LHCb LS2 Upgrade

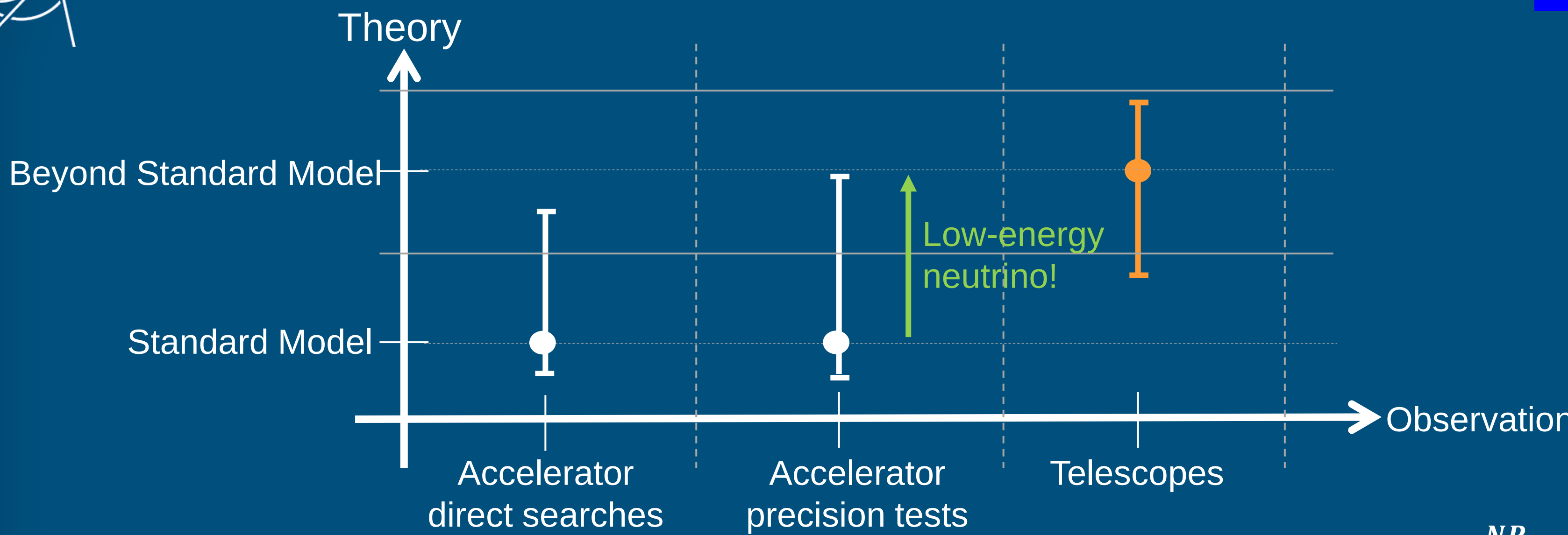
R. Jacobsson

on behalf of the LHCb Collaboration

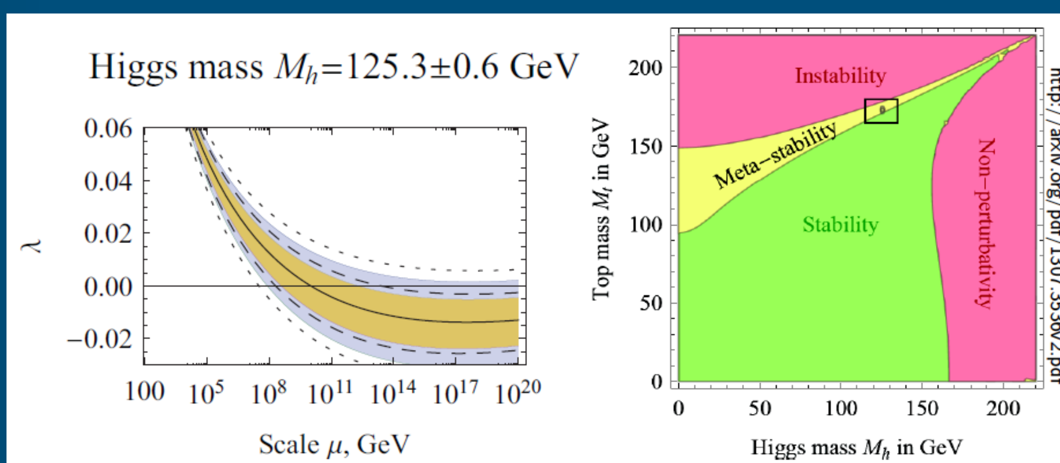
Outline

- Introduction
- LHCb objectives and upgrade motivations
- LHCb features and limitations
- Upgrade strategy
- Physics prospects
- Conclusions

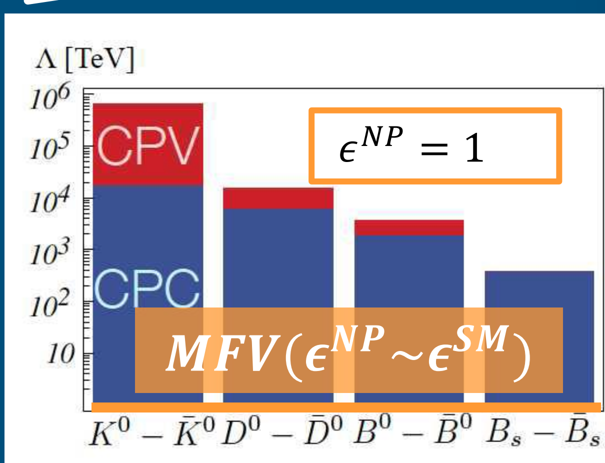
Physics Scenario after LHC Run 1



$$\mathcal{L}_{Eff}^{(6)} = \mathcal{L}_{SM}^{(4)} + \delta C[\frac{\epsilon^{NP}}{\Lambda_{NP}^{2}}]$$



Phys.Lett.B679:369-375,2009



G. Isidori, FCC Injector WG, CERN, 2014-09-29

- No tangible evidence for the scale of the new physics! Precision needed!

In Praise of Precision Measurements

- Precision measurements likely to have the largest discovery potential for new physics
  - Higgs and top precision physics (mainly ATLAS and CMS)
  - (Heavy) flavour precision physics (mainly LHCb, and soon joined by Belle II)
  - Complemented by direct searches at high scales AND low scales (Hidden Sector)

See talk by R. Jacobsson, Thu 16:00

➔ if observed directly, precision measurements allow characterizing the role of the new physics

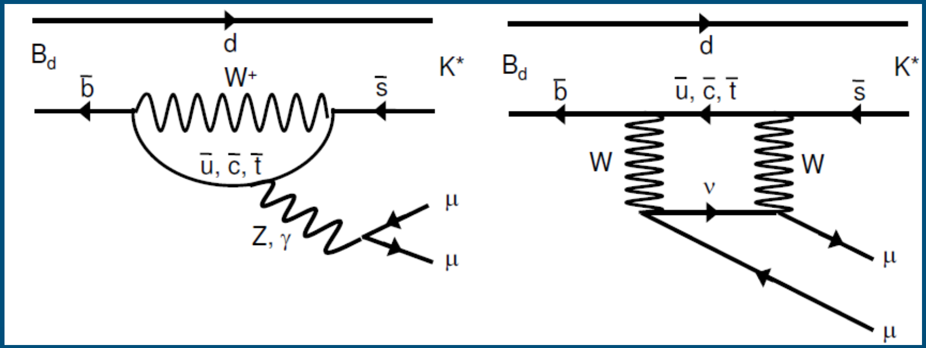
,…or, …

if not, virtual effects may be the only way to set the scale of BSM physics at high energies…

➔ LHCb focus on measuring *indirect* effects of New Physics in CP violation and rare decays using FCNC processes mediated by box and penguin diagrams

- Strongly suppressed processes allow distinguishing NP sources
- Virtual effects allow probing energies much higher than the E_{cms} of the LHC

- New Physics may enter differently in boxes and in penguin contributions
  - ➔ Aim for access to "all" modes



LHCb Objective and Observables

- Beauty and charm flavour sector contains a very large repertoire of decays and topologies
  - Aim at exploring all possible well-predicted observables sensitive to New Physics
  - ➔ Phases: CP violating asymmetries
  - ➔ Amplitudes (masses and couplings): Branching ratios and oscillation frequencies
  - ➔ Helicity structure: Angular distributions
  - Inclusive and less model dependent than direct searches

- Aim: reach experimental sensitivities ≤ theoretical uncertainties
  - Measurements not expected to be limited by systematics → often improves with increasing statistics
  - Theoretical errors often decrease with complementary measurements

  ➔ 10-fold our statistics and improve access to hadronic modes
    - ➔ Increase efficiency of hadronic channels by factor >2
    - ➔ Increase luminosity
    - ➔ Improve output bandwidth and lower p_T to increase sensitivity for charm

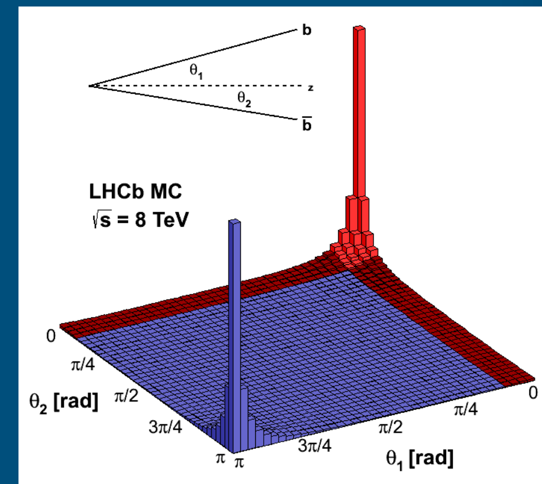
  ➔ Gives access to new modes and observables

$$\sigma_{stat+sys+th} < \delta C[\frac{\epsilon^{NP}}{\Lambda_{NP}^2}]$$

- The flexibility of the trigger in Run 1 was key to the extension of the physics program

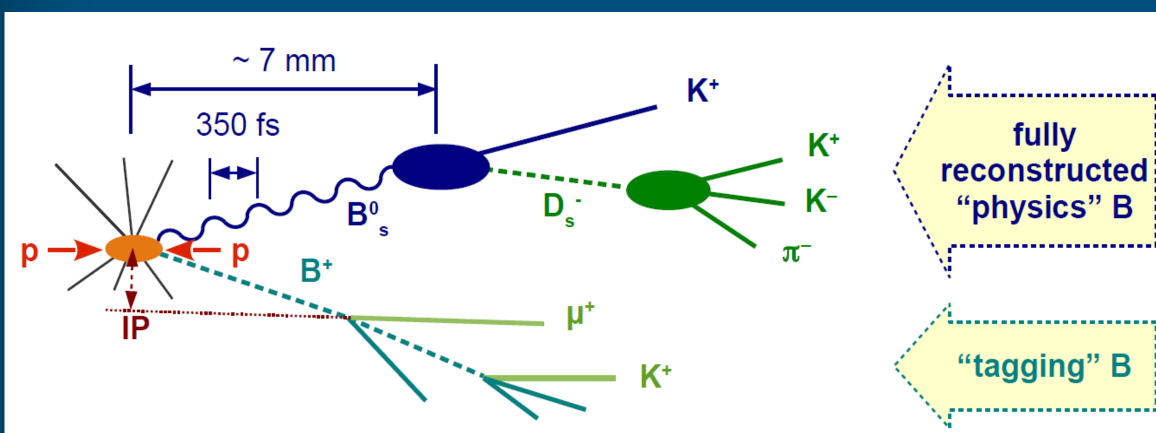
Key Features of LHCb

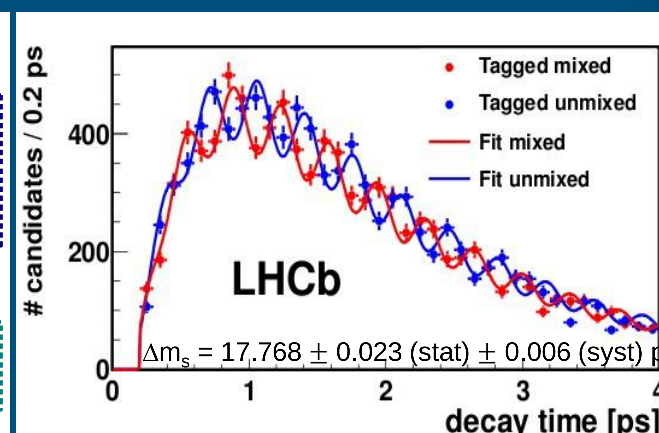
- **Large signal cross-sections**
  - >100 000 → 1 000 000 $b\bar{b}$ pairs per second at LHCb interaction point
  - Access to all quasi-stable b-flavored hadrons B_u (~40%), B_d *(~40%)*, B_s (~10%), and B_c*,* and *B*-baryons Λ_b *(~10%)* , … (arXiv:1111.2357v2, arXiv:1301.5286)
  - $c\bar{c}$ production 20x more



- **The final state $b\bar{b}$ / $c\bar{c}$ pair are Lorentz boosted**
  - → The B / D hadrons appear in the same hemisphere
  - → Very good proper time resolution

- **Flavor tagging**
  - Same side, uses π or *K* emitted together with signal *B / D* hadron
  - Opposite side, detects flavor of partner *B / D* hadron from decay





