The LHCb Upgrade II

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on behalf of the LHCb collaboration

Beauty 2018 conference
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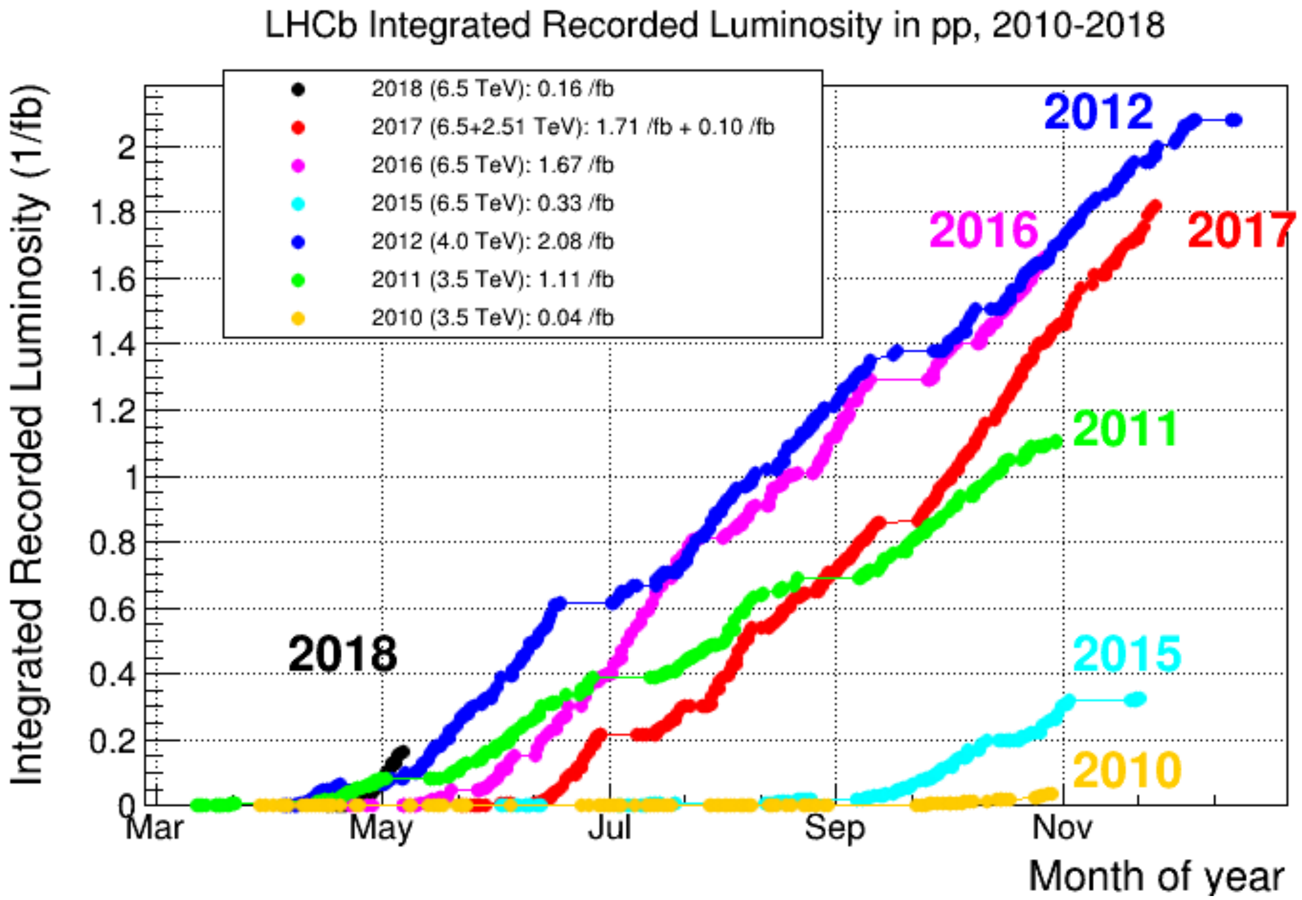
Outline

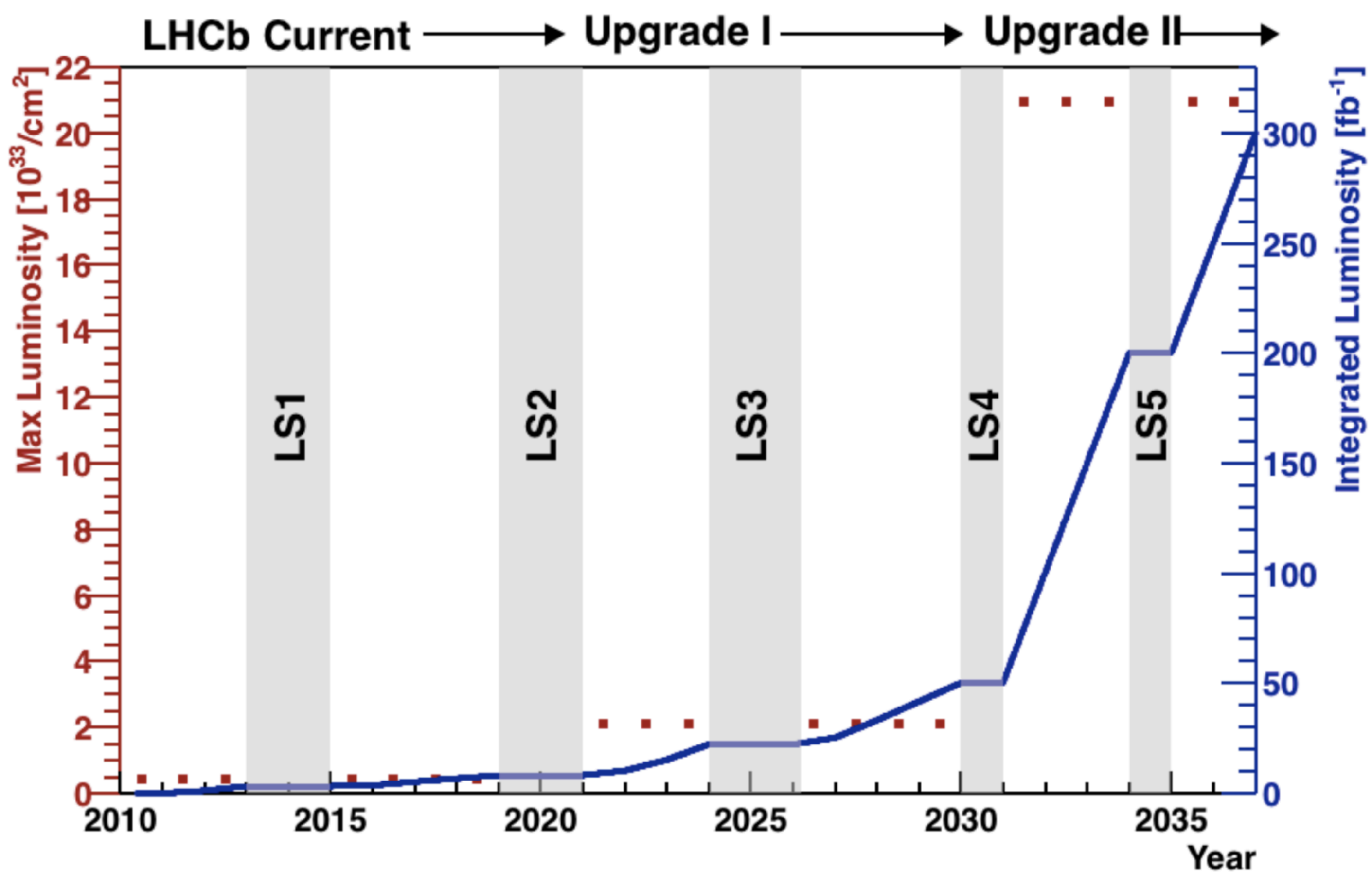
- Introduction
- Physics programme in a nutshell
- Selected benchmark analyses
- Detector developments: tracking, PID, ECAL, TDAQ
- Summary

Introduction

- The flavour physics community has the mandate to perform the most precise determination of the CKM matrix and to search for new phenomena
- LHCb Upgrade II takes full advantage of the capabilities of the HL-LHC for flavour physics
- Ultimate test of CKM, unique new physics searches, and other physics opportunities in the forward direction would become available
- Clearly there are major detector challenges to face that require new ideas and dedicated R&D

LHCb data sample and plans





- Collecting >8 fb^{-1} in Run2 (2018). Major detector upgrade during LS2 (Upgrade I- 2020). Aim at 50 fb^{-1} before 2030
- First detector improvements in PID, tracking, and ECAL during LS3 (Upgrade 1b - 2025)
- Major detector upgrade during LS4 (Upgrade II - 2030). Aim at >300 fb^{-1} after 2030 - ….

LHCb physics program

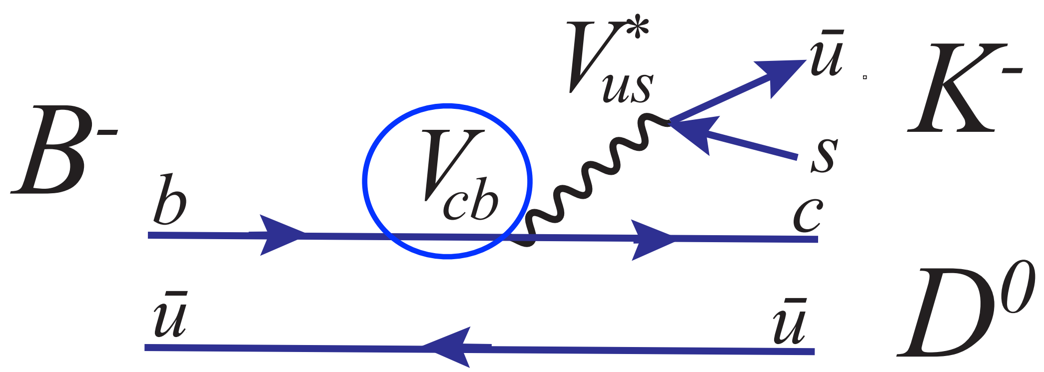
CKM and *CP* violation	sin2β, γ, ϕ_s, $\lvert V_{ub}/V_{cb}\rvert$, CPV in B^0, B_s^0, D^0, b-baryons,…
Rare decays	$B_{(s)}^0 \to \mu^+\mu^-$, $b \to s\mu^+\mu^-$, $b \to s e^+e^-$, $\Sigma^+ \to p\mu^+\mu^-$,…
Spectroscopy	Tetraquarks, **Pentaquarks**, Ξ_{cc}^{++}, Ω_c^*, Ξ_b^{-*},…
Electroweak QCD, Exotica	Z^0, W^+, top, **$H \to c\bar{c}$, Dark photons, Long-lived particles**,..
Ion, Fixed-target	Heavy ions, **p-Gas**, nuclear effects,…

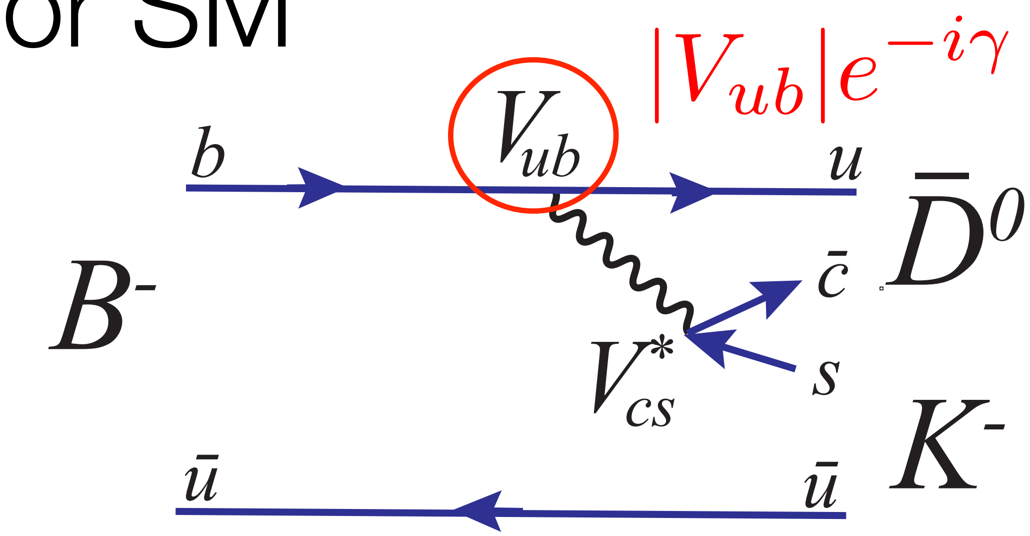
γ from $B^- \to DK^-$ decays

Extracted from tree-level decays

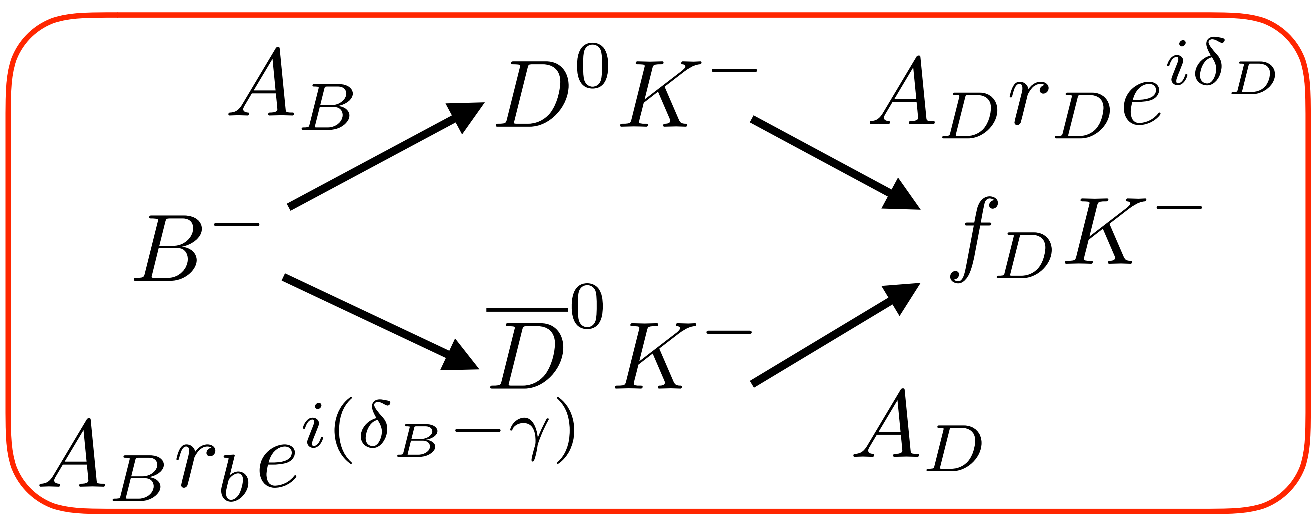
See M. Kenzie talk

Reference measurement for SM





- Exploit interference between amplitudes, e.g.



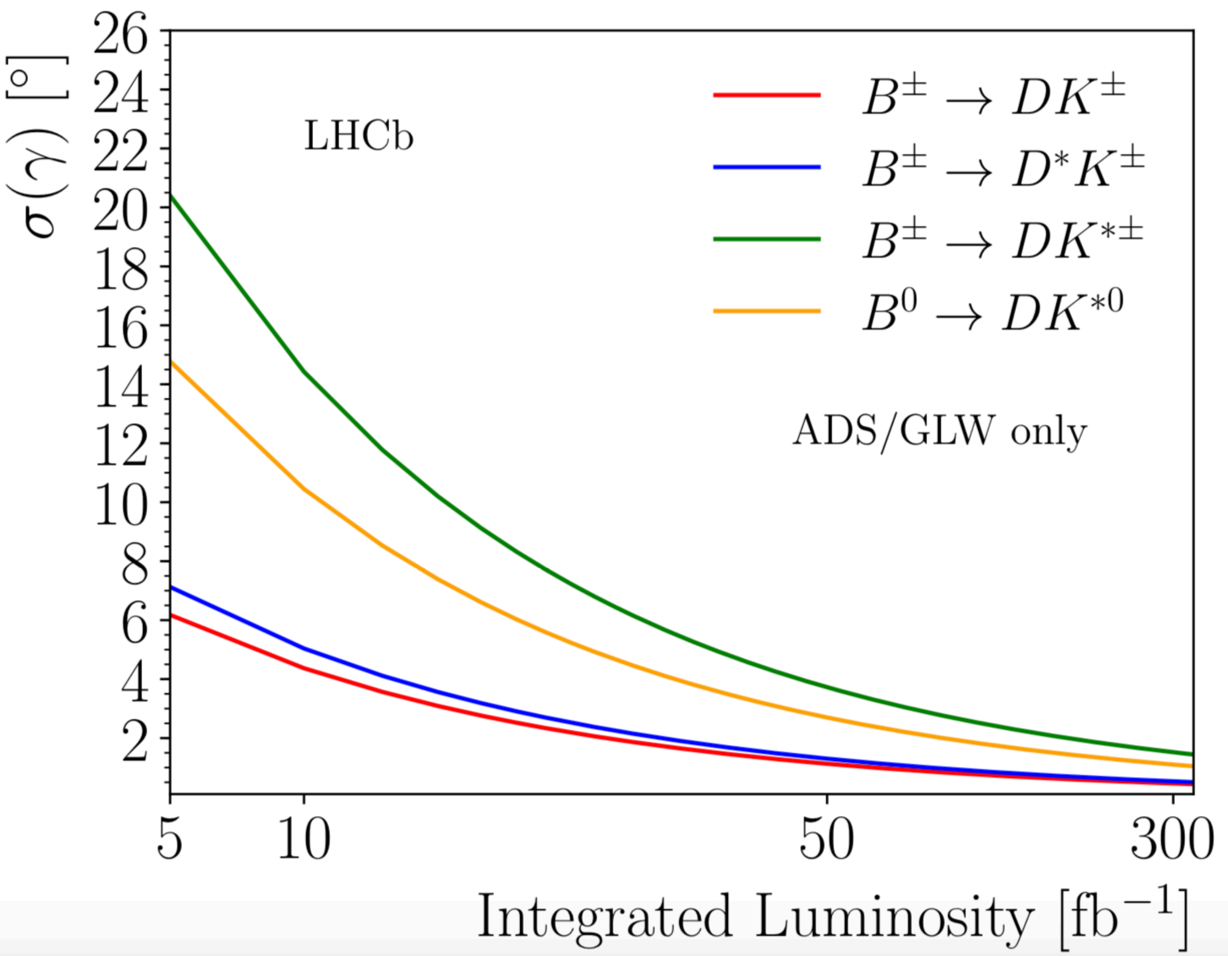
$f_D = \pi^+\pi^-, K^+K^-$	GLW
$K^+\pi^-$	ADS
$K^0_S\pi^+\pi^-$	GGSZ

