Flavour Physics & CP Violation

Lecture 4 of 4

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CERN Summer Student Lecture Programme

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Contents

- Part 1
  - What is flavour physics & why is it interesting?
- Part 2
  - What do we know from previous experiments?
- Part 3
  - What do we hope to learn from current experiments?
- Part 4
  - The future of flavour physics

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”?

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The SM

Input: Symmetries and fields

- Symmetry: 4d Poincare and

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

- Fields:
  - 3 copies of QUDLE fermions

$$Q_L(3,2)_{1/6} \quad U_R(3,1)_{2/3} \quad D_R(3,1)_{-1/3}$$
$$L_L(1,2)_{-1/2} \quad E_R(1,1)_{-1}$$

  - One scalar

$$\phi(1,2)_{+1/2}$$

Y. Grossman The SM (5) CERN, July 9, 2014 p. 7

Then Nature is described by

Output: the most general $\mathcal{L}$

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

- The model can have SSB

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \quad \Rightarrow \quad SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

- This model has a $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ accidental symmetry
- It has 18 parameters, and we measure them all by now
- We then made many tests and the SM basically passes almost all of them

Y. Grossman The SM (5) CERN, July 9, 2014 p. 8

Then

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

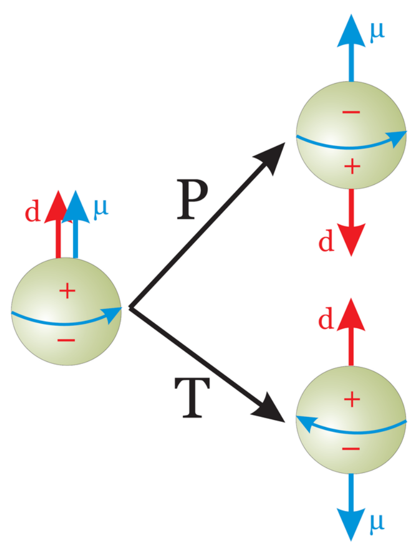
Neutron electric dipole moment

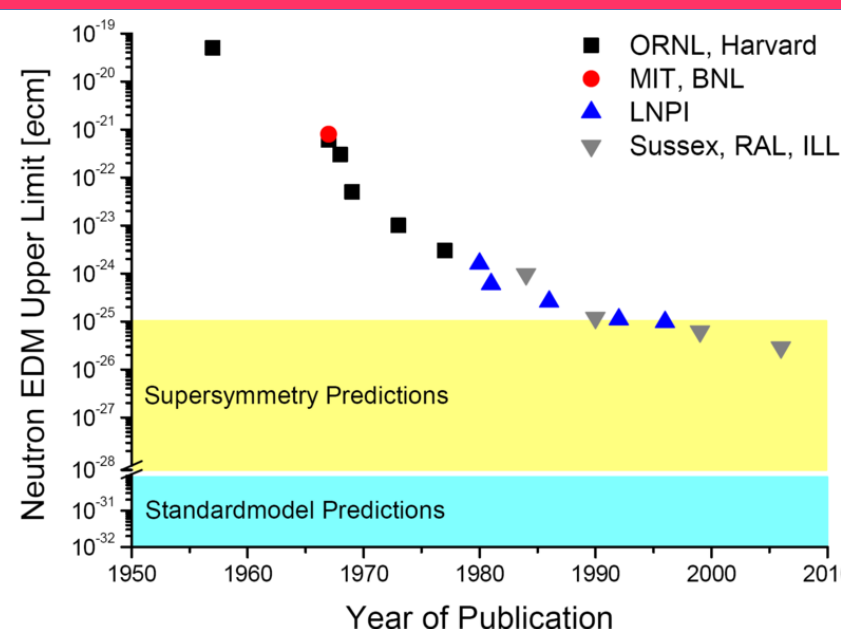
- If the θ_{QCD} parameter is ≠ 0, there is CP violation in the strong interaction

  → observable neutron electric dipole moment

- But: $|d_n| < 2.9 \times 10^{-26}$ e cm (PRL 97 (2006) 131801)

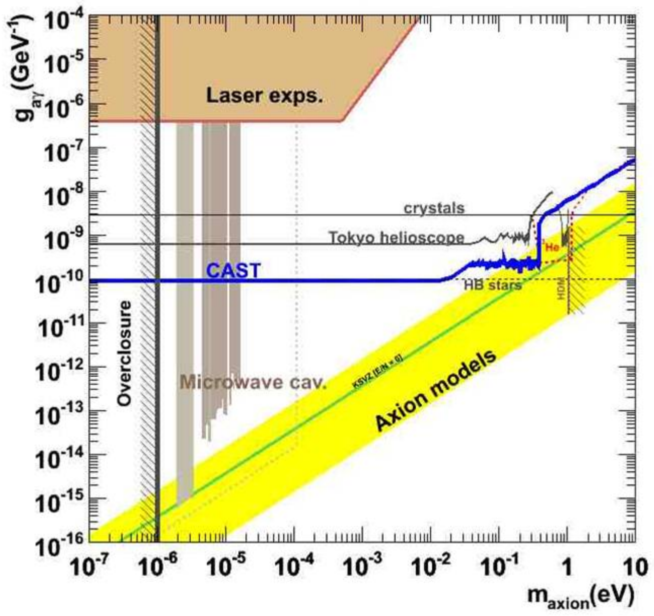
If neutron were the size of the earth, +/– charges separated by < 10 μm





The strong CP problem

- But: $|d_n| < 2.9 \times 10^{-26}$ e cm (PRL 97 (2006) 131801)
- 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

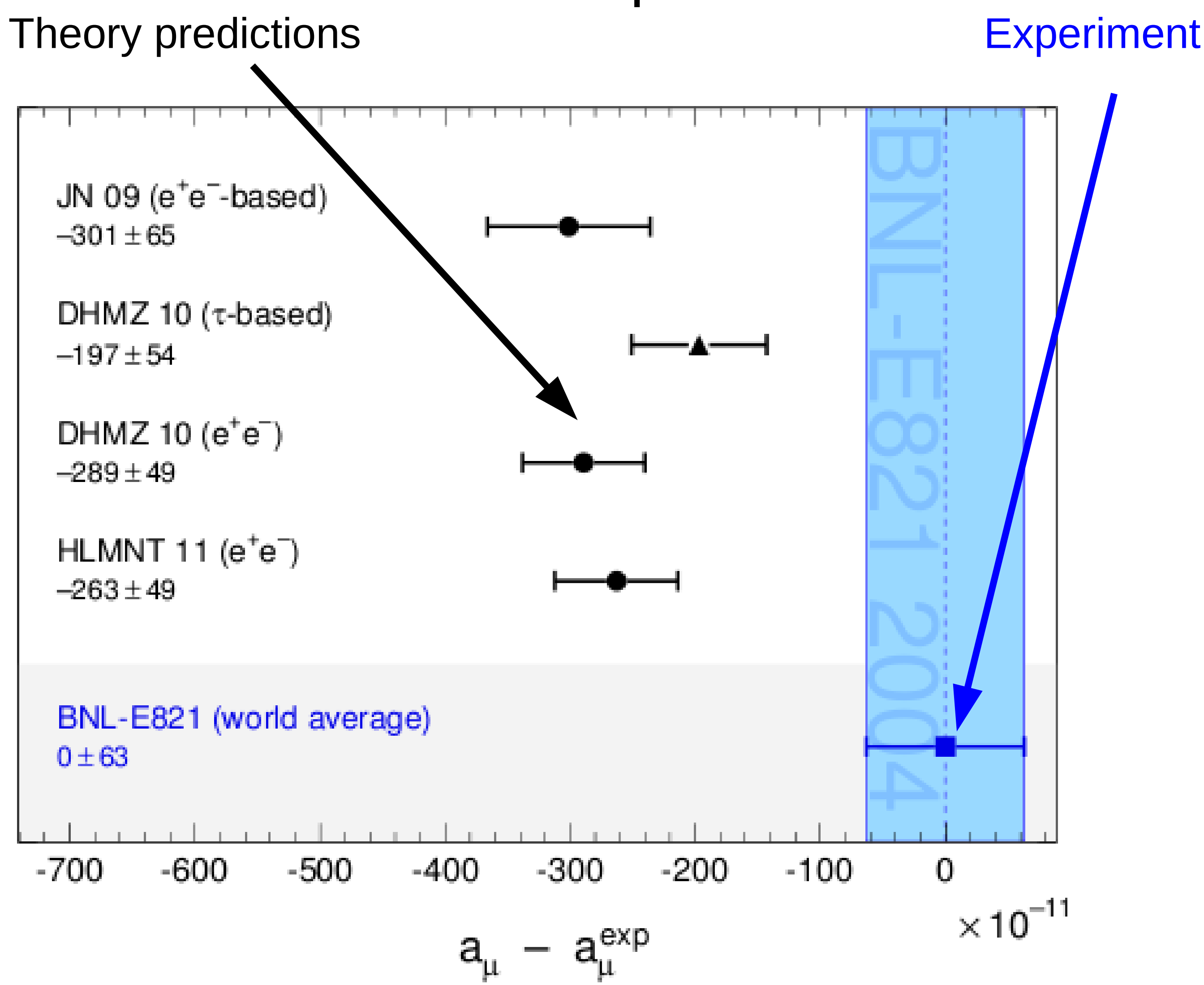
Precision physics with electric & magnetic moments

- 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)
      - $a_e = 0.00115965218178\ (77)$

