Flavour experiment session summary

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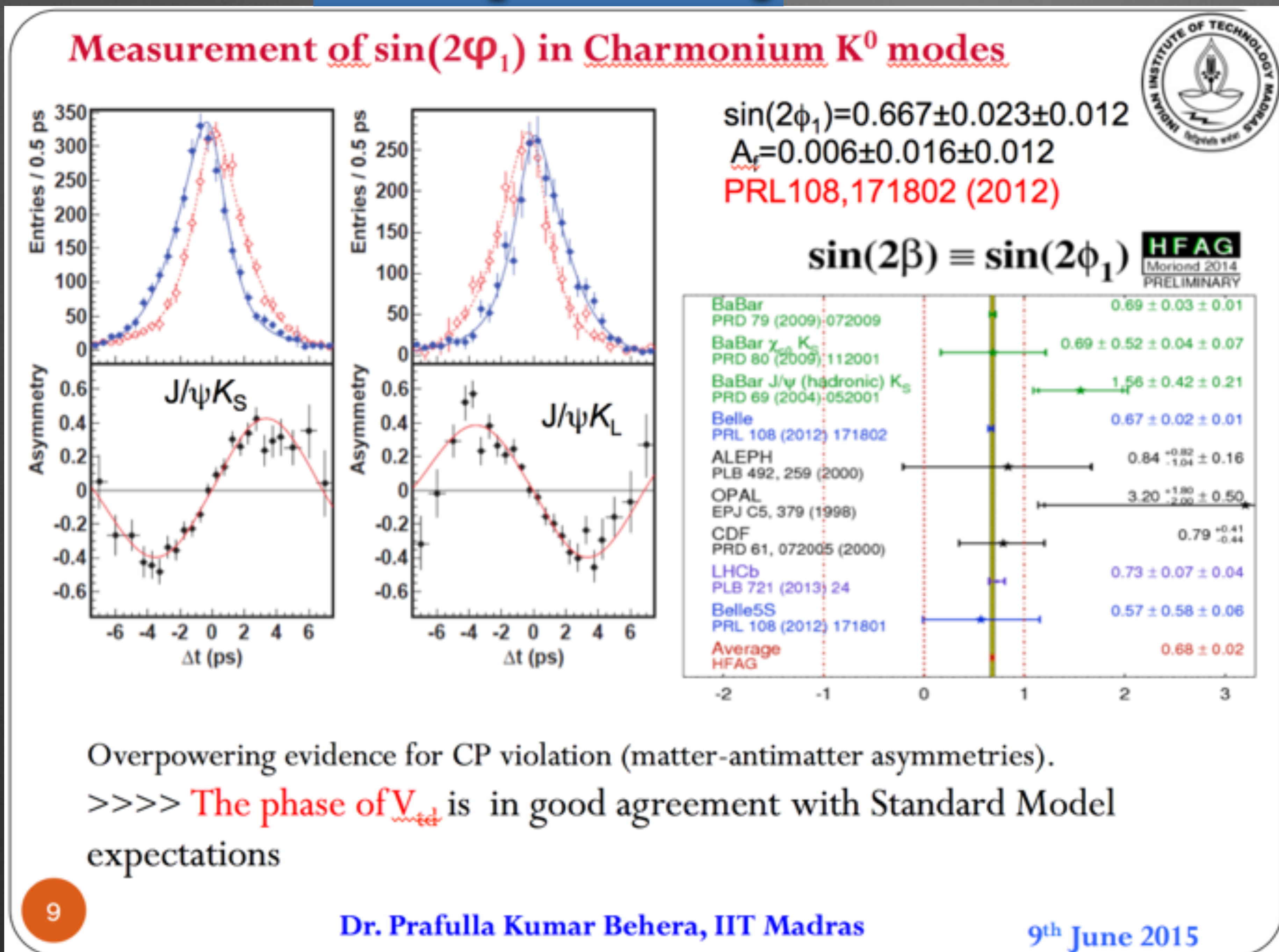
The University of Tokyo
International Workshop on Weak Interactions and Neutrinos (WIN2015)
Friday 12 June 2015

Topics at parallel sessions of the experimental flavour physics

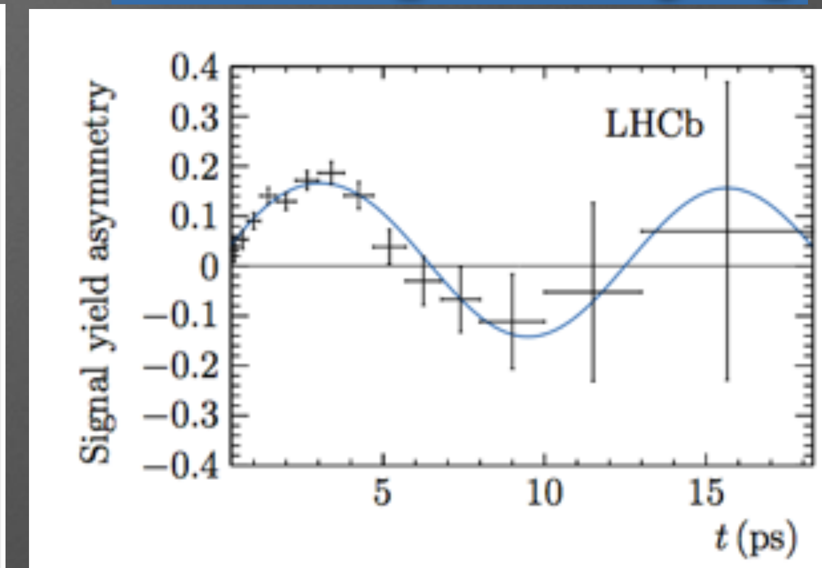
- CP violation, Rare B decays
  - Belle, Belle II, BABAR, LHCb
- Dark photon from BABAR
- LFV Higgs signatures from CMS
- LFV
  - MEG/Mu3e, COMET/mu2e

CP Violation (sin2β from $B^0 \to J/\Psi K^0$)

Belle[Prafulla]



LHCb[Suvayu]



$B^0 \to J/\psi K_S$

S = 0.731±0.035±0.020

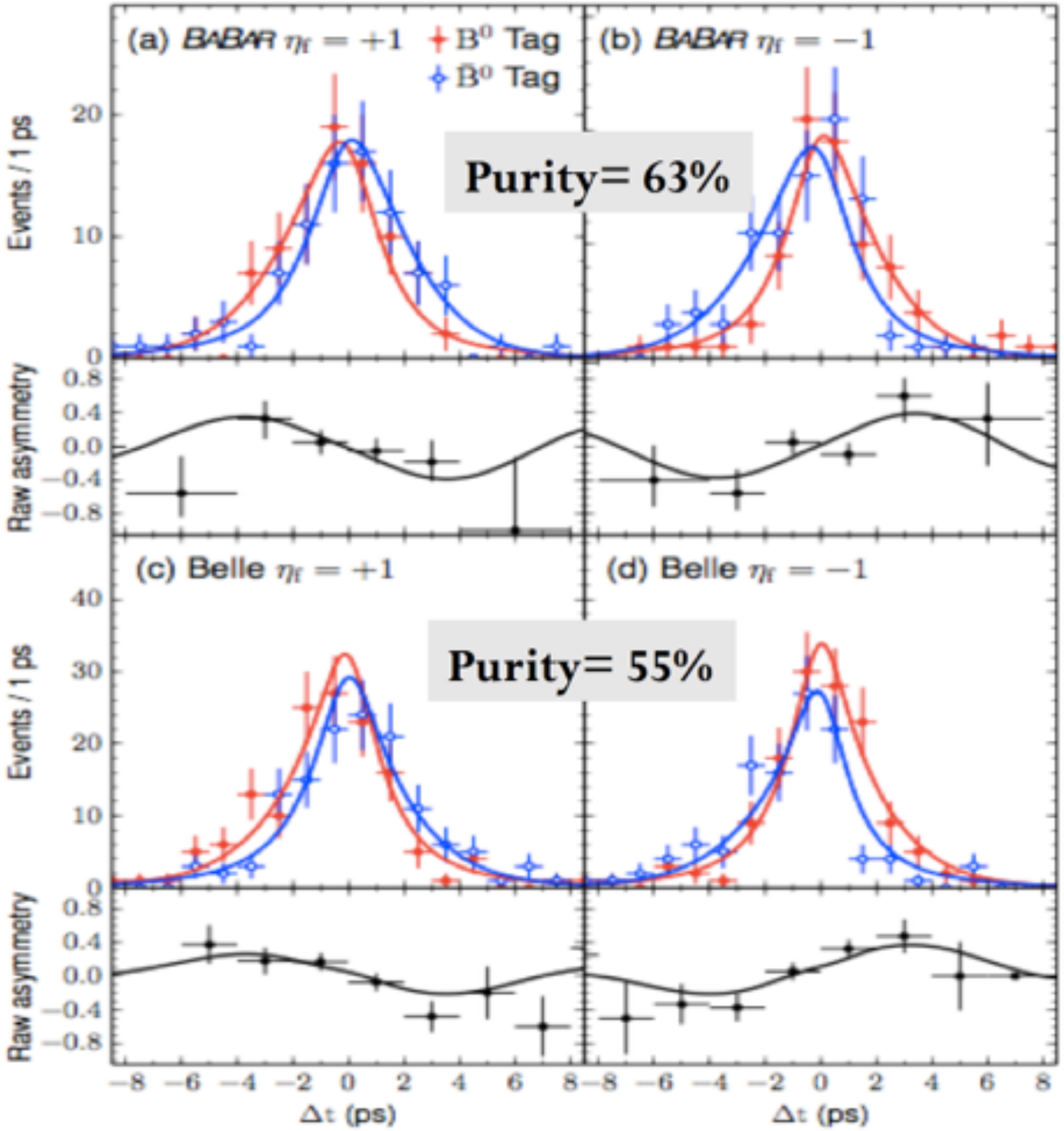
C = -0.038±0.032±0.005

LHCB-PAPER-2015-004

- LHCb updated the result which is consistent with it

- First quantitative test of the Standard Model for CPV

CP violation in $\bar{B}^0 \rightarrow D_{cp}^{(*)} h^0$



Belle[Prafulla]

$\sin(2\varphi_1) = 0.66 \pm 0.10 \pm 0.06$

The measurement is consistent with measurement from $J/\psi K^0$

arXiv:1505.04147
Submitted to PRL

Dr. Prafulla Kumar Behera, IIT Madras

9th June 2015

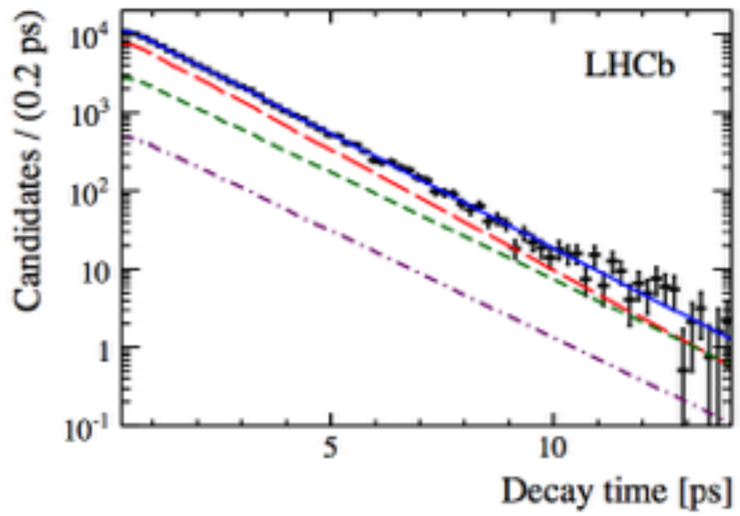
- First combined results from Belle and BABAR, $\sim 1.1 ab^{-1}$
- First observation of the CPV for this mode

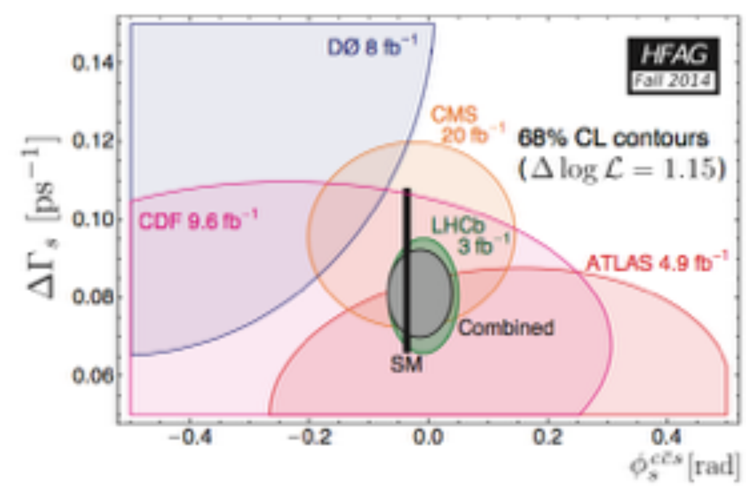
CPV in $B_s \to J/\psi KK$, $J/\psi\pi\pi$

LHCb[Suvayu]

- CP-violating phase ϕs

φ_s: $B_s \longrightarrow J/\psi KK$, $J/\psi\pi\pi$ – results





	LHCb PRL 114 (2015) 041801	ATLAS PRD 90 (2014) 052007	CMS CMS-PAS-BPH-13-012
φ_s (rad)	-0.058±0.049±0.006	0.12±0.25±0.05	-0.03±0.11±0.03
$\Delta\Gamma_s$ (ps^{-1})	0.0805±0.0091±0.0032	0.053±0.021±0.010	0.096±0.014±0.007
Γ_s (ps^{-1})	0.6603±0.0027±0.0015	0.677±0.007±0.004	—

$B_s \longrightarrow J/\psi KK$, $J/\psi\pi\pi$ combined: φ_s = -0.010±0.039 (LHCb)

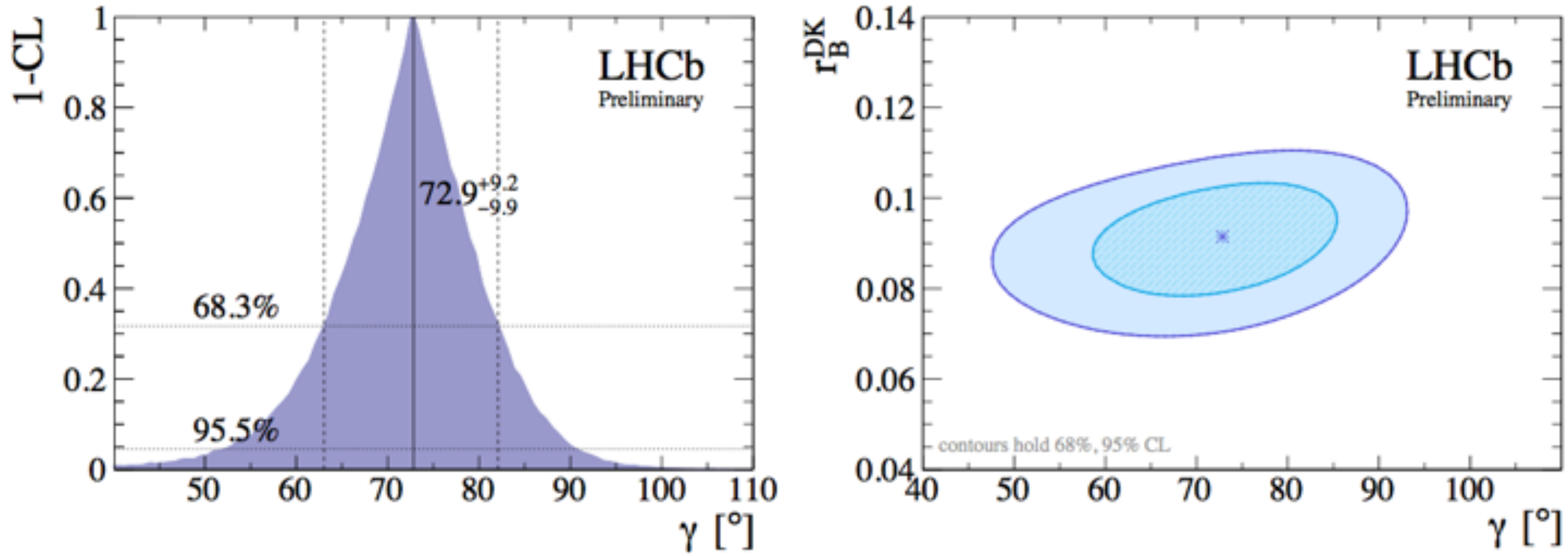
Combined φ_s = -0.015±0.035 (HFAG)

- LHCb, ATLAS, and CMS are contributing. In good agreement with the SM

Combining γ measurements

Combining γ measurements

LHCb[Suvayu]

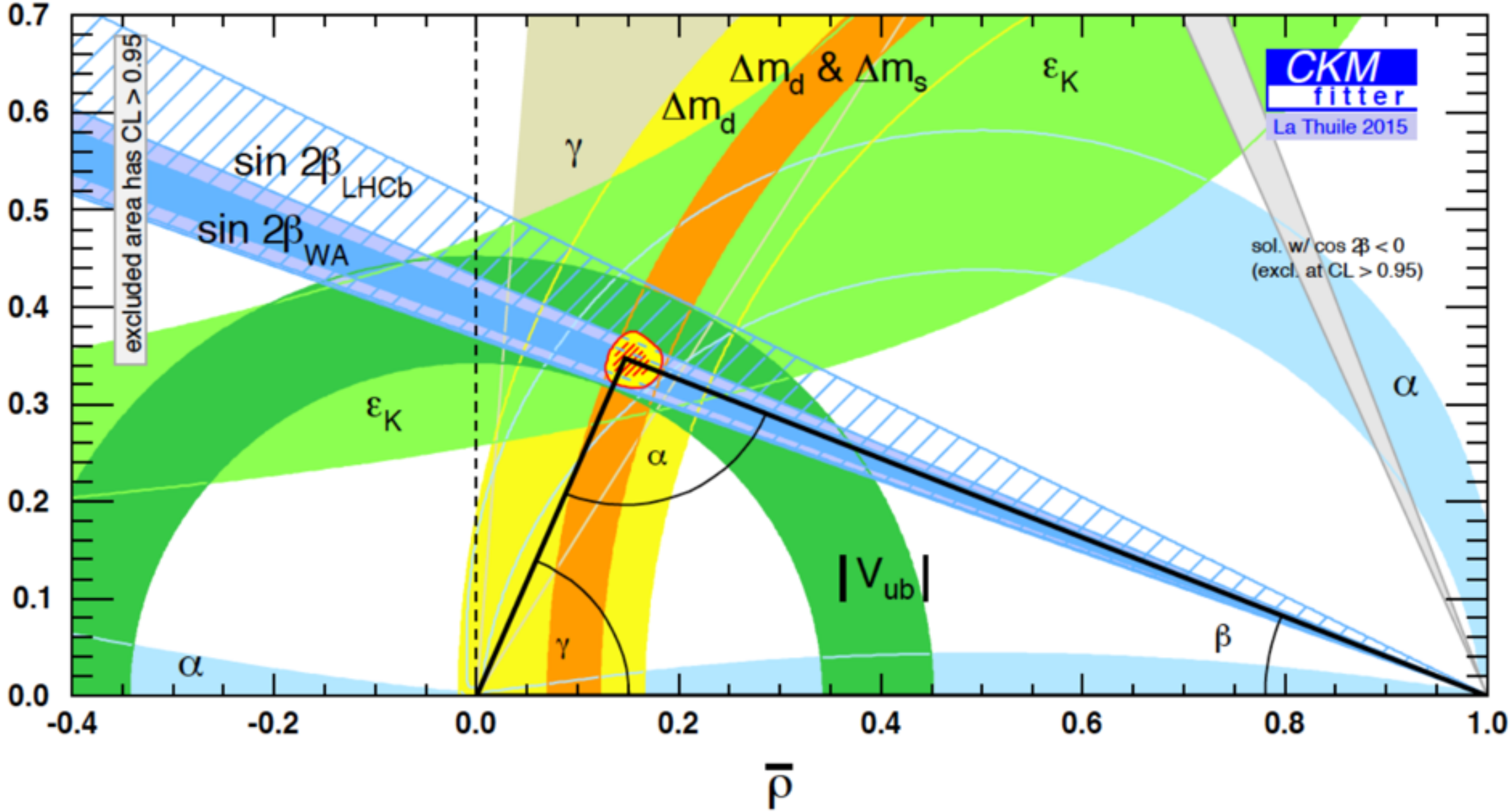


- LHCB-CONF-2014-004
- χ^2 combination of experimental inputs
  - 1/fb & 3/fb: $B^{\pm} \rightarrow DK^{\pm}$ (ADS, GLW, GGSZ, GLS)
  - 1/fb: $B_s \rightarrow D_s K$
- $\gamma = (73^{+9}_{-10})°$: ~30% improvement over the past!

