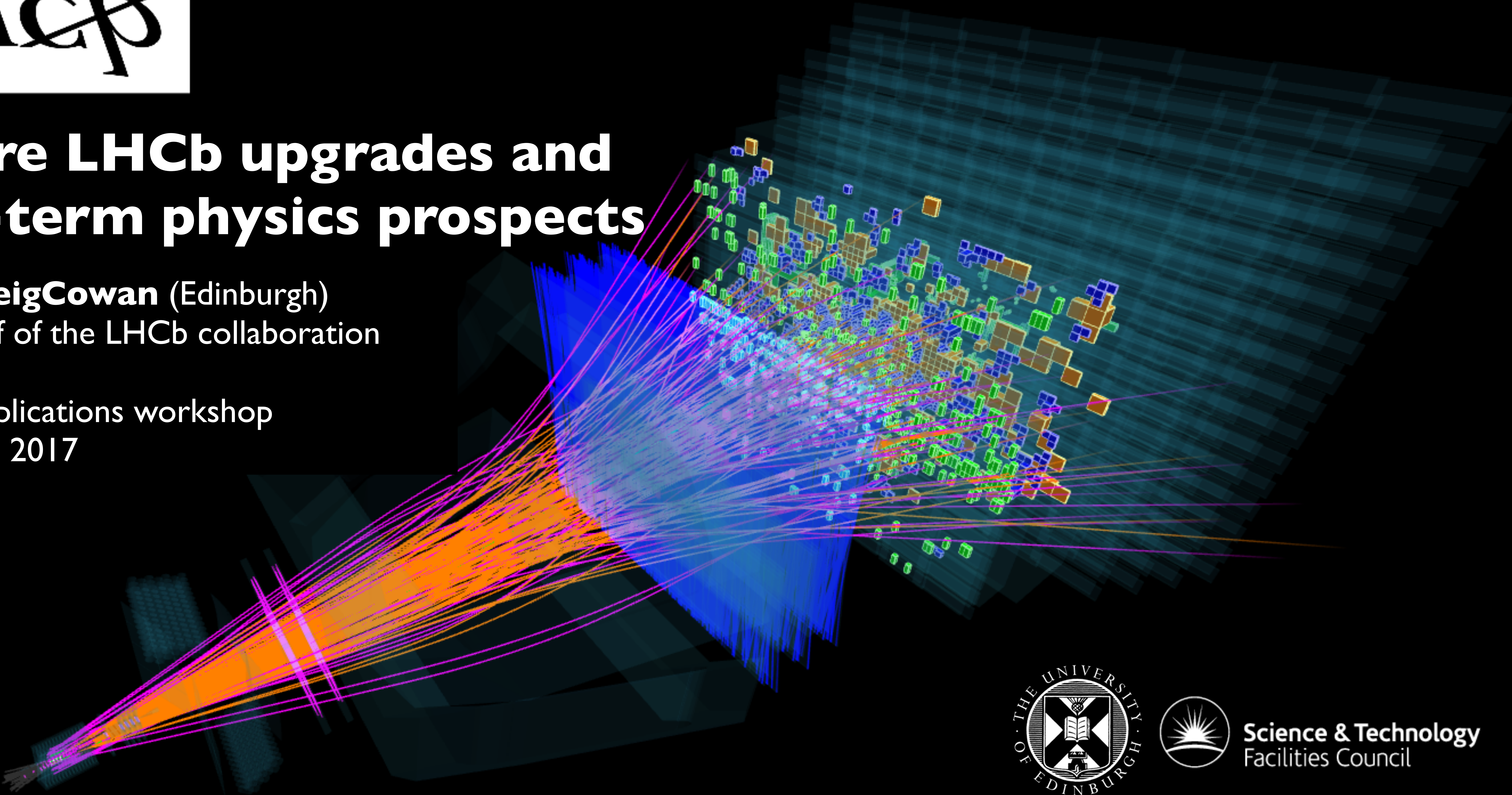
Future LHCb upgrades and long-term physics prospects

@GreigCowan (Edinburgh)
On behalf of the LHCb collaboration

LHCb implications workshop
10th Nov 2017

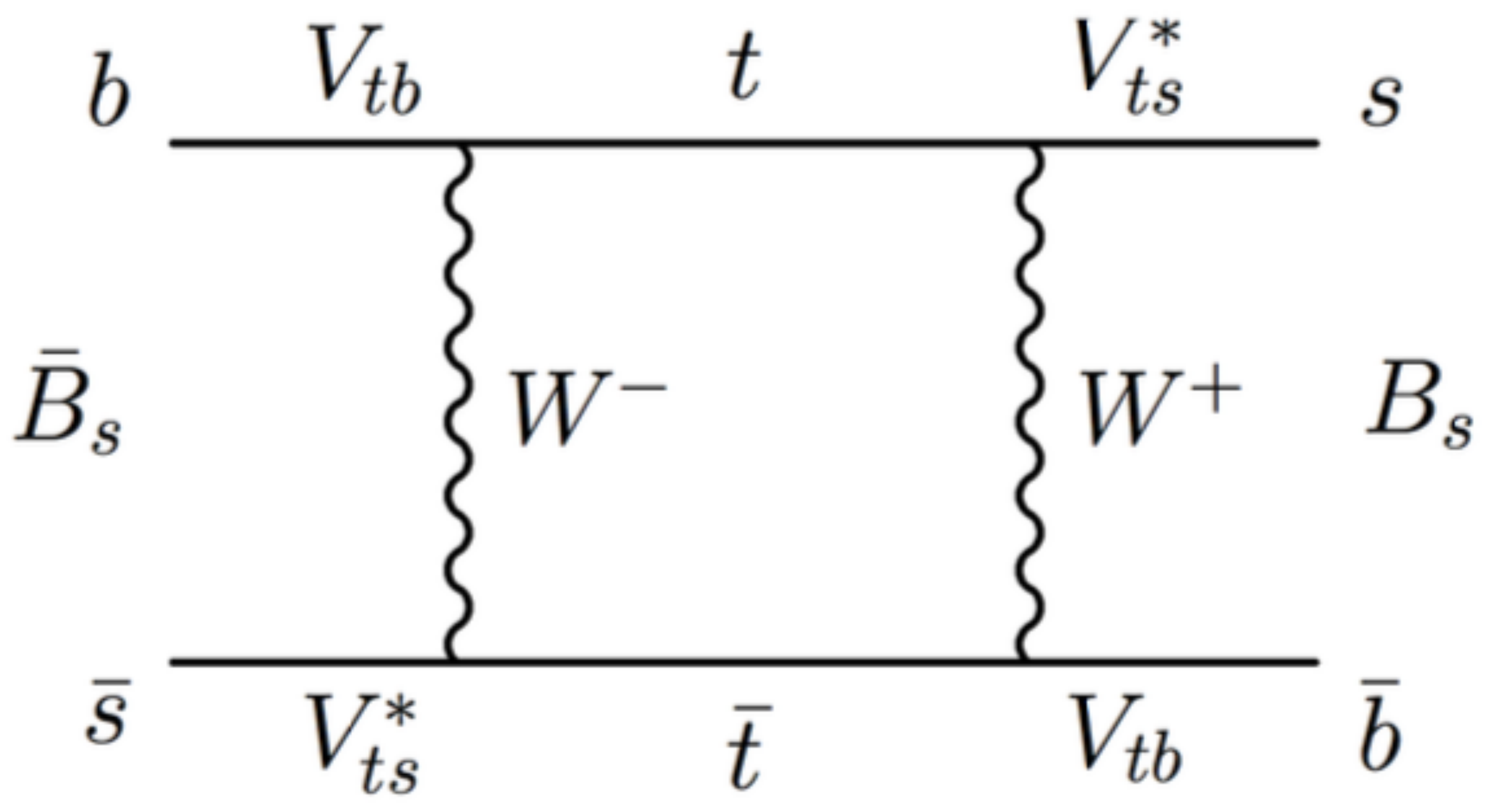


Searching for new physics in heavy flavour

Heavy-quark hadrons provide excellent way to search for new sources of CPV and to probe high energy scales. →

Historical precedent, e.g., B^0 meson mixing led to first indications about top quark mass [PLB 192 (1987) 245] [PLB 186 (1987) 247]

Generic flavour structures ruled out by many orders of magnitude.



Complementarity between flavour and high-pT searches can help us understand what NP is (or is not…)

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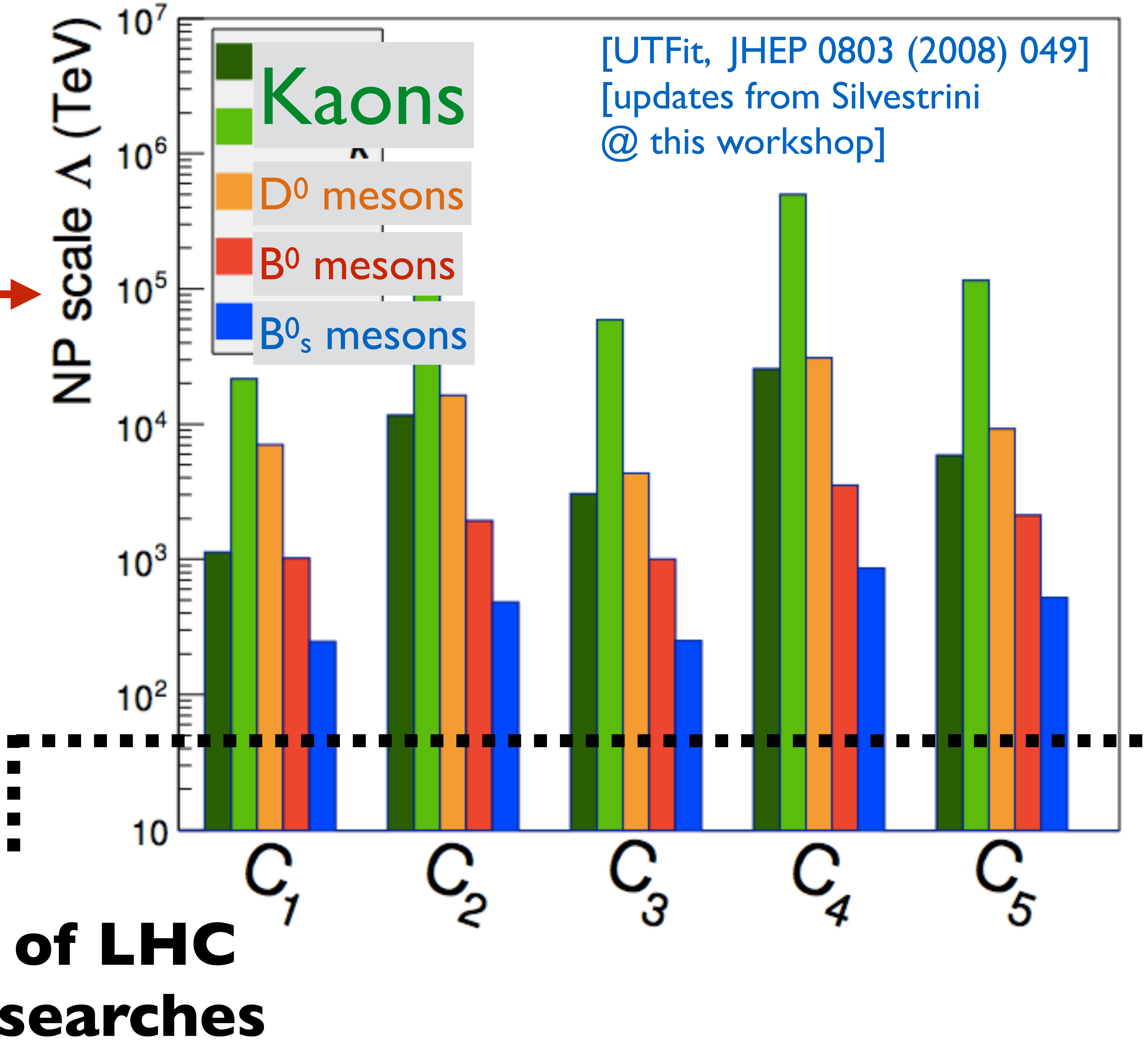

A diverse programme

No sign of "new" physics at ATLAS/CMS but open questions remain (DM, hierarchies, matter-antimatter asymmetry…)

Cast a **wide net** to look for subtle effects of NP that may be masked by large SM processes → **precision is crucial!**

Look for **correlated effects** in different processes to fingerprint the source of any effects that we do see.

Complementarity with ATLAS/CMS and Belle-II.

Excellent case for dedicated heavy-flavour physics experiment @ HL-LHC

LHCb Upgrade II

[CERN-LHCC-2017-003]

EoI submitted to LHCC in February 2017

"A Phase-II Upgrade is proposed for the LHCb experiment in order to ***take full advantage of the flavour-physics*** *opportunities at the HL-LHC…"*

"This project will extend the HL-LHC's capabilities to search for physics beyond the SM, and implements the highest-priority recommendation of the ***European Strategy for Particle Physics****, which is to exploit the full potential of the LHC for a variety of physics goals, including flavour."*

LHCC asked for detailed physics document in May 2018

The next ~20 years...

We are here (Run 2)

LHC phase 2 (HL-LHC) (Run 4 onwards)

visible int/bunch crossing	~1	~1	~6	~6	~55
inst $\mathcal{L}_{LHCb}$ $cm^{-2}s^{-1}$	4×10^{32}	4×10^{32}	2×10^{33}	2×10^{33}	$1\text{-}2\times10^{34}$
$\int dt\, \mathcal{L}_{LHCb}$	3 fb^{-1}	9 fb^{-1}		50 fb^{-1}	300 fb^{-1}
	2011-2012 Run 1	2015-2018 Run 2	2021-2023 Run 3	2026-2029 Run 4	2031-... Run 5/6

LS2: install LHCb upgrade 1 (between Run 2 and Run 3)

Install ATLAS/CMS phase 2 upgrades in LS3
Belle-II finishes at same time (~2025)

The next ~20 years…

We are here

LHC phase 2 (HL-LHC)

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LS2: install LHCb upgrade I

LS3: upgrade I consolidation

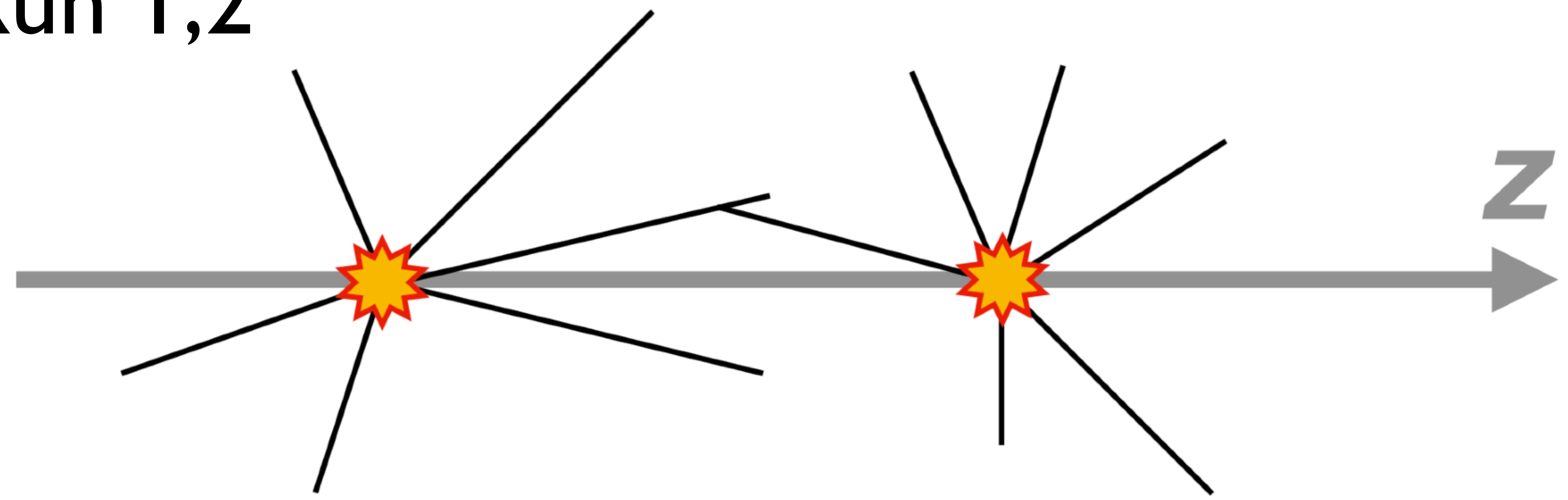
LS4: install LHCb upgrade II

Install ATLAS/CMS phase 2 upgrades in LS3
Belle-II finishes at same time (~2025)

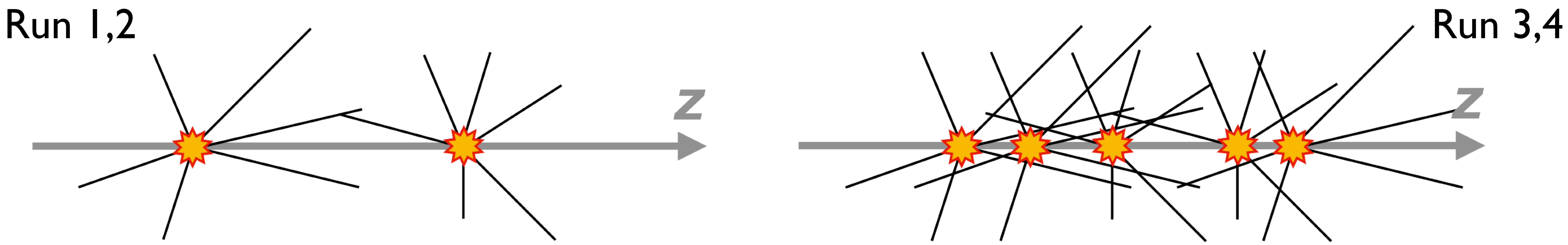
"New" experiments to take advantage of the HL-LHC

Challenges

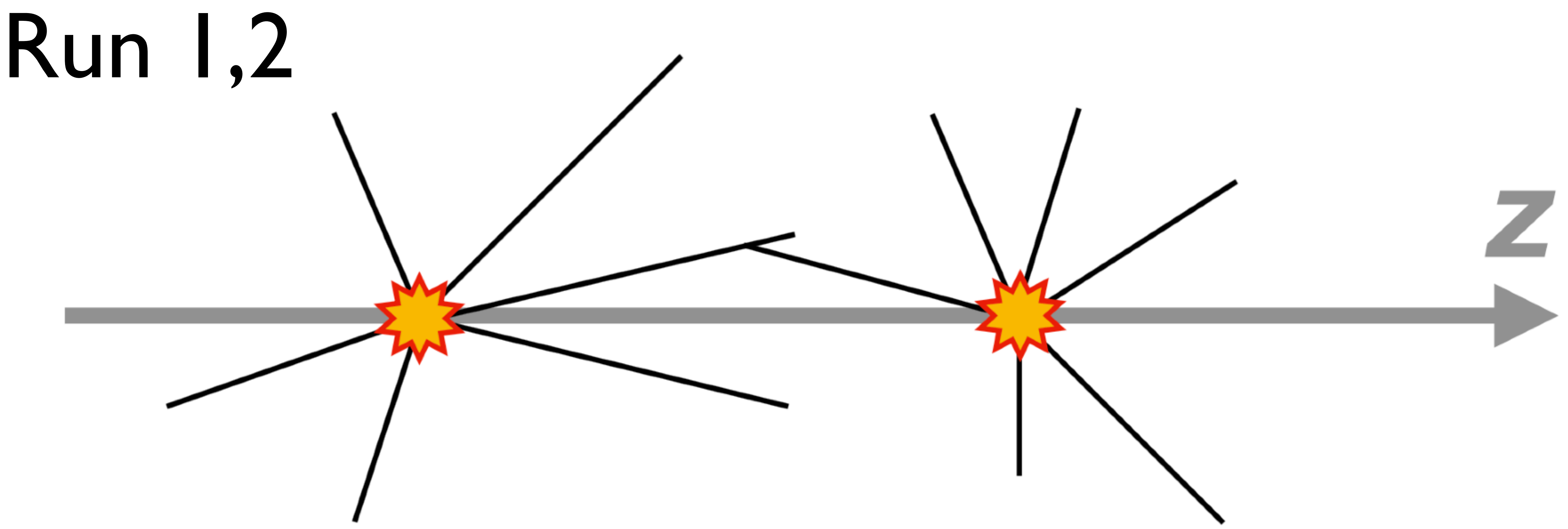
Run 1,2

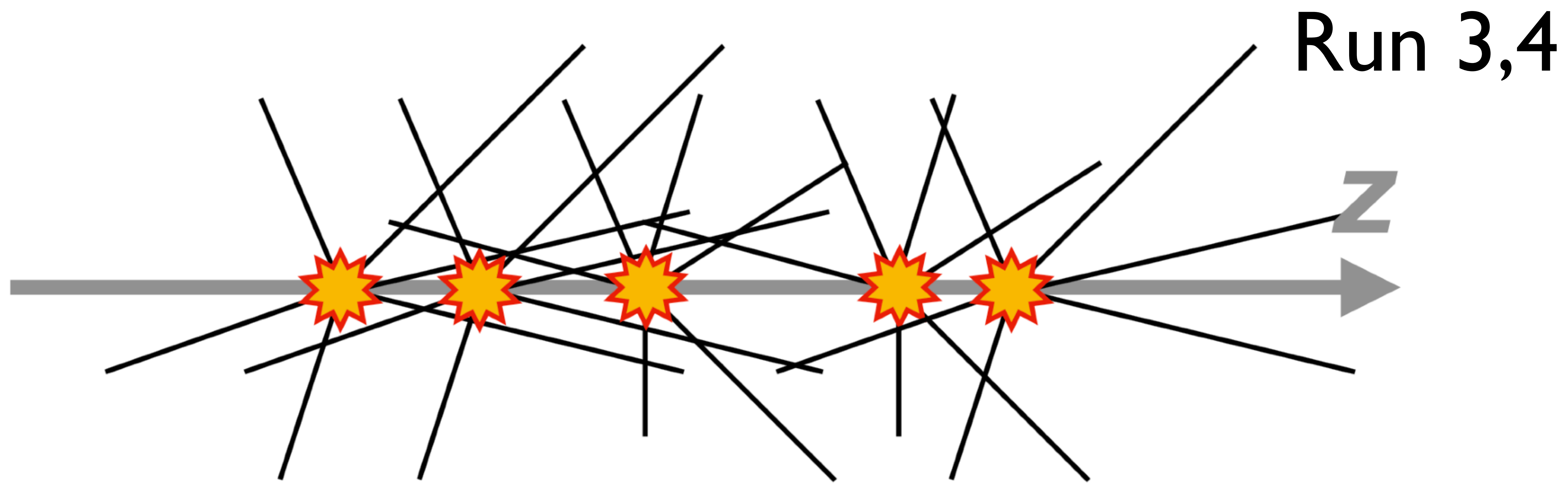


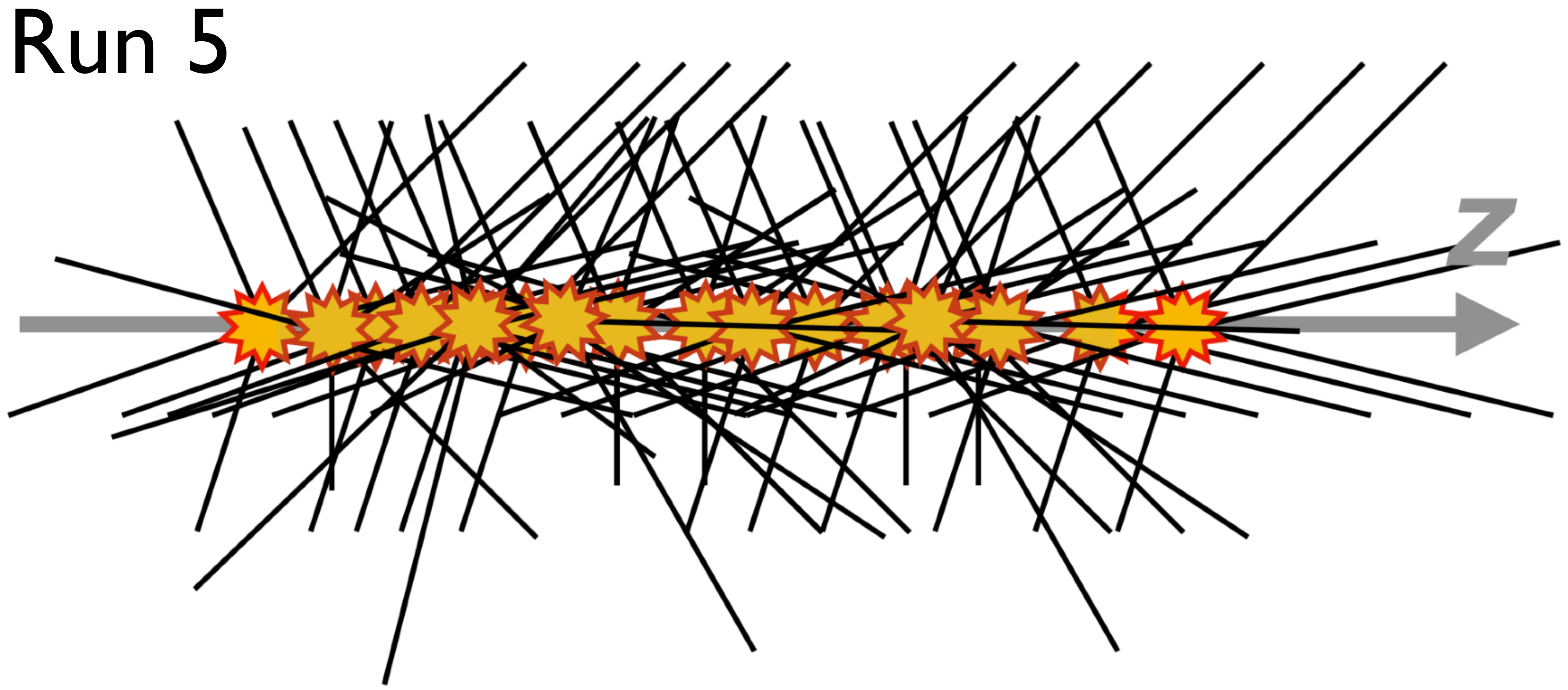
Challenges



Challenges



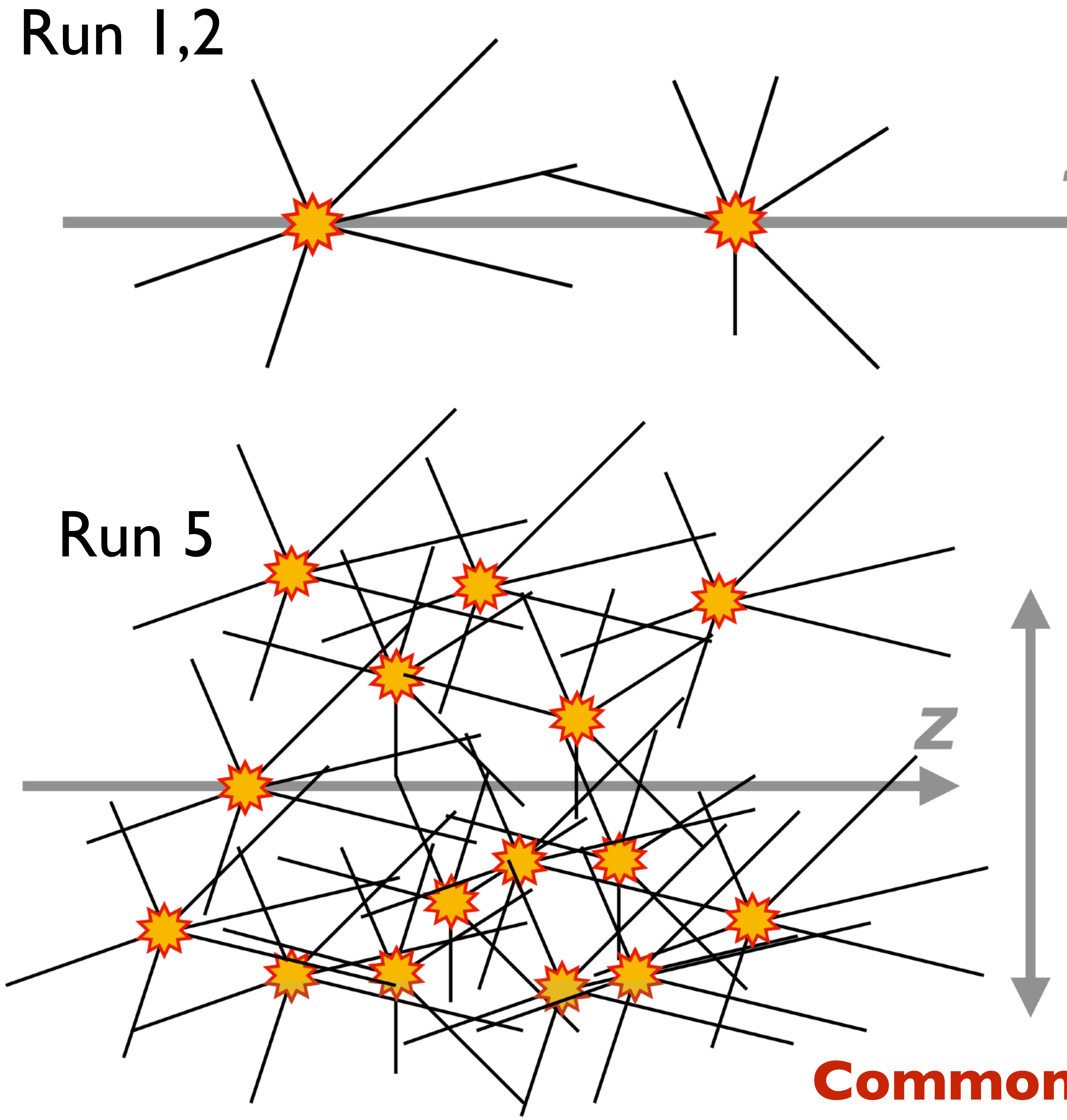




x10 multiplicity
x10 pile-up
x10 radiation damage

} compared to Upgrade I

Challenges



Δt ≈ 300 ps

x10 multiplicity
x10 pile-up
x10 radiation damage

} compared to Upgrade I

Common themes: timing, granularity, radiation hardness

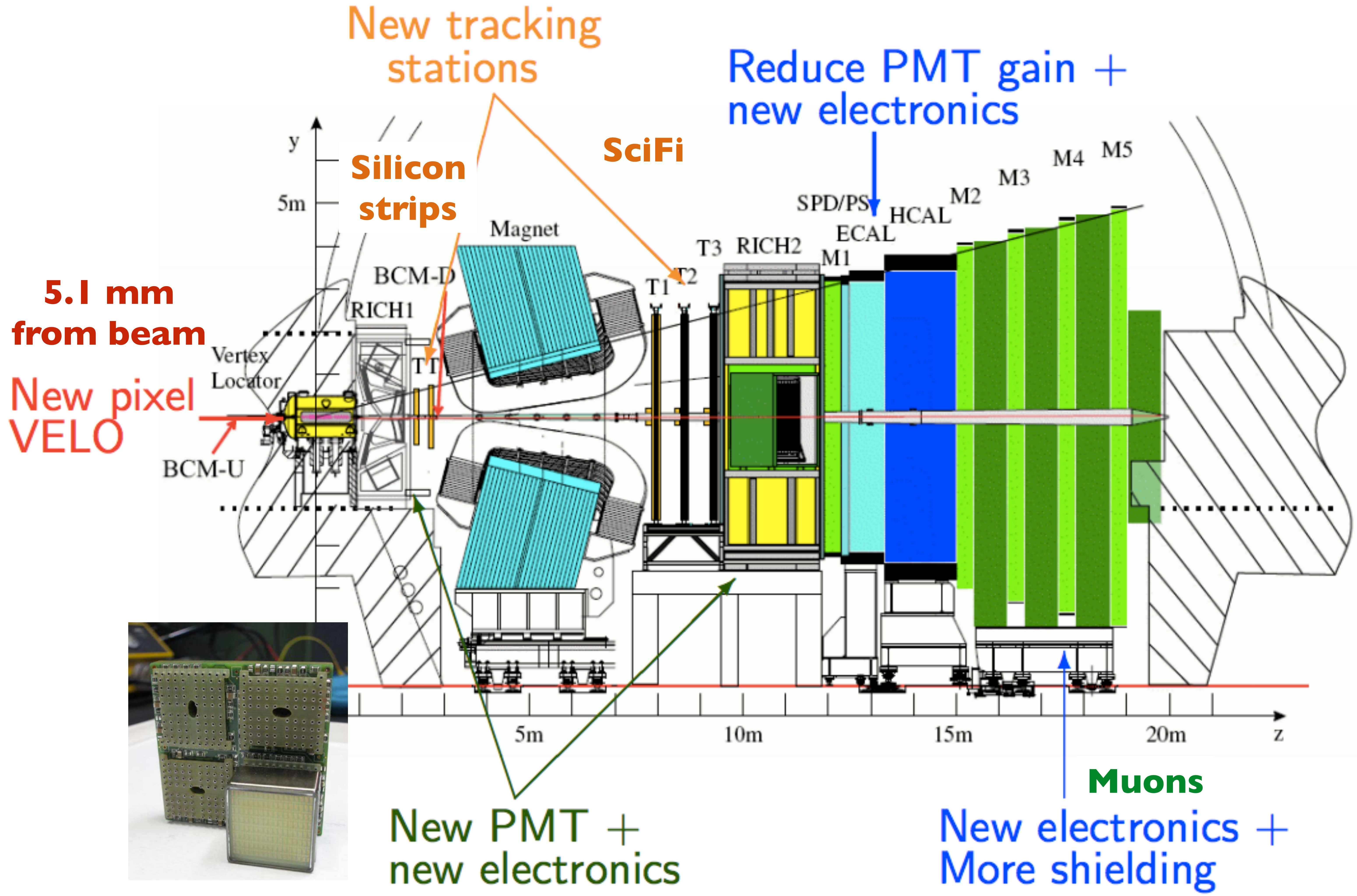
Upgrade I

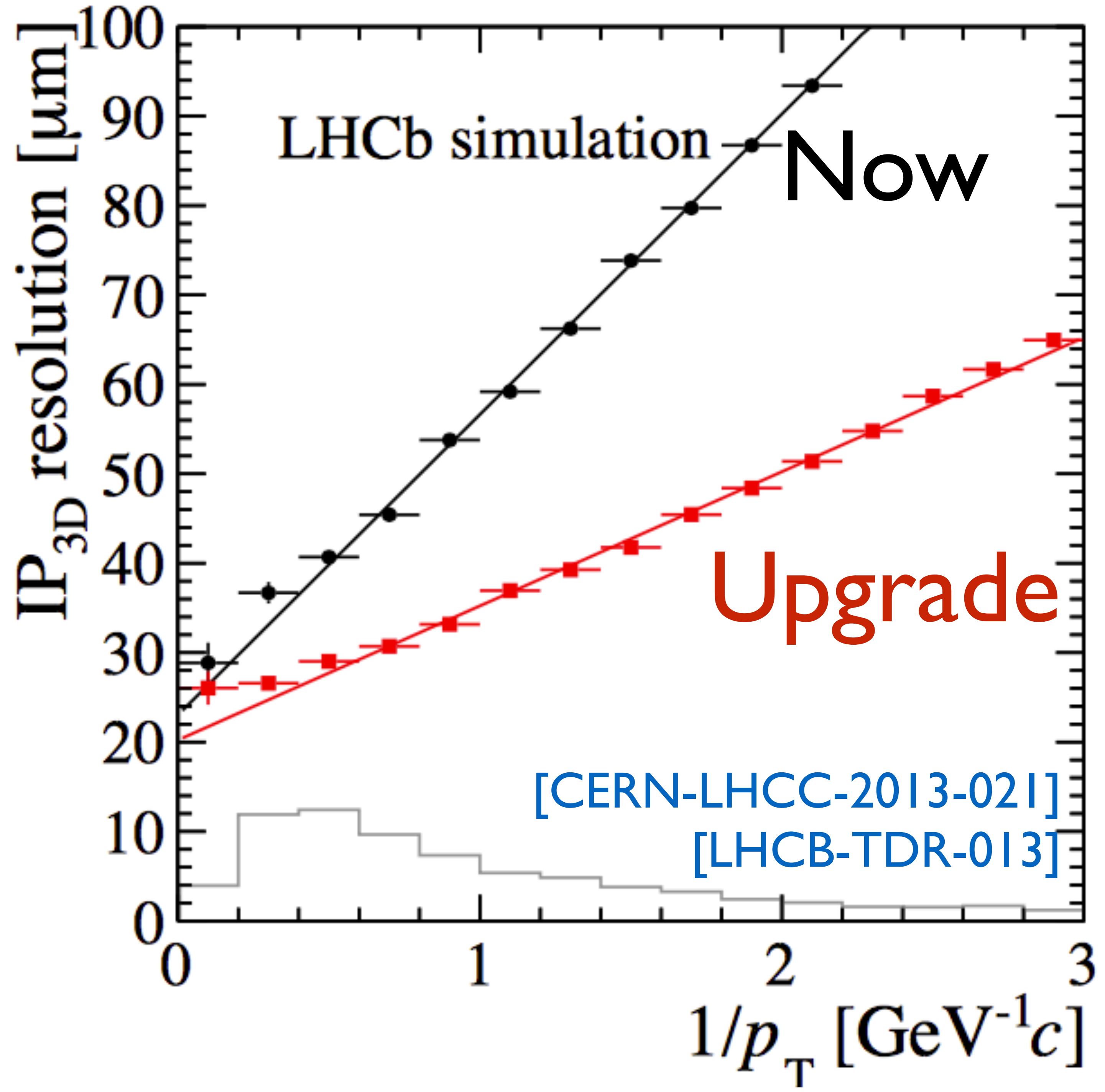
Installation in LS2

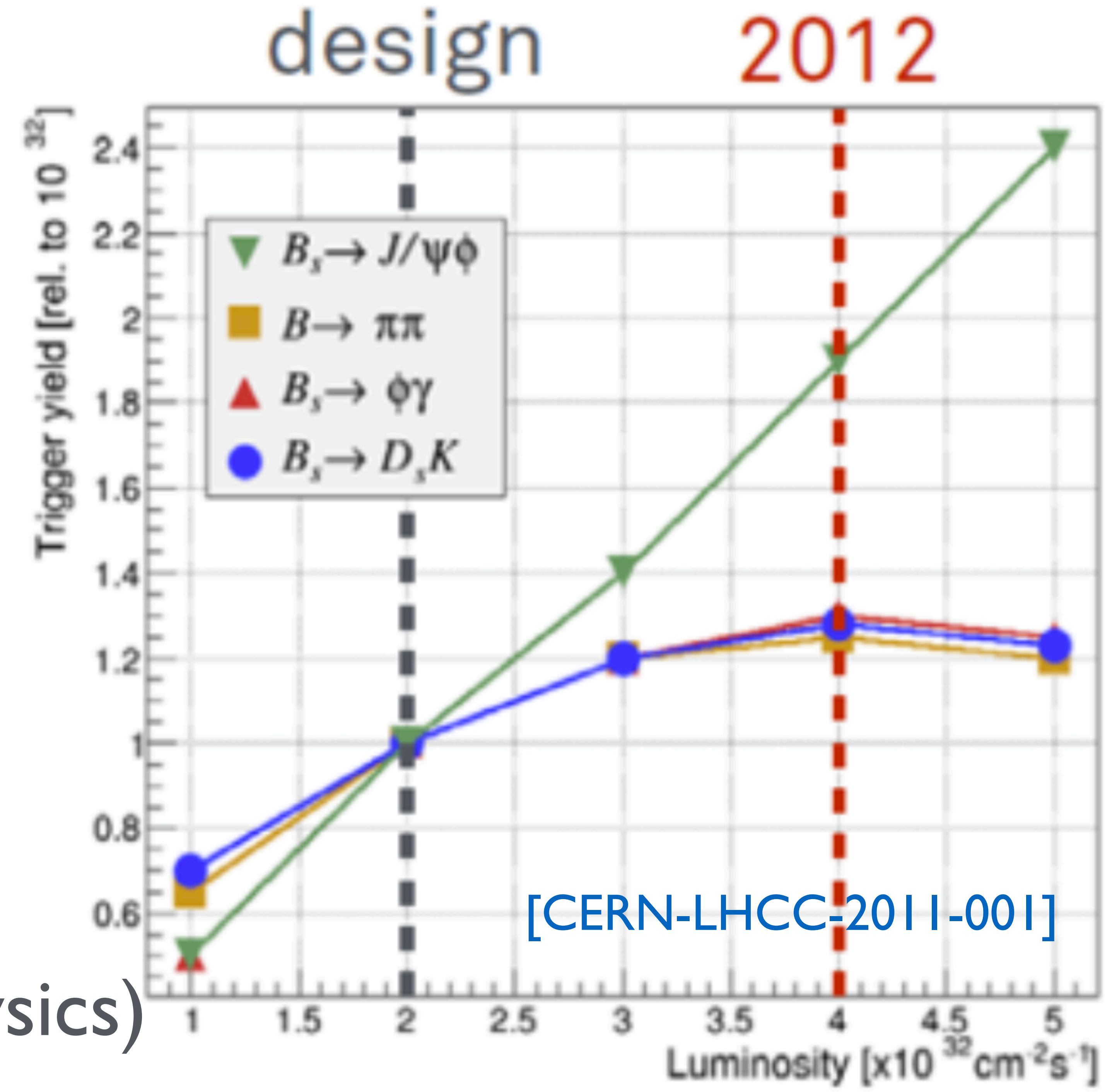
Operation during Run 3

$\mathcal{L} \sim 2 \times 10^{33}$ cm^{-2}s^{-1}

Status of Upgrade I





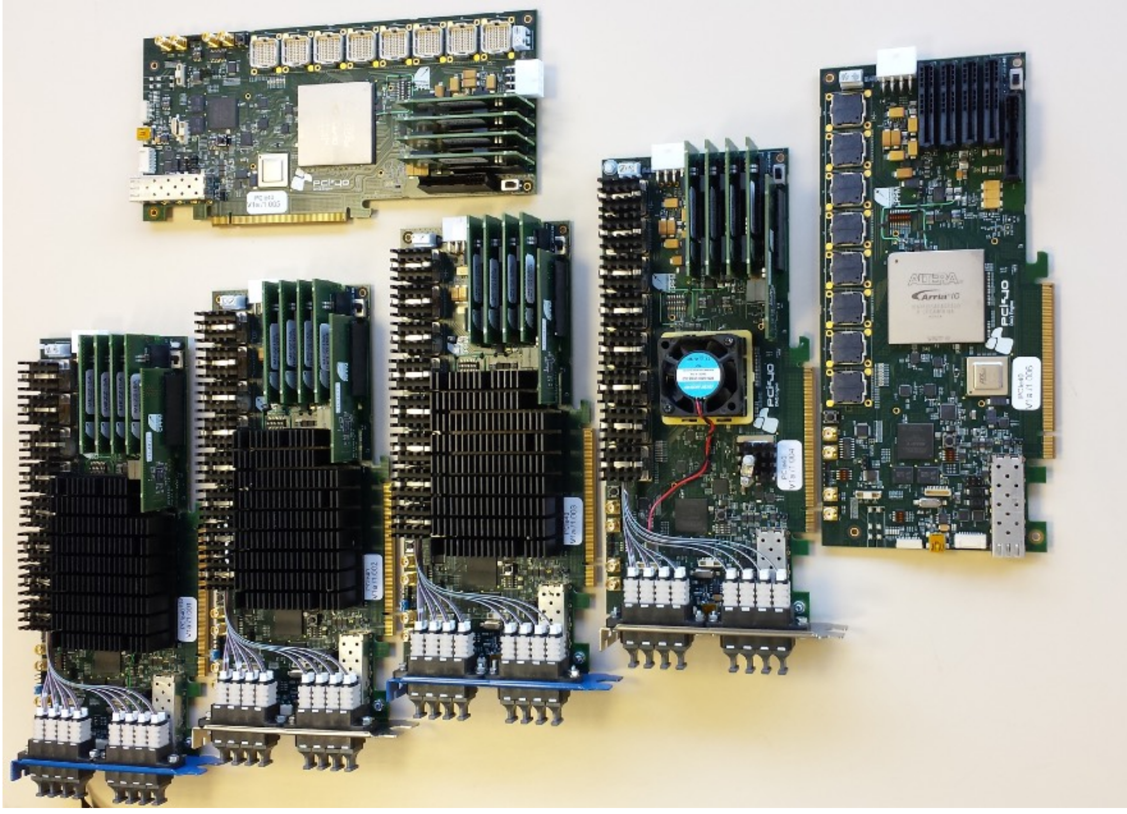


40 MHz readout, flexible software-only trigger

→ Factor 2 increase in efficiency for hadronic B decays (higher for charm, soft physics)

