



Triggers in LHCb

past, present, future

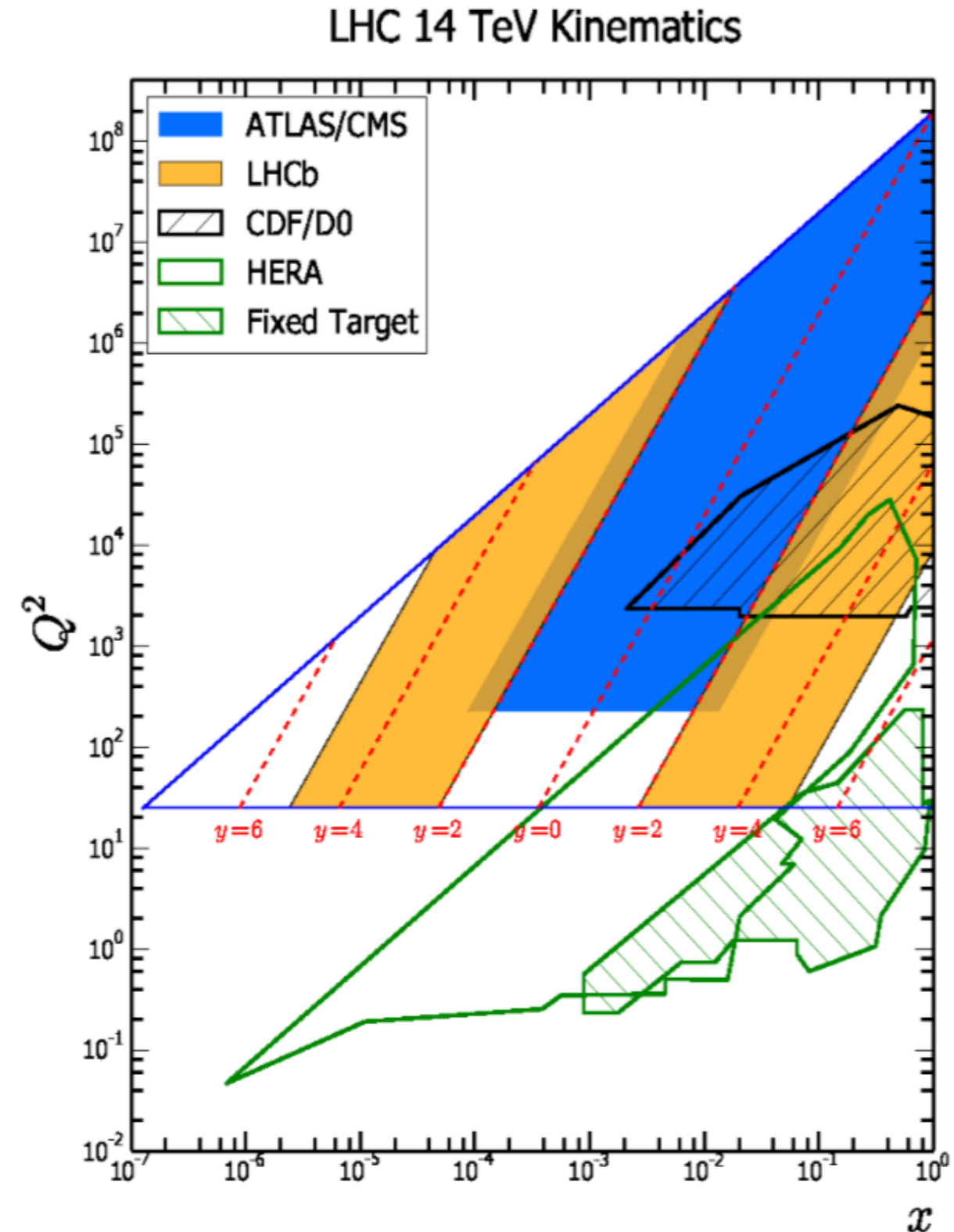
Triggering Discoveries in High Energy Physics II
Feb 1, 2018 ♦ Puebla City, MX

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on behalf of LHCb Collaboration



NRU Higher School of Economics,
Yandex School of Data Analysis

- ◇ LHCb – General purpose detector in forward direction
 - ◇ Physics program is focused on Heavy Flavour physics
- ◇ But LHCb trigger enables and has to enable a wide range of physics
 - ◇ Unique rapidity coverage at hadron collider
- ◇ Rich program of:
 - ◇ Electroweak physics
 - ◇ Production and spectroscopy
 - ◇ Heavy Ion and fixed target physics
 - ◇ Strange physics



New Physics Searches at LHC

Direct observation

- comprehensive searches by Atlas and CMS
- no hints for New Physics yet

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets†	E_{T}^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1-4 j	Yes	36.1	M_{Pl} 7.75 TeV
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_{Pl} 8.6 TeV
	ADD QBH	-	2 j	-	37.0	M_{Pl} 8.9 TeV
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	M_{Pl} 8.2 TeV
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{Pl} 9.55 TeV
RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	G_{KK} mass 4.1 TeV	
Bulk RS $G_{KK} \rightarrow WW \rightarrow qq/\nu$	1 e, μ	1 j	Yes	36.1	G_{KK} mass 1.75 TeV	
ZUED / RPP	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	13.2	KK mass 1.6 TeV	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	36.1	Z' mass 4.5 TeV
	SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	36.1	Z' mass 2.4 TeV
	Leptophobic $Z' \rightarrow bb$	-	2 b	-	3.2	Z' mass 1.5 TeV
	Leptophobic $Z' \rightarrow tt$	1 e, μ	$\geq 1 b, \geq 1 J, \geq 2 j$	Yes	3.2	Z' mass 2.0 TeV
	SSM $W' \rightarrow \ell\nu$	1 e, μ	-	Yes	36.1	W' mass 5.1 TeV
HVT $V' \rightarrow WW \rightarrow qq\bar{q}\bar{q}$ model B	0 e, μ	2 j	-	36.7	V' mass 3.5 TeV	
HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass 2.93 TeV	
LRSM $W'_R \rightarrow tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV	
LRSM $W'_R \rightarrow tb$	0 e, μ	$\geq 1 b, \geq 1 j$	Yes	20.3	W' mass 1.76 TeV	
CI	CI $qqqq$	-	2 j	-	37.0	A 21.8 TeV η_{LL}
	CI $\ell\ell qq$	2 e, μ	-	-	36.1	A 40.1 TeV η_{LL}
	CI $uutt$	2(SS)/ $\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	20.3	A 4.9 TeV $ C_{\text{SM}} = 1$
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1	m_{DM} 1.5 TeV
	Vector mediator (Dirac DM)	0 $e, \mu, 1 \gamma$	$\leq 1 j$	Yes	36.1	m_{DM} 1.2 TeV
	VV $_{\chi\chi}$ EFT (Dirac DM)	0 e, μ	1 j, $\leq 1 j$	Yes	3.2	M_{Pl} 700 GeV
LQ	Scalar LQ 1 st gen	2 e	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV
	Scalar LQ 2 nd gen	2 μ	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV
	Scalar LQ 3 rd gen	1 e, μ	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV
Heavy quarks	VLO $TT \rightarrow Ht + X$	0 or 1 e, μ	$\geq 2 b, \geq 3 j$	Yes	13.2	T mass 1.2 TeV
	VLO $TT \rightarrow Zt + X$	1 e, μ	$\geq 1 b, \geq 3 j$	Yes	36.1	T mass 1.16 TeV
	VLO $TT \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1 J, \geq 2 j$	Yes	36.1	T mass 1.35 TeV
	VLO $BB \rightarrow Hb + X$	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	20.3	B mass 700 GeV
	VLO $BB \rightarrow Zb + X$	2/ $\geq 3 e, \mu$	$\geq 2 b, \geq 1 j$	-	20.3	B mass 790 GeV
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 j	-	37.0	q^* mass 6.0 TeV
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7	q^* mass 5.3 TeV
	Excited quark $b^* \rightarrow bg$	-	1 b, 1 j	-	13.3	b^* mass 2.3 TeV
Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	
Excited lepton ℓ^*	3 e, μ, τ	-	-	20.3	ℓ^* mass 3.0 TeV	
Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.6 TeV	
Other	LRSM Majorana ν	2 e, μ	2 j	-	20.3	M_{Pl} mass 2.0 TeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV
	Multi-charged particles	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV
	Magnetic monopoles	-	-	-	7.0	multi-charged particle mass 795 GeV monopole mass 1.34 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

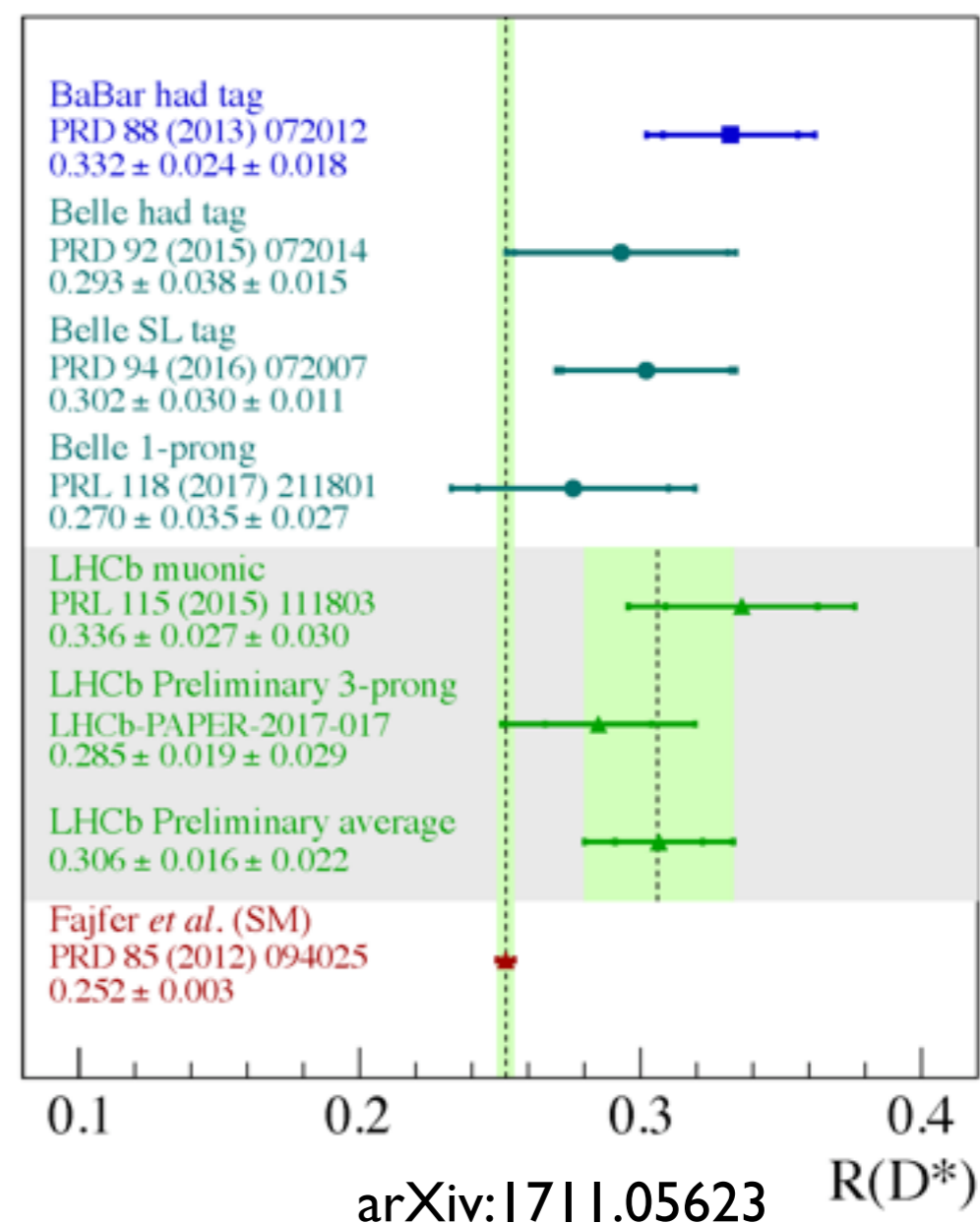
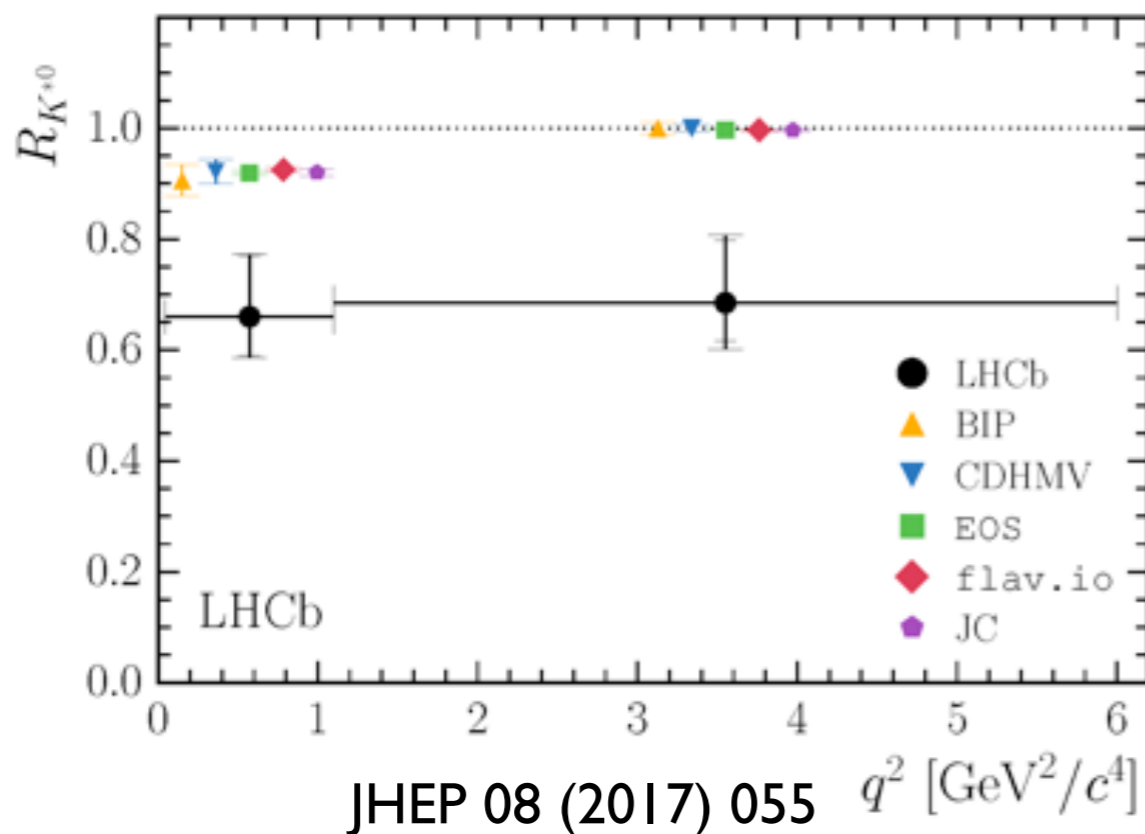
$\sqrt{s} = 7, 8, 13 \text{ TeV}$

Model	e, μ, τ, γ	Jets	E_{T}^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{q}^0$	0	2-6 jets	Yes	36.1	\tilde{q} 1.57 TeV
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{q}^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	\tilde{q} 710 GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{g}^0$	0	2-6 jets	Yes	36.1	\tilde{g} 2.02 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{g}^0$	0	2-6 jets	Yes	36.1	\tilde{g} 2.01 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{g}^0$	0	2-6 jets	Yes	14.7	\tilde{g} 1.7 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{g}^0$	3 e, μ	4 jets	-	36.1	\tilde{g} 1.87 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{g}^0$	0	7-11 jets	Yes	36.1	\tilde{g} 1.8 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{g}^0$	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	\tilde{g} 2.0 TeV
	GMSB (\tilde{g} NLSP)	2 γ	-	Yes	36.1	\tilde{g} 2.05 TeV
	GGM (bino NLSP)	2 γ	-	Yes	36.1	\tilde{g} 2.15 TeV
3 rd gen. squarks direct production	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^0$	0	3 b	Yes	36.1	\tilde{g} 1.92 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}^0$	0-1 e, μ	3 b	Yes	36.1	\tilde{g} 1.97 TeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{b}^0$	0	2 b	Yes	36.1	\tilde{b}_1 950 GeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{b}^0$	2 e, μ (SS)	1 b	Yes	36.1	\tilde{b}_1 275-700 GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}^0$	0-2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1 200-720 GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{t}^0$ or $t\tilde{t}^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	\tilde{t}_1 90-198 GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}^0$	0	mono-jet	Yes	36.1	\tilde{t}_1 90-430 GeV
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1 150-600 GeV
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow t\tilde{t}^0 + Z$	3 e, μ (Z)	1 b	Yes	36.1	\tilde{t}_2 290-790 GeV
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow t\tilde{t}^0 + h$	1-2 e, μ	4 b	Yes	36.1	\tilde{t}_2 320-880 GeV
EW direct	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \ell\ell^0$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^0$ 90-500 GeV
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \ell\ell^0$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^0$ 750 GeV
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \ell\ell^0$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^0$ 760 GeV
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \ell\ell^0$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^0$ 1.13 TeV
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^0$ 580 GeV
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^0$ 270 GeV
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow h\tilde{\chi}_1^0$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_1^0$ 635 GeV
	GGM (bino NLSP) weak prod. $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{\chi}_1^0$ 115-370 GeV
	GGM (bino NLSP) weak prod. $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 γ	-	Yes	36.1	$\tilde{\chi}_1^0$ 1.06 TeV
	Long-lived particles	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	Yes	36.1
Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$		dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^0$ 495 GeV
Stable, stopped $\tilde{\chi}_1^0$ R-hadron		0	1-5 jets	Yes	27.9	$\tilde{\chi}_1^0$ 850 GeV
Stable $\tilde{\chi}_1^0$ R-hadron		trk	-	-	3.2	$\tilde{\chi}_1^0$ 1.58 TeV
Metastable $\tilde{\chi}_1^0$ R-hadron		dE/dx trk	-	-	3.2	$\tilde{\chi}_1^0$ 1.57 TeV
Metastable $\tilde{\chi}_1^0$ R-hadron, $\tilde{\chi}_1^0 \rightarrow q\tilde{q}^0$		displ. vtx	-	Yes	32.8	$\tilde{\chi}_1^0$ 2.37 TeV
GMSB, stable $\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \ell\ell^0 + \tau(e, \mu)$		1-2 m	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$		2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 440 GeV
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow e\tilde{e}^0/\mu\tilde{\mu}^0/\nu\tilde{\nu}^0$		displ. ee/ $\mu\mu$	-	-	20.3	\tilde{g} 1.0 TeV
RPV		LFV $pp \rightarrow \nu_i + X, \nu_i \rightarrow e\mu/\tau\mu$	$e\mu/\tau\mu$	-	-	3.2
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{\nu}_i$ 1.45 TeV
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\nu, e\nu, \mu\nu, \mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^0$ 1.14 TeV
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\nu, e\nu, e\nu, \tau\nu$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^0$ 450 GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}^0, \tilde{g} \rightarrow q\tilde{q}^0$	0	4-5 large-R jets	-	36.1	\tilde{g} 1.875 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}^0, \tilde{g} \rightarrow q\tilde{q}^0$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g} 2.1 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}^0, \tilde{g} \rightarrow q\tilde{q}^0$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g} 1.65 TeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}^0$	0	2 jets + 2 b	-	36.7	\tilde{t}_1 100-470 GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}^0$	2 e, μ	2 b	-	36.1	\tilde{t}_1 480-610 GeV
	Other	Scalar charm, $\tilde{\chi}_1^0 \rightarrow c\tilde{c}^0$	0	2 c	Yes	20.3

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

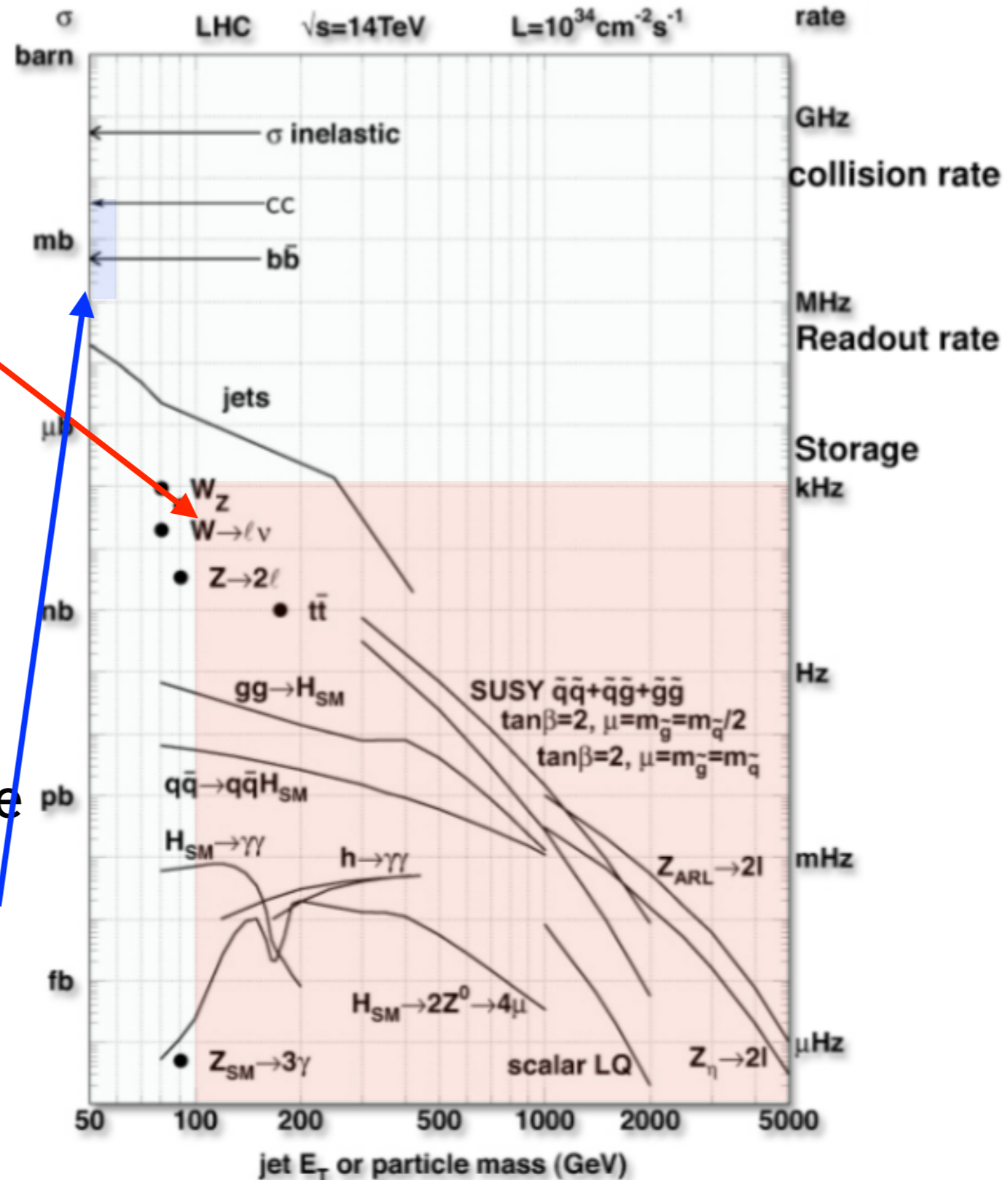
◇ Indirect searches

- ◇ NP driven fine effects in heavy flavour hadrons production and decays
- ◇ Hints are here, need more data for conclusive statements



