Particle Physics in the 2020s

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LHCb week
Oxford
16/09/2019

European Research Council
Established by the European Commission
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particle physics

"big unanswered questions"
about fundamental particles & their interactions
(dark matter, matter-antimatter asymmetry,
nature of dark energy, hierarchy of scales…)

v.

"big answerable questions"
and how we go about answering them
(nature of Higgs interactions, validity of SM up to high scales,
lepton flavour universality, pattern of neutrino mixing, …)

https://cerncourier.com/a/nobel-expectations-for-new-physics-at-the-lhc/

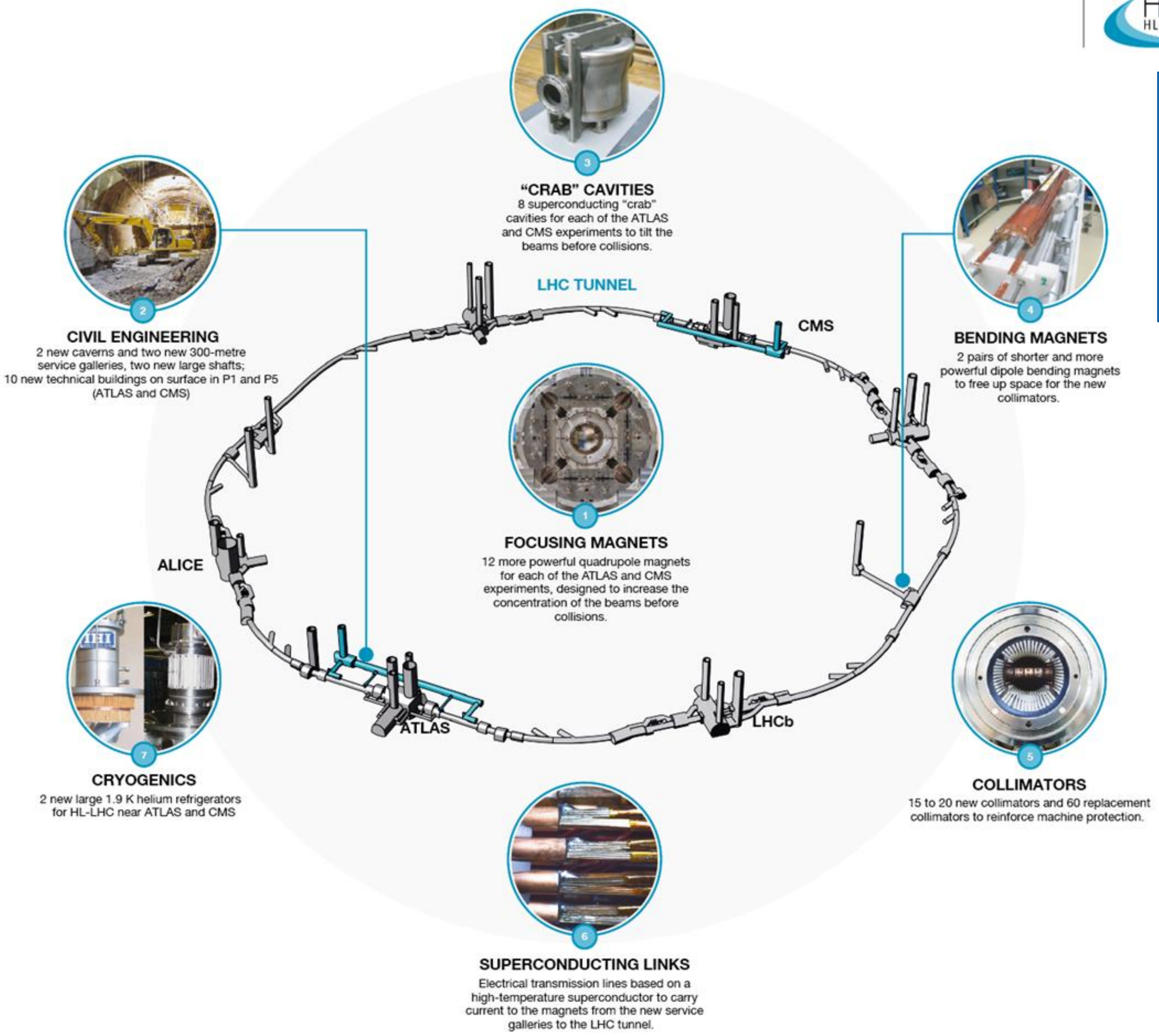
"

I personally expect supersymmetry to be discovered at the LHC

-a Nobel prize-winning theorist [2008]

experiments in the 2020s

High-luminosity LHC



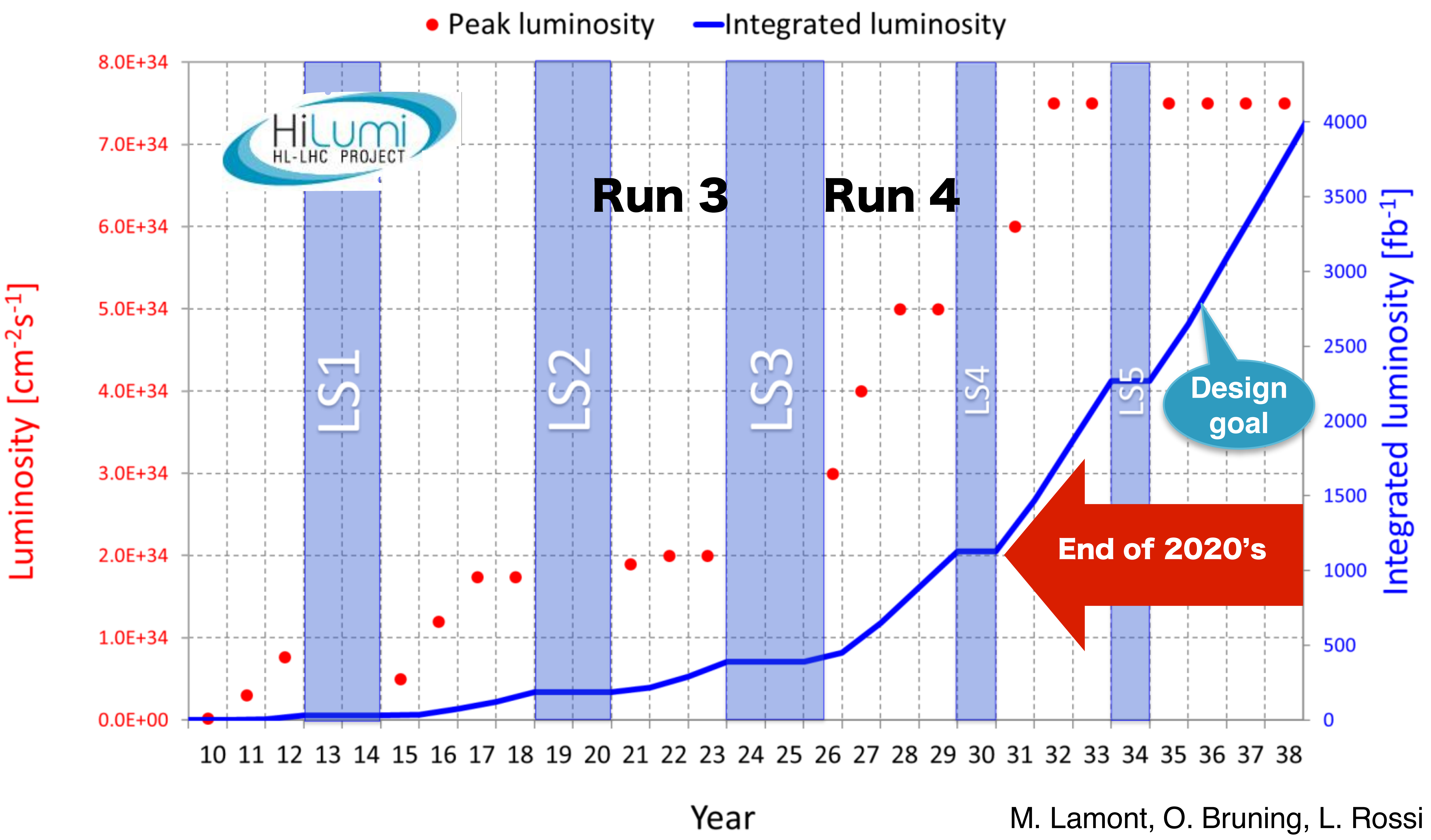
HiLumi HL-LHC PROJECT

Rebuilding ~1.2km of LHC (the most complicated bit!)

But also touches very many other systems around the machine

- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Other NbTi magnets in the IR
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

HL-LHC lumi: 5-7x today's int.lumi by 2030, 20-30x by 2036



M. Lamont, O. Bruning, L. Rossi

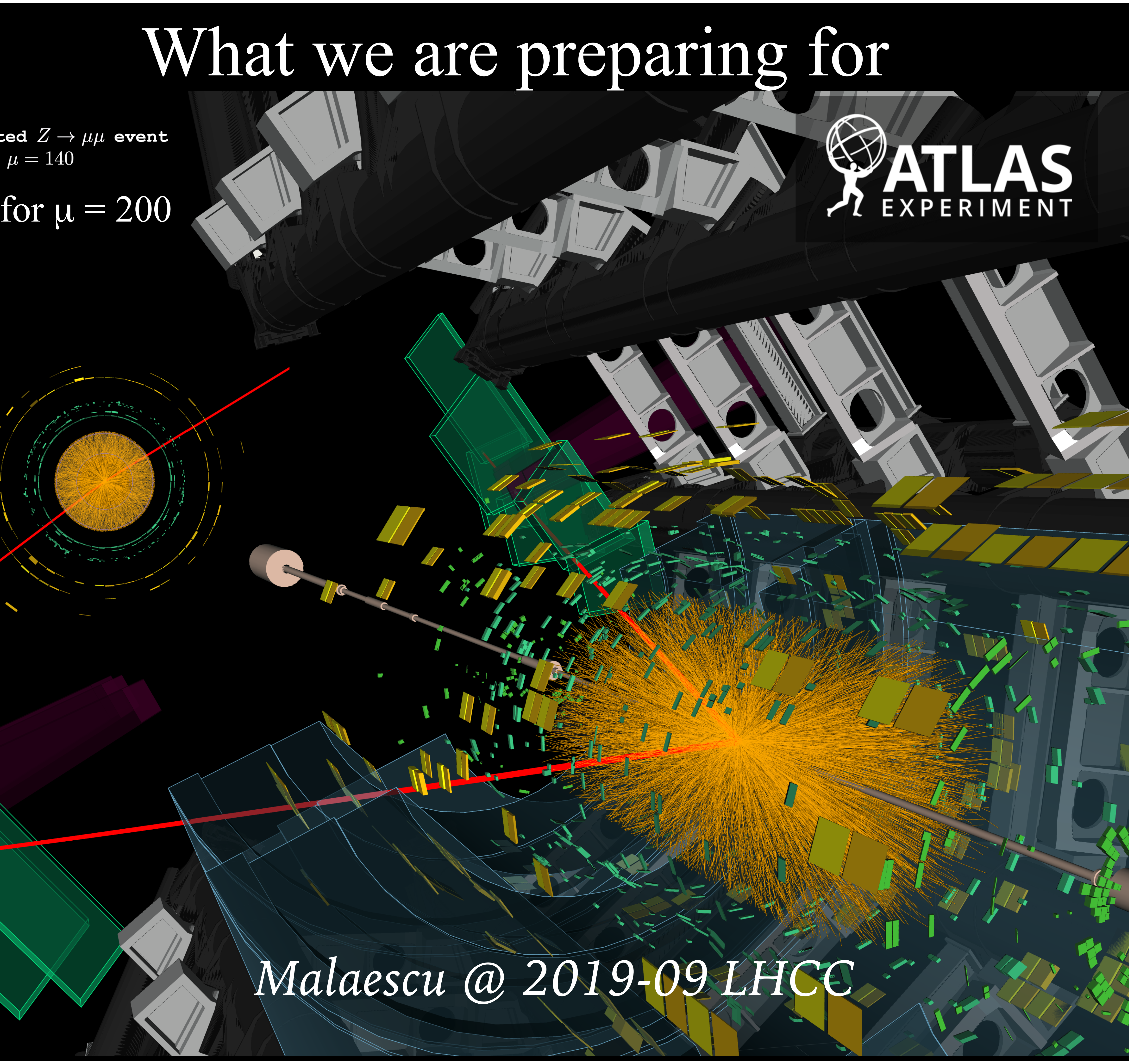
ATLAS and CMS

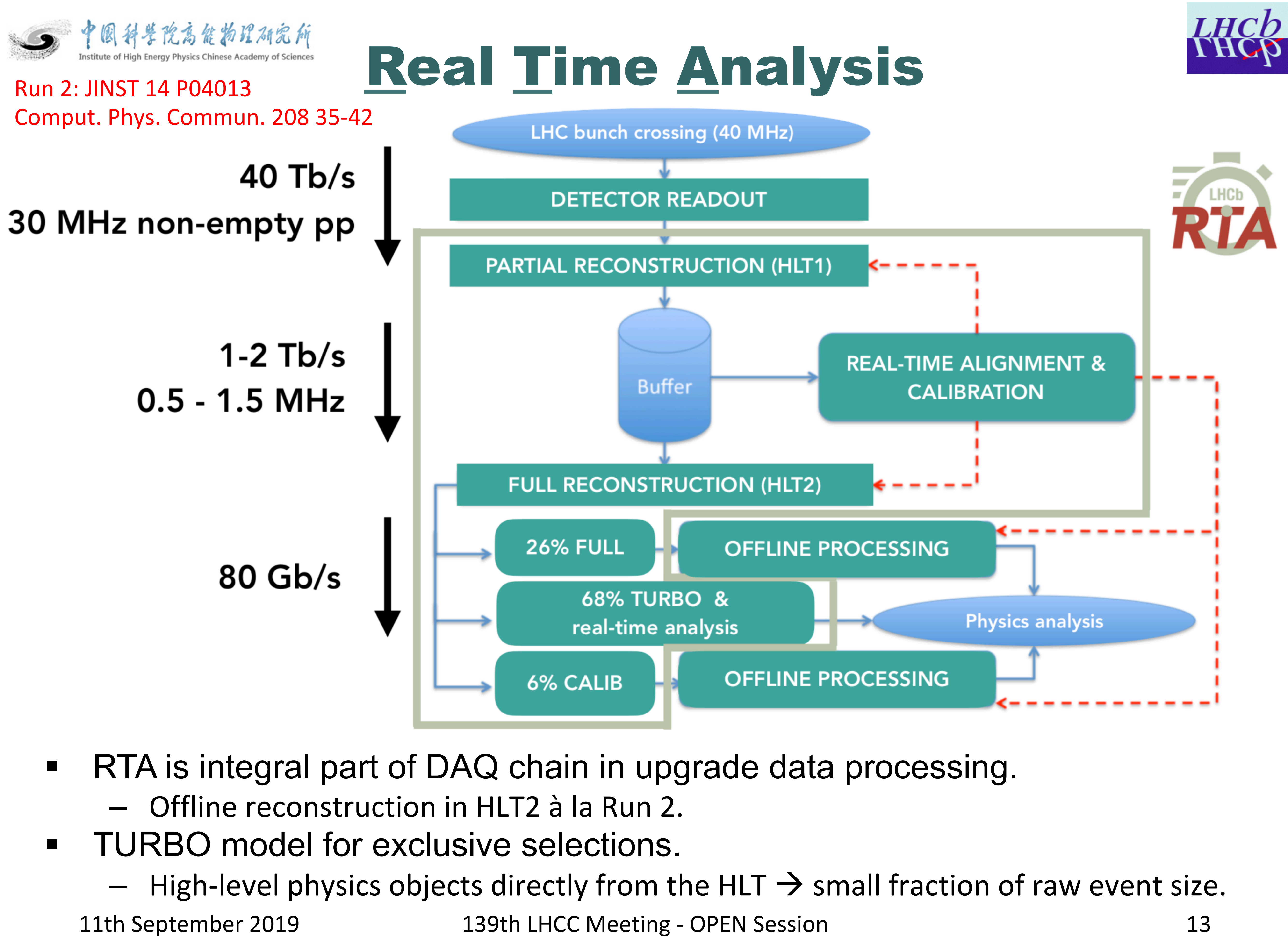
Run 3	Run4	HL-LHC total
300 fb^{-1}	1 ab^{-1}	3 – 4 ab^{-1}

LHCb

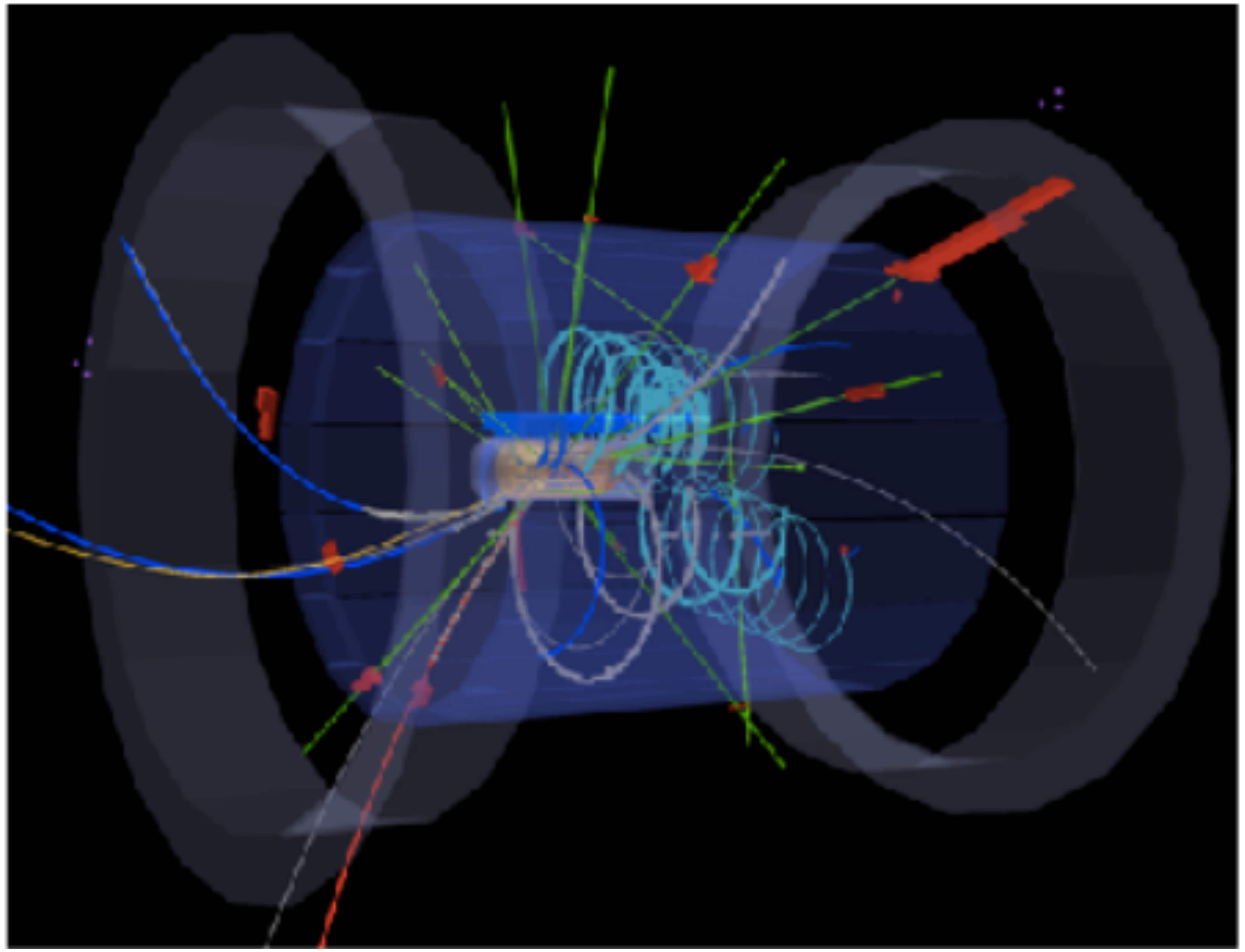
Run 3	Run4	HL-LHC total
23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

huge experimental advances



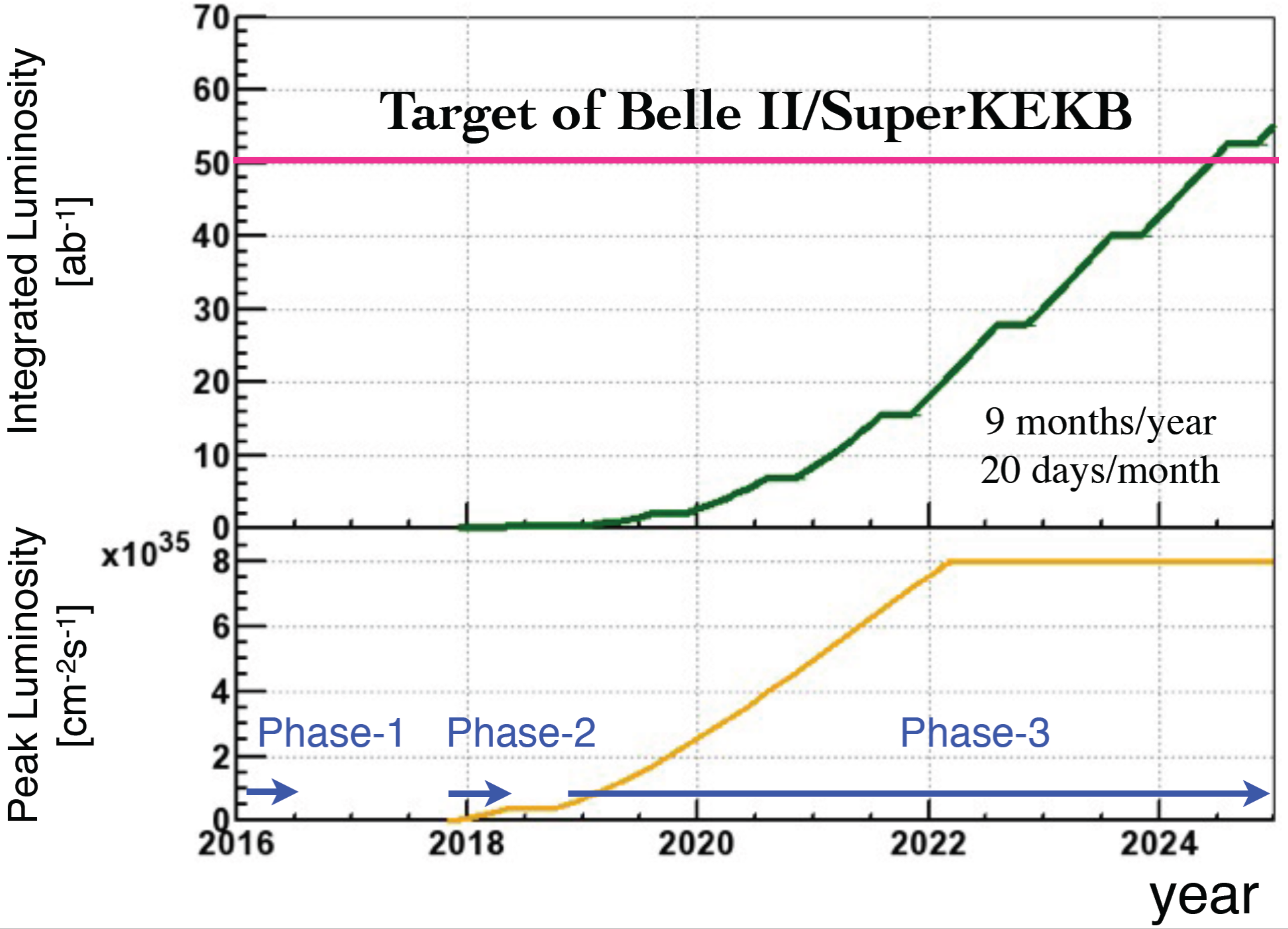


Belle II: 40–50x increase relative to Belle



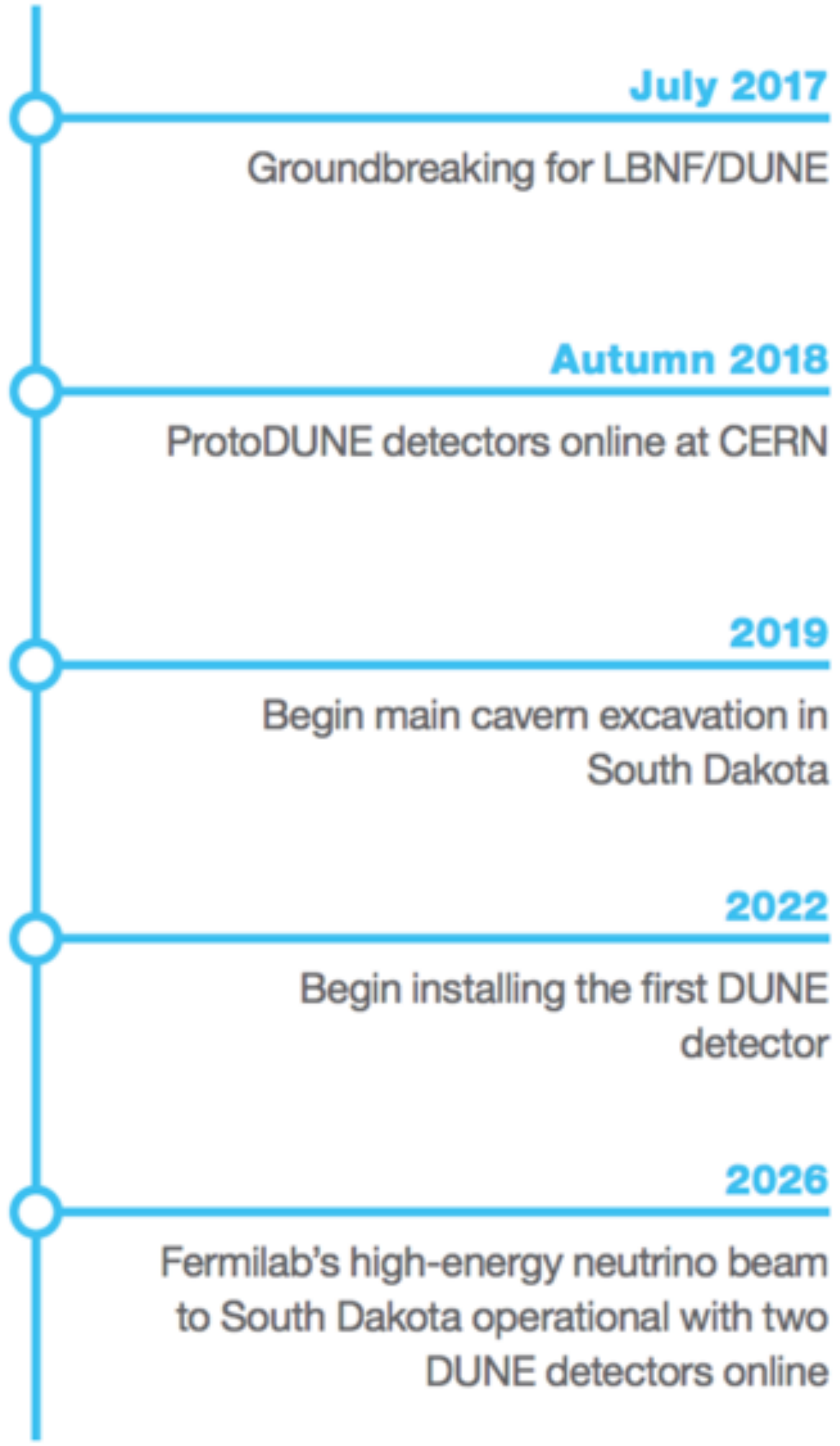
Zupanc (2017)

SuperKEKB luminosity projection



Nova + T2K running; DUNE & Hyper-K starting ~2027

DUNE



HYPER-K

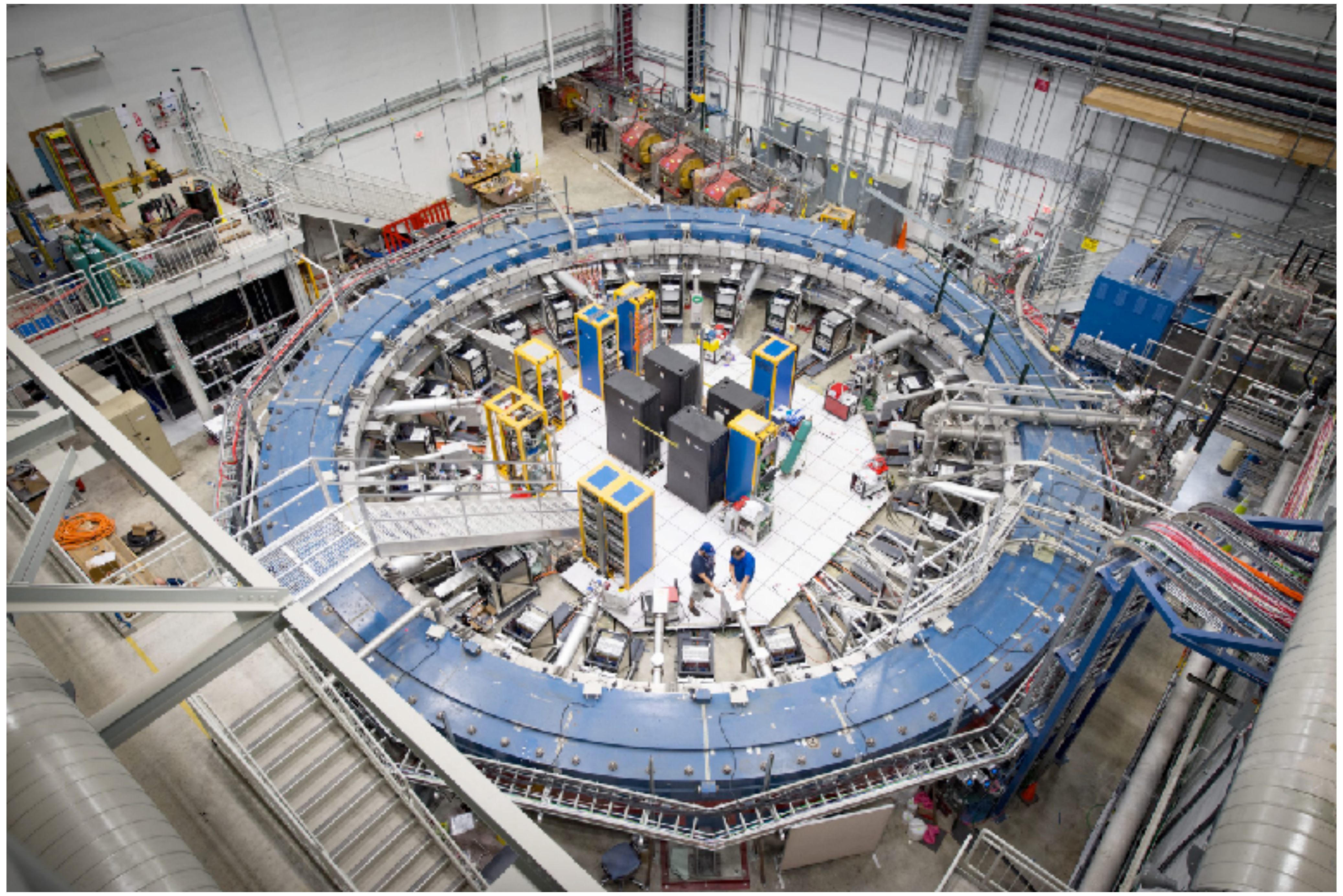
Spring 2020	Final design review of the system
Autumn 2020	Start the design of the system based on the design review
Autumn 2021	Start bidding procedure
Autumn 2022	Start mass production
Autumn 2023	Start final system test
Autumn 2024	Complete mass production
Autumn 2025	Complete system test and get ready for install

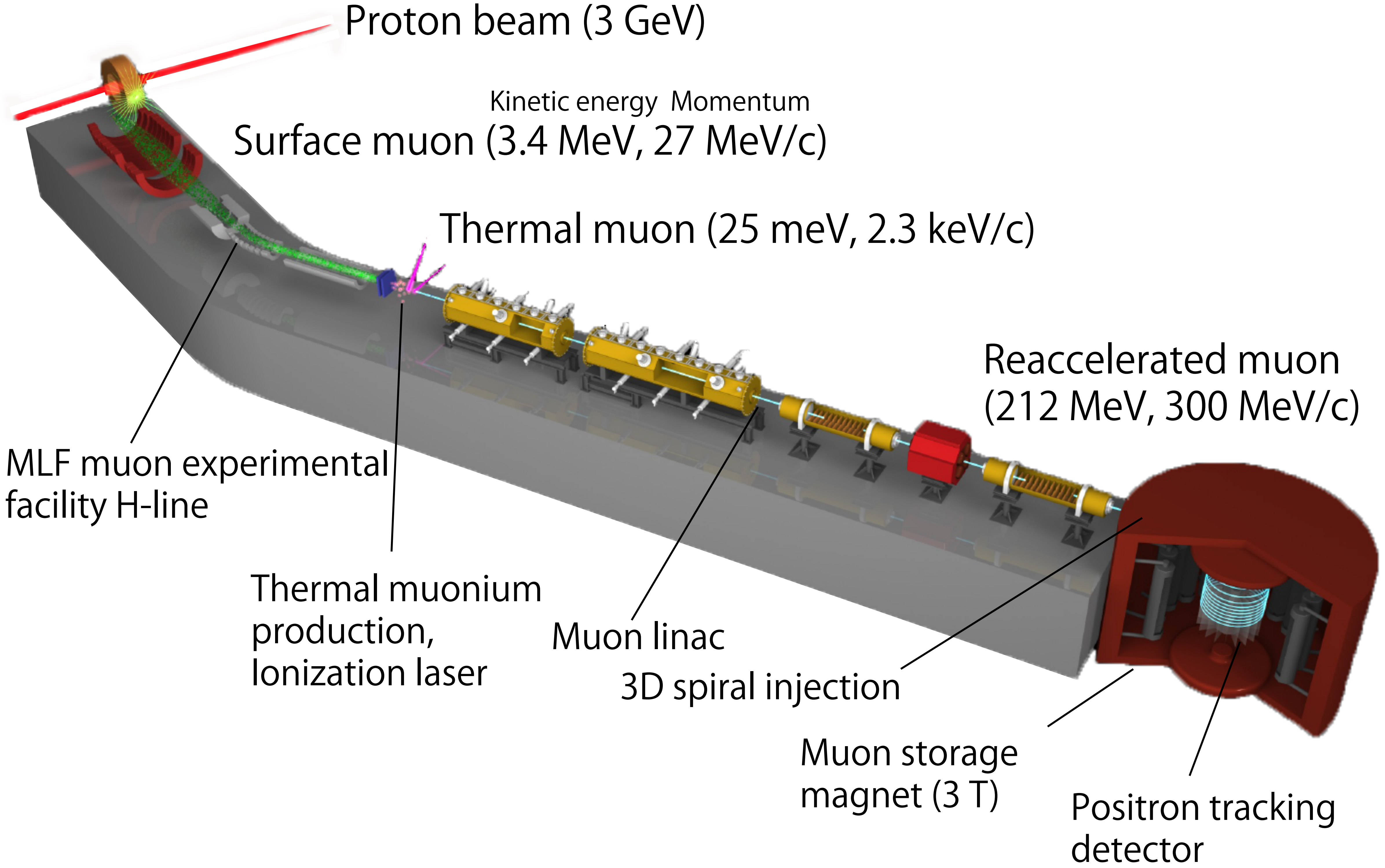
TABLE XXII. Timeline to complete the production for the installation.

muon g-2: Fermilab running for the next few years; also J-PARC

$a_\mu(\mathrm{SM})=(11659182.3\pm0.1\pm3.4\pm2.6)\times10^{-10}$, $a_\mu(\mathrm{exp})=(11659209.1\pm5.4\pm3.3)\times10^{-10}$

$$\Delta a_\mu \equiv a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (26.8 \pm 7.6) \times 10^{-10}$$





Fermilab: has already surpassed BNL data (1st results to come soon?)