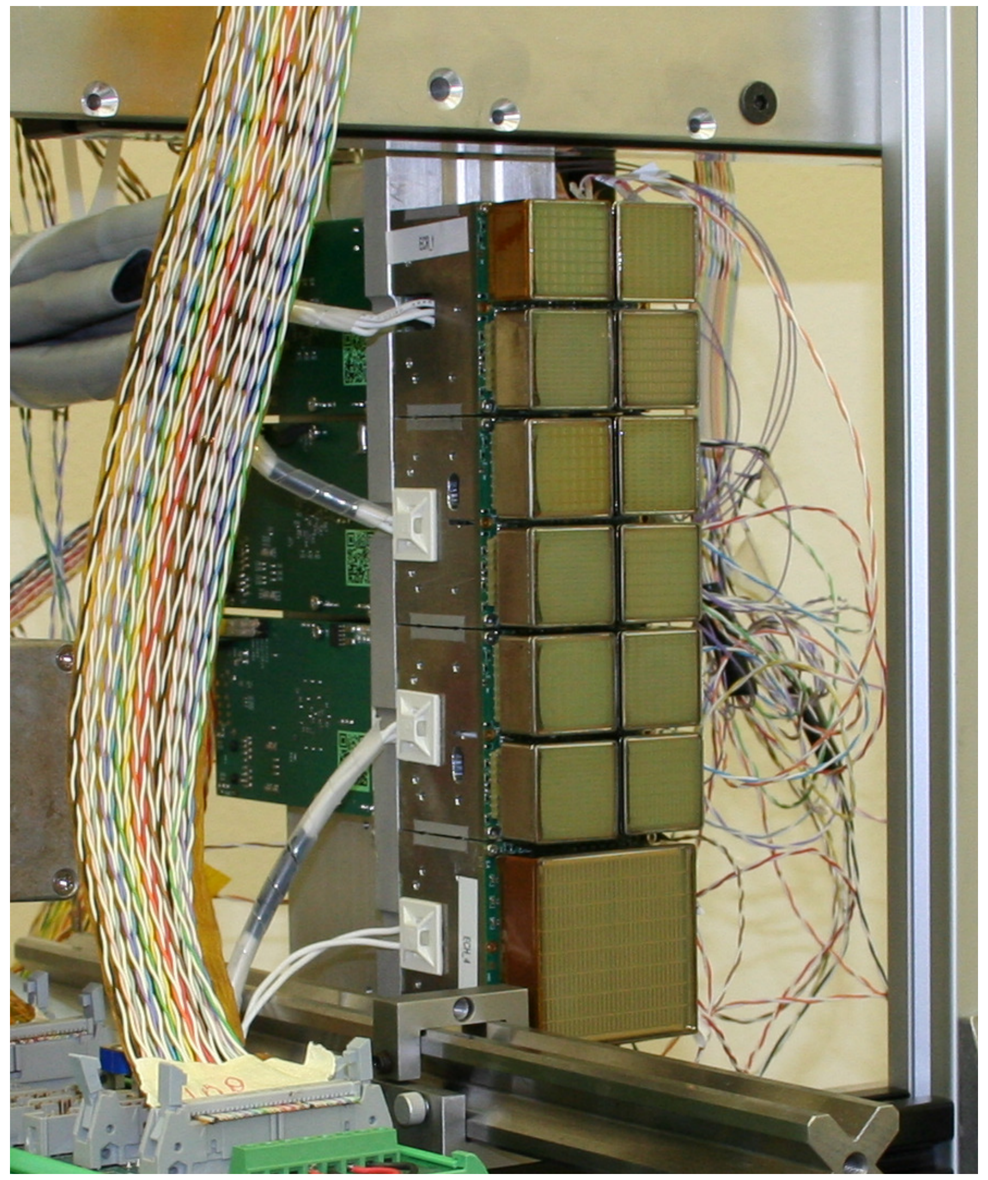
Status of Upgrade I

Significantly advanced production/ construction of many sub-systems

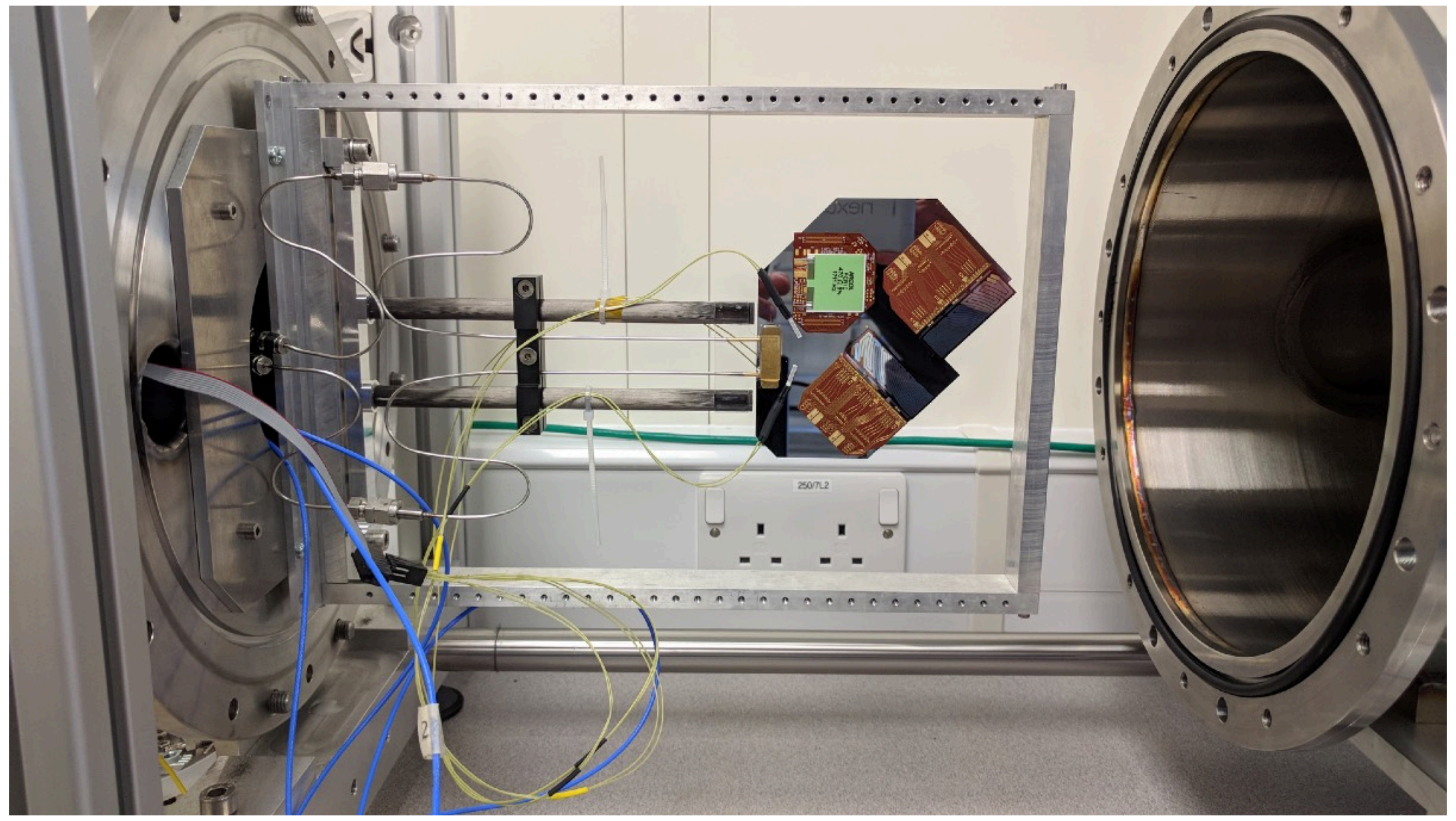


40 MHz read-out

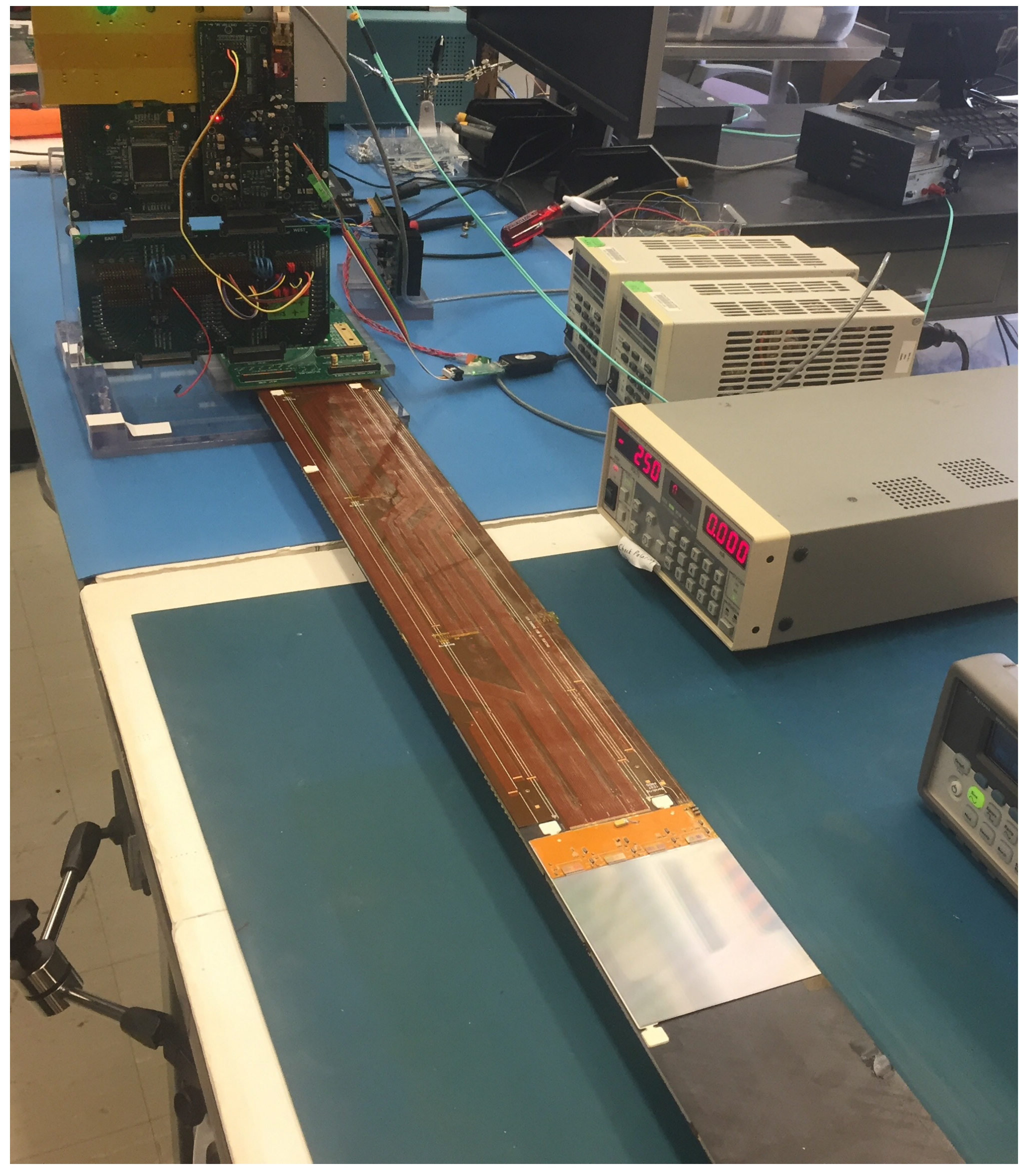
First SciFi modules at LHCb



RICH MAPMTs in test beam



Microchannel VELO module mechanical deflection tests



UT sensor with SALT electronics connected to a stave

Upgrade I consolidation

Installation in LS3

Operation during Run 4

$\mathcal{L} \sim 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$

ECAL

Already planning to replace innermost region of ECAL due to radiation damage

Baseline is tungsten → reduced Moliere radius and shorter ECAL than present, with expected improvements in rad hardness

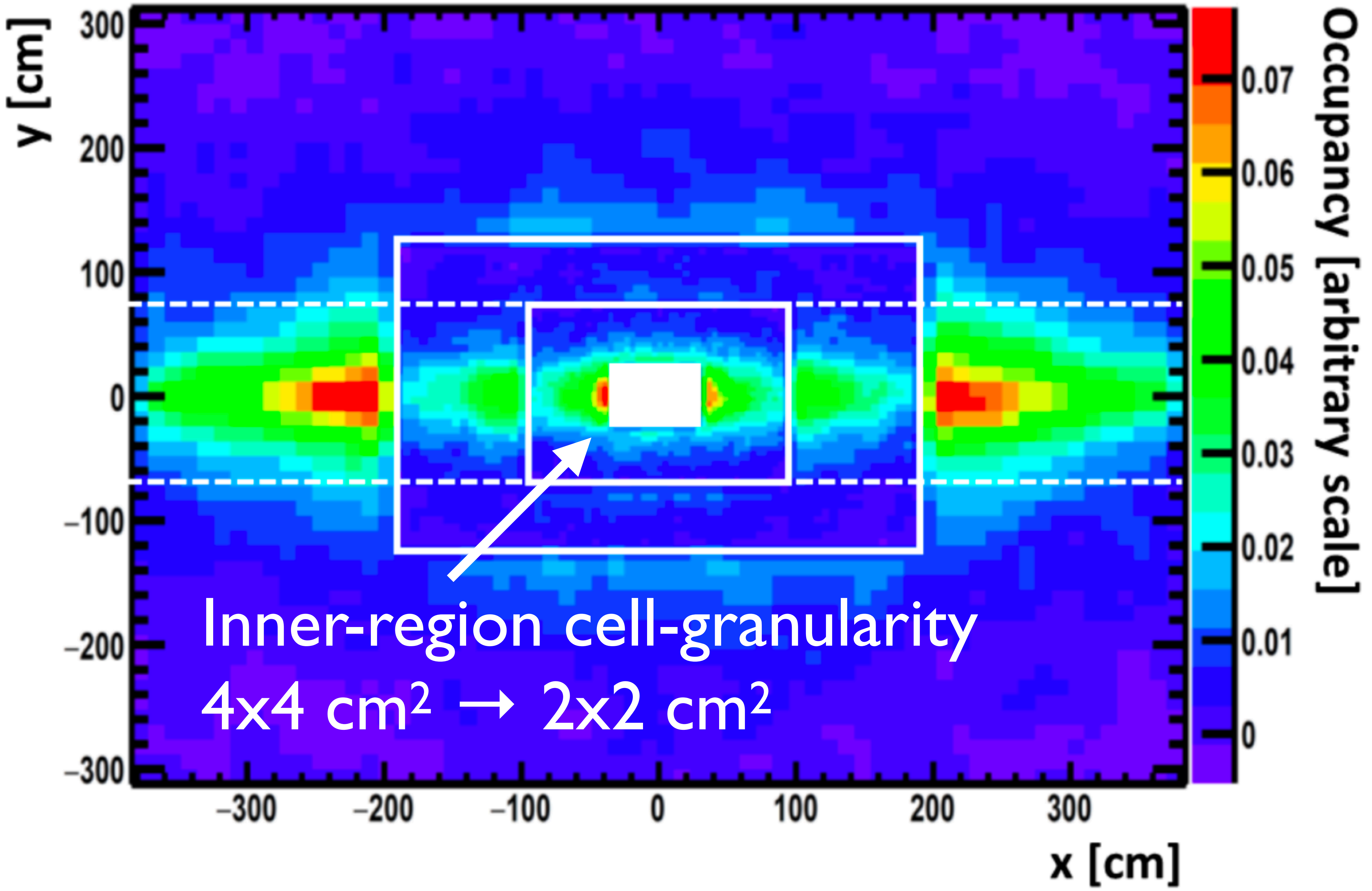
Silicon strips/pads for timing photons to PV → reduction in combinatorial background from pile-up

Improved brem recovery

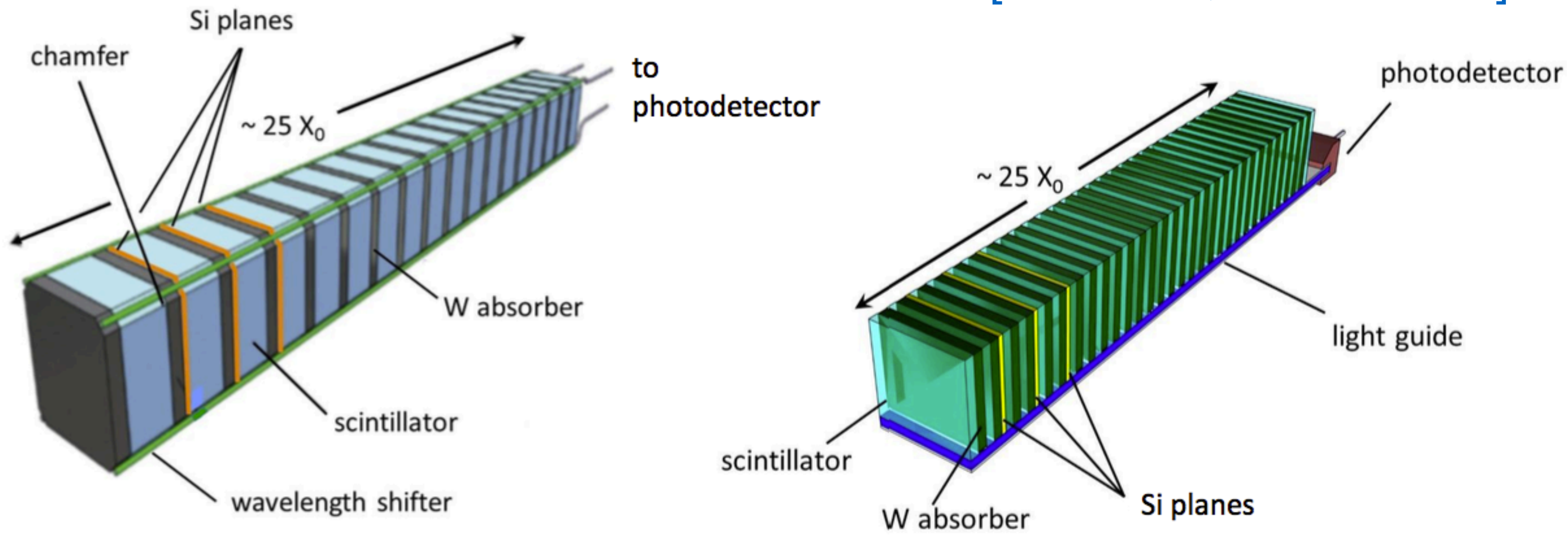
Aim to give significant improvements for decays with π^0, η, electrons, photons

Very strong physics interest e.g., CKM angle α, LFUV, radiative B decays, $D\to\pi\pi\pi^0$, $B^+ \to K^+\pi^0$

[P. Pais, HL-LHC workshop]

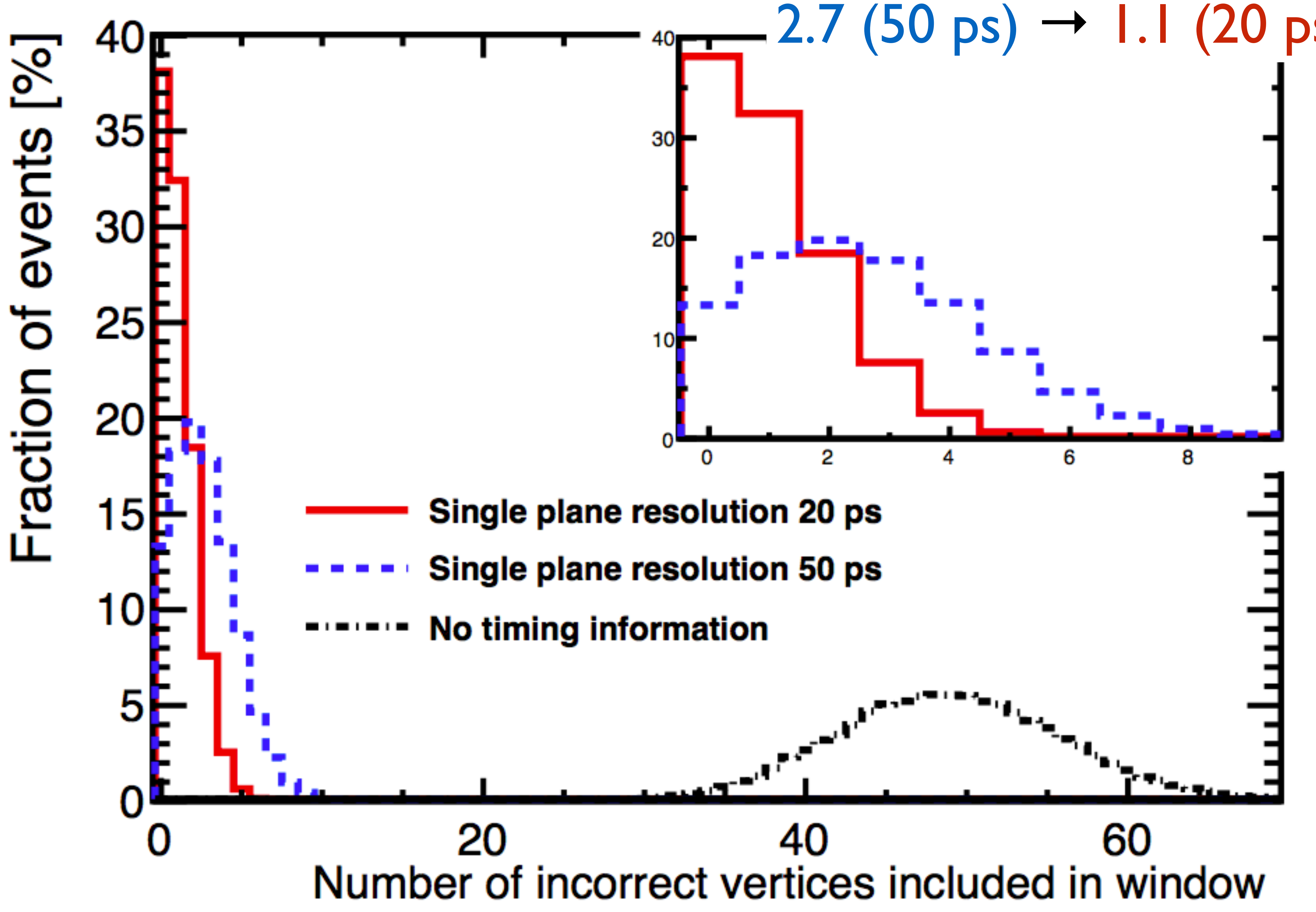


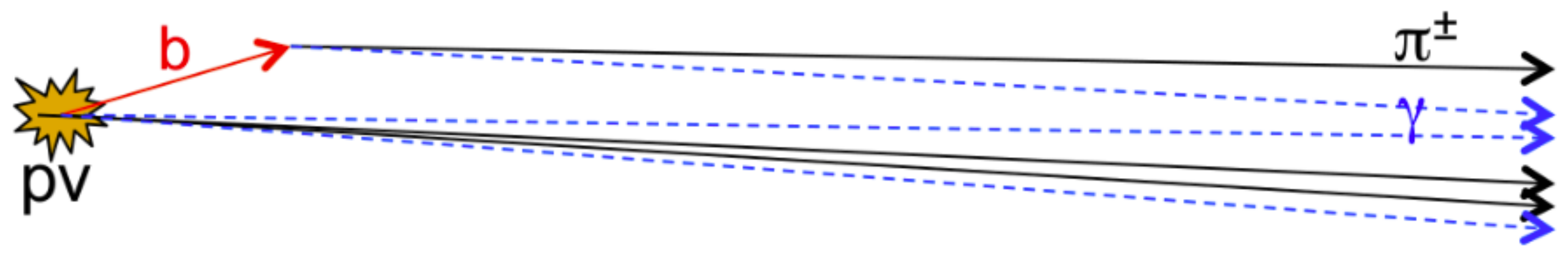
[Becker et al., arXiv:1405.6202]



ECAL: impact of timing

Reduction from
2.7 (50 ps) → 1.1 (20 ps)





π^0 mass resolution (MeV)

	Spatial information from clusters σ_C		Perfect spatial knowledge σ_C	
σ_S	1%	2%	1%	2%
7%	7.5	8.2	4.2	5.2
10%	8.5	9.3	5.5	6.5
15%	10.5	11.3	8.0	8.9

$$\sigma_E/E = \sigma_S/\sqrt{E(\mathrm{GeV})} \oplus \sigma_C$$

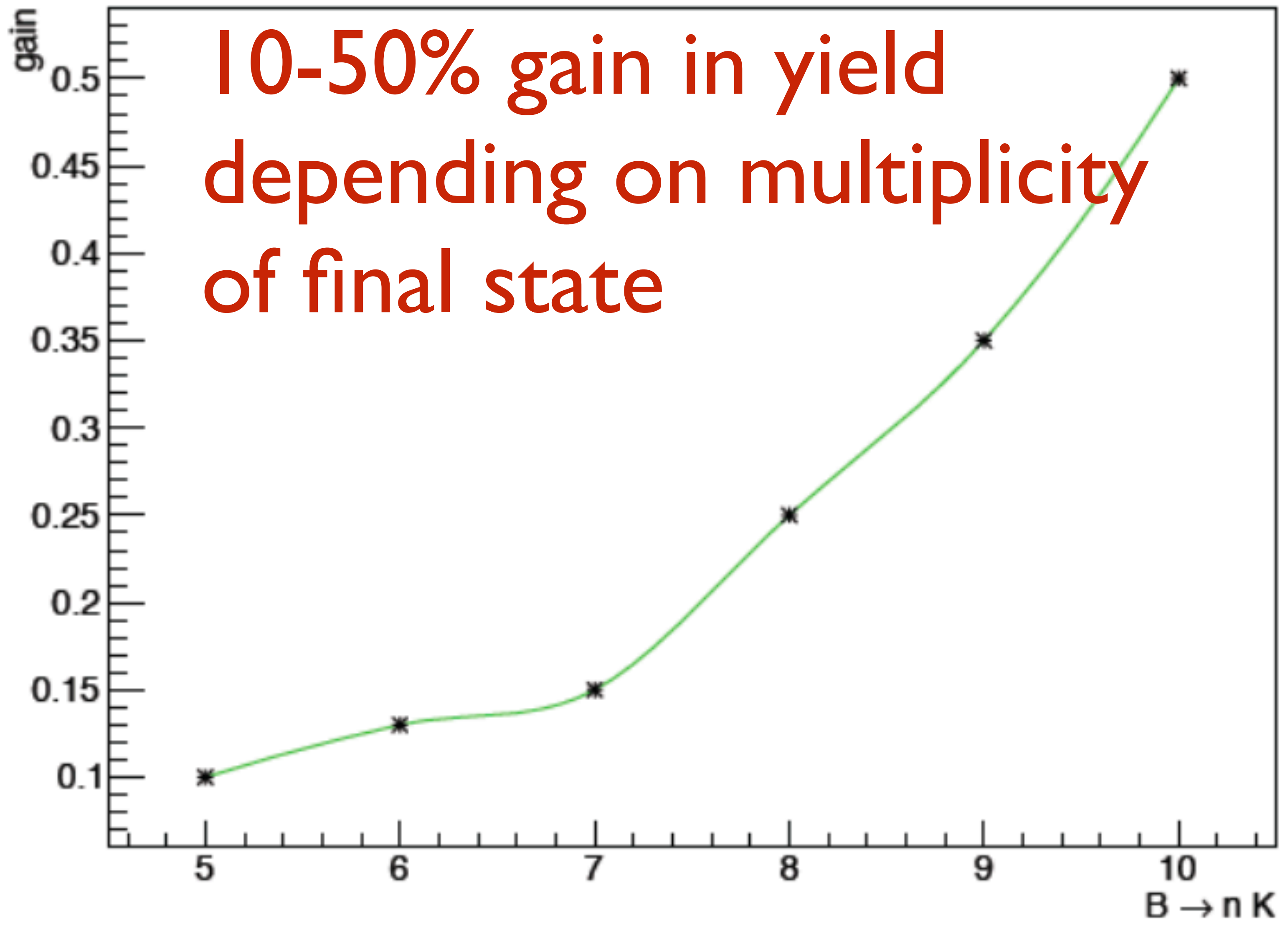
Ongoing R&D: silicon planes, new rad-hard crystals and new rad-hard light guides

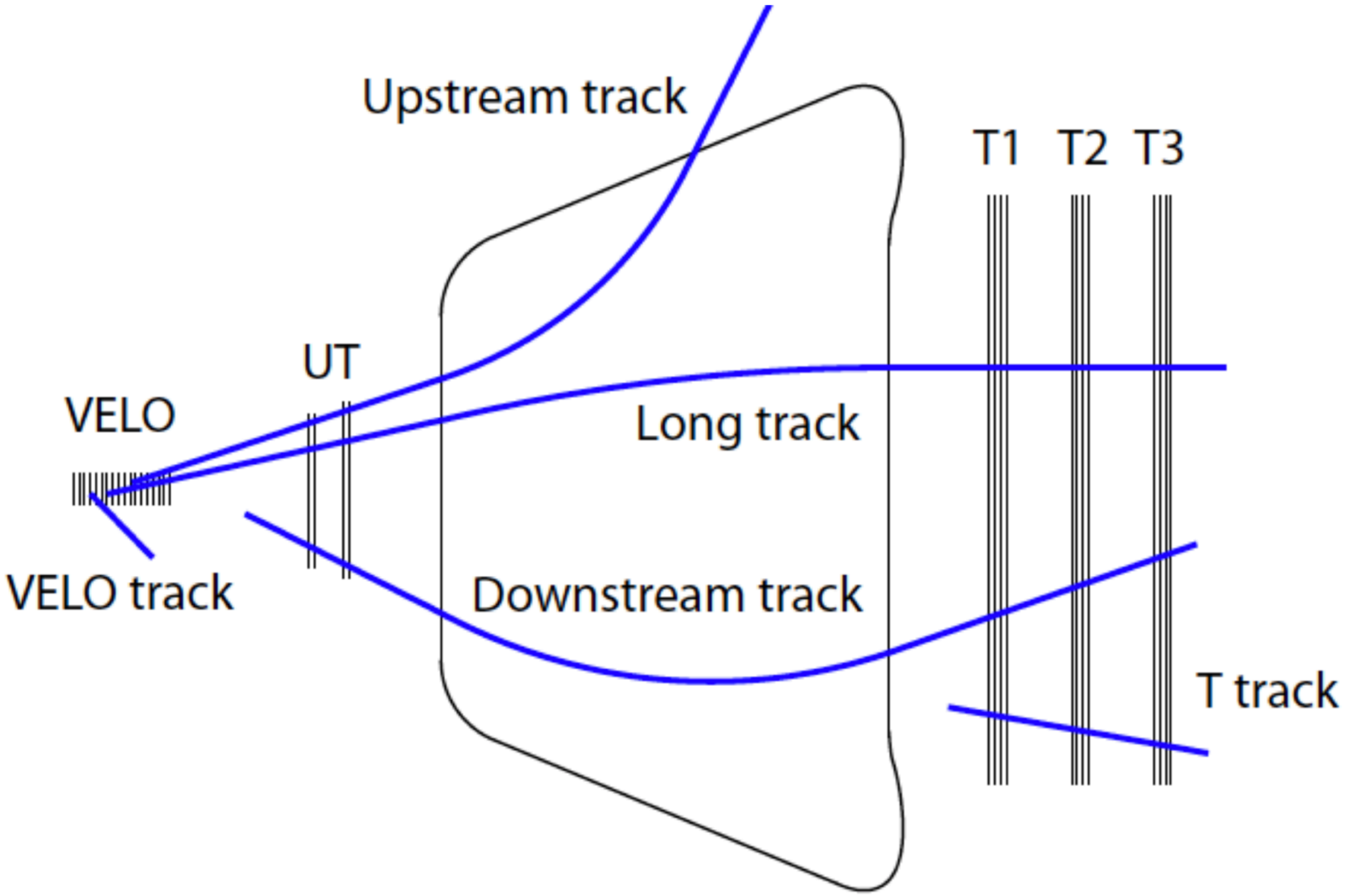
Magnet side stations

Upstream tracks have Δp/p ~ 15%

A **1mm z-segmented tracker** inside magnet will improve efficiency and resolution for events with large track multiplicity

Multi body b/c hadron decays; heavy ions; $D^{*+} \rightarrow D^0\pi^+_{slow}$; $B_{s2}^* \rightarrow B^+K^-$ for improved q^2 res of semileptonic decays; flavour-tagging; gluon PDF





No new material in front of other particles

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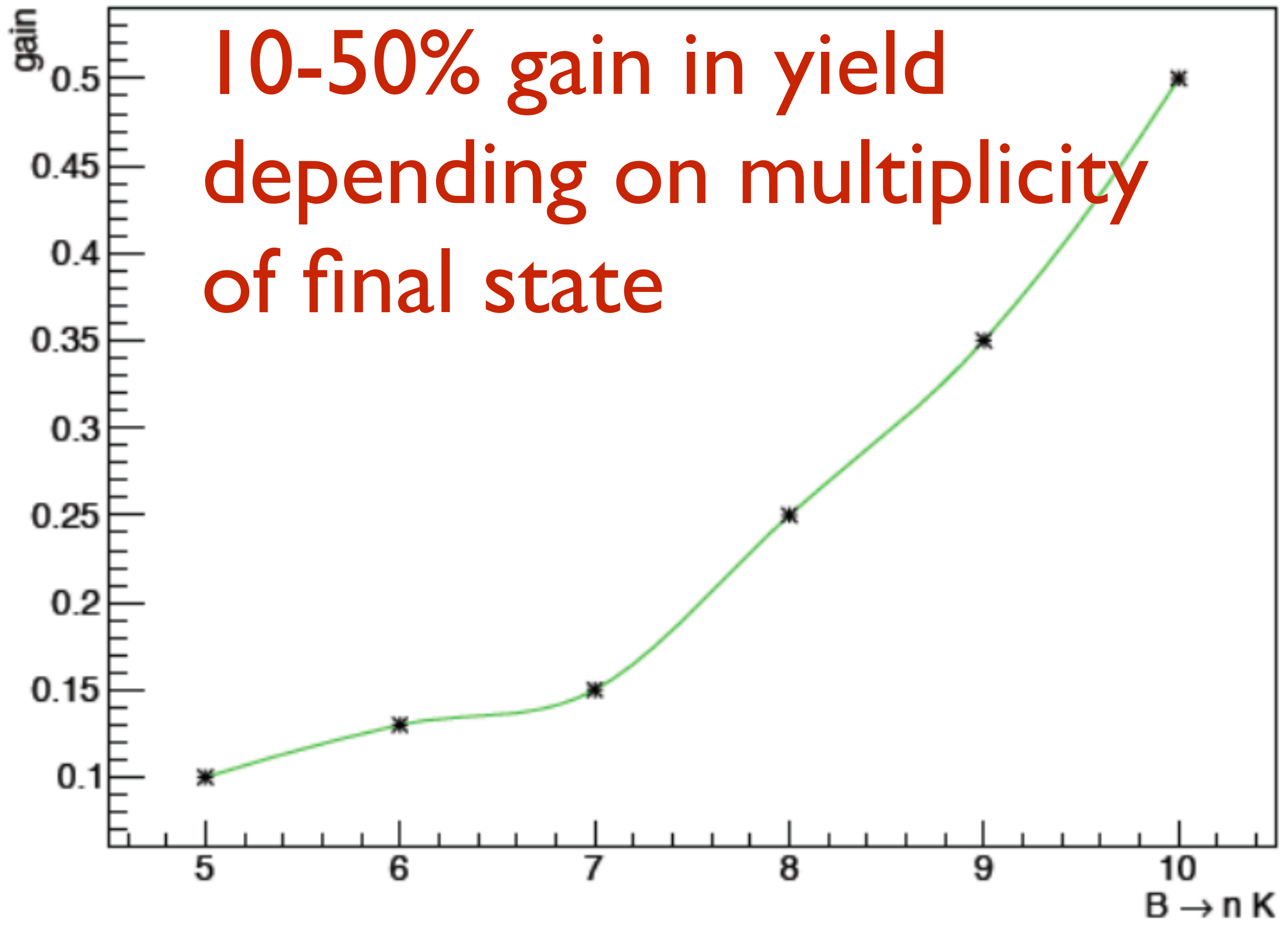

