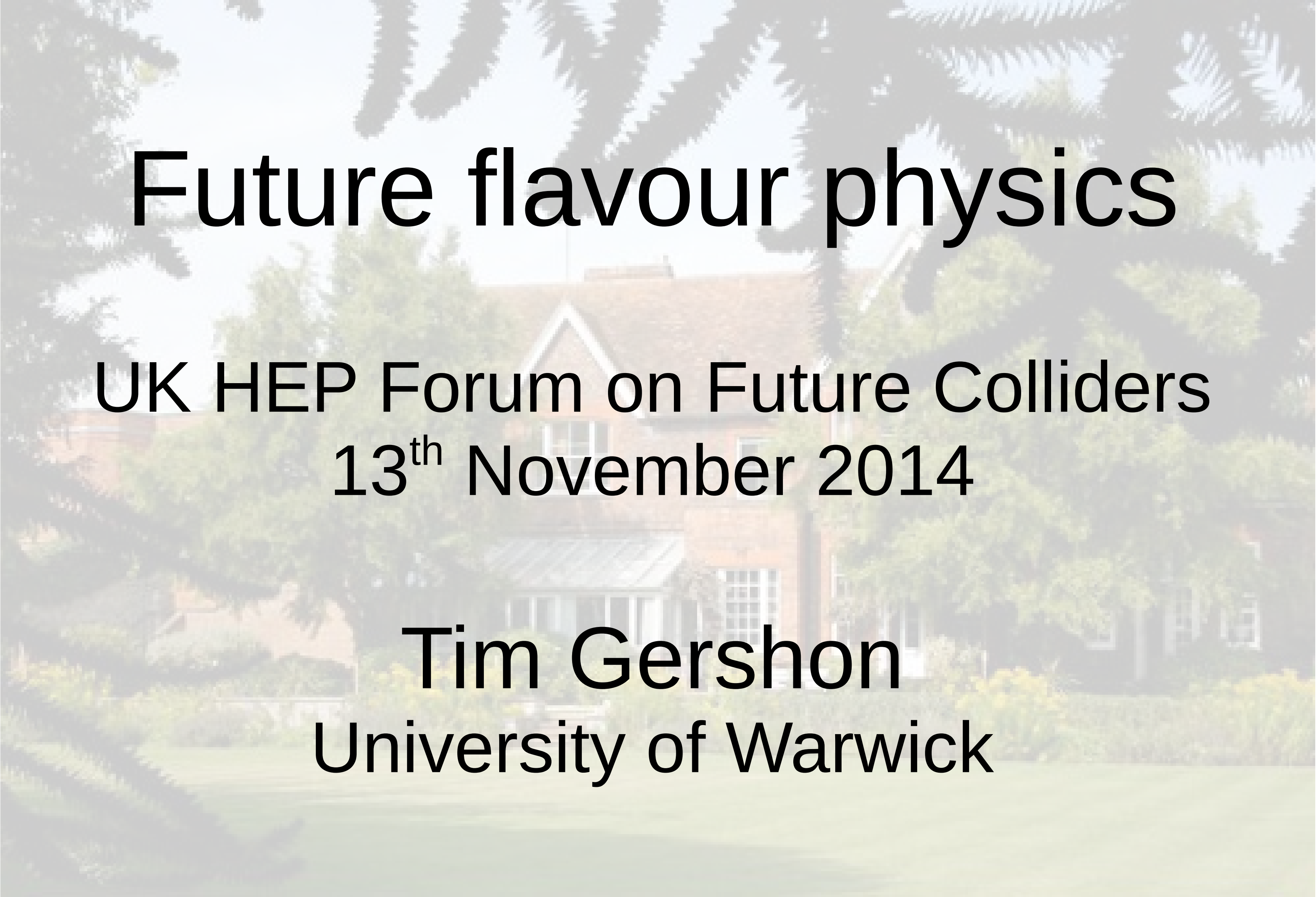


Future flavour physics

UK HEP Forum on Future Colliders
13th November 2014

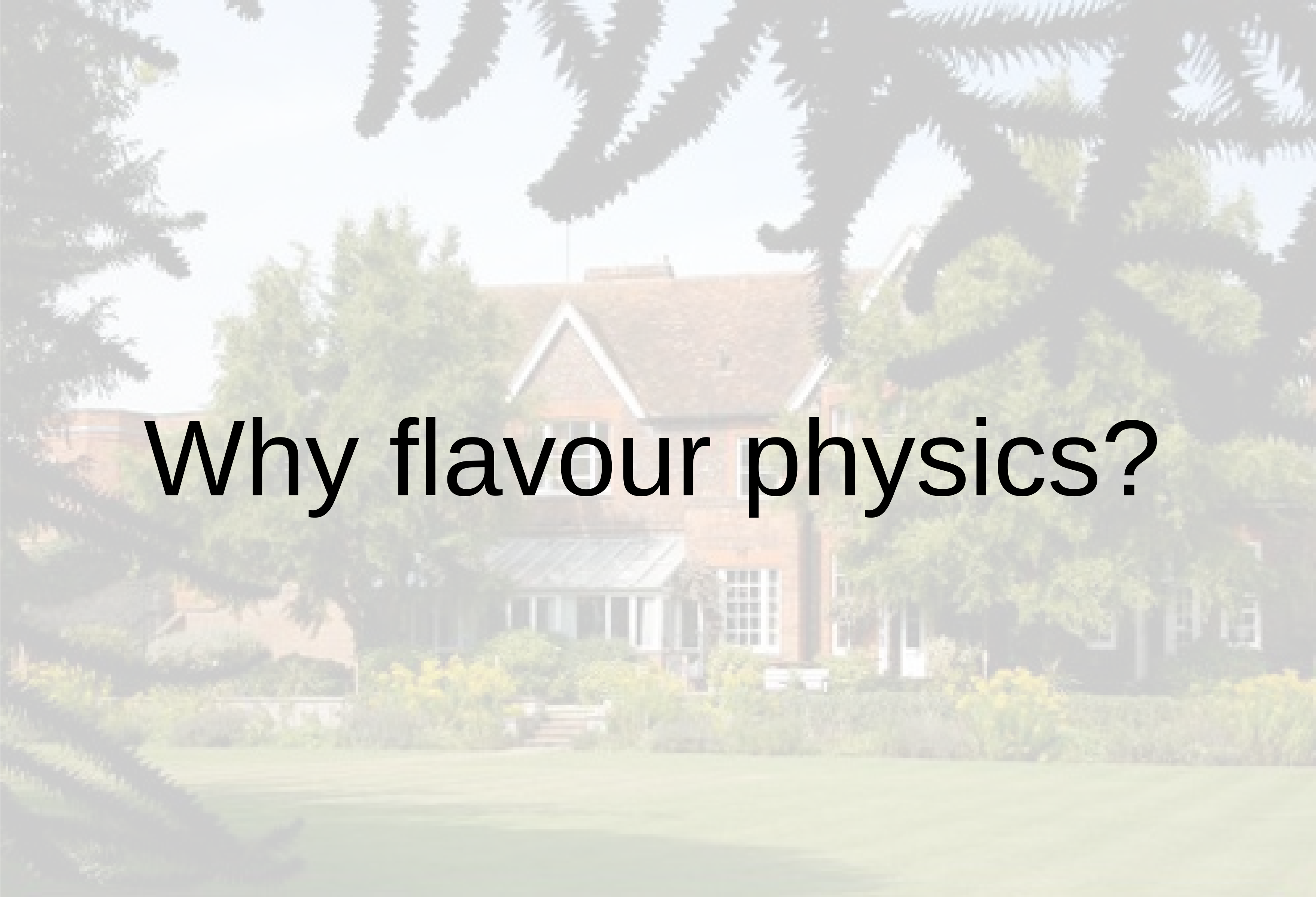
Tim Gershon
University of Warwick

Content

- Why flavour physics, now and future?
- Flavour physics today
  - Key observables for future experiments
- Facilities and expected sensitivities
- Summary

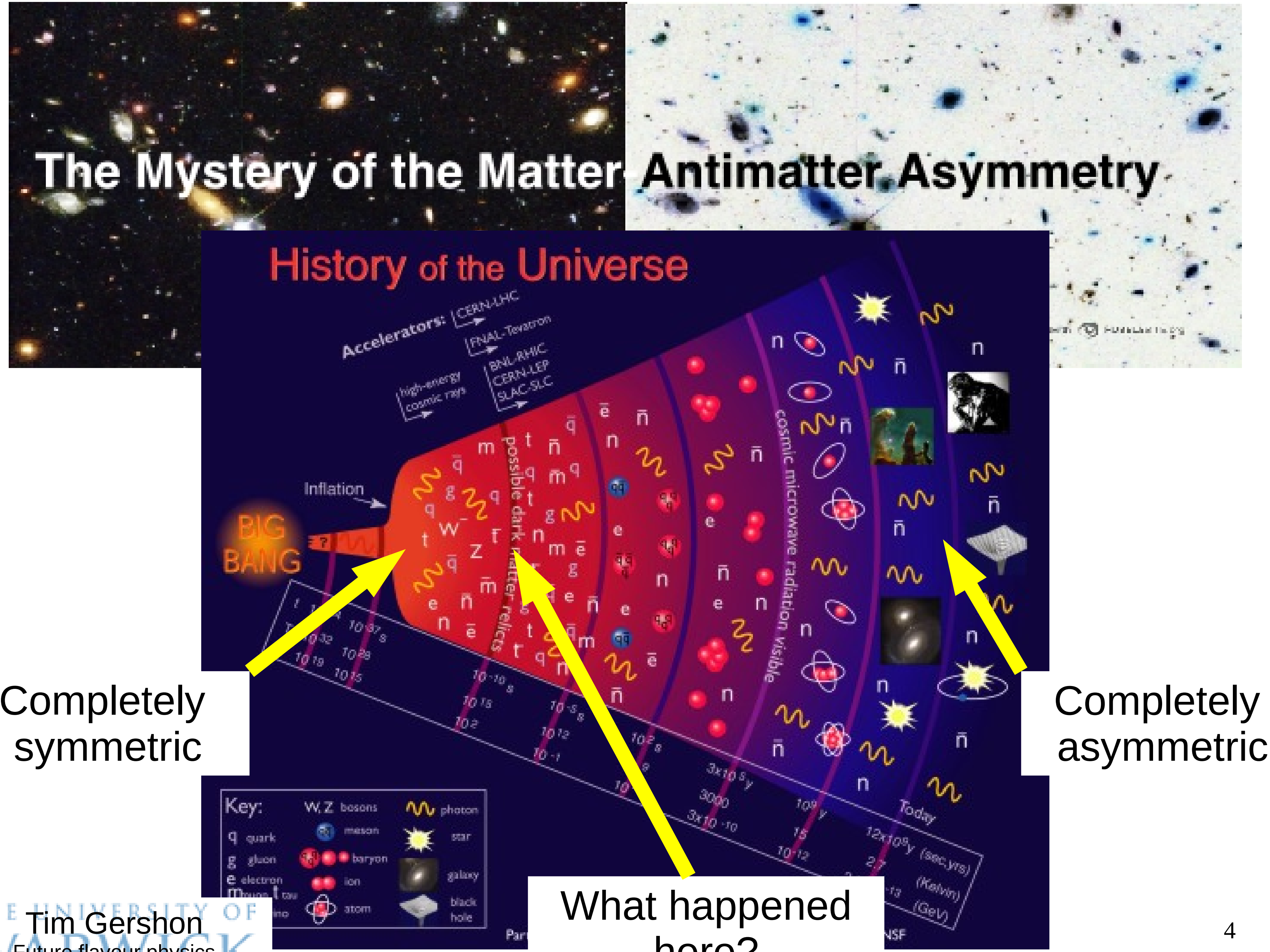
Focus on flavour physics at colliders
i.e. heavy quarks and tau leptons

Following the usual convention, will not discuss top physics
or predominantly-QCD-related observables (production, spectroscopy)



Why flavour physics?

The Mystery of the Matter-Antimatter Asymmetry



Completely symmetric

What happened here?

Completely asymmetric

CP violation and the matter-antimatter asymmetry

- Two important facts
  1) CP violation is one of 3 “Sakharov conditions” necessary for the evolution of a baryon asymmetry in the Universe
  2) The Standard Model (CKM) CP violation is not sufficient to explain the observed asymmetry
- Therefore, there must be more sources of CP violation in nature … but where?
  - extended quark sector, lepton sector (leptogenesis), supersymmetry, anomalous gauge couplings, extended Higgs sector, quark-gluon plasma, flavour-diagonal phases, …
- Testing the consistency of the CKM mechanism provides an excellent chance to find new sources of CP violation

What causes the difference between matter and antimatter?

- In the SM, fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking m_ν=0)
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = U_u U_d^+$$

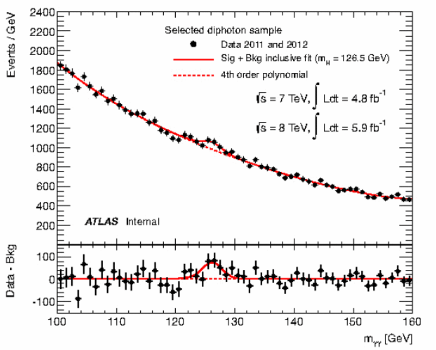
U matrices from diagonalisation of mass matrices

- It is a 3x3 complex unitary matrix
  - described by 9 (real) parameters
  - 5 can be absorbed as phase differences between the quark fields
  - 3 can be expressed as (Euler) mixing angles
  - the fourth makes the CKM matrix complex (i.e. gives it a phase)
    - weak interaction couplings differ for quarks and antiquarks
    - CP violation (only source in SM, $m_\nu = \theta_{QCD} = 0$)

Breaking of the electroweak (gauge) symmetry leads to violation of the CP (discrete) symmetry

Two routes to heaven

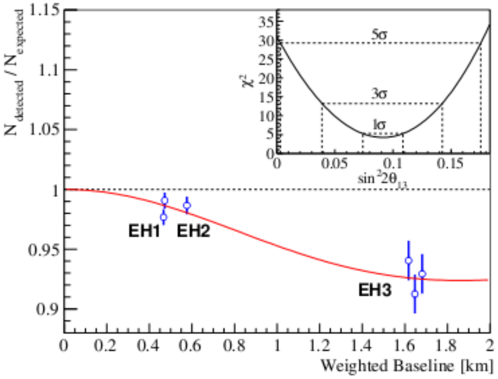
for flavour physics



SM

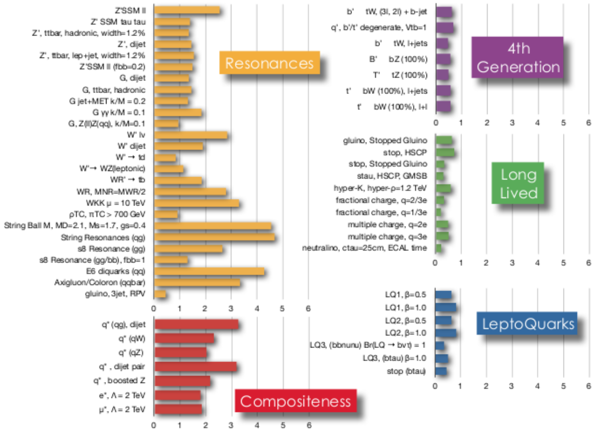
CP violation
(extra sources must exist)

But
- No guarantee of the scale
- No guarantee of effects in the quark sector
- Realistic prospects for CPV measurement in νs due to large θ_{13}



Rare decays
(strong theoretical arguments)

But
- How high is the NP scale?
- Why have FCNC effects not been seen?

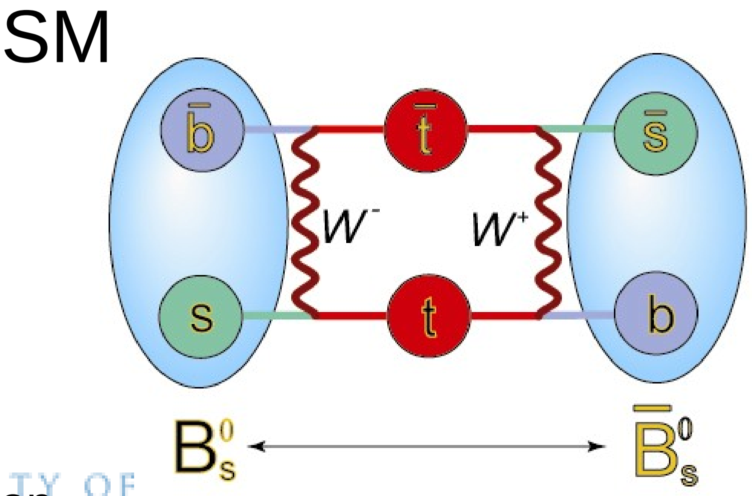


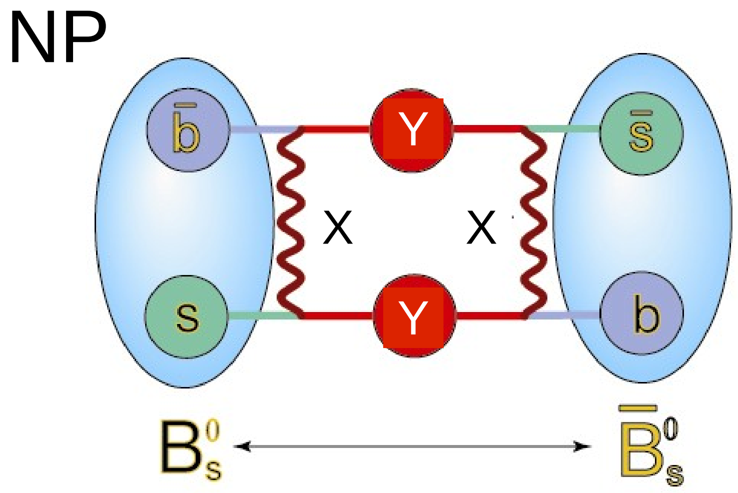
NP

Absence of NP signals at ATLAS/CMS → argument for searches via rare decays stronger

Loop diagrams for discovery

- Contributions from virtual particles in loops allow to probe far beyond the energy frontier
- History shows this approach to be a powerful discovery tool
- Interplay with high-p_T experiments:
  - NP discovered: probe the couplings
  - NP not discovered: explore high energy parameter space

