25-Jun-2013

Rare decays at LHCb

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on behalf of the LHCb Collaboration

The XXI International Workshop
High Energy Physics and Quantum Field Theory
June 23 – June 30, 2013
Saint Petersburg Area, Russia

Outline

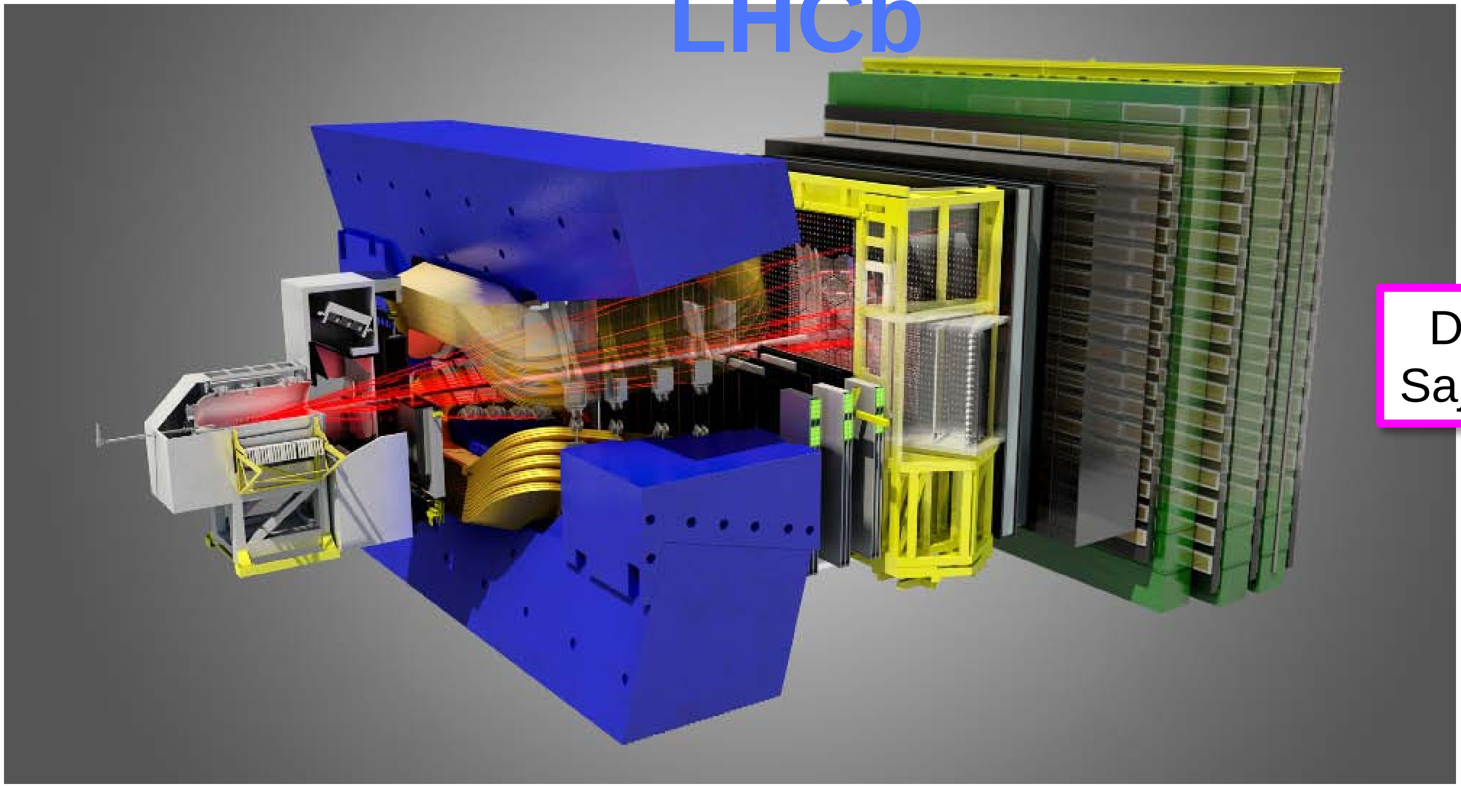
- Motivation
- FCNC in b and c decays
- Rare τ decays

Rare and very rare decays

- Classification
- Global summary plot of BRs/searches, e.g. HFAG arXiv:1207.1158

- *Very* rare → Indrek Sepp, parallel session A, this afternoon
  - Includes first observation of $B_s \rightarrow \mu^+\mu^-$

LHCb



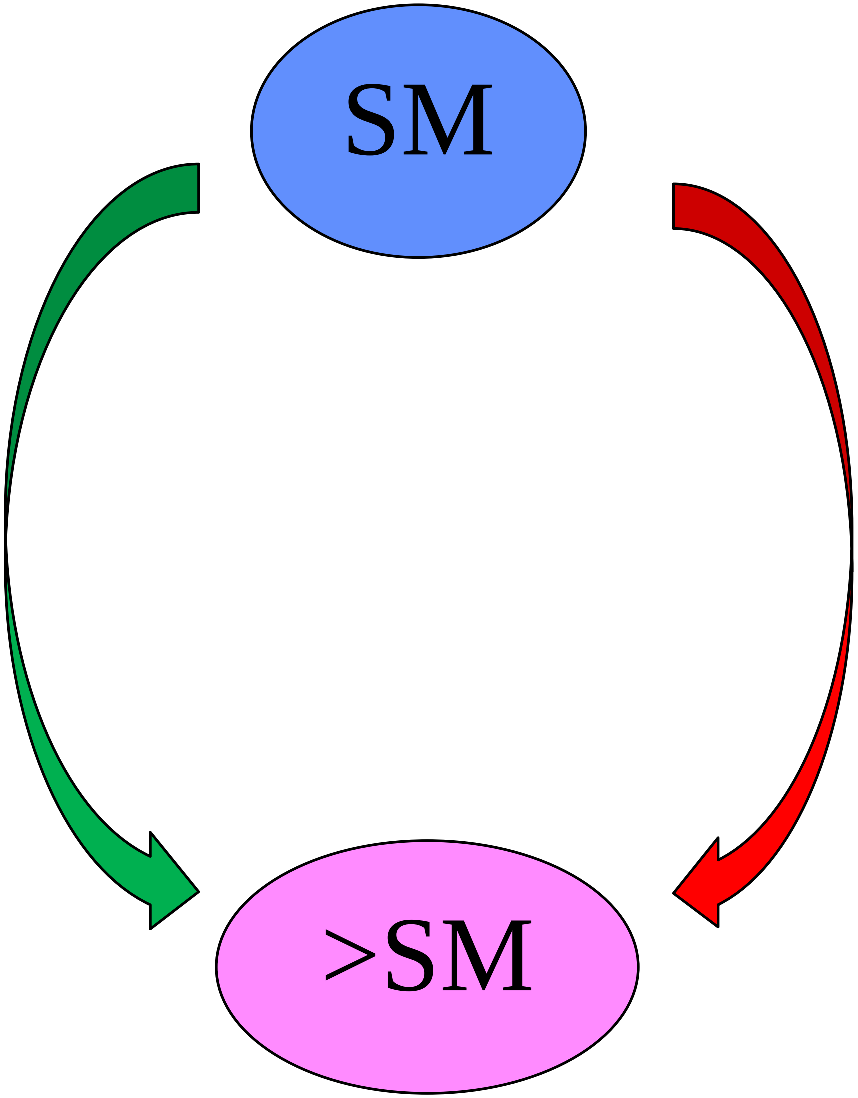
Details in Sajan's talk

- Single-arm spectrometer, fully instrumented in the forward region ($2<\eta<5$)
- Excellent vertex resolution from Si strip detectors around IP (VELO)
- Particle identification from RICH detectors, calorimeter and muon systems
- Primary physics programme is stress testing the Standard Model
  - **Precise measurements**
  - **Indirect searches for physics beyond SM in decays of b, c hadrons and τ decays**
- Rare b decays a very exciting area for LHCb
- $\Delta B=\Delta S=1$ transitions are FCNC processes, highly suppressed in SM

➔ highly sensitive area for new physics to manifest itself (we hope!)

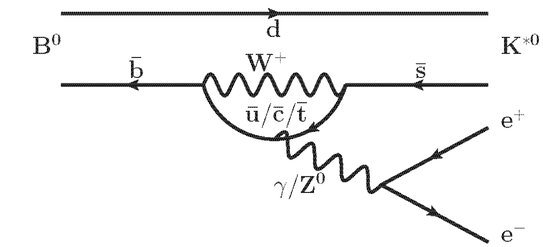
Rare decays

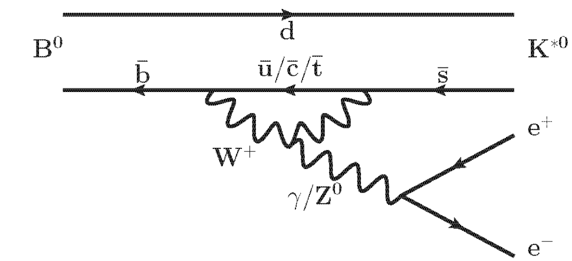
- Using heavy flavour measurements, two routes to finding physics beyond the SM
- CP violation
  - Clearly must exist
- Rare decays
  - FCNC
  - Only via loop, box diagrams as forbidden at tree level
  - Br typically ~10^{-6} or less
- New physics participant may enter in loops as virtual particles
- Indirect probe accesses higher energy scale than direct searches
  - Convenient detection mechanism
  - Not so straightforward to identify the origin - modelling

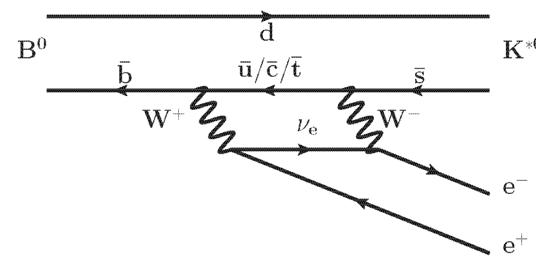


$b \to s\ell^+\ell^-$ processes

- FCNC themselves are highly attractive for experiments
  - Wide variety of angular observables accessible in 4 particle final states
  - Experimental signatures
    - Clean
    - Low backgrounds
- New physics may manifest itself in
  - Rate
  - Angular distributions
  - Asymmetries
- Predictions well-established
  - Varying degrees of theoretical uncertainty
  - Hadronic form factors







Rare decays: recent results

- **All published or submitted** to journal/arxiv (**most recent: 11th June**)
  - Use 1/fb of LHCb data sample (~1/3 of our total from Run I)
- $b \to s\ell^+\ell^-$ $B^0 \to K^* \mu\mu$:"flagship analysis" - use this channel to illustrate angular analysis, amplitudes
  - $B^0 \to K^* \mu\mu$: angular analysis and differential branching fractions
    - arXiv:1304.6325 23 Apr 2013 **First multidimensional angular analysis**
  - $B^0 \to K^* \mu\mu$: CP asymmetry
    - PRL110 (2013) 031801
  - $B_s \to \phi\mu\mu$: Angular analysis and differential branching fraction
    - arXiv:1305.2168 1 May 2013 **First angular analysis**
  - $B^0 \to K^*$ ee: Differential in q^2 branching fraction
    - JHEP 05 (2013) 159 2 May 2013 **First evidence n low q2 region**
  - $\Lambda_b \to \Lambda\mu\mu$: Differential in q^2 branching fraction
    - arXiv:1306.2577 11 Jun 2013 **First at LHC, baryons**
- Search for $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_{(s)} \to \pi^-\mu^+\mu^+$ decays
    - arXiv:1304.6365 25 Apr 2013 **Factor ~50 improvement in limit**
- Searches for LFV and baryon number violation in τ decays
    - arXiv:1304.4518, *to appear in* Phys. Lett. B 724 (2013) xx – 21 May 2013

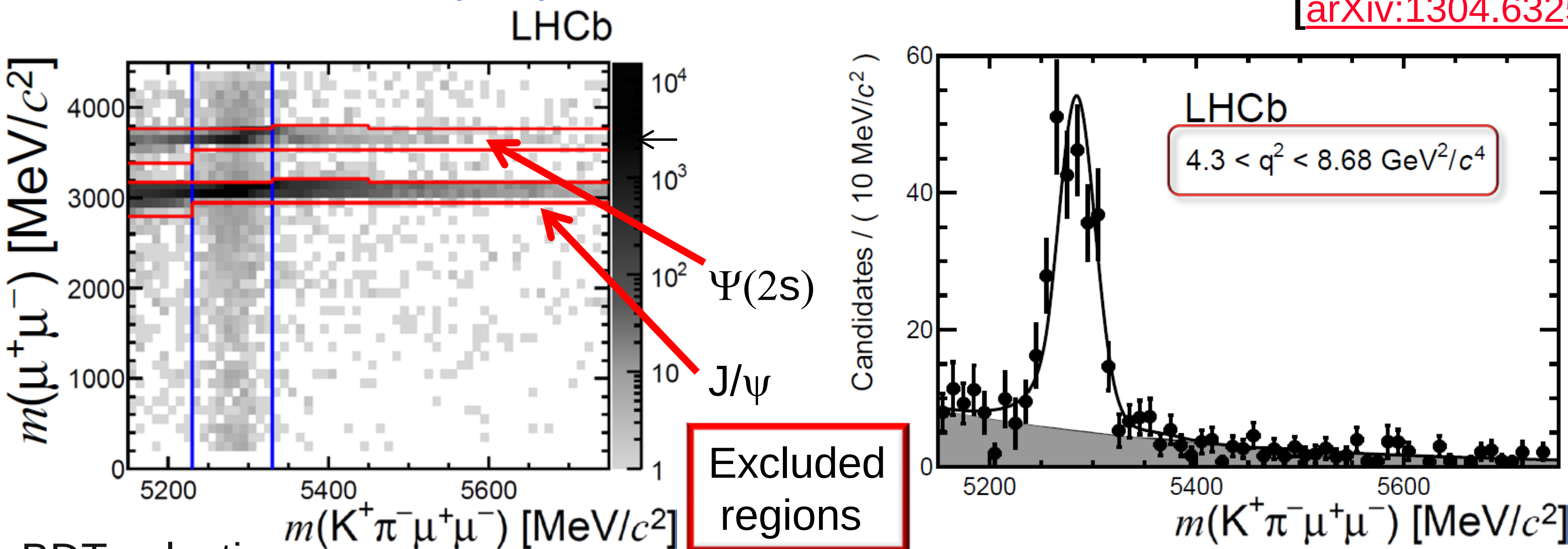
Last week

Rare decays: recent results

- **Slightly less recent, but have to draw line…**
- Search for the decay $B^0_s \to D^{*\mp}\pi^{\pm}$
  - LHCB-PAPER-2012-056 - 13 Mar 2013
- First observation of the decay $B^+ \to \pi^+\mu^+\mu^-$
  - JHEP 12 (2012) 125 – 16 Dec. 2012
- Search for the rare decay $K^0_S \to \mu^+\mu^-$
  - JHEP 01 (2013) 090 – 19 Sep. 2012 Limit is a factor ~30 below the previous measurement.
- Older $b \to s\ell^+\ell^-$
  - $B^0 \to K^*\mu\mu$ isospin asymmetry: JHEP07(2012)133, …
- …

$B^0 \to K^* \mu^+ \mu^-$ branching fraction

[arXiv:1304.6325]

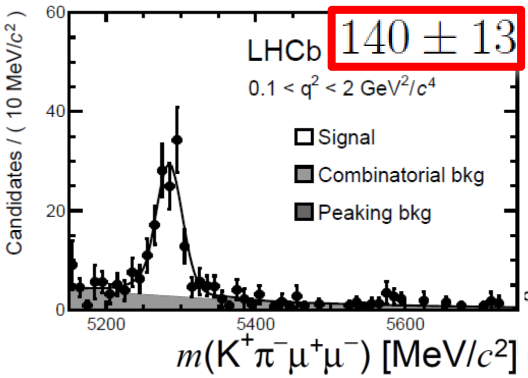


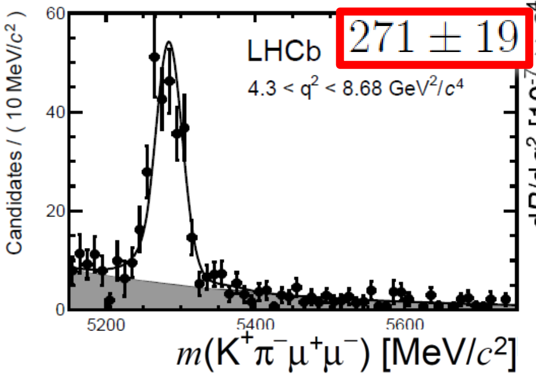
- BDT selection
  - signal $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ (training proxy $B^0 \to K^{*0} J/\psi$ $(J/\psi \to \mu^+\mu^-)$)
  - background from B^0 mass upper sideband
  - Choice of the input variables to avoid biases in $q^2=m^2(\mu\mu)$, angles, mass
  - Loose selection in B^0 candidate vertex fit, flight dist., invariant mass, impact params., p_T , polar angle
  - Final selection from BDT using decay time, flight direction, track/vertex quality, PID of daughters, p_T
- Measure differential BF in each q^2 bin, relative to $B^0 \to K^{*0} J/\psi$
  - $$\frac{d\mathcal{B}}{dq^2} = \frac{1}{q^2_{\max} - q^2_{\min}} \frac{N_{\rm sig}}{N_{K^{*0}J/\psi}} \frac{\varepsilon_{K^{*0}J/\psi}}{\varepsilon_{K^{*0}\mu^+\mu^-}} \times \mathcal{B}(B^0 \to K^{*0}J/\psi) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$$
  - Relative efficiencies from MC (event weights, avoids assumption of $K^*\mu^+\mu^-$ angular distribution

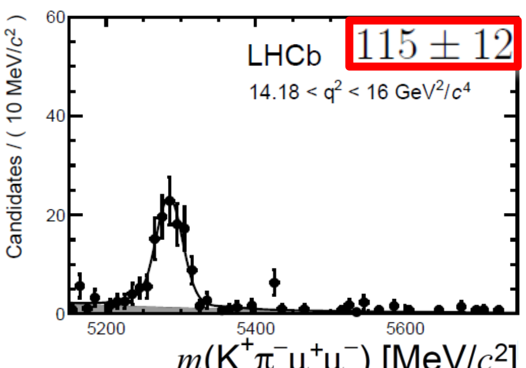
signal decays

$B^0 \to K^* \mu^+ \mu^-$ branching fraction

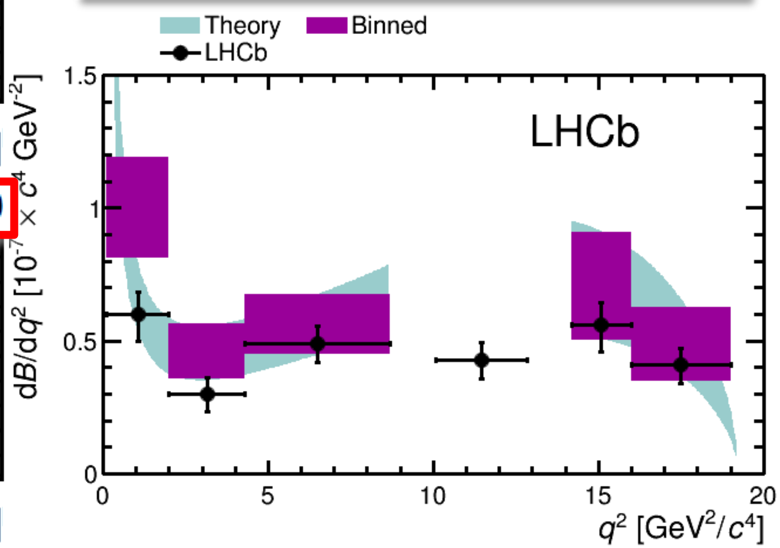
[arXiv:1304.6325]

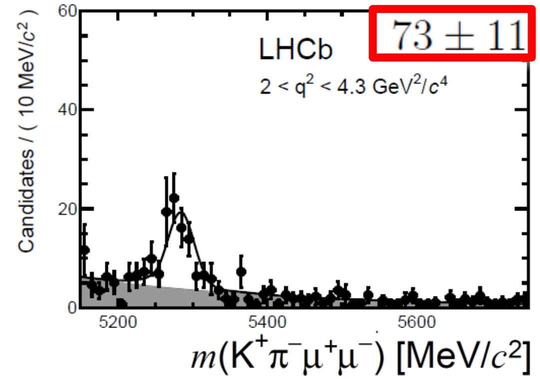


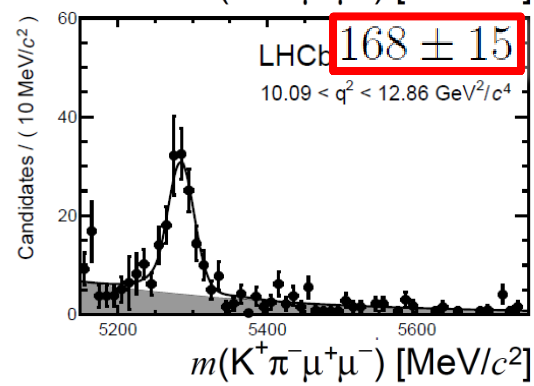


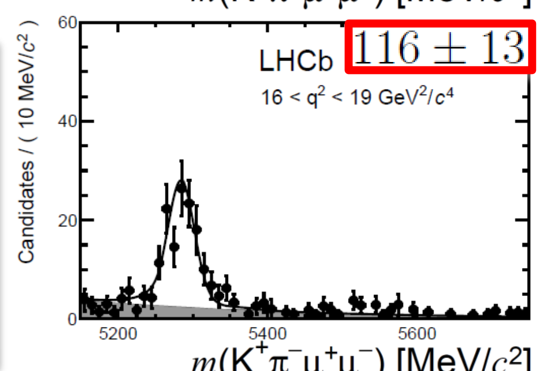


- Uses 1/fb of 7 TeV data
- Most precise measurement of this BR to date





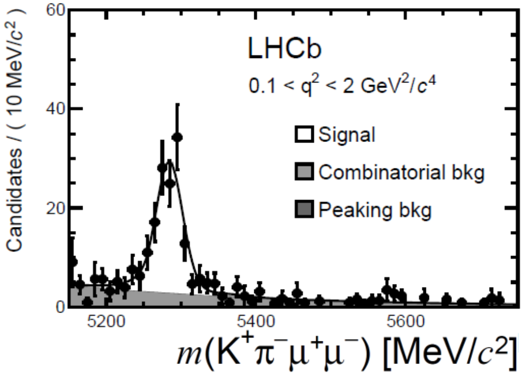


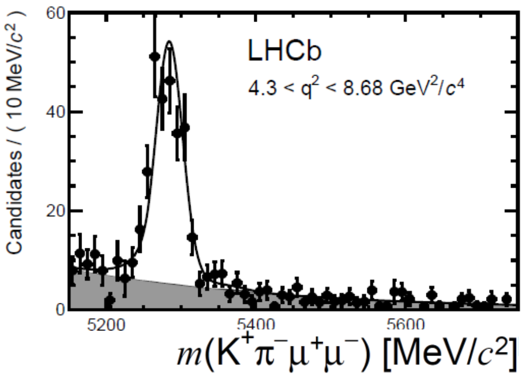


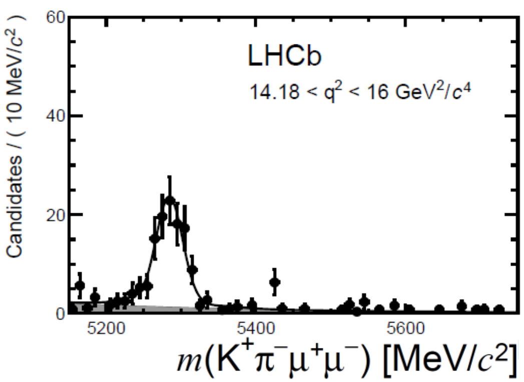
- Systematics dominated by
  - uncertainty on BRs
    - $B^0 \to K^{*0} J/\psi$
    - $J/\psi \to \mu^+\mu^-$
  - Contamination of non-K^{*0} in $m(K^+\pi^-)$ window

