S. Stone

LHCb Highlights & Upgrade

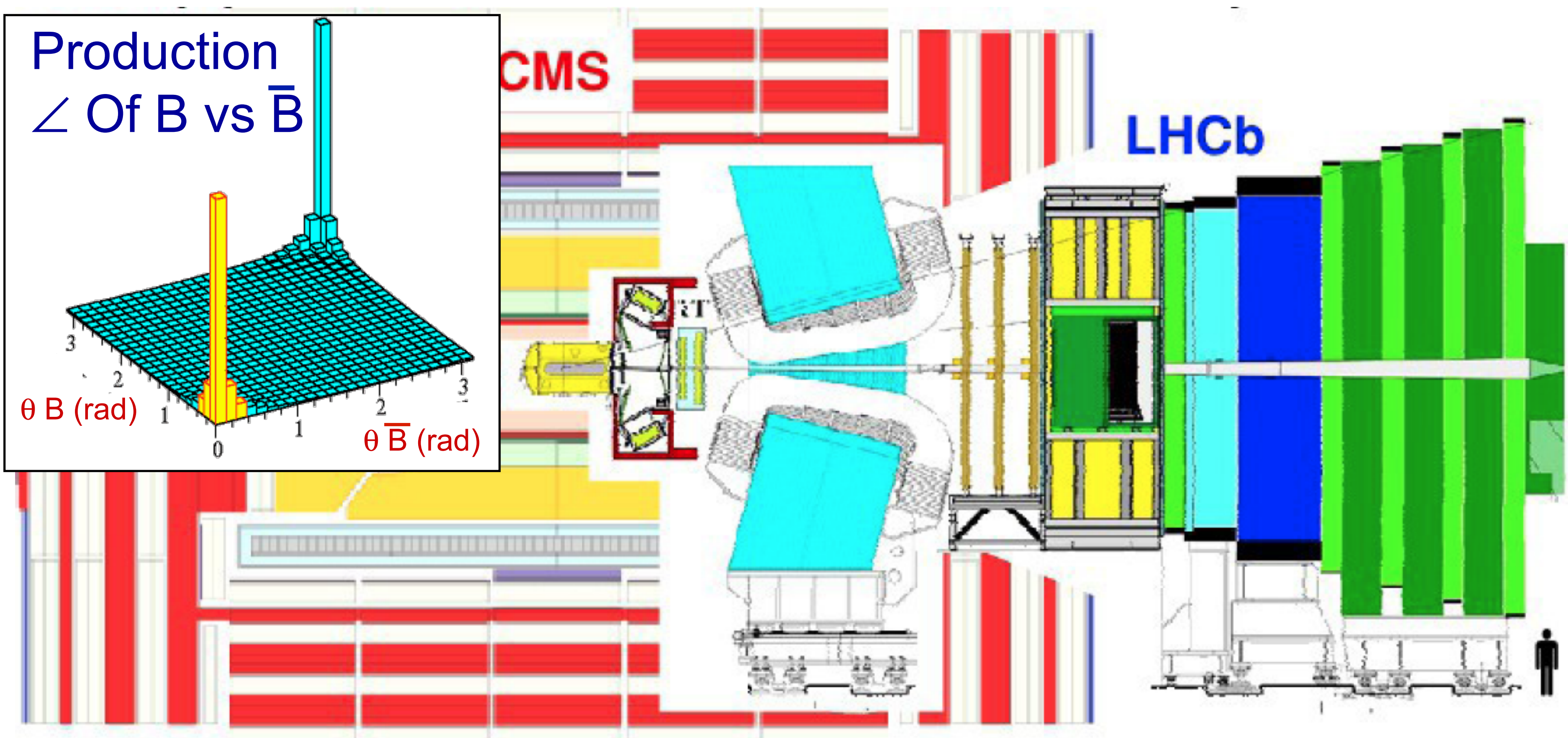
USLUO, Nov. 7, 2013

The LHCb Collaboration

- 667 Authors
- 62 Institutes
- 16 Countries
- 4 Groups from USA:
  Cincinnati, Maryland,
  MIT, Syracuse

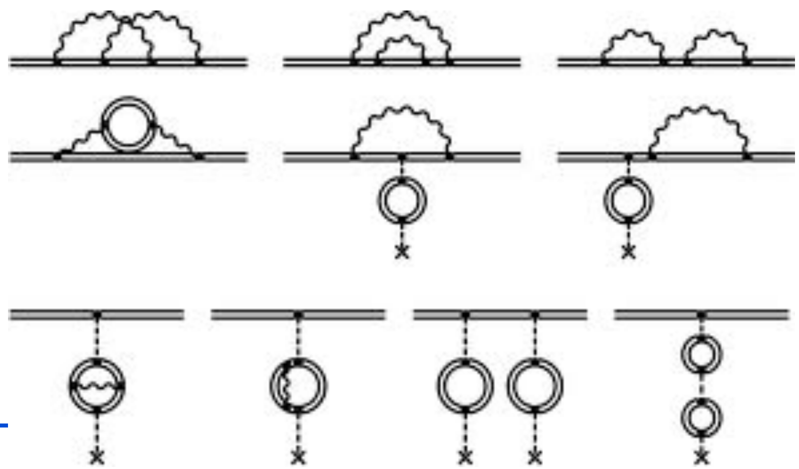
The LHCb Detector

- Complementary to ATLAS & CMS
- Built to exploit correlated $b\bar{b}$ production



Seeking New Physics

- HFP as a tool for NP discovery
  - While measurements of fundamental constants are fun, the main purpose of HFP is to find and/or define the properties of physics beyond the SM
  - HFP probes large mass scales via virtual quantum loops. An example, of the importance of such loops is the Lamb shift in atomic hydrogen
  - A small difference in energy between $2S_{1/2}$ & $2P_{1/2}$ that should be of equal energy at lowest order

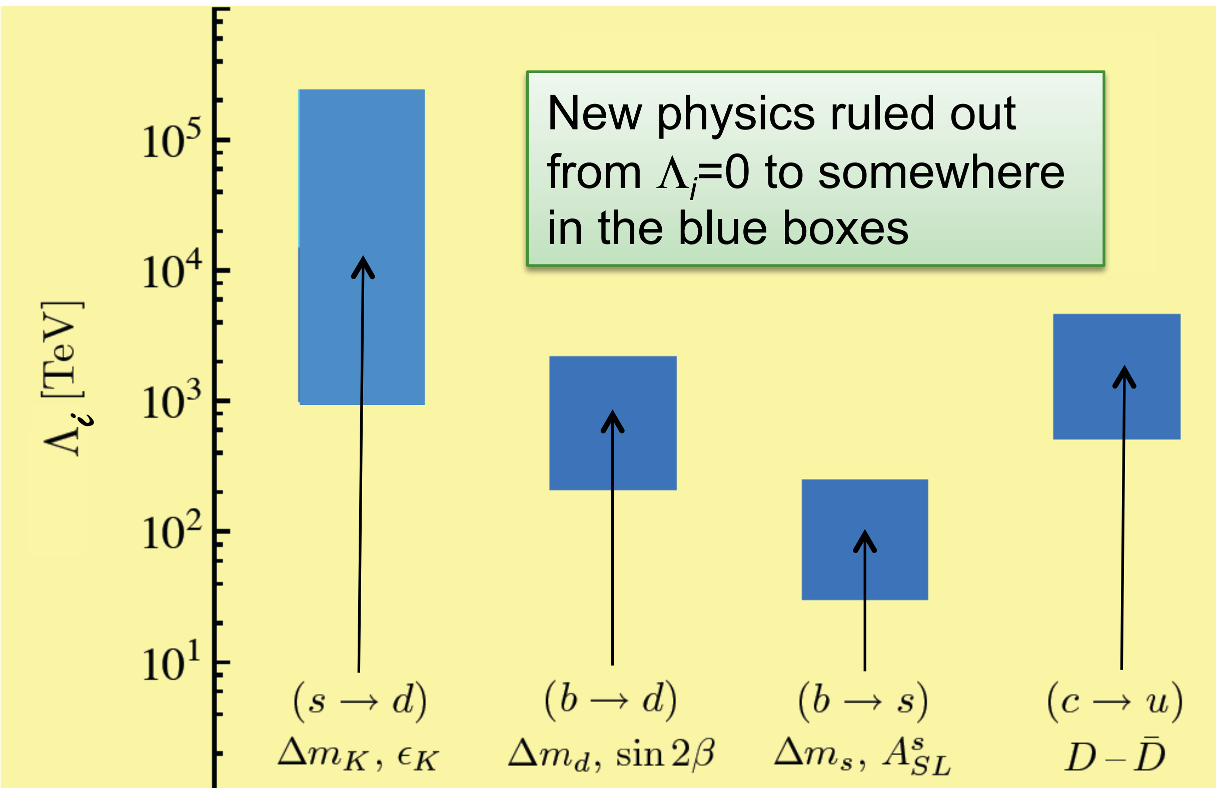


1 TeV Scale New Particles

- Naturalness
  - Higgs is most sensitive to physics of order M=125 GeV, has been pushed to ~1 TeV due to absence of signals. Can be pushed higher. (Soni suggests 10 TeV for KK towers)
  - But corrections to Higgs mass go as M^2, so can't push M too high without getting into fine tuning problem (see Zupan's talk)
  - Need New Physics to cut off quantum corrections
- Suggested NP mechanisms: SUSY, Higgs compositeness, and extra dimensions. Each predicts a rich spectrum of new states

Flavor as a High Mass Probe

- Already excluded ranges if c_i~1
  - $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{c_i}{\Lambda_i^2} \mathcal{O}_i$, take c_i = 1



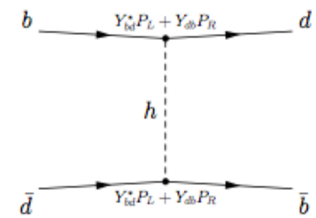
Ways out

1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

See: Isidori, Nir & Perez arXiv:1002.0900; Neubert EPS 2011 talk

Harink: Limits on NP Higgs Yukawa's

Meson Mixing



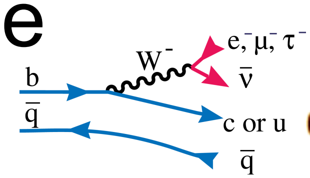
* Meson mixing's powerful:

Technique	Coupling	Constraint	$m_i m_j/v^2$
D^0 oscillations [48]	$\|Y_{uc}\|^2$, $\|Y_{cu}\|^2$	$< 5.0 \times 10^{-9}$	5×10^{-8}
	$\|Y_{uc}Y_{cu}\|$	$< 7.5 \times 10^{-10}$	
B_d^0 oscillations [48]	$\|Y_{db}\|^2$, $\|Y_{bd}\|^2$	$< 2.3 \times 10^{-8}$	3×10^{-7}
	$\|Y_{db}Y_{bd}\|$	$< 3.3 \times 10^{-9}$	
B_s^0 oscillations [48]	$\|Y_{sb}\|^2$, $\|Y_{bs}\|^2$	$< 1.8 \times 10^{-6}$	7×10^{-6}
	$\|Y_{sb}Y_{bs}\|$	$< 2.5 \times 10^{-7}$	
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$	8×10^{-9}
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$	
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$	
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$	

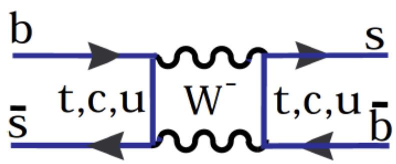
"Natural" models are constrained!