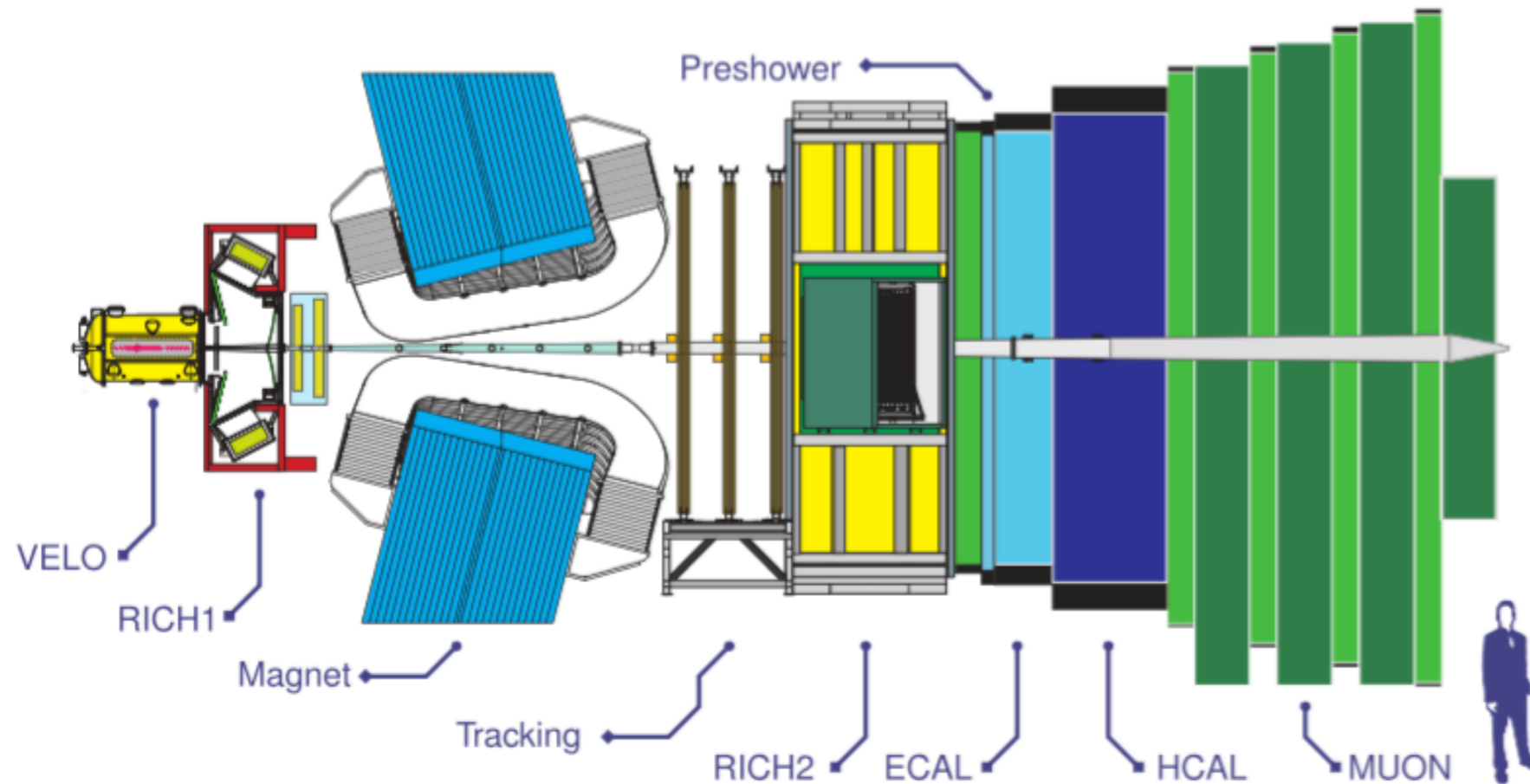
Challenge

- ◇ Direct observation of New Physics requires signal rate at level kHz and below in high- p_T region
- ◇ regular trigger concept is applicable
- ◇ CMS/Atlas use case
- ◇ Indirect observation of New Physics in parameters of heavy quarks decays requires signal rate at level of MHz in low- p_T region
- ◇ new trigger concepts are necessary
- ◇ LHCb use case



LHCb Detector

JINST 3 (2008) S08005, Int. J. Mod. Phys. A30 (2015) I530022

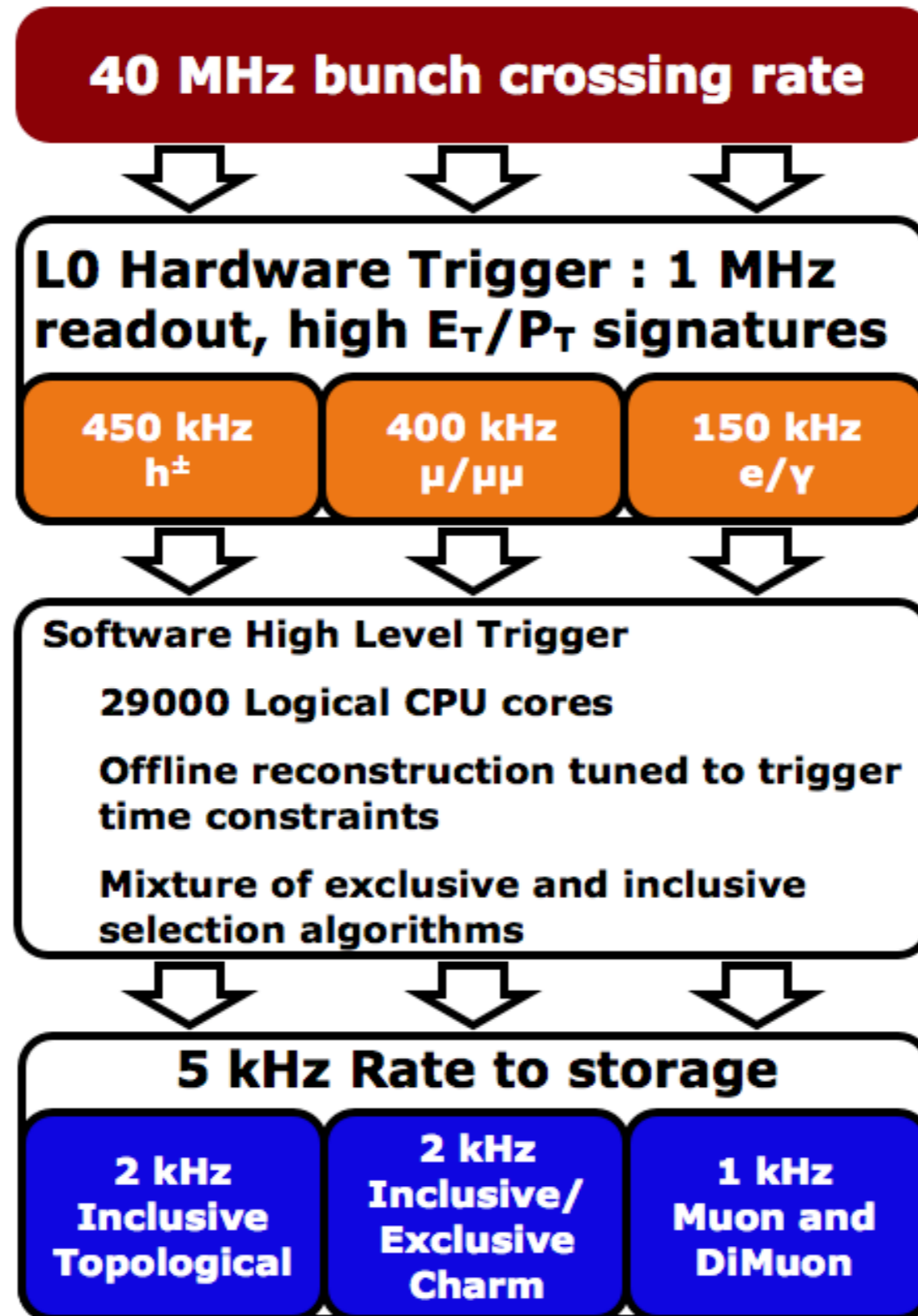


- ◇ LHCb was built to study beauty and charm at the LHC
 - ◇ Precise particle identification (RICH + MUON)
 - ◇ Excellent decay time resolution: $\sim 45\text{fs}$ (VELO)
 - ◇ High purity + Efficiency with flexible **trigger**

Run I

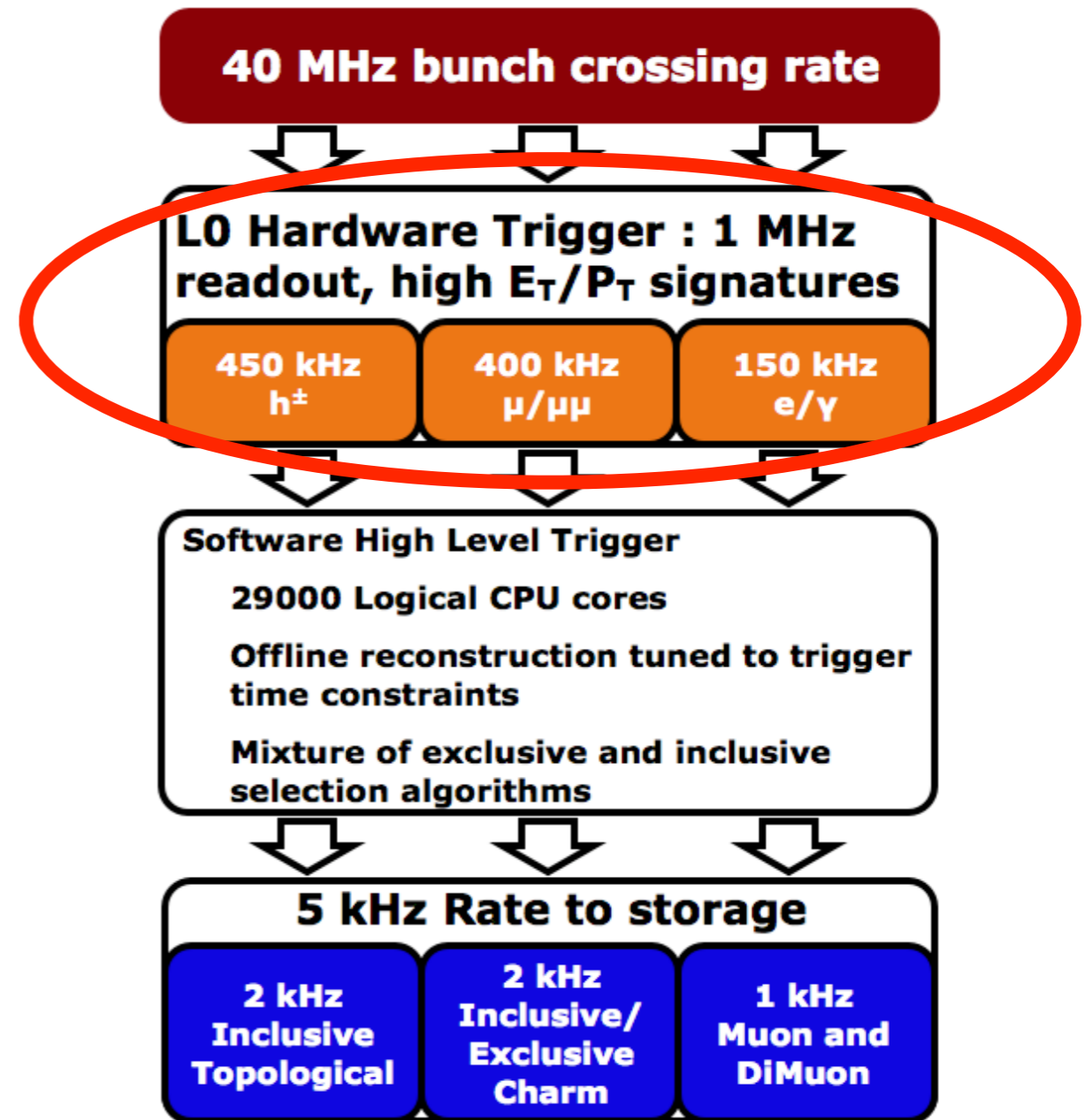
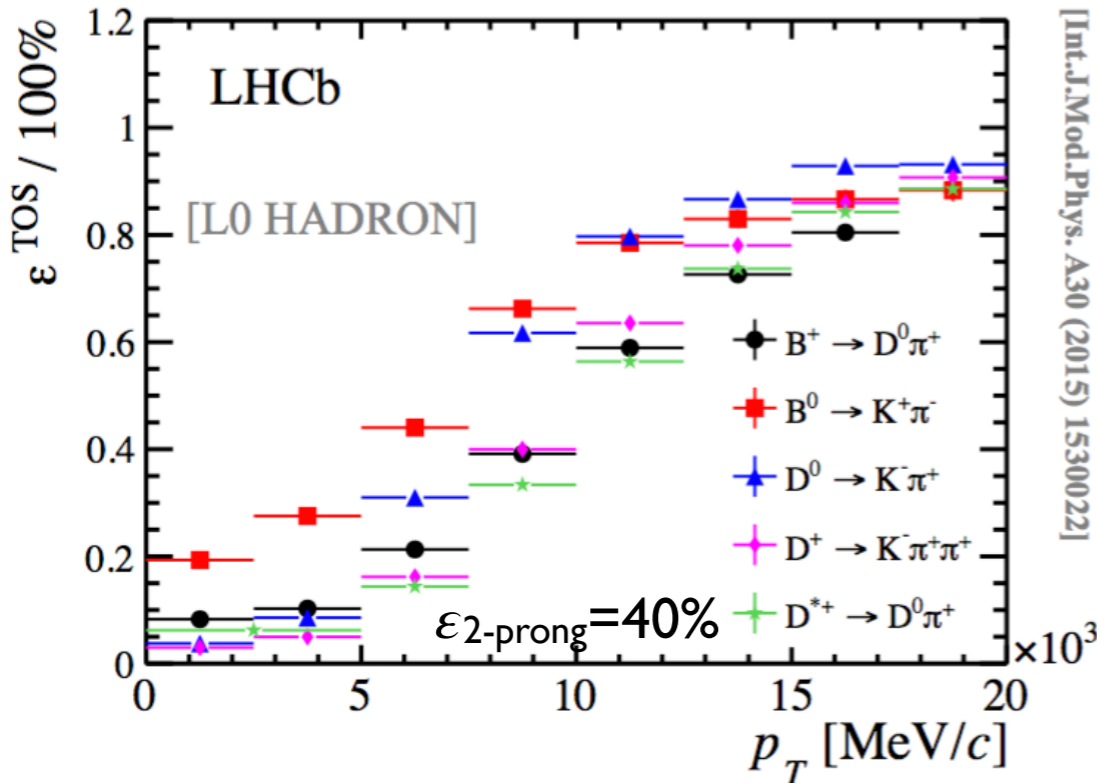
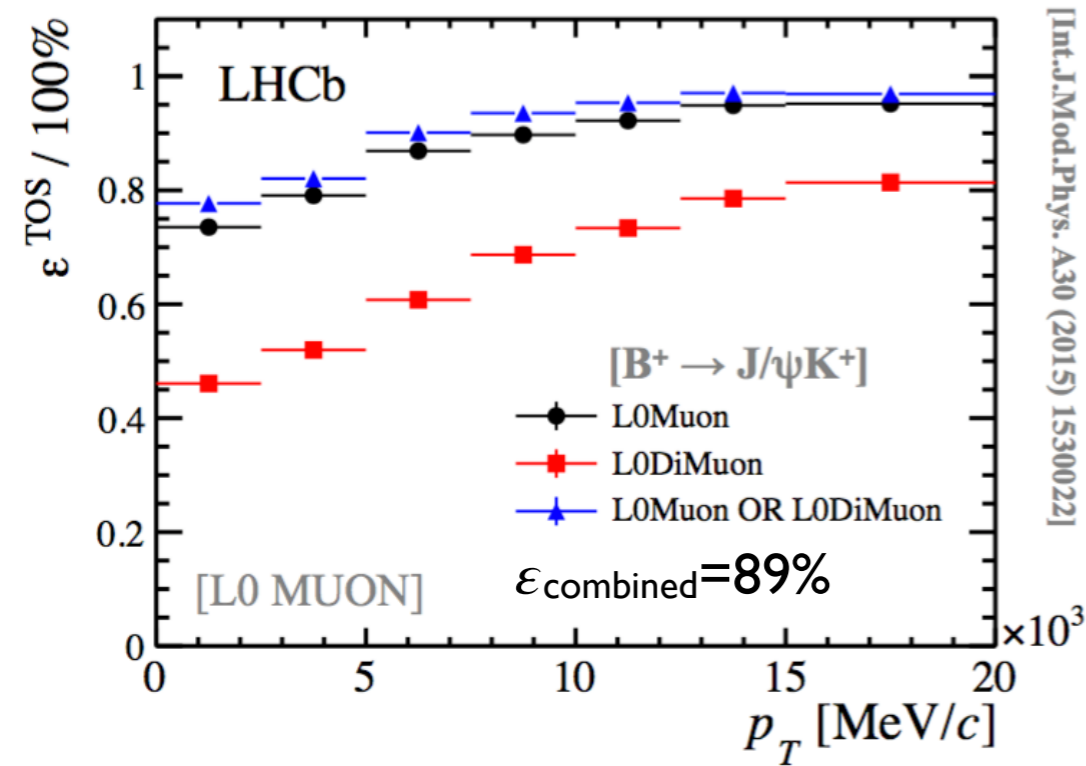
2010-2012, LHCb ran at 7 and 8 TeV @ LHCb $\mathcal{L}_{\text{inst}} \sim 4 \cdot 10^{32} \text{ /cm}^2\text{/s}$