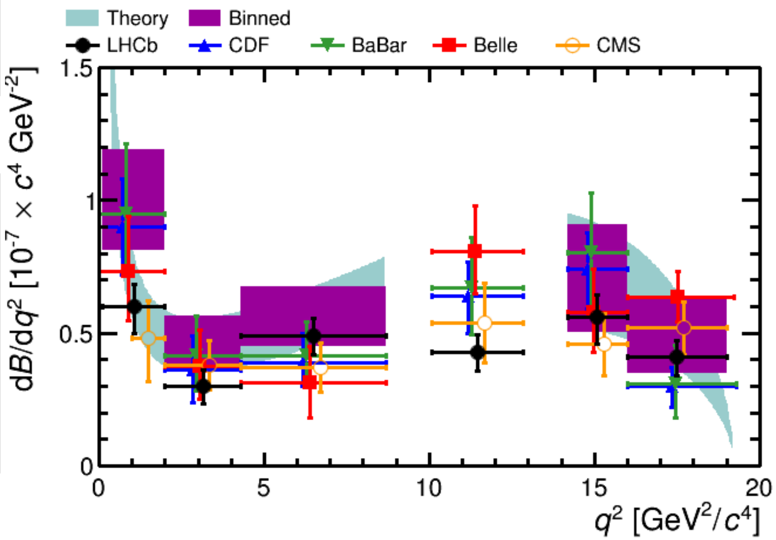
$B^0 \to K^{*}\mu^+\mu^-$ branching fraction

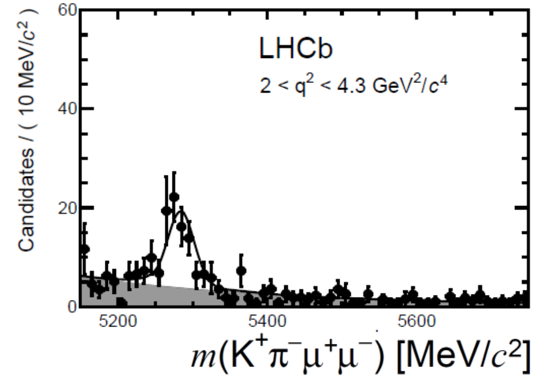
[arXiv:1304.6325]

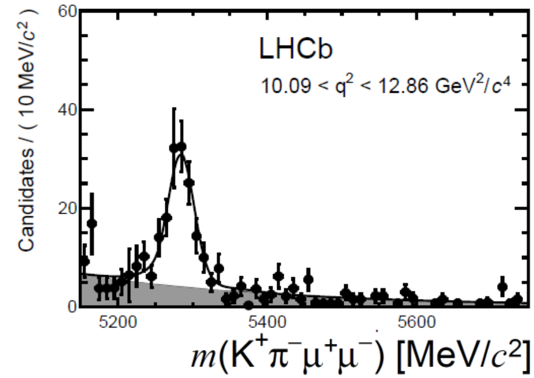


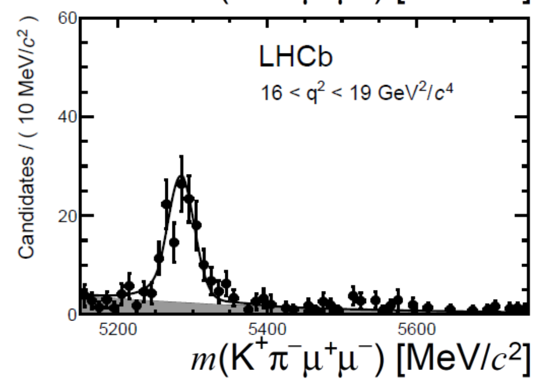












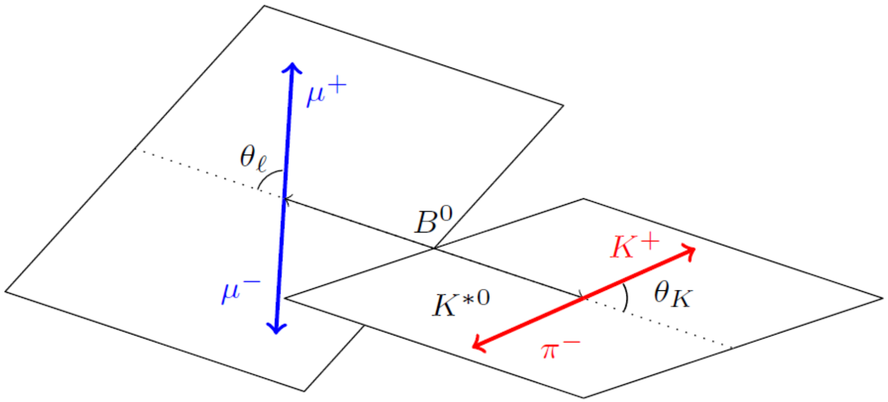
All data consistent with SM

CDF: Phys. Rev. Lett. 108 081807
Babar: Phys. Rev. D. 73. 092001
Belle: Phys. Rev. Lett. 103 (2009)171801
CMS: CMS-PAS-BPH-11-009

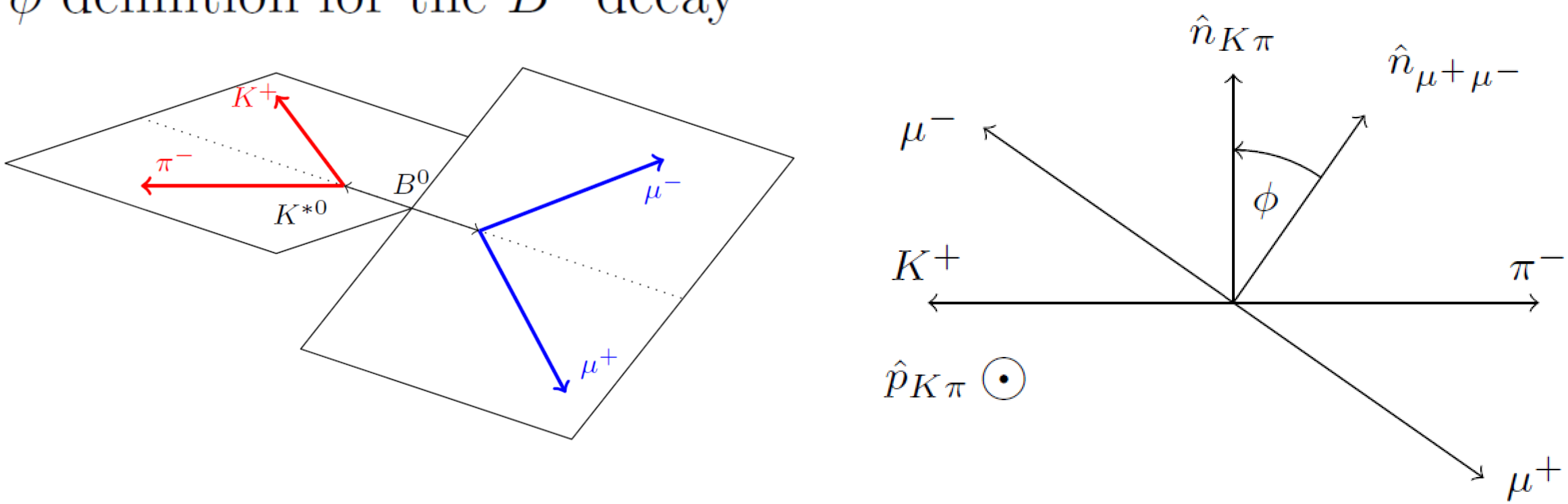
$B^0 \to K^{*}\mu^{+}\mu^{-}$ angular analysis

- 4 particle final state
- 3 decay angles

θ_K and θ_ℓ definitions for the B^0 decay



ϕ definition for the B^0 decay



$B^0 \to K^* \mu^+ \mu^-$ angular analysis

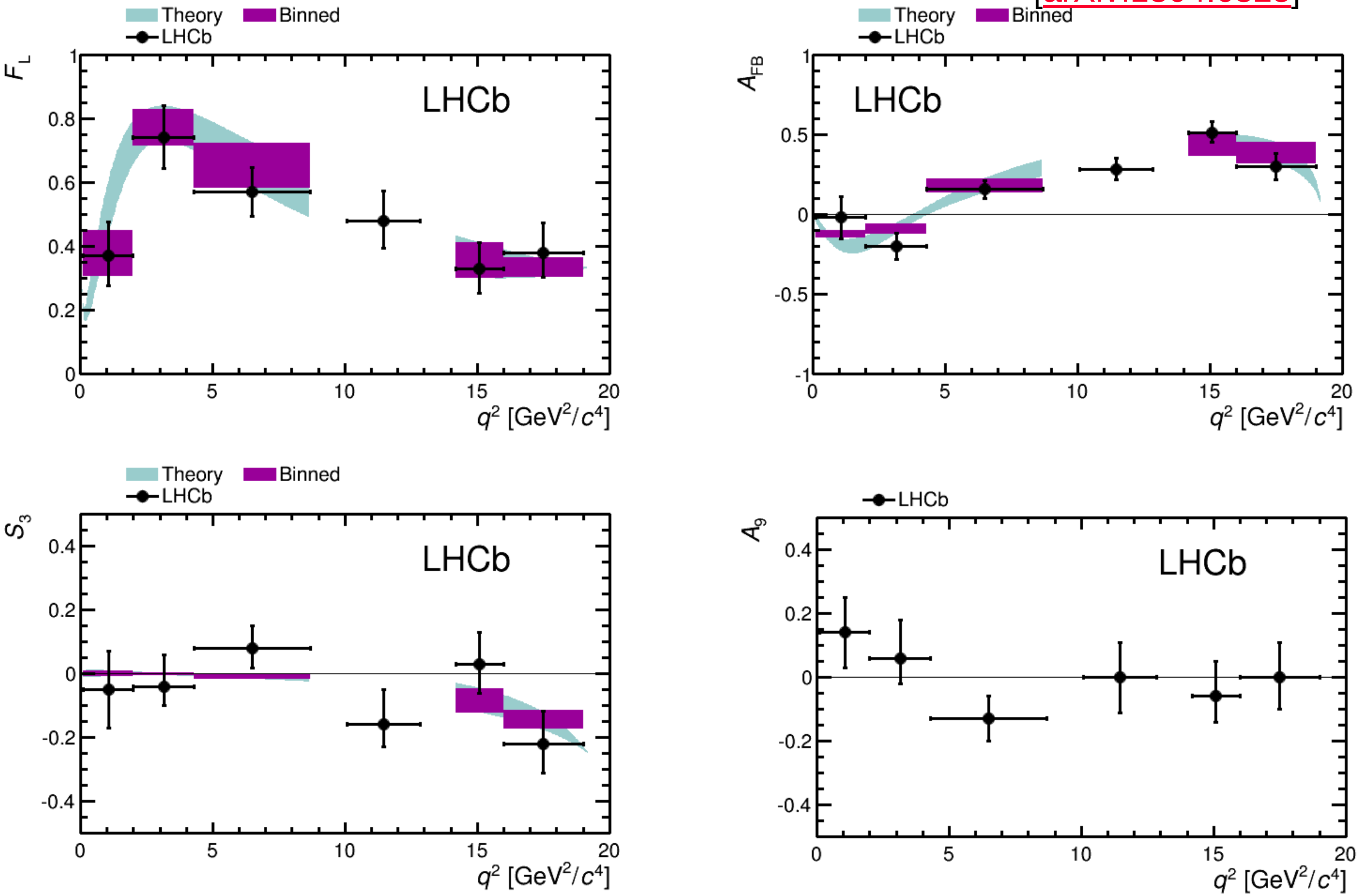
- Branching fraction measured differential in q^2 and 3 decay angles
- Limited statistics: $\phi + \pi \quad \text{if } \phi < 0$
- Parametric in 4 angular observables F_L, A_{FB}, S_3, A_9, from CP asymmetries and averages of decay amplitudes
- Theoretical uncertainties smaller in angular analysis (hadronic form factors)

The first simultaneous fit to all angles

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} \propto \Big[F_\mathrm{L}\cos^2\theta_K + \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) - F_\mathrm{L}\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_\mathrm{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Big]$$

$B^0 \rightarrow K^* \mu^+ \mu^-$ angular analysis

[arXiv:1304.6325]



$B^0 \rightarrow K^* \mu^+ \mu^-$ angular analysis

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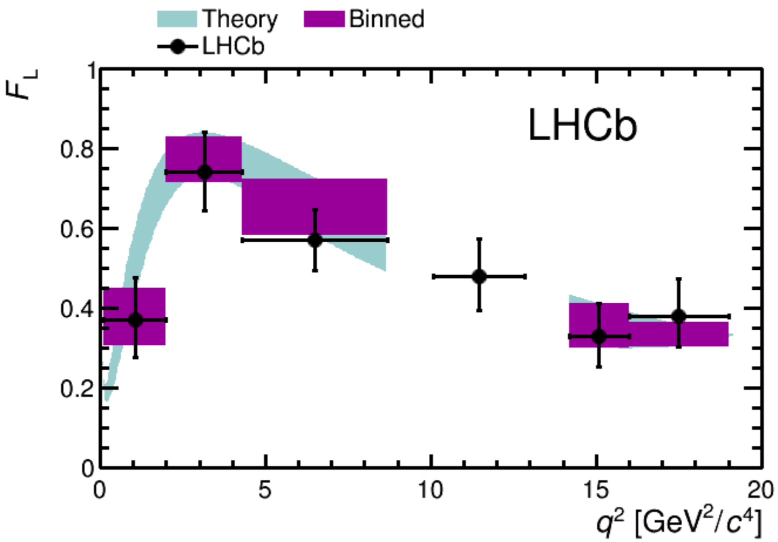
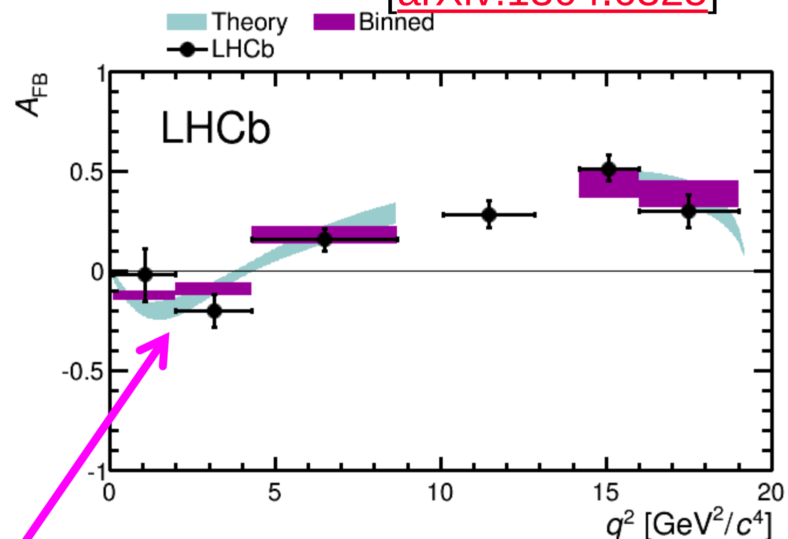
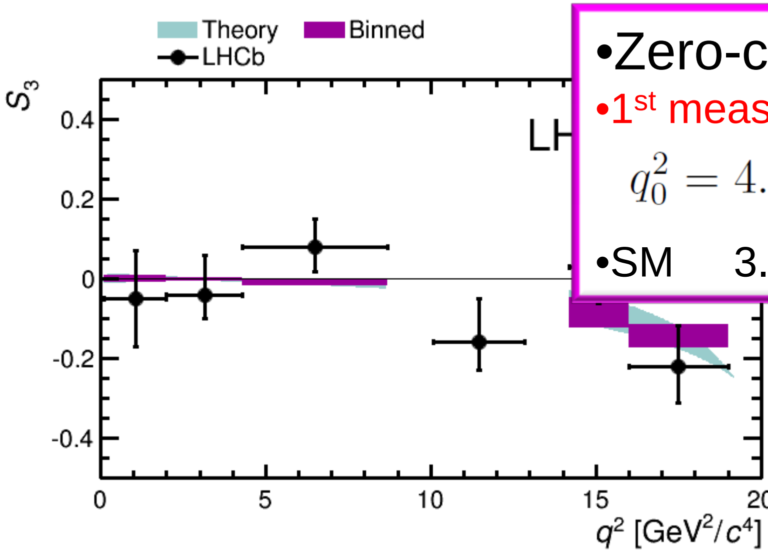
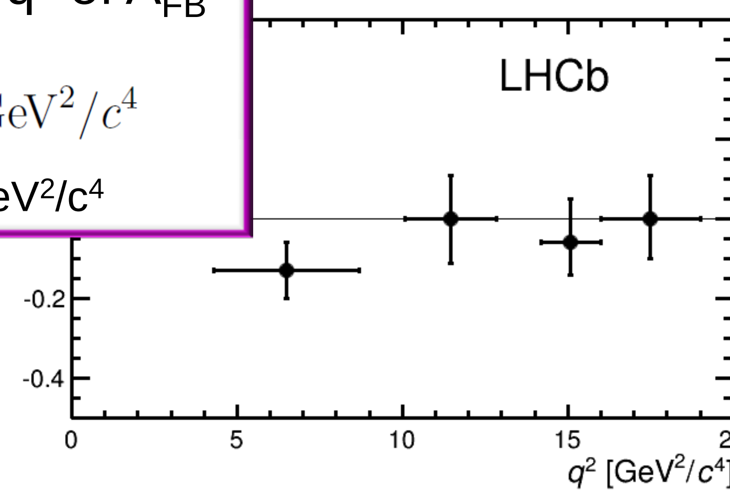








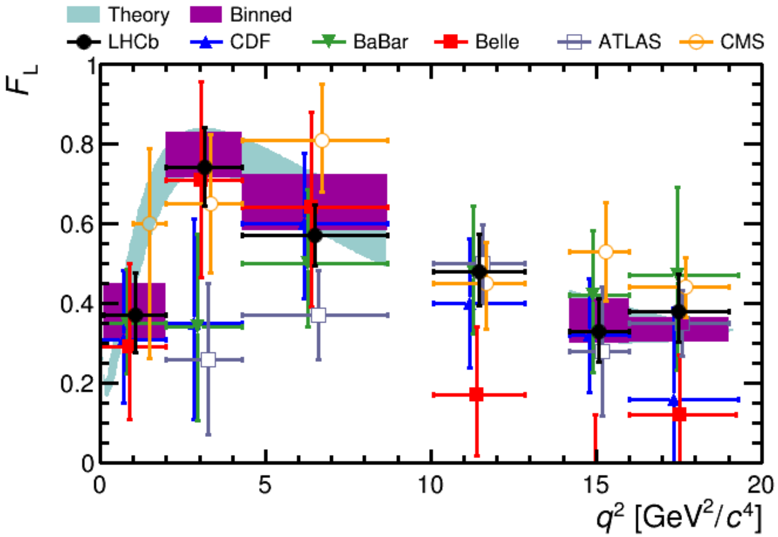
- Zero-crossing q^2 of A_{FB}
- 1st measurement

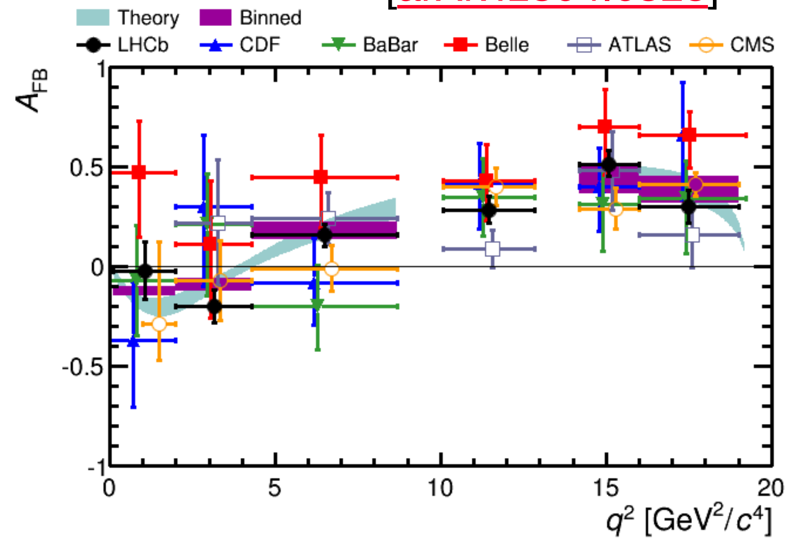
$$q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2/c^4$$

