Flavour Physics & CP Violation

Lecture 4 of 4

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Contents

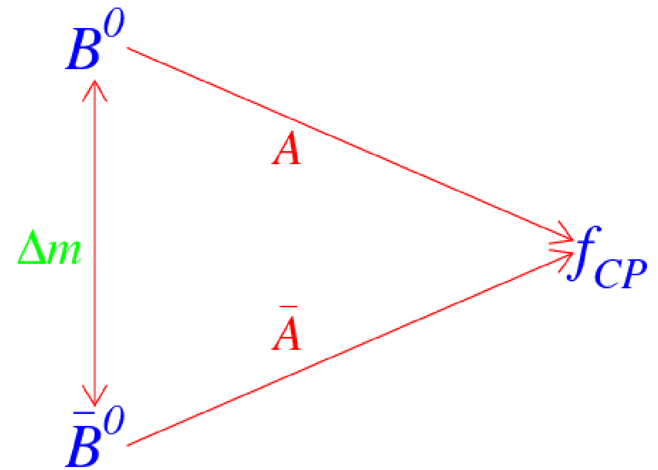
CP violation in decay

(or “direct CP violation”)

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$



$$\left|\frac{q}{p}\right| \neq 1$$ CP violation in mixing

$$\left|\frac{\bar{A}}{A}\right| \neq 1$$ CP violation in decay

$$\Im\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$ CP violation in interference between mixing and decay

n.b. historical classification of CP violation as “direct” and “indirect” is of little use nowadays (though often misused!)

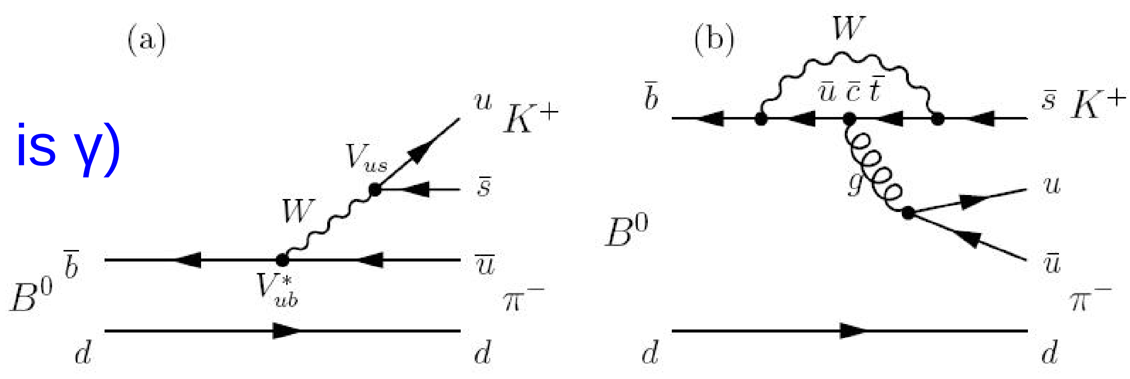
CP violation in decay

- Condition for CPV in decay: $|\bar{A}/A| \neq 1$
- Need $\bar{A}$ and A to consist of (at least) two parts
  - with different weak (φ) and strong (δ) phases
- Often realised by "tree" and "penguin" diagrams

$$A = |T| e^{i(\delta_T - \phi_T)} + |P| e^{i(\delta_P - \phi_P)} \qquad \bar{A} = |T| e^{i(\delta_T + \phi_T)} + |P| e^{i(\delta_P + \phi_P)}$$

$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\,|T||P| \sin(\delta_T - \delta_P) \sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2\,|T||P| \cos(\delta_T - \delta_P) \cos(\phi_T - \phi_P)}$$

Example: B → Kπ
(weak phase difference is γ)



Feynman tree (a) and penguin (b) diagrams for the $B_d^0 \to K^+\pi^-$ decay

The famous penguin story

Penguin diagram

From Wikipedia, the free encyclopedia

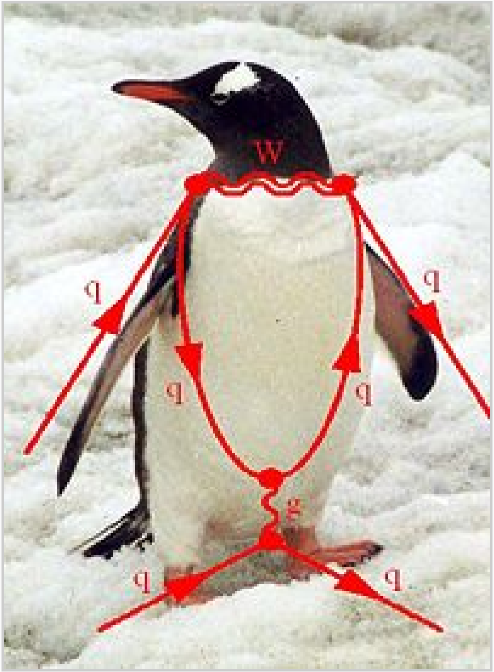
In quantum field theory, **penguin diagrams** are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They were first isolated and studied by Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov.[1] The processes which they describe were first directly observed in 1991 and 1994 by the CLEO collaboration.

Origin of the name

[edit]

John Ellis was the first to refer to a certain class of Feynman diagrams as **penguin diagrams**, due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis:[2]

> Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.



Example of a penguin diagram

The famous penguin story

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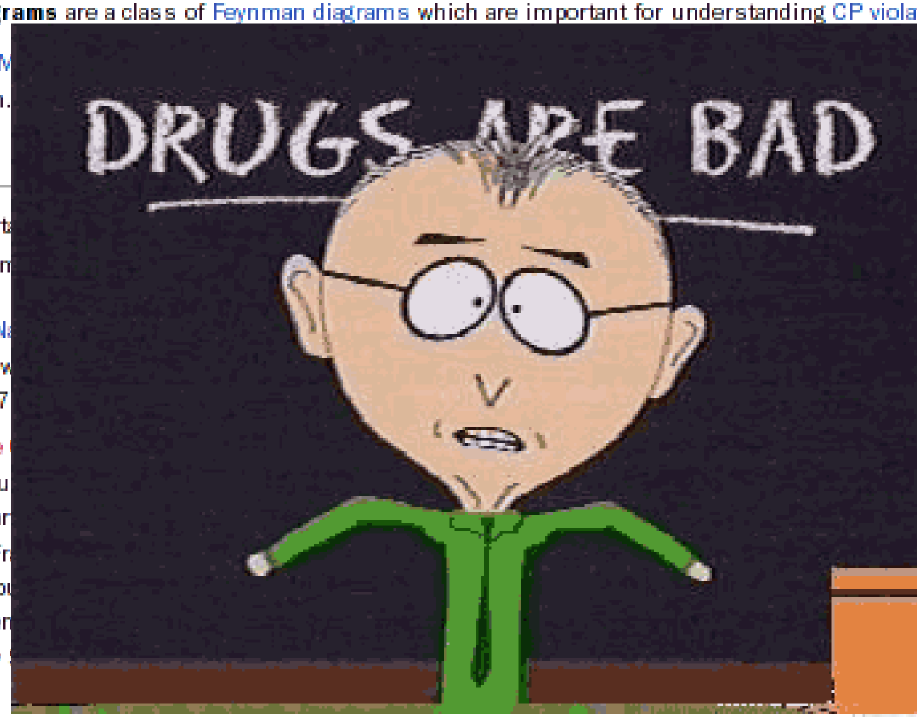

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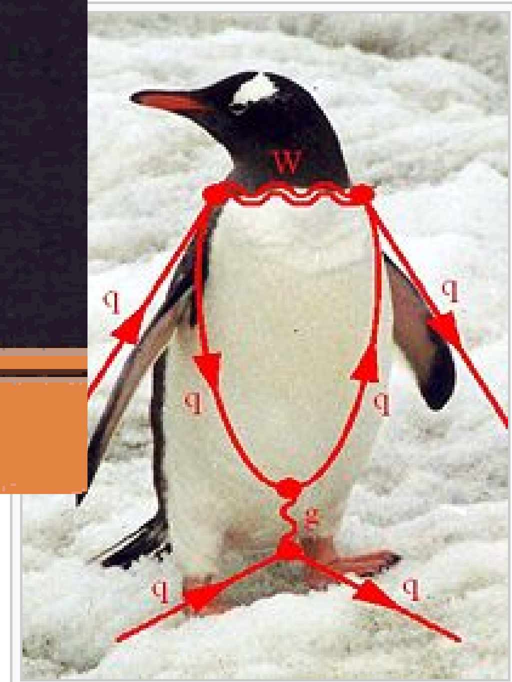


Example of a penguin diagram

Direct CP violation in B→Kπ

- Direct CP violation in B→Kπ sensitive to γ

too many hadronic parameters ⇒ need theory input

NB. interesting deviation from naïve expectation

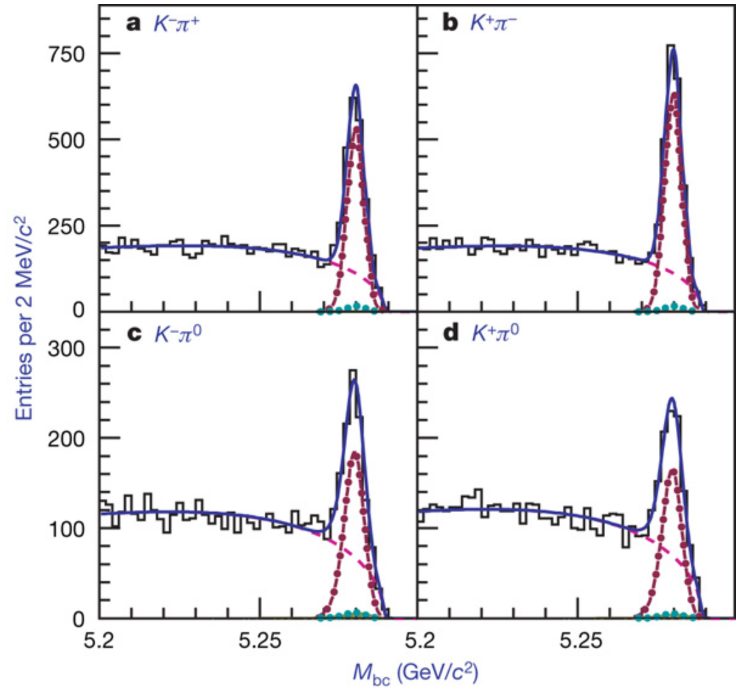
Belle Nature 452 (2008) 332

"Kπ puzzle"

$A_{CP}(K^-\pi^+) = -0.082 \pm 0.006$

$A_{CP}(K^-\pi^0) = +0.040 \pm 0.021$

HFAG averages



Could be a sign of new physics …
… but first need to rule out possibility of
larger than expected QCD corrections