Run 1 Trigger

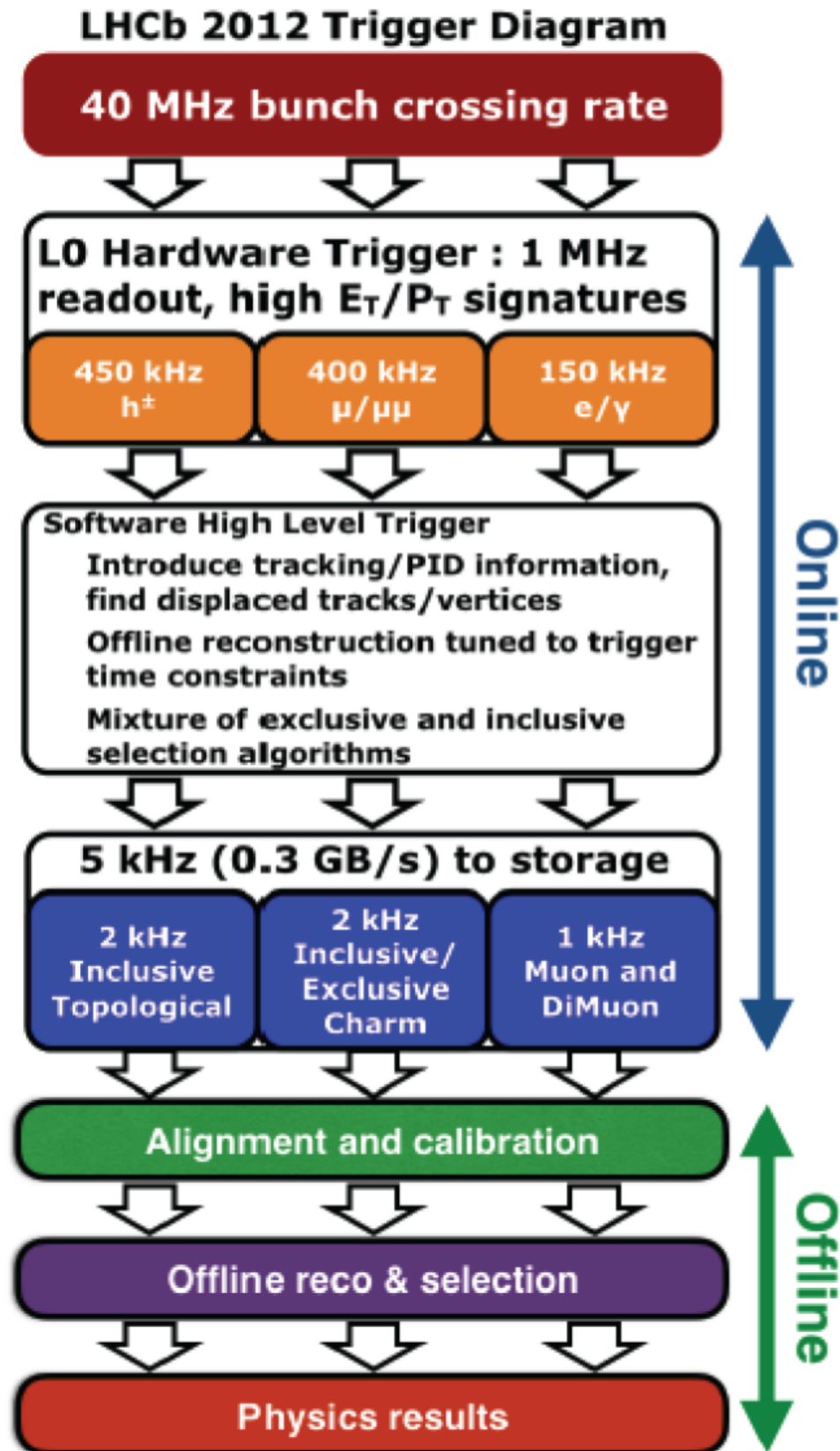


Hardware Trigger L0

- Reduce from bunch crossing rate to ~1 MHz

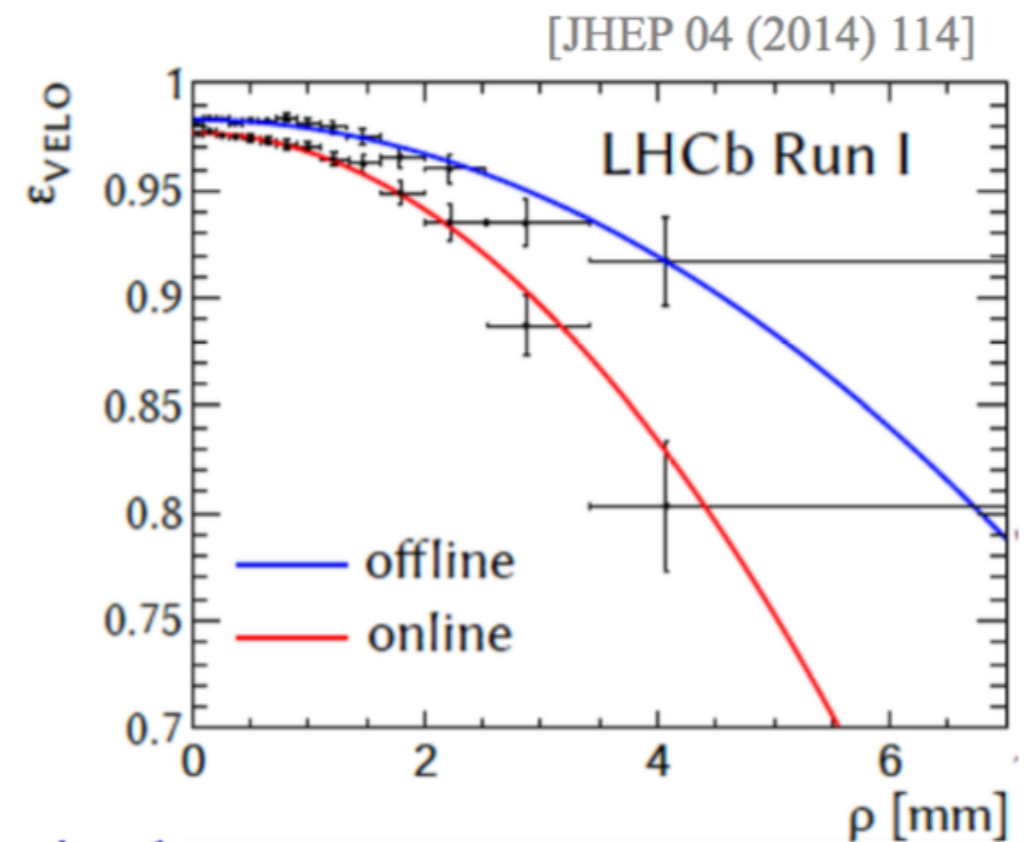


Online vs Offline



- ◇ Online: compromise between performance and stringent timing requirements
- ◇ Offline: best available performance without stringent timing requirements
- ◇ Differences: pattern recognition, detector alignment and calibration, candidate selection

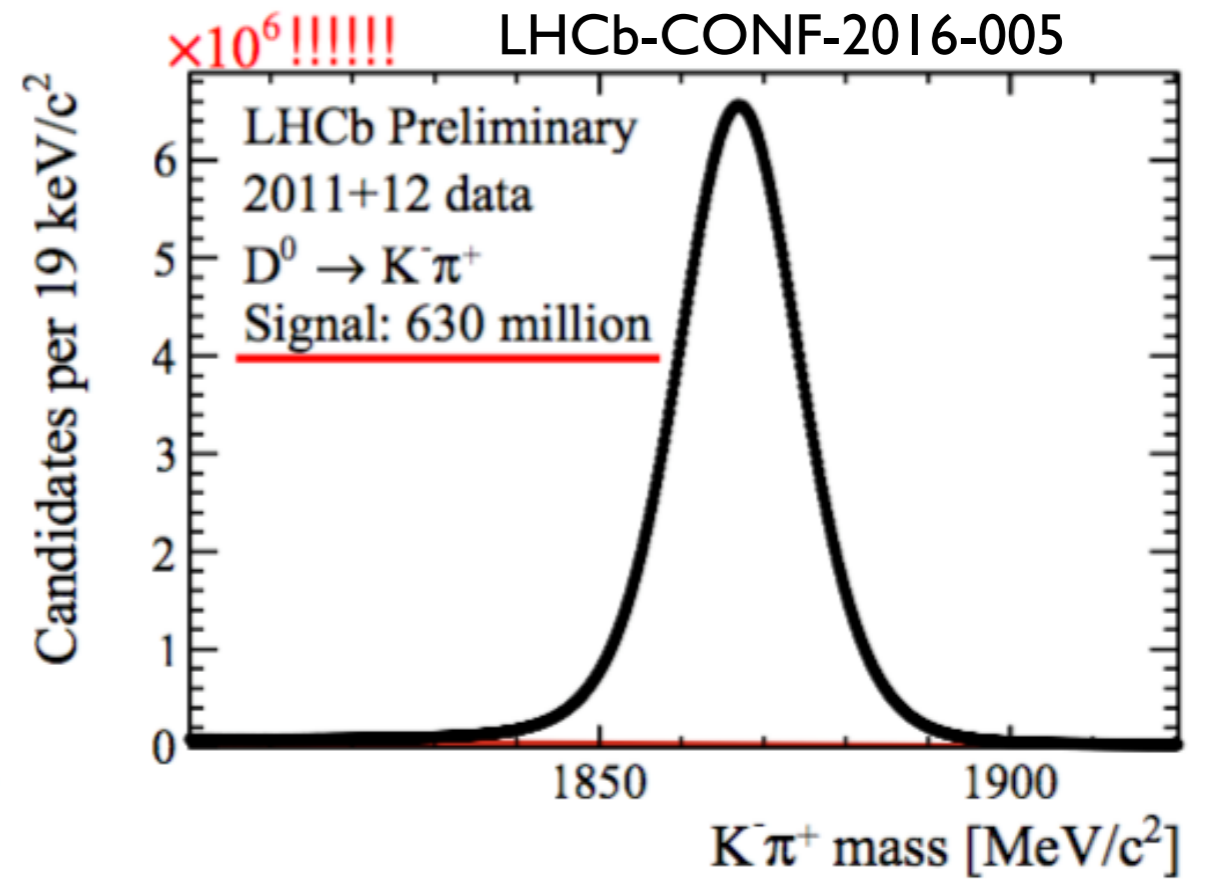
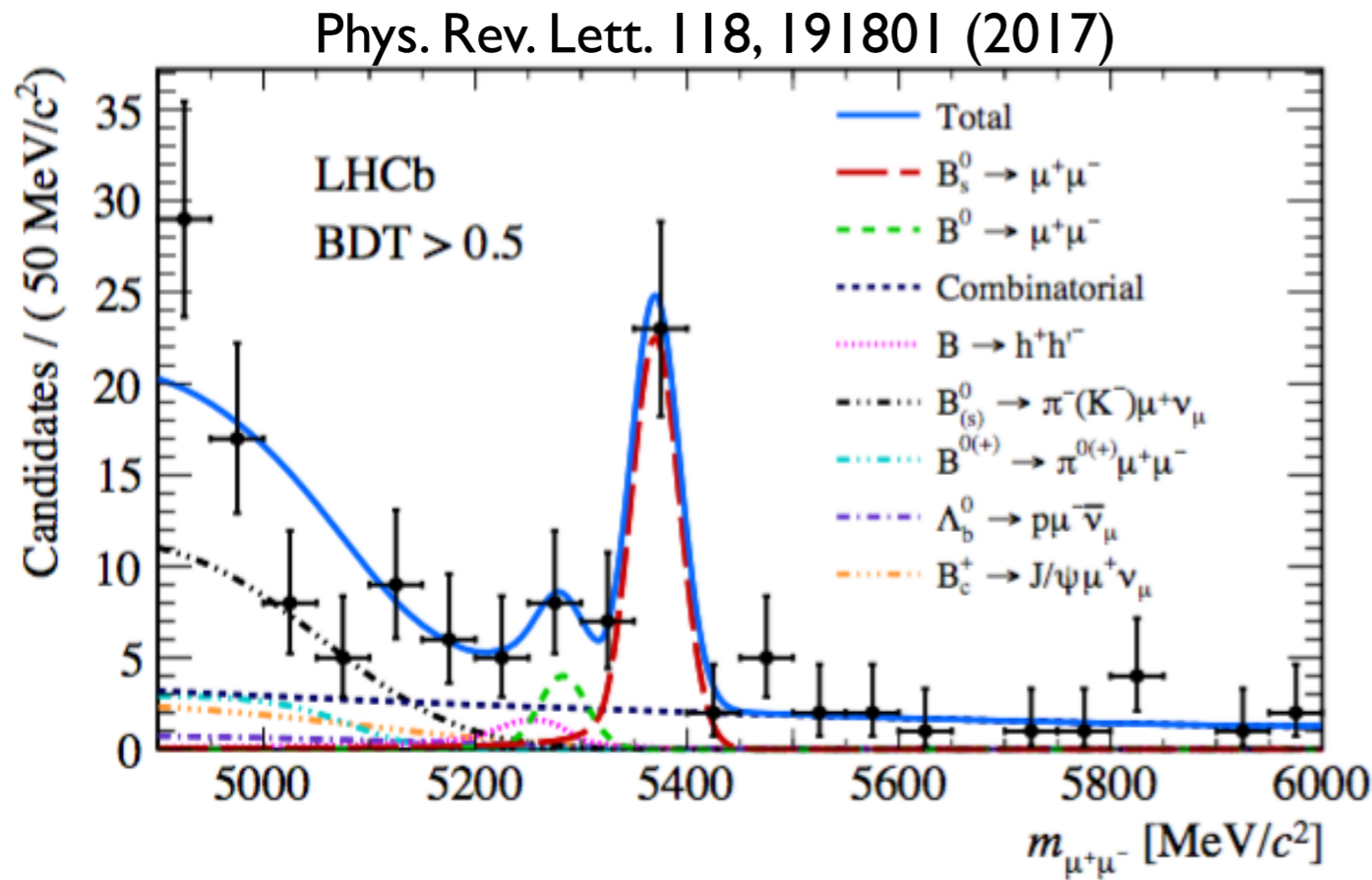
- ◇ Necessary to store full event for the offline processing
 - ◇ limits the total number of stored events
 - ◇ charm streams are especially affected
- ◇ Extra systematics due to differences between online and offline selections



RUN 2

2015-2018, LHCb runs at 13 TeV @ LHCb $\mathcal{L}_{\text{inst}} \sim 4 \cdot 10^{32} \text{ /cm}^2\text{/s}$

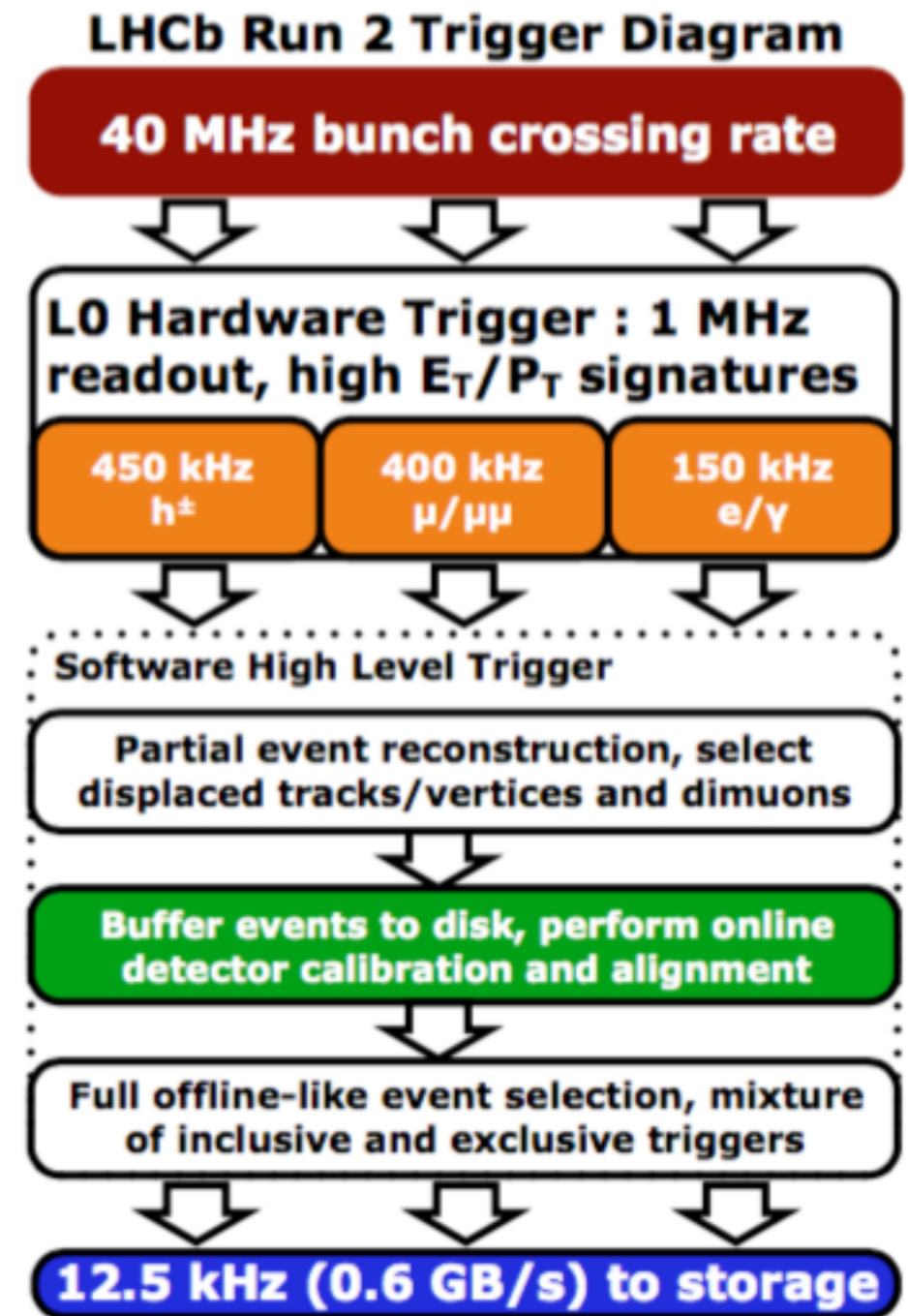
Challenges



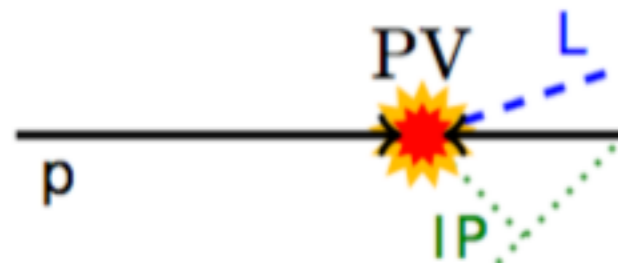
- ◇ The LHCb trigger has to cover extremes in data taking
 - ◇ High efficiency to collect rare decays like $B_s^0 \rightarrow \mu^+\mu^-$
 - ◇ High purity for enormous charm signals like $D^0 \rightarrow K^-\pi^+$
 - ◇ Must be flexible to operate in both extremes simultaneously
 - ◇ After readout, HLT has access to 100% of event in software

Run 2 LHCb Trigger

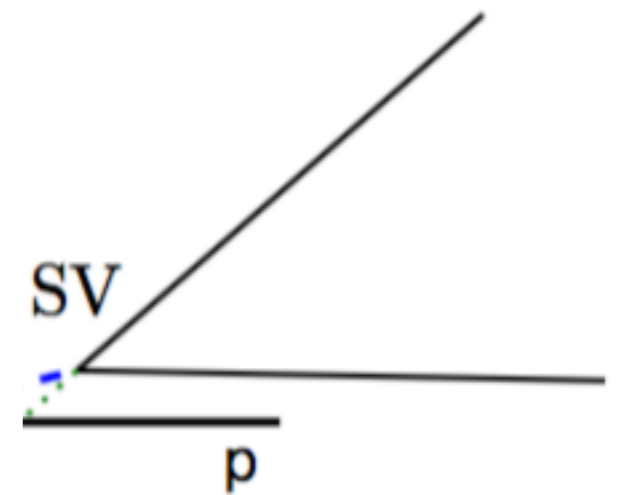
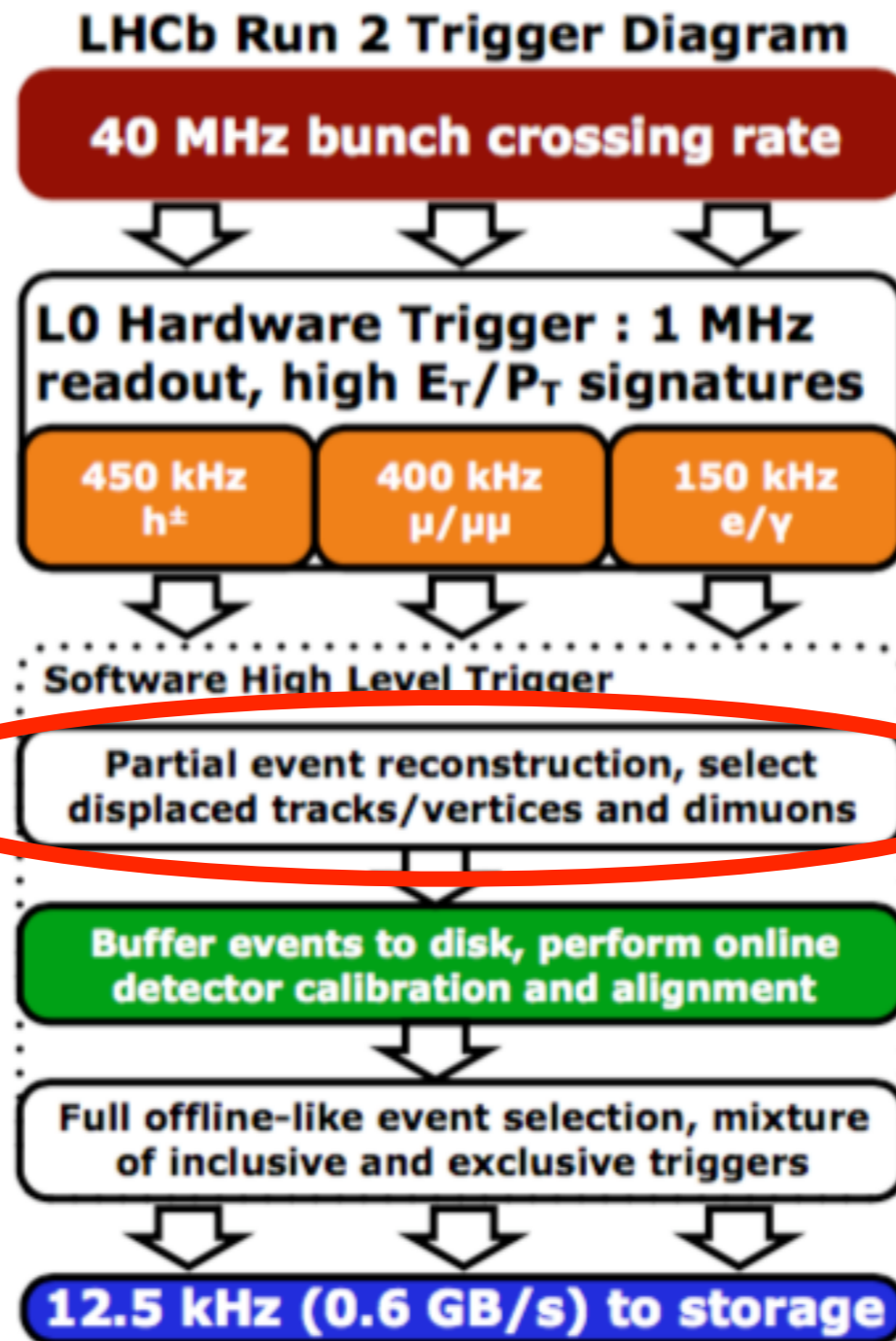
- ◇ Three levels, each has more time than the last:
 - ◇ Level-0 trigger buys time to readout the detector with Calo, Muon p_T thresholds: **40MHz \rightarrow 1MHz**
 - ◇ Events built at 1MHz, sent to HLT farm (~27000 physical cores)
 - ◇ HLT1 has 40 \times more time, fast tracking followed by inclusive selections **1MHz \rightarrow 100kHz**
 - ◇ HLT2 has 400 \times more time than L0: Full event reconstruction, inclusive + exclusive selections using whole detector **\rightarrow 12.5kHz**
- ◇ Flexibility comes from software-centric HLT design



HLT1 Topological Trigger



- ◇ B^\pm mass ~ 5.28 GeV, d_{rel} (GeV)
- ◇ $\tau \sim 1.6$ ps, Flight distance ~ 4 mm
- ◇ Important signature: D_{charm} from $B \rightarrow J/\psi X, J/\psi \mu^+\mu^-$
- ◇ Underlying HLT1 strategy
 - ◇ Fast reconstruction
 - ◇ Inclusive triggering
 - ◇ ~ 100 kHz output



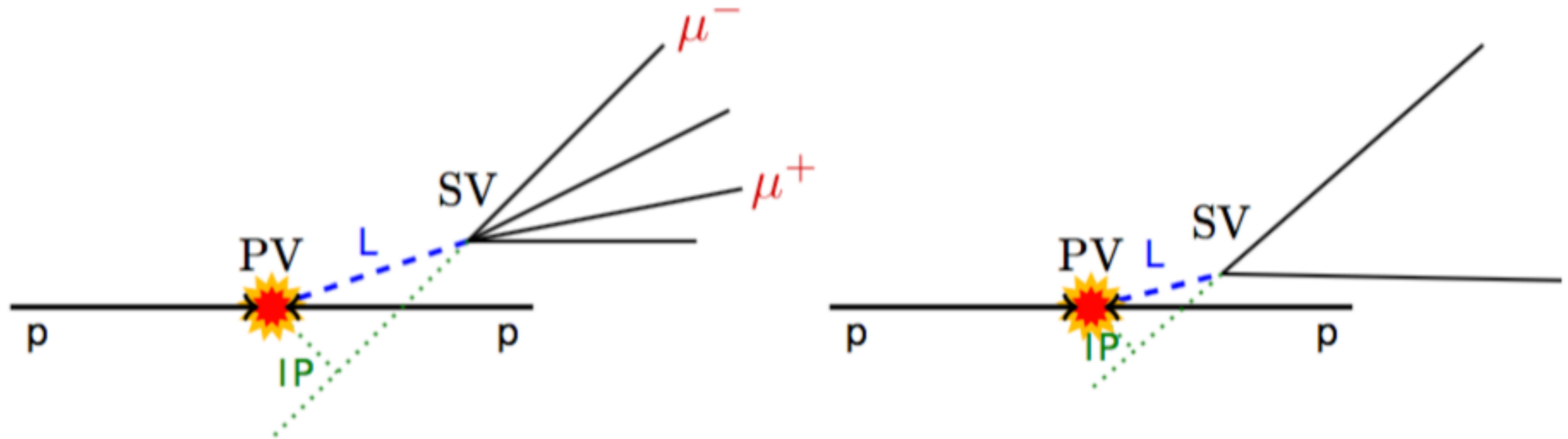
appreciable

distance ~ 4 mm

'secondary' charm

Internal Muon ID

HLT1 Topological Trigger



◇ B^\pm mass ~ 5.28 GeV, daughter $p_T \sim 0$ (1 GeV)

◇ $\tau \sim 1.6$ ps, Flight distance ~ 1 cm

◇ Important signature: Detached muons from $B \rightarrow J/\psi X, J/\psi \rightarrow \mu\mu$

◇ D^0 mass ~ 1.86 GeV, appreciable daughter p_T

◇ $\tau \sim 0.4$ ps, Flight distance ~ 4 mm

◇ Also produced as 'secondary' charm from B decays.