- SM 3.9 - 4.4 GeV^2/c^4

$B^0 \to K^* \mu^+ \mu^-$ angular analysis

[arXiv:1304.6325]





<u>All experiments consistent with SM</u>

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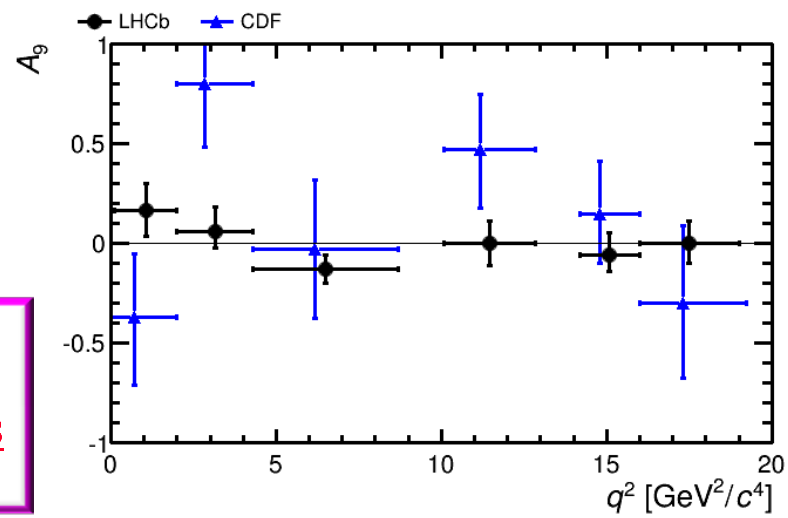
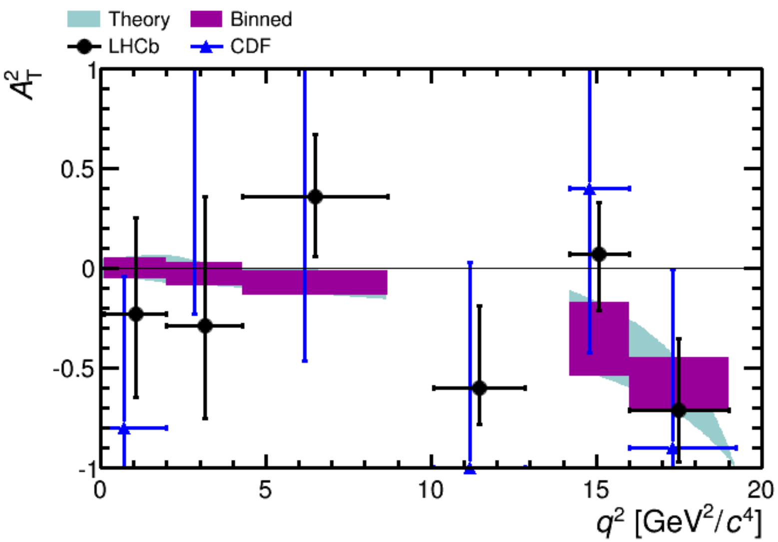


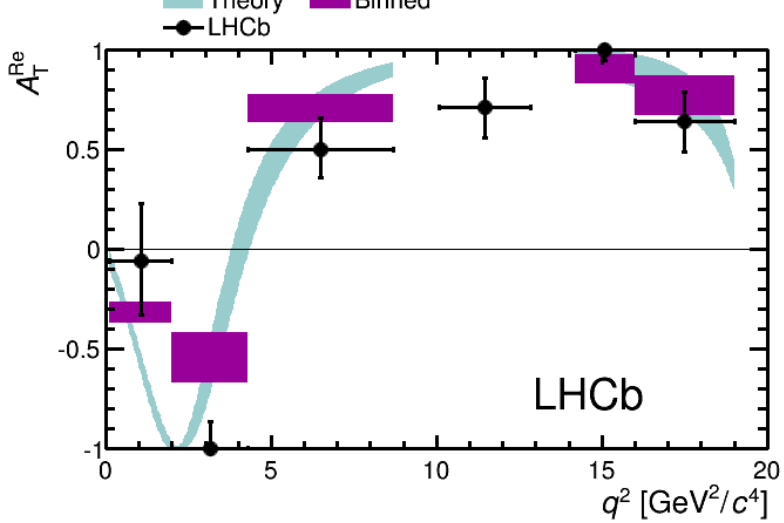
<u>SM predictions</u>

Bobeth,Hiller,van Dyk,Wacker, JHEP 01 (2012) 107
Beneke,Feldmann,Seidel,Eur.Phys.J.C41(2005) 173
Ali,Kramer,Zhu, Eur.Phys.J.C47(2006) 625

$B^0 \to K^* \mu^+ \mu^-$ angular analysis

[arXiv:1304.6325]



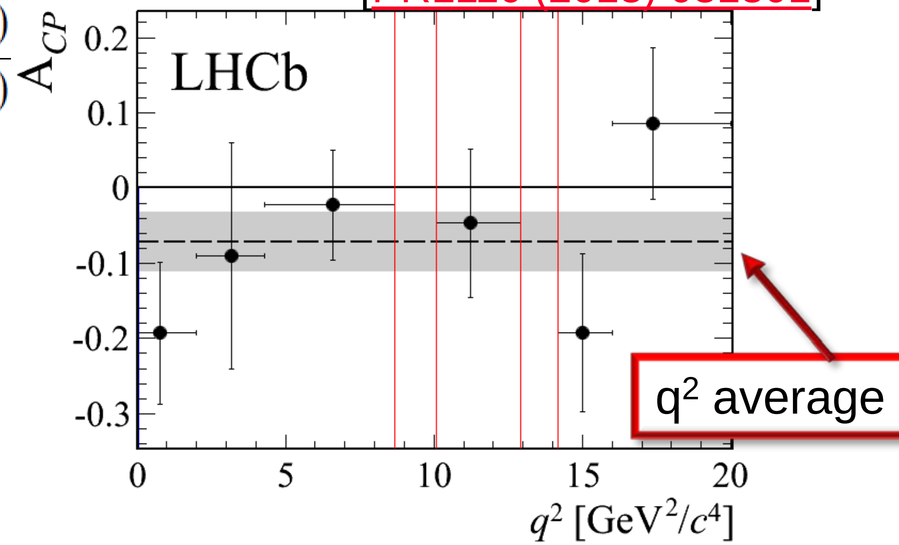


- Alternative fits for transverse amplitudes variables
  - A_T^{Re} and A_T^2
  - theoretically cleaner
- $S_3 = ½ (1-F_L) A_T^2$
- $A_{FB} = 3/4 (1-F_L) A_T^{Re}$

$B^0 \to K^*\mu^+\mu^-$ CP asymmetry

$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}$$

[PRL110 (2013) 031801]



- ~900 signal decays
- Systematics from non-cancelling sources of asymmetry accounted for:
  - Kinematics of signal/normalisation modes
  - Detection of μ^+, μ^-
  - Mass fit model
- $\mathcal{A}_{CP}$ measured in simultaneous fit in 6 q^2 bins, to 8 invariant mass distributions:
- $B^0 \to K^{*0}\mu^+\mu^-$, $B^0 \to J/\psi K^{*0}$
- B^0, $\bar{B}^0$
- Two magnet polarities

- Most precise to date

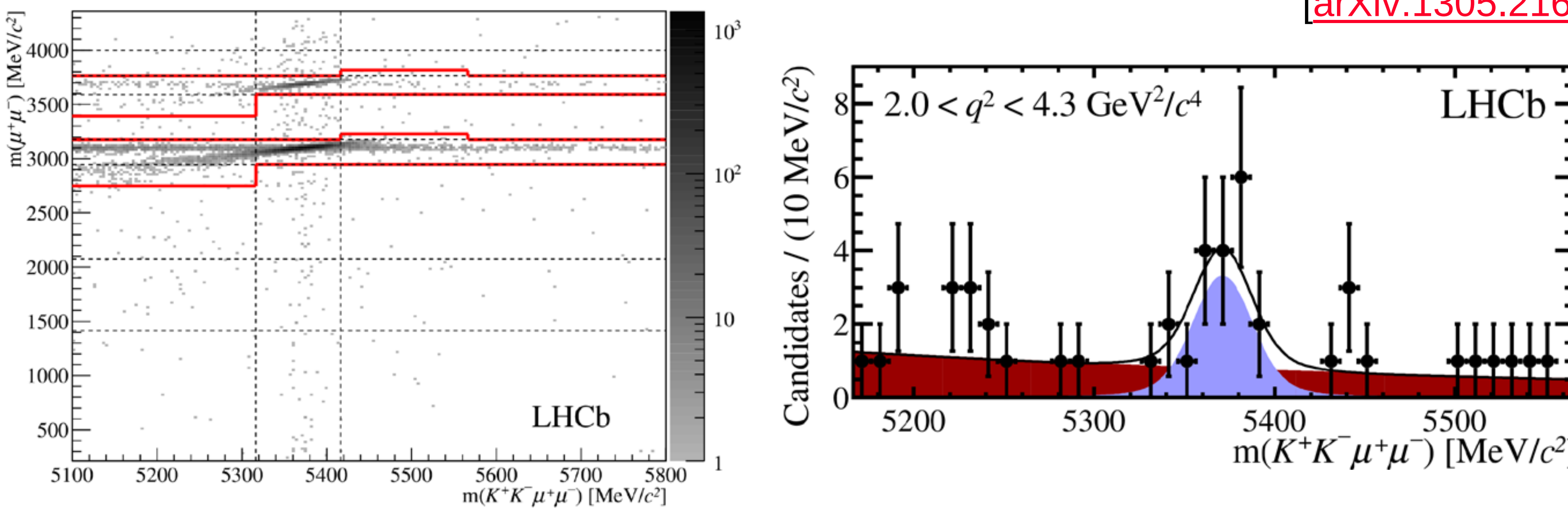
$$\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.072 \pm 0.040 \pm 0.005.$$

- Consistent with Belle, BaBar ☺
- SM: $\mathcal{A}_{CP}$ up to to 10^{-3}) ☹
- NP models, e.g. up to 0.15

[Alok,Datta,Dighe,Duraisamy,Ghosh,London,JHEP11(2011)122]

$B^0_s \rightarrow \phi\mu^+\mu^-$ branching fraction

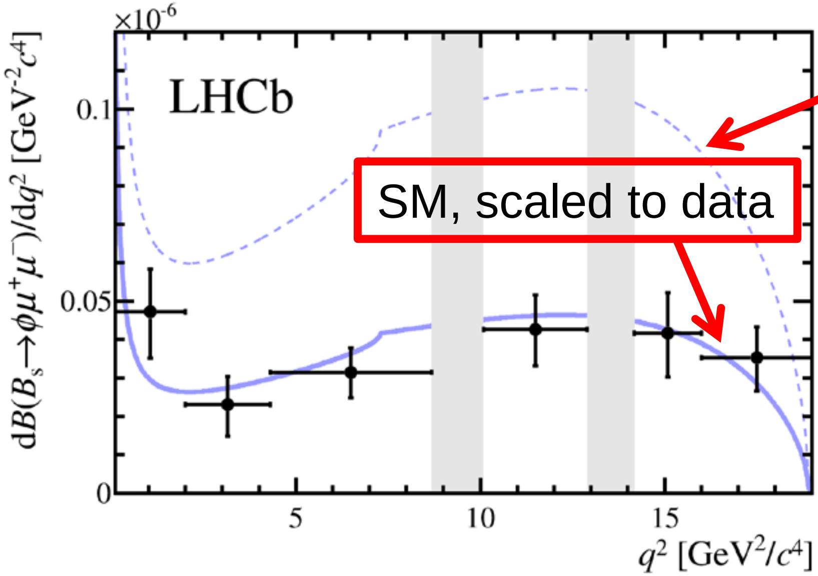
[arXiv:1305.2168]



- Selection ~ $B^0_s \rightarrow K^{*0}\mu\mu$, BDT combining kinematic, PID, topological variables
  - Signal proxy $B^0_s \rightarrow J/\psi\,\phi\ (J/\psi \rightarrow \mu^+\mu^-)$ background $B^0_s \rightarrow \phi\mu^+\mu^-$ (mass sidebands)
  - Extended maximum liklihood fit
    - signal: double Gaussian function, parameters from proxy decays
    - Background: exponential
- Measure differential BF in 6 q² bin, relative to $\mathcal{B}(B^0_s \rightarrow J/\psi\,\phi)$
  - $$\frac{d\mathcal{B}(B^0_s \rightarrow \phi\mu^+\mu^-)}{dq^2} = \frac{1}{q^2_{\max} - q^2_{\min}} \frac{N_{\rm sig}}{N_{J/\psi\,\phi}} \frac{\epsilon_{J/\psi\,\phi}}{\epsilon_{\phi\mu^+\mu^-}} \mathcal{B}(B^0_s \rightarrow J/\psi\,\phi)\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$$
  - Relative efficiencies from MC (in each q² bin)
- Most precise measurement of this BR to date

$B^0_s \to \phi\mu^+\mu^-$ branching fraction

[arXiv:1305.2168]



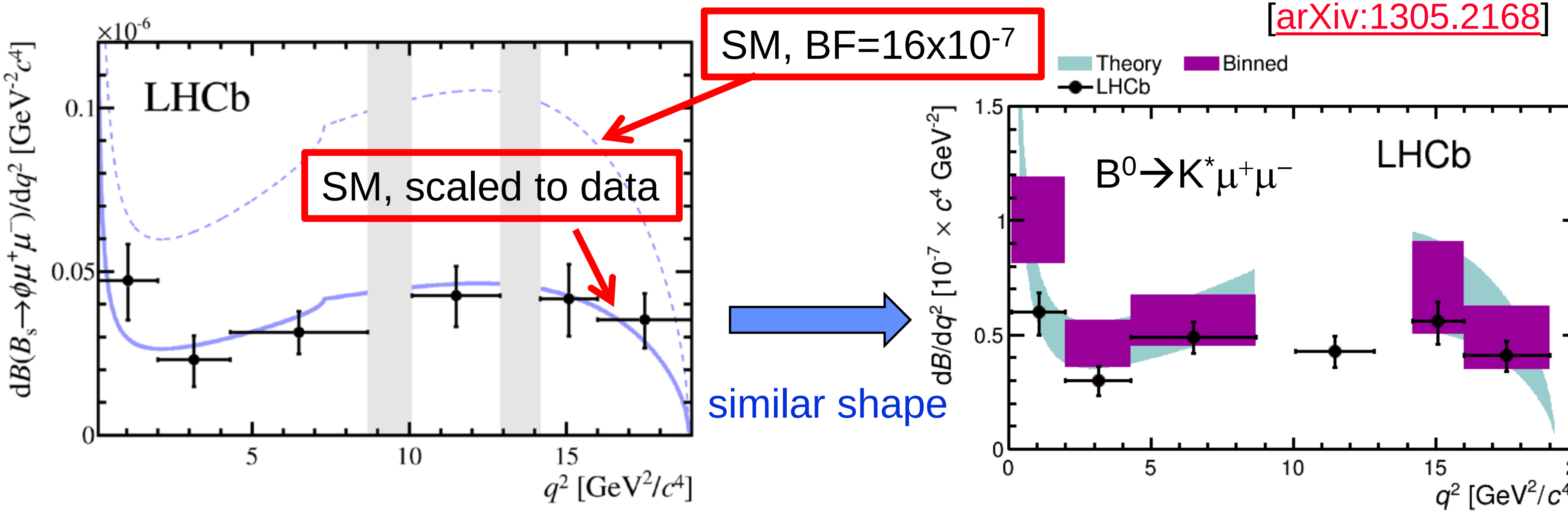
Consistent with CDF
[PRL 107 (2011) 201802]
[CDF public 10894 (2012)]

- Sum over 6 bins, converted to absolute BF
- Using LHCb $\mathcal{B}(B^0_s \to J/\psi\,\phi) = (10.50 \pm 1.05) \times 10^{-4}$
  - Phys. Rev. D87 (2013) 072004
- Measured
  - $\mathcal{B}(B^0_s \to \phi\mu^+\mu^-) = (7.07\,^{+0.64}_{-0.59} \pm 0.17 \pm 0.71) \times 10^{-7}$
- SM prediction (14.5-19.2) x 10^{-7}
  - Uncertainties from form factors ~20-30%

Geng&Liu, J.Phys.G29(2003)1103
Erkol&Turan, Eur.Phys.J.C25(2002)575
U. Yilmaz, Eur.Phys.J.C58(2008)555
Chang&Gao, Nucl.Phys.B845(2011)

$B^0_s \to \phi\mu^+\mu^-$ branching fraction

[arXiv:1305.2168]



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Erkol&Turan, Eur.Phys.J.C25(2002)575
U. Yilmaz, Eur.Phys.J.C58(2008)555
Chang&Gao, Nucl.Phys.B845(2011)

$B^0_s \rightarrow \phi\mu^+\mu^-$ angular analysis

- Parametrise angular distributions in terms of 4 observables: F_L, A_6, S_3, A_9
- Simulation used to correct for angular acceptance
  - Dominates systematics
- Integrate over 2 angles
  - 2d max. liklihood fits in each angle and B^0_s mass
  - No A_{FB} as not flavour tagged
  - Repeated in 6 q^2 bins

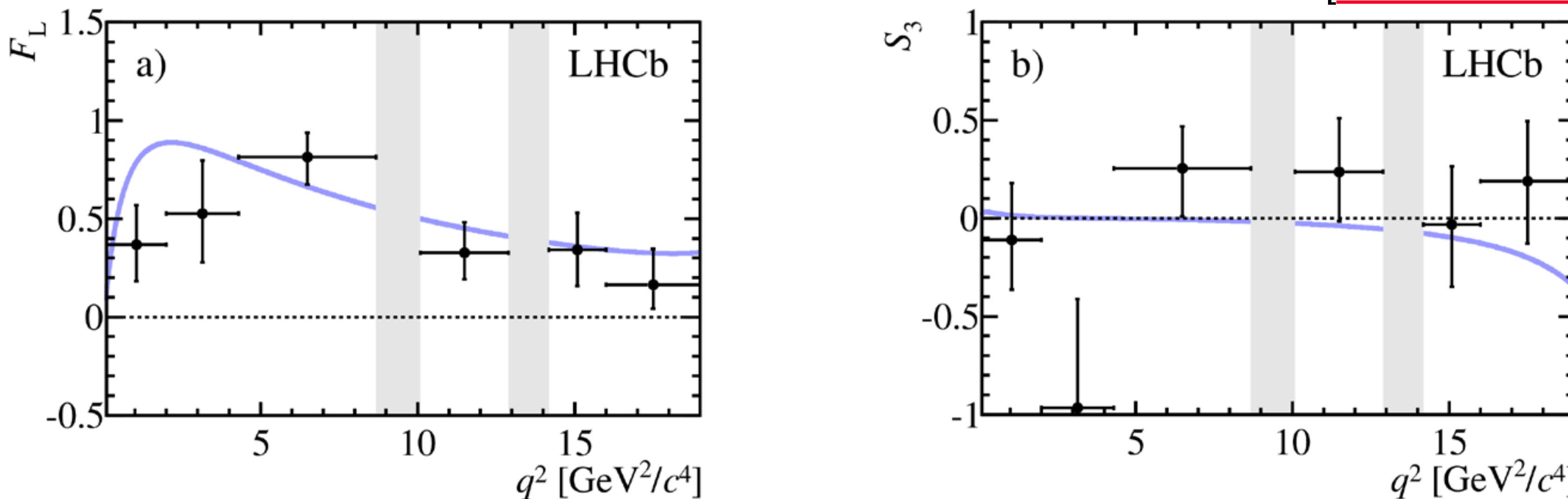
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_K} = \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) + \frac{3}{2}F_\mathrm{L}\cos^2\theta_K$$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell} = \frac{3}{8}(1-F_\mathrm{L})(1+\cos^2\theta_\ell) + \frac{3}{4}F_\mathrm{L}(1-\cos^2\theta_\ell) + \frac{3}{4}A_6\cos\theta_\ell$$

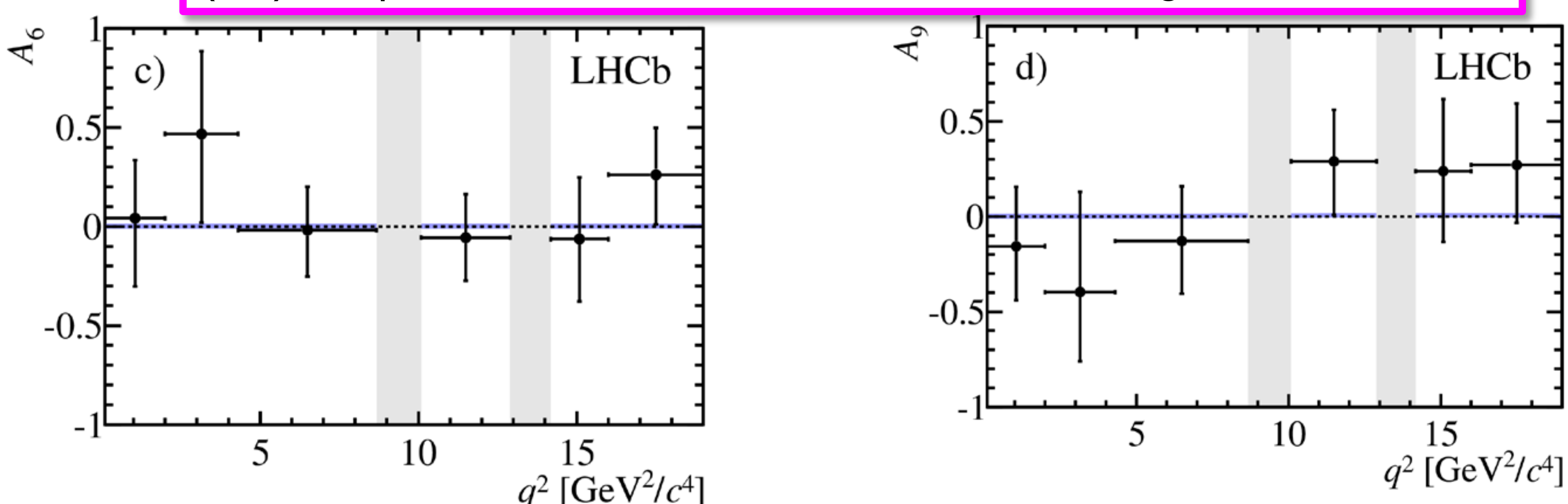
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\Phi} = \frac{1}{2\pi} + \frac{1}{2\pi}S_3\cos 2\Phi + \frac{1}{2\pi}A_9\sin 2\Phi$$