J-PARC: independent systematics, moving from R&D to construction

direct detection dark matter experiments

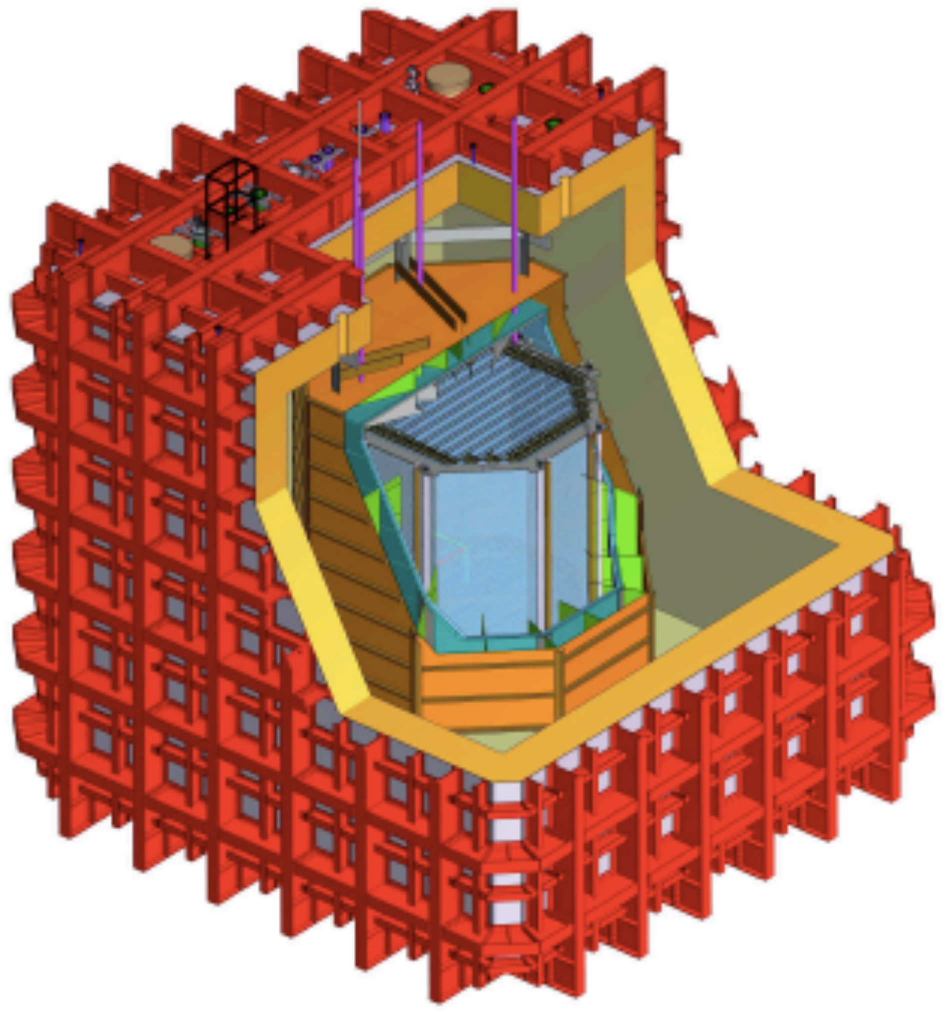
Global Argon Dark Matter Collaboration

DEAP-3600 (running)

DarkSide-50 (running)

miniCLEAN

ArDM

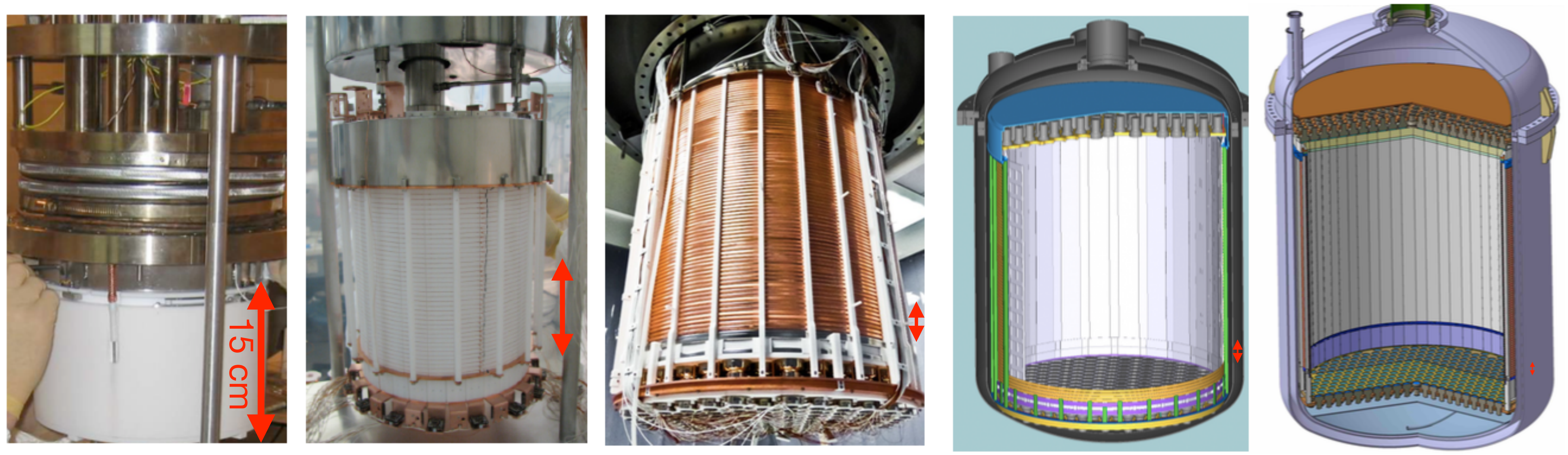


DarkSide-20k
2022~

~300 tonnes

ARGO
2029~

Slide credit: Y. Wang



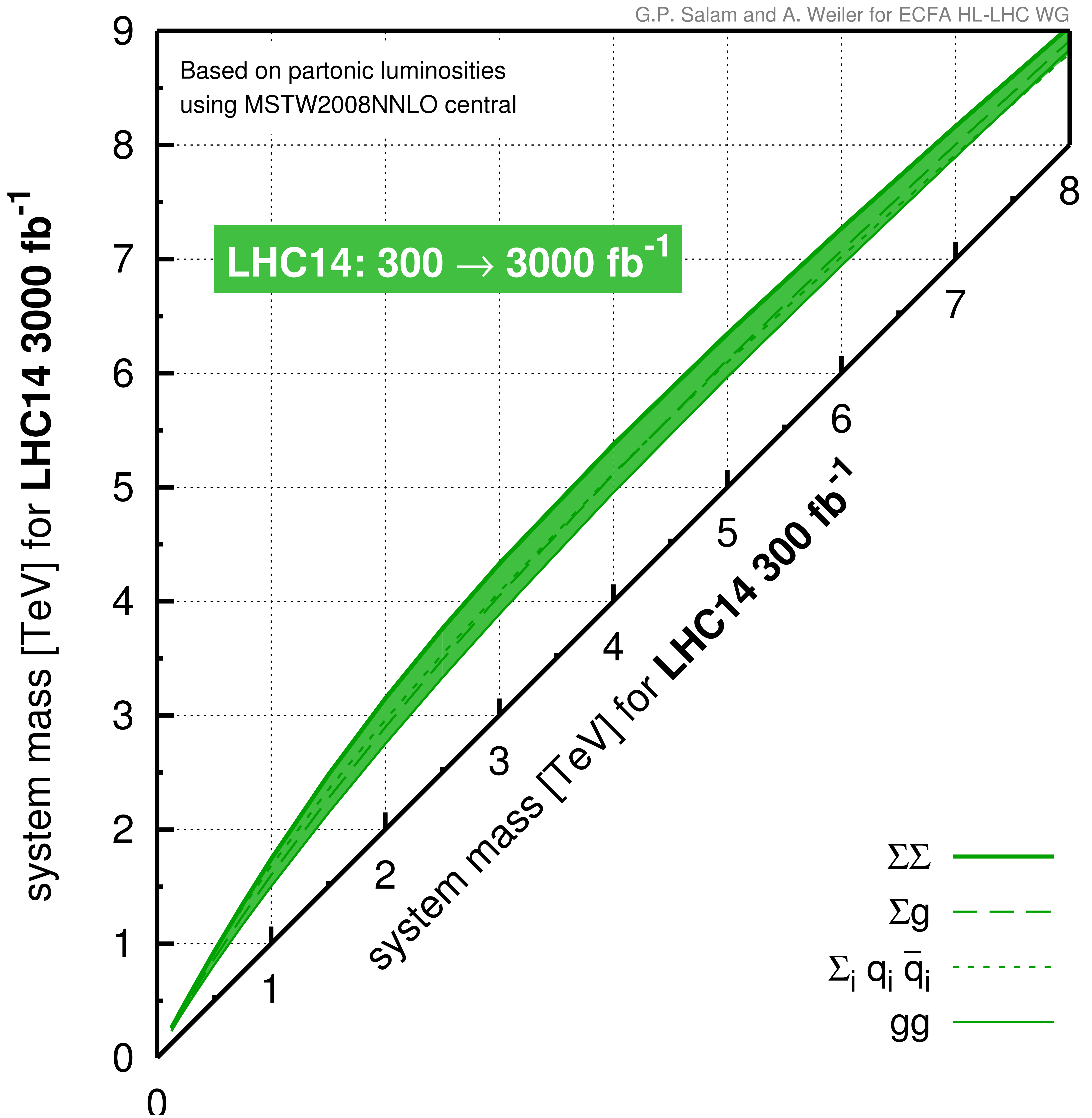
XENON10	XENON100	XENON1T	XENONnT	DARWIN
2005 – 2007	2008 – 2016	2012 – 2018	2019 – 2023	2025 –
~15 kg	~62 kg	~2 t	~5.9 t	40 t
15 cm	30 cm	1 m	1.5 m	2.6 m
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

many ongoing & medium and small experiments

- NA61
- NA62
- NA64
- Compass
- HPS
- SeaQuest
- KATRIN
- …

direct new-particle searches

Rules of thumb for direct searches

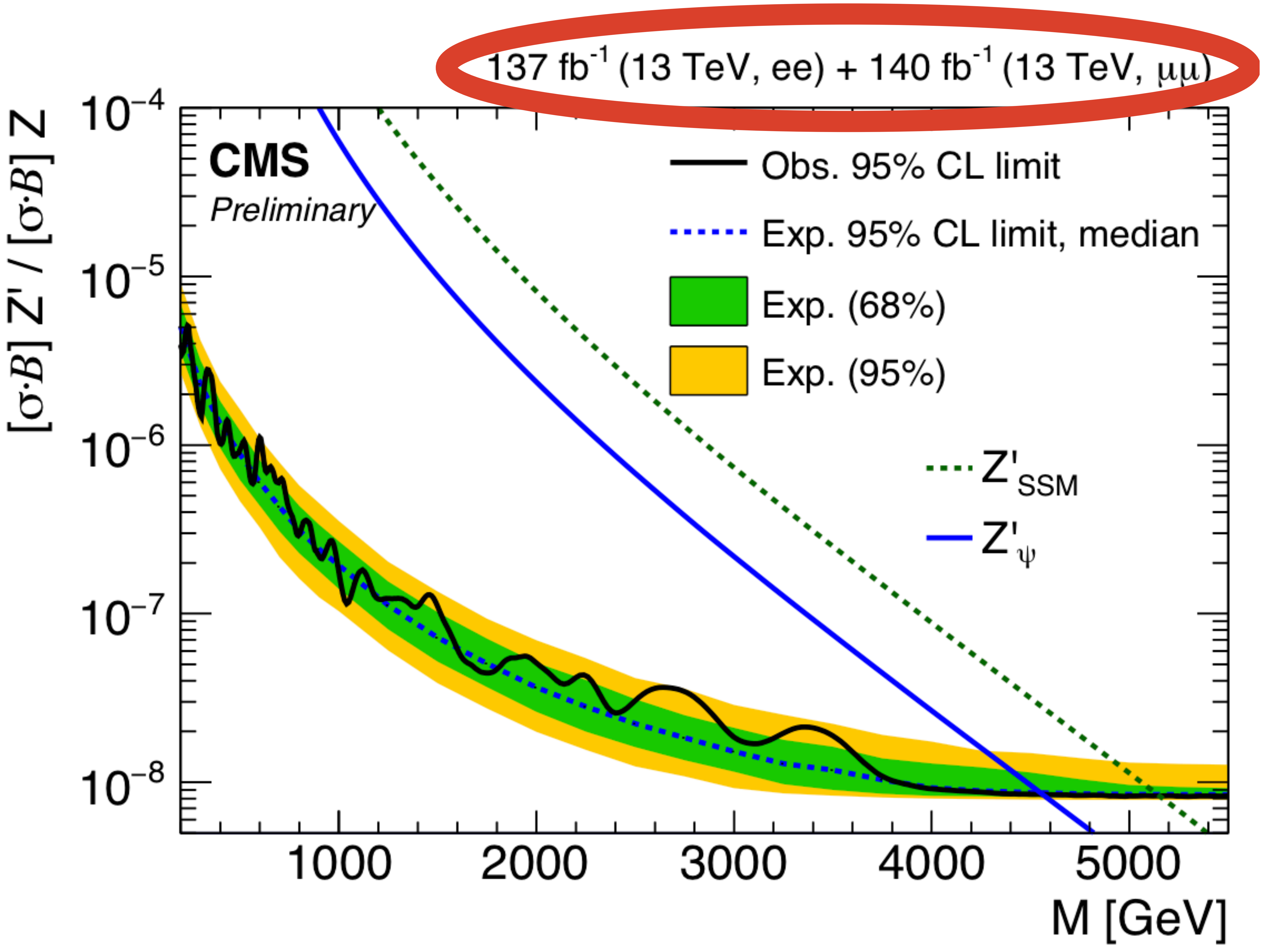


- x10 increase in luminosity → increase in direct (total) mass reach of $\delta M = (0.06 - 0.09)\sqrt{s}$
- Valid in range $0.15 \lesssim M/\sqrt{s} \lesssim 0.6$
- Roughly 1 TeV increase in mass reach at LHC for each $\times 10$ in luminosity
- Proportionally more significant for searches at lower end of mass scale

Z' (or A') → leptons

one of the simplest searches,
reaching some of the highest scales probed at LHC

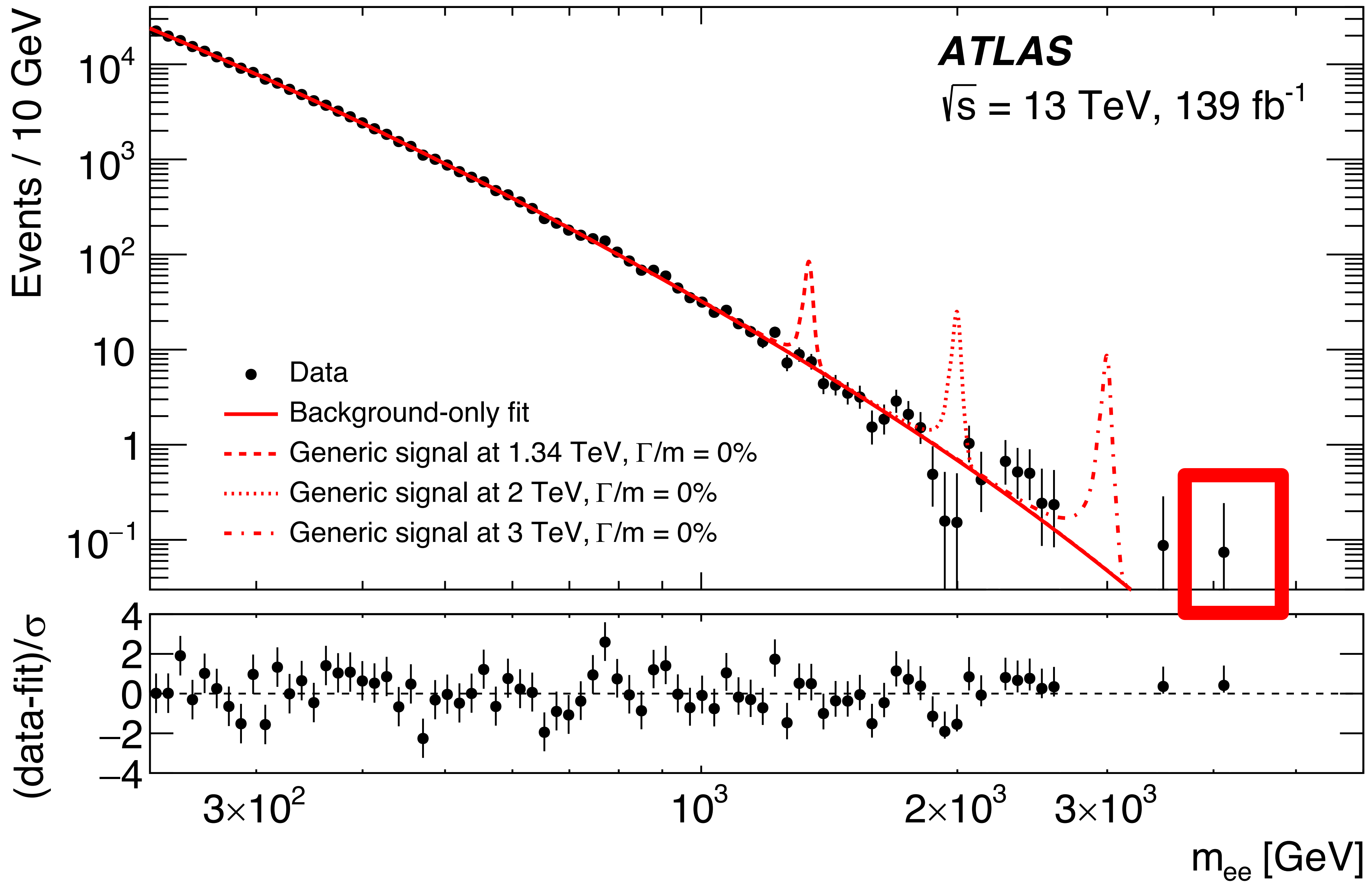
The status today



Search for particles decaying to two muon or two electrons

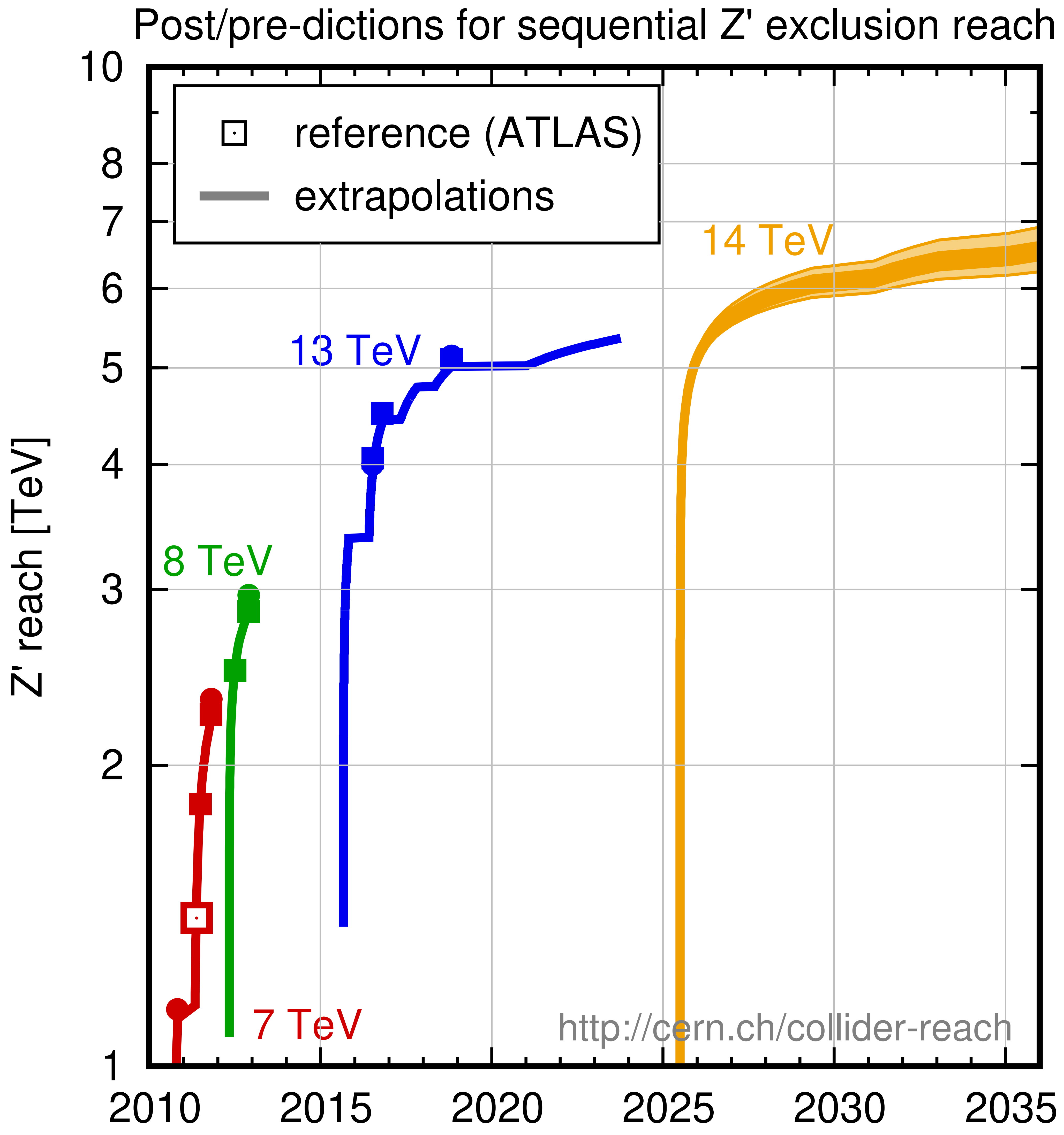
Limits on benchmark models (95% CL):

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1



Phys. Lett. B 796 (2019) 68

Z' past & future @ LHC



Past decade saw exceptionally fast direct exploration at high end of energy frontier.

× 5 in reach in 2010 – now

Next 10 (15) years will see much slower progress, ~ 20% (30%) increase in reach

End of energy frontier exploration?

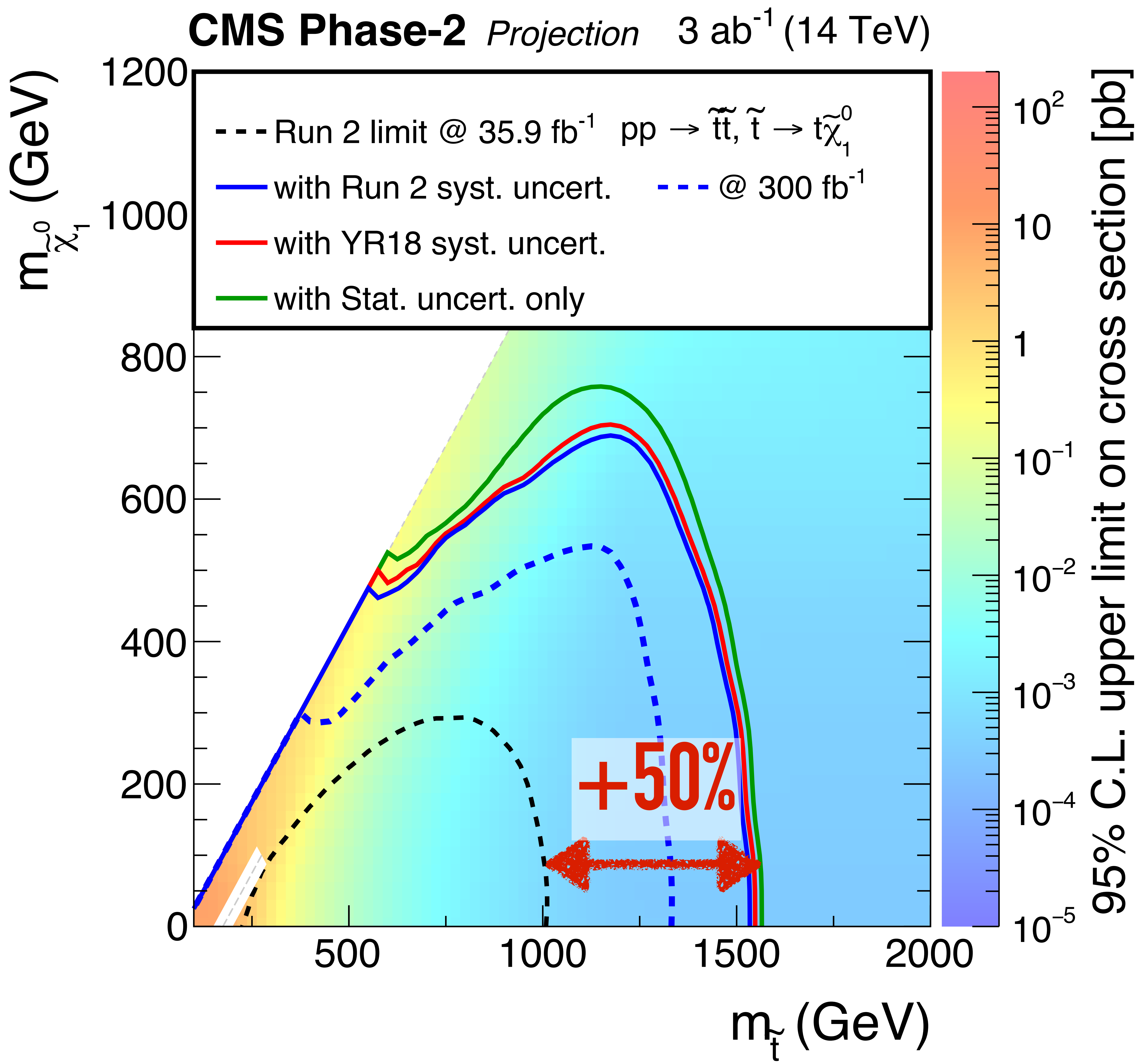
Sequential SM Z' exclusion reach
long-term pp(bar) view: phases of fast, then slow energy frontier increase are normal
100 TeV pp, 30ab-1, from 2043
100 TeV pp
30ab-1 from 2063
40 TeV pp
12ab-1 from 2043
14 TeV pp, 3ab-1
13 TeV pp
8 TeV pp
7 TeV pp
1.96 TeV pp̄
1.80 TeV pp̄
0.63 TeV pp̄
Z' → l+l-
points: UA1/CDF/D0/ATLAS/CMS
lines: collider-reach extrapolation
year adjusted when only one lepton channel used
Z'SSM limit [TeV]
year in which data recorded
GPS + AW 2019 (with http://cern.ch/collider-reach)


Sequential SM Z' exclusion reach
long-term pp(bar) view: phases of fast, then slow energy frontier increase are normal
average increase in reach roughly × 2 / decade
100 TeV pp, 30ab-1, from 2043
100 TeV pp 30ab-1 from 2063
40 TeV pp 12ab-1 from 2043
14 TeV pp, 3ab-1
13 TeV pp
8 TeV pp
7 TeV pp
1.96 TeV pp̄
1.80 TeV pp̄
0.63 TeV pp̄
year adjusted when only one lepton channel used
GPS + AW 2019 (with http://cern.ch/collider-reach)
Z'SSM limit [TeV]
year in which data recorded
100
70
50
30
20
10
7
5
3
2
1
0.7
0.5
0.3
0.2
0.1
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090

are LHC searches over? NO!

exciting action may be happening
at lower end of LHC reach

e.g. stop searches



stops play big role in fine tuning (accessible masses lower than for Z')

