % $\pi \to K$ rate for $> 90\%$ K identification efficiency
- Clean **muon identification:** $\pi \to K$ rate of 1% for 98% μ identification efficiency
- Excellent **mass resolution:** typically 7-20 MeV

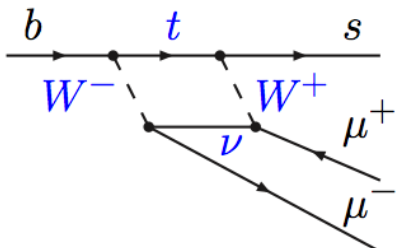
1. FCNC decay searches
2. $B \to \ell^+ \ell^- K^{(*)}$ decays
3. Photon polarization in $b \to s\gamma$ transition

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

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

CKM and helicity suppressed in the SM, theory prediction:



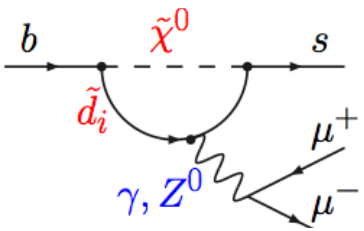


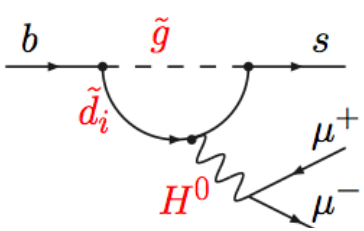
$$BR(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$BR(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

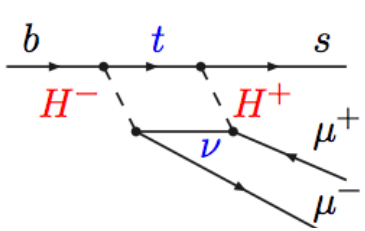
Bobeth et al. PRL 112 101801 (2014)

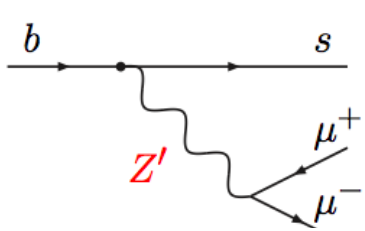
NP: (pseudo) scalars in models with extended Higgs sector: MSSM, 2HDM etc.

$\Rightarrow$ enhancement in branching fraction possible $\left(C_{S,P}^{MSSM}\right)^2 \propto \left(\frac{m_b m_\mu tan^6\beta}{M_A^2}\right)^2$



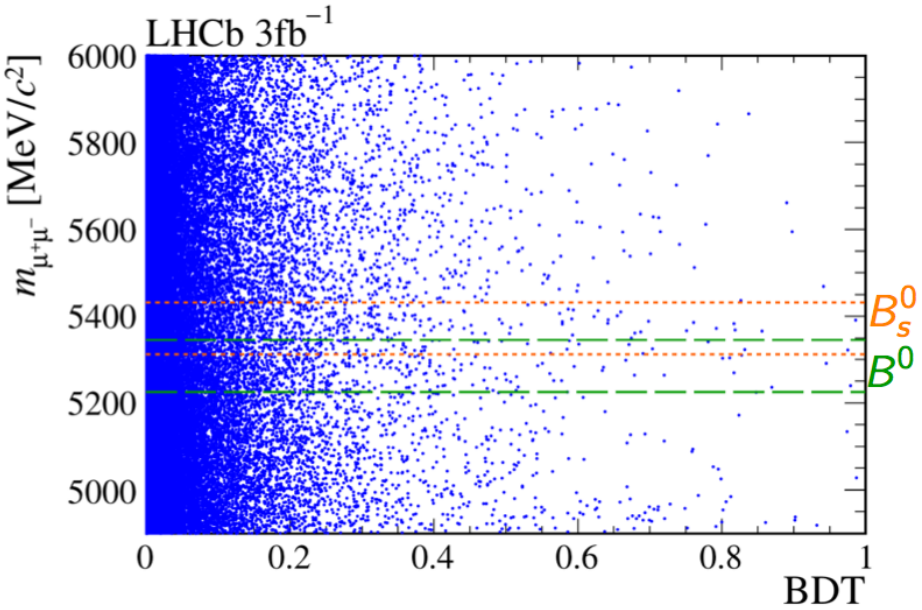






$B^0_{(s)} \to \mu^+\mu^-$ analysis strategy

Phys. Rev. Lett. 111 (2013) 101805



Analysis strategy shared by rare decay searches at LHC*b*

- Perform analysis in bins of dimuon invarian mass and a multivariate classifier (BDT) which rejects combinatorial background
  ⇒ BDT is calibrated on data
- Particle identification cuts to reject specific B (or D) decays
- BR normalized to a well known channel

For $B^0_{(s)} \to \mu^+\mu^-$ decays, the BDT is calibrated on a $B^0_{(s)} \to h^+h'^-$ data sample and the BR is normalized to $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$

Combined LHC*b* and CMS result

LHCb-CONF-2013-012, CMS-PAS-BPH-13-007

Naive combination of LHC*b* and CMS results v/s theory prediction (Likelihood combination in preparation)

$BR(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

$BR(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$

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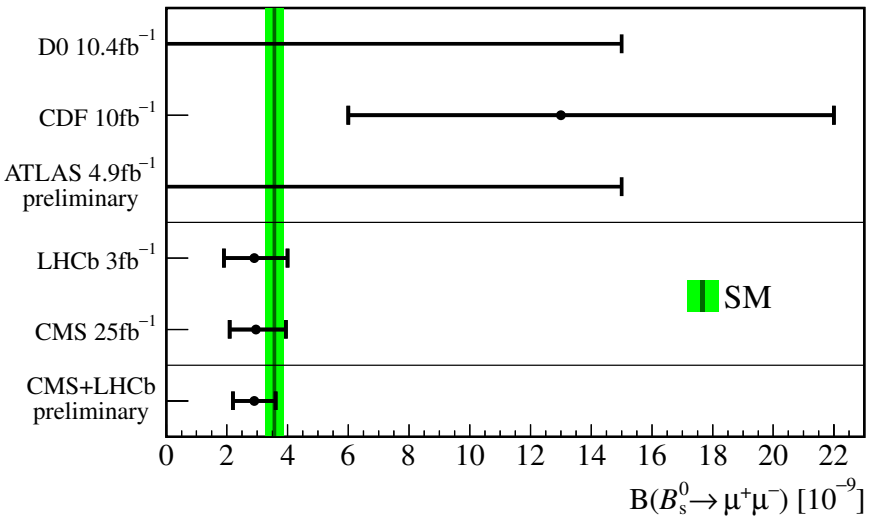
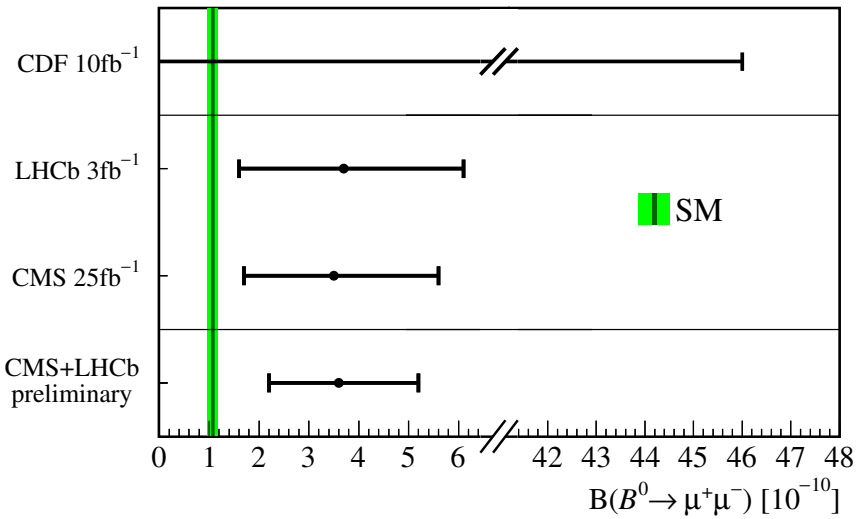