- Belle $(68^{+15}_{-14})°$
- BABAR $(69^{+17}_{-16})°$

- Most recent unitarity triangle fit

globally speaking, consistent with the SM picture



Lepton Universality (B→D(*)τν)

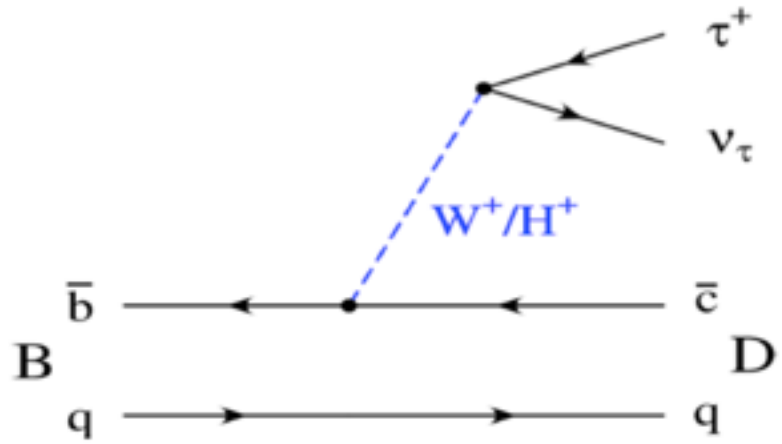
Ratio affected by charged Higgs

Belle[Prafulla]

LHCb[Jose Angel]

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

- Process with third generation quarks and leptons



New physics could change:

- Branching fraction
- Tau polarization
- Effect could be different for D and D*

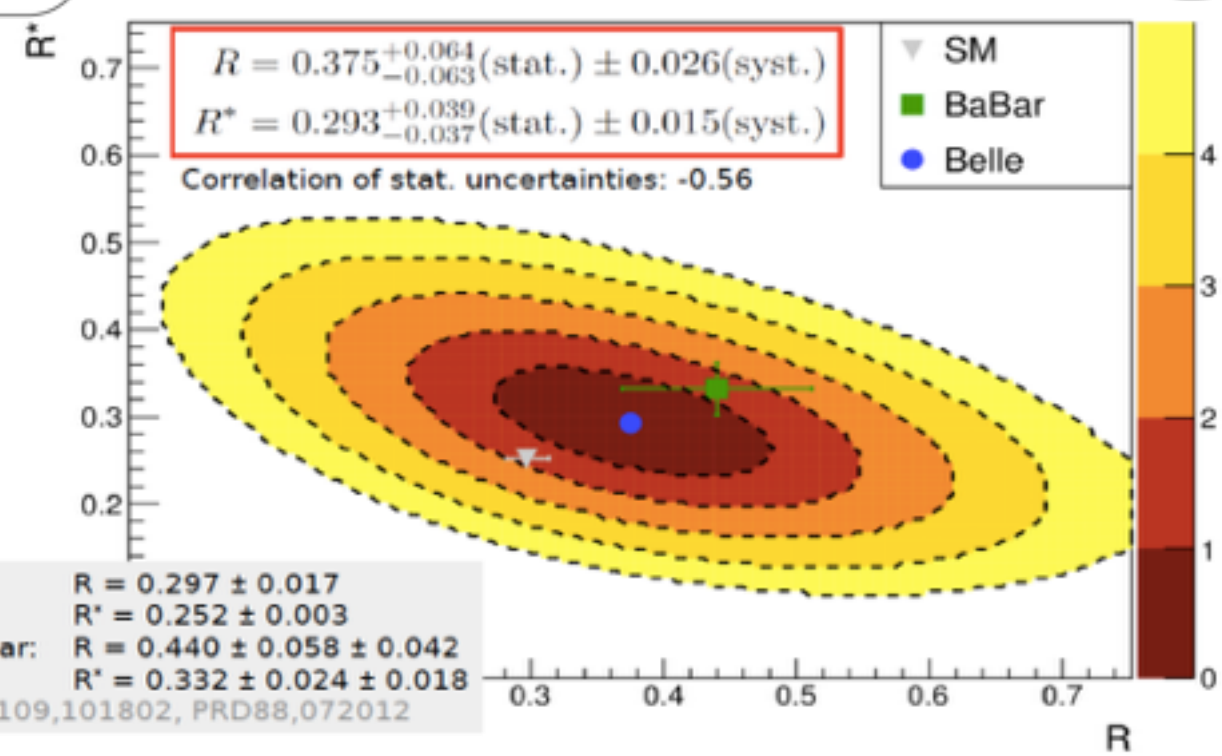
Experimental Challenge: 2 (hadronic tau decay) or 3 (leptonic tau decay) undetected neutrinos

$$R = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)} \qquad R^* = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)}$$

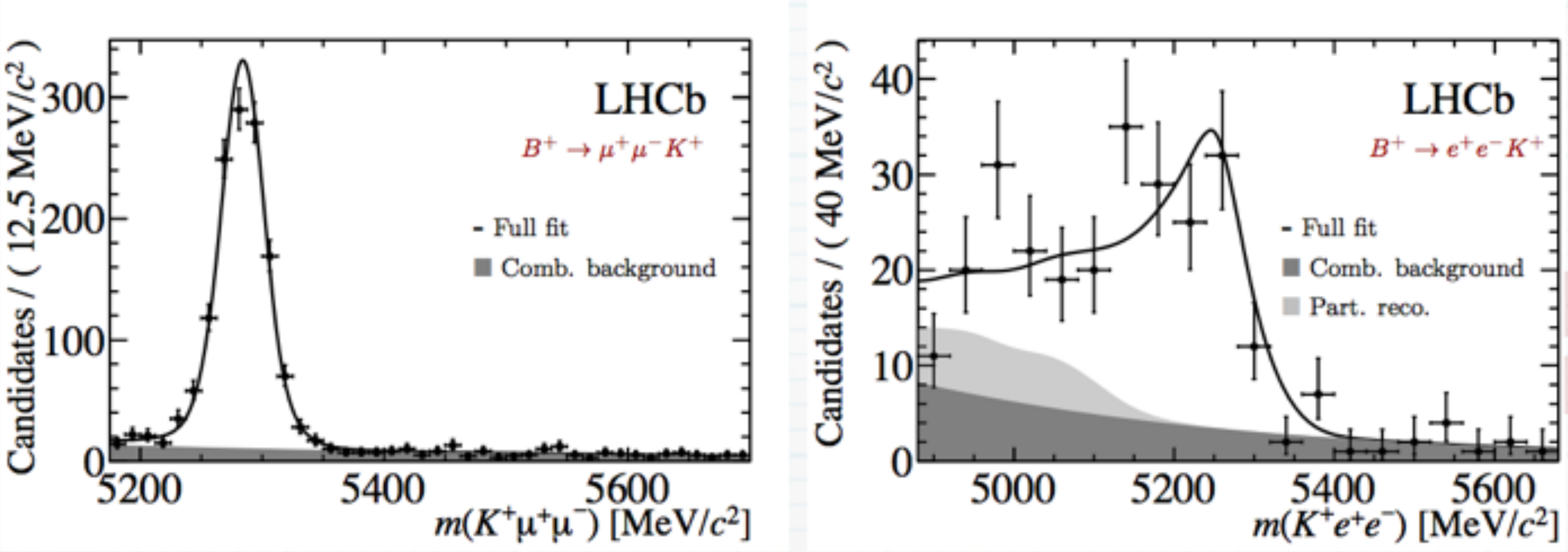
ℓ^- = e^- or μ^-

- Belle result consistent with SM within 2σ
- Consistent with LHCb new result
  - R(D*)=0.336±0.027±0.03
- Cf. Belle result is consistent with 2HDM of type II at $\tan\beta/m_{H+}=0.5c^2$/GeV

Result



Lepton Universality $B^+ \to K^+ l^+ l^-$



e trigger
172±20 candidates

- Systematic dominated for the inv mass parameterization and trigger efficiencies

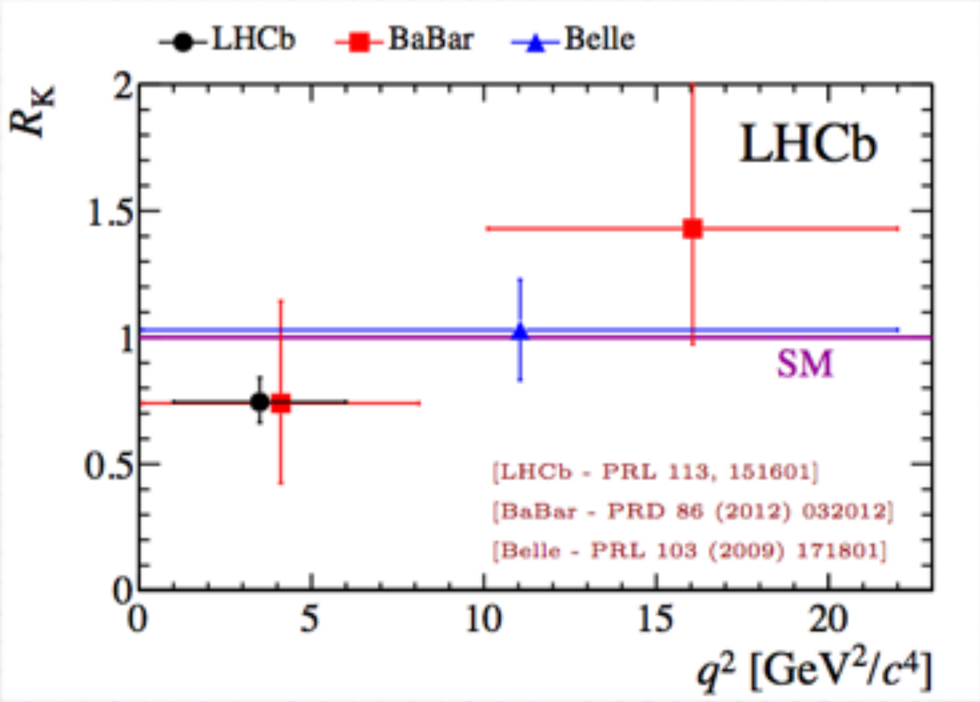
q^2 in [1,6] GeV^2/c^4

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

- Consistent with SM at 2.6 σ
  - *A Z' with different coupling with e and μ?*
- Branching Ratio of $B^+ \to K^+ e^+ e^-$

$$[1.56^{+0.19}_{-0.15}(\text{stat})\ ^{+0.06}_{-0.04}(\text{syst})] \times 10^{-7}.$$

- Consistent with SM predictions!

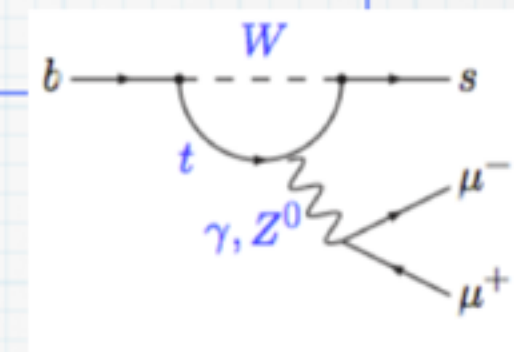


LHCb q^2 [1,6] GeV^2/c^4

Phys. Rev. Lett **113** (2014) 151601

LHCb[Jose Angel]

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

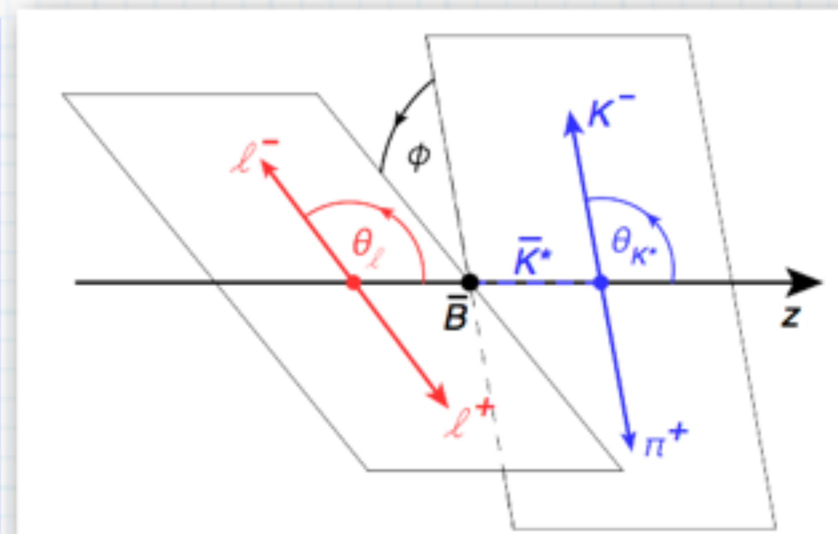


◆ Angular Analysis $B \to K^* \mu^+ \mu^-$

SM: JHEP **08** (2013) 131

- Forward backward muon asymmetry, SM $q^2_0 \sim 4\ \mathrm{GeV}^2/c^4$
- Full angular distribution, observables sensible to $C^{(')}_7$, $C^{(')}_9$, $C^{(')}_{10}$ and form factors.

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



- Depends on F_L, A_{FB}, S_i, observables, that are sensible to $C^{(')}_7$, $C^{(')}_9$, $C^{(')}_{10}$ and form factors.
- Additional "optimized" observables, with cancellation of leading form-factor uncertainties

