Physics priorities and theory needs

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on behalf of the LHCb collaboration

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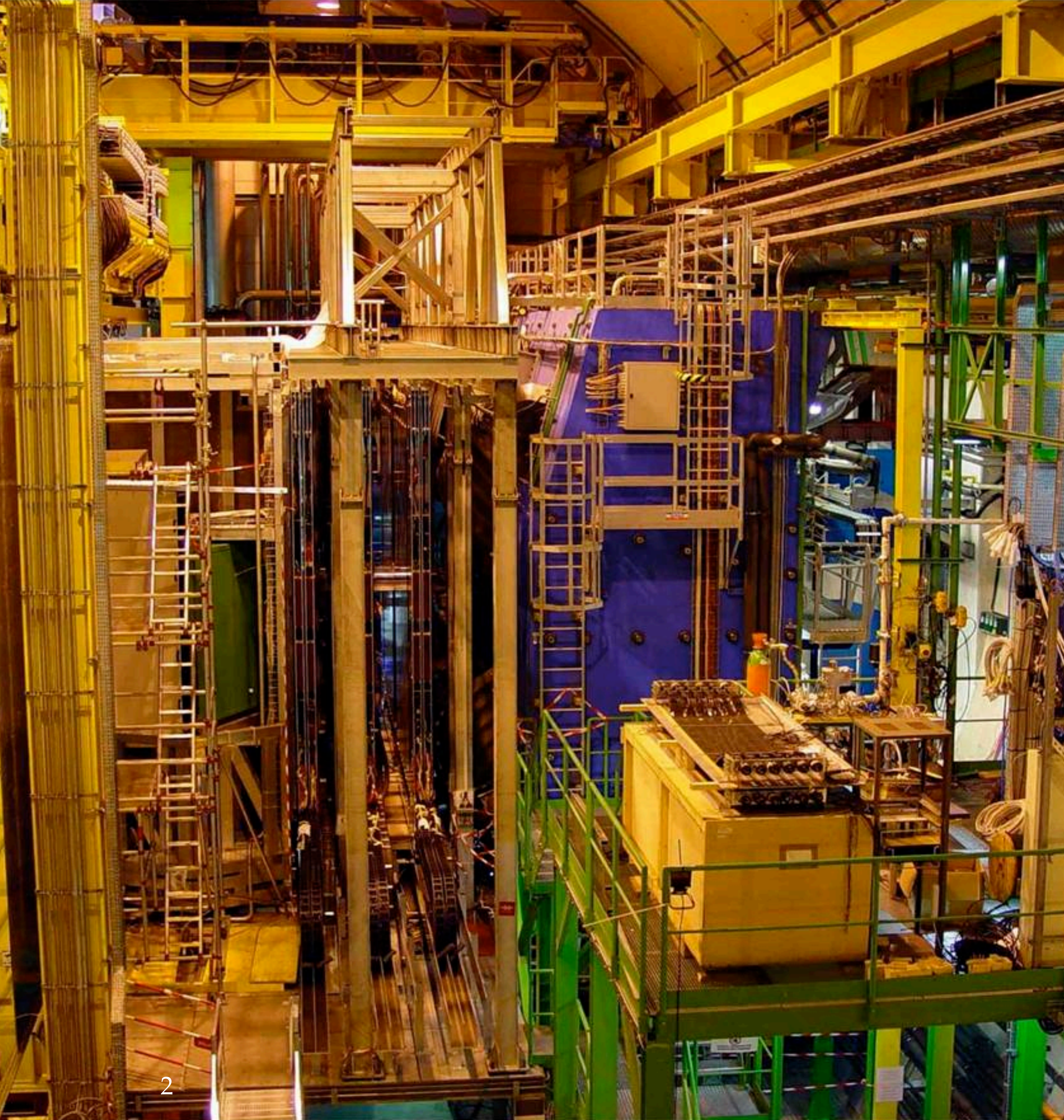
Content

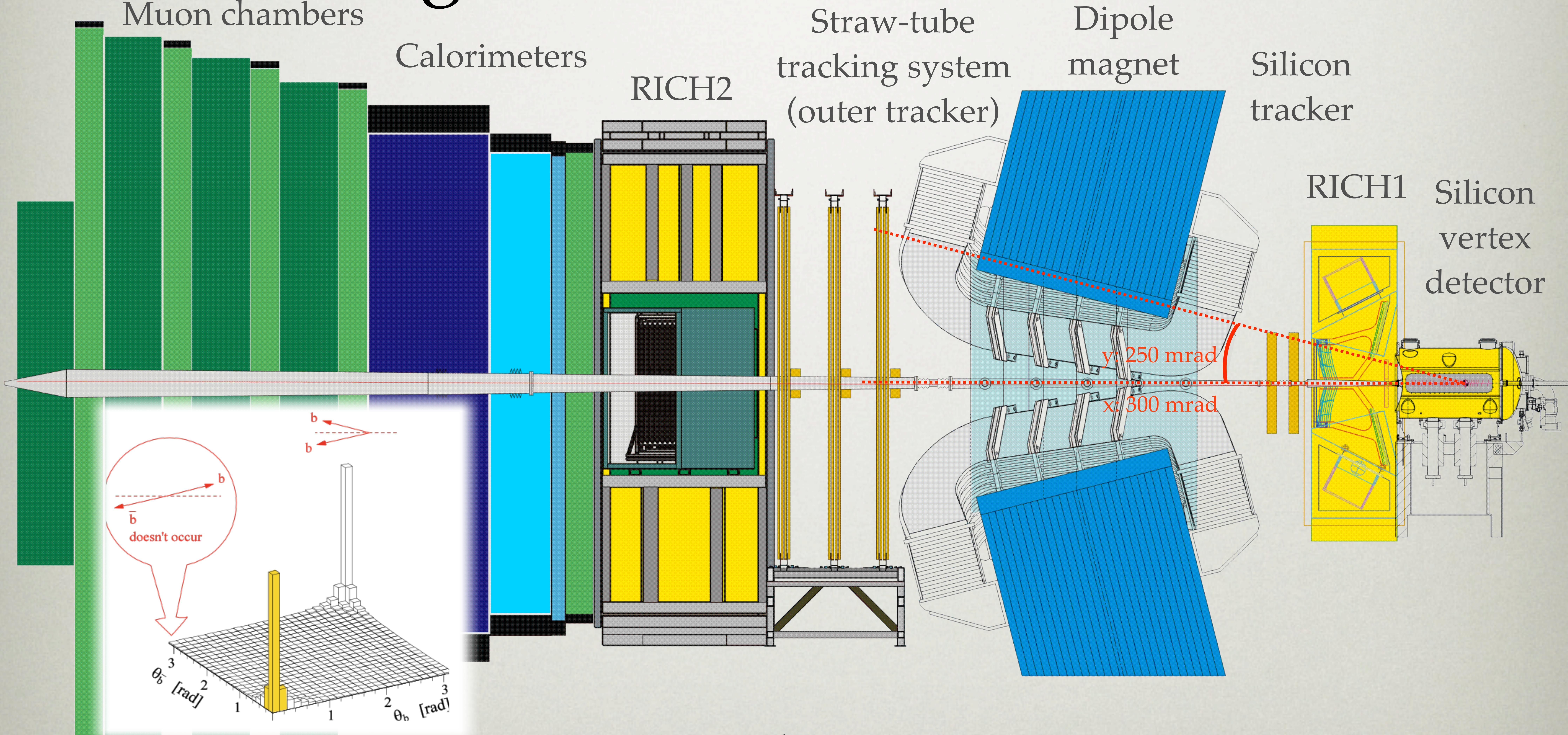
- Motivation for pursuing flavour physics at the LHC
- Technical highlights of LHCb
- Tour of the main physics priorities of LHCb
    - includes highlighting where improved phenomenology might help (no comment on how difficult this might be)



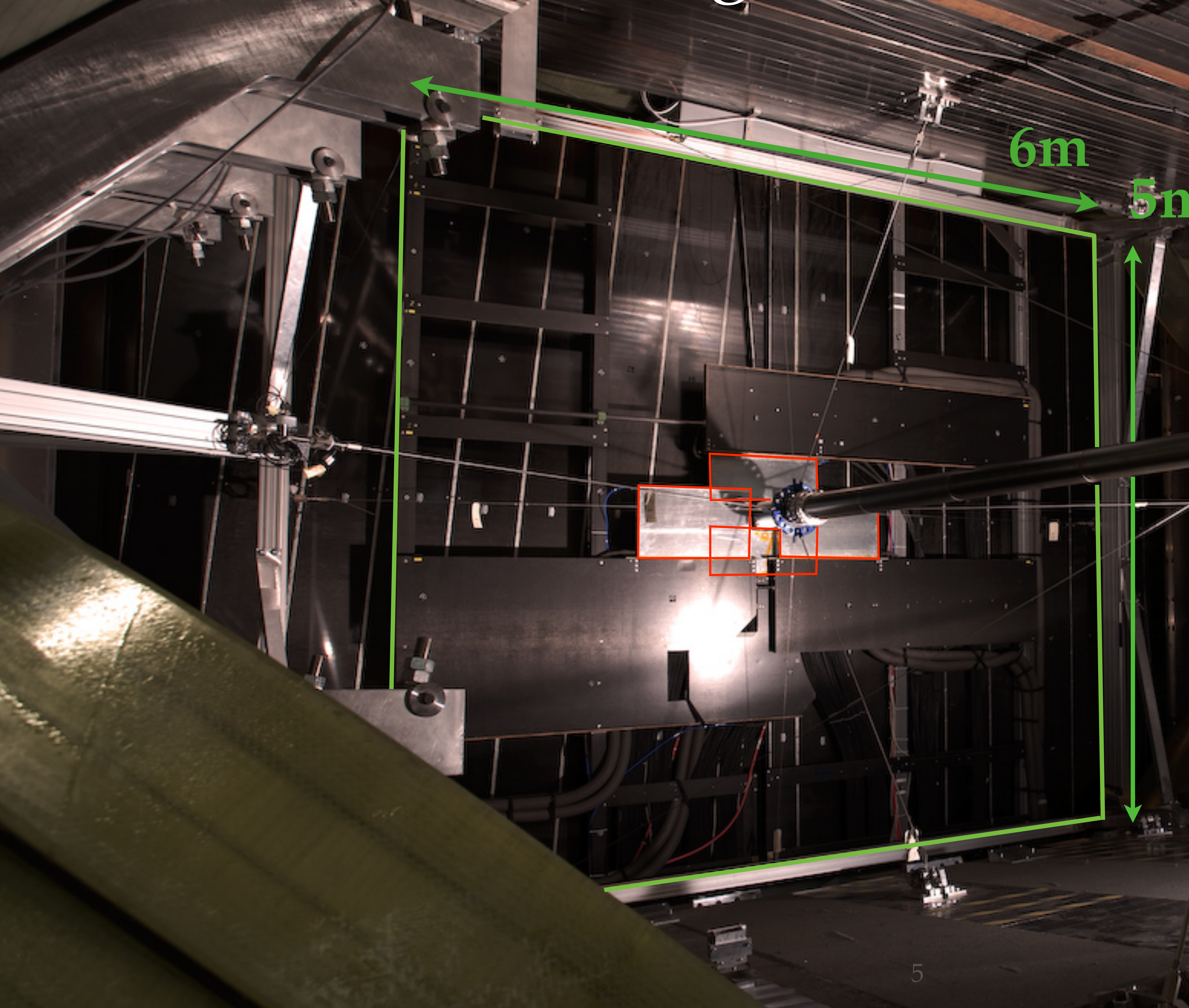
Why pursue flavour physics?

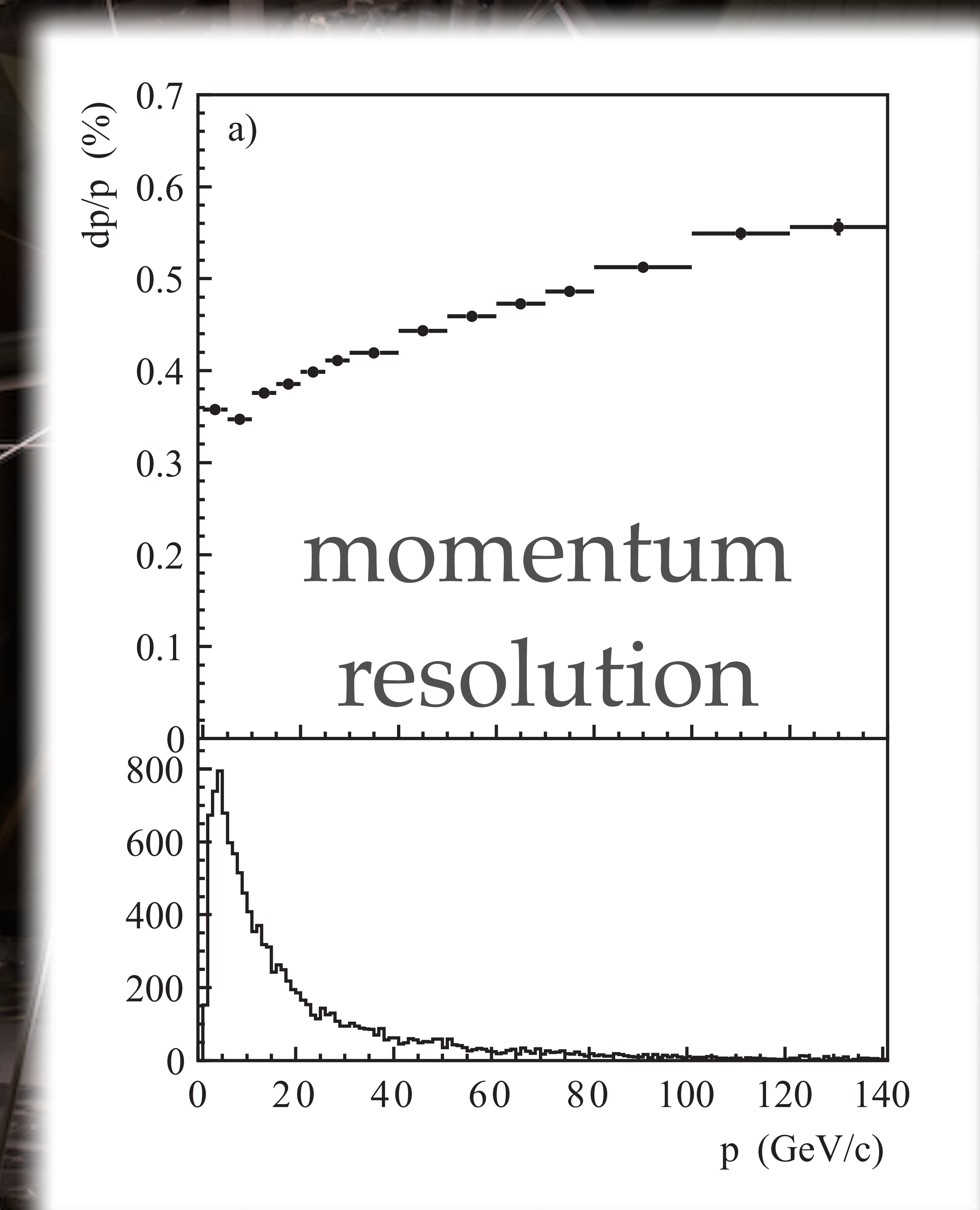
- Flavour physics has been an essential tool in construction of SM:
  - GIM mechanism → prediction of charm
  - CP violation in Kaons → 3 quark generations
  - Neutral currents → predated the Z^0 discovery by 10 years
  - B_d-mixing rate → required a heavy (>115 GeV) top
- Let's assume the same potential is there in the future!
  - Precise measurements of low energy observables, eg. B-decays, a priori expected to reveal presence and nature of new physics at TeV scale and beyond
- B-physics is already very constraining on the character of BSM models, eg. motivating MFV
- Entirely complementary to the high-energy frontier probes at ATLAS & CMS
  - Tools for the efficient extrapolation of LHCb results for the GPDs are very desirable

Instrumenting the forward region of LHC collisions



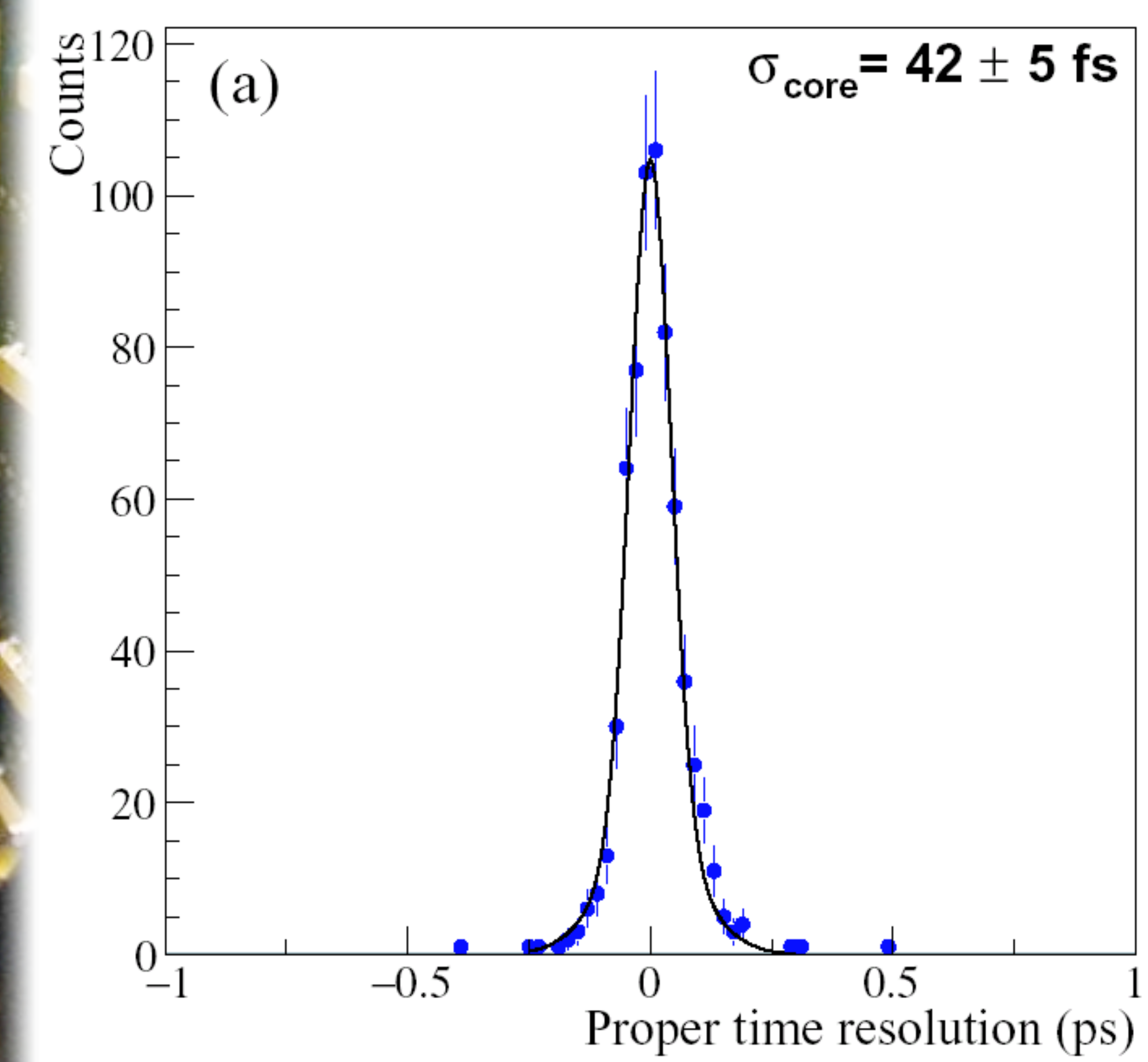
Excellent tracking and momentum resolution





