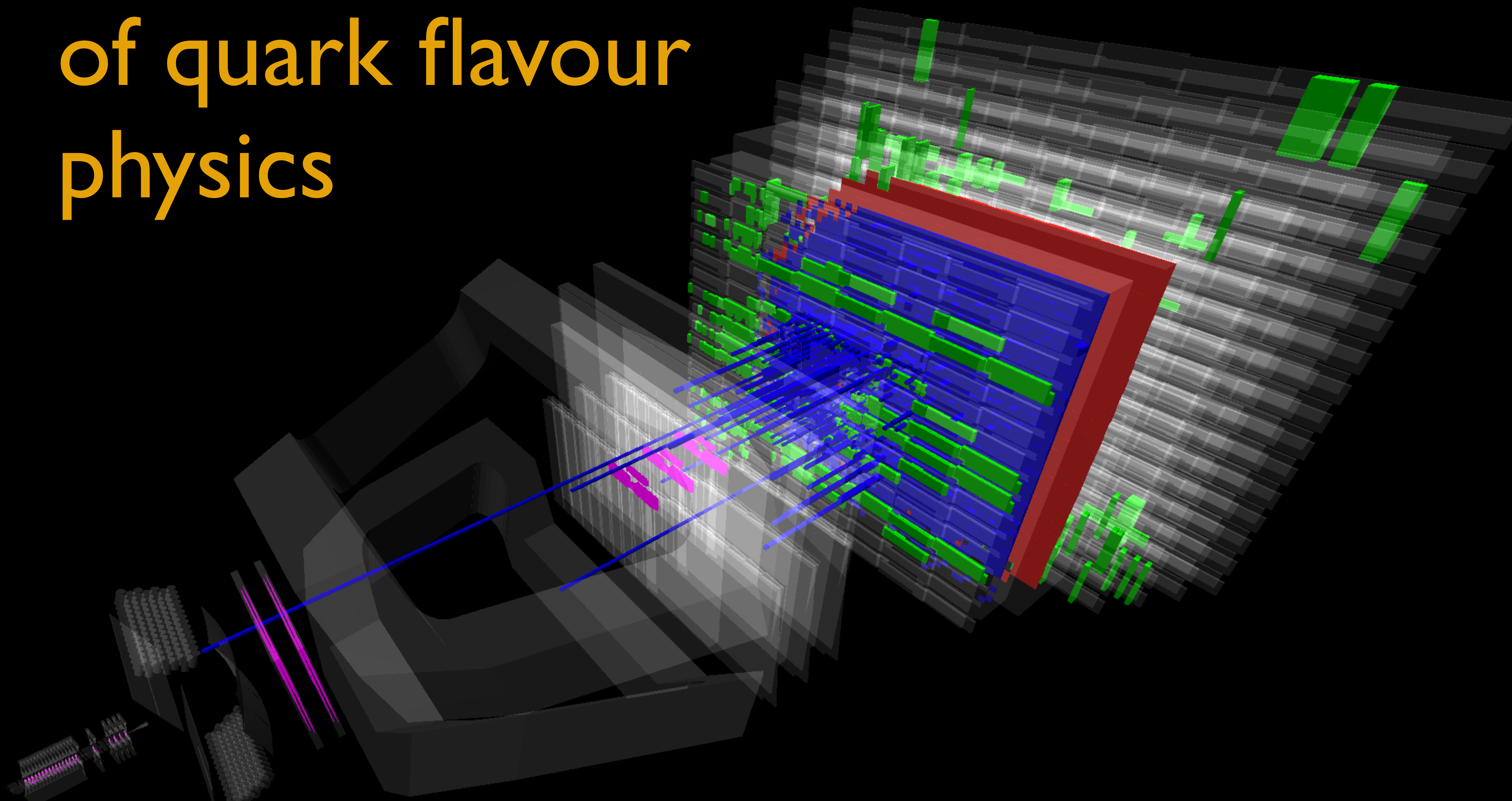
Recent results and prospects of quark flavour physics

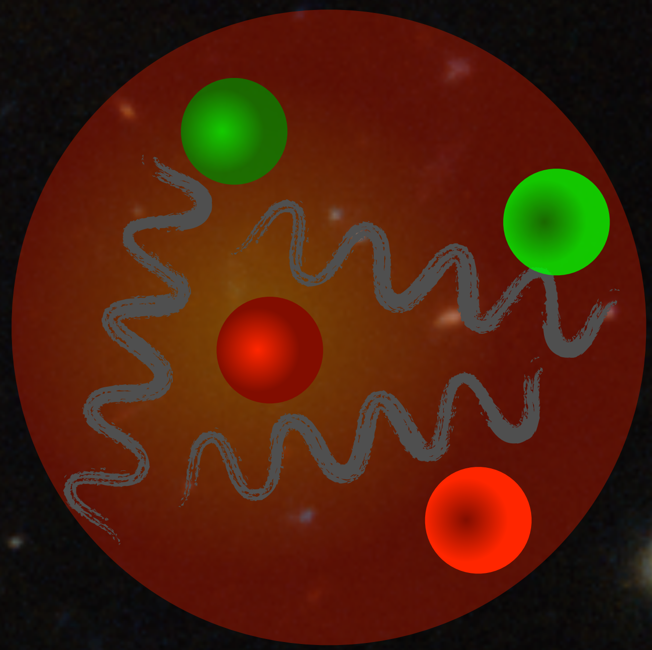


Marco Gersabeck (The University of Manchester)

Particle Physics Seminar, Liverpool, 3/6/2015

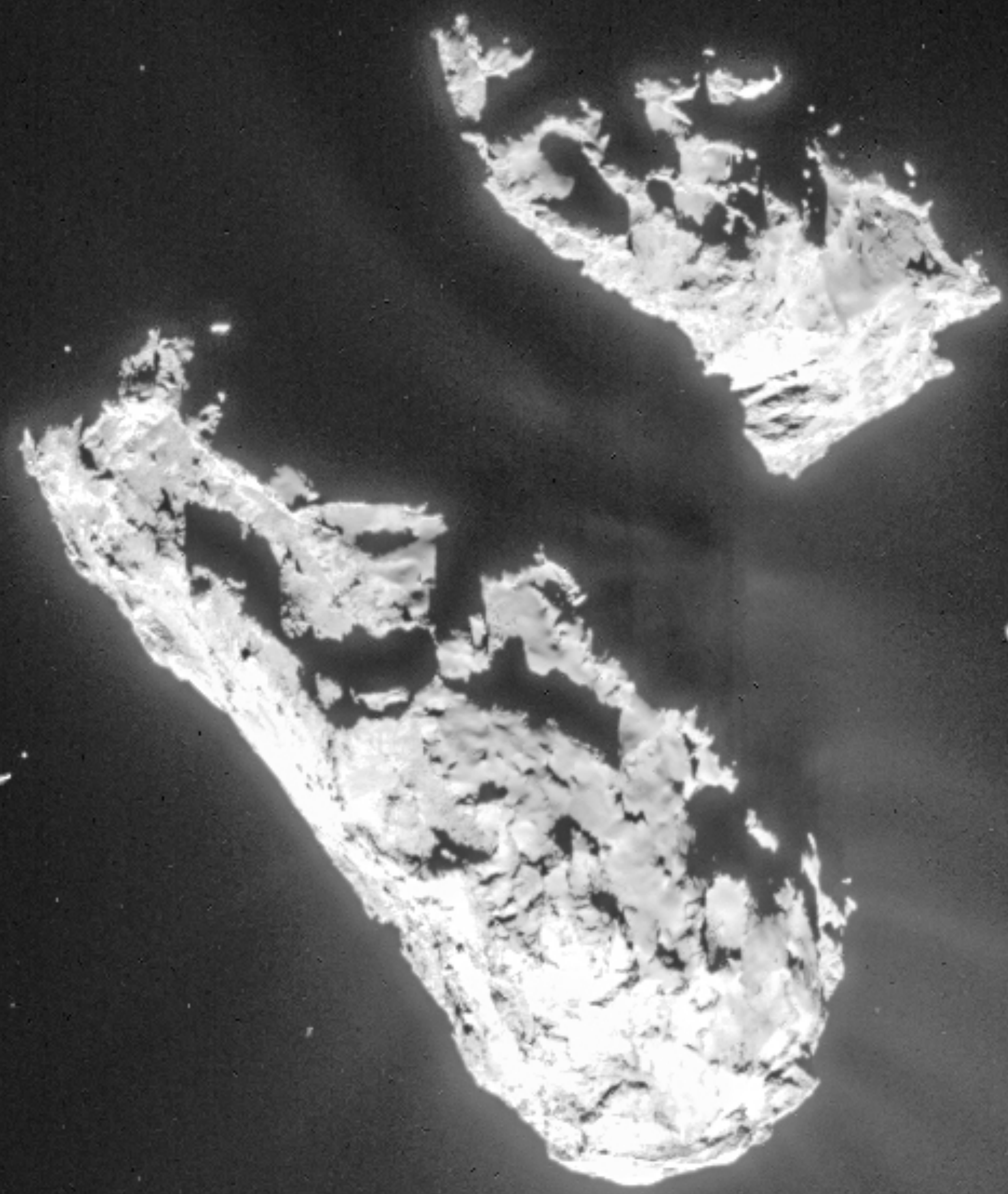
Two roads to discovery

New particles = New planets



ESA/Hubble

Direct searches

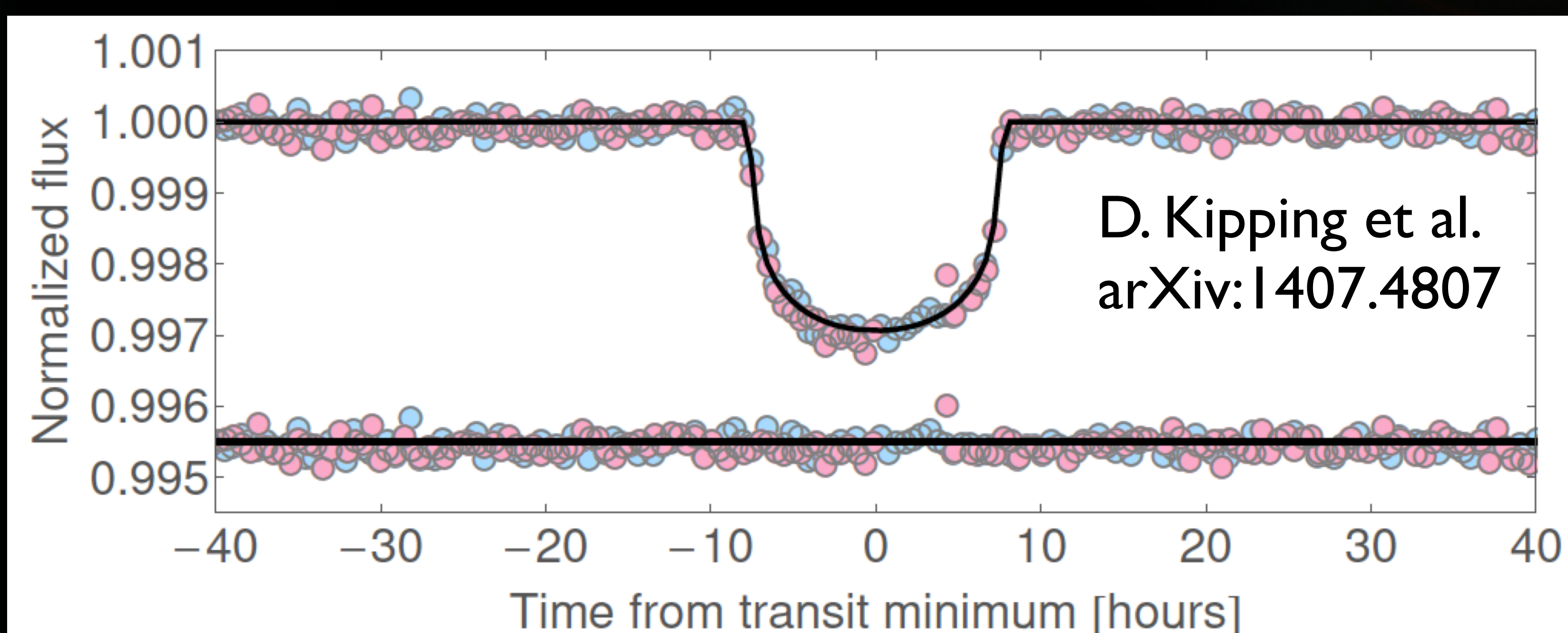


Reach limited by amount of fuel

ESA/Rosetta/NAVCAM

Indirect searches

Look for subtle deviations
in known processes



David A. Aguilar (CfA)

The University of Manchester

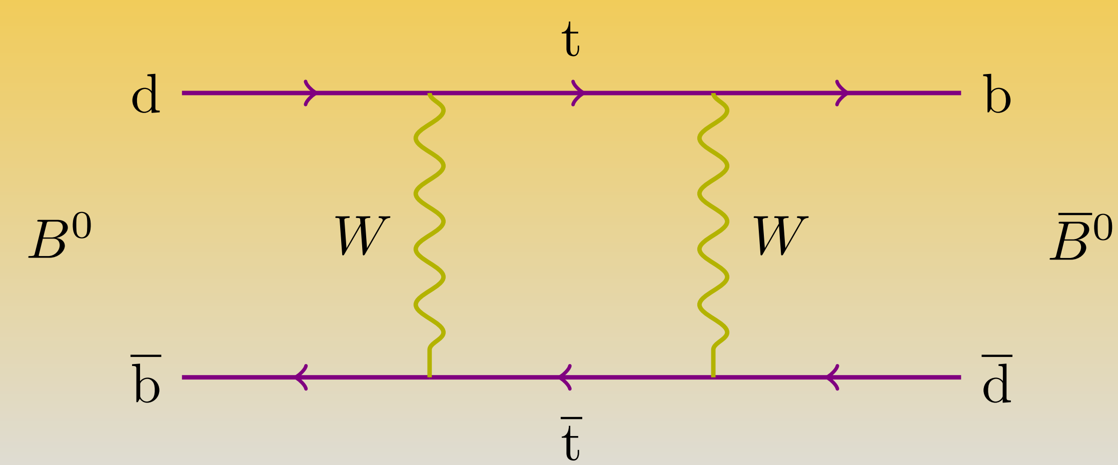
Flavour physics: Fast-tracking discoveries

- K^0-$\overline{K}^0$ mixing and smallness of $K^0 \rightarrow \mu^+\mu^-$
  - ➡ GIM mechanism predicts charm quark in 1970
- Kaon CP violation
  - ➡ KM mechanism predicts bottom and top quarks in 1973
    - Charm & bottom quarks discovered: 1974+1977
- B^0-$\overline{B}^0$ oscillations discovered in 1987
  - ➡ Requires m_{top} > 50 GeV to deactivate GIM cancellation
    - Top quark discovered: 1995

Flavour physics:

Fast-tracking discoveries

Then: ARGUS, 10^5 $B\overline{B}$ decays, probing 0.1 TeV
Now: LHCb, 10^{11} $B\overline{B}$ decays, probing 100 TeV



- K^0-$\overline{K}^0$ mixing
  - ➡ GIM mech
- Kaon CP vio
  - ➡ KM mecha
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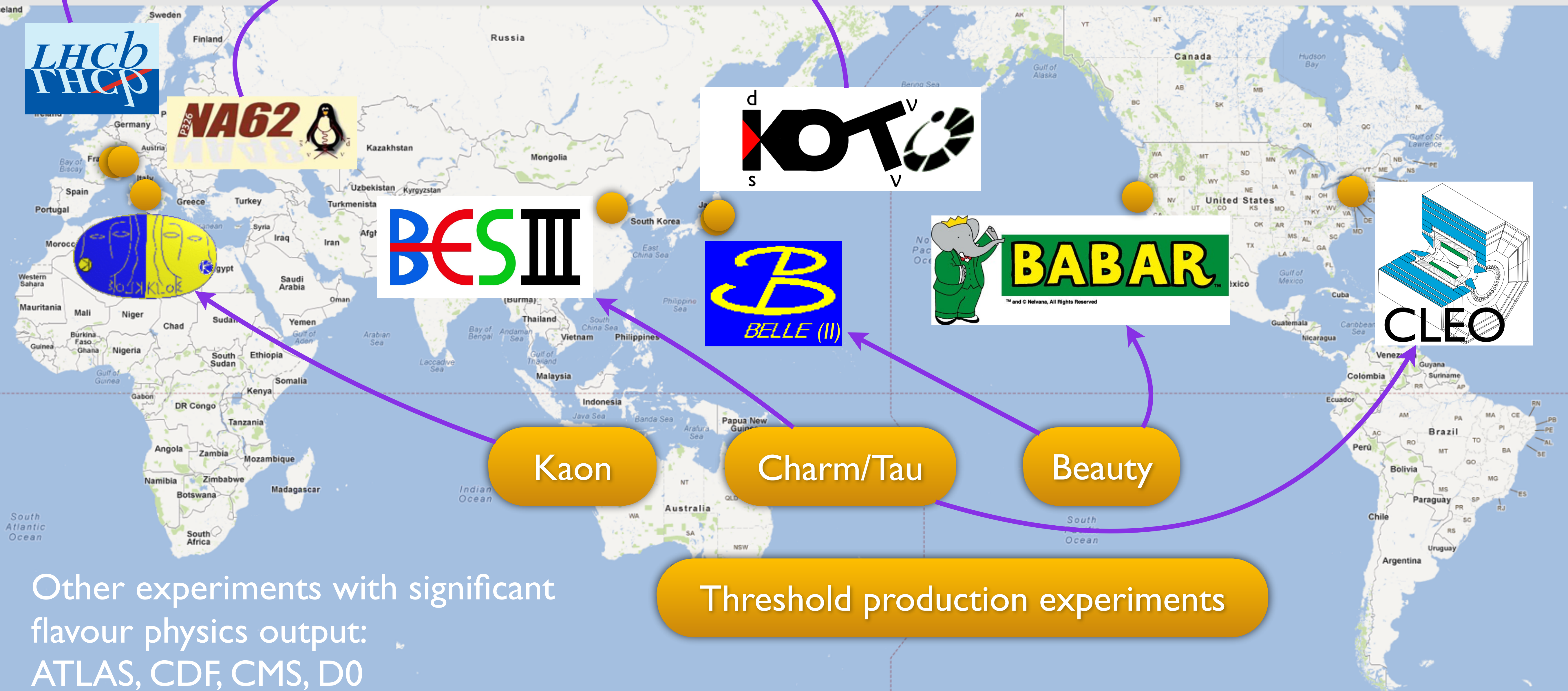
Flavourful experiments

High-energy proton-proton collisions
→ General purpose flavour experiment

Fixed target rare kaon decay experiments



Kaon

Charm/Tau

Beauty

Threshold production experiments

Other experiments with significant flavour physics output:
ATLAS, CDF, CMS, D0

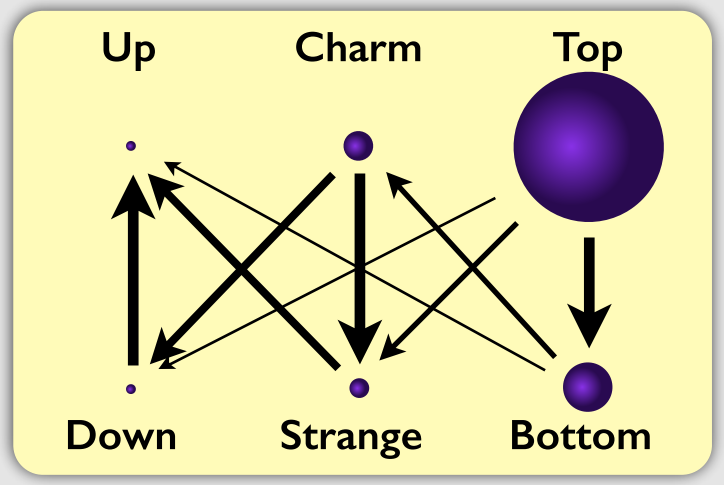
Outline

- A closer look at KM mechanism
  - ➡ Selected highlights
- The needles in the haystack
  - ➡ Rare decays
- A brief visit to the particle zoo
  - ➡ Other physics areas
- Future directions
  - ➡ Upgrade programmes

CKM matrix

- Unitary matrix combining flavour and mass eigenstates

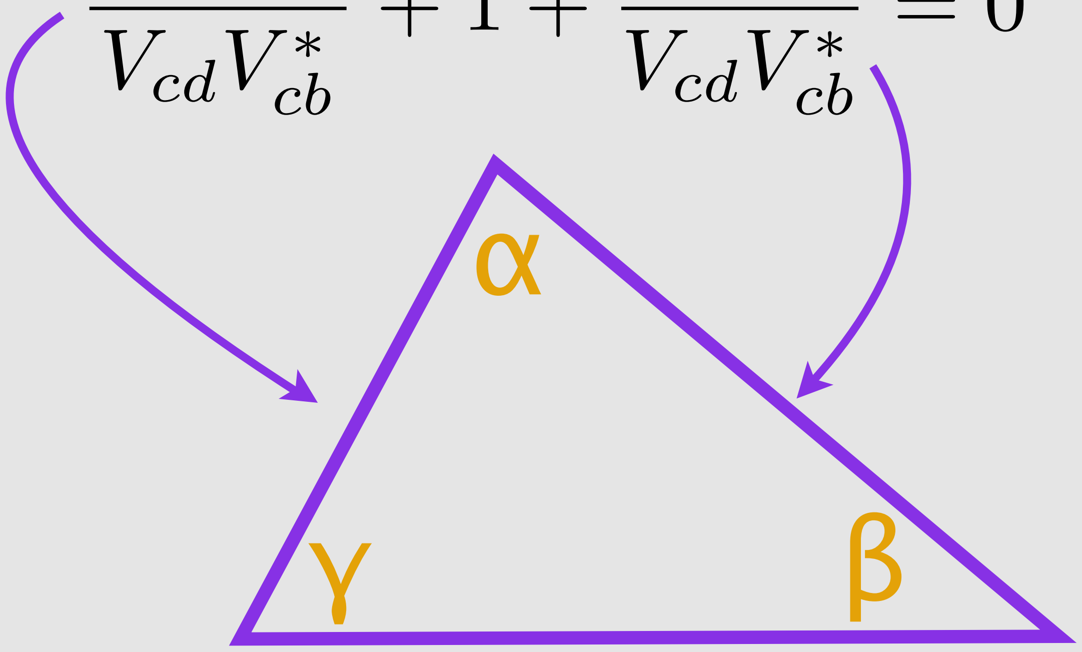
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- Unitarity relations lead to triangles in complex plane

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

B_d triangle



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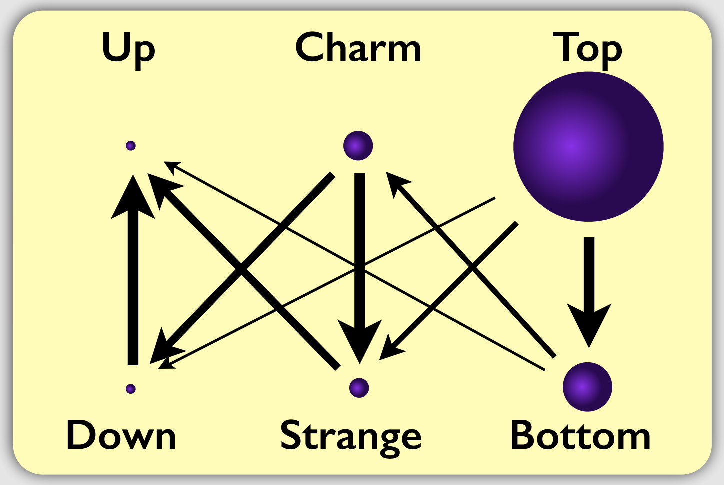

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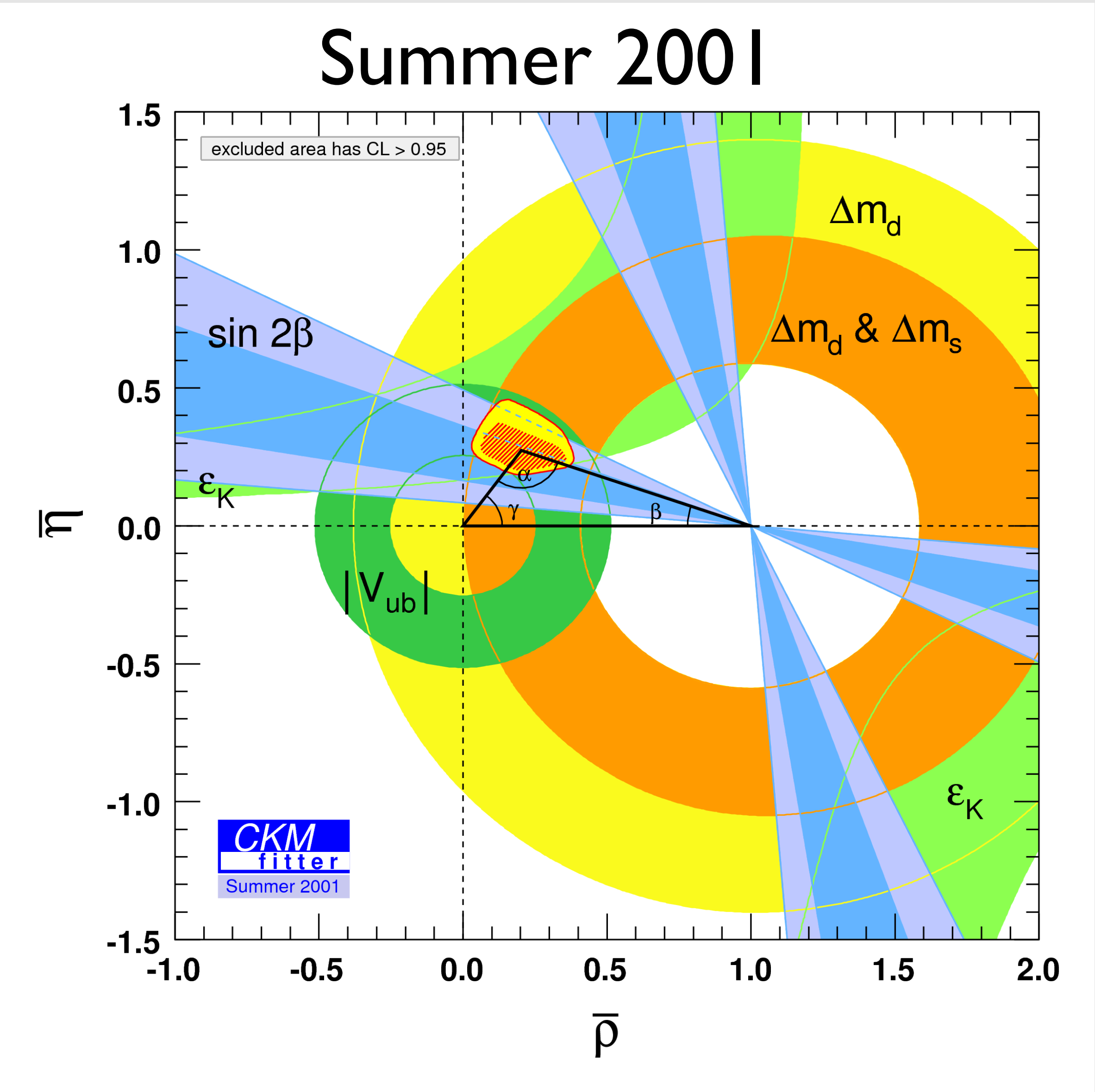
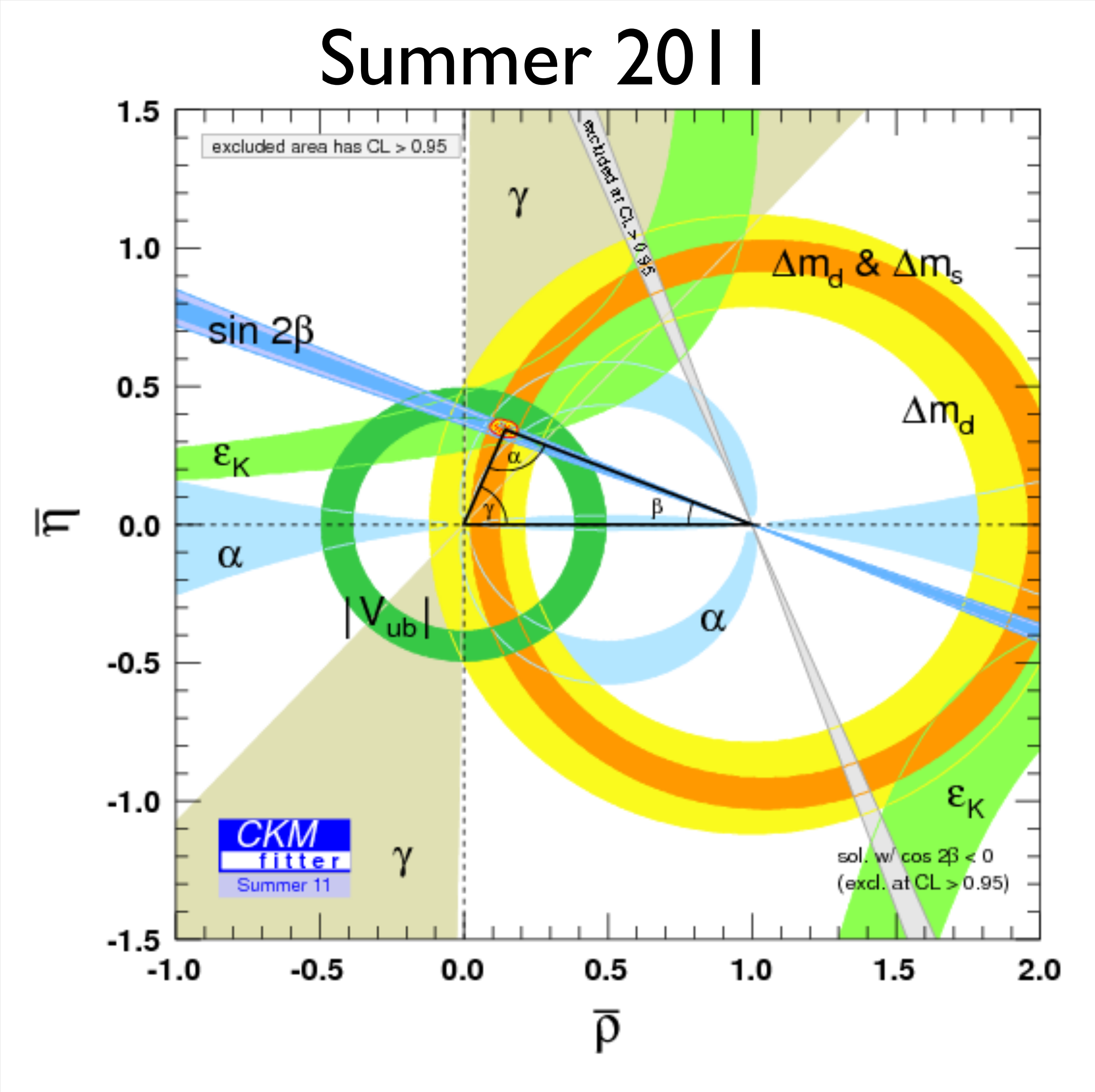
$$\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*} + 1 + \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = 0$$ B_s triangle

$$\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*} + 1 + \frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} = 0$$ D triangle

