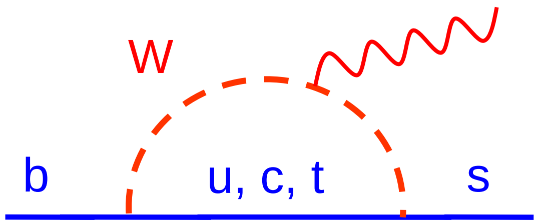
Flavour Physics Conference
ICISE, Quy Nhon, July 27 - August 2, 2014

Ulrich Uwer • Heidelberg University
LHCb Collaboration

Facilities

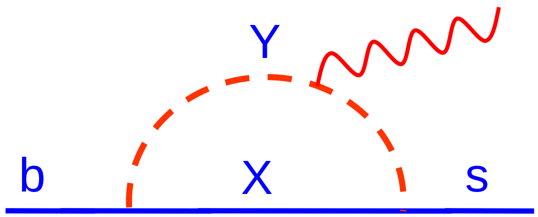
“New Physics” in Quantum-Loops

Standard Model



+

„New Physics“



$$\mathcal{A}_{SM} + \mathcal{A}_{NP}$$

$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \boxed{\frac{c_{NP}}{\Lambda^2}} \right)$$

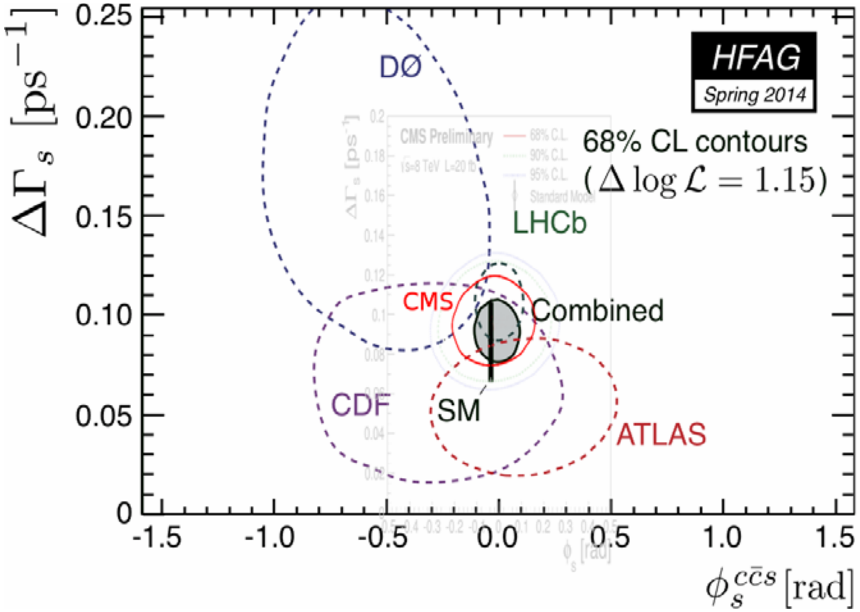
← Probes physics at >>TeV-scale

We know by now: New Physics contributions are small.

- Clean Standard Model predictions
- Precise measurements (high statistics, incl. control channels)

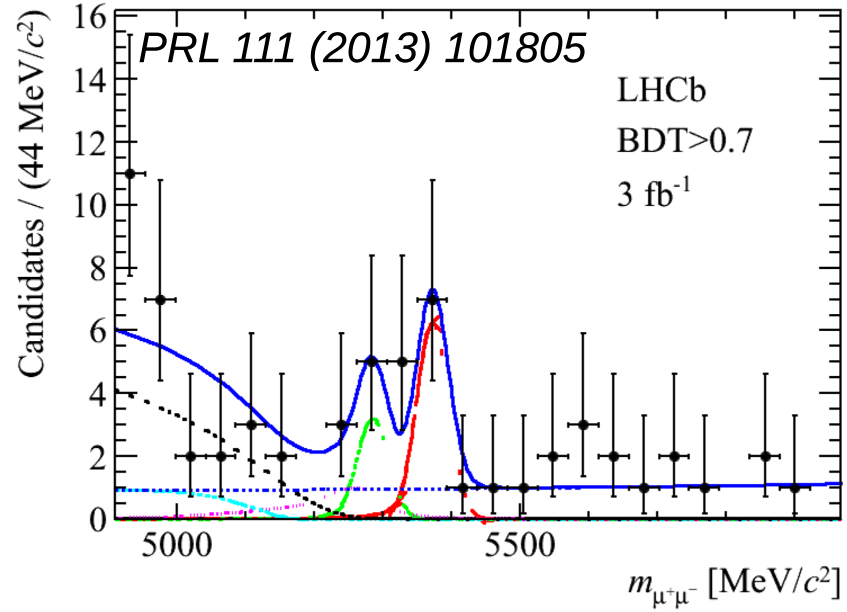
Standard Model withstands Challenges

B_s mixing phase ϕ_s



P. Řezniček, Beauty 2014

BR($B_s \to \mu\,\mu$)



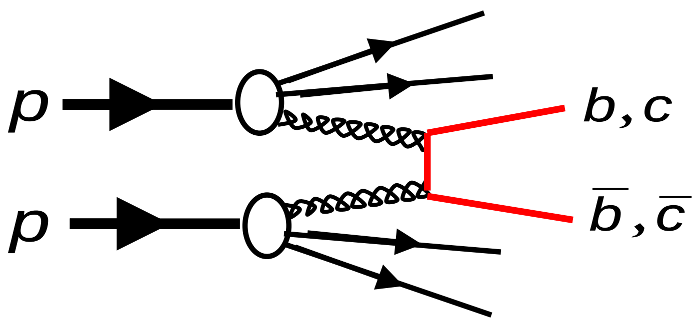
Theo. uncertainty: ±0.0016 rad
Exp. error (best): ±0.07 rad

Theo. uncertainty: ±6%
Exp. error (best): ±24%

Theoretical precision not reached → Highest intensities!
Remember: CPV in Kaon decays only at ~10^{-3}.

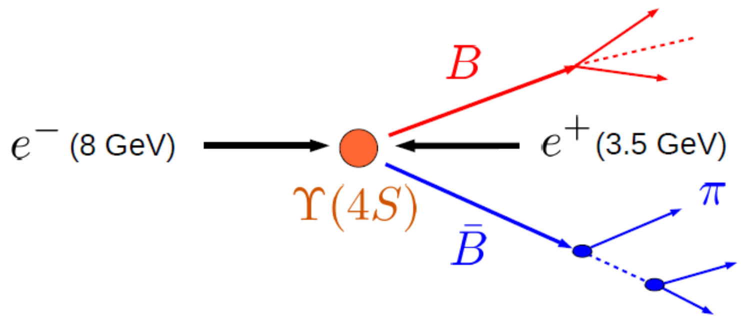
B-Physics at the Intensity Frontier

LHC @ 14 (13) TeV



$$\sigma_{bb}(14\,TeV) \approx 500\,\mu b$$
$$\rightarrow 10^{10}\, b\bar{b} \text{ events/fb}^{-1}$$

SuperKEKB & Belle II



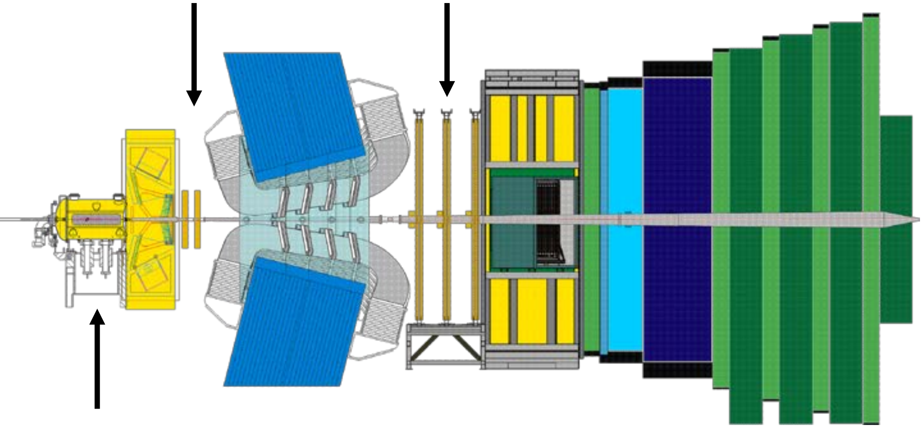
$$\sigma_{BB} \approx 1\,nb$$
$$\rightarrow 10^{9}\, B\bar{B} \text{ events/ab}^{-1}$$

	LHC era		High-lumi LHC era		
	2010-2012	2015-2018	2020-2022	2025-2028	2030+
ATLAS & CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	→	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}
Belle II		0.5 ab^{-1}	25 ab^{-1}	50 ab^{-1}	-