The result rules out significant SUSY phase space and places constraints on *any* new (pseudo)scalar particles [e.g. arXiv:1310.2556]

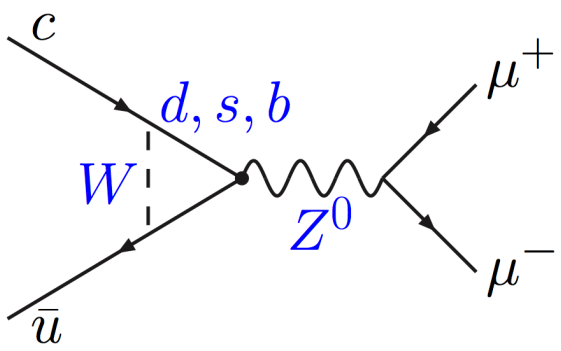
Rare decays of charm mesons

$D^0 \to \mu^+\mu^-$ decay - I

PLB 725(2013) 15-24

D mesons provide a unique window into up type FCNCs

- ✓ Effective GIM cancellation. SM BR $\sim 10^{-18}$!!
- ✗ SM dominated by long distance contribution
- $10^{-13} < BR(D^0 \to \mu^+\mu^-) < 6 \times 10^{-11}$
  G. Burdman et al. PRD 66 (2002)
- Could be upto 10^{-9} in some NP models



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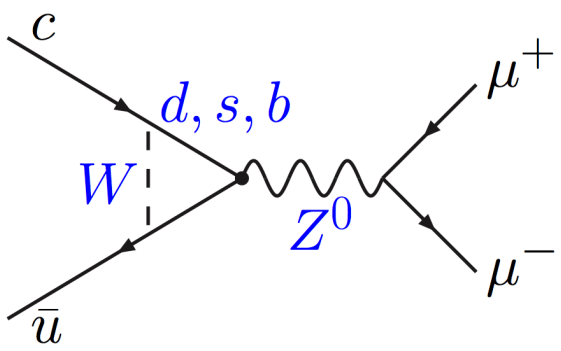
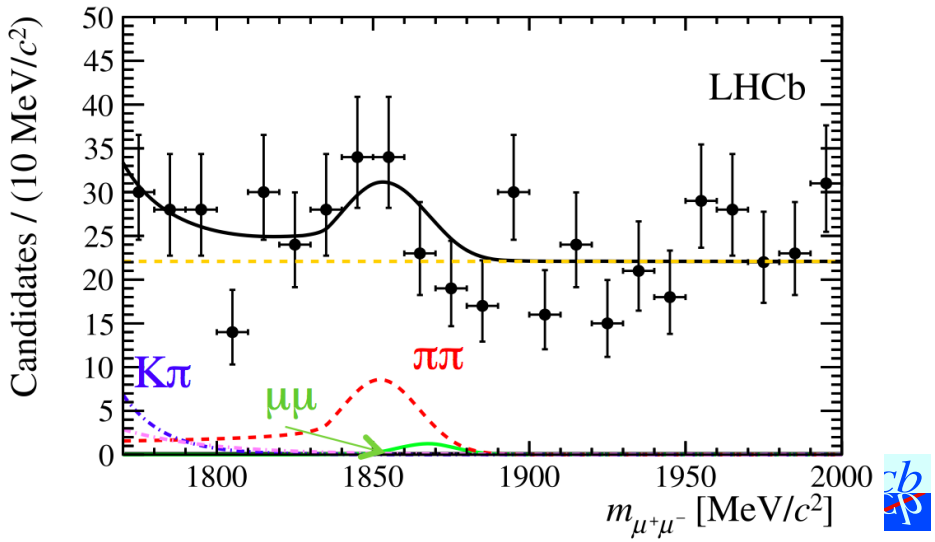


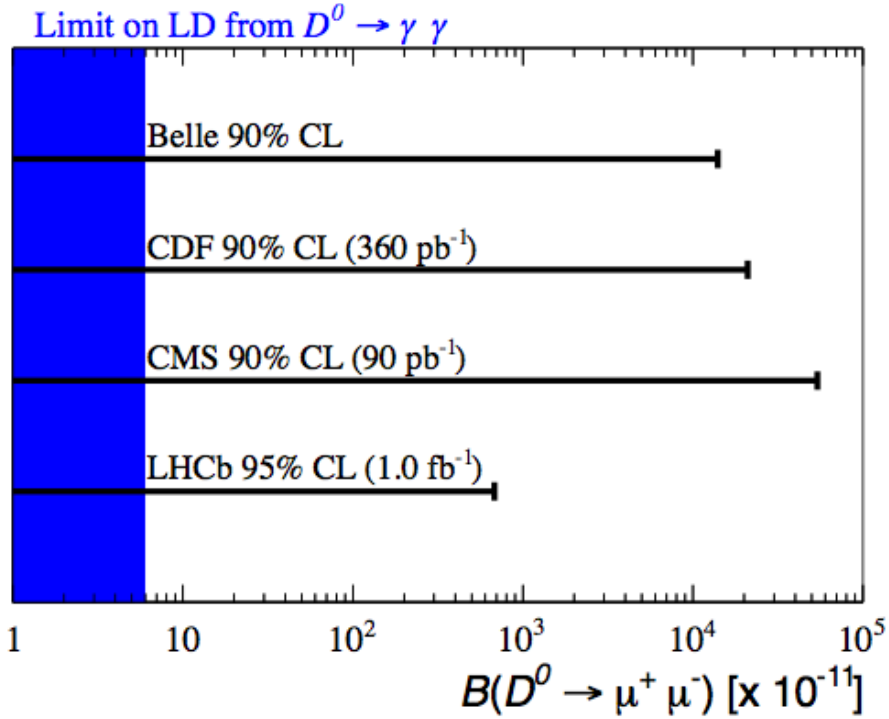
LHC*b* analysis

- D^{*+} tagged sample of $D^{*+} \to D^0(\mu^+\mu^-)\pi^+$
- Use BDT to reject combinatorial background
- Yield extracted from 2D fit to m(D^0) and $\Delta m(D^{*+} - D^0)$
- Normalize to $D^0 \to \pi^+\pi^-$



$D^0 \to \mu^+\mu^-$ decay - II

PLB 725(2013) 15-24



Belle
[PRD 81 (2010) 091102]
CDF
[PRD 82 (2010) 091105]
CMS
[CMS-PAS-BPH-11-017]
LHCb
[PLB 725 (2013) 15-24]

