Precision measurements

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Opening comment

- Following the Higgs boson discovery, most experimental particle physics could be said to be precision measurements
  - studies of known SM particles
    - H, t, W, Z, B, D, K, ν, ...
  - searches for deviations from precise SM predictions
    - EWPO, H couplings, CKM unitarity triangle fits, $(g\text{-}2)_\mu$, ...
  - searches for very rare phenomena
    - $H \to \tau\mu$, $B \to \mu\mu$, $K \to \pi\nu\bar{\nu}$, $\mu \to e\gamma$, $0\nu2\beta$, proton decay, EDMs, DM searches, ...
- I will cover only aspects related to heavy flavour physics
  - CP violation and rare decays
  - no claim these are the most precise measurements being performed!

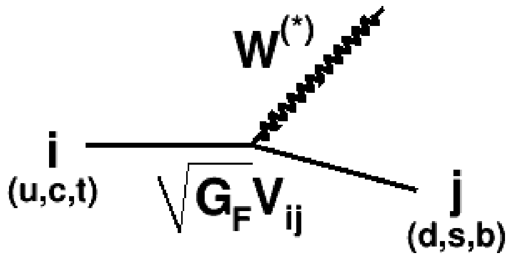
Precision measurements in heavy flavour physics

with a bias towards results from the LHC

but with rather few 13 TeV results

after all, precision measurements take time …
but see the talk by Barbara Storaci this afternoon

Quark flavour mixing
a.k.a. CKM phenomenology

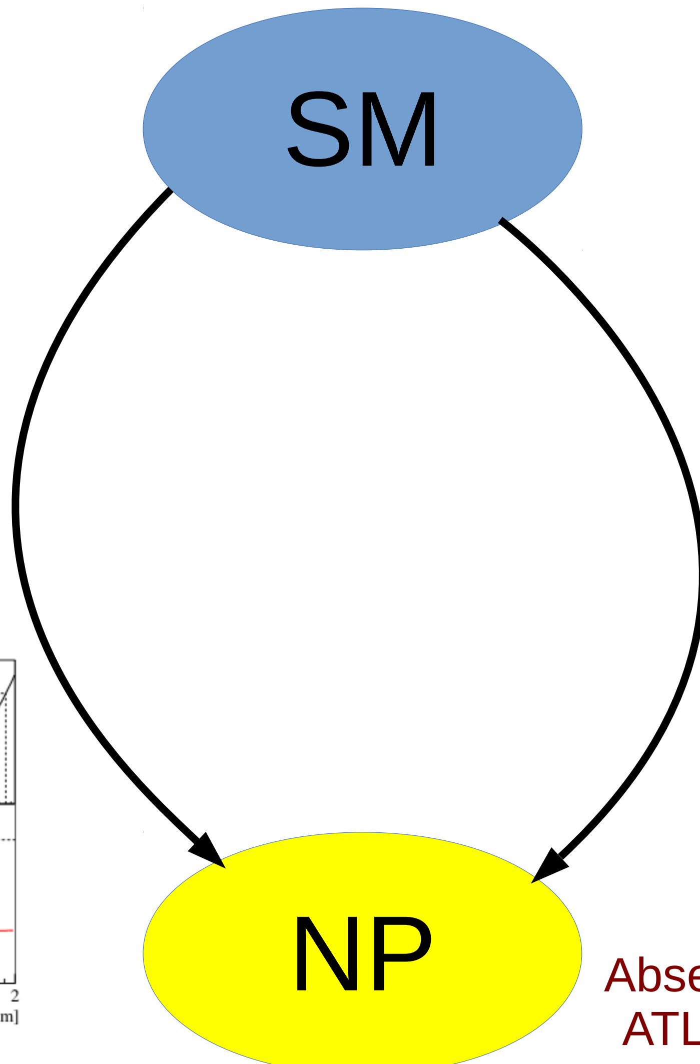


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- CKM theory is highly predictive
  - huge range of phenomena over a massive energy scale predicted by only 4 independent parameters (+ G_F + m_q + QCD)
- CKM matrix is hierarchical
  - distinctive flavour sector of Standard Model not necessarily replicated in extended theories → strong constraints on NP models
- CKM mechanism introduces CP violation
  - only source of CP violation in the Standard Model ($m_\nu = \theta_{QCD} = 0$)

Two routes to heaven

for quark flavour physics

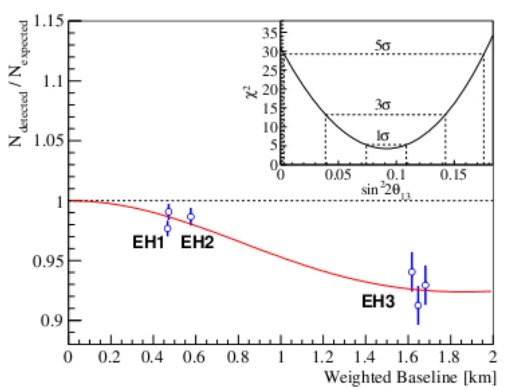


CP violation

(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}

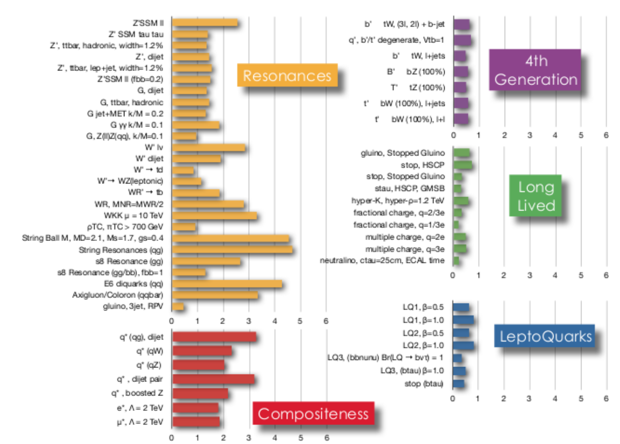


Rare decays

(strong theoretical arguments)

But

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

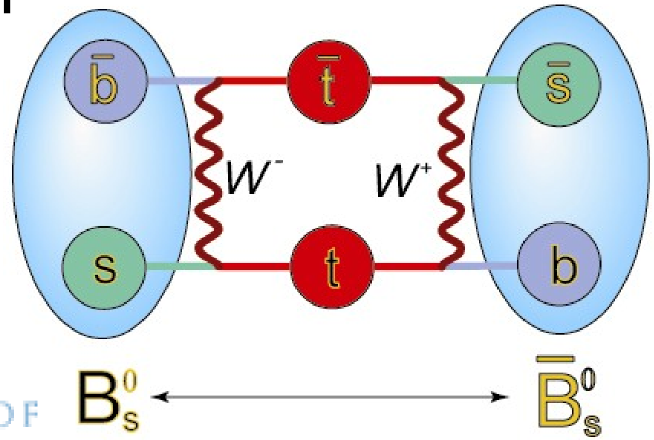


Absence of clear NP signals at ATLAS/CMS → argument for searches via rare decays stronger

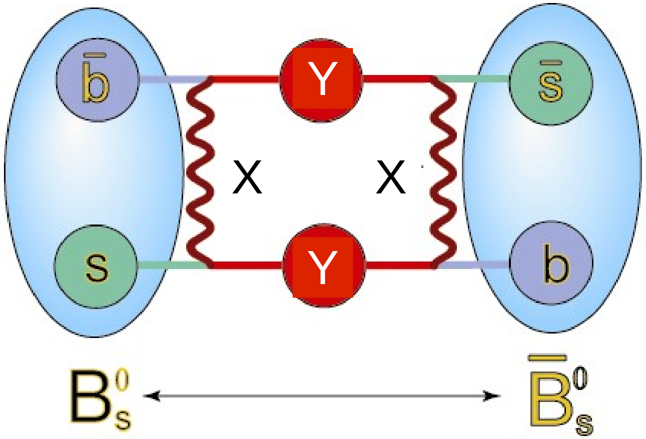
Loop diagrams for discovery

- 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
- NP contributions to tree-level processes also possible in some models

SM



NP



CP violation & the Unitarity Triangle

The Unitarity Triangle

http://ckmfitter.in2p3.fr
see also http://www.utfit.org

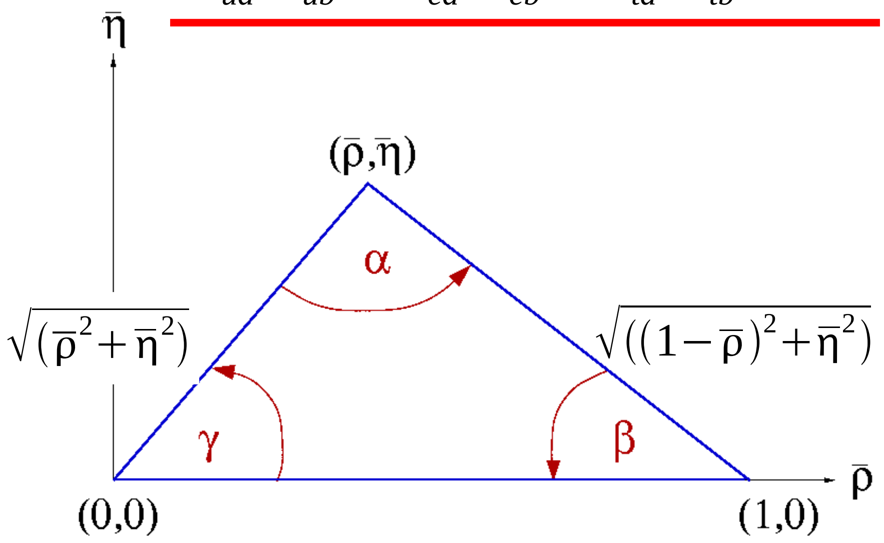
- The CKM matrix must be unitary

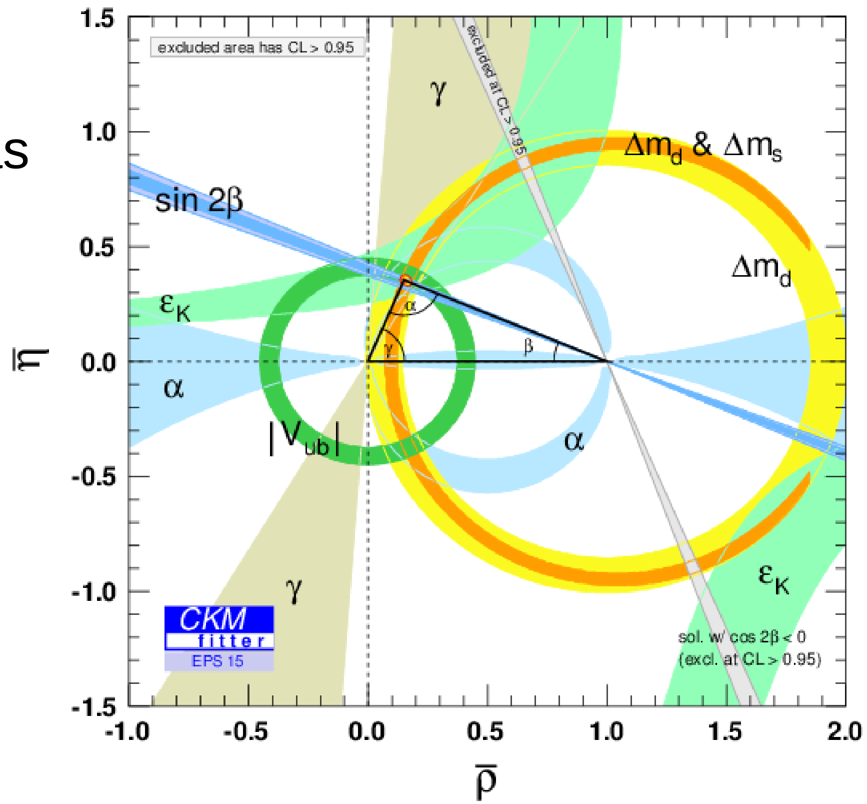
$$V_{CKM}^{+} V_{CKM} = V_{CKM} V_{CKM}^{+} = 1$$

- Provides numerous tests of constraints between independent observables, such as

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$





Consistency of measurements tests the Standard Model and provides model-independent constraints on New Physics

$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu/\Lambda_b \to \Lambda_c\mu\nu$

Nature Phys. 11 (2015) 743

- Long standing discrepancy between exclusive and inclusive determinations of both V_{ub} and V_{cb}

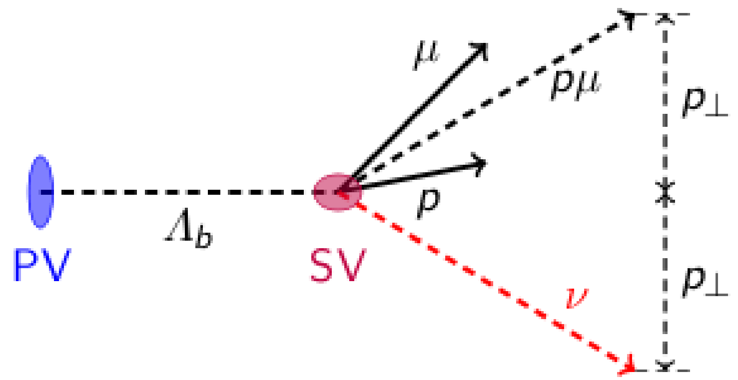
PDG 2014

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

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

- Use of b baryon decays provides complementary alternative to B mesons
- At LHCb, exploit displaced vertex to reconstruct corrected mass

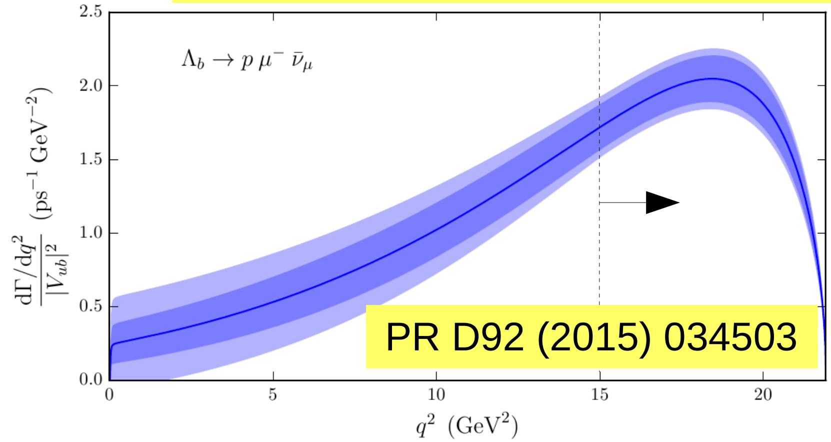
$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$



$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

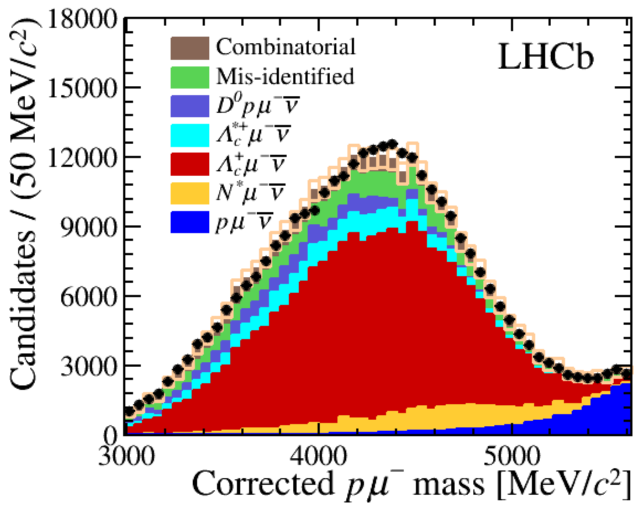
Nature Phys. 11 (2015) 743

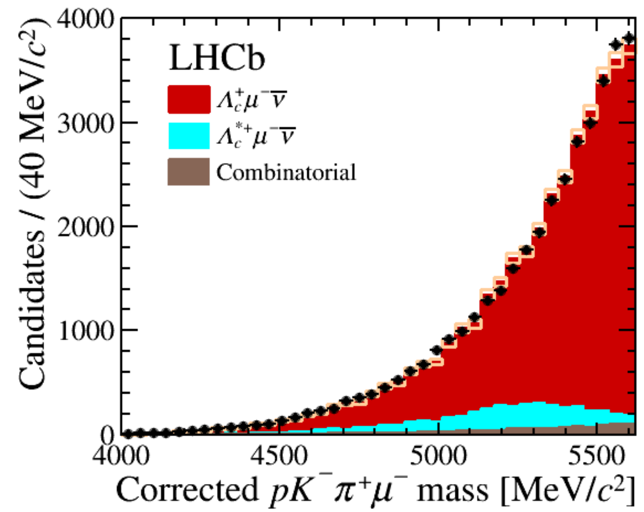
- Can then reconstruct $q^2 = m(\mu\nu)^2$
  - Select events with $q^2 > 15$ GeV^2
  - Highest rate, best resolution & most reliable theory (lattice) predictions



PR D92 (2015) 034503

- Use isolation MVA to suppress background
- Fit M_{corr} to obtain signal yields





$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

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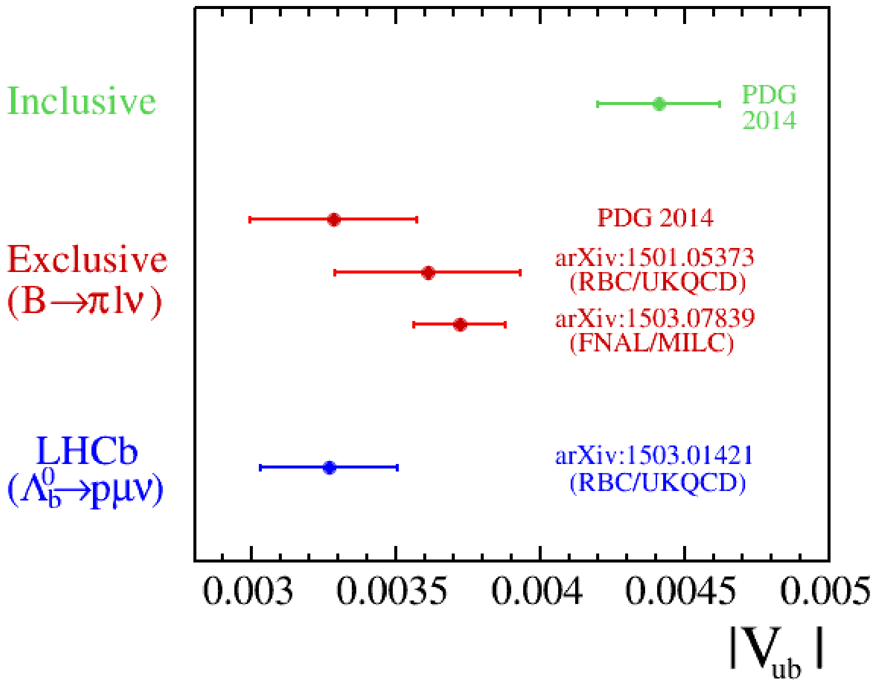
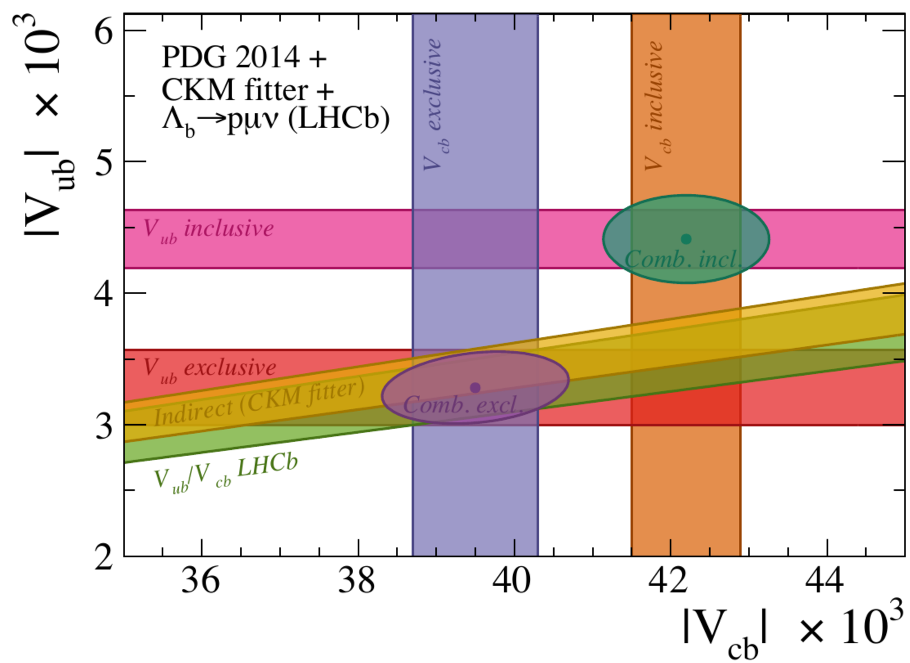