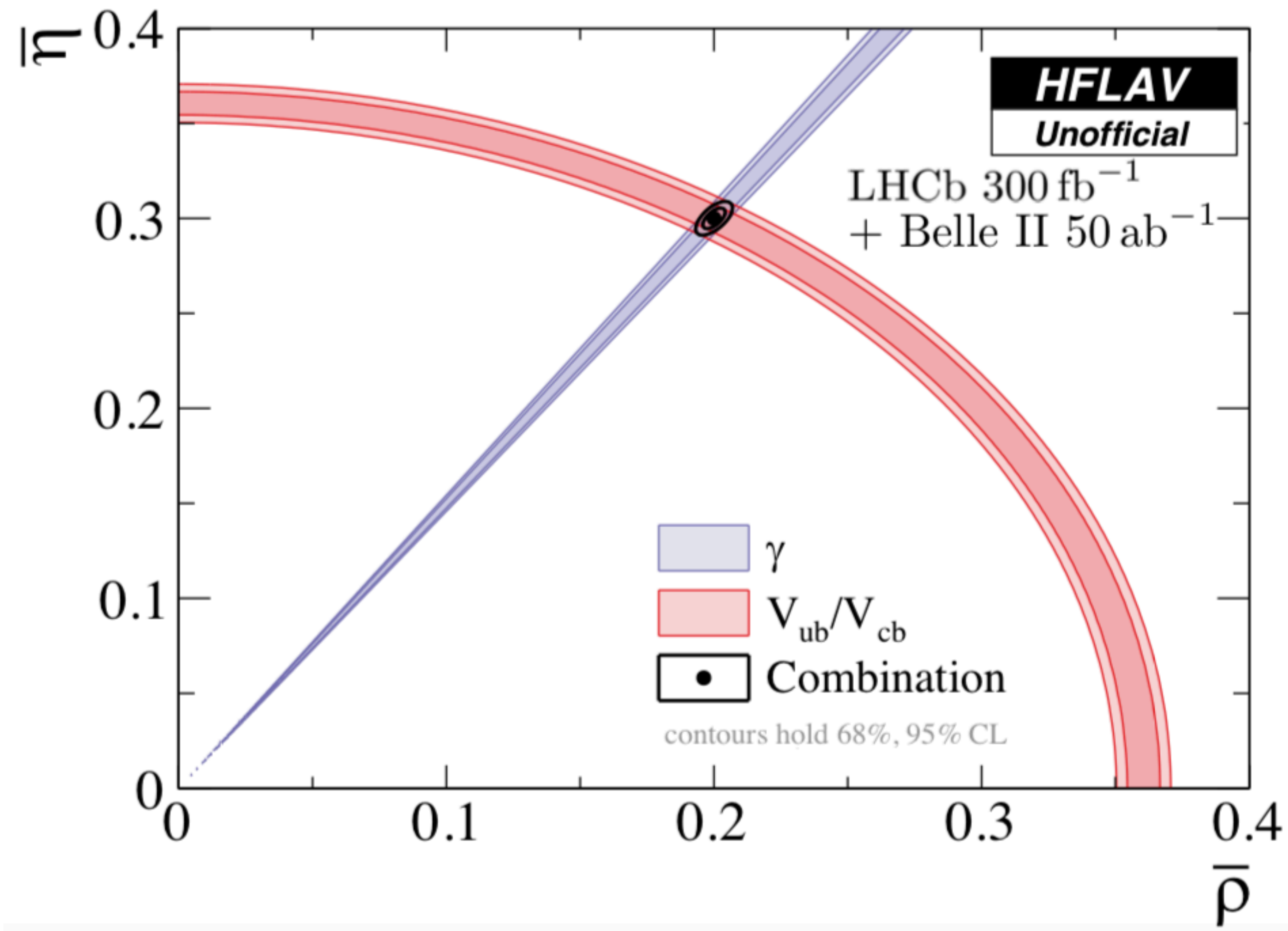
GLW: Gronau, London, Wyler PLB 253 (1991) 483, PLB 265 (1991) 172

ADS: Atwood, Dunietz, Soni PRL 78 (1997) 3257

GGSZ: Giri, Grossman, Soffer, Zupan PRD68 (2003) 054018

Ultimate γ sensitivity





- Uncertainty of 0.35° with 300 fb^{-1}, through a combination of measurements
- Comparison of γ measurements from different B^+, B_d^0, B_s^0, Λ_b^0 modes will become possible

CP violation in $B_{(s)}$ mixing

- So-called semi-leptonic asymmetry

$$A_{SL} = \frac{\text{Prob}(\bar{B}^0 \to B^0) - \text{Prob}(B^0 \to \bar{B}^0)}{\text{Prob}(\bar{B}^0 \to B^0) + \text{Prob}(B^0 \to \bar{B}^0)} = \frac{|p/q|^2 - |p/q|^2}{|p/q|^2 + |p/q|^2}$$

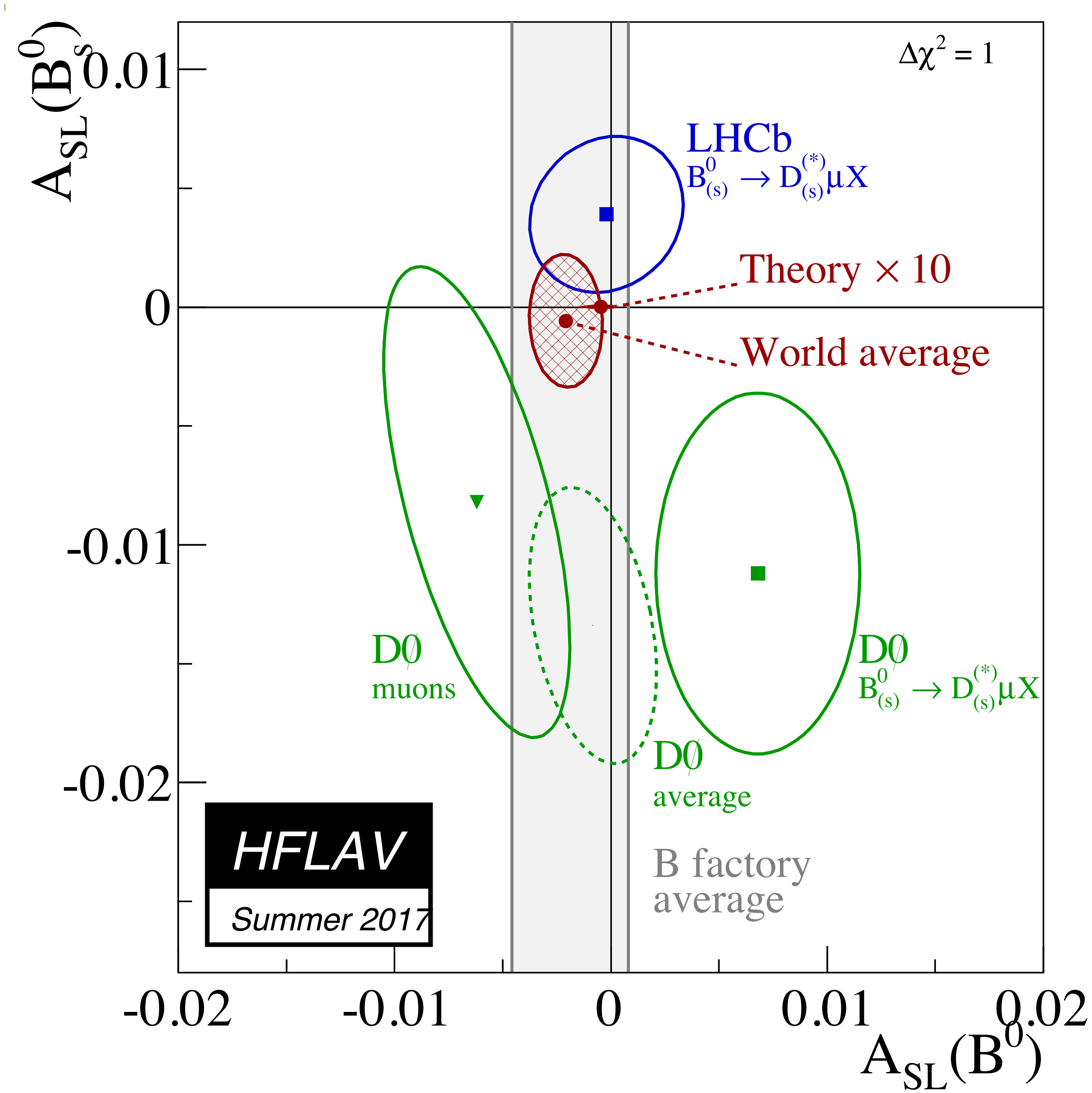
- SM predictions:

$$A_{SL}^{SM} = \begin{cases} -(4.7 \pm 0.6) \times 10^{-4} \text{ for } B_d^0 \\ +(2.2 \pm 0.3) \times 10^{-5} \text{ for } B_s^0 \end{cases}$$

- World average:

$$A_{SL}^{exp} = \begin{cases} -(2.1 \pm 1.7) \times 10^{-3} \text{ for } B_d^0 \\ -(0.6 \pm 2.8) \times 10^{-3} \text{ for } B_s^0 \end{cases}$$

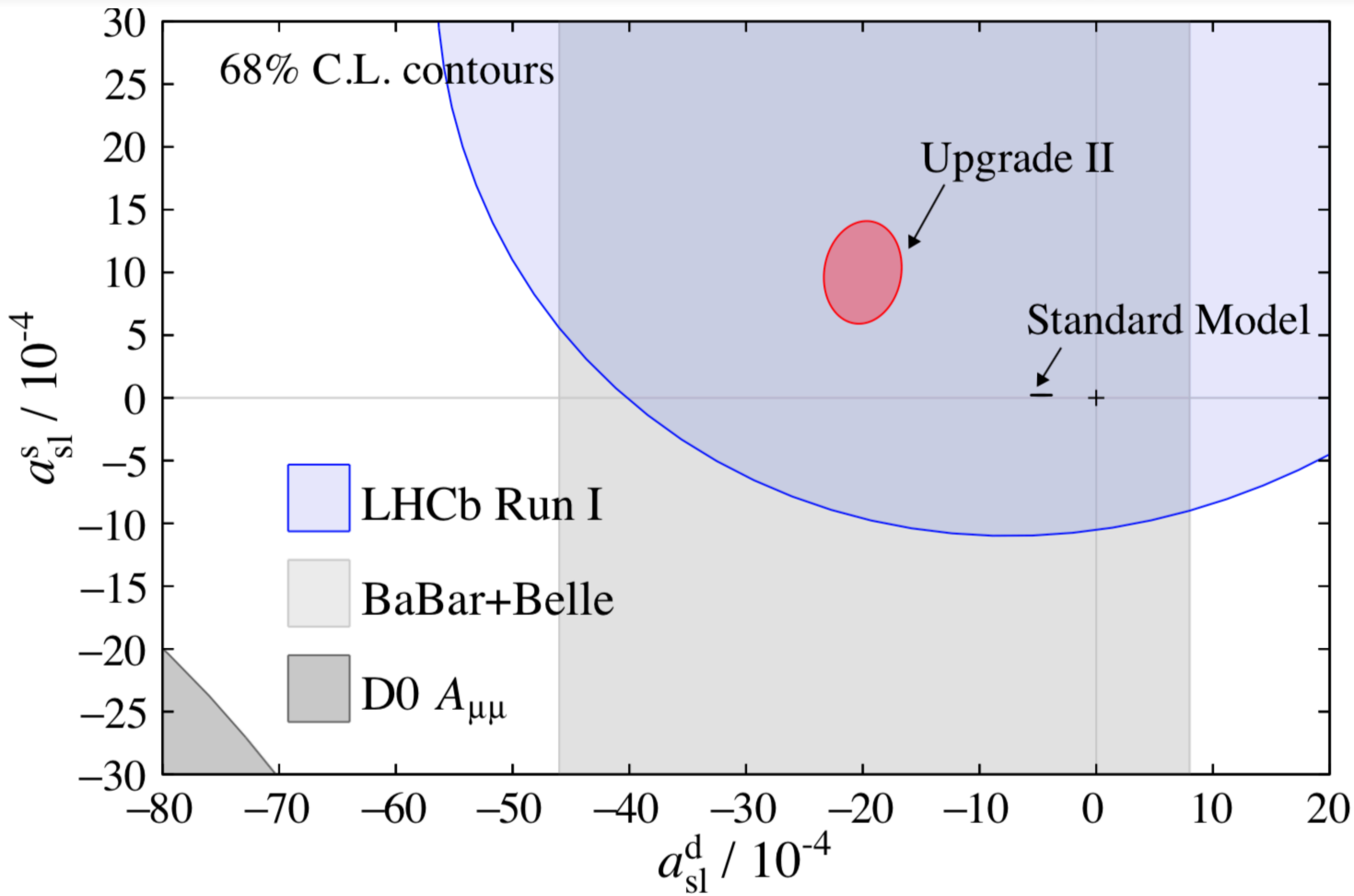
Phys.Rev.Lett. 117 (2016) no.6, 061803



Experimental average in agreement with SM predictions

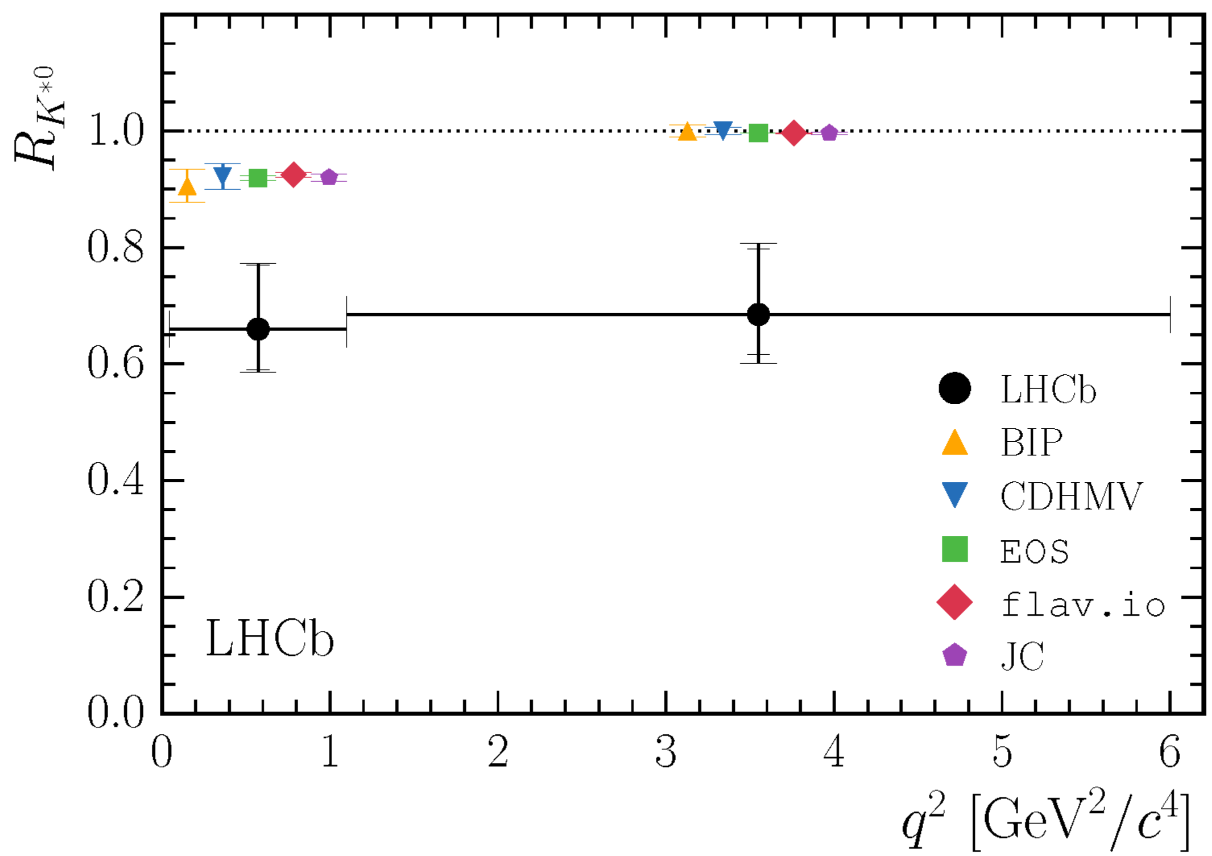
Rev.Mod.Phys. 88 (2016) no.4, 045002

Future landscape for semileptonic asymmetries



	Current theory [28, 169]	Current LHCb [171, 172]	Upgrade II uncertainty
a_{sl}^{s}	$(+2.2 \pm 0.3) \times 10^{-5}$	$(+3.9 \pm 3.3) \times 10^{-3}$	2.7×10^{-4}
a_{sl}^{d}	$(-4.7 \pm 0.6) \times 10^{-4}$	$(-0.2 \pm 3.6) \times 10^{-3}$	2.2×10^{-4}

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



See A. Puig talk

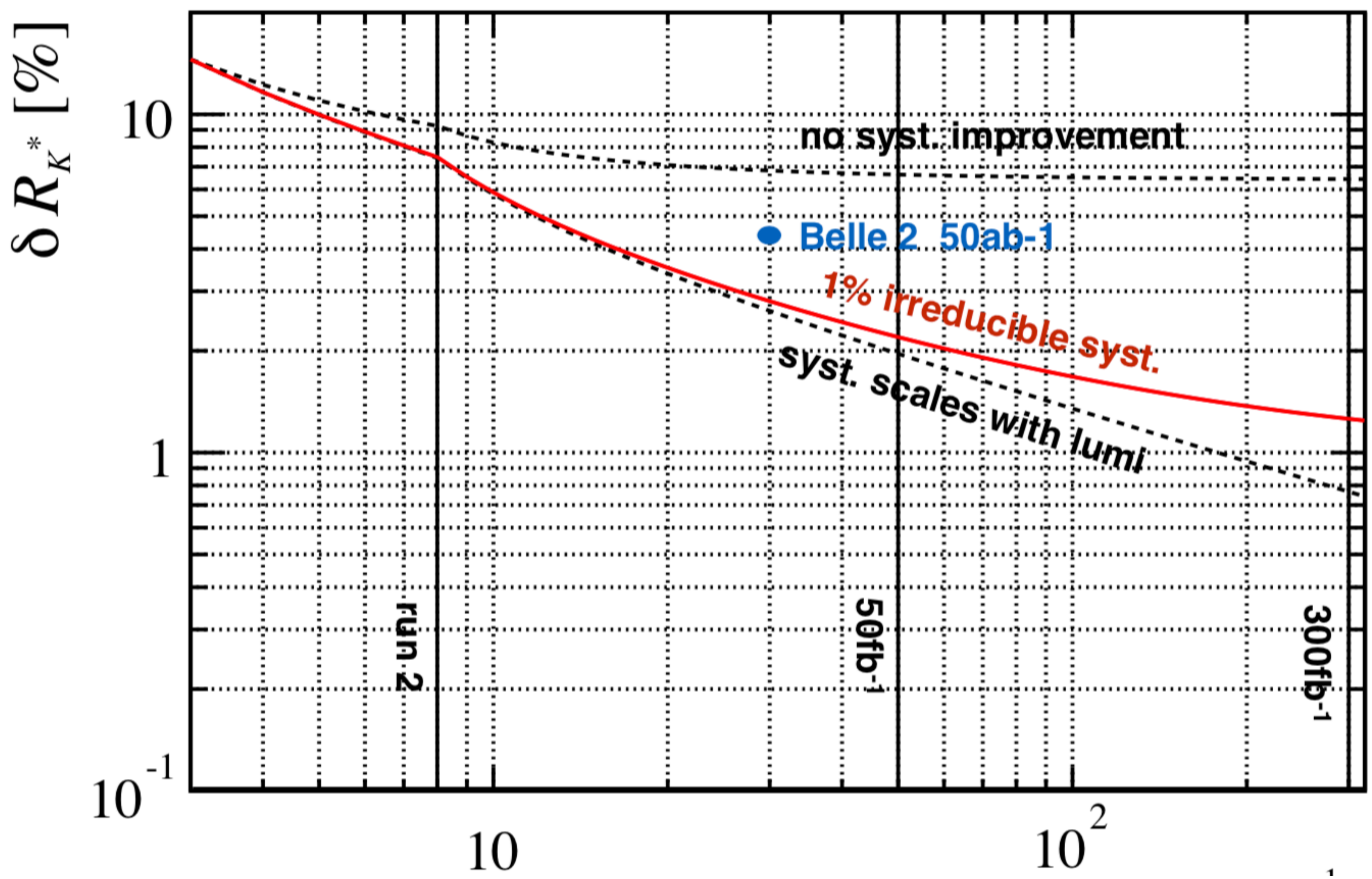
3fb^{-1} [JHEP 08 (2017) 055]

$$R_{K^{*0}} = \frac{BR(B^0 \to K^{*0}\mu^+\mu^-)}{BR(B^0 \to K^{*0}e^+e^-)}$$

$$R_{K^{*0}} = \begin{cases} 0.66\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \ \text{GeV}^2/c^4\,, \\ 0.69\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\ \ \text{GeV}^2/c^4\,. \end{cases}$$