+ 3 more

CKM and beyond

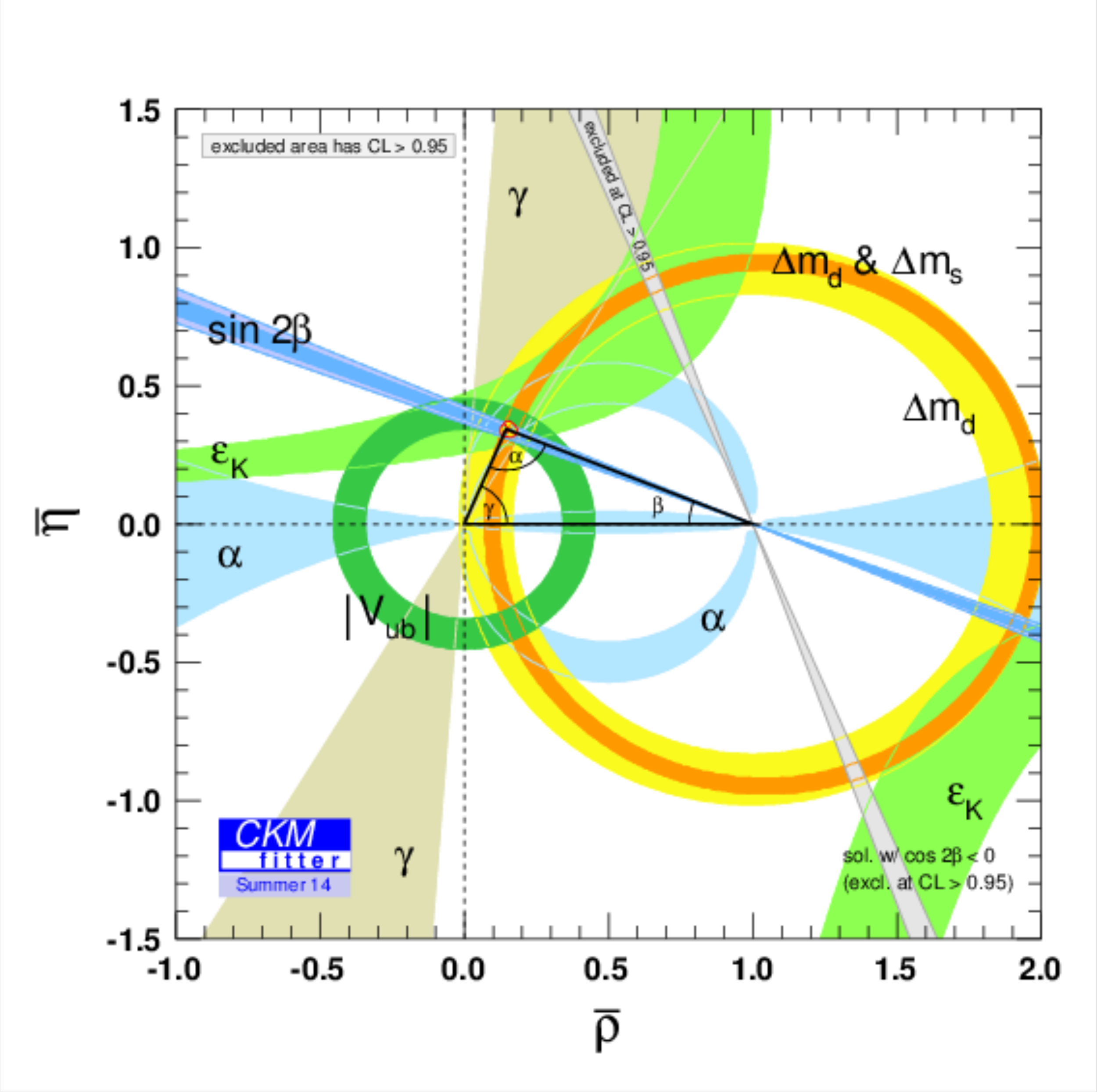




- A decade of precision measurements
- Huge success for BaBar and Belle

CKM today

- 2010-2020
  - ➡ Enter LHCb
- Looking for these little ripples caused by particles beyond the standard model



Measuring sin(2β)

- Based on golden channel $B^0 \to J/\psi K_S$
- Primary objective of B-factories
- Measure time-dependent CP asymmetry of
  - ➡ $B^0 \to J/\psi K^0$, $K^0 \to \pi^+\pi^-$ and charge conjugate
- Amplitude proportional to $\sin(2\phi_{weak})$
  - ➡ $A(t) = S \sin(\Delta m \cdot t) - C \cos(\Delta m \cdot t)$

S → sin(2β)

C → CP violation in decay, expected ~0

$$\left(\frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}}\right)\left(\frac{V_{cs}^*V_{cb}}{V_{cs}V_{cb}^*}\right)\left(\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right) = \left(\frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}}\right)\left(\frac{V_{cd}^*V_{cb}}{V_{cd}V_{cb}^*}\right) = \left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right)\left(\frac{V_{cd}^*V_{cb}}{V_{td}^*V_{tb}}\right)$$

B^0-$\overline{B}^0$ mixing

K^0-$\overline{K}^0$ mixing

$B^0 \to J/\psi K^0$ decay

(β) - (-β)
=2β

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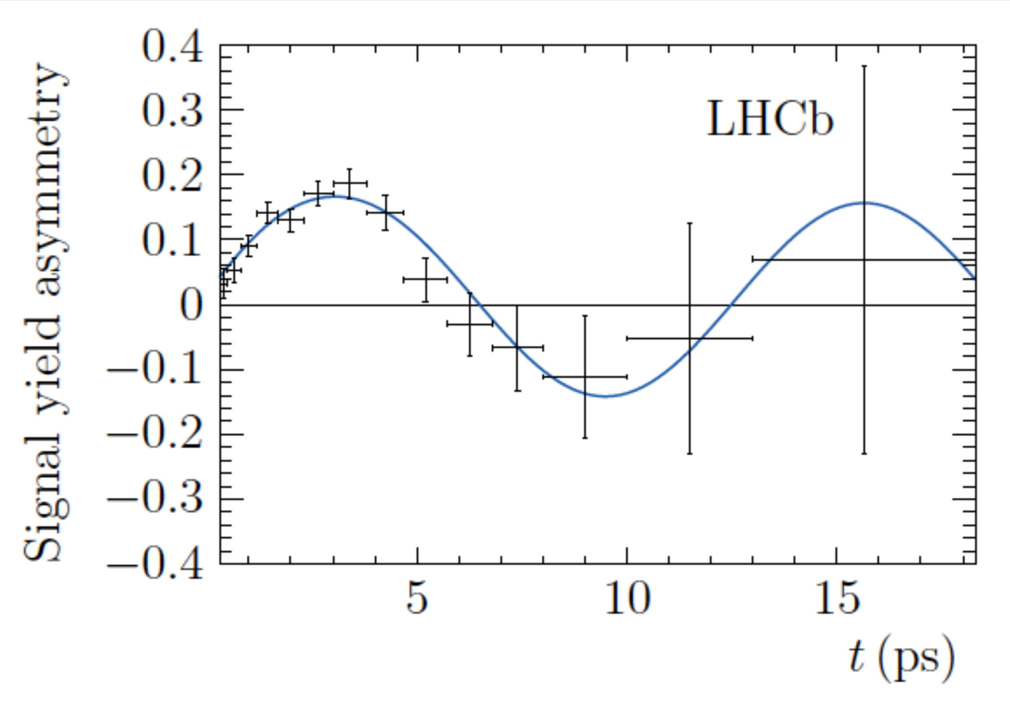
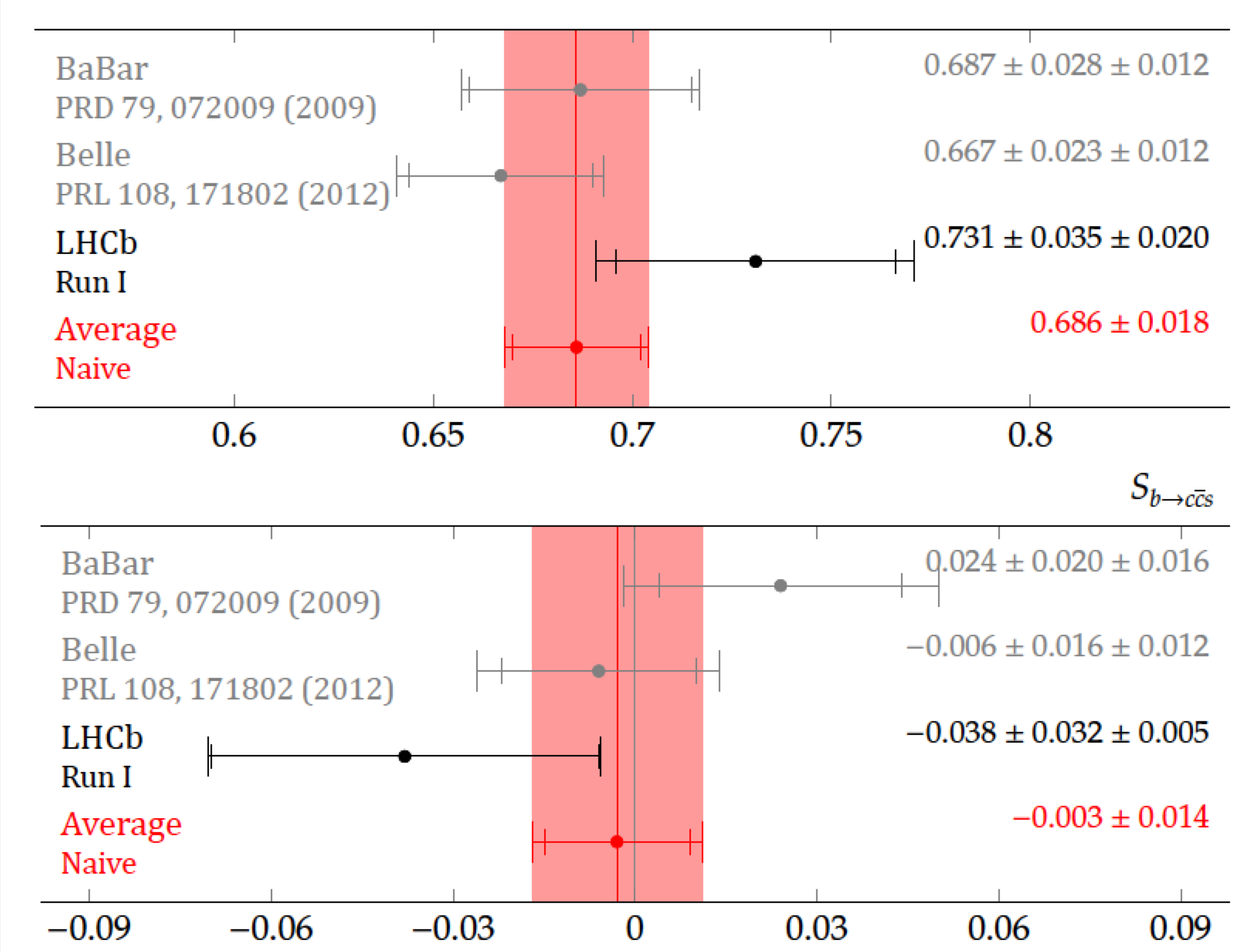
New LHCb results

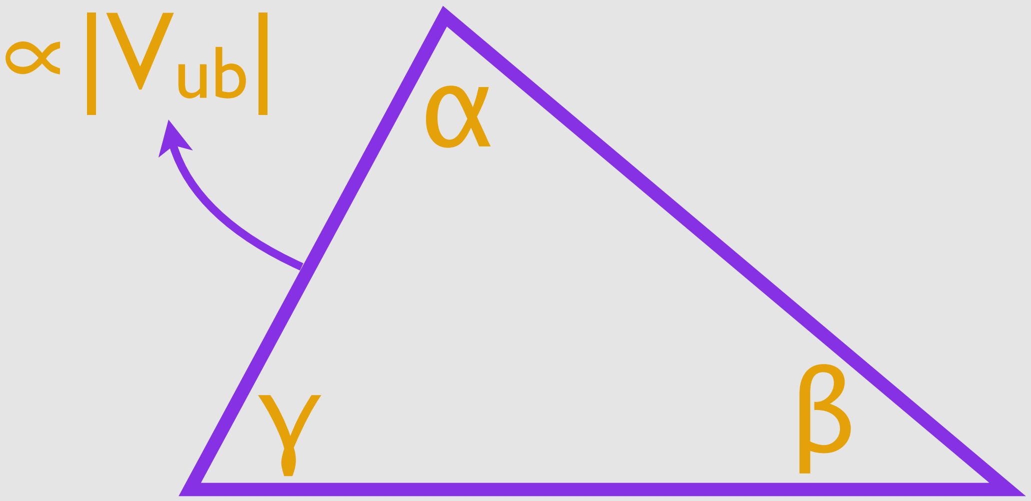
- Full run-1 data
  - ➡ 42k candidates
- Improved flavour tagging
  - ➡ $\varepsilon D^2 = 3\%$





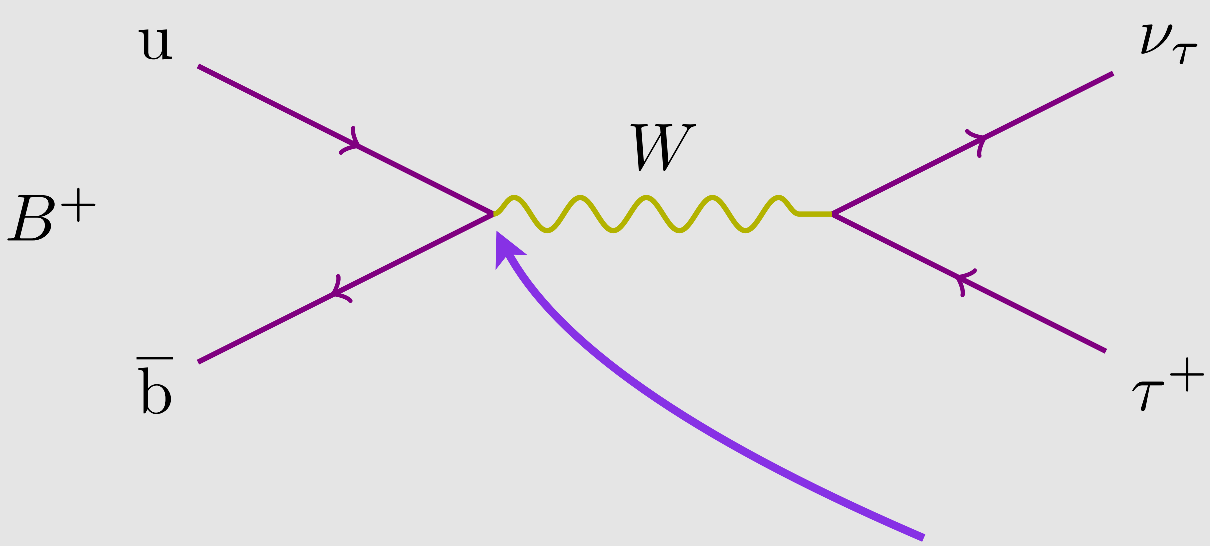
arXiv:1503.07089, accepted by JHEP

$|V_{ub}|$

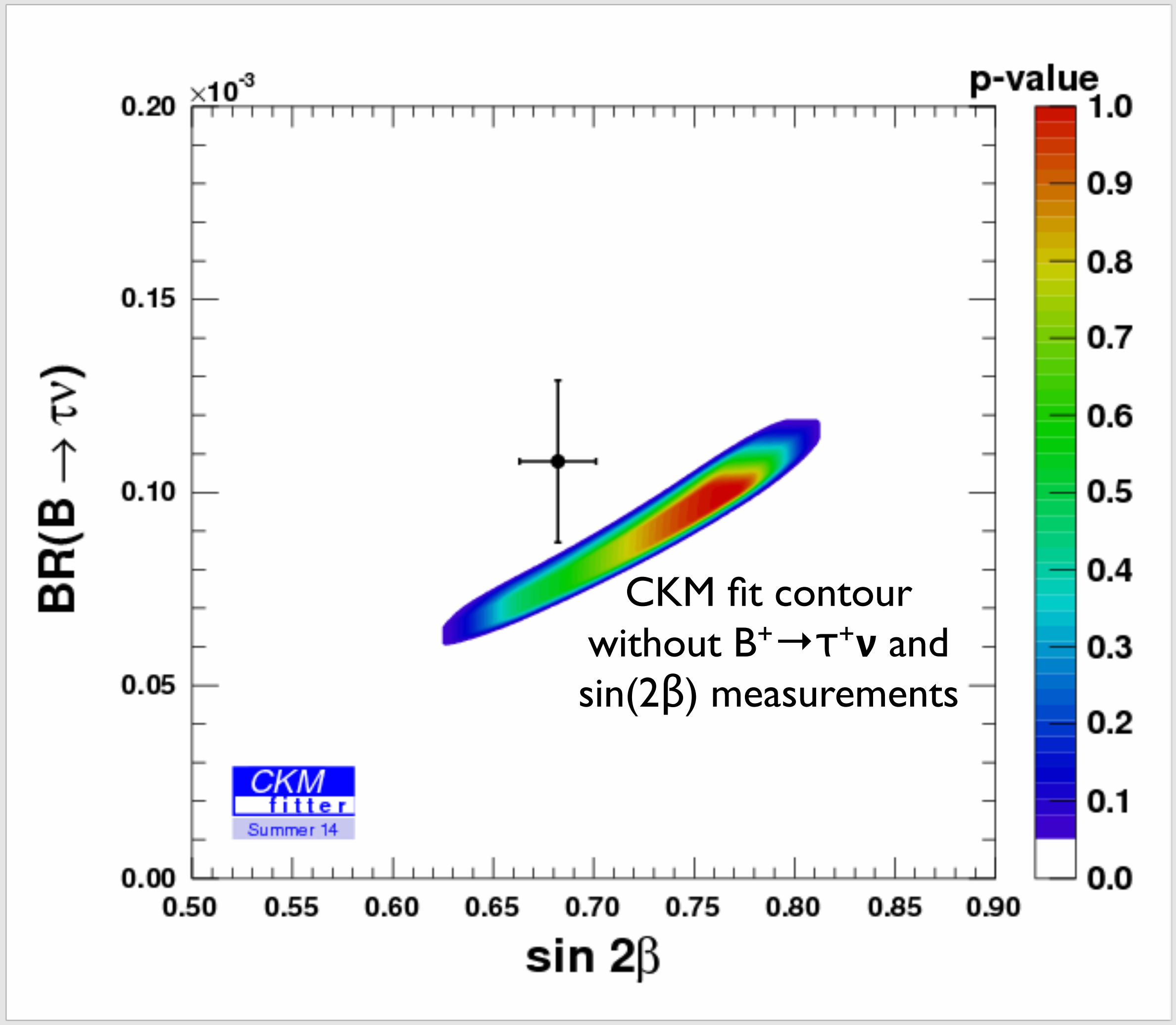


- Complementary measurement to sin(2β)
  - ➡ Angle vs opposite side
  - ➡ Inconsistency would signal new physics
- Access through (semi-)leptonic decays
  - ➡ $b \to u l \nu$ transitions
- Inclusive vs exclusive measurements
  - ➡ $B^0 \to \pi^- l^+ \nu$
  - ➡ $B^+ \to \tau \nu$

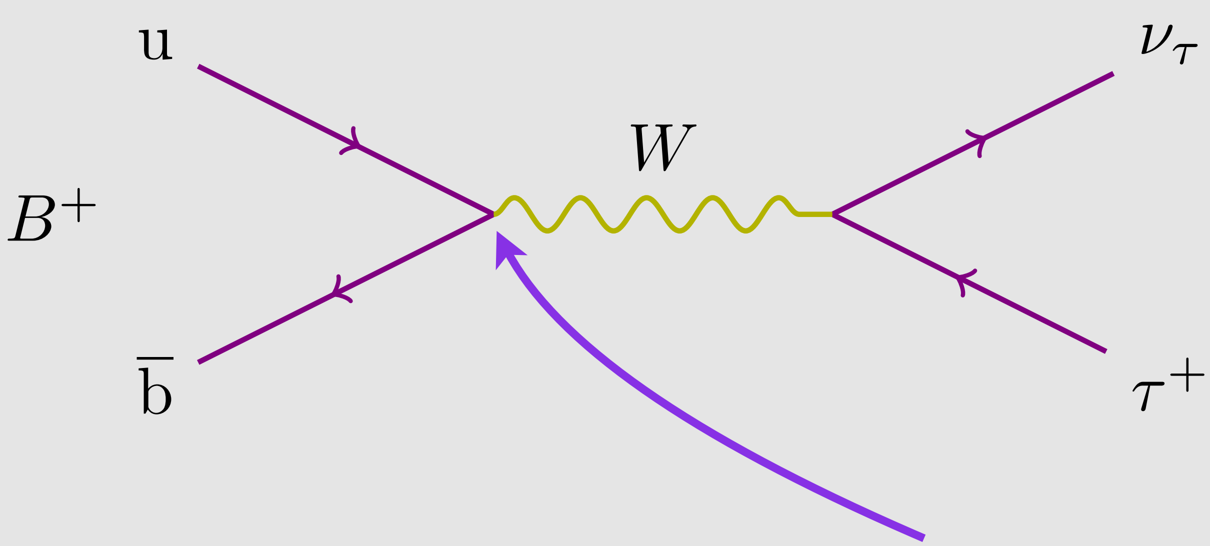
$B^+ \rightarrow \tau^+ \nu$



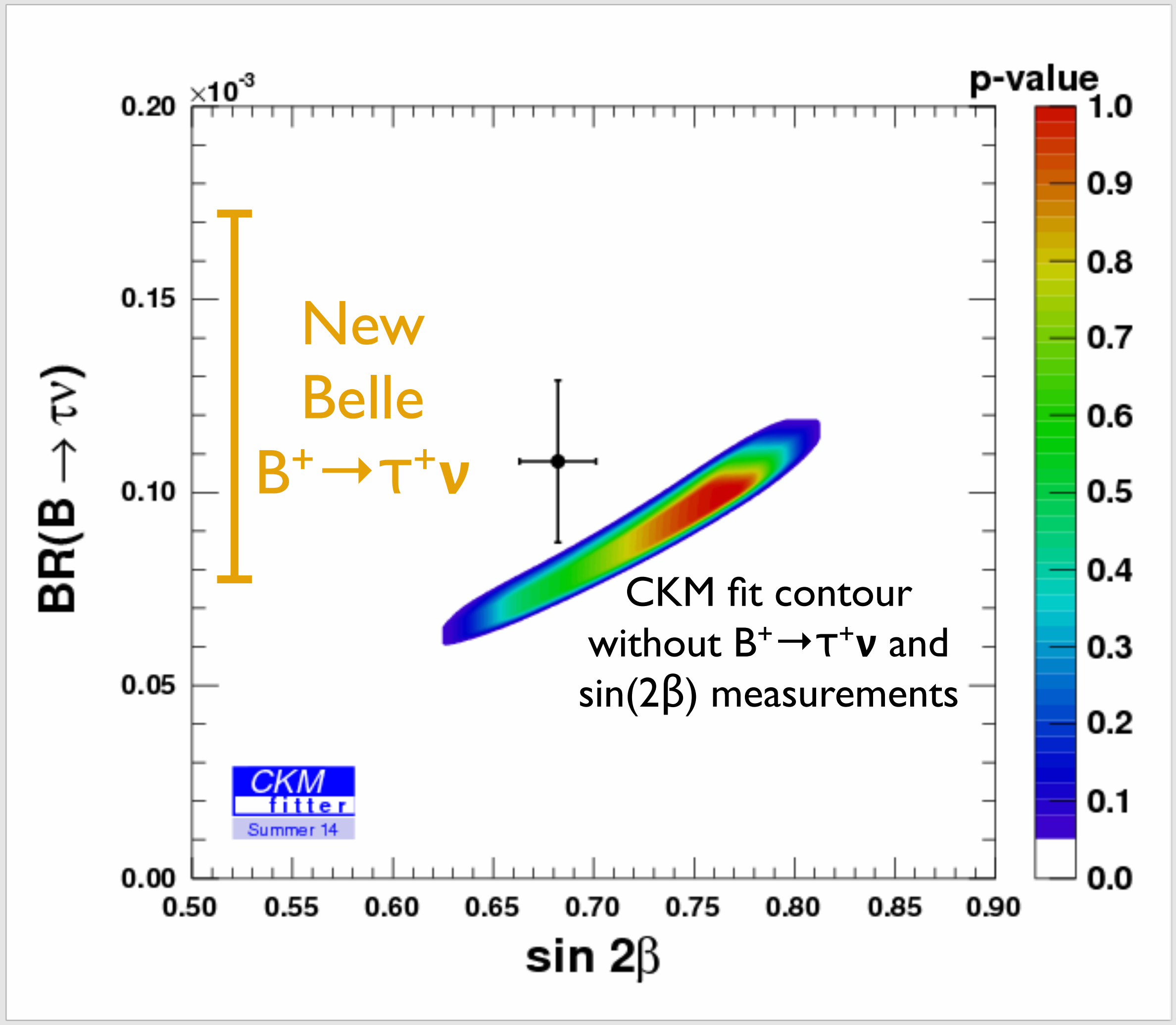
- Proportional to $|V_{ub}|$
- Slight discrepancy between sin(2β) and BR(B→τν)



$B^+ \to \tau^+ \nu$

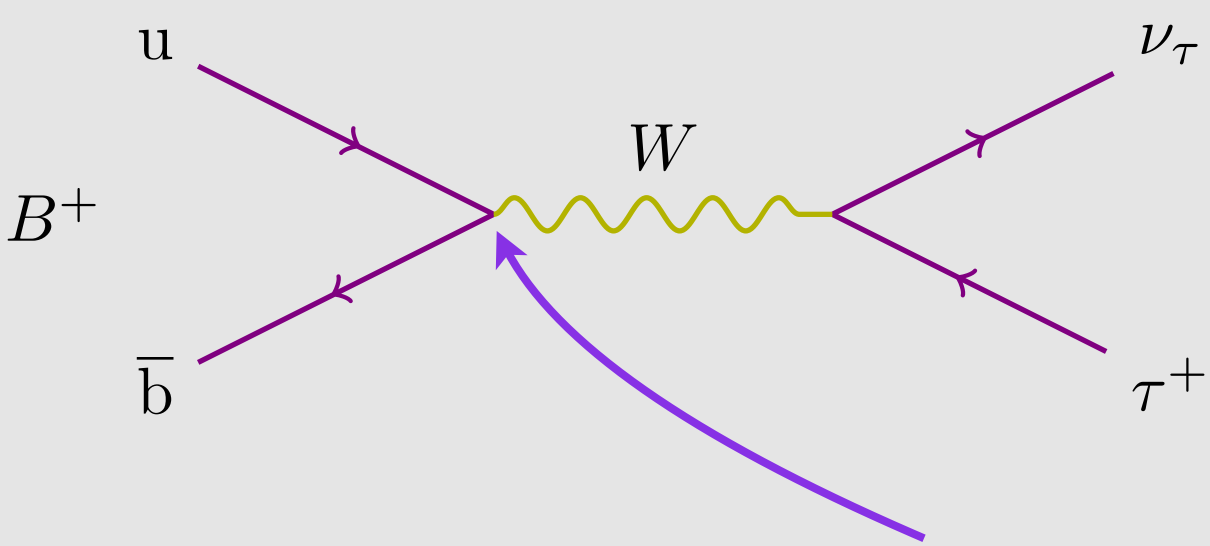


- Proportional to $|V_{ub}|$
- Slight discrepancy between $\sin(2\beta)$ and $BR(B \to \tau\nu)$



Belle, $B^+ \to \tau^+ \nu$, arXiv:1409.5269

$B^+ \to \tau^+ \nu$



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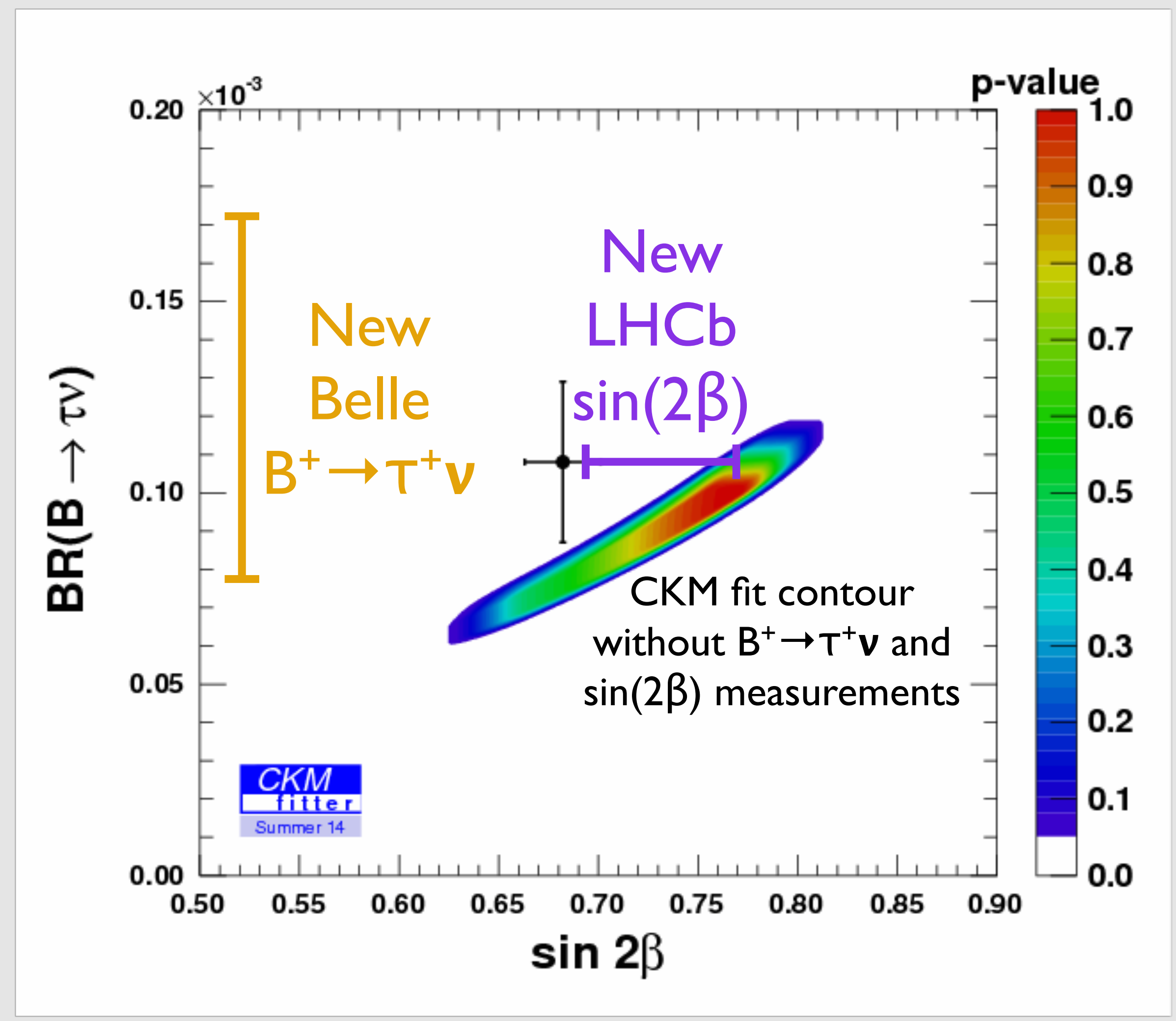

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LHCb, sin(2β), arXiv:1503.07055