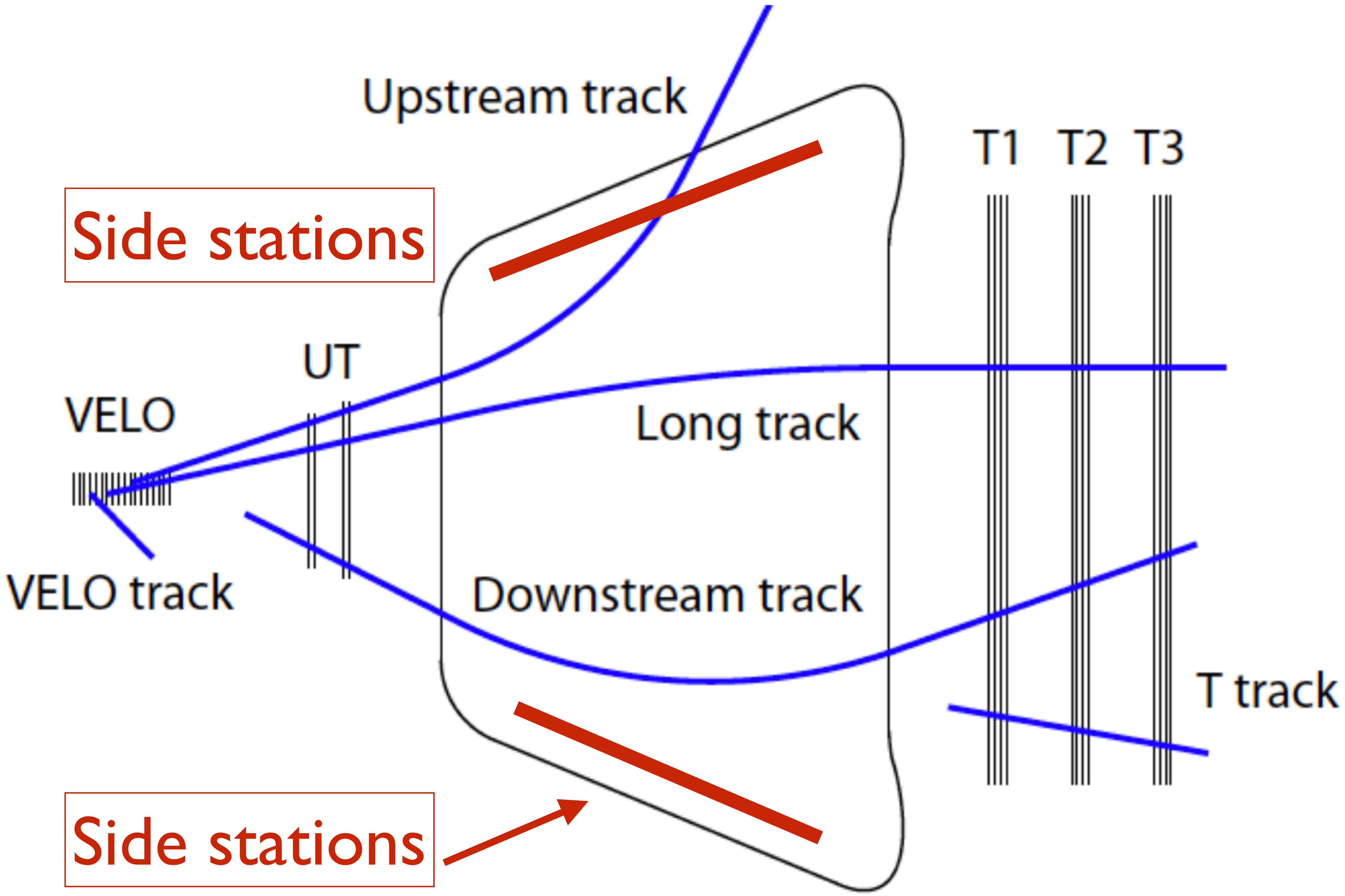

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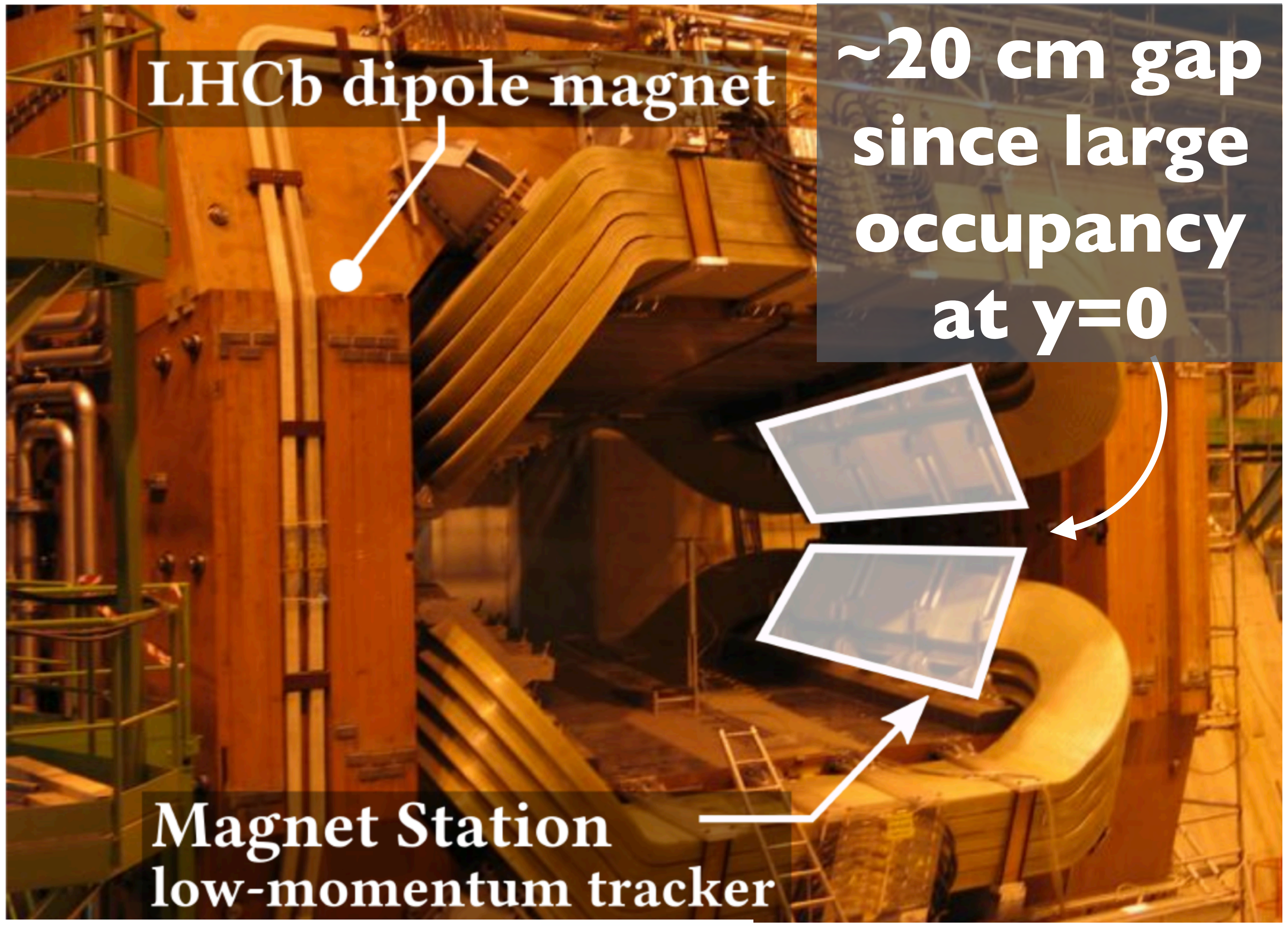
Magnet side stations

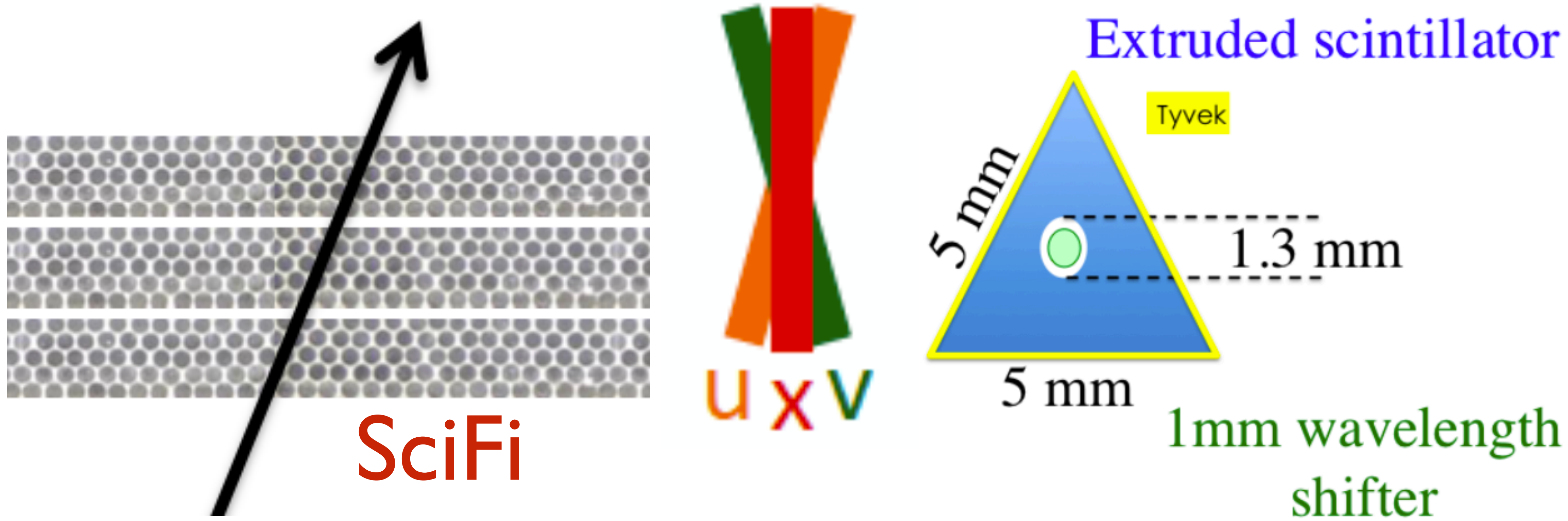
Benefit from experience with the SciFi tracker that is currently being installed for Upgrade 1.

Join scintillating fibres to clear fibres for photon routing outside of LHCb acceptance (lower radiation) to SiPMs.

Alternative: use extruded scintillator bars (triangular geometry) with embedded wavelength shifting fibres.

Work needed on reconstruction algorithms to enable use in the Upgrade I/II trigger.



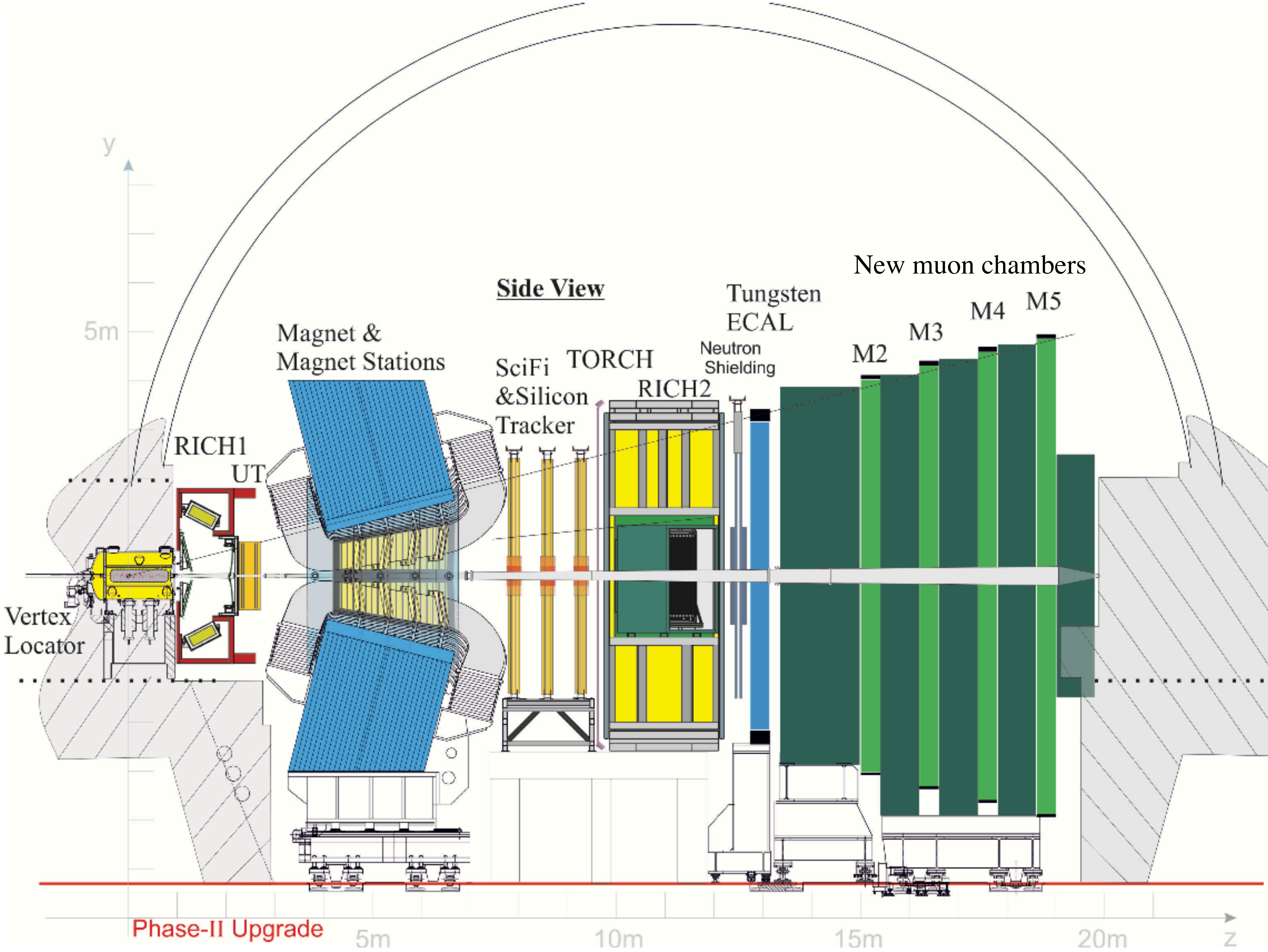


Upgrade II

Installation in LS4

Operation during Run 5

$\mathcal{L} \sim 1\text{-}2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$



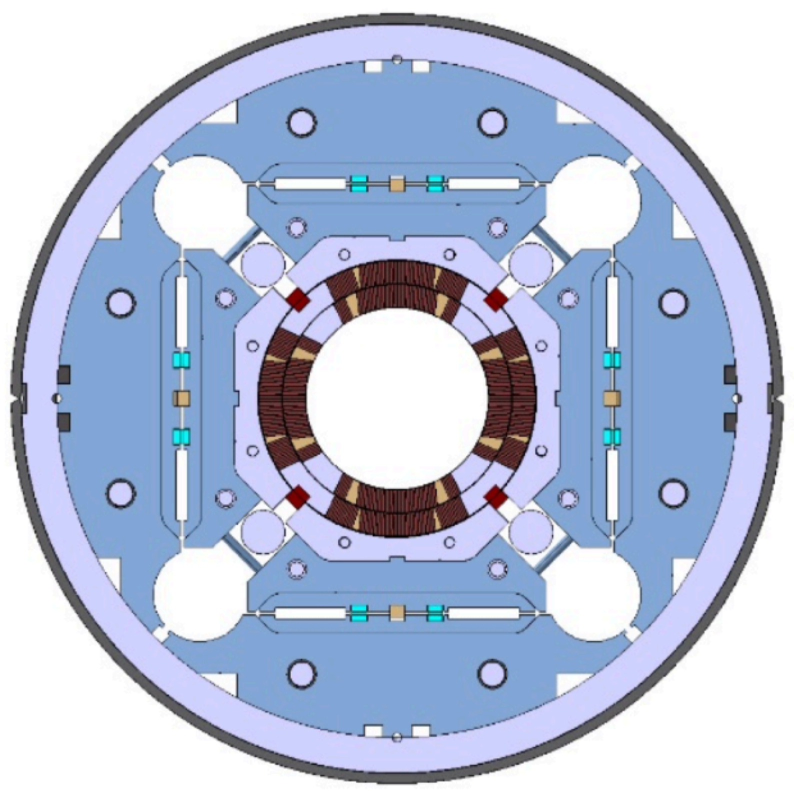
Looks similar to Upgrade I

LHC machine considerations

300/fb is baseline target as IP8 inner-triplet magnets require (expensive) replacement beyond this.

300/fb possible during HL-LHC lifetime (40-50/fb/year), with **minimal impact on ATLAS/CMS**, but needs reduced β* and further investigations on the shielding around IP8.

[CERN-ACC-2016-0007]

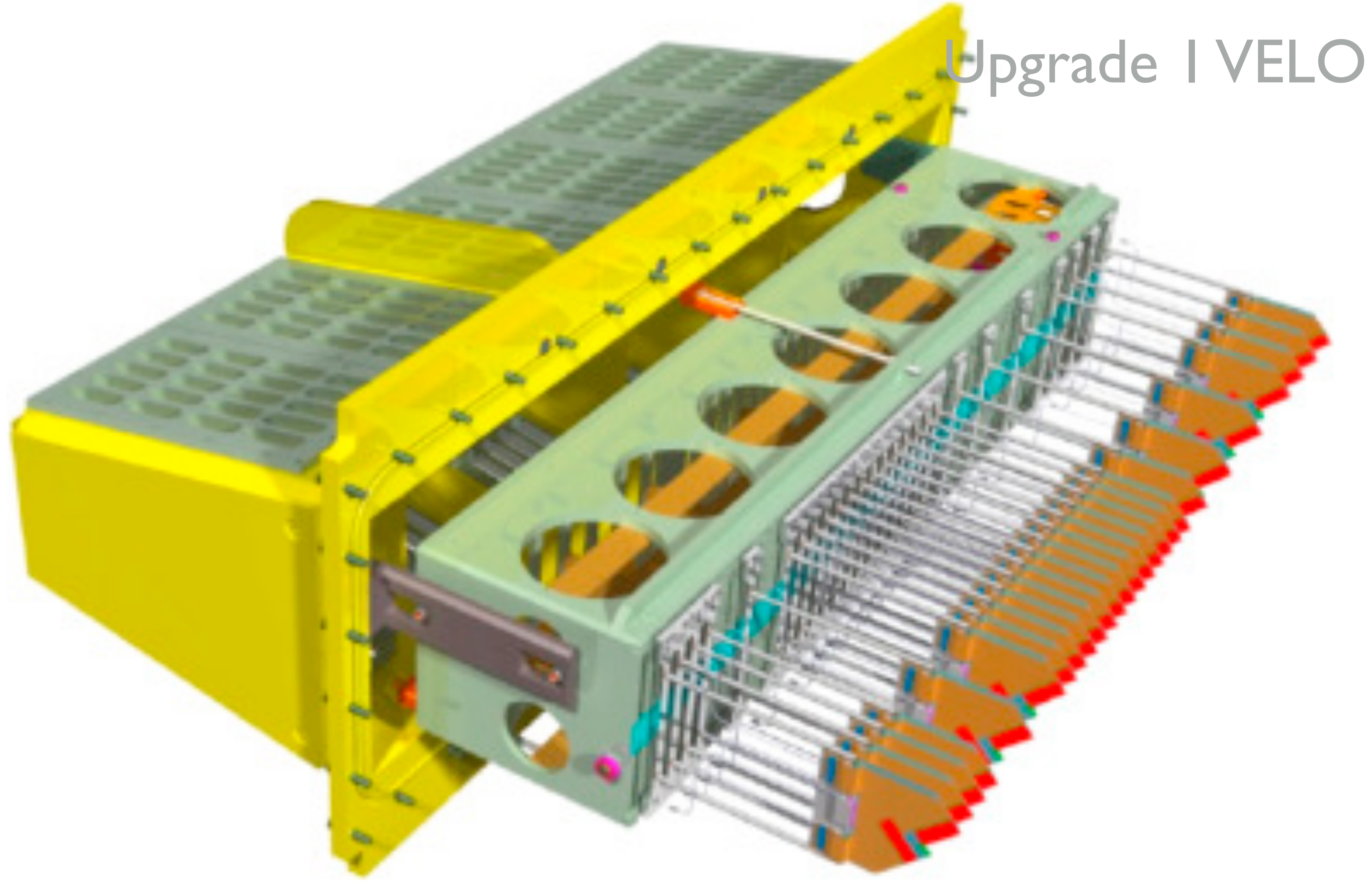


[CERN-LHCC-2017-003]

	β^* [m]	Maximum $\mathcal{L}$ [$\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$] −	+	$\int \mathcal{L}\,dt$ [fb^{-1}/yr] −	+
Upgrade I (best case)	3	1.04	0.78	10	10
Can be done	2	1.53	1.04	39	31
	2	1.53	1.04	43	31
Challenging	1	2.90	1.66	48	42
	1	2.90	1.66	73	48
	1	2.90	1.66	80	48

Equalisation of luminosity between MagUp/MagDown needs further study → important for **systematics** evaluation

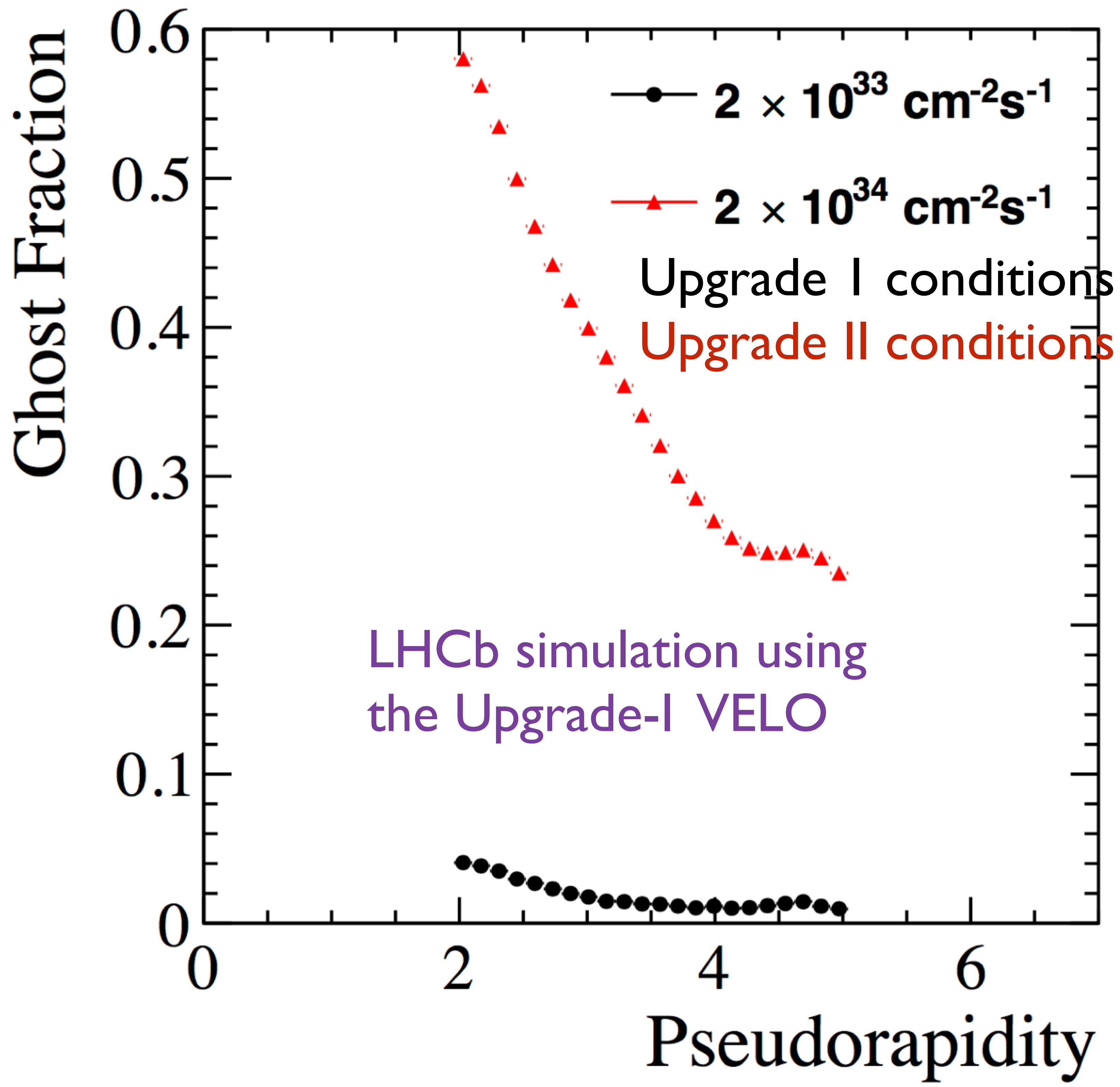
Vertex Locator



Likely based on Upgrade-I VELO (55 μm Si pixels).

Would like access to shorter lifetimes, better PV and IP resolution and real-time alignment

compared to Upgrade I {
- **x10 multiplicity → small pixels**
- **x10 pile-up → timing**
- **x10 radiation damage → replacement**



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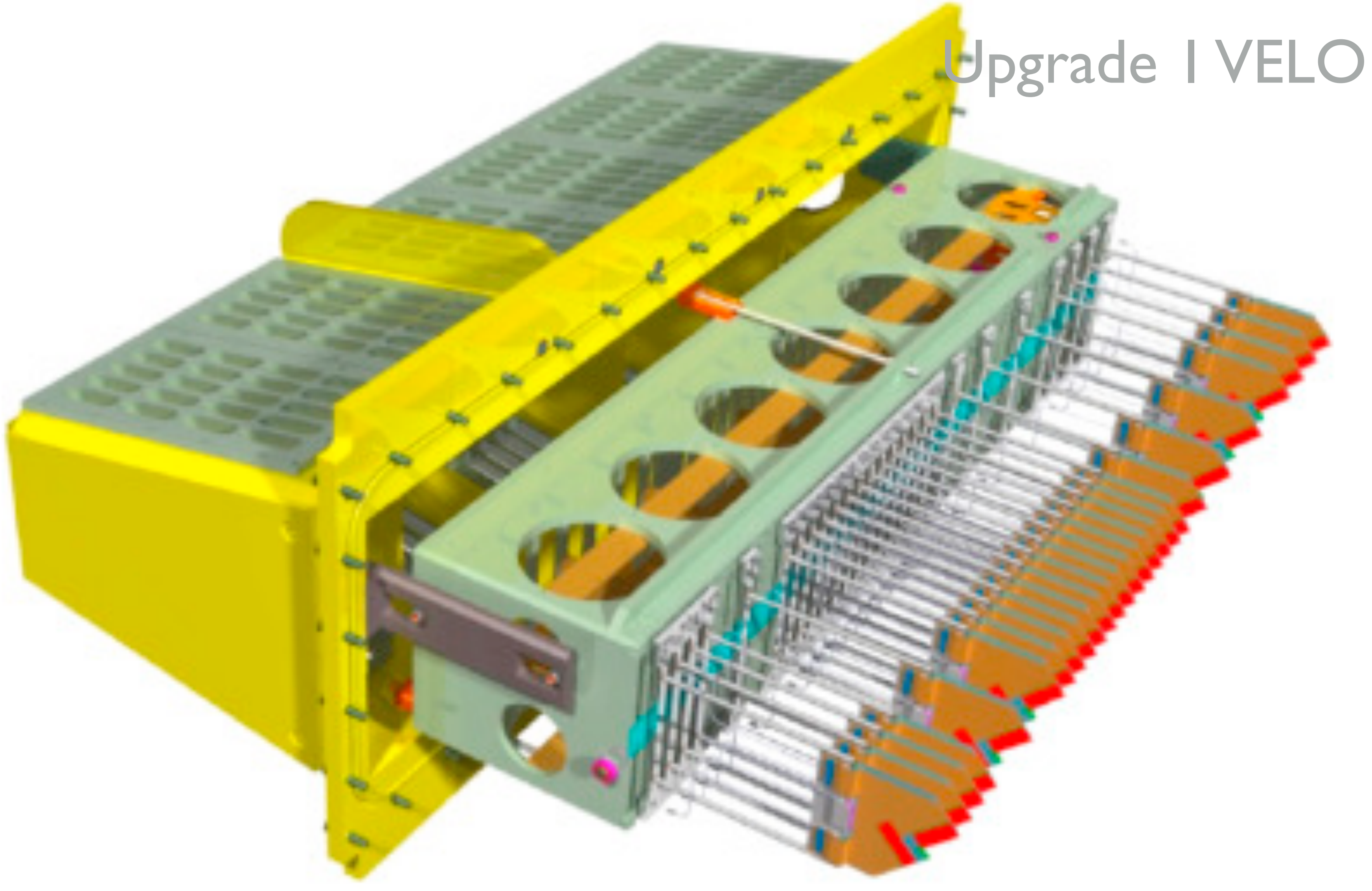

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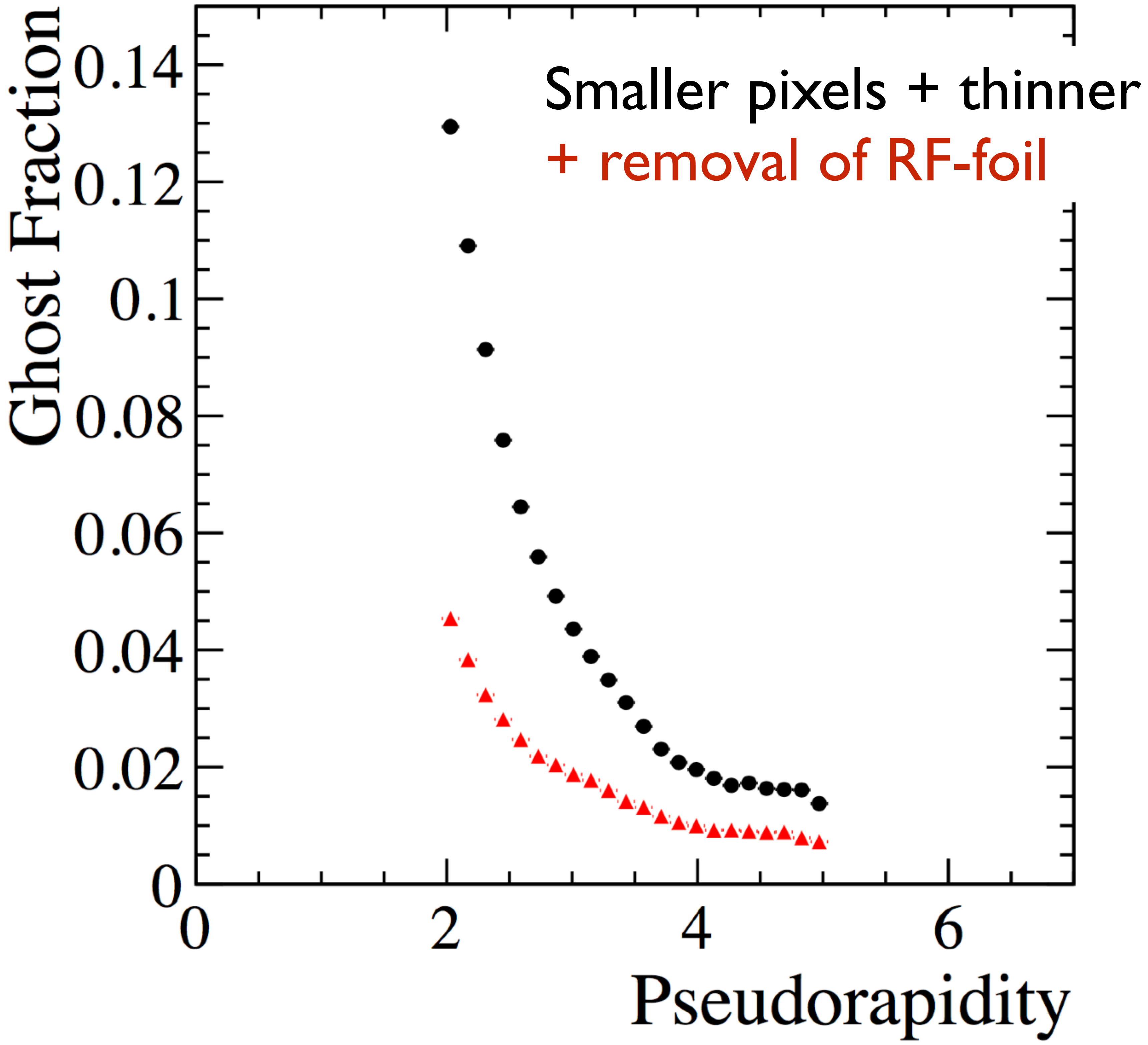
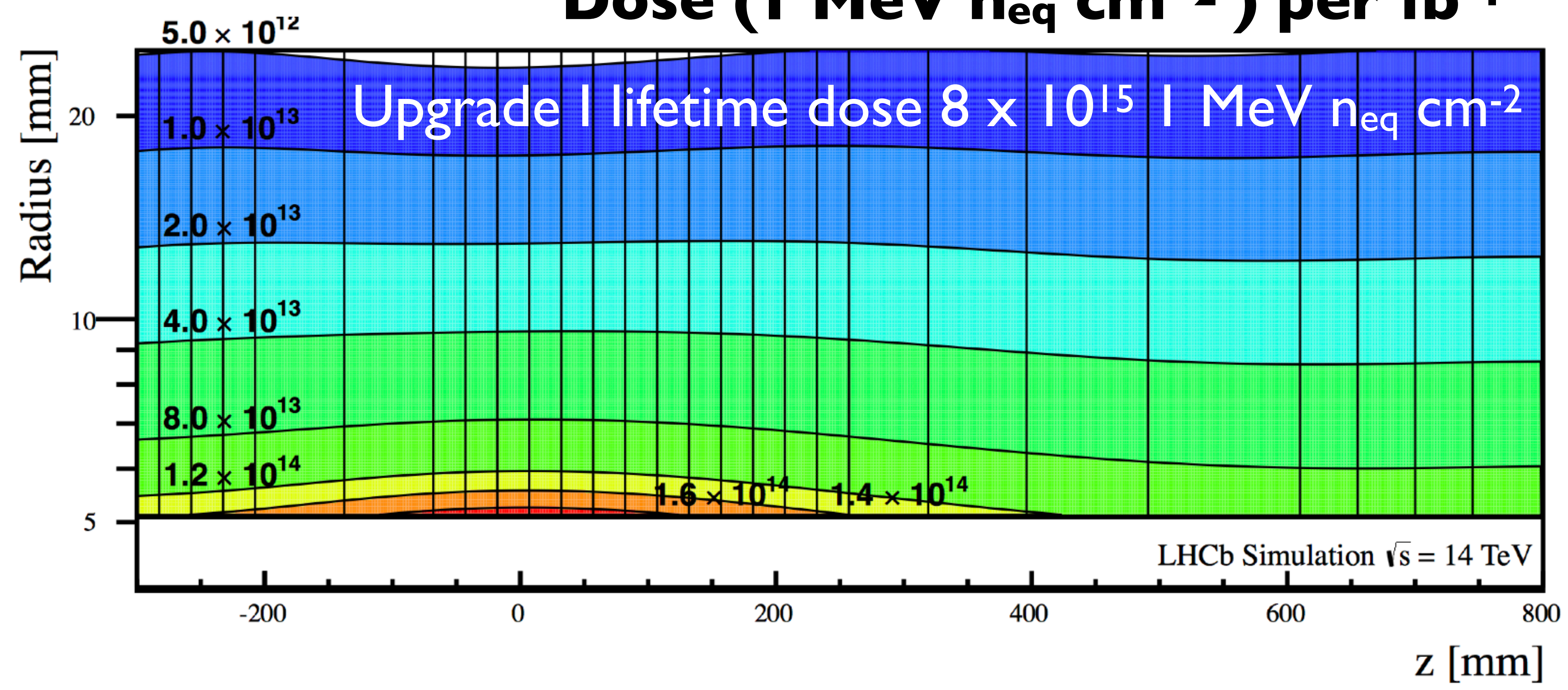


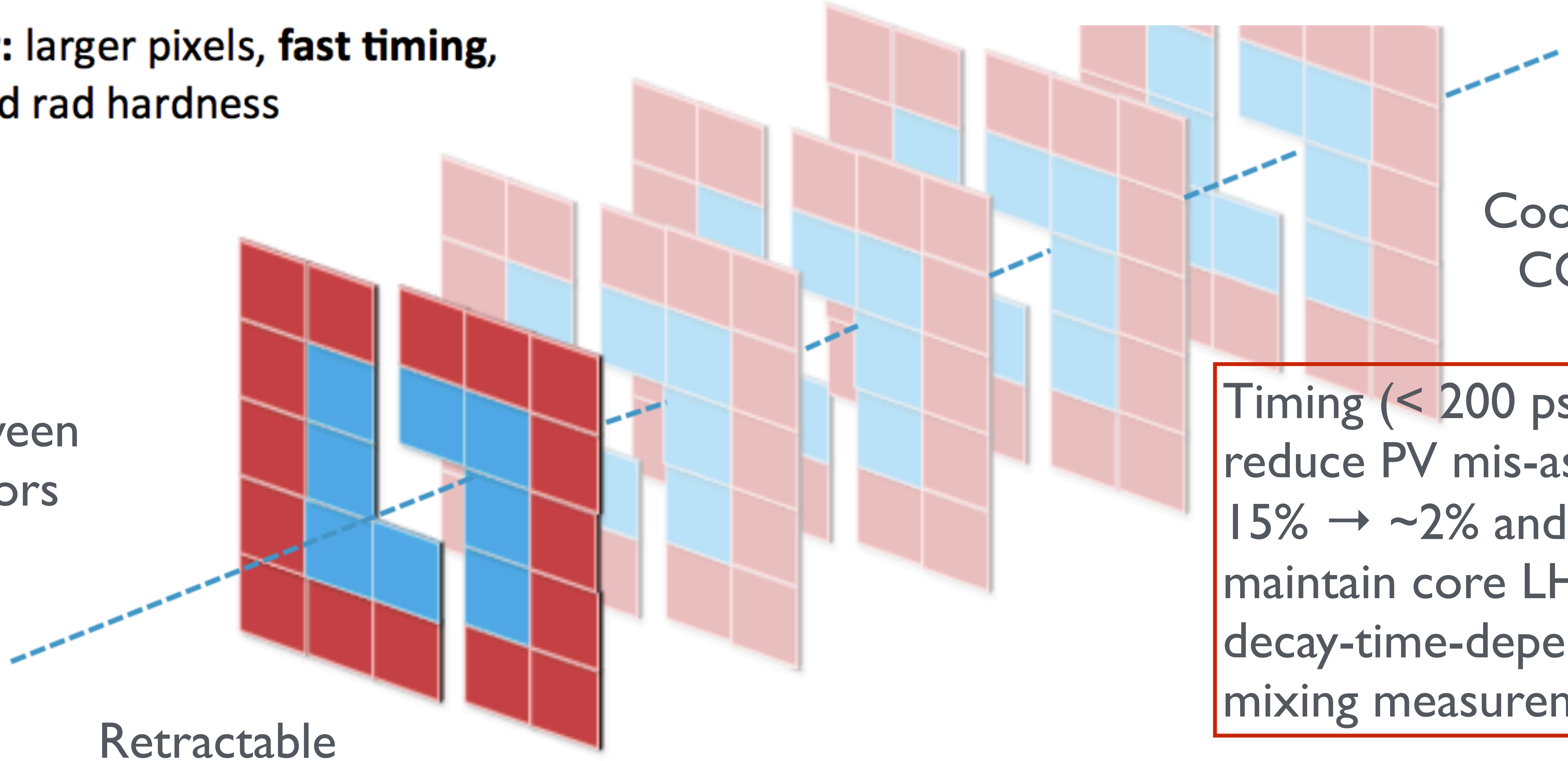
Recover Upgrade-I performance using smaller pixels (27.5 μm), thinner sensors (100 μm), optimised pattern recognition

Vertex Locator



Main modules have two technologies:

- **Small-r:** small pixels, radiation hard, timing information optional
- **Large-r:** larger pixels, **fast timing**, reduced rad hardness



Cooling from evaporative CO_2 in microchannels

Minimal RF protection between beam and sensors

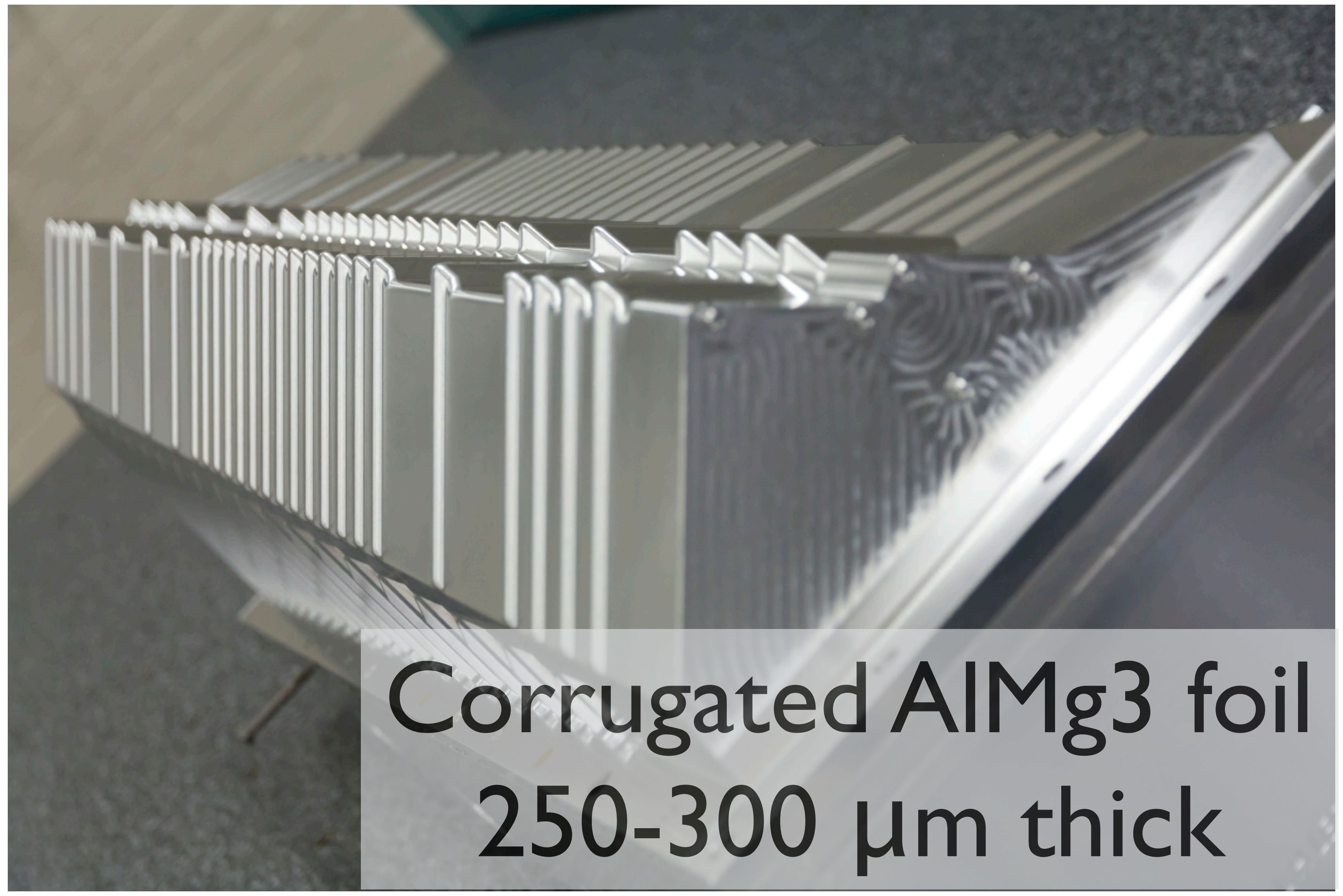
Timing (< 200 ps per pixel) will reduce PV mis-association rate from 15% → ~2% and is essential to maintain core LHCb programme of decay-time-dependent CPV and mixing measurements

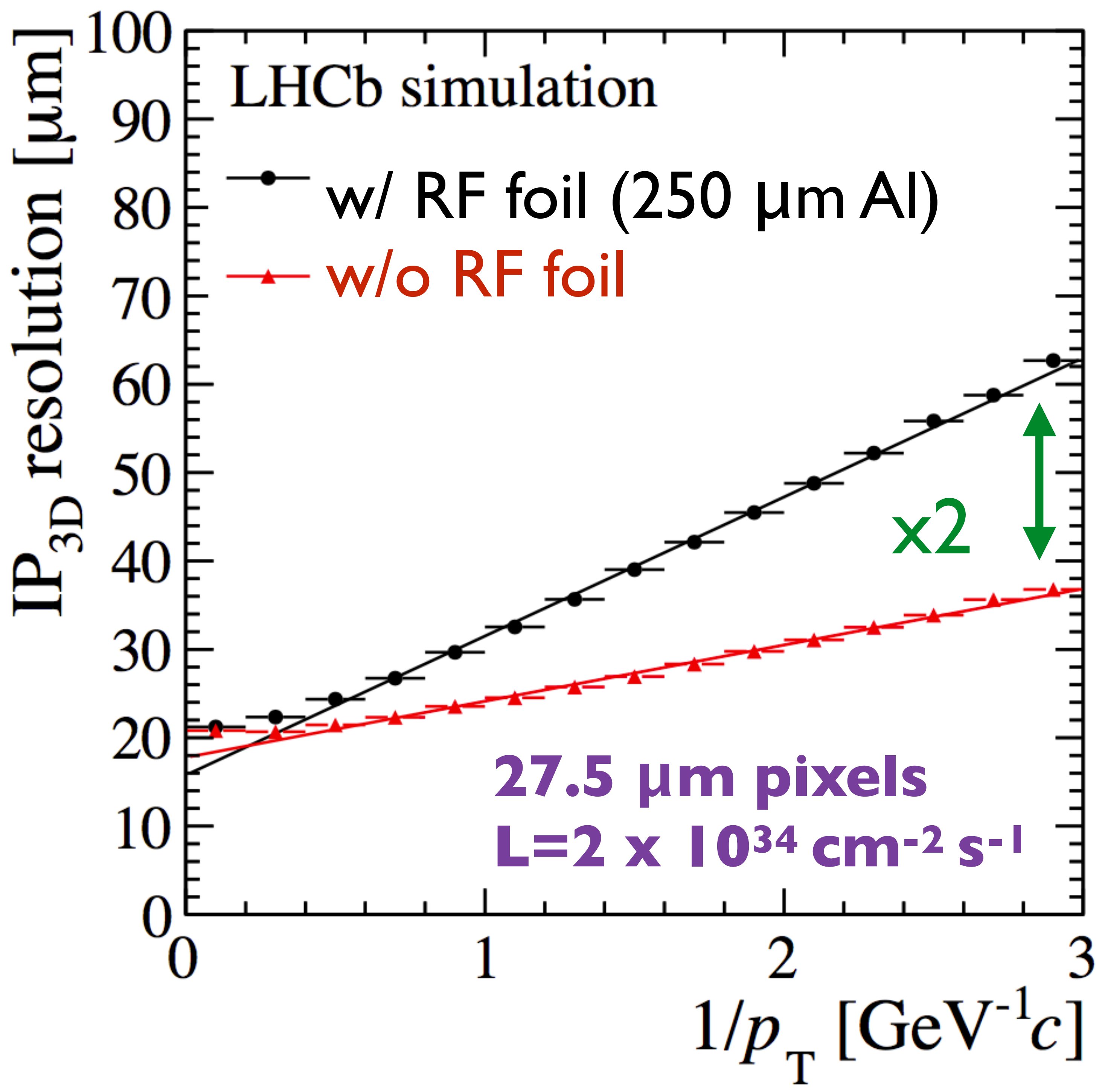
Retractable modules (as now)

Starting point: use same z-layout as Upgrade-I
Use similar-sized sensor units (15x15mm^2 per square)

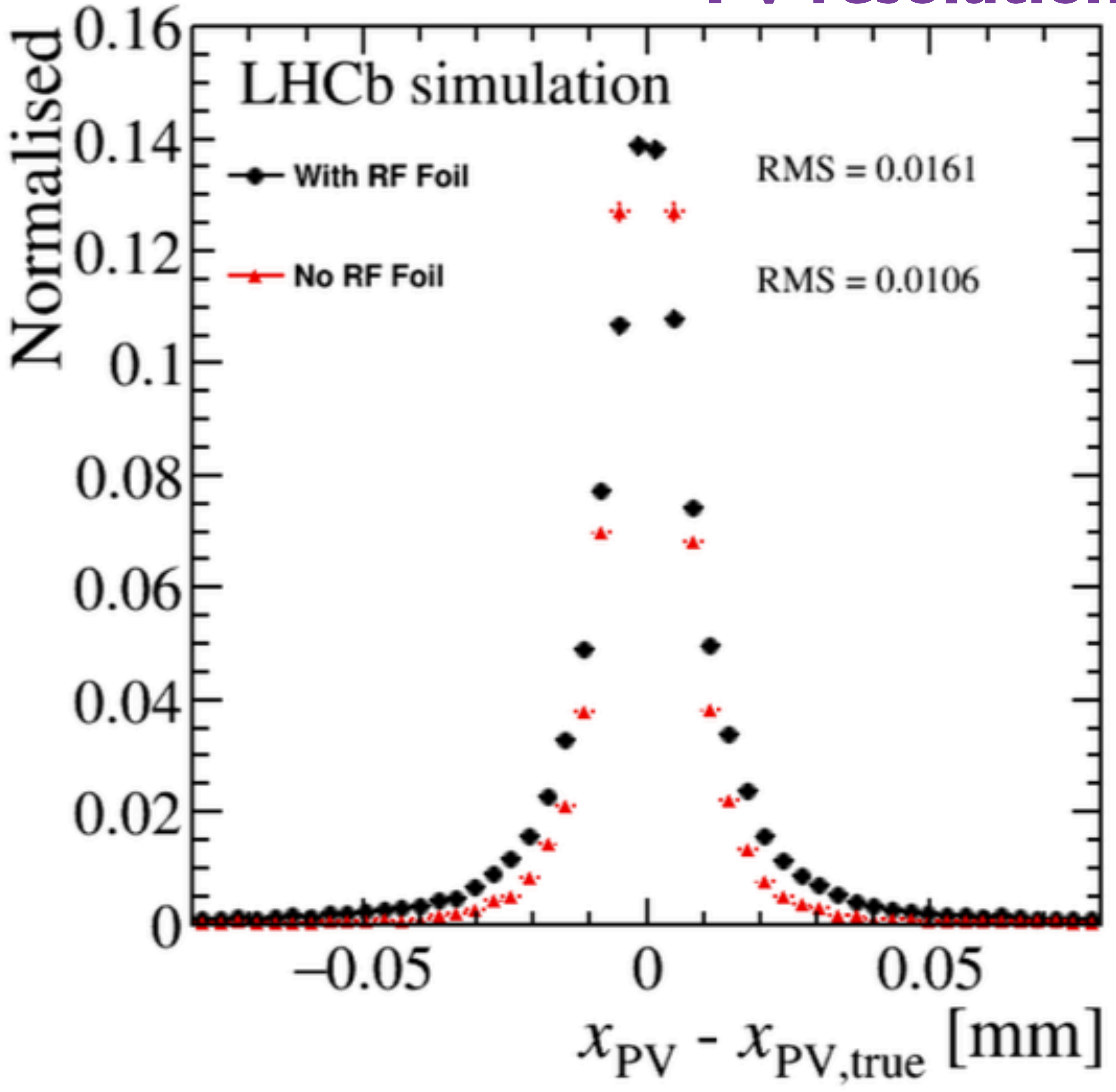
[M. Williams, HL-LHC workshop]

Removing the RF foil?