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

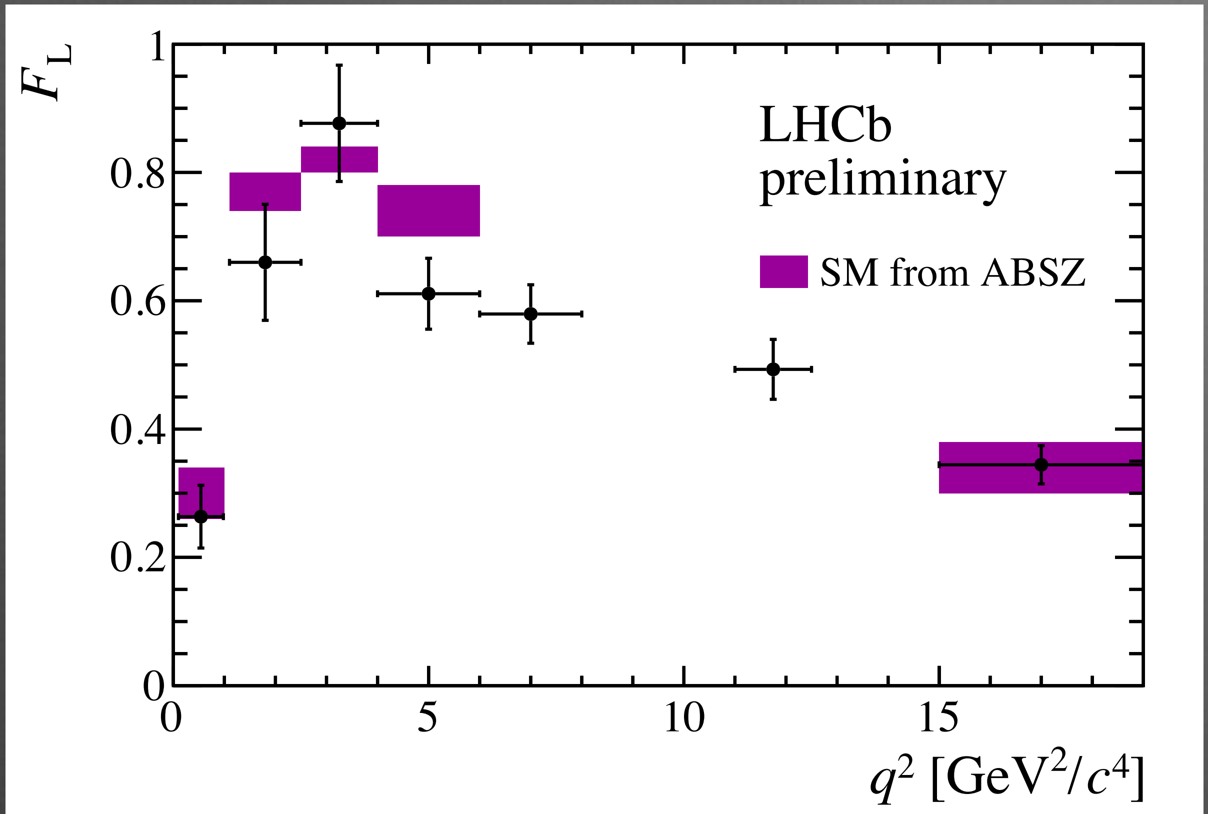
JHEP **01** (2013) 048

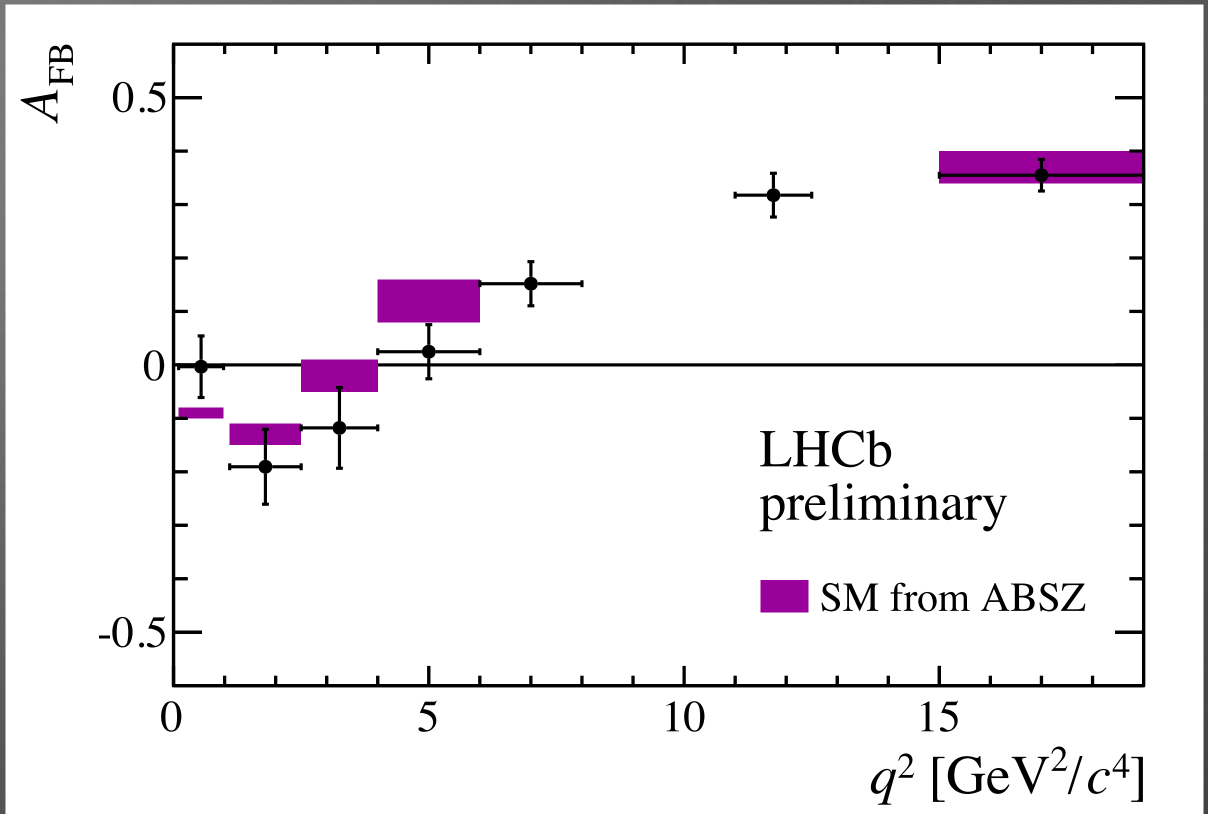
LHCB-CONF-2015-002

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

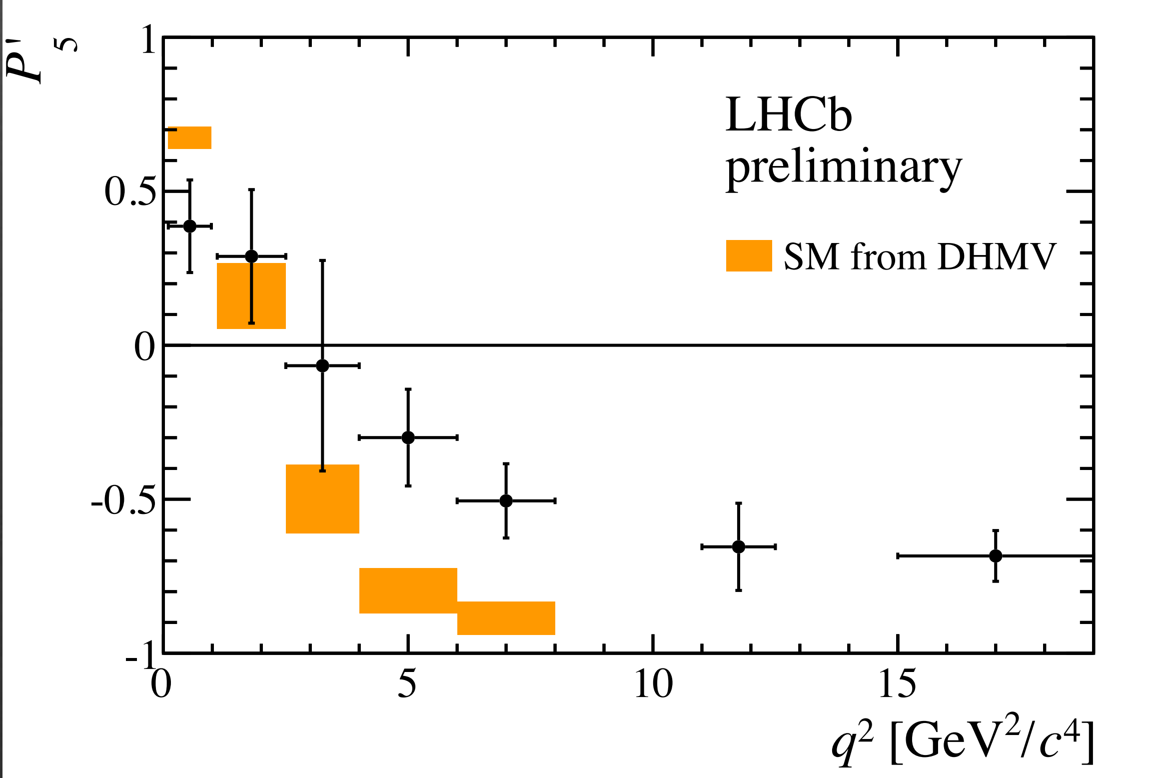
LHCb[Jose Angel]

SM: arXiv:1503.05534, arXiv:1411.3161





SM: JHEP **1412** (2014) 124

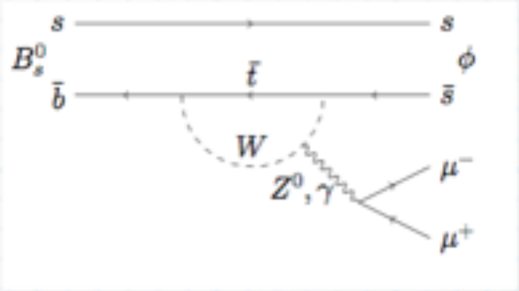


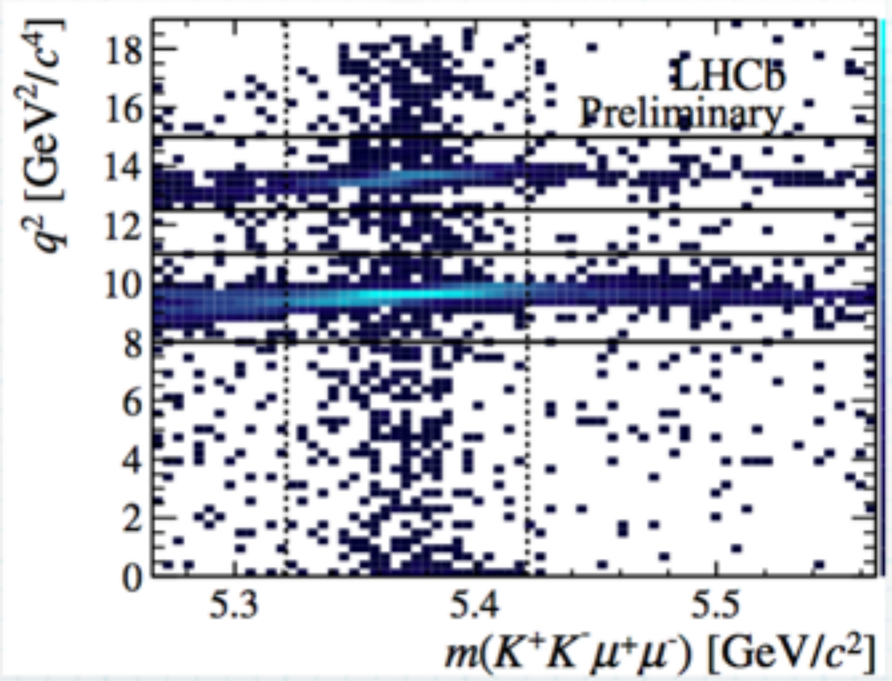
- zero-crossing point of A_{FB} in agreement with SM
- 2 bins with 2.9σ
- naive local significance 3.7σ

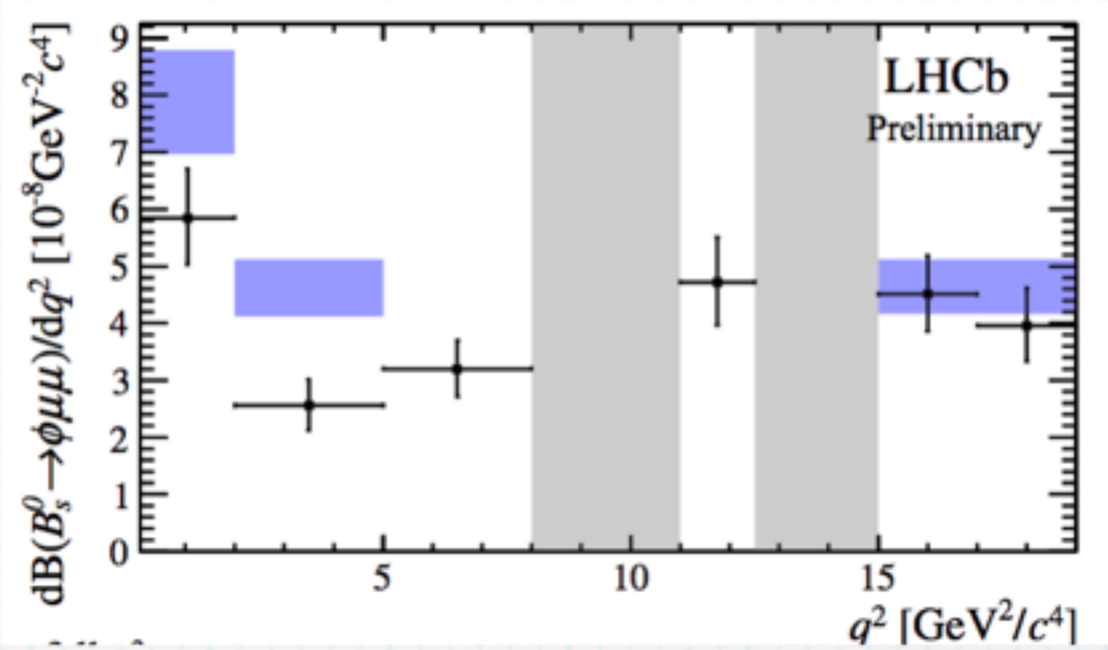
Branching ratio and Angular Analysis $B_s \to \phi(K^+K^-)\,\mu^+\mu^-$

◆ Branching ratio and angular analysis

- similar to $B \to K^*\mu^+\mu^-$, but production suppressed and not flavour specific final state

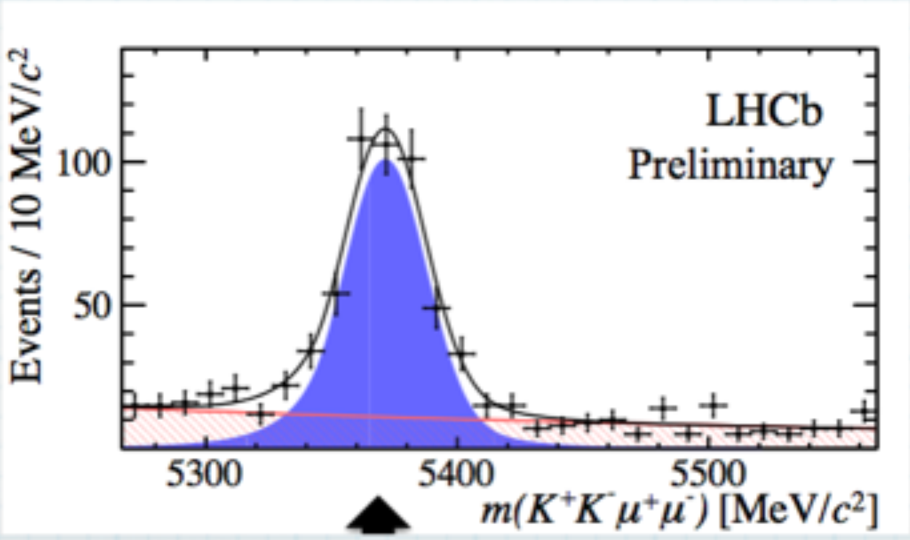






432±24 candidates

SM: arXiv:1503.05534, arXiv:1411.3161



- most precise measurement
- 3 σ tension in $1<q^2<6$ GeV^2/c^2

$$\frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)} = (7.40^{+0.42}_{-0.40} \pm 0.16 \pm 0.21) \times 10^{-4},$$

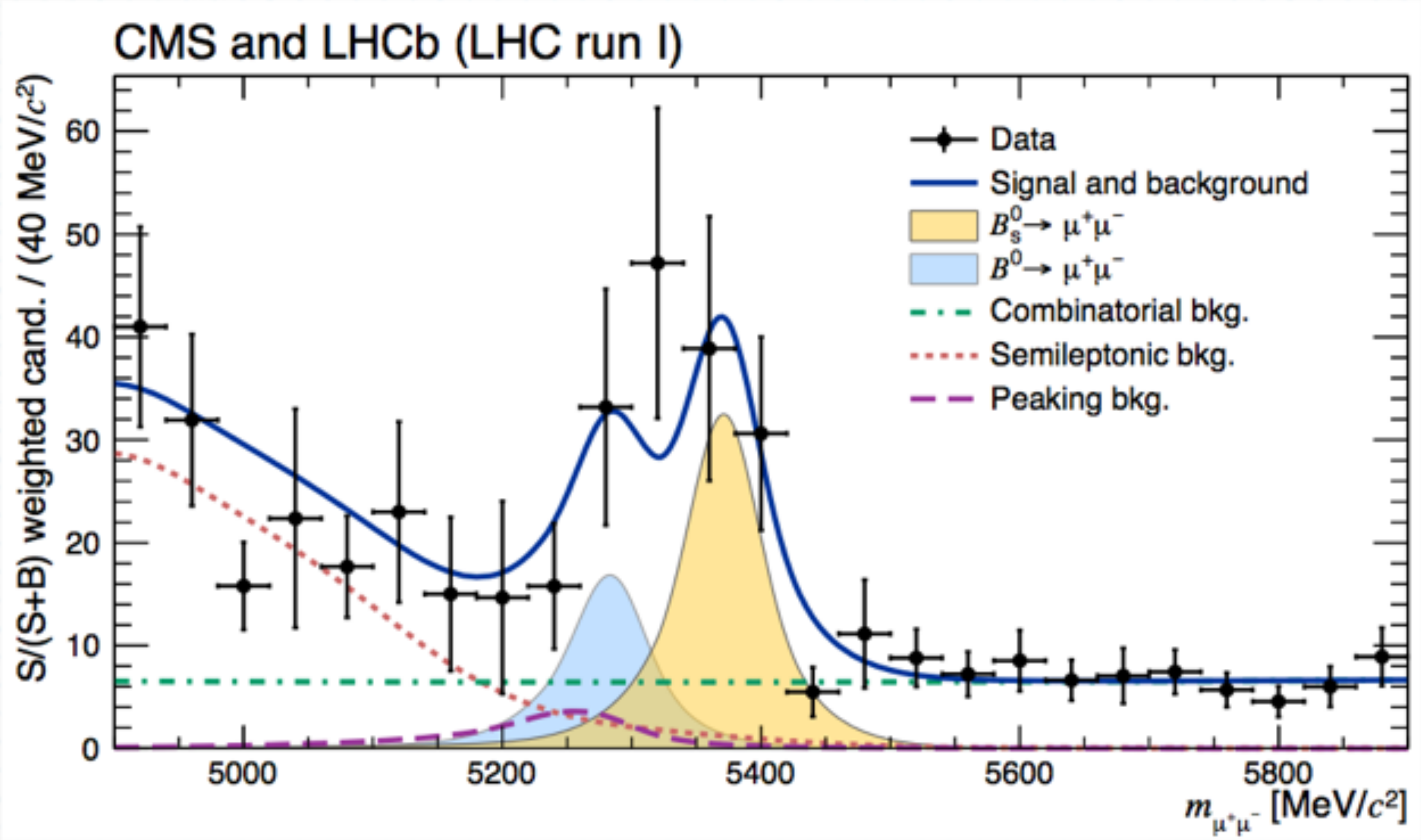
$$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (7.97^{+0.45}_{-0.43} \pm 0.18 \pm 0.23 \pm 0.60) \times 10^{-7}$$

LHCB-PAPER-2015-023

$B_{(s)} \to \mu\mu$ (very rare decay)

LHCb[Jose Angel]

- Combined LHCb and CMS search
  - simultaneous analysis, shared signal and nuisance parameters



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

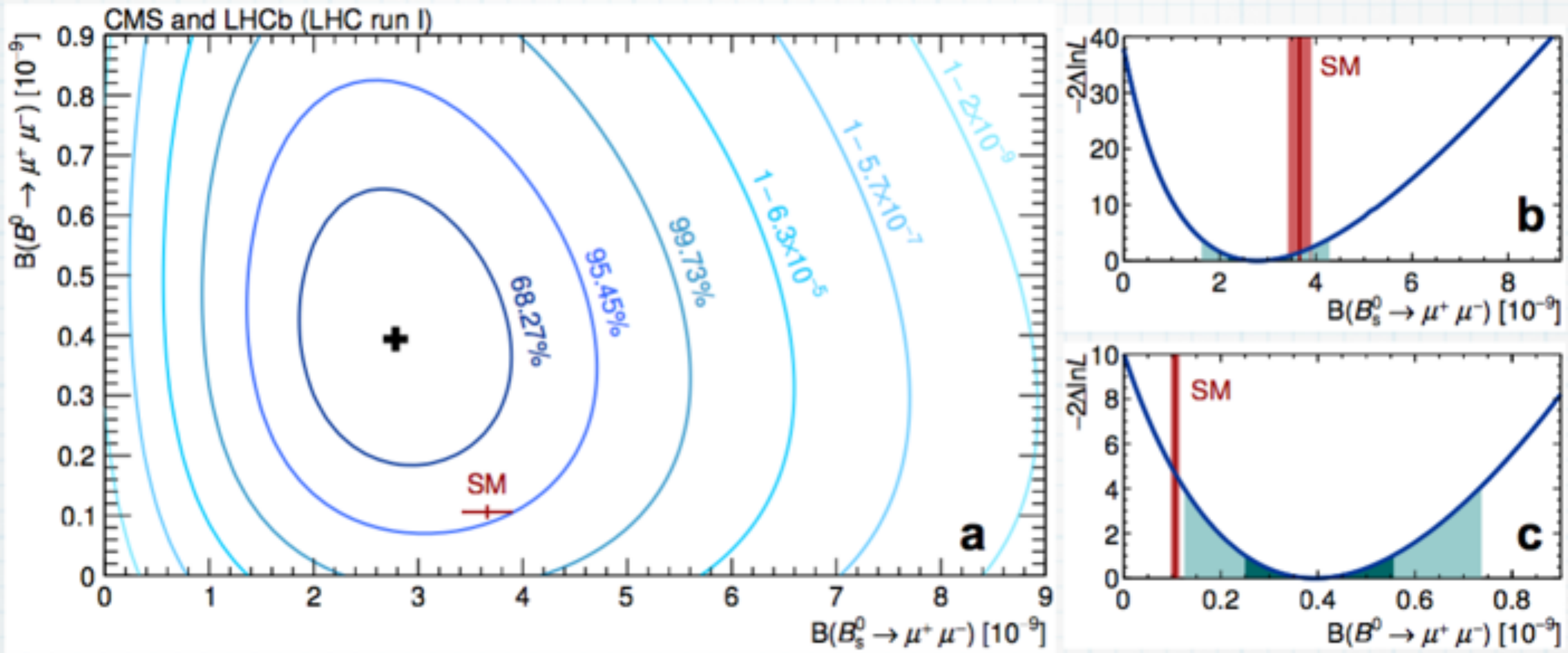
  - $B_s \to \mu\mu$ first observation (6.2 σ) and $B \to \mu\mu$ with 3σ significance!
  - In agreement with SM!, stringent constraint for BSM!