Generic Analyses

- NP via $\Delta F=2$ processes
- Compare tree (no NP) with

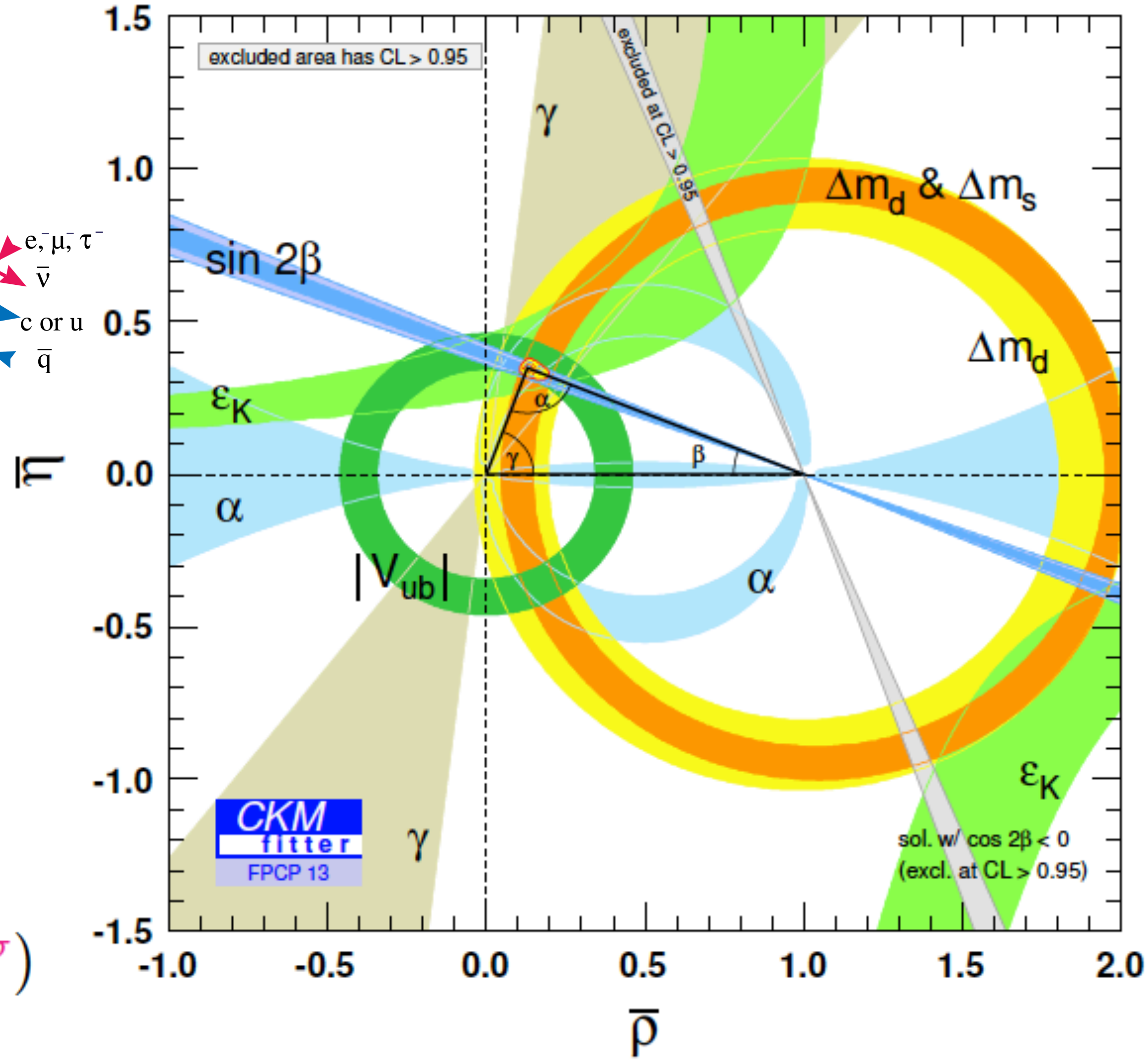


  loop processes (mixing, CP NP?)