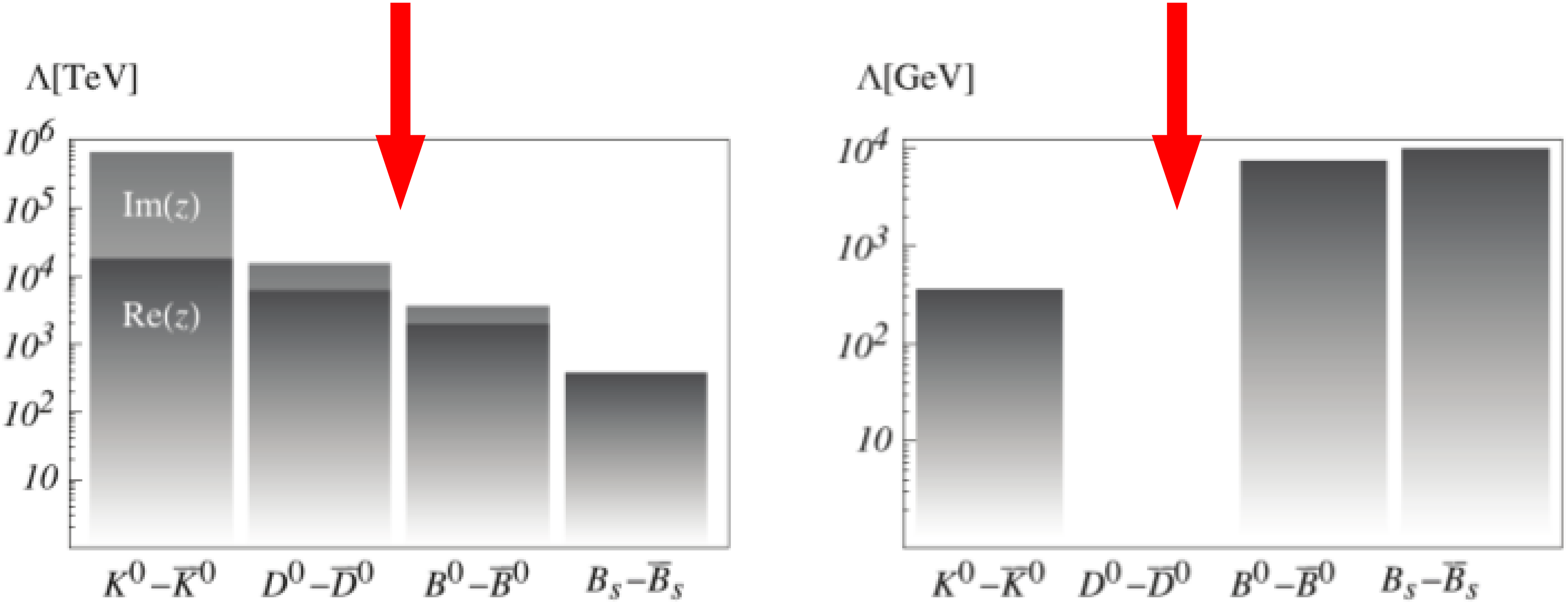




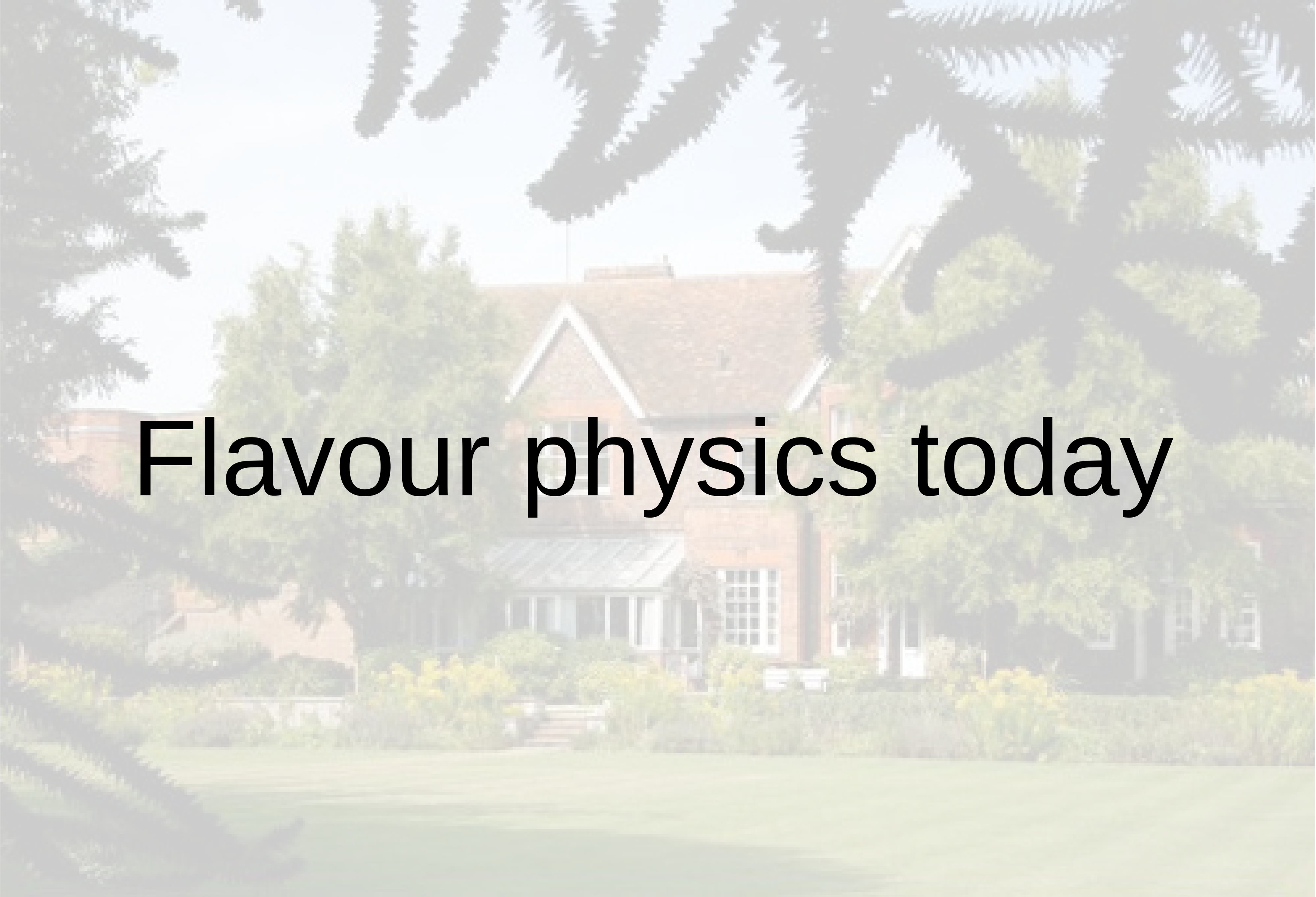
Loop diagrams for discovery

Limits on NP scale

Generic coupling MFV (i.e. SM-like) coupling

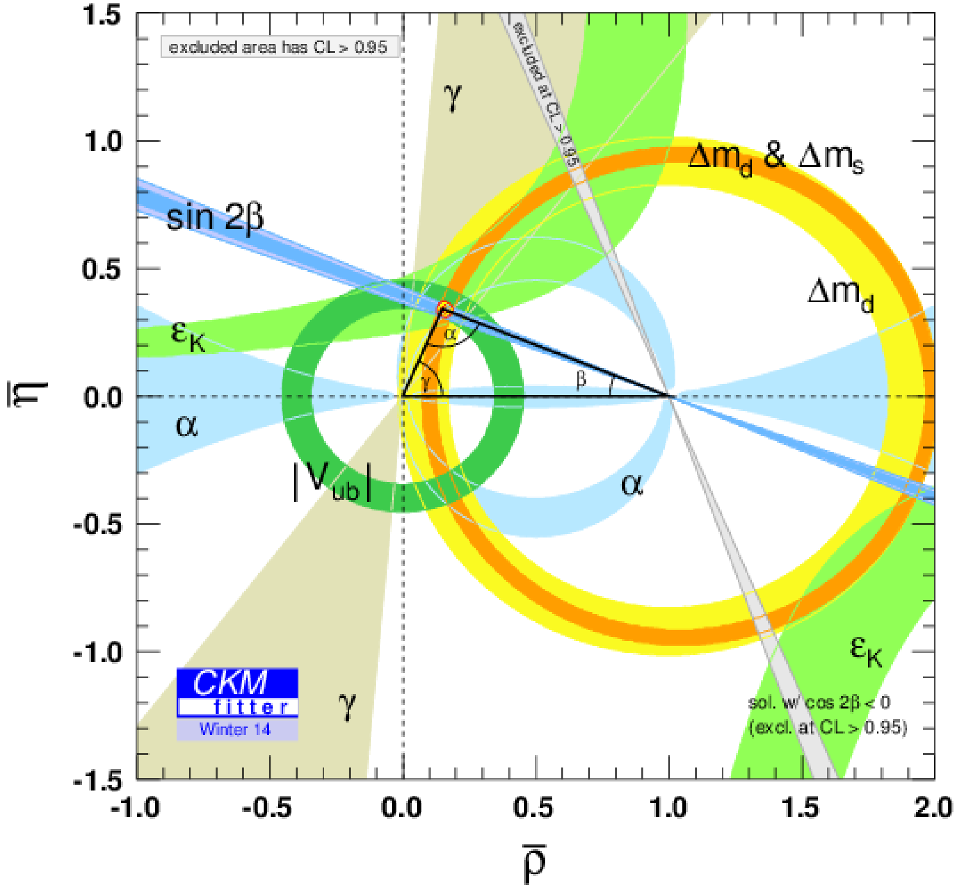


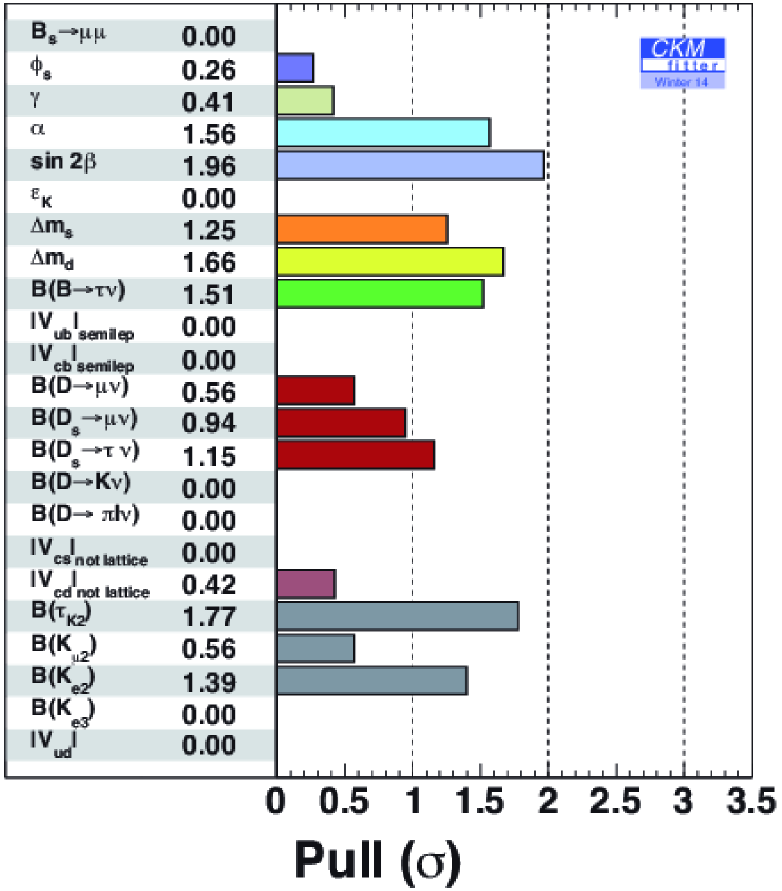
J. Kamenik
Mod.Phys.Lett. A29 (2014) 1430021



Flavour physics today

CKM fits



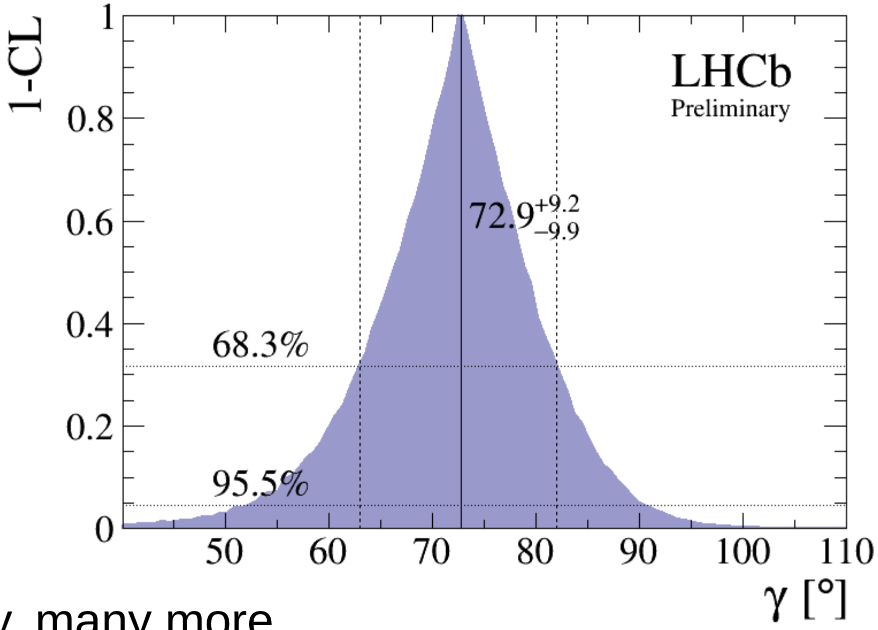


Excellent overall consistency with the CKM paradigm
But this plot does not tell the whole story

γ from B → DK

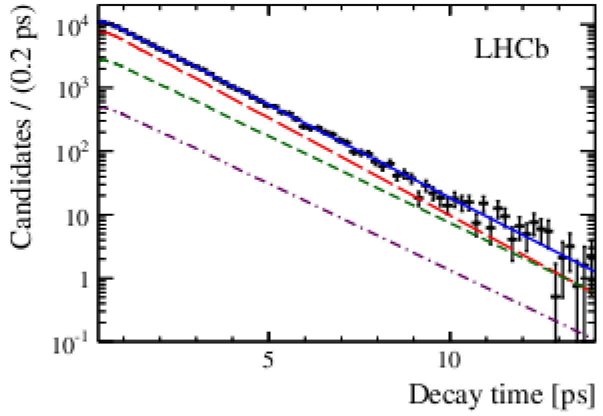
- Determination of the CKM phase with negligible theoretical uncertainty
- Sensitivity to γ from numerous channels
  - $B^+ \to DK^+$ ($D \to K_S hh$)
  - $B^+ \to DK^+$ ($D \to hh'$)
  - $B_s \to D_s K$
  - $B^0 \to DK^{*0}$ ($D \to hh'$)
    - $B^0 \to DK\pi$ ($D \to hh'$)
  - $B^+ \to DK^+$ ($D \to K_S K\pi$)
  - $B^+ \to DK^+$ ($D \to K3\pi$, 4h, $hh'\pi^0$)
  - $B^0 \to DK^{*0}$ ($D \to K_S hh'$)
  - $B^+ \to DK^+\pi\pi$ ($D \to hh'$, $K_S hh'$, etc.)
  - $B^+ \to D^*K^+$ ($D \to hh'$, $K_S hh'$, etc.) … and many, many more

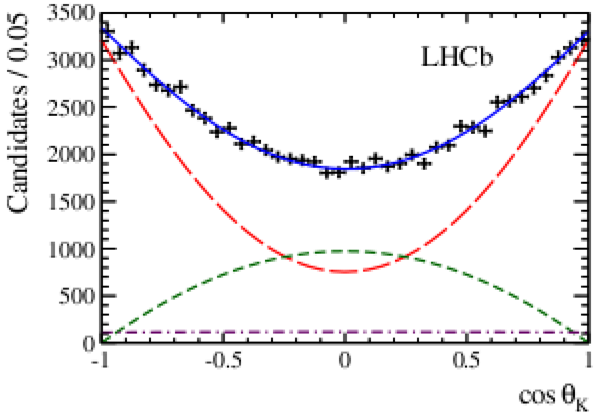
LHCb-CONF-2014-004



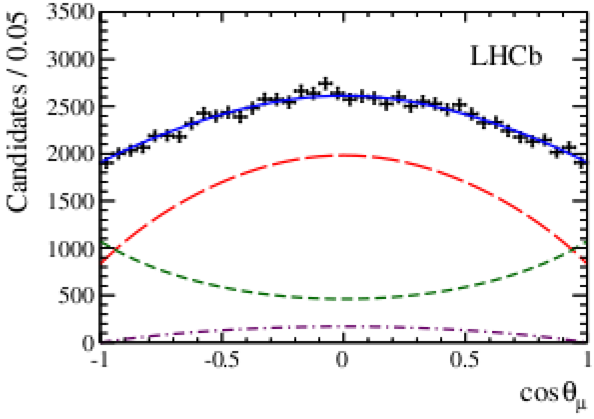
Colour code: 3/fb; 1/fb; not yet

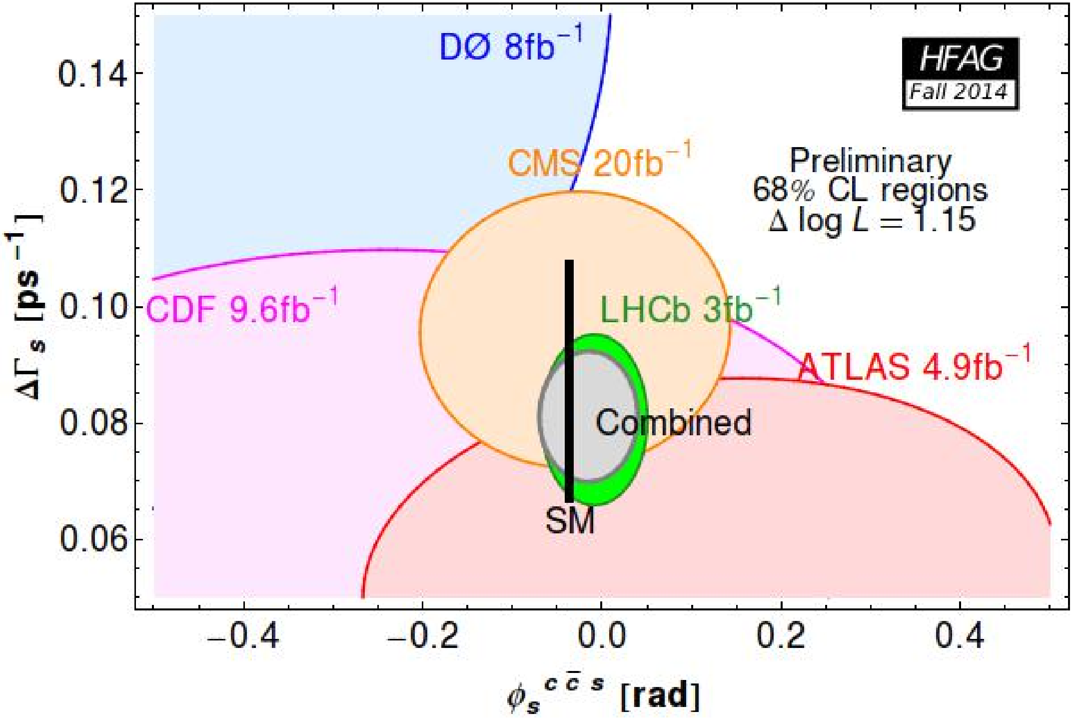
CP violation in $B_s \to J/\varphi$ (etc.) – φ_s