$B^0_s \to \phi\mu^+\mu^-$: Angular analysis

[arXiv:1305.2168]



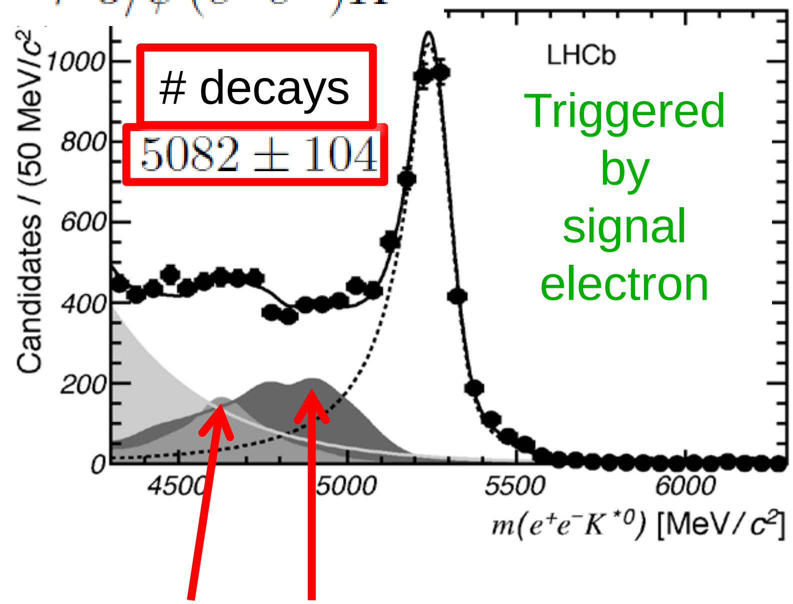
(LO) SM predictions consistent with measured angular observables



$B^0 \rightarrow K^* e^+ e^-$ branching fraction

- Low q^2 region more sensitive to photon polarisation
  - Extend reach using electrons
  - Not previously observed at low q^2
- Use q^2 region 30-1000 MeV/c^2
- Experimentally hard below 30 MeV/c^2
  - Multiple scattering, decay plane definition degraded
  - Background from increases rapidly $B^0 \rightarrow K^{*0}\gamma$
- Account for bremmstrahlung upstream of magnet to avoid biases
- Many sources of background identified
  - Dominated by $B \rightarrow K^*\eta \ (\eta \rightarrow \gamma e^+ e^-)$
  - Not peaking in signal region
- Use BDT to enhance selection

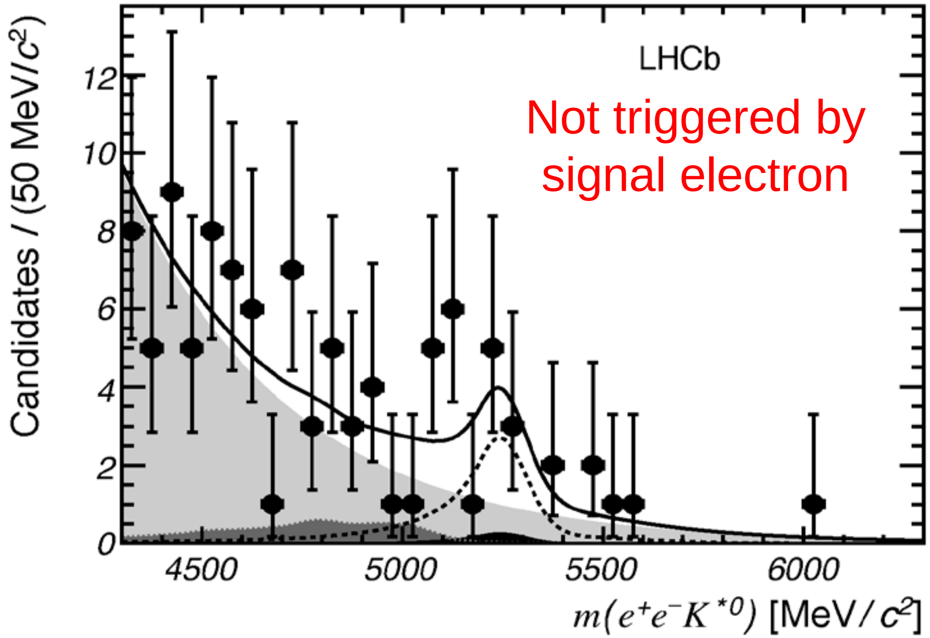
$B^0 \rightarrow J/\psi(e^+e^-)K^{*0}$ [JHEP05(2013)159]

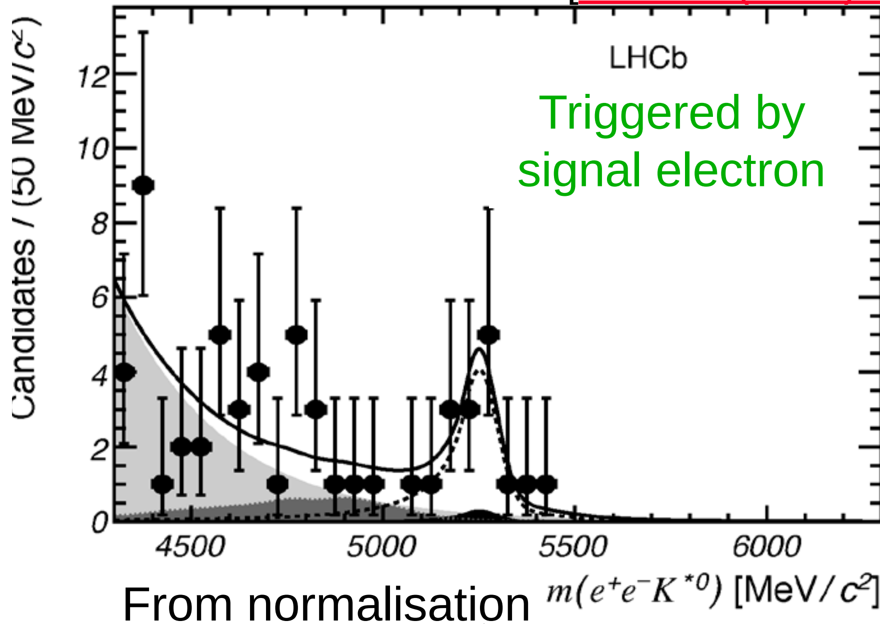


- Partially reconstructed backgrounds well-modelled

$B^0 \rightarrow K^* e^+ e^-$ branching fraction

[JHEP05(2013)159]





From normalisation

$$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\,\mathrm{MeV}/c^2} = (3.1\,^{+0.9}_{-0.8}\,^{+0.2}_{-0.3} \pm 0.2) \times 10^{-7}$$

- Normalised to $B^0 \to J/\psi(e^+e^-)K^{*0}$
- Signal resolution, and background type/rate depend on hardware trigger
- 2 mutually exclusive trigger selections
- Measurement limited by sample size
- 4.6σ significance from background

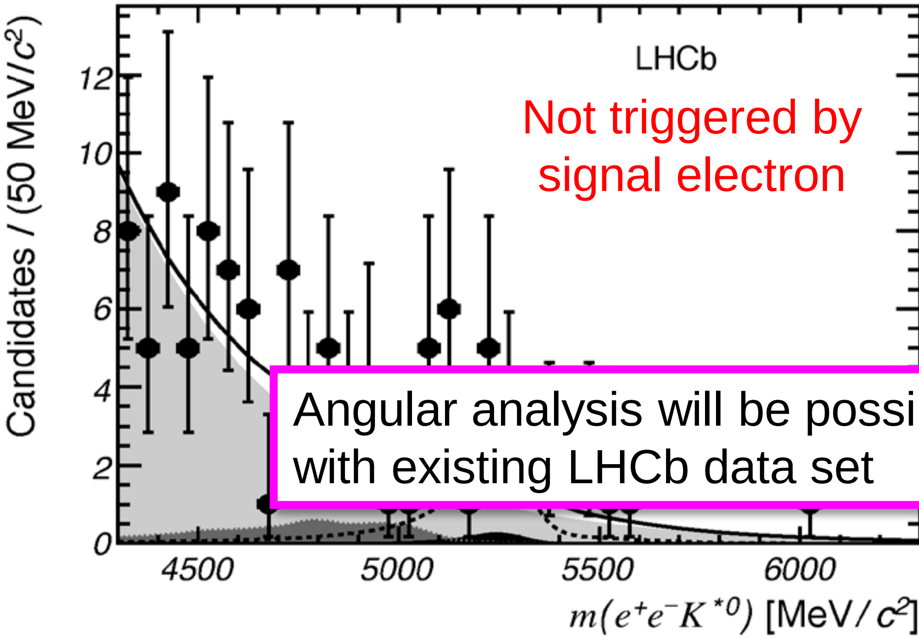
- Agrees with SM $\mathcal{B}$ prediction ☹
  - $(2.43^{+0.66}_{-0.47}) \times 10^{-7}$

    [Jager & Camalich, JHEP 05 (2013) 043]
  - 2.35×10^{-7}

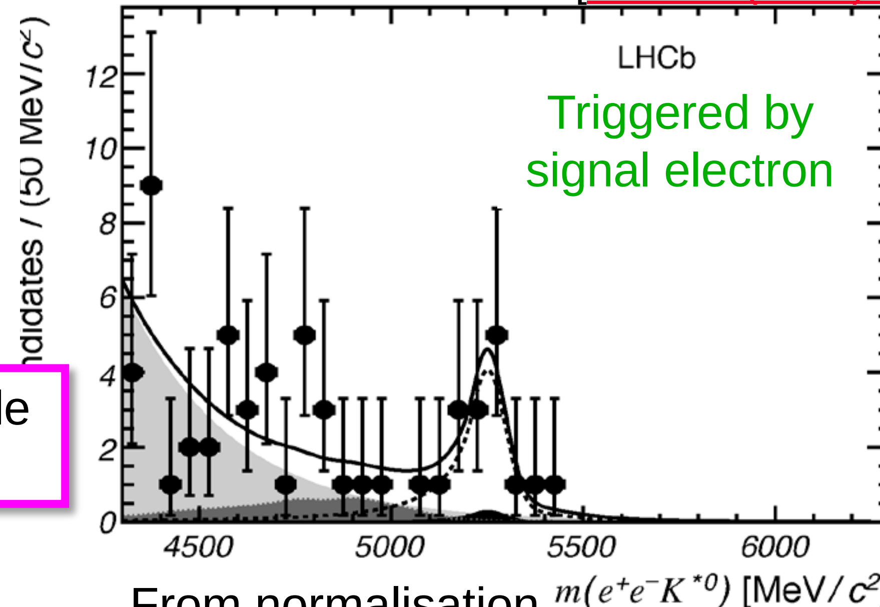
    [Y. Grossman & Pirjol, JHEP 06 (2000) 029]

$B^0 \rightarrow K^* e^+ e^-$ branching fraction

[JHEP05(2013)159]



Angular analysis will be possible with existing LHCb data set



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  - 2.35×10^{-7}

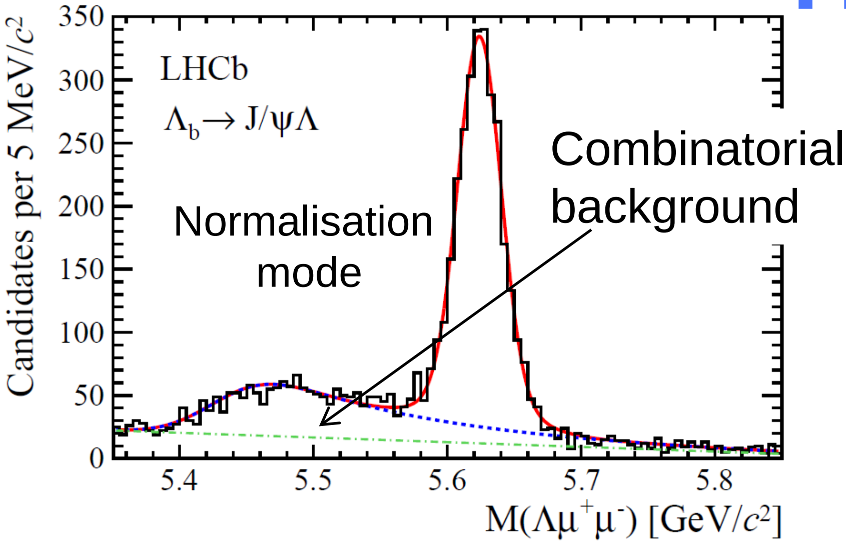
    [Y. Grossman & Pirjol, JHEP 06 (2000) 029]

$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$ branching fraction

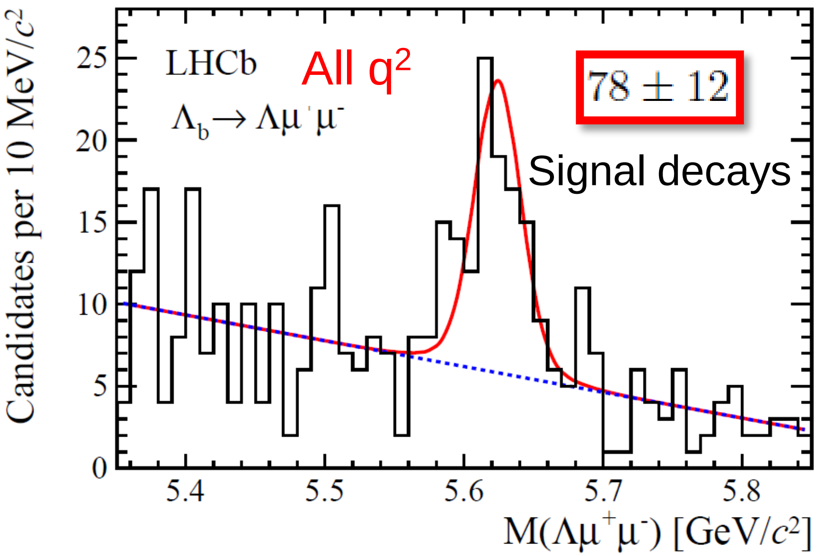
- First measurement at LHC
- Extends the b→s FCNC study into baryonic sector
- Non-zero initial spin gives access to helicity structure not available in mesonic state
- Theory less-well developed than in meson case
  - Less experimental data
- Selection
  - Final state has long lived Λ, so consider behaviour of decay products within/beyond acceptance of our vertex detector
  - ANN selection, kinematic and topological observables
  - Distinctive kinematics allow us to not require PID except μ (gains efficiency)
- Measured relative to $\Lambda_b^0 \rightarrow J/\psi\,\Lambda$ ($J/\psi \rightarrow \mu^+\mu^-$)
  - Signal for training from MC
  - Training background from upper mass sideband of Λ_b^0 mass spectrum

Yields

[arXiv:1306.2577]



$\Lambda_b^0 \to J/\psi\,\Lambda$



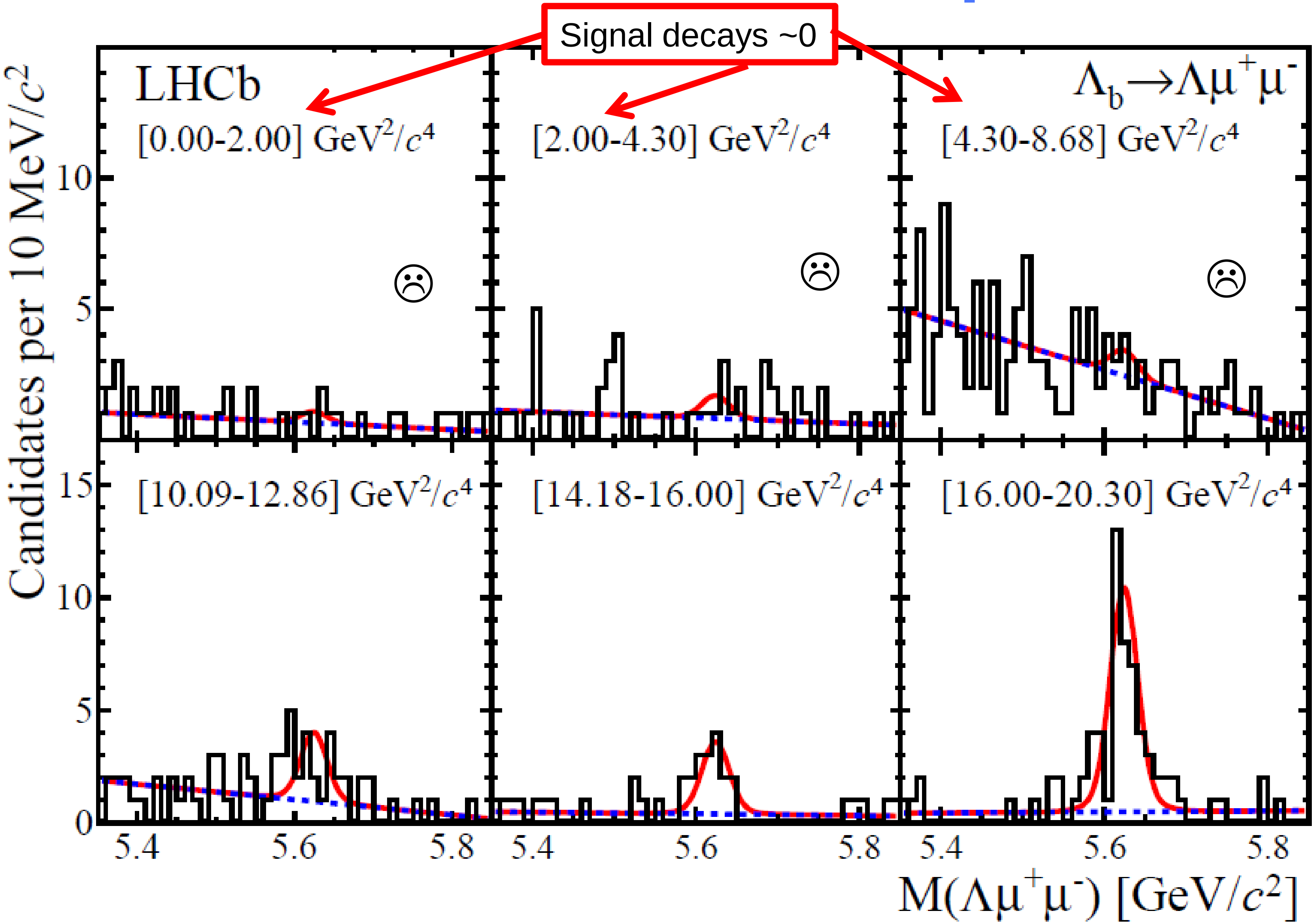
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

- Backgrounds
  - $B^0 \to J/\psi K^0_S \ (K^0_S \to \pi^+\pi^-)$
  - Broad shape, peaks below Λ_b^0
  - Account for in fit (shape from MC)
- For normalisation mode
  - Double Gaussian, common mean, relative fractions from MC, otherwise free

- Backgrounds
  - $B^0 \to K^0_S\mu^+\mu^-$ with $\pi \to p$ mis-id
  - Estimate rate negligible
- For signal mode
  - Double Gaussian, parameters from normalisation mode data

Candidates vs. q^2

[arXiv:1306.2577]

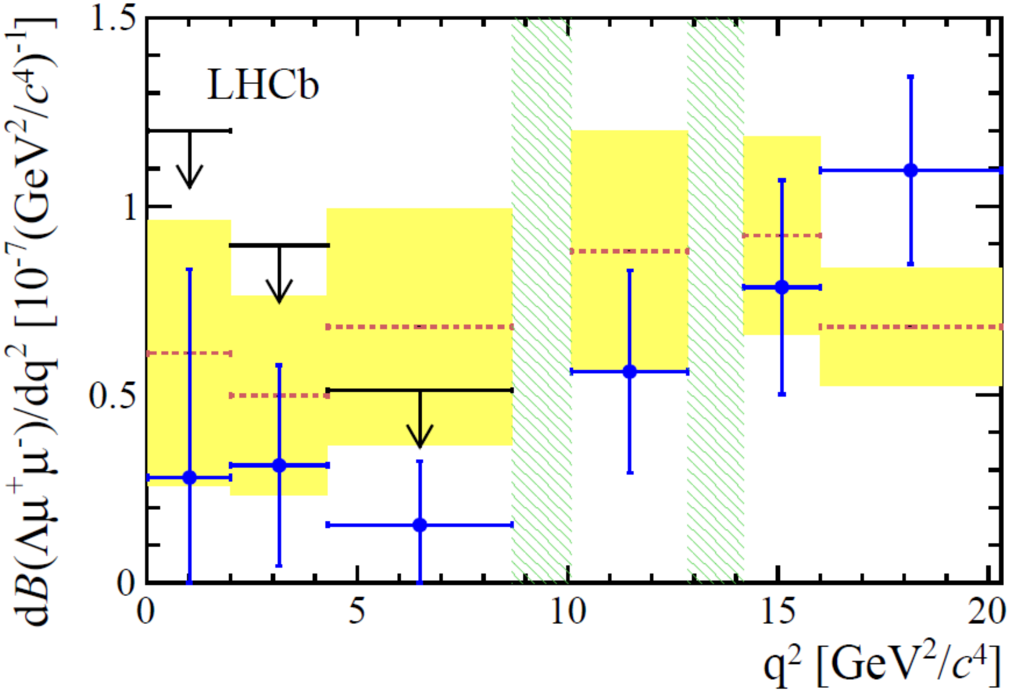


$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$ signal yields

[arXiv:1306.2577]

q^2 interval [GeV^2/c^4]	N_S	N_B	Statistical significance
0.00 – 2.00	2 ± 3	34 ± 6	0.8
2.00 – 4.30	4 ± 3	42 ± 7	1.4
4.30 – 8.68	4 ± 5	134 ± 12	1.0
10.09 – 12.86	13 ± 5	52 ± 8	3.4
14.18 – 16.00	14 ± 4	20 ± 5	4.9
16.00 – 20.30	44 ± 7	24 ± 6	9.8
Integrated yield	78 ± 12	310 ± 19	8.9