Tensions with the SM at 2.1-2.3σ and 2.4-2.5σ in the two q^2 regions, respectively

Evolution of R_{K^*} error



- Assumption: constant ECAL performance
- Systematics from limited modelling of bremsstrahlung
- Reduced material before the magnet would help

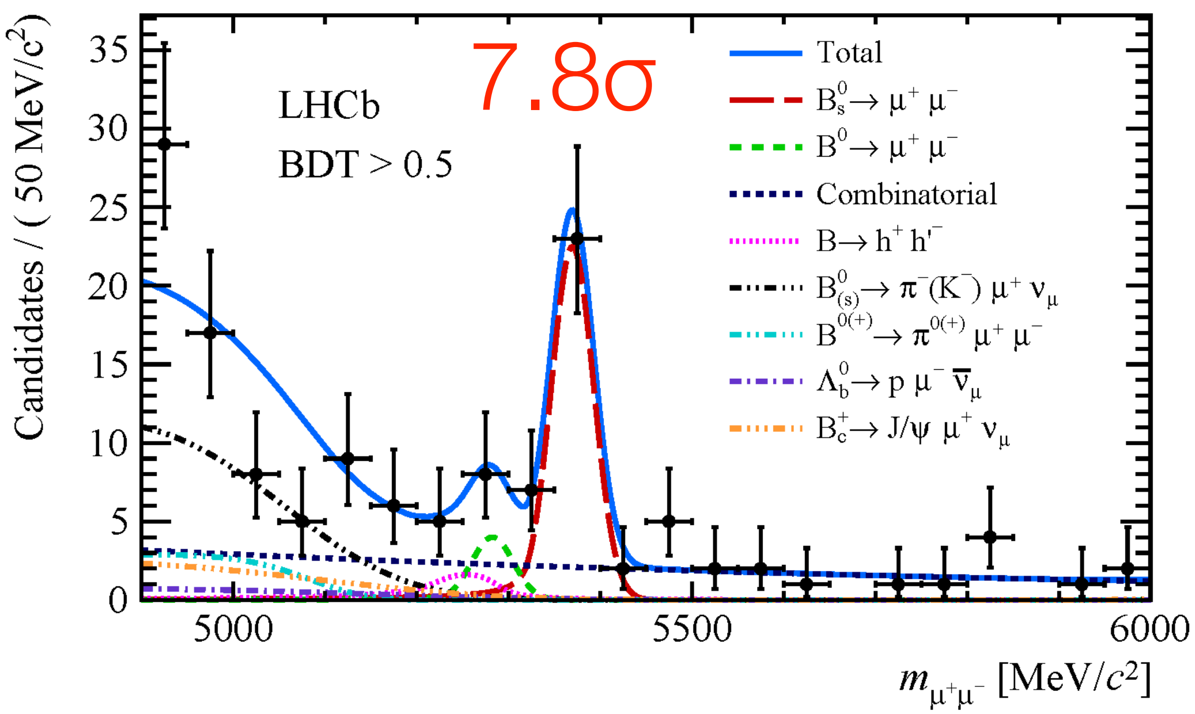
Observable ($1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$)		Run 1 result	$8\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
R_K	$B^+ \to K e^+ e^-$	$0.745 \pm 0.090 \pm 0.036$ [313]	0.04	0.015	0.006
$R_{K^{*0}}$	$B^0 \to K^{*0} e^+ e^-$	$0.69 \pm 0.11 \pm 0.05$ [312]	0.06	0.020	0.008
R_ϕ	$B^0_s \to \phi e^+ e^-$	–	0.13	0.05	0.02
R_{pK}	$\Lambda^0_b \to p K e^+ e^-$	–	0.08	0.03	0.01
R_π	$B^+ \to \pi^+ e^+ e^-$	–	–	0.06	0.03

$B_s \to \mu^+\mu^-$ results and prospects

First observation in single experiment 4.4fb^{-1} **PRL 118, 191801 (2017)**

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

See M. Rama talk

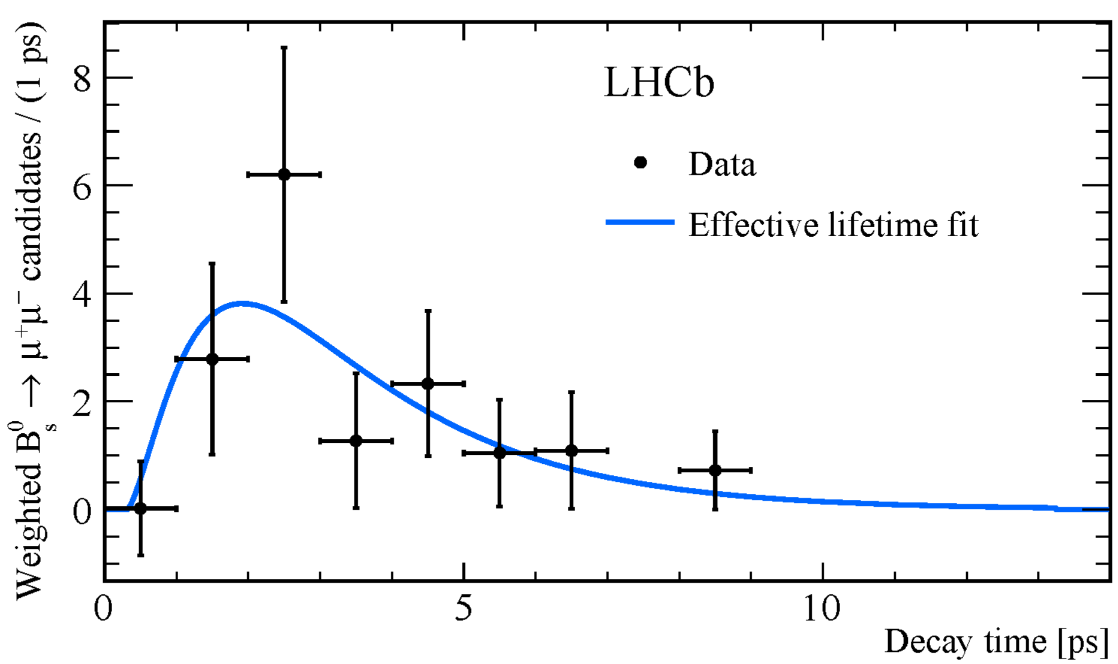


Prospects with 300 fb^{-1}:

$$R \equiv \frac{BF(B^0 \to \mu^+\mu^-)}{BF(B_s^0 \to \mu^+\mu^-)}$$

$$\sigma(R) \sim 10\%$$

$$\sigma(\tau_{\mu^+\mu^-}) \sim 0.03\text{ps}$$



$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

First effective lifetime measurement

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1 - y_s^2}\left[\frac{1 + 2A_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1 + A_{\Delta\Gamma}^{\mu^+\mu^-} y_s}\right]$$

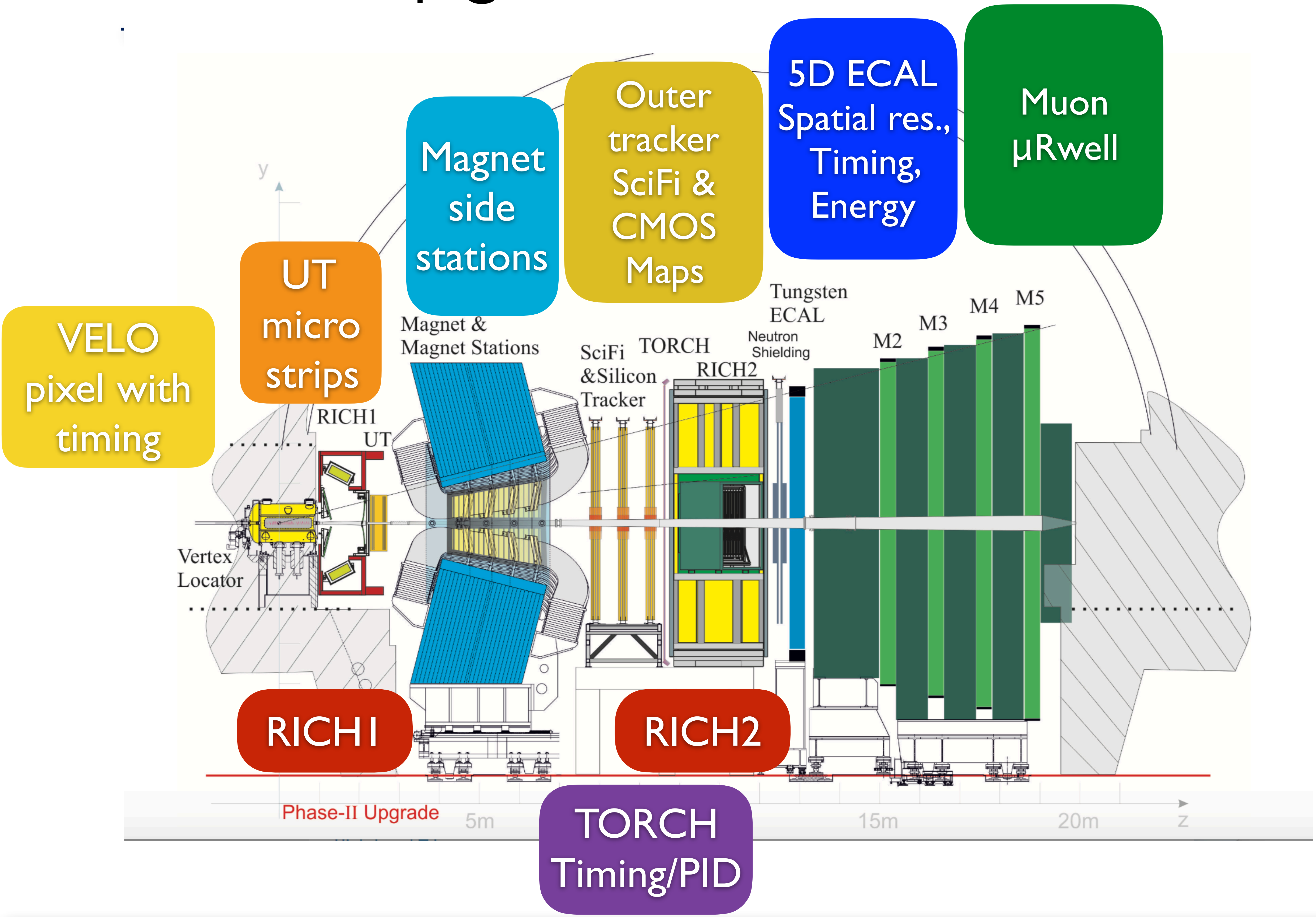
discriminate different NP models

Upgrade II detector

Detector challenges

- Aim at $\mathscr{L}=2\times10^{34}\ cm^{-2}s^{-1}$, about 55 visible interactions per crossing
- Tracking: 1500-3500 charged particles/crossing, fluence in excess of 10^{15} 1MeV n_{eq}/cm^2
- PID: cope with high occupancy, upgrade the coverage at low ~10 GeV, and high momenta ~100 GeV
- ECAL: sustain radiation dose ≲200 Mrad, energy resolution $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$, reduce Moliere radius
- TDAQ: biggest data processing challenge in HEP history
- Detectors must be faster, harder, finer, stronger, smarter

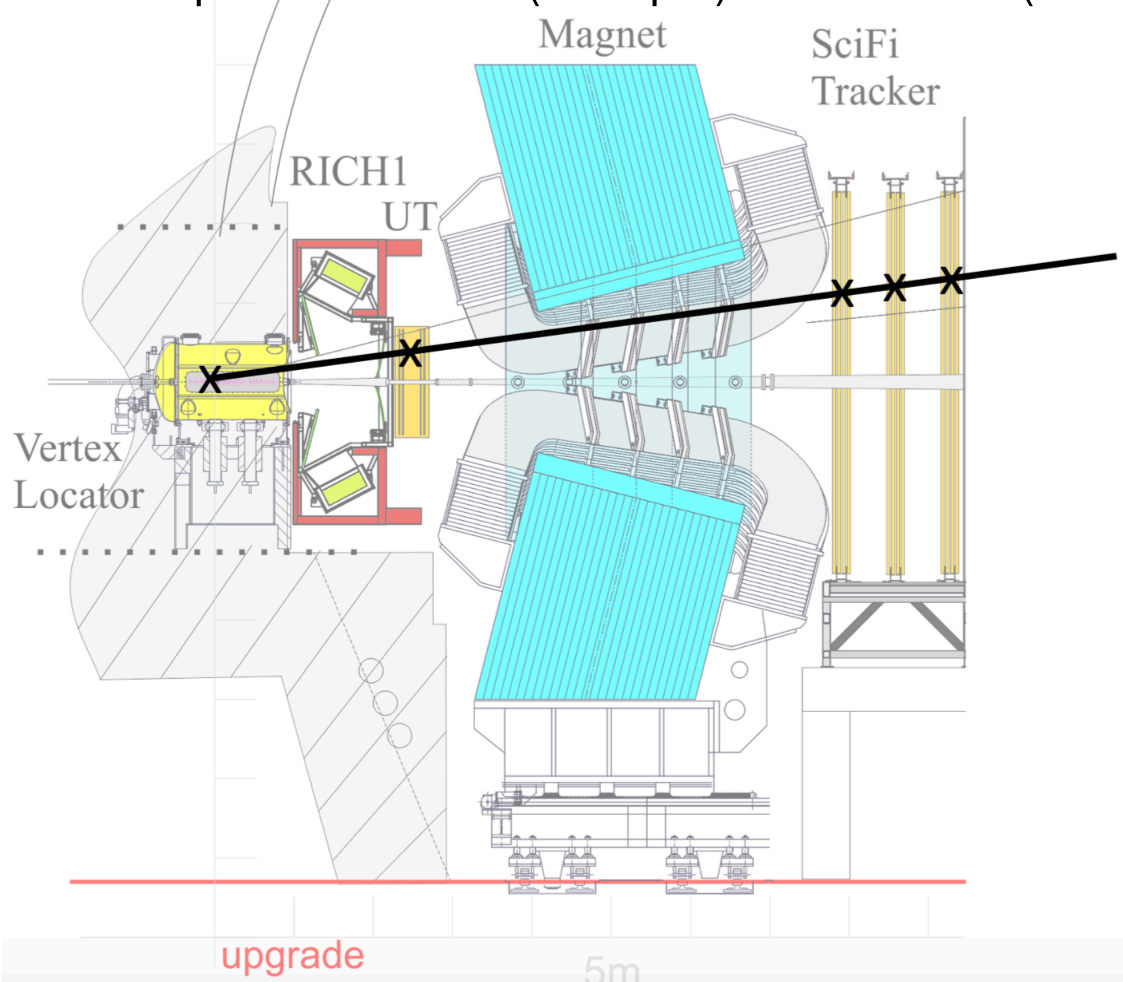
LHCb Upgrade II detector



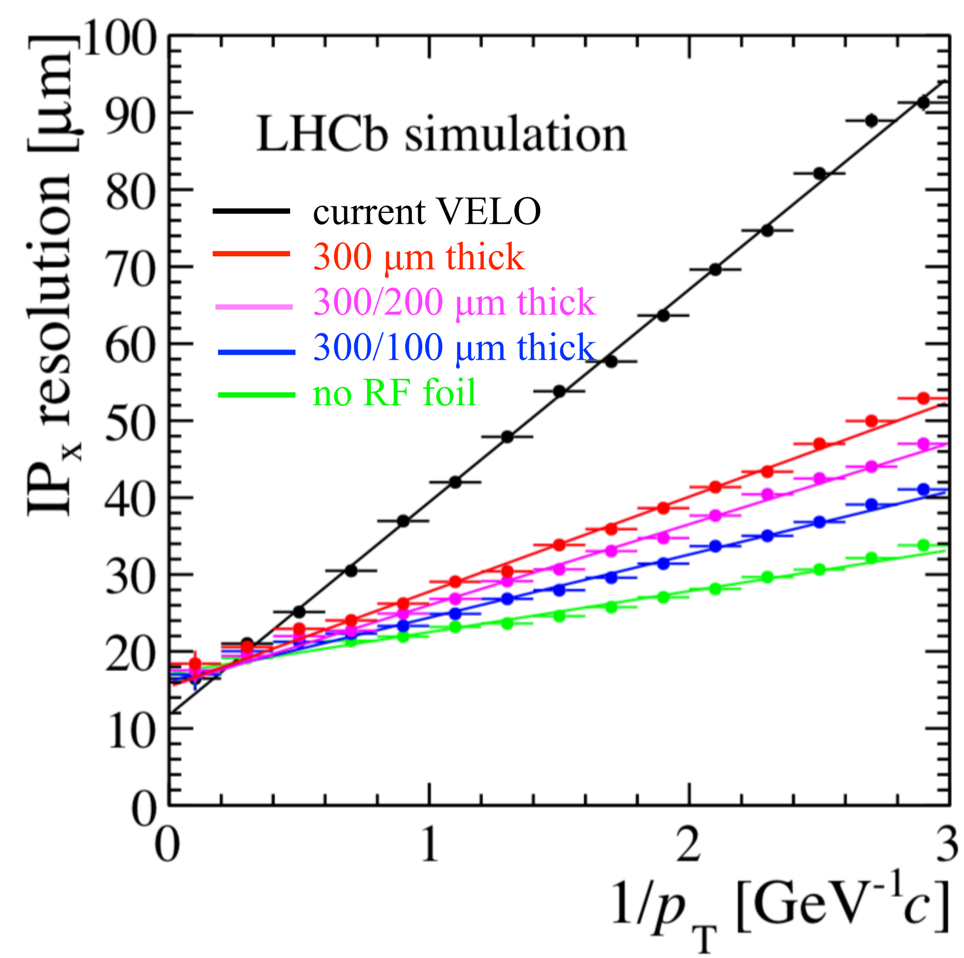
Tracking

- Use fast timing detectors for 4D track reconstruction: suppress ghost tracks, improve PV determination
- Reduced material and granularity: improve resolution, reduce occupancy (and bremsstrahlung for electrons)

Time stamp for tracks (<30ps) / vertices (<10ps)