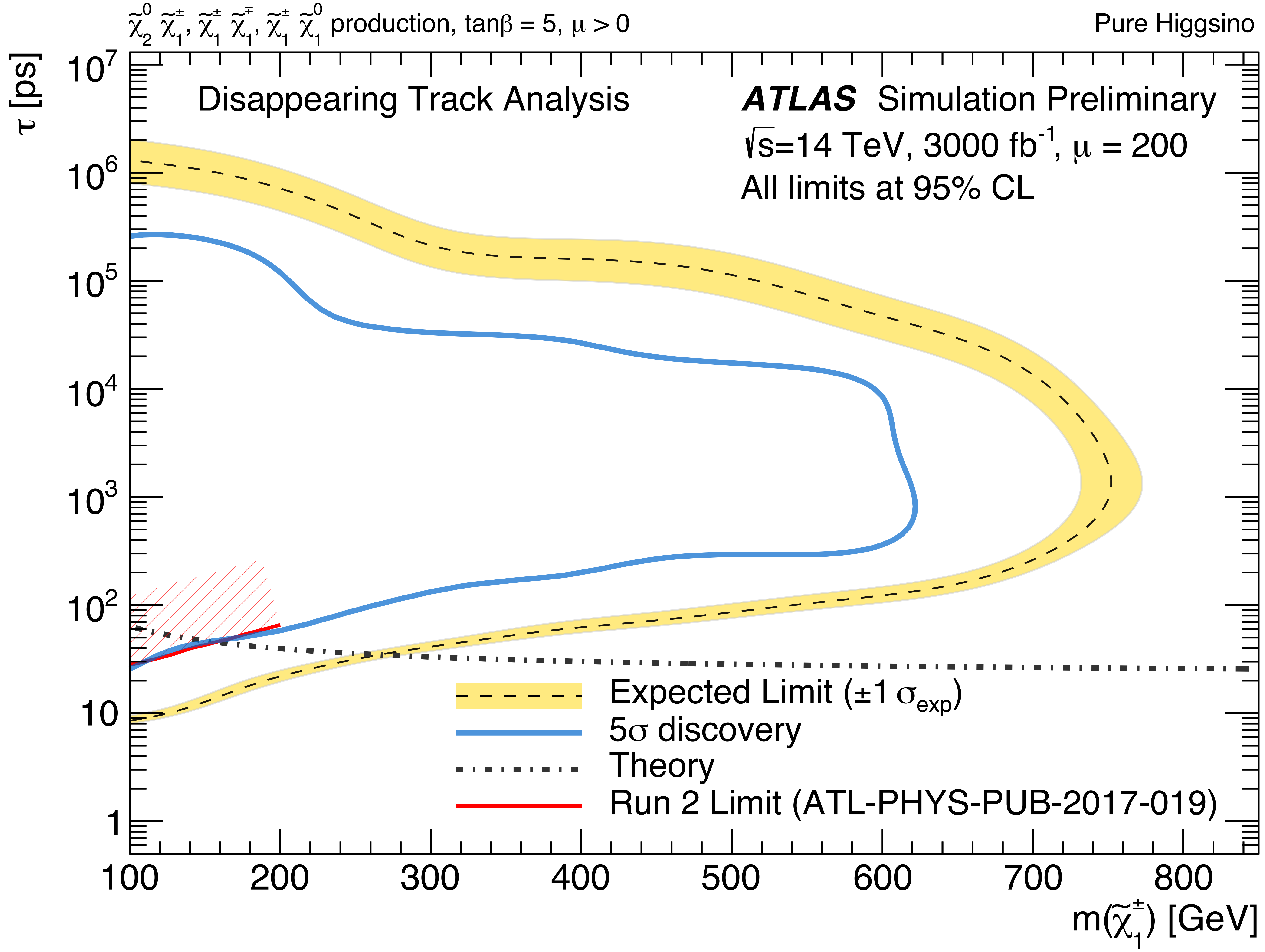
fractional gain in $m_{\tilde{t}}$ is 50%

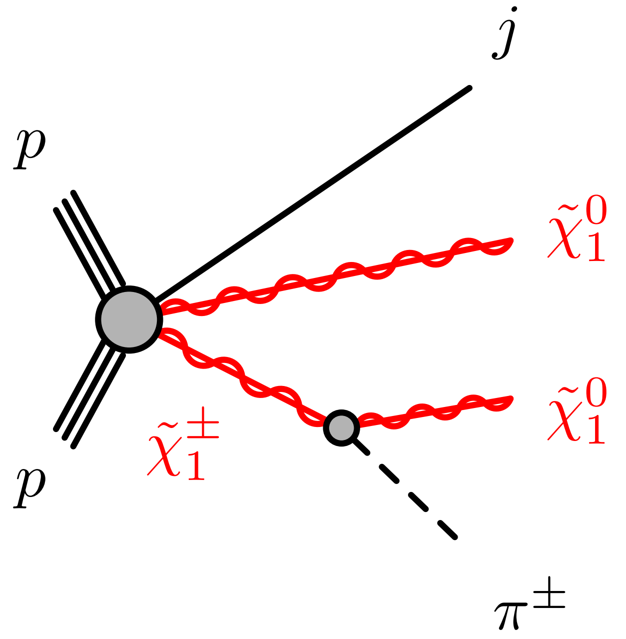
(relative to 36 fb^{-1})

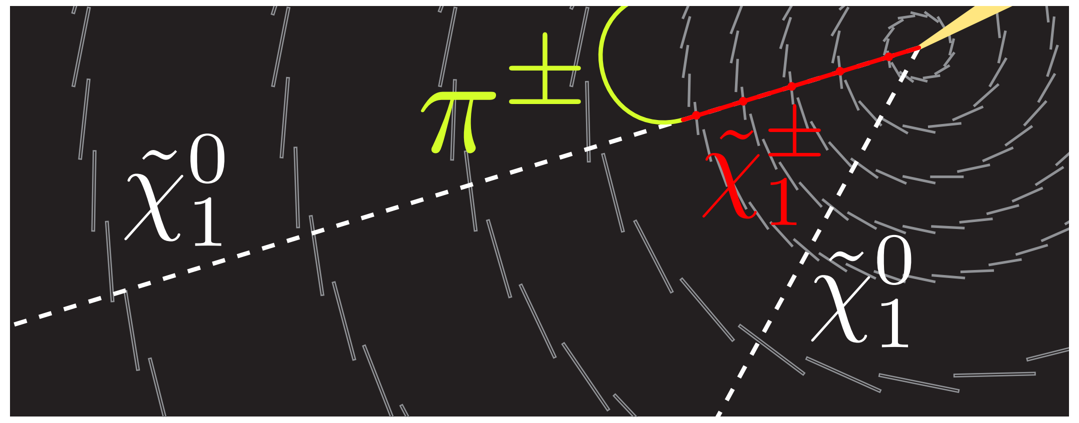
NB: this is for $\times 80$ in luminosity, so would expect $\sim +1$ TeV increase in $m_{\tilde{t}}$ reach (+2 TeV for system mass of $2m_{\tilde{t}}$)

are projections too conservative or are there serious show-stoppers?

disappearing track analyses

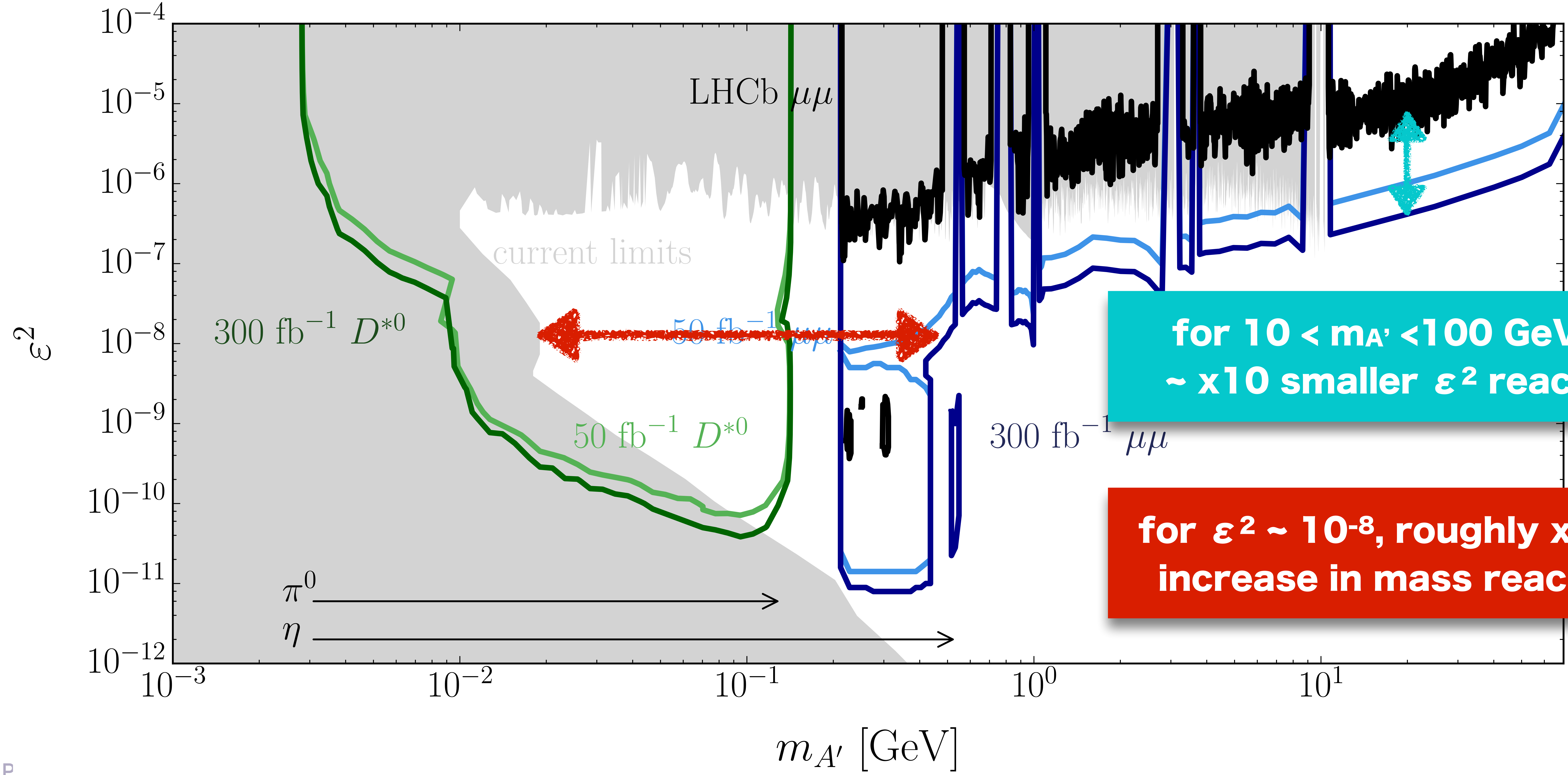






LHC lumi increase & detector upgrades bring unprecedented reach for processes with small cross sections (& sometimes weird signatures)

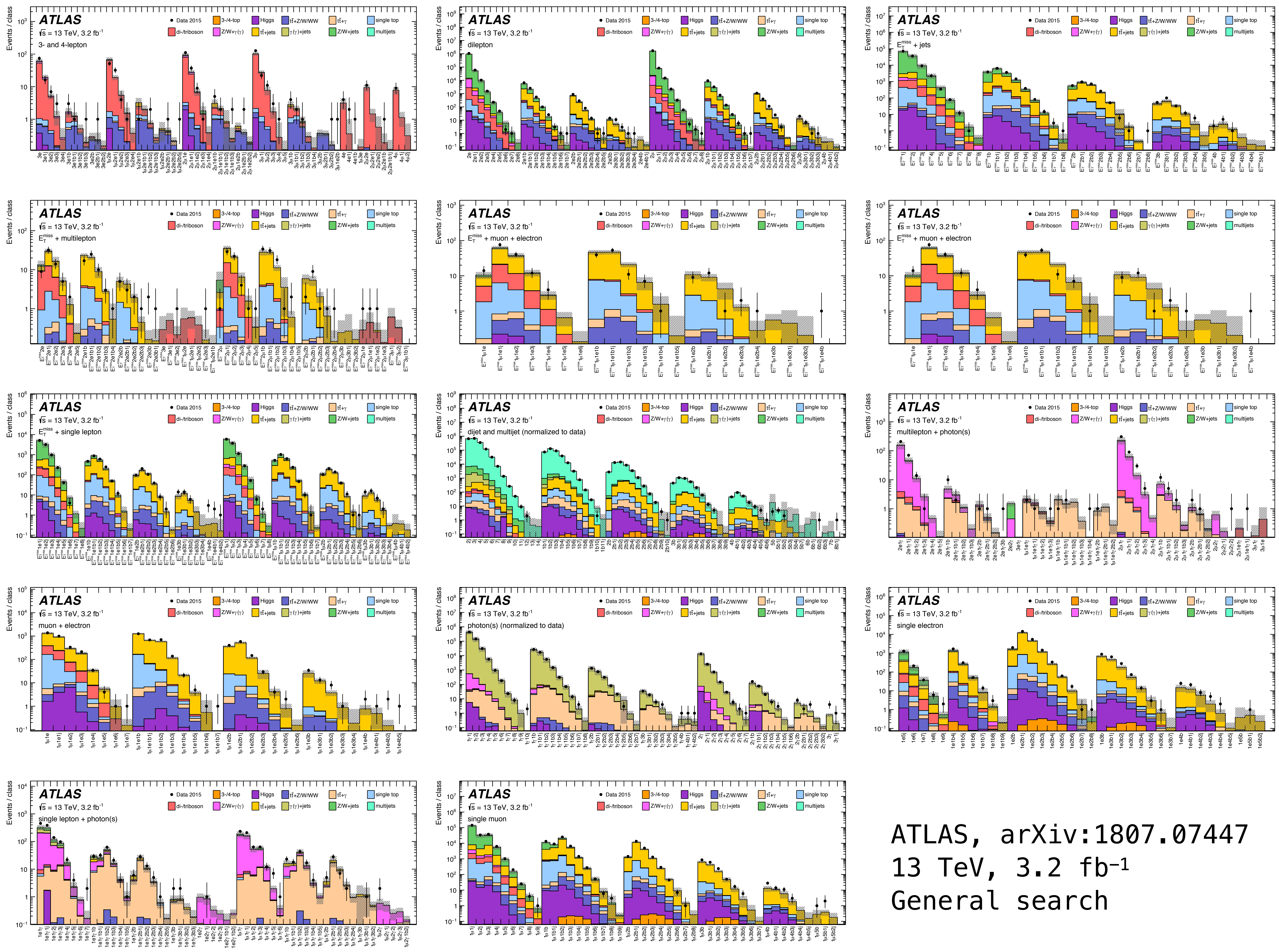
extreme lower end: A′ searches at LHCb



for 10 < $m_{A'}$ <100 GeV, ~ x10 smaller ε^2 reach

for ε^2 ~ 10^{-8}, roughly x20 increase in mass reach!

General searches (including an example with 704 event classes)



ATLAS, arXiv:1807.07447
13 TeV, 3.2 fb^{-1}
General search

As we move into regime where mass reach evolves more slowly, what's the best strategy?

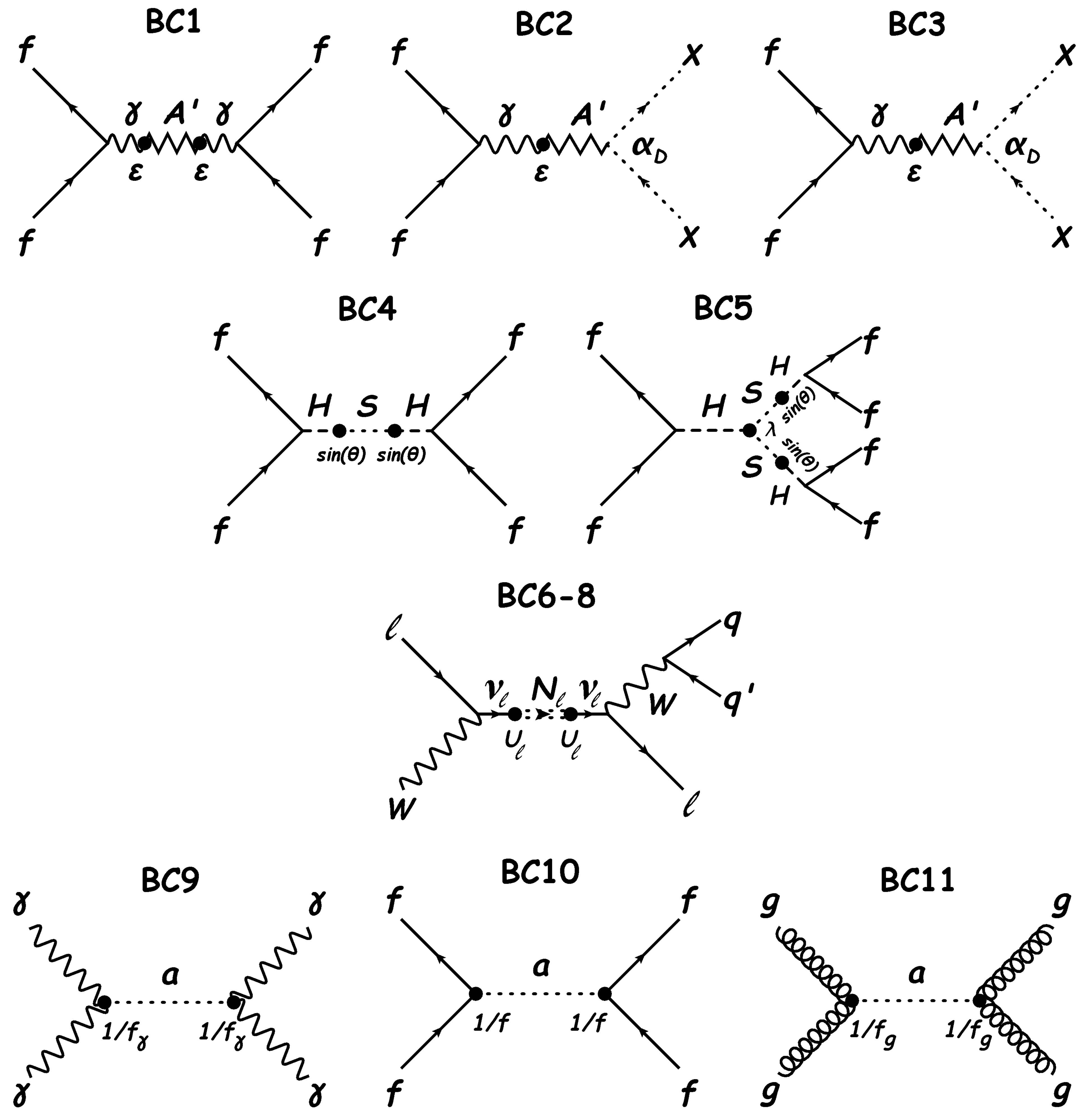
Can/should searches be automated?

Can they be incorporated into generic searches, freeing up time/ thought for novel searches?

direct
(mostly) non-LHC
searches

mainly based on material from
Physics Beyond Colliders report, arXiv:1902.00260

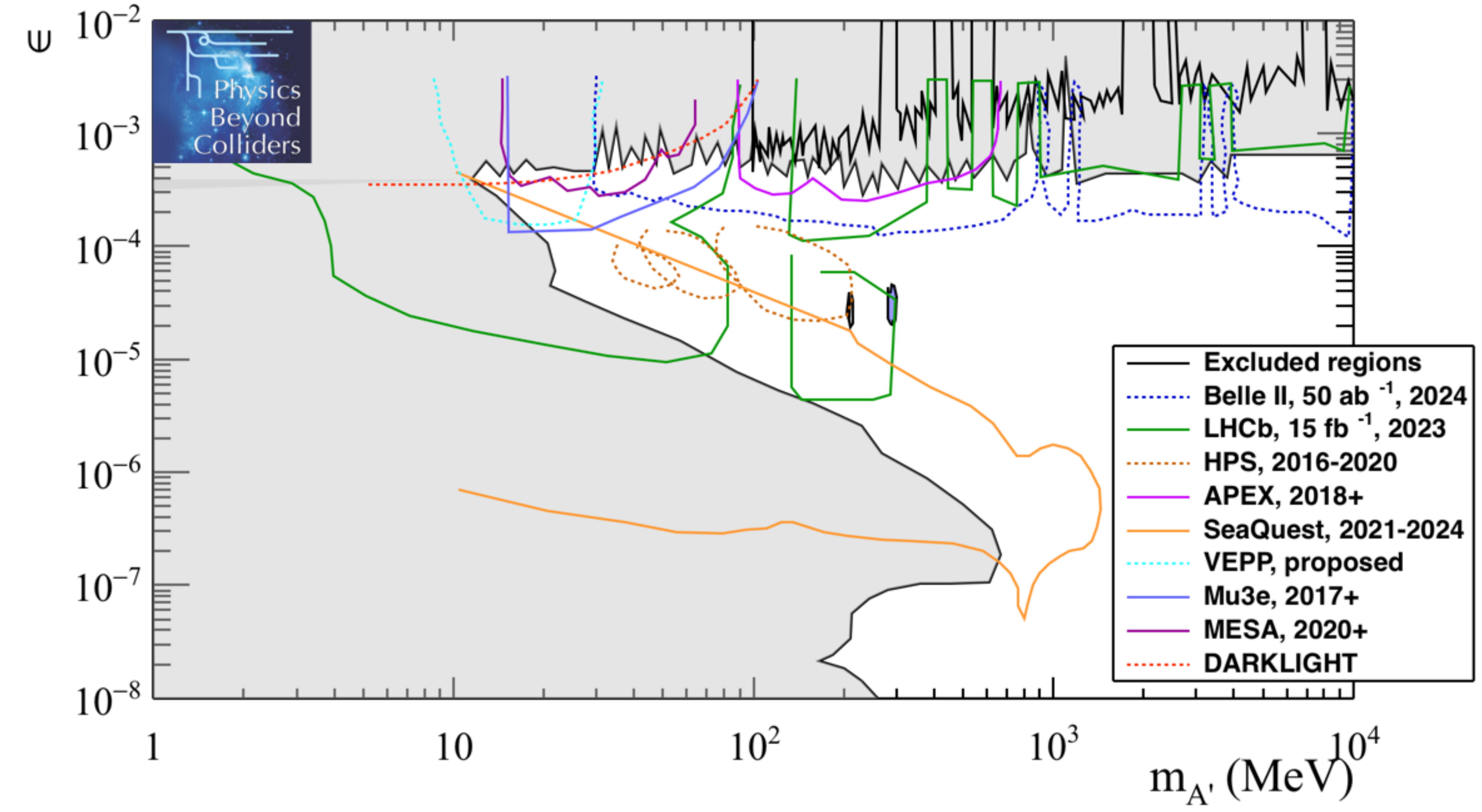
hidden sectors: a few simplified models, a plethora of experiments

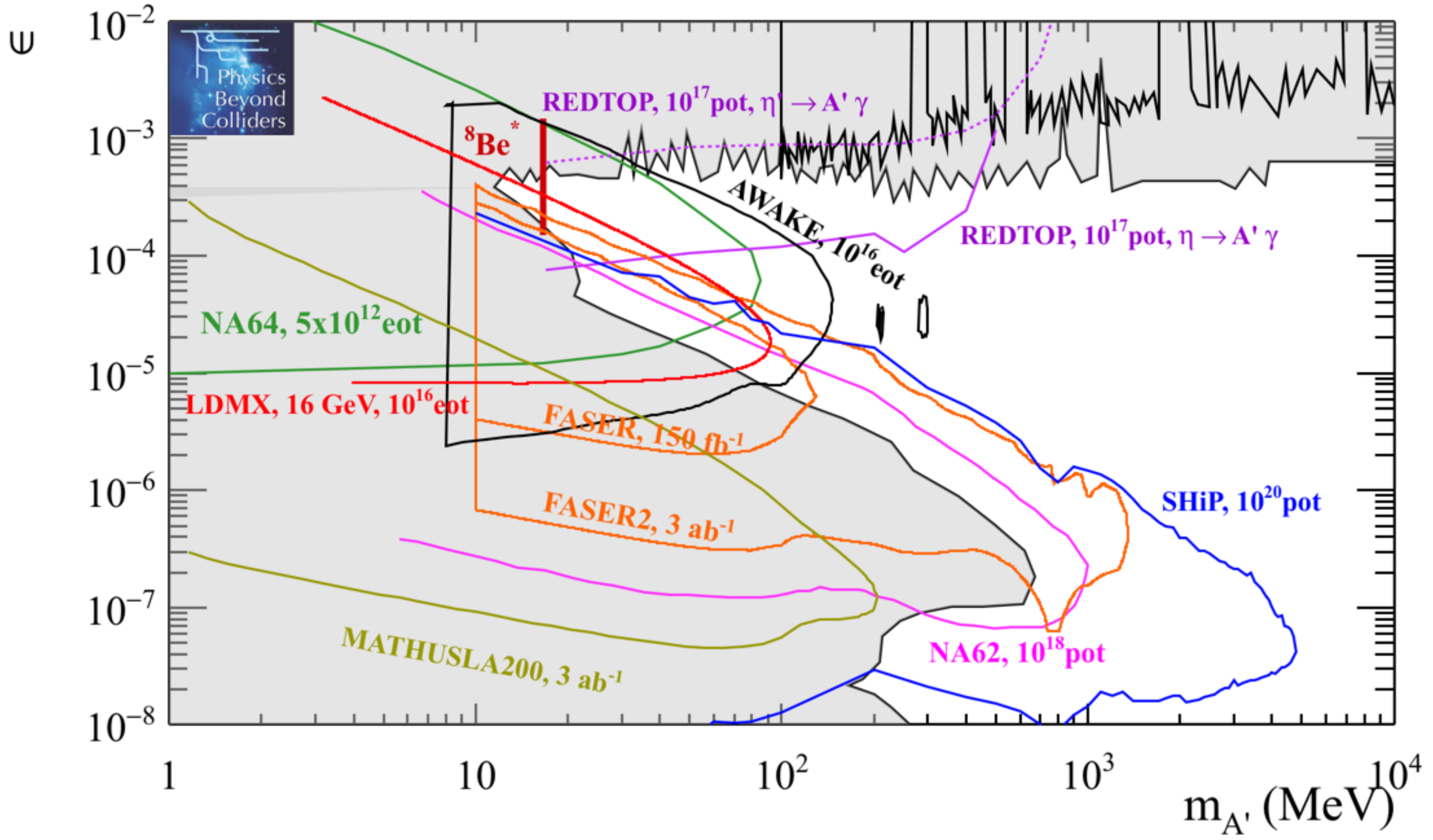


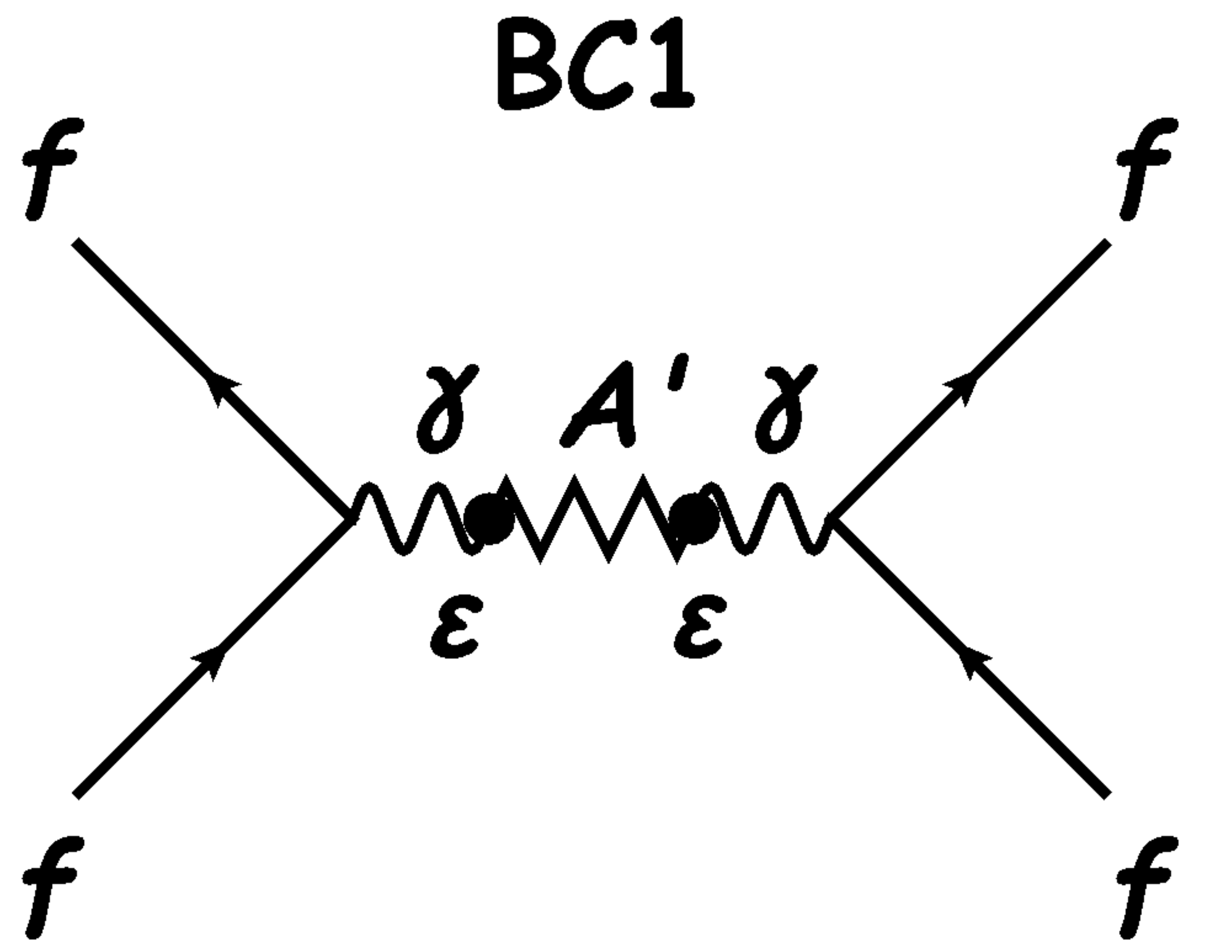
past years have seen resurgence of excitement about light(ish) dark sectors