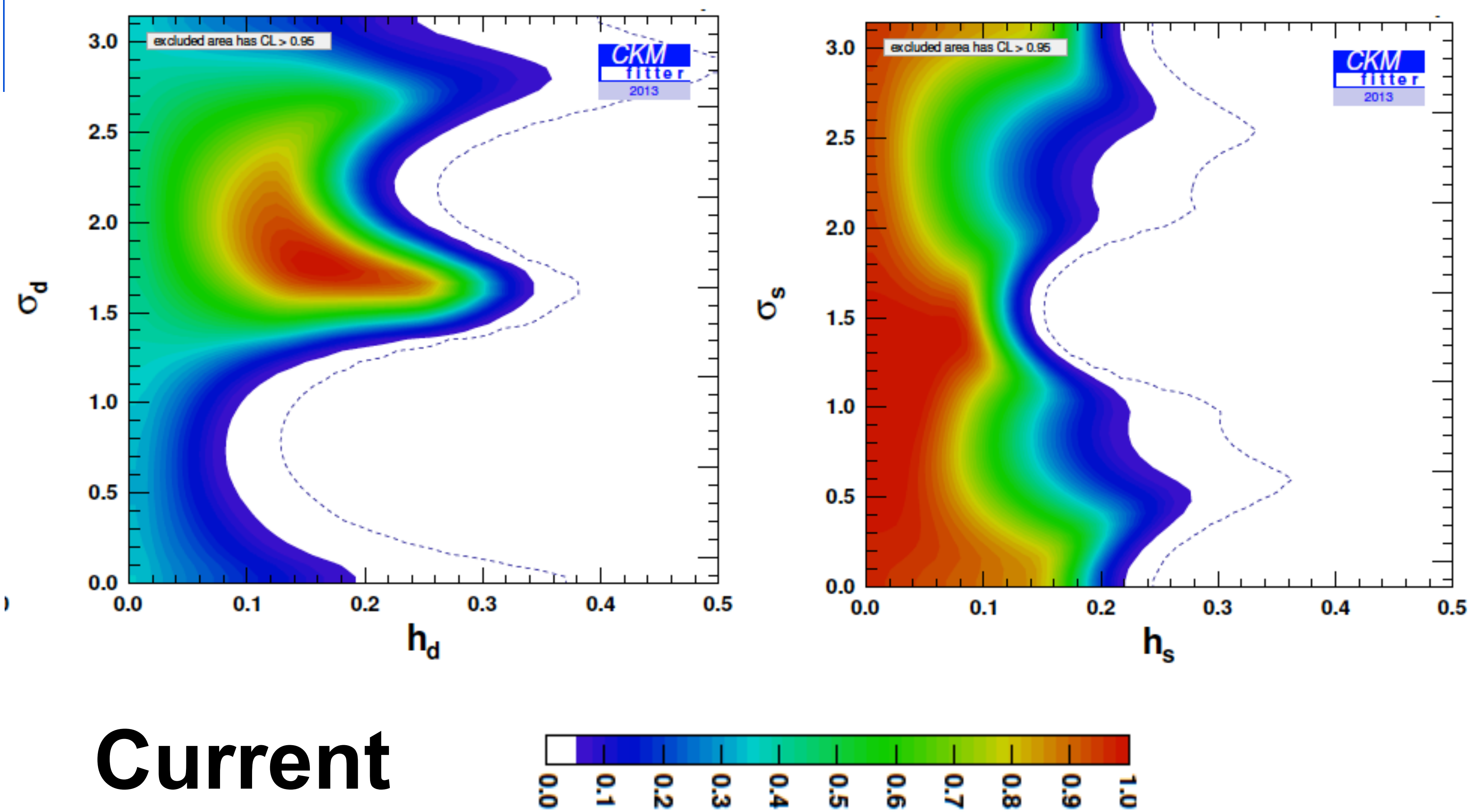


  - Parameterize NP

$$M_{12} = M_{12}^{\rm SM} \times \left(1 + h\, e^{2i\sigma}\right)$$



95% cl Limits



Current

So New Physics amplitudes ~20% are still allowed

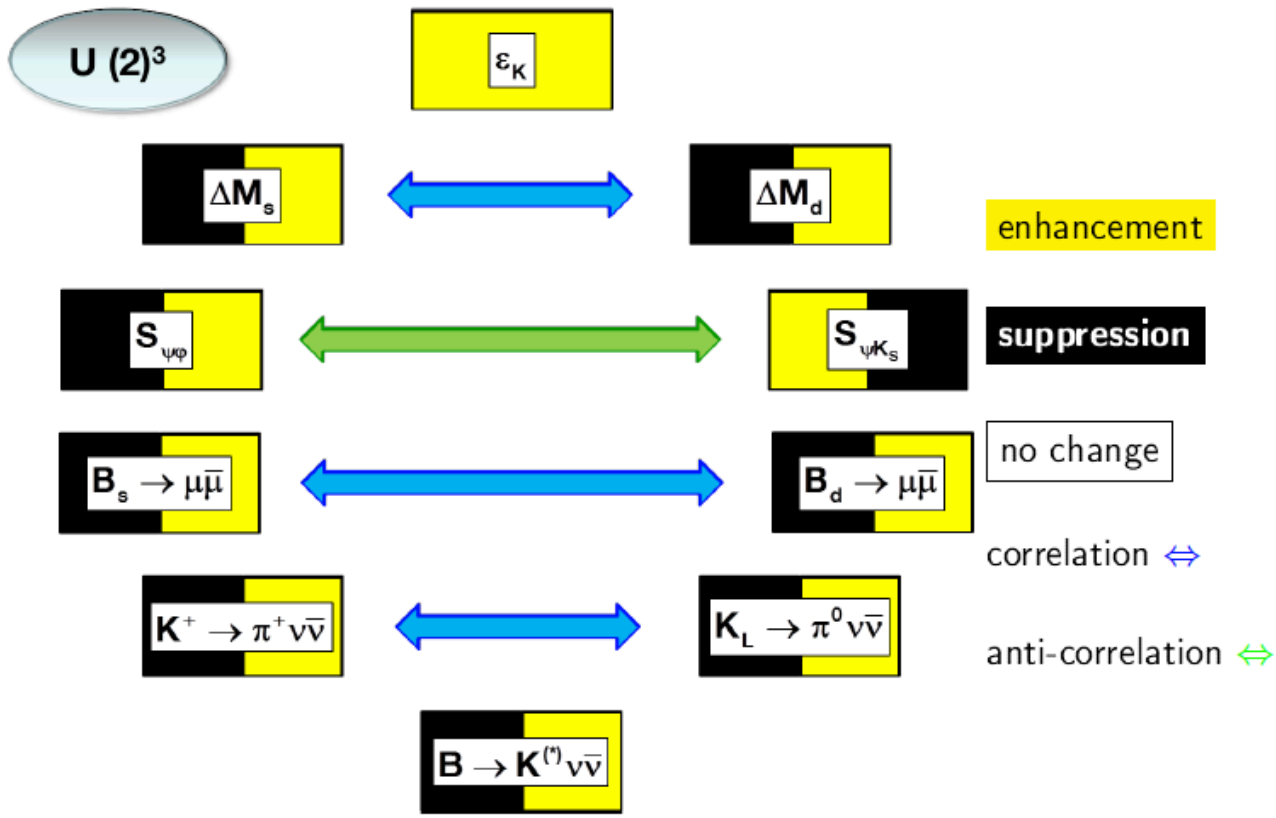
J. Charles et. al, arXiv:1309.2293

Top Down Analyses

- Here we pick a model and work out its consequences in many modes
- Example

Girrbach

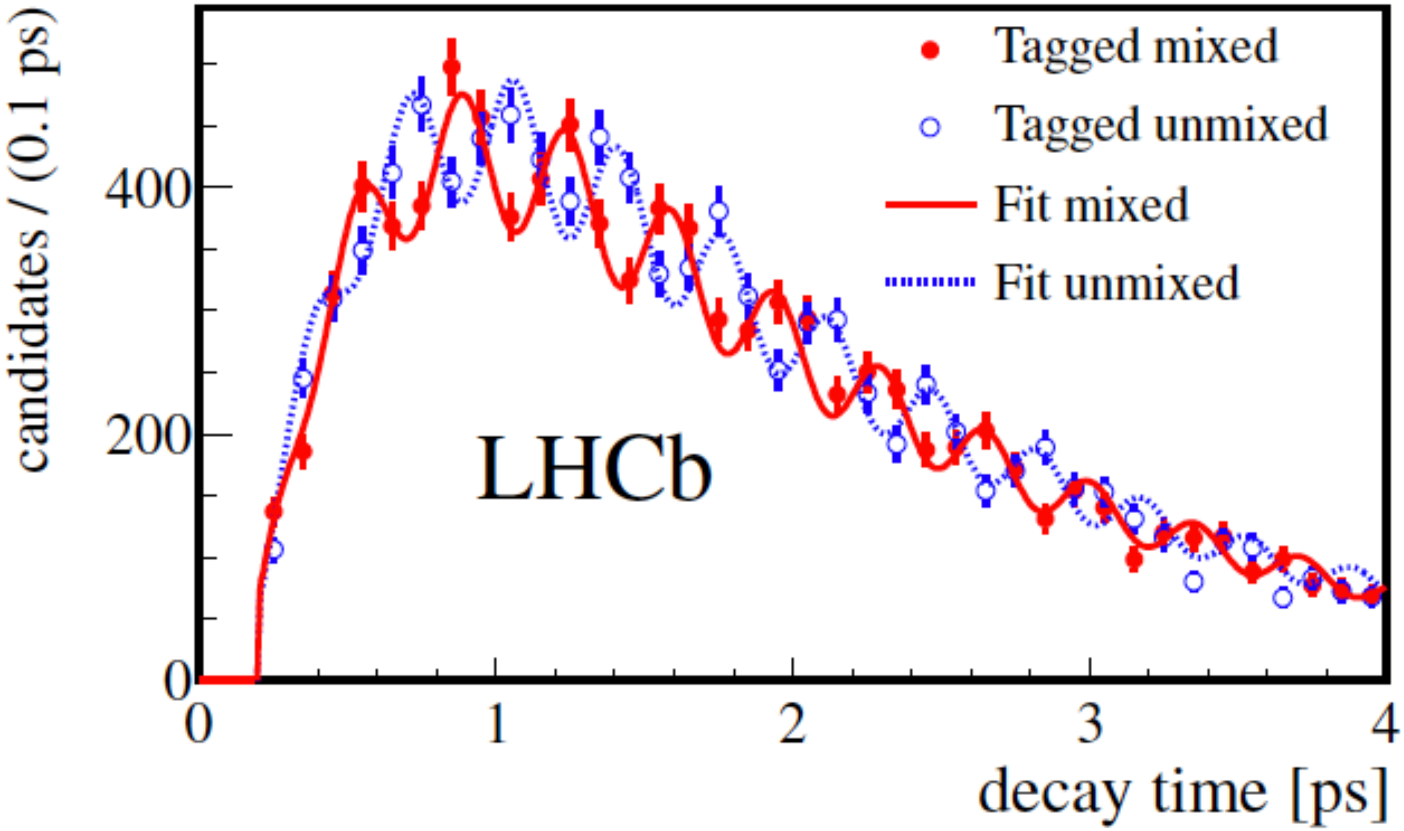
& Buras



A few b decay results

"The success of the LHCb experiment has so far been a nightmare for all flavour physicists…" Gauld, Goetz and Haisch arXiv:1310:1082

Δm_s from $B_s \to D_s^+ \pi^-$



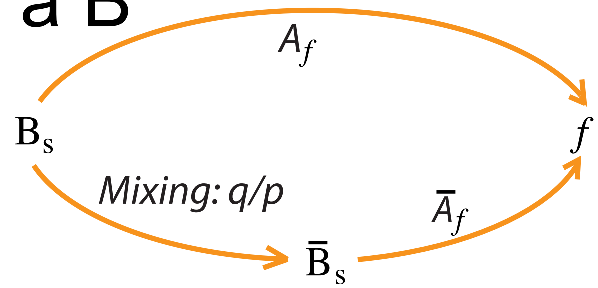
$\Delta m_s = 17.768 \pm 0.023$ (stat) ± 0.006 (syst) ps^{-1}

WORLD'S BEST!

CPV in $B_s \to J/\psi X$

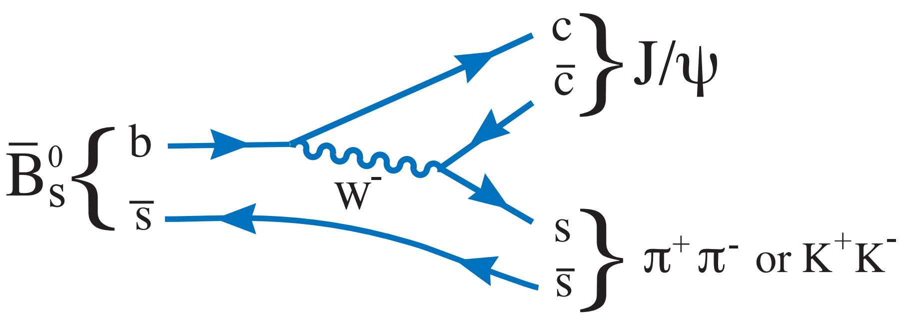
- CP violation means, for example, that a B will have a different decay rate than a $\bar{B}$
- Can occur via interference

  between mixing & decay



- For f =J/ψ φ or J/ψ f_0

$$d[f(t)] = \frac{\Gamma\left(\bar{M}\to f\right) - \Gamma\left(M\to f\right)}{\Gamma\left(\bar{M}\to f\right) + \Gamma\left(M\to f\right)}$$

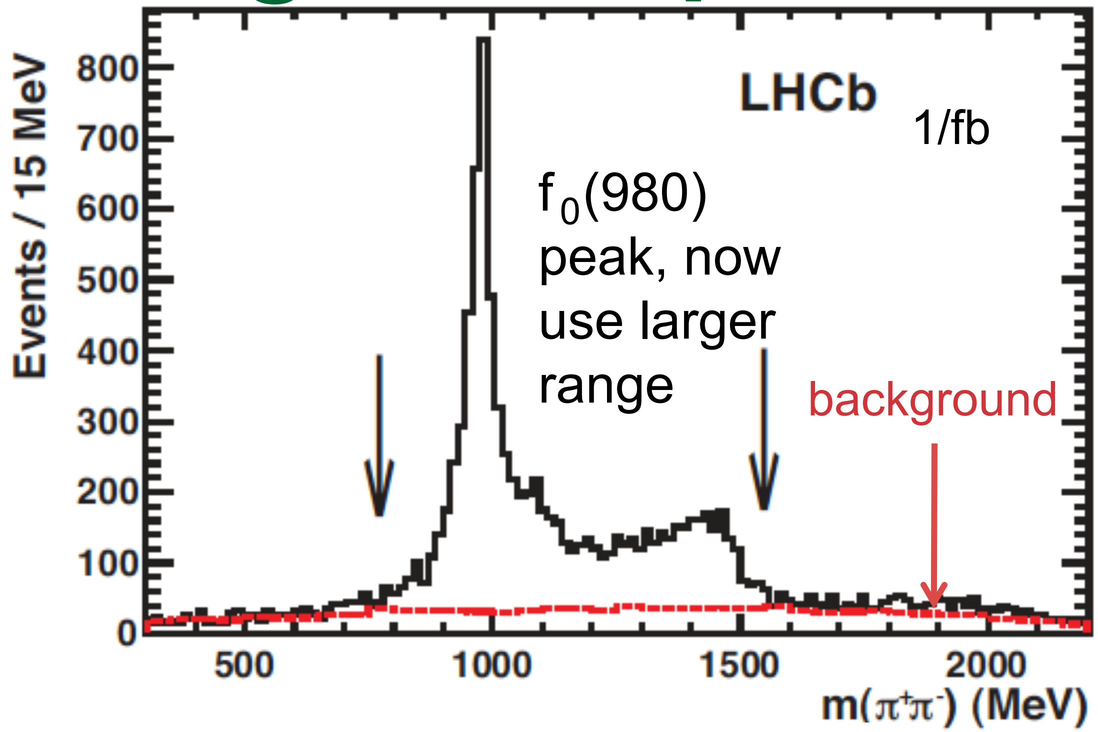


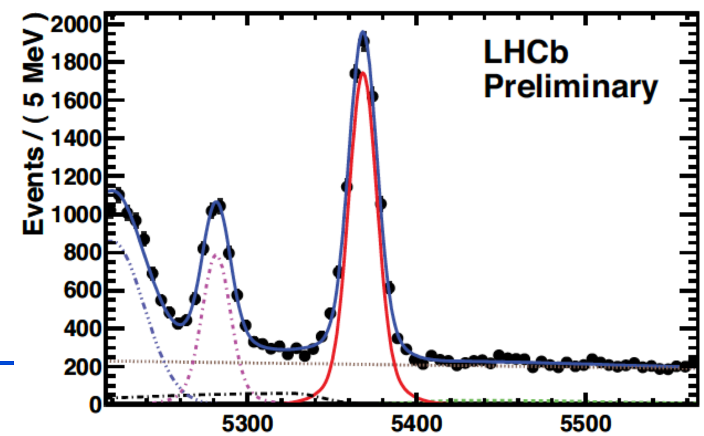
$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -2^\circ$$

- Small CPV expected, good place for NP to appear

ϕ_s from $B_s \to J/\psi\pi^+\pi^-$

- f_0 Mode predicted by Stone & Zhang, found by LHCb
- In region between arrows, measured to be >97.7% CP-odd @95% cl
- $a[f(t)] \sim 2\sin\phi_s \sin(\Delta M t)$
- $\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$ rad

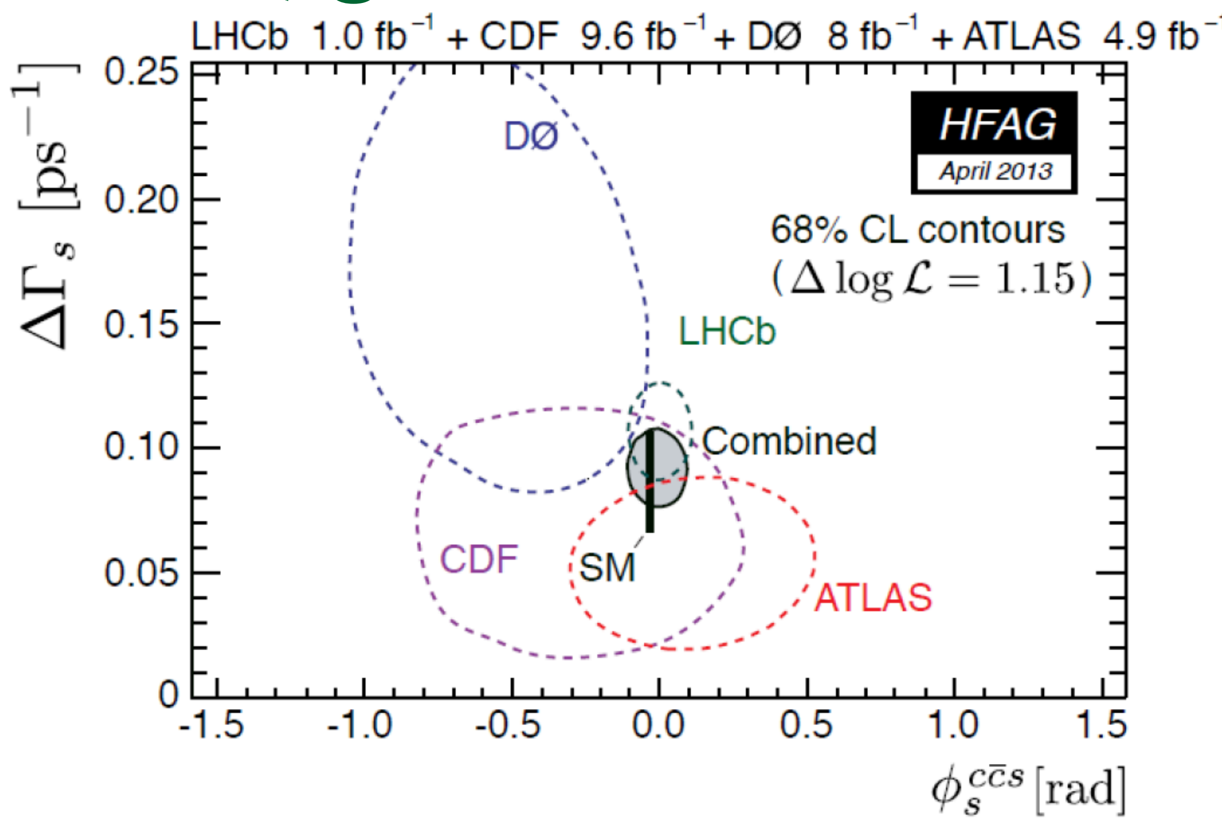




B_s Invariant mass distribution [MeV]