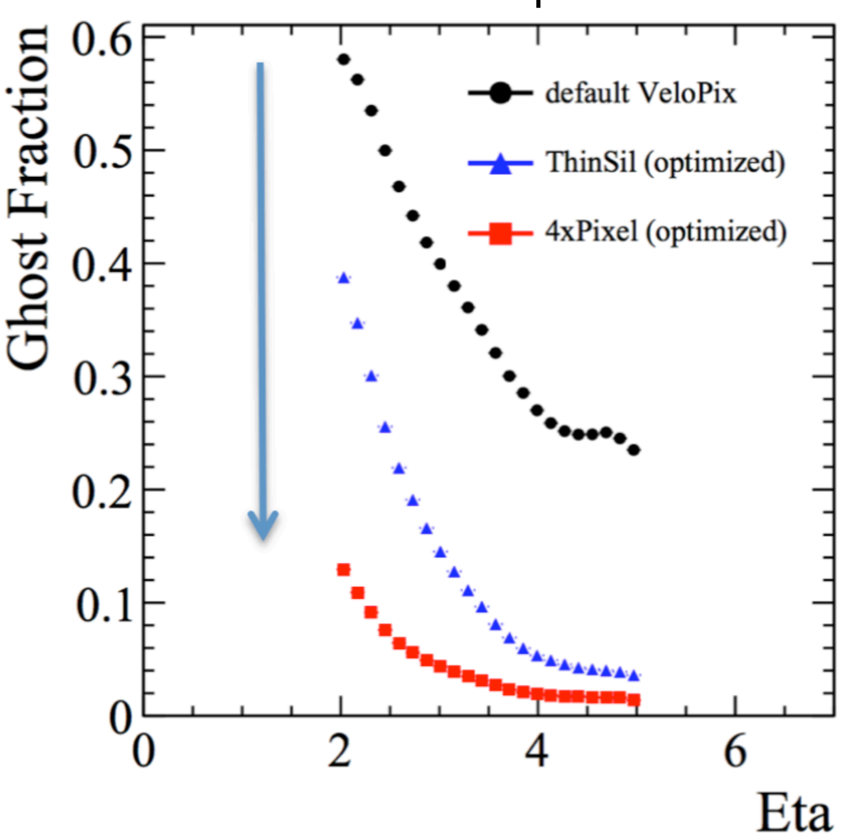
Reduced VELO material (RF shield)



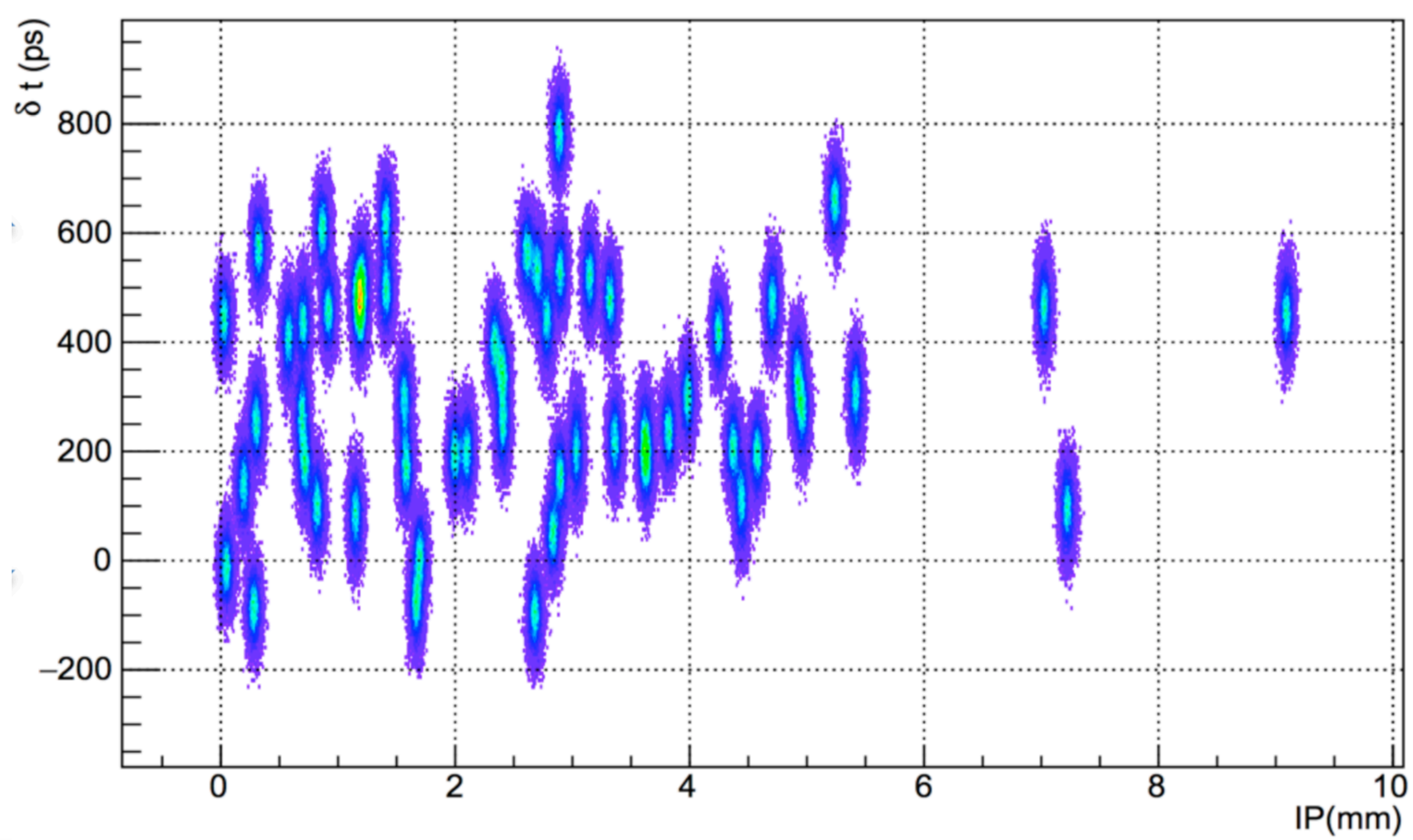
VELO pixel

- Hybrid pixel: high resistivity sensor + FEE chip
  - reduced pixel size <55 μm pitch
  - add timing information <100 ps resolution
  - radiation hardness at Grad: sensor and FEE (65 or 28nm)

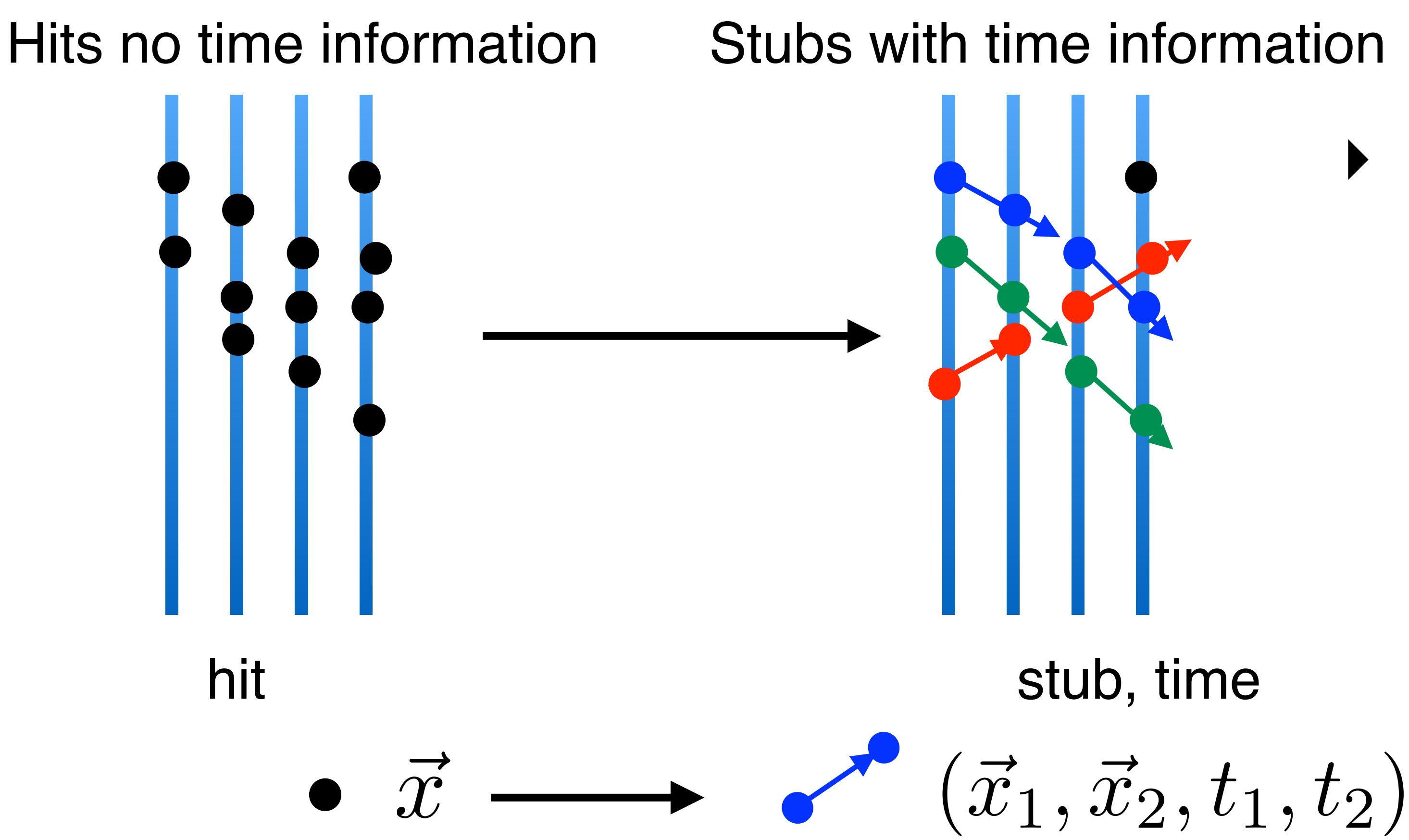
Reducing pixel size to 27.5μm, Si thickness 100μm



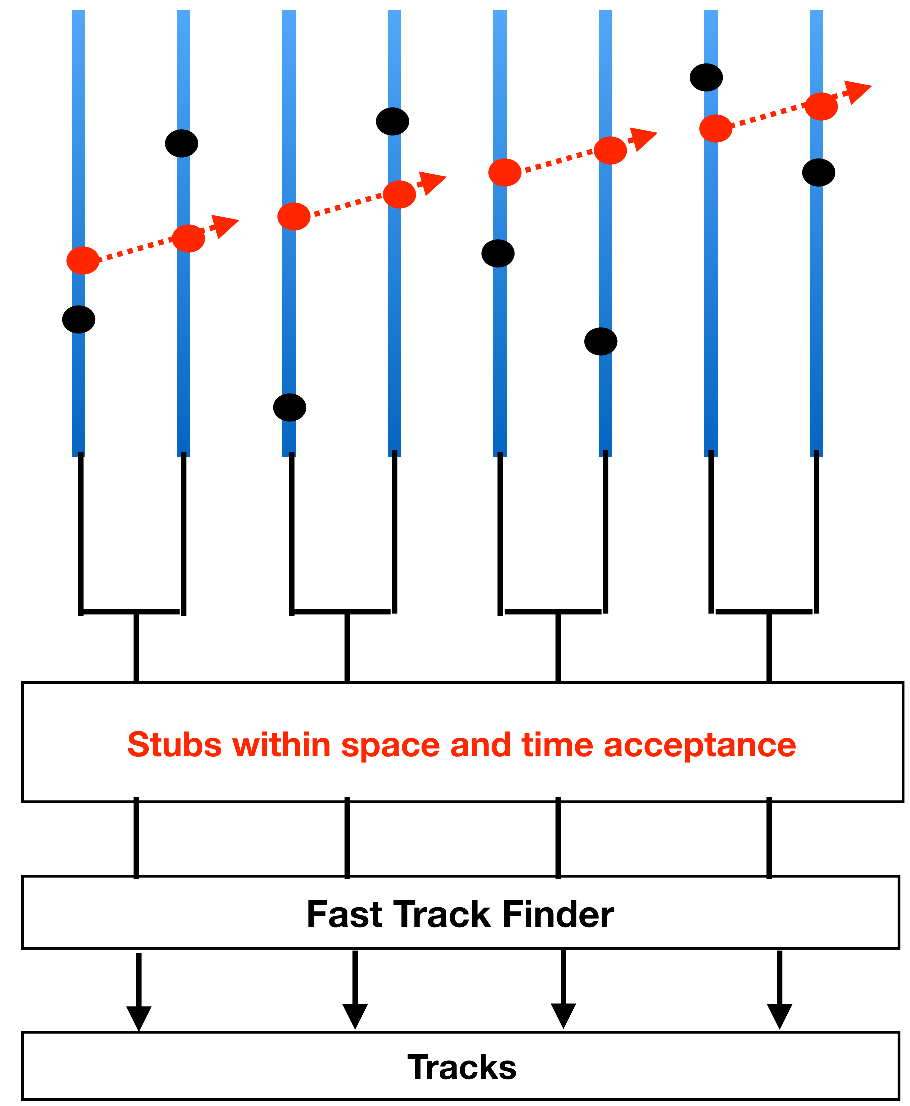
Space-time separation of charged tracks



Fast tracking using space-time info



- Detectors have to be designed for fast tracking and triggering



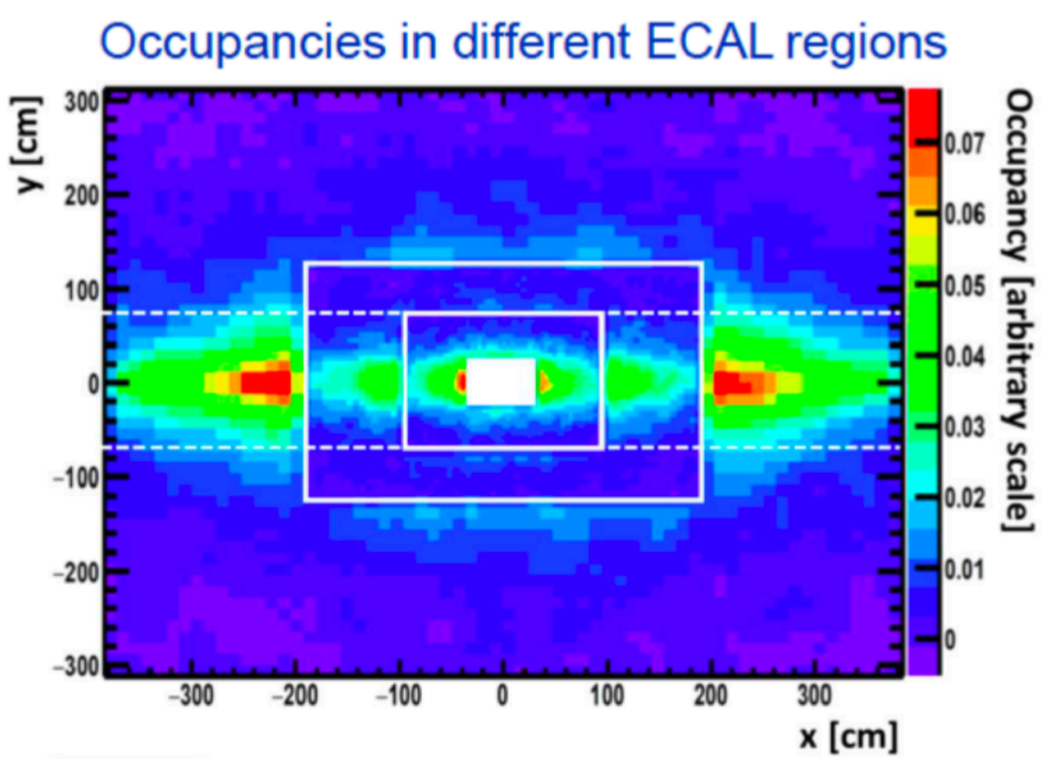
- One approach being pursued:
  - Specialised fast track finding processors to relieve HLT workload
  - Hardware accelerators with high data bandwidth, i.e. FPGA

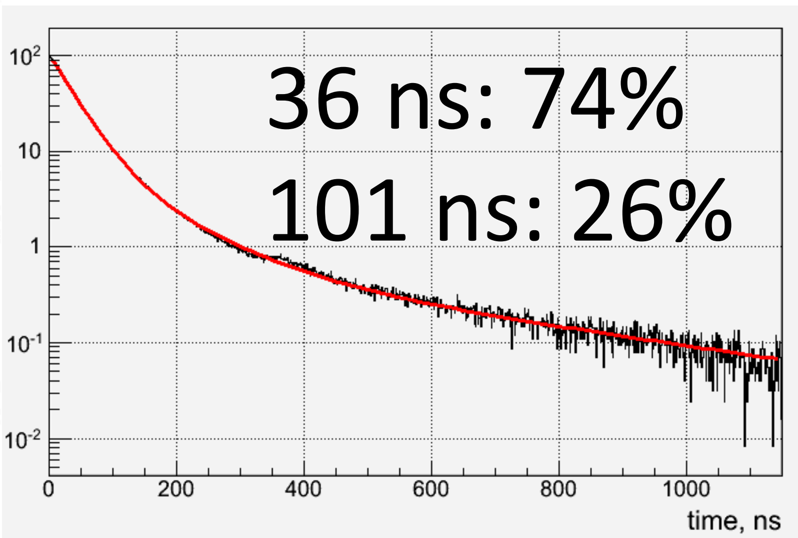
N. Neri *et al.*, JINST 11 (2016) no.11, C11040

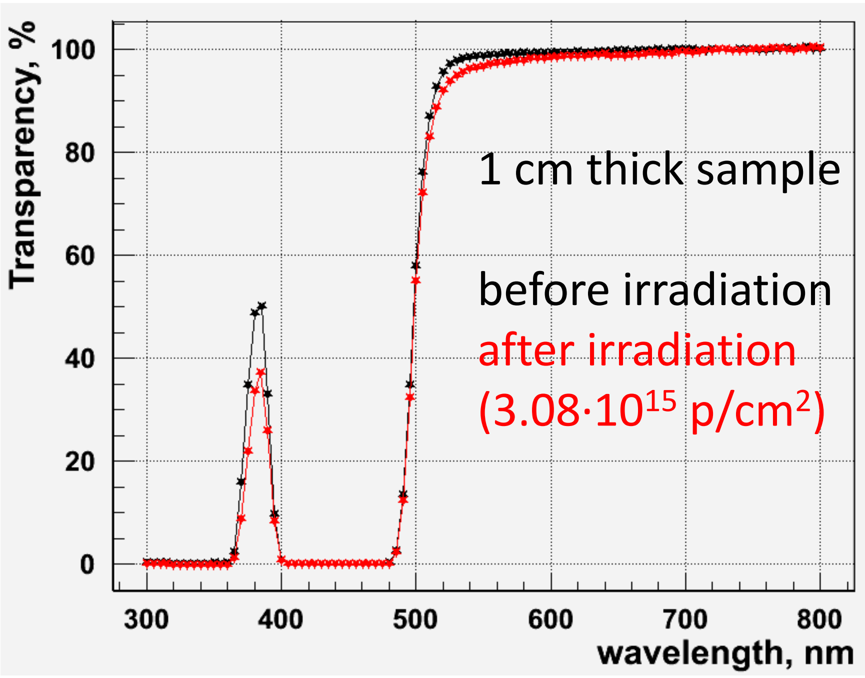
ECAL requirements

- Rebuild ECAL in high occupancy region
- Reduced Moliere radius ~2-3 cm and cell size 2x2 cm^2 in inner region (12x12 cm^2 outer region)
- Rad-hard fast scintillator plus a timing info for pile-up mitigation

