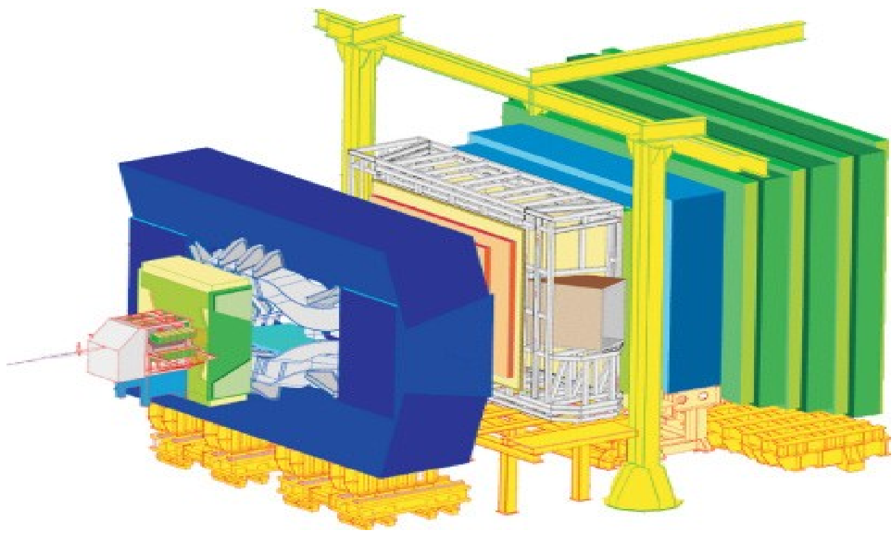
# Searches for New Physics with the LHCb experiment

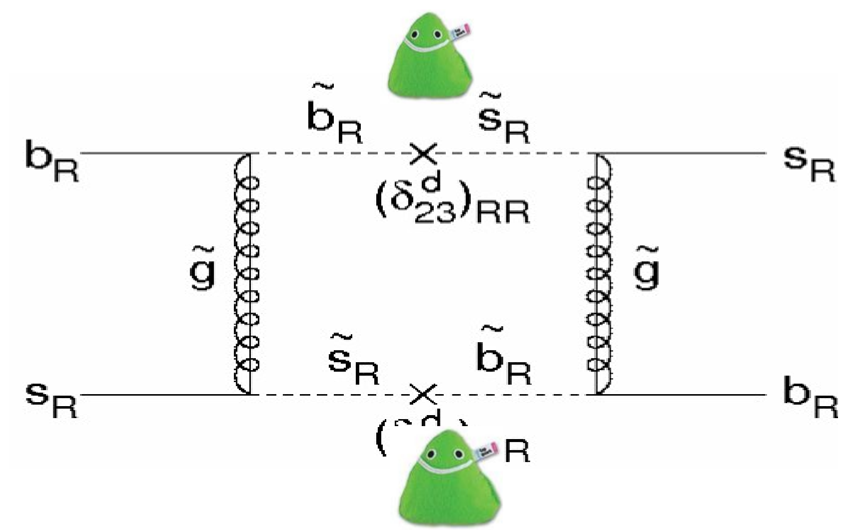


Amsterdam Particle Physics Symposium
November 30$^{th}$ – December 2$^{nd}$ 2011

Wouter Hulsbergen (Nikhef)
on behalf of the LHCb collaboration

# Two frontiers in the search for New Physics

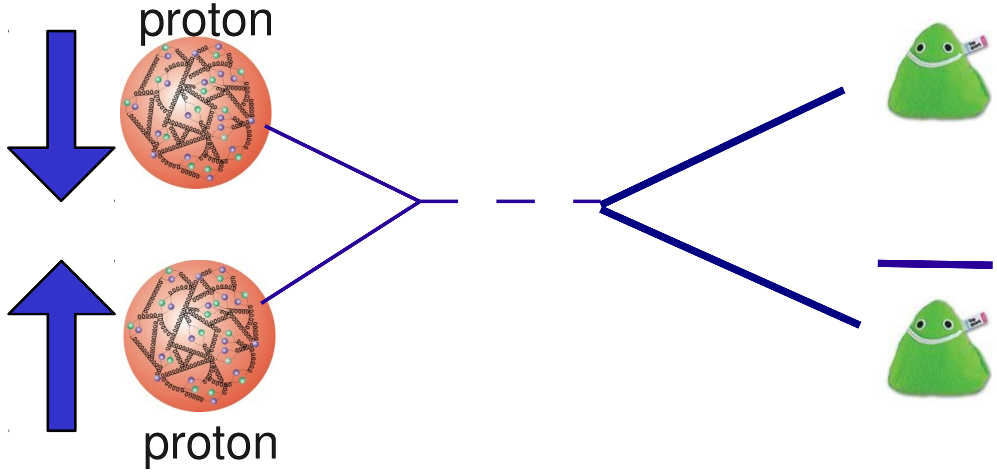
## 1. the *virtual* energy frontier




discovery of NP in
low-energy observables

selected topics:
* CPV in mixing
* lepton flavour violation

## 2. the *absolute* energy frontier



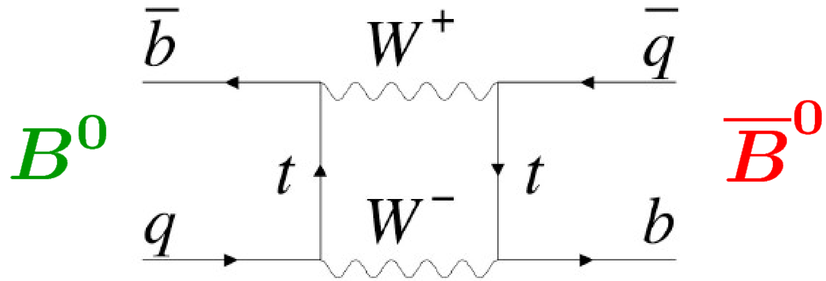

discovery of NP by direct
production of new particles

'complementary' to GPDs:
forward acceptance

selected topics (plans only):
* top
* long-lived heavy particles

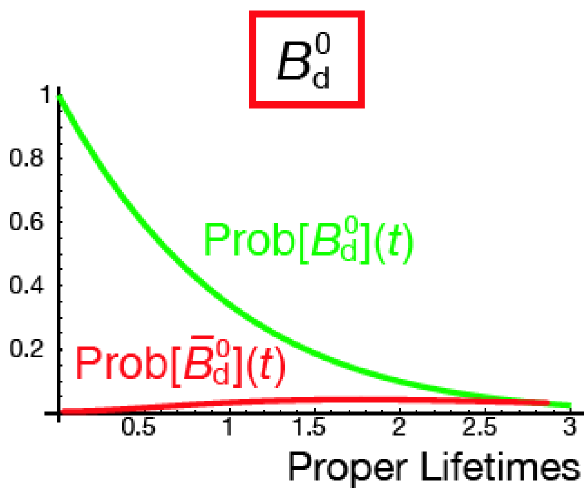
# Neutral meson mixing

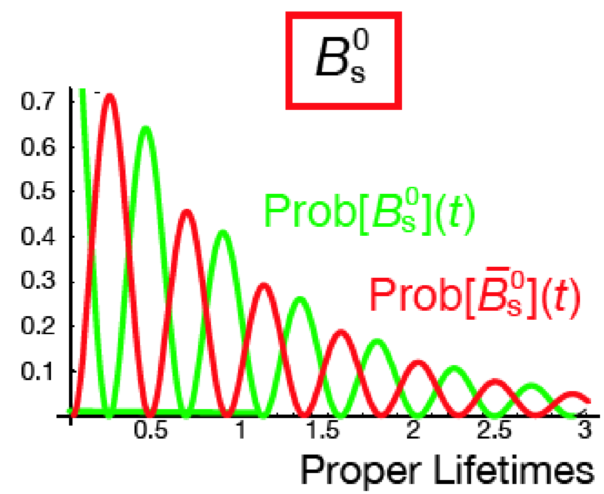
- neutral meson flavour states mix via this loop diagram




- heavy (H) and light (L) mass eigenstates are mixture of flavour states

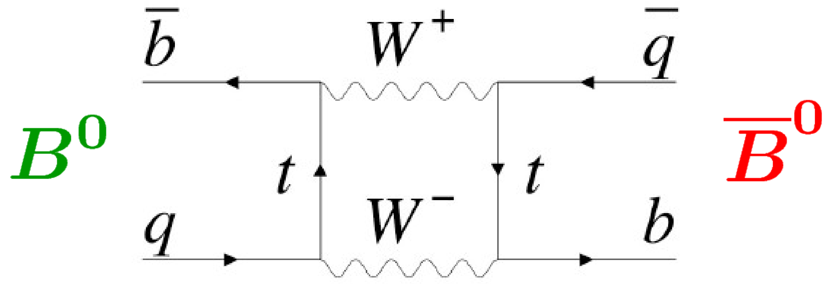
$$
\begin{aligned}
|B_L\rangle &= p\,|B^0\rangle + q\,|\overline{B}^0\rangle \\
|B_H\rangle &= p\,|B^0\rangle - q\,|\overline{B}^0\rangle
\end{aligned}
$$



# Neutral meson mixing

- neutral meson flavour states mix via this loop diagram




- phenomenology described in terms of 5 observables

$$\boxed{m \equiv \frac{m_H + m_L}{2}} \qquad \boxed{\Gamma \equiv \frac{\Gamma_H + \Gamma_L}{2}} \qquad \boxed{\Delta m \equiv m_H - m_L \simeq 2|M_{12}|}$$

$$\boxed{\Delta\Gamma \equiv \Gamma_L - \Gamma_H \simeq 2|\Gamma_{12}| \cos\tilde{\phi}} \qquad \boxed{1 - \left|\frac{q}{p}\right|^2 \simeq \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\tilde{\phi}}$$

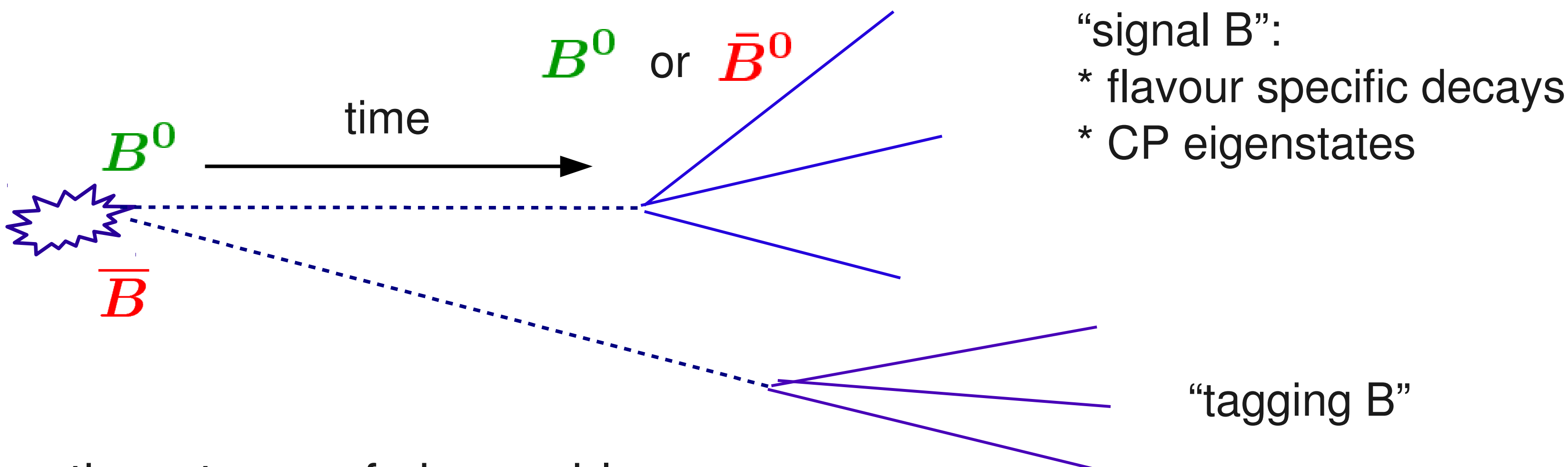
**CP violation, small in SM**

**clean predictions in SM**

- M12 and $\Gamma$12: mixing amplitudes via off-shell and on-shell states, respectively
- CP violating phase $\tilde{\phi}$ is their relative phase: $\tilde{\phi} = \arg(-M_{12}/\Gamma_{12})$
  - in SM close to zero both in Bs and Bd system

# Experimental observables in B mixing

- decay time allows to observe time-evolution




- three types of observables

1. oscillation frequency:

$$\boxed{A^{\text{mix}}(t) = \frac{N^{B^0\overline{B}^0|\overline{B}^0B^0} - N^{B^0B^0|\overline{B}^0\overline{B}^0}}{N^{B^0\overline{B}^0|\overline{B}^0B^0} + N^{B^0B^0|\overline{B}^0\overline{B}^0}} = \cos(\Delta m_q t)}$$

2. CPV in mixing:

$$\boxed{a_{fs} \equiv \frac{N^{B^0B^0} - N^{\overline{B}^0\overline{B}^0}}{N^{B^0B^0} + N^{\overline{B}^0\overline{B}^0}} = \frac{1 - |q/p|^4}{1 + |q/p|^4}}$$

