LHCb upgrade and physics prospect
LHCb 升级和物理展望

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第八届全国重味物理与量子色动力学研讨会 / HFQCD 2026
2026 年 4 月 26 日 @ 重庆

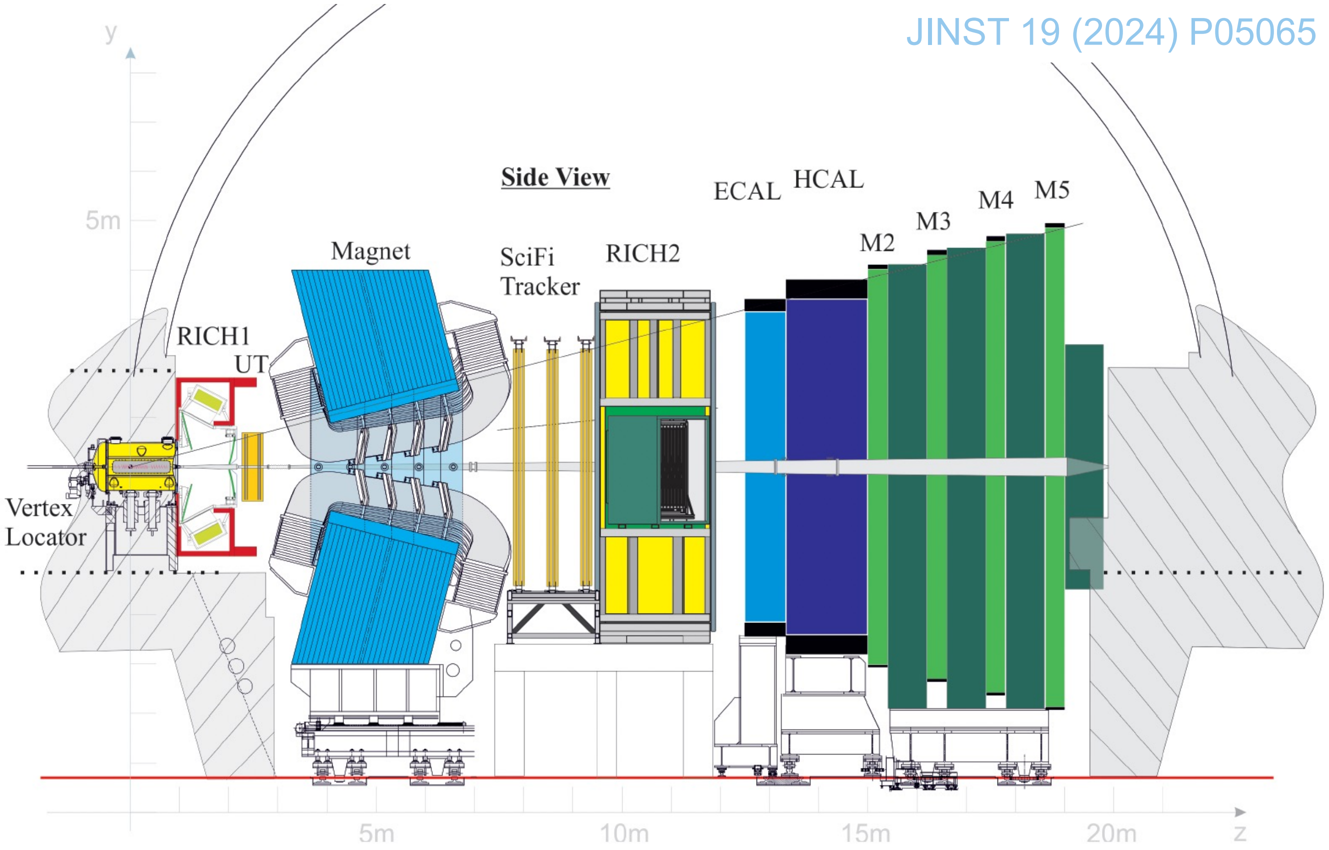
Content

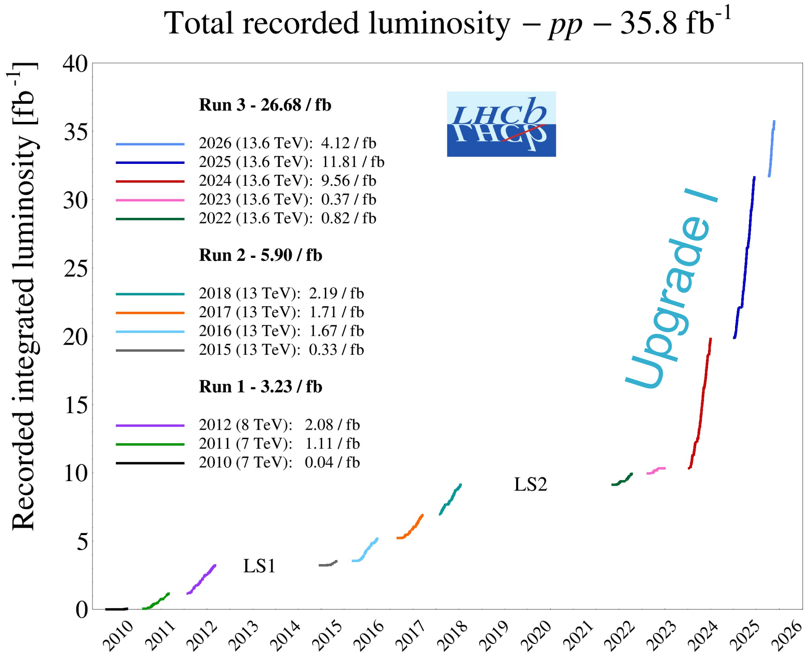
- LHCb status and Upgrade II
  - With a focus on Chinese contribution:
    Upstream Tracker
    ECAL

- Physics prospects
  - An example: potential for T_{bc} search

LHCb detector … upgraded!

- Single-arm spectrometer at LHC dedicated for heavy flavour physics





$4.0\times10^{32}cm^{-2}s^{-1}$ (×5)

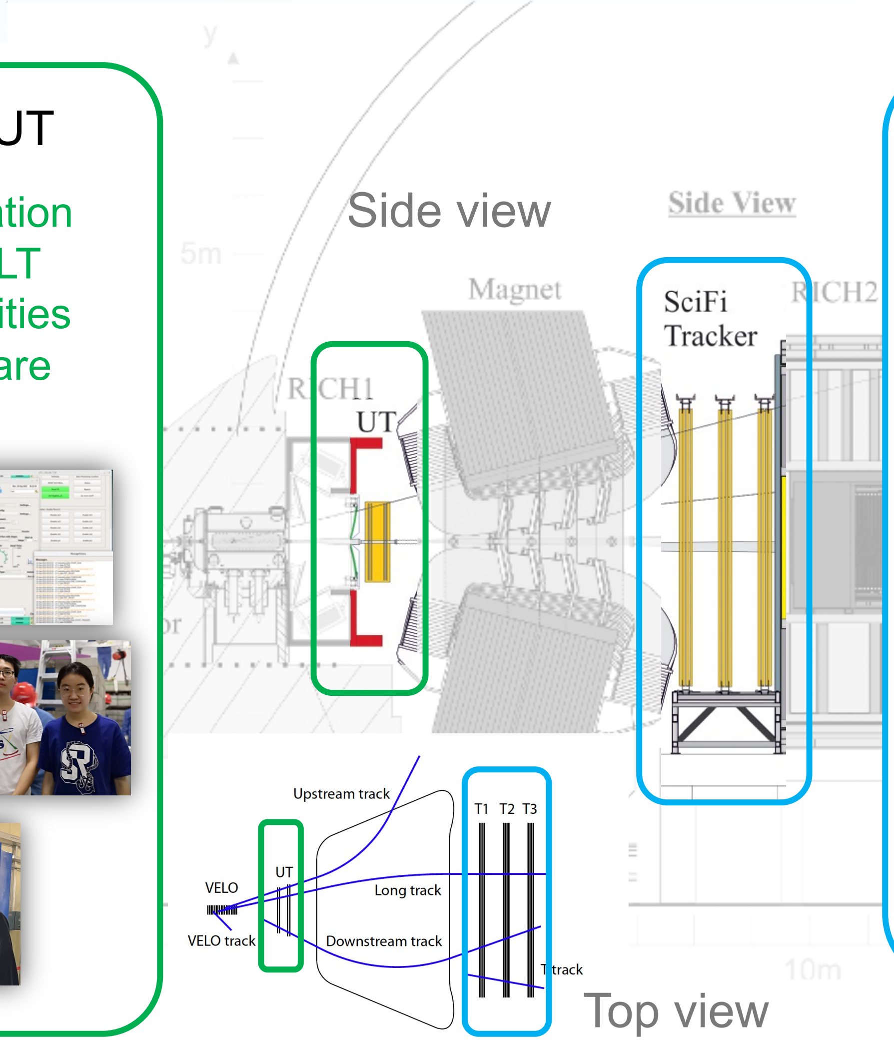
$\rightarrow 2.0\times10^{33}cm^{-2}s^{-1}$

Already > 25 fb^{-1} in Run3

LHCb-China contribution in tracking system

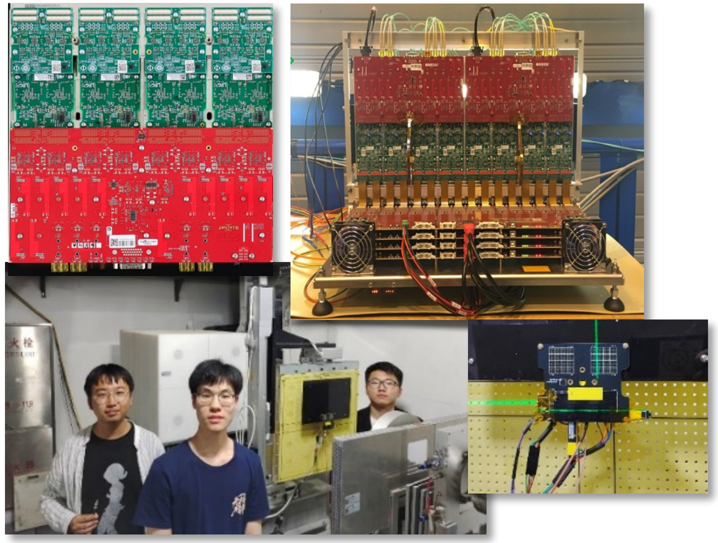
Upstream Tracker / UT

- UT installation & operation
- Irradiation study of SALT chip with Chinese facilities
- Control & safety software



Scintillator Fiber Tracker / SciFi

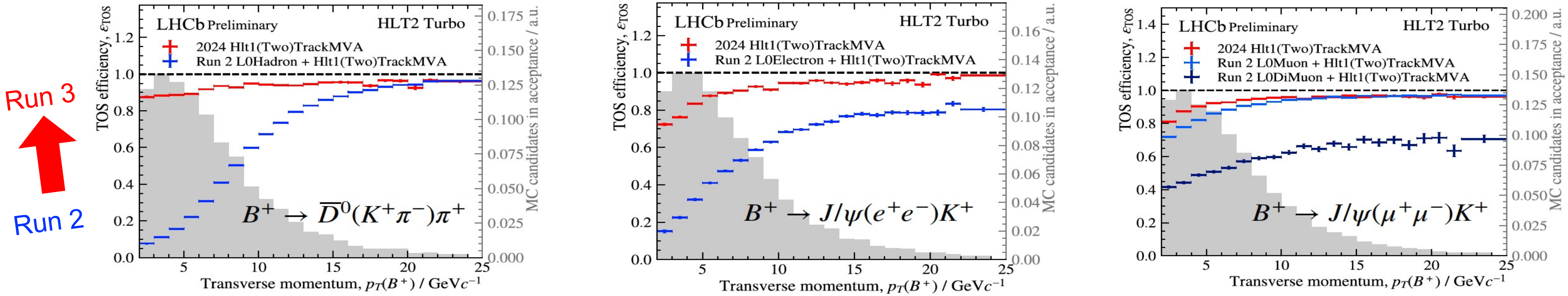
- FE board design and production (>2500 PCB)
- Quality assurance system
- Study of radiation damage on SiPM