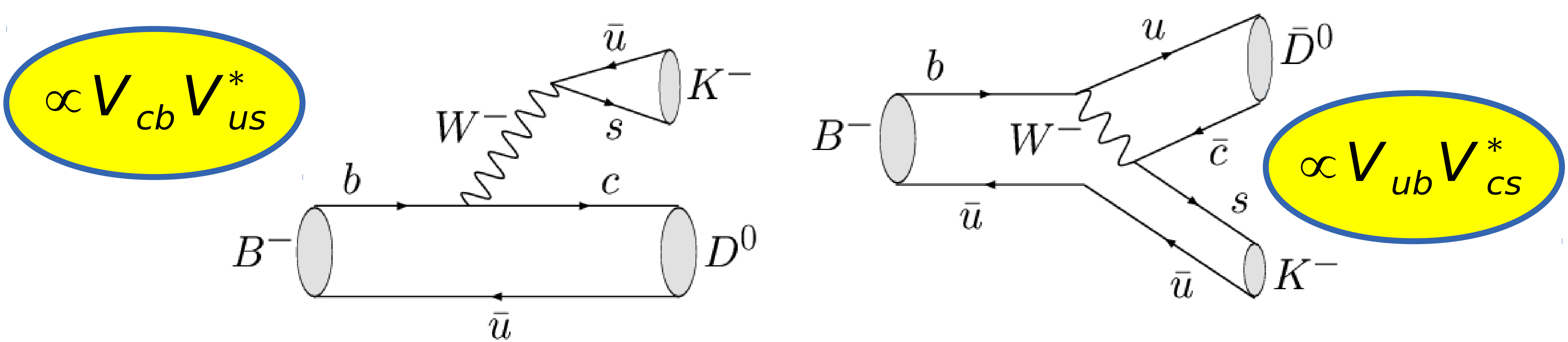
Importance of γ from B→DK

- 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

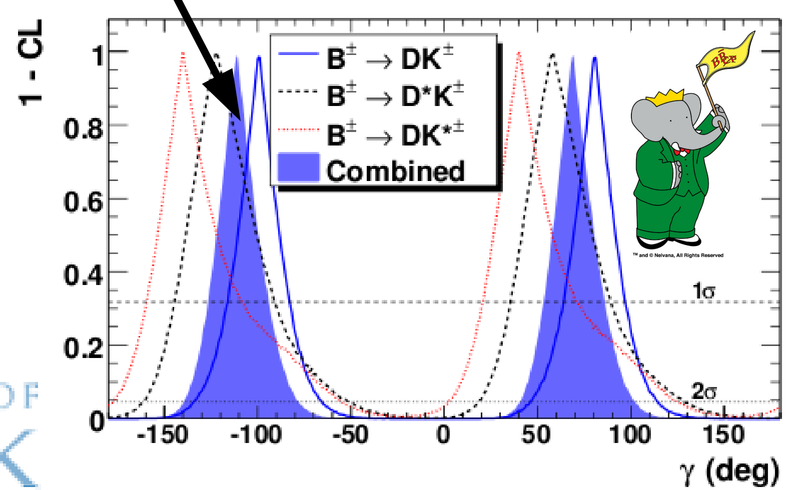


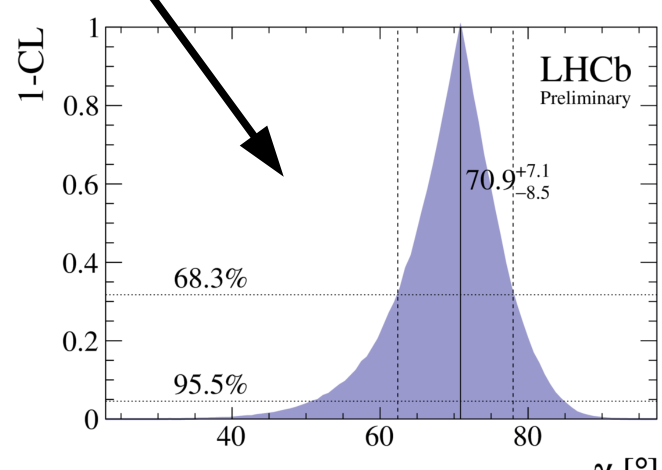
Variants use different B or D decays
require a final state common to both D^0 and $\bar{D}^0$

γ from combination of $B^+ \to DK^+$ modes

BaBar PRD 87 (2013) 052015
Belle CKM2012 preliminary
LHCb PLB 726 (2013) 151
& LHCb-CONF-2016-001

- All direct CP violation effects caused by γ in the Standard Model
- Only those in B→DK type processes involve only tree-level diagrams
  - enable determination of γ with negligible theoretical uncertainty
- Several different B and D decays can be used
- Combination includes results from GLW/ADS (D→hh) & GGSZ (D→$K_S$hh)
- Sensitivity: BaBar & Belle each ~16°; latest LHCb ~7°





Strong CP?

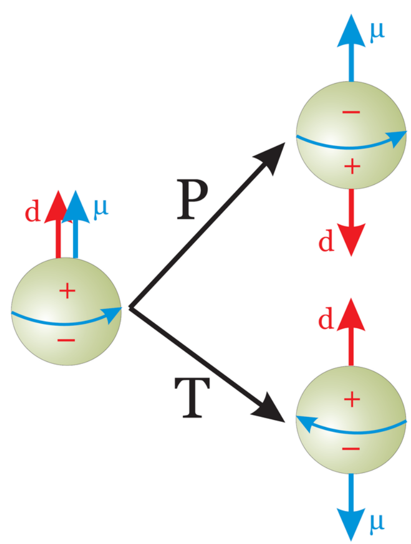
- I've told you that the CKM matrix is the only source of CP violation in the Standard Model.
- Is this true? What is “the Standard Model”?
  - depends in detail on who you ask
  - one reasonable definition:
    - the most general Lagrangian satisfying certain axioms (Lorentz invariance, local gauge symmetry) with a specified set of fields
- In this case, there is a term

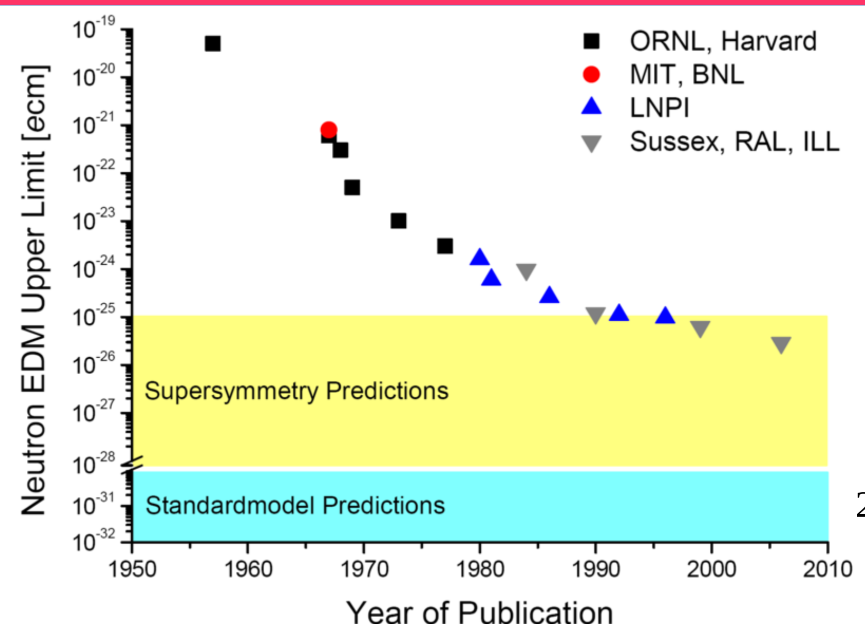
$$\mathcal{L}_{QCD} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

Neutron electric dipole moment

- If the θ_{QCD} parameter is $\neq 0$, there is CP violation in the strong interaction
  - $\rightarrow$ observable neutron electric dipole moment
- But: $|d_n| < 3.0 \times 10^{-26}$ e cm (PR D92 (2015) 092003)

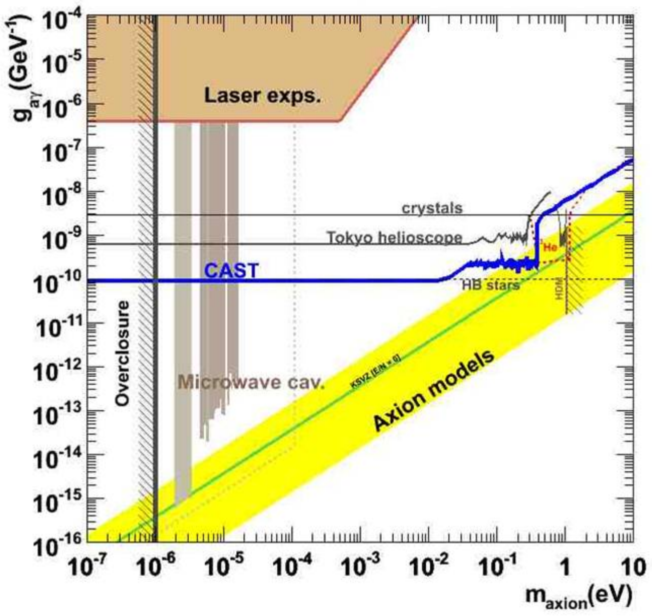
If neutron were the size of the earth, +/– charges separated by < 10 μm





The strong CP problem

- But: $|d_n| < 3.0 \times 10^{-26}$ e cm (PR D92 (2015) 092003)
- Corresponds to $\theta_{QCD} < 10^{-9}$
  - Why is it so small? Is it zero?
  - Does some new symmetry forbid it?
  - e.g. Peccei-Quinn theory
    - predicts the axion



    - various experiments (e.g. CAST, PVLAS, ADMX) search for axions, which are also a potential dark matter candidate

Precision physics with electric & magnetic moments

- Electric dipole moments are CP violating
  - essentially zero in the SM, but can be much larger BSM with sources of flavour-conserving CPV

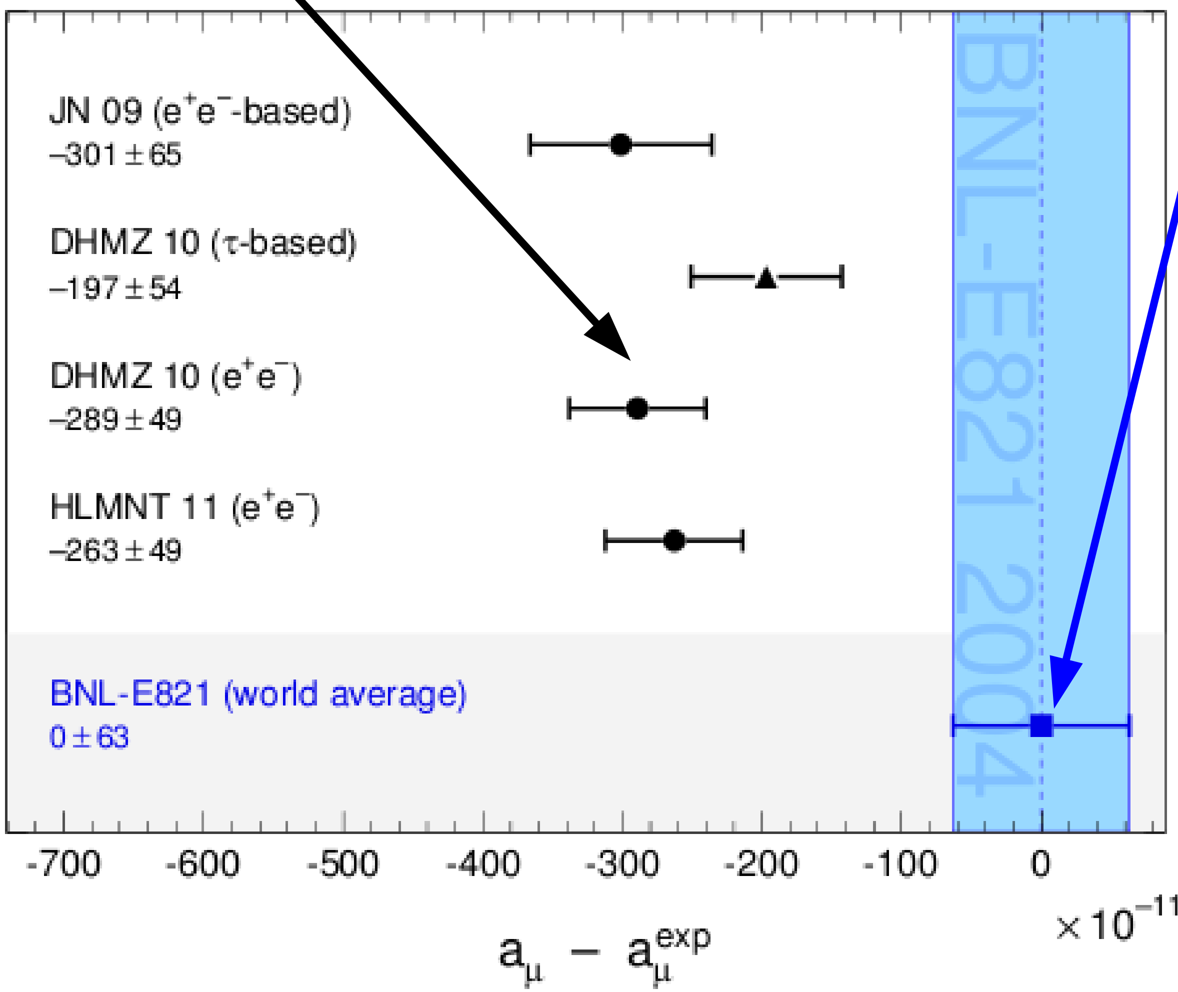
  $|d_e| < 8.7 \times 10^{-29}$ e cm [Science 343 (2014) 6168, 269]

- Magnetic dipole moments are CP conserving
  - sensitive to the structure of quantum fields
    - Dirac predicted $g_e = 2$ (RQM)
    - Schwinger predicted $a_e = (g_e–2)/2 = 0.0011614$ (QED)
    - a_e now calculated to 10 loops in QED (PRL 109 (2012) 111807)
      - $a_e = 0.00115965218178\ (77)$

$(g-2)_\mu$

Theory predictions

Experiment



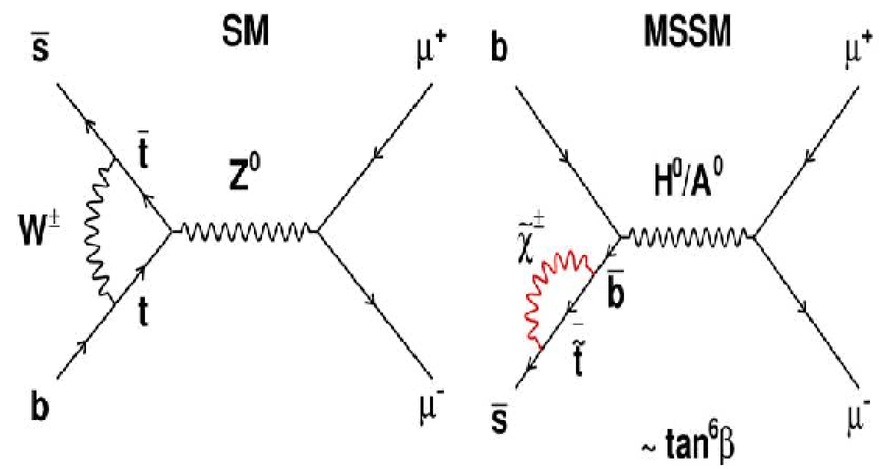
New experiment at FNAL will reduce uncertainty by factor ~2
Improvements in theory uncertainties also anticipated