LHC*b* limit with $1\,\text{fb}^{-1}$:

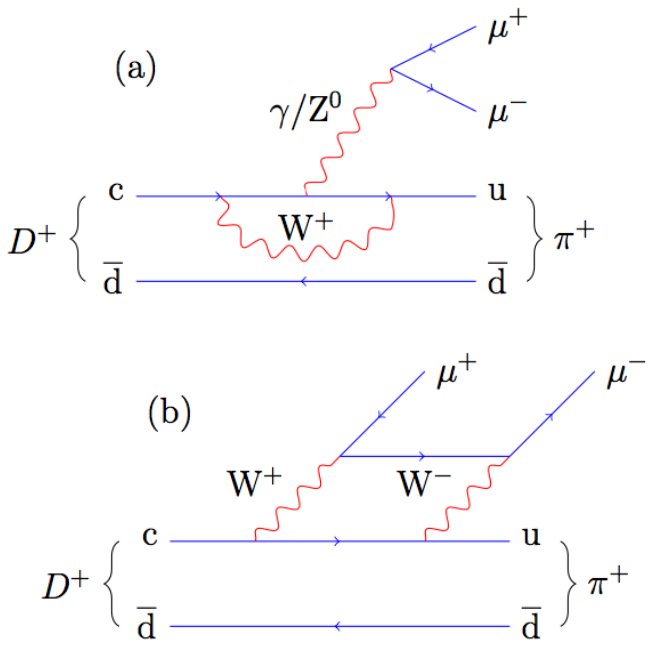
$$BR(D^0 \to \mu^+\mu^-) < 6.2(7.6) \times 10^{-9} \text{ at } 90(95)\% \text{ CL}$$

$D^+ \to \pi^+\mu^+\mu^-$ decay - I

PLB 724(2013) 203-212

Another $c \to u$ transition

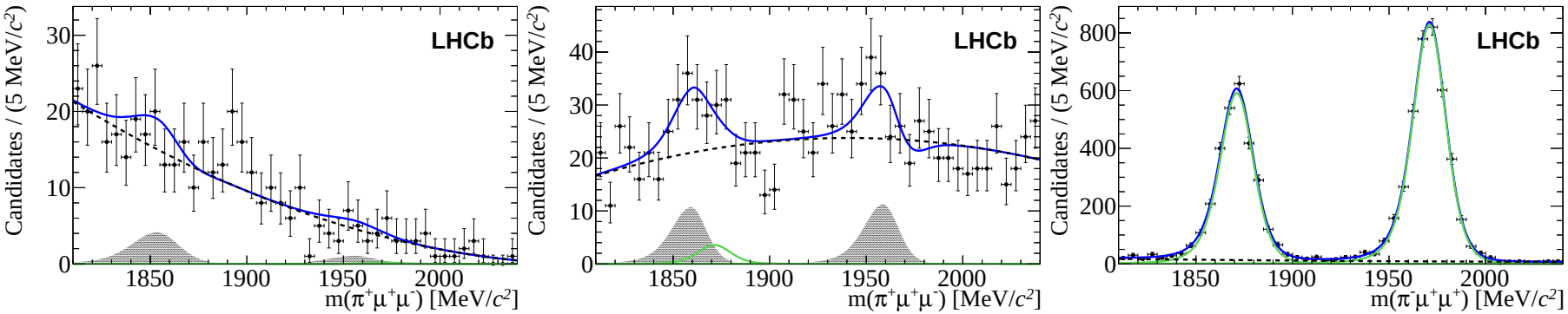
- Background from $D^+_{(s)} \to \pi^+\pi^-\pi^+$ decays
- Also from ρ, ω and ϕ resonances in the μ^+ μ^- system
- Search for signal performed in $250 < m_{\mu^+\mu^-} < 252$ and $1250 < m_{\mu^+\mu^-} < 2000$ MeV
- Normalize to $D^+ \to \phi(\mu^+\mu^-)\pi^+$



$D^+ \to \pi^+\mu^+\mu^-$ decay - II

PLB 724(2013) 203-212

$250 < m_{\mu^+\mu^-} < 252$ $1250 < m_{\mu^+\mu^-} < 2000$ $\phi \to \mu^+\mu^-$ region



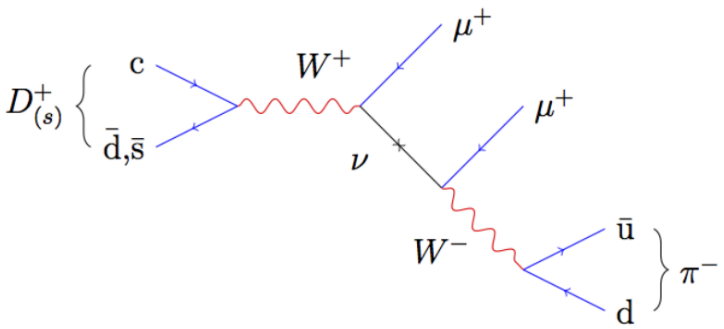
Gray shaded area shows the $D^+_{(s)} \to \pi^+\pi^-\pi^+$ background

Green line shows the best fit to $D^+ \to \pi^+\mu^+\mu^-$

$D^+ \to \pi^- \mu^+ \mu^+$ decay

PLB 724(2013) 203-212

Lepton number violating decay; can be mediated by Majorana neutrinos

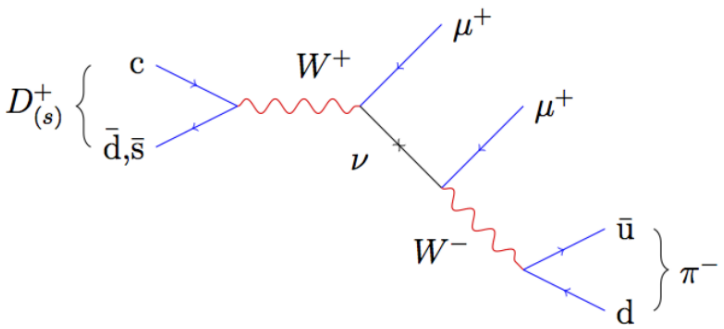


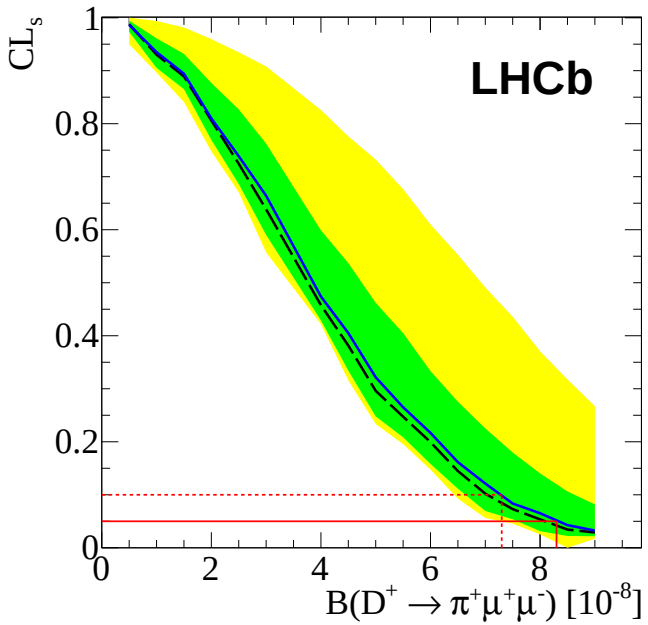
- Strategy and normalization same as $D^+ \to \pi^+ \mu^+ \mu^-$
- Analysis performed in bins of $m_{\pi^+\mu^-}$