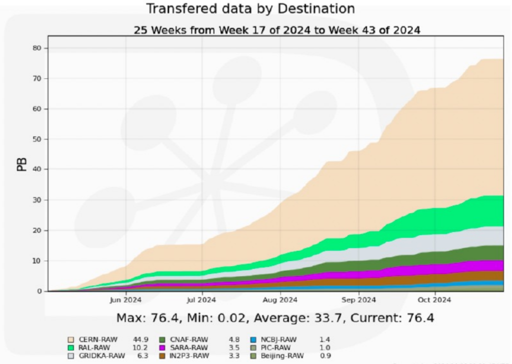
Run3 Performance

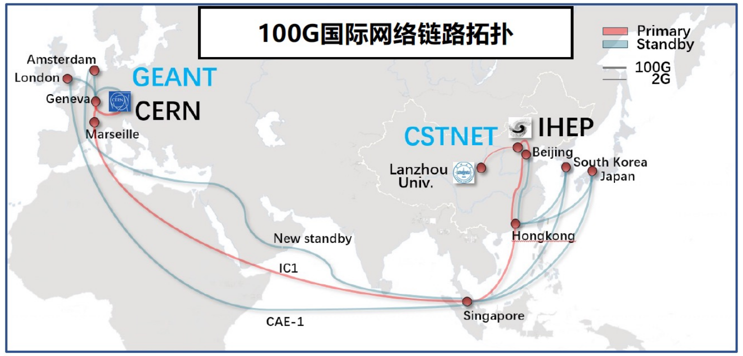
- Trigger efficiency significantly improved – removal of L0 working
  - For hadron and electron as intended, and also for muons

LHCb-Figure-2024-030



- Efficient use of CPU on WLCG grid to process huge amount of data
  - > 75 PB transferred from online farm
  - Contribution from Beijing Tier-1, Lanzhou Tier-2 operating since 2024

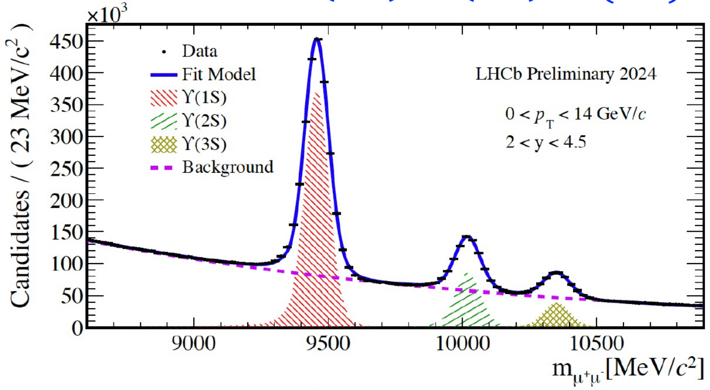




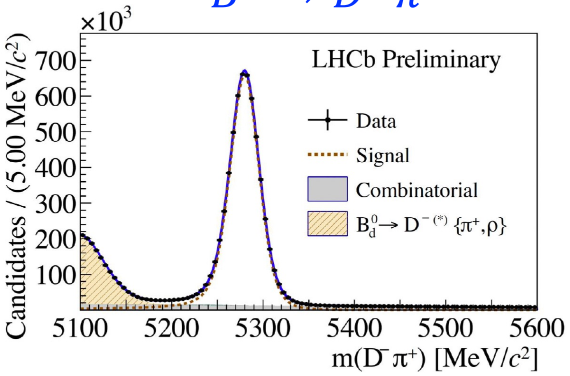
Performance

- First glimpse at the mass peaks …

$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$

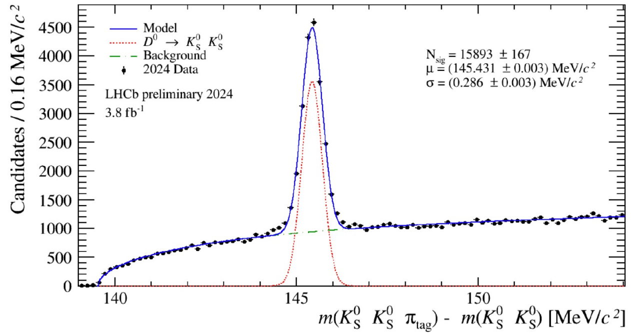


$B^0 \rightarrow D^- \pi^+$



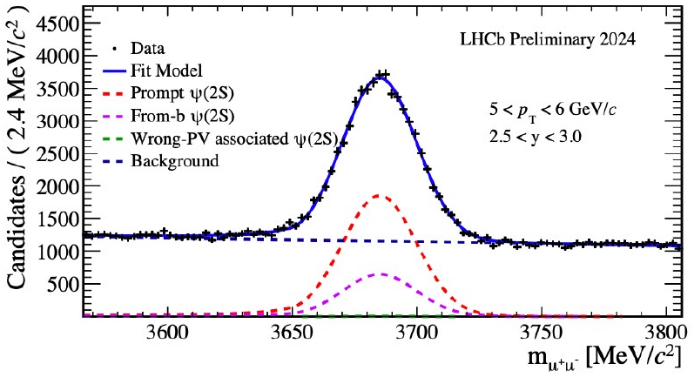
1.1e6 per fb^{-1}, 3× Run2

$D^* \rightarrow D^0(K_S K_S)\, \pi$

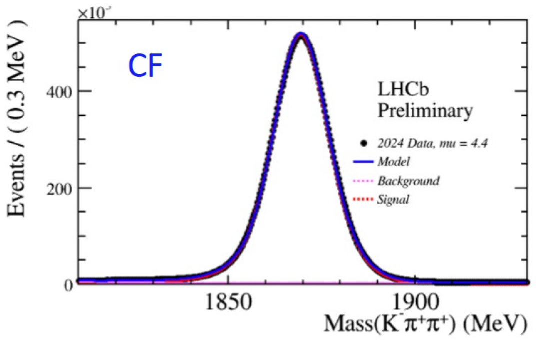


3.6× Run2

$\psi(2S)$

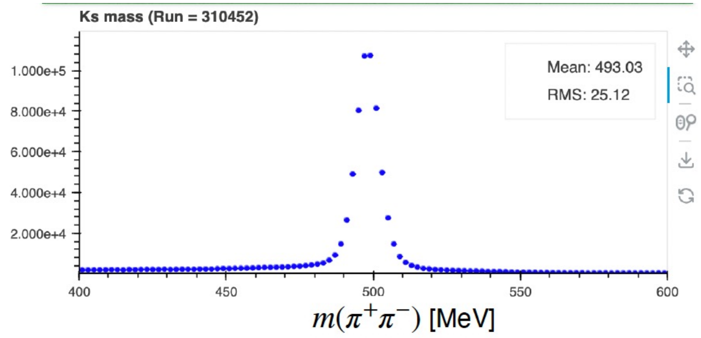


$D^+ \rightarrow K^- \pi^+ \pi^+$



1.8e6 per pb^{-1}, 2.8× Run2

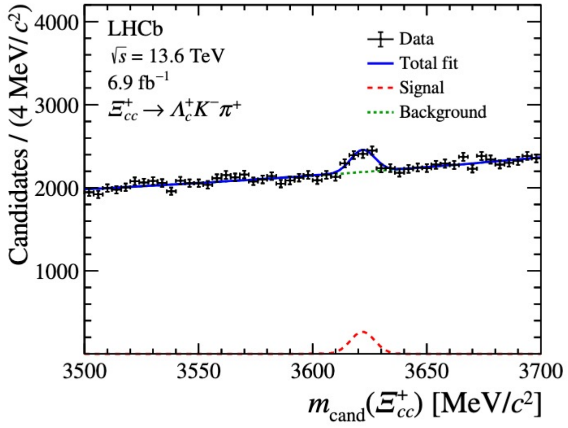
$K_S \rightarrow \pi^+ \pi^-$ at PbPb run

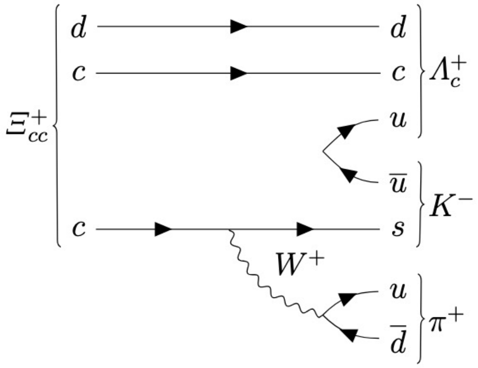


From performance to results

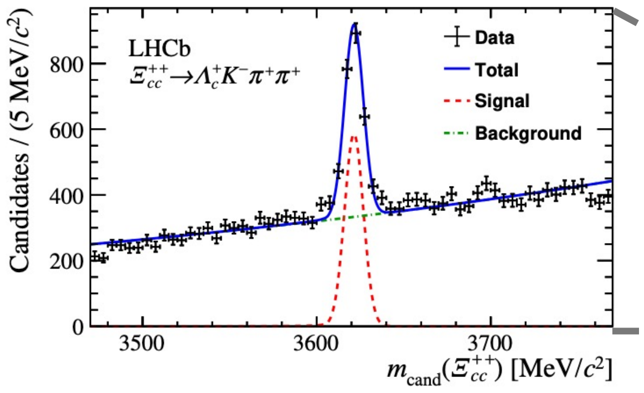
- First new particle discovered at upgrade LHCb: Ξ_{cc}^{+}
- But let's take a closer look at the doubly charged Ξ_{cc}^{++} yield

