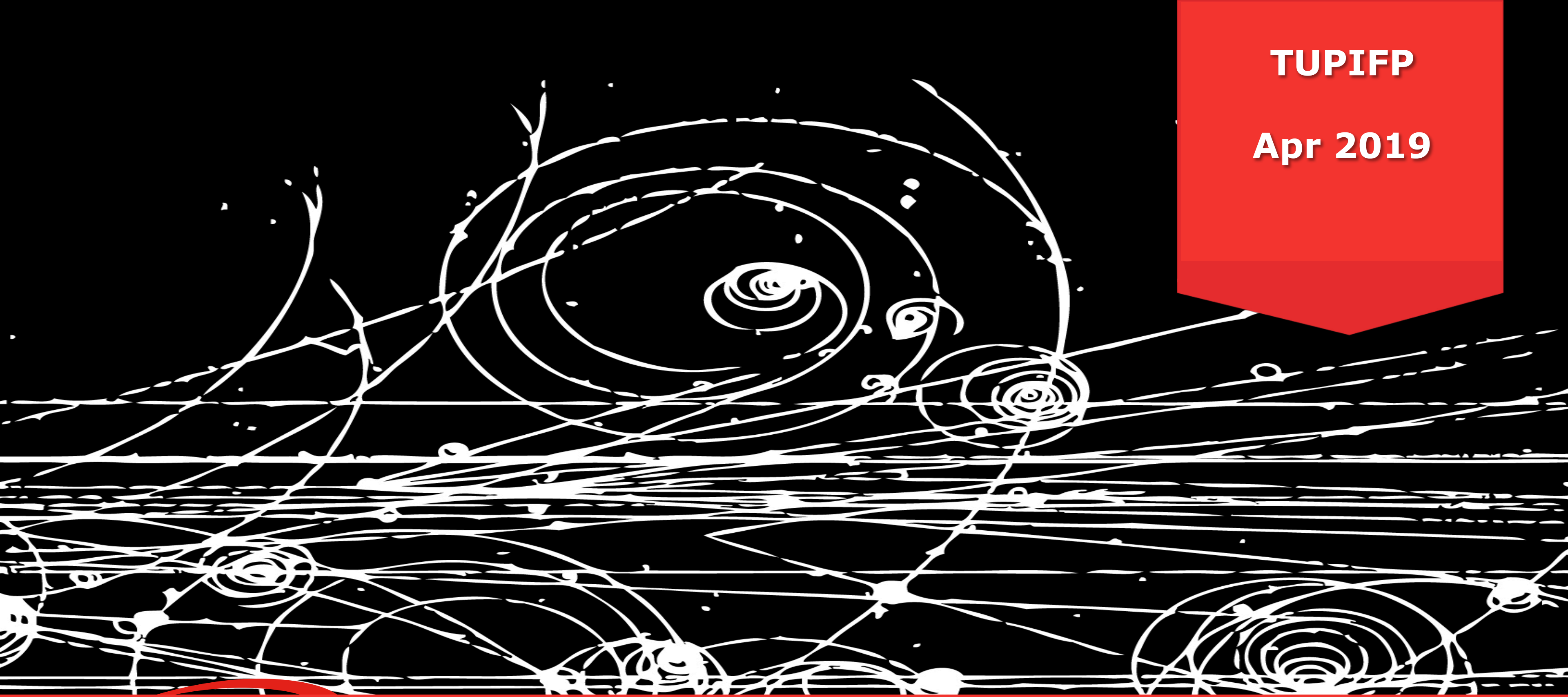
TUPIFP

Apr 2019



Lessons learned from LHCb
about making precise flavour measurements

Niels Tuning

Nikhef

On the menu

- Introduction: Precision measurements
- Recent highlights
- Where do we come from?
- What brought us here?
  - Lumi levelling
  - Trigger
  - Magnet flips
  - Data driven
    - Tracking
    - PID
    - Control channels
- **Lessons learned from LHCb**

Flavour physics has a track record…

GIM mechanism in $K^0 \to \mu\mu$

Weak Interactions with Lepton-Hadron Symmetry*

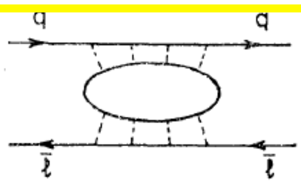
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.

splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \to \mu^+ + \mu^-$, $K^+ \to \pi^+ + l + \bar{l}$, etc., involving neutral lepton

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving **four, not three,** fundamental fermions; the weak interactions are medi-

new quantum number $\mathcal{C}$ for charm.



Glashow, Iliopoulos, Maiani,
Phys.Rev. D2 (1970) 1285

CP violation, $K_L^0 \to \pi\pi$

27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have

three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is **not a pure eigenstate of CP.** Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$

Christenson, Cronin, Fitch, Turlay,
Phys.Rev.Lett. 13 (1964) 138-140

$B^0 \leftrightarrow \bar{B}^0$ mixing

DESY 87-029
April 1987

OBSERVATION OF B^0-$\bar{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ 90% CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson (≈ pion) decay constant
$m_b < 5\,\mathrm{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$ s	B meson lifetime
$\lvert V_{td}\rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50\,\mathrm{GeV}/c^2$	**t quark mass**

ARGUS Coll.
Phys.Lett.B192:245,1987

Flavour physics has a track record…

Rare decay implies 2nd up quark "discovery" of charm?

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S. L. Glashow, J. Iliopoulos, and L. Maiani†
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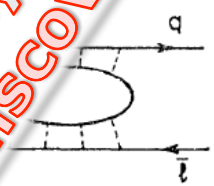

CP violation implies 3rd family: "discovery" of bottom?

2

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Mixing implies heavy quark: "discovery" of top?

DESY 87-029
April 1987

OBSERVATION O … G

The AR

In summary, the combined evidence of the in … s, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ le … B^0-$\bar{B}^0$ mixing has been observed and is substantial.

Parameters

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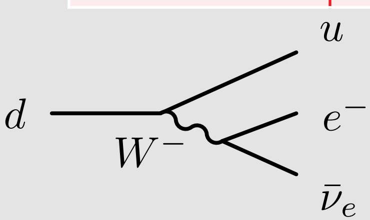
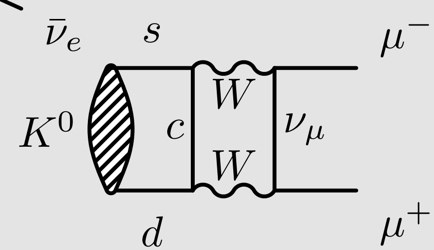
$\tau_b < 1$…	B meson lifetime
$\vert V_t$…	Kobayashi-Maskawa matrix element
	QCD correction factor [17]
	t quark mass

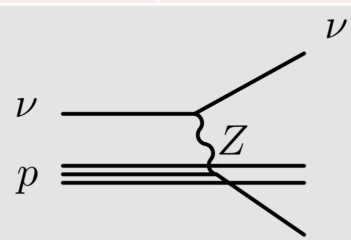
Precise flavour measurements

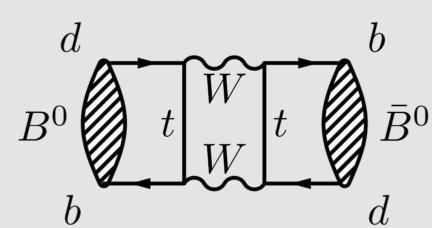
- Historical record of indirect discoveries:

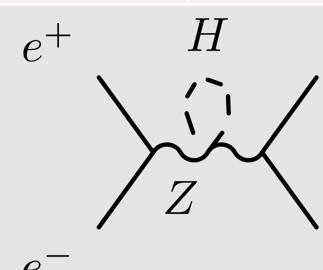
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	*W→eν*	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	*Υ*	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?











Precise flavour measurements

- Direct discoveries rightfully higher valued:

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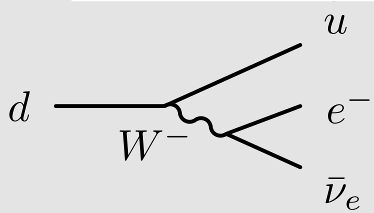
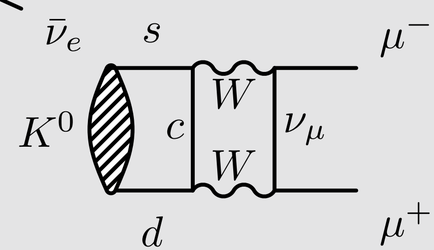
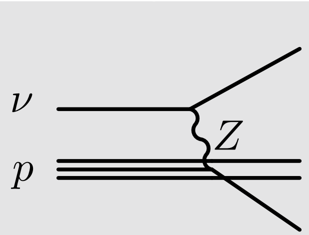
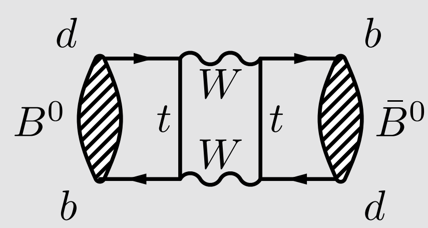
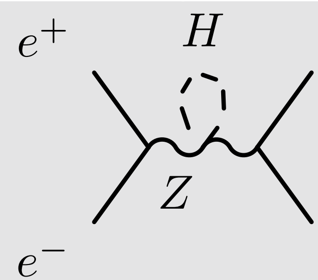


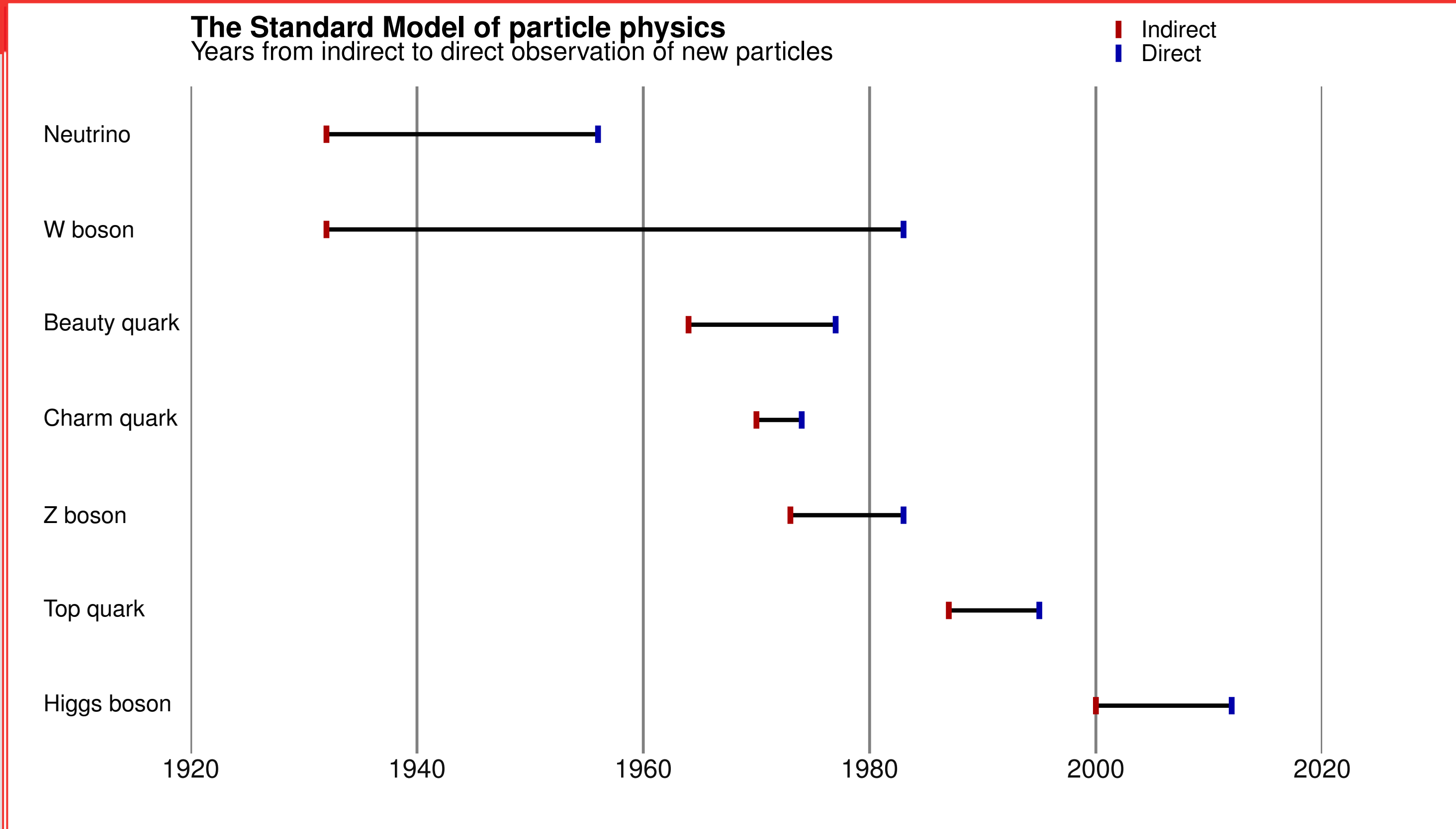




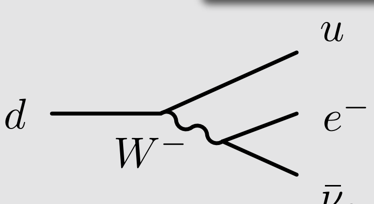


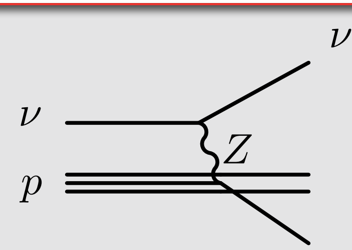


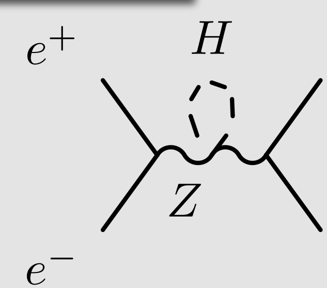
Precise flavour measurements

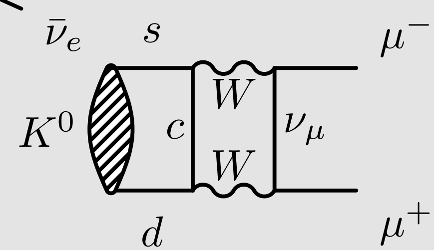


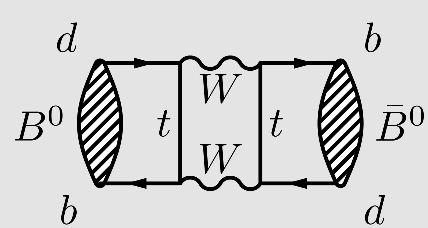
Compilation by F. Dettori





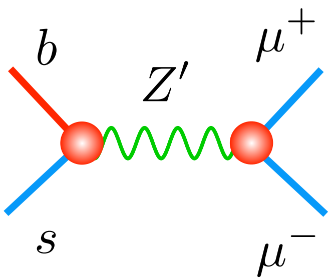






Precise flavour measurements

- Depending on your model, sensitive to multi-TeV scales, eg:



$$\mu_{B_s\to\mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2\,|V_{tb}^* V_{ts}|^2}\,\frac{v^2}{\Lambda^2}$$