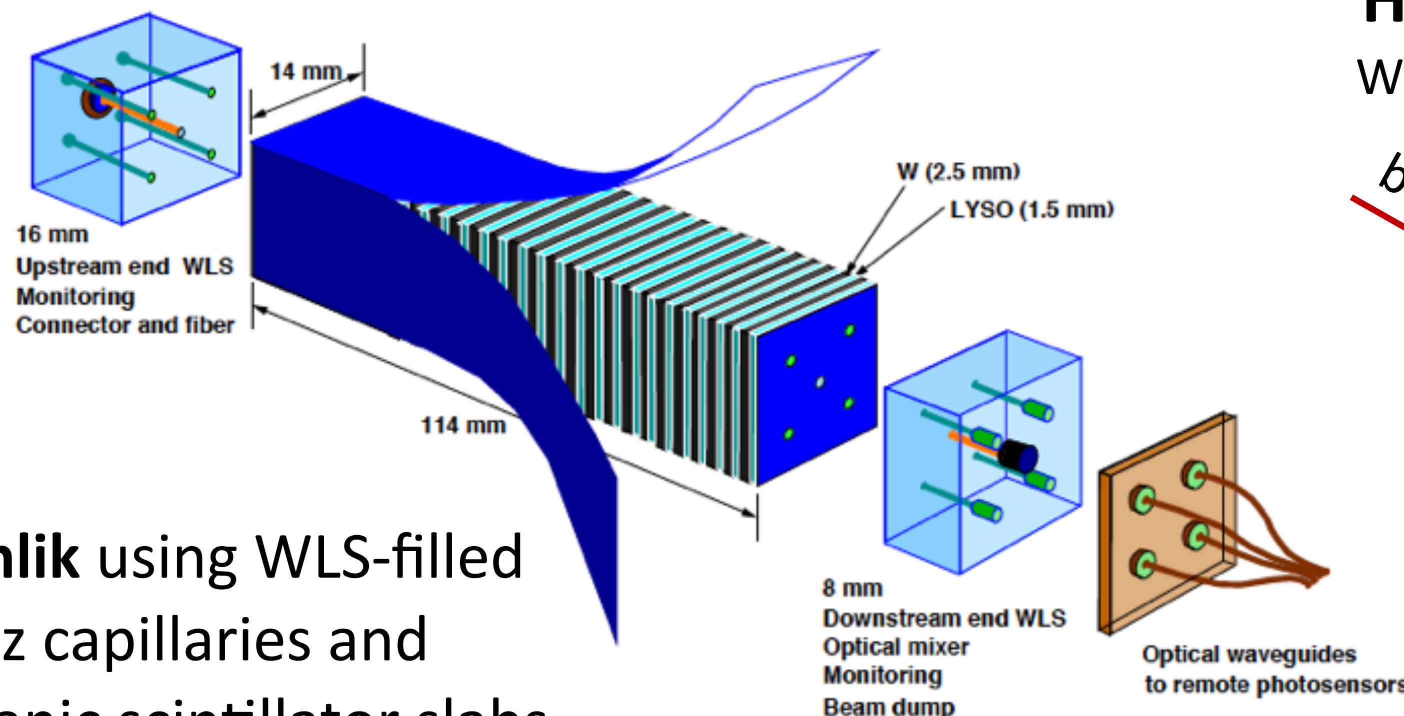
GAGG: fast and rad-hard scintillator







ECAL technologies

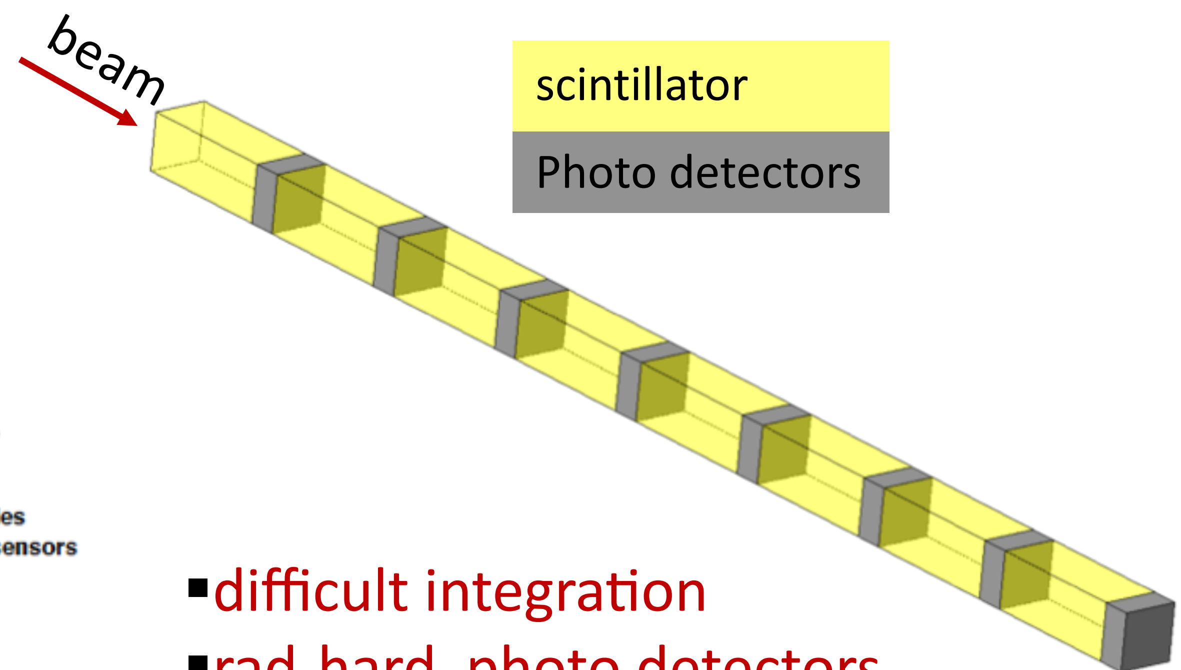


Shashlik using WLS-filled quartz capillaries and inorganic scintillator slabs

- complexity of production

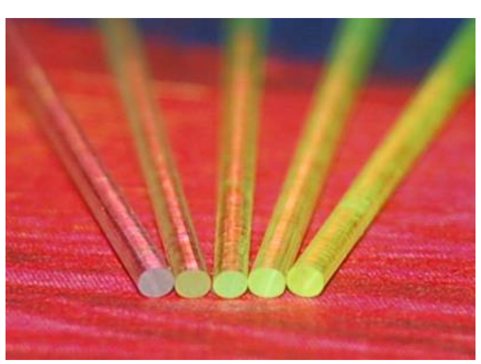
Homogeneous calorimeter

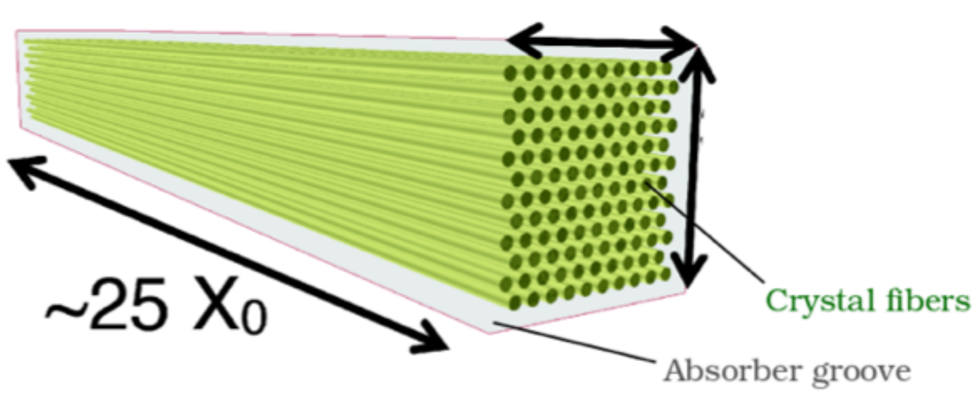
With longitudinal segmentation as an option.



- difficult integration
- rad-hard photo detectors

Crystal SpaCal





- rad tolerance can be worse (long light path)

Evaluate different technologies

Under study: performance, construction, operations, cost

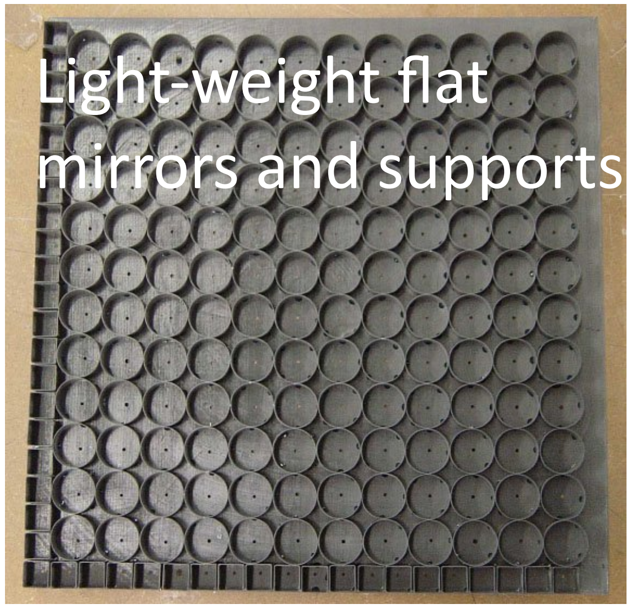
Timing: separate detector or with ECAL itself

RICH

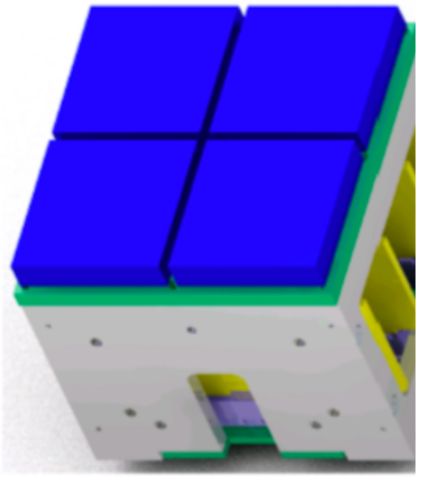
- Improve single photon resolution and yield

$$\sigma_p = \sigma_{\text{chromatic}} \oplus \sigma_{\text{emission point}} \oplus \sigma_{\text{pixel}}$$

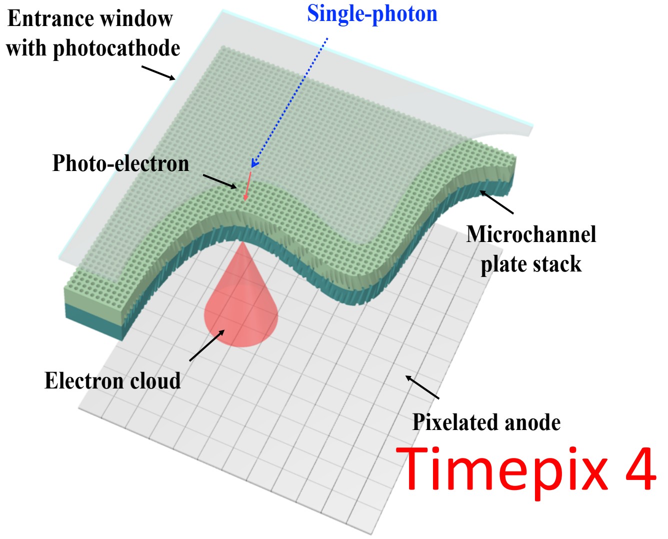
  - chromatic, green-enhanced photodetector QE (SiPM)
  - emission point, flat light mirror to reduce aberrations
  - pixel, photodetector granularity ~1mm
  - add timing (TORCH TOF aims at 15 ps per track)



SiPM arrays

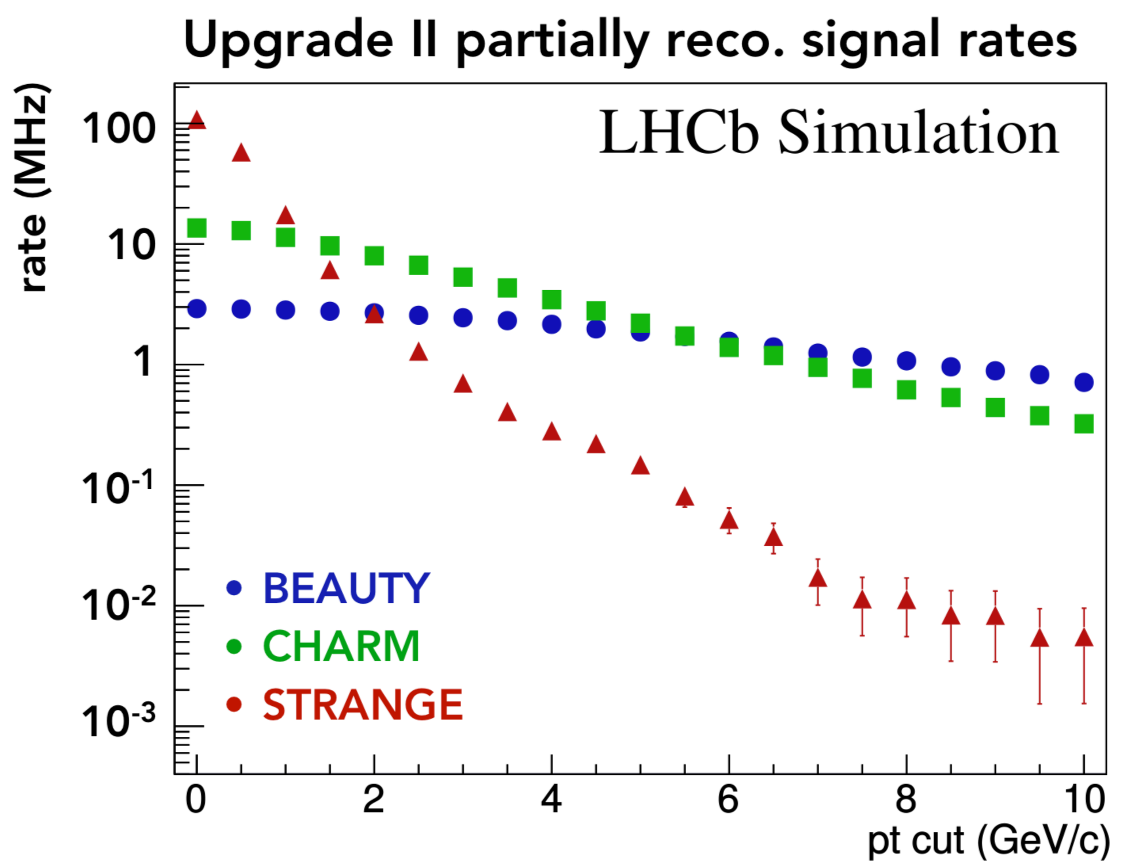


Vacuum devices

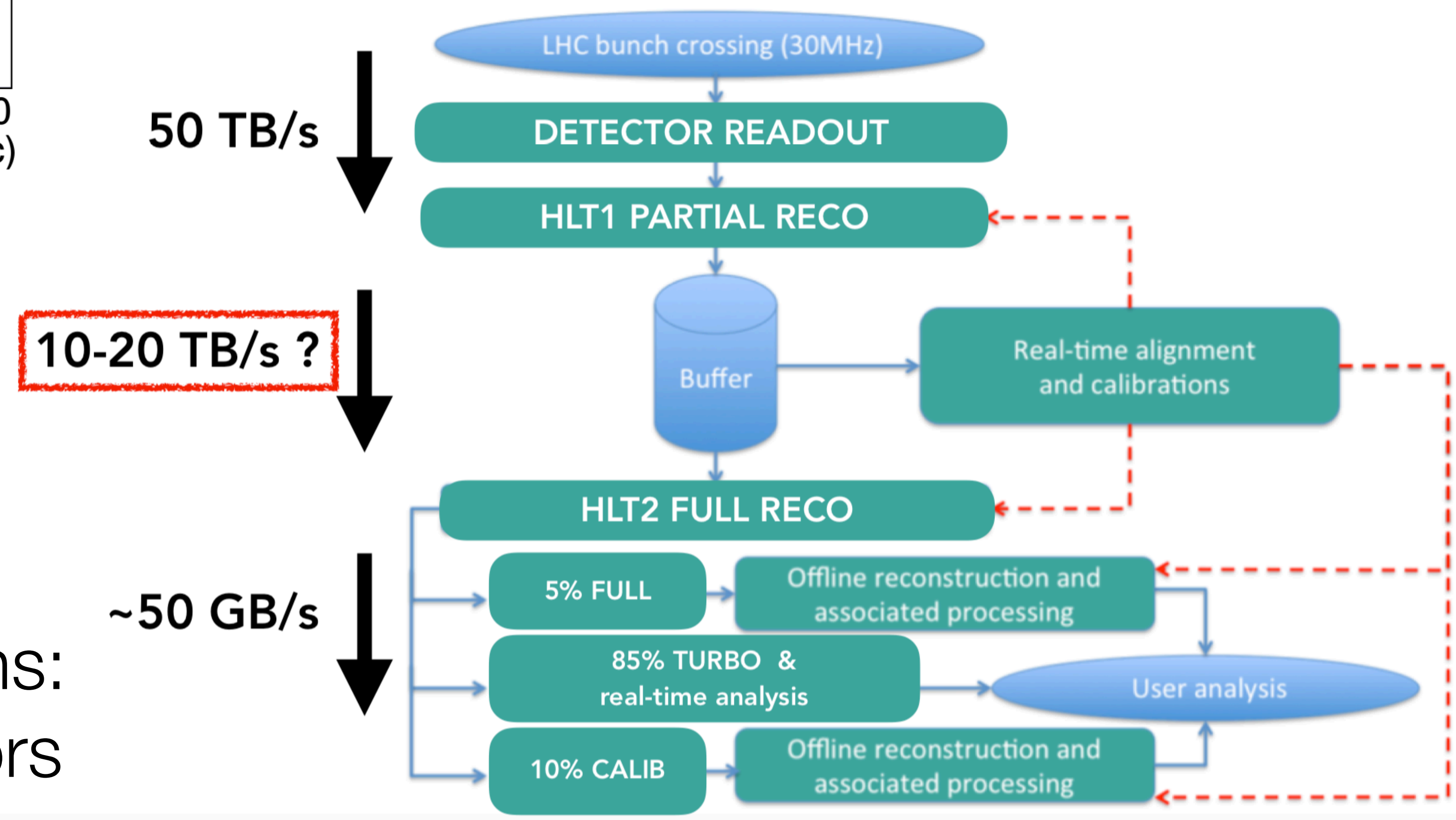


TORCH prototype

TDAQ challenges



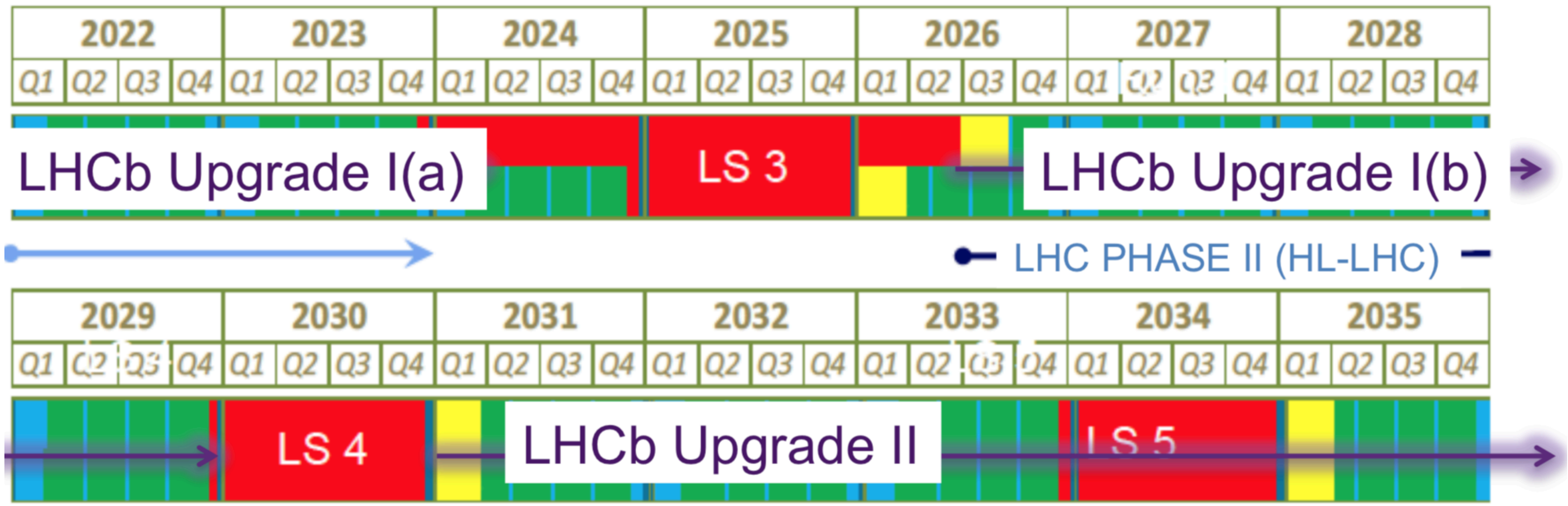
- Upgrade II must process similar (or larger) data volume as GPD
- Full software trigger is a challenging solution under study