ϕ_s results

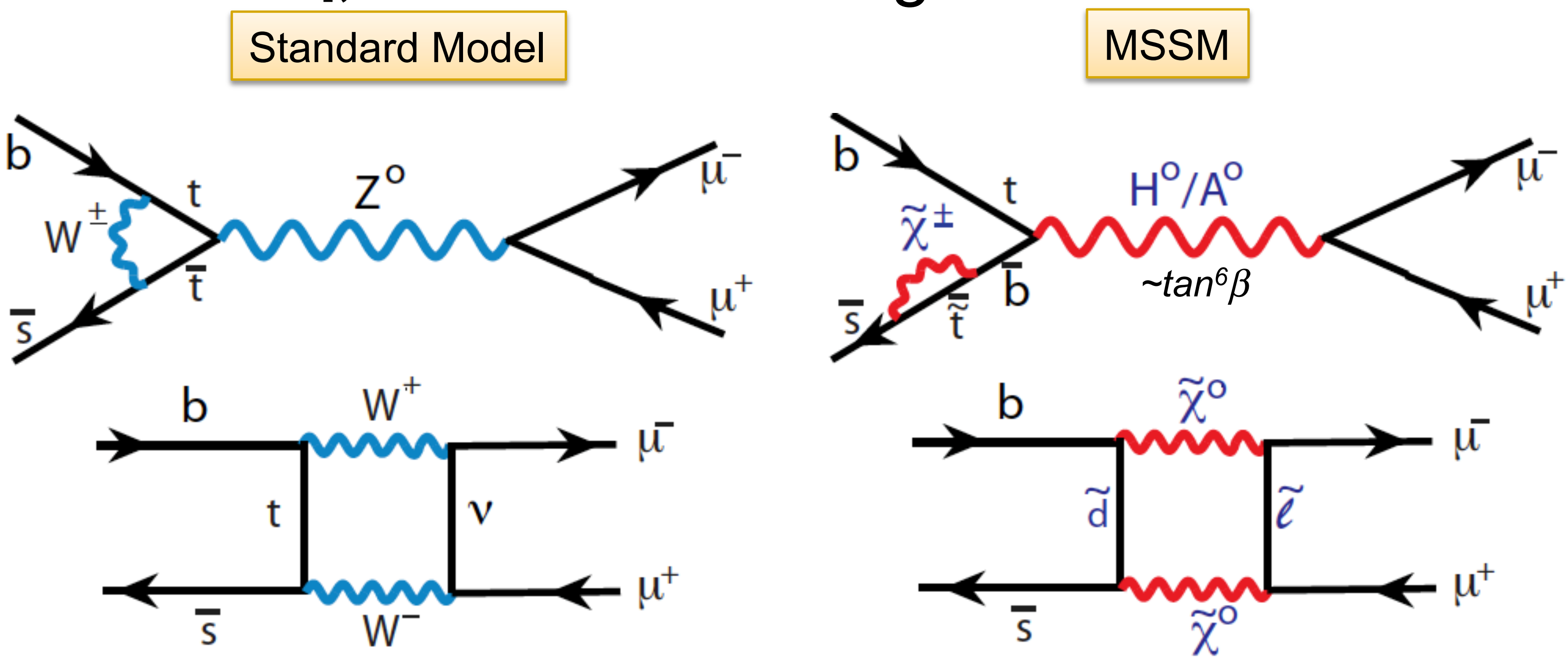
$B_s \rightarrow J/\psi\phi$



Combined LHCb values: $\Gamma = 0.661 \pm 0.04 \pm 0.006$ (ps^{-1}).
$\Delta\Gamma = 0.106 \pm 0.011 \pm 0.007$ (ps^{-1}), $\phi_s = 0.01 \pm 0.07 \pm 0.01$ (rad)
Indications of large ϕ_s from CDF/D0 not confirmed

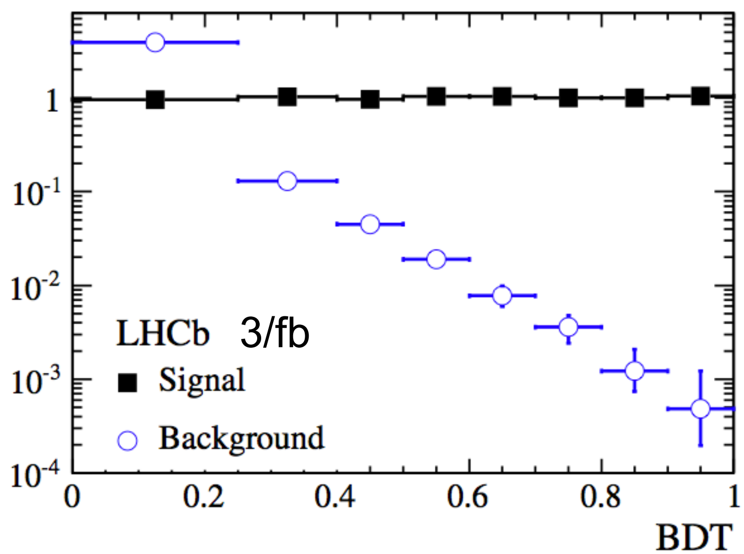
$B_s \to \mu^+\mu^-$

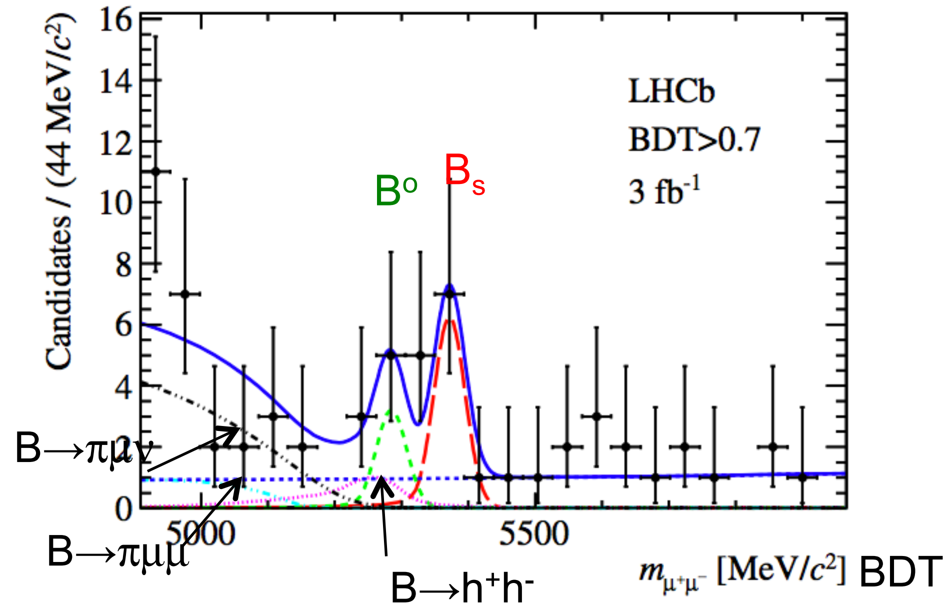
- SM branching ratio is $(3.2\pm0.2)\times10^{-9}$ [Buras arXiv: 1012.1447], NP can make large contributions.

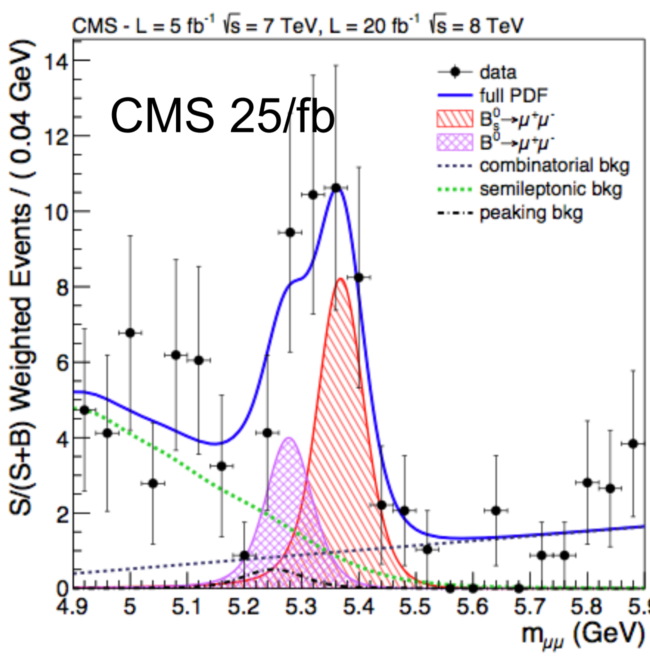


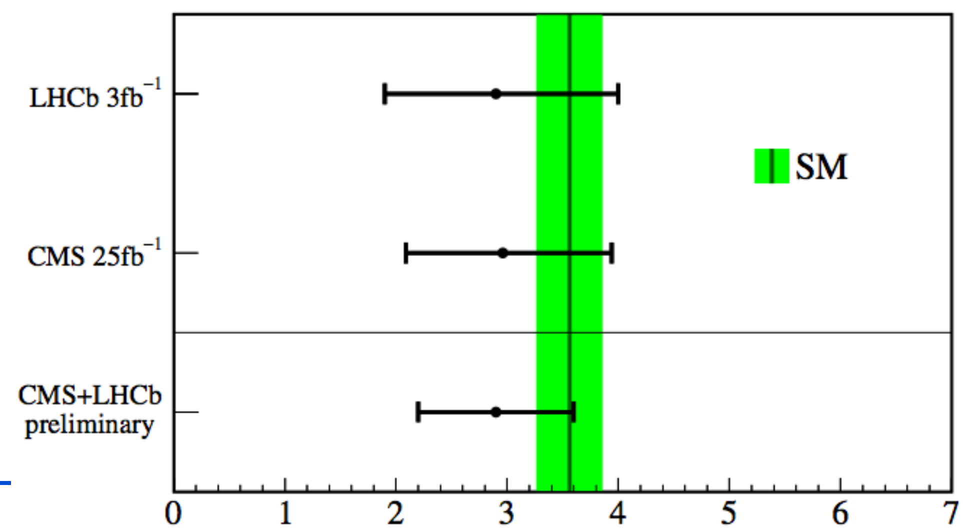
- Many NP models possible, not just Super-Sym