Upgrade-Project

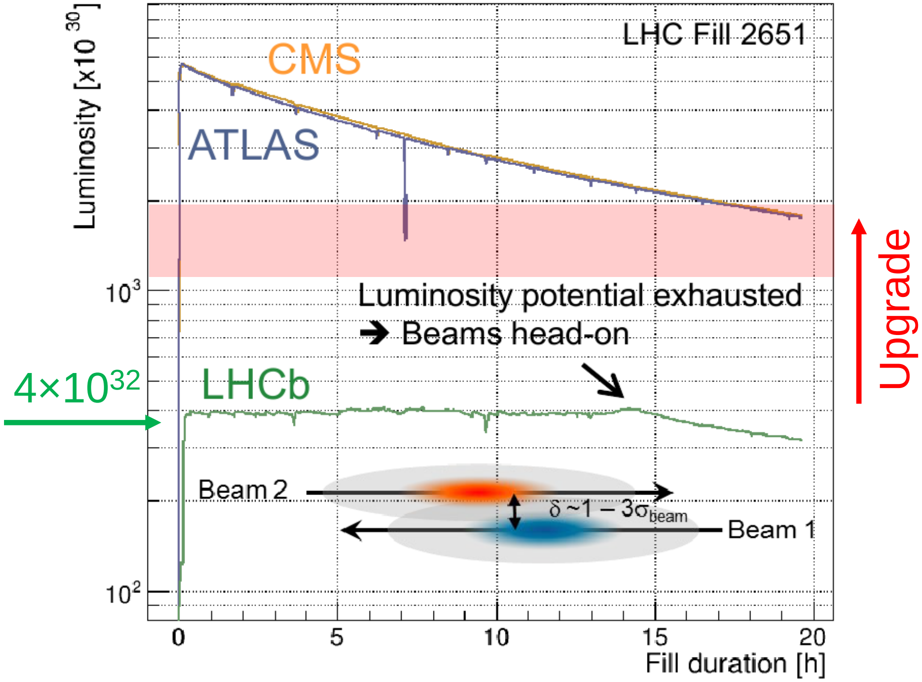
CERN-LHCC-2012-007

Tracking System



VELO

40 MHz readout for RICHs, Calo, Muon System



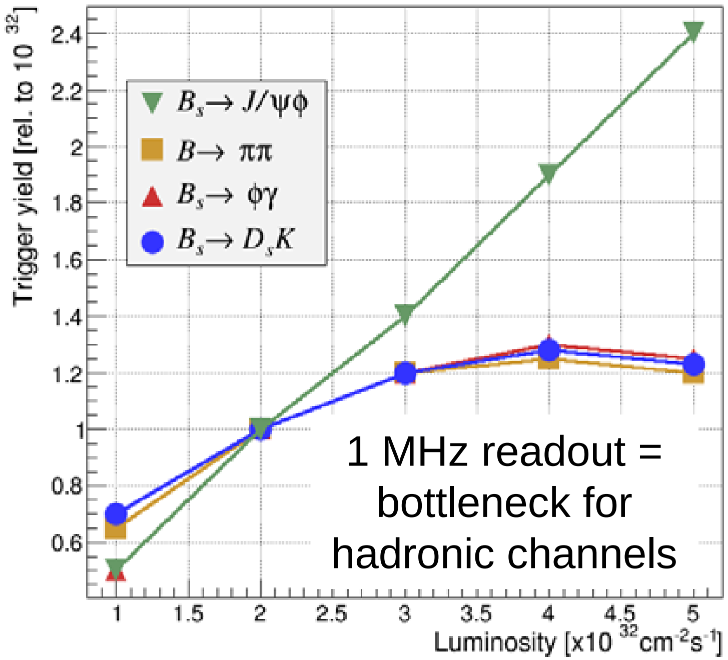
See also talk by Wander Baldini

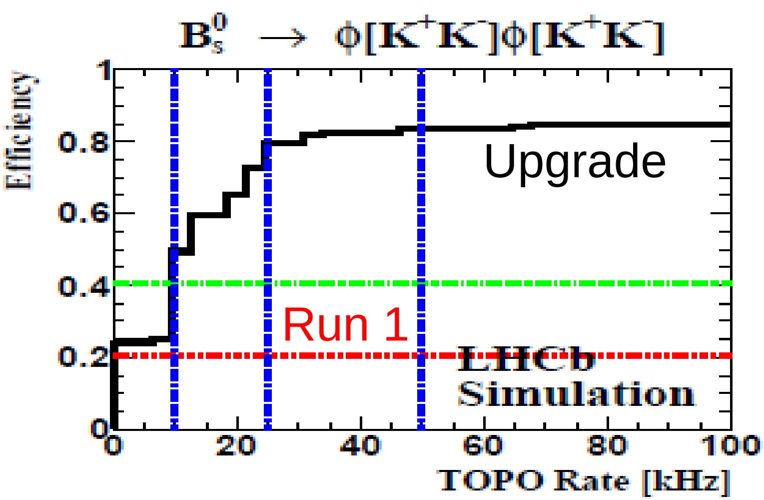
LHCb Upgrade:

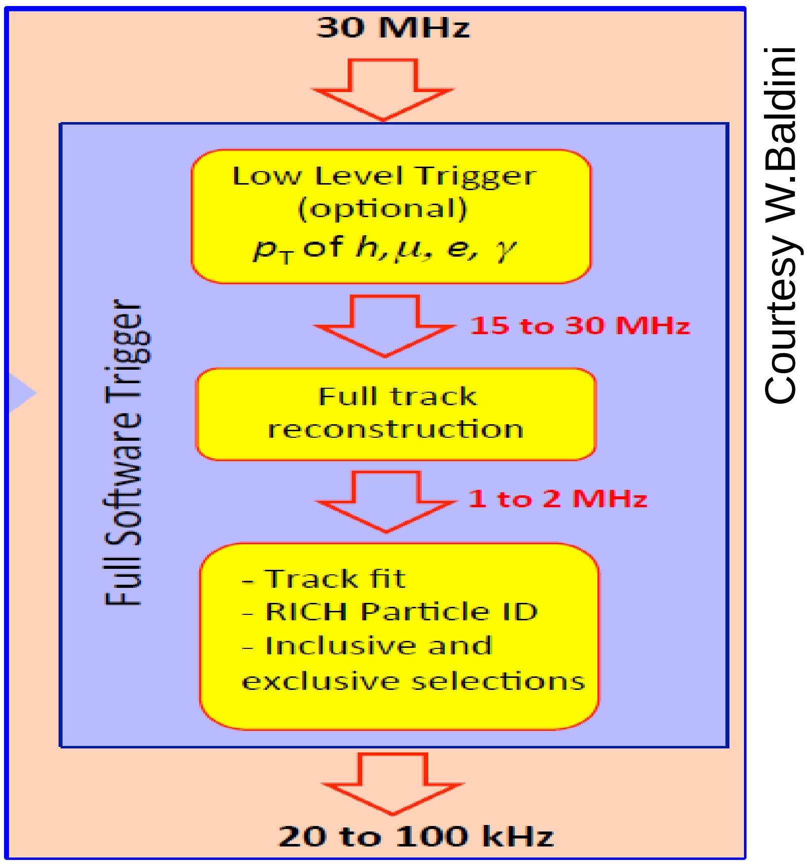
- Increase levelled luminosity up to 2×10^{33} $cm^{-2}s^{-1}$ (pile-up ~8):
- Fully flexible & efficient software trigger up to 40 MHz input
- Record 20 – 100 kHz
- Upgrade VELO and Tracker (adapt to higher occupancy and radiation load)

Trigger-Upgrade

CERN-LHCC-2014-016







Efficient and selective software trigger: Increase luminosity and signal yields!

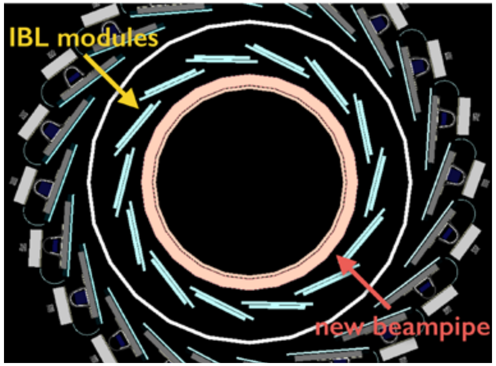
e.g.: purely hadronic $B_s \to \phi\phi$

LHCb-Pub-2014-031

Upgrades relevant for B-Physics

P. Řezníček, Beauty 2014

See also talk by Marco Bomben

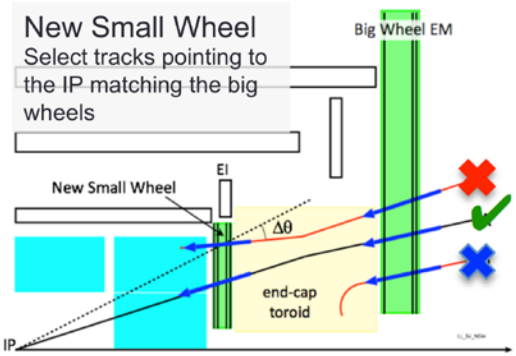


LS1 — Phase 0

IBL pixel layer at R=32 - 38mm:
More robust track reconstruction
Better impact parameter resolution

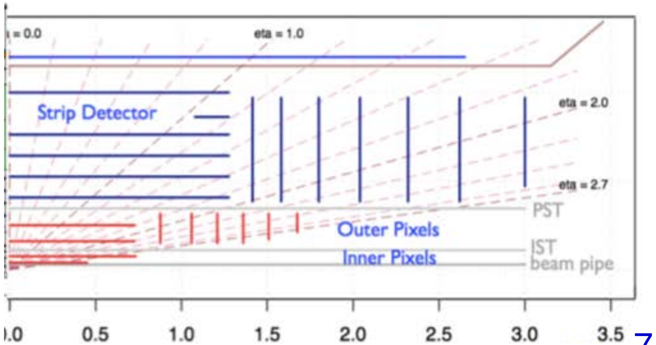
LS2 — Phase 1

Increase trigger robustness for high lumi:
New small muon wheel (muon trigger)
Fast track-trigger (tracks before L2)
→ topological selections at HW level
→ Offline like selection in L2 / evt filter



LS3 — Phase 2

New Inner Tracker for high-lumi :
cope with higher occupancy and
radiation damage (pile-up ~ 200)



Muon trigger efficiency crucial

Upgrades relevant for B-Physics

CERN-LHCC-2012-016

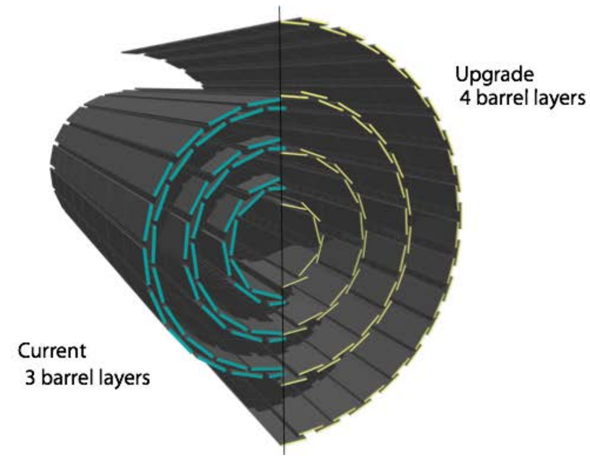
See also talk by Franco Simonetto

LS1

LS2

Phase 1

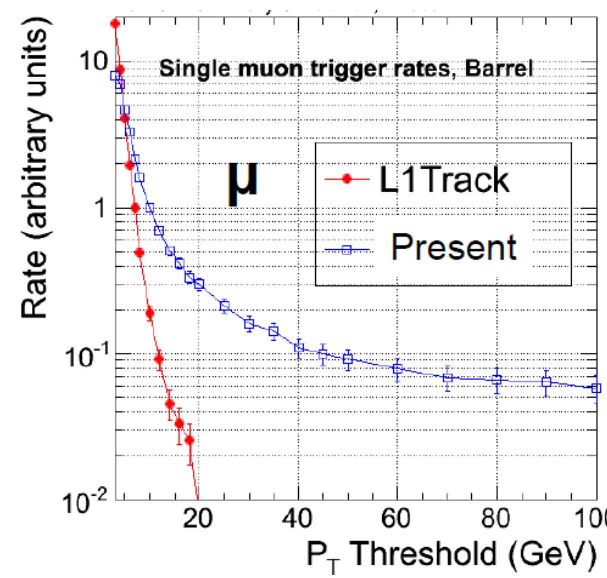
New pixel detector (3 → 4 layers):
- closer to beam pipe, less material
- improves resolution for low-p_t tracks (important for B physics)



LS3

Phase 2

Upgraded tracker:
- Less material, better p_t resolution
- Special p_t modules used in L1 trigger → high efficiency at reduced fake rate

