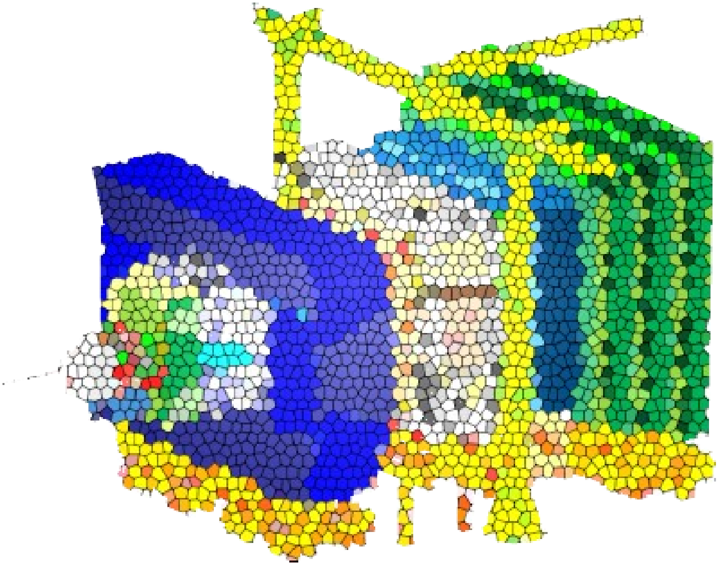
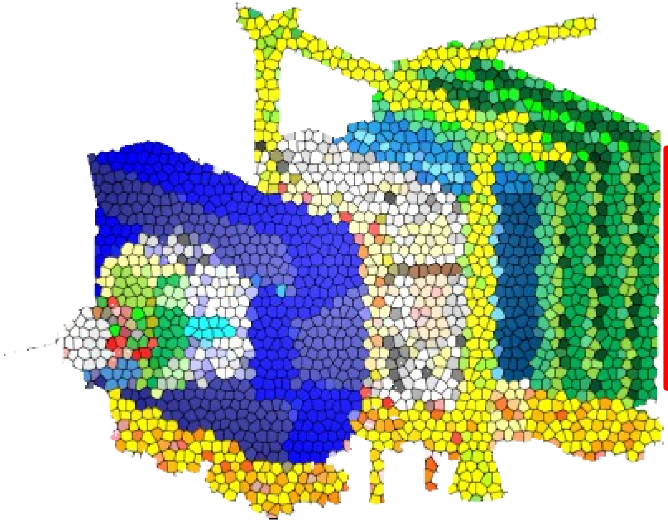


Physics vs. Detector

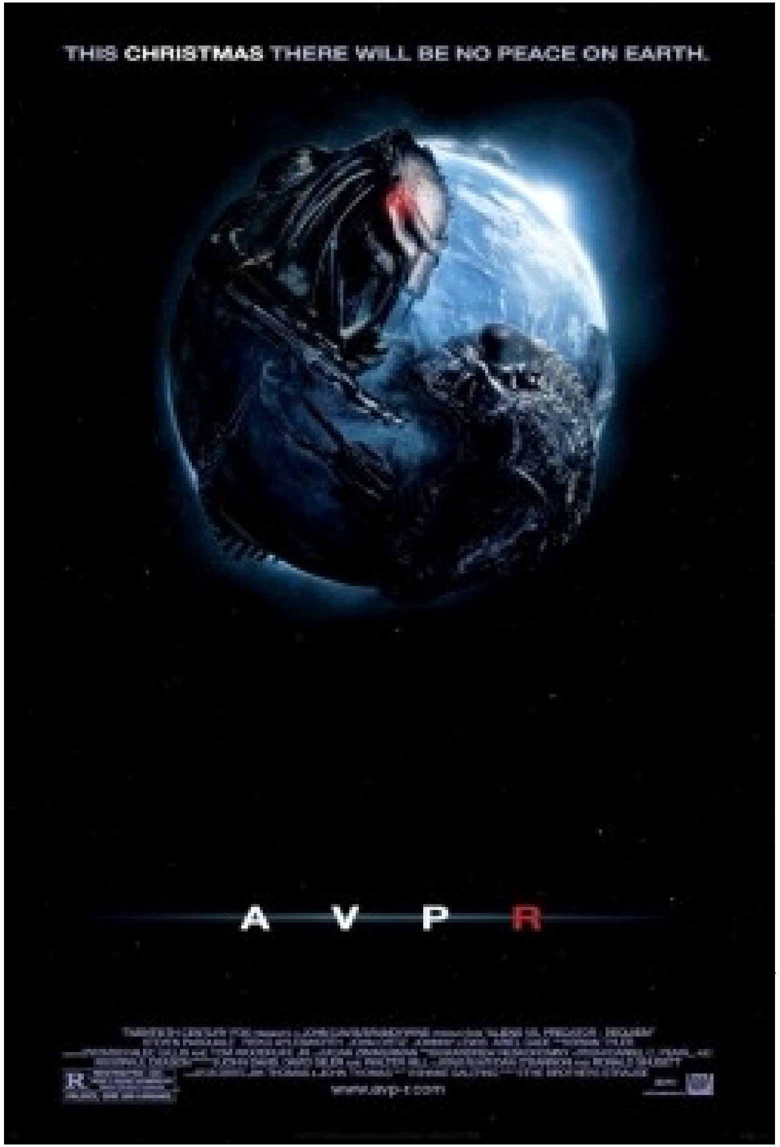
Tim Gershon
University of Warwick

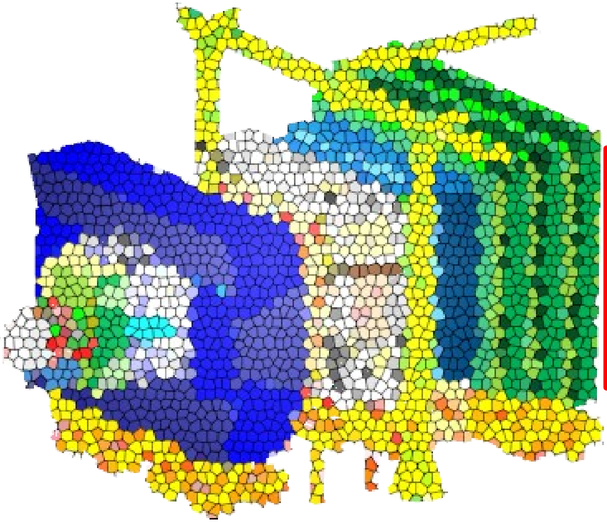
6th Workshop on LHCb Upgrade II
Barcelona, 29 March 2023

Thanks to V. Gligorov, M. Palutan, Y. Amhis, E. Thomas, R. Forty and others for input