Evidence for $B_s \to \mu^+\mu^-$



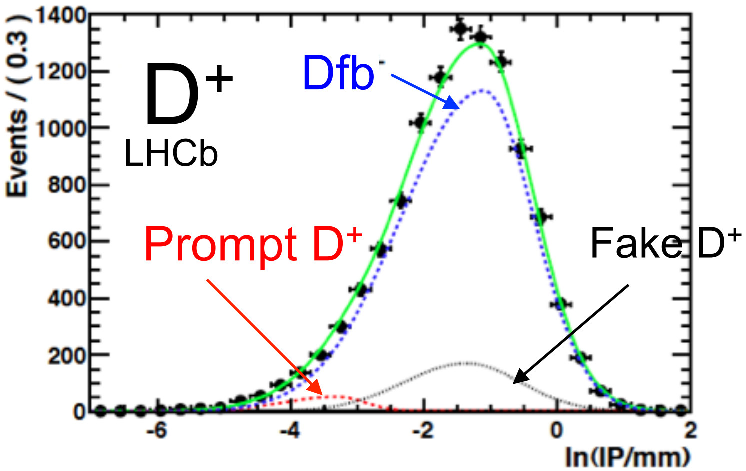


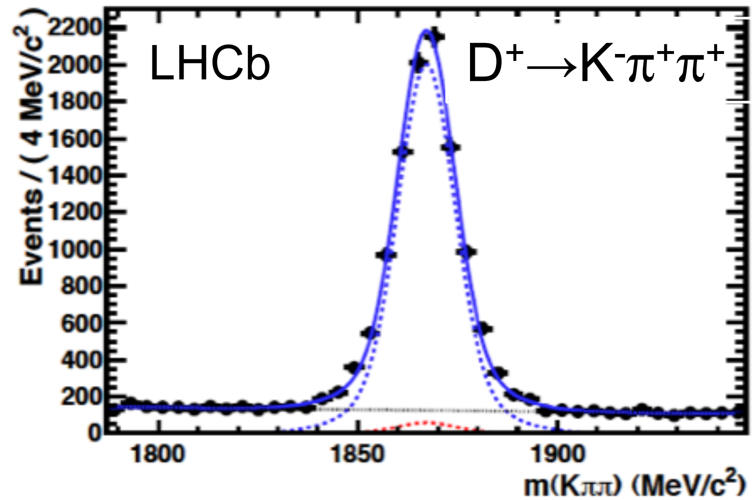




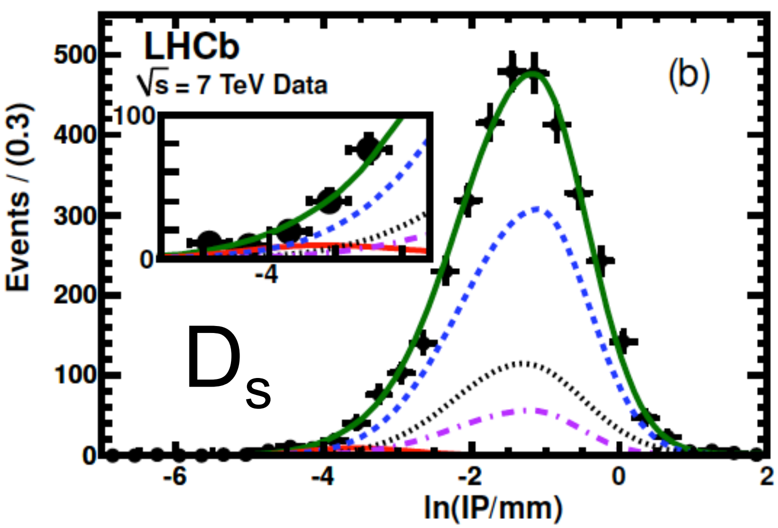
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.96^{+0.97}_{-0.85} \pm 0.17\right) x10^{-9}$$

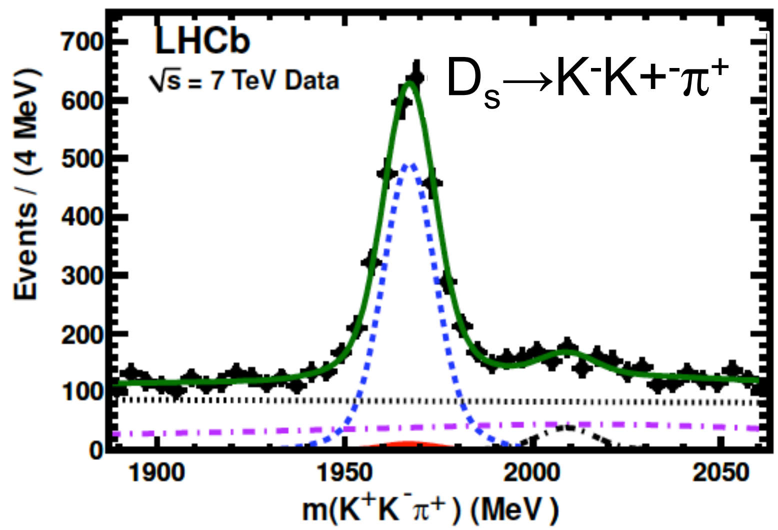
Production fractions: $B\rightarrow DX\mu\nu$ use equality of Γ_{sl} & known τ's





Must know $\#B_s$ to measure $\mathcal{B}$

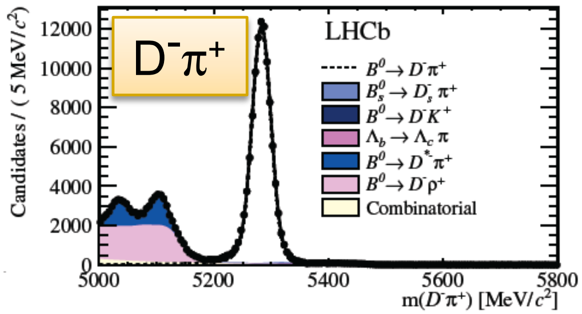


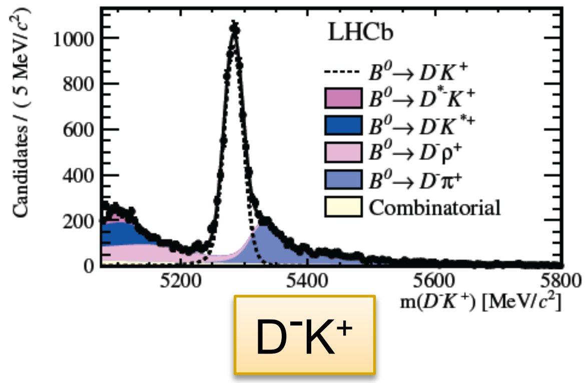


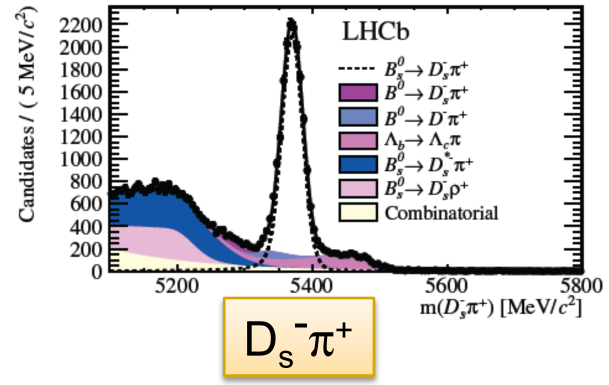
3/pb

Also D^o, Λ_b

Also B→Dh⁻





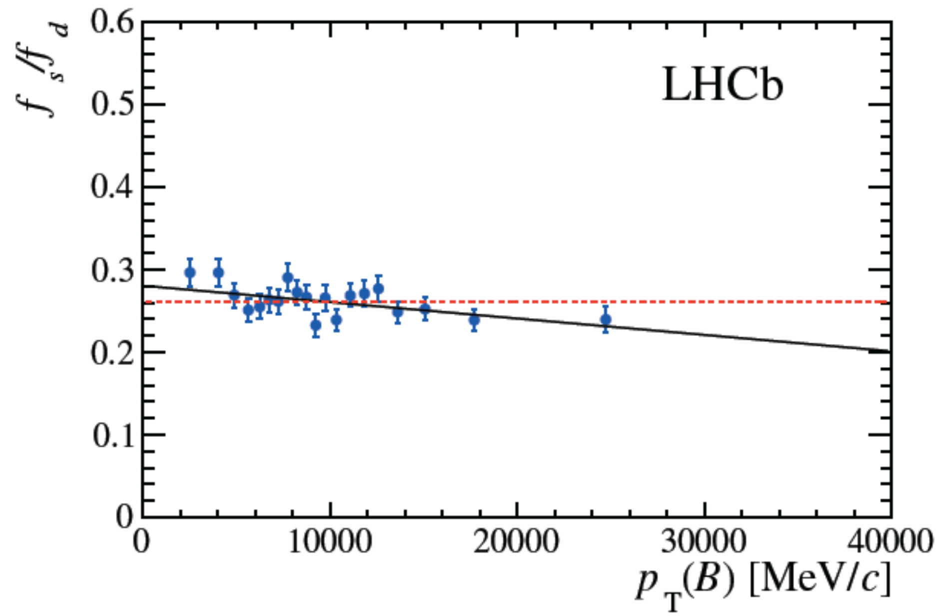


- LHCb measures

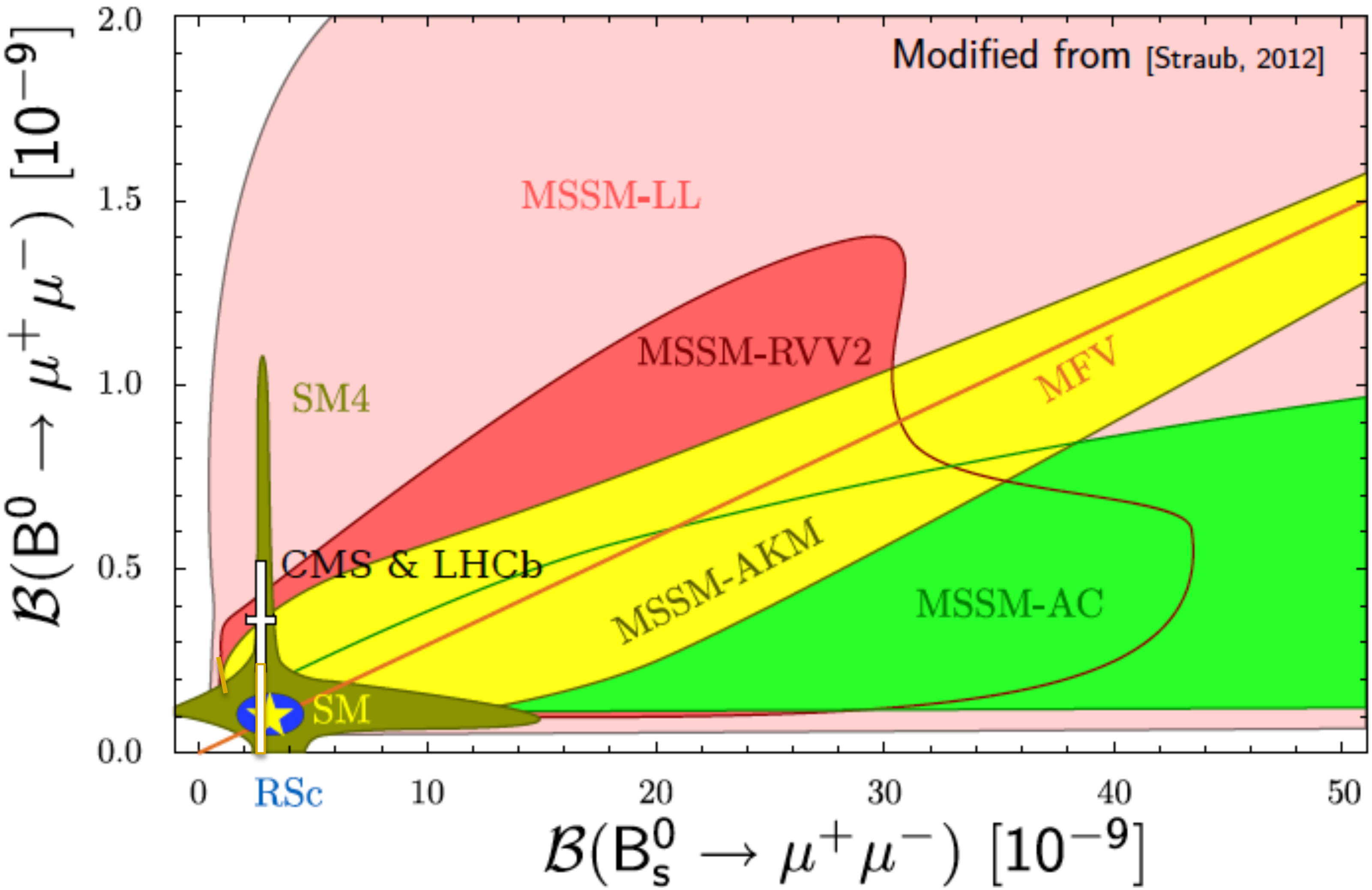
f_s/f_d=0.259±0.015

- Used by CMS & ATLAS
- P_t dependence now

evident, CMS/ATLAS implications



Another Top Down Ex.



a_{sl}

- By definition
$$a_{sl} = \frac{\Gamma(\bar{M}\to f) - \Gamma(M\to \bar{f})}{\Gamma(\bar{M}\to f) + \Gamma(M\to \bar{f})}$$

