Summary of Flavour Physics Results

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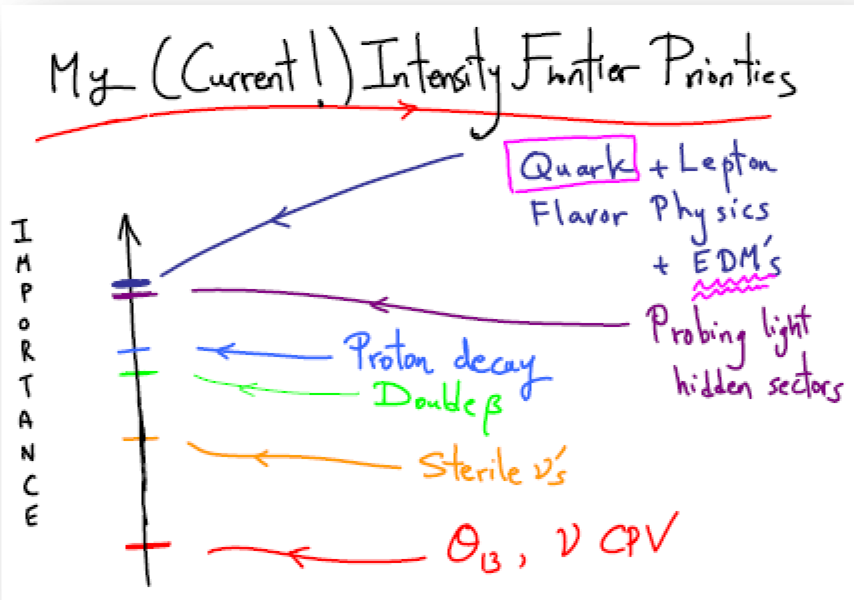
On behalf of the LHCb collaboration

Introduction

Flavour physics – a matter of taste ?

The physics of flavor is the flavor of physics

Harald Fritzsch, Summary talk ICFP 2001,
Zhang-Jia-Jie. Hunan, China (5-6/2001)



Nima Arkani-Hamed,
Intensity Frontier Workshop,
11-12/2011

Whether or not you share these "strong" opinions …

Flavour physics is everywhere

Flavour lets us probe very high scales …

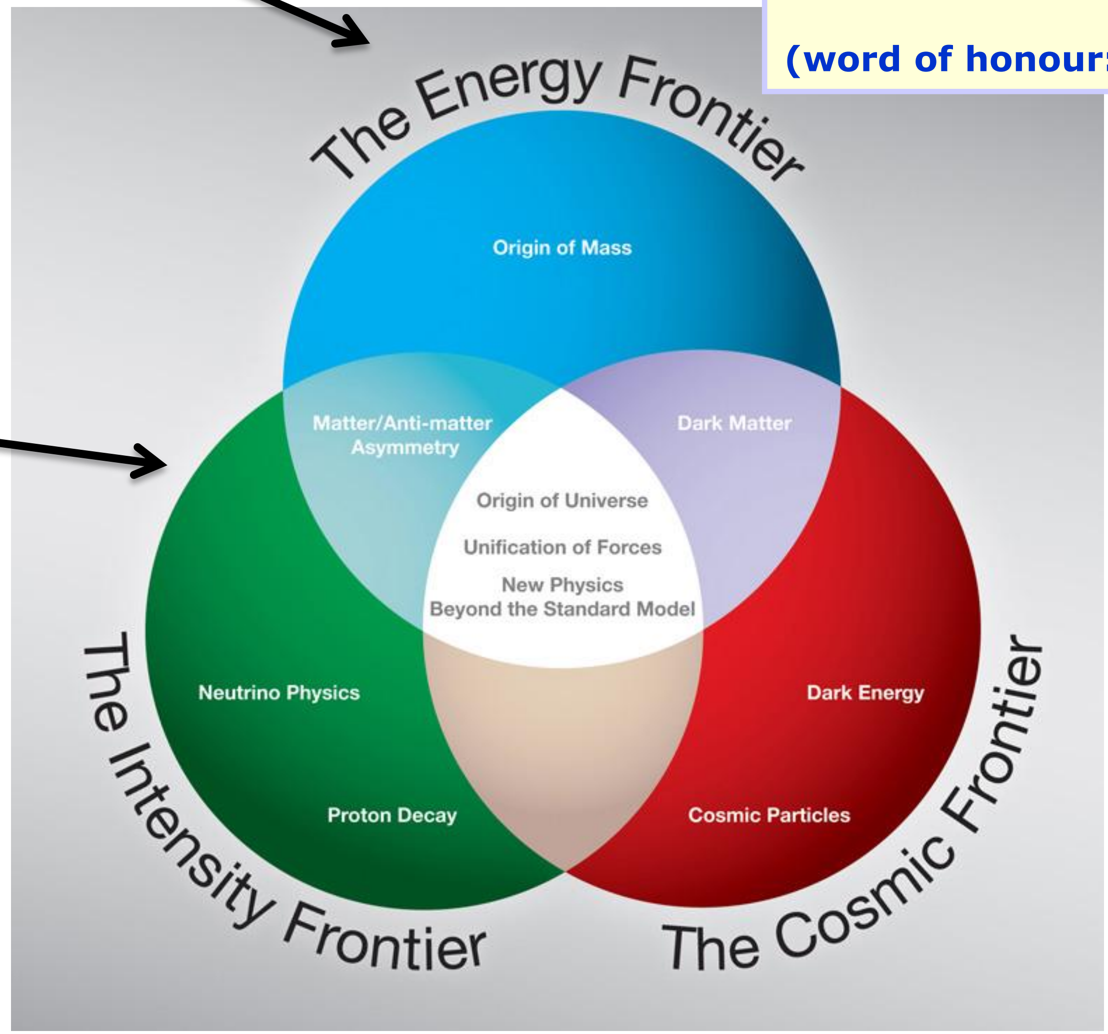
… i.e. beyond the Energy Frontier !

(word of honour: precision)

Production of New Physics particles if energy sufficient

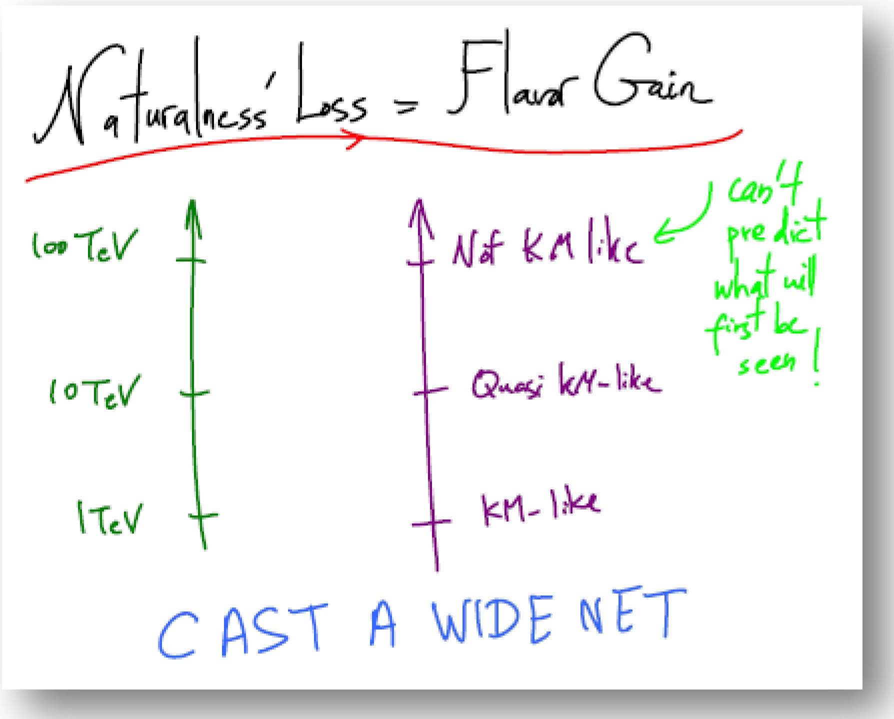
Precision tests of the SM
- Can probe >> TeV scale
- Can provide info on couplings *and* phases of new particles, if observed

Typically require large stats



(3 <u>complementary</u> ways of exploring HEP …)

Flavour physics – precision SM tests and search for NP



Nima Arkani-Hamed, Intensity Frontier Workshop, 11-12/2011

Post-LHC

(Fill the blanks …)

LHC

- Probing higher and higher scales
- And still no sign of NP
→ naturalness less likely
& chances to see NP in flavour ↑

Pre-LHC

- Belief in light new particles O(1 TeV)
→ avoid fine-tuning problem
- But absence of NP effects observed
→ some level of fine-tuning present in flavour sector

time

Highlight of recent results

- ***Precision tests in decays well predicted in the SM***
- ***Null tests with decays suppressed or forbidden in the SM***

Selected topics – disclaimer

Has to be selective – time constraints

- **Will focus on flavour physics in the quark sector**
- **And lepton flavour violation with muons**

Topics not covered

- **Flavour physics in the neutrino sector**

➡ ***See Daya Bay special talk (session 22B2x), T2K plenary talk (Nov. 25 morning)***

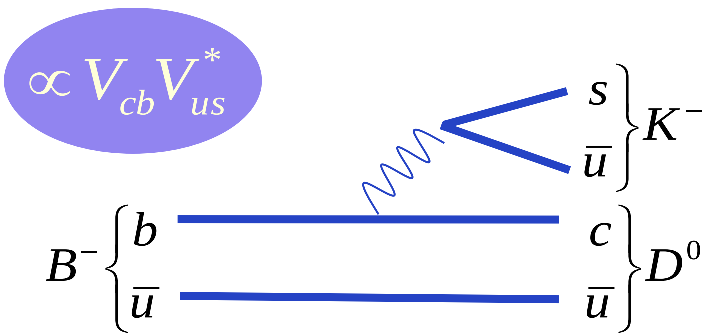
CKM angle γ

➡ ***See Matthew Williams's talk on γ from $B \rightarrow DK$ decays at LHCb (session 21B1c)***

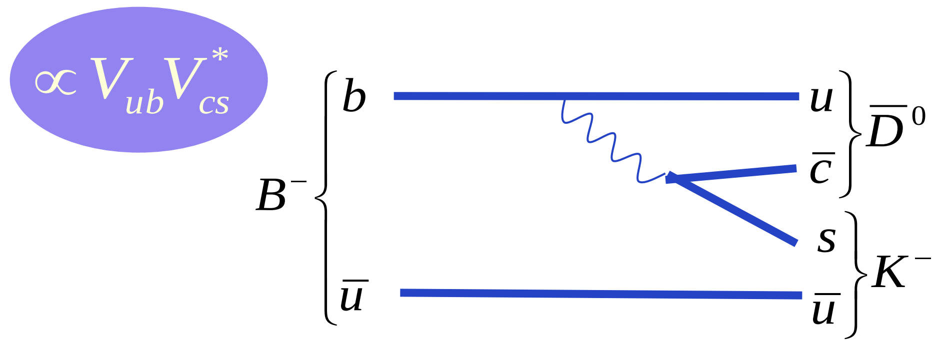
$$\gamma = arg(-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*})$$

CKM γ with tree-level decays

- ❑ **Tree-level decays ⇔ SM benchmark modes since no NP contributions !**
- ❑ **Same $D/\overline{D}$ final states ↔ sensitivity to γ via interference**



- colour allowed



- colour suppressed

- Relative magnitude of suppressed amplitude: $\mathbf{r_B}$
- Relative weak phase: $-\gamma$
- Relative strong phase: δ_B

***Various methods** (no tagging needed)*

- ❑ **ADS: common flavour state, eg. $K\pi$, $KK\pi\pi$**
- ❑ **GLW: CP eigenstates, e.g. K^+K^-, $\pi^+\pi^-$, $K_s\pi^0$, $K_s\phi$**
- ❑ **GGSZ: self-conjugate, e.g. K_shh**

Model-independent GGSZ with $B^\pm \to (K_S h^+ h^-)_D K^\pm$

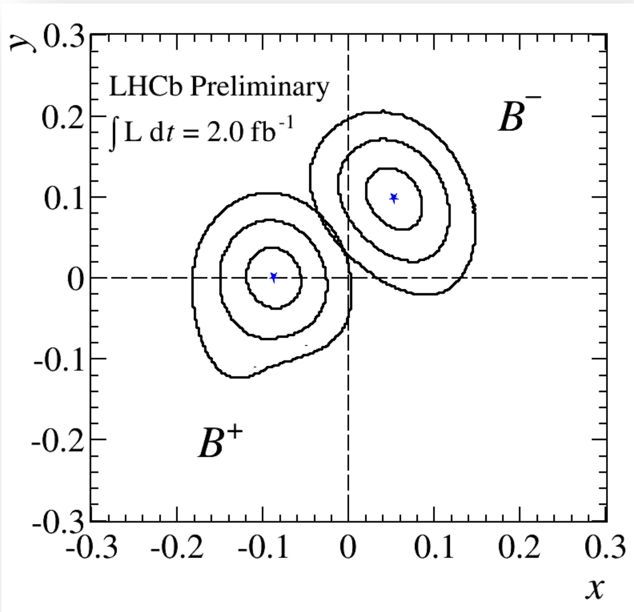
Analysis

- 2012 data sample (2 fb^{-1})

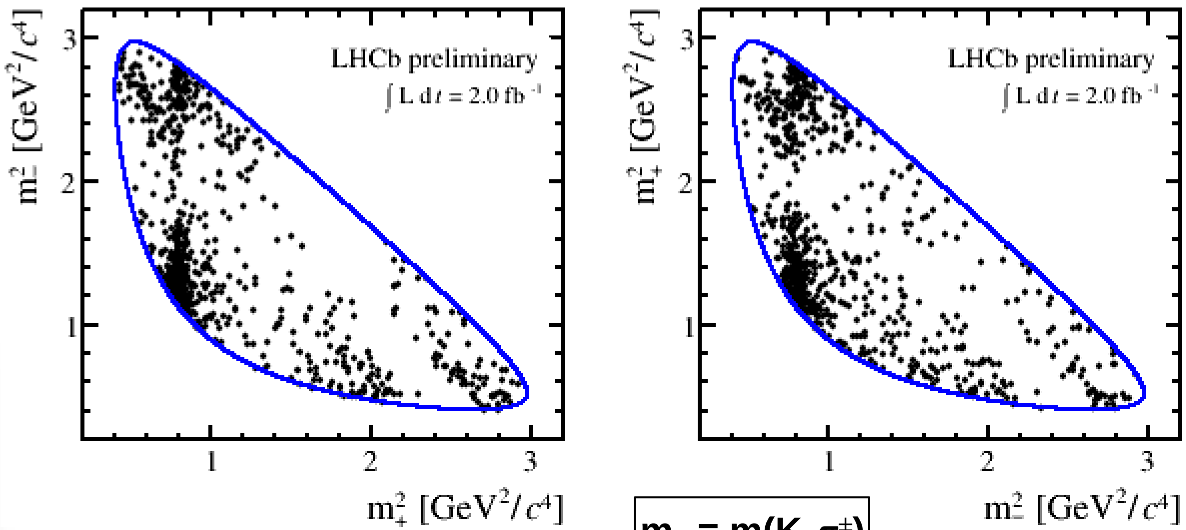
Observables

$$x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$$

$$y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$$



$B^+ \to (K_S \pi^+ \pi^-)_D K^+$ | **$B^- \to (K_S \pi^+ \pi^-)_D K^-$**



$m_\pm = m(K_S\pi^\pm)$

$$x_+ = (-8.7 \pm 3.1 \pm 1.6 \pm 0.6) \times 10^{-2}$$
$$x_- = (5.3 \pm 3.2 \pm 0.9 \pm 0.9) \times 10^{-2}$$
$$y_+ = (0.1 \pm 3.6 \pm 1.4 \pm 1.9) \times 10^{-2}$$
$$y_- = (9.9 \pm 3.6 \pm 2.2 \pm 1.6) \times 10^{-2}$$

Input: δ-variation across Dalitz from CLEO [PRD 82, 112006 (2010)]

LHCb-CONF-2013-004

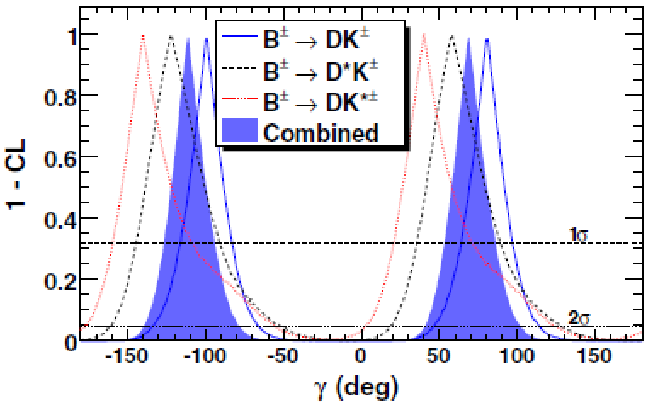
CKM γ – combinations

Impressive agreement between direct measurements & fits !

From direct measurements

BaBar

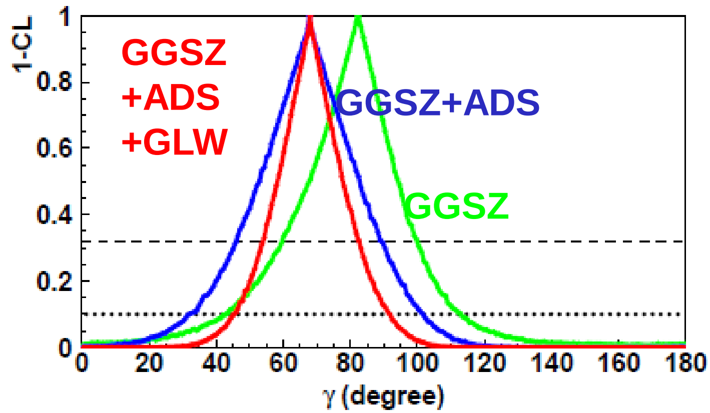
$\gamma = \left(69^{+17}_{-16}\right)^\circ$



PRD 87, 052015 (2013)

Belle

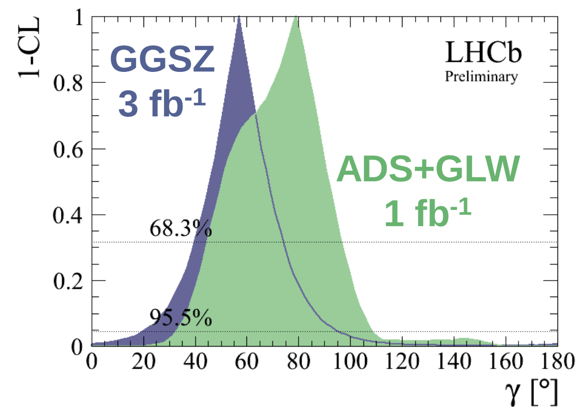
$\gamma = \left(68^{+15}_{-14}\right)^\circ$



arXiv:1301.2033 [hep-ex]

LHCb

$\gamma = (67 \pm 12)^\circ$



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Predictions from global fits

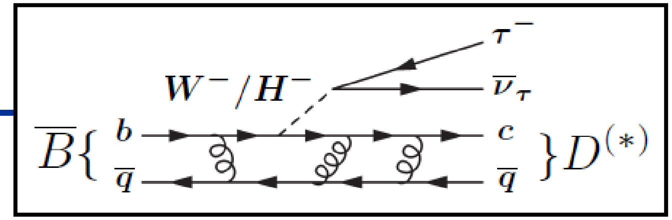
- CKMfitter (as of FPCP2013) : $\gamma = \left(69.7^{+1.3}_{-2.8}\right)^\circ$
- UTfit (post-EPS2013) : $\gamma = (70.3 \pm 3.5)^\circ$

(fits without γ measurements in)

☞ *Expect updates from LHCb with meas. on full 3 fb^{-1} dataset …*

More precision tests

B → D$^{(*)}$ τ ν – a hint of physics BSM ?



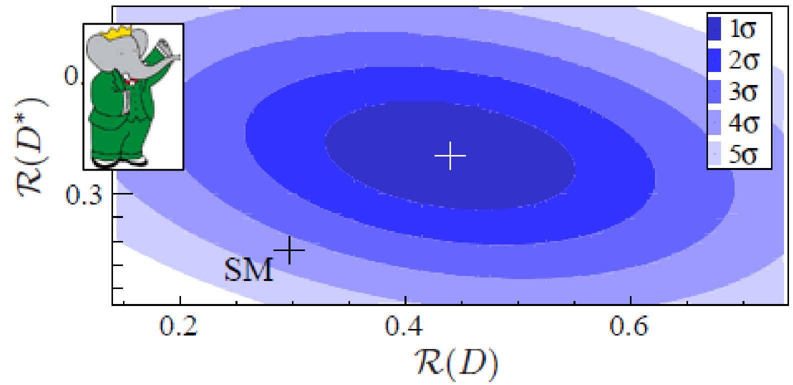
Physics

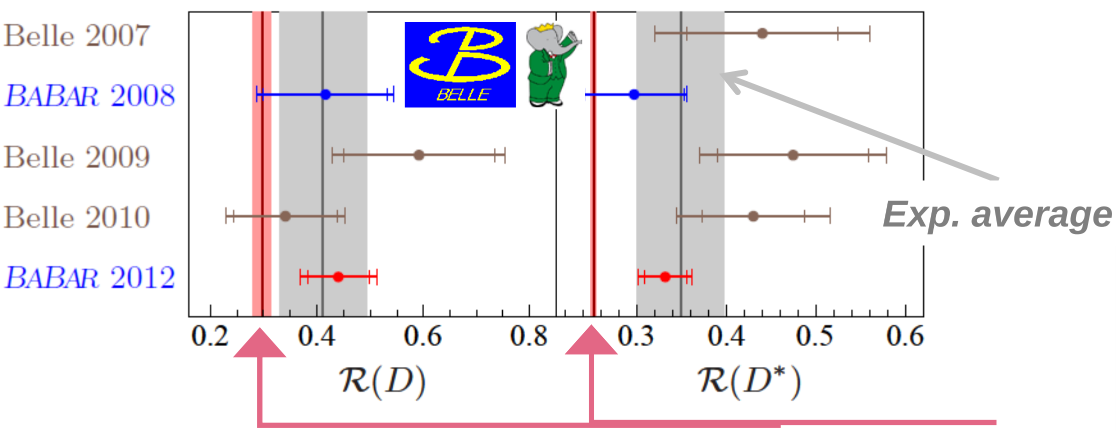
- Ratio R(D$^{(*)}$) = BF(B→D$^{(*)}$τν) / BF(B→D$^{(*)}$lν) sensitive to (BSM) charged Higgs (l=e,μ)
- And theoretically clean: 6% (2%) uncertainty for the D$^{(*)}$ mode

Experimental situation

- Latest BaBar measurement with full dataset: agreement of both R with SM expectations excluded 3.4σ [PRL 109, 101802 (2012); PRD 88, 072012 (2013)]
- Final Belle result to come …

PRD 88, 072012 (2013)





SM predictions

[taken from PRD 88, 072012 (2013)]

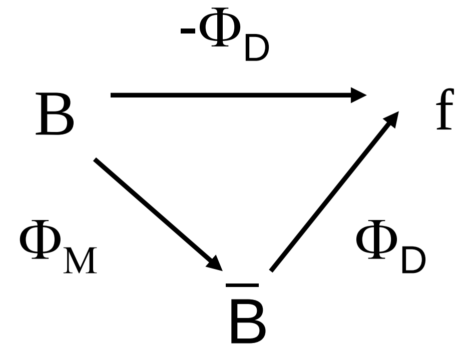
These results are not compatible with a charged Higgs boson in the type II 2HDM, and, together with $B \to X_s\gamma$ measurements, exclude this model in the full $\tan\beta$–m_{H^+} parameter space. More general charged Higgs models, or NP contributions with nonzero spin, are compatible with the measurements presented here.