$D^+ \to \pi^-\mu^+\mu^+$ decay

PLB 724(2013) 203-212

Lepton number violating decay; can be mediated by Majorana neutrinos





- Strategy and normalization same as $D^+ \to \pi^+\mu^+\mu^-$
- Analysis performed in bins of $m_{\pi^+\mu^-}$

Results at 90 (95) % CL

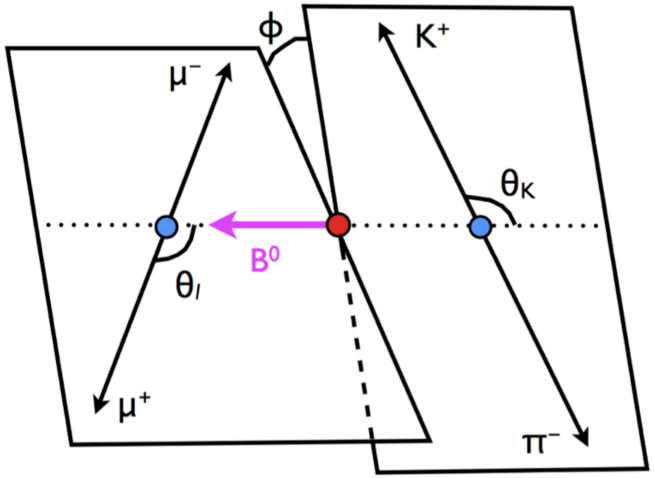
$$BR(D^+ \to \pi^+\mu^+\mu^-) < 7.3(8.3) \times 10^{-8}$$
$$BR(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1(4.8) \times 10^{-7}$$
$$BR(D^+ \to \pi^-\mu^+\mu^+) < 2.2(2.5) \times 10^{-8}$$
$$BR(D_s^+ \to \pi^-\mu^+\mu^+) < 1.2(1.4) \times 10^{-7}$$

A factor of 50 improvement upon previous results

$B \to \ell^+ \ell^- K^{(*)}$decays

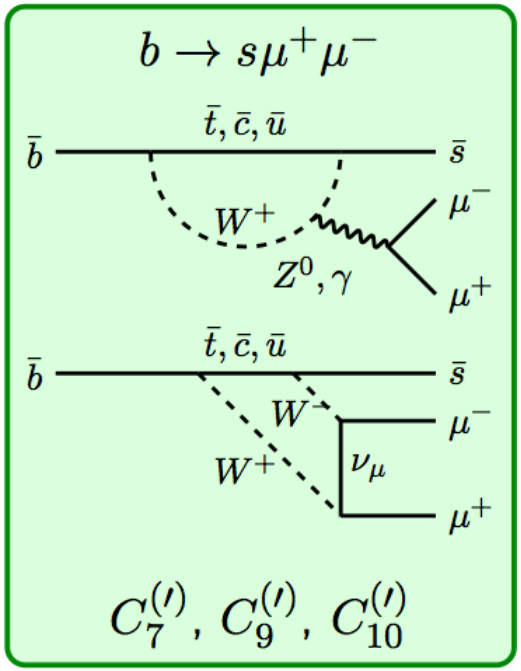
$B_d^0 \to K^{*0}\mu^+\mu^-$

The decay can be described by three angles (θ_l, θ_K, ϕ) and the dimuon invariant mass (q^2)



- ✓ Sensitive to O_7, O_9 and O_{10} and their right handed counter parts
- ✗ Theory uncertainty due to form factors
- ✓ Look at angular observables where some uncertainties cancel at leading order
- ✓ The decay rate an be written as a function of the K^{*0} polarization amplitudes

  ⇒ construct observables to measure the interference between them



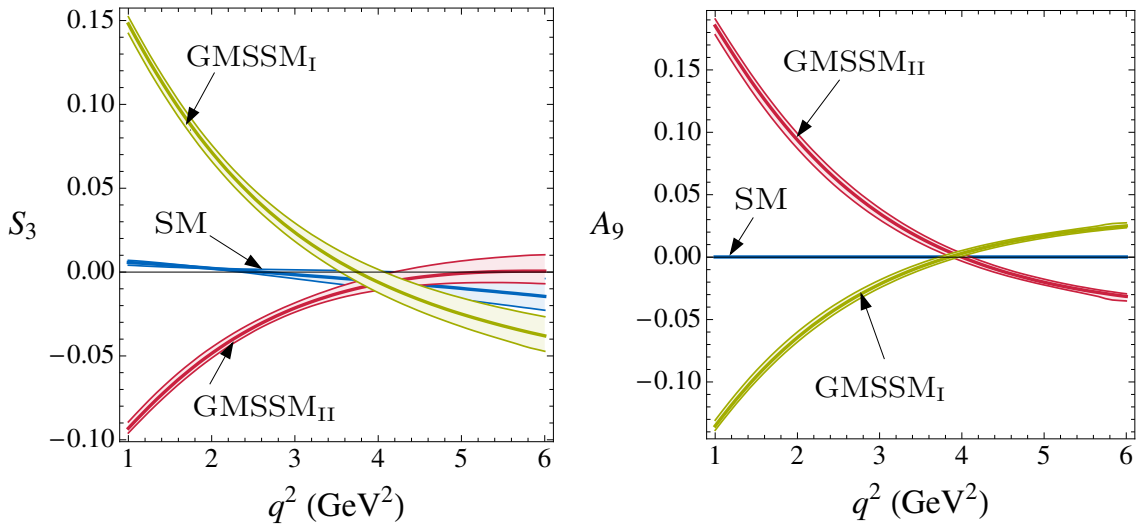
$B_d^0 \to K^{*0}\mu^+\mu^-$ Angular analysis

[JHEP 08 (2013) 131]

Using a folding rechnique over the ϕ angle, the decay rate can be written as a function of only 4 variables (compared to 12)

A_{FB}	The dimuon forward backward asymmetry
F_L	Fraction of longitudinal K^{*0} polarization
A_T^2/S_3	Asymmetry sensitive to the (virtual) photon polarization
A_9	A CP asymmetry

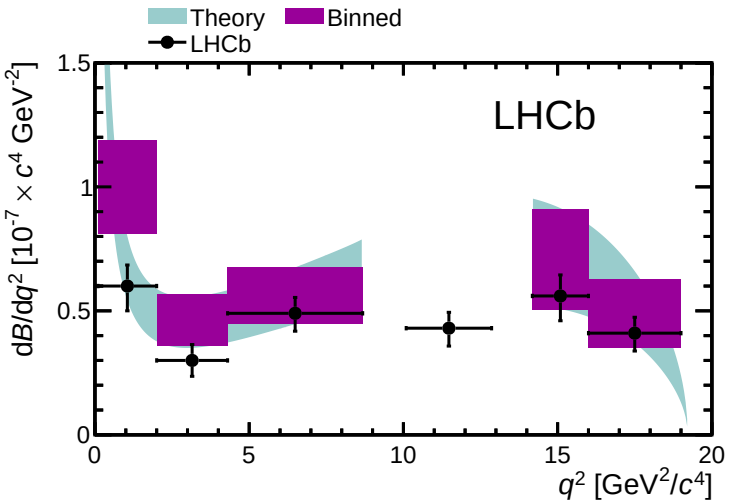
Powerful (and many) probes of NP. Example from Generalized Supersymmetric Model

