Outlook for experimental HEP
or "what to keep an eye on in particle physics between now and 2095"
Lecture I

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University of Oxford

2022 European School of HEP, Israel
11-12 December 2022

The imposing fortress of the Standard Model

This appears impregnable, but with innovation and determination
it can be breached, and the prize of New Physics seized….

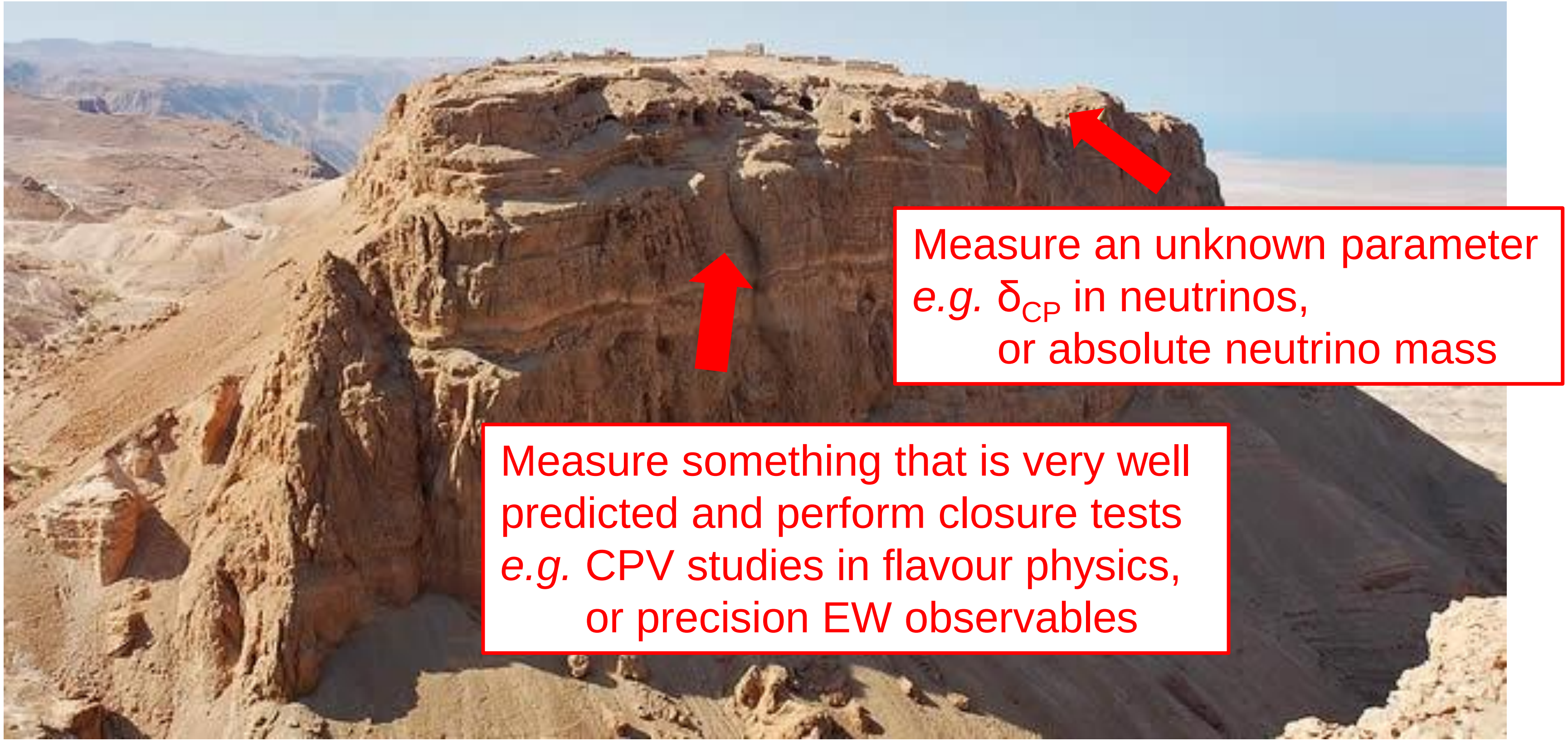
An early example of experimental assault

It took the Romans 3 months. So far the Standard Model has resisted longer.

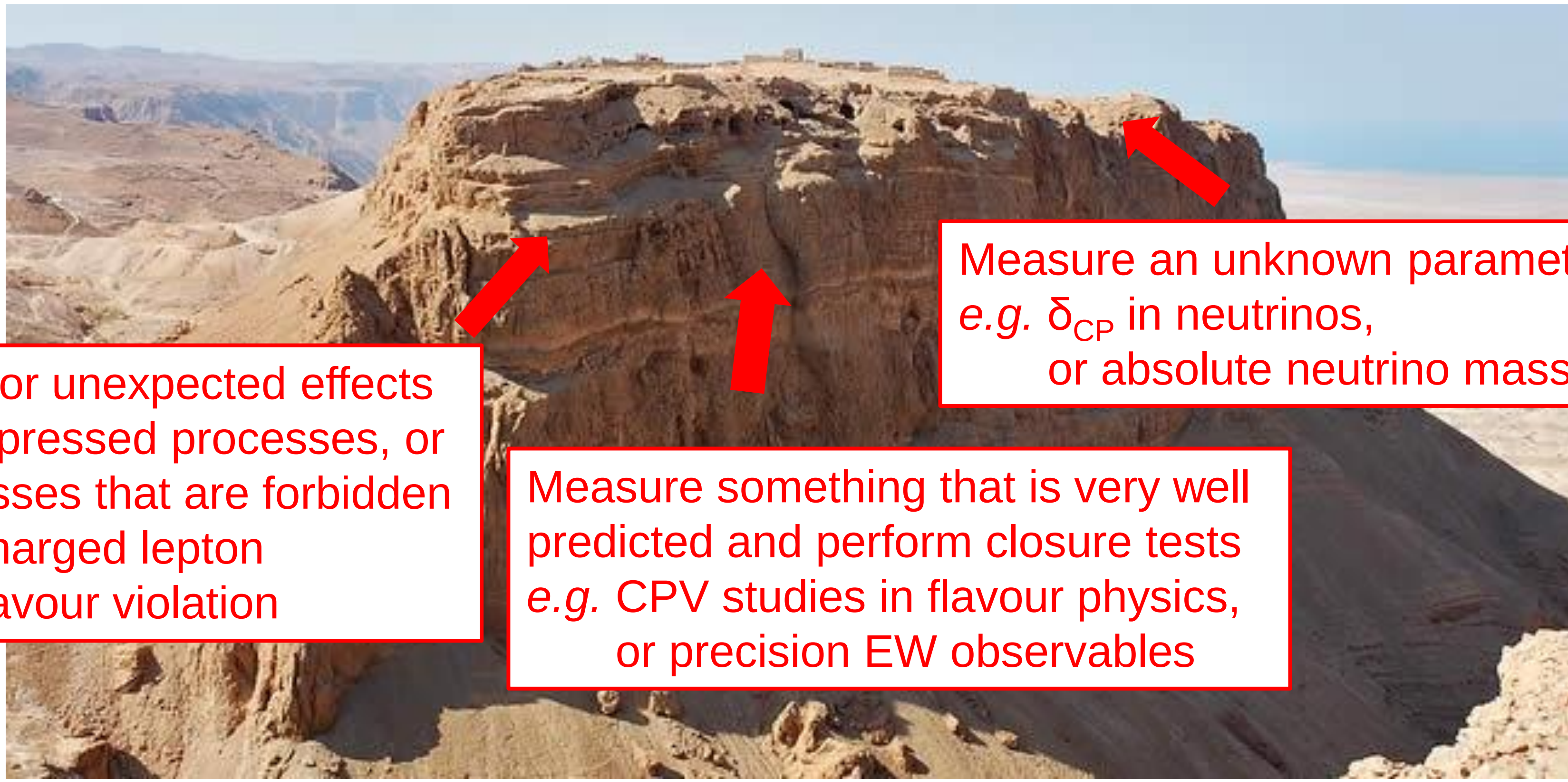
The attack on the Standard Model: diverse approaches are required

Measure an unknown parameter
e.g. δ_{CP} in neutrinos,
or absolute neutrino mass

The attack on the Standard Model: diverse approaches are required



The attack on the Standard Model: diverse approaches are required

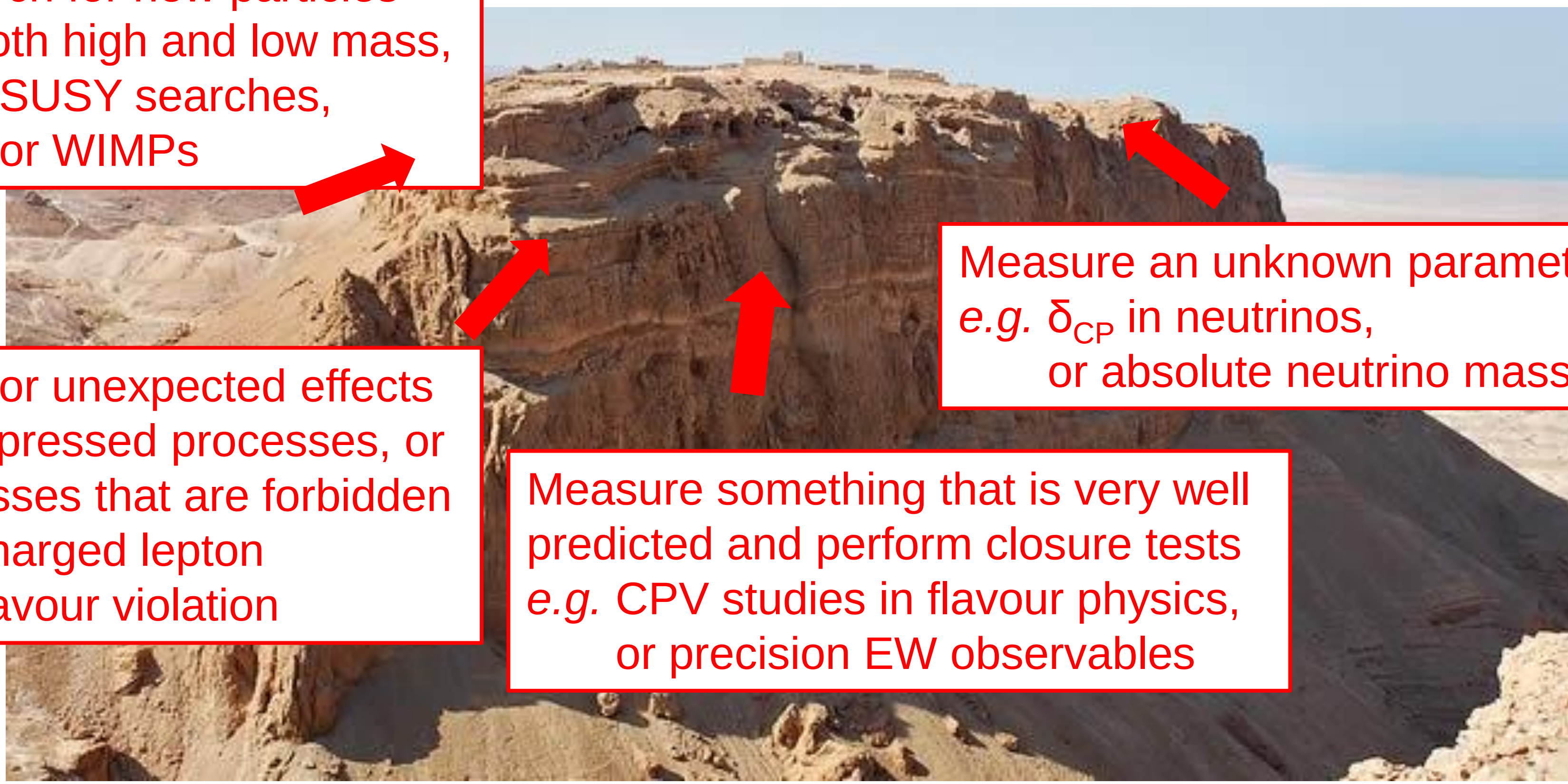


Measure an unknown parameter
e.g. δ_{CP} in neutrinos,
or absolute neutrino mass

Look for unexpected effects in suppressed processes, or processes that are forbidden
e.g. charged lepton flavour violation

Measure something that is very well predicted and perform closure tests
e.g. CPV studies in flavour physics,
or precision EW observables

The attack on the Standard Model: diverse approaches are required



Search for new particles of both high and low mass, *e.g.* SUSY searches, or WIMPs

Measure an unknown parameter *e.g.* δ_{CP} in neutrinos, or absolute neutrino mass

Look for unexpected effects in suppressed processes, or processes that are forbidden *e.g.* charged lepton flavour violation

Measure something that is very well predicted and perform closure tests *e.g.* CPV studies in flavour physics, or precision EW observables

And we should never be discouraged by failure

Lecture outline

Lecture I

- Future neutrino physics
- FIP and WIMP searches
- Flavour physics

Lecture II

- Future high-energy colliders

In all cases focusing on the *future*.
this means experiments starting ~ now, approved to start in a few years, or proposed for the longer time scale.

Lecture outline

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- FIP and WIMP searches
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Getting my excuses in early:

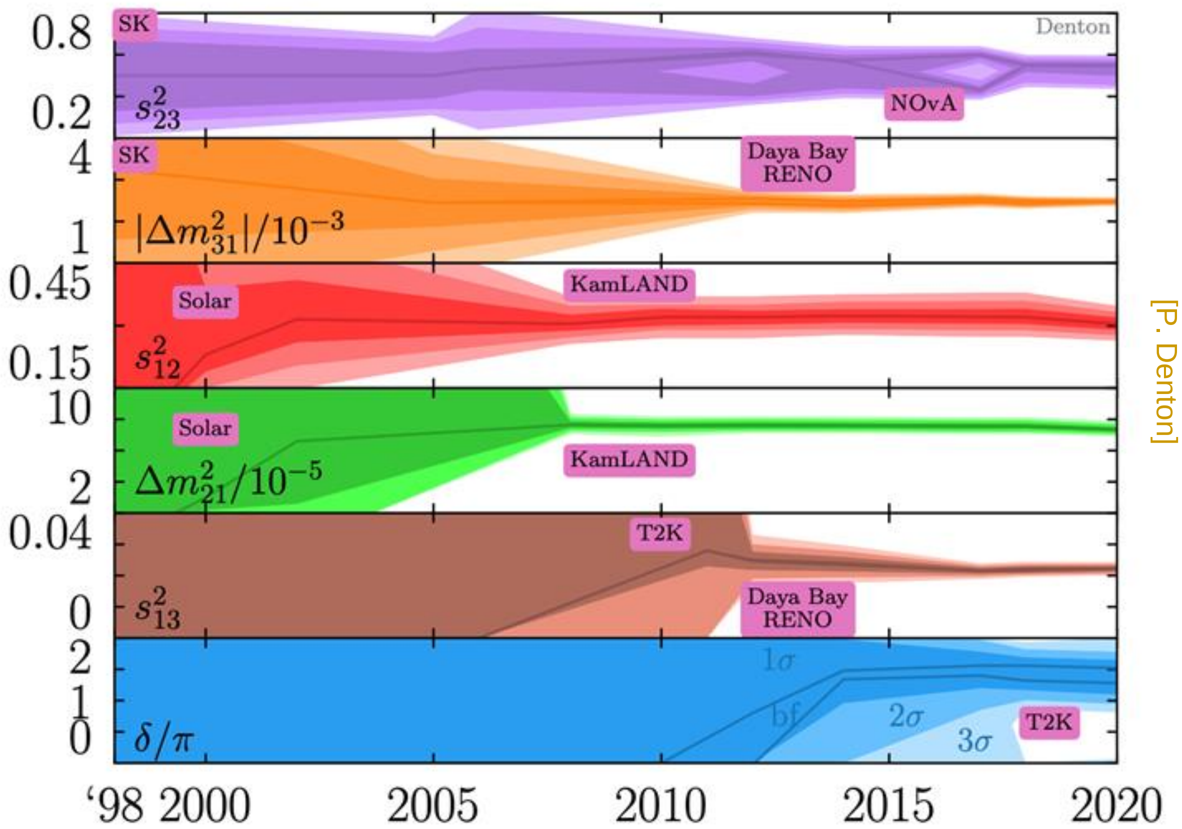
- I cannot be comprehensive, so concentrate on those experiments that are sensitive to 'New Physics'. This means no mention of hadron spectroscopy (*e.g.* FAIR), heavy-ion and nuclear physics (*e.g.* EIC) *etc*.
- Many other topics omitted (*e.g.* particle astrophysics).
- Even within topics, I am not comprehensive (*e.g.* neutrino observatories).
- Finally, I give large weight to flavour physics and the FCC.

Future of neutrinos

- Open questions in neutrino-oscillations physics
- DUNE, Hyper Kamiokande and JUNO
- Absolute neutrino mass and neutrinoless double-beta decay

Neutrino-oscillation physics: 20 year of progress

In the past two decades solar, atmospheric, reactor and accelerator experiments have greatly increased our knowledge of the neutrino-oscillation parameters.

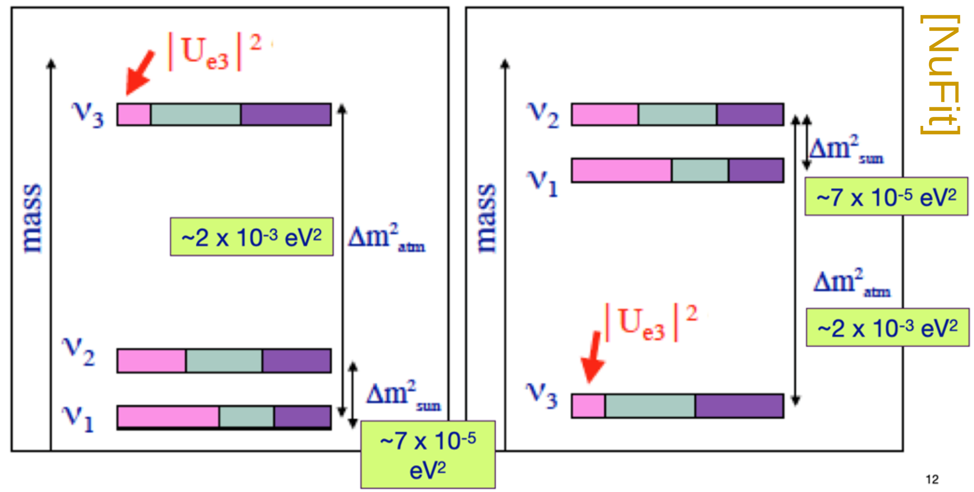


[P. Denton]

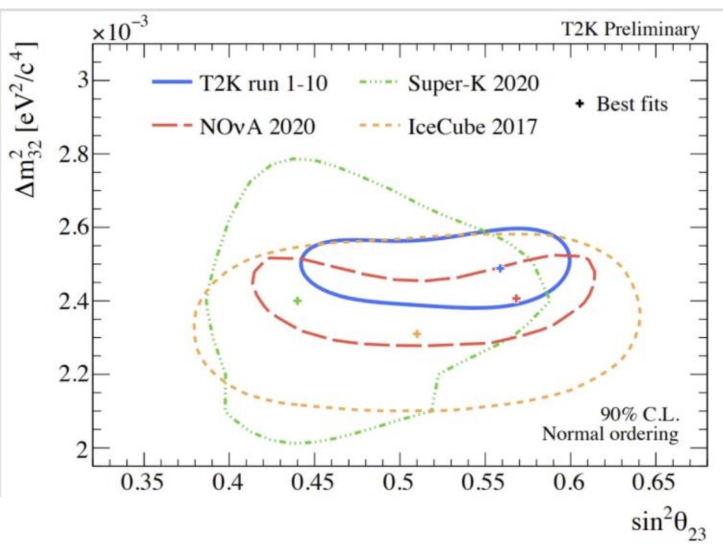
However, many open questions remain…

Neutrino-oscillation physics: open questions

What is the mass ordering ?



[NuFit]



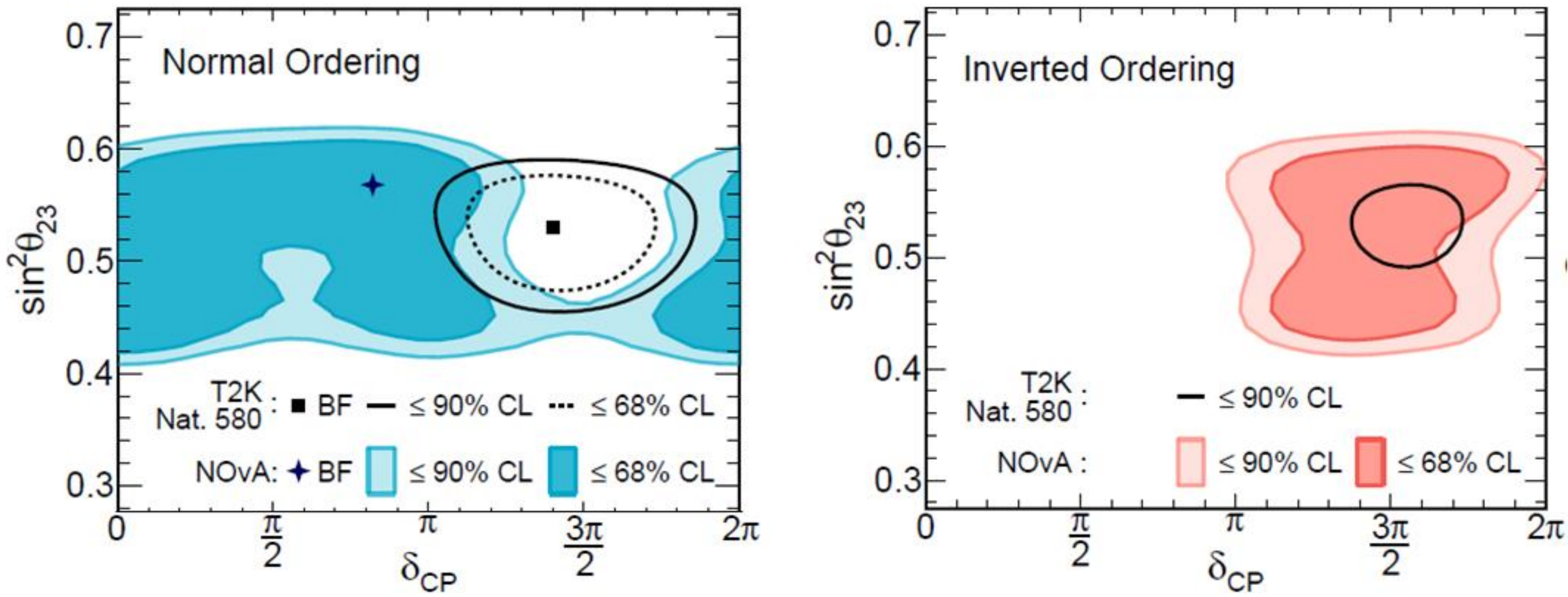
[arXiv:2105.06732]

Is mixing between 2 and 3 maximal (*i.e.* $\sin^2\theta_{23} = 0.5$) ? Which octant is θ_{23}? (T2K & NOvA prefer upper, Super K lower)

Is there CPV, and if so what is the value of δ_{CP} ?

Neutrino-oscillation physics: open questions

First hints on value of δ_{CP} from current accelerator experiments, T2K & NOvA, but not entirely consistent. Both experiments will continue to run & ~double sample size.



[T2K, Nature 580 (2020) 339, Erratum, Nature 583 (2030) E16]
[NOvA, PRD 106 (2022) 032004]

Open questions for next generation of experiments: DUNE, Hyper K and JUNO.

Long-baseline neutrino experiments

Majority of mixing parameters, including δ_{CP} can be probed using $\upsilon_\mu \rightarrow \nu_e$ and $\overline{\upsilon_\mu} \rightarrow \overline{\upsilon_e}$ oscillations over long baselines – raison d'être for DUNE and Hyper K.

υ_e appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(A-1)\Delta]}{(A-1)^2}$$
$$+ \ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin[A\Delta]}{A} \frac{\sin[(A-1)\Delta]}{(A-1)} \cos\Delta$$
$$- \ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin[A\Delta]}{A} \frac{\sin[(A-1)\Delta]}{(A-1)} \sin\Delta$$

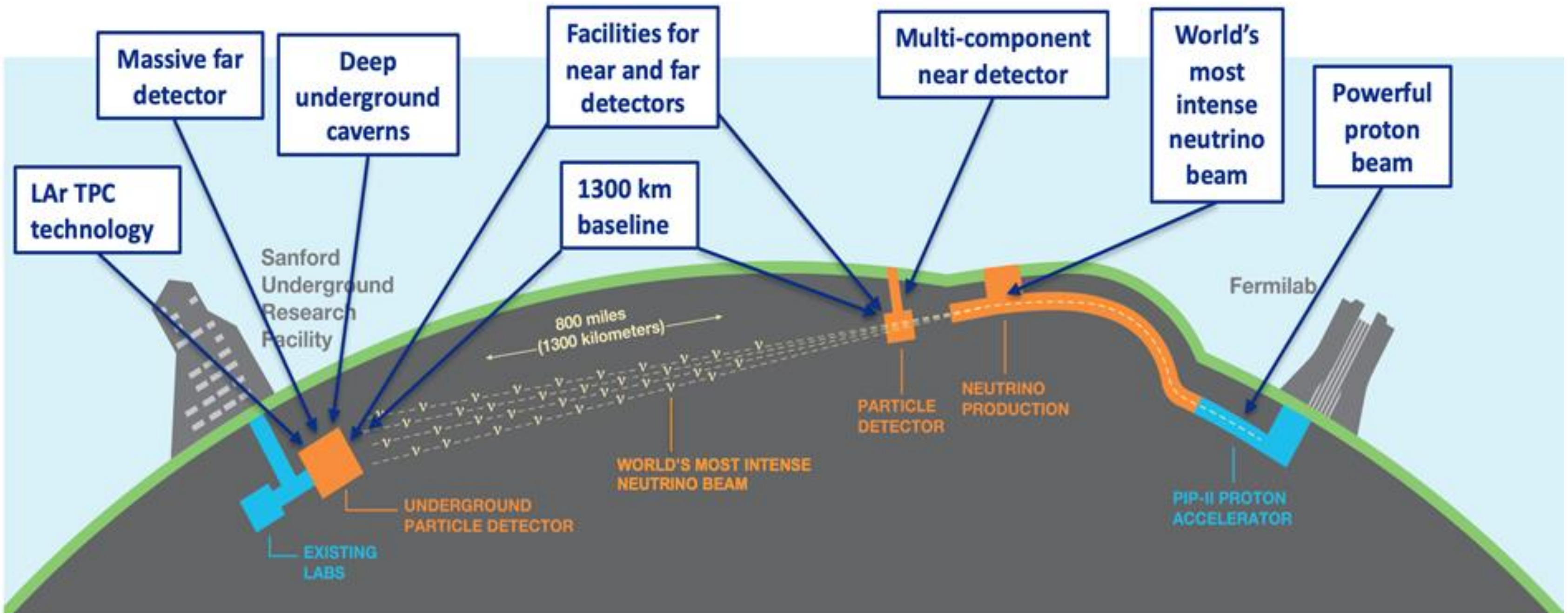
with $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$ $\quad \Delta = \frac{\Delta m^2_{31} L}{4E}$ $\quad A = G_F N_e \frac{L}{\sqrt{2}\Delta}$ (L = baseline, E = energy).

For $\overline{\upsilon_\mu} \rightarrow \overline{\upsilon_e}$ then $\delta_{CP} \rightarrow -\delta_{CP}$ (CPV) and $A \rightarrow -A$ (matter asymmetry).

υ_e appearance – mass hierarchy, δ_{CP} and octant of θ_{23}

υ_μ disappearance – high precision $|\Delta m_{32}|$ and $\sin^2 2\theta_{23}$

Deep Underground Neutrino Experiment (DUNE)



Hyper Kamiokande – the franchise continues

Hyper Kamiokande
(~2027-)

Super Kamiokande (1996-)

Kamiokande
(1983-1996)

[S. King]

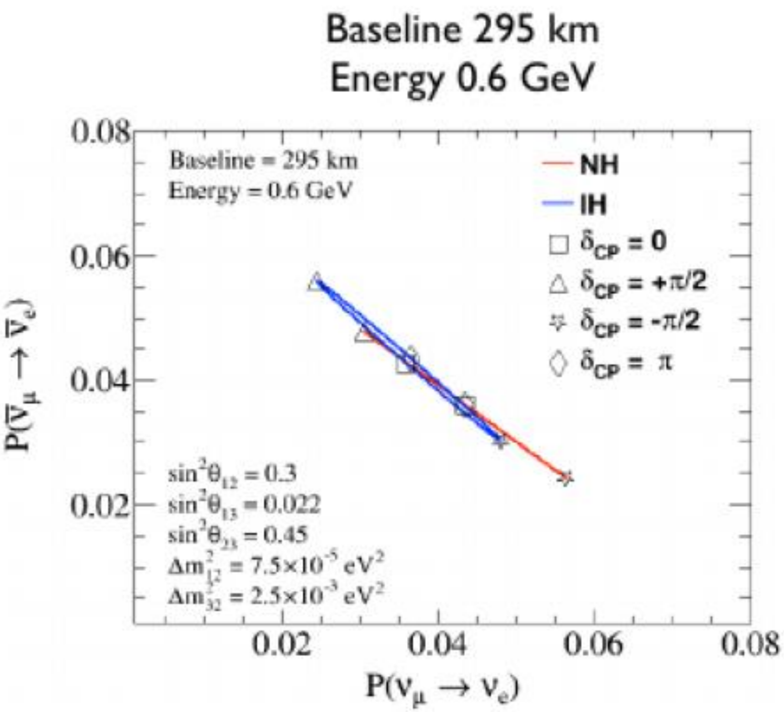
Many physics goals (solar, supernova, atmospheric neutrinos; nucleon decay), however principal task is to collect data from upgraded J-PARC neutrino beam.

DUNE and Hyper Kamiokande, compared

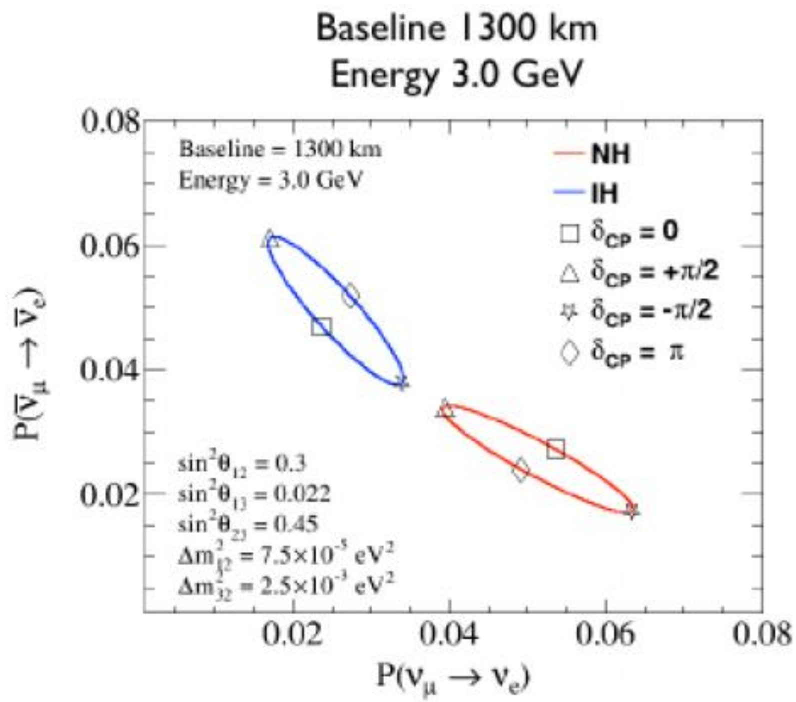
DUNE	Hyper Kamiokande
1285 km baseline (gives sensitivity to matter effects)	295 km baseline (reduces correlation between CPV and matter effects)
Wide-band, on-axis beam, 1.2 MW, 120 GeV protons, 1.1 x 10^{21} P.O.T. / year, flux peaks at 2.5 GeV	Narrow-band, 2.5^{o} off-axis beam, 1.3 MW, 30 GeV protons, 2.7 x 10^{22} P.O.T. / year, flux peaks at 0.6 GeV
40 kt detector mass (when complete), LArTPC	187 kt detector mass, water Cherenkov
Fine-grained detector – access all charged-current cross-section channels	Focus on charged-current quasi-elastic events
Possible upgrade: 2.4 MW beam	Additional intermediate detector IWCD (1 kt water Cherenkov) to measure unoscillated spectra
	Possible upgrade: second detector in Korea (baseline 1100 km)

DUNE and Hyper Kamiokande – consequences of baseline choice

With very long baseline, matter effect dominates → δ_{CP} & mass ordering disentangle.