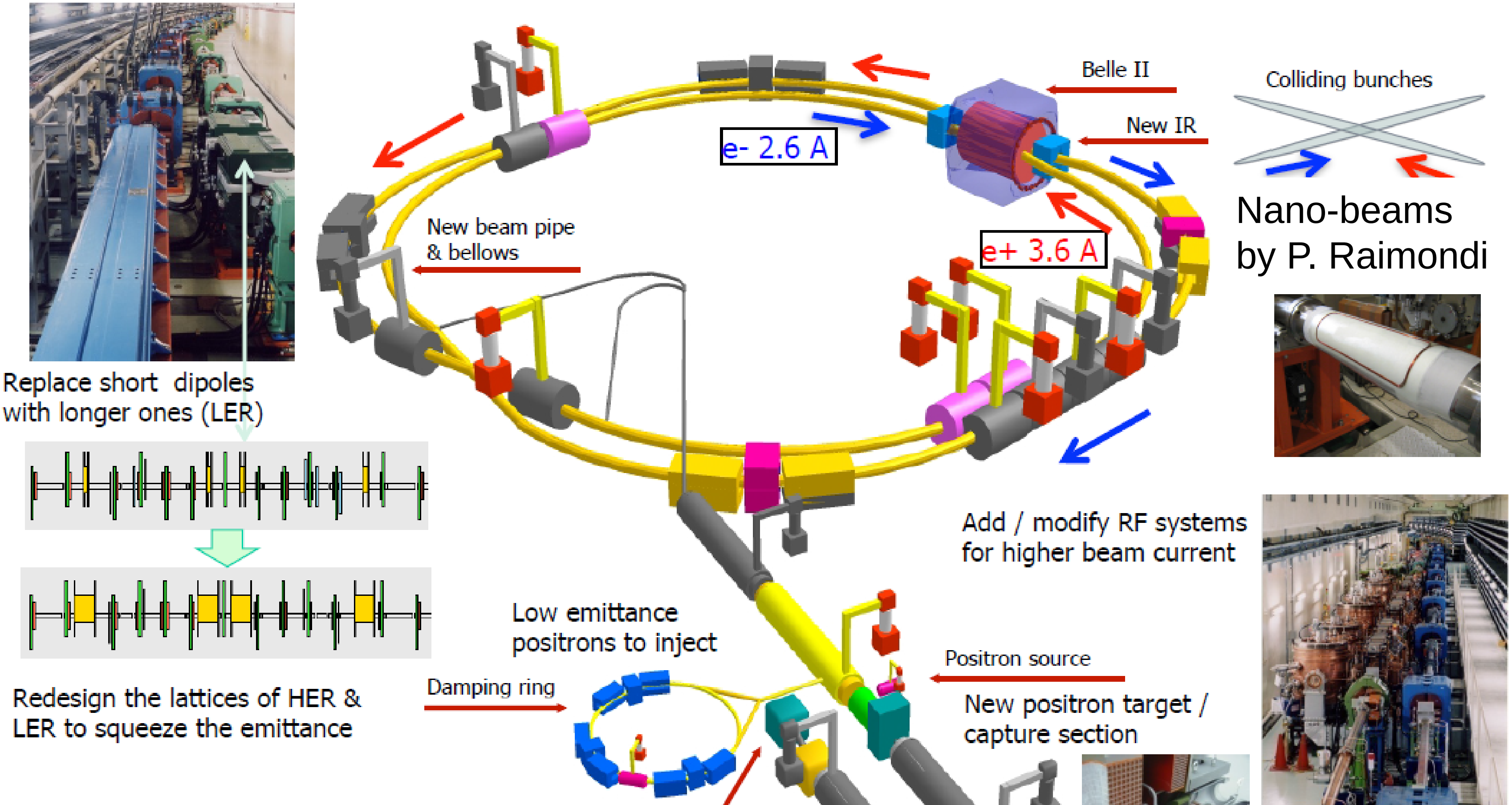


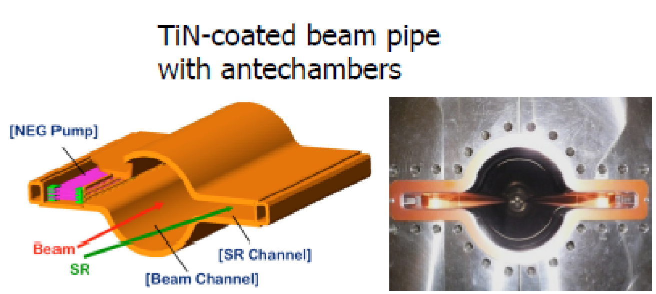
T.Camporesi, CERN-RRB

Muon trigger efficiency crucial

KEKB → SuperKEKB (nano-beam)

Slide by A.Schwartz





To get 40x higher luminosity

$$\mathcal{L}_{\rm peak} = 8 \times 10^{35} {\rm cm}^{-2} {\rm s}^{-1}$$

Detector Upgrade:

Slide by
A.Schwartz

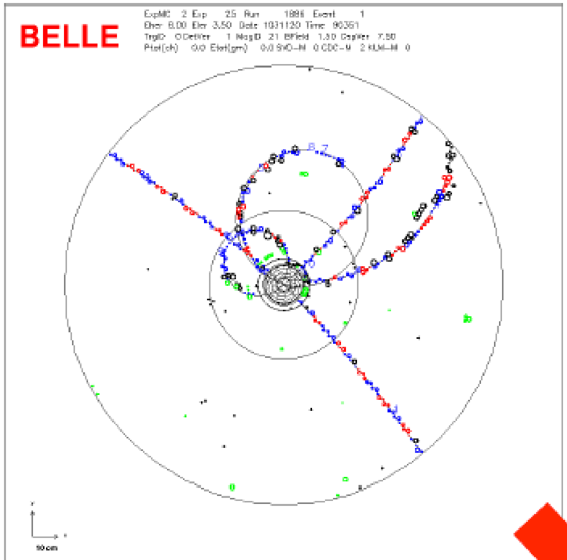
Challenges:

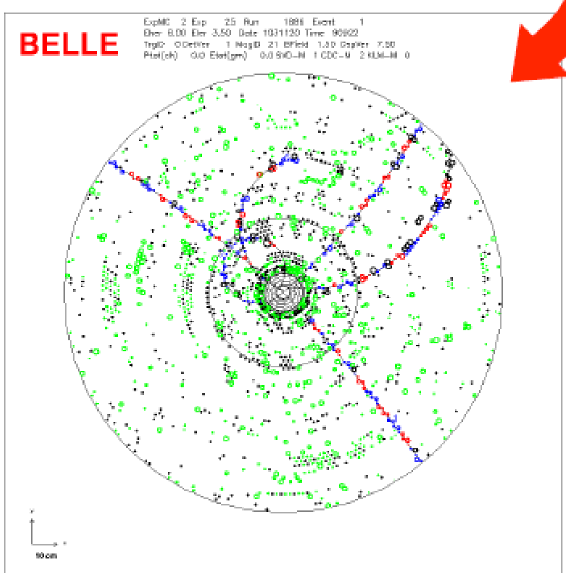
Higher background (×20), higher event rate (×10)
- *radiation damage and occupancy*
- *fake hits and pile-up noise in the EM*

Targeted improvements:
- *Increase hermiticity*
- *Increase K_S efficiency*
- *Improve IP and secondary vertex resolution*
- *Improve π/K separation*
- *Improve π^0 efficiency*
- *Add PID in endcaps*
- *Add μ ID in endcaps*

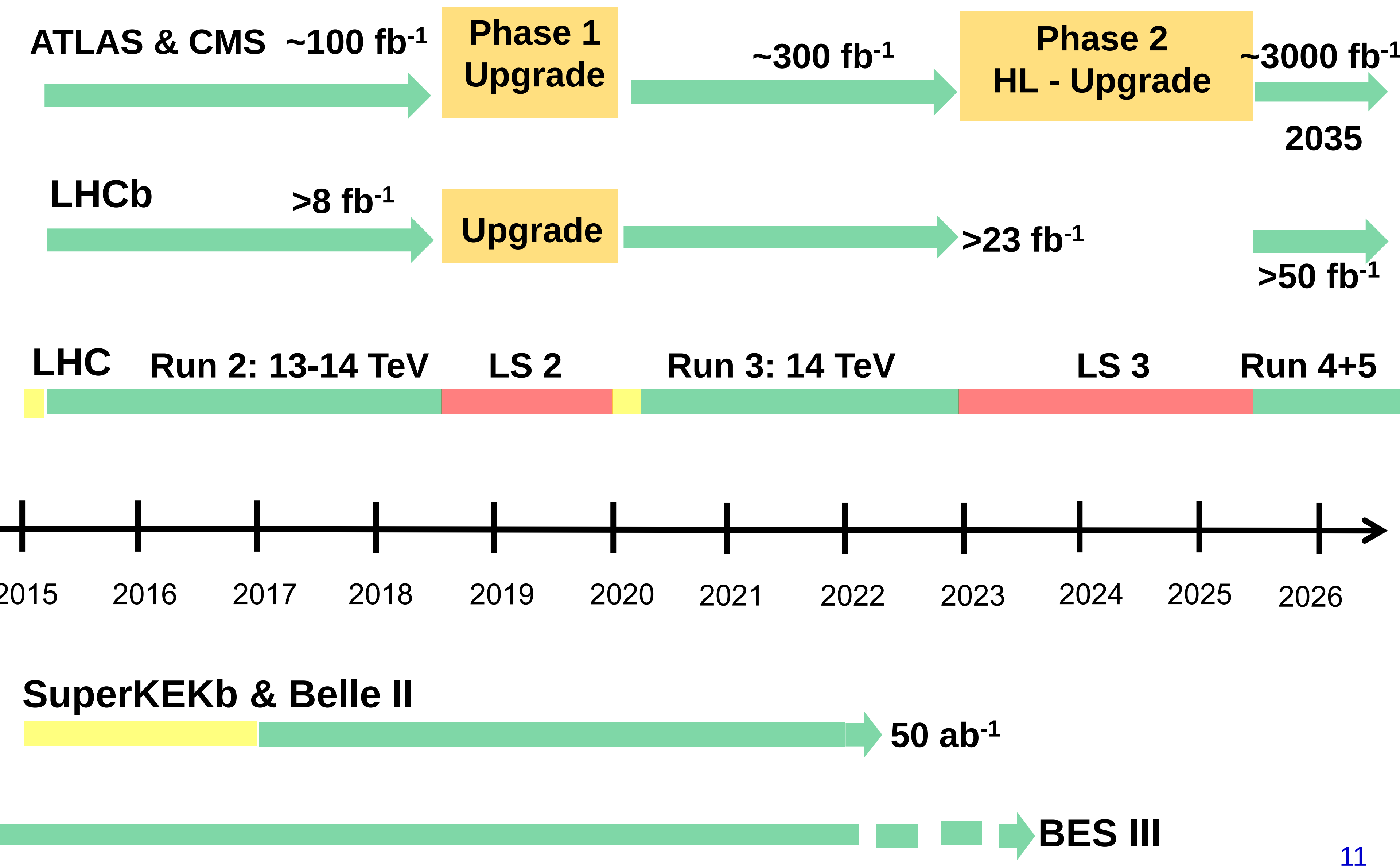
Detector Choices:
- SVD: 4 DSSD lyrs → 2 DEPFET l ... SSD lyrs
- CDC: small cell, long le ...
- ACC+TOF → ima ... +Aerogel RICH
- ECL: wav ... pting
- KLM ... Scintillator +SiPM (end-caps)