3. CPV in interference between mixing and decay (next slide)

# Time-dependent CPV

- common final state ➔ **mixing induced CPV**

$$\begin{tikzcd} B^0 \arrow[rr, "\phi_{\mathrm{D}}"] \arrow[dr, "\phi_M"'] & & \boldsymbol{f} \\ & \overline{B^0} \arrow[ur, "-\phi_{\mathrm{D}}"'] & \end{tikzcd}$$

- if ***f*** is *CP eigenstate*, time dependent CP violation with pattern

$$\boxed{A_{CP}(t) \equiv \frac{N(\overline{B}^0 \to f) - N(B^0 \to f)}{N(\overline{B}^0 \to f) + N(B^0 \to f)} = \sin\phi_f \ \sin(\Delta m_q t)}$$

$$\phi_f = \phi_M - 2\phi_D$$

- 'golden' modes:

$$B_d \to \psi K_s : \quad \phi_{J/\psi K_s} = 2\beta \stackrel{SM}{=} 50° - 55°$$

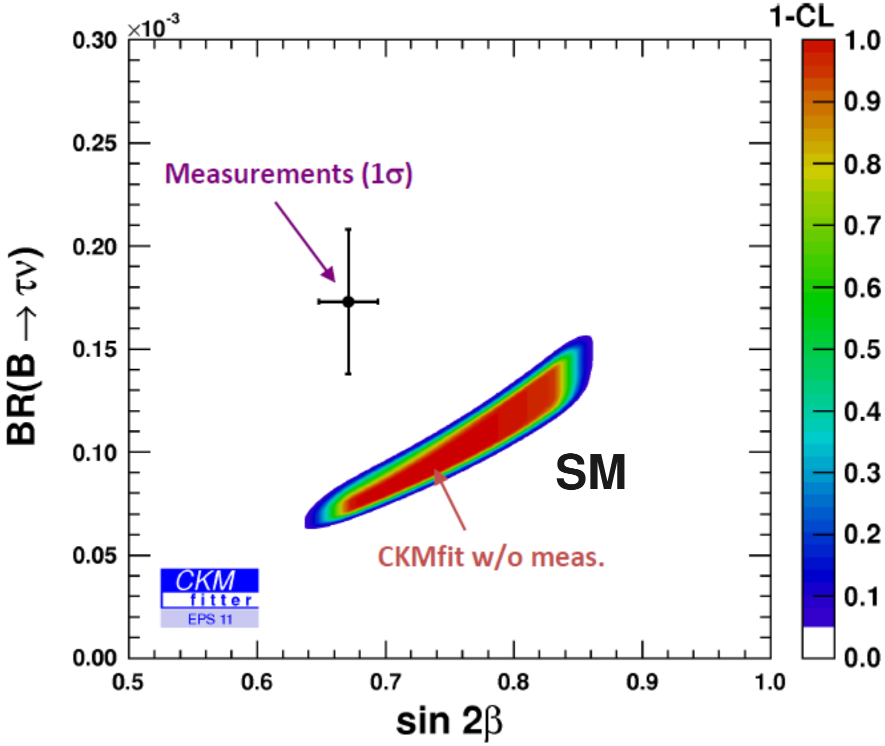
$$B_s \to \psi\phi : \quad \phi_{J/\psi\phi} = -2\beta_s \stackrel{SM}{=} -2.1° \pm 0.1°$$

(SM predictions from CKMFitter, PRD83,036004 and UFTit 2010 )

- new phase in mixing ➔ $\phi_f = \phi_f^{SM} + \delta\tilde{\phi}^{\mathrm{NP}}$

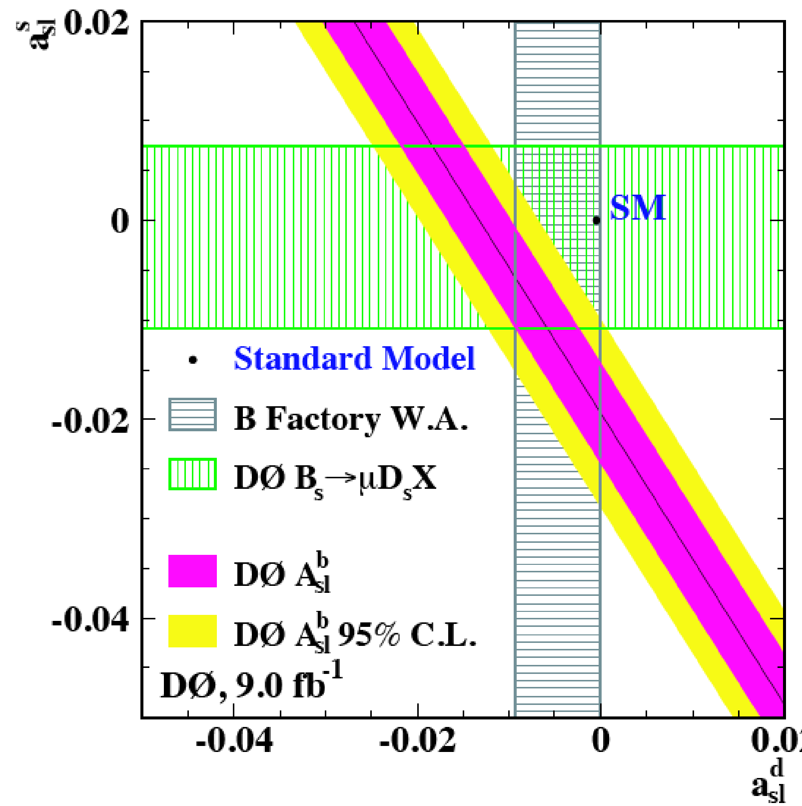
# New physics hints in mixing ?

### B-factories: CPV in Bd mixing?




$$\sin(2\beta^{SM} + \delta\tilde{\phi}_d^{\mathrm{NP}})$$

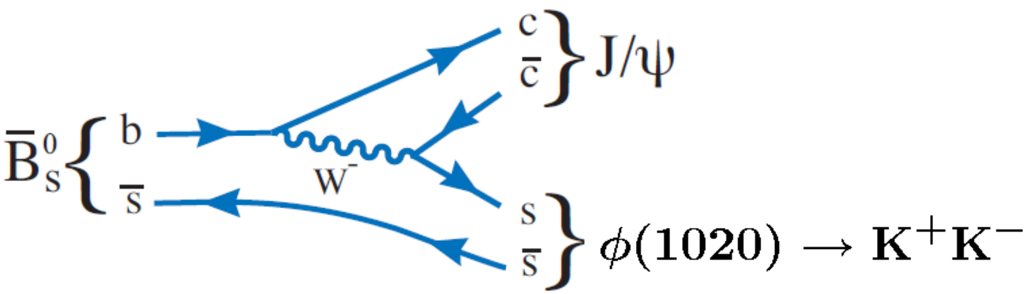
### D⊘: CPV in Bd or Bs mixing?



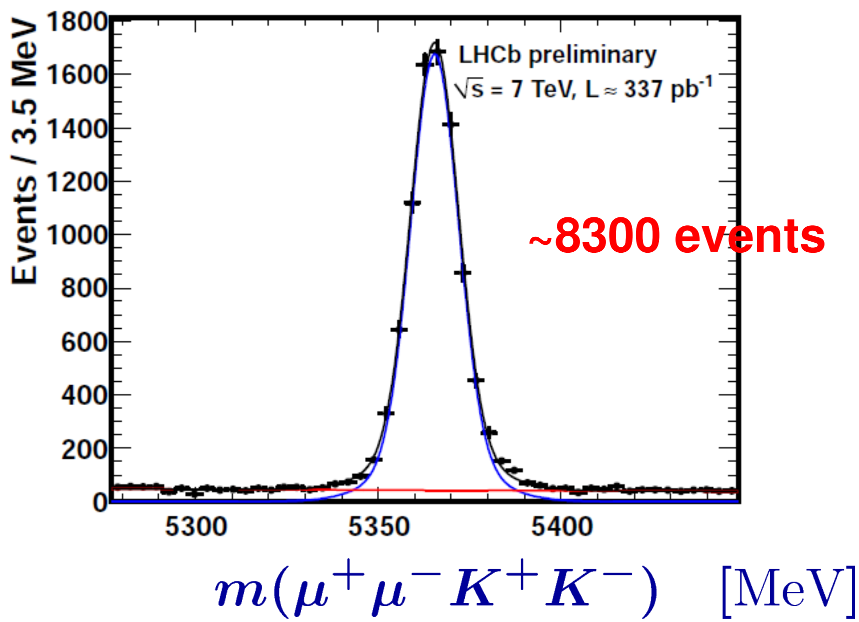

$$a^q_{\mathrm{sl}} = \frac{\Delta\Gamma_q}{\Delta m_q}\tan\tilde{\phi}_q$$

# TD CP violation in the $B_s$-system at LHCb

- two most interesting modes:




- narrow $\phi$ resonance --> clean
- vector-vector final state

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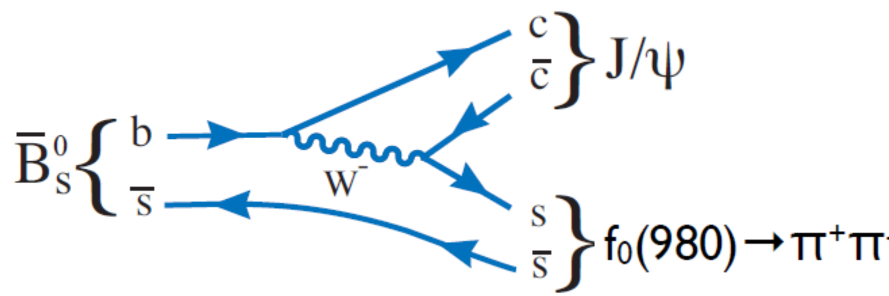
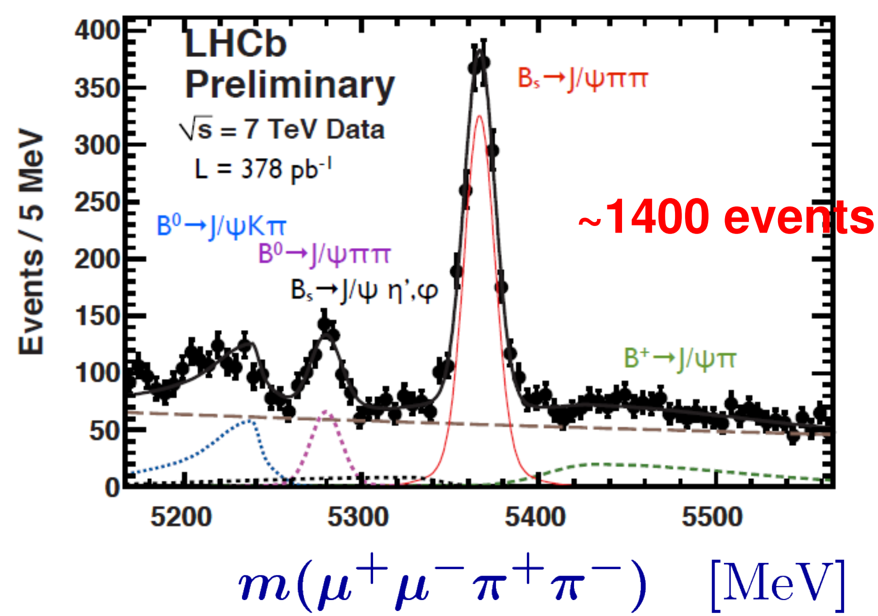