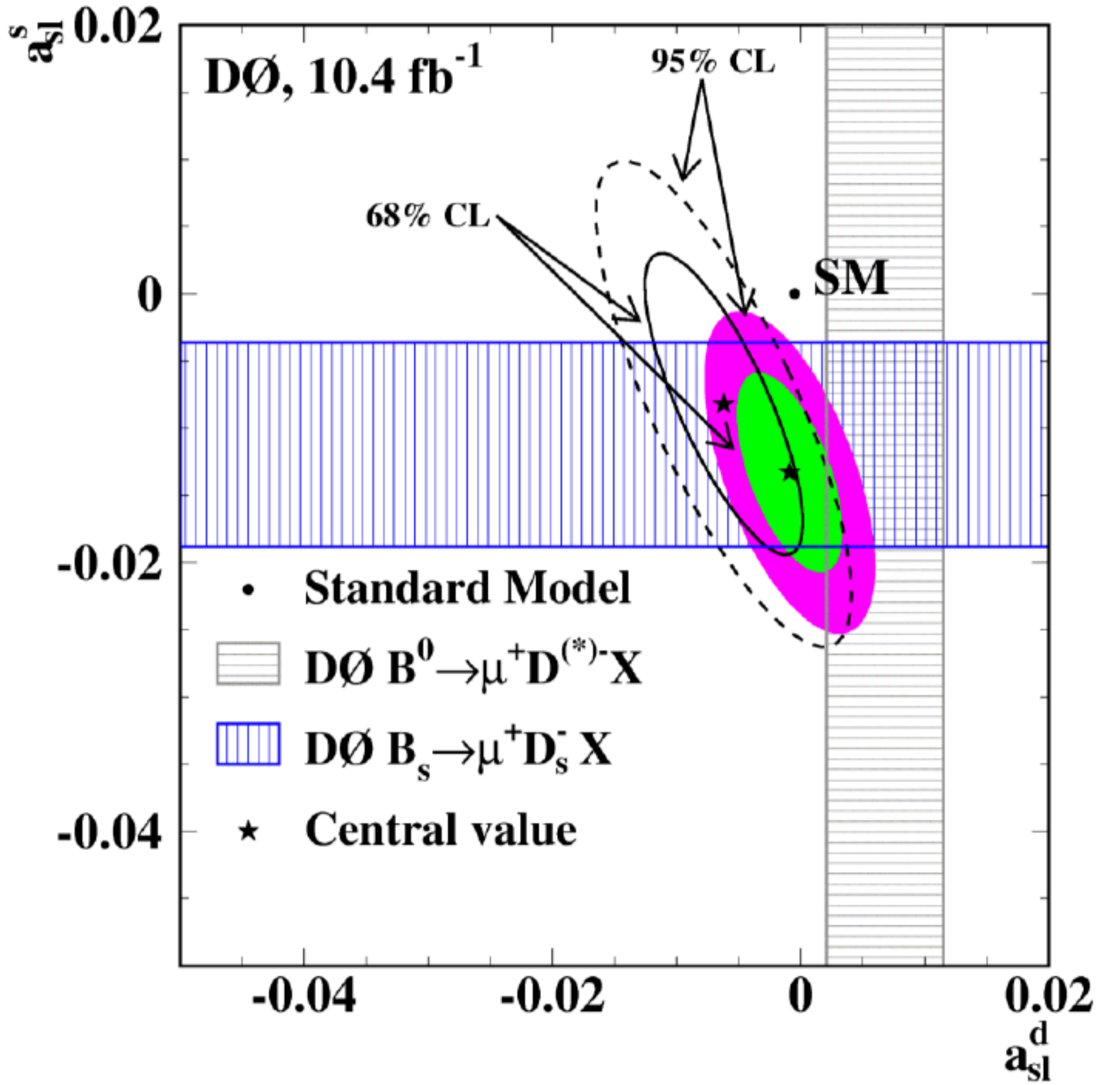
  at t=0 $\bar{M}\to \bar{f}$ is zero as is $M\to f$

- Here *f* is by construction flavor specific, $f \neq \bar{f}$
- Can measure eg. $\bar{B}_s \to D_s^+\mu^-\nu$, versus $B_s \to D_s^-\mu^+\nu$,
- Or can consider that muons from two B decays can be like-sign when one mixes and the other decays, so look at $\mu^+\mu^+$ vs $\mu^-\mu^-$
- a_{sl} is expected to be very small
- In SM (B^o) a_{sl}^d =-4.1x10^{-4}, (B_s) a_{sl}^s =+1.9x10^{-5}

arXiv:1205.1444 [hep-ph]

a_{sl} according to D0

- a^s_{sl}=(-1.33±0.58)%
- a^d_{sl}=(-0.09±0.29)%
- 3.1σ from SM using also $\mu^+\mu^+$ versus $\mu^-\mu^-$
- Source: Borrisov talk CERN Oct. 29, 2013