See also talk by ´Doris Kim





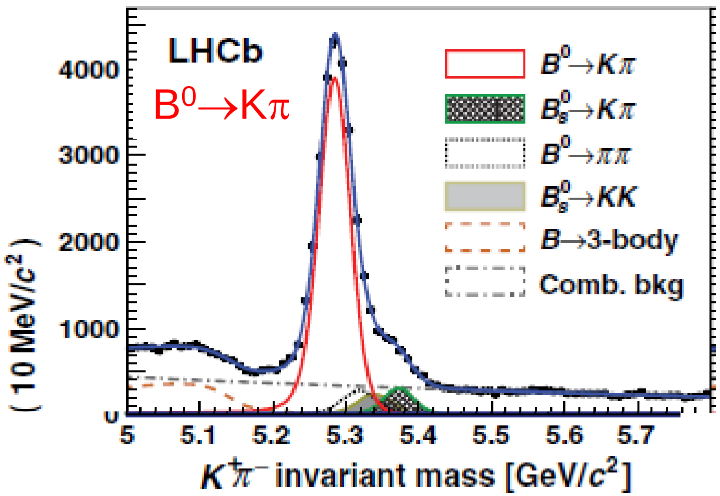
Timeline of heavy flavor experiments



Hadron Collider versus B-Factory

p → ← p

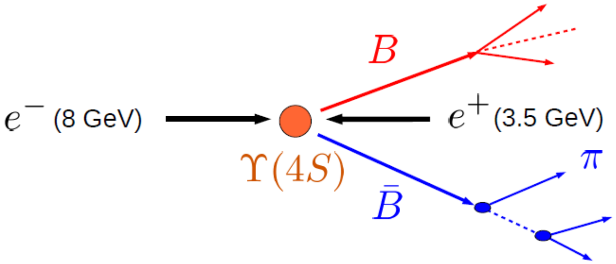
- Copious production of all b-hadrons, in particular B_s and b-baryons
- Large boost:
- excellent time-resolution
- good non-B backgr. suppression
- High efficiency for multi-particle FS



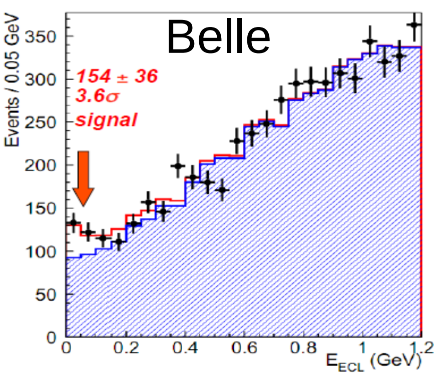
PRL 110, 221601 (2013)

e^+ → ← e^-

- Coherent $B^0\bar{B}^0$ production → tagging
- High efficiency for neutrals γ, π^0, K_s,K_L
- Full reconstruction of $\bar{B}$ → B beam: ν reconstruction in semi-lept decays



PRD 82, 071101(R) (2010)



BR($B^+ \to \tau^+\nu$)

SM: 1.1×10^{-4}

HFAG: $\pm0.22\times10^{-4}$

Belle2: $\pm0.05\times10^{-4}$

experimental differences → physics complementarity

Physics Complementarity*)

LHCb

ATLAS & CMS

- Rare decays: $B_{d,s} \to \mu\mu$
- B_s system
- b-baryons
- Spectroscopy
- CKM phases (β, γ)
- Gluonic penguins
- EW penguins
- Charm physics
- Semileptonics: Mixing, A_{SL}
- Semileptonics: V_{xb}
- $B\to\tau\nu$, $D\tau\mu$,
- $B\to K^*\nu\nu$
- τ-physics

Some only LHCb, some only Belle II

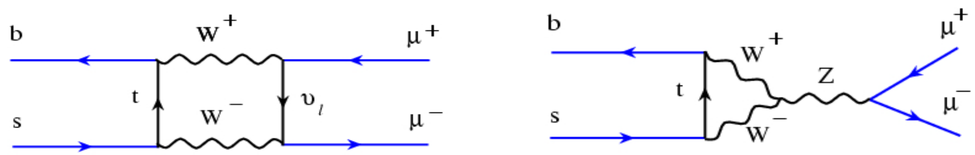
On-going

Belle II

*) Caveat: I am probably missing “your” favored channel/field

Rare decays: $B_{s,d} \rightarrow \mu\mu$

CMS PAS FTR-13-022
LHCb-Pub-2013-015



Highly suppressed: *Bobeth et al., 2014*

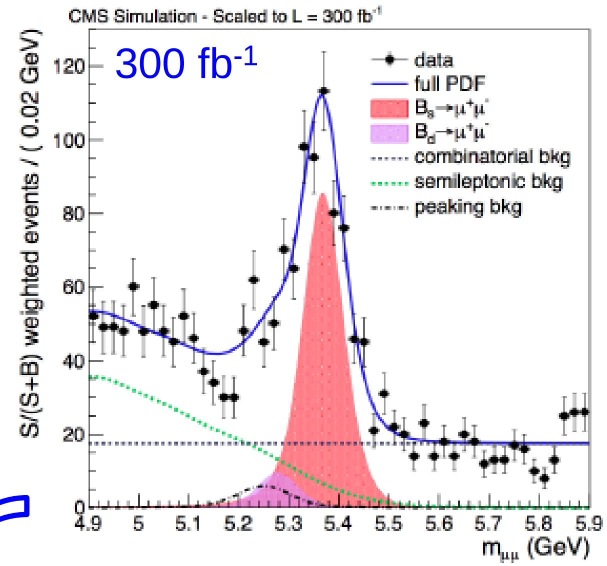
$BR(B_s \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

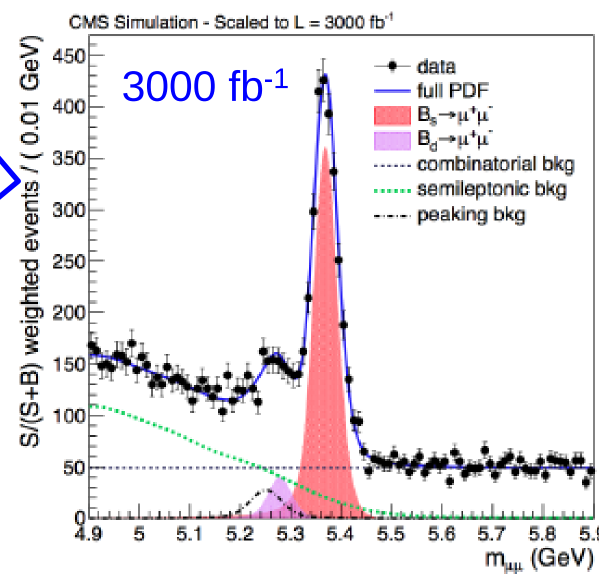
$BR(B_d \rightarrow \mu^+\mu^-) = (1.1 \pm 0.1) \times 10^{-10}$

Phase II upgrade of CMS tracker

	$BR(B_s \rightarrow \mu\mu)$	$BR(B_d \rightarrow \mu\mu)$ / $BR(B_s \rightarrow \mu\mu)$
Theory	±6%	±5%
Today*)	±24%	--
LHCb (50 fb^{-1})	±6%	±40%
CMS (300 fb^{-1})	±12%	±47%
CMS (3000 fb^{-1})	±12%	±21%

*) Average CMS and LHCb

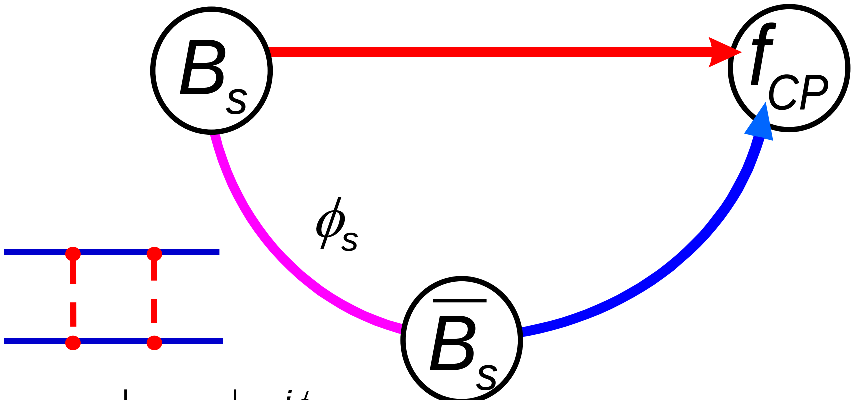




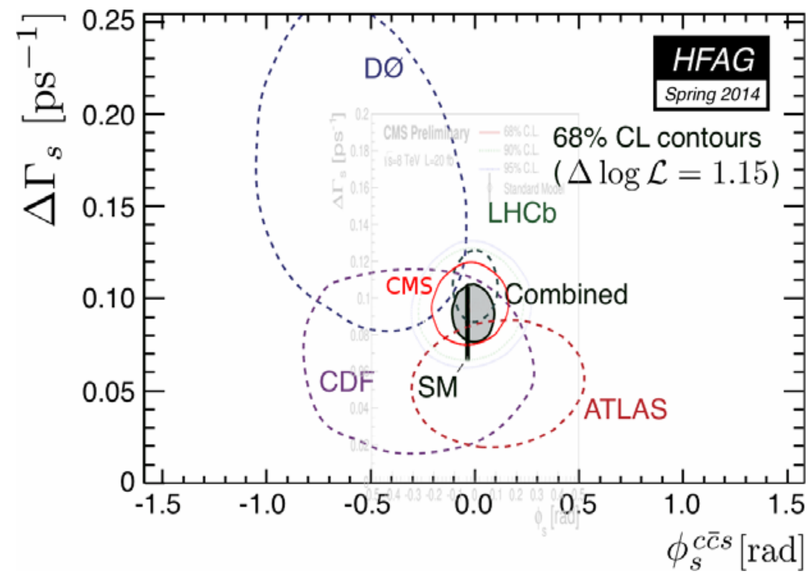
M. Galanti Beauty (2014) & CMS PAS FTR-13-022

B_s-mixing: ϕ_s and CPV in mixing

Mixing phase ϕ_s using $B_s \to J/\psi\phi$:



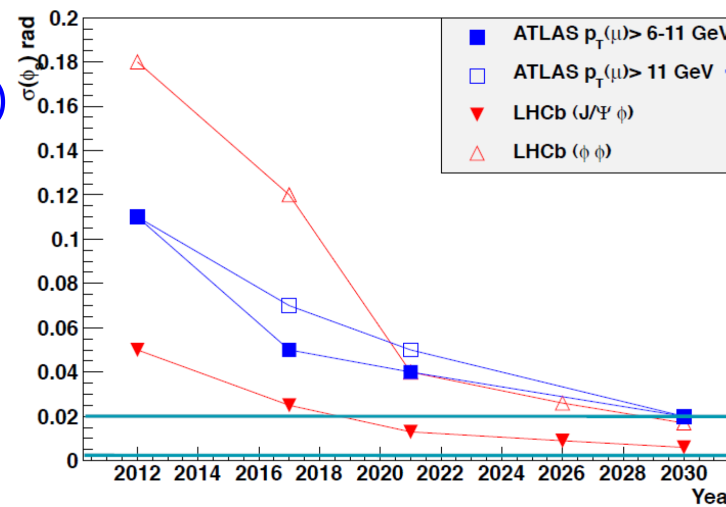
$$A_{mix} = |A_{mix}| e^{i\phi_s}$$



P. Řezniček, Beauty 2014

Measurements by ATLAS, CMS and LHCb:

LHCb (50 fb^{-1}): $\delta\phi_s \approx \pm 0.009$ (SM -0.036 ± 0.003)



M.H.Schune, ECFA Workshop

CPV in mixing: $P(B_s \to \overline{B}_s) \neq P(\overline{B}_s \to B_s)$

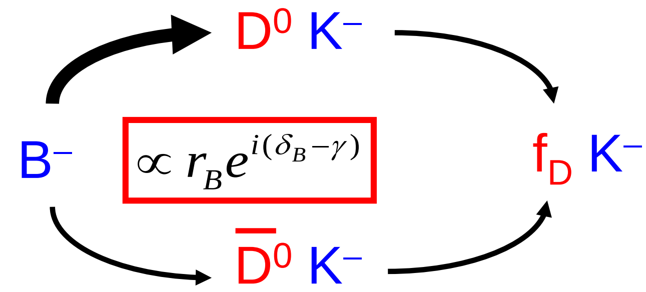
LHCb (50 fb^{-1}): $\delta A_{SL}(B_s) \approx \pm 0.5\times10^{-3}$ (SM:10^{-4})

LHCb (Run 1 expect.): $\approx \pm 3\times10^{-3}$

CKM Angle γ

Tree decays: (LHCb & Belle II)

Measurement of direct CPV in $B \to DK$ decays
Ultimate precision reached from many channels.
Challenging LHC: many tracks, low-p_T,
hadronic triggers, PID.



Tree + box: (LHCb)

Time-dependent measurement of direct CPV in $B_s \to D_s K$ decays.

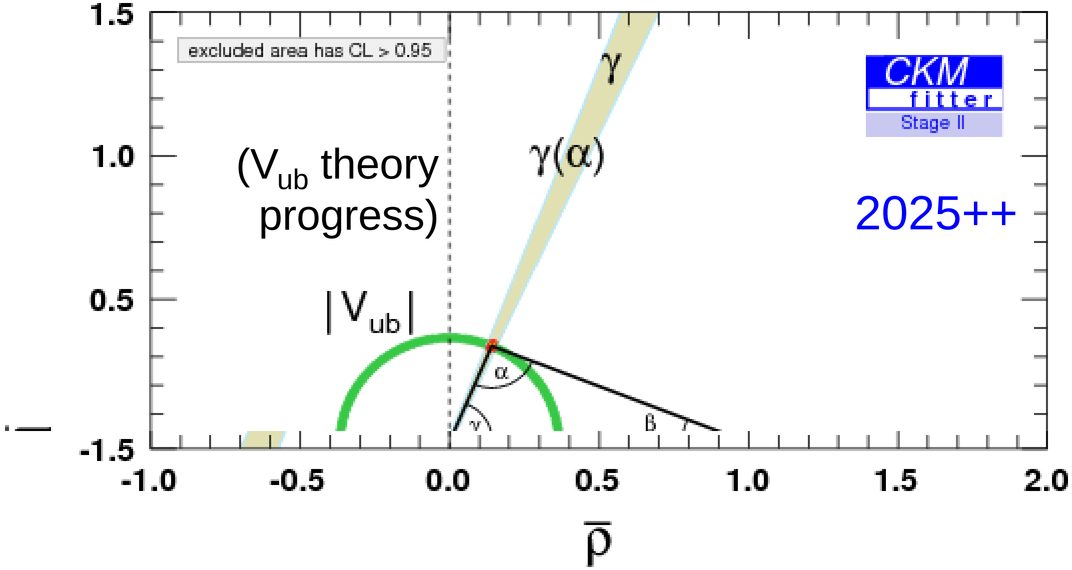
	LHCb[1)]		Belle II[2)]	
	Run1	$50fb^{-1}$	Belle I	$50ab^{-1}$
γ (tree)	7°	1.1°	15°	1 - 1.5°
$\gamma(B_s \to D_s K)$	17°	2.4°		

1) *LHCb-Conf-2013-006*
LHCb-Pub-2013-015

2) Phys. Rev. D 81, 112002 (2010)
arXiv:1311.1076 (Snowmass report)

CKM Metrology

LHCb-Pub-2013-015
arXiv:1311.1076

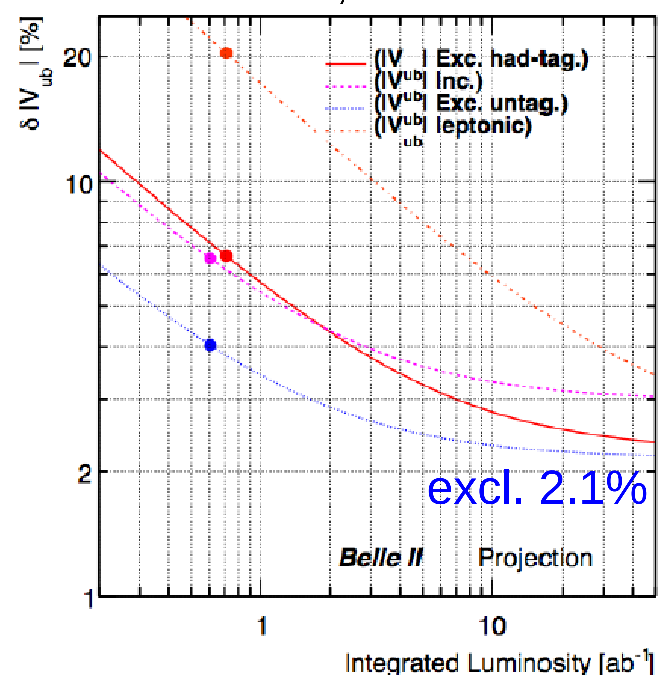


Belle II: Measures inclusive / exclusive $|V_{ub}|$ ⇨

$|V_{ub}|$ determination:

experimental error

A.Schwartz, FPCP 2014



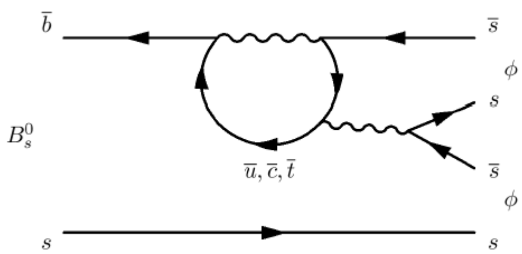
	WA	LHCb (50 fb^{-1})	Belle II (50 ab^{-1})
α	4°	--	1°
β	0.8°	0.31°	0.2°

b →s Gluonic Penguins

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

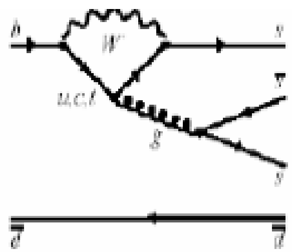
B_s^0

$B_s \to \phi\phi, K^*K^*$

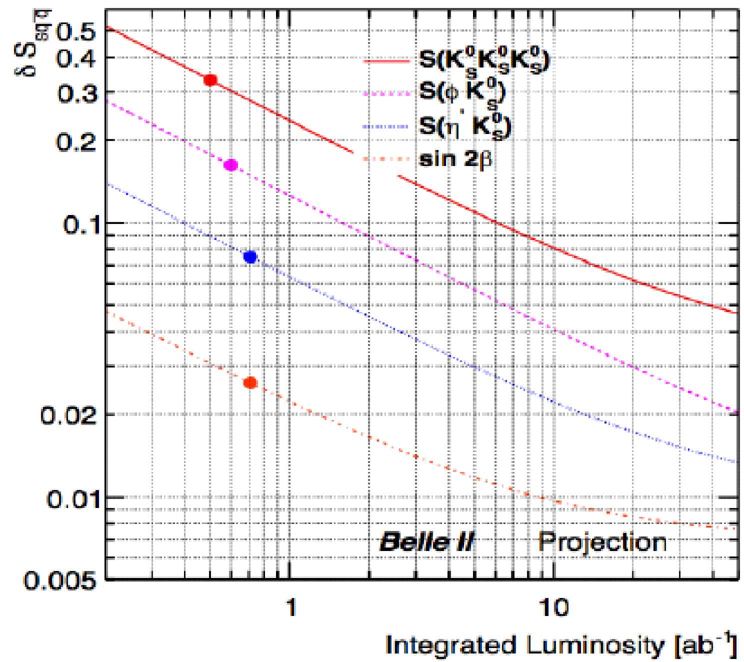


$\delta\phi_s (\phi\phi) \approx \pm 0.15$ (LHCb 3fb^{-1})

B_d^0



$B^0 \to \phi K^0$
$B^0 \to \eta' K^0$
$B^0 \to K^0 K^0 K^0$

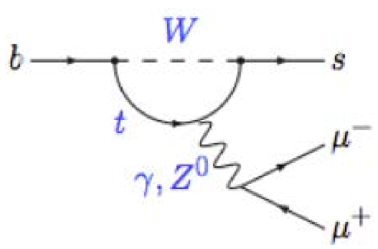


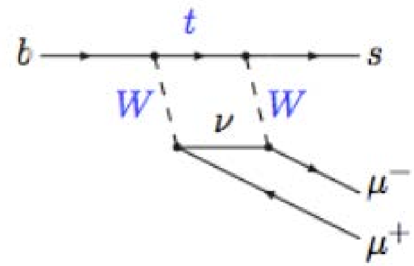
A.Schwartz, FPCP 2014

	LHCb[1)]	Belle II[2)]
$\phi_s^{eff}(B_s\to\phi\phi)$	0.026	
$\phi_s^{eff}(B_s\to K^*K^*)$	0.029	
$2\beta^{eff}(B\to\phi K_s)$	0.04	0.04
$2\beta^{eff}(B\to\eta' K_s)$		0.03