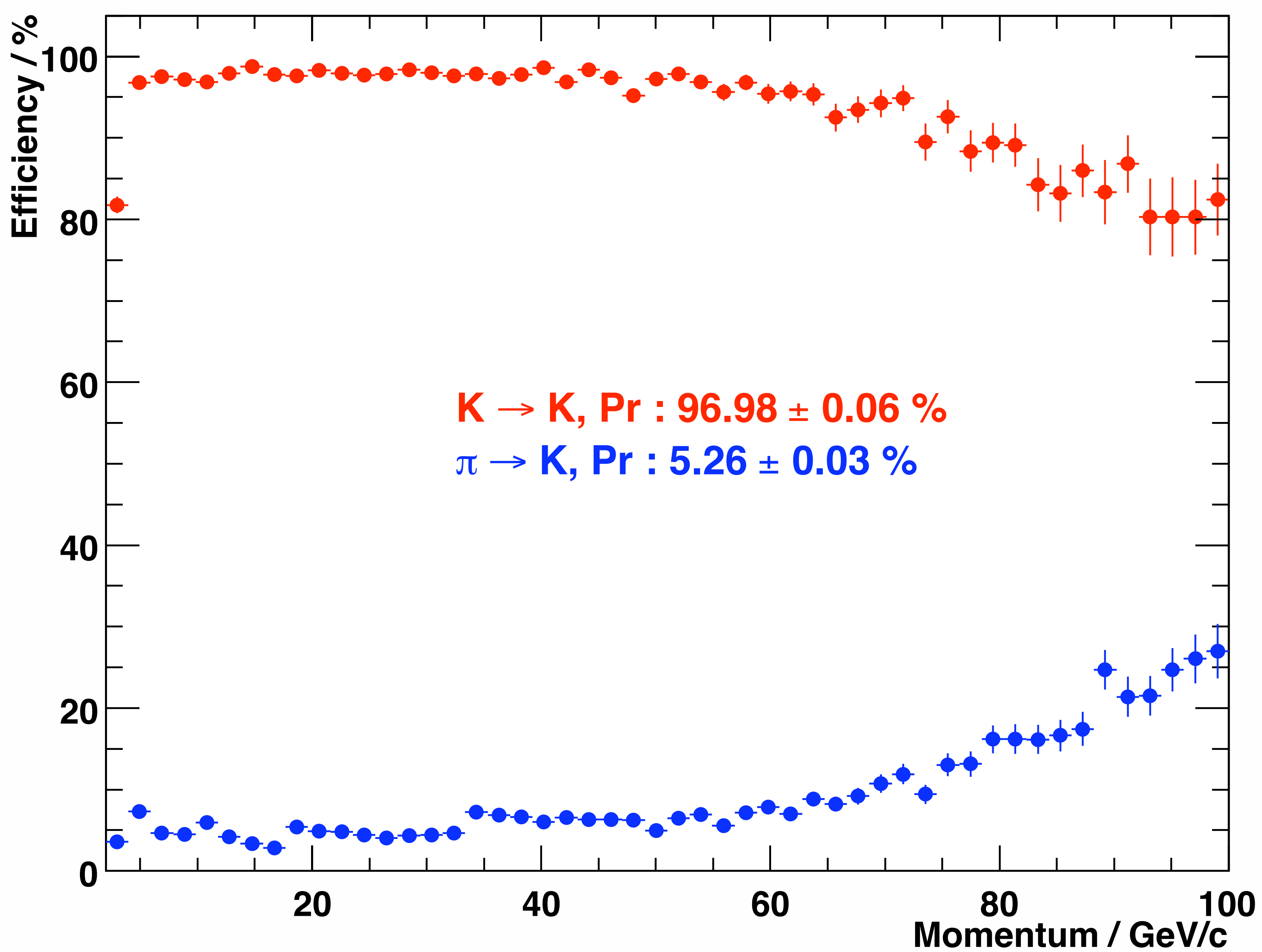
A silicon vertex locator approaches the LHC collisions to within 8mm

proper-time resolution

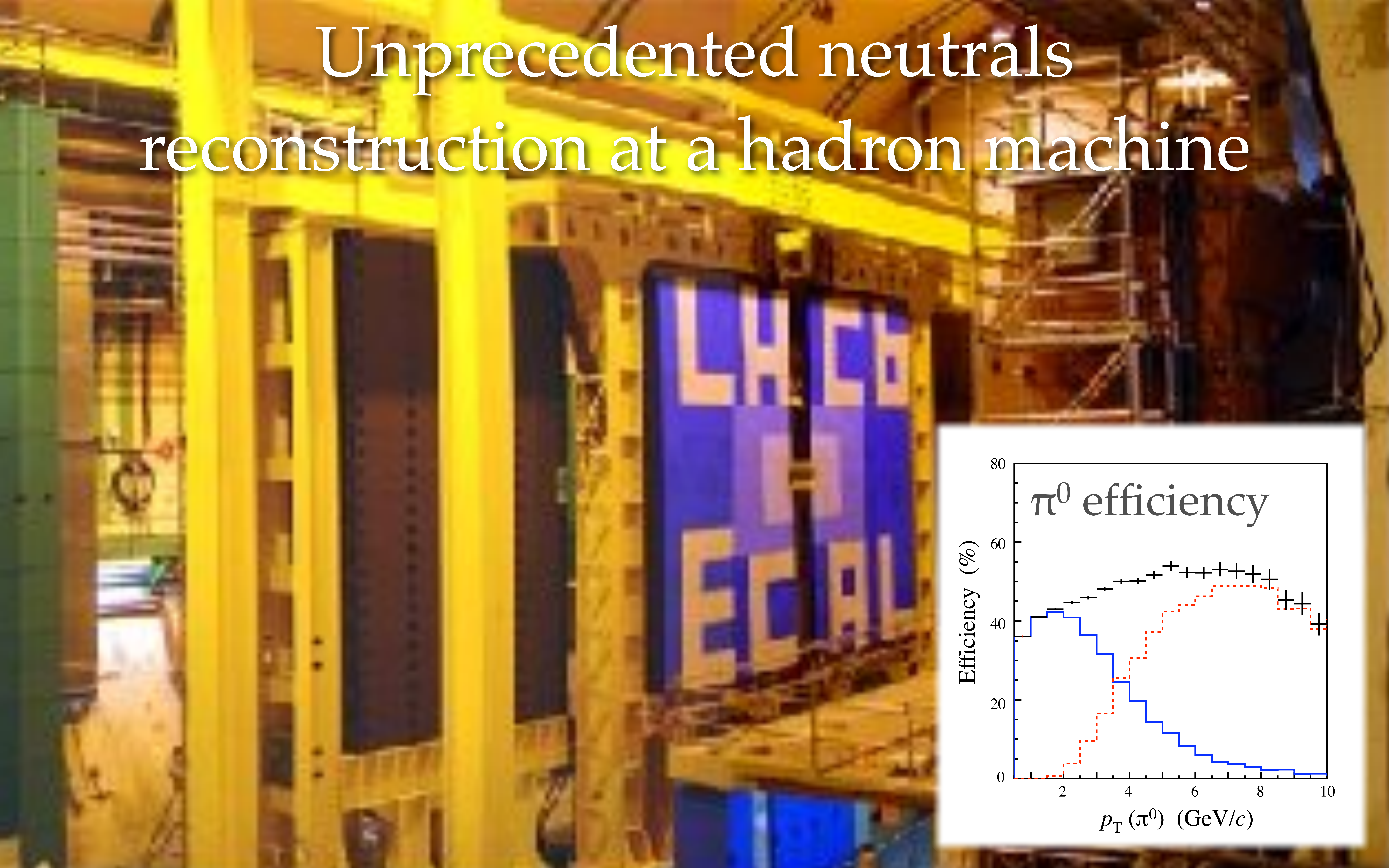


RICH: Dedicated particle identification

PID performance

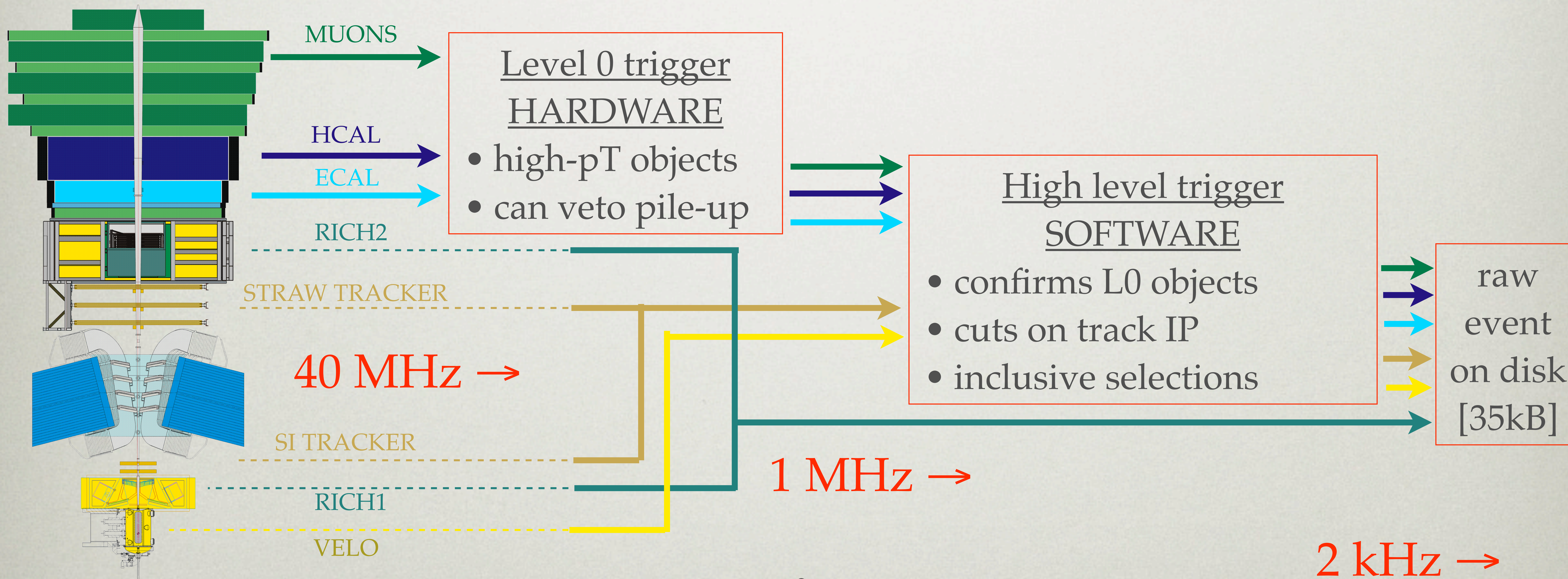


Unprecedented neutrals reconstruction at a hadron machine



Flexible, high-rate trigger

- Modes of interest have BF (10^{-3} – 10^{-9}). Inelastic cross-section 80mb; 30 particles/unit-rapidity
- LHCb makes heavy use of a software trigger. Allows flexibility in its design and greater transparency in its application (no need for emulation - rerun the actual trigger!)



LHCb physics ambitions

Core LHCb programme

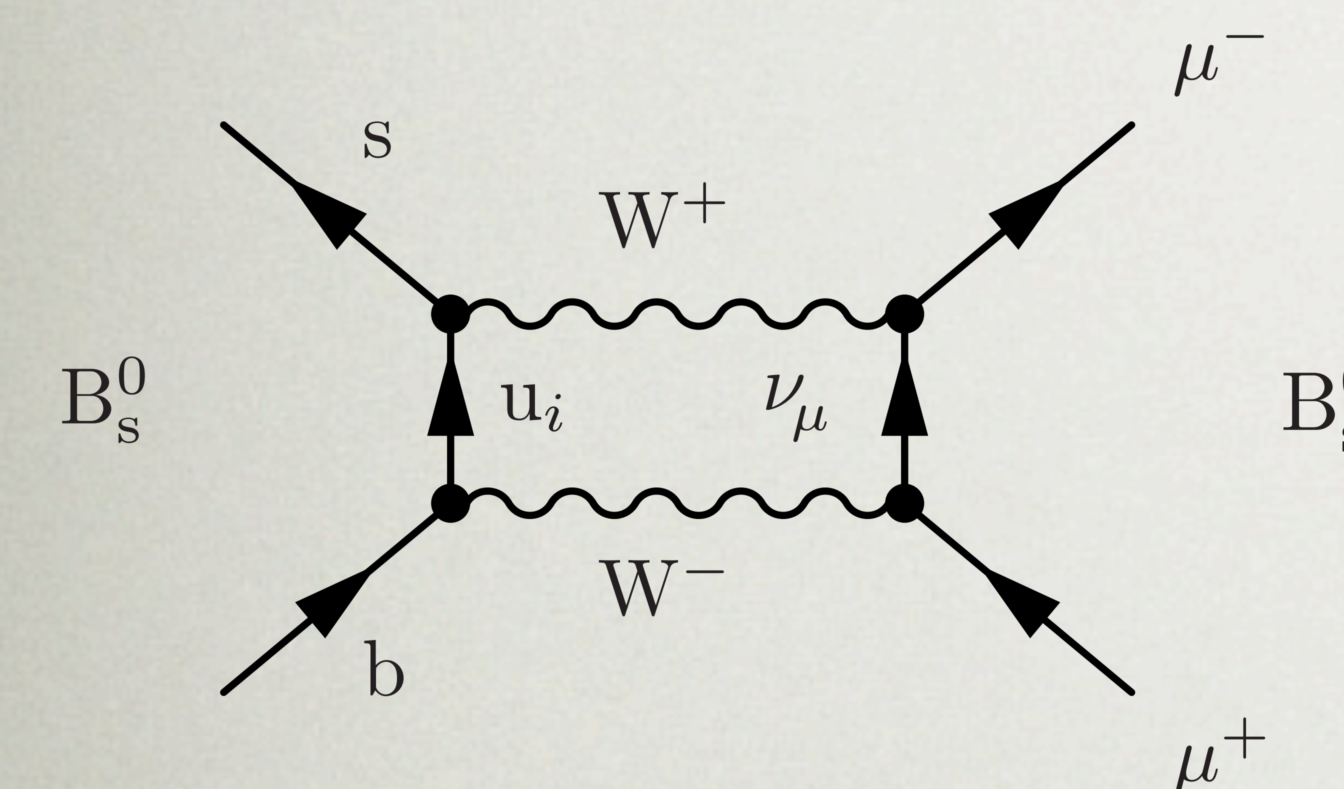
- CPV in B_s-mixing
  - $B_s \to J/\psi\phi$, $B_s \to \phi\phi$, [...]
- precision CKM-parameter determination
  - $B_s \to D_sK$, $B_d \to D^0K$, $B_{s[d]} \to h^+h^-[K^0]$, [...]
- Rare B-decays
  - $B_d \to K^{*0}\mu\mu$, $B_s \to \mu\mu$, [...]
- Radiative penguin B-decays
  - $B_d \to K^{*0}\gamma$, $B_s \to \phi\gamma$, [...]

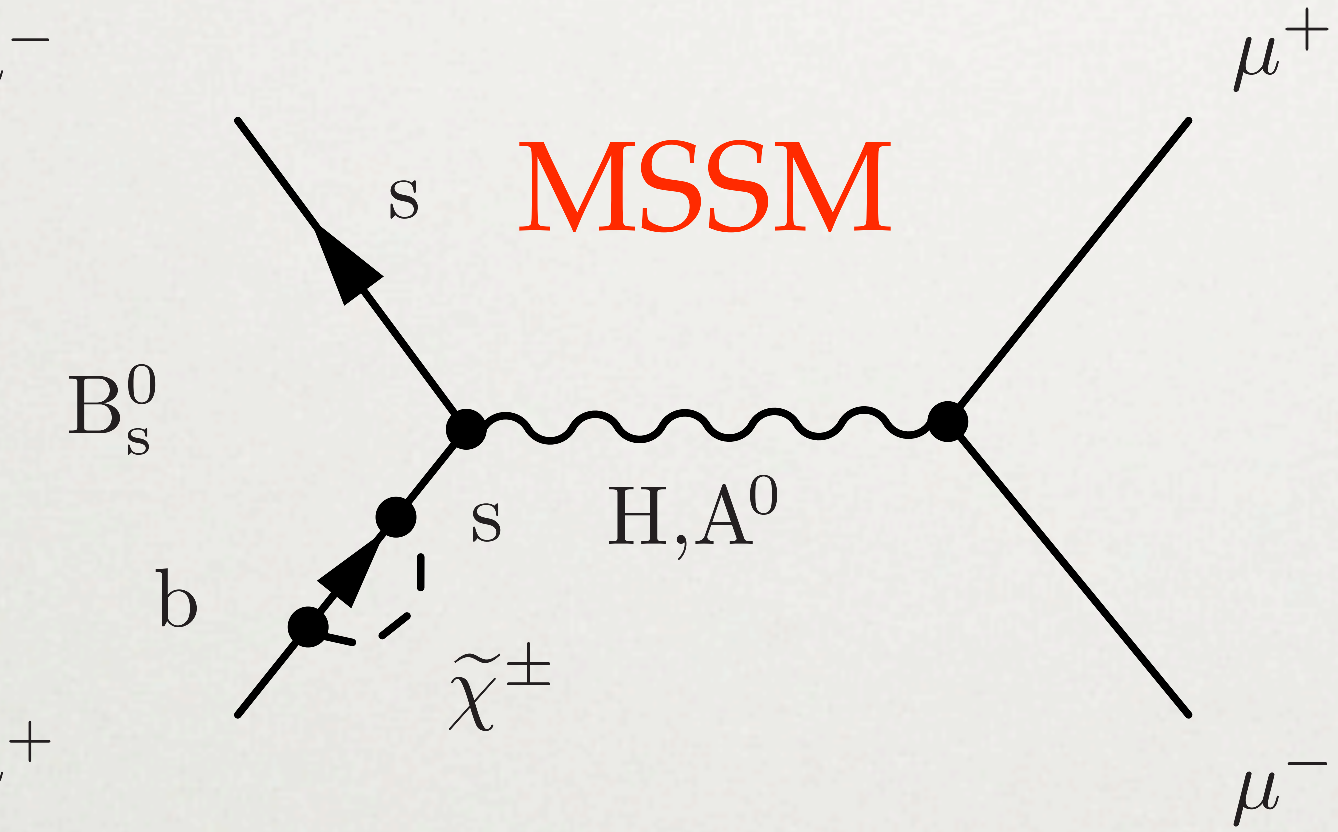
Also...

- CPV in D-mixing
- direct CPV search in D-decays
- very rare D-decays
- Exotic meson spectroscopy
- b-baryon properites
- B_c mass and lifetime
- Lepton flavour violation in tau decays
- Hidden valley particle searches
- [non-SM] Higgs → bbbb
- heavy-quark production at 14 TeV
- Forward electroweak production

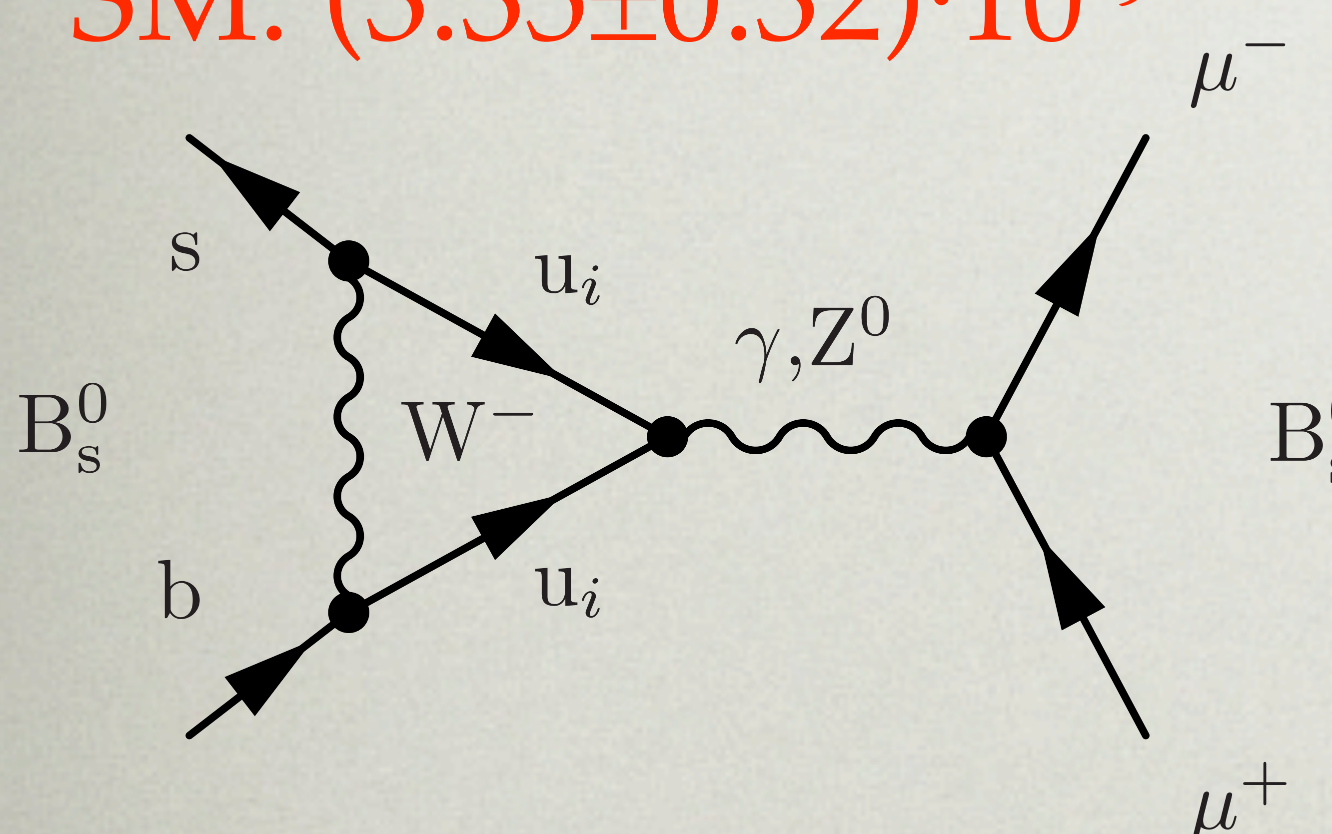
$B_s \rightarrow \mu^+\mu^-$

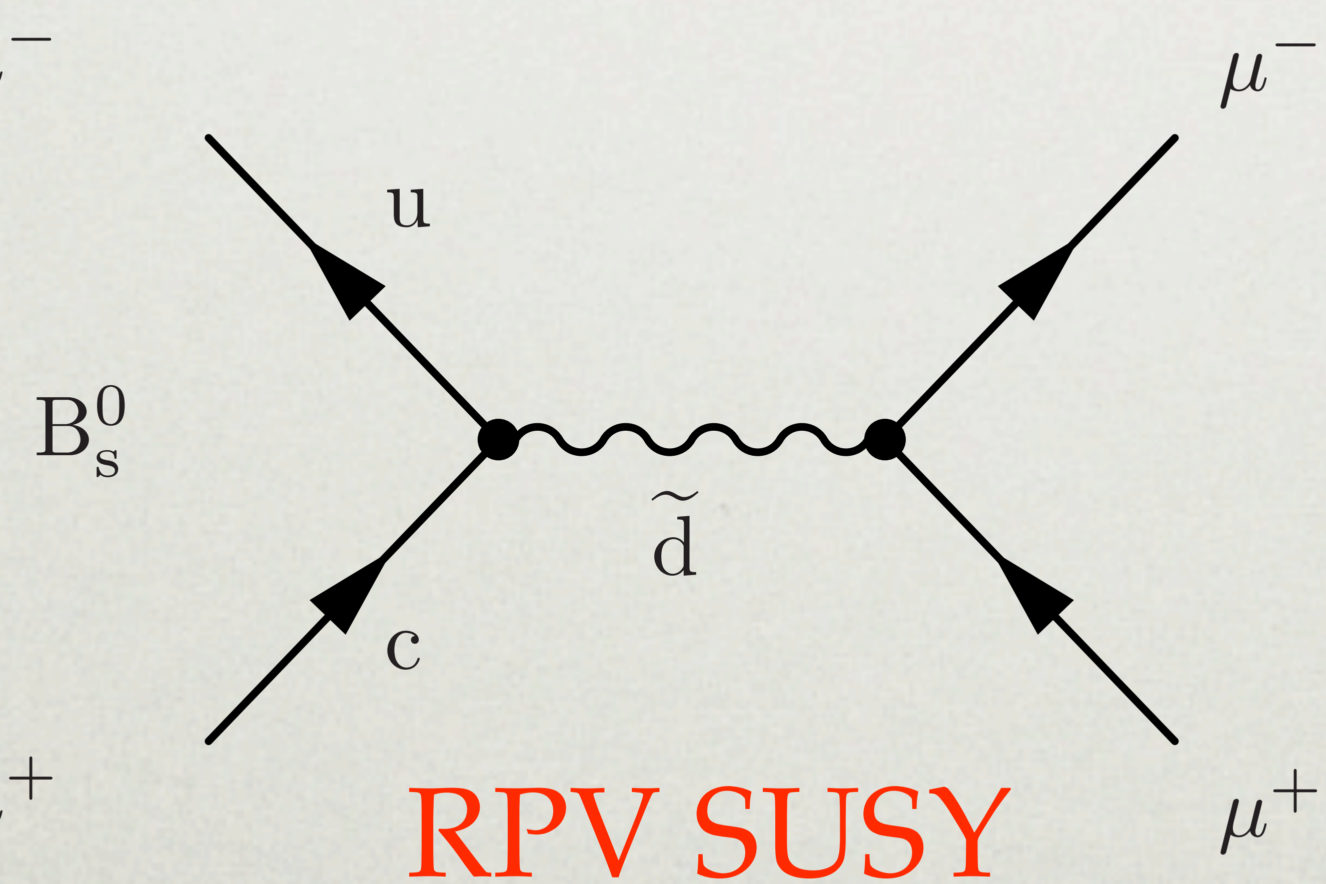
- This FCNC mode is heavily suppressed in the SM, and so useful for new-physics searches