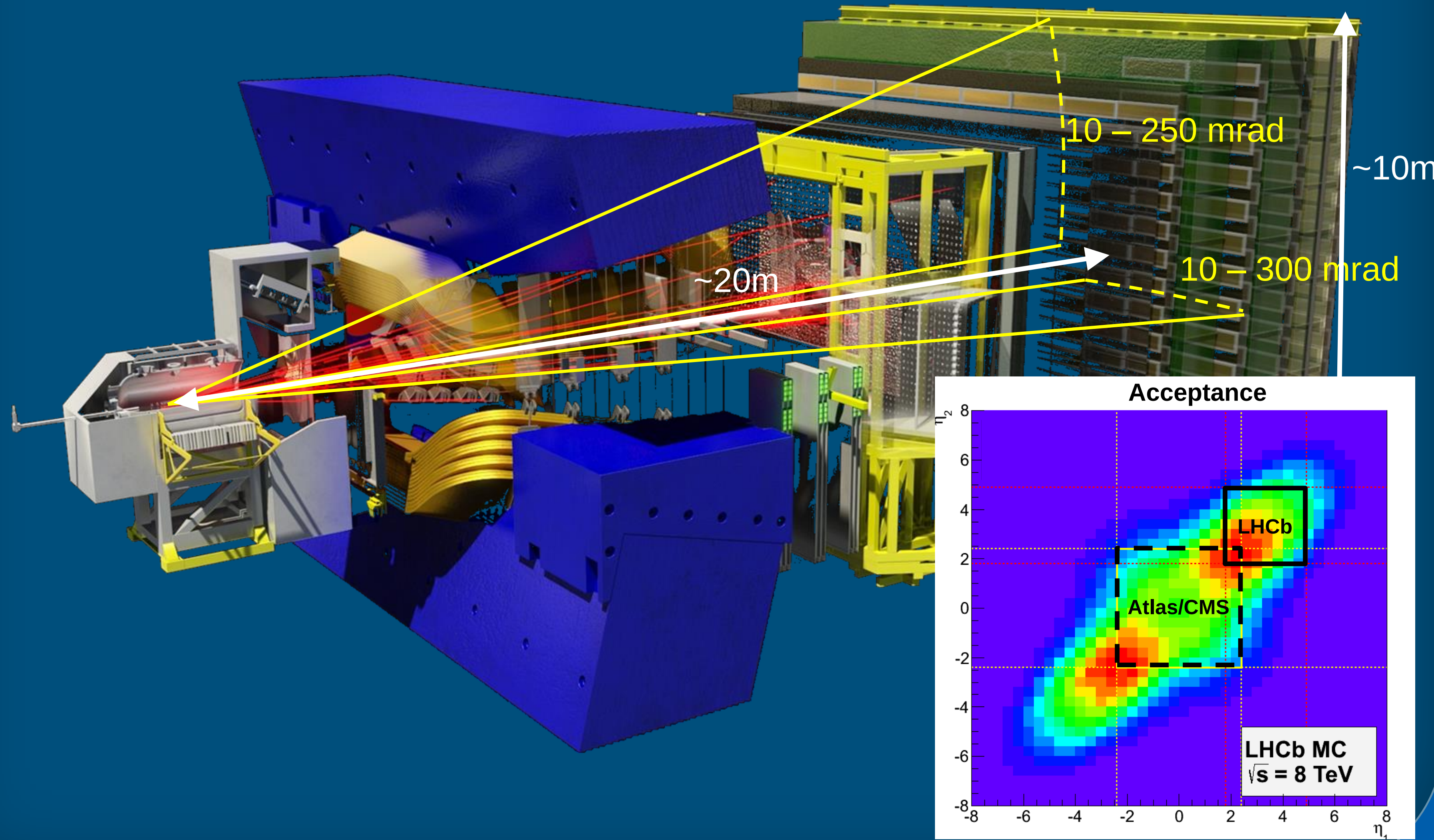
New J.Phys 15 (2013) 053021

The need for low pT, the large particle flux, and full reconstruction requires operating at reduced pileup

LHCb Detector

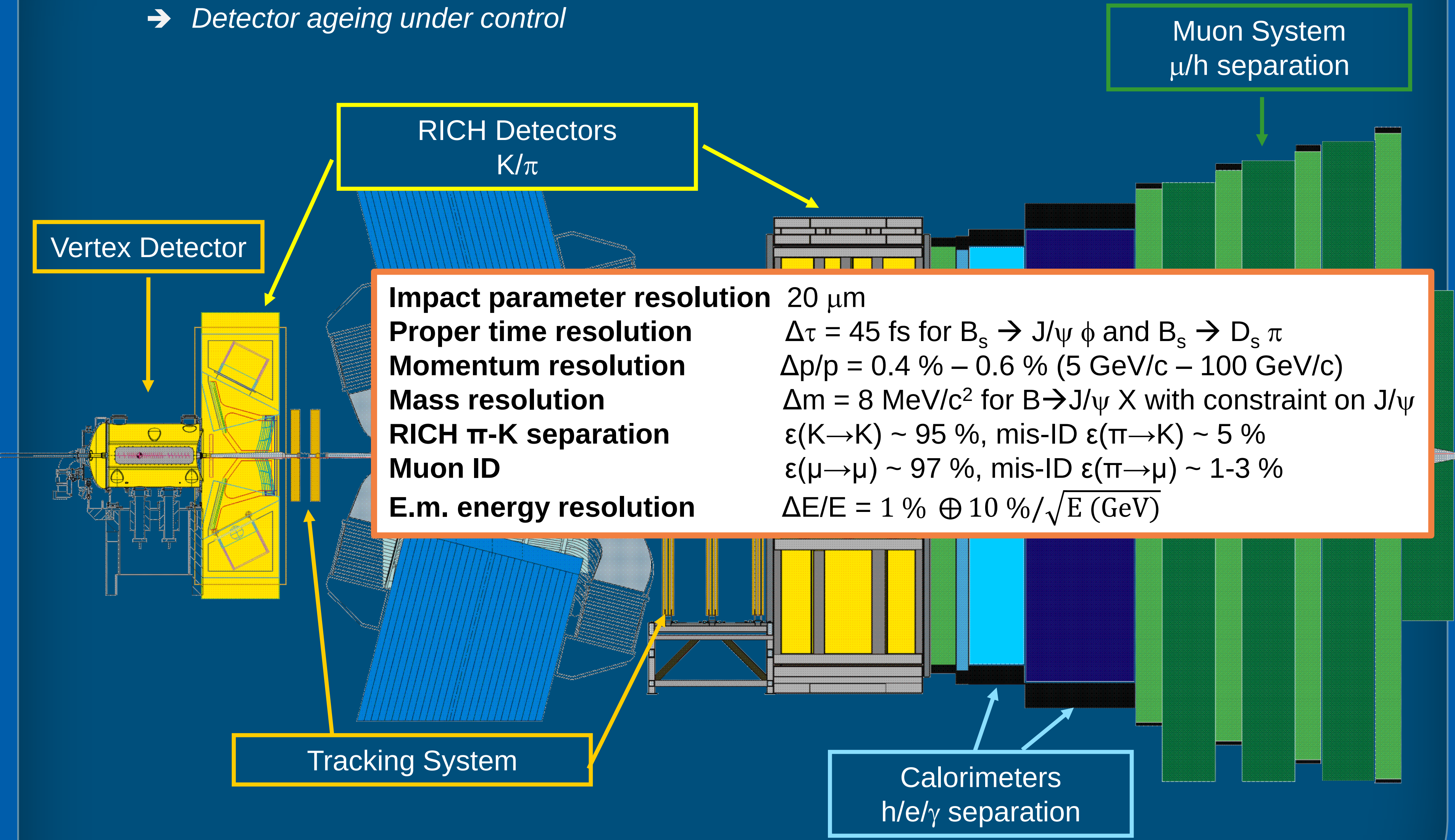
Covers ~4% of the solid angle, but captures ~40% of the heavy quark production cross-section

- Acceptance $2 < \eta < 5$ with entire detector



Current LHCb Detector Performance

- *Extremely good performance in the pileup environment*
- *Detector ageing under control*

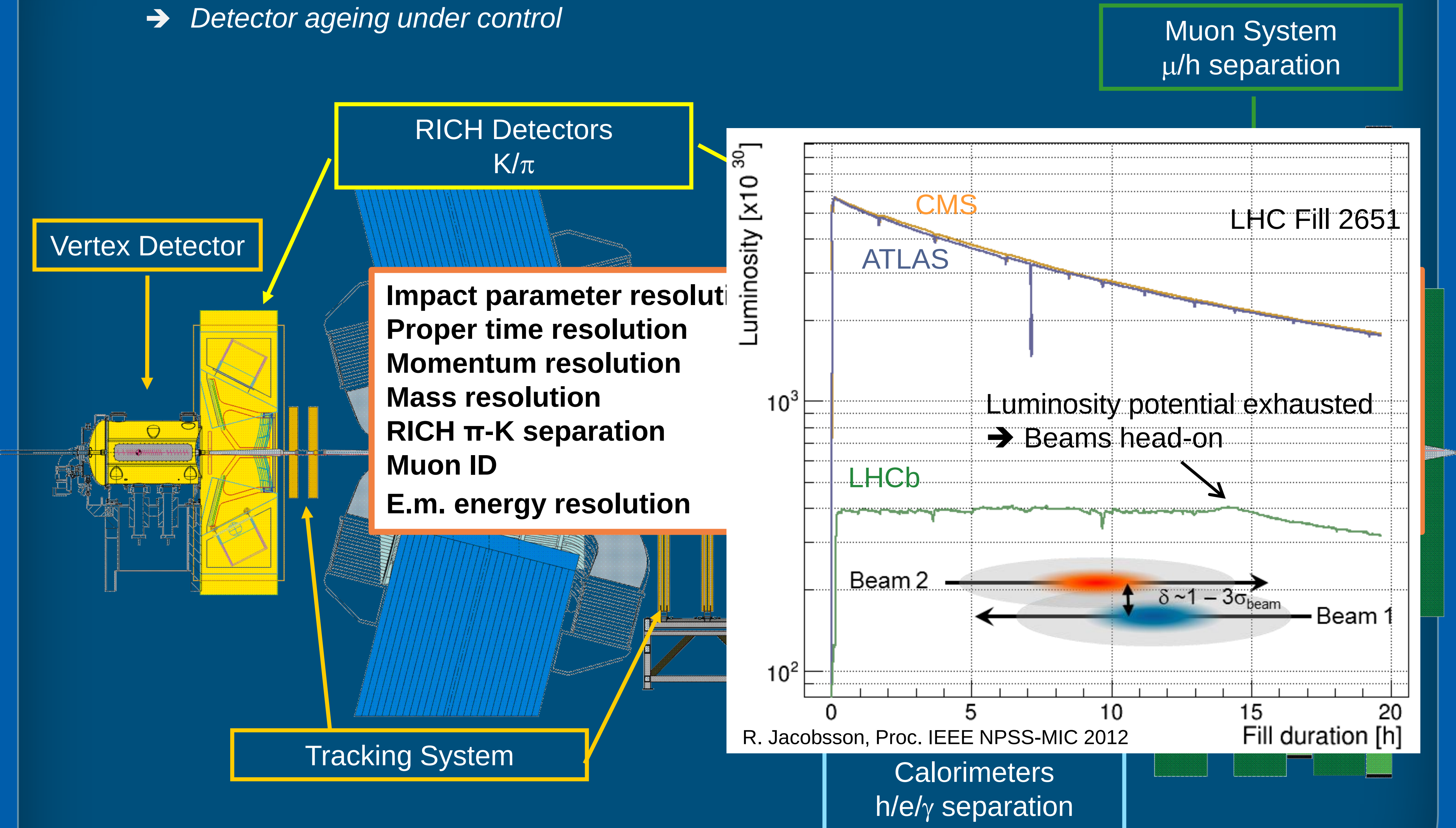


Impact parameter resolution	20 μm
Proper time resolution	$\Delta\tau$ = 45 fs for $B_s \rightarrow J/\psi\ \phi$ and $B_s \rightarrow D_s\ \pi$
Momentum resolution	$\Delta p/p$ = 0.4 % – 0.6 % (5 GeV/c – 100 GeV/c)
Mass resolution	Δm = 8 MeV/c^2 for $B \rightarrow J/\psi\ X$ with constraint on J/ψ
RICH π-K separation	ε(K→K) ~ 95 %, mis-ID ε(π→K) ~ 5 %
Muon ID	ε(μ→μ) ~ 97 %, mis-ID ε(π→μ) ~ 1-3 %
E.m. energy resolution	$\Delta E/E = 1\ \% \oplus 10\ \%/\sqrt{E\ (\mathrm{GeV})}$

- *Achieve at least same performance with upgraded detector at significantly higher pileup/occupancy*