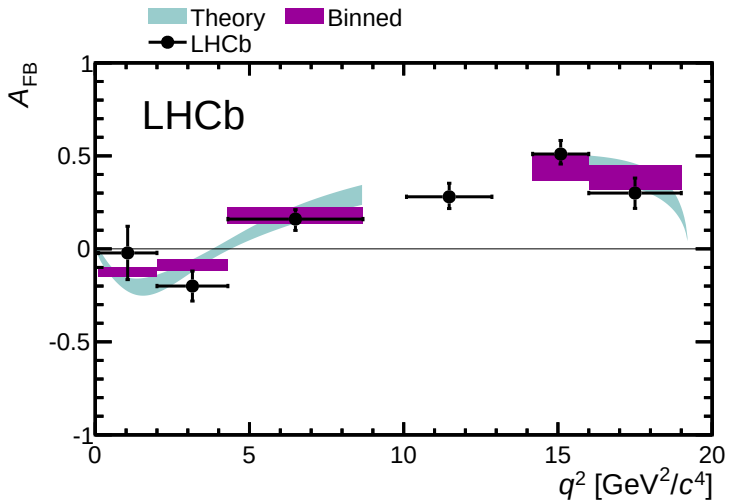


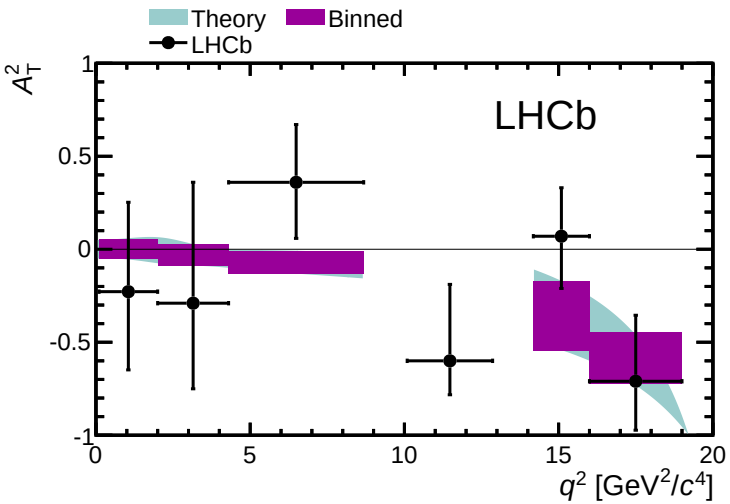
Example of theory predictions (From JHEP 0901:019,2009)

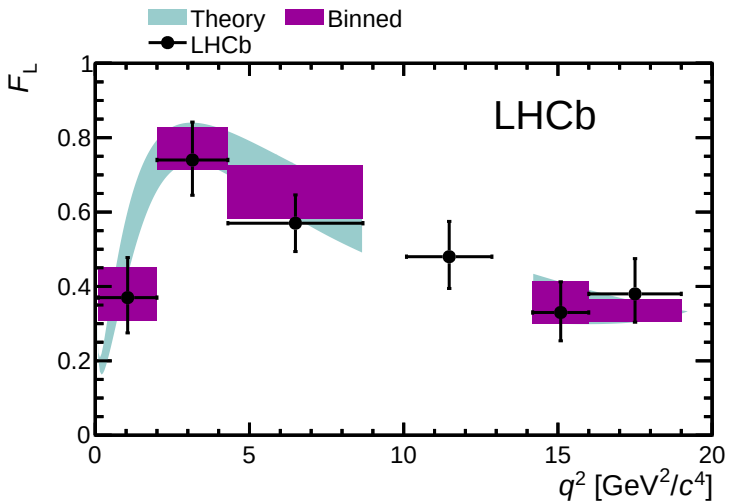
$B_d^0 \to K^{*0}\mu^+\mu^-$ results

[JHEP 08 (2013) 131]









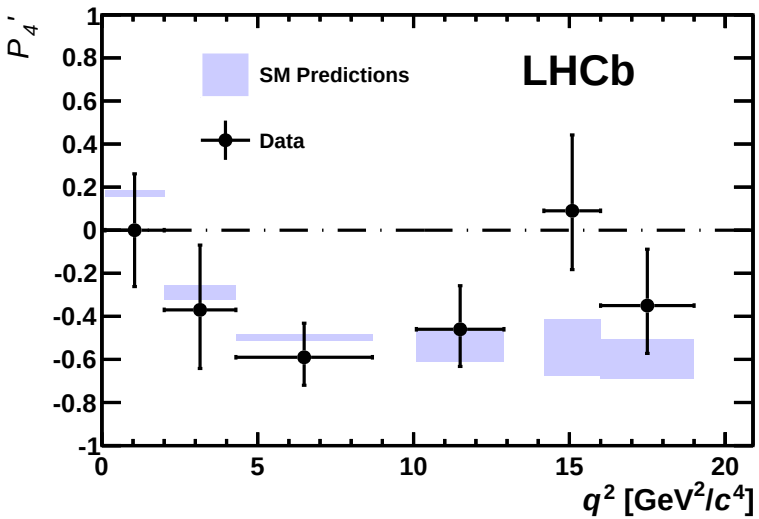
Theory predictions from JHEP 07 (2011) and references therein.

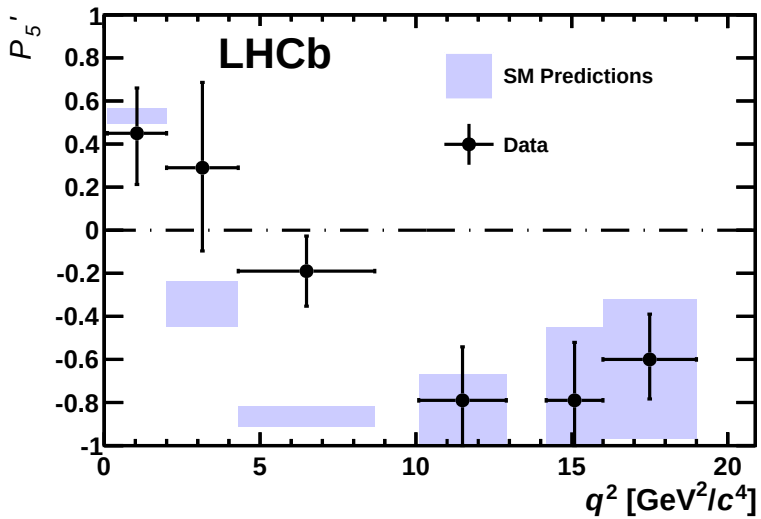
$B_d^0 \to K^{*0}\mu^+\mu^-$ angular analysis - II

PRL 111 191801 (2013)