Analysed in terms of a range of minimal models

dark photon production & decay



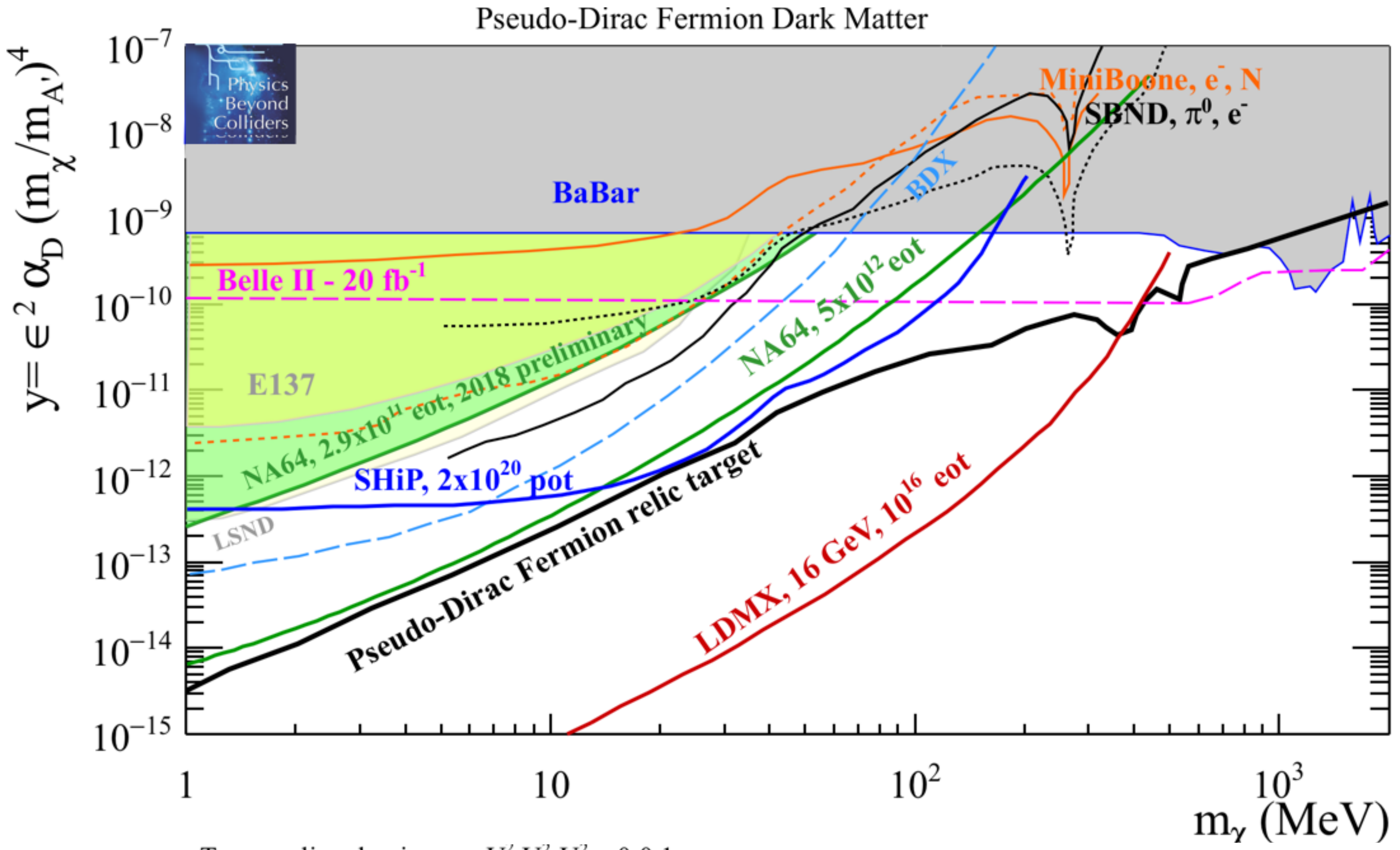


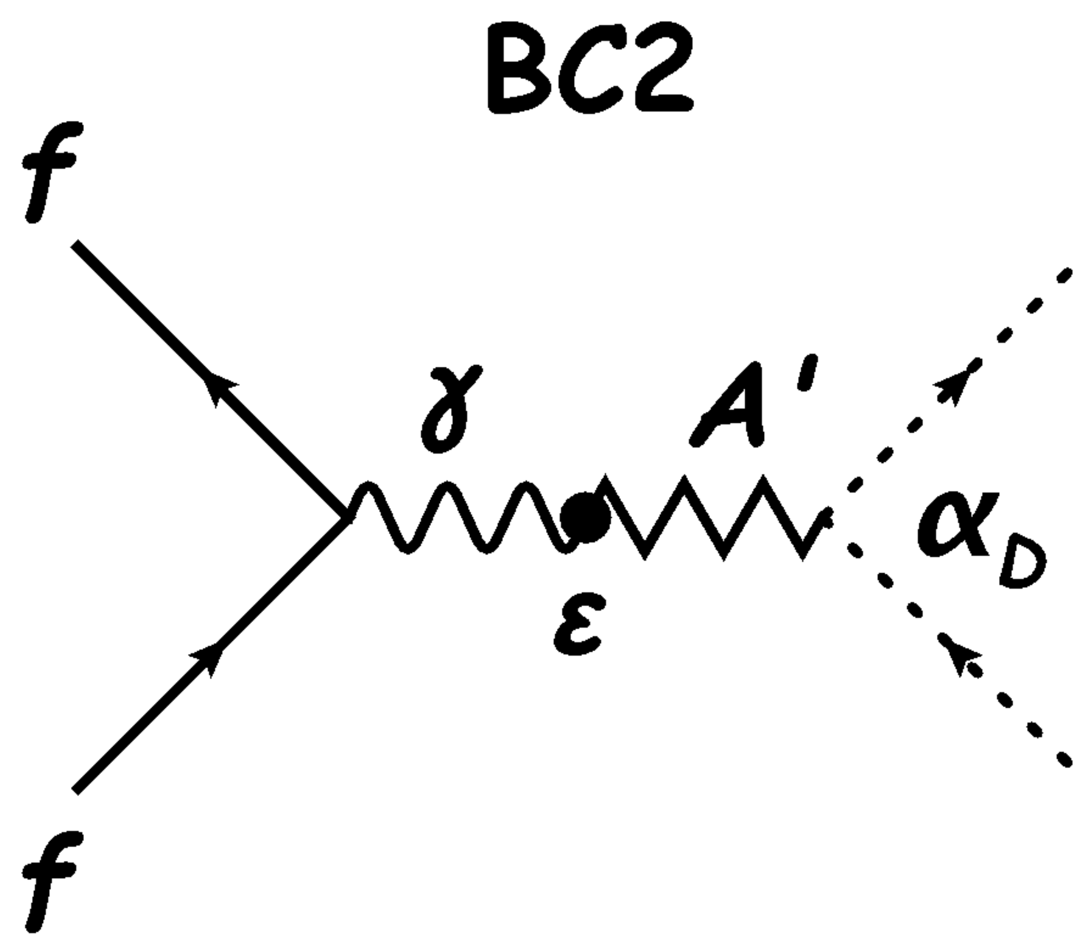


all-time favourite #1

many new experiments proposed to study it

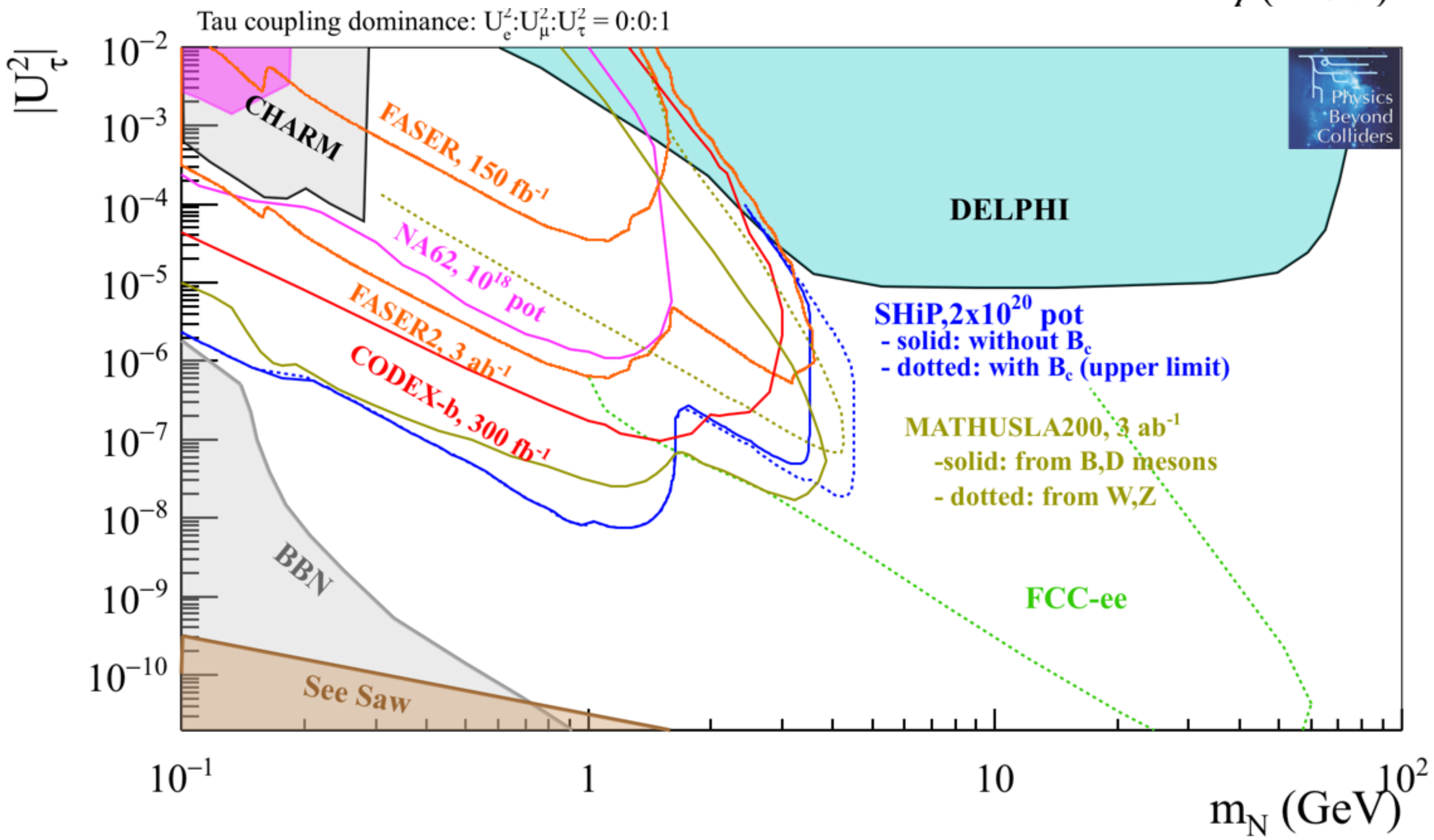
& suggestions to use approved experiments to probe similar regions

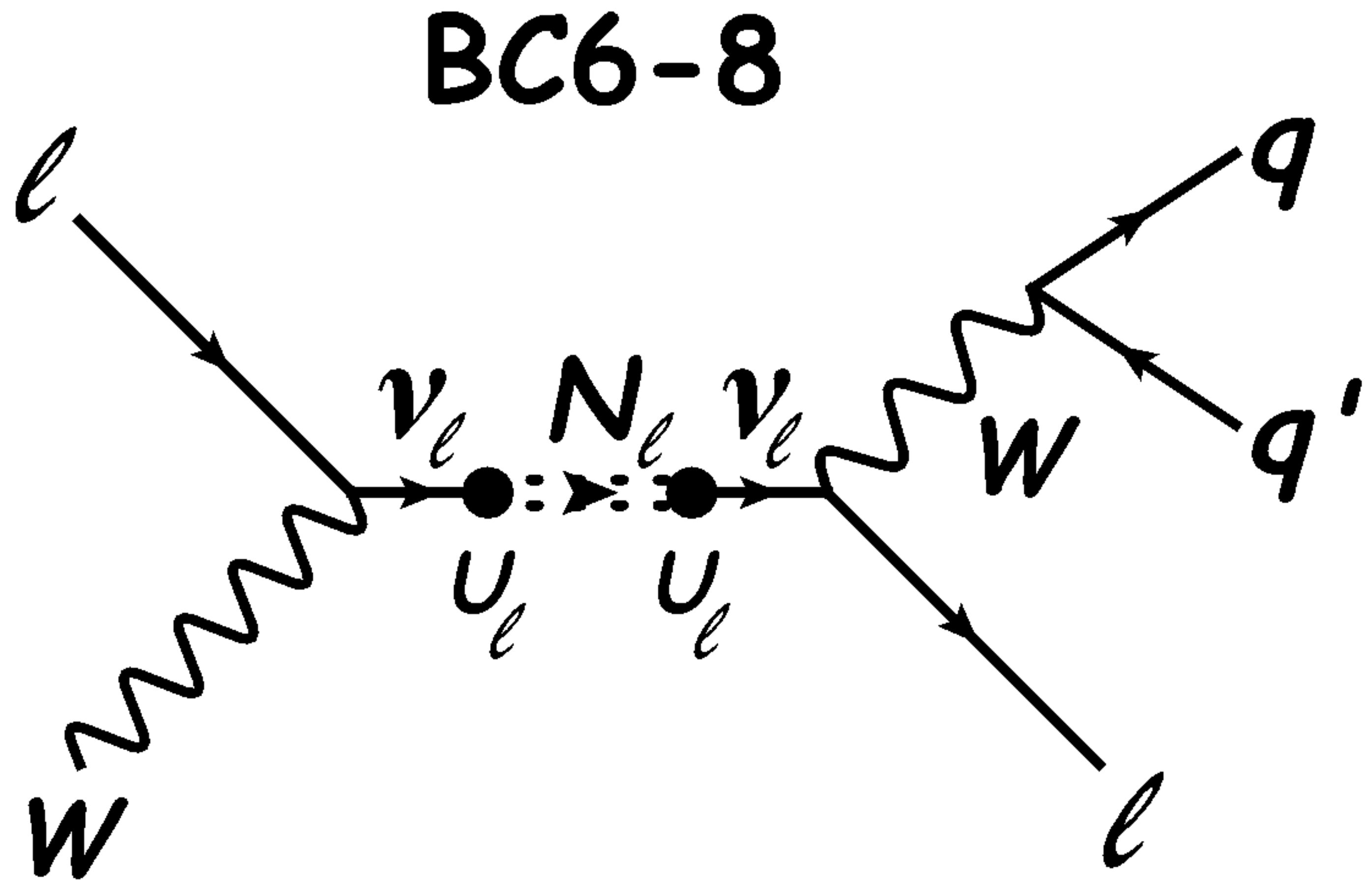




dark photon → dark "matter"

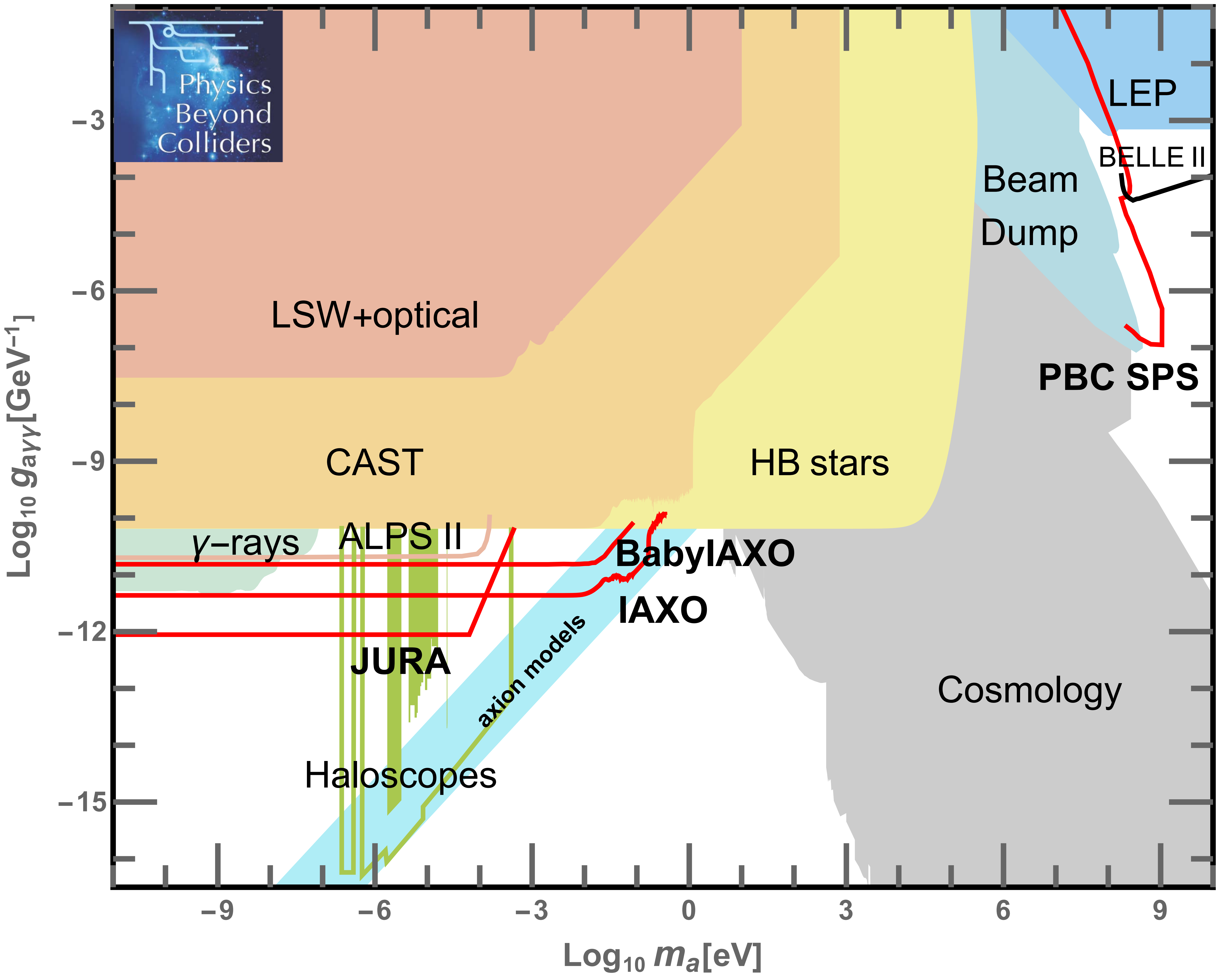
search for it either my looking for missing energy, or through decays of X (model dep.)

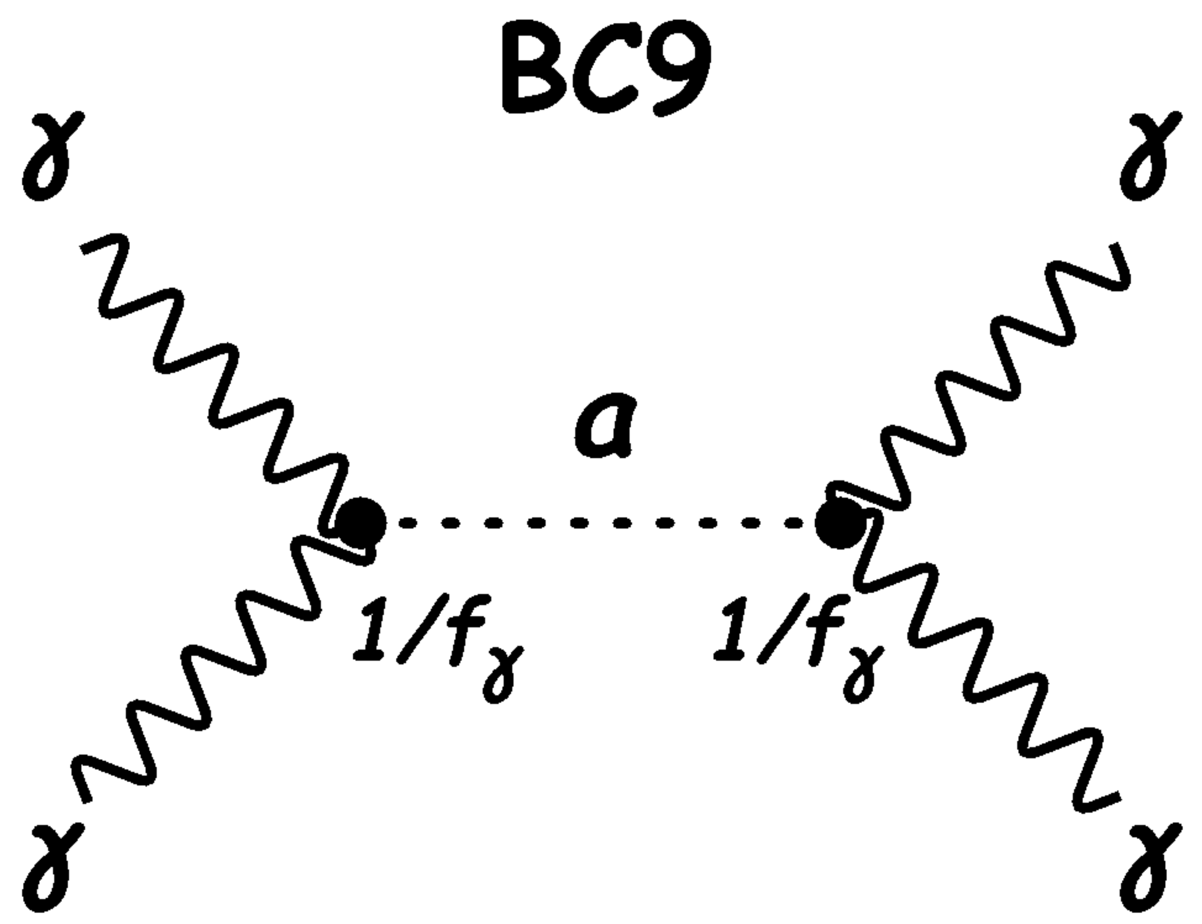




heavy-neutral leptons coupling to τ's

Axions





axion: all-time favourite #2

could be a dark-matter candidate

diversity of experiments probing it is even greater than for other channels

dark matter

https://www.pbs.org/newshour/science/large-hadron-collider-gears-find-dark-matter-new-particles-second-run

“

Finding dark matter and studying it will be the biggest challenge for the Large Hadron Collider’s second run

-a large LHC experiment’s spokesperson [2015]

dark matter

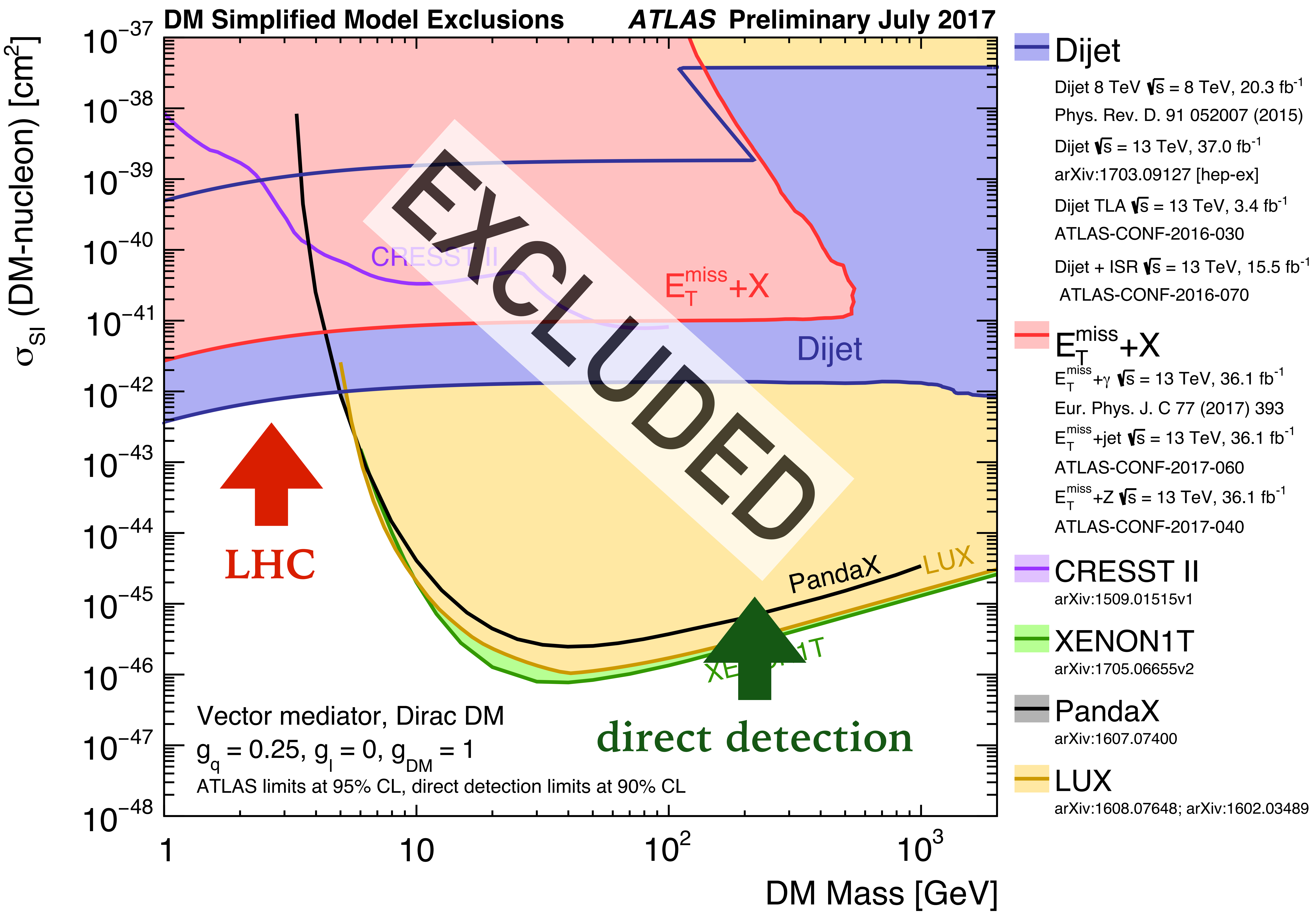

Observations from starlight
Observations from 21 cm hydrogen
Velocity (km s⁻¹)
100
50
Expected from the visible disk
Rotation curve of spiral galaxy Messier 33
10,000
20,000
30,000
40,000
Distance (light years)

Looking beyond the SM: searches for dark matter at LHC & elsewhere

Classic dark-matter candidate: a weakly-interacting massive particle (**WIMP**, e.g. from supersymmetry).

Masses ~ GeV upwards

(search interpretations strongly model dependent)



musn't be (too) disappointed at lack of dark matter signal at LHC (& elsewhere)

Evidence for dark matter exists since the 1930s.

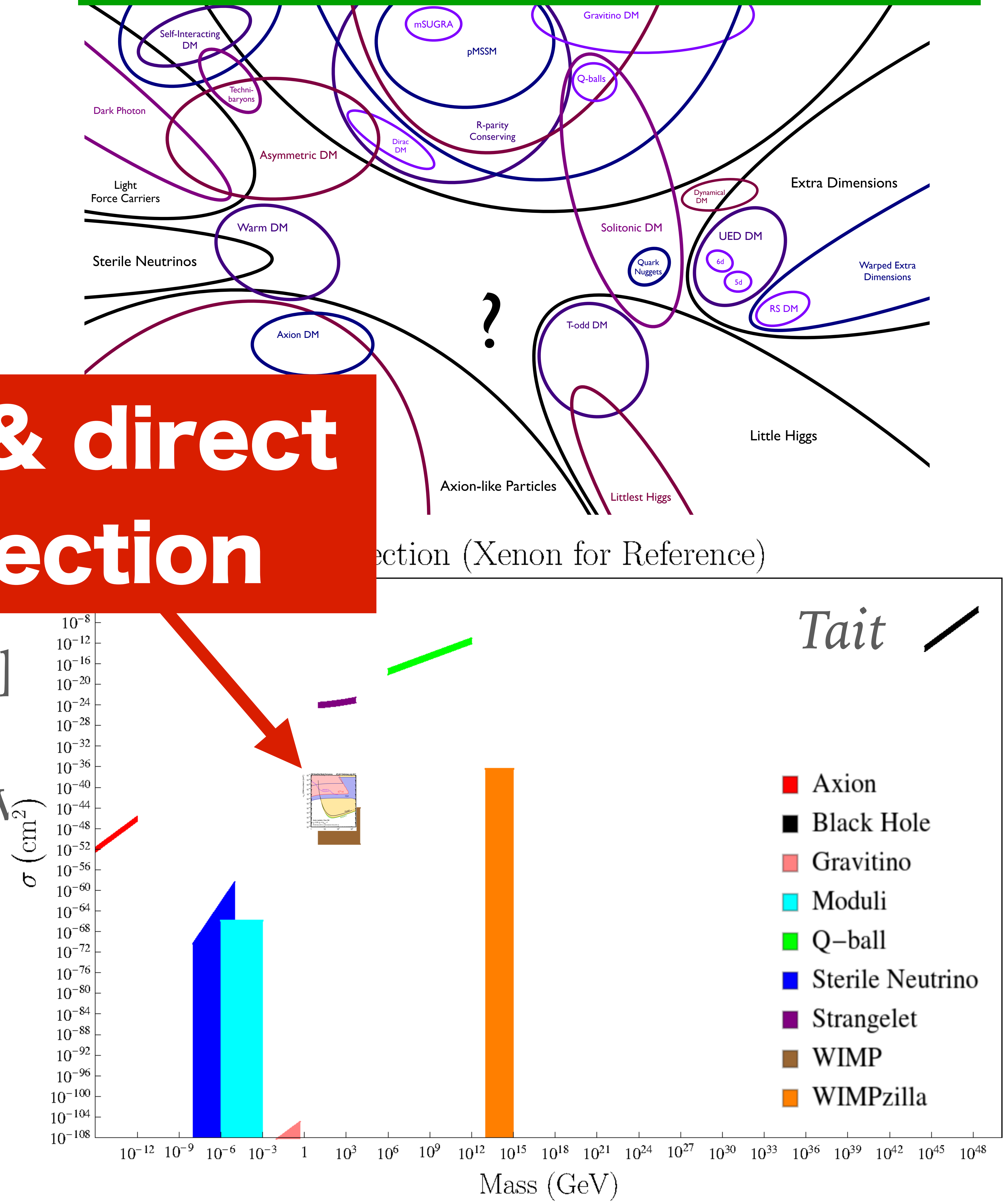
Today we know that

- **there are many possible models**
- **the range of parameters they span i**

We must deploy full ingenuity in searching for dar

But must also recognise that it has remained elusiv
finding it in any given year are small!