- Data reduction and pileup suppression using TURBO stream and timing information
- R&D ongoing for other solutions: FPGA tracking, HW accelerators

Conclusion and perspectives

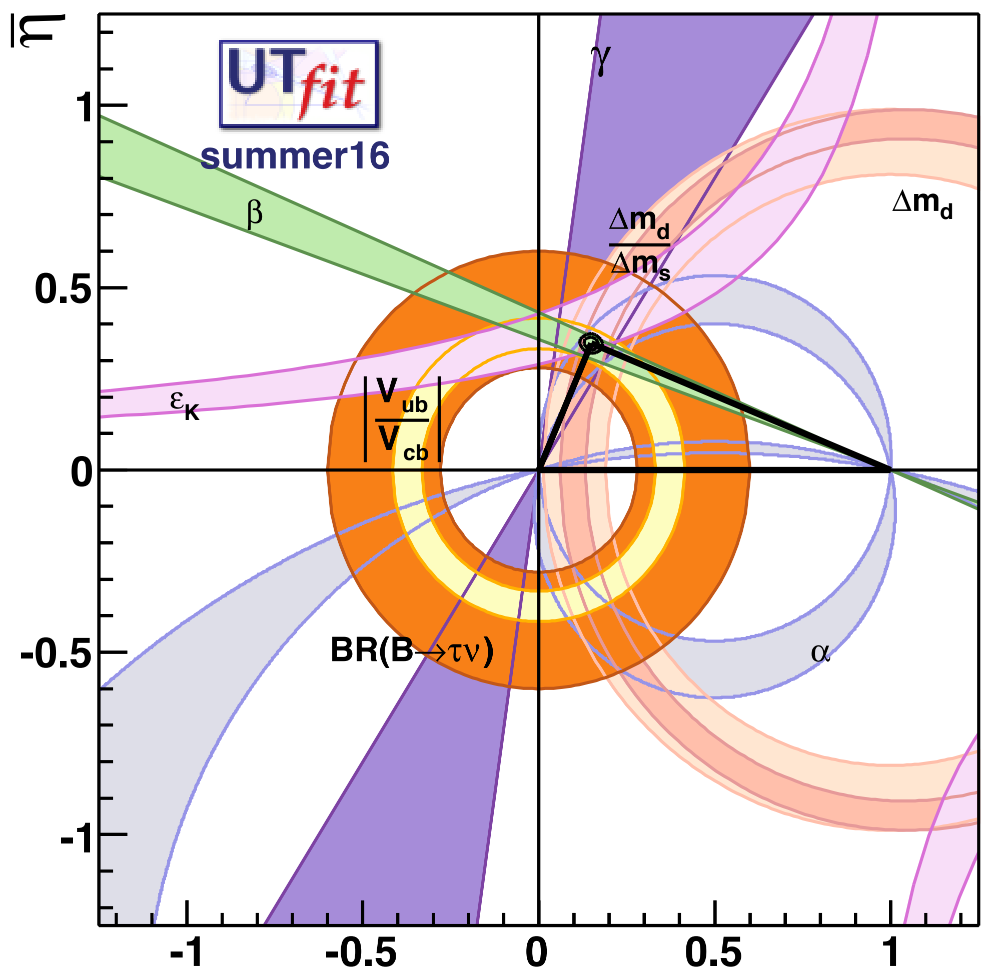
- LHCb is the only LHC experiment with some hints of new physics
- LHCb Upgrade II (1b): a unique opportunity at HL-LHC

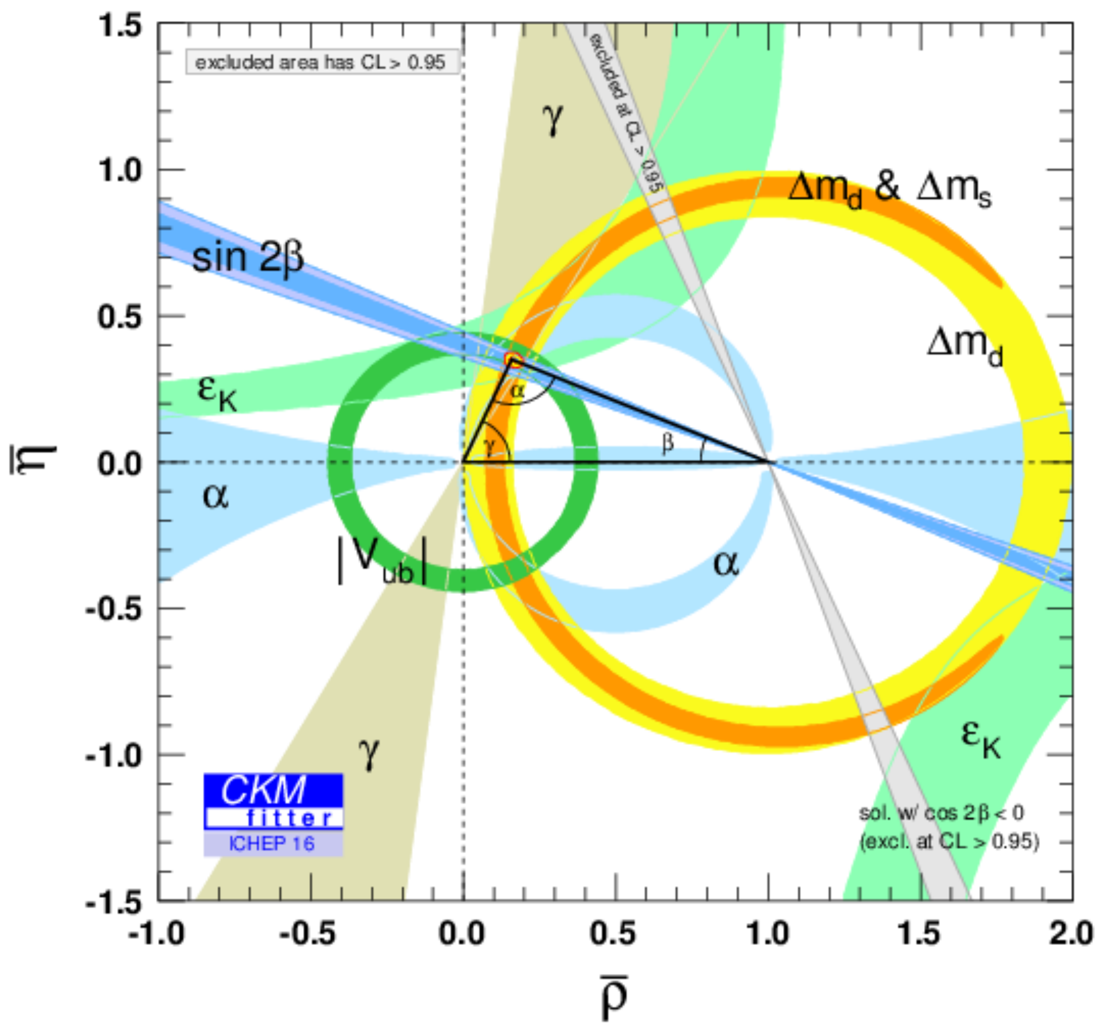


- Ultimate test of CKM, unique new physics searches in FW region
- Many detector challenges -we have not all the answers yet- …but it's worth it. If interested, you're welcome to join the enterprise!

Backup slides

The Unitarity Triangle in the LHC era





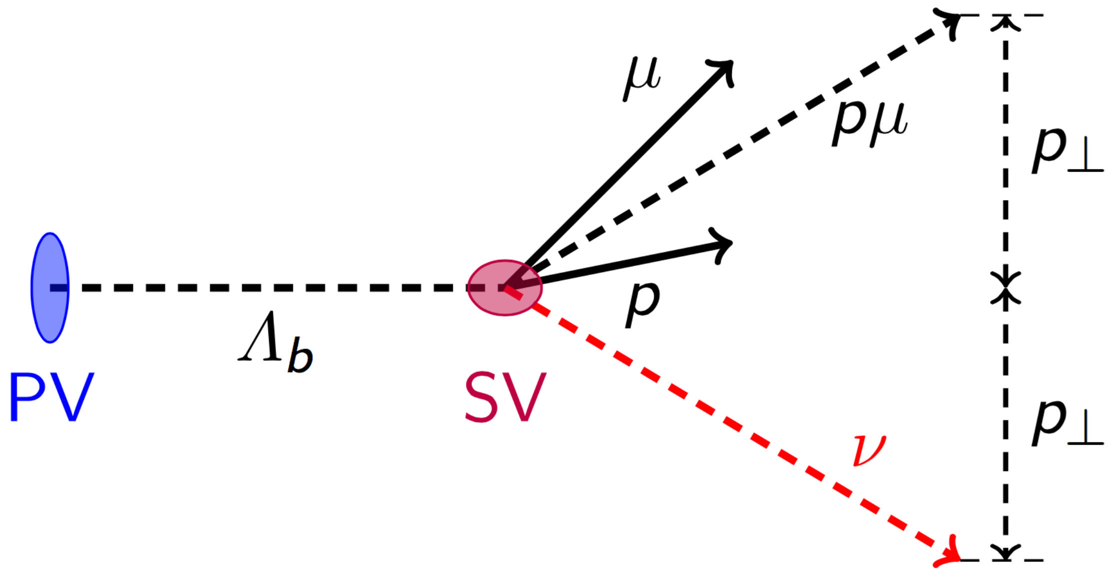
$\bar{\rho}$ = 0.153±0.013
$\bar{\eta}$ = 0.343±0.011

$\bar{\rho}$ = 0.160±0.008
$\bar{\eta}$ = 0.350±0.006

Overall picture is consistent with SM, $\bar{\rho}$ determined at 8% and $\bar{\eta}$ at 3% precision. Still room for new physics

$|V_{ub}/V_{cb}|$ measurement with $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$

2fb^{-1} data at 8 TeV - Nature Phys. 11 (2015) 743-747



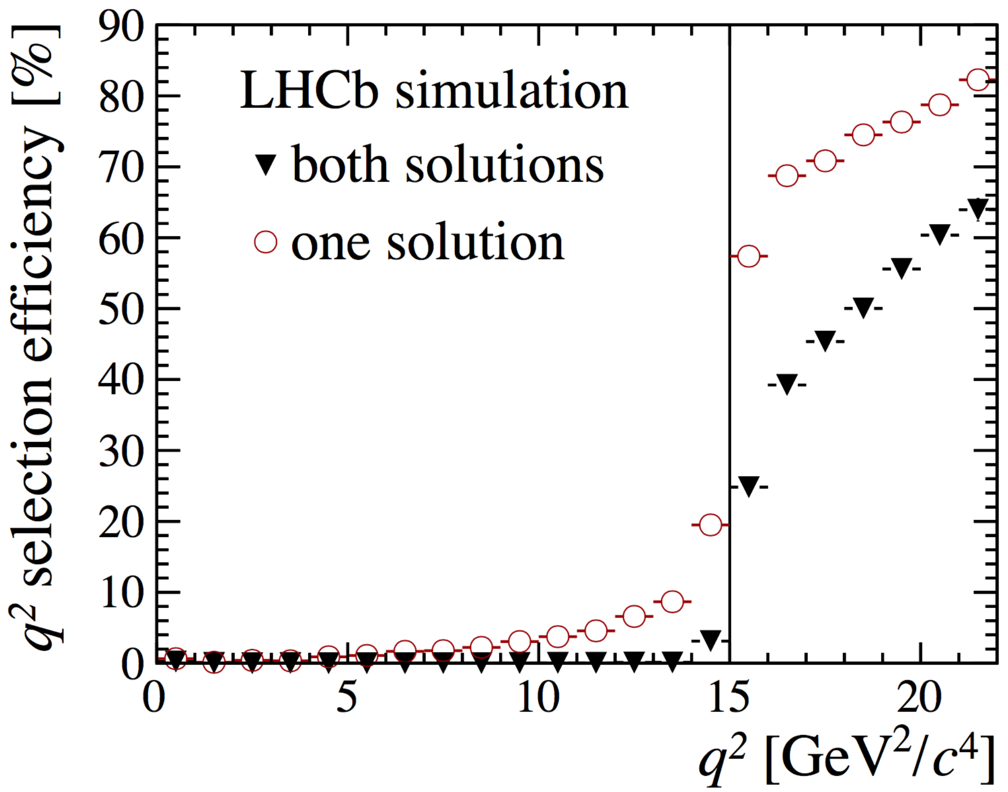
Normalise yields to $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$, V_{cb} mediated decay, cancel many systematic uncertainties

Apply tight vertex cut, PID on proton and muon, track isolation to reject 90% of background (using boosted decision tree)

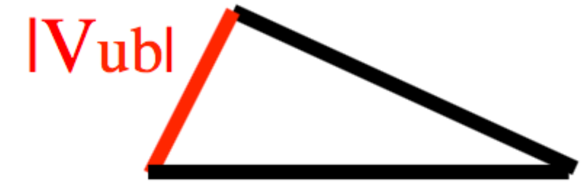
Use corrected mass to reconstruct the signal and retain events with $\sigma(M_{\rm corr}) < 100\text{MeV}$

$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$

- Use Λ_b^0 flight direction and mass to determine q^2 with two-fold ambiguity (neutrino). Require both solutions >15 GeV^2, minimise migration to low q^2 bins



$|V_{ub}/V_{cb}|$ results



2fb^{-1} data at 8 TeV - Nature Phys. 11 (2015) 743-747

Measure:

$$|V_{ub}|^2 = |V_{cb}|^2 \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)_{q^2>15\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)_{q^2>7\mathrm{GeV}^2}} R_{FF}$$

world average	measured	LQCD [1]
$(39.5 \pm 0.8) \times 10^{-3}$	$(1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$	0.68 ± 0.07

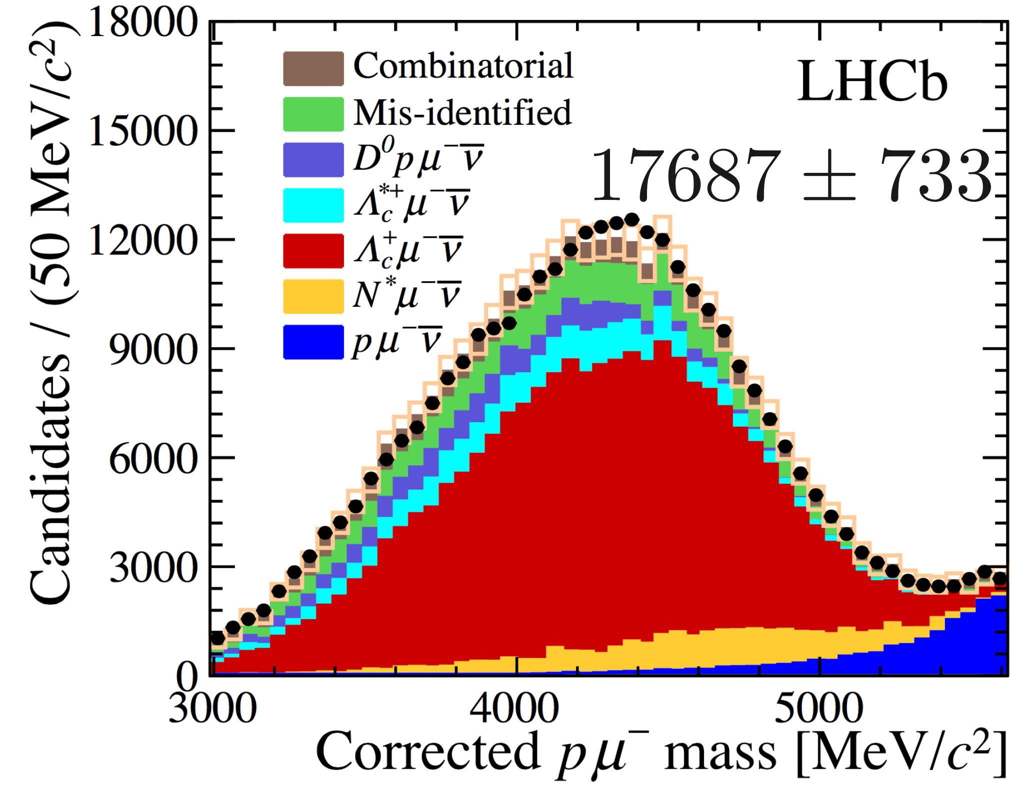
[1] W. Detmold, C. Lehner, and S. Meinel, arXiv:1503.01421

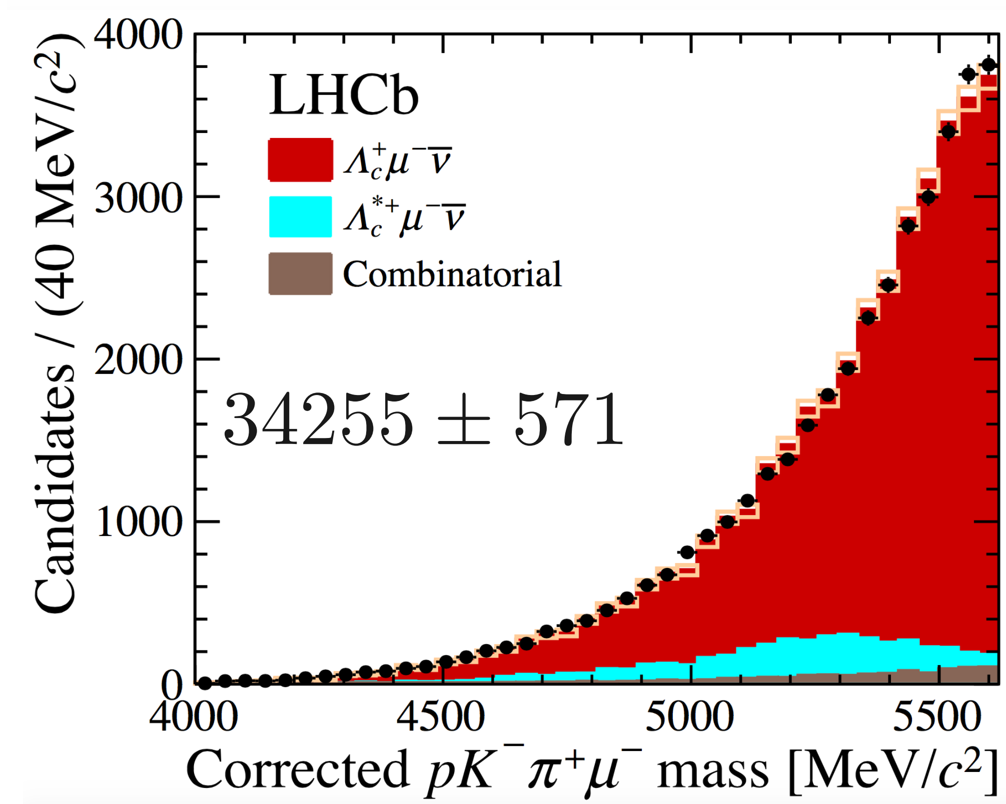
Most precise measurement

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$$

exp. LQCD $|V_{cb}|$

- Background contributions estimated using ad hoc control samples
- Largest exp. uncertainty from $\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$
- Important and independent determination of V_{ub} from B factories