$\mu_{B\to\mu\mu}$ is ratio BR^{exp}/BR^{SM}

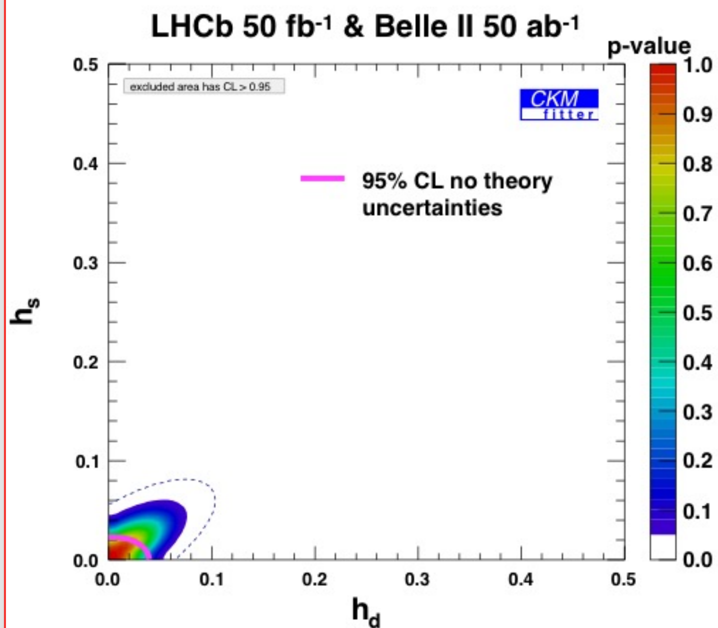
$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\text{TeV}\,, & \text{anarchic tree} \\ 0.6\,\text{TeV}\,, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016
arXiv:1510.03341

Precise flavour measurements

- Depending on your model, sensitive to multi-TeV scales, eg:

[Charles et al., 1309.2293]



$$M_{12}^q = (M_{12}^q)_{\rm SM}\,\left(1 + h_q e^{2i\sigma_q}\right)$$

h_q parametrizes magnitude of NP in B_q mixing

$$h_d \lesssim 5\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 2\cdot 10^3\,\text{TeV}, & \text{anarchic tree} \\ 1.4\,\text{TeV}, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

Recent highlights

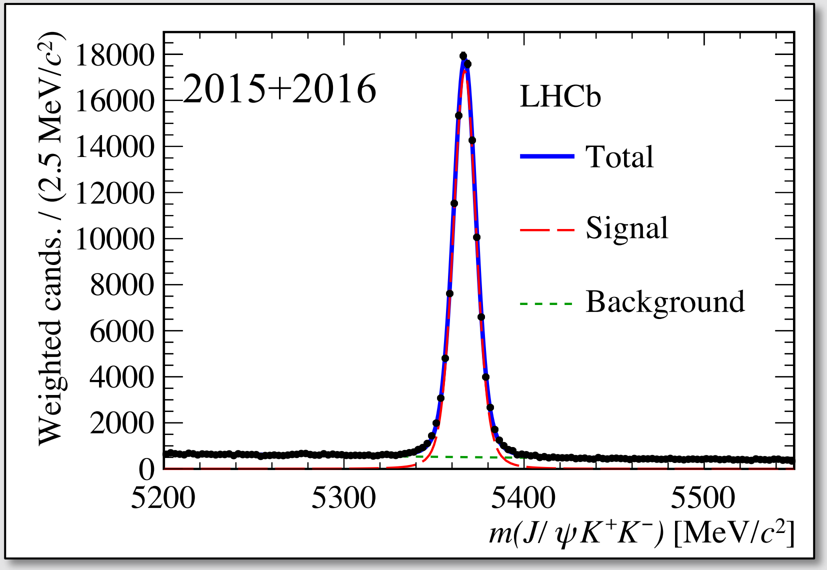
- φ_s
- R_K
- Exotic spectroscopy
- ΔA_{CP}

ϕ_s

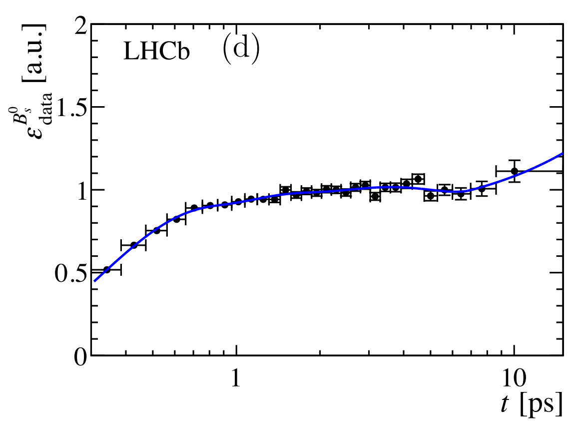
$117\,000\ B_s^0 \to J/\psi K^+K^-$

Parameter	Value
ϕ_s [rad]	$-0.080 \pm 0.041 \pm 0.006$
$\lvert\lambda\rvert$	$1.006 \pm 0.016 \pm 0.006$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0041 \pm 0.0024 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0772 \pm 0.0077 \pm 0.0026$
Δm_s [ps^{-1}]	$17.705 \pm 0.059 \pm 0.018$

- Largest systematic:
  - Decay time bias
  - Decay time efficiency



Source	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	ϕ_s [rad]	$\lvert\lambda\rvert$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass width parametrisation	0.0006	0.0005	-	-	0.05	0.009	-	0.0002	0.001
Mass factorisation	0.0002	0.0004	0.004	0.0037	0.01	0.004	0.0007	0.0022	0.016
Multiple candidates	0.0006	0.0001	0.0011	0.0011	0.01	0.002	0.0003	0.0001	0.001
Fit bias	0.0001	0.0006	0.001	-	0.02	0.033	-	0.0003	0.001
C_{SP} factors	-	0.0001	0.001	0.0010	0.01	0.005	-	0.0001	0.002
Quadratic OS tagging	-	-	-	-	-	-	-	-	-
Time res.: statistical	-	-	-	-	-	-	-	-	-
Time res.: prompt	-	-	-	-	-	0.001	-	-	0.001
Time res.: mean offset	-	-	0.0032	0.0010	0.08	0.001	0.0002	0.0003	0.005
Time res.: Wrong PV	-	-	-	-	-	0.001	-	-	0.001
Ang. acc.: statistical	0.0003	0.0004	0.0011	0.0018	-	0.004	-	-	0.001
Ang. acc.: correction	0.0020	0.0011	0.0022	0.0043	0.01	0.008	0.0001	0.0002	0.001
Ang. acc.: low-quality tracks	0.0002	0.0001	0.0005	0.0014	-	0.002	0.0002	0.0001	-
Ang. acc.: t & σ_t dependence	0.0008	0.0012	0.0012	0.0007	0.03	0.006	[illegible]	0.0010	0.003
Dec.-time eff.: statistical	0.0002	0.0003	-	-	-	-	0.0012	0.0008	-
Dec.-time eff.: $\Delta\Gamma_s = 0$ sim.	0.0001	0.0002	-	-	-	-	[illegible]	0.0005	-
Dec.-time eff.: knot pos.	-	-	-	-	-	-	-	-	-
Dec.-time eff.: p.d.f. weighting	-	-	-	-	-	-	0.0001	0.0001	-
Dec.-time eff.: kin. weighting	-	-	-	-	-	-	0.0002	-	-
Length scale	-	-	-	-	-	-	-	-	0.004
Quadratic sum of syst.	0.0024	0.0019	0.0061	0.0064	0.10	0.037	0.0015	0.0026	0.018



LHCb-PAPER-2019-013

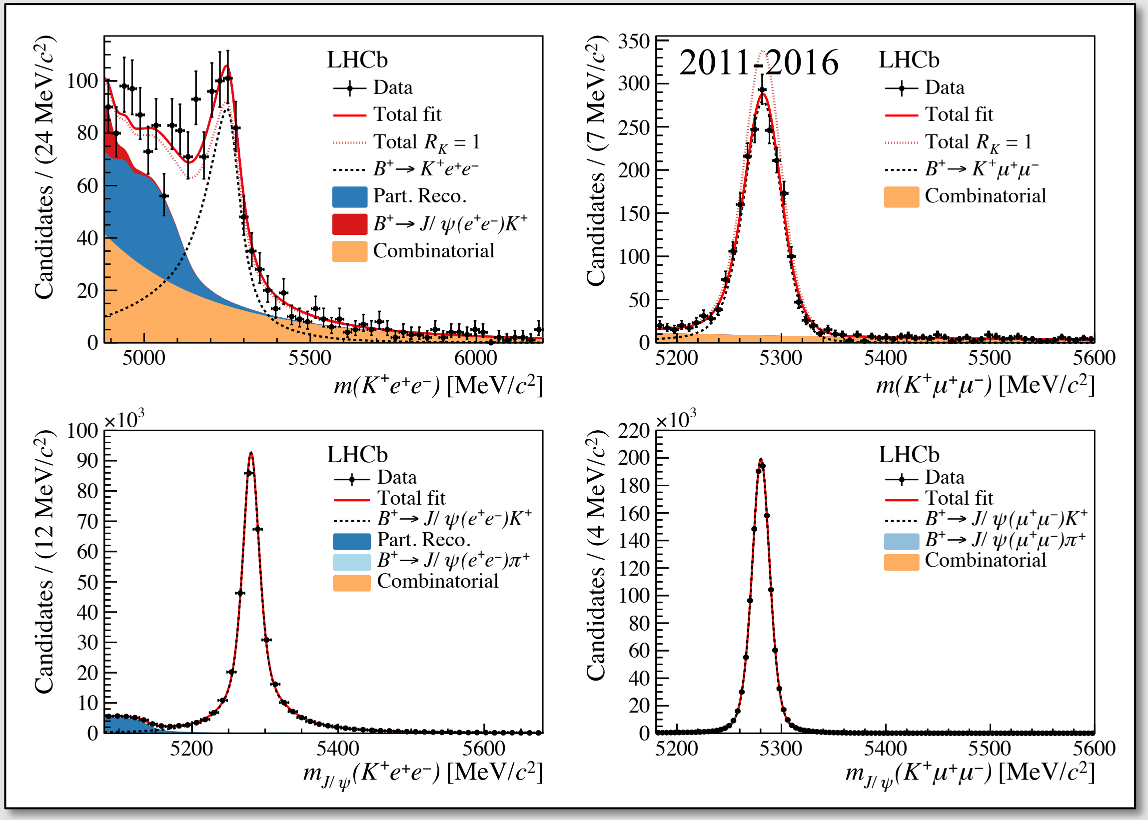
R_K

$1943 \pm 49 \;\; B^+ \to K^+\mu^+\mu^-$

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

$$R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$$

- Largest systematic:
  - Mass model



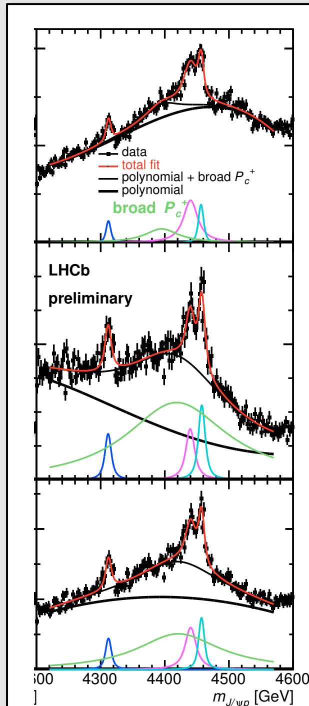
LHCb-PAPER-2019-009, arXiv:1903.09252

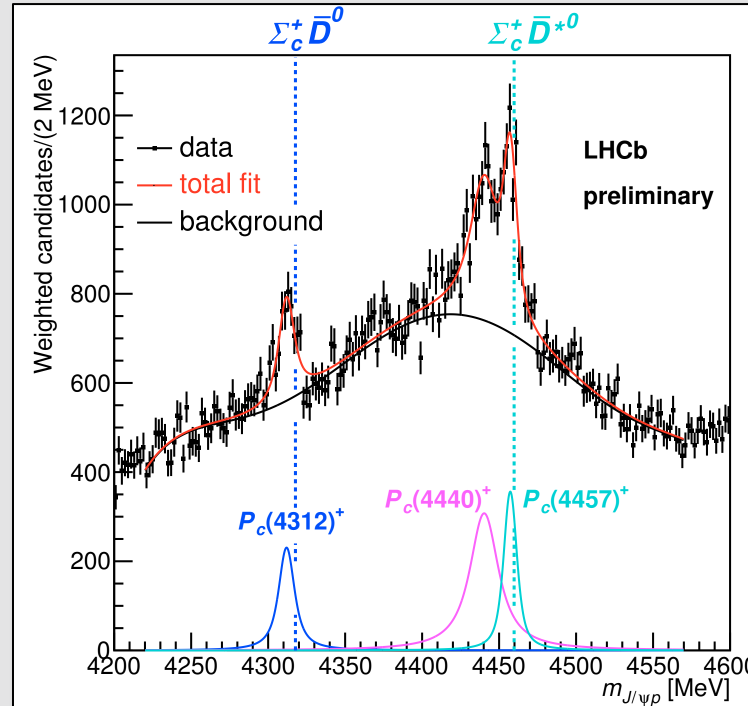
Exotics (Pentaquark)

$246\text{k}\ \Lambda_b^0 \to J/\psi p K^-$

$$\mathcal{R} \equiv \mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)/\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)$$

- Largest systematic
  - Background models





LHCb-PAPER-2019-014

State	M [MeV]	Γ [MeV] (95% CL)	$\mathcal{R}$
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$ (< 27)	$(0.30 \pm 0.07^{+0.34}_{-0.09})\%$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$ (< 49)	$(1.11 \pm 0.33^{+0.22}_{-0.10})\%$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$ (< 20)	$(0.53 \pm 0.16^{+0.15}_{-0.13})\%$

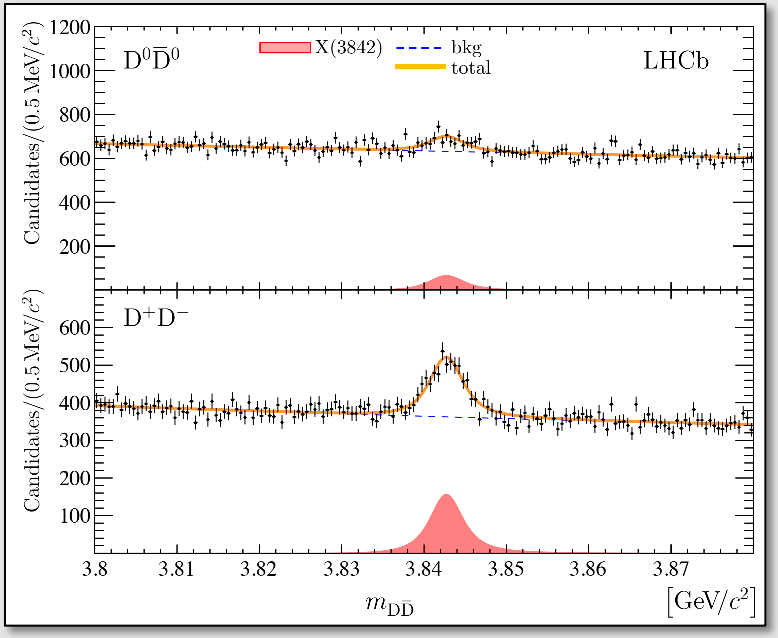
Therefore, verification of the $P_c(4380)^+$ awaits completion of the amplitude analysis of this new data sample.