PV resolution



Surrounds VELO sensors, providing secondary vacuum and RF isolation.

Introduces significant material → multiple scattering and degradation of track-finding efficiency, mass and vertex resolutions → more difficulty suppressing backgrounds

Has complex geometry that is difficult to simulate → could we remove it?

[G. Ciezarek, HL-LHC workshop]

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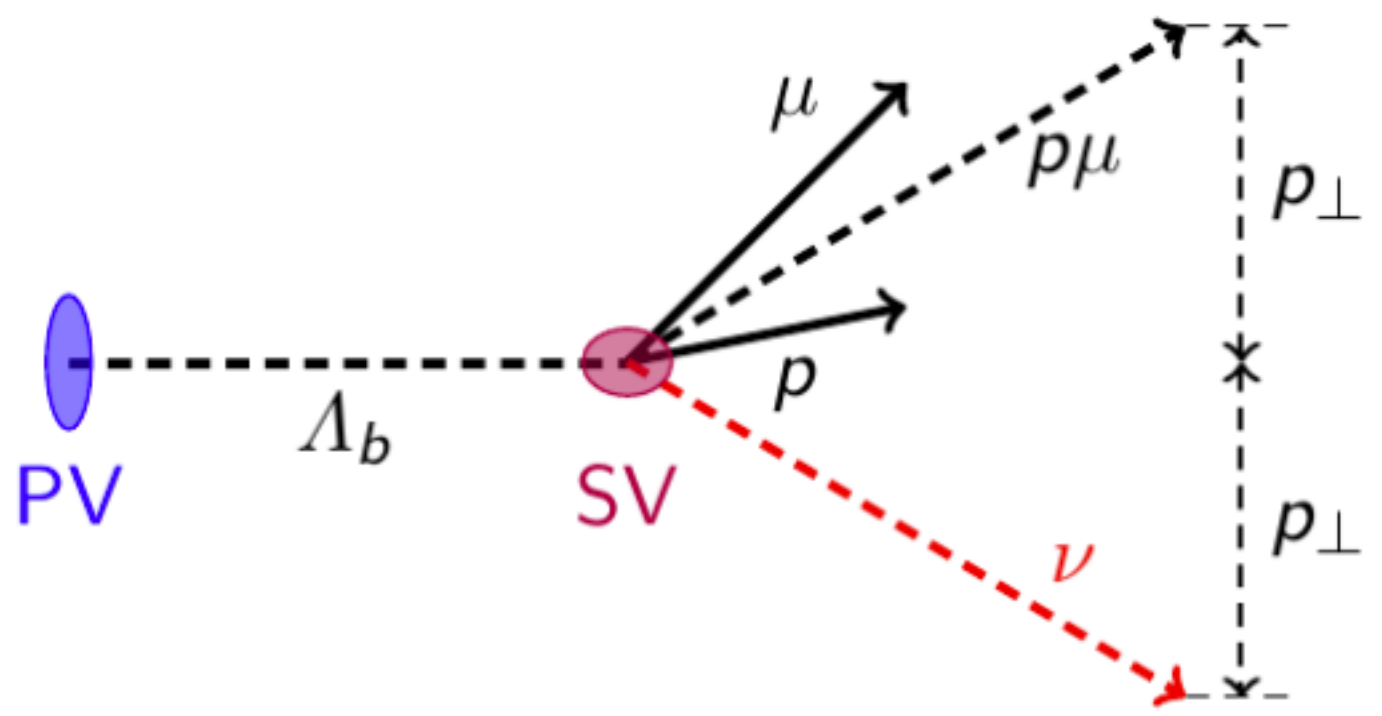
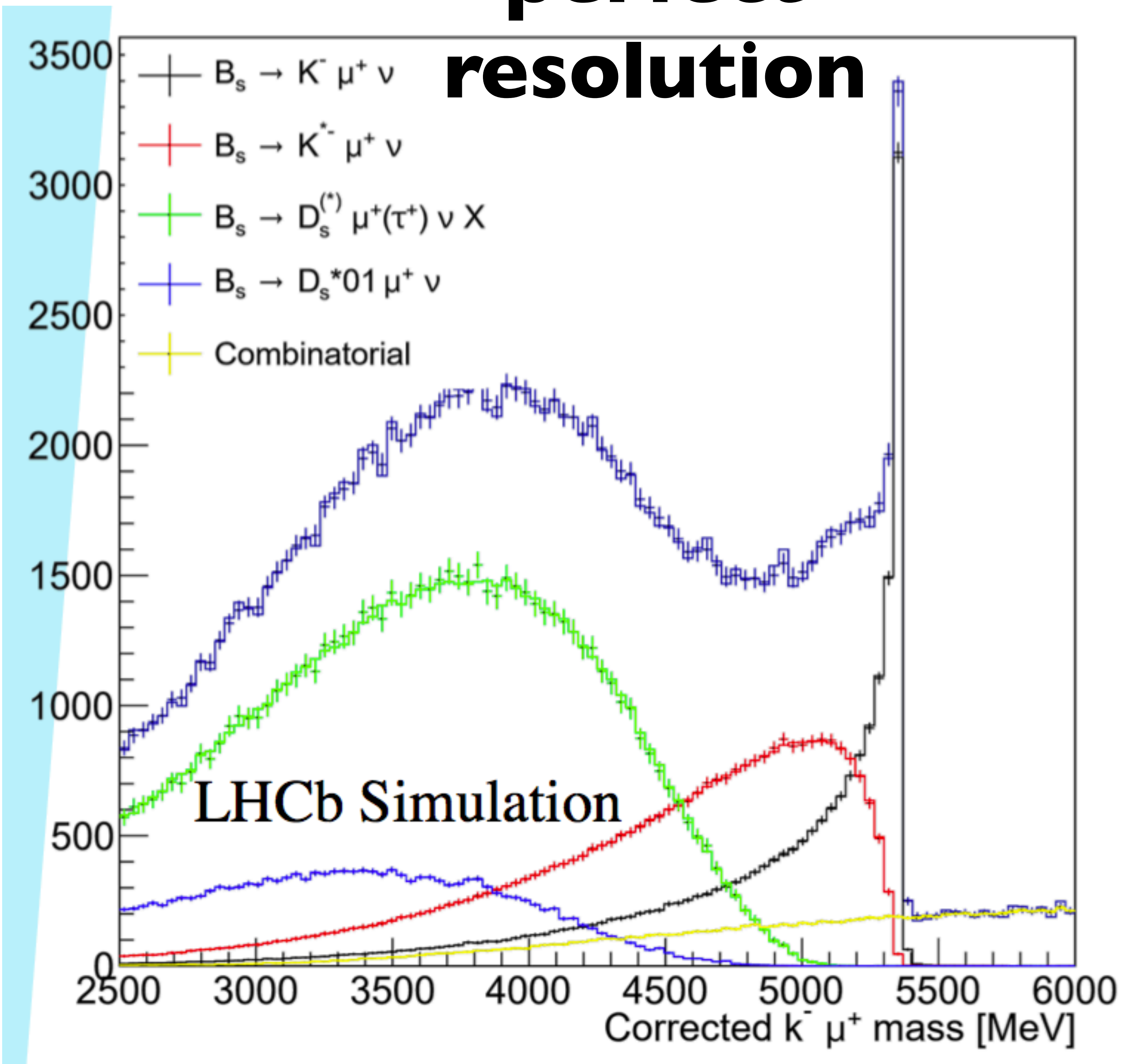


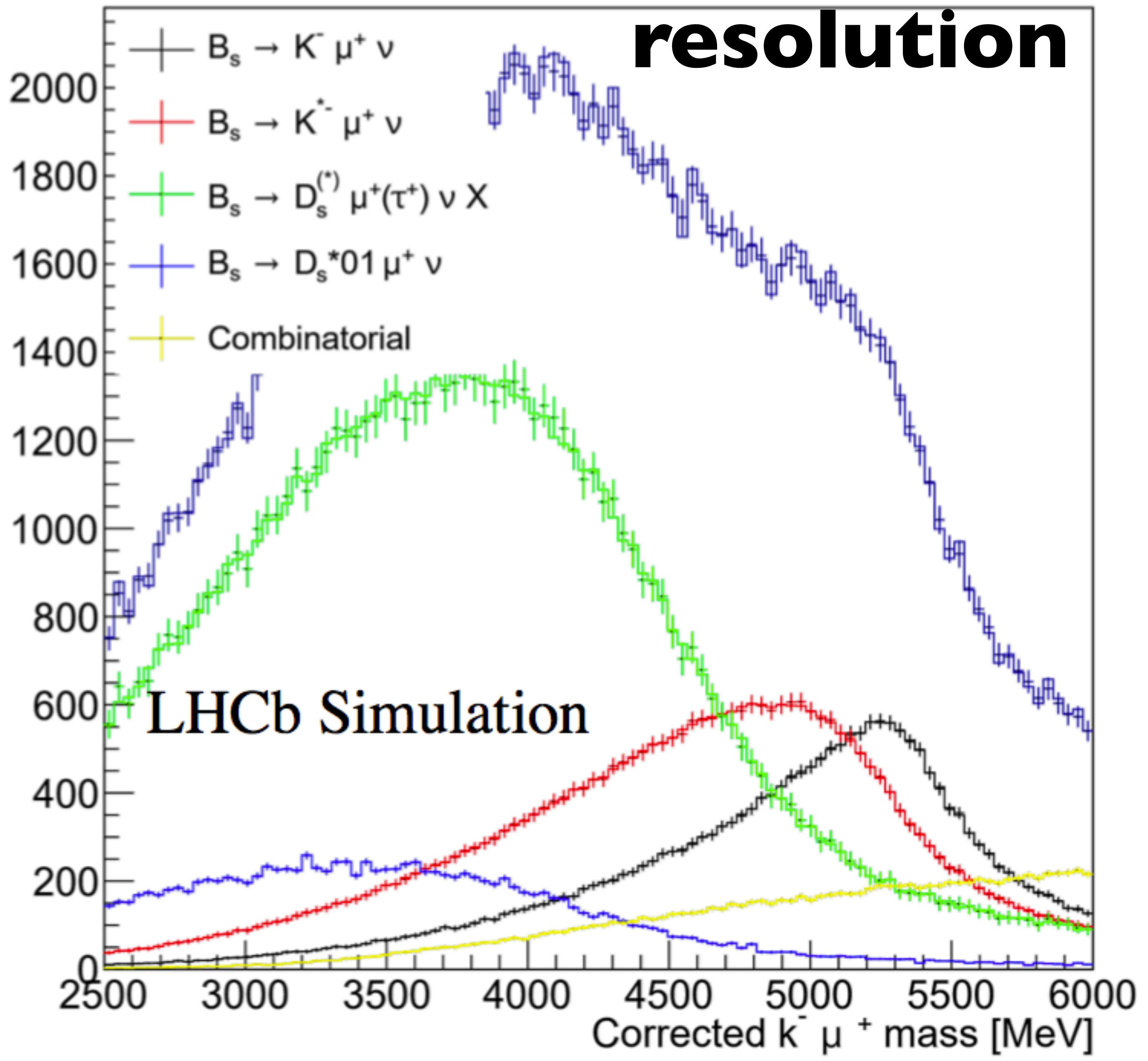
$$M_{corr} = \sqrt{p_\perp^2 + M_{reco}^2} + p_\perp$$

e.g. $\boldsymbol{B_s \rightarrow K^+\mu^-\upsilon}$ for measuring $|V_{ub}|$

perfect resolution



current VELO resolution



[I. Smith, HL-LHC workshop]

M_{corr} resolution dominated by secondary vertex resolution

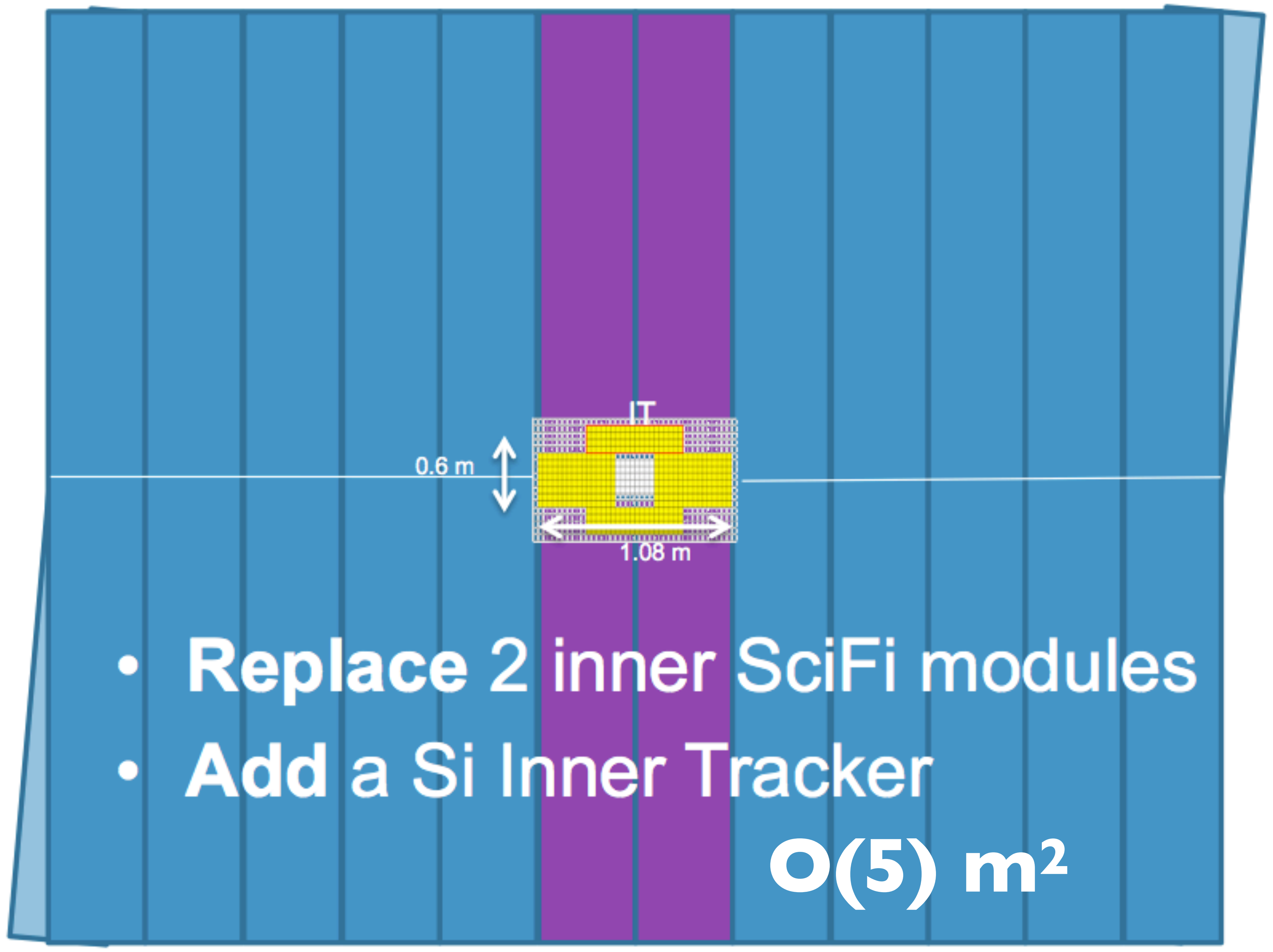
No RF foil gives **25% gain in effective luminosity** from fit resolution alone

++ expect higher combinatorial bkg rejection, better association to PV, better q^2 resolution

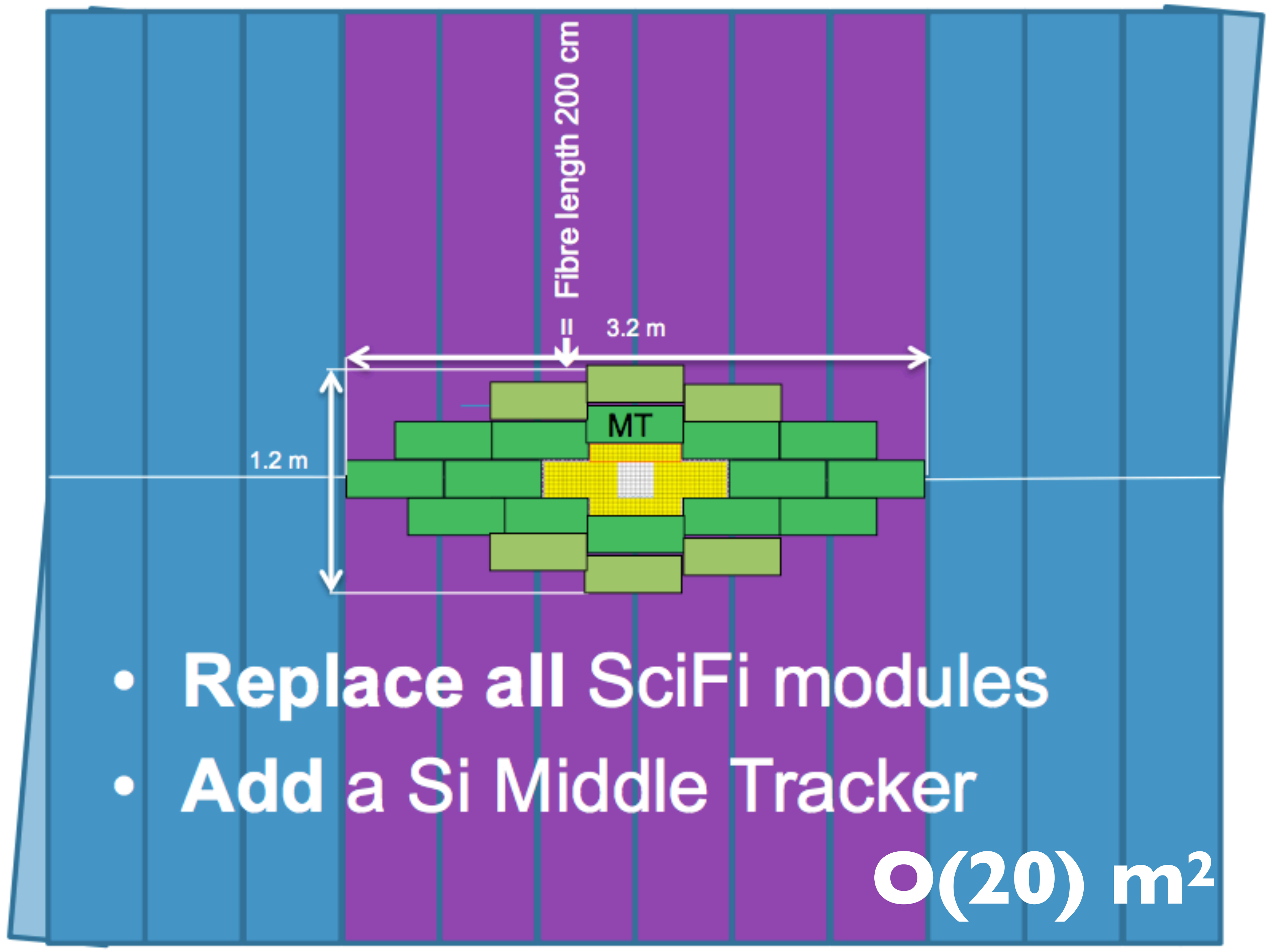
Tracking stations

Produce **shorter fibre mats** after completion of Upgrade I

Upgrade I consolidation



Upgrade II



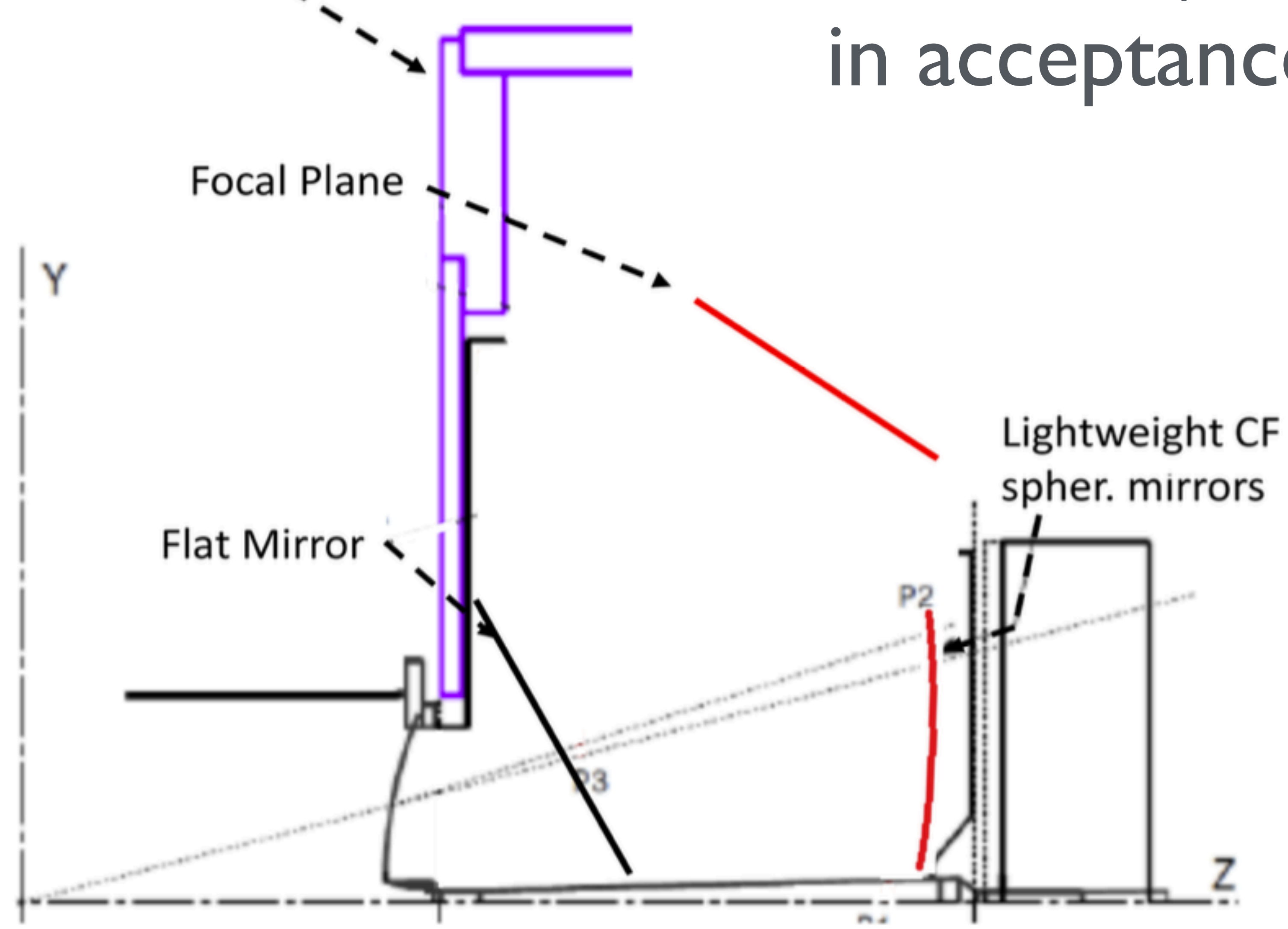
R&D challenge: radiation hardness, both for the fibres and the SiPM readout (should survive 300/fb)

Occupancy in outer region will be similar to that of the inner region in Upgrade I. Reduction in fibre diameter to 200µm will help reduce occupancy.

HV-CMOS is candidate technology for Silicon inner tracker.

Particle identification

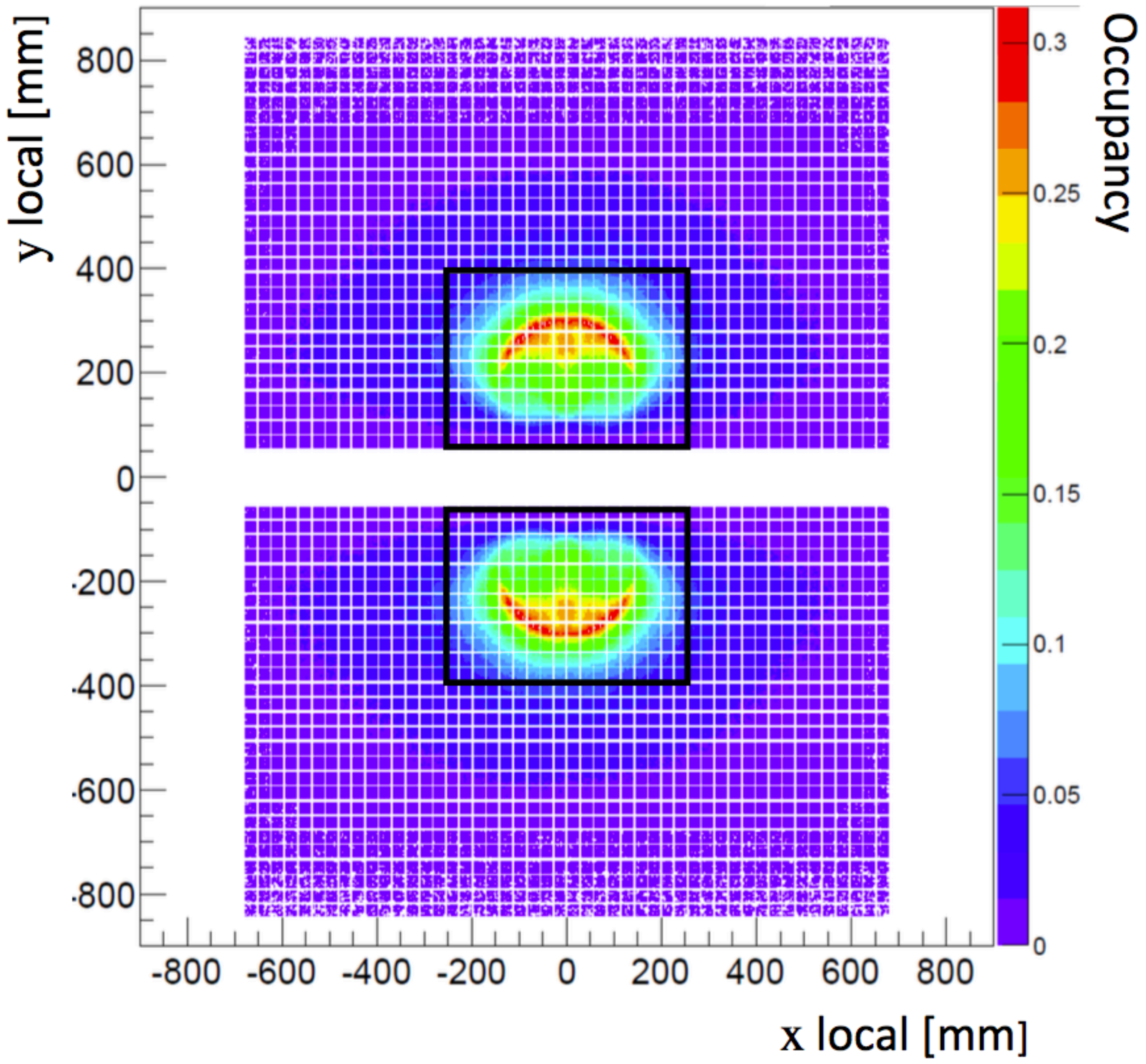
Flat mirror (1%X_0) in acceptance



RICH-I peak occupancies will exceed 100% in Upgrade II

→ Increase pixel **granularity** 7 → 1 mm^2 using SiPMs

→ Increase the focal length of the detector



Timing could limit effective occupancy by associating hits with specific PV

Use of SiPMs/MCPs would allow removal of magnetic shielding.
SiPMs give lower chromatic dispersion → better resolution

LS3 consolidation gives possibility to install new detectors in the inner region of RICH photodetector plane → improved PID in Run 4

TORCH

[ERC-2011-ADG]

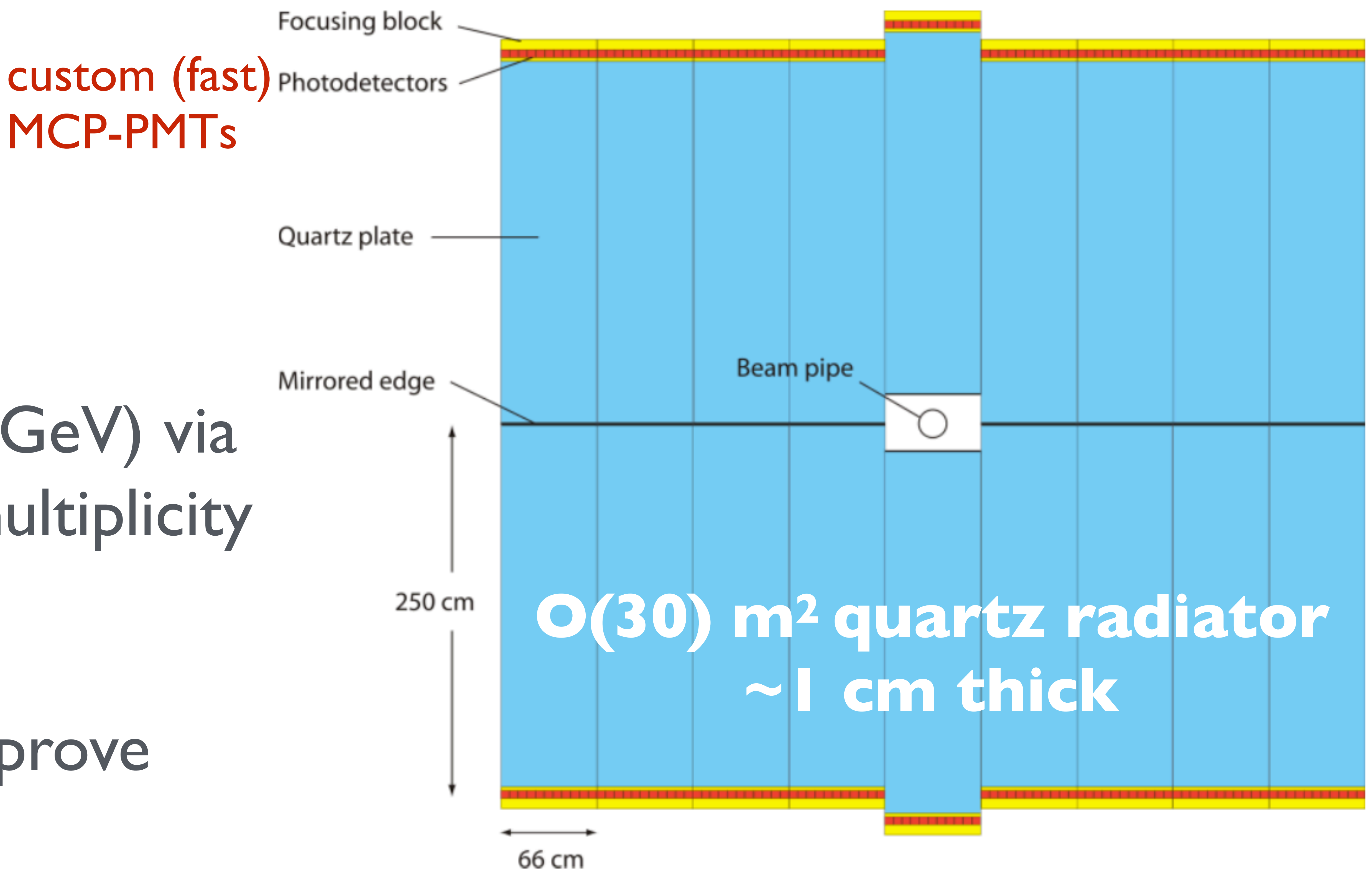
Time Of Internally Reflected CHereknov Light.

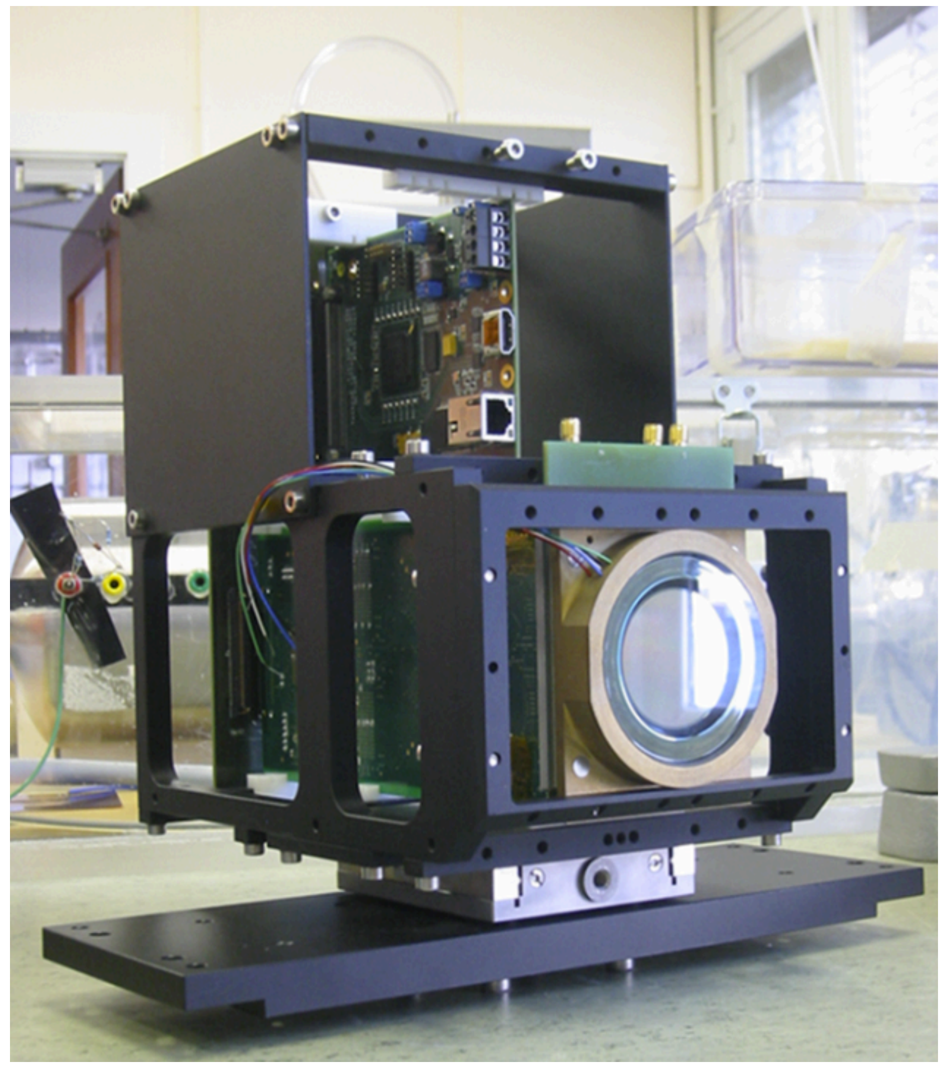
PID for low-momentum particles (<10 GeV) via ToF → improvements for flavour-tagging, high-multiplicity final states where we have gap in capability

Compare TORCH and VELO time-stamps to improve **track matching**

Combined with a converter can **time high energy photons for vertex association**

Demonstrator has resolution of 85 ps/photon. Goal is 70 ps/photon → **15 ps/track** with 30 photons/track.