Latest LHCb results
arXiv:1411.3104

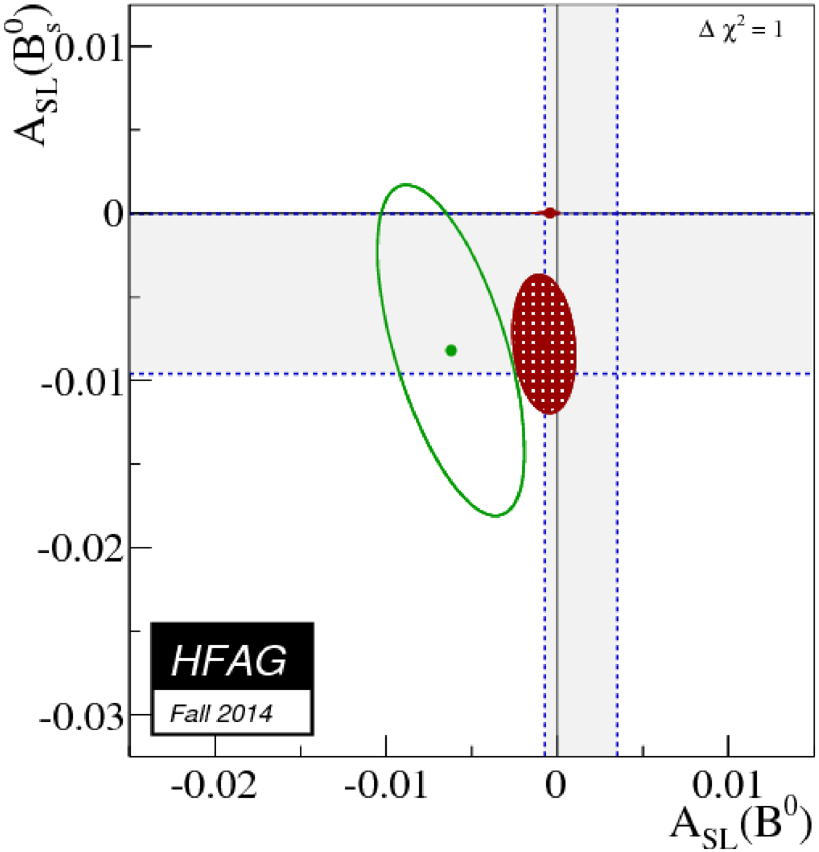




Important contributions from CMS & ATLAS

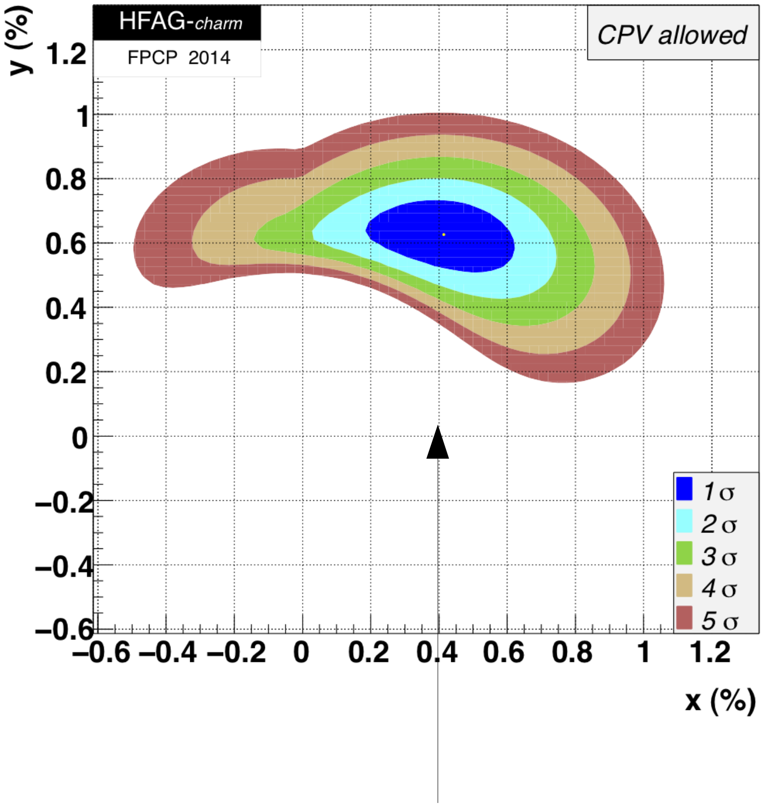
CP violation in B_s^0 mixing

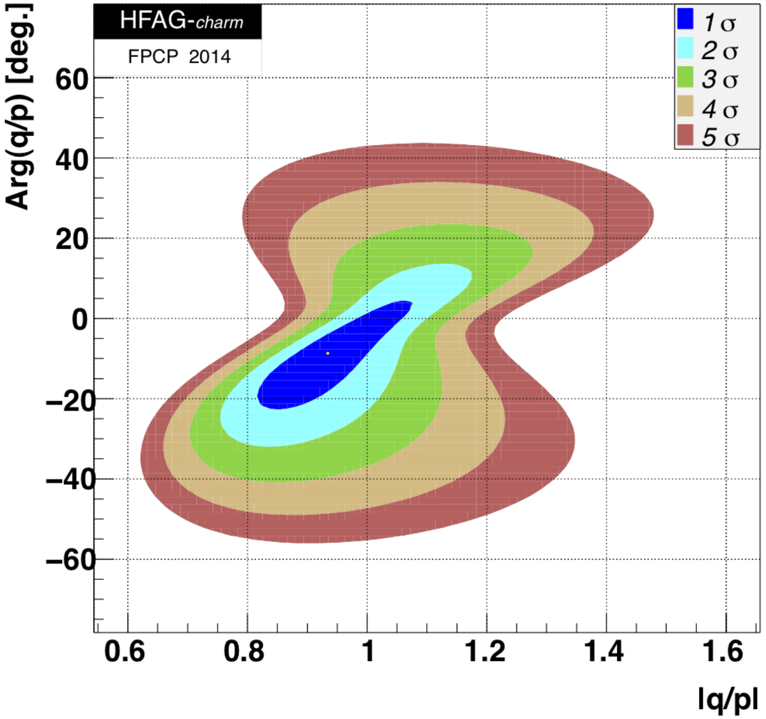
- Anomalous D0 dimuon result not confirmed, but neither refuted, by separate measurements of A_{SL} in B^0 and B_s^0 systems
  - possible explanation involving $\Delta\Gamma_d$ also not confirmed
- SM uncertainty is invisible in this plot – need much improved measurements



Latest results on $A_{SL}(B^0)$ from LHCb (arXiv:1409.8586) and BaBar (arXiv:1411.1842)

CP violation in charm mixing





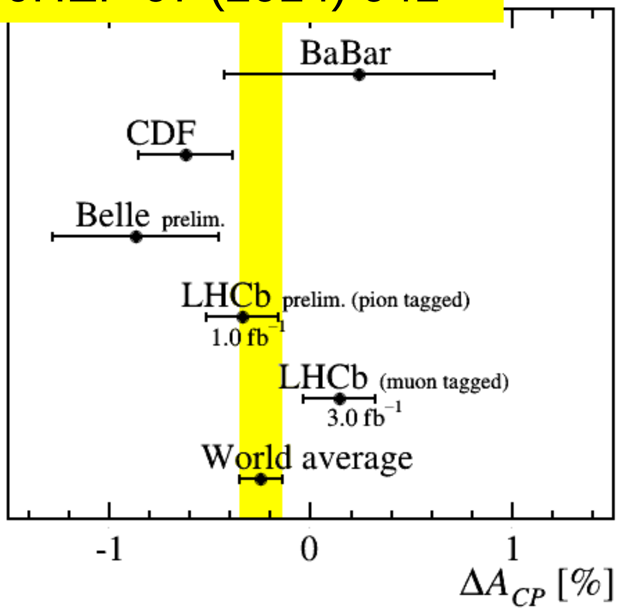
Need improved precision on $x = \Delta m/\Gamma$ to be sensitive to φ_D = arg(q/p) through observables that depend on $x \sin \varphi_D$

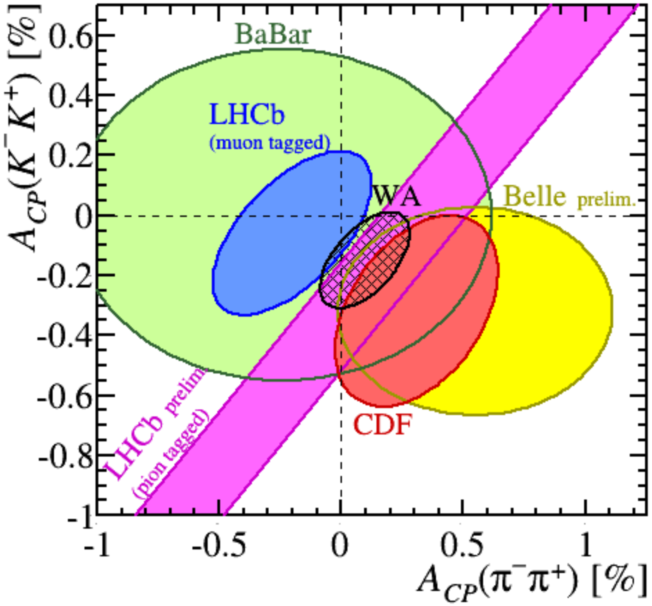
Much stronger constraints on |q/p| & φ_D assuming no DCPV, but still room for NP effects in charm mixing

How large can CP violation in D be?

Excitement over past years arising from $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$

JHEP 07 (2014) 041

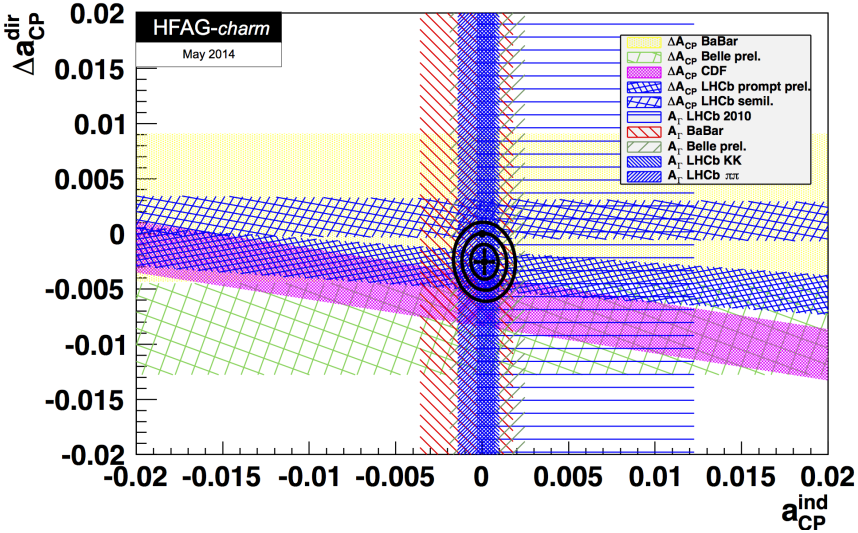




Latest results give world averages of $|A_{CP}(K^+K^-)| \sim |A_{CP}(\pi^+\pi^-)| \sim 10^{-3}$, with opposite sign, as originally expected.

(CP violation effect not significantly non-zero)

At this precision will need several A_{CP} measurements to resolve NP from SM contributions



Tim Gershon
Future flavour physics

V_{xb} inclusive vs. exclusive problem

Over the last ~5 years, a discrepancy between inclusive and exclusive determinations of V_{xb} from semileptonic B decays has emerged

PDG 2006

$$|V_{cb}| = (41.7 \pm 0.7) \times 10^{-3} \text{ (inclusive)} \qquad |V_{ub}| = (4.40 \pm 0.20 \pm 0.27) \times 10^{-3} \text{ (inclusive)},$$

$$|V_{cb}| = (40.9 \pm 1.8) \times 10^{-3} \text{ (exclusive)}. \qquad |V_{ub}| = (3.84 \,^{+0.67}_{-0.49}) \times 10^{-3} \text{ (exclusive)}.$$

PDG 2014

$$|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \text{ (inclusive)} \qquad |V_{ub}| = (4.41 \pm 0.15 \,^{+\,0.15}_{-\,0.17}) \times 10^{-3} \text{ (inclusive)},$$

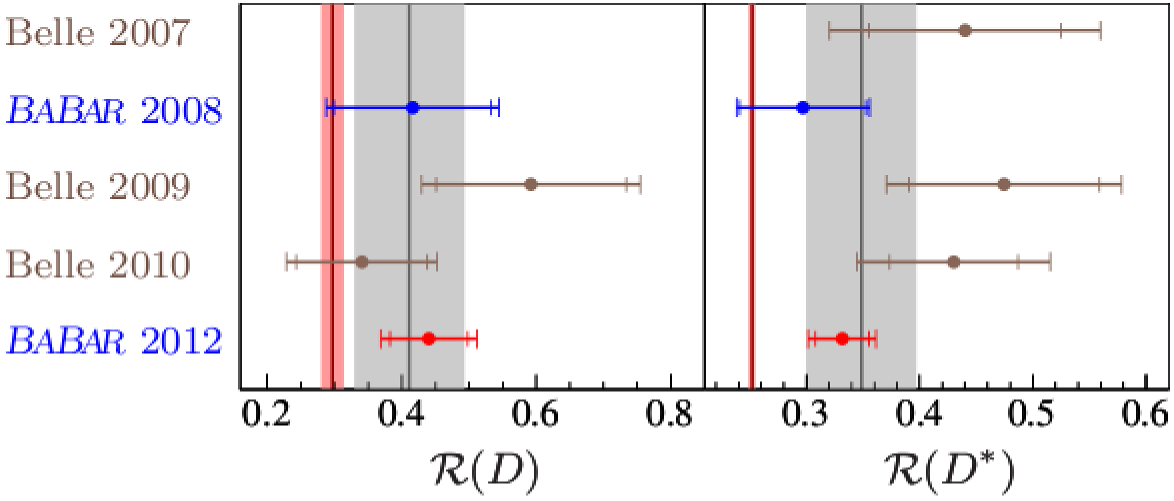
$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)} \qquad |V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \text{ (exclusive)}.$$

n.b. Significant progress in lattice calculations helps reduction of uncertainties in exclusive determination (together with new experimental results)

This problem needs to be understood

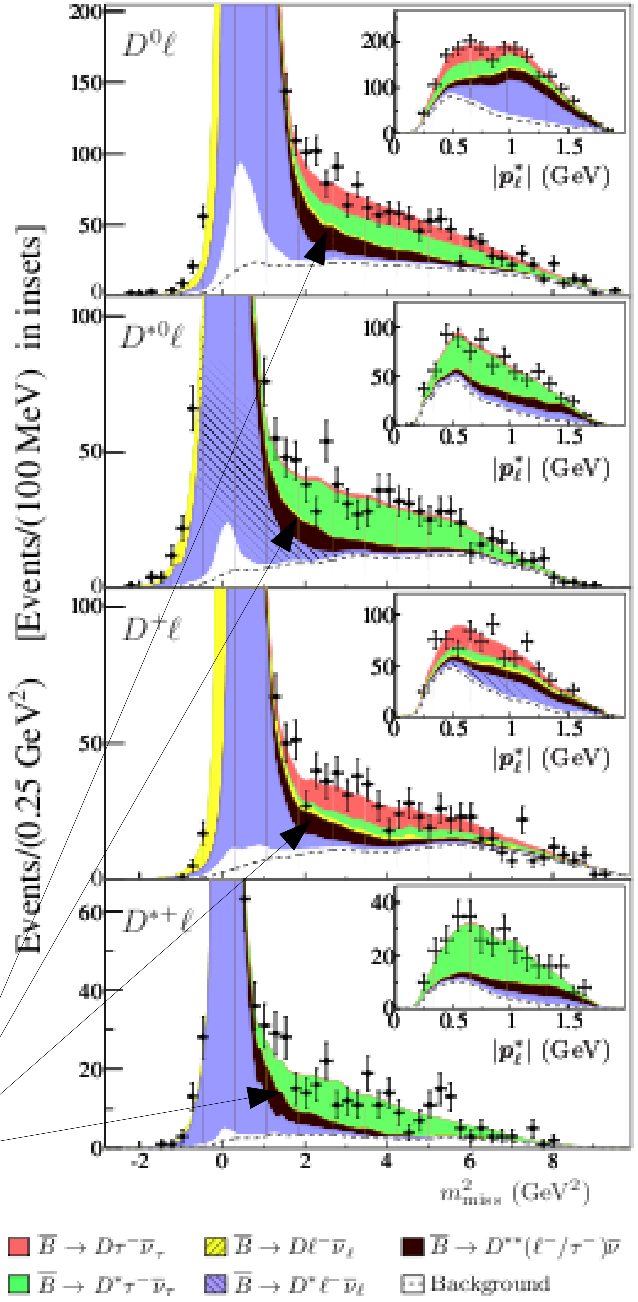
Lepton universality – $D^{(*)}\tau\nu$

Excess of $B \to D^{(*)}\tau\nu$ relative to $D^{(*)}\mu\nu$ & $D^{(*)}e\nu$



BaBar PRL 109 (2012) 101802 & PRD 88 (2013) 072012

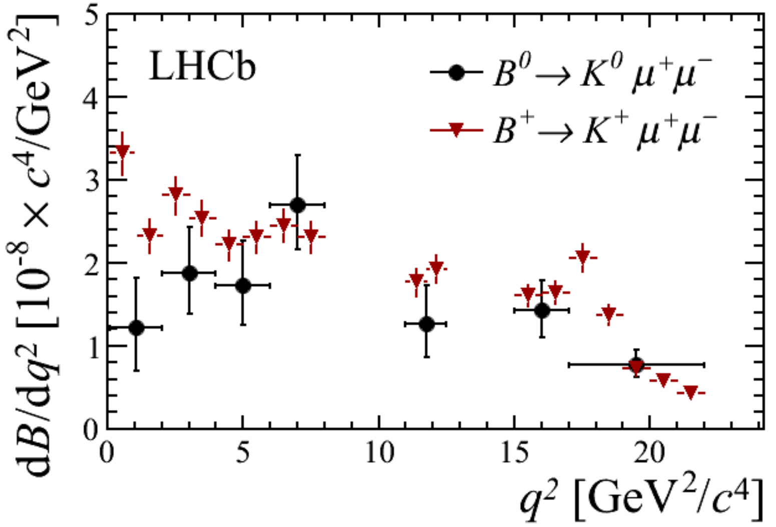
New Belle/LHCb data urgently needed!