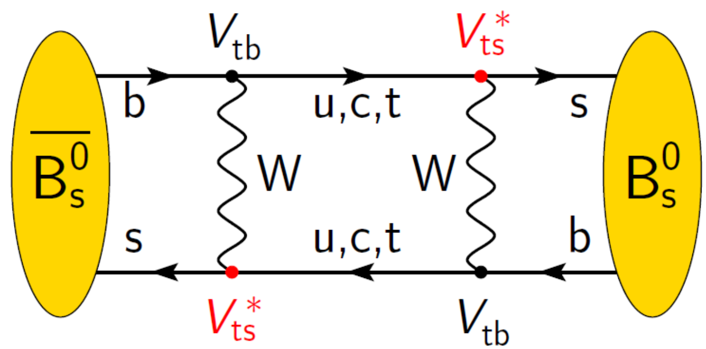
Measurements of ϕ_s

➡ ***See Mika Vesterinen's talk on asymmetries in semileptonic B decays at LHCb (session 25B2a)***

The B_s mixing phase ϕ_s

- CP violation observable phase $\phi_s = \Phi_M - 2\,\Phi_D$
- CP violation in interference between "mixed" and "unmixed" decays





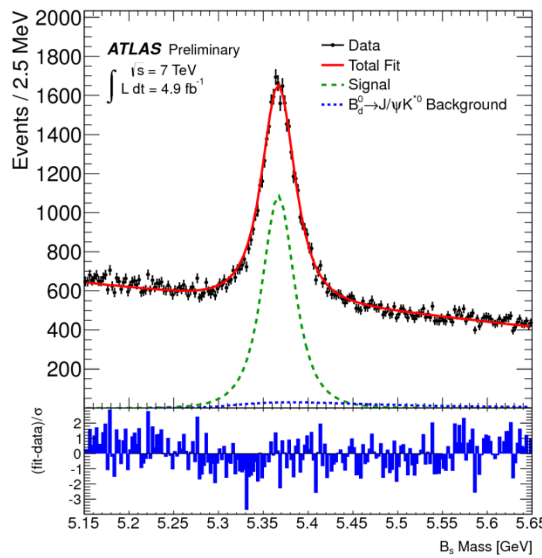
Standard Model expectations

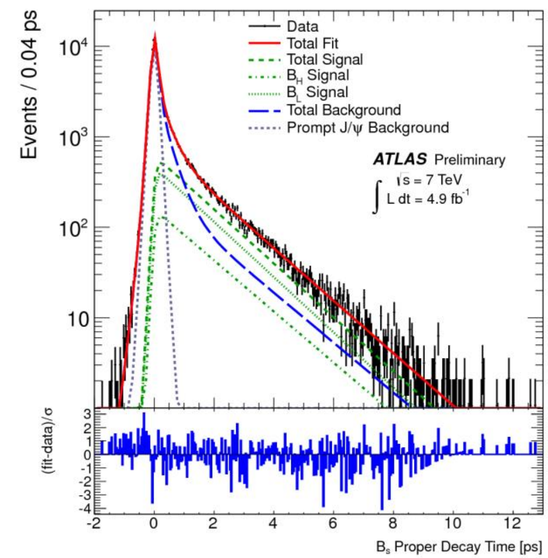
- Small and precisely predicted
- ϕ_s (SM) = $-2\arg[\,-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)\,] \approx 2\beta_s$
  $= (-0.0363 \pm 0.0016)$ rad
  [Phys. Rev. D84, 033005 (2011)]

- But New Physics could induce large deviations (non-SM CPV via mixing)

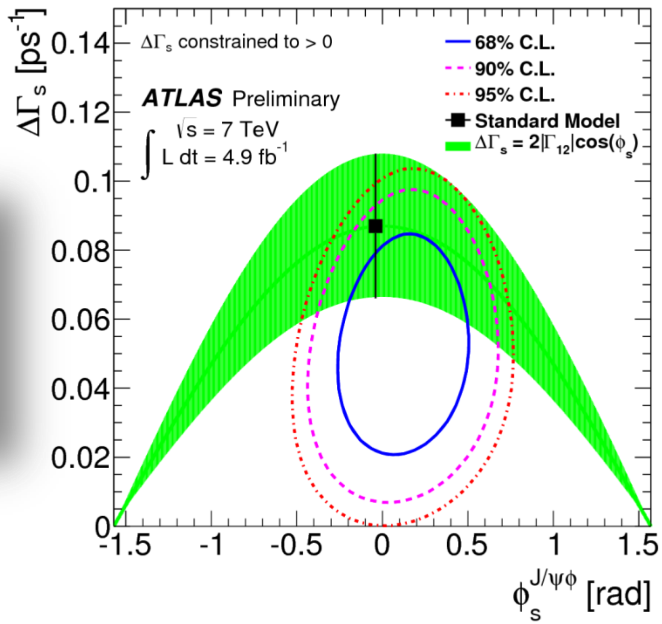
Flavour tagged TD analysis of $B_s \to J/\psi\, \phi$ – $\Delta\Gamma_s$ and ϕ_s

- 2011 data sample: 4.9 fb^{-1}
- 22670±150 B_s meson candidates
- A_0, $A_{||}$: CP-even components
- $A_\perp$: CP-odd component
- δ : corresponding strong phases
- S-wave component compatible with 0





$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$



$$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{ps}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$
$$|A_0(0)|^2 = 0.529 \pm 0.006(\text{stat.}) \pm 0.011\ (\text{syst.})$$
$$|A_{||}(0)|^2 = 0.220 \pm 0.008(\text{stat.}) \pm 0.009\ (\text{syst.})$$
$$\delta_\perp = 3.89 \pm 0.46\ (\text{stat.}) \pm 0.13\ (\text{syst.})\ \text{rad}$$

$$\phi_s \simeq -2\beta_s \qquad \beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$$

ATLAS-CONF-2013-039

ϕ_s @ LHCb – present and future

Latest LHCb results

- **The most precise to date, from combined fit of $B_s \to J/\psi KK$ and $B_s \to J/\psi\pi\pi$ data, 1 fb^{-1}**

$$
\begin{aligned}
\phi_s &= 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad}, \\
\Gamma_s &= 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) } \mathrm{ps}^{-1} \\
\Delta\Gamma_s &= 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) } \mathrm{ps}^{-1}
\end{aligned}
$$

PRD 87, 112010 (2013)

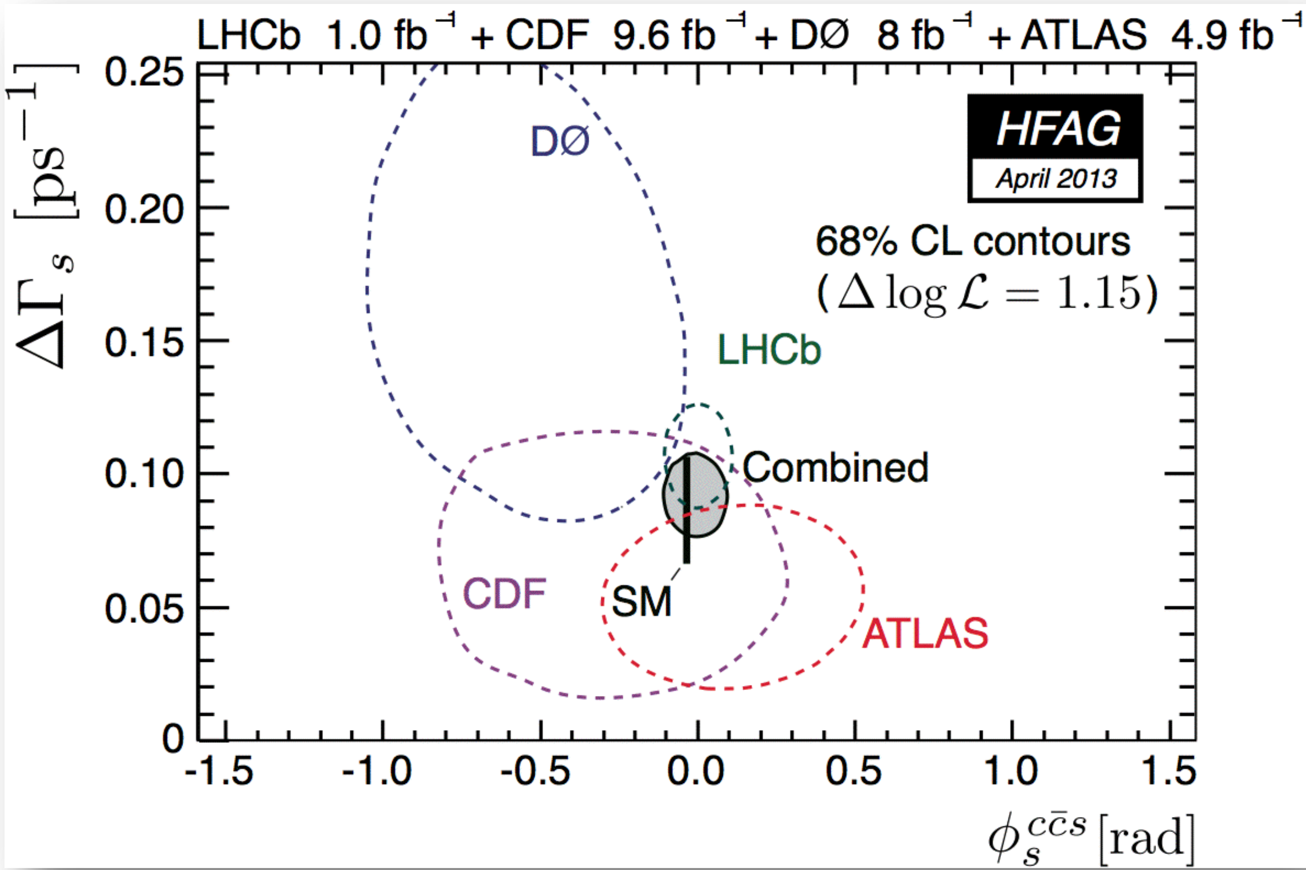
☞ ***Expect update with full run-I 3 fb^{-1} dataset …***

Other measurements

- **$B_s \to \psi(2S)\,\phi$, $B_s \to J/\psi\,\eta^{(\prime)}$, $B_s \to \phi\,\phi$, $B_s \to D_s\,D_s$, $B_s \to K^*\,K^*$**

ϕ_s from $B_s \to J/\psi\ h^+ h^-$ – combinations

(h=K,π)



☞ ***LHCb update with full run-I 3 fb^{-1} dataset very interesting***

CP violation in B decays

See Angelo Carbone's talk on B lifetimes, mixing and CP violation at LHCb (session 21B1c)

See Jessica Prisciandaro's talk on charmless B decays at LHCb (session 21C1b)

CP asymmetries in charmless 3-body B decays

- Decay modes involving non-negligible penguin diagram contributions

- LHCb has published a series of measurements of CP asymmetries in charmless 3-body B decays of the type $B^{\pm} \rightarrow h^{\pm} h^{+} h^{-}$ ($h=K,\pi,p$)

$$A_{CP}(B^{\pm} \to f^{\pm}) \equiv \Phi[\Gamma(B^{-} \to f^{-}), \Gamma(B^{+} \to f^{+})]$$

$$\Phi[X,Y] \equiv (X-Y)/(X+Y)$$

- CP asymmetries measured inclusively (i.e. averaged across the Dalitz plane) and in localised regions of the DP

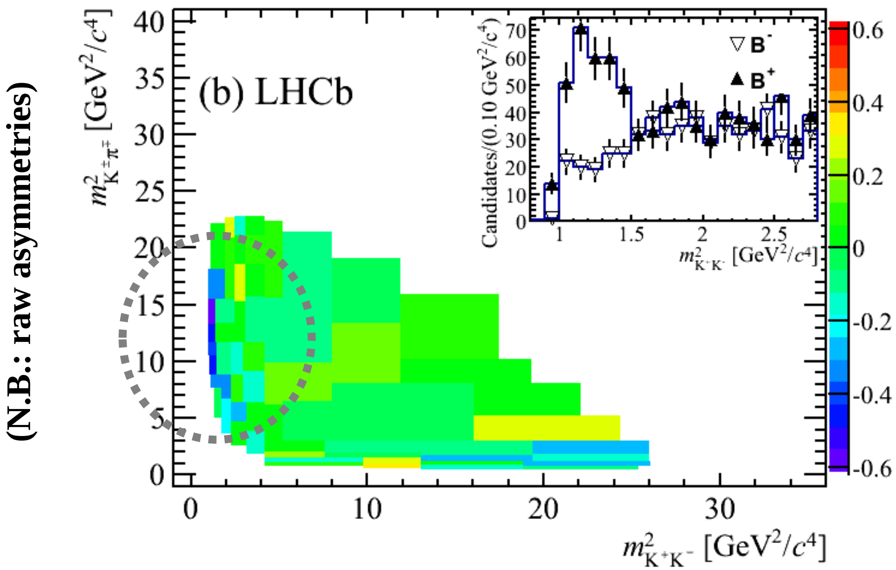
- All analyses on the 2011 data sample (1.0 fb^{-1})

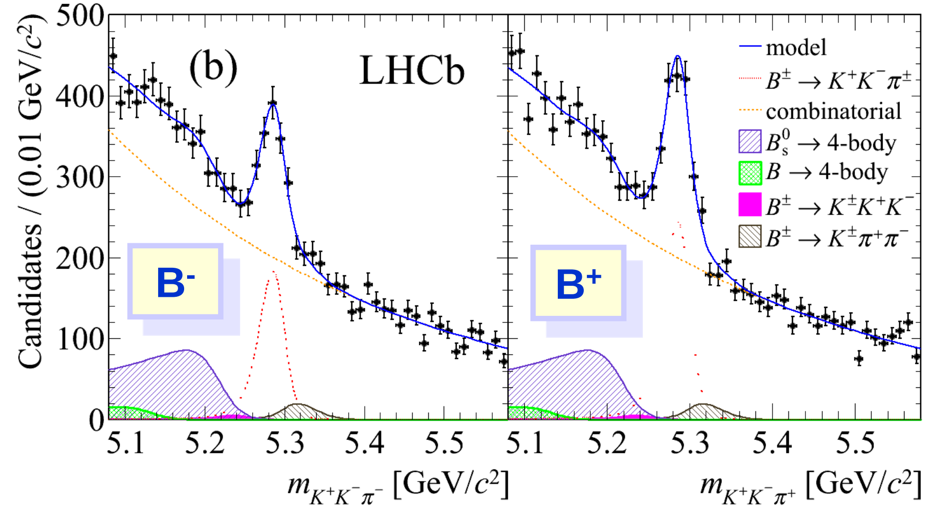
- Measurements in the following decays:
  - $B^{\pm} \rightarrow K^{\pm} \pi^{+} \pi^{-}$ and $B^{\pm} \rightarrow K^{\pm} K^{+} K^{-}$ decays [PRL 111, 101801 (2013)]
  - $B^{\pm} \rightarrow \pi^{\pm} \pi^{+} \pi^{-}$ and $B^{\pm} \rightarrow \pi^{\pm} K^{+} K^{-}$ decays [arXiv:1310.4740 [hep-ex]]
  - Baryonic mode $B^{\pm} \rightarrow p \bar{p} K^{\pm}$ [PRD 88, 052015 (2013)]

A_{CP} in $B^\pm \to h^+ h^- \pi^\pm$ decays – example of $B^\pm \to K^+ K^- \pi^\pm$

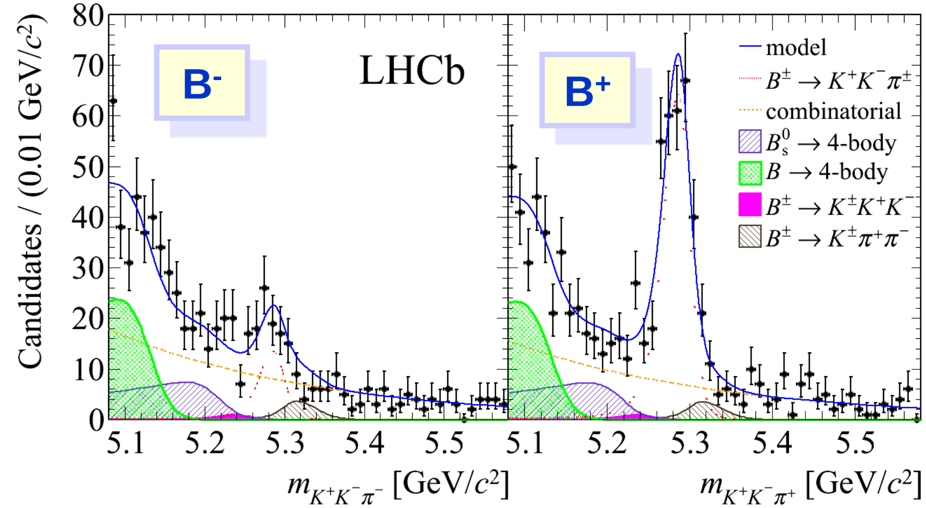
Inclusive CP asymmetry:

$$A_{CP}(B^\pm \to K^+K^-\pi^\pm) = -0.141 \pm 0.040 \pm 0.018 \pm 0.007$$





$m^2_{K^+K^-} < 1.5\,\mathrm{GeV}^2/c^4$



Regional CP asymmetry:

$$A^{reg}_{CP}(B^\pm \to K^+K^-\pi^\pm) = -0.648 \pm 0.070 \pm 0.013 \pm 0.007$$

arXiv:1310.4740 [hep-ex]

A_{CP} in in charmless 3-body B decays – outlook

- **Large asymmetries observed in localised areas in $B^\pm \to K^\pm h^+ h^-$ decays !**
- **But no such effects observed in baryonic mode $B^\pm \to p \overline{p} K^\pm$**

- **Results triggering major theoretical interest**
- **Great interest in understanding the origin of such large asymmetries in $B^\pm \to h^\pm h^+ h^-$**
  - **New mechanisms for CP asymmetries?**

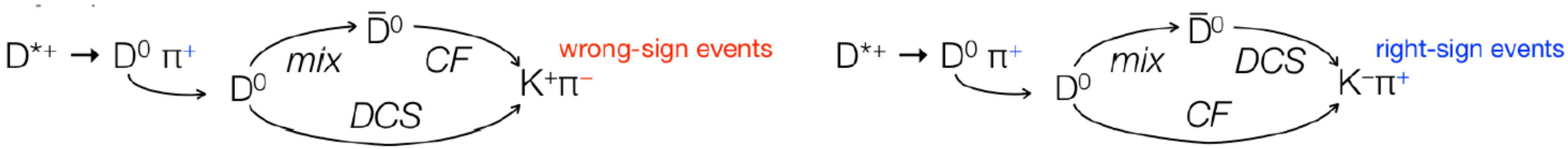
☞ ***Updates with full run-I 3 fb^{-1} dataset will be extremely interesting …***

Charm physics

See Diego Tonelli's talk on charm mixing and CP violation in LHCb decays (session 25B1a)

Mixing in the charm sector

- D⁰ mixing established by LHCb **[PRL 110, 101802 (2013)]**



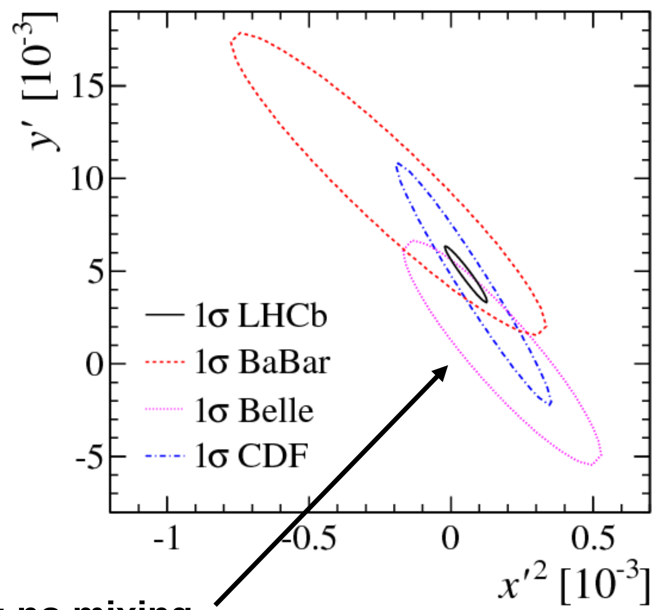
- Measurement of D^0 mixing parameters and searches for CP violation via TD decay rate of wrong-sign to right-sign modes

$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

- Full run-I data sample – 3.0 fb^{-1}

- Most precise measurement of mixing parameters

$$x'^2 = (5.5 \pm 4.9) \times 10^{-5} \quad y' = (4.8 \pm 1.0) \times 10^{-3}$$
$$R_D = (3.568 \pm 0.066) \times 10^{-3}$$



(0,0): no mixing

$$\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\overline{D}^0 \to K^+\pi^-) = -\sqrt{R_D}e^{-i\delta}.$$

arXiv:1309.6534 [hep-ex]