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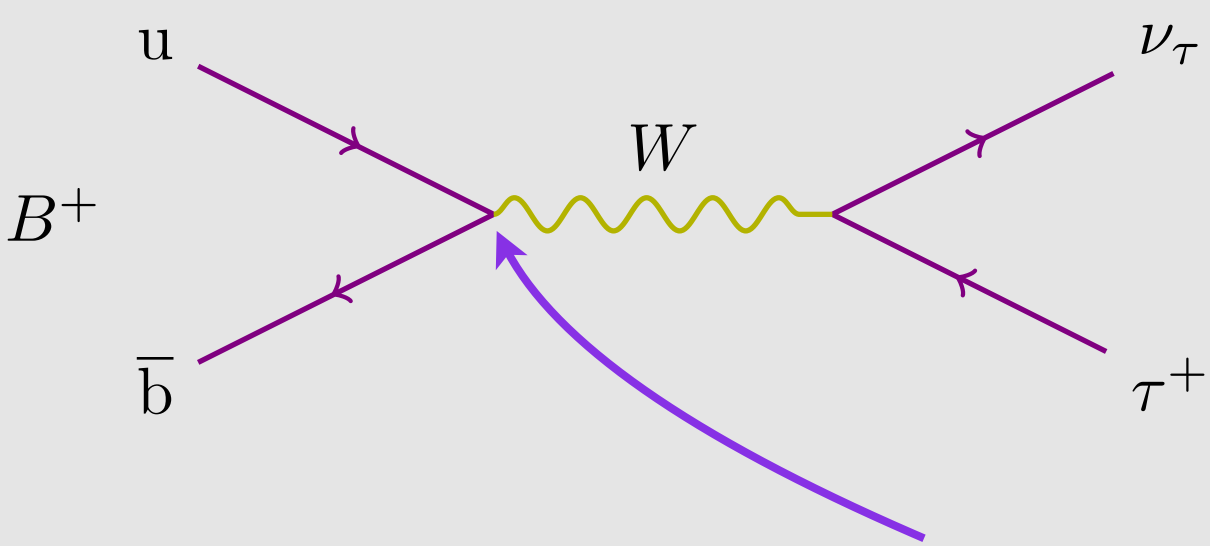
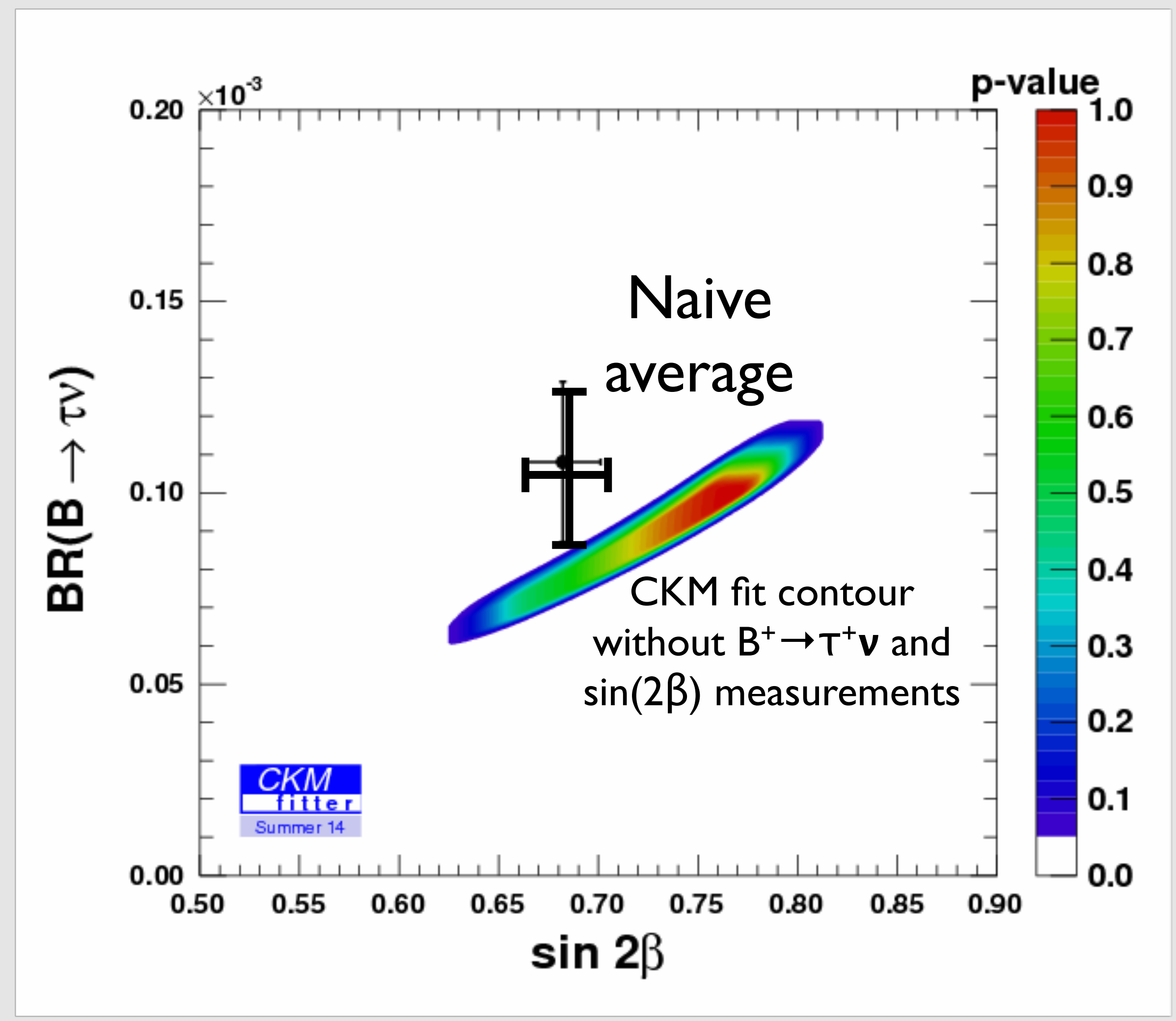


- Proportional to $|V_{ub}|$
- Slight discrepancy between sin(2β) and BR($B \to \tau\nu$)



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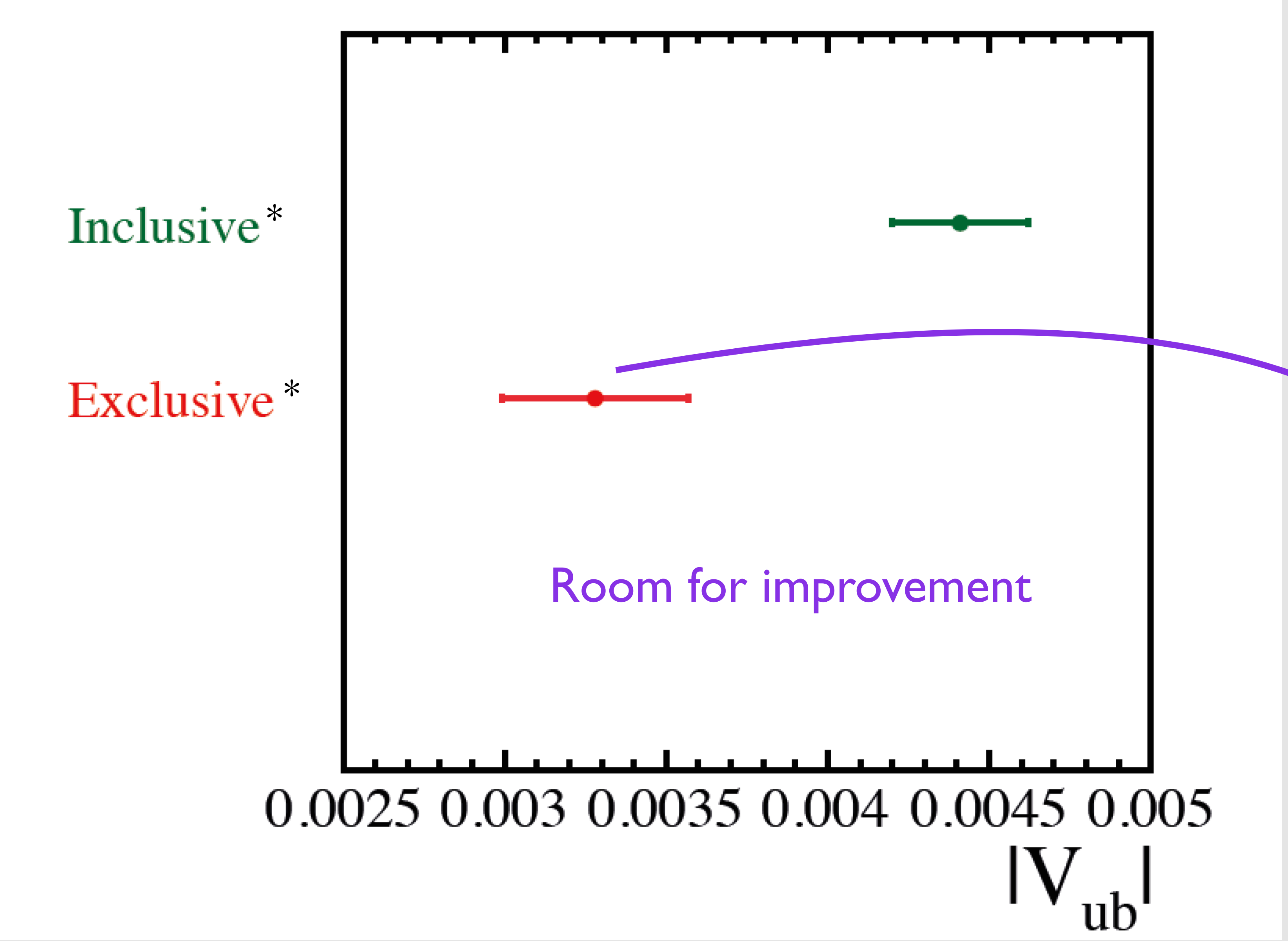
PDG 2014

$\bar{b} \to \bar{u} l^+ \nu$

$B^0 \to \pi^- l^+ \nu$

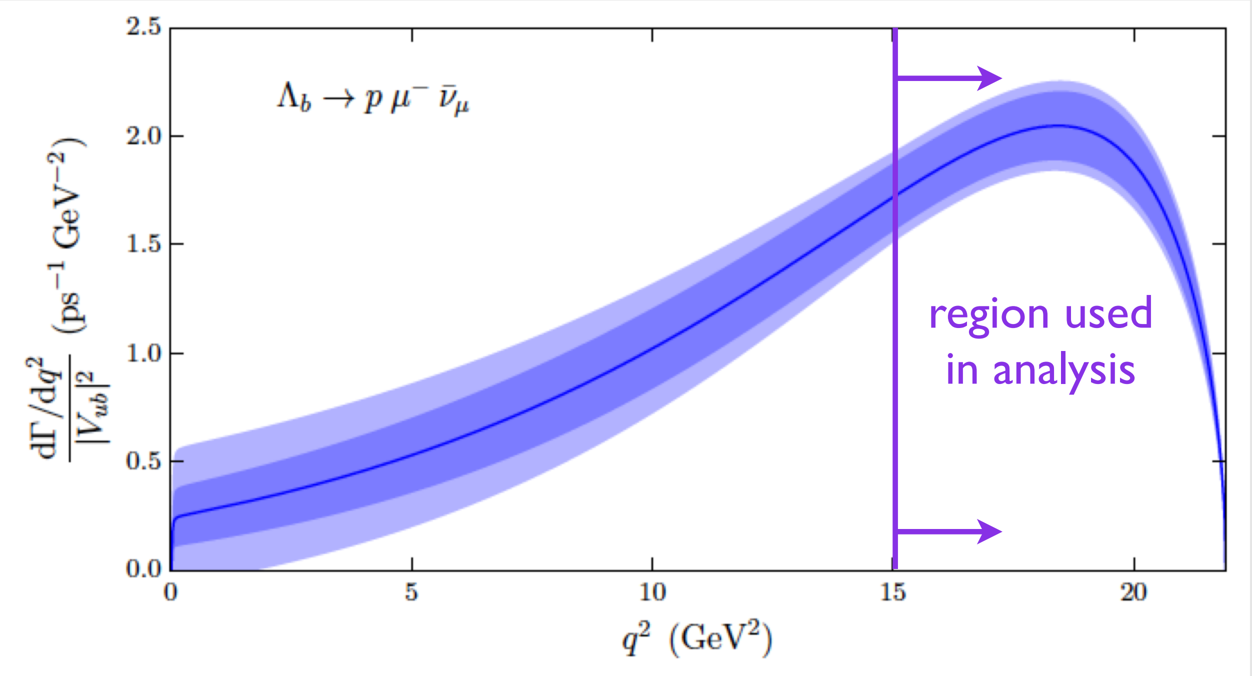


confirmed two weeks ago by updated BaBar measurement

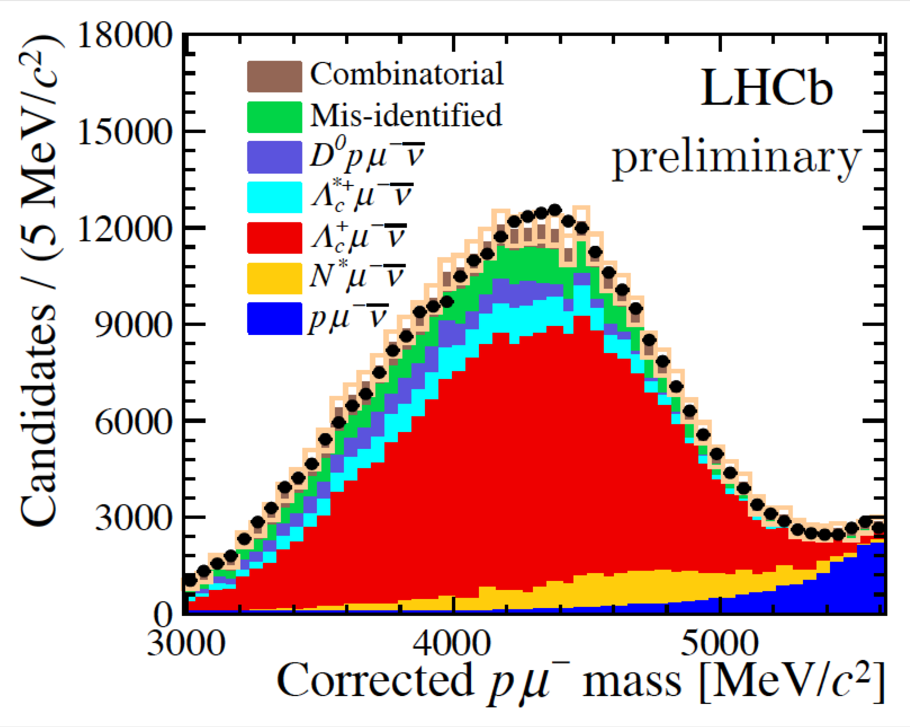
*from Kowalewski, Mannel in PDG 2014:
Inclusive: average of BLNP, GGOU, DGE determination
Exclusive: BCL parametrisation of q^2 range and FNAL/MILC results

New opportunities

- LHCb has access to Λ_b baryons
- Can use these to measure the ratio of
  - ➡ $\Lambda_b \to p\mu\upsilon$ to $\Lambda_b \to \Lambda_c\mu\upsilon$
  - ➡ Measures $|V_{ub}|^2$ / $|V_{cb}|^2$
  - ➡ Use theory input to measure relative acceptance in q^2
    → W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421



- Large data samples allow tight cuts to obtain high purity
  - ➡ Using 2012 data corresponding to 2 fb^{-1}



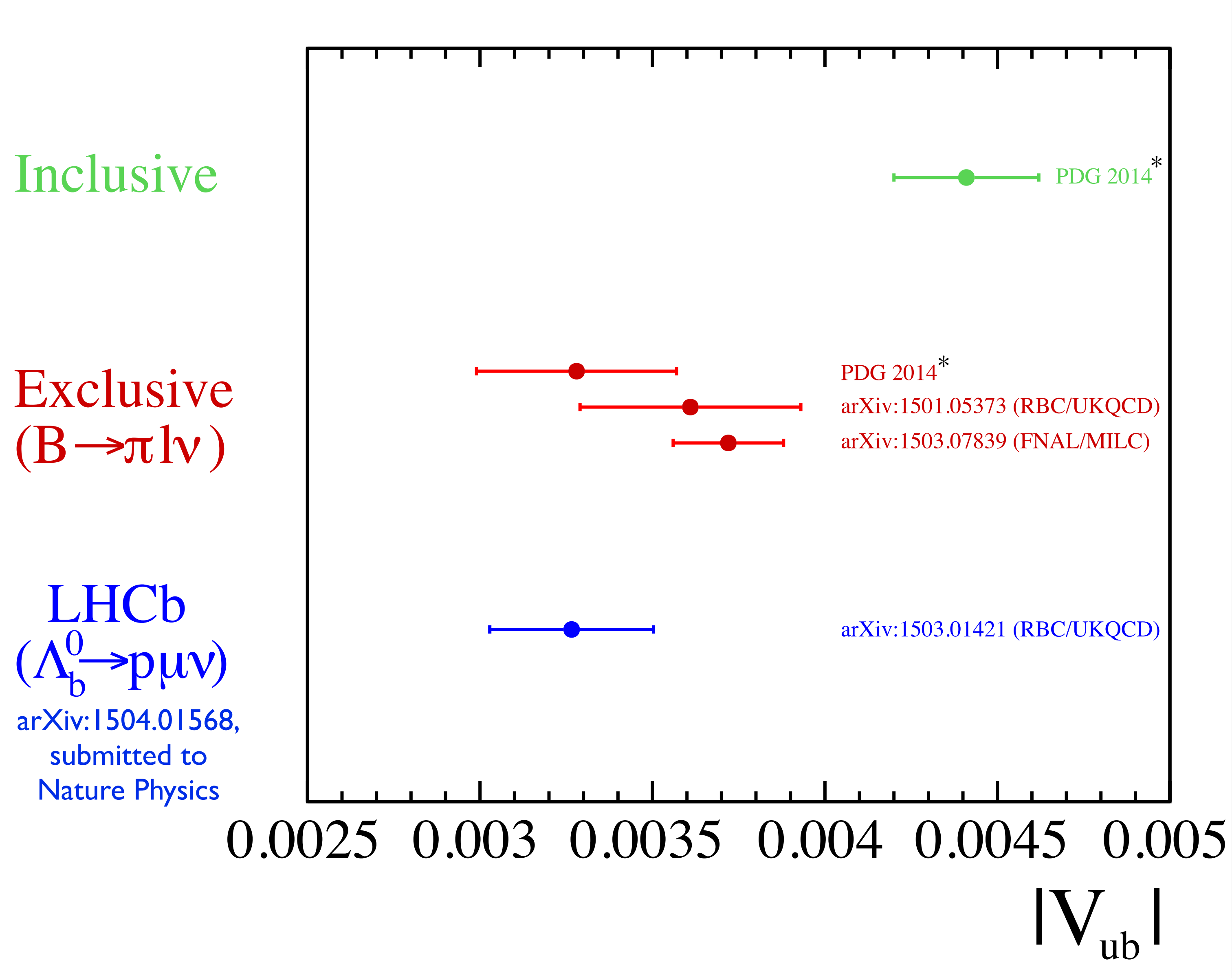
arXiv:1504.01568, submitted to Nature Physics

Results

$\bar{b} \rightarrow \bar{u} l^+ \upsilon$

$B^0 \rightarrow \pi^- l^+ \upsilon$

$\Lambda_b \rightarrow p \mu \upsilon$



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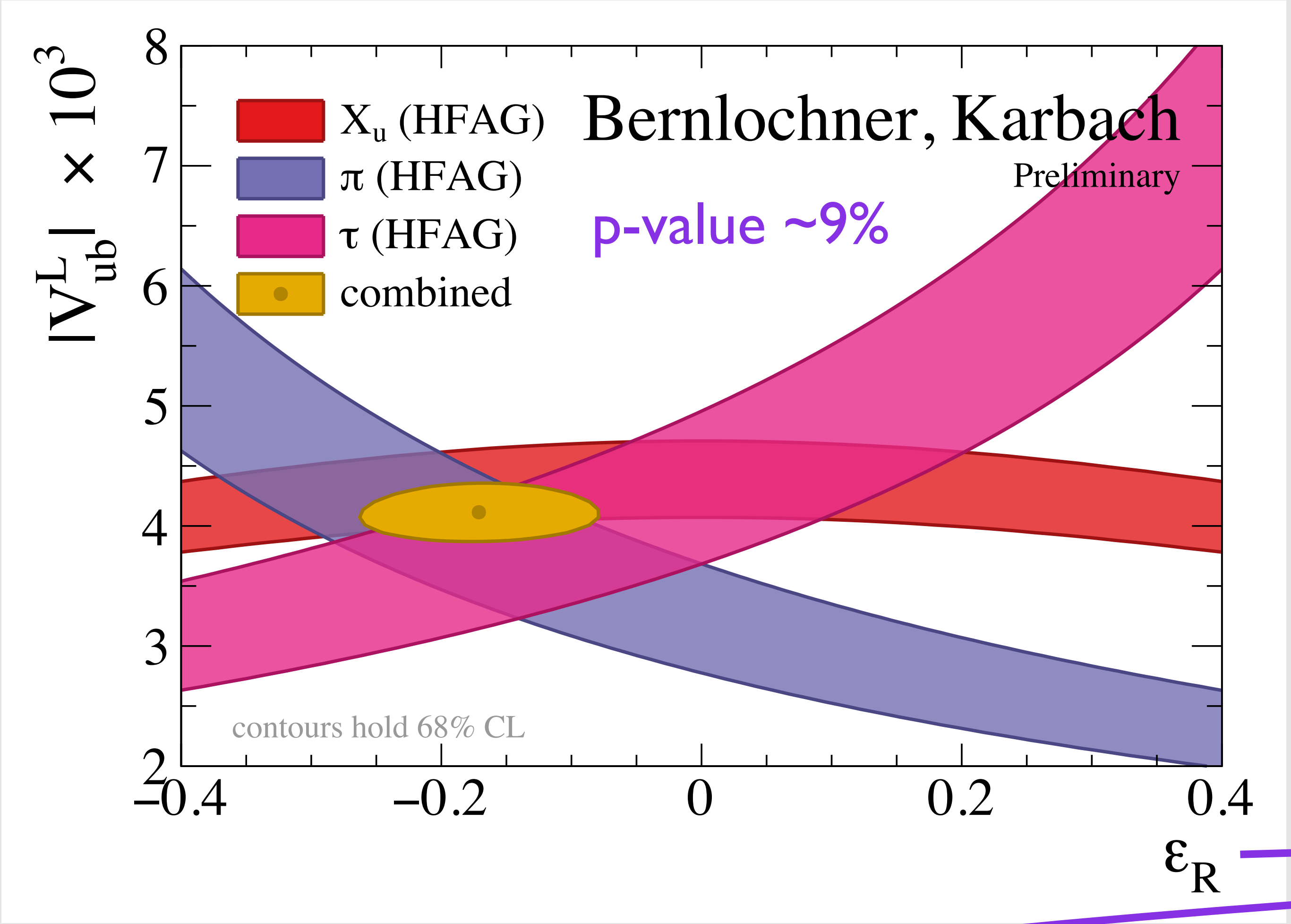
New physics?



→ see also
Bernlochner, Ligeti, Turczyk, PRD90 (2014) 094003
Crivellin, PRD81 (2010) 031301

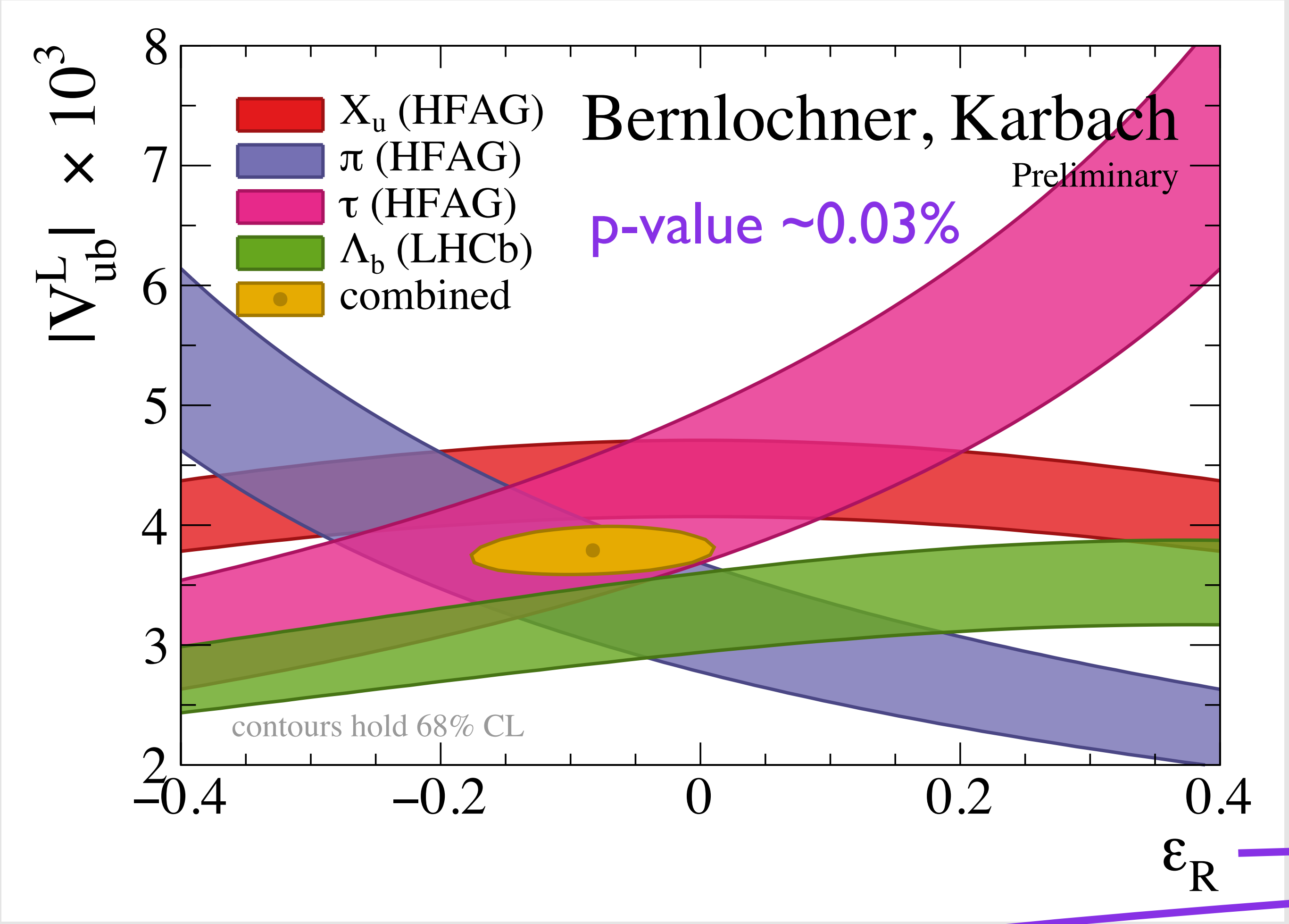
Fraction of right-handed current

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^{L} \left(\bar{u}\gamma_\mu P_L b + \epsilon_R\, \bar{u}\gamma_\mu P_R b\right)\left(\bar{\nu}\gamma^\mu P_L \ell\right) + \text{h.c.}$$

- Right-handed currents affect different $|V_{ub}|$ extractions in different ways

Decay	$\lvert V_{ub}\rvert \times 10^3$	ϵ_R dependence
$B \to \pi\,\ell\bar{\nu}$	3.23 ± 0.30	$1 + \epsilon_R$
$B \to X_u \ell\bar{\nu}$	4.39 ± 0.21	$\sqrt{1+\epsilon_R^2}$
$B \to \tau\,\bar{\nu}_\tau$	4.32 ± 0.42	$1 - \epsilon_R$

New physics?



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More fun with semileptonics

- Lepton universality test with favoured B-meson decays

$$R(D^*) = \mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$$

- Sensitive to physics beyond the SM
  - ➡ Particularly to charged Higgs
- B-factory measurements point at deviation from SM

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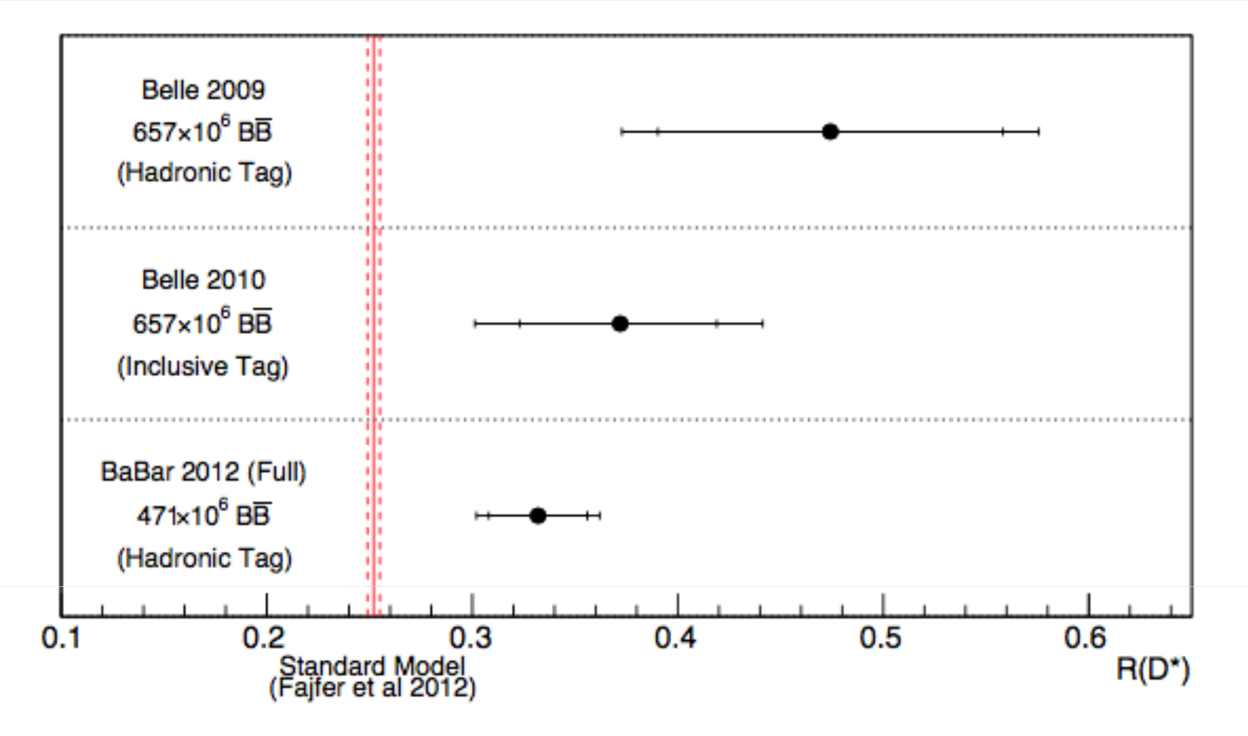

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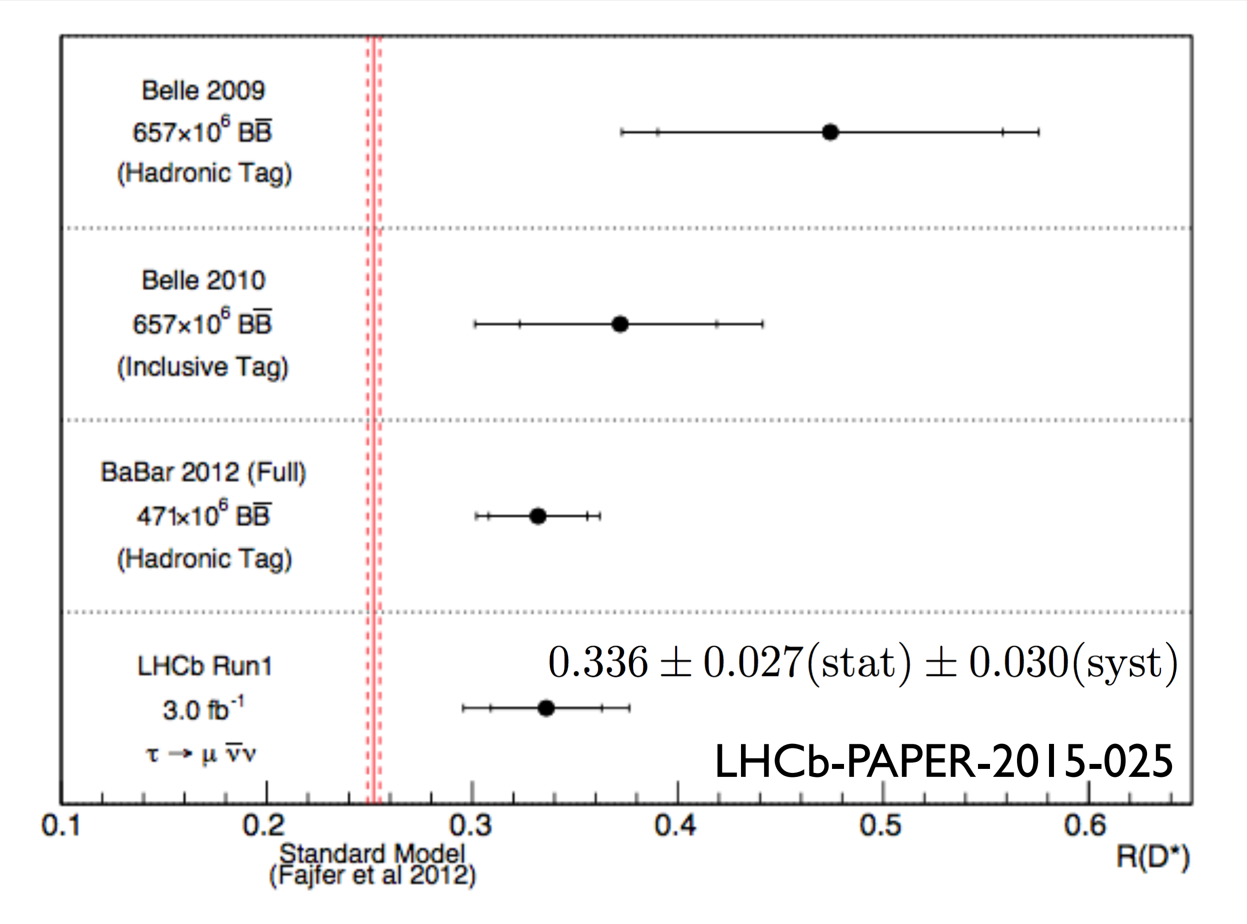
New at FPCP