Exotics (Tetraquark)

$2070 \pm 190 \quad X(3842) \to D^+D^-$

$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV}/c^2$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}\,,$$

- Largest systematic
  - D mass
  - Resolution



LHCb-PAPER-2019-005

Source	X(3842) σ_m [MeV/c^2]	σ_Γ [MeV]
Signal model	0.02	0.02
Resolution		0.31
Background model		0.13
Momentum scale	0.07	—
D-meson masses	0.10	—
Sum in quadrature	0.12	0.35

ΔA_{CP}

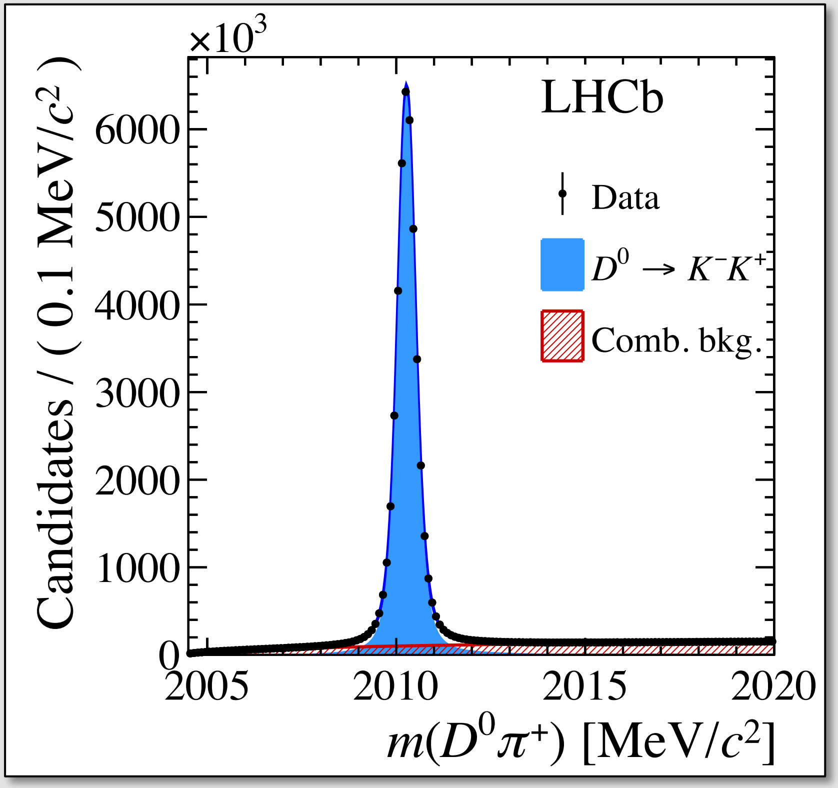
53 million $D^0 \to K^- K^+$

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- Largest systematic uncertainty
  - Mass model
    - (Even here statistics dominated…)

Source	π-tagged $[10^{-4}]$
Fit model	0.6
Mistag	–
Weighting	0.2
Secondary decays	0.3
B^0 fraction	–
B reco. efficiency	–
Peaking background	0.5
Total	0.9



PAPER-2019-006 arXiv:1903.08726

Lessons learned from LHCb

Lots of "lessons" learned on wide span of flavour physics

- CP violation
- Leptons
- Charm
- Exotica

➢ No obvious experimental shortcoming emerging,
which prevents further improvements

On the menu

- Introduction: Precision measurements
- Recent highlights
- Where do we come from?
- What brought us here?
  - Lumi levelling
  - Trigger
  - Magnet flips
  - Data driven
    - Tracking
    - PID
    - Control channels
- **Lessons learned from LHCb**

Where do we come from

- Some history

Where do we come from

LHC-B

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

- LHC-B Letter-of-Intent 1995

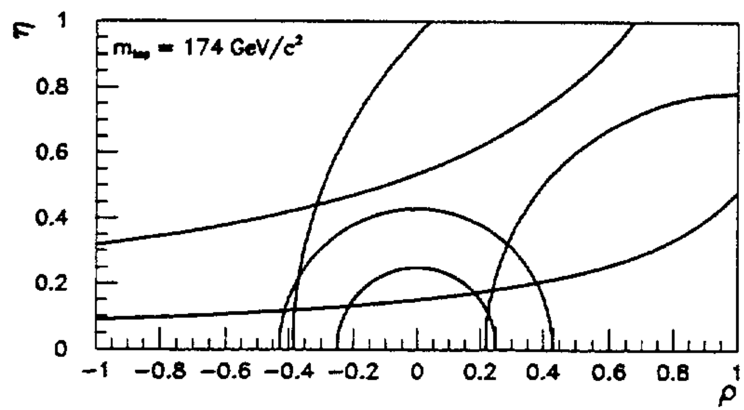


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

(top not yet discovered…)

Where do we come from

- Letter-of-Intent 1995

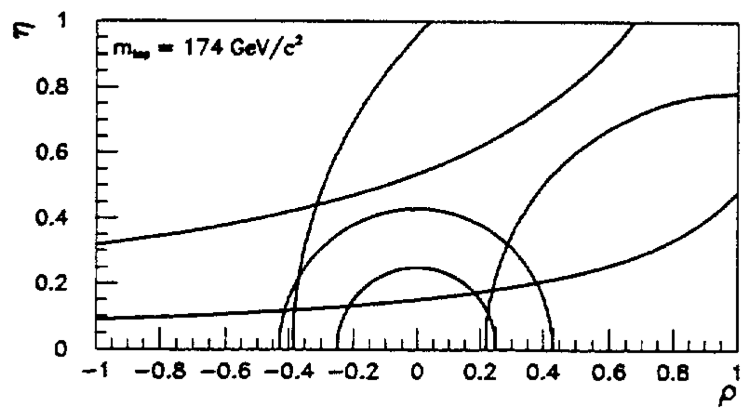


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

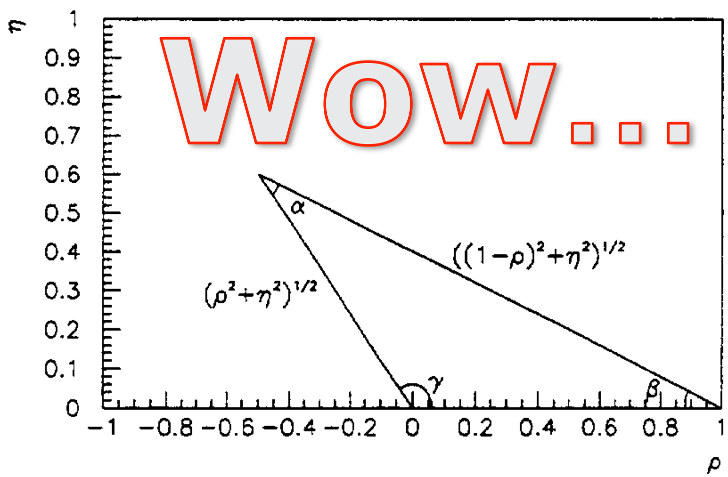


Figure 2.2: The Unitarity Triangle

Vintage Triangle !?

UT → VT

Where do we come from

Letter-of-Intent 1995:

- Annual event yield estimates:
  - N($B^0_s \rightarrow J/\psi\varphi$) = 246k
  - N($B^0_s \rightarrow \mu^+\mu^-$) = 30
  - N($B^0 \rightarrow K^*\mu^+\mu^-$) = 17k
  - Assuming L=1.5 x 10^{32} cm^{-2}s^{-1}
- Achieved:
  - 3x larger instantaneous luminosity
  - 2x lower event yields

Event Sample	Visible B.R.	Events On Tape
$B_d \rightarrow \pi^+\pi^-$ 0.5x10^{-5}	$2.0 \cdot 10^{-5}$	110k
$B_d \rightarrow J/\psi K^o_s\ (\mu\mu)$	$2.1 \cdot 10^{-5}$	340k
$B_d \rightarrow J/\psi K^o_s\ (ee)$	$2.1 \cdot 10^{-5}$	183k
$B_d \rightarrow J/\psi K^*\ (\mu\mu)$	$6.3 \cdot 10^{-5}$	1,270k
$B_d \rightarrow J/\psi K^*\ (ee)$	$6.3 \cdot 10^{-5}$	679k
$B_d \rightarrow \bar{D}^0 K^*\ (K\pi K\pi)$	$8.0 \cdot 10^{-7}$	3k
$B_s \rightarrow D_s^- \pi^+$	$1.4 \cdot 10^{-4}$	171k
$B_s \rightarrow D_s^- \pi^+\pi^+\pi^-$	$3.5 \cdot 10^{-4}$	277k
$B_s \rightarrow D_s^- K^+$	$1.1 \cdot 10^{-5}$	13k
$B_s \rightarrow D_s^+ K^-$	$5.3 \cdot 10^{-6}$	6k
$B_s \rightarrow J/\psi\,\phi\ (\mu\mu)$	$4.2 \cdot 10^{-5}$	246k
$B_s \rightarrow J/\psi\,\phi\ (ee)$	$4.2 \cdot 10^{-5}$	133k
$B_s \rightarrow \mu^+\mu^-$	$4.0 \cdot 10^{-9}$	10^{-3}? 30
$B_d \rightarrow \mu^+\mu^- K^*$	$2.9 \cdot 10^{-6}$	17k
$B_u \rightarrow \bar{D}^0 K^+ (K\pi)$	$1.5 \cdot 10^{-5}$	76k
$B_u \rightarrow \bar{D}^0 K^+ (K\pi\pi\pi)$	$3.1 \cdot 10^{-5}$	117k

?

Same?

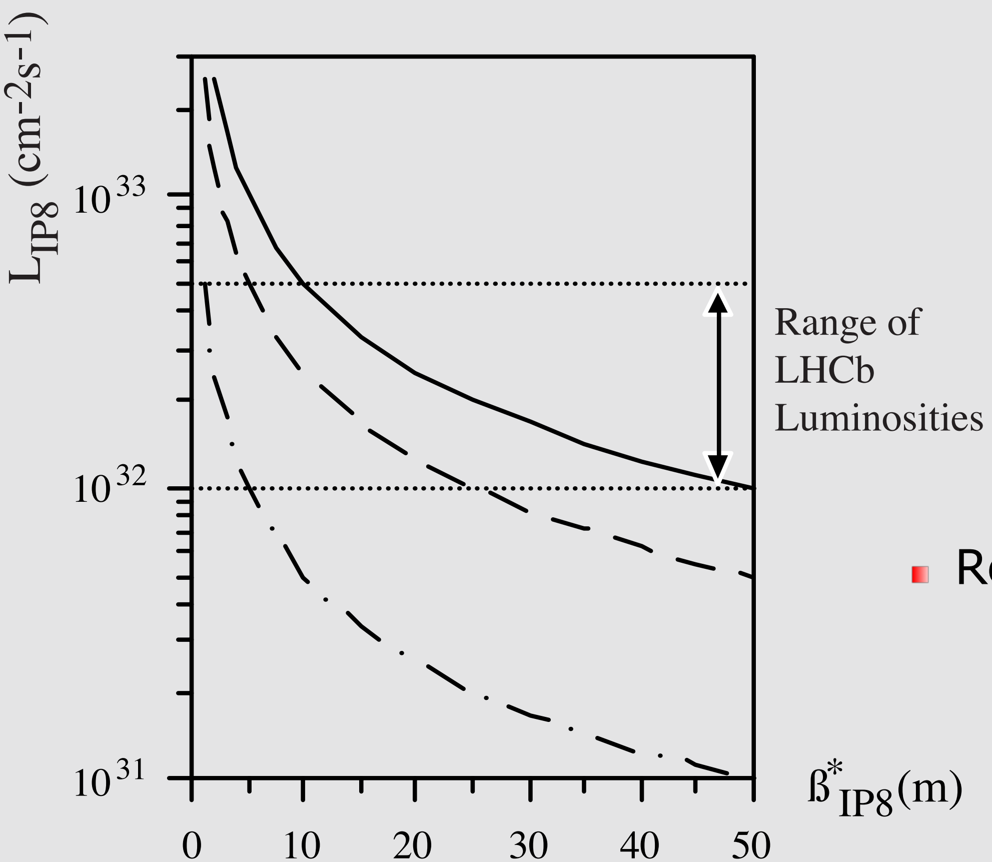
Table 1.1: The calculated number of "Events on Tape" in single-interaction bunch crossings, using the Level-1 and Level-2 trigger efficiencies from Chapt. 10 $\mathcal{L} = 1.5 \cdot 10^{32}$ cm^{-2} s^{-1}, and assuming no losses in Level-3. Note that reconstruction and tagging efficiencies are not included in this table. For $B_d \rightarrow \pi^+\pi^-$ the branching fraction, 2×10^{-5}, is used, as it has become the "standard" for comparing different experiments. Recent measurements[11] indicate that the actual value may be smaller. The predicted branching fraction for $B_s \rightarrow \mu^+\mu^-$ is from Ref. [12].

Where do we come from

- Technical Proposal 1998
  - Event yields closer…
  - Assuming L=2 x 10^{32} $cm^{-2}s^{-1}$

Table 1.1: Expected numbers of events reconstructed offline in one year (10^7 s of data taking) with an average luminosity of 2×10^{32} cm^{-2} s^{-1}, for some channels.

Decay Modes	Visible Br. fraction	Offline Reconstr.
$B_d^0 \to \pi^+\pi^-$ + tag	0.7×10^{-5}	6.9 k
$B_d^0 \to K^+\pi^-$	1.5×10^{-5}	33 k
$B_d^0 \to \rho^+\pi^-$ + tag	1.8×10^{-5}	551
$B_d^0 \to J/\psi K_S$ + tag	3.6×10^{-5}	56 k
$B_d^0 \to \overline{D}^0 K^{*0}$	3.3×10^{-7}	337
$B_d^0 \to K^{*0}\gamma$	3.2×10^{-5}	26 k
$B_s^0 \to D_s^-\pi^+$ + tag	1.2×10^{-4}	35 k
$B_s^0 \to D_s^- K^+$ + tag	8.1×10^{-6}	2.1 k
$B_s^0 \to J/\psi\phi$ + tag	5.4×10^{-5}	44 k



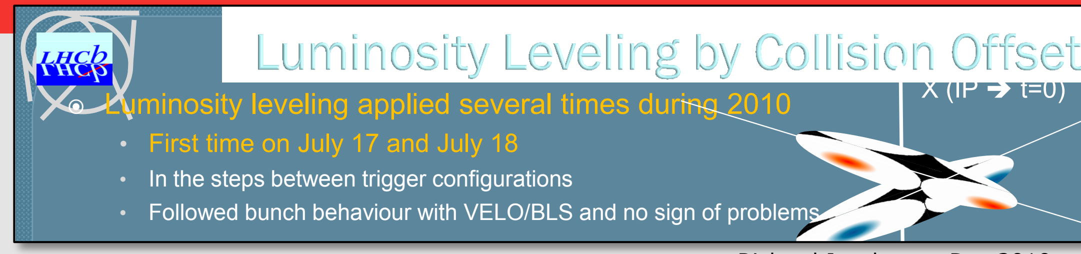
- Reoptimized LHCb (TDR 2003)
  - Assuming *average* L= 2 x 10^{32} $cm^{-2}s^{-1}$

teraction point. The luminosity L is assumed to decrease exponentially with a 10-hour lifetime in the course of 7-hour fills, with an average value of 2×10^{32} cm^{-2}s^{-1} (implying a maximum value of $\sim 2.8 \times 10^{32}$ cm^{-2}s^{-1} at start of fill). In practice,

What brought us here?   Lumi levelling

- Trade-of between
  - High L: statistics
  - Low L: clean events
    - + higher data rate! Network is limited by (rate x multiplicity)

What brought us here? Lumi levelling



Richard Jacobsson, Dec 2010

- Trade-of between
  - High L: statistics
  - Low L: clean events

- Operate continuously at constant optimal *L* !