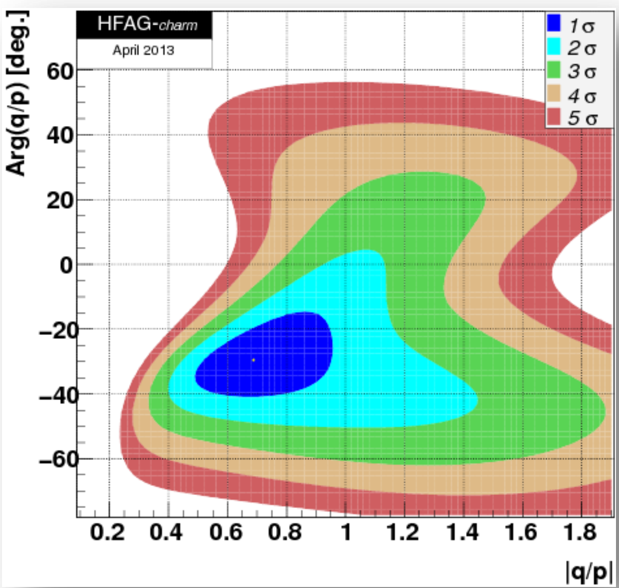
No sign of charm CPV – example of TD D→hh analysis

- 2011 data sample: 1.0 fb^{-1}
- Measurement of the asymmetry of decay widths of D^0 and $\bar{D}^0$ to CP eigenstates
  - Effectively measurement of indirect CP

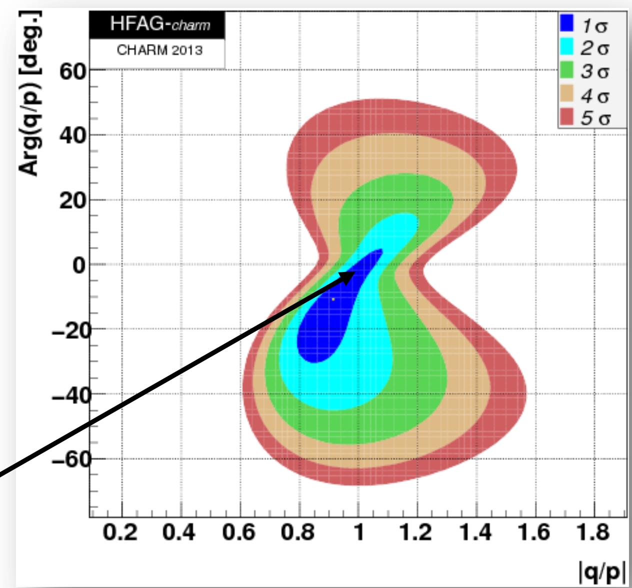
$$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$$
$$A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$$

$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\bar{\Gamma}}}{\hat{\Gamma} + \hat{\bar{\Gamma}}}$$

- Impact on global fits of charm mixing (incorporating CPV effects)



New average



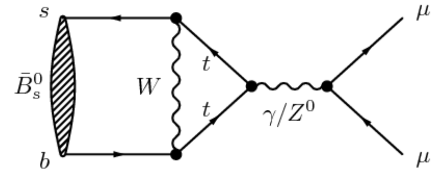
(1,0): no CPV

arXiv:1310.7201 [hep-ex]

Searches for NP effects in rare decays

➡ ***See Simon Wright's talk on studies of $b \to (s,d)(\mu\mu,\gamma)$ transitions at LHCb (session 25B2a)***

Searching for $B_s \to \mu^+ \mu^-$ …



Standard Model expectations

- **Helicity suppressed FCNC**

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\rm SM} = (3.23 \pm 0.27) \times 10^{-9}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-)^{\rm SM} = (1.07 \pm 0.10) \times 10^{-10}$$

[EPJC 72, 2172 (2012)]

- **Time-integrated BF accounting for $\Delta\Gamma_s \neq 0$** **[JHEP 07 (2013) 077]**

$$\overline{\rm BR}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.56 \pm 0.18) \times 10^{-9}$$

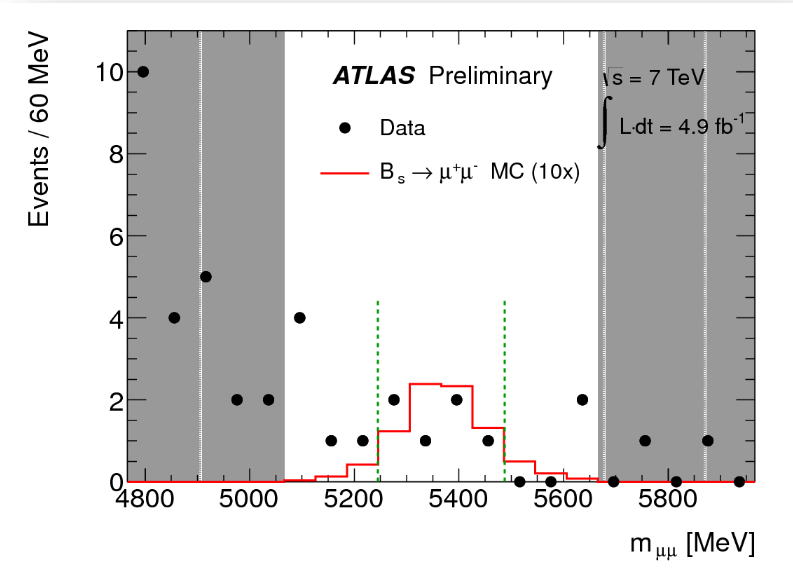
First and most recent searches

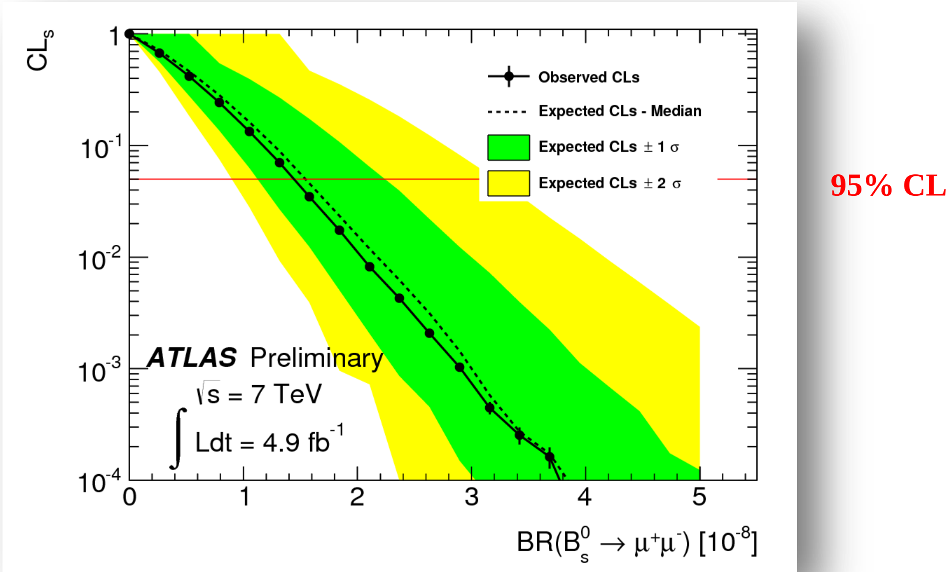
- **1984: CLEO** **[PRD 30, 2279 (1984)]**
- **…**
- **CDF** **[PRD 87, 072003 (2013)]**, **D0** **[PRD 87, 072006 (2013)]**
- **ATLAS** **[ATLAS-CONF-2013-076]**, **CMS** **[JHEP 04 (2012) 033]**, **LHCb** **[PRL 110, 021801 (2013)]**

Search for $B_s \to \mu^+ \mu^-$ with the full 2011 dataset

- 2011 data sample: 4.9 fb^{-1}
- BF measured wrt BF($B \to J/\psi K$)
- Multivariate selection & usage of CL_s method

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.5\ (1.2) \times 10^{-8} \text{ at } 95\%\ (90\%)\ \text{CL}$$





ATLAS-CONF-2013-076

$B_s \to \mu^+ \mu^-$ – 1st evidence by CMS & LHCb !

$$B(B_s \to \mu^+\mu^-) = \left(2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)\right)\times 10^{-9}$$

(Stat. significance: 4.0 σ)

$$B(B^0 \to \mu^+\mu^-) = \left(3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)\right)\times 10^{-10}$$

(Stat. significance: 2.0 σ)

$B(B^0 \to \mu^+\mu^-) < 6.3\ (7.4)\times 10^{-10}$ at 90% (95%) CL

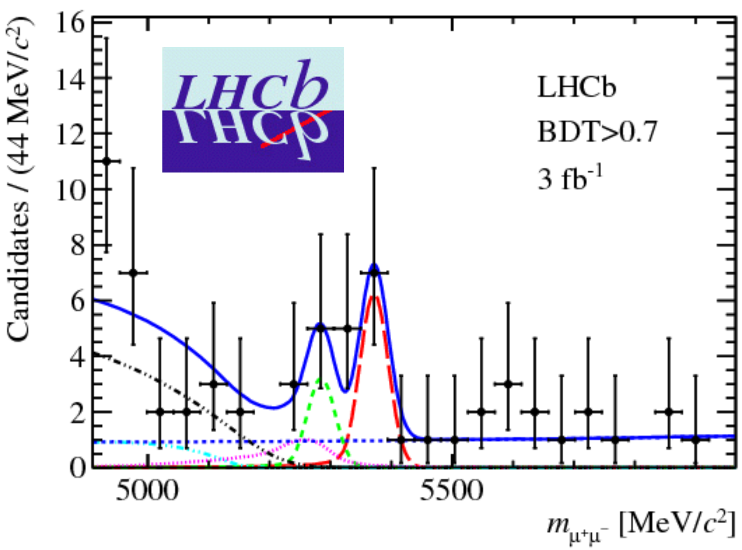
$$B(B_s \to \mu^+\mu^-) = \left(3.0^{+1.0}_{-0.9}\right)\times 10^{-9}$$

(Stat. significance: 4.3 σ)

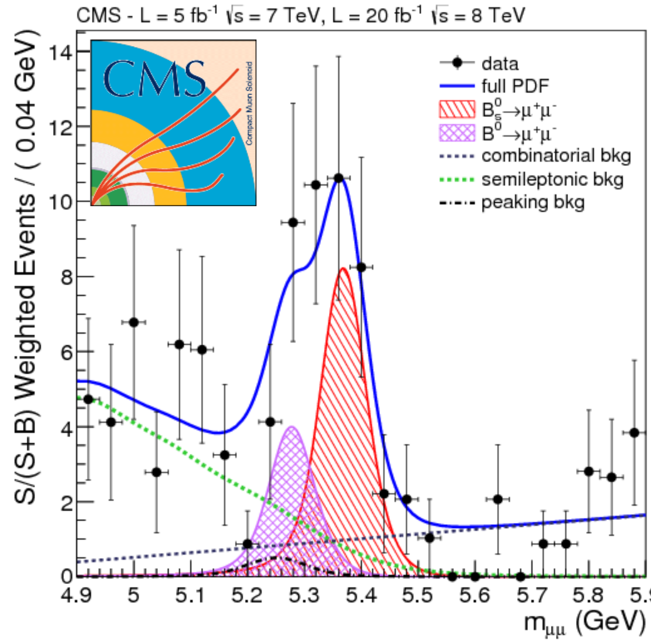
$$B(B^0 \to \mu^+\mu^-) = \left(3.5^{+2.1}_{-1.8}\right)\times 10^{-10}$$

(Stat. significance: 2.0 σ)

$B(B^0 \to \mu^+\mu^-) < 9.2\ (11)\ \ 10^{-10}$ at 90% (95%) CL



PRL 111, 101805 (2013)



PRL 111, 101804 (2013)

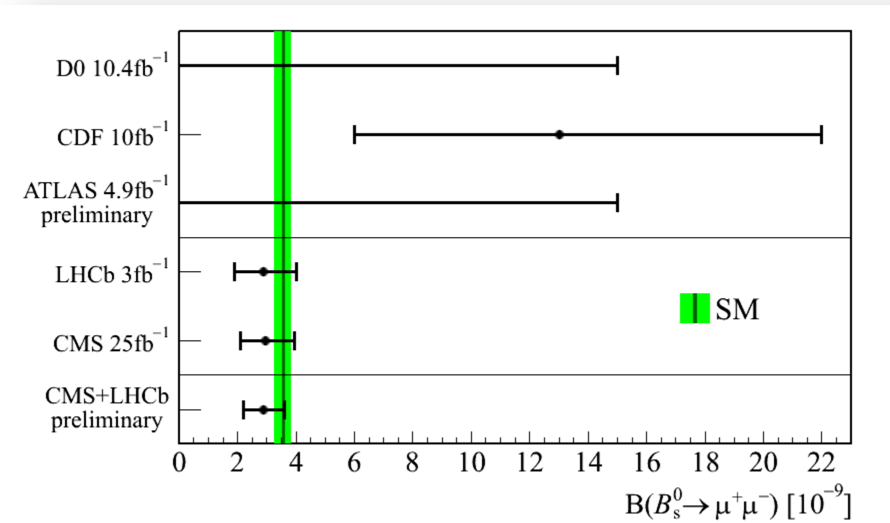
$B_s \to \mu^+ \mu^-$ – CMS+LHCb combination and 1st observation !

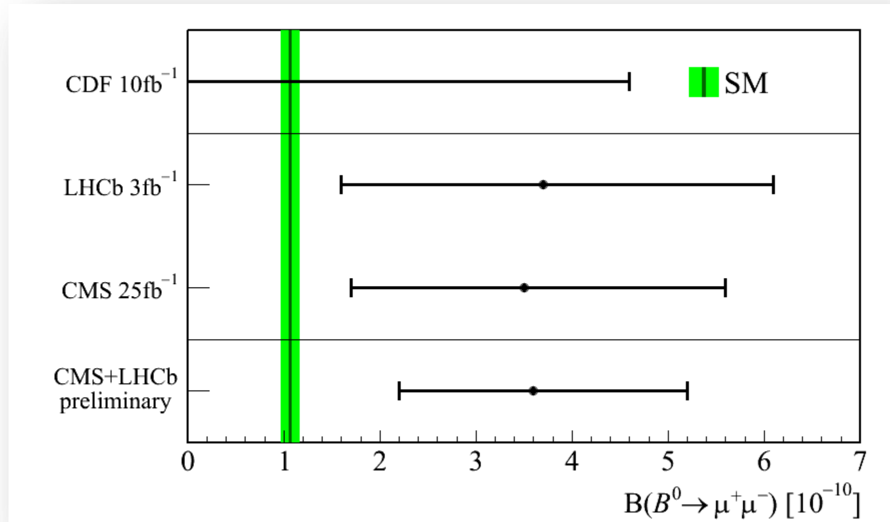
1st observation of $B_s \to \mu^+ \mu^-$

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

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

B^0 statistical significance < 3σ





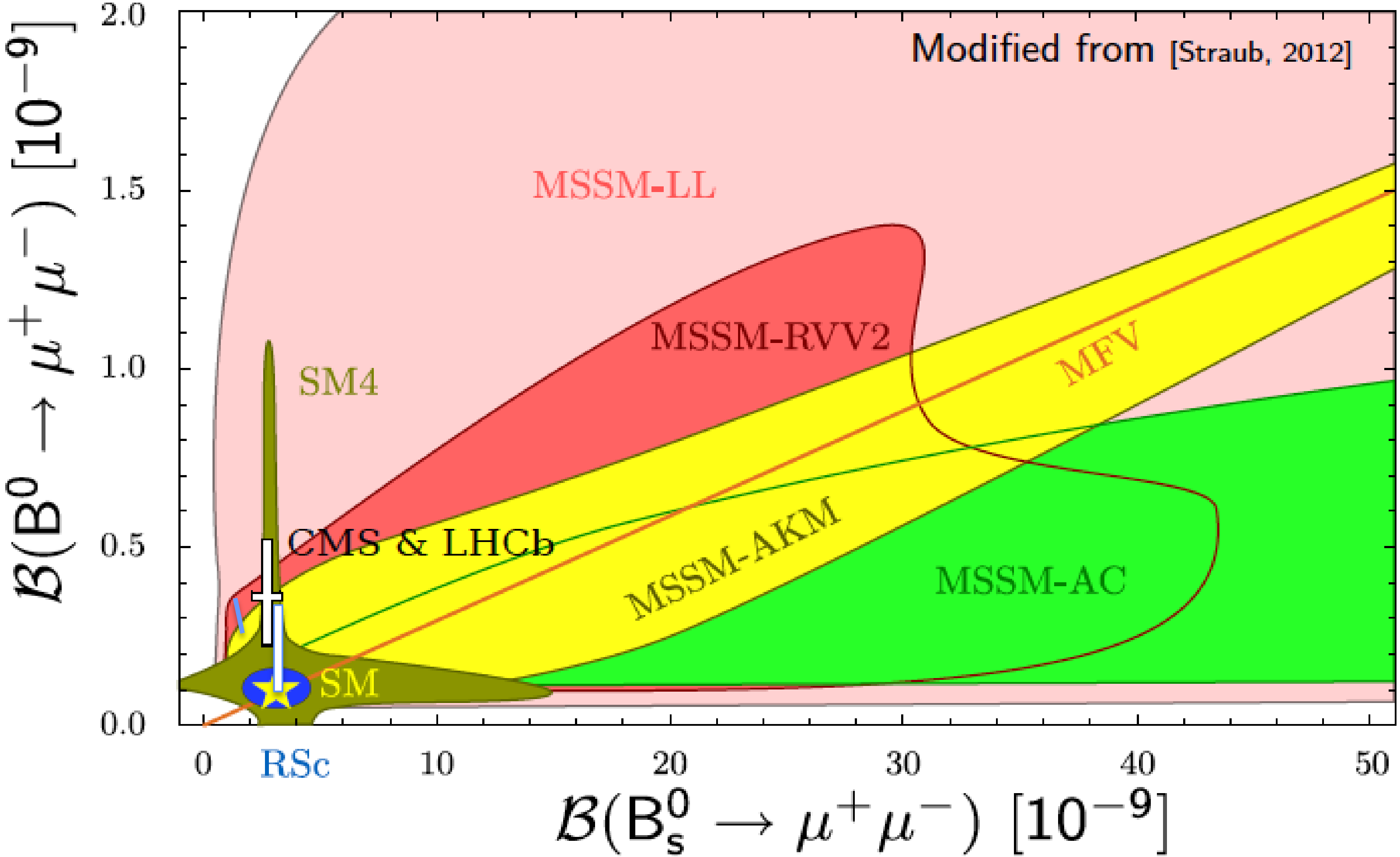
☞ ***Joint CMS+LHCb publication in preparation for Nature …***

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

$B_s \to \mu^+ \mu^-$ – constraints on BSM models

- Very significant constraints !

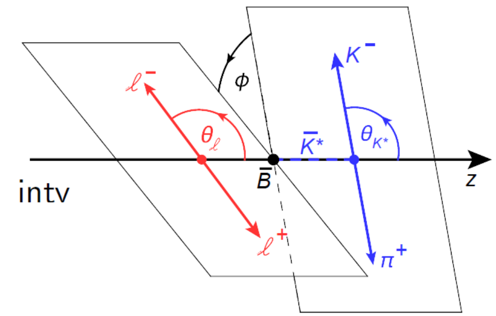
arXiv:1012.3893 [hep-ph]



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

Physics

- ❑ b → s FCNC decay mediated by electroweak box and penguin diagrams in the SM



Quantities of interest

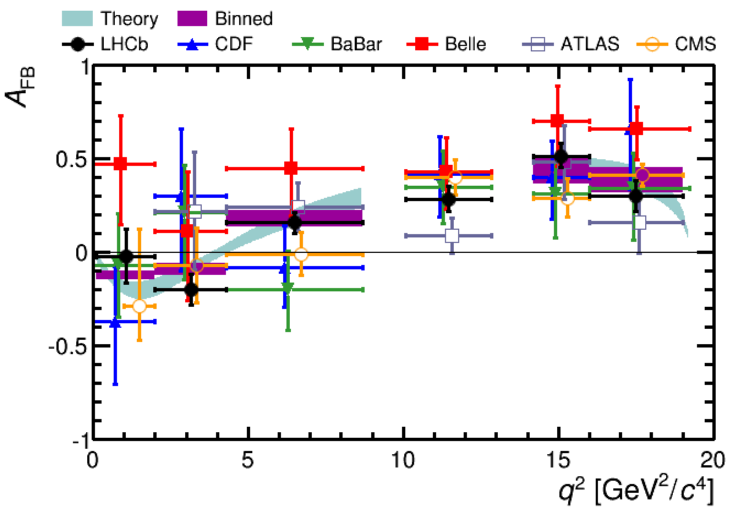
- ❑ A_{FB} : forward-backward asymmetry
- ❑ F_L : fraction of the K* longitudinal polarisation
- ❑ Differential branching fraction as a function of q^2 (= dimuon invariant mass square)

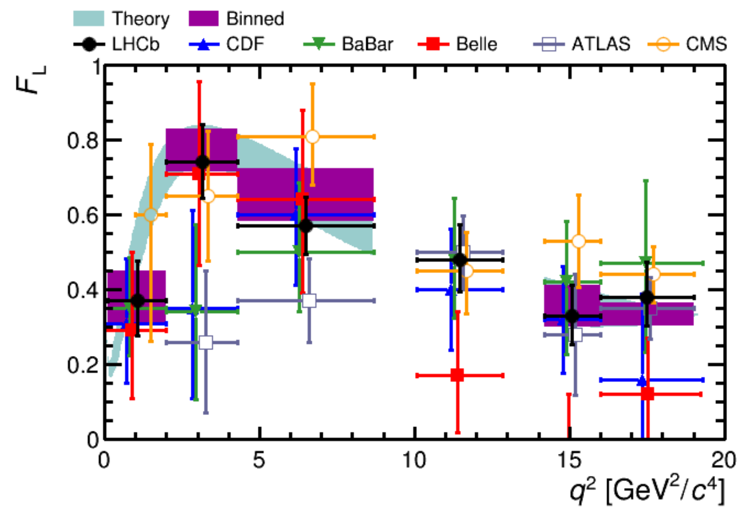
$$\begin{aligned}\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\Phi} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\ &- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\Phi \\ &+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\Phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\Phi \\ &+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\Phi \\ &+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\Phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\Phi\Big]\end{aligned}$$