Back to B physics

Rare Decays

$B_{(s)}^0 \to \mu^+\mu^-$
Killer app. for new physics discovery

- Very small in the SM
  - no tree-level FCNC
  - CKM suppression
  - helicity suppression

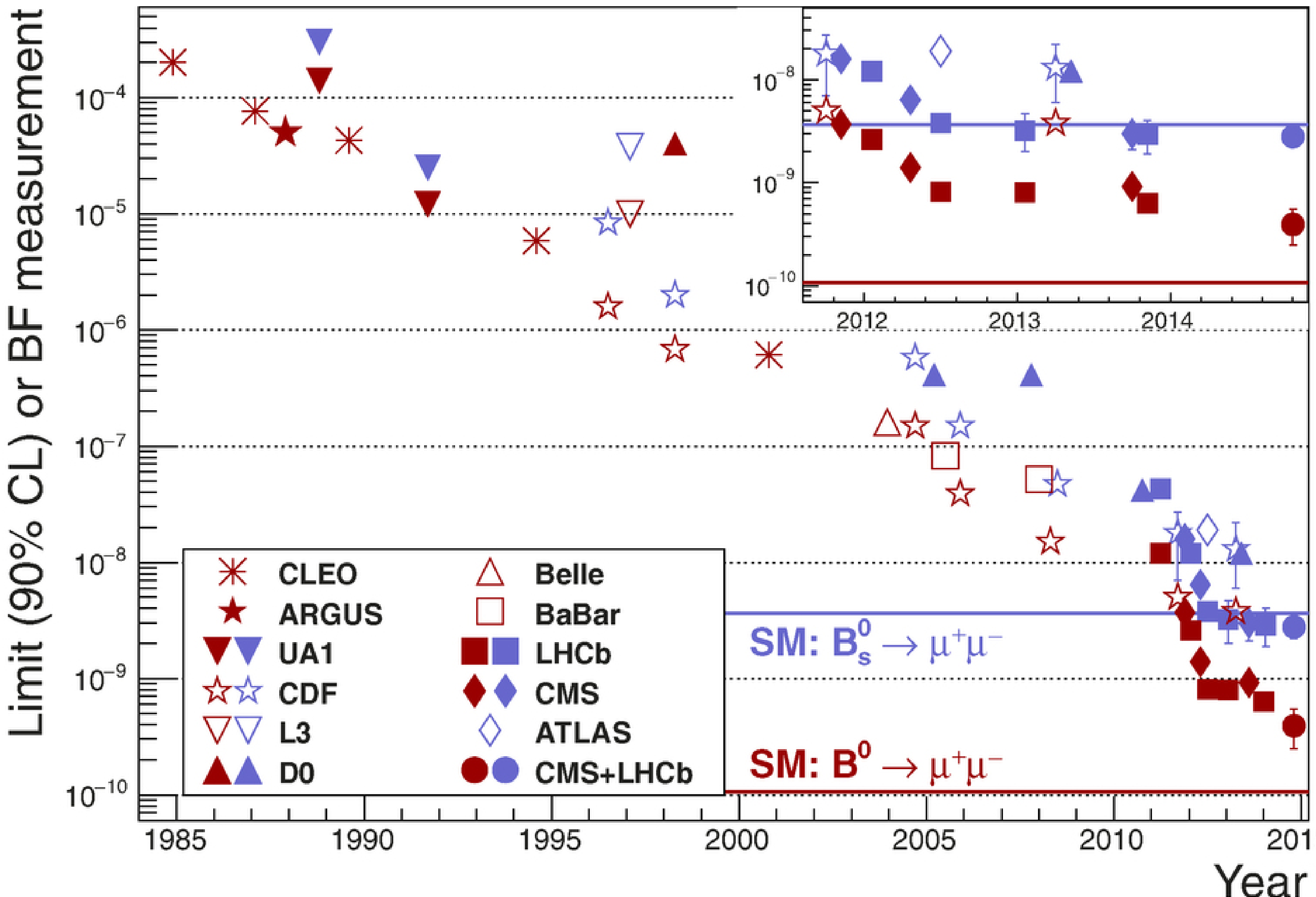


- Huge NP enhancement possible (tan β = ratio of Higgs vevs)

$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

- Clean experimental signature

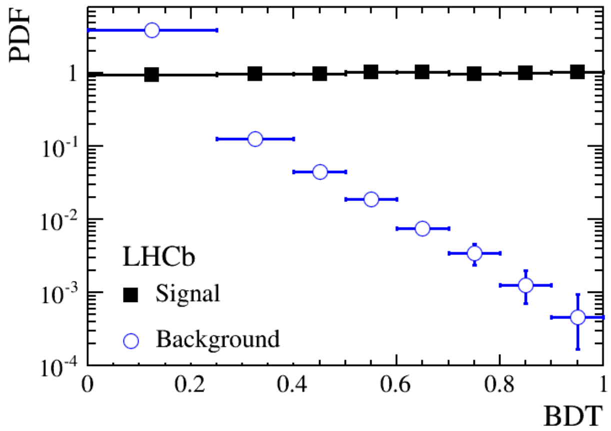
$B_{(s)}^0 \to \mu^+\mu^-$



Searches over 30 years

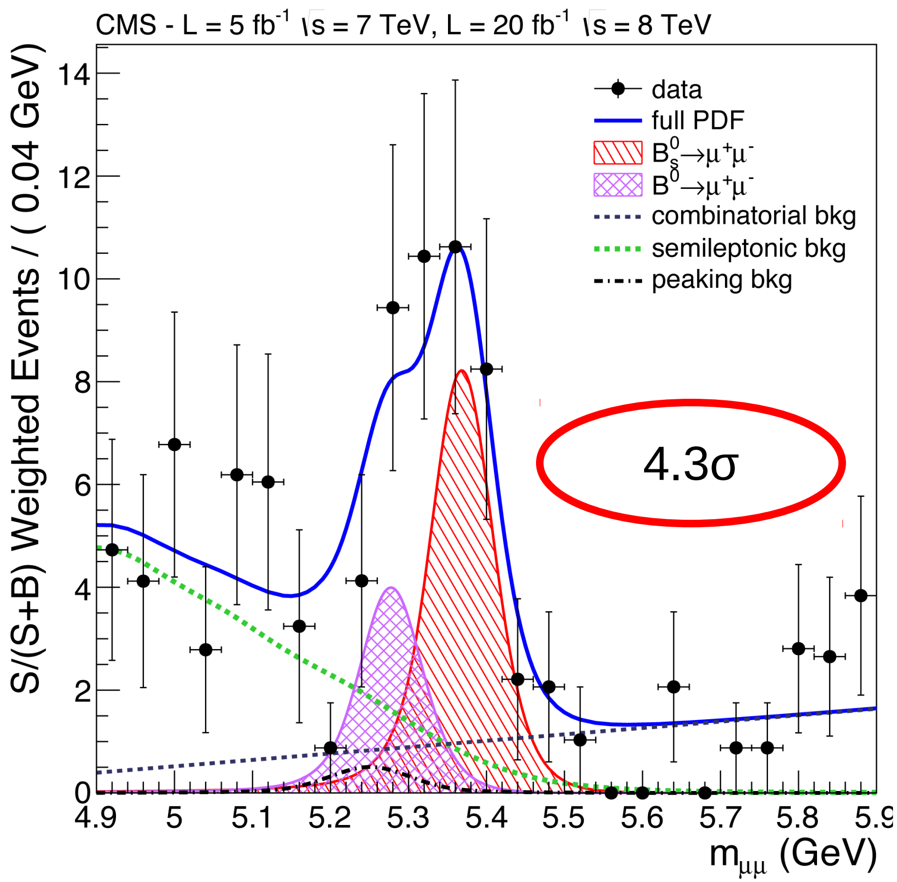
$B_{(s)}^0 \to \mu^+\mu^-$ – analysis ingredients

- Produce a very large sample of B mesons
- Trigger efficiently on dimuon signatures
- Reject background
  - excellent vertex resolution (identify displaced vertex)
  - excellent mass resolution (identify B peak)
    - also essential to resolve B^0 from B_s^0 decays
  - powerful muon identification (reject background from B decays with misidentified pions)
- Typical to combine various discriminating variables into a multivariate classifier
  - e.g. Boosted Decision Trees algorithm



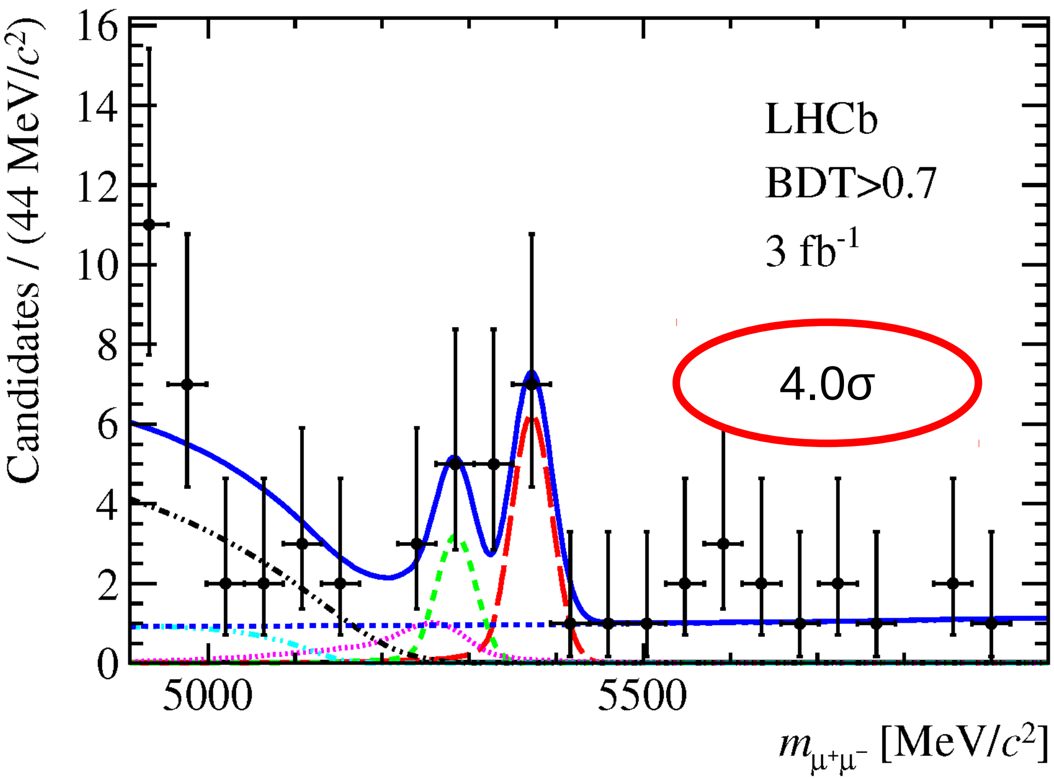
$B_{(s)}^0 \to \mu^+\mu^-$
latest results from CMS & LHCb

CMS PRL 111 (2013) 101804



Events weighted by S/(S+B)