- Can introduce different angular foldings to access different angular terms
- Observables where form-factor uncertainties cancel at leading order

$$P'_{4,5} = S_{4,5} / \sqrt{F_L(1-F_L)}$$





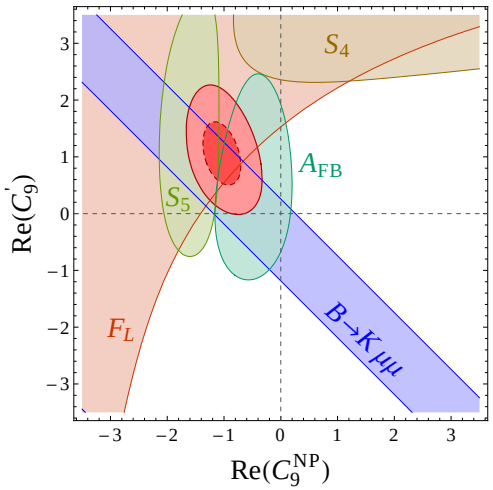
Theory predictions from JHEP, 1305:137, 2013

A local discrepancy of 3.7σ observed in P'_5. Probability to observe at least one bin as discrepant or more is 0.5%

Explaining the P_5' anomaly [in progress]

- **LHC*b* measurement was followed by a lot of theoretical activity**
- Conclusions differ because different inputs have been used in these analyses

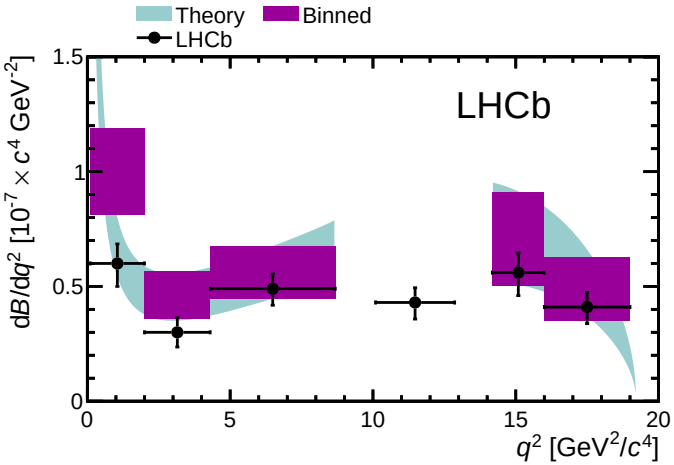
  e.g. using only high q^2 LHC*b* measurements, the discrepancy becomes smaller

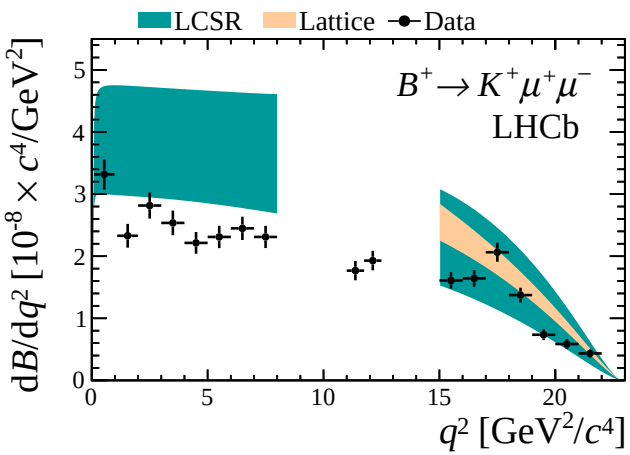


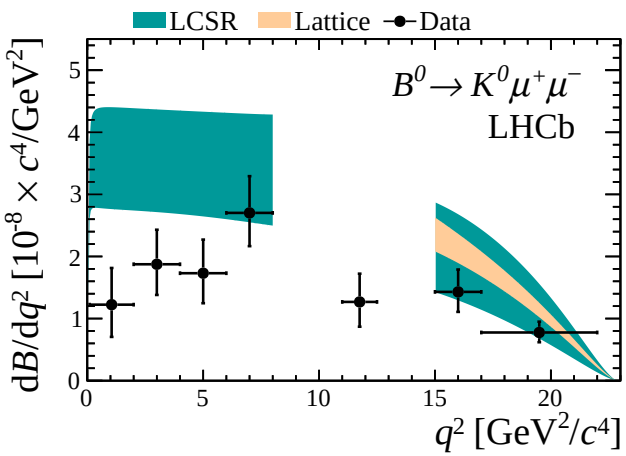
Decotes-Genon, Matias, Virto PRD 88 074002 (2013)	Global fit to $b \to s\gamma$ and $b \to sll$ data Find a 4.5σ discrepancy from SM. Fit favours $C_9^{NP} = -1.5$
Altmannshofer, Straub EPJC 73 2646 (2013)	Global analysis, discrepancy of 3σ, can be described by modified $C_9^{(\prime)}$. Can be explained by a flavour changing Z'
JHEP 01 (2014) 069	Also favour a Z' but at a higher mass
Beaujean, Bobeth, van Dyk Eur. Phys. J. C 74 (2014) 2897	Float form-factor undertainties and use high q^2 bins. The discrepancy becomes 2σ
Jaeger and Camalich JHEP 05 (2013) 043	Also try to address the size of form factor uncertainties in the large recoil (low q^2) region

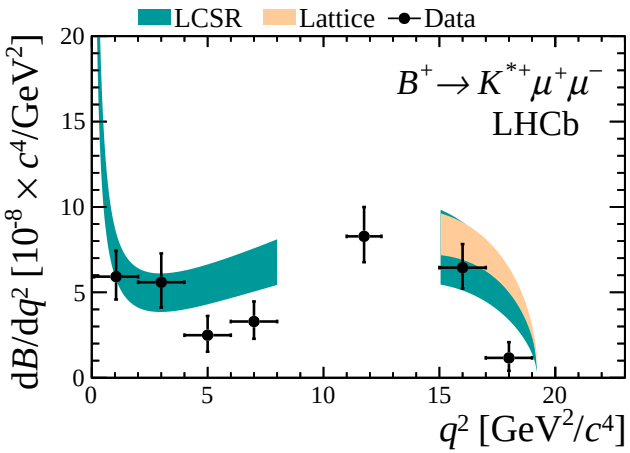
Differential branching fractions of $B \to K^{(*)}\mu^+\mu^-$

- If $C_9^{NP} = -1.5$, we expect to see a suppression of the $B \to K^{(*)}\mu^+\mu^-$ rate