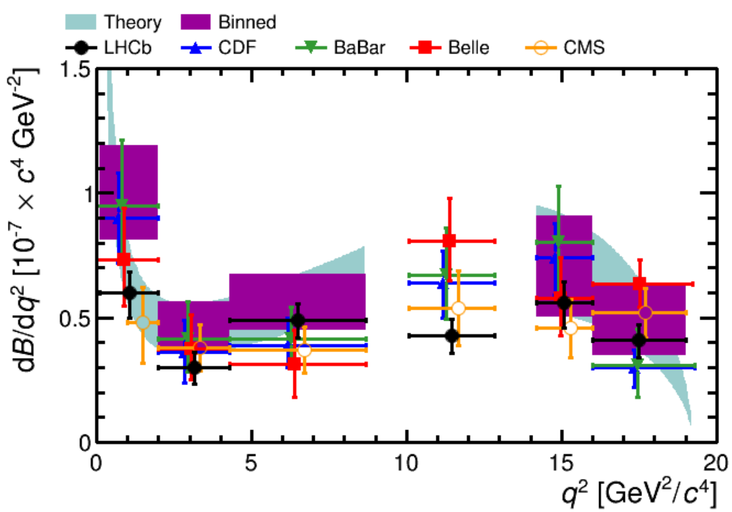
- ❑ Also new form-factor independent observables, see next slides

$B^0 \to K^{*0} \mu^+ \mu^-$ angular analysis on 2011 data

Very good agreement with theory and between experiments





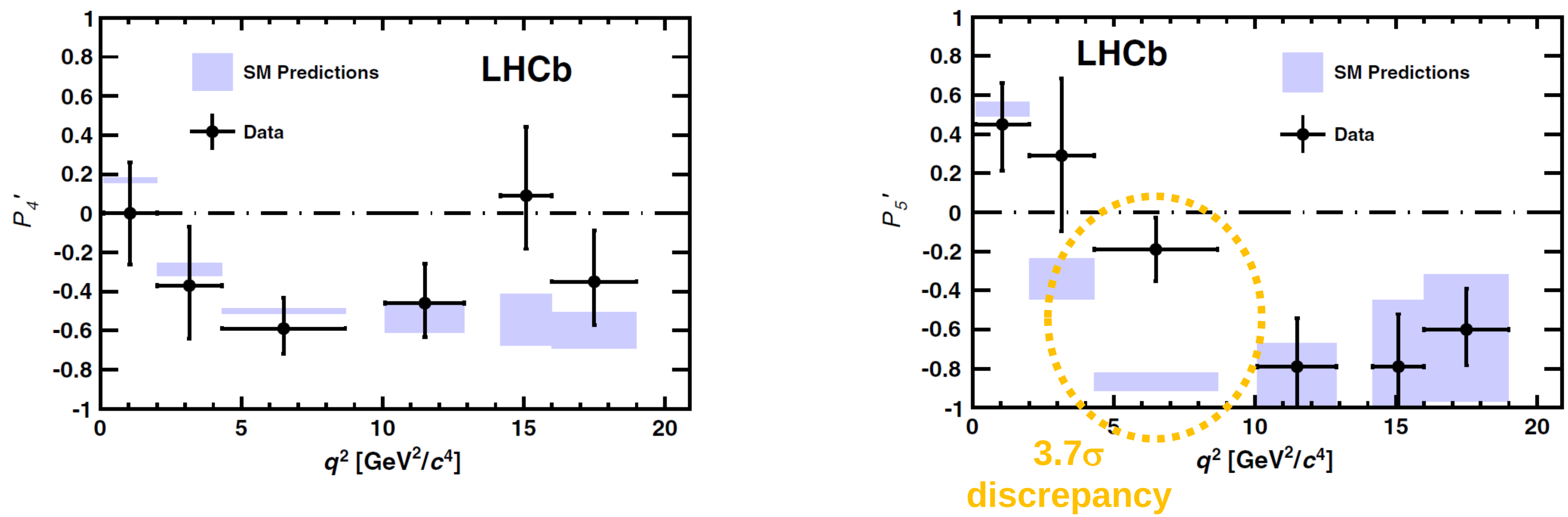


JHEP 08 (2013) 131

$B^0 \to K^{*0} \mu^+ \mu^-$ – form-factor independent observables

- Previous observables suffer from large-ish theoretical uncertainties
  - Due to uncertainties in hadronic form factors (long-distance effects)
- Observables defined as combinations of F_L and S_i, with small form-factor uncertainties, especially at low q^2 [JHEP 05 (2013) 137]
- LHCb performed an analysis of the 2011 data sample in the new basis defined by F_L, $A_T^2 = 2S_3/(1-F_L)$, $A_T^{Re} = 4/3 \times A_{FB}/(1-F_L)$ and $P'_i = S_i/\sqrt{[F_L(1-F_L)]}$ (i=4,5,6,8)

$\Rightarrow$ Tension between data and the SM prediction in one bin of P'_5 …
… raising considerable theoretical interest …



☞ ***LHCb update with full run-I 3 fb^{-1} dataset very interesting***

PRL 111, 191801 (2013)

Discovery of neutrino mixing

↓

LFV with neutral leptons

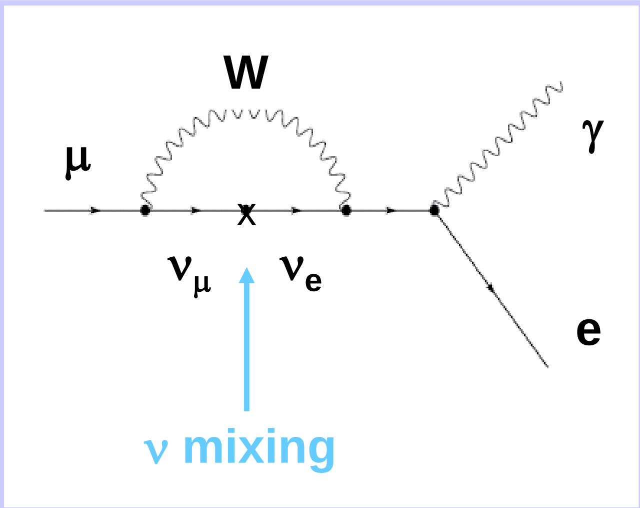
↓

One expects to find LFV also with charged leptons

Lepton flavour violation

⇨ *See Ricardo Vazquez Gomez's talk on searches for very rare decays at LHCb (session 21C1b)*

LFV μ processes

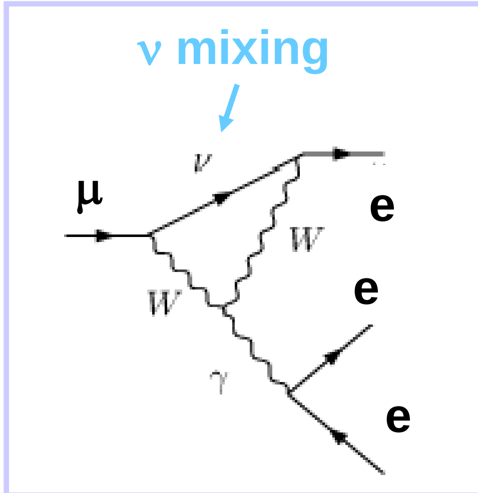


$\mu \to e\ \gamma$

$\mu \to e\ \gamma\gamma$

$\mu \to e\ e\ e$

$\mu \to e$ *conversion in nuclei*



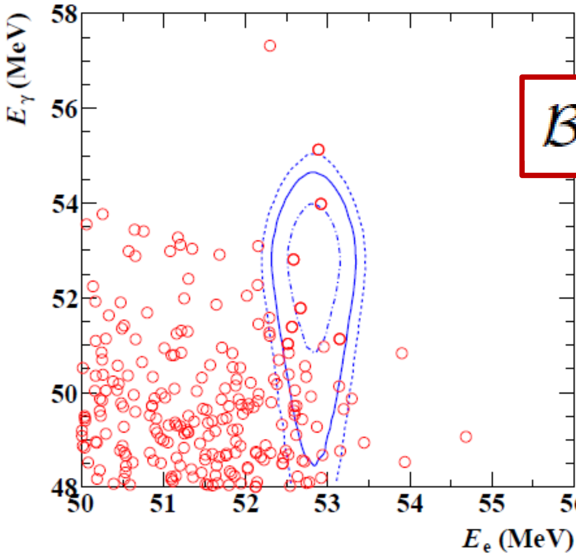
- **Other measurements looking for NP with muons involve: muonium $\mu^+e^- \to$ anti-muonium μ^-e^+ conversion and the g-2 anomalous moment of the μ**

$\mu^+ \to e^+ \gamma$ – latest result from MEG

http://meg.web.psi.ch

- 2009-11 sample: 3.6×10^{14} stopped μ^+ on target !

(2011 sample ≈ 2× 2009-10 sample)



$$\mathcal{B} < 5.7 \times 10^{-13} \text{ at } 90\% \text{ C.L.}$$

Current best UL !

(4× more stringent than previous)

Dataset	$\mathcal{B}_{\rm fit} \times 10^{12}$	$\mathcal{B}_{90} \times 10^{12}$	$\mathcal{S}_{90} \times 10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

→ **2009-10 sample re-analised with improved reconstruction**

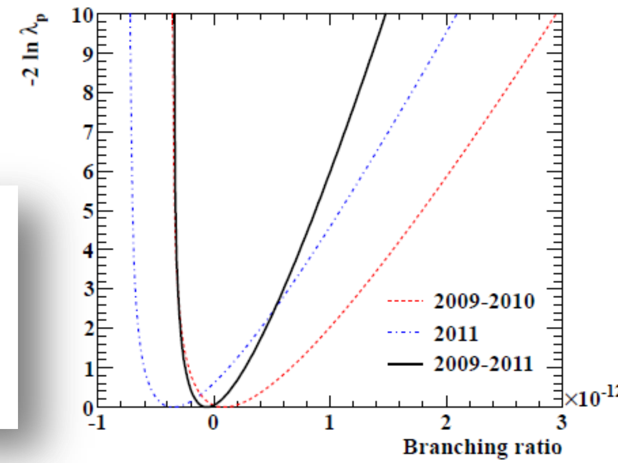


FIG. 3: Observed profile likelihood ratios (λ_p) as a function of the branching ratio for the 2009–2010 combined data, the 2011 data alone and the combined 2009–2011 data sample.

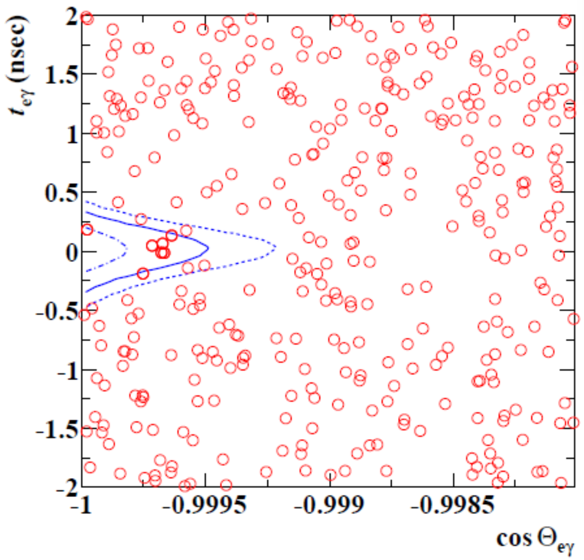
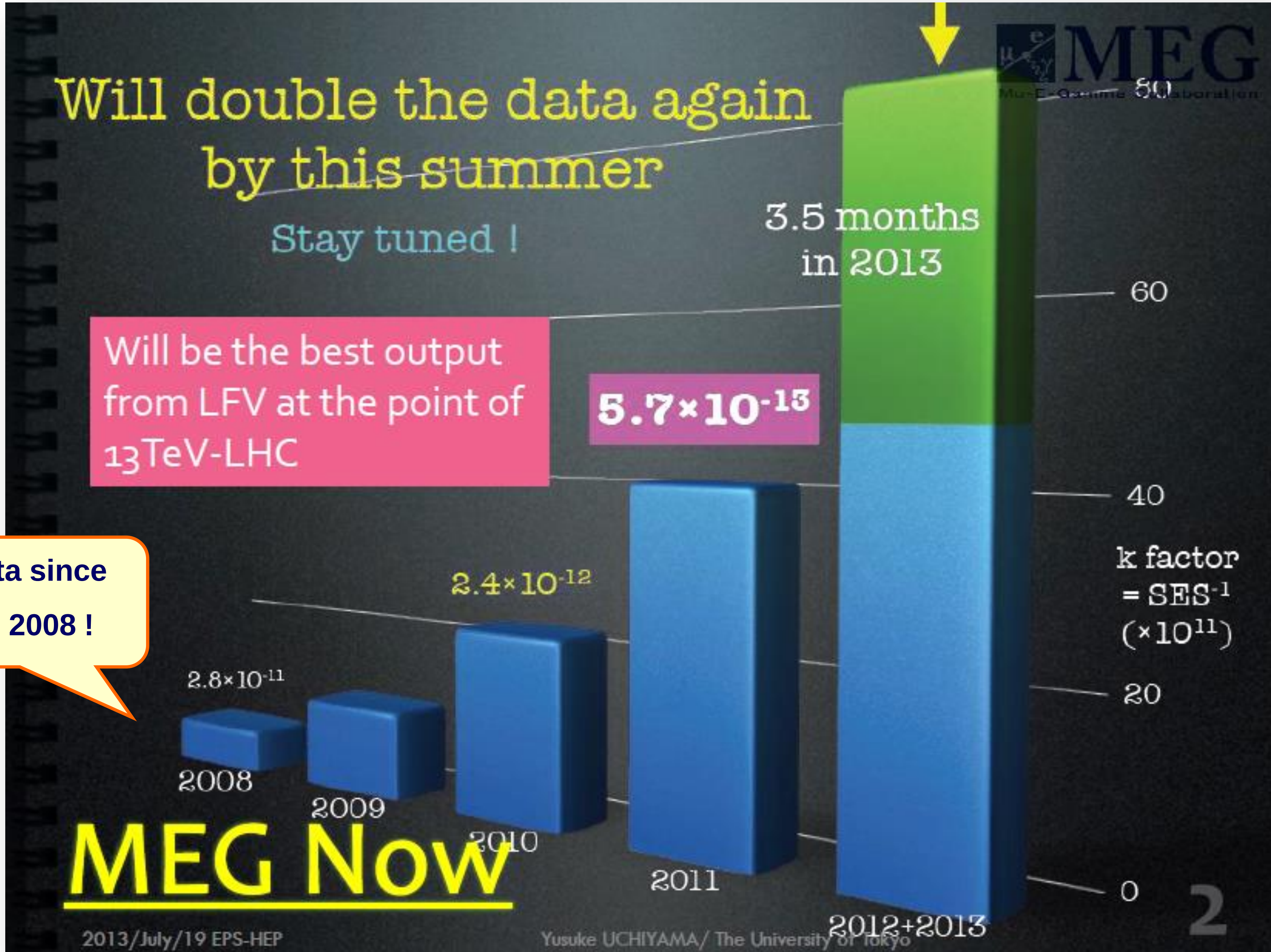


FIG. 2: Event distributions for the combined 2009–2011 dataset in the (E_e, E_γ)- and $(\cos\Theta_{e\gamma}, t_{e\gamma})$-planes. In the top (bottom) panel, a selection of $|t_{e\gamma}| < 0.244$ ns and $\cos\Theta_{e\gamma} < -0.9996$ with 90% efficiency for each variable ($52.4 < E_e < 55$ MeV and $51 < E_\gamma < 55.5$ MeV with 90% and 74% efficiencies for E_e and E_γ, respectively) is applied. The signal PDF contours (1, 1.64 and 2 σ) are also shown.

PRL 110, 201801 (2013)
arXiv:1303.0754 [hep-ex]

$\mu^+ \rightarrow e^+ \gamma$ results with MEG – a recap



Took data since
12 Sep. 2008 !

(taken from Y.Uchiyama, EPS-HEP talk, 19/07/2013)

Flavour with top quarks

Test of CPT invariance – top/anti-top mass difference

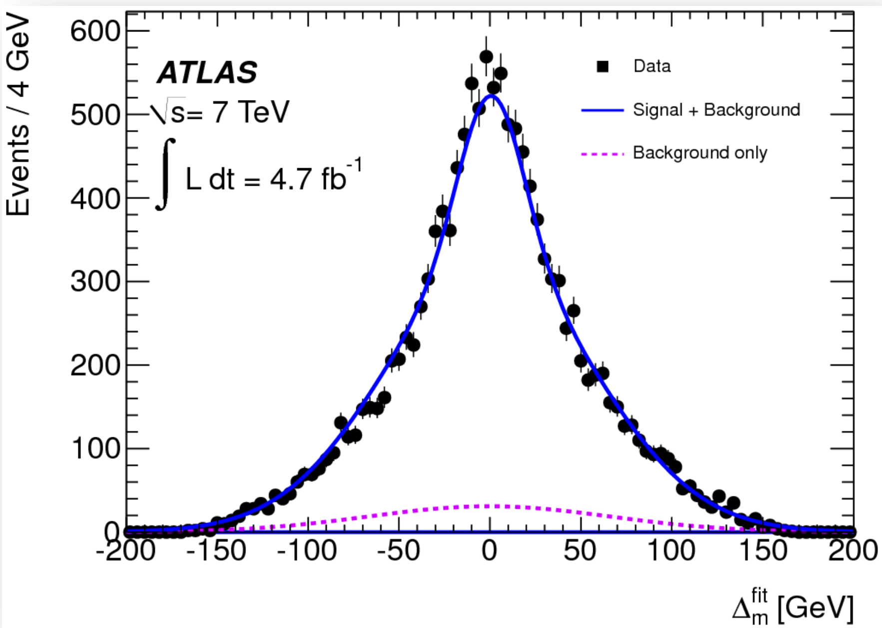
☞ **Top quark is unique: it decays before hadronising ⇒ only quark for which a direct measurement of its mass is possible !**

$$\Delta m \equiv m_t - m_{\bar{t}} = 0.67 \pm 0.61(\text{stat}) \pm 0.41(\text{syst})\ \text{GeV}$$

Channel	Muon	Electron
Data	8854	4941
SM $t\bar{t} \to W^+bW^-\bar{b}$	7700^{+1600}_{-1700}	4500^{+900}_{-1000}
W/Z + jets	320 ± 90	160 ± 40
Single top	300 ± 50	170 ± 30
Diboson	5 ± 1	3 ± 1
Multi-jet	220 ± 110	110 ± 60
Total expected (SM)	8550^{+1600}_{-1700}	4900^{+900}_{-1000}

Table 1: The observed number of events in data, the expected numbers of events from signal and background processes and the total number of events, after all selection requirements. Uncertainties shown include statistical and total systematic uncertainties added in quadrature.

❑ **Data sample: ttbar production in 4.7 fb^{-1} @ $\sqrt{s}$ = 7 TeV**



❑ **Fit to reconst. top/anti-top quark mass ≠**

$$\Delta_m^{\text{fit}} = q_\ell \times (m_{b\ell\nu}^{\text{fit}} - m_{bjj}^{\text{fit}})$$

- **Product of lepton charge and fitted top quark masses with leptonically and hadronically decaying W bosons**

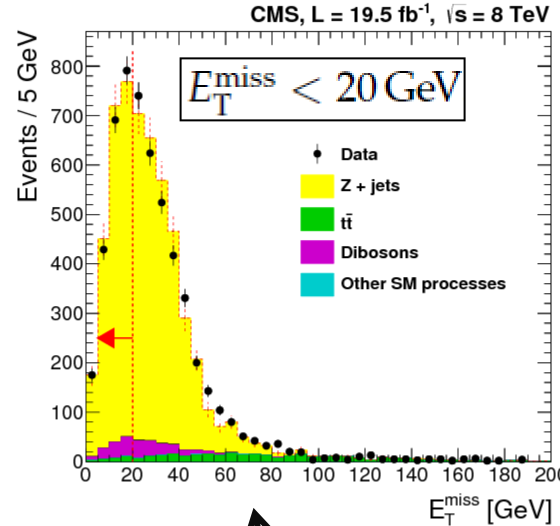
☞ ***LHCb plans to measure the ttbar production asymmetry (measured ≠ 0 by CDF/D0)***

arXiv:1310.6527 [hep-ex]

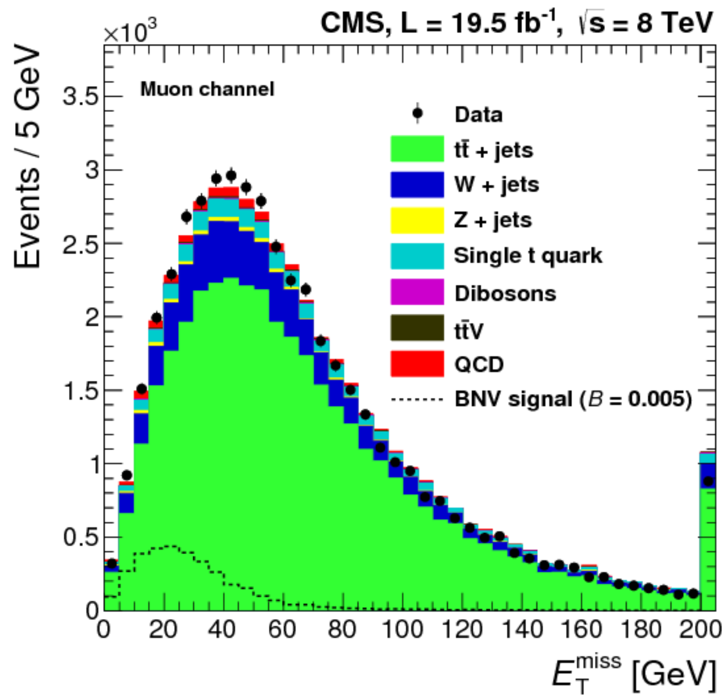
Baryon number violation in top-quark decays

- **2012 data sample: 19.5 fb^{-1}**
- **Event selection: ttbar events**
  - 1 top following the SM hadronic decay to 3 jets
  - 1 top following a BNV decay with 1 lepton (e or μ), 2 jets, no neutrino

BNV decays $t \to \bar{b}\bar{c}\mu^+$ ($\bar{t} \to bc\mu^-$) and $t \to \bar{b}\bar{u}e^+$ ($\bar{t} \to bue^-$)



1st limits on a BNV process involving the top quark



Validation of simulation for selection of low-E_T^{miss} events with sample enriched with Z (→μμ) + 4 jets events

95% CL upper limits on BF of BNV τ → lepton + 2 jets:

- 0.0016 for the μ channel
- 0.0017 for the e channel

arXiv:1310.1618 [hep-ex]