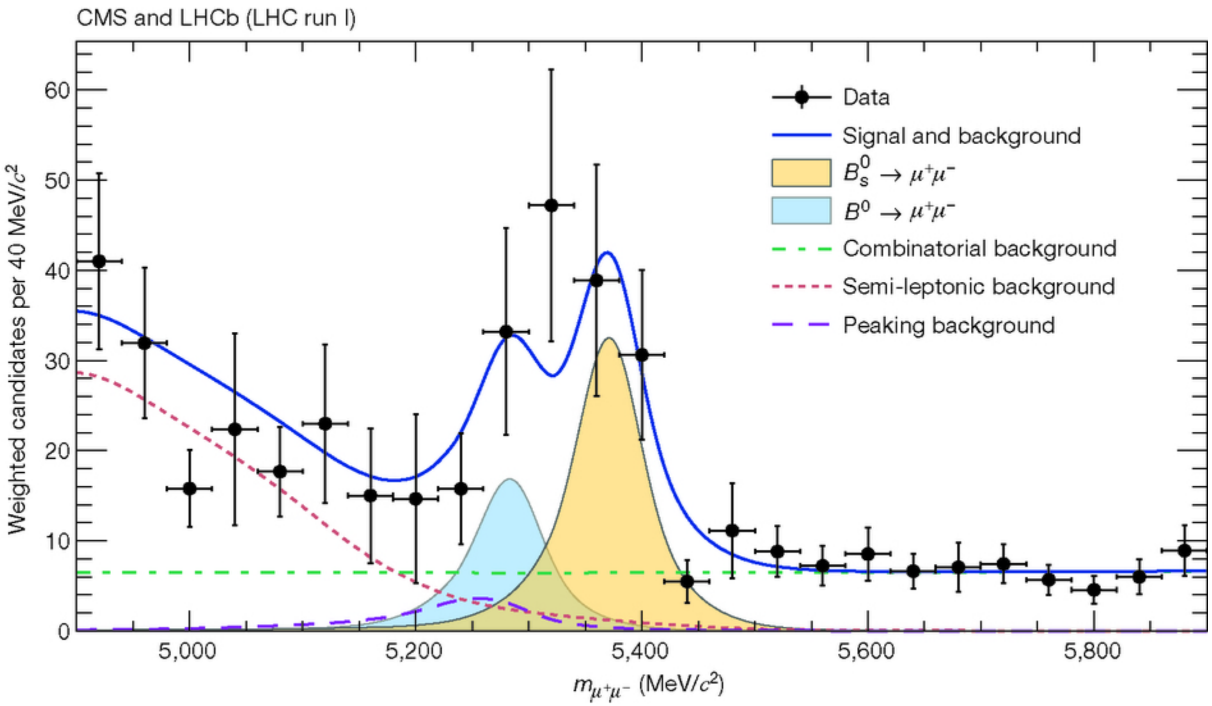
LHCb PRL 111 (2013) 101805



Only events with BDT > 0.7

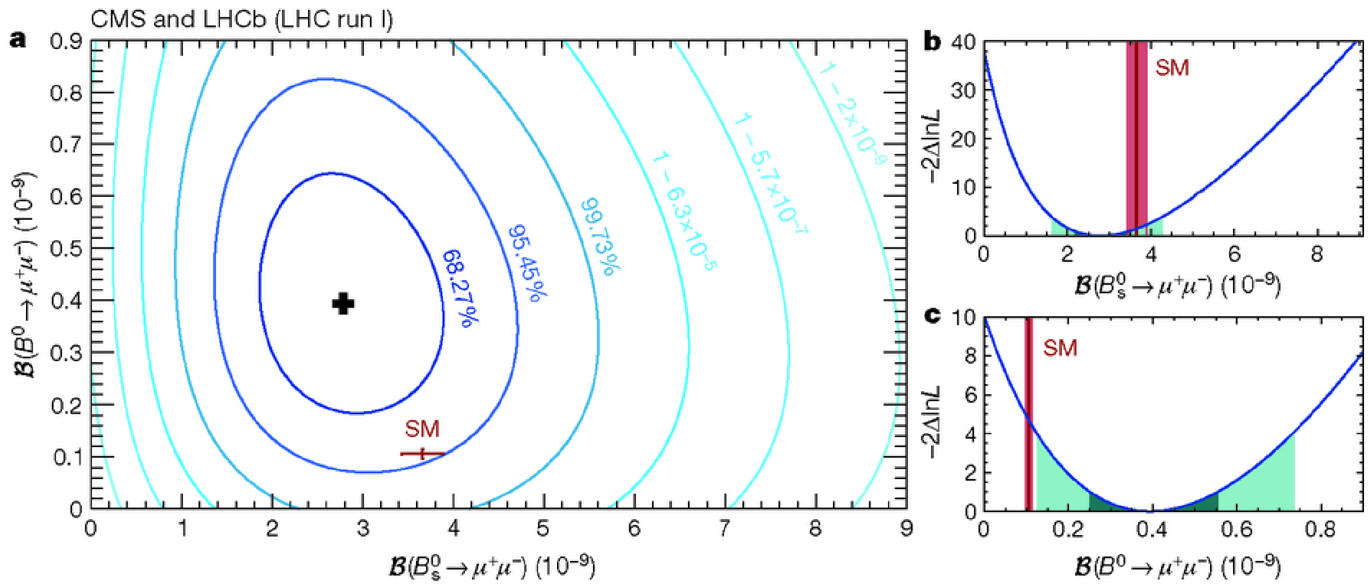
$B_s \to \mu^+\mu^-$

Nature 522 (2015) 68



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

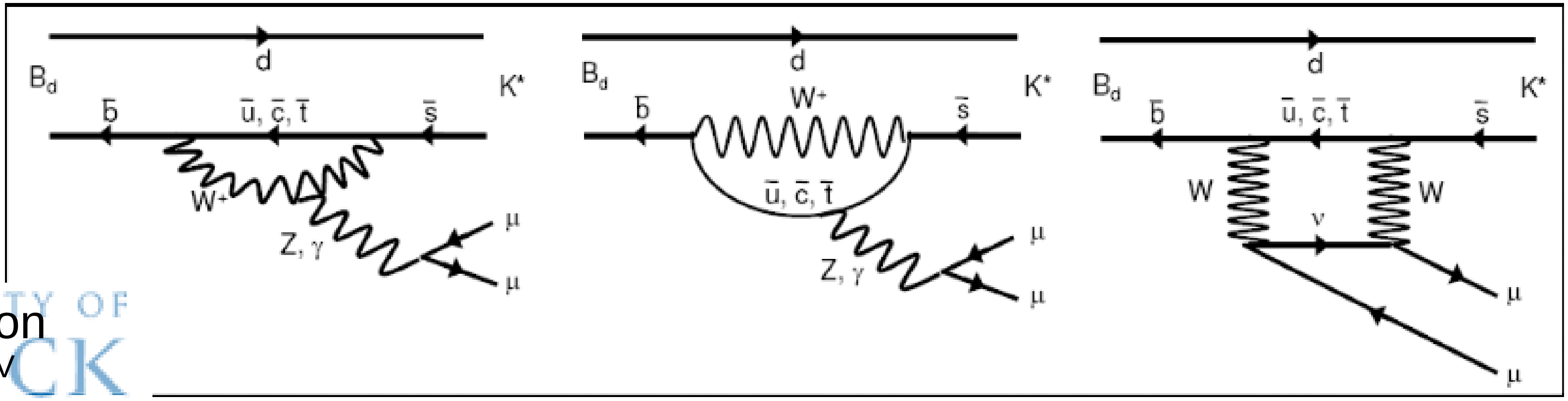
Results consistent with SM at 2σ level



Recent results from ATLAS not included (arXiv:1604.04263)

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

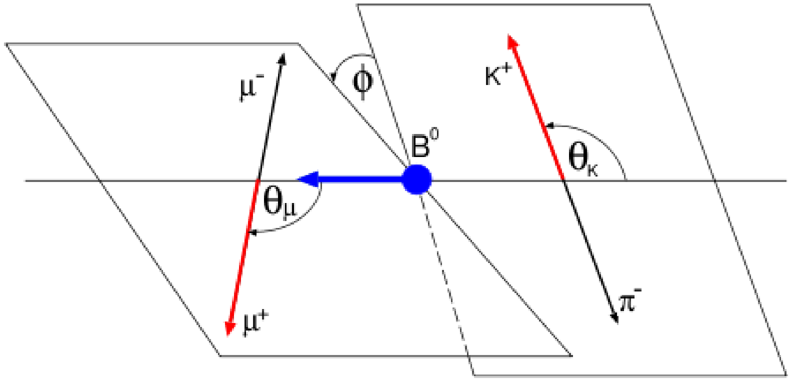
- $b \to sl^+l^-$ processes also governed by FCNCs
  - rates and asymmetries of many exclusive processes sensitive to NP
- Queen among them is $B_d \to K^{*0}\mu^+\mu^-$
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions (at least at low q^2)



Angular analysis of B→K*μ⁺μ⁻

- Differential decay distribution

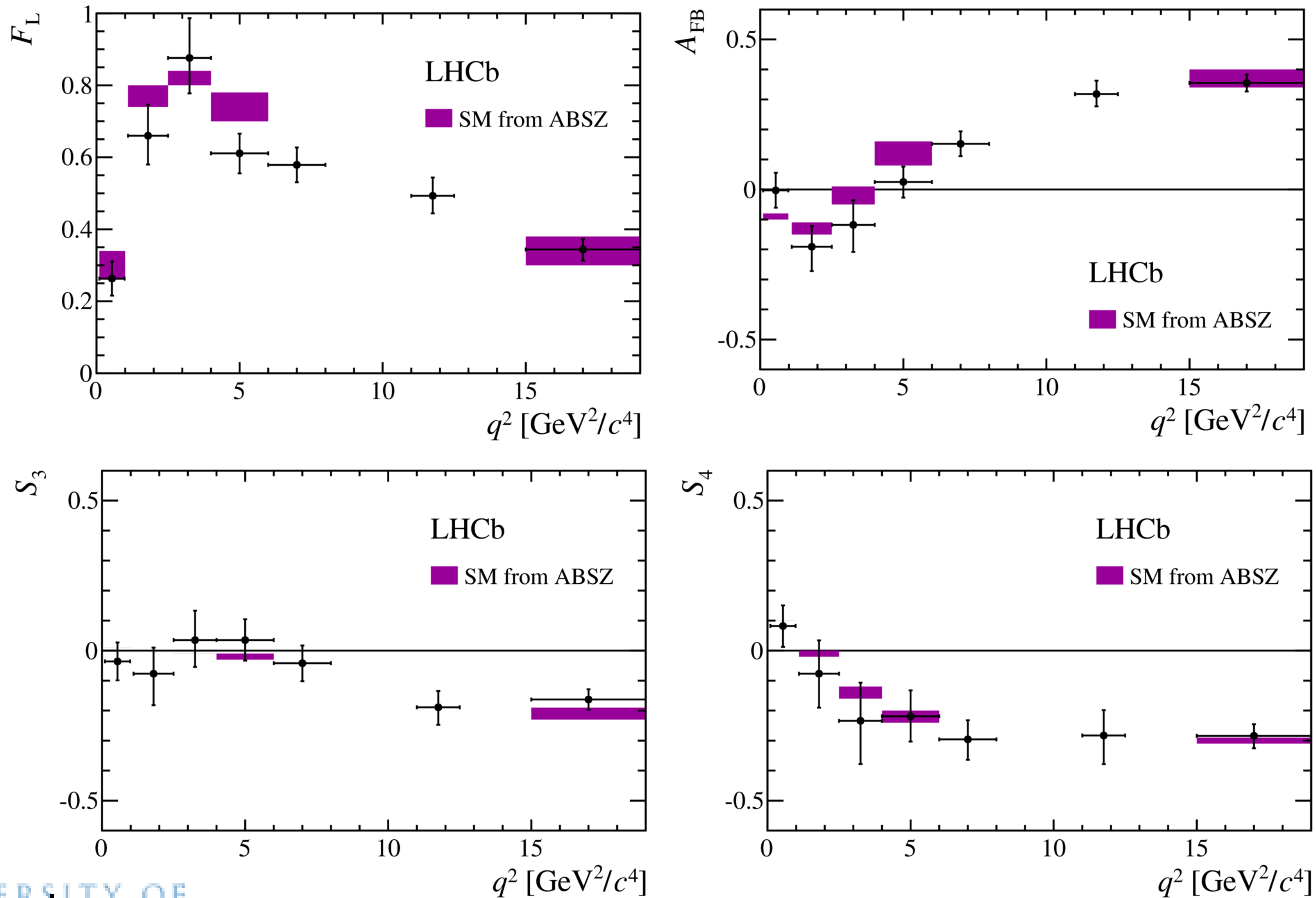
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$