Snowmass non-WIMP dark matter report, 1310.8642

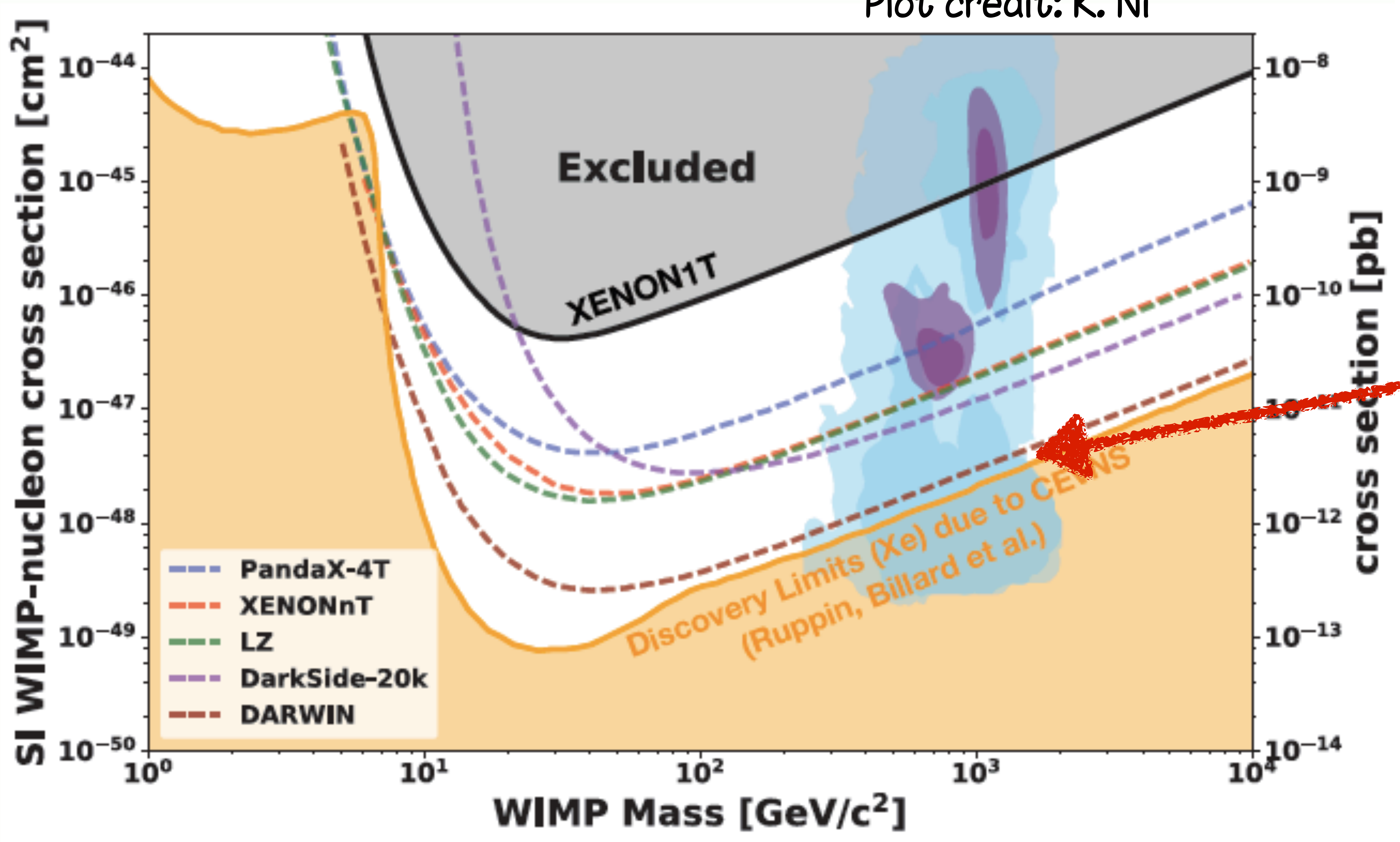


LHC & direct detection

Figure 1. *Graphical representation of the (incomplete) landscape of candidates. Above, the landscape of dark matter candidates due to T. Tait. Below, the range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark matter candidates have an enormous range of masses and interaction cross sections.*

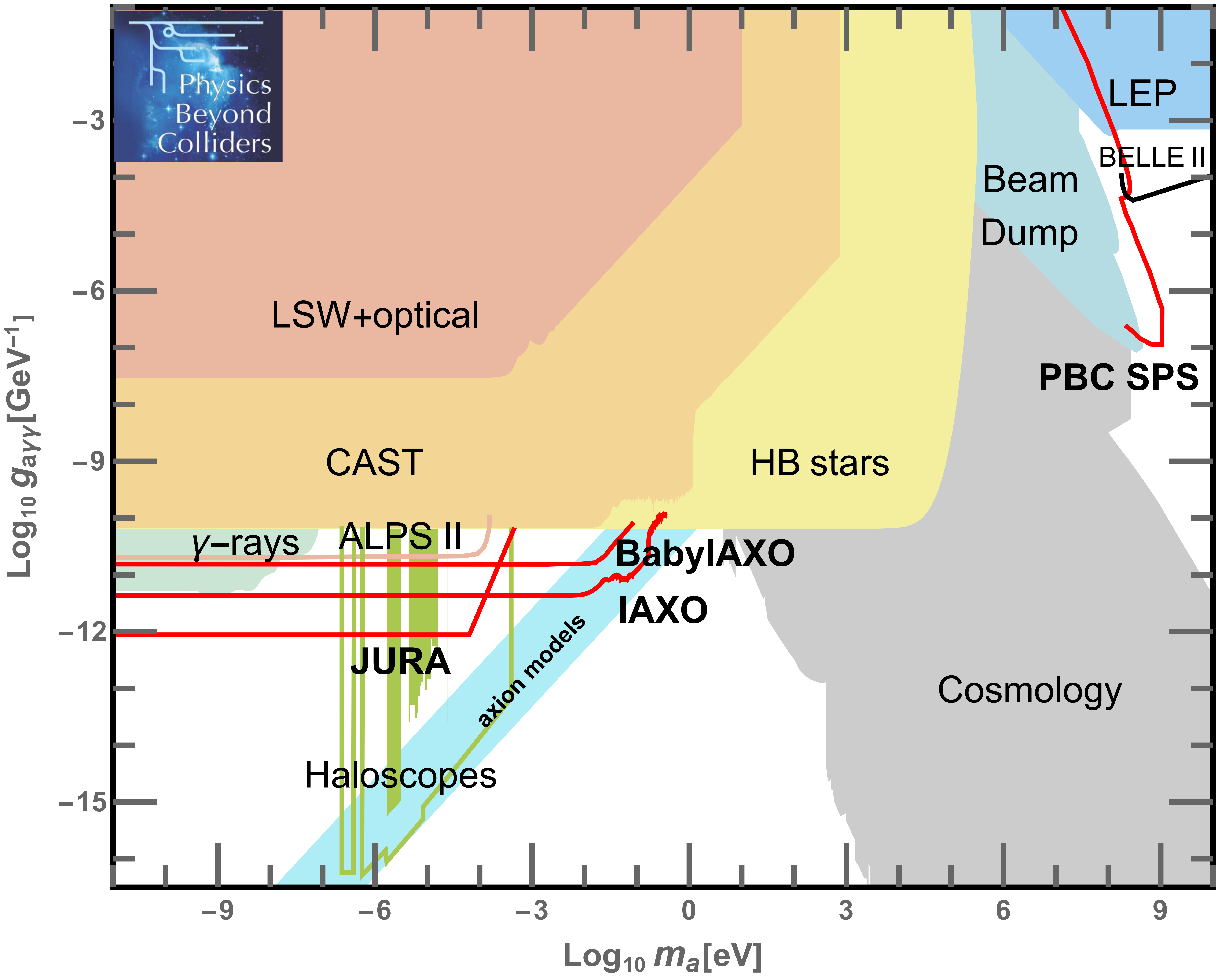
Future of Heavy WIMPs Searches

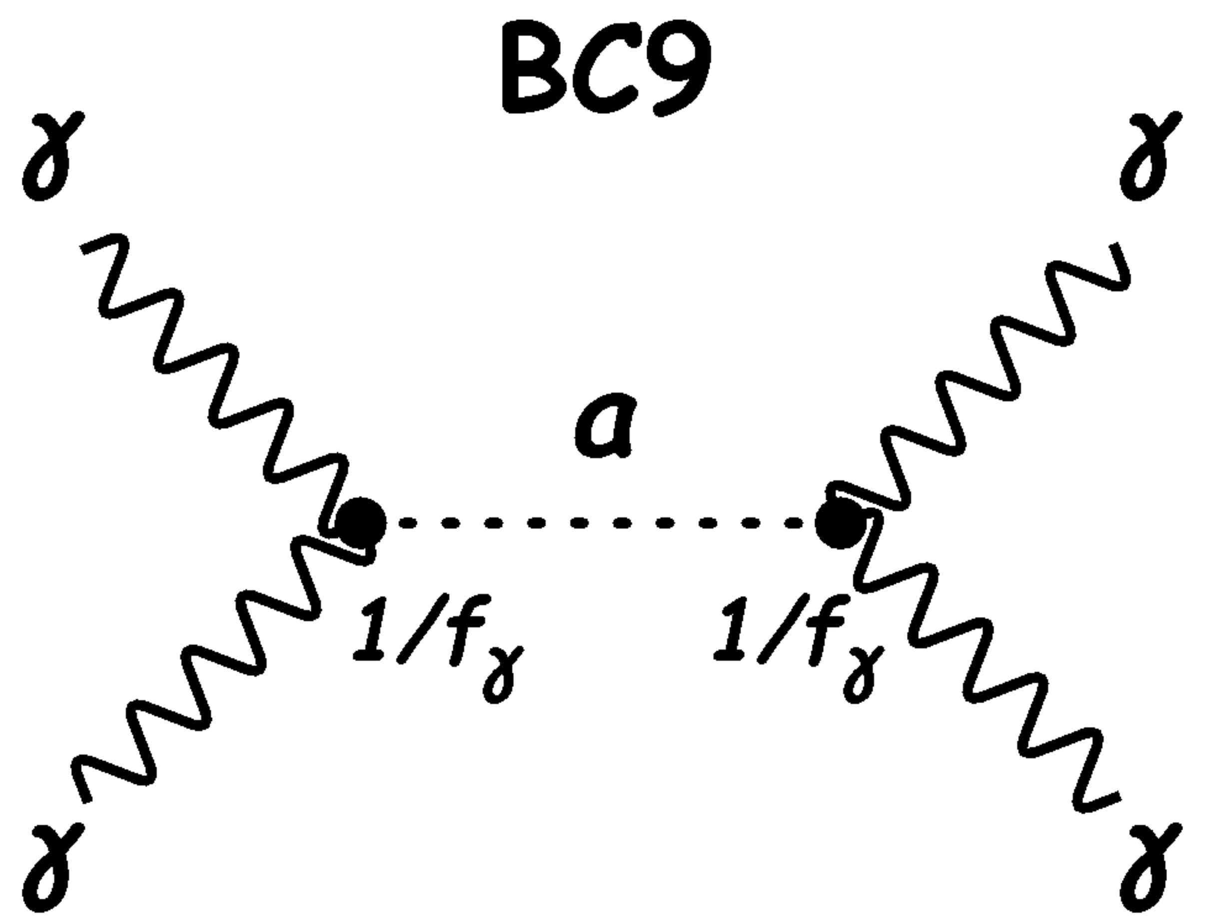
Plot credit: K. Ni



e.g. expected reach of Darwin, due to start ~ 2026

Axions





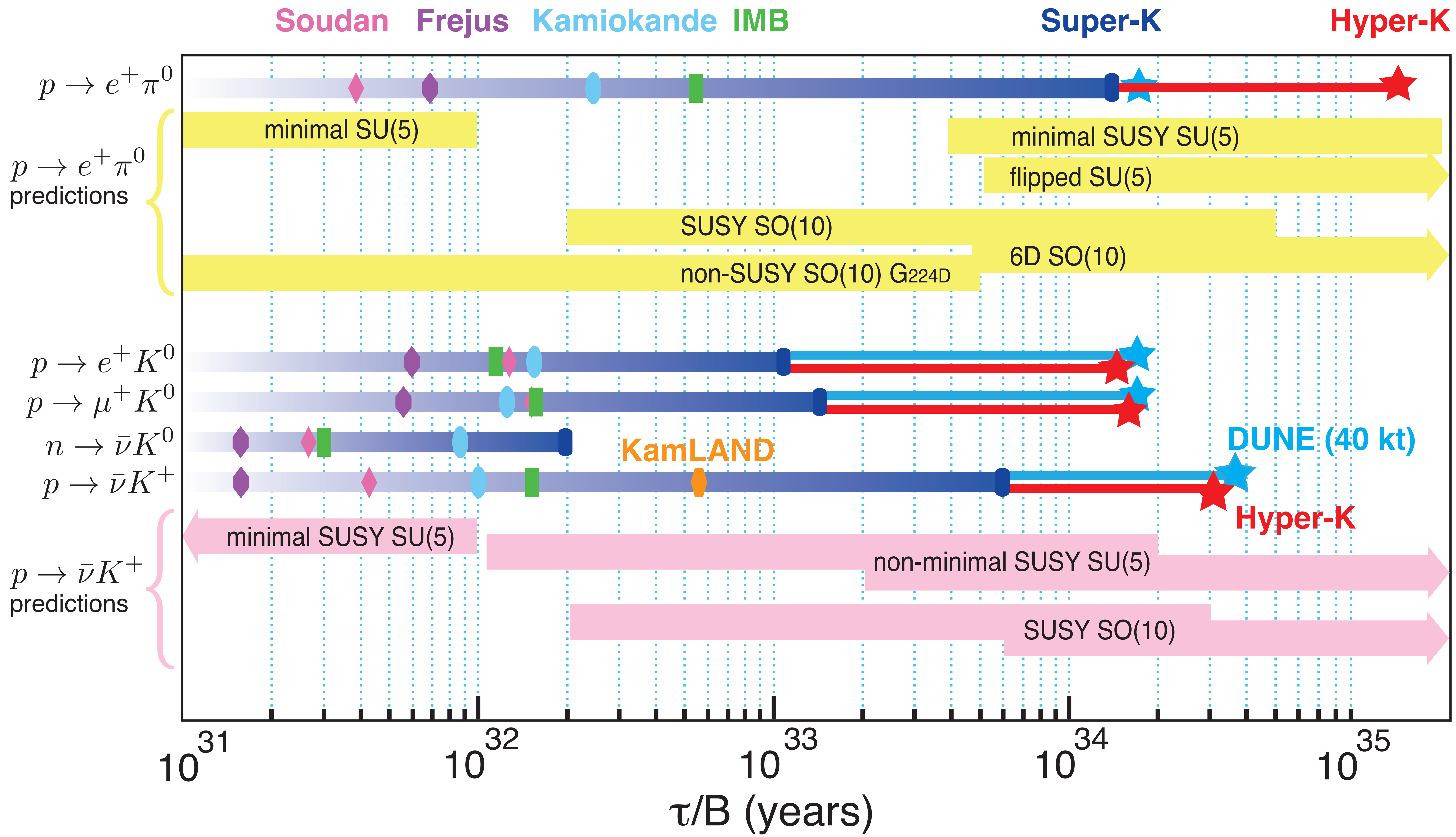
axion: all-time favourite #2

could be a dark-matter candidate

diversity of experiments probing it is even greater than for other channels

indirect searches

null results so far: proton decay



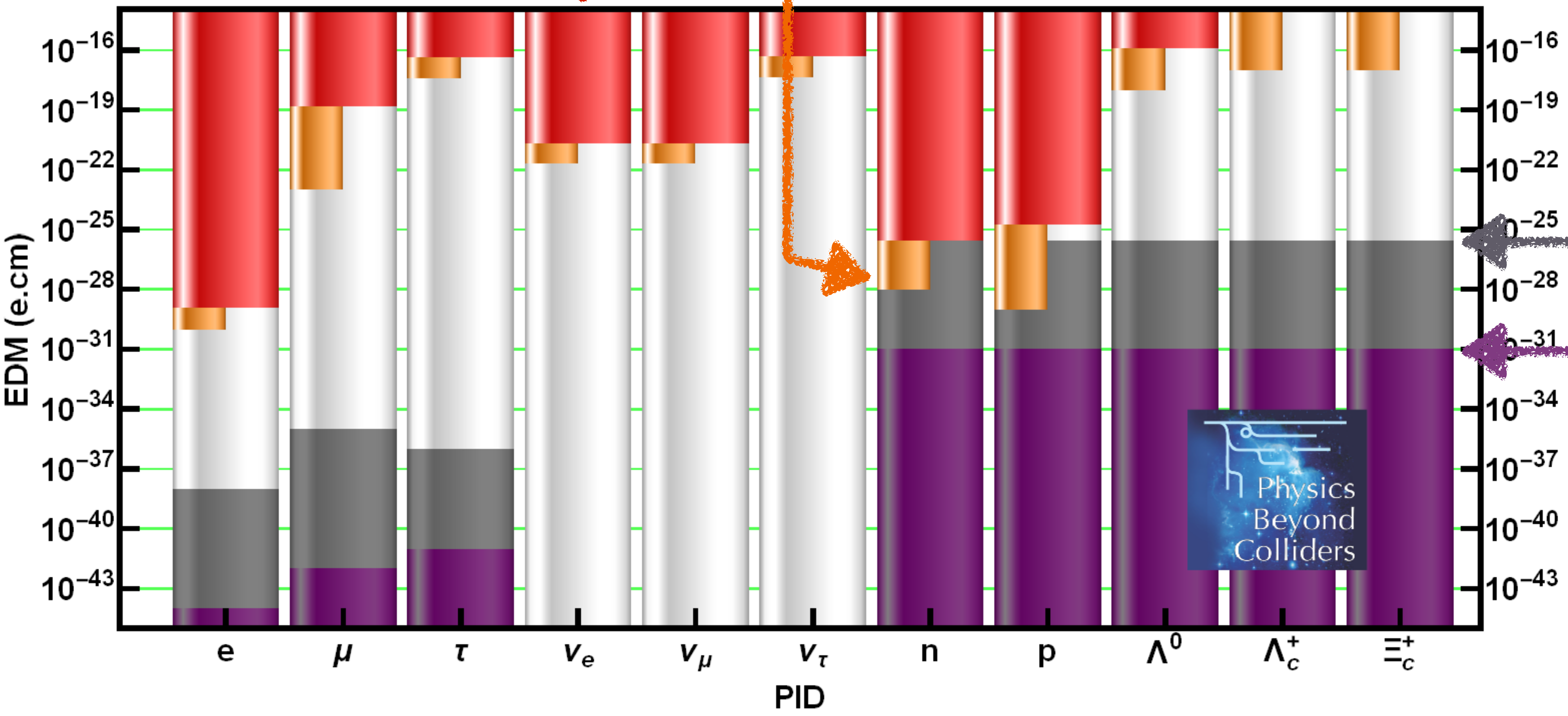
DUNE and hyper-K due to come online ~ 2025

Not just neutrino physics, but also searches

null results so far: electric dipole moments

current limits

expected limit in next decade



EDM that would be induced if QCD θ param. is at today's limit

SM (CKM) contribution

arXiv:1902.00260 (PBC)

Almost any measurement ≡ indirect search

- whether flavour, electroweak / Higgs, high-p_T jets, etc.
- there's a chance your measurement is sensitive to physics at some scale $\Lambda \gg M_{observed}$, where new new physics appears as small higher-dimension **effective** operator

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{\Lambda^2}\sum_k \mathscr{O}_k + \cdots$$

- you may think it's the measurement that matters: e.g. establishing a fundamental parameter of the SM to higher precision (that's part of a physicist's legacy)
- or you may think of increased precision as an indirect route to higher Λ

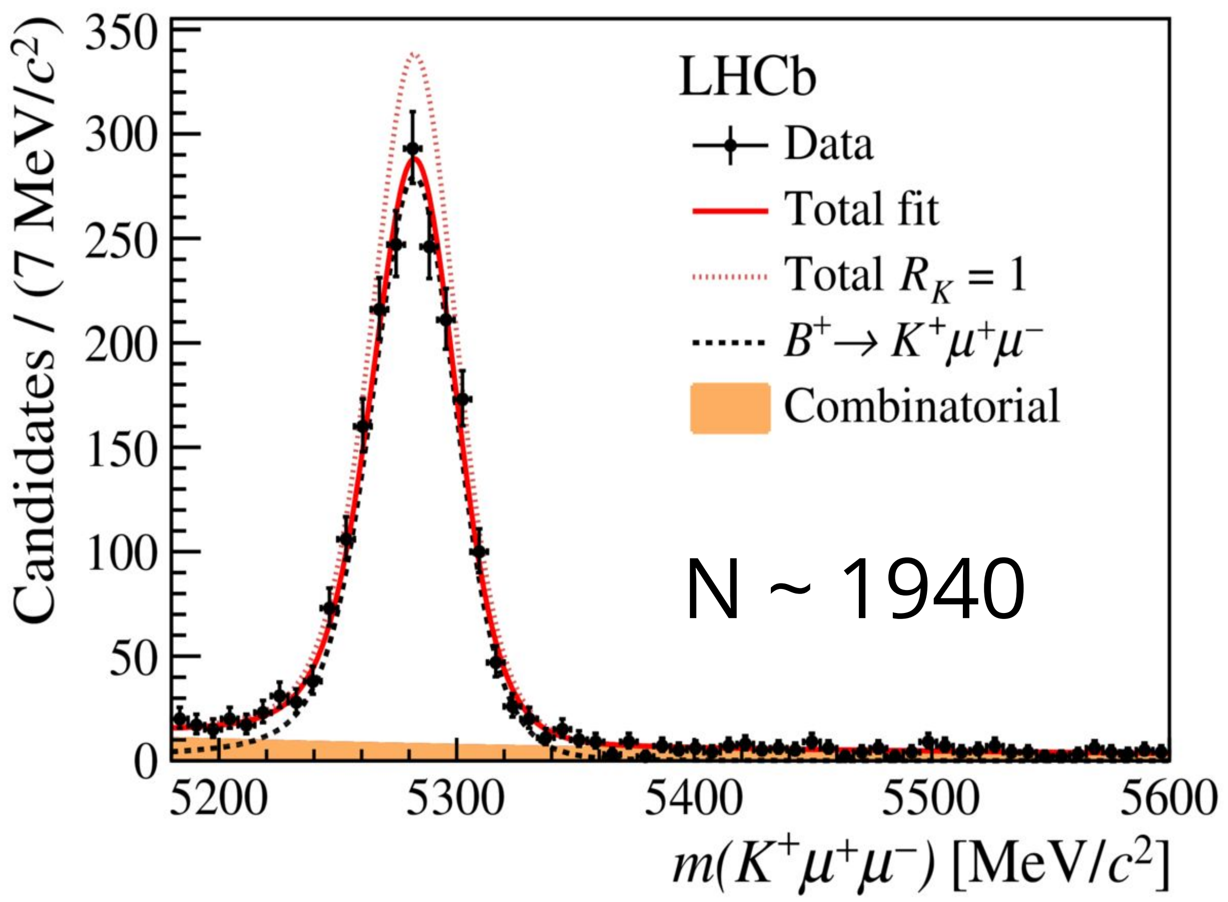
flavour physics

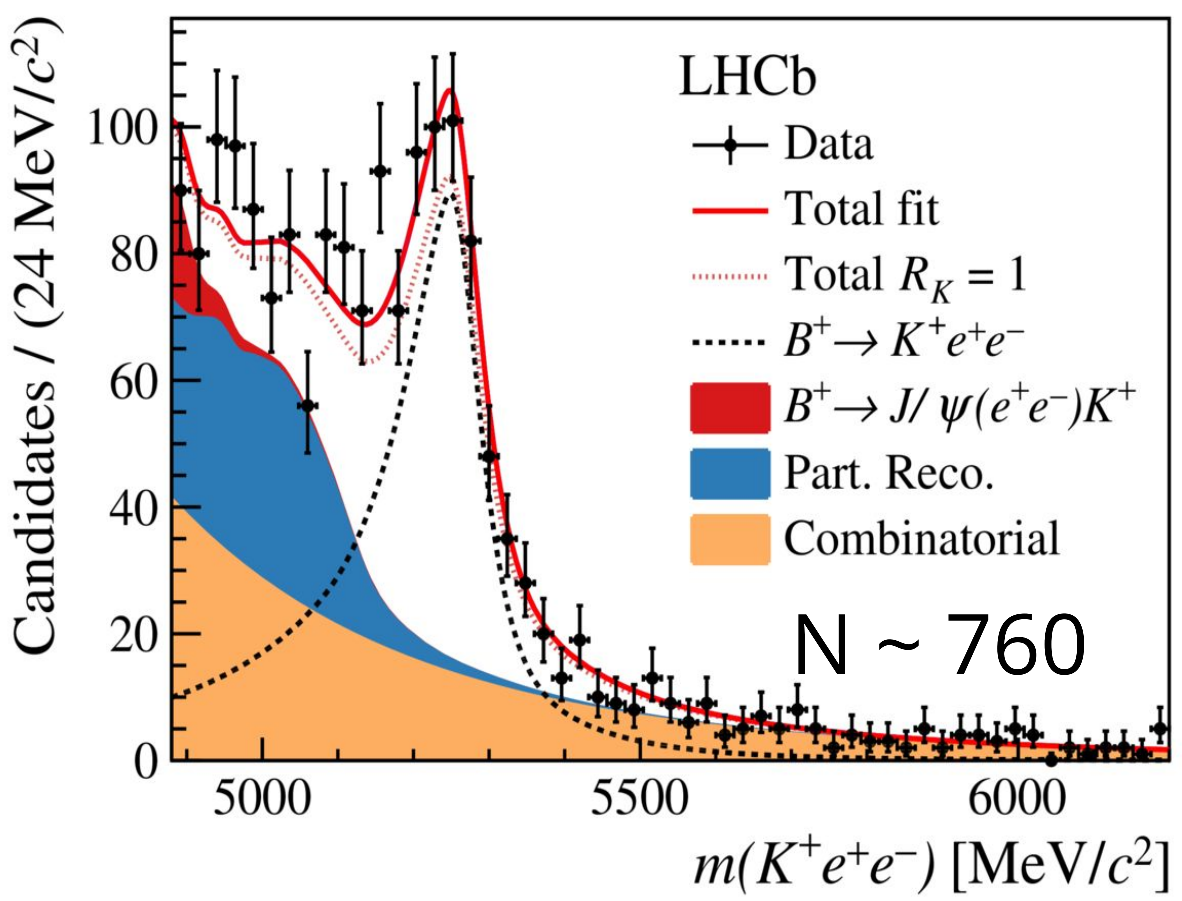
B anomalies: concentrate on R_K (lepton flavour violation)

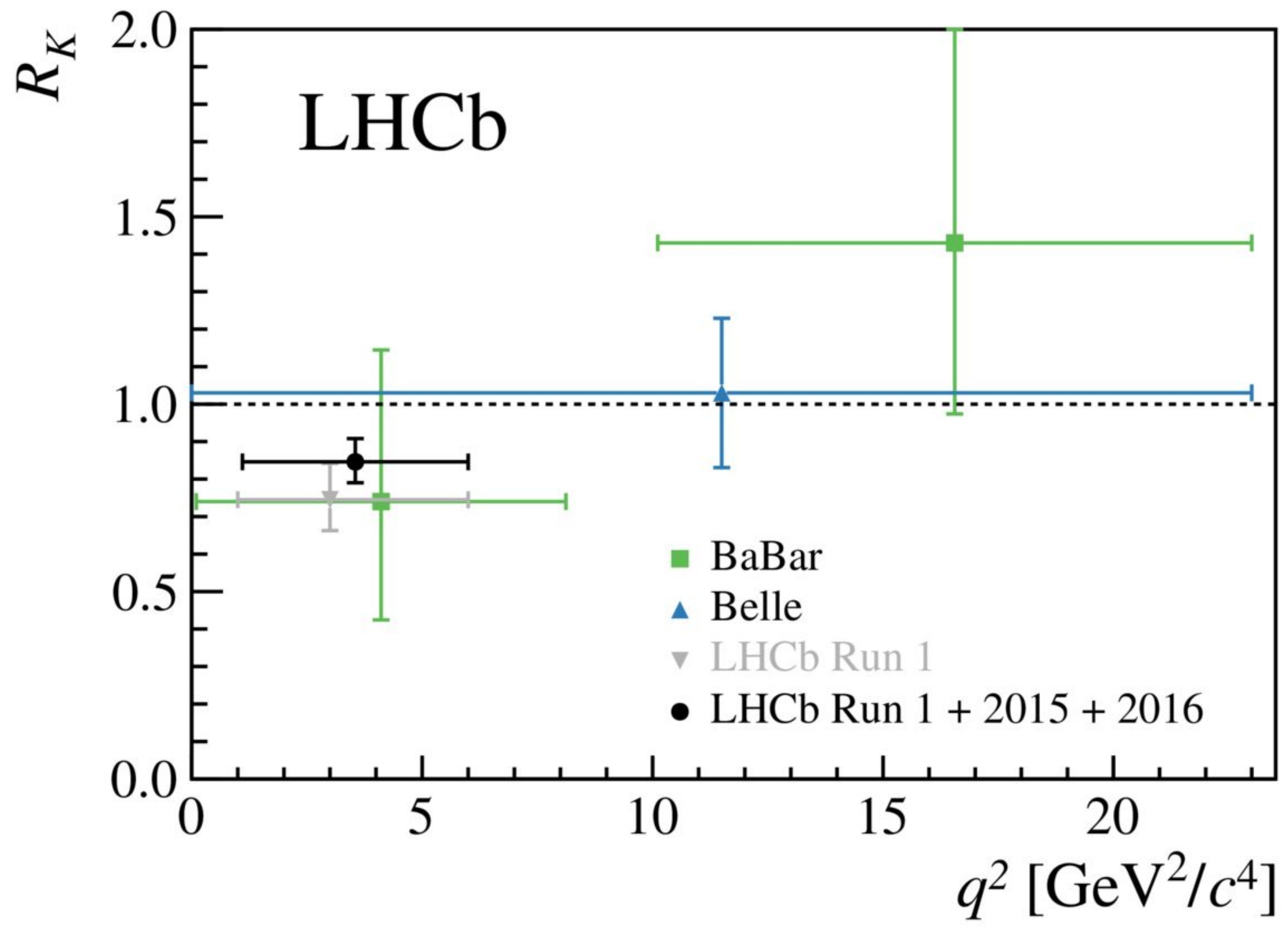
Updated R_K from LHCb

PRL 122 (2019) 191801

Factor 2 larger yields than in previous analysis
still statistically dominated by electron mode







compatible with previous analysis and ~2.5σ from SM

$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

Still x2 B decays recorded by LHCb to be analysed!

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Carla Marin @ LP2019

Projections at LHCb and Belle II

in ~ 1 year ?

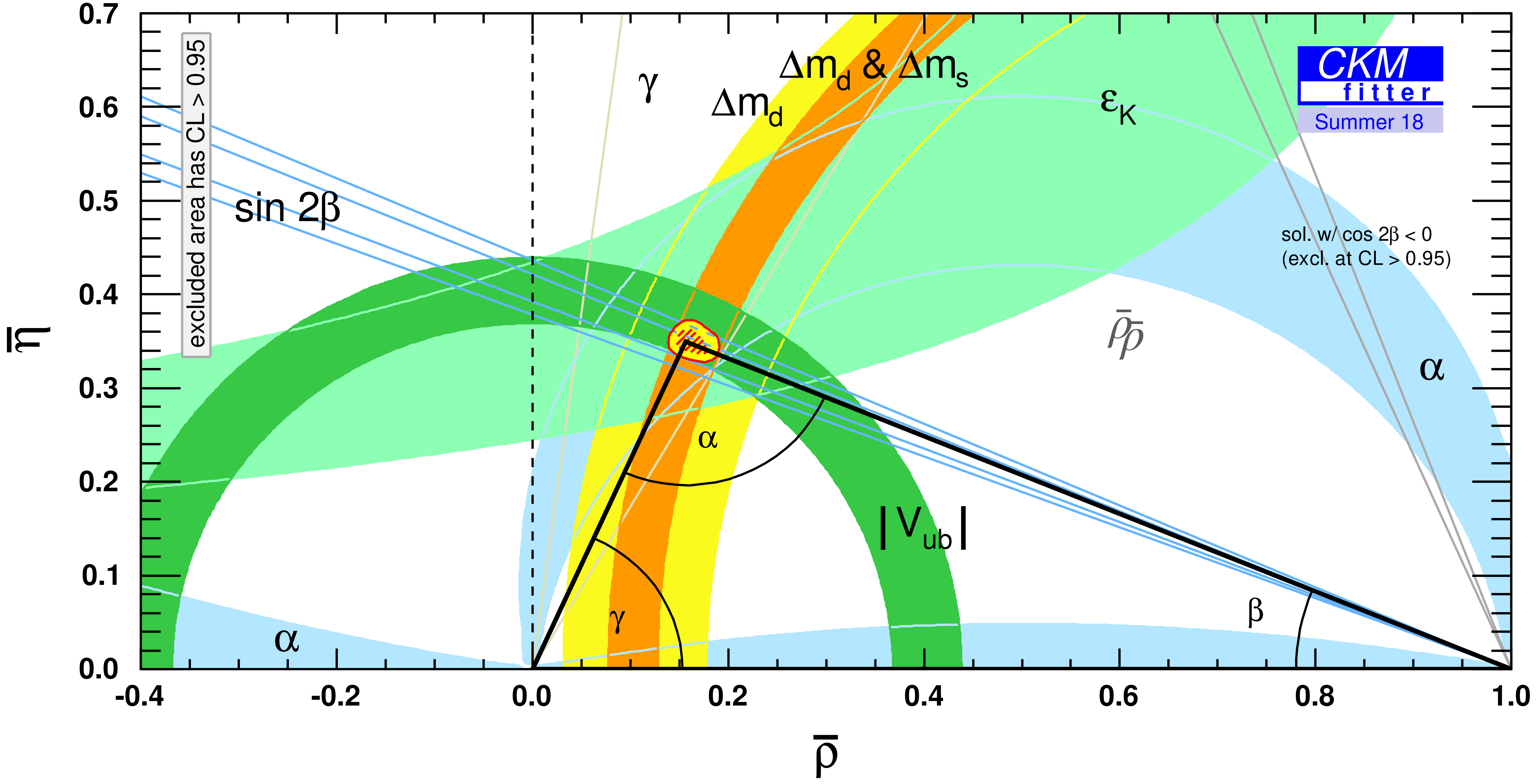
by 2025?