Upgrade II physics programme

Classical flavour-physics
CKM, CP violation, rare decays…

Searches for new phenomena
LFV, dark photons, exotic QCD…

Most beauty/charm measurements are **statistically limited** and many observables have SM predictions with **small theory uncertainties**

CKM angle γ

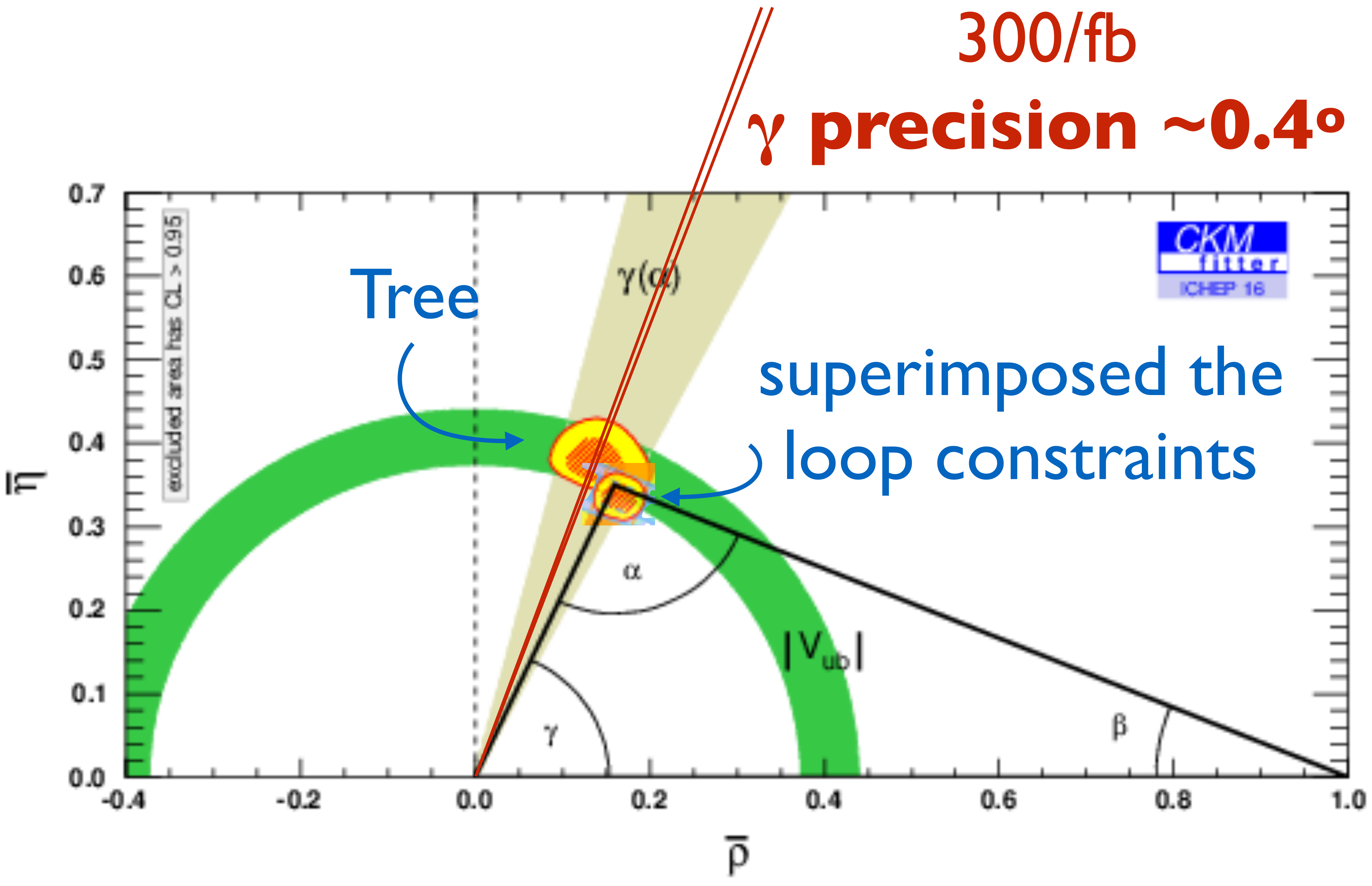
Only CP-violating parameter that can be measured from tree-level decays. $|\delta\gamma| \leq O(10^{-7})$ assuming no NP in trees [Brod, Zupan JHEP 1401 (2014) 051]

1° from individual modes will give sensitivity to NP at tree-level [Brod et al., PRD 92, 033002 (2015)]

Improvements in ECAL and low-momentum tracking will bring new modes into the game. e.g., multi body decays ($D \to 4h$) and decays with neutrals ($D \to hhh\pi^0$)

300/fb

γ precision ~0.4°



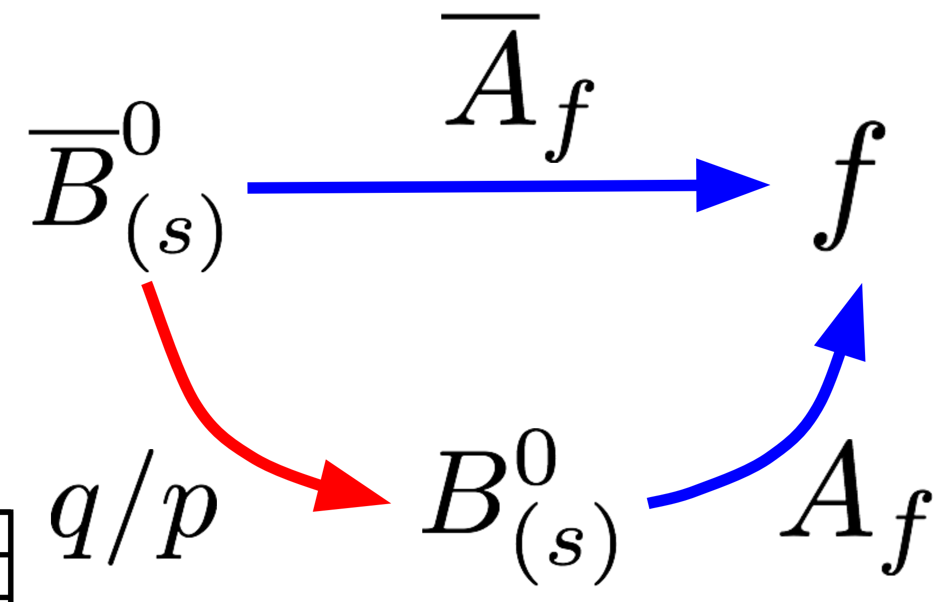
With 300/fb could use $B_c^+ \to D_{(s)}^+ D$ decays, which have larger interference ⇒ more sensitive to γ

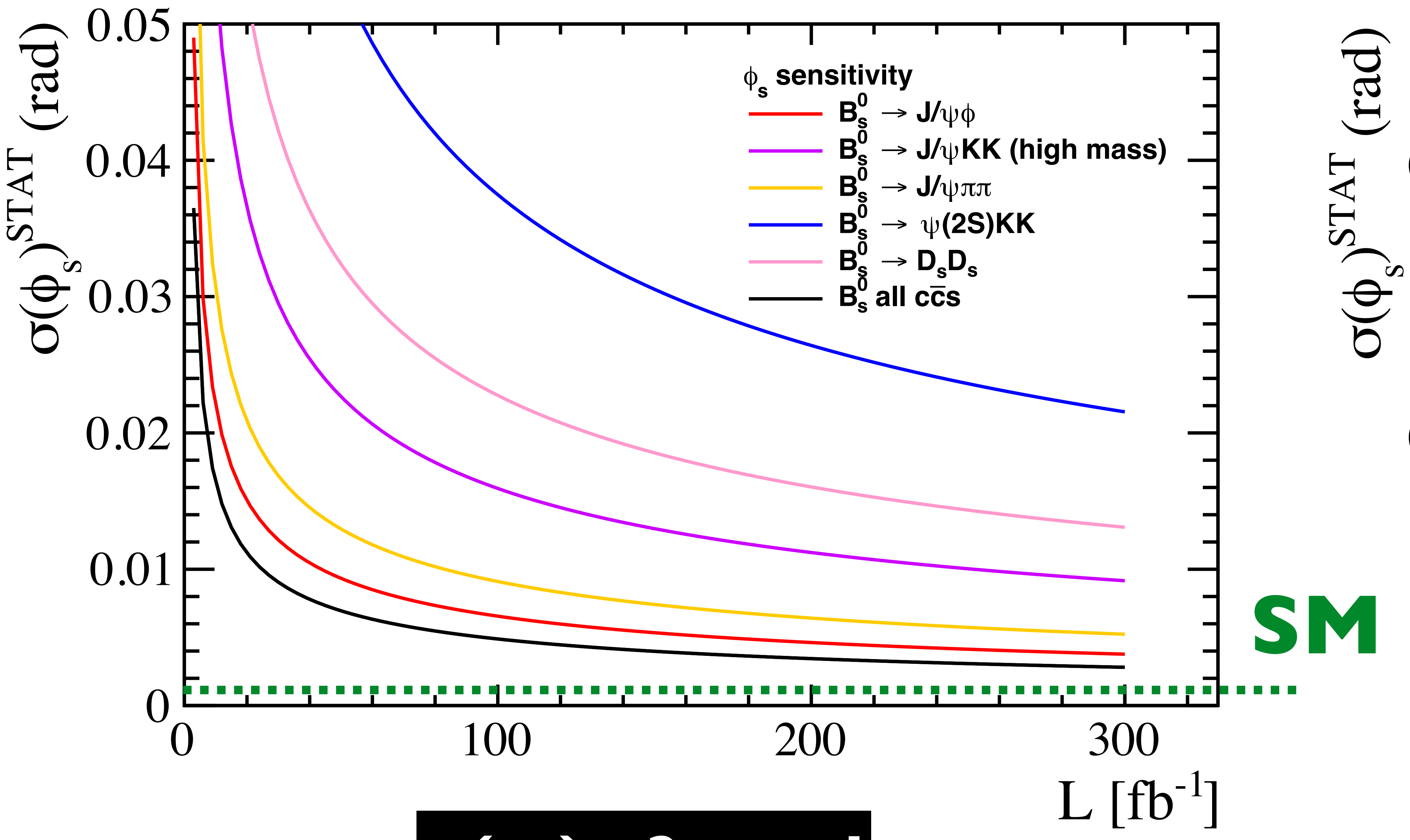
Input from BES-III for D meson strong phases

Belle-II expects ~1.5° in 2025

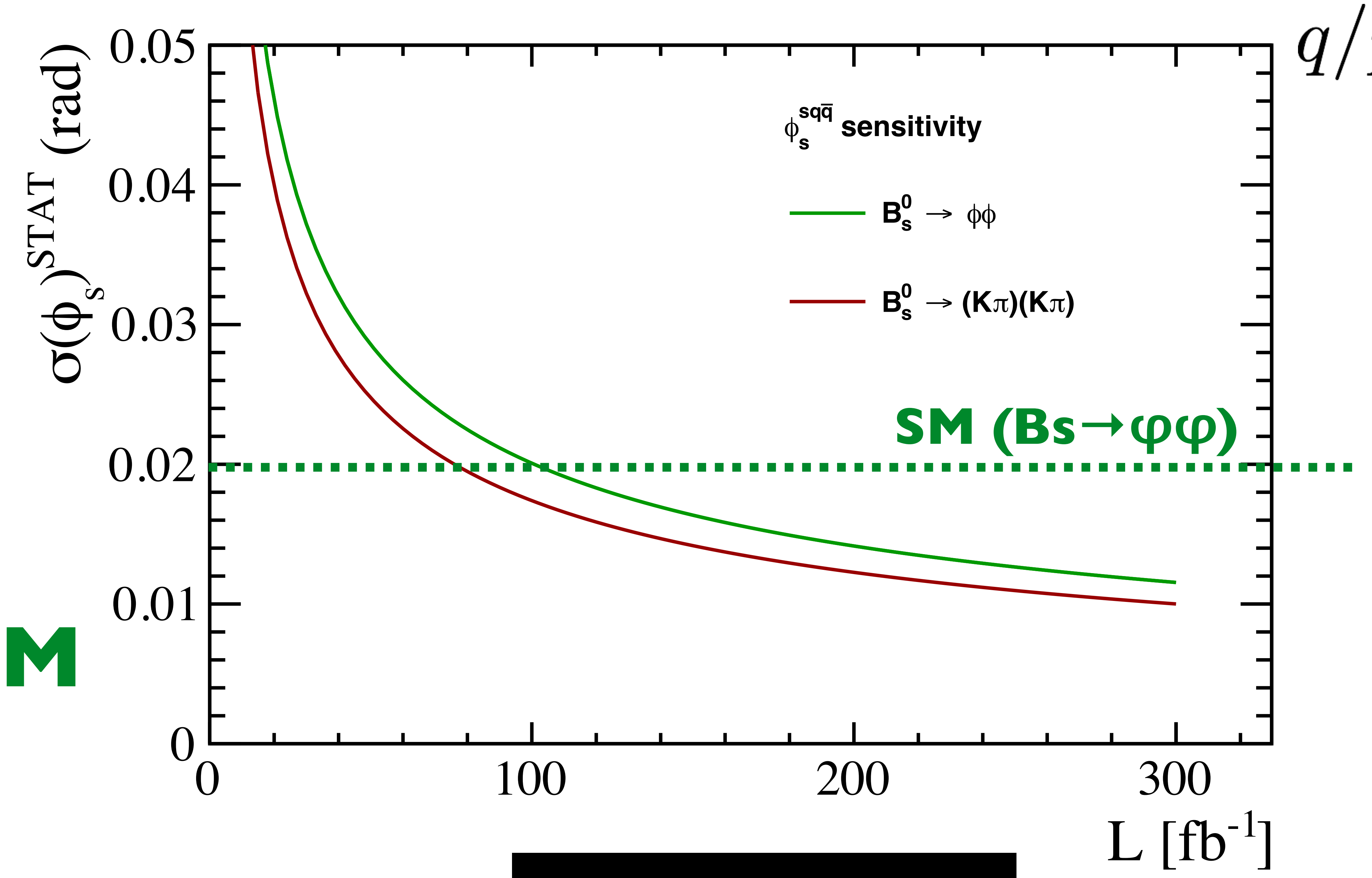
[F Dordei, this workshop]

CP violation in B mixing/decay





σ(φs) ~3 mrad



σ(φs) ~10 mrad

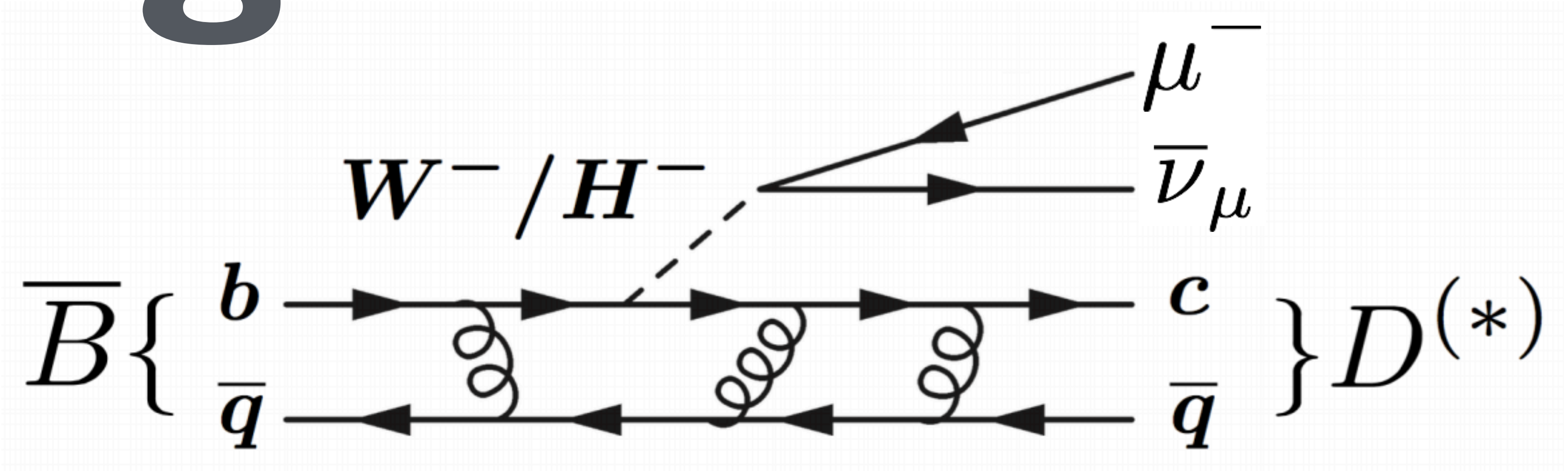
Other loop-dominated modes become interesting B → $K_S$hh, hhπ^0… due to the more efficient hadron trigger and improved ECAL in Upgrade era.

Penguin pollution via SU(3) symmetries: must study Cabbibo-suppressed decays like B_s → J/ψK*, B_s → J/ψK_S, B → J/ψπ^0, B → J/ψω

[K De Bruyn, this workshop]

CP violation in B mixing

$$A_{sl} = \frac{\Gamma(\overline{B}^0 \to B^0 \to f) - \Gamma(B^0 \to \overline{B}^0 \to \overline{f})}{\Gamma(\overline{B}^0 \to B^0 \to f) + \Gamma(B^0 \to \overline{B}^0 \to \overline{f})} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_M$$



Must control detection asymmetries at $O(10^{-4})$

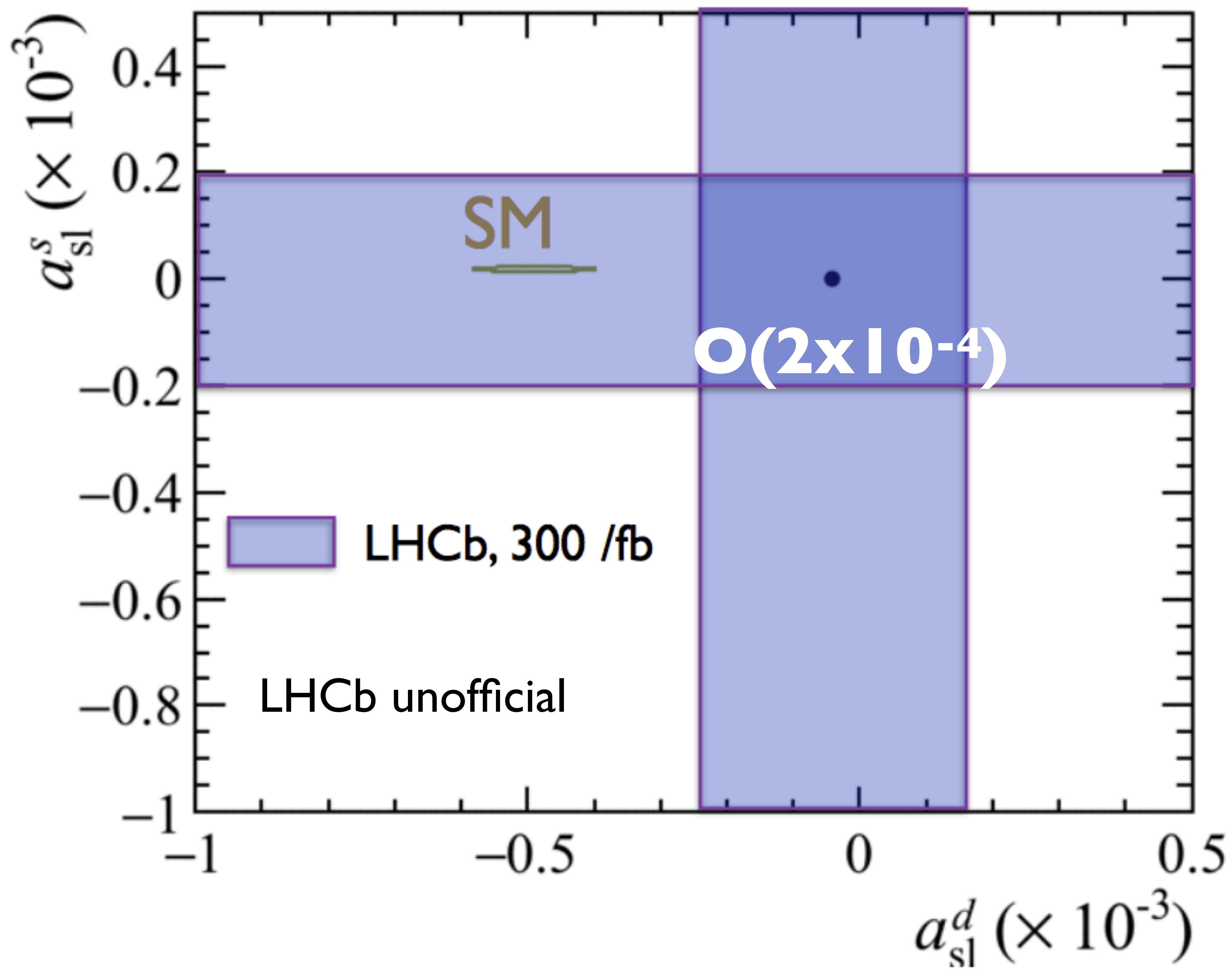
In Run 1 we used large $D^+ \to K_S\pi^0$ control samples to understand detector-induced asymmetries. Can we sustain this with equal MagUp/Down statistics?

→ Move to MC-based efficiencies and relative data/MC corrections?

SV resolution is essential to maintain/improve performance for the corrected-mass observable

→ Removal of RF foil?

Tiny in the SM - [Artuso et al., arXiv:1511.09466]



Charm physics

Upgrade II:

→ 10's MHz of charm **meson** + **baryon** decays ➾ 10^{-4} precision, allowing us to measure SM CP violation

→ Precision measurement of small mixing params gives strong constraints on NP scale

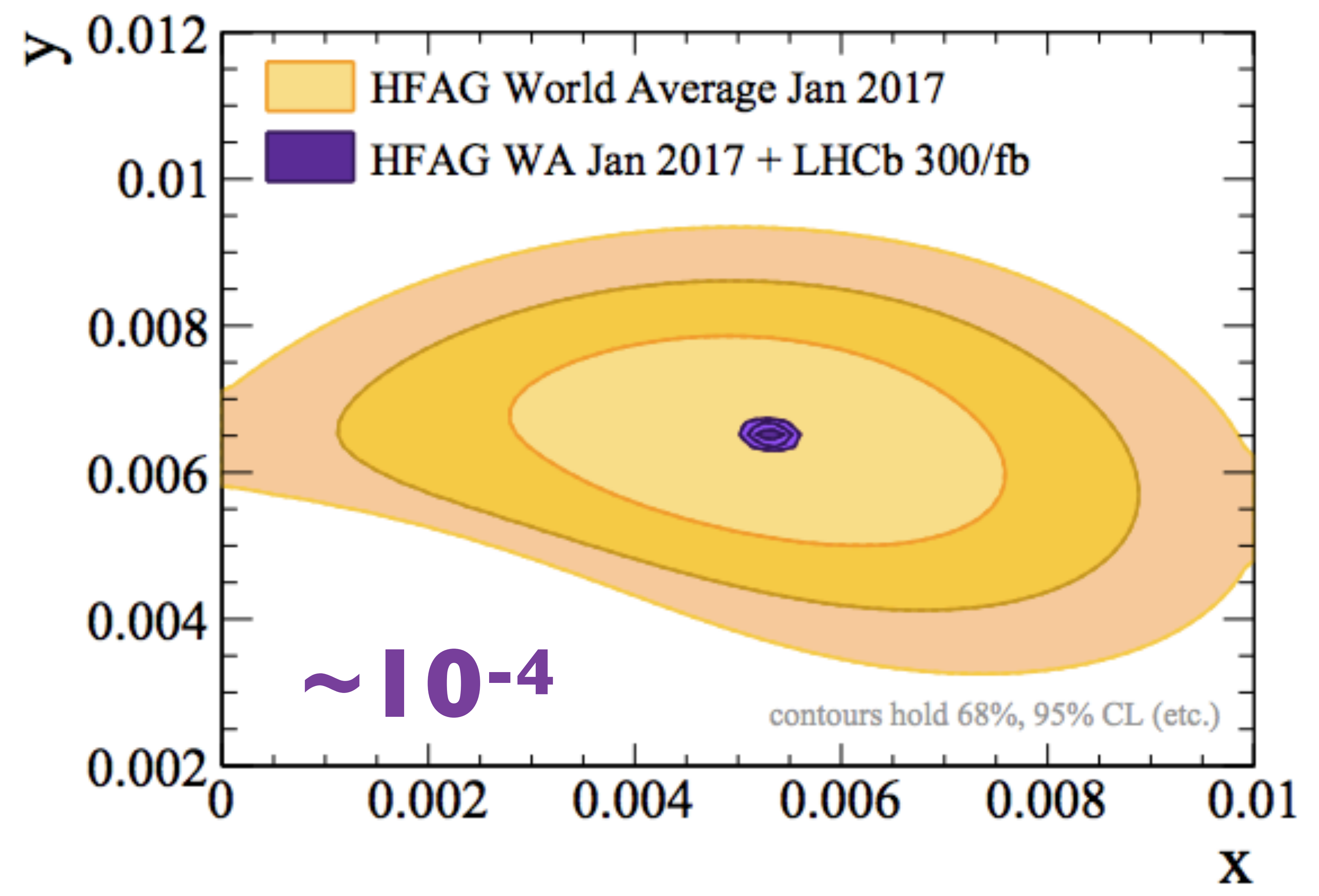
→ Success relies on use of real-time analysis

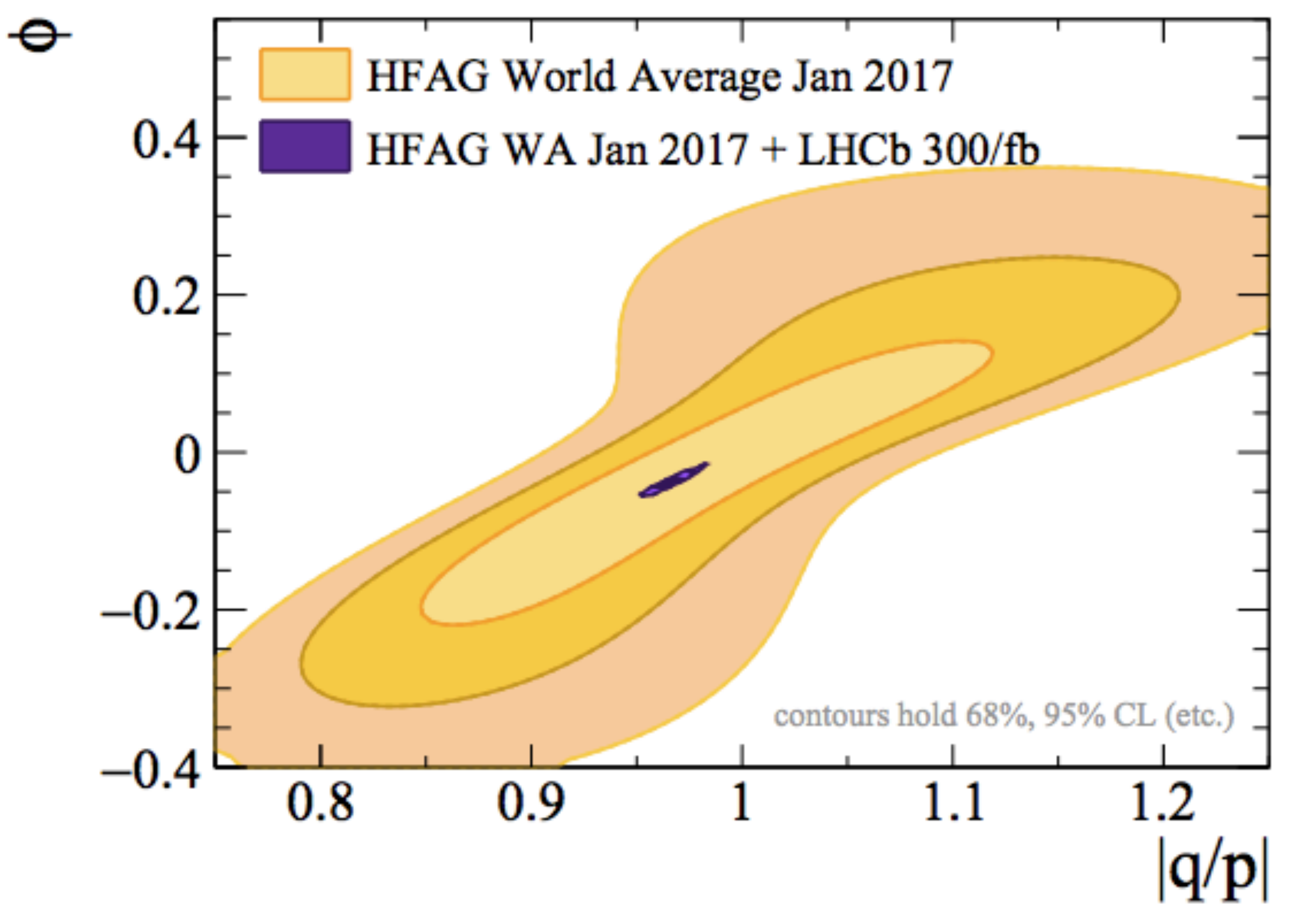
No other facility can do this

Precision measurement of CKM γ requires understanding D mixing/CPV in $B \rightarrow DK$ decays

Rare charm decays ($D \rightarrow \mu^+\mu^-$, angular obvs in $D \rightarrow h^+h^-\mu^+\mu^-$)

[PRL 119 (2017) 181805]





[J. Brodzicka, this workshop]

Rare decays and anomalies

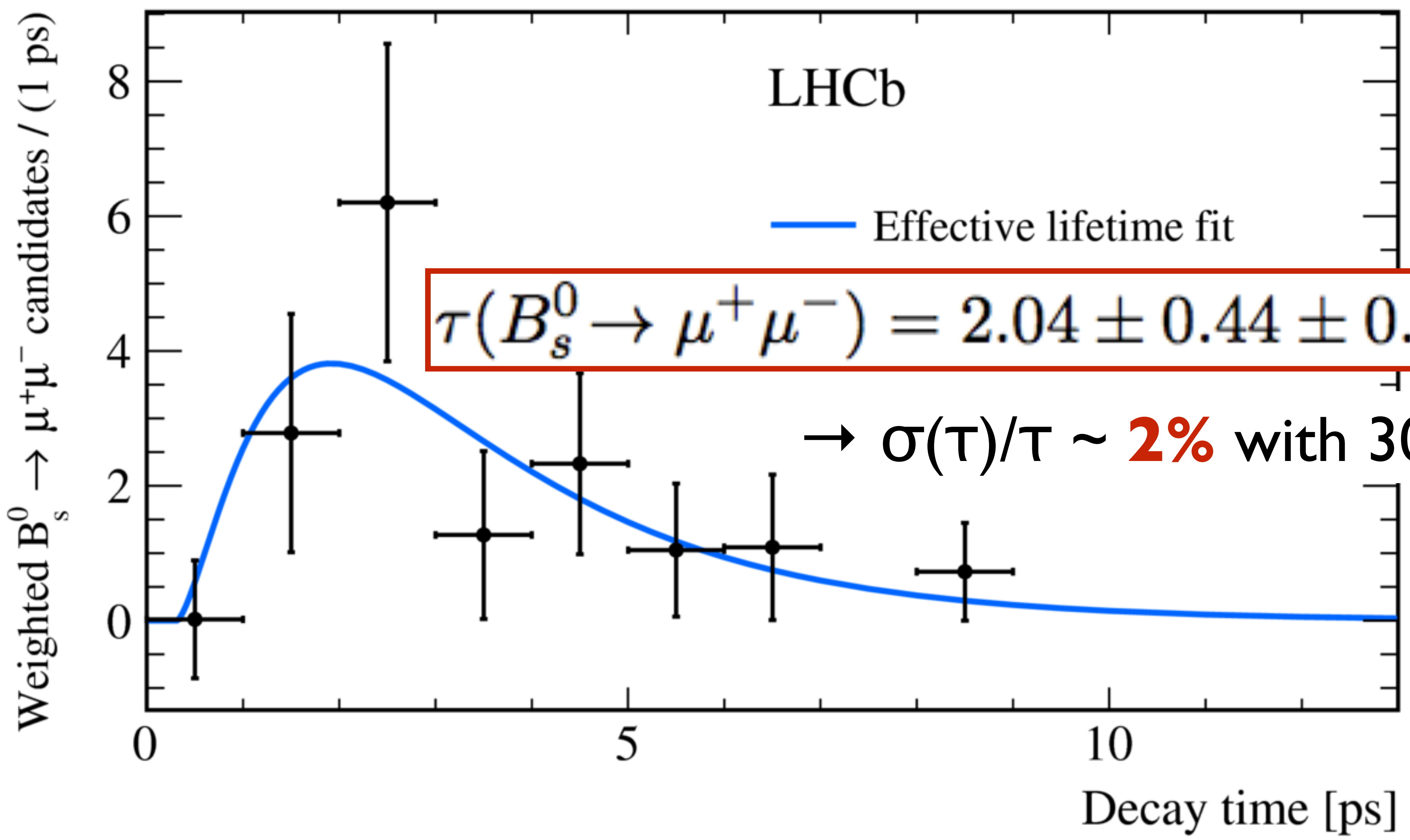
"The anomalies…will be either confirmed or ruled-out…
independently" by LHCb and Belle II by ~2025 [Albrecht et al, 1709.10308]

Not-so rare decays

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\text{right-handed part}}]$$

Decay	Run I	300 fb^{-1}
$B_s^0 \to \mu^+\mu^-$	15	2 700
$B_s^0 \to \mu^+\mu^-$ (tagged*)	-	80
$B^\mp \to K^\mp \mu^+\mu^-$	4 700	858 000
$B^0 \to K^{*0} \mu^+\mu^-$	2 400	438 000
$B^+ \to \pi^+ \mu^+\mu^-$	90	16 400
$B^0 \to \rho^0 \mu^+\mu^-$	40	7 300
$B^\mp \to K^\mp e^+e^-$ ($q^2 \in [1,6]$)	250	91 300
$B^0 \to K^{*0} e^+e^-$ ($q^2 \in [1,6]$)	110	40 200
$B_s^0 \to \phi\gamma$	4 000	743 000
$B_s^0 \to \phi\gamma$ (tagged*)	-	22 300

* Assuming 3% flavour-tagging power
** Assuming factor two improvement in electron modes from L0 removal



→ $\sigma(\tau)/\tau$ ~ **2%** with 300/fb

Qualitatively new observables

- flavour-tagged analyses — $R_\pi = R_K$?
- b → dγ , b → d l^+l^- transitions for CP, angular analyses, tests of LFU
- Baryon decays unique to LHCb: $\Lambda_b \to \Lambda\gamma$, $\Omega_b \to \Omega\gamma$, $\Xi_b \to \Xi\gamma$

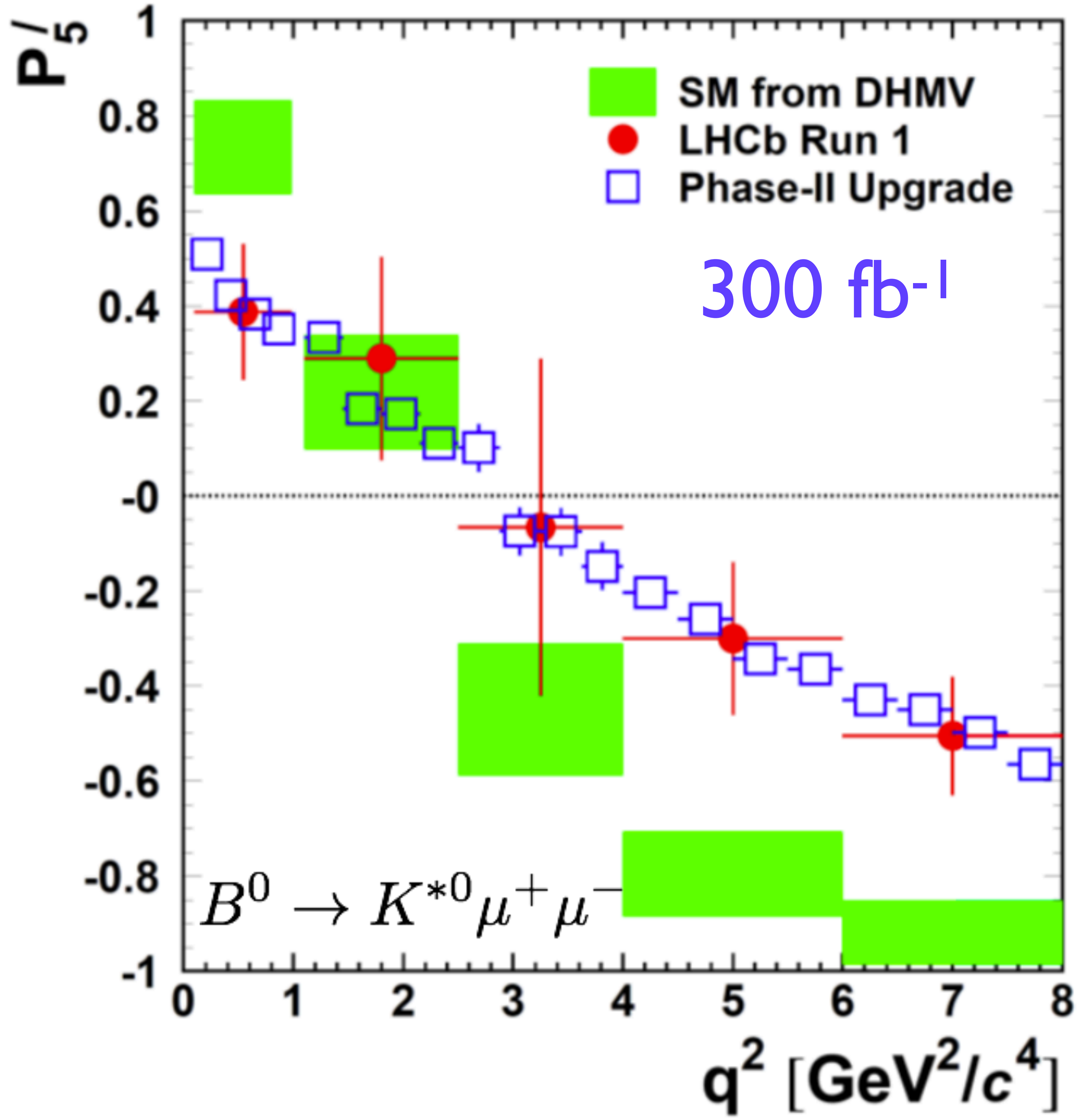
Theoretically clean, sensitive to scalar operators.