S_i terms related to Wilson coefficients and form factors

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

JHEP 02 (2016) 104



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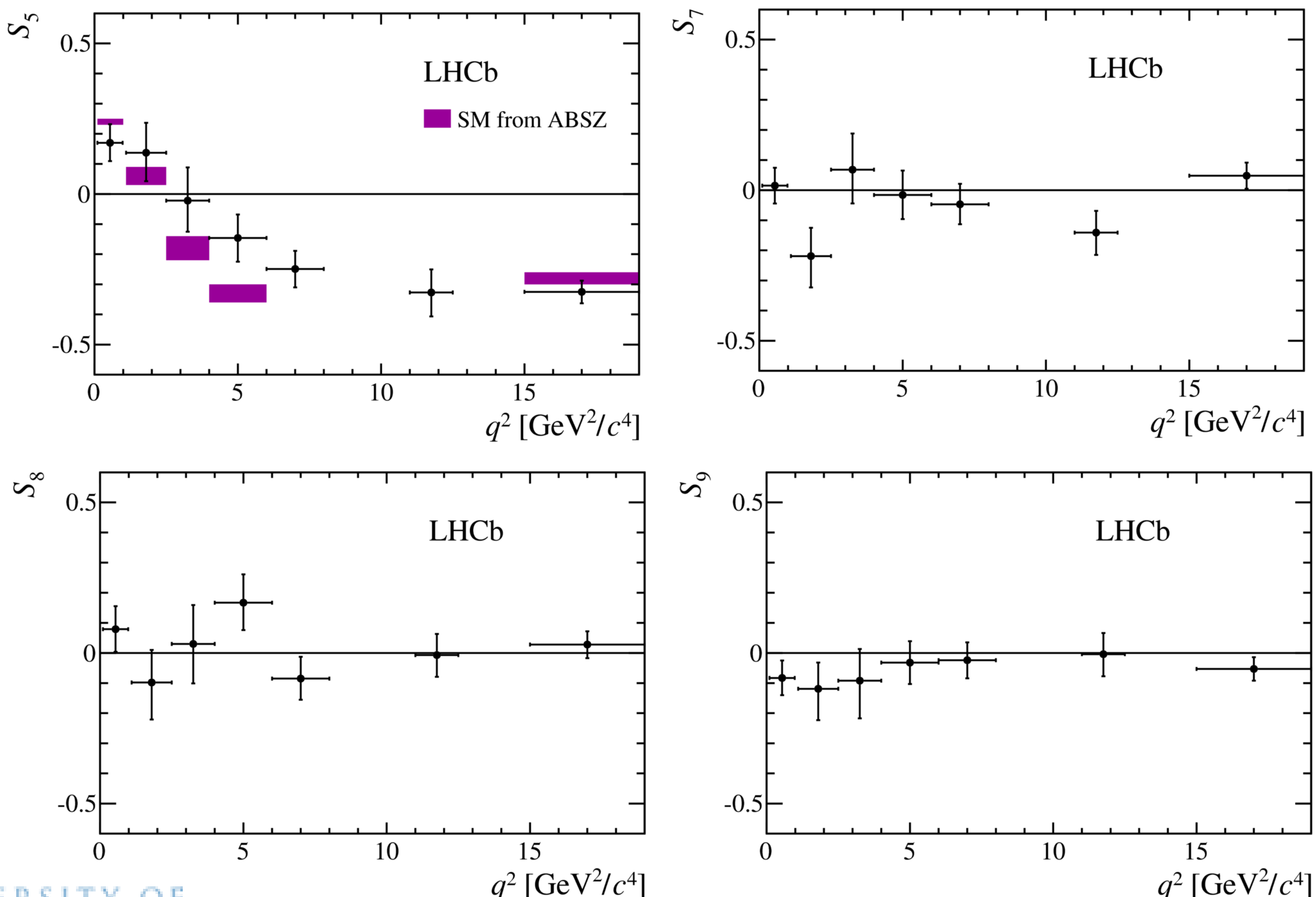
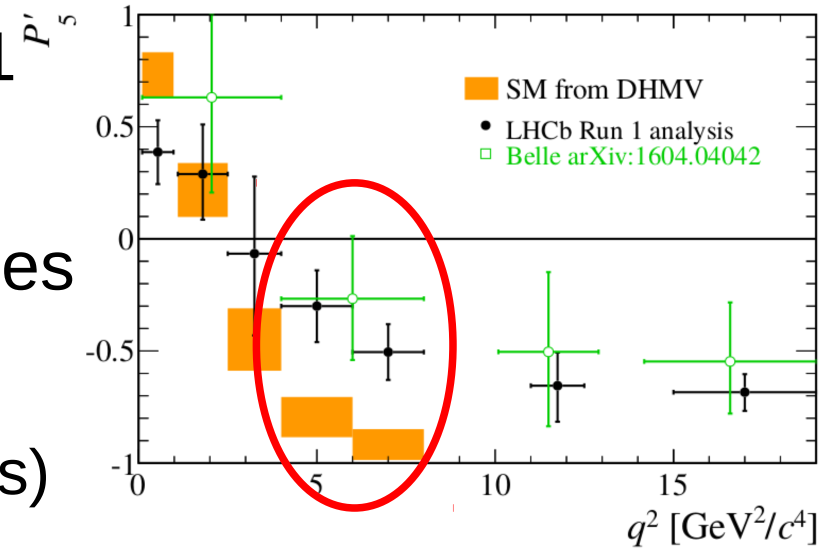
JHEP 02 (2016) 104



Tension in P_5'

JHEP 02 (2016) 104

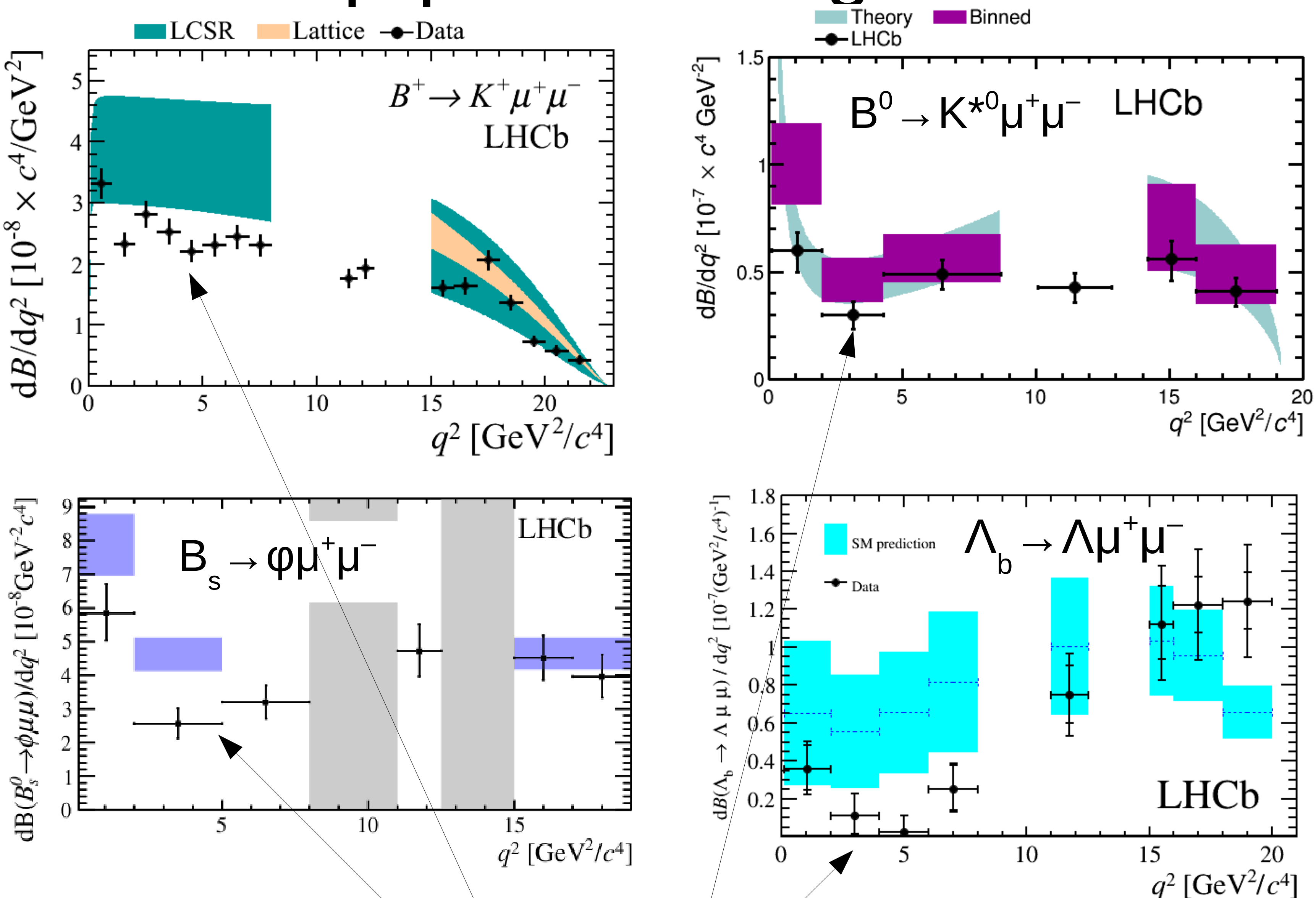


- Dimuon pair is predominantly spin-1
- either vector (V) or axial-vector (A)
- There are 6 non-negligible amplitudes
- 3 for VV and 3 for VA
- expressed as $A^{L,R}_{0,\perp,\parallel}$ (transversity basis)
- P_5' related to difference between relative phase of longitudinal (0) and perpendicularly ($\perp$) 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 $C_9^{(\prime)}$ & $C_{10}^{(\prime)}$)

$b \to s\mu^+\mu^-$ branching fractions

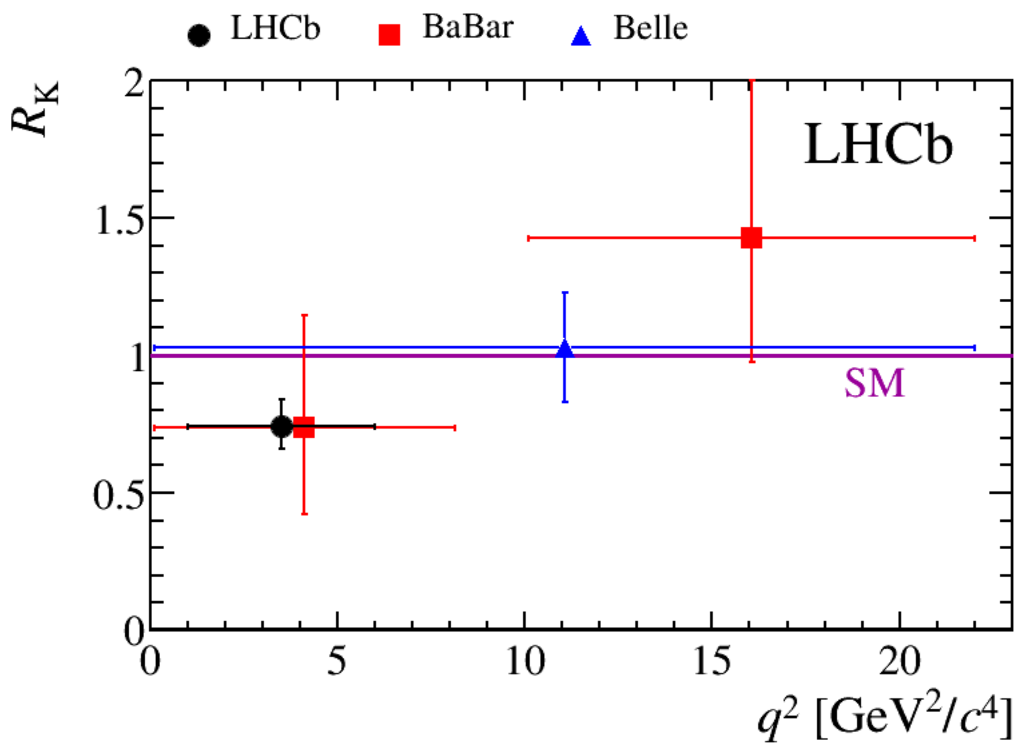


Trend to be below SM prediction at low q^2?

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) – negligible theoretical uncertainty



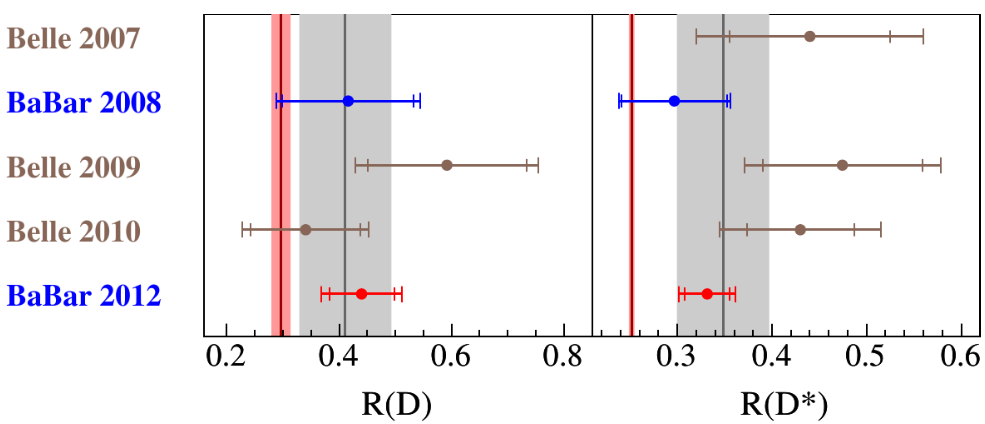
$$R_K(1 < q^2 < 6\ \text{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$$