Current LHCb Detector Performance

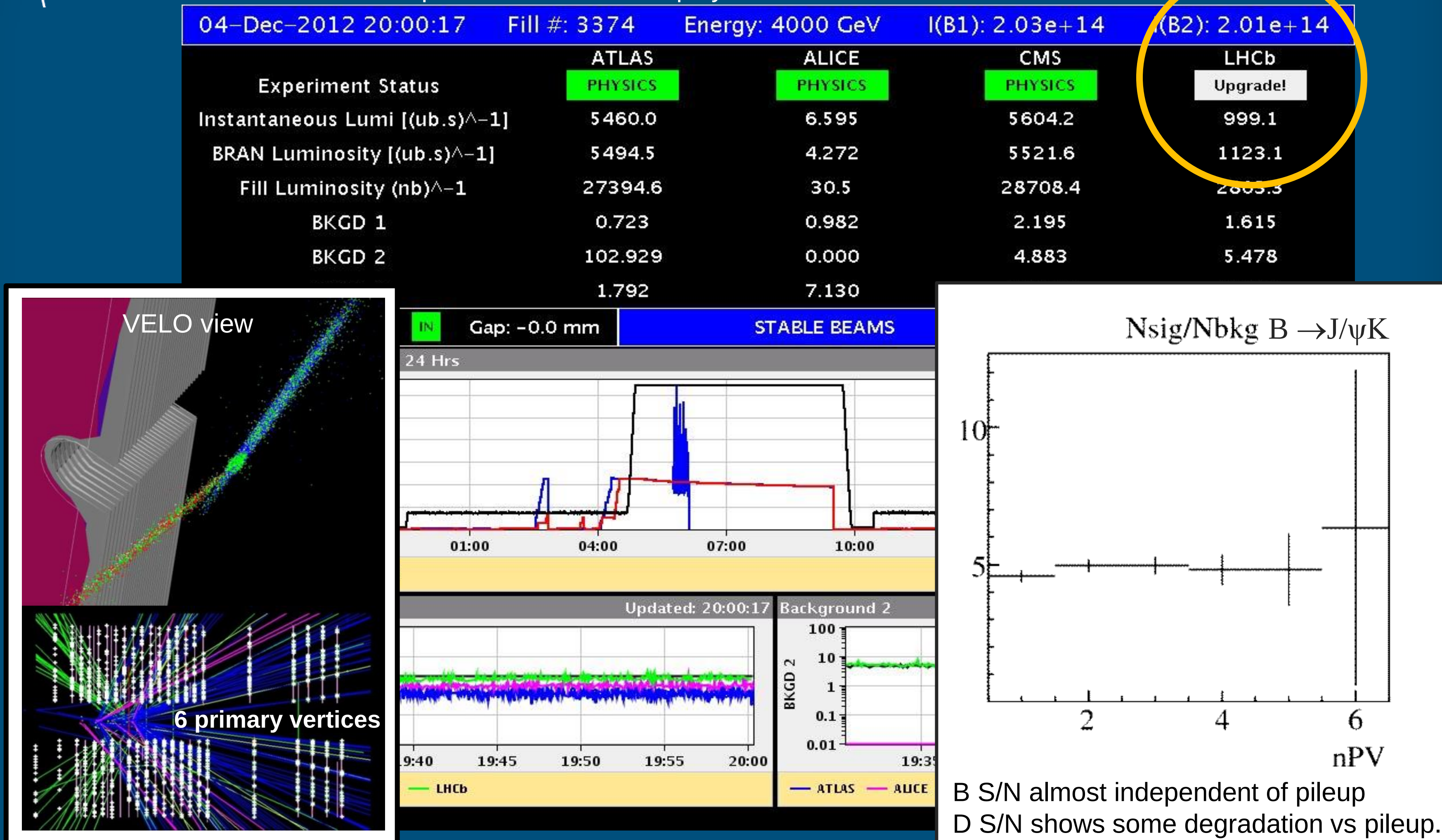
- ➔ *Extremely good performance in the pileup environment*
- ➔ *Detector ageing under control*



- *Achieve at least same performance with upgraded detector at significantly higher pileup/occupancy*

Upgrade "Deja-vu"

LHC web-based experiment overview display



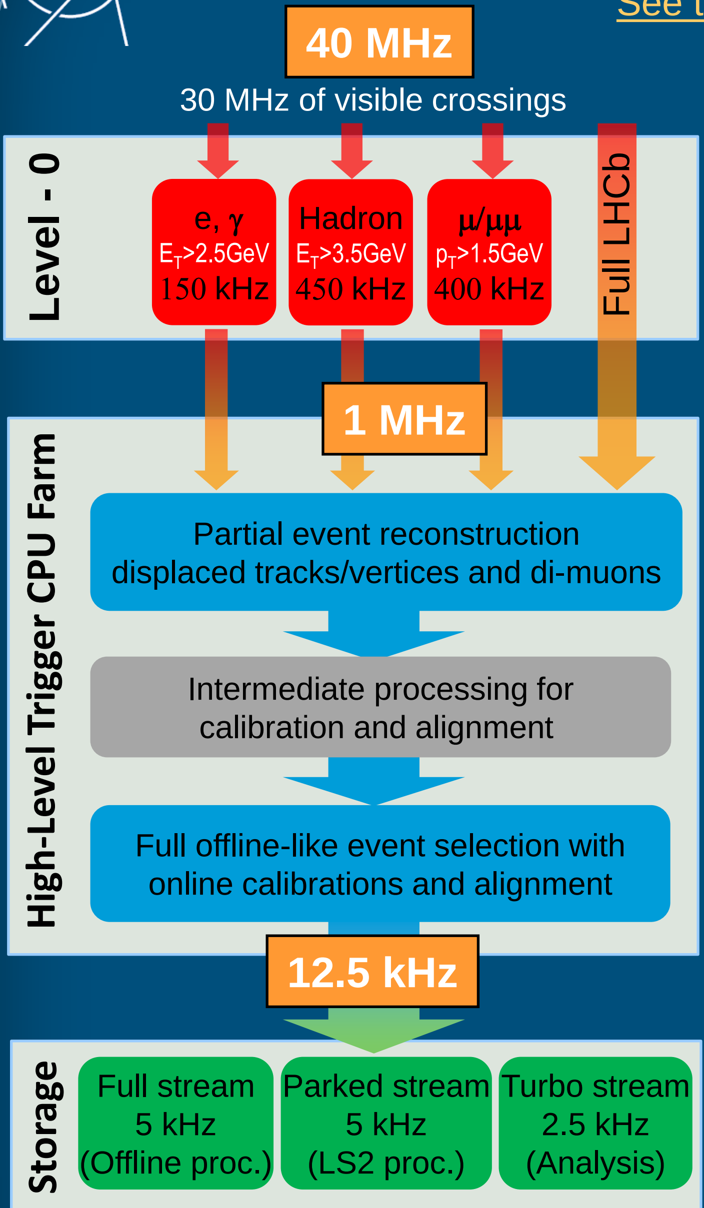
B S/N almost independent of pileup
D S/N shows some degradation vs pileup.

CERN/LHCC 2011-001

- ➔ Demonstrated *forward* high precision tracking and particle ID even with pileup
- ➔ Further demonstration of the concepts for the LHCb upgrade

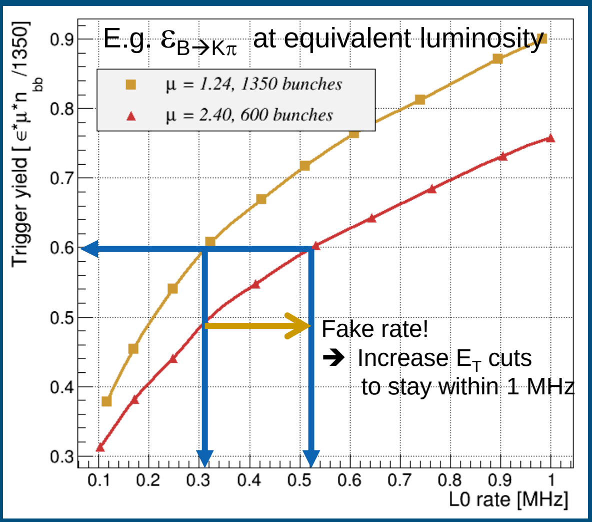
Current Trigger Architecture & Limitation

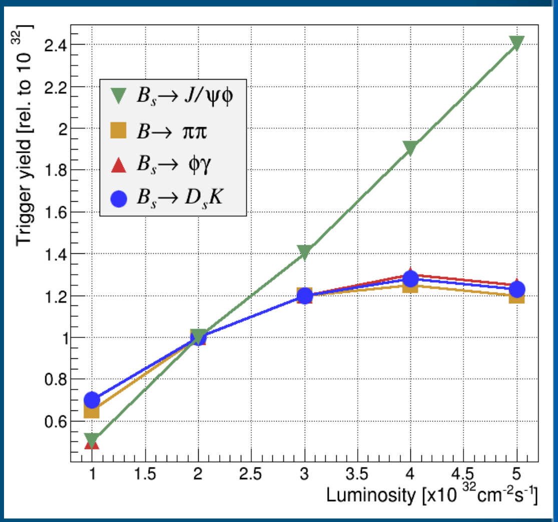
See talk by J. Albrecht, Friday 16:00



- Performances at 8 TeV in 2012 (L0 x HLT)
  - B decays with μμ: ε ~ 90 %
  - B decays with hadrons: ε ~ 30 %
  - Charm decays: ε ~ 10 %
  - ➔ About half the interesting B decays are lost
- Limitation: FE readout time=900ns ➔ max 1.1 MHz

CERN/LHCC 2011-001





➔ Pt does not discriminate in hadronic modes, saturates

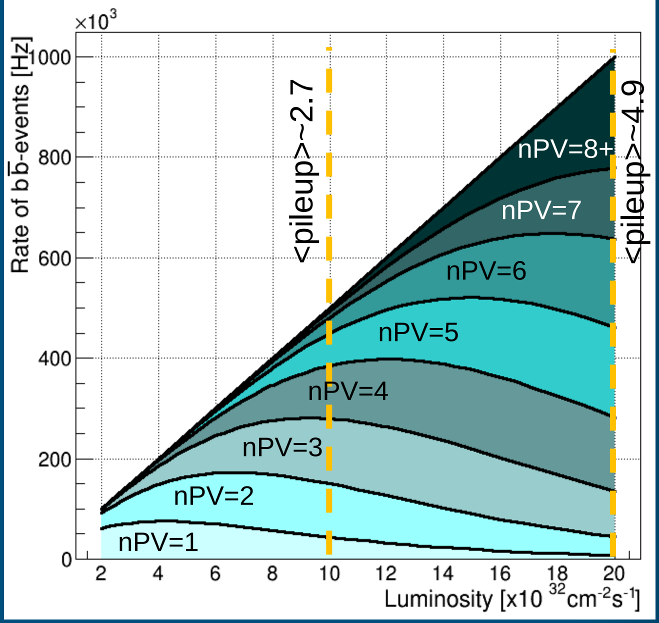
➔ Efficient selection requires full detector

➔ IP, p_T of tracks, and PID

Global LHCb Upgrade Strategy

Baseline: Target L= $2x10^{33}$ $cm^{-2}s^{-1}$

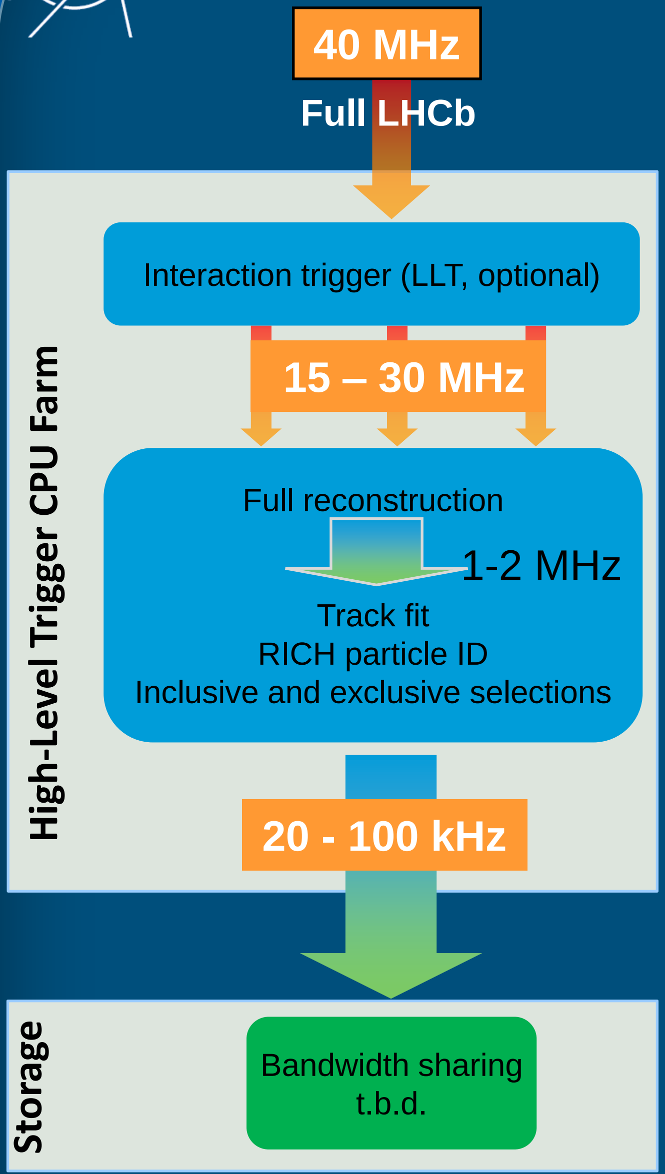
1. Remove First Level Trigger ➔ Full detector readout at 40 MHz up to CPU farm
2. Replace all FE and BE electronics
3. Implement a fast high-level software trigger based on full topology
4. Replace main tracking and improvements to PID
   - Geometry and granularity for fast full reconstruction
   - Guarantee radiation longevity (>50 fb^{-1})
5. Final output bandwidth at >20 kHz



- Ultimate trigger flexibility to adjust to physics scene!