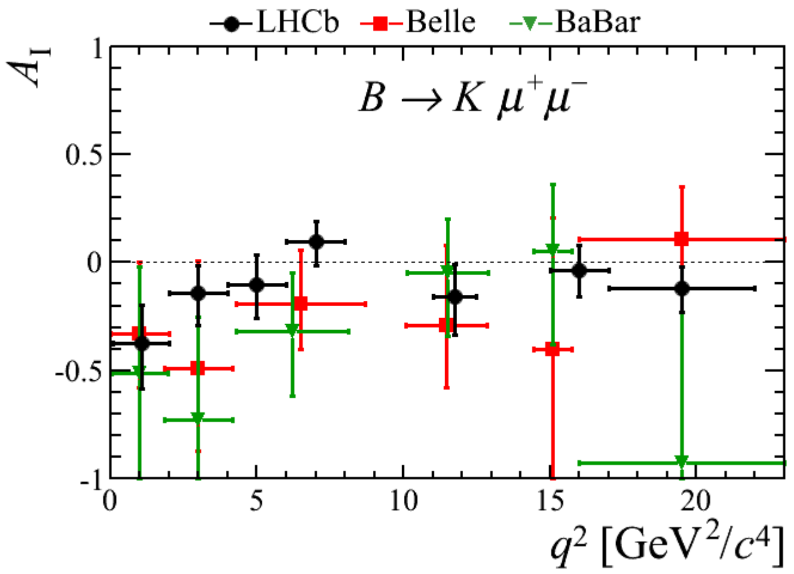
Need also improved knowledge of
$b \to c l\nu$ background shapes

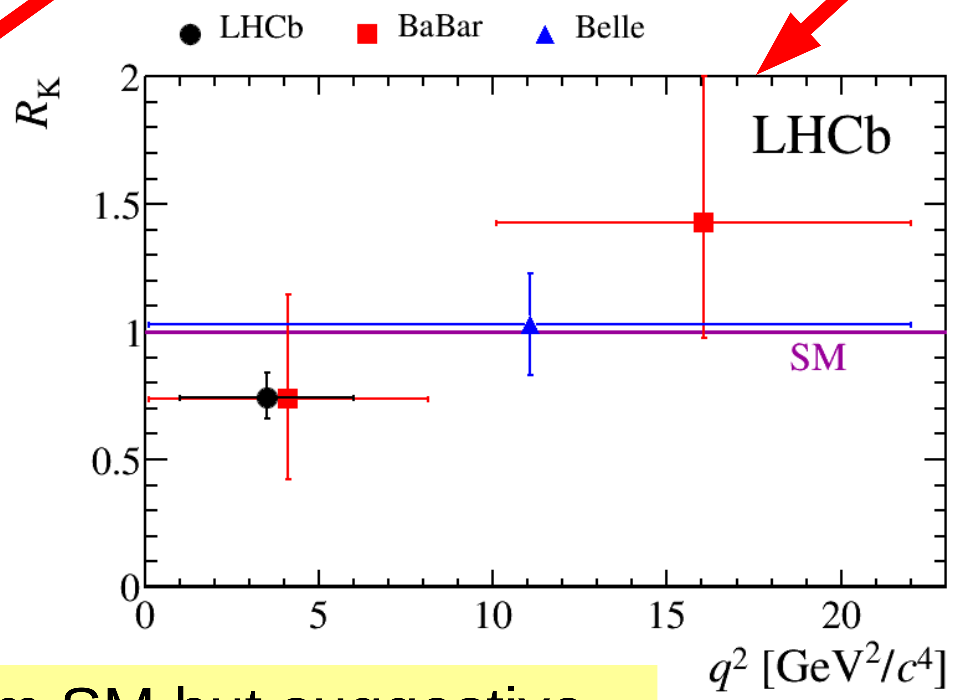
Lepton universality – R_K

JHEP 06 (2014) 133 &
PRL 113 (2014) 151601



Deficit of B → $K\mu^+\mu^-$ compared to expectation
To reduce uncertainties, measure isospin asymmetry (A_I) or $K\mu^+\mu^-/Ke^+e^-$ ratio (R_K)

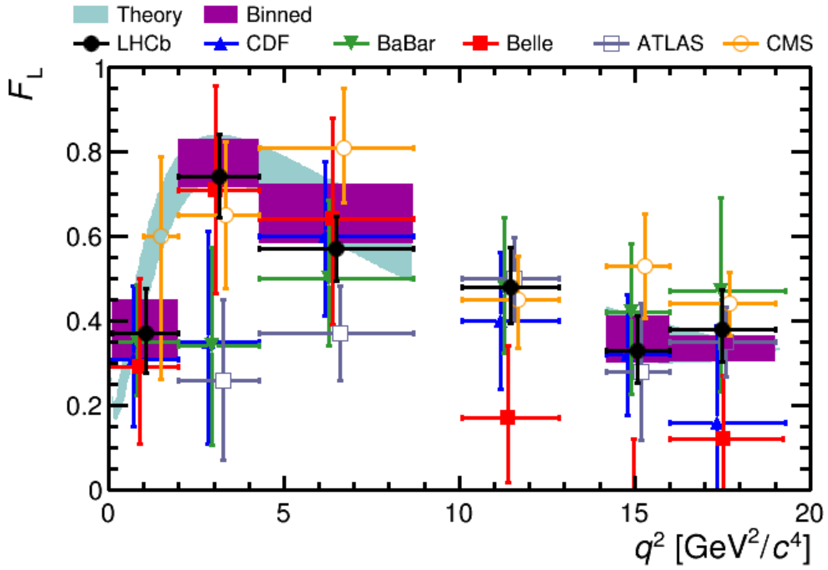


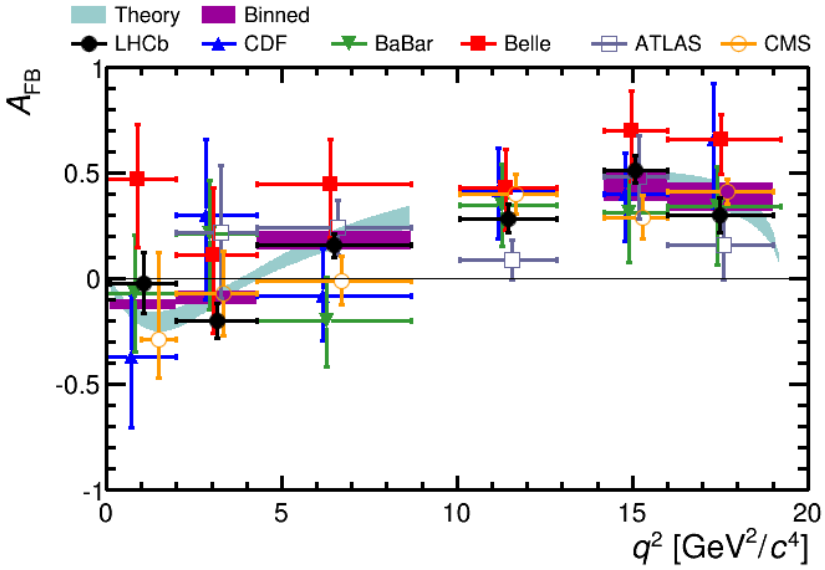


<3σ from SM but suggestive

Angular analyses of $B^0 \to K^{*0}\mu^+\mu^-$

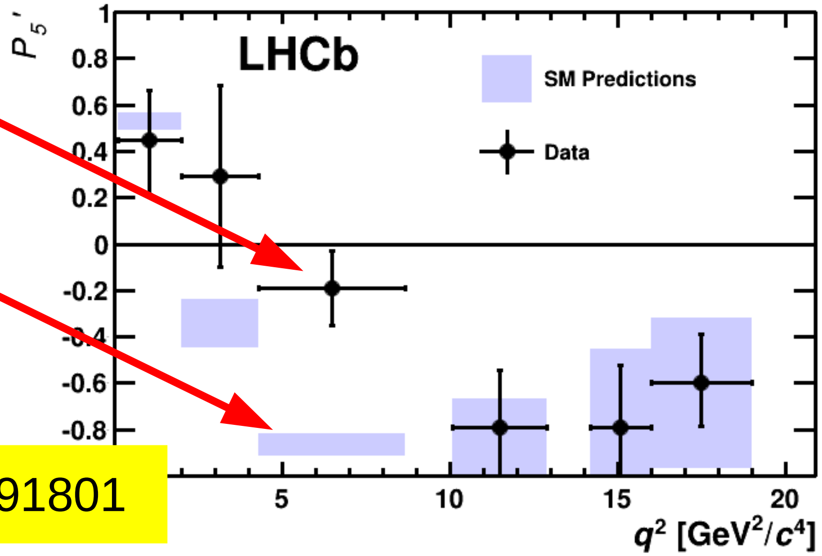
LHCb JHEP 08 (2013) 131, CDF PRL 108 (2012) 081807, BaBar PR D86 (2012) 032012
Belle PRL 103 (2009) 171801, ATLAS-CONF-2013-038, CMS PL B727 (2013) 77





Good agreement with SM in most, but not all, observables. Improved measurements needed.

Reduced QCD uncertainties, but by how much? More theory work needed.



PRL 111 (2013) 191801

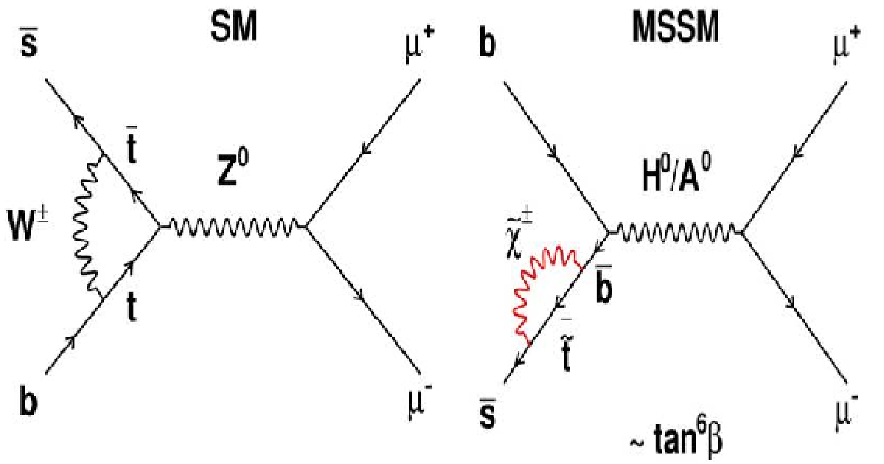
$B_s \to \mu^+\mu^-$

Killer app. for new physics discovery

Very rare in Standard Model due to

- absence of tree-level FCNC
- helicity suppression
- CKM suppression

… all features which are not necessarily reproduced in extended models



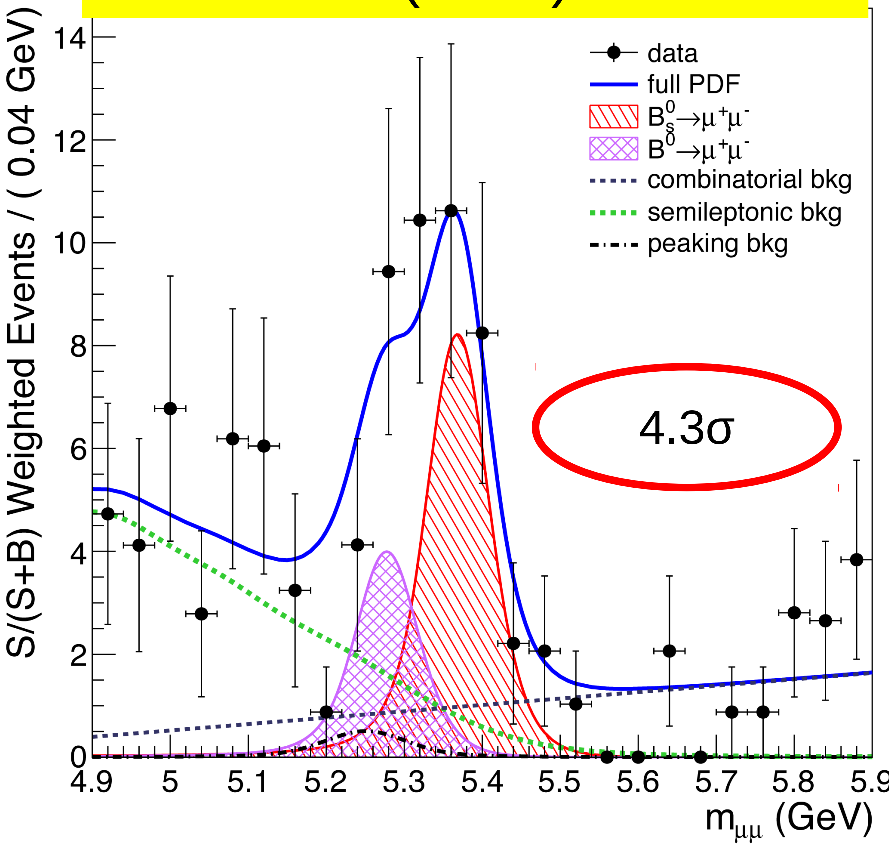
$$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = (3.65 \pm 0.23) \times 10^{-9}$$

PRL 112 (2014) 101801

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta / M^4_{A0}$$

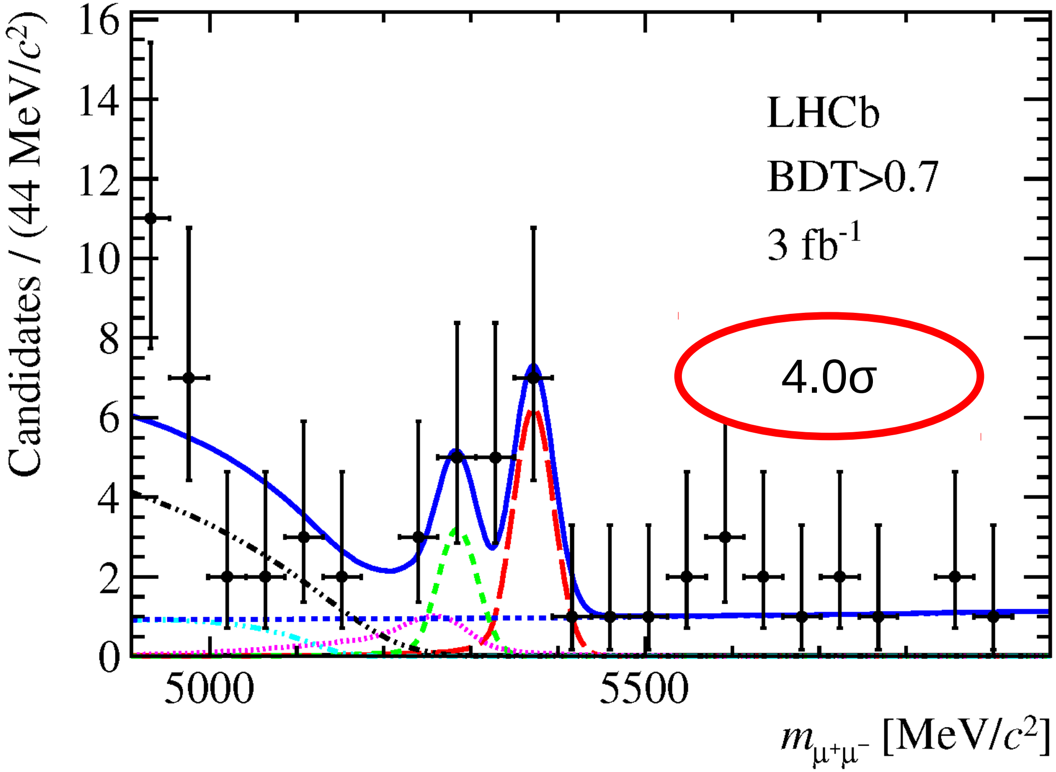
$B_{(s)}^0 \to \mu^+\mu^-$

CMS
PRL 111 (2013) 101804



Events weighted by S/(S+B)

LHCb
PRL 111 (2013) 101805

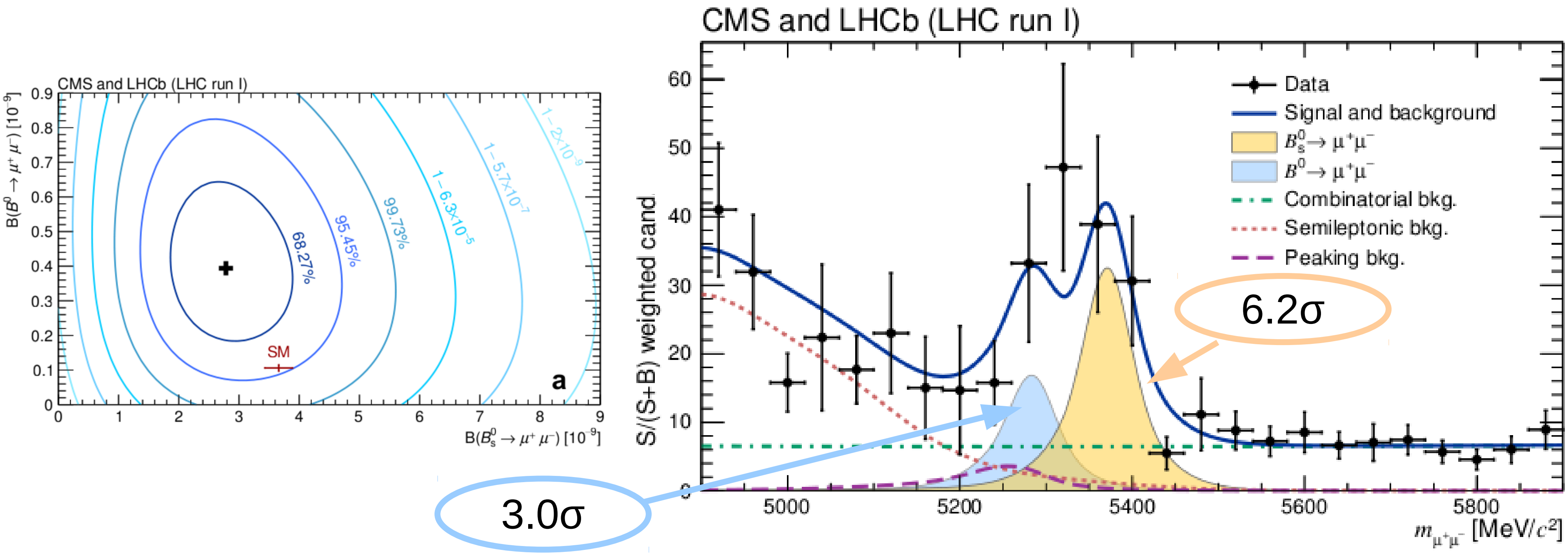


Only events with BDT > 0.7

Updated results confirm earlier evidence from LHCb (PRL 110 (2013) 021801)