- BF about 20% of Bs->J/ψφ
- vector-pseudo-scalar final state




LHCB-CONF-2011-051

# TD CP violation in the $B_s$-system at LHCb

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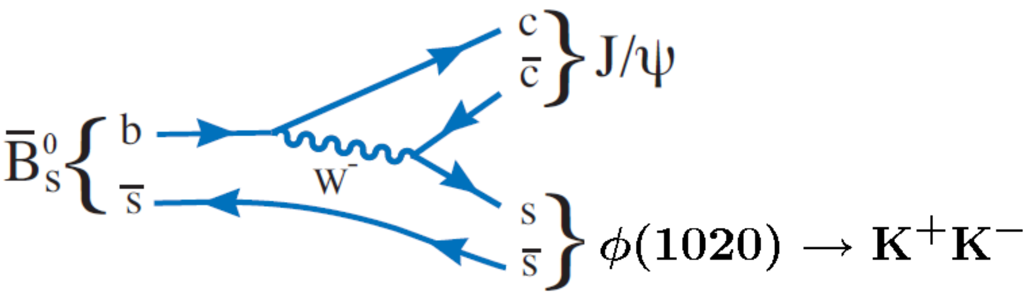
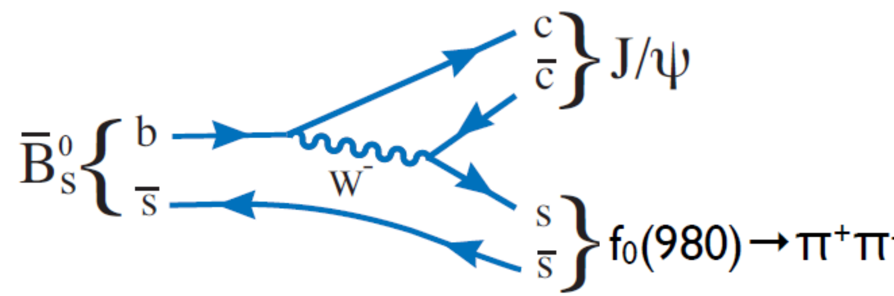
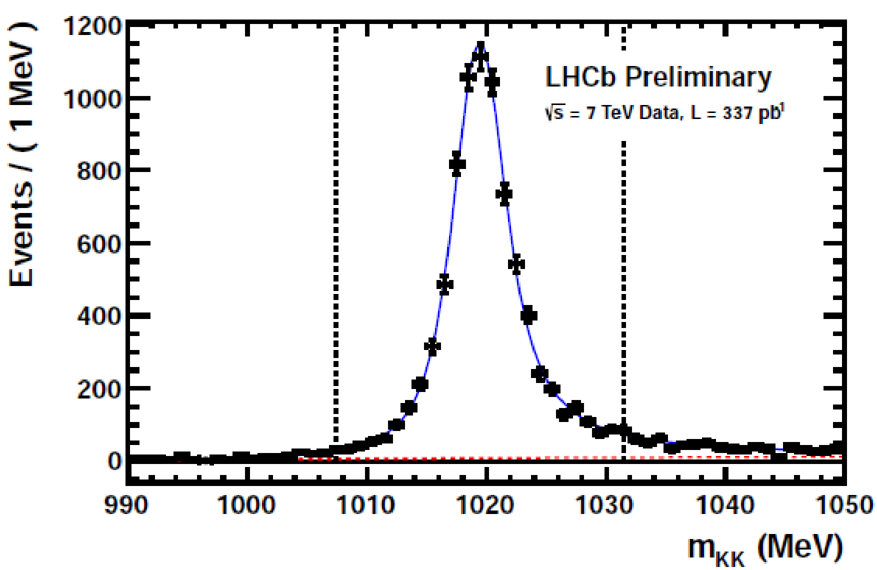


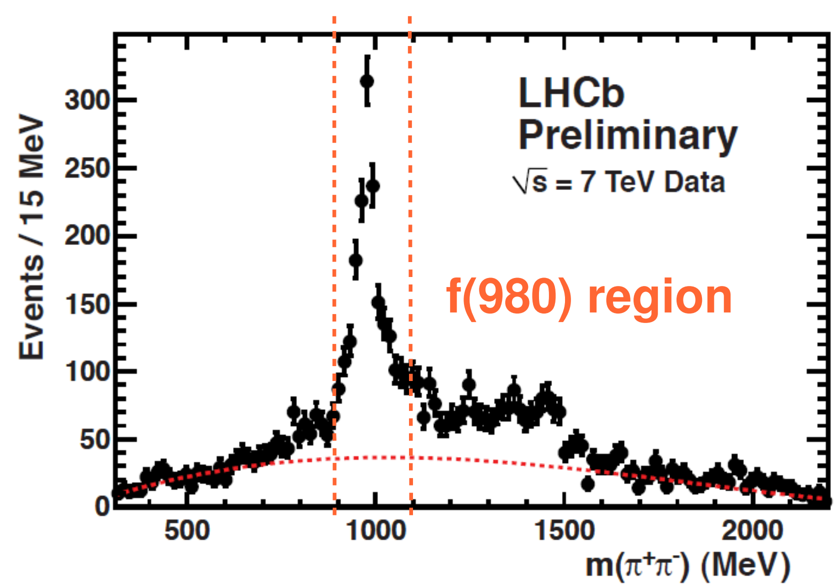

- narrow φ resonance --> clean
- vector-vector final state

- BF about 20% of Bs->J/ψφ
- vector-pseudo-scalar final state




$m(K^+K^-)$ [MeV]

LHCB-CONF-2011-049




$m(\pi^+\pi^-)$ [MeV]

LHCB-CONF-2011-051

# Time-dependent CPV ($\Delta\Gamma \neq 0$)

- common final state ➔ **mixing induced CPV**

$$\begin{tikzcd}
B^0 \arrow[rr, "\phi_{\mathrm{D}}"] \arrow[dr, "\phi_M"'] & & \boldsymbol{f} \\
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- if ***f*** is *CP eigenstate*, time dependent CP violation with pattern

$$\boxed{A_{CP}(t) \equiv \frac{N(\overline{B}^0) - N(B^0)}{N(\overline{B}^0) + N(B^0)} = \frac{\eta_f \ \sin(\phi_f) \ \sin(\Delta m_q t)}{\cosh(\Delta\Gamma_q t) - \eta_f \cos(\phi_f) \sinh(\Delta\Gamma_q t/2)}}$$

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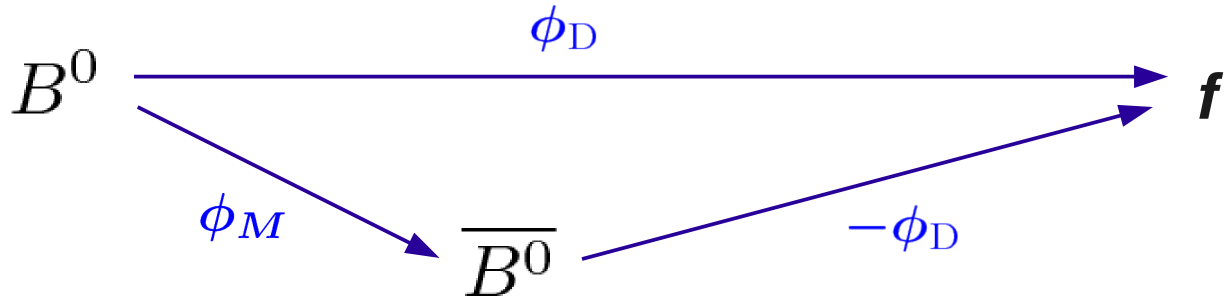


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- ambiguity: $(\phi_s, \Delta\Gamma_s) \longleftrightarrow (\pi - \phi_s, -\Delta\Gamma_s)$

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- ambiguity: $(\phi_s, \Delta\Gamma_s) \longleftrightarrow (\pi - \phi_s, -\Delta\Gamma_s)$

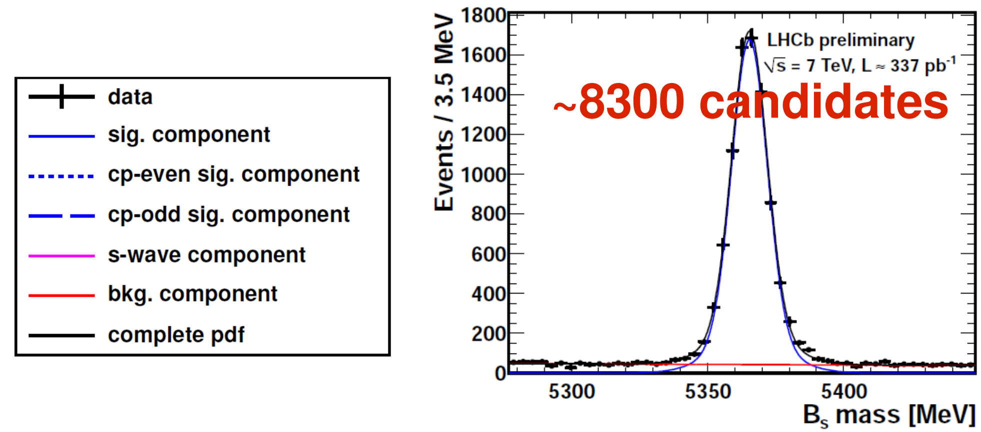
- CP eigenvalue of final state: $\eta_f = (-1)^L$
  - Bs->J/ψ f0: CP-odd
  - Bs->J/ψφ : mixture of CP-odd and CP-even

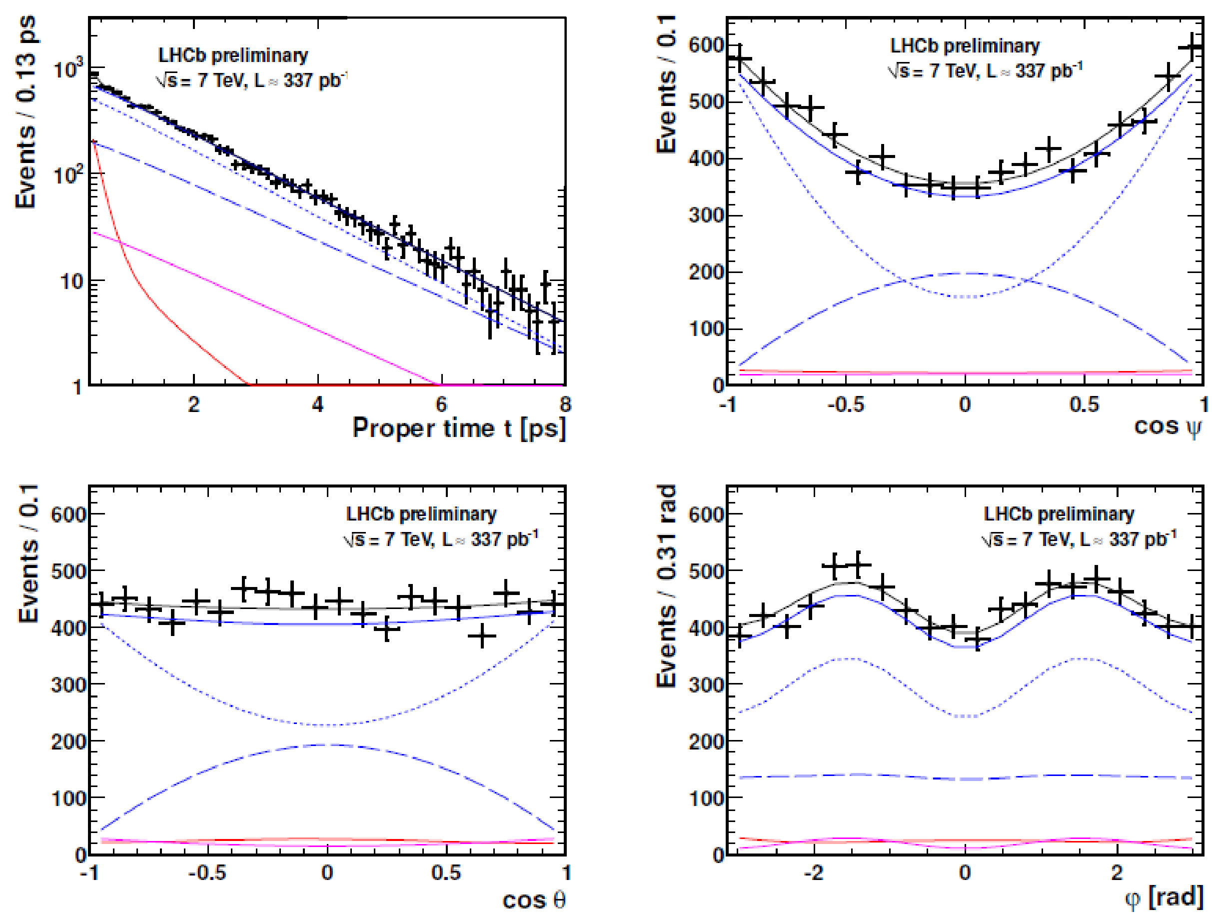
➔ needs 'angular analysis': include 4-body decay-angles in fit procedure

# MLL fit for Bs->J/ψφ

- MLL fit to mass, time, angles and flavour tag decision
- fit for **9** physics parameters
  - **amplitudes: 3 sizes and 3 phases**
  - $\Gamma_s$, $\Delta\Gamma_s$, $\phi_s$
- $\Delta m_s$ taken from $B_s$->$D_s\pi$
- goodness of fit, using "point-to-point dissimilarity test" (*) gives P-value of 0.44

(*) see eg. M. Williams, JINST 5 (2010) P09004 [arXiv:1006.3019 [hep-ex]]