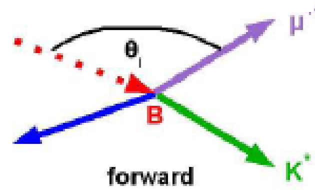
1) *LHCb-PUB-2013-015*
2) *arXiv:1311.1076 (Snowmass report)*

Electroweak Penguins: $B^0 \to K^* \mu\mu$



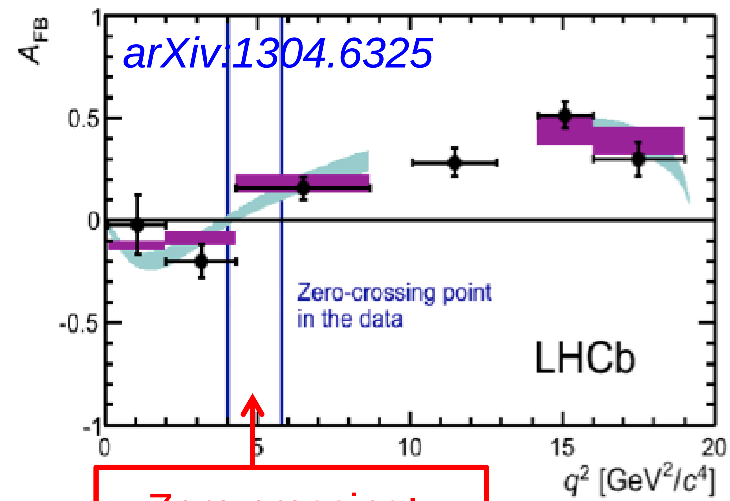


$$A_{FB}(q^2) = \frac{N_F - N_B}{N_F + N_B}$$



LHCb-Pub-2013-015, arXiv:1311.1076

Error	Theory	LHCb 50 fb^{-1}	Belle II 50 ab^{-1}
q_0^2 (A_{FB})	±7%	1.9%	5%



Zero crossing:
$q_0^2 = 4.9 \pm 0.9$ GeV²

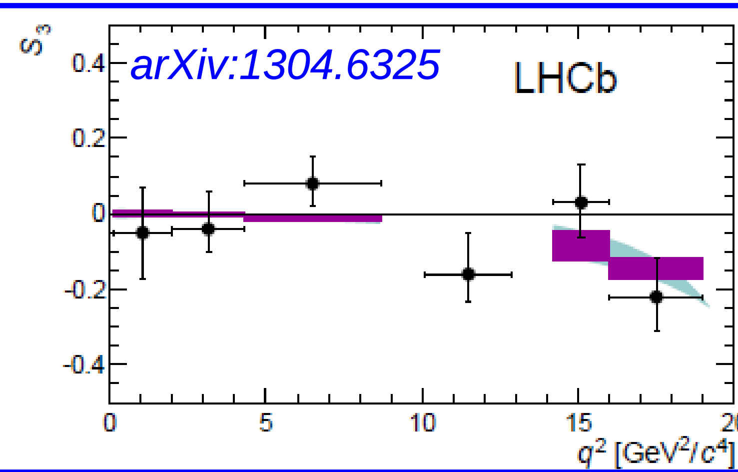
±18%

Results by ATLAS & CMS.

Full angular analysis exploits the data much better

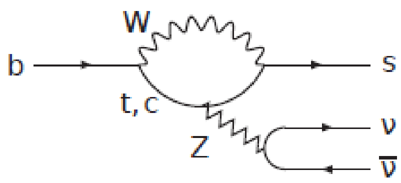
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\overline{\Gamma})}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi} = F_L \cdot f(\theta_\ell,\theta_K,\phi) + \sum S_i \cdot f_i(\theta_\ell,\theta_K,\phi)$$

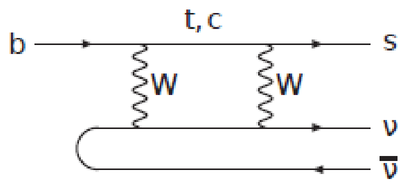
LHCb S_3: ±0.04 (Run 1) → ±0.007 (50 fb^{-1})



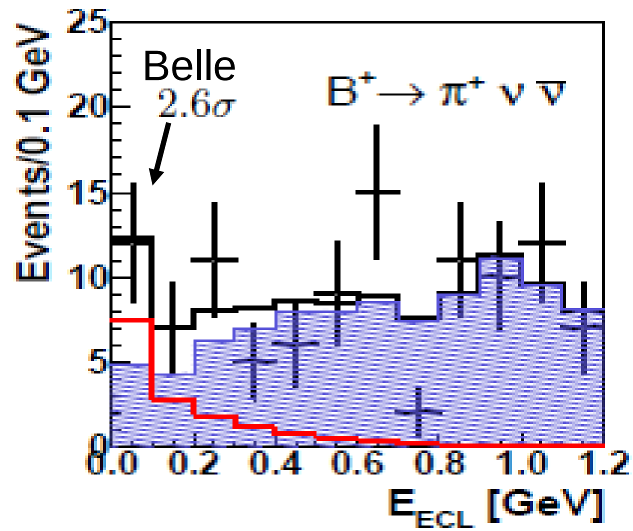
More Electroweak Penguins

$B \to h^{(*)} \nu\nu$



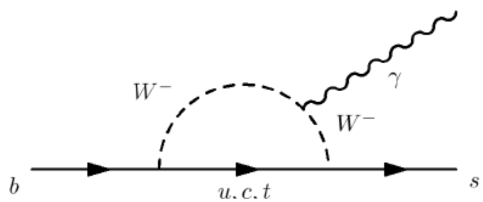


arXiv:1303.3719



Belle II (50 ab^{-1}): $\delta BR(B \to K\nu\nu) \approx \pm 1.0 \times 10^{-6}$

$b \to s\,\gamma$



- Inclusive $B \to X_{d,s}\,\gamma$ (Belle II)
- Exclusive $B \to K^*\gamma$, $\rho\,\gamma$ (Belle II, LHCb), $B_s \to \phi\gamma$ (LHCb)

Test of CPV: $\delta A_{CP}(K^*\gamma) < \pm 1\%$ (Belle II)

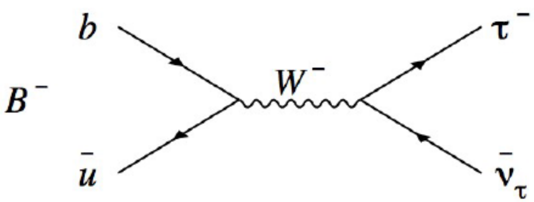
- Photon polarization (Belle II, LHCb)

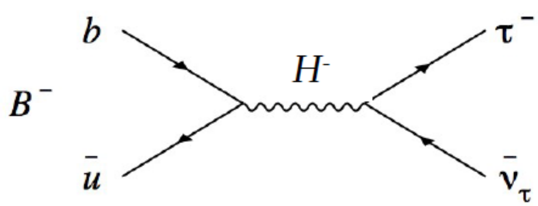
Recent LHCb measurement of photon polarization in $B^+ \to K^+ \pi\pi\gamma$

LHCb-PAPER-2014-001

Constrains on charged Higgs from $B\to\tau\nu$

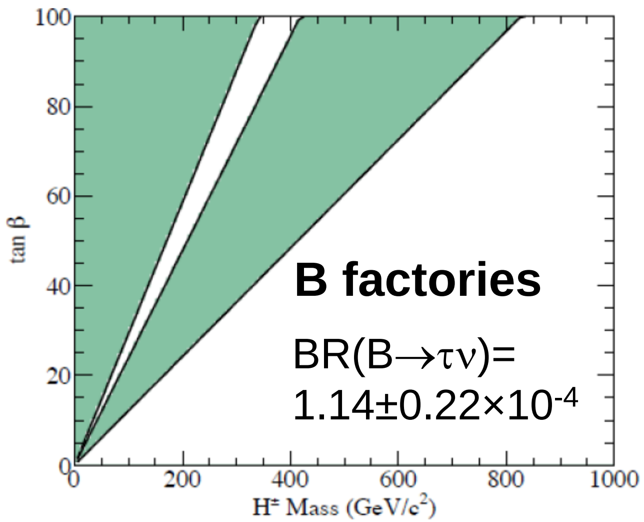
S. Yashchenko, SM@LHC 2014

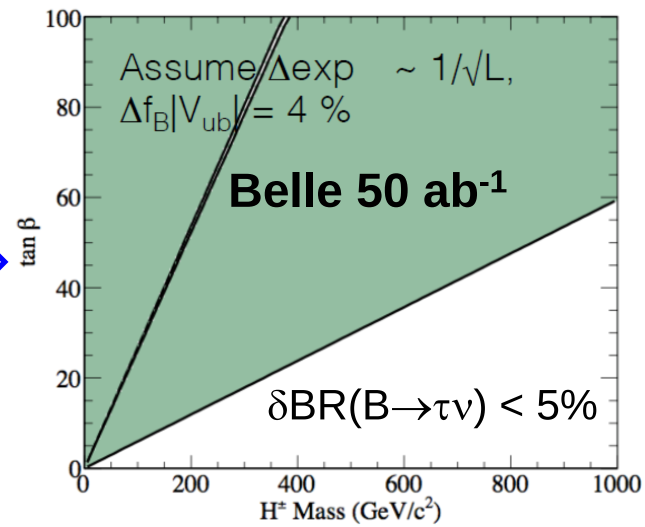




SM — 2HDM(TypeII)

$$\mathcal{B} = \underbrace{\frac{G_F^2}{8\pi}\tau_B f_B^2 |V_{ub}|^2 m_B^3 \left(1-\frac{m_\tau^2}{m_B^2}\right)^2\left(\frac{m_\tau}{m_B}\right)^2}_{\equiv\,\mathcal{B}^{SM}} \times \underbrace{\left(1 - m_B^2\frac{\tan^2\beta}{m_{H^\pm}^2}\right)^2}_{\equiv\, r_H}$$





CP Violation in Charm

CP asymmetry from eff. lifetime differ.