$B_{(s)}^0 \to \mu^+\mu^-$ – combined results

NEW! Combination of CMS & LHCb data
Submitted to Nature



6.2σ

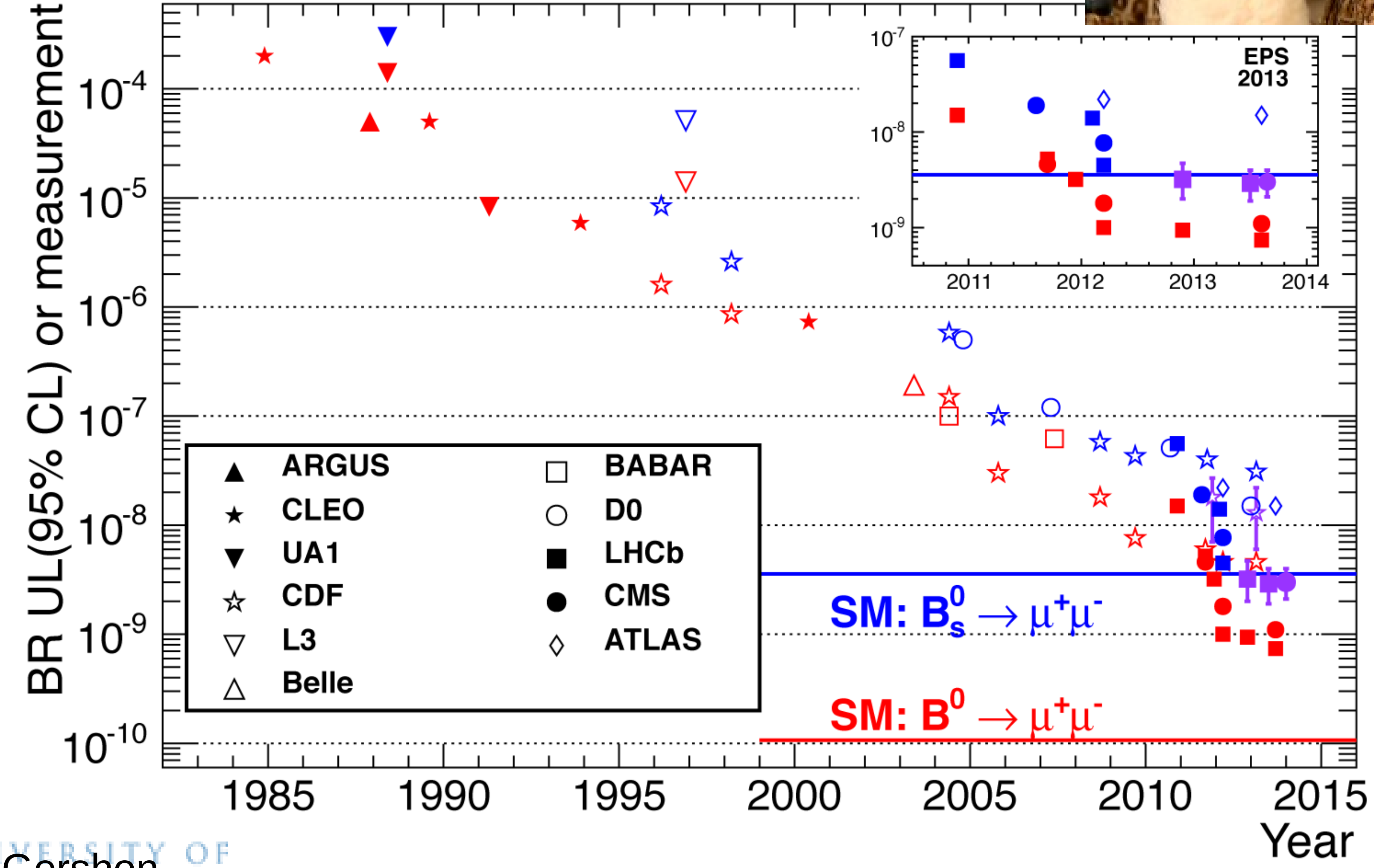
3.0σ

Next:

- Precision measurements of $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
- Measure effective lifetime for $B_s^0 \to \mu^+\mu^-$
- Search for other leptonic decays (e.g. $B_s^0 \to \tau^+\tau^-$)

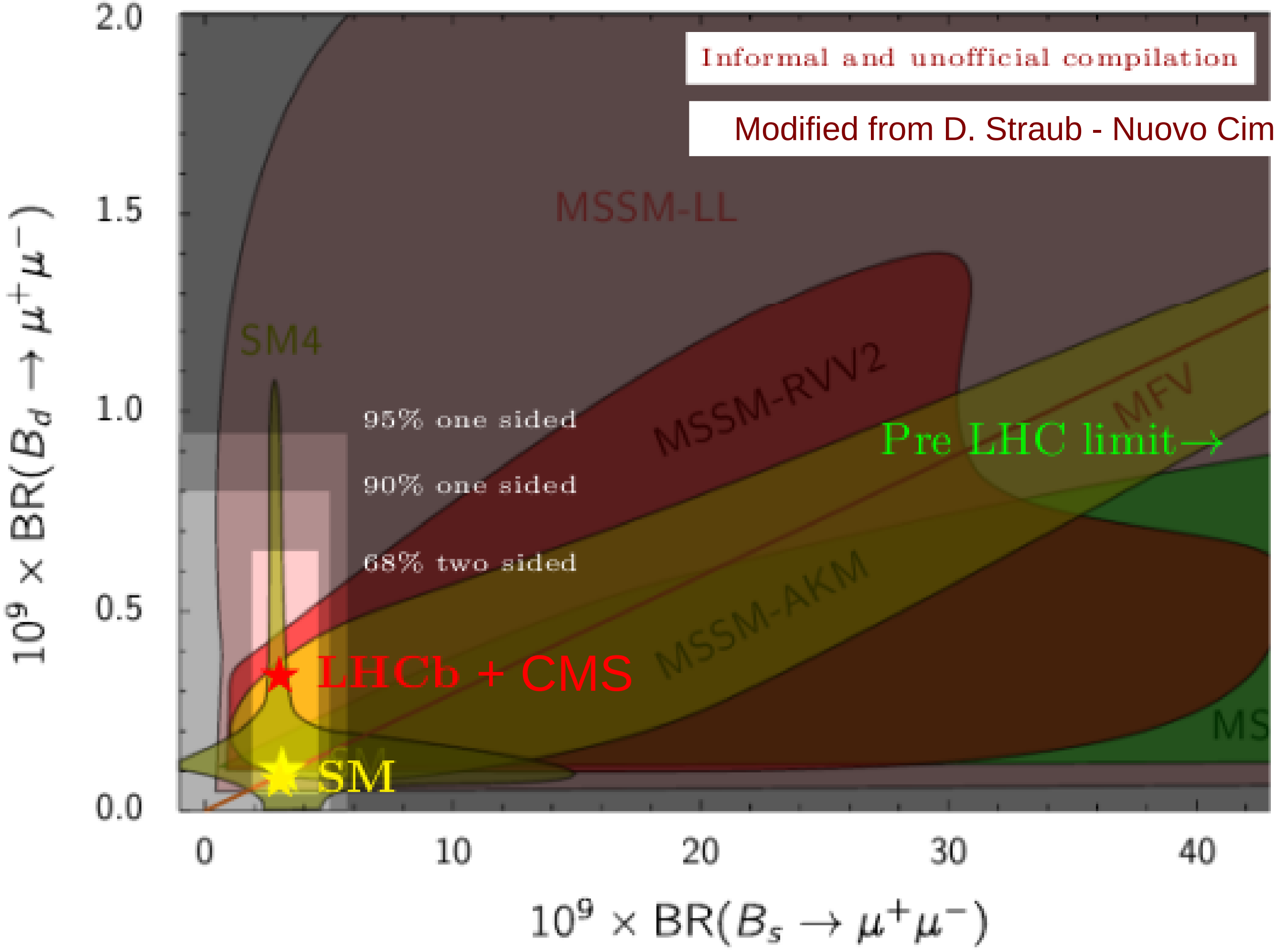
$B_{(s)}^0 \to \mu^+\mu^-$

Order of magnitude improvement every ~ 5 years



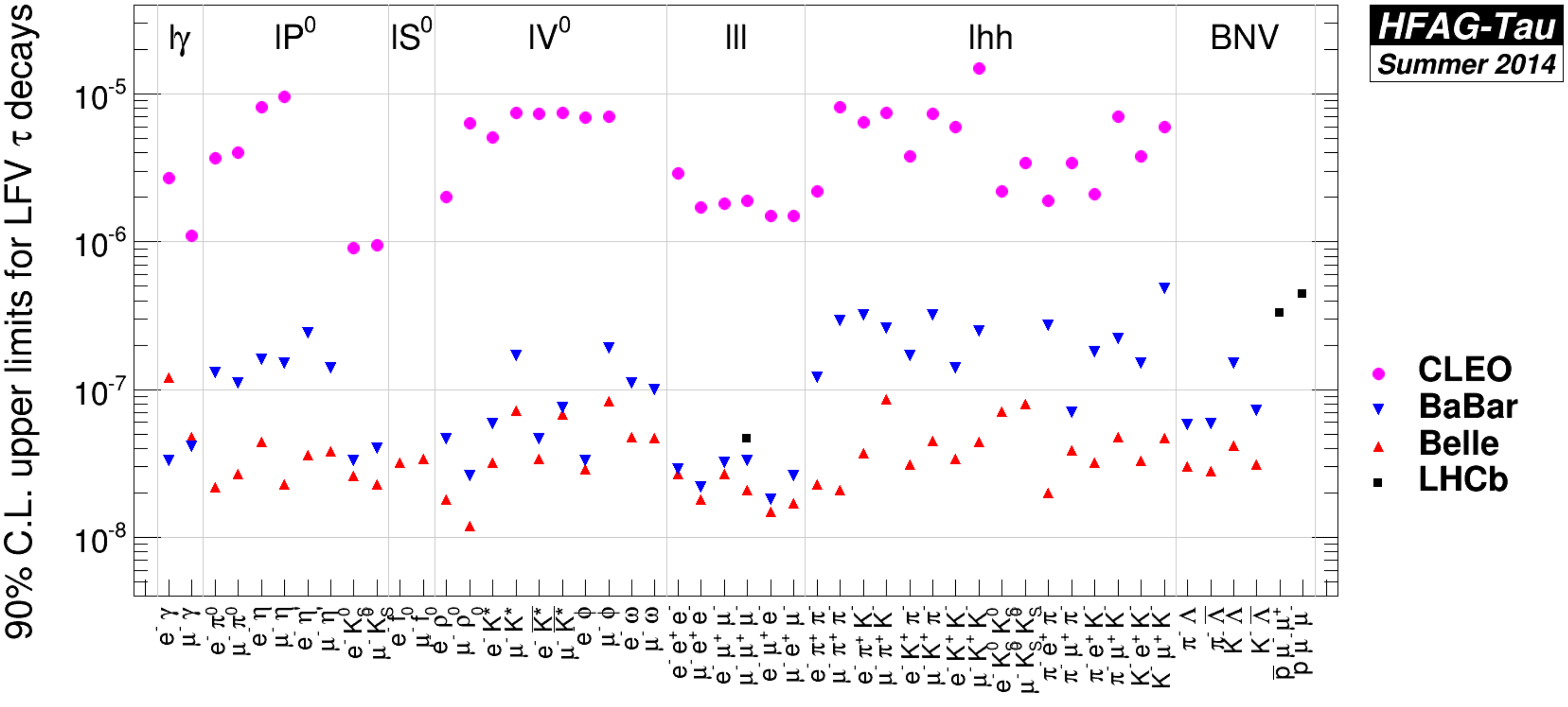
Searches over 30 years

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



Modified from D. Straub - Nuovo Cim. C035N1 (2012) 249

Charged lepton flavour violation



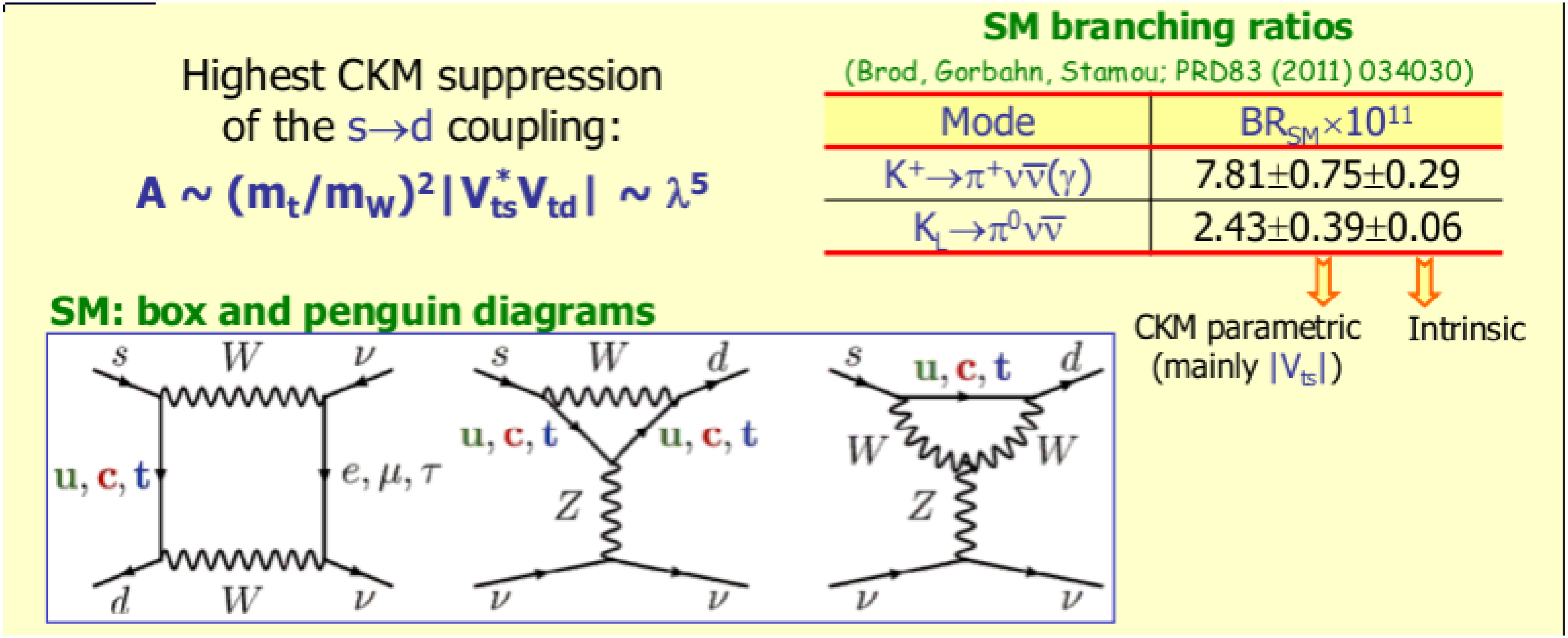
No evidence for lepton flavour violation, in τ decays or anywhere else

Key observables

- To condense physics case for future facilities, viz flavour physics, useful to define subset of key observables
  - CP violation: γ, φ_s, φ_D, ΔA_{CP}
  - CKM and lepton universality: $|V_{ub}|$, $D^{(*)}\tau\nu$, R_K
  - Rare decays: $B(B^0 \to \mu^+\mu^-)$, $P_5'(K^*\mu^+\mu^-)$, $B(K \to \pi\nu\bar{\nu})$

Future facilities

The holy grail of kaon physics: $K\to\pi\nu\nu$



Highest CKM suppression
of the $s\to d$ coupling:

$A \sim (m_t/m_W)^2|V_{ts}^*V_{td}| \sim \lambda^5$

SM branching ratios

(Brod, Gorbahn, Stamou; PRD83 (2011) 034030)

Mode	$BR_{SM}\times10^{11}$
$K^+\to\pi^+\nu\bar{\nu}(\gamma)$	$7.81\pm0.75\pm0.29$
$K_L\to\pi^0\nu\bar{\nu}$	$2.43\pm0.39\pm0.06$

CKM parametric (mainly $|V_{ts}|$)