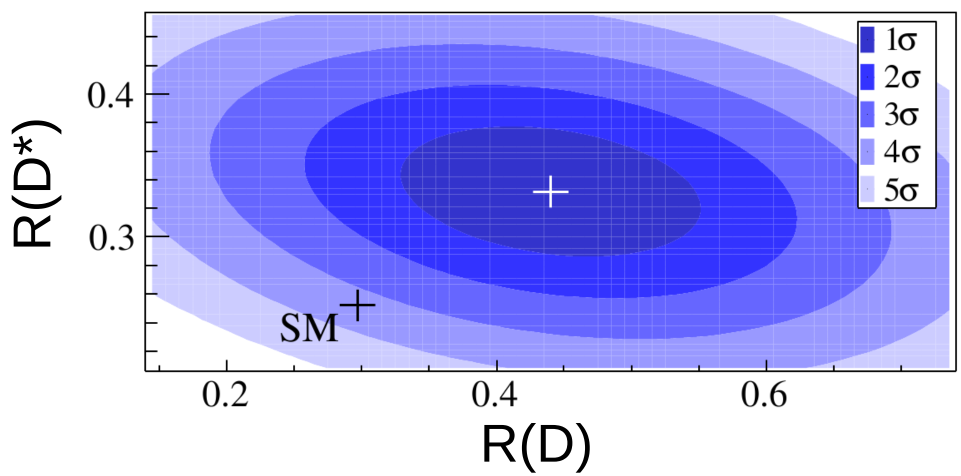
<3σ from SM but suggestive

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

- 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

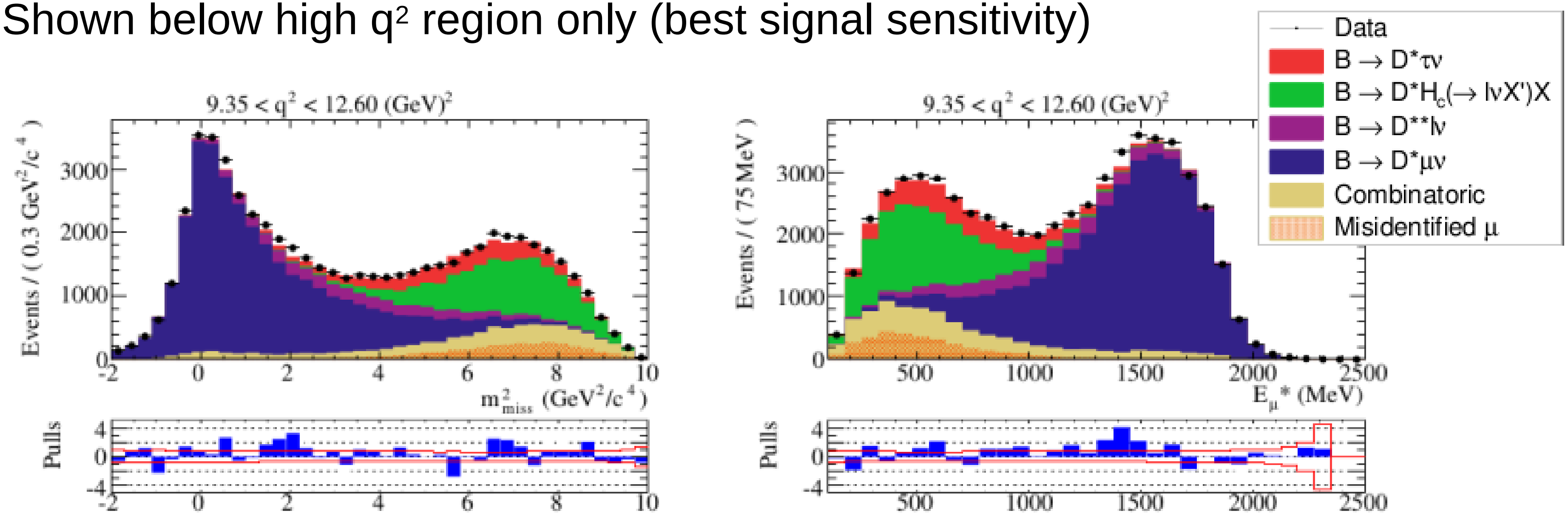




$B \to D^* \tau \nu$ at LHCb

PRL 115 (2015) 112001

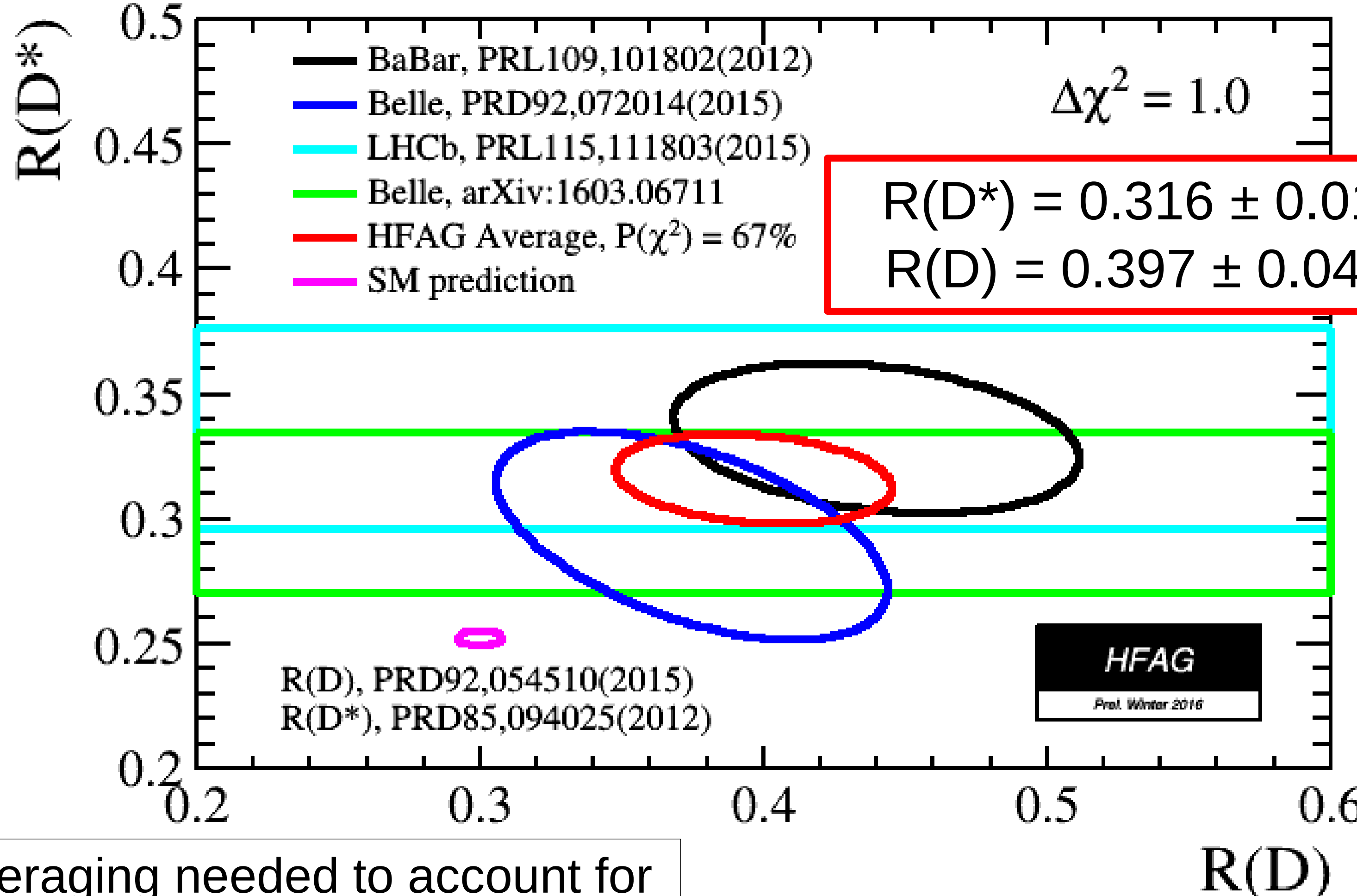
- Identify $B \to D^* \tau \nu$, $D^* \to D\pi$, $D \to K\pi$, $\tau \to \mu \nu \bar{\nu}$
  - Similar kinematic reconstruction to $\Lambda_b \to p \mu \nu$
    - Assume $p_{B,z} = (p_{D^*} + p_\mu)_z$ to calculate $M_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$
  - Require significant B, D, τ flight distances & 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)



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

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

Tension with SM at 4.0σ

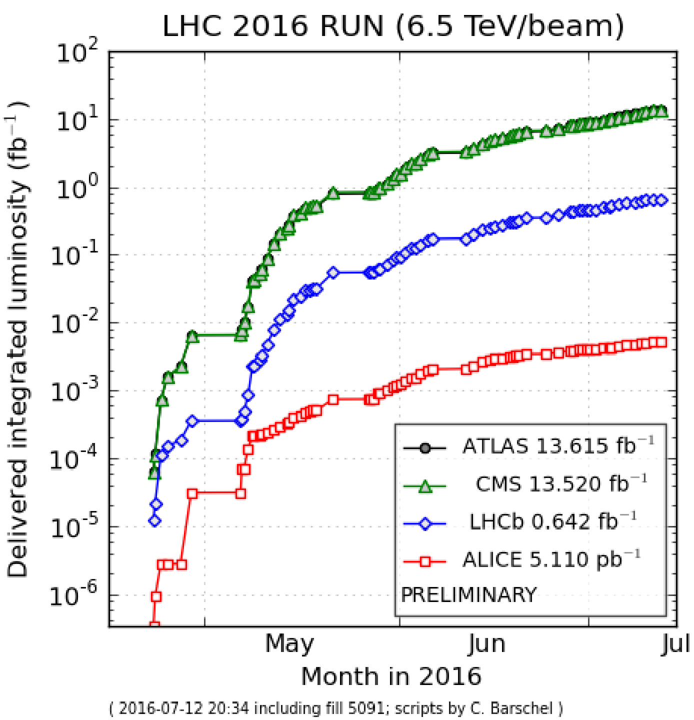


R(D*) = 0.316 ± 0.016 ± 0.010
R(D) = 0.397 ± 0.040 ± 0.028

Careful averaging needed to account for statistical and systematic correlations

Summary of rare decays

- Accumulating hints of non-SM effects?
  - in particular related to lepton universality
  - observables with negligible theoretical uncertainty
  - various models proposed that can explain effects
- It is easy to see patterns, yet there may be none
  - no single effect with 5σ significance
- Need more data!
  - many results still to come from Run I
  - … and Run II is happening



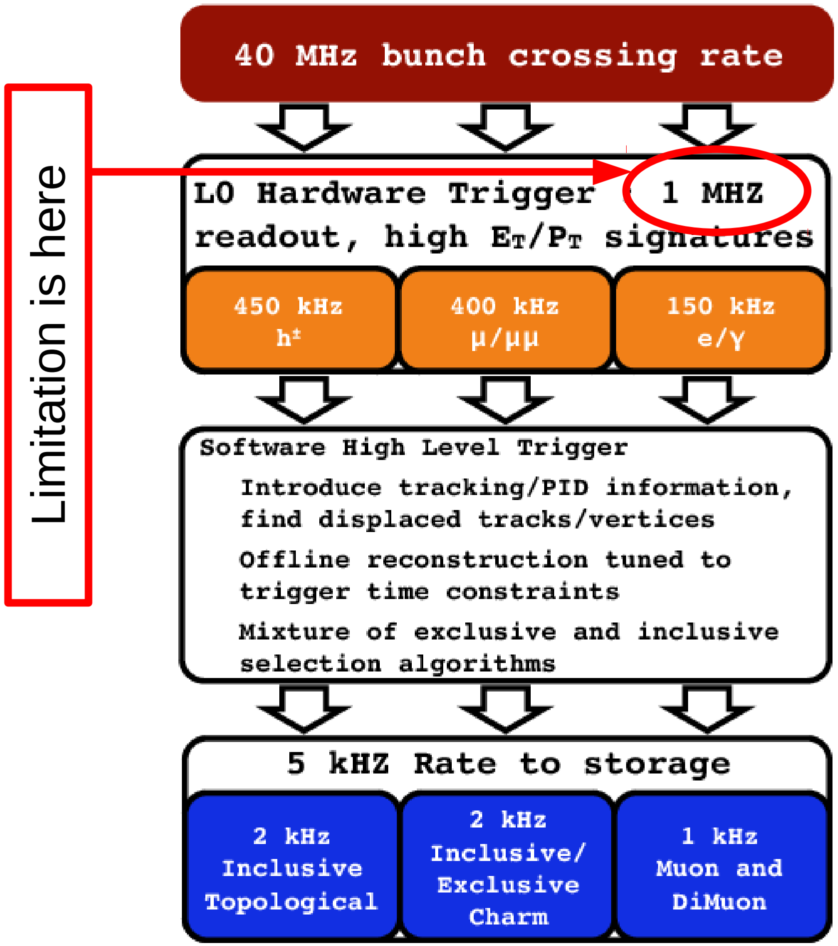
Future flavour physics projects

LHCb upgrade

- To fully exploit LHC potential for heavy flavour physics will require an upgrade to LHCb
  - full readout & trigger at 40 MHz to enable high L running
  - "high L" = 10^{33}/cm^2/s (so independent of machine upgrade)
  - planned for 2018 shutdown

- Physics case:
  - "exploration" of 1st phase will become "precision studies"
  - new opportunities for exploration open up (e.g. testing consistency of CP violation in tree vs. loop processes)