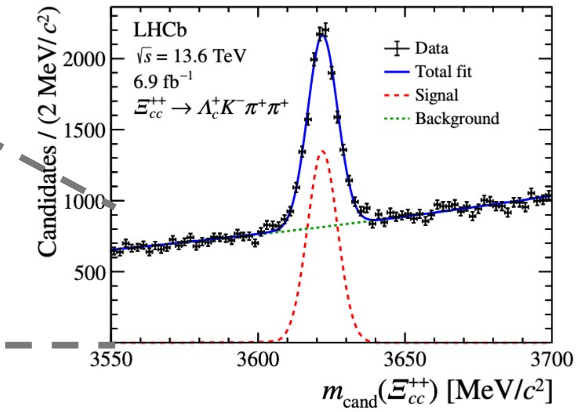
arXiv: 2603.28456

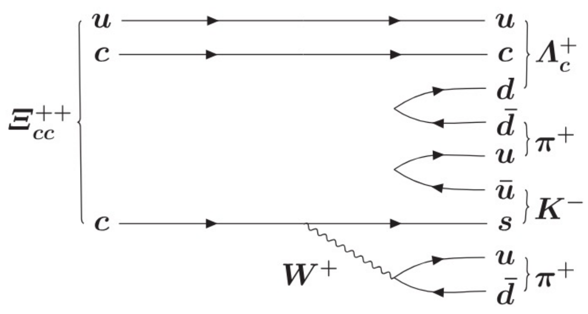




JHEP 02 (2020) 049



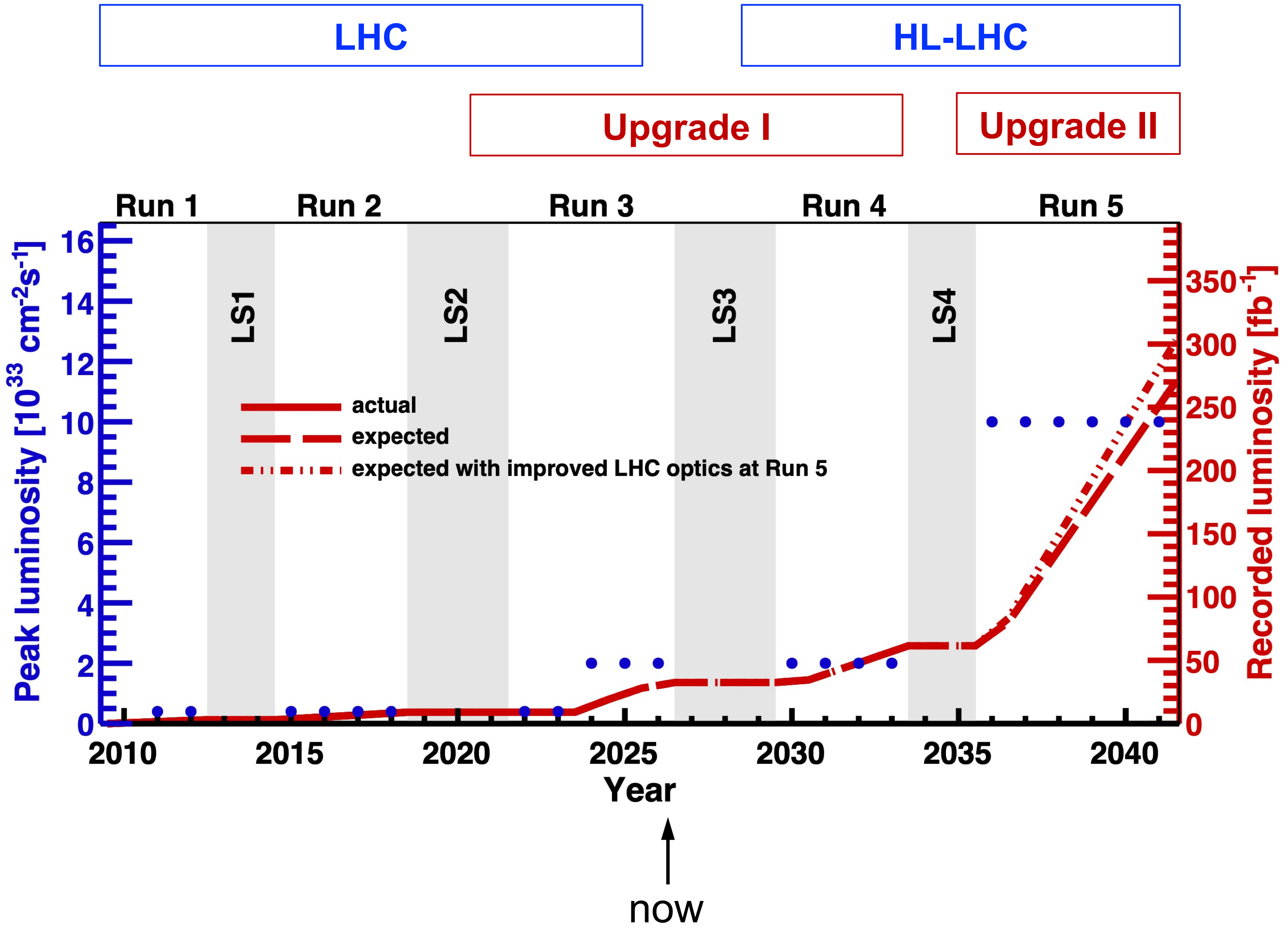




5.6 fb^{-1} @ 13 TeV, 2016-2018
Ξ_{cc}^{++} Yield: 285 / fb^{-1}. in Run 2

6.9 fb-1 @ 13.6 TeV, 2024
Ξ_{cc}^{++} Yield: 1,262 / fb^{-1}. in Run3

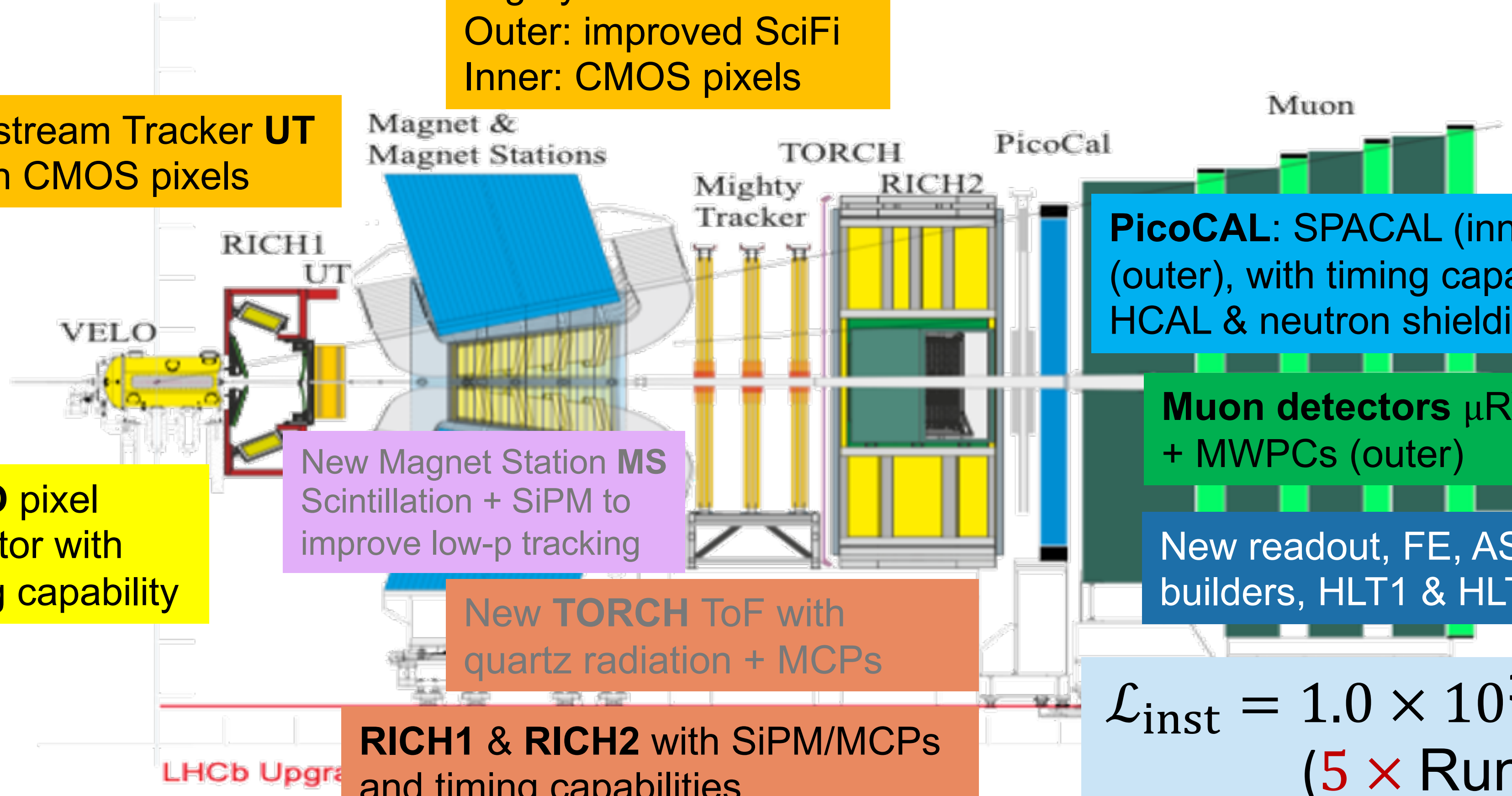
Upgrade II



- Upgrade II to fully exploit flavour physics potential in HL-LHC
- Target luminosity:
  - $1.0 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
  - 300 fb^{-1}
- High-lumi operation challenges:
  - Pile-up: $\mu \sim 1 \rightarrow 5$ (UI) $\rightarrow 40$ (UII),
  - High multiplicity ($\rightarrow$ occupancy)
  - Severe radiation damage
  - High data rates (200 Tb/s)

Expression of interest	CERN-LHCC-2017-003
Physics case	CERN-LHCC-2018-027
Framework TDR	CERN-LHCC-2021-012
Scoping Document	CERN-LHCC-2024-010

… an ultimate flavour experiment at HL-LHC



Mighty Tracker **MT**
Outer: improved SciFi
Inner: CMOS pixels

Upstream Tracker **UT** with CMOS pixels

PicoCAL: SPACAL (inner) + Shashlik (outer), with timing capabilities
HCAL & neutron shielding removed

Muon detectors μRWELL (inner) + MWPCs (outer)

New Magnet Station **MS**
Scintillation + SiPM to improve low-p tracking

VELO pixel detector with timing capability

New readout, FE, ASICs, event builders, HLT1 & HLT2 farms …

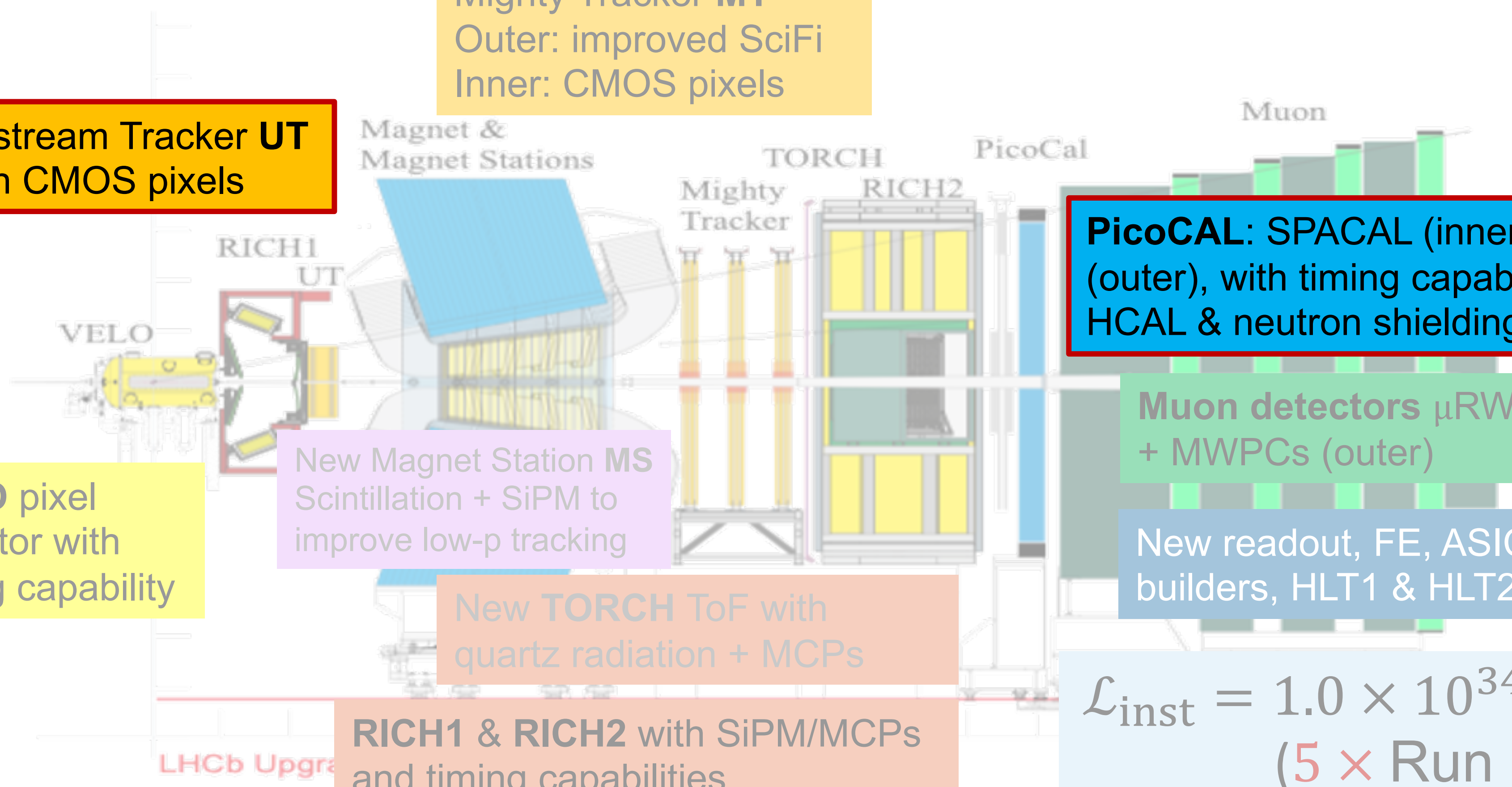
New **TORCH** ToF with quartz radiation + MCPs