Observables	Belle 0.7 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K $(1 < q^2 < 6 \text{ GeV}^2)$	28%	11%	3.6%

R_X precision	LHCb today	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	$0.846^{+0.060+0.016}_{-0.054-0.014}$	0.043	0.025	0.017	0.007

**If current central value persists,
by 2025 LHCb will have 6σ
and Belle II will have 4σ**

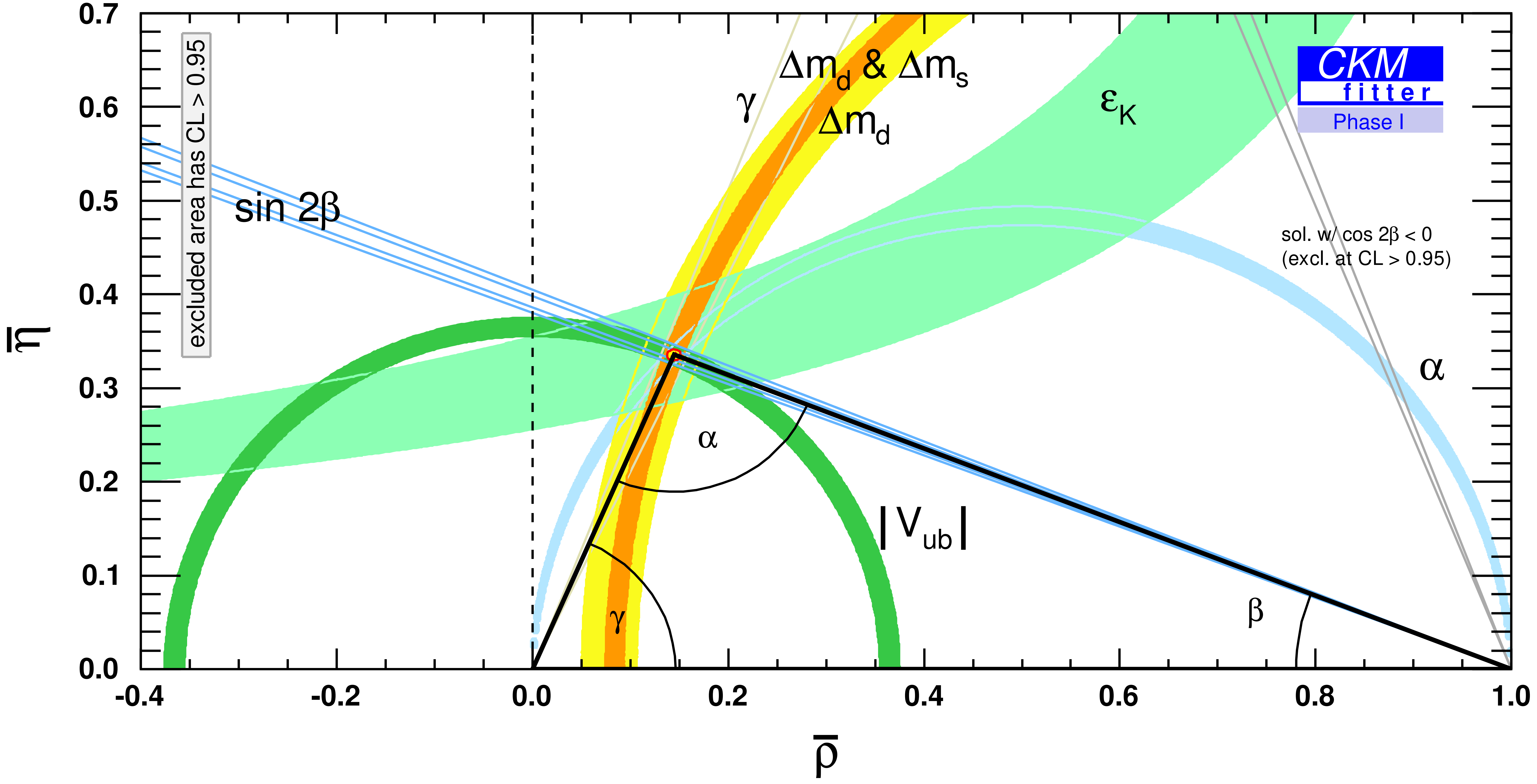
CKM fits (today)



Summer 2018

$$\delta\bar{\rho} = 0.085$$
$$\delta\bar{\eta} = 0.083$$

CKM fits (late 2020's)

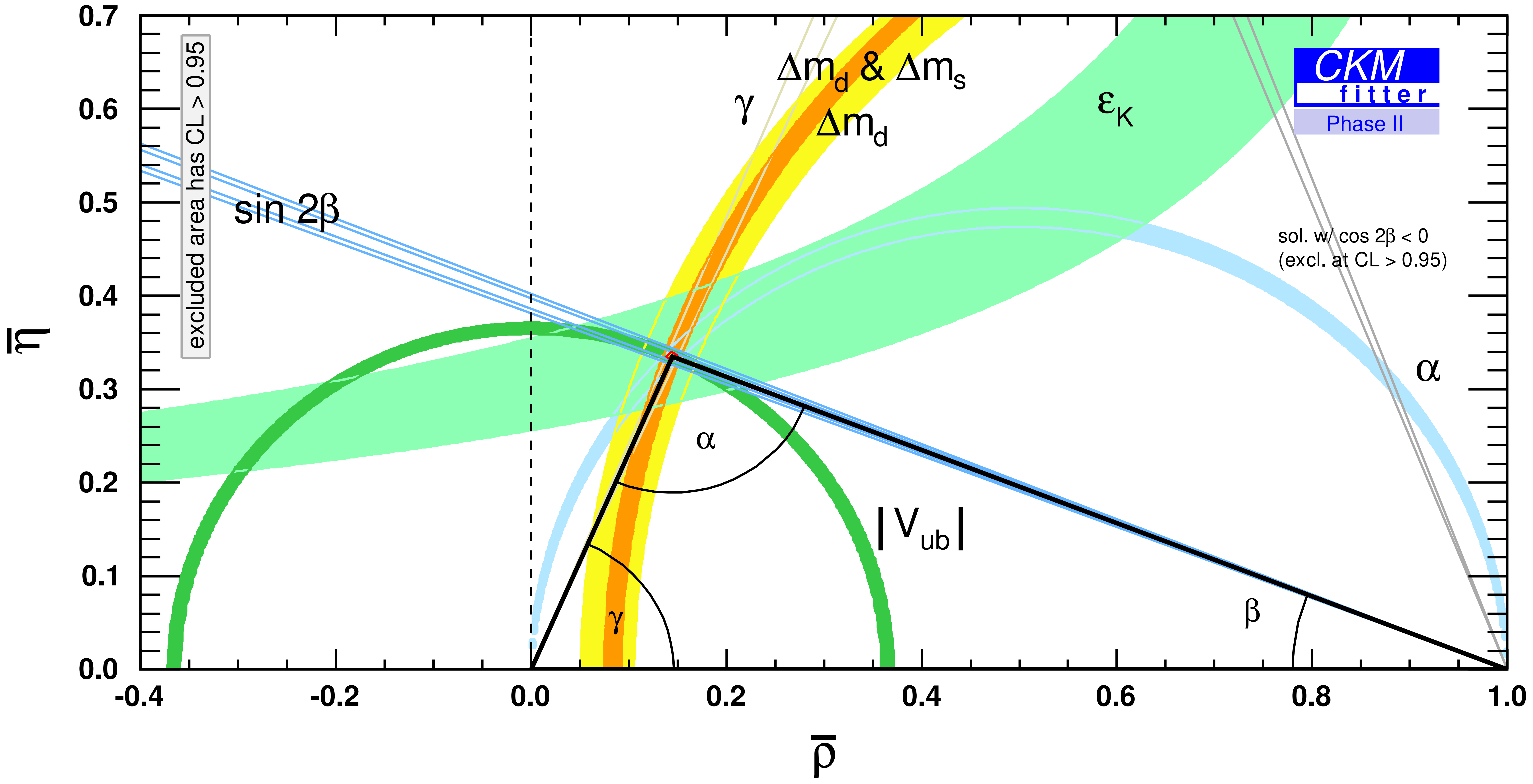


Phase I

LHCb at 23 fb^{-1}
CMS/ATLAS at
300 fb^{-1}
Belle II at 50 ab−1.

$$\delta\bar{\rho} = 0.027$$
$$\delta\bar{\eta} = 0.024$$

CKM fits (~2035)



Phase II

LHCb at 300 fb^{-1}, CMS/ATLAS at 3000 fb^{-1} Belle II at 50 ab−1.

$$\delta\bar{\rho} = 0.018$$

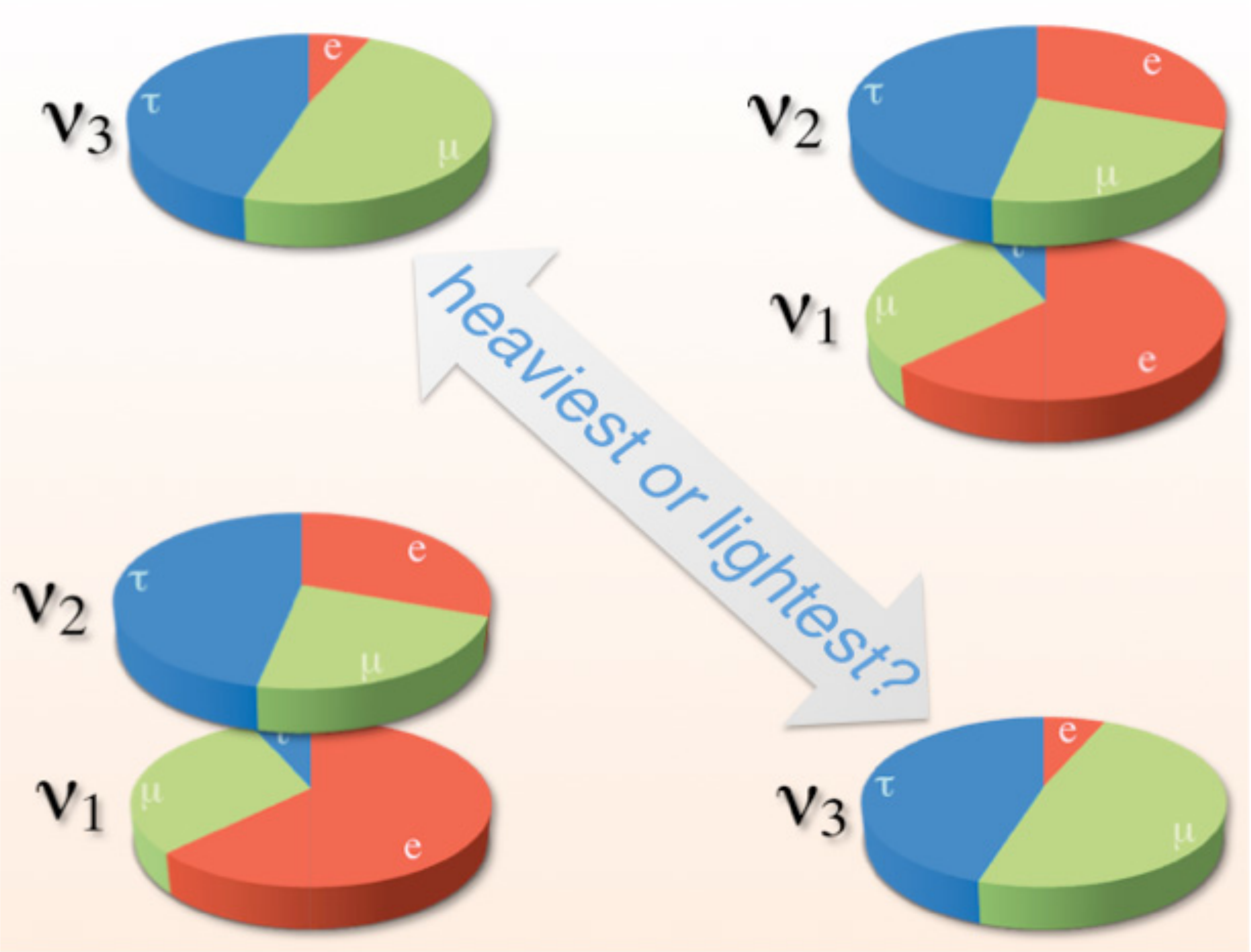
$$\delta\bar{\eta} = 0.015$$

& far more other topics than I can do justice to, cf. arXiv:1812.07638 (HL-LHC flavour plans)

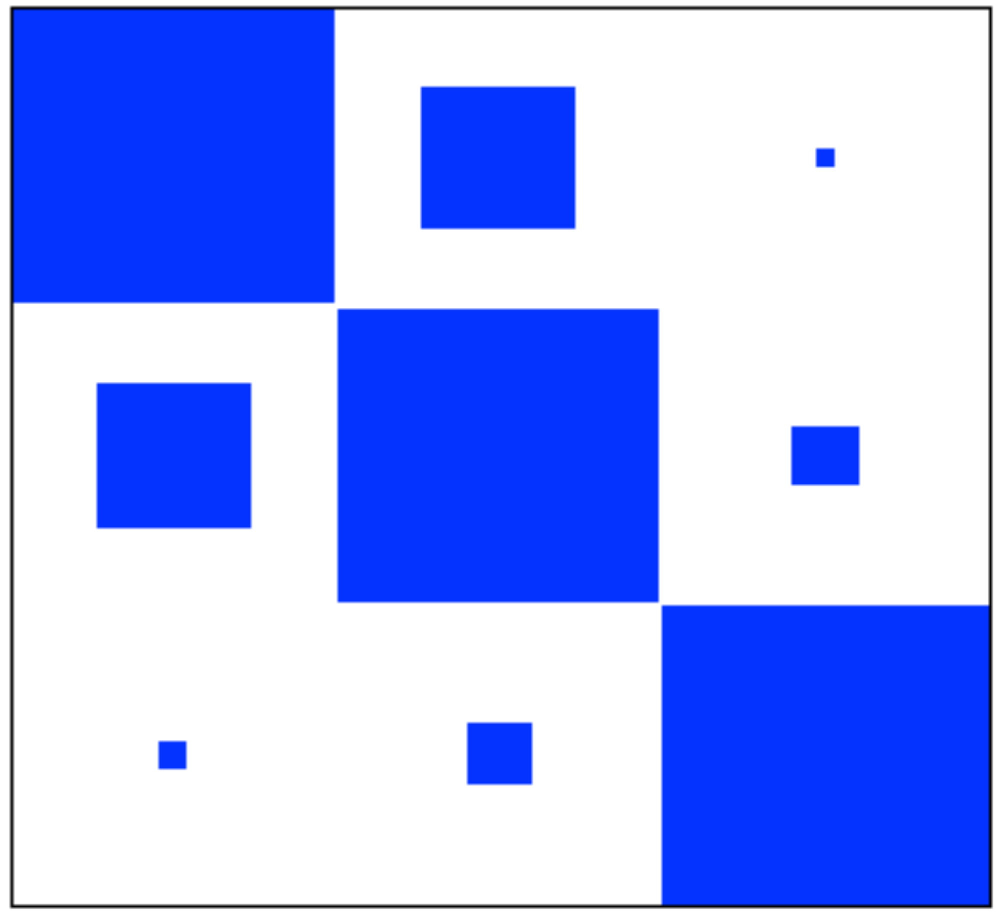
neutrinos

Questions in neutrino physics

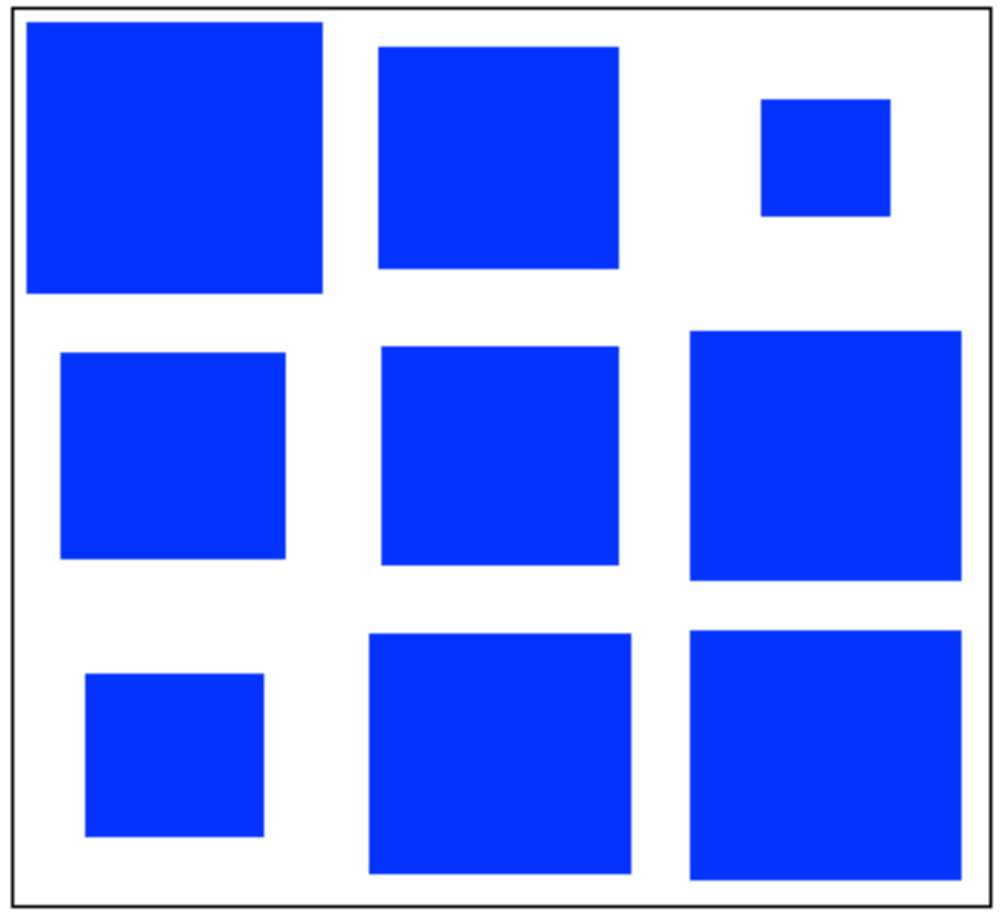
- Mass ordering
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



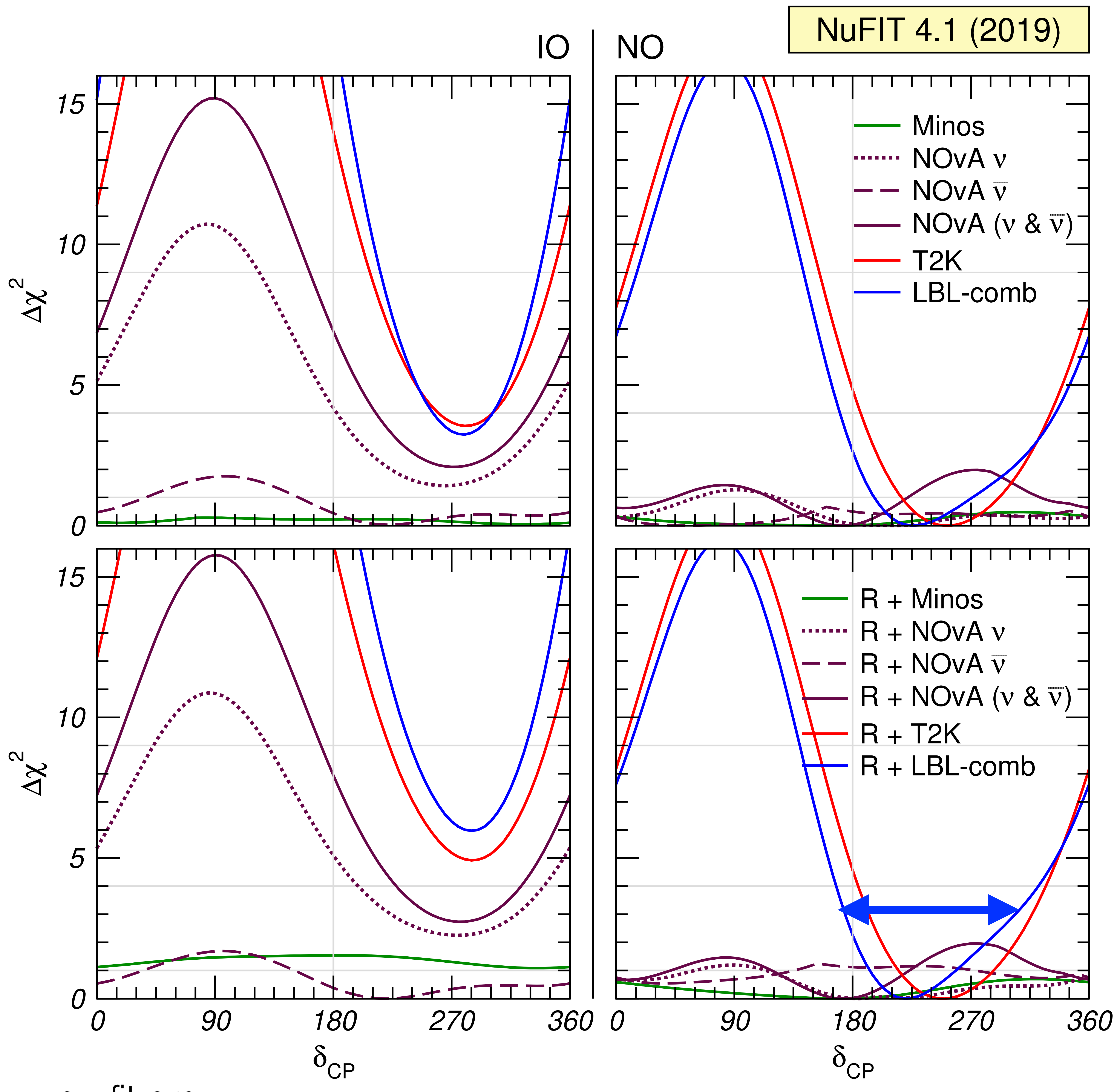
Quark mixing



Neutrino mixing



this & other ν material from Mark Messier @ LP19



www.nu-fit.org
JHEP 01 (2019) 106 [arXiv:1811.05487]

current status:

hints of CP violation

normal hierarchy preferred

CPV hints driven by T2K data
When combined with other data, δ_{CP}=180^o is allowed within 2σ

Significance of normal hierarchy increases to just over 3σ in combination

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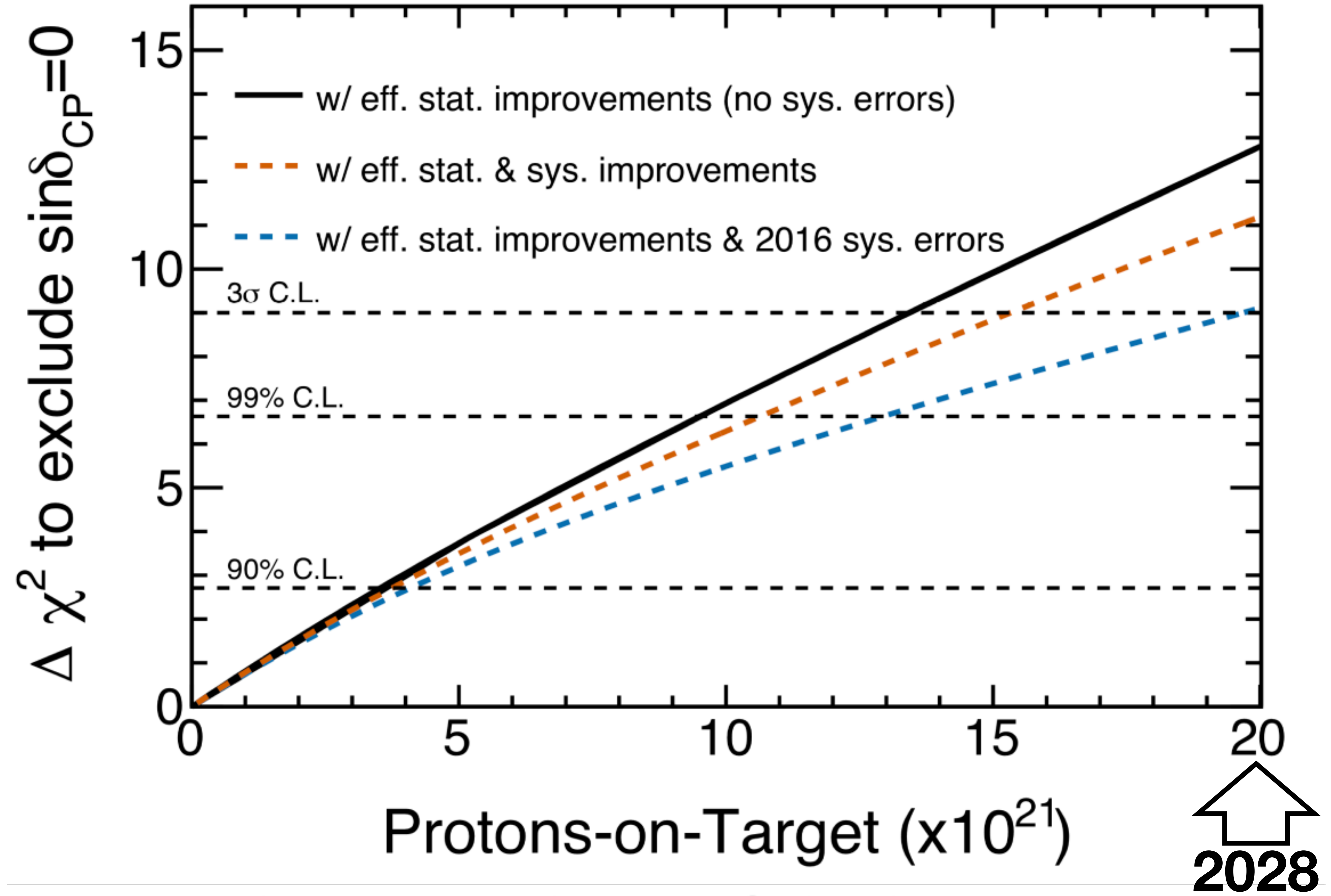
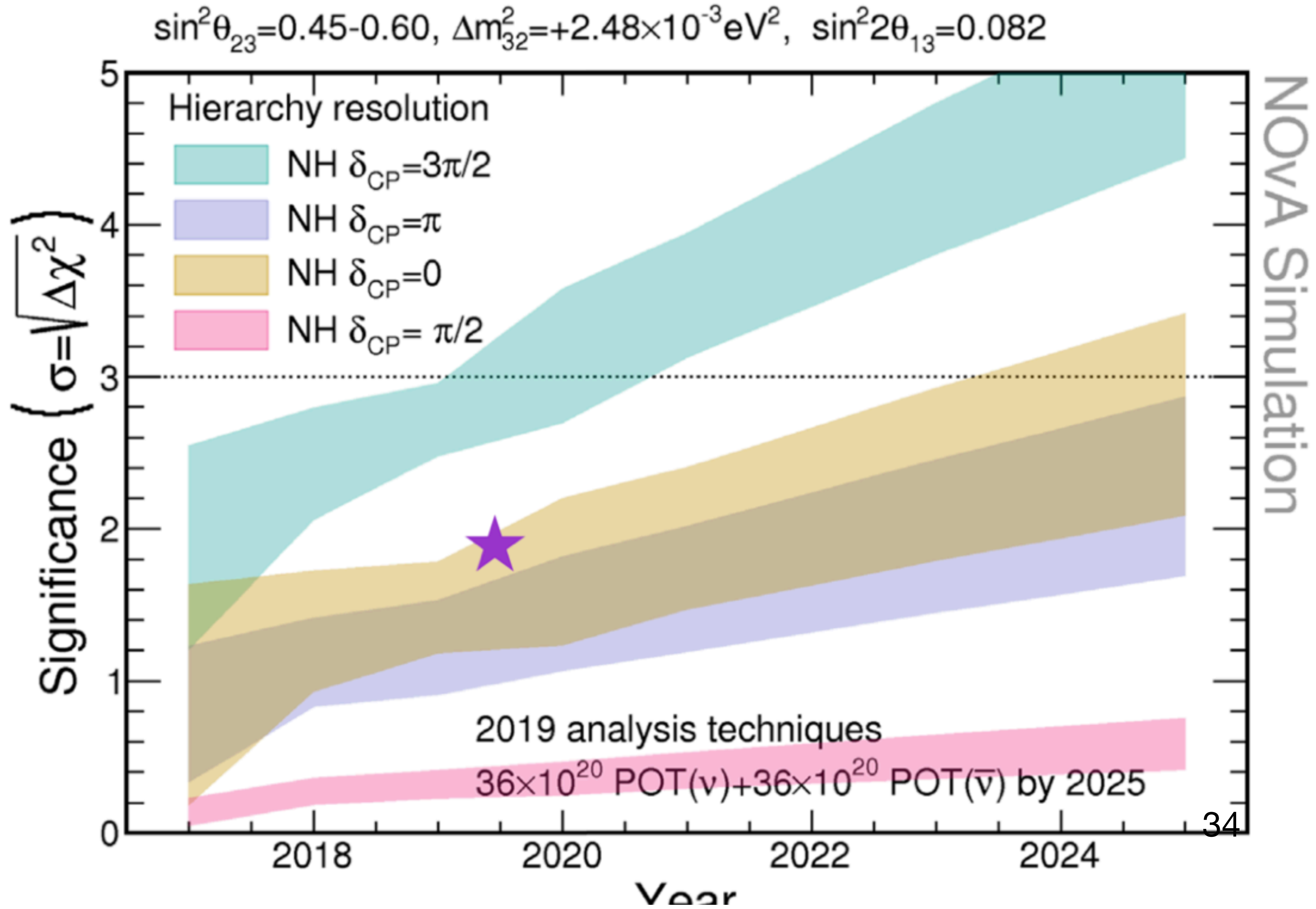
prospects for mid/late 2020s