$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\mathrm{expt}) \pm 0.004(\mathrm{lattice})$$

- Rules out models with RH currents
- Compatible with UT fit (β,γ)

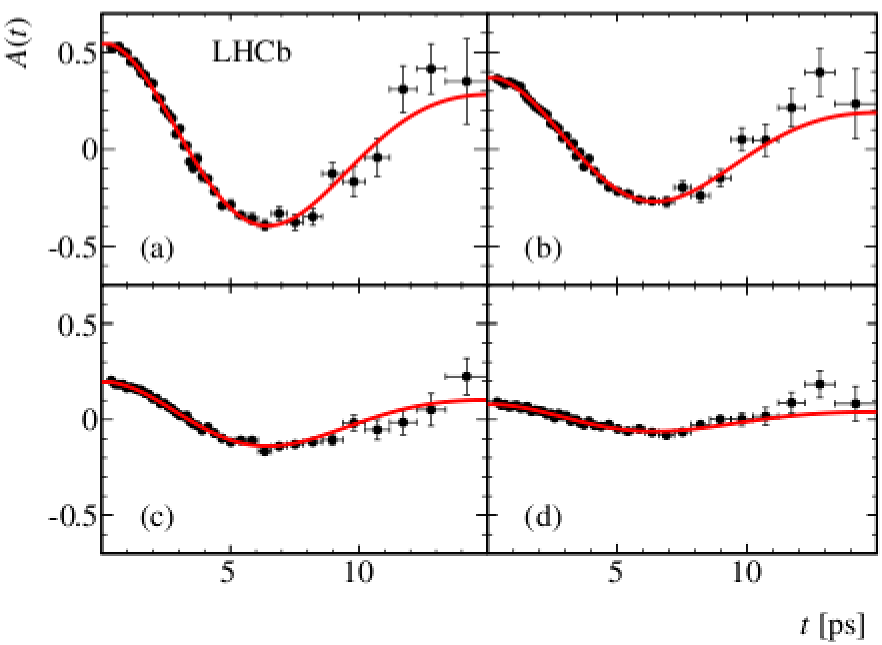
$|V_{td}/V_{ts}|$ from $\Delta m_d/\Delta m_s$

LHCb-PAPER-2015-031

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ \mathrm{ps}^{-1}$
(LHCb NJP 15 (2013) 053021)

- Δm_s now precisely known
- limitation on knowledge of UT side from lattice (improving fast) and Δm_d
- new measurement uses $B^0 \to D^{(*)-}\mu\nu$ decays

latest lattice calculations:
arXiv:1603.04306, arXiv:1602.03560



$\Delta m_d = (505.0 \pm 2.1\ \mathrm{(stat)} \pm 1.0\ \mathrm{(syst)})\ \mathrm{ns}^{-1}$

single most precise determination
precision of previous world average

only 2012 $B^0 \to D^-\mu\nu$
data shown

$|V_{td}/V_{ts}|$ from $\Delta m_d/\Delta m_s$

LHCb-PAPER-2015-031

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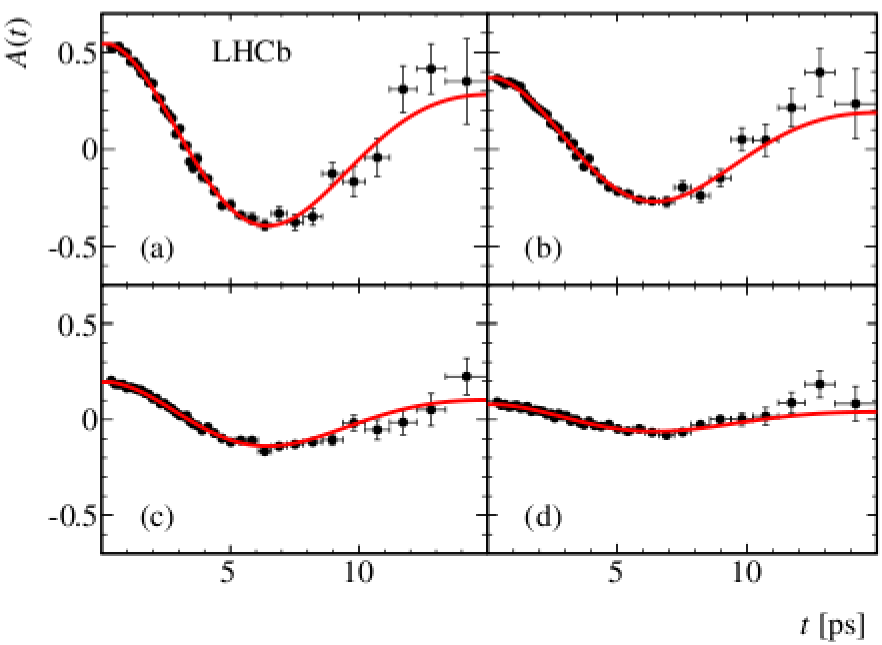
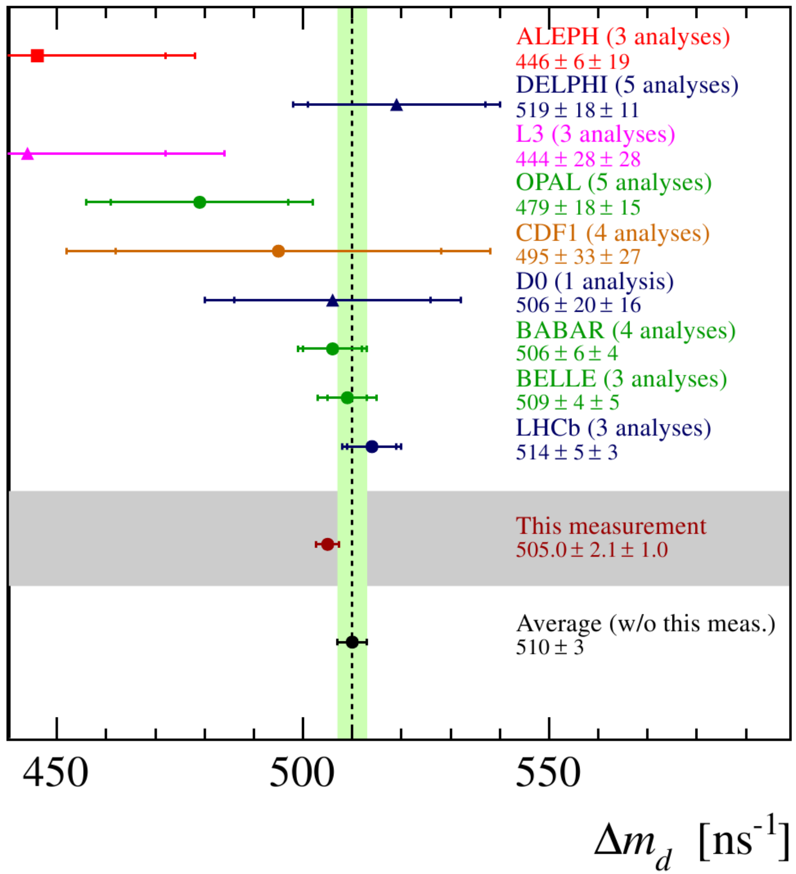


only 2012 $B^0 \rightarrow D^-\mu\nu$ data shown



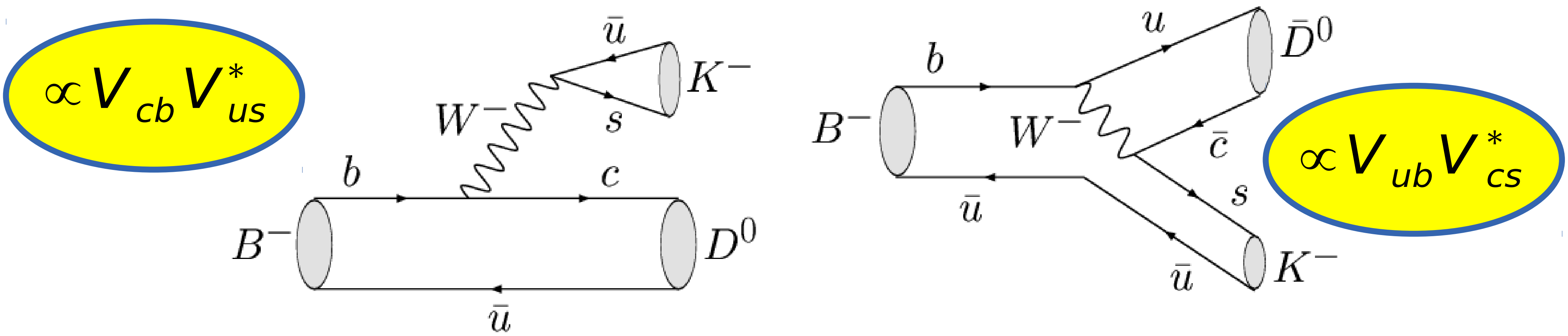
Importance of γ from B→DK

- γ plays a unique role in flavour physics

the only CP violating parameter that can be measured through tree decays (*)

(*) more-or-less

- A benchmark Standard Model reference point
  - doubly important after New Physics is observed

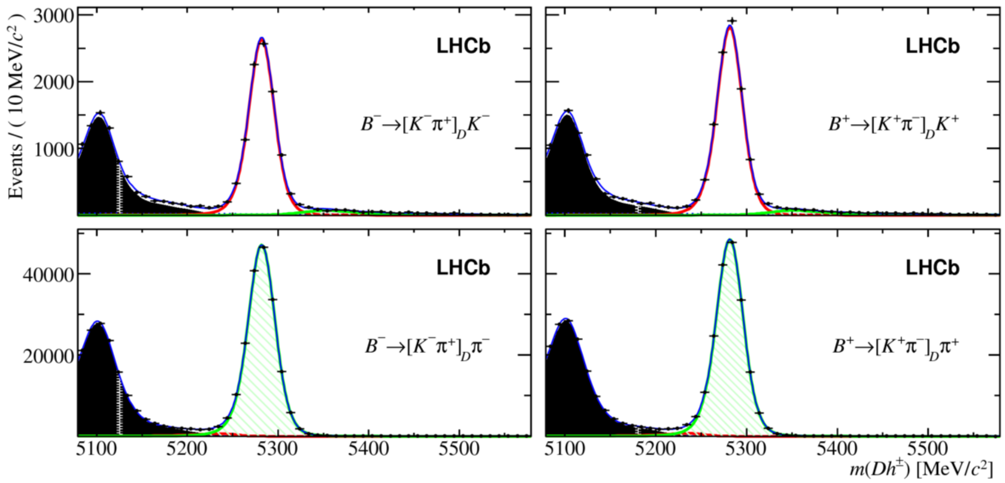


Variants use different B or D decays
require a final state common to both D^0 and $\overline{D}^0$

γ from $B^+ \to DK^+$, $D \to KK, \pi\pi, K\pi$

LHCb-PAPER-2016-003

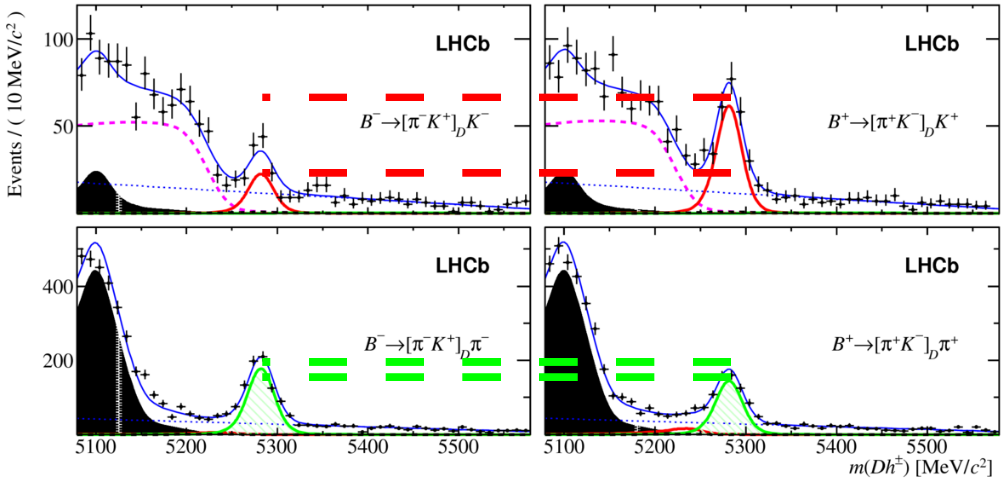
D → Kπ (favoured)



small asymmetries due to production and detection effects

B → Dπ control mode helps to separate effects

D → πK ("ADS" suppressed)



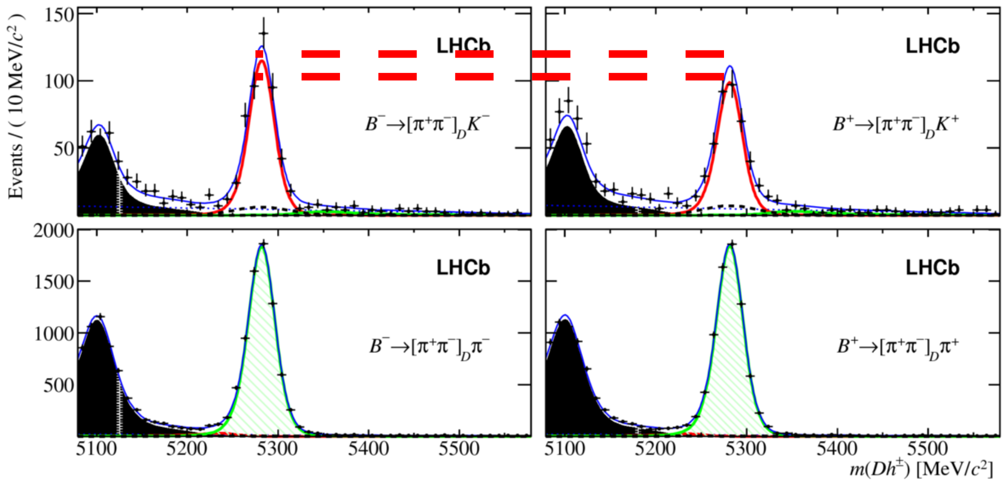
large CP violating asymmetries – first 5σ observation in a single B → DK channel

effects also possible in B → Dπ

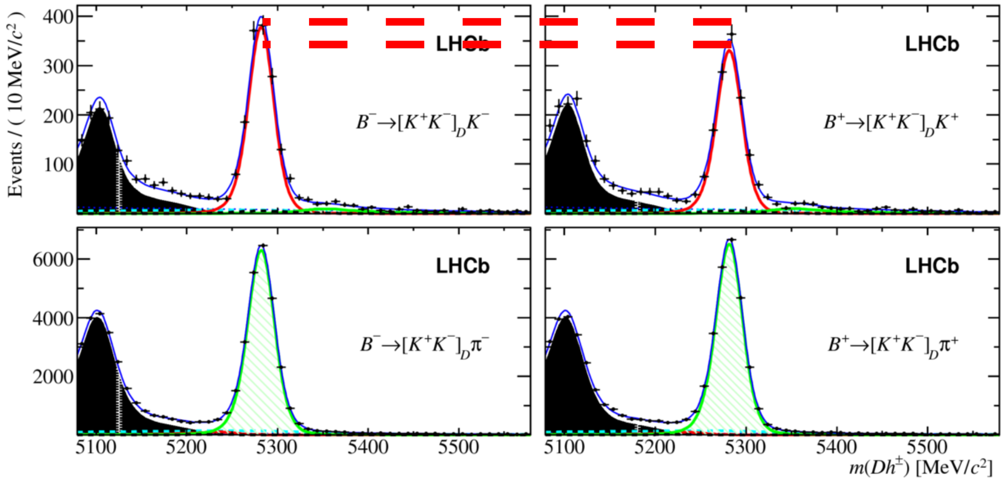
γ from $B^+ \to DK^+$, $D \to KK, \pi\pi, K\pi$

LHCb-PAPER-2016-003

$D \to \pi\pi$ ("GLW" CP+ state)



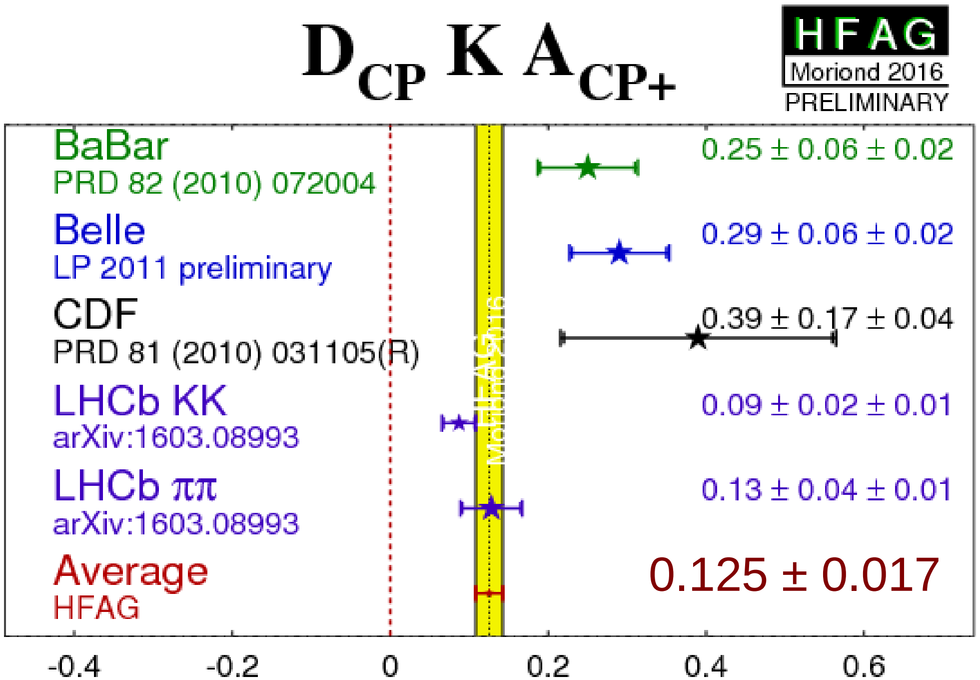
$D \to KK$ ("GLW" CP+ state)