RICH1 & **RICH2** with SiPM/MCPs and timing capabilities

$$\mathcal{L}_{\text{inst}} = 1.0 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$$

(5 × Run 3)

Chinese LHCb team playing essential roles



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with CMOS pixels

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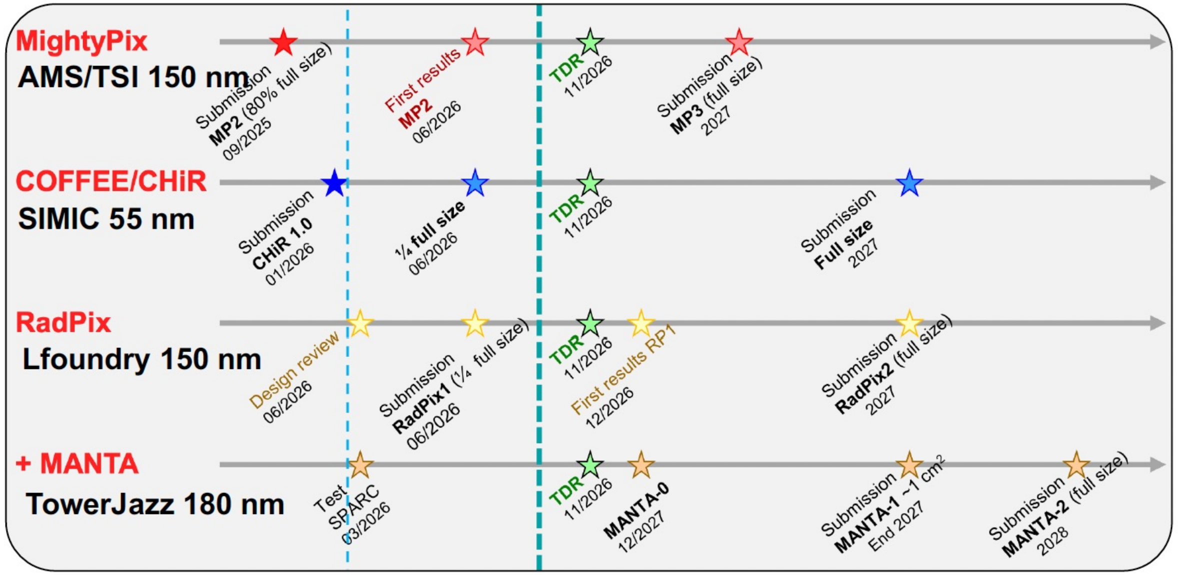
(5 × Run 3)

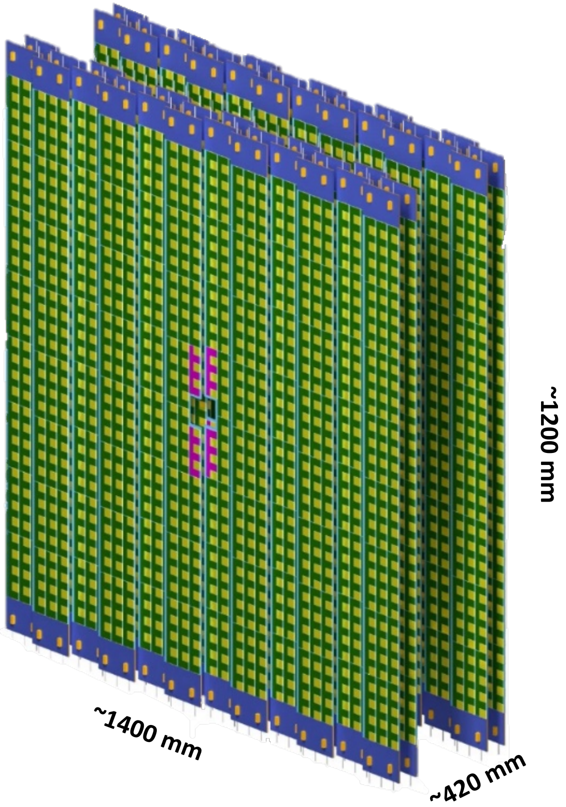
Upstream Pixel Tracker (UP)

- Challenges for UT due to higher luminosity
  - Max hit rate ~160 MHz/cm^2) → higher granularity
  - Ability to tag 25ns bunches → good timing resolution
  - Increased radiation level:

    NIEL up to 3×10^{15} n_{eq}/cm^2, TID up to 240 MRad
- A monolithic CMOS based pixel detector proposed
  - Sensor options: HVCMOS / small electrode CMOS



now



6.8 m^2 active area in ‘middle-scenario’

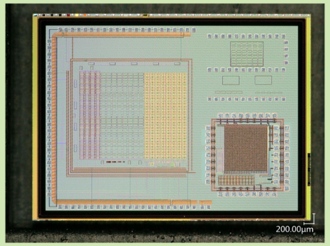
UP: COFFEE sensors

- Advanced 55nm CMOS R&D driven by Chinese groups using domestic foundry

COFFEE 2

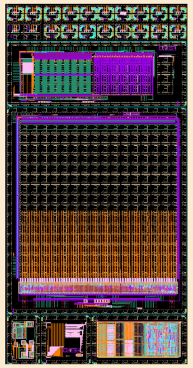
First HVCMOS 55nm prototype chip

- Breakdown at -70V
- Responsive to laser, X-/beta-ray sources



CHiR (COFFEE-HiRes)

- Validation of process modification
- Key design feature



COFFEE

CMOS SENSOR IN FIFTY-FIVE NM PROCESS

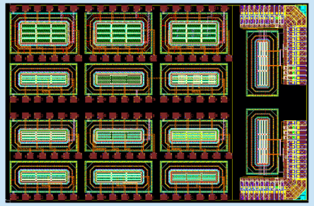
NIM A1069 (2024) 169905
JINST 20 (2025) C10011

Quarter-size chip submission

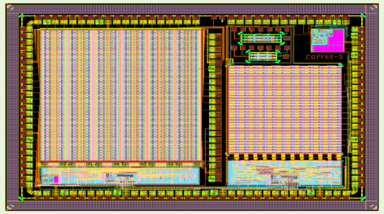
… | 2022 | 2023 | 2024 | 2025 | 2026 | 2027

Submission timeline

COFFEE1
- Prototype in LL process
- Validation of deep N-well structure



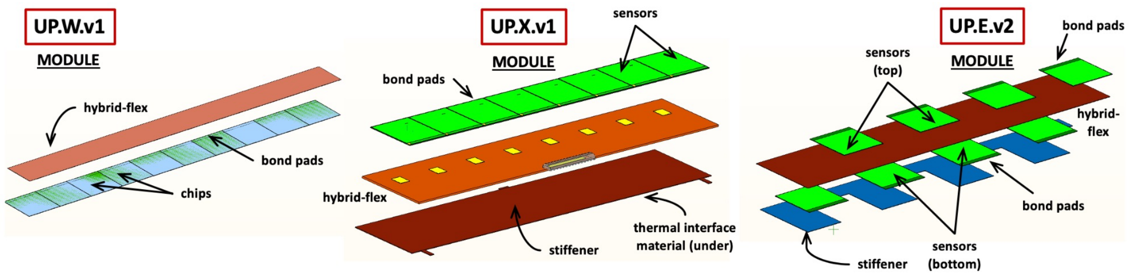
COFFEE3
- Two pixel arrays with data-driven readout
- Designed for good timing resolution and moderate power consumption

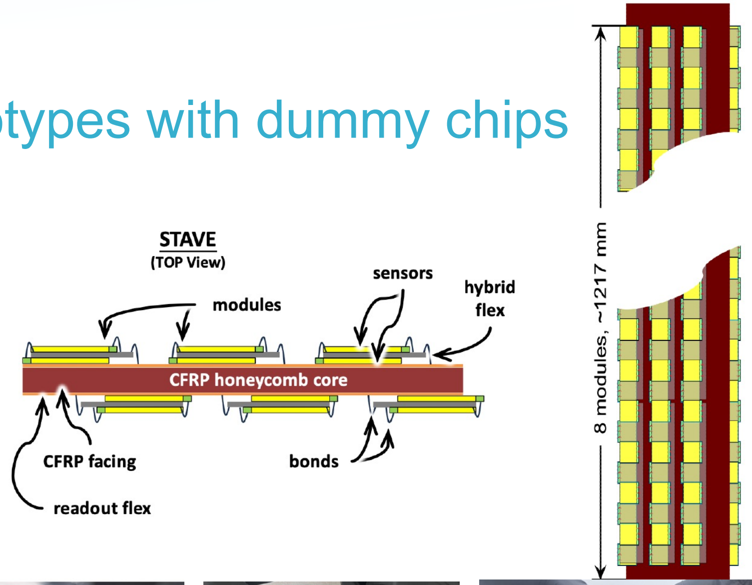


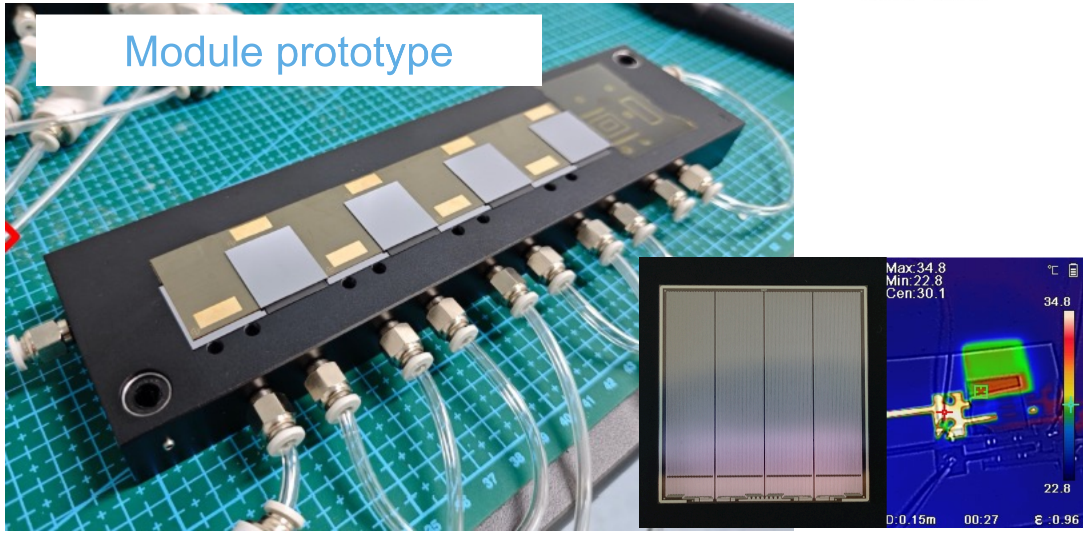
Large prototype planned ~end 2027

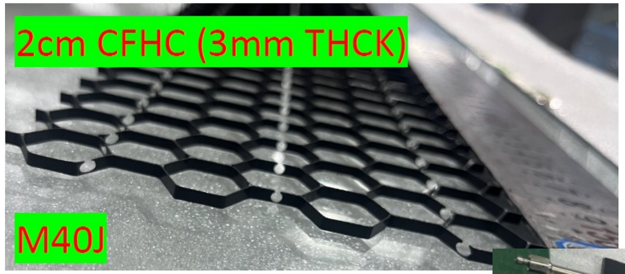
UP: design concept & prototyping

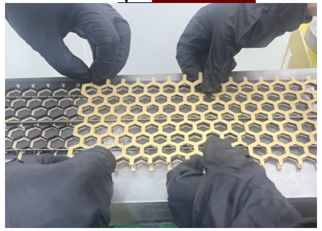
- Three module concept designs
  - Unique gapless design proposed by Chinese groups; prototypes with dummy chips
  - Mechanical prototypes of light-weight bare stave