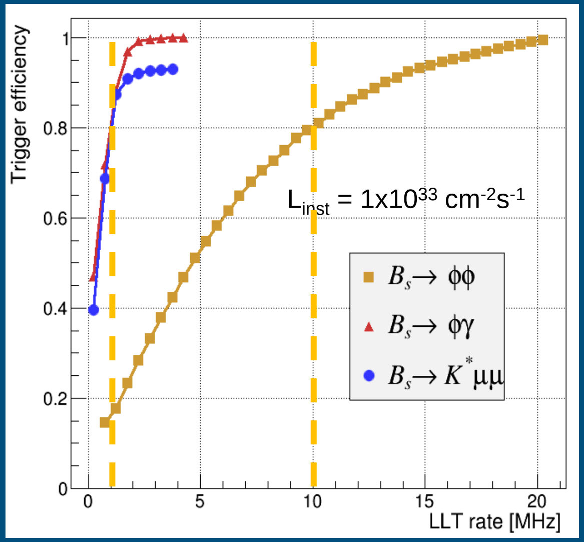
- Trigger challenge
  - 2% of bunch crossings with b-hadron decay in VELO
  - 25% of bunch crossings with c-hadron decay in VELO
  - 2 light long-lived hadrons decay in VELO every bunch crossing
  - ➔ Background suppression ➔ signal classification

Upgrade Trigger Architecture

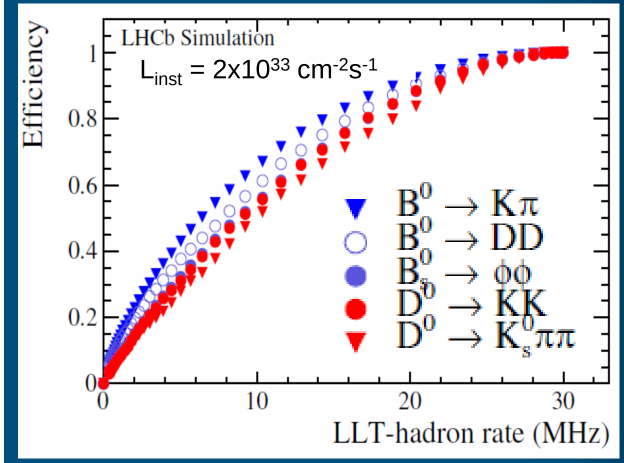


- Optional interaction pre-trigger in software (LLT): 15 – 30 MHz
  - E.g. Lower E_T/p_T cuts of e, γ, hadron, μ

CERN/LHCC 2011-001



CERN/LHCC 2014-16

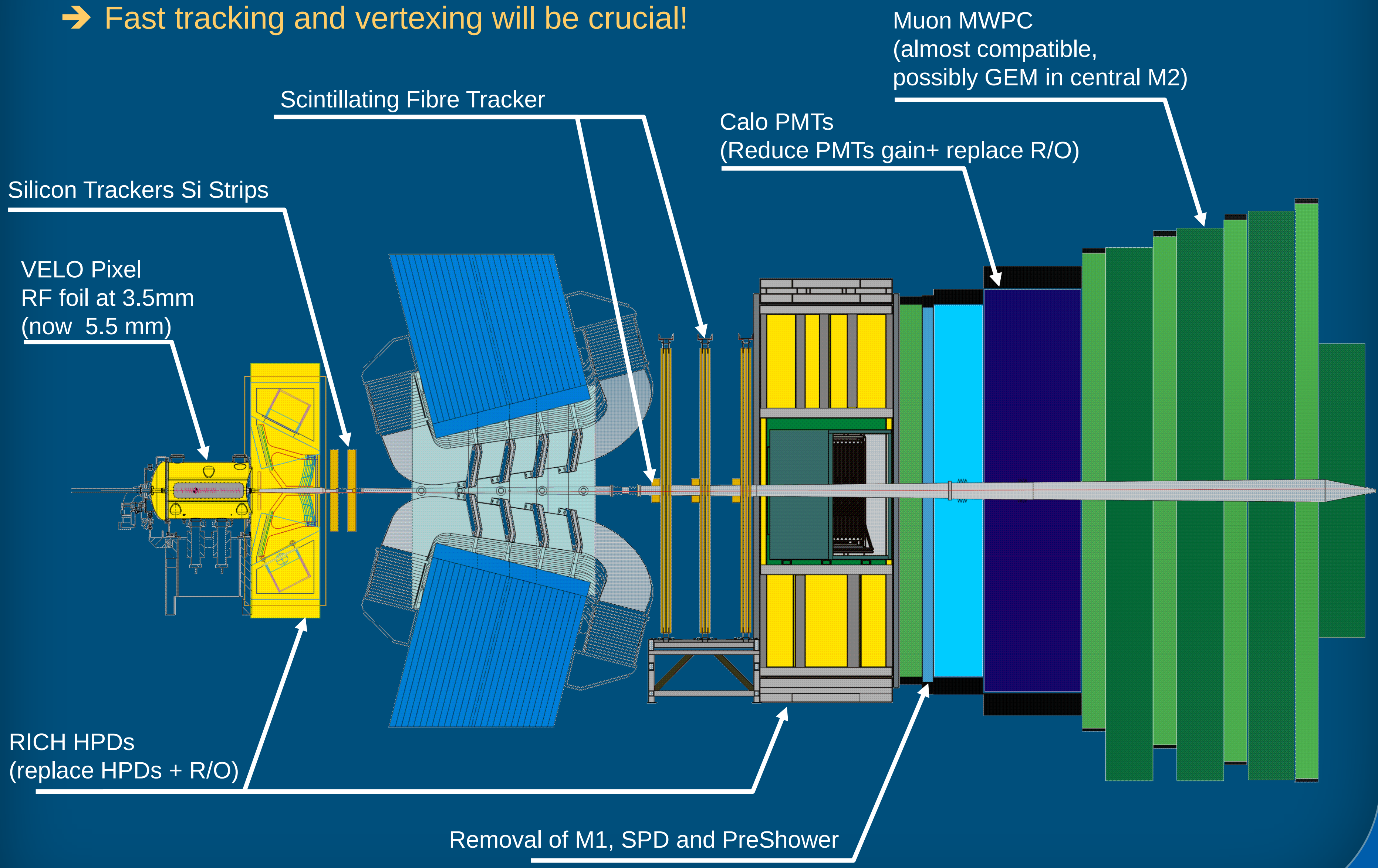


Decay	Run 1 L0xHLT	Upgrade@25kHz
$B^0 \to K^*[K\pi]\mu\mu$	89%	94%
$B_s \to \phi[KK]\phi[KK]$	20%	79%
$B^0 \to D^-[K\pi\pi]\mu\nu$	63%	81%
$\Lambda_b \to p\mu\nu$	54%	59%
$B^+ \to \pi KK$	36%	86%
$B_s \to J/\psi[\mu\mu]\phi[KK]$	91%	93%
$B^0 \to D^+[K\pi\pi]D^-[K\pi\pi]$	18%	56%

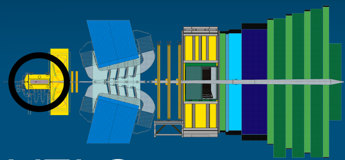
Detector Upgrades

Main detector replacement concern the tracking system

➔ Fast tracking and vertexing will be crucial!



VELO Upgrade

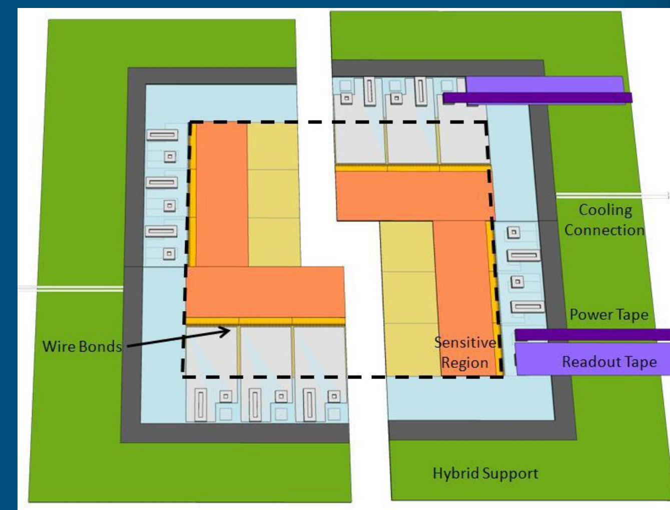


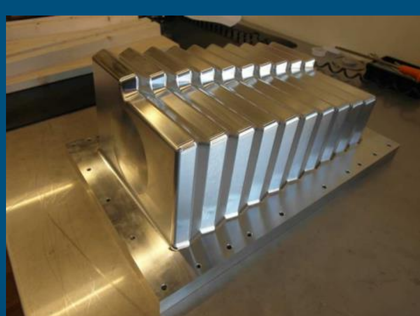
Current VELO:

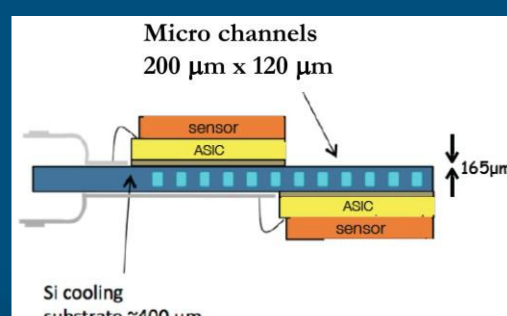
Rϕ silicon micro-strip with pitch 83-101 μm at 8mm from beam with 300μm RF foil

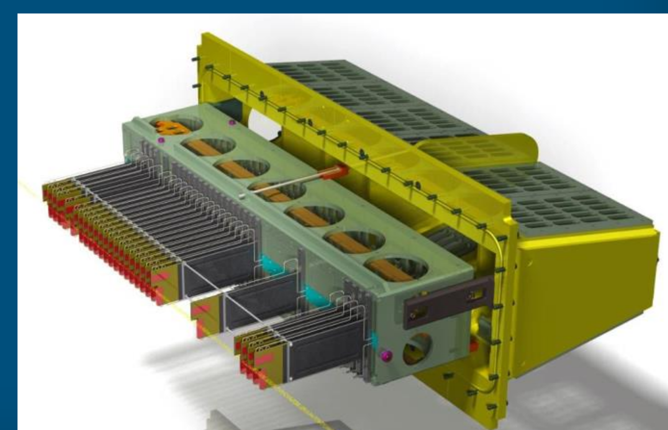
Upgrade:

- Higher granularity and improved resolution
  - ➔ 55×55 μm² silicon pixel
  - ➔ Reduced sensor distance to beam (5mm)
  - ➔ Thinner RF foil ~150 μm
  - ➔ VeloPix readout chip with 130 nm technology to sustain ~400 MRad
- Cooling challenge
  - Close to beam: ~ $8 \times 10^{15}\ n_{eq}cm^{-2}$ for 50 fb^{-1}
  - Cool to -10ºC to -15ºC to prevent thermal runaway
  - ➔ Micro-channel CO_2 cooling





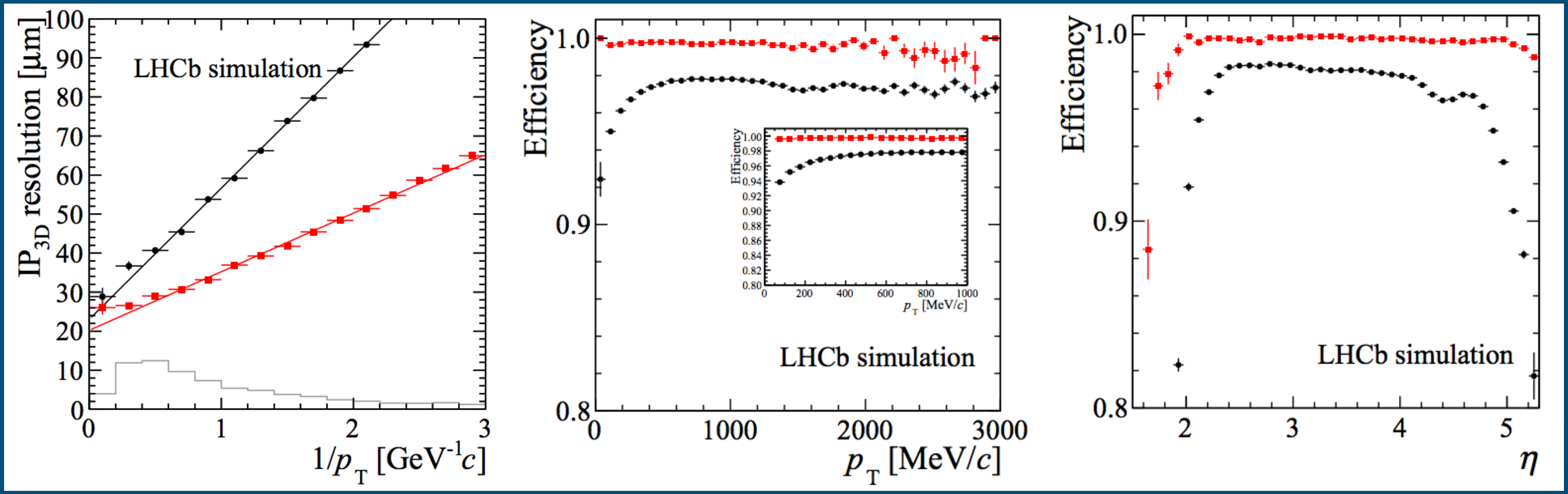


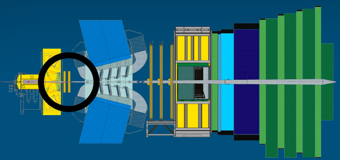


VELO Upgrade Performance

- Superior performance compared to current VELO (worse performance, wouldn't even weork!)
  - Better impact parameter resolution due to reduced material budget
  - Reduced ghost rate due to pixels
  - Improved efficiency over full range in p_T, ϕ, η

Simulated events @ L = 2×10^{33} cm^{-2}s^{-1}:

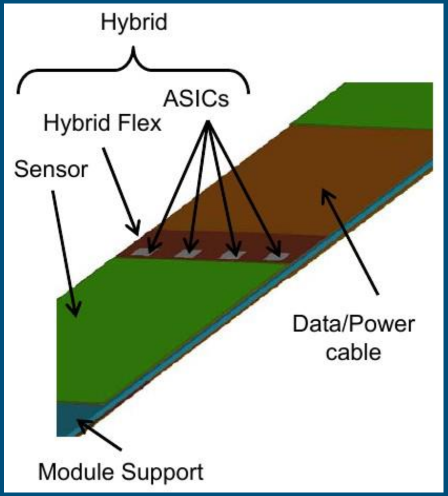


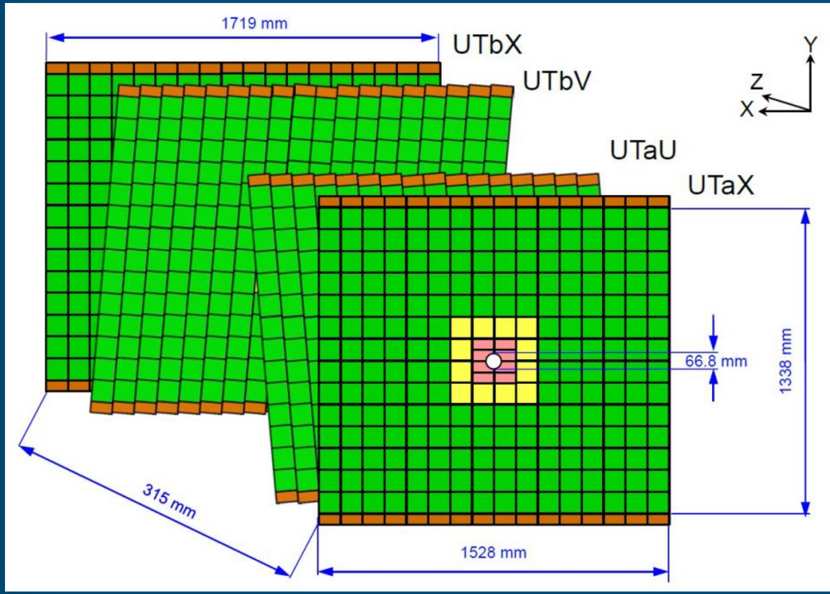


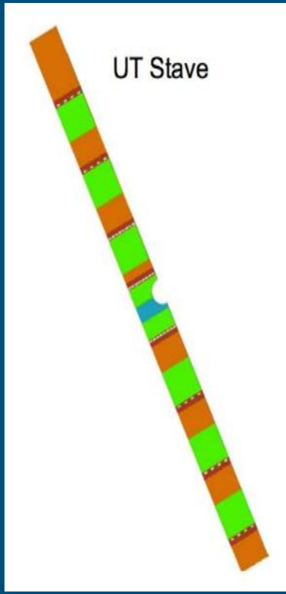
Upstream Tracker

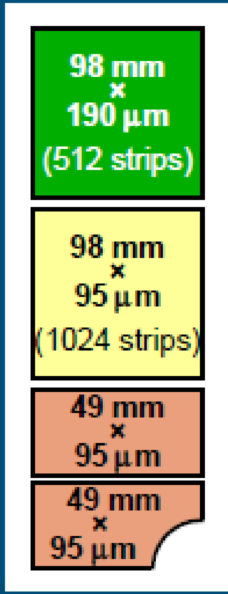
- Redone with Si strip technology: four layers of Si micro-strips
  - Less material with thinner sensors (500 μm → 250 μm)
  - Better coverage by overlapping sensors
  - Readout strip geometry adapted to particle flux
  - Closer to beam pipe improve small-angle acceptance
  - → Fast VELO-UT momentum measurement
  - → Reduce fake VELO-IT/OT tracks

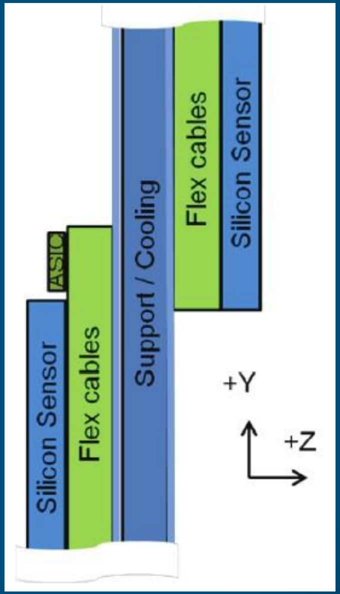
  - Bi-phase CO_2 cooling in stave support









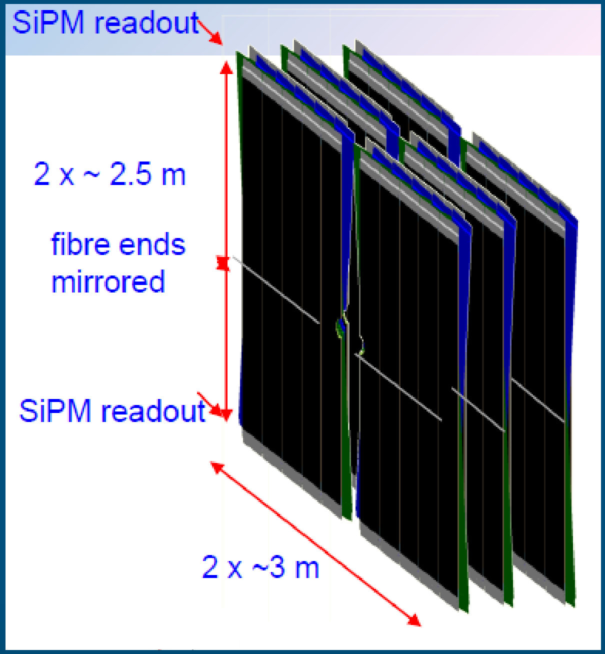


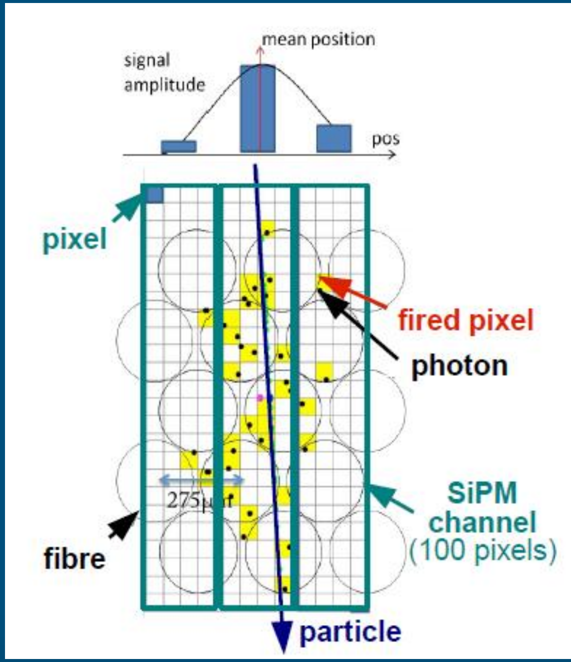
Downstream Tracker - SciFi

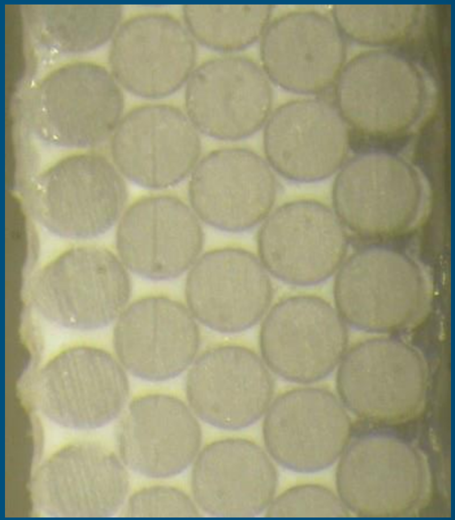
- Replacing completely straw tube and inner Si strips: Scintillating Fibres (SciFi)
  - Five layers of 2.5 m long scintillating fibres with 250 μm diameter
  - Need to keep the fibres straight to ~50 μm and flat to ~200 μm over 2.5m
  - Silicon Photo-Multiplier (SiPM) readout
  - Neutron damage to SiPM: cooled to –40ºC

➔ Expected performance: 60 – 100 μm spatial resolution

➔ Fast track reconstruction in trigger

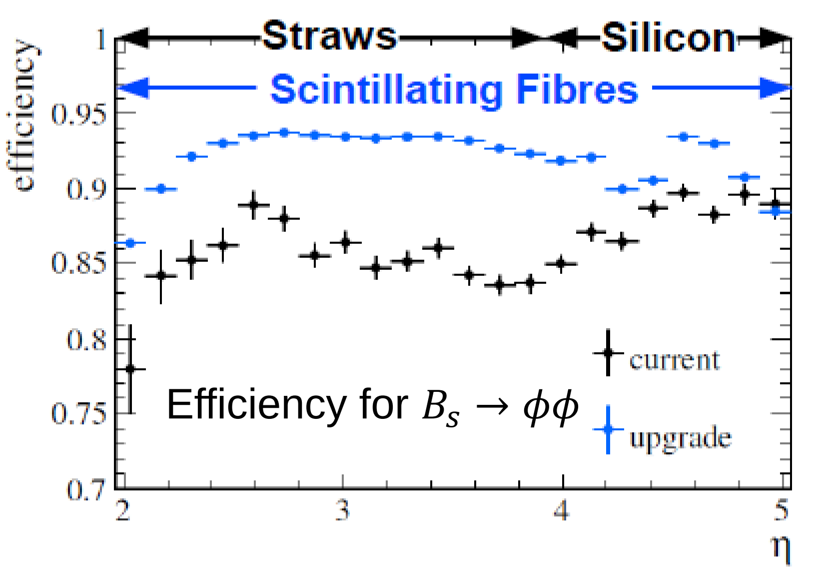


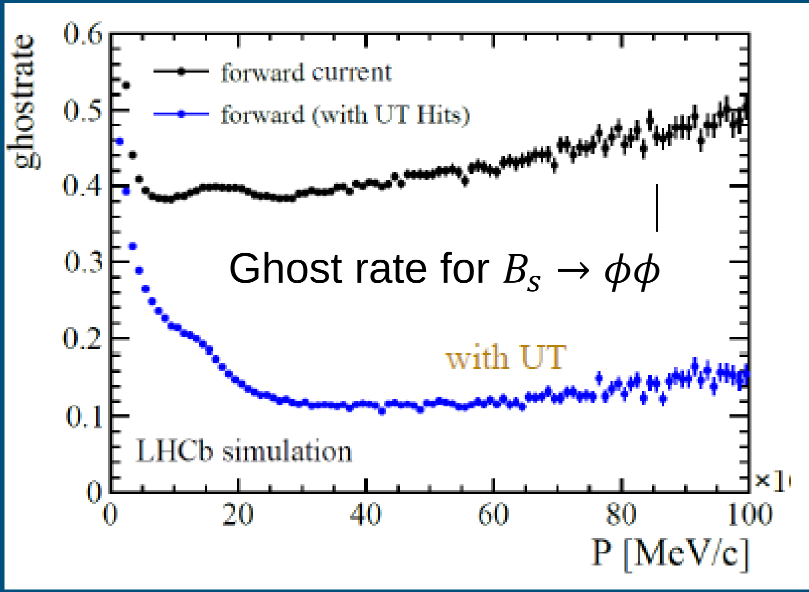




Tracking Performance

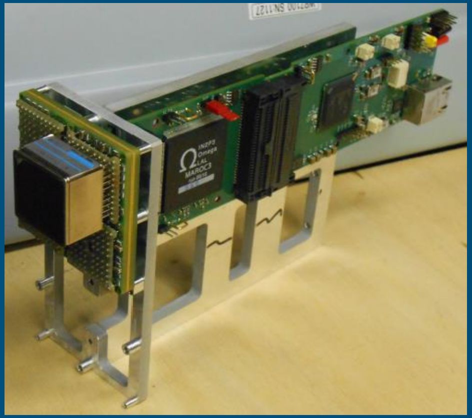
Comparing forward pattern recognition performance between current Si strips/straw tubes with Si strips/SciFi at L = 2×10^{33} cm^{-2}s^{-1}:





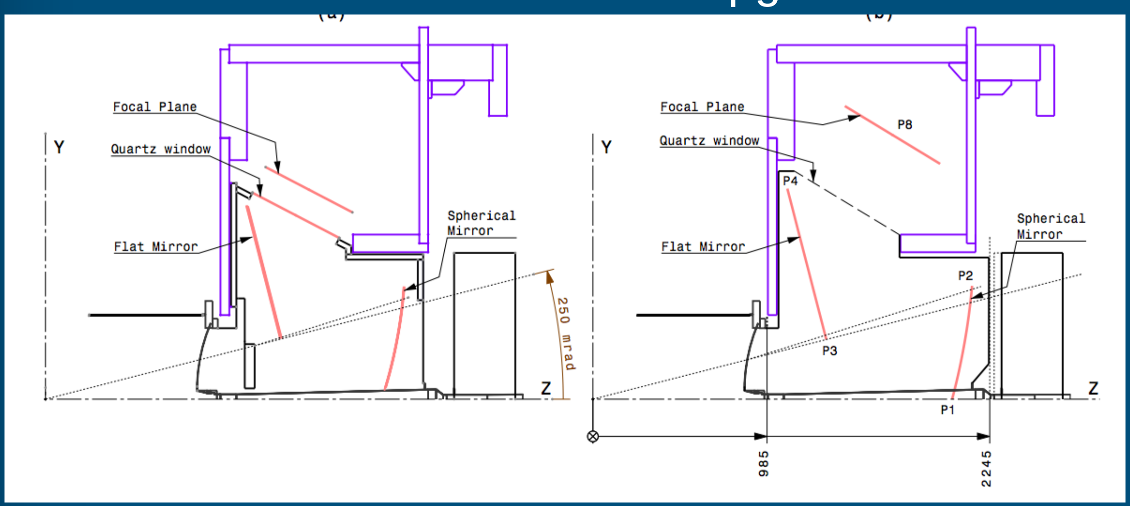
- With 10 × current CPU farm track reconstruction fits into 50 % of estimated HLT time budget of 13 ms

RICH Upgrade

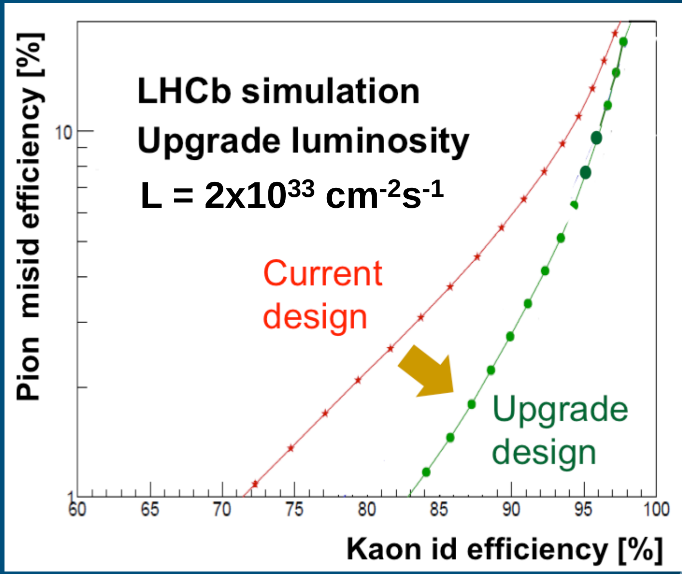


- Partial upgrade of both RICH1 and RICH2:
  - Replace HPDs with integrated FE electronics for MaPMT
  - Re-optimize RICH1 mirror optics
  - Spread out rings within current gas enclosure to compensate for higher occupancy