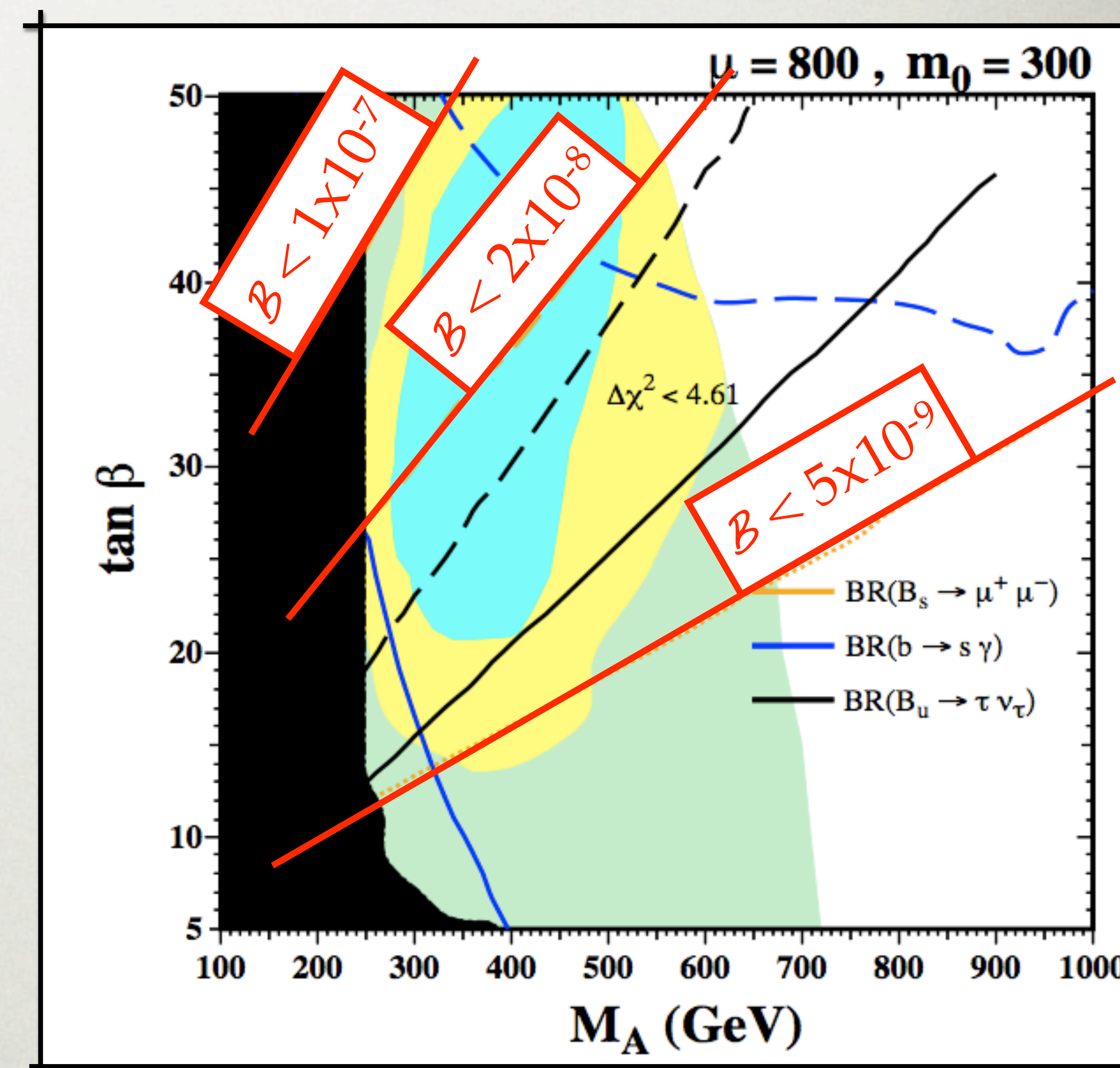




SM: $(3.35 \pm 0.32) \cdot 10^{-9}$

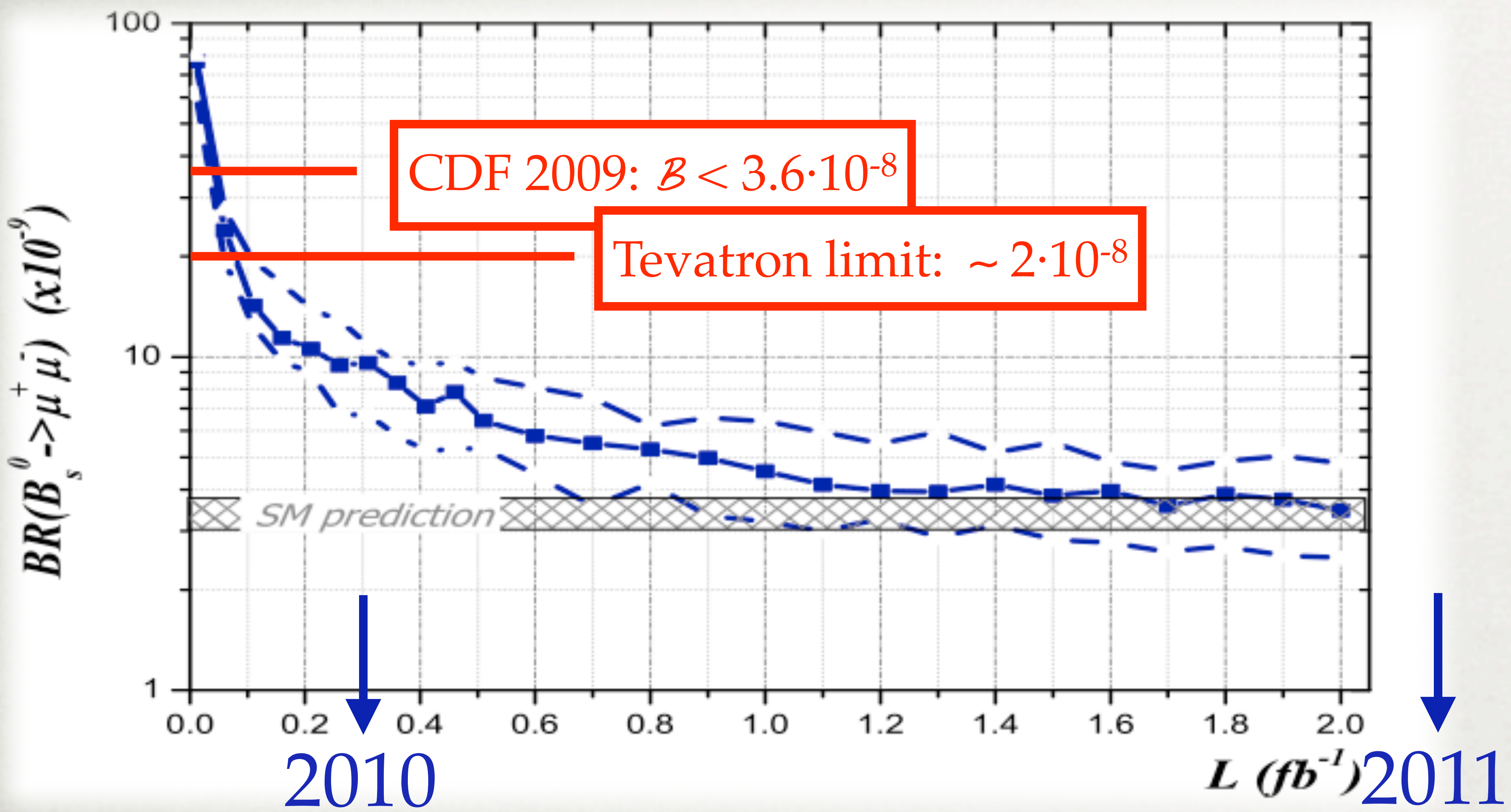


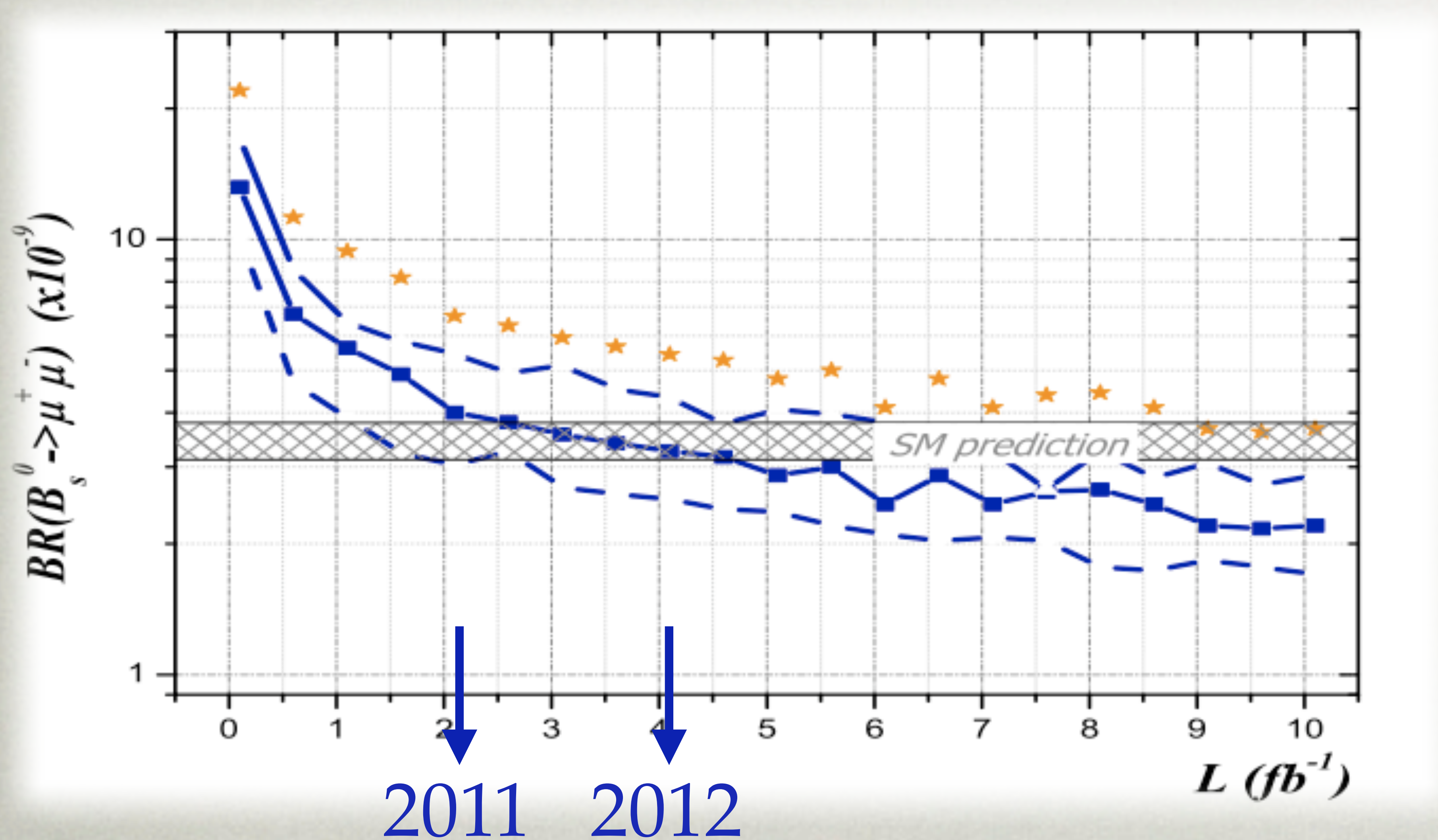




NUHM-MSSM parameter space. J.Ellis et al. hep/ph:0709.0098v2

$B_s \rightarrow \mu^+\mu^-$: expected sensitivity





- FCNC are heavily suppressed in the SM, so make a rich area for new-physics searches at LHC
  - ATLAS and CMS can be competitive in this area with nominal luminosity
- Note, the following ratio is calculable to O(3%)

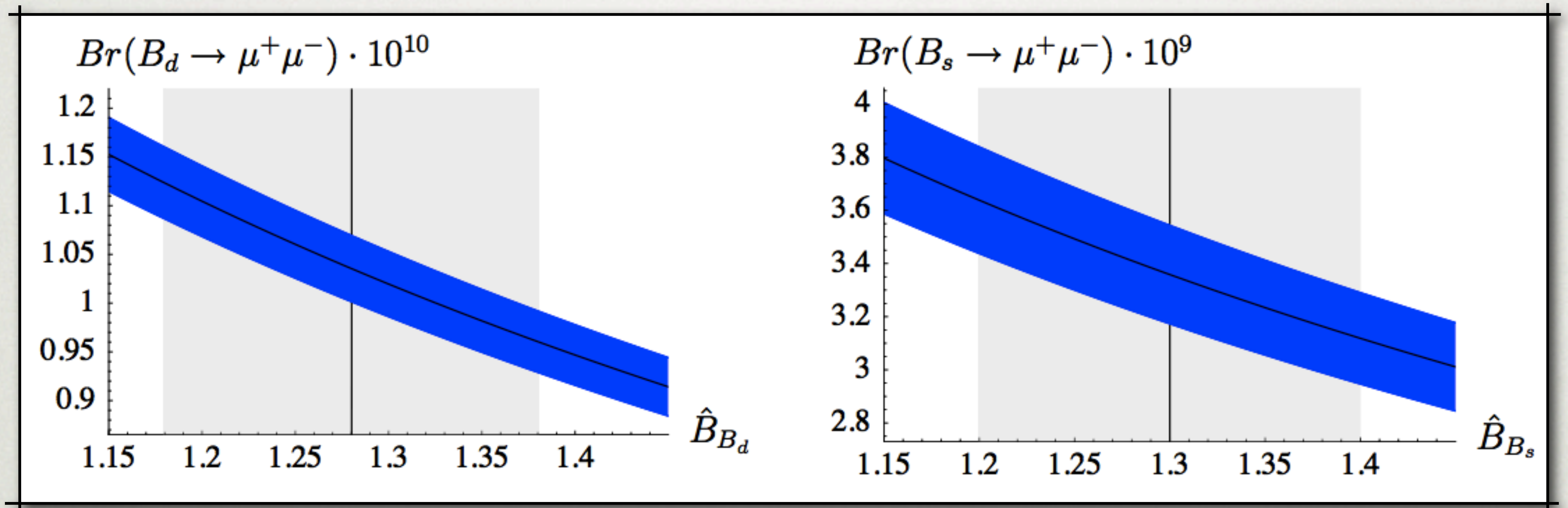
$$\frac{\mathcal{B}_{SM}(B_s \rightarrow \mu^+\mu^-)}{\mathcal{B}_{SM}(B_d \rightarrow \mu^+\mu^-)}$$

Buras hep-ph/0303060

Although the observation of a 10^{-10} process is a probably a job for the LHCb *upgrade*

$B_s \to \mu^+\mu^-$: phenomenological input

- Limiting uncertainty is hadronic parameters, B_B, calculated from the lattice. Will need revision.

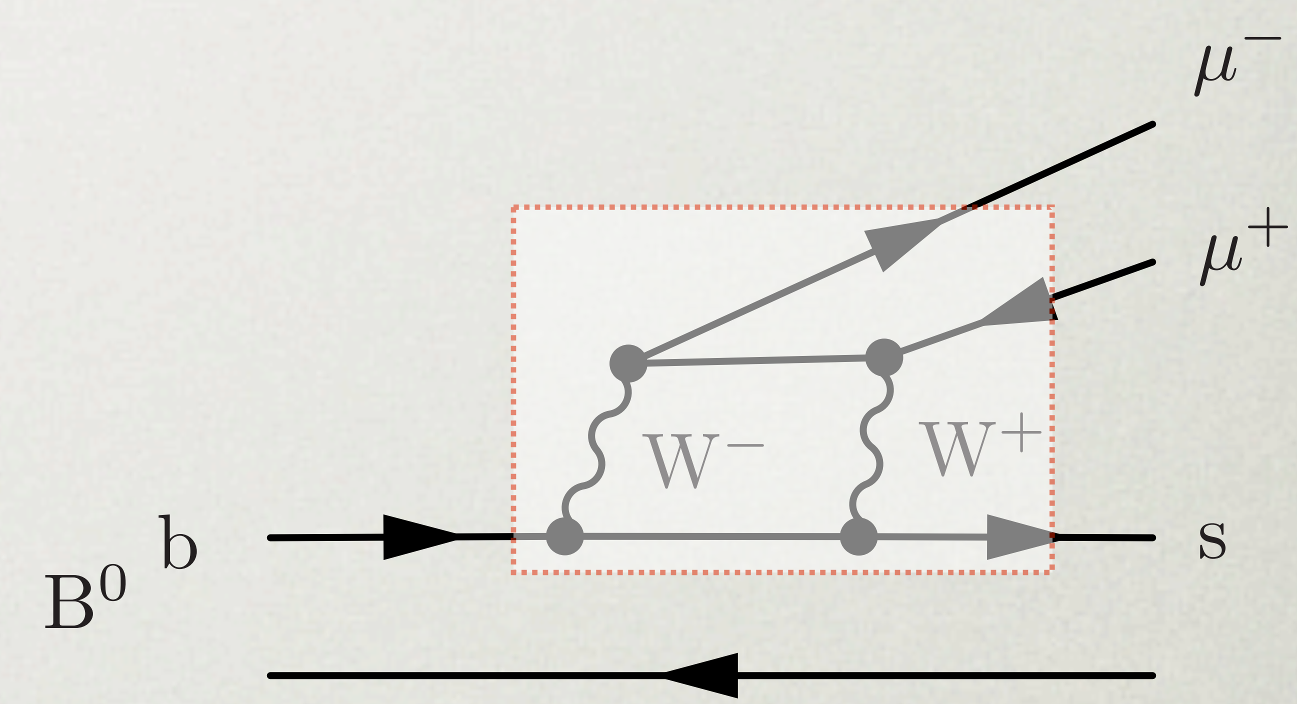


- This FCNC is an excellent candidate to be the first place new-physics is observed
  - The theoretical community should be ready for it!
- We are also looking at the congruent D decay
  - Dominated by long-range effects in the SM, conceivably higher in certain BSM constructs
  - $\mathcal{B}_{SM}(D^0 \to \mu^+\mu^-) \approx 10^{-13}$, $\mathcal{B}_{RPV\text{-}MSSM}(D0 \to \mu^+\mu^-) < 10^{-8}$

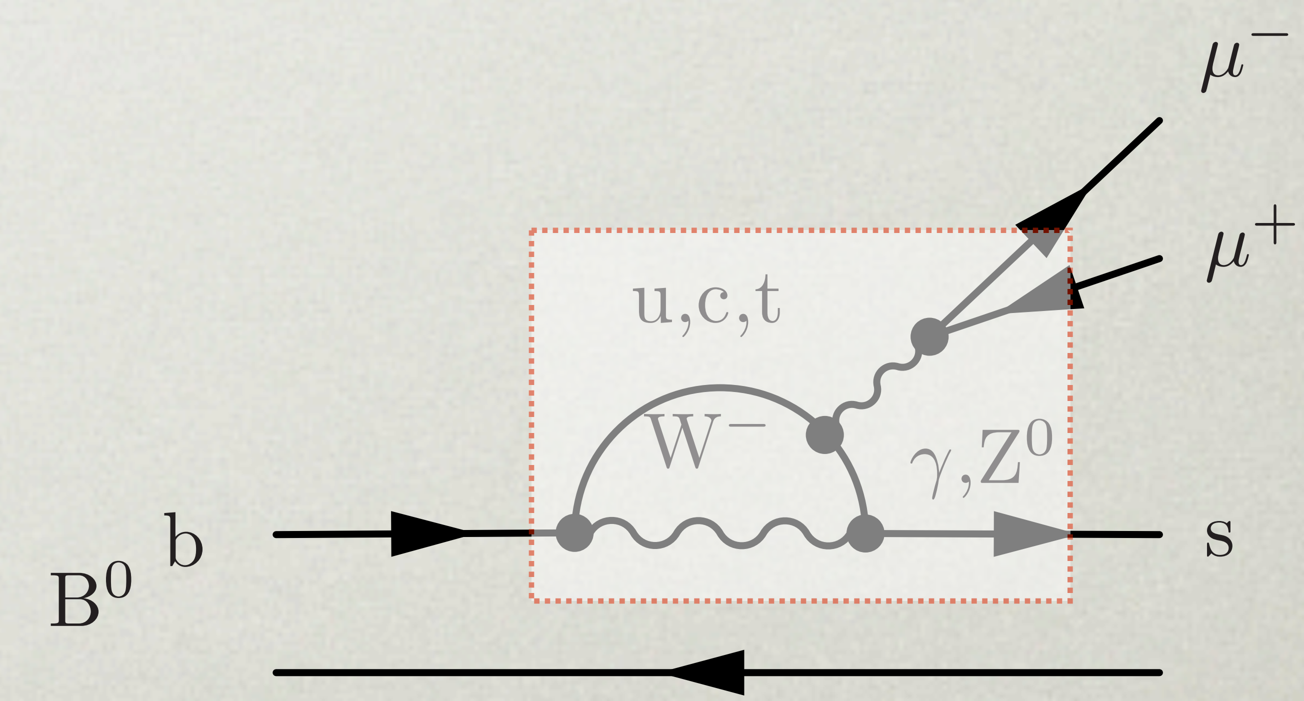
$B \to K^{*0} \ell^+ \ell^-$

- A rare decay, first observed at Belle, $\mathcal{B}_{\text{EXP}}(B^0 \to K^{*0}\mu^+\mu^-) = (1.22^{+0.38}_{-0.32}) \cdot 10^{-6}$
- Has received a lot of attention due to the predicability of many of the physical variables
- Phenomenology usually expressed as a operator product expansion of a effective theory

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1}^{10} [C_i \mathcal{O}_i + C_i' \mathcal{O}_i'] \right)$$