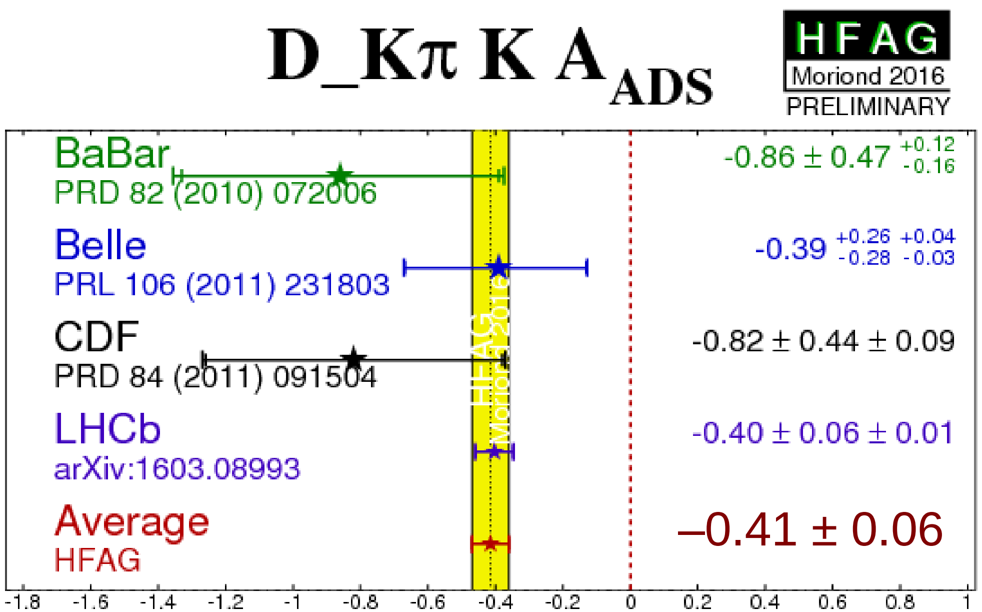


CP violating asymmetries visible
but not 5σ significant

γ from $B^+ \to DK^+$, $D \to KK, \pi\pi, K\pi$

LHCb-PAPER-2016-003





Measurements reaching percent level precision

Some tension in the A_{CP+} average (χ^2 = 16/4 dof) but no other sign of experimental disagreements

γ from $B^0 \to DK^{*0}$, $D \to K_S\pi\pi$, K_SKK

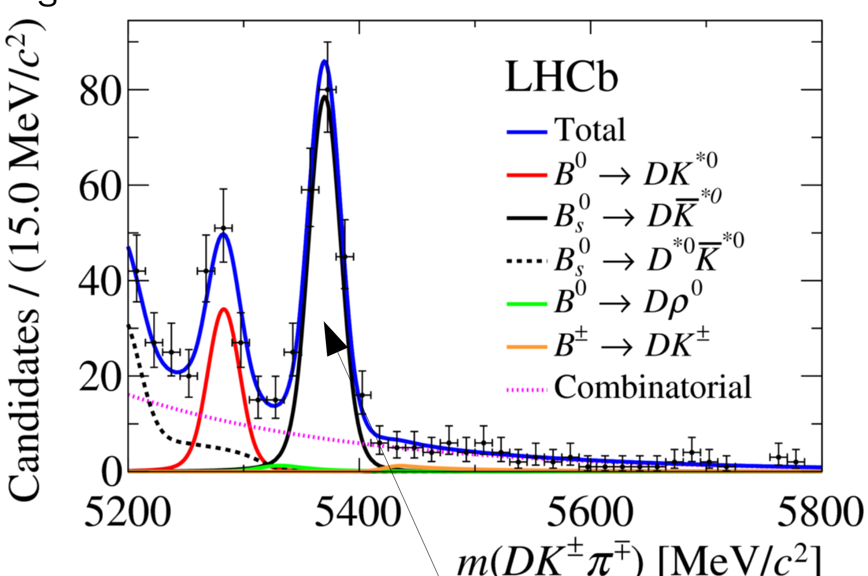
LHCb-PAPER-2016-006,7

$B^0 \to DK^{*0}$ rarer, but with larger interference effects, than $B^+ \to DK^+$

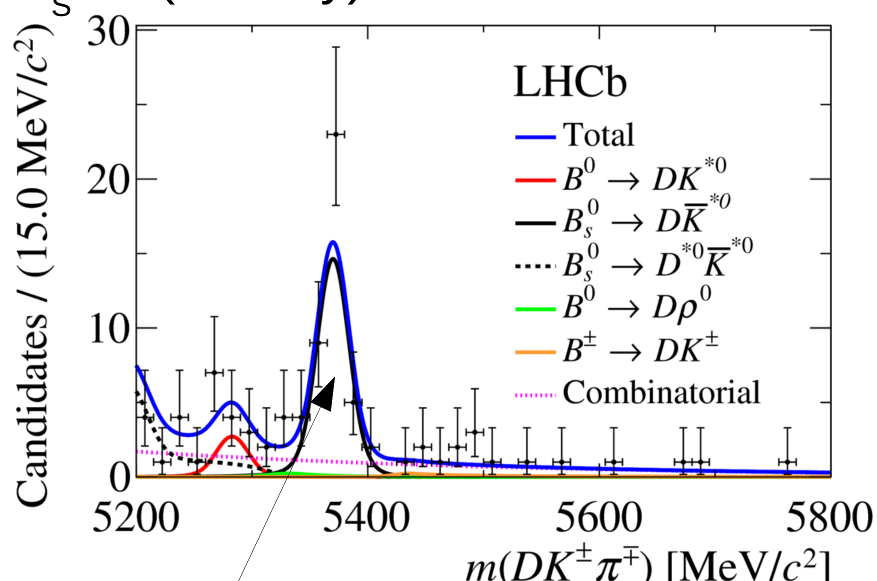
$D \to KK,\pi\pi$, $K\pi$ previously studied in PR D90 (2014) 112002

Now consider "GGSZ" modes with both model-independent (LHCb-PAPER-2016-006) and -dependent (LHCb-PAPER-2016-007) analyses

$D \to K_S\pi\pi$ (both MI & MD)



$D \to K_SKK$ (MI only)



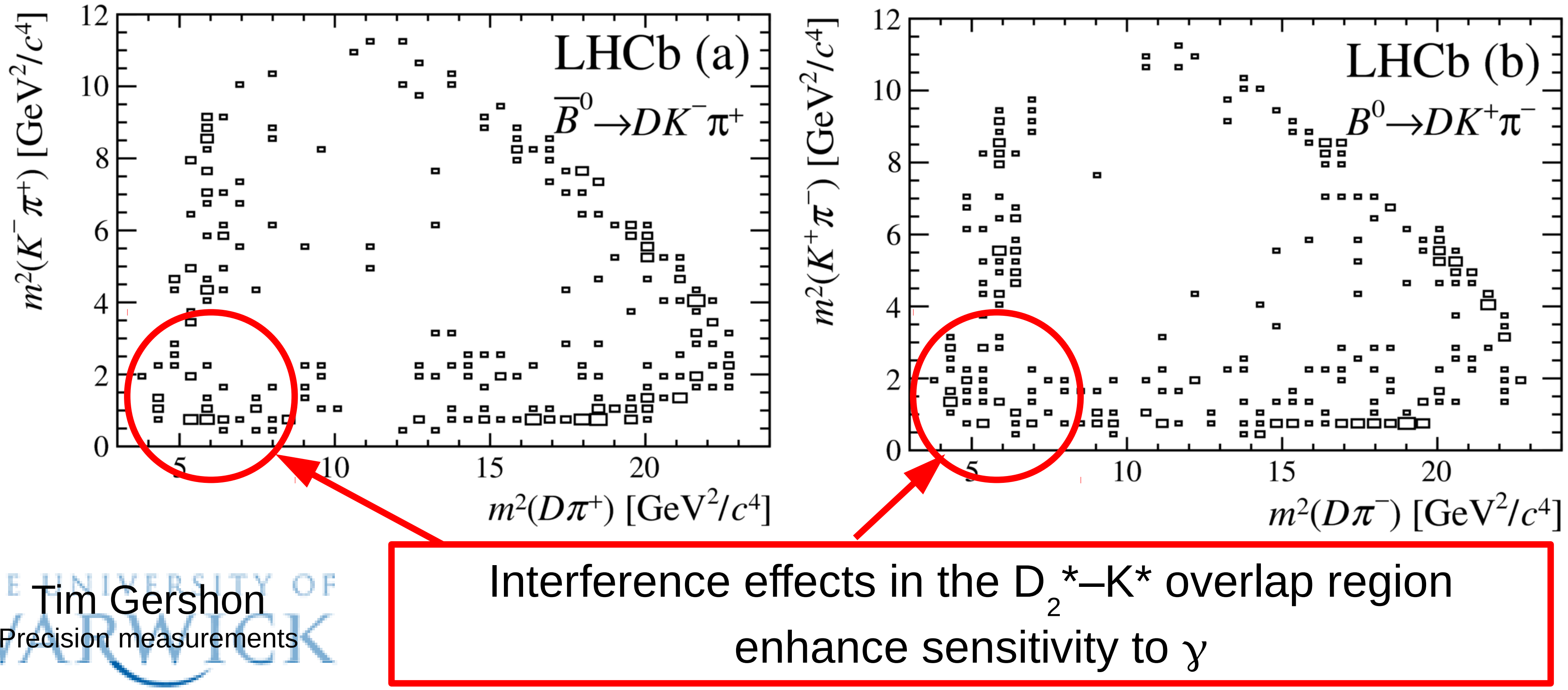
B_s^0 decays to same final states provide control channels

γ from $B^0 \to DK^{*0}$

LHCb-PAPER-2015-059

For $B^0 \to DK^{*0}$, width of the K^{*0} resonance introduces a dilution factor that depends on the $B^0 \to DK^+\pi^-$ Dalitz plot

This has been studied with $D \to K\pi$ (LHCb-PAPER-2015-017), KK and $\pi\pi$ (LHCb-PAPER-2015-059) decays



γ combination

LHCb-CONF-2016-001

Many observables with sensitivity to γ

- $B^+ \to DK^+$, $D \to h^+h^-$, GLW/ADS, $3\,\mathrm{fb}^{-1}$ [4]
- $B^+ \to DK^+$, $D \to h^+\pi^-\pi^+\pi^-$, quasi-GLW/ADS, $3\,\mathrm{fb}^{-1}$ [4]
- $B^+ \to DK^+$, $D \to h^+h^-\pi^0$, quasi-GLW/ADS, $3\,\mathrm{fb}^{-1}$ [5]
- $B^+ \to DK^+$, $D \to K^0_S h^+h^-$, model-independent GGSZ, $3\,\mathrm{fb}^{-1}$ [6]
- $B^+ \to DK^+$, $D \to K^0_S K^+\pi^-$, GLS, $3\,\mathrm{fb}^{-1}$ [7]
- $B^0 \to DK^+\pi^-$, $D \to h^+h^-$, GLW-Dalitz, $3\,\mathrm{fb}^{-1}$ [8]
- $B^0 \to DK^{*0}$, $D \to K^+\pi^-$, ADS, $3\,\mathrm{fb}^{-1}$ [9]
- $B^0 \to DK^{*0}$, $D \to K^0_S\pi^+\pi^-$, model-dependent GGSZ, $3\,\mathrm{fb}^{-1}$ [10]
- $B^+ \to DK^+\pi^+\pi^-$, $D \to h^+h^-$, GLW/ADS, $3\,\mathrm{fb}^{-1}$ [11]
- $B^0_s \to D^{\mp}_s K^{\pm}$, time-dependent, $1\,\mathrm{fb}^{-1}$ [12],

[4] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with two- and four-body D meson decays*, LHCb-PAPER-2016-003, in preparation.

[5] LHCb collaboration, R. Aaij *et al.*, *A study of CP violation in $B^\mp \to Dh^\mp$ ($h = K, \pi$) with the modes $D \to K^\mp\pi^\pm\pi^0$, $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$*, Phys. Rev. **D91** (2015) 112014, arXiv:1504.05442.

[6] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CKM angle γ using $B^\pm \to DK^\pm$ with $D \to K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$ decays*, JHEP **10** (2014) 097, arXiv:1408.2748.

[7] LHCb collaboration, R. Aaij *et al.*, *A study of CP violation in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ decays with $D \to K^0_S K^\pm\pi^\mp$ final states*, Phys. Lett. **B733** (2014) 36, arXiv:1402.2982.

[8] LHCb collaboration, R. Aaij *et al.*, *Constraints on the unitarity triangle angle γ from Dalitz plot analysis of $B^0 \to DK^+\pi^-$ decays*, LHCb-PAPER-2015-059, submitted to Phys. Rev. Lett.

[9] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP violation parameters in $B^0 \to DK^{*0}$ decays*, Phys. Rev. **D90** (2014) 112002, arXiv:1407.8136.

[10] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CKM angle γ using $B^0 \to DK^{*0}$ with $D \to K^0_S\pi^+\pi^-$ decays*, LHCb-PAPER-2016-007, in preparation.

[11] LHCb collaboration, R. Aaij *et al.*, *Study of $B^- \to DK^-\pi^+\pi^-$ and $B^- \to D\pi^-\pi^+\pi^-$ decays and determination of the CKM angle γ*, Phys. Rev. **D92** (2015) 112005, arXiv:1505.07044.

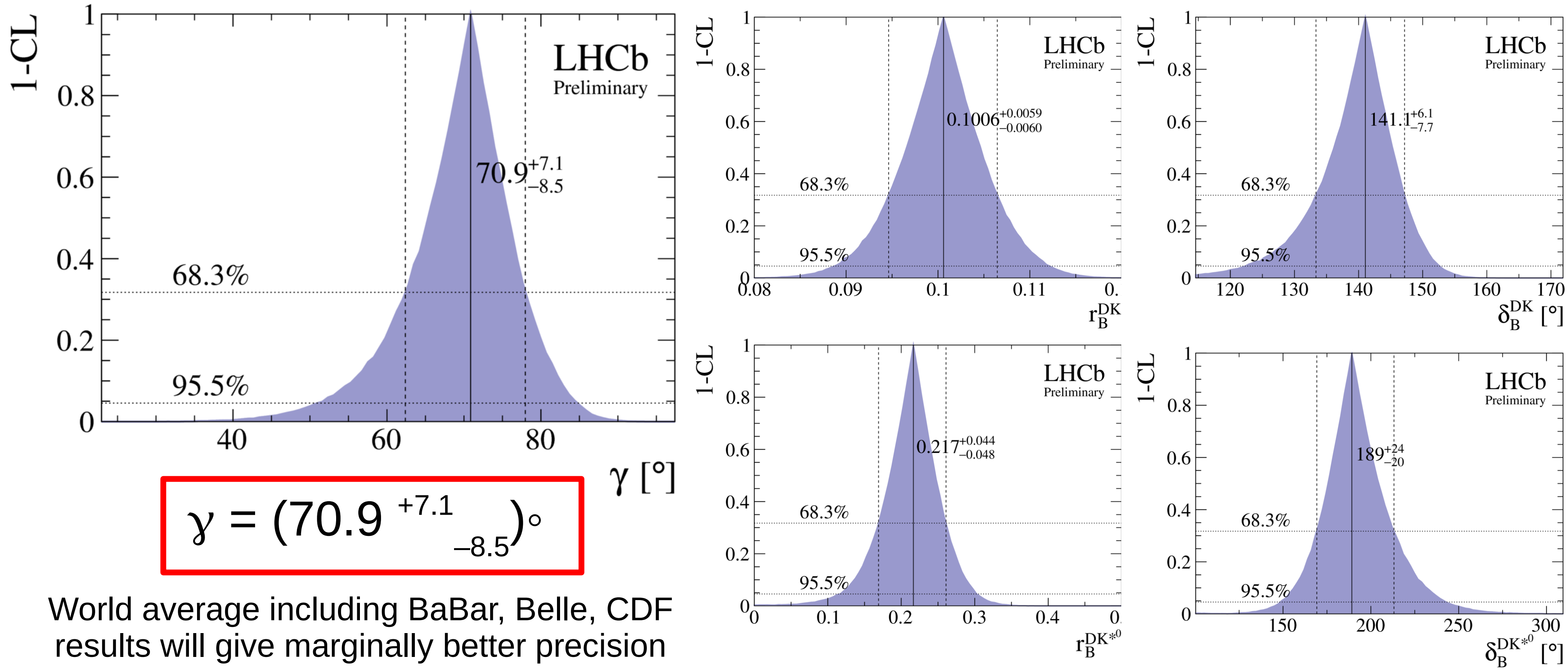
[12] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP asymmetry in $B^0_s \to D^\mp_s K^\pm$ decays*, JHEP **11** (2014) 060, arXiv:1407.6127.

New results discussed on previous slides

γ combination

LHCb-CONF-2016-001

Many observables with sensitivity to γ



$\gamma = (70.9\ ^{+7.1}_{-8.5})^{\circ}$

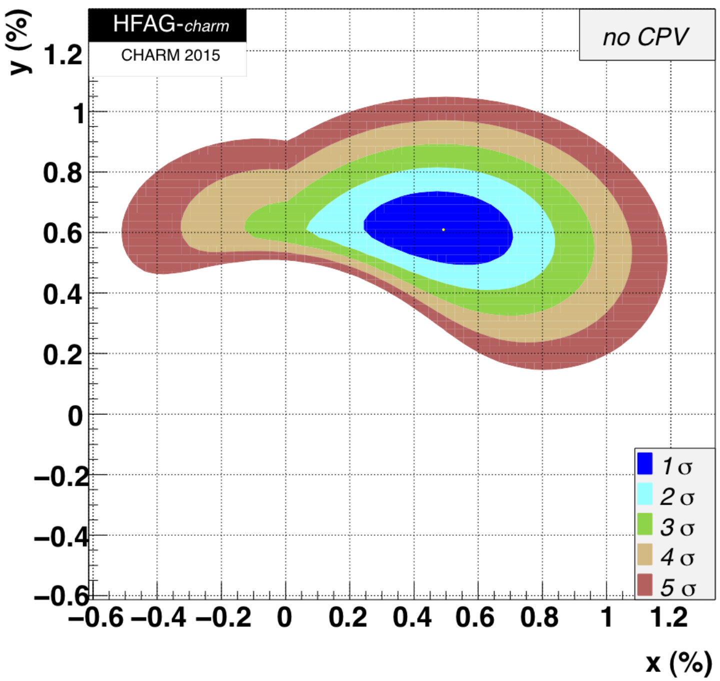
World average including BaBar, Belle, CDF results will give marginally better precision

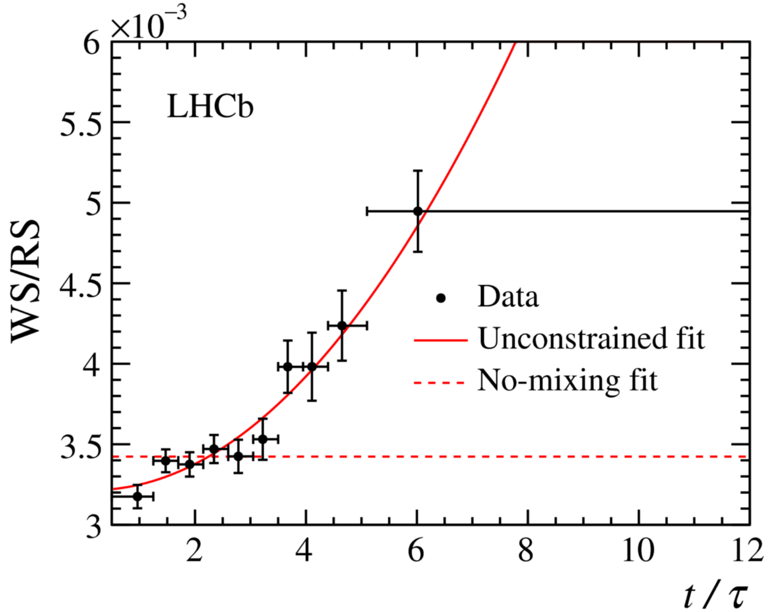
Not yet at desired precision, but great progress

Charm mixing with D→Kπππ

LHCb-PAPER-2015-057

Multibody charm decays also of interest to study charm oscillations (also to constrain hadronic parameters needed in the γ fit)