What brought us here? Lumi levelling

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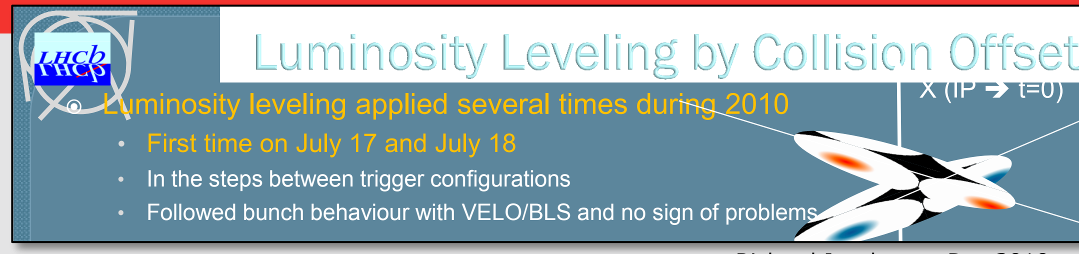
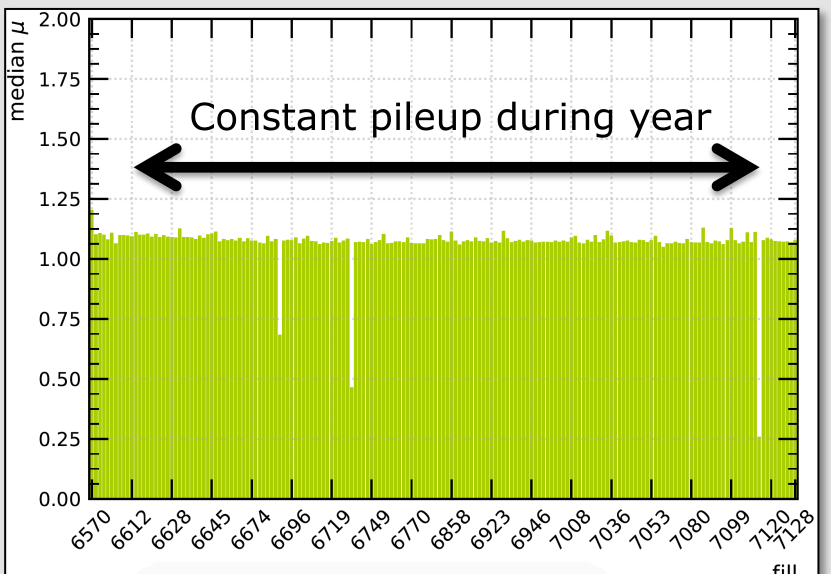
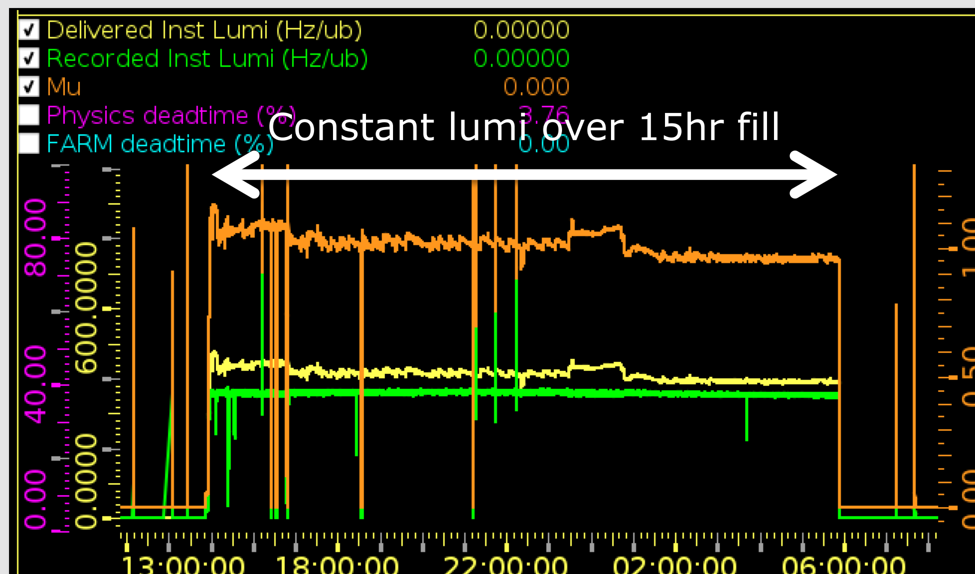


Richard Jacobsson, Dec 2010

- Operate continuously at constant optimal *L* !
  - Displace beams at start of fill, then move closer when protons disappear
  - In 2018 also employed by ATLAS/CMS





What brought us here? Low sys or low stats?

- Main physics results dominated by statistical uncertainty (run-1) :

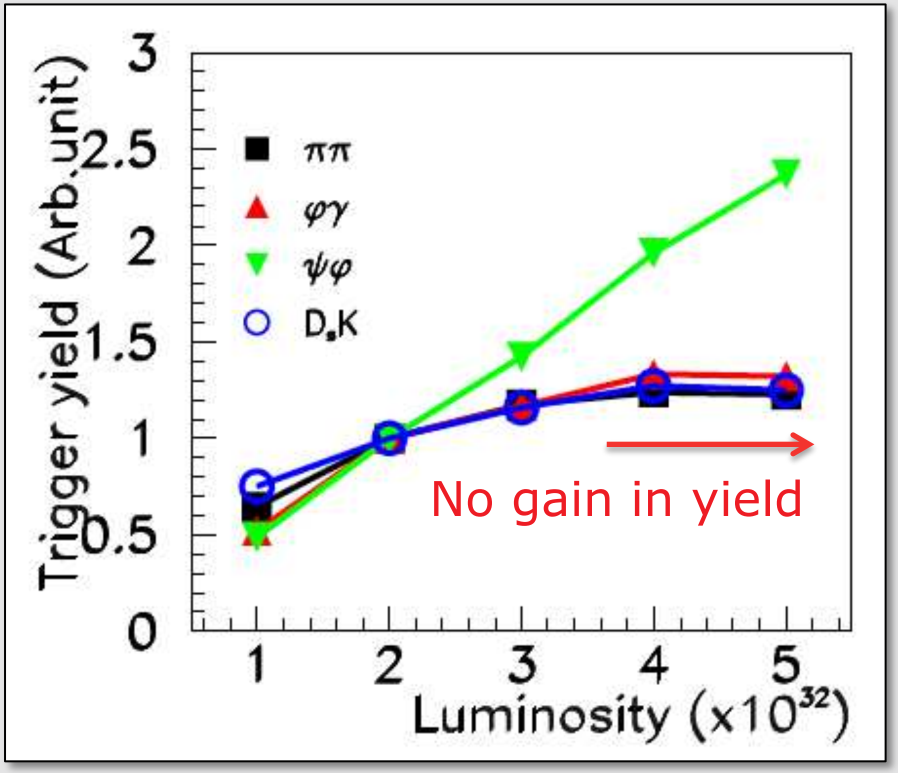
Observable	Current LHCb	σ(stat)/σ(sys)	Largest source of systematic
EW Penguins			
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	2.5	Mass shape & trigger eff
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	2.2	MC correction & residual bkgd
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	3	Δm_s, time res, tagging, det asymmetry
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	-	
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [609]	8	Decay time: bias and efficiency
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	8	Angular efficiency
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	8	Decay time resolution
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	5	Acceptance (angular and time)
$a_{\rm sl}^s$	33×10^{-4} [211]	1.3	Track reco asymmetry
$\vert V_{ub}\vert / \vert V_{cb}\vert$	6% [201]	0.5	External BR(Λ_c)
$B_s^0, B^0 \to \mu^+\mu^-$			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	6	f_d/f_s
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	9	Decay time acceptance
$S_{\mu\mu}$	–		
$b \to c\ell^-\bar{\nu}_l$ **LUV studies**			
$R(D^*)$	0.026 [215, 217]	1	MC sample size
$R(J/\psi)$	0.24 [220]	1	$F(B_c \to J/\psi)$ form factor
Charm			
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	2.7	Mass model
A_Γ ($\approx x \sin\phi$)	2.8×10^{-4} [240]	2.8	Contribution from sec b→D*X decays
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	2	Contribution from sec b→D*X decays

Physics Case for an LHCb Upgrade II, CERN-LHCC-2018-027

Event sample size, *aka* statistics

- Sample size ~ trigger eff x luminosity

- Increasing luminosity implies tighter trigger selection…
  - Marginal gain…
  - Trigger yield is flat:



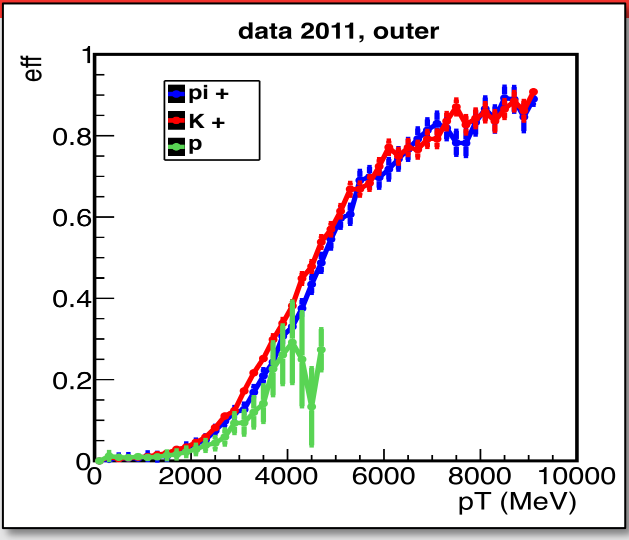
Letter of Intent for the LHCb Upgrade, CERN-LHCC-2011-001

➢ Solution: *improve the trigger*

What brought us here? Trigger

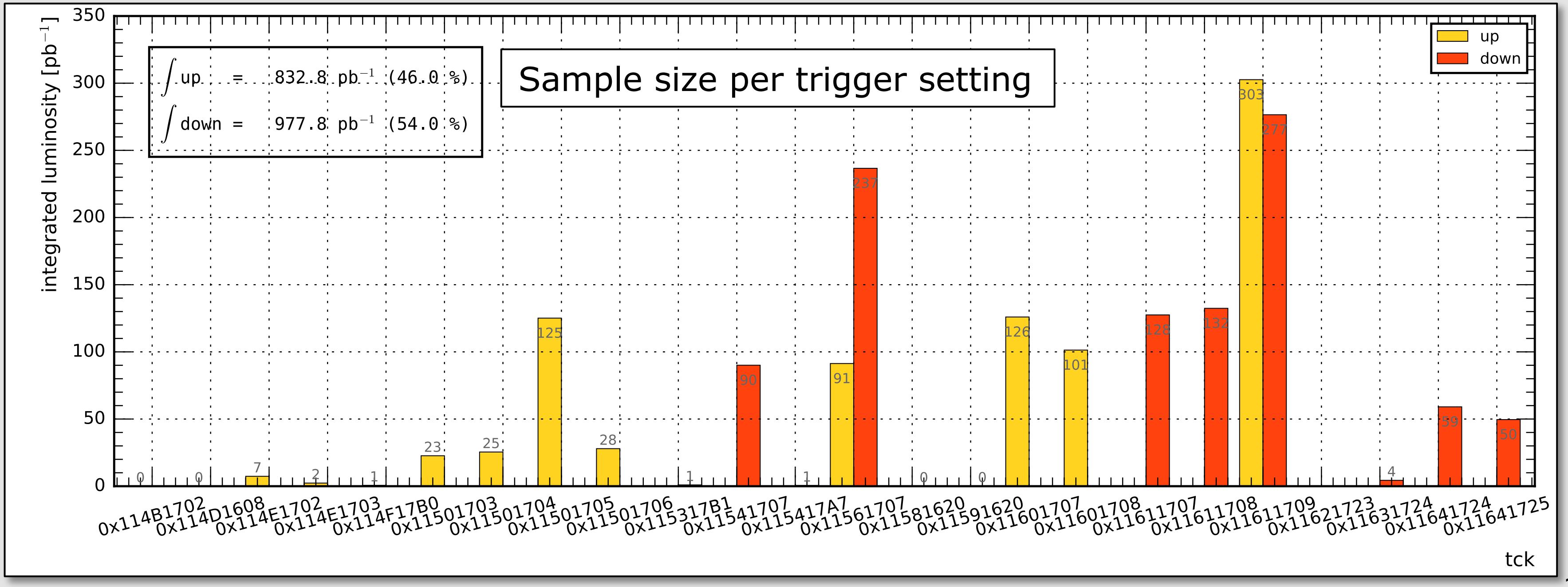
- Low level trigger: *Knowledge of efficiency*

$$\varepsilon_{\text{hadron}} = \frac{N(\text{TIS and TOS})}{N(\text{TIS})}$$



LHCb-PUB-2011-026

- High level trigger: *Stability*



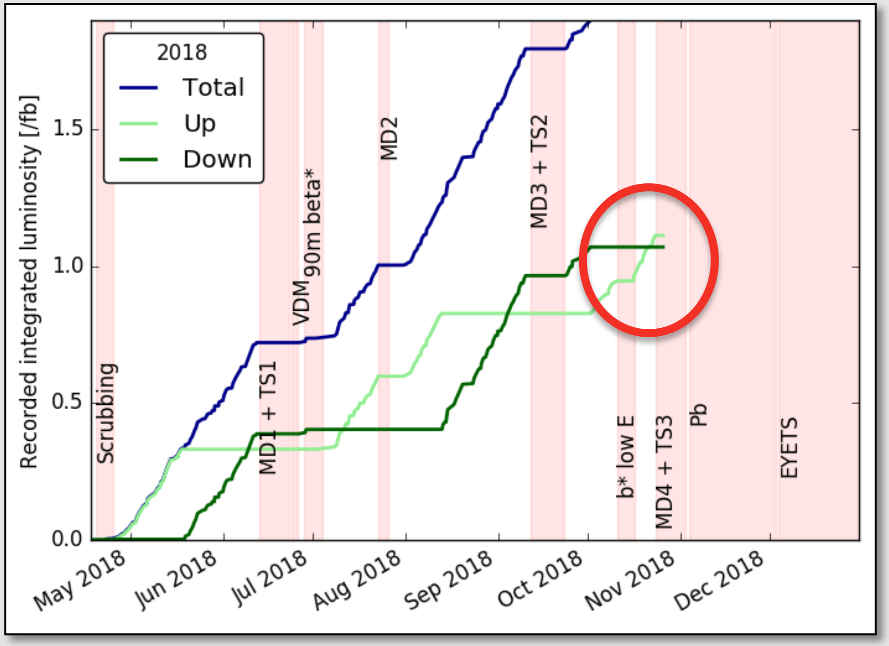
What brought us here?   Magnet flips

- Many precision measurements rely on asymmetries
  - Charge asymmetries
  - Angular asymmetries
  - Differences of asymmetries
- D0 could do A_{fs}, CDF not

What brought us here? Magnet flips

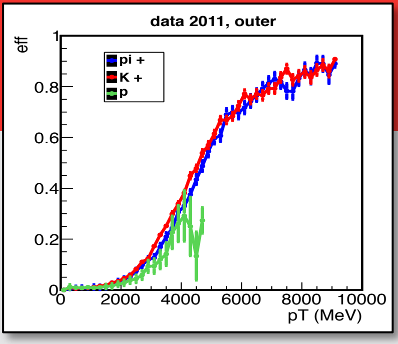
- Many precision measurements rely on asymmetries
  - Charge asymmetries
  - Angular asymmetries
  - Differences of asymmetries
- D0 could do A_{fs}, CDF not

- Detector asymmetries cancel by flipping the magnet polarity
  - Carefully matched the two data sets



	Recorded Lumi (pb^{-1})
UP	1110
DOWN	1070
Total	2180

What brought us here? Data driven



LHCb-PUB-2011-026

- L0 calorimeter efficiency
  - Using $D^0 \to K^- \pi^+$, $B^0 \to J/\psi(ee)K^*$
- Tracking efficiency
  - Tag-and-probe with $J/\psi \to \mu^+\mu^-$

Data	Magnet up		Magnet down	
	Positive	Negative	Positive	Negative
2010	94.1 ± 1.3	96.0 ± 1.3	$99.3^{+0.7}_{-1.8}$	$98.4^{+1.6}_{-1.7}$
2011	97.0 ± 0.3	97.3 ± 0.3	97.2 ± 0.3	97.4 ± 0.3
2012	96.2 ± 0.2	96.2 ± 0.2	96.2 ± 0.2	96.3 ± 0.2