Current RICH1 | Upgrade RICH1



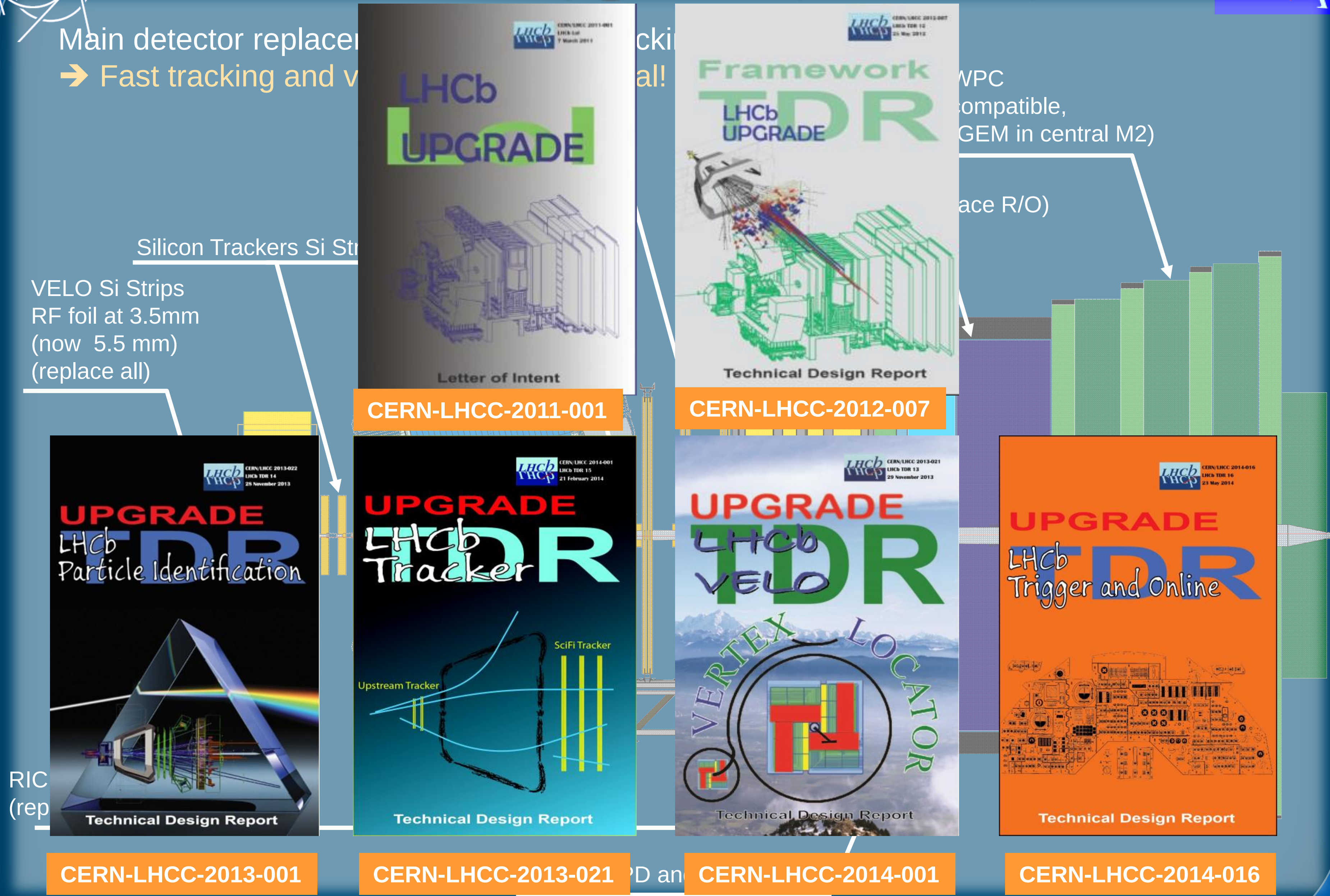
Upgraded K/π performance



Detector Upgrades (All done!)

Main detector replace[…] […]cki[…]

➔ Fast tracking and v[…] […]al!



Luminosity Projection up to 2029

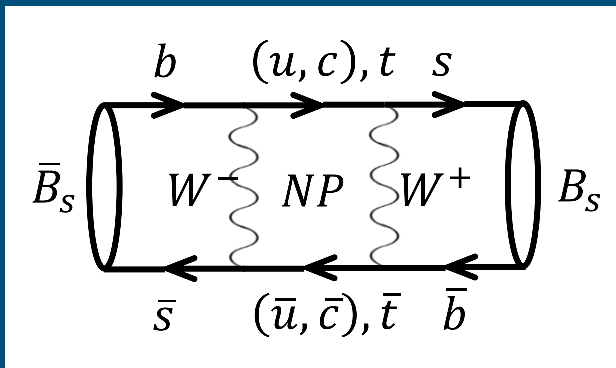
Luminosity projection based on experience in Run 1 and updated schedules:

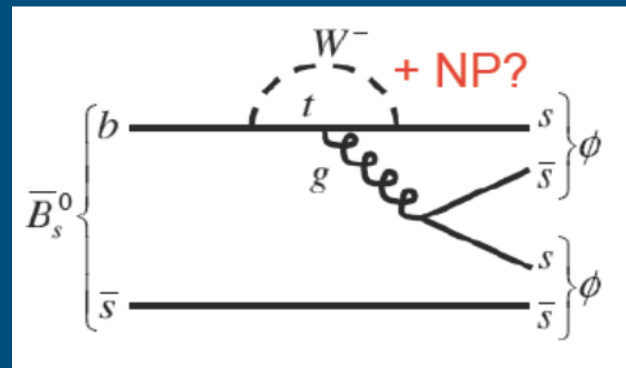
Event yield:

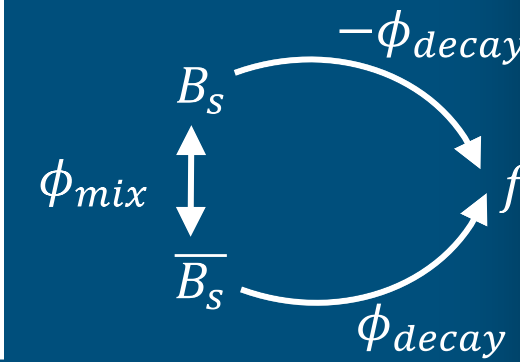
- 2015 – x 2 from σ(8 TeV → 13 TeV)
- 2020 – x 2 on hadronic efficiency

Example of prospects: ϕ_s

- CP violating weak phase from the interference between mixing and decay of B_s





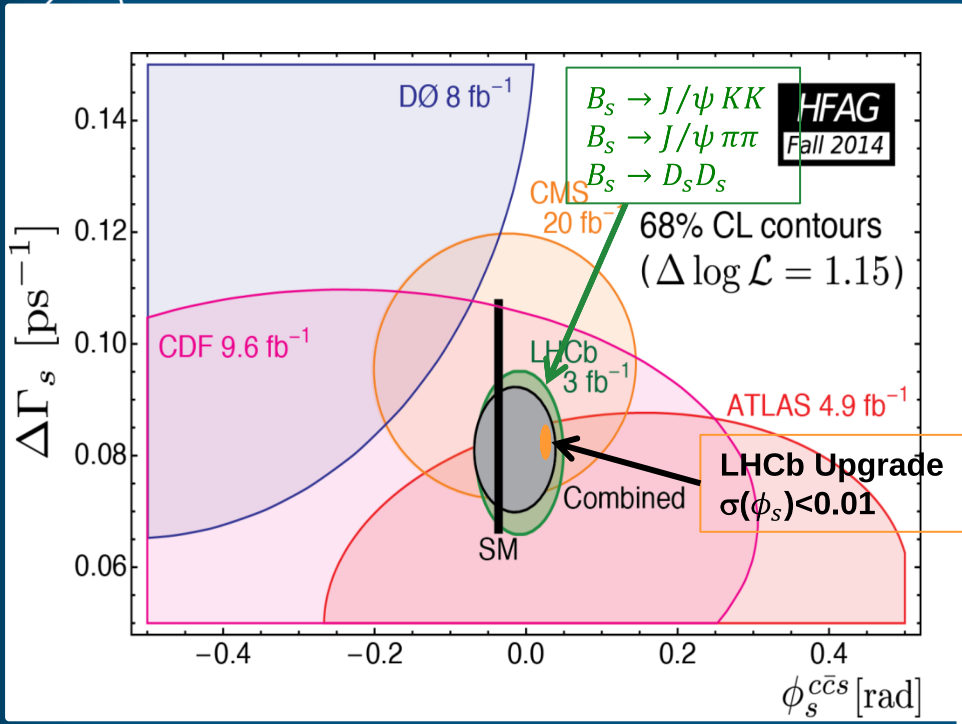


$$\phi_s = \phi_{mix} - 2\phi_{dec}$$

- Final state with charm: Tree-level decay → $\phi_s^{c\bar{c}s}$
  - $B_s \to J/\psi\,\phi,\ B_s \to J/\psi\, f^0,\ B_s \to D_s D_s$
  - Sensitive to NP in mixing

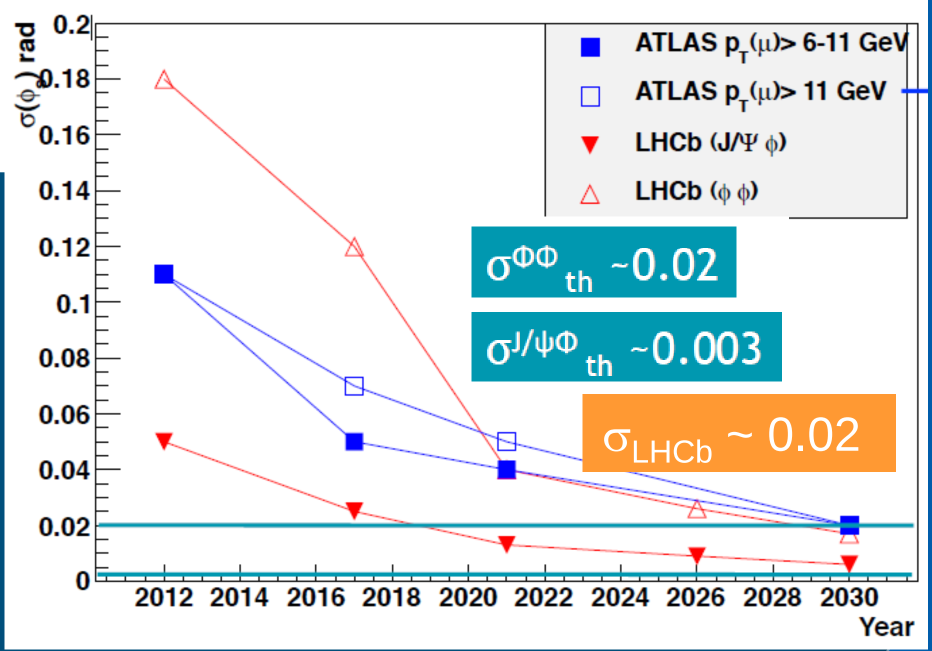
- Final state with strange: Gluonic penguin → $\phi_s^{s\bar{s}s}$ = 0 in SM due to cancellation
  - $B_s \to \phi\phi,\ B_d \to \phi K_s,\ B_d \to \eta' K_s$
  - SM null test
  - Sensitive to NP in mixing and decay

Example of prospects: ϕ_s



arXiv:1411.3104

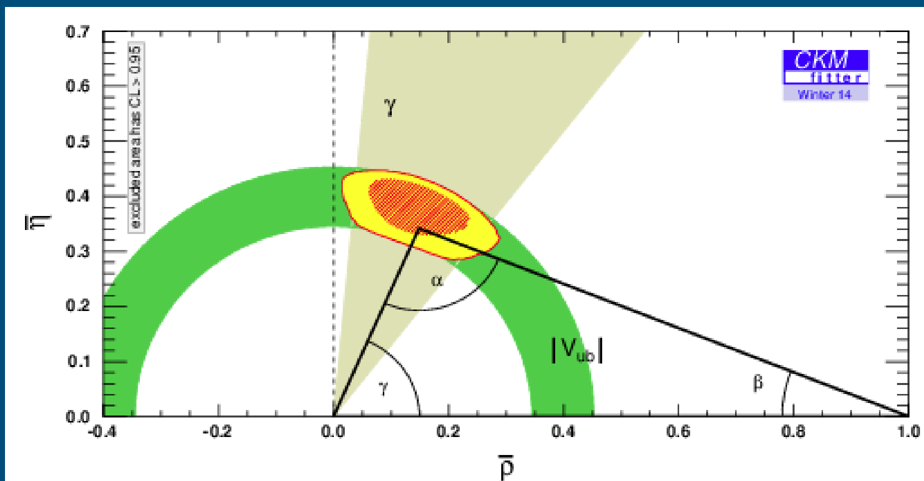
Expected future sensitivity on ϕ_s with 50 fb^{-1}