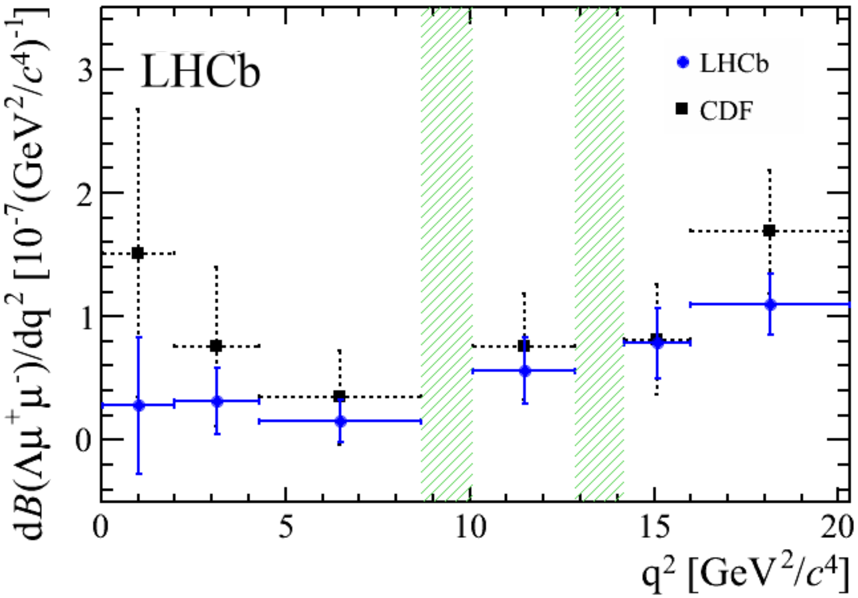
- Significance from fits

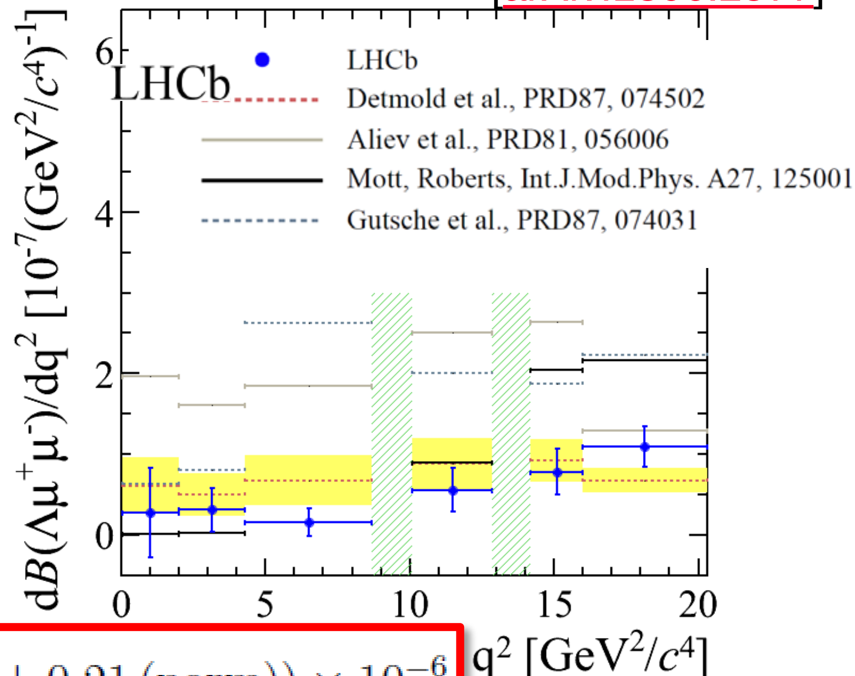


SM: Detmold, Lin, Meinel, Wingate, Phys.Rev.D87(2013)074502

Differential branching fractions

[arXiv:1306.2577]





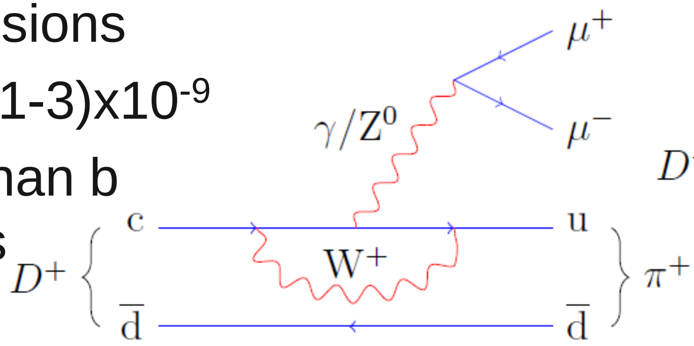
$$\mathcal{B}(\Lambda_b^0 \to \Lambda\mu^+\mu^-) = (0.96 \pm 0.16\,(\mathrm{stat}) \pm 0.13\,(\mathrm{syst}) \pm 0.21\,(\mathrm{norm})) \times 10^{-6}$$

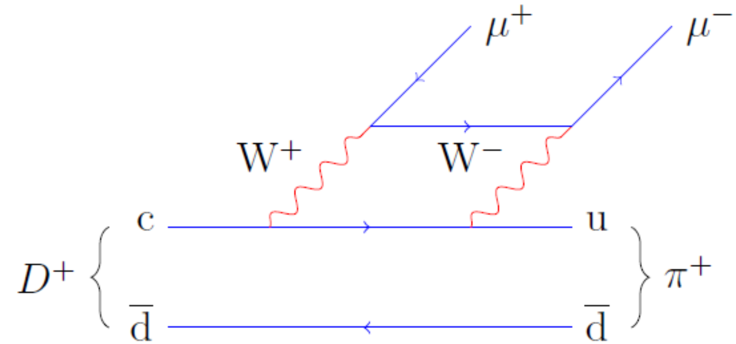
- Consistent with 1st observation of this mode by CDF
- Significant signal so far observed for $q^2 > m^2_{J/\psi}$
- Upper limits set in lowest 3 q^2 bins

- Consistent with SM
- Clearly statistics limited
  - but we have 2x already under study
- New theoretical activity welcome ☺
- Full angular analysis coming…

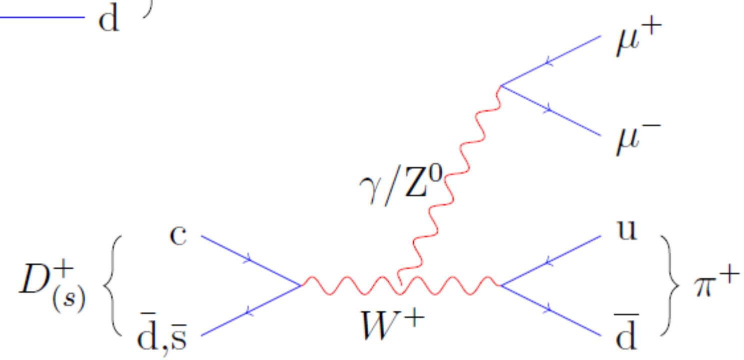
Rare charm searches for $D^{+}_{(s)} \to \pi^{\pm}\mu^{+}\mu^{\mp}$

- FCNC c→u $\mu^{+}\mu^{-}$ decays
- Large GIM suppressions
- SM B(c→u $\mu^{+}\mu^{-}$)~(1-3)x10^{-9}
- More suppressed than b case as no t quarks in loops
- Can be enhanced by non-SM contributions

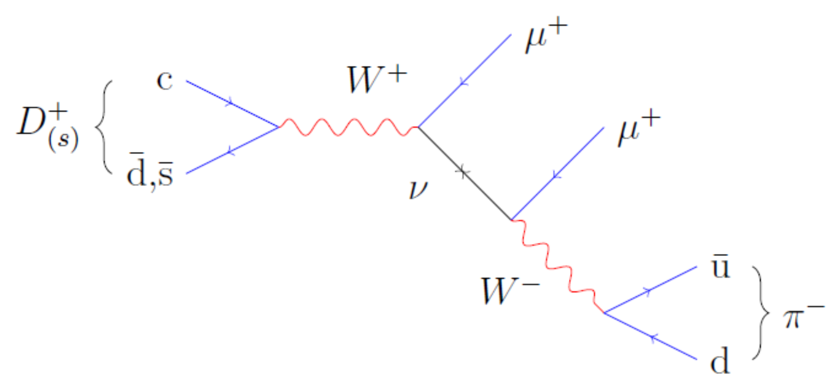




- Weak annihilation



- LNV decay forbidden in SM as required exotic e.g. Majorana ν

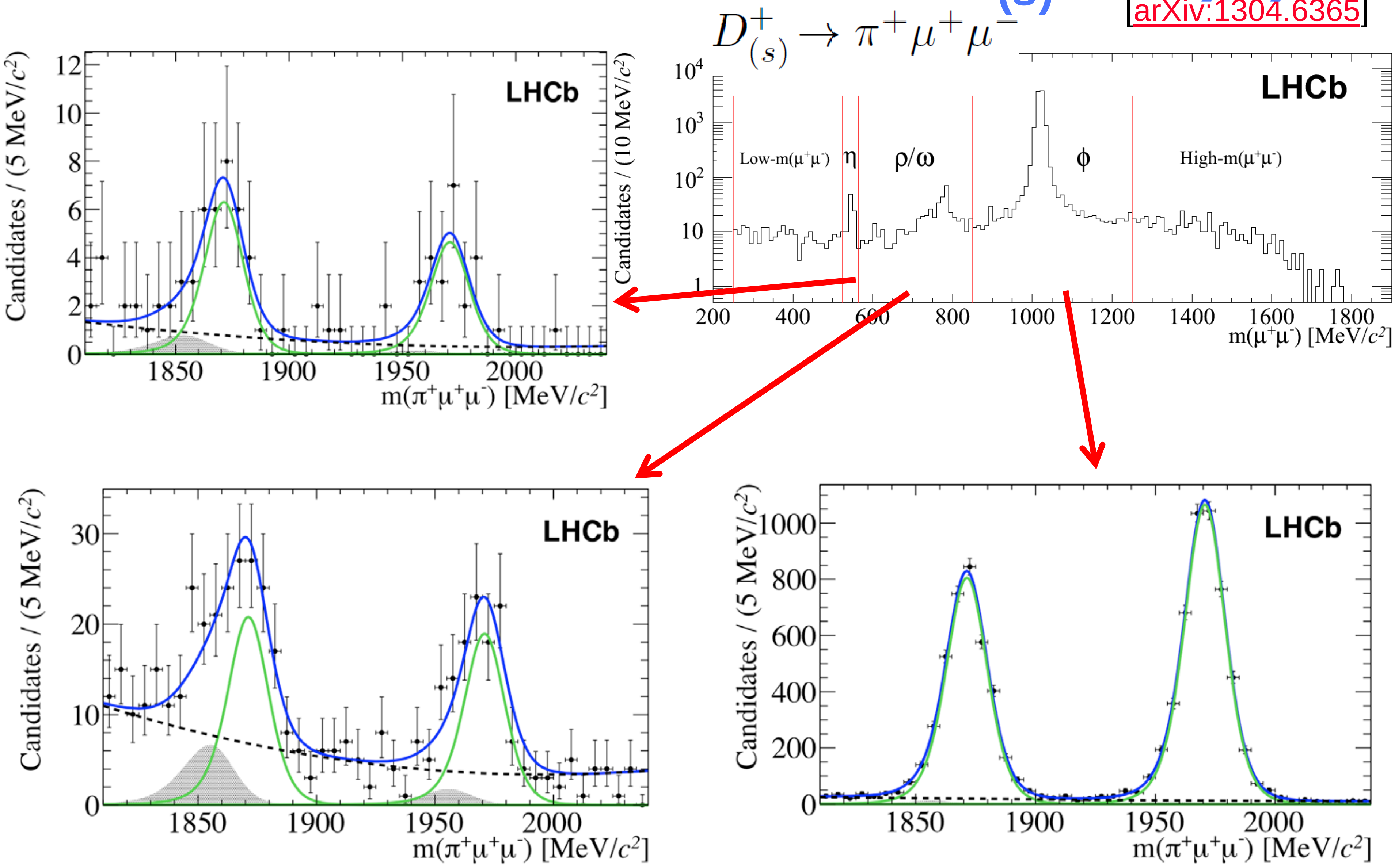


Rare charm searches for $D^+_{(s)} \to \pi^+ \mu^+ \mu^-$

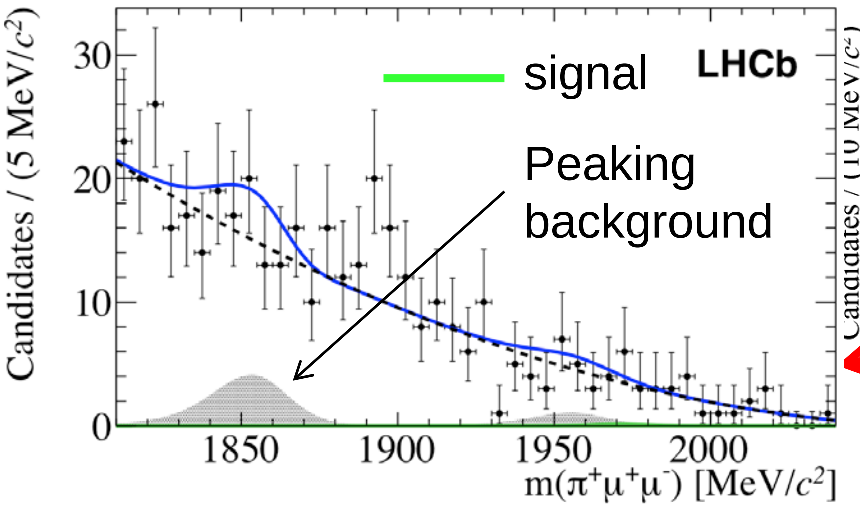
- $D^+_{(s)}$ reconstructed from 3 good tracks, vertex quality, $D^+_{(s)}$ flight direction, …
- BDT classifies candidates as signal/background using topological and kinematic observables
  - Training Signal is MC $D^+ \to \pi^+ \mu^+ \mu^-$
  - Background $D^+_{(s)} \to \pi^+ \mu^+ \mu^-$ mass sidebands
    - Independent 2010 data, 36/pb, not use elsewhere in analysis
- Dominant background is $D^+_{(s)} \to \pi^+ \pi^+ \pi^-$
  - Peaking background extracted from fit with looser PID and alternative mass hypothesis
- Normalisation channel $D^+_{(s)} \to \phi\ (\mu^+ \mu^-)$ pi
  - Also used as proxy for pid study, optimmise significance by fitting…
- Analysis carried out in
  - 5 bins of $m(\mu^+ \mu^-)$ bins for FCNC
  - 4 bins of $m(\mu^+ \pi^-)$ for LNV) search – separate above/below resonance regions

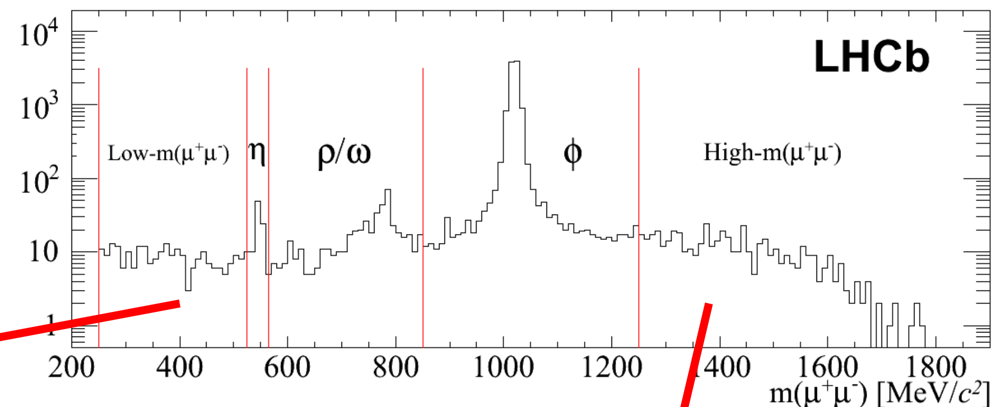
Rare charm searches for $D^{+}_{(s)} \rightarrow \pi^{+}\mu^{+}\mu^{-}$

[arXiv:1304.6365]



Limits for rare charm $D^+_{(s)} \to \pi^+\mu^+\mu^-$ [arXiv:1304.6365]

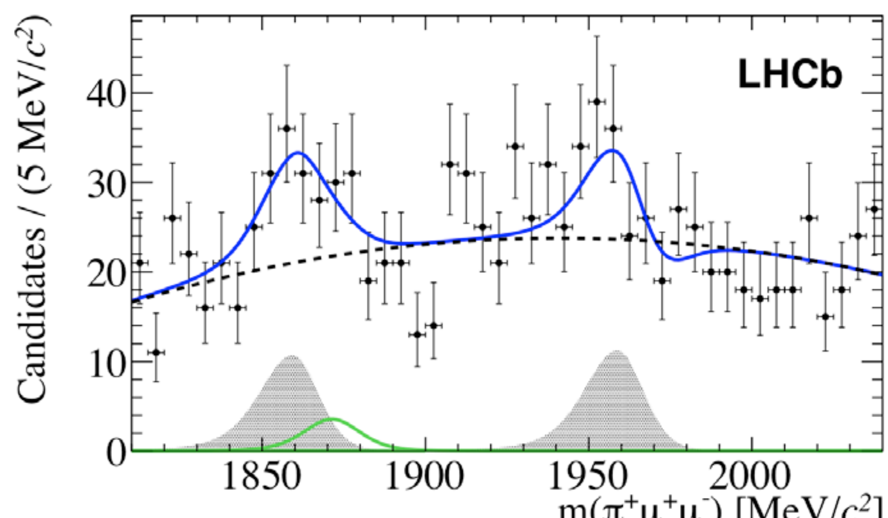




- Look for new physics away from known resonance regions
  - low and high mass regions
- No excess signal observed
- Limits set at 90 (95) %CL (extrapolate to total $\mathcal{B}$ using phase space model)

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3\,(8.3) \times 10^{-8}$$
$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1\,(4.8) \times 10^{-7}$$

  - ~50x stronger than previous



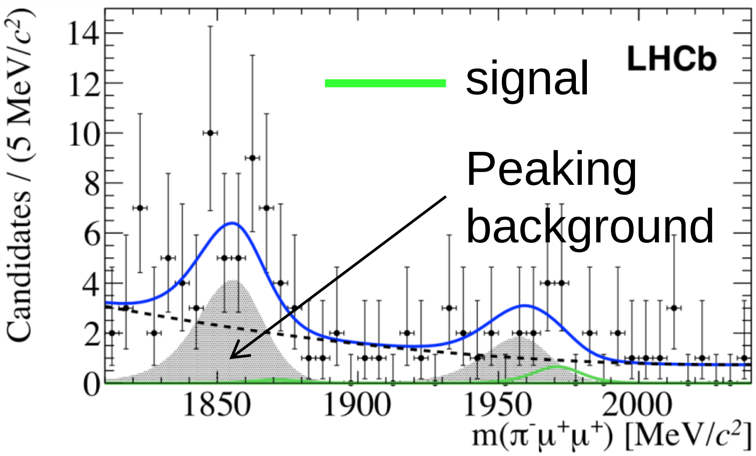
Limits for rare charm $D^+_{(s)} \to \pi^- \mu^+ \mu^+$

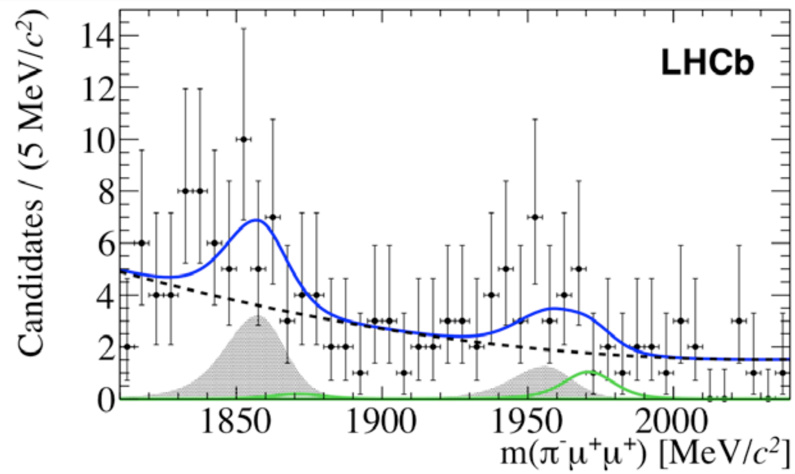
[arXiv:1304.6365]

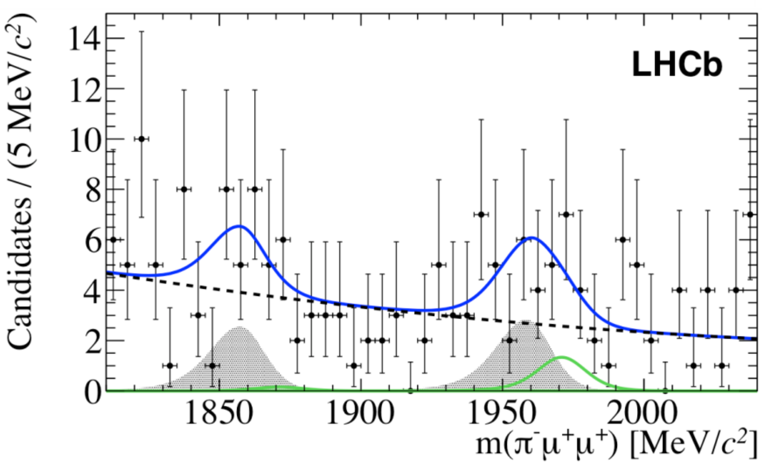
Limits set at 90 (95) % CL (extrapolate to total B using phase space model)