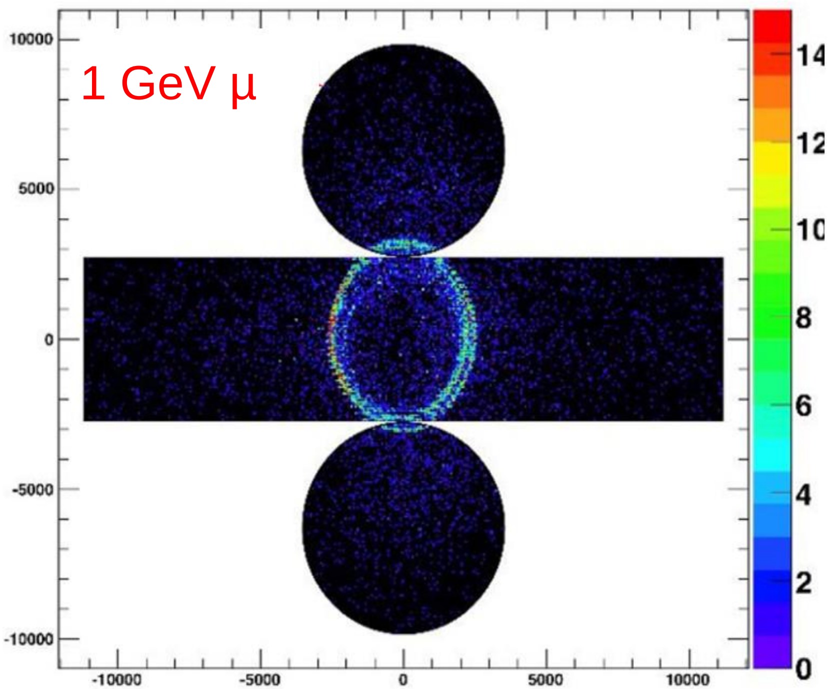
(Hyper-K like)

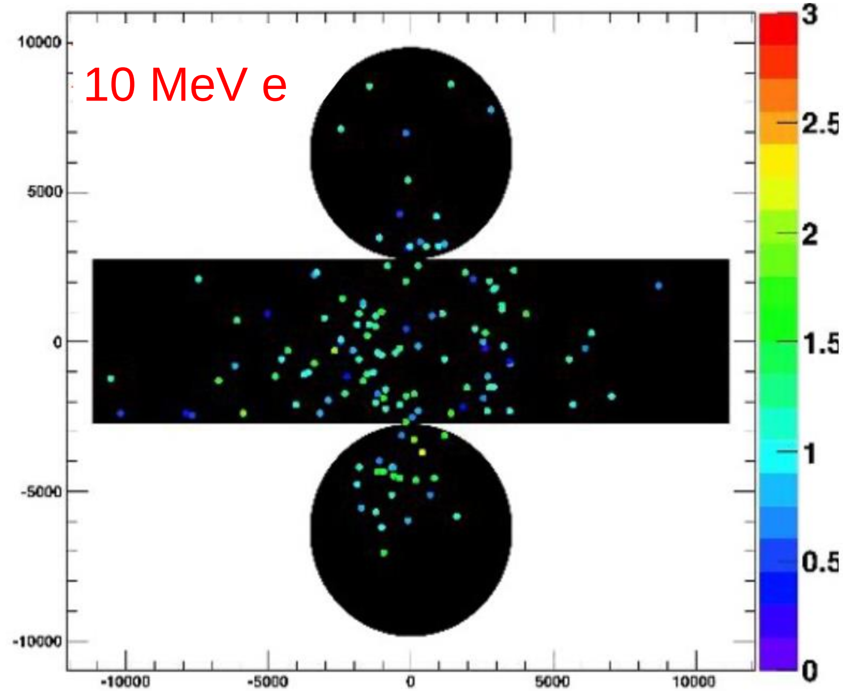


(DUNE like)

[J. Dawson]

Simulated neutrino events in Hyper K



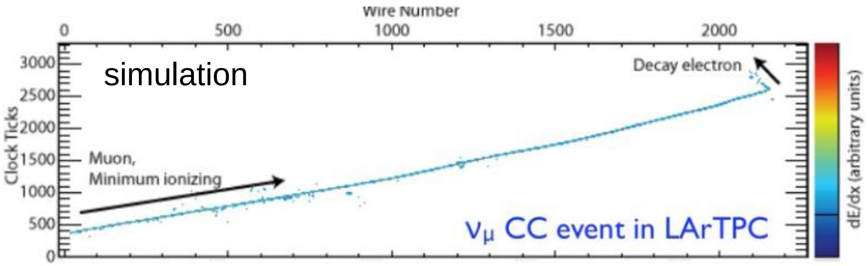


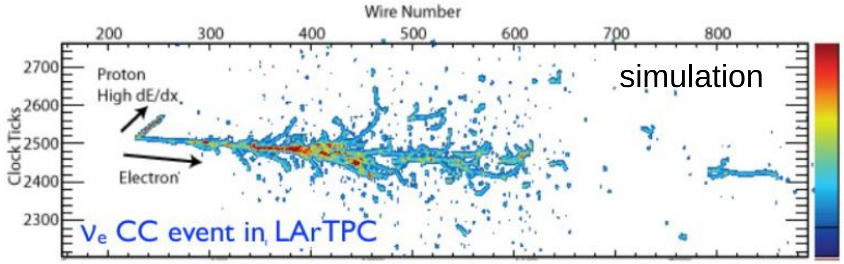
PMT time → vertex position
Ring geometry → direction

‘Brightness’ → momentum
‘Sharpness’ → PID

DUNE LArTPC

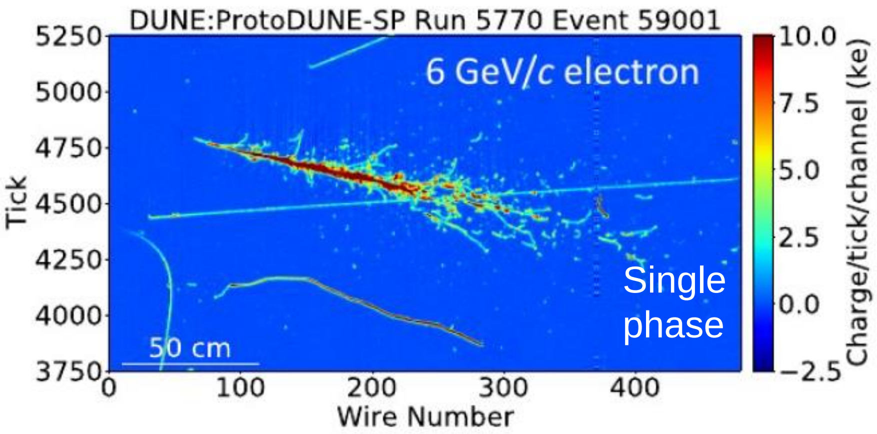
LArTPCs will provide excellent calorimetric and spatial resolution. Technology is now well established (for single phase detectors): ICARUS, MicroBoonE *etc*. Three 17 kt modules foreseen (horizontal & vertical drift). Technology for fourth is open.



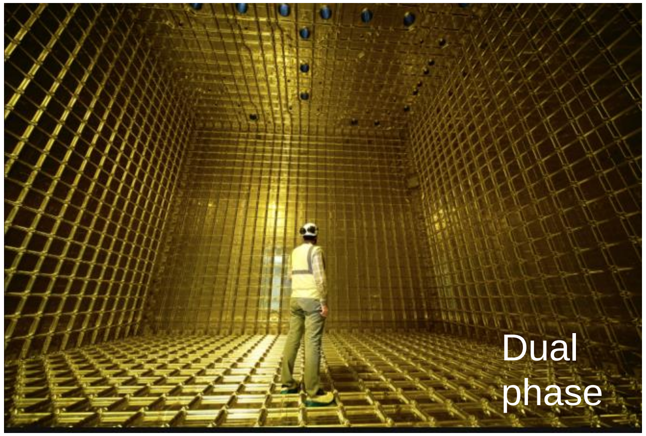


[J. Dawson]

Both single-phase and dual-phase prototypes under evaluation at CERN.



JINST 15 (2020) 12, P12004

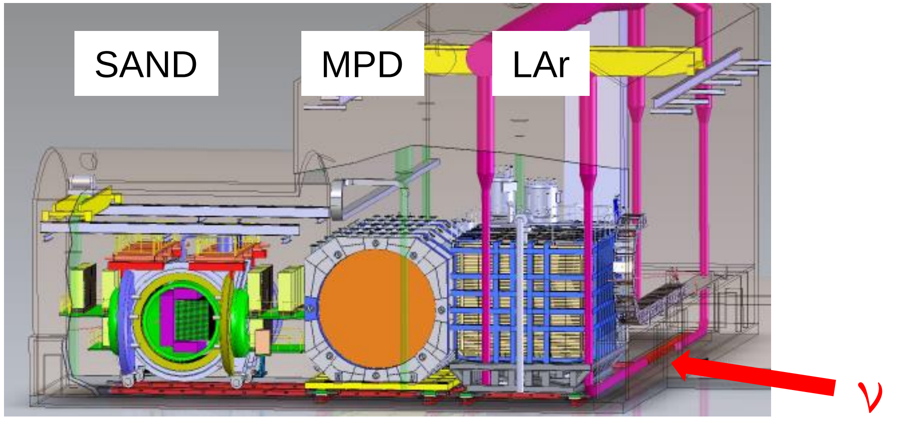


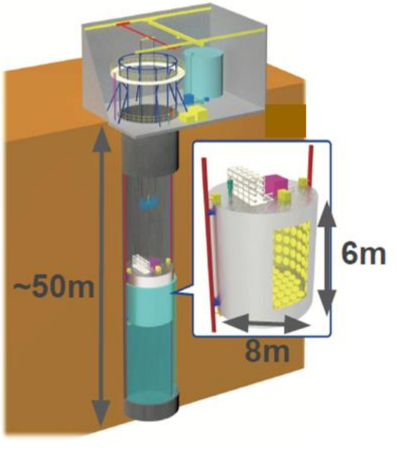
Near (and intermediate) detectors

Near detectors essential in reducing systematics, by characterising beam and allowing beam flux and interaction cross sections to be disentangled.

DUNE near detectors

- 3D tracking scintillating fibres
- Multipurpose detector (gaseous Ar TPC, ECAL & magnet)
- LAr TPC



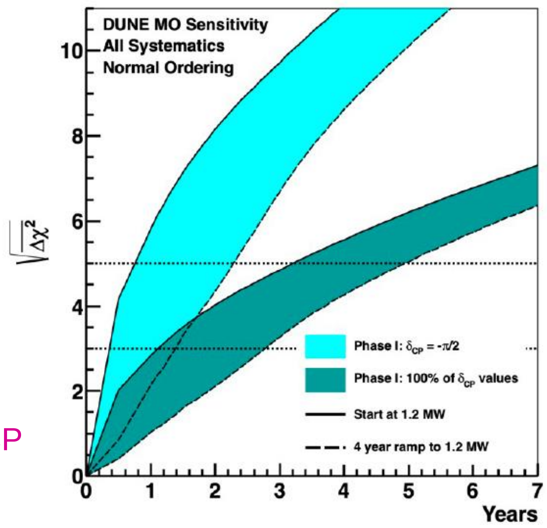


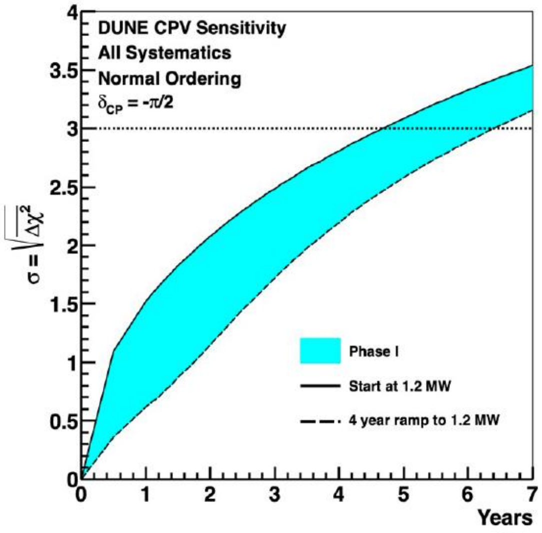
Hyper Kamiokande will use refurbished set of near detectors built for T2K together with an Intermediate Water Cherenkov Detector at a baseline of ~1 km. This is movable, allowing measurements at different off-axis angles.

DUNE plans and physics reach

Phase 1: begin data taking early 2030s with two far detectors

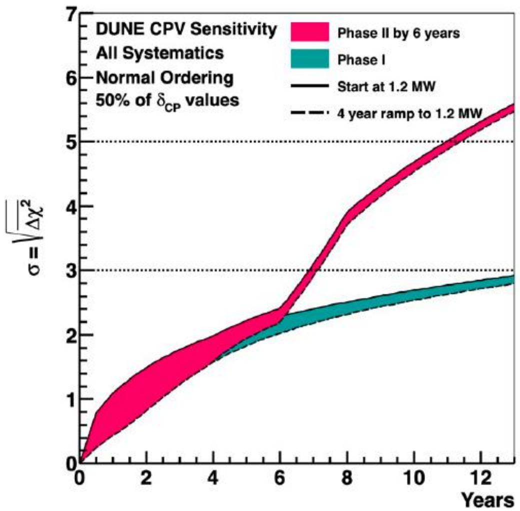
Physics goals:
- unambiguous result for mass ordering
- 3σ CPV signal at maximal δ_{CP}



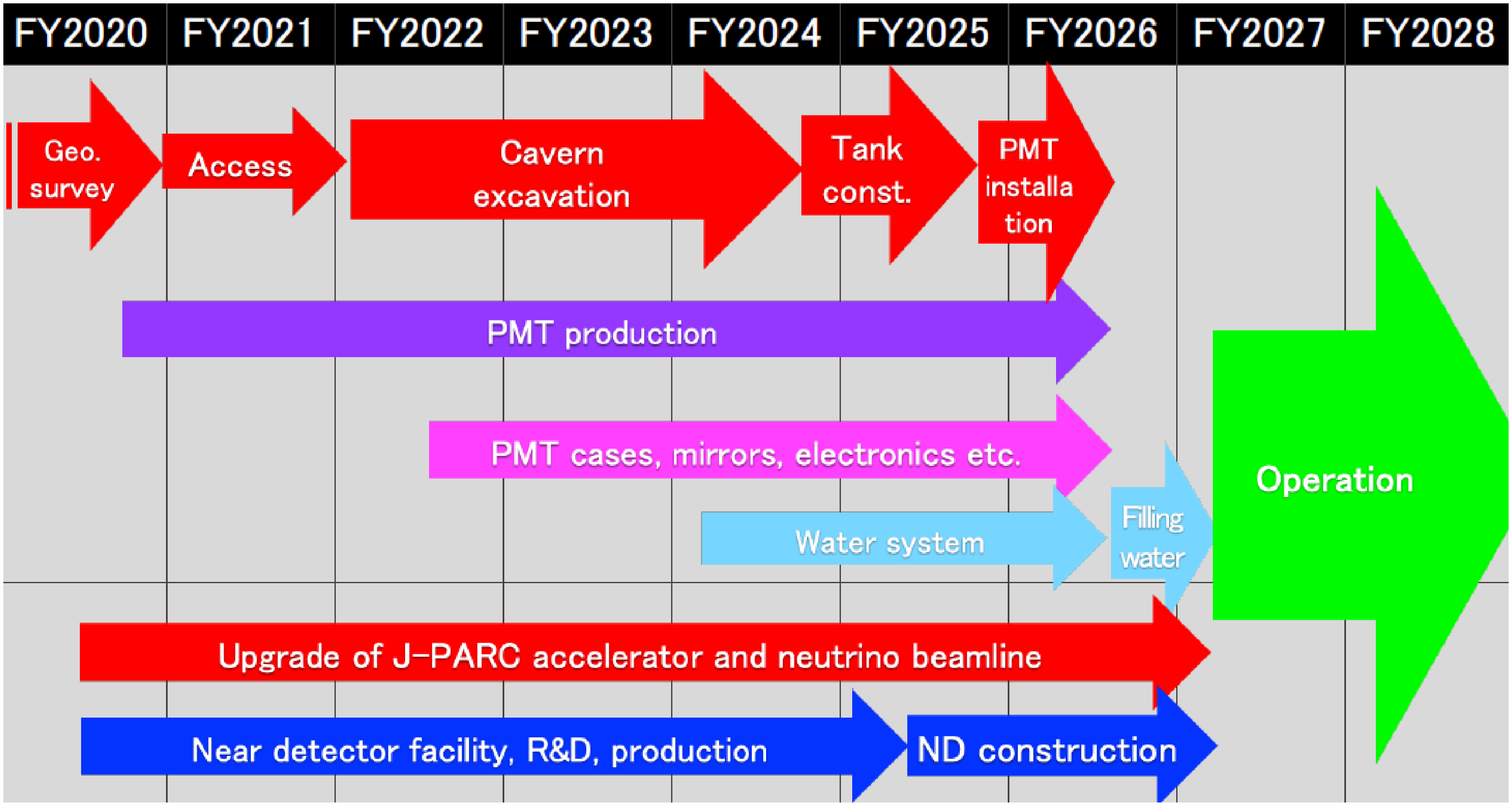


Phase 2: four far detectors (+3 years), enhanced system of near detectors, and 2.4 MW beam (+6 years)

Physics goals:
- 5σ CPV signal for 50% of δ_{CP}
- Precision δ_{CP} , Δm^2_{32}, θ_{23}, θ_{13}



Hyper-Kamiokande schedule

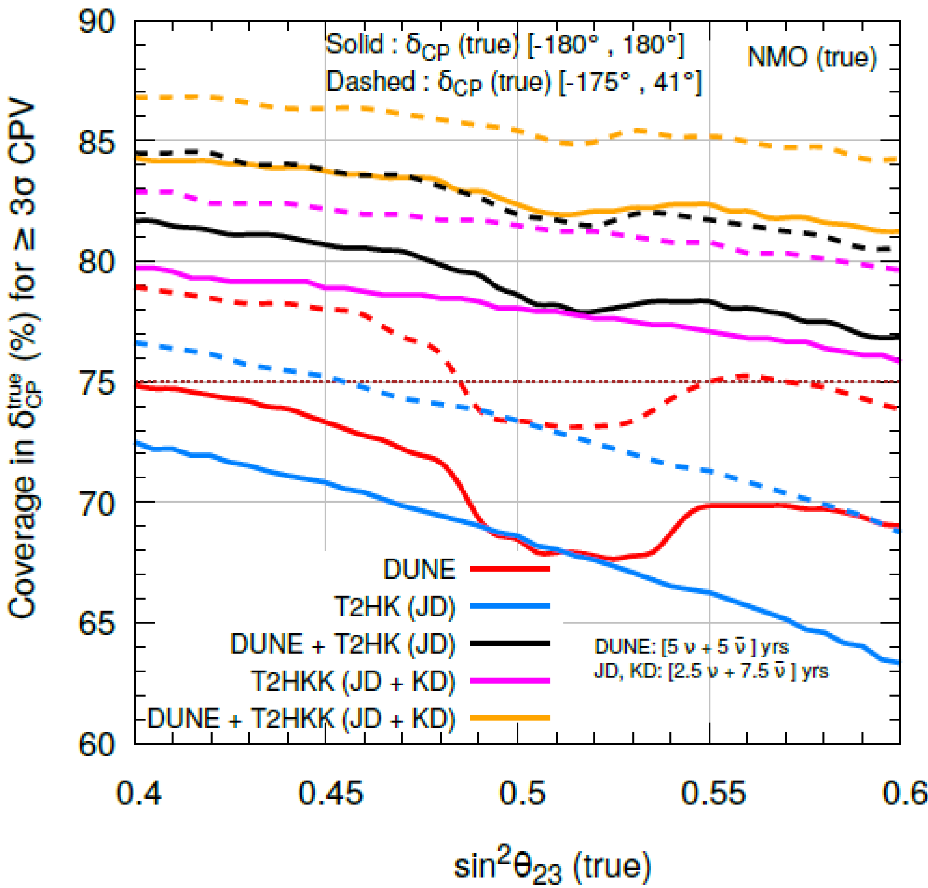


[M. Smy]

DUNE and Hyper-K complementarity

Sensitivity to CPV varies with $\sin^2\theta_{23}$. DUNE has a dip at $\sin^2\theta_{23} \sim 0.5$ due to matter effects. Much to be gained from having two (or more) experiments !

Coverage for CPV 3σ discovery for DUNE, Hyper K, and combinations thereof.



[arXiv:2211.10620]

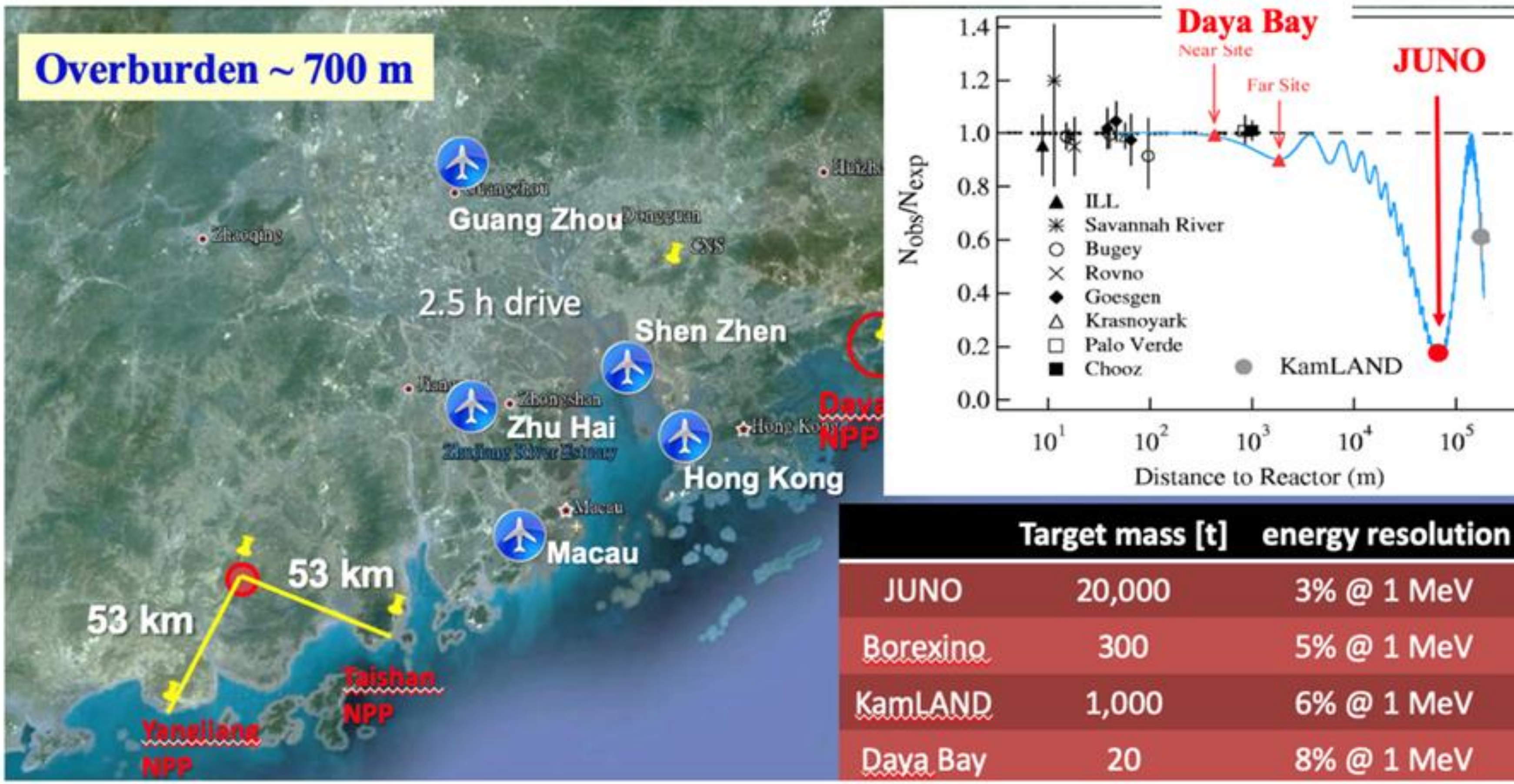
Dotted line – scan over restricted values of δ_{CP}.

JD – baseline Hyper K in Japan

KD – with addition of Korean detector

Jiangmen Underground Neutrino Observatory (JUNO)

Next generation reactor experiment: 20 kt liquid-scintillator detector, 18000 PMTs.



	Target mass [t]	energy resolution
JUNO	20,000	3% @ 1 MeV
Borexino	300	5% @ 1 MeV
KamLAND	1,000	6% @ 1 MeV
Daya Bay	20	8% @ 1 MeV

JUNO physics reach

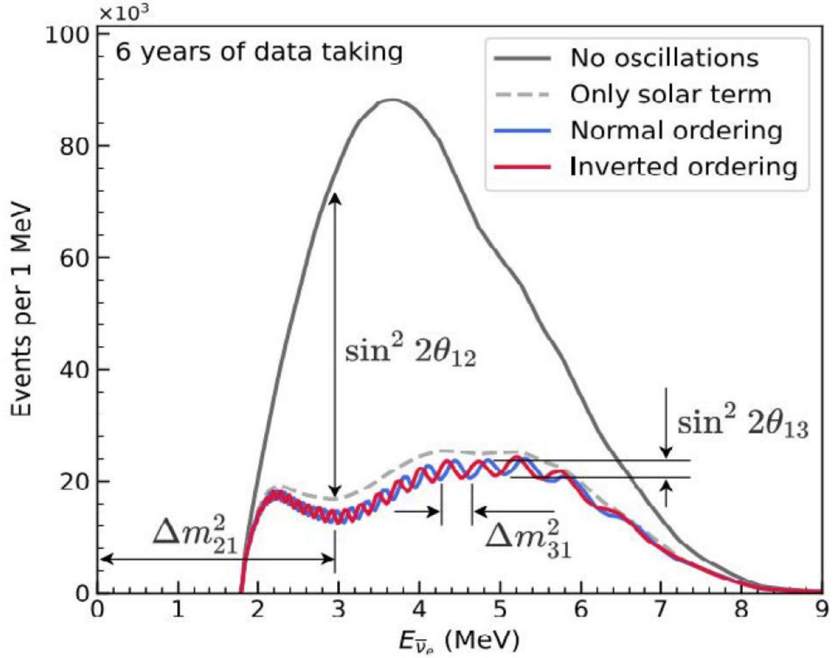
Principal goal: determination of mass ordering, with ~3σ in 6 years.

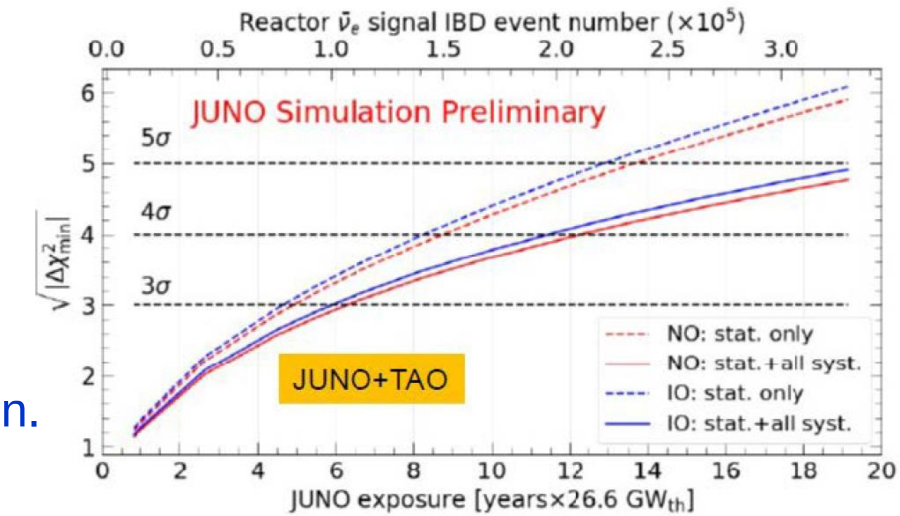
Also good sensitivity to $\sin^2 2\theta_{12}$, $\sin^2 2\theta_{13}$, Δm_{21}^2 and Δm_{31}^2.

Aim to achieve through excellent energy resolution of ~3% at 1 MeV & better than 1% control of non-linearities.

High emphasis on photon yield (scintillator transparency, PMT geometrical coverage and efficiency), calibration *etc*.

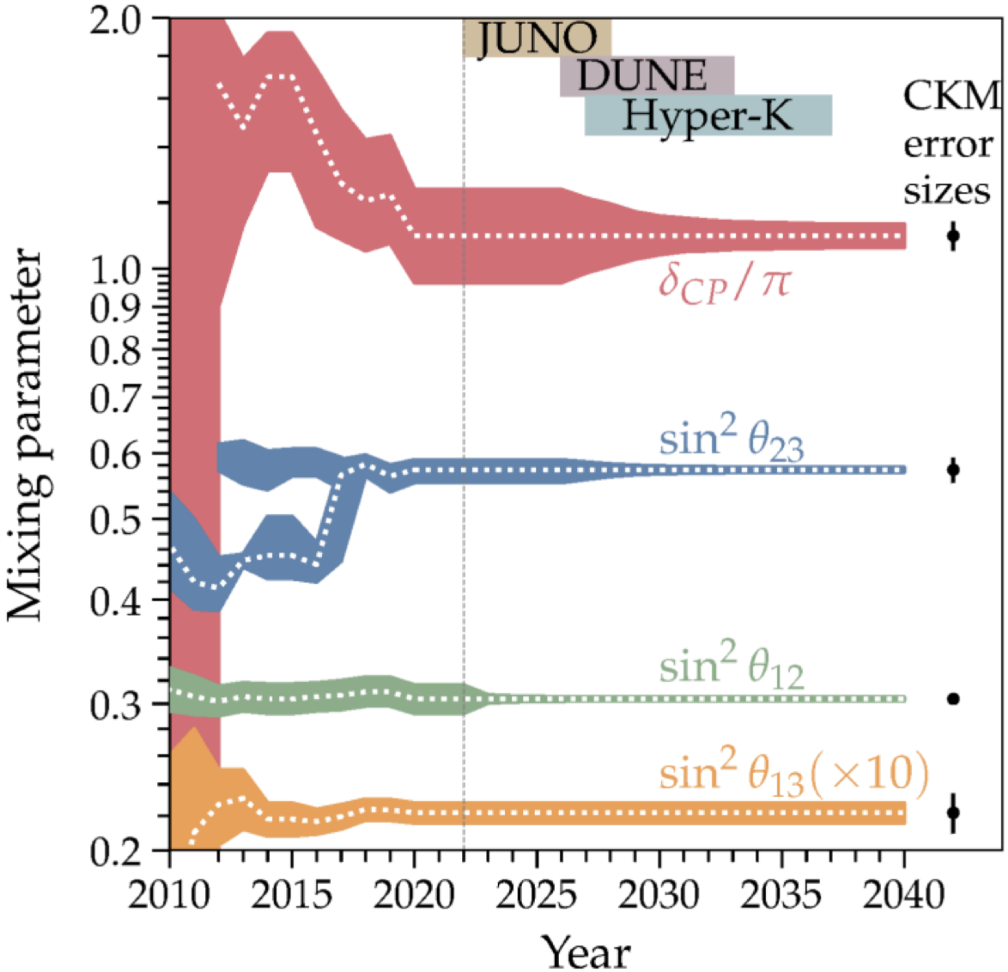
TAO (Taishan Antineutrino Observatory): near detector, also with excellent resolution.