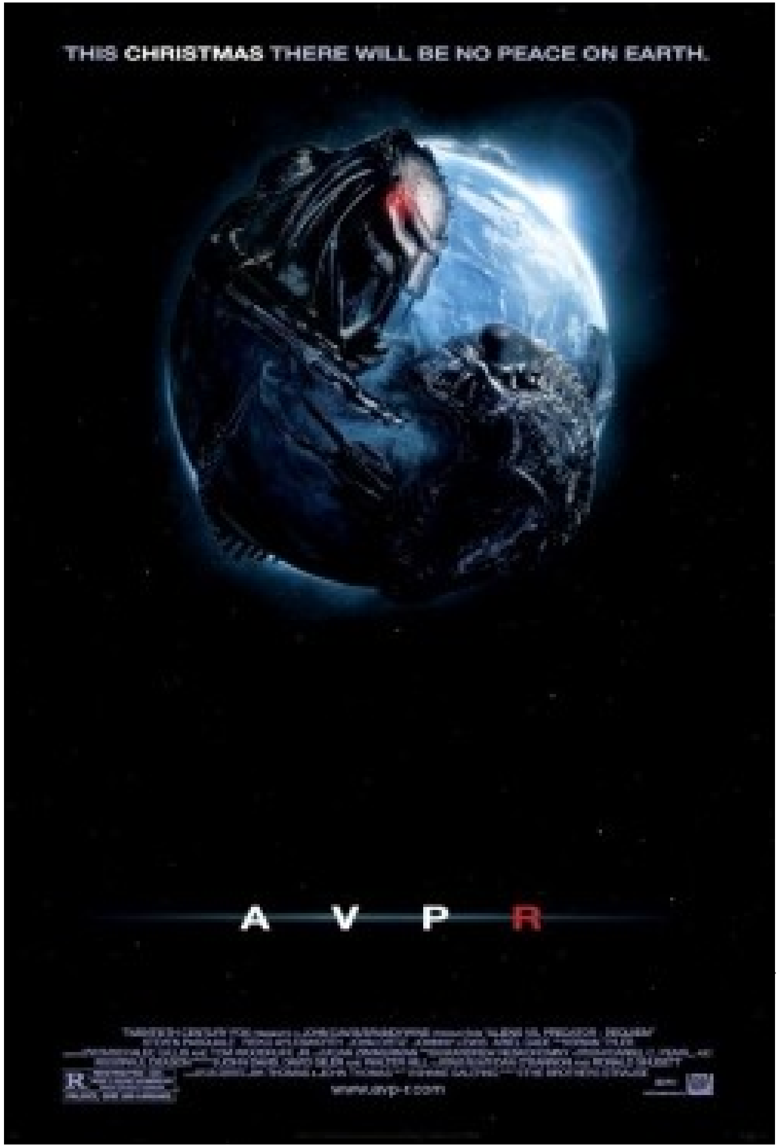


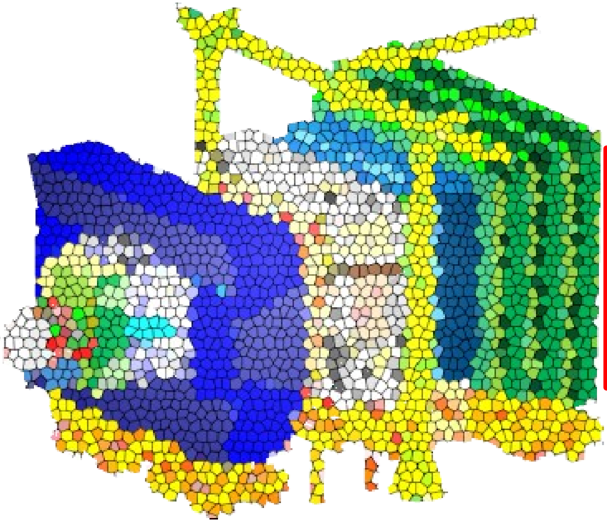
Physics vs. Detector





Physics vs. Detector
Upgrade II





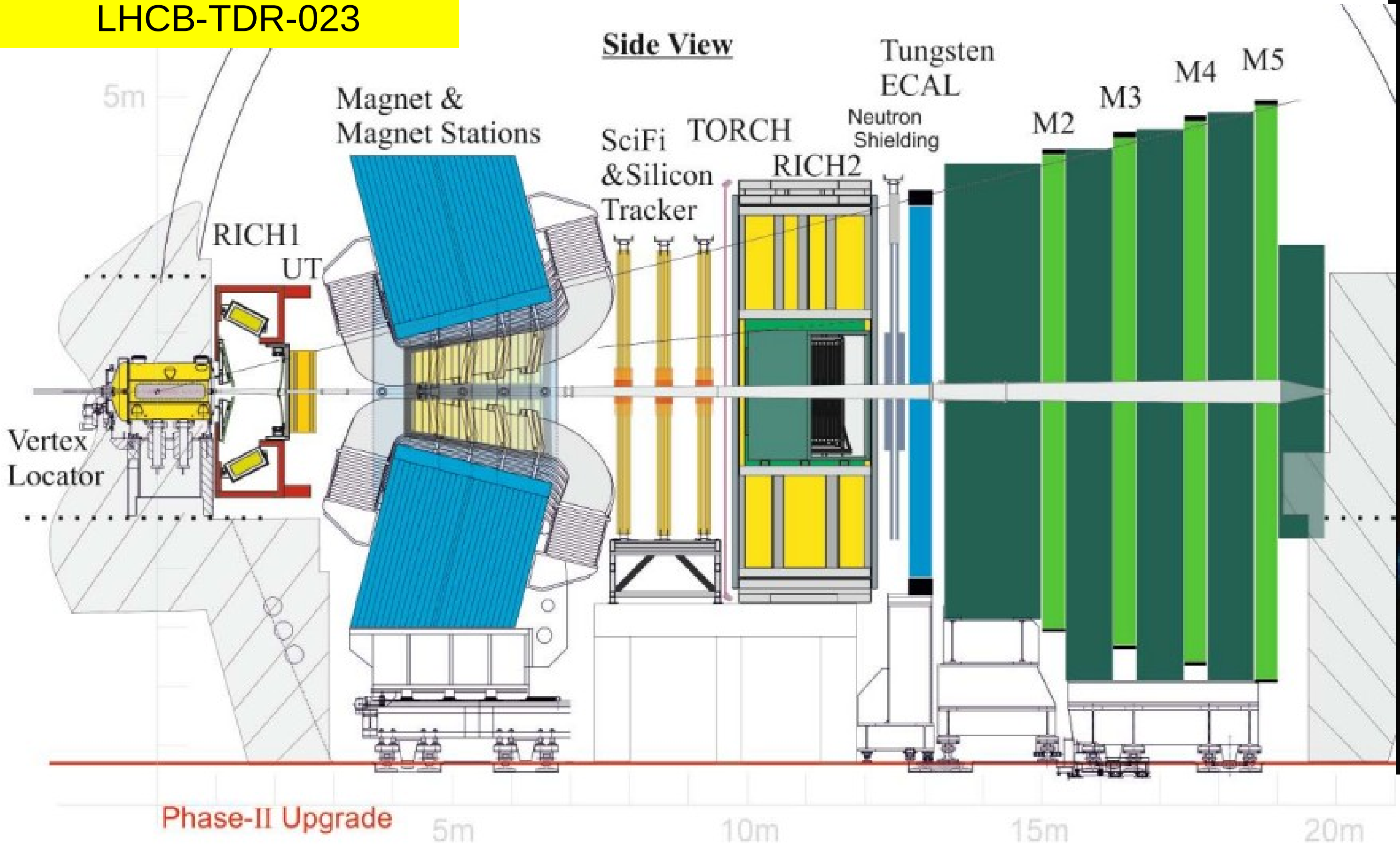
Physics vs. Detector
Upgrade II
Ultimate Precision

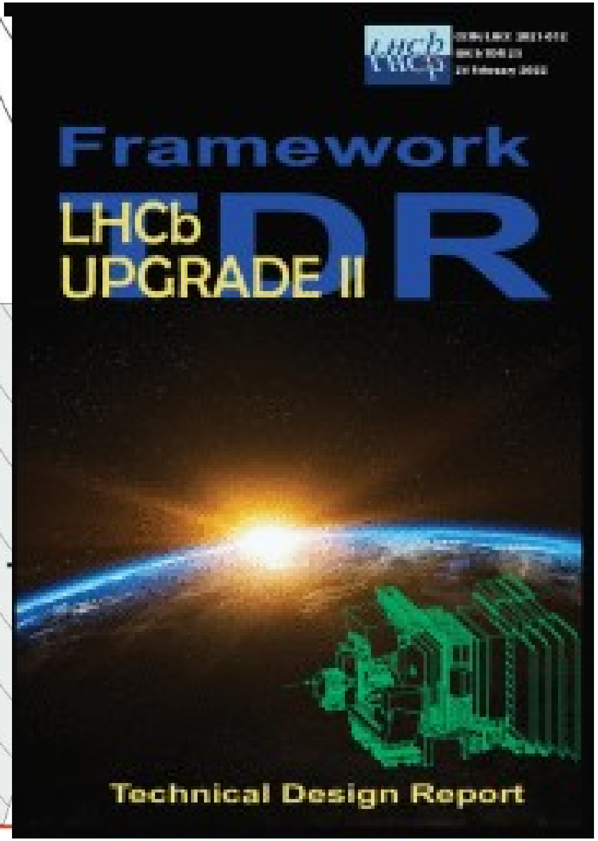
Content

- Physics case as of FTDR
- Going beyond $\sqrt{N}$
- Scoping
- Thinking radical

Physics Case as of FTDR

LHCB-TDR-023





LHCB-TDR-023

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_{\rm S}^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

Some “current LHCb” numbers now out-of-date

Improved precision here mostly “just” from luminosity scaling

Beyond √N scaling

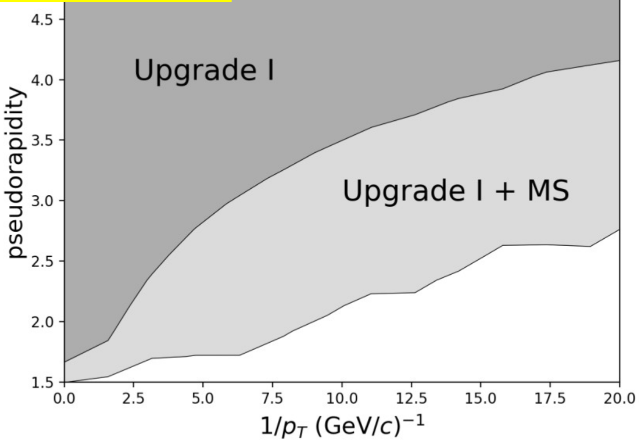
- Increase from 50/fb → 300/fb is significant
  - Energy reach scales roughly as $N^{1/4}$: $6^{1/4} \approx 1.6$
    - controversial statement: comparable to changing √s from 14 to 22 TeV
- Original → Upgrade I:
  - gained not only from 9/fb → 50/fb but also improved trigger efficiency
    - canonical factor of 2 gain for hadronic modes generally assumed
- Are there other gains we might make for Upgrade 2?
  - yes, and we propose to make some of them in FTDR
  - but we do not yet have full simulation to quantify properly the impact

Acceptance

- We lose most of our statistics due to acceptance
  - worst for low p_T tracks, and high multiplicity final states
  - [long-lived particles also have other issues, not discussed here]
- Can get some of it back with magnet stations