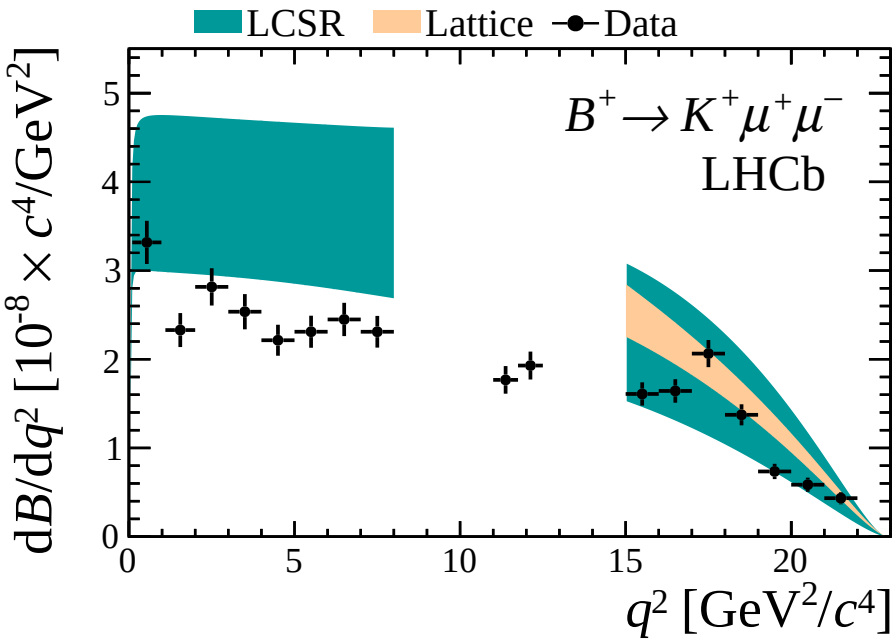




LHCb results from JHEP 08 (2013) 131 and JHEP 06 (2014) 133

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

- The decays rates and P_5' seem to be compatible with a negative C_9^{NP}
- LHC*b* has recently observed $c\bar{c}$ contribution in the high q^2 region ($\sim 18\ MeV^2/c^4$) which has so far not been included in theory predictions
- Correcting the theory prediction for $c\bar{c}$ contribution could explain the P_5' and the low q^2 discrepancy (arXiv:1406.0566)



LHC*b*: JHEP 06 (2014) 133

Lepton universality and Z'

LHCb-PAPER-2014-024

- If the P_5' and the differential decay rates are indeed due to a Z', could proble its couplings to leptons. Lepton universality requires that:

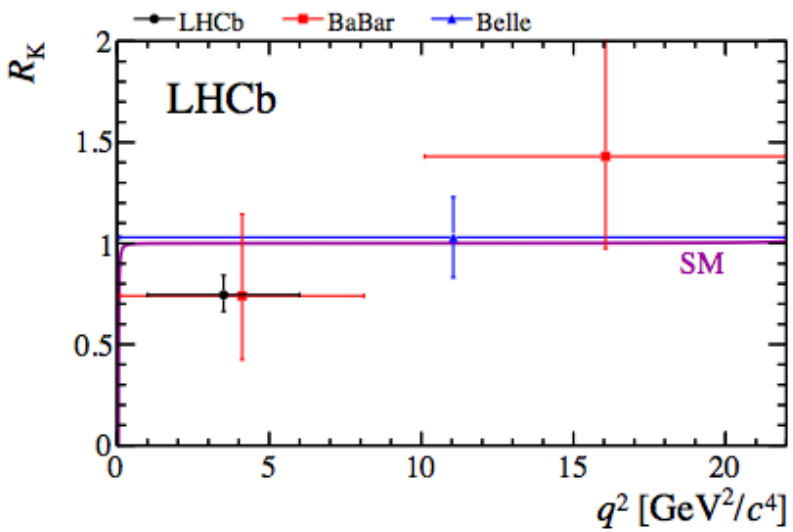
$$R_K = \frac{\int dB(B^+ \to K^+\mu^+\mu^-)/dq^2}{\int dB(B^+ \to K^+e^+e^-)/dq^2} = 1 \pm \mathcal{O}(10^{-3})$$

- For the e^+e^- mode, difficult to determine efficiency due to bremstrahlung. $\Rightarrow$ Take double ratio with respect to the $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$ modes

LHC*b* measurement with $3\,\text{fb}^{-1}$

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

R_K measurement in the K^* mode is ongoing.

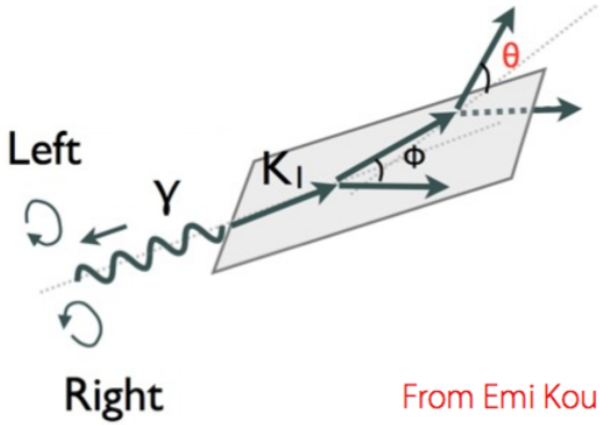


Photon polarization in $b \to s\gamma$ transition

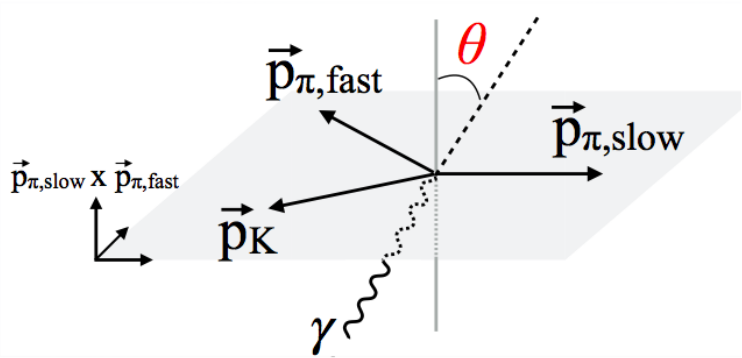
Photon polarization in $B^+ \to K^+\pi^-\pi^+\gamma$

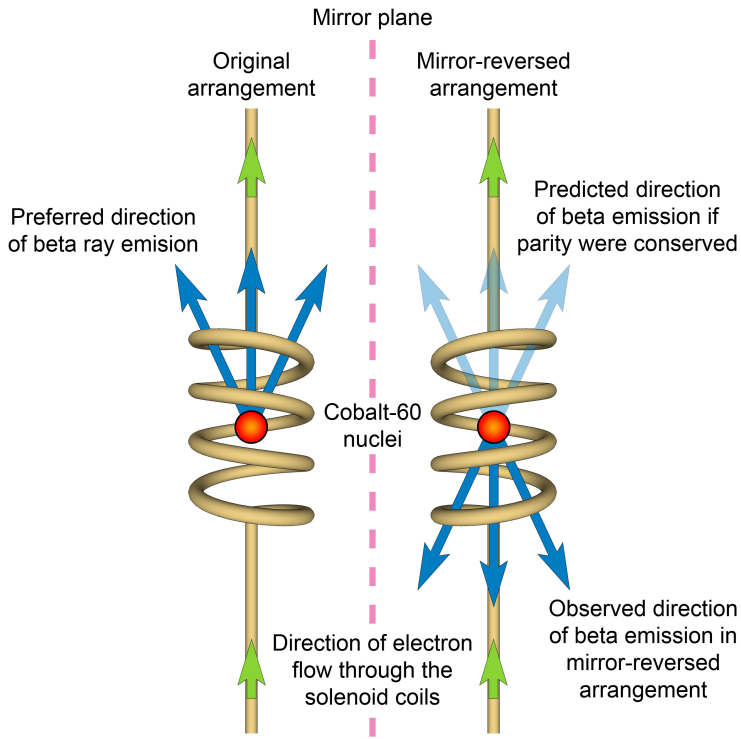
Measure the up-down asymmetry of the photon direction in the frame formed by the two pions