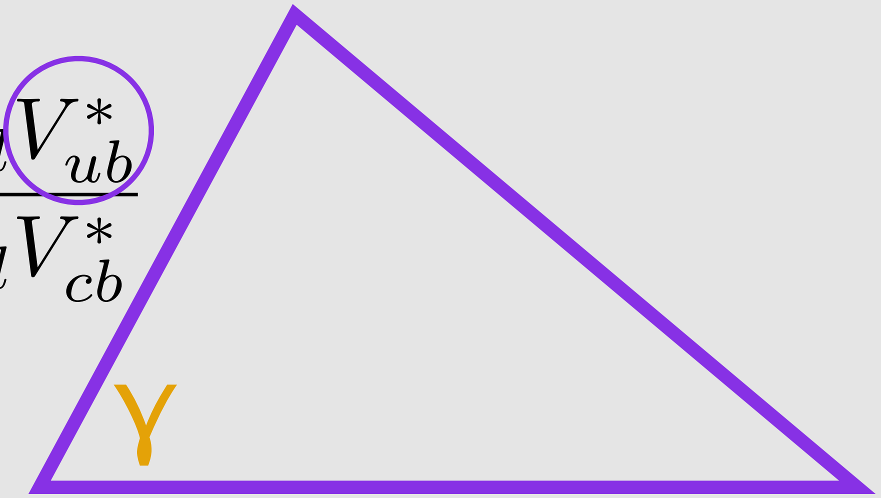
New LHCb measurement

- Using $\tau \to \mu \upsilon_\tau \bar{\upsilon}_\mu$ decays
  - ➡ Reconstruct $D^{*+}\mu^-$ in both cases
- Systematic uncertainty dominated by reducible effects
  - ➡ Sample size to extract fit templates
  - ➡ Background estimate from mis-identified muons

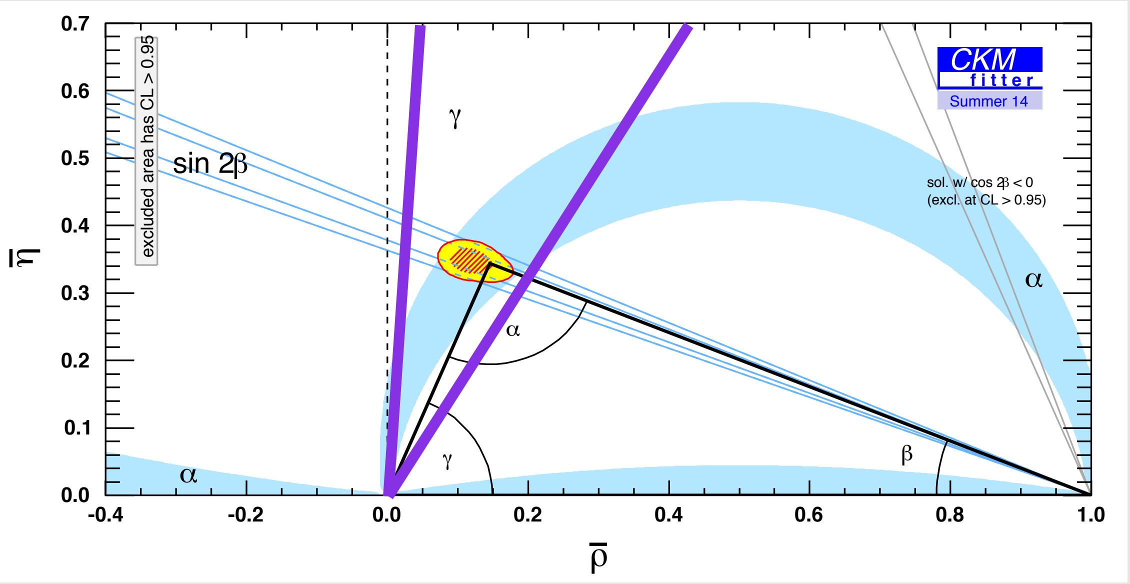


Measuring γ

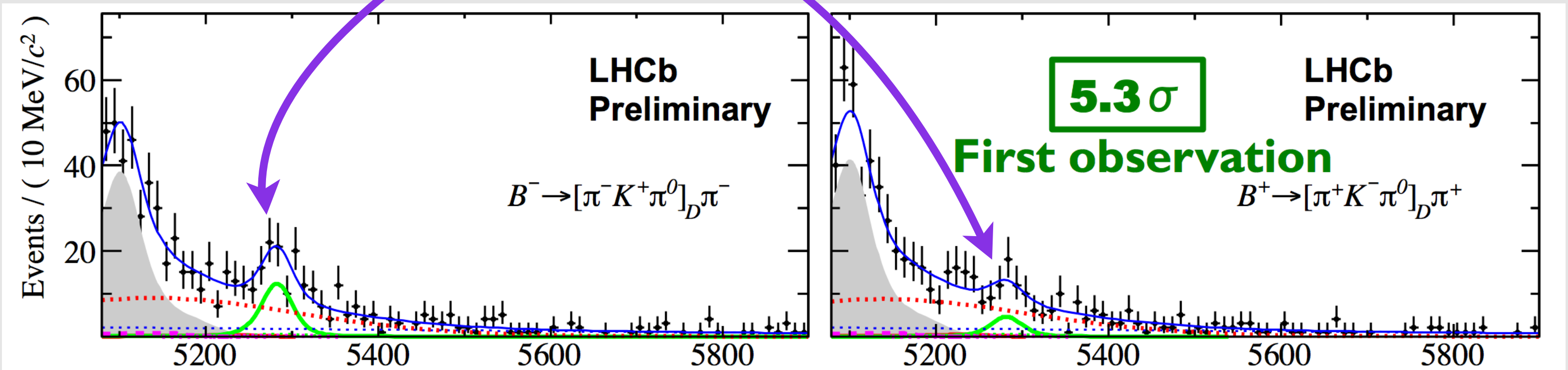
$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$



- Essentially measuring the phase of V_{ub}
- Least well measured CKM angle
- Measure CP violation in $B_{(s)} \to D_{(s)}hX$ decays
- Same idea as sin(2β)
  - ➡ But no tagging needed
- Many different methods
  - ➡ Combinations of B and D decays
  - ➡ Time-integrated and time-dependent



CP violation in $B^- \to D(K^+\pi^-\pi^0)\pi^-$



arXiv:1504.05442, submitted to PRD

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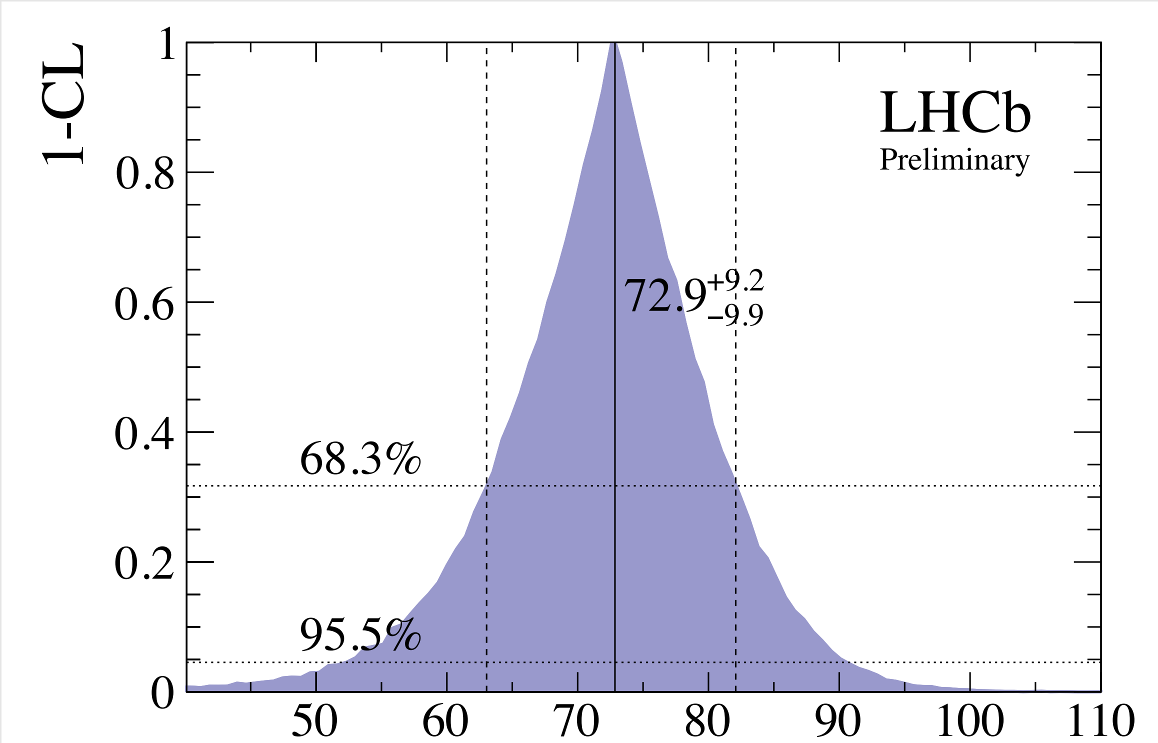
A multitude of methods

- Methods for $B^{(0,-)} \to Dh$ ($h=\pi, K, K^*$) decays
  - ➡ Observables are time-integrated ratios of rates and rate asymmetries
- ADS
  - ➡ Measure favoured B decay with doubly Cabibbo-suppressed D decay and vice versa
- GLW
  - ➡ Measure favoured/suppressed B decays with D decaying into CP eigenstate
- GGSZ
  - ➡ Measure favoured/suppressed B decays with D decaying into multi-body final state including Dalitz analysis
- In addition using $B_s \to D_s K$ decays
  - ➡ Need to perform time-dependent measurement of rates and asymmetries

Improving γ precision

- Combining LHCb measurements of $B_{(s)} \to DK^{(*)}$ decays
- Precision better than 10°
- Not yet including all run-1 data
- BaBar average*:
  - ➡ (70±18)°
- Belle average*:
  - ➡ (73±14)°
- All based on tree decays
  - ➡ SM measurements
  - ➡ Access to beyond SM particles through loops in γ measurements using $B \to hh(h)$ decays



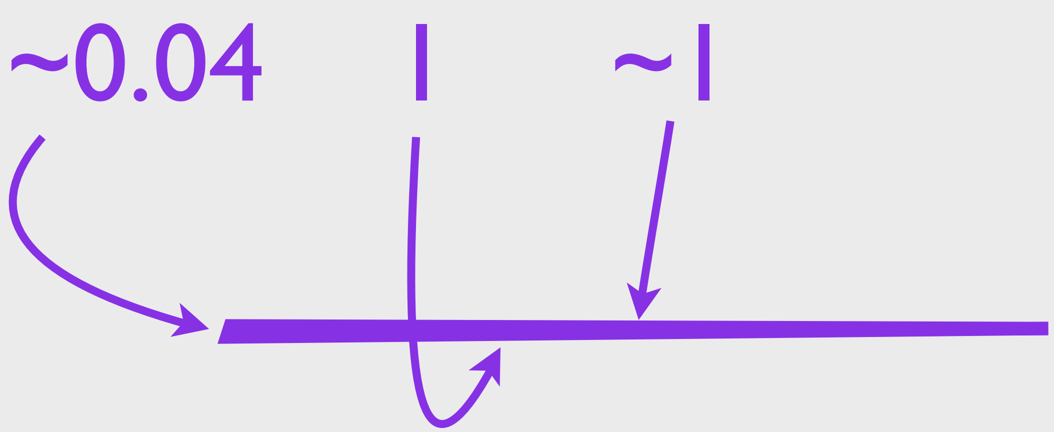
LHCb-CONF-2014-004

*CKMFitter Summer 2014

Mixing and CP violation in B_s mesons

$$\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*} + 1 + \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = 0$$

B_s triangle



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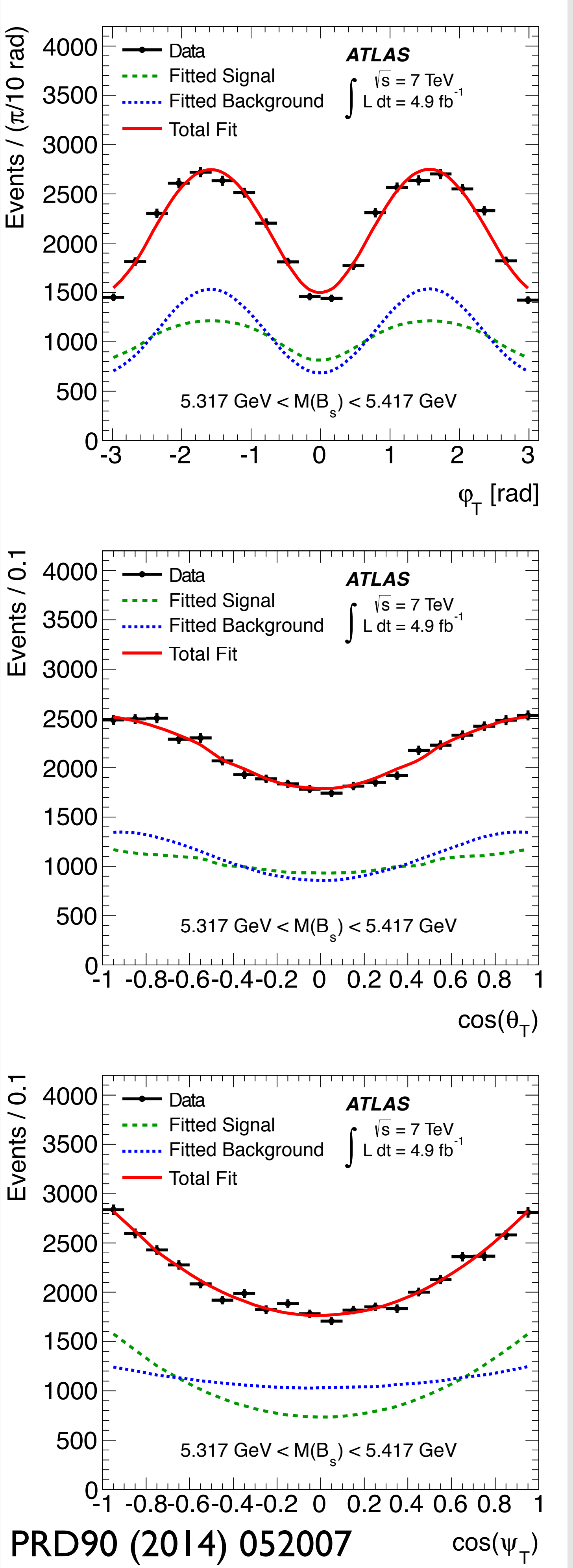
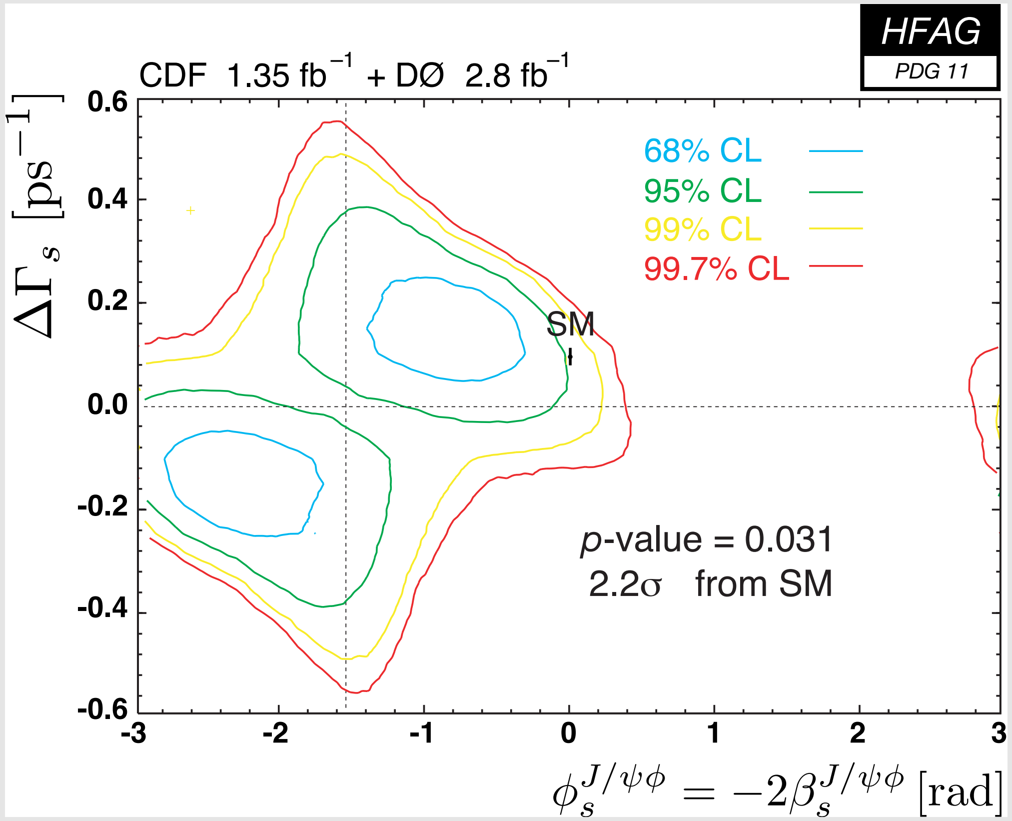
$\sin(2\beta_s)$

- Equivalent to $\sin(2\beta)$ for B_d system
- Tiny SM prediction:
  - ➡ $\beta_s \sim 1.0°$
    → CKMFitter 2014, Lenz, Nierste 2011
- Golden channel:
  - ➡ $B_s \to J/\psi\phi \to \mu^+\mu^- K^+ K^-$
- Requires time-dependent angular analysis
- Can also use
  - ➡ $B_s \to J/\psi K^+ K^-$, $B_s \to J/\psi \pi^+ \pi^-$, $B_s \to D_s^+ D_s^-$
- Measurement closely linked to width difference
  - ➡ B_s mass eigenstates predicted to have non-zero $\Delta\Gamma_s$



PRD90 (2014) 052007

Latest results



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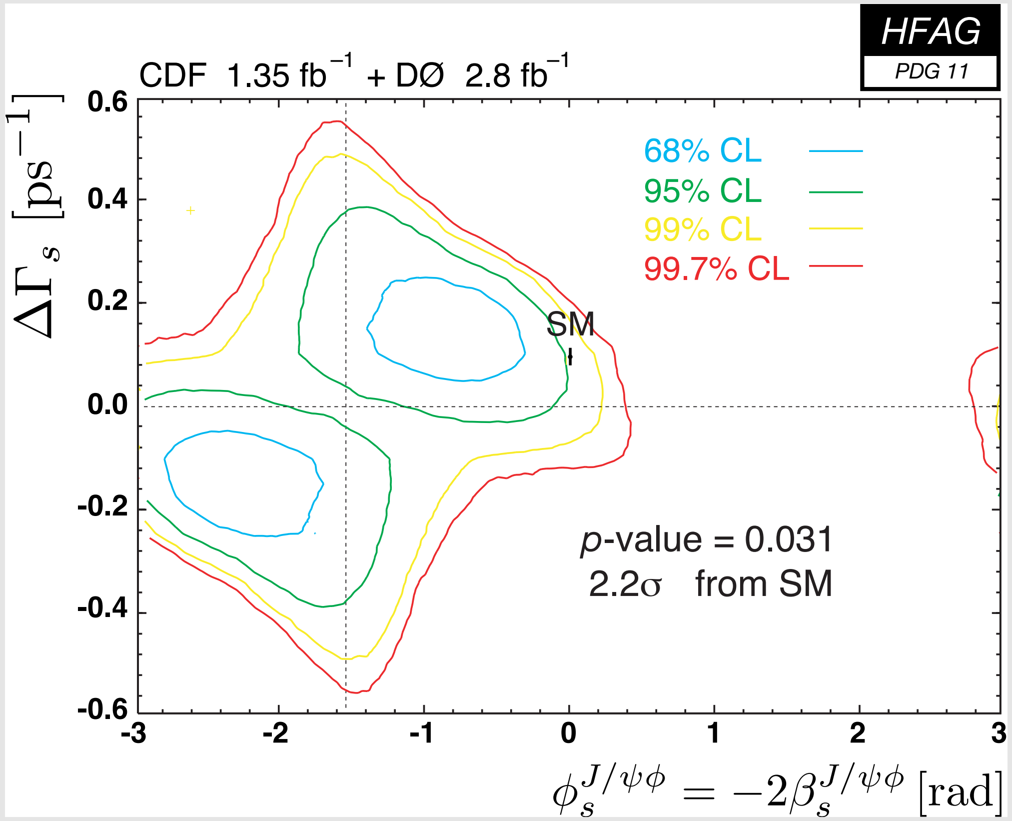
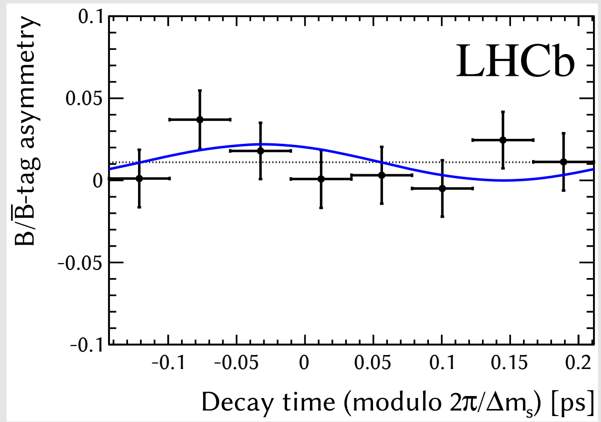


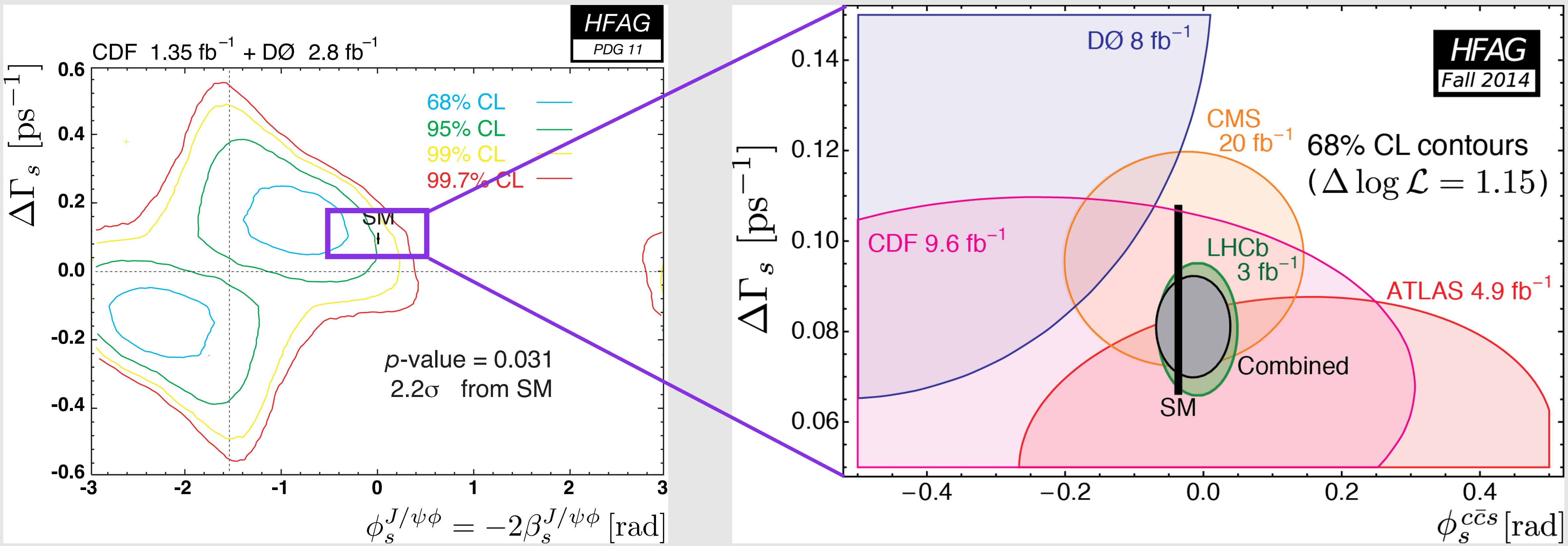
A. Lenz 2013

Latest results



Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\phi$	9.6 fb^{-1}	[−0.60, 0.12], 68% CL	$0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$0.053 \pm 0.021 \pm 0.010$	[4]
CMS	$J/\psi\phi$	20 fb^{-1}	$-0.03 \pm 0.11 \pm 0.03$	$0.096 \pm 0.014 \pm 0.007$	[5][p]
LHCb	$J/\psi K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$0.0805 \pm 0.0091 \pm 0.0033$	[6]
LHCb	$J/\psi\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	[7]
LHCb	$J/\psi h^+h^-$	3.0 fb^{-1}	-0.010 ± 0.039(tot)	—	[6][a]
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	[8]
All combined			-0.015 ± 0.035	$+0.081 \pm 0.007$	

[a] LHCb combination of $J/\psi K^+K^-$ [6] and $J/\psi\pi^+\pi^-$ [7].
[p] Preliminary.



- Theory prediction of $\Delta\Gamma_s$ confirmed
- Still room for anomalous weak phase
- Need very large data sample to achieve sufficient precision

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Charm

$$\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*} + 1 + \frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} = 0$$

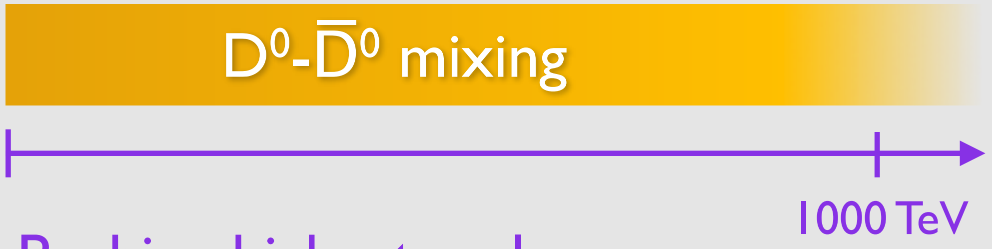
D triangle

~1 1 ~0.002

Hardly a triangle

Charm: hardly a triangle

- Only up-type quark to form weakly decaying hadrons
  - ➡ Unique physics access
- Mixing
  - ➡ Huge cancellations
  - ➡ Theoretically difficult
- CP violation
  - ➡ Predictions even smaller
- Need highest precision
- Huge LHCb dataset
  - ➡ Blessing and a curse



Probing highest scales

→ Isidori, Nir, Perez, ARNPS 60 (2010) 355

Need 1000 lifetimes to see a full D^0-$\overline{D}^0$ oscillation

→ Not enough charm in the universe!