Charm mixing parameters <1%

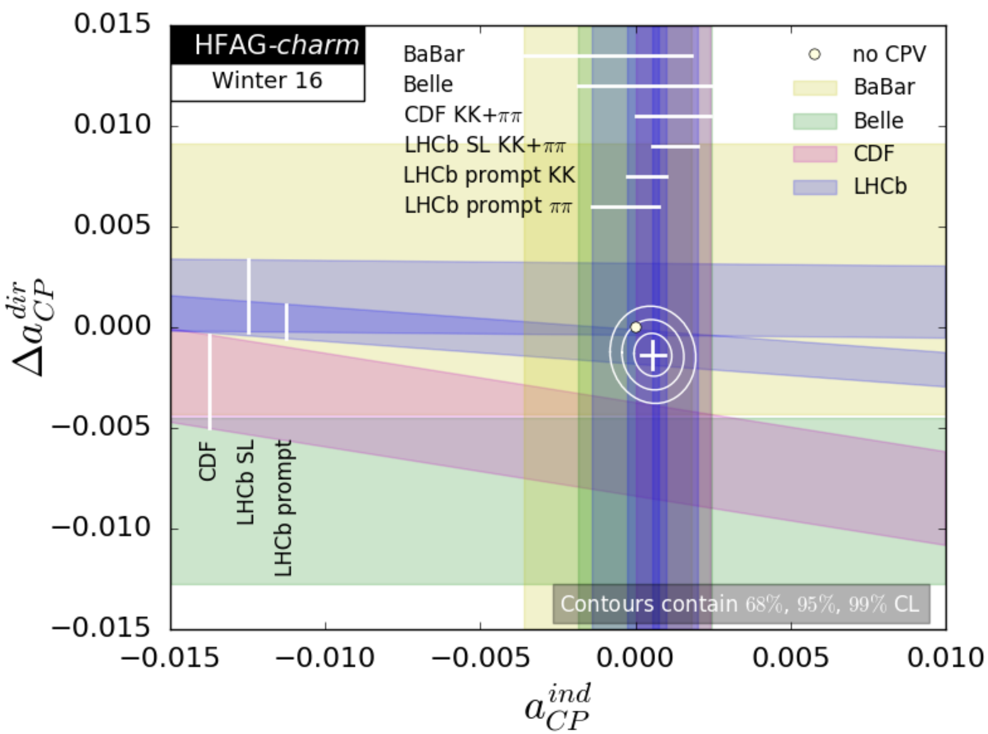
Still not established whether
$x \equiv \Delta m_D/\Gamma_D \neq 0$

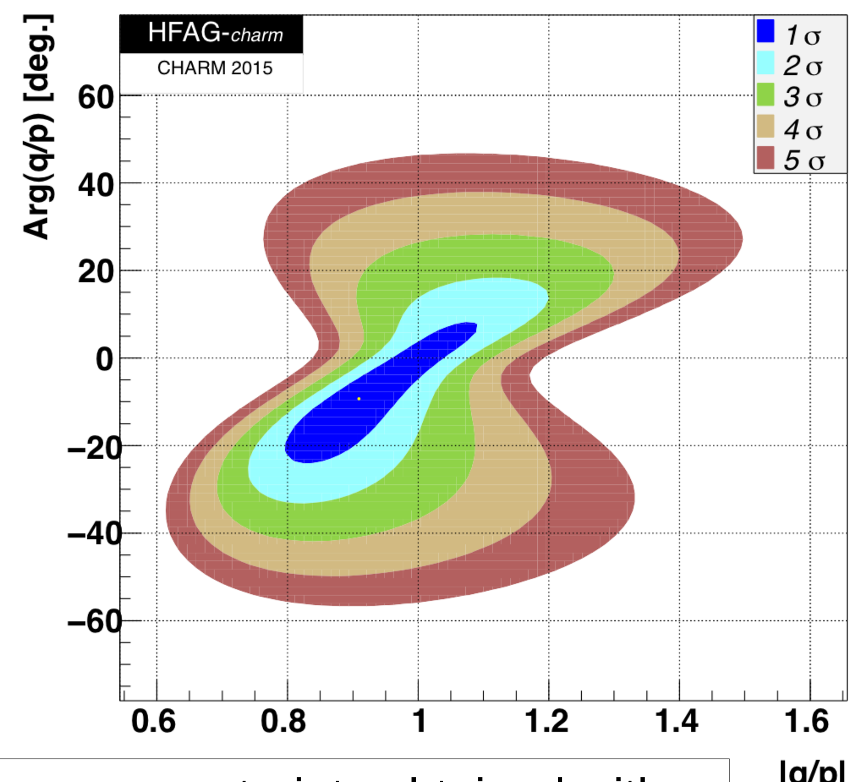
Charm CP violation

LHCb-PAPER-2015-055

No evidence for CP violation in the charm system, whether in mixing, decay or mixing-decay interference

Latest: $\Delta A_{CP} \equiv A_{CP}(D\to KK) - A_{CP}(D\to\pi\pi) = (-0.10 \pm 0.08 \pm 0.03)\ \%$





Much stronger constraints obtained with minimal assumption on CPV in decays

Charm CP violation

LHCb-PAPER-2015-055

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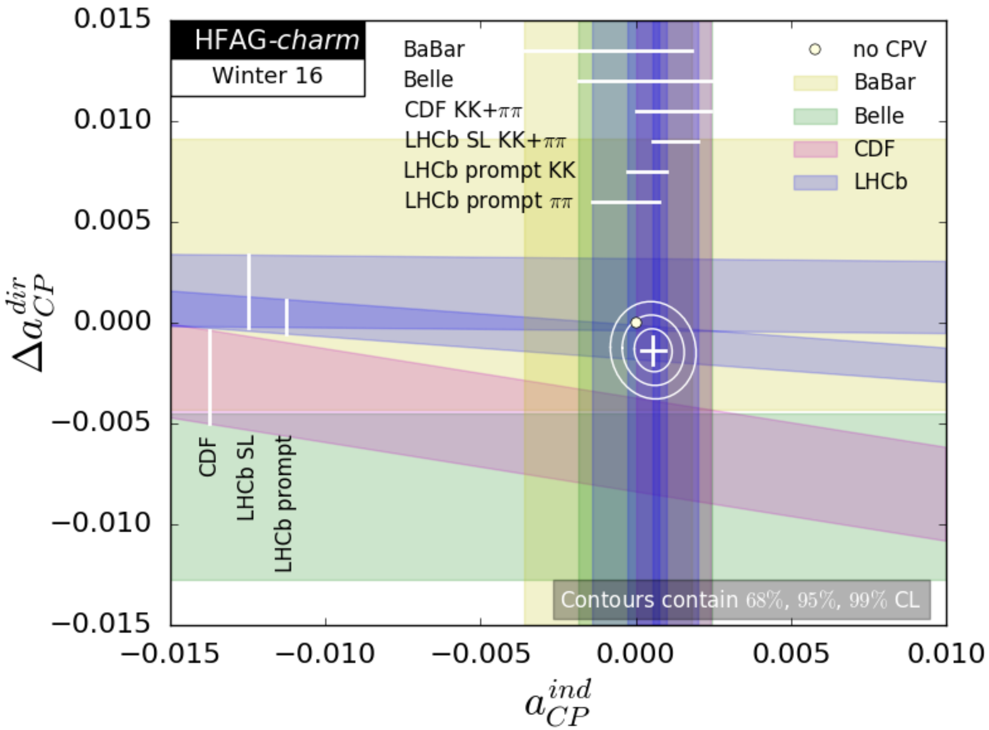
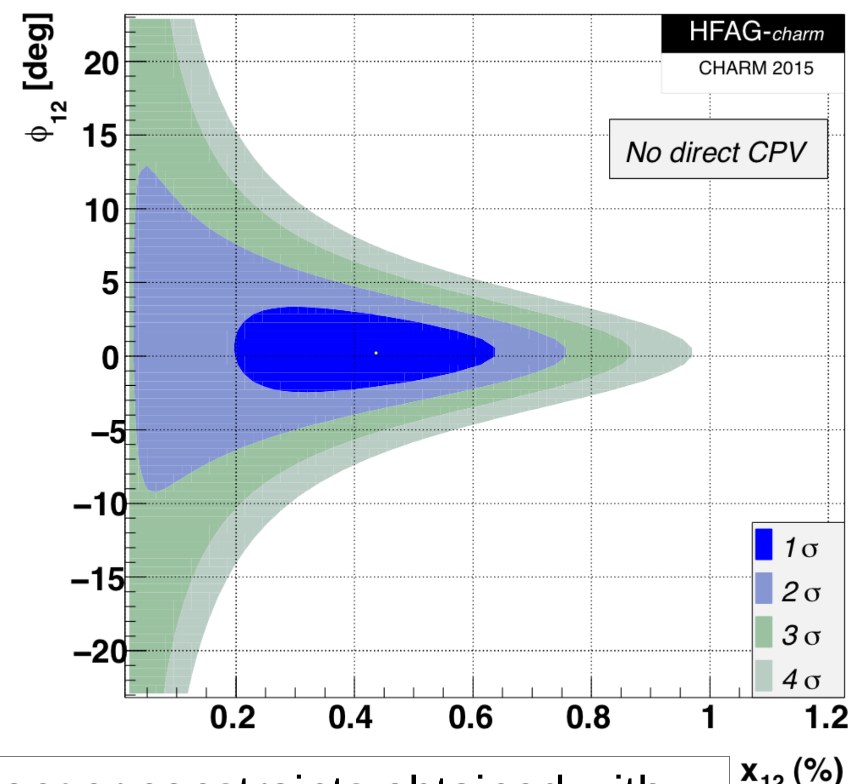
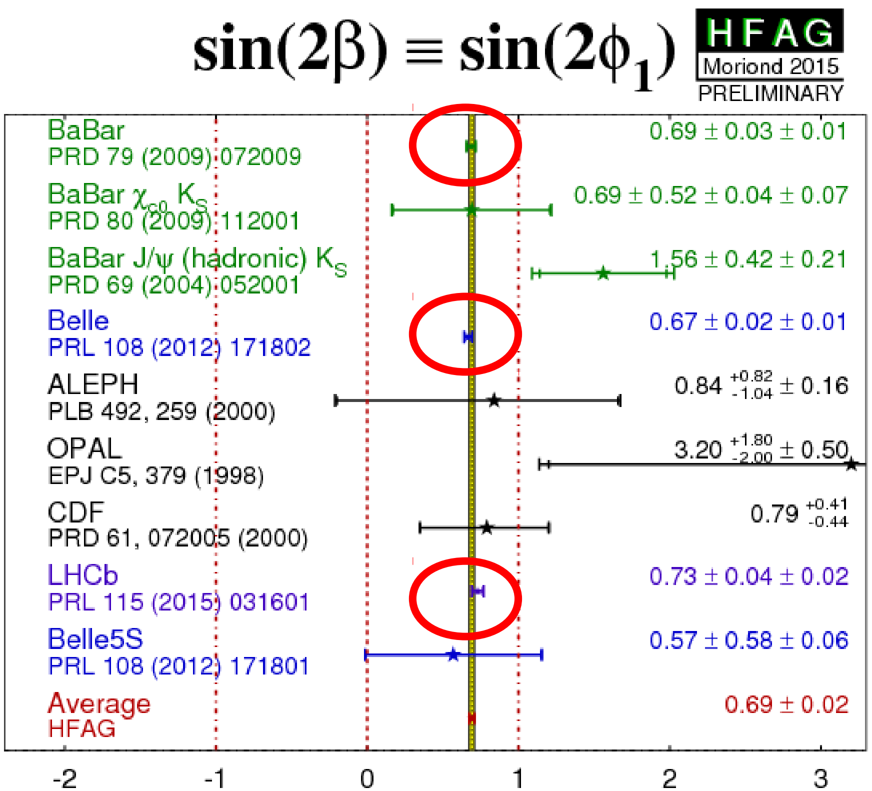


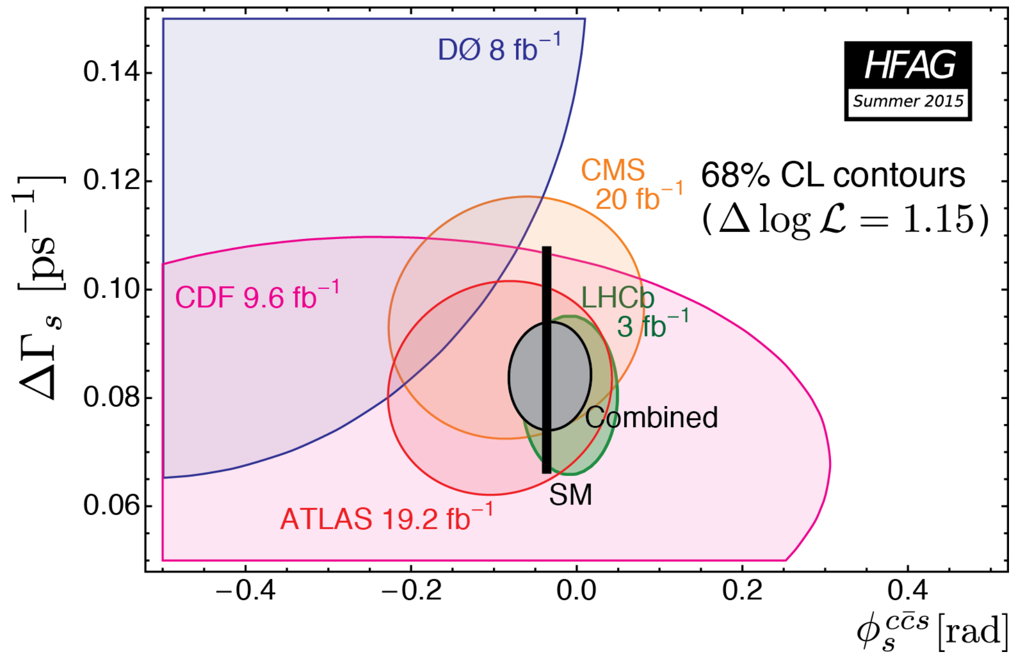


Much stronger constraints obtained with minimal assumption on CPV in decays

B^0 and B_s^0 mixing phases: sin(2β) & φ_s

PRL 115 (2015) 031601



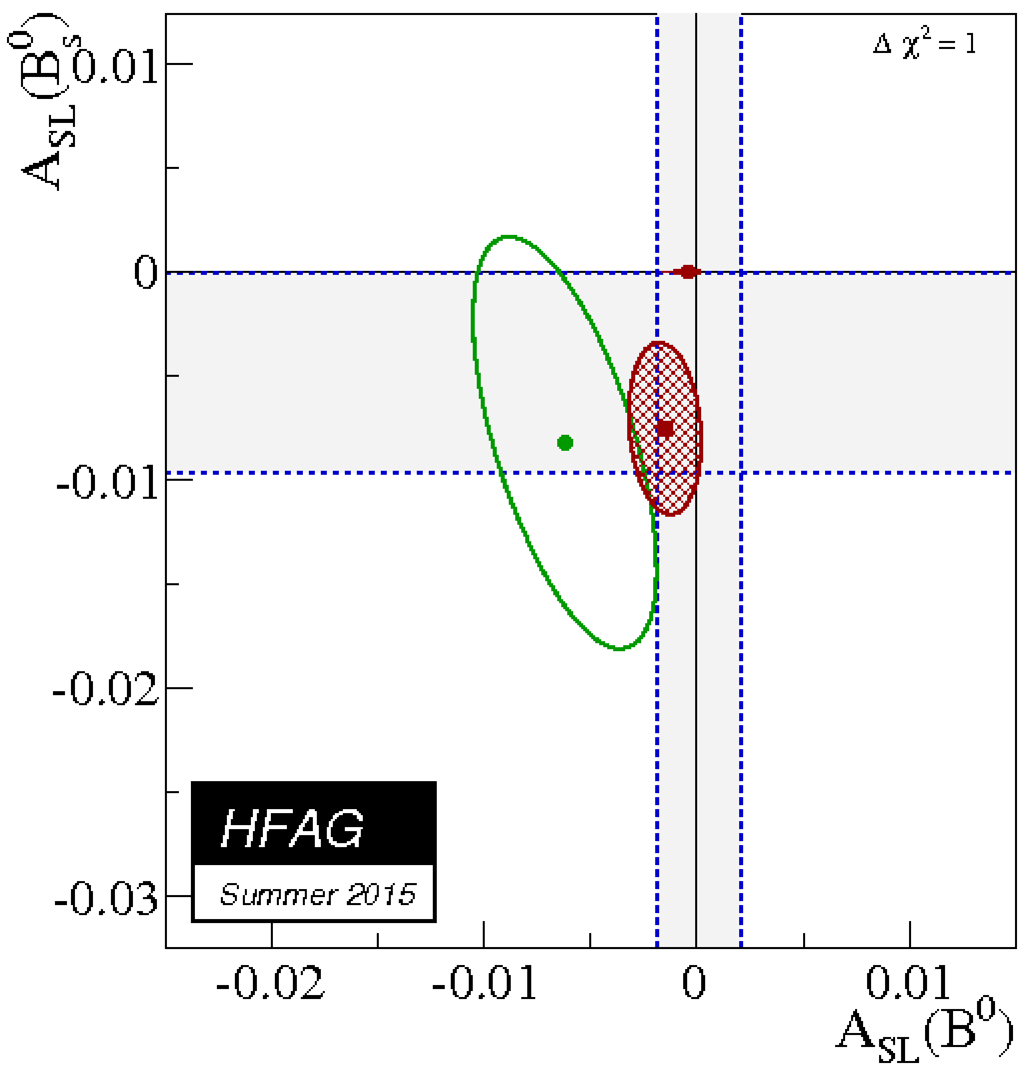


LHCb: PRL 114 (2015) 041801;
PL B736 (2014) 186;
ATLAS: arXiv:1601.03297;
CMS: PL B757 (2016) 97

Possible penguin pollution controlled by SU(3) partners
LHCb: PL B742 (2015) 38, JHEP 11 (2015) 082

CP violation in $B^0_{(s)}$ mixing

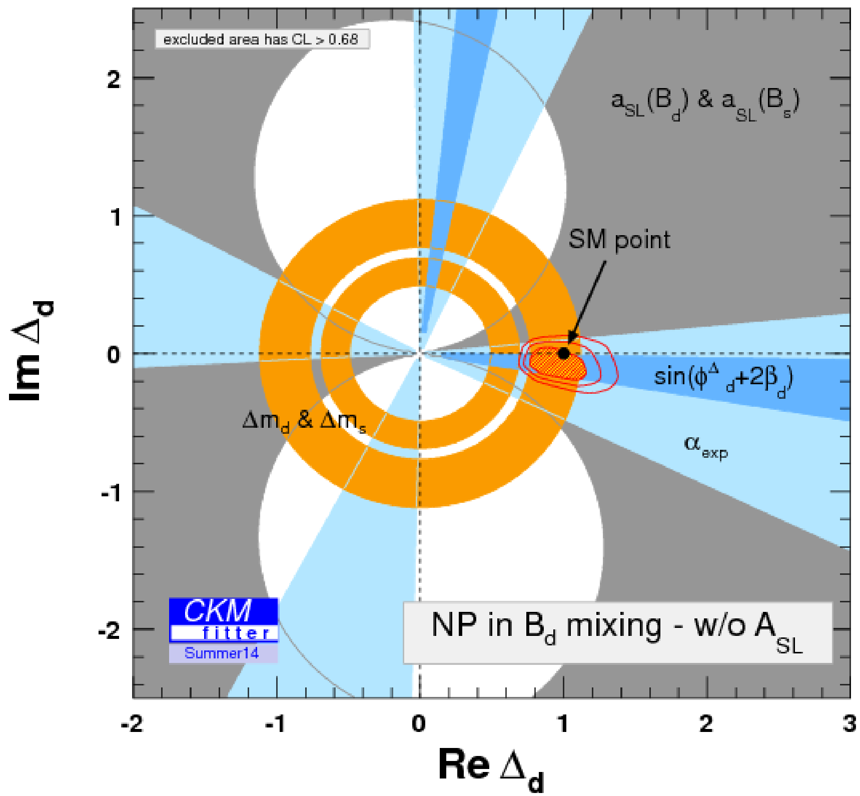
- Evidence of non-SM CP violation in inclusive dimuon asymmetry from the D0 collaboration
  - PRD 89 (2014) 012002
- Semileptonic asymmetries $A_{SL}(B^0)$ and $A_{SL}(B_s^0)$ however consistent with SM ~ (0,0)
  - $A_{SL}(B^0)$ by BaBar, Belle, LHCb, D0
  - $A_{SL}(B_s^0)$ by LHCb (1/fb), D0
    - final LHCb Run I analysis in progress
- Possibility of additional contributions to inclusive dimuon asymmetry under investigation
  - PR D87 (2013) 074020

