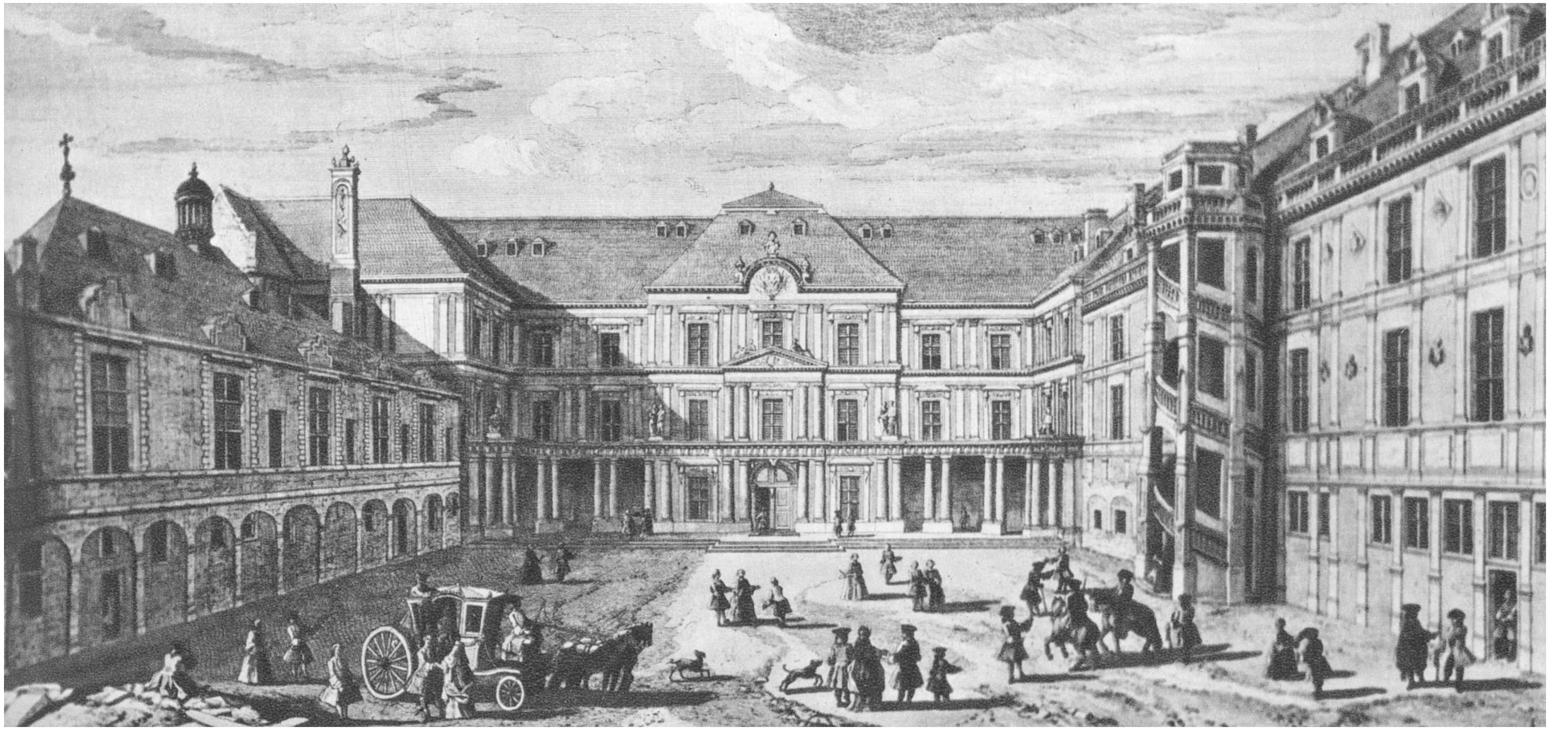


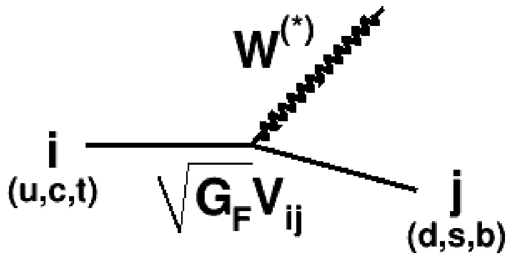
CP violation and rare decays

Tim Gershon
University of Warwick

Blois2015: 27th Rencontres de Blois on "Particle Physics and Cosmology"
4th June 2015

European Research Council

Quark flavour mixing
a.k.a. CKM phenomenology

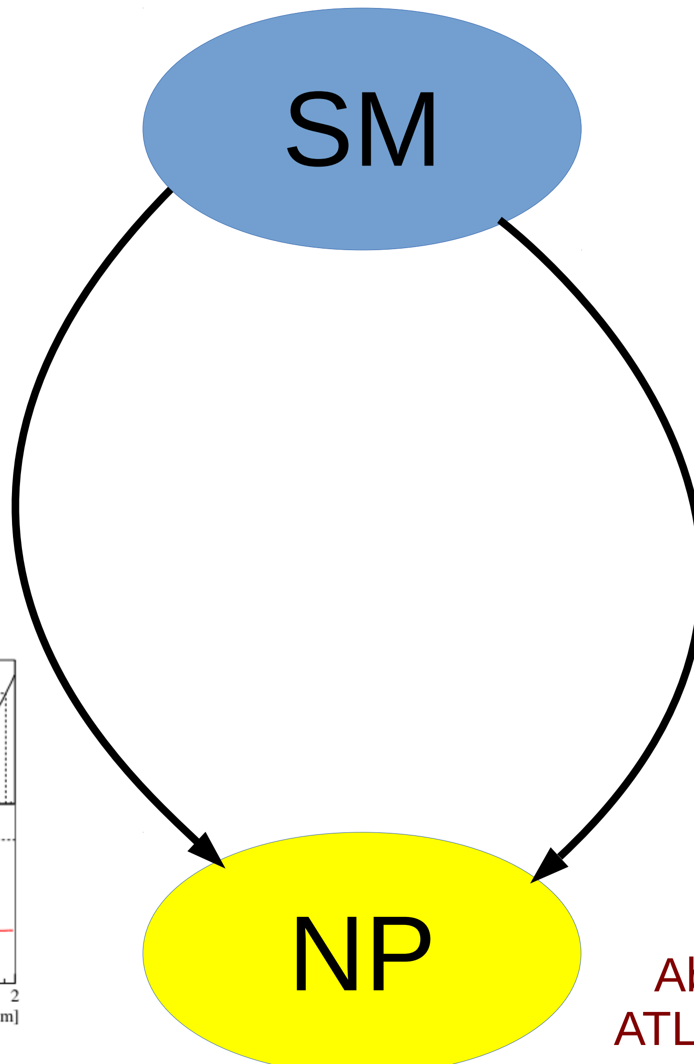


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}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

- 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 ($m_\nu = \theta_{QCD} = 0$)

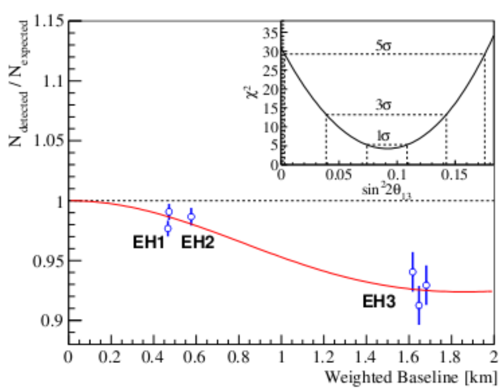
Two routes to heaven

for quark flavour physics



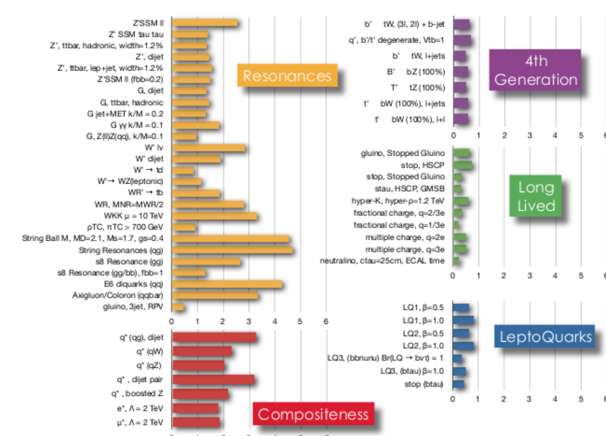
CP violation
(extra sources must exist)

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?

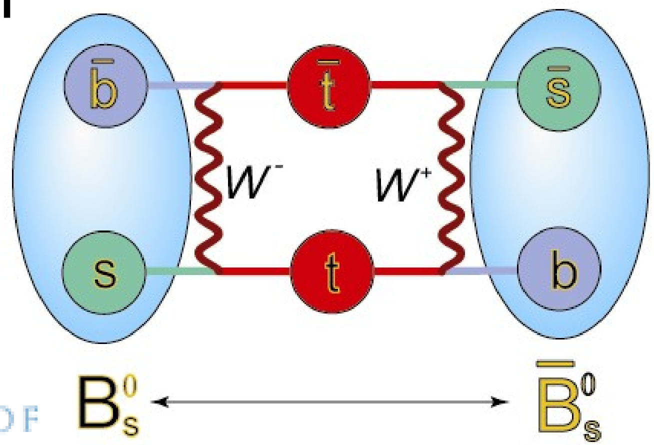


Absence of NP signals at ATLAS/CMS → argument for searches via rare decays stronger

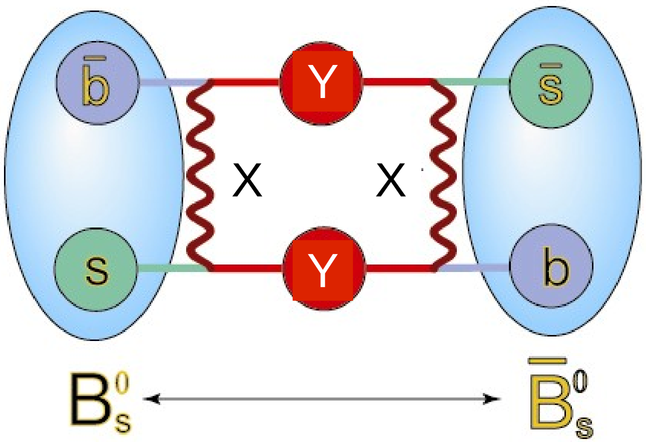
Loop diagrams for discovery

- 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



Content of this talk

Focus on areas with recent experimental progress

Towards New SM In 12 Steps

1. **CKM from Trees** — γ & V_{ub}
2. **Lattice**
3. **$\Delta F=2$ Observables** — $\sin(2\beta)$
4. $B_{s,d} \to \mu^+\mu^-$, $B_{s,d} \to \tau^+\tau^-$ — $B_{d,s} \to \mu\mu$
5. $B^+ \to \tau^+\nu_\tau$ — $B \to D^{(*)}\tau\nu$
6. $B \to X_s\gamma$, $B \to K^*\gamma$
7. $B \to X_s l^+l^-$, $B \to K^*(K) l^+l^-$ — $B^0 \to K^*\mu\mu$ & $B_s \to \phi\mu\mu$
8. $K \to \pi\nu\bar{\nu}$ — NA62 & K0T0
9. $B \to X_s\nu\bar{\nu}$, $B \to K^*(K)\nu\bar{\nu}$
10. ε'/ε
11. **Charm, Top**
12. **LFV, EDMs, $(g-2)_{\mu,e}$**