Production & spectroscopy

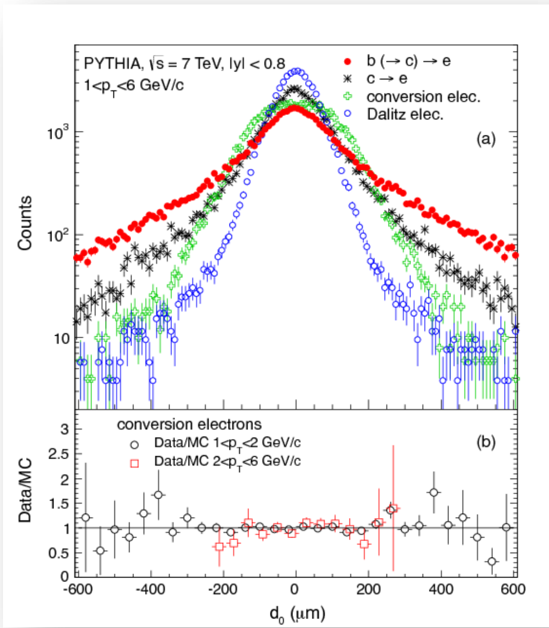
See Yiming Li's talk on b and c hadron production and spectroscopy at LHCb (session 24B2b)

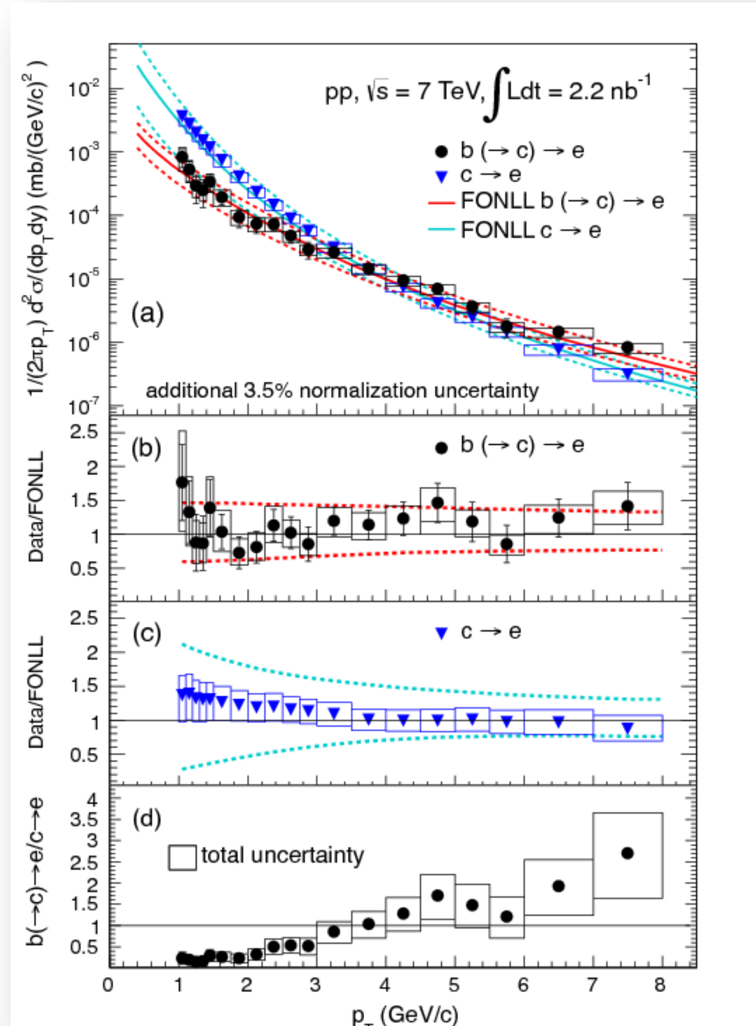
See Stefano de Capua's talk on onia production and spectroscopy at LHCb (session 24B2b)

See Xavier Cid Vidal's talk on EW gauge bosons & Higgs-like particle searches at LHCb (session 21B1a)

Electron production x-section from beauty hadrons

- ❑ Study of production of electrons at low p_T from semi-leptonic decays of beauty hadrons
- ❑ ≠ source of electrons discriminated by transverse impact parameter d_0





- ❑ Cross-section measurement @ √s = 7 TeV
- ❑ Good agreement with perturbative QCD predictions (FO with NLL resummation)

PLB 721, 13 (2013)

XYZ states – new X(3872) production in e^+e^-

BESIII

- X(3872) first observed a decade ago by Belle
- Subsequently confirmed by CDF, D0 and BaBar

PRL 91, 262001 (2003)
PRL 93, 072001 (2004)
PRL 93, 162002 (2004)
PRD 71, 071103 (2005)

- LHCb recently measured its quantum numbers to be $J^{PC}=1^{++}$!

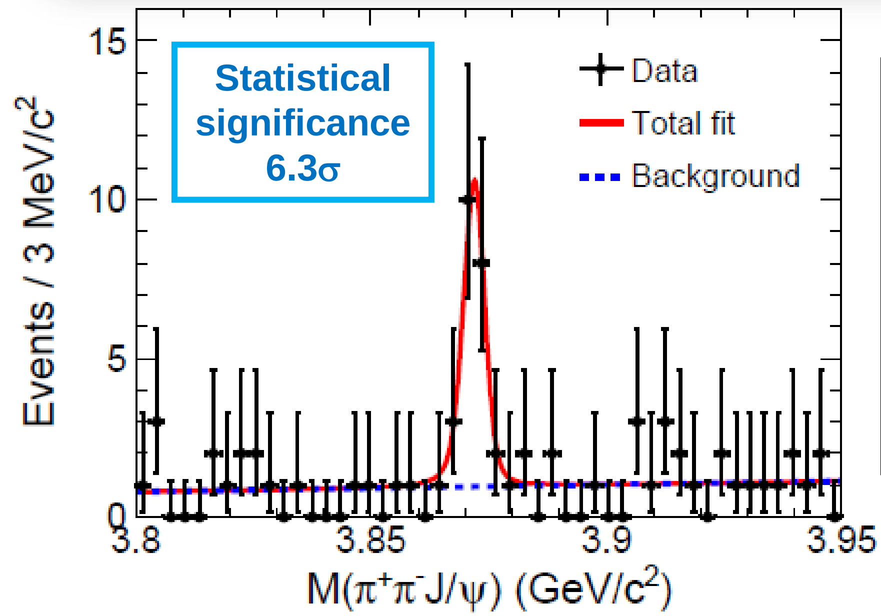
See LHCb talk by Stefano de Capua (session 24B2b)

PRL 110, 222001 (2013)

Observation of $e^+e^- \to \gamma X(3872)$ at BESIII

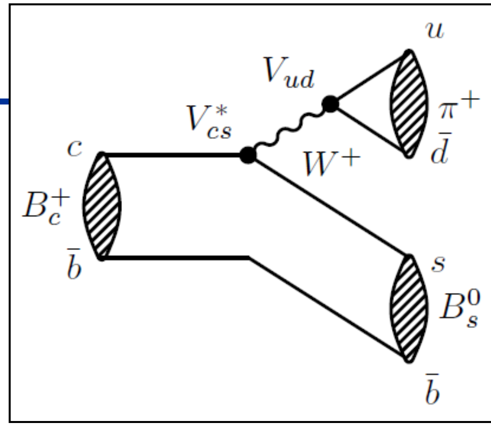
- New X(3872) production mode :

  - BESII also provides a mass measurement (in agreement with the PDG) and production cross-sections @ various centre-of-mass energies



arXiv:1310.4101 [hep-ex]

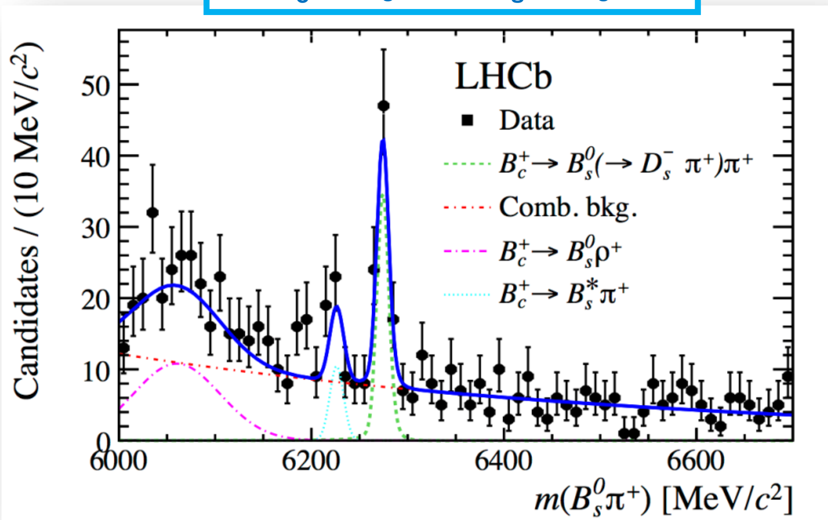
$B_c \to B_s \pi$ – 1st observation



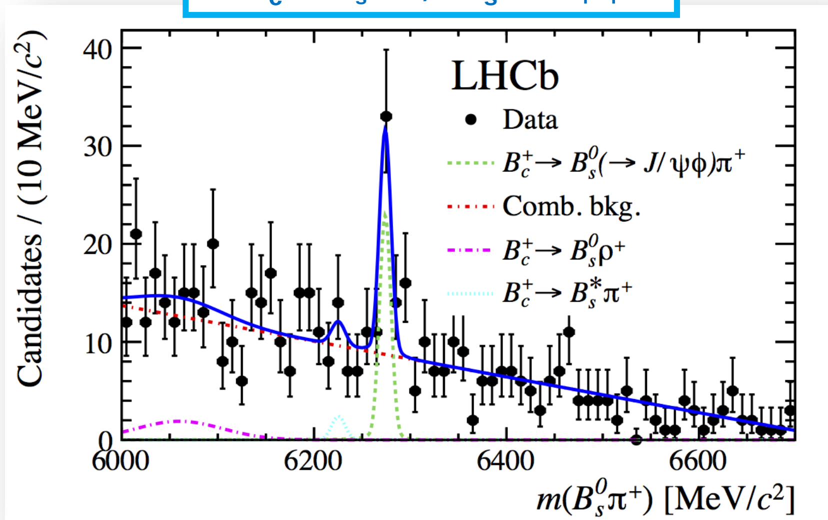
- Full LHCb run I dataset
  1 fb^{-1} @ 7 TeV, 2 fb^{-1} @ 8 TeV
- B_s reconstructed in 2 modes:

1st observation of a B-meson weak decay to another B meson

$B_c \to B_s \pi$, $B_s \to D_s \pi$



$B_c \to B_s \pi$, $B_s \to J/\psi\ \phi$



- Under reasonable assumptions, BF~10%, i.e. largest exclusive BF of any weak B meson decay

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = \left(2.37 \pm 0.31\,(\text{stat}) \pm 0.11\,(\text{syst})\,^{+0.17}_{-0.13}\,(\tau_{B_c^+})\right) \times 10^{-3}$$

(in $2 < \eta(B) < 5$)

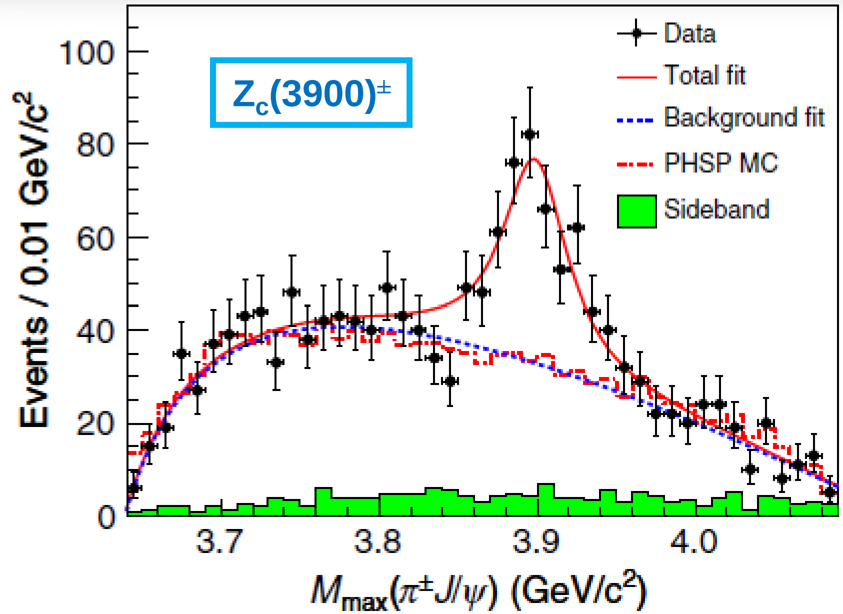
LHCb-PAPER-2013-044
PRL 111, 181801 (2013)

XYZ states – selection of recent results

BESIII

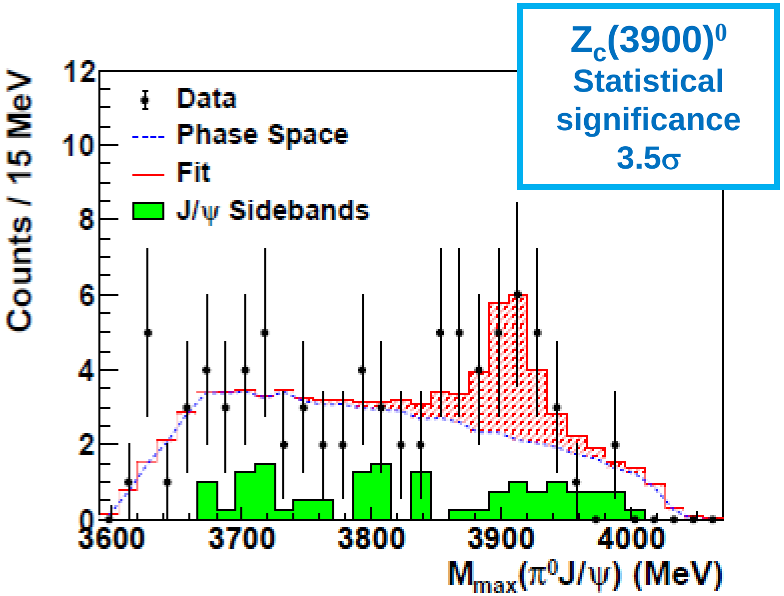
- Studies of Y(4260) – not a conventional charmonium state?
- Obs. charged charmonium-like $Z_c(3900)^{\pm}$ in $e^+ e^- \to (J/\psi\ \pi^+)\ \pi^-$ @ 4260 MeV
- $Z_c(3900)^{\pm}$ couples to charmonium, is charge 1
  $\Rightarrow$ tetraquark, DD* molecule?

Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV



PRL 110, 252001 (2013)

arXiv:1304.3036 [hep-ex]



- $Z_c(3900)^{\pm}$ seen also by Belle, confirmed with CLEO-c data …
- In fact CLEO-c claims at the same time evidence for the neutral isospin partner $Z_c(3900)^0$!

Belle: PRL 110, 252002 (2013)
CLEO-c: arXiv:1304.3036 [hep-ex]

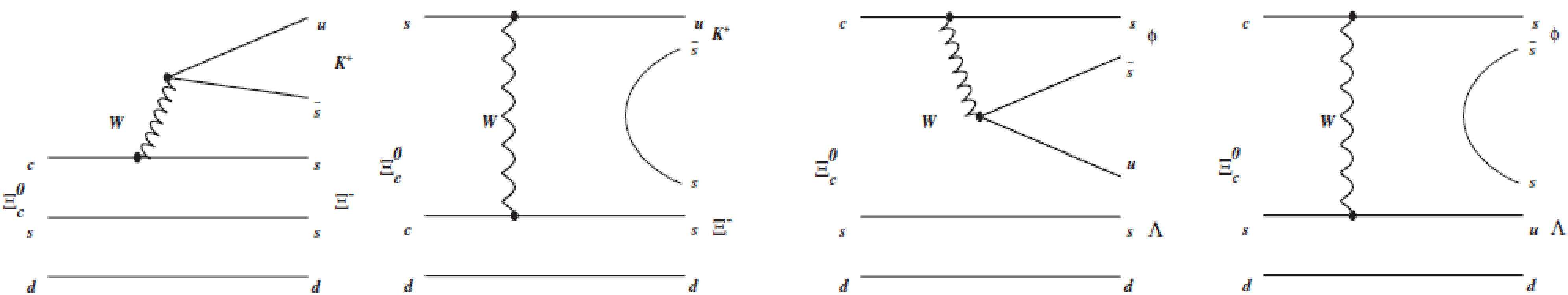
Charm baryon spectroscopy – example of the Ξ_c^0

- Very little is known e.g. about the heavy Ξ_c^0 meson (likewise for Ξ_c^+)
- Even more true as far as BFs are concerned

PDG: pdglive.lbl.gov/

Ξ_c^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$pK^-K^-\pi^+$	seen	676
$pK^-\overline{K}^*(892)^0$	seen	413
$pK^-K^-\pi^+$ no $\overline{K}^*(892)^0$	seen	676
ΛK_S^0	seen	906
$\Lambda\overline{K}^0\pi^+\pi^-$	seen	787
$\Lambda K^-\pi^+\pi^+\pi^-$	seen	703
$\Xi^-\pi^+$	seen	875
$\Xi^-\pi^+\pi^+\pi^-$	seen	816
Ω^-K^+	seen	522
$\Xi^-e^+\nu_e$	seen	882
$\Xi^-\ell^+$ anything	seen	–

- W-internal emission diagrams usually colour suppressed in charmed meson decays …
  … same for charmed baryon decays?



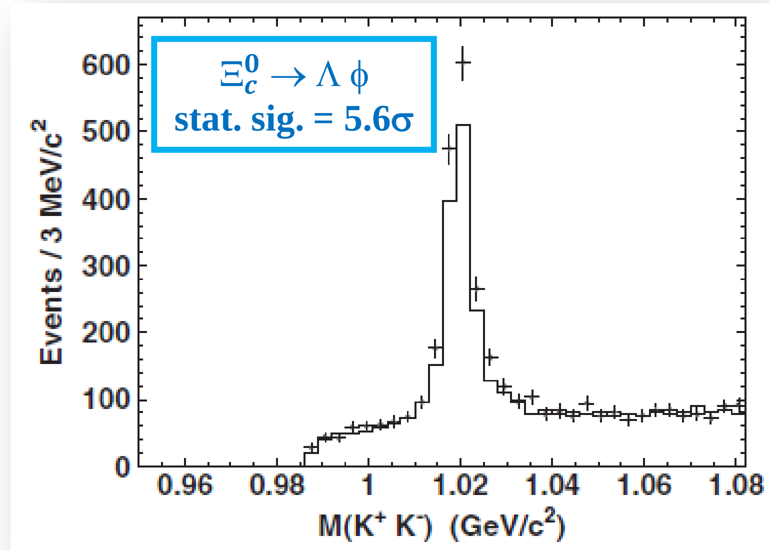
1st observation of Cabibbo-suppressed Ξ_c^0 decays

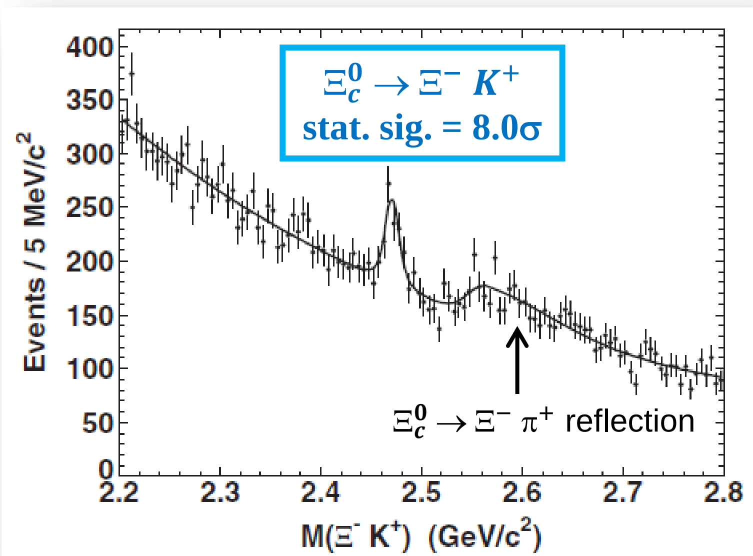
- W-internal emission diagrams not colour suppressed in Ξ_c^0 decays

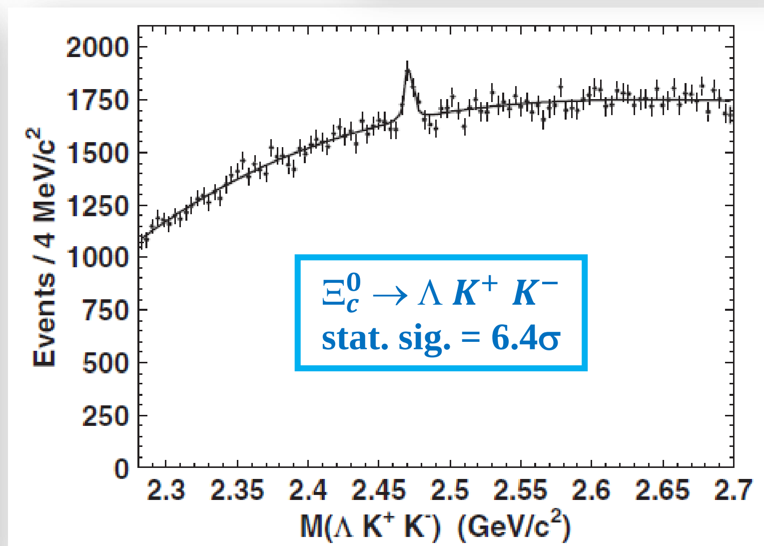
$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^- K^+)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = (2.75 \pm 0.51 \pm 0.25) \times 10^{-2}$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda K^+ K^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = (2.86 \pm 0.61 \pm 0.37) \times 10^{-2}$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda \phi)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = (3.43 \pm 0.58 \pm 0.32) \times 10^{-2}$$







Data sample:
711 fb^{-1} @ Υ(4S)

PRD 88, 071103(R) (2013)

Future prospects

LHCb upgrade

Physics motivation

- Very precise measurements to match level of theoretical uncertainties of various observables
- New physics effects bound to be very small given present constraints

Experimental motivation

- Assuming linear increase of luminosity with time, need various years to double stats once ~ 8fb^{-1} will be collected by 2018
- Trigger efficiency for hadronic modes saturates with present trigger system