Also ~50x stronger than previous

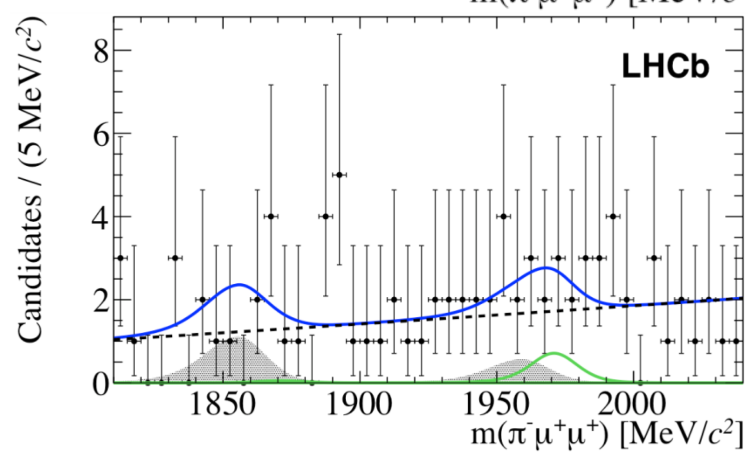
$$\mathcal{B}(D^+ \to \pi^- \mu^+ \mu^+) < 2.2\,(2.5) \times 10^{-8}$$
$$\mathcal{B}(D_s^+ \to \pi^- \mu^+ \mu^+) < 1.2\,(1.4) \times 10^{-7}$$







m



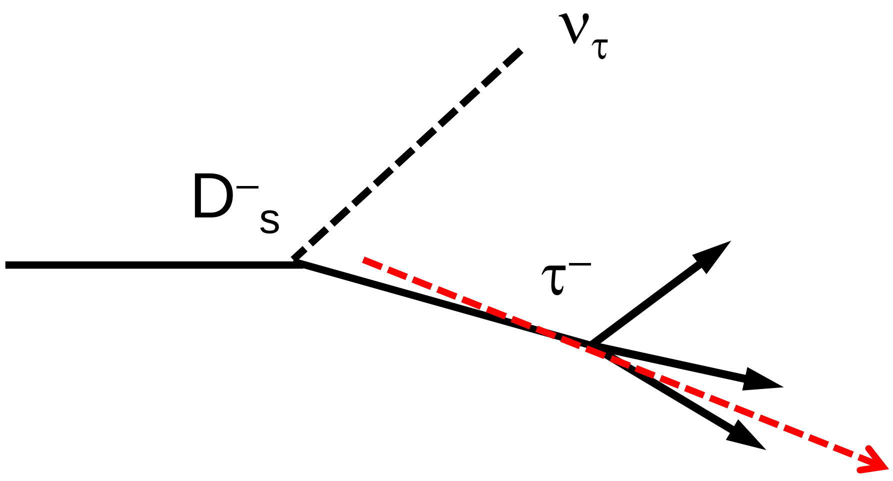
LFV and baryon number in τ decays

- Charged Lepton Flavour Violation and Baryon Number Violation would be clear signals of BSM physics
- τ are an ideal place for these studies
  - Large cross-section, inclusive ~ 80μb at LHC
- SM predictions for LFV, $\mathcal{B}$ <10^{-40}
  - We use $\tau^- \to \mu^-\mu^+\mu^-$
  - Current best limit (Belle) $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \times 10^{-8}$ @ 90%CL
- BNV
  - Studied in modes $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$
  - $|\Delta(B-L)| = 0$ in most models (angular momentum)
  - LFV follows
  - These modes never previously studied
- Calibration and normalisation mode $D_s^- \to \phi\pi^-$ ($\phi \to \mu^+\mu^-$)
- Discuss LFV in $\tau^- \to \mu^-\mu^+\mu^-$ then BNV in $\tau^- \to \bar{p}\mu^+\mu^-$

LFV in $\tau \rightarrow \mu\mu\mu$ decays

Selection

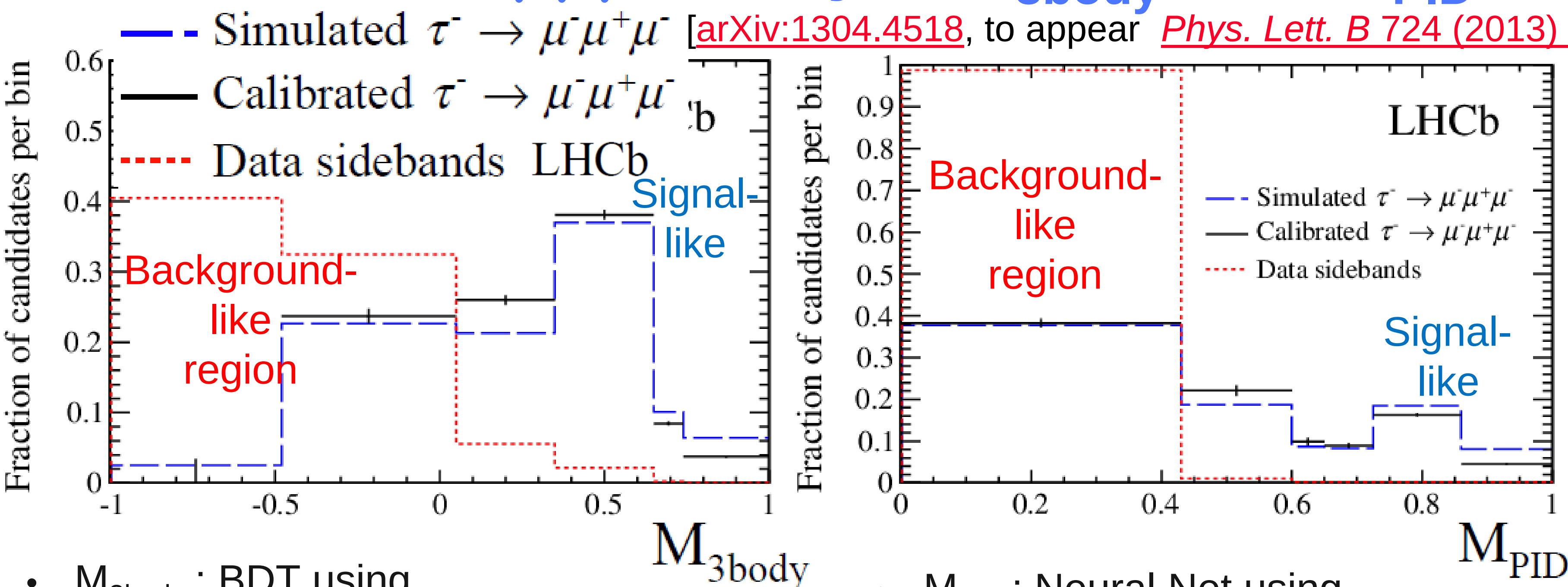
- Loose cut-based selection
- Blinded mass windows $\sim 3\sigma_m$ around m_τ
- Separate signal from background using 2 liklihoods & invariant mass
  - M_{3body}
    - 3 body decay topology
  - M_{PID}
    - Muon identification for 3 candidates
  - m_τ



- Decay vertex displaced from primary vertex
  - 3 good quality tracks, p_T>0.3GeV/c
  - Pointing of 3-track momentum consistent with flight direction (low Q-values)
- Decay time ~heavy meson or τ
- Invariant mass = m_τ ±20 MeV/c^2

LFV in $\tau \rightarrow \mu\mu\mu$ decays: M_{3body} and M_{PID}

[arXiv:1304.4518, to appear *Phys. Lett. B* 724 (2013) xx]

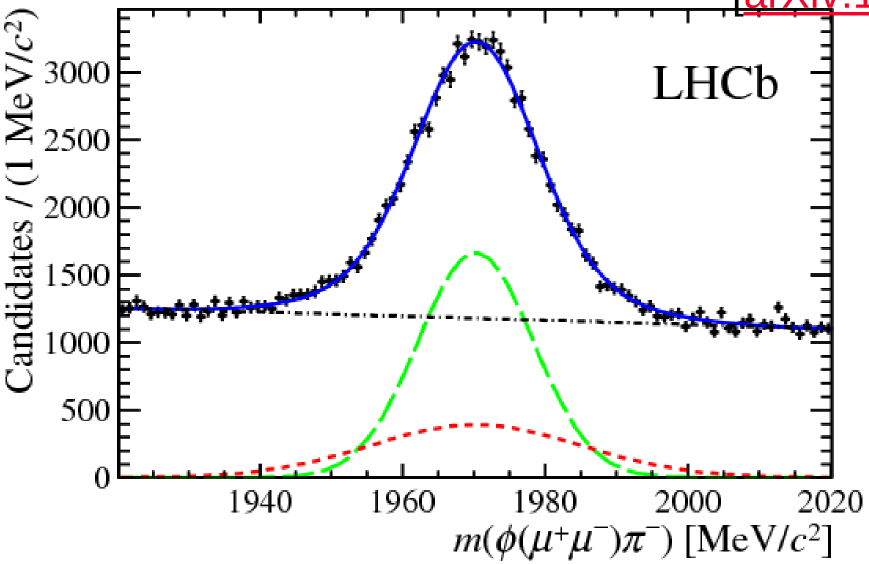


- M_{3body} : BDT using
  - Topology: vertex separation and pointing
  - Kinematics: p_T of τ
- Trained using MC for signal and background
  - Fractions of heavy quark backgrounds scaled to $D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-$ data
  - Calibrated with data
  - Binning iterated to optimise

- M_{PID} : Neural Net using
  - Quantify each of 3 particles compatibility with m (RICH, CALO, MUON)
  - Lowest value of 3 particles
- Calibrated using $J/\psi \rightarrow \mu^+\mu^-$ data
- Lowest M_{3body} and M_{PID} bins
  - Do not improve expected sensitivity
  - → removed

LFV in τ → μμμ decays: invariant mass

[arXiv:1304.4518, to appear in *Phys. Lett. B* 724 (2013) xx]

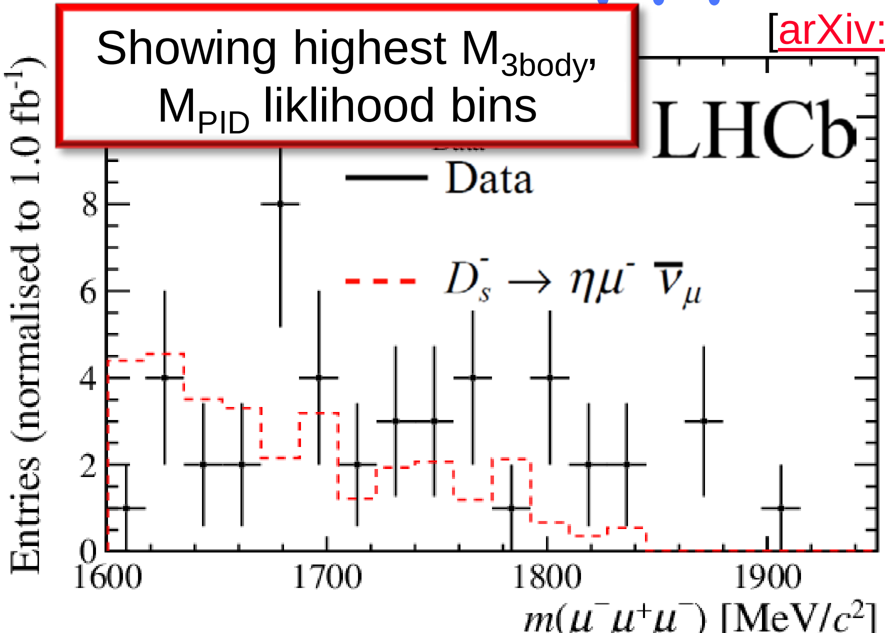


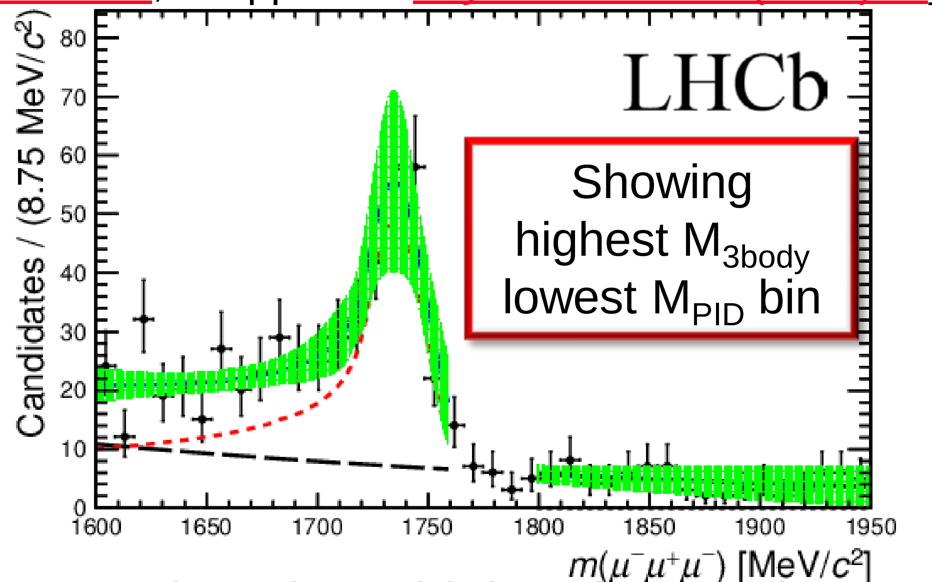
- Fit also gives yield of normalisation mode
- Additional mass cuts to eliminate specific backgrounds

- Signal
  - Shape from 2 Gaussian fit (common mean) to $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ data
  - Narrower Gaussian accounts for ~70% of yield
  - Widths from signal MC scaled by data/MC for $D_s^- \to \phi(\mu^+\mu^-)\pi^-$

LFV in τ → μμμ decays: backgrounds

[arXiv:1304.4518, to appear in *Phys. Lett. B* 724 (2013) xx]



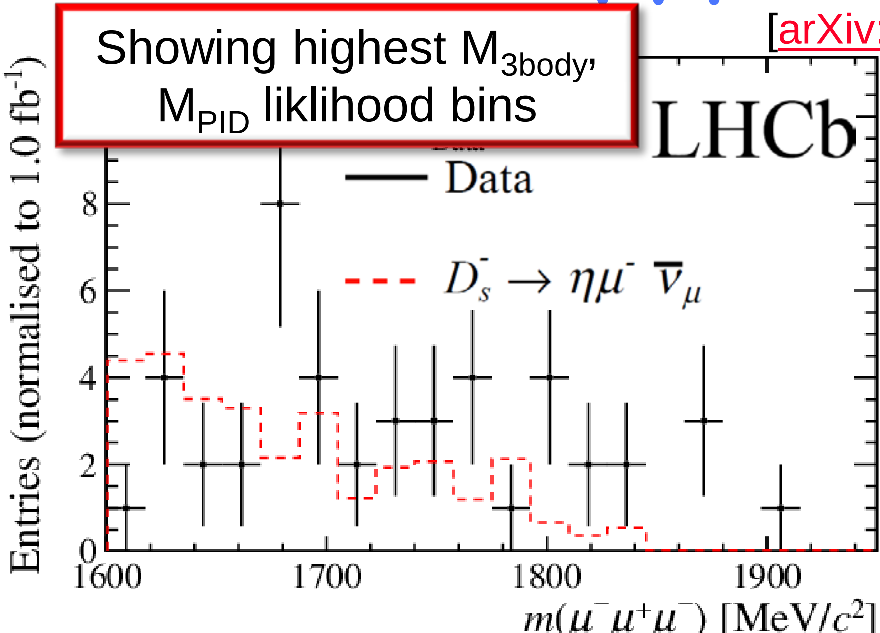


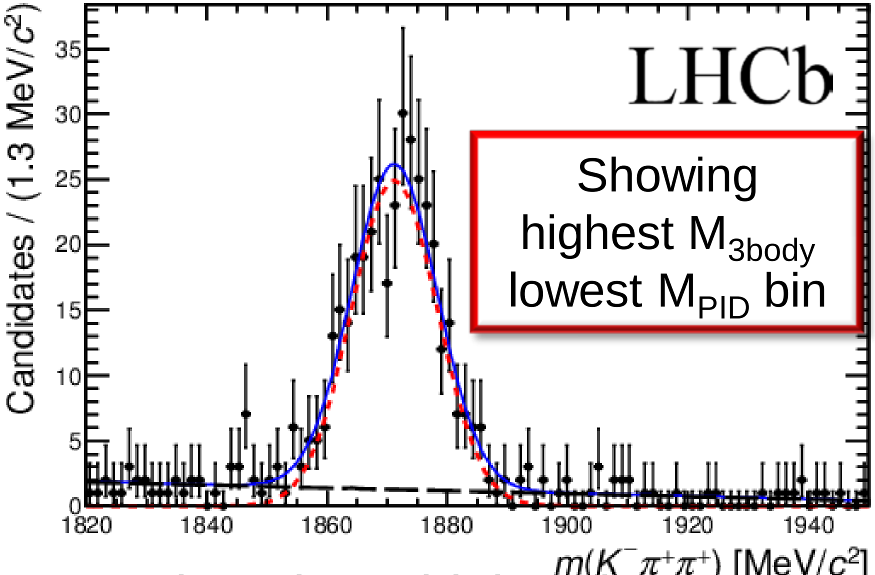
- Dominant background is combinatorial in final selection
  - Linear functions
- Peaking backgrounds
  - 3 real muons $D_s^- \rightarrow \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$
  - Irreducible contribution
  - Reject if any μμ mass<450MeV/c2
  - Fit remaining ~20% of this as linear

- Fit to data sidebands to estimate background in signal box
- Strong peaking background from 3 particles mis-identified as muons (lowest M_{PID} bin)

LFV in τ → μμμ decays: backgrounds

[arXiv:1304.4518, to appear in *Phys. Lett. B* 724 (2013) xx]





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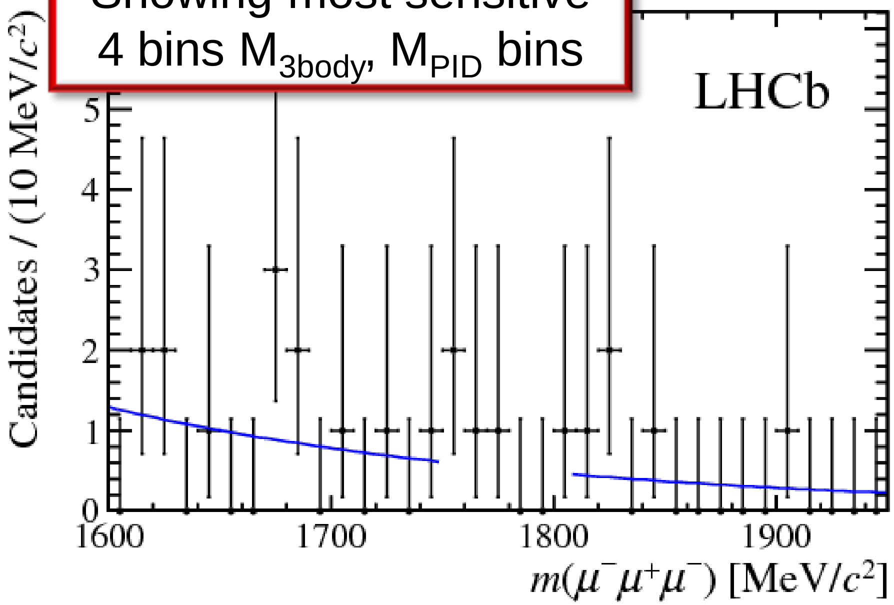
  - Irreducible contribution
  - Reject if any μμ mass<450MeV/c2
  - Fit remaining ~20% of this as linear

- Fit to data sidebands to estimate background in signal box
- Strong peaking background from 3 particles mis-identified as muons (lowest M_{PID} bin)
- Refit with $K^-\pi^+\pi^+$ hypothesis
- Justifies exclusion of lowest M_{PID} bin

LFV in τ → μμμ decays: backgrounds

[arXiv:1304.4518, to appear in *Phys. Lett. B* 724 (2013) xx]

Showing most sensitive 4 bins M_{3body}, M_{PID} bins



- No peaking background remains
  - Treat as exponential, interpolate to signal region (~1760-1800 MeV/c^2)
- Normalisation relative to $D_s^- \to \phi(\mu^+\mu^-)\pi^-$
  - ~48k selected
- Correction factor ... absolute σ or lumi required), signal/calibration
- Other factors from data (LHCb, PDG, BaBar

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \mathcal{B}(D_s^- \to \phi(\mu^+\mu^-)\pi^-) \times \frac{f_\tau^{D_s}}{\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)} \times \frac{\epsilon_{\rm cal}^{\rm REC\&SEL}}{\epsilon_{\rm sig}^{\rm REC\&SEL}} \times \frac{\epsilon_{\rm cal}^{\rm TRIG}}{\epsilon_{\rm sig}^{\rm TRIG}} \times \frac{N_{\rm sig}}{N_{\rm cal}} = \alpha \times N_{\rm sig}\,,$$

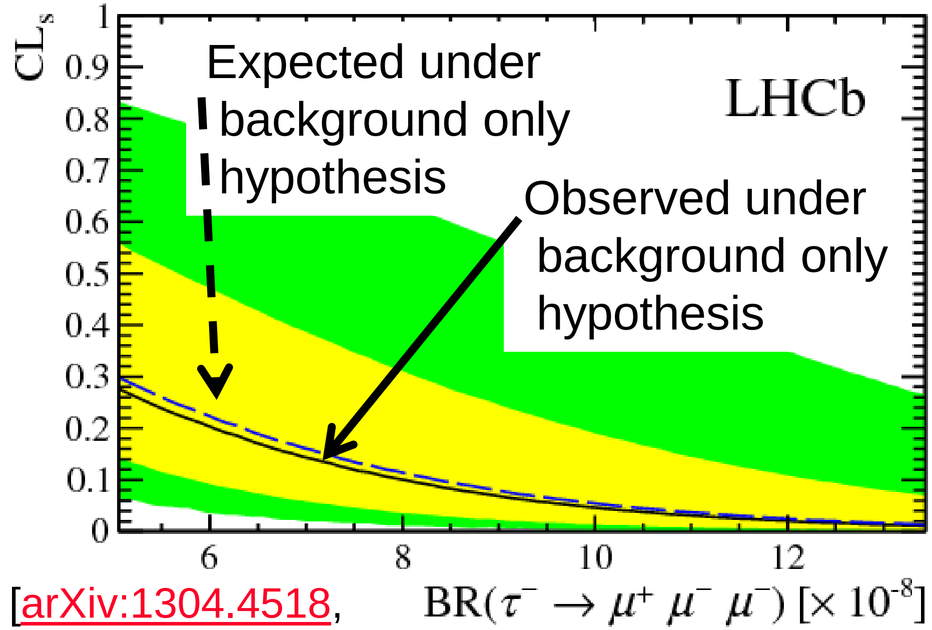
Normalisation for τ → μμμ , pμ⁺μ⁻ decays