Clock from Buras & Girrbach, RPP 77 (2014) 086201

The Unitarity Triangle

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

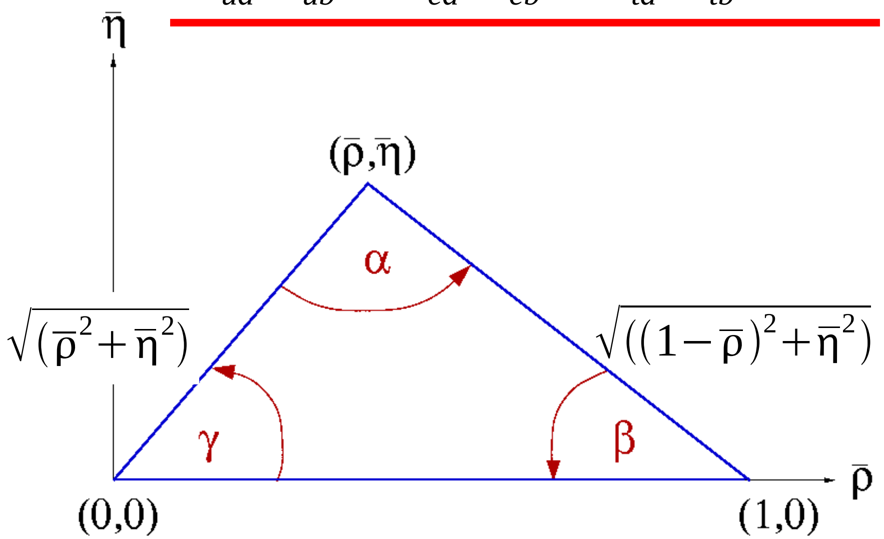
- The CKM matrix must be unitary

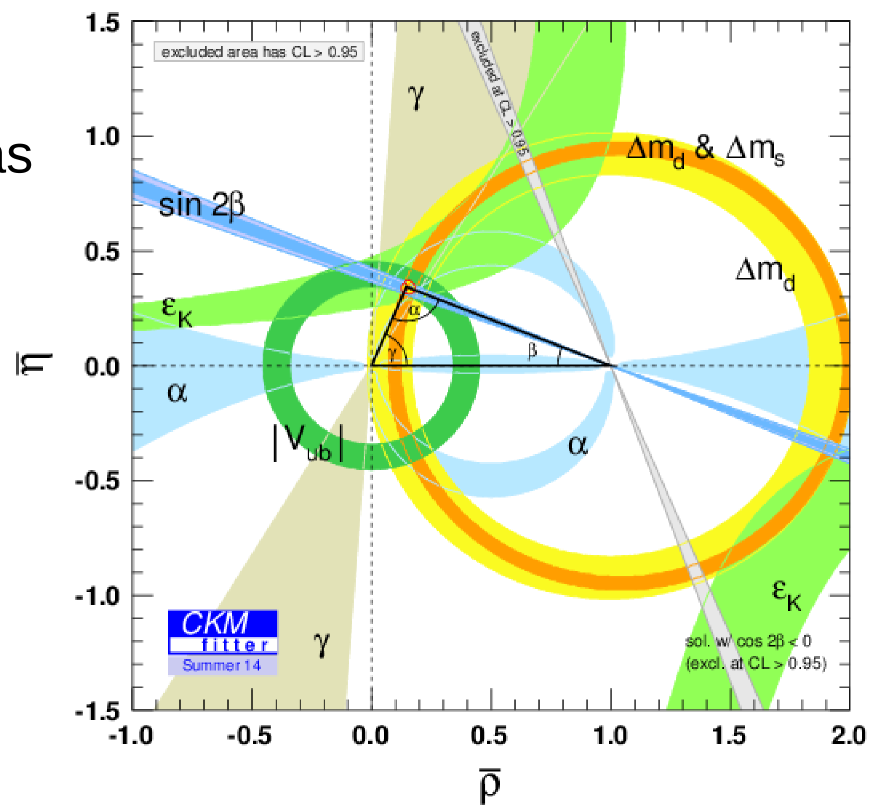
$$V^{+}_{CKM} V_{CKM} = V_{CKM} V^{+}_{CKM} = 1$$

- 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

CP violation

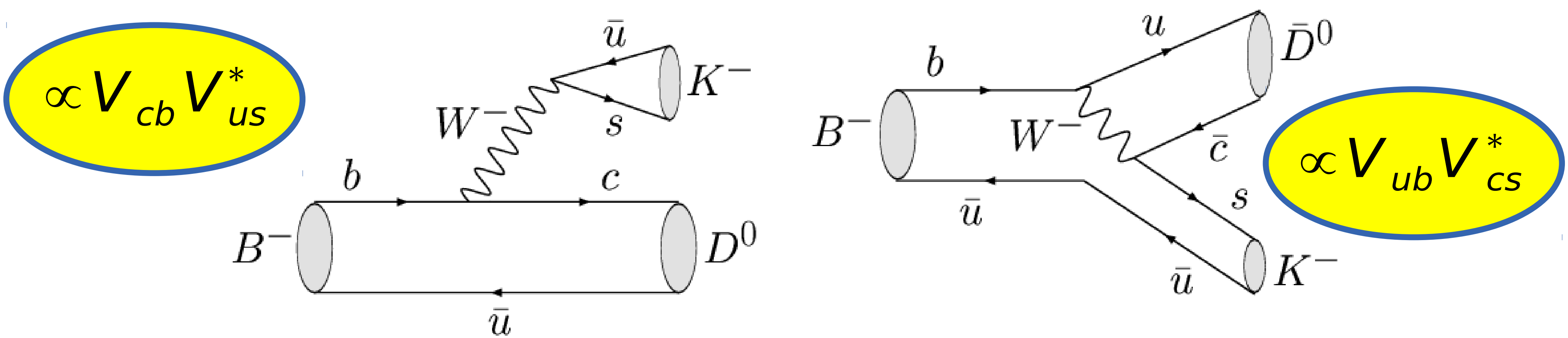
Importance of γ from B→DK

- 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

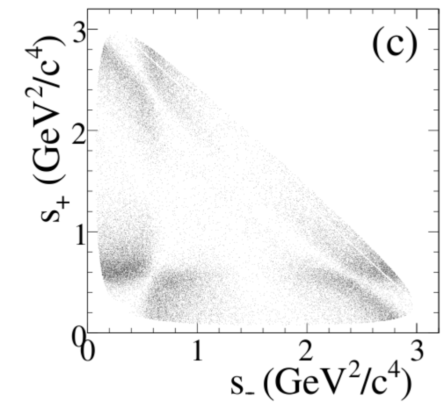


Variants use different B or D decays
require a final state common to both D^0 and $\overline{D}^0$

$D \to \pi^+\pi^-\pi^0$ – a quasi-CP eigenstate

PRL 99 (2007) 251801

- Seminal Dalitz plot analysis from BaBar
  - Gives the parameter $x_0 = 0.850$ (without uncertainty)
  - Relation to fractional CP-even content: $x_0 = 2F_+ - 1$

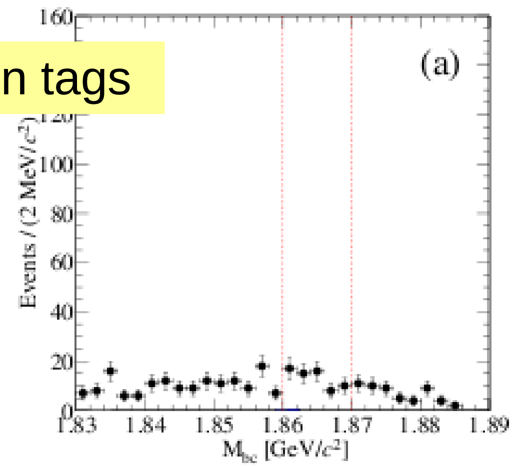


- Exploit CLEOc $\Psi(3770) \to D\overline{D}$ data for direct measurement of CP content: $F_+ = 0.973 \pm 0.017$

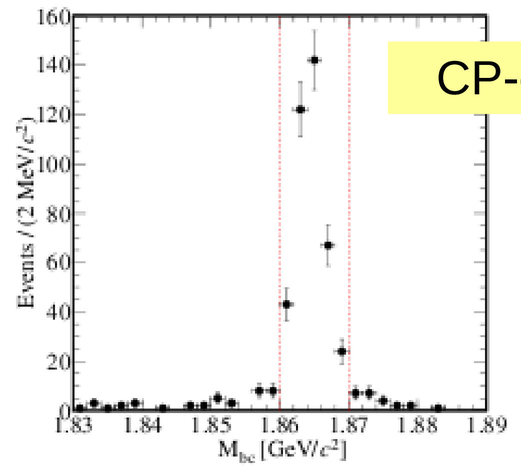
PLB 740 (2015) 1 & arXiv:1504.05878

Unexpected!