# Fit result for Bs->J/ψφ

- result for mixing parameters (preliminary, LHCb-CONF-2011-049)

$$\begin{aligned}\phi_s^{J/\psi\phi} &= 0.13 \pm 0.18 \text{ (stat)} \pm 0.07 \text{ (syst) rad},\\ \Gamma_s &= 0.656 \pm 0.009 \text{ (stat)} \pm 0.008 \text{ (syst) ps}^{-1}\\ \Delta\Gamma_s &= 0.123 \pm 0.029 \text{ (stat)} \pm 0.011 \text{ (syst) ps}^{-1}\end{aligned}$$

systematics:
- angular acceptance
- decay time acceptance

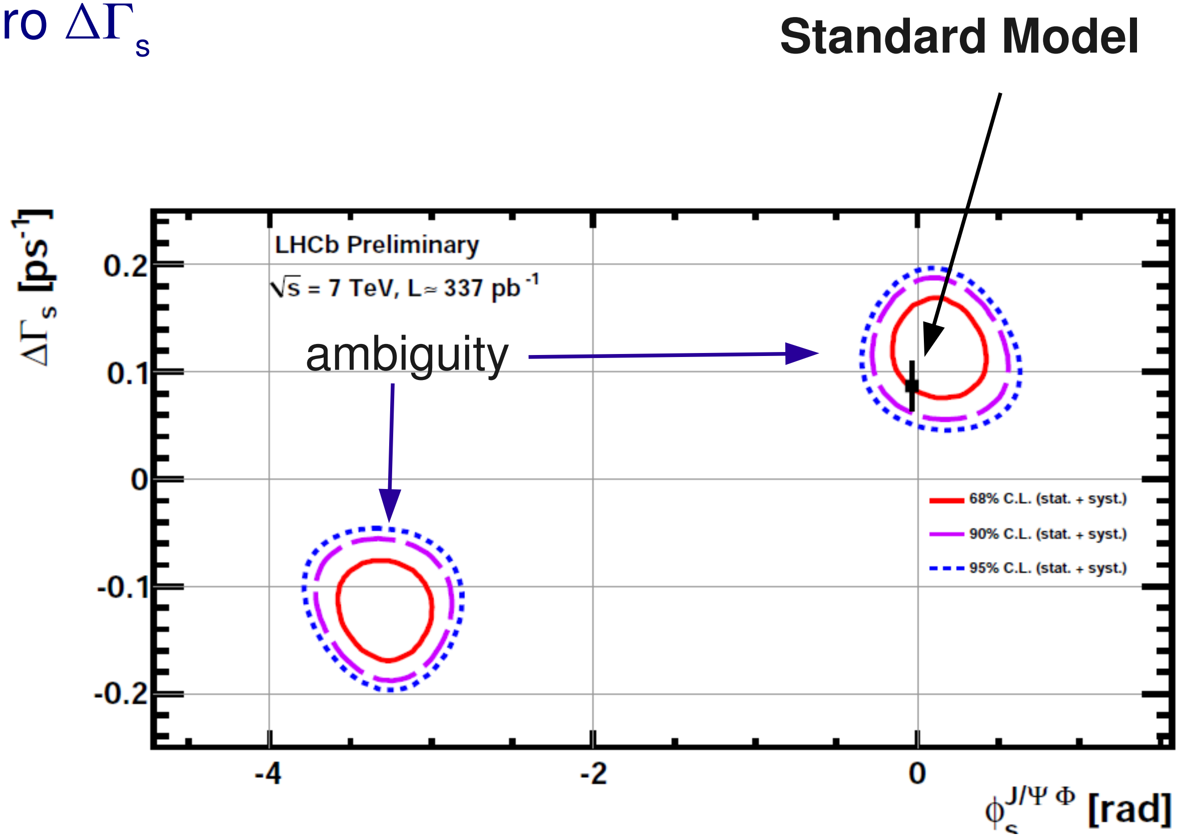
  - most precise results for single experiment
  - first 4σ evidence for non-zero $\Delta\Gamma_s$

- consistent with SM prediction

$$\phi_s^{J\psi\phi,SM} = -0.036 \pm 0.002$$

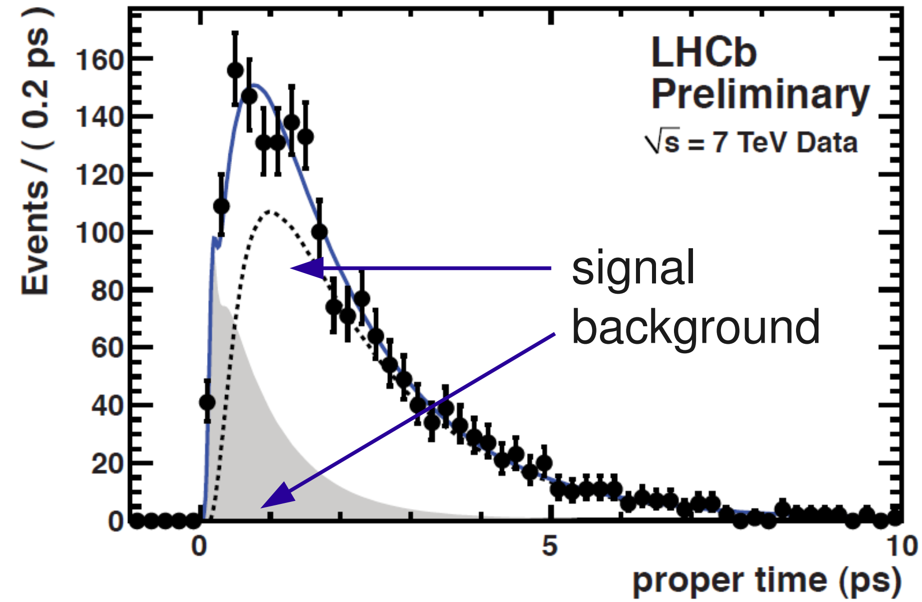
$$\Delta\Gamma^{\mathrm{SM}} = 0.082 \pm 0.021 \mathrm{ps}^{-1}$$

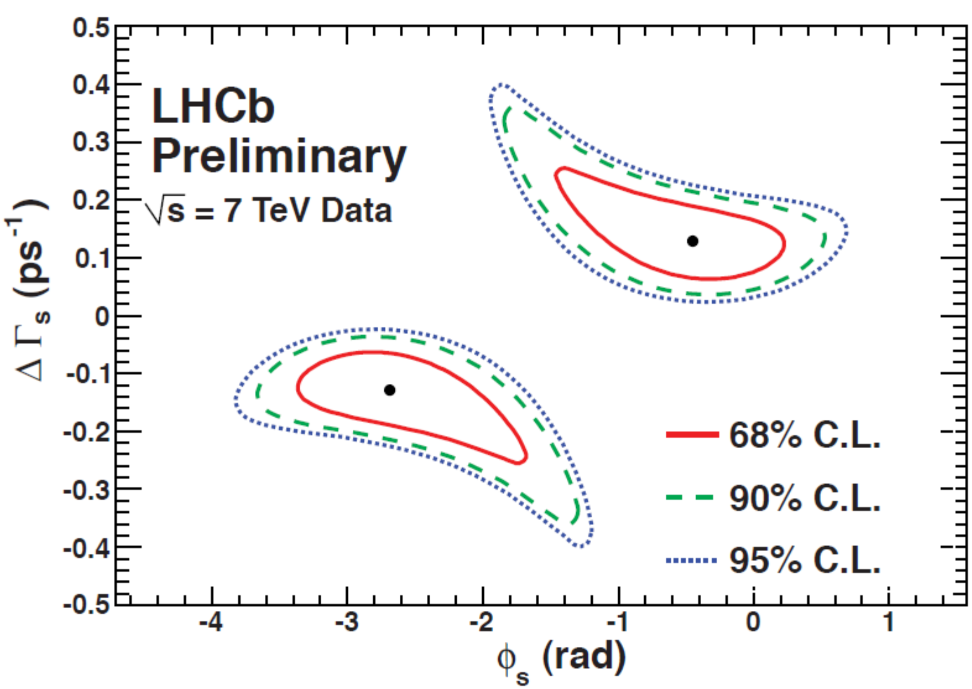
**(Lenz and Nierste, arXiv: 1102.4274, CKM fitter, arXiv:1106.4041 )**



# Fit result for Bs->J/ψ f0

- fit to mass, time and flavour tag
- fit for **2** physics parameters
  - $\Delta\Gamma_s$, $\phi_s$
  - $\Gamma_s$: taken from $B_s$->J/ψφ
  - $\Delta m_s$: taken from $B_s$->$D_s\pi$




- fit result (preliminary, LHCb-CONF-2011-051)

$$\phi_s = -0.45^{+0.45}_{-0.57}$$
$$\Delta\Gamma_s = 0.128^{+0.057}_{-0.043}$$

- fixing $\Delta\Gamma_s$ to result from $B_s$->J/ψφ

$$\phi_s = -0.44 \pm 0.44 \pm 0.02$$

# Combining Bs->J/ψφ and Bs->J/ψf0

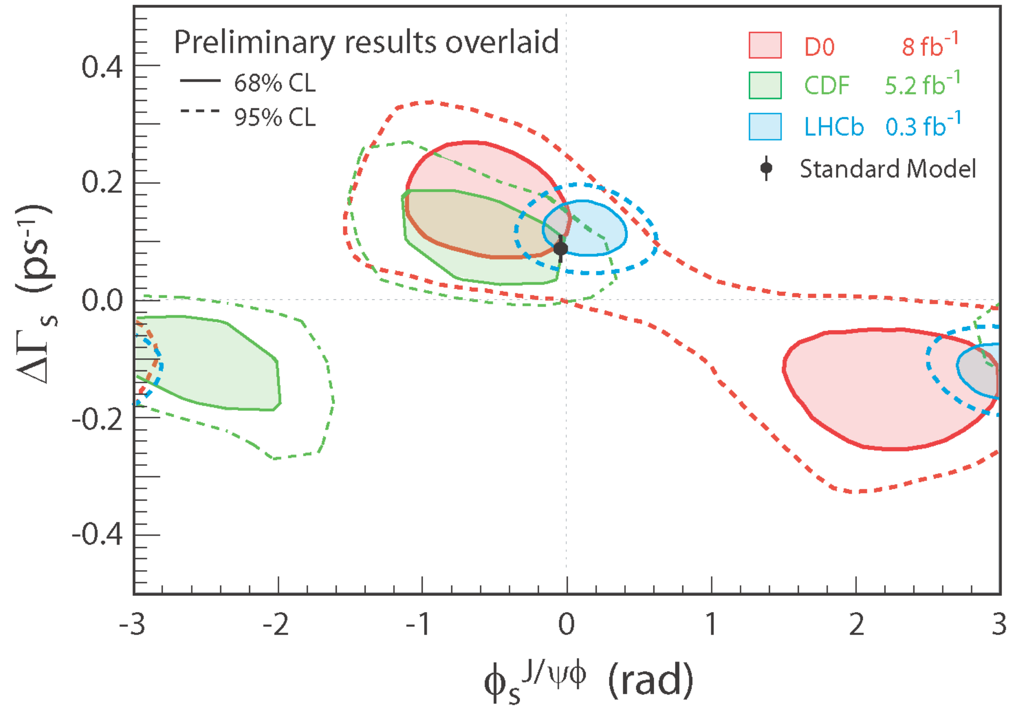
- simultaneous fit to both samples

  $$\phi_s \;=\; \mathbf{0.03 \pm 0.16 \pm 0.07}$$

  (prelim, LHCb-CONF-2011-056)

- TDCPV gives no evidence for NP in Bs mixing .... *yet*

CDF/LHCb/D0 results




- next steps
  - resolve ambiguity by fitting S-wave phase in bins of M(KK) (Y. Xie et al., JHEP 0909:074, (2009))
  - add more data (2.5x more recorded!)
  - add same-side Kaon tagger (~1.5x more tagging power!)

# What do we learn from this?

- NP models usually only consider contributions to $M_{12}$

$$M_{12} = M_{12}^{\rm SM}\, r^{\rm NP} e^{i\tilde{\phi}} \qquad \tilde{\phi} = \tilde{\phi}^{\rm SM} + \tilde{\phi}^{\rm NP}$$

*unexpected mixing frequency?*

*anomalous CPV and $\Delta\Gamma$?*

$$\boxed{\Delta m_s^{\rm lhcb} = 17.725 \pm 0.041 \pm 0.026\ {\rm ps}^{-1}}$$

$$\boxed{\Delta m_s^{\rm SM} = 16.8^{+2.6}_{-1.5}\ {\rm ps}^{-1}}$$

[PRD.83, 036004 (2011)]

$$\boxed{\phi_s^{\rm lhcb} = 0.03 \pm 0.16 \pm 0.07}$$

$$\boxed{\phi_s^{\rm SM} = -0.036 \pm 0.002}$$

[PRD.83, 036004 (2011)]

$$\boxed{\Delta\Gamma^{\rm lhcb} = 0.123 \pm 0.029 \pm 0.011 {\rm ps}^{-1}}$$

$$\boxed{\Delta\Gamma^{\rm SM} = 0.082 \pm 0.021 {\rm ps}^{-1}}$$

[Lenz&Nierste,2011]