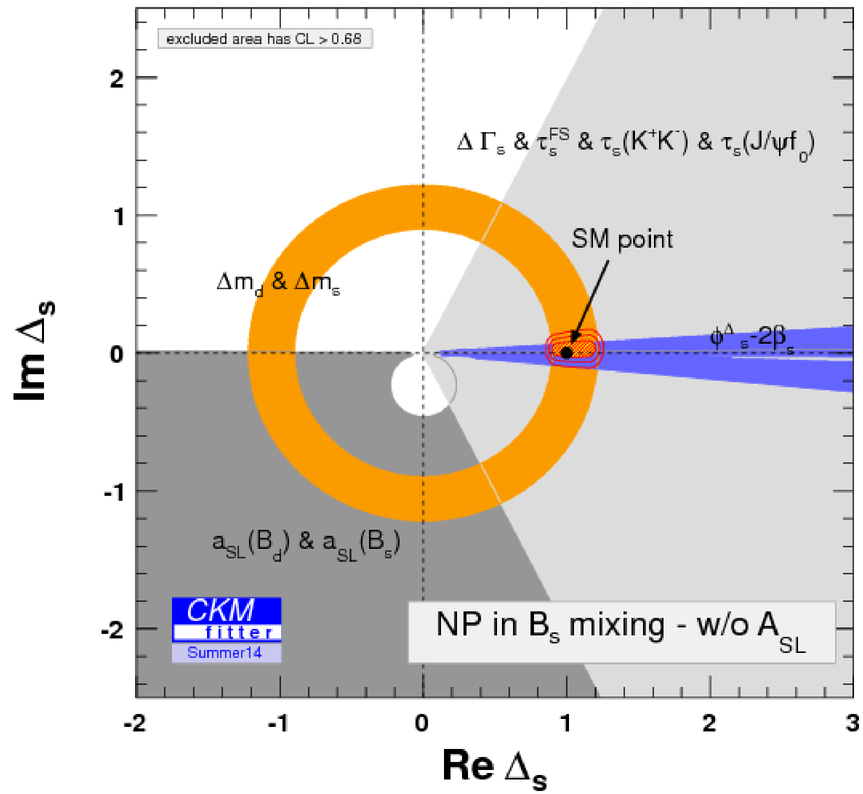


Limits on BSM contributions to ΔB=2

Define $M_{12}^{q} = M_{12}^{SM,q}\,\Delta_q$ and obtain constraints on (Re Δ_q, Im Δ_q)

(here not including anomalous D0 dimuon asymmetry result)



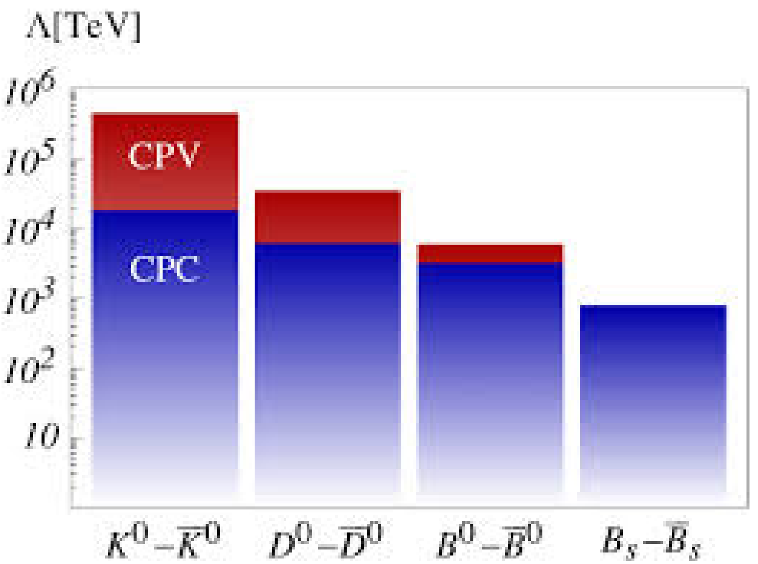


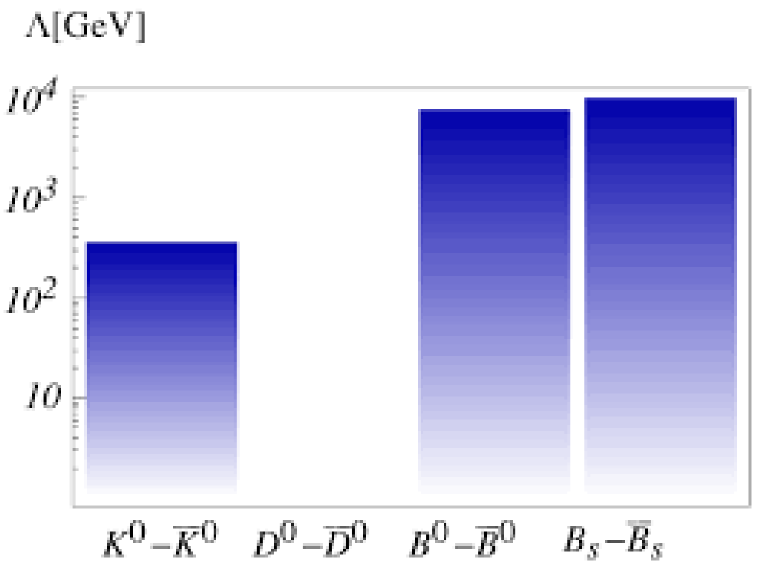
Rare (and some not so rare) decays

Kaon physics

- SM amplitudes most suppressed in kaons
  - Best NP sensitivity
  - Plots for ΔF=2, but also true for rare decays
    - Kaon ΔF=2 sensitivity limitation from lattice – great recent progress (e.g. PRL 115 (2015) 212001)

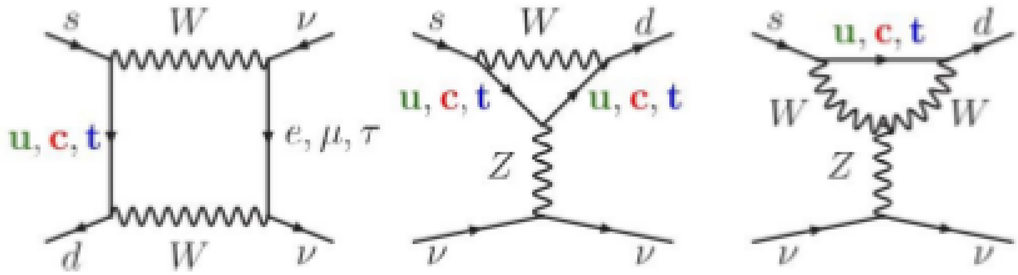
- Particularly interesting in MFV models
  - Same flavour suppression as SM





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

- FCNC loop processes: s→d coupling and highest CKM suppression



- Very clean theoretically: Short distance contribution. No hadronic uncertainties.
- SM predictions [Buras et al. arXiv:1503.02693], [Brod, Gorbahn, Stamou, Phys. Rev.D 83, 034030 (2011)]

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30)\cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (8.4 \pm 1.0)\cdot 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05)\cdot 10^{-11} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6)\cdot 10^{-11}$$

- Experiments:

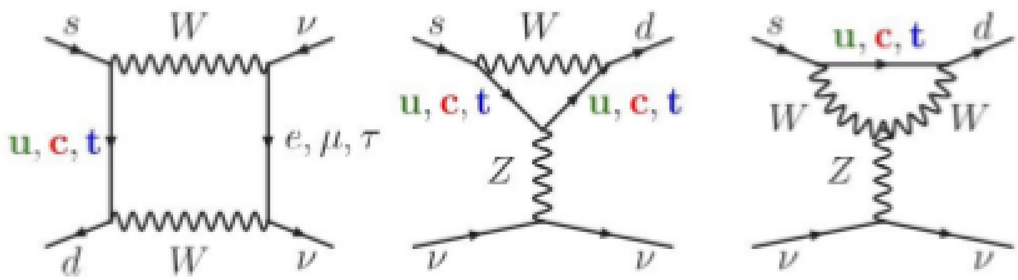
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$ Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)

$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}$ (90% C. L.) Phys. Rev. D 81, 072004 (2010)

Slide by G. Ruggiero, Moriond EW 2016

The holy grail of kaon physics: $K \rightarrow \pi\nu\bar{\nu}$

- FCNC loop processes: s→d coupling and highest CKM suppression



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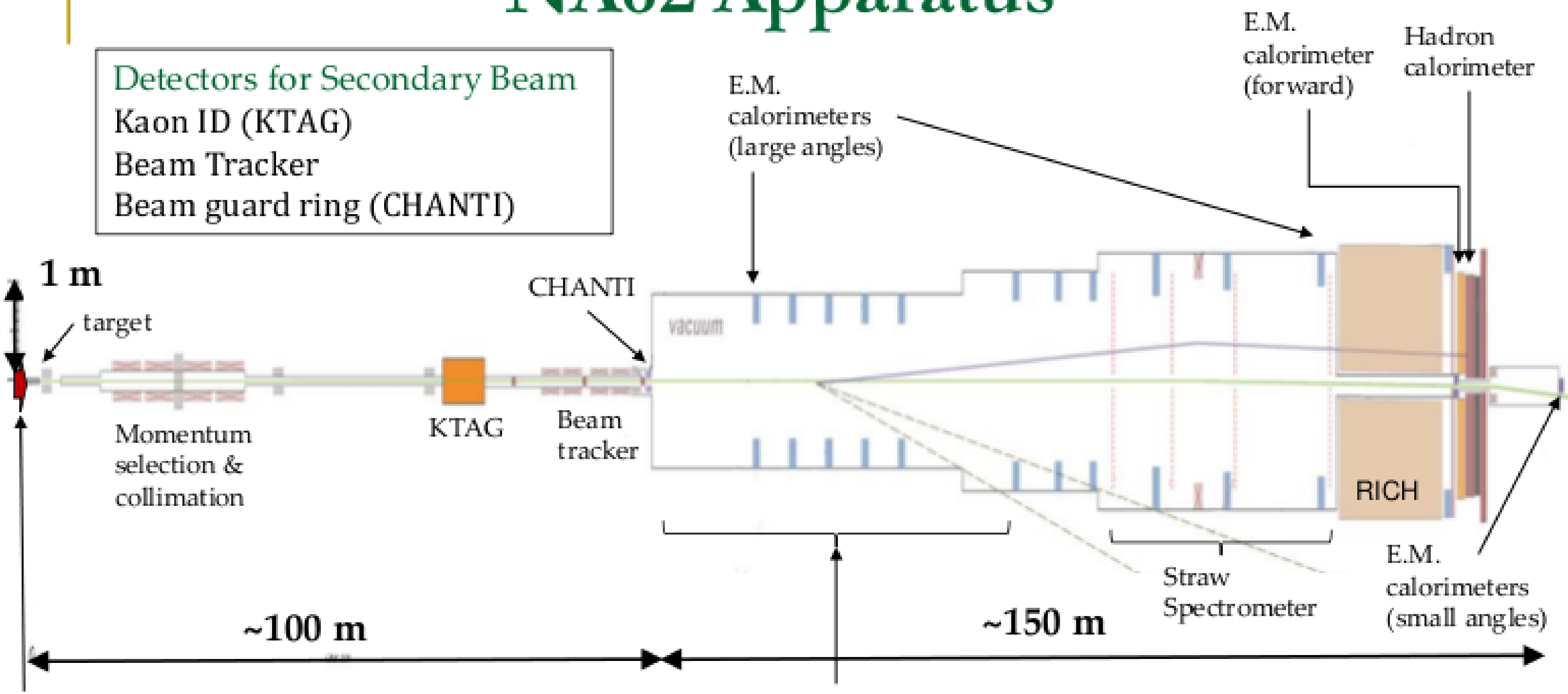
- Future experiments

$\mathrm{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ NA62 @ CERN: aim for ~10% BF measurement

$\mathrm{BR}(K_L \rightarrow \pi^0 \nu\bar{\nu})$ K0T0 @ J-PARC: aim for observation at SM BF

NA62 Apparatus

Detectors for Secondary Beam
Kaon ID (KTAG)
Beam Tracker
Beam guard ring (CHANTI)



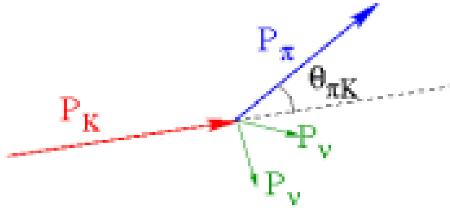
SPS proton	Secondary Beam	Kaon Decay
400 GeV	75 GeV/c, $\Delta p/p \sim 1\%$	~5 MHz
10^{12} p/s	X,Y Divergence < 100 μrad	$4.5 \times 10^{12}/year$
3.5 s spill	K(6%), π(70%), p(23%)	60 m length
	Total rate: 750 MHz	10^{-6} mbar vacuum
	Beam size: 6.0 × 2.7 cm²	

Detectors for decay products
Charged particle tracking
Charged particle time stamping
Photon detection
Particle ID

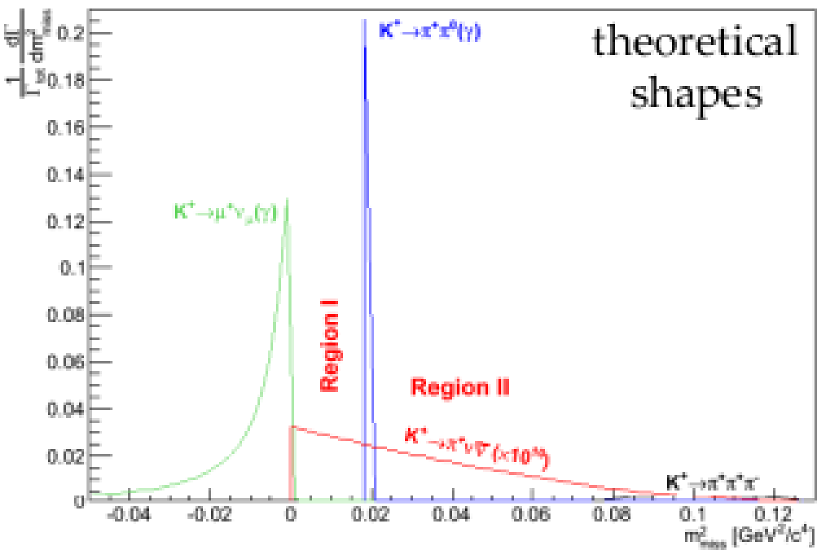
Slide by G. Ruggiero, Moriond EW 2016

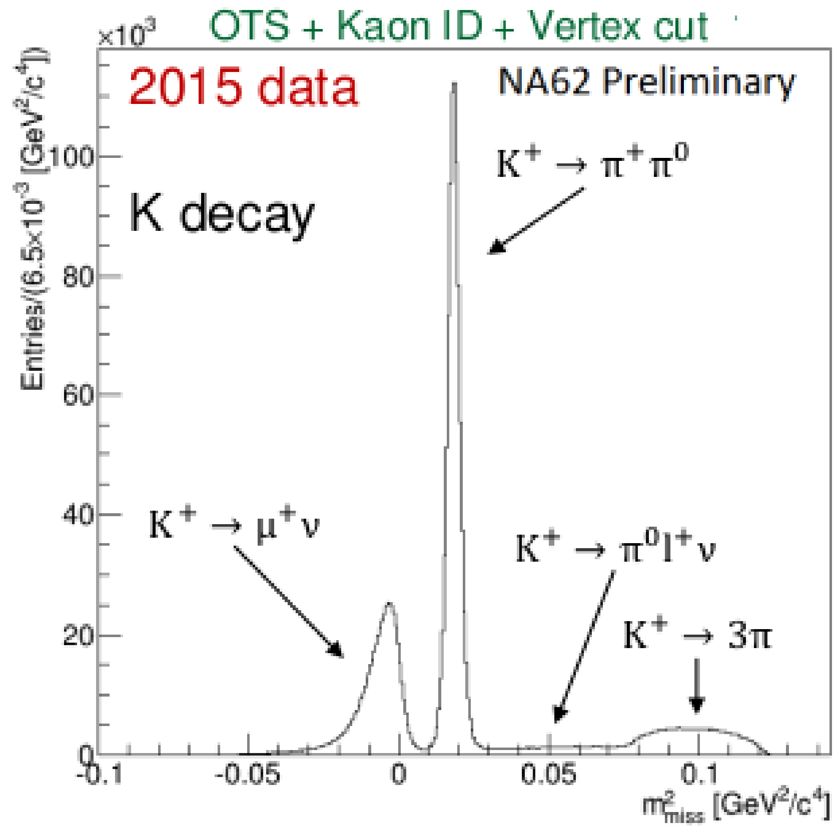
Scheme for $K^+ \to \pi^+ \nu \bar{\nu}$ Analysis

- Signal

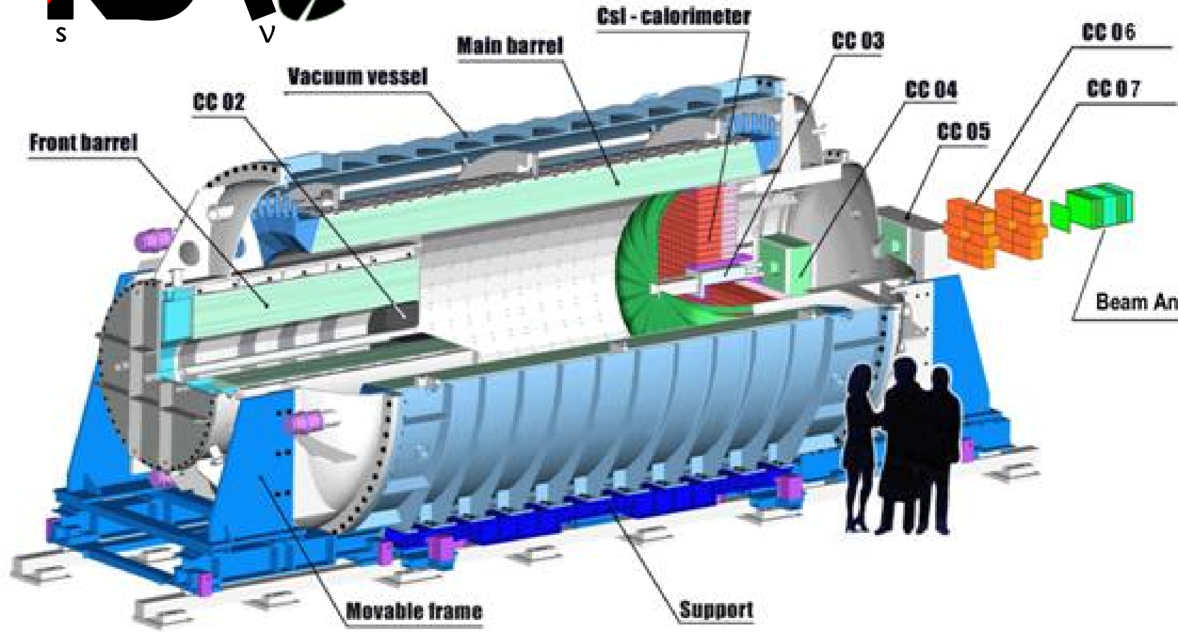


- Background: K⁺ decay modes; beam activity
- Kinematics: $m^2_{miss} = (P_K - P_{\pi^+})^2$