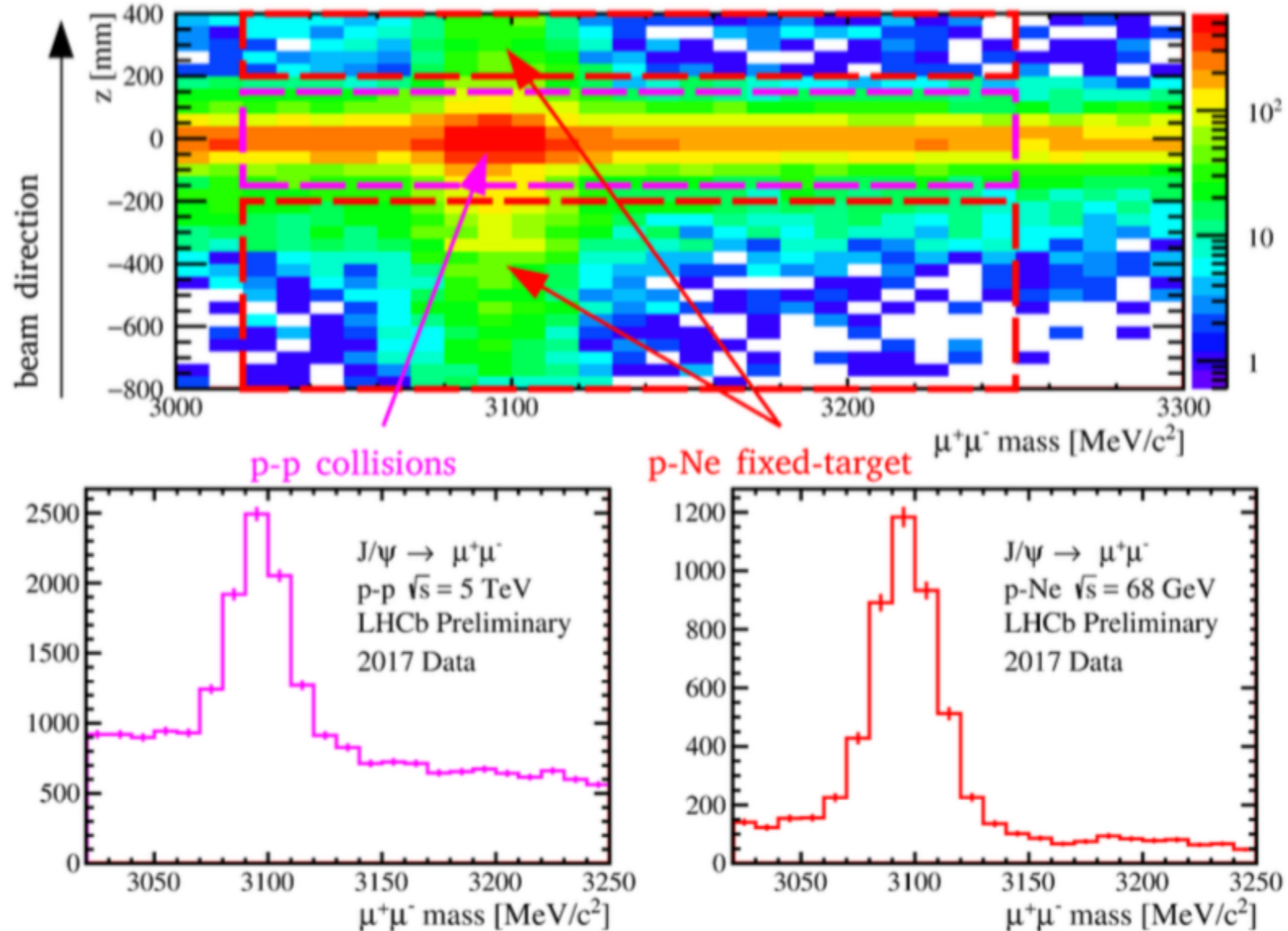
◇ Underlying HLT1 strategy:

◇ Fast reconstruction: Primary Vertices, High p_T tracks, optional Muon ID

◇ Inclusive triggering using MVAs on 1&2-track signatures:

◇ ~ 100 kHz output rate

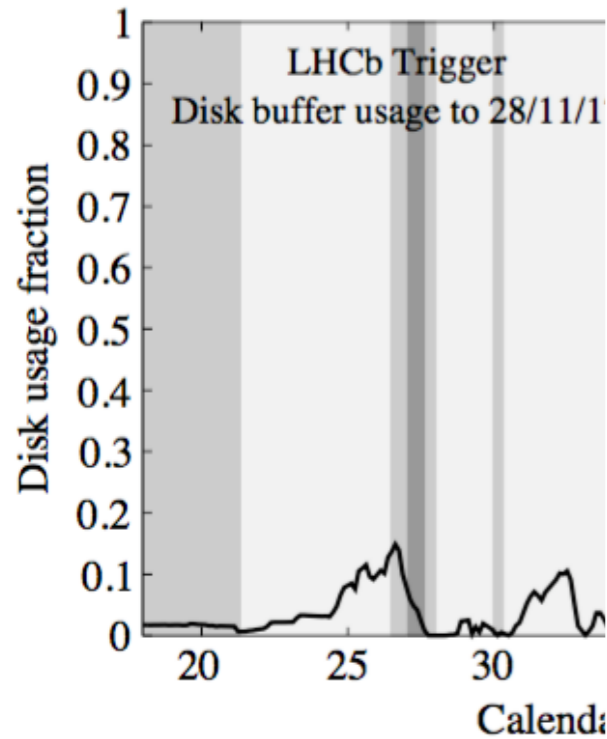
Flexibility on Software HLT1



- ◇ 5 TeV LHC run in the end of 2017
- ◇ both p-p collision and p-Ne fixed target at the same time
- ◇ clear J/ψ signals in both pp and p-Ne at first software trigger stage

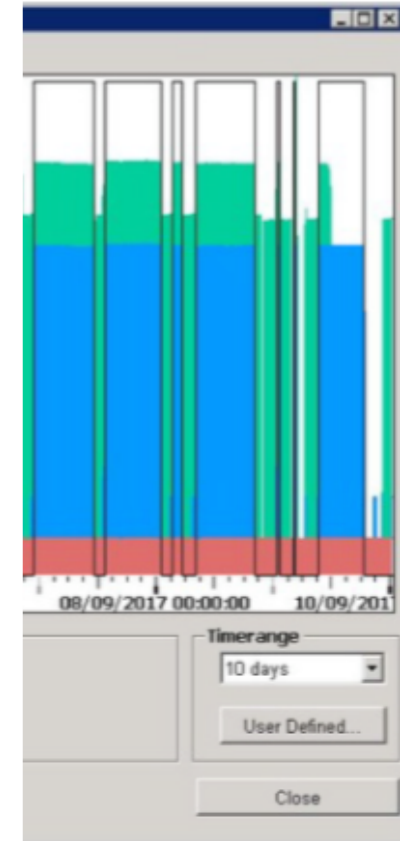
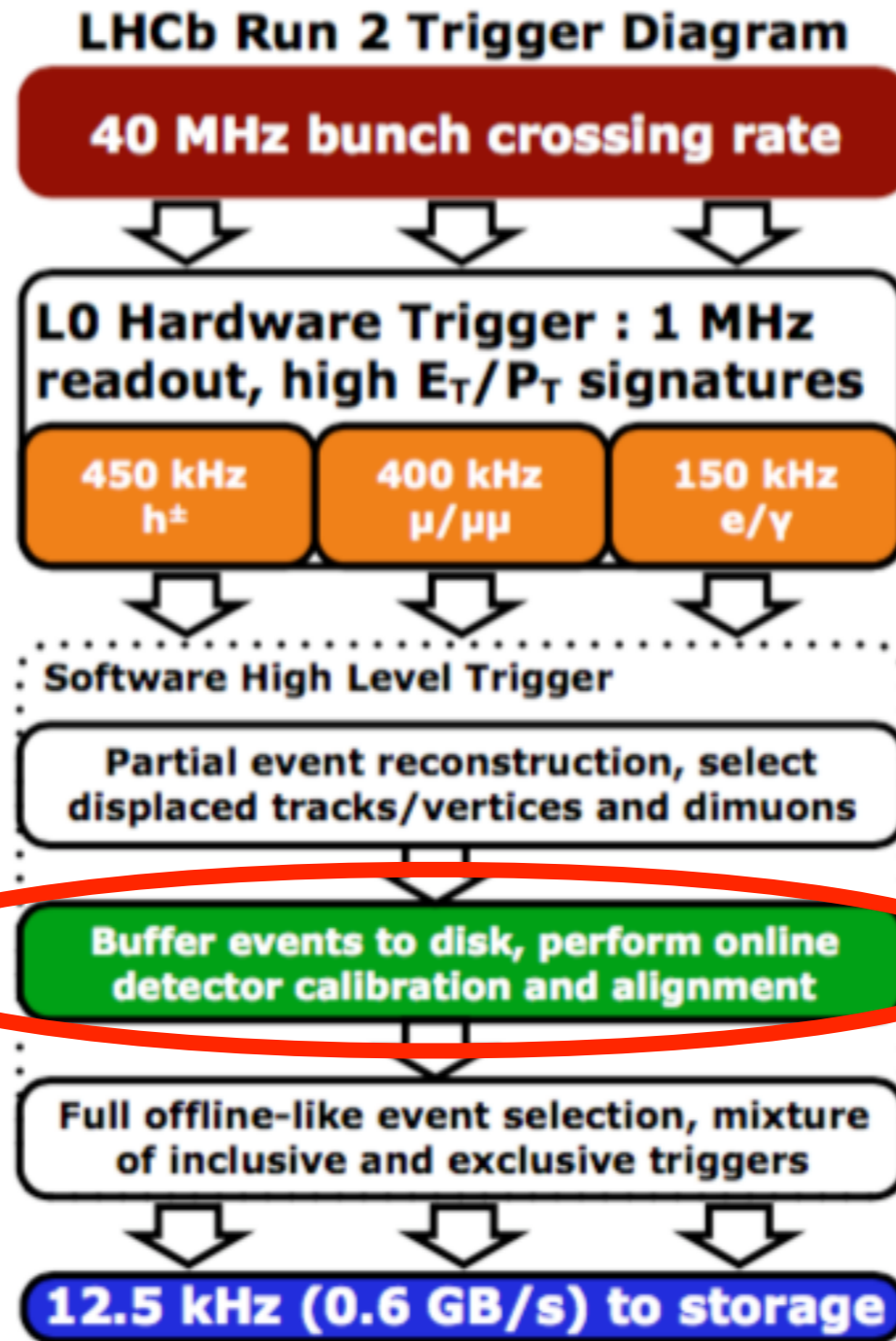
Disk Buffer

Disk Buffer



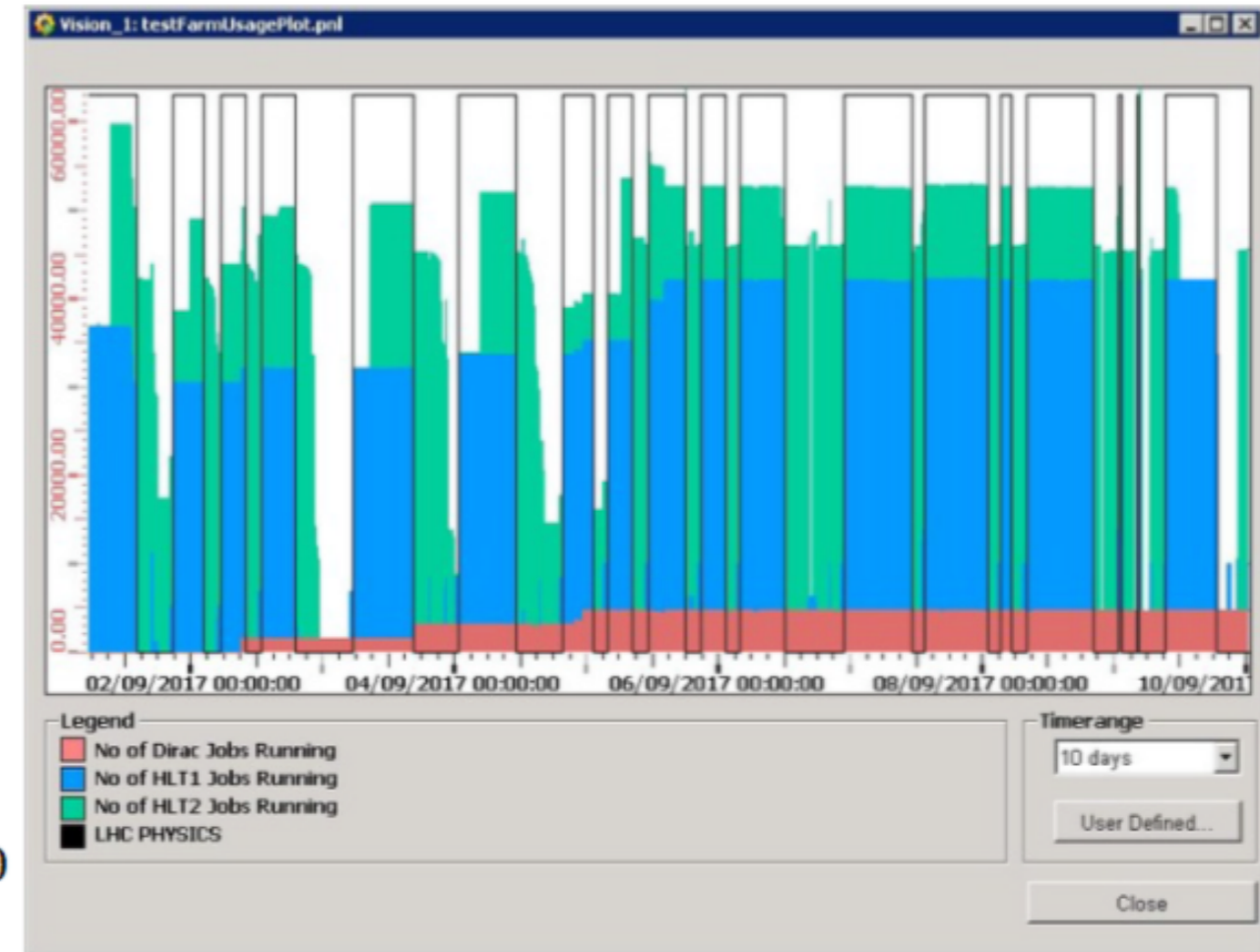
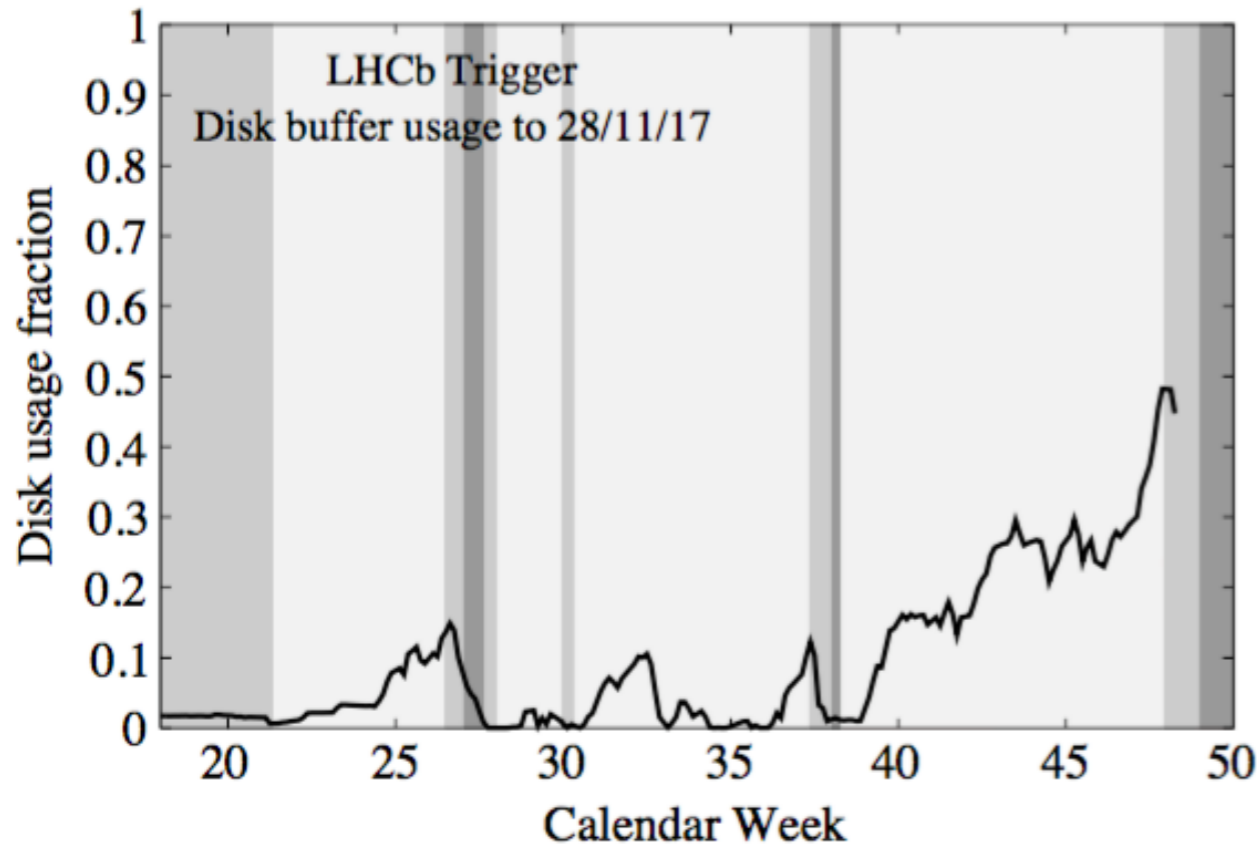
- ▶ HLT Farm is off-the
- ▶ HLT1 accepted eve
- ▶ HLT2 throughput i
- ▶ Effectively doubles for simulation
- ▶ Asynchronous HLT