$(g-2)_\mu$



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

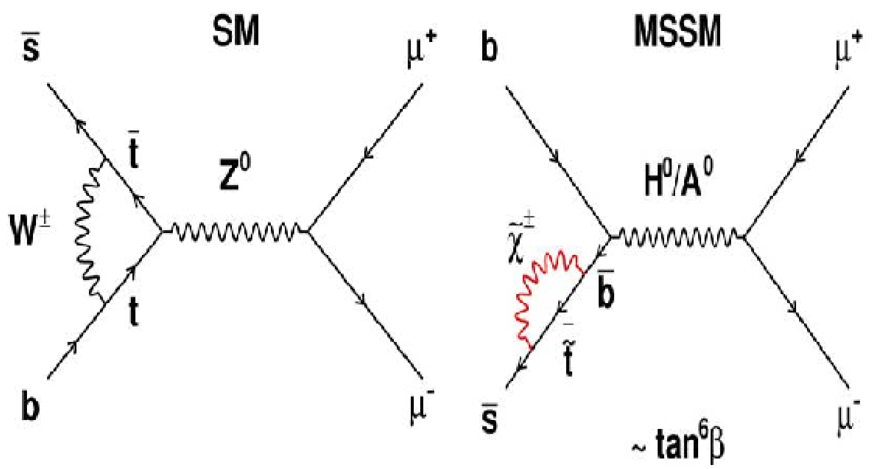
Back to B physics

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

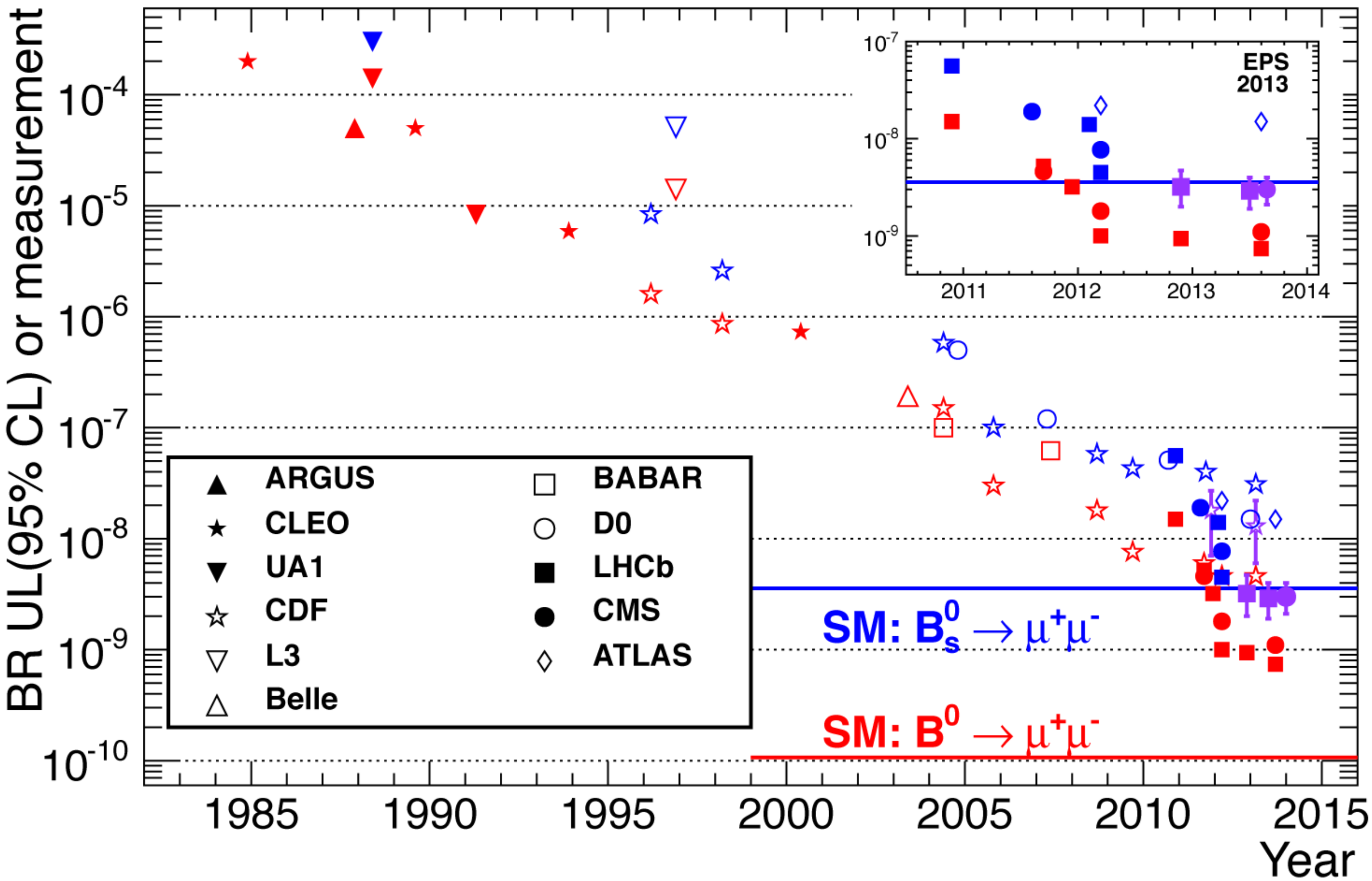


- Huge NP enhancement possible (tan β = ratio of Higgs vevs)

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

- Clean experimental signature

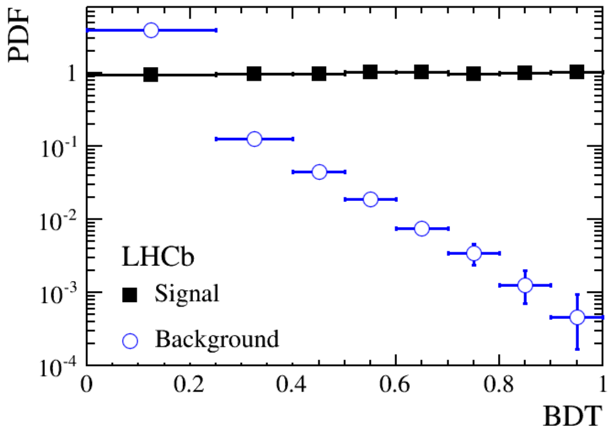
$B_{(s)}^0 \to \mu^+\mu^-$



Searches over 30 years

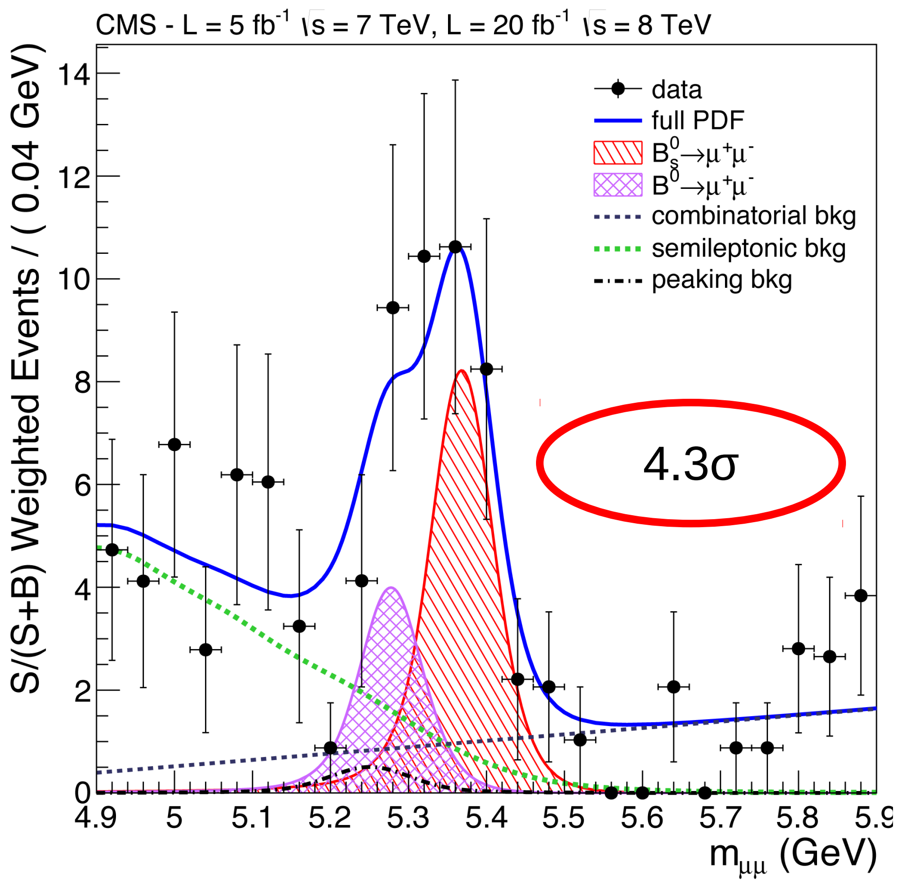
$B_{(s)}^0 \to \mu^+\mu^-$ – analysis ingredients

- 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



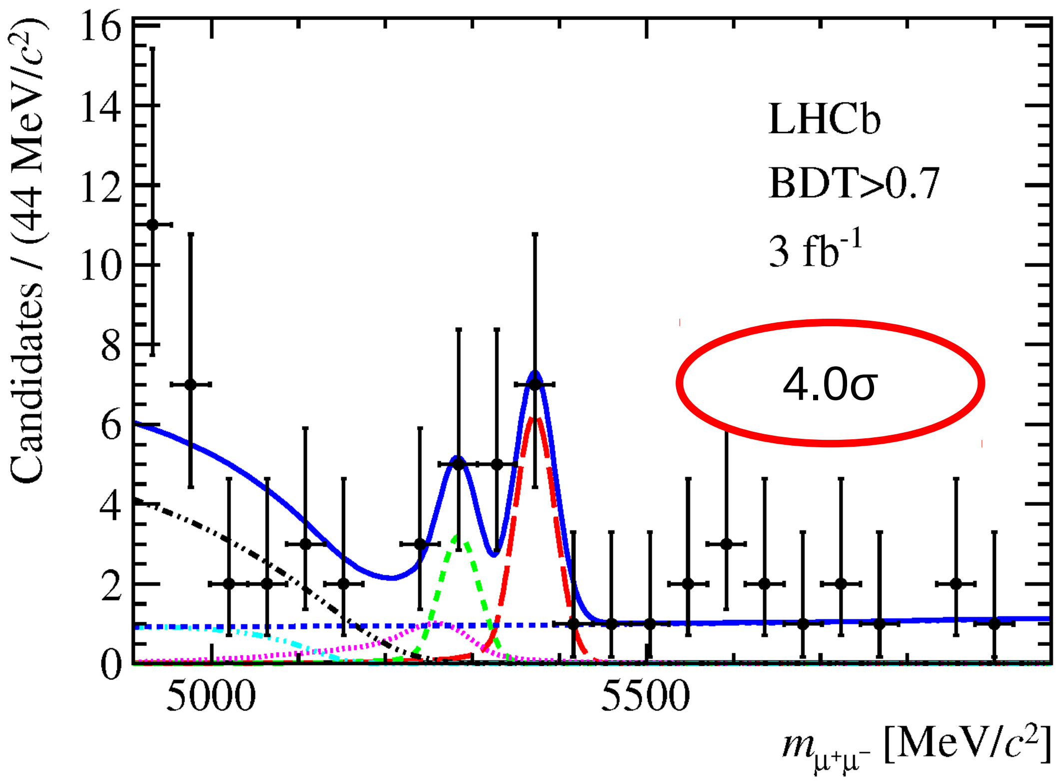
$B_{(s)}^0 \to \mu^+\mu^-$
latest results from CMS & LHCb

CMS PRL 111 (2013) 101804



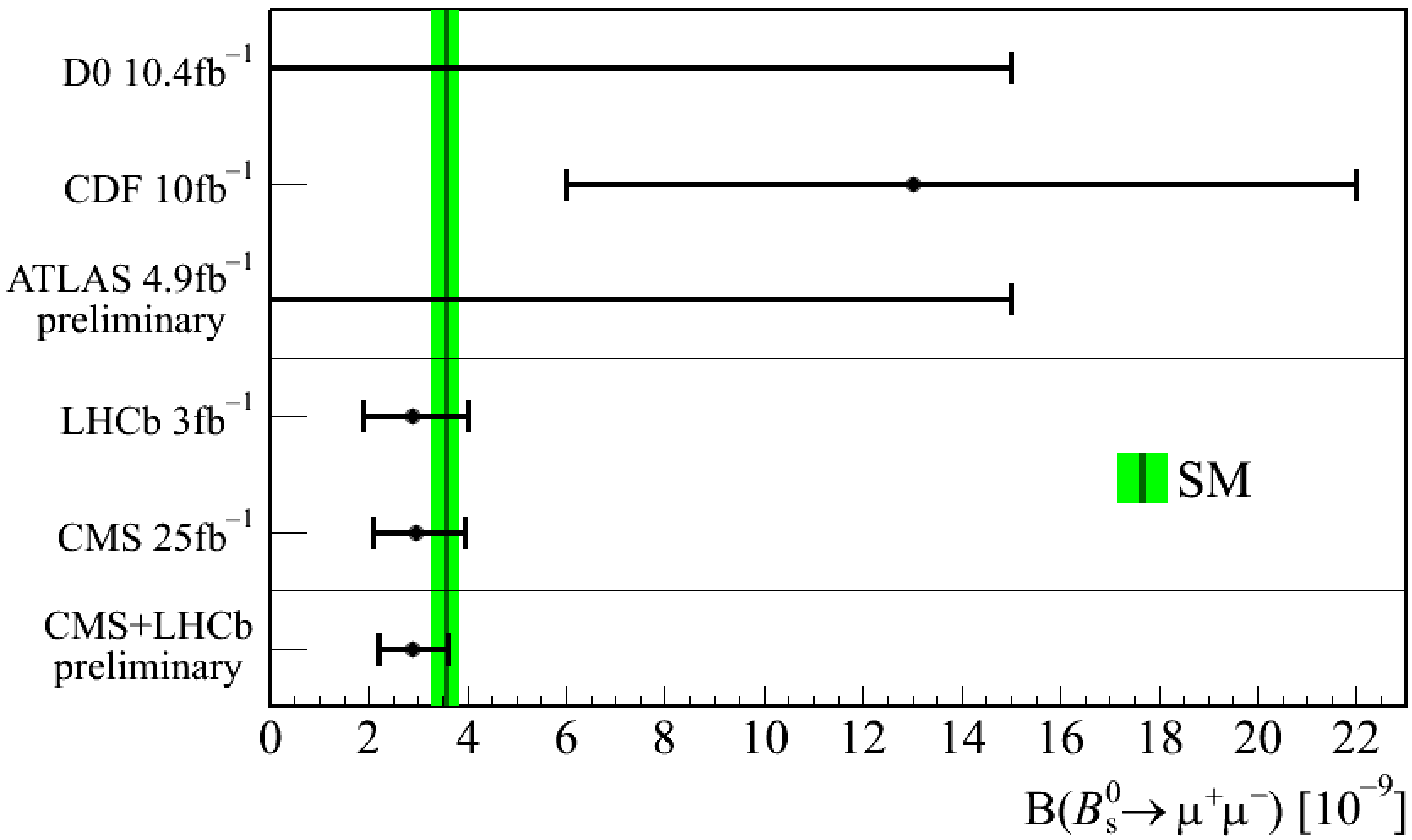
Events weighted by S/(S+B)