	$\tau^- \to \mu^-\mu^+\mu^-$	$\tau^- \to \bar{p}\mu^+\mu^-$	$\tau^- \to p\mu^-\mu^-$
$\mathcal{B}(D_s^- \to \phi(\mu^+\mu^-)\pi^-)$	$(1.33 \pm 0.12) \times 10^{-5}$		
$f_\tau^{D_s}$	0.78 ± 0.05		
$\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)$	0.0561 ± 0.0024		
$\epsilon_{\rm cal}{}^{\rm REC\&SEL}/\epsilon_{\rm sig}{}^{\rm REC\&SEL}$	1.49 ± 0.12	1.35 ± 0.12	1.36 ± 0.12
$\epsilon_{\rm cal}{}^{\rm TRIG}/\epsilon_{\rm sig}{}^{\rm TRIG}$	0.753 ± 0.037	1.68 ± 0.10	2.03 ± 0.13
$\epsilon_{\rm cal}{}^{\rm PID}/\epsilon_{\rm sig}{}^{\rm PID}$	n/a	1.43 ± 0.07	1.42 ± 0.08
$N_{\rm cal}$	$48\,076 \pm 840$	$8\,145 \pm 180$	
α	$(4.34 \pm 0.65) \times 10^{-9}$	$(7.4 \pm 1.2) \times 10^{-8}$	$(9.0 \pm 1.5) \times 10^{-8}$

$$
\begin{aligned}
\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) \\
&= \mathcal{B}(D_s^- \to \phi(\mu^+\mu^-)\pi^-) \times \frac{f_\tau^{D_s}}{\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)} \times \frac{\epsilon_{\rm cal}^{\rm REC\&SEL}}{\epsilon_{\rm sig}^{\rm REC\&SEL}} \times \frac{\epsilon_{\rm cal}^{\rm TRIG}}{\epsilon_{\rm sig}^{\rm TRIG}} \times \frac{N_{\rm sig}}{N_{\rm cal}} \\
&= \alpha \times N_{\rm sig} \,,
\end{aligned}
$$

Limits

$\mathcal{M}_{\mathrm{PID}}$	$\mathcal{M}_{\mathrm{3body}}$	Expected	Observed
0.43 – 0.6	−0.48 – 0.05	345.0 ± 6.7	409
	0.05 – 0.35	83.8 ± 3.3	68
	0.35 – 0.65	30.2 ± 2.0	35
	0.65 – 0.74	4.3 ± 0.8	2
	0.74 – 1.0	1.4 ± 0.4	1
0.6 – 0.65	−0.48 – 0.05	73.1 ± 3.1	64
	0.05 – 0.35	18.3 ± 1.5	15
	0.35 – 0.65	8.6 ± 1.1	7
	0.65 – 0.74	0.4 ± 0.1	0
	0.74 – 1.0	0.6 ± 0.2	2
0.65 – 0.725	−0.48 – 0.05	45.4 ± 2.4	51
	0.05 – 0.35	11.7 ± 1.2	6
	0.35 – 0.65	5.3 ± 0.8	3
	0.65 – 0.74	0.8 ± 0.2	1
	0.74 – 1.0	0.4 ± 0.1	0
0.725 – 0.86	−0.48 – 0.05	44.5 ± 2.4	62
	0.05 – 0.35	10.6 ± 1.2	13
	0.35 – 0.65	7.3 ± 1.0	7
	0.65 – 0.74	1.0 ± 0.2	2
	0.74 – 1.0	0.4 ± 0.1	0
0.86 – 1.0	−0.48 – 0.05	5.9 ± 0.9	7
	0.05 – 0.35	0.7 ± 0.2	1
	0.35 – 0.65	1.0 ± 0.2	1
	0.65 – 0.74	0.5 ± 0.0	0
	0.74 – 1.0	0.4 ± 0.1	0



[arXiv:1304.4518, to appear in *Phys. Lett. B 724 (2013) xx*]

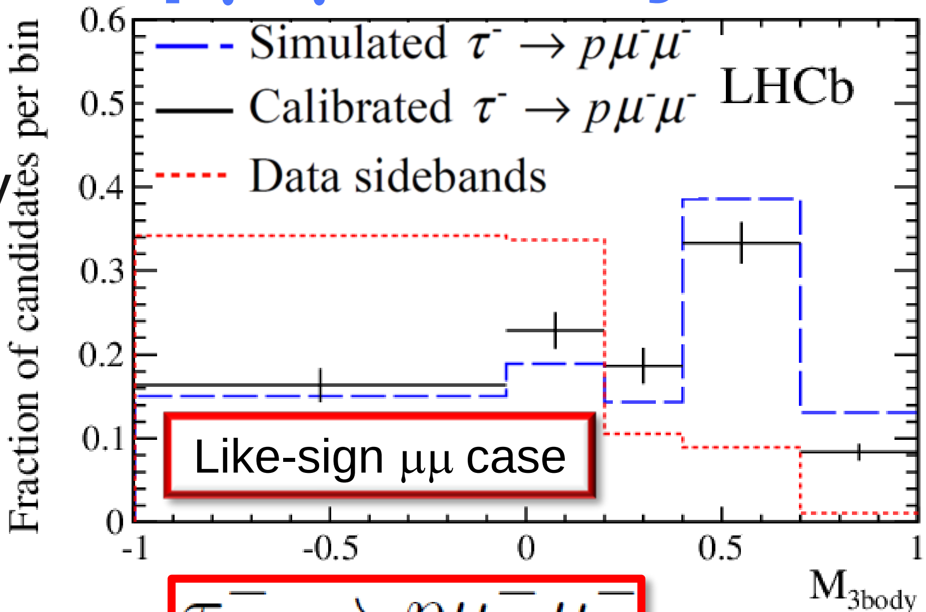
- No excess in signal region, set 90 (95)% CL

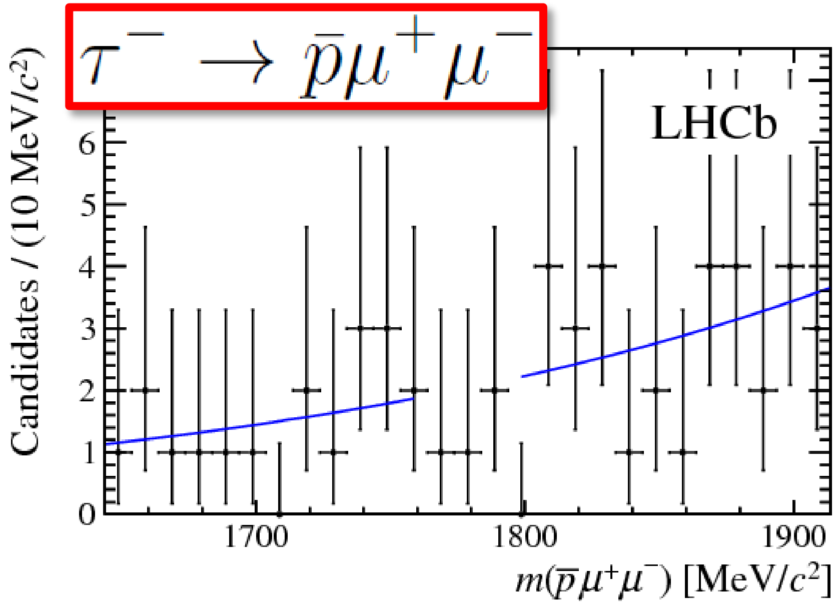
$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) \; < \; 8.0\ (9.8) \times 10^{-8}$$

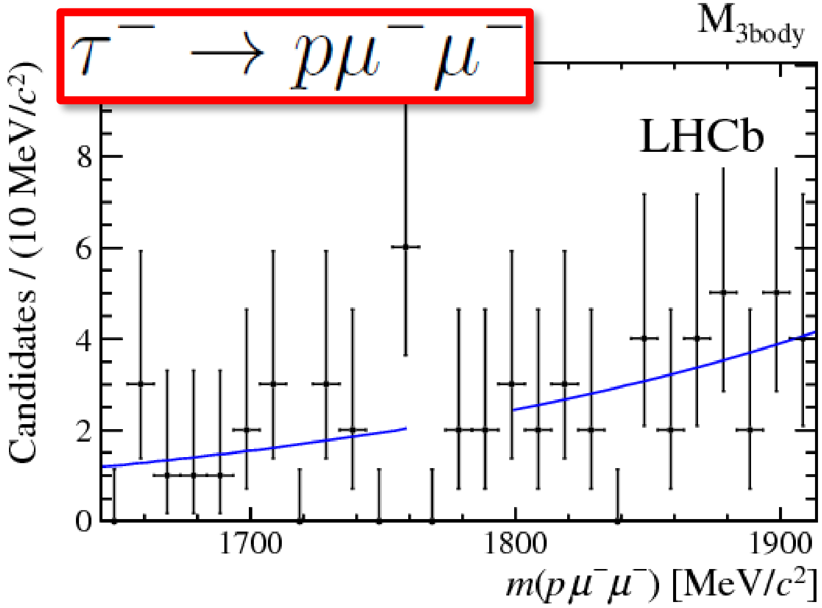
- Phase space decay model
- Compatible with tighter Belle limit
- 1st limit set at hadron collider

LFV/BNV in $\tau^+ \rightarrow p\mu^+\mu^-$ decays

- Very similar to 3 μ mode
- Differs by replacing M_{PID} by cuts
- Also no significant signal found



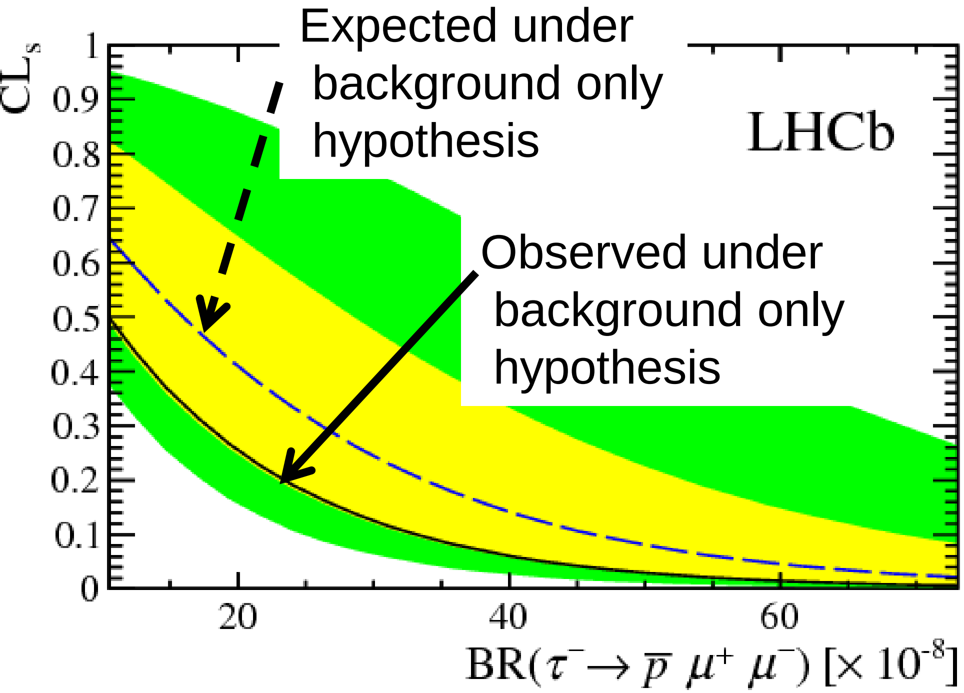




Limits

[arXiv:1304.4518, to appear in *Phys. Lett. B* 724 (2013) xx]

	$\tau^- \to \bar{p}\mu^+\mu^-$		$\tau^- \to p\mu^-\mu^-$	
$\mathcal{M}_{3\text{body}}$	Expected	Observed	Expected	Observed
$-0.05 - 0.20$	37.9 ± 0.8	43	41.0 ± 0.9	41
$0.20 - 0.40$	12.6 ± 0.5	8	11.0 ± 0.5	13
$0.40 - 0.70$	6.76 ± 0.37	6	7.64 ± 0.39	10
$0.70 - 1.00$	0.96 ± 0.14	0	0.49 ± 0.12	0

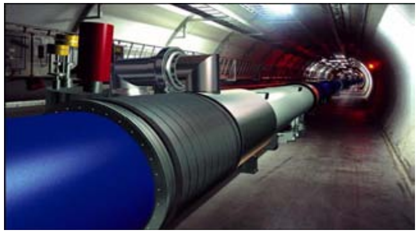


- No significant excess in signal region, set 90 (95)% CL
- 1st limits set on this mode

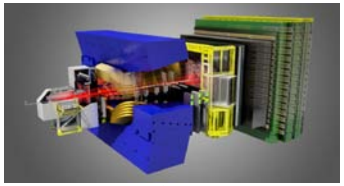
$$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3\ (4.3) \times 10^{-7}$$
$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4\ (5.7) \times 10^{-7}$$

Conclusions

- Rare decays are one of the best ways to search for physics beyond the Standard Model



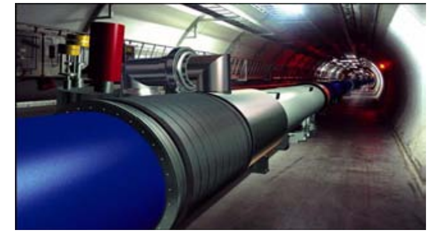
- LHC provides the enabling b production rates
- LHCb are exploiting these to stress-test the SM and relatives



- Several of measurements presented are world's best ☺
- The SM is (so far) consistent with the data ☹
- In all cases we have 2x more data already under study
- Still chance for discovery (discoveries?)

Conclusions

- Rare decays are one of the best ways to search for physics beyond the Standard Model



- LHC provides the enabling b production rates
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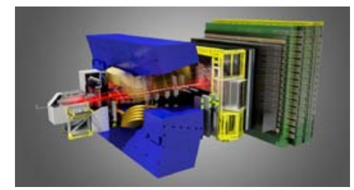
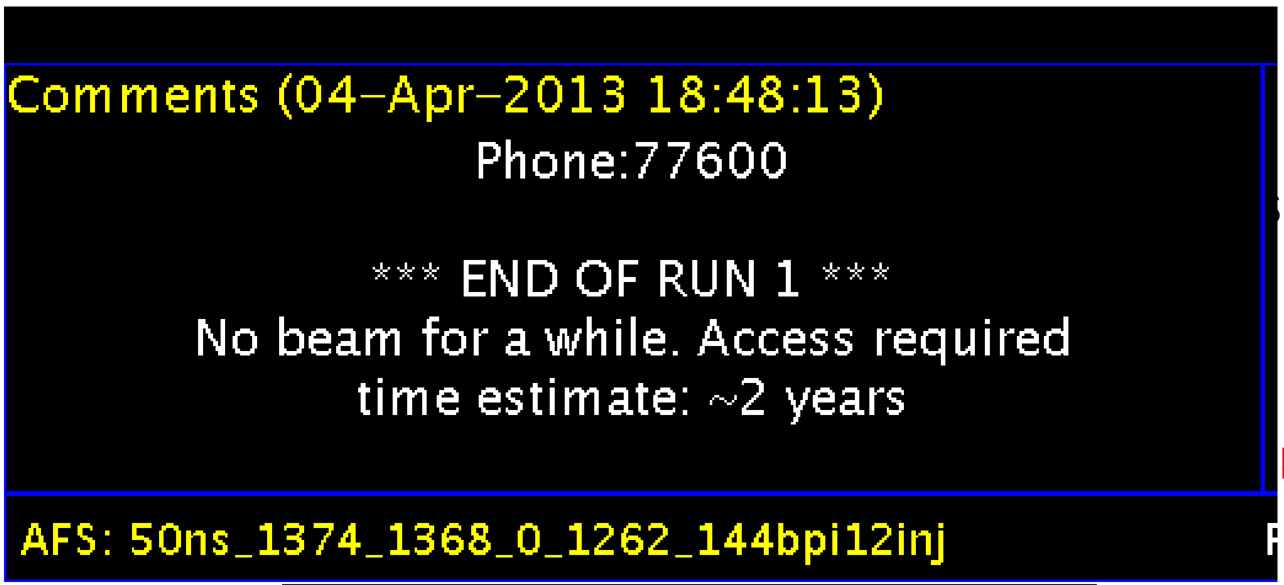


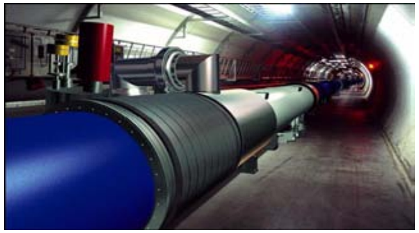


- s best ☺
-
- r study
- Still chan

More data coming soon

Conclusions

- Rare decays are one of the best ways to search for physics beyond the Standard Model



- LHC provides the enabling b production rates
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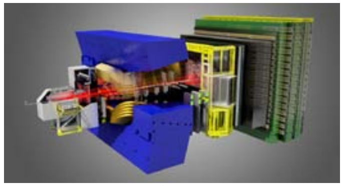


- Several of measurements presented are world's best ☺
- The SM is (so far) consistent with the data ☹
- In all cases we have 2x more data already under study
- Still chance for discovery (discoveries?)

Backup

Limits for rare charm $D^+_{(s)} \to \pi^+\mu^+\mu^-$

[arXiv:1304.6365]

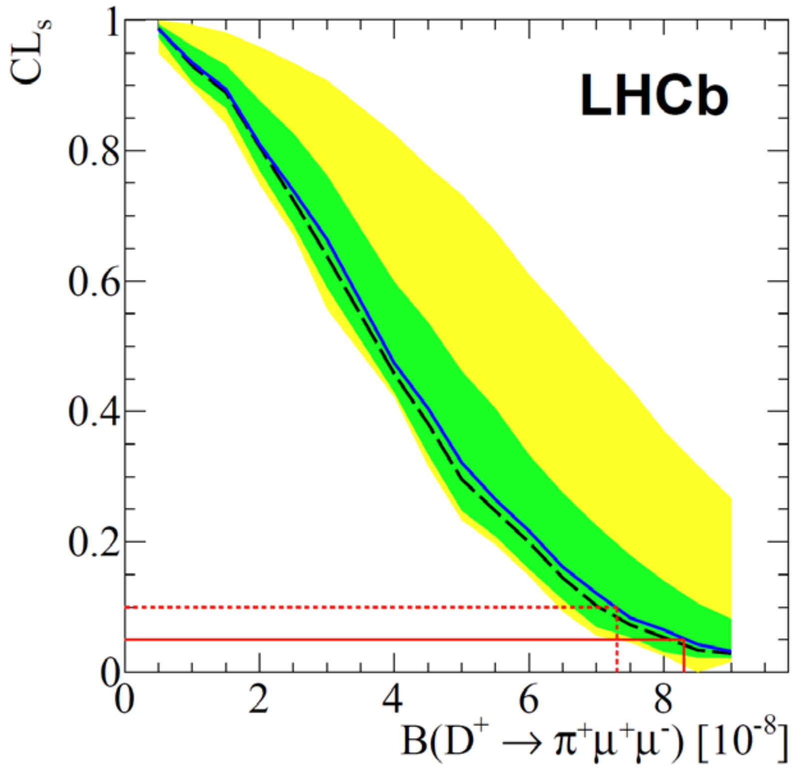


Figure 5: Observed (solid curve) and expected (dashed curve) CL_s values as a function of $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$. The green (yellow) shaded area contains the $\pm1\sigma$ ($\pm2\sigma$) interval of possible results compatible with the expected value if only background is observed. The upper limits at the 90% (95%) CL are indicated by the dashed (solid) line.