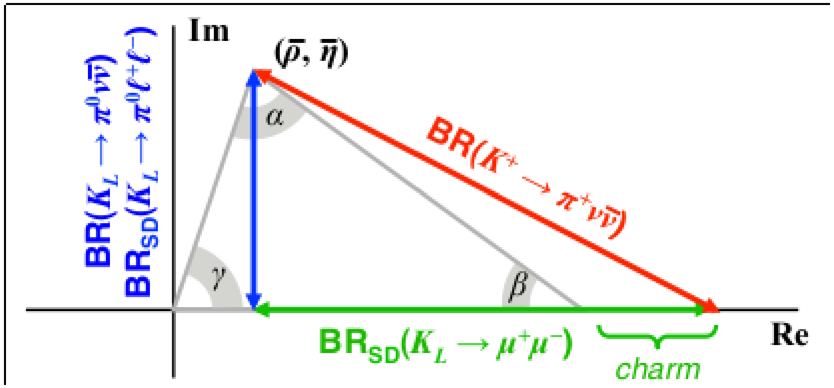
Intrinsic

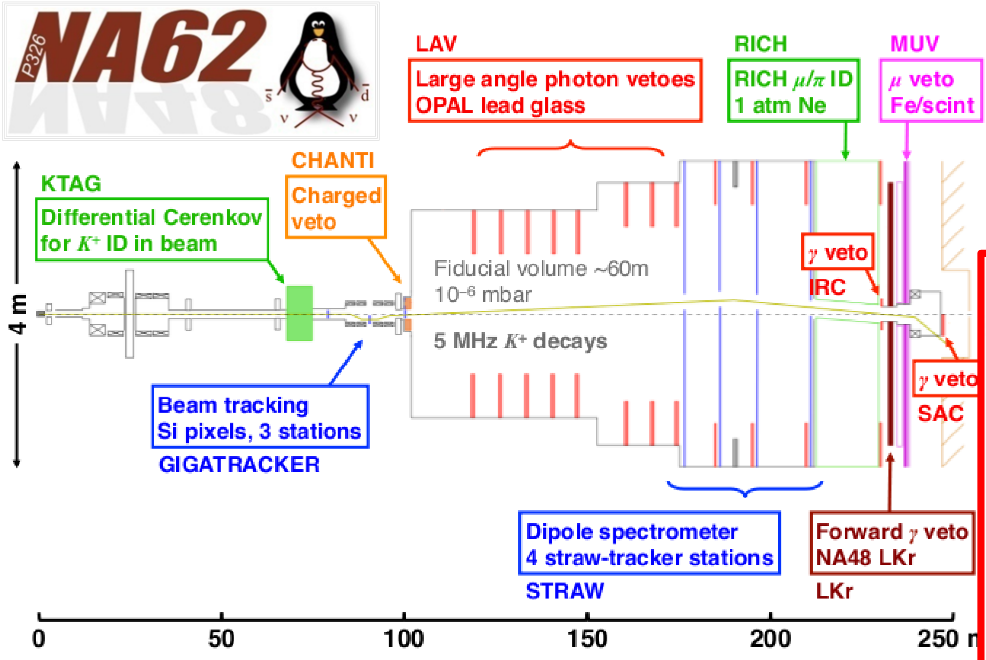
SM: box and penguin diagrams

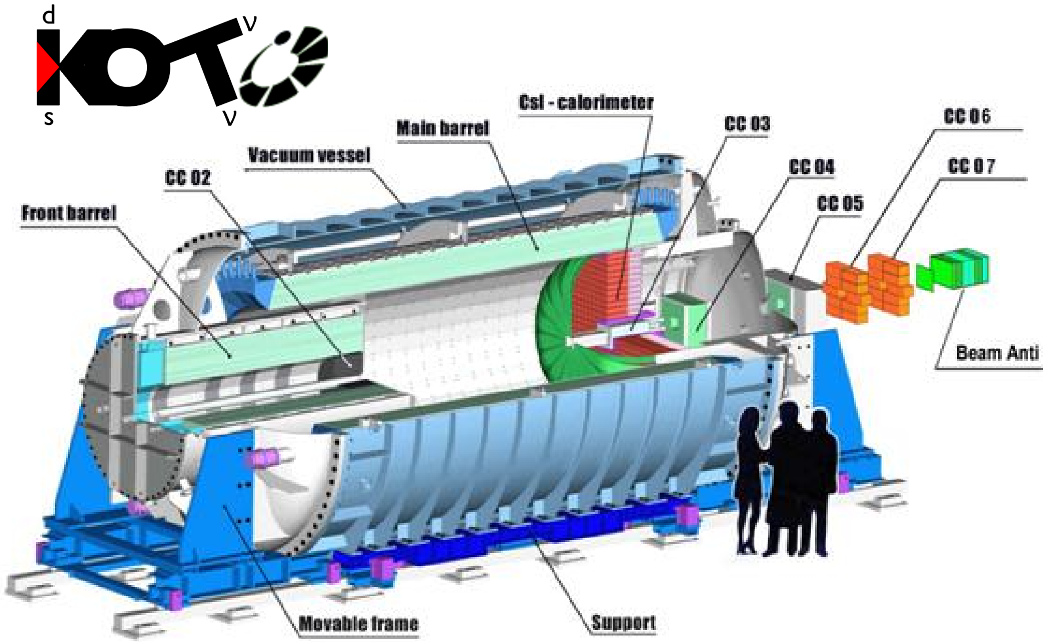
Next generation experiments should measure these decays for the 1st time

- $K^+\to\pi^+\nu\nu$ (NA62, CERN + ORKA, FNAL)
- $K^0\to\pi^0\nu\nu$ (K0T0, J-PARC)

$K \to \pi\nu\bar{\nu}$ experiments





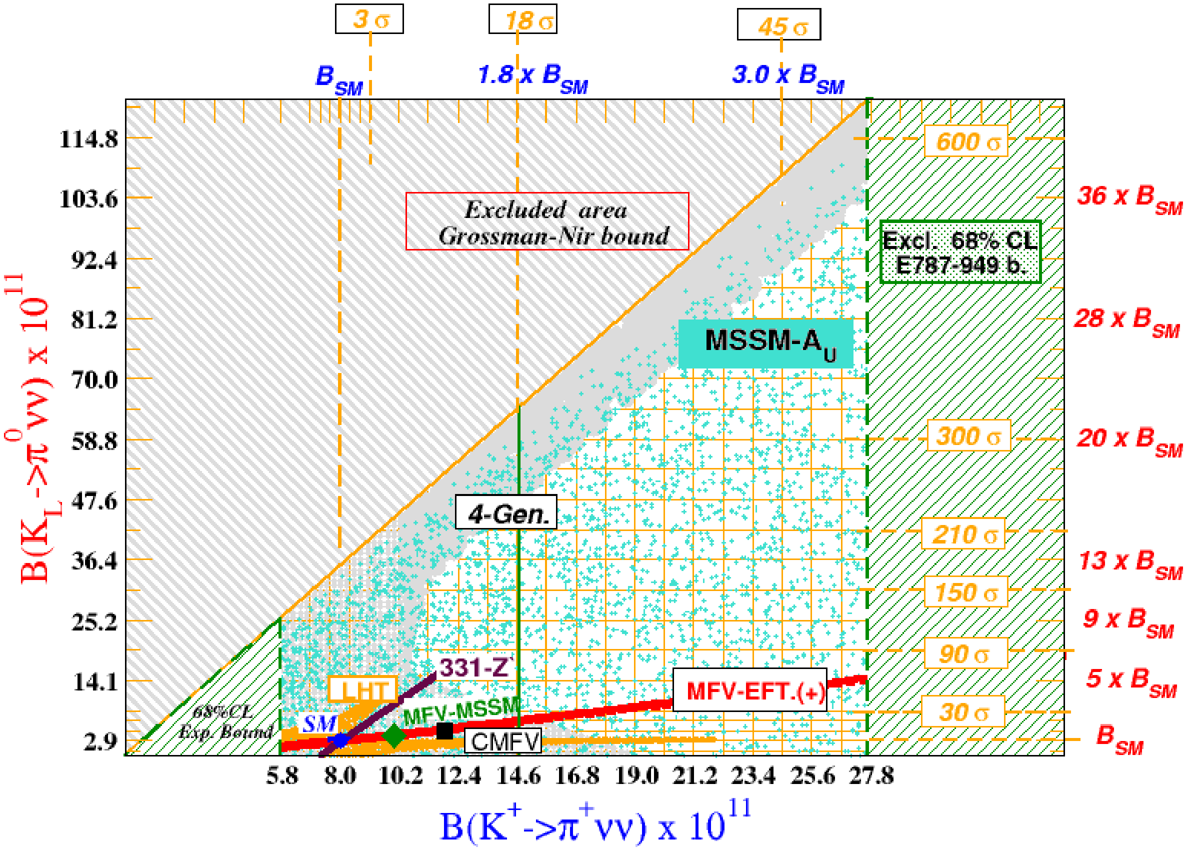


- KOTO completed detector construction for 1st physics run and took physics data in May 2013
  - Original goal: to cross the Grossman-Nir limit
  - Achieved: ~4 day run with 24kW beam; accumulated ~1/5 of planned POT
- We are now analyzing the data, expecting we can improve KEK-E391a upper limit.
- Preparation for next-level physics run is also underway.
  - Fabrication of Inner Barrel, etc…

From J-PARC PAC meeting Sept.2013

$K \to \pi\nu\bar{\nu}$ expectations

- NA62: collect O(100) SM events, with <10 background, 2015-16
  - Engineering run ongoing now
- KOTO: first run (2013) terminated due to radiation accident
  - 100 hours of data – achieved similar sensitivity (10^{-8}) to KEK-E391a
  - Next run expected in 2015. Should improve sensitivity by ~20
  - Then progress ...

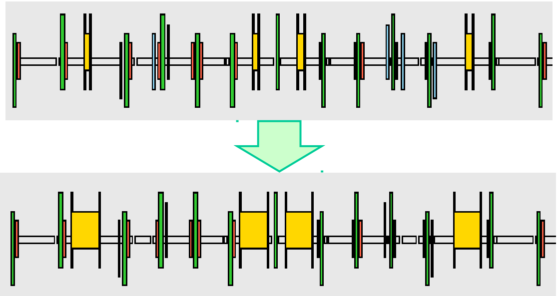


τ-charm factory

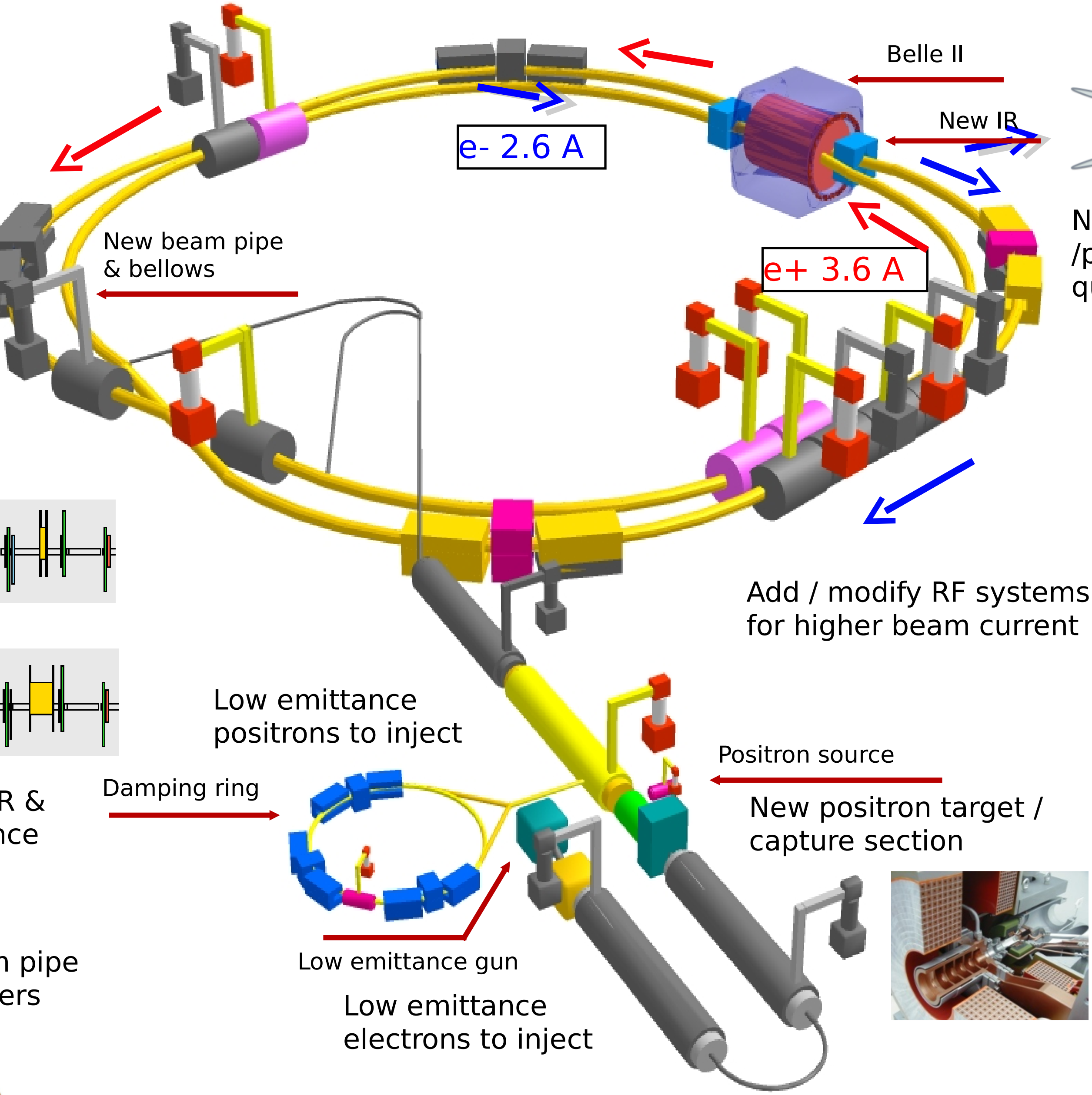
- Various ideas for a next generation τ-charm factory, to go beyond BESIII
  - BINP, Russia http://ctd.inp.nsk.su cost 300 M€ + detector
    - “approved” but funding unclear; cheaper options being considered
  - Cabibbo lab., Italy (???)
  - IHEP, China (HIEPAF)
- Typically √s = 2-7 GeV, peak $L \sim 10^{35}/\mathrm{cm}^2/\mathrm{s}$
- Physics programme primarily QCD & hadronic physics
  - Some unique potential for charm & (polarised) τ physics

KEKB to SuperKEKB

Replace short dipoles with longer ones (LER)



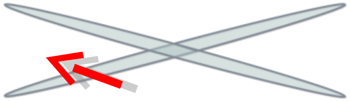
Redesign the lattices of HER & LER to squeeze the emittance



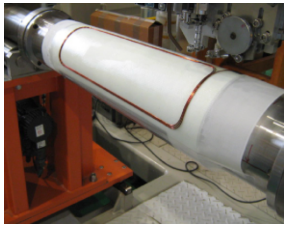
Low emittance positrons to inject

Low emittance electrons to inject

Colliding bunches



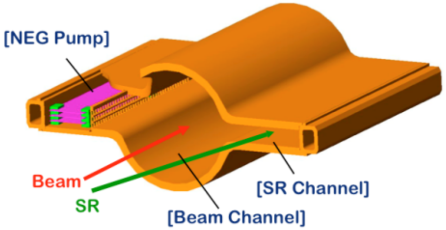
New superconducting /permanent final focusing quads near the IP



Add / modify RF systems for higher beam current

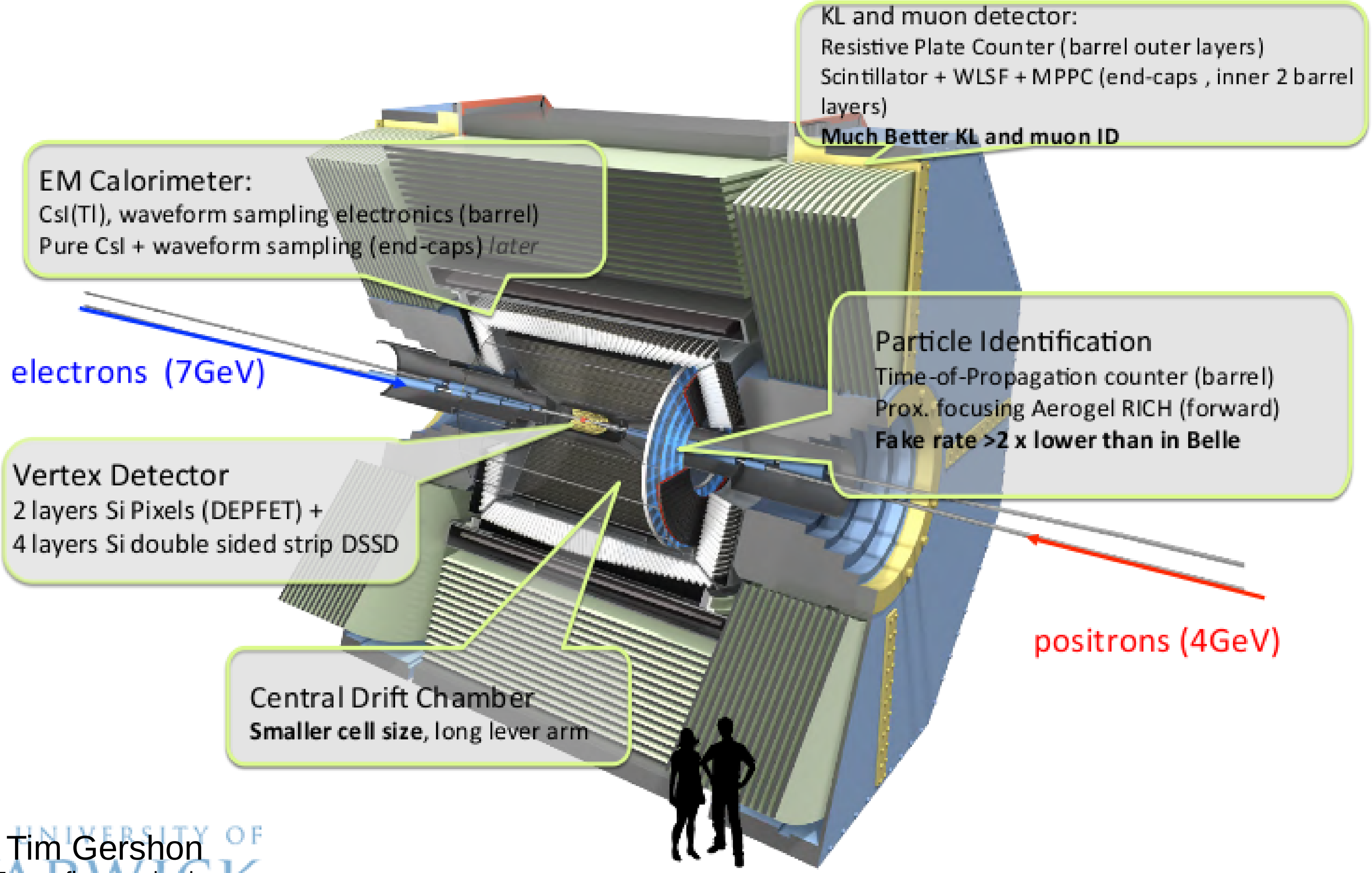
New positron target / capture section

TiN-coated beam pipe with antechambers



To obtain x40 higher luminosity

Belle II detector



KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)
Much Better KL and muon ID