LHCb PRL 111 (2013) 101805



Only events with BDT > 0.7

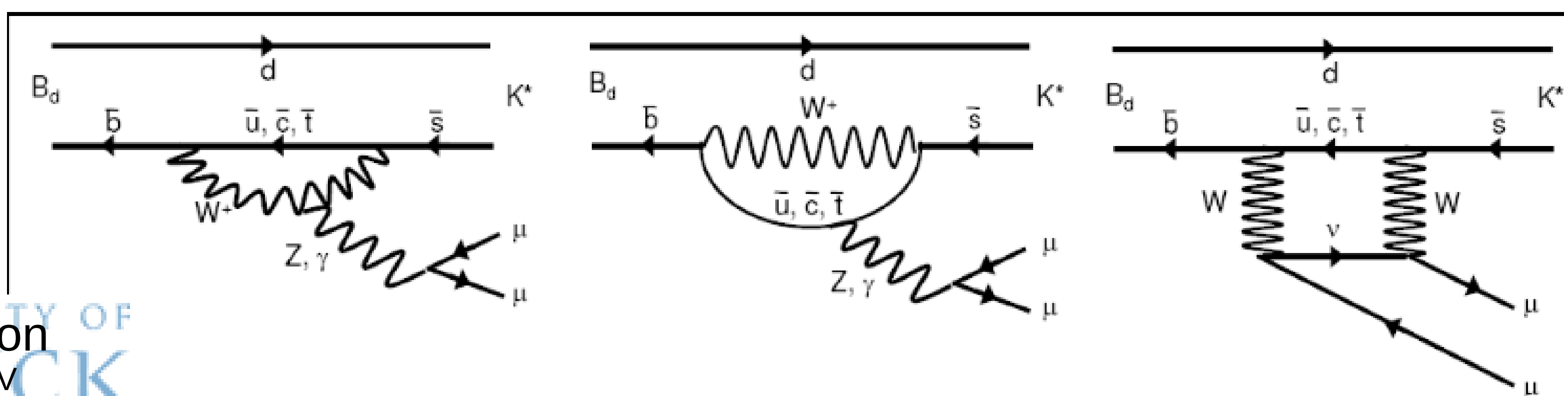
$B_{(s)}^0 \to \mu^+\mu^-$ – combined results



$B(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

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

- $b \to s l^+ l^-$ 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)



Operator Product Expansion

Build an effective theory for b physics

- take the weak part of the SM
- integrate out the heavy fields (W,Z,t)
- (like a modern version of Fermi theory for weak interactions)

$$\mathcal{L}_{\text{(full EW}\times\text{QCD)}} \longrightarrow \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}\times\text{QCD}}\left(\begin{smallmatrix}\text{quarks} \neq t \\ \text{\& leptons}\end{smallmatrix}\right) + \sum_n C_n(\mu)\, Q_n$$

Q_n – local interaction terms (operators), C_n – coupling constants (Wilson coefficients)

Wilson coefficients

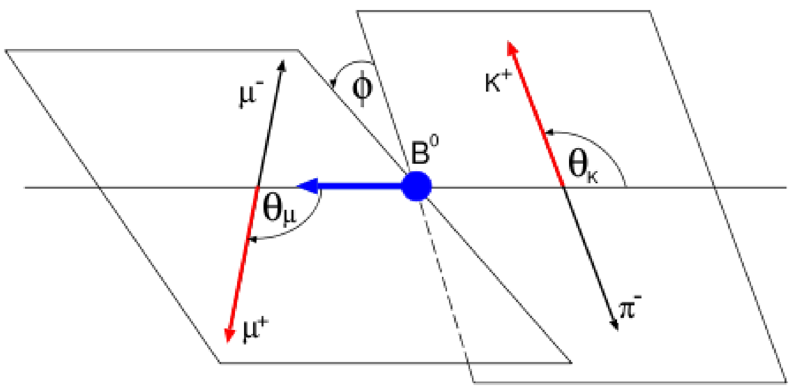
- encode information on the weak scale
- are calculable and known in the SM (at least to leading order)
- are affected by new physics

For K*μμ we care about C_7 (also affects $b \to s\gamma$), C_9 and C_{10}

Theory of B→K*μ⁺μ⁻

- Given for inclusive $b \to s\mu^+\mu^-$ for simplicity
  - physics of exclusive modes ≈ same but equations are more complicated (involving form factors, etc.)
- Differential decay distribution

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_l} = \frac{3}{8}\left[(1+\cos^2\theta_l)\, H_T(q^2) + 2\,\cos\theta_l\, H_A(q^2) + 2\,(1-\cos^2\theta_l)\, H_L(q^2)\right]$$



$$H_T(q^2) \propto 2q^2\left[\left(C_9 + 2C_7\frac{m_b^2}{q^2}\right)^2 + C_{10}^2\right],$$

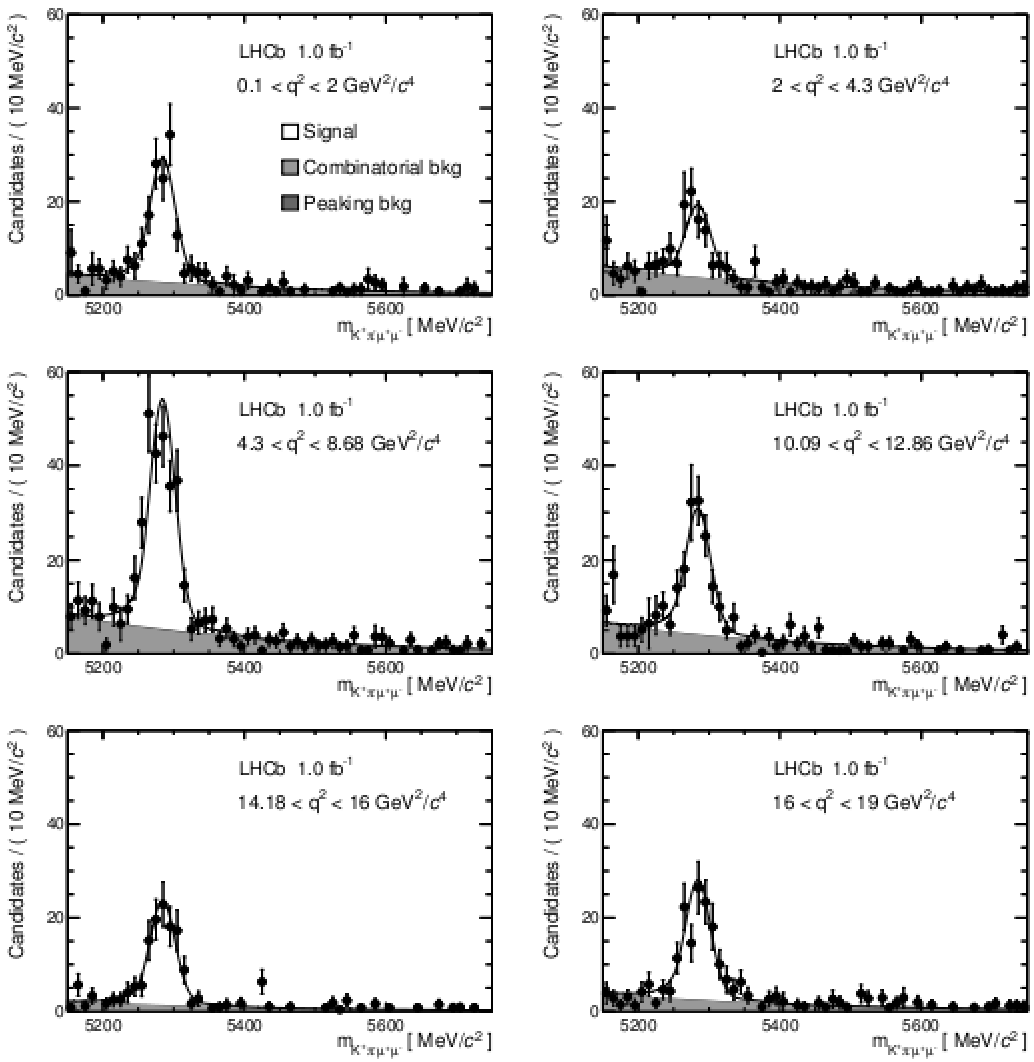
$$H_A(q^2) \propto -4q^2 C_{10}\left(C_9 + 2C_7\frac{m_b^2}{q^2}\right),$$

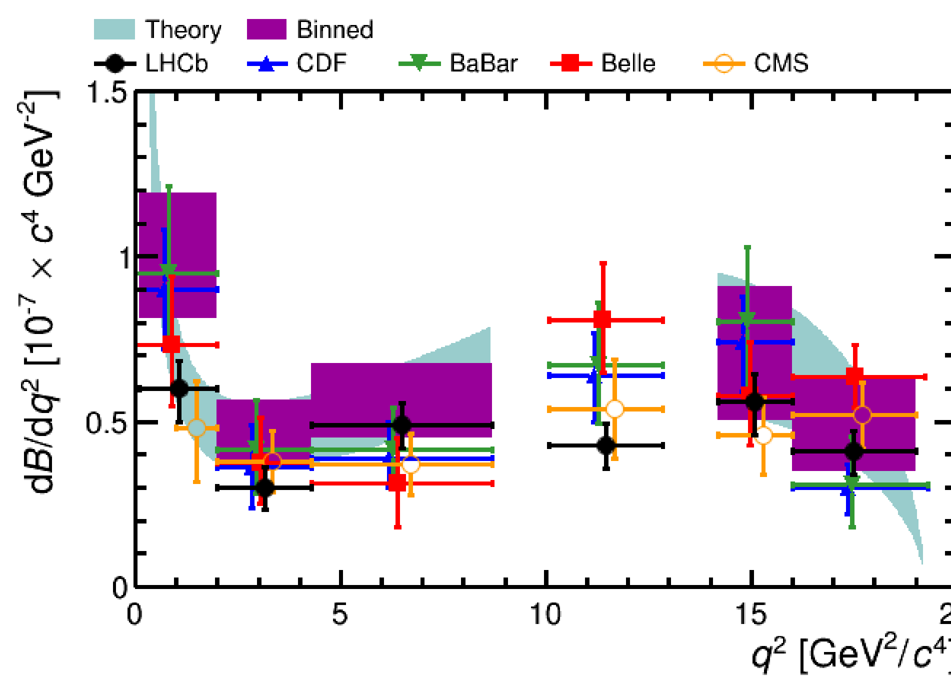
$$H_L(q^2) \propto \left[(C_9 + 2C_7)^2 + C_{10}^2\right].$$

This term gives a forward-backward asymmetry

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

LHCb JHEP 08 (2013) 131
See also CDF PRL 108 (2012) 081807,
BaBar PRD 86 (2012) 032012,
Belle PRL 103 (2009) 171801,
ATLAS-CONF-2013-038 &
CMS PLB 727 (2013) 77





Analysis performed in bins of dimuon invariant mass squared (q^2)