$$A_\Gamma \equiv \frac{\tau(\overline{D}^0 \to f) - \tau(D^0 \to f)}{\tau(\overline{D}^0 \to f) + \tau(D^0 \to f)}$$

$$\approx -a_{CP}^{ind}$$

f = KK, ππ

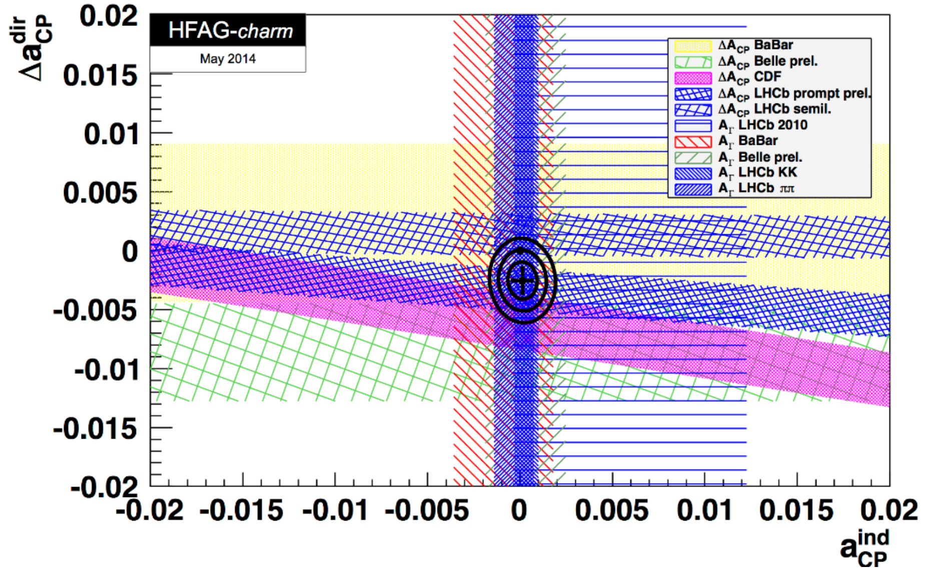
CP asymmetry from decay rates

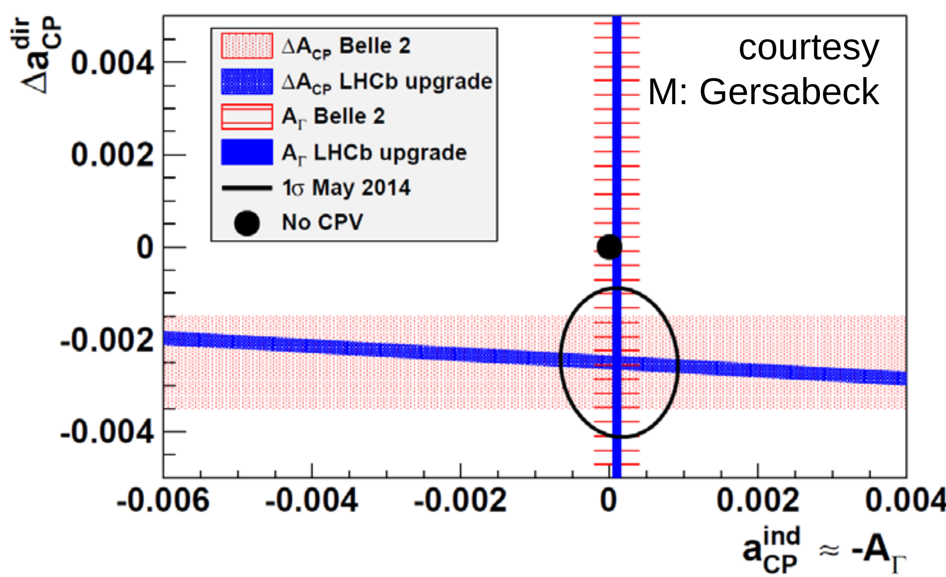
$$A_{CP}(f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

A_{CP} experimentally challenging →

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

$$= \left(1 + y\cos\phi\frac{\langle t\rangle}{\tau}\right)\Delta a_{CP}^{dir} + \left(\frac{\Delta\langle t\rangle}{\tau}\right) a_{CP}^{ind}$$





courtesy M: Gersabeck

LHCb
arXiv:1405.2797

$A_{CP}(KK) = -0.06 \pm 0.18$
$A_{CP}(\pi\pi) = -0.20 \pm 0.22$
→ future!

Conclusion

- We have reached already an impressive precisions in many B measurements.
- LHC has been proven to be a high-intensity B factory able to provide precision results: LHCb, ATLAS&CMS (muon channels)
- With the LHC upgrades (in particular for LHCb) and Belle II we enter a new era of B physics
  $\rightarrow$ Different experimental approaches guarantee complementarity!

  From Phillip Urquijo's talk:
  We will test scales up to 20 (2) TeV trees (loops).
- The future is bright and we can expect surprises!

Backup

A lesson from the past

A special search at Dubna was carried out by E. Okonov and his group. They have not found a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays of K_L^0 into charged particles [13] (Anikina et al., JETP, 1962). At that stage the search was terminated by administration of the Lab. The group was unlucky.

Approximately at the level 1/350 the effect was discovered by J.Christensen, J.Cronin, V.Fitch and R.Turlay [14] at Brookhaven in 1964 in an experiment the main goal of which was $K_L \to K_S$ regeneration in matter.

L.B. Okun, Spacetime and vacuum as seen from Moscow, Int. J. Mod. Phys. A 17S1 (2005) 105.

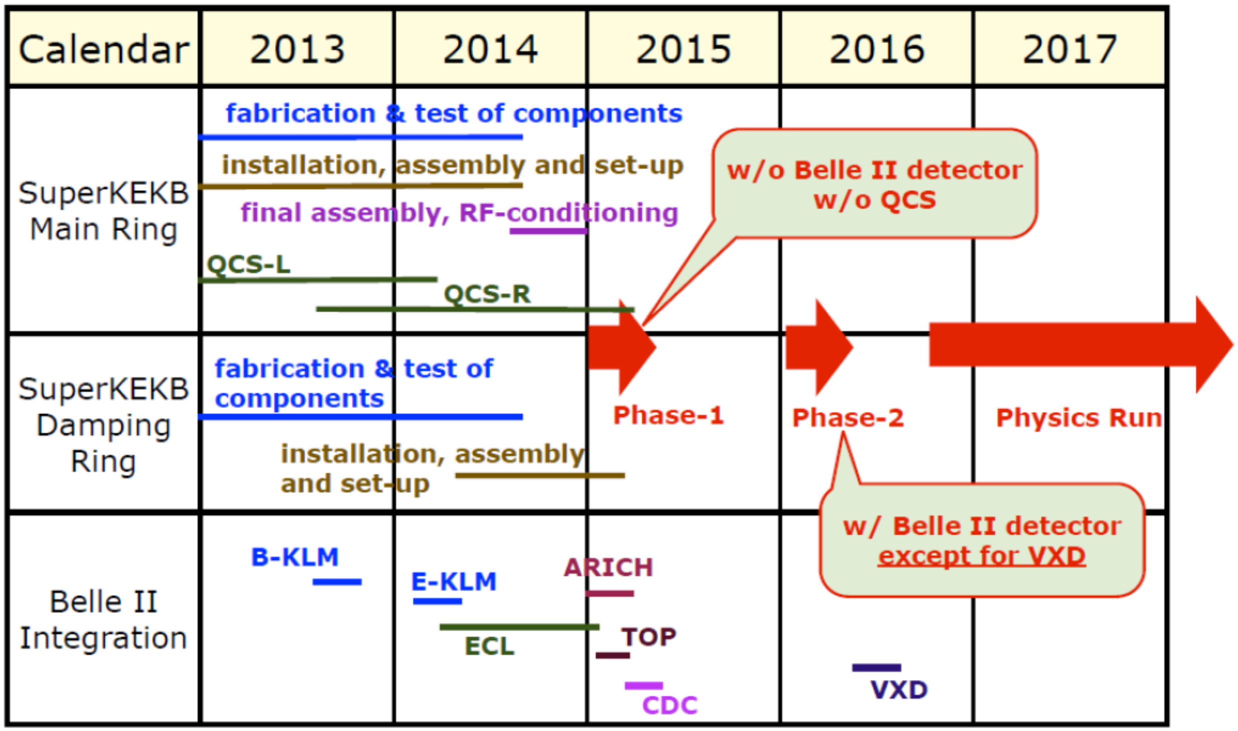
LHCb Upgrade: Key Measurements

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Key Measurement of Belle II

Observable	SM theory	Current measurement (early 2013)	Belle II * ($50\,\mathrm{ab}^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.018
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.011
α from $B \to \pi\pi$, $\rho\rho$		$\pm 5.4^\circ$	$\pm 1^\circ$
γ from $B \to DK$		$\pm 11^\circ$	$\pm 1.5^\circ$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.035
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.07
$A_{\mathrm{CP}}(B \to X_{s+d}\,\gamma)$	< 0.005	0.06 ± 0.06	± 0.005
A^d_{SL}	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 3\%$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\gg 5\sigma$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 6\%$
$\mathcal{B}(B \to K^{(*)}\nu\overline{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 30\%$
$\mathcal{B}(B \to X_s \ell^+\ell^-)$ $(1 < q^2 < 6\,\mathrm{GeV}^2)$	1.6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$A_{\mathrm{FB}}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing	7%	18%	5%
$\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ $(q^2 > 16\,\mathrm{GeV}^2)$	$9\% \to 2\%$	11%	2.1%

adapted from **arXiv:1311.1076** COMMUNITY PLANNING STUDY: SNOWMASS 2013
with modifications(*) for Belle II projections, reported at BPAC 2014