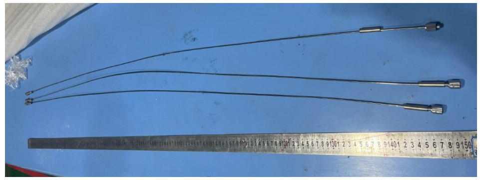






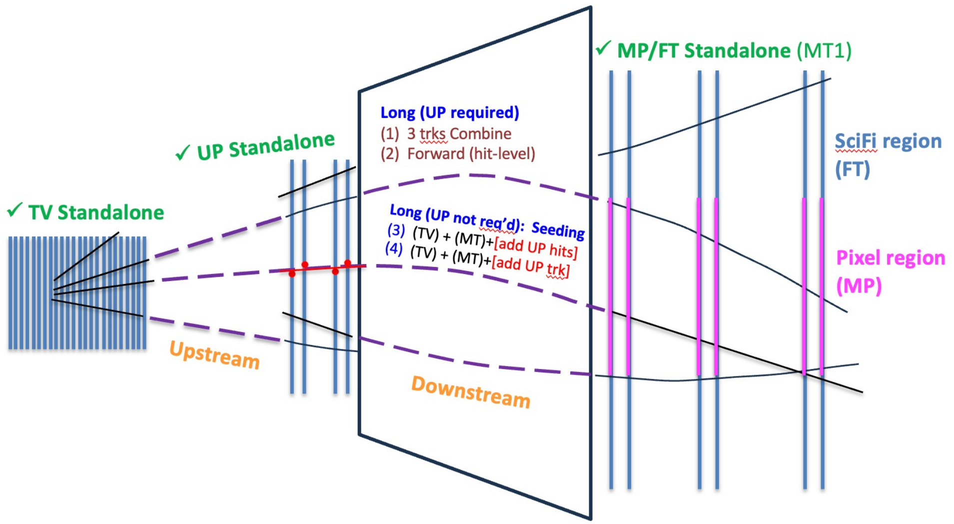




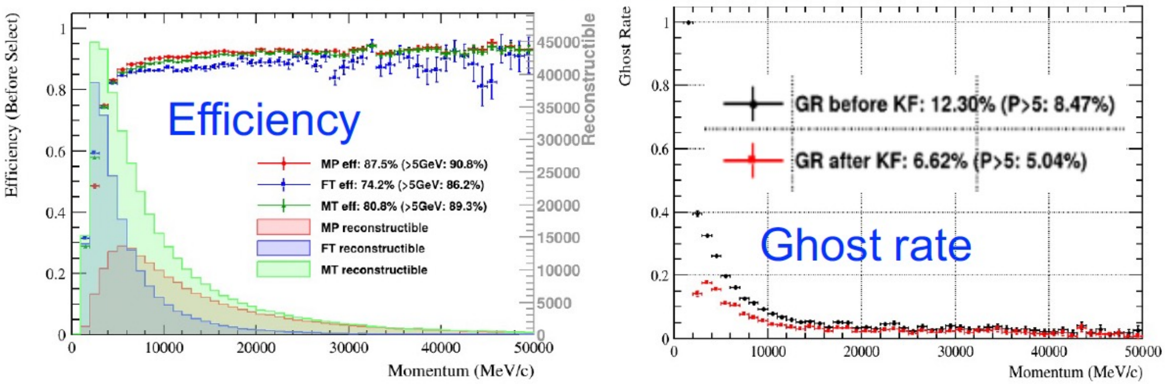


UP: simulation and performance

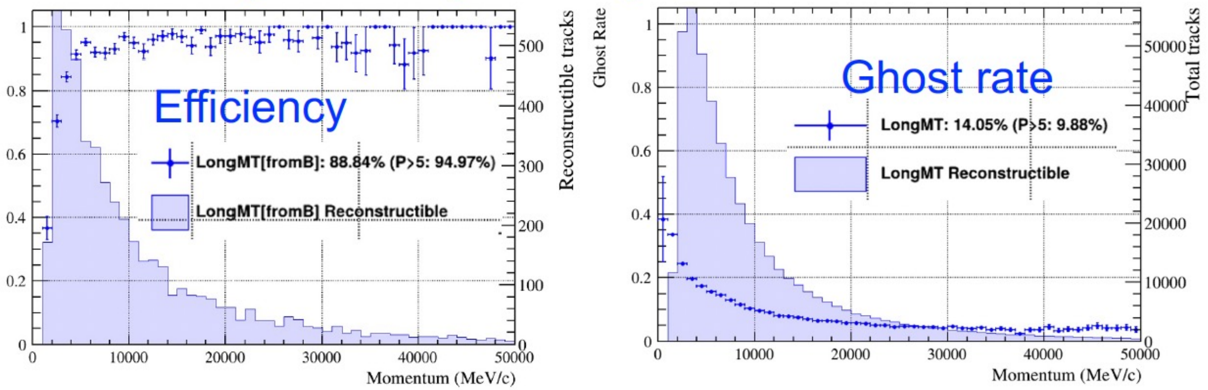
- Standalone UP tracking possible with pixel sensors
- More possibilities in tracking algorithms
  - Forward alg.: VELO → UP / MT
  - Match alg.: VELO + MT → + UP
  - Backward alg. (new!): combine all 3 standalone tracks
- Merging all algorithms give good performance (eff ~95%, ghost rate O(%)) as of now, under >8 times more tracks!



Long Tracks by "backward alg"



Long Tracks by all 3 algs. after clone killer



UP: organization

- Collaborations of 12 groups from China, France, Mongolia and US
  - Chinese groups playing leading role

Project Leader: Jianchun Wang / IHEP,
Deputy: Tomasz Skwarnicki / Syracuse, Benjamin Audurier / IRFU

WPs	Work Packages and Sub-WPs	Leaders
WP.0	TDR preparation	Marina Artuso / Syracuse
WP.1	Simulation, reconstruction and performance	Xuhao Yuan / IHEP, Steve Blusk / Syracuse
1.1	Detector description and simulation software	Xiaokang Zhou / CCNU
1.2	Reconstruction and performance study	Peilian Li / UCAS
WP.2	Pixel sensor chip development	Yiming Li / IHEP, Fabrice Guilloux / IRFU
2.1	Sensor chip design	Xiaomin Wei / NPU, Yang Zhou / IHEP
2.2	Sensor chip evaluation	Elisabeth Niel / LLR, Hui Zhang / IHEP
WP.3	Module and stave	Ray Mountain/Syracuse, Jiesheng Yu/HNU, Manuel Guittiere/Subatech
3.1	Design and prototyping	*(Xuhao Yuan / IHEP),* Theo Bigourdan / Subatech
3.2	Stave mechanical and thermal study	Yi Yang / HNU, (Arnaud Cadiou / Subatech)
3.3	Module evaluation	Charlotte Riccio / IRFU
WP.4	Overall mechanics, installation and cooling	Arnaud Cadiou / Subatech
4.1	Mechanical support	Meriadeg Guillamet / Subatech
4.2	Detector integration and installation	Meriadeg Guillamet / Subatech, Bassem Khanji / Syracuse
4.3	Cooling system	Hangyi Wu / Syracuse
WP.5	Data acquisition system	Kai Chen / CCNU, Zijun Xu / IHEP
5.1	Overal readout scheme	*(Jiachun Wang / IHEP)*
5.2	UP-specific firmware	*(Kai Chen / CCNU)*
5.3	Control and monitoring	*(Zijun Xu / IHEP)*
5.4	DAQ system for evaluation and production	*(Marina Artuso/ Syracuse)*
WP.6	Electronics	Kai Liu / LZU, Christophe Renard / Subatech
6.1	Design of FE electronics	Zhiqiang Fu / LZU
6.2	HV and LV systems	Kechen Li / HTU

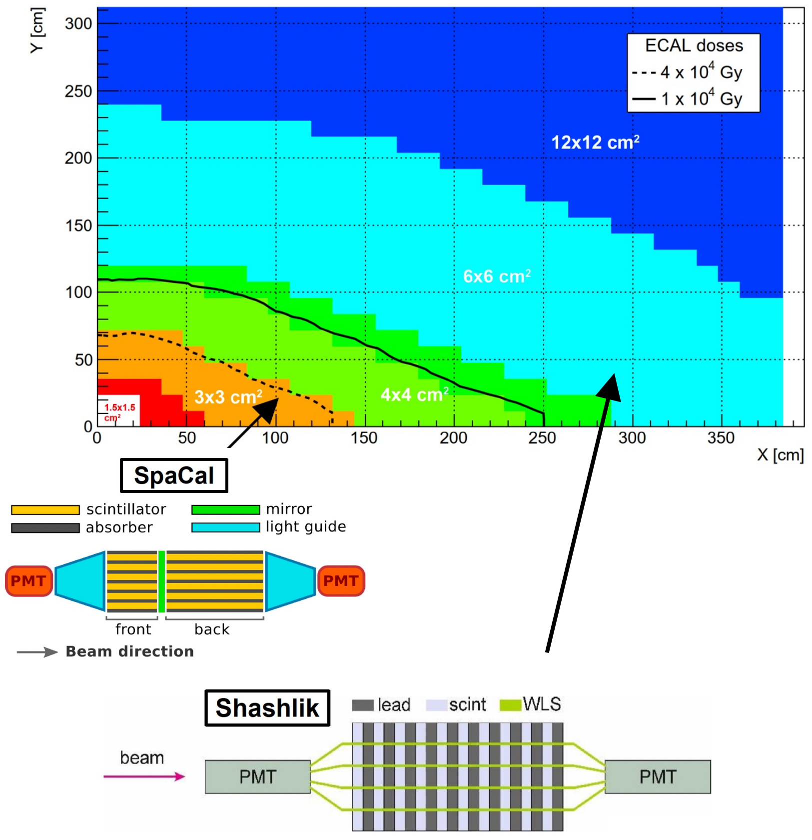

1st UP workshop @ Beijing


2nd UP workshop @ Paris

ECAL → PicoCAL

- Maintaining ECAL performance
- Inner part using SpaCal and outer keeps Shashlik technology
- Timing of O(10) ps expected