LHCb, JINST 10 (2015) no.02, P02007, arXiv:1408.1251

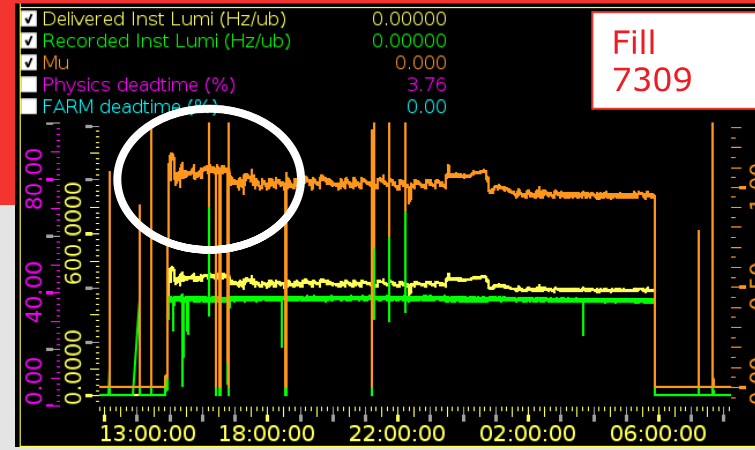
- Particle identification
  - Dedicated control samples

Species	**Low momentum**	**High momentum**
$e^\pm$	$B^+ \to J/\psi K^+$ with $J/\psi \to e^+e^-$	
$\mu^\pm$	$B^+ \to J/\psi K^+$ with $J/\psi \to \mu^+\mu^-$	$J/\psi \to \mu^+\mu^-$
$\pi^\pm$	$K^0_S \to \pi^+\pi^-$	$D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$
$K^\pm$	$D^+_s \to \phi\pi^+$ with $\phi \to K^+K^-$	$D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$
$p, \bar{p}$	$\Lambda^0 \to p\pi^-$	$\Lambda^0 \to p\pi^-$; $\Lambda^+_c \to pK^-\pi^+$

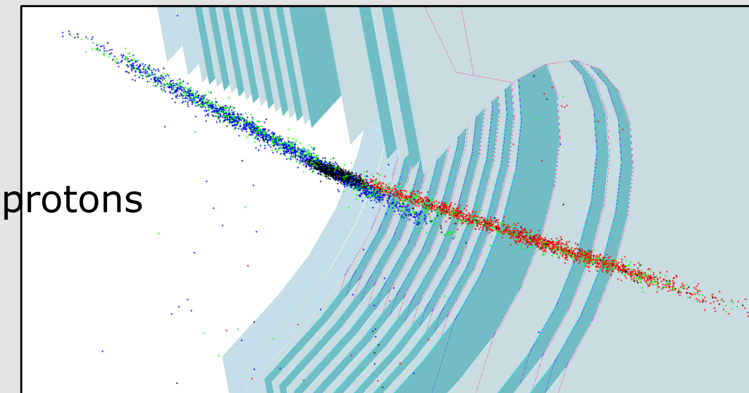
LHCb, EPJ Tech.Instrum. 6 (2019) 1, arXiv:1803.00824

- Control channels for analyses:
  - $B^0 \to J/\psi K^*$ for $B^0_s \to J/\psi\varphi$
  - $B^0 \to J/\psi K^+$ for $B^0 \to K^+e^+e^-$
  - $B^0 \to D^-\pi^+$ for $B^0_s \to D_s^-\pi^+$
  - $B^0_s \to D_s^-\pi^+$ for $B^0_s \to D_sK$
  - …

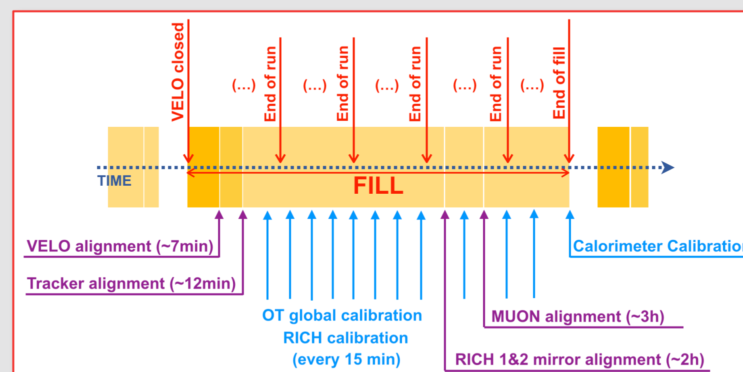
Lessons from operations



- Luminosity monitoring
  - Dependent on single detector:
    - failure requires timely understanding
  - ➢ Implement more robust monitoring



- Luminosity measurement
  - Gas injection system extremely valuable
    - ATLAS/CMS relied on LHCb for LHC satellite protons
  - ➢ Keep (and improve) gas injection system
- Monitoring
  - Occasionally detector problems or bugs could have been caught faster
  - ➢ More precise monitoring of all trigger rates
- Real time alignment
  - Events are parked at 100 kHz
  - Selection to 5 kHz *after* event calibration
  - ➢ 1-to-1 correspondence to offline

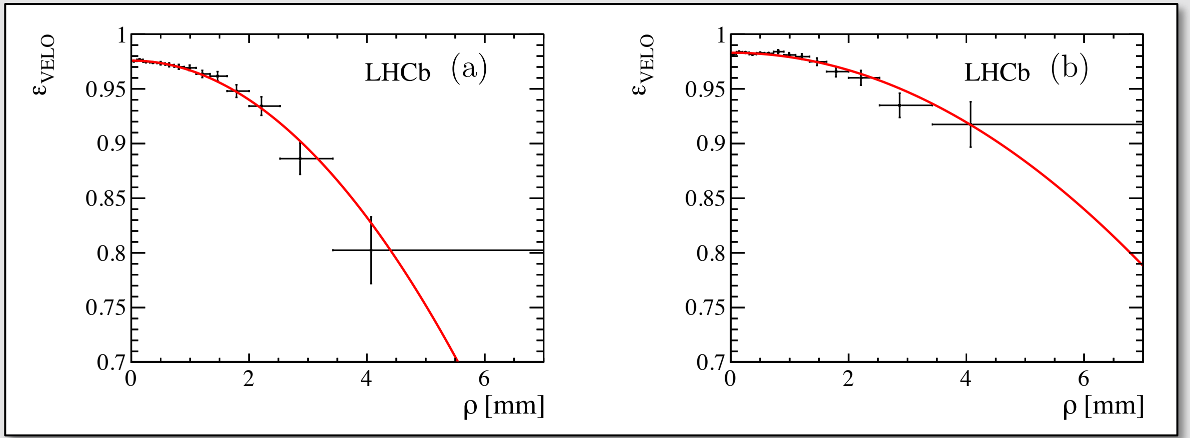


Lessons from/for analysis

- $B \rightarrow J/\psi X$
  - Time acceptance
- $B \rightarrow K e^{+} e^{-}$
  - Bremstrahlung correction
- Time-dependent B^0_s analysis
  - Flavour tagging:
    - Incl tagging?
    - OT time? PID coverage (p_T, eta)?
- Open Charm
  - magnet polarity
  - Crossing angle
- Electro-weak, jets
  - HCAL PMT gain
- Heavy-ion:
  - Simultaneous operation of pp and pPb

Lessons from/for analysis: Decay time acc

- *B→ J/ψX*
  - Time acceptance
  - Long living B mesons
    - Decay off-axis
    - Pattern recognition less efficient



LHCb, arXiv:1402.2554, Measurements of the B^+, B^0, B_s^0 meson and Λ^0_b baryon lifetimes

Lessons from/for analysis: Decay time acc

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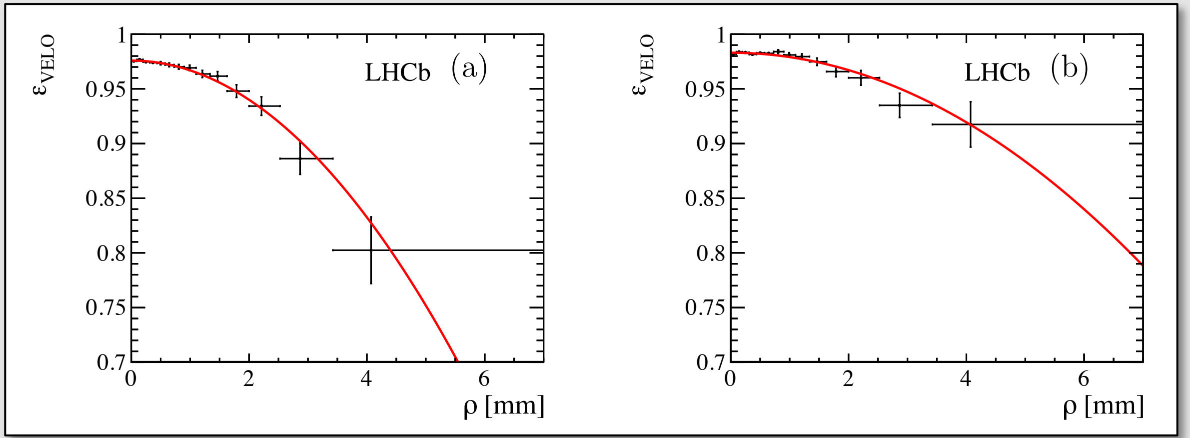

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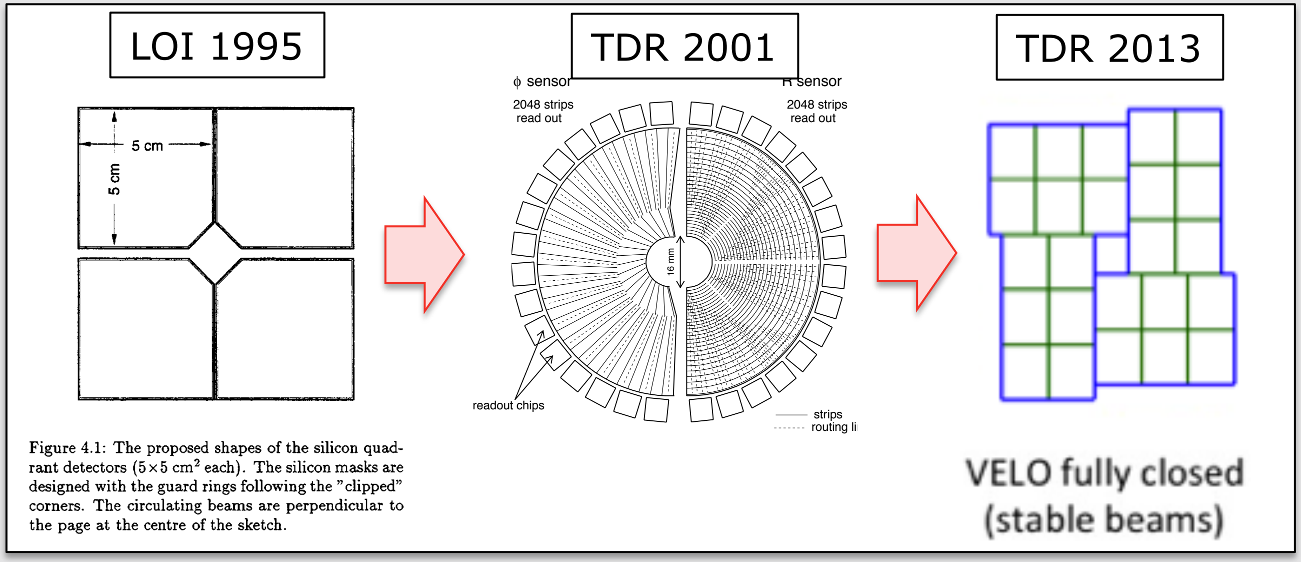
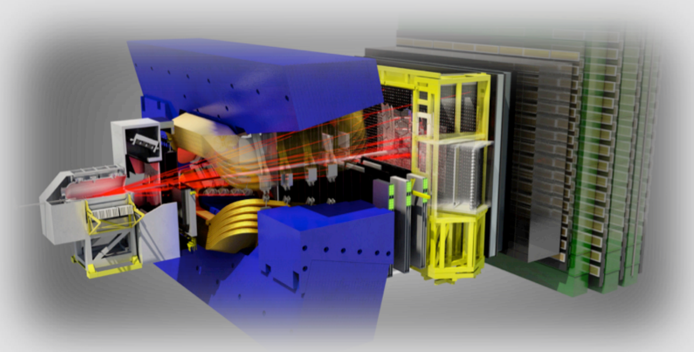


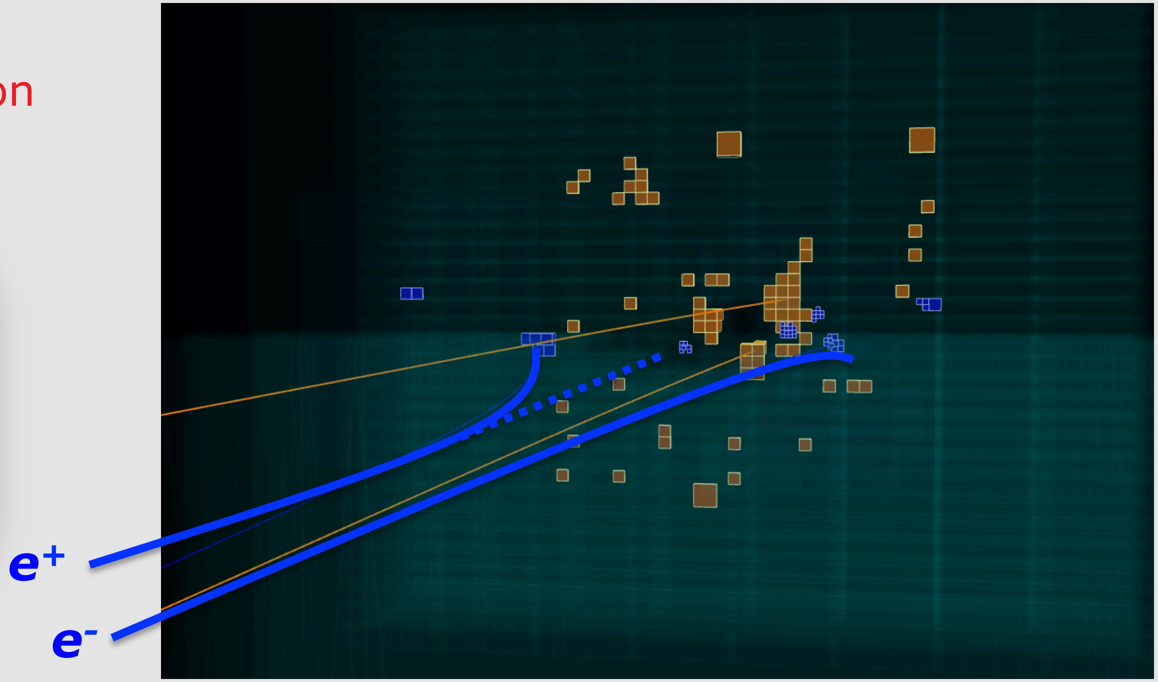
Figure 4.1: The proposed shapes of the silicon quadrant detectors (5×5 cm² each). The silicon masks are designed with the guard rings following the "clipped" corners. The circulating beams are perpendicular to the page at the centre of the sketch.