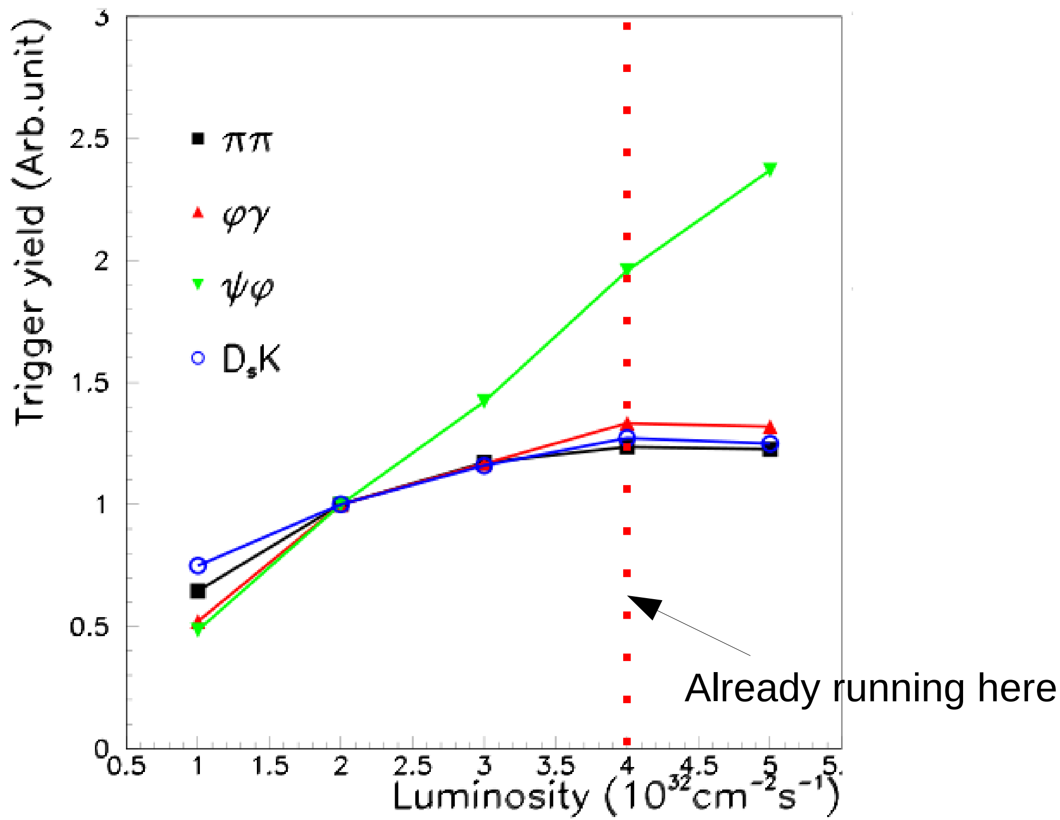
LHC upgrade and the all important trigger



higher luminosity

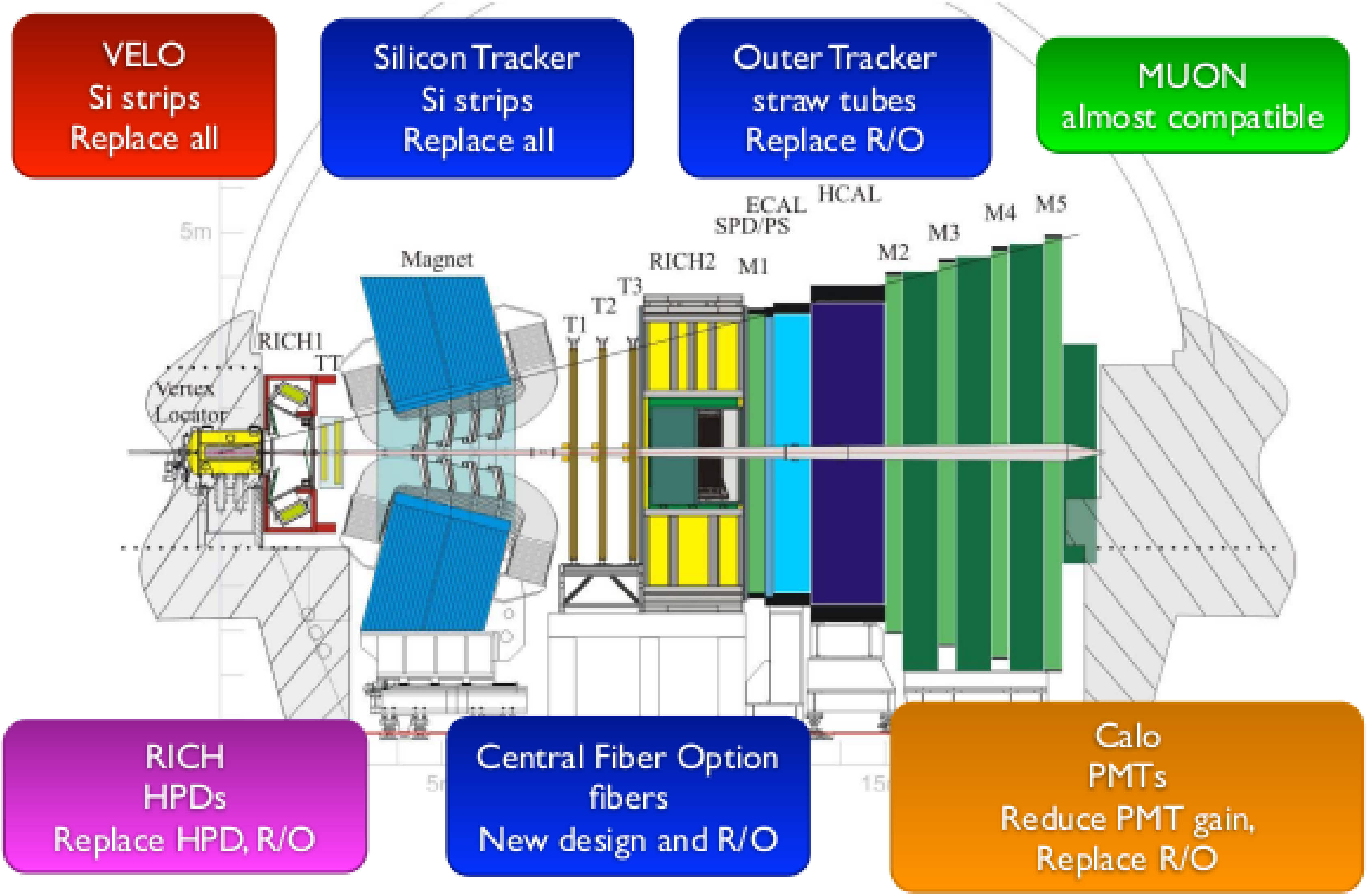
→ need to cut harder at L0 to keep rate at 1 MHz

→ 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

LHCb detector upgrade



Upgrade – expected sensitivities

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\text{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.

- sample sizes in most exclusive B and D final states far larger than those collected elsewhere
- no serious competition in study of B_s decays and CP violation

Other future flavour experiments

- SuperKEKB/Belle2
  - $B \to \tau\nu$, inclusive measurements, τ physics, …
- Rare kaon decays
  - $K^+ \to \pi^+\nu\bar{\nu}$ (NA62, CERN); $K^0 \to \pi^0\nu\bar{\nu}$ (K0T0, J-PARC)
- Muon to electron conversion (charged lepton flavour violation)
  - COMET/PRIME (J-PARC); mu2e (FNAL)
  - also MEG upgrade & μ3e (PSI)
- Various electric & magnetic dipole experiments
  - $(g-2)_\mu$ in FNAL & J-PARC