arXiv:1411.4413, Nature **552** (2015) 68

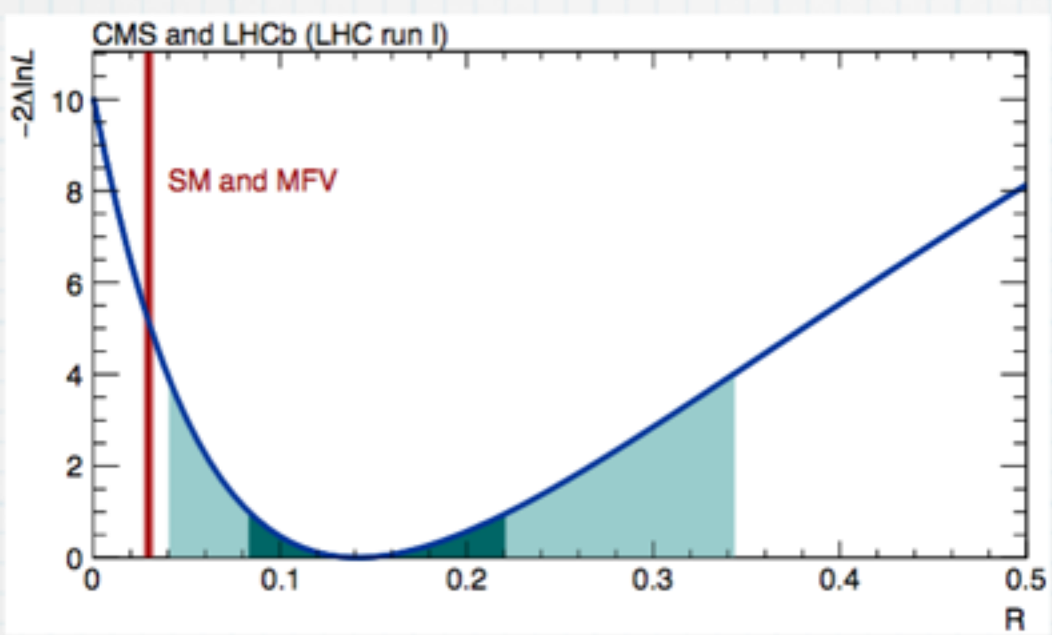
LHCb[Jose Angel]

$B_{(s)} \to \mu\mu$

- likelihood scan



- Determination of the BR ratio



- SM ratio prediction PRL **112** (2014) 101801

$0.0295^{+0.0028}_{\;\;0.0025}$

- Measured for first time

$$R = \frac{\mathcal{B}(B^0 \to \mu\mu)}{\mathcal{B}(B^0_s \to \mu\mu)} = 0.14^{+0.08}_{-0.06}$$

- Compatible with SM at 2.3 σ

arXiv:1411.4413, Nature **552** (2015) 68

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CKM elements from semileptonic decays: |Vub|

LHCb[Suvayu]

- Constrains apex of the triangle
  - Measured from decays with $b \to u l \nu$ transitions
- Current status: inconsistent

	$\lvert V_{ub} \rvert$
exclusive ($B \to \pi l \nu$)	$(3.28 \pm 0.29) \times 10^{-3}$
inclusive (all $b \to u l \nu$)	$(4.41 \pm 0.15) \times 10^{-3}$

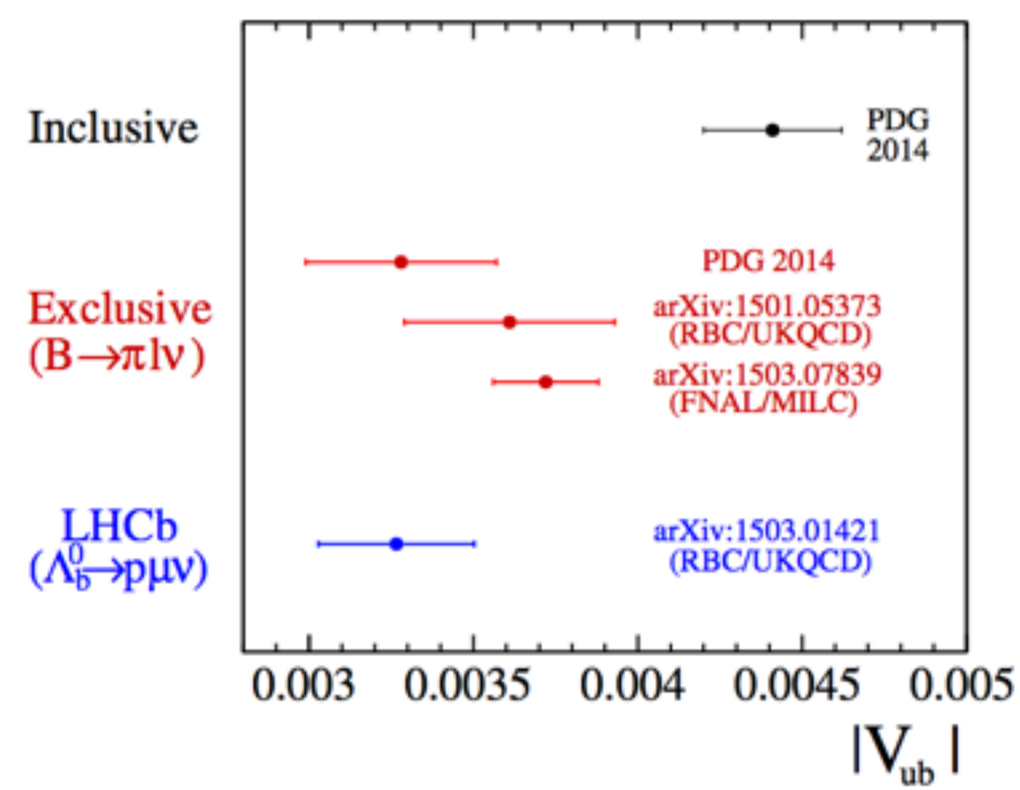
- Use baryonic decays at LHCb

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p \mu^- \bar{\nu})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu})} R_{FF}$$

Form factor ratio from Lattice QCD

Using $|V_{cb}|$ from world avg:

$|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$



- LHCb confirms the existing incompatibility with those using an inclusive sample of final states by using a baryonic decay

Belle II [Martin]

Prospects of B Physics

Why Belle II?

But plenty of stuff still improvable...

Issues, that could still be addressed by a flavour factory:

- Baryon asymmetry in cosmolgy
  → New Sources of CPV in quarks/charged leptons
- quark and lepton flavour & mass hierarchy
  → higher symmetry, massive new particles, extended gauge sector
- 19 free parameters
  → Extensions of SM might relate some (GUTs)
- Dark Matter, strong CP problem,...
  → hidden dark sector, axions,...
- finite neutrino masses, maybe SeeSaw
  → lepton flavour violation (tau)

Indirect searches for new physics

- nature of XYZ-states;
- decay structures (intermediate resonances, hadronisation,...) & excited states
- ...

Better handling of difficult to calculate QCD.

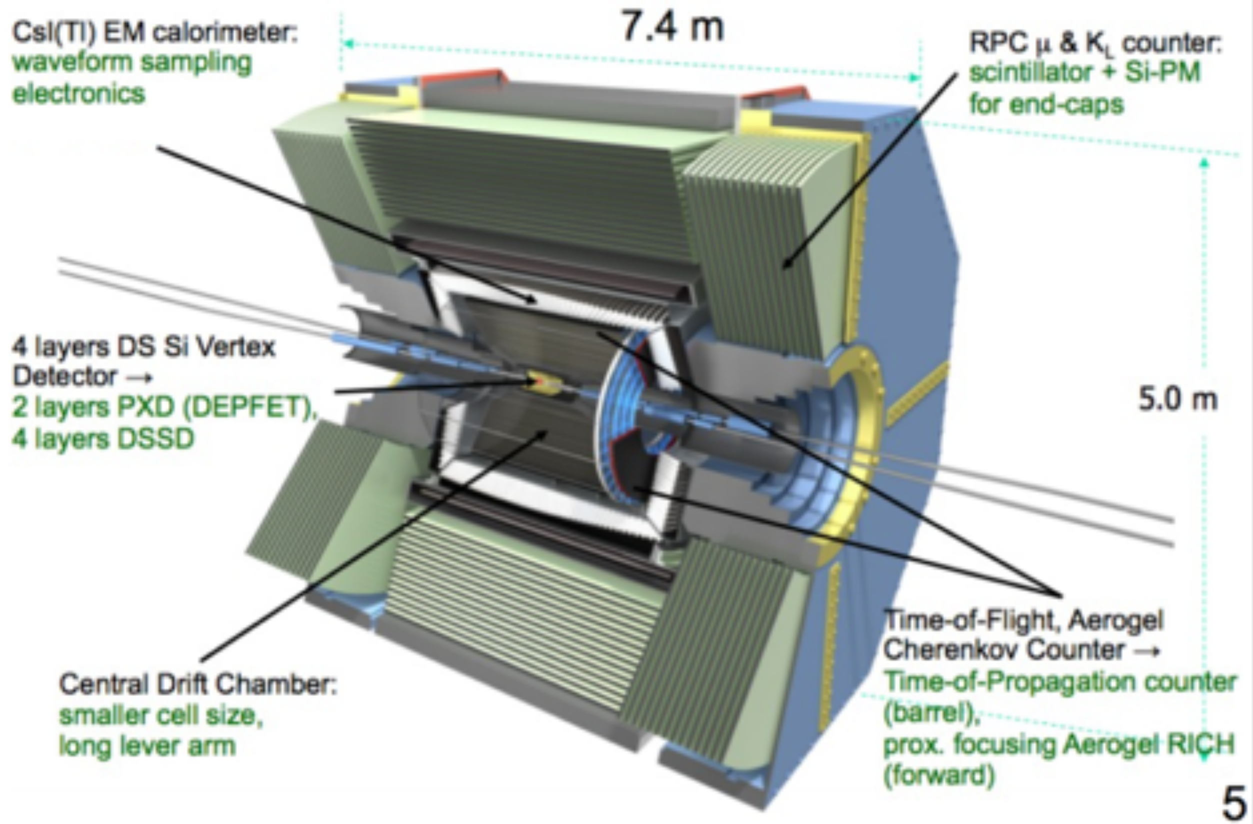
4

Belle II [Martin]

The Detector

Targeted improvements:

- *Increase hermiticity.*
- *Increase K^0_s efficiency.*
- *Improve IP and secondary vertex resolution.*
- *Improve K/π separation.*
- *Improve π^0 efficiency.*
- *Add PID in endcaps.*
- *Add μ ID in endcaps.*
- Higher low momentum effieciency tracking



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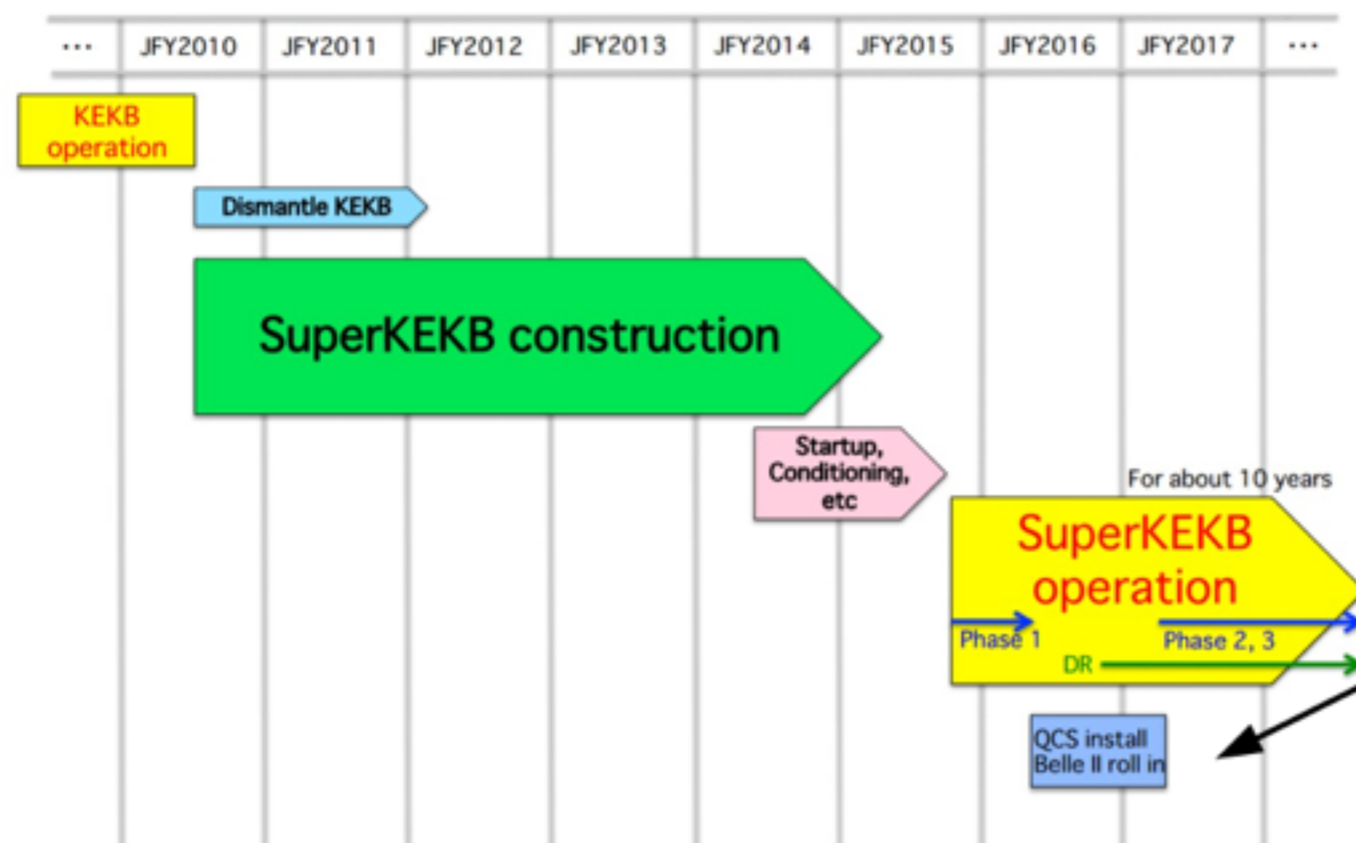
- Higher luminosity ($8\times10^{35}\,cm^{-2}s^{-1}$)
- Improvement of reconstruction, analysis technique
- non-B measurement in 2017, Silicon roll-in in 2018

Plans, Plans, Plans



First roll-in without silicon detectors; physics program for data taken in that mode is under investigation;

Silicon roll-in in 2018;

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What Can We Expect?

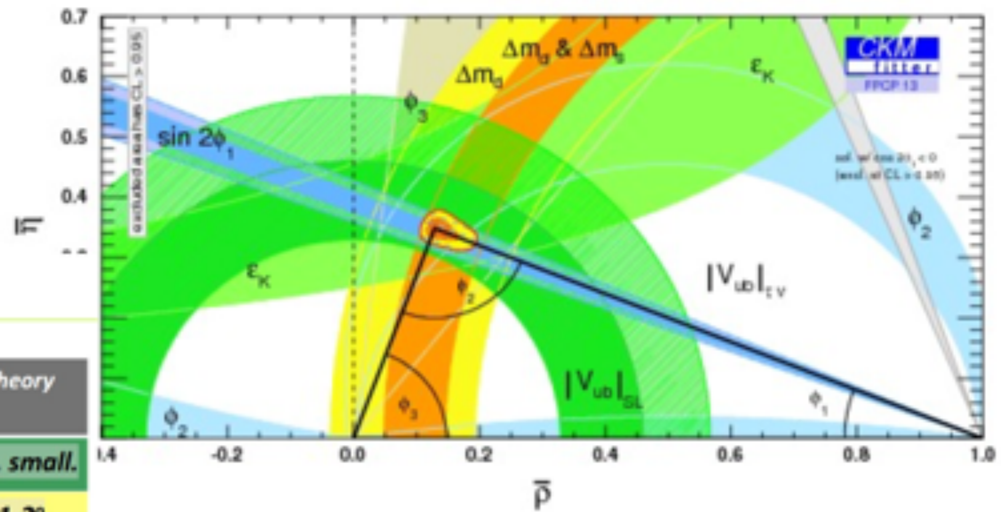
Belle II [Martin]

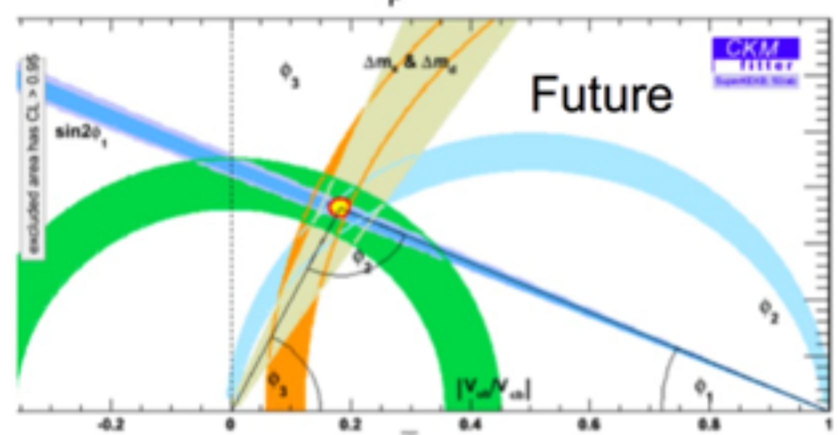
Summary of CKM Metrology

	Belle	BaBar	Global Fit CKMfitter	LHCb Run-2	Belle II 50 ab^{-1}	LHCb Upgrade 50 fb^{-1}	Theory
φ_1: ccs	0.9°		0.9°	0.6°	0.3°	0.3°	v. small.
φ_2: uud	4° (WA)		2.1°		1°		~1-2°
φ_3: DK	14°		3.8°	4°	1.5°	1°	negl.
$\lvert V_{cb}\rvert$ inclusive	1.7%		2.4%		1.2%		
$\lvert V_{cb}\rvert$ exclusive	2.2%				1.4%		
$\lvert V_{ub}\rvert$ inclusive	7%		4.5%		3.0%		
$\lvert V_{ub}\rvert$ exclusive	5.5%			7.2%	2.4%		
$\lvert V_{ub}\rvert$ leptonic	14%				3.0%		