Neutrino-oscillation physics: long-term prospects

JUNO, DUNE and Hyper-K, along with experiments such as ORCA & Icecube, will enable neutrino mass ordering to be established, have good chance of observing CPV, and provide precise determination of other mixing matrix parameters.

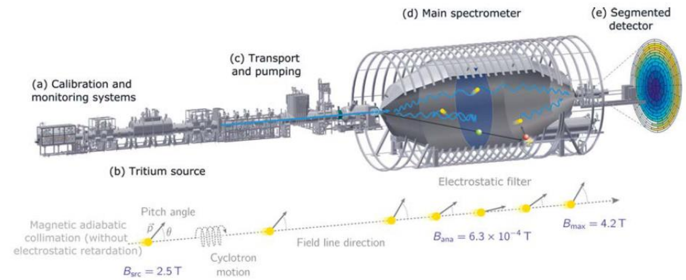


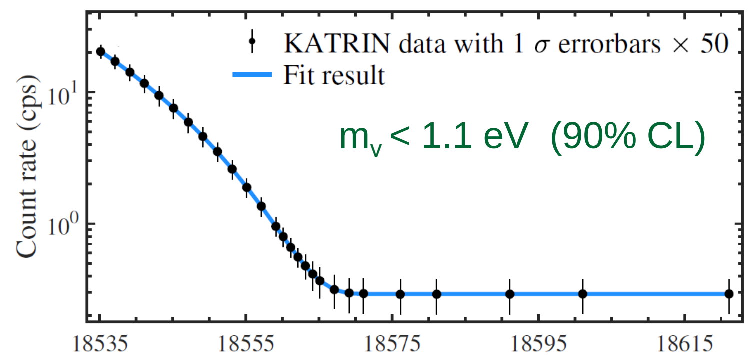
sensitivity depends on other parameters

maybe known to ~1% , and octant probed with good sensitivity

Measurements of absolute neutrino mass

Classical approach to setting limits on mν is through endpoint of spectrum in tritium beta decay. Current brand leader is the KATRIN experiment.





[PRL 123 (2019) 221802]

Aim to reach $m_\nu \sim 0.2$ eV before becoming systematics limited.

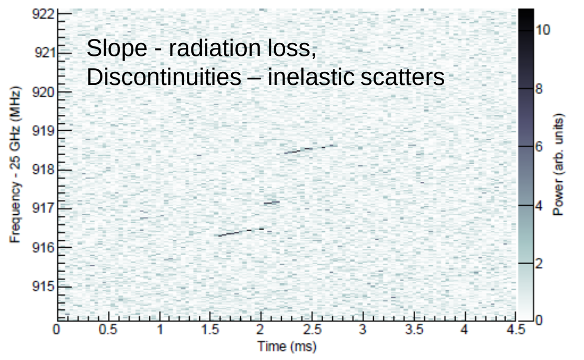
Alternative avenues: low temperature calorimetric measurements with electron capture of ^{163}Ho (Q value 2.83 keV) – HOLMES and ECHO experiments.

m_ν – towards sub 0.1 eV sensitivity

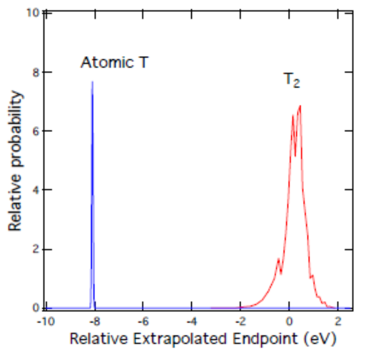
Project 8: Cyclotron Radiation Emission Spectroscopy (CRES) [arXiv:2203.07349]

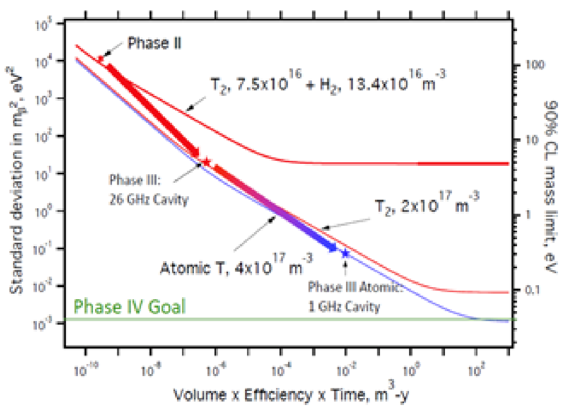
Measure cyclotron frequency of emitted electrons in a magnetic field, which gives an excellent measure of their kinetic energy.

"Never measure anything but frequency" I. Rabi



Eventually move to atomic (rather) than molecular tritium, to avoid systematics associated with expected endpoint, that introduce an irreducible uncertainty of ~0.1 eV.

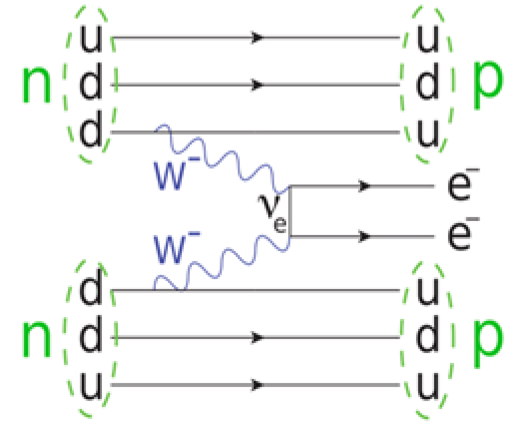




Several proof-of-principle experiments successful. Aim for m_ν < 0.4 eV in Phase III (5 years) and ultimately m_ν<0.04 eV in Phase IV.

Are neutrinos their own antiparticles ?

The search for neutrinoless double beta decay has reached an important checkpoint, with ~100 kg experiments finishing / soon to finish.

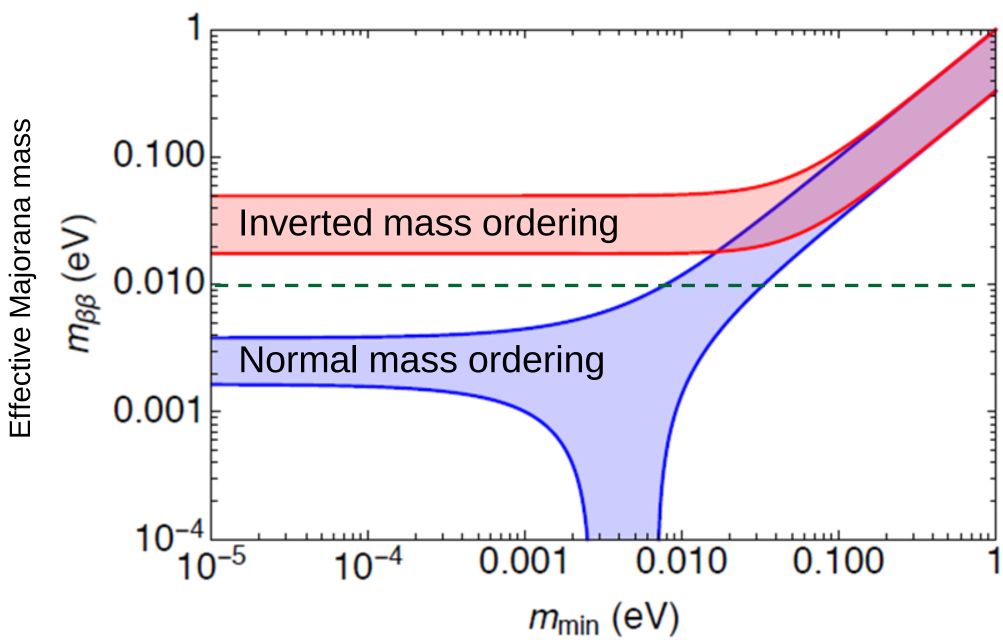


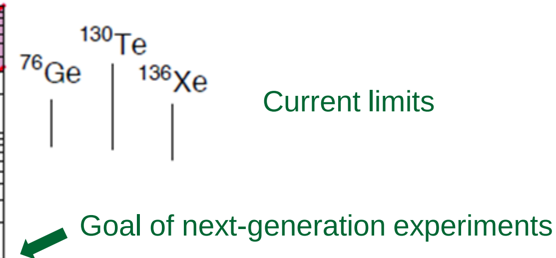
^{125}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs

^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs

^{130}Te (CUORE): $T_{1/2} > 3 \times 10^{25}$ yrs

If neutrino is Majorana, then when signal appears depends on mass ordering.

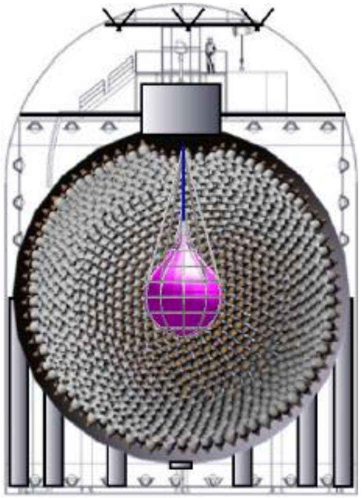




Next generation ~ton experiments will aim for up to two order of magnitude improvements in $T_{1/2}$, to cover all of inverted ordering region, and good bite of normal ordering.

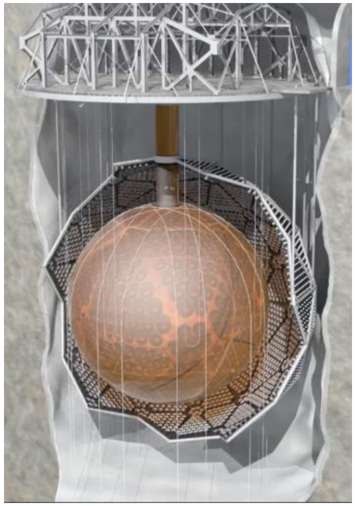
Next generation neutrinoless double-beta decay experiments

KamLAND2-Zen future



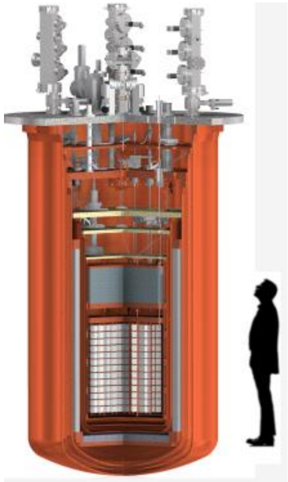
1 t of Xe; improved energy resolution; $m_{\beta\beta}$~20 meV

SNO+ Phase II



Add up to 4 t of ^{130}Te; loading will begin in 2024; probe below inverted ordering

CUPID



CUORE upgrade with scintillating bolometers $m_{\beta\beta}$ ~ 10-20 meV

LEGEND-200, -1000

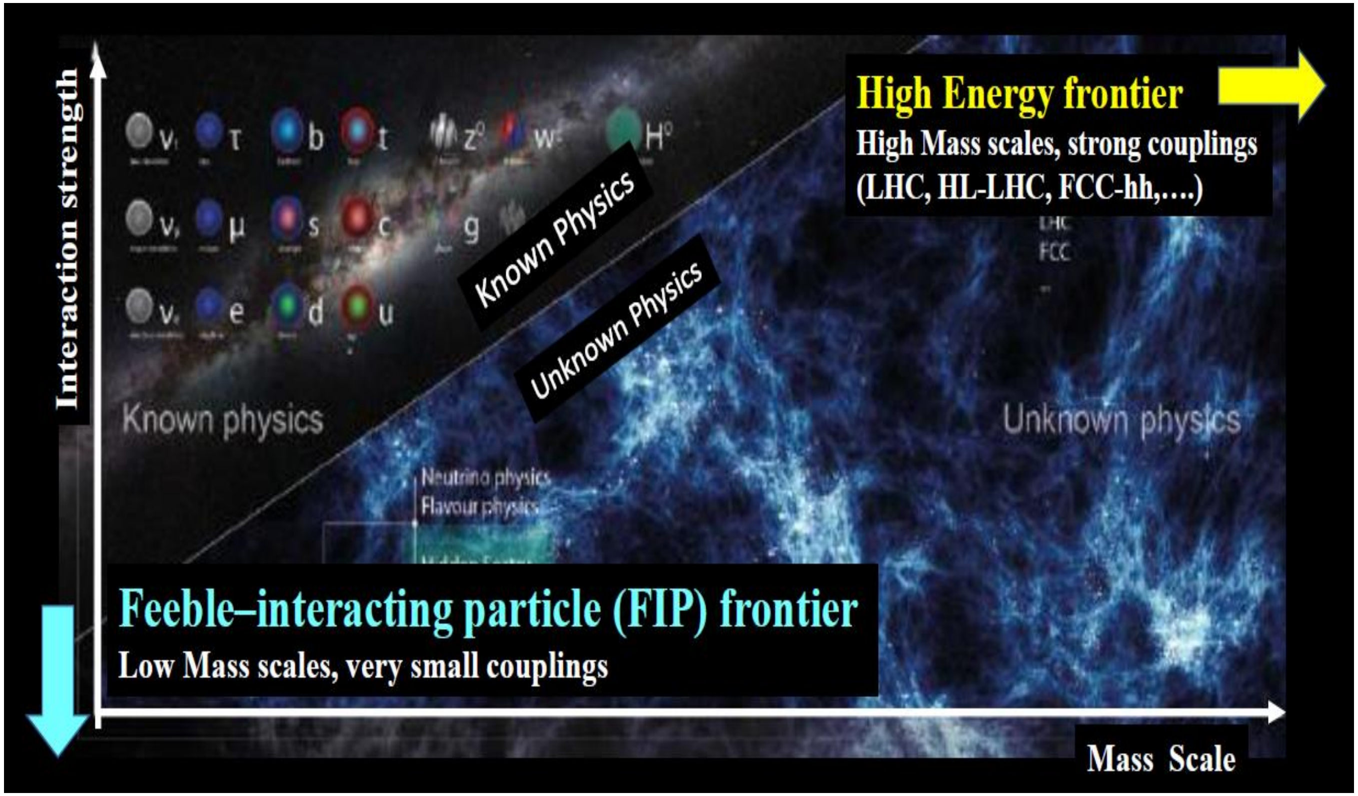
Based on GERDA technology; ultimate goal $T_{1/2}$ ~ 10^{28} yr

And many others: AMoRE, NEXT, nEXO…   diverse technologies and approaches.

Future searches for FIPs and dark matter

FIPs: a paradigm shift in New Physics searches

Lack of any signal (so far) for heavy new particles at LHC has focused attention on possibility to find light New Physics, that couples very weakly to SM particles.

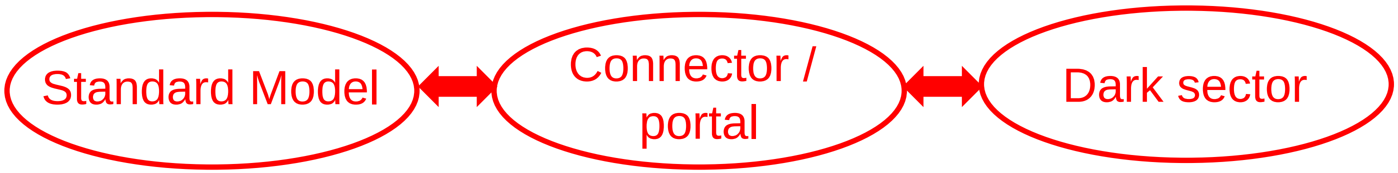


[G. Lanfranchi]

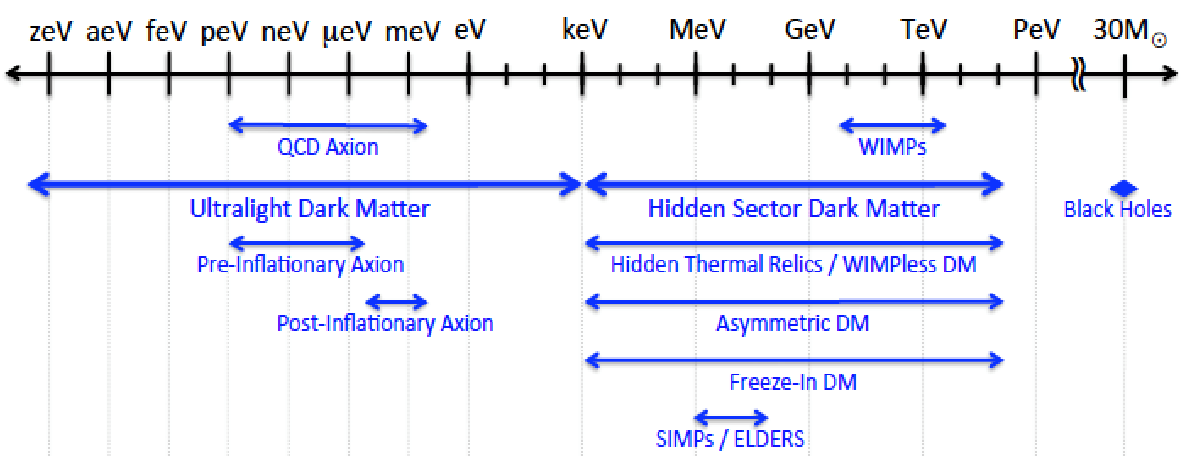
This is the frontier of Feeble Interacting Particles (FIP), a.k.a. the Hidden Sector.

FIPs and dark matter

The dark sector can communicate with SM particles through connector particles.



Any stable dark sector particle is a dark matter candidate. Experimentally, we can search for portal particles, *e.g.* dark photon, dark Higgs, axion, sterile neutrino…

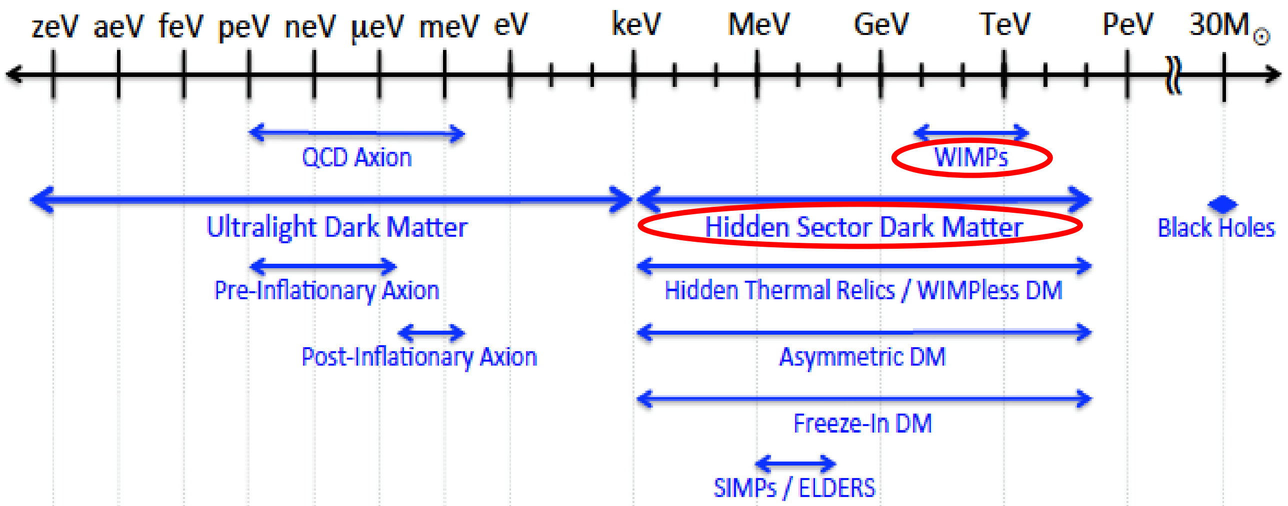


[G. Lanfranchi]

Possible dark matter candidates – 80 orders of magnitude

FIPs and dark matter

Probing this extended range of possible dark-matter candidates requires a Very diverse range of experimental techniques, most of which we will not discuss (*e.g.* astroparticles, interferometry/gravitational waves, axion helioscopes…)



[G. Lanfranchi]

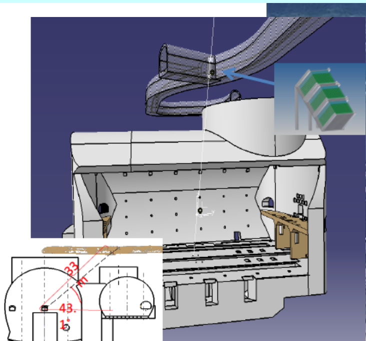
However, we will devote a few slides to the search for long-lived FIPs in MeV-GeV region, and also the status and prospects of classical WIMP searches.

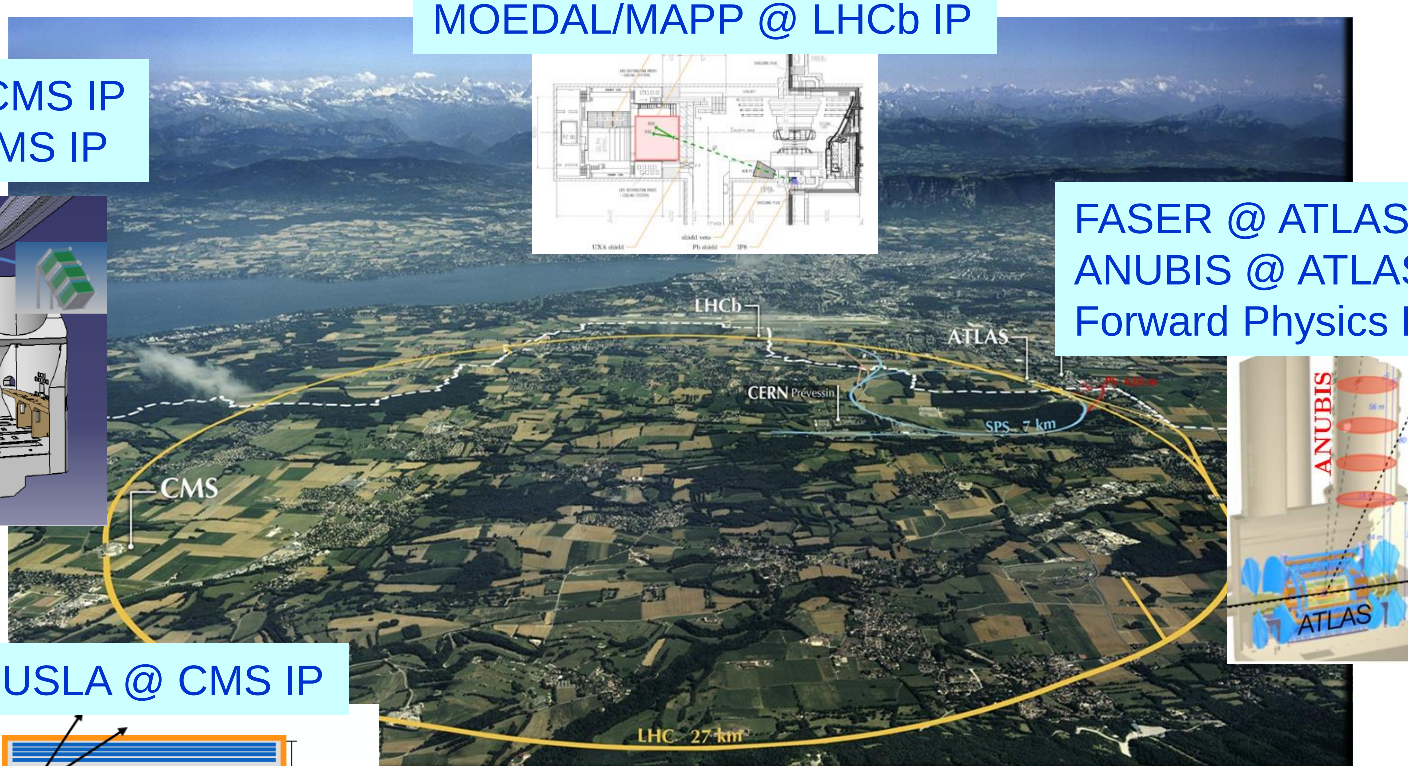
The search for FIPs at the LHC

Several planned (& existing) dedicated experiments at LHC, many of which are sensitive to long lived particles (a topic also pursued in ATLAS, CMS, LHCb).

CODEX-b @ LHCb IP
MOEDAL/MAPP @ LHCb IP

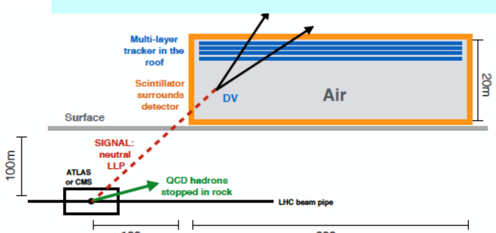
MilliQan @ CMS IP
FACET @ CMS IP





FASER @ ATLAS IP
ANUBIS @ ATLAS IP
Forward Physics Facility

MATHUSLA @ CMS IP

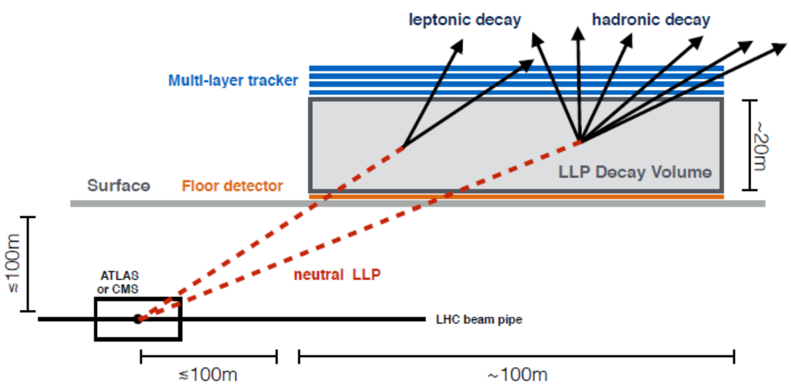


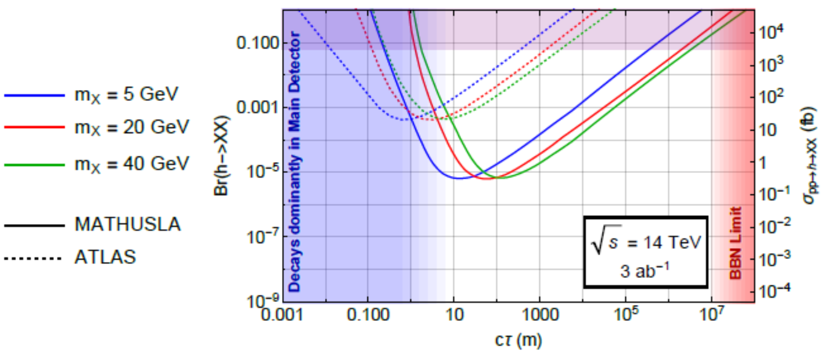
The search for FIPs at the LHC

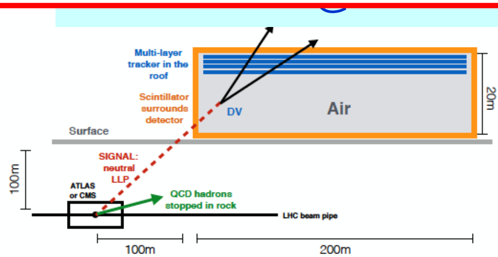
Several planned (& existing) dedicated experiments at LHC, many of which are sensitive to long lived particles (a topic also pursued in ATLAS, CMS, LHCb).

CODEX-b @ LHCb IP
MOEDAL/MAPP @ LHCb IP

MATHUSLA – a closer look:



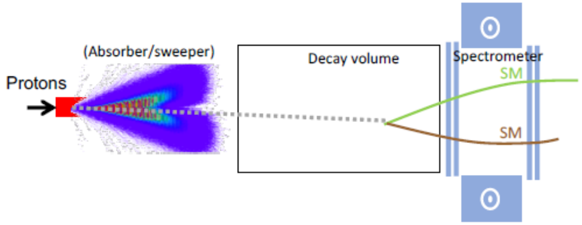


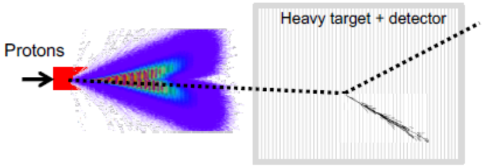


The search for FIPs at beam dumps

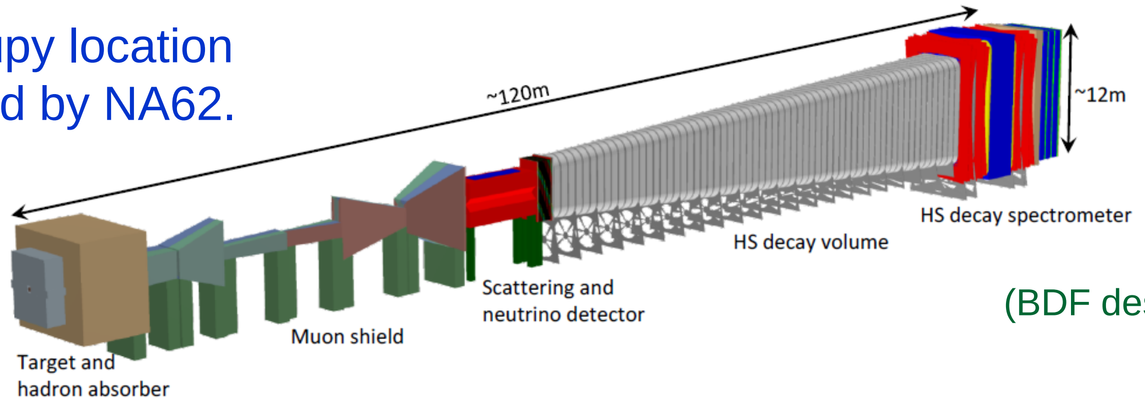
Beam dump of high-intensity proton beam produces an enormous flux of charm mesons, which can decay into FIPs. SHiP experiment proposed to take advantage of this opportunity in new beam line at CERN SPS (Beam Dump Facility: BDF). Not pursued for financial reasons, but now being reconsidered for SPS ECN3 line.

Two search strategies: decay to SM particles, and scattering signature.





It would occupy location currently used by NA62.



(BDF design)

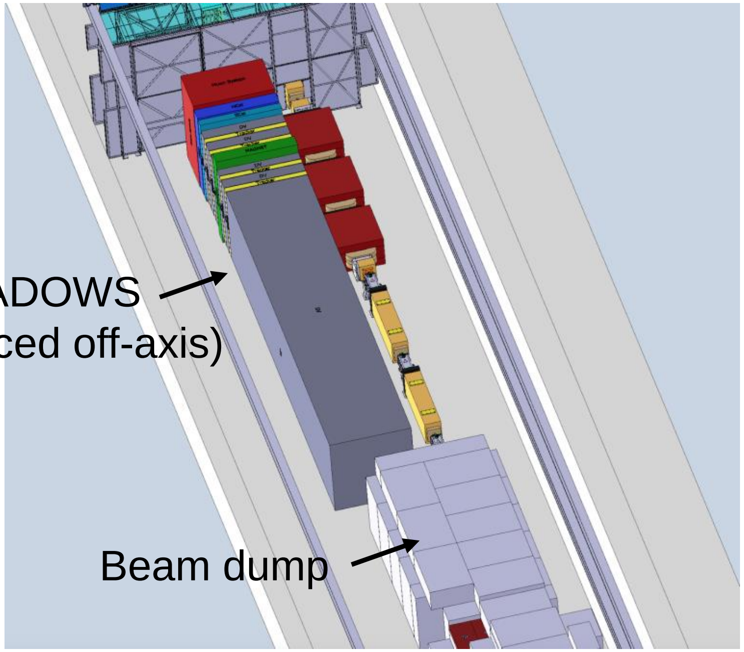
Excellent sensitivity for many hidden sector particles.