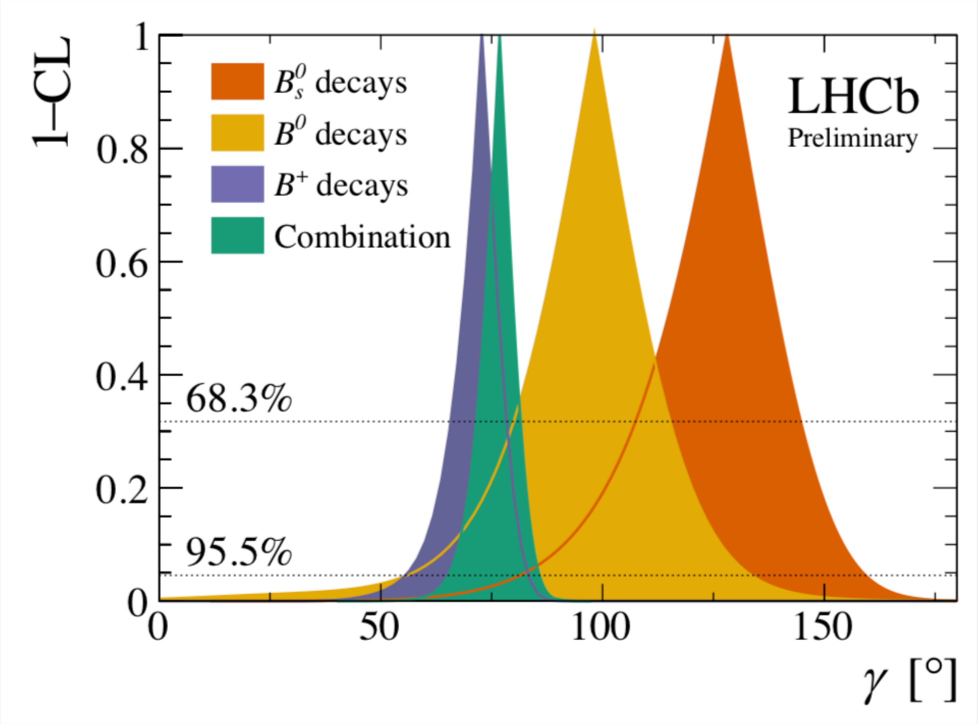


γ from combination of measurements

Combination of B→DK measurements

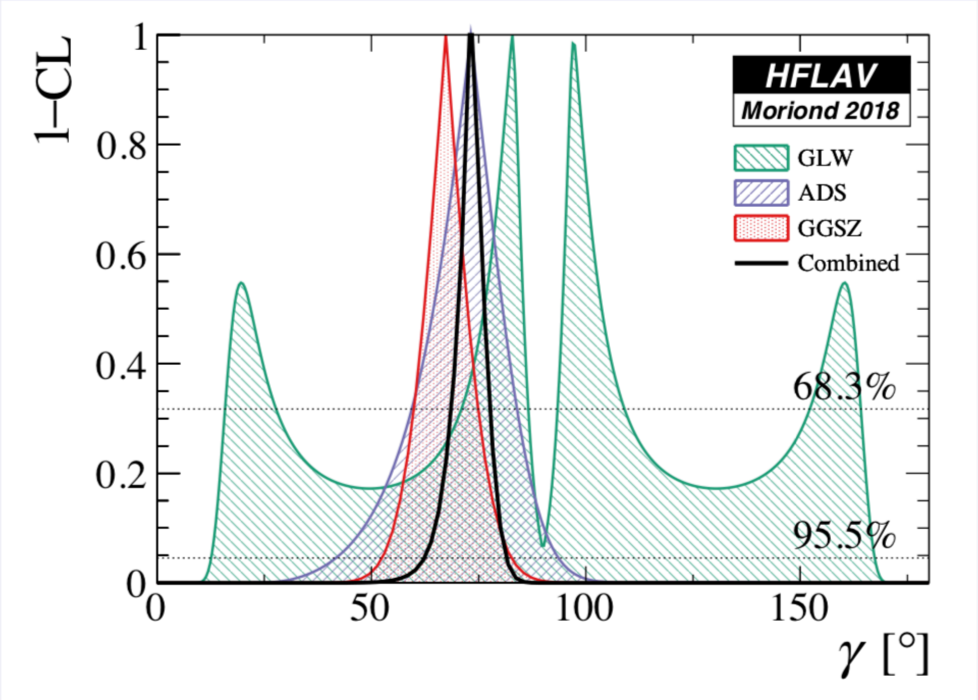
LHCb Average - [LHCb-CONF-2018-002]

$\gamma = (74.0^{+5.0}_{-5.8})^\circ$



World Average (HFLAV) - [Spring update]

$\gamma = (73.5^{+4.2}_{-5.1})^\circ$



Indirect constraints are: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ $(\sim 2\sigma)$

Comparison between B_s^0 and B^+ initial states $\sim 2\sigma$

BaBar $\gamma = (69^{+17}_{-16})^\circ$ PRD 87, 052015 (2013)

Belle $\gamma = (68^{+15}_{-14})^\circ$ arXiv:1301.2033 (2013)

See M. Kenzie talk

$B_{(s)}$ flavour oscillations

Flavour oscillations occur when flavour eigenstates differ from mass eigenstates

$$|B_{L,H}\rangle = q|B^0\rangle \pm q|\overline{B}^0\rangle$$

- Study time evolution of flavour defined states: $\Delta m = m_H - m_L > 0 \quad \Delta\Gamma = \Gamma_L - \Gamma_H$

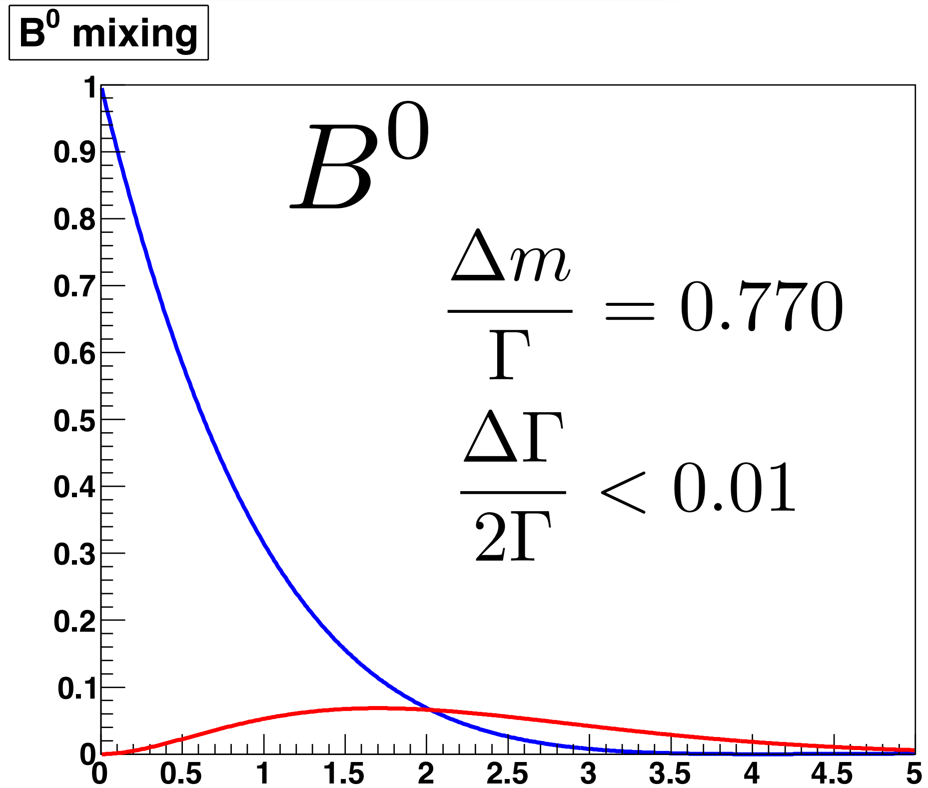
$$\mathrm{Prob}(B^0 \to B^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) + \cos(\Delta m t)]$$

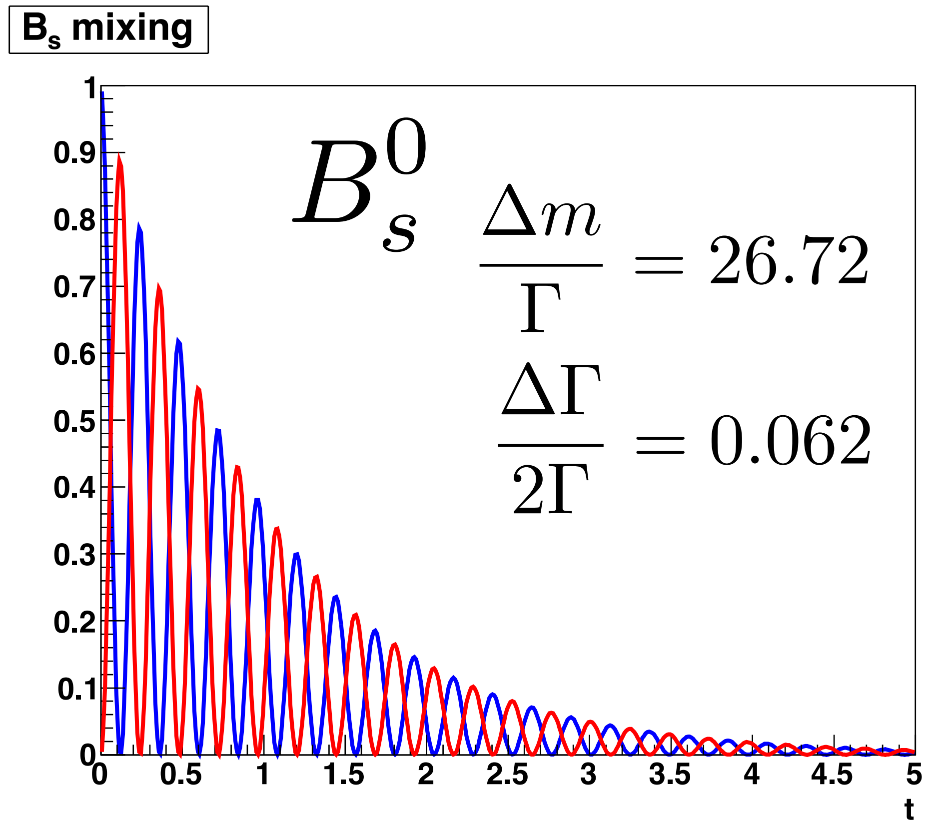
$$\mathrm{Prob}(B^0 \to \overline{B}^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) - \cos(\Delta m t)]|q/p|^2$$

$$\mathrm{Prob}(\overline{B}^0 \to B^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) - \cos(\Delta m t)]|p/q|^2$$

$$\mathrm{Prob}(\overline{B}^0 \to \overline{B}^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) + \cos(\Delta m t)]$$

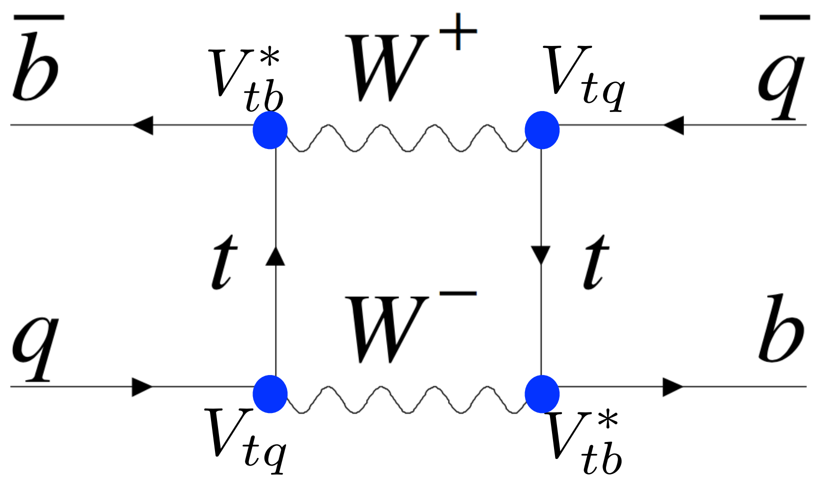
- In SM $\Delta\Gamma>0$ (very small for B^0) and $|q/p|\sim1$, very small CPV in B^0 and B_s mixing





Measurement of Δm_d and Δm_s

Flavour oscillations via box diagram

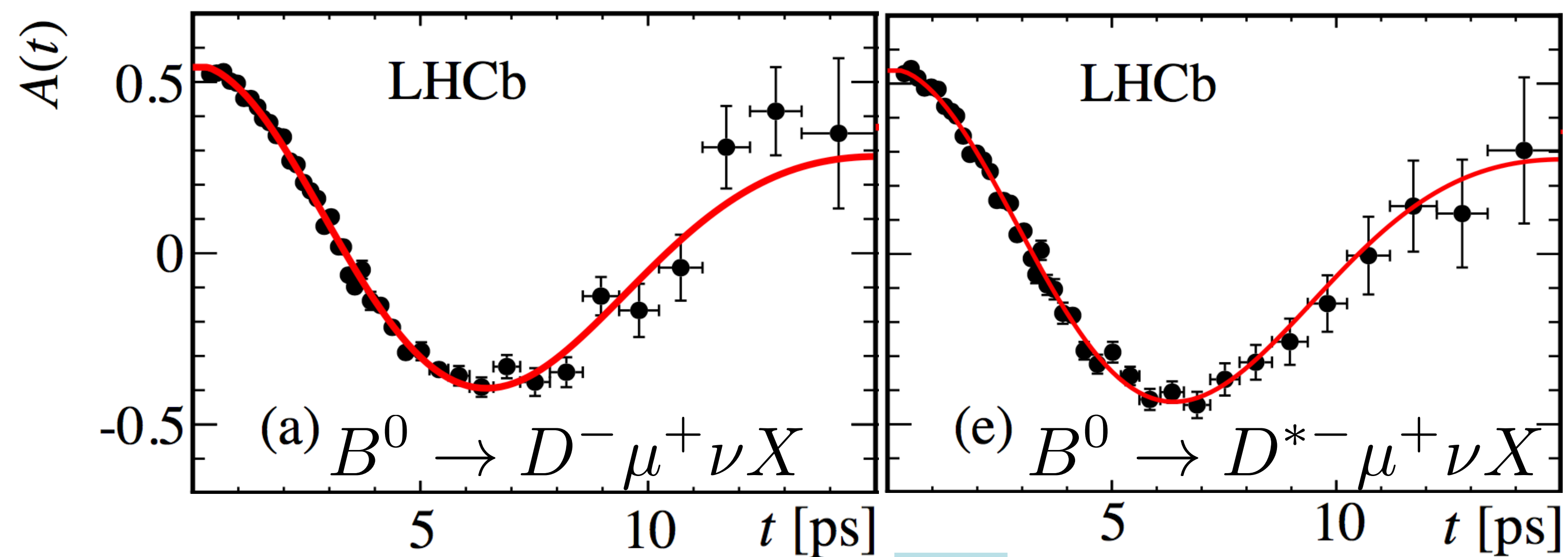


$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 (1.206 \pm 0.019)^2$$

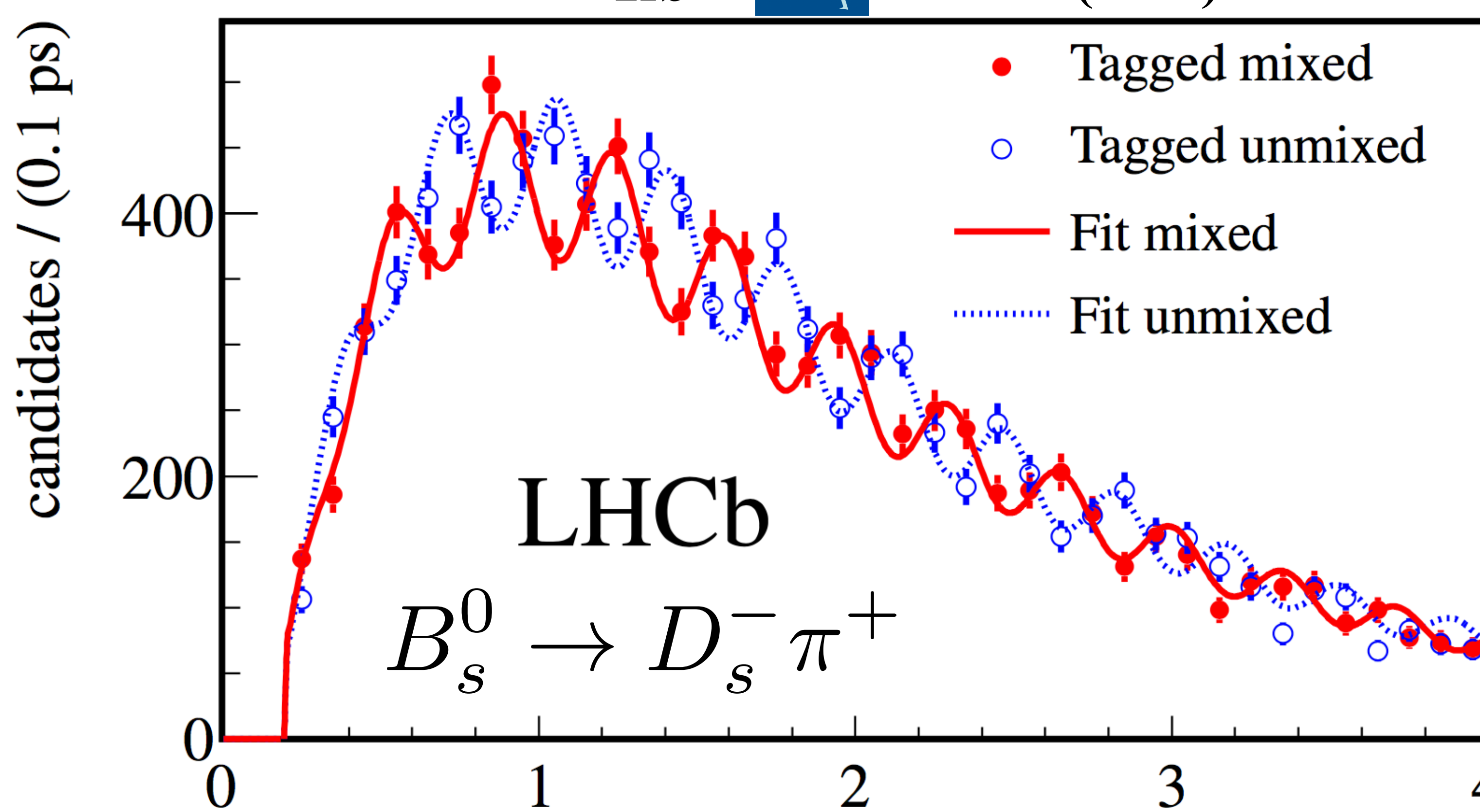
MILC, PRD 93 (2016) 113016

Theory uncertainty from LQCD dominates extraction of $|V_{ts}/V_{td}|$

$\Delta m_d = (505.0 \pm 2.1 \pm 1.0)\,\mathrm{ns}^{-1}$ **3fb^{-1}** **EPJC 76 (2016) 412**