Not so far from a canonical factor 2

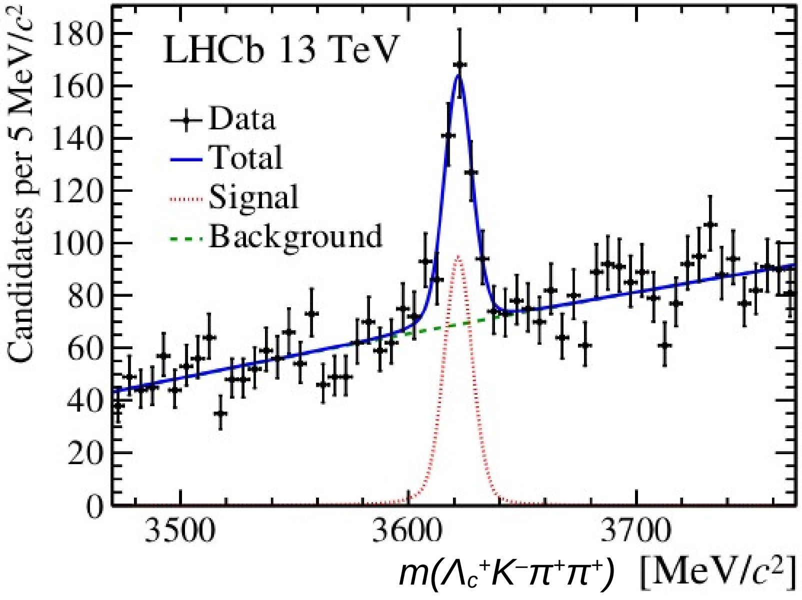
LHCB-TDR-023



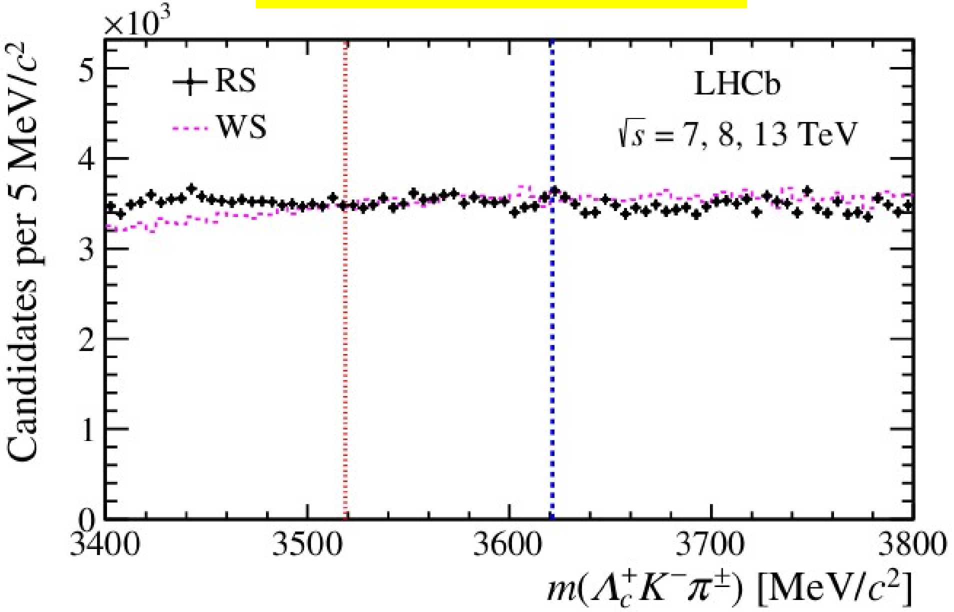
channel	≥8 SciFi hits	SciFi+MS hits	gain
$\gamma \to e^+e^-$ ($p_{T,\gamma}$ >10 MeV/c)	0.245	0.98	4.1
$\rho^0 \to \pi^+\pi^-$	0.530	0.780	1.5
$K^0_S \to \pi^+\pi^-$	0.384	0.720	1.9
$K^{*0} \to K^\pm\pi^\mp$	0.479	0.704	1.5
$D^{*+} \to D^0 + \pi^\pm$ ($\pi^\pm$ in MS)	0.33	0.67	2.0
$D^{*0} \to D^0 + e^+e^-$ (e^+e^- in MS)	0.22	0.66	3.0
$D^+_s \to D^0 + K^+$ (K^+ in MS)	0.74	0.89	1.20
$\chi_{c1}(3872) \to J/\psi + \pi^+\pi^-$ ($\pi^+\pi^-$ in MS)	0.51	0.73	1.43
$B^+ \to (J/\psi \to e^+e^-\gamma)\,K^+$	0.70	0.83	1.3
$\Omega_c^{*0}(3067) \to (\Xi_c^+ pK^-\pi^+)\,K^+$	0.63	0.80	1.27
$B^+ \to \left(D^0 \to \left(K^0_S \to \pi^+\pi^-\right)\pi^+\pi^-\right)K^+$	0.34	0.56	1.7
γ+pomeron $\to J/\psi \to e^+e^-$	0.57	0.69	1.18
γ+pomeron $\to \rho^0 \to \pi^+\pi^-$	0.39	0.58	1.49
$\gamma + \gamma \to e^+e^-$	0.008	0.03	3.8

Vertexing

LHCb-PAPER-2017-018



LHCb-PAPER-2019-029



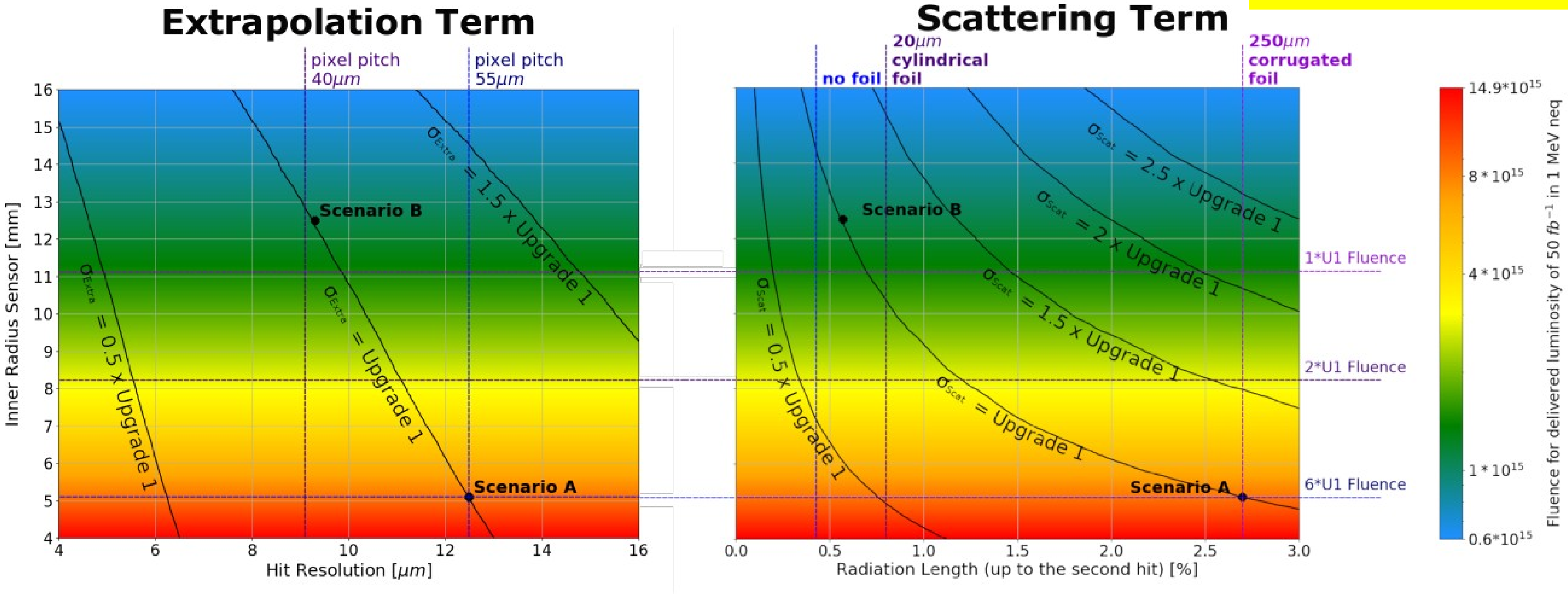
Why do we observe the Ξ_{cc}^{++} (left), but not the Ξ_{cc}^{++} (right)?

Likely explanation: $\tau(\Xi_{cc}^{++}) \sim 250$ fs [LHCb-PAPER-2018-019]; $\tau(\Xi_{cc}^{+}) \sim 80$ fs [predicted]

VELO performance enough to separate Ξ_{cc}^{++}, but not Ξ_{cc}^{+}, from PV background

Pushing beyond “iso-performance”

LHCB-TDR-023



The whole LHCb physics programme benefits from improved VELO performance

Short-lived particles benefit the most

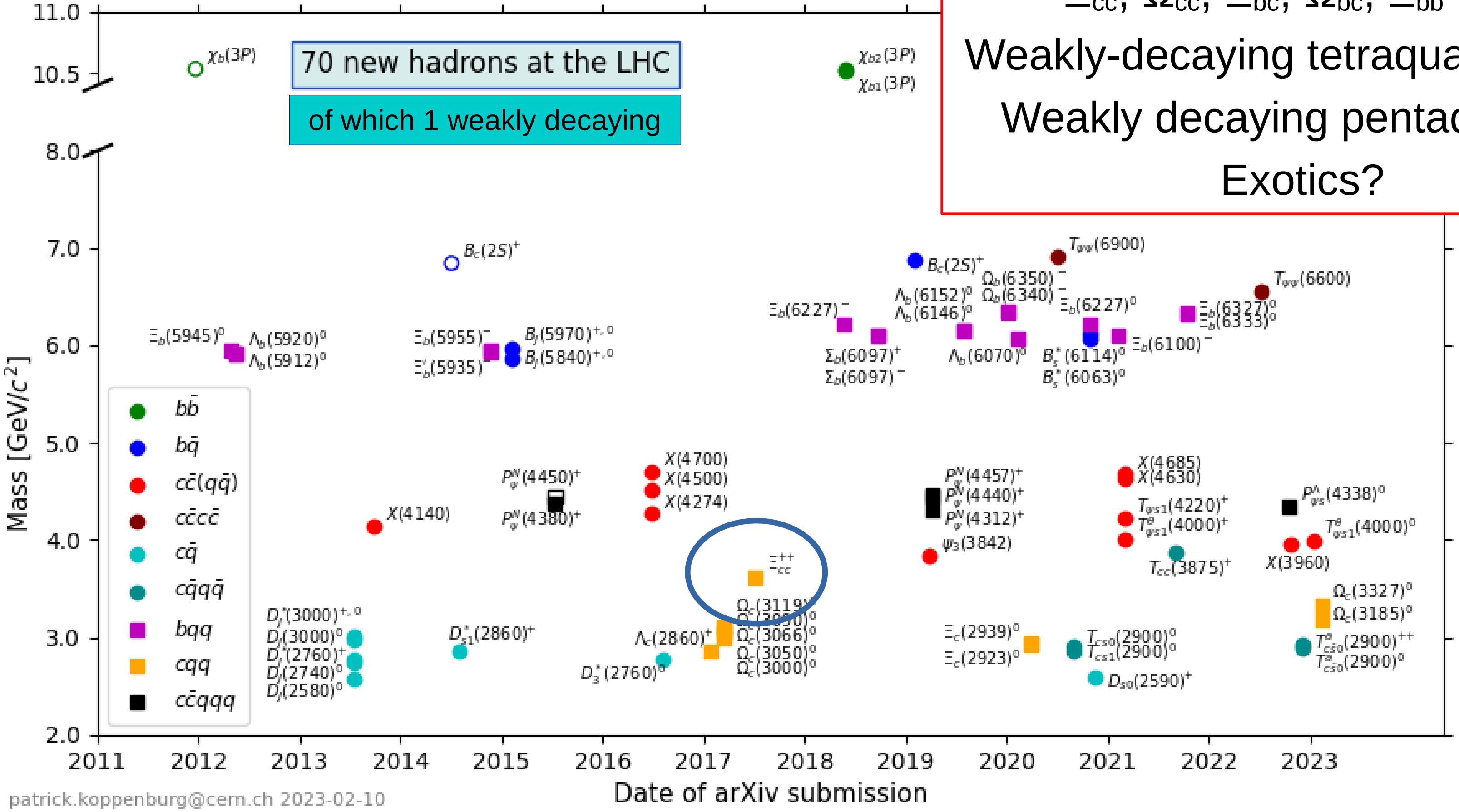
Discoveries within reach with better vertexing

Ξ_{cc}, Ω_{cc}, Ξ_{bc}, Ω_{bc}, Ξ_{bb} , Ω_{bb}

Weakly-decaying tetraquarks? [T_{bb}]

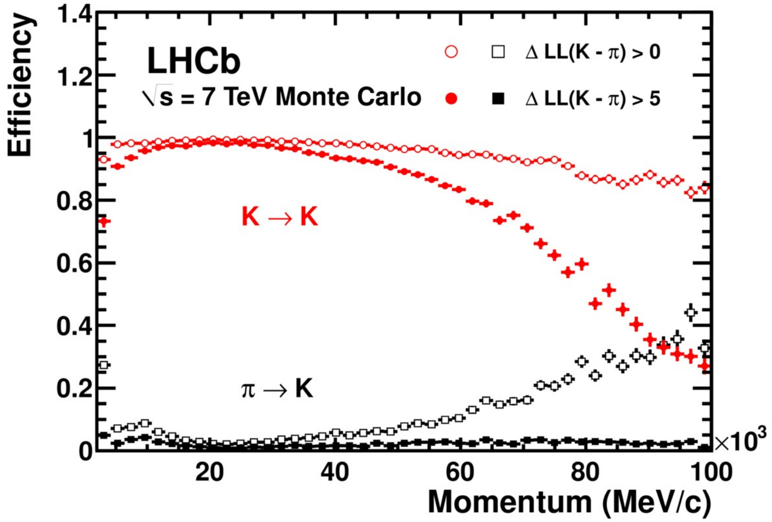
Weakly decaying pentaquarks?