~3σ/expt for hierarchy and CP violation

T2K will run until 2028 with improvements to beam intensity up to 1.3 MW

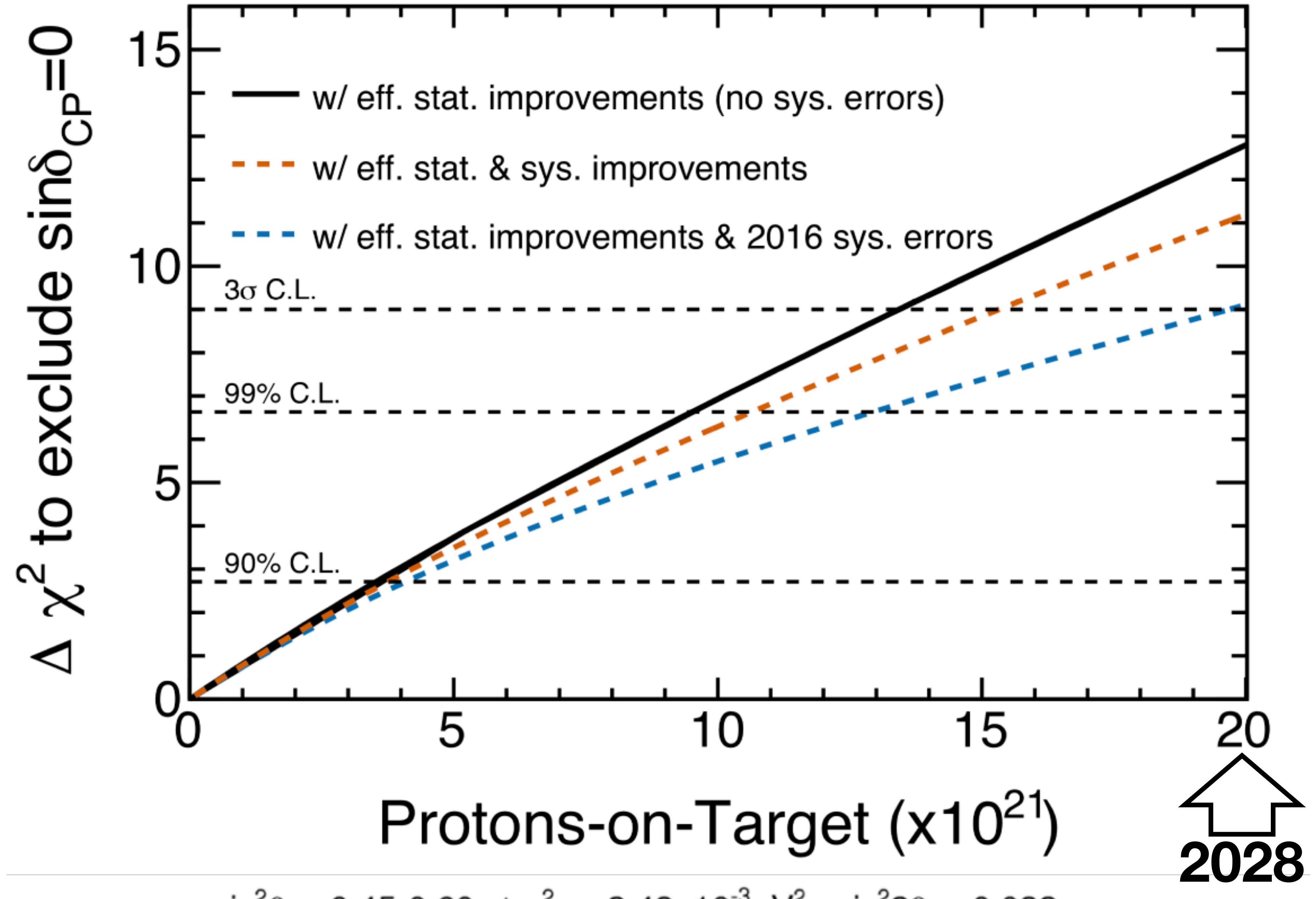


NOvA will run to 2025 with improvements to beam intensity up to 0.9 - 1 MW



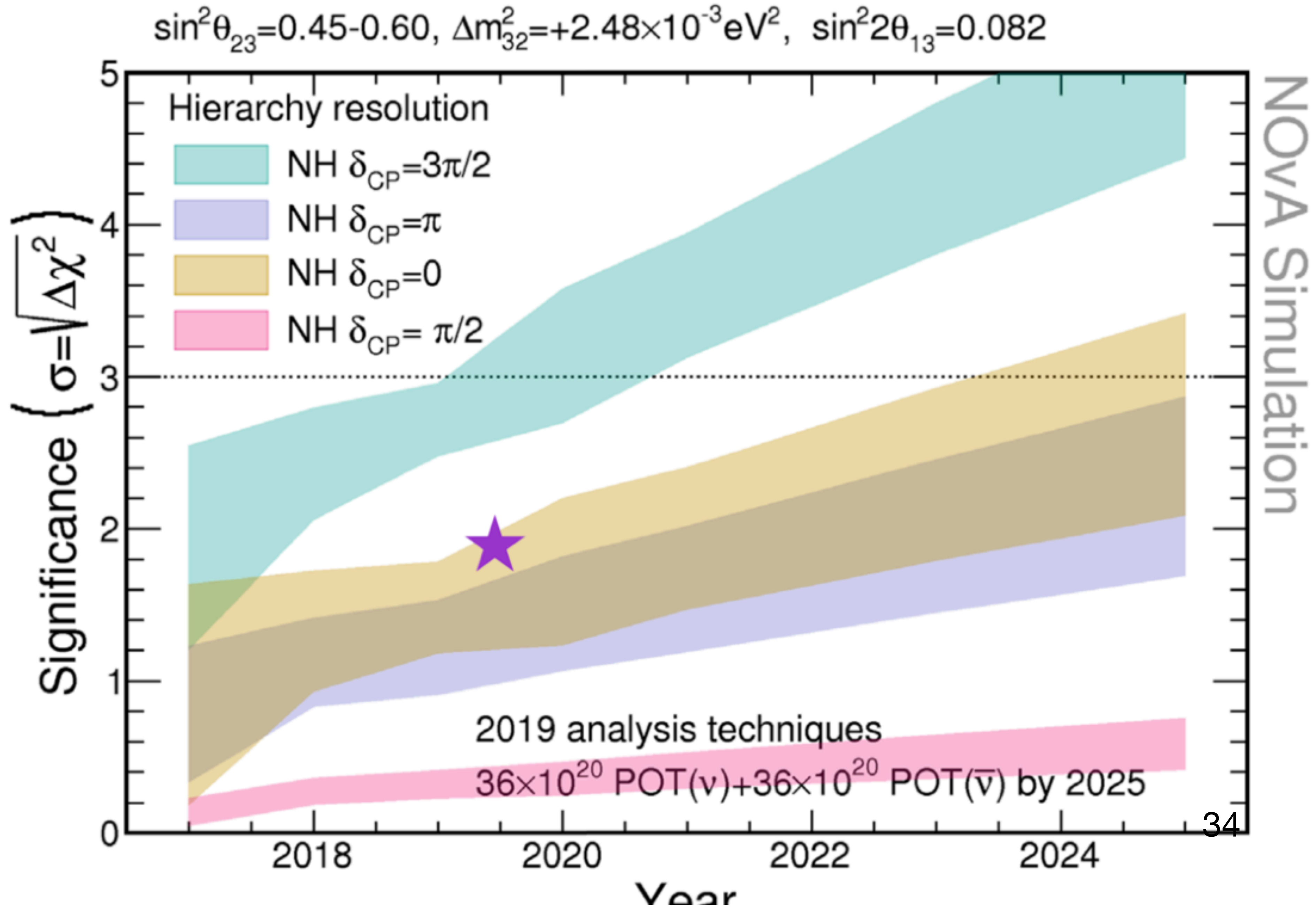
Collaborations working toward a joint fit

T2K will run until 2028 with improvements to beam intensity up to 1.3 MW

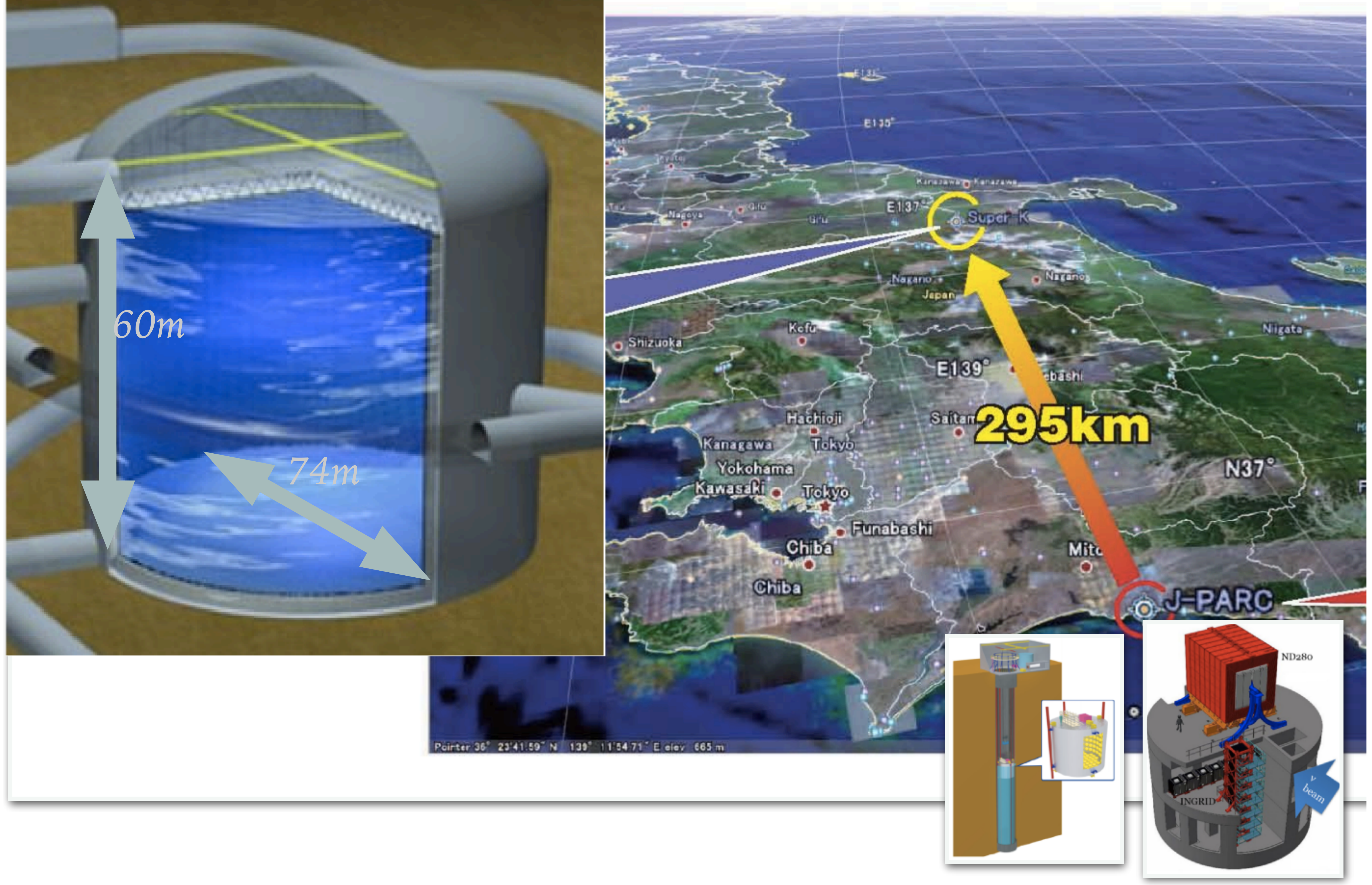


prospects for mid/late 2020s

NOvA will run to 2025 with improvements to beam intensity up to 0.9 - 1 MW

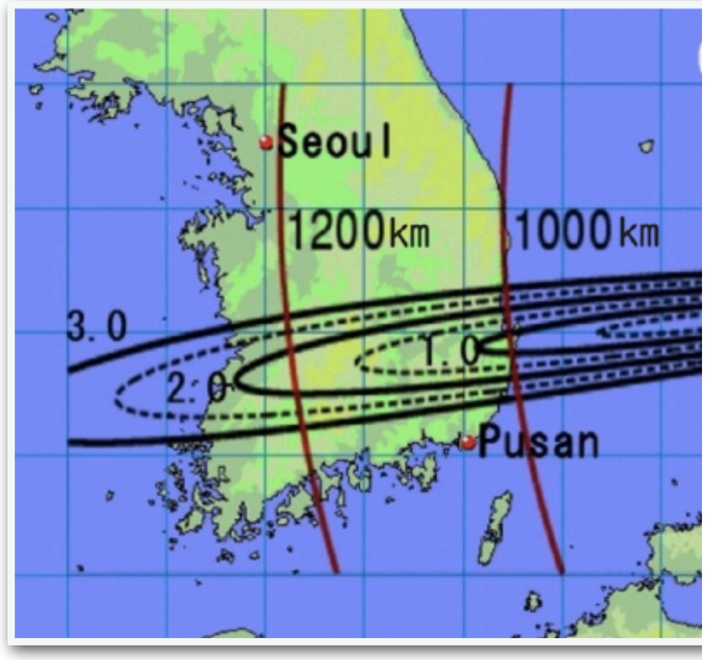


Collaborations working toward a joint fit

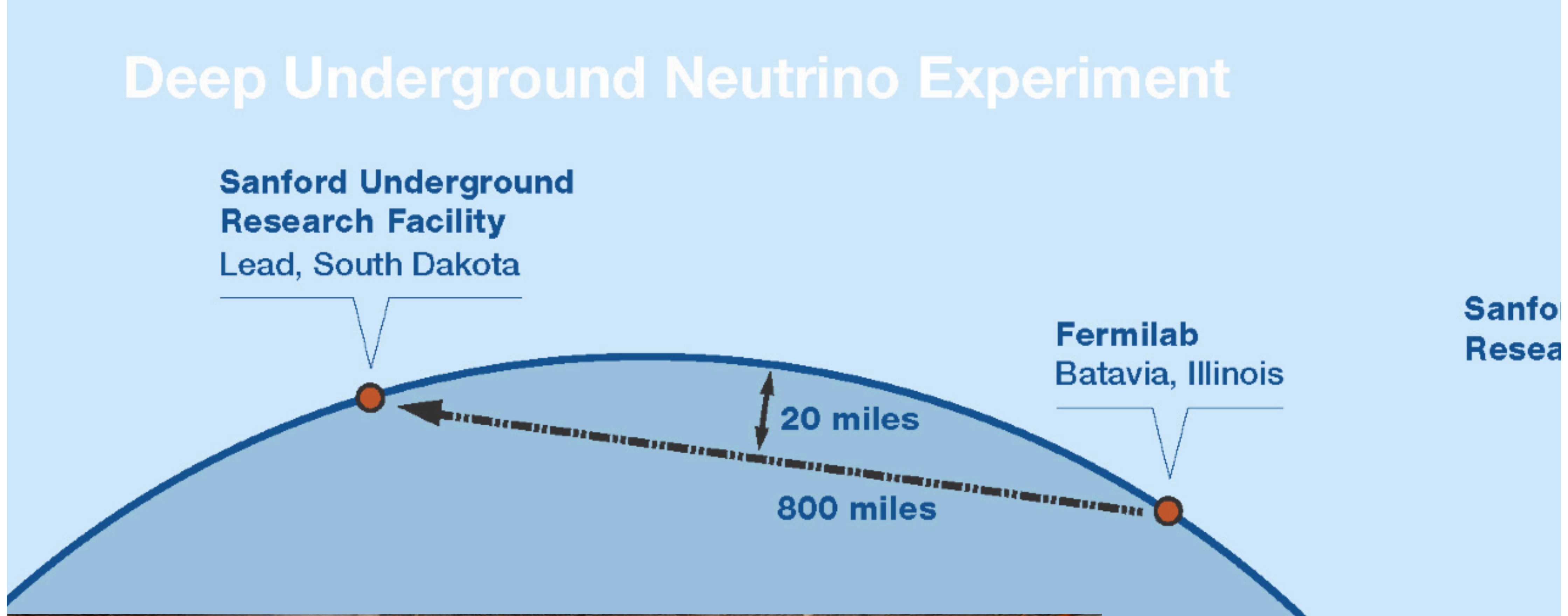


Hyper-Kamiokande Experiment

Upgrade beam to 1.3 MW
260 kt far detector
Expected data taking from 2027
Exploring possibility of 2nd detector in Korea



>5σ resolution of mass hierarchy
>5σ resolution of CP violation

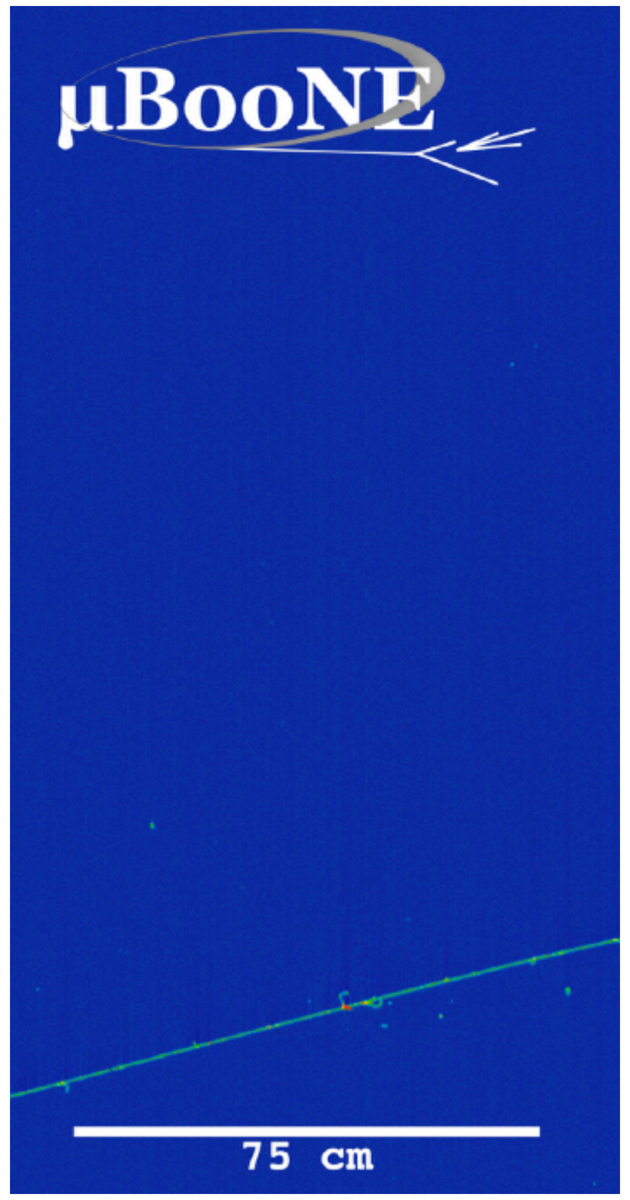


Groundbreaking, July 2017

DUNE Experiment

Upgrade beam to 1.2 then 2 MW
4x17 kt detector modules with millimeter resolution located 4850 feet underground
Successful prototype program at CERN
Data taking by ~2027

>5σ resolution of mass hierarchy
>5σ resolution of CP violation

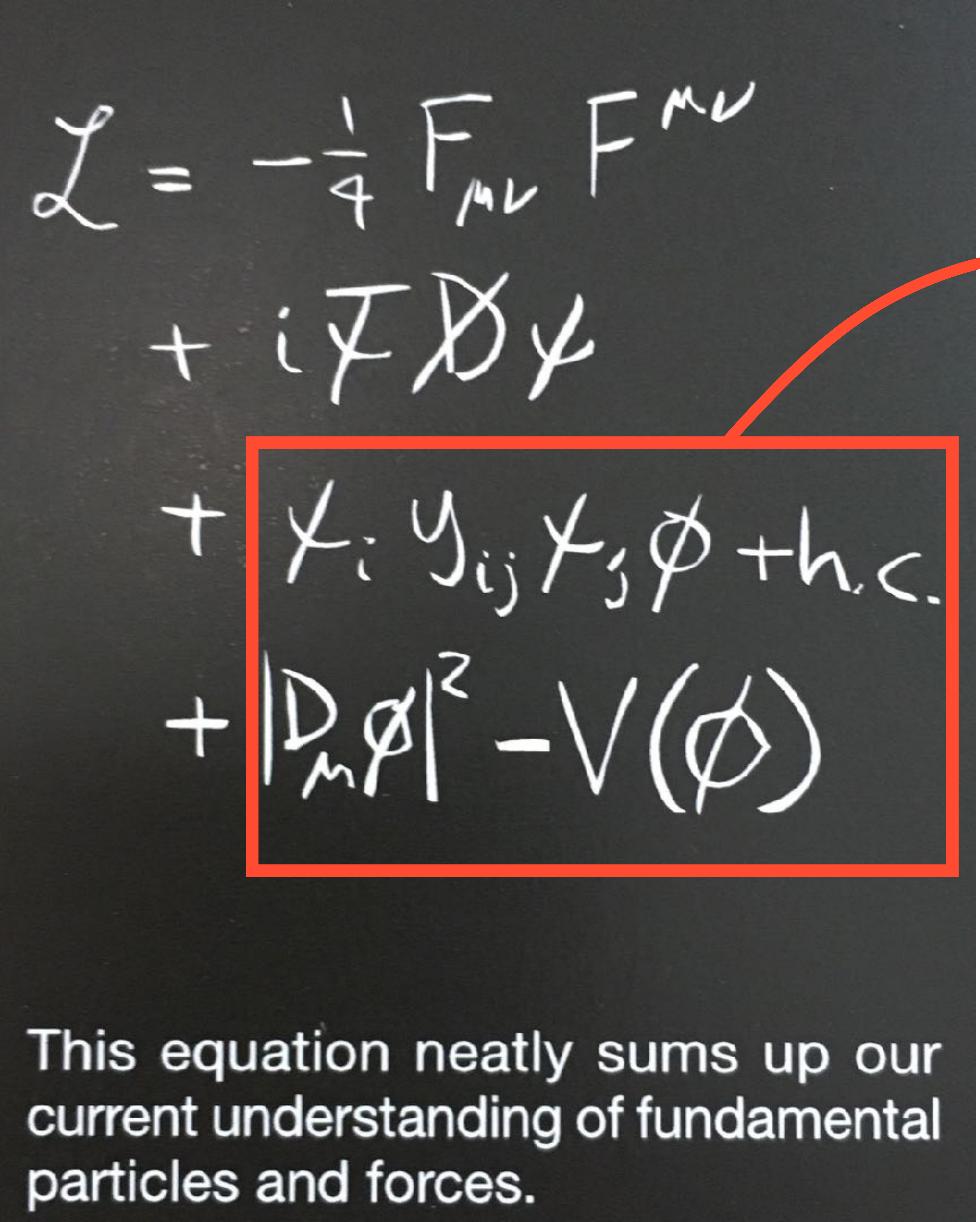


Higgs physics

two dimensions to progress:

(1) seeing new kinds of fundamental coupling (Yukawas, HHH)

(2) precision



Higgs sector

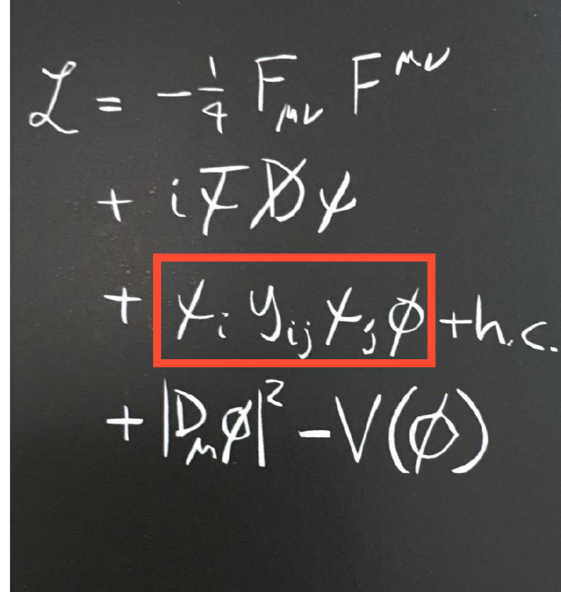
until 7 years ago none of these terms had ever been directly observed.

Discovery of Higgs was **start of a new chaper in particle physics**

Many interactions **qualitatively new** relative to the earlier successful probes on the SM (gauge)

and fundamental to nature of our universe

Why do Yukawa couplings matter?
(1) Because, within SM conjecture, they're what give masses to all quarks

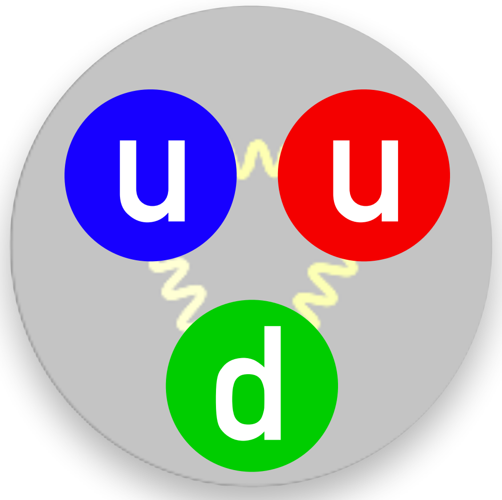


This equation neatly sums up our current understanding of fundamental particles and forces.

Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

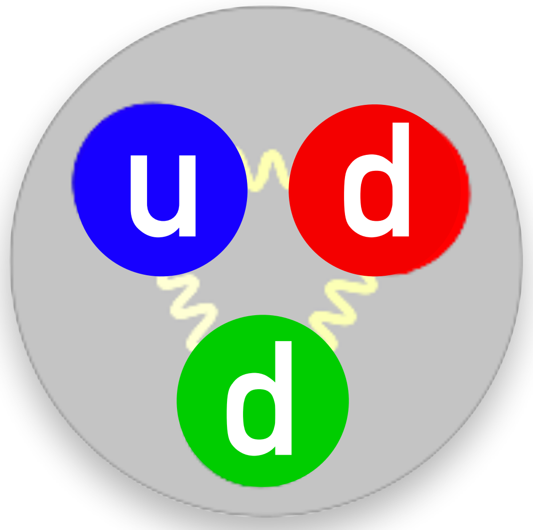
proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

proton
mass = 938.3MeV



So protons are **lighter** than neutrons,
→ protons are stable.

neutron
mass = 939.6MeV

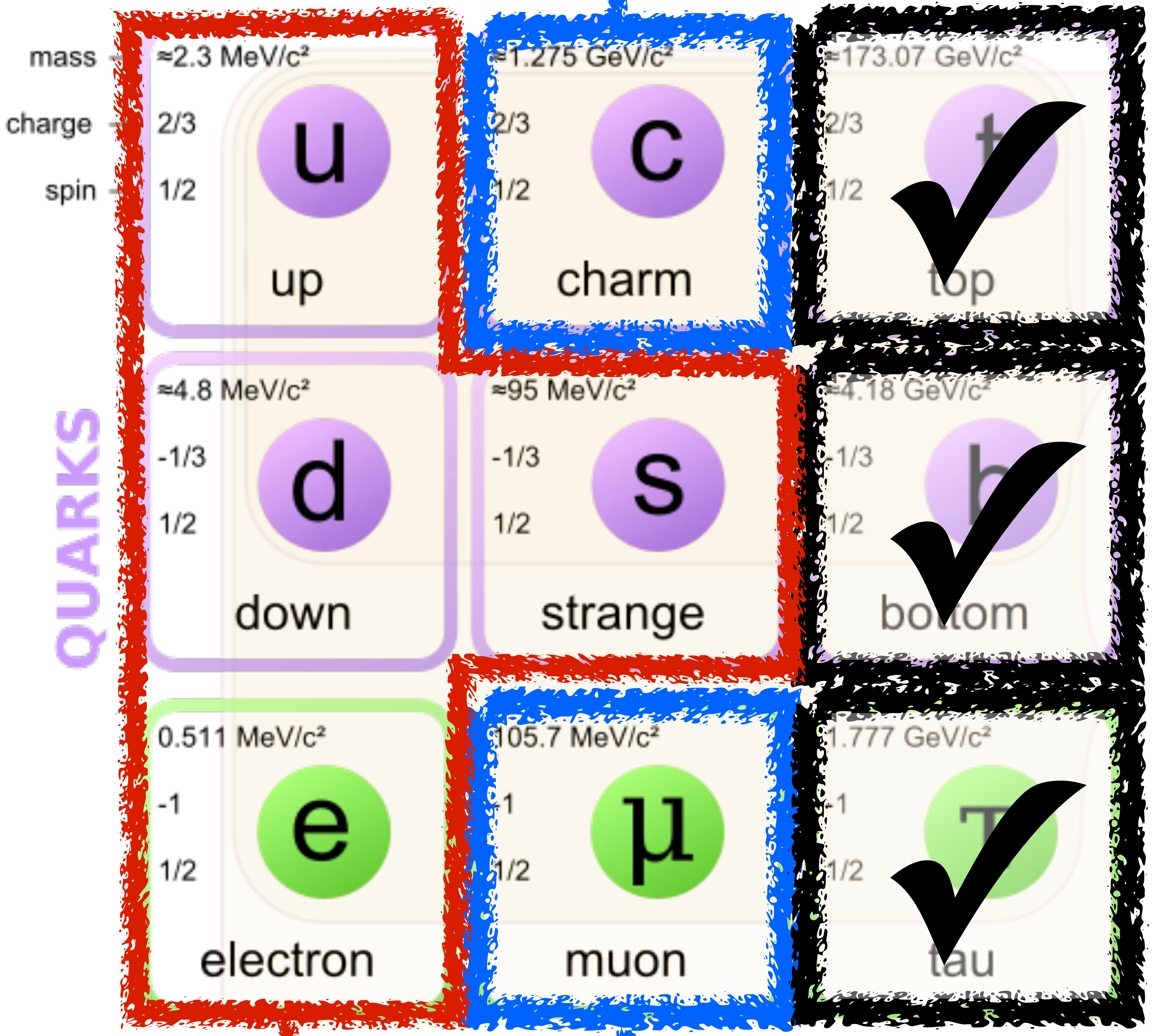


Which gives us the hydrogen atom,
& chemistry and biology as we know it

Yukawas

today: no evidence yet
(1 in 35 decays)
needs an e+e−
or ep collider

overall normalisation
(related to Higgs width):
needs an e+e− collider

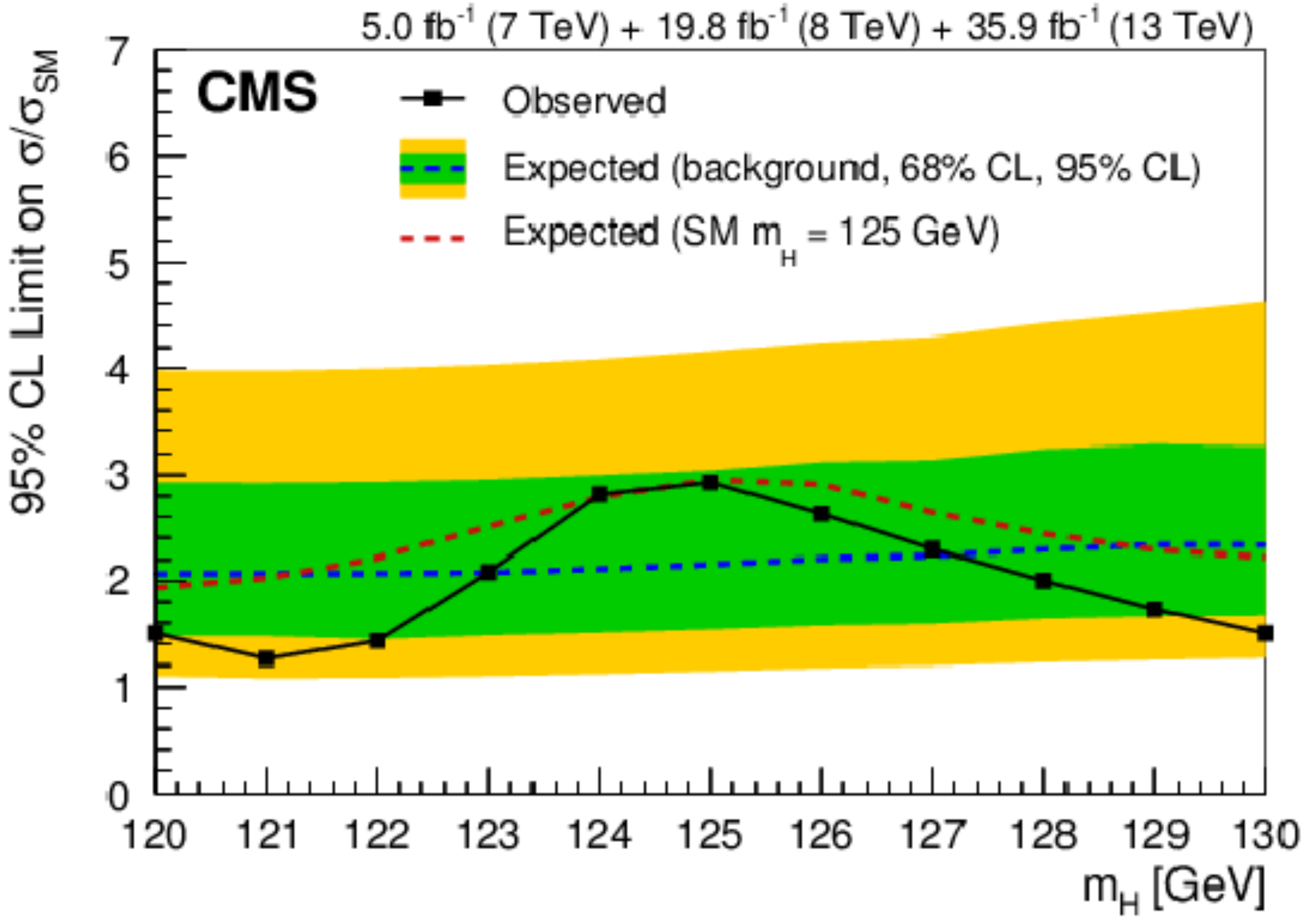


today: no evidence yet
(1 in 4000 decays)
no clear route to
establishing SM
couplings at 5σ

today: no evidence yet
(1 in 4570 decays)
observable at the LHC
within about 10 years.

by 2030: ~ 4σ evidence for 2nd generation Yukawa (H → μμ)