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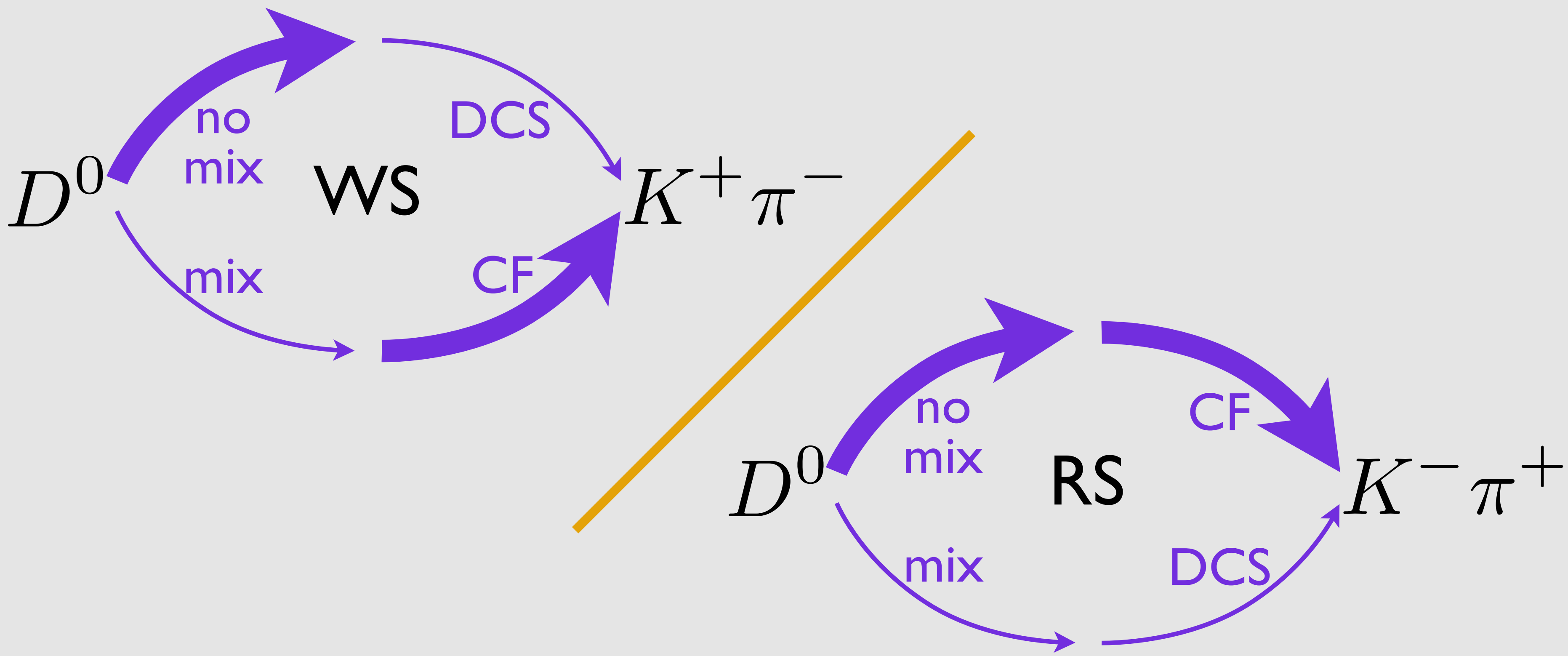
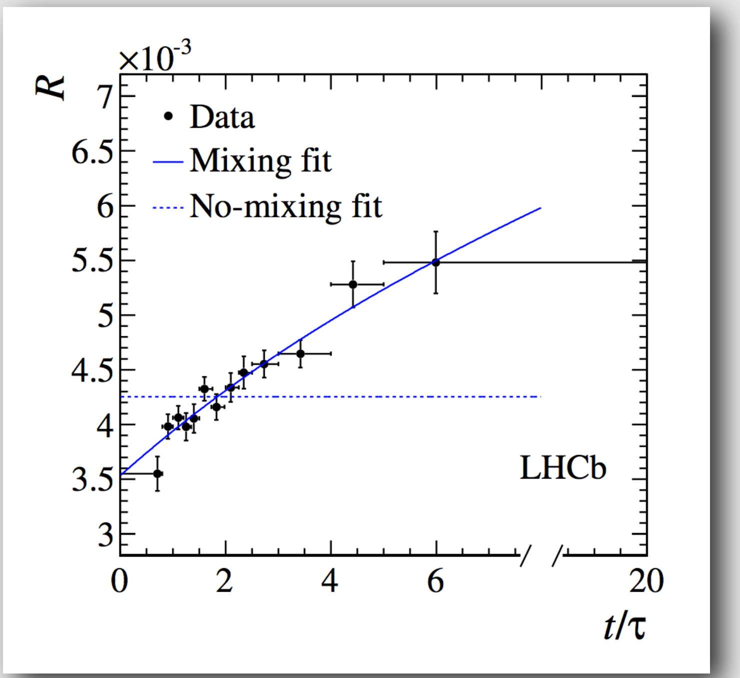
Mixing discovery



Using roughly
8.4×10^6 RS
and
3.6×10^4 WS
candidates

$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2+y'^2}{4}(\frac{t}{\tau})^2$$

- First single-experiment measurement >5σ significance
- Rotation of mixing parameters by strong phase difference: x,y → x',y'



PRL 110 (2013) 101802

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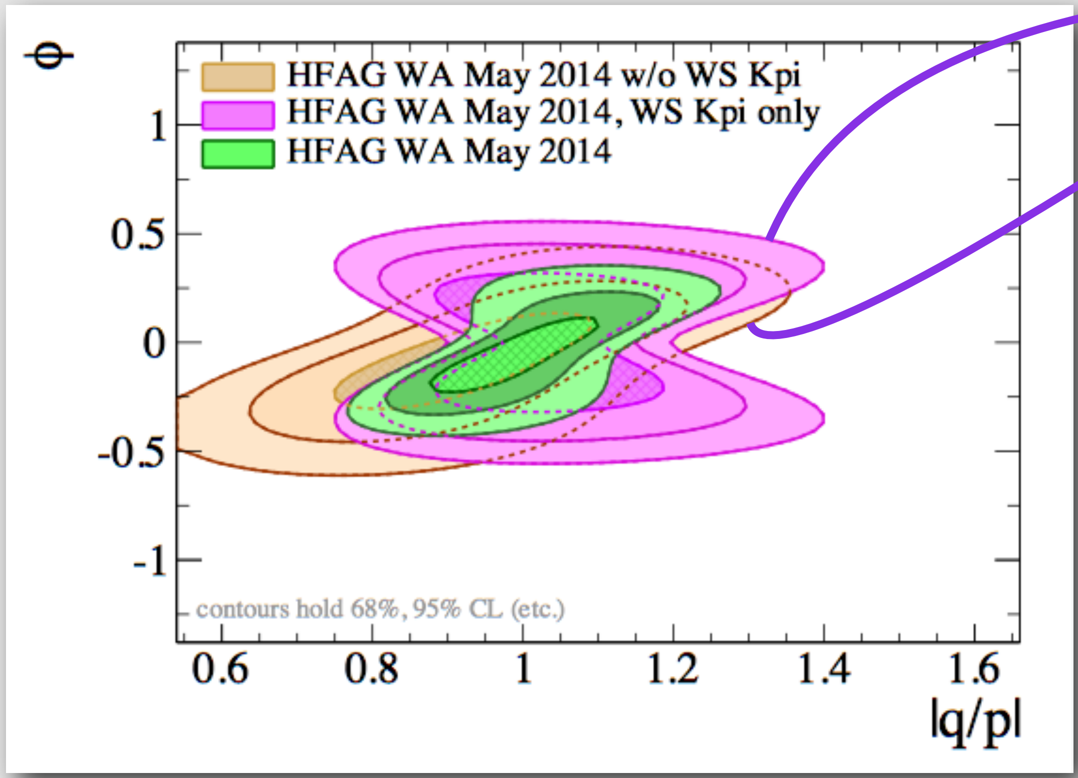
On strong phases

- Measurements of strong phases are only possible with quantum-entangled charm states
  - ➡ $\psi(3770) \to D\bar{D}$
- Only running experiment
  - ➡ BESIII at BEPC collider in Beijing
- Essential input to exploit large LHCb charm samples fully
  - ➡ Need best possible sensitivity to measure tiny effects in charm

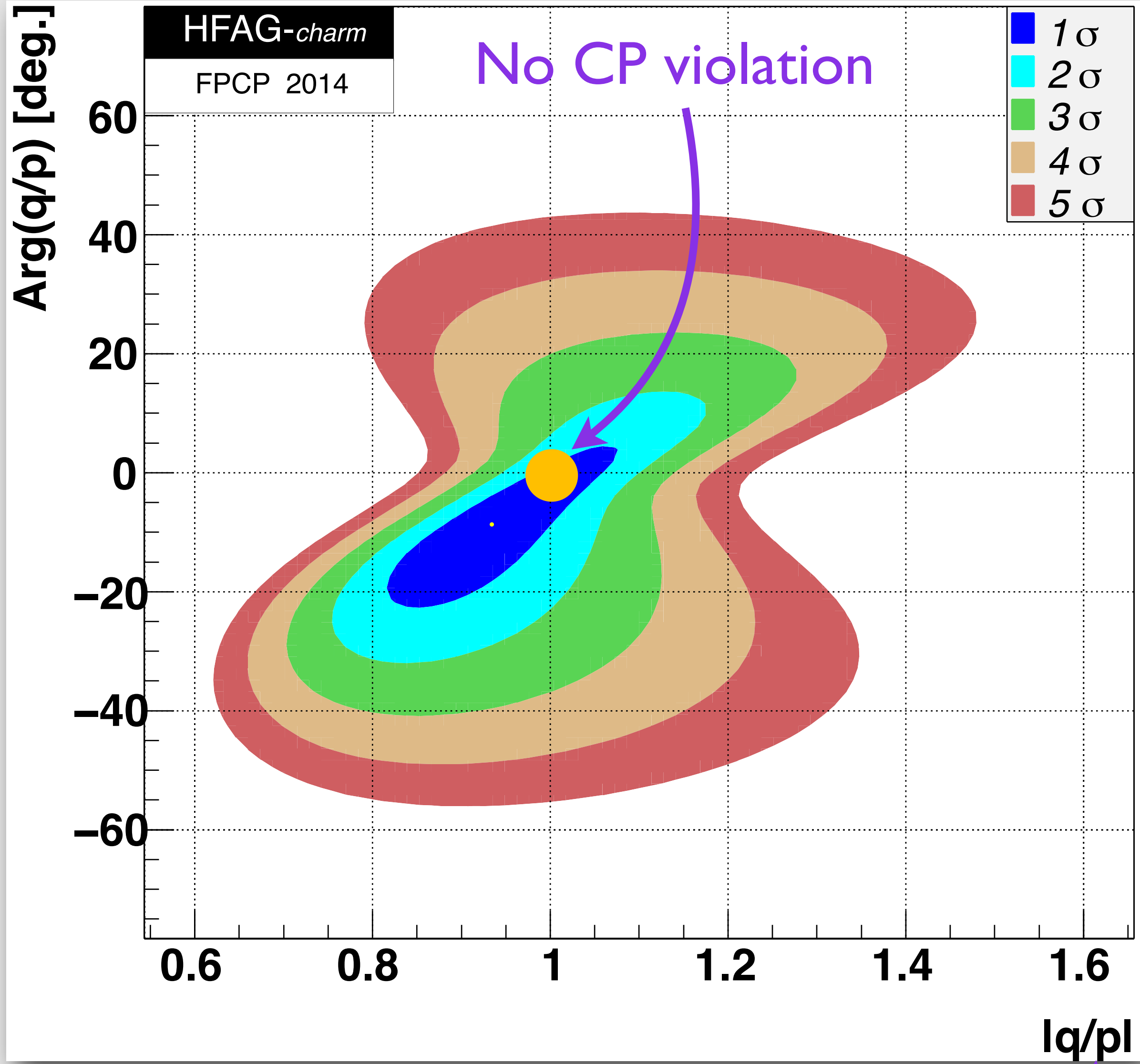
Mixing-related CP violation



Measurement based on D→Kπ decays

Measurements based on D→KK,ππ,K_Sππ decays

CP violating weak phase



No CP violation

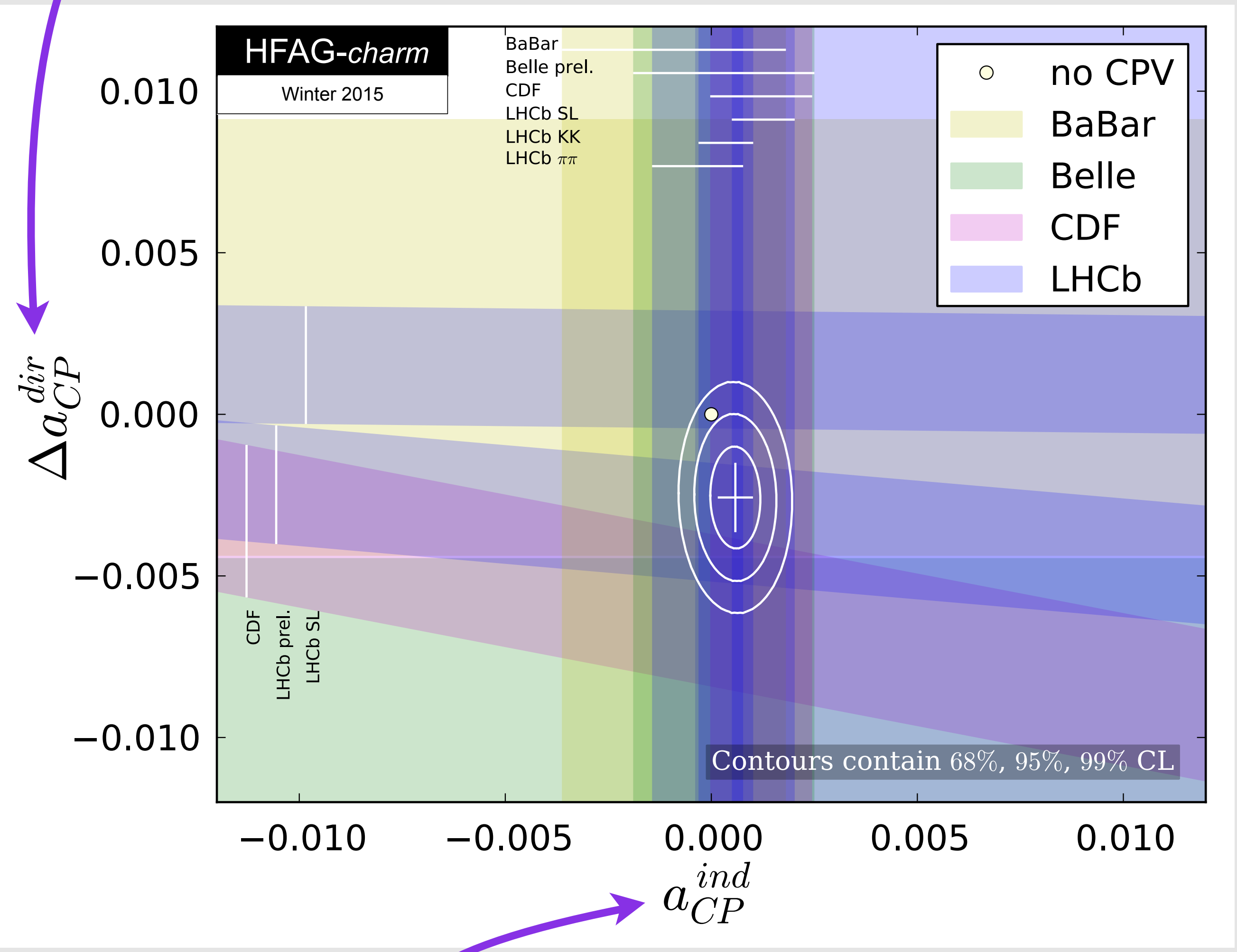
Asymmetry in mixing rate

- A range of measurements contributing
  - ➡ Combine and conquer
- Now dominated by LHCb
- Consistent with CP symmetry

CP violation

- World's best precision on charm CP violation
  - ➡ Achieved sub-10^{-3} precision
- LHCb dominating the picture
- Agreement with CP violation hypothesis at 1.8% level

CP violation in decay



Mixing-related CP violation

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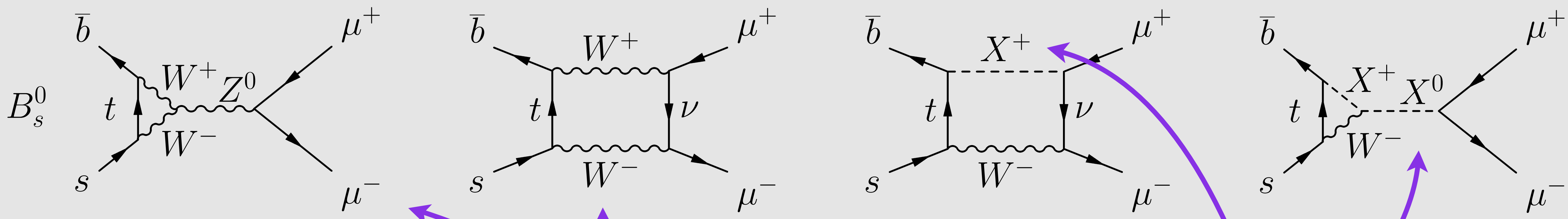
Rare decays

~~Needles in the haystack~~

Precision needle stack physics

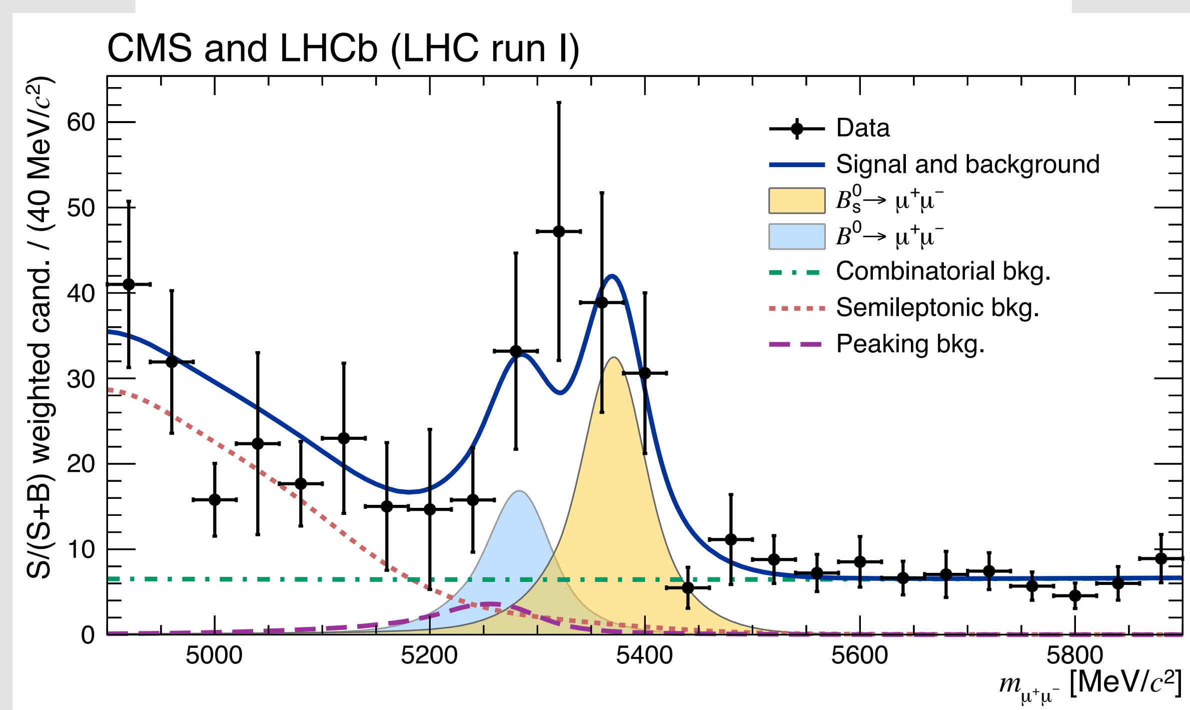
$B_{(s)} \to \mu^+\mu^-$



- Very rare decays
  - ➡ Precise SM predictions and high sensitivity to BSM physics

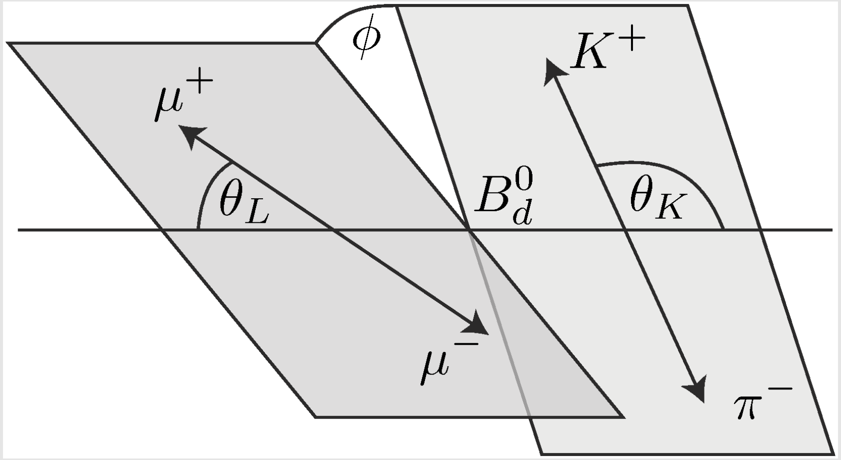
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

- Joint analysis by CMS and LHCb
- First observation of $B_s \to \mu^+\mu^-$
- First evidence for $B_d \to \mu^+\mu^-$
- No disagreement with SM
- Now measure B_d/B_s ratio, lifetime, …
  - ➡ Need much more data

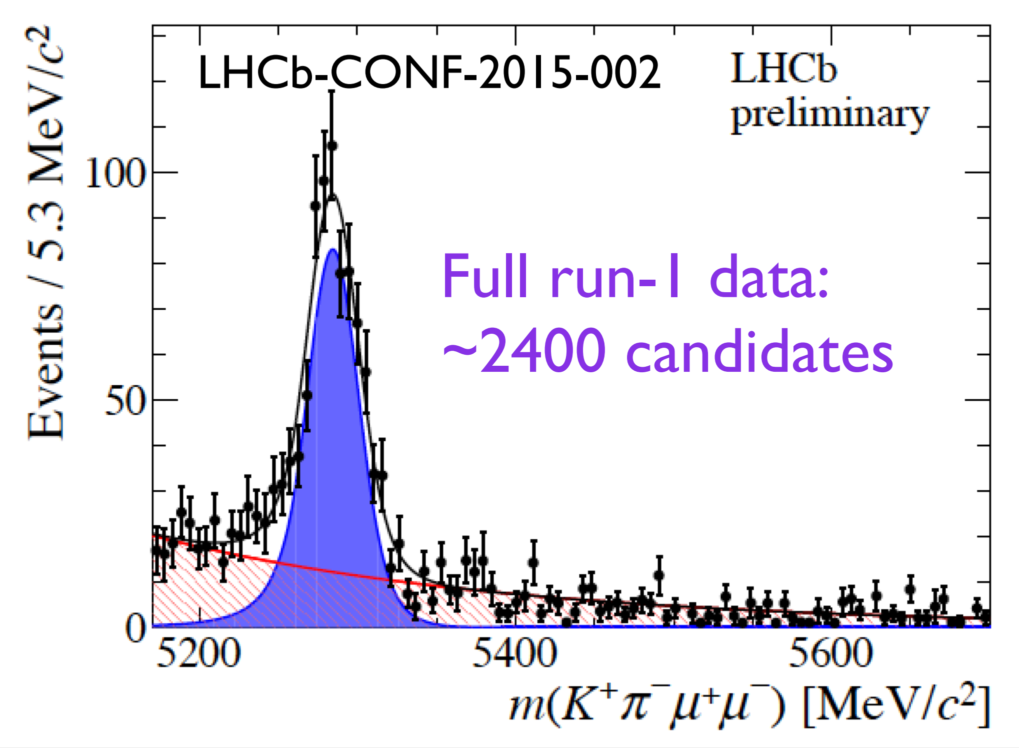


To be published in Nature tomorrow

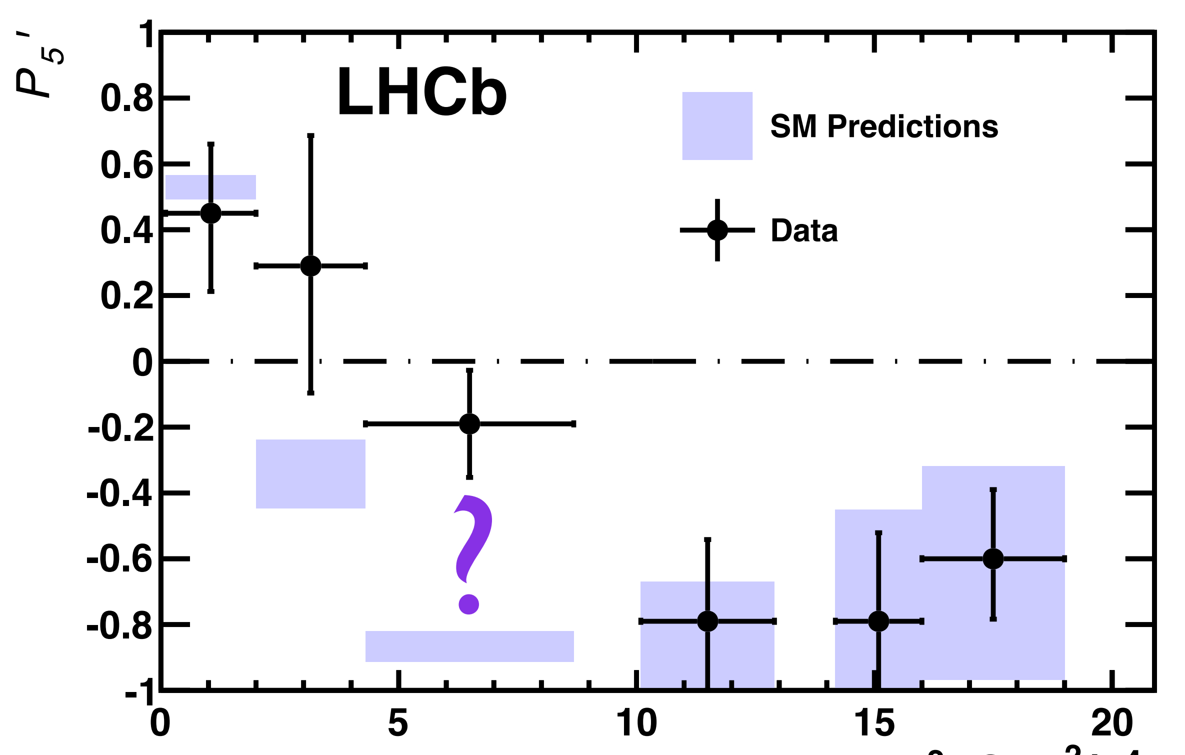
$B_d \to K^* \mu^+ \mu^-$



- Flavour-changing neutral current decay
  - ➡ Particular sensitivity to electromagnetic penguins
- Angular analysis can unravel contributions from different physics processes
  - ➡ Forward-backward asymmetry of muons, A_{FB}
  - ➡ Longitudinal polarisation fraction of K^*, $F_L \propto \cos^2\theta_K$
  - ➡ Further angular observables, S_i (i=3,4,5,6)
  - ➡ Derived observables with reduced form-factor dependence, $P_i' = S_i/\sqrt{F_L(1-F_L)}$



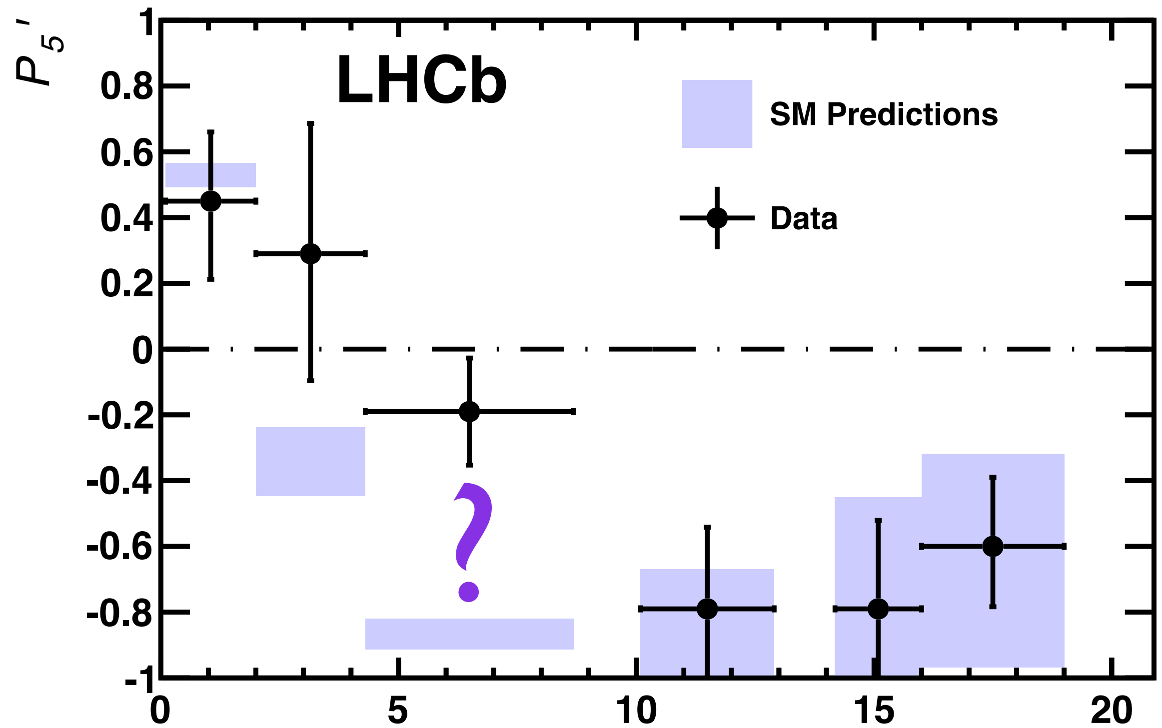
$B_d \rightarrow K^*\mu^+\mu^-$ results



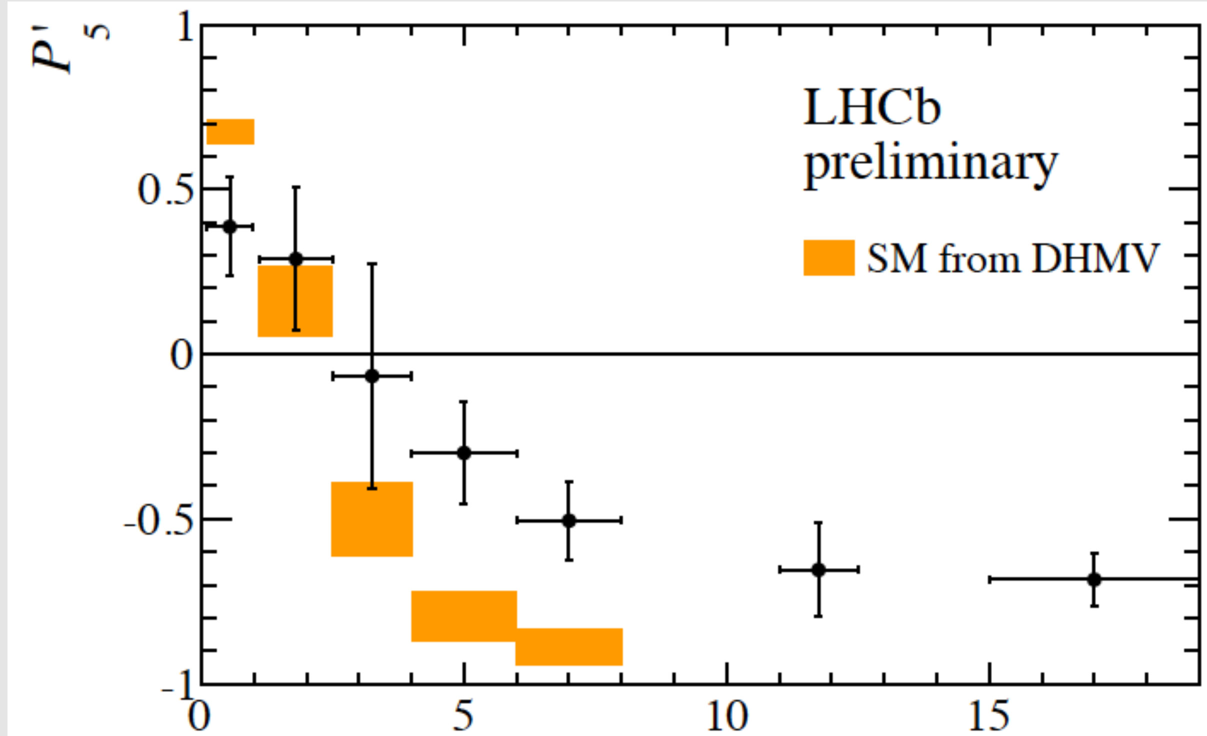
PRL 111 (2013) 191801

- Some slight surprise in P_5'

$B_d \to K^{*}\mu^{+}\mu^{-}$ results



PRL 111 (2013) 191801

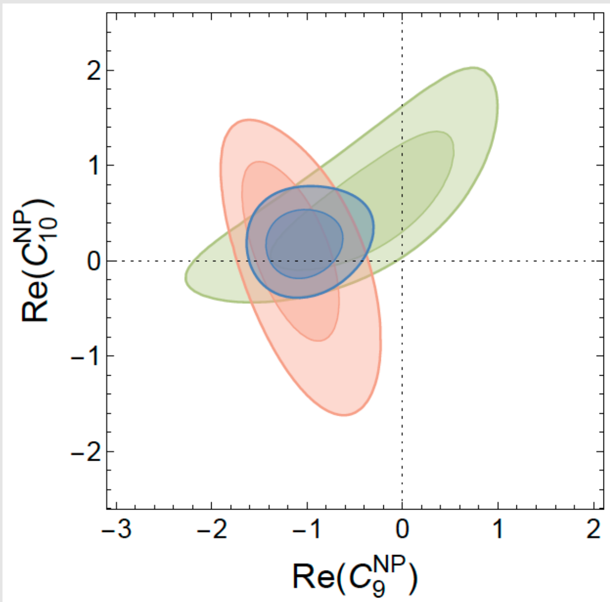


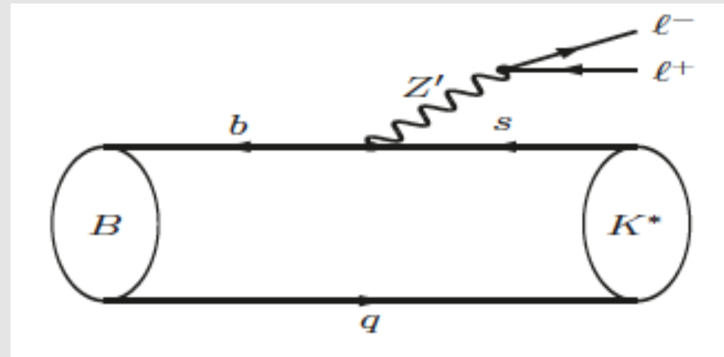
LHCb-CONF-2015-002

- Some slight surprise in P_5’
- Now measured at higher precision

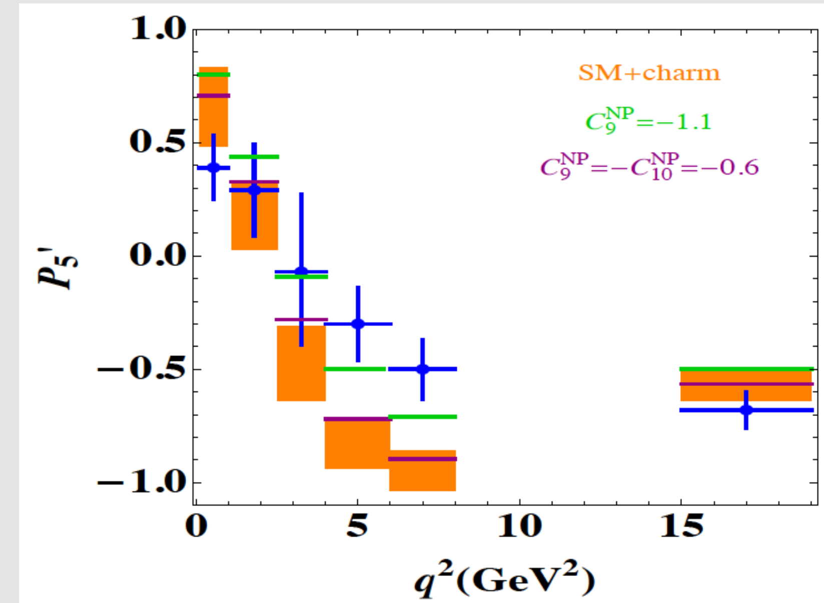
SM prediction from Descotes-Genon, Hofer, Matias, Virto, JHEP 1412 (2014) 125

Theory perspective





Z' still possible within indirect and direct constraints



- "All [New Physics model] consistency tests* we have done so far are nicely fulfilled with 3 fb^{-1} showing robustness of data." (Matias @ Moriond EW)
- "q^2 dependence indicates that (unexpectedly) huge charm effect mimicking $C_9^{NP} < 0$ at intermediate q^2 could solve the tensions as well." (Straub @ Moriond EW)

* **Relevant Observables included**: $B \to K^*\mu^+\mu^-$ ($P_{1,2}$, $P'_{4,5,6,8}$, F_L in all 5 large-recoil + low-recoil), $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0\mu^+\mu^-$, $\mathcal{B}_{B\to X_s\gamma}$, $\mathcal{B}_{B\to X_s\mu^+\mu^-}$, $\mathcal{B}_{B_s\to\mu^+\mu^-}$, $A_I(B \to K^*\gamma)$, $S_{K^*\gamma}$

Many more LHCb results adding to the picture!