Experiment: No result; Moderate precision; Precise; Very Precise

Theory: Moderate precision; Clean / LQCD; Clean





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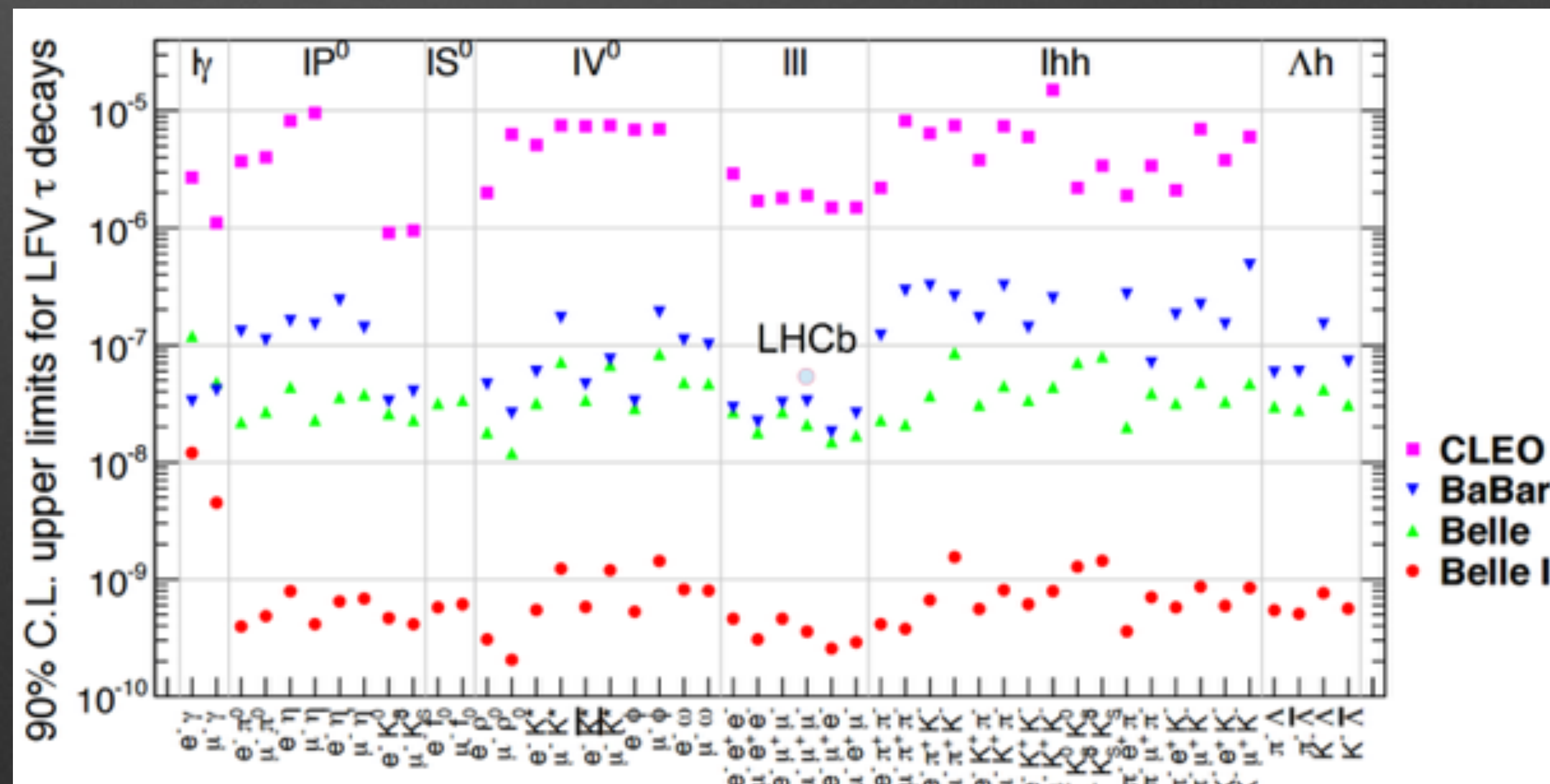
- Better determination of CKM matrices
- Plenty of τ, too



We will have lots of tau-leptons!

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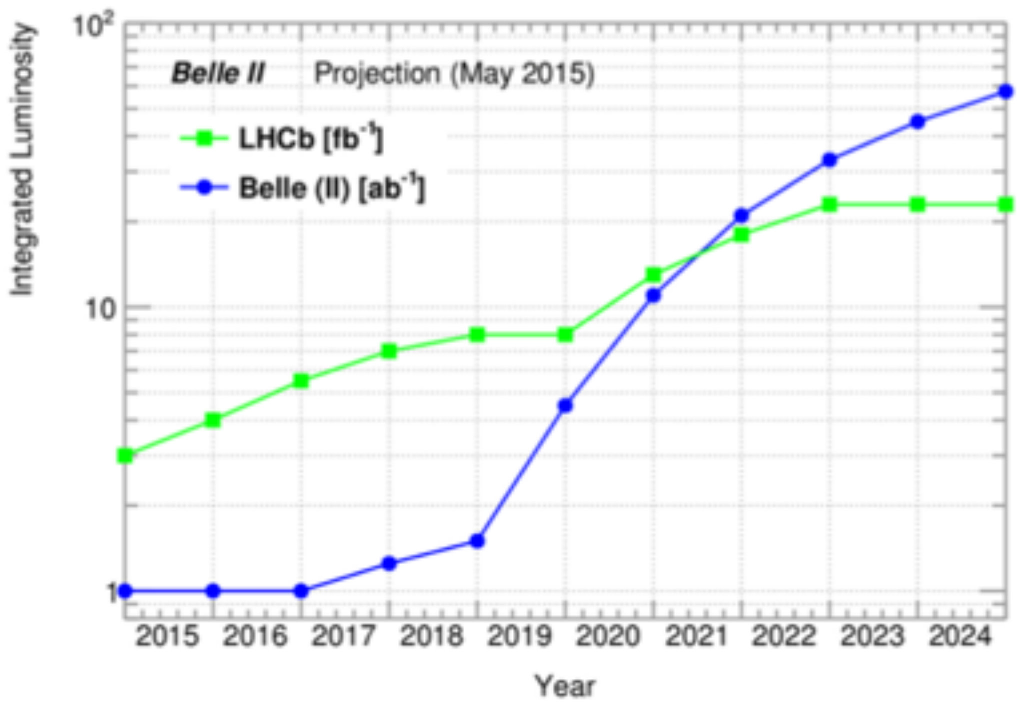
LHCb & Belle II



- Belle II will have larger dataset eventually:

Belle II	50 ab^{-1}
LHCb	50 fb^{-1}

- Complement each other
- Modes with γ in the final state: $B^{\pm} \to [D\gamma]_{D^*}K^{\pm}$
  - Easier at Belle II/e^+e^- colliders
- Time dependent B_s decays and baryonic decays
  - Only feasible at LHCb
- LHCb already exploring extensions to well established techniques
  - quasi-GLW/GLS: $D \to \pi K \pi^0$, $D \to hh\pi^0$ ($h \in \{K,\pi\}$)
  - CKM angle γ (φ_3) from $B^0 \to D^0K^*$, $B^0 \to D^0K\pi$[6]

[6]LHCb-PAPER-2015-017

LFV Decays of the Higgs Boson (H→τμ)

CMS[Colin]

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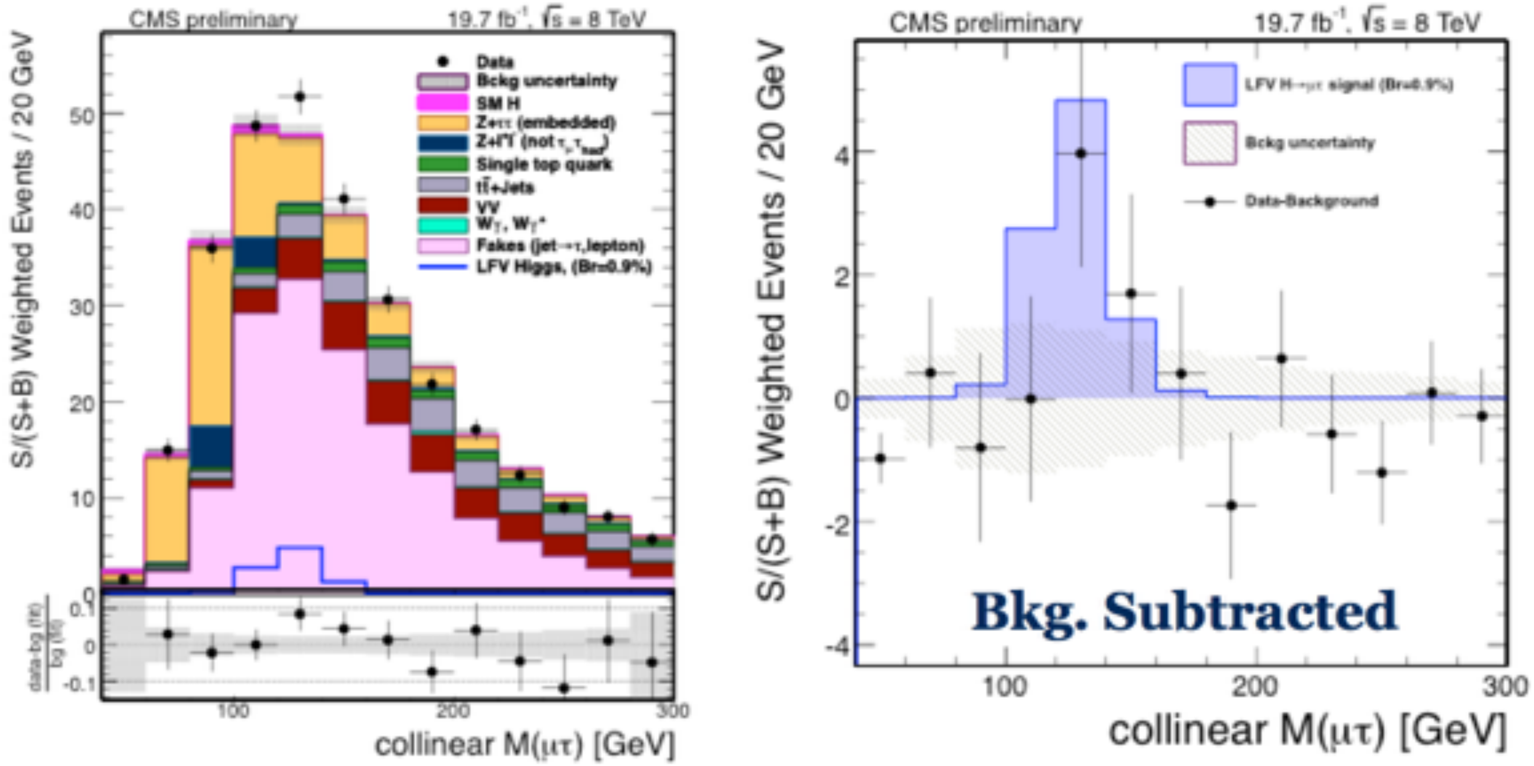
Weighted M_{coll} Distributions

24

Combined channels and categories bins weighted by significance (S/(S+B))



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Branching Ratio Limits

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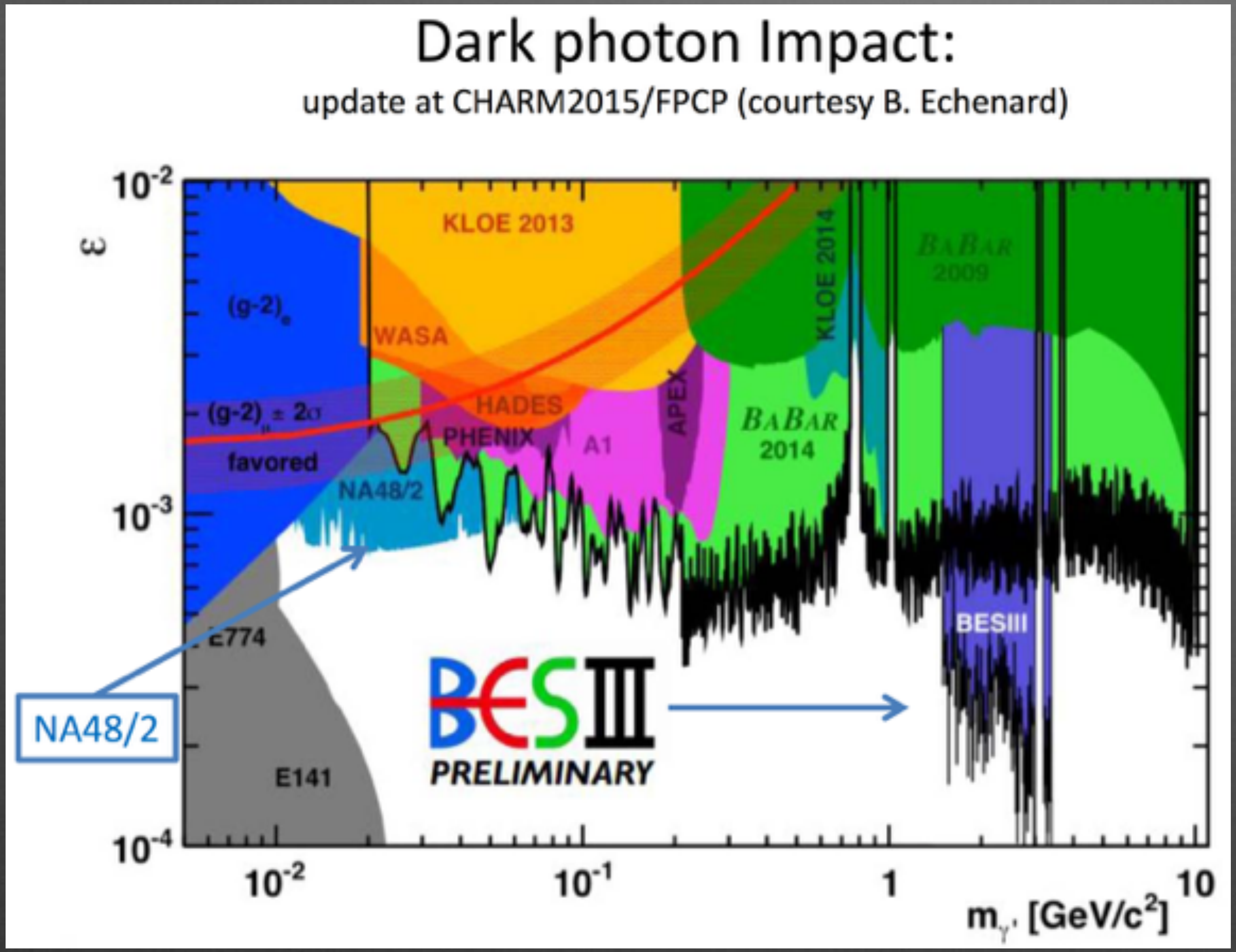
	Expected (%)	Observed (%)	Best Fit (%)
τμ	< 0.75 (±0.38)	< 1.57	0.84 $^{+0.40}_{-0.37}$

Combined excess is 2.4 standard deviations which corresponds to local p-value of 0.007 at M_H=125 GeV

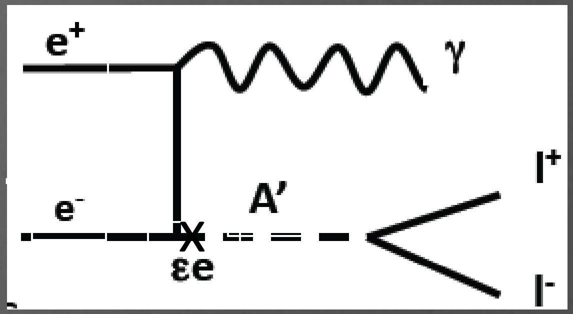
- First direct, dedicated search for LFV Higgs @ 125GeV
- Slight excess with 2.4σ
- Limit is approximately an order of magnitude higher than previous limits

- CMS Run 1 paper on H→eτ and H→eμ will be submitted in a few weeks
- ATLAS will have results on LFV Higgs search for the summer conferences

Dark photon search by BABAR



BABAR[Jacques]



- Gauge boson of new U(1)', A' with MeV-GeV mass
- A' couples to dark sector particles
- BABAR all inclusive search in $e^+e^- \to \gamma A'$ improved the constraints by an order of magnitude in the $0.2<m_{A'}<10\mathrm{GeVc}^2$

Lepton Flavour Violation of Charged Leptons (cLFV)

MEG[Angela]

- Lepton flavour is preserved into the SM ("accidental" symmetry)
    - not related to the theory gauge
    - naturally violated in SM extentions

LFV of neutral leptons confirmed
-neutrino oscillations-

Lepton Flavour Violation of Charged Leptons (cLFV)

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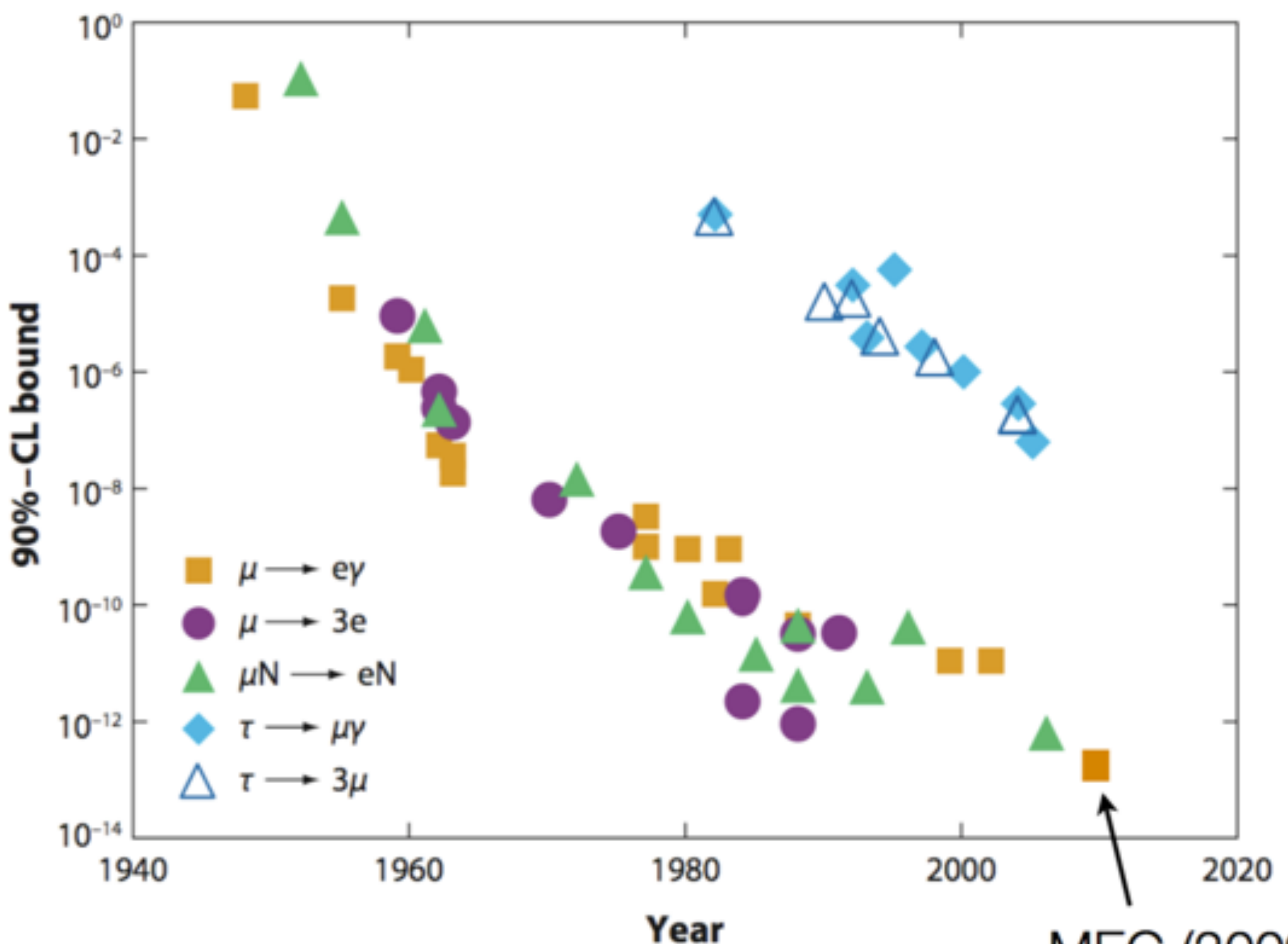