CP-even tags



CP-odd tags

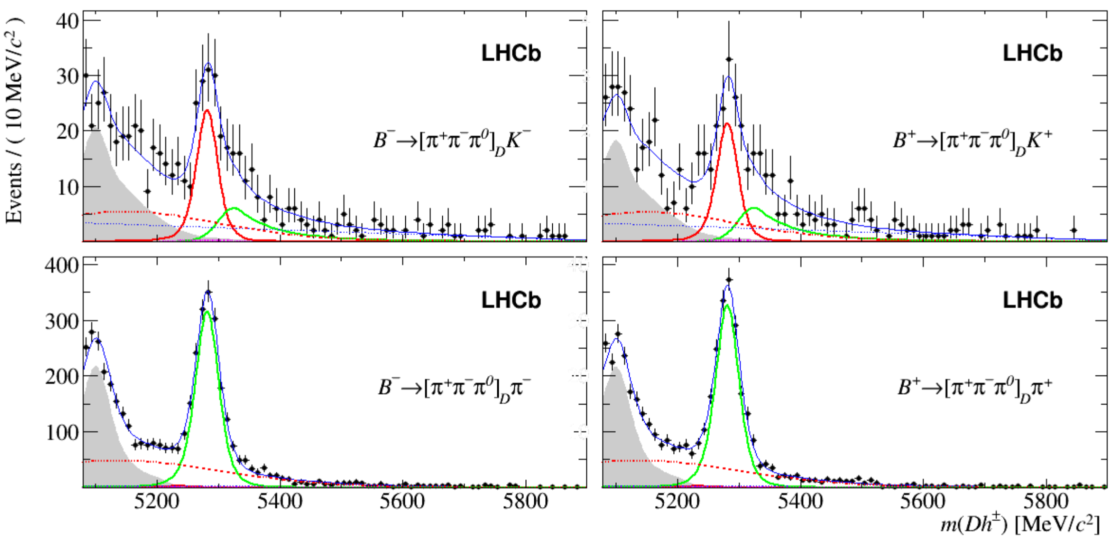


New decay modes for γ

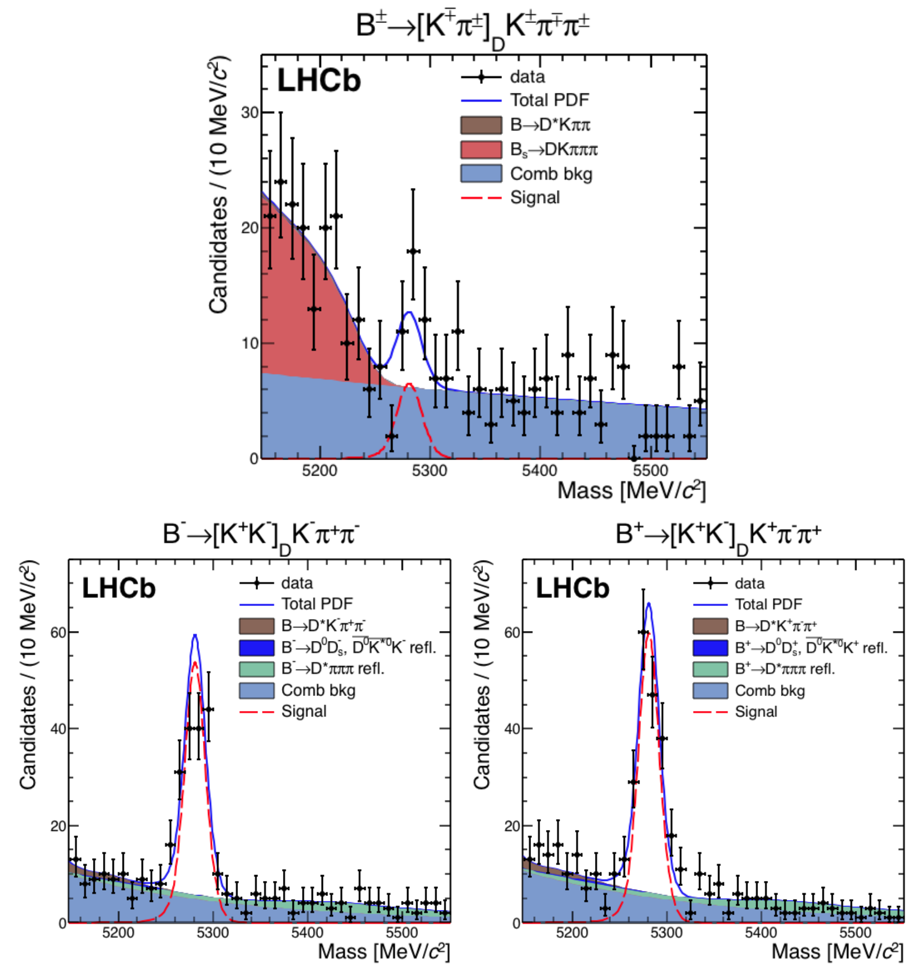
arXiv:1504.05442

arXiv:1505.07044

$B \to DK$, $D \to \pi^+\pi^-\pi^0$
also $B \to DK$, $D \to K^+K^-\pi^0$

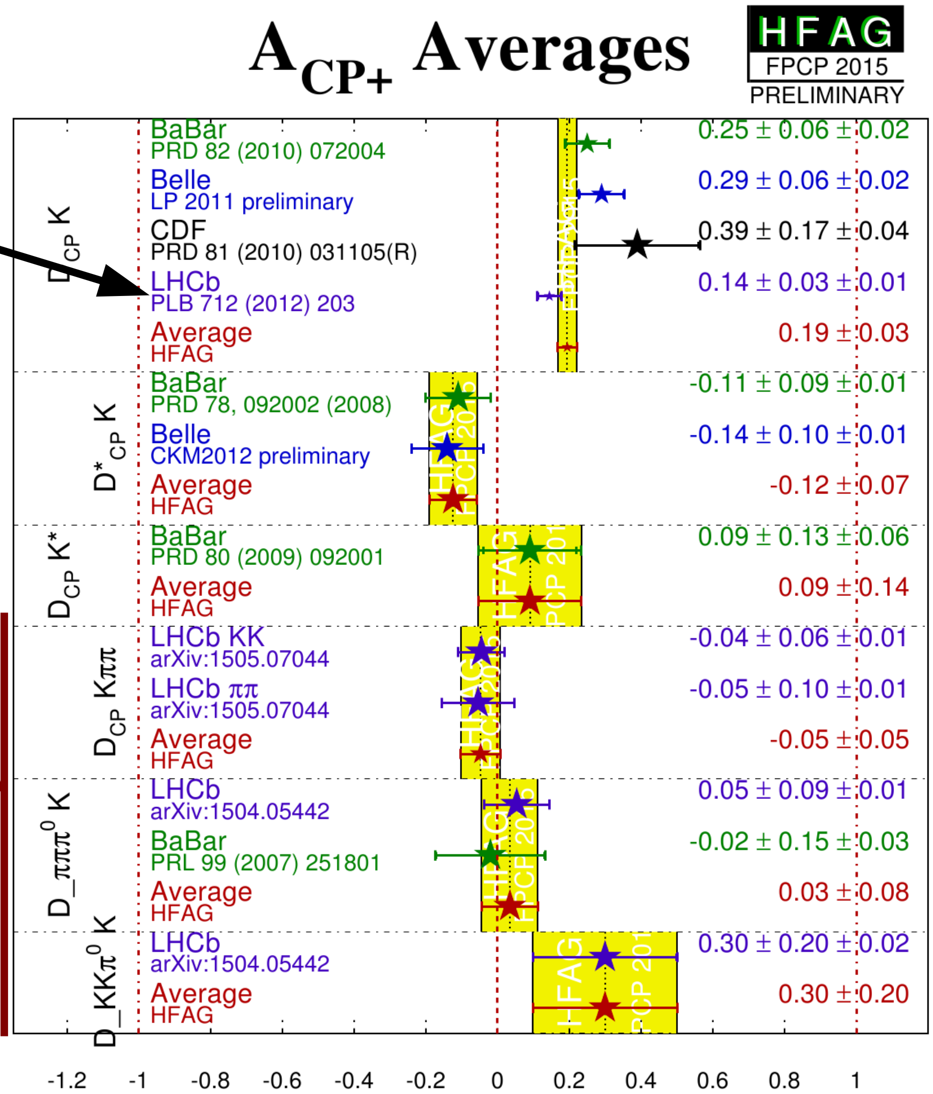


$B \to DK\pi^+\pi^-$,
$D \to K^+\pi^-$, K^+K^-, $\pi^+\pi^-$



γ status

- Most precise channel is $D_{CP}K$ (awaiting LHCb update with full Run I sample)
- New LHCb results with competitive sensitivity
- LHCb only combination, without latest results (but including measurements not shown in plot to right), gives $\gamma = (73\,^{+9}_{-10})^\circ$



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

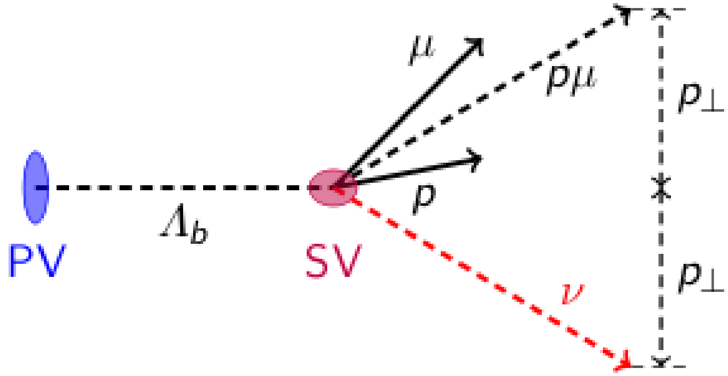
arXiv:1504.01568

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

$$|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \text{ (inclusive)} \qquad |V_{ub}| = (4.41 \pm 0.15\,^{+\,0.15}_{-\,0.17}) \times 10^{-3} \quad \text{(inclusive)},$$
$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)} \qquad |V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \quad \text{(exclusive)}.$$

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

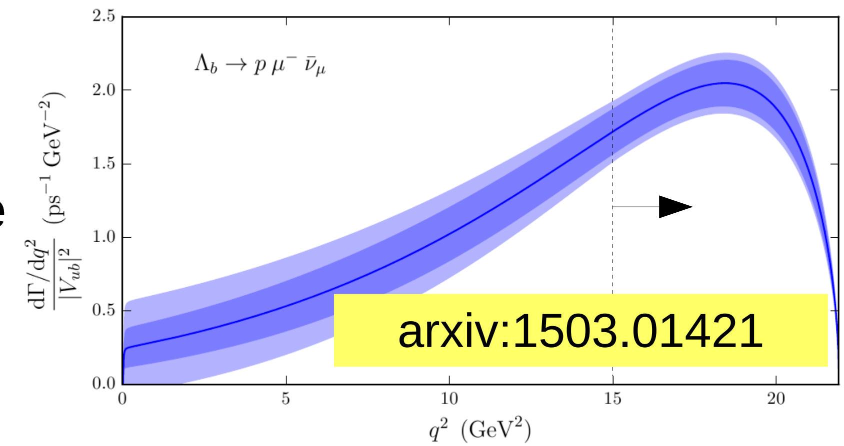
$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$



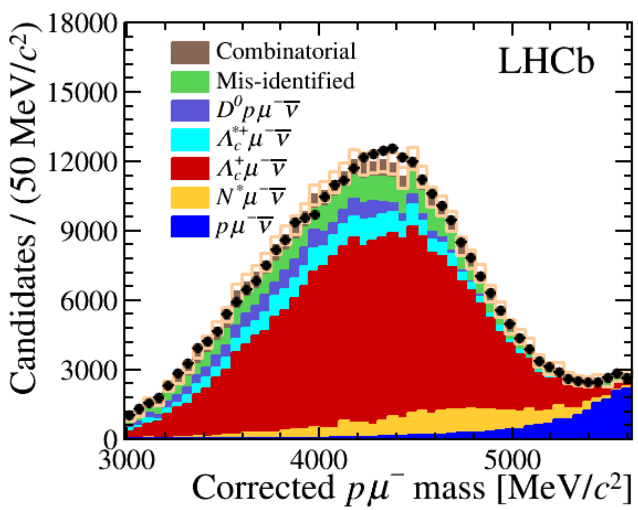
$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

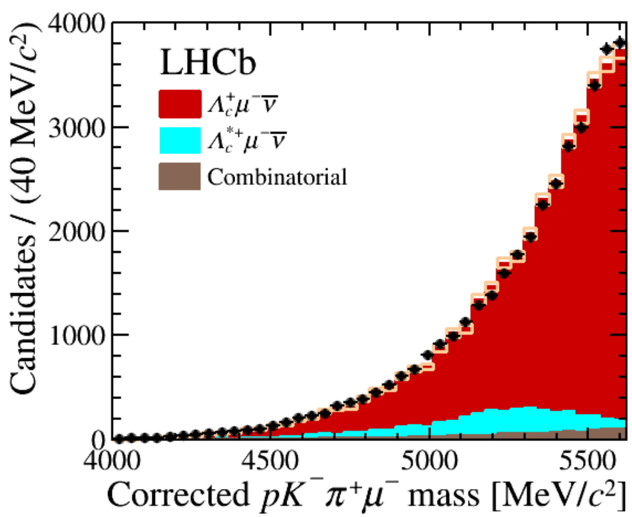
arXiv:1504.01568

- 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



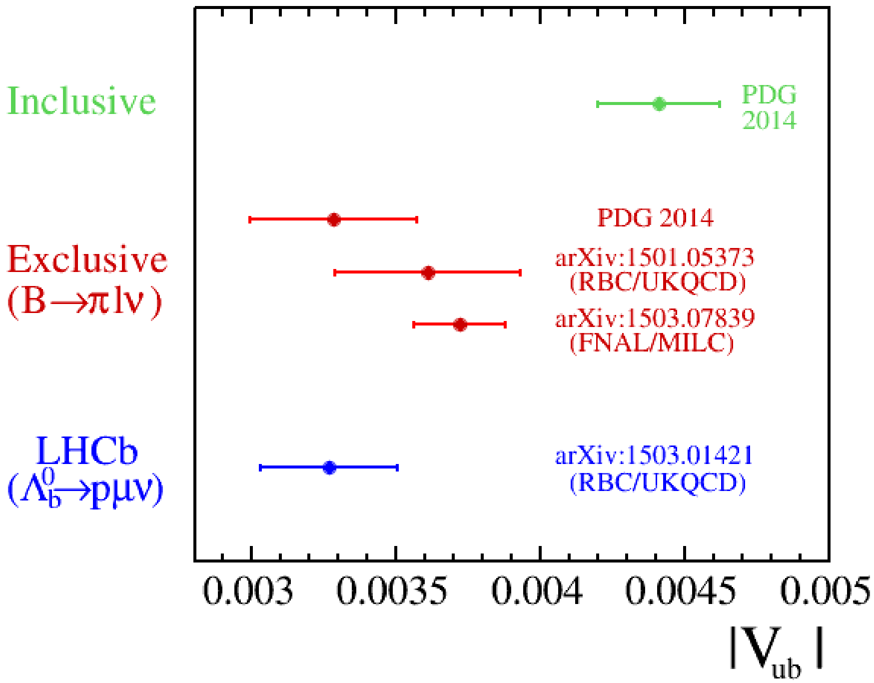
- Use isolation MVA to suppress background
- Fit M_{corr} to obtain signal yields