Exotics?



Particle identification

LHCb-DP-2012-003
(old plot, just illustrative)

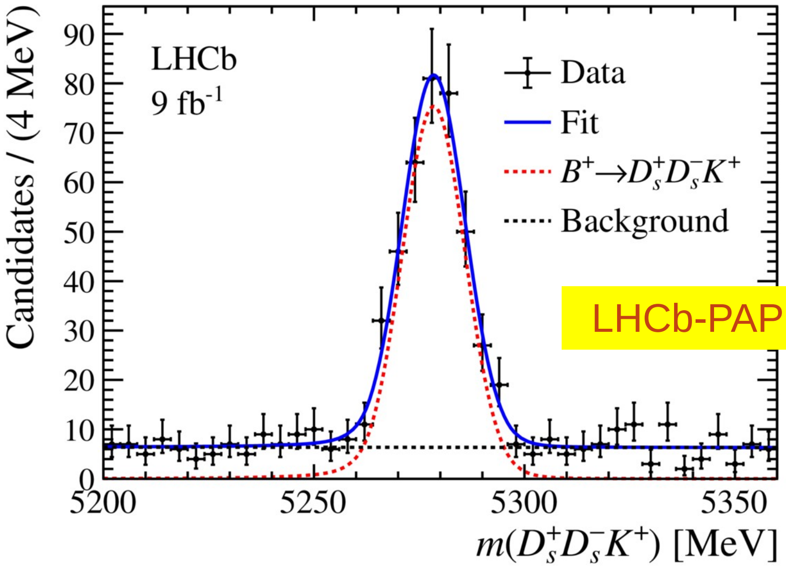


Our programme includes many decays with large numbers of final-state tracks (new record – 9 – in LHCb-PAPER-2023-008)

Often multiple kaons: example below 7 tracks/5 kaons

More tracks ↔ more likely one has low momentum

Small gains add up



LHCb-PAPER-2022-019

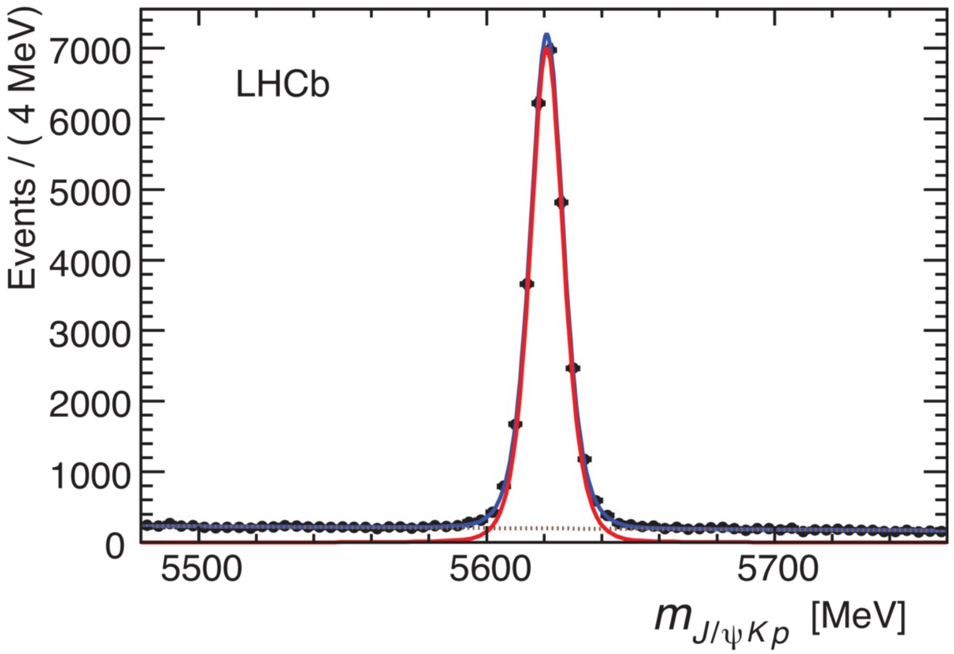
Particle ID for deuterons and other light nuclei would open new possibilities

Work in progress (e.g. LHCb-FIGURE-2020-013)