Solution

- Upgrade with full readout at 40 MHz and availability of full event information from first-stage software trigger

LHCb upgrade – expected sensitivity

Expected statistical uncertainties before and after the upgrade, compared to theory

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\ \%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^\mp K^\pm)$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\ K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

(taken from A. Schopper, ECFA Hl-LHC Workshop, Aix-les-Bains, Oct. 2013 - LHCb-TALK-2013-324)

Belle II @ super $e^+ e^-$ B-factory SuperKEKB

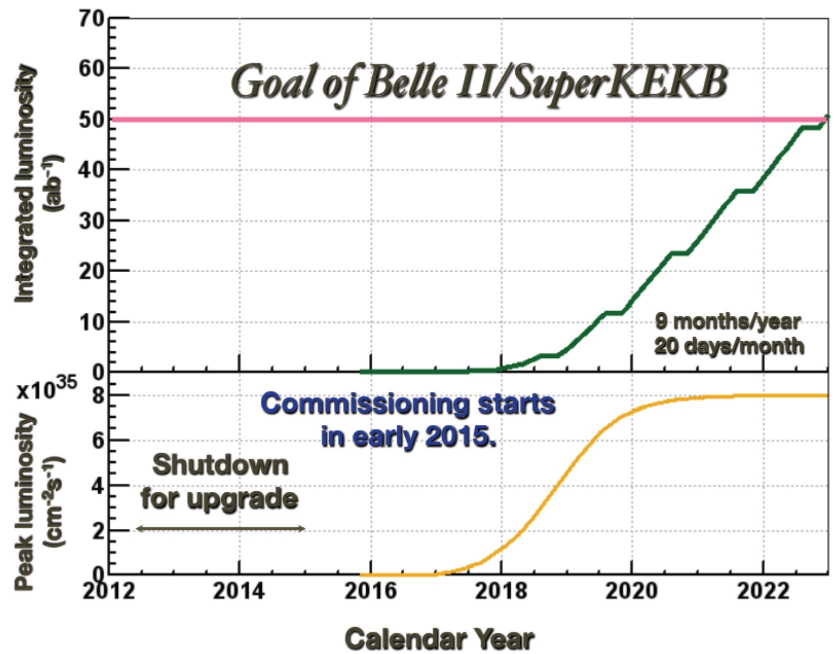
http://www-superkekb.kek.jp/

Physics motivation (very short)

- ❑ Very rich *and* complementary physics programme to that of LHC(b)
  - Belle II particularly suited for study of final states with neutrals (π^0, neutrinos)
- ❑ CPV in B & D decays, LFV in τ decays, rare decays

SuperKEKB

- ❑ Design instantaneous luminosity 8×10^{35} cm^{-2} s^{-1}
- ❑ Data mostly @ $\Upsilon(4S)$ resonance
  - 4 (7) GeV for the e^+ (e^-) beam
- ❑ Goal to deliver 50 ab^{-1} by 2022-23



Belle II

- ❑ Upgrade of Belle detector
  - Detector commissioning due in 2015
- ❑ Physics run by (late) 2016

http://belle2.kek.jp/

➡ *See Belle II plenary talk for a full report (session 22B1x)*

Super e^+e^- charm-τ factory @ BINP, Novosibirsk

Design proposal

http://www.inp.nsk.su/index.en.shtml

❑ **Super charm-τ factory @ Budker Institute of Nuclear Physics (BINP) in Novosibirsk**

- **Beam energy from 1.0 to 2.5 GeV**
- **Peak instantaneous luminosity ~ 10^{35} cm^{-2} s^{-1} @ 2 GeV**
- **Electrons longitudinally polarised @ IP**

Main physics goals

❑ **Charmonium, precision charm & τ, exotics**

Project status

❑ **Included in 2012 in government's top-6 mega projects for evaluation for funding**

❑ **R&D ongoing**

References

❑ **Homepage (including CDR):** https://ctd.inp.nsk.su/c-tau/

❑ **Project proposal: E. Levichev,** Phys. Part. Nucl. Lett. 5, 554-559 (2008)

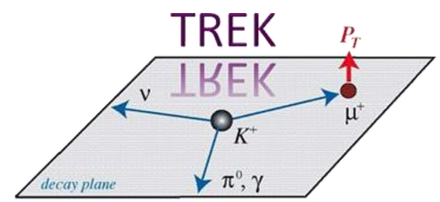
Ultra rare kaon decays – future(-ish) experiments

Golden modes

- BF($K^+ \rightarrow \pi^+ \nu \nu$) ~ 7.8×10^{-11} known very well known theoretically, sensitive to $|V_{td}|$
- BF($K_L \rightarrow \pi^0 \nu \nu$) ~ 2.4×10^{-11} known very well known theoretically

Experiment	Goal	Location	Data run
NA62	O(100) $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events	CERN	2014
ORKA	O(1000) $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events	Fermilab	2016-7, if approved
K0TO	1st obs. with O(100) $K_L \rightarrow \pi^0 \nu\bar{\nu}$ events	J-PARC	03/2013, 05/2013-
TREK	T-violation in $K^+ \rightarrow \pi^0 \mu^+ \nu$	J-PARC	2016

(Longer-term Project X @ Fermilab not included)



Remember …

- BNL E787 & E949 experiments: 7 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ candidate events observed

➡ *See NA62 talk on rare and forbidden decays (session 21B2c)*

Future LFV experiments – overview

$\mu \to e\ \gamma$

- MEG upgrade: 10-fold increase in sensitivity on BF, down to 5×10^{-14}

$\mu \to e\ e\ e$

- Approved experiment Mu3e @ PSI
  - Sensitivity on BF down to 10^{-16}

http://www.psi.ch/mu3e

$\mu \to e$ conversion

- Approved experiment DeeMe @ J-PARC
  - Sensitivity on CR down to ~10^{-14}

DeeMe http://deeme.hep.sci.osaka-u.ac.jp/

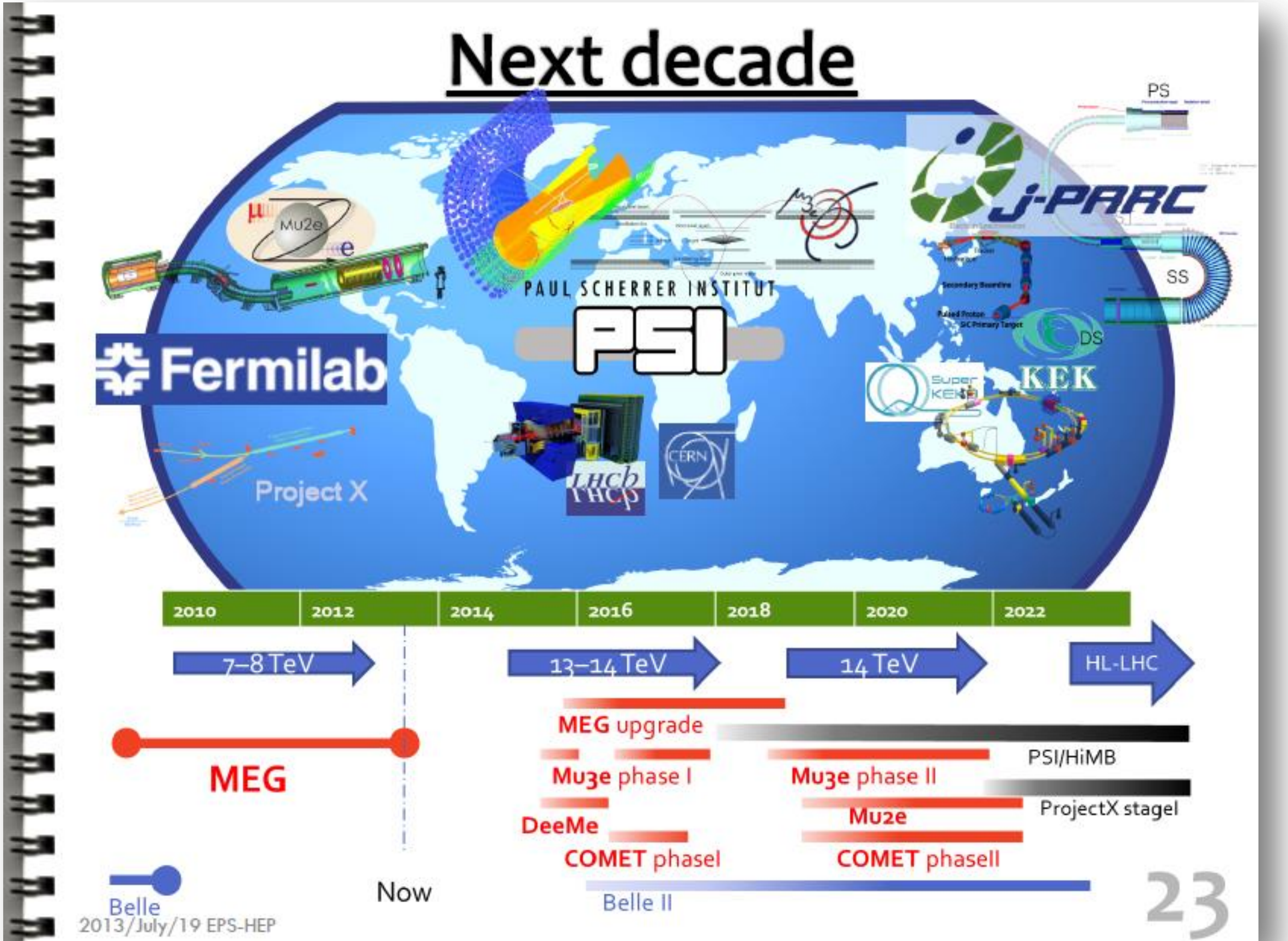
- COMET & PRIME @ J-PARC
  - Sensitivity on CR down to 10^{-16} and then 10^{-18}

http://comet.kek.jp/

- Approved experiment Mu2e @ Fermilab
  - Sensitivity on CR down to a few $\times10^{-17}$

http://mu2e.fnal.gov/

Future LFV experiments – overview



(taken from Y.Uchiyama, EPS-HEP talk, 19/07/2013)

Conclusions & outlook

Conclusions and outlook

- ❑ Flavour physics is a powerful tool to look for New Physics
  - Precision measurements & probe at mass scales not attainable with GPDs

- ❑ LHC is a flavour factory
- ❑ Other environments/experiments also providing crucial "flavoured" data

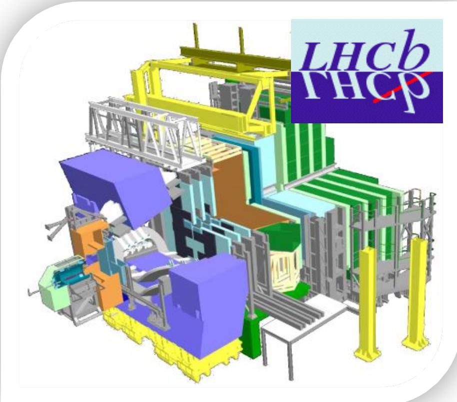
- ❑ So far, most results consistent with the CKM paradigm
- ❑ But hints/tensions seen in a few observables

- ❑ Many more exciting results to be expected, reaching new levels of precision
- ❑ Flavour physics has a bright future ahead …
  … not only with results on existing data, but also from outstanding prospects with future facilities such as the LHCb upgrade, Belle II, NA62

Back-up slides

Flavour physics results – where are they ?

Experiment	Link to physics results
ALICE	http://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults
ATLAS	http://twiki.cern.ch/twiki/bin/view/AtlasPublic
BaBar	http://www-public.slac.stanford.edu/babar/Publications.aspx
Belle	http://belle.kek.jp/belle/publications.html
BESIII	http://bes3.ihep.ac.cn/pub/publications.htm
CDF	http://www-cdf.fnal.gov/physics/physics.html
CMS	http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
D0	http://www-d0.fnal.gov/results/
LHCb	http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/lhcb_papers.php



The LHCb experiment

Mission statement :

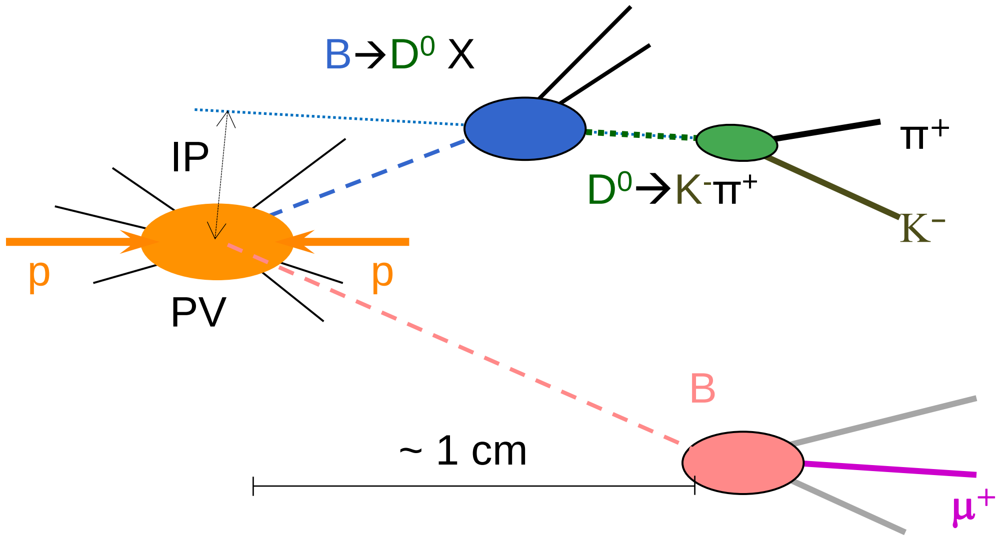
- Indirect searches for New Physics using heavy flavour particles
- Study CP violation and rare decays of heavy hadrons and leptons

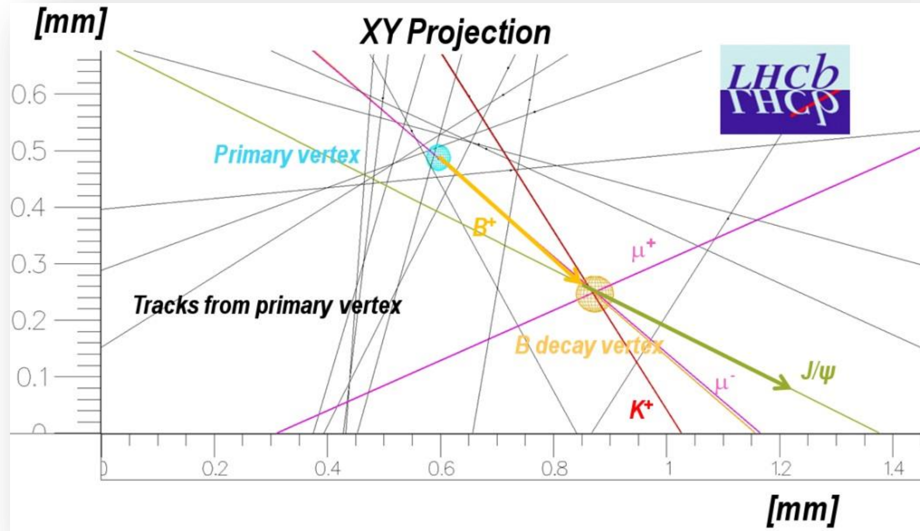
Approach :

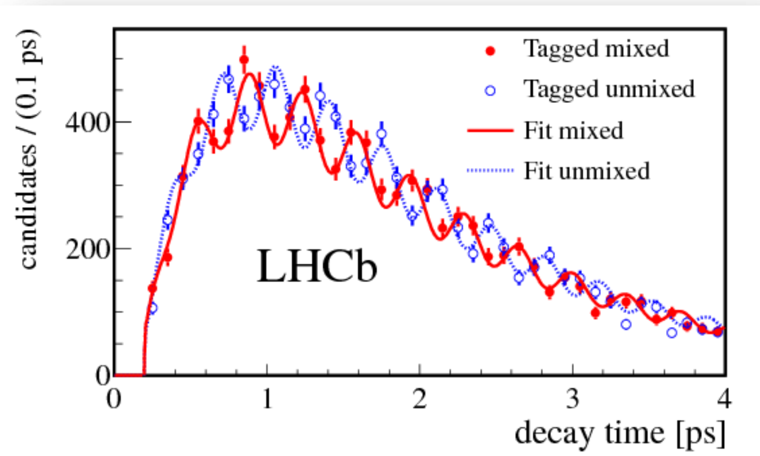
- Focus mainly on loop-mediated processes giving access to scales > LHC production scale, i.e. the TeV

The LHCb collaboration

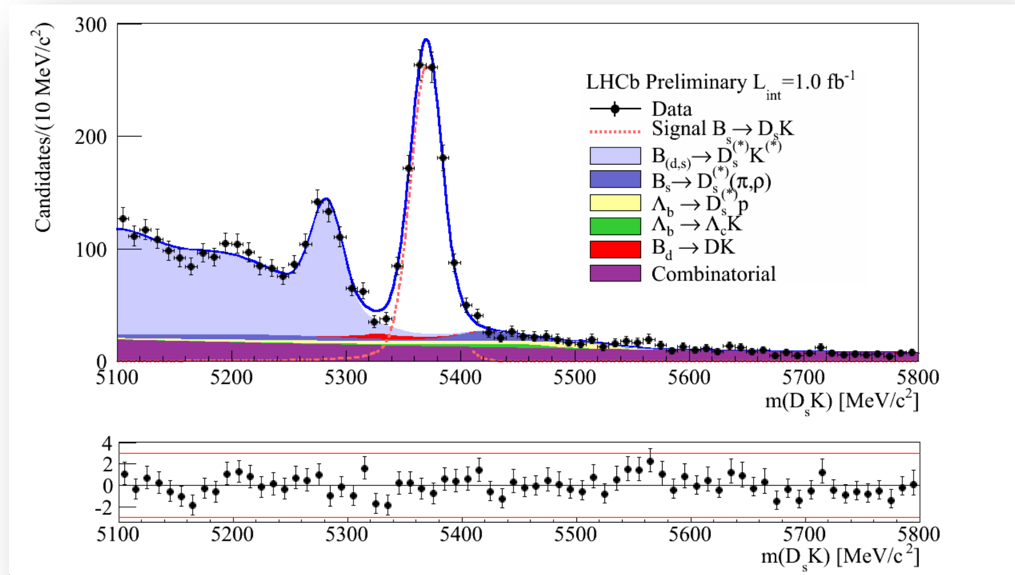
LHCb physics programme – system requirements





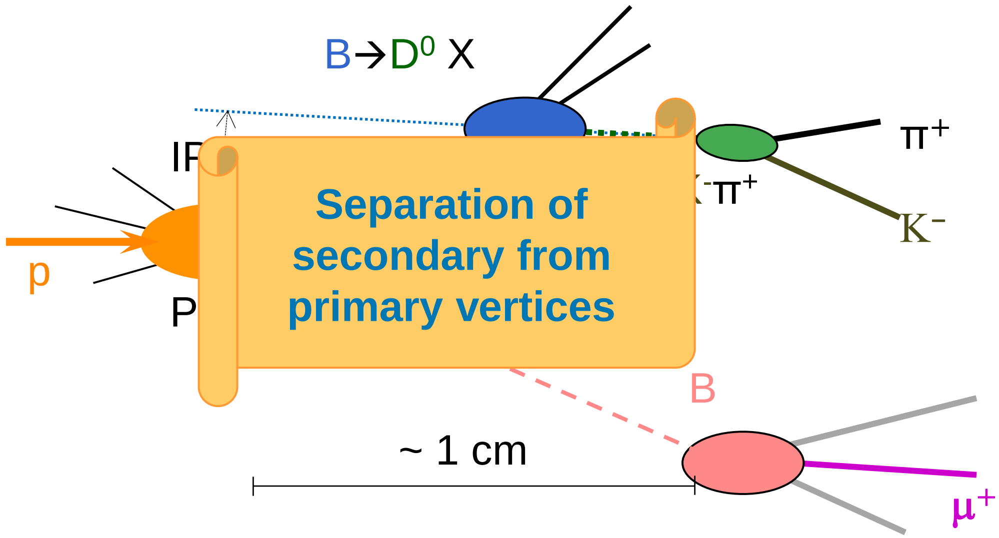


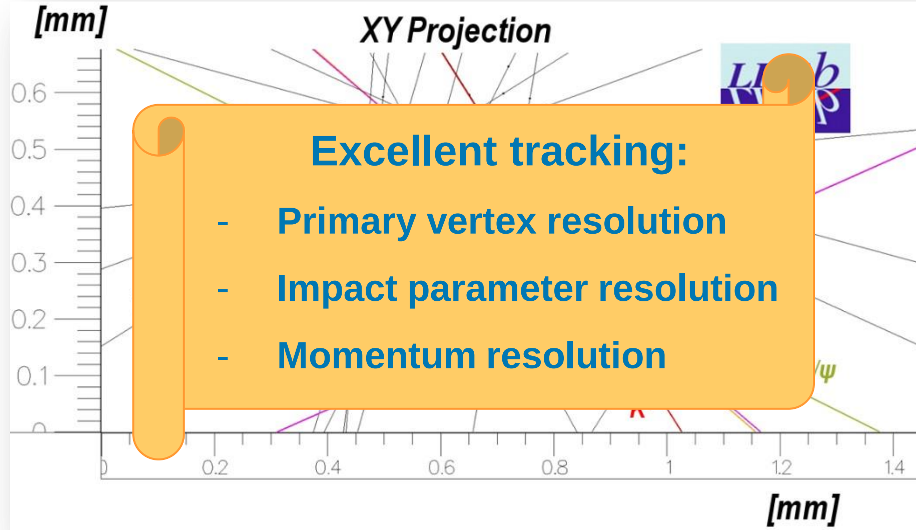
New J. Phys. 15, 053021 (2013)