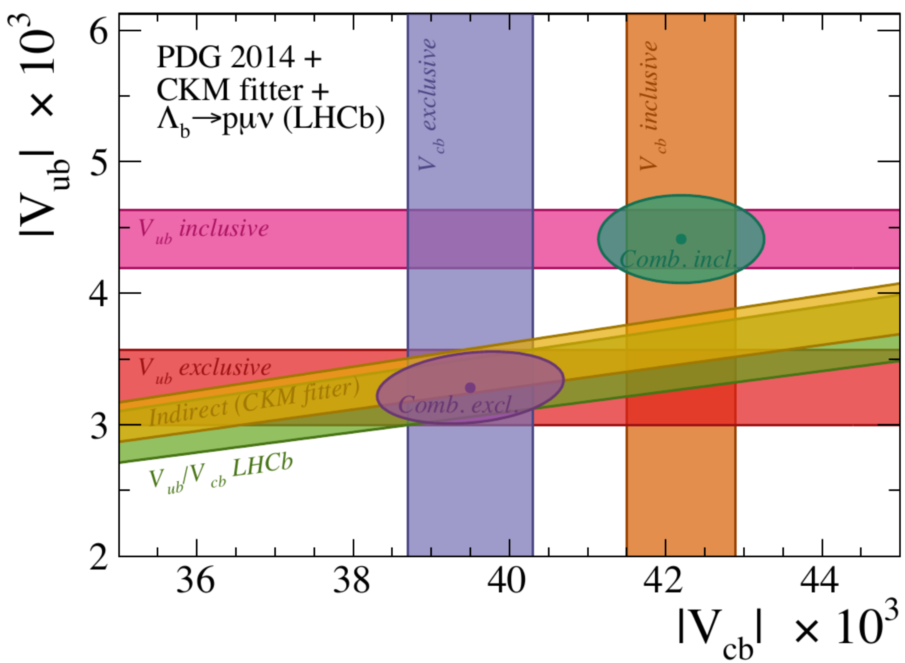




$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

arXiv:1504.01568





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

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

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

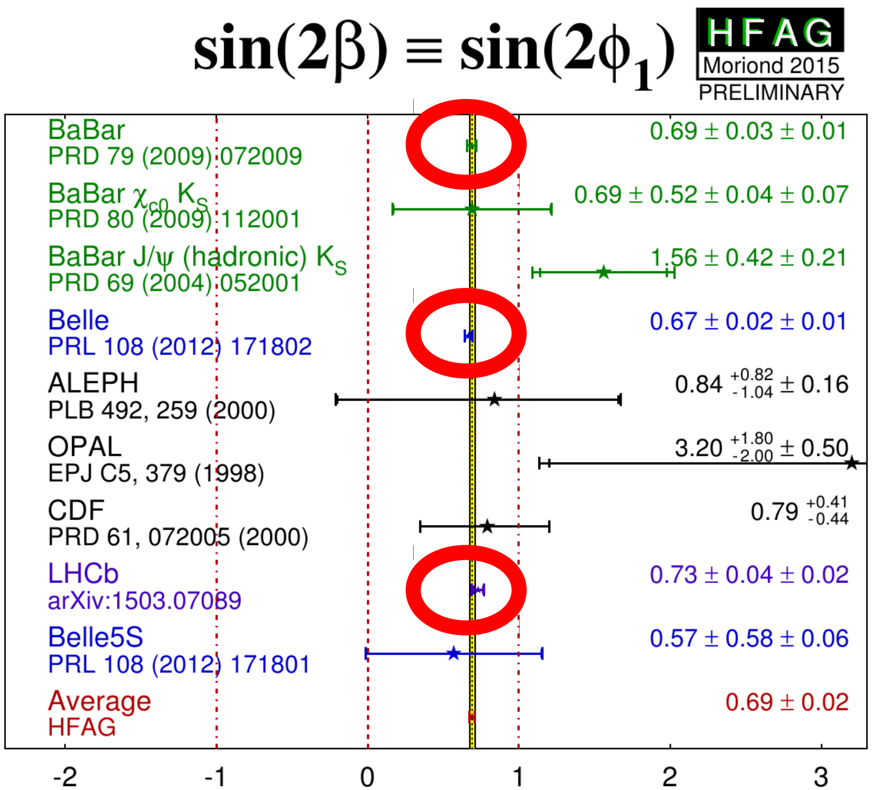
sin(2β)

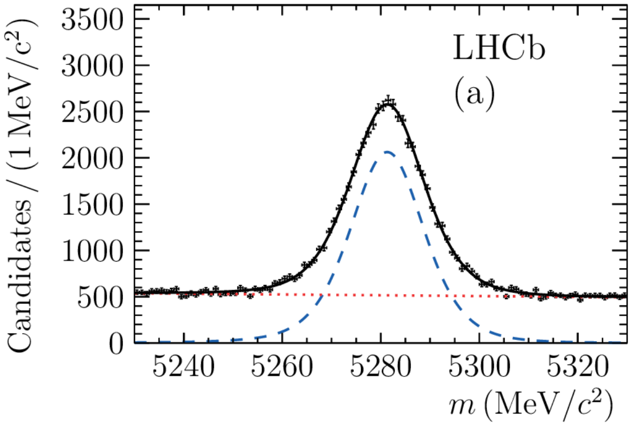
Decay-time dependent CP asymmetry in $B^0 \to J/\psi K_S$

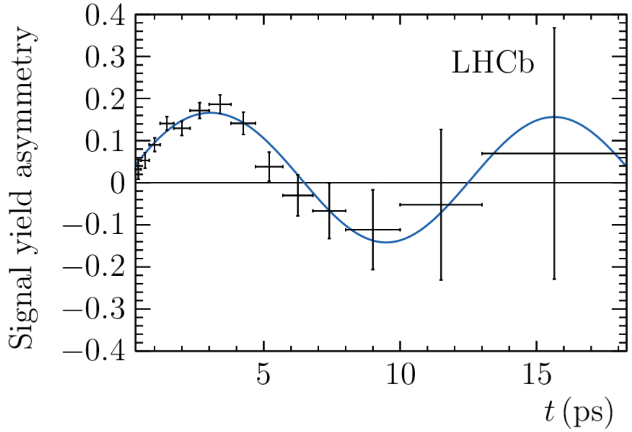
arXiv:1503.07089

→ golden mode to measure sin(2β)

Previously measured by BaBar & Belle … now LHCb becomes competitive





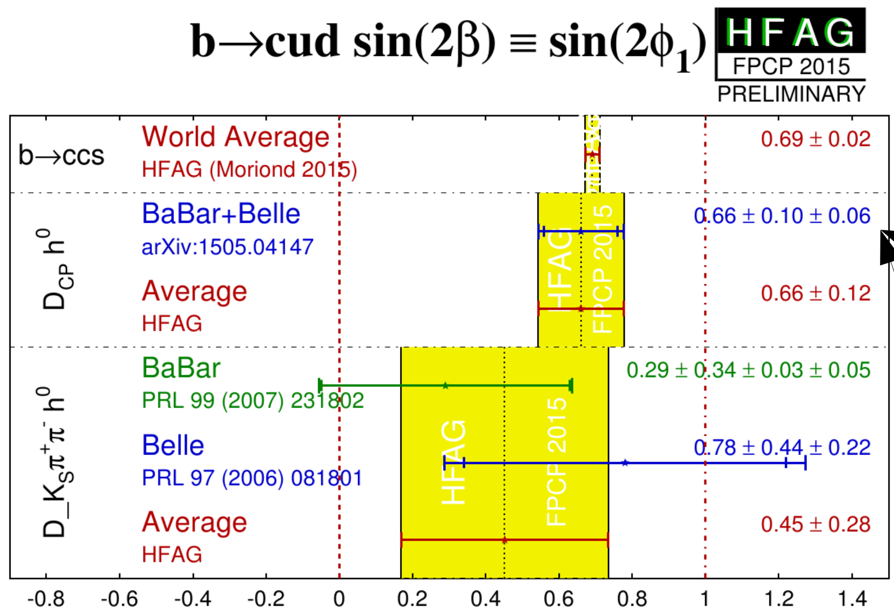


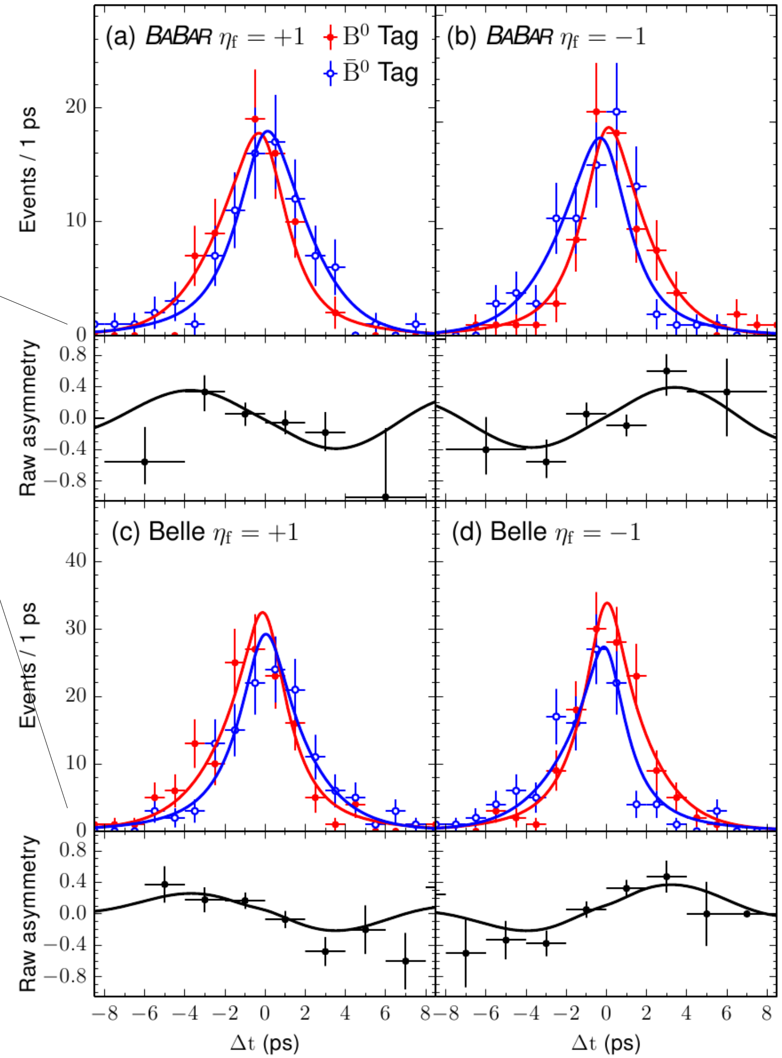
At this precision, penguin effects start to be a concern

sin(2β) without penguins

arXiv:1505.04147

Possible to measure sin(2β) from $b \to c\bar{u}d$ transitions – no penguin possible
Yields lower compared to J/ψK_S → combined BaBar+Belle analysis