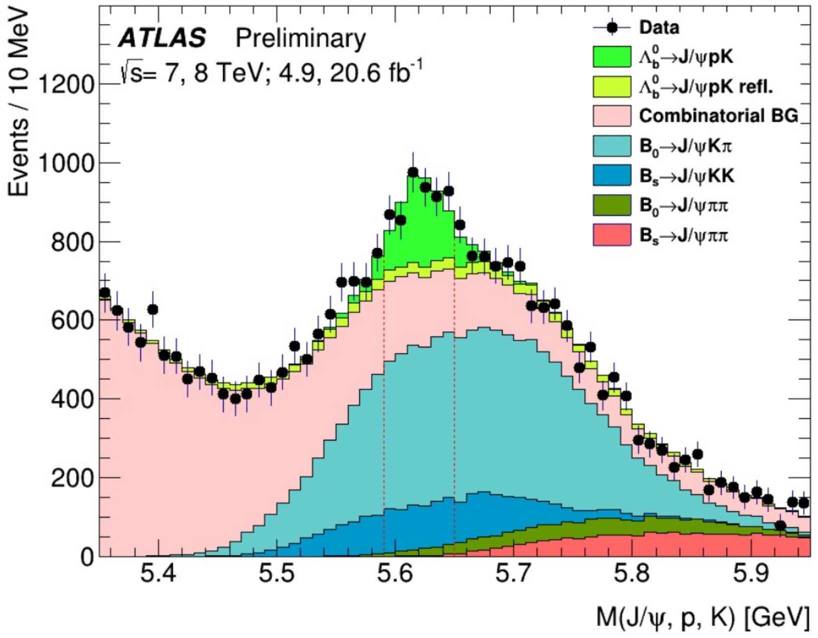
Clear potential impact of TORCH

In case you forget importance of PID

LHCb-PAPER-2015-029

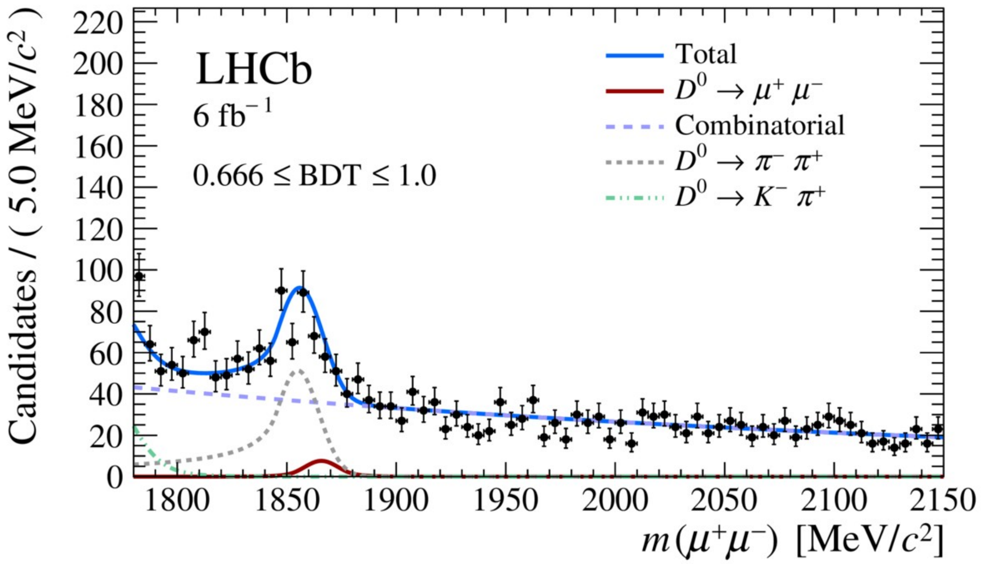


ATLAS-CONF-2019-048



In case you forget importance of PID

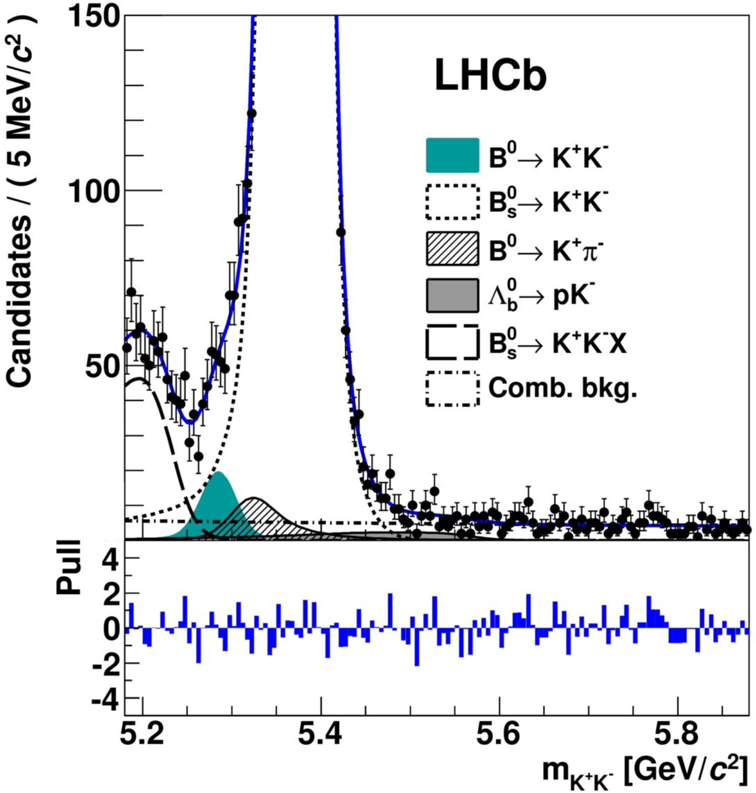
LHCb-PAPER-2022-029



For many modes we are at the limit of what the current detector can achieve

Having (even) better PID & mass resolution would have big impact here

LHCb-PAPER-2016-036

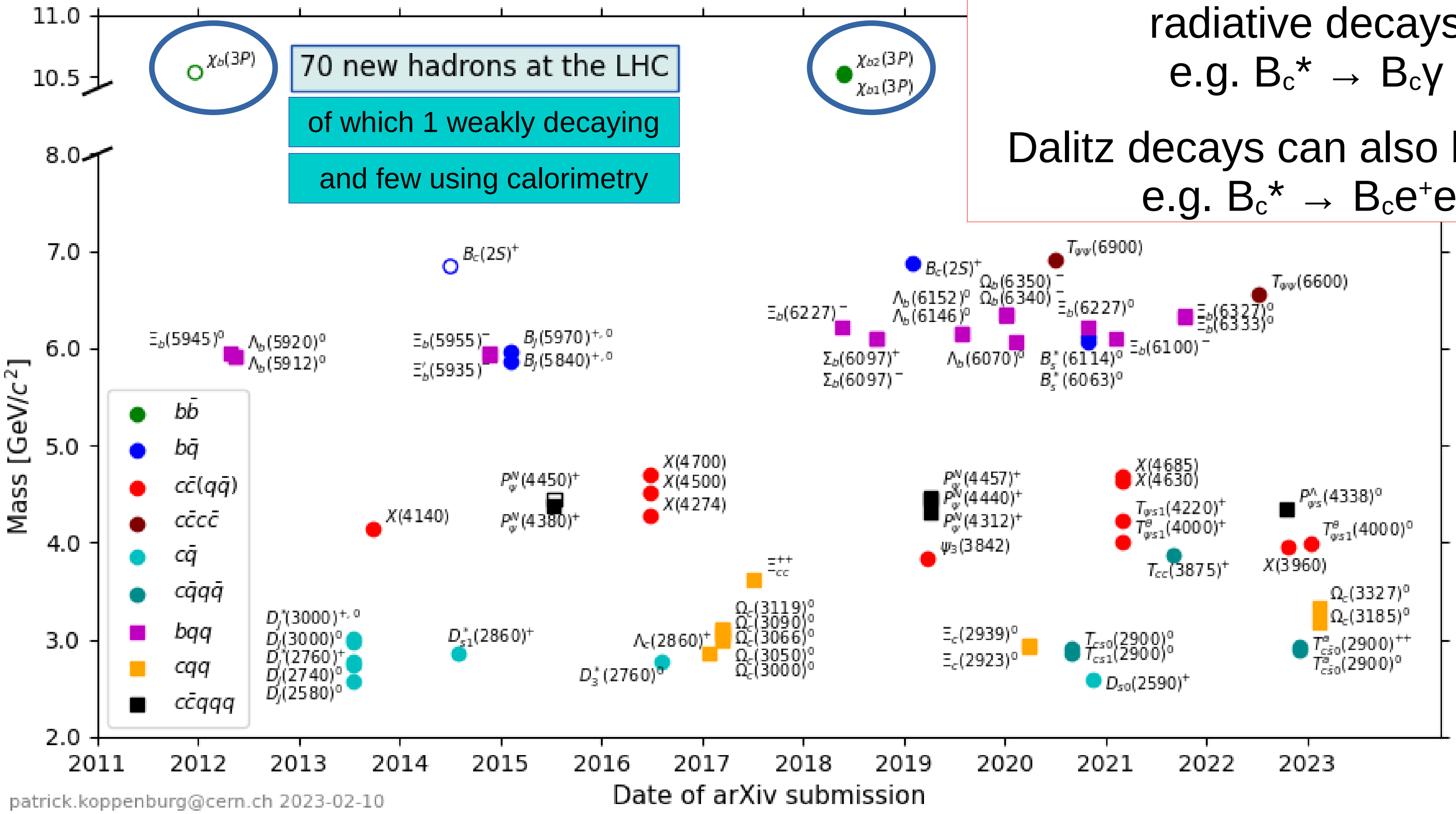


Discoveries within reach with calorimetry

70 new hadrons at the LHC

of which 1 weakly decaying

and few using calorimetry



Many states with dominant radiative decays
e.g. $B_c^* \rightarrow B_c\gamma$

Dalitz decays can also be used
e.g. $B_c^* \rightarrow B_c e^+e^-$

Performance

- It is not just about the detector – we also have to exploit the data efficiently
- Out of 660+ LHCb papers to date
  - ~25 involve electrons ($b \to s e^+ e^-$, similar with LFV, $Z \to e^+ e^-$, $J/\psi \to e^+ e^-$)
  - ~25 with photons ($b \to s\gamma$, $\chi_{c1/2} \to J/\psi\gamma$, η, η', ω)
  - ~3 with fully reconstructed $D^{*0} \to D^0\pi^0/D^0\gamma$ or $D_s^* \to D_s\gamma$
  - ~10 with π^0 in D decay plus 1 with π^0 in B decay
  - nothing yet with deuterons …
- These analyses are hard
  - but we can make them easier through development of common tools ...
  - to make us more productive and give better return on detector investment

Scoping

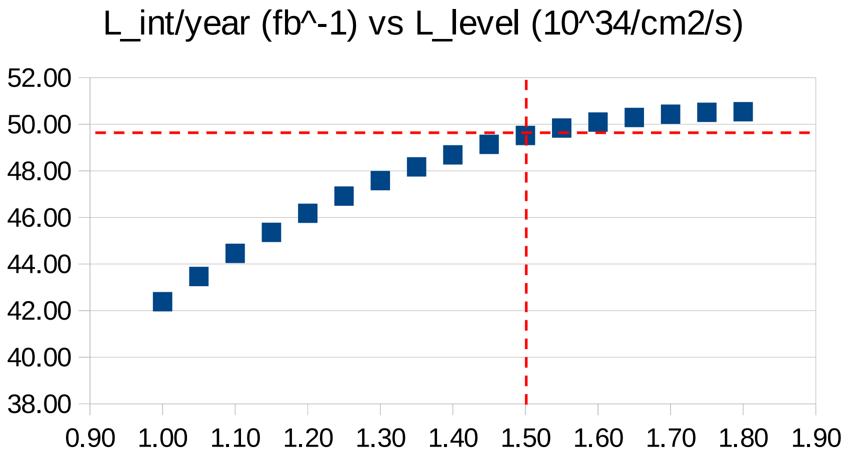
LHCB-TDR-023

- If FTDR baseline is beyond reach, how do we best make savings?
- Requires trade-off:
  - physics (performance) vs. detector (cost)
- Cannot be purely objective
  - which channels do we optimise for?
  - reduce “big ticket” items? consider some subdetectors as “optional extras”?
- Performance comparisons
  - vs. Run 1+2 or Upgrade I? vs. the best possible?
- More discussion in subdetector talks

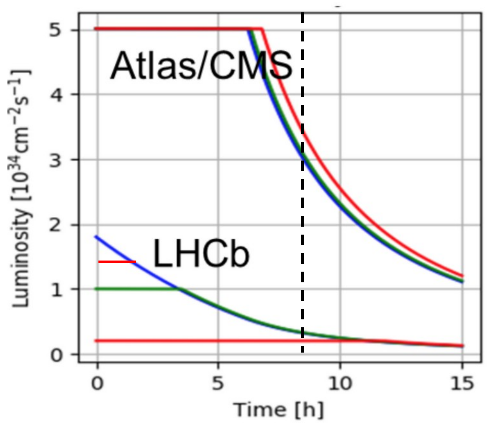
Detector	Baseline (kCHF)
VELO	14800
UT	8900
Magnet Stations	2300
MT-SciFi	22400
MT-CMOS	19500
RICH	15600
TORCH	9900
ECAL	34800
Muon	7100
RTA	17400
Online	8900
Infrastructure	13500
Total	175100

Luminosity

- Target integrated luminosity is 300/fb
  - risky to compromise: Upgrade I replacement would allow us to reach >100/fb
- Peak luminosity is still a handle
  - drives maximum occupancy/data transfer rate/RTA complexity
- Simple model: vary L_{level} for fixed parameters:
  - $L_{peak} = 1.8 \times 10^{34}/cm^2/s$
  - τ_{beam} = 6.1 hours
    - [exponential decay]
  - t_{fill} = 8 hours
  - 175 fills/year



LHCB-TDR-023 &
CERN-ACC-NOTE-2018-0038



Luminosity

Example: reduce L_{level} from 1.5 → 1.25; reduce maximum occupancies by 17%
Double levelling time from 1.1 → 2.2 hours; reduce L_{int}/year by 5%

- Peak luminosity is still a handle
  - drives maximum occupancy/data transfer rate/RTA complexity
- Simple model: vary L_{level} for fixed parameters:
  - $L_{peak} = 1.8 \times 10^{34}/cm^2/s$
  - τ_{beam} = 6.1 hours
    - [exponential decay]
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LHCB-TDR-023 &
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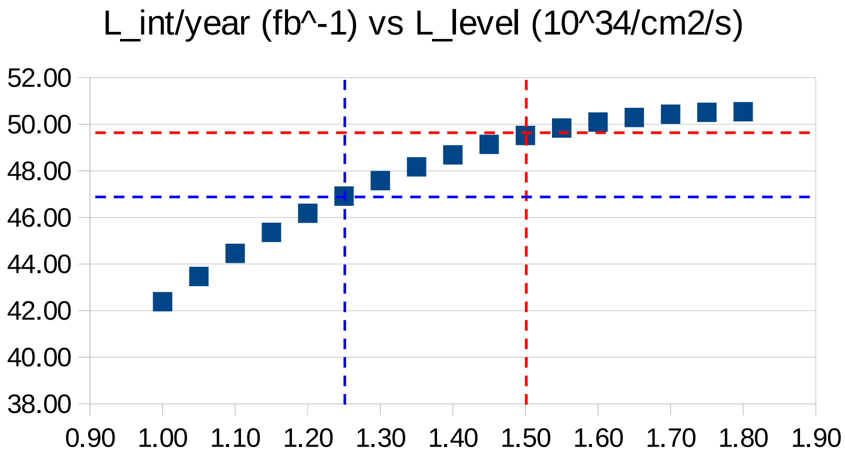
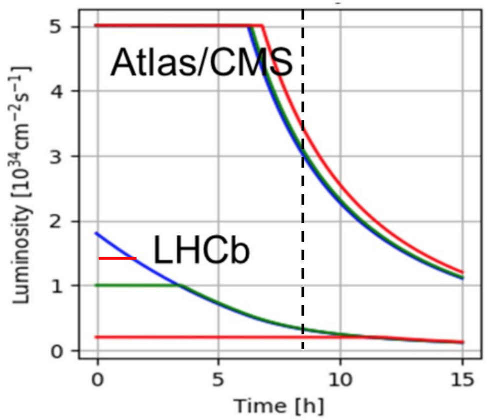
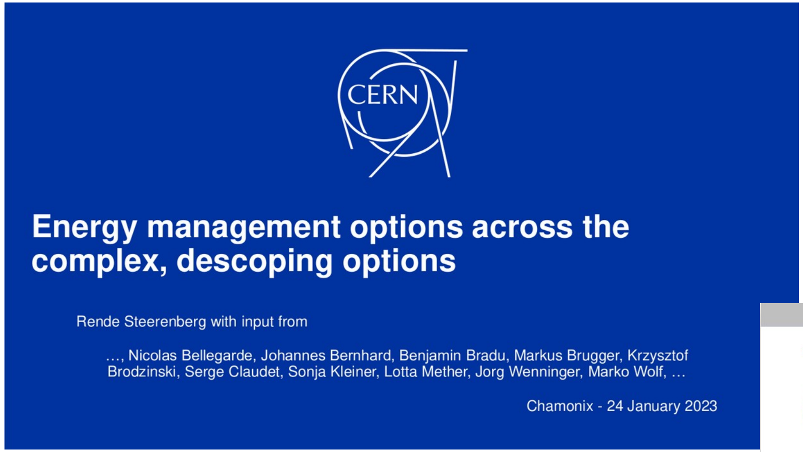