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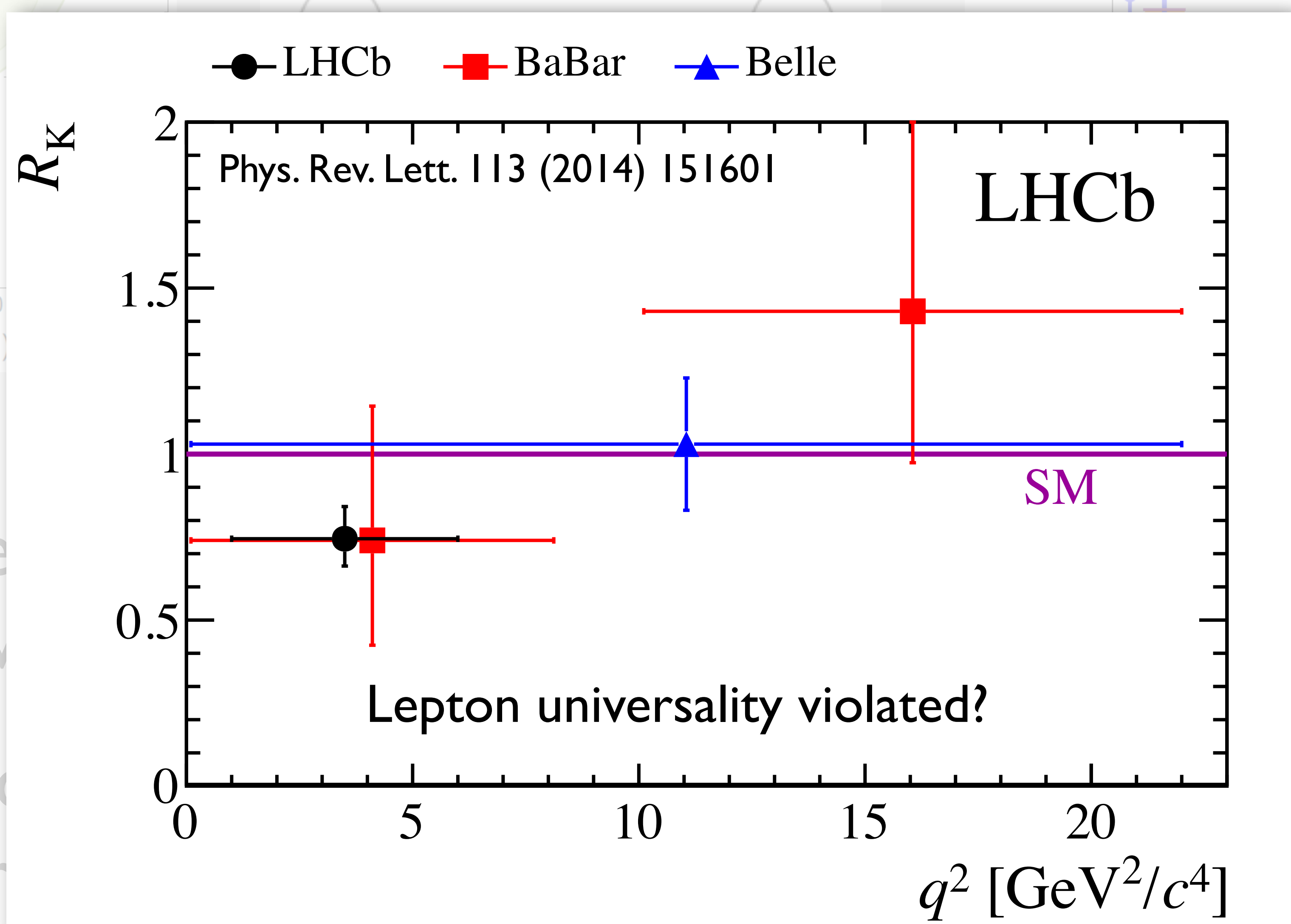
Theory perspective

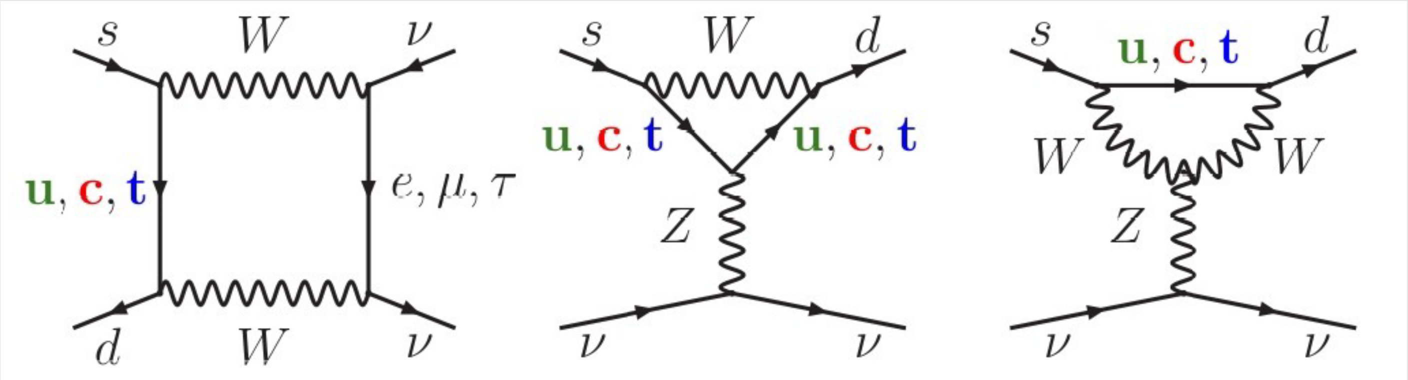


- “All ... * we have ... b^{-1} show ...
- “q^2 ... ly) huge char... ediate q^2 could solve the tensions as well.” (Straub @ Moriond EW)

* **Relevant Observables included**: $B \to K^*\mu^+\mu^-$ ($P_{1,2}$, $P'_{4,5,6,8}$, F_L in all 5 large-recoil + low-recoil), $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0\mu^+\mu^-$, $\mathcal{B}_{B\to X_s\gamma}$, $\mathcal{B}_{B\to X_s\mu^+\mu^-}$, $\mathcal{B}_{B_s\to\mu^+\mu^-}$, $A_I(B \to K^*\gamma)$, $S_{K^*\gamma}$

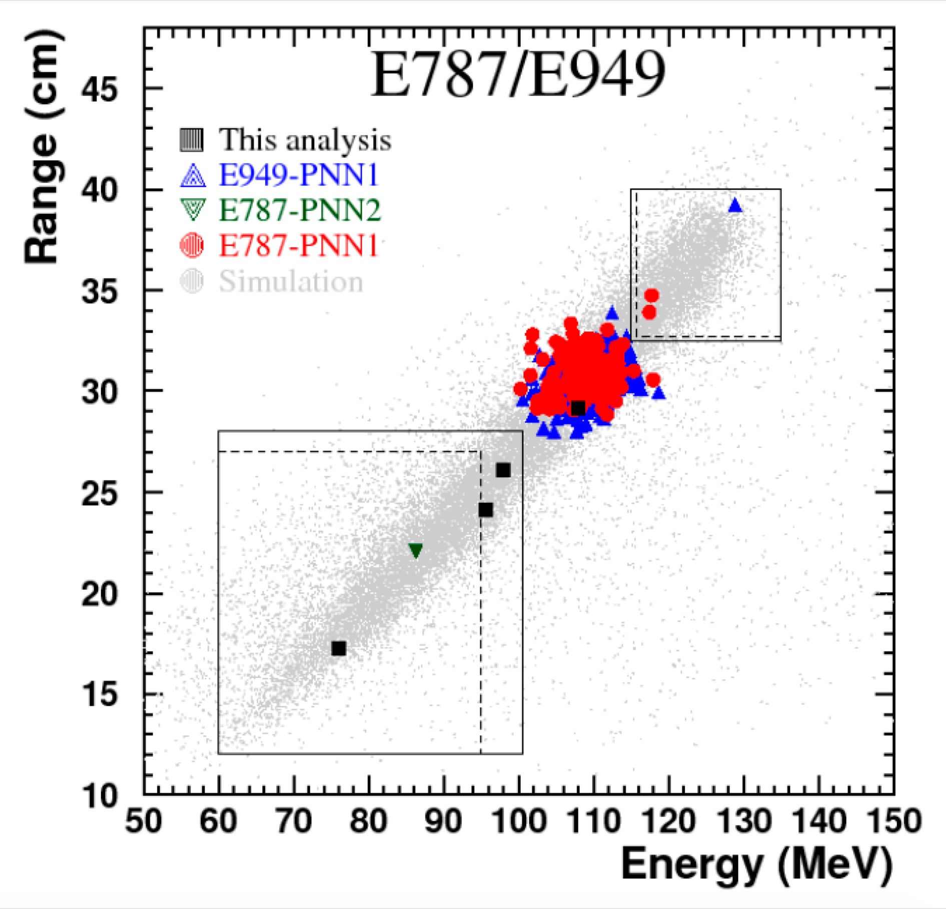
Many more LHCb results adding to the picture!

$K^+ \to \pi^+ \nu\bar{\nu}$



- Precise SM predictions
  - ➡ $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (7.8 \pm 0.8 \pm 0.3) \times 10^{-11}$
- Sensitive to contributions from beyond SM
- Dedicated experiment running at CERN
  - ➡ NA62
- Experimental challenge
  - ➡ Final state with only one out of three particles detectable
- Aim
  - ➡ Collect 100 events at SM BR

Previous experiments

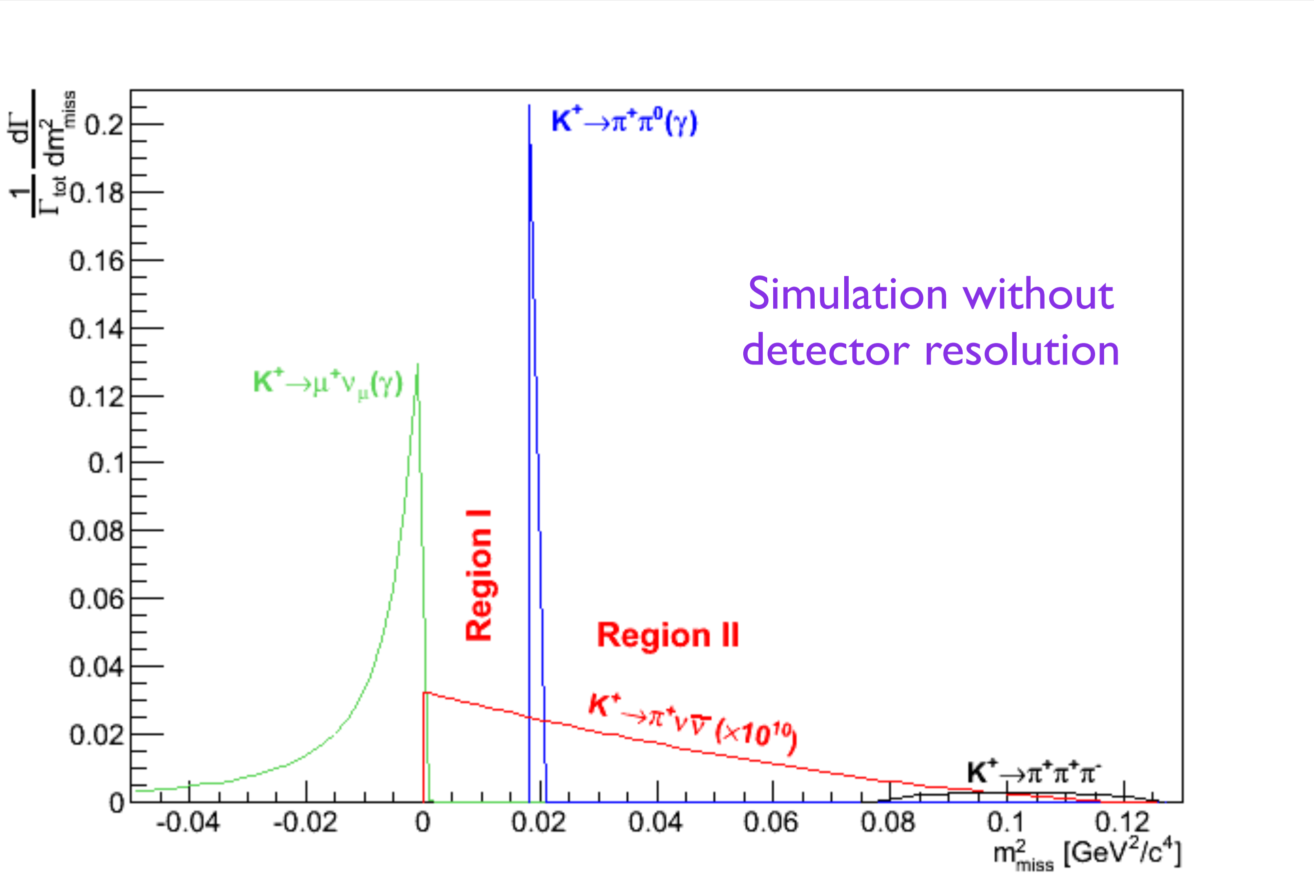


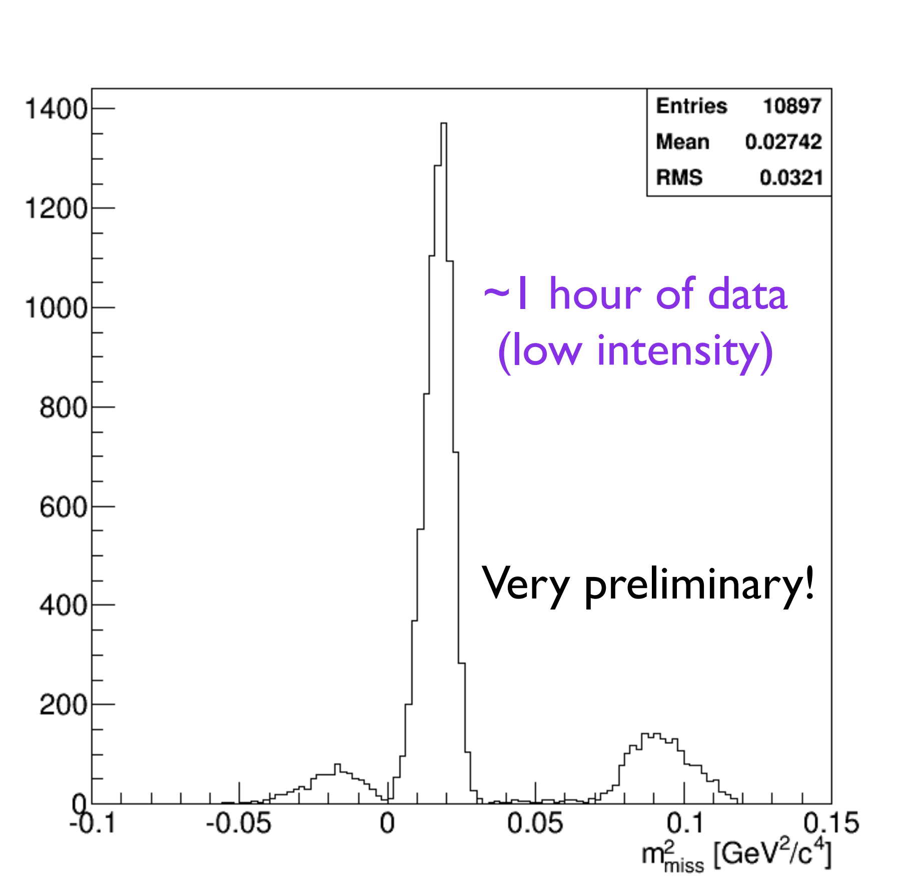
$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.7 \pm 1.1) \times 10^{-10}$

PRD 77 (2008) 052003, PRD 79 (2009) 092004

First NA62 data

- Close to online snapshot
  - ➡ No kaon tracker, no photon rejection, no alignment, preliminary reconstruction, …
- Distributions match expectations for this level of reconstruction
  - ➡ Promising for final performance
- Physics runs starting 2015





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A brief visit to the particle zoo

Other physics areas

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Some examples

Exotica
- X(3872)
- $Z(4430)^-$
- Tetraquarks?

Central exclusive production
- Improving HERA PDF measurements
- J/ψ, X(3872), Υ production
- Forward shower counters

. . .

Production & Spectroscopy
- $\Xi_b'^-$, Ξ_b^{*-}
- Hadron decays to Spin-3 state

Electroweak physics
- Associated W/Z production
- Forward energy flow
- Top production

Heavy ion collisions
- Ridge analysis
- Production in p-Pb collisions

Forbidden decays
- Lepton-flavour violation
- τ decays

→ link to all >260 LHCb papers

Some examples

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Exotica
X(3872)
$Z(4430)^-$
Tetraquarks?

Improving HERA PDF measurements

J/ψ, X(3872), Υ production

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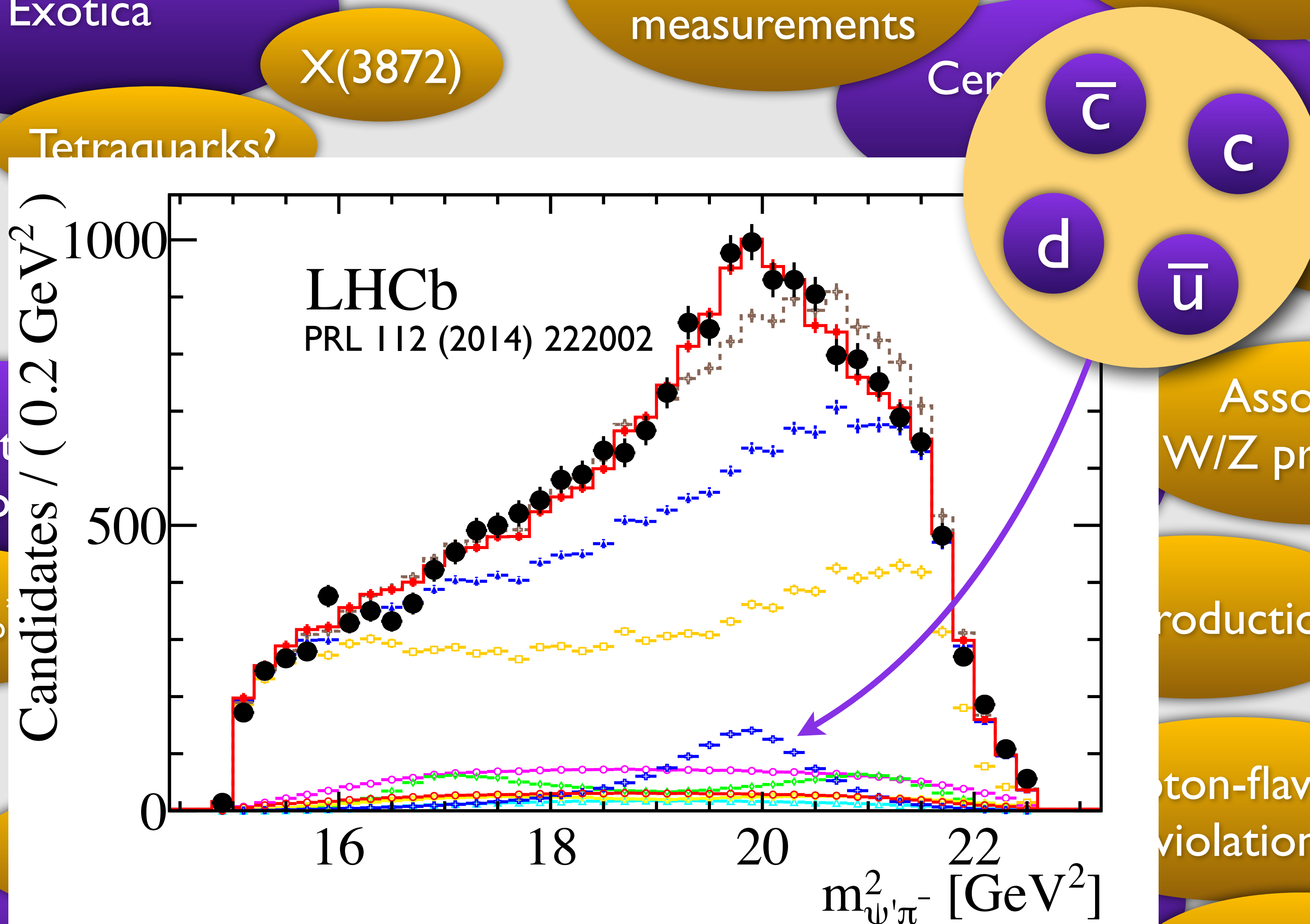

→ link to all >260 LHCb papers

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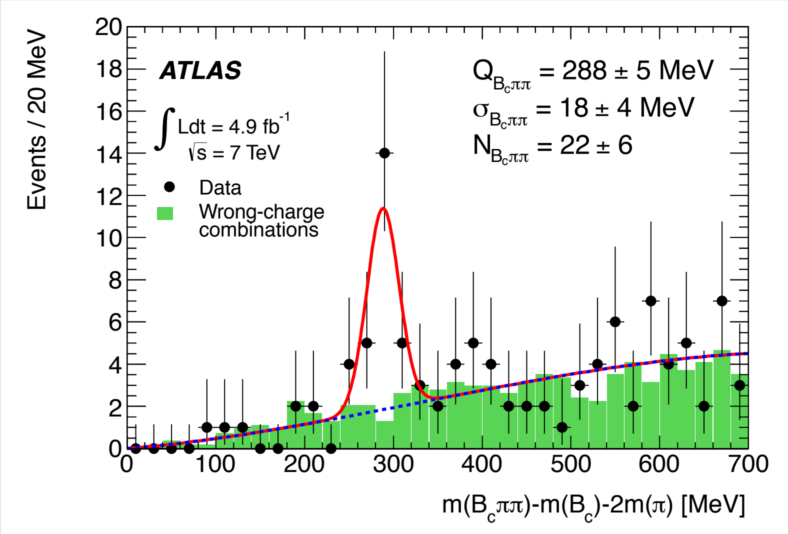
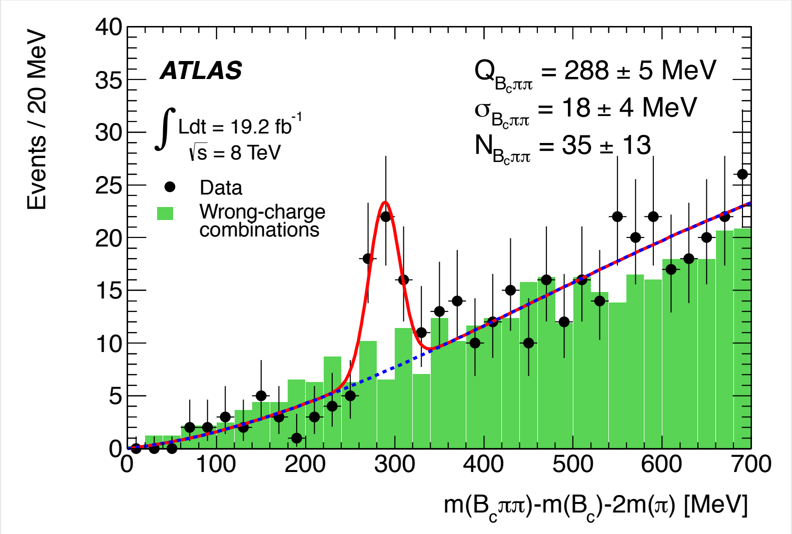
New states

- Excited B_c meson state found
  - ➡ $B_c(2S)$, ATLAS, PRL 113 (2014) 212004
- Two excited beauty baryons found
  - ➡ Ξ_b', Ξ_b^*, LHCb, PRL 114 (2015) 062004
- And others also from Belle, BESIII, CMS, …
- Slowly completing the quark model

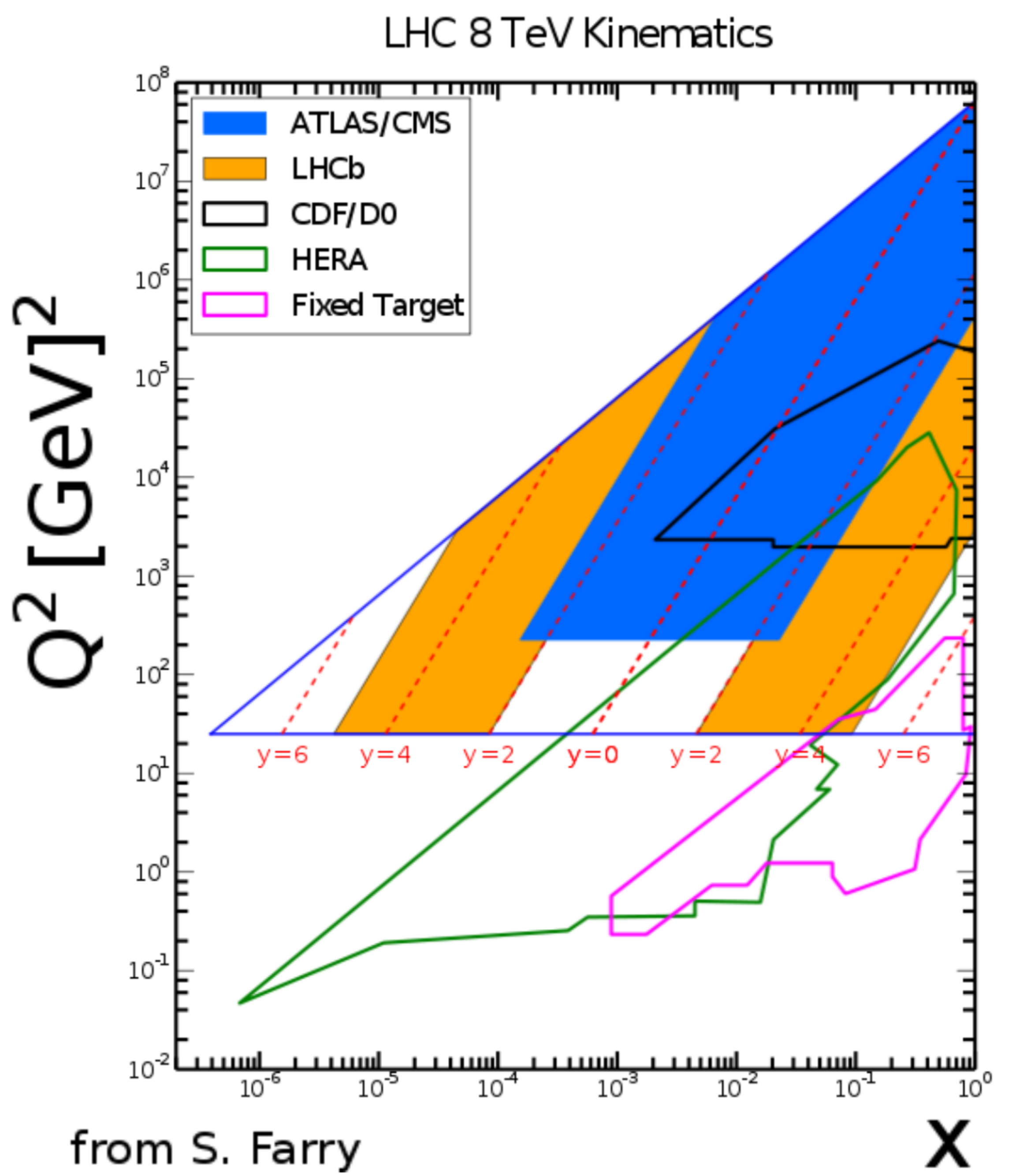




Italic Pig

Lison Bernet

Proton structure

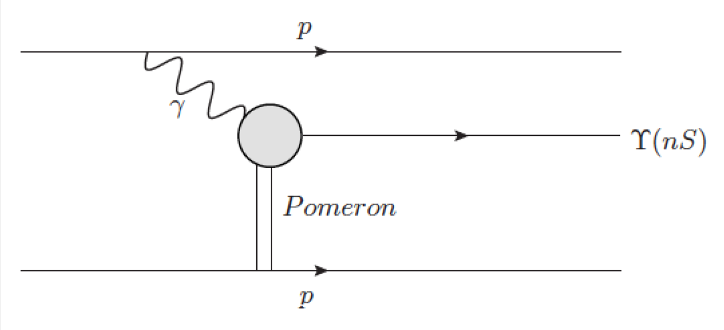


from S. Farry

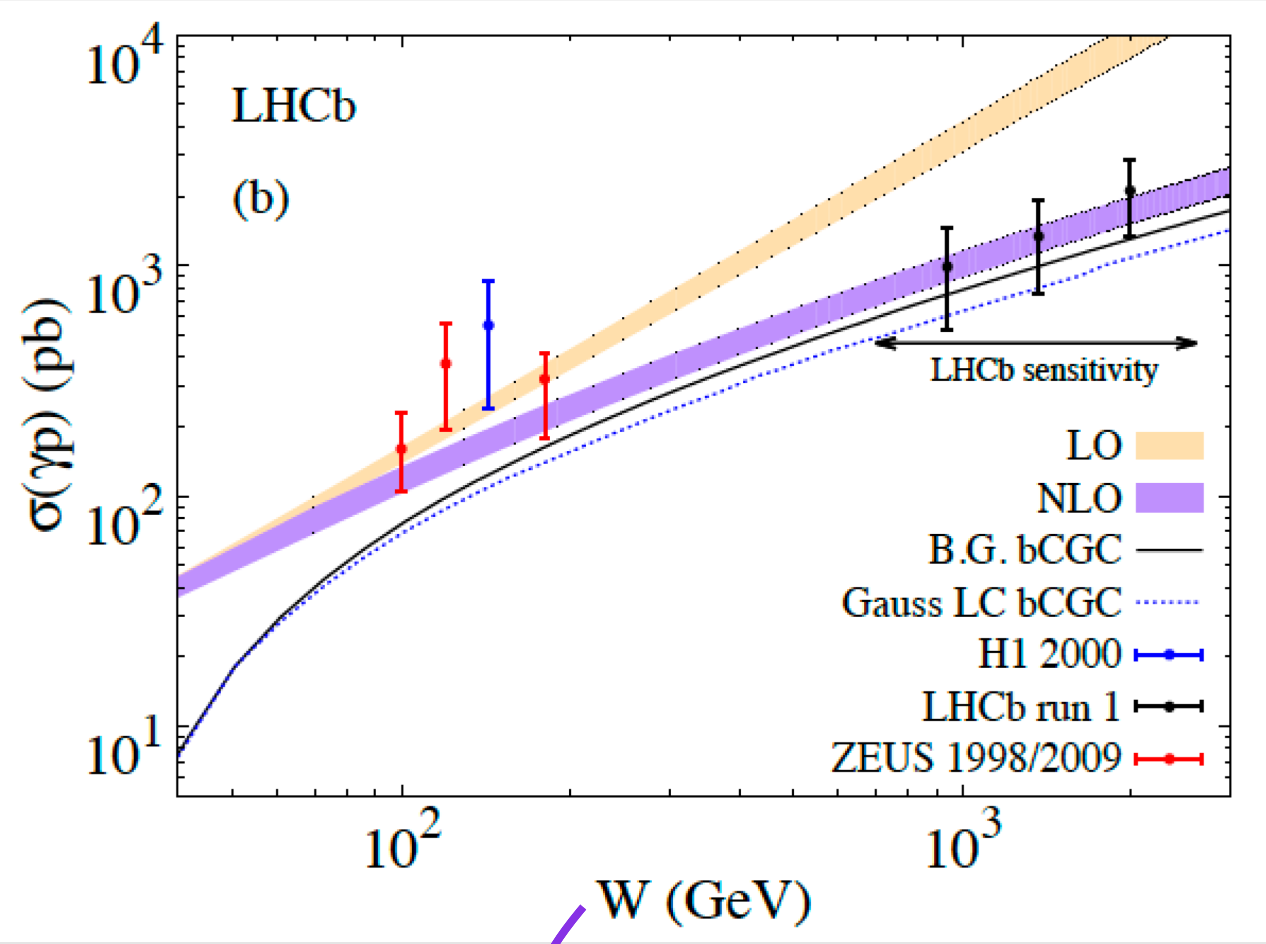
$$Q^2(x) = e^{\pm 2y} x^2 s$$

- Unique kinematic range
  - ➡ High-energy collisions
  - ➡ Forward acceptance
- Probing very low Bjorken-x at much higher momentum transfer compared to HERA