The search for FIPs at beam dumps

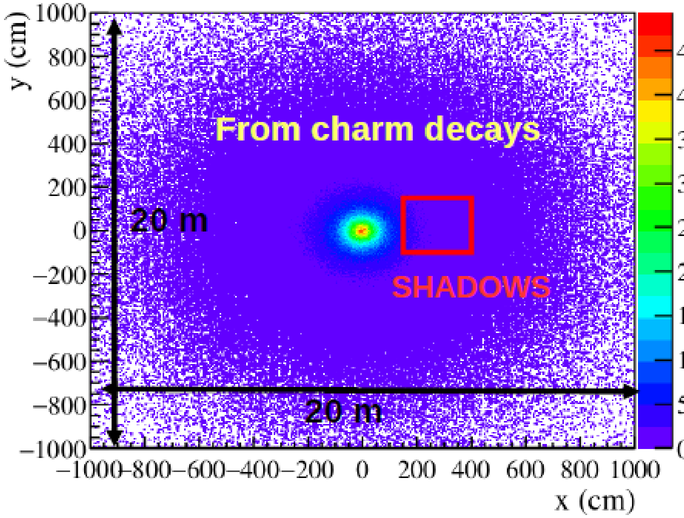
Alternative proposal for FIP physics at same location is SHADOWS experiment. This could be situated behind HIKE (next generation NA62 kaon experiment).

SHADOWS (placed off-axis)

Beam dump



Heavy Neutral Lepton →πμ



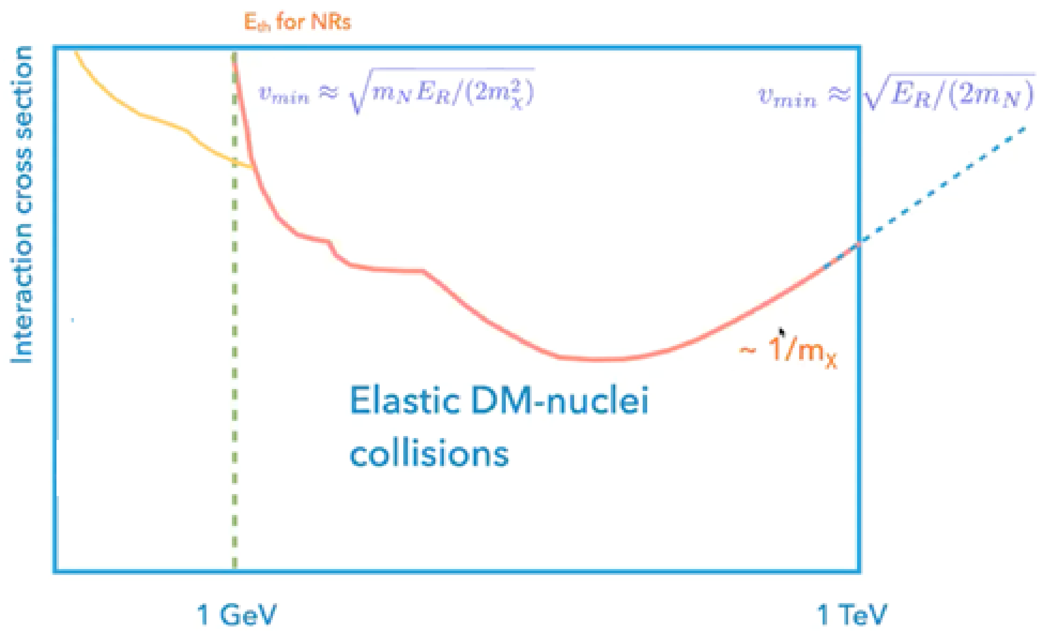
[A. Paoloni]

Good signal off-axis, and much lower background.

If approved, this could begin operation around 2028.

On the hunt for dark matter: classical WIMP searches through nuclear recoil

Classical approach: search for elastic collisions of WIMPs with nuclei with very low momentum transfers. Sensitivity to WIMPs in GeV to TeV range.



Thresholds of a few keV and light nuclei probe down to GeV masses.

On the hunt for dark matter: classical WIMP searches through nuclear recoil

Spin-independent cross section upper limits at 60 GeV WIMP mass

10^{-41} cm^2 in ~1998 to few x 10^{-47} cm^2 in ~2018

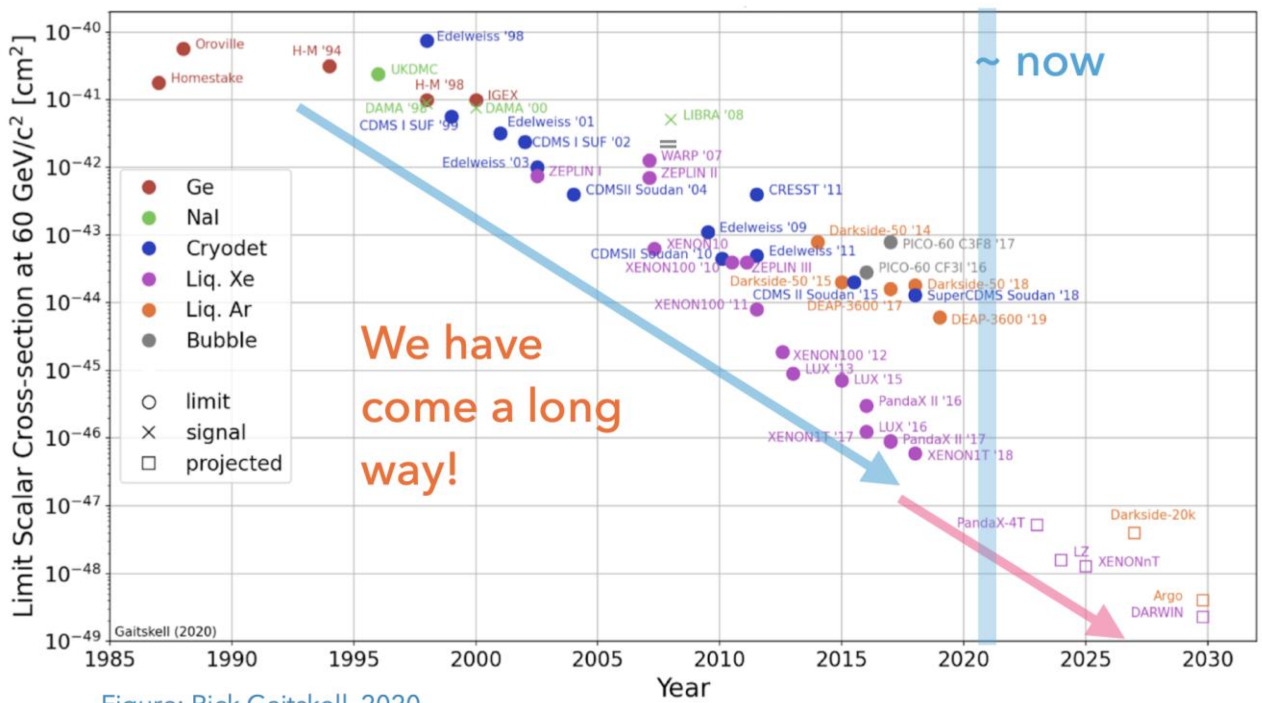
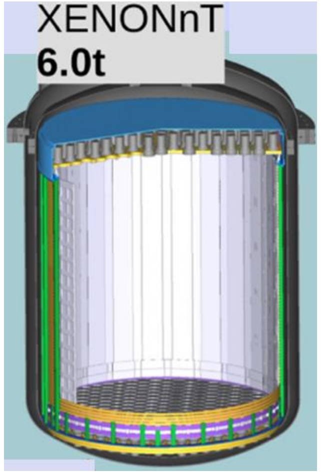


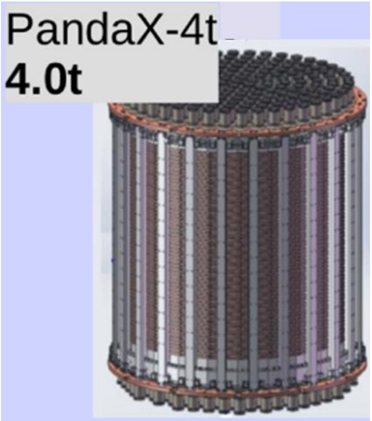
Figure: Rick Gaitskell, 2020

WIMP searches – state of the art

Several complementary experiments starting / about to start.

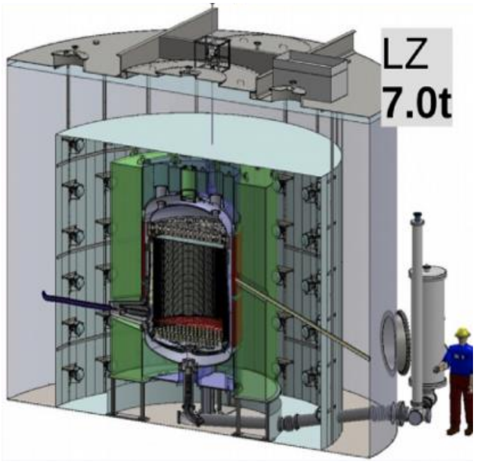
LXe

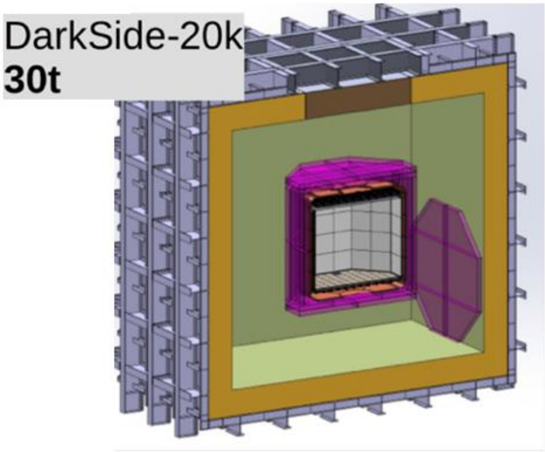




LXe

LXe





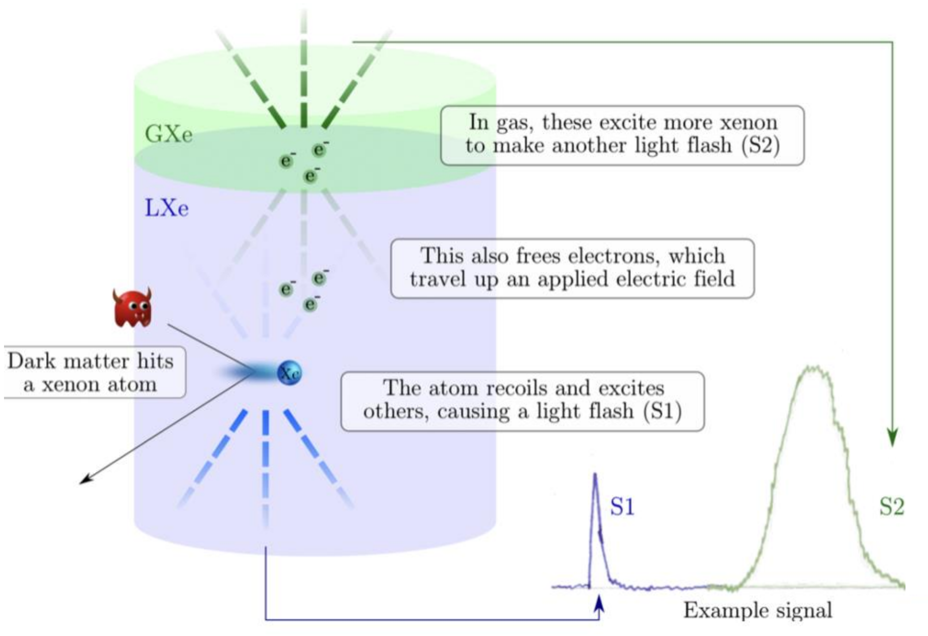
LAr

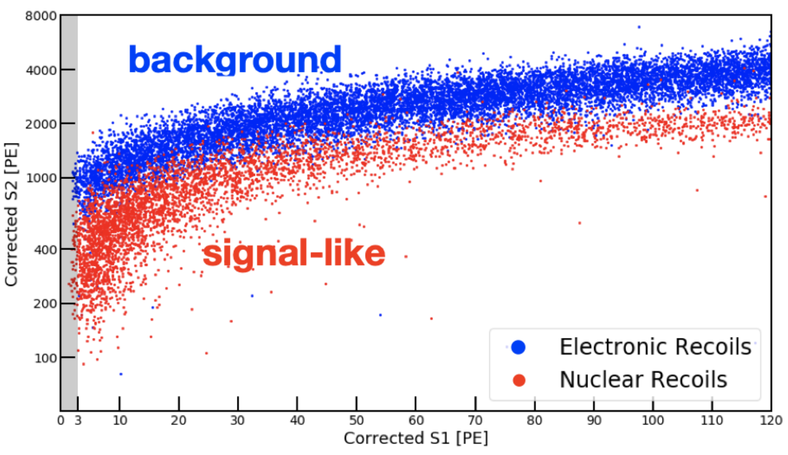
start ~2025

Dual-phase concept

Noble liquid/gas experiments use dual phase signals to suppress background.

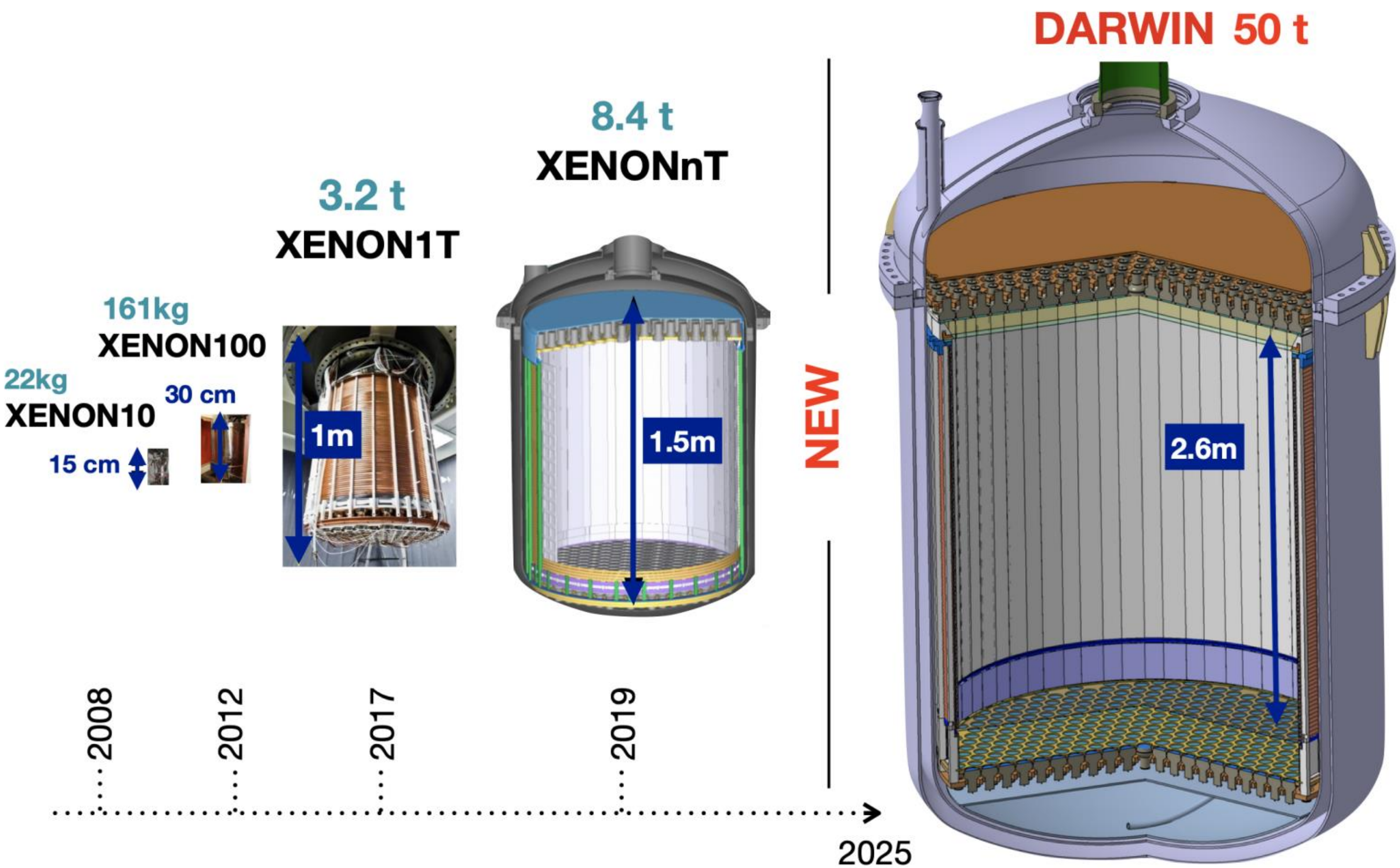
[https://science.purdue.edu/xenon1t/?tag=s2-only]



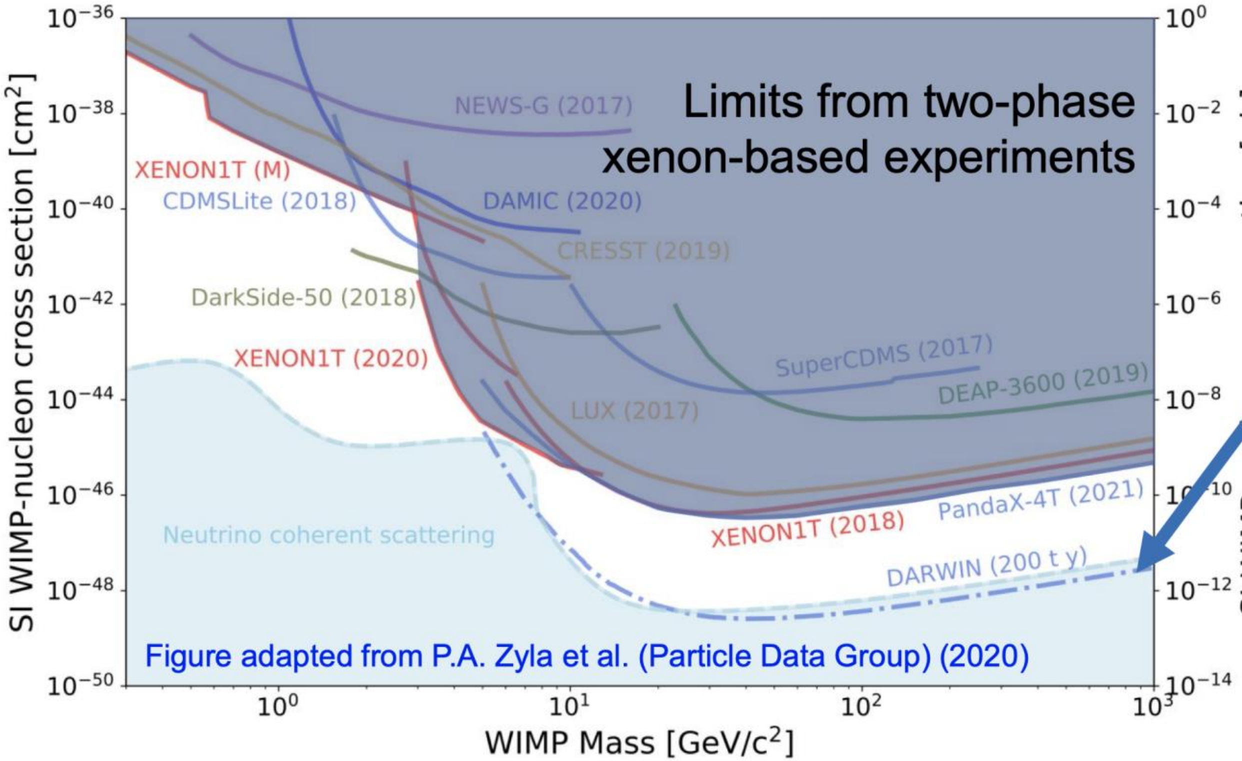


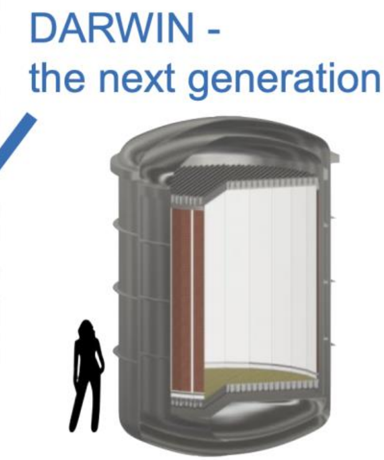
'S1' 'S2'

Future liquid Xe detectors: DARWIN



Future liquid Xe detectors: DARWIN

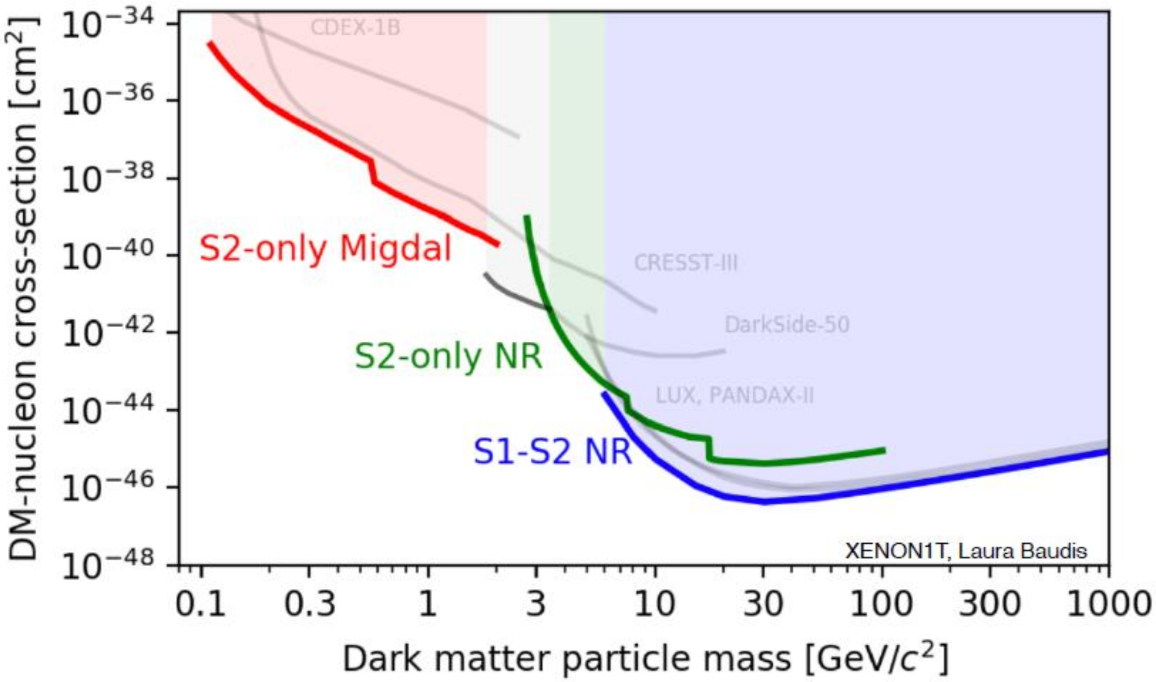




- Larger target mass and lower backgrounds;
- Two photon / charge-sensor arrays (top and bottom);
- Double-wall cryostat;
- Water-filled outer shield;
- Neutron and muon veto.

The quest for MeV scale WIMPs: harnessing electrons

Searches can be extended to lower mass DM by looking for scattering of electrons, or through the Migdal effect, where an atomic electron is emitted through excitation.

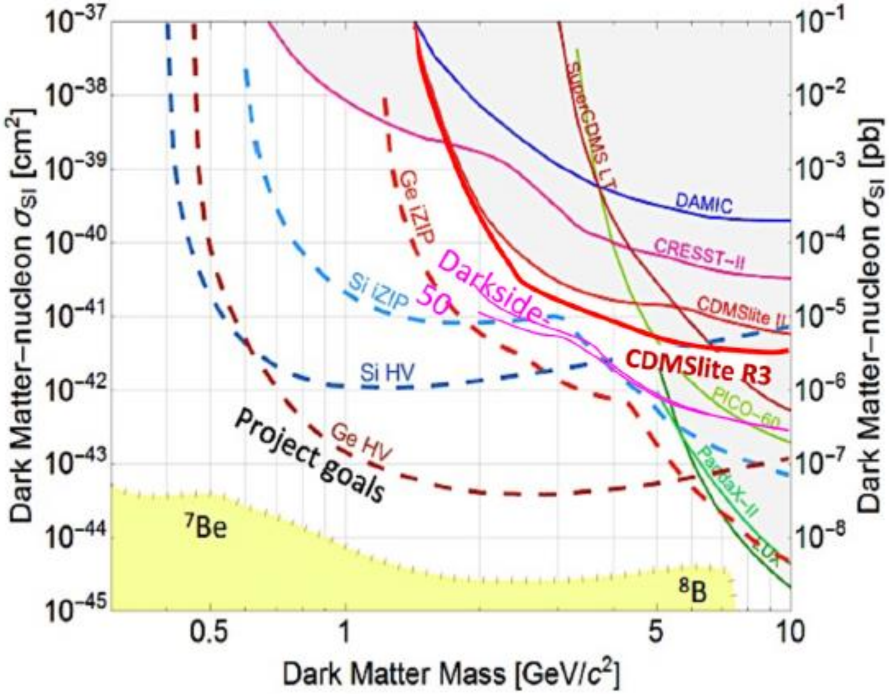


In principle can be exploited in LXe/LAr by looking for S2-only signals with correct profile, but this is a delicate business, which future experiments must develop.

The quest for MeV scale WIMPs: harnessing electrons

Alternative approach: detect scattered electrons in cryogenic calorimeters.

e.g. SuperCDMS at SNOLAB, a Ge/Si detector benefitting from many years of accumulated experience with earlier experiments – under construction.



[M. Wilson]

Complemented by CCD based detectors. Future examples: DAMIC-M, Oscura.

Future of flavour

(here ‘flavour’ = quarks & charged leptons)

- Why persevere with flavour studies ?
- Belle II
- LHCb Upgrades I and II
- Super Tau Charm Factory
- Future kaon physics
- CLFV and muon g-2

(NB: FCC-ee also has a key role to play! See tomorrow’s lecture.)

Why persevere with flavour studies ?

Devil's advocate: given that CKM mechanism does a good job, and given that we have seen key suppressed decays, *e.g.* $B^0_s \to \mu\mu$, at ~ the SM BF, why continue?

The big picture answer:

- The SM is incomplete;
- Many of the mysteries in the SM (& the cosmos) are related to flavour;
- Flavour observables can probe much higher mass scales than direct searches

And some specific considerations:

- We *know* there are important phenomena still to be observed (*e.g.* mixing-induced CPV in B^0_s system, mixing related CPV in charm, $B^0 \to \mu\mu$ *etc.*);
- Similarly, there are many important measurements that can be made, which are unfeasible with current sample sizes (*e.g.* electroweak Penguin studies with $b \to d l^+ l^-$ decays, or precise study of P_5' with $B^0 \to K^* e^+ e^-$);
- A very large number of current observables are *theoretically clean* &/or *statistics limited*, so higher precision is strongly motivated (*e.g.* $\sin 2\beta$, γ, φ_s, R_K, R_{K^*}, $BR(B^0_s \to \mu\mu)/BR(B^0 \to \mu\mu)$ *etc*);
- A rich field where surprises are guaranteed (*e.g.* no one was expecting charm mixing, direct charm CPV, the X(3872), pentaquarks…).

Unwise to assume ~10% (or even 0.1%) is 'good enough'

Courtesy Browder and Soni

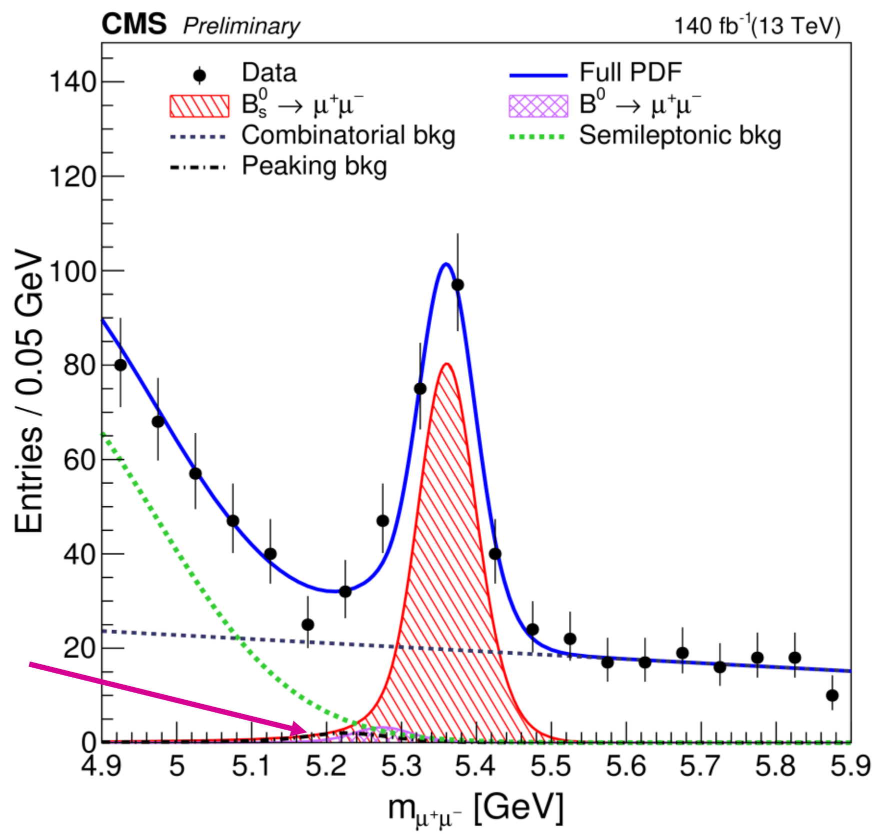
"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

BR ($K^0_L \rightarrow \pi\pi$) ~ 2 x 10^{-3} Cronin, Fitch *et al.* , 1964

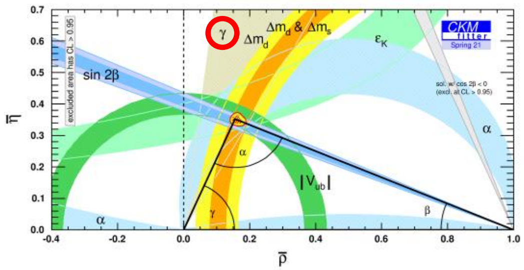
Example of known unknowns: BF($B^0 \to \mu\mu$)

Finding $B^0 \to \mu\mu$ and measuring the ratio BF($B^0 \to \mu\mu$)/BF($B_s \to \mu\mu$) (~ 3% in SM) is an essential next step in flavour studies. The ratio of BFs is theoretically pristine, and also serves as an excellent test of Minimal Flavour Violation.