$$\phi_s = \phi_s^{SM} + \tilde{\phi}^{\rm NP}$$

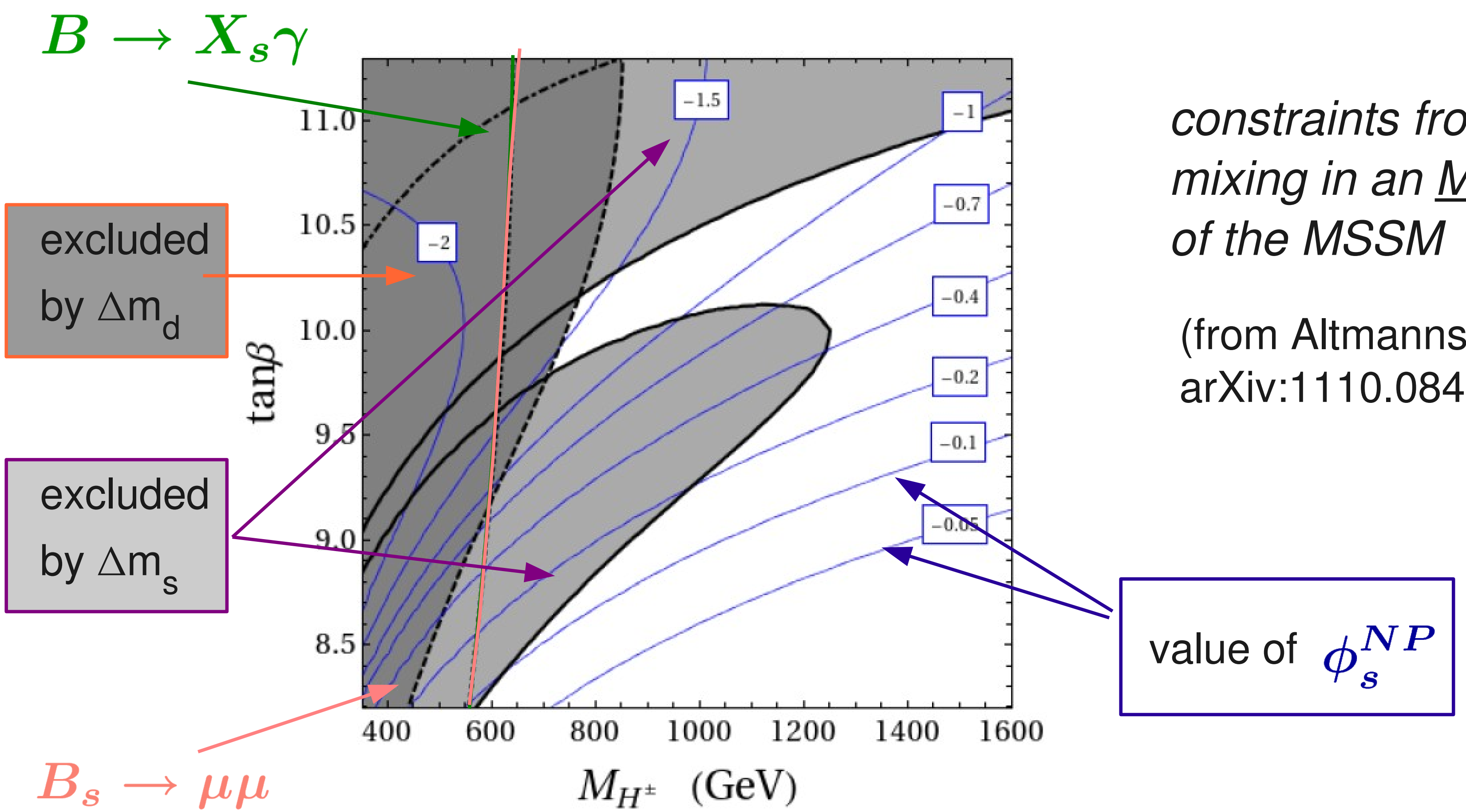
$$\Delta\Gamma \approx \Delta\Gamma^{SM} \cos(\tilde{\phi}^{\rm NP})$$

# What do we learn from this?

- NP models usually only consider contributions to $M_{12}$

$$M_{12} = M_{12}^{\rm SM}\, r^{\rm NP} e^{i\tilde\phi} \qquad \tilde\phi = \tilde\phi^{\rm SM} + \tilde\phi^{\rm NP}$$

- constraints depend on assumed flavour structure of NP sector




*constraints from Bd and Bs mixing in an <u>MFV extension</u> of the MSSM*

(from Altmannshofer and Carena, arXiv:1110.0843)

# $B_s \to \mu\mu$: shown by Niels Tuning this morning

## $B^0_s \to \mu\mu$ : Branching Ratio

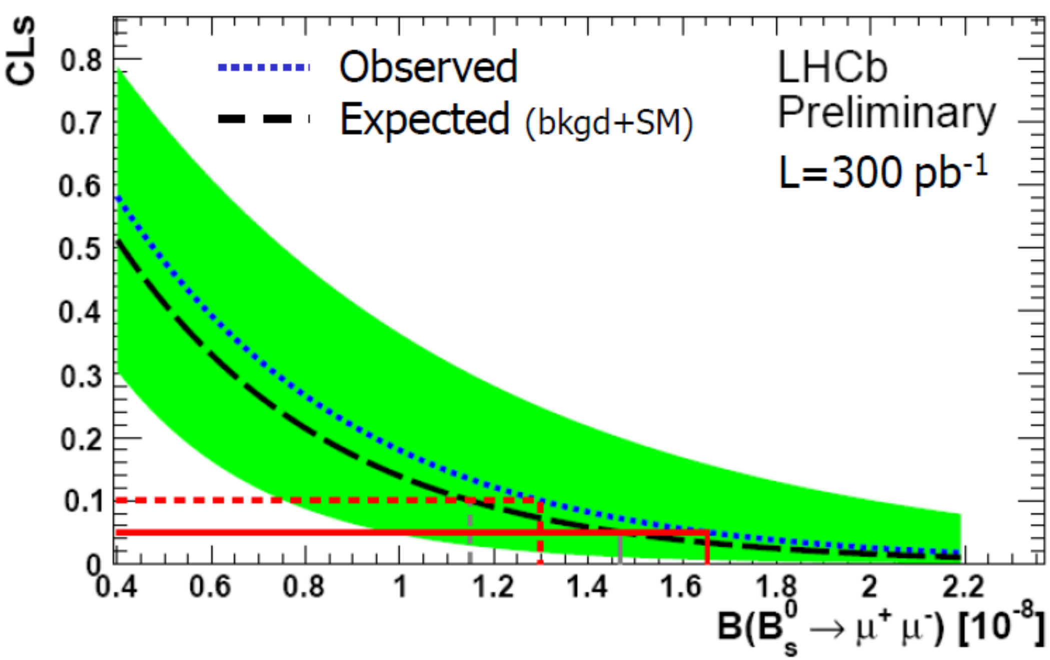
$BR(B^0_s \to \mu\mu)_{SM} = (0.32 \pm 0.02) \times 10^{-8}$

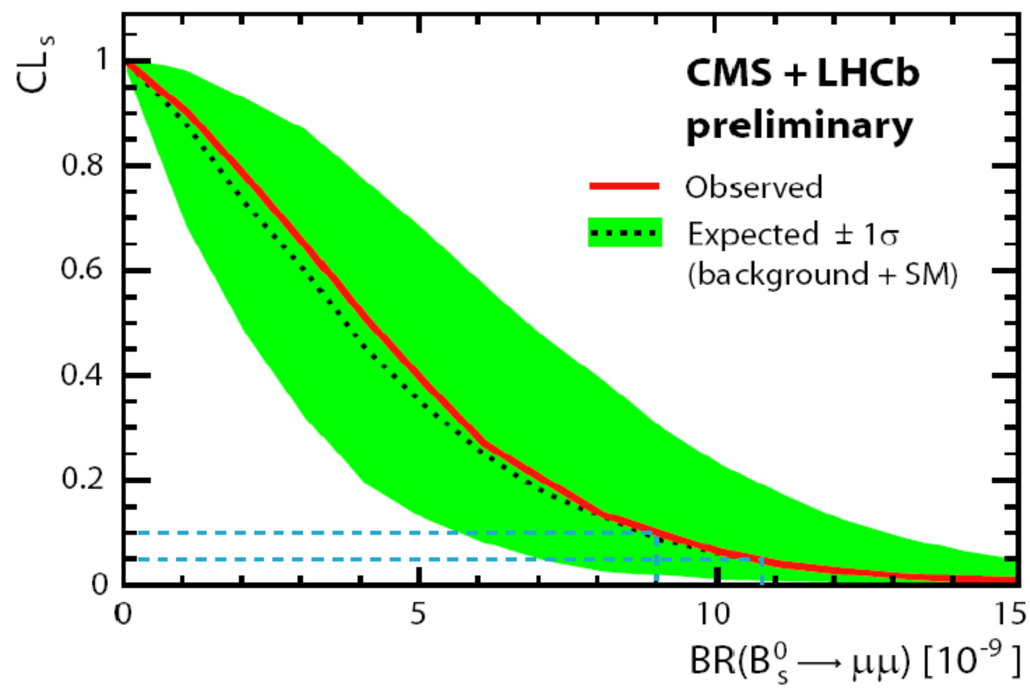
- Expected limit: $BR(B^0_s \to \mu\mu) < 1.5 \times 10^{-8}$
- Observed limit: $BR(B^0_s \to \mu\mu) < 1.6 \times 10^{-8}$
- p-value background only: 14%

LHCb only

CMS + LHCb

Observed limit: **$BR(B^0_s \to \mu\mu) < 1.08 \times 10^{-8}$** @95%CL



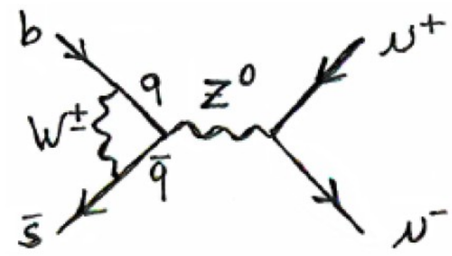




- no signals yet. what does this mean?

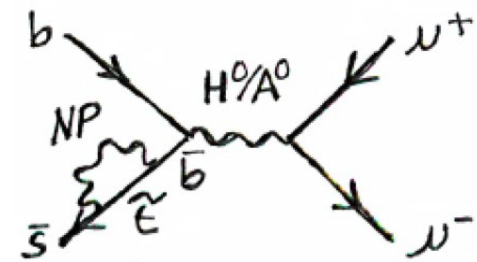
# Constraints on New Physics from $B_s \to \mu\mu$

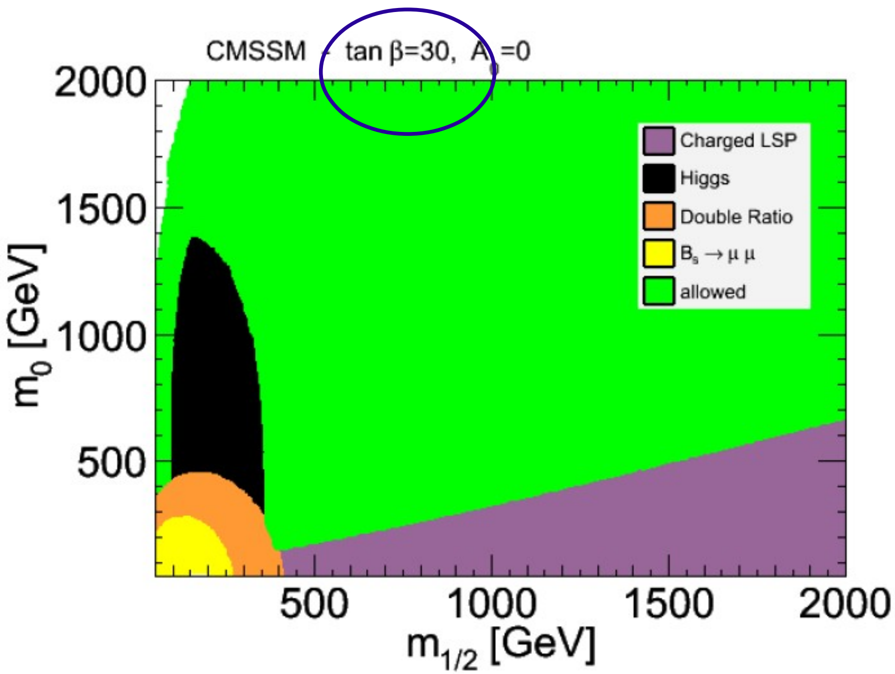
- in MSSM Bs->mumu receives contribution ~$(\tan\beta)^6$
- leads to strong constraints, especially at large $\tan\beta$
- for example, in CMSSM:

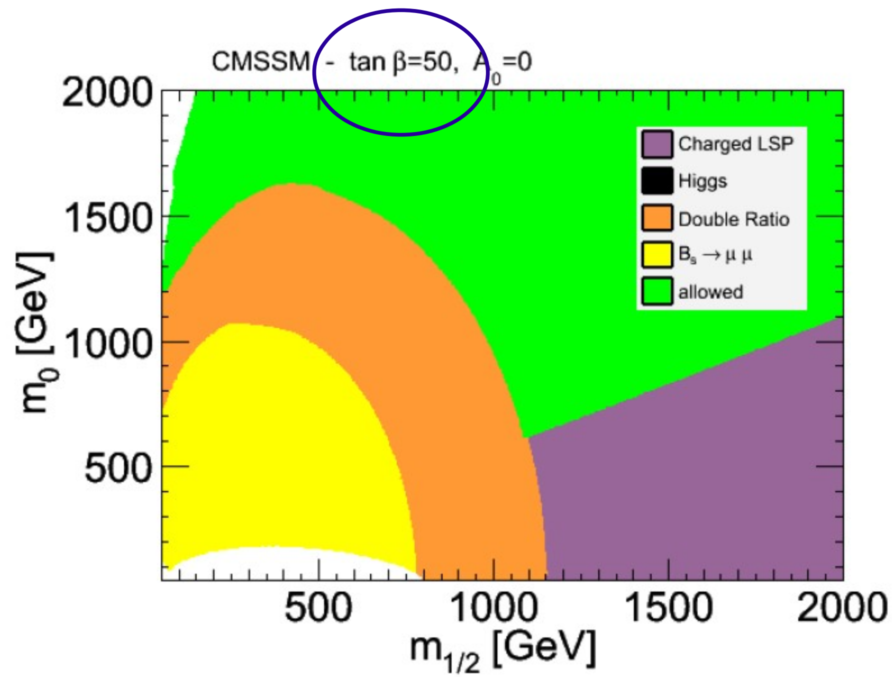
SM




MSSM



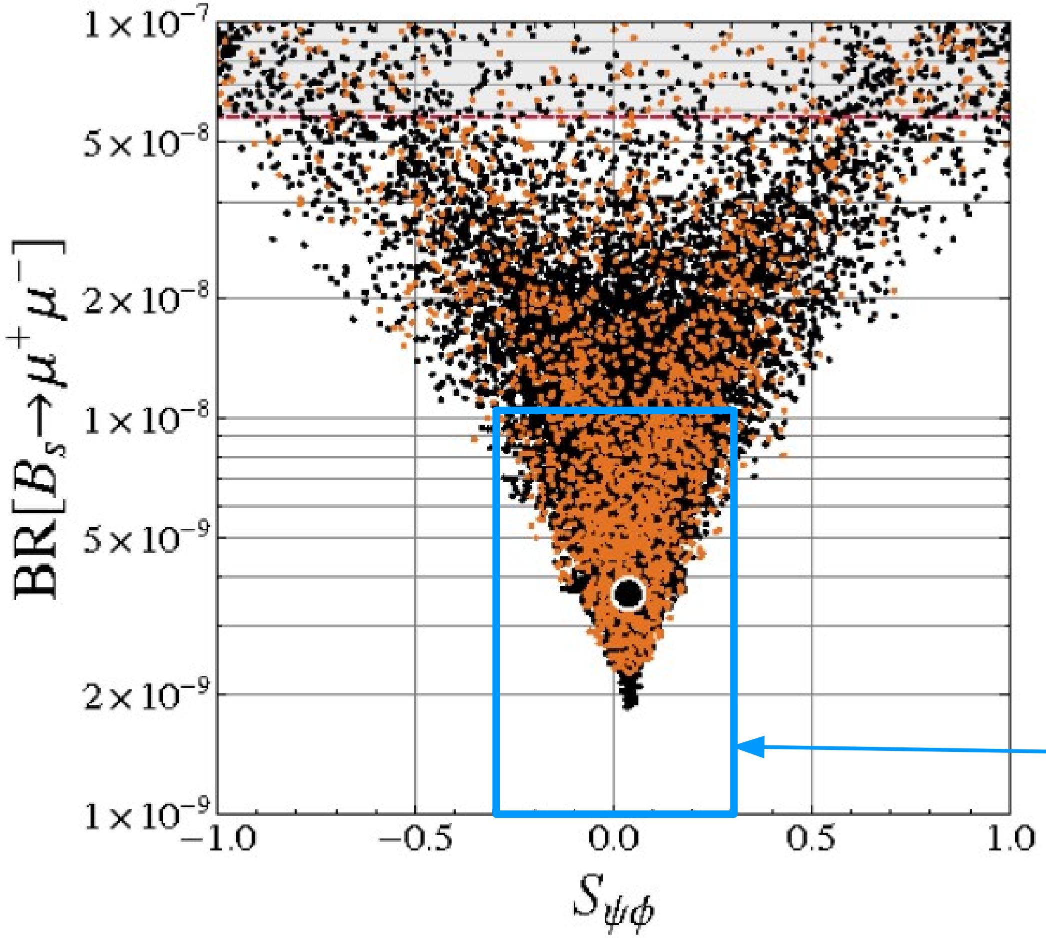




arXiv:2208.3018

- strongest Bs->mumu constraints from ratio $\eta \equiv \left(\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_u \to \tau\nu)}\right) \Big/ \left(\frac{\mathrm{BR}(D_s \to \tau\nu)}{\mathrm{BR}(D \to \mu\nu)}\right)$
- for other recent analyses, see e.g. arXiv:1104.3572,

# Combining BF($B_s \to \mu\mu$) and $\phi_s$

- in many models, correlation between enhancements in BF($Bs \to \mu\mu$) and $\phi_s$




*Correlation between BF($Bs \to \mu\mu$) and $\phi_s$ in "abelian flavour model" by Agashe and Corone.*

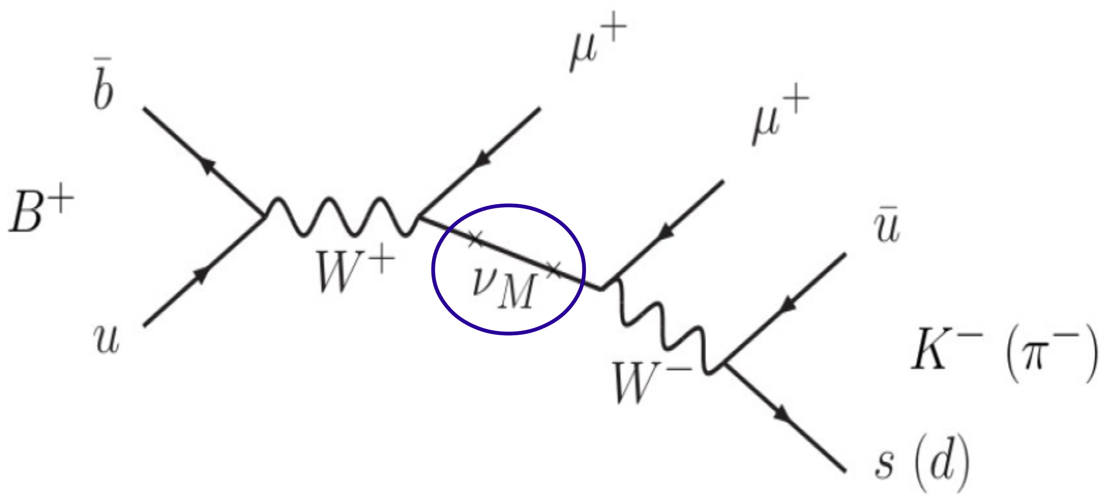
(from Altmannshofer et.al, arXiv: 0909.1333)

new LHCb/CMS constraints

- combining many flavour physics observables gives most powerful constraints
  - for overview see e.g. Buras, "Flavour theory: 2009", arXiv:0910.1032

# Lepton Flavour Violation in B Decays

- B-decays with **like-sign** di-muons probe 'medium-heavy' Majorana neutrinos

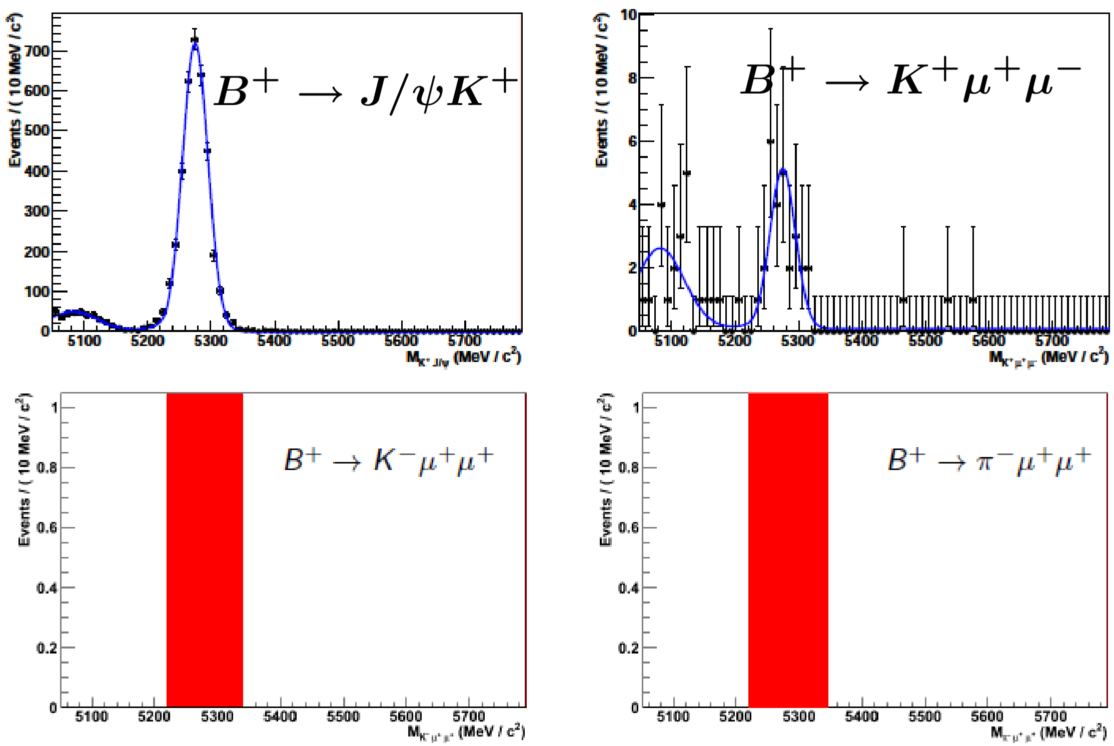



- limit on BF can be interpreted as limit on coupling between majorana neutrino and W and neutrino

- LHCb looks for different final states
  - in $B^+ \to \pi^- \mu^+ \mu^+$ and $B^+ \to K^- \mu^+ \mu^+$
    **arXiv:1110.0730 (hep-ex)**, submitted to PRL
  - in $B \to D\, \mu^+ \mu^+$ and $B \to D\, \pi\, \mu^+ \mu^+$,
    to be submitted to PRD soon

# Search for $B^+ \to K^-\mu^+\mu^+$ and $B^+ \to \pi^-\mu^+\mu^+$

- analysis strategy
  - use $B^+ \to J/\psi K^+$ for optimization and normalization
  - use $B^+ \to K^+\mu^+\mu^-$ sidebands to estimate combinatorial background




unlike sign dimuons in 36/pb

like sign dimuons in 36/pb ... observe **no events**, (not even in sidebands)

- limits in 36/pb (**arXiv:1110.0730 (hep-ex)**, submitted to PRL

$$\mathcal{B}(B^+ \to K^-\mu^+\mu^+) < 5.4\,(4.1) \times 10^{-8} \text{ at } 95\%\,(90\%) \text{ CL},$$
$$\mathcal{B}(B^+ \to \pi^-\mu^+\mu^+) < 5.8\,(4.4) \times 10^{-8} \text{ at } 95\%\,(90\%) \text{ CL}.$$

**improve >30 over existing (CLEO) limits**

**>30x more data recorded: watch winter conferences!**
**D decays also understudy: expect to improve B-factory limits by factor 100**

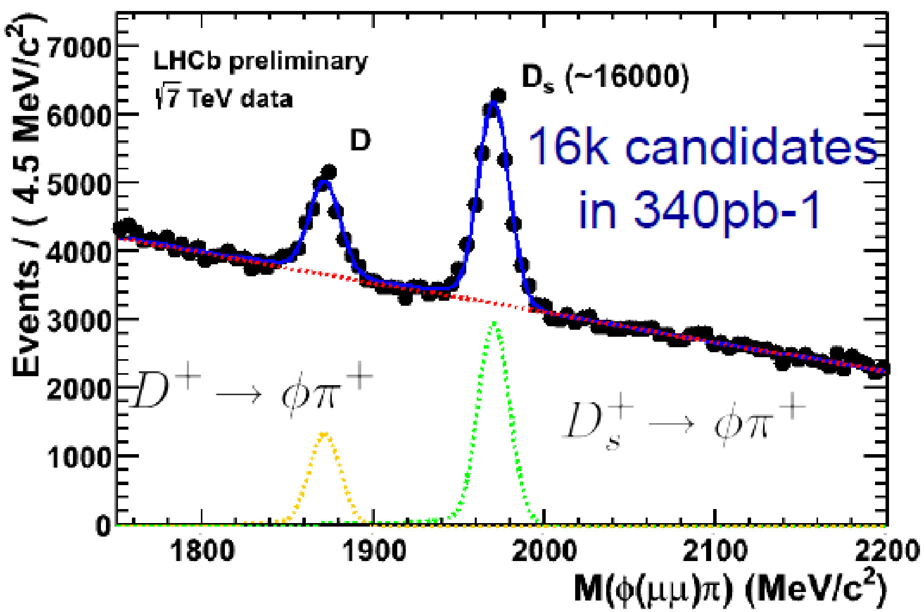
# LVF in tau decays: $\tau \rightarrow \mu\mu\mu$

- $\tau \rightarrow \mu\mu\mu$ extremely rare in SM, but BF up to 10^-8 in BSM
  - current limit: BF<2.1 10^-8 (Belle)

*sources of tau leptons at LHCb*

| Decay chain | Probability (%) |
|---|---|
| $D_s \to \tau$ | 78.3 |
| $D_s \to \tau$ | 68.9 |
| $B_x \to D_s \to \tau$ | 9.4 |
| $D^+ \to \tau$ | 4.9 |
| $D^+ \to \tau$ | 4.7 |
| $B_x \to D^+ \to \tau$ | 0.2 |
| $B_x \to \tau$ | 16.8 |