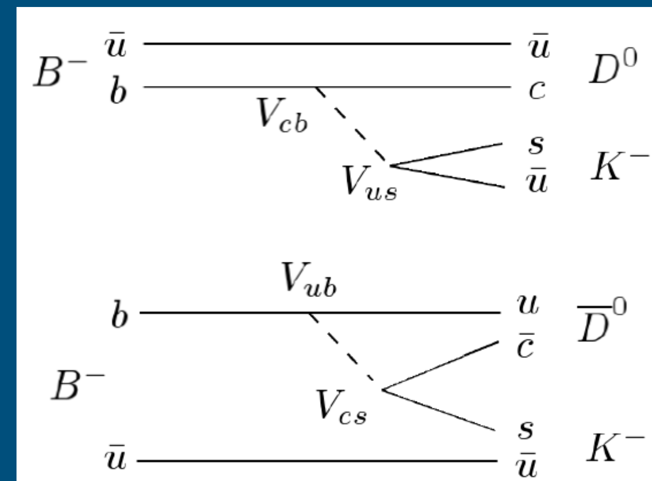


Benefit from better decay time resolution and increased decay time acceptance of the upgraded VELO

Example of prospects: γ

- Largest uncertainties in CKM matric are coming from $\gamma = \frac{|V_{ud}||V_{ub}^*|}{|V_{cd}||V_{cb}^*|}$ and $\frac{|V_{ub}|}{|V_{cb}|}$
  - Improved knowledge about CKM matrix help constraining NP contributions in rare decays
  - → Distinguish penguin contributions





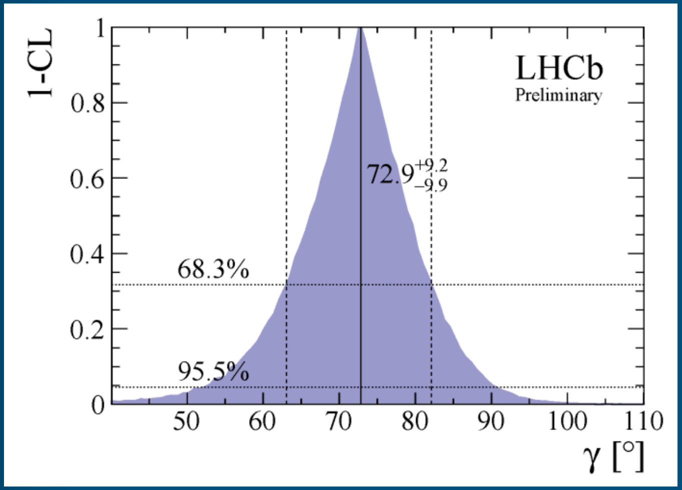
- The angle γ can be measured by comparing V_{cb} and V_{ub} mediated transitions
  - γ from purely trees: $B^\pm \to D^{(*)}K^{(*)}$ → SM reference with almost no theory uncertainty
  - $B_s \to D_s K^\pm$, loop (mixing) + tree (decay) → sensitive to NP in B_s mixing
  - γ from loop-mediated charmless decays $B \to h^+h^-$, $B^+ \to K^+\pi^+\pi^-$ → penguin sensitive to NP

Example of prospects: γ

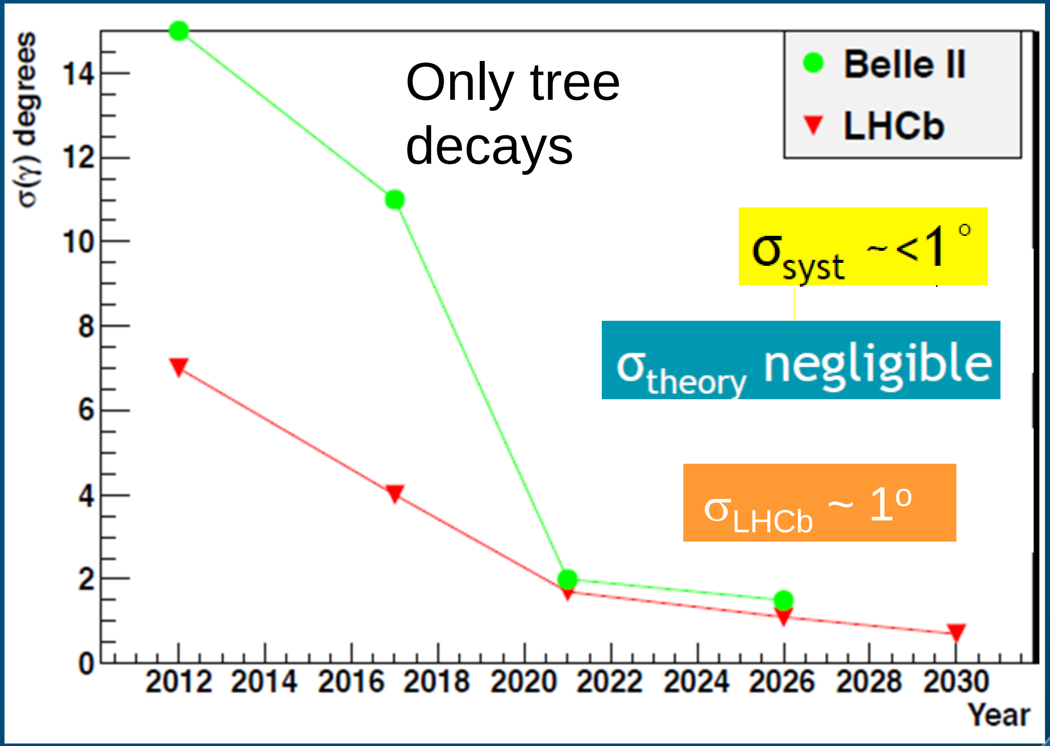
- LHCb can do them all
  - Ultimate precision from combination of many measurements with different sensitivity
  - Comparisons between tree/ loop-mediated for NP

Decay mode	γ sensitivity
$B \to DK$ with $D \to hh'$, $D \to K\pi\pi\pi$	1.3°
$B \to DK$ with $D \to K^0_S\pi\pi$	1.9°
$B \to DK$ with $D \to 4\pi$	1.7°
$B^0 \to DK\pi$ with $D \to hh'$, $D \to K^0_S\pi\pi$	1.5°
$B \to DK\pi\pi$ with $D \to hh'$	$\sim 3^\circ$
Time-dependent $B_s \to D_s K$	2.0°
Combined	$\sim 0.9^\circ$

Current status



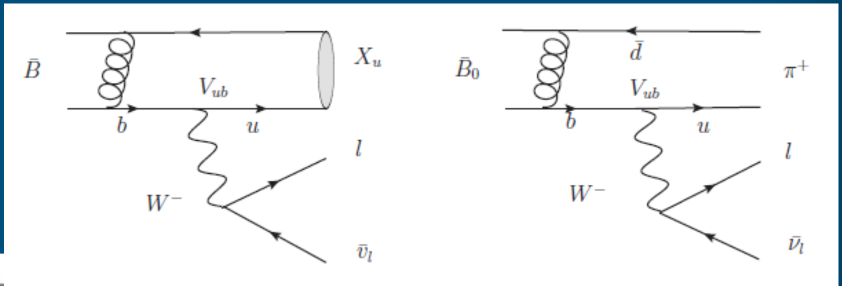
Expected future sensitivity on γ with 50 fb^{-1}



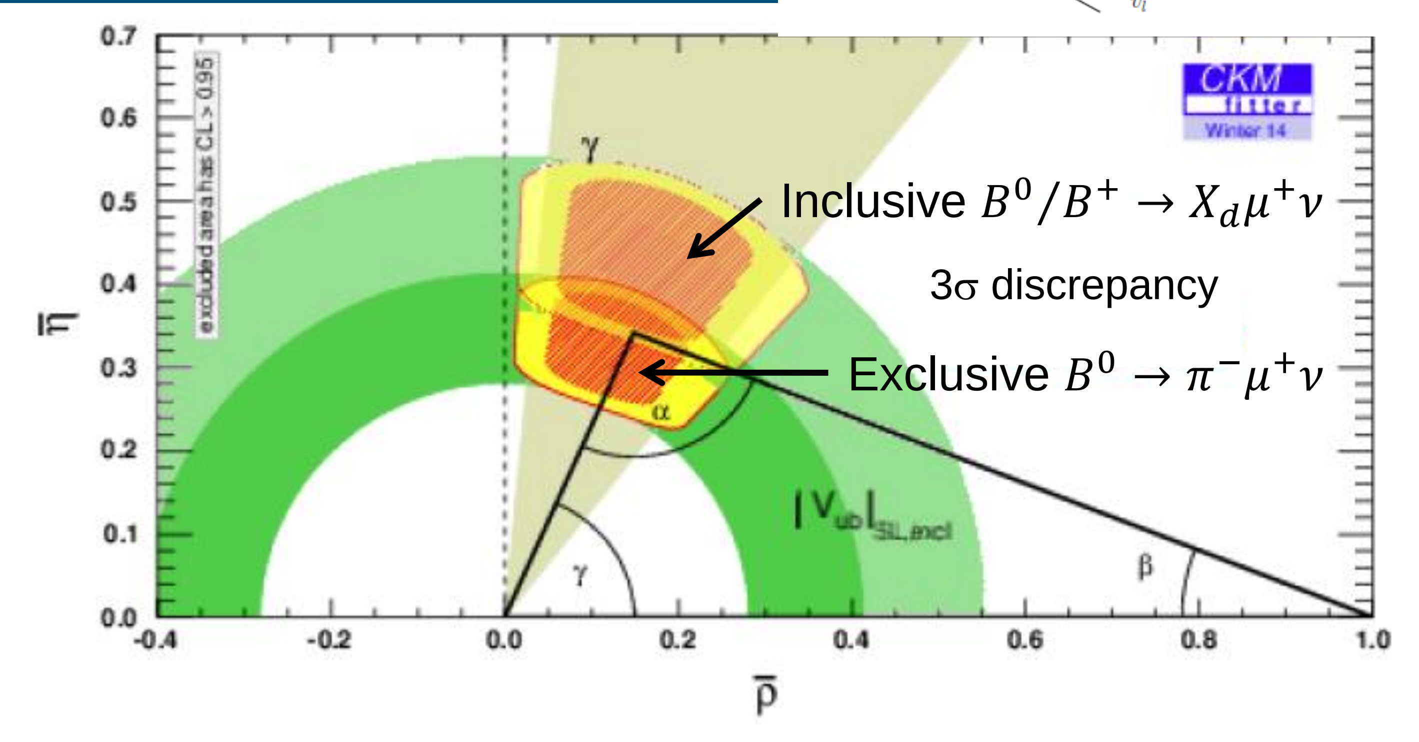
Fully hadronic B decays
➔ Major improvement with software trigger in Upgrade

Example of prospects : $|V_{ub}|$

- Normally reserved for B factories - $B \rightarrow \tau\nu$
- LHCb should be able to make a valuable contribution in semi-leptonic decays
  - Large pion background → use kaons and protons
  - $\Lambda_b \rightarrow p\mu^-\nu$
  - $B_s \rightarrow K^-\mu^+\nu$
  - $B_c \rightarrow D^0\mu^+\nu$



Current status

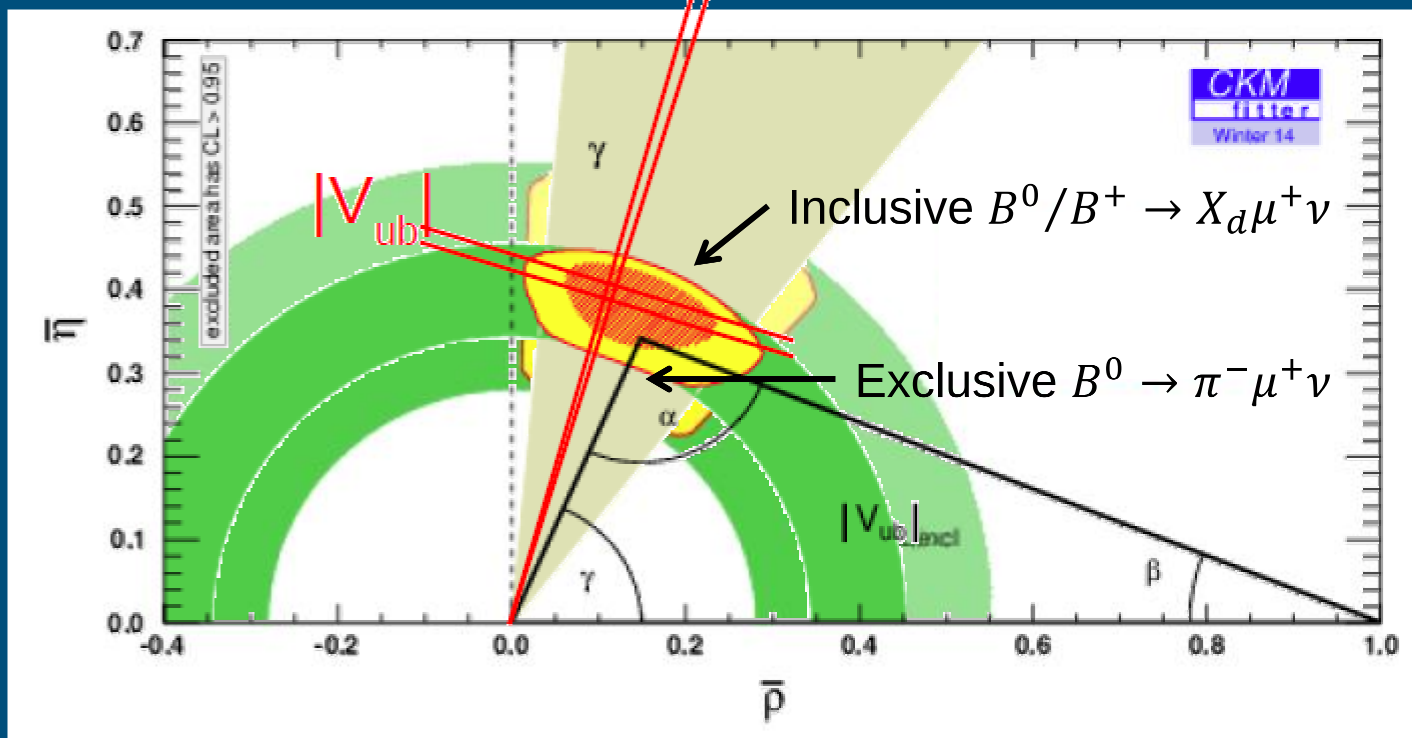


Example of prospects : $|V_{ub}|$

- Should be possible to reach a few percent precision

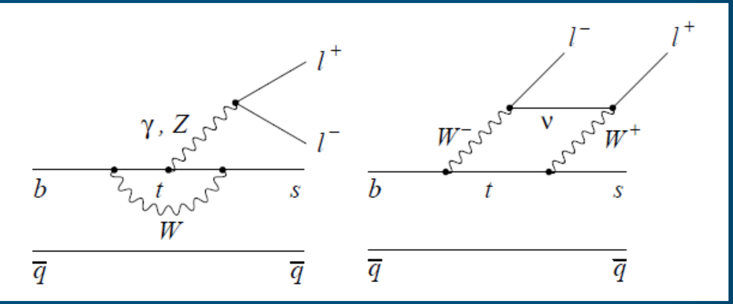
Benefit from RICH performance in Upgrade on K, π, p separation 2 – 100 GeV/c
Lepton pair invariant mass from using information about B flight direction with VELO