[CMS-PAS-BPH-21-006]

Example of known unknowns: value of CKM γ with sub-degree precision



CKM paradigm drives Unitarity Triangle at leading order, but very possible New Physics is still present. Need ever more precise measurements of Triangle parameters.

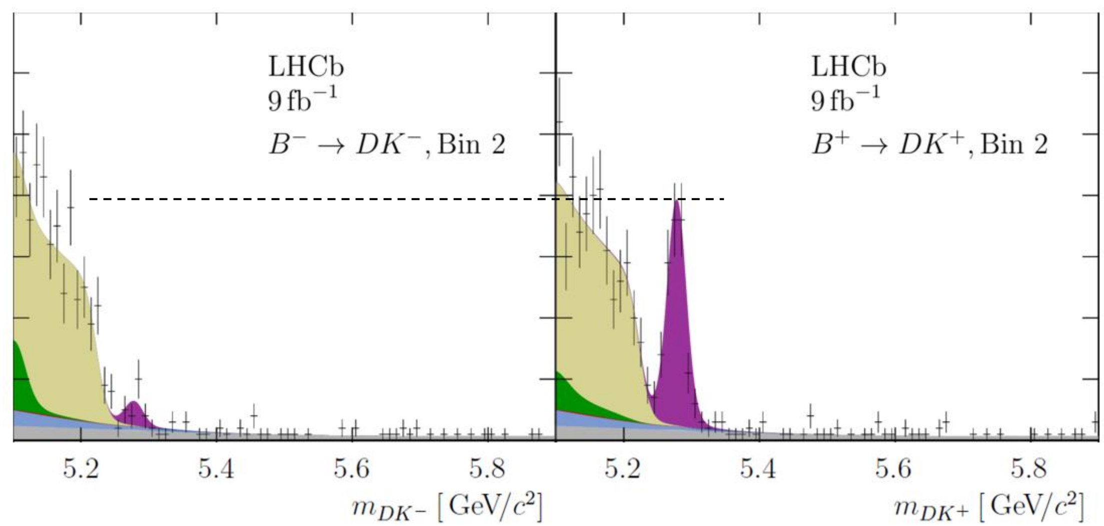
Excellent example is angle γ, which can be determined in B→DK decays with negligible theoretical uncertainty.

$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^{o}$$

[LHCb-CONF-2022-03]

Statistically limited !

Largest CPV asymmetry ever observed – LHCb B→D(K3π)K



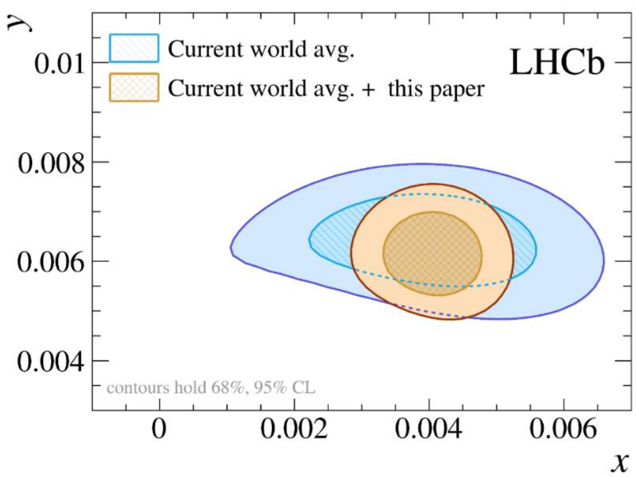
[LHCb, arXiv:2209.03692]

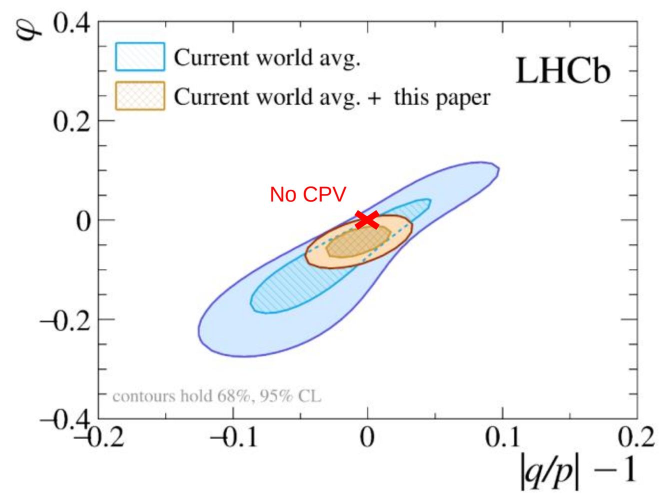
Also important to improve measurements of sin2β, φ_s (*i.e.* CPV in $B_s \to J/\psi\varphi$)…

Example of known unknowns: is there New Physics in charm mixing CPV?

CPV has been seen in the kaon and B sector in mixing-related phenomena, but not in the D^0 system*, where a priori it is known to be extremely small within SM. New Physics could enhance this. LHCb Run 1-2 data have made big advances….

e.g. Improvement in mixing parameters (x,y) and CPV parameters (φ, |q/p|) from Run 1-2 LHCb $D^0 \to K^0_S \pi\pi$ mixing analysis [PRL 127 (2021) 111801].





Highly desirable to improve precision on CPV parameters by ~ order of magnitude.

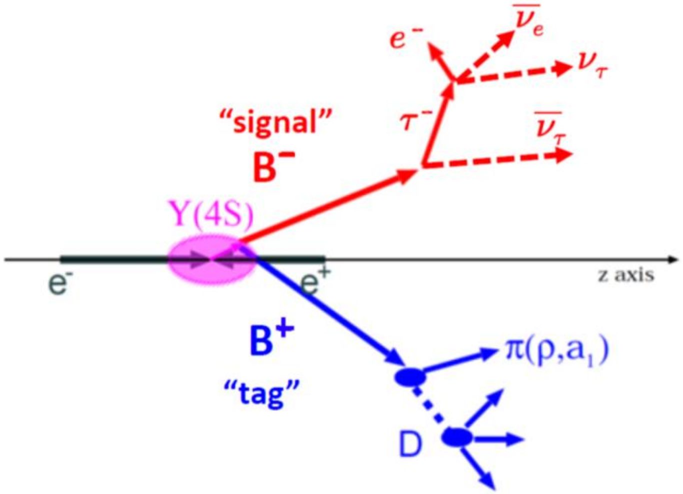
* CPV has been seen in decay amplitudes (*i.e.* 'direct') [PRL 122 (2019) 211803]. Larger samples are needed to fully characterise this phenomenon also.

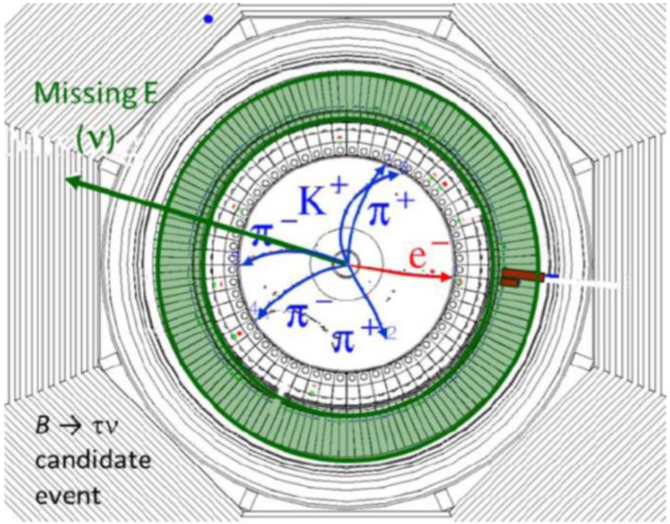
Why Belle II ?

B production at the Υ(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

e.g. B→τν





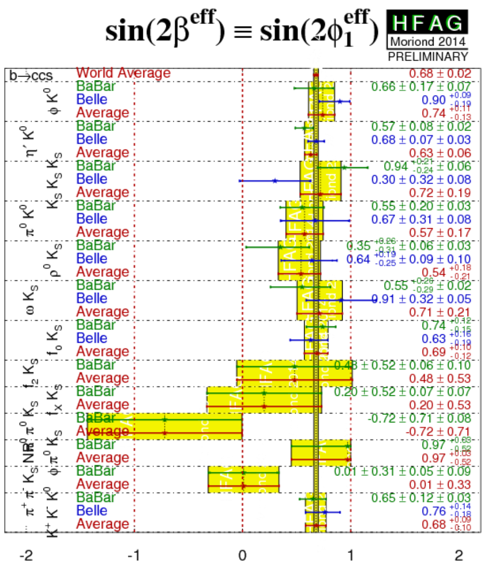
Why Belle II ?

B production at the Υ(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

e.g. most modes suitable for sin2β measurements involving Penguin loops (b→ccbar s) are rather tough at LHCb…



…and other important decays *e.g.* $D^0 \to \gamma\gamma$, $B^0 \to \pi^0\pi^0$… are essentially inaccessible.

Why Belle II ?

B production at the Υ(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

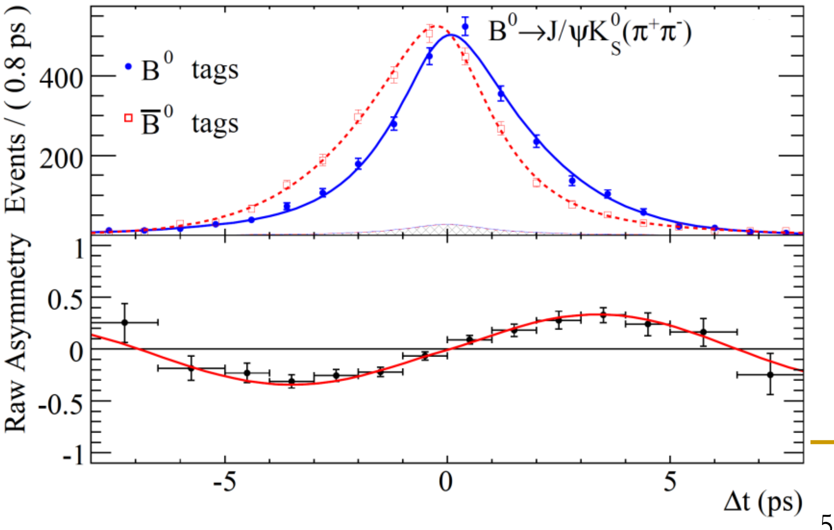
- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

- Coherent B^0B^0bar production at Υ(4S) makes flavour tagging easier and compensates for lower sample sizes in time-dependent CP measurements.

e.g. in sin2β measurement with $B^0 \to J/\psi K_S$

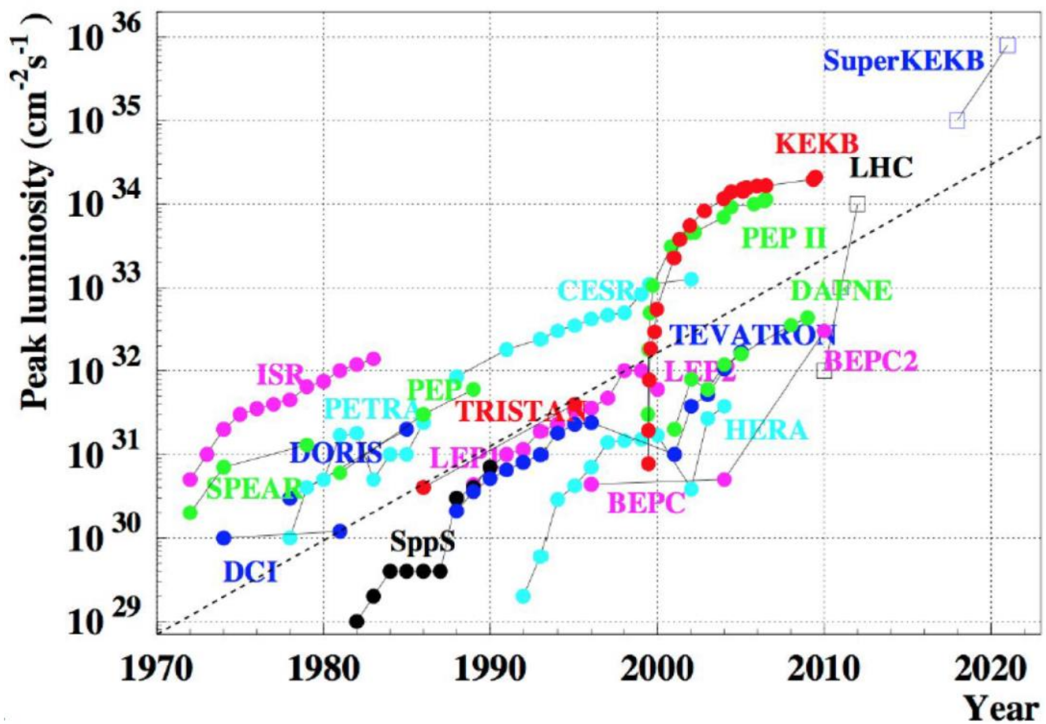
ε (tag effective) BaBar ~ 31 %
[PRD 79 (2009) 072009]

ε (tag effective) LHCb ~ 3 %
[PRL 115 (2015) 031601]

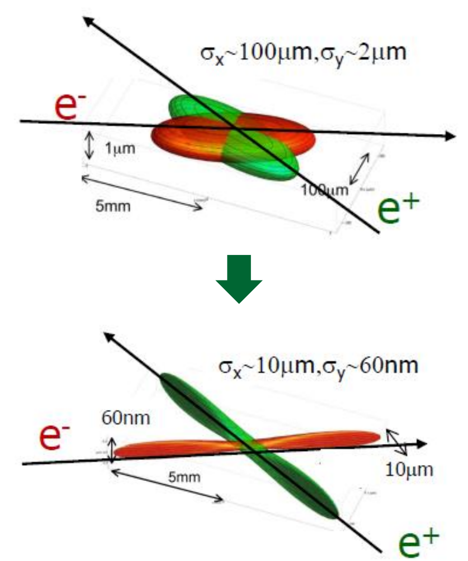


SuperKEKB

SuperKEKB goals: luminosity of 6×10^{35} $cm^{-2}s^{-1}$ and 50 ab^{-1} by 2034



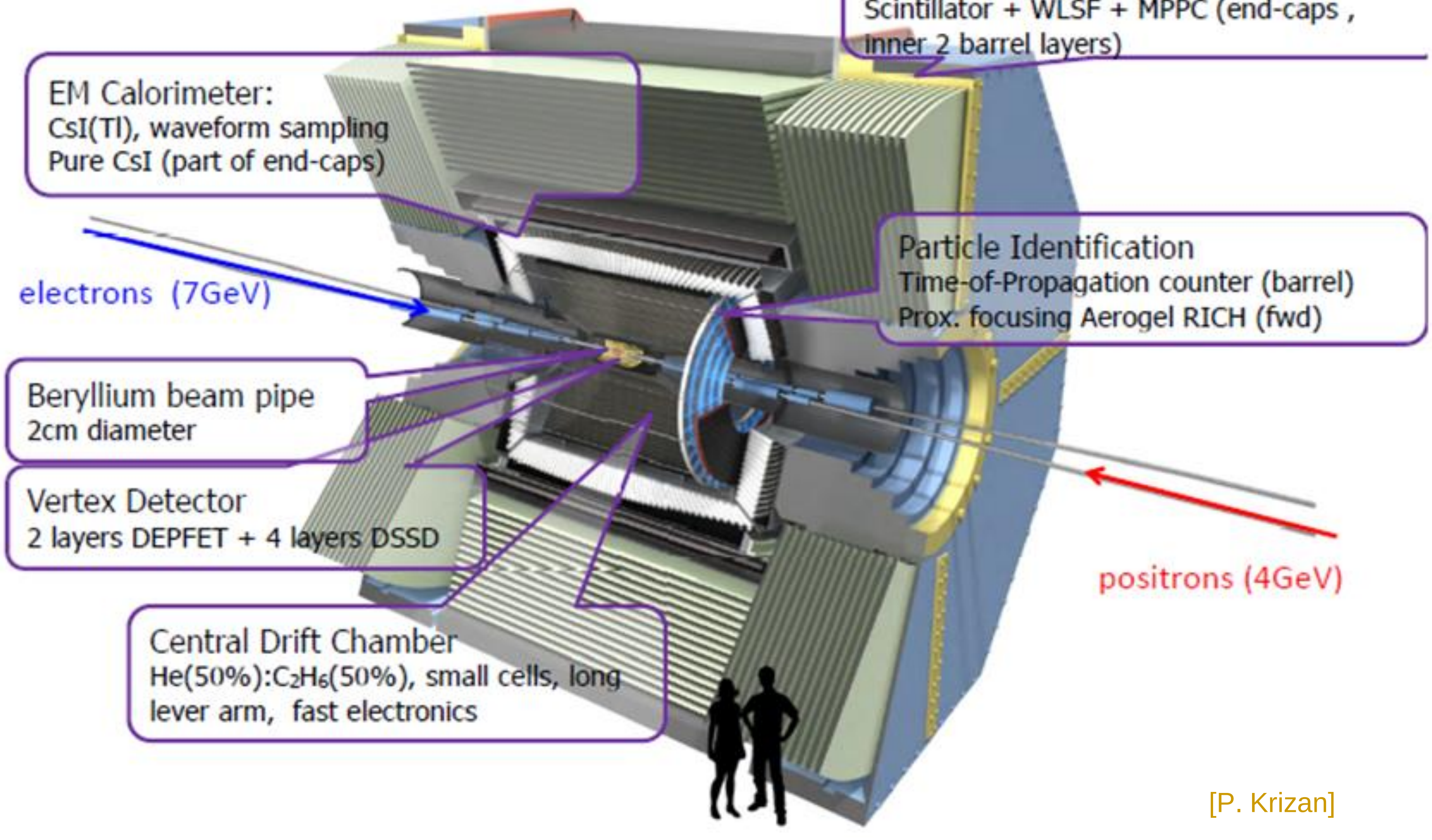
KEKB→SuperKEKB: increase currents & move to nano-beam scheme



An ambitious 40-fold increase in luminosity on KEKB, to be achieved by squeezing the beams by ~1/20 and doubling the currents.

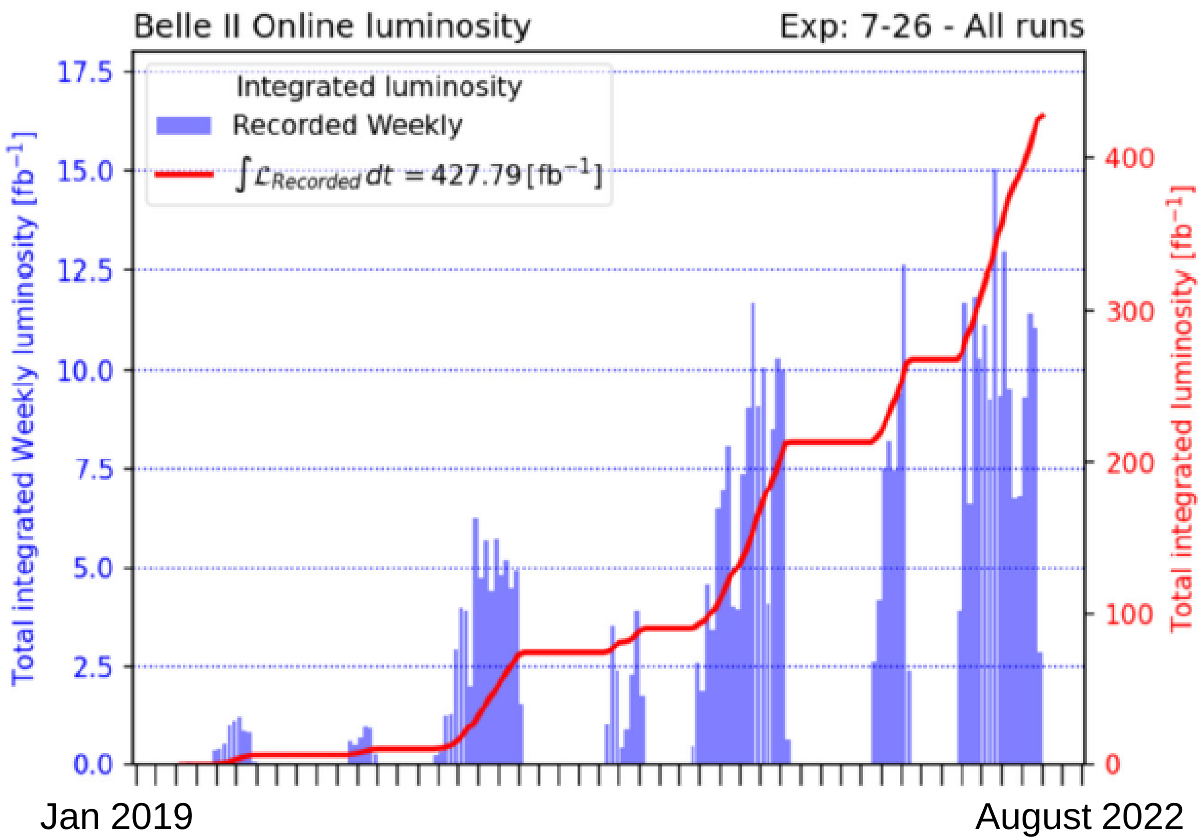
Belle II detector

All sub-detectors upgraded from Belle, except for ECL crystals and part of the barrel KLM.



[P. Krizan]

SuperKEKB and Belle II – the story so far



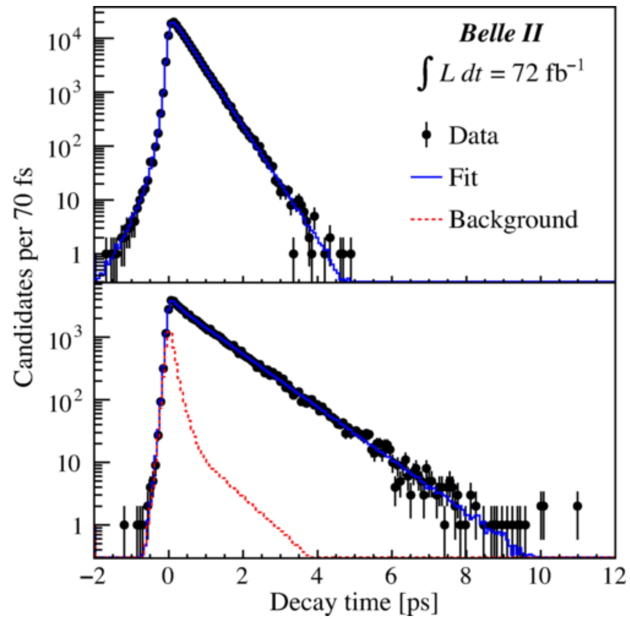
Reached world record instantaneous luminosity: 4.7 x 10^{34} $cm^{-2}s^{-1}$
Integrated luminosity until now (shutdown): 428 fb^{-1} (similar to BaBar).

Belle II physics performance with early data

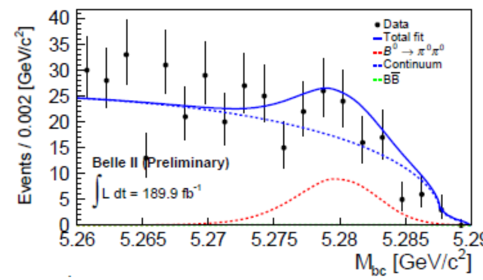
World best charm lifetimes !

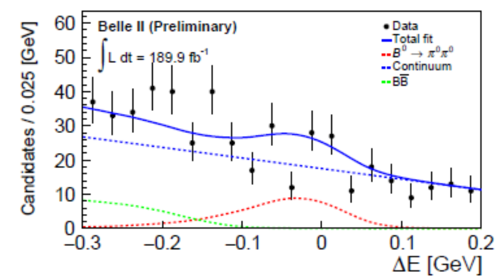
Factor of two improvement in proper-time resolution w.r.t. Belle.

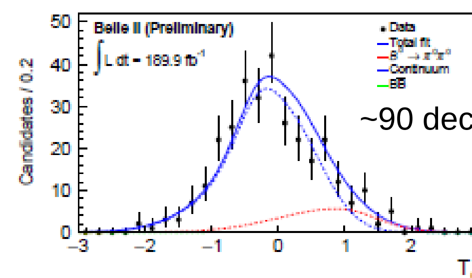
[PRL 127 (2021) 21801]



$B^0 \to \pi^0\pi^0$ BF and A_{CP} (impossible at LHCb)





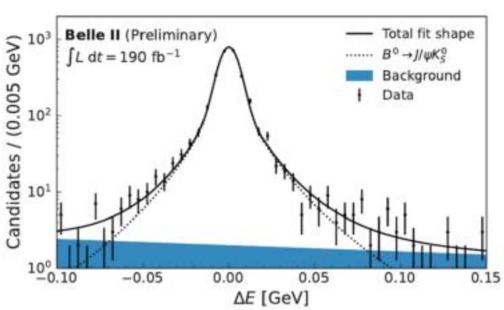


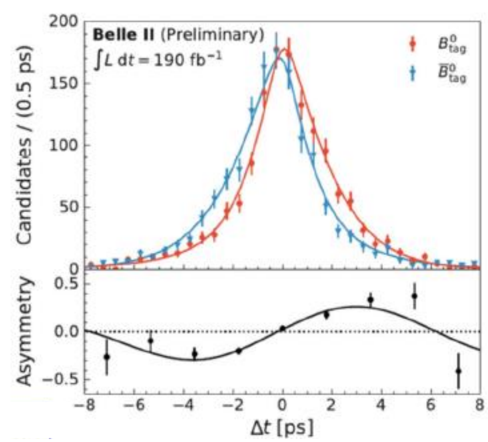
~90 decays

(log of BDT selection variable)

[J. Skorupa, ICHEP 2022]

Proof-of-principle sin2β measurements with early data.

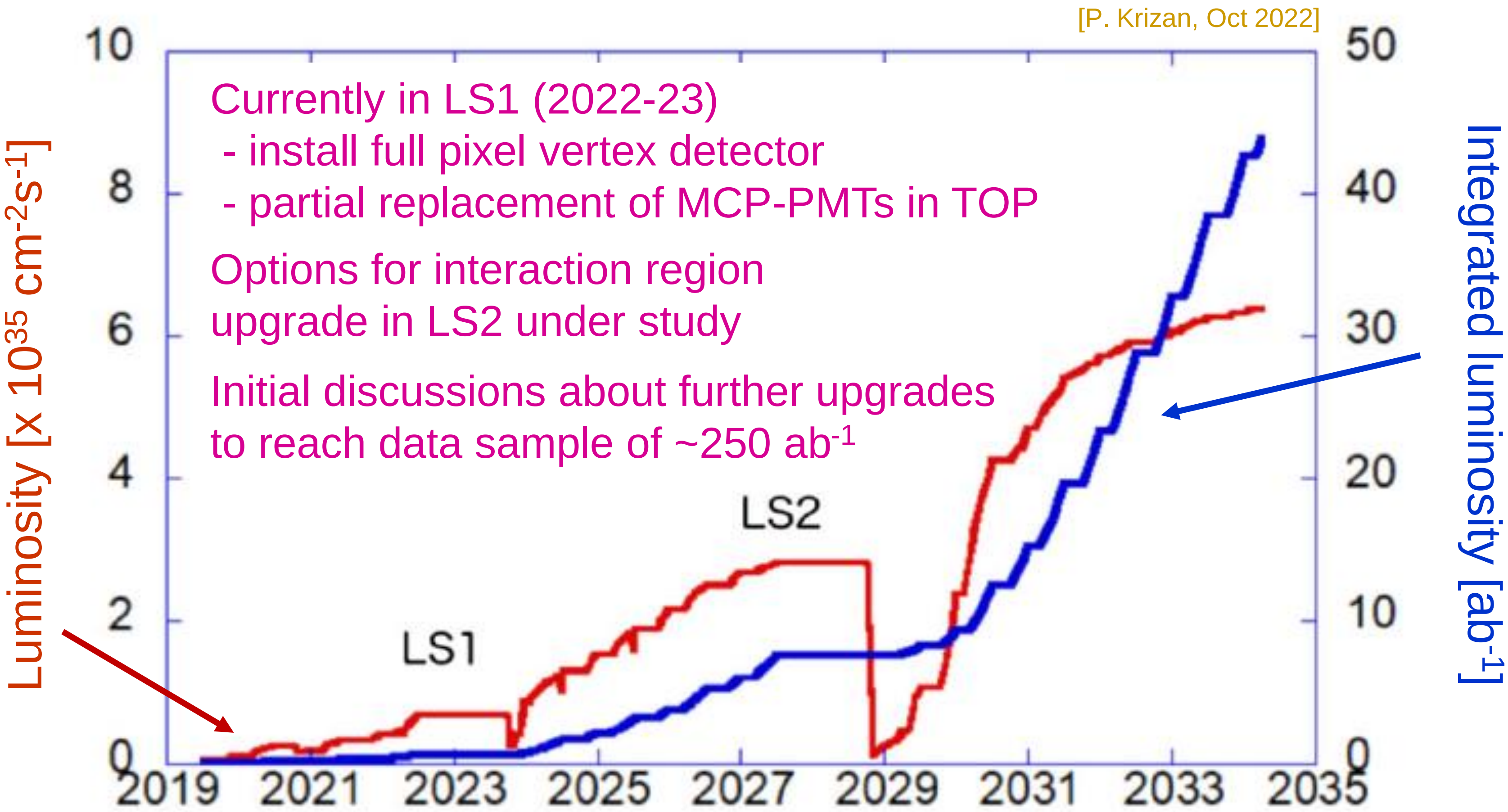




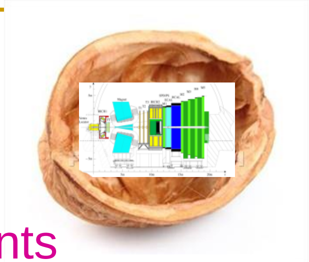
[C. La Licata, ICHEP 2022]

Similar to Belle sensitivity, with ~1/4 of the data.

SuperKEKB and Belle II roadmap



LHCb Upgrade I in a nutshell



Indirect search strategies for New Physics, *e.g.* precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive following the experience of Runs 1 & 2 that direct signals are elusive

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond Run 2 requires significant changes.