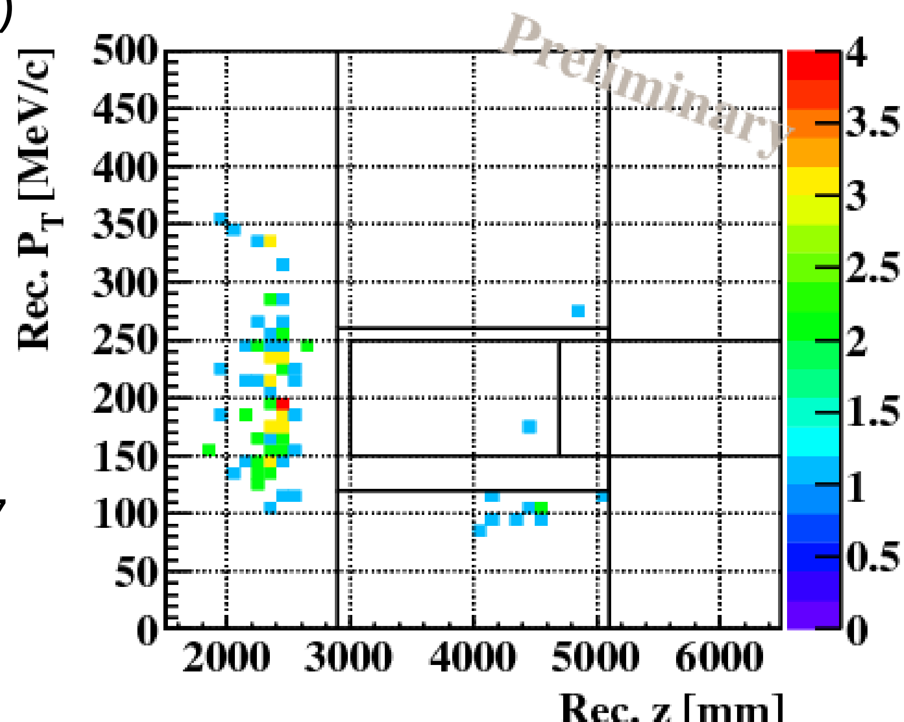




- Resolution close to design
- Further background suppression from downstream particle identification and photon vetoes
- Data-taking continues in 2016



- 1 event found in signal box (2013 data)
  - 0.36 ± 0.16 expected
- Main background from hadronic interactions
  - Significant improvements in background rejection obtained
- Much increased (>5x) data sample in 2015; more in 2016/7
  - Reach Grossman-Nir bound by 2017



Details in talk by H. Nanjo, KEKFF 2015

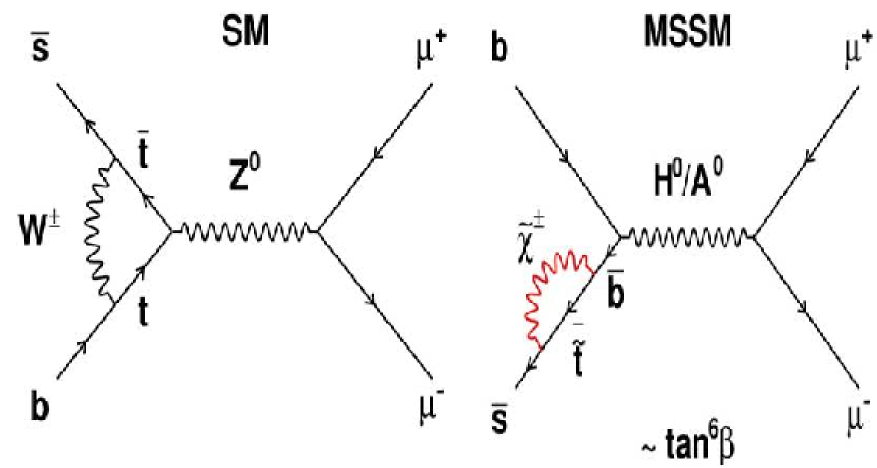
$B_s \to \mu^+\mu^-$

Nature 522 (2015) 68

Killer app. for new physics discovery

Very rare in Standard Model due to
- absence of tree-level FCNC
- helicity suppression
- CKM suppression

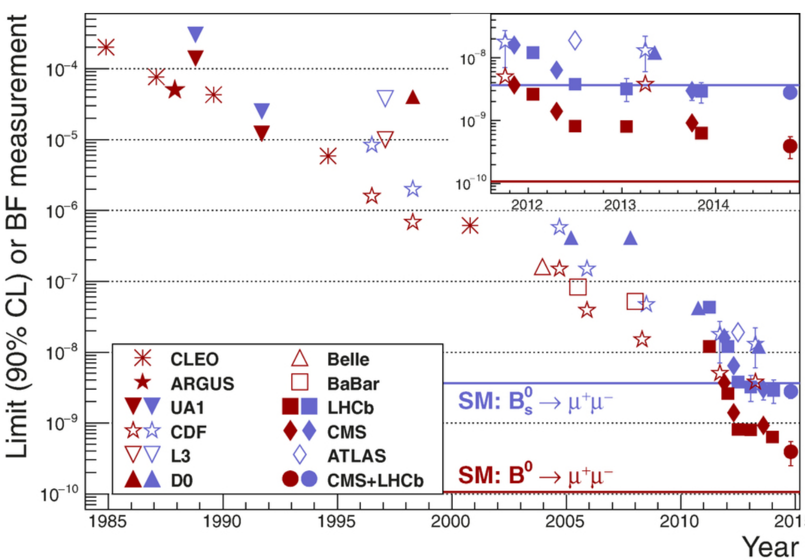
… all features which are not necessarily reproduced in extended models



$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = (3.66 \pm 0.23) \times 10^{-9}$

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

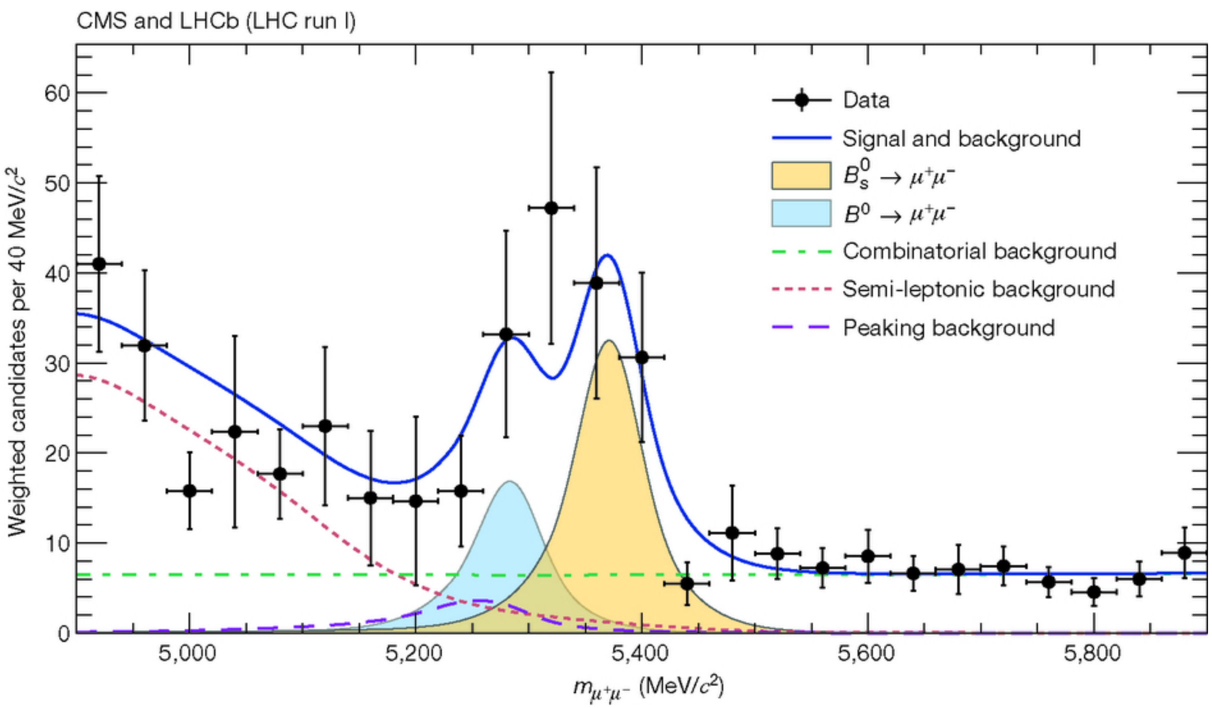
Intensively searched for over 30 years!



Tim Gershon
Precision measurements

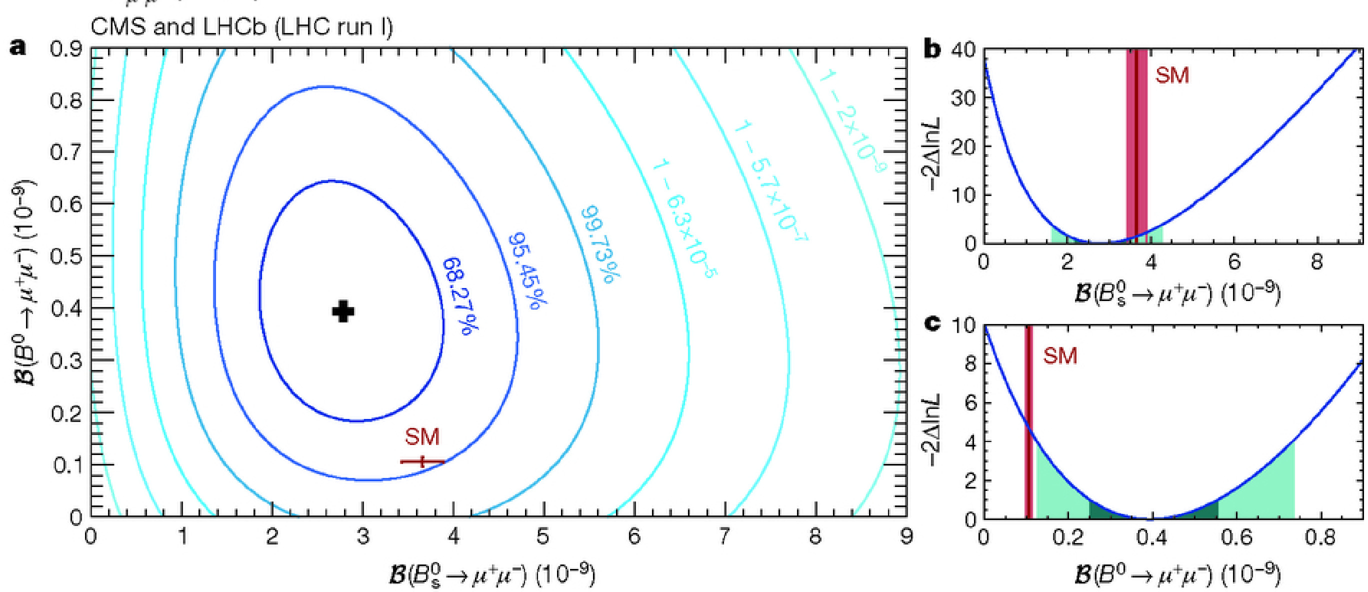
$B_s \to \mu^+\mu^-$

Nature 522 (2015) 68



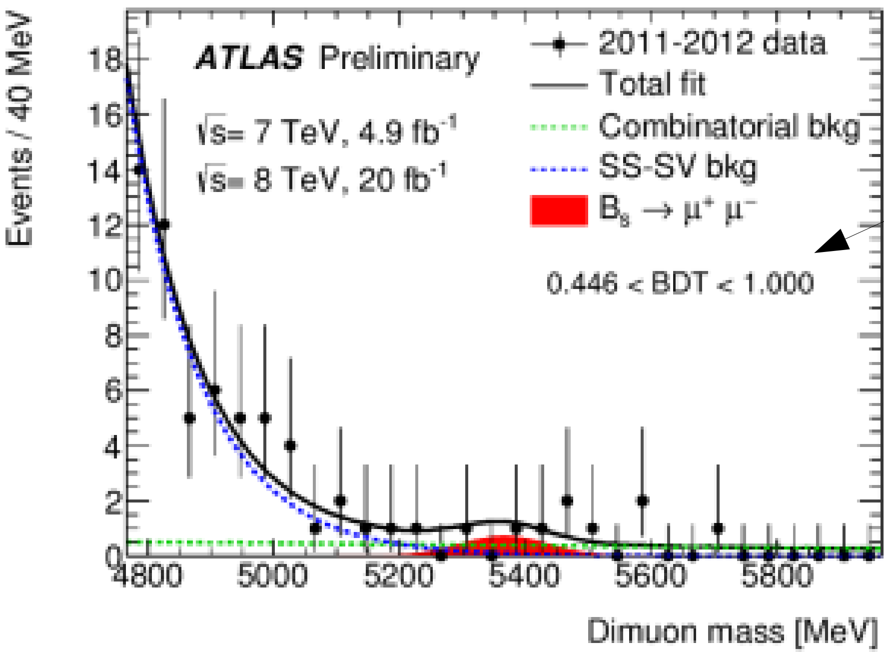
Combination of CMS and LHCb data results in first observation of $B_s \to \mu^+\mu^-$ and first evidence for $B^0 \to \mu^+\mu^-$

Results consistent with SM at 2σ level



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

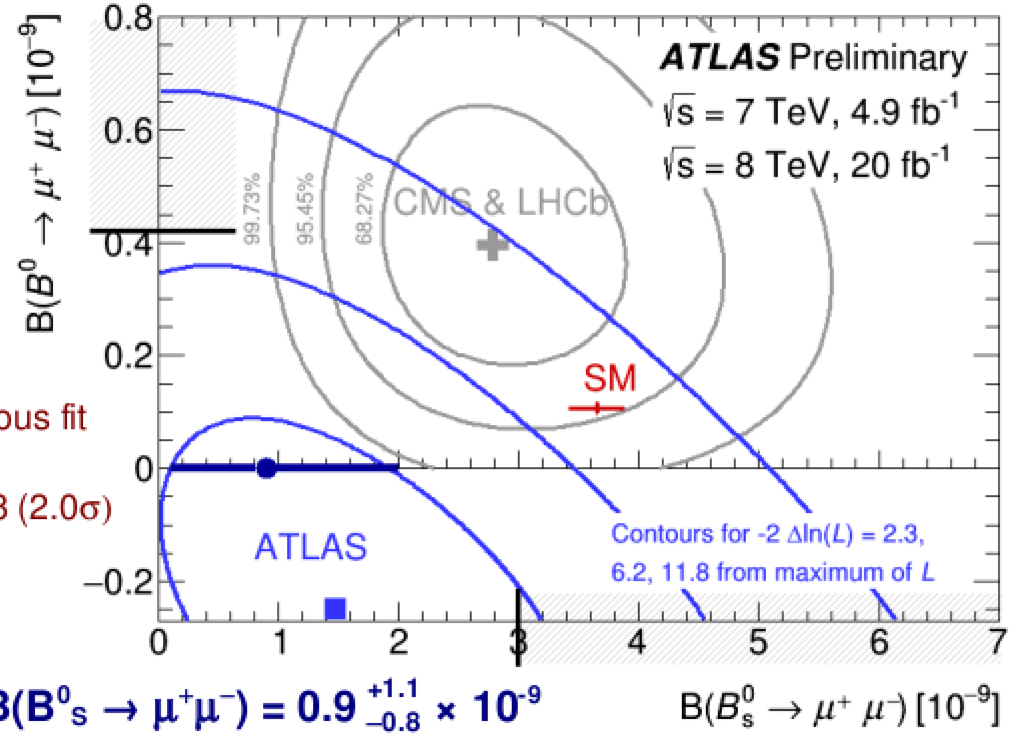
ATLAS preliminary
Moriond 2016



Cleanest of 3 BDT bins

Able to distinguish B^0 and $B_s^{\ 0}$ peaks

$B(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ at 95% CL



compatibility
of the simultaneous fit
with the SM:
p-value = 0.048 (2.0σ)

$B(B^0_s \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$

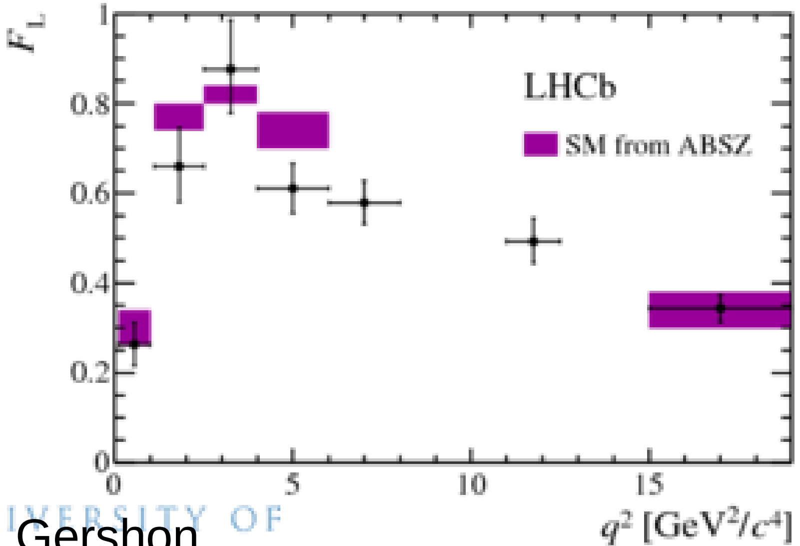
Sensitivity comparable to CMS and LHCb

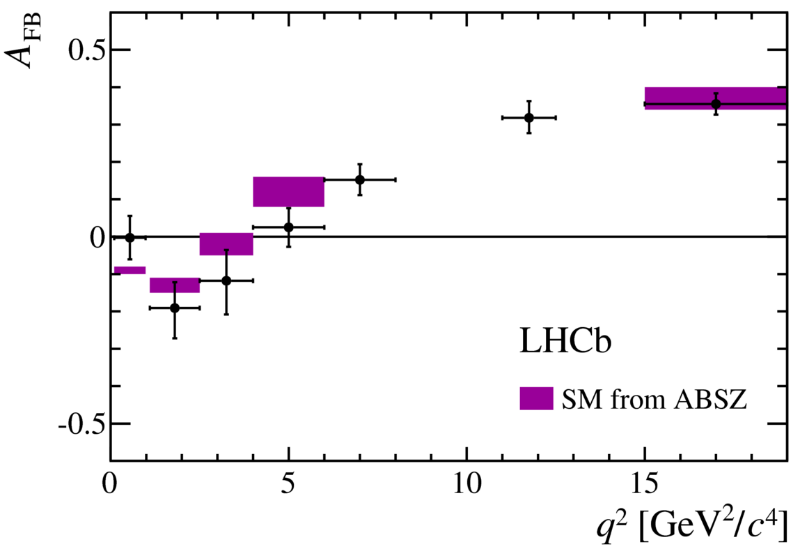
One to watch in Run 2

Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104

- $B^0 \rightarrow K^{*0}\mu^+\mu^-$ provides superb laboratory to search for new physics in $b \rightarrow sl^+l^-$ FCNC processes
  - rates, angular distributions and asymmetries sensitive to NP
  - experimentally clean signature
  - many kinematic variables … with clean theoretical predictions
- Full set of observables measured – only a subset shown