LFV of neutral leptons confirmed -neutrino oscillations-

LFV of charged leptons not yet observed

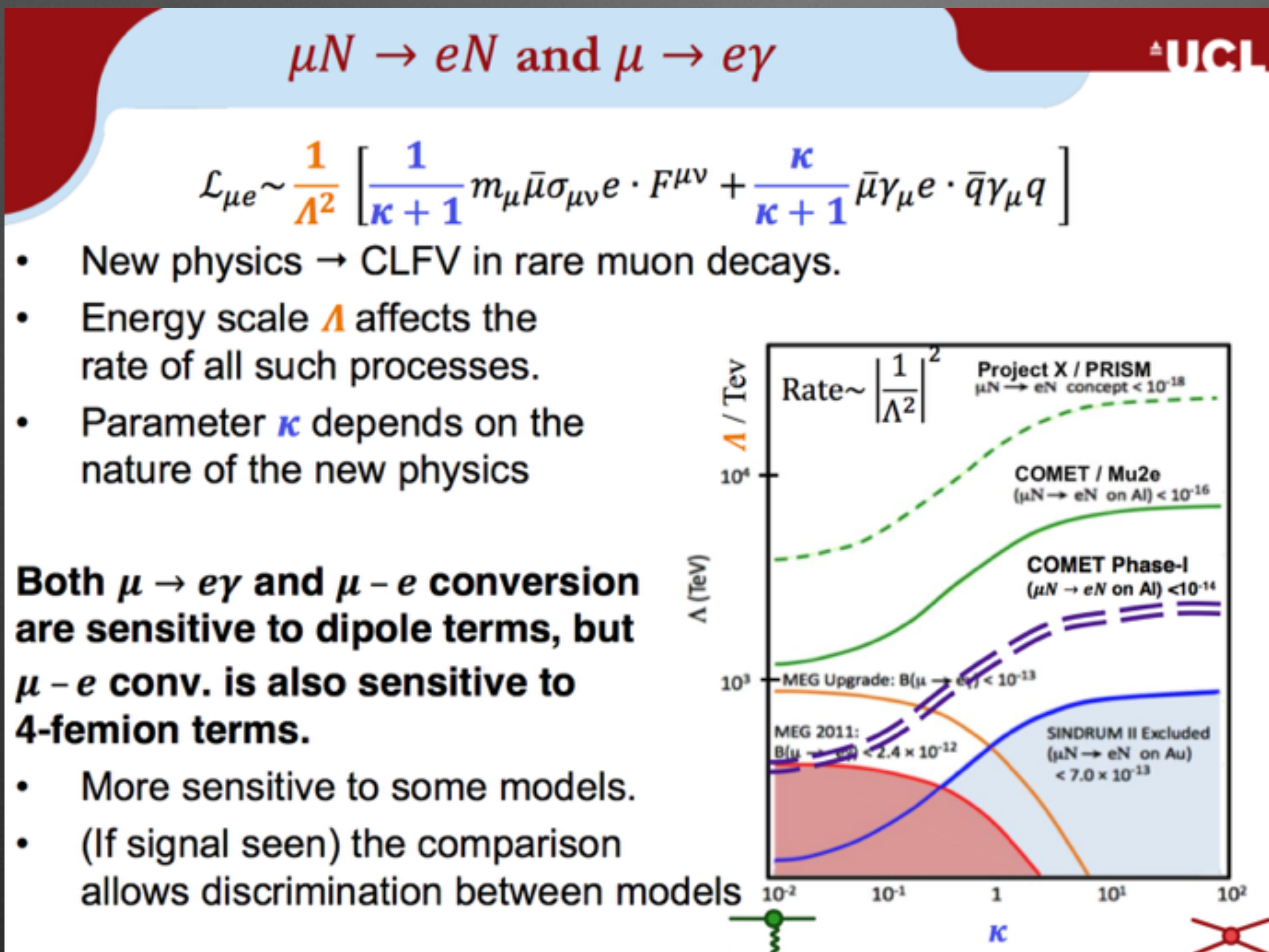
4

$$B(\mu^+ \rightarrow e^+ \gamma) < 5.7\text{x}10^{-13}$$

- Final result of MEG (2009-2013, double statistics) will come soon

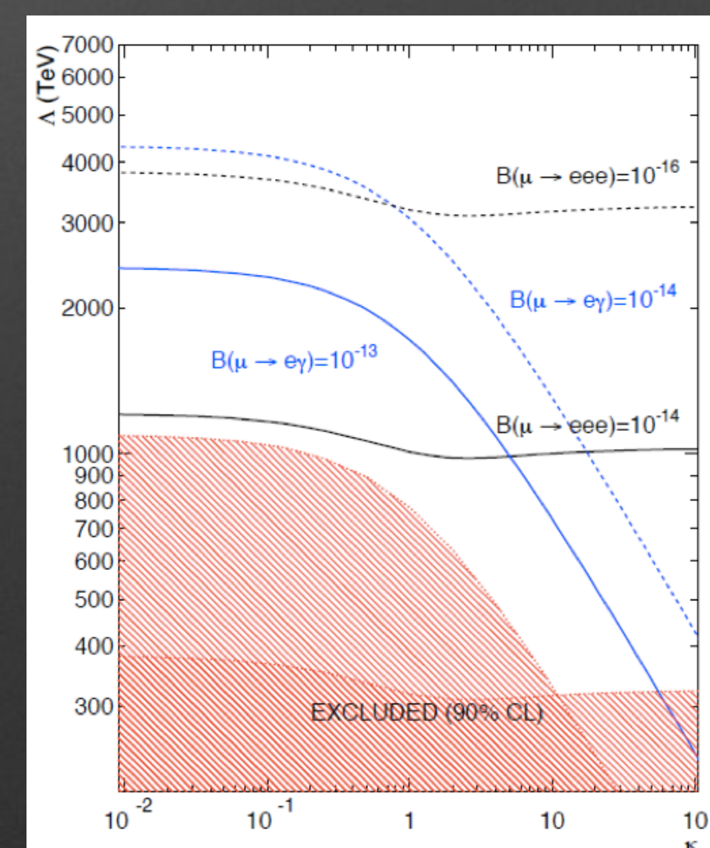
Next muon LFV

- After the MEG, there is no ongoing experiment which searches for muon lepton flavour violation
- Next plans : MEG II, mu3e at PSI, COMET at J-PARC, and Mu2e at FNAL

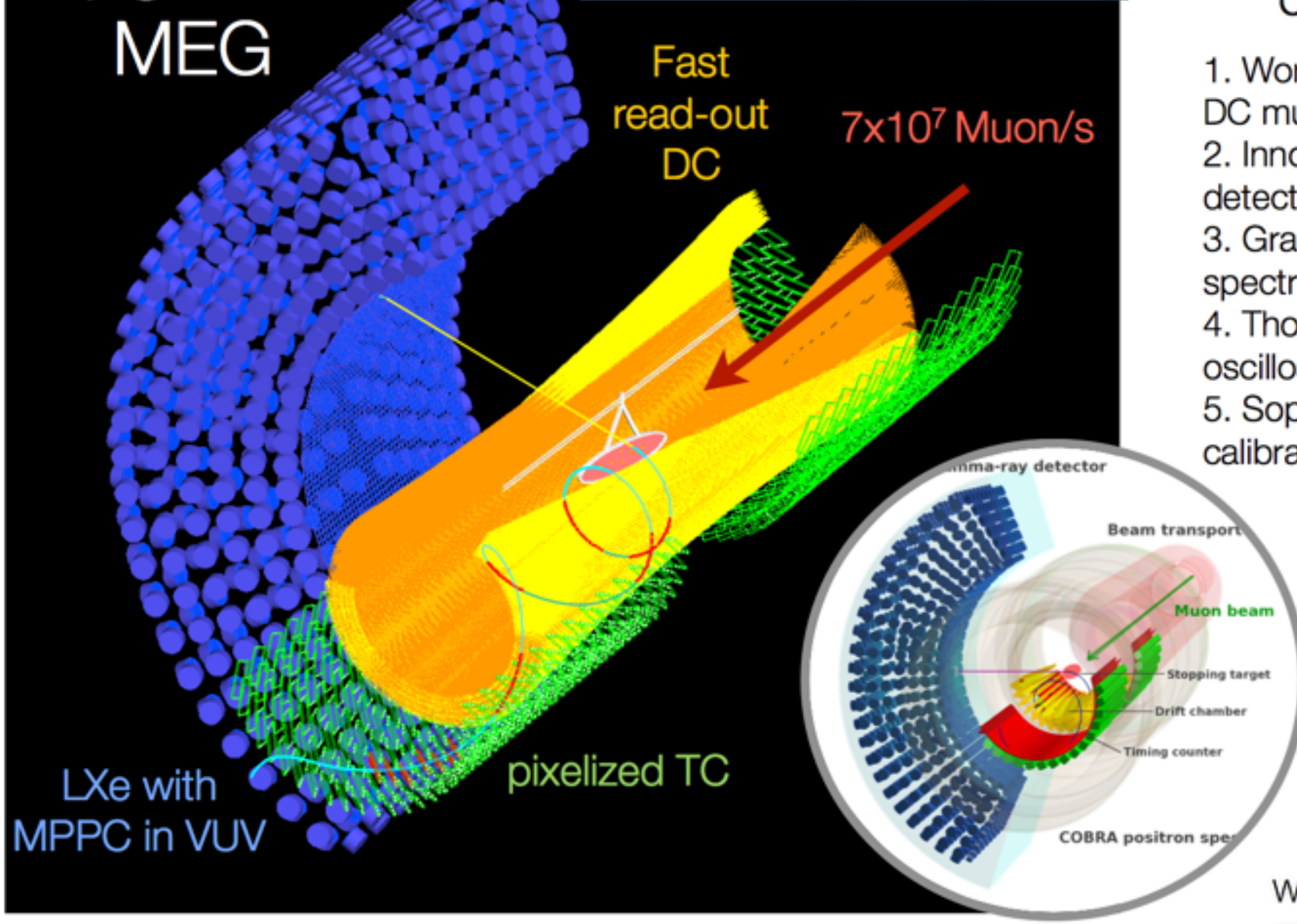


COMET/mu2e [Phillip]

μ→3e and μ→eγ



MEG II [Angela]



Kept the key elements of MEG

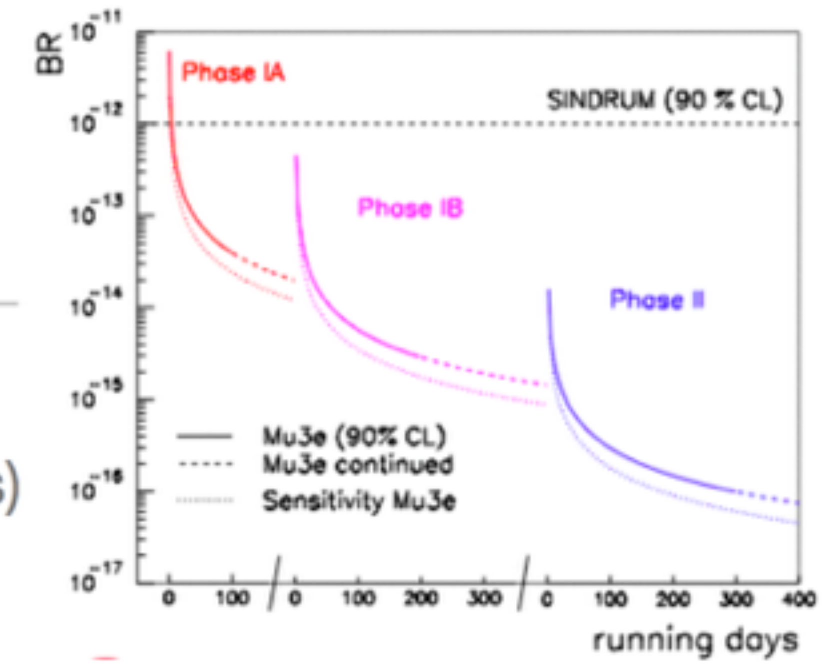
1. World's most intense DC muon beam @ PSI
2. Innovative LXe γ-ray detector
3. Gradient B-field e^+-spectrometer
4. Thousends virtual oscilloscopes (DAQ)
5. Sophisticated calibration methods

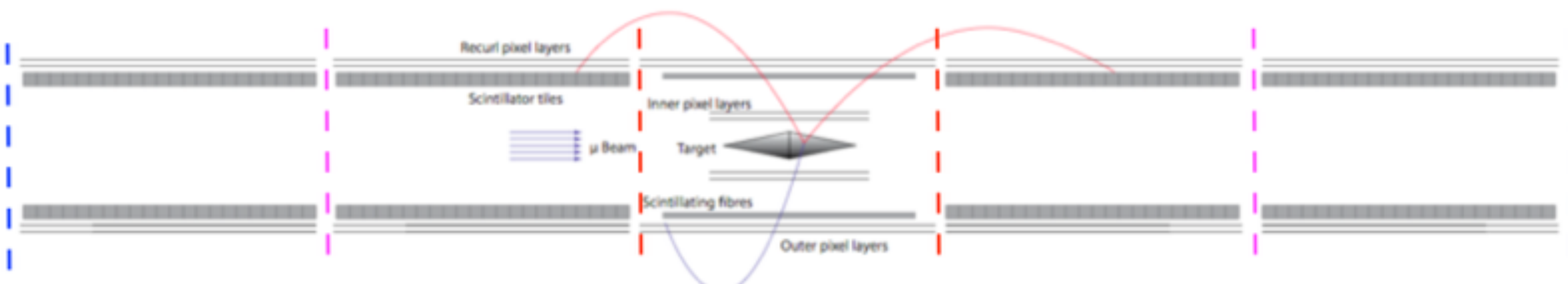
MEG Now

- MEG II : one order of magnitude better sensitivity than MEG
- In 2016, engineering run and physics run

Mu3e staging approach

- Phase IA 201x (piE5 beam line: $O(10^7)$ mu/s)
- Phase IB 201x+1 (piE5 beam line: $O(10^8)$ mu/s)
- Phase II 201x+2 (new beam line: $O(10^9)$ mu/s)

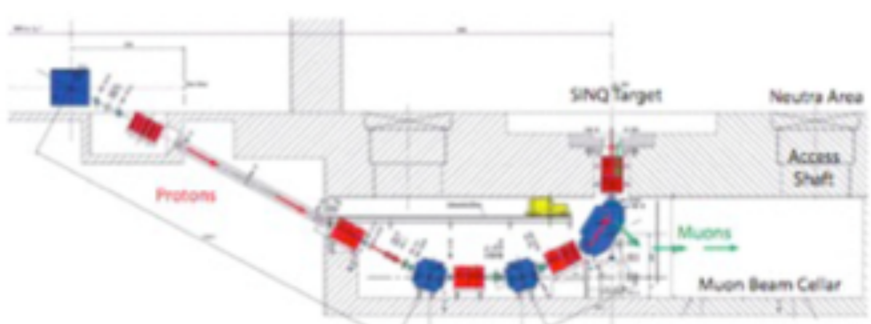


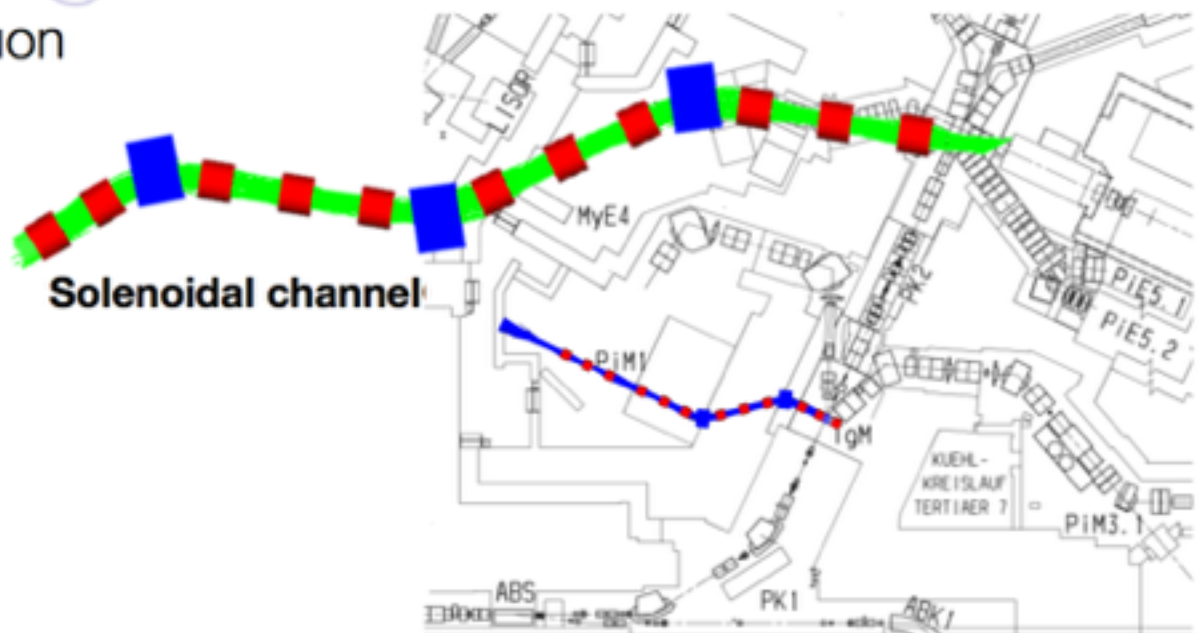


Feasibility study of a High Intensity Muon Beam (HIMB) line.