First observation of CP violation in $b \to c\bar{u}d$ transitions

Rare (and some not so rare) decays

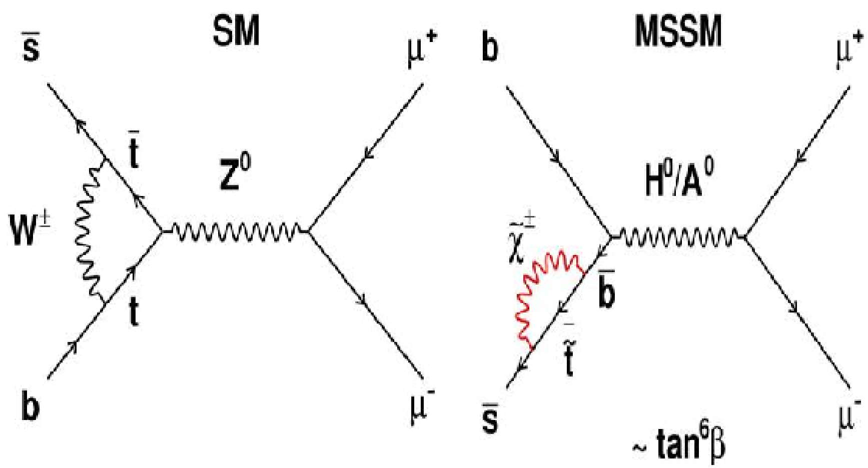
$B_s \to \mu^+\mu^-$

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

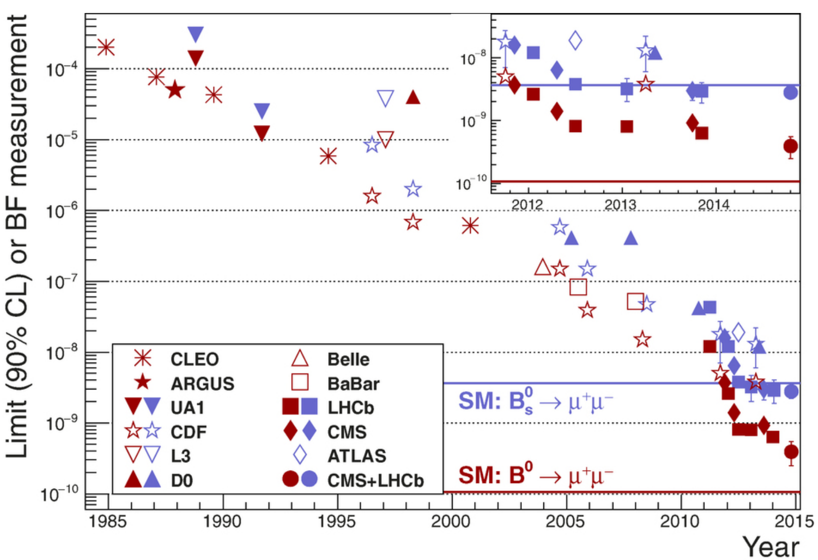
… all features which are not necessarily reproduced in extended models



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

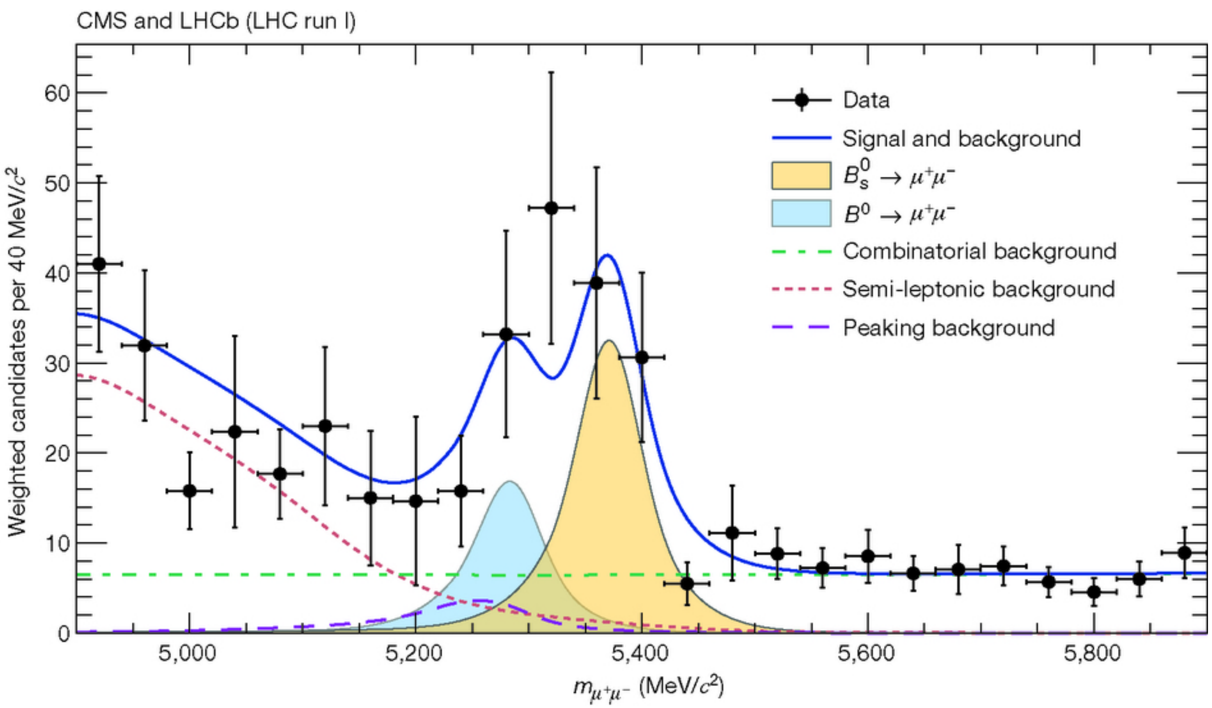
$\mathcal{B}(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta / M^4_{A0}$

Intensively searched for over 30 years!