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

LHCb JHEP 08 (2013) 131
See also CDF PRL 108 (2012) 081807, BaBar PRD 86 (2012) 032012,
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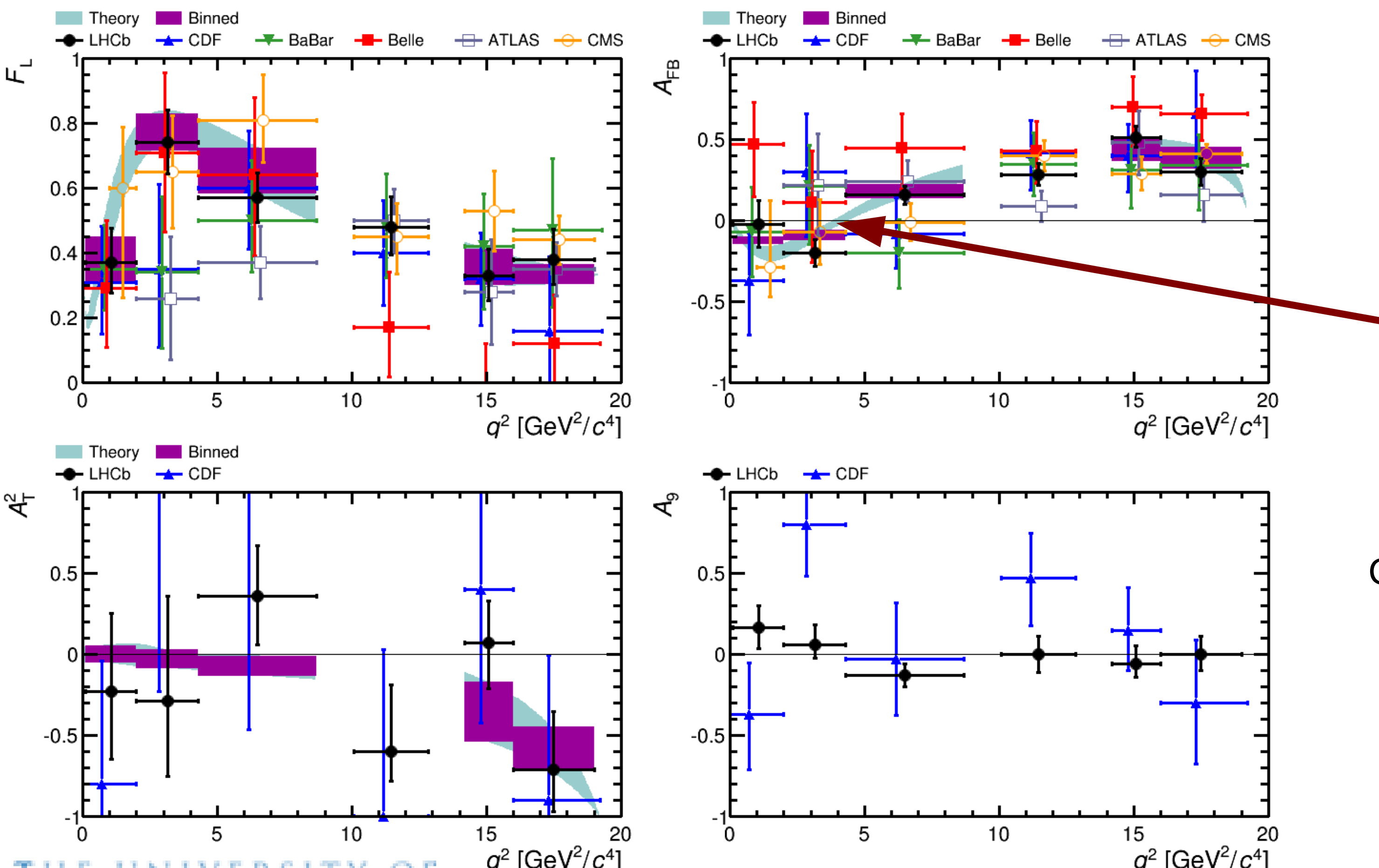


First measurement of zero-crossing point of A_{FB}

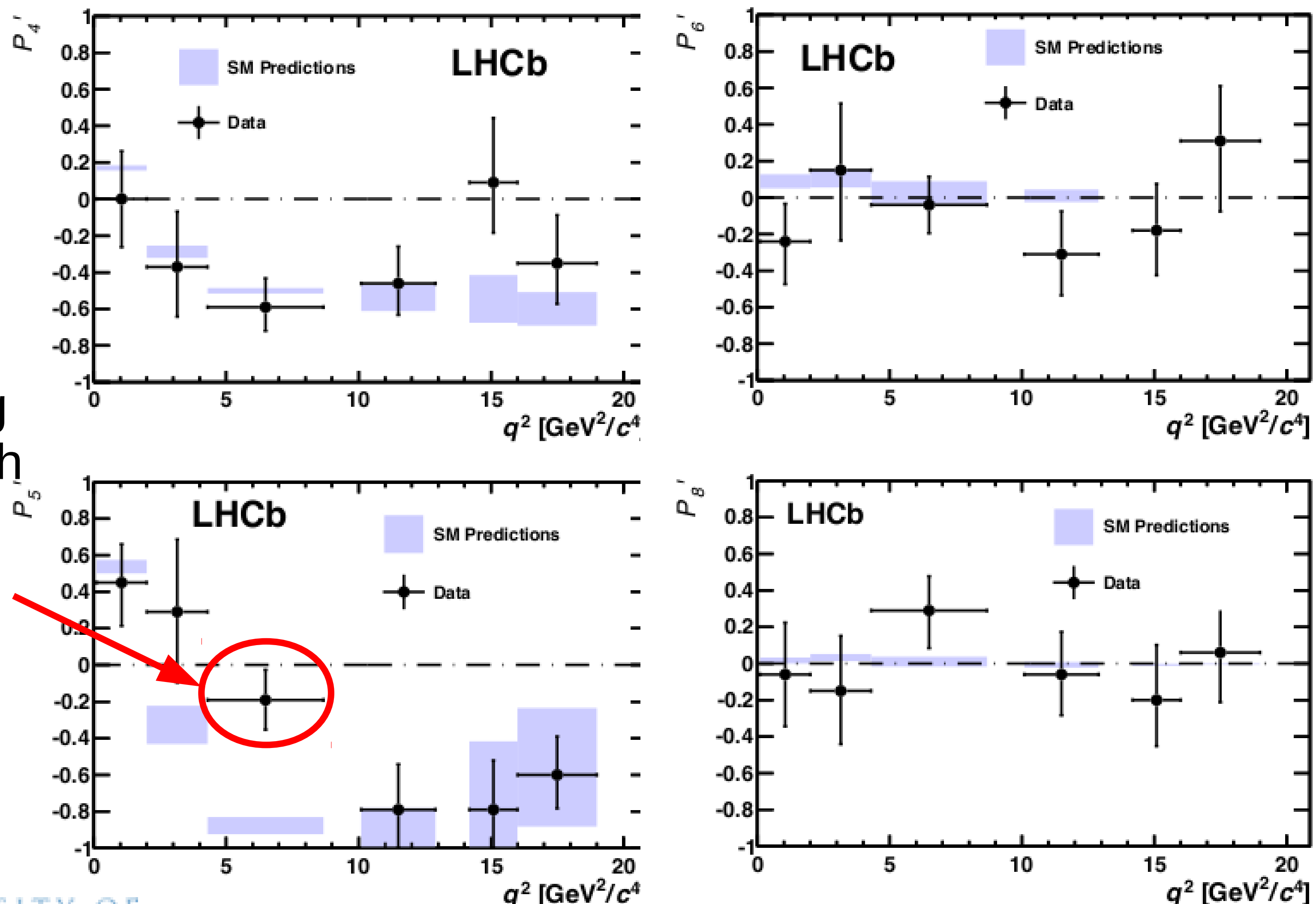
$q^2_0 = (4.9 \pm 0.9)\ \mathrm{GeV}^2/c^4$

Consistent with SM expectation

New observables in $B^0 \rightarrow K^{*0}\mu^+\mu^-$

LHCb PRL 111 (2013) 191801

Interesting tension with the SM prediction



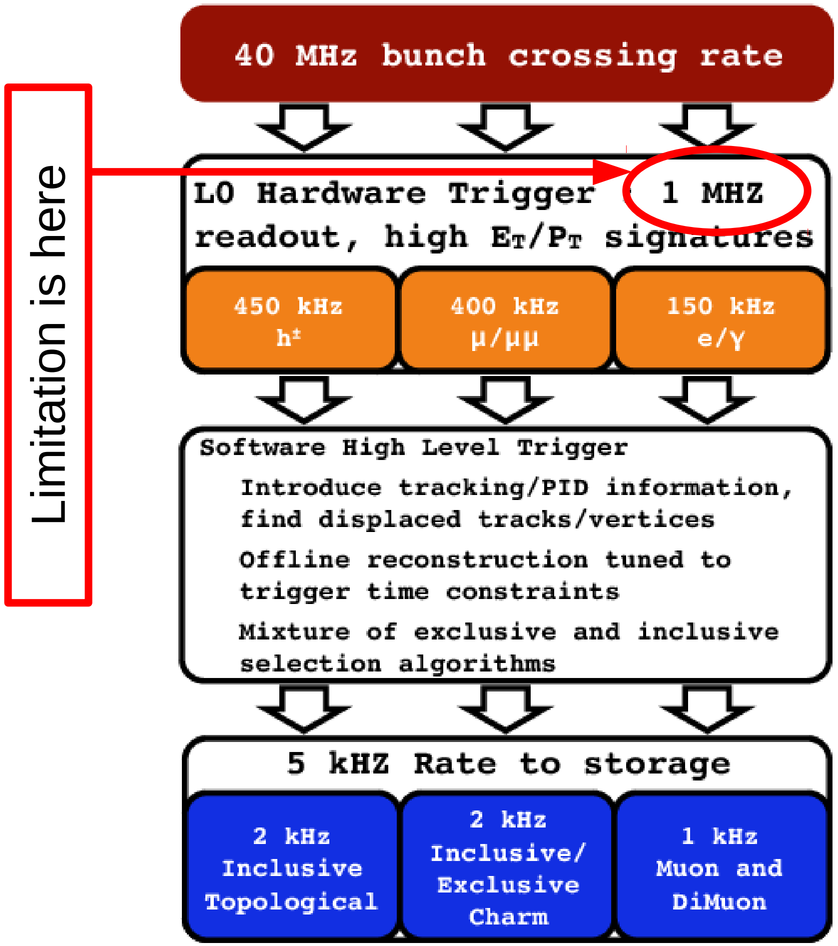
Future flavour physics projects

LHCb upgrade

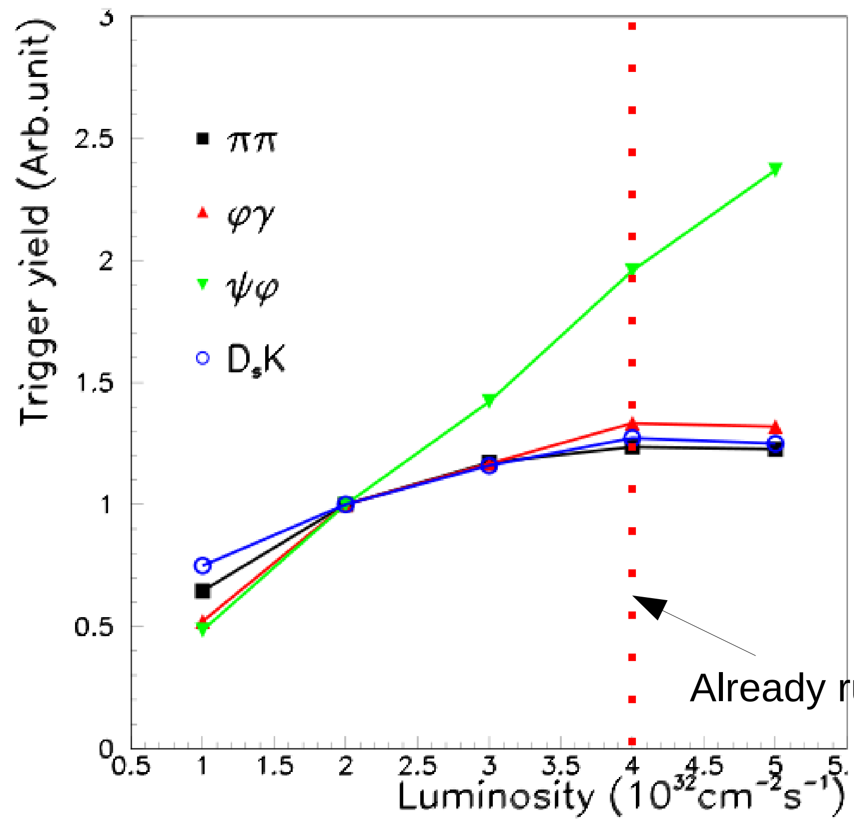
- To fully exploit LHC potential for heavy flavour physics will require an upgrade to LHCb
  - full readout & trigger at 40 MHz to enable high L running
  - "high L" = $10^{33}/cm^2/s$ (so independent of machine upgrade)
  - planned for 2018 shutdown