~12% uncertainty on $BR(B_d)/BR(B_s)$, cf. 5-10% theory uncertainty → constrains flavour structures of BSM

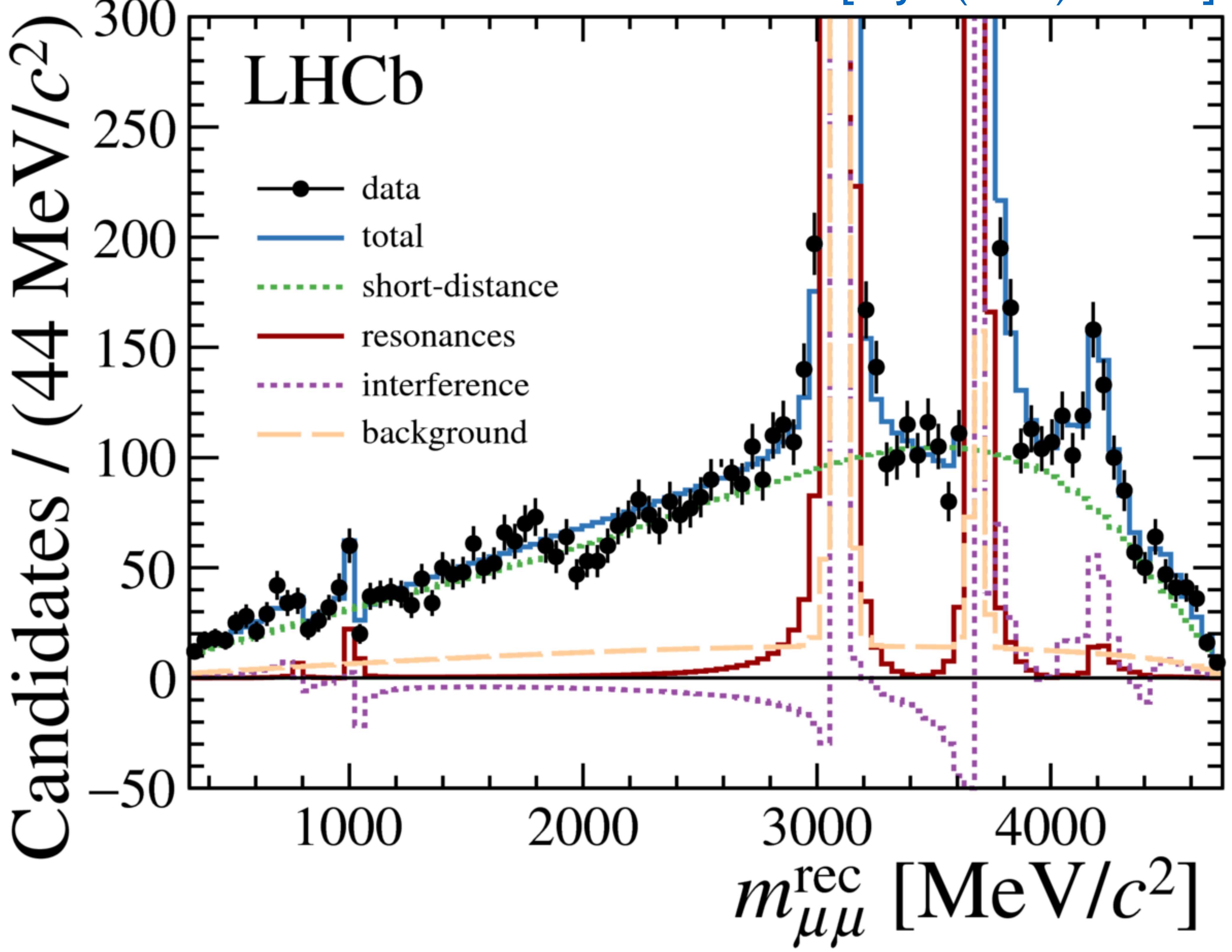
[P. Alvarez Cartelle, HL-LHC workshop]
[S. Bifani, Implications workshop]

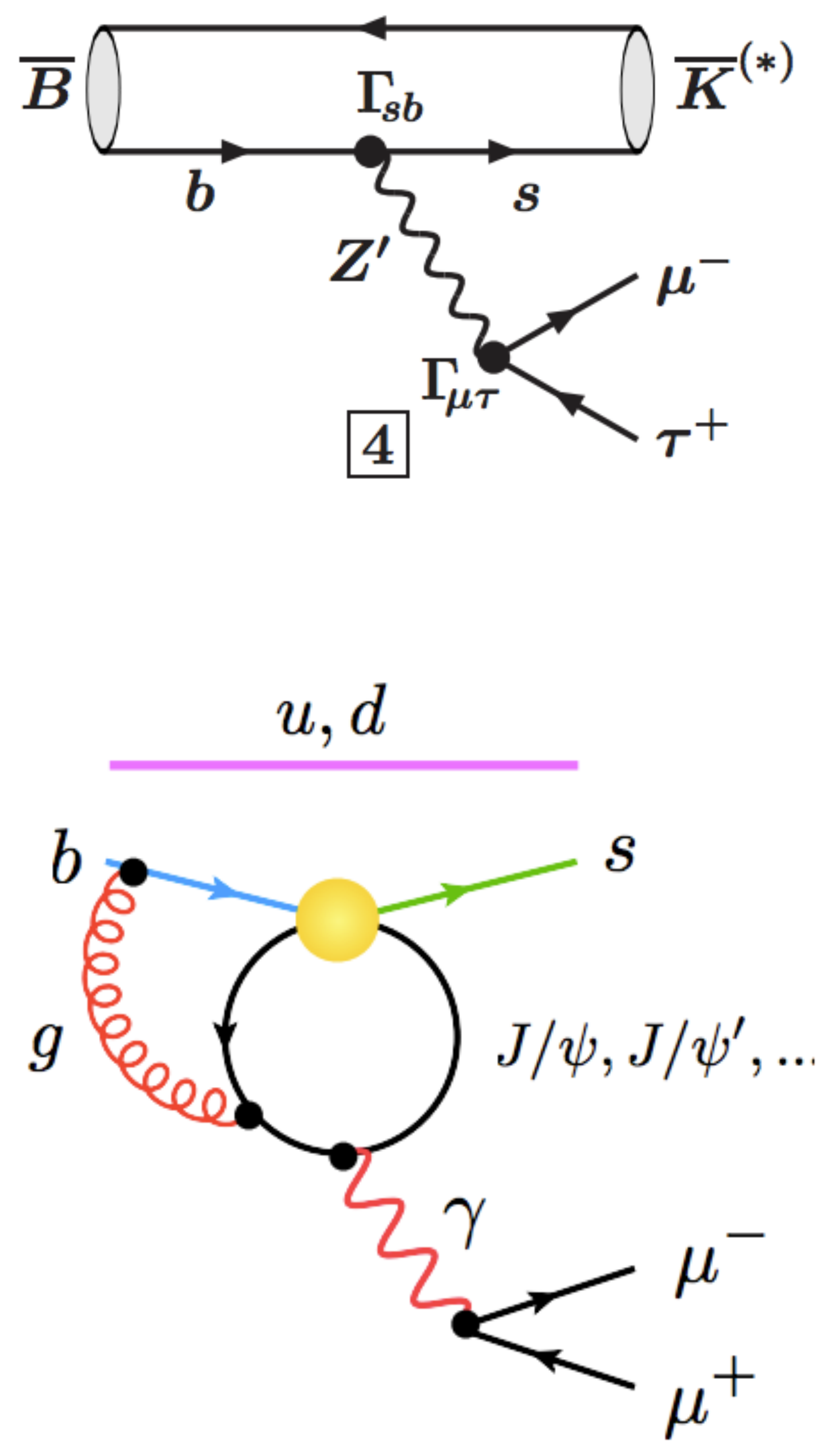
[De Bruyn et al., PRL 109 (2012) 041801]
[D'Ambrosio et al., NPB 645 (2002) 155]

Understanding anomalies



[EPJC (2017) 77:161]





Systematic uncertainties will be < 0.01 (and many will scale with sqrt(N))

Use data to constrain size of charmonium contributions

[P. Alvarez Cartelle, HL-LHC workshop]
[S. Bifani, Implications workshop]

[Lyon and Zwicky, arXiv:1406.0566]
…
[Blake et al., arXiv:1709.03921]

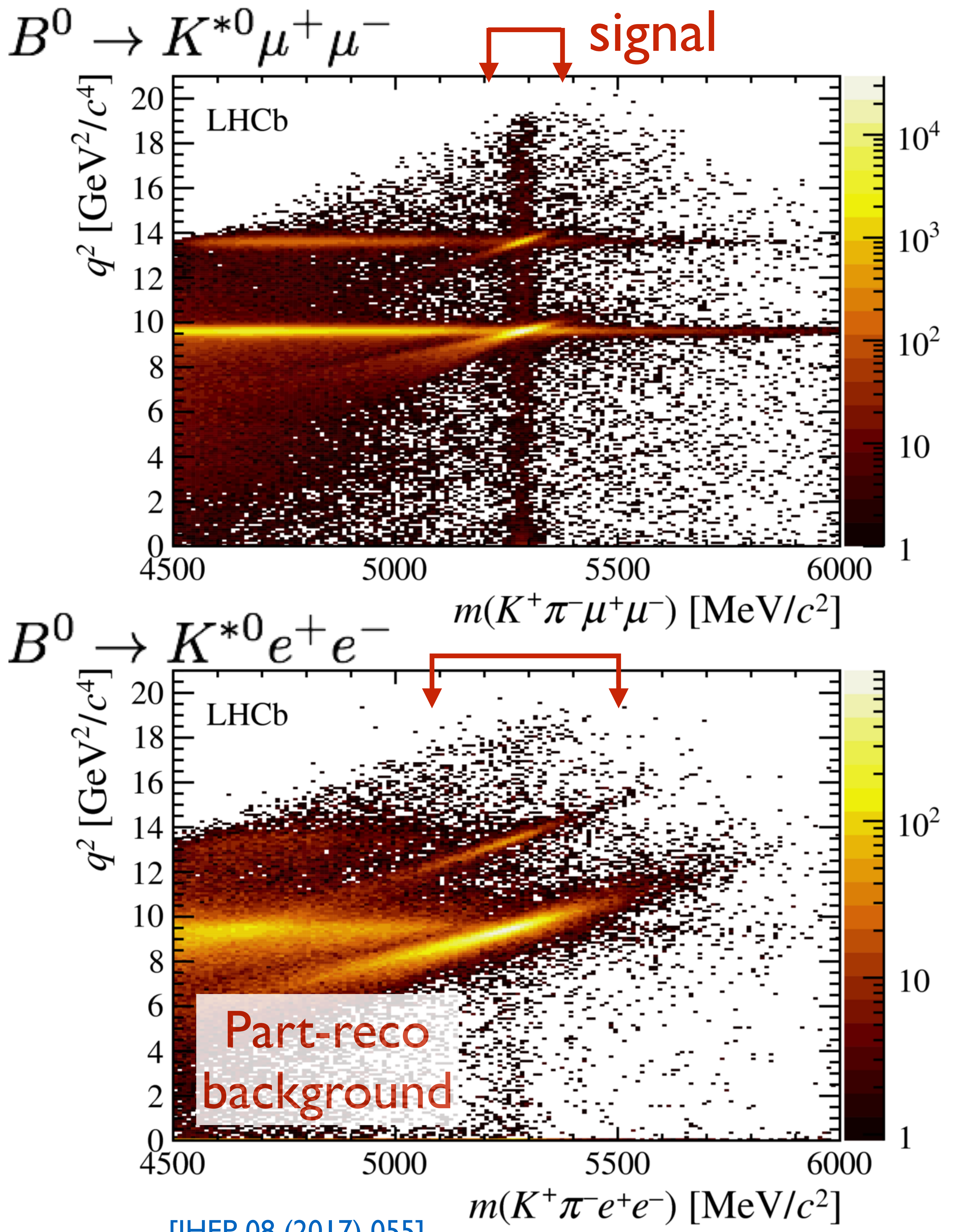
Muons, electrons, taus

LFU will play a large role in Upgrade II physics case

Challenges: electrons emit a lot of Bremsstrahlung as they traverse LHCb → degraded momentum/mass resolution, migration between q^2 regions, more background

Improvements: Reduce the amount of material in LHCb (e.g., RF-foil), improve ECAL granularity, better Brem recovery algorithms

Expect 1-2% precision on R(K) etc…, cf. 1% theory



[P. Alvarez Cartelle, HL-LHC workshop]

[JHEP 08 (2017) 055]

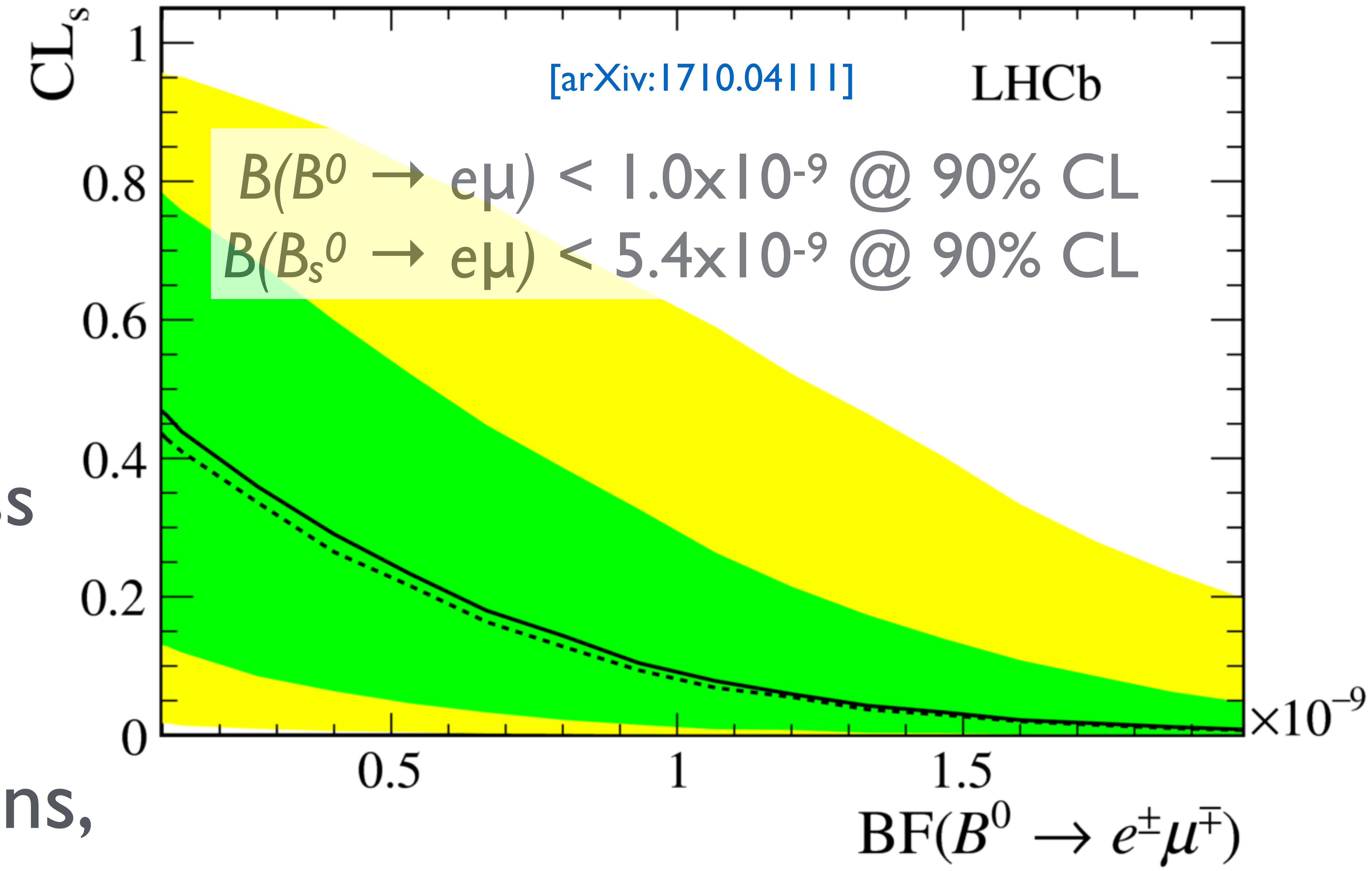
Lepton-flavour violation

Also:
BR($\tau \to \mu\mu\mu$) < 4.6x10^{-8} [LHCb JHEP 02 (2015) 121]
BR($D \to e\mu$) < 1.3x10^{-8} [LHCb PLB 754 (2016) 167]

LFV branching fractions enhanced to 10^{-11} in certain models of leptoquarks, Z'

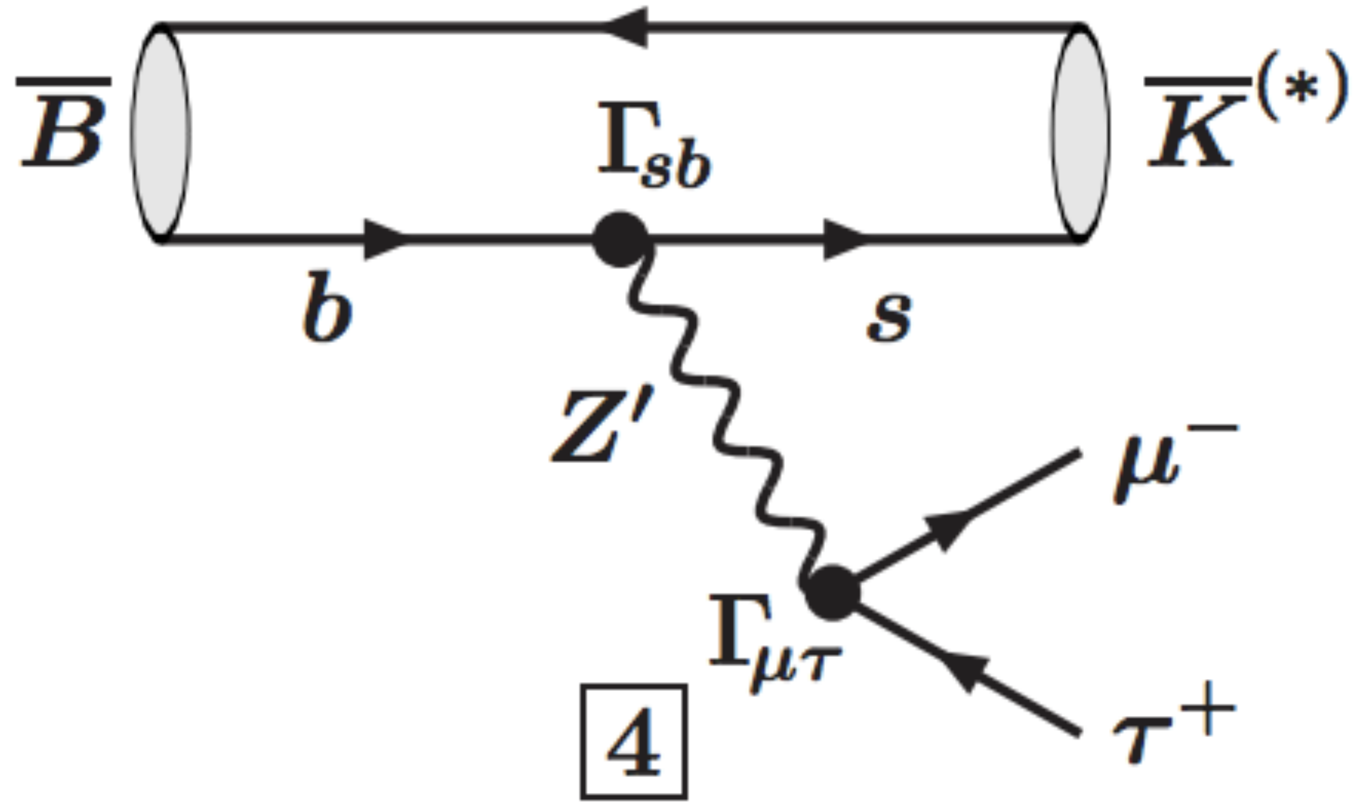
[Medeiros Varzielas, Hiller, JHEP 06 (2015) 072]
[Becirevic et al., PRD 94 (2016) 115021]

Translate BR limits into limits on leptoquark mass



Opportunity to study decays with tau-leptons, which are less constrained by existing data [BaBar PRD 86, 012004 (2012)] and often enhanced in NP models

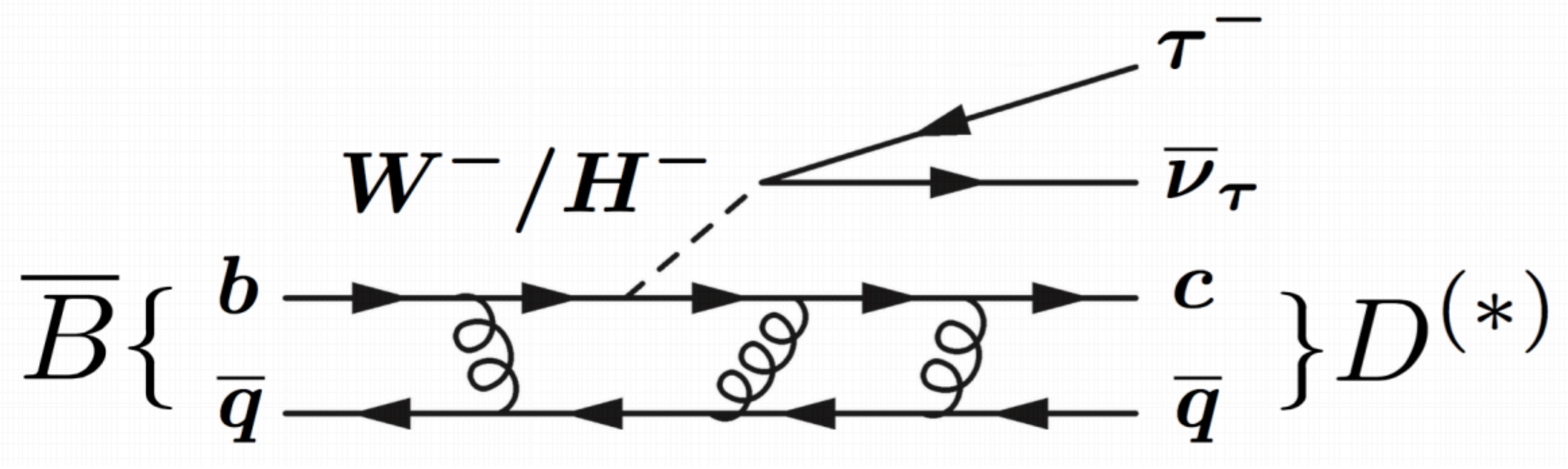
e.g., $B^+ \to K^+\mu^-\tau^+$ predicted to be 10^{-6}

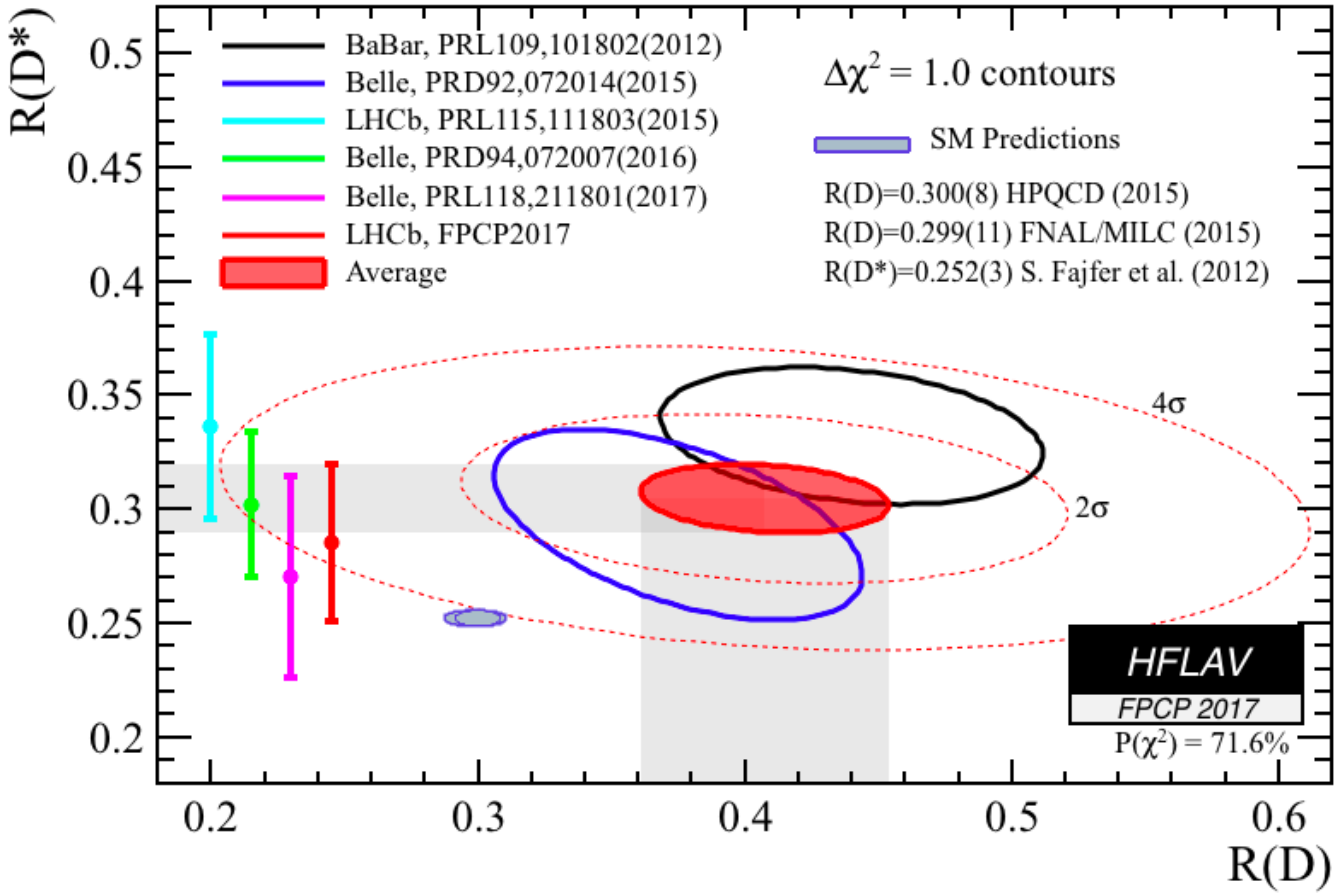


[Glashow et al., Phys. Rev. Lett. 114 (2015) 091801]
[Crivellin et al., Phys. Rev. D 92 (2015) 054013]
[Guadagnoli and Lane PLB 751 (2015) 54]

R(Xc)

$$R(X_c) = \frac{\mathcal{B}(X_b \to X_c \tau \nu)}{\mathcal{B}(X_b \to X_c \ell \nu)}$$





HFLAV average ~4σ from precise SM prediction

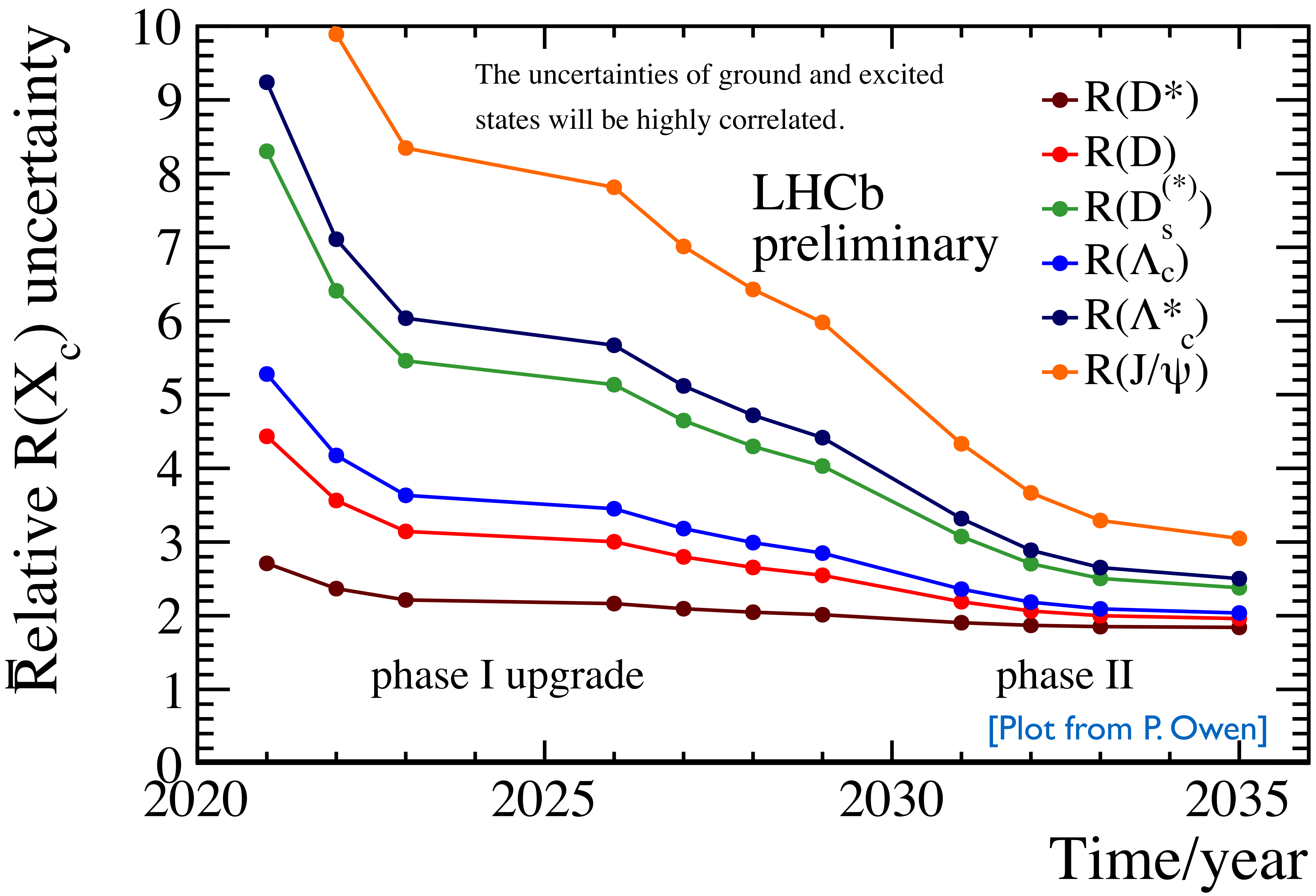
$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

Systematically limited due to size of simulation samples for bkg templates)

New! 3-prong τ decays [arXiv:1708.08856] [arXiv:1711.02505]

New! R(J/ψ) is 2σ from SM [LHCb-PAPER-2017-035]

R(X$_c$) projections



Opportunities:

Upgraded ECAL can reduce feed-down from e.g. neutral $D^{*0} \to D^0\pi^0$ decays.

Better vertex resolution → better rejection of additional charged tracks

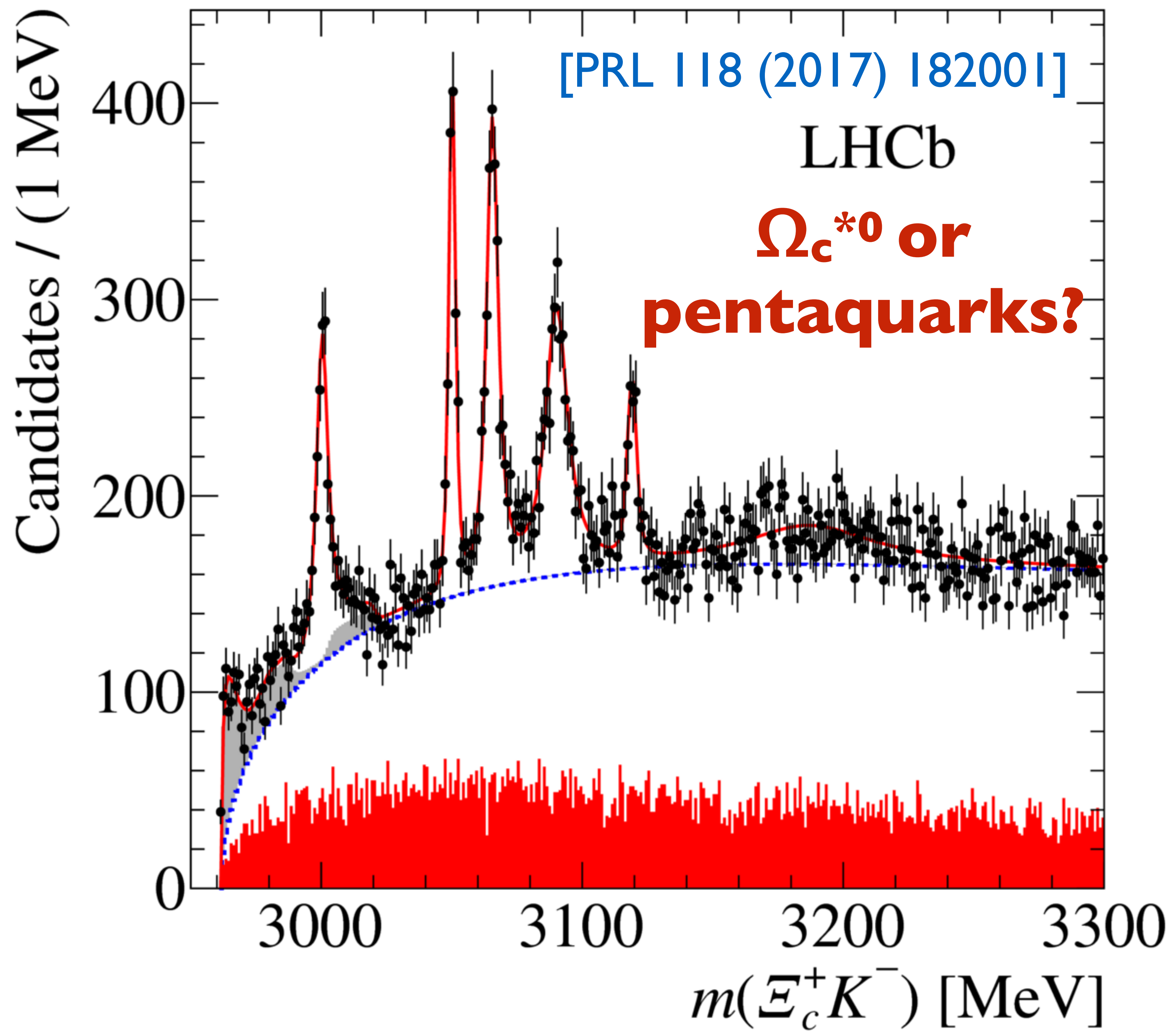
Magnet tracking stations will improve acceptance (→ rejection) of slow pions.

With 300/fb will have millions of $B \to D^*\tau\upsilon$ events → **measure D*/τ polarisation, angular observables**

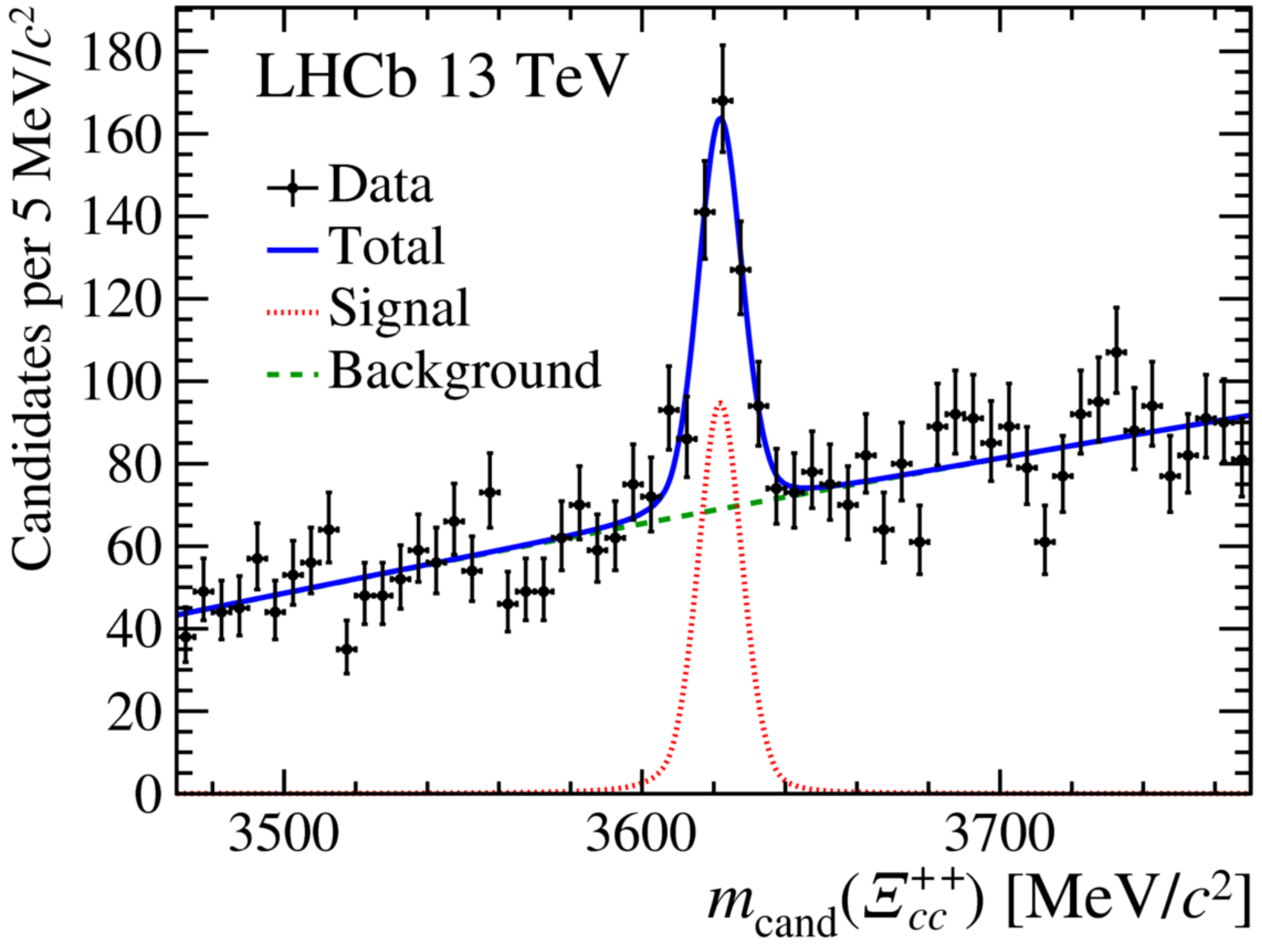
~2% systematic floor from irreducible uncertainties on efficiencies and background shapes (strong assumptions)

Take home message: huge improvement expected for B_s, B_c, Λ_b modes that are inaccessible to Belle-II

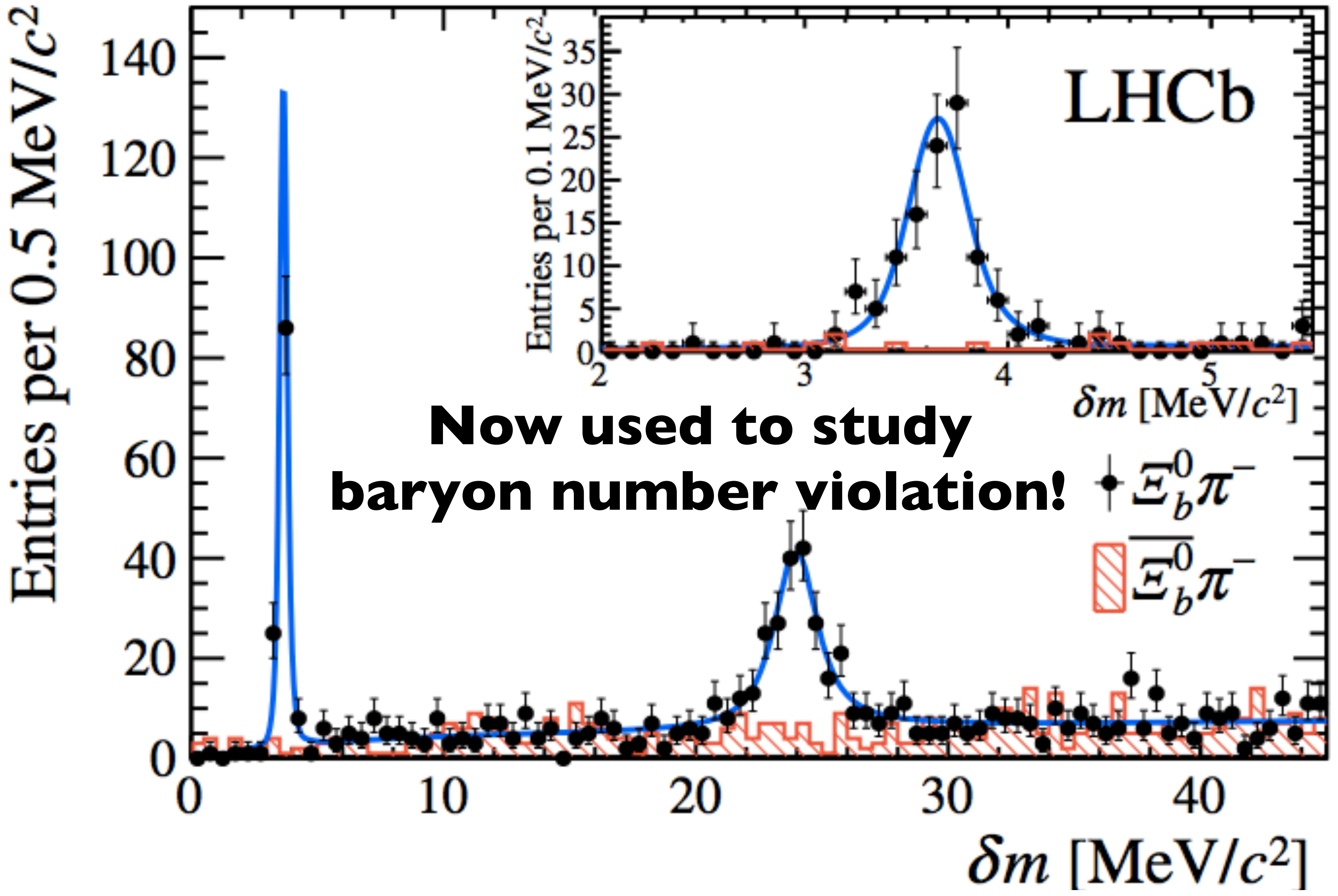
Spectroscopy

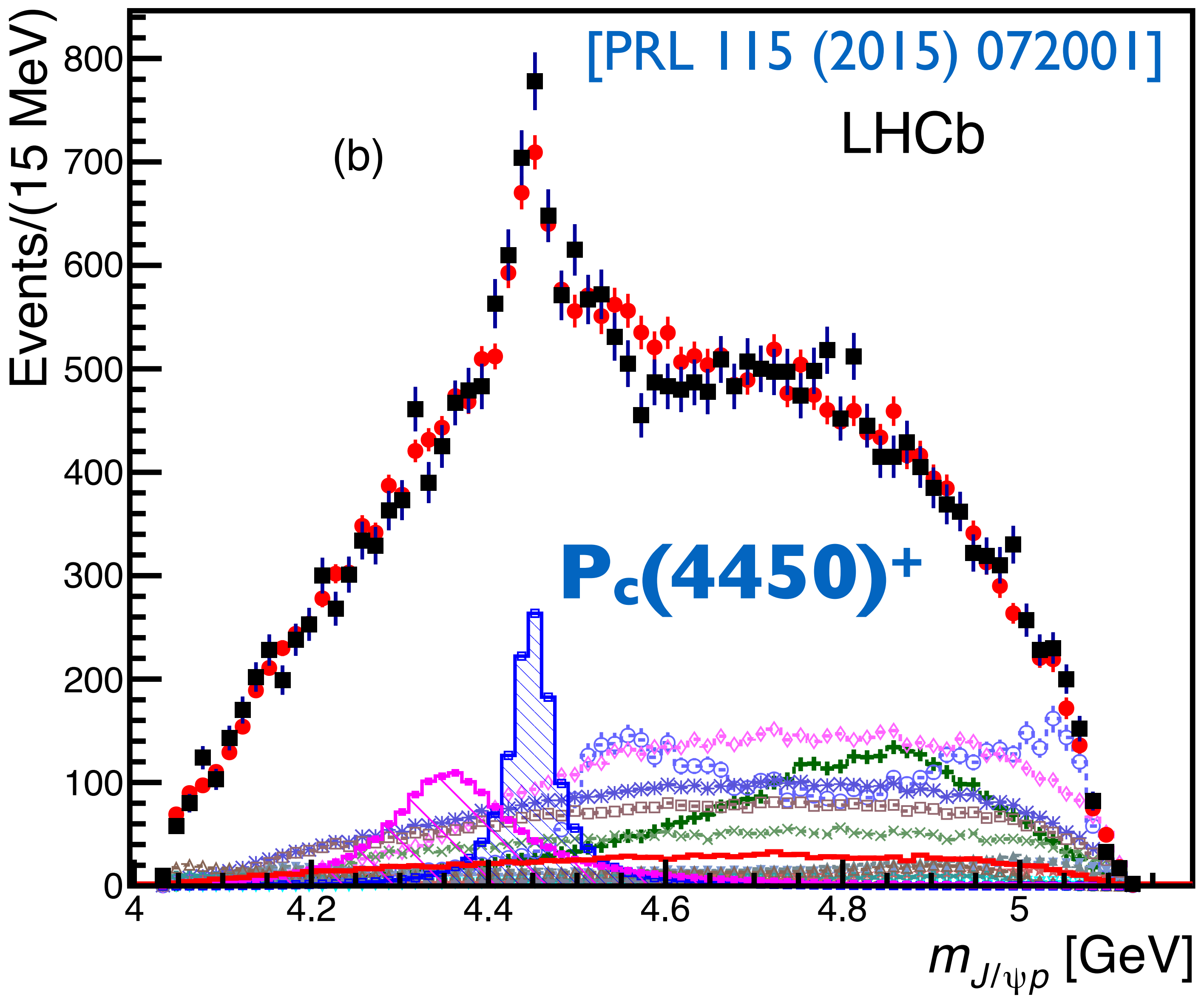


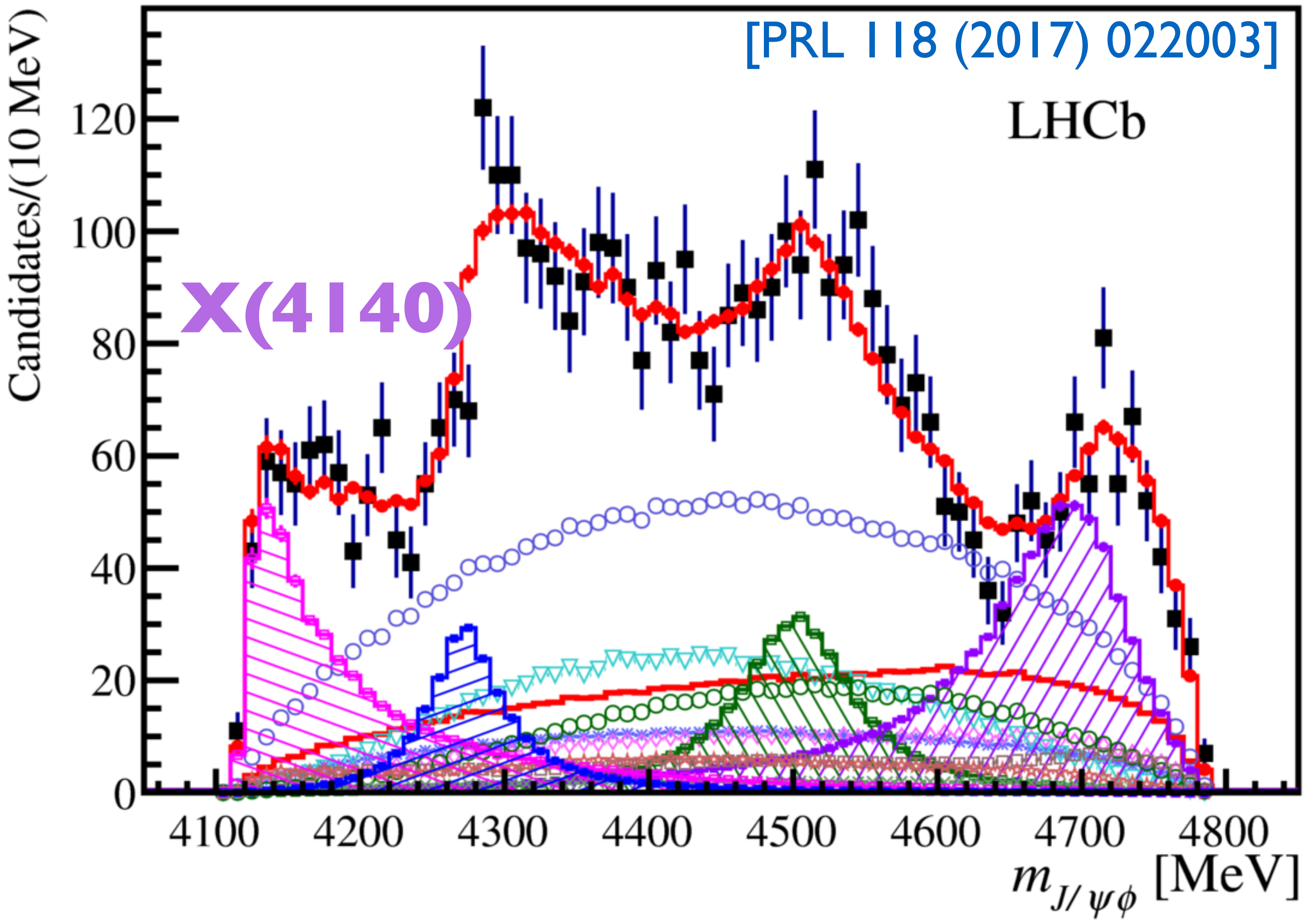
[PRL 119 (2017) 112001]



[PRL 119 (2017) 181807]



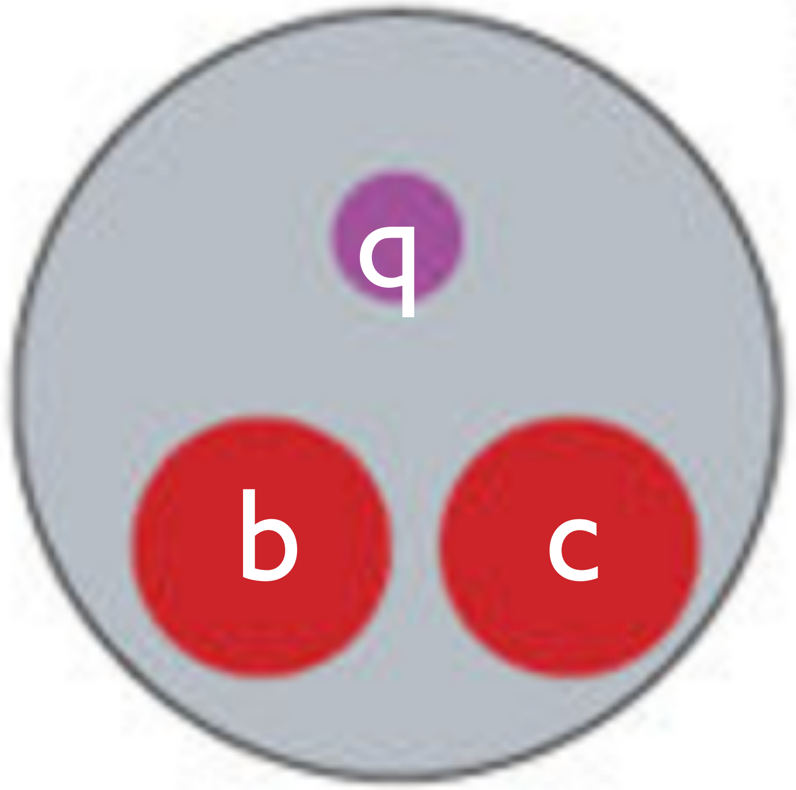




ECAL and low-momentum tracking to enhance our capabilities with high multiplicity decays and with neutrals e.g., $\Lambda_b \rightarrow \chi_{cJ} p K$

[LHCb, PRL 119 (2017) 062001]

Doubly-heavy hadrons



Upgrade II: measure lifetime + mass of doubly-heavy baryons
e.g., O(10^3) Ξ_{bc} baryons for particular modes: $\Xi_{bc} \to J/\psi \Lambda_c^+ K^-$

Upgrade II: search for $B_c^+ \to D_s^+ D^0 D^0$, then look for doubly-charmed tetraquarks $T_{cc}^+ \to D_s^+ D^0$. May have O(100) events in 300/fb [M. Pappagallo, HL-LHC workshop]

Could we find a tetra/pentaquark with **4/5 different** quark flavours?