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

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

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

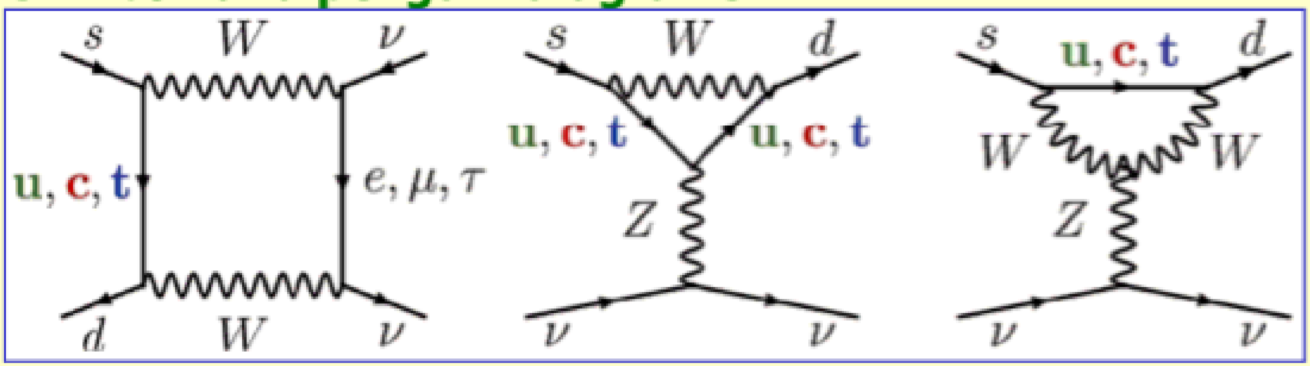
SM branching ratios

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

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

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

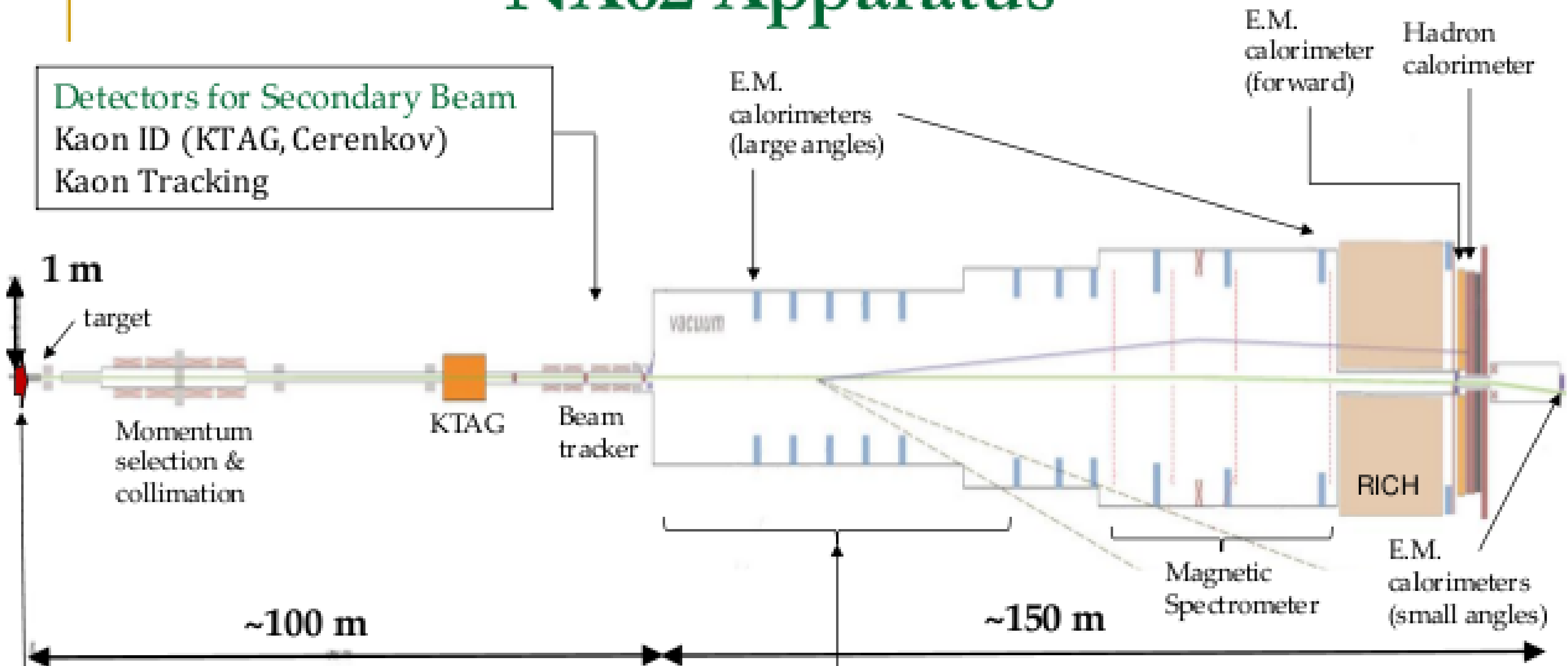
SM: box and penguin diagrams

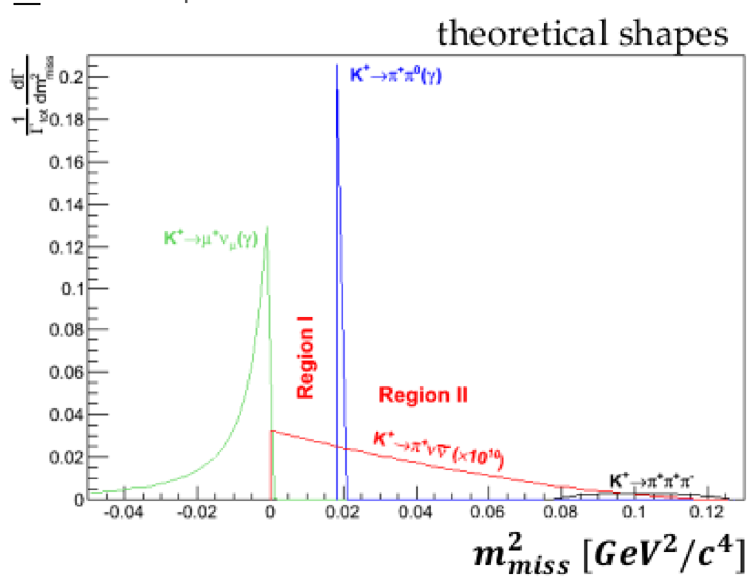


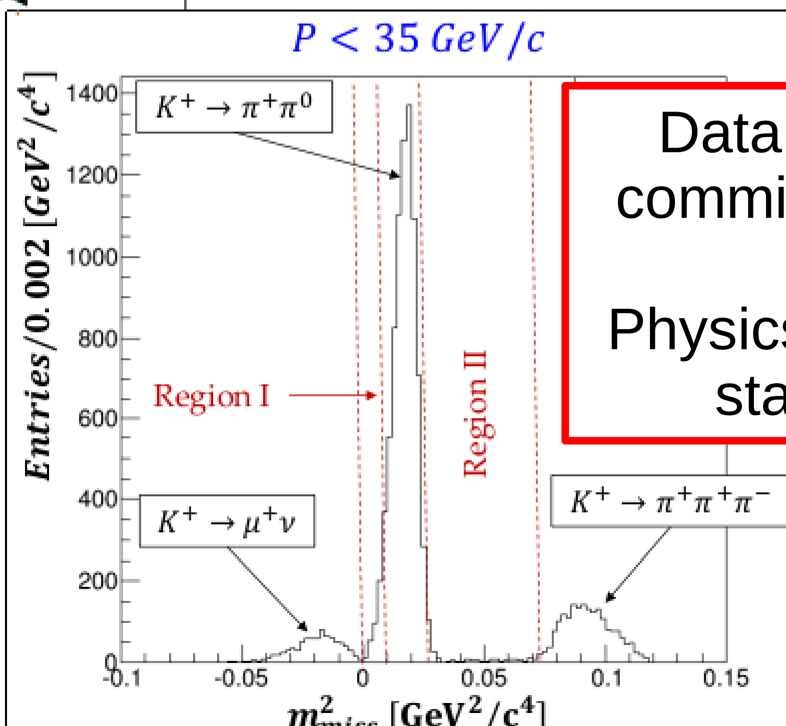
Next generation experiments should measure these decays for the 1st time

- $K^+ \to \pi^+ \nu\bar{\nu}$ (NA62, CERN)
- $K^0 \to \pi^0 \nu\bar{\nu}$ (K0T0, J-PARC)
- Proposals also at FNAL

NA62 Apparatus



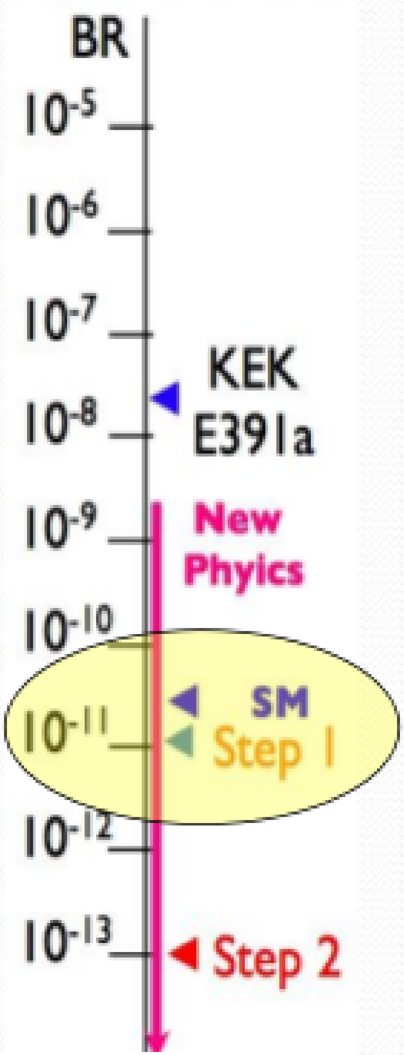


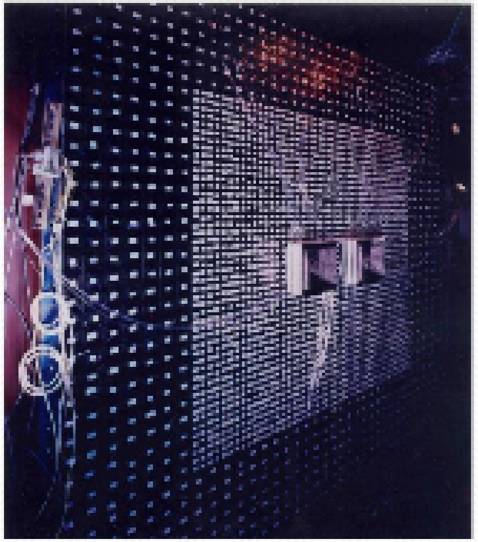


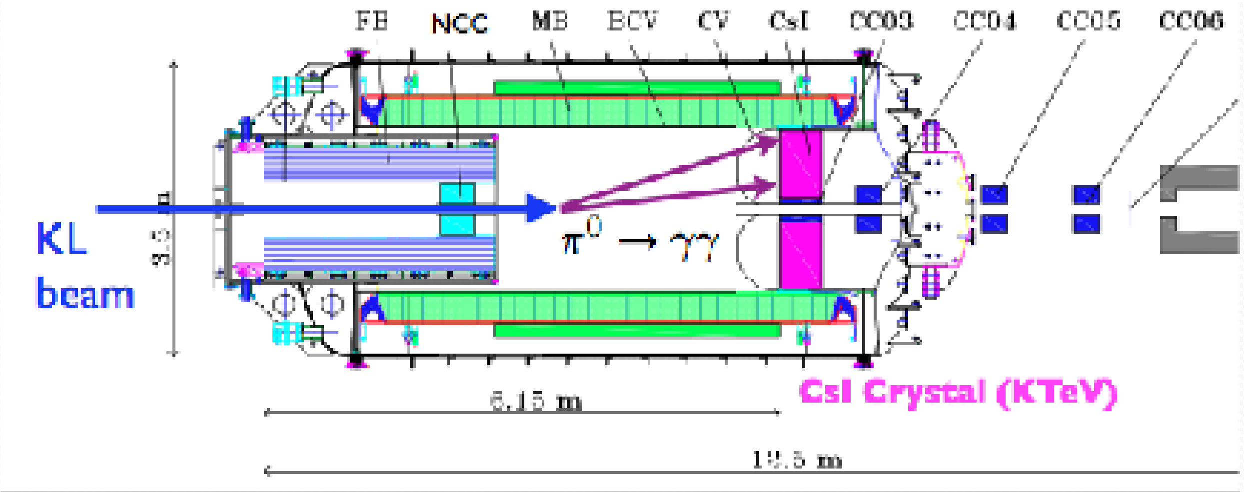
Data from 2014 commissioning run

Physics data taking starts 2015

KOTO at JPARC



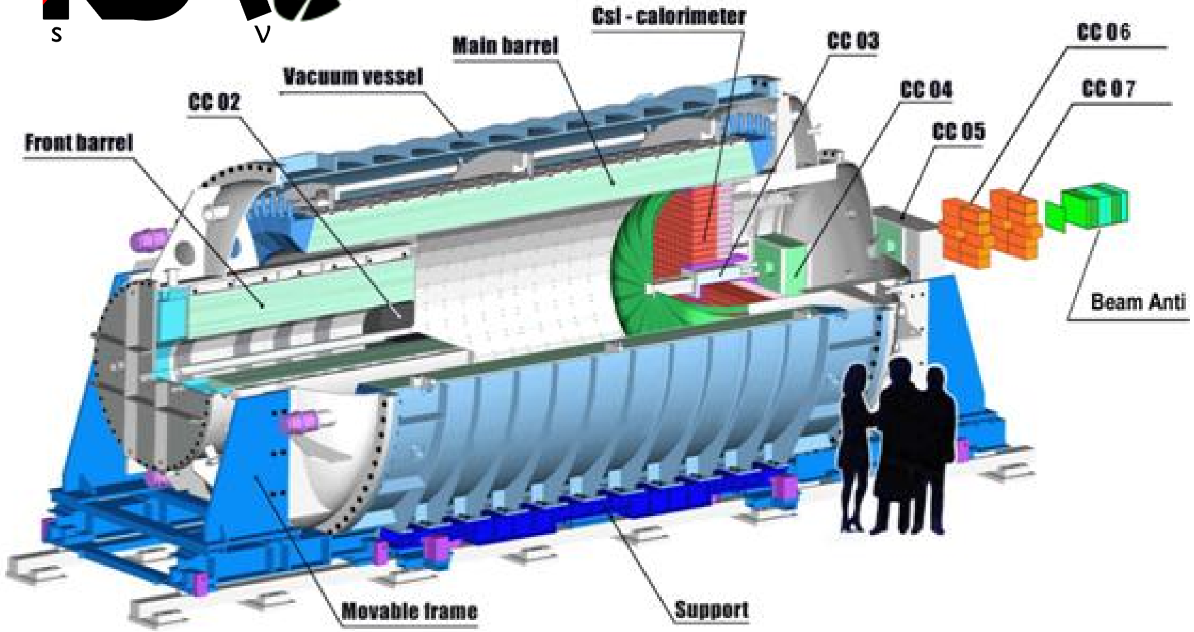




Data taking May 2013, ended by radiation incident

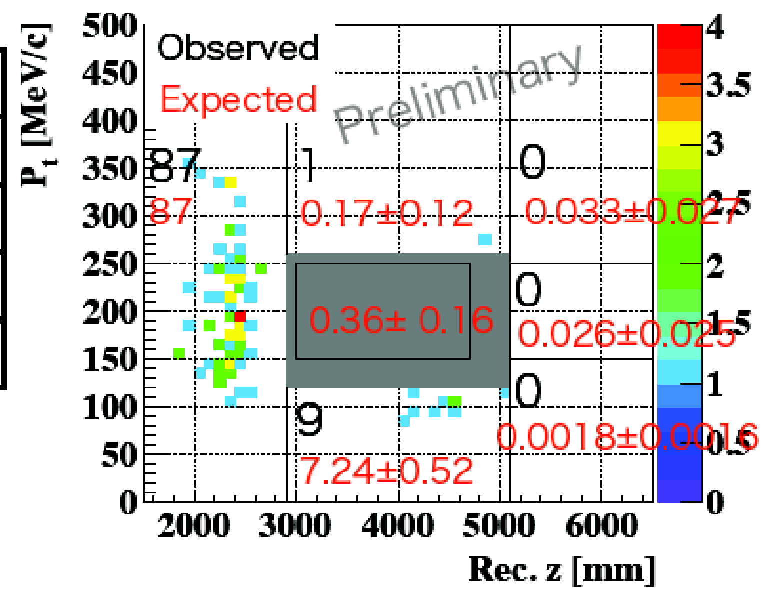
Allows first results & detailed background studies

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)

The need for more precision

- "Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

  – A.Soni

- "A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \rightarrow \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky."

  – L.Okun

(remember: $B(K_L^0 \rightarrow \pi^+\pi^-) \sim 2\ 10^{-3}$)

Summary

- We still don't know:
  - why there are so many fermions in the SM
  - what causes the baryon asymmetry of the Universe
  - where exactly the new physics is …
  - … and what it's flavour structure is
- Prospects are good for progress in the next few years
- We will have a continuing programme of flavour physics into the 2020s and perhaps beyond
  - complementary to the high-p_T programme of the LHC

References and background reading

- Reviews by the Particle Data Group
  - http://pdg.lbl.gov/
- Heavy Flavour Averaging Group (HFAG)
  - http://www.slac.stanford.edu/xorg/hfag/
- CKMfitter & UTfit
  - http://ckmfitter.in2p3.fr/ & http://www.utfit.org/
- Review journals (e.g. Ann. Rev. Nucl. Part. Phys.)
  - http://nucl.annualreviews.org
- Proceedings of CKM workshops
  - Phys.Rept. 494 (2010) 197, eConf C100906
- Books
  - CP violation, I.I.Bigi and A.I.Sanda (CUP)
  - CP violation, G.C.Branco, L.Lavoura & J.P.Silva (OUP)