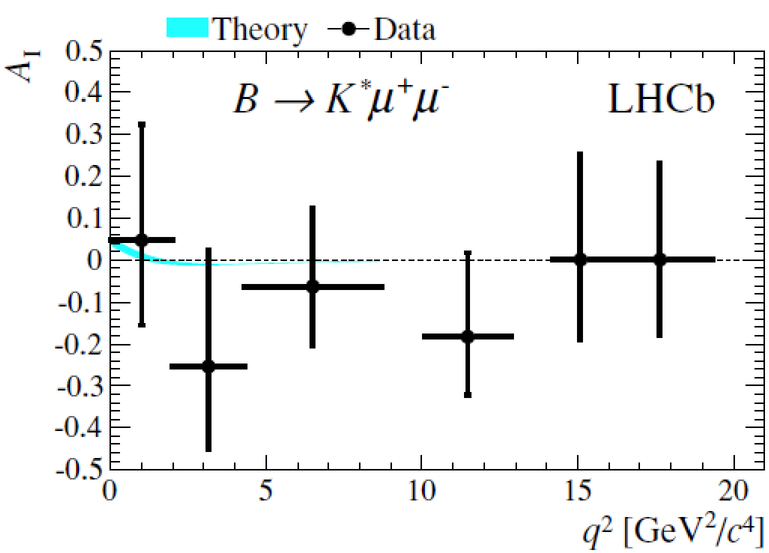
$B^0 \rightarrow K^* \mu^+ \mu^-$ isospin asymmetry I

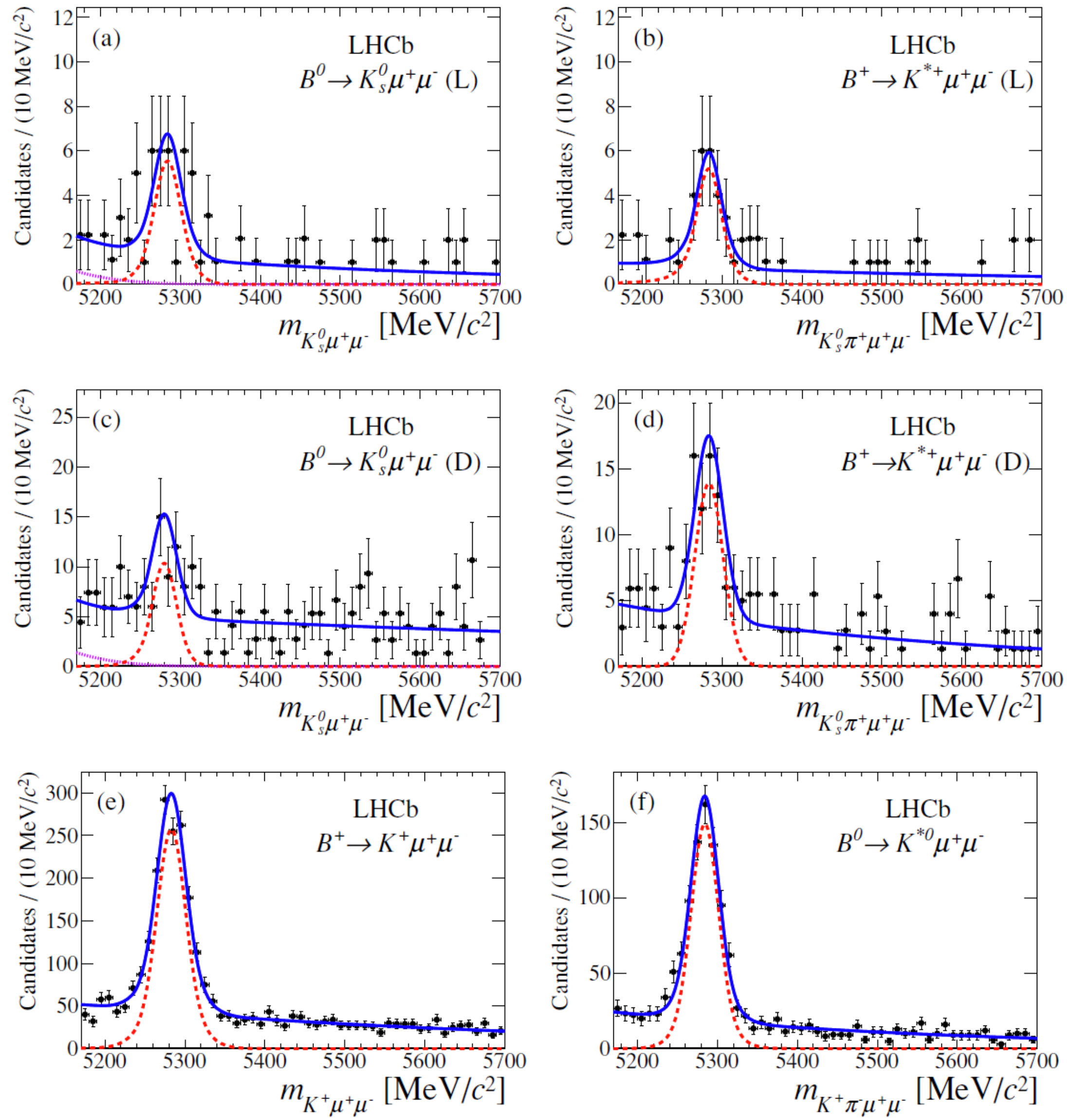
[JHEP07(2012)133]

$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}}$$

$$\mathcal{B}(B^0 \to K^0\mu^+\mu^-) = (0.31^{+0.07}_{-0.06}) \times 10^{-6}$$

$$\mathcal{B}(B^+ \to K^{*+}\mu^+\mu^-) = (1.16 \pm 0.19) \times 10^{-6}$$





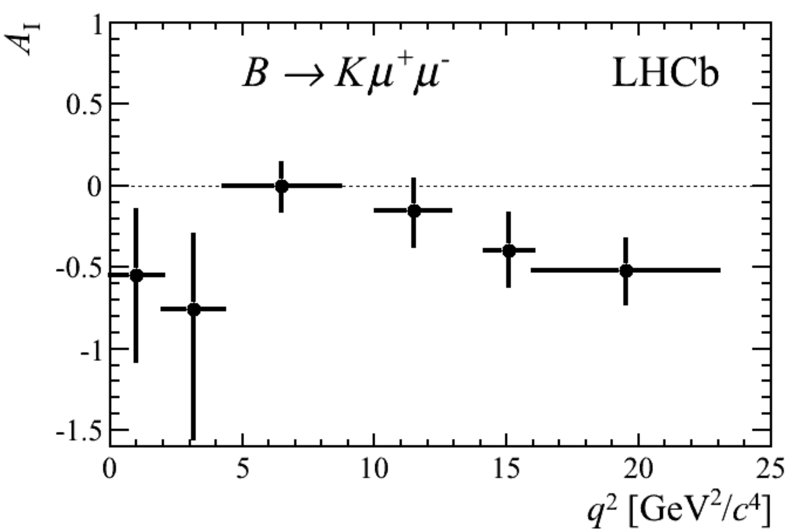
$B^0 \to K^* \mu^+ \mu^-$ isospin asymmetry II

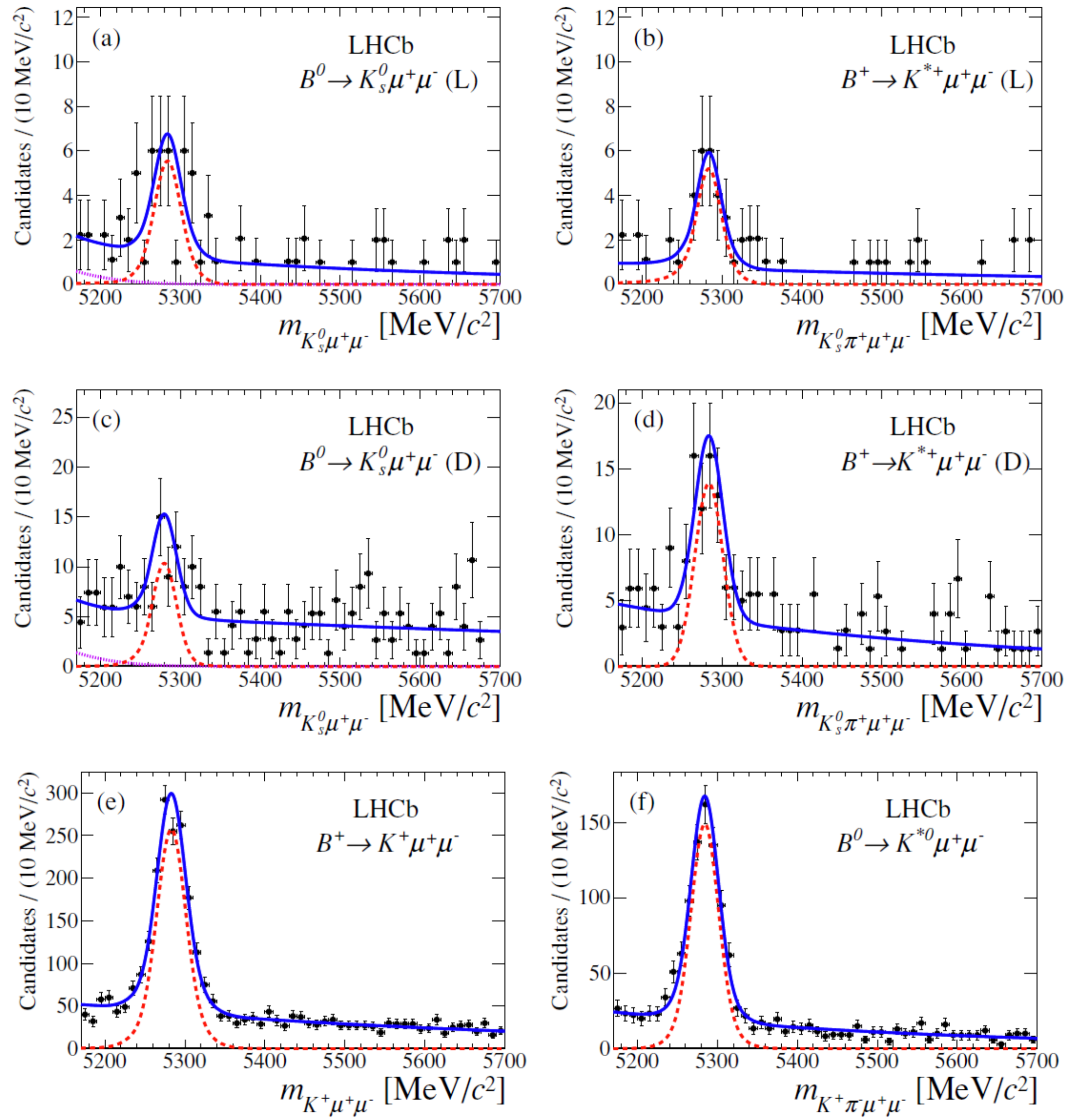
[JHEP07(2012)133]

$$A_{\rm I} = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}}$$

$$\mathcal{B}(B^0 \to K^0 \mu^+\mu^-) = (0.31^{+0.07}_{-0.06}) \times 10^{-6}$$

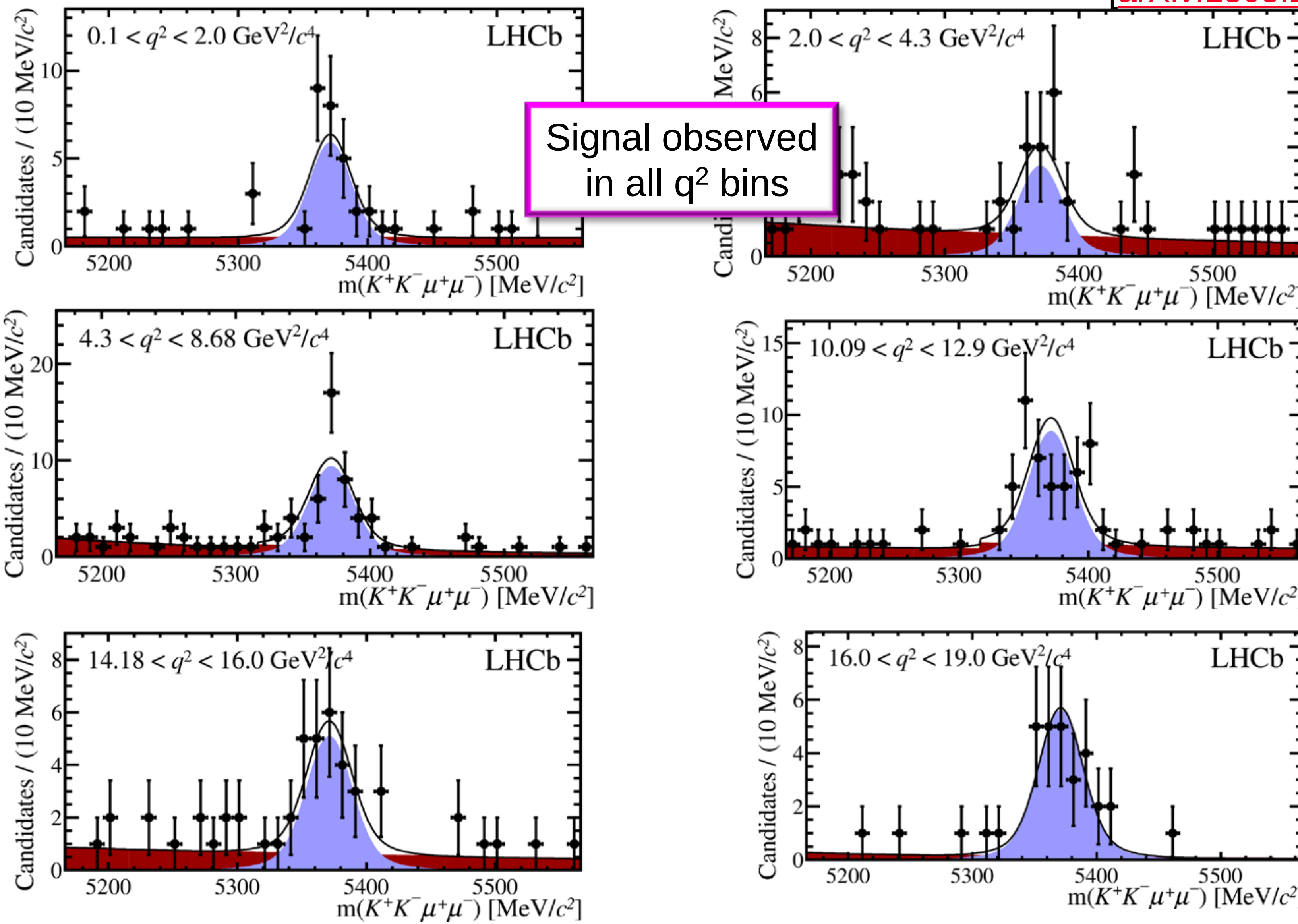
$$\mathcal{B}(B^+ \to K^{*+} \mu^+\mu^-) = (1.16 \pm 0.19) \times 10^{-6}$$





$B^0_s \rightarrow \phi\mu^+\mu^-$ branching fraction

[arXiv:1305.2168]



Signal observed in all q^2 bins

Search for decay $B^0_s \to D^{*\mp}\pi^{\pm}$

- Not covered today

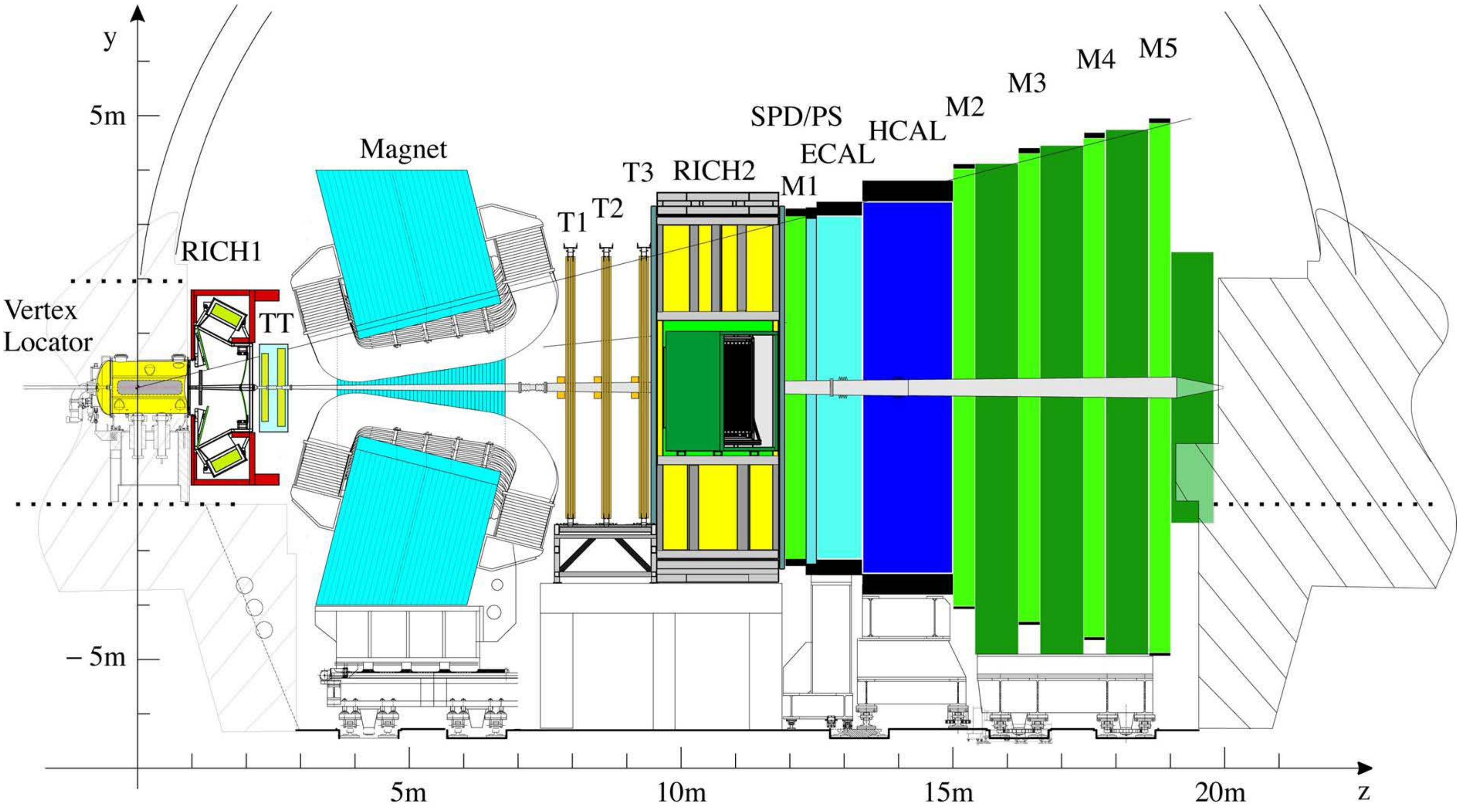
First observation of the decay $B^+ \to \pi^+ \mu^+ \mu^-$

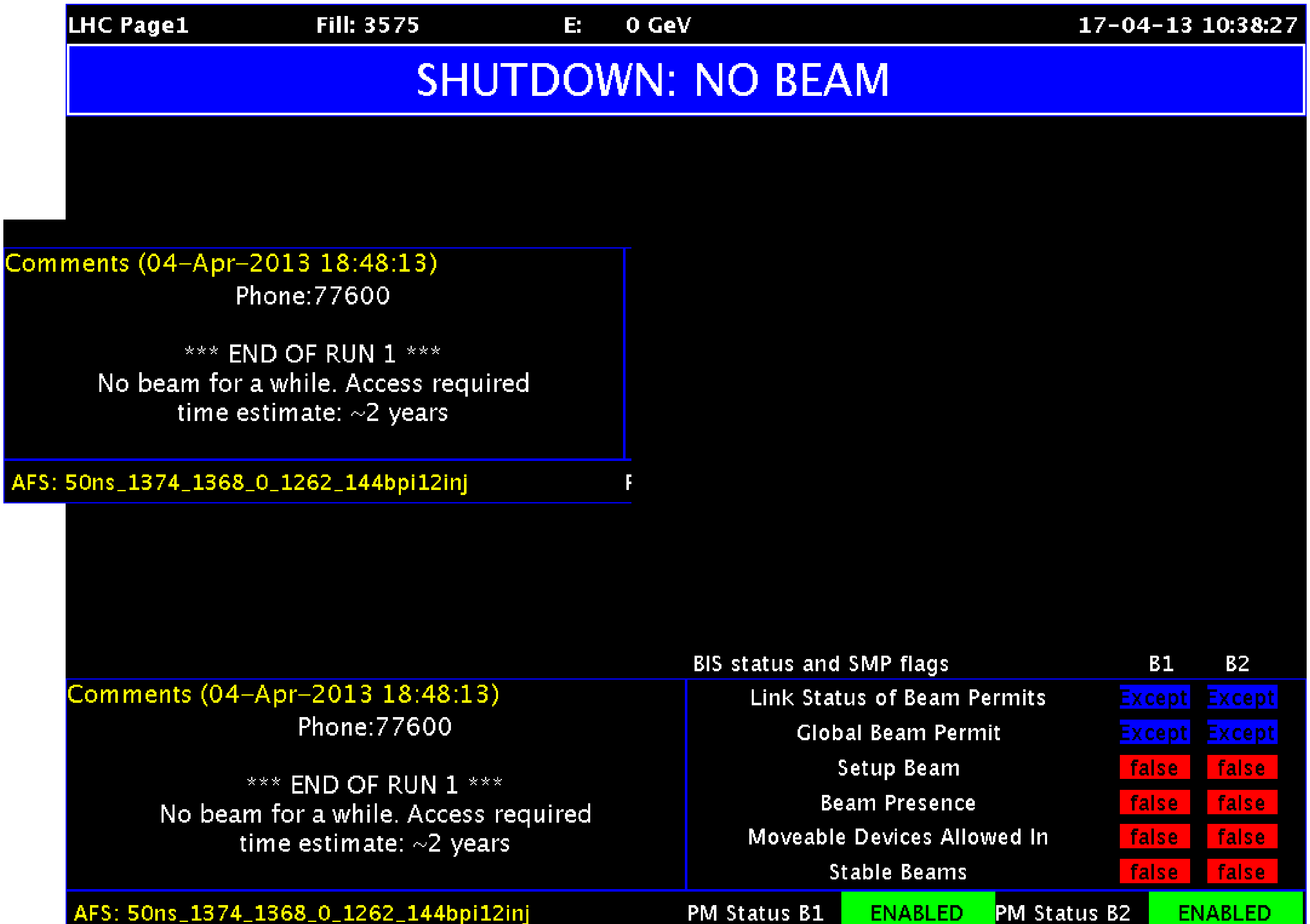
- Not covered today

Search for the rare decay $D^0 \to \mu^+\mu^-$

- Not covered today, see Indrek

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2\,(7.6) \times 10^{-9} \ \text{at} \ 90\% \ \ (95\%) \ \text{confidence level}$$


y
5m
− 5m
Magnet
RICH1
Vertex
Locator
TT
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z


LHC Page1
Fill: 3575
E: 0 GeV
17-04-13 10:38:27
SHUTDOWN: NO BEAM
Comments (04-Apr-2013 18:48:13)
Phone:77600
*** END OF RUN 1 ***
No beam for a while. Access required
time estimate: ~2 years
AFS: 50ns_1374_1368_0_1262_144bpi12inj
Comments (04-Apr-2013 18:48:13)
Phone:77600
*** END OF RUN 1 ***
No beam for a while. Access required
time estimate: ~2 years
AFS: 50ns_1374_1368_0_1262_144bpi12inj
BIS status and SMP flags
B1
B2
Link Status of Beam Permits
Except
Except
Global Beam Permit
Except
Except
Setup Beam
false
false
Beam Presence
false
false
Moveable Devices Allowed In
false
false
Stable Beams
false
false
PM Status B1
ENABLED
PM Status B2
ENABLED