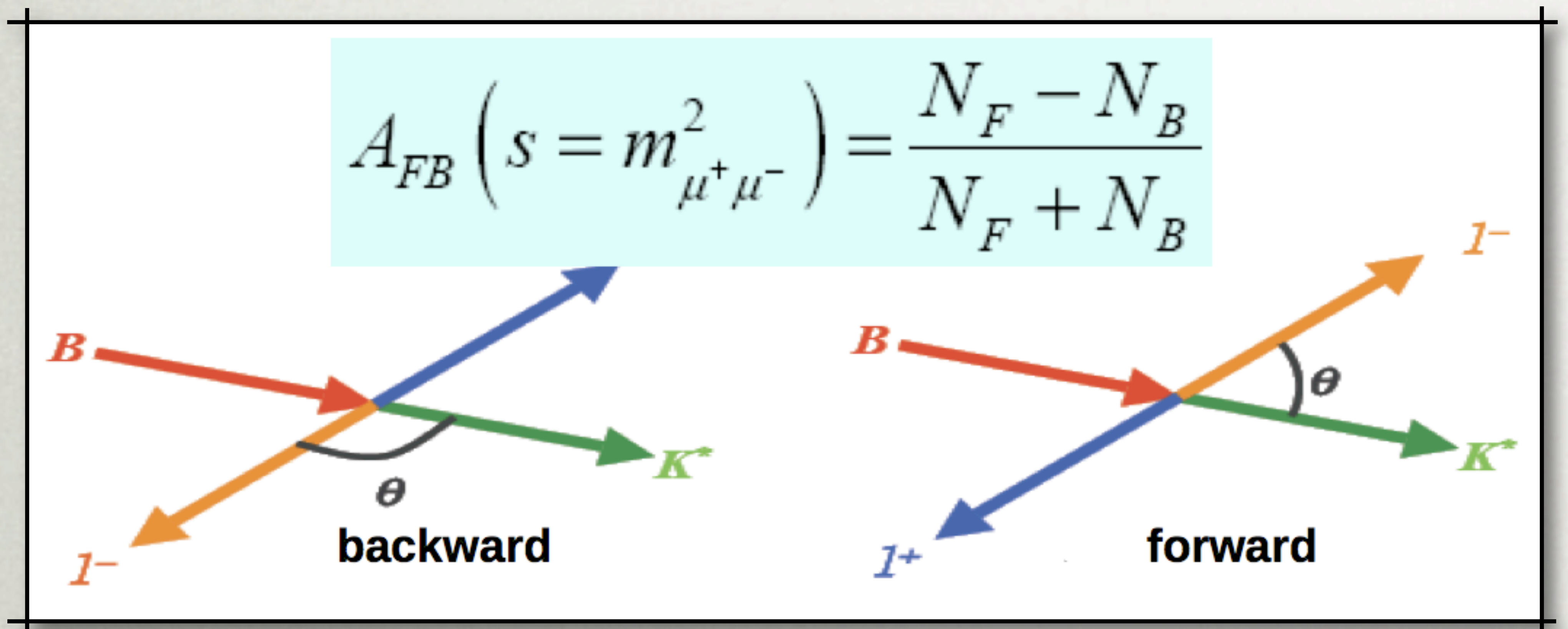


- The C_i are the Wilson coefficients and quantitatively describe the short-range physics
- Dominated by C_7, C_9, C_{10} in the SM
  - new physics enhances the effect of other operators
- LHCb also evaluating: $B_s \to \phi \mu^+\mu^-$, $B^0 \to \rho\, \mu^+\mu^-$, $D^0 \to \rho\, \mu^+\mu^-$
  - Although sparse literature for $b \to d$ & $c \to u$

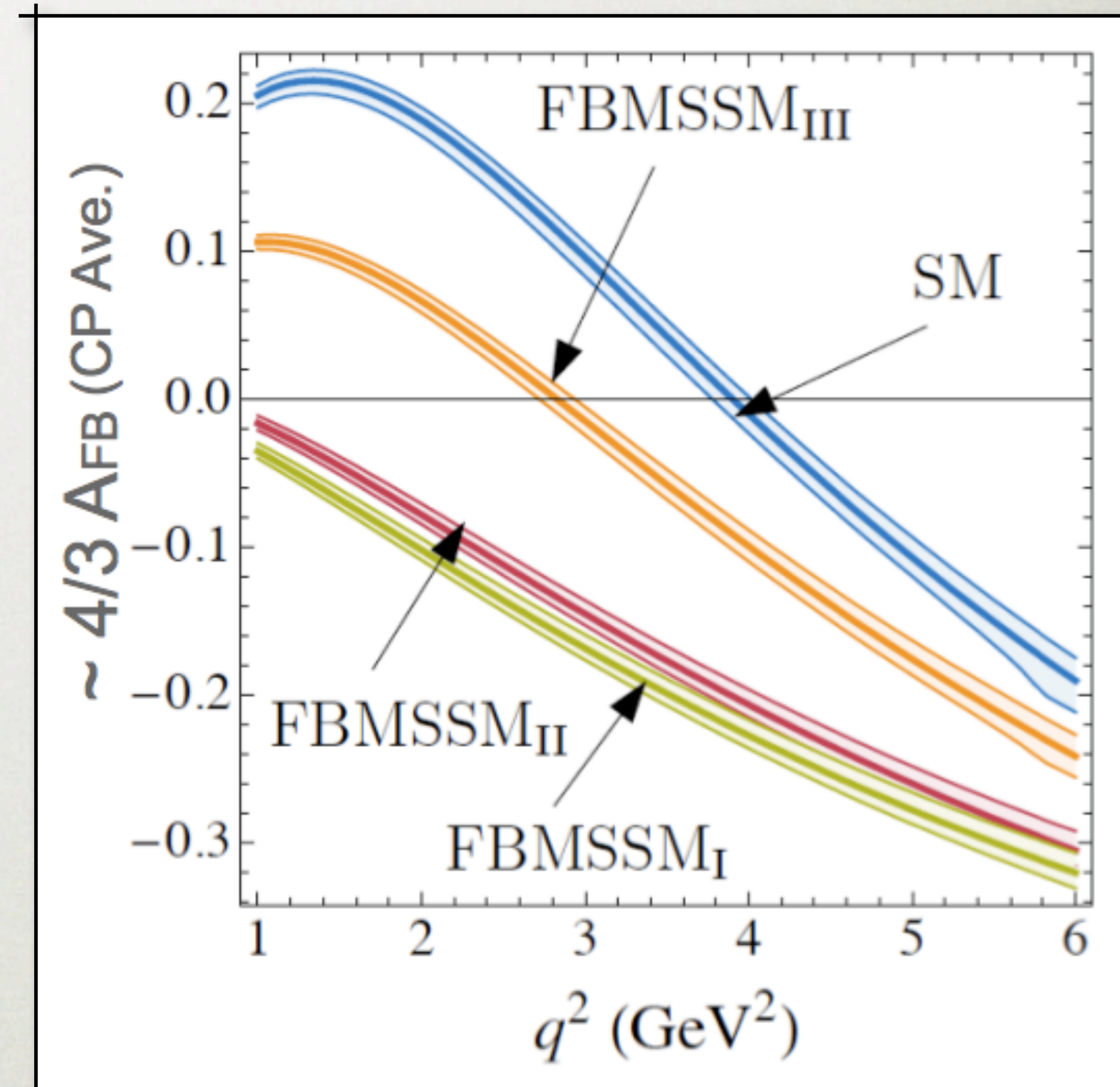


Observables in $B \to K^{*0} \ell^+ \ell^-$

- Angular observables offer small theoretical errors, yet are experimentally assessable
  - e.g. forward-backward asymmetry of $\mu^+\mu^-$



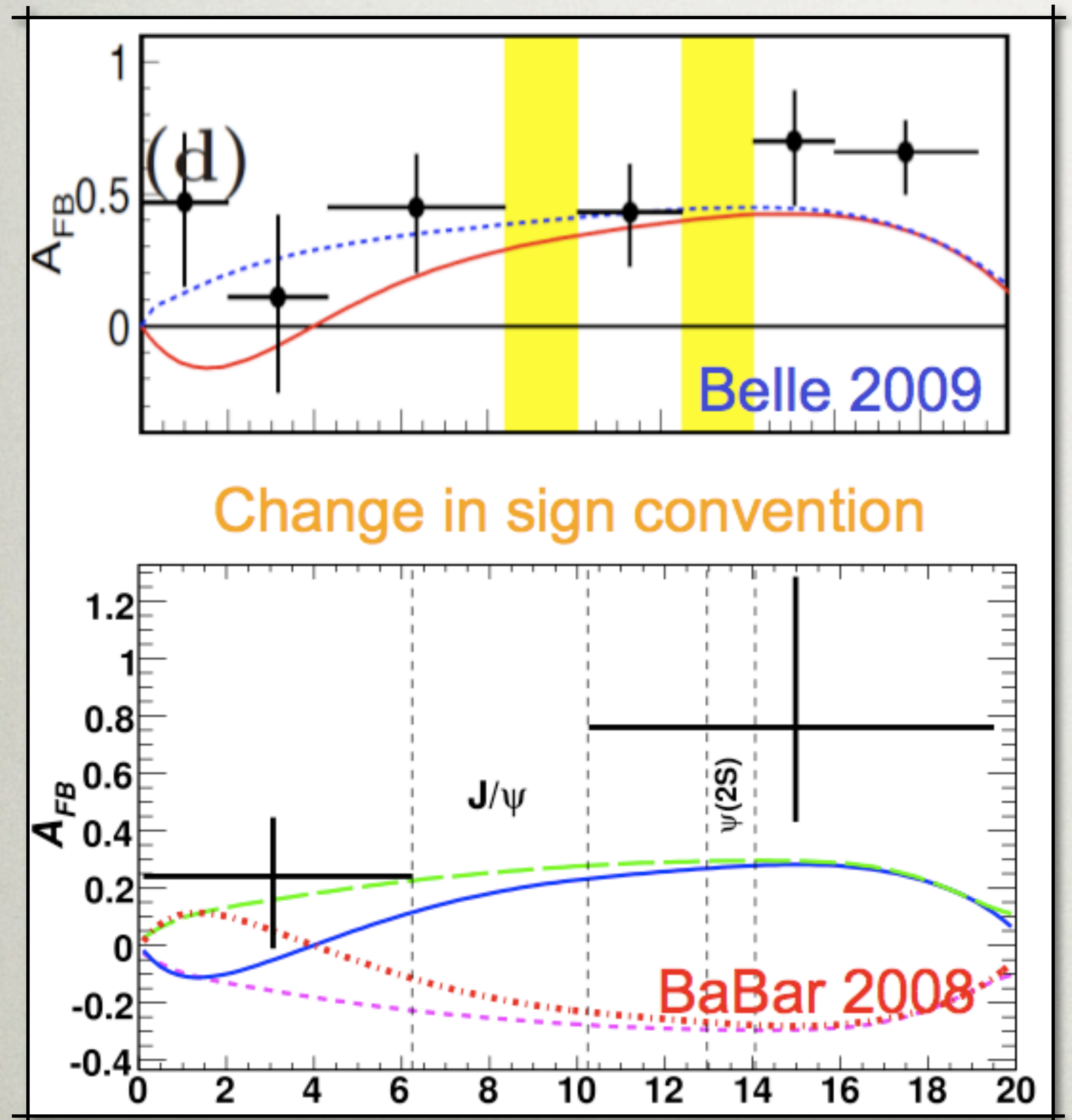
  - Deviations with many new-physics models
  - Precise measure of the zero-crossing point with less than one-year's data

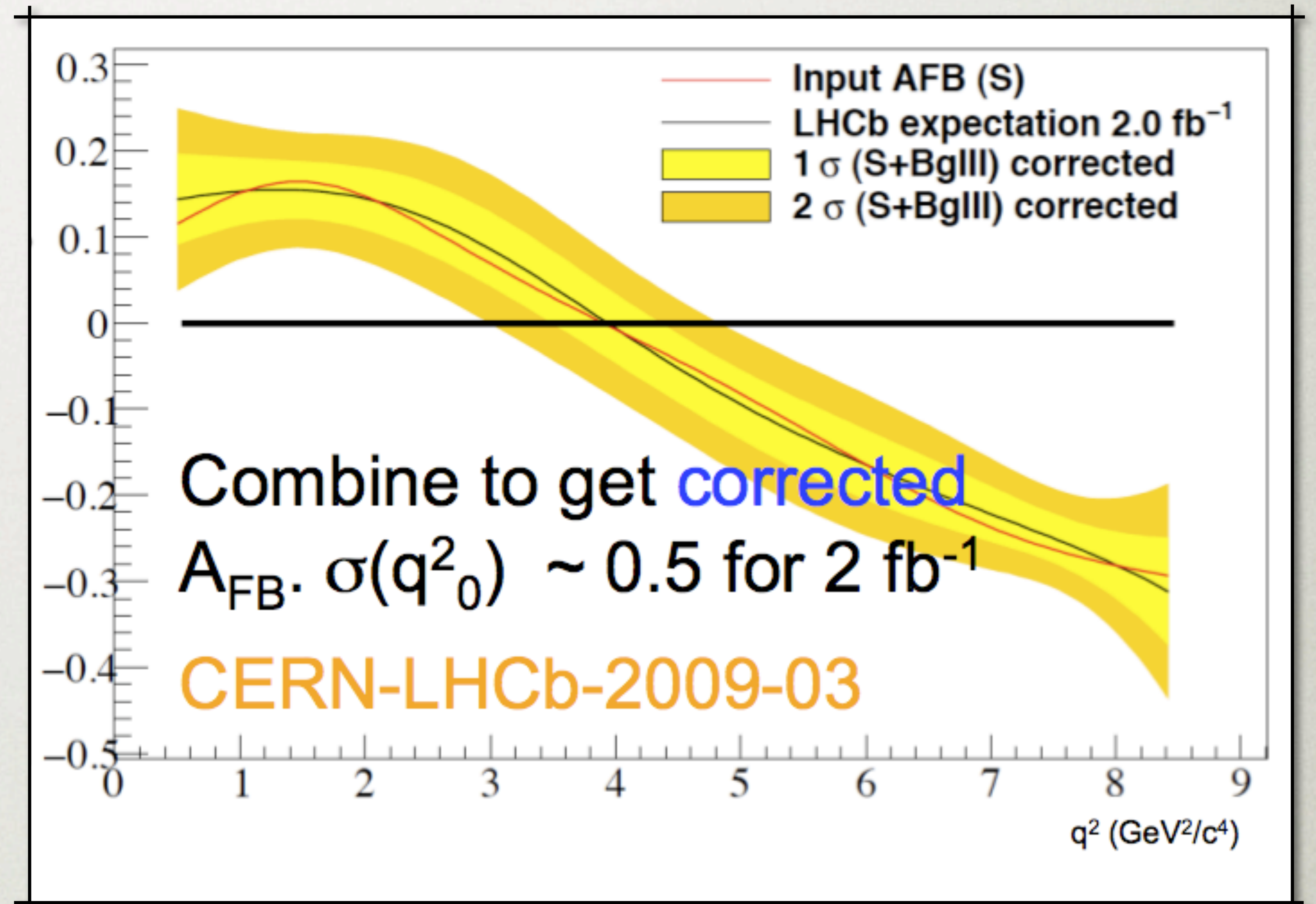


Altmannshofer et al. JHEP 0901:019

Current status and prospect at LHCb

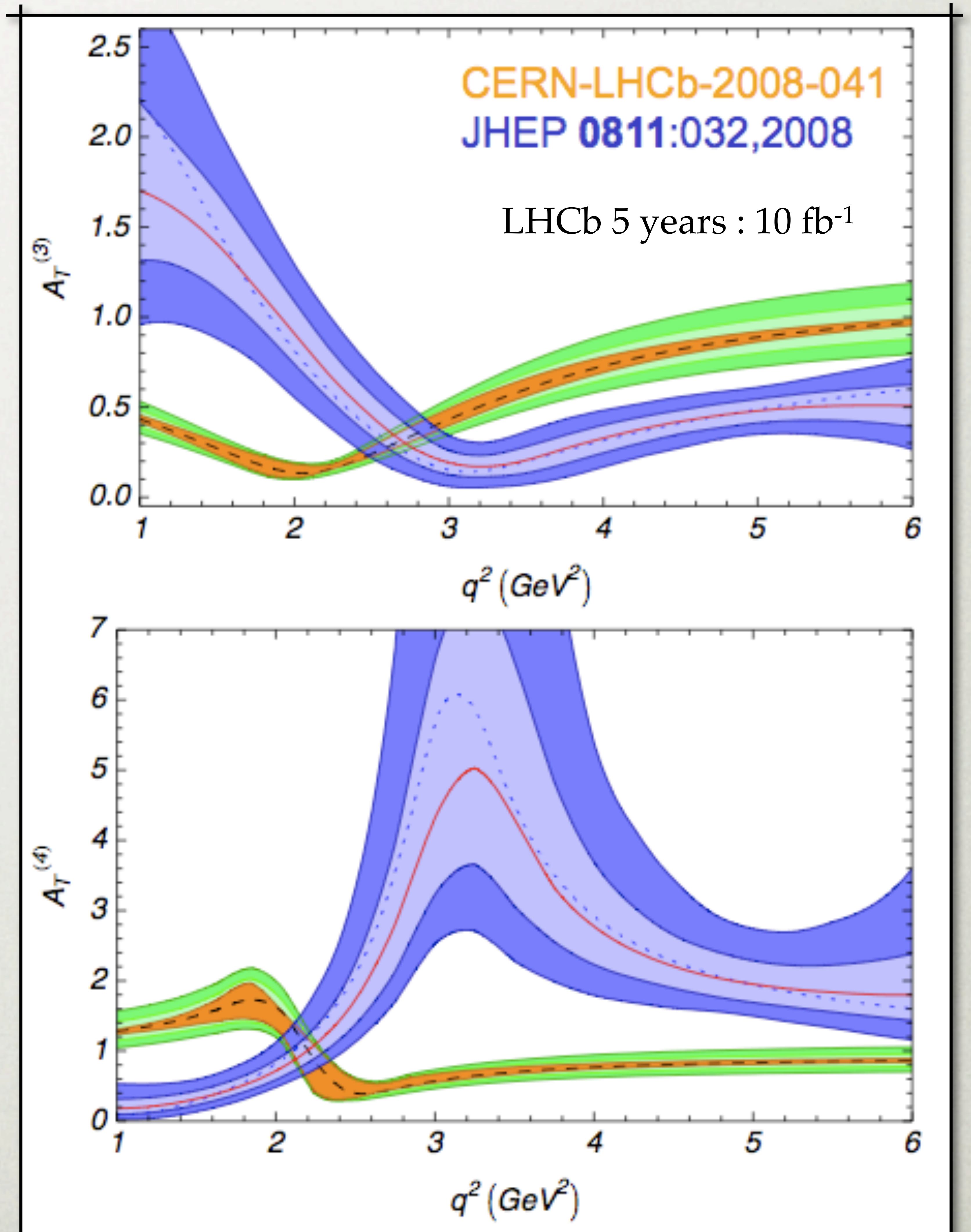
- Next year, LHCb will gather more data that the B-factories.
- And by end 2011, with more than 6400 events...



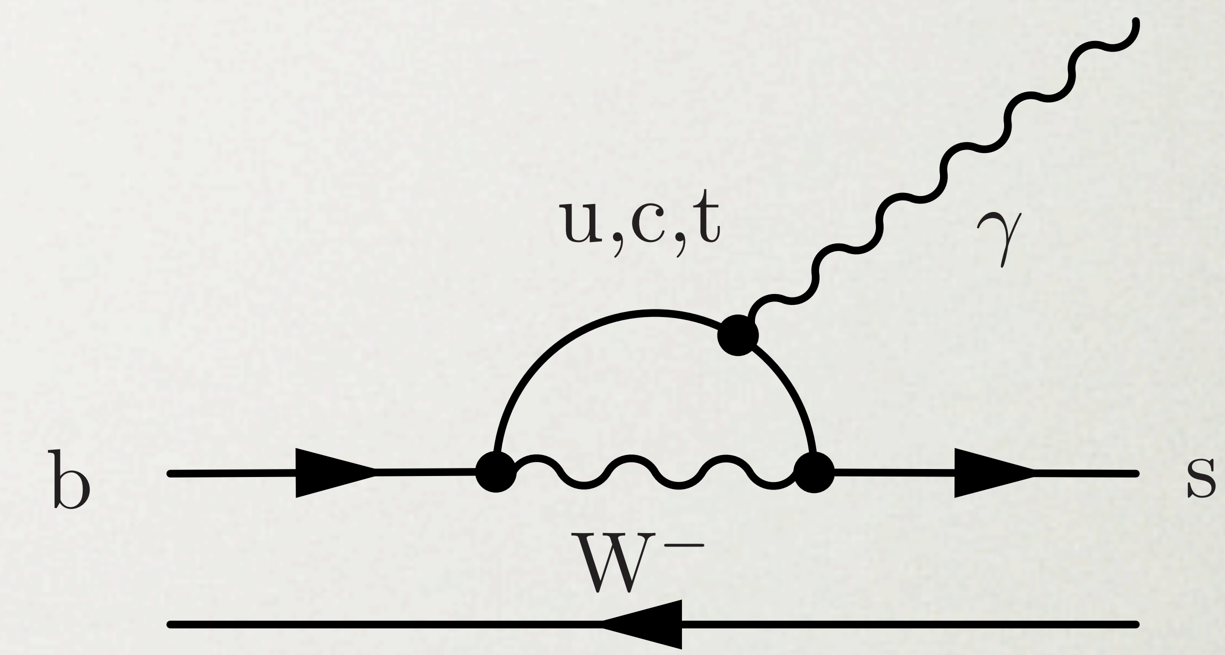


Full angular analysis at LHCb

- With the 10 fb^{-1} yield (5 years), a full fit for the spin amplitudes may be performed (fit convergence observed with 2 fb^{-1} in MC)
- Many observables can be formed from the amplitudes
  - e.g.: observable $A_T^{(3)}$ and $A_T^{(4)}$ are optimised for sensitivity to the right-handed C'_7 (right-handed EW penguin)
- Analysis is restricted to a small range in $q^2(\mu\mu)$ due to theoretical framework constraints ($E(K^*) \approx m_B$) from QCDf/SCET
  - Plenty of data at $q^2 > 6$ GeV^2 if the phenomenology estimates improve



Radiative penguins



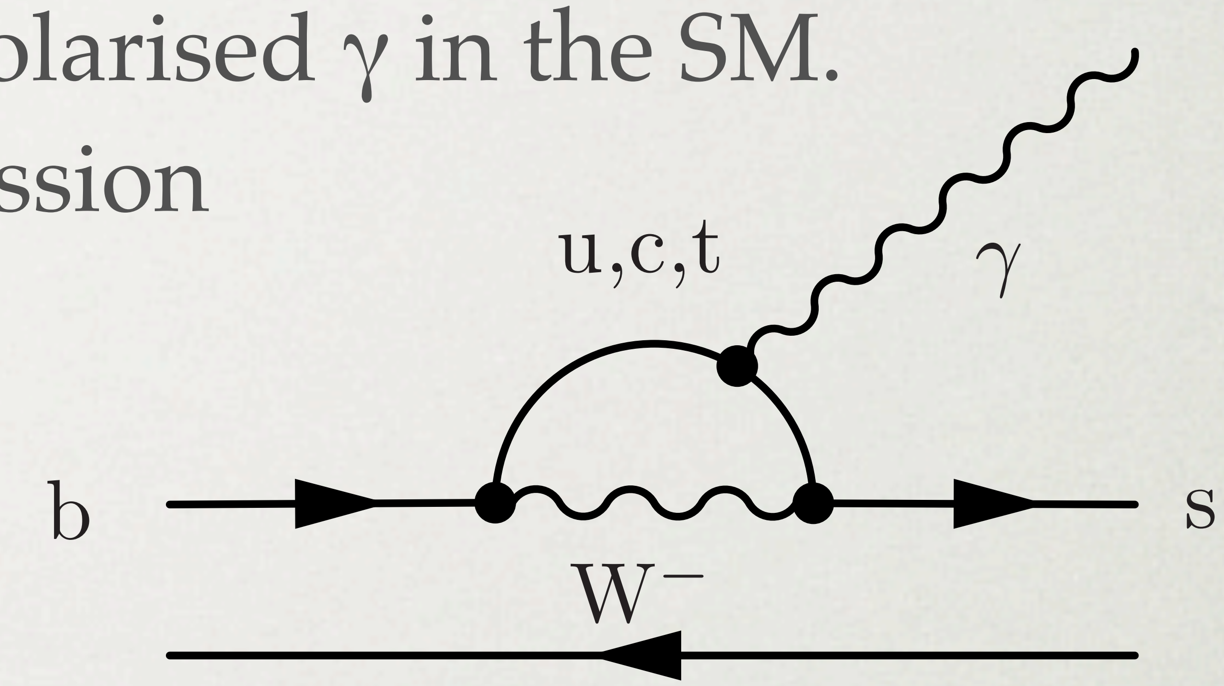
- Inclusive $b \to s\gamma$ results are in agreement with SM
  - $\mathcal{B}_{EXP'T}(b \to s\gamma) = (355 \pm 24 \pm 10 \pm 3) \cdot 10^{-6}$ [HFAG]
  - $\mathcal{B}_{NNLO}(b \to s\gamma) = (315 \pm 23) \cdot 10^{-6}$ [E>1.6 GeV]
- And places the strongest constrains on BSM models
- LHCb cannot perform inclusive measurements. Exclusive BF calculations have large QCD uncertainty. A challenge to phenomenologists!
  - $\mathcal{B}_{EXP'T}(B^0 \to K^{*0}\gamma) = (40.1 \pm 2.0) \cdot 10^{-6}$
  - $\mathcal{B}_{CALC}(B^0 \to K^{*0}\gamma) = (46 \pm 14) \cdot 10^{-6}$
  - $\mathcal{B}_{EXP'T}(B^0 \to \phi\gamma) = (57\,^{+0.18}_{-0.12} \pm 12) \cdot 10^{-6}$
  - $\mathcal{B}_{CALC}(B^0 \to \phi\gamma) = (43 \pm 14) \cdot 10^{-6}$