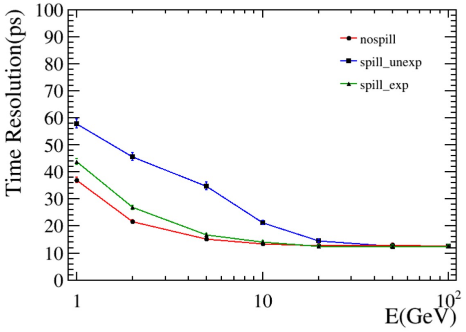
CERN-LHCC-2023-005

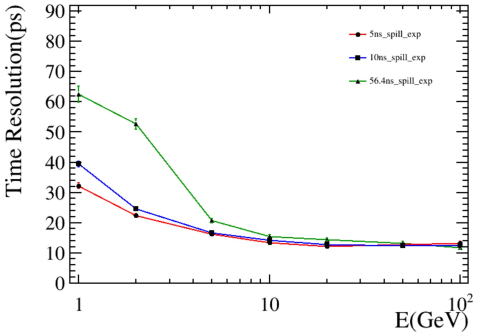


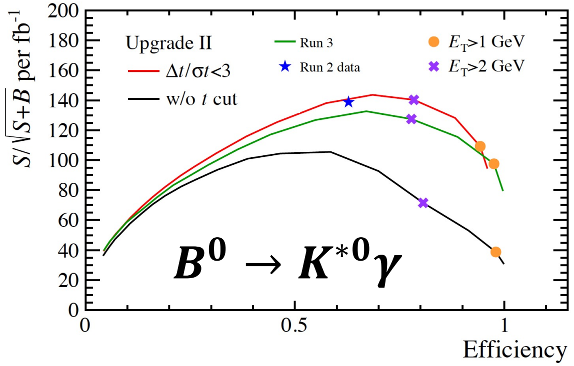
- Chinese groups active in the R&D:
  - Simulation and optimization
  - 3D-printed tungsten absorber
  - GAGG crystal fibre development
  - Light guide
  - SiPM R&D
  - SpaCal module assembly
  - …

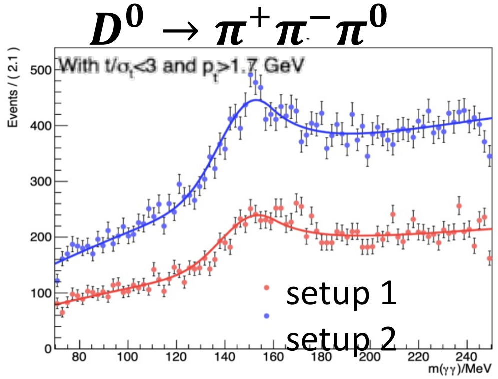
PicoCAL: progress

- Software and simulation
  - Performance studies: decay time impact; timing information
  - Software development & optimization of reconstruction algorithm in full swing towards U2 TDR

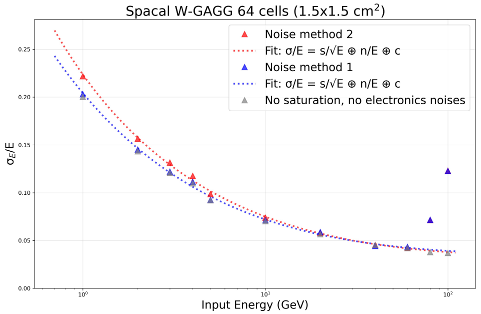


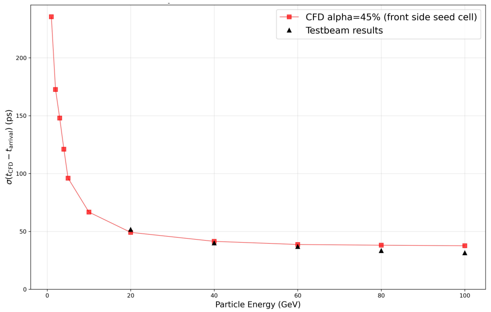






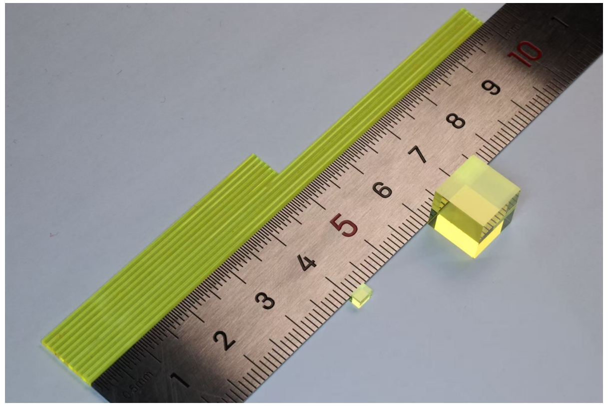
- Templated pulse method developed for digitization, and used in official simulation framework
- Integration of reconstruction algs



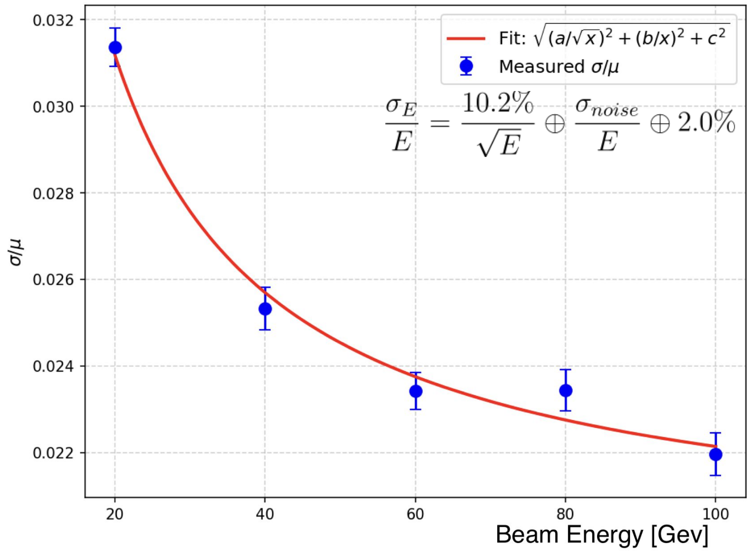


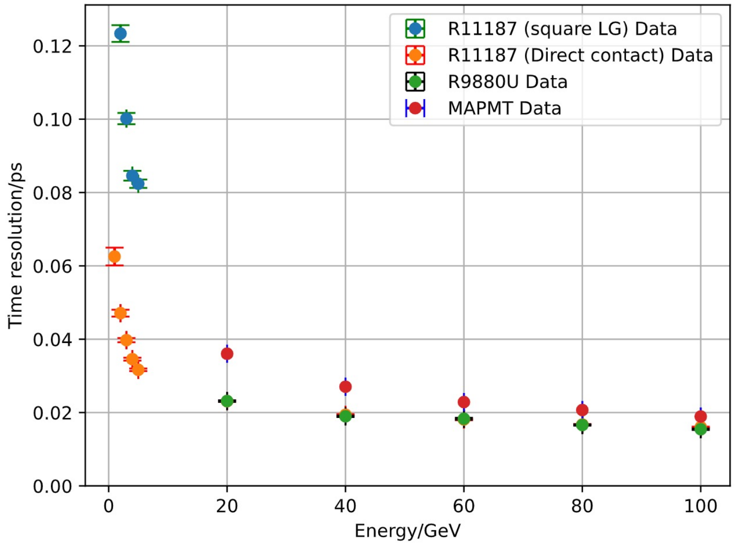
PicoCAL: progress

- Software and simulation
- Fast GAGG crystal fibre development
  - Collaborating with SiPAT (电科芯片)+CERN starting from end of 2021
  - Gradually reducing effective decay time τ_{eff}: 50 ns (2022) → 20 ns (2024) → 8 ns (2025)
  - SpaCal-W-GAGG prototype with GAGG with $\tau_{\text{eff}} \approx 20$ ns, testbeam at SPS+DESY



Increase doping , LY decrese, time resolution increase



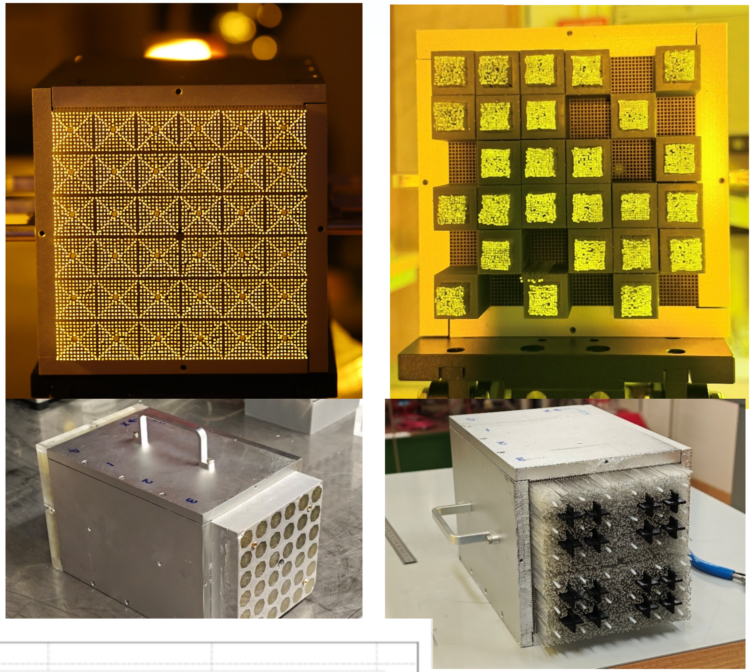


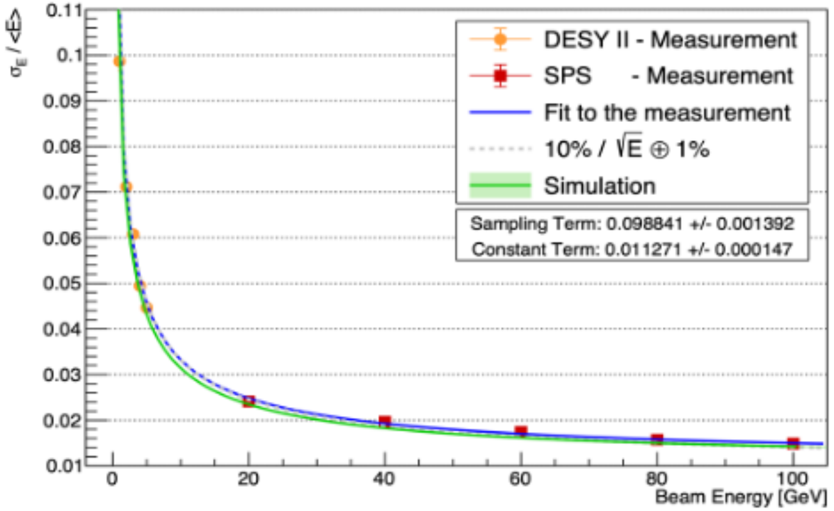
PicoCAL: progress

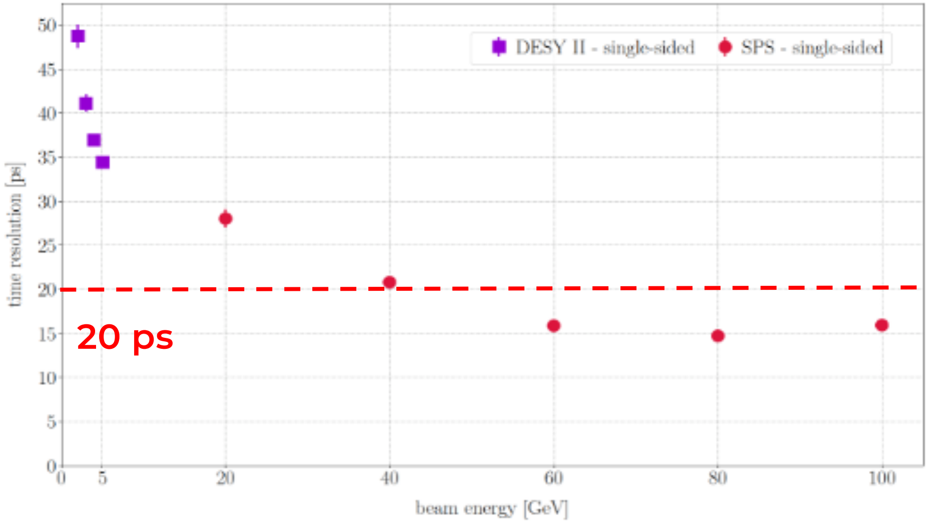
Both use W absorbers
from China group

CNPP.cn 雷佳 LASERADD

- Software and simulation
- Fast GAGG crystal fibre development
- 3D printed tungsten absorbers
    - Co-developed with LaserAdd (雷佳)
- LS3 SpaCal-W-Polystyrene module assembly
    - Modules assembled in Beijing and tested at CERN beams