Aim: **$O(10^{10})$ mu/s)**

HIMB@SINQ

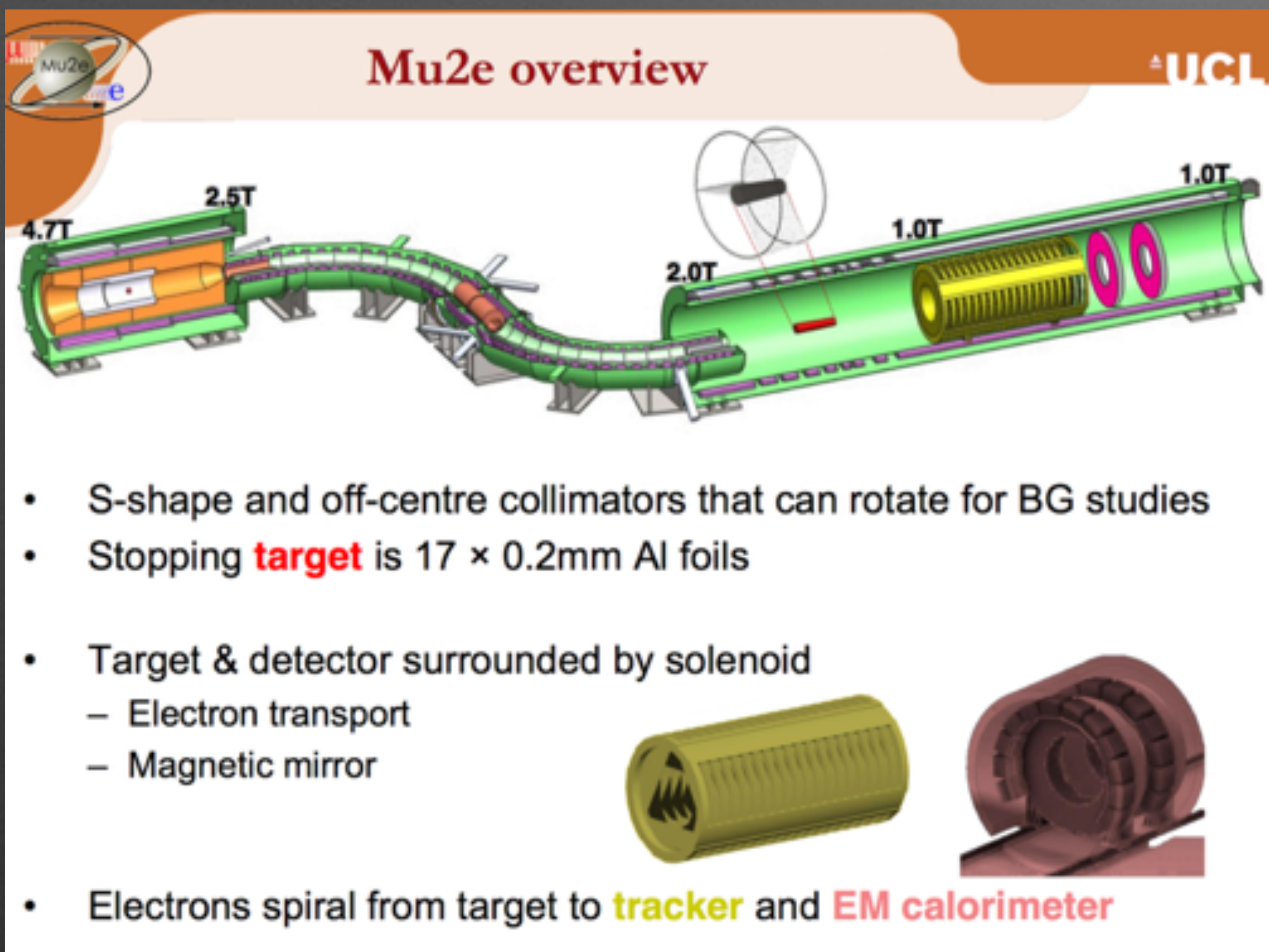


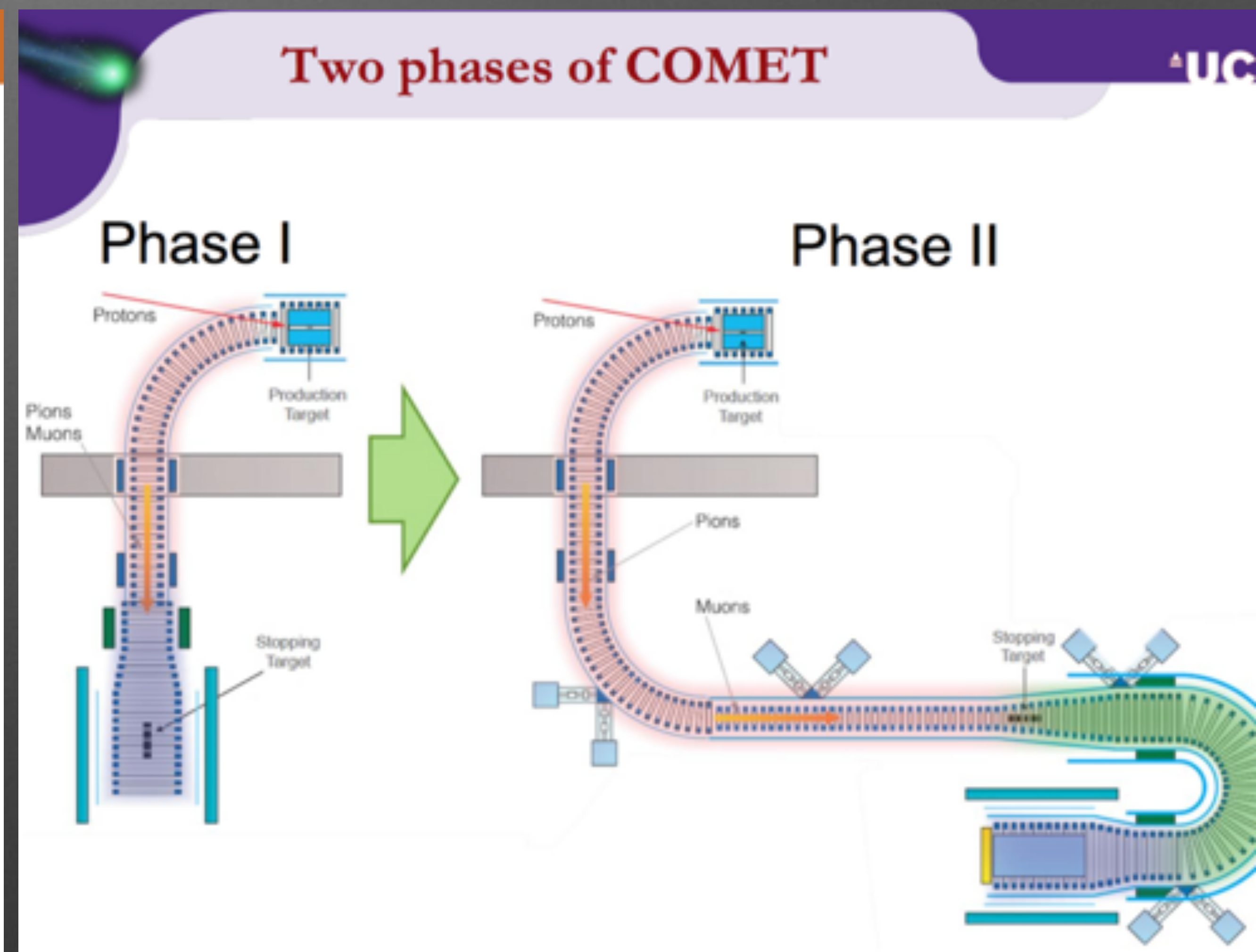


The compact muon beam line (CMBL)

- The MEGII and the phase IA and IB of Mu3e have similar beam requirements $O(10^8)$ mu/s, 28 MeV/c
- the CMBL allows both experiments to co-exist

COMET/mu2e [Phillip]

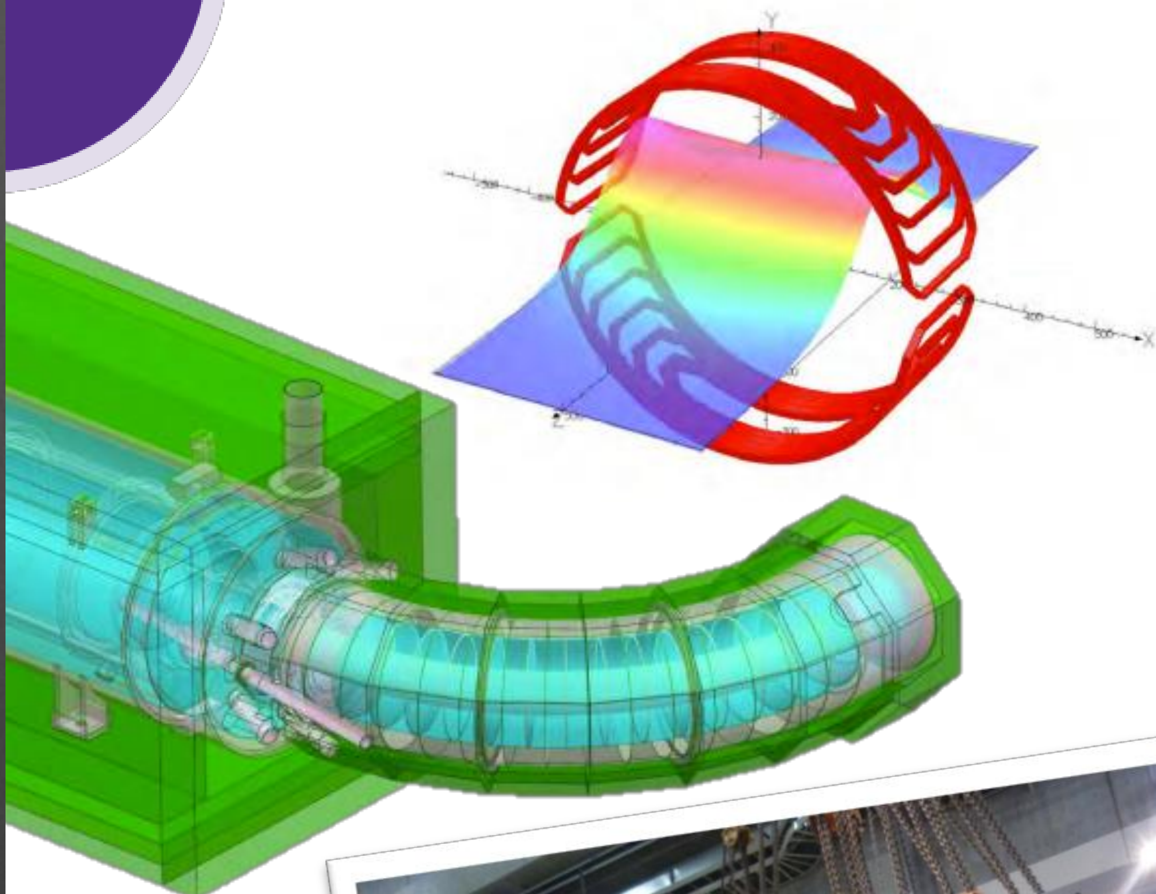




Phase I has 2 goals:

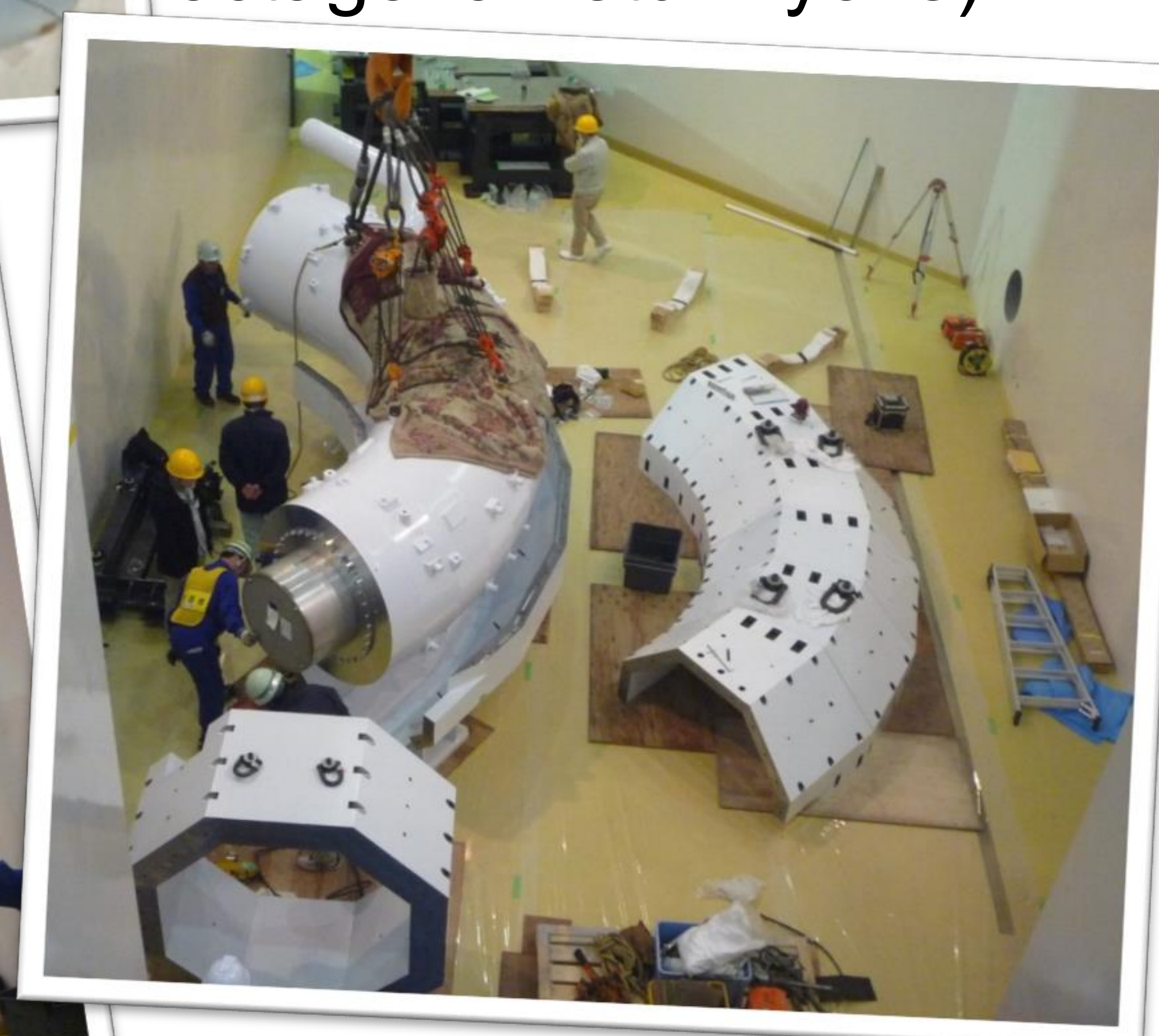
- Investigate backgrounds for phase II
- Perform search at 100× sensitivity of SINDRUM-II

Transport Solenoid

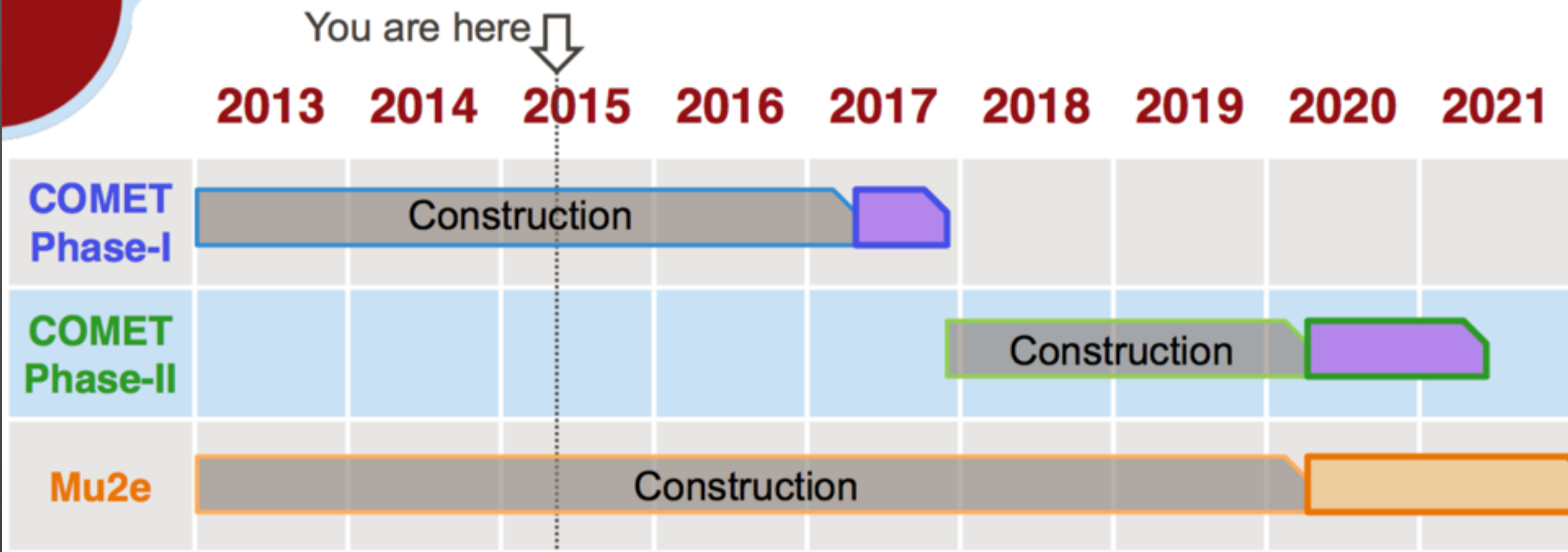


◀ Corrective dipoles

▼ Completed 90° muon transport arc (including octagonal return yoke)



Timelines



2014: 7×10^{-13} **90% U.L.** [SINDRUM-II] (since 2004)

~2017: 3×10^{-15} **S.E.S.** [COMET Phase-I] (~ 6mo)

~2021: 3×10^{-17} **S.E.S.** [COMET Phase-II & Mu2e]

beyond 2021: PRISIM /PRIME @J-PARC**?** [Goal 3×10^{-19}]

Mu2e × ProjectX @FNAL**?**

Summary

- Results of CP violation, unitarity triangle fit are consistent with the SM

- Hints for new physics?

  - Lepton universality, Angular Analysis $B \to K^* \mu^+ \mu^-$, branching ratio of $Bs \to \phi(K^+K^-)\mu^+\mu^-$, $Br(B^0 \to \mu\mu)$, $|Vub|$, $H \to \tau\mu$, etc…

  - More data from LHCb, Belle II, ATLAS/CMS will be available soon.

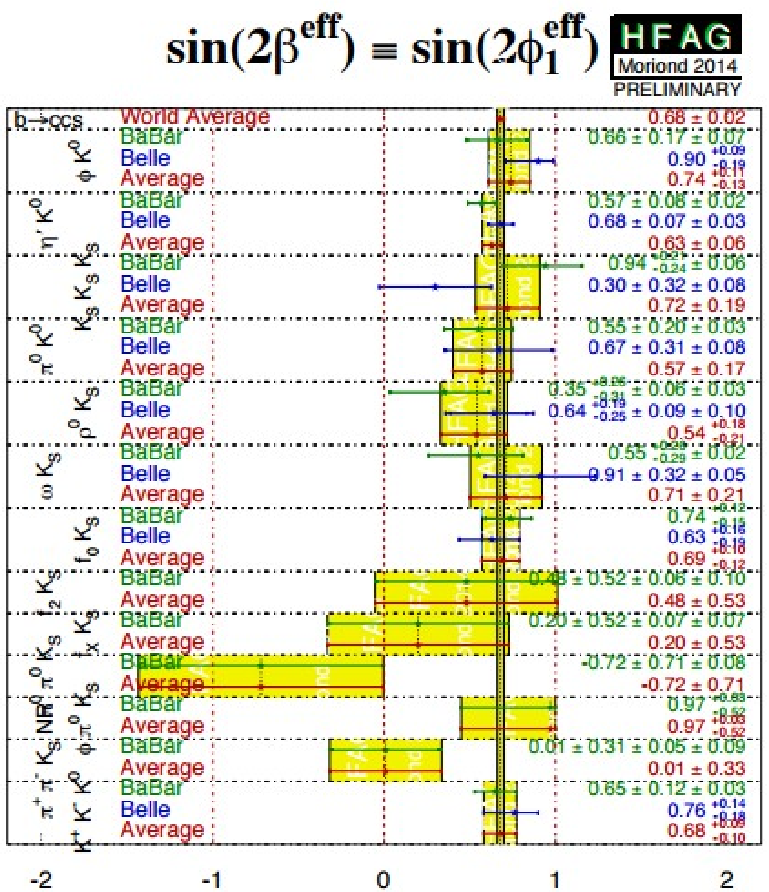
- Lepton flavour violation experiment will be available soon. MEGII, Mu3e, COMET, and mu2e. The MEG final result will come this year.