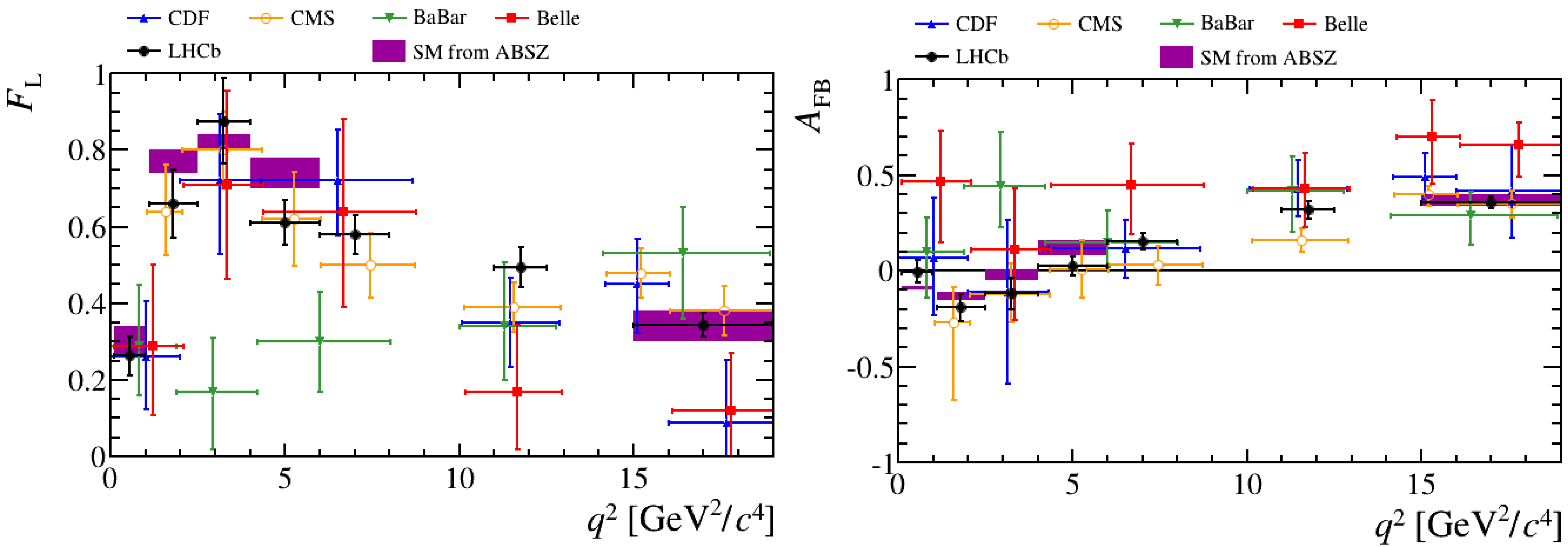


Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104

Comparison to other experiments
(until now, only LHCb does a full angular analysis)

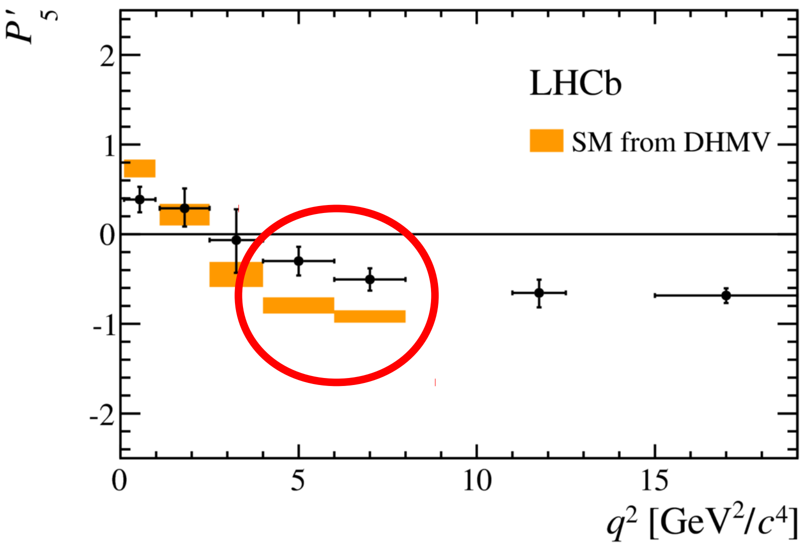
CMS (PLB 753 (2016) 424) quite competitive,
especially at high q^2



Tension with SM in the P_5' observable

JHEP 02 (2016) 104

- Dimuon pair is predominantly spin-1
  - either vector (V) or axial-vector (A)
- There are 6 non-negligible amplitudes
  - 3 for VV and 3 for VA ($K^{*0}\mu^+\mu^-$)
  - expressed as $A^{L,R}_{0,\perp,\parallel}$ (transversity basis)



- P_5' related to difference between relative phase of longitudinal (0) and perpendicularly ($\perp$) polarised amplitudes for VV and VA
  - constructed so as to minimise form-factor uncertainties

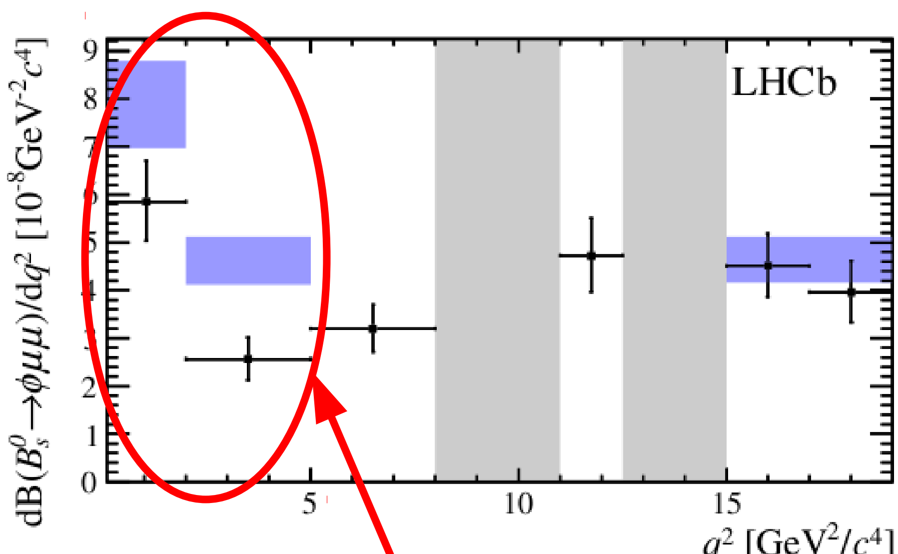
$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^{\mathrm{L}}A_\perp^{\mathrm{L}*} - A_0^{\mathrm{R}}A_\perp^{\mathrm{R}*}\right)}{\sqrt{\left(|A_0^{\mathrm{L}}|^2 + |A_0^{\mathrm{R}}|^2\right)\left(|A_\parallel^{\mathrm{L}}|^2 + |A_\parallel^{\mathrm{R}}|^2 + |A_\perp^{\mathrm{L}}|^2 + |A_\perp^{\mathrm{R}}|^2\right)}}$$

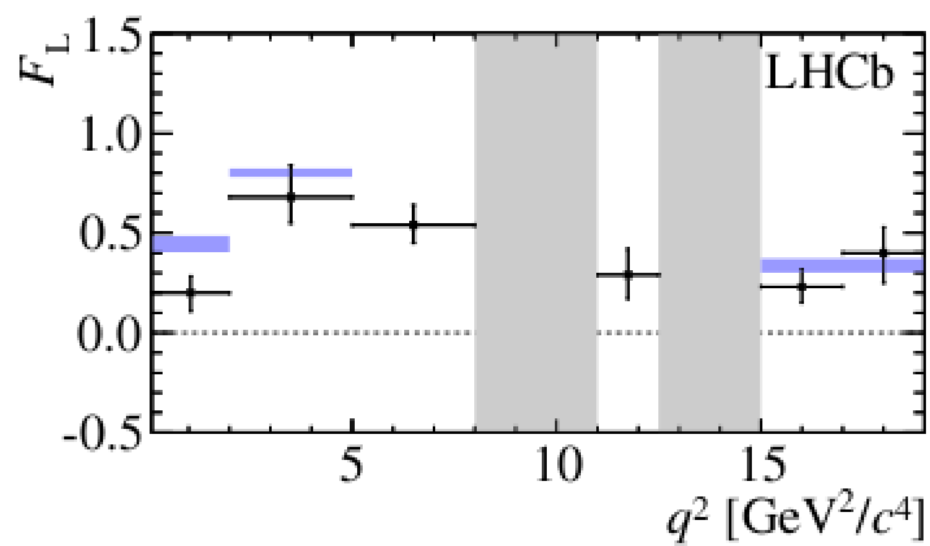
Sensitive to NP in V or A couplings (Wilson coefficients $C_9^{(\prime)}$ & $C_{10}^{(\prime)}$)

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

JHEP 09 (2015) 179

- Full angular analysis performed
- Not self-tagging → complementarity to $K^{*0}\mu^+\mu^-$
  - only a subset of many observables shown





Tension in branching fraction, but angular observables consistent with SM

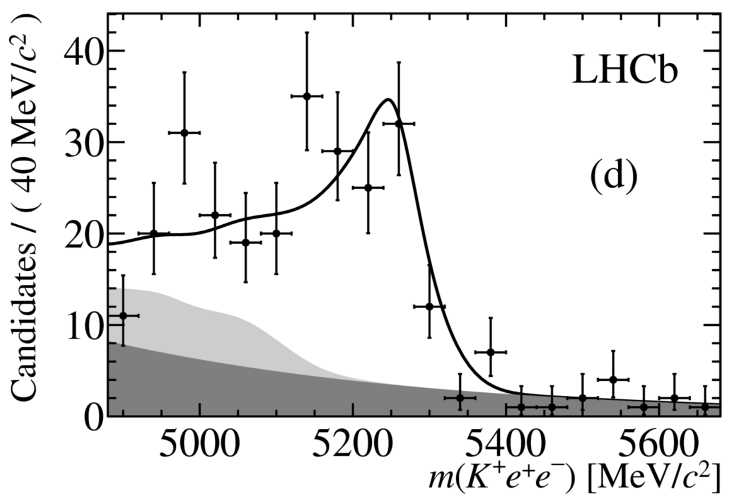
Consistent picture in $b \to sl^+l^-$ branching fractions

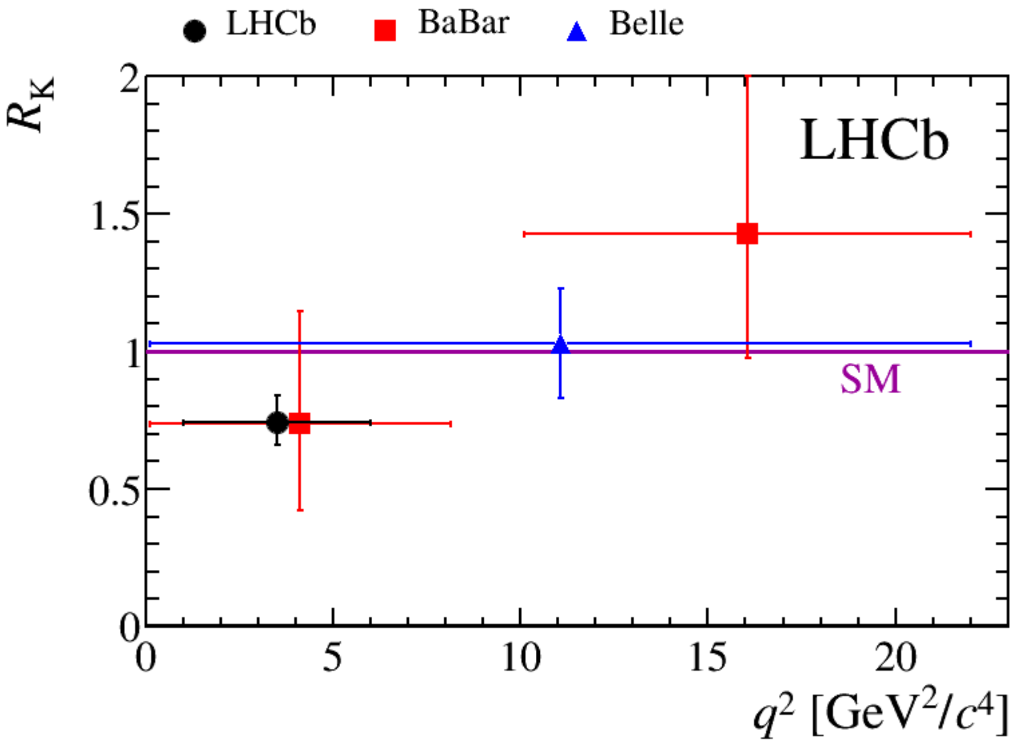
Lepton universality – R_K

PRL 113 (2014) 151601

Deficit of $B \to K\mu^+\mu^-$ compared to expectation
also seen in $K\mu^+\mu^-/Ke^+e^-$ ratio (R_K)

Example mass fit for Ke^+e^-
Note huge tail due to energy loss





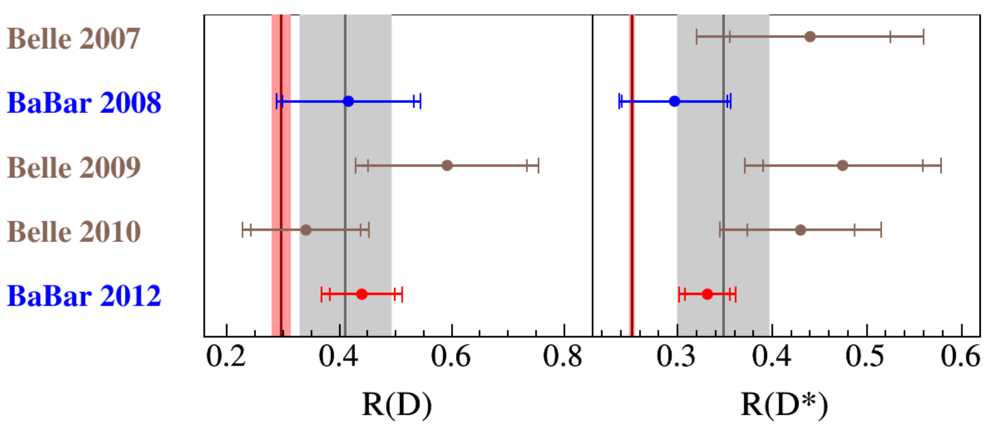
$$R_K(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$$

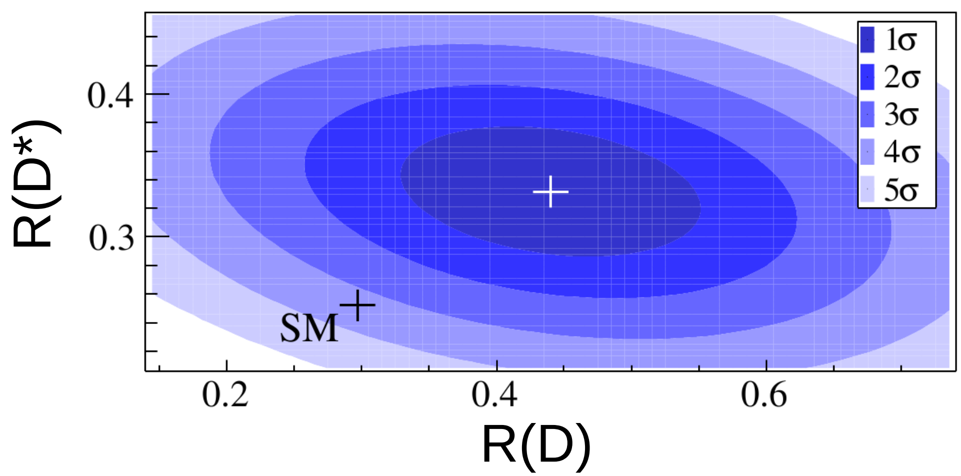
Only 2.6σ from SM but suggestive

$B \to D^{(*)}\tau\nu$

- Powerful channel to test lepton universality
  - ratios $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\mu\nu)$ could deviate from SM values, e.g. in models with charged Higgs
- Heightened interest in this area
  - anomalous results from BaBar
  - other hints of lepton universality violation, e.g. R_K , $H \to \tau\mu$

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

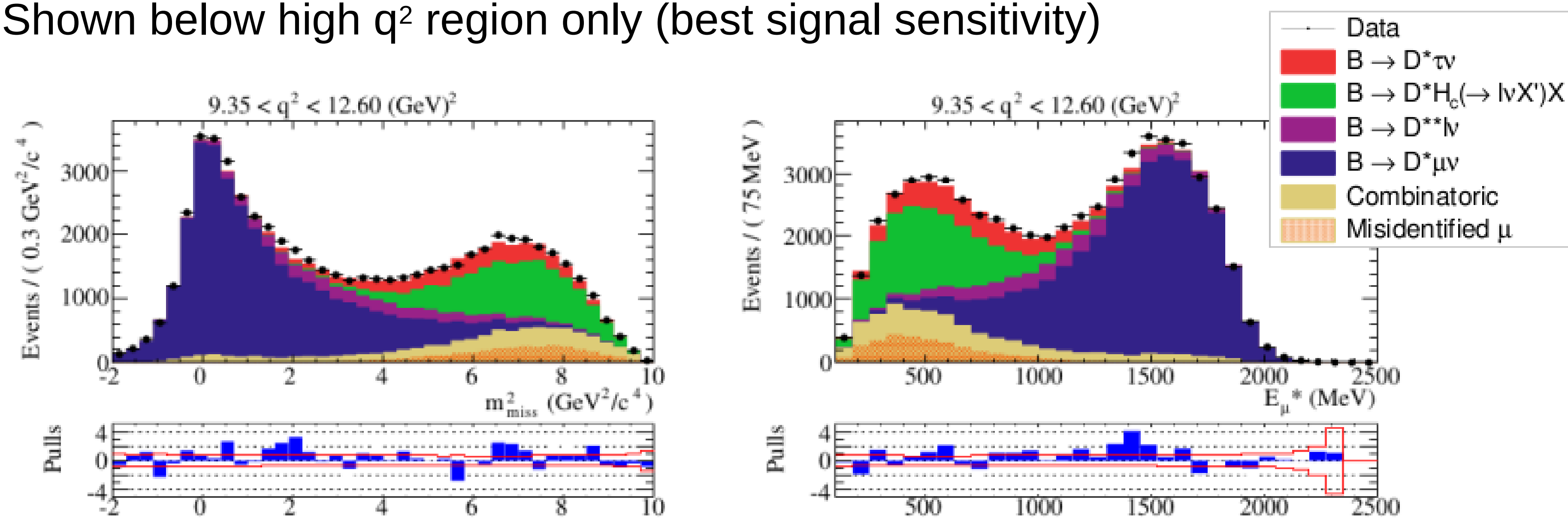




$B\to D^{*}\tau\nu$ at LHCb

PRL 115 (2015) 112001

- Identify $B\to D^{*}\tau\nu$, $D^{*}\to D\pi$, $D\to K\pi$, $\tau\to\mu\nu\bar{\nu}$
  - Similar kinematic reconstruction to $\Lambda_b\to p\mu\nu$
    - Assume $p_{B,z} = (p_{D^*} + p_\mu)_z$ to calculate $M_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$
  - Require significant B, D, τ flight distances & use isolation MVA
- Separate signal from background by fitting in M_{miss}^2, q^2 and E_μ
  - Shown below high q^2 region only (best signal sensitivity)

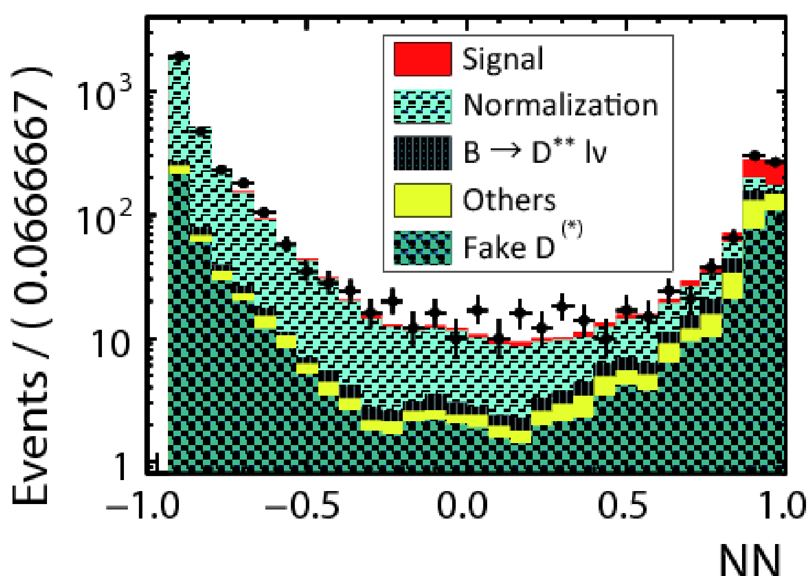


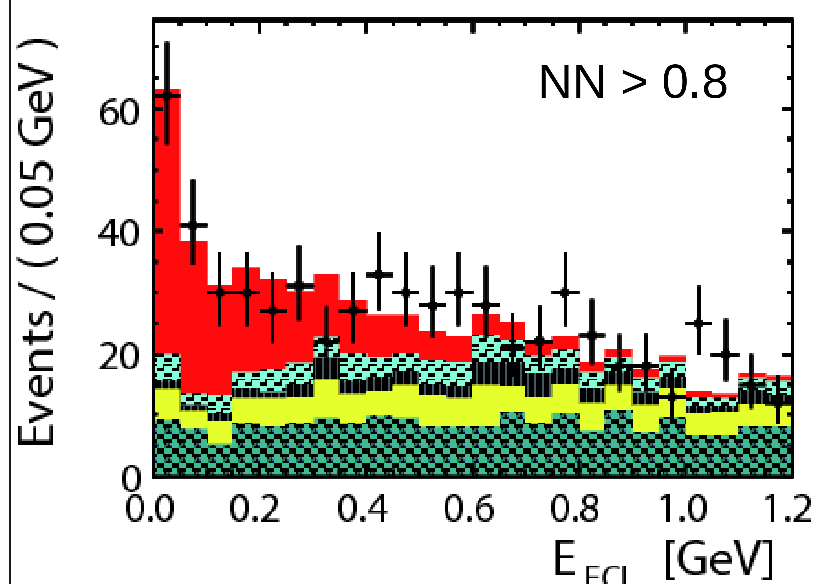
$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