◇ This needs man



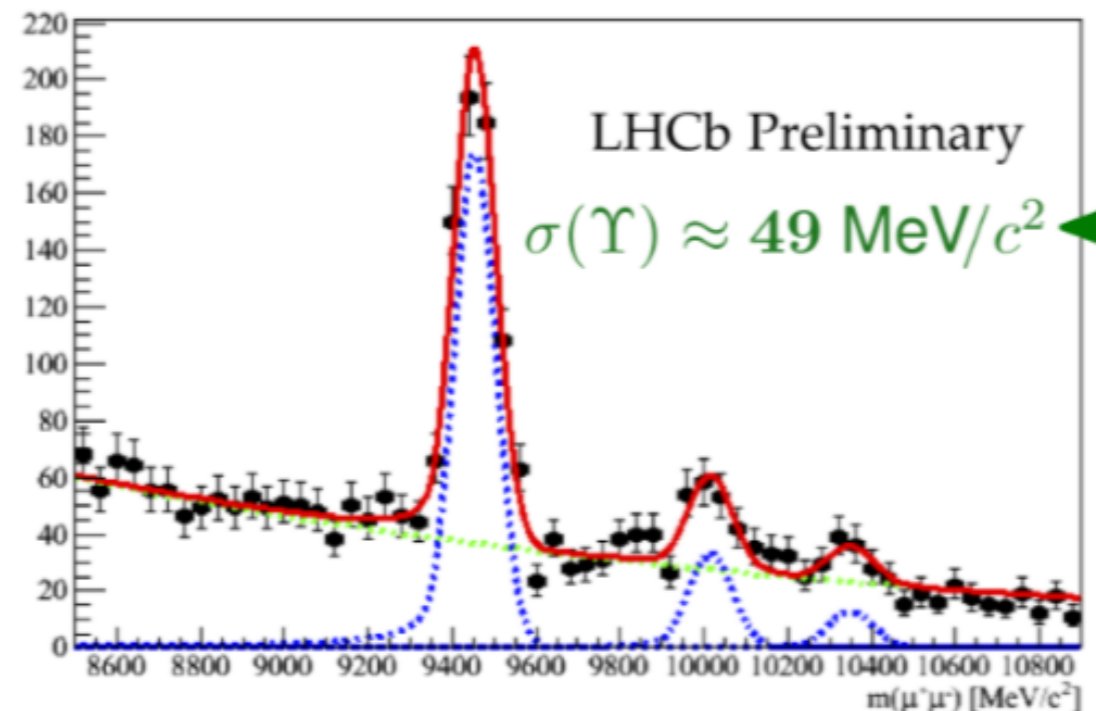
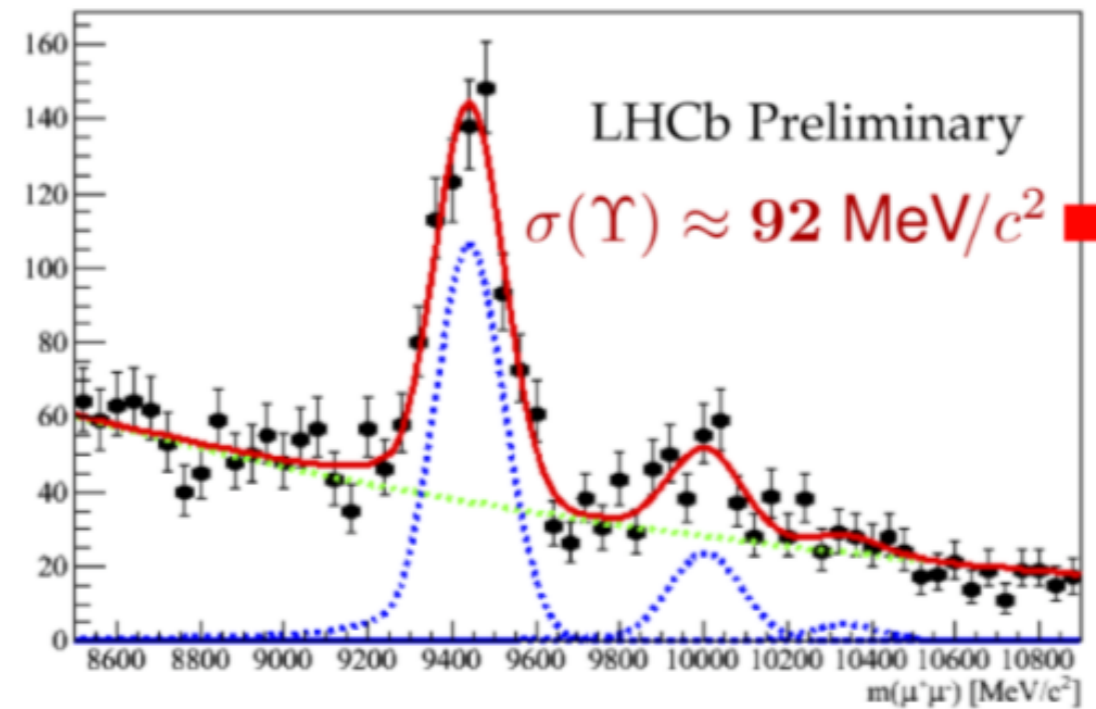
/ contingency
running
, excess used

Disk Buffer

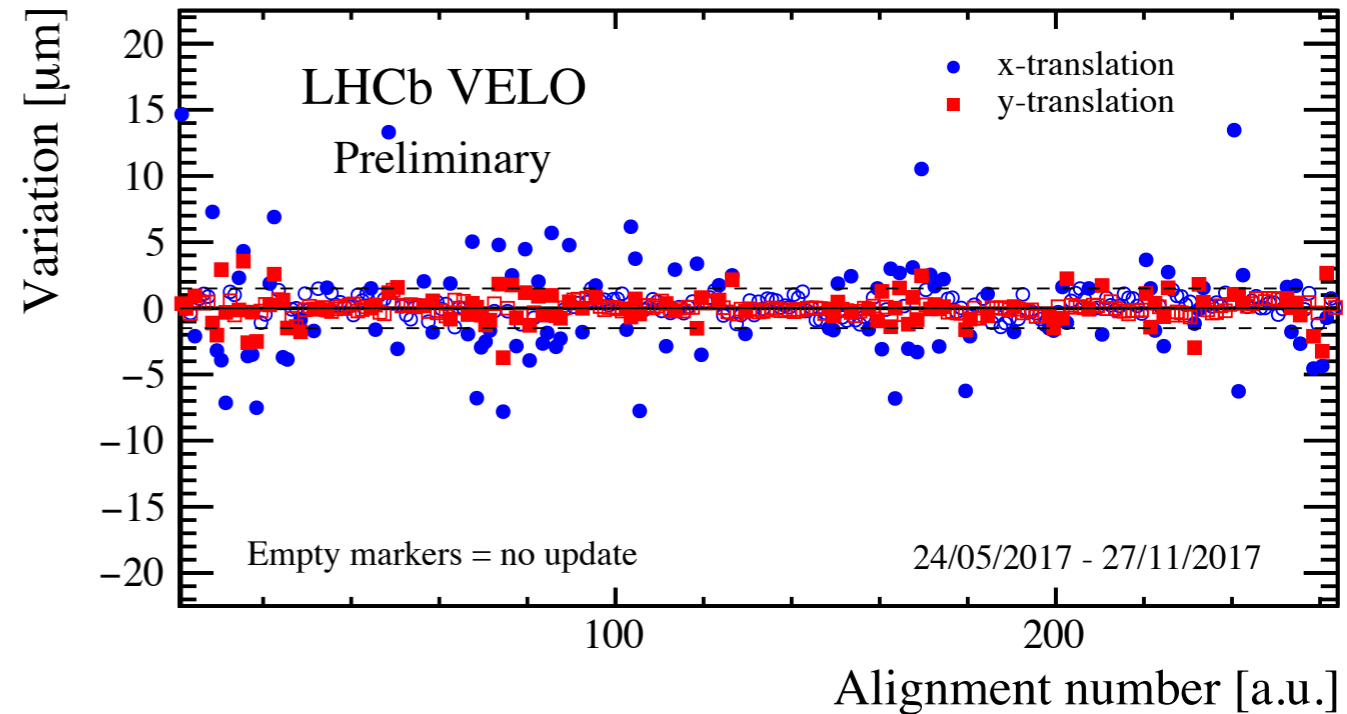
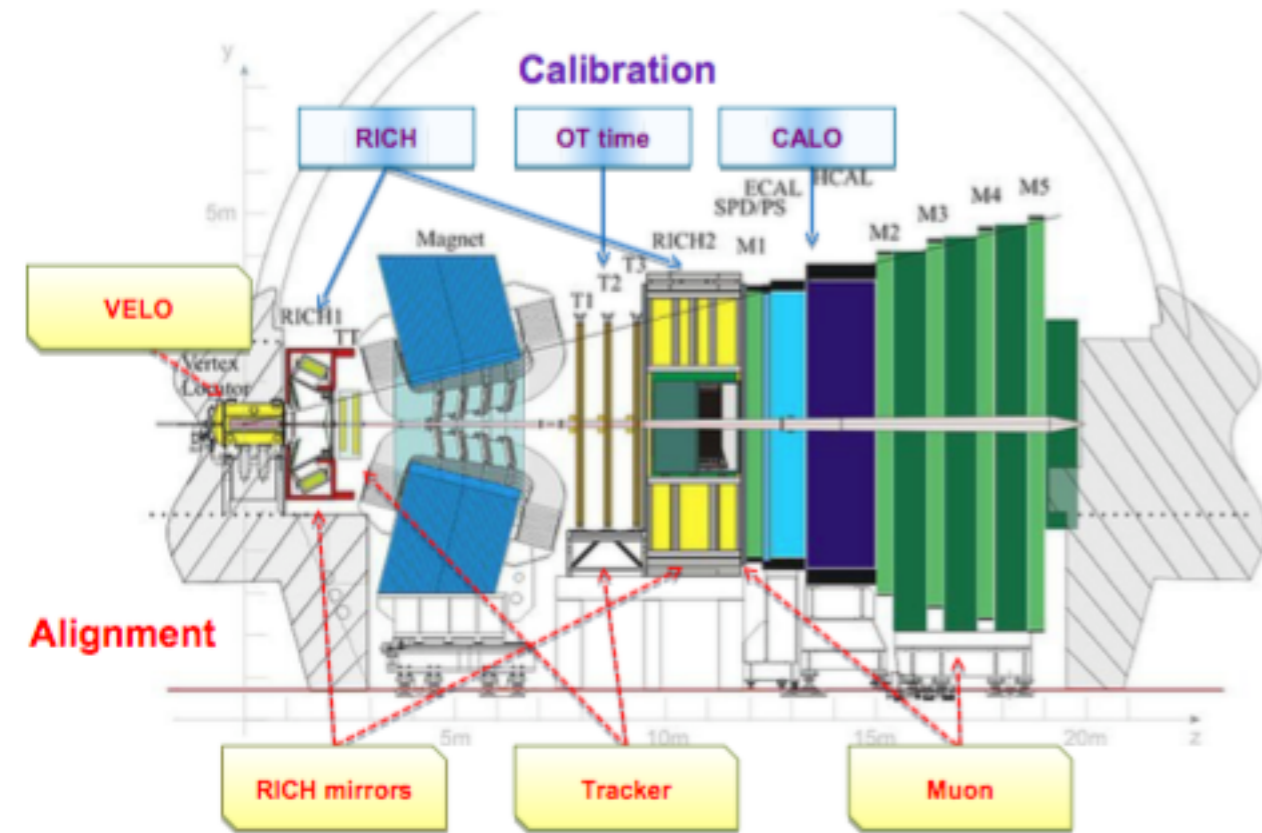


- ◇ Off-the shelf servers: 11PB disk capacity
- ◇ Accepts HLT1 events written to the disk in-fill at 100kHz: 2 week contingency
- ◇ HLT2 throughput in-fill is 30kHz out of fill 90kHz when HLT1 isn't running
- ◇ Effectively doubles trigger CPU capacity: farm is used twice for HLT, excess used for simulation

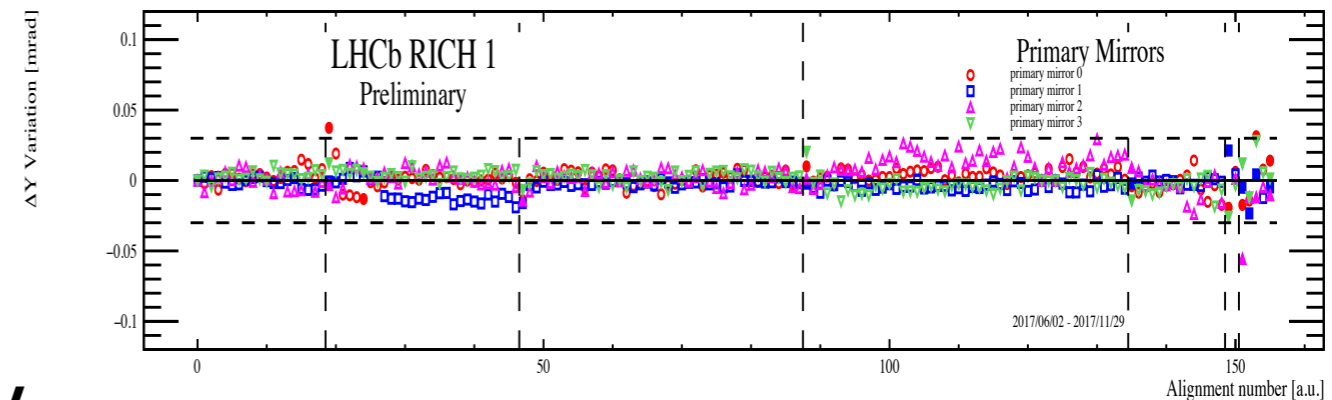
- ◇ With Run 2 signal rates, efficient & pure output requires full reconstruction at HLT2
- ◇ online selections \equiv offline selections
 - ◇ Reduces systematic uncertainties and workload for analysts
 - ◇ Alignment and calibration of full detector in the trigger needed
- ◇ While HLT1 is written to disk, alignment & calibration tasks run



Detector Aligned and Ready for HLT2

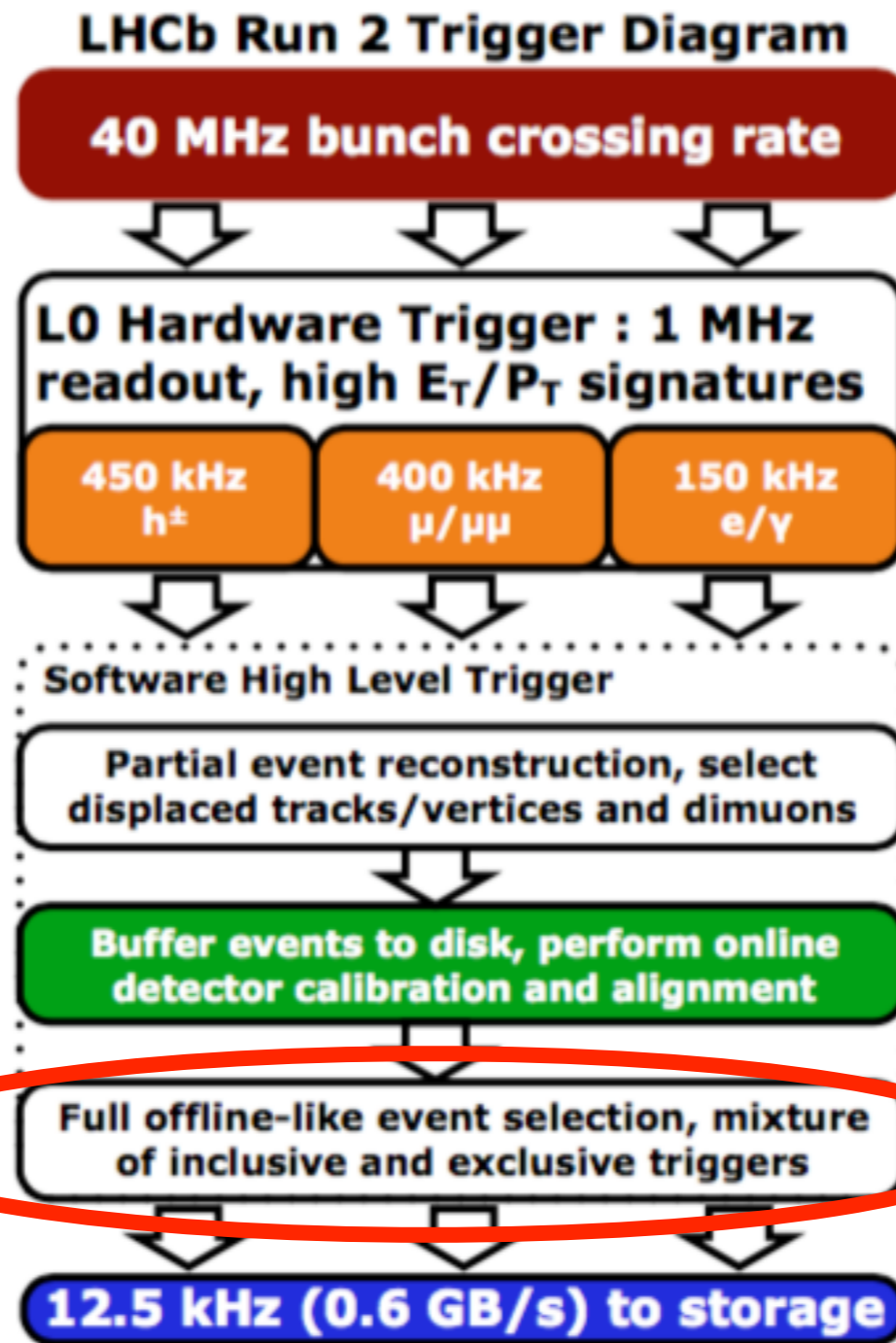


- ◇ All detectors are aligned & calibrated in-situ using the 100kHz HLT1 output rate
- ◇ Updates applied automatically if needed prior to HLT2 starting



HLT2

- ◇ HLT2 performs calibrated detector
- ◇ Reconstructed
- ◇ Selections of a
- ◇ Combination of
 - ◇ Main B physi
- ◇ Offline storage nominal LHC ye
- ◇ Even in Run 2, charm at 100kE



aligned and
 reduced offline
 event possible
 ctions
 MVA
 assuming a
 ciency losses for

- ◇ HLT2 performs full event reconstruction using aligned and calibrated detector information
 - ◇ Reconstructed objects in HLT identical to those produced offline
 - ◇ Selections of arbitrary complexity on the entire event possible
 - ◇ Combination of inclusive & exclusive trigger selections
 - ◇ Main B physics trigger: Inclusive, topology-based MVA
- ◇ However...
 - ◇ Offline storage capacity limits us to 700MB/s assuming a nominal LHC year
 - ◇ Even in Run 2, this would mean significant efficiency losses for charm at 100kB/event...

Phys. Rev. Lett. 116, 191601 (2016)

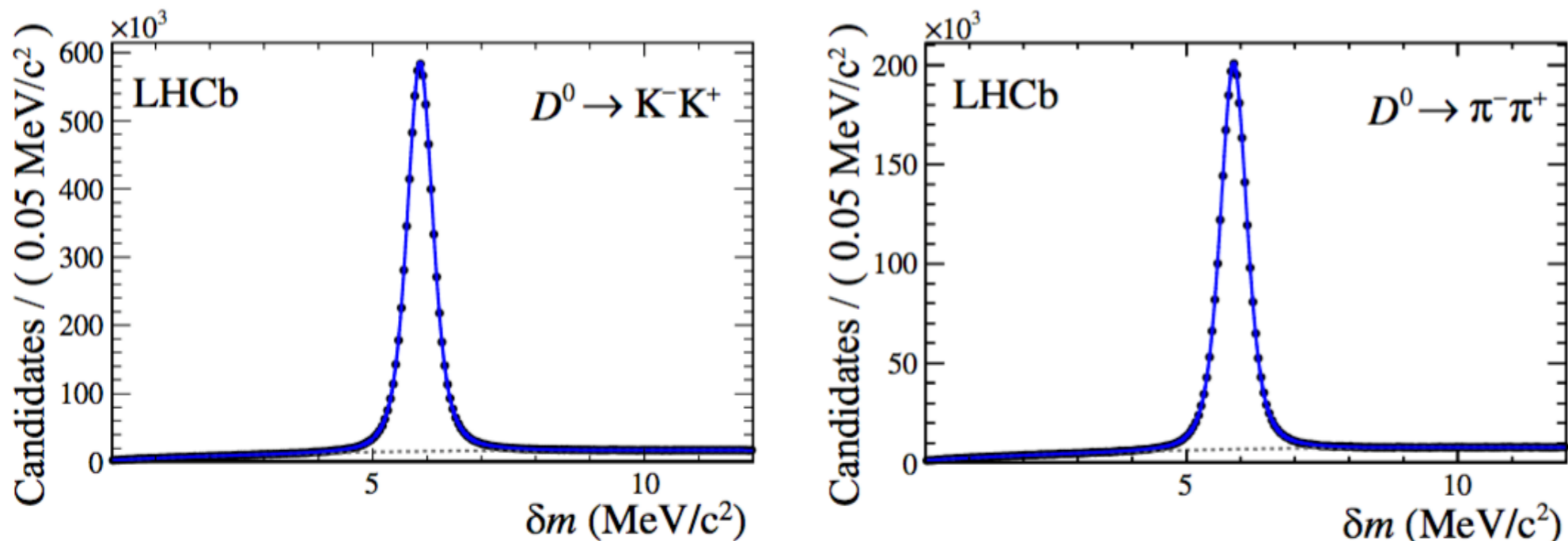
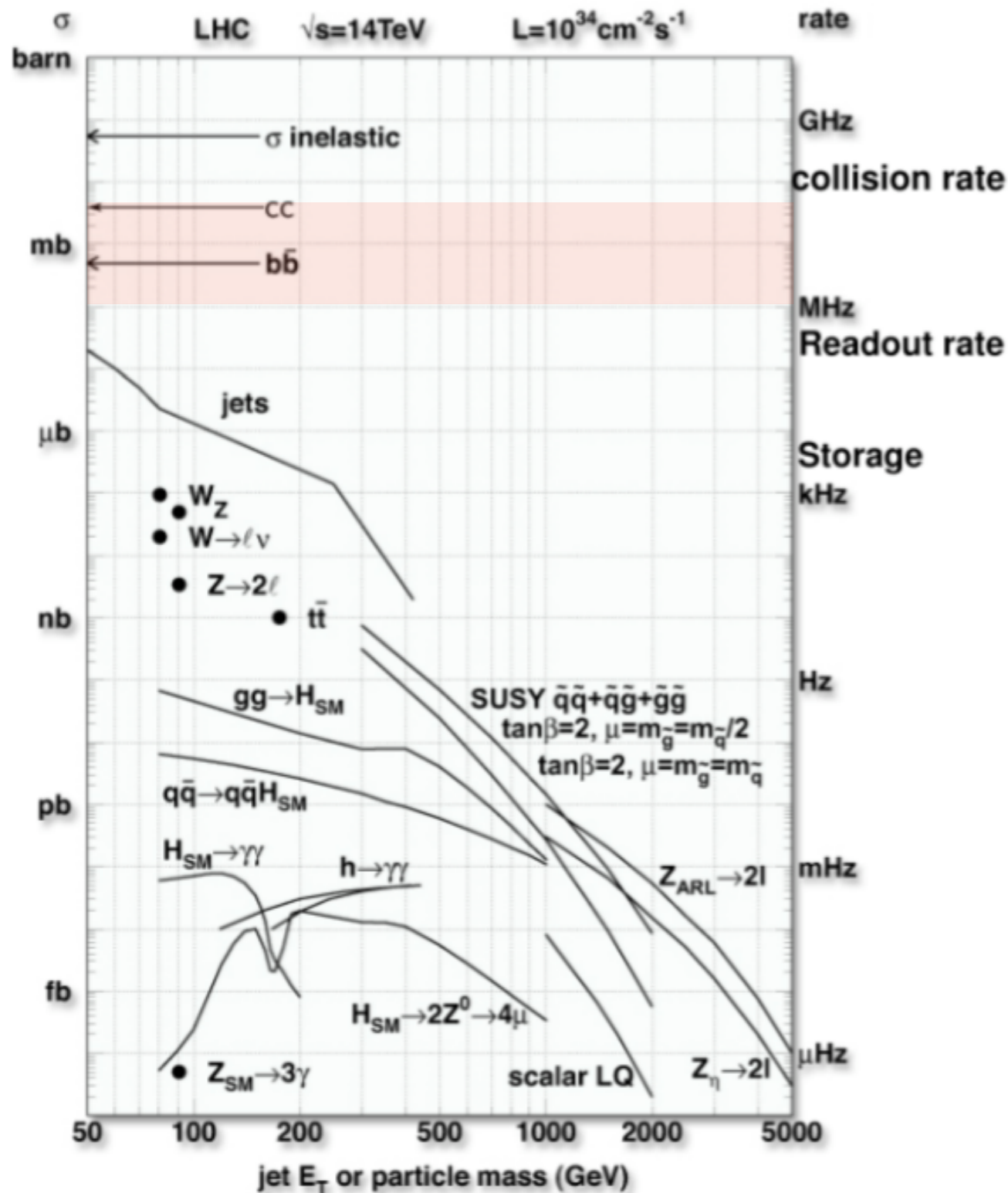