Central exclusive production



- Can measure central exclusive production
  - ➡ Signal tracks plus otherwise empty detector
  - ➡ Mediated through pompon exchange
- New Υ production results allow to judge on convergence of theory prediction
  - ➡ Probe gluon PDF at low x
- Much increased potential during run-2
  - ➡ Installed forward shower counters



pϒ invariant mass

1505.08139, submitted to JHEP

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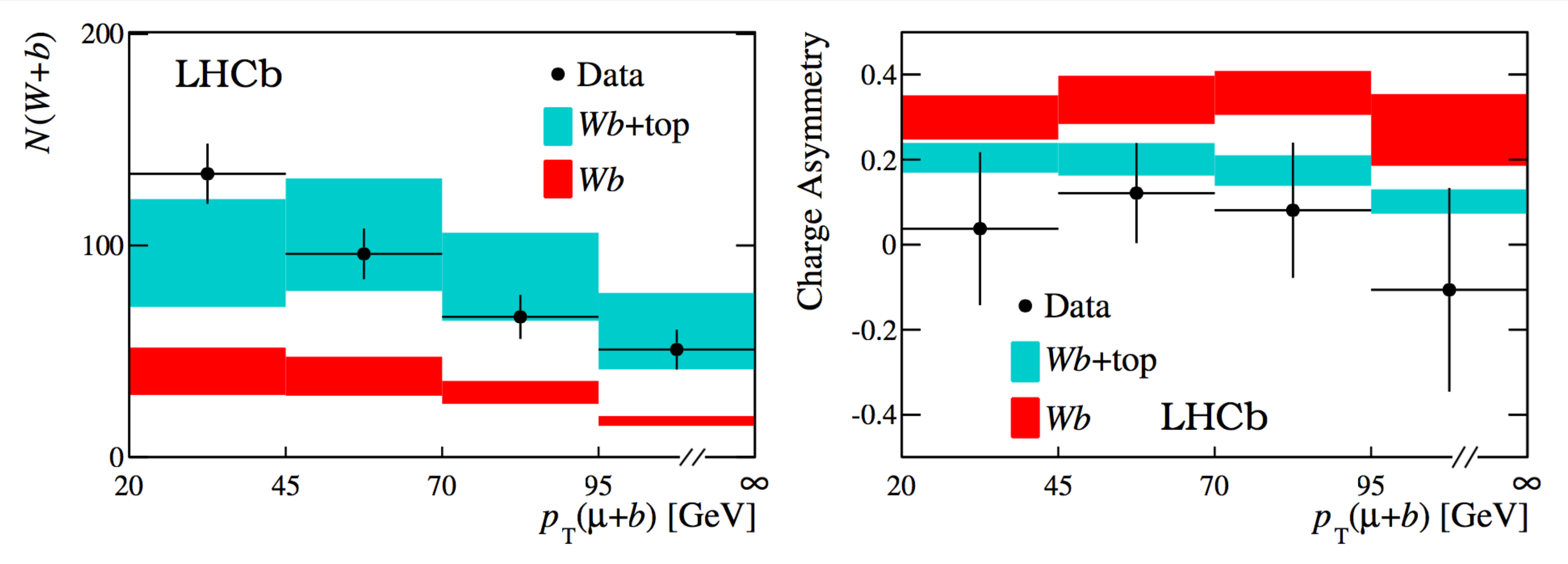
Top production

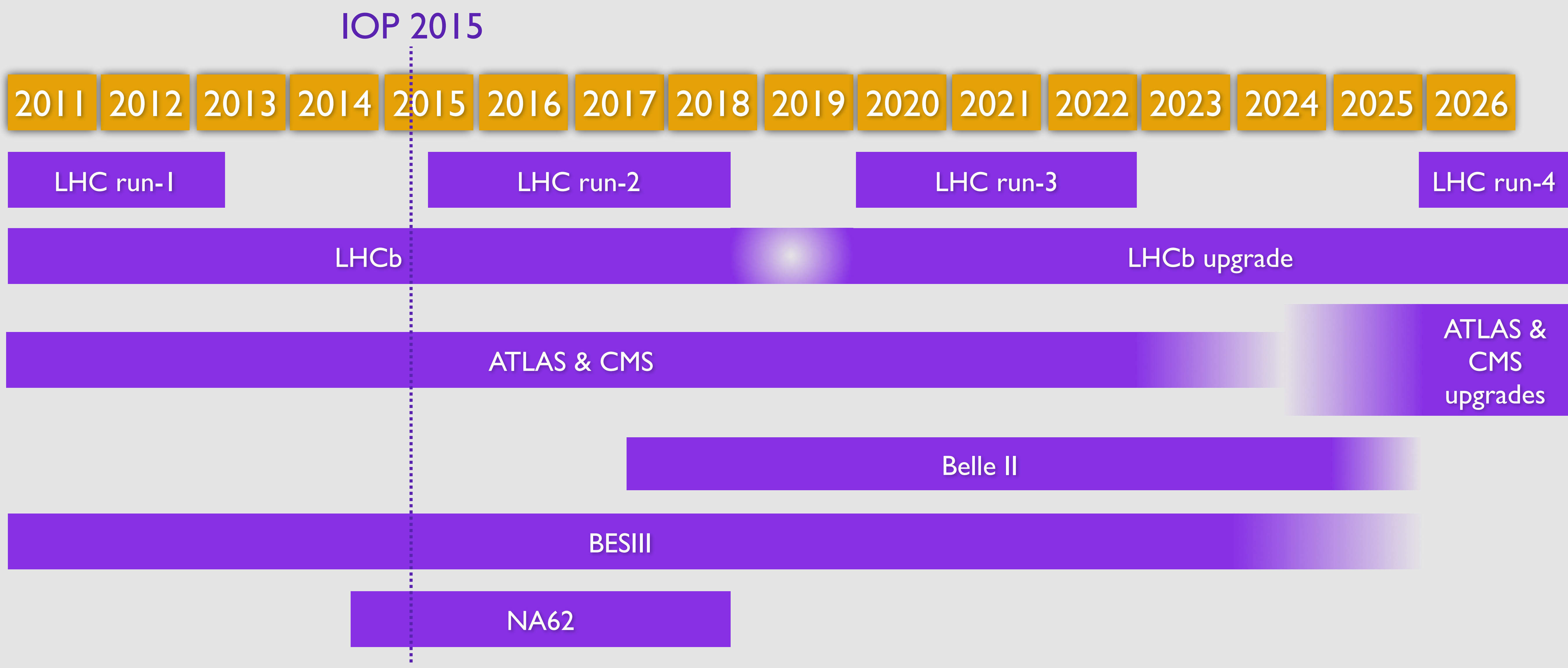
- Combined measurement of single-top and $t\bar{t}$ production in forward region
- Based on μ + b-jet reconstruction
- b and c jet tagging
  arXiv:1504.07670, accepted by JINST
  ➡ 2 BDTs, secondary vertex detection, corrected mass
- W+b,c production (asymmetry) measurement
  arXiv:1505.04051, submitted to PRD
- 5.4σ observation of top production
  arXiv:1506.00903, submitted to PRL



Future directions

Upgrading flavour experiments

A flavourful decade



- Plus lots of activity on charged lepton flavour
  - ➡ MEG, mu3e, mu2e, COMET, g-2, …

NA62

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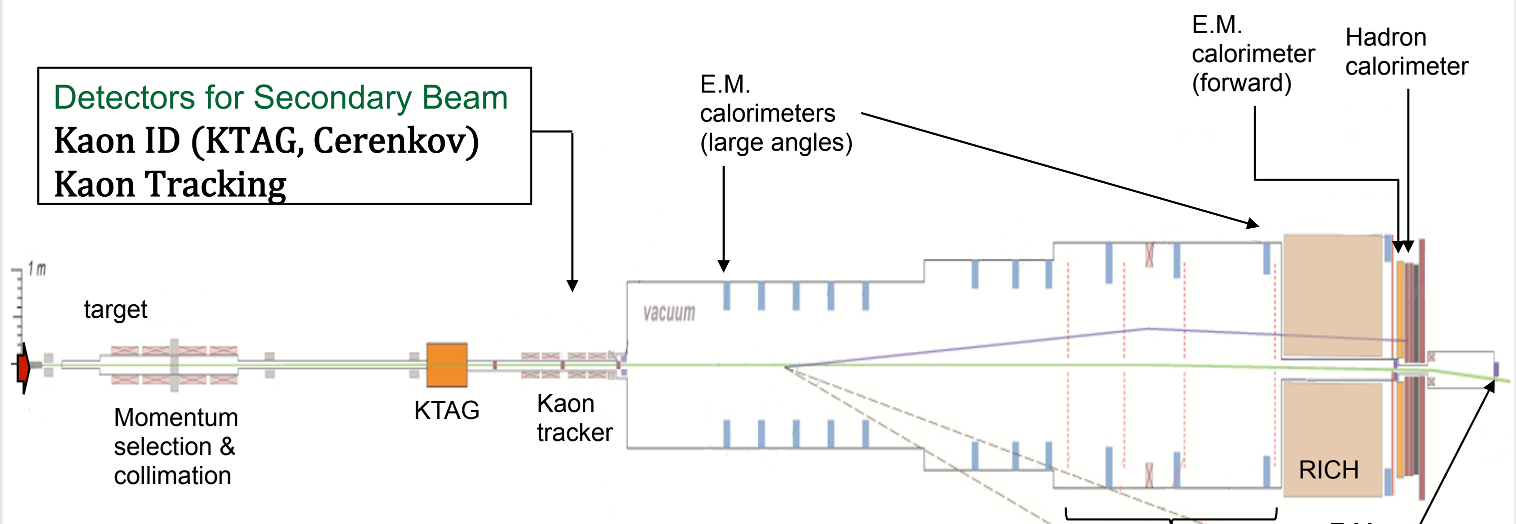
IOP 2015

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026

NA62

- NA62
  - ➡ Pilot run for detector commissioning in 2014
  - ➡ Detector completion in 2015
  - ➡ Runs scheduled until LS2



Fixed target experiment with initial kaon tracking and hermetic coverage

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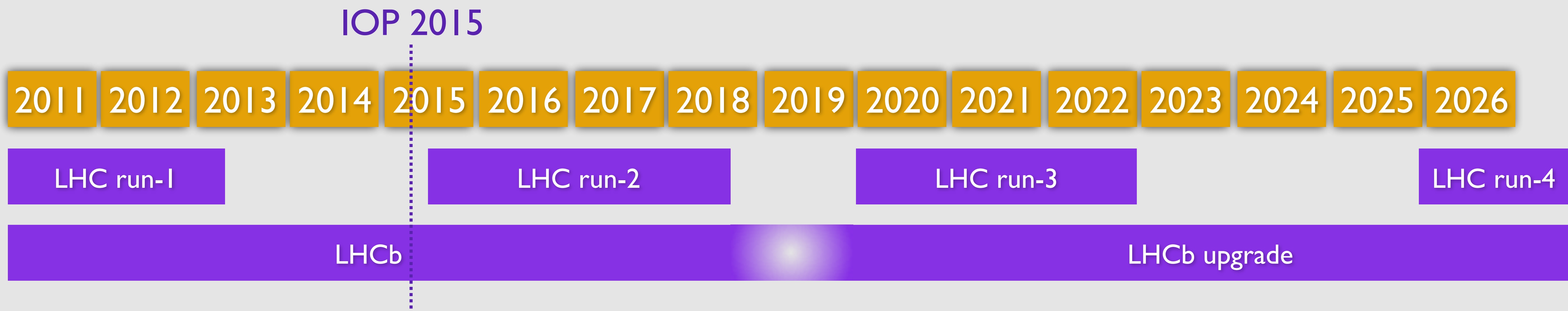
LHCb upgrade

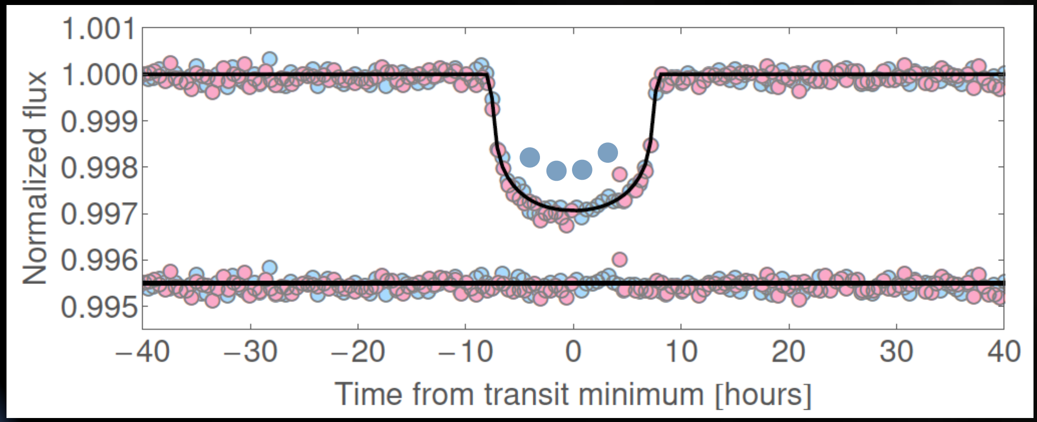


- R&D ongoing and on schedule
- Installation planned for LHC long shutdown 2
- Major construction project
  - ➡ Vertex Locator and RICH built in UK
- Full software trigger
  - ➡ Massively improved trigger efficiencies
  - ➡ Offline quality reconstruction in trigger
- Maintain/improve current level of detector performance

Conclusion

- LHC(b) now taken over leading role in flavour physics
- No smoking gun signal for physics beyond the SM
  - ➡ Several hints demand more precise and complementary measurements as well as advances on the theoretical side
- Good chance that strong signals will emerge with run-2
  - ➡ Including from NA62
- Need LHCb upgrade to probe to Standard Model level precision
- Next decade will be flavourful
  - ➡ Belle II, BESIII, COMET, g-2, LHCb run-2, LHCb upgrade, MEG, mu2e, mu3e, NA62

Conclusion



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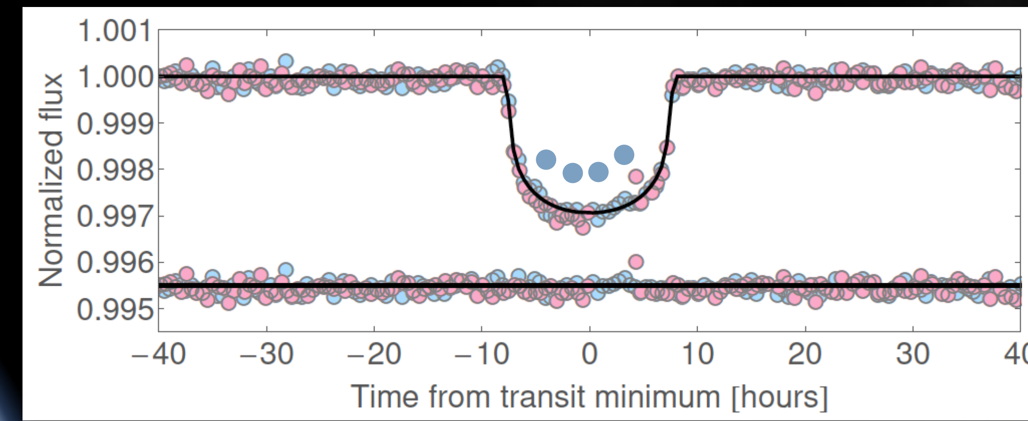
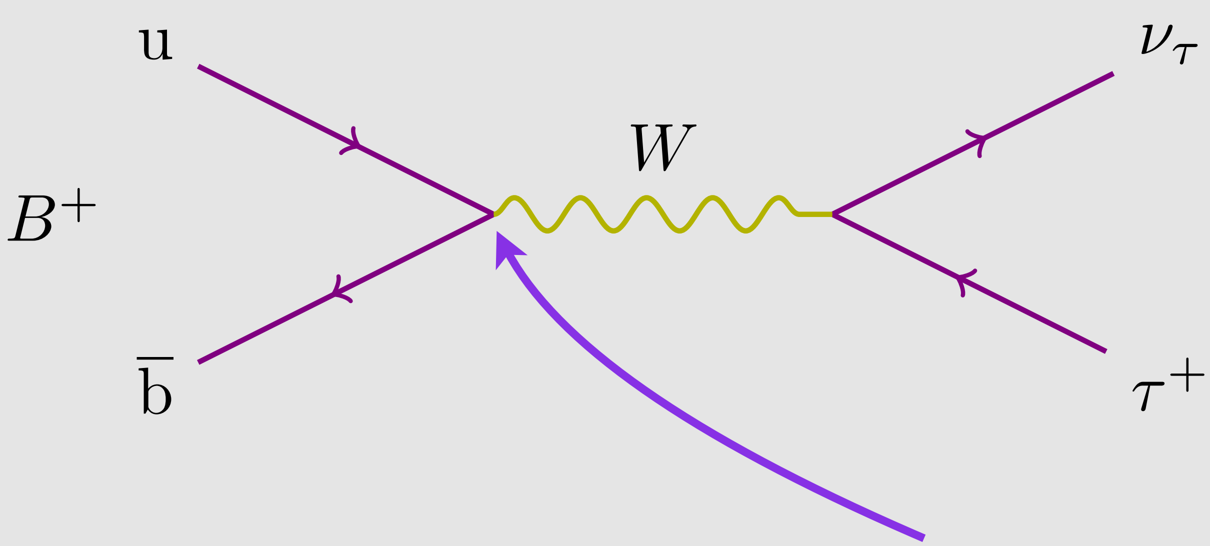
- Many thanks to
  - Wolfgang Altmannshofer
  - Pete Clarke
  - Greig Cowan
  - Markus Cristinziani
  - Wolfgang Gradl
  - Iskander Ibragimov
  - Moritz Karbach
  - Patrick Koppenburg
  - Sören Lange
  - Frank Meier
  - Matthew Molson
  - Franz Muheim
  - Patrick Owen
  - Chris Parkes
  - Darren Price
  - Guiseppe Ruggiero
  - Will Sutcliffe
  - Philip Urqijo
  - Rainer Wanke

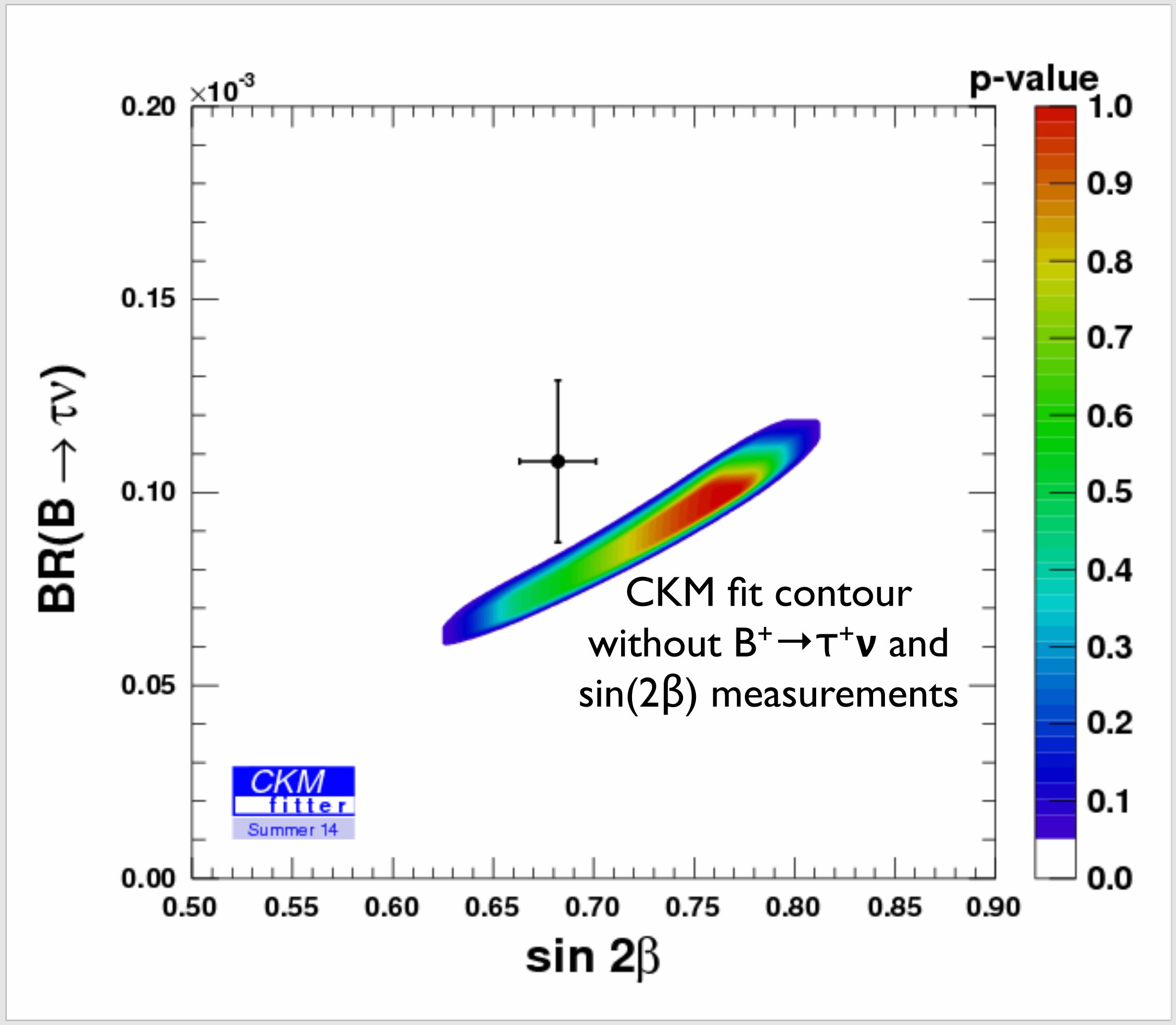


BACKUP

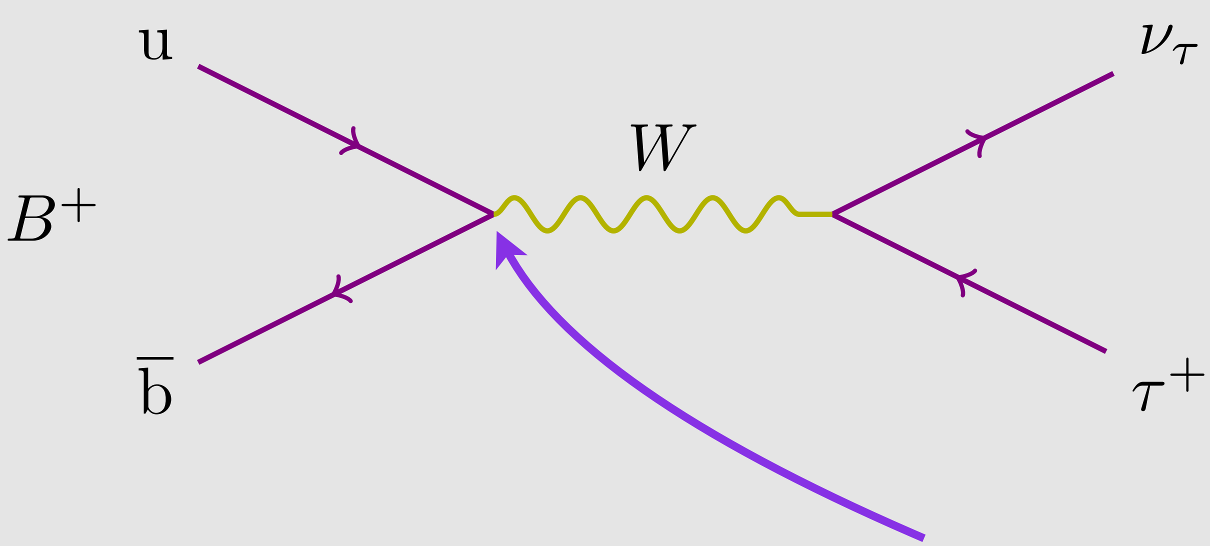
$B^+ \to \tau^+ \nu$



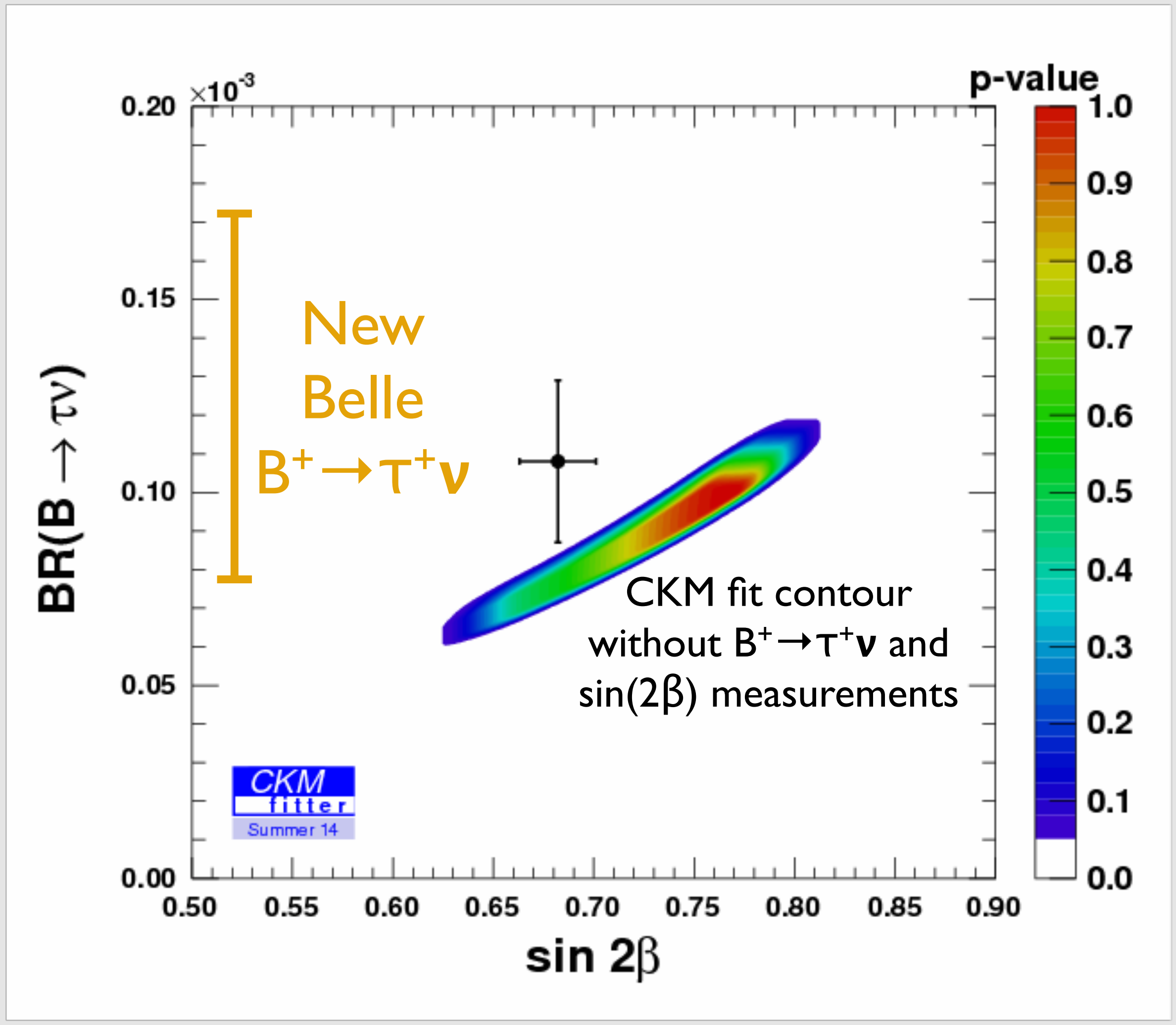
- Proportional to $|V_{ub}|$
- Slight discrepancy between sin(2β) and BR($B \to \tau\nu$)