B → D$^{(*)}$τν at Belle

PR D92 (2015) 072014
& arXiv:1603.06711

- Reconstruct one B in Υ(4S) → B$\overline{\text{B}}$ event
  - Either hadronic (PR D92 (2015) 072014) or semileptonic (arXiv:1603.06711) decay mode
    - First application of semileptonic tagging for B → D$^{(*)}$τν
  - Look for signal in the recoil

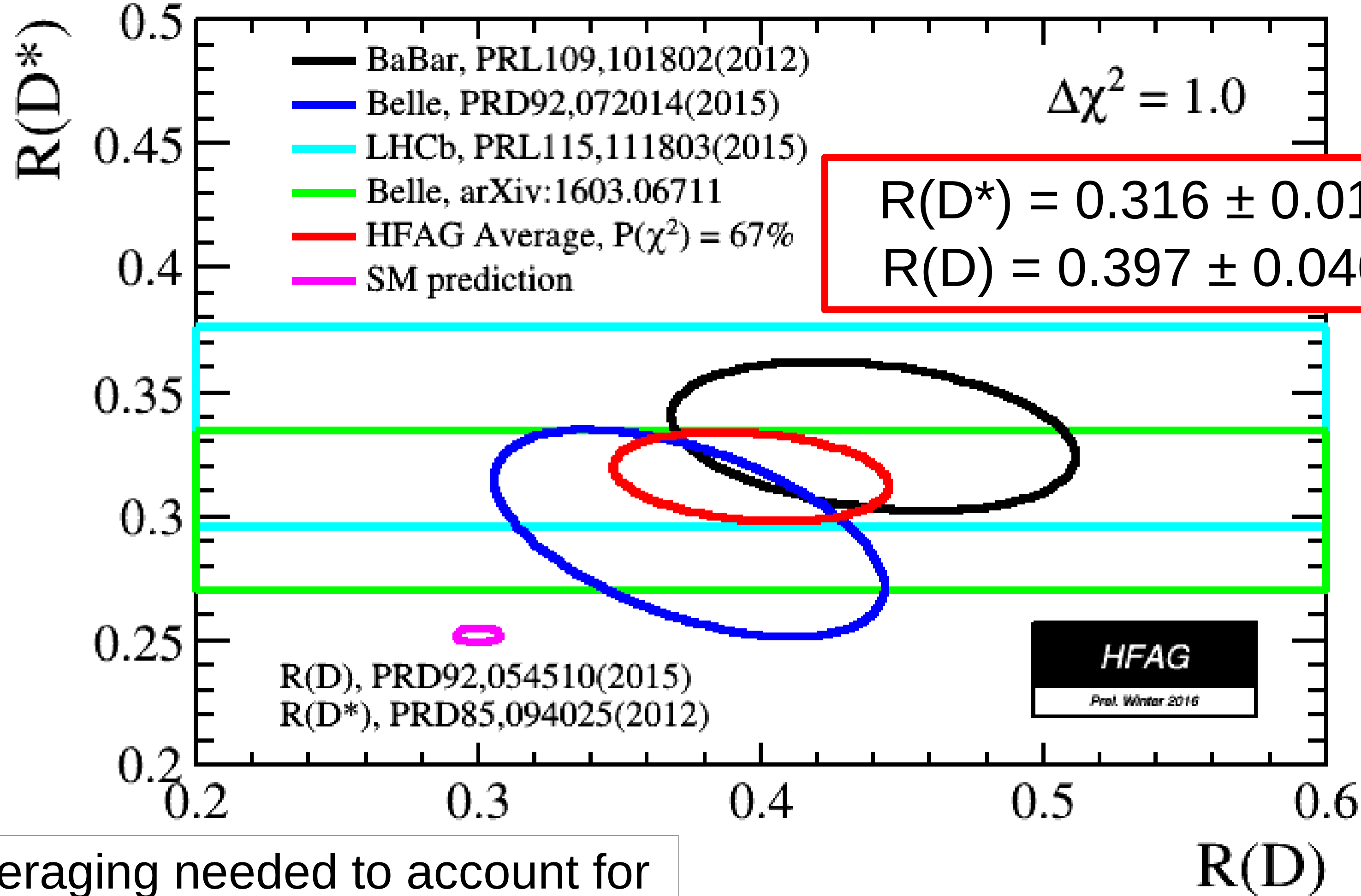




R(D*) = 0.302 ± 0.030 ± 0.011

$B \to D^{(*)}\tau\nu$

Tension with SM at 4.0σ



$R(D^*) = 0.316 \pm 0.016 \pm 0.010$
$R(D) = 0.397 \pm 0.040 \pm 0.028$

Careful averaging needed to account for statistical and systematic correlations

Summary

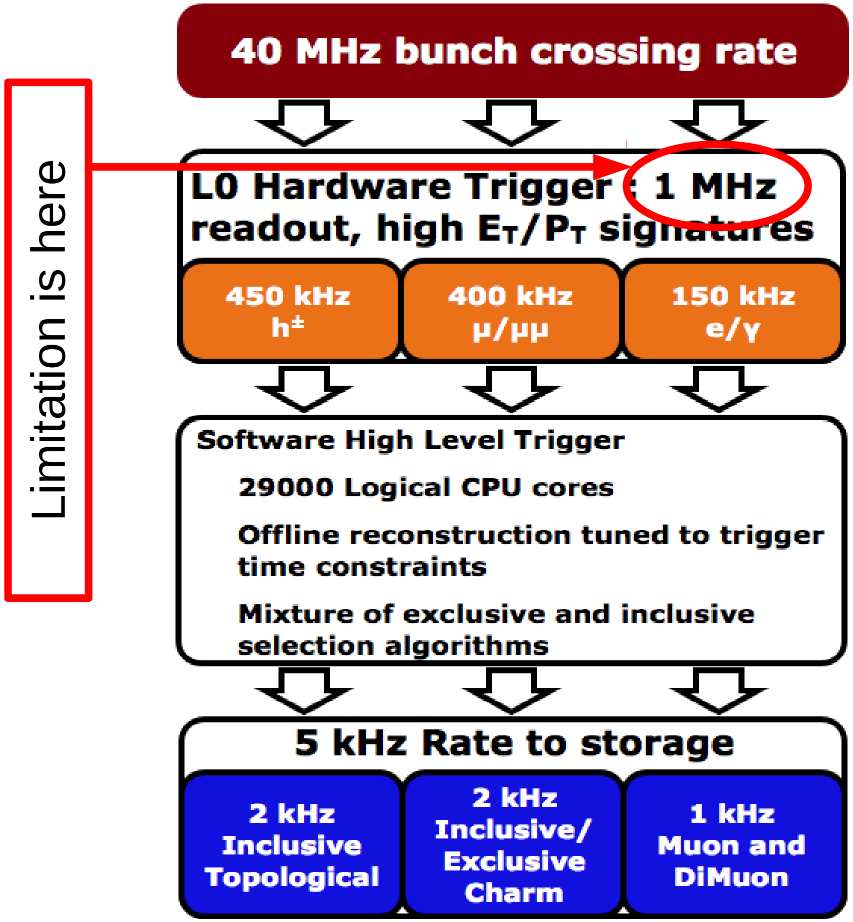
- Huge range of results in quark flavour physics
  - Impossible to cover everything – sorry for omissions
- Several interesting "tensions" to keep an eye on
  - Inclusive vs. exclusive $|V_{ub}|$ & CKM fit
  - Hints of lepton non-universality in R_K, R(D) & R(D*)
  - Rates in $b \rightarrow sl^+l^-$ & P_5'
- Much to look forward to
  - NA62 & KOTO
  - More results from LHC Run I & II (LHCb & ATLAS & CMS)
  - LHCb upgrade & Belle II


BACK UP!

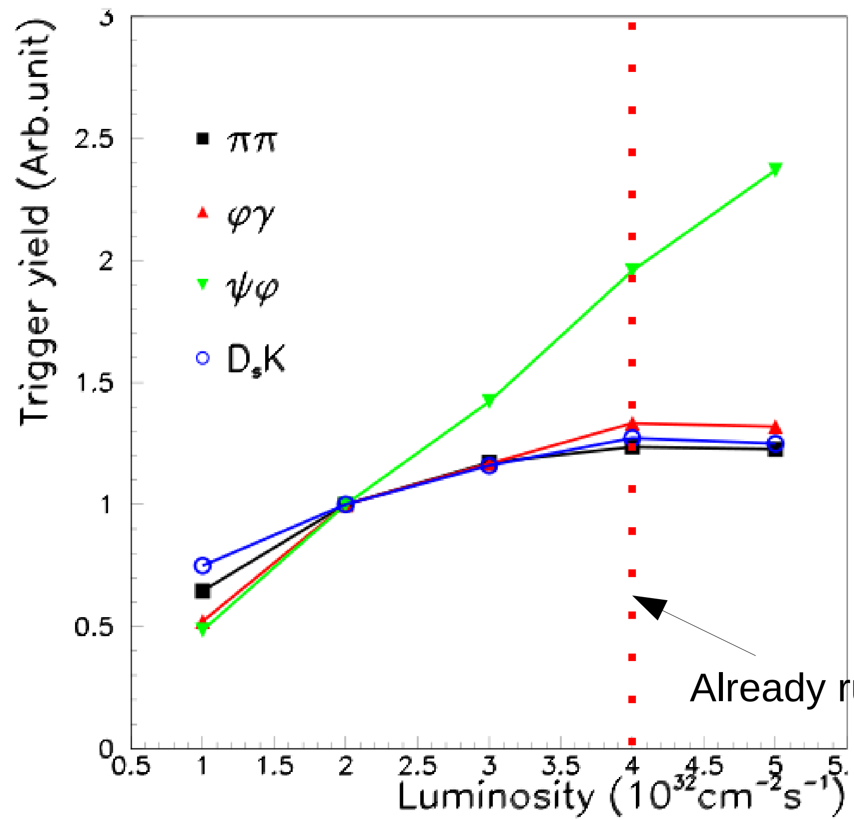
Beyond Run II – the LHCb Upgrade

- 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)
- Upgrade will be performed during LSII (now expected to be 2019-20)
  - Restart data taking in 2021 at instantaneous luminosity up to 2 $10^{33}/cm^2/s$
  - Upgrade detector qualified to accumulate 50/fb

LHC upgrade and the all important trigger

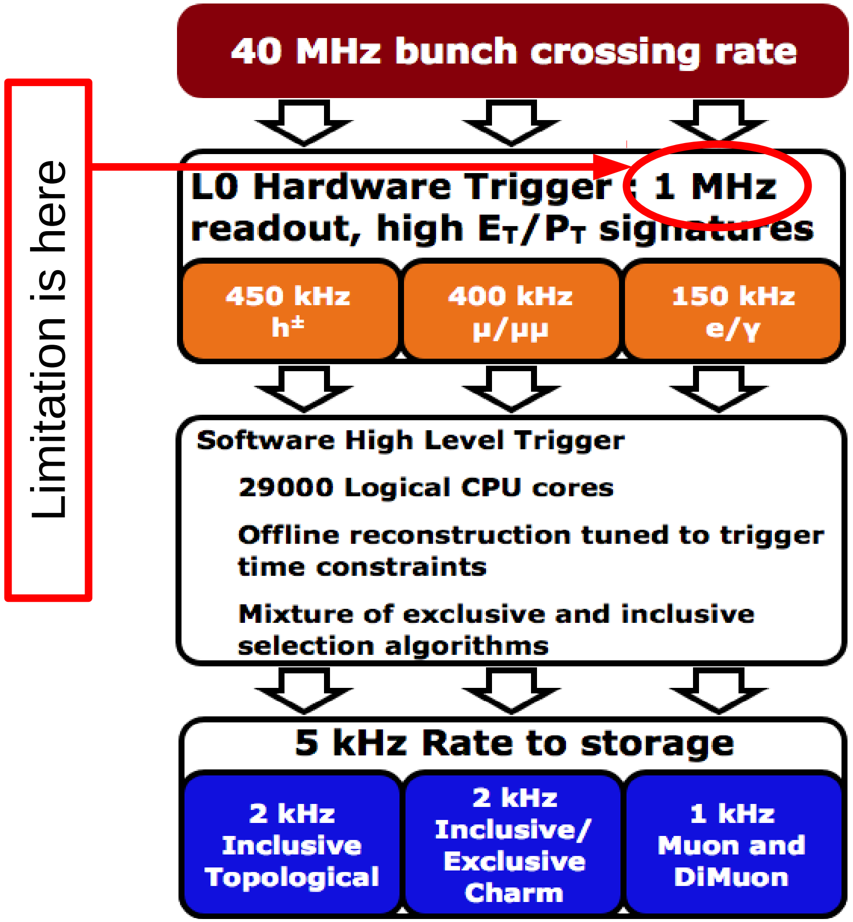


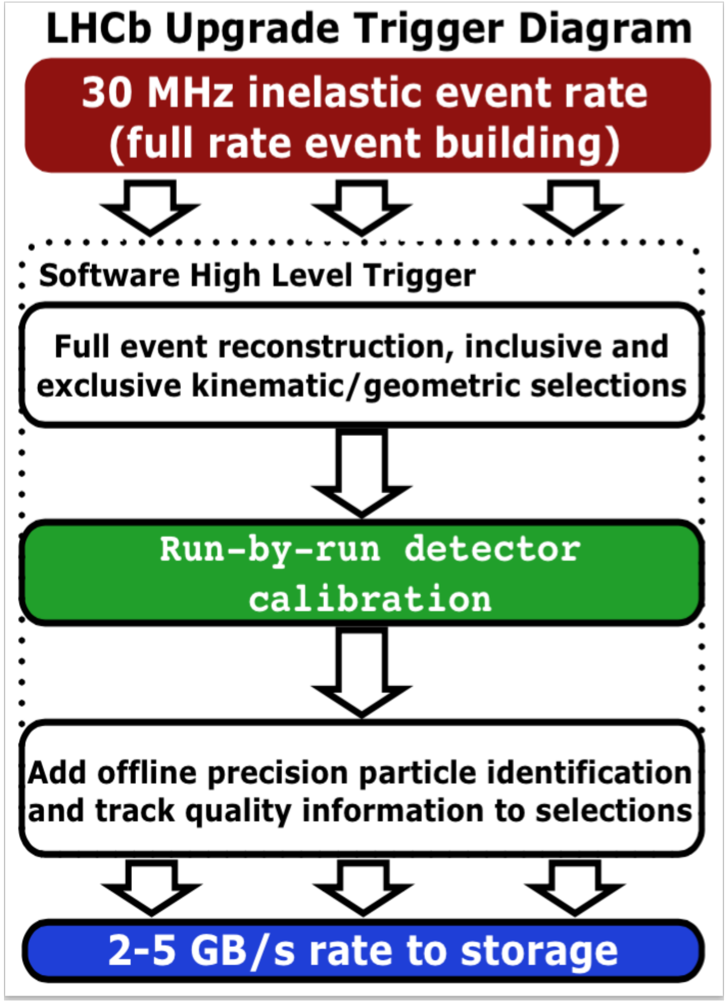
higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



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

LHC upgrade and the all important trigger

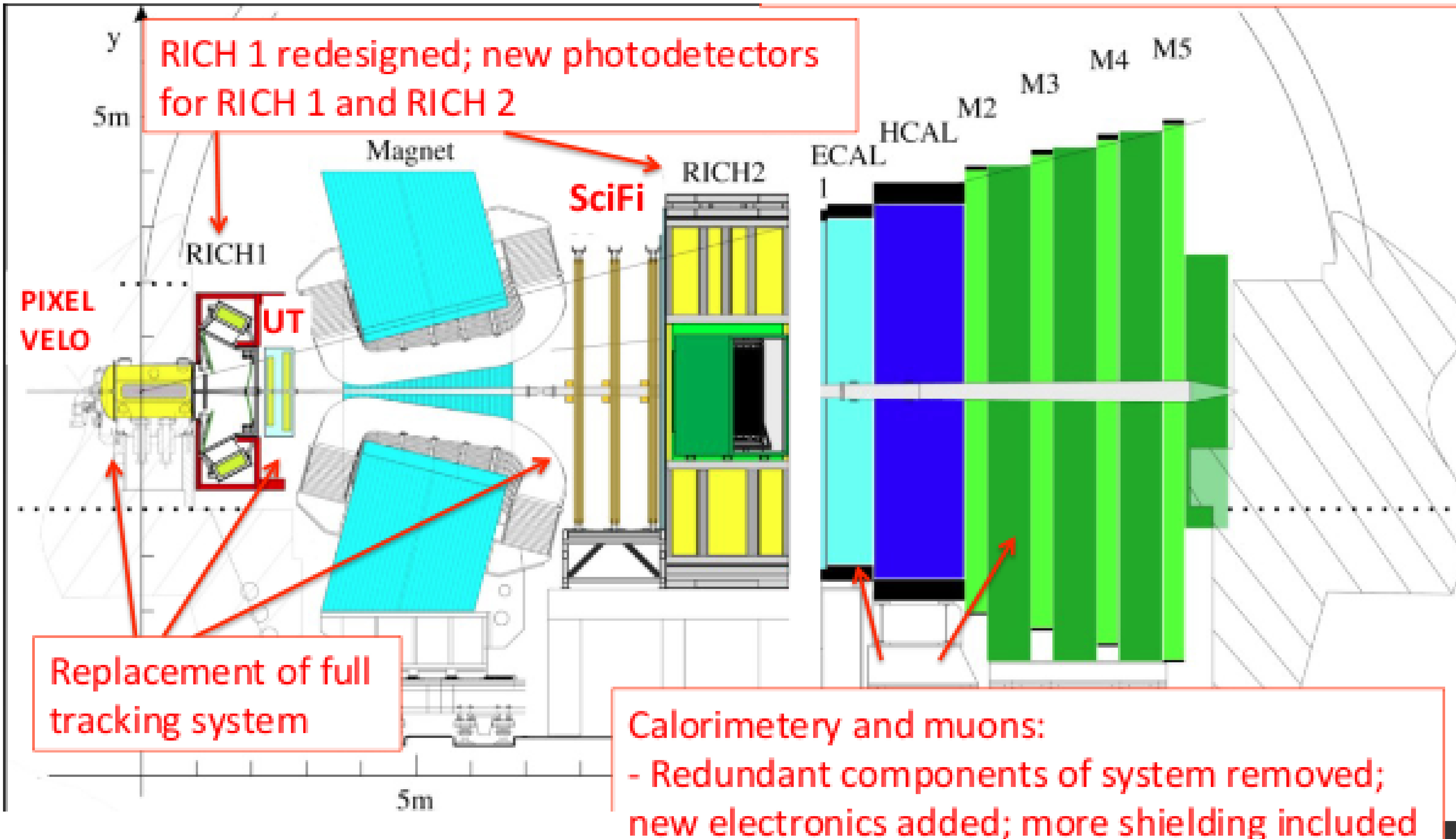




- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

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

LHCb detector upgrade



+ 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**	–