- 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

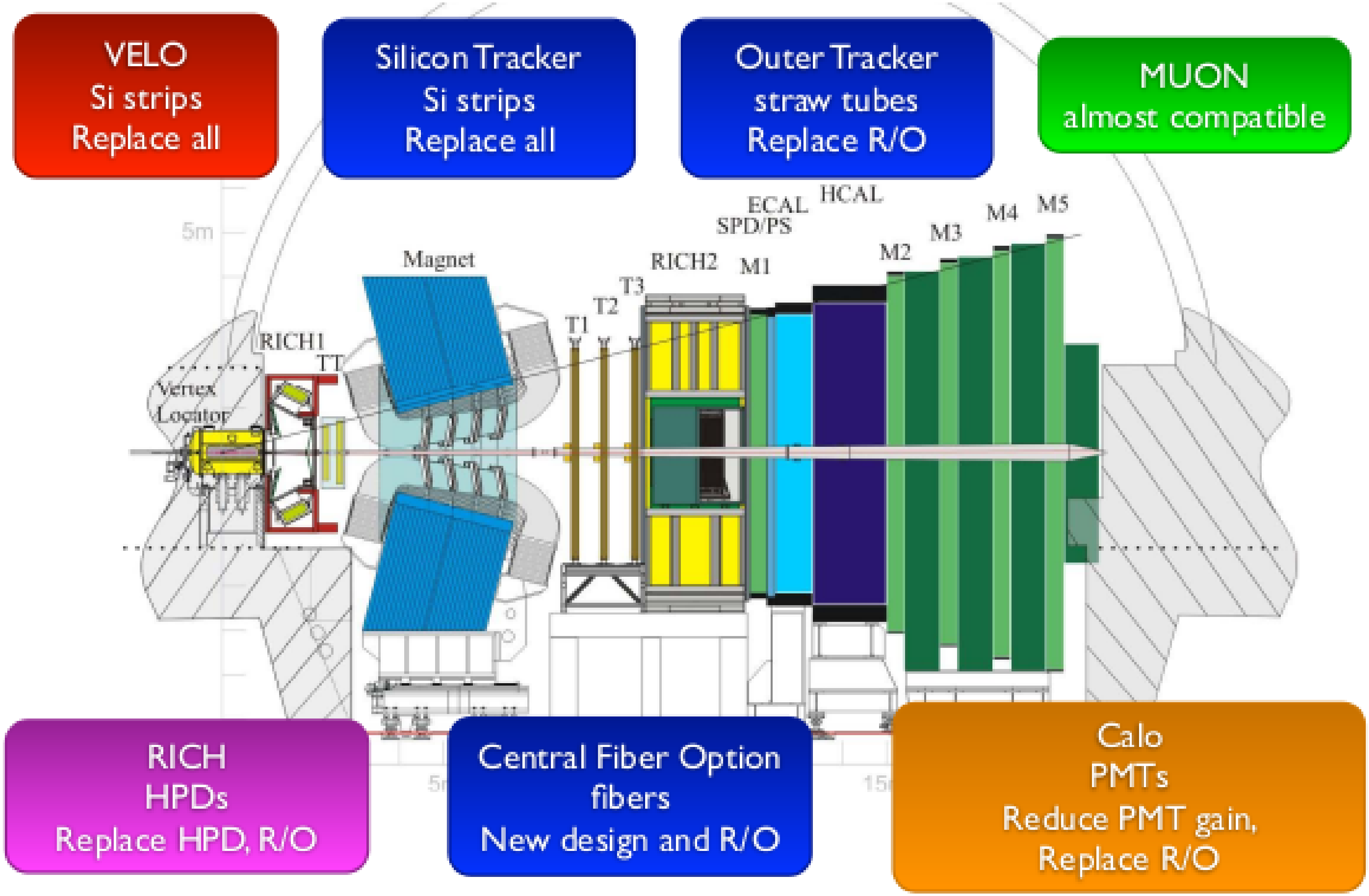


higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



- 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



LHCb upgrade timeline

- 2011
  - Letter of Intent: CERN-LHCC-2011-001
- 2012
  - Framework TDR: CERN-LHCC-2012-007
    - Endorsed by LHCC and approved by CERN Research Board (minutes)
    - LHCb upgrade features prominently in draft European Strategy for Particle Physics
  - See also arXiv:1208.3355 for physics discussion
- 2013
  - Sub-detector TDRs ← now approved
- 2014-17
  - Final R&D, production and construction
- 2018 (LS2)
  - Installation of upgraded LHCb detector (requires 18 months)

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
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	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
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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 %	$\sim 10\,\%$
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}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	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

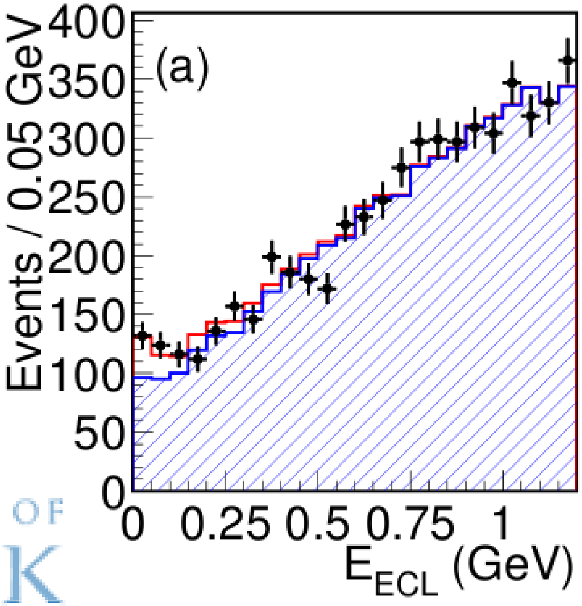
- SuperKEKB/Belle2 & SuperB
  - $B \to \tau\nu$, inclusive measurements, τ physics, …
- Rare kaon decays
  - $K^+ \to \pi^+\nu\nu$ (NA62, CERN); $K^0 \to \pi^0\nu\nu$ (K0T0, J-PARC)
- Muon to electron conversion (charged lepton flavour violation)
  - COMET/PRIME (J-PARC); mu2e (FNAL)

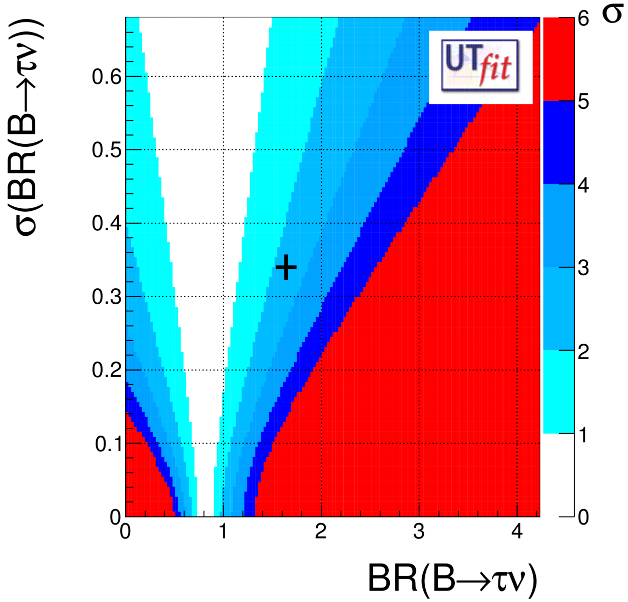
$B \to \tau\nu$ and charged Higgs limits

- Pure leptonic decays of charged B mesons very clean
  - clean SM prediction
  - clean effect of charged Higgs boson (2HDM or SUSY)

$$BR(B^+ \to l^+ \nu)^{SM} = \frac{G_F m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \qquad BR(B^+ \to l^+ \nu)^{NP} = BR(B^+ \to l^+ \nu)^{SM} \left(1 - \frac{m_B^2}{m_H^2} \tan^2\beta\right)^2$$

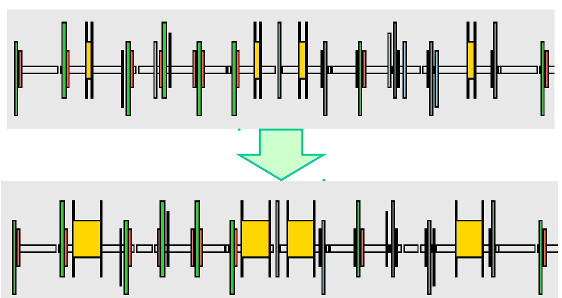
Belle PRD 82 (2010) 071101



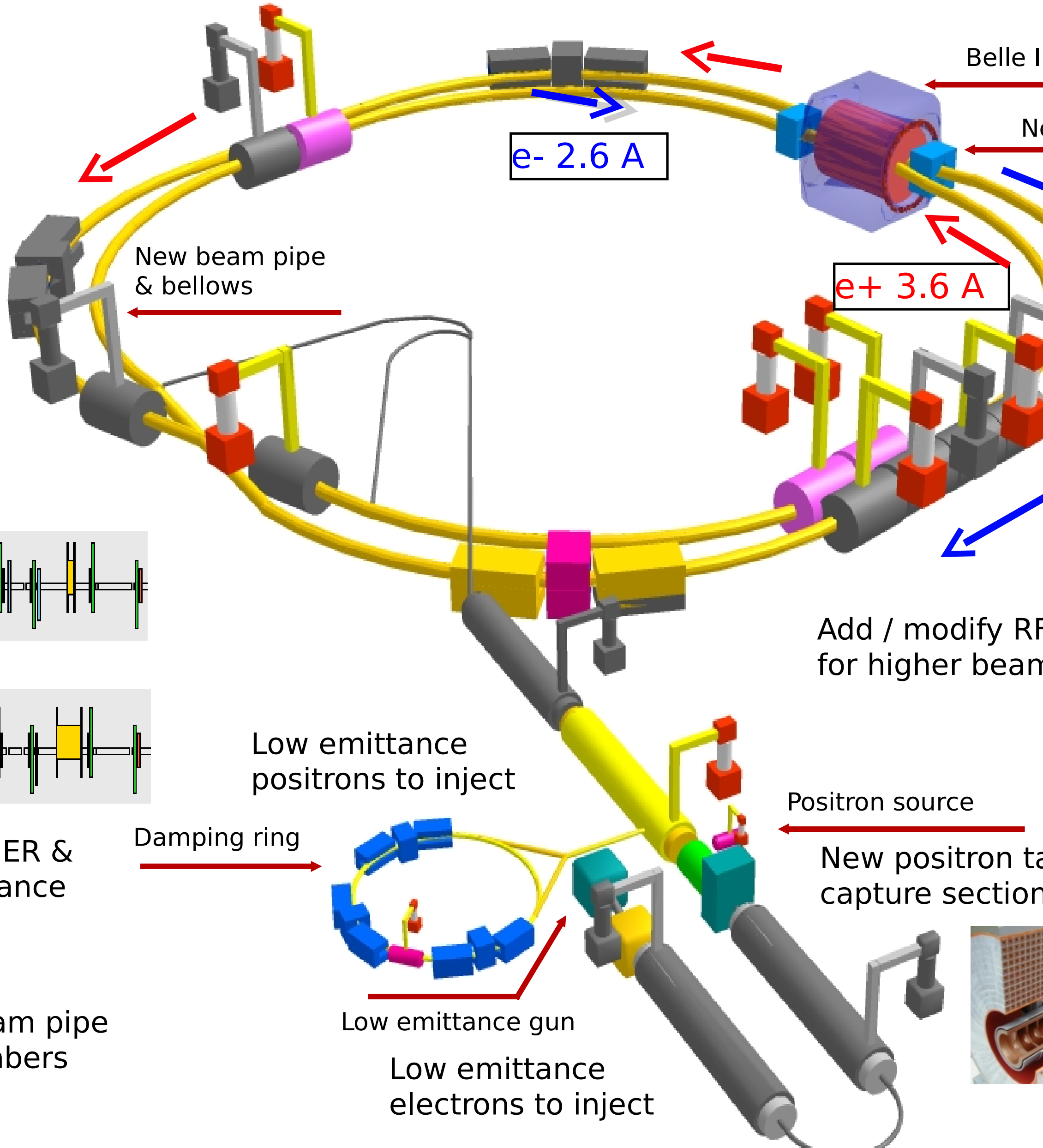


KEKB to SuperKEKB

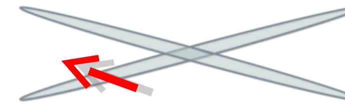
Replace short dipoles with longer ones (LER)



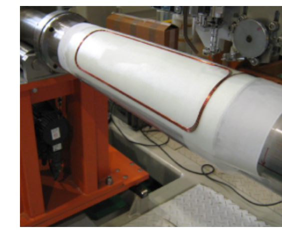
Redesign the lattices of HER & LER to squeeze the emittance