Conceptually similar to the P-parity violation experiment of Wu et. al (1956)



From Emi Kou





LHC*b* analysis of $B^+ \to K^+\pi^-\pi^+\gamma$

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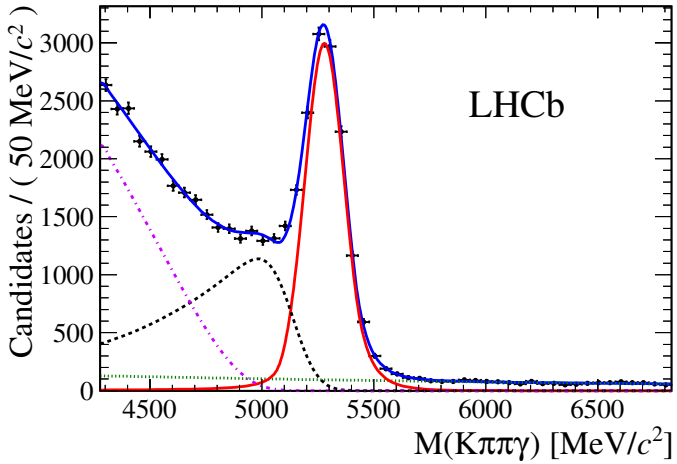

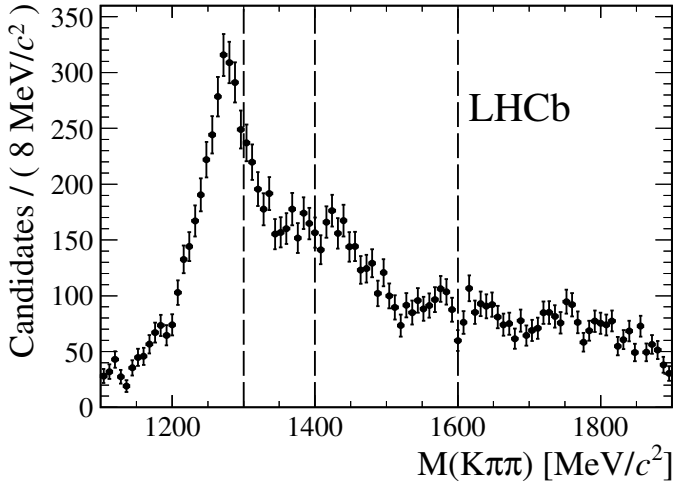

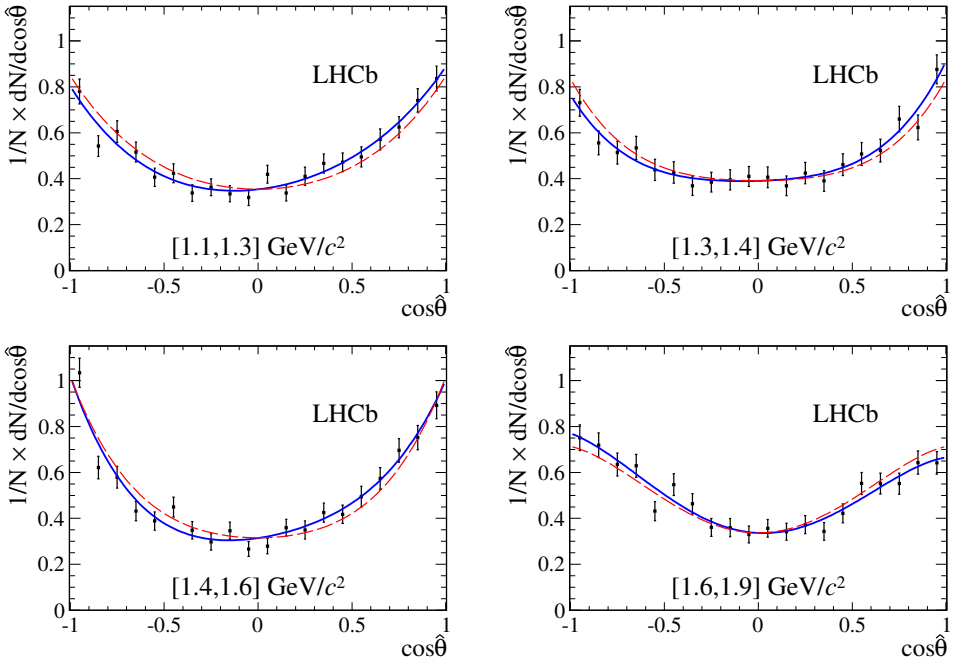

- Observed over 13000 B^+ signal candidates in $3\,\text{fb}^{-1}$
- The analysis is performed in bins of background subtracted $m_{K\pi\pi}$

Results

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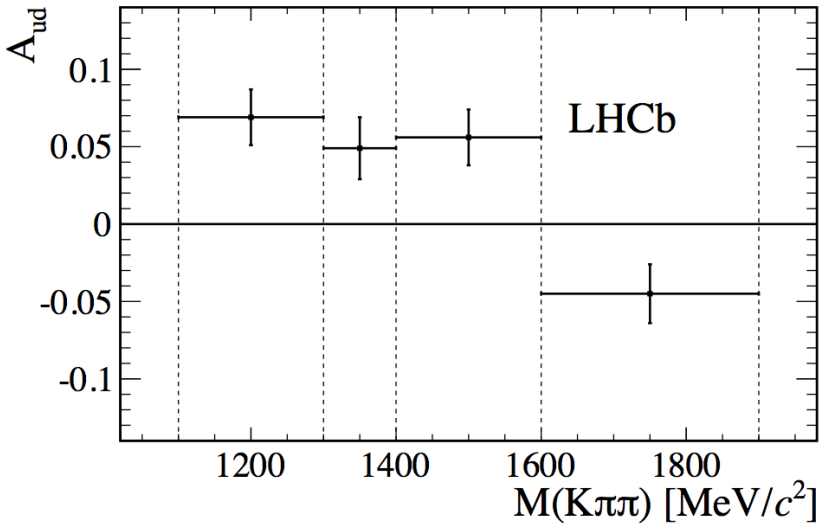
- Combining the absolute A_{ud} in the four bins, the photon polarization is observed to be different from zero at 5.2σ
- Theoretical input required in order to actually measure the value of the polarization and interpret it in terms on NP

First experimental observation of a non-zero photon polarization in $b \to s\gamma$ transition!



Summary

- LHCb is well suited to study rare heavy flavour decays
  ⇒ Large b and c production x-sections, excellent particle identification capability
- Most stringent limits on FCNC decays of up and down type quarks
  ⇒ NP phase space is shrinking rapidly
- $B \to \mu^+ \mu^- K^{(*)}$ decays show interesting anomalies (P_5').
  ⇒ Theoretical interpretation is under way, so is the update of $B_d \to K^{*0} \mu^+ \mu^-$ with full statistics
  ⇒ Measurement of the τ couplings of the Z' and analysis of $B_s \to \phi \mu^+ \mu^-$ can shed more light
- LHCb also produced the first ever observation of a non-zero photon polarization in $b \to s\gamma$ decays
  ⇒ Theory input required to actually *measure the value* of the polarization
- Other rare decay results e.g. lepton flavour violation in B and τ decays
  ⇒ Link to LHCb public results page