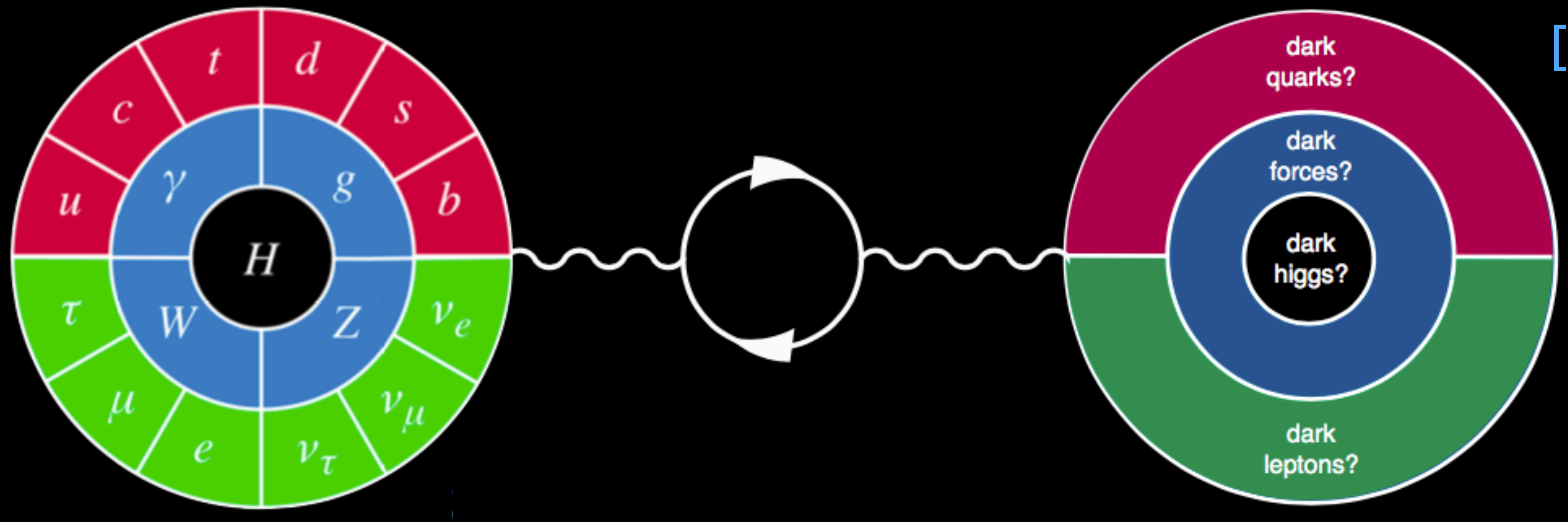
Challenges: short lifetimes (for weak decays) and high multiplicity final states

Sensitivity enhanced via improved IP resolution (removal of RF-foil), timing to reduce combinatorial background and low momentum tracking (magnet stations)

[M. Charles, this workshop]
[D. Savrina, this workshop]

Dark sectors

[M Borsato, HL-LHC workshop]
[C.Vazquez Sierra, this workshop]

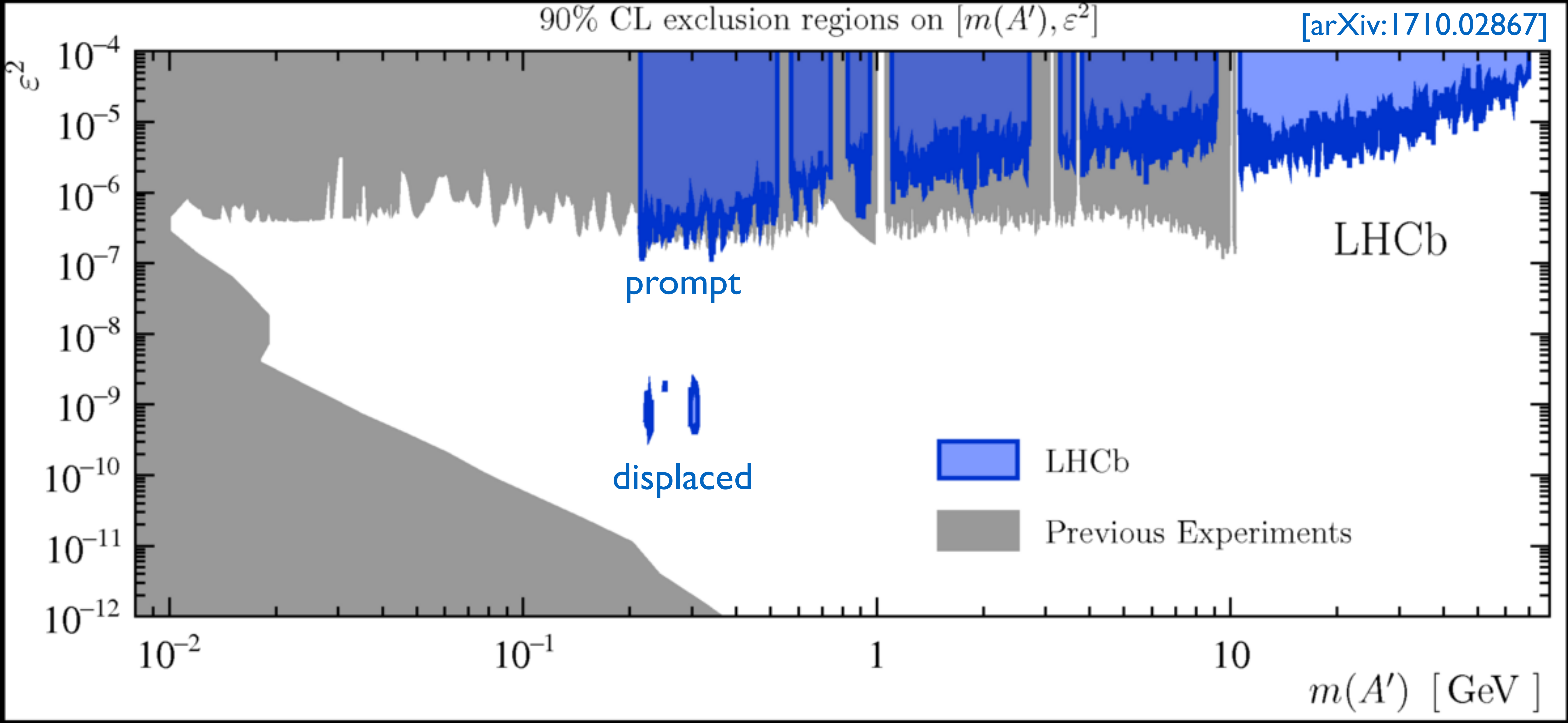


Dark photon models can explain several anomalies, e.g., muon g-2; positron/electron fraction in cosmic rays…

LHCb requirements:

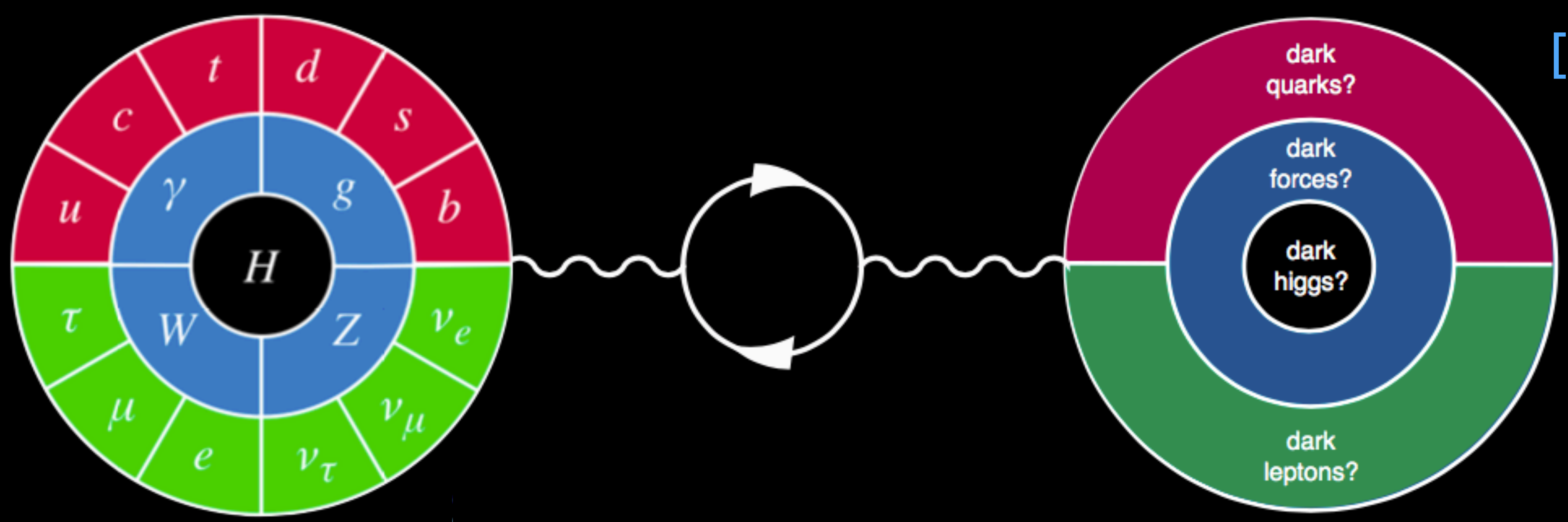
1. excellent SV resolution
2. particle-ID
3. real-time data analysis for low p_T electrons in $D^* \to D^0 \gamma(e^+e^-)$

Magnet chambers would help with soft A’ decays to e^+e^- (efficiency and/or resolution)



Dark sectors

[M Borsato, HL-LHC workshop]
[C.Vazquez Sierra, this workshop]



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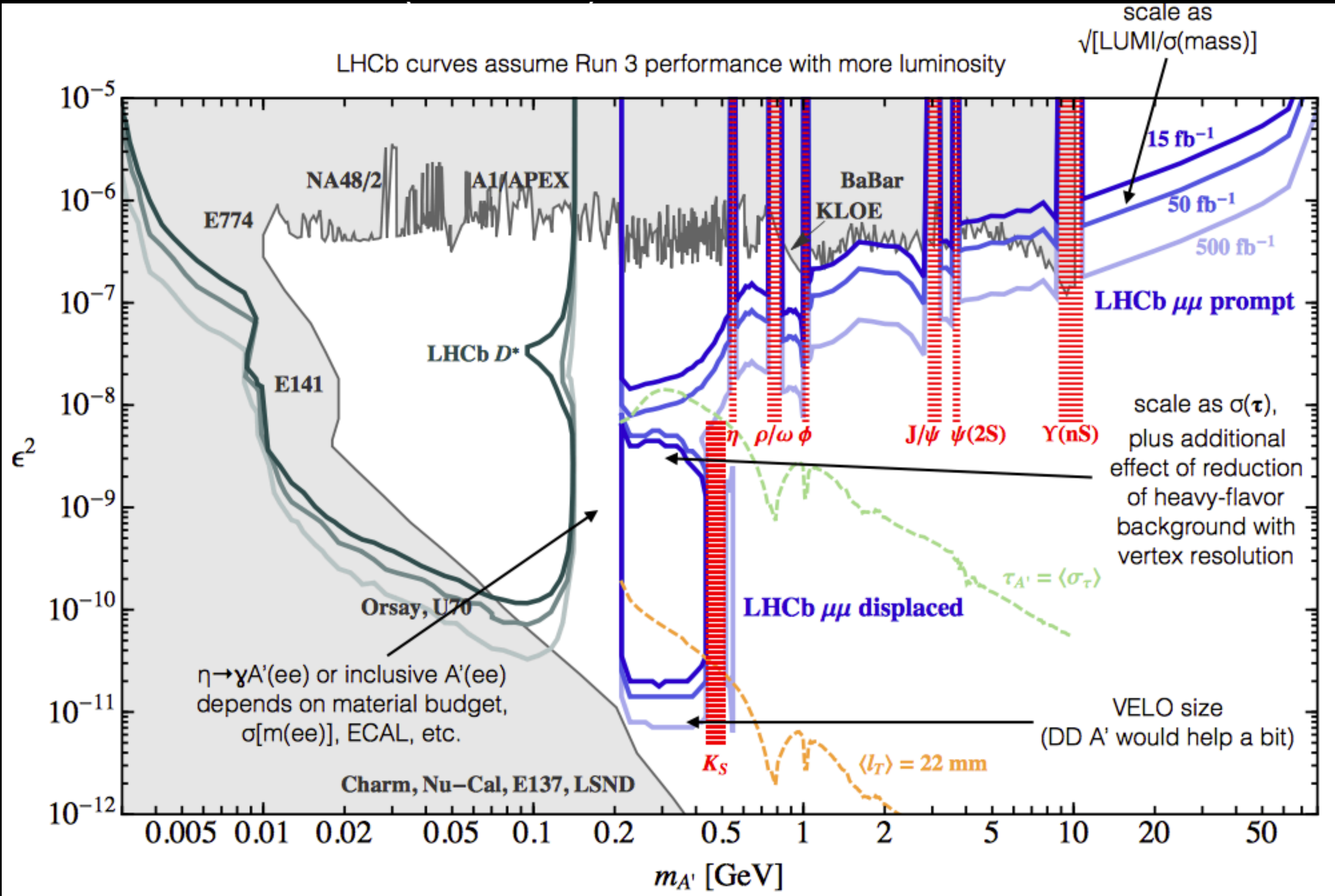


Inclusive A' → μμ [Ilten et al., arXiv:1603.08926]
Radiative charm decays [Ilten et al., arXiv:1509.06765]

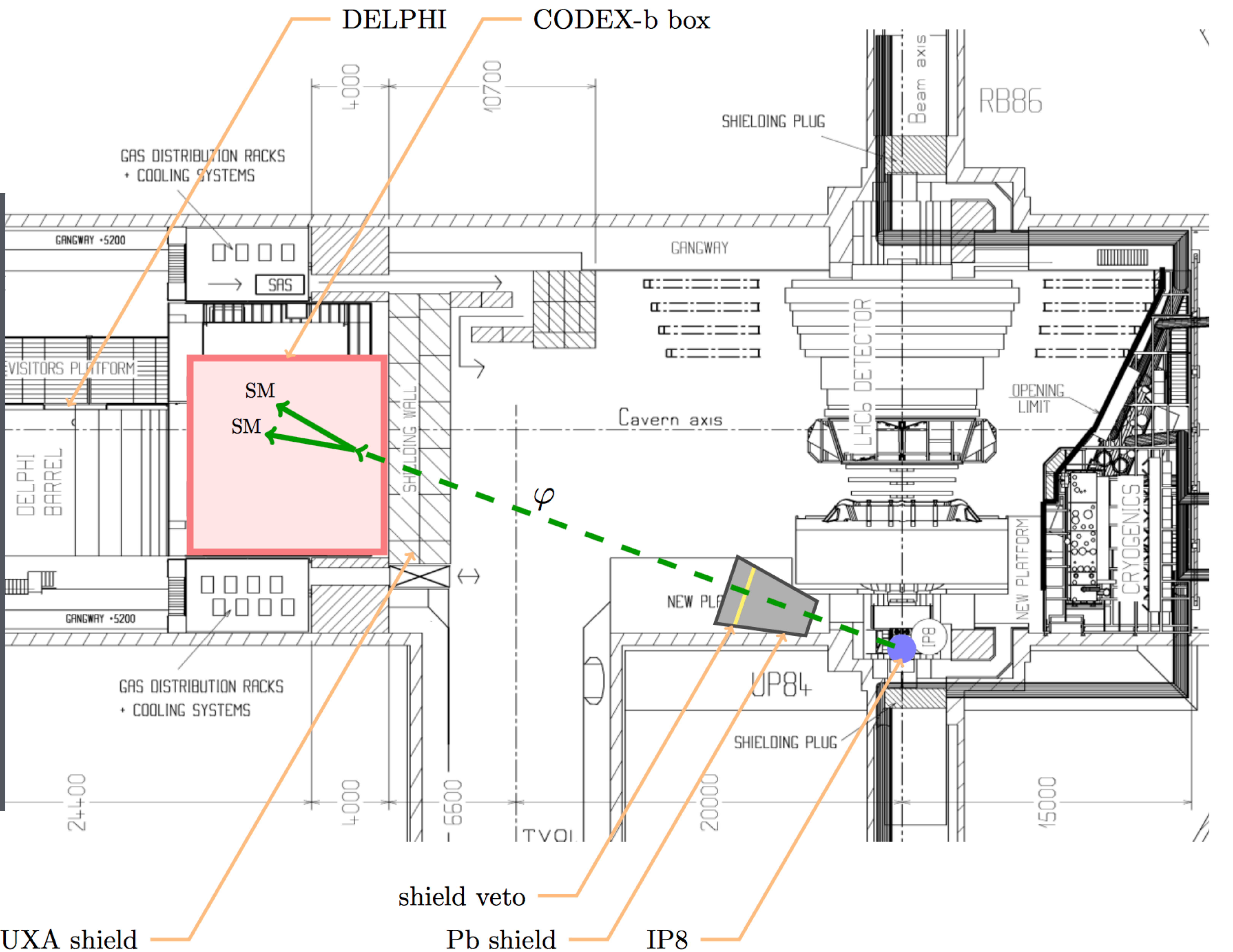
CODEX-b

Search for decay-in-flight of BSM long-lived particles (i.e., those with small coupling/mixing with SM sector)

Excellent sensitivity to inclusive Higgs portal production in B decays

Proposal to make use of DAQ being removed from LHCb cavern in 2020

O(10) m³ volume to be instrumented; ~1% of tracking area of MATHUSLA



Complementary to LHCb core programme

[Gligorov et al., arXiv:1708.09395]
[D. Robinson, this workshop]

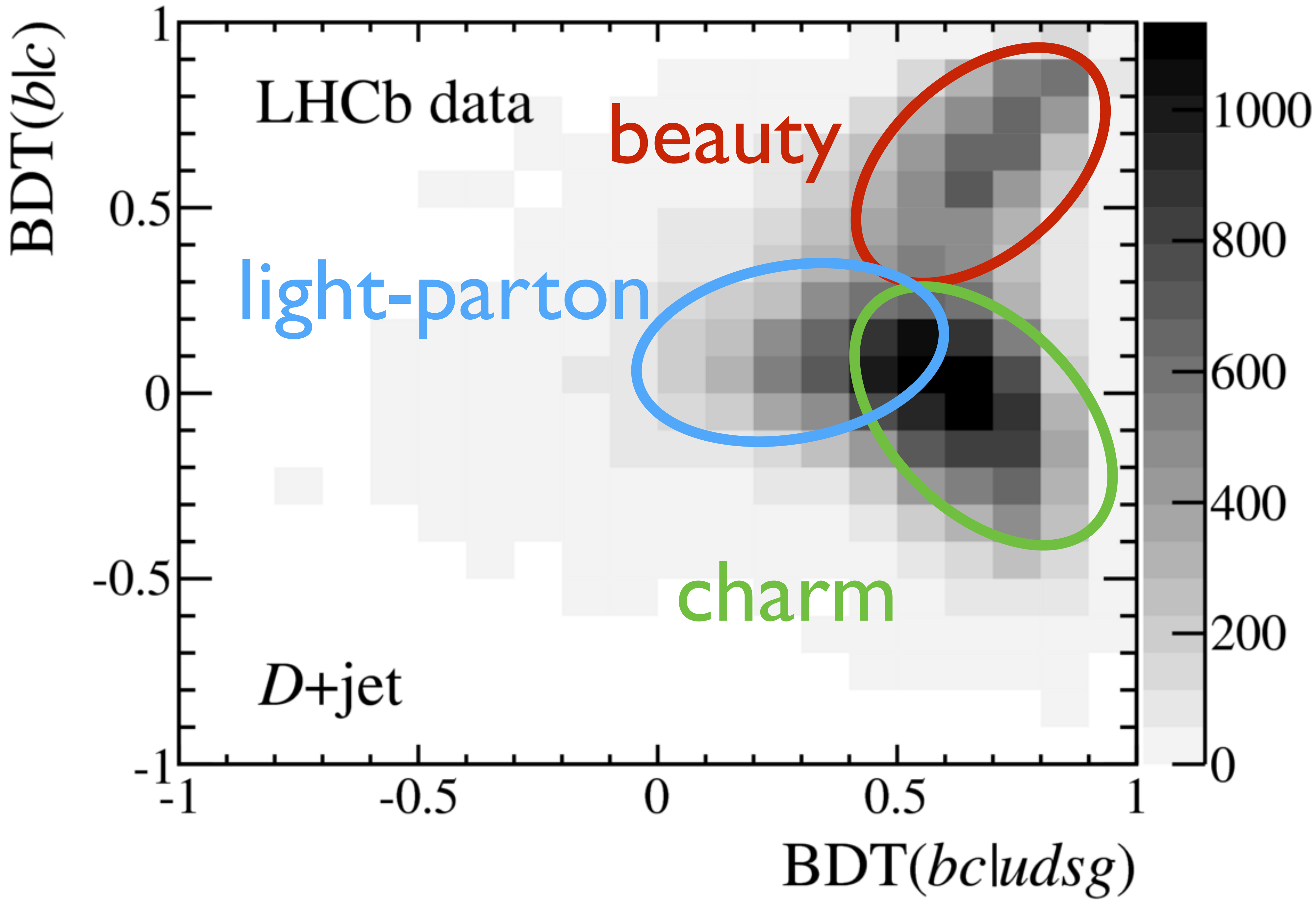
Higgs → $c\bar{c}$

For jets with pT > 20 GeV and 2.2 < η < 4.2: efficiency for identifying b(c) jets is ~65%(25%) with a probability for misidentifying a light-parton jet of 0.3%

Power comes mainly from the VELO, based upon secondary vertex properties.

Improvements in IP-resolution translate directly into improved c-tagging efficiency.

[JINST 10 (2015) P06013]



$\sigma(pp \to VH) \times BR(H \to c\bar{c}) < 9.4$ pb @ 95 % CL (**6200 x SM**) [LHCB-CONF-2016-006]

Jet tagging also used to measure:
[LHCb top, PRL 115 (2015) 112001]
[LHCb Wc Wb, PRD 92 (2015) 052001]
[LHCb Wcc Wbb, PLB 767 (2017) 110]

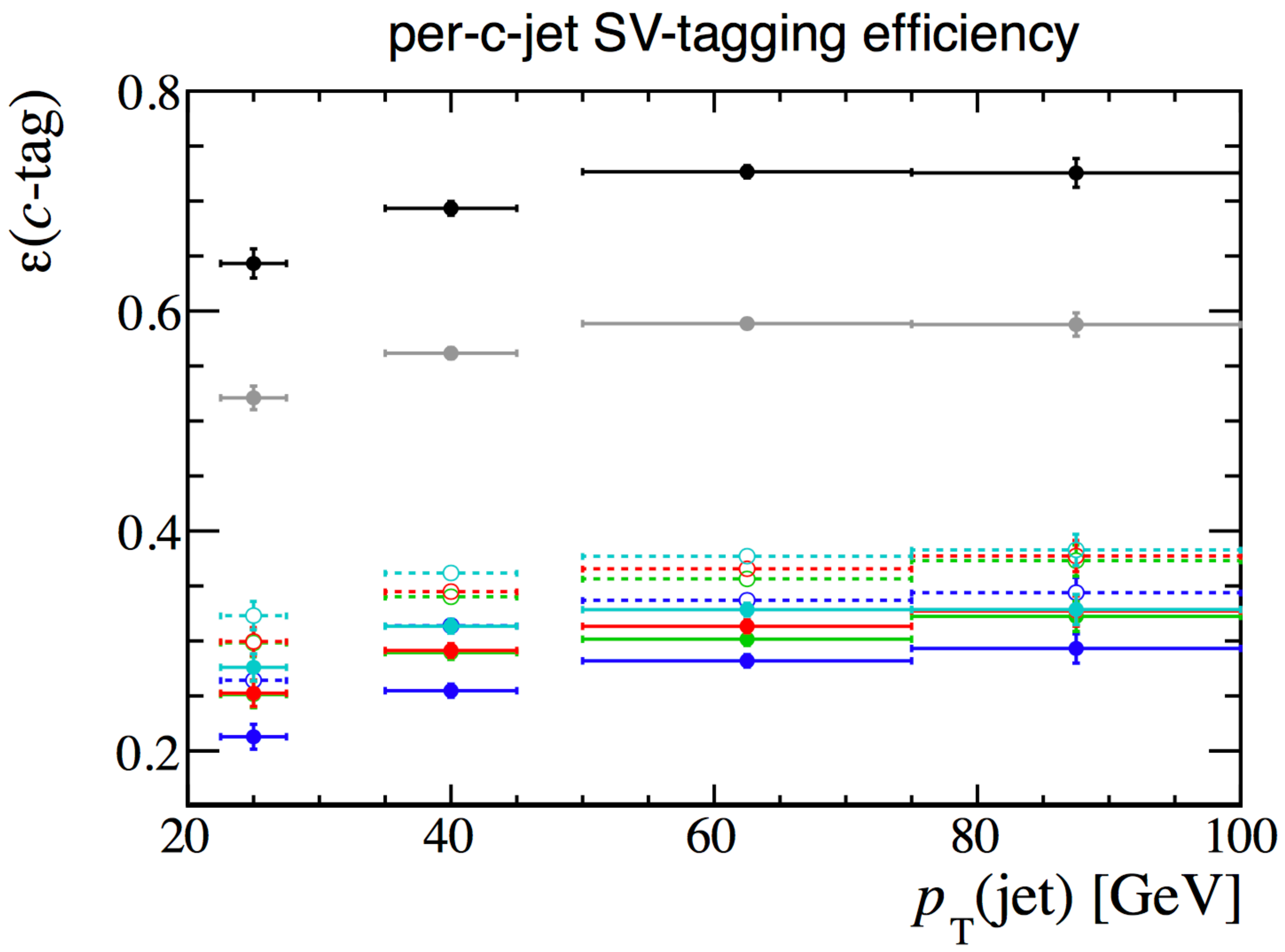
[O Augusto, HL-LHC workshop]

Higgs → $c\bar{c}$

$\sigma(pp \to VH) \times BR(H \to c\bar{c}) < 9.4$ pb @ 95 % CL (**6200 x SM**) [LHCB-CONF-2016-006]

⇒ **50 x SM** with 300/fb @ 14 TeV, w/o analysis improvements

⇒ **5-10 × SM** with projected c-tagging improvements in Upgrade II, due to better SV resolution



Perfect detector, i.e. has true SV in kinematic fiducial region.

Perfect IP resolution, but including RECO efficiency (assumed to be same as Run 1, which may not be true), etc.

Phase-II Scenario 2
Phase-II Scenario 1
Run 3
Run1
Solid: IP $X^2 > 16$ (as in Run 1)
Dashed: IP $X^2 > 9$

Would benefit from removal of RF foil

[M.Williams, Elba workshop]

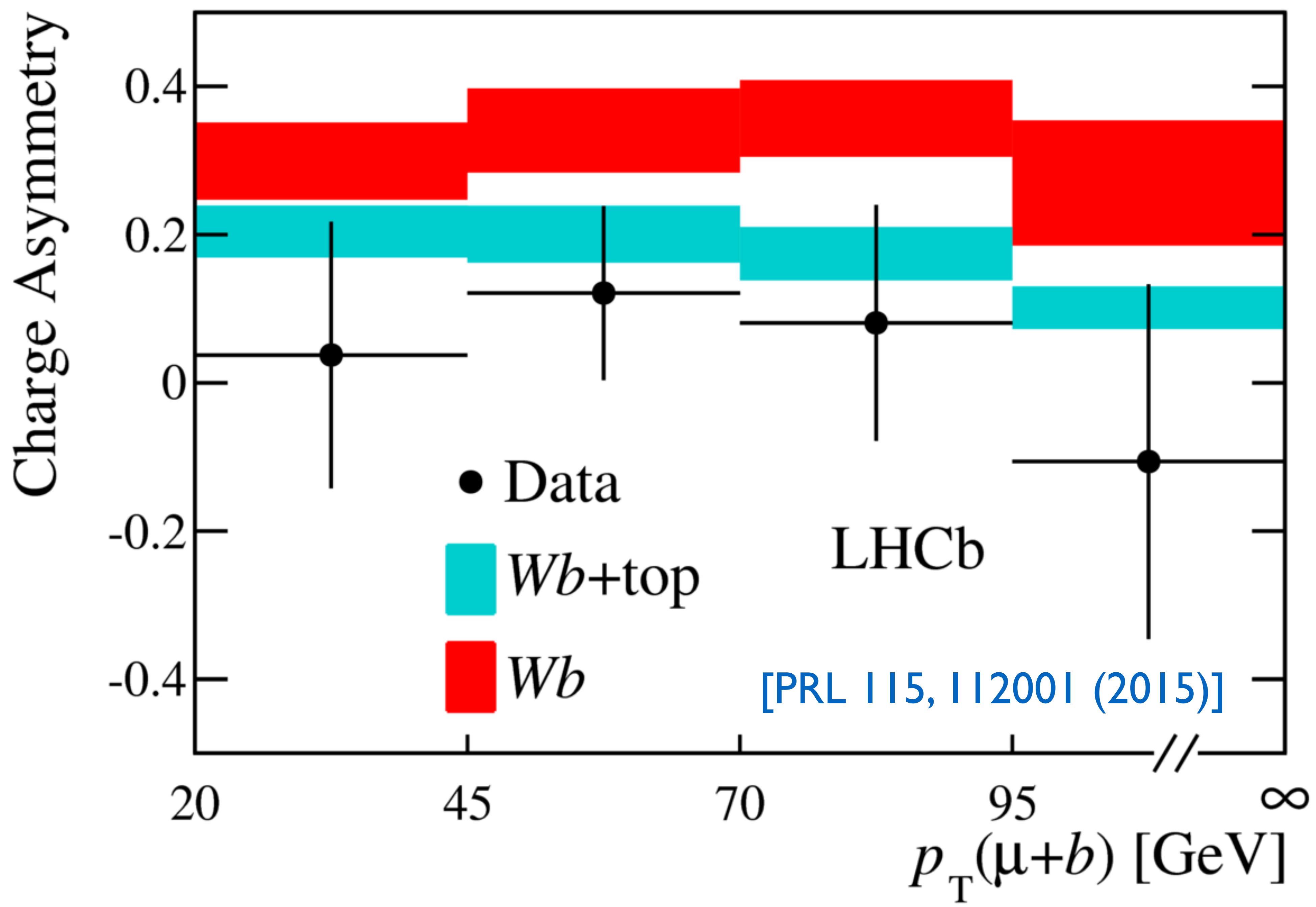
Top physics

[Kagan et al., PRL 107 (2011) 082003]
[Gauld, JHEP 02 (2014) 126]
[Gauld, PRD 91 (2015) 054029]

Enchancement of ttbar production at forward rapidities via qqbar + qg scattering, relative to gg-fusion.

Measure double-differential cross-section to constrain the gluon PDFs that are input to many SM predictions.

Measure charge asymmetries that are sensitive to BSM. Observation of 5σ asymmetry may be possible with Run 4 data, but more precision required to discriminate between NP models.



Increasing LHC collision energy to 15 TeV?
→ increase in top cross-section by ~25% [W. Barter]

SM physics in the forward region

Can add significantly to current knowledge using our complementary phase space to ATLAS/CMS

→ $\sigma(\sin^2\theta_W)^{300/fb} \sim 7 \times 10^{-5}$

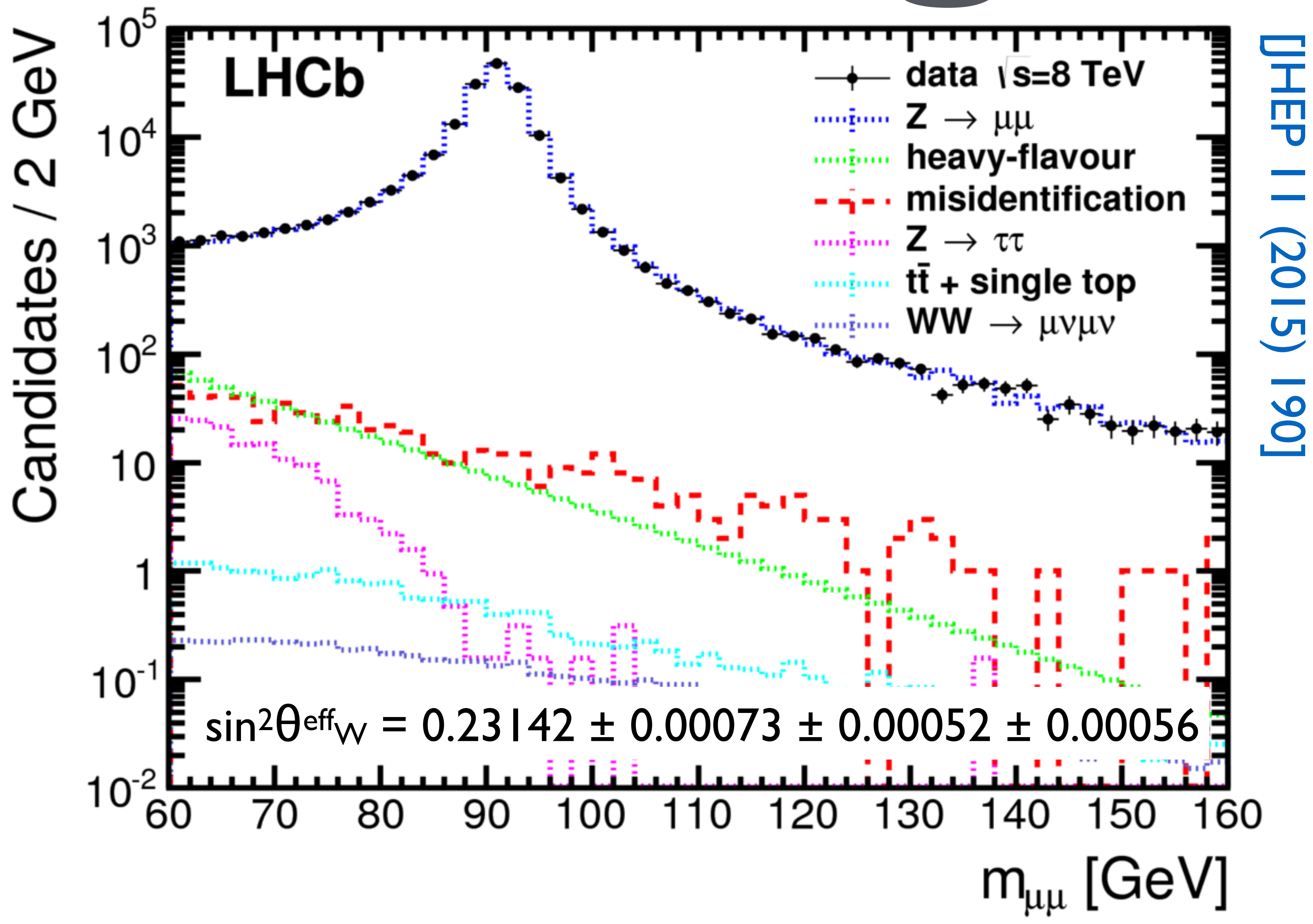
→ PDF uncertainty in forward region is anti-correlated with those in GPDs such that $\delta m_W(GPD+LHCb) < \delta m_W(GPD+GPD)$

[Bozzi et al., EPJC (2015) 75]

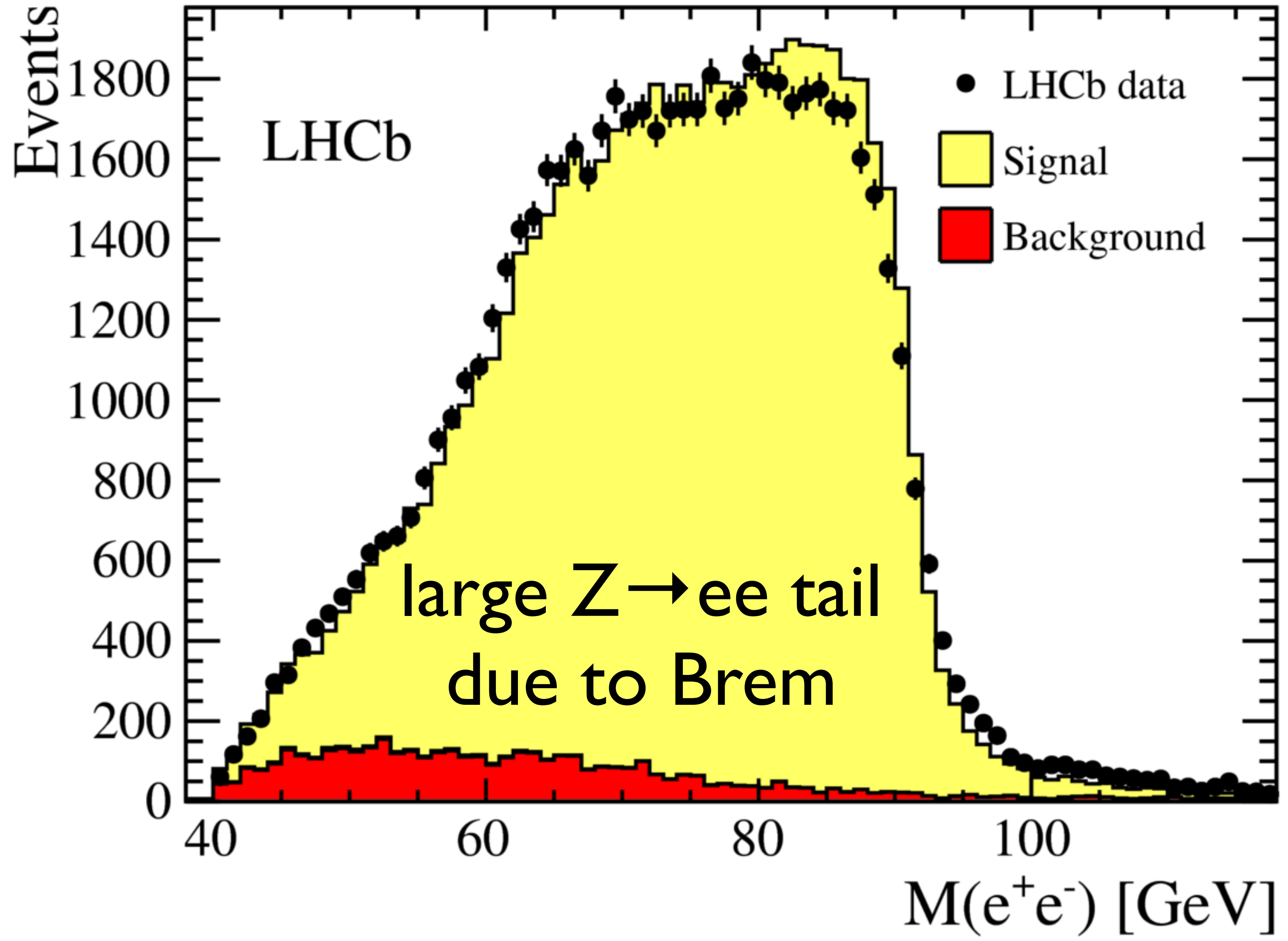
High-pT electron reconstruction could be significantly improved with better ECAL that does not saturate at 10 GeV.