The LHCb Upgrade

1) Full software trigger
- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

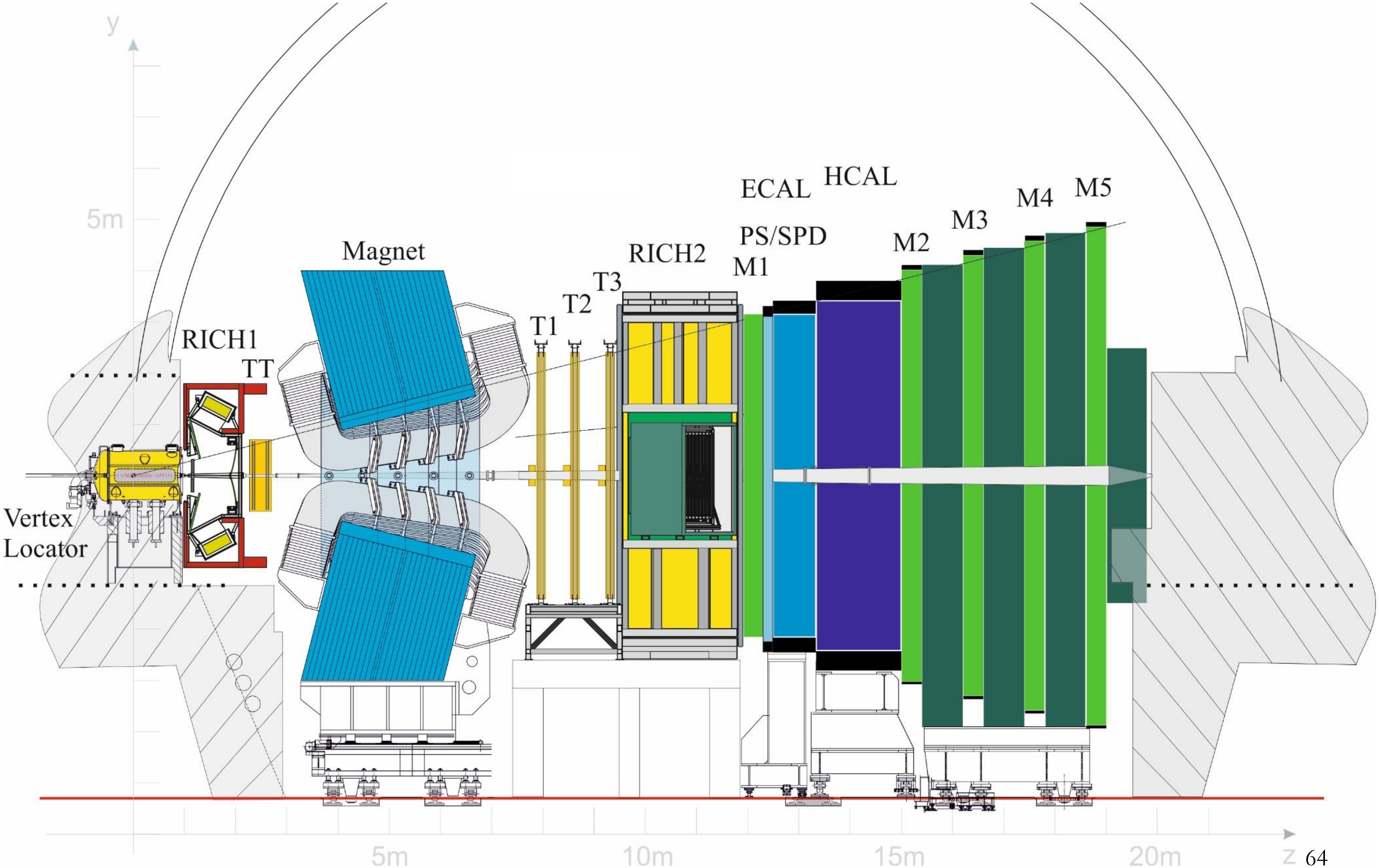
2) Raise operational luminosity to 2 x 10^{33} cm^{-2} s^{-1} (5x Run 2 value)

Necessitates redesign of several sub-detectors & overhaul of readout

Upgrade I will yield hadronic samples > 10x those available from Runs 1 & 2.

(And flexible trigger will allow for much wider range of measurements).

Run 1 & 2 detector



Required modifications

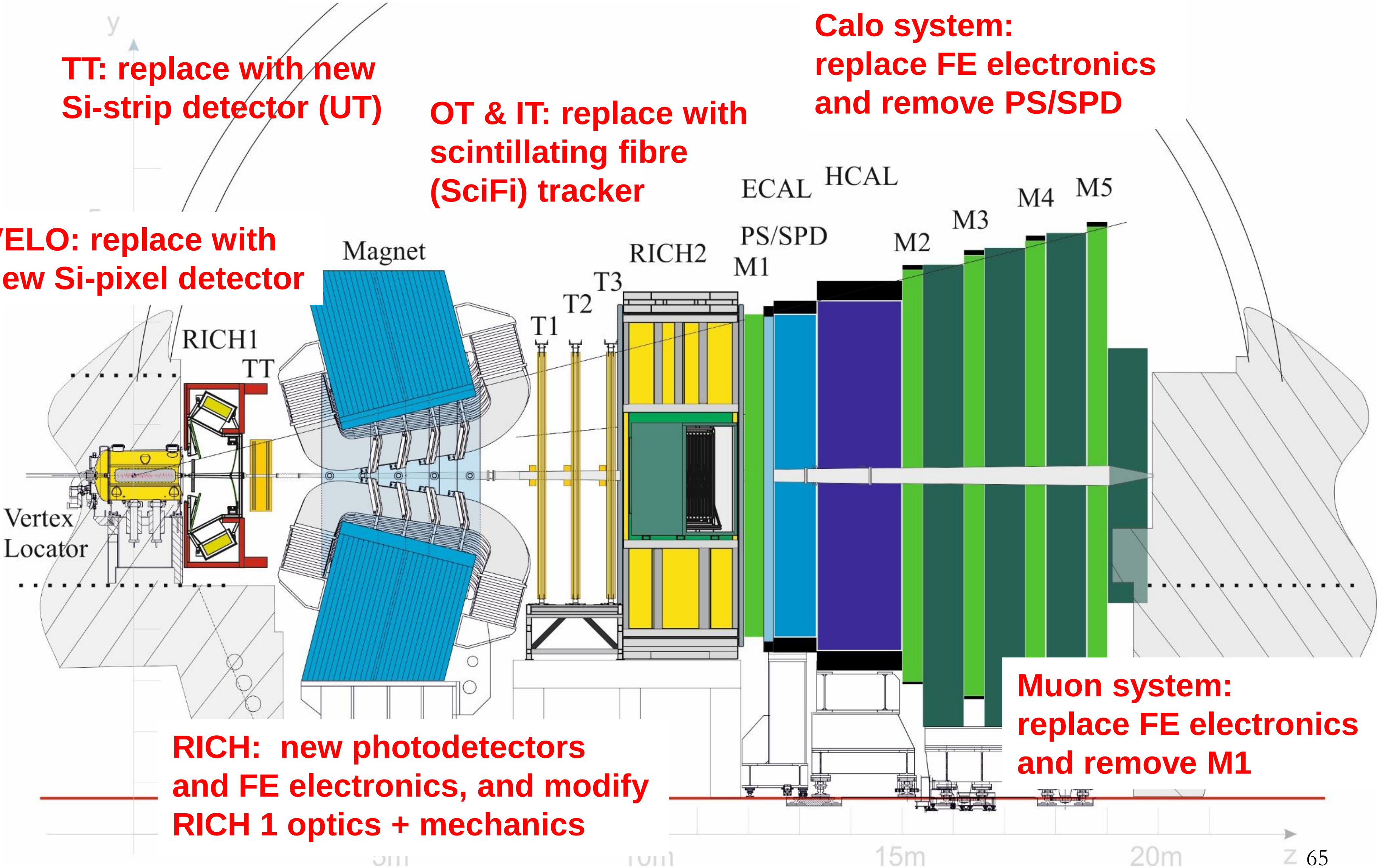
Full s/w trigger →
Replace read-out boards and DAQ

TT: replace with new Si-strip detector (UT)

OT & IT: replace with scintillating fibre (SciFi) tracker

Calo system: replace FE electronics and remove PS/SPD

VELO: replace with new Si-pixel detector



Muon system: replace FE electronics and remove M1

RICH: new photodetectors and FE electronics, and modify RICH 1 optics + mechanics

Required modifications

Full s/w trigger → Replace read-out boards and DAQ

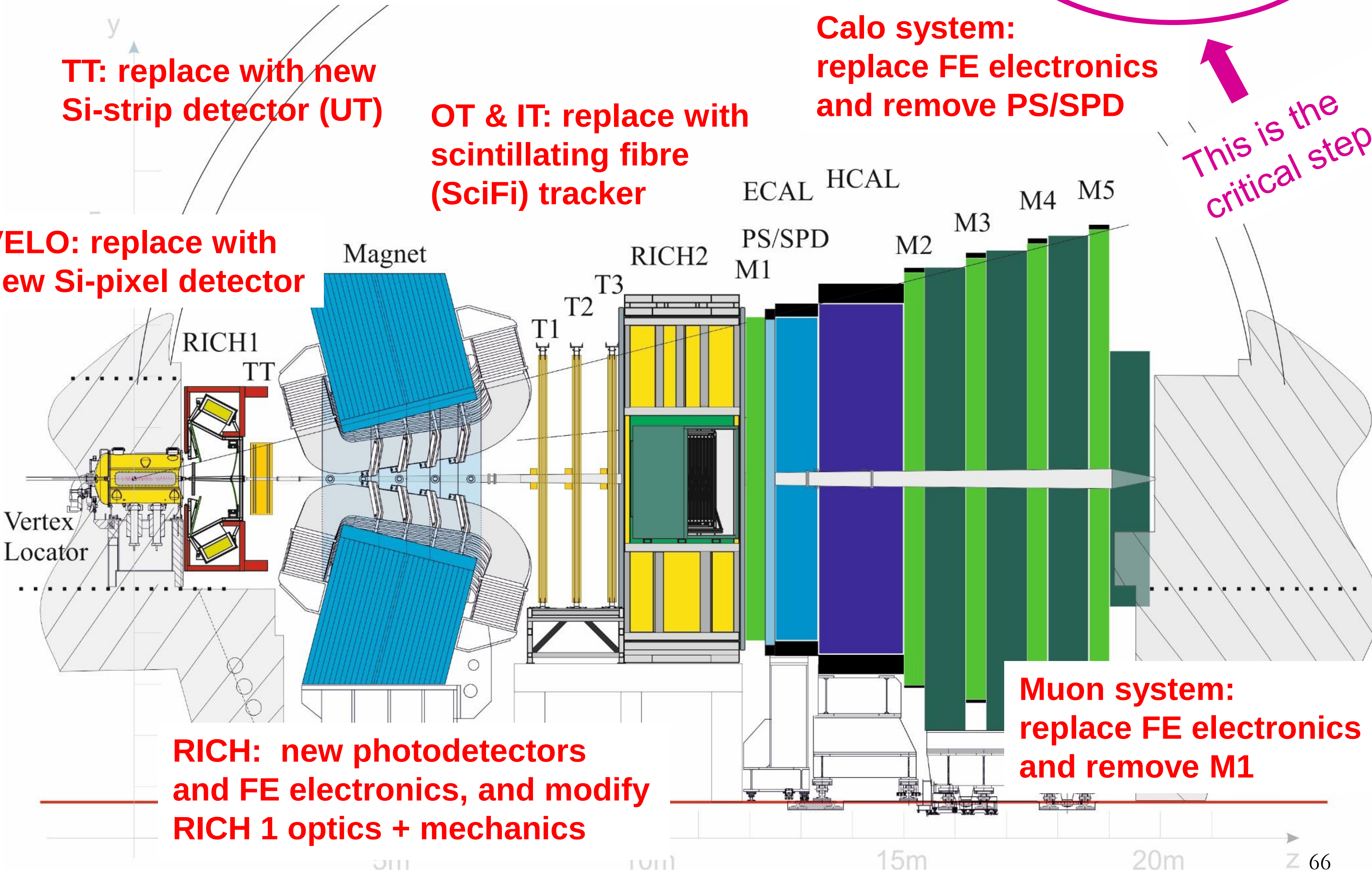
This is the critical step !

Calo system: replace FE electronics and remove PS/SPD

TT: replace with new Si-strip detector (UT)

OT & IT: replace with scintillating fibre (SciFi) tracker

VELO: replace with new Si-pixel detector

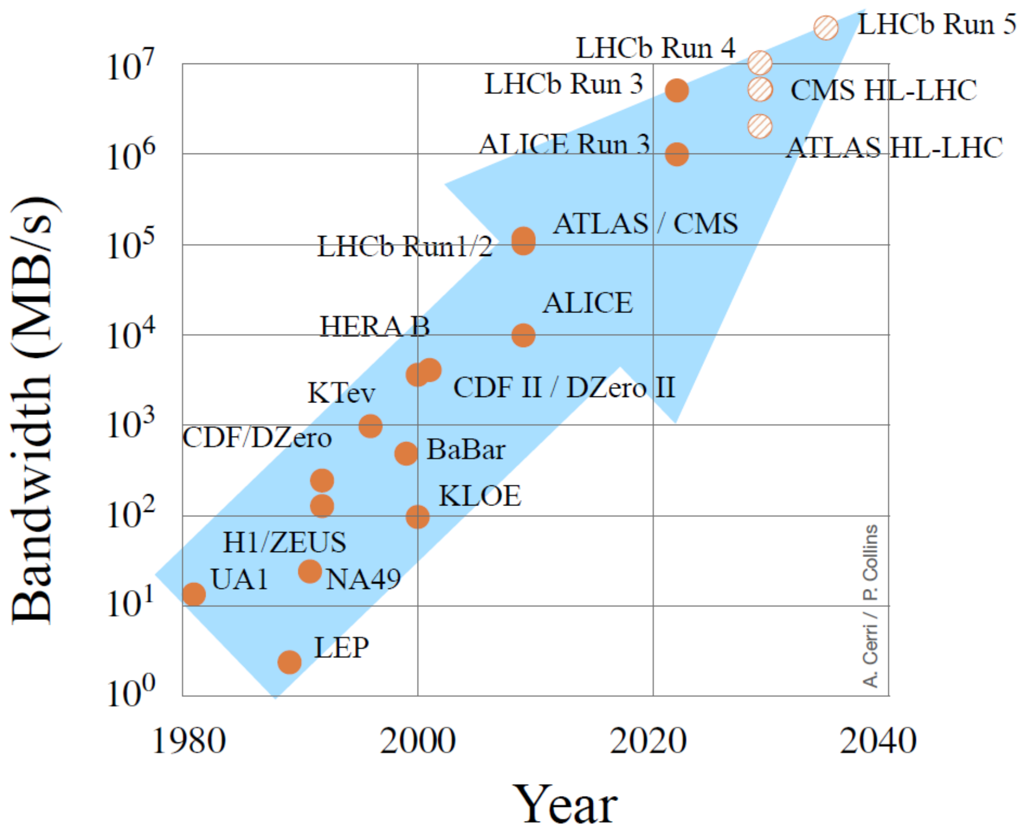


Muon system: replace FE electronics and remove M1

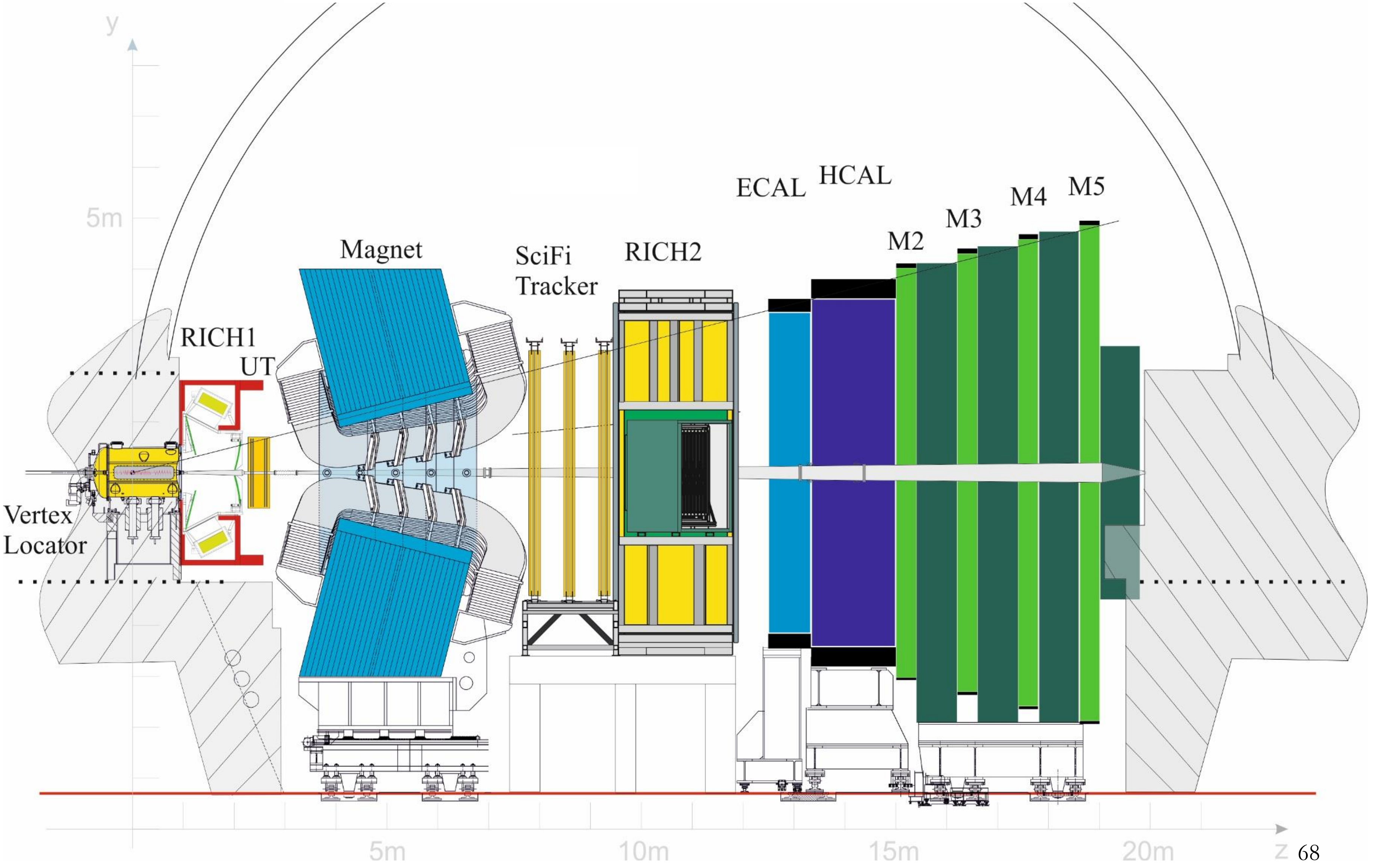
RICH: new photodetectors and FE electronics, and modify RICH 1 optics + mechanics

Entering new territory

A full software trigger at the LHC has huge implications for DAQ & data throughput.



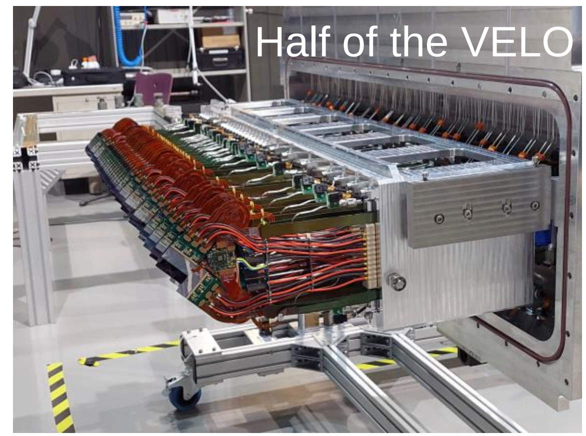
Upgrade I detector

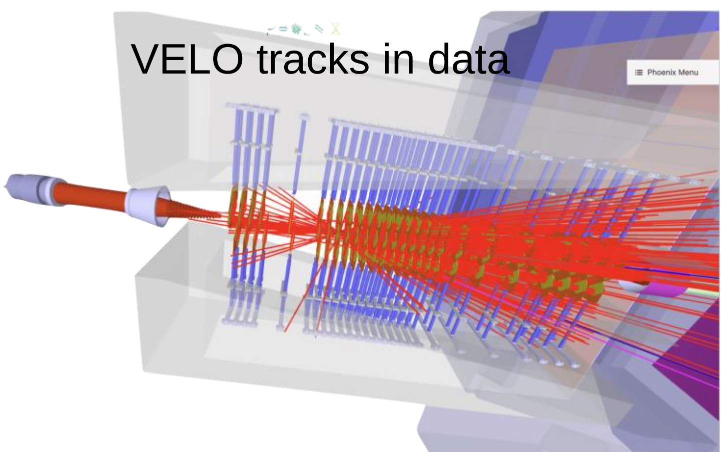


Upgrade I is now ! Example: the VELO

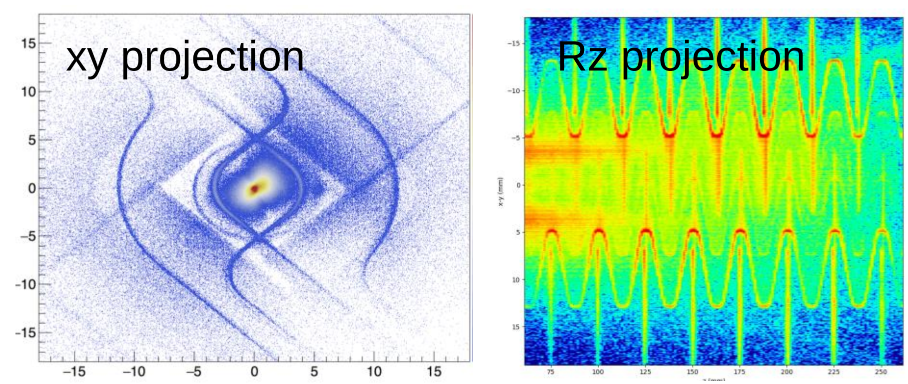
2022 has been a commissioning year (all detectors in place apart from UT).

Upgrade-I VELO is a pixel detector, cooled with CO_2 within microchannels. 'Open' during injection; 'closed' during physics with RF foil only 3 mm away from beam.

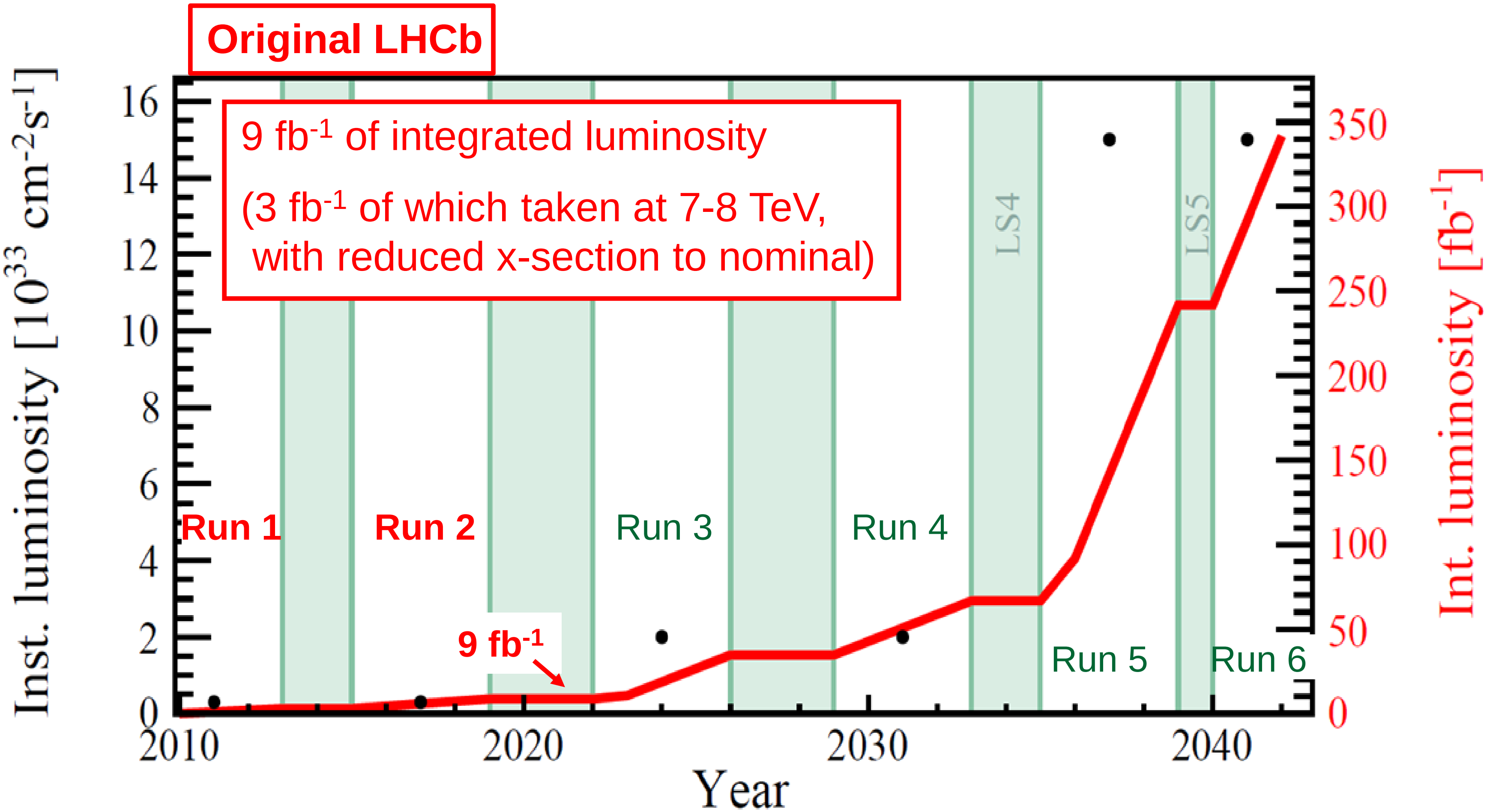




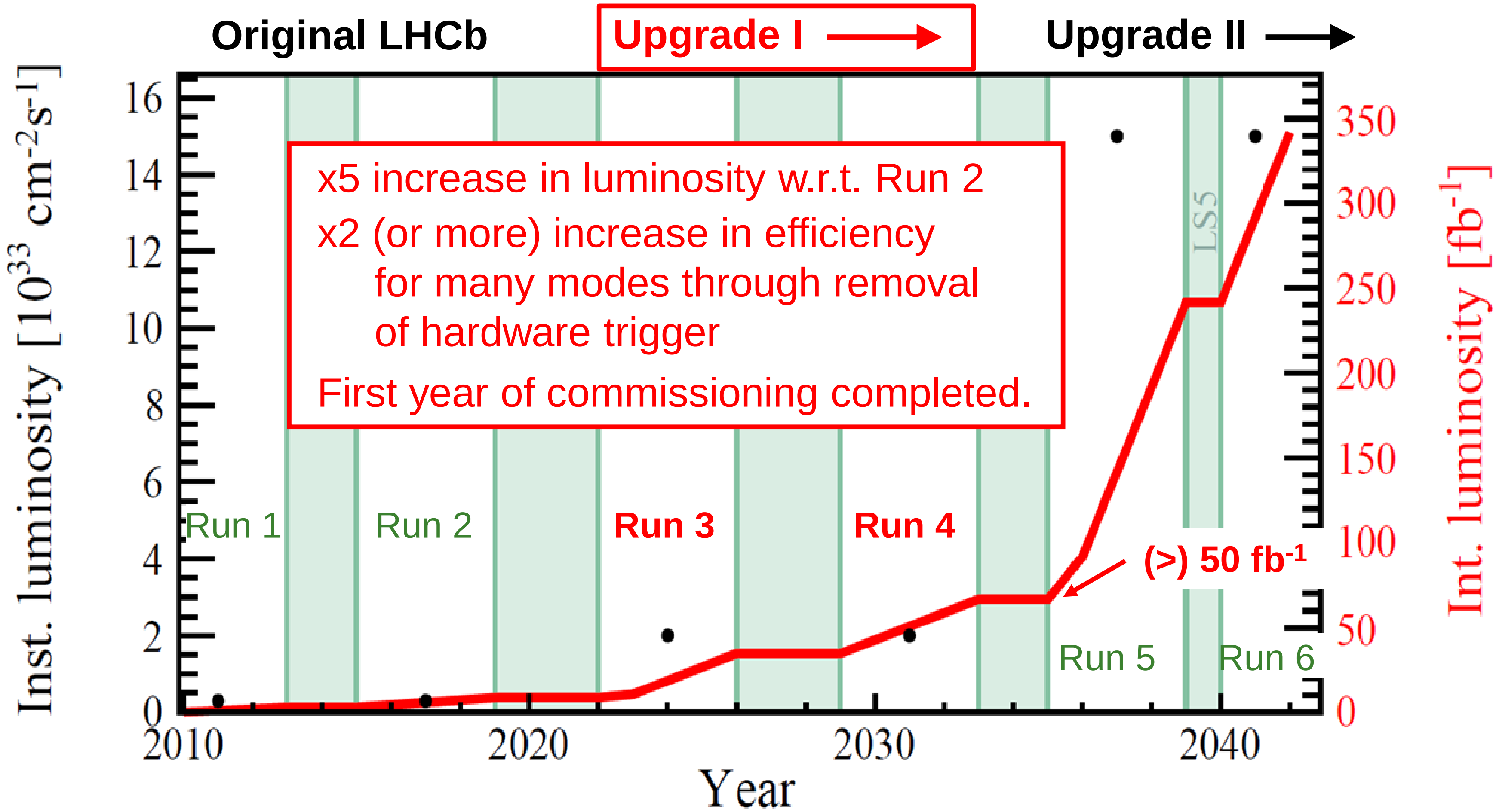
Material vertices



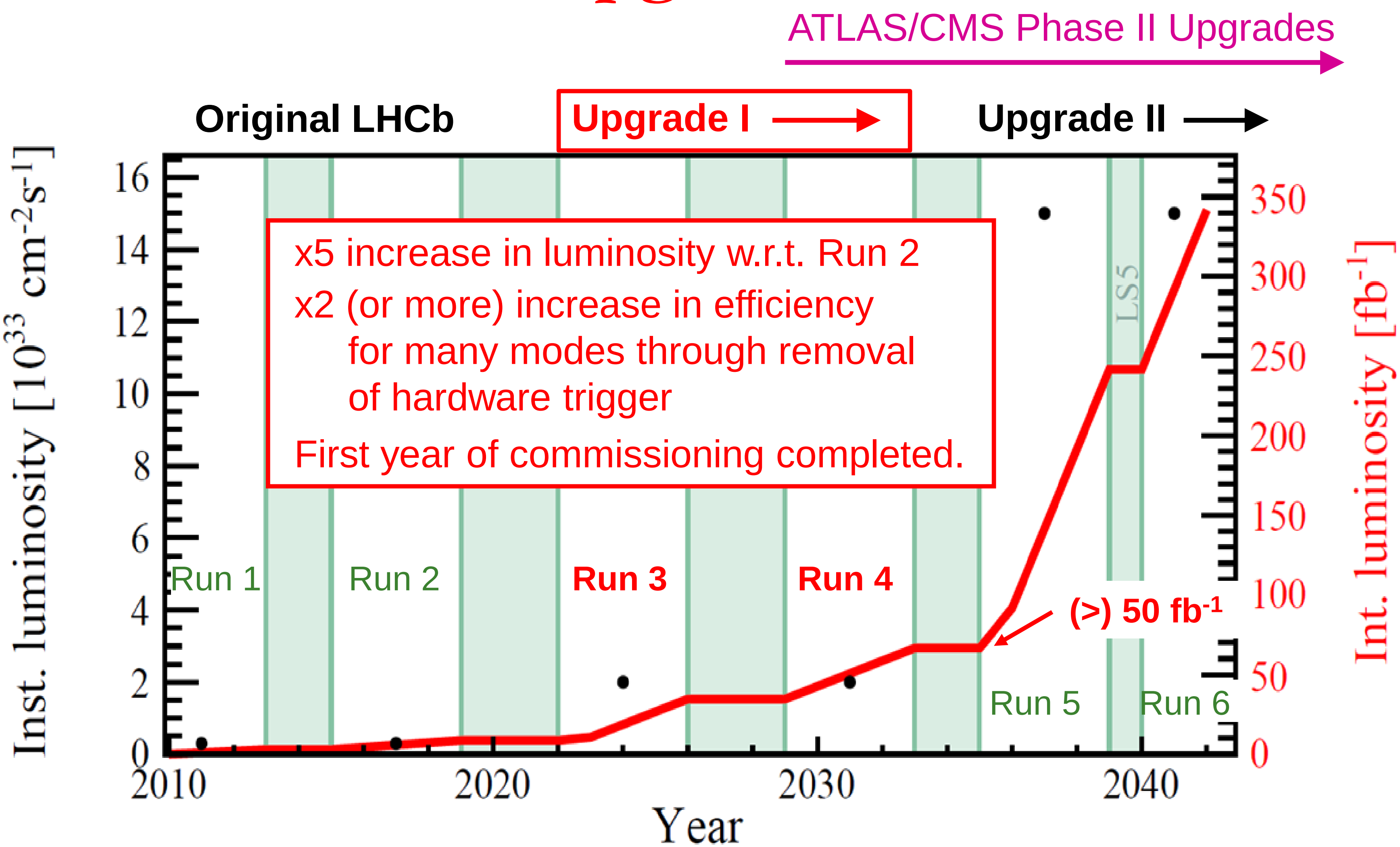
LHCb timeline: Upgrades I and II



LHCb timeline: Upgrades I and II



LHCb timeline: Upgrades I and II



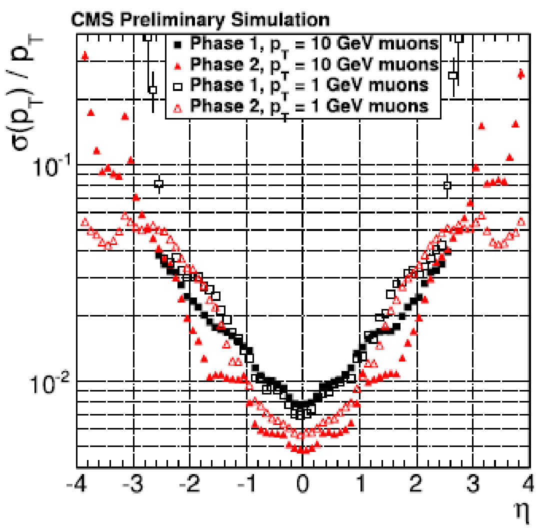
Run 4 is also when the High Luminosity LHC will begin. This makes little difference for LHCb Upgrade I, but is when ATLAS and CMS Phase II Upgrades will start.