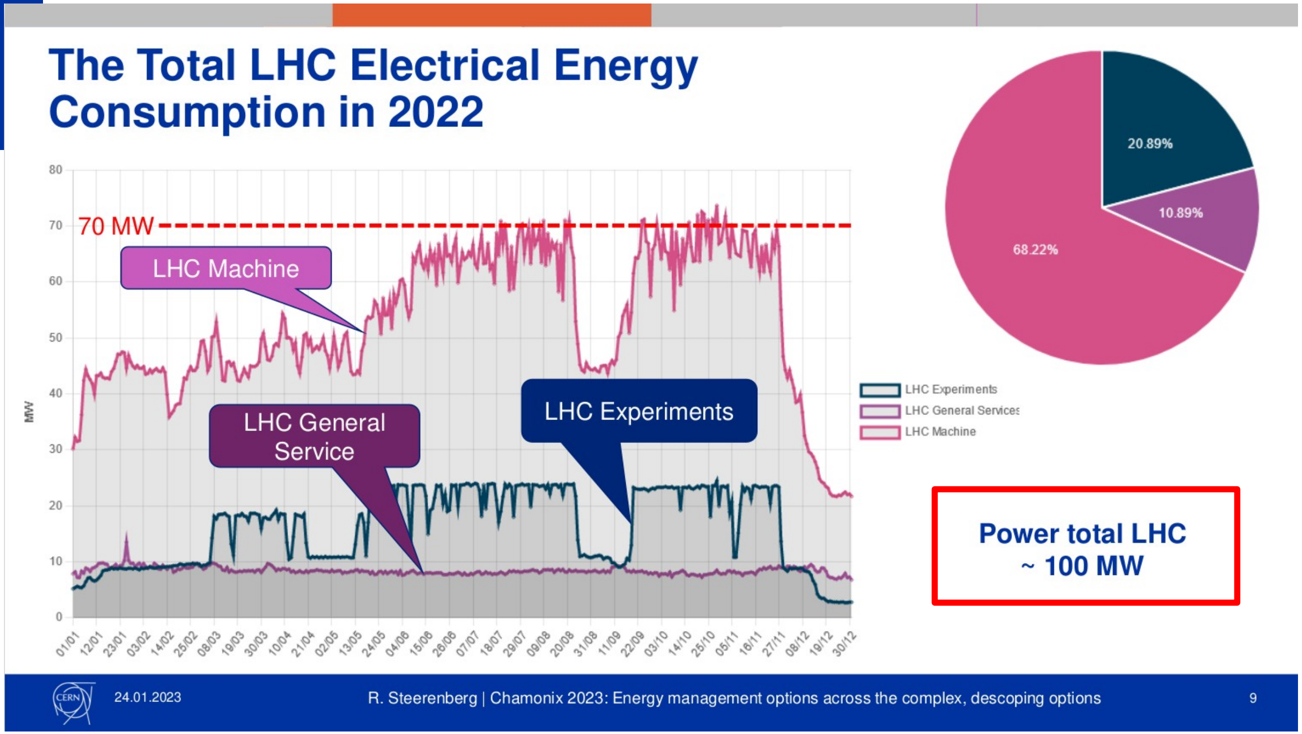


Thinking radical



R. Steerenberg at LHC Chamonix workshop 2023
https://indico.cern.ch/event/1224987/contributions/5153695/

LHCb magnet consumes 4.6 MW



Energy management options across the complex, descoping options

Rende Steerenberg with input from

…, Nicolas Bellegarde, Johannes Bernhard, Benjamin Bradu, Markus Brugger, Krzysztof Brodzinski, Serge Claudet, Sonja Kleiner, Lotta Mether, Jorg Wenninger, Marko Wolf, …

Chamonix - 24 January 2023

R. Steerenberg at LHC Chamonix workshop 2023
https://indico.cern.ch/event/1224987/contributions/5153695/

Potential energy saving options on the LHC side

- **Cryogenics – Heat load**
  - *See presentations by B. Bradu and L. Mether*
  - Whenever possible switch to economy mode, but take ~24 hr overhead into account
- **Reduced running period**
  - Addressed later in this presentation
- **Switching off ALICE and LHCb magnets as soon as beam will be off for more than 5 hours**
  - Note: These magnets are not made for frequent powering cycles….

24.01.2023 R. Steerenberg | Chamonix 2023: Energy management options across the complex, descoping options 13

LHCb magnet consumes 4.6 MW

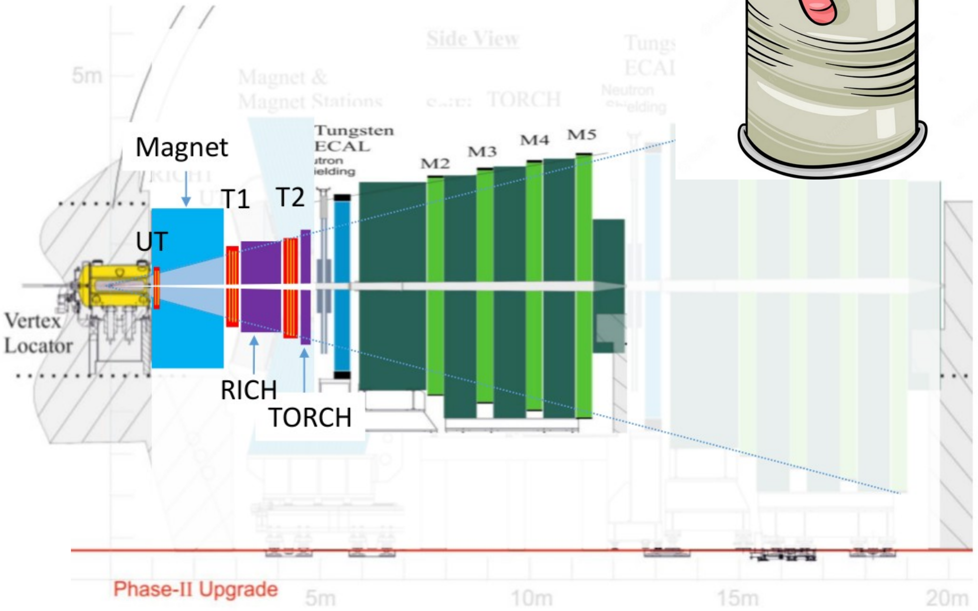
Power cycling limit unknown ...

What if we have to replace the magnet?

a.k.a. What if we want to replace the magnet?

- Opens possibility to rethink many aspects of the detector design & re-optimise cost/performance
- e.g. LHCb′ proposal (M. Merk, R. Forty and others)

- New superconducting magnet
  - upfront cost vs. lower electricity bill
- Same ∫Bdl = 4 Tm
  - but over shorter distance
- Remove RICH1 and squeeze in z
  - reduce total length by factor ~2
- Keep same acceptance
  - reduce detector area by factor 4
  - corresponding reduction in detector cost



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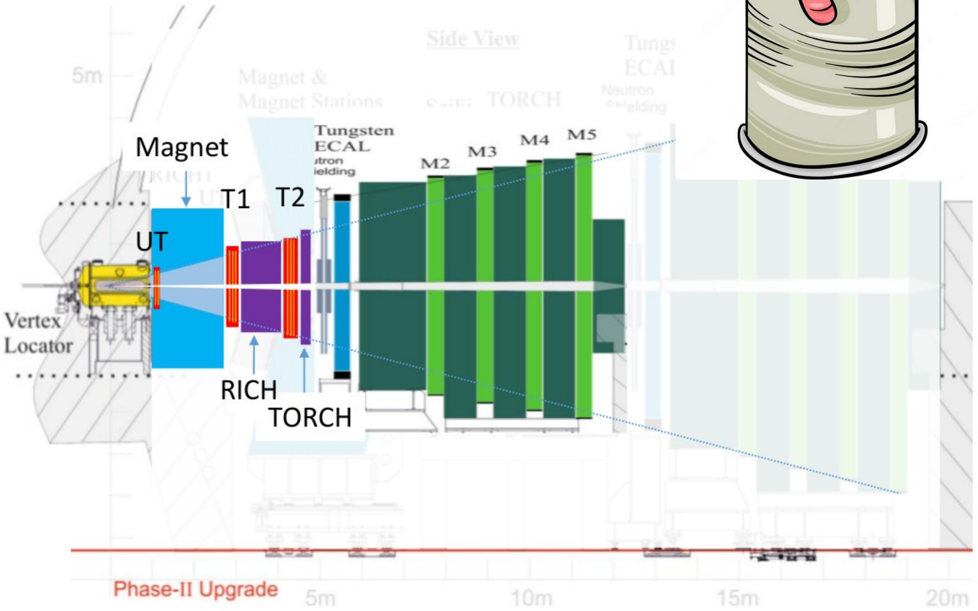
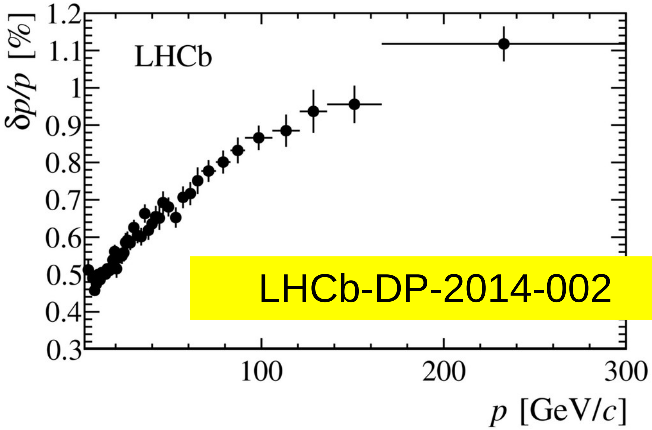
Why?