Expected future sensitivity on γ and $|V_{ub}|$



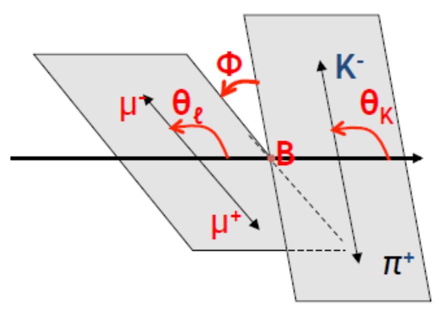
Example of prospects: $b \to s l^+ l^-$

- Electroweak penguin/box diagram sensitive to NP ➔ Helicity stucture
  - Measure photon polarization, photon dominance at low q^2
  - Sensitive to models with right-handed currents
  - $B_d \to K^* \mu^+ \mu^-$, $B_s \to \phi \mu^+ \mu^-$
  - System described by $q^2 = M^2(ll)$ and three angles
  - ➔ Angular analysis



E.g. $A_{FB}(q^2) = \frac{\Gamma(\cos\theta_{Bl^+}>0) - \Gamma(\cos\theta_{Bl^+}<0)}{\Gamma(\cos\theta_{Bl^+}>0) + \Gamma(\cos\theta_{Bl^+}<0)}$, $A_{FB}(q^2) = 0$

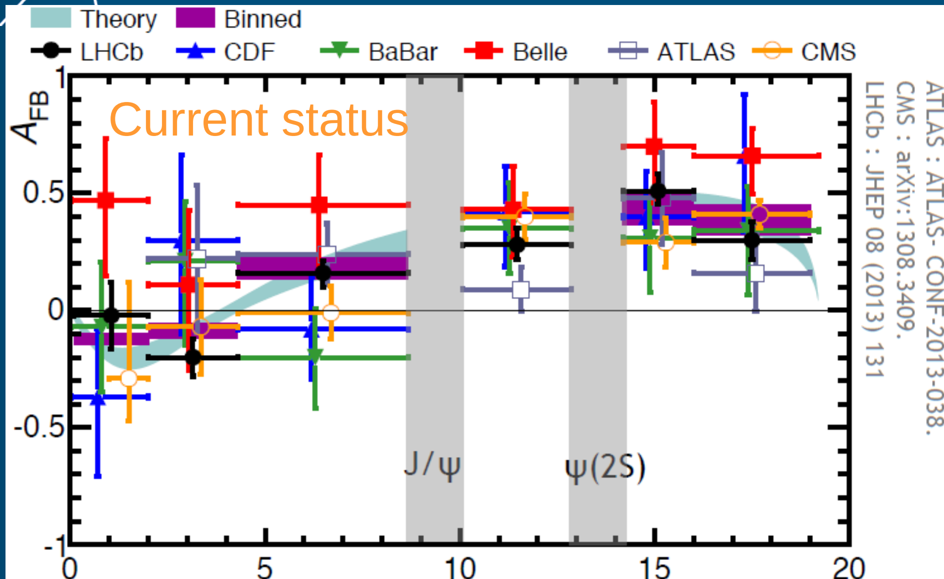
E.g. $A_T^{(2)}(q^2) = \frac{|A_\perp(q^2)|^2 - |A_\parallel(q^2)|^2}{|A_\perp(q^2)|^2 + |A_\parallel(q^2)|^2}$



➔ Currently only area with some interesting deviations

- Radiative penguins $b \to s\gamma^{(*)}$ complementary searches for NP: $B_d \to K^*\gamma$, $B_s \to \phi\gamma$

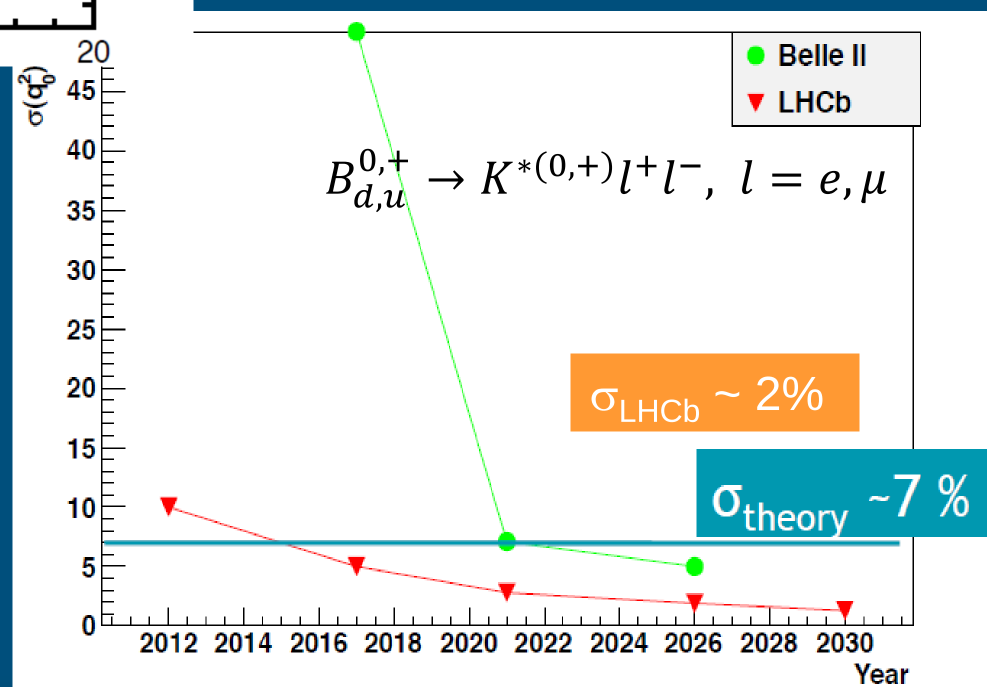
Example of prospects: $b \to sll$



$B^0 \to K^{*0}\mu^+\mu^-$

➔ LHCb: $q_0^2 = 4.9 \pm 0.9\ \mathrm{GeV}^2/c^4$

Expected future sensitivity on q_0^2 with 50 fb^{-1}



Example of prospect: Charm CPV

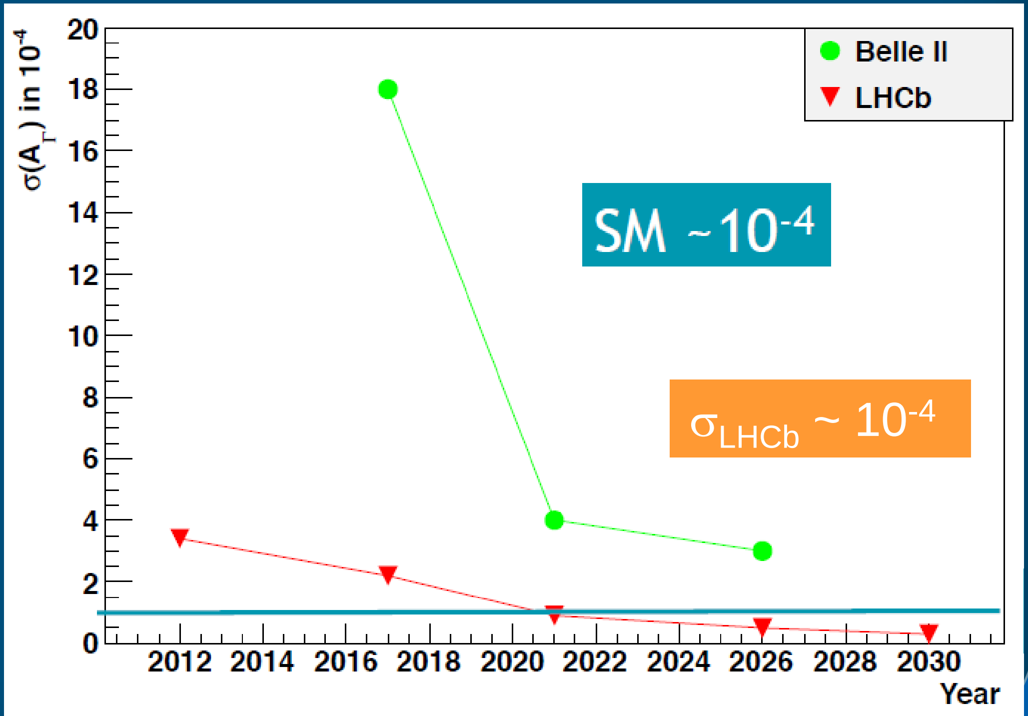
- Indirect CP violation in charm mixing expected to be very small in SM ($\sim 10^{-4}$)
  - ➔ D^0 only neutral system with FCNC decays with up type quarks

- Measure $A_\Gamma = \frac{\tau(\overline{D^0}\to h^+h^-) - \tau(D^0\to h^+h^-)}{\tau(\overline{D^0}\to h^+h^-) + \tau(D^0\to h^+h^-)}$ with $D^0 \to KK$ and $D^0 \to \pi\pi$

  → $A_\Gamma \neq 0$: indirect CP violation

  → $A_\Gamma(D^0 \to KK) \neq A_\Gamma(D^0 \to \pi\pi)$: Direct CP violation

The fully hadronic software trigger and the improved impact parameter resolution of the Upgrade are crucial



Upgrade Physics Prospects

- Currently 3.2 fb^{-1} of integrated luminosity ➔ 200++ papers and counting
- Expect +5 fb^{-1} in 2015 – 2018 Run 2 ➔ Far from σ_{theory} still in 2018
  - ➔ + >50 fb^{-1} for the upgrade

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 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)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	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%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 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°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	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	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

+ a wealth of additional physics

- ➔ Diversity and non-spectator effect of the B_c system, and baryons
- ➔ Lepton universality, lepton flavour violation, searches for long-lived portals
- Production measurements and spectroscopy, QCD, PDFs, and EW
- …and quarkonium and Z production in pA and possibly also AA collisions

Conclusions

- LHCb has fought hard to earn the title of Forward GPD
  - LHCb has demonstrated forward tracking and particle ID in pileup environment
  - A very rich physics precision program – well beyond the initial objectives
  - Continuing on this the LHCb upgrade is largely a trigger upgrade with the ultimate flexibility!
- Folding in efficiencies and luminosity, upgrade get up to 20 times more hadronic evts/s !
  - Challenging, but realistic

→ Upgrade allows reaching theoretical uncertainties and opens the door to new observables

→ LHCb entering now F. Maltoni's "Phase 2 legacy measurements" of $\mathcal{L}_{Eff}^{(6)}$

- The LHCb Upgrade has been fully approved by CERN and is in the production phase.
  - Installation and commissioning in LS2 2018-2020
- Hungry for flavour!

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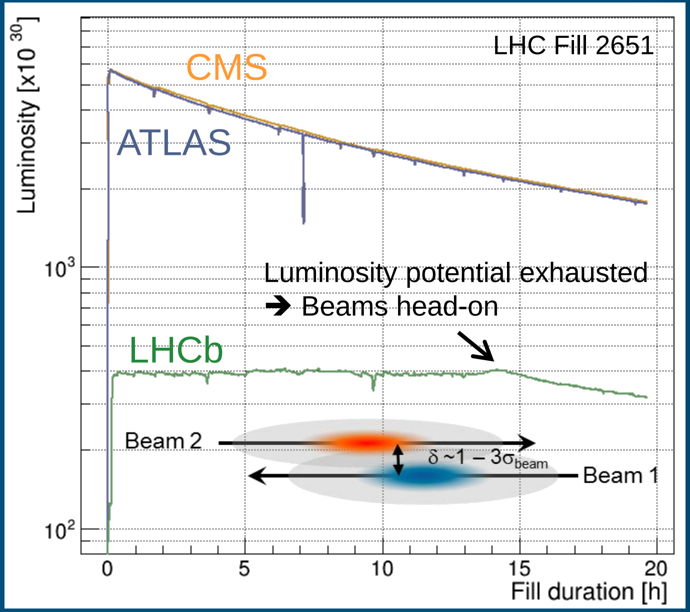
EXTRA SLIDES

(Operational Novelties in Run 1/2)

Operational developments to maximize LHCb physics yield

1. Luminosity control
   - Stable luminosity (pileup) through-out fills / months
     - Same trigger configuration
     - Stable detector performance and radiation effects
     - ➔Reduced systematics
     - ➔95% of the total integrated luminosity was recorded within 3% of the optimal luminosity 2011-2012



R. Jacobsson, Proc. IEEE NPSS-MIC 2012

2. Deferred triggering in High-Level Trigger Farm
   - HLT1 accepted events written on local farm node disks and processed asynchronously during fill and inter-fill time

3. Online alignment and calibrations ➔ Trigger Turbo Stream
   - Allow direct analysis of Golden physics modes

4. LHCb dipole polarity switches

   ➔Systematics from residual detector asymmetries averaged out by flipping dipole polarity every 1-2 weeks

➔ All of which will continue to be crucial in the future