Figure 1: Fit to the δm spectra, where the D^0 is reconstructed in the final state (left) K^-K^+ and (right) $\pi^-\pi^+$. The dashed line corresponds to the background component in the fit.

$$\Delta A_{CP} = (-0.10 \pm 0.08 \text{ (stat)} \pm 0.03 \text{ (syst)}) \%,$$

- ◇ For indirect studies of SM and New Physics huge signal datasets are necessary to achieve good sensitivity

Event Bandwidth Limitations



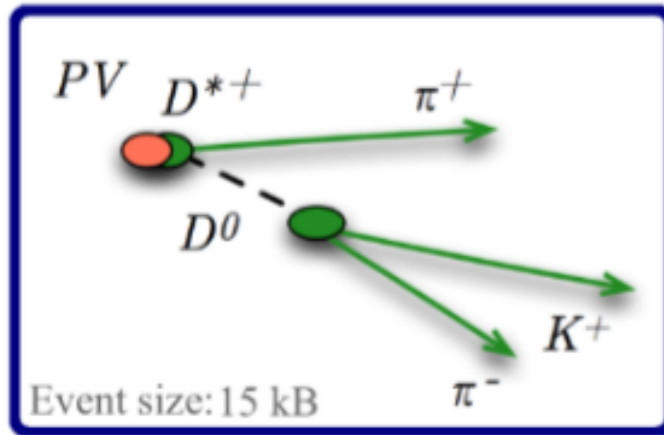
- ◇ 700Mb/s @ 100kB/events
- ◇ Significant losses for charm and beauty analyses
- ◇ charm suffers more

- ◇ Trade between event rate and event size for particular physics analyses
 - ◇ NB: events are fully reconstructed after HLT2
- ◇ Can drop RAW content, can drop low level objects, can drop unnecessary high level objects
 - ◇ keeping only high level objects necessary for the analysis
- ◇ Reverse HEP Physics analysis paradigm
 - ◇ from:
 - ◇ store generic data objects, then develop precise analysis techniques using any necessary objects
 - ◇ to:
 - ◇ thoughtfully develop analysis techniques in advance, then run analysis on trigger objects, and store all those objects, which are necessary to get solid analysis result
- ◇ Turbo stream @ LHCb
 - ◇ similar approaches: Data Scouting @ CMS, Trigger Level Analysis @ Atlas

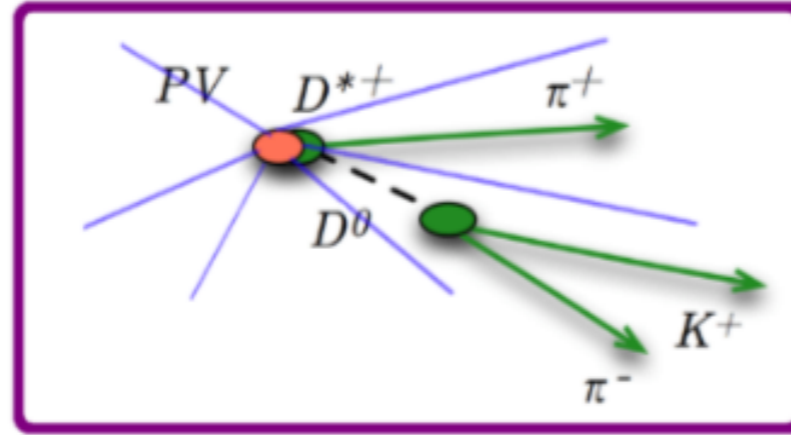
Turbo

arXiv:1604.05596

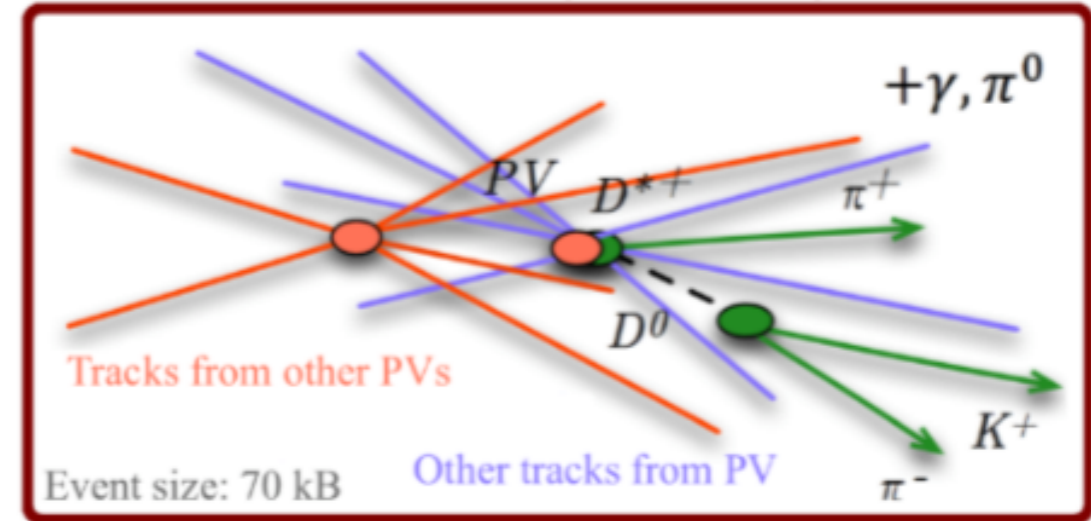
TURBO (since 2015)



TURBO SP new 2017



TURBO++ (since 2016)

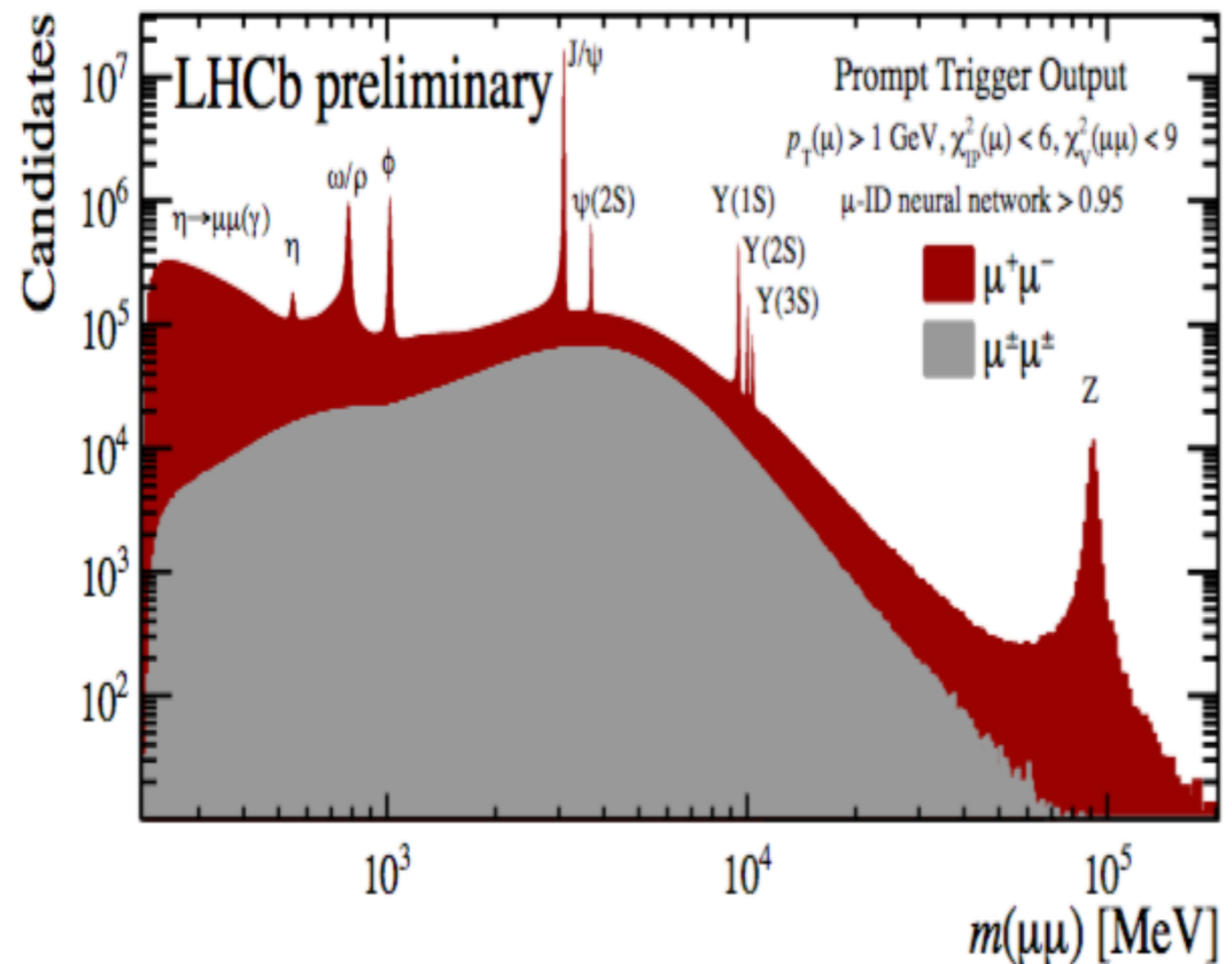


Event size

- ◇ Turbo is the LHCb paradigm for reduced event format data
- ◇ Dedicated high statistics calibration event samples are used to derive necessary detector performance parameters directly from data
- ◇ High degree of flexibility: Save only as much of the event as is needed for analysis
 - ◇ Keep all reconstructed objects, drop the raw event: 70kB
 - ◇ Keep only objects used to trigger: 15kB
 - ◇ 'Selective Persistence' objects used to trigger + user-defined selection: 15 → 70kB

- ◇ In 2017:
 - ◇ 528 trigger lines at HLT2.
50% are Turbo
 - ◇ 25% of the trigger rate is Turbo but it counts for only 10% of the bandwidth
 - ◇ Many analyses would not be possible without Turbo

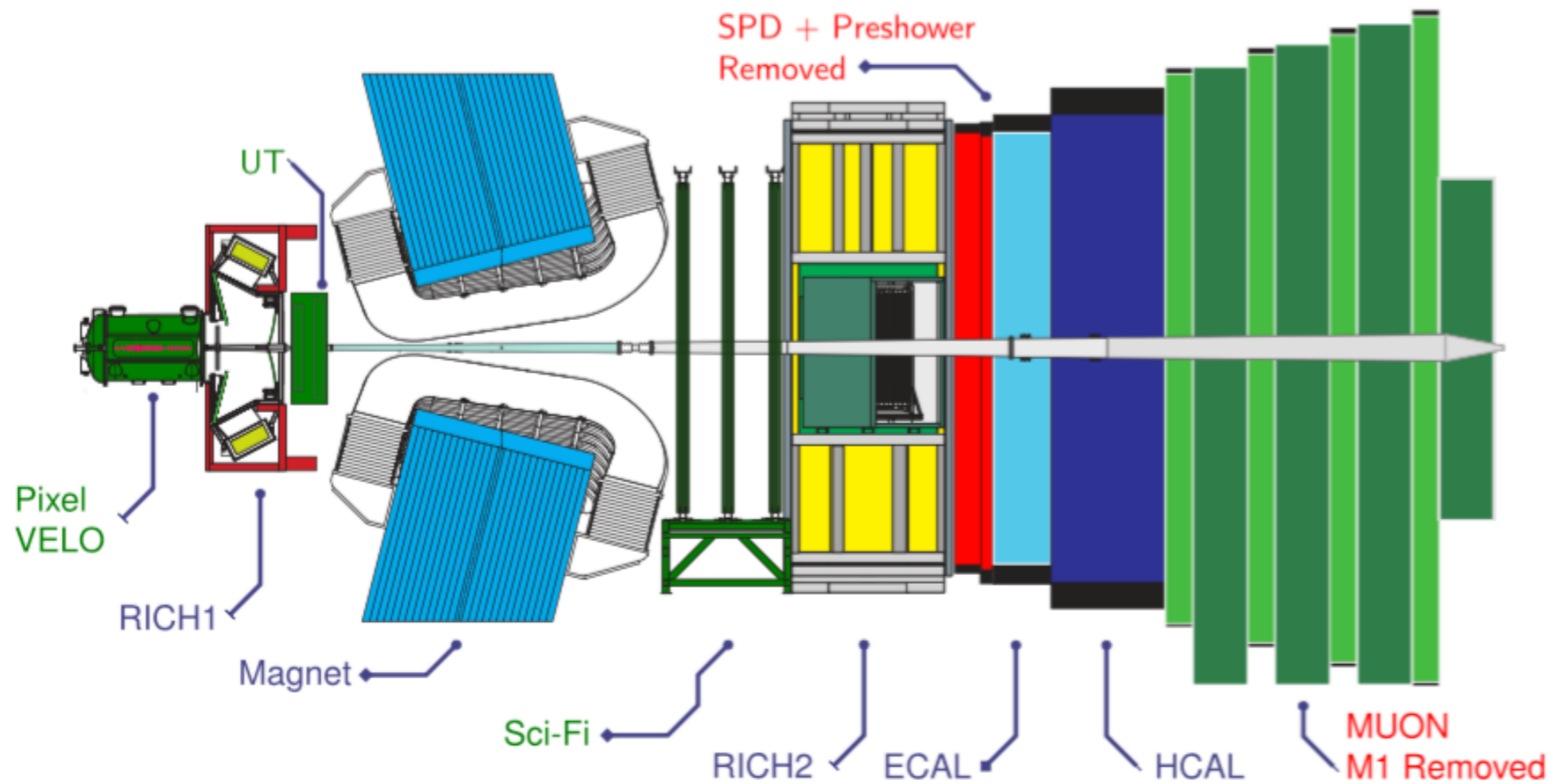
Search for dark photons produced in 13 TeV pp collisions



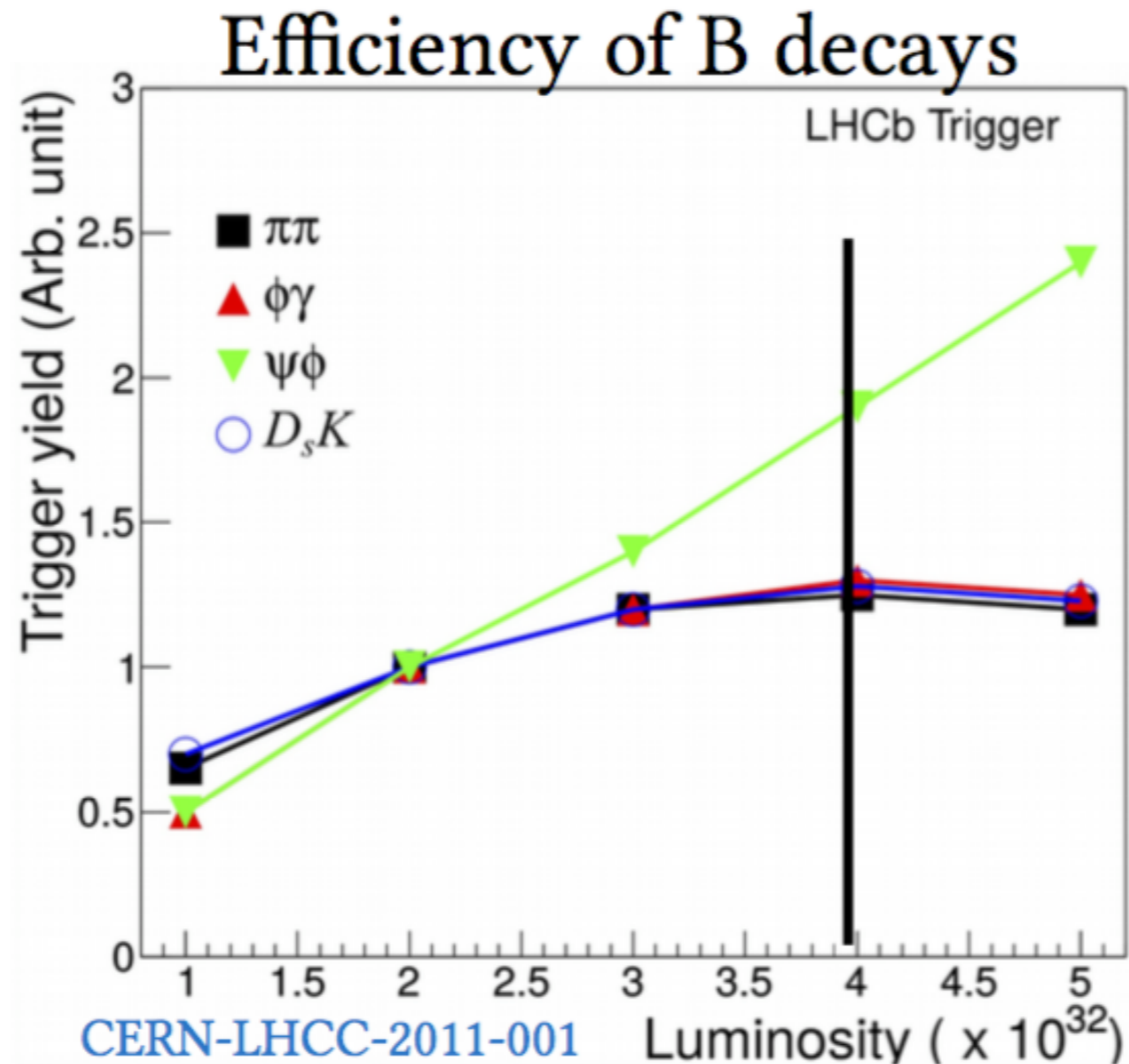
RUN 3

From 2021, LHCb will run at 14 TeV @ LHCb $\mathcal{L}_{\text{inst}} \sim 2 \cdot 10^{33} \text{ /cm}^2\text{/s}$

The First LHCb Upgrade



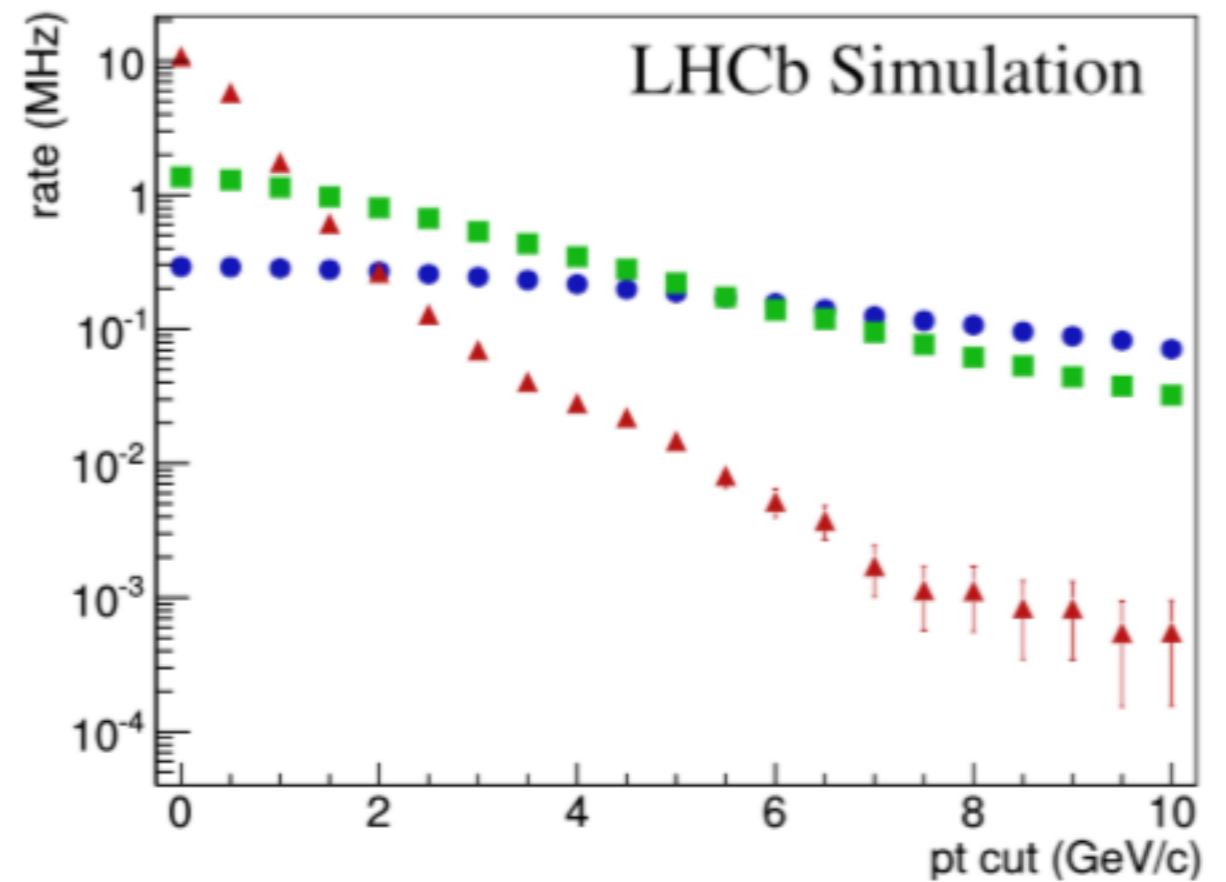
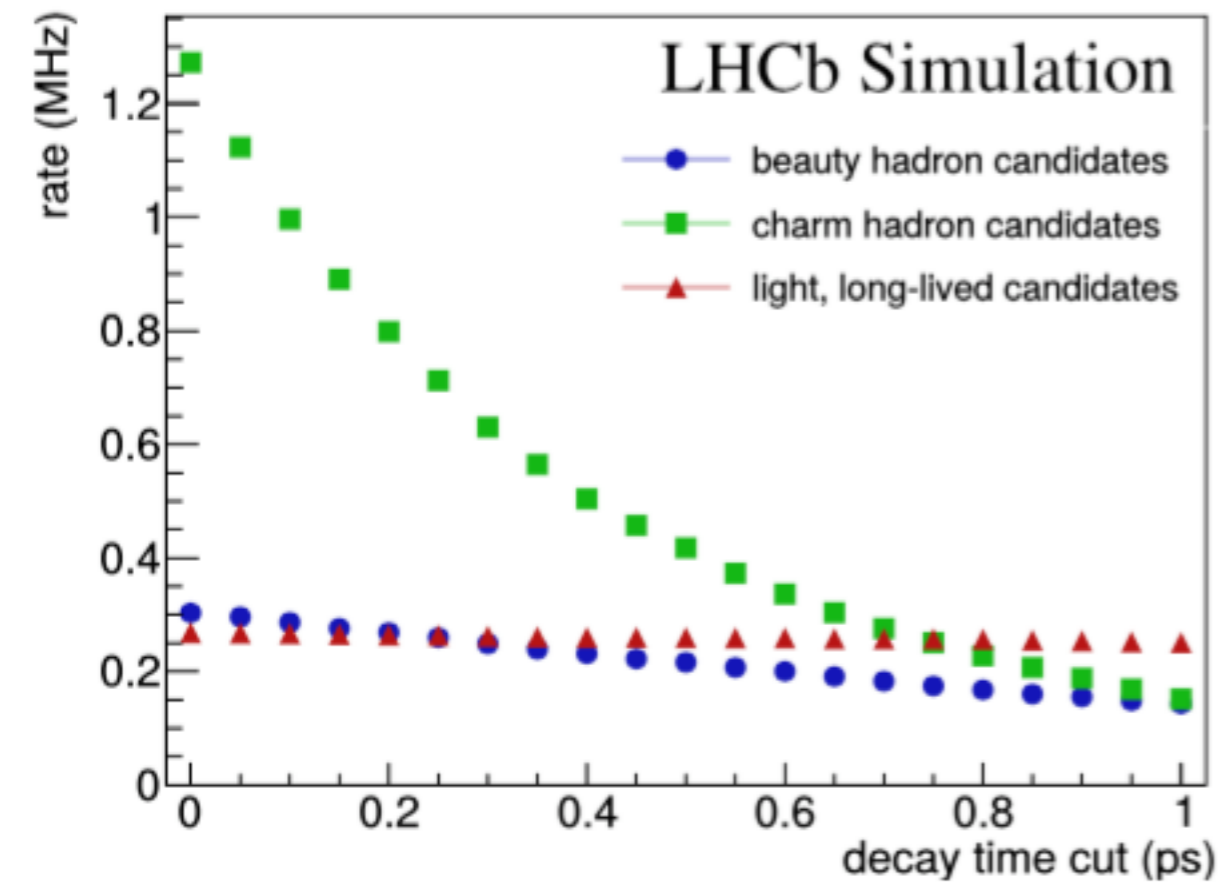
- ◇ VELO moves from r, φ strips to pixels:
 - ◇ LHCb-TDR-013
- ◇ RICH replaces photon detectors, SPD, PRS, M1 removed:
 - ◇ LHCb-TDR-014
- ◇ Trackers replaced: scintillating fibers + silicon microstrips:
 - ◇ LHCb-TDR-015
- ◇ The readout & trigger gets upgraded:
 - ◇ LHCb-TDR-016