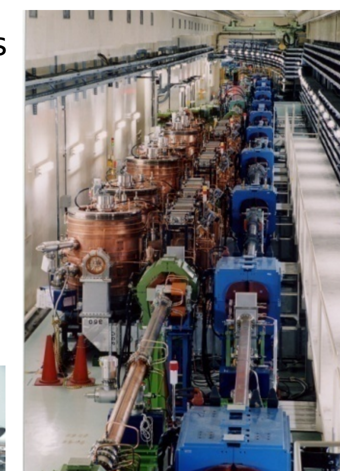


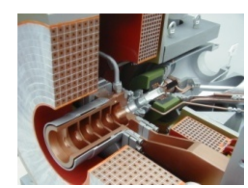
Colliding bunches



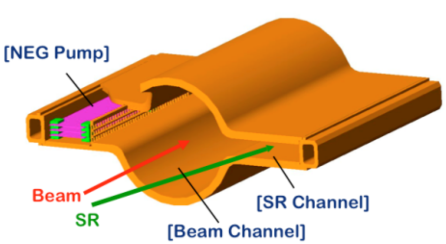
New superconducting /permanent final focusing quads near the IP





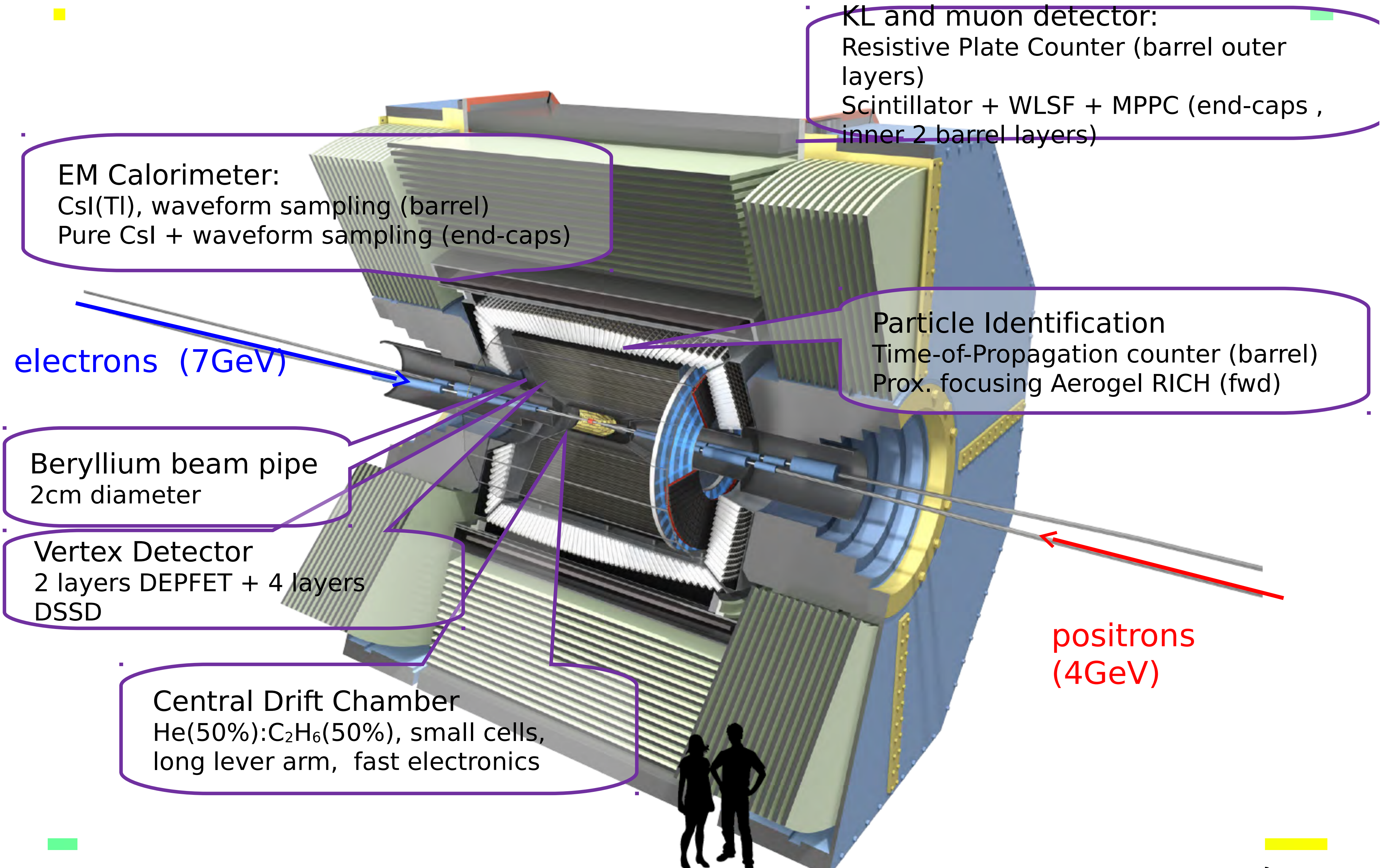


TiN-coated beam pipe with antechambers

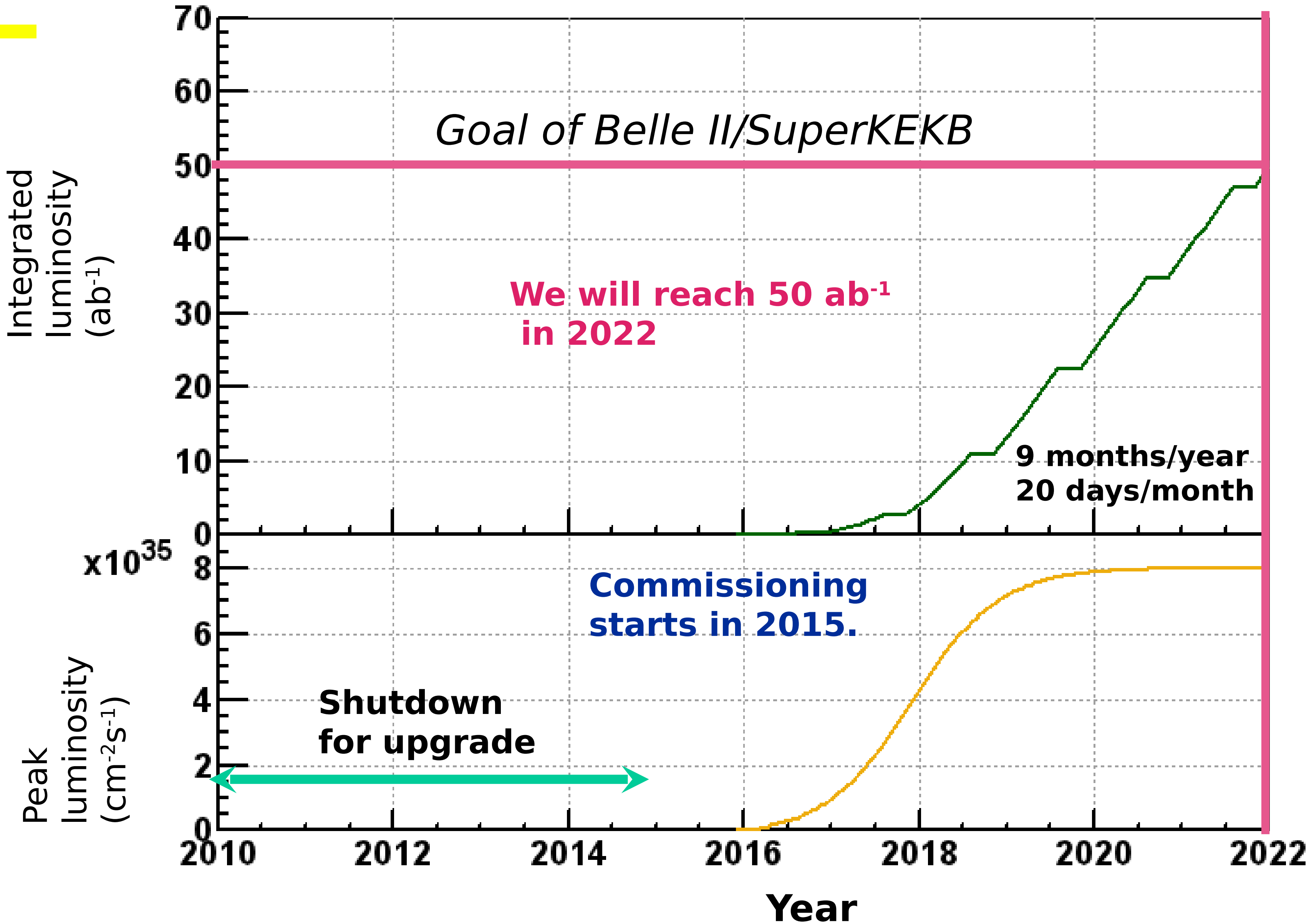


To obtain x40 higher luminosity

Belle II Detector



Schedule



Goal of Belle II/SuperKEKB
We will reach 50 ab-1 in 2022
9 months/year
20 days/month
Commissioning starts in 2015.
Shutdown for upgrade
Integrated luminosity (ab-1)
Peak luminosity (cm-2s-1)
x10^35
Year
70
60
50
40
30
20
10
0
8
6
4
2
0
2010
2012
2014
2016
2018
2020
2022

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

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

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

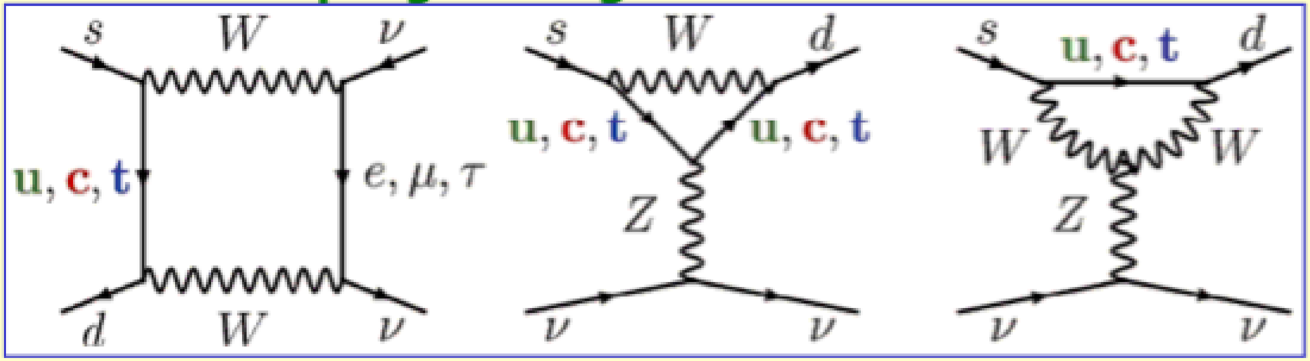
SM branching ratios

(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

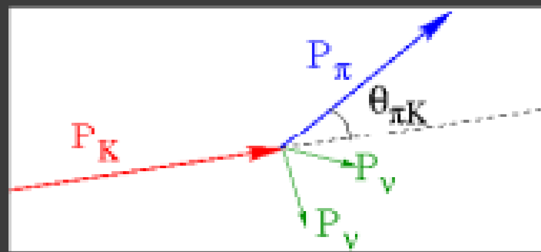
SM: box and penguin diagrams



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

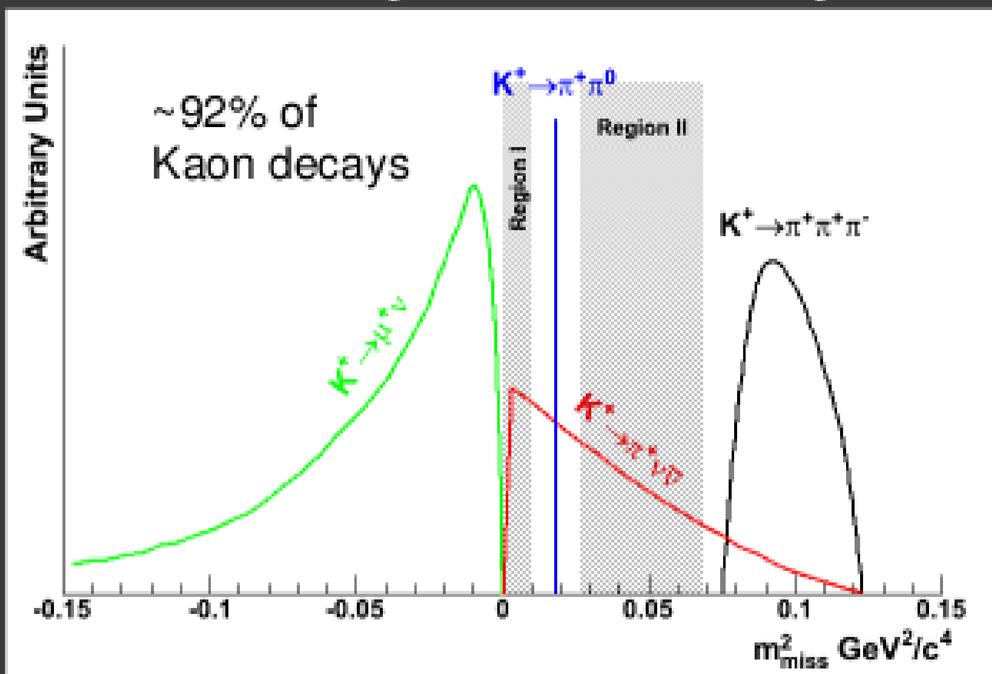
- $K^+ \rightarrow \pi^+\nu\nu$ (NA62, CERN)
- $K^0 \rightarrow \pi^0\nu\nu$ (K0T0, J-PARC)
- Proposals also at FNAL