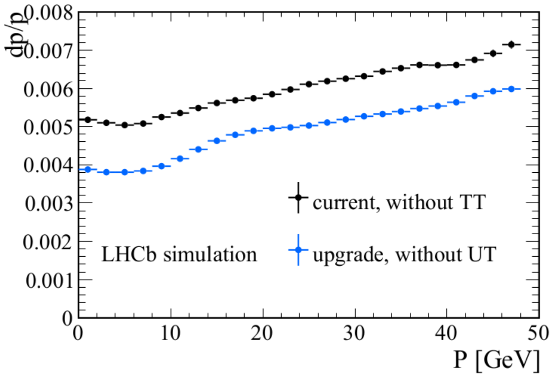
Why is the LHCb magnet 4 Tm?

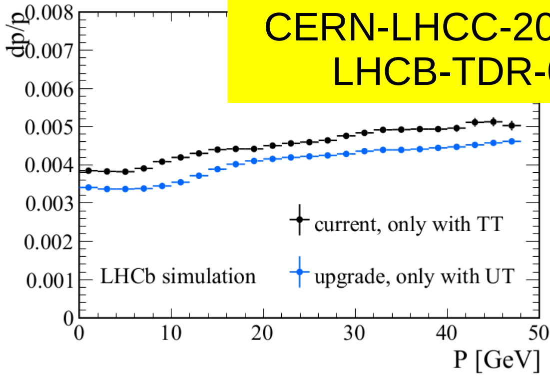
CERN-LHCC-2000-007
LHCb-TDR-1

- “Tracking detectors in and near the magnetic field have to provide momentum measurement for charged particles with a precision of about 0.4% for momenta up to 200 GeV/c. This demands an integrated field of 4 Tm for tracks originating near the primary interaction point.”
- Not achieved for Run 1+2, nor expected for Run 3+4

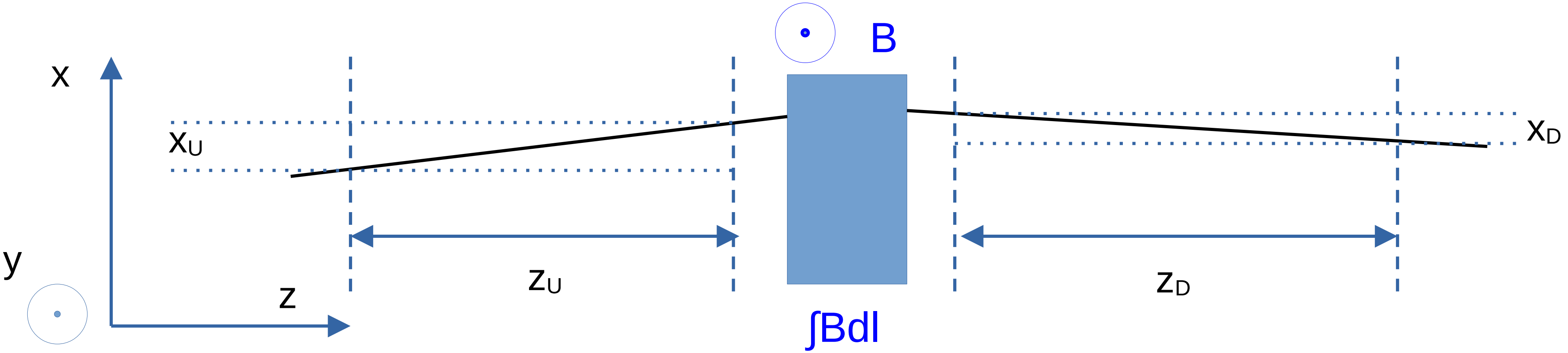


LHCb-DP-2014-002





CERN-LHCC-2014-001
LHCB-TDR-015



Change in slope due to B field $(x_D/z_D) - (x_U/z_U) = \Delta p_x/p_z = q \int Bdl/p$

[using small angle approximation with tracks approximately aligned with z-axis]

So $p = q \int Bdl / [(x_D/z_D) - (x_U/z_U)] = q\, z_U z_D \int Bdl / [z_U x_D - z_D x_U]$

Consider uncertainties only in x_U & x_D

$$\delta p/p = [p/(|q| \int Bdl)] \times \sqrt{[(\delta x_U/z_U)^2 + (\delta x_D/z_D)^2]}$$

Take $z_U \sim z_D \sim 1$m and $\delta x_U \sim \delta x_D \sim 40$ µm, then for a 100 GeV/c track

$$\delta p/p \sim 20 \times 10^{-3} \text{ Tm} / \int Bdl$$

i.e. with ∫Bdl = 4 Tm can achieve δp/p ~ 0.5% at 100 GeV/c

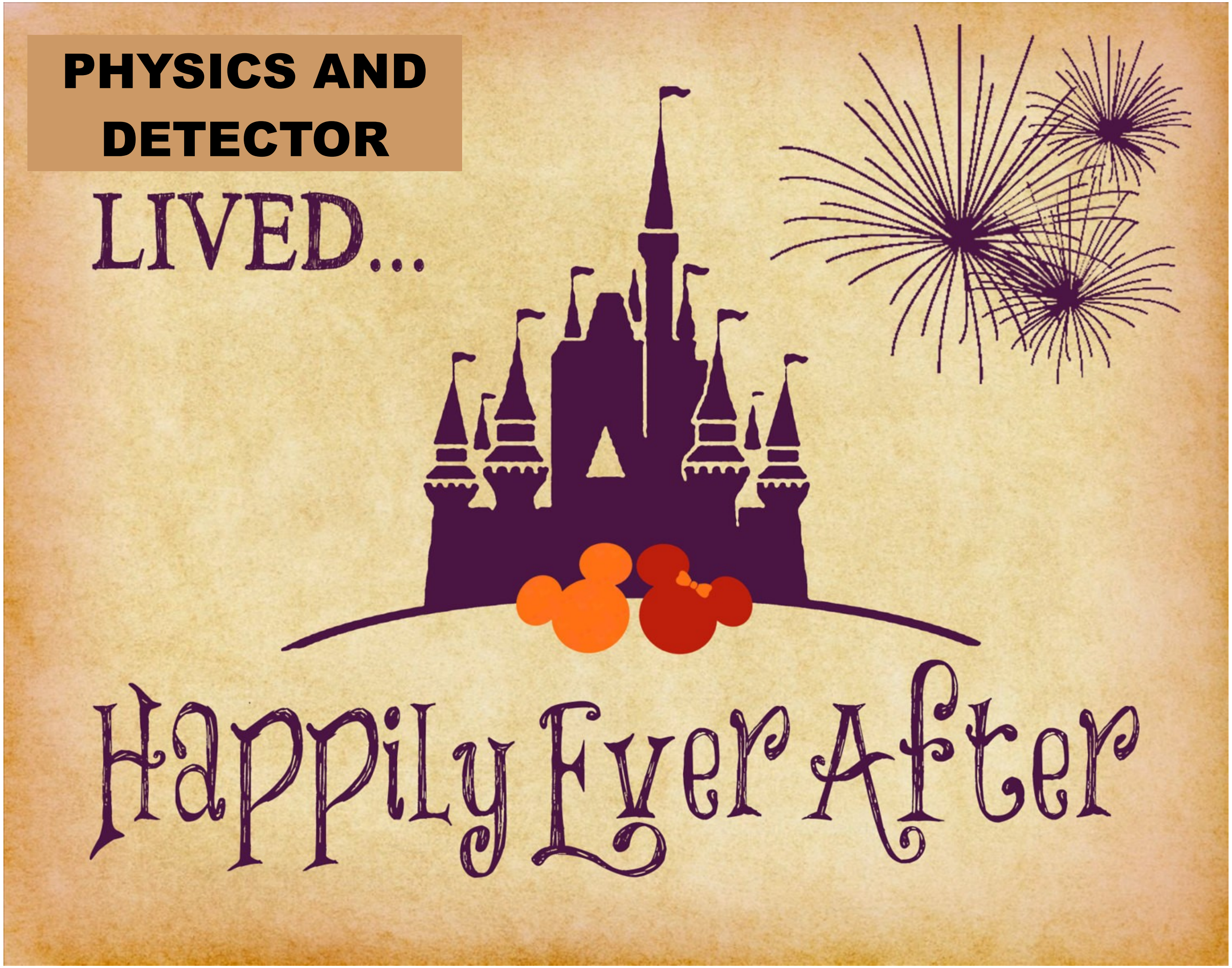
For proper studies, see F. Blanc and R. Quagliani in RTA WP6 meeting, and talk later

How to optimise?