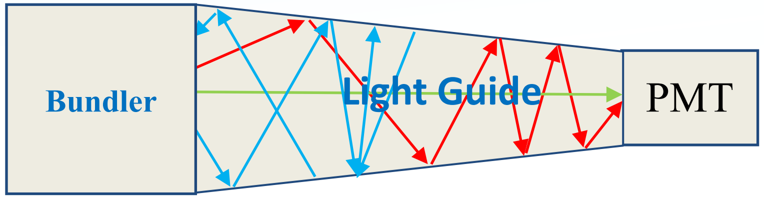




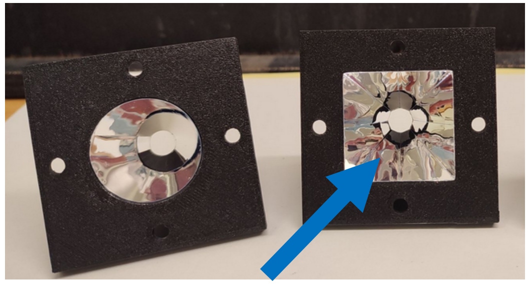
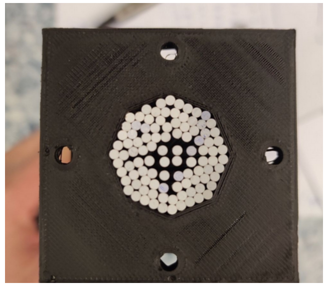


PicoCAL: progress

- Software and simulation
- Fast GAGG crystal fibre development
- 3D printed tungsten absorbers
- LS3 SpaCal-W-Polystyrene module assembly
- Light-guide system development
  - Radiation-hard hollow light-guide and new fiber bundle process with Chinese provider
- PMT R&D started, collaborating with NNVT(北方夜视)+IHEP



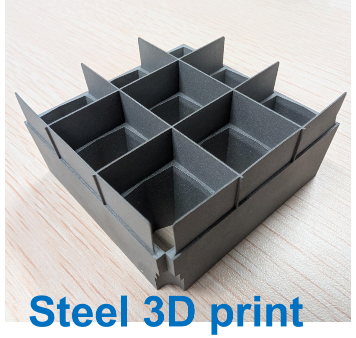
Test light guide and bundler

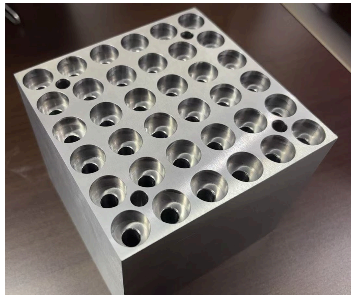



ESR reflection film

Test different production method


Resin 3D print


Steel 3D print


CNC machining

ECAL/PicoCal management structure

ECAL organisation towards LS3 enhancement

ECAL Upgrade Project Leader: Philipp R.
(since July 2024)

WP1: Absorbers
CERN & China*
Hubert G.
Sergey K. & J. Wang

WP2: Optics assembly (fibers & lightguides)
Maryland & Milano & China*
Matteo S. & Z. Yuan

WP3: Organic & crystal fibers R&D
CERN & China*
Etiennette A. & Ming Z.

WP4: PMT & HV & LED system
CERN, ICCUB, CSIC, Maryland, Cincinnati, Bologna, Milano
Phoebe H. & Yuri G. & Conor H.

WP5: Electronics
IJCLab, LPC, LAPP, ICCUB, CSIC, Syracuse
Patrick R. & Christophe B.

WP6: Infrastructure (incl. cabling)
CERN, LAPP, Imperial
Rolf L. & Andrei G.

WP7: Detector Software
CERN, China*, La Salle, Milano-Bicocca, Padova, MIT, Syracuse
Marco P. & Liupan A.

WP8: Testbeam coordination & analysis
CERN & All
Loris M. & Daniele M.

* China: Peking, Tsinghua, Wuhan, SCNU

Upgrade II physics potential

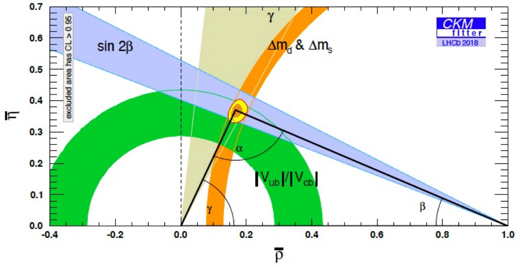
Physics Prospects

- Statistics is powerful
- Some gain can be expected

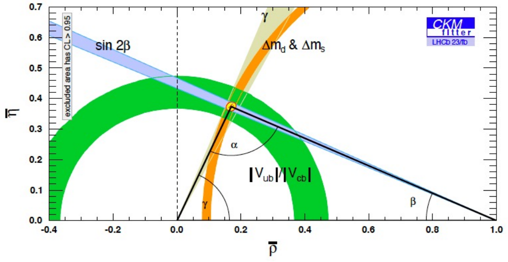
Observable	LHCb current	LHCb (23 fb^{-1})	LHCb (300 fb^{-1})
CKM tests			
γ (all modes)	$4°$ [784, 931]	$1.5°$	$0.35°$
γ ($B_s^0 \to D_s^+ K^-$)	$(^{+17}_{-22})°$	$4°$	$1°$
$\sin 2\beta$	0.04 [932]	0.011	0.003
ϕ_s ($B_s^0 \to J/\psi\phi$)	49 mrad [933]	14 mrad	4 mrad
ϕ_s ($B_s^0 \to D_s^+ D_s^-$)	170 mrad [825]	35 mrad	9 mrad
$\phi_s^{s\bar{s}s}$ ($B_s^0 \to \phi\phi$)	154 mrad [936]	39 mrad	11 mrad
a_{sl}^s	33×10^{-4} [938]	10×10^{-4}	3×10^{-4}
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [847]	3%	1%
Charm			
$\Delta\mathcal{A}^{CP}$	2.9×10^{-4} [790]	1.7×10^{-4}	3.0×10^{-5}
A_Γ	1.3×10^{-4} [877]	4.2×10^{-5}	1.0×10^{-5}
$B^0_{(s)} \to \mu^+\mu^-$			
$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$	71% [661, 662]	34%	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	14% [661, 662]	8%	2%
EW penguins			
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044 [703]	0.025	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.10 [709]	0.031	0.008
LFU tests			
R_{D^*} ($B^0 \to D^{*-}\ell^+\nu$)	0.026 [941, 942]	0.007	0.002
$R_{J/\psi}$ ($B_c^+ \to J/\psi\ell^+\nu$)	0.24 [943]	0.07	0.02

Physics case for Upgrade II, CERN-LHCC-2018-027, arXiv:1808.08865
Chen et al, Frontiers of Physics 18 (2023) 44601

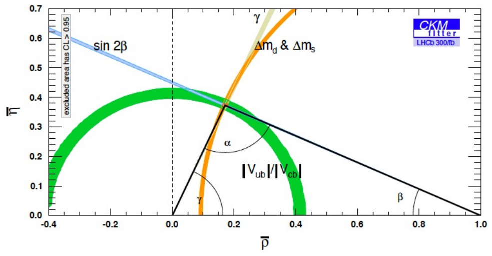
Run 2



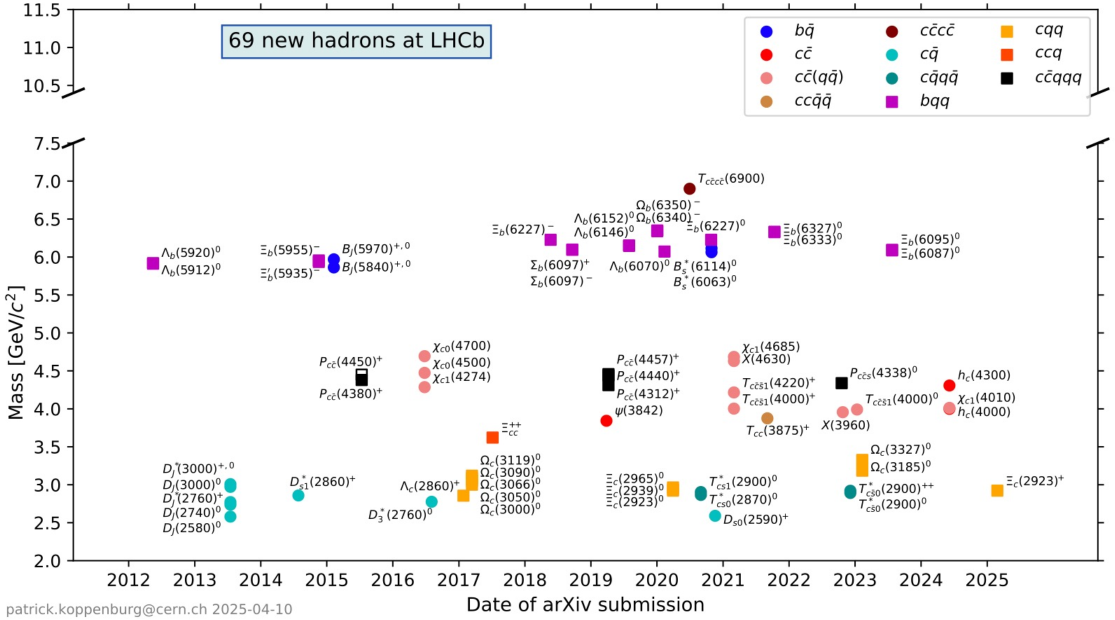
Run 3



Upgrade II



- Some not



https://www.nikhef.nl/%7Epkoppenb/particles.html

??

Baryons?
(bqq, ccq,
bcq, bbq,…)

Tetraquark?

Pentaquarks?