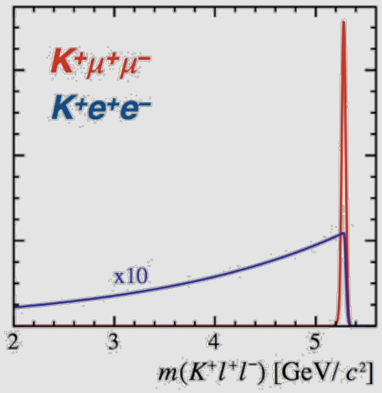
- Pixel detector more robust

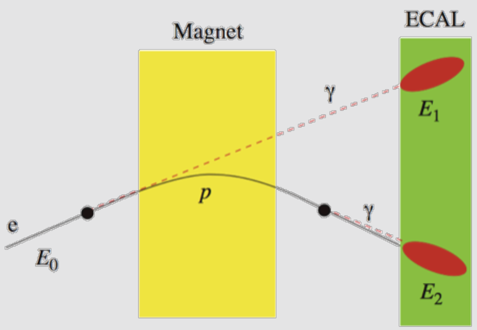
Lessons from/for analysis: Bremstrahlung

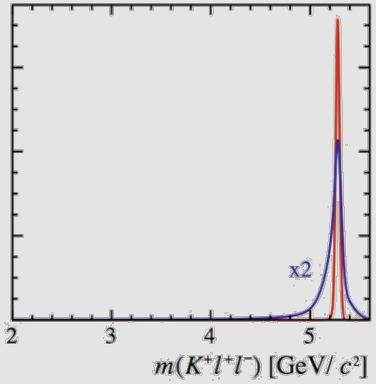
- $B \rightarrow Ke^{+}e^{-}$
  - Bremstrahlung correction





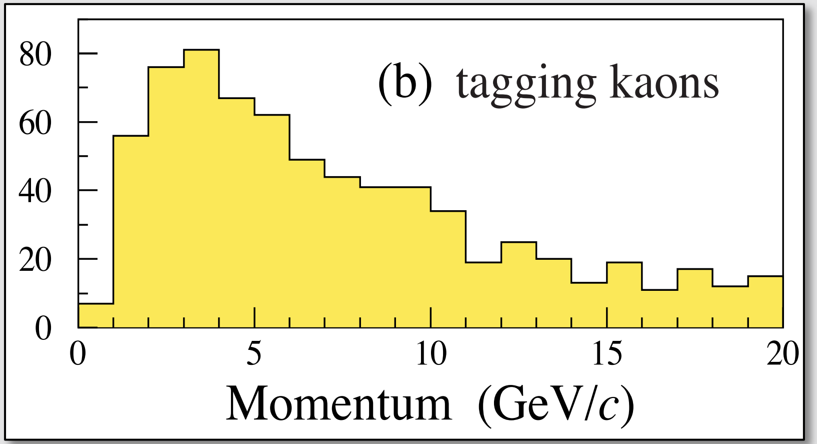




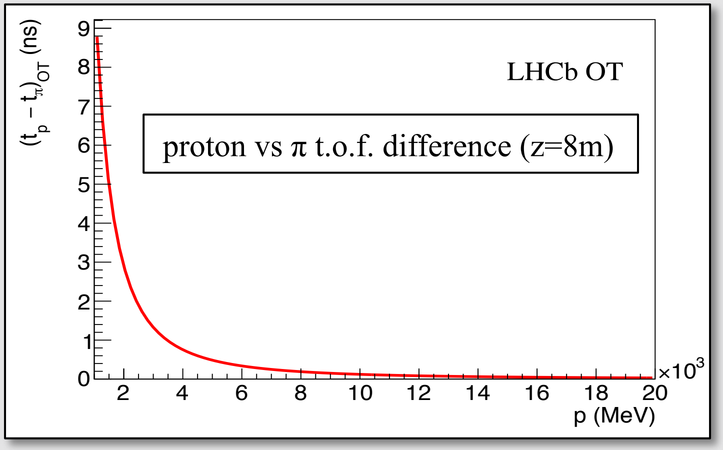


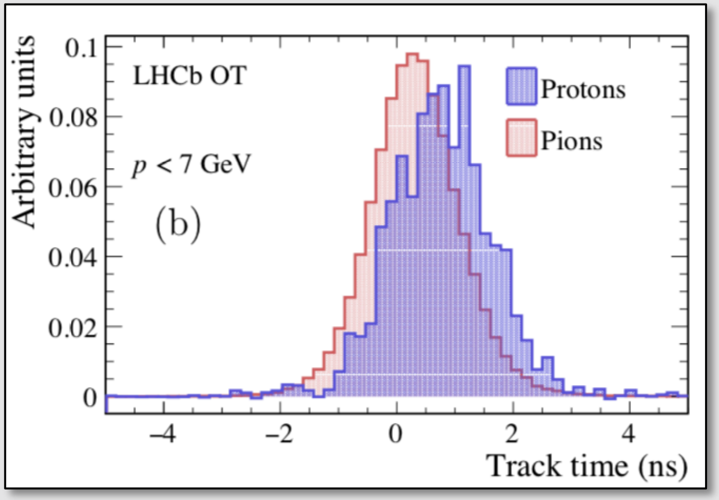
Lessons from/for analysis: Flavour tagging

- Tagging: from fragmentation → *low momentum*
- Outer Tracker time resolution: ~0.6 ns / track
  - Time-of-flight difference proton vs pion at z=8m: ~1 ns



LHb, RICH TDR, LHCC-2000--037



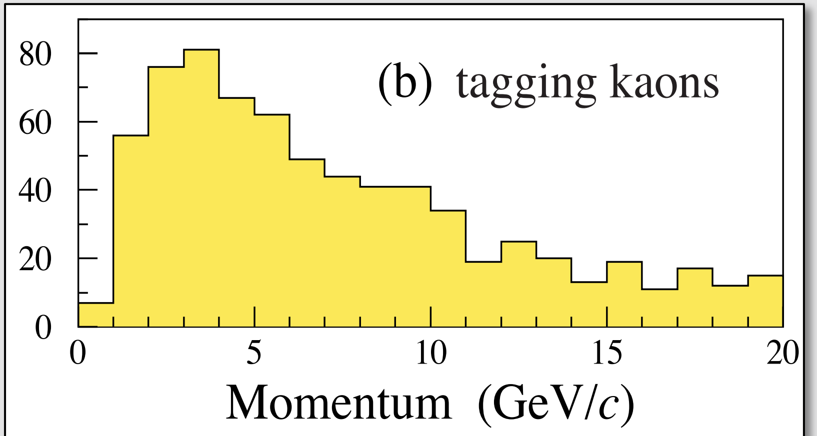


  - Use of timing has the future

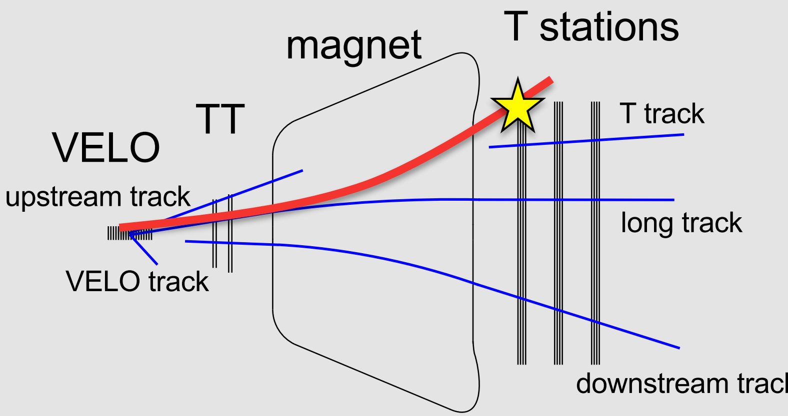
LHCb coll., Ph. d'Argent et al., JINST 12 (2017) P11016
Improved performance of the LHCb Outer Tracker in LHC Run 2

Lessons from/for analysis: Flavour tagging

- Tagging: from fragmentation → *low momentum*
- Improve coverage for low momenta



LHb, RICH TDR, LHCC-2000--037

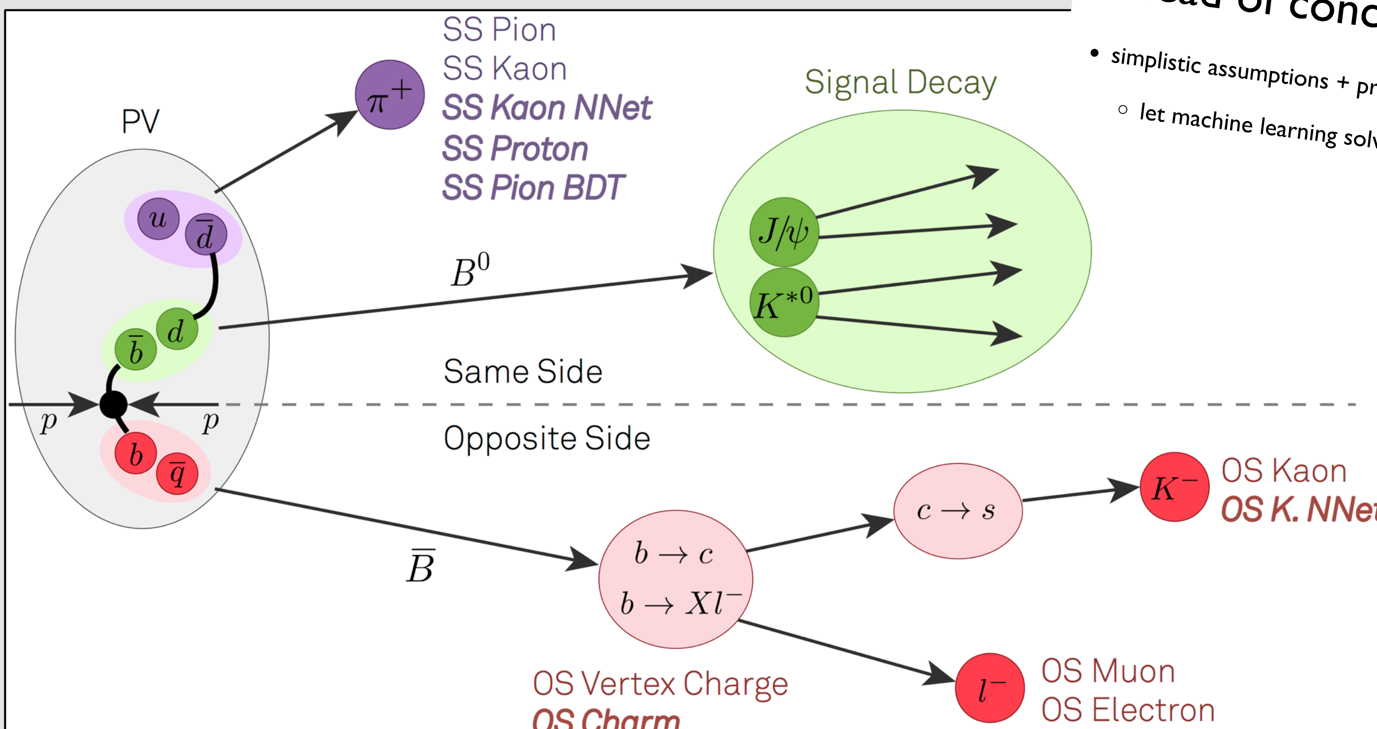


- No extra detectors in run-3 yet
- Could use tracks with *single* hit in T stations
  - Also useful for high-multiplicity decays
    - $D^{*+} \rightarrow D^0 \pi^+$
    - $D^0 \rightarrow K\pi\pi\pi$
    - $B \rightarrow DD$
    - ...

Lessons from/for analysis: Flavour tagging

D.Derkach, T.Likhomanenko, A.Rogozhnikov,
IML workshop, March 2017

- Inclusive tagging
  - use all (non-signal) tracks from event
  - let machine guess *which* tracks are tagging & *how* charge is connected to flavour
  - estimate probability
    - decisionTrain uses *oblivious* tree
    - adaptive versions of *stochastic gradient descent*
    - Tagging with *attention* (by assigning weights in a *softmax*-like manner)
    - logistic regression and *isotonic* regression



Instead of conclusion

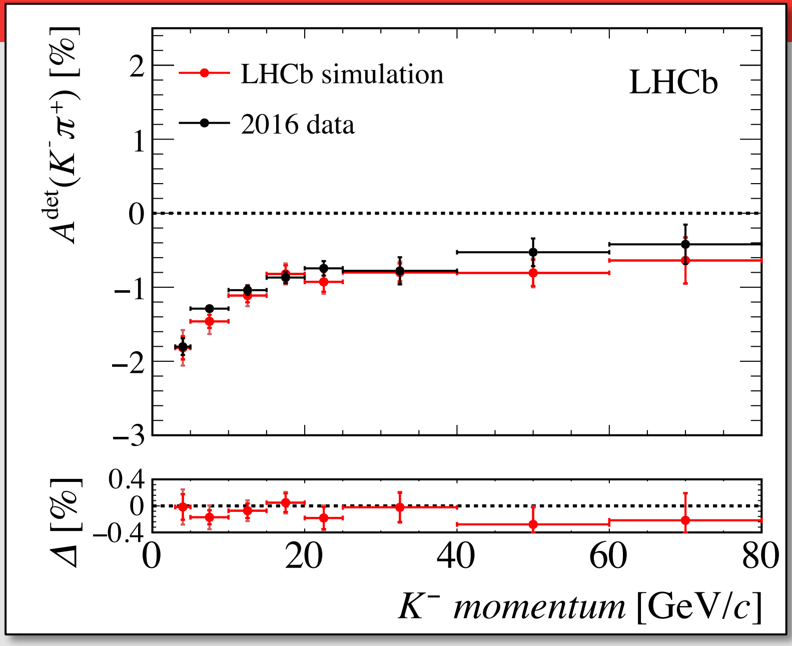
- simplistic assumptions + probability theory can give huge boost
  - let machine learning solve the whole problem is a nice idea

Lessons from/for analysis: Charm

- Huge statistics
  - Asymmetry of kaon interaction rate

$$A^{\text{det}}(K^-\pi^+) = (-0.89 \pm 0.15\,(\text{stat}) \pm 0.06\,(\text{syst}))\% \text{ in } 2015,$$
$$A^{\text{det}}(K^-\pi^+) = (-1.03 \pm 0.06\,(\text{stat}) \pm 0.06\,(\text{syst}))\% \text{ in } 2016.$$

- Magnet polarity
  - Take equal samples



LHCb-PUB-2018-004, *Measurement of the instrumental asymmetry for K‑+-pairs at LHCb in Run 2*

Lessons from/for analysis: Charm

- Huge statistics
  - Asymmetry of kaon interaction rate

$$A^{\text{det}}(K^-\pi^+) = (-0.89 \pm 0.15\,(\text{stat}) \pm 0.06\,(\text{syst}))\% \text{ in } 2015,$$
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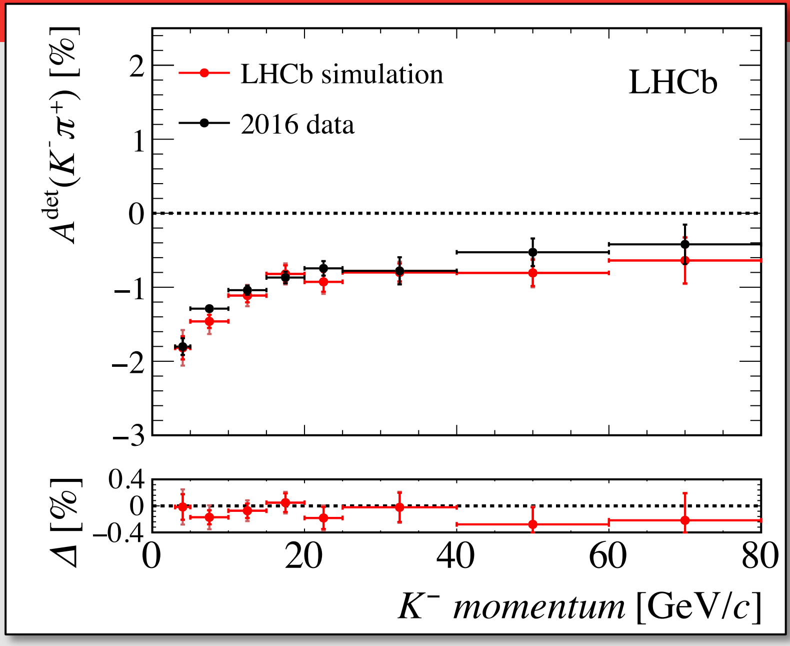