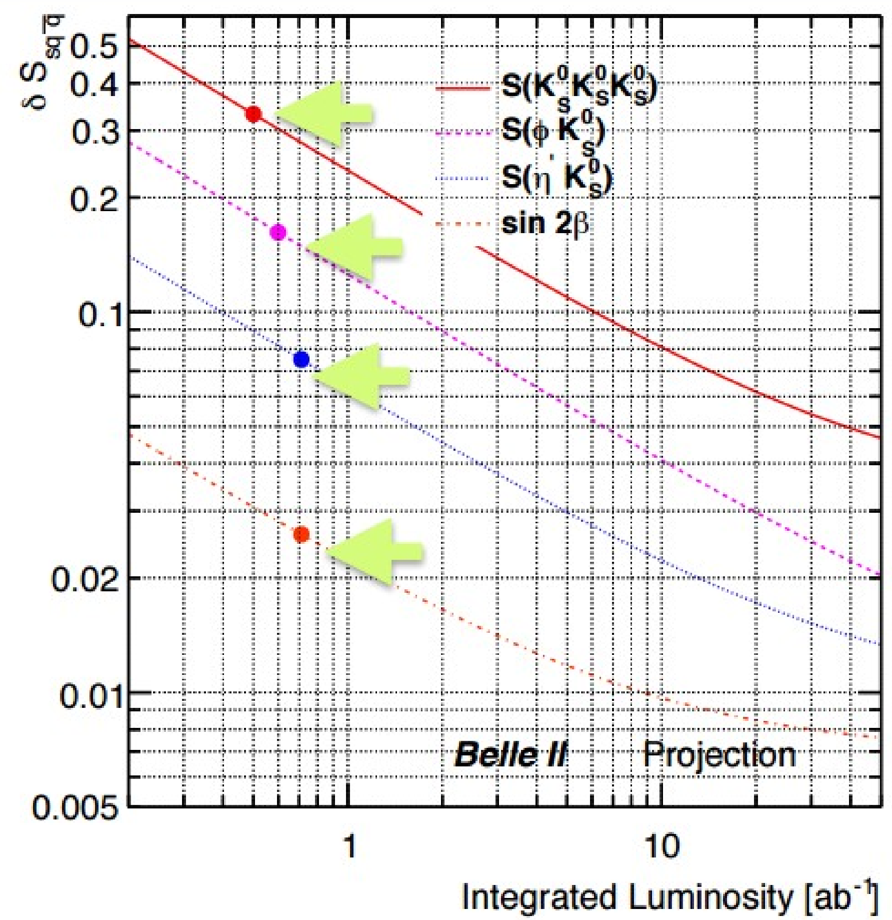
Backup

Belle II

b→s Penguin ϕ_1

Belle, B → η' K0, JHEP 1410, 165 (2014)
Belle, B → ω Ks0, PRD 90 012002 (2014)





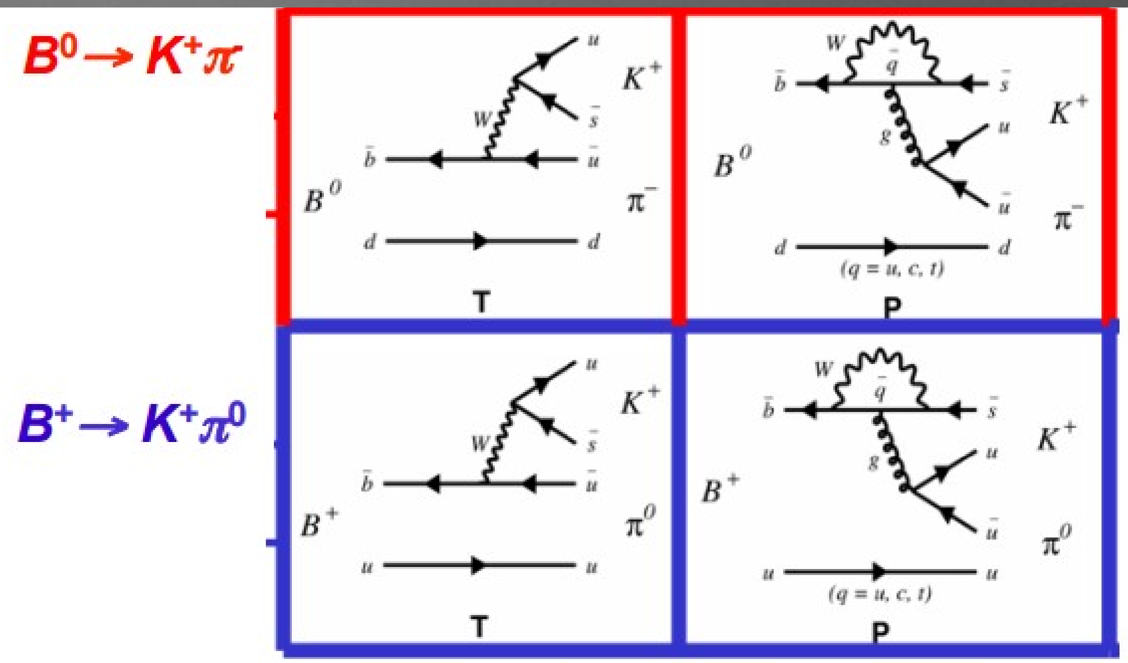
These analyses are currently totally dominated by the statistical uncertainty!

	Observables	Belle or LHCb (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 8 fb^{-1}(2018)	LHCb 50 fb^{-1}
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	0.053	0.018	0.2	0.04
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	0.028	0.011		
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	0.100	0.033		
	$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	± 0.18			0.12	0.03
	$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	± 0.19			0.13	0.03
Direct CP in hadronic Decays	$\mathcal{A}(B \to K^0\pi^0)$	$-0.05 \pm 0.14 \pm 0.05$	0.07	0.04		

Belle II

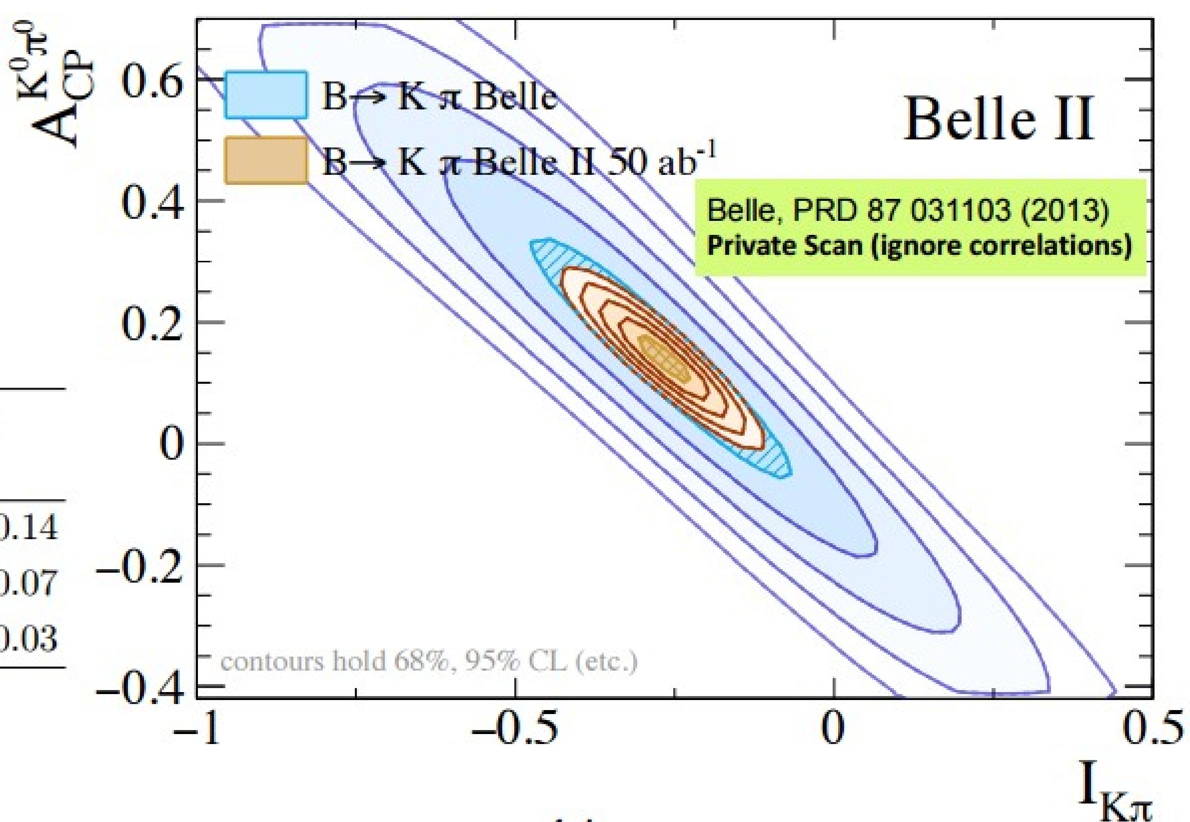
- A_{CP} in hadronic modes cannot be understood w/out full isospin analysis.

➡ Need neutral modes.



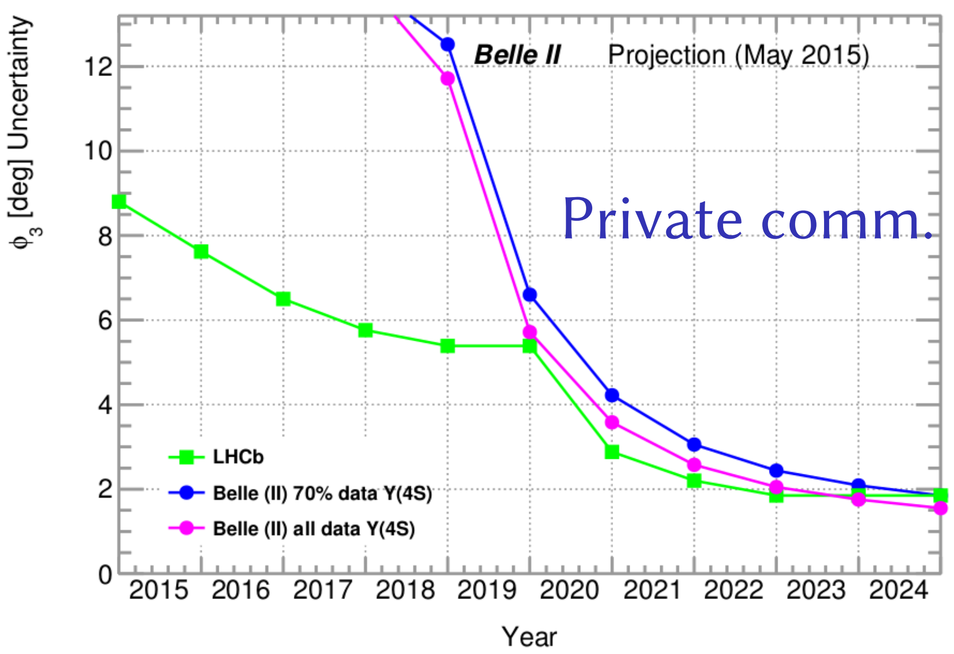
$$
\begin{aligned}
& I_{K\pi} \cdot \mathcal{B}(B^0 \to K^+\pi^-) \\
= \; & A_{CP}^{K^+\pi^-} \cdot \mathcal{B}(B^0 \to K^+\pi^-) + A_{CP}^{K^0\pi^-} \cdot \mathcal{B}(B^+ \to K^0\pi^-)\frac{\tau_{B^0}}{\tau_{B^+}} \\
- \; & 2A_{CP}^{K^0\pi^0} \cdot \mathcal{B}(B^0 \to K^0\pi^0) + 2A_{CP}^{K^+\pi^0} \cdot \mathcal{B}(B^+ \to K^+\pi^0)\frac{\tau_{B^0}}{\tau_{B^+}}
\end{aligned}
$$

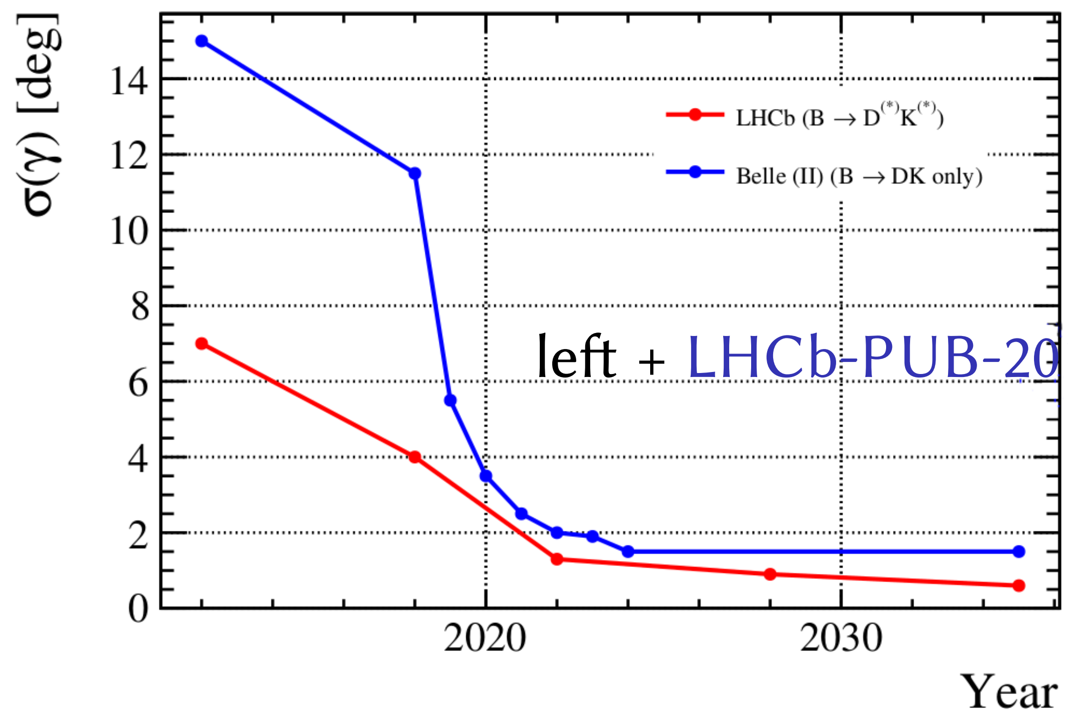
Scenario	$A^{K^0\pi^0}$			$I_{K\pi}$
	Value	Stat.	(Red., Irred.)	
Belle	0.14	0.13	(0.06, 0.02)	0.27 ± 0.14
Belle + $B \to K^0\pi^0$ at Belle II 5 ab^{-1}		0.05	(0.02, 0.02)	0.27 ± 0.07
Belle II 50 ab^{-1}		0.01	(0.01, 0.02)	0.27 ± 0.03



Explore this for πK^*, ρK, ρK^*!

LHCb & Belle II in the context of γ (φ_3)





left + LHCb-PUB-2014-040

Table: LHCb precision on $\gamma(\varphi_3)$

year	2012	2018	2022	2028	2035
$\gamma(^\circ)$	7	4	1.3	0.9	0.6

- LHCb upgrade before Run III (2020–22)
- 2028+: HL-LHC

- Belle II: considering only $B \to DK$ decays
- see also: talk by Greig Cowan @ HL-LHC

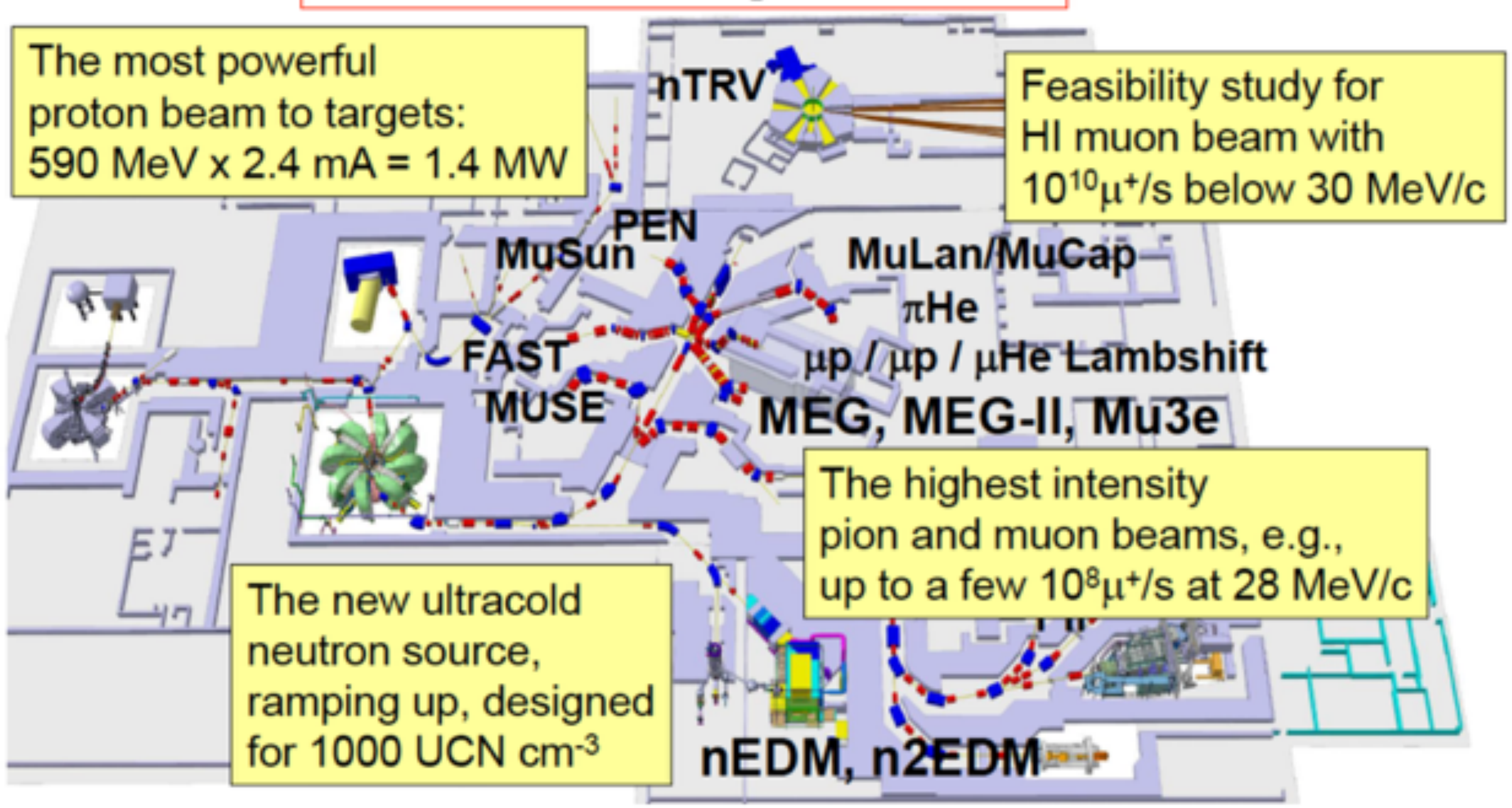
Before the parallel session,

There was a comprehensive overview talk
by Tatsuya Nakada

Very Brief Look for Future

- Important to realise that flavour physics can be done at “small” laboratories in “small” countries.

PSI in CH as an example (K. Kirch)



Overview talk by Tatsuya Nakada

To conclude

- The Standard Model will remain as a theory hard to crack. Although we know that there is physics beyond the Standard Model, we have little idea what it is.
- Without this, there is no success guaranteed research programme (B factories and LHC had the Standard Model). We need to look for everywhere. But resources are limited and making choices are being asked.
- I personally believe studies of rare phenomena and precision measurements have a big potential, but on hadron, leptons, gauge boson, Higgs or all of them?