NA62 Technique: Decay in Flight

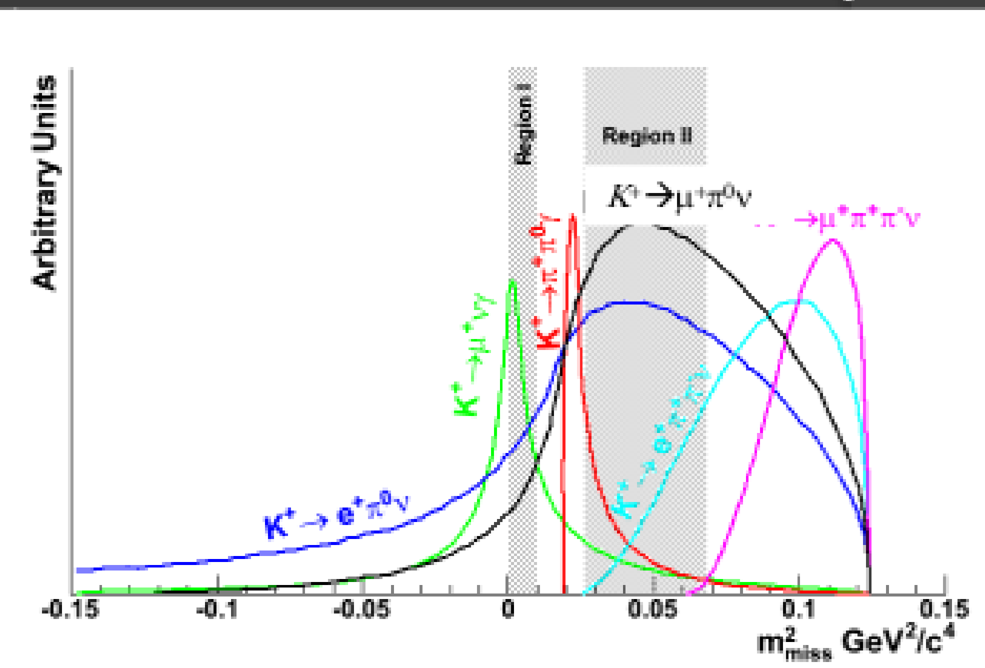


$$m^2_{miss} = (\tilde{p}_K - \tilde{p}_\pi)^2$$

Kinematically Constraint Decays

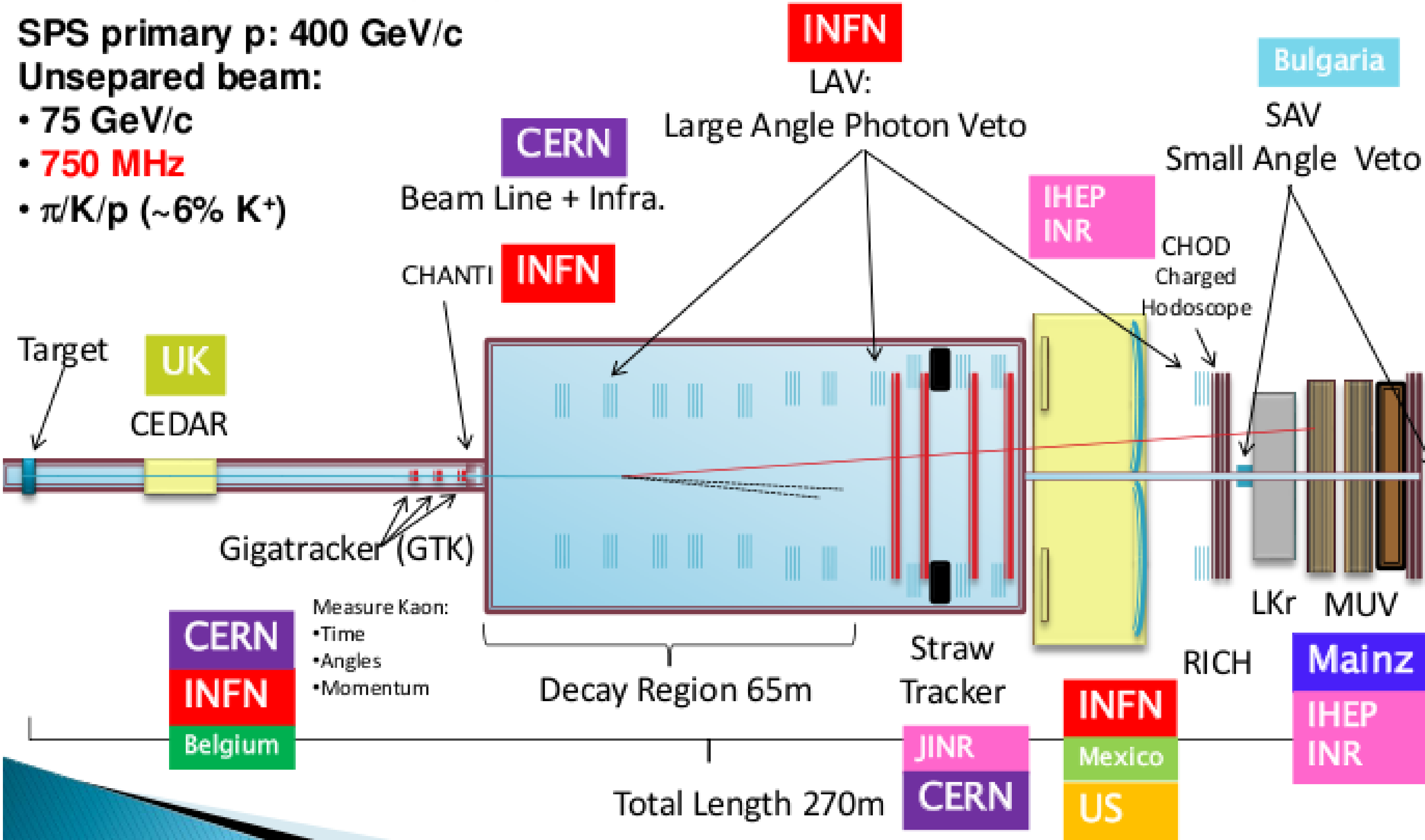


Unconstraint Decays

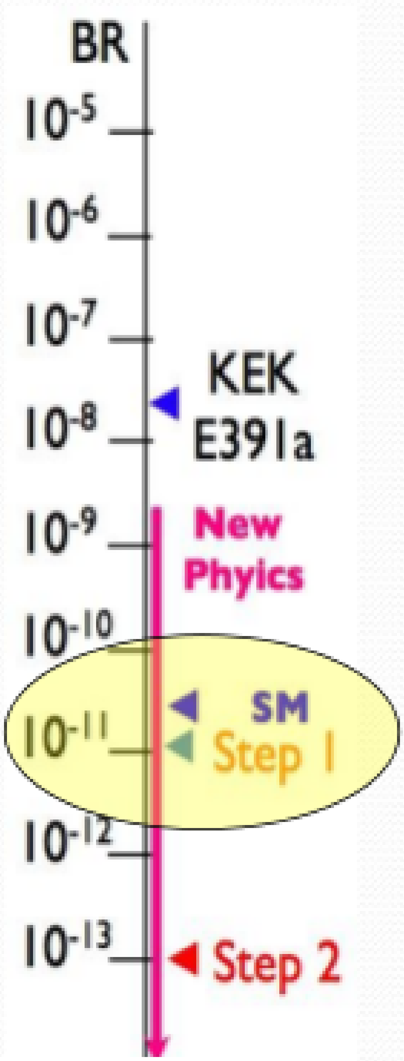


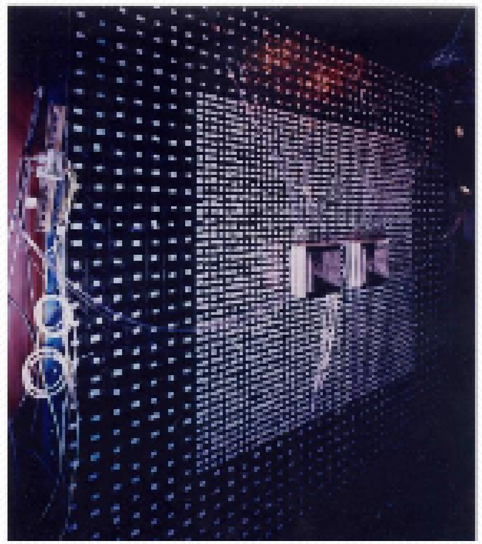
NA62: $K^+ \rightarrow \pi^+ \nu \nu$ in–flight @ CERN–SPS

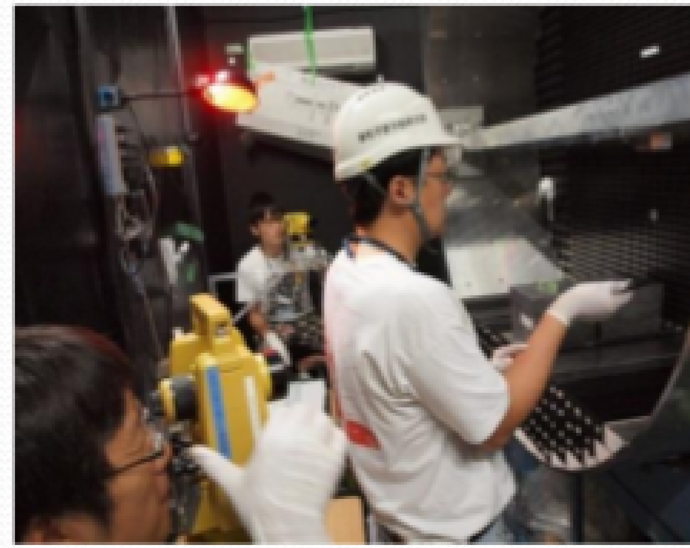
SPS primary p: 400 GeV/c
Unsepared beam:
- **75 GeV/c**
- **750 MHz**
- **π/K/p (~6% K^+)**

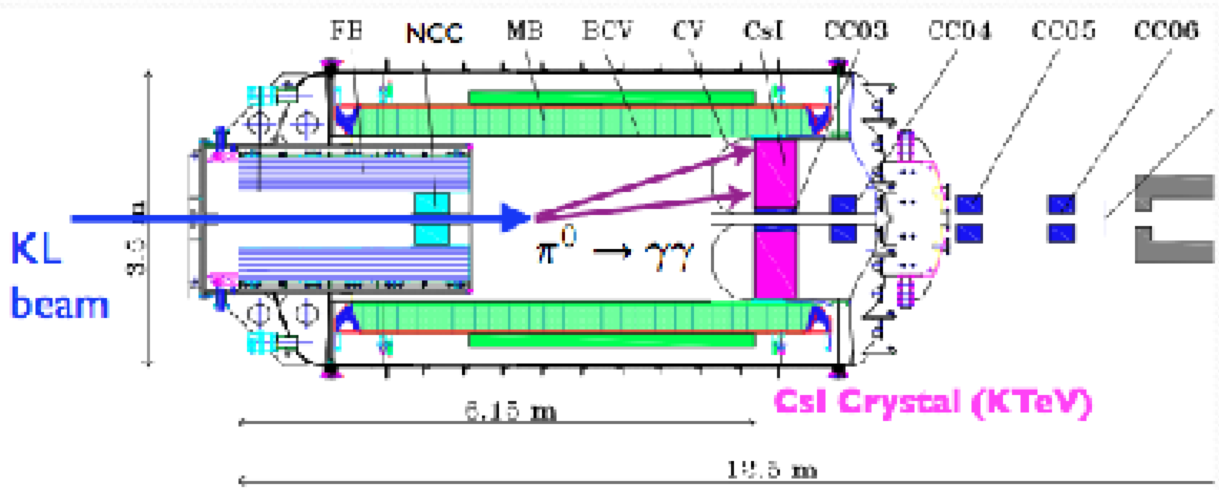


KOTO at JPARC









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 need a continuing programme of flavour physics into the 2020s
  - complementary to the high-p_T programme of the LHC