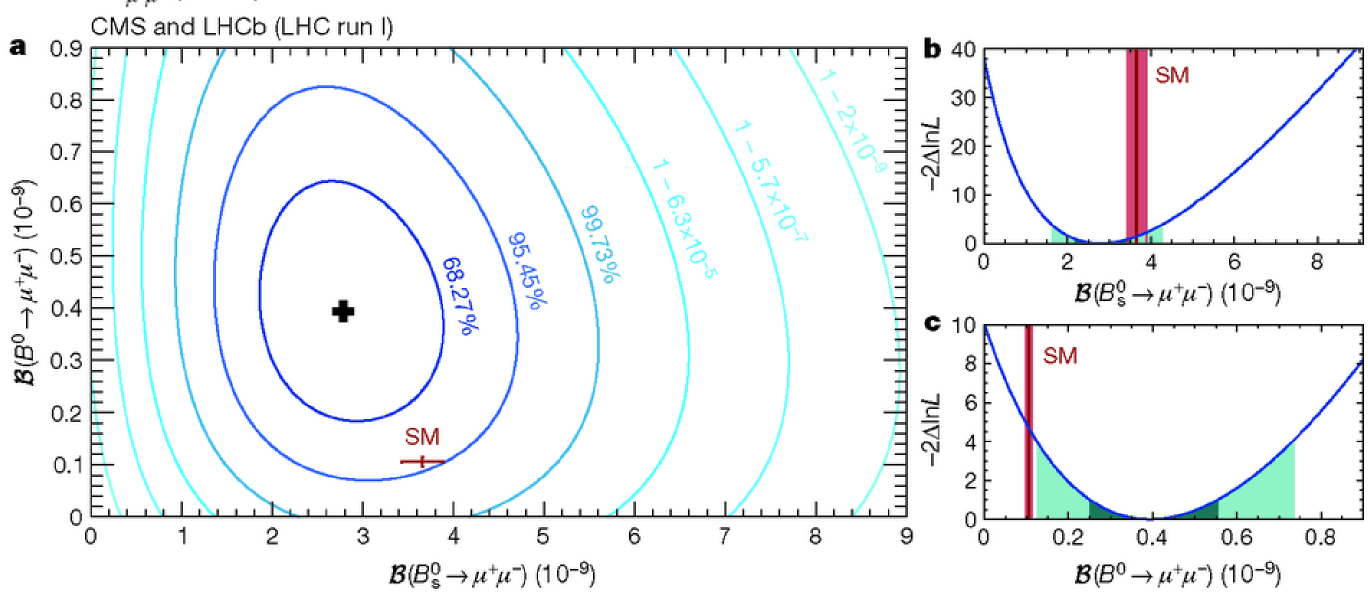
$B_s \to \mu^+\mu^-$

Nature 522 (2015) 68



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

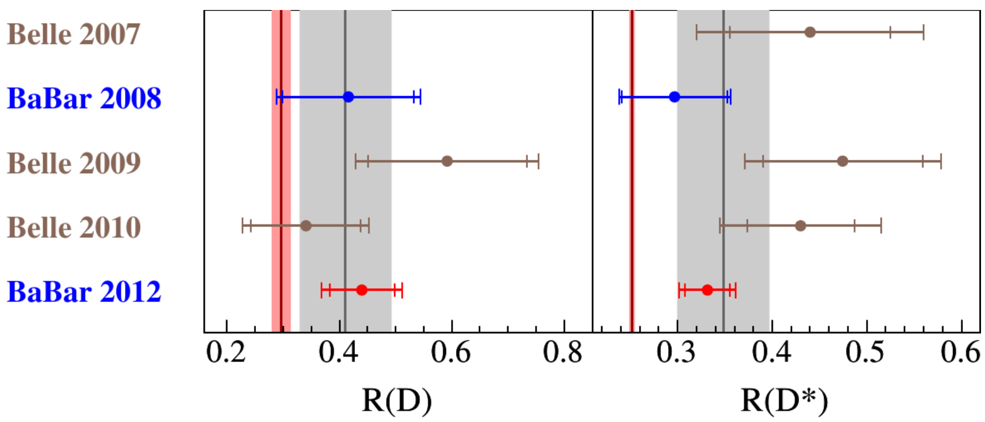
Results consistent with SM at 2σ level

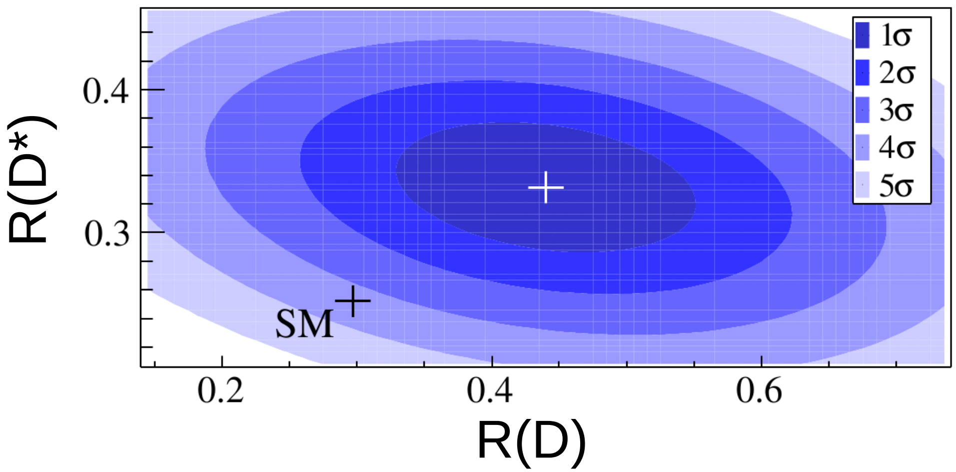


$B \to D^{(*)}\tau\nu$

- 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

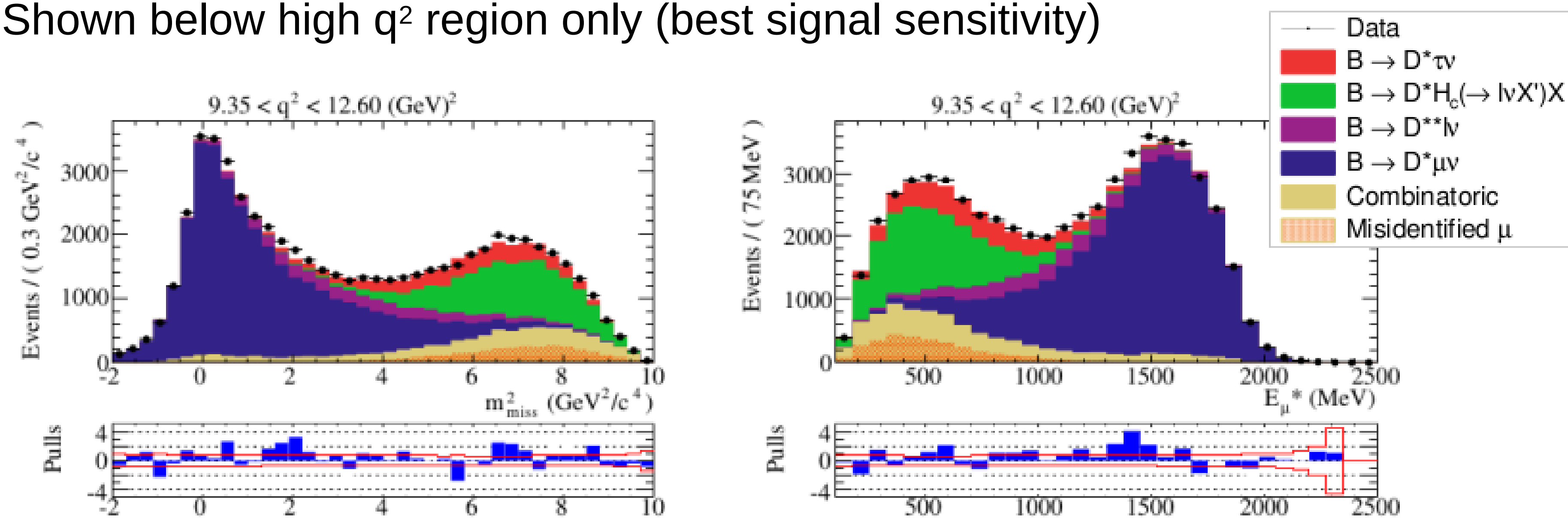




$B \to D^*\tau\nu$ at LHCb

LHCb-PAPER-2015-025

- 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)



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

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

Belle preliminary

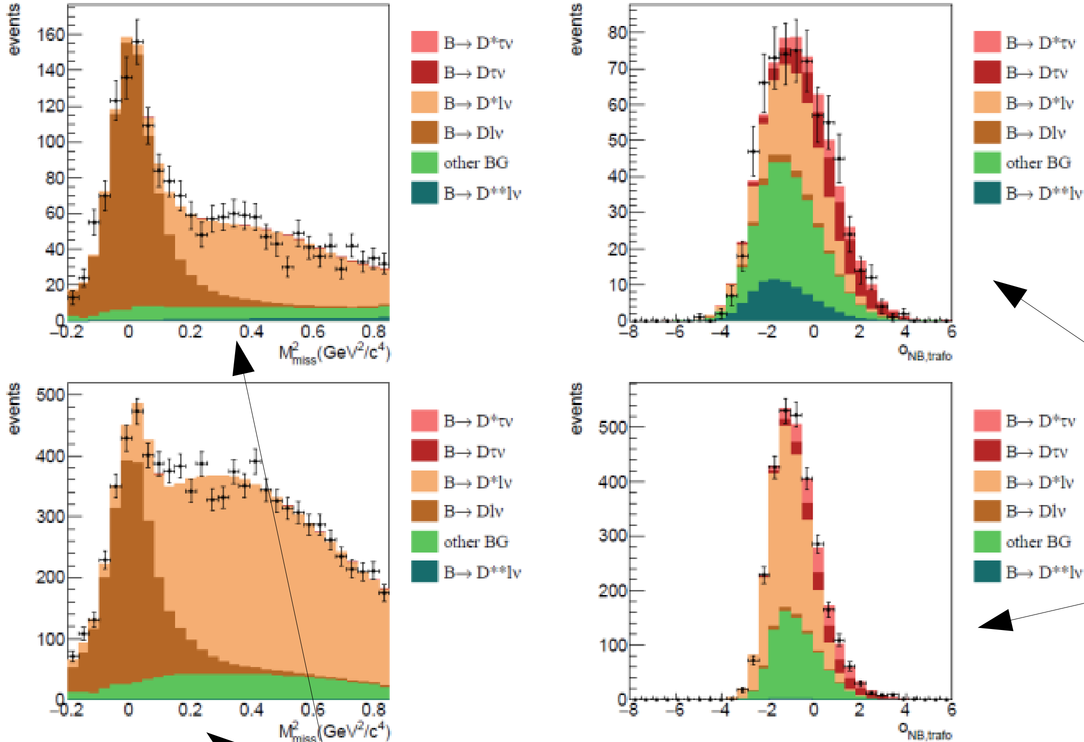
- Reconstruct one B in $\Upsilon(4S) \to B\bar{B}$ event
  - Look for signal in the recoil
    - several D & D* decay modes; $\tau \to \mu\nu\bar{\nu}$ or $e\nu\bar{\nu}$
  - Use low M_{miss}^2 region to separate $D^{(*)}\tau\nu$ from $D^{(*)}l\nu$
  - For $M_{miss}^2 > 0.85$ GeV^2, use neural network to separate $D^{(*)}\tau\nu$ from $D^{**}\tau\nu$
    - NN inputs include M_{miss}^2 , q^2, p_l, E_{ECL}, $N(\pi^0)$

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

Belle preliminary

$D^+\ell^-$

$D^0\ell^-$

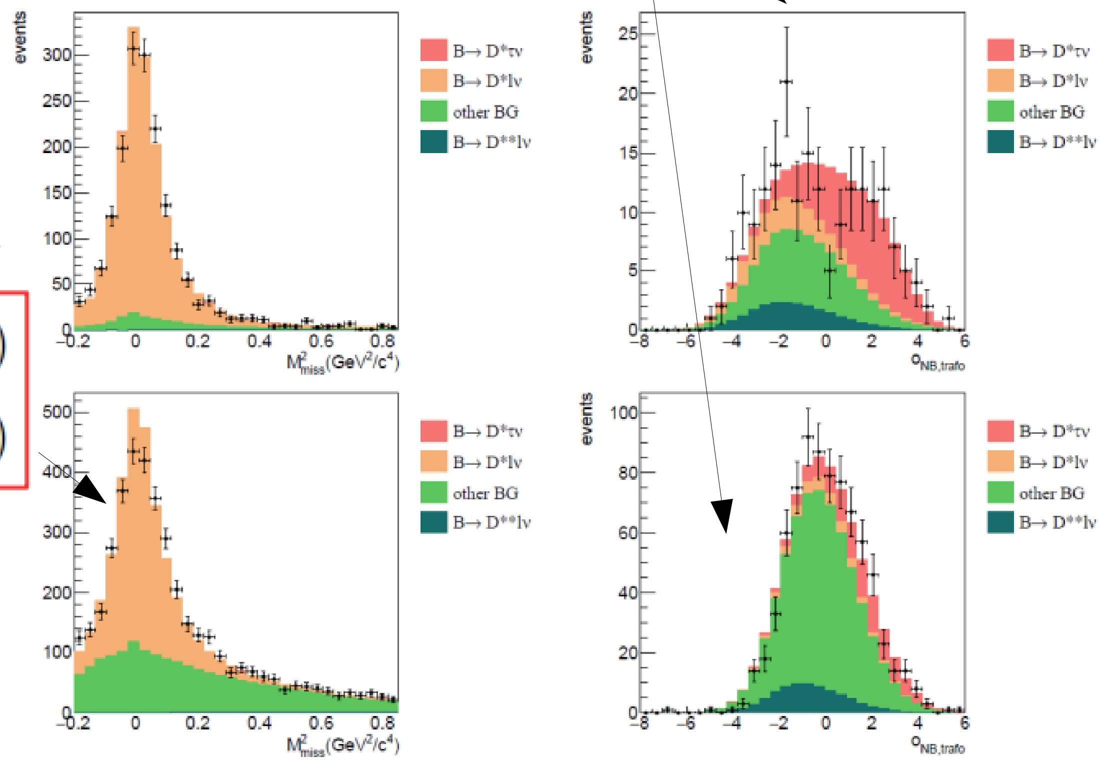


NN

$M_{miss}{}^2$

$D^{*+}\ell^-$

$D^{*0}\ell^-$



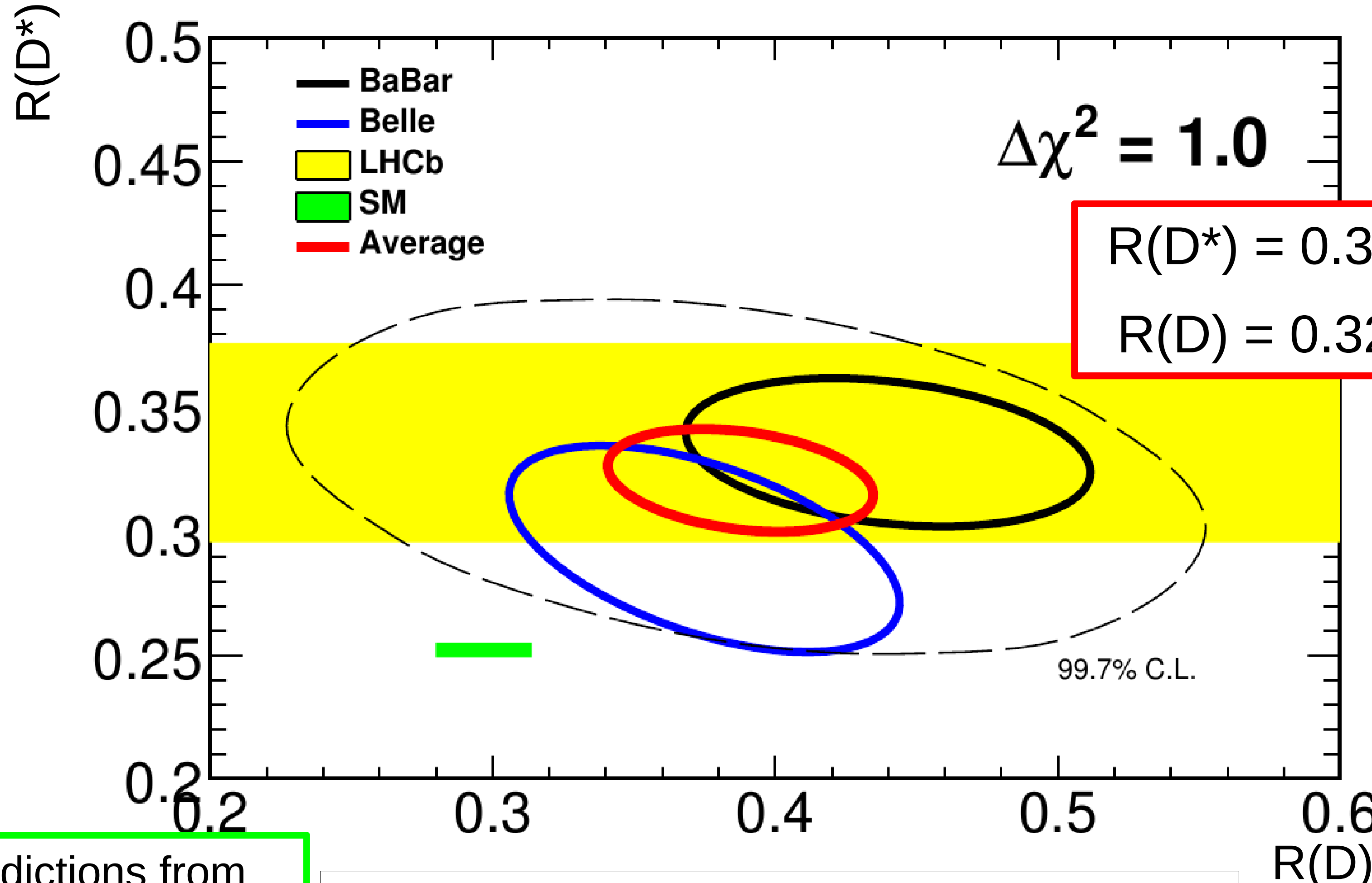
$$R = 0.375^{+0.064}_{-0.063}(\text{stat.}) \pm 0.026(\text{syst.})$$