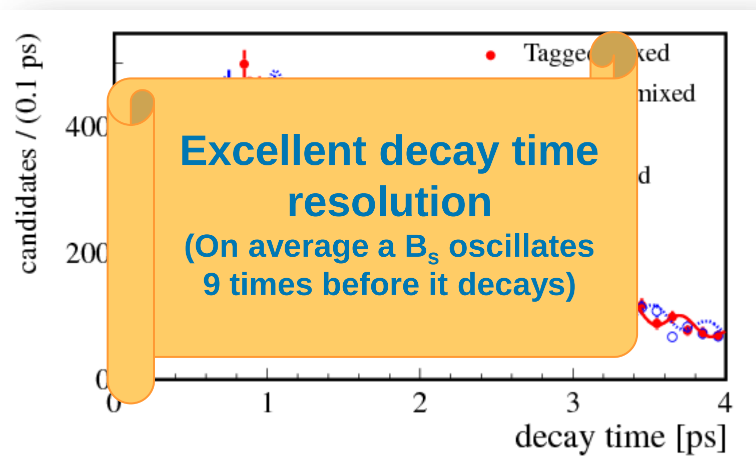


LHCb-CONF-2012-029

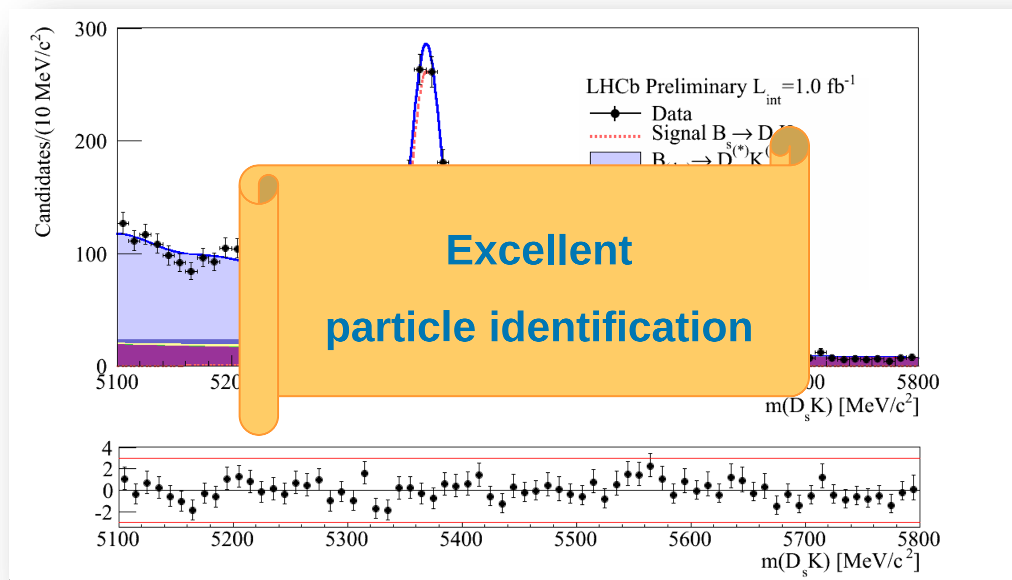
LHCb physics programme – system requirements







New J. Phys. 15, 053021 (2013)

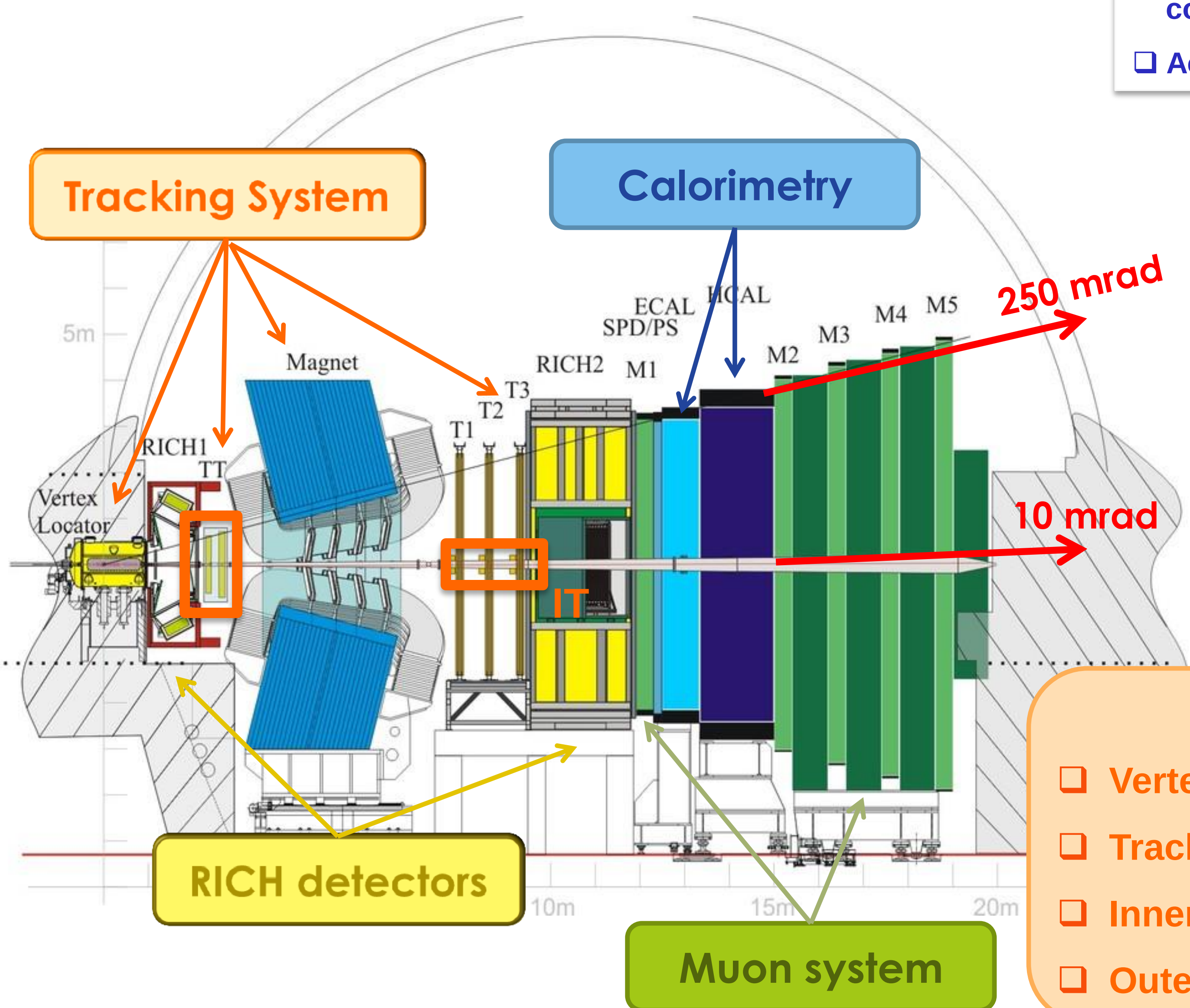


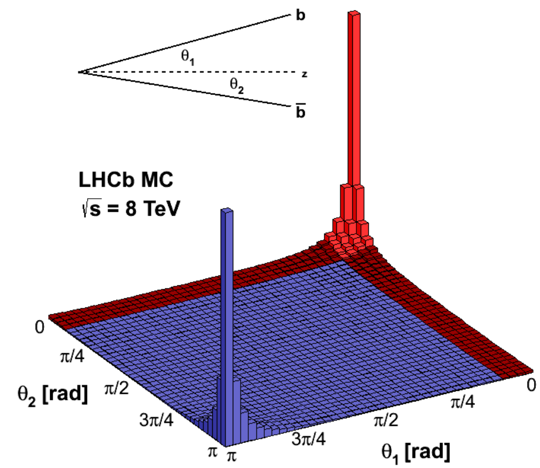
LHCb-CONF-2012-029

The LHCb detector

Heavy-flavour production at the LHC :

- Large production cross-section, correlated in forward/backward region
- Access to all b-hadrons: B_x, Λ_b, etc.





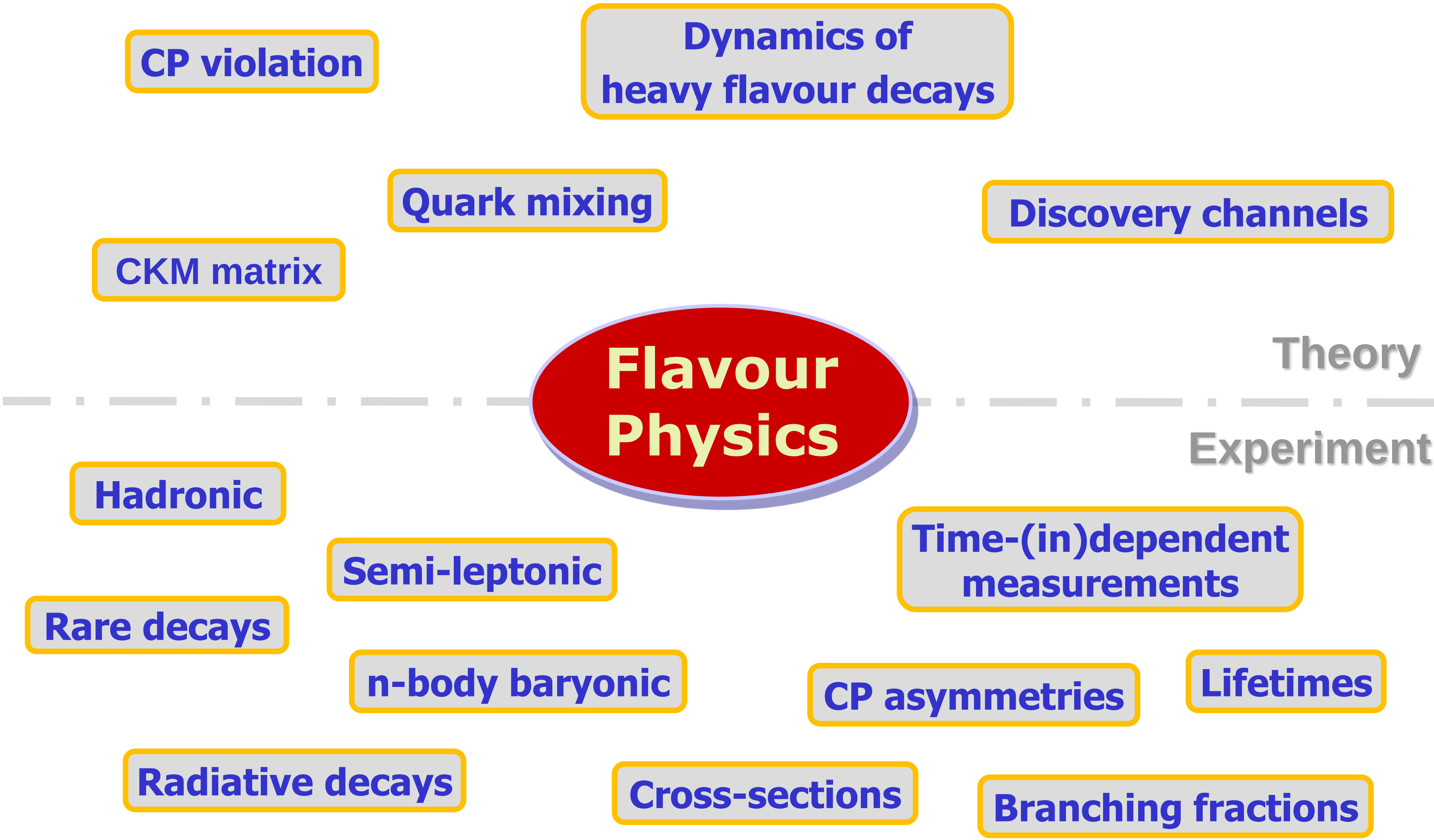
Tracking System

- Vertex Locator
- Tracker Turicensis
- Inner Tracker

} Si micro-strips

- Outer Tracker } straw tubes

(LHCb) flavour physics programme (not comprehensive!)



LHCb physics working group overview

B decays to charmonium

- B_s mixing parameters
- CP violation measurements
- $B \to J/\psi$ X and related decays

B decays to open charm

- CKM γ angle from $B \to D K$ family
- B decays to double charm
- Rare hadronic B decays

Rare decays

- Leptonic, electroweak, radiative decays
- SM forbidden processes

Charm physics

- Mixing and CP violation
- Open charm prod. & spectroscopy
- Rare charm decays

Charmless B decays

- Studies of $B \to h\, h^{(\prime)}$ and $B \to h\, h^{(\prime)}\, h^{(\prime\prime)}$
- $B \to V V$ decays
- Rare charmless B decays

Semileptonic B decays

- Search for CP violation in mixing
- Form factors
- Rare decays

B hadrons & quarkonia

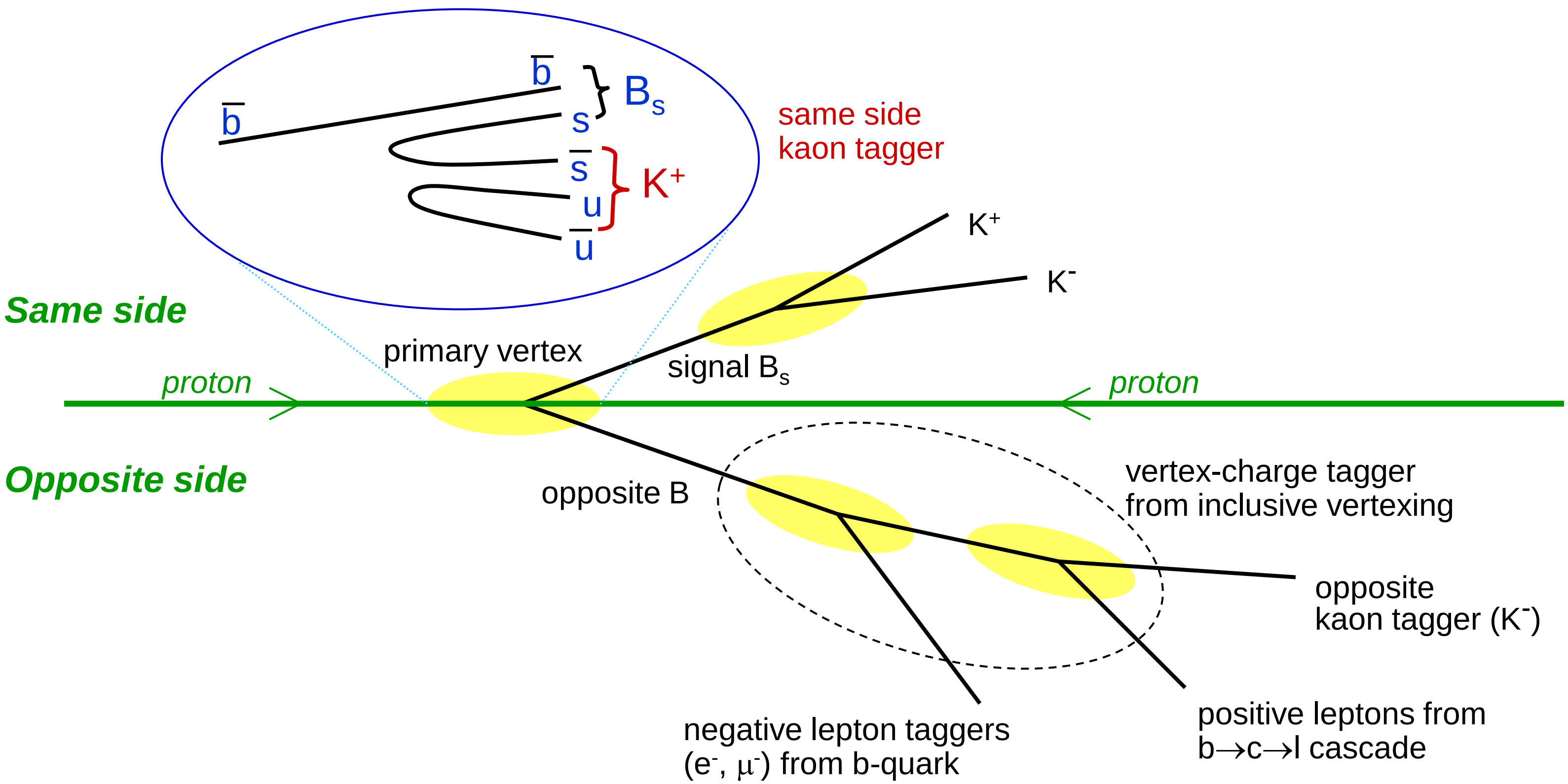
- Production and spectroscopy of B hadrons and quarkonia

QCD, electroweak & exotica

- “Soft” & “hard” QCD
- Electroweak boson production, PDFs
- New long-lived particles

LHCb – flavour tagging

- Various taggers = particles / objects from which to extract tagging info
- 2 main categories: opposite- and same-side taggers



LHC(b) run I

LHC operation

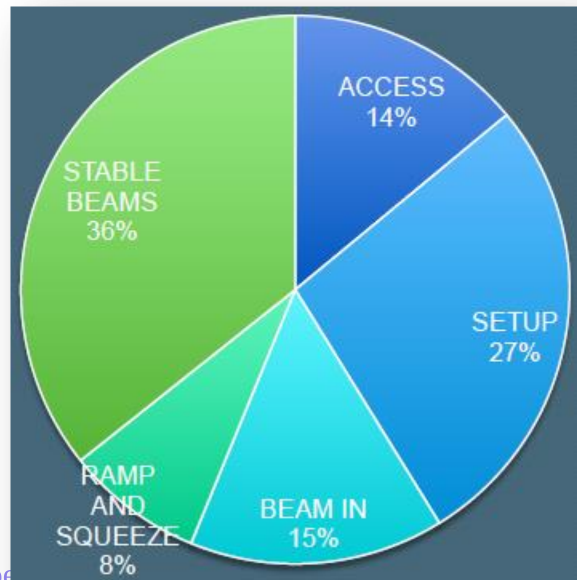
As everyone knows …

Design:
- $\sqrt{s}$ = 14 TeV
- 2808 bunches, 25 ns spacing
- L = $2*10^{32}$ $cm^{-2}s^{-1}$
- Average number of visible pp interactions / bunch crossing (μ) =0.5

Reality (2011+2012):
- $\sqrt{s}$=7 TeV / 8 TeV
- ≈1300 bunches, 50 ns spacing
- L ≈ $2\text{-}4*10^{32}$ $cm^{-2}s^{-1}$
- Higher pile-up: <μ> ≈ 1.4 / 1.7
- Luminosity levelling
- Exceeding design by factor two

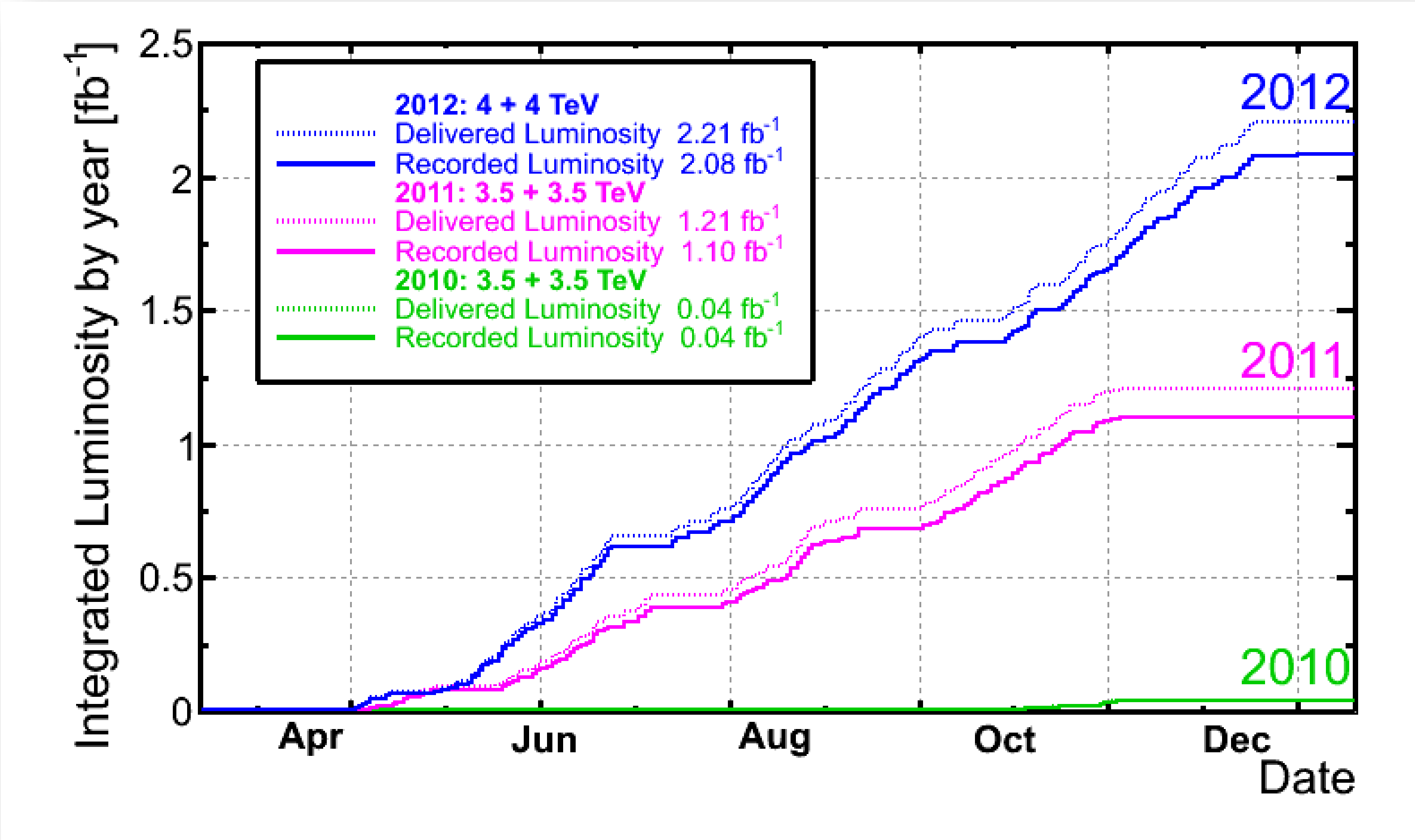
- ❑ **Excellent performance of the accelerator !**