A. Ali et al. Eur. Phys. J. C 55 (2008) 577

- LHCb will reconstruct more than 11,000 $B^0 \to \phi\gamma$ and 70,000 $B^0 \to K^{*0}\gamma$ by end 2011
  - i.e 3 $B^0 \to \phi\gamma$ / hour [c.f. 1/day with Belle running at the $\Upsilon(5s)$]
  - background estimated from generic Monte Carlo to be <6,000 in the same period

Photon polarisation in $B^0 \to \phi\gamma$

- Since left-handed u,c,t couples to W^-, expect mostly left-polarised γ in the SM. Current theory limitation O(10%) from internal gluon emission
  B. Grinstein et al. PRD71,011504



- Polarisation → distinguishable final state → no mixing
  - but, inspecting formalism of $B \to f^{CP}\gamma$ ...

$$\Gamma_{\overset{(-)}{B}{}^0_s \to f^{CP}\gamma}(t) = |A|^2 \exp^{-\Gamma_s t} \left(\cosh \frac{\Delta\Gamma_s t}{2} - \mathcal{A}^{\Delta} \sinh \frac{\Delta\Gamma_s t}{2} + \mathcal{C} \cos \Delta m_s t \overset{(-)}{+} \mathcal{S} \cos \Delta m_s t \right)$$

0

If ϕs is small (SM), final term → 0; tagging not needed

$$\mathcal{C} \approx 0$$
$$\mathcal{S} \approx \sin 2\psi \sin \phi_s$$
$$\mathcal{A}^{\Delta} \approx \sin 2\psi \cos \phi_s$$

~1 if ϕ_s is SM

$$\tan\psi = \left| \frac{\mathcal{A}(\overline{B}^0{}_{(s)} \to f^{CP}\gamma_R)}{\mathcal{A}(\overline{B}^0{}_{(s)} \to f^{CP}\gamma_L)} \right|$$

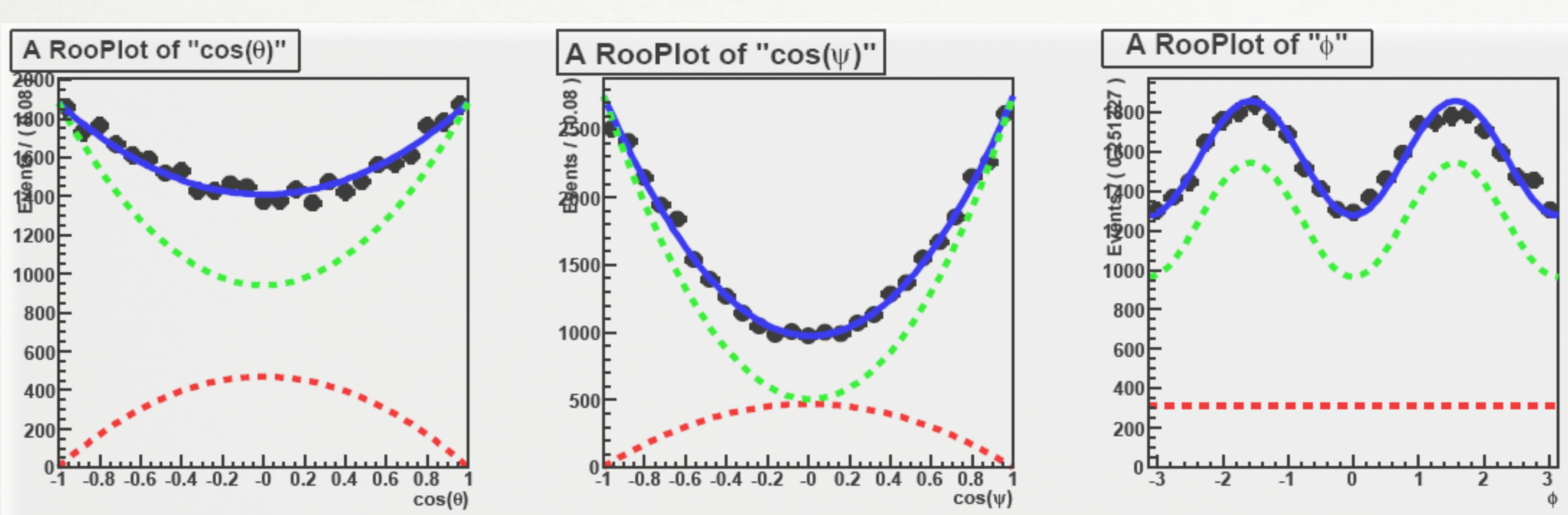
... shows time-dependent CP-violation probes the proportion of "wrong" γ polarisation

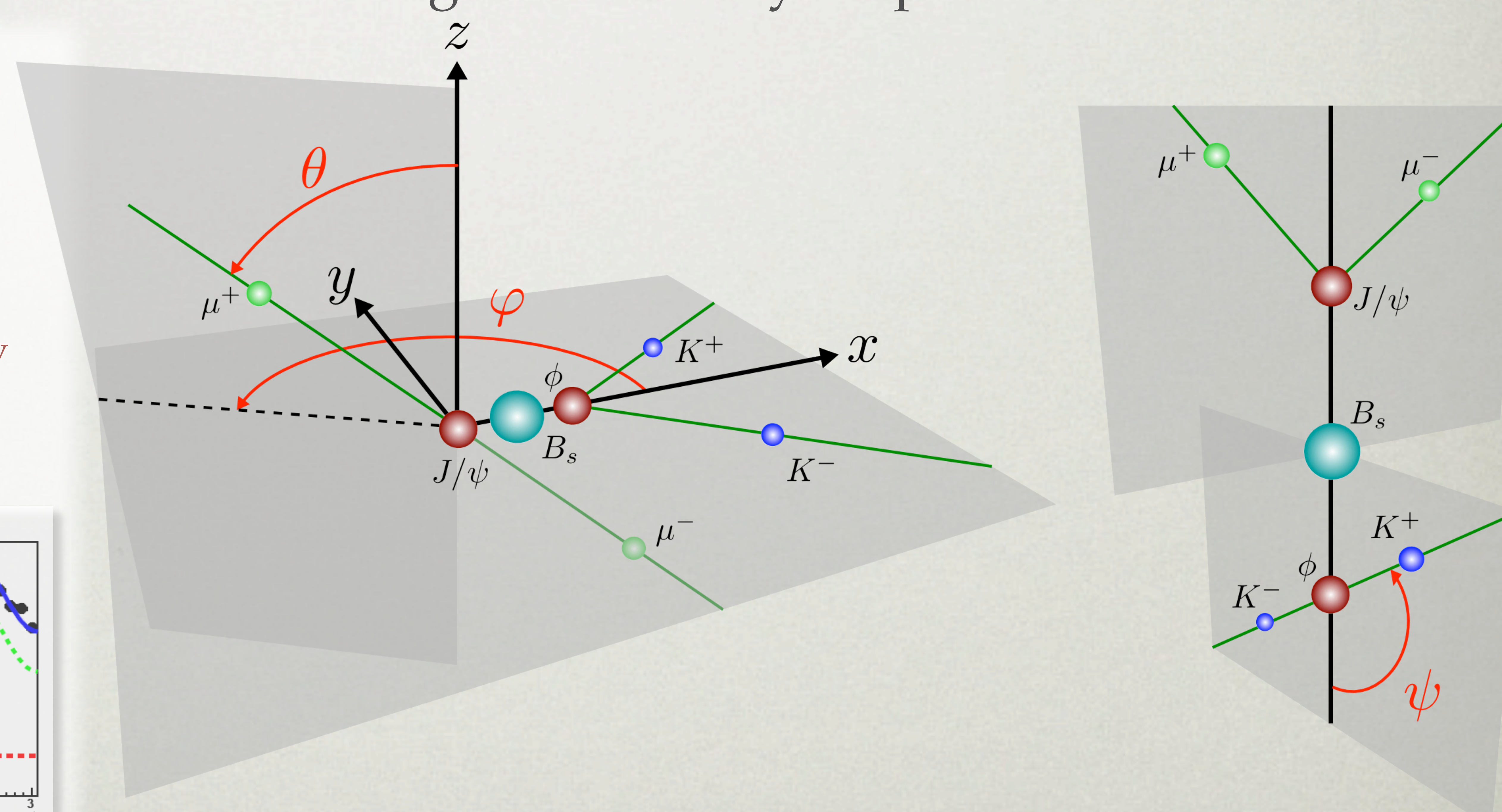
- At LHCb we expect $\sigma(\tan\psi) \approx$ 0.11 by end 2011; and <0.05 with 10 fb^{-1}. Then theory limits.
- Also developing: $B^+ \to \phi K^+\gamma$, $B^0 \to \rho^0\gamma$, $B^0 \to \omega\gamma$

CP-violation in B_s-mixing

- The CP-violating weak-phase in B_s-mixing is completely analogous to that in B_d-mixing
- The golden-mode for B_d is $B^0 \to J/\psi\, K_S^0$ [exemplified by Belle,Babar]. For B_s use $B_s \to J/\psi\, \phi$.
- This is P→VV: B_s is a pseudoscalar (spin=0), ϕ and J/ψ are vectors mesons ($J^{PC} = 1^{--}$)
- Well-establish angular analysis used to extract CP-eigenstate decay amplitudes

  - In the B_s rest frame, ϕ and J/ψ have relative orbital momentum ℓ =0,1,2
  - Since $CP|f\rangle = (-1)^{\ell}|f\rangle$, final state is mixture of CP even (ℓ =0,2) and CP odd (ℓ =1)
  - Three angles θ, φ, ψ describe directions of final decay products $J/\psi \to \mu\mu$ and $\phi \to K^+K$ from which the CP+ and CP- components may be extracted



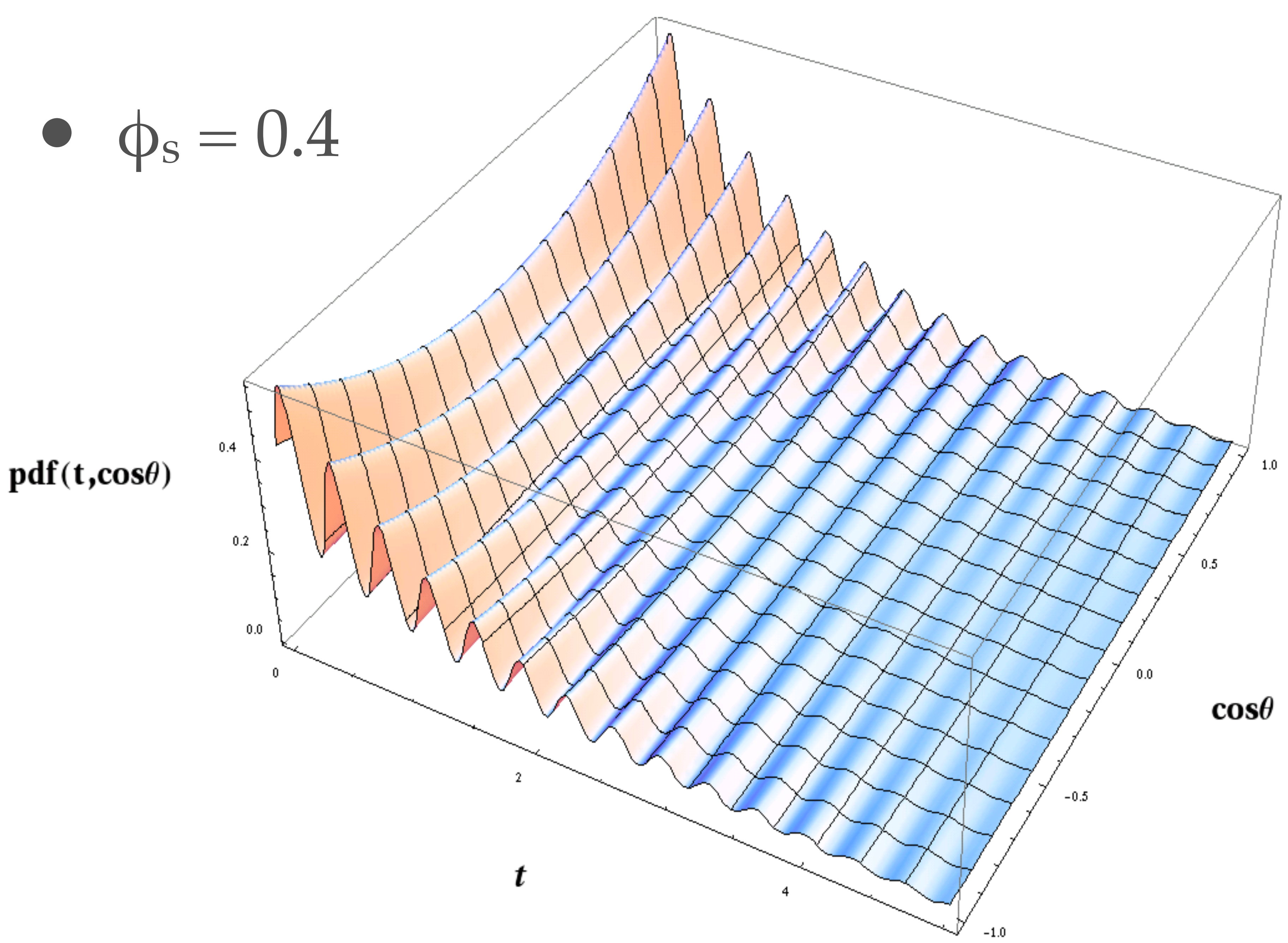


Imaging the B_s oscillations

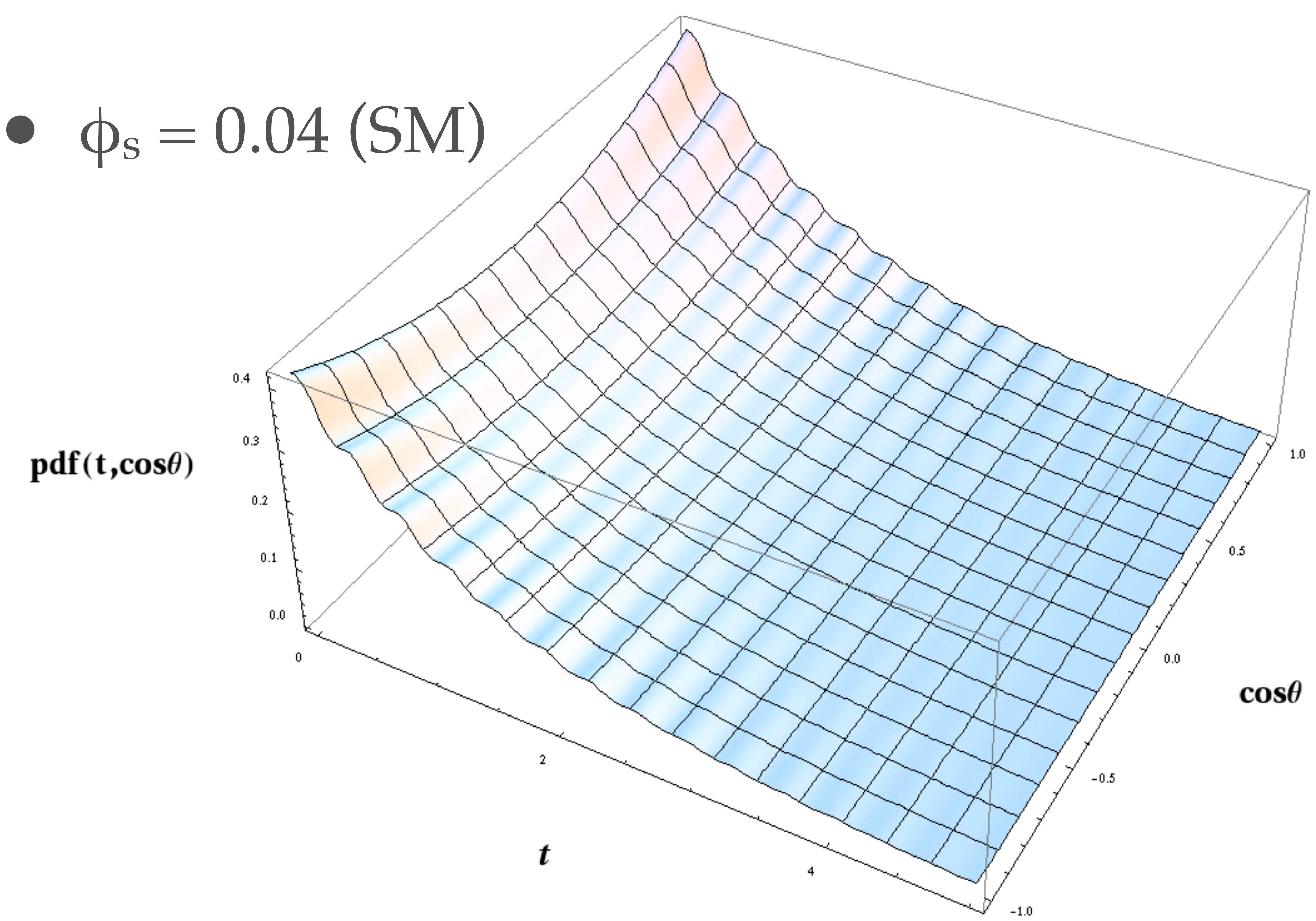
- For this visualisation, integrate $\frac{d\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d(\cos\theta)\, d\phi\, d(\cos\psi)}$ over two of the observables, ϕ and $\cos\psi$