ATLAS and CMS Phase II Upgrades

In Runs 1 and 2 ATLAS and CMS have already made high quality B-physics measurements in modes with di-muon final states.

New capabilities of experiments after Phase-II Upgrade (CMS in particular) will strengthen their capabilities in flavour physics

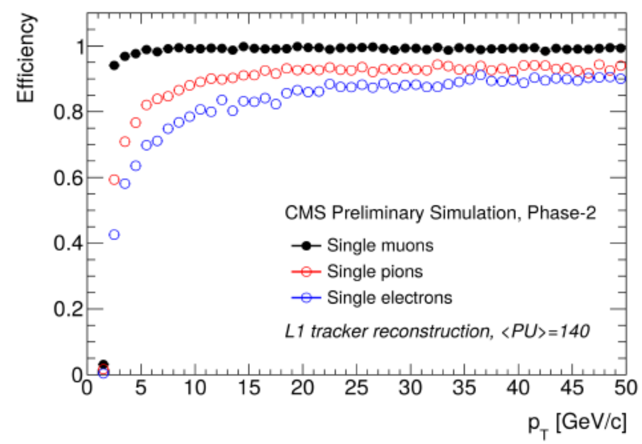
e.g. new CMS tracker



Jeremiah Mans, ECFA HL LHC, Aix-les-Bains, Oct 2014

Significantly improved p resolution

e.g. CMS new L1 track trigger

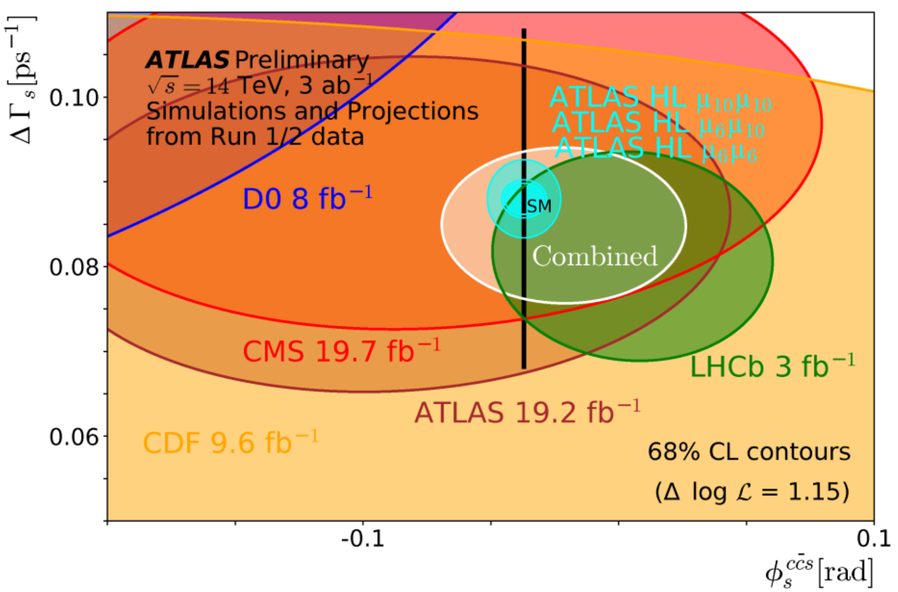


Anders Ryd, ECFA HL LHC, Aix-les-Bains, Oct 2014

Could allow CMS to accumulate large samples even in hadronic modes!

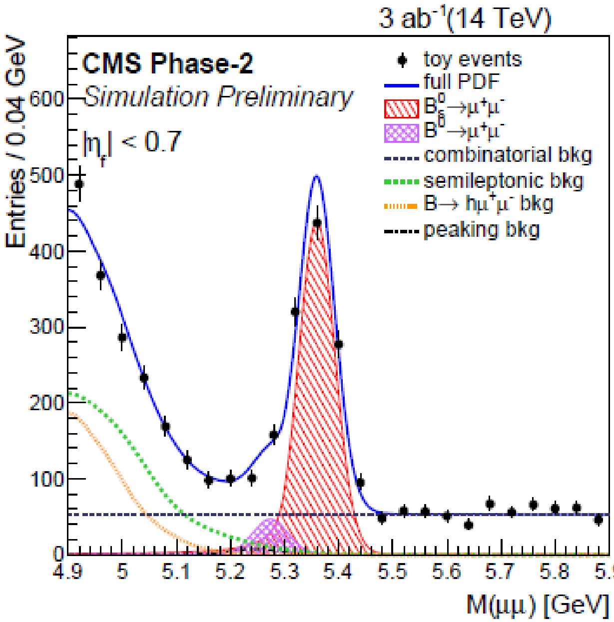
B-physics prospects at the HL-LHC with ATLAS and CMS

ATLAS prospects for φ_s with 3 ab^{-1} for different trigger thresholds.



[ATL-PHYS-PUB-2018-041]

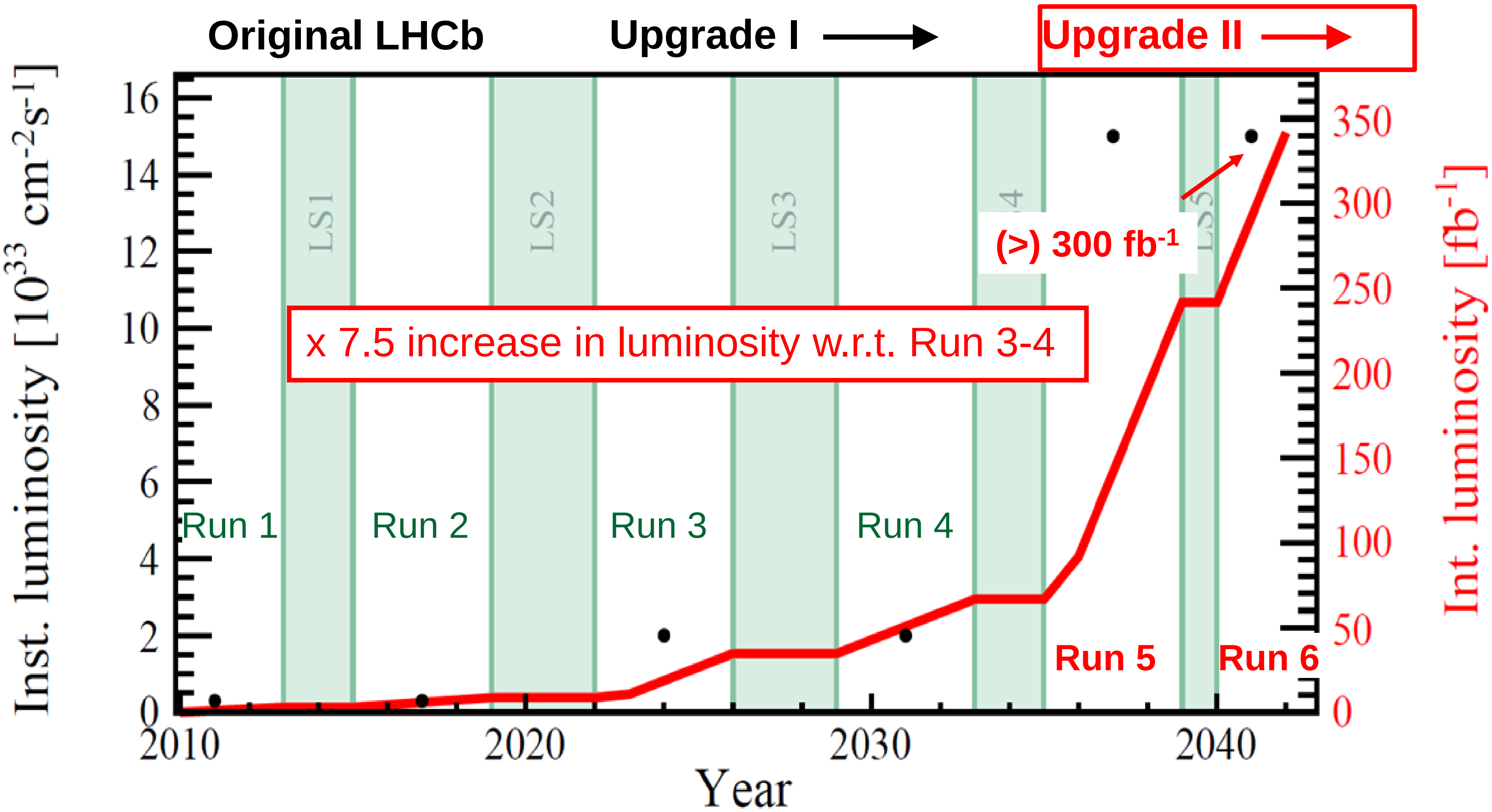
CMS prospects for $B^0_{(s)} \rightarrow \mu\mu$ in barrel region with 3 ab^{-1}.



[CMS-PAS-FTR-18-013]

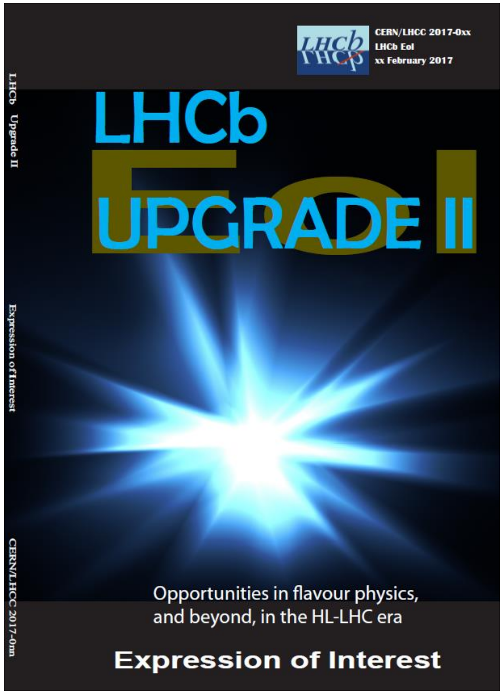
Also see recent Snowmass White Paper [ATL-PHYS-PUB-2022-018,CMS-PAS-FTR-22-001].

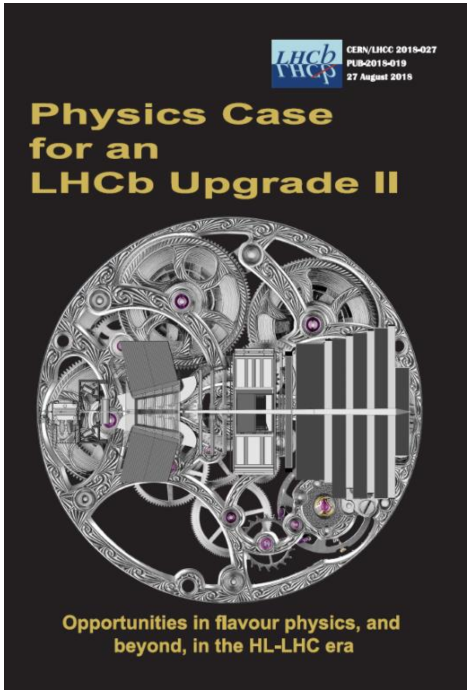
LHCb timeline: Upgrades I and II



LHCb Upgrade II

Steady progress towards plans for an Upgrade II, that will operate in Runs 5 and 6.





[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012]

Now part of the CERN baseline plan. Framework TDR recently approved by LHCC.

LHCb Upgrade II

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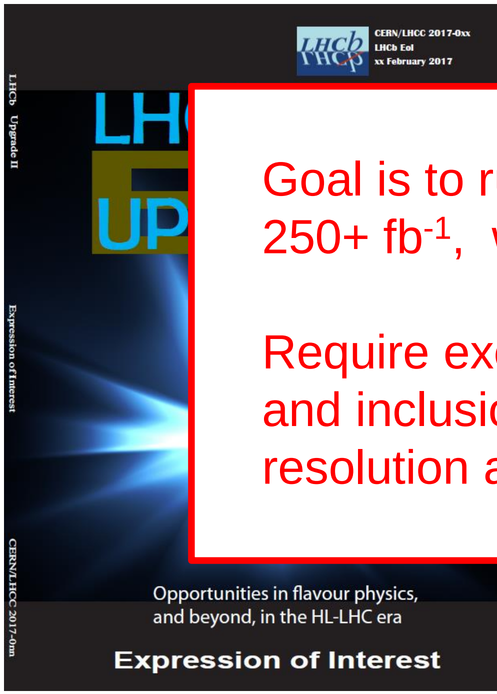
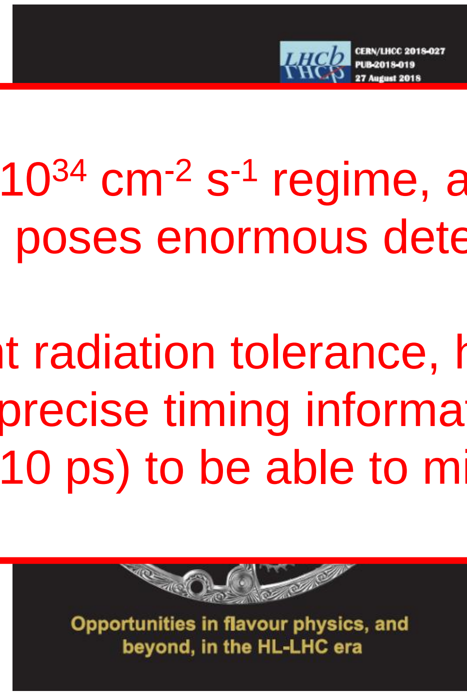
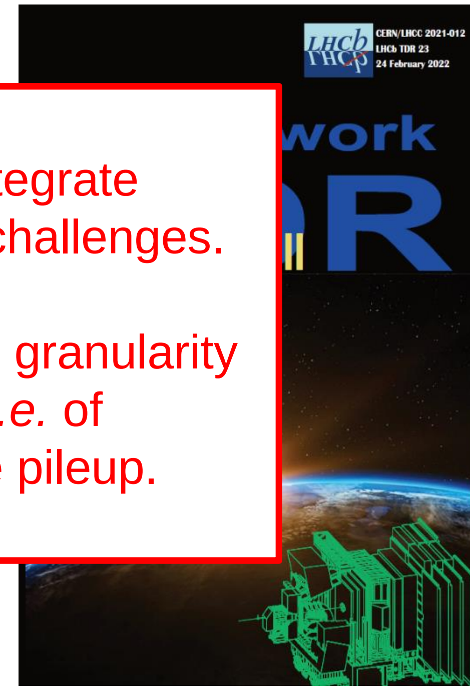






Goal is to run in 10^{34} cm^{-2} s^{-1} regime, and integrate 250+ fb^{-1}, which poses enormous detector challenges.

Require excellent radiation tolerance, higher granularity and inclusion of precise timing information (*i.e.* of resolution a few 10 ps) to be able to mitigate pileup.

[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012]

Now part of the CERN baseline plan. Framework TDR recently approved by LHCC.

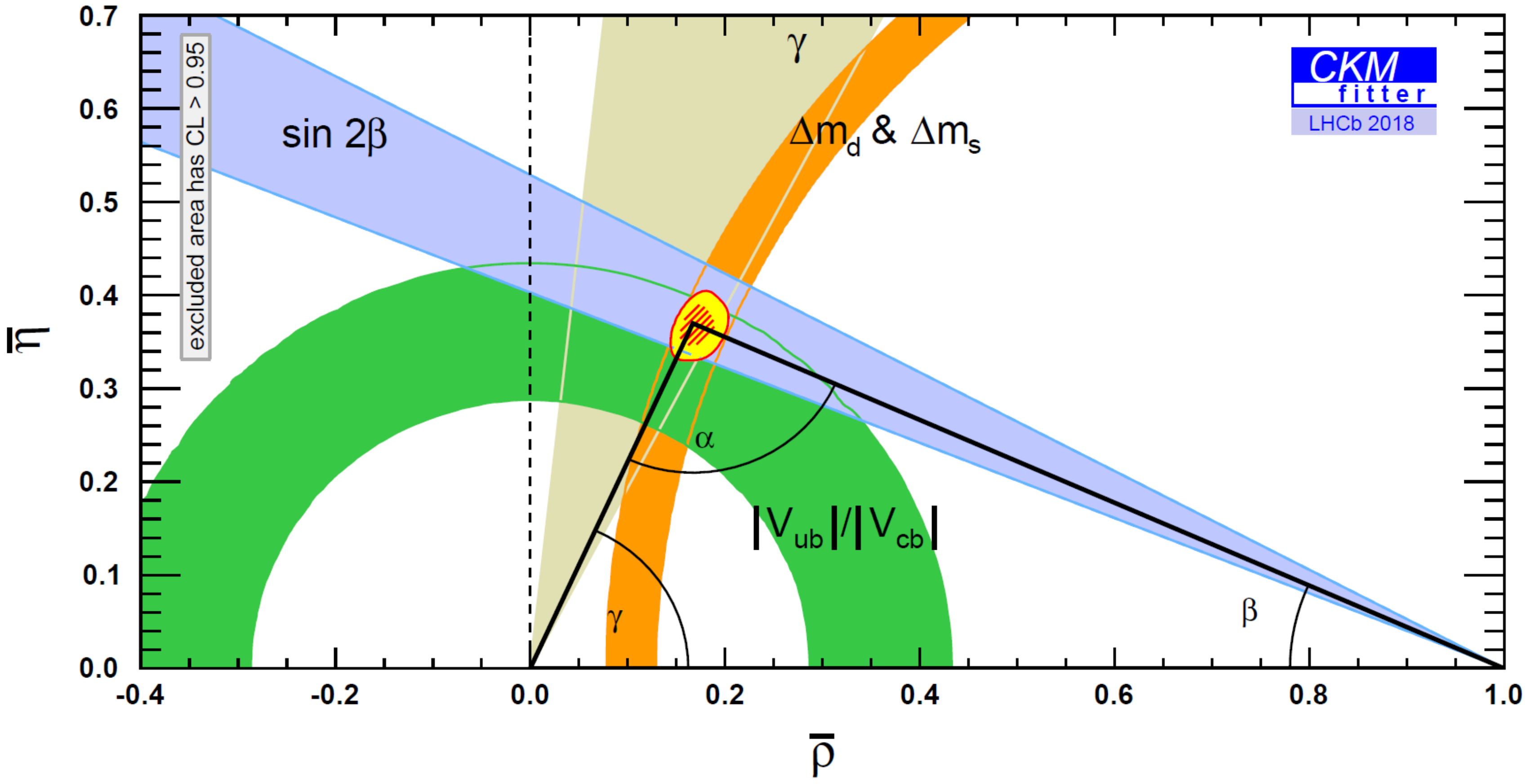
Projected uncertainties for representative observables

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I ($23\,\mathrm{fb}^{-1}$)	Upgrade I ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
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_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{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 ($D^0 \to K_{\mathrm{s}}^0\pi^+\pi^-$)	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
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	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

[CERN-LHCC-2021-012]

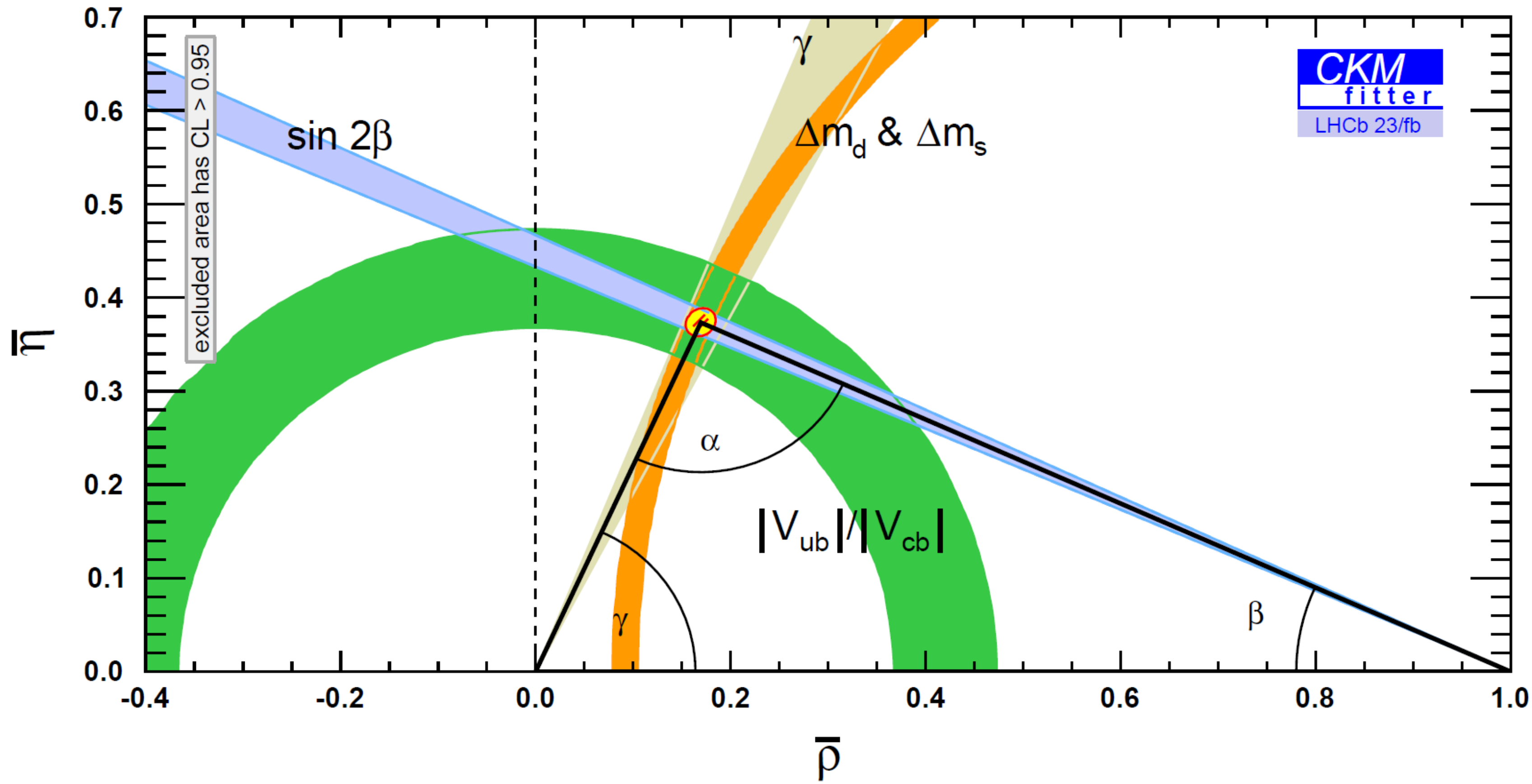
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): 2018 status



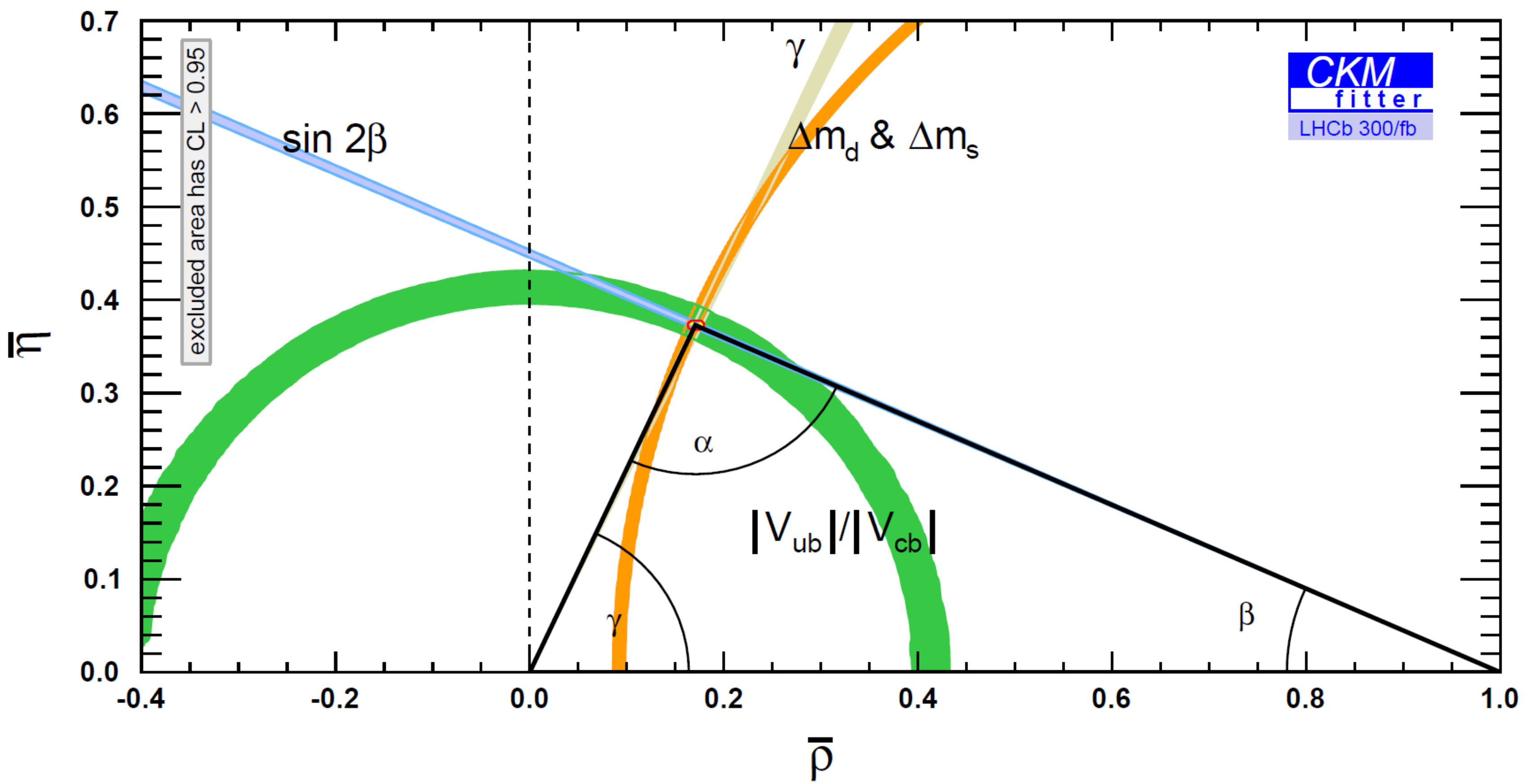
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): start of HL-LHC



Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): after Upgrade II

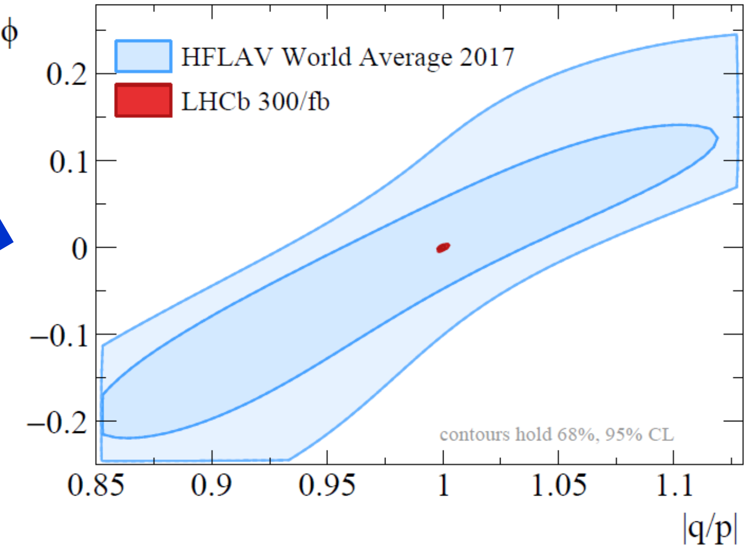


Charm physics potential of LHCb Upgrade II

Upgrade II will allow for an order-of-magnitude improvement in precision in current benchmark analyses, such as ΔA_{CP} [arXiv:1808.08865].

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

New measurements will become accessible. Exquisite precision will be attainable in searches (and studies) of CPV in mixing-related phenomena (*i.e.* characterised by φ and |q/p|).

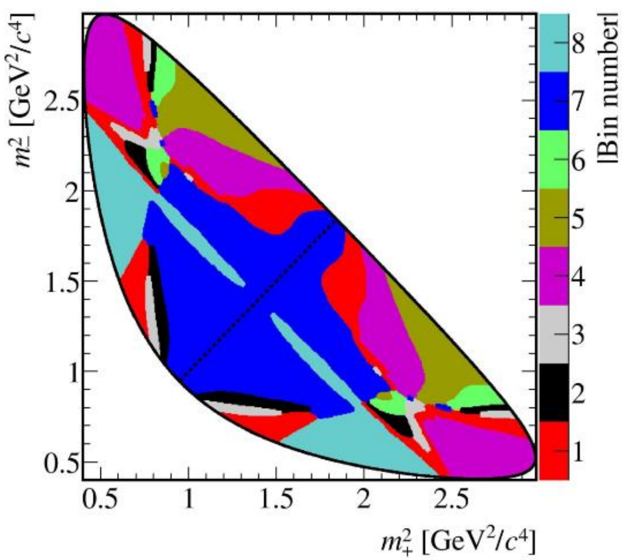


Super Tau Charm Factory (STCF)

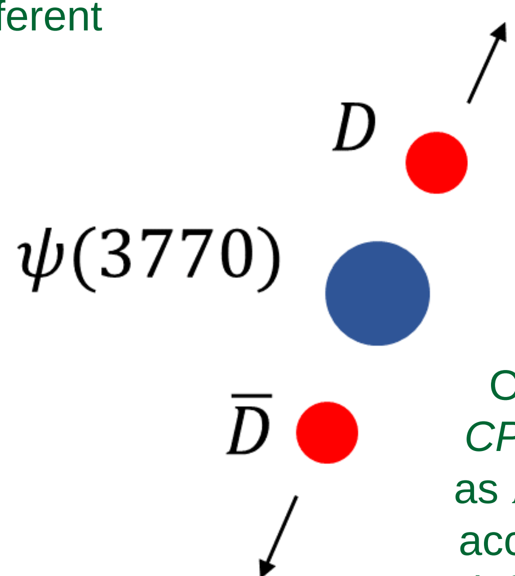
There is another collider project under consideration that will be very valuable for flavour physics, which is a Super Tau Charm Factory in China (early 2030s).