- tau production at LHC almost exclusively from Ds and B decays
  - ~8 x $10^9$ taus per 1/fb in LHCb
  - trigger efficiency for $\tau \rightarrow 3\mu$ is ~50%
- analysis strategy: normalize to $D_s^+ \rightarrow \phi(\mu^+\mu^-)\pi^+$



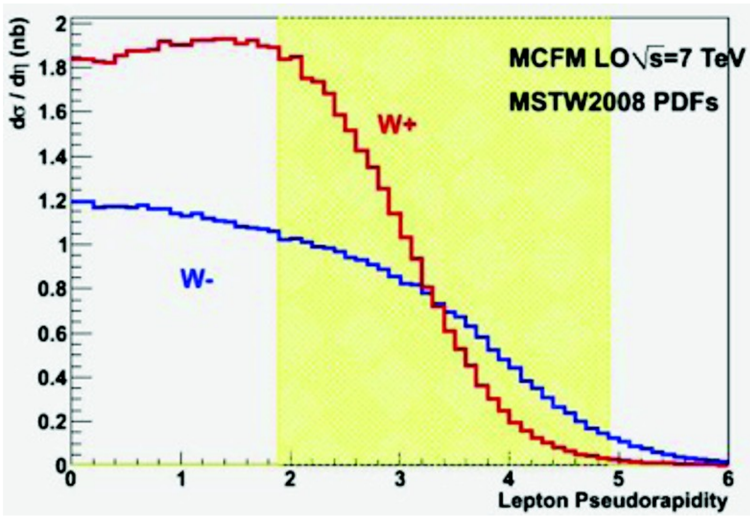

- preliminary analysis of backgrounds: reach Belle limit with 2011 data
- LHCb can also put first limit on **$\tau \rightarrow p\mu\mu$** at O(10^-7) level with 2011 data

# How about the *absolute* energy frontier?

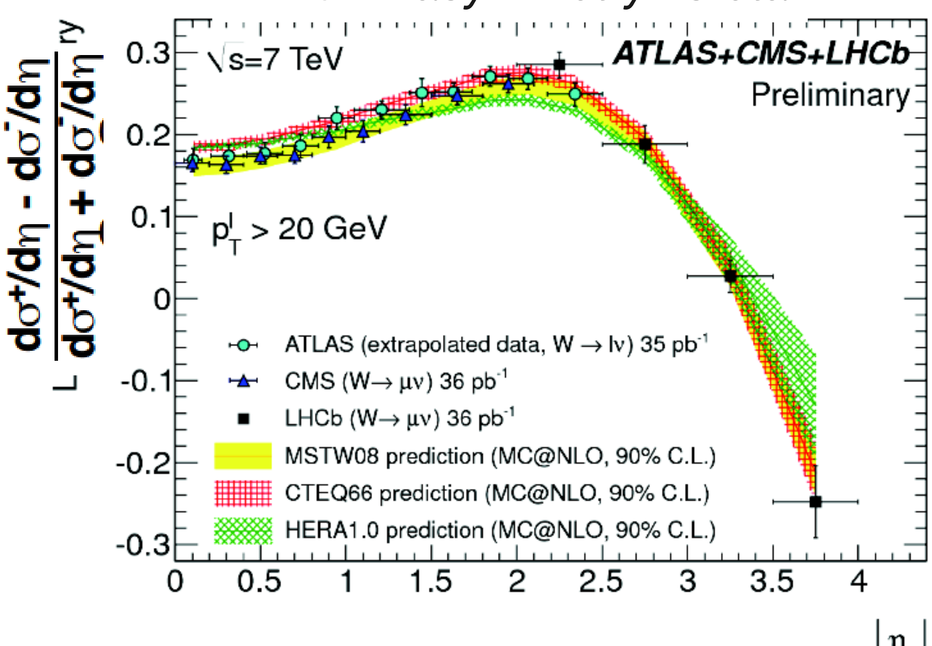
- LHCb wasn't build for this, but still interesting
  - unique pseudo rapidity coverage: **2< $\eta$ < 5**
  - low pT lepton triggers
  - large boost, precise vertexing (tau, B tagging)
- subset of things we (will) look at
  - W, Z, DY production in forward region (LHCb−CONF−2011−039)
    - sensitivity to parton distribution functions in previously unexplored territory
  - high energy tau leptons
    - calibrate using Z->tautau and lepton universality (LHCb−CONF−2011−041)
    - from there on, look for anomalous tau production (e.g. from SUSY)
  - top-anti-top production asymmetry
  - new long-lived, heavy particles

# Example: W acceptance and asymmetry

*17% (16%) of W- (W+) in LHCb acceptance*

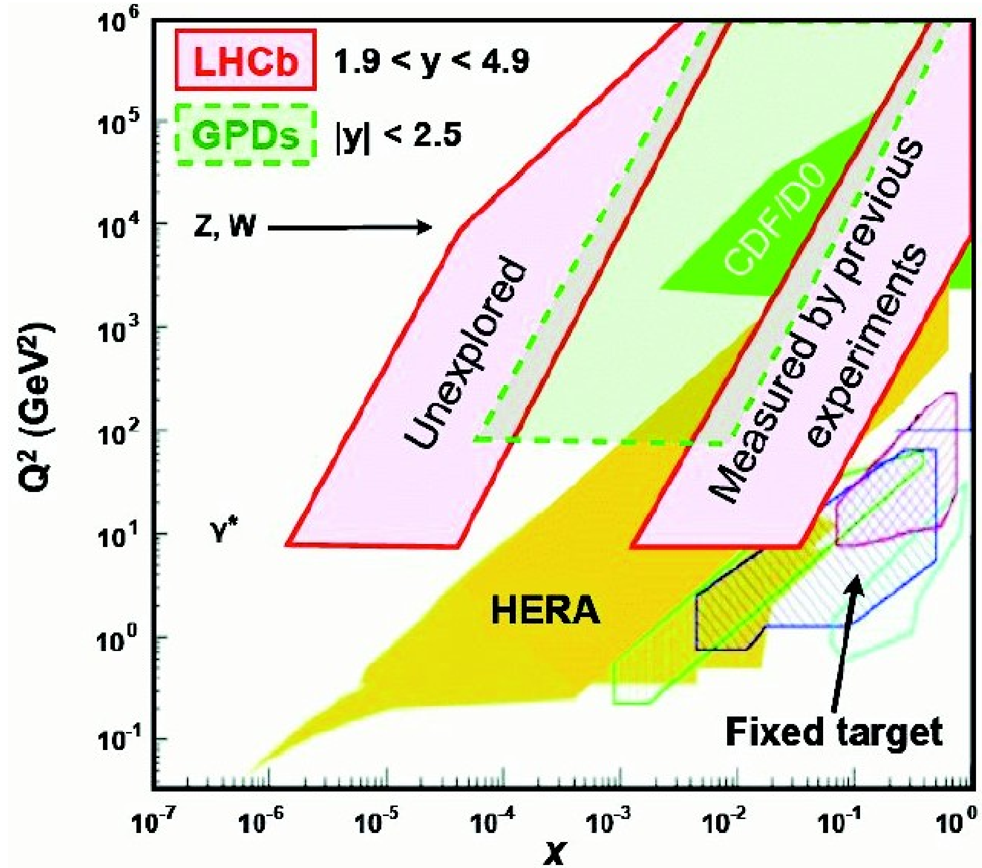



*W+/W- asymmetry vs eta*




(LHCb-CONF-2011-039)

LHCb acceptance



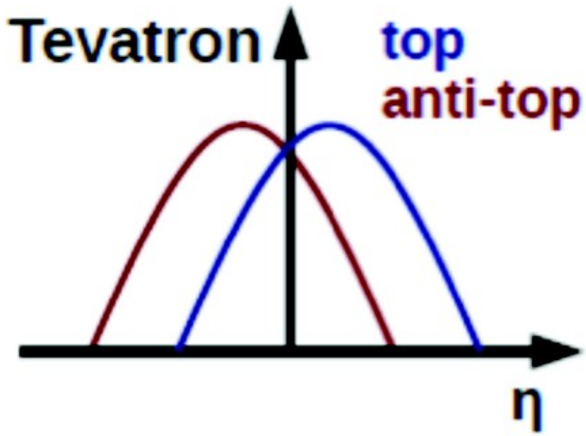

cross-section measurements at LHCb constrain PDFs which have large uncertainty at large rapidity

# Top anti-top A_FB

- at the Tevatron have $p\bar{p} \to t\bar{t}X$

$$\Delta y = y_t - y_{\bar{t}}$$

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




- measurements at Tevatron show deviation from SM

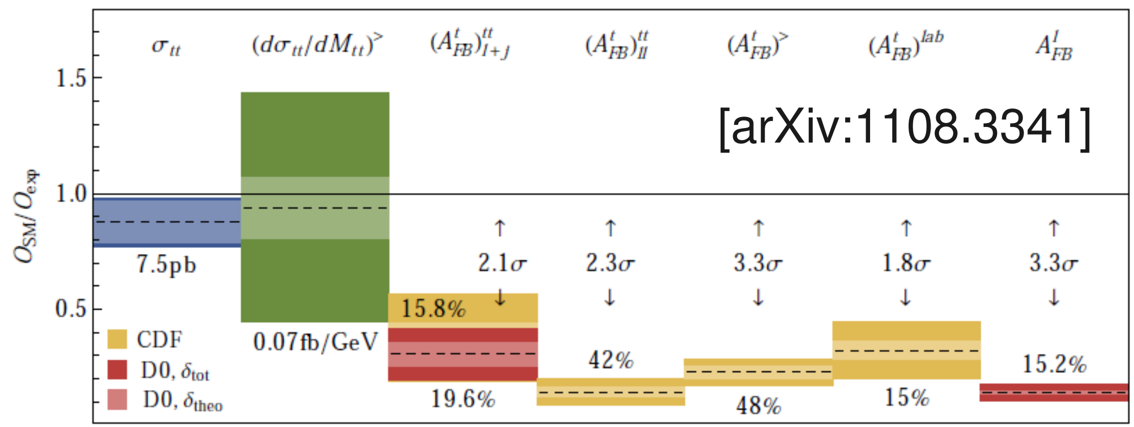


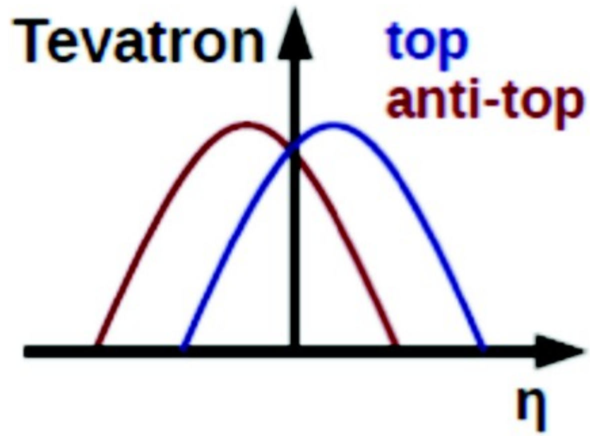

**Figure 1:** Top-antitop production at the Tevatron. The ratio $O_{\mathrm{SM}}/O_{\mathrm{exp}}$ is displayed for the total cross section $\sigma_{t\bar{t}}$ and its invariant mass distribution $(d\sigma/dM_{t\bar{t}})^{>}$ for $M_{t\bar{t}} \in [0.8, 1.4]$ TeV. The inclusive asymmetry in the parton frame is shown for the lepton + jets channel, $(A_{\mathrm{FB}})^{t\bar{t}}_{l+j}$, besides its bin $(A^t_{\mathrm{FB}})^{>}$ for high invariant mass $M_{t\bar{t}} > 0.45$ TeV, as well as for the dilepton channel, $(A^t_{\mathrm{FB}})^{t\bar{t}}_{ll}$. The asymmetry in the laboratory frame is denoted by $(A^t_{\mathrm{FB}})^{\mathrm{lab}}$, and $A^l_{\mathrm{FB}}$ is the charged lepton asymmetry. Numbers correspond to the central measured values [1].