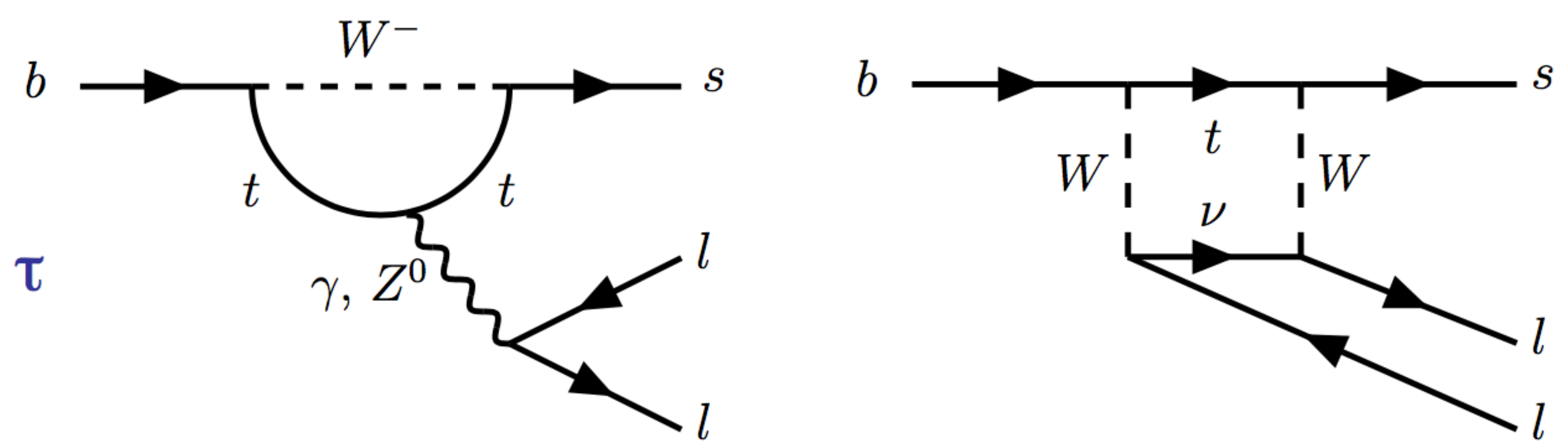
1fb^{-1} **NJP 15 (2013) 053021**



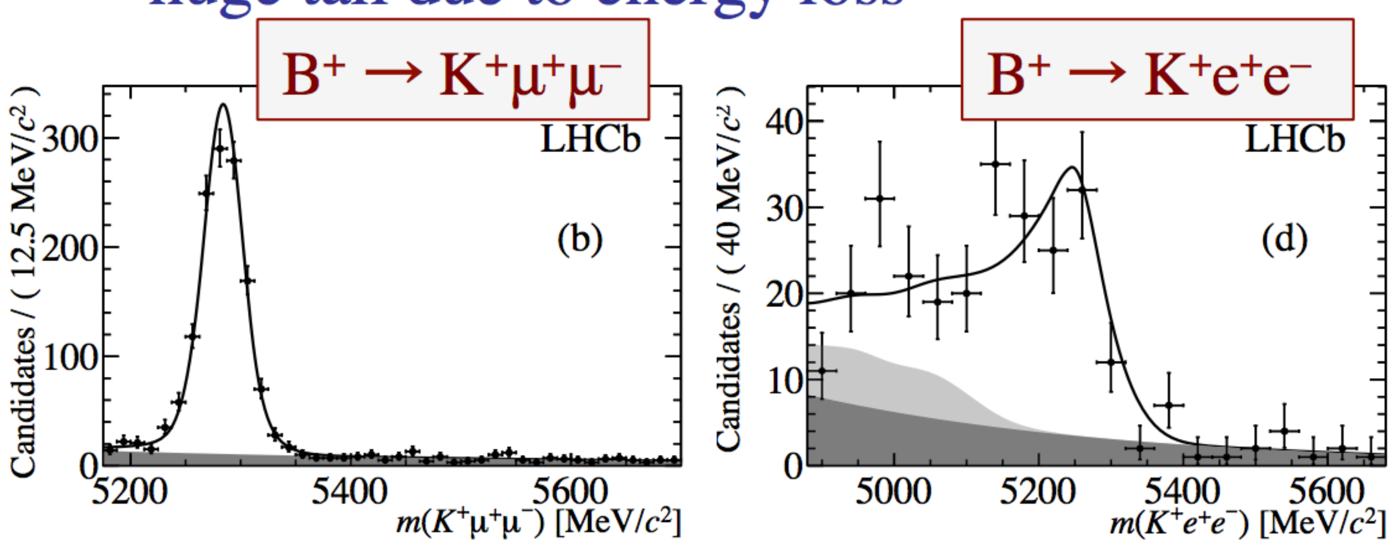
$\Delta m_s = 17.768 \pm 0.023(\mathrm{stat}) \pm 0.006(\mathrm{syst})\,\mathrm{ps}^{-1}$

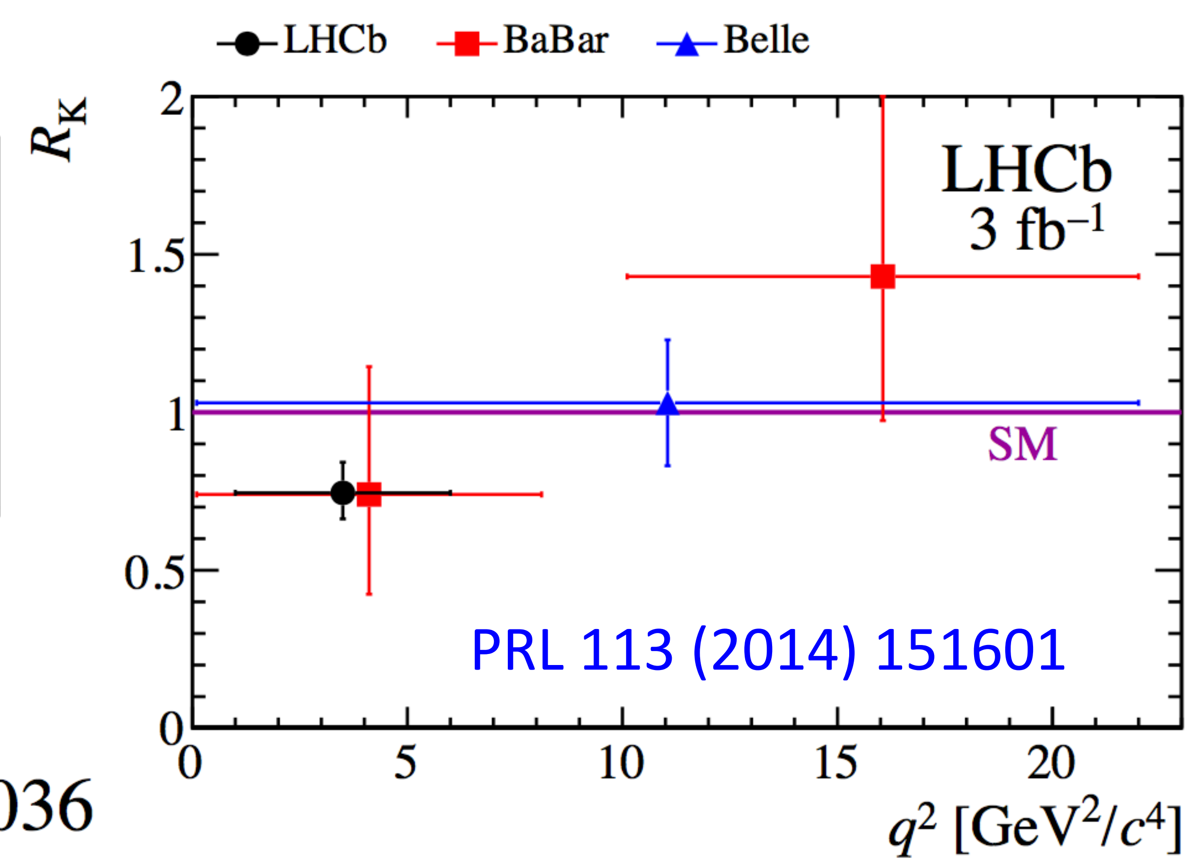
$B^+ \to K^+\ell^+\ell^-$ and lepton universality

- **Lepton Flavour Universality (LFU) in the SM:**
  - same EW couplings for ℓ = e, μ, τ



- **LHCb:**
  - electron reconstruction challenging, huge tail due to energy loss





  - for low q² region ($1<q^2<6$ GeV²/c⁴):

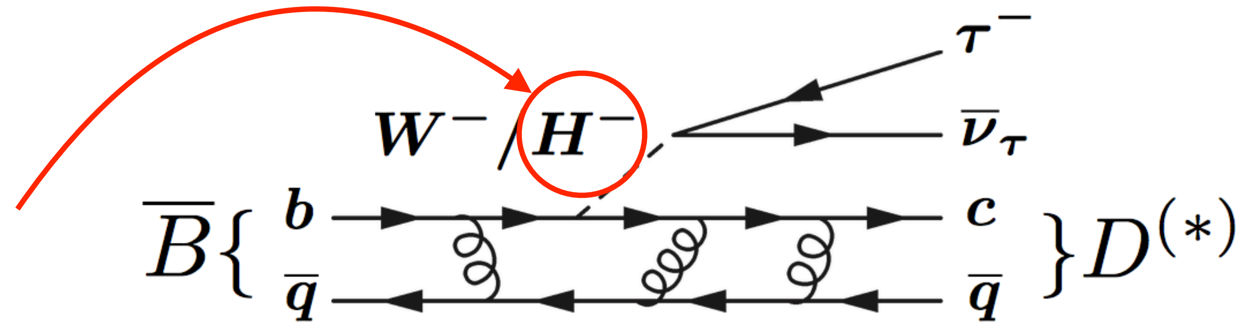
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

2.6σ from SM value of $1 \pm O(10^{-3})$

Test of lepton flavour universality

LFU test with $B \to D^{(*)}\ell\nu$

tree level decay, sensitive to possible H^+ contribution

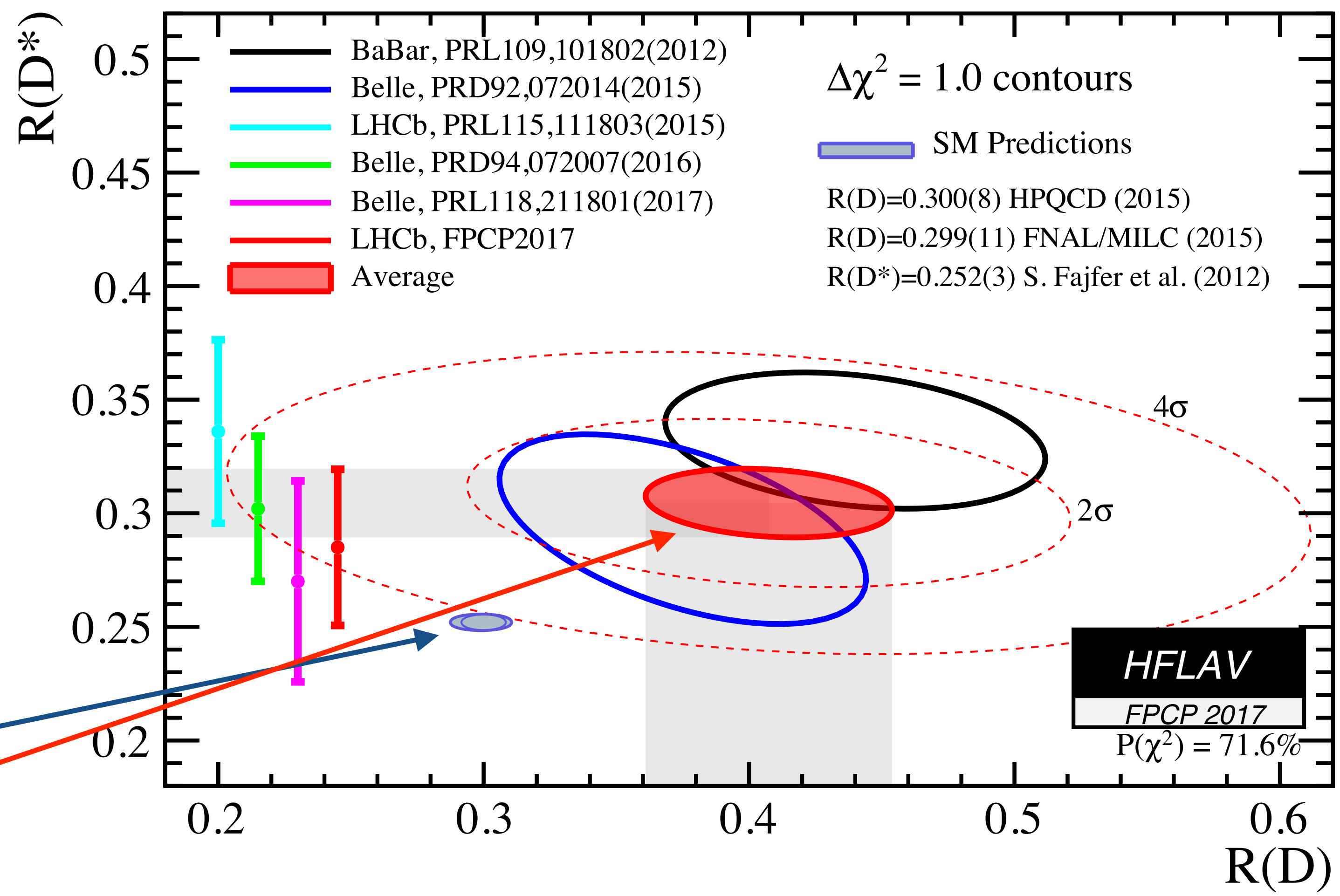


R(D) and R(D*) definition

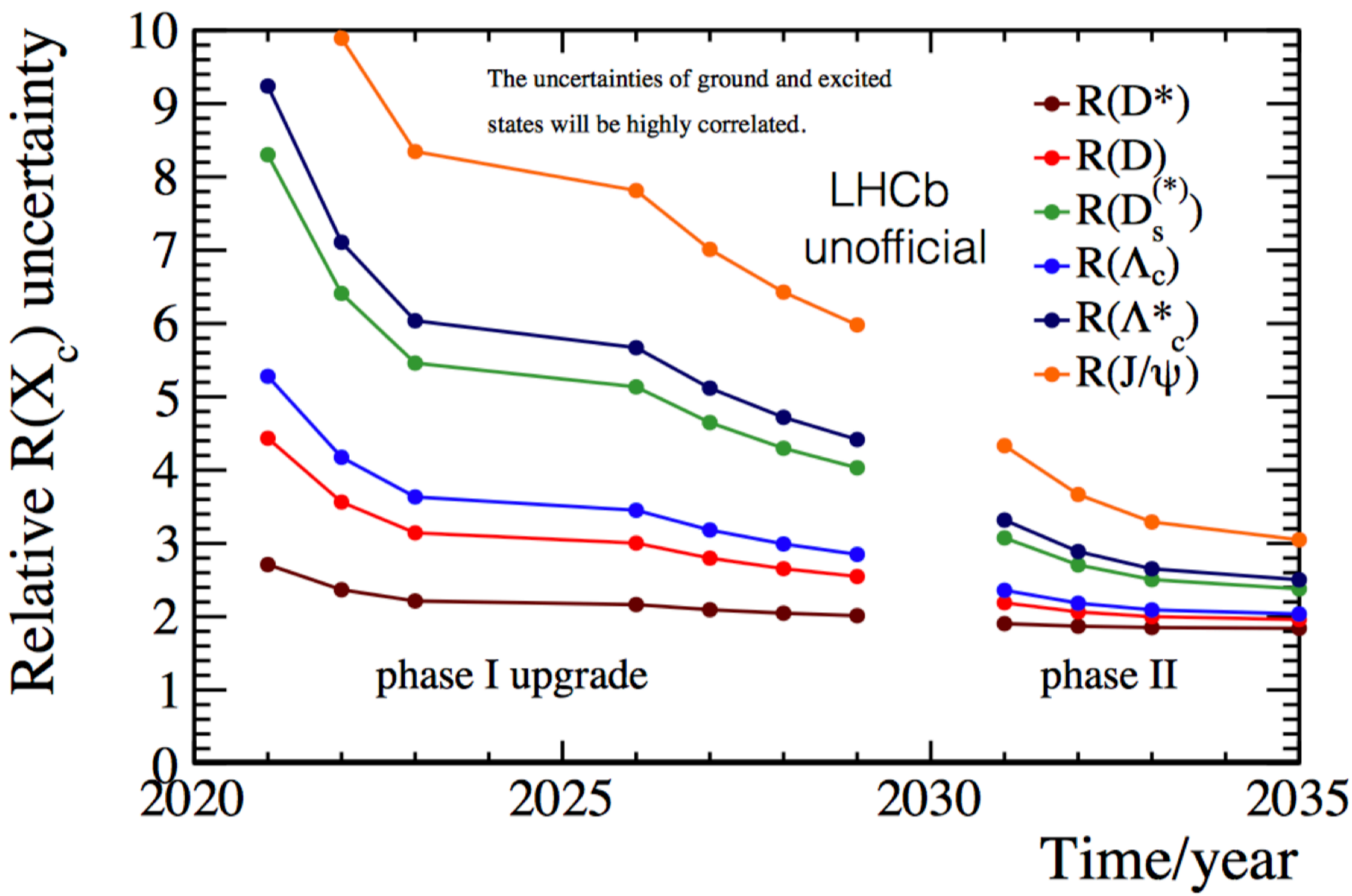
$$R(D^{(*)}) = \frac{B^0 \to D^{(*)-}\tau^+\nu_\tau}{B^0 \to D^{(*)-}\ell^+\nu_\tau}$$

$$\ell = \mu, e$$

- Experimental challenge
  - tau reconstruction, missing neutrinos
- **4.1σ** from **SM** at (**2D average**)



Semitauonic measurements



Phase-II will substantially benefit R(Xc) measurements of B_s, Λ_b^0, B_c hadrons, not accessible at Belle II

TDAQ R&D

- R&D for alternative solutions is ongoing
  - specialised processors for real-time tracking (link)
  - HW accelerators for event filtering e.g. FPGA (link), GPU
  - identify and store only the interesting part of each event, e.g. select only 1 out 55 *pp* interactions

FPGA tracking processors

CPU-FPGA accelerator

Flexibility: change functions

Acceleration: wrt CPU

Integration: I/O >1 Tbps