EM Calorimeter:
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) *later*

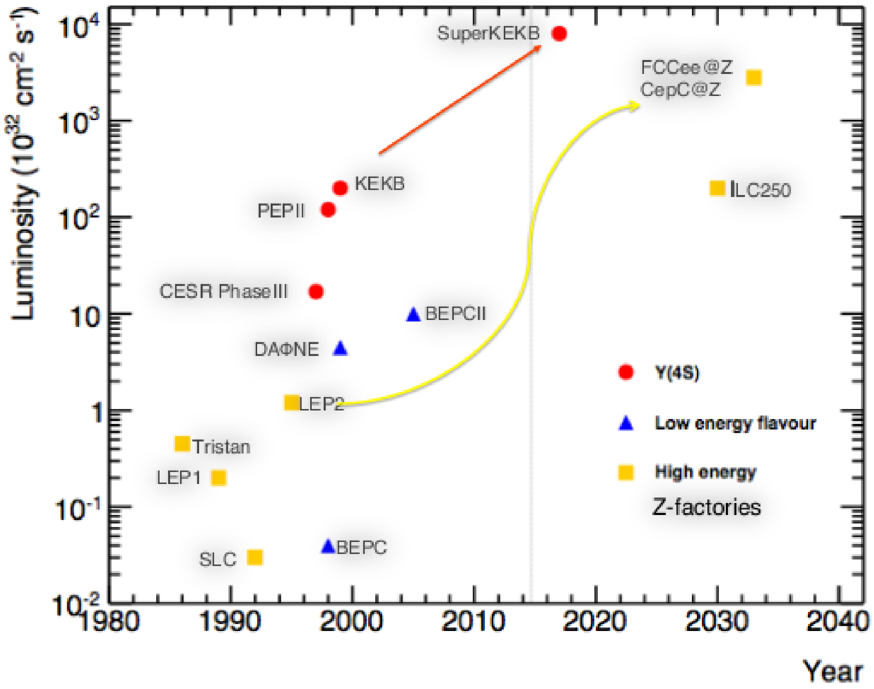
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)
Fake rate >2 x lower than in Belle

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

Central Drift Chamber
Smaller cell size, long lever arm

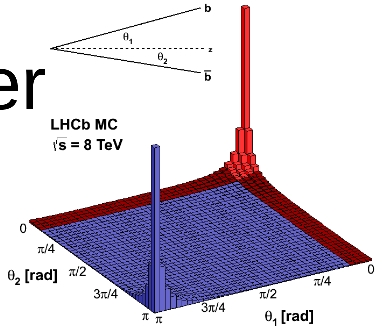
Belle II expectations

- Aiming to start physics data-taking in 2017-8
- Peak luminosity of ~ 10^{36}/cm^2/s
- Accumulate 50/ab in ~5 years
  - > 50x Belle data
  - Broad physics programme
  - … but mainly $\Upsilon(4S) \to B\bar{B}$
  - Coherent production – high ε_{TAG}
  - Highly efficient trigger
  - Quasi-hermetic detector
  - Reconstruction of neutral (γ, π^0, K_L) or missing (ν, χ) particles

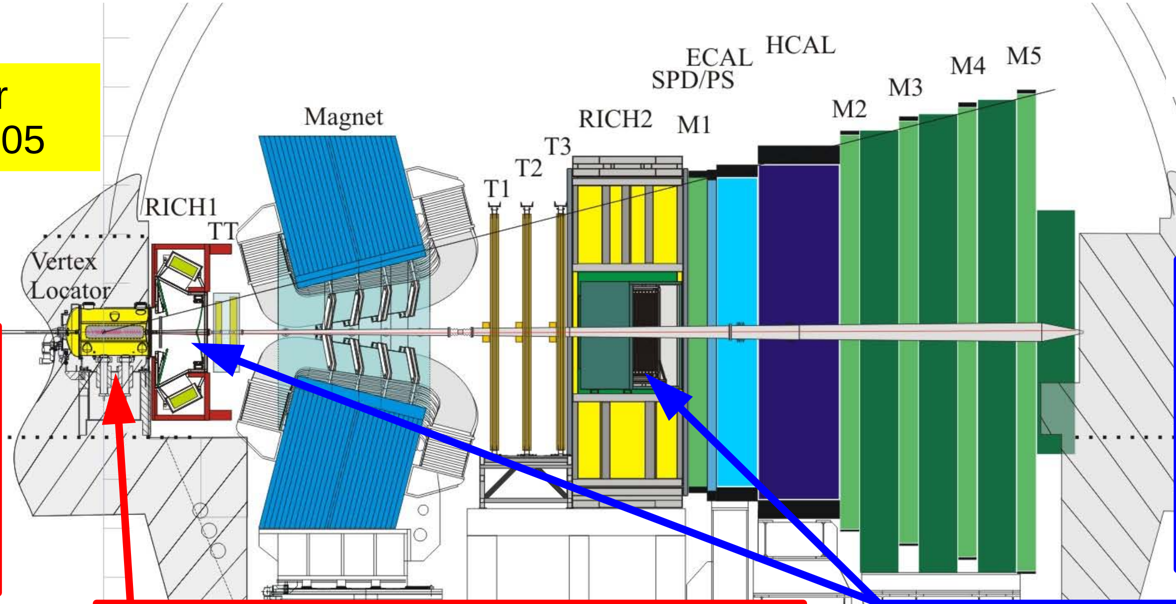


The LHCb detector

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- Optimal (?) design is a forward spectrometer



The LHCb Detector
JINST 3 (2008) S08005



Precision primary and secondary vertex measurements

Excellent K/π separation capability

The LHCb trigger

JINST 8 (2013) P04022

Challenge is

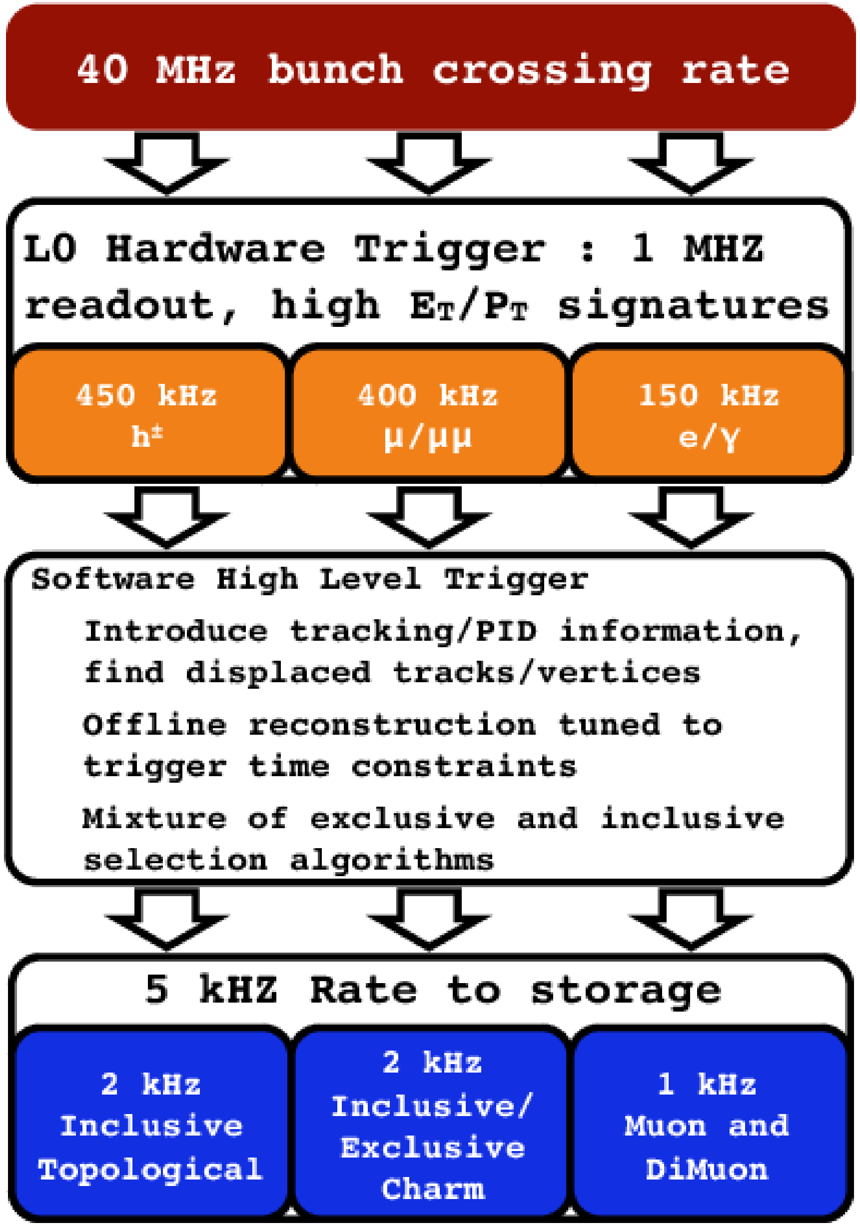
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles

- high p_T signals (muons)
- displaced vertices



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHZ readout, high E_T/P_T signatures

450 kHz $h^\pm$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

Introduce tracking/PID information, find displaced tracks/vertices

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHZ Rate to storage

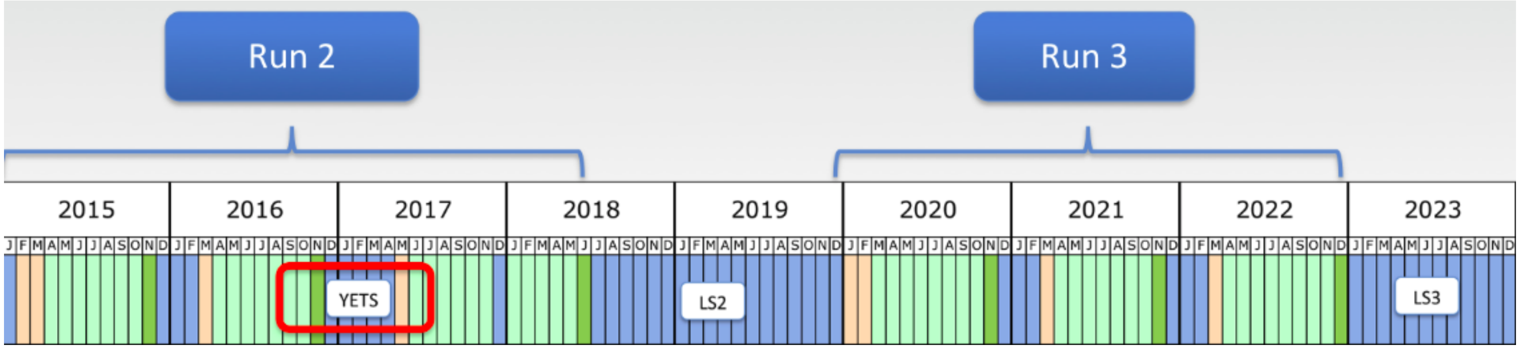
2 kHz Inclusive Topological

2 kHz Inclusive/Exclusive Charm

1 kHz Muon and DiMuon

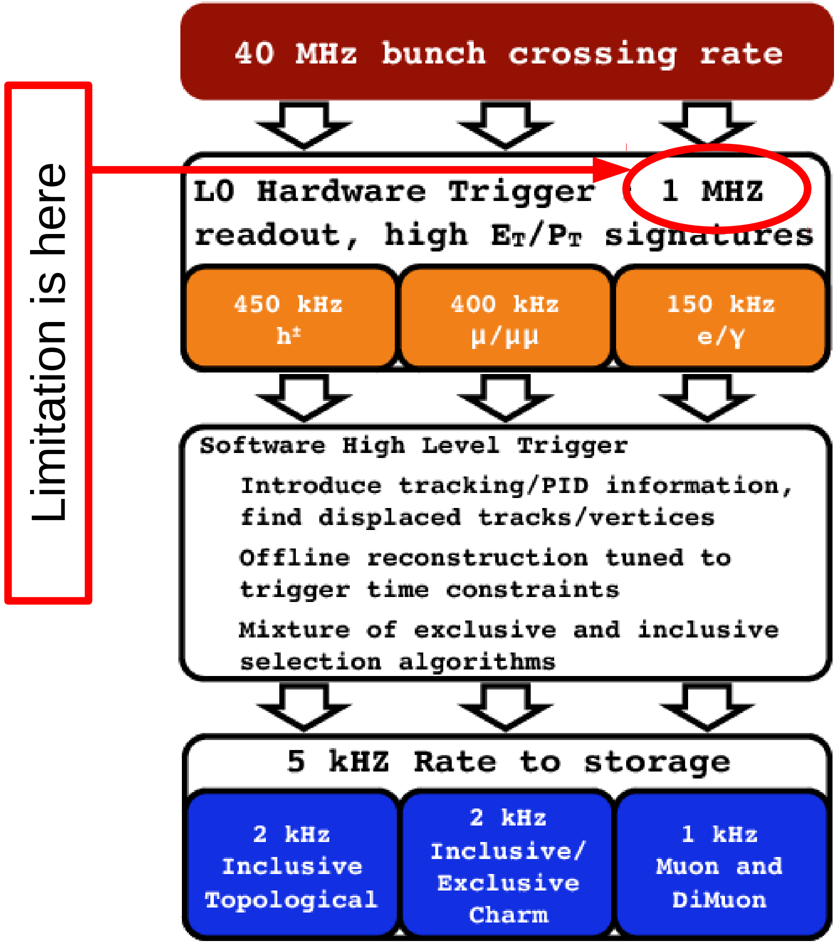
LHCb plan

- Beyond LHC Run II, the data-doubling time for LHCb becomes too long
  - Due to 1 MHz readout limitation and associated hardware (L0) trigger
- However, there is an excellent physics case to push for improved precision and an ever-broader range of observables
- Will upgrade the LHCb detector in the LHC LS2 (2018-20)
  - Upgrade subdetector electronics to 40 MHz readout
  - Make all trigger decisions in software
  - Operation at much higher luminosity with improved efficiency
    - order of magnitude improvement in precision (compared to today)



LHCb upgrade operation from 2020 for 10+ years

LHC upgrade and the all important trigger



Limitation is here

40 MHz bunch crossing rate

L0 Hardware Trigger 1 MHZ
readout, high E_T/P_T signatures

450 kHz $h^\pm$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

Introduce tracking/PID information, find displaced tracks/vertices

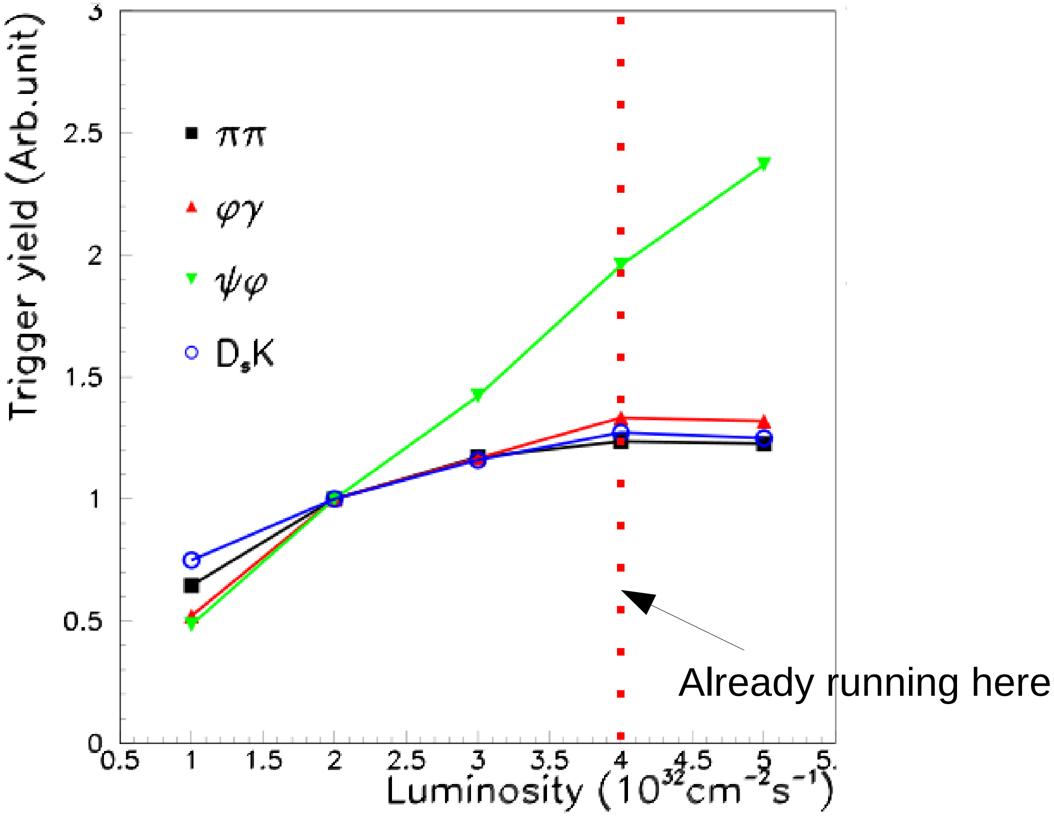
Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHZ Rate to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency

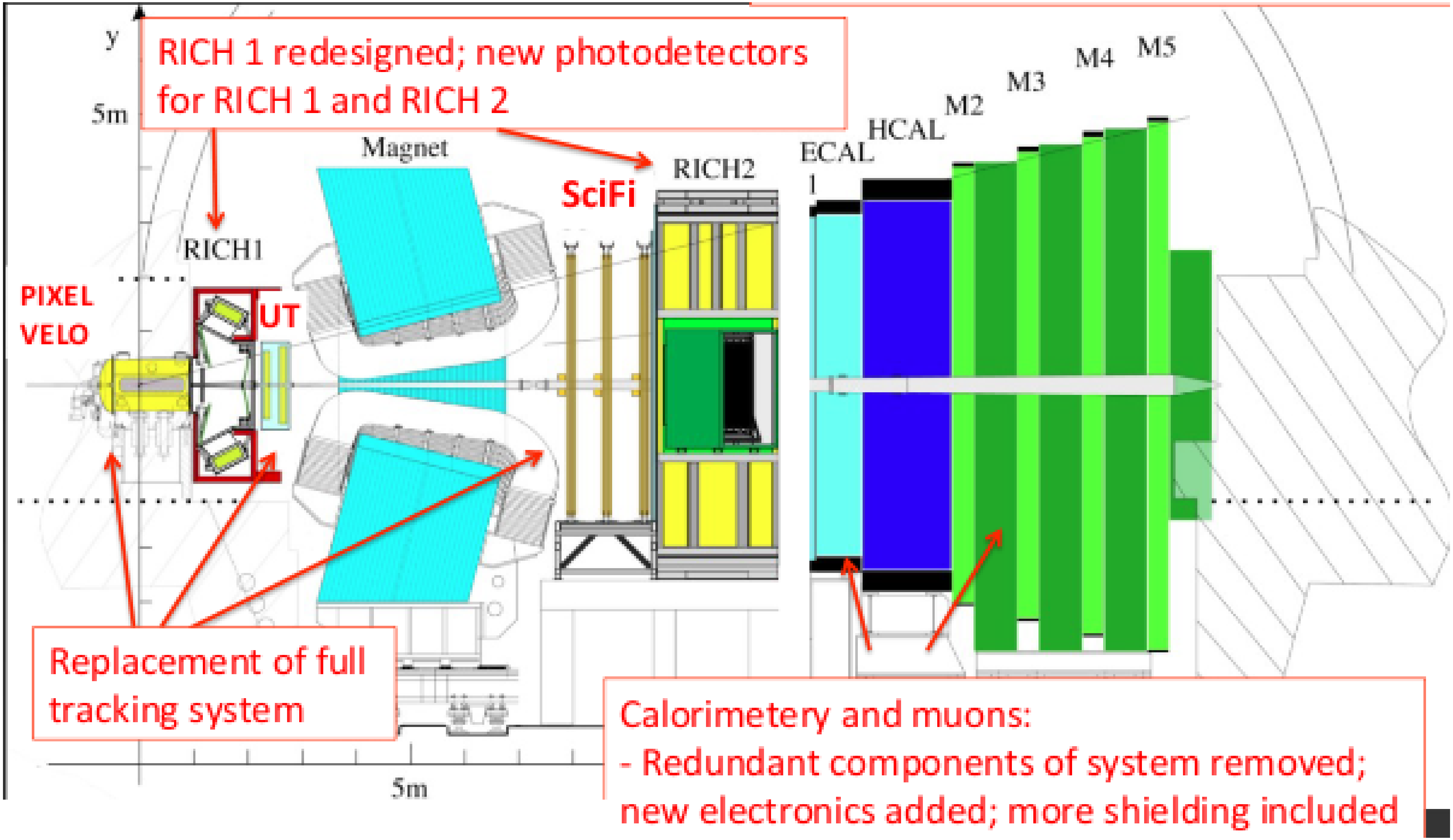


Already running here

- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

LHCb-TDR-{13,14,15,16}

LHCb detector upgrade



RICH 1 redesigned; new photodetectors for RICH 1 and RICH 2

Replacement of full tracking system

Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

+ novel trigger and offline data management strategies

LHCb & upgrade sensitivities

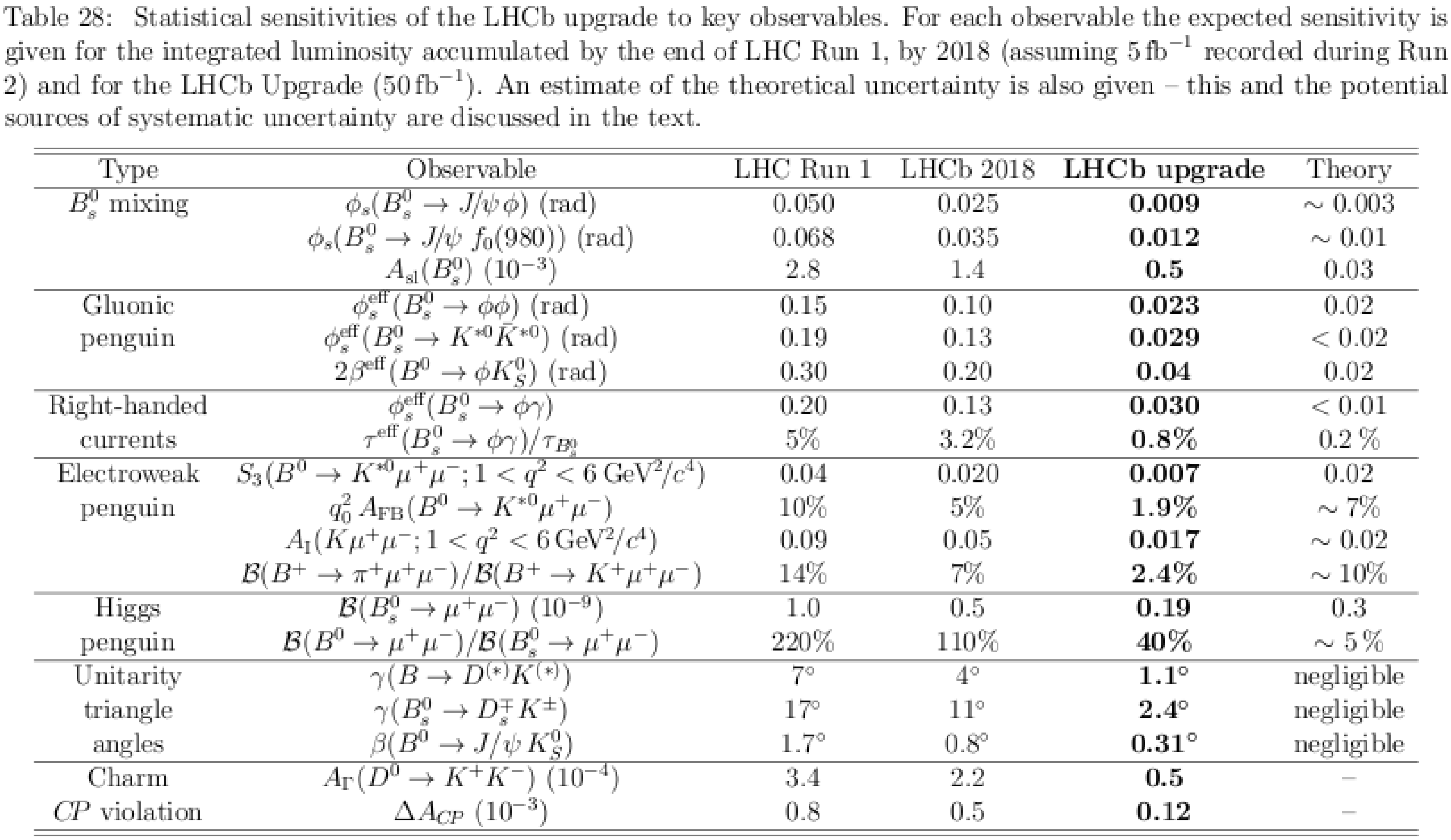
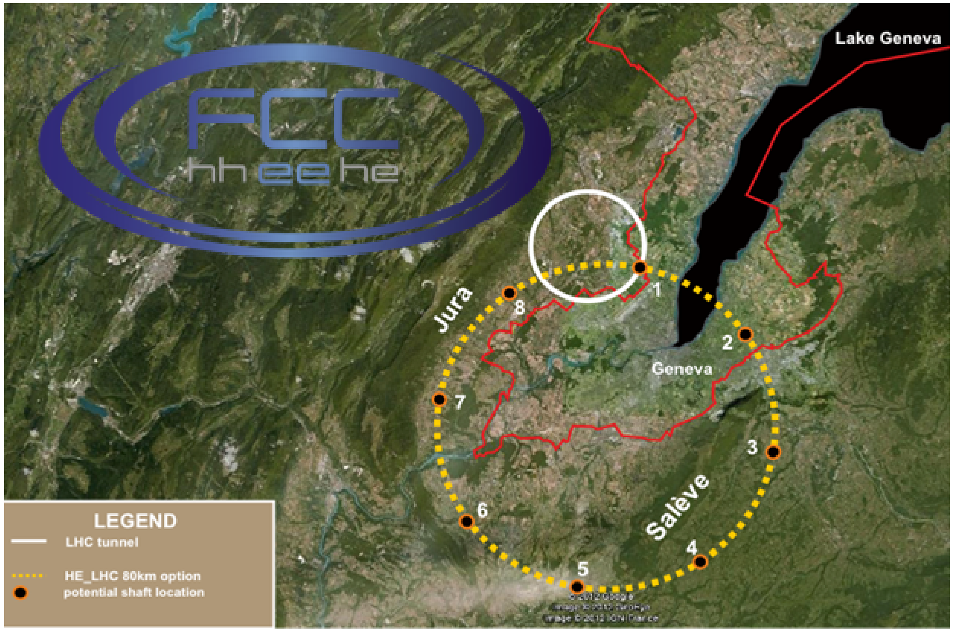
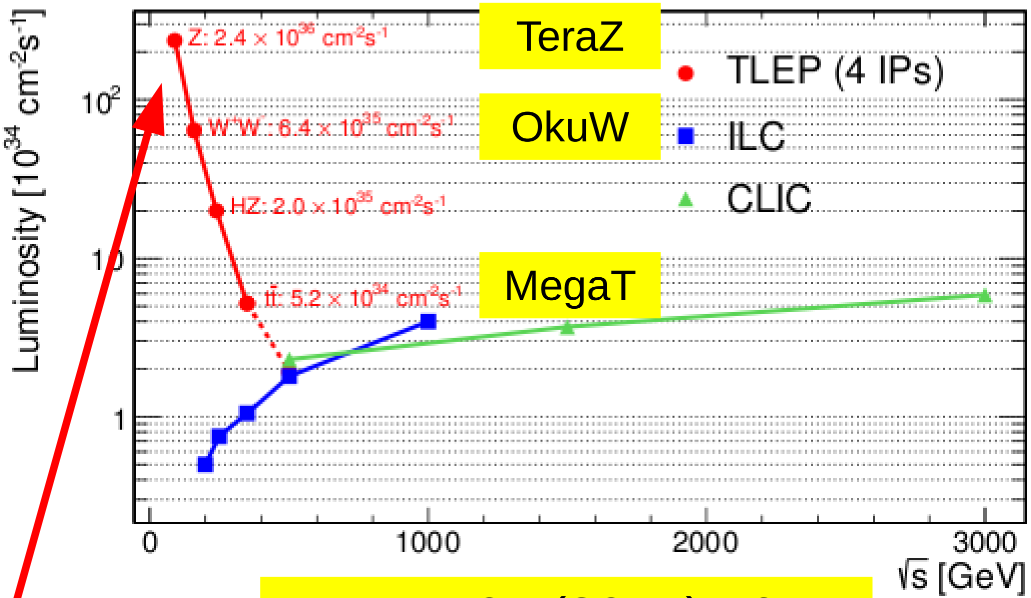


Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 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)	0.15	0.10	**0.023**	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%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 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**	–

Future circular colliders





JHEP 01 (2014) 164

- Future circular collider (FCC) study ongoing at CERN
  - pp, ee, ep & heavy ion options
  - e^+e^- esp. interesting for flavour physics
- Similar studies elsewhere globally (e.g. China)

TeraZ gives O(10^{12}) Z events in 1 year
$B(Z\rightarrow b\bar{b}, c\bar{c}, \tau\tau)$ ~ 15, 12, 3%

Need thought about what can be done with these samples:
e.g. <10% precision on $B(B_s\rightarrow\tau\tau)$

(Obviously good prospects for top physics at these facilities)

Other possibilities

- Cross-section σ(pp → $b\bar{b}$X) increases slowly between √s = 14 TeV & 100 TeV
  - also, all SM physics boosted into forward region
  - does not preclude flavour physics measurements at such a machine, but hard to argue for a dedicated experiment?
- Have not discussed flavour physics at ILC/CLIC/μ collider
  - marginal to their physics programmes (except top, of course)
- HL-LHC offers more luminosity than LHCb-upgrade can take
  - most likely, our most abundant source of b&c hadrons for the foreseeable future – should make best possible use of it
  - dedicated track triggers for CMS &/or ATLAS upgrades?
  - a dedicated ("ultimate") flavour experiment beyond the LHCb upgrade?

Summary

	γ	φ_s	φ_D	ΔA_{CP}	$\lvert V_{ub} \rvert$	$D^{(*)}\tau\nu$	R_K	$B \to \mu\mu$	P_5'	$K \to \pi\nu\nu$
NA62 & KOTO										✔✔
τ / charm			✔	✔						
Belle II	✔✔		✔✔	✔	✔✔	✔✔	✔✔		✔✔	
LHCb upgrade	✔✔	✔✔	✔✔	✔✔	**?**	**?**	✔✔	✔✔	✔✔	
ATLAS & CMS (HL)		✔					**?**	✔✔	✔	

✔✔ – World-leading ✔ – Potential, but less precise **?** – to be seen

Selection of key observables and attribution of scores highly subjective (could equally include sin(2β), $A_{SL}(B^0, B_s^0)$, $\tau \to \mu\gamma$, $B \to K\nu\bar{\nu}$, $B \to \tau\nu$, ...)

Summary

	γ	φ_s	φ_D	ΔA_{CP}	$\lvert V_{ub}\rvert$	$D^{(*)}\tau\nu$	R_K	$B\to\mu\mu$	P_5'	$K\to\pi\nu\nu$
NA62 & KOTO										✓✓
τ / charm			✓	✓						
Belle II	✓✓		✓✓	✓	✓✓	✓✓	✓✓		✓✓	
LHCb upgrade	✓✓	✓✓	✓✓	✓✓	?	?	✓✓	✓✓	✓✓	
ATLAS & CMS (HL)		✓					?	✓✓	✓	

Exciting prospects for the next decade and beyond

✓✓ – World leading ✓ – Potential, but less precise **?** – to be seen

Selection of key observables and attribution of scores highly subjective (could equally include sin(2β), $A_{SL}(B^0, B_s^0)$, $\tau\to\mu\gamma$, $B\to K\nu\bar{\nu}$, $B\to\tau\nu$, ...)

Back up

Studies for ECFA HL-LHC workshop

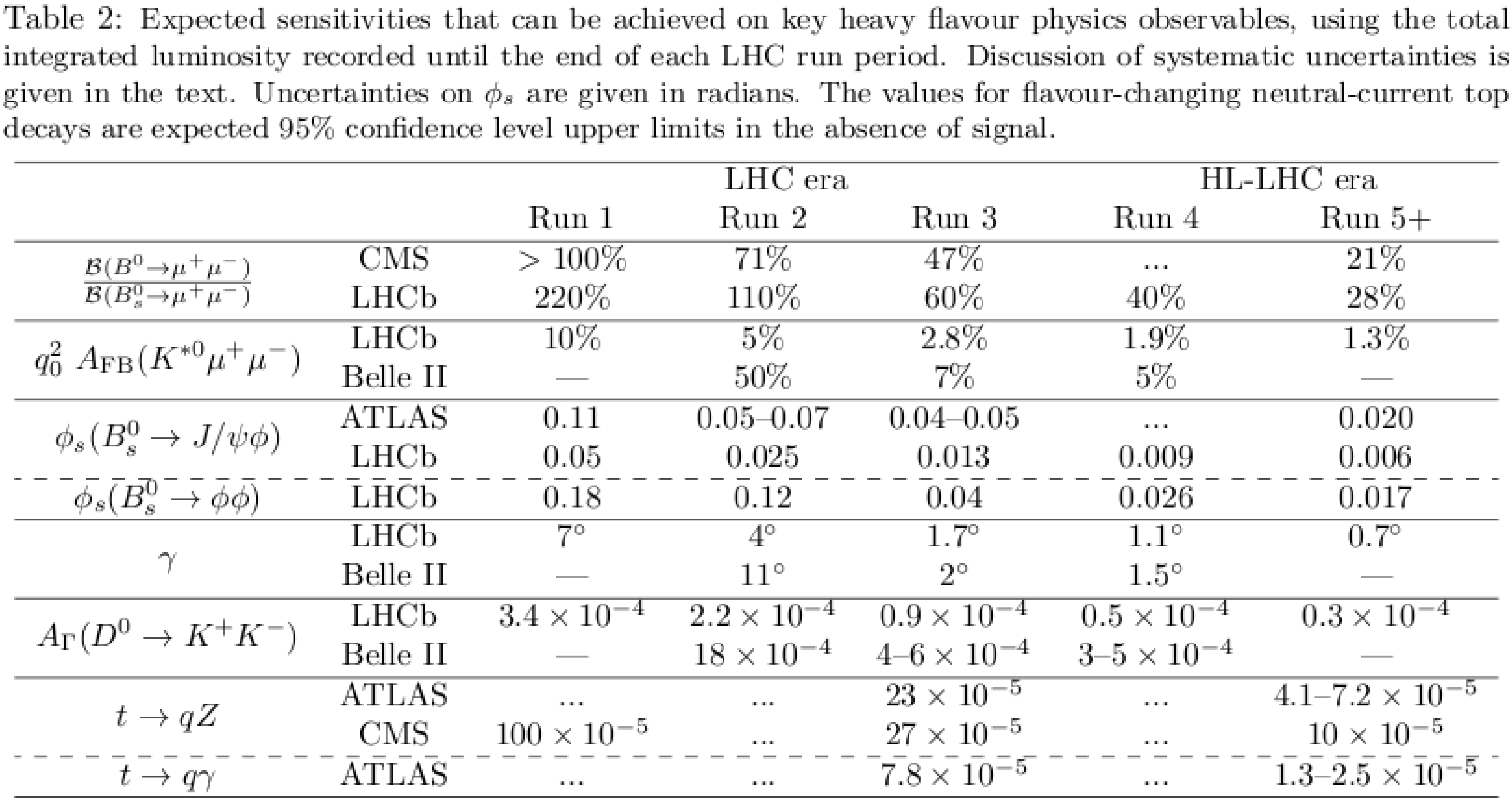


Table 2: Expected sensitivities that can be achieved on key heavy flavour physics observables, using the total integrated luminosity recorded until the end of each LHC run period. Discussion of systematic uncertainties is given in the text. Uncertainties on ϕ_s are given in radians. The values for flavour-changing neutral-current top decays are expected 95% confidence level upper limits in the absence of signal.

			LHC era		HL-LHC era	
		Run 1	Run 2	Run 3	Run 4	Run 5+
$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_s\to\mu^+\mu^-)}$	CMS	$> 100\%$	71%	47%	…	21%
	LHCb	220%	110%	60%	40%	28%
$q_0^2\ A_{\rm FB}(K^{*0}\mu^+\mu^-)$	LHCb	10%	5%	2.8%	1.9%	1.3%
	Belle II	—	50%	7%	5%	—
$\phi_s(B^0_s\to J/\psi\phi)$	ATLAS	0.11	0.05–0.07	0.04–0.05	…	0.020
	LHCb	0.05	0.025	0.013	0.009	0.006
$\phi_s(B^0_s\to\phi\phi)$	LHCb	0.18	0.12	0.04	0.026	0.017
γ	LHCb	7°	4°	1.7°	1.1°	0.7°
	Belle II	—	11°	2°	1.5°	—
$A_\Gamma(D^0\to K^+K^-)$	LHCb	3.4×10^{-4}	2.2×10^{-4}	0.9×10^{-4}	0.5×10^{-4}	0.3×10^{-4}
	Belle II	—	18×10^{-4}	$4\text{–}6\times10^{-4}$	$3\text{–}5\times10^{-4}$	—
$t\to qZ$	ATLAS	…	…	23×10^{-5}	…	$4.1\text{–}7.2\times10^{-5}$
	CMS	100×10^{-5}	…	27×10^{-5}	…	10×10^{-5}
$t\to q\gamma$	ATLAS	…	…	7.8×10^{-5}	…	$1.3\text{–}2.5\times10^{-5}$