- Amplitude of wiggles $\propto \sin\phi_s$

- $\phi_s = 0.4$

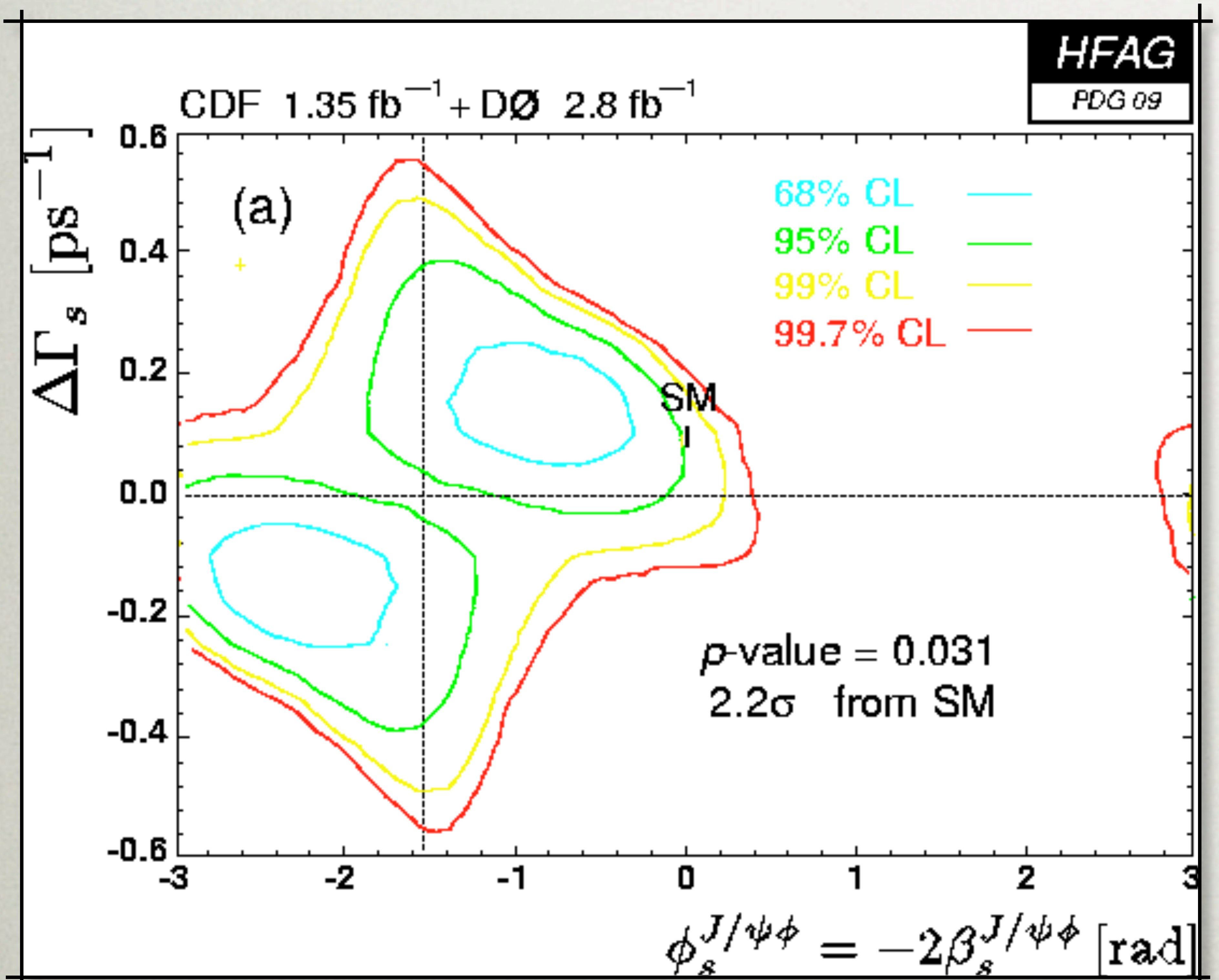


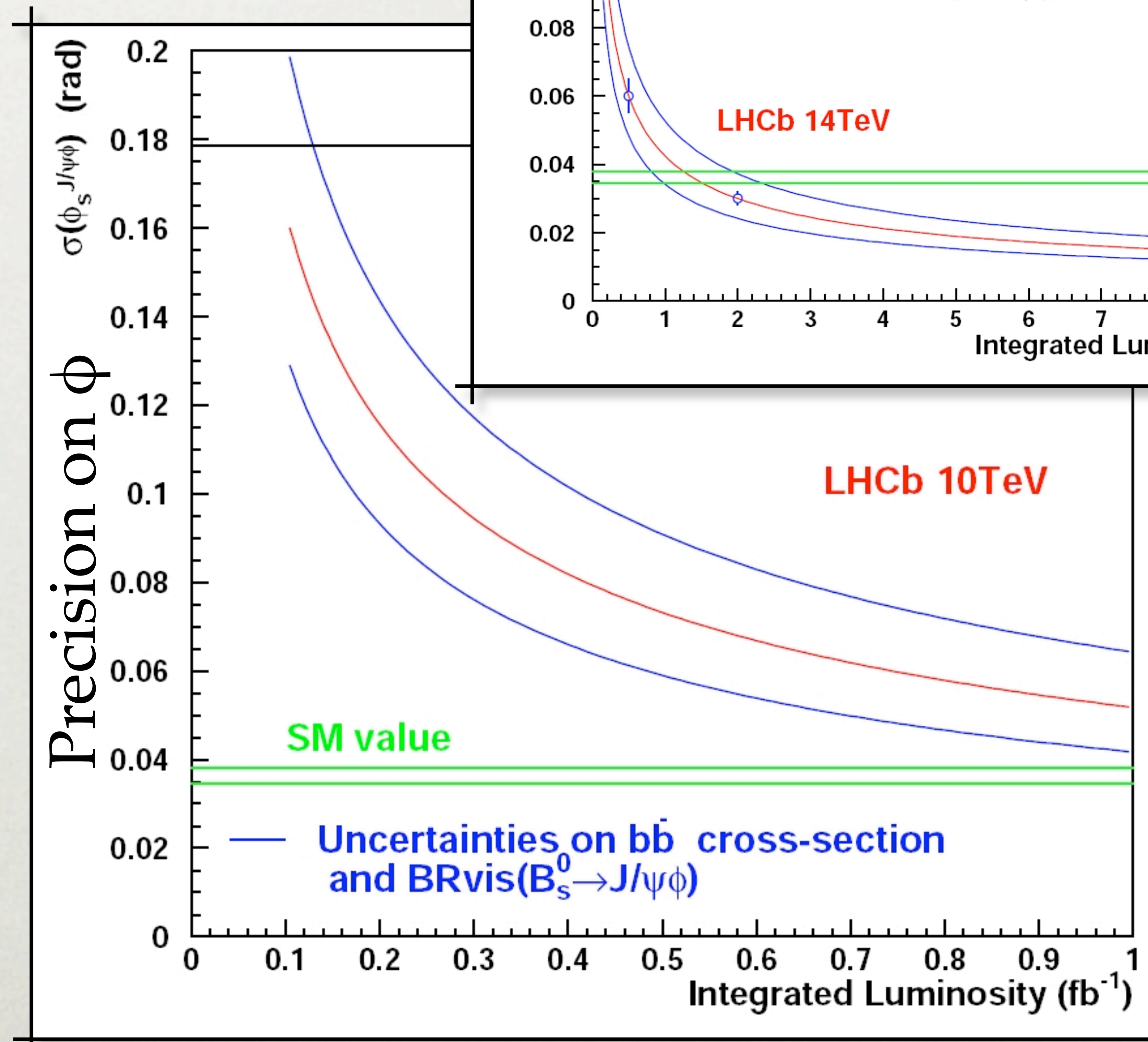
- $\phi_s = 0.04$ (SM)

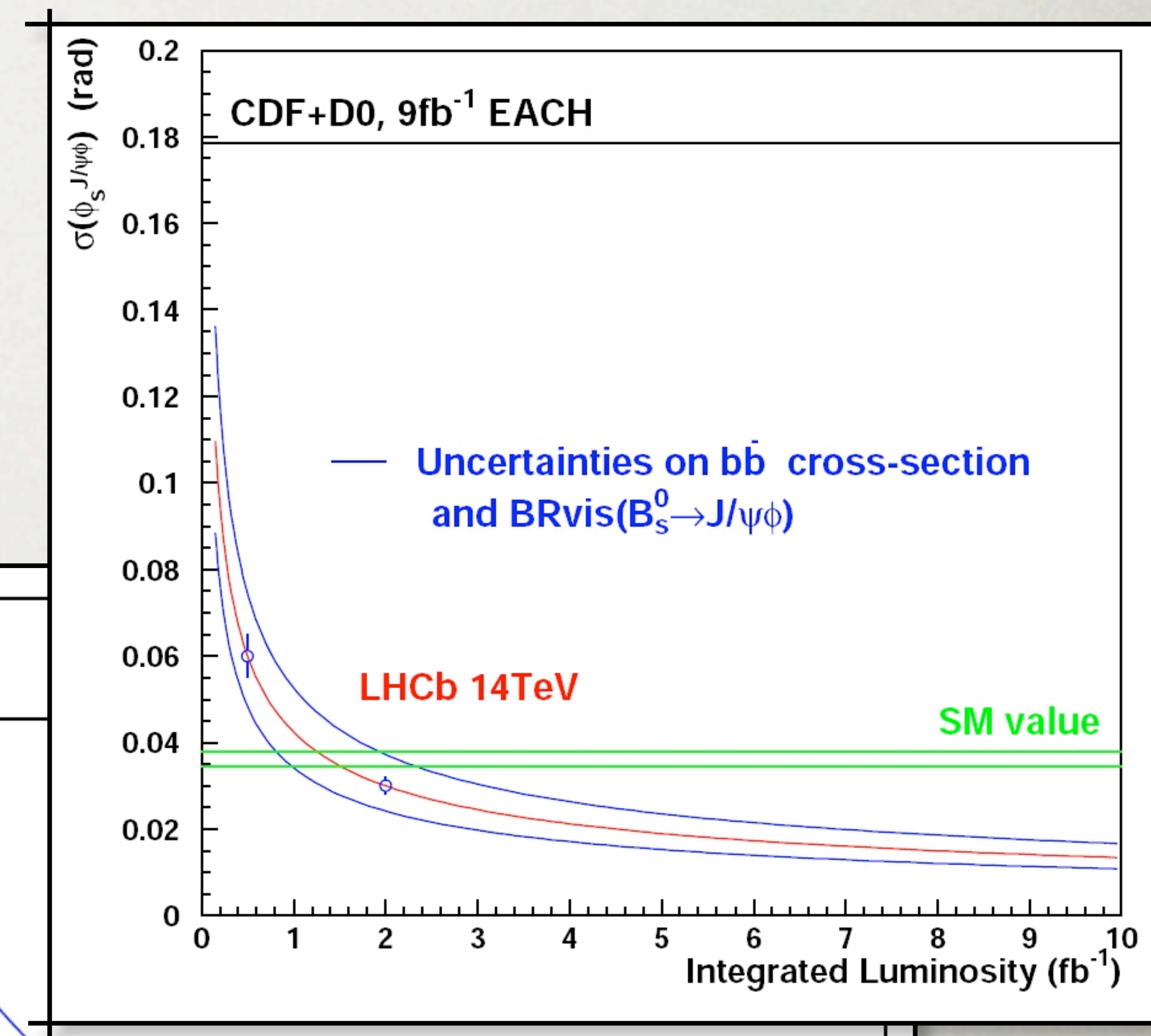


Status and prospect for $B_s \to J/\psi\,\phi$

- The CDF and D0 data shows an interesting, but not significant deviation from the SM in the same direction
- Imagine the Tevatron central value is 'correct', then LHCb will measure 5σ deviation from the SM in 2010

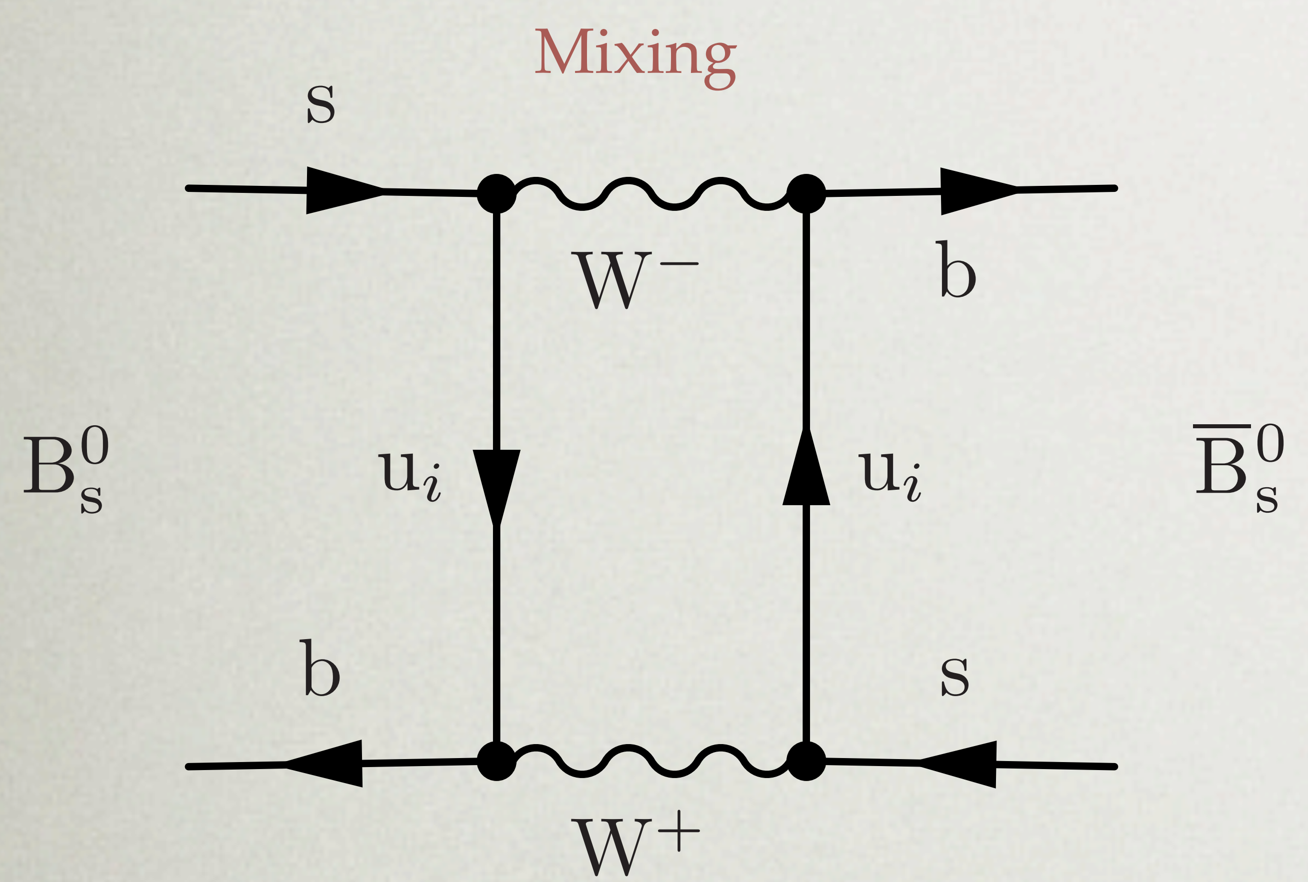


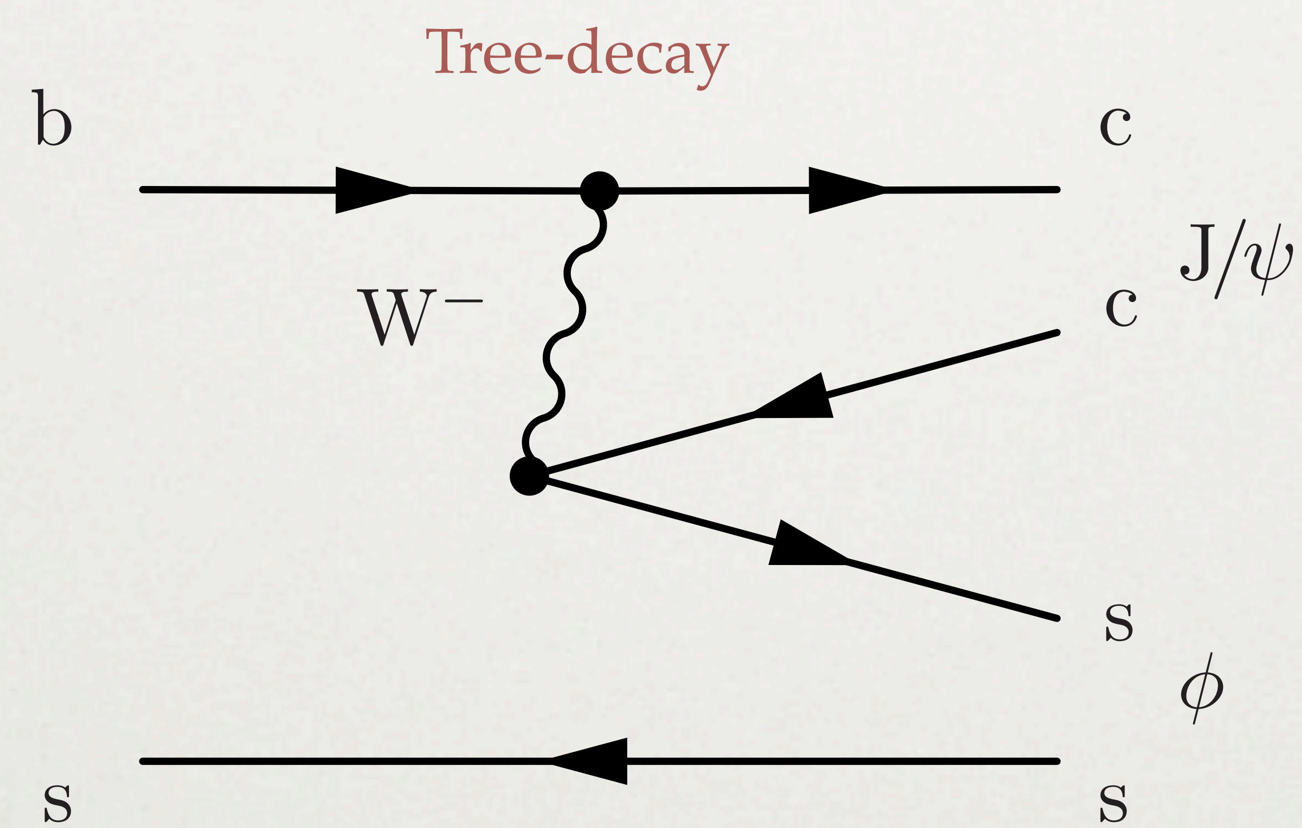


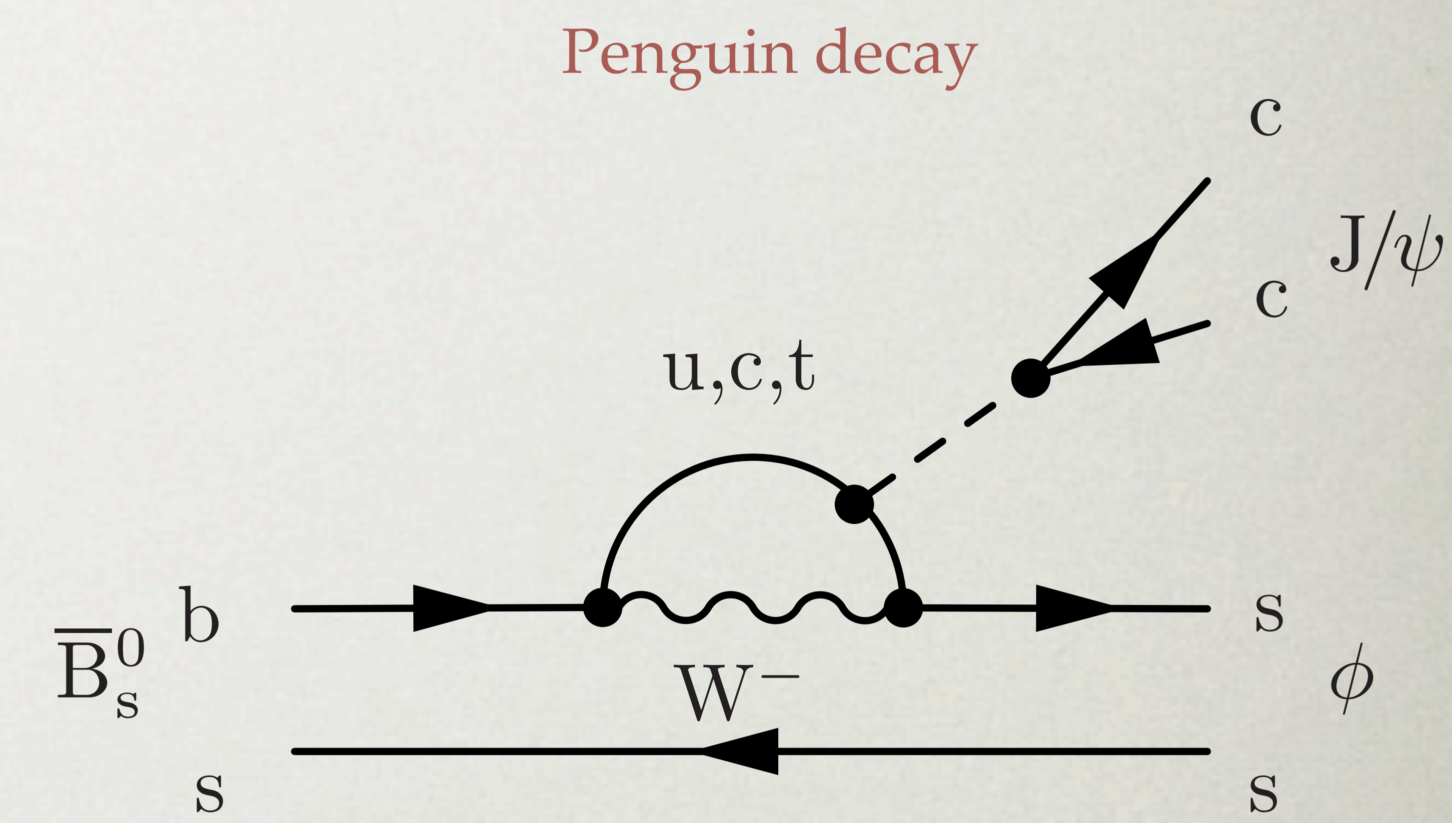


Penguin pollution ?

- $B_s \to J/\psi\ \phi$ is one of the flagship LHCb analyses but penguin pollution may become an issue if the ϕ_s is around the SM expectation







$$A(\overline{b} \to \overline{c}c\overline{s}) = V_{cs}V^*_{cb}(A_{Tree} + P_c) + V_{us}V^*_{ub}P_u + V_{ts}V^*_{tb}P_t$$

$$= V_{cs}V^*_{cb}(A_{Tree} + P_c - P_t) + V_{us}V^*_{ub}(P_u - P_t)$$

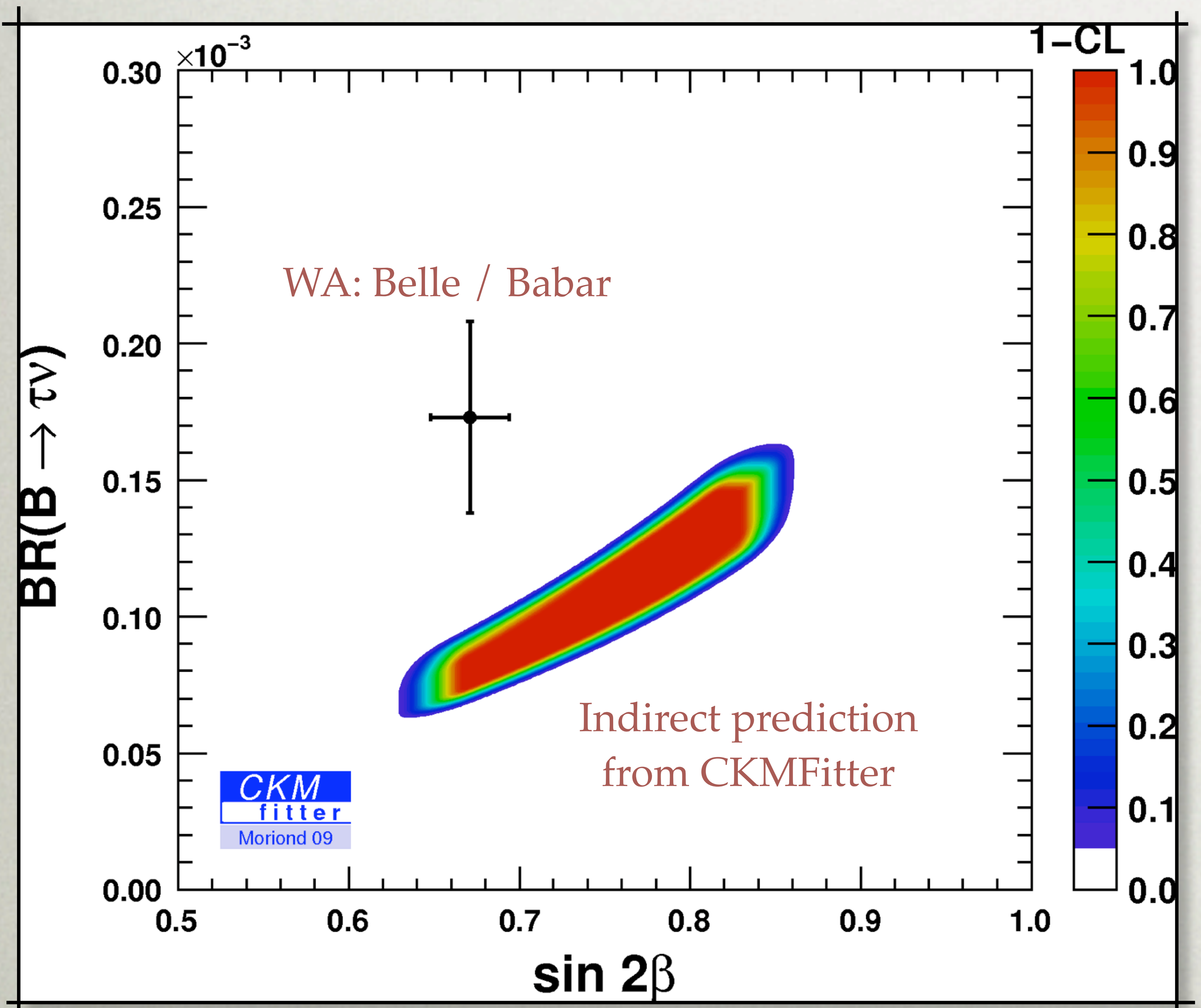
$$V_{ts}V^*_{tb} = -V_{cs}V^*_{cb} - V_{us}V^*_{ub}$$