$$R^* = 0.293^{+0.039}_{-0.037}(\text{stat.}) \pm 0.015(\text{syst.})$$

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

Tension with SM seems to persist

Very preliminary & unofficial average



R(D*) = 0.390 ± 0.047

R(D) = 0.322 ± 0.021

SM predictions from PRD 85 (2012) 094025

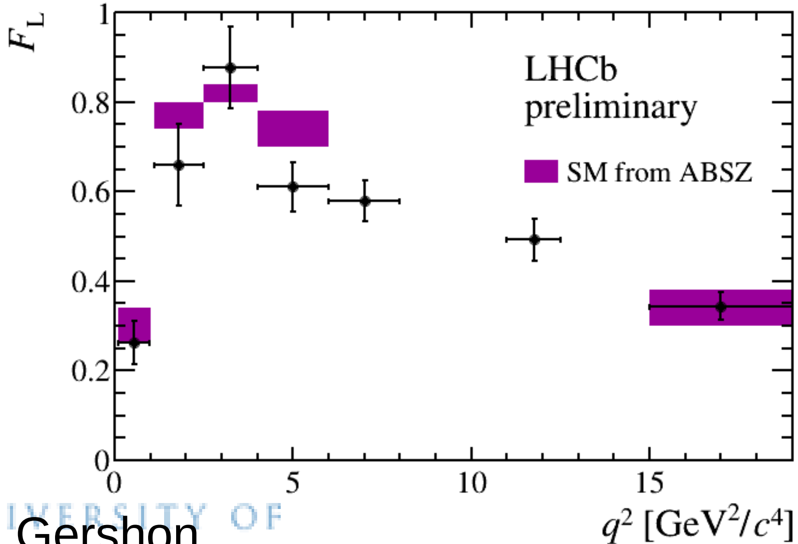
Careful averaging needed to account for statistical and systematic correlations

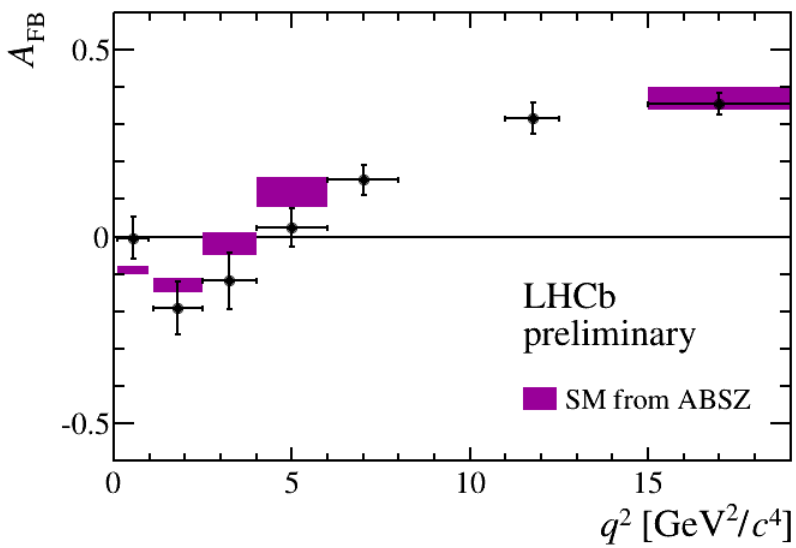
Thanks to M. Rotondo

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

LHCb-CONF-2015-002

- $B^0 \to K^{*0}\mu^+\mu^-$ provides superb laboratory to search for new physics in $b \to sl^+l^-$ 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

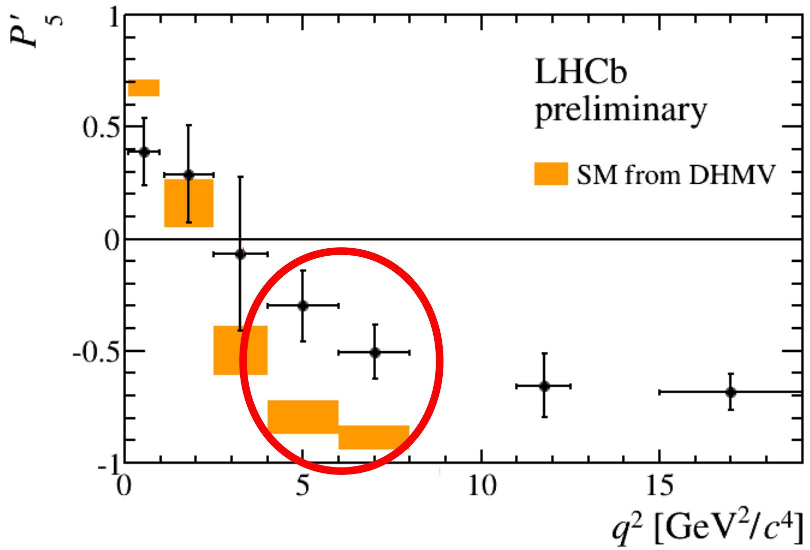




Tension in P_5'

LHCb-CONF-2015-002

- 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
  - expressed as $A^{L,R}_{0,\perp,\parallel}$ (transversity basis)



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

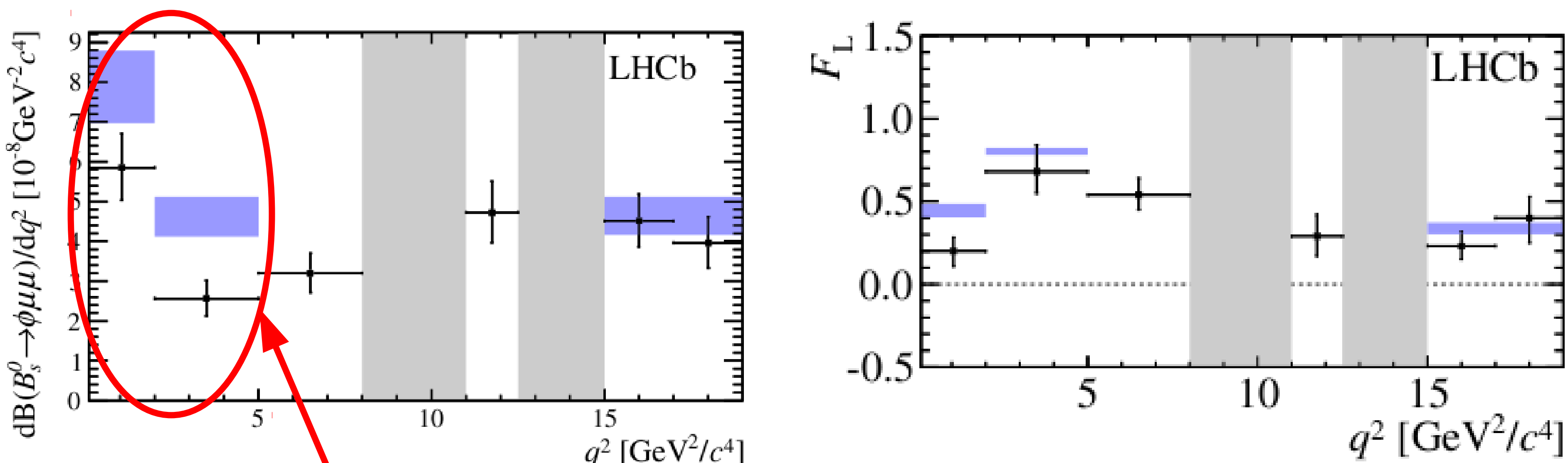
$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}\right)}{\sqrt{\left(|A_0^L|^2 + |A_0^R|^2\right)\left(|A_\parallel^L|^2 + |A_\parallel^R|^2 + |A_\perp^L|^2 + |A_\perp^R|^2\right)}}$$

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

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

LHCb-PAPER-2015-023

- 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

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

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

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

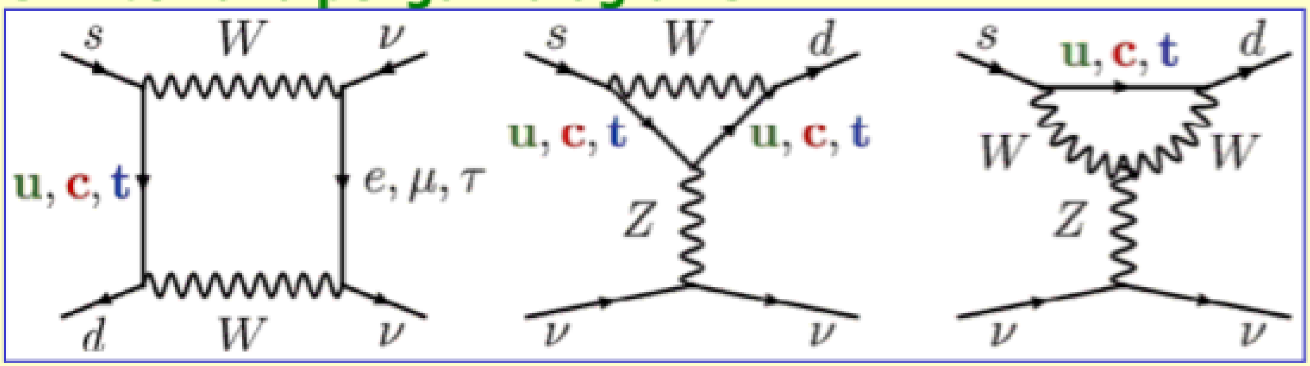
SM branching ratios

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

Mode	$BR_{SM} \times 10^{11}$
$K^+ \rightarrow \pi^+ \nu\bar{\nu}(\gamma)$	$7.81 \pm 0.75 \pm 0.29$
$K_L \rightarrow \pi^0 \nu\bar{\nu}$	$2.43 \pm 0.39 \pm 0.06$