- ❑ **E. g. ~ 200 proton physics days in 2012:**

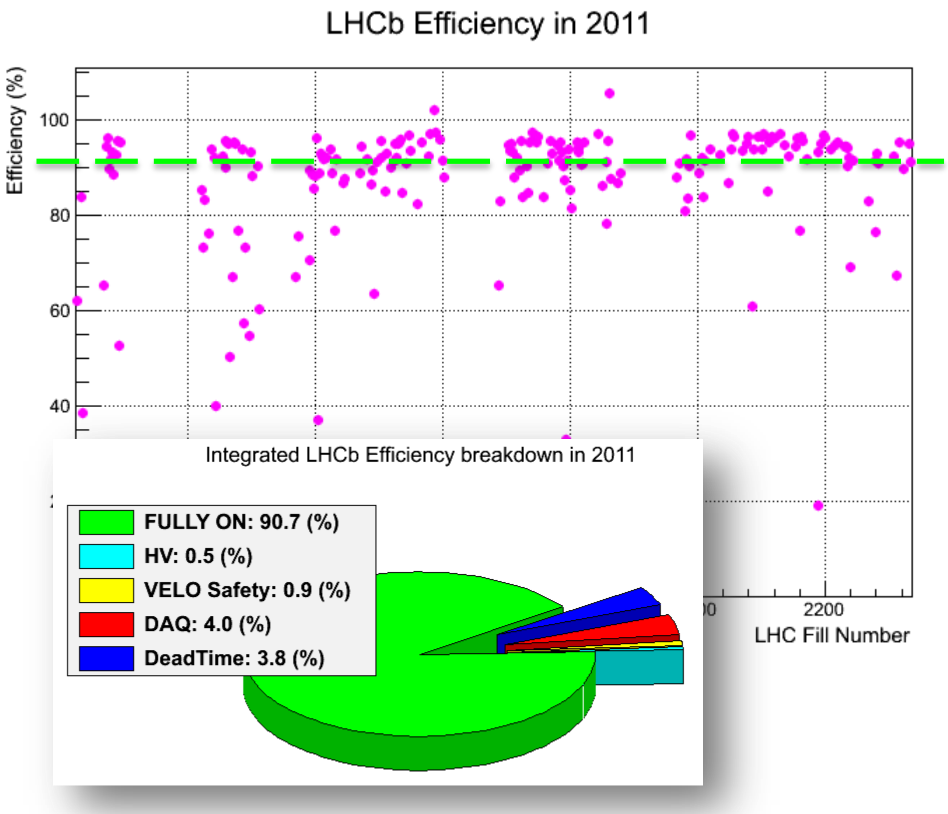


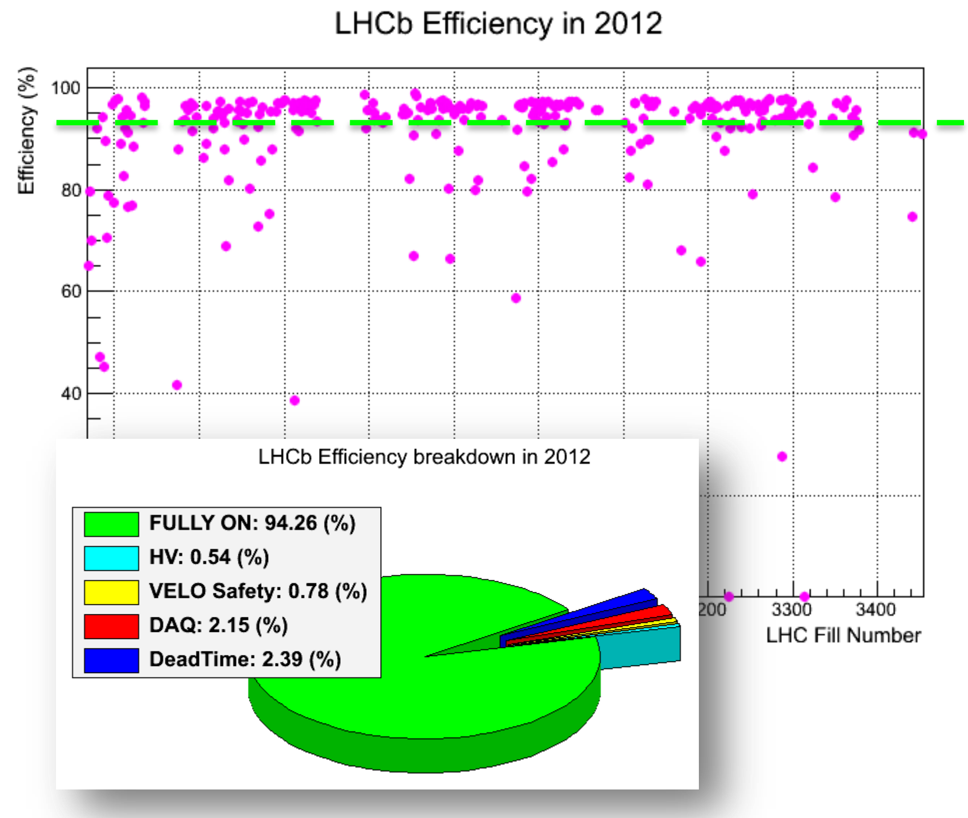
LHC operation – luminosity of pp collisions in Run I

- Total recorded lumi in run I: 3.2 fb^{-1}



LHCb operation – run I data taking efficiency



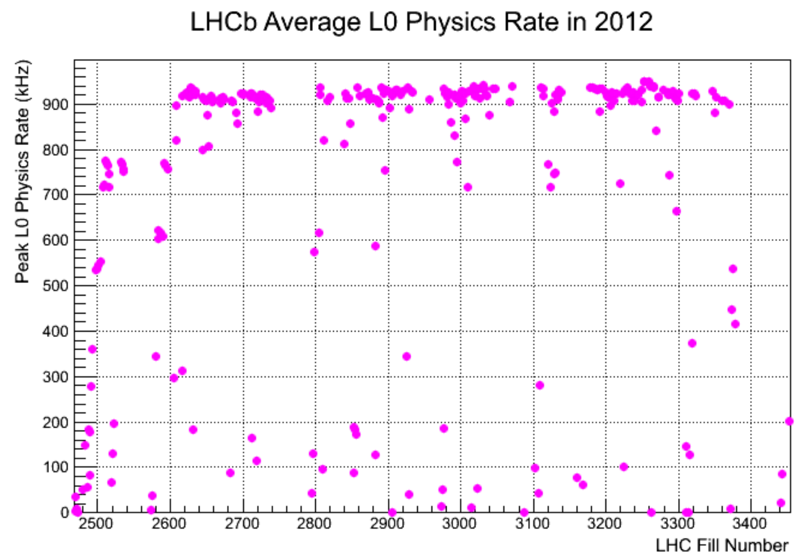


Conclusions :

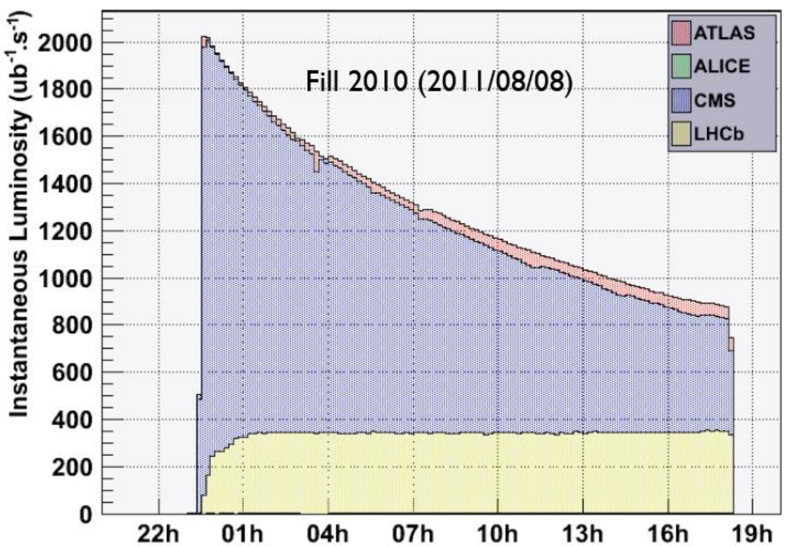
- LHCb improved with time – run I average operational eff. ~ 93%
- VELO safety = closing (~210 s to close and restart the DAQ)
- VELO close to optimal from early on ;-)

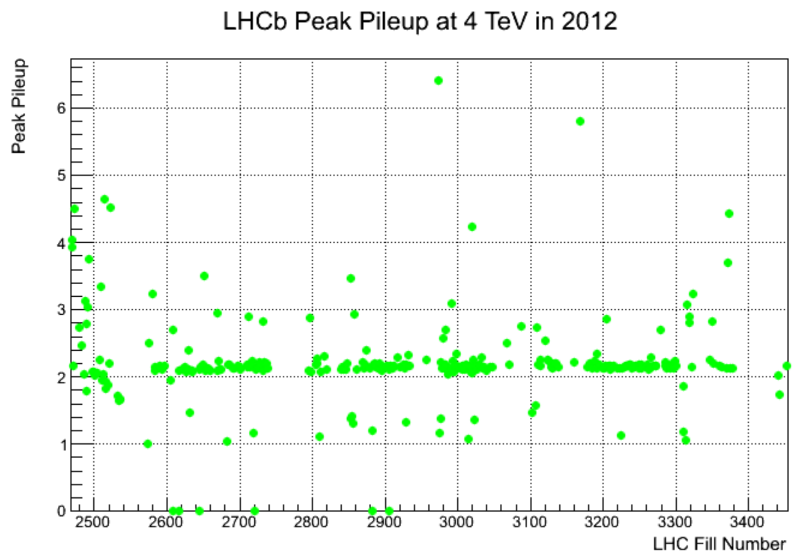
LHCb operation – run I achievements

- ❑ **We invented luminosity levelling**
  - **- Now completely automated and being copied by other experiments**
- ❑ **We have a versatile trigger**
  - **- Very quick reactions to changing conditions, fixes, etc.**
- ❑ **We use deferred triggering routinely**
  - **- It actually makes operations safer and simpler**



Hardware trigger @ 900 kHz

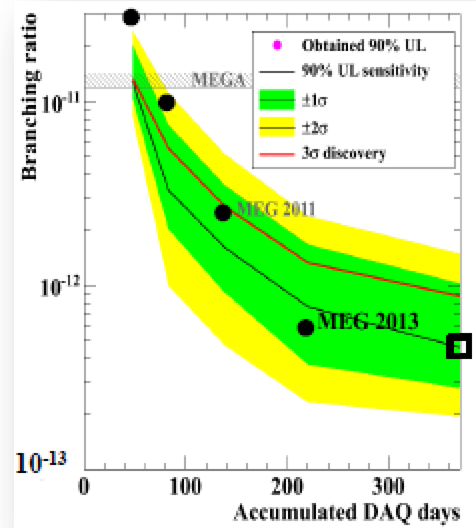




Avg. 2 interactions/crossing

Future prospects

MEG upgrade – 10-fold increase in sensitivity ⇔ ~5×10^{-14}

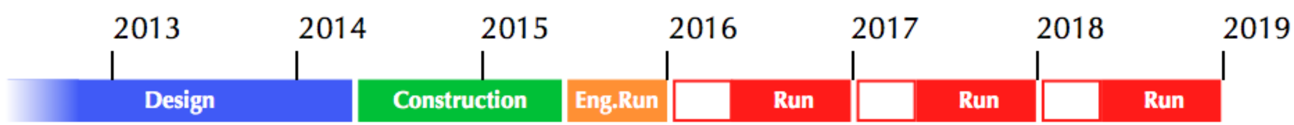


Why

- ❑ MEG sensitivity starts to saturate due to finite background
  ⇒ not possible to go down to $O(10^{-14})$
- ❑ Present performance on electrons worse than designed
- ❑ But interesting from physics point of view
  - No BSM signal @ LHC so far
  - Other LFV experiments are not for the immediate future

Approved upgrade!

- ❑ Proposal submitted to PSI at end of 2012 [arXiv:1301.7225]
- ❑ Approved by PSI committee in Jan. 2013



Timescale

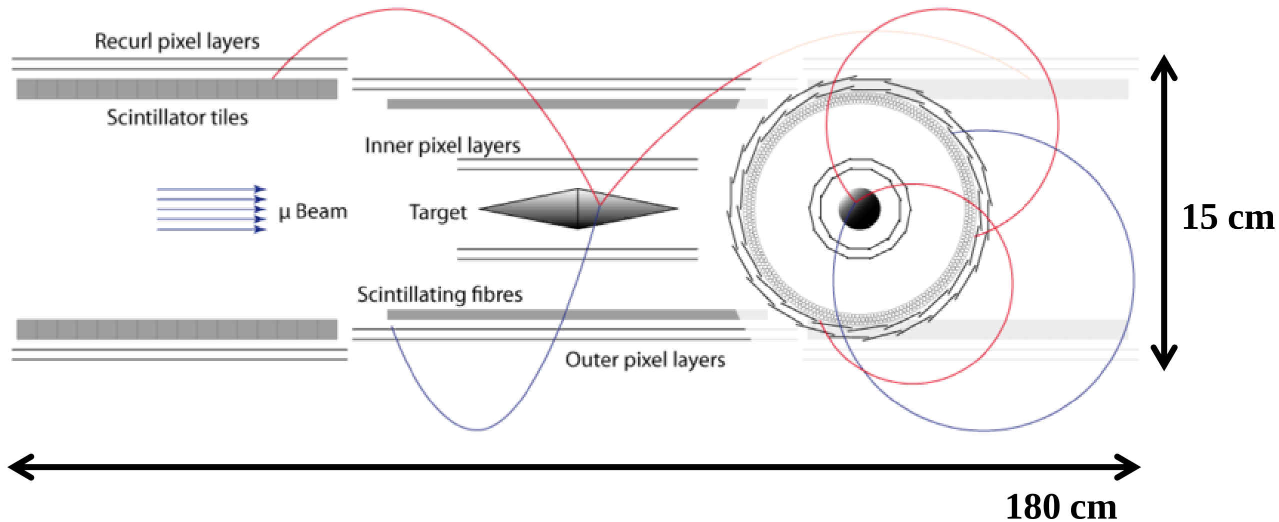
- ❑ On a time scale pre-HL-LHC …

$\mu \to 3e$: the Mu3e experiment @ PSI

http://www.psi.ch/mu3e

Goal

- Reach a sensitivity 4 orders of magnitude lower than previous experiments !
  - Best UL, BF ($\mu \to 3e$) < 1.0 x 10^{-12} @ 90% C.L., from SINDRUM, 1988)
  - Sensitivity on BF down to 10^{-16}



Timescale

2013 Technical design report

2014 Detector construction

2015 Installation and commissioning at PSI

2015+ Data taking at up to a few 10^8 muons/s (sensitivity ~ 10^{-15})

2017+ Construction of a new muon beam line at PSI

2017++ Data taking at up to few 2×10^9 muon/s (sensitivity ~ 10^{-15})

$\mu \to e$: the COMET/PRIME experiment @ J-PARC

Goal :

- Achieve a sensitivity down to 10^{-16} (COMET) and then 10^{-18} with an upgrade (PRISM/PRIME) !

Planning :

- Engineering run in 2016 (for 1 year)
- Data taking in 2017

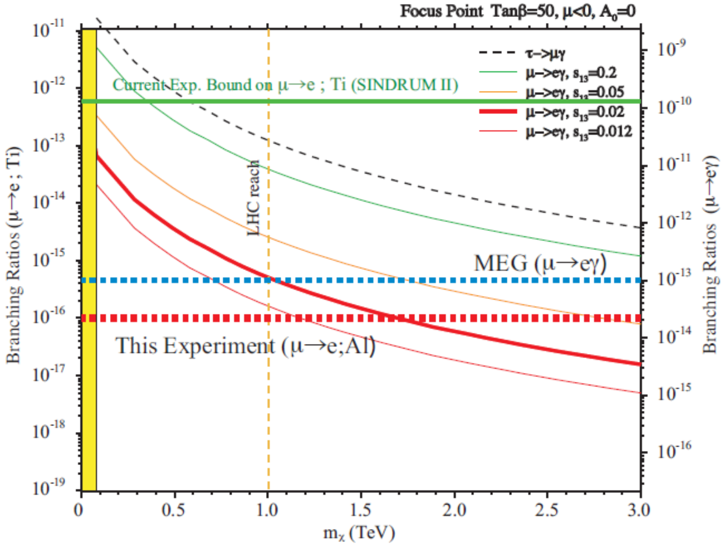


Figure 1.7: Prediction of the branching ratio of $\mu^- - e^-$ conversion in Ti in the SUSY-Seesaw models as a function of SUSY mass scale (neutralino). The sensitivity of the proposed experiment is also shown.

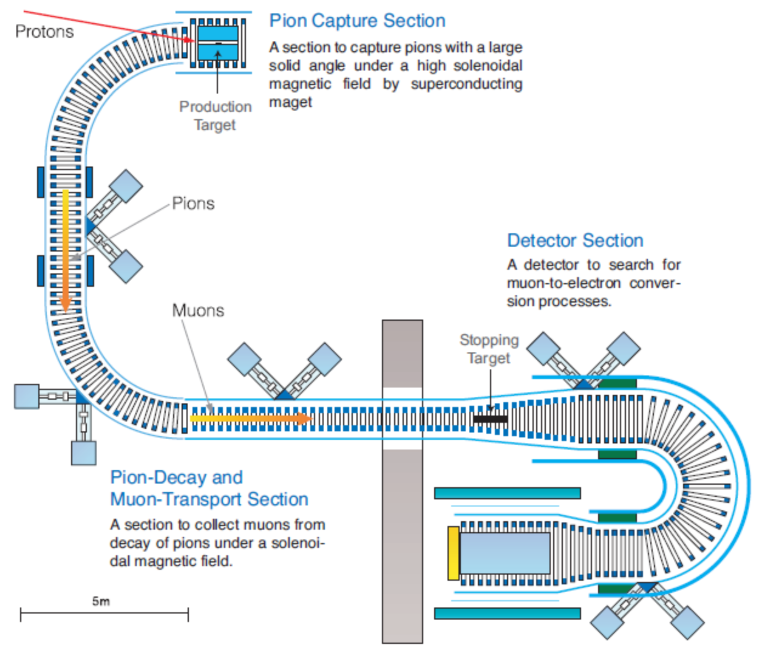


Figure 3.1: Schematic layout of the muon beamline and detector for the proposed search for $\mu^- - e^-$ conversion, the COMET experiment.

Note: COMET/PRISM results will effectively probe $BF(\mu \to e\gamma)$ in SUSY models given that $CR(\mu \to e \text{ in N}) \sim \alpha_{em} \times BF(\mu \to e\gamma)$

$\mu \rightarrow e$: the Mu2e experiment @ Fermilab

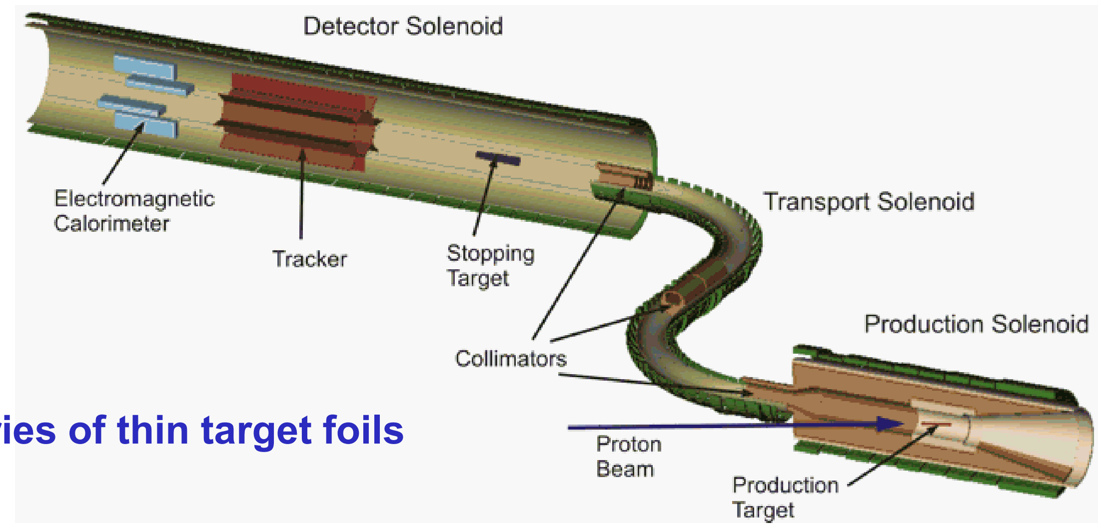
Goal :

- ❑ Achieve a sensitivity down to a few 10^{-17} !

http://mu2e.fnal.gov/

Planning :

- ❑ Construction to start ~ 2013
- ❑ Data taking to start ~ 2019



Exp. set up :

- ❑ Beam of slow μ's stopped in a series of thin target foils
- ❑ μ's captured into atomic orbits
- ❑ Standard μ decays in orbit $\Rightarrow$ electron continuous energy spectrum
- ❑ μ conversion to electron $\Rightarrow$ mono-energetic electron with energy=end-point energy of continuous spectrum

ν CP violation & NMH experiment proposal @ ESS

Neutrino source and detector

http://europeanspallationsource.se/

- ❑ **Complement high-intensity proton beam from the European Spallation Source (ESS) being built in Lund**
  - **2.5 GeV 5 MW superconducting LINAC with 1.25×10^{16} protons on target / second**
    (2 orders of magnitude more intense than other planned proton drivers for ν beams)
  - **1^{st} beams @ ESS expected by 2019, full operation in 2025**

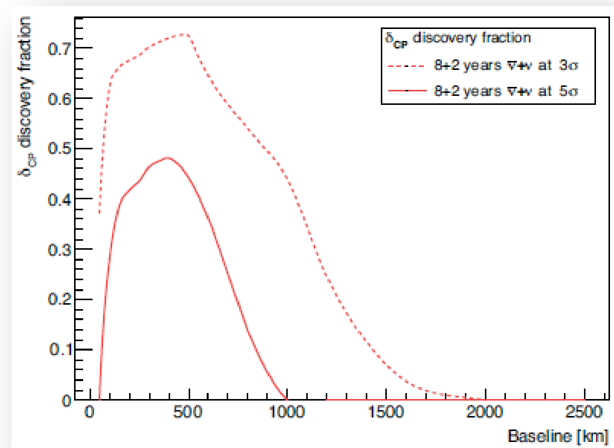
- ❑ **And produce a high-intensity ν super-beam of mean energy ~ 350 MeV**

- ❑ **Megaton water Cherenkov detector - detection of ν_e appearance in ν_μ beam**
  - **E.g. @ Gaspenberg mine (SE) 540 km from ESS @ depth=1232 m**

Expected sensitivity

- ❑ **2 (8) years of data taking with a ν (anti-ν) beam**
  ⇒ coverage on CP-violating phase δ
  up to 48% (73%) of angular range at 5σ (3σ)

- ❑ **Determine NMH at 3σ level over most of range of δ**



(Other) Physics programme

- ❑ **Study of supernovae / solar / atmospheric / geo neutrinos**

- ❑ **Proton decay up to a lifetime ~ 10^{35} years**

E. Baussan et al.,
arXiv:1212.5048 [hep-ex]