$\propto A\lambda^2(1-\lambda^2/2)$ $\quad\quad$ $\propto A\lambda^4(\rho + i\eta)$

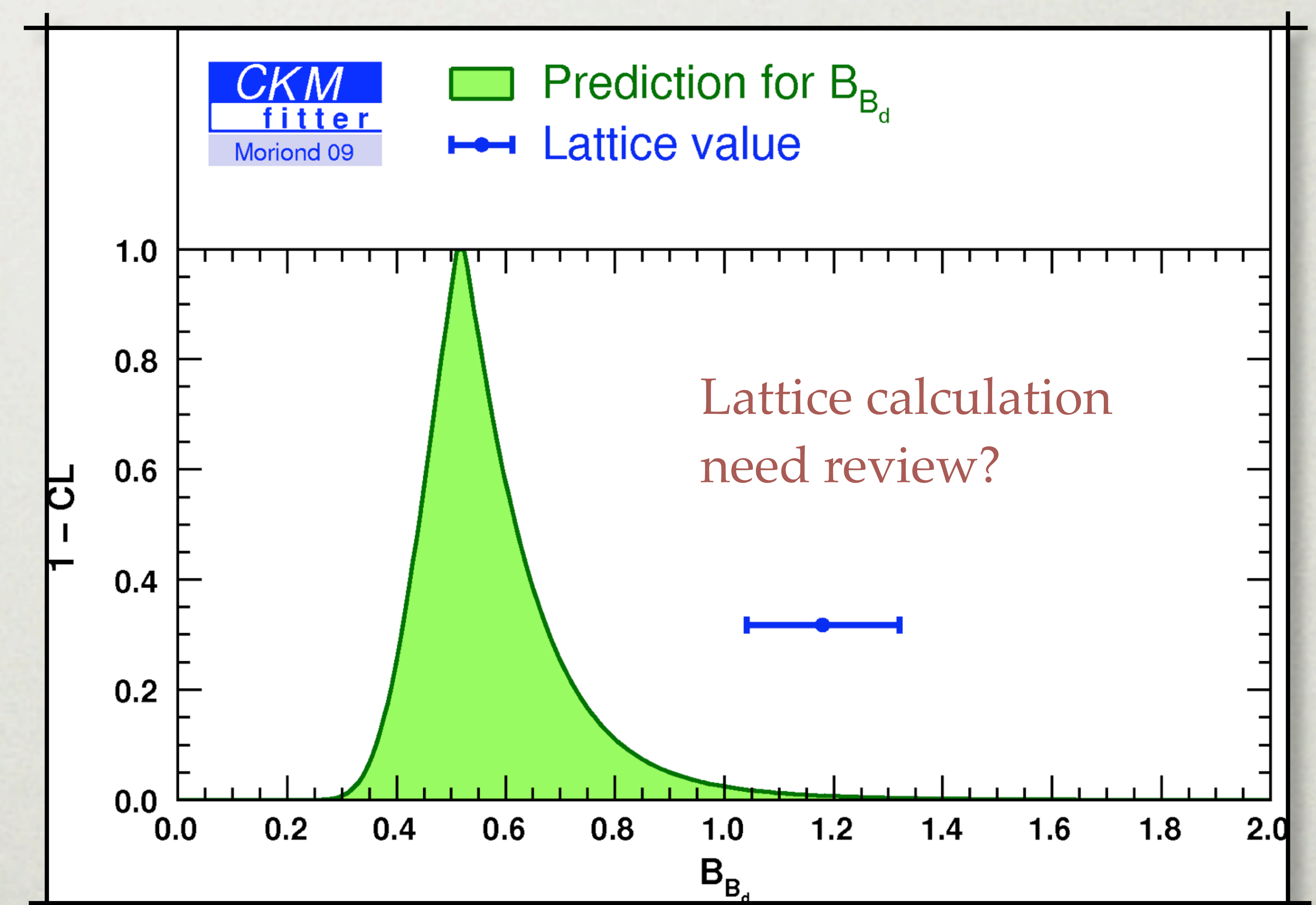
- Improved estimate of the penguin amplitude is highly desirable
  - Current estimates range from 10^{-3} hep-ph/0812.4796 to 0.1 hep-ph/0810.4248

$B^+ \to \tau^+ \nu$

- Not really an LHCb topic, but interesting enough to be worth mentioning
- 2.4σ discrepancy appearing between $\mathcal{B}(B^+ \to \tau^+ \nu)$ and sin2β. Illuminated here by *CKMFitter*
- When combined with Δm_d, $\mathcal{B}(B^+ \to \tau^+ \nu)$ is dependent on just one lattice parameter, B_{Bd}:

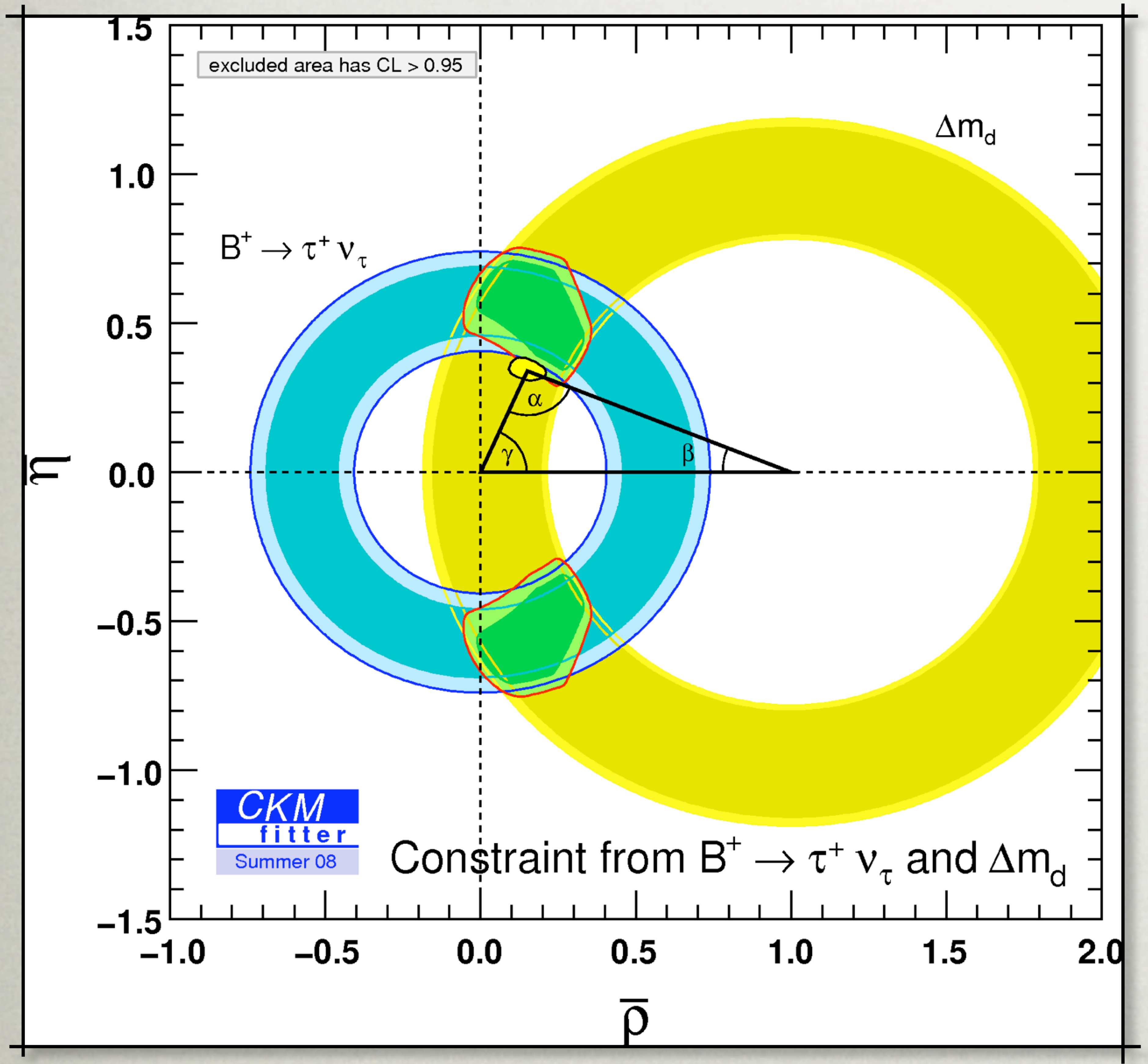


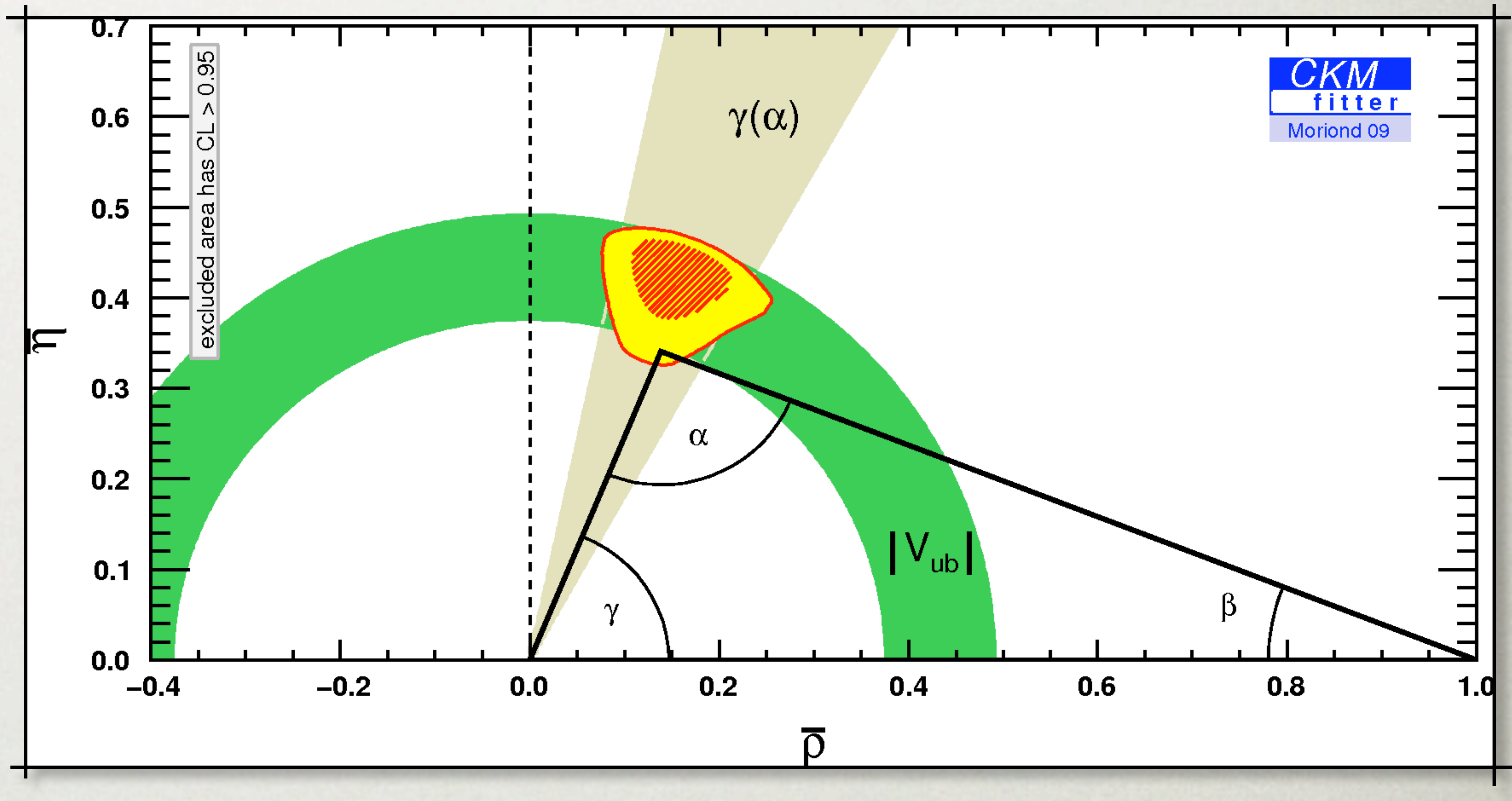
$$\frac{\mathcal{B}(\mathrm{B} \to \tau\nu)}{\Delta \mathrm{m_d}} = \frac{3\pi}{4} \frac{m_\tau^2 \tau_B}{m_\mathrm{W}^2 \eta_\mathrm{B} S[x_t]} \left(1 - \frac{m_\tau^2}{m_\mathrm{B}^2}\right)^2 \frac{\sin^2\beta}{\sin^2\gamma} \frac{1}{|V_\mathrm{ud}|^2 B_{\mathrm{B}_d}}$$



$B^+ \to \tau^+ \nu$ result in the ρ-η plane

- Intriguing movement away from the global-fit ρ-η apex (which includes observables containing loops) with both $\mathcal{B}(B^+ \to \tau^+ \nu)$ and tree-level measurements (notably $|V_{ub}|$)

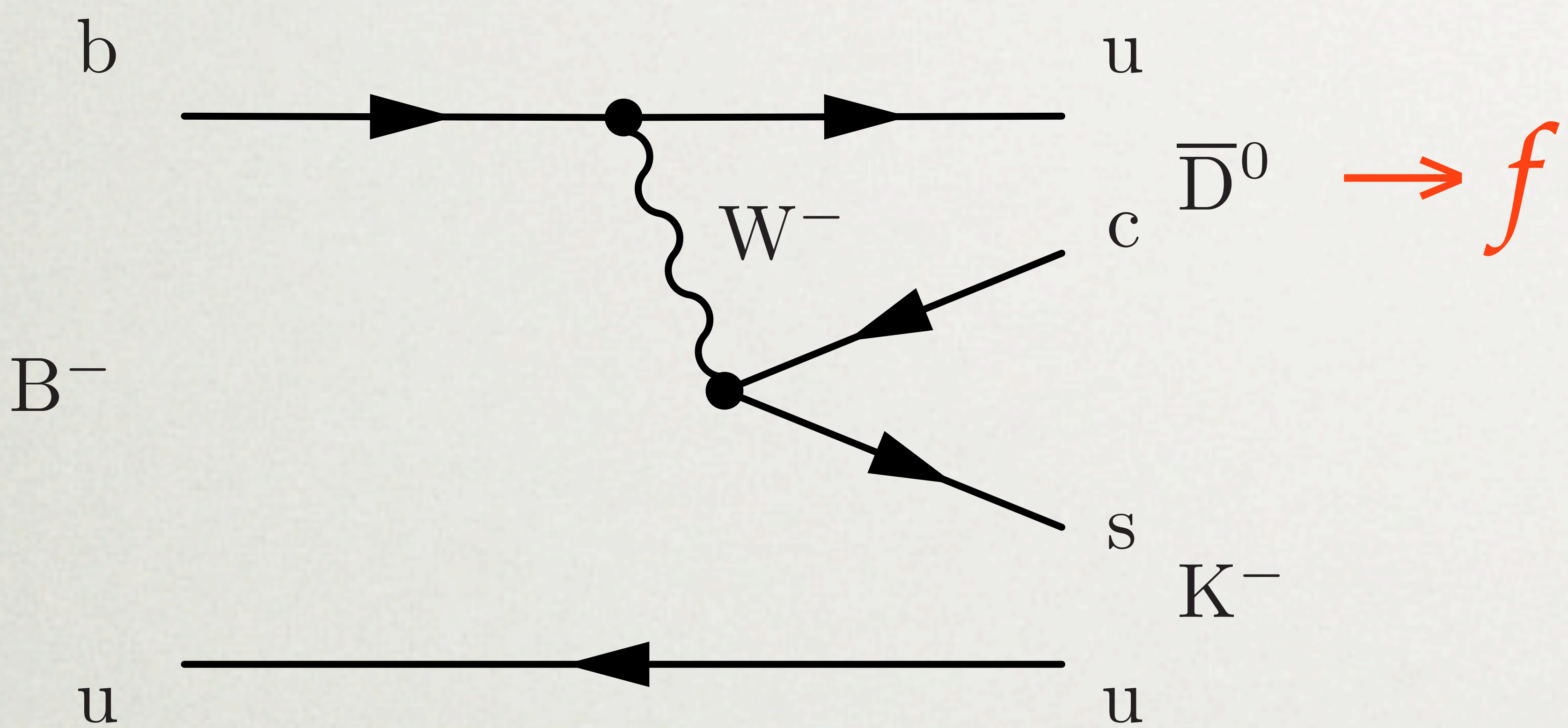


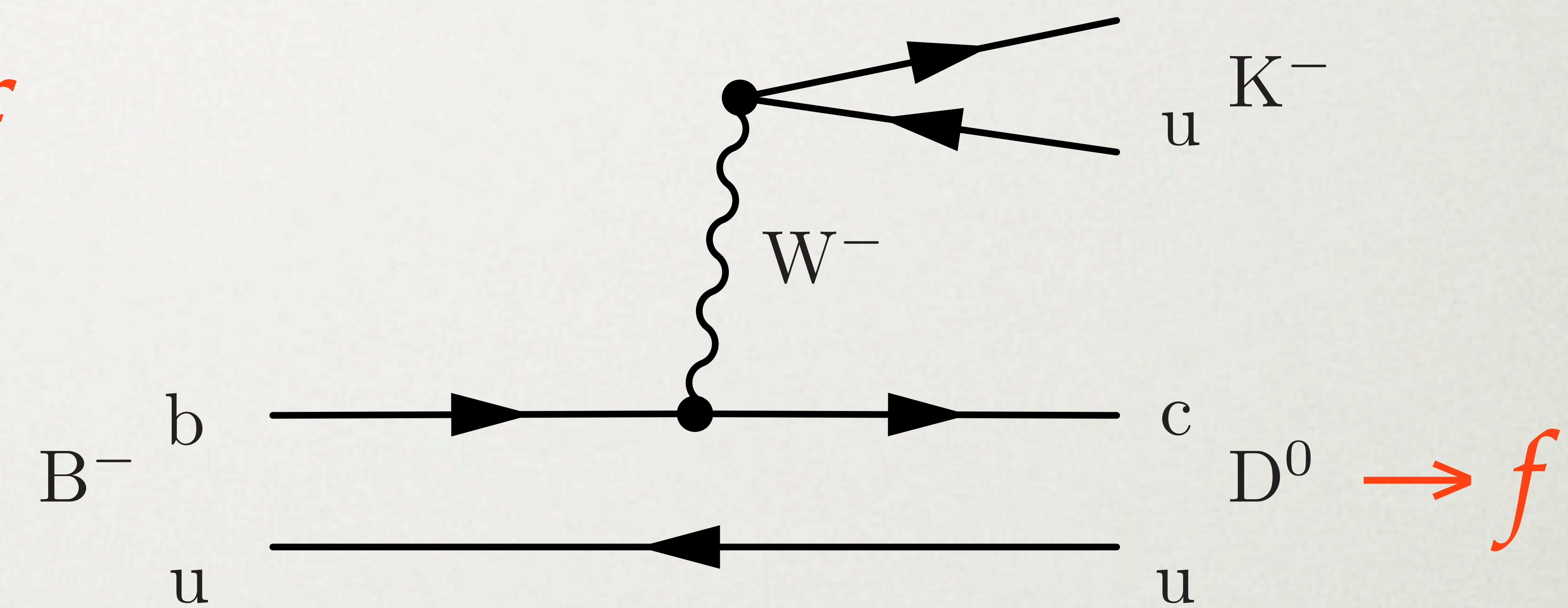


- The examination of CKM metrology using tree-level processes is becoming increasingly important. LHCb will help tackle this with the world's most precise, tree-level γ measurement in 2010...

γ_{CKM}

- Tree-level (no penguin, theoretically clean) measure of the Standard Model, CKM phase





where *f* can be:

CP eigenstate

- K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$, $K_S\phi$, $K_S\omega$ ...

DCS flavour eigenstate

- $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$ ...

SCS self-conjugate state

- $K_S\,\pi^+\pi^-\pi^0$, $K_S\,K^+K^-$, $\pi^+\pi^-\pi^0$ ...

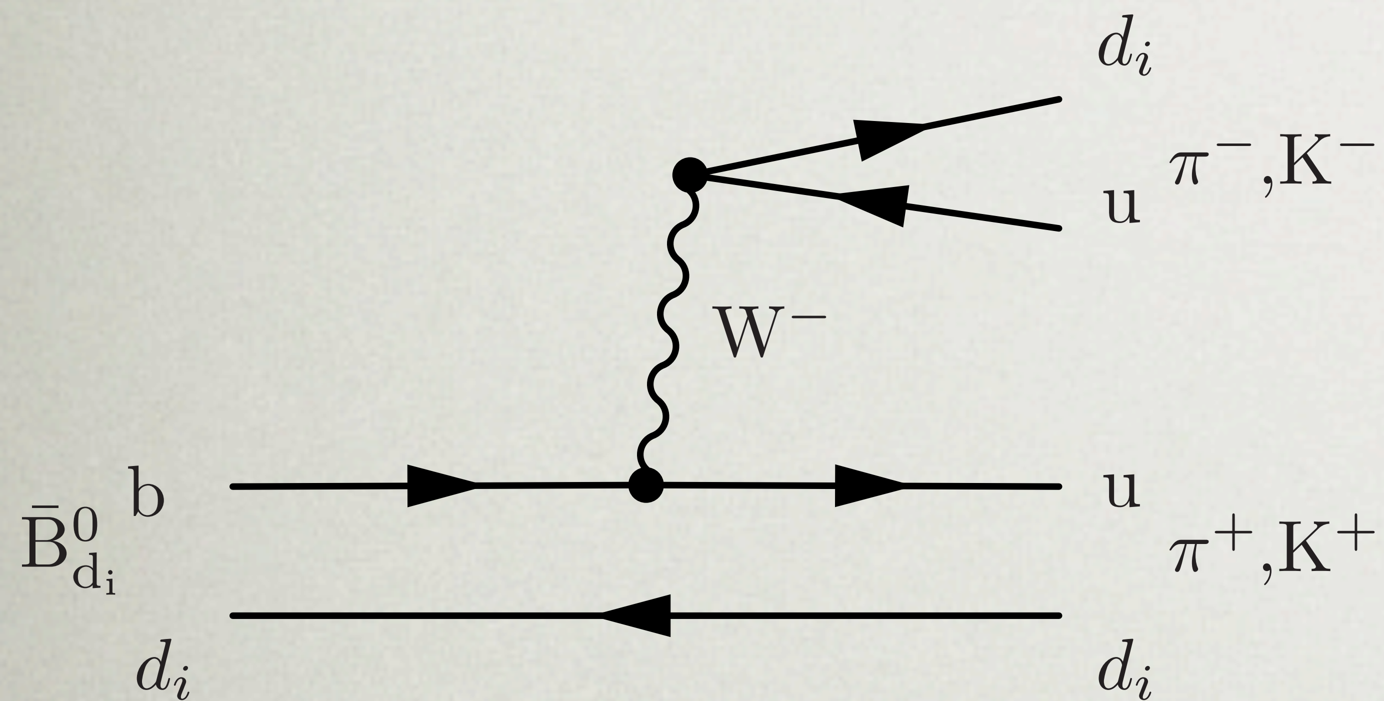
- Also works for: $B^\pm \rightarrow D^*K^\pm$, $B^\pm \rightarrow D^0K^{*\pm}$, $B^0 \rightarrow D^0K^{*0}$ and $B \rightarrow D^0K\pi$
- Small BF, but lot of correlated information!