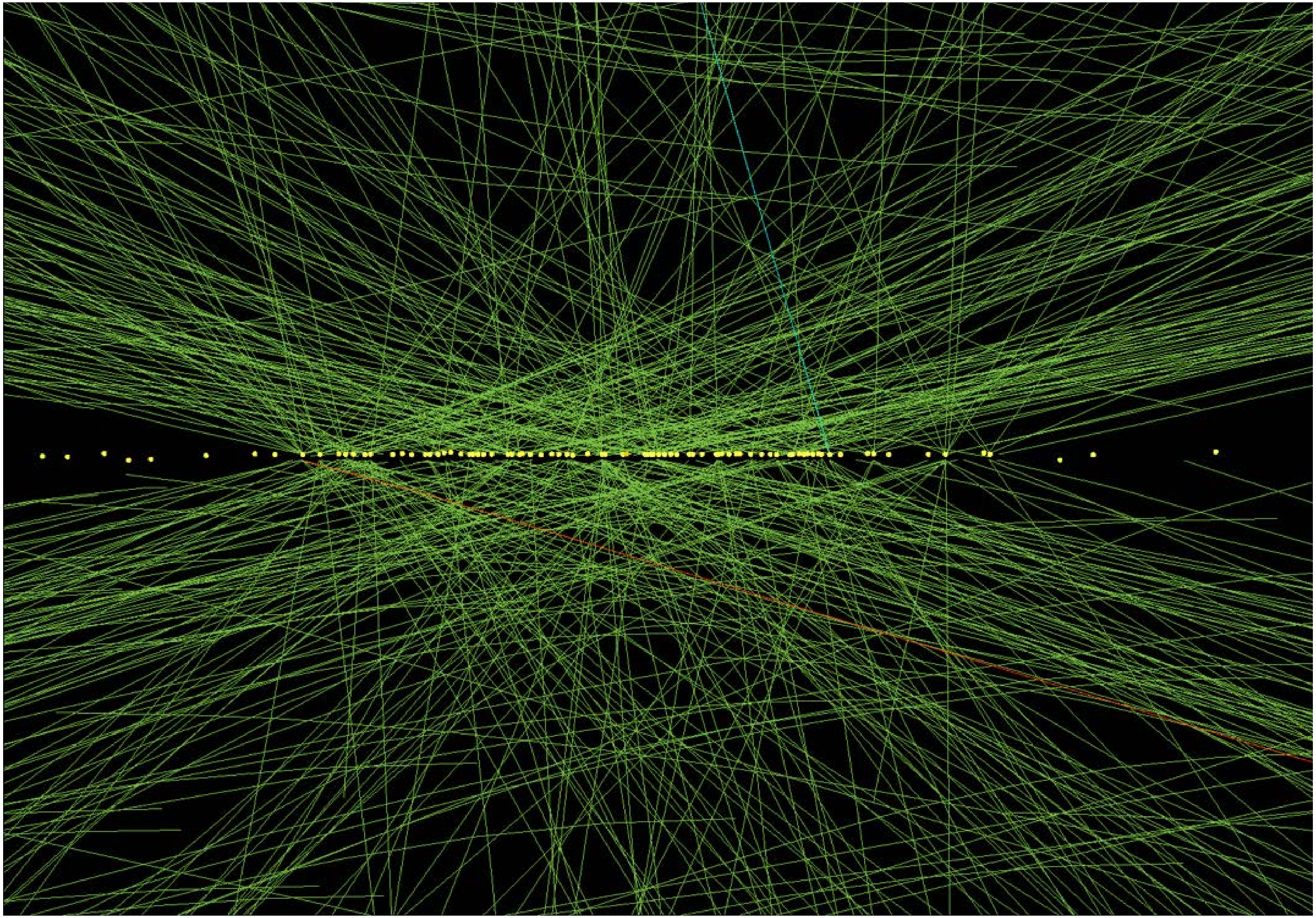

Calendar
2013
2014
2015
2016
2017
SuperKEKB Main Ring
fabrication & test of components
installation, assembly and set-up
final assembly, RF-conditioning
QCS-L
QCS-R
w/o Belle II detector
w/o QCS
SuperKEKB Damping Ring
fabrication & test of components
installation, assembly and set-up
Phase-1
Phase-2
Physics Run
w/ Belle II detector
except for VXD
Belle II Integration
B-KLM
E-KLM
ARICH
ECL
TOP
CDC
VXD

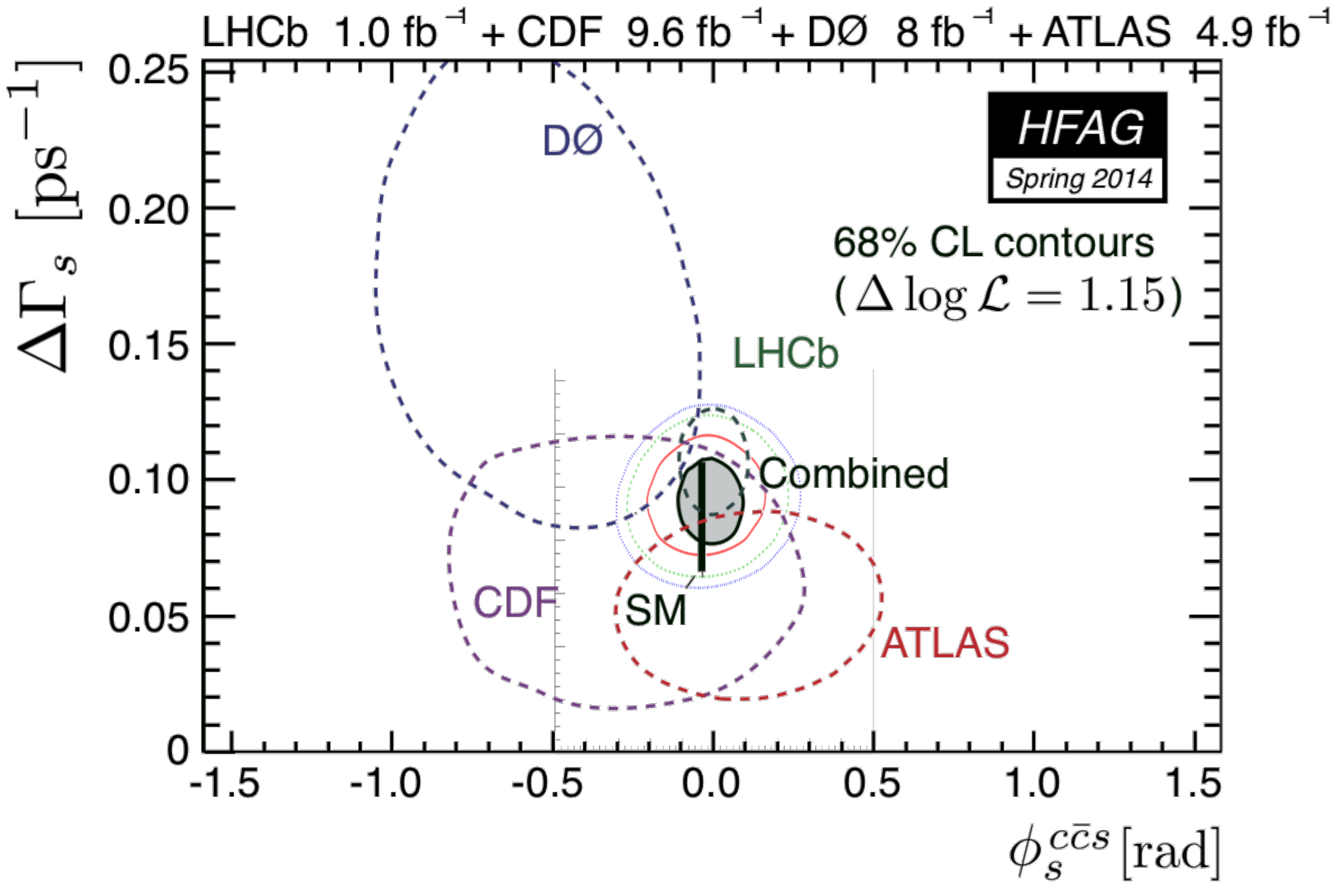
Timeline

LHC schedule beyond LS1

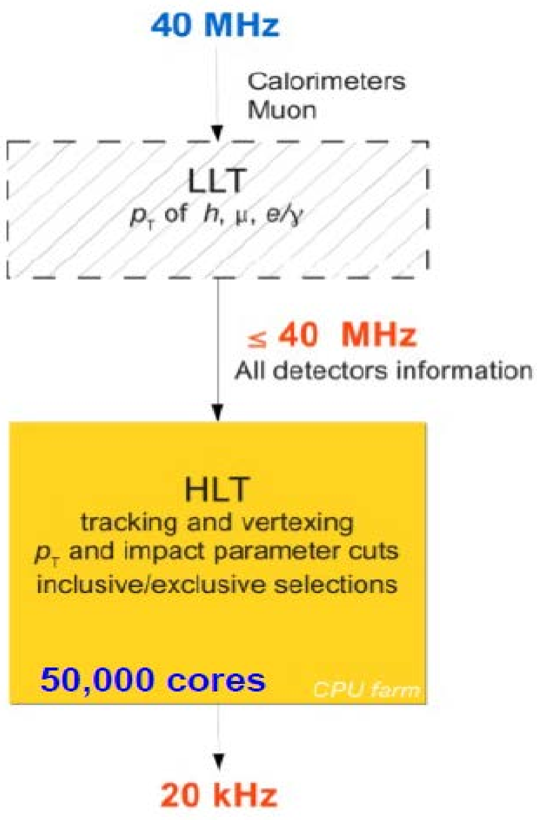
Only EYETS (19 weeks) (no Linac4 connection during Run2)
LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)
LS3 LHC: starting in 2023 => 30 months + 3 BC
injectors: in 2024 => 13 months + 3 BC

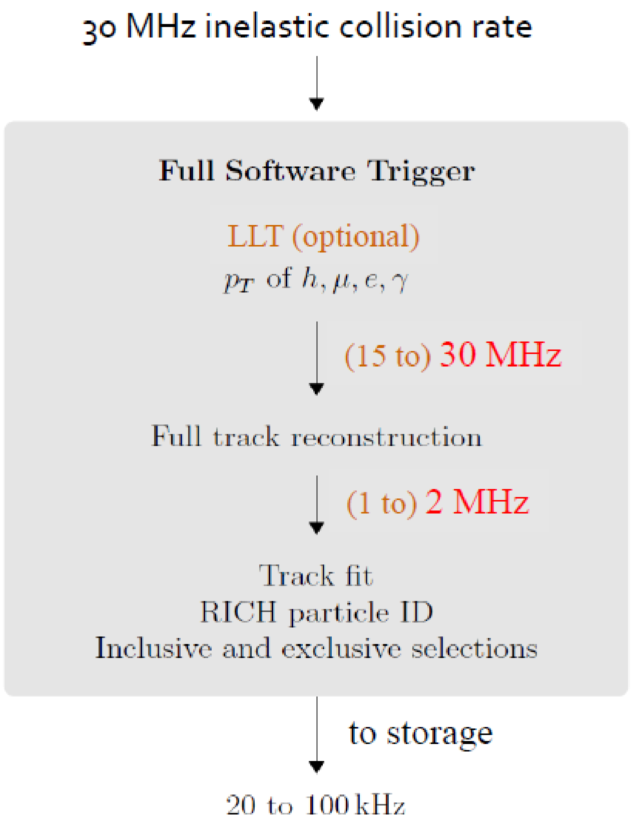
LHC - Pileup





LHCb 1.0 fb⁻¹ + CDF 9.6 fb⁻¹ + DØ 8 fb⁻¹ + ATLAS 4.9 fb⁻¹
HFAG
Spring 2014
68% CL contours
$(\Delta \log \mathcal{L} = 1.15)$
DØ
LHCb
Combined
CDF
SM
ATLAS
$\Delta\Gamma_s$ [ps^{-1}]
0.25
0.20
0.15
0.10
0.05
0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
$\phi_s^{c\bar{c}s}$ [rad]


40 MHz
Calorimeters
Muon
LLT
p_T of h, μ, e/γ
≤ 40 MHz
All detectors information
HLT
tracking and vertexing
p_T and impact parameter cuts
inclusive/exclusive selections
50,000 cores
CPU farm
20 kHz


30 MHz inelastic collision rate
Full Software Trigger
LLT (optional)
p_T of h, μ, e, γ
(15 to) 30 MHz
Full track reconstruction
(1 to) 2 MHz
Track fit
RICH particle ID
Inclusive and exclusive selections
to storage
20 to 100 kHz