$B^+ \to \tau^+ \nu$

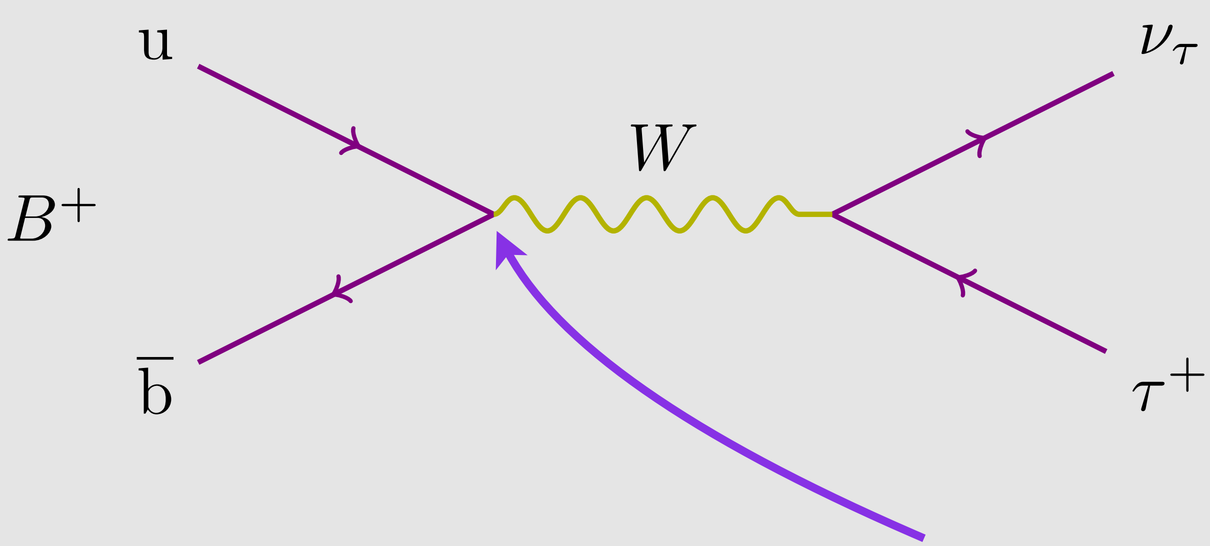


- Proportional to $|V_{ub}|$
- Slight discrepancy between sin(2β) and BR(B→τν)

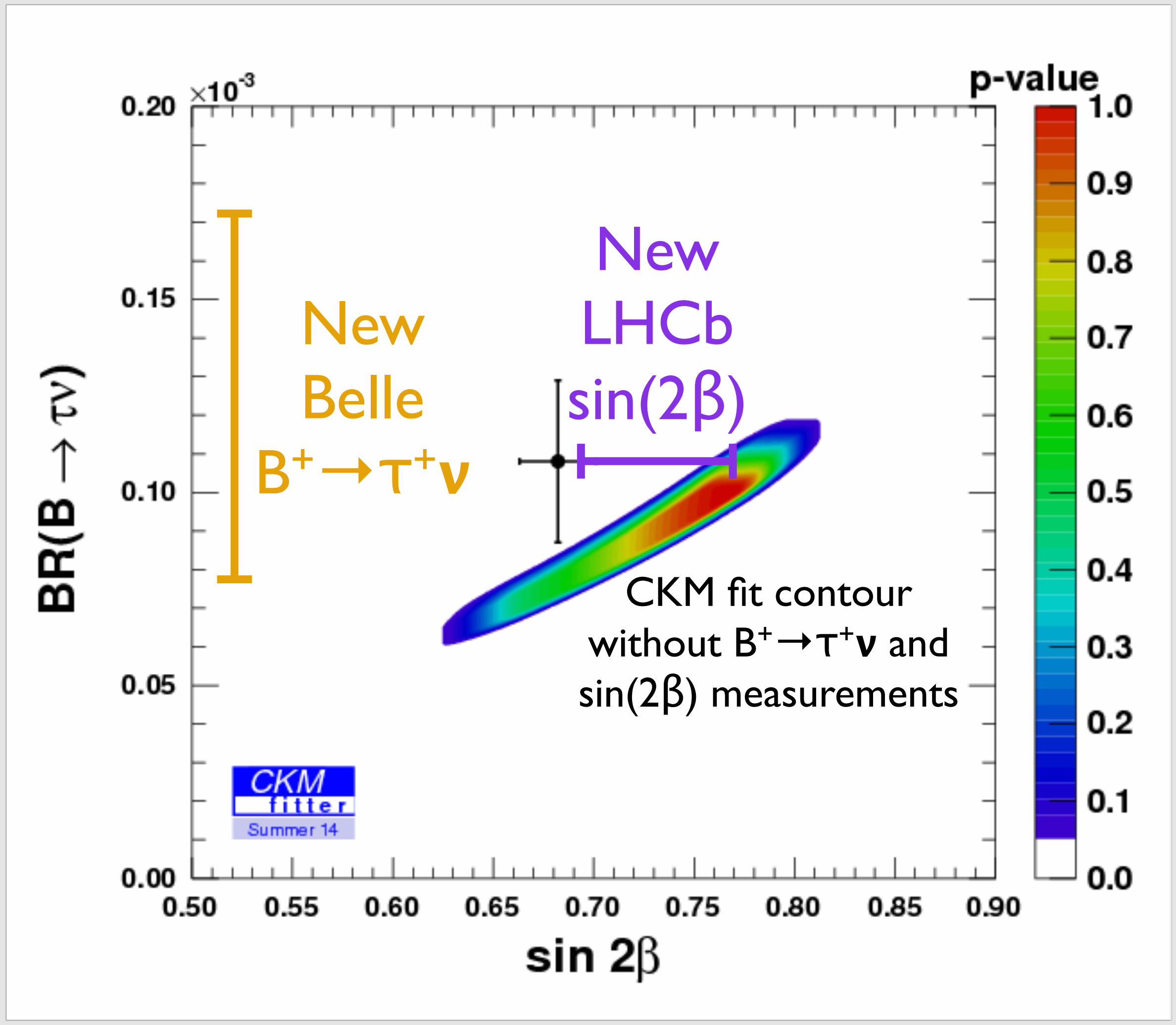


Belle, $B^+ \to \tau^+ \nu$, arXiv:1409.5269

$B^+ \to \tau^+ \nu$

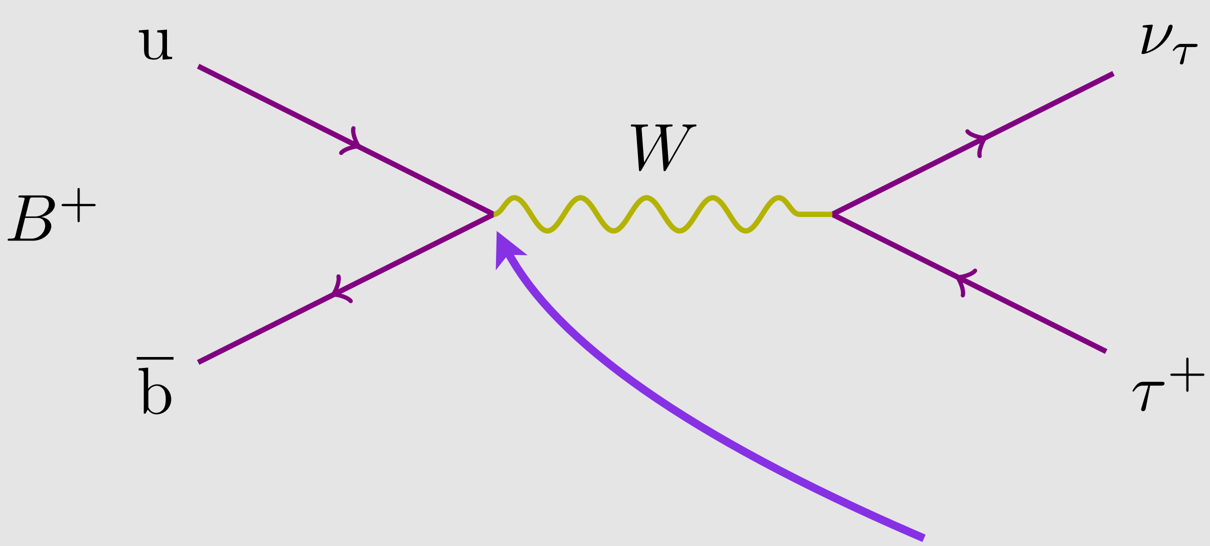


- Proportional to $|V_{ub}|$
- Slight discrepancy between $\sin(2\beta)$ and $BR(B \to \tau\nu)$



Belle, $B^+ \to \tau^+ \nu$, arXiv:1409.5269
LHCb, $\sin(2\beta)$, arXiv:1503.07089

$B^+ \to \tau^+ \nu$



- Proportional to $|V_{ub}|$
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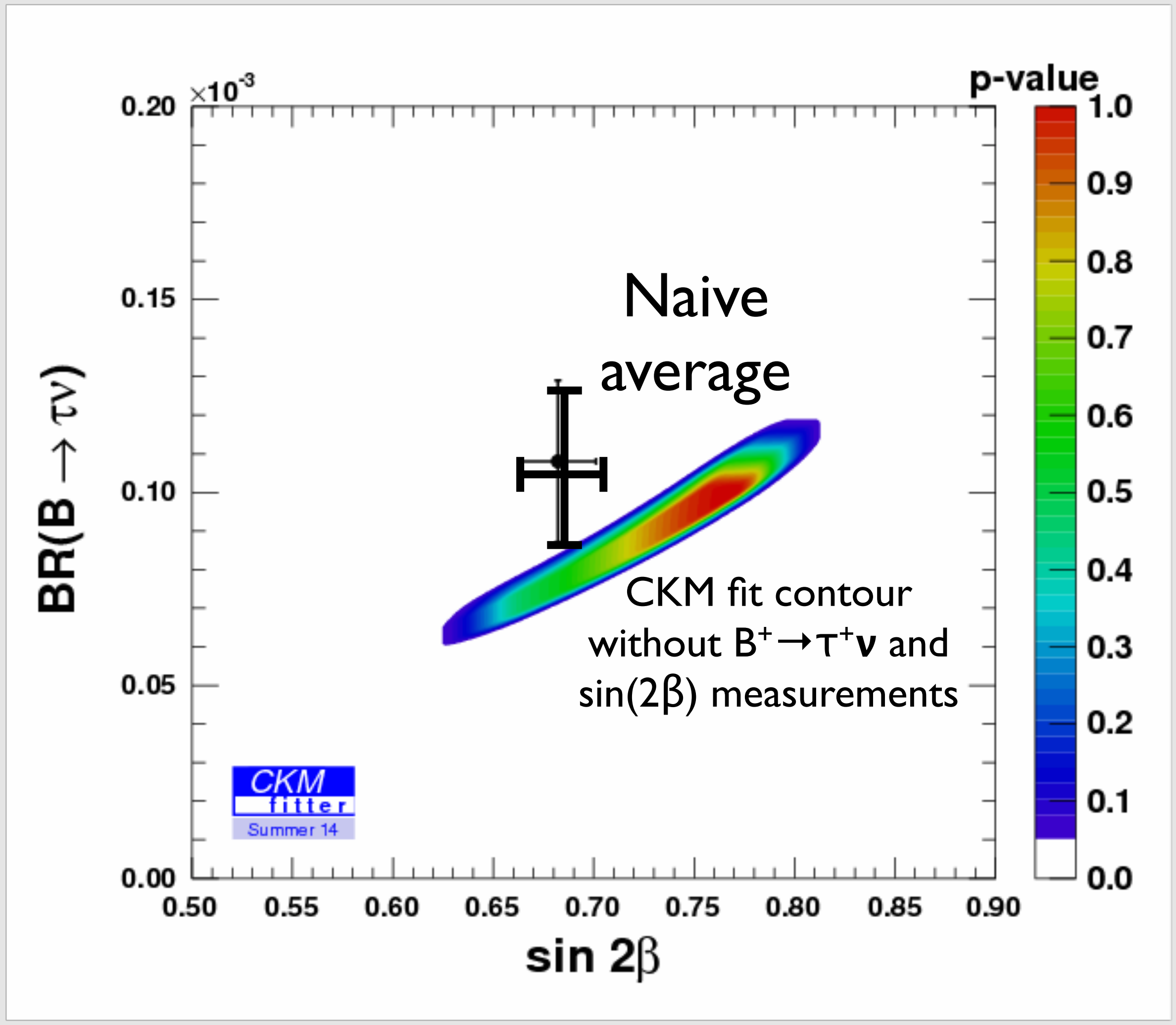
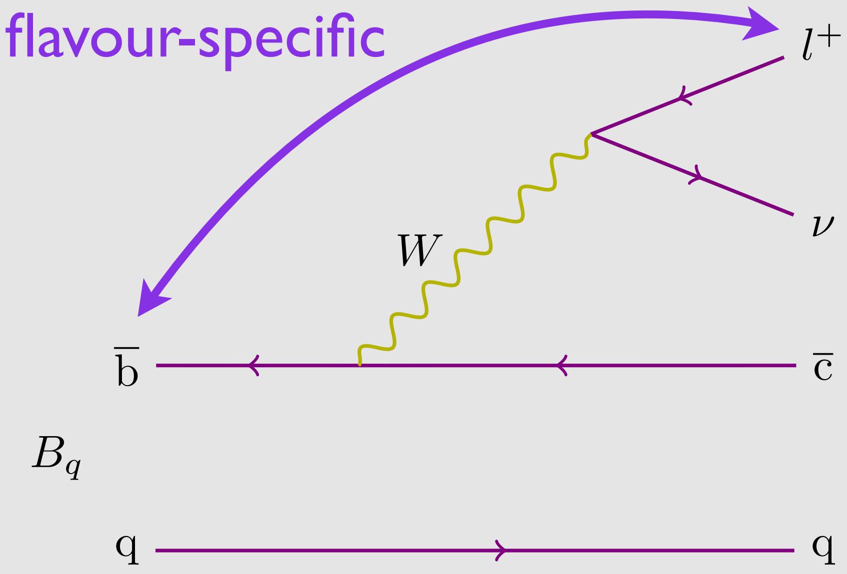


Belle, $B^+ \to \tau^+ \nu$, arXiv:1409.5269
LHCb, $\sin(2\beta)$, arXiv:1503.07089

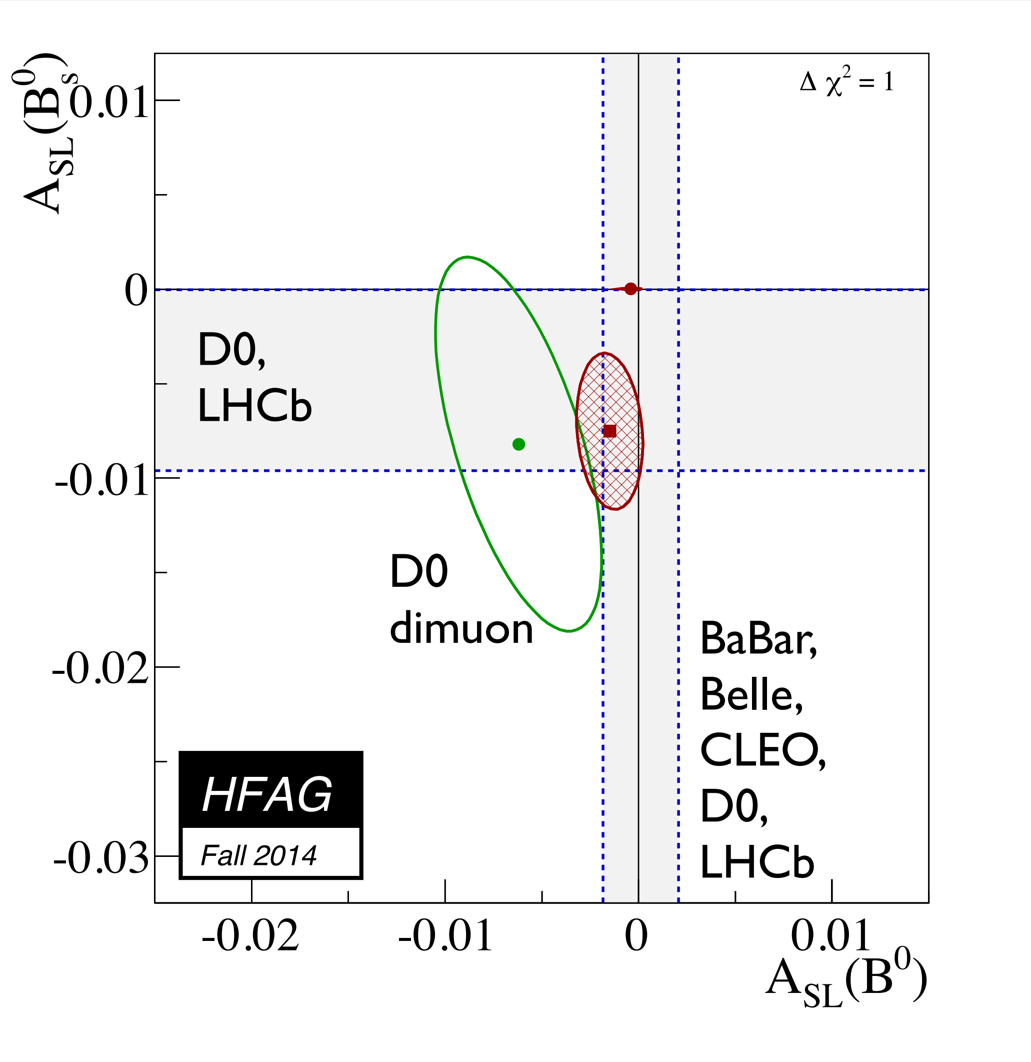
CP violation in mixing



- Look for $\bar{B} \to l^+$ decays
  - ➡ Forbidden directly, requires $\bar{B} \to B$ oscillation
- Measure asymmetry of $\bar{B} \to l^+$ and $B \to l^-$ rates
  - ➡ CP violation in mixing
- SM expectation far below current sensitivity
- Can measure this separately for B_d and B_s mesons
  - ➡ Separate access to $A_{sl}(B_d)$ & $A_{sl}(B_S)$
- Alternatively look for same-sign lepton pairs and compare l^+l^+ with l^-l^-
  - ➡ Measures combination of $A_{sl}(B_d)$ & $A_{sl}(B_S)$

Latest results

- D0 dimuon measurement differs from SM by about 3σ
  - ➡ Difficult to motivate by non-SM physics
- Direct measurements of $A_{sl}(B_d)$ & $A_{sl}(B_S)$ show agreement with SM
- Possible differences in SM contribution to observables?
- LHCb has best single measurement of $A_{sl}(B_d)$
  - ➡ Full run-1 update of $A_{sl}(B_s)$ in progress

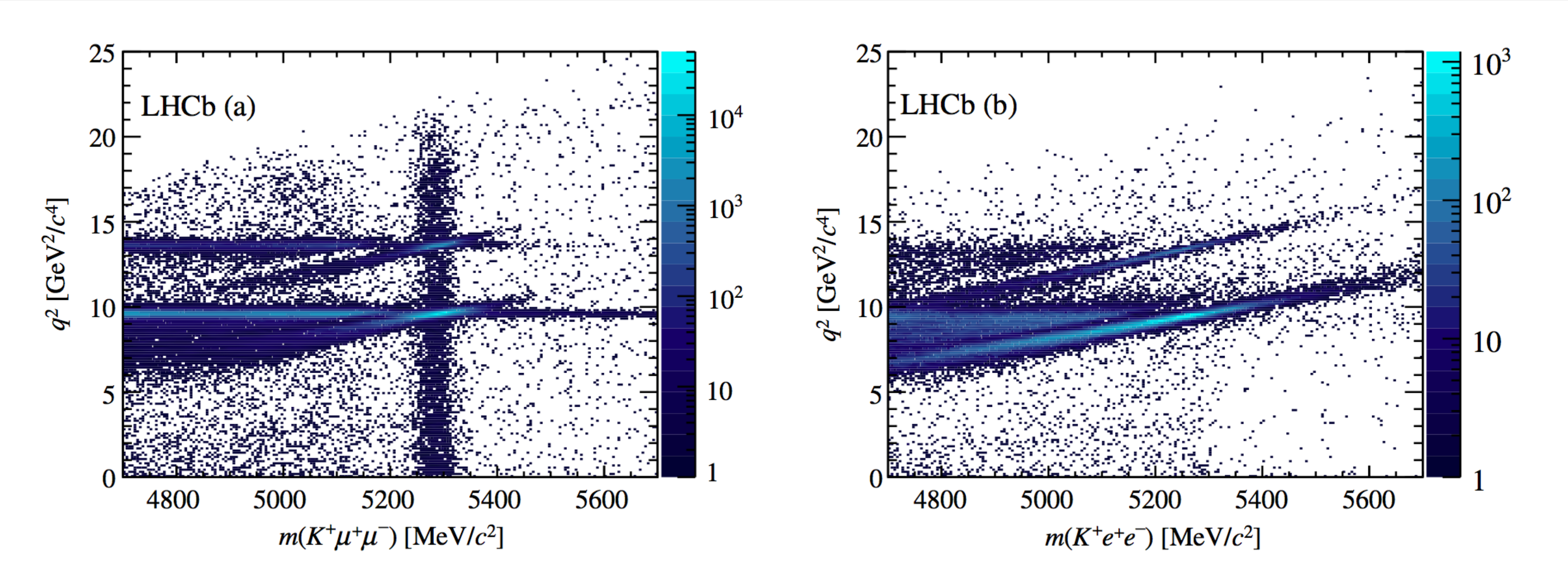


Testing lepton universality

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+\to K^+\mu^+\mu^-]}{dq^2}\, dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+\to K^+e^+e^-]}{dq^2}\, dq^2},$$

$1 < q^2 < 6\ \mathrm{GeV}^2/c^4$

$$R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst}).$$

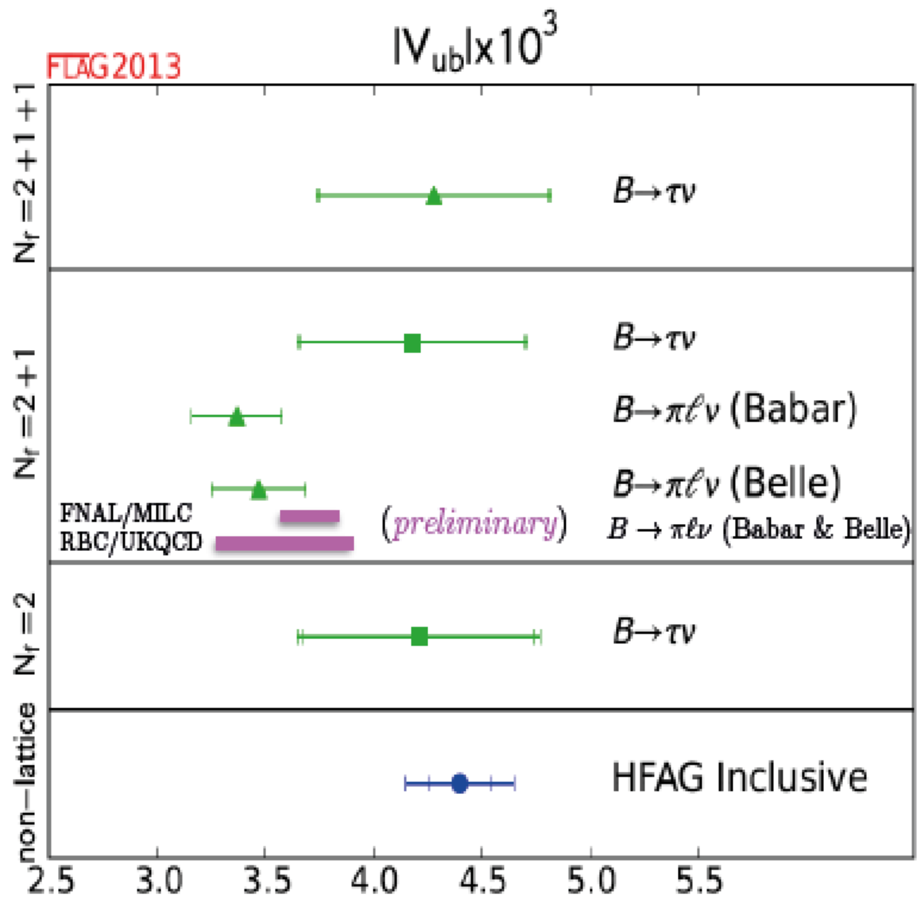


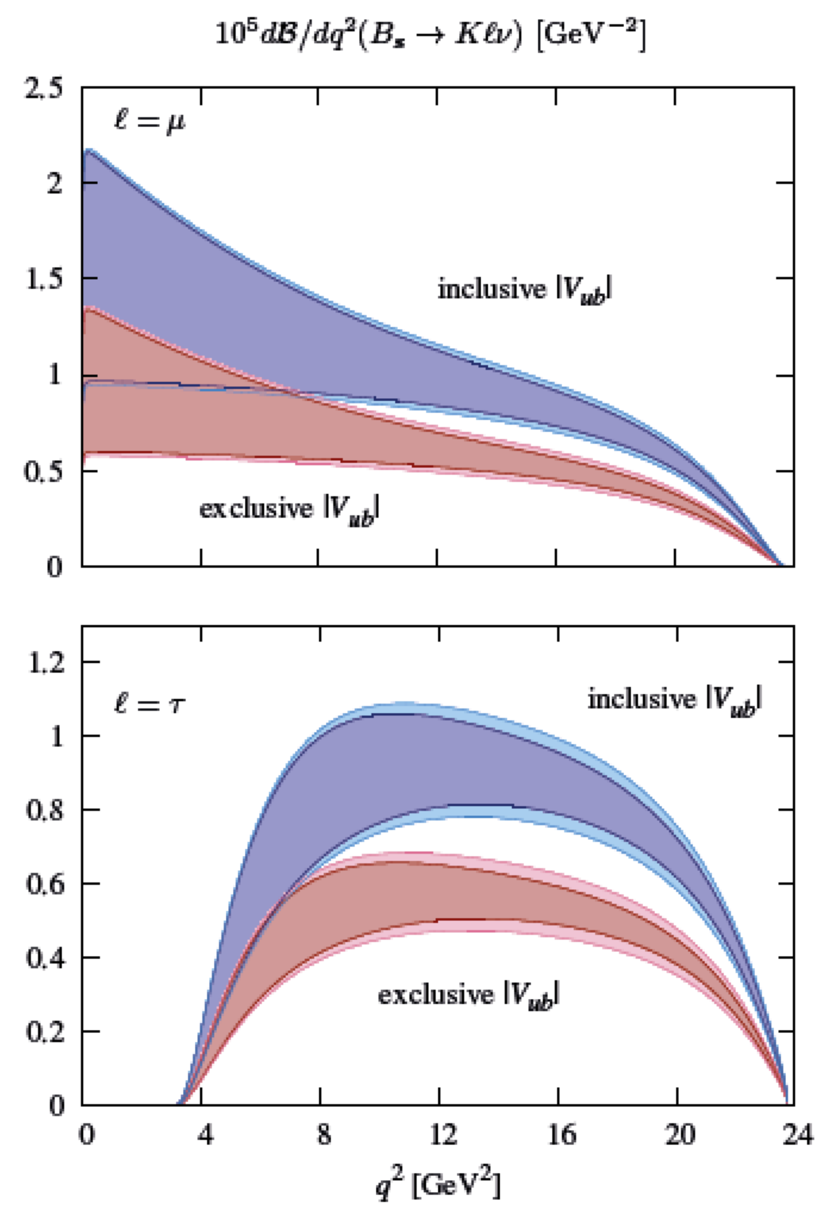
$\sin(2\beta)$ systematics

Origin	σ_S	σ_C
Background Tagging Asymmetry	0.0179 (2.5 %)	0.0015 (4.5 %)
Tagging calibration	0.0062 (0.9 %)	0.0024 (7.2 %)
$\Delta\Gamma_d$	0.0047 (0.6 %)	—
Δm_d	—	0.0034 (10.3 %)
Fraction of wrong PV component	0.0021 (0.3 %)	0.0011 (3.3 %)
z-scale	0.0012 (0.2 %)	0.0023 (7.0 %)
Upper decay time acceptance	—	0.0012 (3.6 %)
Low decay time acceptance	—	—
Decay time resolution calibration	—	—
Decay time resolution offset	—	—
Correlation between mass and decay time	—	—
Production asymmetry	—	—
Sum	0.020 (2.7 %)	0.005 (15.2 %)

$|V_{ub}|$ with new lattice results

Summary





- most precise $|V_{ub}|$ to date (2.4σ from inclusive)
- lattice errors ≈ experimental errors
- multiple, varied calculations of form factors
- need $d\mathcal{B}/dq^2$ with commensurate error

CKM 2014, Vienna, Austria C. Bouchard 19

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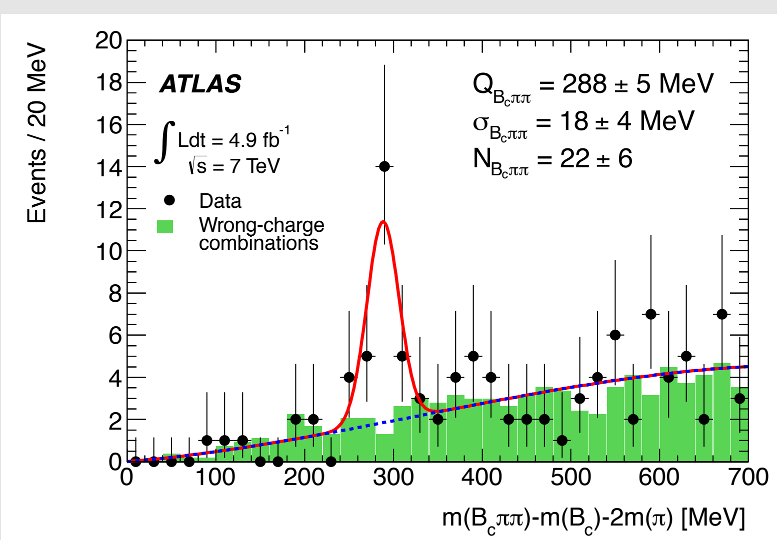
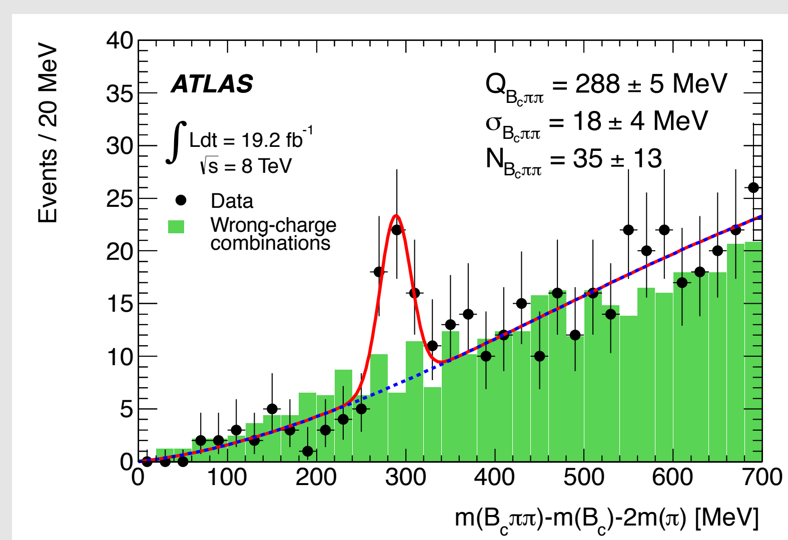
New states

- Excited B_c meson state found
  - ➡ $B_c(2S)$, ATLAS, PRL 113 (2014) 212004
- Two excited beauty baryons found
  - ➡ Ξ_b', Ξ_b^*, LHCb, PRL 114 (2015) 062004
- And others also from Belle, BESIII, CMS, …
- Slowly completing the quark model
- More exotic particles
  - ➡ XYZ states





Key sensitivities

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Table 28: 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. Note that operation in Run 5 and beyond assumes integrating luminosity beyond the proposed total for the LHCb upgrade of 50 fb^{-1}. Uncertainties on ϕ_s are given in radians.

	LHC era			HL-LHC era	
	Run 1	Run 2	Run 3	Run 4	Run 5+
$\phi_s(B_s^0 \to J/\psi\phi)$	0.05	0.025	0.013	0.009	0.006
$\phi_s(B_s^0 \to \phi\phi)$	0.15	0.10	0.029	0.018	0.012
$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$	220%	110%	60%	40%	28%
$q_0^2\ A_{\mathrm{FB}}(K^{*0}\mu^+\mu^-)$	10%	5%	2.8%	1.9%	1.3%
γ	7°	4°	1.3°	0.9°	0.6°
$A_\Gamma(D^0 \to K^+K^-)$	3.4×10^{-4}	2.2×10^{-4}	0.7×10^{-4}	0.4×10^{-4}	0.3×10^{-4}

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More key sensitivities

Table 27: 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)	0.049	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	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	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°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	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	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–