Z → ττ, radiative decays…

Maintain as broad a physics programme as possible



[JHEP 11 (2015) 190]



[JHEP 05 (2015) 109]

[C Khurewathanakul, HL-LHC workshop]
[L Sestini, this workshop]

3rd LHCb workshop on future upgrades

LAPP
Laboratoire d'Annecy-le-Vieux
de Physique des Particules

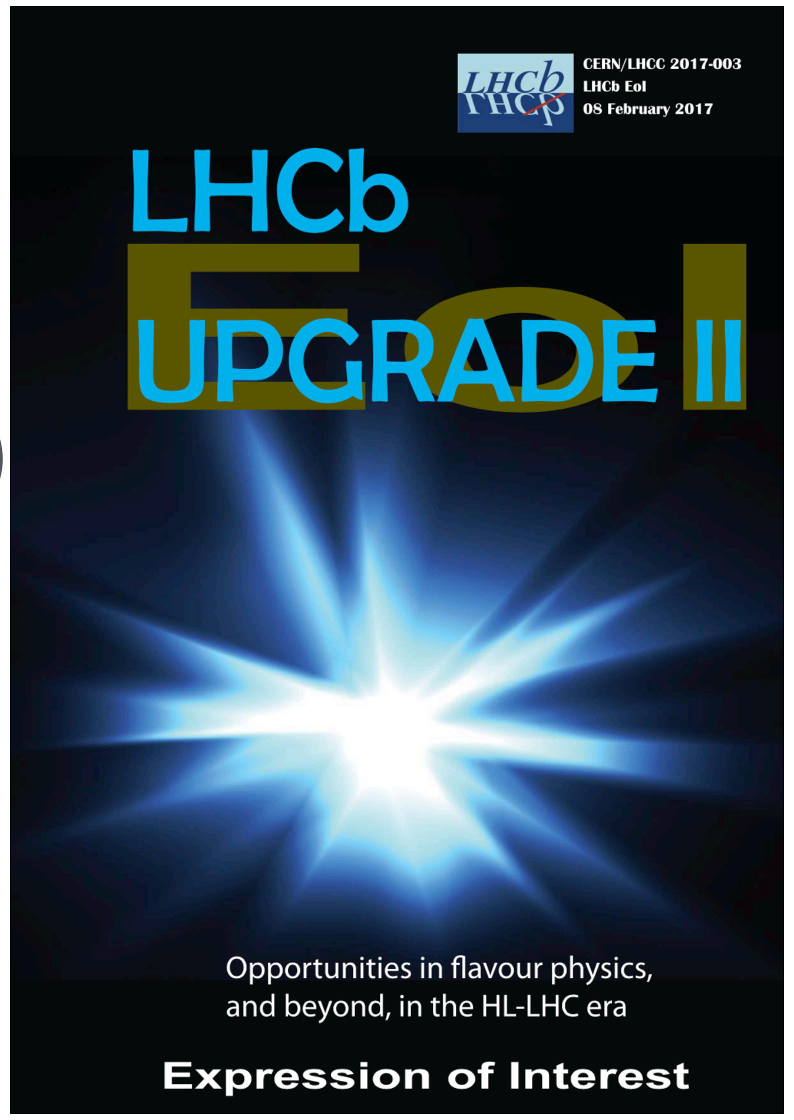
Annecy will host (21st -23rd March 2018)

Open to theorists and potential new collaborators

Previous meetings: Manchester (2016), Elba (2017)

Take-home messages

[CERN-LHCC-2017-003]



Upgrade I construction on track for Run 3

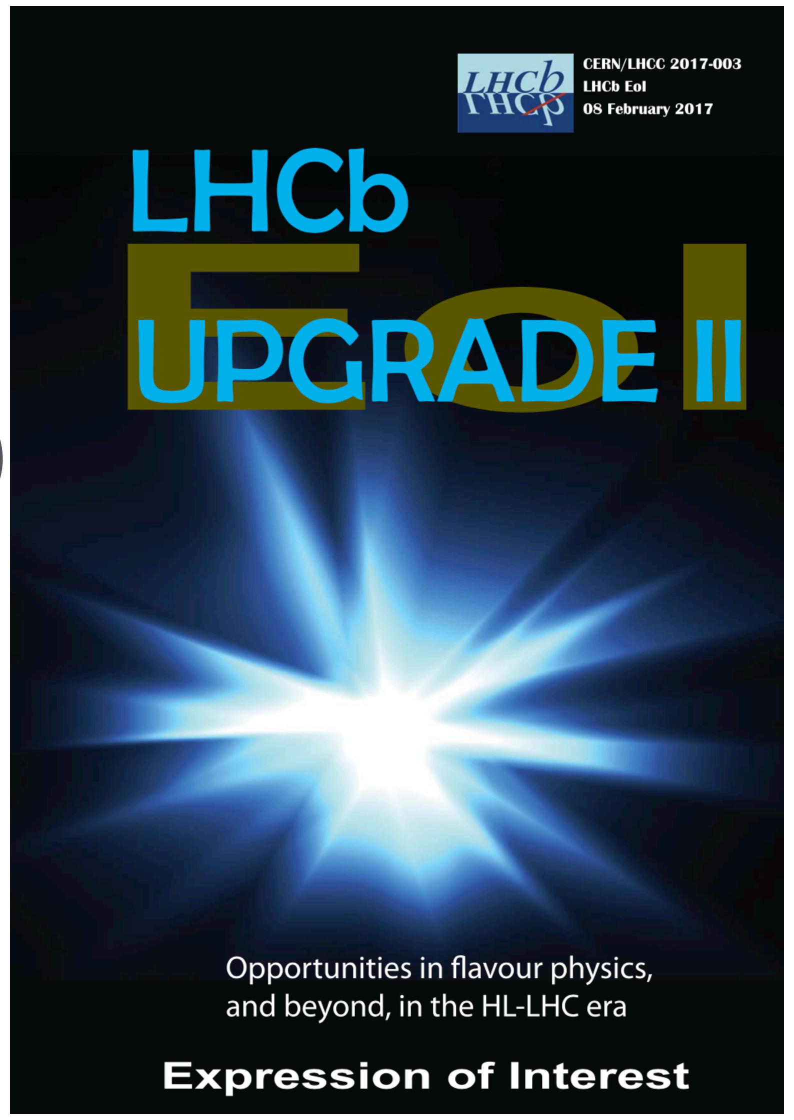
Upgrade I consolidation in LS3 to enhance specific areas (ECAL, low momentum tracking)

Upgrade II for Run 5 required to exploit flavour-physics at 1-2 x 10^{34} $cm^{-2}s^{-1}$

Fast timing, high granularity, radiation hardness will be crucial

Take-home messages

[CERN-LHCC-2017-003]



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Upgrade I consolidation in LS3 to enhance specific areas (ECAL, low momentum tracking)

Upgrade II for Run 5 required to exploit flavour-physics at 1-2 x 10^{34} $cm^{-2}s^{-1}$

Fast timing, high granularity, radiation hardness will be crucial

Large gains in classical programme that is statistically limited (CKM…)

Qualitatively new observables will open up ($b \to d l^+ l^-$, LFV…)

What else is waiting to be found? (rare-strange decays, heavy ions, exotic spectroscopy, dark sectors, Higgs…)

Let's seize the opportunity!

Backup

Muon system

High occupancy expected close to beam-pipe (up to 3 MHz/cm^2)

HCAL provides input to L0 trigger, which will no longer be needed in Run 3.

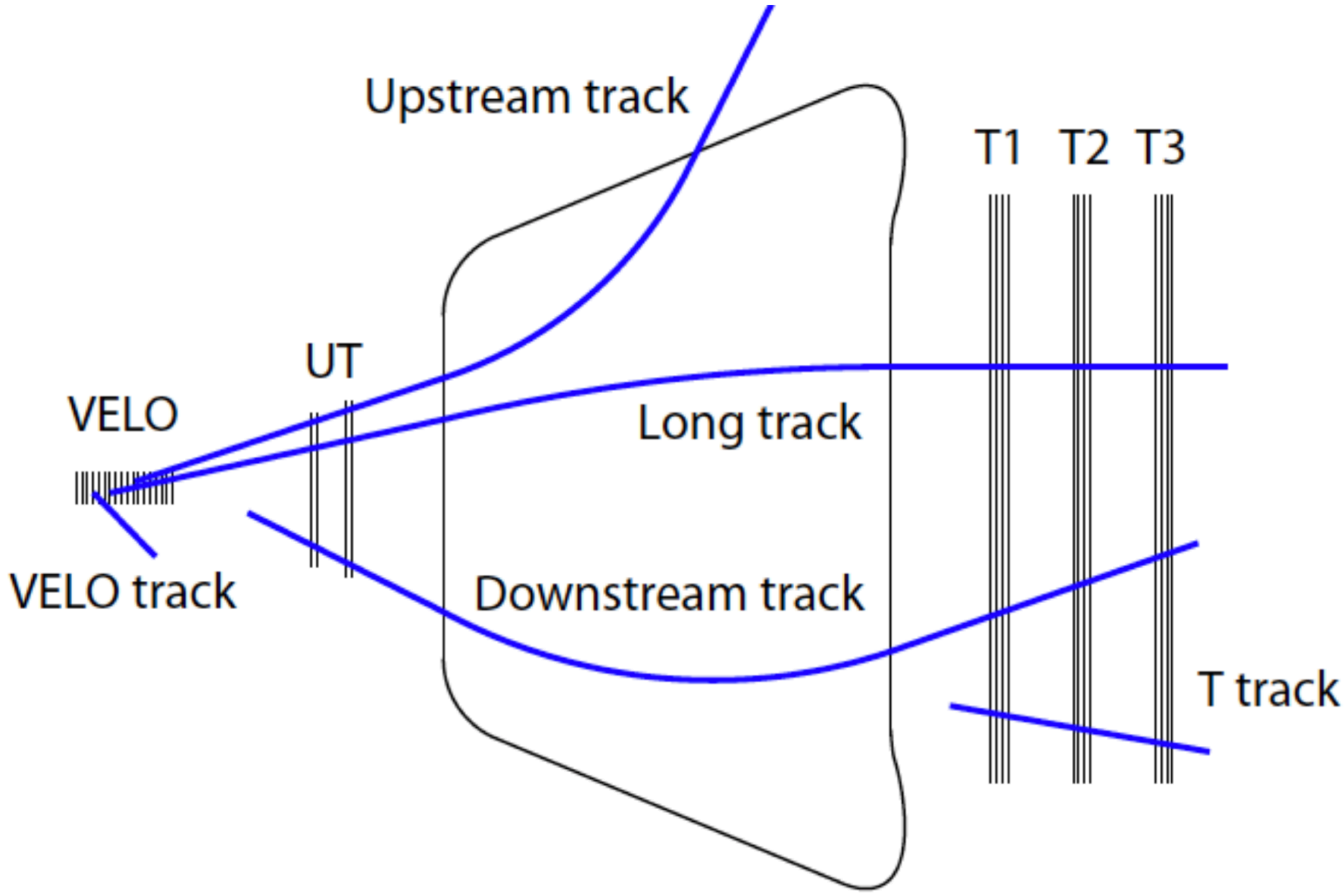
Replace HCAL with additional iron shielding to halve rate in the muon chambers, but will require pT > 1 GeV.

New μ-RWELL high-rate (and cheap!) detectors in the innermost region, with increased granularity.

LS3 consolidation: replace ageing modules with spares.

Trigger and data processing

Speed of reconstruction algorithms is crucial with 40 MHz readout → sub-detector timing information allows better pattern recognition for track reconstruction and better rejection of combinatorial background



Ongoing R&D: dedicated processing units (e.g., RETINA) to perform downstream tracking to improve efficiency for decay modes involving long-lived particles ($D^0 \rightarrow K_S K_S$, also Λ baryons)

Huge data samples with 300/fb → require **huge simulation samples** to validate analysis and evaluate detector efficiencies.

Leveraging latest computing tech (GPUs, multicore, commercial clouds, fast simulation) will be crucial.

Heavy ions

Excellent PID

LHCb has unique capabilities for pA and AA physics

Improved granularity in upgrade-II will allow access to higher centrality AA collisions.

Fixed-target mode:

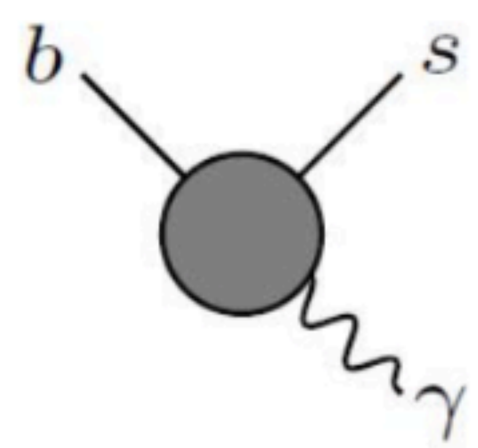
SMOG can be used to study collisions on noble gases. e.g., production cross-section of anti-protons has relevance in astrophysics.

Bent crystal can be used to measure EDM and MDM of charm-baryons.

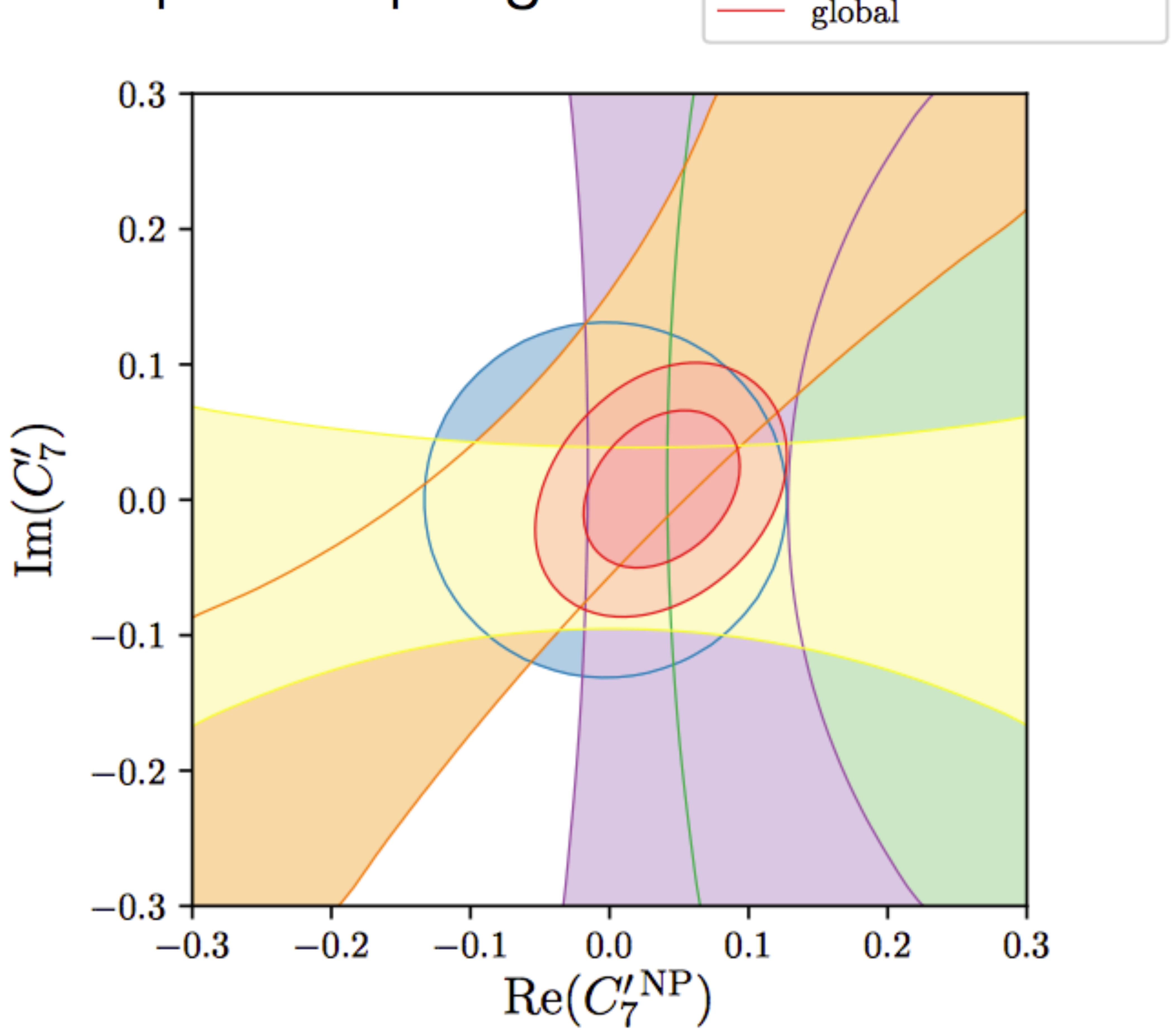
[Winn, HL-LHC workshop]

Radiative decays

$$\Gamma \sim e^{-\Gamma t}[\cosh(\frac{\Delta\Gamma t}{2}) - A^{\Delta} \sinh(\frac{\Delta\Gamma t}{2})$$
$$\pm C\cos(\Delta m t) \mp S\sin(\Delta m t)]$$



i=7 photon penguin



Qualitatively new observables e.g., flavour-tagged analyses

$\sigma(A^{\Delta})$ = 0.3 (run 1) → 0.02 (run 5)

Baryon decays unique to LHCb: $\Lambda_b \to \Lambda\gamma$, $\Omega_b \to \Omega\gamma$, $\Xi_b \to \Xi\gamma$

Low q^2 B → K*ee will continue to provide most stringent constraint

Downstream tracking efficiency improvements will help with long-lived particles and ECAL granularity/timing with mass resolution

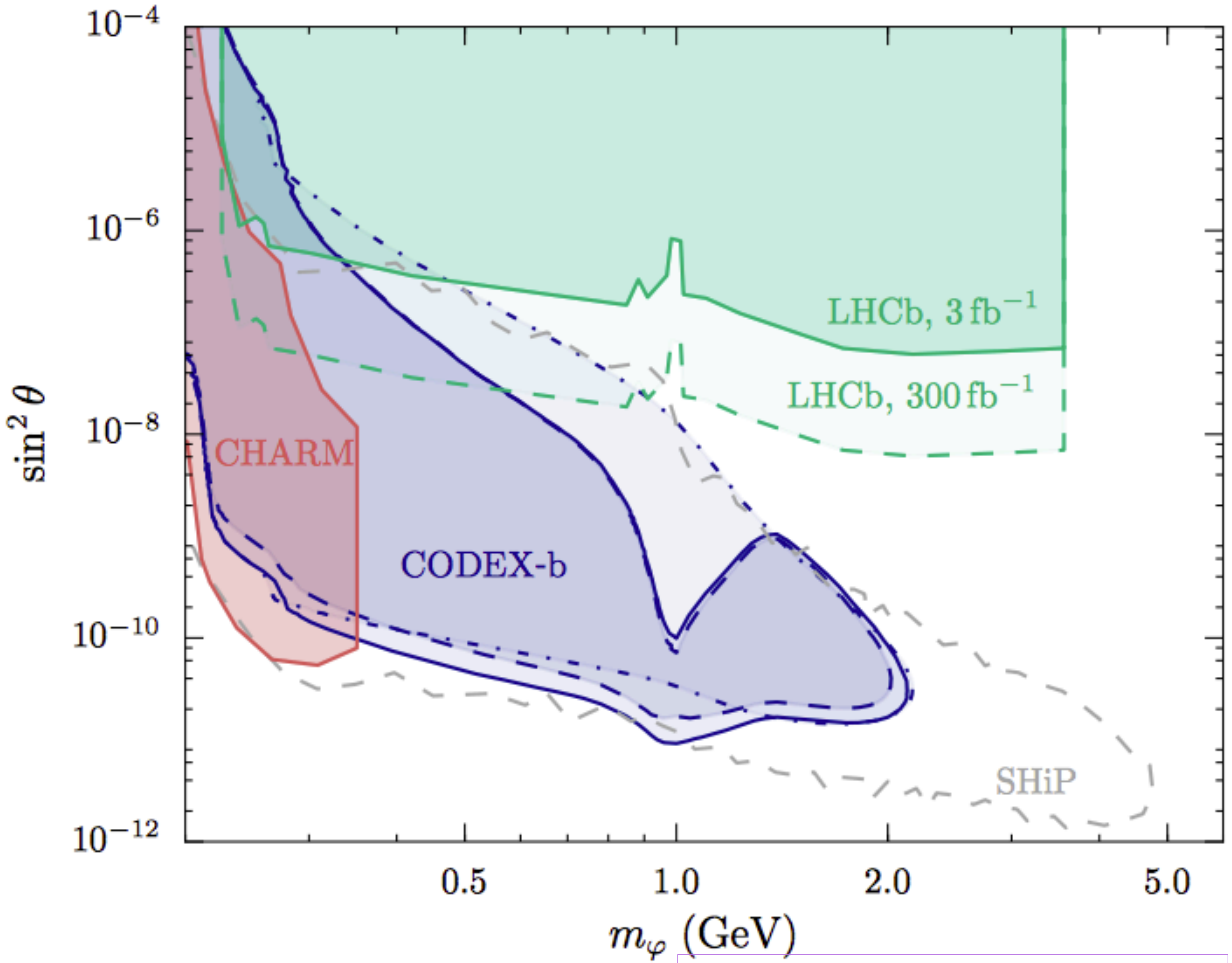
[Paul, Straub JHEP 04 (2017) 027]

CODEX-b

Excellent sensitivity to inclusive Higgs portal production in B decays

Has sensitivity to Higgs → dark photon decays

Complementary to LHCb core programme



[Gligorov et al., arXiv:1708.09395]
See Vava's talk from this morning for more details

Direct CPV in charm

$$A_{raw} \equiv \frac{N(D^0 \to K^-K^+) - N(\bar{D}^0 \to K^-K^+)}{N(D^0 \to K^-K^+) + N(\bar{D}^0 \to K^-K^+)}$$

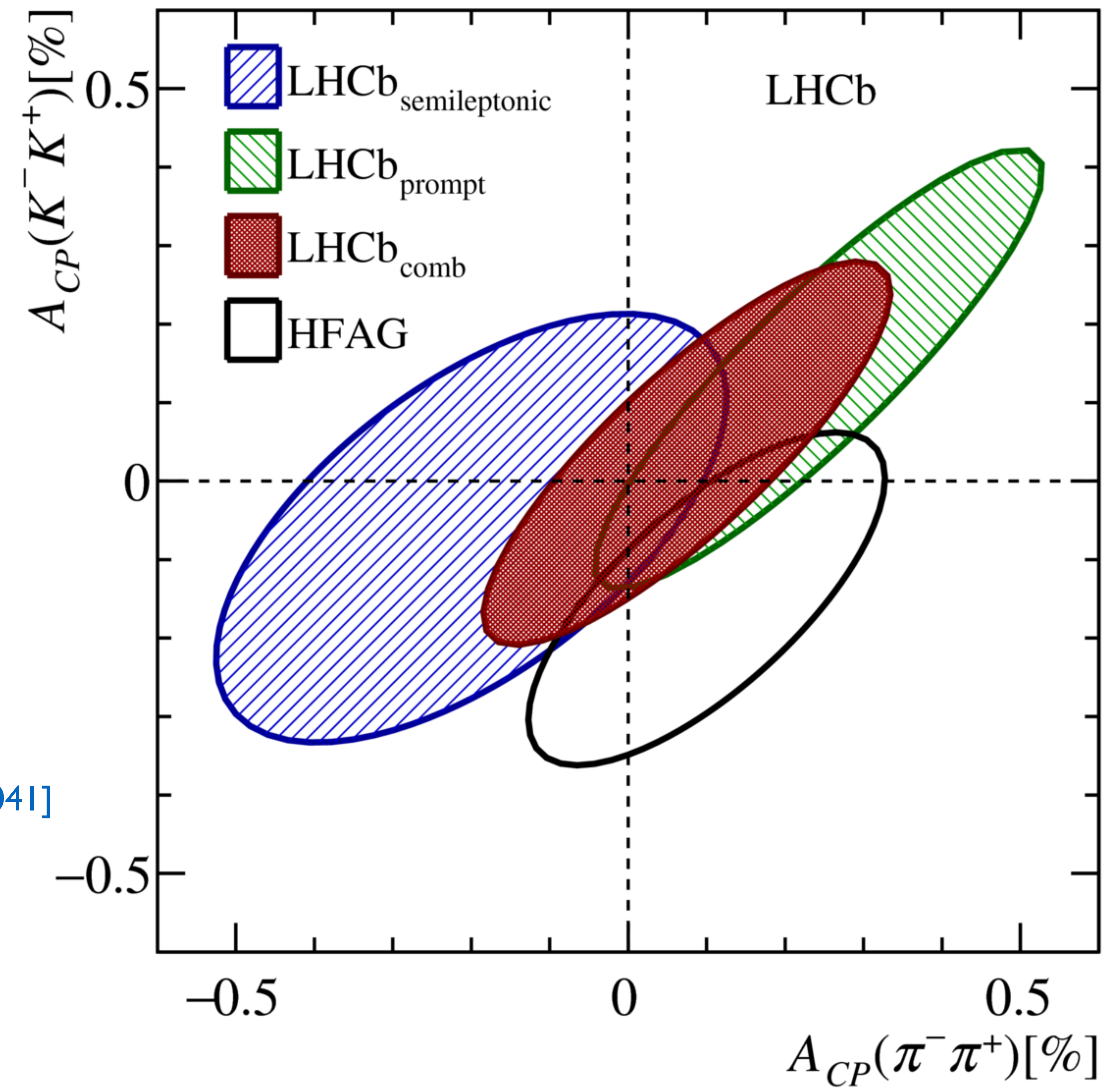
$$A_{CP}(D^0 \to K^-K^+) = A_{raw}(D^0 \to K^-K^+) - \boxed{A_P(D^{*+}) - A_D(\pi_s^+)}$$

Prompt-tagged sample [PLB 767 (2017), 177]

Multiple control channels to assess production and detection asymmetries (dominate systematics).

Combine results from semileptonic-tagged sample. [JHEP 07 (2014) 041]

$$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$
$$A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\text{stat}) \pm 0.11\,(\text{syst}))\%$$



O(‰) precision, but no signs of CPV

now looking in other modes

$D^{\pm}_{(s)} \to \eta'\pi^{\pm}$ [PLB 771 (2017) 21]

$D^0 \to \pi\pi\pi\pi$ [PLB 769 (2017) 345]

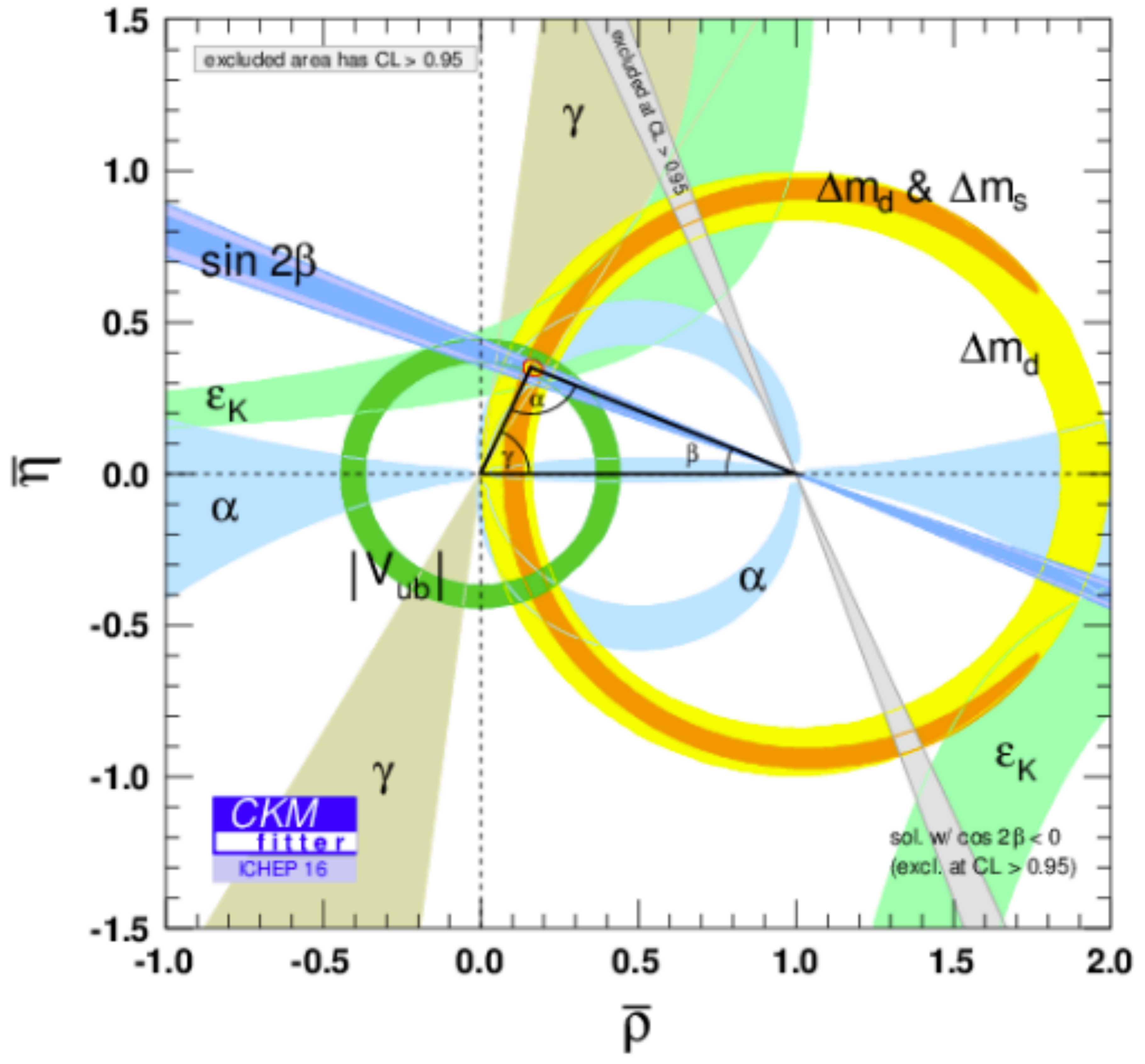
Expect > 10^9 decays in 300/fb ⇒ $O(10^{-5})$ precision

CKM angle α

α is measured via **isospin** analyses of the B→ππ, B→ρρ and B→ρπ decays. All final states must be measured, including those with **neutral particles**.

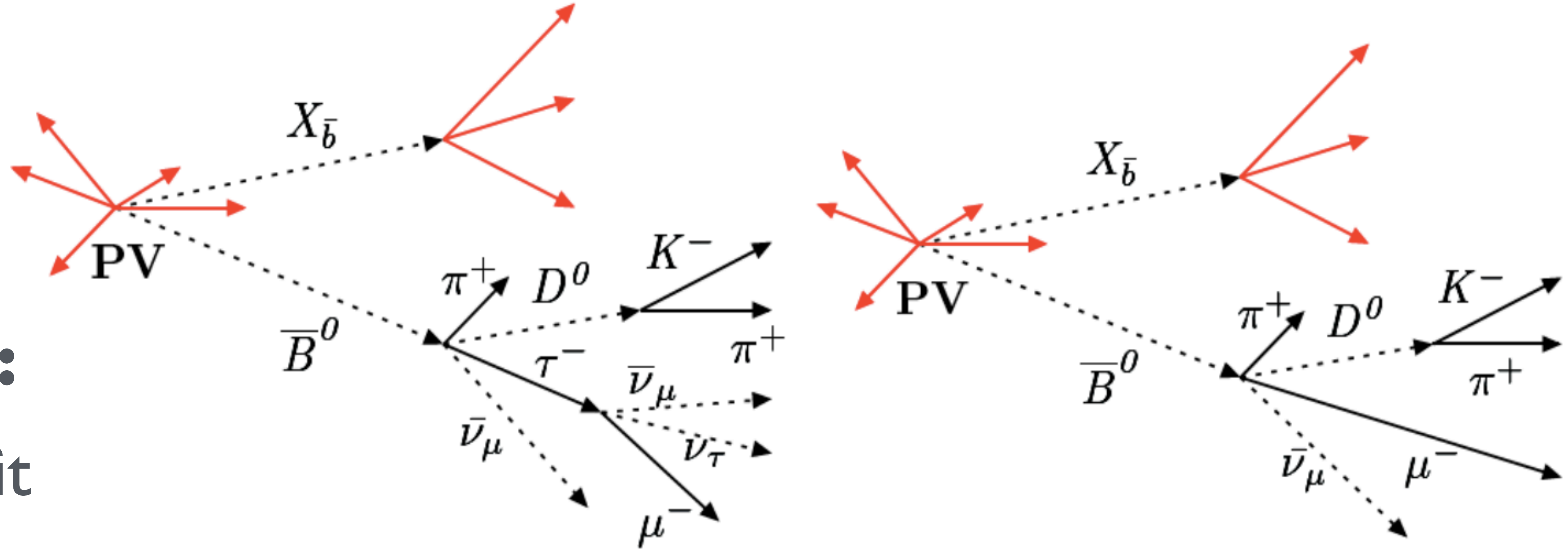
Improvements in the ECAL performance (resolution and background rejection) would allow LHCb to contribute more.

σ(α) ~ 4° [Charles et al., arXiv:1705.02981]



R(D*)

$$R(D^*) \equiv \frac{\mathcal{B}(\overline{B^0} \to D^{*+}\tau\nu_\tau)}{\mathcal{B}(\overline{B^0} \to D^{*+}\mu\nu_\mu)}$$



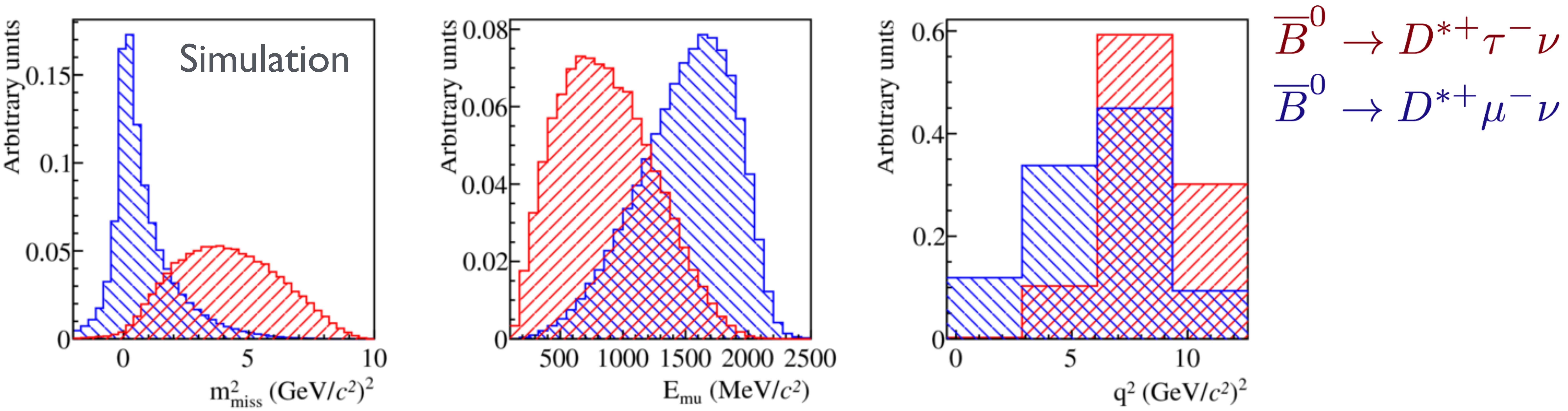
Experimental challenges at LHCb:

Missing neutrino, so no narrow peak to fit

Signal and normalisation mode have identical final state

Background from partially reconstructed decays

$$\mathcal{B}(\tau \to \mu\nu_\mu\nu_\tau) = (17.41 \pm 0.04)\%$$



Challenges

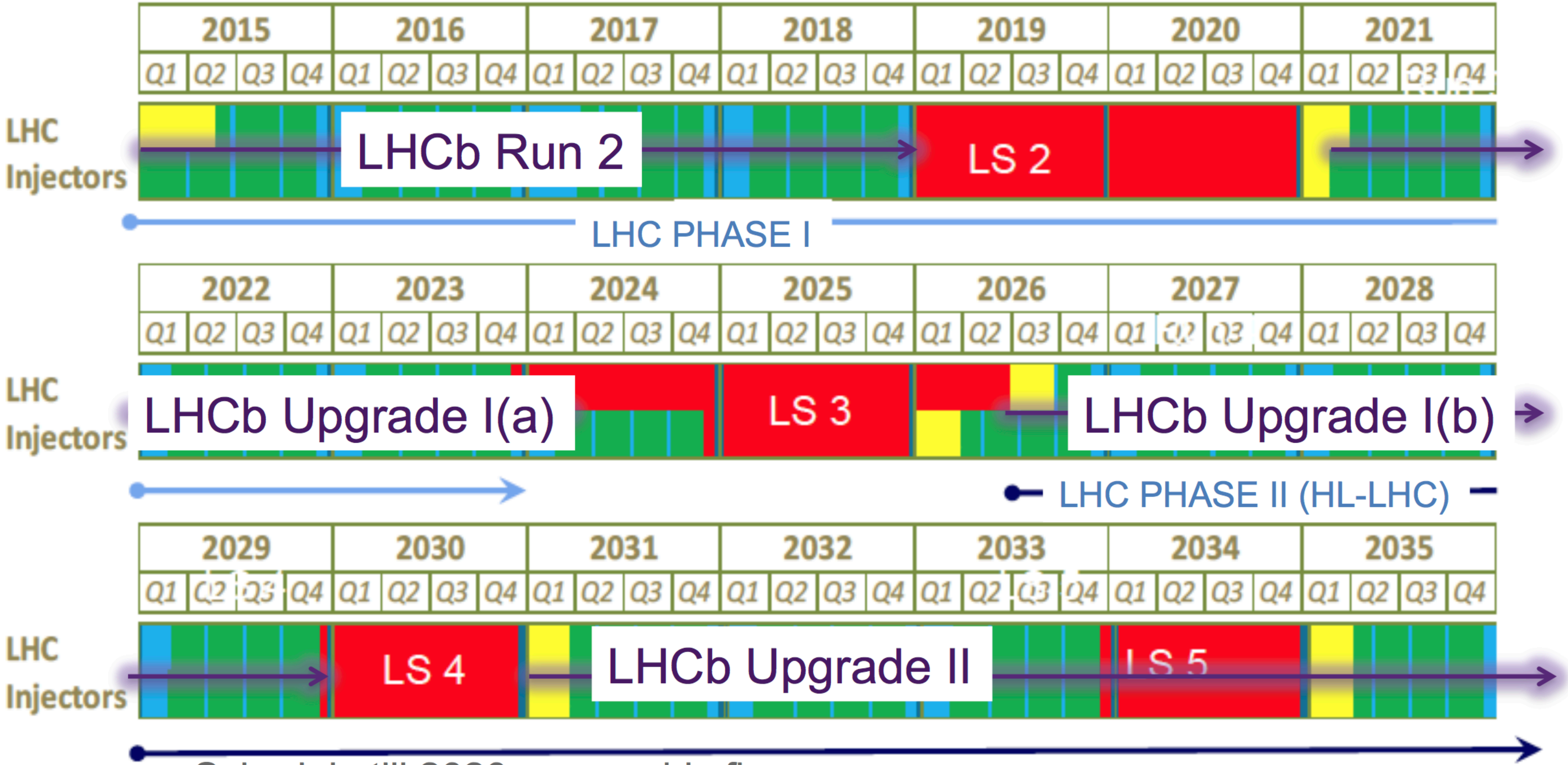
How do we do precision flavour physics with a pile-up of ~55?

How do we retain (or improve upon) the current excellent detector performance in PID, momentum and vertex resolution while also improving calorimetry and low momentum tracking?

Would like physics reach to be more than just scaling of luminosity. What could we do with an improved detector that we can't do now?

Common themes: improved granularity, radiation hardness and fast timing

LHC schedule



- Schedule till 2020 reasonably firm
- GPD main upgrades (phase II) scheduled for LS3
- HL-LHC upgrade in LS3
- **Belle II finishes ~ 2025**

Physics
Shutdown
Beam commissioning
Technical stop