CPV measurements at LHCb and Belle II depend on model-independent inputs from (originally) CLEO-c and (now) BES III. Quantum-correlated $D\bar{D}$ production in $e^+e^- \to \psi(3770) \to D\bar{D}$ allows unique access to hadronic phases in decay.

e.g. for γ and charm-mixing studies need to know hadronic phase information in different regions of $D \to K_S^0\pi^+\pi^-$ Dalitz plot



Meson reconstructed as $e.g.\, D \to K^+K^-$, so *CP* even

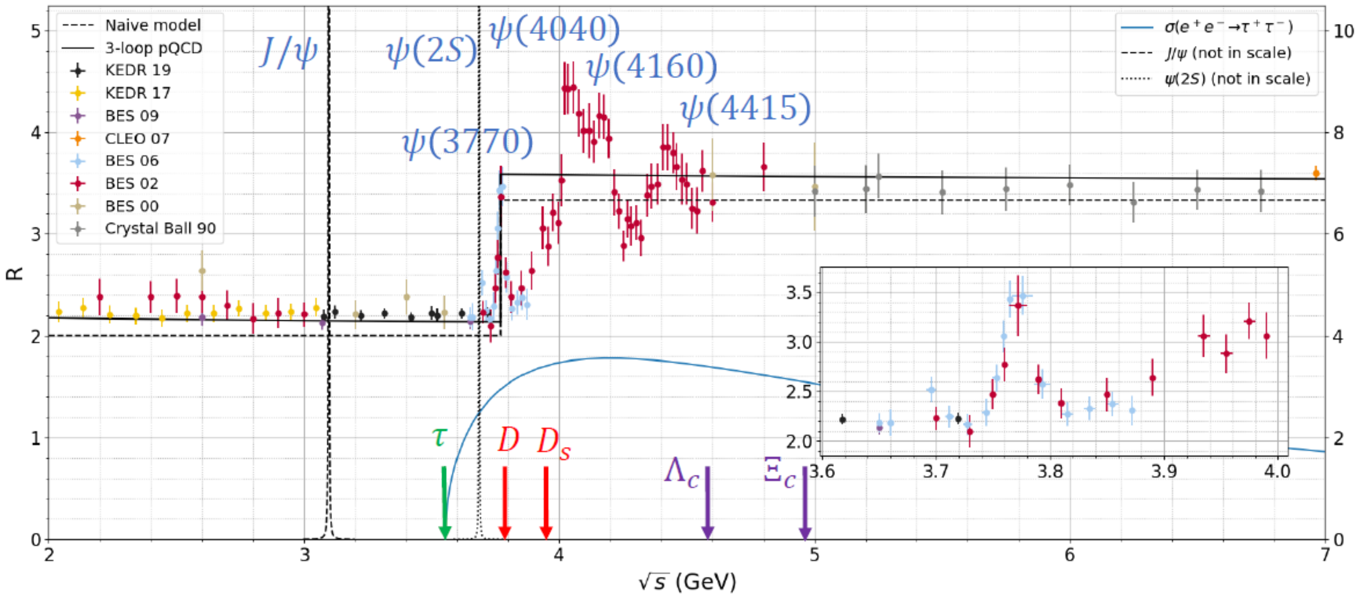


Other meson must be *CP* odd. If reconstructed as $D \to K_S^0\pi^+\pi^-$ this gives access to hadronic phase information in Dalitz plot

Super Tau Charm Factory (STCF)

There is another collider project under consideration that will be very valuable for flavour physics, which is a Super Tau Charm Factory in China (early 2030s).

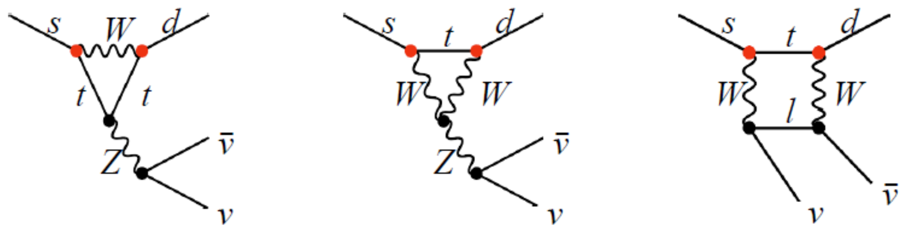
STFC will operate at luminosities of ~10^{35} cm^{-2}s^{-1} and allow sample sizes of ~100x those at BES III – improved hadronic phase information vital for LHCb Upgrade II.



It will also deliver produce Huge samples at other low energy points, allowing for super precise studies in charm, QCD, spectroscopy and tau physics.

Flavour studies with kaons

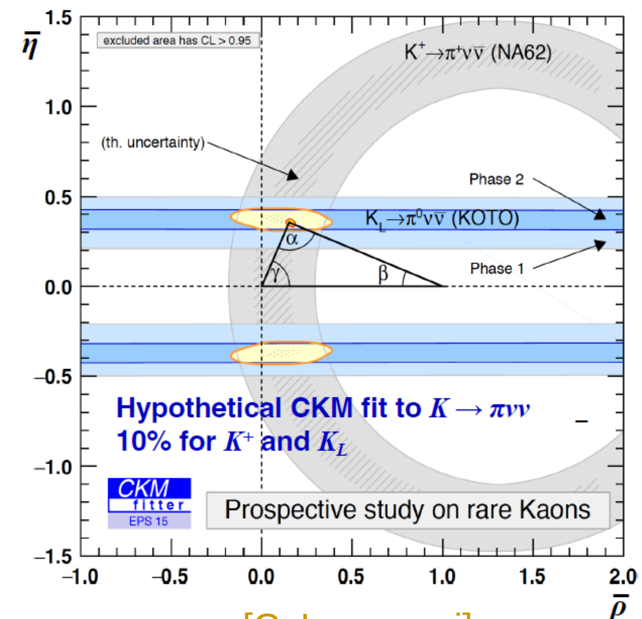
Kaon sector very important in foundation of SM, & rare-decay studies continue to be an important New Physics probe. The poster-child decays are the very rare (~ 10^{-11}), but theoretically clean & well predicted, modes $K^+ \to \pi^+ \nu\bar{\nu}$ & $K_L^0 \to \pi^0 \nu\bar{\nu}$.



$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

[JHEP 1511 (2015) 033, EPJ C82 (2022) 615, arXiv:2109.11032, arXiv:2105.02868]



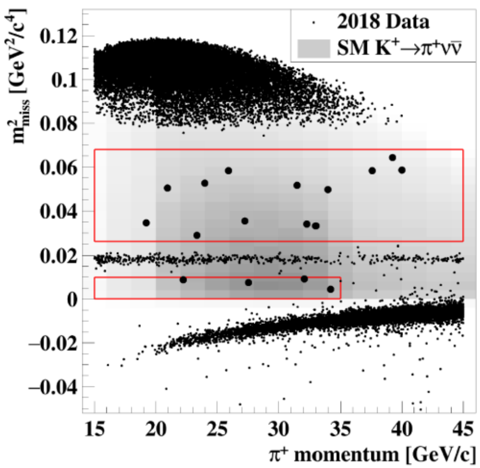
[C. Lazzeroni]

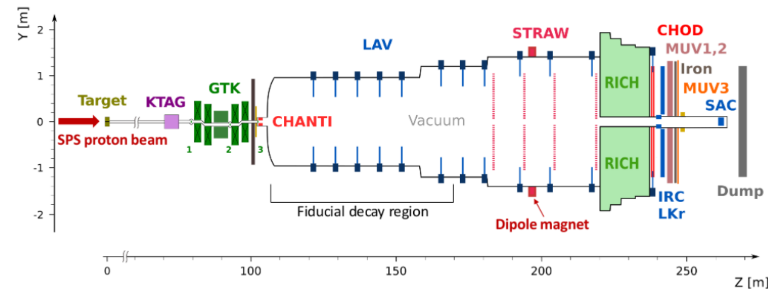
i.e. non-parametric uncertainties, 0.5% for K_L and 3.5% for K^+.

Rare kaon decays: current status

$K^+ \to \pi^+ \nu \bar{\nu}$ NA62, with 2018 data, see 20 events, with background of 7. Compatible with SM expectation and 3.4σ evidence of decay.

[JHEP 06 (2021) 093]





$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$$

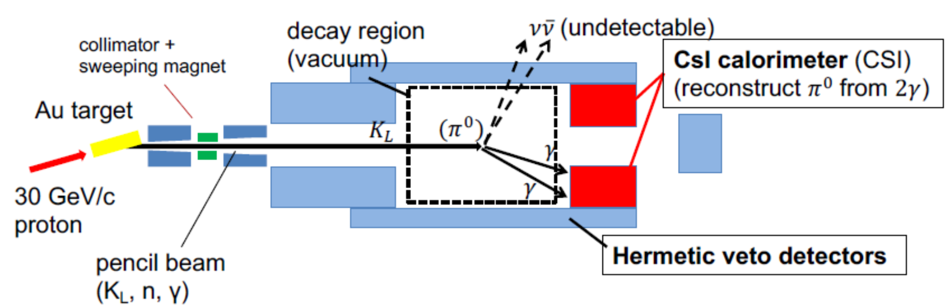
With data up to LS3 expect to reach ~10%.

$K_L^0 \to \pi^0 \nu \bar{\nu}$ KOTO experiment

Unforeseen backgrounds found at analysis stage [PRL 126 (2021) 121801] which will be tackled in future runs.

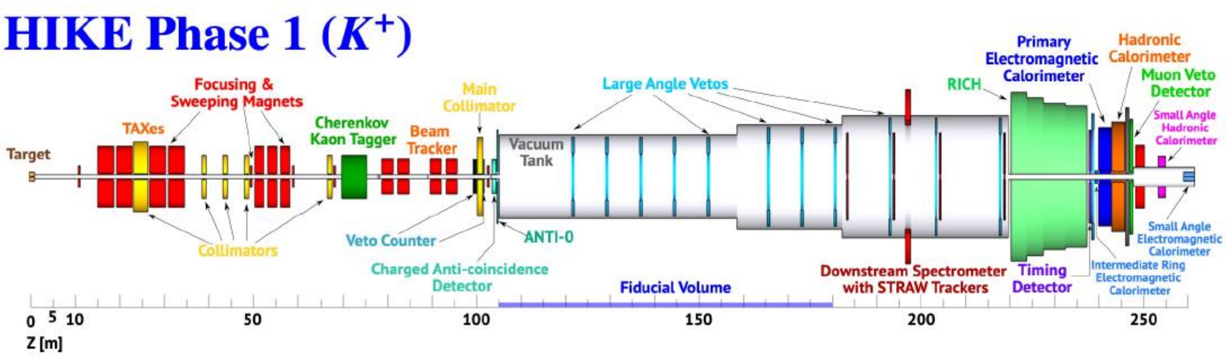
BR < 4.9 x 10^{-9} at 90% C.L.

$K_L \to \pi^0 \nu \bar{\nu}$: $(\pi^0 \to)$ 2γ + nothing

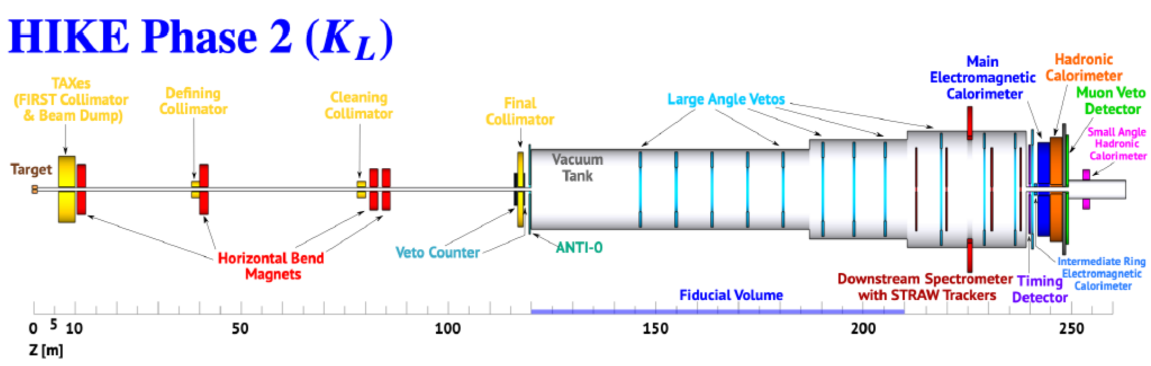


Rare kaon decays: future plans

Ambitious plans for next-generation kaon experiments in NA62 hall post LS3.



Improved timing and detector will make it possible to run at higher intensity and collect ~100 $K^+ \to \pi^+ \nu\bar{\nu}$ decays per year.



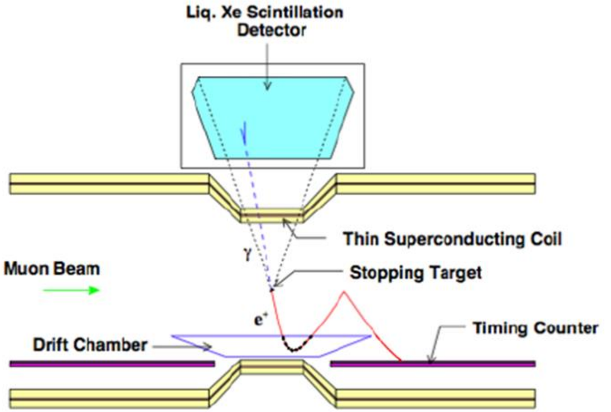
Would aim to observe $K_L^0 \to \pi^0 \nu\bar{\nu}$. A further upgrade (Phase 3, a.k.a. KLEVER) would be able to make precise BF measurement.

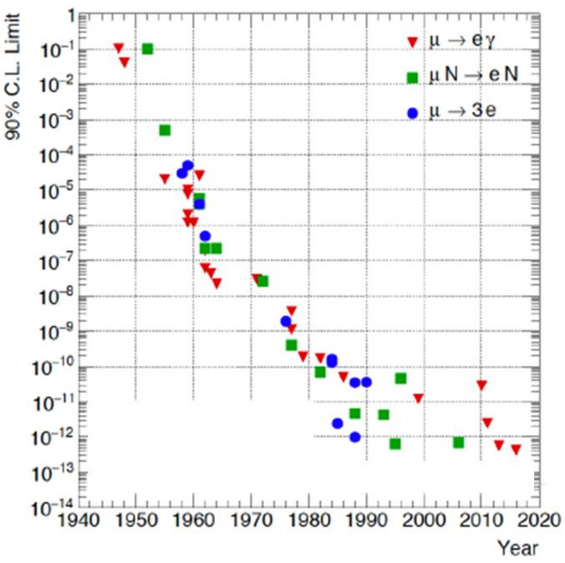
Charged Lepton Flavour Violation: μ→eγ

Observation of Charged Lepton Flavour Violation (CFLV) would be a clear signature of New Physics. Several flagship channels in muon sector.

Best limit on $\mu \to e\gamma$ set by MEG at PSI:

$BF(\mu \to e\gamma) < 4.2 \times 10^{-13}$ @ 90% C.L.
[MEG, EPJ C76 (2016) 434]



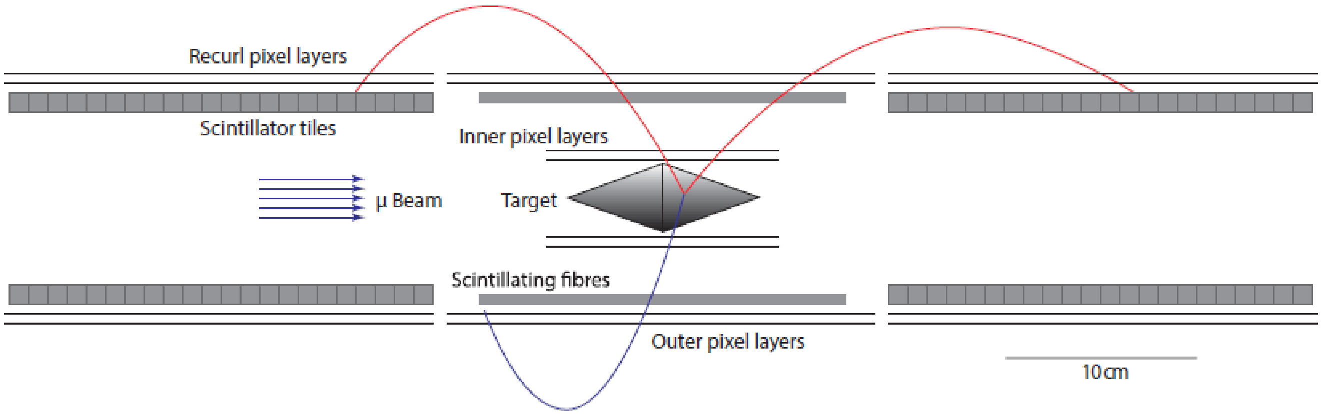


MEGII drift chamber

MEGII benefits from upgrade of all subdetectors and aims for 10x better limit. Currently data taking (?)

Charged Lepton Flavour Violation: μ→eee

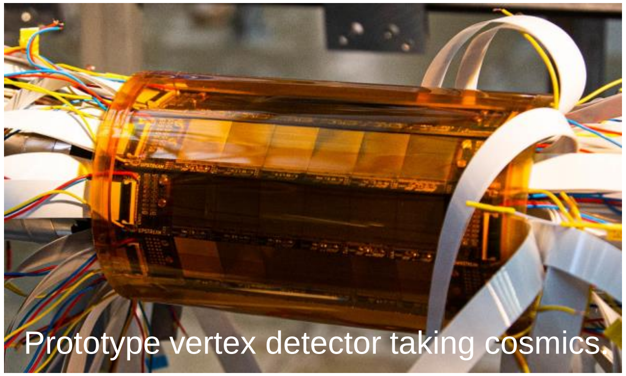
Mu3e will use (like MEGII) the high-intensity PSI 1.4 MW continuous muon beam.



[arXiv:2204.00001, arXiv:2009.11690]

Four layers of HV-MAPS surrounding the stopping target. Thinned to 0.1% X0 per layer. In order to optimise momentum resolution allow tracks to 'recurl' in field so that second set of measurements can be made.

Aim for initial limit of 2 x 10^{-15}, which could be improved by order of magnitude if beam is upgraded (`HiMB' – a project for 2028, which would also benefit MEGII if achieved).



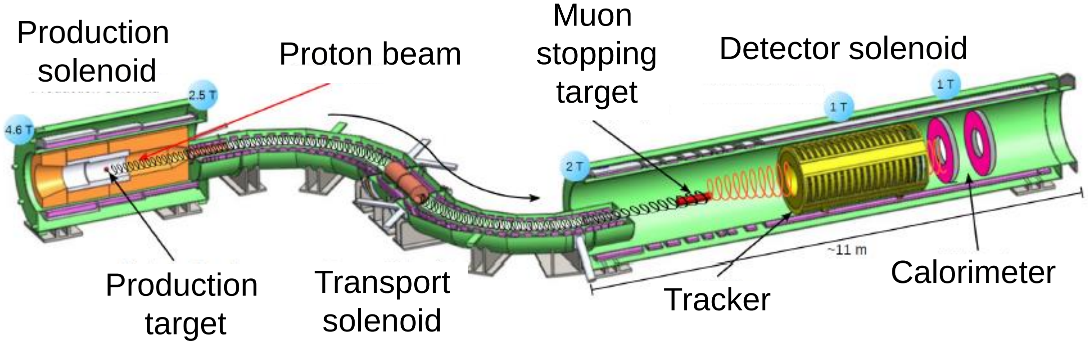
Prototype vertex detector taking cosmics.

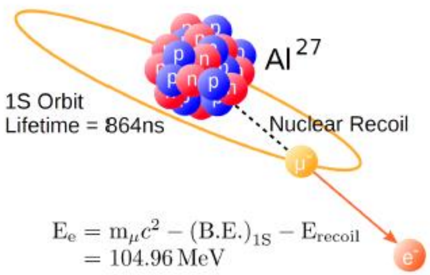
[N. Berger]

Charged Lepton Flavour Violation: muon conversion

CLFV would allow a muon captured by an atom to convert: $\mu^- N \rightarrow e^- N$. Upper limit on rate of conversion per capture set at 7 x 10^{-13} (90% CL) by SINDRUM II [EPJ C47 (2006) 337]. Two new experiments aim for 10^{-17}-10^{-18} level.

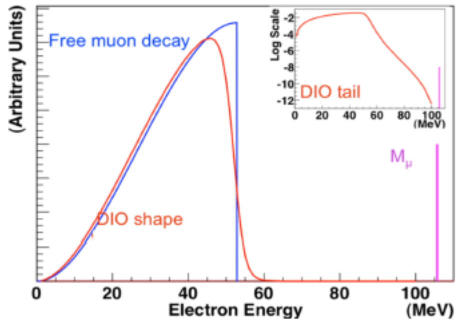
Mu2e at Fermilab





Muons from pion decay transported into second solenoid, and focused on target. Number of captures measured by X-rays from cascade Into 1s state.

Principal background: muon decay in orbit.

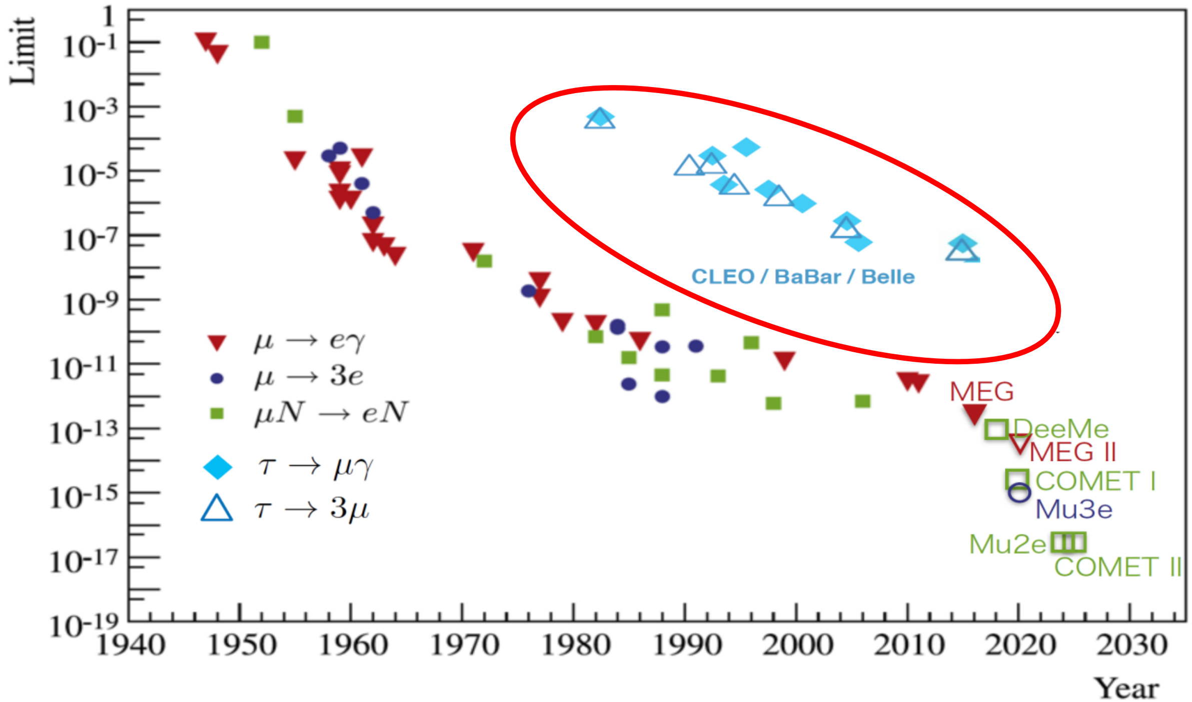


[S. Miscetti]

COMET at J-PARC uses similar (but not identical) technique. Both experiments should be entering commissioning stage in 2023.

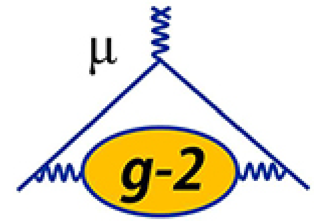
Charged Lepton Flavour Violation: tau decays

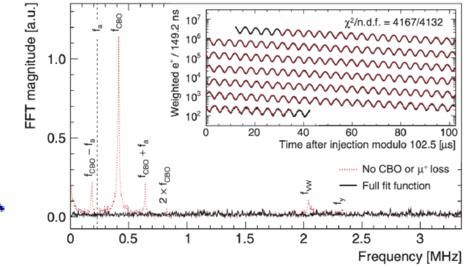
Limits on CLFV in 3rd generation are much weaker, but New Physics effects could be larger. Golden modes include $\tau \to \mu\gamma$ and $\tau \to \mu\mu\mu$, with limits at 10^{-8} level set by B-factories and LHCb. Future sensitivities will approach or reach 10^{-10}, with best performance expected from Belle II and FCC-ee.



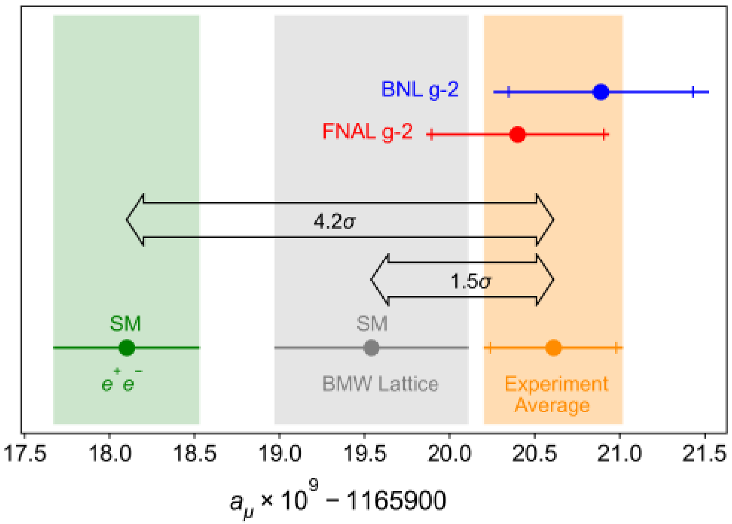
Complementary results come from Z or B or D decays to CLFV final states.

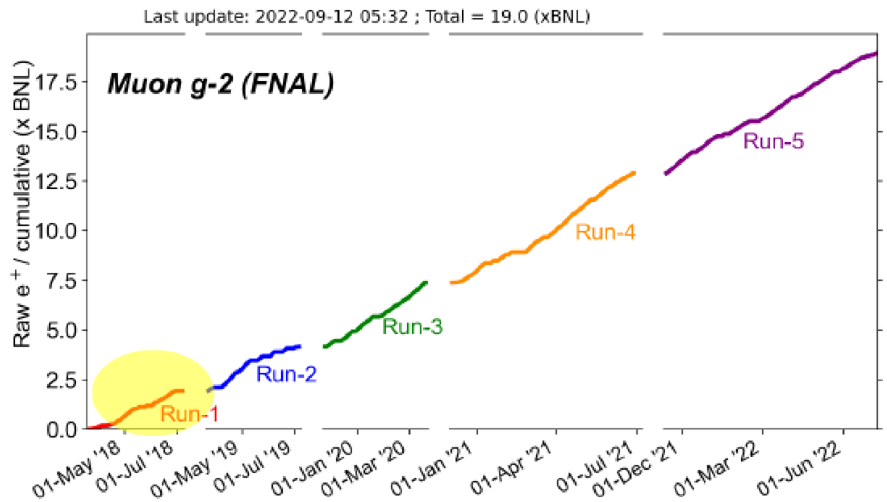
Anomalous magnetic moment of muon (g-2)





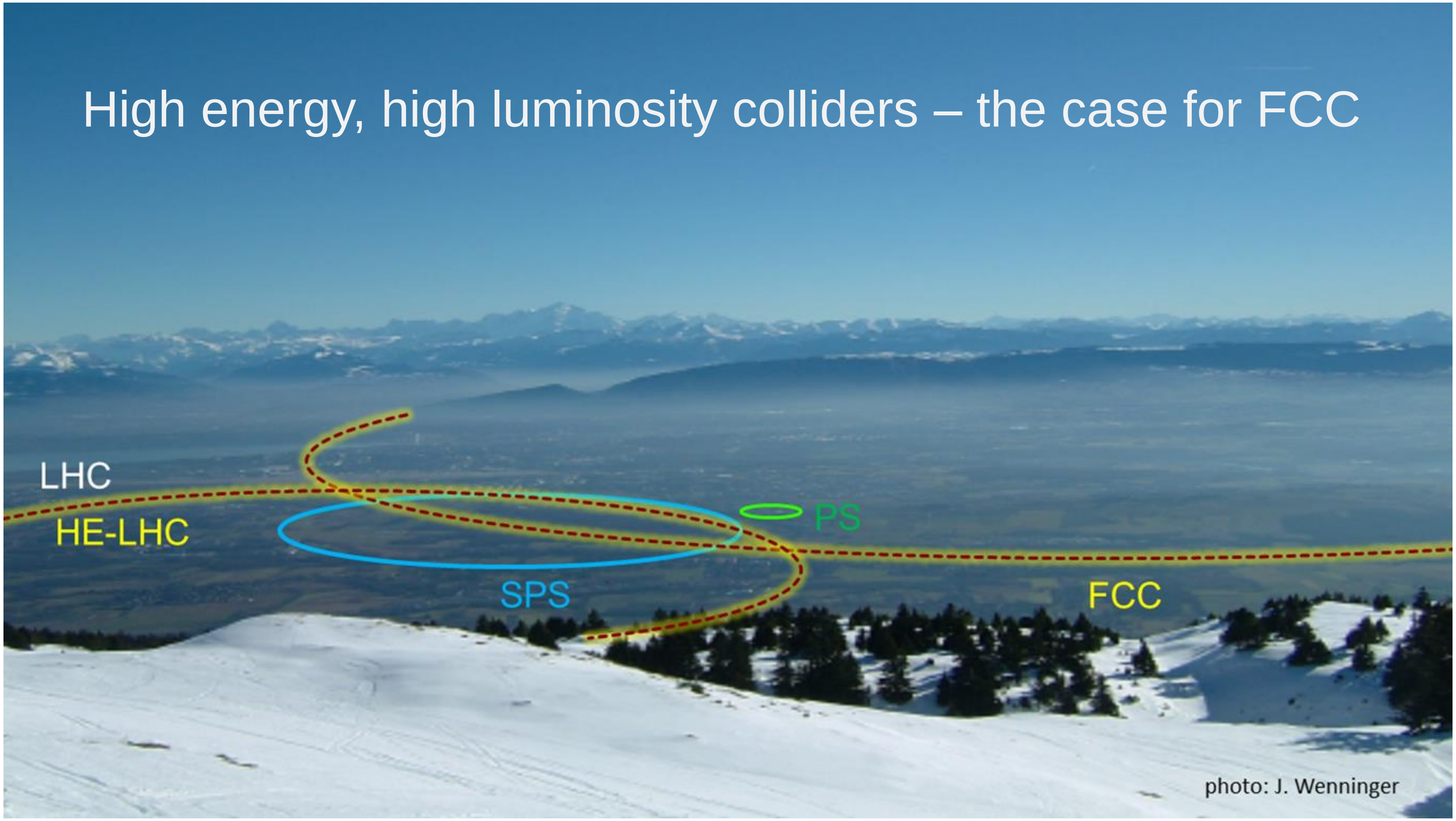
Recent measurement of (g-2) of muon at FNAL [PRL 126 (2021) 141801] confirms old BNL result and is in significant tension with SM, although recent BMW lattice calculation muddies waters. FNAL will improve precision by ~2.5 with final sample.





J-PARC E34 experiment, due to begin in 2027, will use very different approach and will cross-check FNAL measurement. It seems, however, that puzzle has a theoretical component, and so experiments that can help inform the predictions (*e.g.* MUonE muon-electron scattering experiment at CERN) are welcome.

Tomorrow's lecture



Backups