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

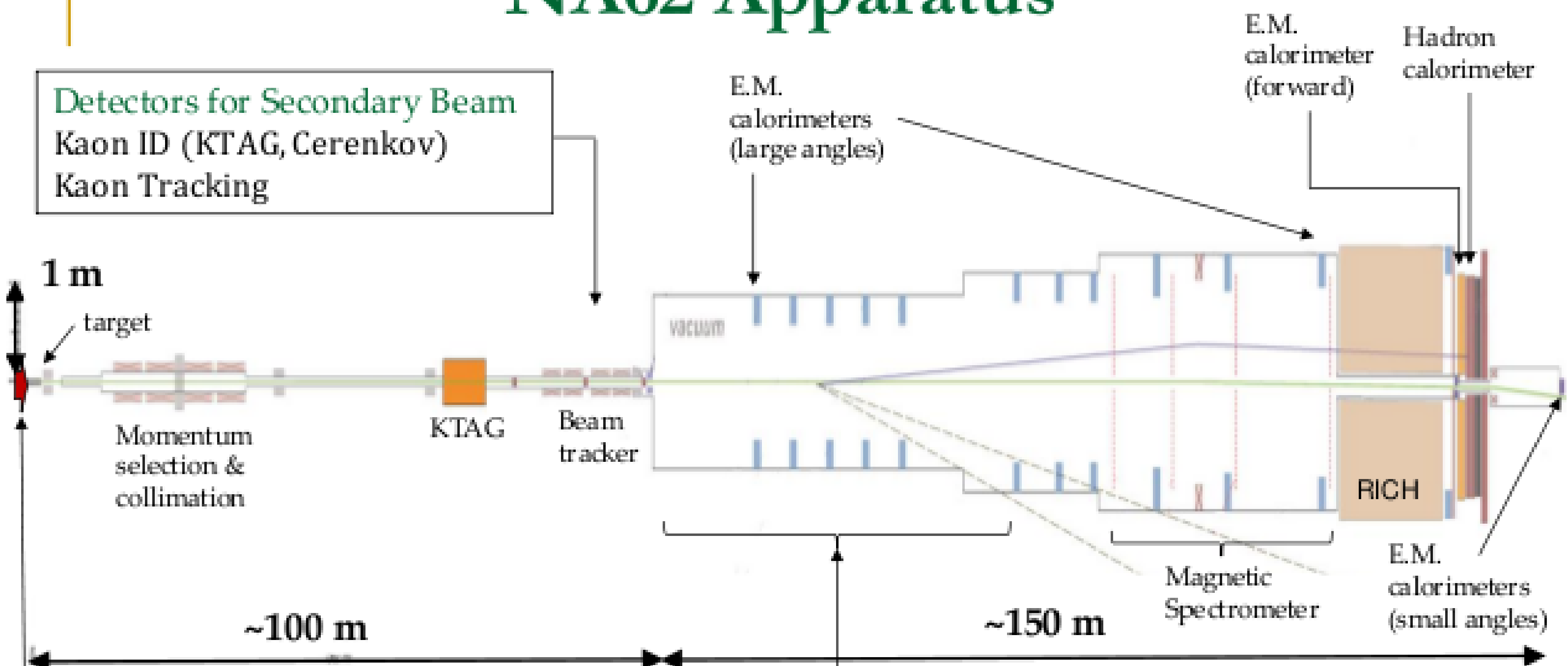
SM: box and penguin diagrams

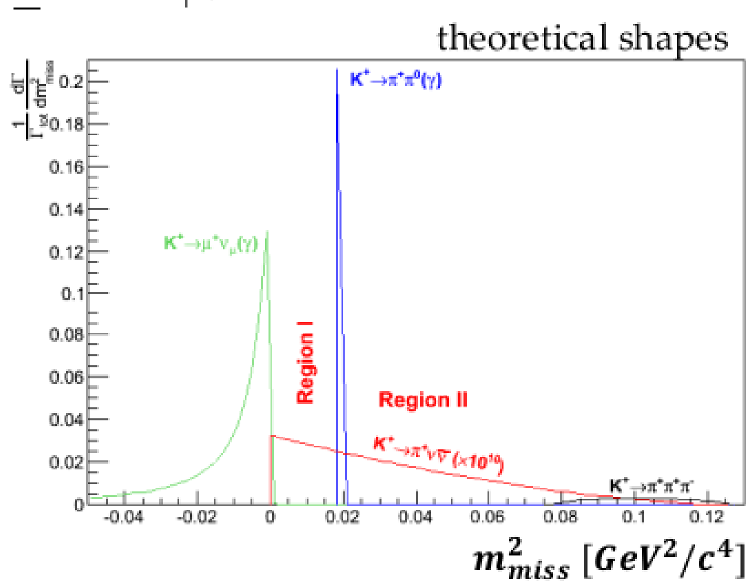


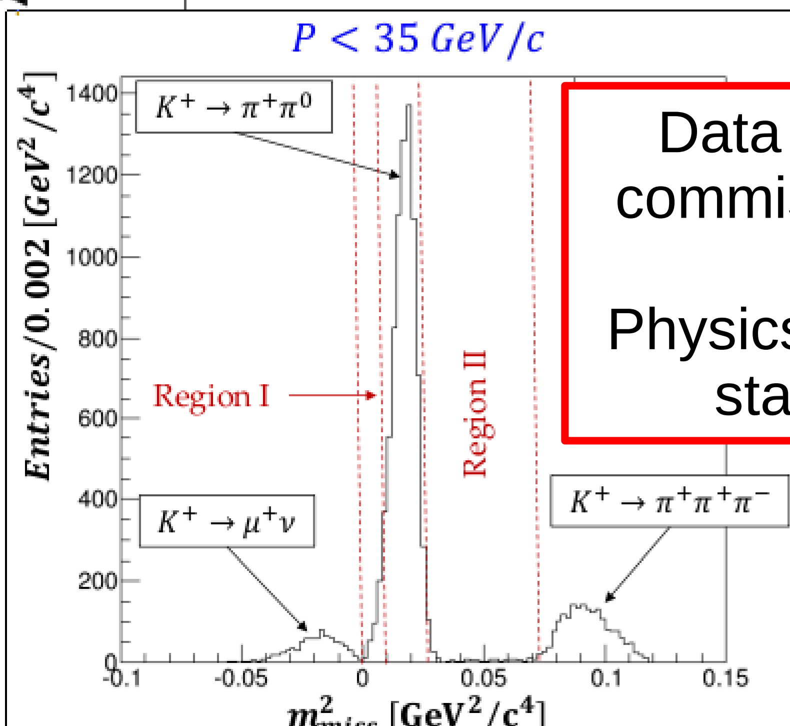
Next generation experiments should measure these decays for the 1st time

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

NA62 Apparatus







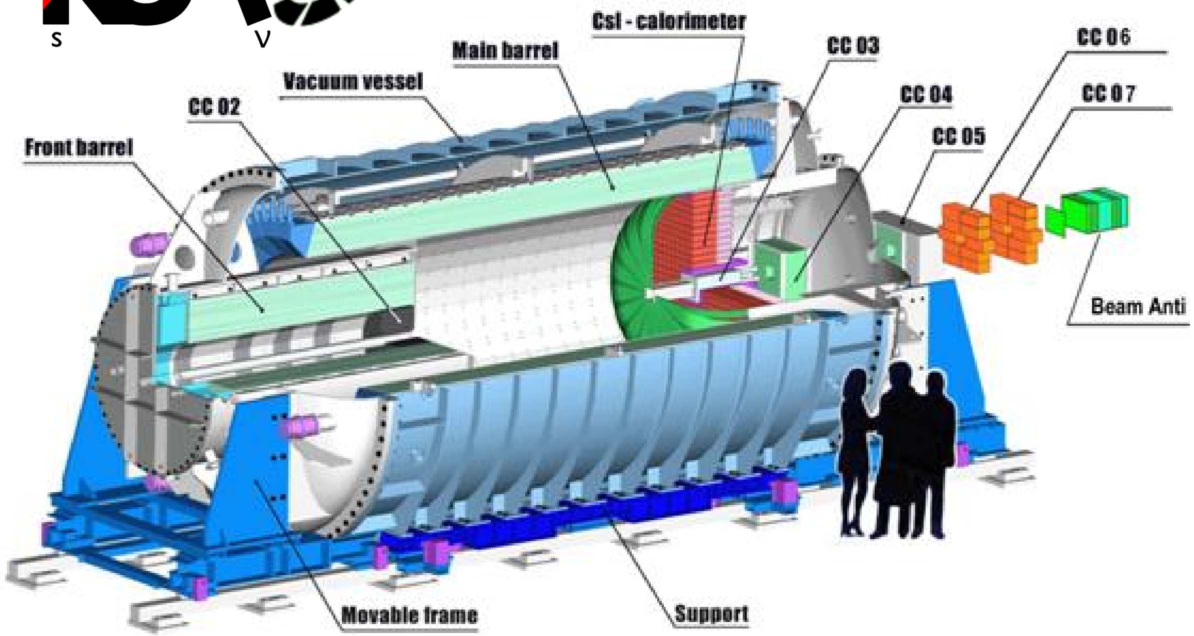
Data from 2014 commissioning run

Physics data taking starts 2015

Data taking May 2013, ended by radiation incident

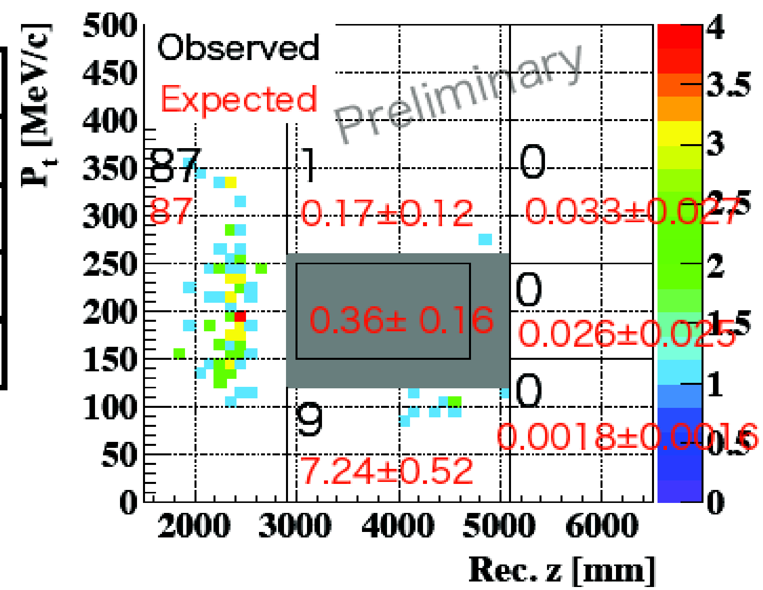
Allows first results & detailed background studies

Data taking restarted April 2015, expect large improvement with 2015 data



- Summary of #BG inside the signal box

BG source	#BG
Hadron interaction events	0.18±0.15
Kaon decay events	0.11±0.04
Upstream events	0.06±0.06
Sum	0.36± 0.16



- Sensitivity of the 1st physics run $= 1.29\times10^{-8}$

(cf) S.E.S. of KEK E391a: 1.11×10^{-8}

- Observed 1 event in the box (consistent with BG expectation)

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 $|V_{ub}|$
  - Hints of lepton non-universality in R(D) & R(D*)
  - Rates in $b \to s l^+ l^-$ & P_5'
- Much to look forward to
  - NA62 & KOTO
  - More results from LHC Run I & II (LHCb & ATLAS & CMS)
  - LHCb upgrade & Belle II