a_{sl} not D0

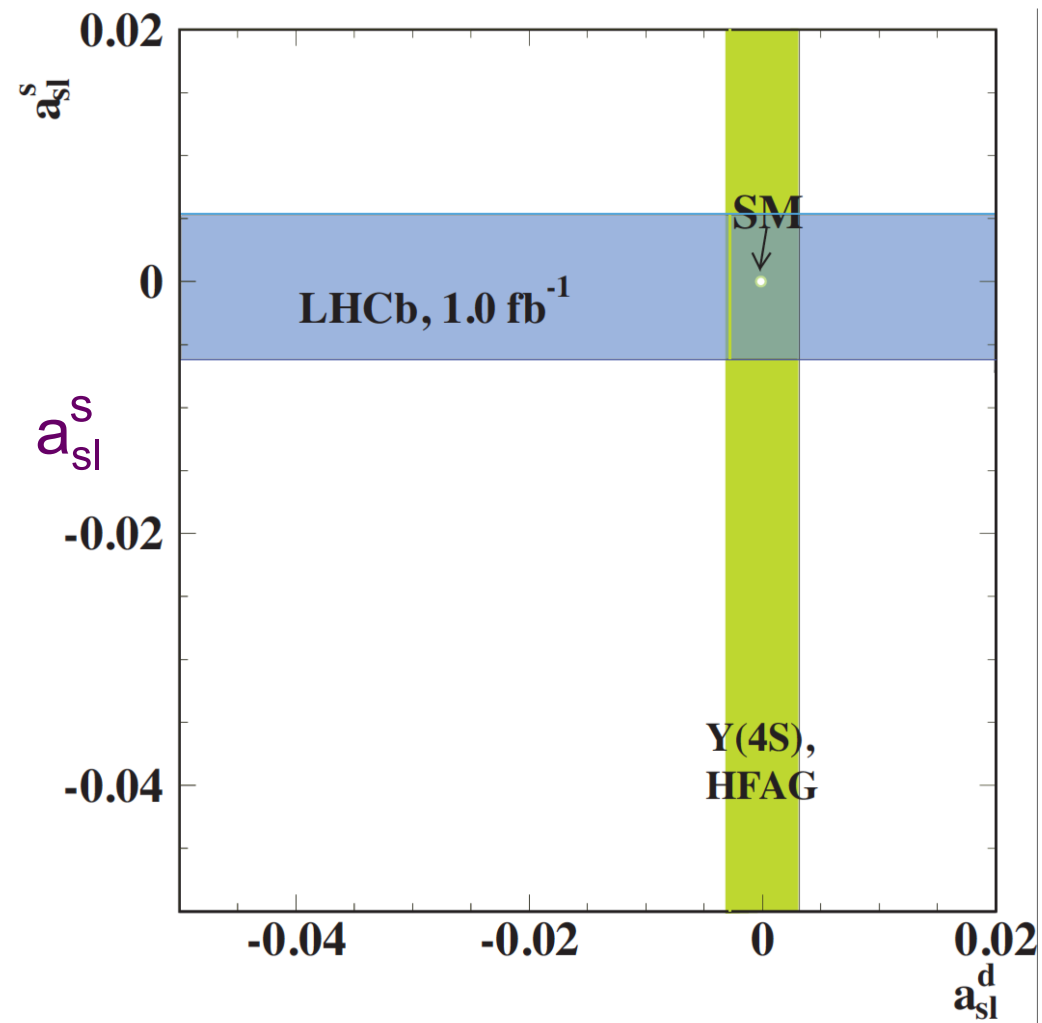
- LHCb finds

$$a_{sl}^{s} = (-0.06 \pm 0.50 \pm 0.36)\%$$

- B-factory

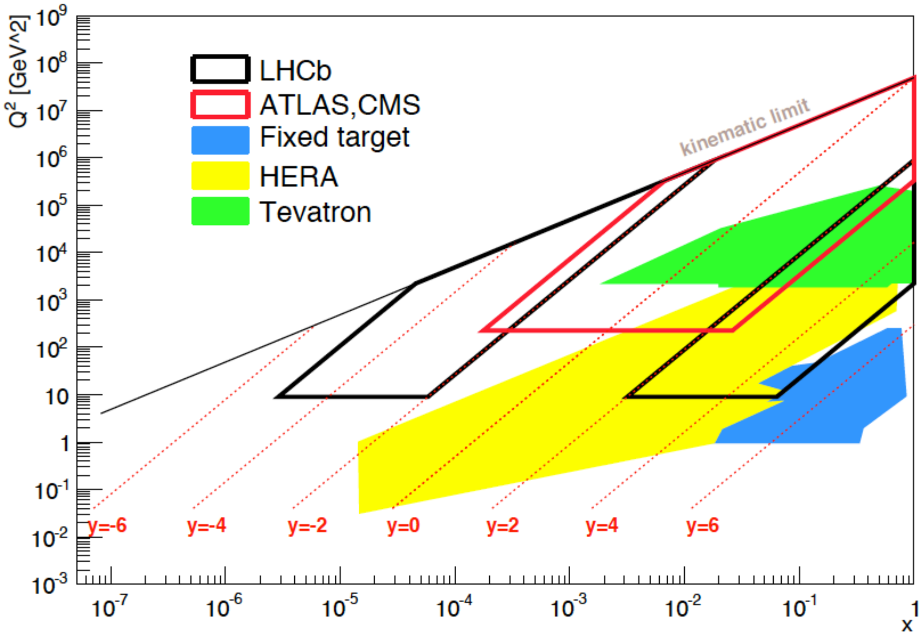
$$a_{sl}^{d} = (-0.02 \pm 0.31)\%$$

- Results consistent with SM
- Used 1/fb, now analyzing 3/fb



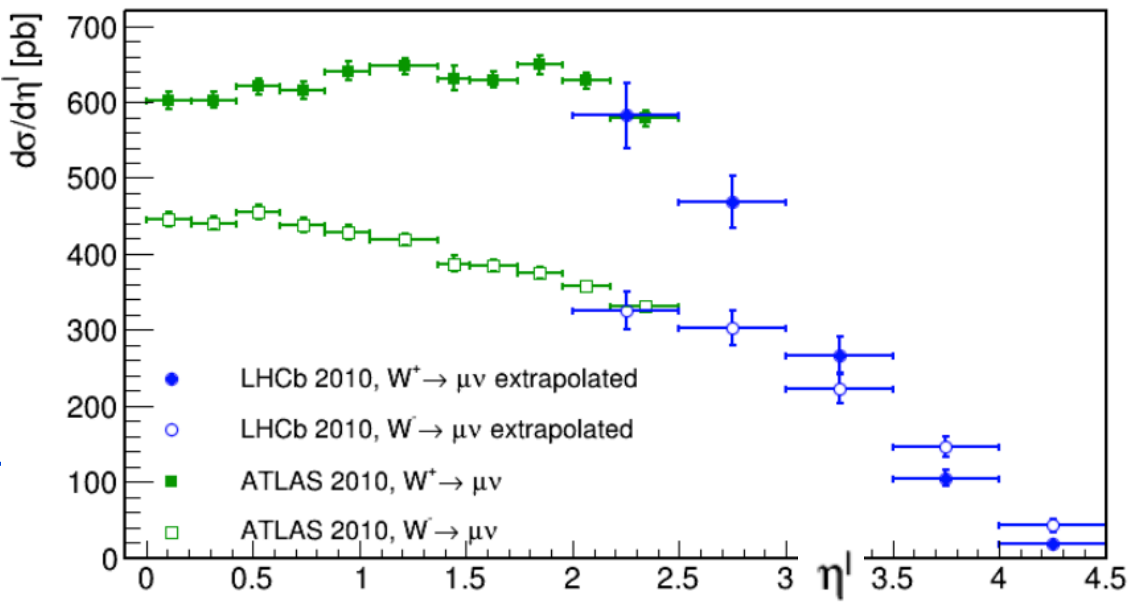
A sample of other results

Electroweak



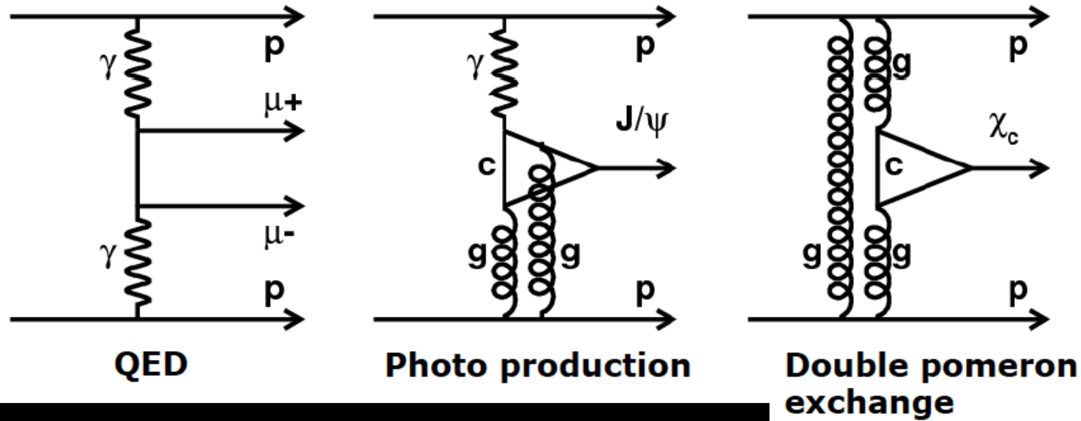
- Unique x-Q^2 regions for structure function studies