- ◇ Hadronic signal trigger rates saturate for higher luminosity
 - ◇ consequence of total trigger rate throttling by E_T cut at L0

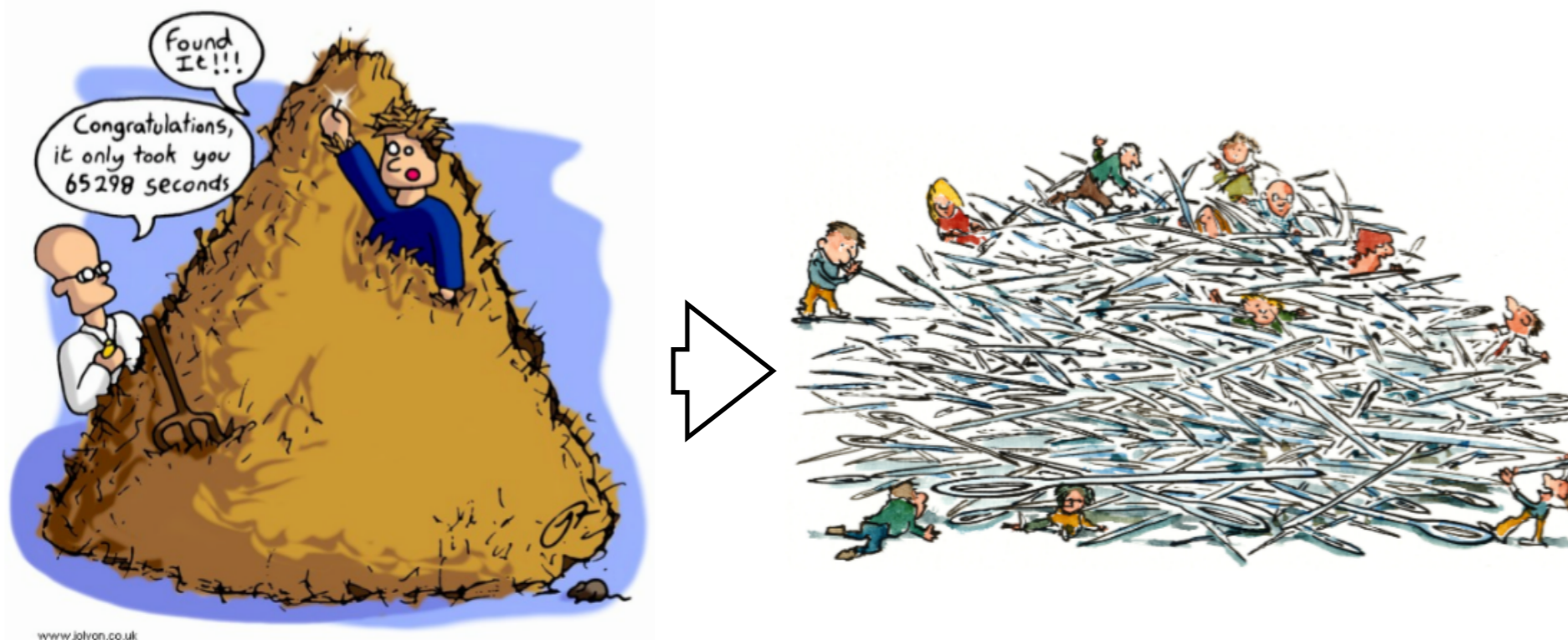
MHz Signal Era

LHCb-PUB-2014-027



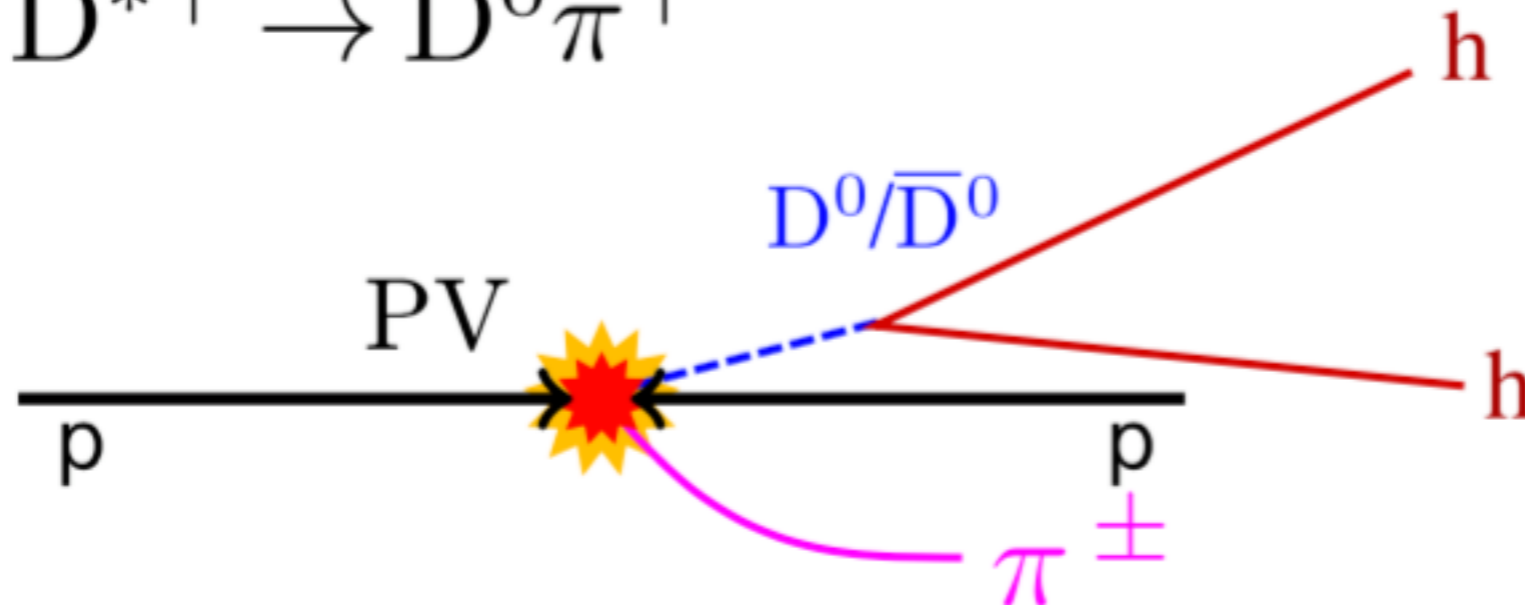
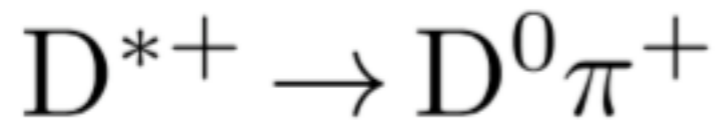
- ◇ LHCb will take 5× more collisions per second
- ◇ Readout becomes a bottleneck as signal rates → MHz even after simple trigger criteria
 - ◇ 24% (80GB/s) of events contain reconstructable charm hadron
 - ◇ 2% (27GB/c) of events contain a beauty hadron
 - ◇ 1GB/s for Run 2 offline readout
 - ◇ higher throughput is expected after upgrade

Change in Trigger Paradigm



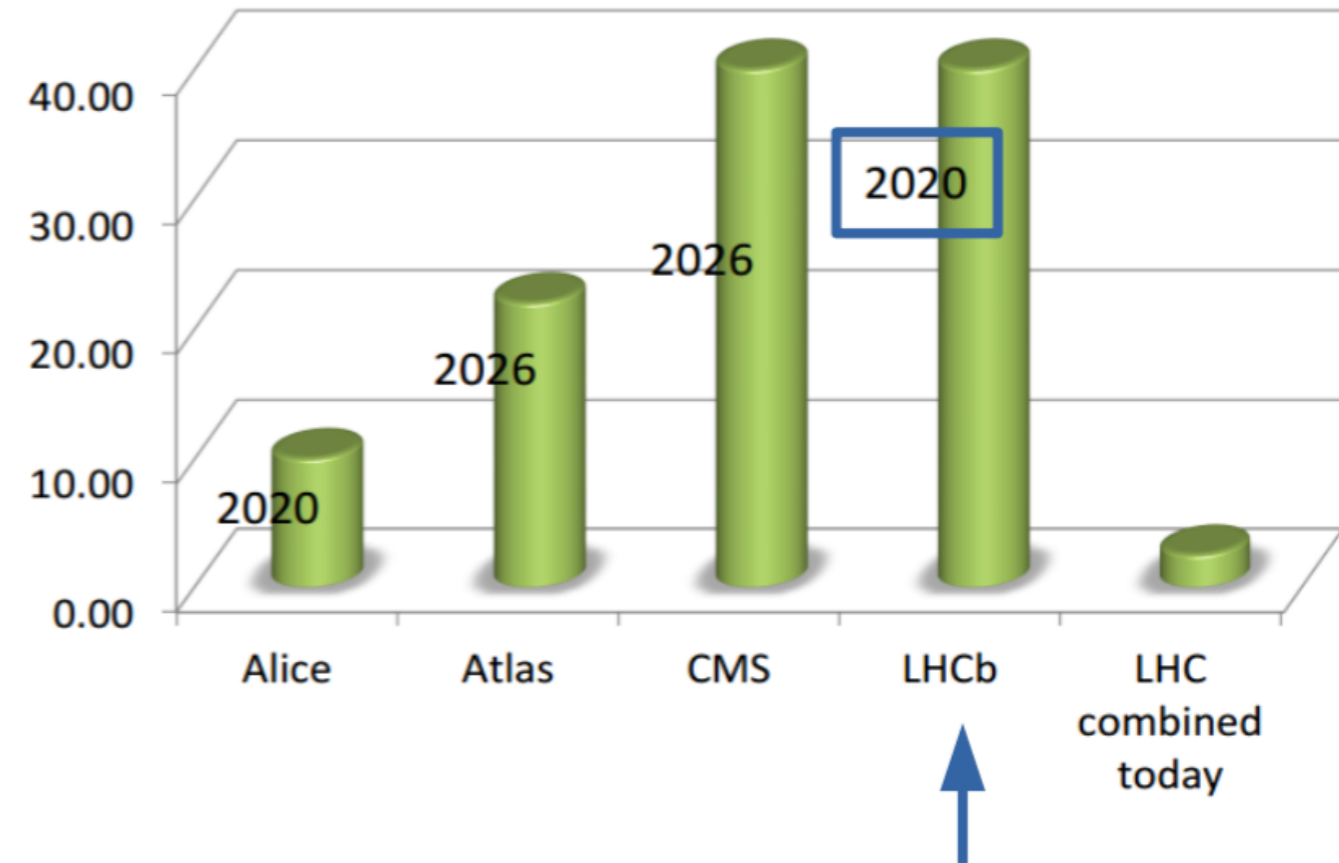
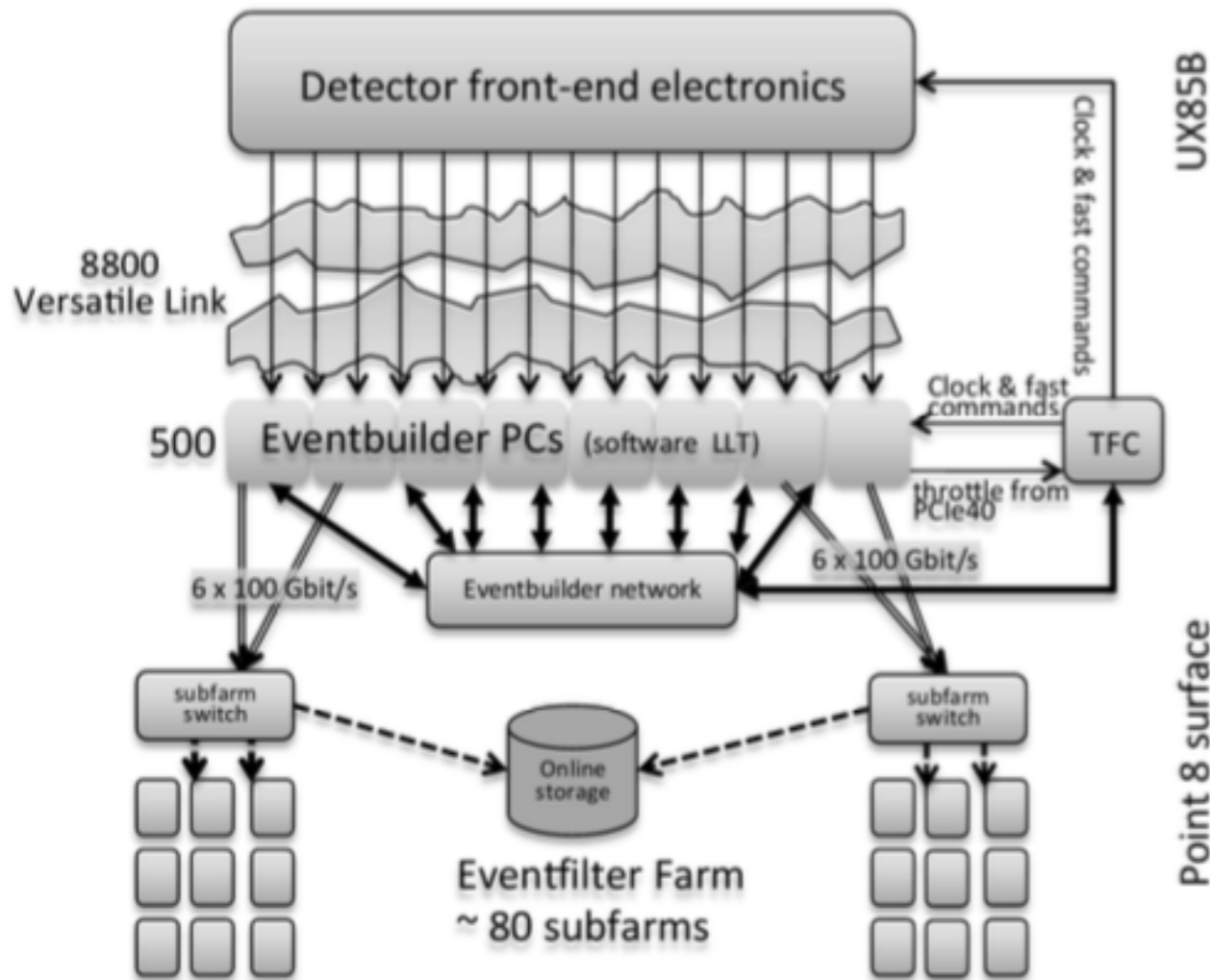
- ◇ From: which (trivial) backgrounds we could reject
 - ◇ categorise signals from backgrounds
- ◇ To: which signal we could afford to throw away
 - ◇ categorise different signals
- ◇ Most triggers must be exclusive

Example: Charm Mixing



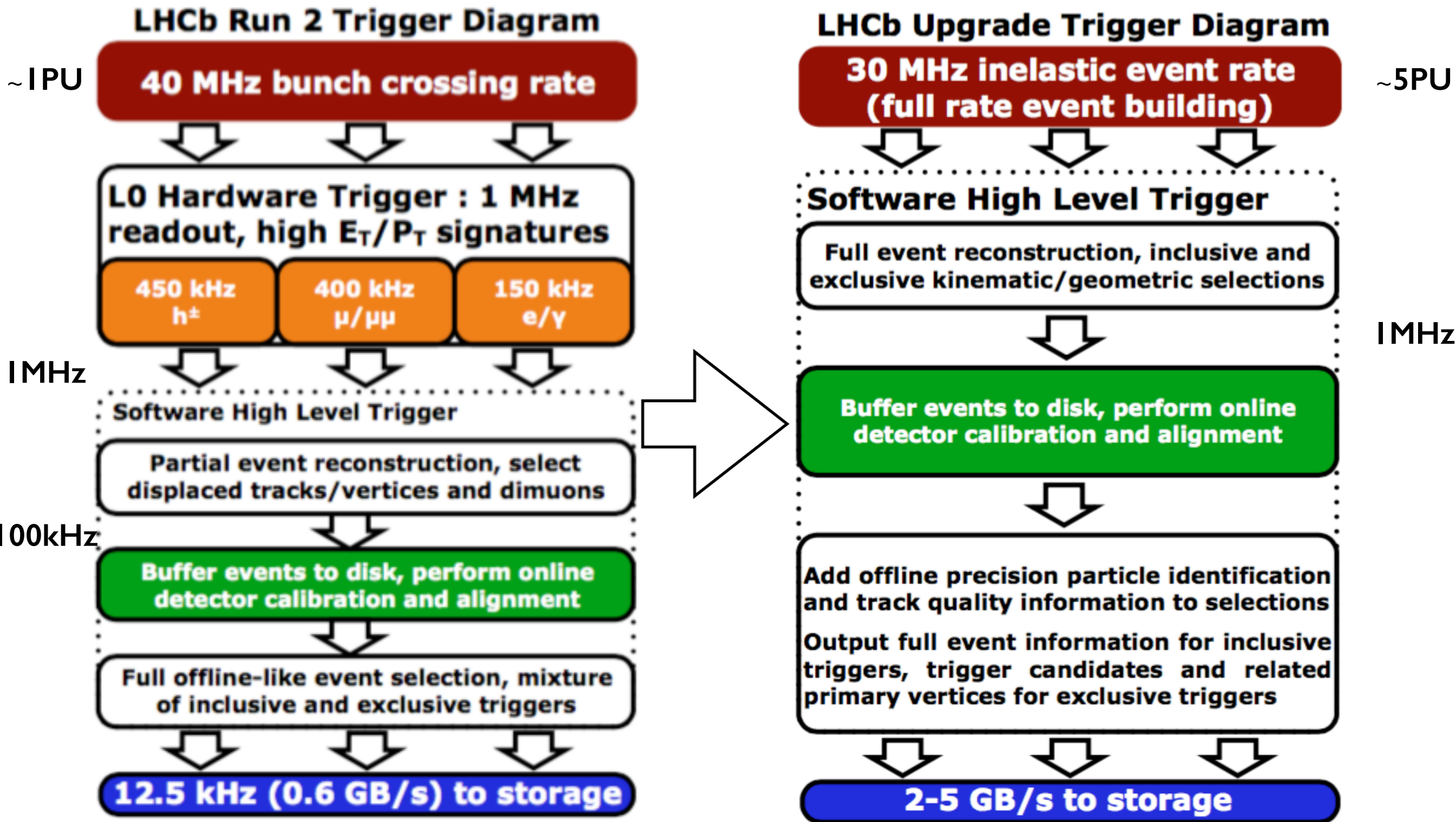
- ◇ Cabibbo favoured $D^0 \rightarrow K^- \pi^+$ is $300\times$ more abundant than DCS $D^0 \rightarrow K^+ \pi^-$
- ◇ Want to keep 100% of the 'interesting' DCS mode
 - ◇ but prescale the CF mode
 - ◇ cannot be done using simple 'trigger' criteria
- ◇ Full reconstruction + Particle ID in the trigger needed to make this possible
 - ◇ Phys. Rev. Lett. 111, 251801 (2013)

Solution: Readout Directly to Software



- ◇ Get rid of hardware trigger
- ◇ Detector readout at the LHC bunch crossing frequency
- ◇ Full reconstruction is available @HLT farm
 - ◇ 40 Tbit/s event building and filtering