LHCb-PUB-2018-004, *Measurement of the instrumental asymmetry for K↑+-pairs at LHCb in Run 2*

- Crossing angle
  - "Internal" crossing angle flips with magnet polarity
    - causes an asymmetry when averaging over magnet polarities
  - Ideal scenario: change of external crossing angle to compensates internal crossing angle
    - identical total angle for both polarities

Year	$\theta_x^{internal}$ [µrad]	$\theta_x^{external}$ [µrad]	$\theta_y^{external}$ [µrad]
2011	270	−250	0
2012	236	0	100
2015	145	−250	0
2016	145	−250	0

Source	Particles	$\mathcal{O}$[%]
Cross-sections	π^+, K^+, p	0, 1, 3
IT cables	Hadrons, e	0.2
OT geometry	All	0.2
Beam spot	All, small for muons	0.2
Velo geometry	All	0.3
Beam crossing angle	All	0.5
Inner tracker defects	All	0.1

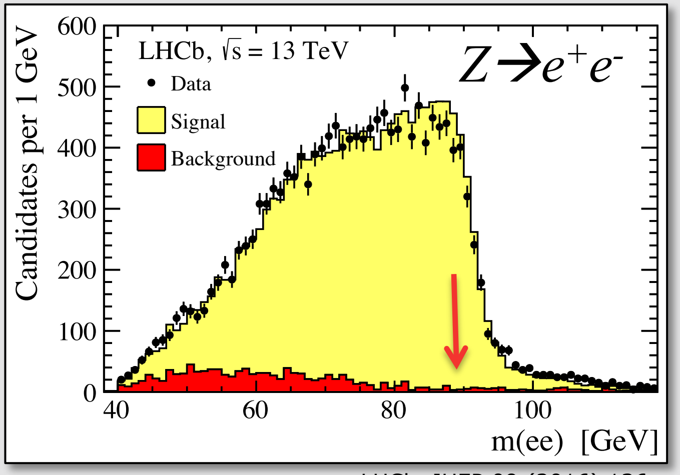
L. Dufour & J. van Tilburg, LHCb-INT-2018-006, *Decomposition of simulated detection asymmetries in LHCb*

Lessons from/for analysis: Jets, Heavy Ions

Jets

- B decay products: lower energy scale
- Jets: higher energy scale

- Increase calorimeter dynamic range?
  - More noise, worse Bremstrahlung recovery…



LHCb, JHEP 09 (2016) 136

Heavy Ions

Lessons from/for analysis: Jets, Heavy Ions

Jets

Heavy Ions

- Rich programme:
  - Pb-Pb collider
  - P-Pb collider
  - p fixed target
  - Pb fixed target
    - He, Ne, Ar targets
- Simultaneous operation (non-)colliding bunches

E (Z TeV)	$\sqrt{s_{NN}}$					
	pp		Pb-p		Pb-Pb	
	$\sqrt{s}=2E$		$\sqrt{s}=2E\sqrt{r}$		$\sqrt{s}=2Er$	
1.38	2.76	2013				
2.51	5.02	2015 2017				
3.5	7	2011	4.40		2.76	2010 LHCb off
4	8	2012	5.02	2013 2016	3.15	
6.37			8.00		5.02	2015 2018
6.5	13	2015- 2018	8.16	2016	5.13	

Lesson learned…: Errata

- 15 errata
  - 4 errata: VELO simulation mistake
  - 2 errata: bugs
  - 9 errata: minor
- Only small fraction of all papers! But need to stay vigilant

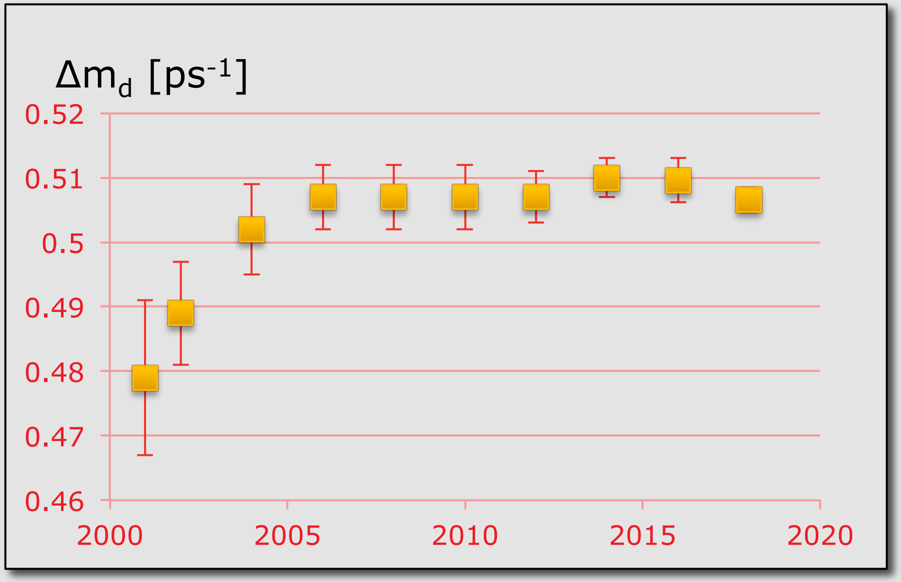
Title	Erratum	Mistake	Effect
Measurement of CKM angle gamma in B→DK	JHEP 1810 (2018) 107	Figure: label	Minor
Measurement of CP observables in B→DK*	JHEP 1805 (2018) 067	Wrong systematics	No consequence
Measurement of the J/ψ pair production at 13 TeV	JHEP 1710 (2017) 068	Track eff: double metal layer	Severe
Measurement of the b-quark production at 13 TeV	PRL 119 (2017) 169901	Track eff: double metal layer	Severe
Measurement of charm mixing and CP violation	PRD96 (2017) 099907	Swapped systematics	Minor
Measurement of S-wave fraction and B^0→K*μμ	JHEP 1704 (2017) 142	Eff: fast sim, and $m_{K\pi}$ range	~10%
Constraints on UT angle gamma from B→DKπ	PRD94 (2016) 079902	Figure: contours	Minor
First observation of the rare B→DKπ decay	PRD93 (2016) 119902	Value 10^{-4} instead of 10^{-6}	Typo
Measurements of prompt charm production at 13 TeV	JHEP 1705 (2017) 074	Track eff: double metal layer	Severe
Measurement of forward J/ψ production at 13 TeV	JHEP 1705 (2017) 063	Track eff: double metal layer	Severe
Measurement of the ratio of BR RD*	PRL 115 (2015) 159901	Incorrect asterisk	Typo
Differential BR and angular analysis of Λ_b→Λμμ	JHEP 1809 (2018) 145	Sign mistake for $\Lambda_b$bar	Severe
First observation and amplitude analysis of B→DKπ	PRD93 (2016) 119901	Value 10^{-4} instead of 10^{-6}	Typo
Observation of CP violation in B→DK decays	PLB713 (2012) 351	Publisher: twice same fig	Typo
Measurements of BR of B→Dπππ and Λ_b→Λ_cπππ	PRD85 (2012) 039904	Typo on "%" and charges	Typo

For details on tracking efficiency: V.Gligorov, arXiv:1806.10912

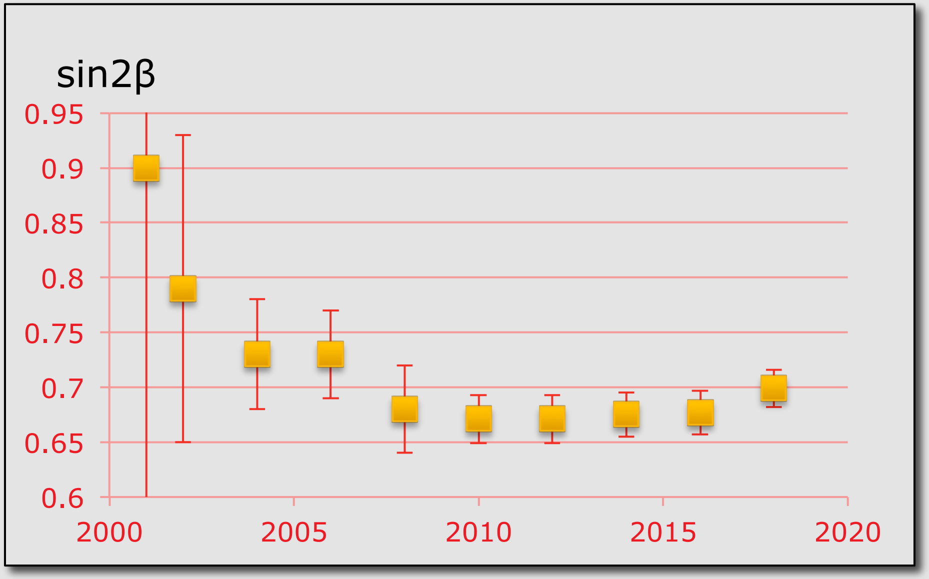
Lessons learned from LHCb

- Progress of last two decades!

Δm_d



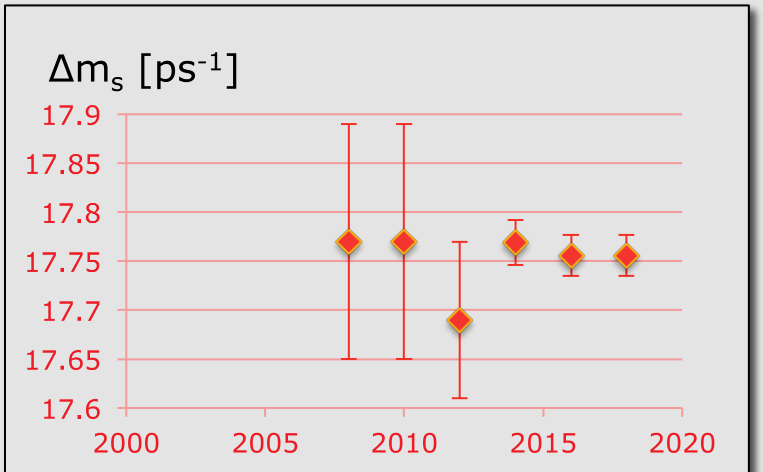
$\sin 2\beta$



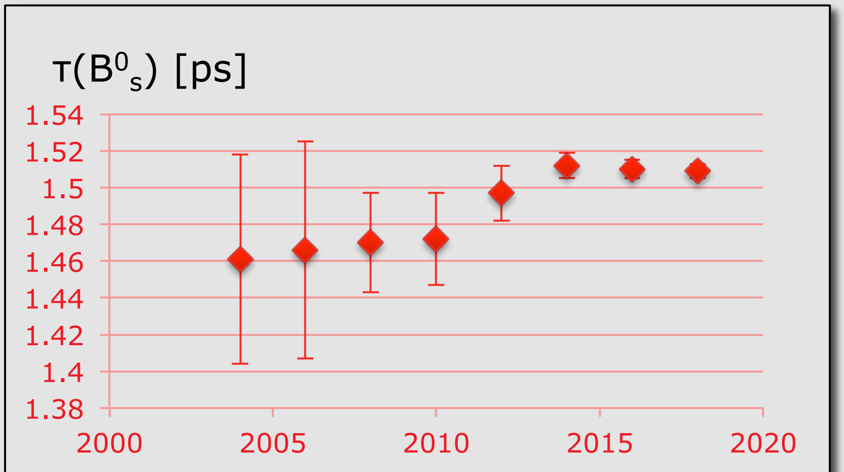
Lessons learned from LHCb

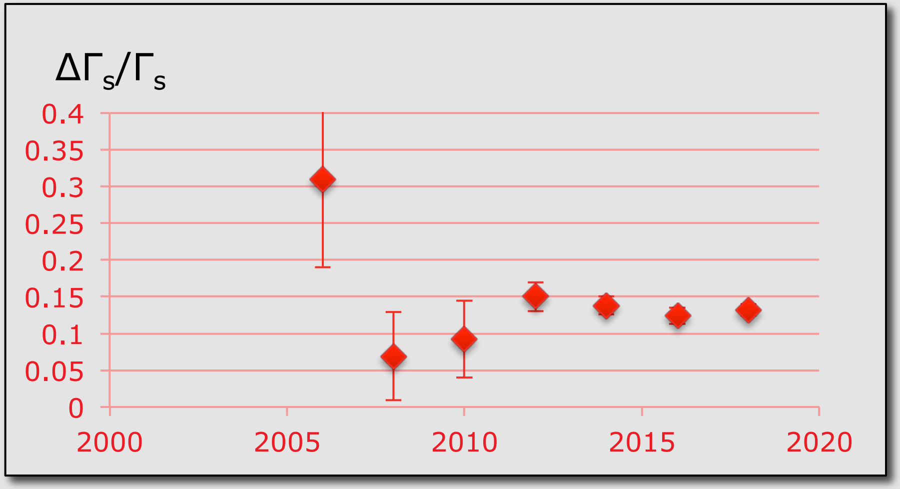
- Progress of last ~~two~~ decade!

Δm_s



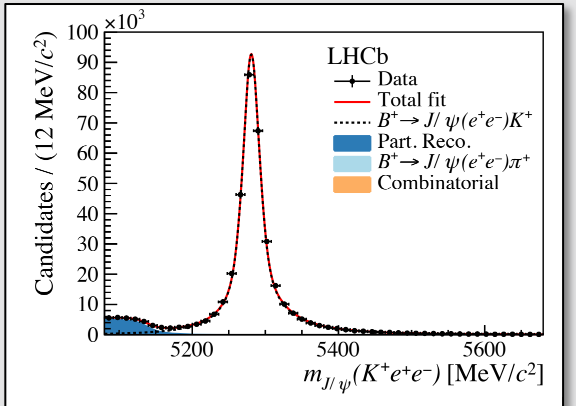
τ_{Bs}



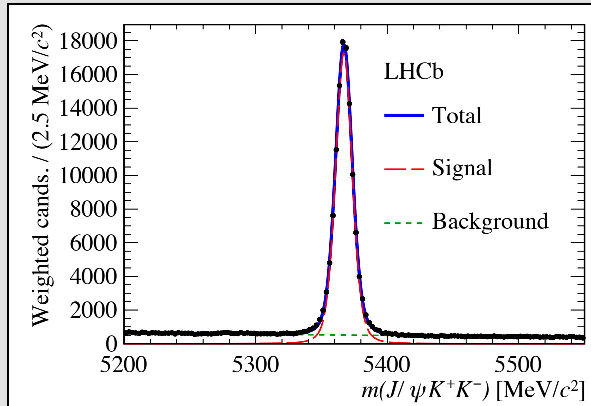


$\Delta\Gamma_s/\Gamma_s$

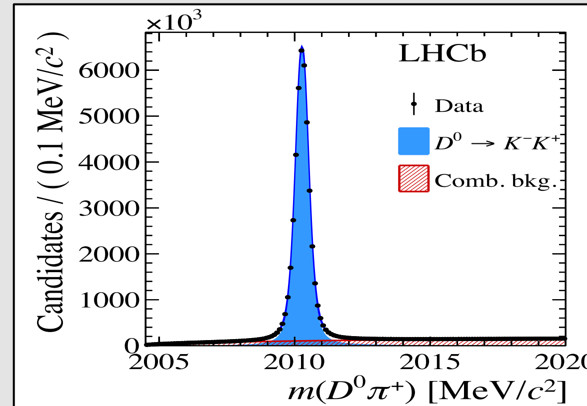
Lessons learned from LHCb



$B^+ \rightarrow J/\psi(ee)K^+$



$B_s^0 \rightarrow J/\psi(\mu\mu)\varphi$



$D^{+*} \rightarrow D^0(K^+K^-)\pi^+$

- Precision physics is possible at forward hadronic experiment

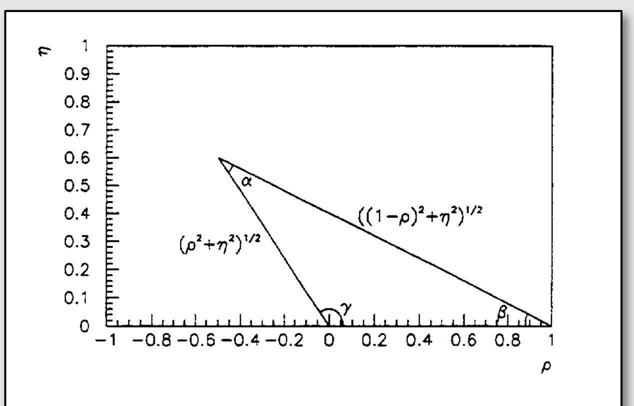
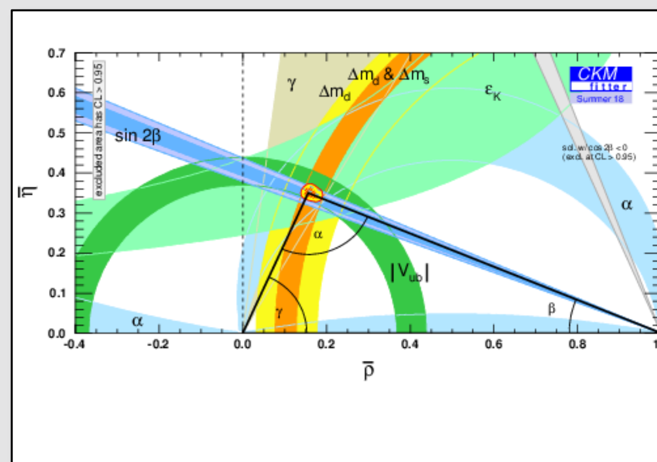