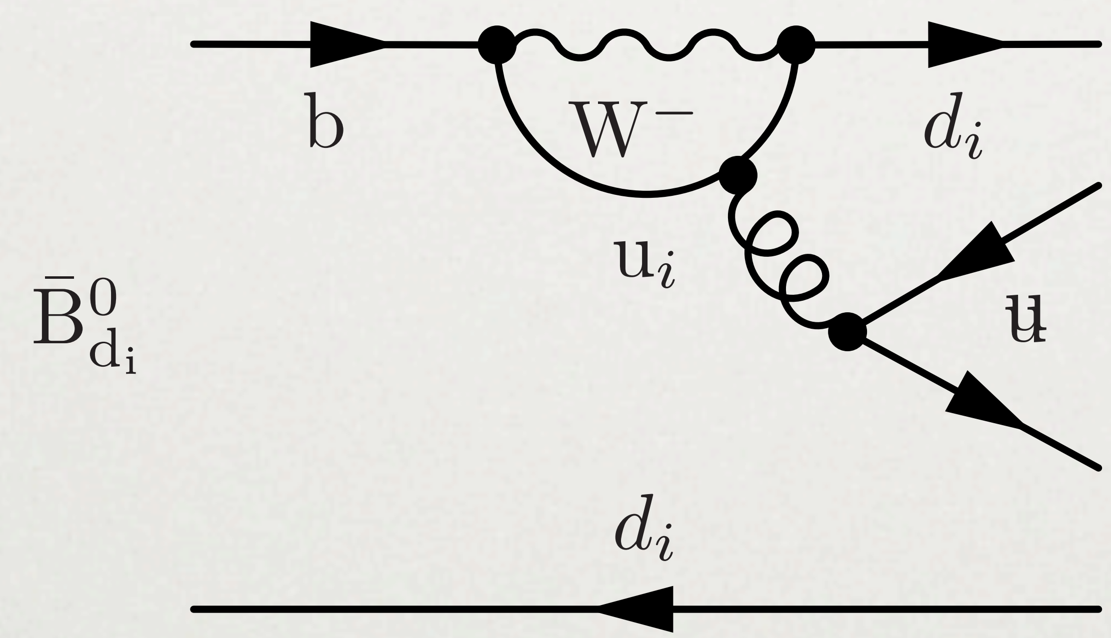
- Current world average is $\gamma = 70^{+27}_{-29}{}^\circ$
  - relative strong phase, $\delta_B = 110^{+22}_{-27}{}^\circ$
- LHCb expected precision by end 2011:

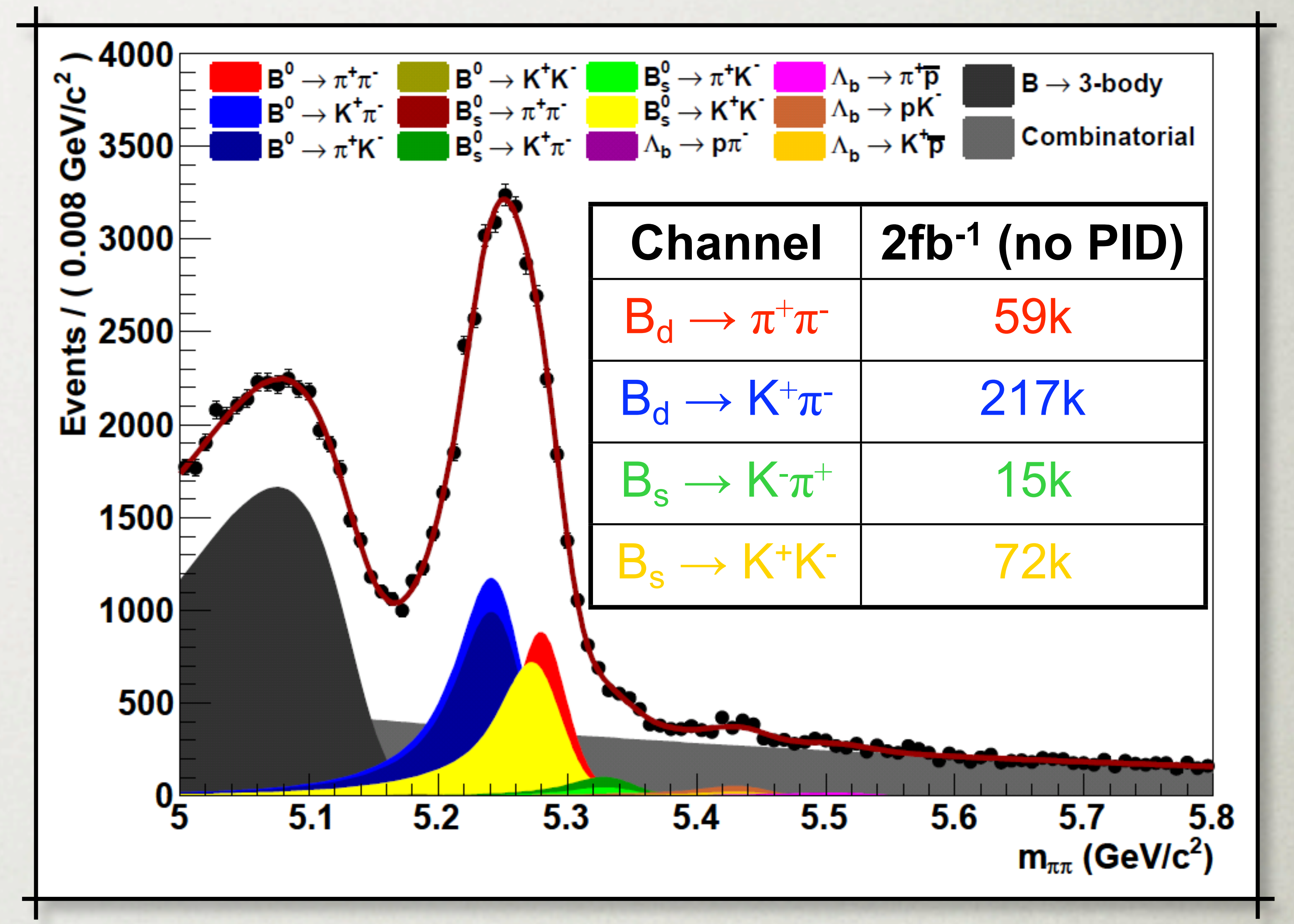
δ_{B^0} (°)	0	45	90	135	180
σ_γ for 0.5 fb^{-1} (°)	8.1	10.1	9.3	9.5	7.8
σ_γ for 2 fb^{-1} (°)	4.1	5.1	4.8	5.1	3.9

Loop-mediated γ measurements

- With a "standard candle" measurement in-hand, other modes that are sensitive γ can be used as a probe of new-physics
  - $B_S \to D_S K$, $B \to K\pi\pi$ and ... $B^0 \to h^+h^-$







- Analysis of $B^0 \to h^+h^-$ requires measuring four TD asymmetries depend on 7 physics parameters

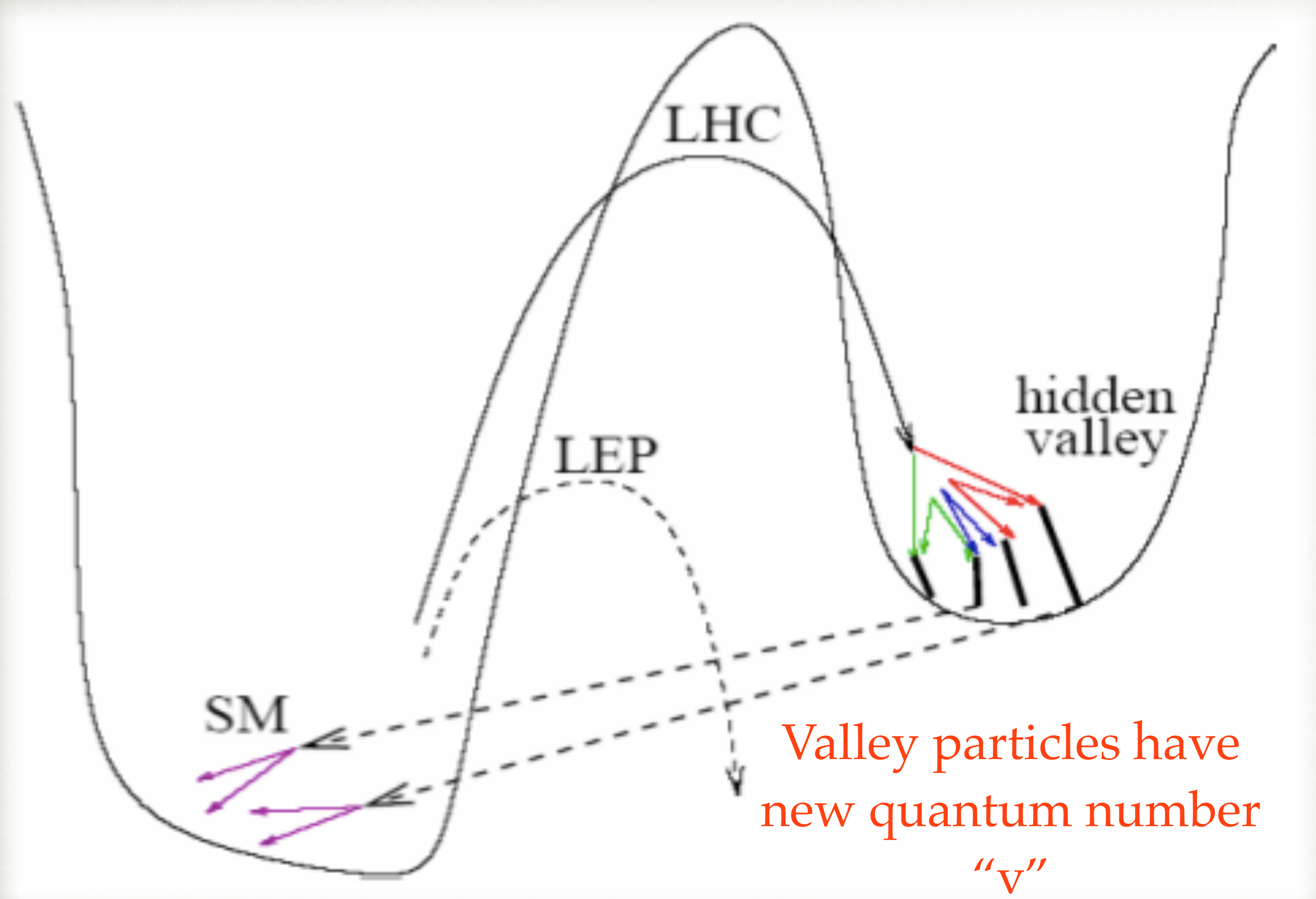
$$\frac{\Gamma(B_q \to f) - \Gamma(\overline{B}_q \to f)}{\Gamma(B_q \to f) + \Gamma(\overline{B}_q \to f)} = \frac{A^{dir}_{CP}\cos(\Delta m_q t) - A^{mix}_{CP}\sin(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) - A_{\Delta\Gamma_q}\sinh(\Delta\Gamma_q t/2)}$$

- Takes the penguin contribution in its stride by assuming U-Spin (d<->s) symmetry !
- With ϕ_d from $J/\psi K_S$ system is solvable

- Mass and PID likelihoods separate modes.
- Extraction of γ allows for U-spin breaking at the 20% level. Is this theoretically realistic?
- With 2fb^{-1}, find $\sigma(\gamma) = 7°$, $\sigma(\phi_s) = 0.05$ rad

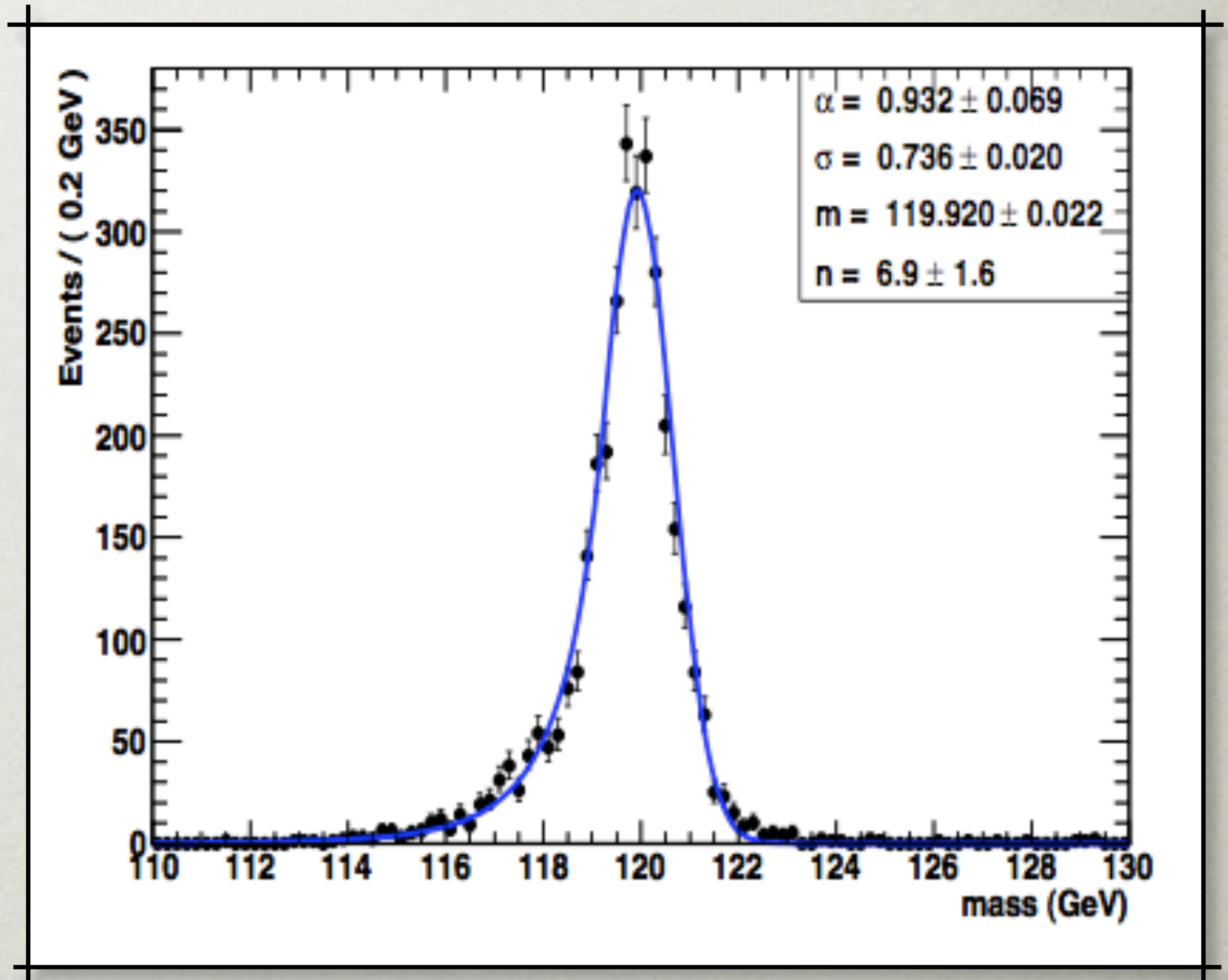
Other ideas...

- Lepton flavour violation:
  - LFV is a reality as neutrinos oscillate ... LFV with charged leptons implies new physics
  - LHCb is now mounting a serious effort for the most targetable ($\tau \to \mu\mu\mu$, $\tau \to V^0\mu$ ...)
  - Discovery of BF < 10^{-9} conceivable - theoretical motivation certainly useful
- Hidden valley - some neutral "v"-hadrons can decay into SM particles after a non-zero lifetime

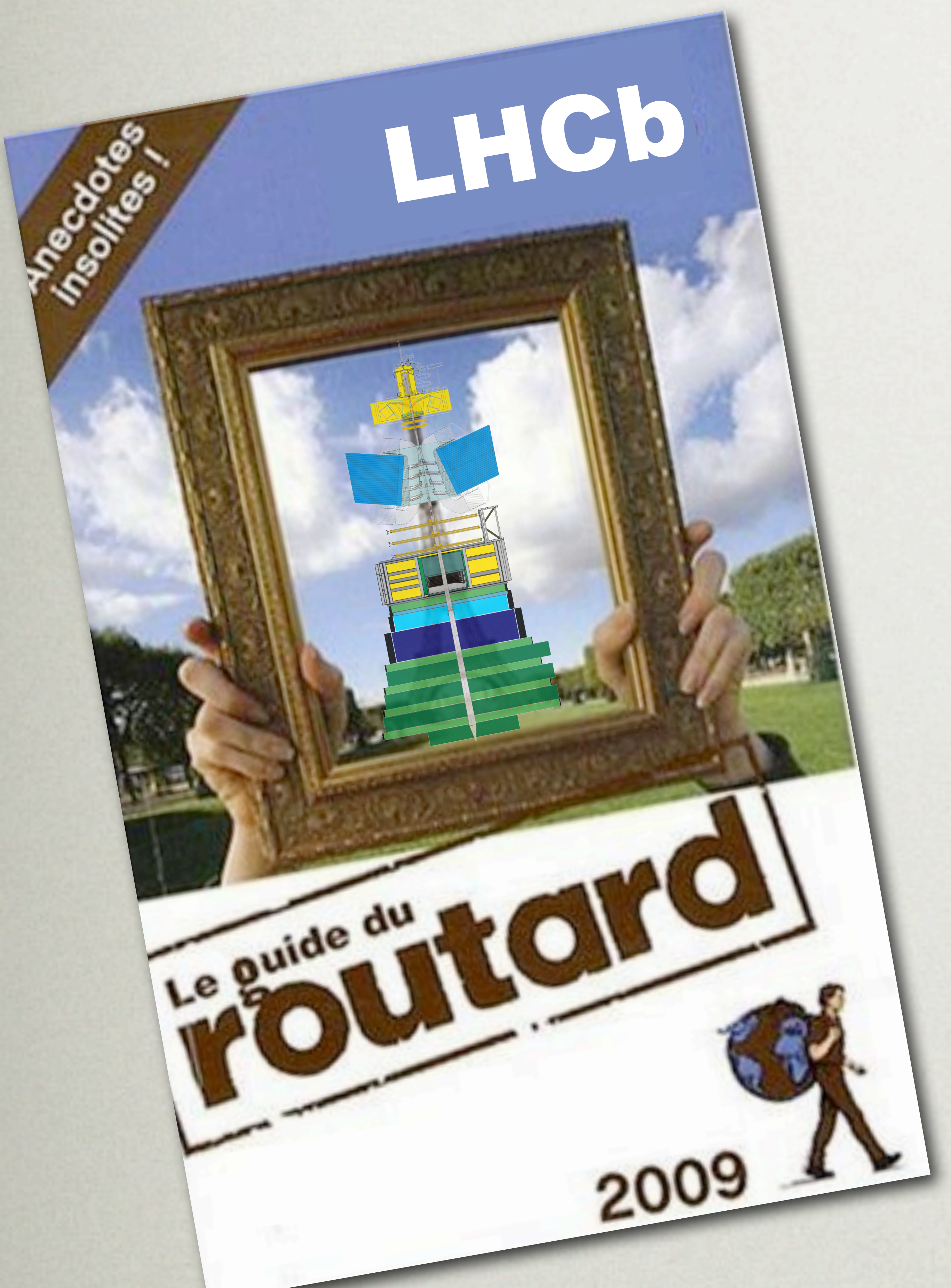


- Studied Higgs decay:

  $H \to \rho_v \rho_v \to \mu\mu\mu\mu$ with M_H=120GeV, $M\rho_v$=35GeV, $\tau\rho_v$=10 ps
- tot. efficiency = 2.2%
- trigger selection is 'work in progress'



Precision flavour physics is an exciting part of the LHC programme



- Several mature analyses legitimately vying to be the first place that new physics is observed; many areas where theory input helps!

And new ideas are always welcome!

- $B^{\pm}$, B^0, B_s, B_c,Λ_b,D_s,$D^{\pm}$,D^0,B^*,η_b ... Time-dependence: no problem!
- BFs down to 10^{-9} [hadronic], 10^{-10} [muonic] are conceivable
- Heavy, quasi-stable [BSM] particles would have clear signature
- Electroweak & heavy-quark production anomalies at high eta
- Lepton flavour violating [tau] decays look possible
- Muon or kaon decays easiest, K_S possible, as are π^0 and γs
- But decays with neutrinos or missing energy searches won't work

Ce qui se passe en France

- LAPP, Annecy (contact: Bolek Pietrzyk)
  - Participation à « CKMfitter »
  - Mesure de la phase du mélange du méson B_s, β_s, dans le canal $B_s \rightarrow J/\Psi\ \eta$
- LPNHE Paris (contact: Maurice Benayoun)
  - Violation directe de CP dans $B^\pm \rightarrow \pi^+\pi^- K^\pm$
    - en particulier par les interférences des $\rho(770)$, $\omega(782)$ et $f_2(1270)$
  - Détermination de l'angle γ du triangle d'unitarité
  - Violation directe de CP dans le canal $B^\pm \rightarrow \eta'(\pi^+\pi^-\ \gamma)\ K^\pm$
- CPPM Marseille (contact: Renaud Le Gac)
  - Mesure de β_s dans $Bs \rightarrow J/\Psi\phi$
  - Désintégrations rares : BR ($B_s \rightarrow \mu\mu$) Mesure de β_s dans $B_s \rightarrow J/\Psi\phi$
  - Désintégrations rares : BR ($B_s \rightarrow \mu\mu$)
- LPC Clermont (contact: Pascal Perret)
  - $\Lambda_b \rightarrow \Lambda$+méson-vecteur (violation de T): $\Lambda_b \rightarrow \Lambda\ (p\pi^-)\ J/\psi\ (\mu^+\mu^-\{\gamma\})$ + mesure du temps de vie du Λ_b
  - Mesure de Δm_s avec $B_s \rightarrow D_s\ \rho$
  - Mesure de α avec $B_d \rightarrow \rho\ \pi$
  - Mesure de γ avec $B_s \rightarrow K^*\ \pi$
  - Participation à « CKMfitter »
- LAL Orsay (contact: Marie-Hélène Schune)
  - Etude des mode $B_s \rightarrow D_s\ \rho(\pi\pi^0)$ et $B \rightarrow D\rho(\pi\pi^0)$
  - Physique du B_c et mesure de la section efficace bb
  - Recherche de nouvelle physique avec $B_d \rightarrow K^*e^+e^-$
  - Mesure de γ avec $B^0 \rightarrow D^0K^*$
  - Physique du charme, (violation de CP avec D0→ KKππ et désintégrations radiatives)