# Top anti-top A_FB

- at the Tevatron have $p\bar{p} \longrightarrow t\bar{t}X$

$$\Delta y = y_t - y_{\bar{t}}$$

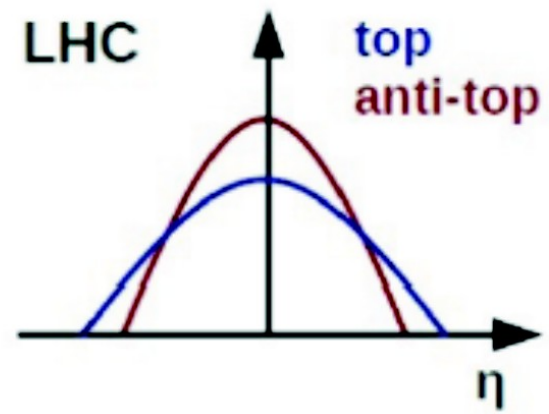
$$A_{\rm FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$




- at the LHC have $pp \longrightarrow t\bar{t}X$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

$$A_c = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$




ATLAS, 0.7/fb: $A_c = -0.024 \pm 0.016 \pm 0.023$

CMS, 1.09/fb: $A_c = -0.016^{+0.030}_{-0.030}{}^{+0.010}_{-0.019}$

consistent with SM,
but at small rapidity

# Top anti-top asymmetry in LHCb

- LHCb doesn't have 4pi acceptance. proposal by Kagan e.a. (arXiv:1103.3747)
  - look for single top, then measure difference in top and anti-top production at large rapidity
  - most promising channel: t --> W b, with W --> $\mu\nu$ and one b-jet

- expected backgrounds
  - W + light jet
  - W + b jet (not from top)
  - b b-bar
  - single top
  - ..
- measurement looks complicated, but not impossible

➔ time-scale: 'summer'

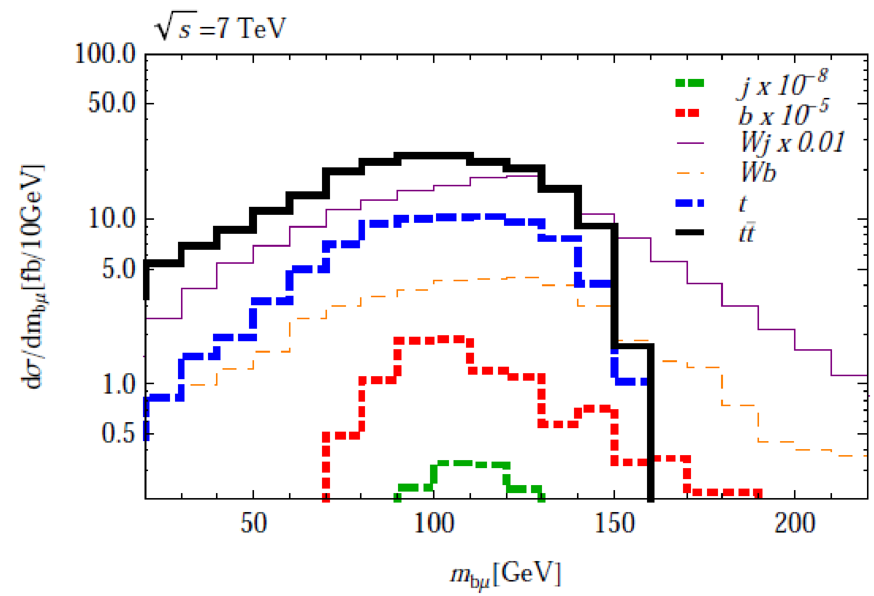



FIG. 1: The $t\bar{t}$ signal and background distributions as a function of the invariant mass of the candidate $b$ and muon, $m_{b\mu}$, see text for details. The curves from top to bottom (at $m_{b\mu}$ = 100 GeV) are for $t\bar{t}$, $Wj$, single top, $Wb$, $bb$, and $jj$.

(from arXiv:1103.3747)

note: generator simulation only!

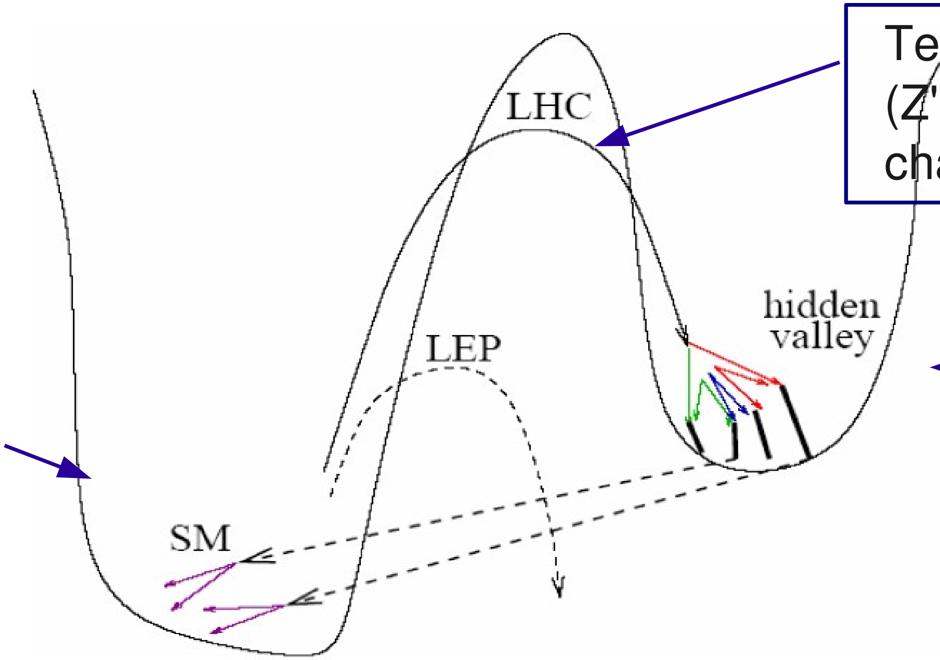
# Searches for long-lived heavy particles

- new long-lived heavy particles featured in many BSM models, e.g.
  - LSP in SUSY theories with a bit of R-parity violation
  - light right-handed neutrinos
  - R-hadrons
  - Hidden Valley

- for example, Strassler and Zurek: *“Sector with non-abelian gauge group with a new quantum number „v”(analogous to charge → v = 0, ±1),which couple weakly to the standard model via higher-dimension operators, and which has a mass gap.”*

TeV scale operators (Z' or loops of particles charged under both groups)

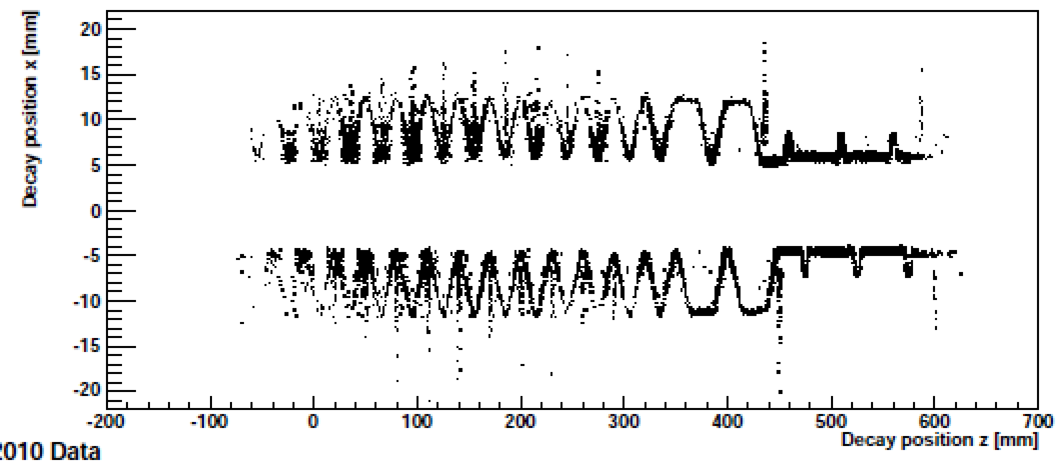
SM particles charged in $G_{SM}$ neutral in $G_V$

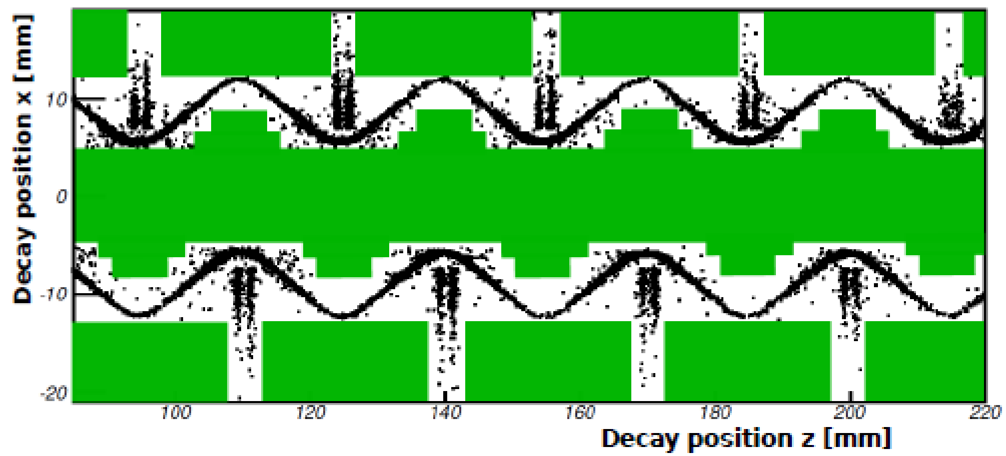



V particles: neutral in $G_{SM}$ charged in $G_V$

# Search 1: heavy displaced vertices

- look for vertices in LHCb vertex detector
- main backgrounds
  - material interactions
  - B decays
- typical reach
  - 1ps – 100ps
  - 10 Gev – 100 GeV
- complementary ATLAS/CMS
  - more boost, smaller lifetime
  - high trigger efficiency
- work in progress ...
  ... first results expected in spring



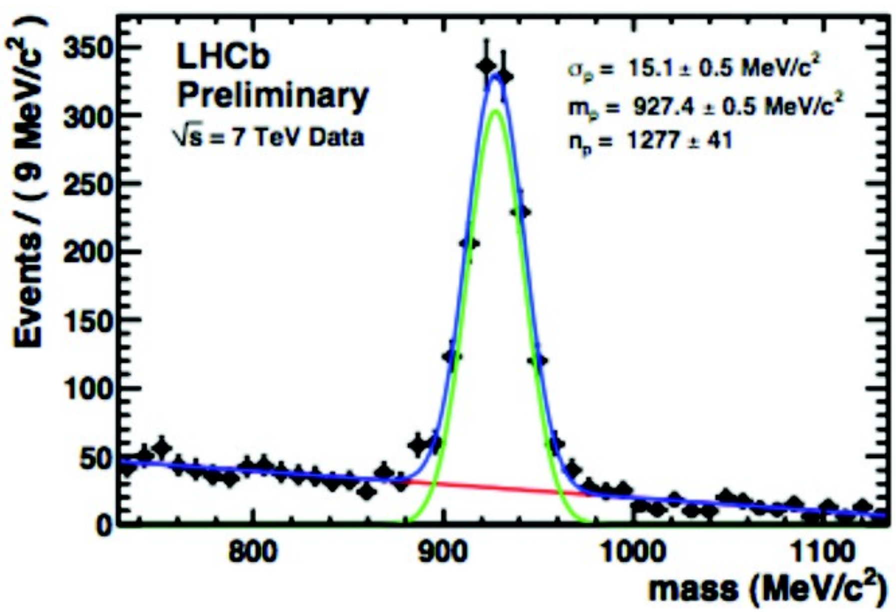



# Search 2: charged massive particles

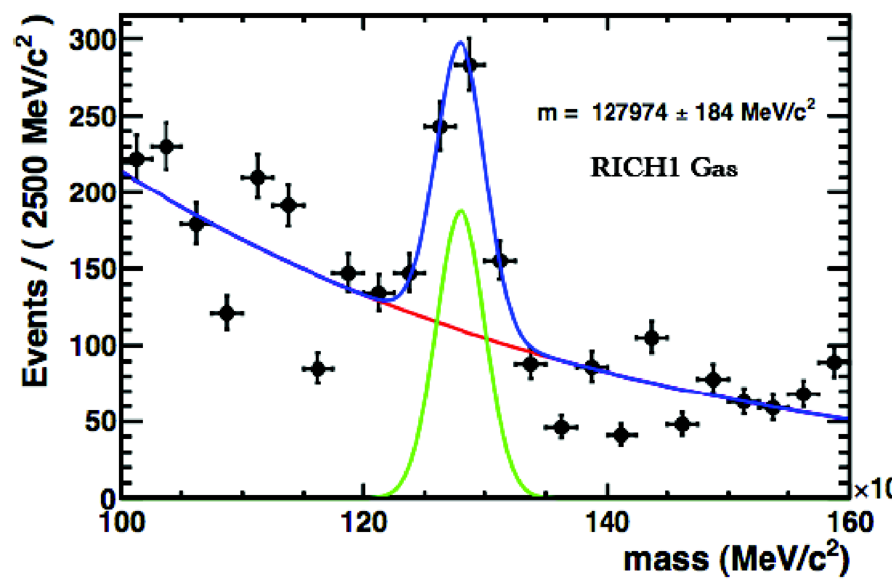
- heavy, charged particle --> low *velocity*
  - ATLAS/CMS, DCF, D0: dE/dX
  - LHCb: cherenkov angle in RICH

$$m = \frac{p}{\gamma\beta}$$

proton mass in data




simulated GSMB stau of 124 GeV




- analysis in progress: not yet clear if backgrounds can be controlled sufficiently to set competitive limits

# summary/outlook

- LHCb experiment concentrates on low-energy observables
  - CP violation (CKM metrology, CPV in mixing)
  - rare decays
  - lepton flavour violation

  see talk by N. Serra tomorrow

- starting up effort to extend program to physics beyond flavour
  - exploit unique rapidity range, displaced vertex trigger
  - look at anomalous production of tau, top, long-lived heavy particles
- stay tuned!