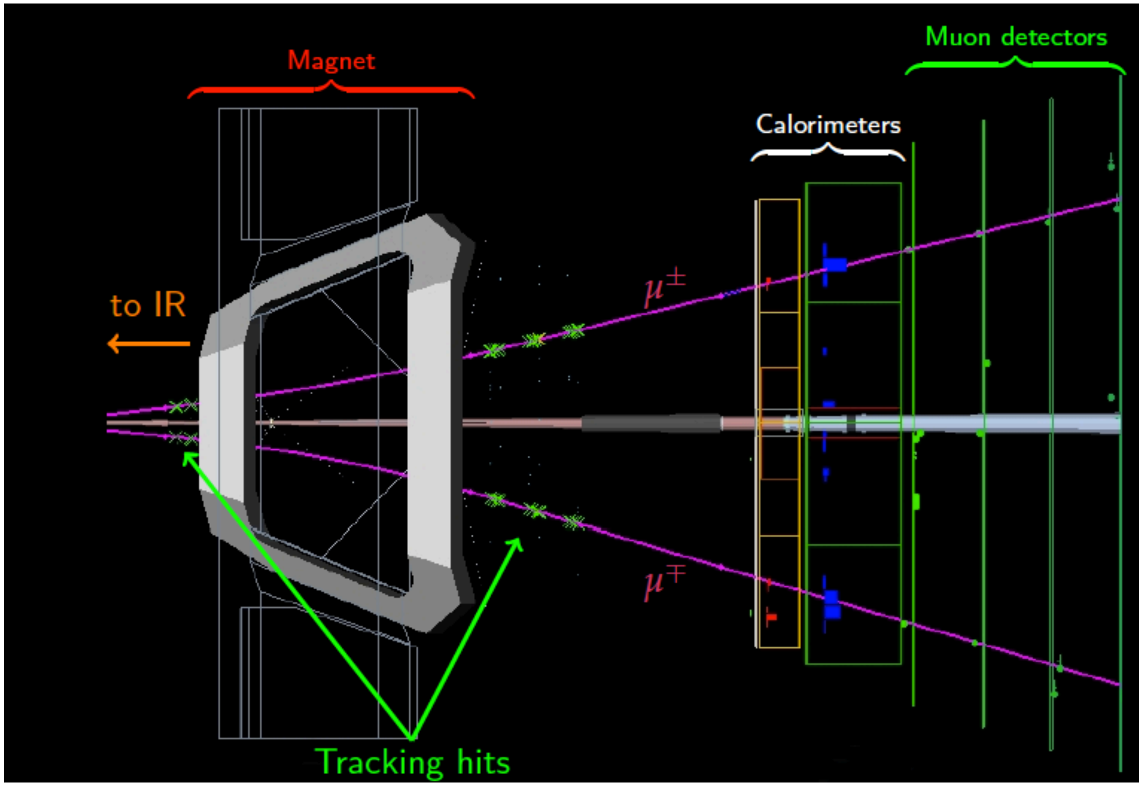
LHCb-CONF-2013-005

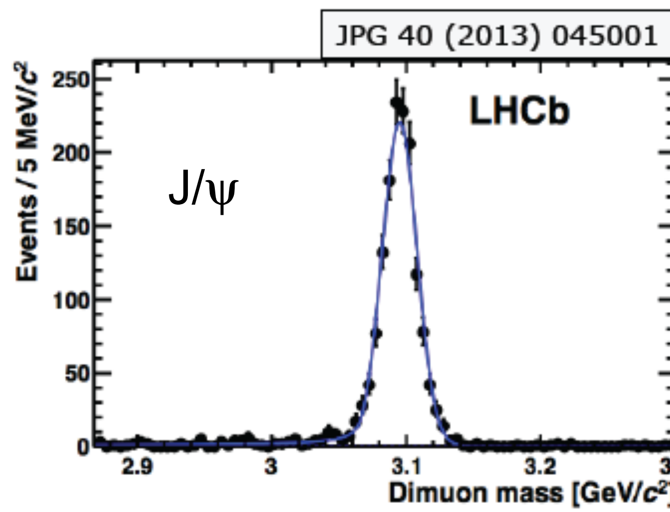


Central exclusive production

Related phenomena where the colourless object creates a particle

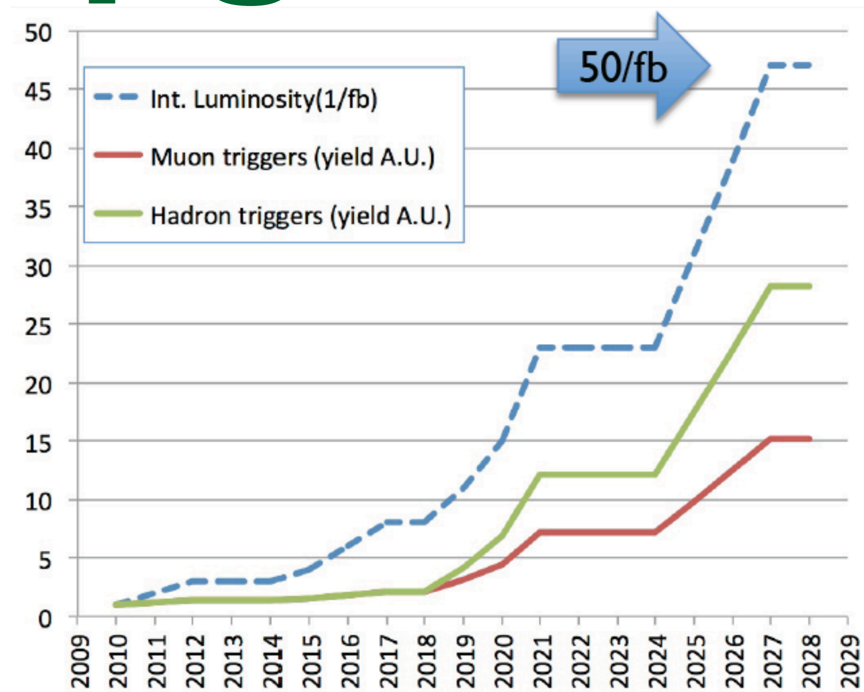






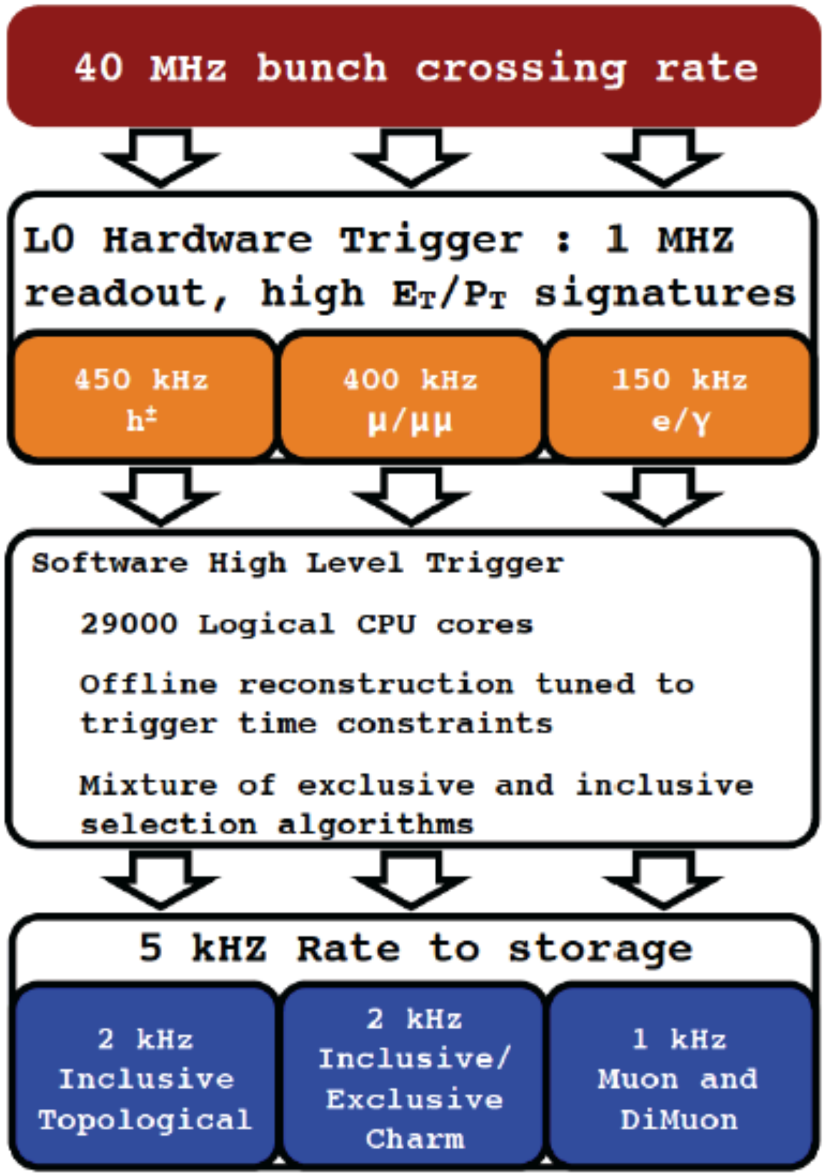
LHCb Upgrade

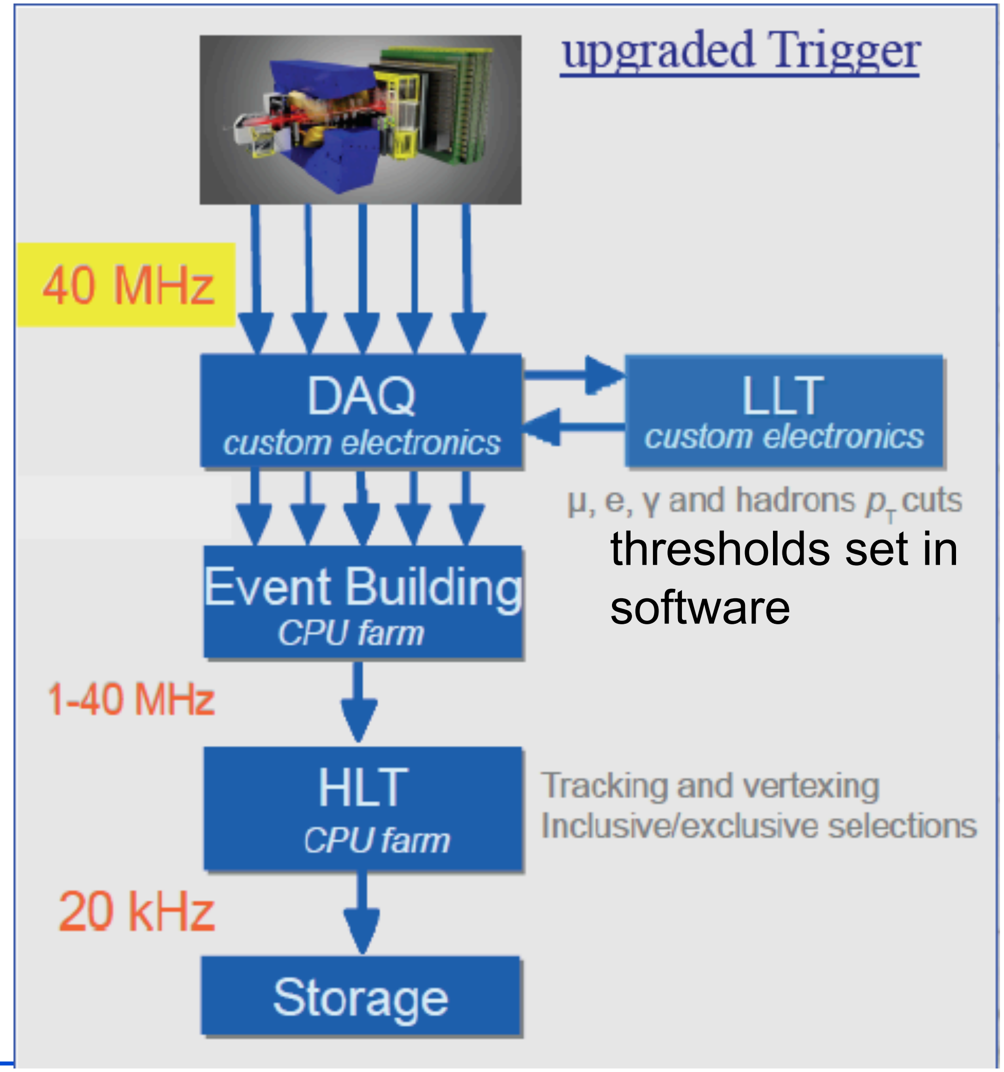
- Increase instantaneous $\mathcal{L}$ by x(5-10)
- Relies on triggering at ~40 MHz without hard wired cuts



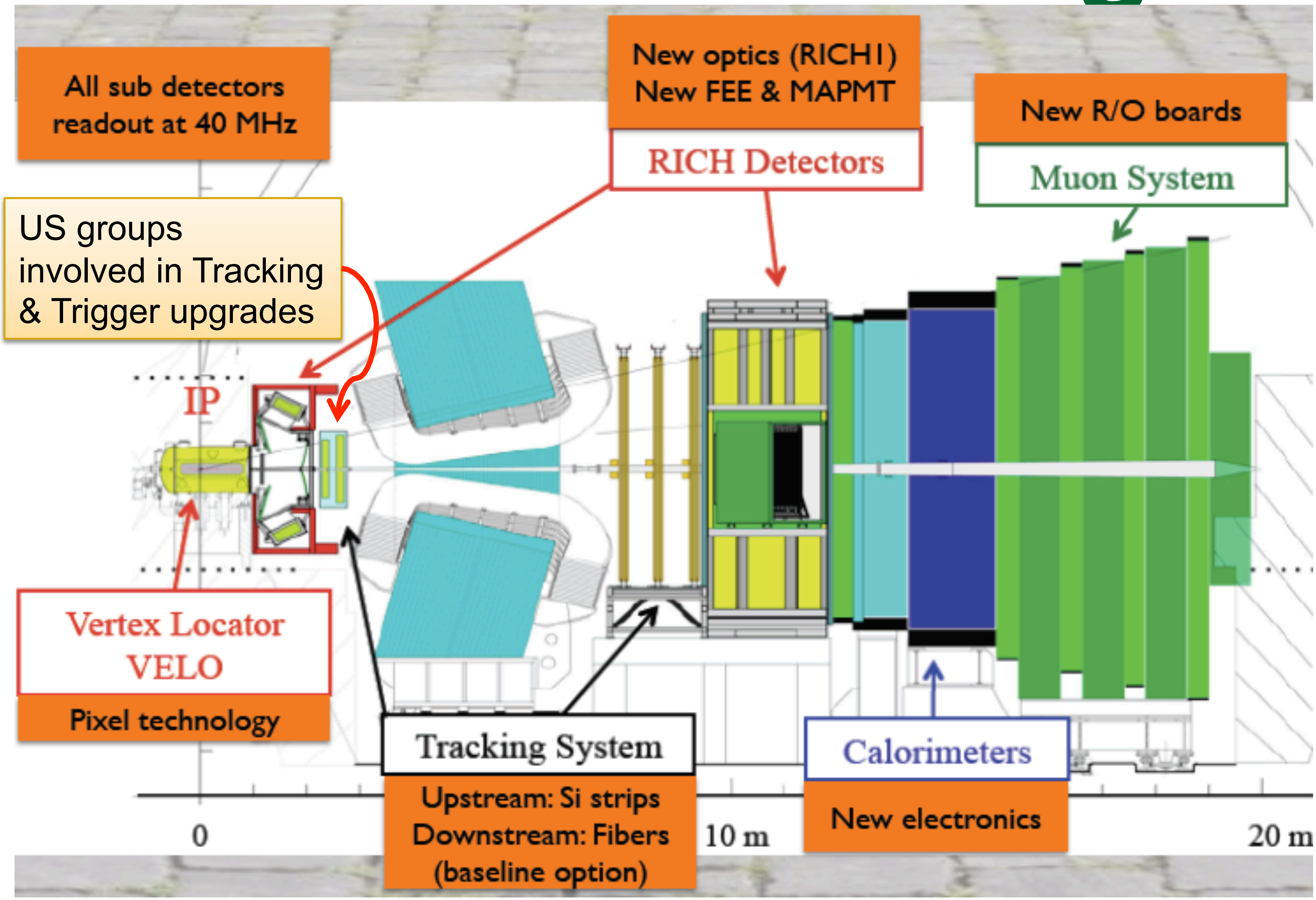
- Requires replacing all electronics except calorimeter & muon, including rebuilding VELO, Tracking & replacing RICH HPD's
- Allows significant extension of NP mass range

Trigger Changes





Detector Changes



Upgrade physics

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**	–

EPJC 73, 2373 (2013)

Conclusions

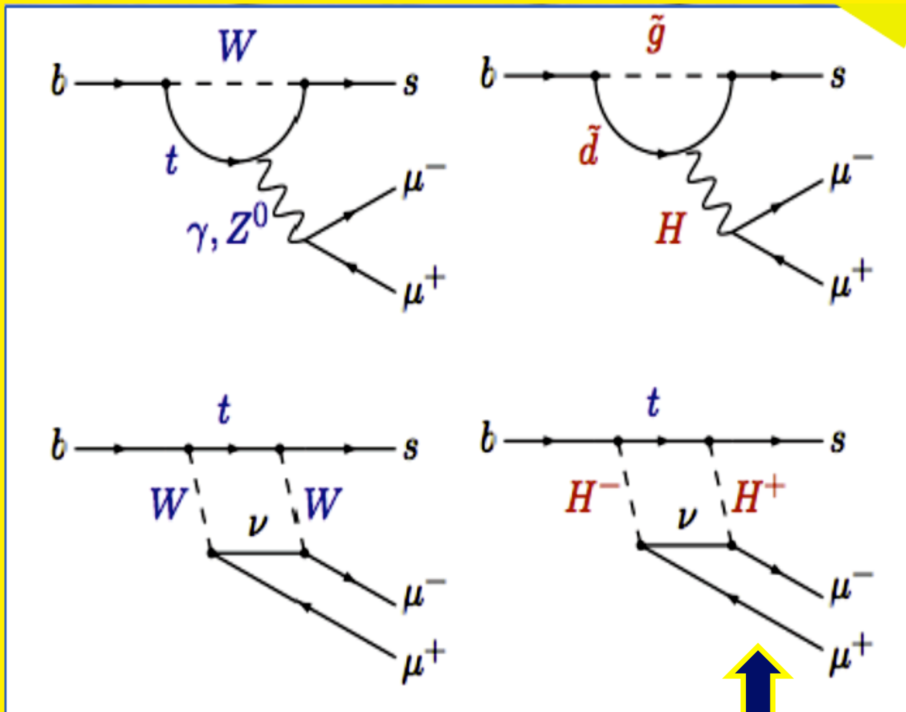
- LHCb is searching for and limiting New Physics (NP), especially in rare and CP violating b & c decays
- Other important research directions in other areas: light meson structure $q\bar{q}$ versus tetraquark, exotic mesons, central exclusive production, electroweak….
- The upgrade will allow much more sensitive searches in a variety of areas
- From Snowmass Report of the Quark Flavor Physics Working Group arXiv:1311.1076: "In particular, U.S. contributions to LHCb & Belle II should be encouraged because of the richness of the physics menus of these experiments & their reach for NP

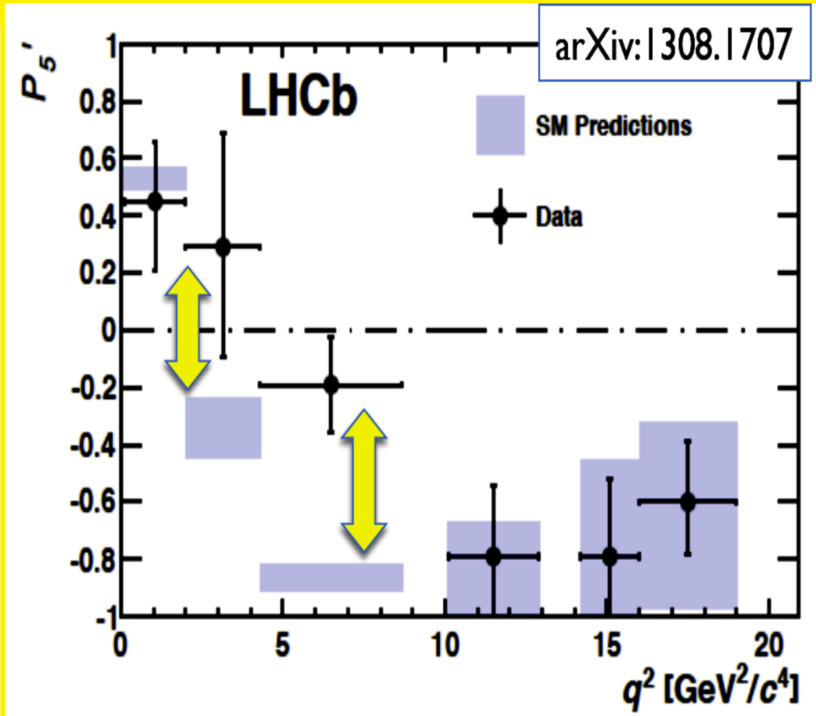
The End

$B \to K^*\mu^+\mu^-$

Measuring angular variables in (penguin-dominated) $B^0 \to K^*\mu\mu$ decays

One of these (P'_5) shows a local 3.7σ deviation from SM predictions





From 1/pb, 3/pb available, understudy

A great deal of theoretical interest (NP ?), but controversial