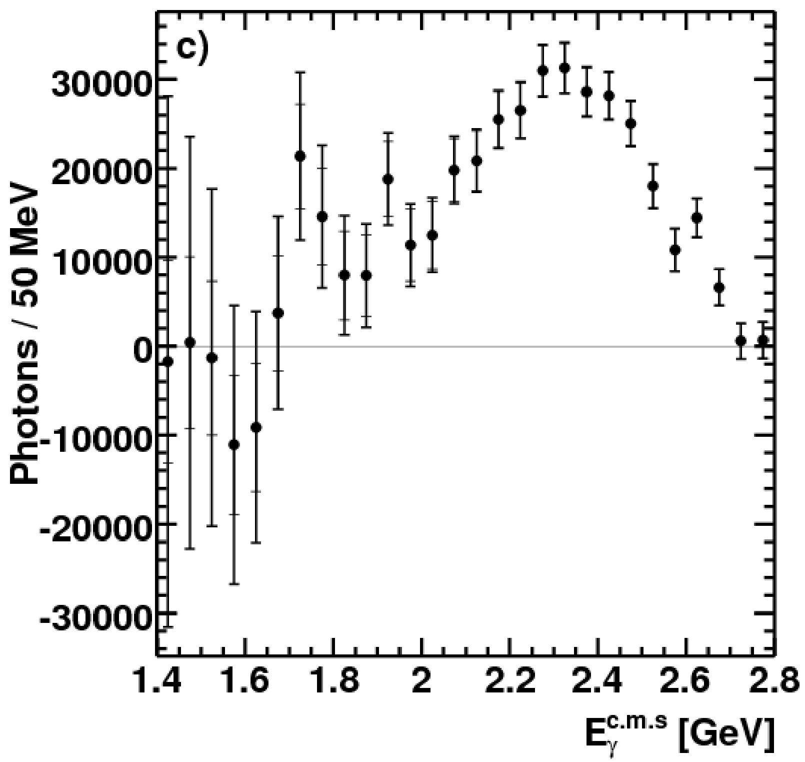
References and background reading

- 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)

Back up

$b \to s\gamma$ rate and photon energy spectrum

Archetypal FCNC probe for new physics



Belle PRL 103 (2009) 241801

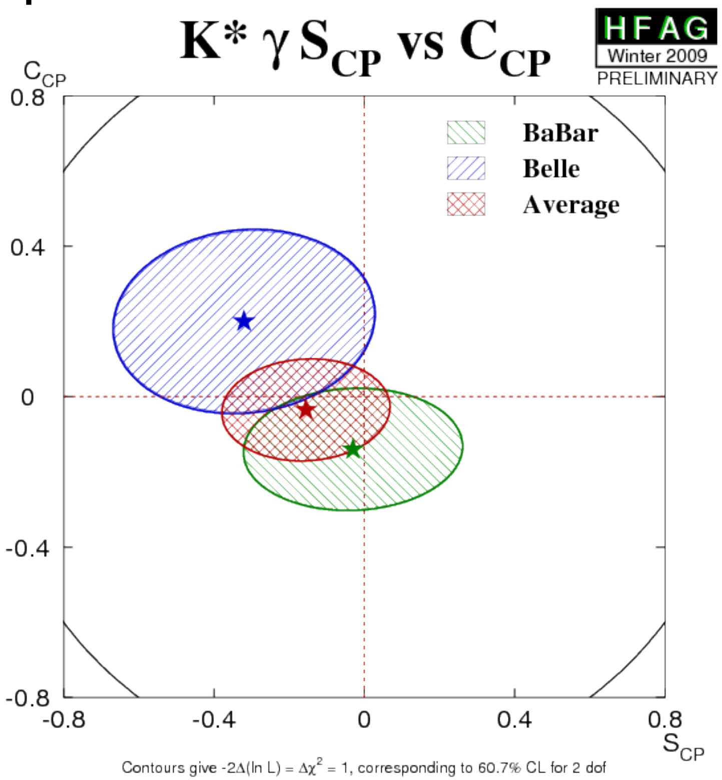
$$B(B \to X_s \gamma)_{E_\gamma > 1.7\ GeV} = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$$

consistent with the SM prediction

… but SM also predicts that the photon is polarised

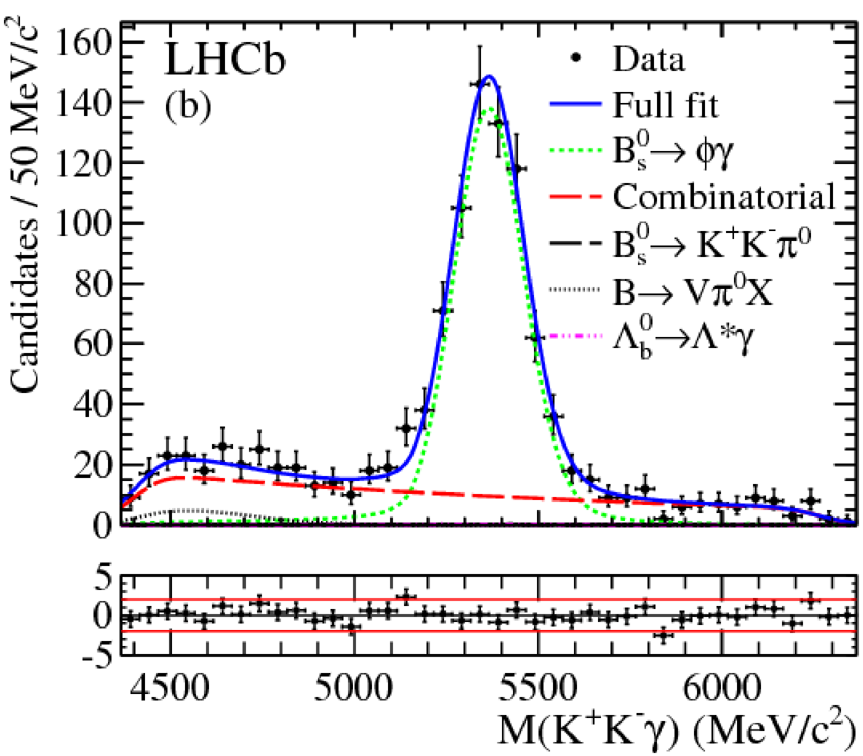
b→sγ photon polarisation measurement

- Search for time-dependent asymmetry
  - Observable effect requires NP: left-handed current & new CP phase



Excellent prospects for LHCb with $B_s \to \varphi\gamma$

NPB 867 (2013) 1



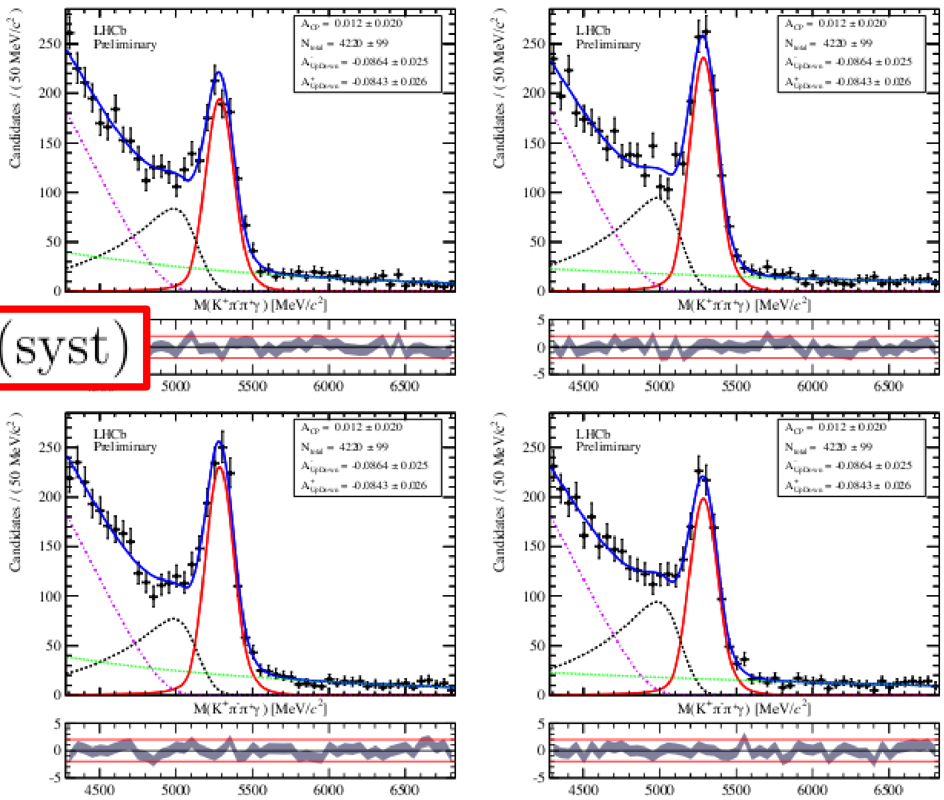
First measurement of photon polarisation in b→sγ transitions

- New LHCb measurement
  - uses $B^+ \to K^+\pi\pi\gamma$ decays
  - compare γ direction relative to $K^+\pi\pi$ plane

LHCb-CONF-2013-009

$$\mathcal{A}_{\rm ud} = -0.085 \pm 0.019\,({\rm stat}) \pm 0.003\,({\rm syst})$$

A_{ud} proportional to polarisation (unfortunately, constant of proportionality has large uncertainty)



Effective operators

$$\mathcal{H}_W^{\Delta B=1,\Delta C=0,\Delta S=-1} = 4\frac{G_F}{\sqrt{2}}\Big(\lambda_c^s\big(C_1(\mu)Q_1^c(\mu) + C_2(\mu)Q_2^c(\mu)\big)$$
$$+\lambda_u^s\big(C_1(\mu)Q_1^u(\mu) + C_2(\mu)Q_2^u(\mu)\big) - \lambda_t^s \sum_{i=3}^{10} C_i(\mu)Q_i(\mu)\Big)$$

where the $\lambda_q^s = V_{qb}^* V_{qs}$ and the operator basis is given by

$$Q_1^q = \bar{b}_L^\alpha \gamma^\mu q_L^\alpha \, \bar{q}_L^\beta \gamma_\mu s_L^\beta \qquad Q_2^q = \bar{b}_L^\alpha \gamma^\mu q_L^\beta \, \bar{q}_L^\beta \gamma_\mu s_L^\alpha$$
$$Q_3 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \qquad Q_4 = \bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q \bar{q}_L^\beta \gamma_\mu q_L^\alpha$$
$$Q_5 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \qquad Q_6 = \bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q \bar{q}_R^\beta \gamma_\mu q_R^\alpha$$
$$Q_7 = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \qquad Q_8 = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q e_q \bar{q}_R^\beta \gamma_\mu q_R^\alpha$$
$$Q_9 = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \qquad Q_{10} = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q e_q \bar{q}_L^\beta \gamma_\mu q_L^\alpha$$

$$Q_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_L^\alpha \sigma^{\mu\nu} F_{\mu\nu} s_L^\alpha$$
$$Q_{8g} = \frac{g_s}{16\pi^2} m_b \bar{b}_L^\alpha \sigma^{\mu\nu} G_{\mu\nu}^A T^A s_L^\alpha$$
$$Q_{9V} = \frac{1}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \, \bar{l}\gamma_\mu l$$
$$Q_{10A} = \frac{1}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \, \bar{l}\gamma_\mu \gamma_5 l$$

Four-fermion operators (except $Q_{7\gamma}$ & Q_{8g}) – dimension 6

Future projects