An example: search for T_{bc}

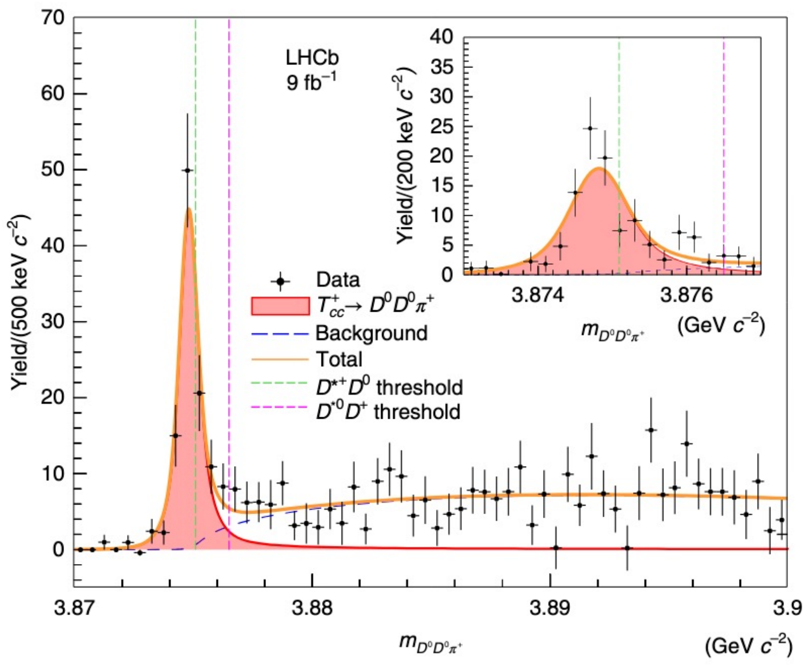
- T_{cc} $(cc\bar{u}\bar{d})$ discovery in $DD\pi^+$ final state

- Similar tetraquark states $T_{bc}(bc\bar{u}\bar{d})$?
  - Mass prediction around BD threshold (-50, 120)MeV

W. Chen, T.G.Steele, S.-L. Zhu, PRD 89 (2014) 054037
M. Karliner, J.L.Rosner, PRL 119 (2017) 202001
T.F.Carames, J.Vijande, A. Valcarce, PRD 99 (2019) 014006
A.Radhakrishnan, M.Padmanath, N.Mathur, PRD 110 (2024) 034506
S.Meinel, M.Pflaumer, M.Wagner, PRD 106 (2022) 034507
W.L.Wu, Y.Ma, Y.-K. Chen, L.Meng, S.-L. Zhu, PRD 110 (2024) 094041

Above BD threshold:
D.Ebert, R.N.Faustov, V.O.Galkin, W.Lucha, PRD 76 (2007) 114015
E.J.Eichten, C. Quigg, PRL 119 (2017) 202002
J.-B. Cheng, S.-Y. Li, Y.-R. Liu, Z.-G. Si, T. Yao, CPC 45 (2021) 043102
Y. Song, D. Jia, Comm. Theo. Phys. 75 (2023) 055201

  - If $m(T_{bc}) > m(B) + m(D)$ can decay strongly



Nature Phys. 18 (2022) 7

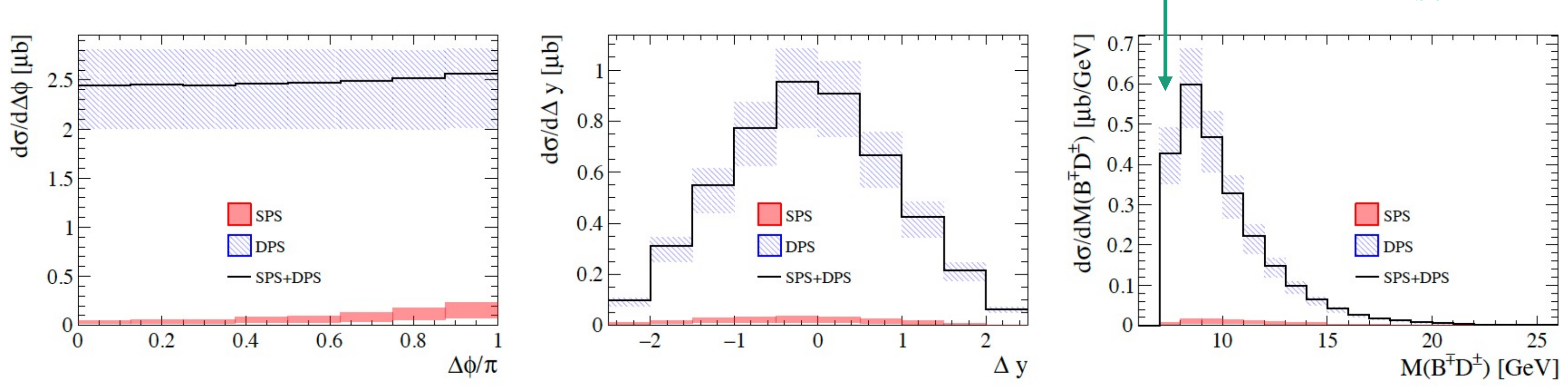
Background to strongly decaying T_{bc}

M.Feng, YL, H.-S. Shao,
accepted by CPC

- Main background: associate production of B and D mesons
- Use MadGraph_aMC@NLO to simulate SPS & DPS contribution

$$T_{bc} \to B^- D^+ ,$$
$$B^- \to J/\psi(\to \mu^+\mu^-)K^- ,$$
$$D^+ \to K^- \pi^+ \pi^+ ,$$

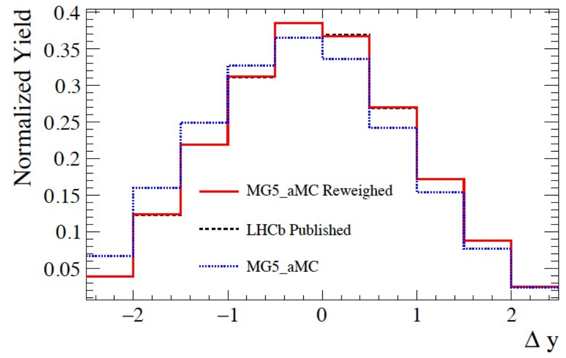
Where to look for T_{bc}



σ_{eff} = 15 mb
also scanned for 5, 30 mb

Using published LHCb B and D production paper to weight DPS contribution

$$\sigma(BD) = \frac{\sigma(B)\times\sigma(D)}{\sigma_{\text{eff}}}$$



T_{bc} assumption

M.Feng, YL, H.-S. Shao, accepted by CPC

- Cross-section prediction
  - Optimistic: 103 nb — A. Ali, Q. Qin, W. Wang, PLB 785 (2018) 605
  - Pessimistic: 0.3 nb — Y.-Q. Chen, S.-Z. Wu, PLB 705 (2011) 93
  - Intermediate: 18 nb

$$\sigma(T_{bc}) \approx \sigma(T_{cc}^{+}) \times \frac{\sigma(\Xi_{bc})}{\sigma(\Xi_{cc})} \approx 45 \times 0.4 \approx 18 \text{ nb},$$

Derived from Tcc; Tcc xsec prediction from A. Ali, I. Ahmed, M.J.Aslam, PLB 855 (2024) 138779
Xibc/Xicc ratio from J.W.Zhang, X.G.Wu, T. Zhong PRD 83 (2011) 034026

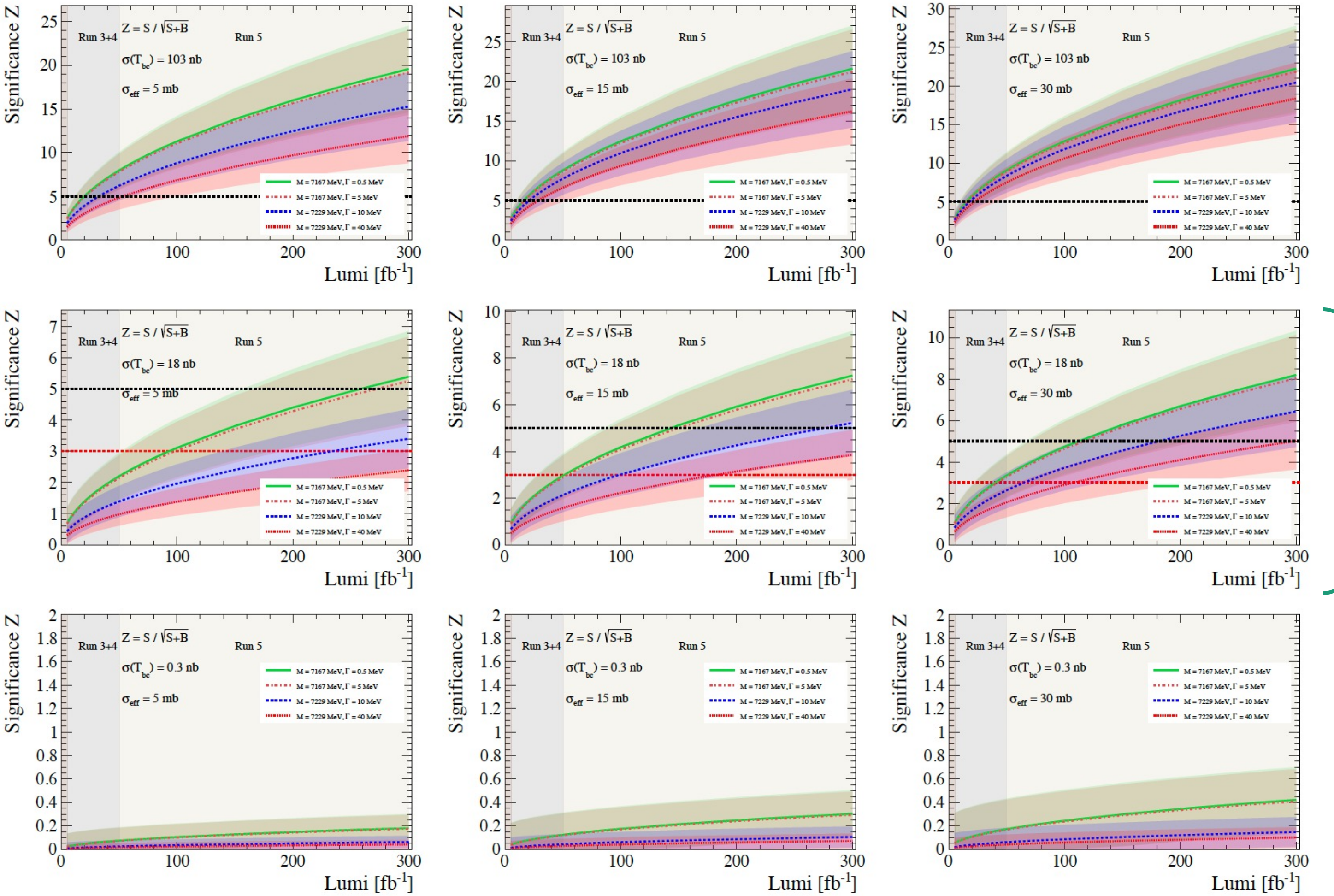
- Mass / Width

$m(T_{bc})$ **[MeV]**	$\Gamma(T_{bc})$ **[MeV]**	$\sigma(T_{bc})$ **[nb]**
7167	0.5	0.3, 18, 103
	5	0.3, 18, 103
7229	10	0.3, 18, 103
	40	0.3, 18, 103

Sensitivity to strongly decaying Tbc

M.Feng, YL, H.-S. Shao,
accepted by CPC

	σ_{eff} = 5 mb	σ_{eff} = 15 mb	σ_{eff} = 30 mb
$\sigma(T_{bc})$ = 103 nb			
$\sigma(T_{bc})$ = 18 nb			
$\sigma(T_{bc})$ = 0.3 nb			



Run 3+4

Run 5

Data after Upgrade II needed for 5σ discovery in most parameter space!

Summary

- LHCb is taking data at full speed after Upgrade I with improved performance, especially trigger efficiency for hadronic final states
- Development for Upgrade II is ongoing with innovative technologies
- LHCb-China contributed in U1, and leading in many aspects in UII activities exploiting domestic technology
- Upgrade II will be a rich mine for heavy flavour physics, and QCD

Thank you and stay tuned