- Feasibility of magnet replacement to be discussed tomorrow [H. Schindler]
  - huge implications, including for potential LS3 enhancements
- **If** we consider it, should optimise field strength together with acceptance
  - i.e. not obliged to stick to ±300 mrad in bending plane
  - add large angle acceptance and give up hot region close to beam pipe?
- Lower field strength → lower cost & better acceptance [how much?]
- Higher field strength → better resolution
- Lots of questions … not many answers … and not much time
  - Note: LHCb-TDR-9 published 2003, aiming for commissioning 2007

Summary

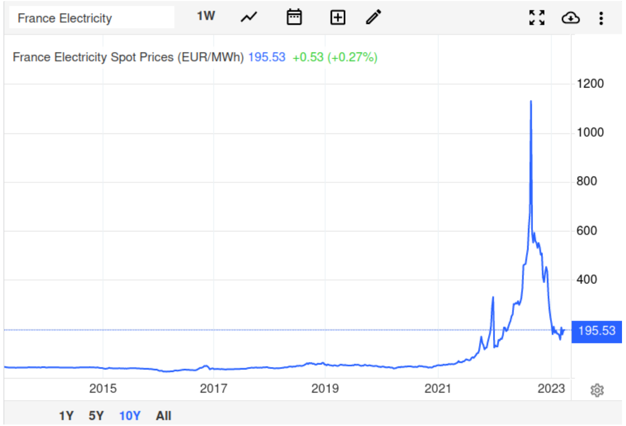
- We have presented an excellent physics case in the FTDR
  - Supported by European Strategy for Particle Physics: “The full physics potential of the HL-LHC … including flavour physics … should be exploited”
- Still a lot of work to do
  - R&D in all subdetectors to achieve necessary performance (or better)
  - full Upgrade 2 simulation needed to study impact of detector design choices
    - both positive impacts of baseline design, and negative impacts of cost-saving
    - I haven’t even mentioned timing, pile-up, ghost-rates, etc.
- Energy crisis + inflation + global geopolitics present new challenges
  - not a reason to “rip it up and start again”
  - rather: understand the genuine constraints, and then optimise accordingly


PHYSICS AND
DETECTOR
LIVED...
Happily Ever After

Back up

How much does running the magnet cost?

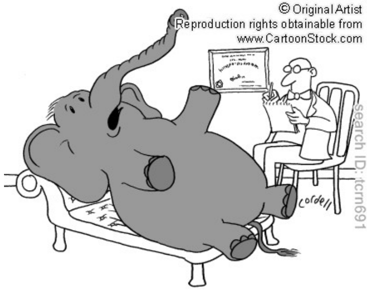
https://tradingeconomics.com/france/electricity-price



- Assume magnet on 50% of the time per run year, and 6 years Run 5+6: 25,000 hours
- 4.6 MW consumption at current energy cost ~200 €/MWh
  → 24 M€ [was factor 5 smaller pre-energy crisis]
  - Actual cost 2022 ~0.5 MCHF
- Does not appear in Upgrade II cost table, but must be paid
  - Environmental impact must also be accounted for fully
- N.B. Energy costs of online farm also non-negligible
  - Studied in https://inspirehep.net/literature/1868467 →

Architecture	Energy per trigger (mJ)	Gain	Total gain
E5-2630-v4 Xeon			
Before SW optimization	39.9	1.0x	
w/Physics optimizations	21.0	1.9x	1.9x
w/SIMD optimizations	8.4	2.5x	4.8x
7502 EPYC			
w/SIMD optimizations	3.2	2.6x	12.5x
Event Building Node, NR			
1 GPU	3.1	1.03x	12.9x
2 GPUs	2.4	1.29x	16.6x
3 GPUs	2.1	1.15x	19.0x
Dedicated GPU machine			
4 x 2080 Ti + 2 Network Cards	2.8	1.14x	14.3x
5 x 2080 Ti + 3 Network Cards	2.5	1.12x	16.0x
Pure GPU machine			
8 x 2080 Ti + Onboard Network	2.1	1.15x	19.0x

There will be many other problems if CERN has to pay 200 €/MWh for energy



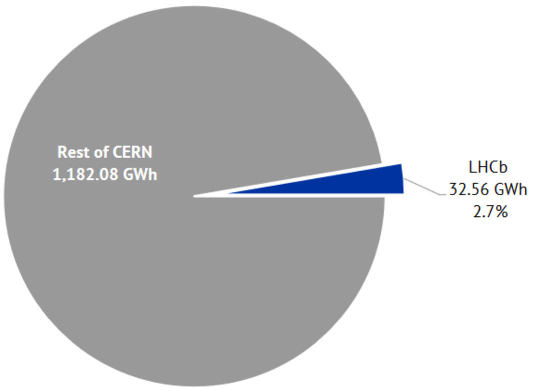
"Whenever I walk in a room, everyone ignores me."

Annual Consumption in 2022

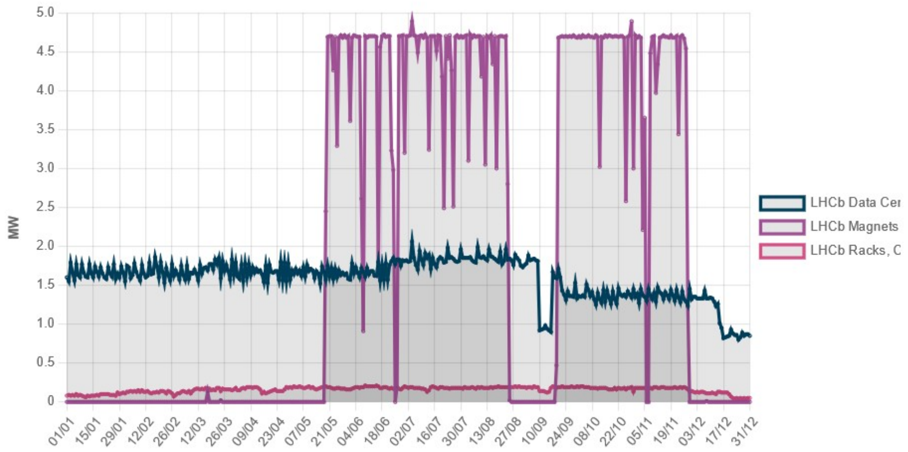
32.56 GWh

Virtual Invoice

1.05 M€



Daily Average Power of LHCb in 2022

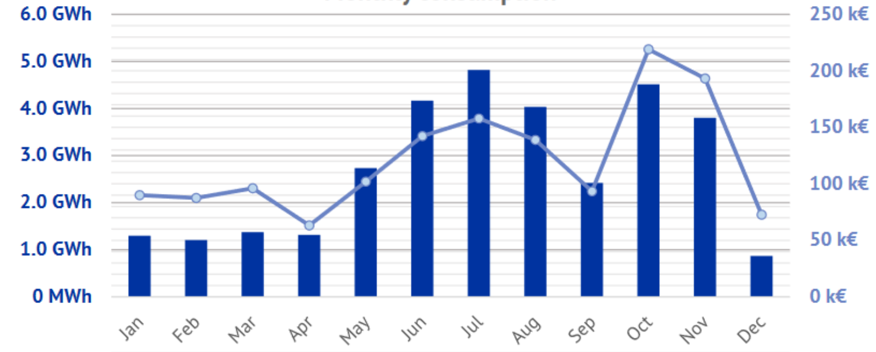


Virtual Electricity Invoice

LHCb

Year 2022

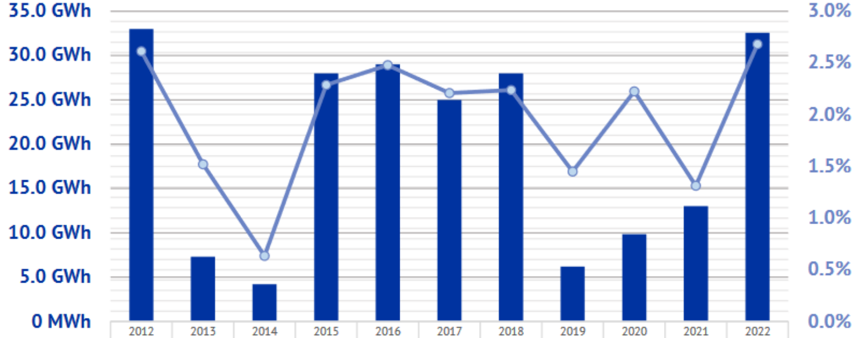
Monthly consumption



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Energy	1.3 GWh	1.2 GWh	1.4 GWh	1.3 GWh	2.7 GWh	4.2 GWh	4.8 GWh	4.0 GWh	2.4 GWh	4.5 GWh	3.8 GWh	870 MWh
Cost	51 k€	48 k€	56 k€	36 k€	75 k€	115 k€	131 k€	111 k€	66 k€	179 k€	153 k€	34 k€
Monthly price (€/MWh)	39.15	39.70	40.44	27.32	27.30	27.55	27.12	27.59	27.30	39.73	40.22	38.89

Nota: the one-off rebates in June and December (ARENH + advancing the YETS) have been equally distributed across the year to preserve the seasonal prices.

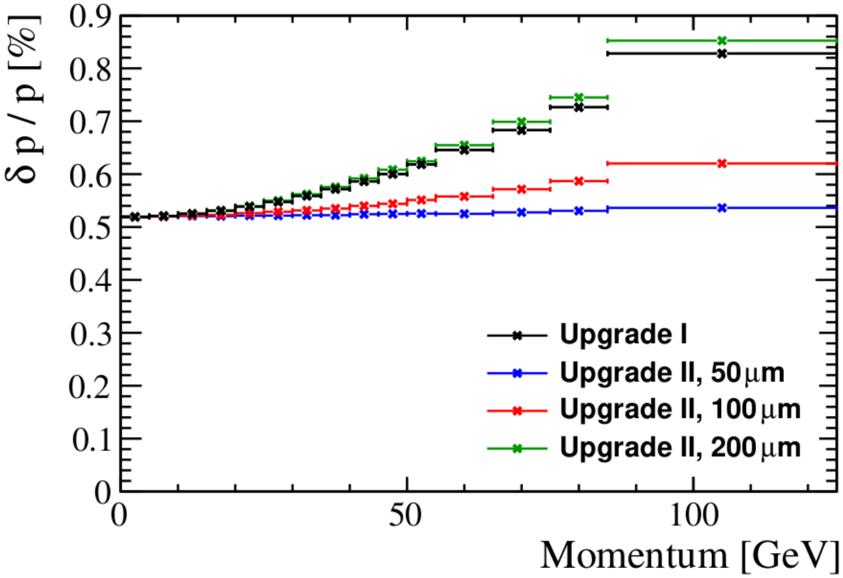
Evolution of consumption in the last years



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Energy	33.0 GWh	7.3 GWh	4.2 GWh	28.0 GWh	29.0 GWh	25.0 GWh	28.0 GWh	6.2 GWh	9.8 GWh	13.0 GWh	32.6 GWh
CERN Fraction	3%	1.5%	0.6%	2.3%	2.5%	2.2%	2.2%	1.4%	2.2%	1.3%	2.7%

Momentum resolution in FTDR

LHCB-TDR-023



- Simplified model with Gluckstern parametrisation
  - $(\delta p/p)^2 = A^2_{ms} + (p \times B_{res})^2$
- With 100 μm MT pixels
  - B_{res} = 100 μm/√12 ~ 30μm
- δp/p ~ 0.6% at 100 GeV/c
- Dominated by constant A_{ms} term
  - B_{res} term contribution ~ 0.3%
- Consistent with back-of-envelope!