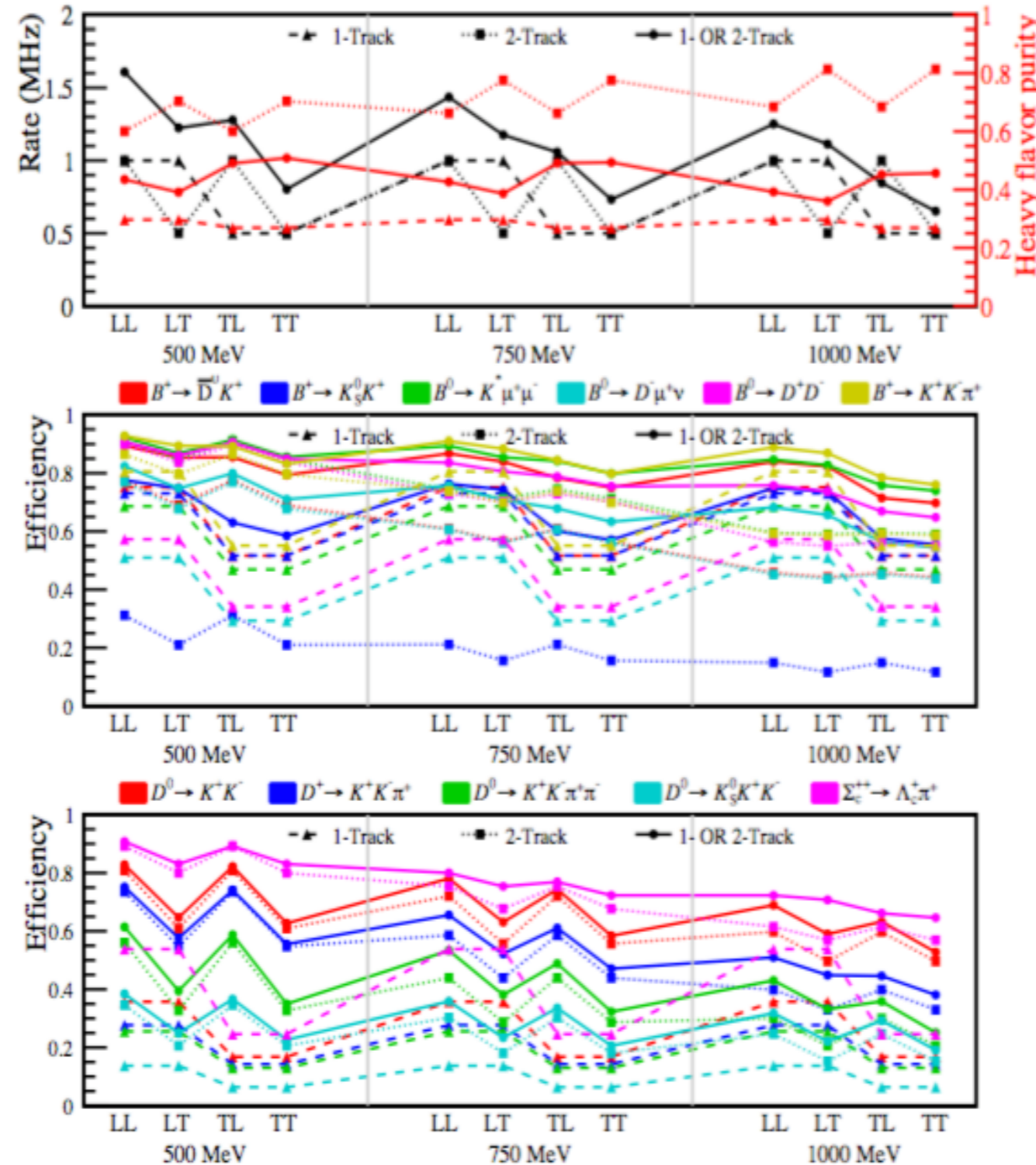
The Run 3 Trigger



Software “L1” trigger

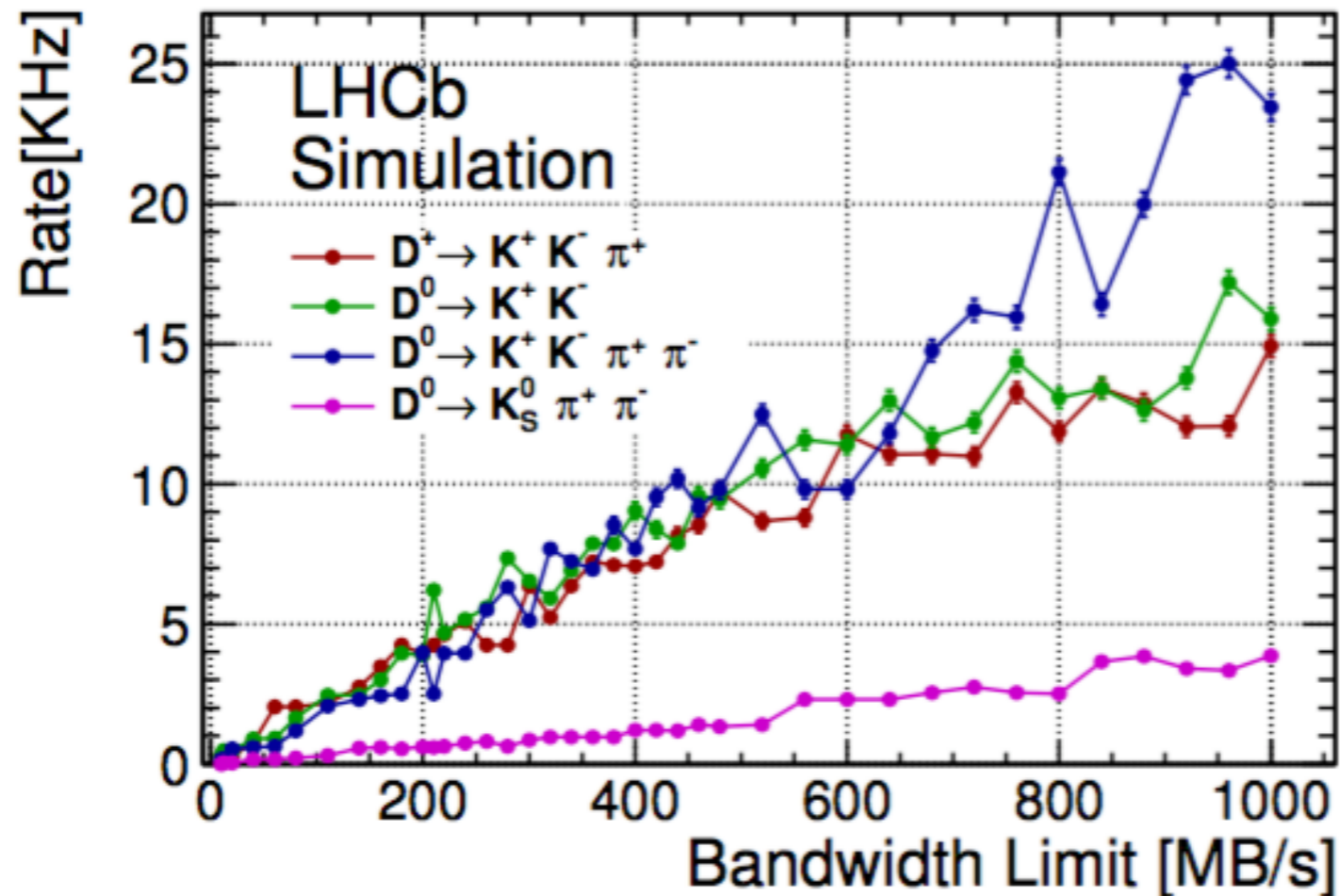
LHCb-PUB-2017-006

- ◇ 1- and 2- track performance under study
- ◇ MVA parameters for Loose and Tight configurations
- ◇ Several tracking thresholds 500 → 1000 MeV
- ◇ Results with minimal changes from Run 2:
 - ◇ 1-track needs more work
 - ◇ 2-track performance is good already



Software “L2” Trigger

LHCb-PUB-2017-006



- ◇ Turbo paradigm: More exclusive selections than in Run 2, with wide adoption of MVAs
- ◇ With many (> 500) trigger lines, sharing output bandwidth equitably is a challenge
- ◇ Genetic algorithm based procedure makes this easier, [analysts decide between event size and output rate](#)

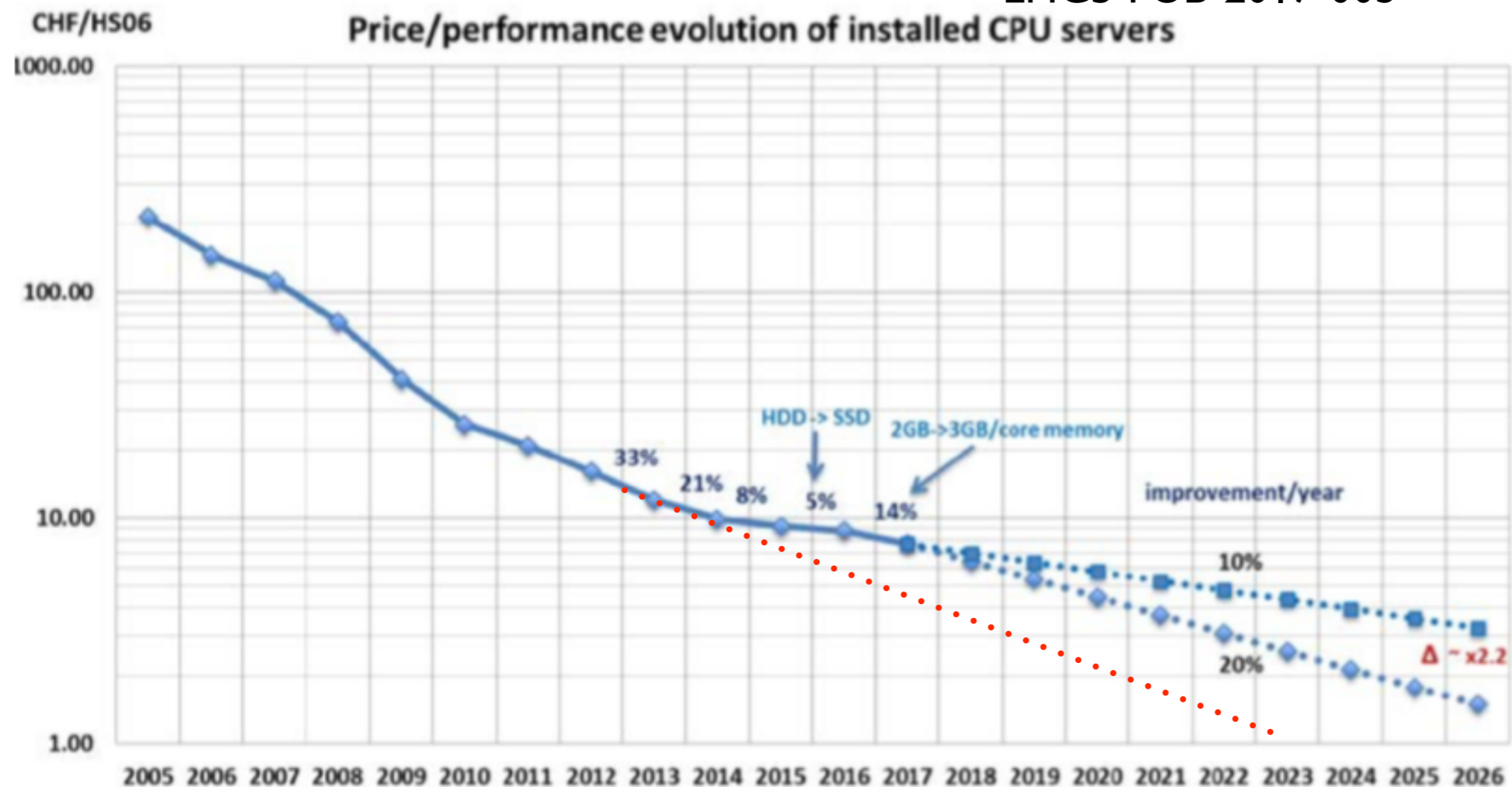
No Free Cheese

- ◇ Throwing away most of the event means care must be taken
 - ◇ Turbo relies on never needing to reprocess:
 - ◇ Online monitoring & data quality are even more important
 - ◇ In Run 2 the disk buffer allows up to 2 weeks of safety margin
 - ◇ Not so in Run 3, where buffer will have O(days)
 - ◇ Integration testing, real-time monitoring & robust procedures are critical components of the trigger
- 👍 In Run 2, we have never needed to reprocess thanks to these procedures

Computing Throughput

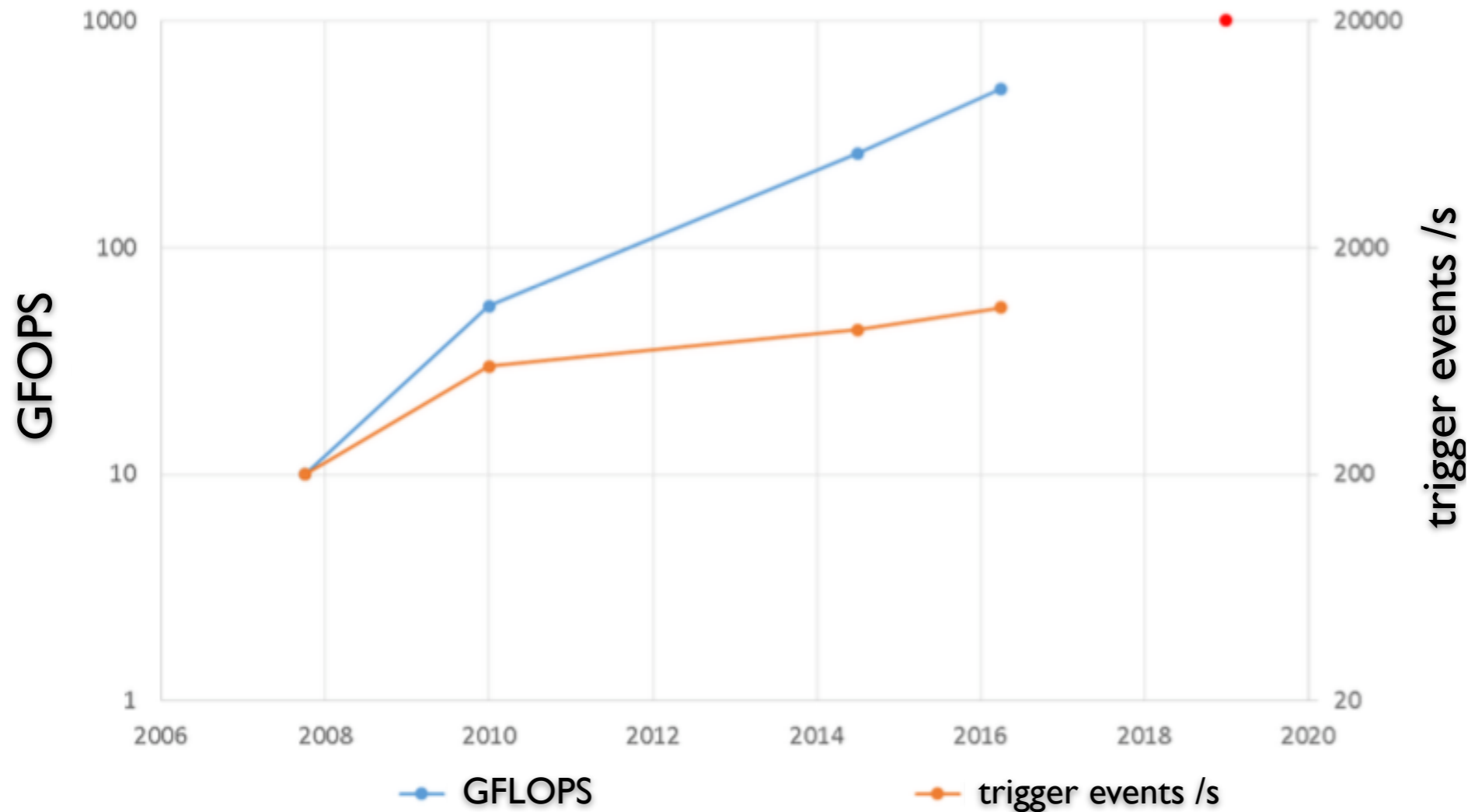
- ◇ Upgrade phase 1 starts taking data in 2021
- ◇ Upgrade farm budget: 1000 computing nodes
- ◇ Goal: Throughput $> 30\text{MHz}$

LHCb-PUB-2017-005



- ◇ Throughput extrapolated from 2012 hardware: 33MHz
- ◇ from 2017 hardware: 5MHz

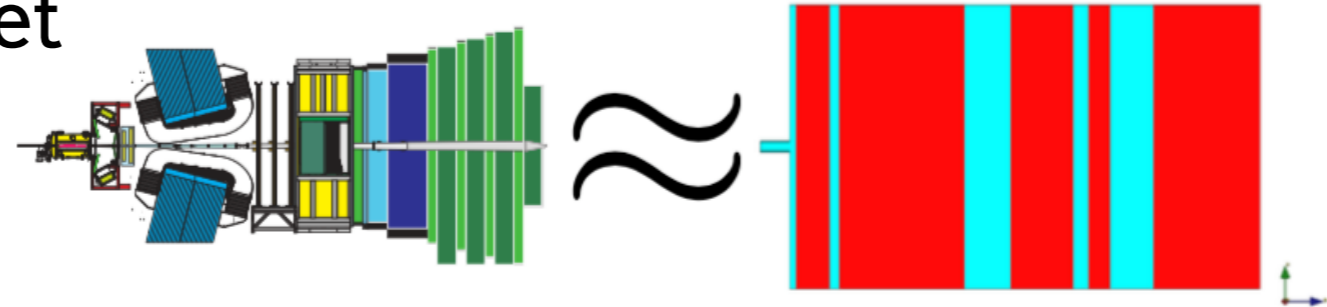
Multithreading



- ◇ Clock frequencies aren't increasing as fast, but the FLOPS are there
- ◇ Number of processors per CPU core are increasing (multi-threading)
- ◇ and more instructions per clock cycle (vectorisation)
- ◇ LHCb is moving from multiprocessing to a multithreading model

Algorithms Speed Up

- ◇ Many areas to improve
- ◇ E.g. track fit (Kalman Filter) uses a significant fraction of HLT1 budget

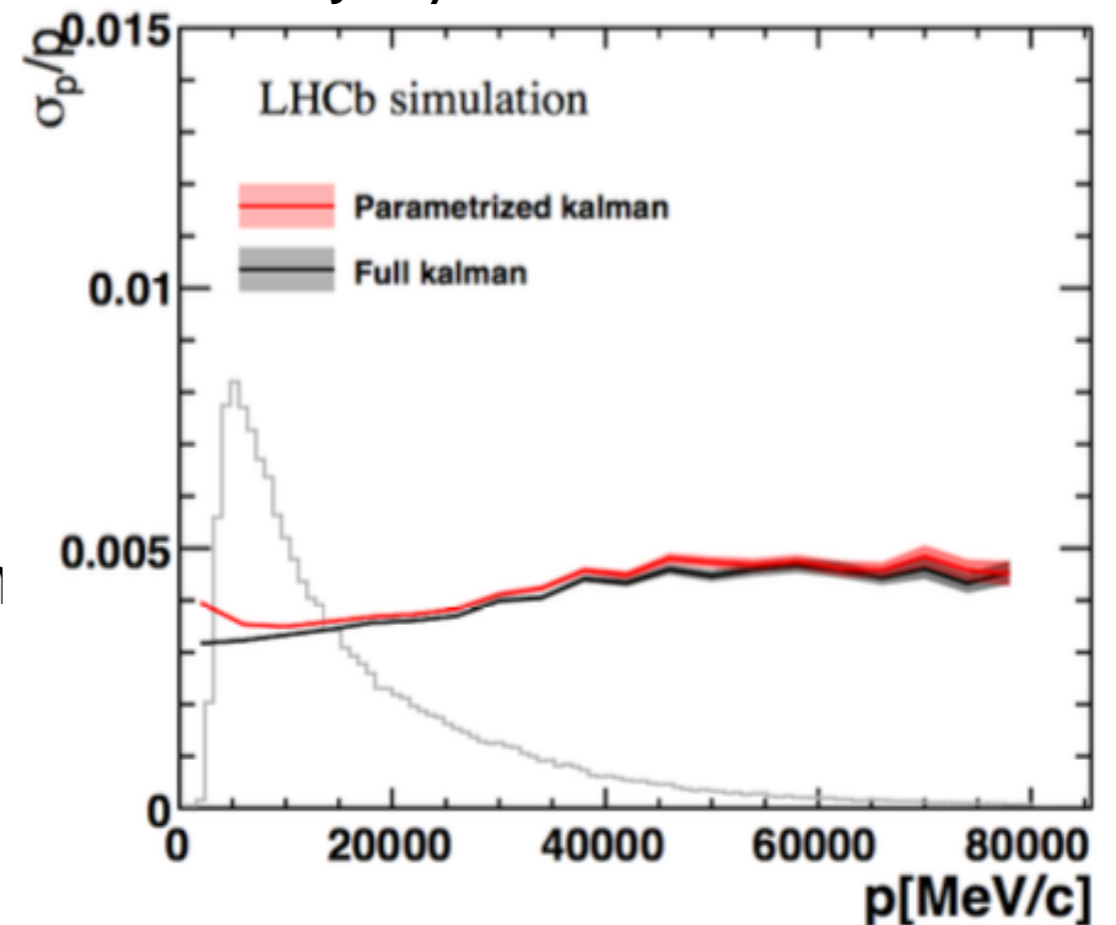


- ◇ Run 1: Material lookup + B-field propagation
- ◇ Run2: Material map replaced with a simplification

- ◇ For the upgrade, one step further:

- ◇ "Parameterised Kalman"
- ◇ Replace both material and B-field with analytic functions
- ◇ Much faster and already excellent performance

2017 J. Phys.: Conf. Ser. 898 032052



Conclusions

- ◇ LHCb signal rates in the Upgrade change the definition of a trigger:
 - ◇ 'Rejects background' → 'categorises signal'
 - ◇ 'Reduces rate' → 'Reduces bandwidth'
- ◇ In order to efficiently categorise MHz signals, LHCb will use a triggerless readout
- ◇ Offline quality selections mean only subset of the event has to be saved for analysis
 - ◇ Not only possible, necessary to keep high efficiency for signals
Requires fully aligned & calibrated detector in the trigger
 - ◇ Run 2 has shown that this is the way to go for Run 3
- ◇ Not without its challenges: Extensive upgrades to the software as well as the detector