Figure 2.2: The Unitarity Triangle



Thank you

Lessons learned from LHCb
about making precise flavour measurements

Operations:

All:	Trigger stability, monitoring
Elec:	L0 ECAL constants
HCAL:	mu
Elec:	Bremstrahlung correction July 2016
Vtx:	Bunch lengthening
All:	Real time alignment (Muon Null alignment Aug 2018)
All:	More bugs: TISTOS, ALLSAMEBPV 2018, FT SSp Sspi
Lumi:	SMOG

MC:

VELO:	double metal layer, x-sec (erratum)
Muon:	2011 acceptance (?)
SL:	MC stats

Analysis:

B2OC:	L0 had eff
RD:	ang analysis K*mumu (erratum)
B2CC:	Time acceptance, beta factor (VeloPIX)
Flavour tagging:	OT time? Incl tagging? PID coverage PIDCALIB pT eta?
Charm/SL:	magnet polarity, DeltaACP, see Laurent!
QEE:	HCAL PMT gain
IFT:	Simultaneous operation of pp and pPb

The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

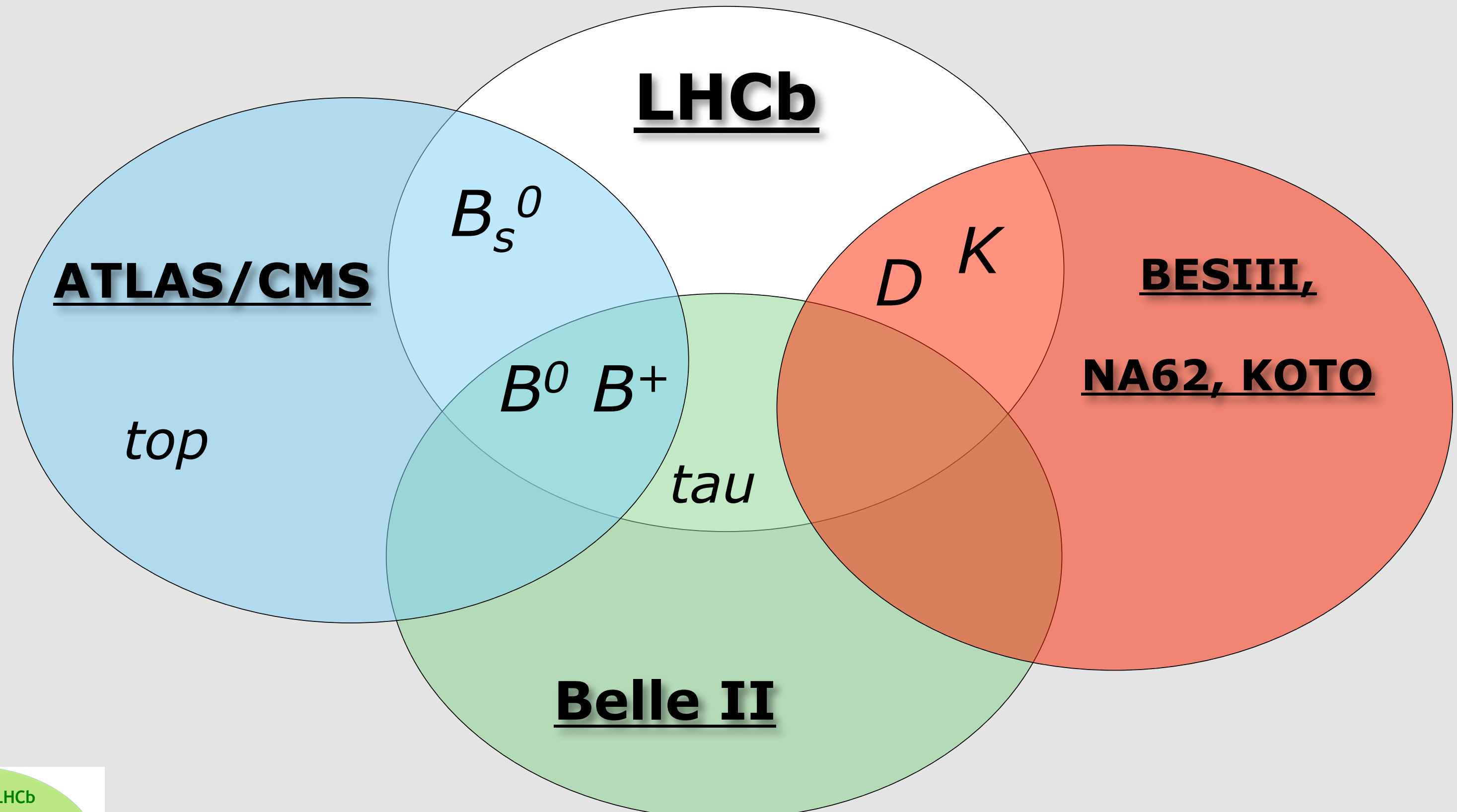
– A.Soni

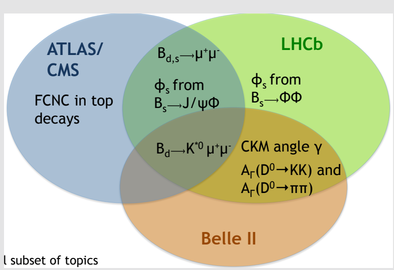
- “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

– L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

Playing field: heavy flavour



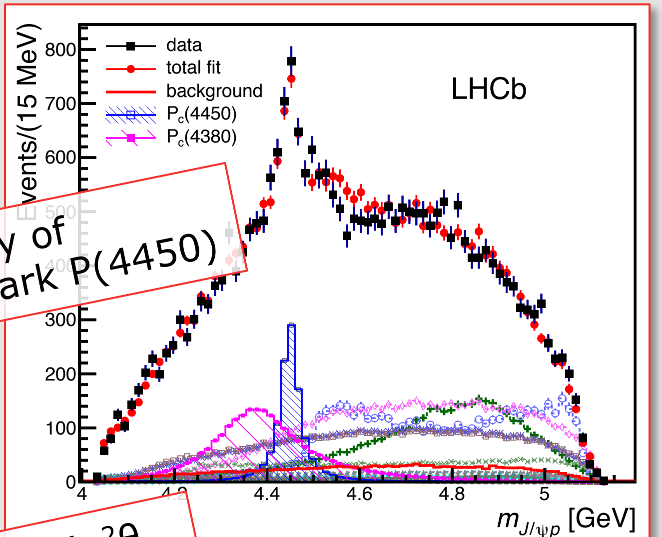


Sketch adopted from Marie-Hélène Schune ECFA2013, 1 Oct 2013

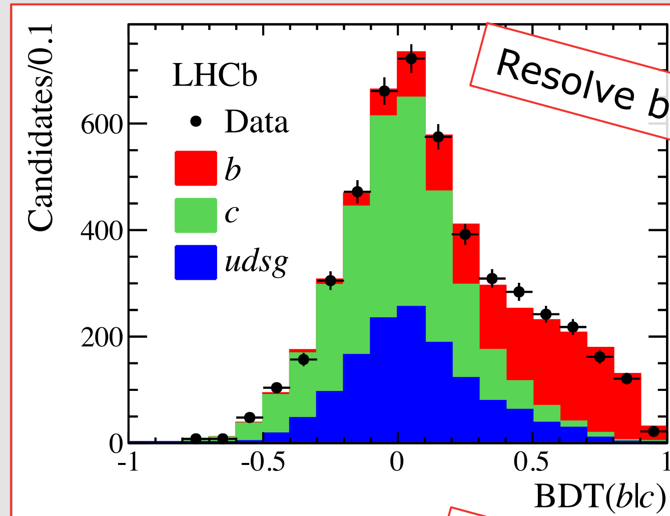
LHCb = more than flavour

pdfs, jets, heavy-ion, EW, exotic states…

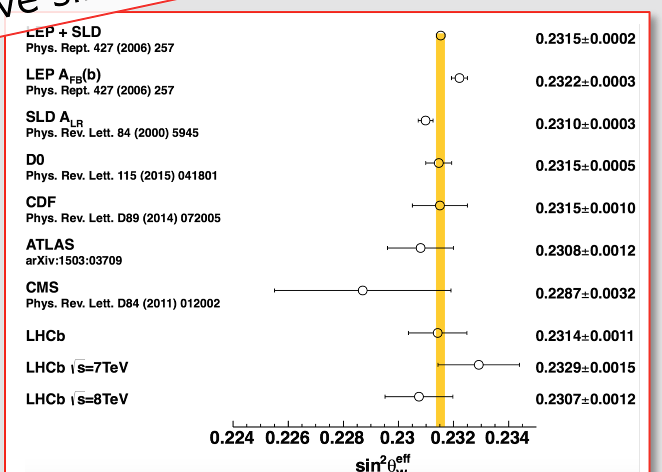
Discovery of pentaquark P(4450)



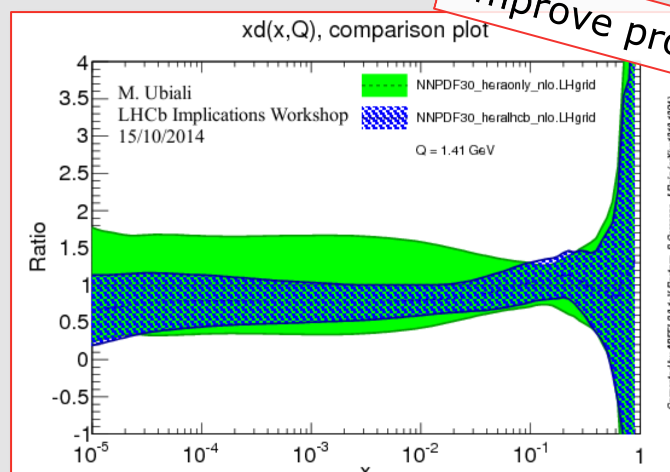
Resolve b and c jets



Impressive $\sin^2\theta_W$

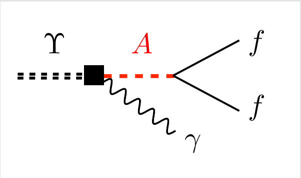


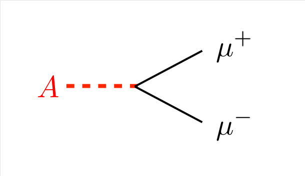
Improve proton pdf's

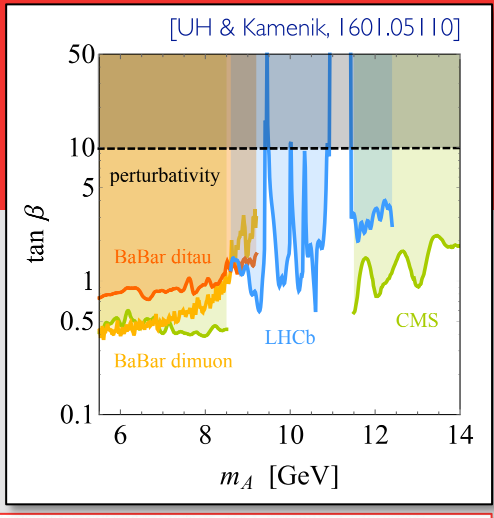


Searches
Dark photons, Majorana, light scalars

- Light scalars
  - A→μμ

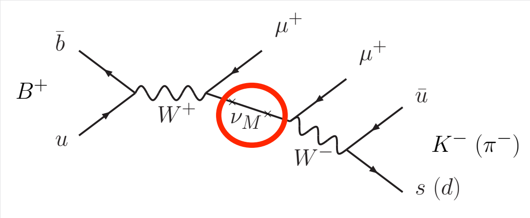


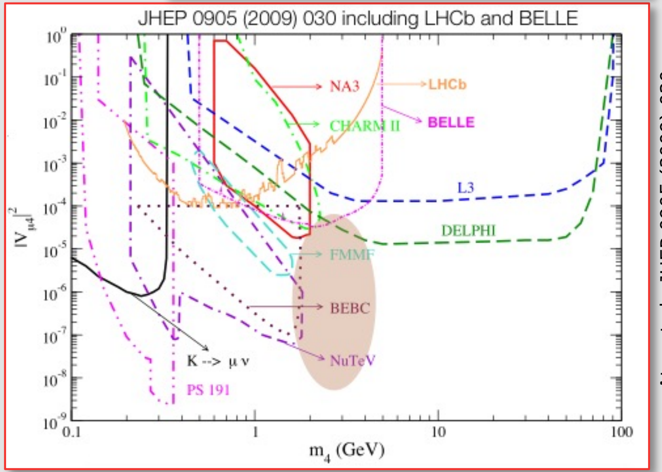




Haisch et al., PRD93 (2016) 055047

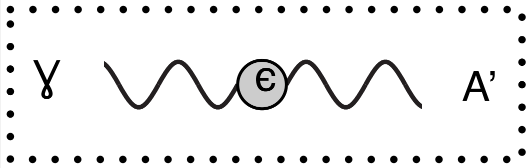
- Majorana neutrino’s
  - $B^+ \to \pi^- \mu^+ \mu^+$

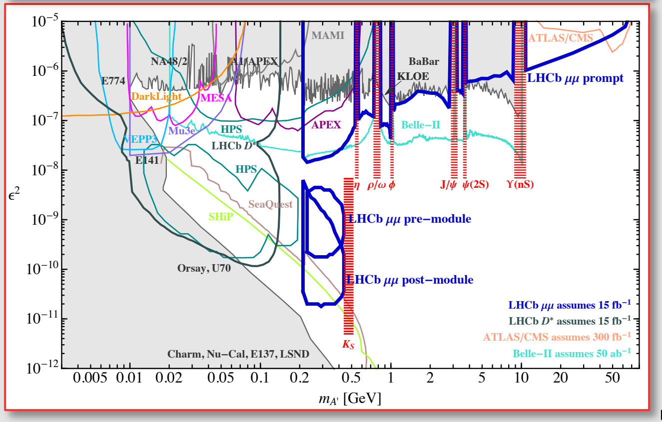




Atre et al., JHEP 0905 (2009) 030

- Dark photons
  - $D^{*0} \to D^0 \gamma$, $A \to \mu\mu$





Ph.Ilten et al PRL 116 (2016) 251803