H→μμ

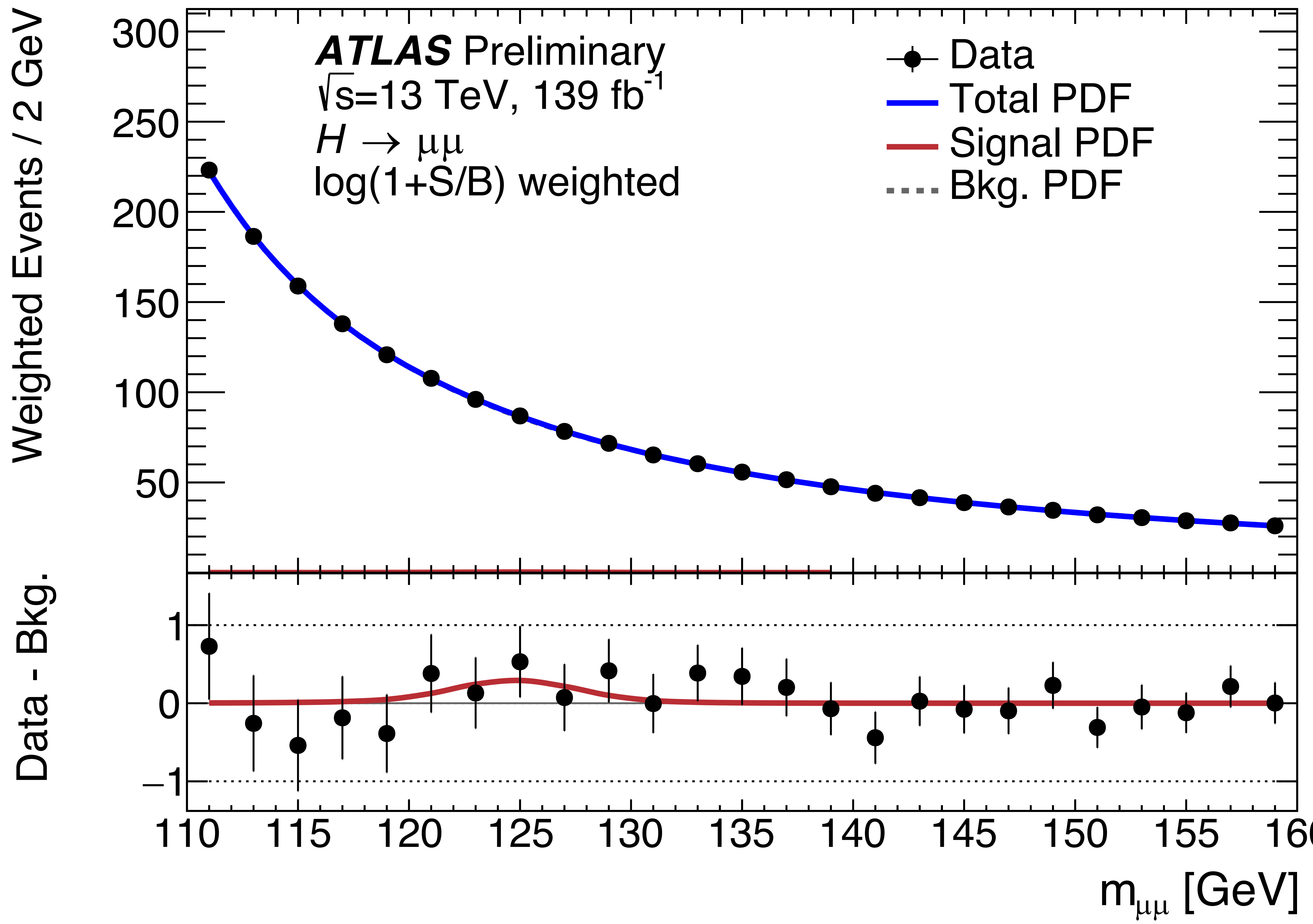


μ_{CMS}=1.0 ± 1.0(stat) ± 0.1(syst) (RunI+2016)

Obs.(exp.): 0.9 σ (1.0σ)

PhysRevLett.122.021801

- Expected sensitivity: 1.5σ, observed 0.8σ, σ(obs) / σ(SM) = 0.5 ± 0.7



ATLAS-CONF-2019-028

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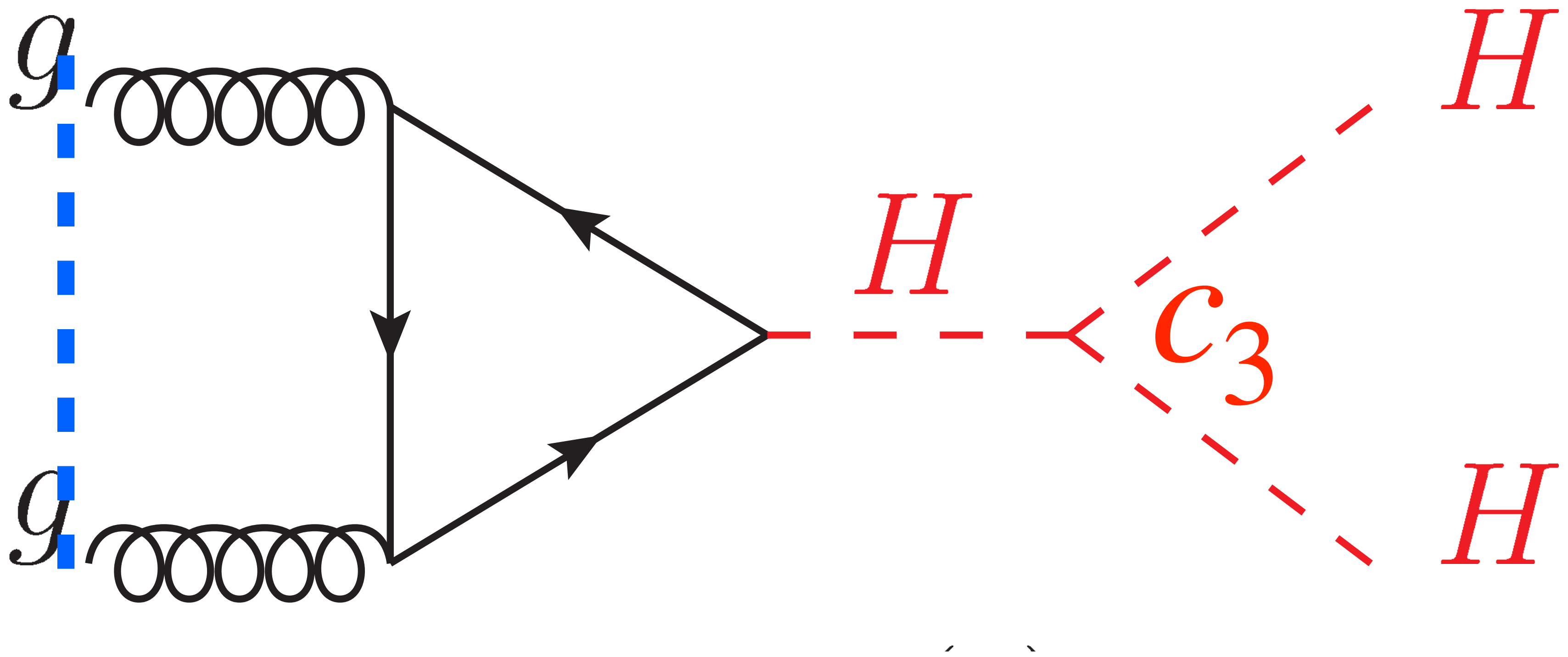
$$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \text{ ?}$$



Higgs precision today — ATLAS & CMS at ~ 8 – 10% level (theory at 5%)

ATLAS-CONF-2019-029: γγ channel

$\sigma_{\text{fid}} = 65.2 \pm 4.5\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 0.3\,(\text{theo.})\,\text{fb}\,,$ SM prediction of 63.6 ± 3.3 fb

CMS HIG-19-001-pas (137fb⁻¹): 4-lepton channel

$$\mu_{\text{inclusive}} = 0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$$

$$\sigma_{\text{fid.}} = 2.73^{+0.30}_{-0.29} = 2.73^{+0.23}_{-0.22}(\text{stat.})^{+0.24}_{-0.19}(\text{syst.})\text{ fb} \qquad \sigma^{\text{SM}}_{\text{fid.}} = 2.76 \pm 0.14\text{ fb}$$

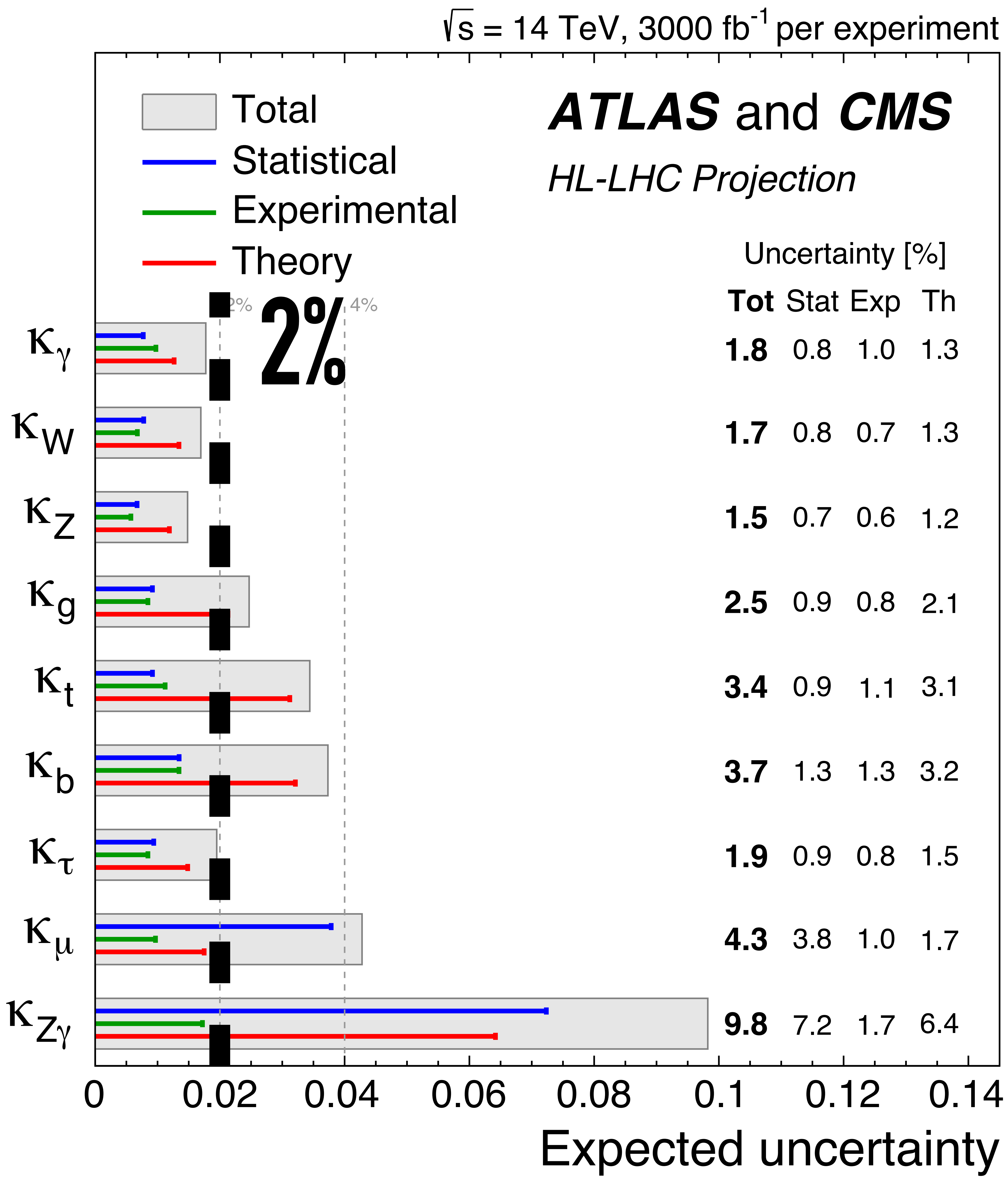
ATLAS 2019-025 (139fb⁻¹): 4-lepton channel

σ_{tot} [pb]	=	54.7	±4.9	±2.3	SM = 55.7 ± 2.8
σ_{sum} [fb]	=	3.24	±0.31	±0.11	SM = 3.41 ± 0.18

ATLAS 2019-032: γγ and 4-lepton channel

σ_{tot} [pb] $= 55.4^{+4.3}_{-4.2}$ pb ($\pm 3.1(\text{stat.})\,^{+3.0}_{-2.8}(\text{sys.})$) SM = 55.6 ± 2.5 pb

HL-LHC official Higgs coupling projections (by 2036)

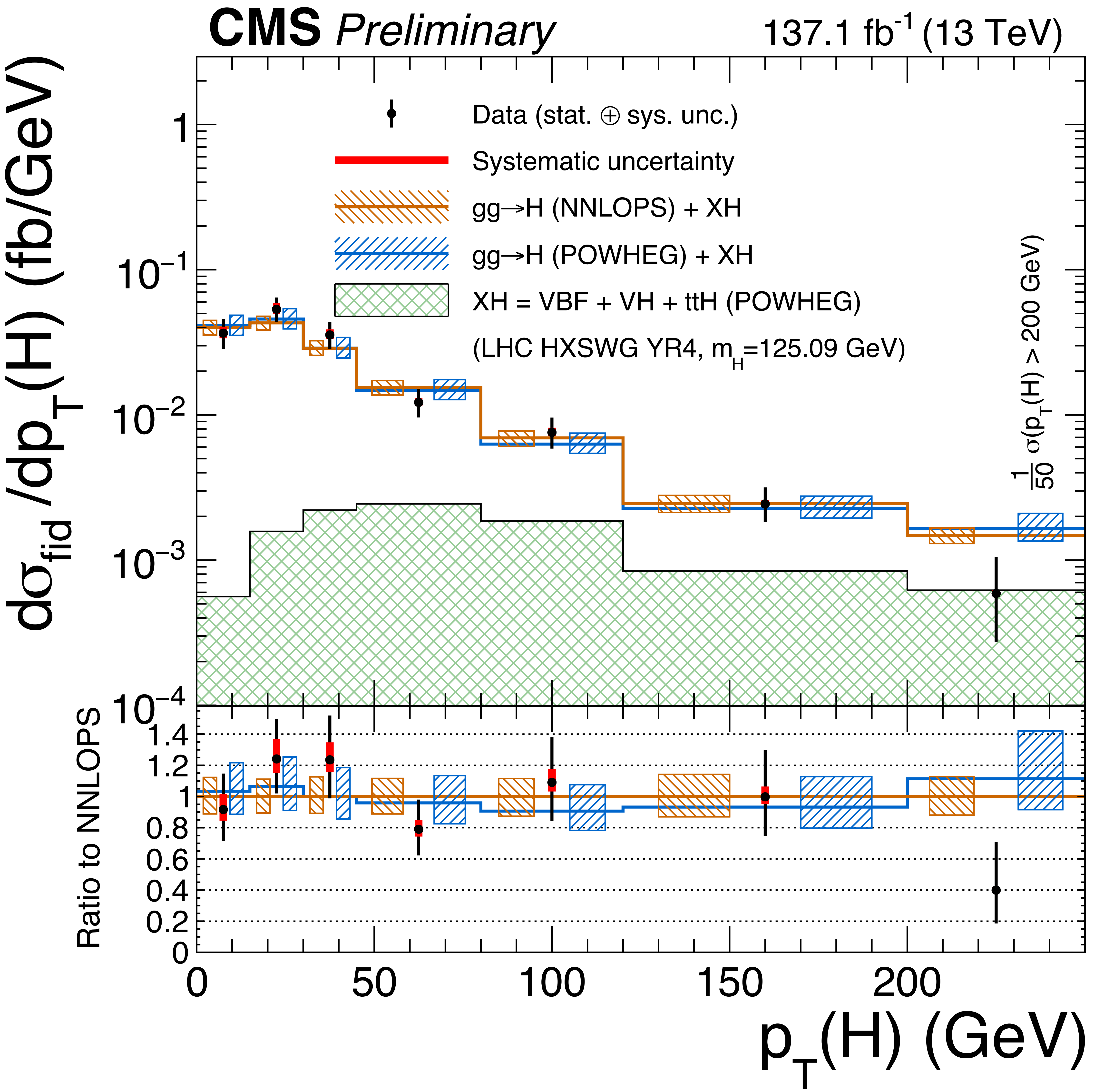


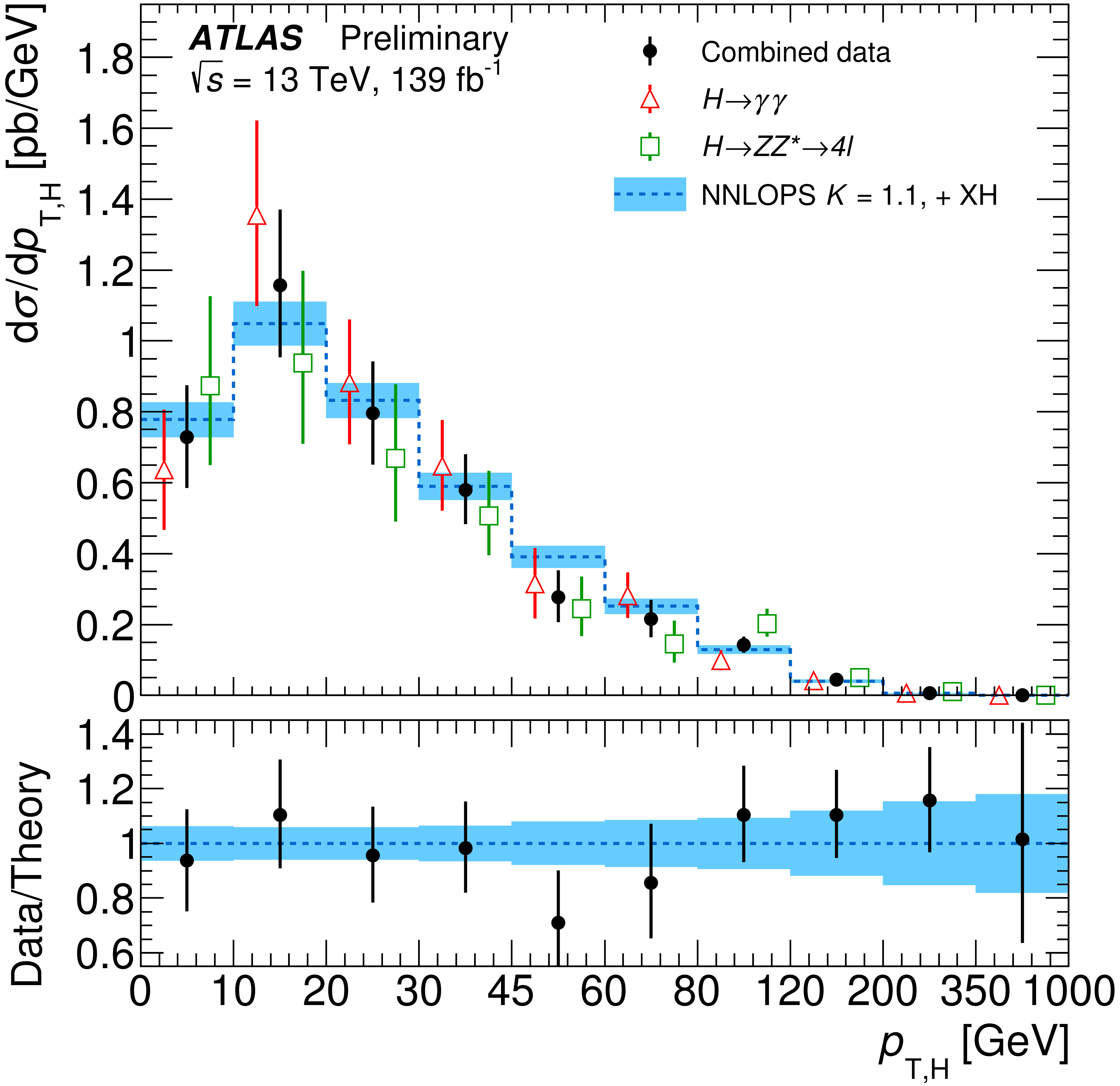
Right now, Higgs coupling precisions are in the 10% range.

We wouldn't consider electromagnetism established (textbook level) if we only knew it to 10%

HL-LHC can deliver 1–2% for a range of couplings

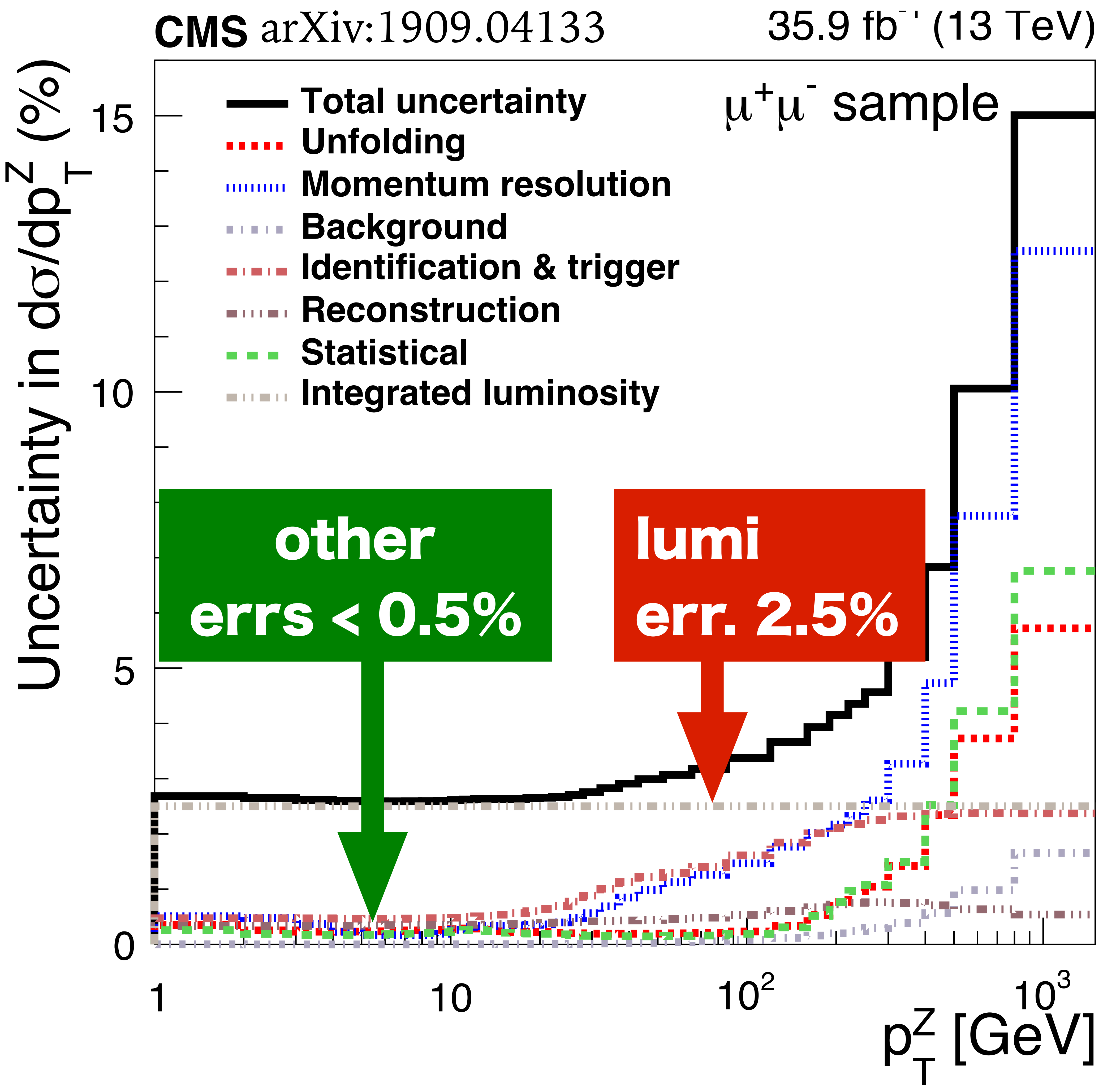
Higgs p_T distributions





LHC precision physics

Z production: playground for LHC precision



LHCb 13 TeV, 1607.06495

$$\sigma_Z^{\ell\ell} = 194.3 \pm 0.9 \pm 3.3 \pm 7.6\,\text{pb},$$

$\pm 0.5\%$ *(stat.)* $\pm 1.7\%$ *(exp.)* $\pm 3.9\,\%$ *(lumi.)*

ATLAS 8 TeV, 1512.02192

$m_{\ell\ell}$ [GeV]	66–116
$\sigma(Z/\gamma^* \to \ell^+\ell^-)$ [pb]	537.10
Statistical uncertainty [%]	0.03
Detector uncertainty [%]	0.40
Background uncertainty [%]	0.06
Model uncertainty [%]	0.19
Total systematic uncertainty [%]	0.45
Luminosity uncertainty [%]	**2.8**

Luminosity: LHCb is in the lead (at least with 8 TeV data)

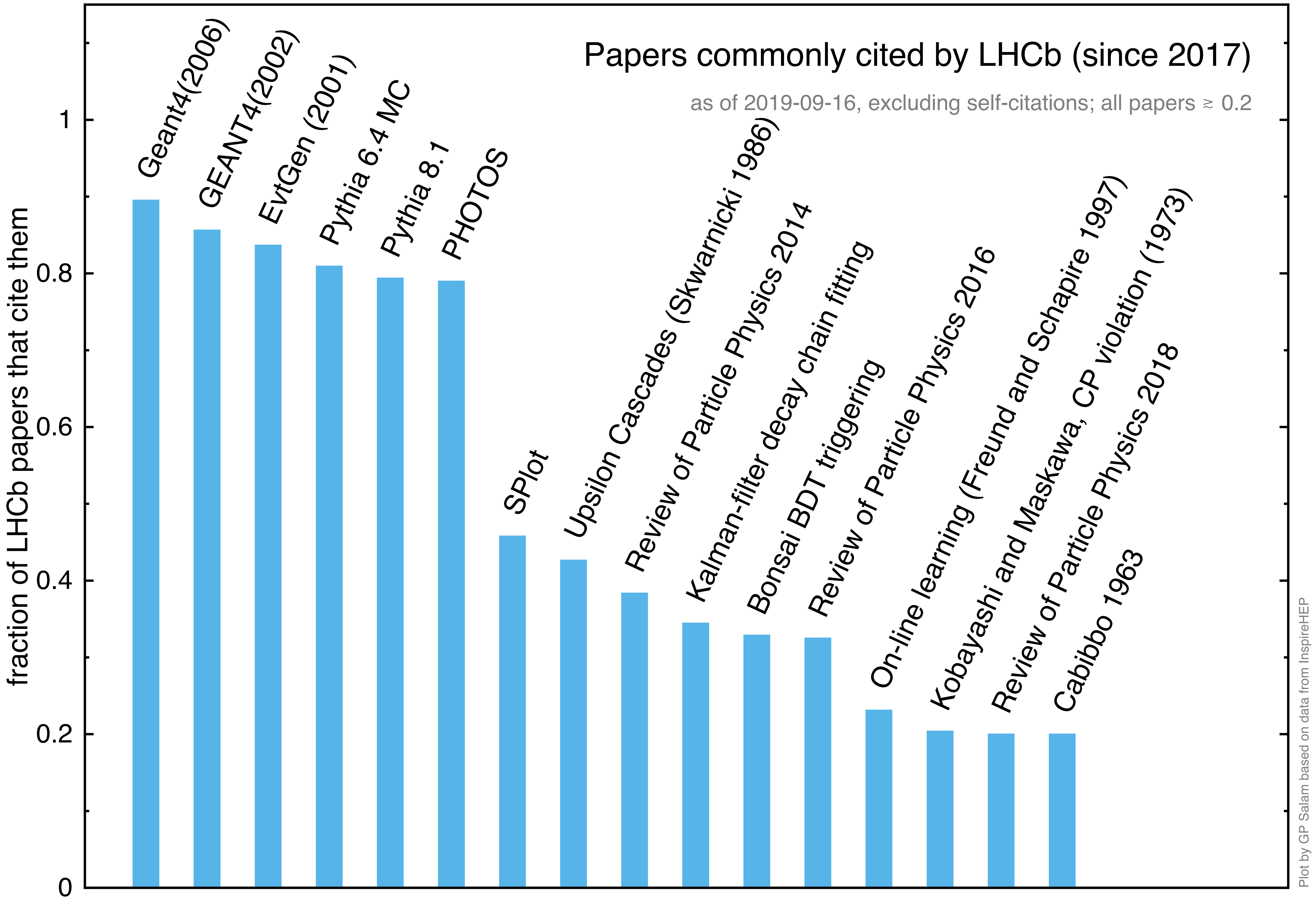
Experiment	ALICE	ATLAS	CMS		LHCb	
pp running period	2010	2012	2012		2012	
$\sqrt{s}$ (TeV)	7.0	8.0	8.0		8.0	
Absolute-calibration method	*vdM*	*vdM*	*vdM*	*vdM*	Combined	BGI
Calibration uncertainty $\Delta\,\sigma_{vis}/\,\sigma_{vis}$ (%)	3.5	1.2	2.3	1.47	1.12	1.43
μ or total–rate dependence (%)	-	1.4	< 0.1		0.17	
Long-term stability (%)	1.5	0.6	1.0		0.22	
Subtraction of luminosity backgrounds (%)	3.0	0.2	0.5		0.13	
Other luminosity-dependent effects (%)	1.5		0.5		-	
Total luminosity uncertainty (%)	5.0	1.9	2.6	1.5	1.2	1.5

→ Appdx

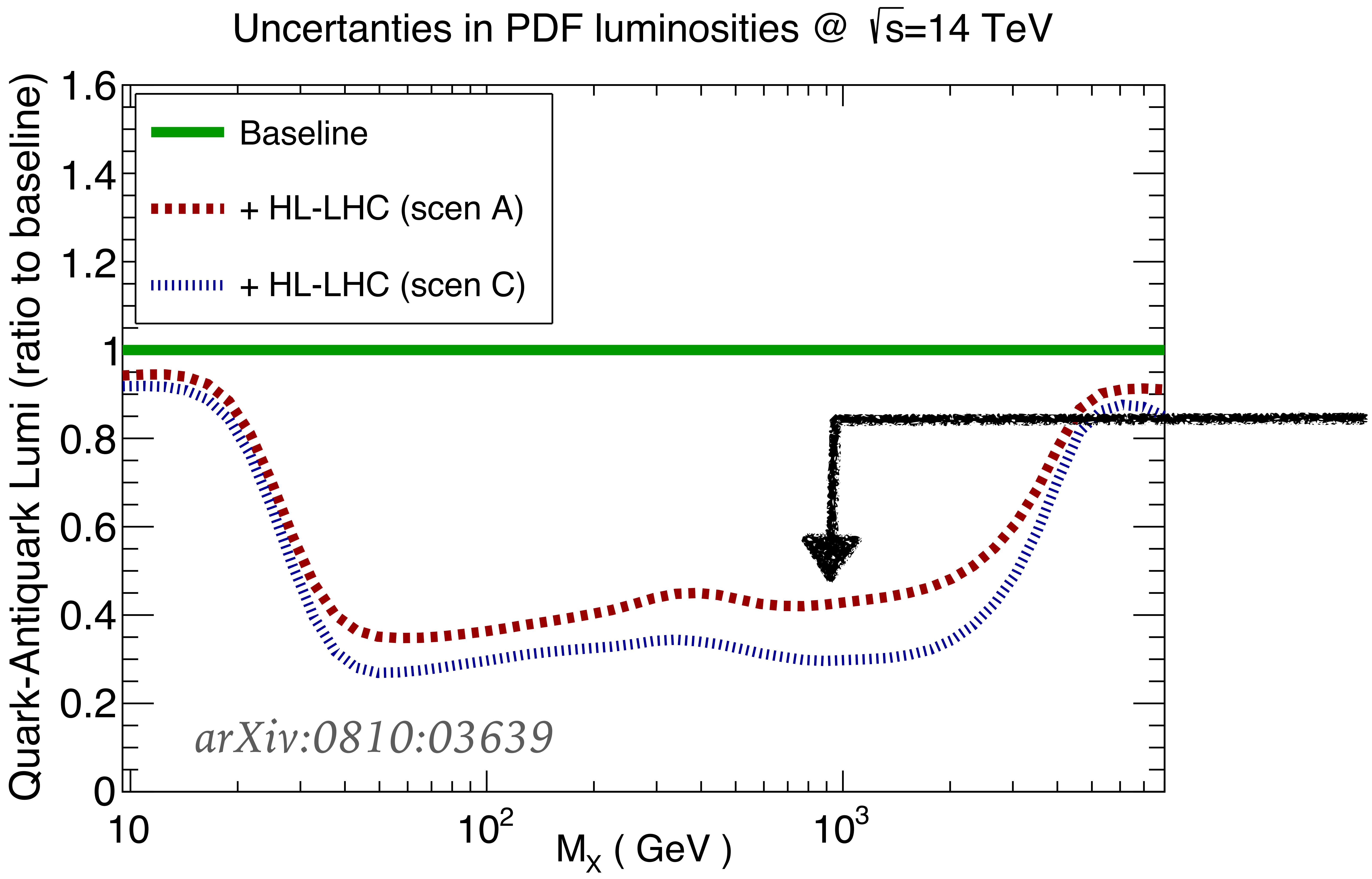
to what extent can (should) luminosity determination be transferred & combined between LHC experiments?

progress in precision will require advances on a whole **ecosystem** of tools

corresponding LHCb plot

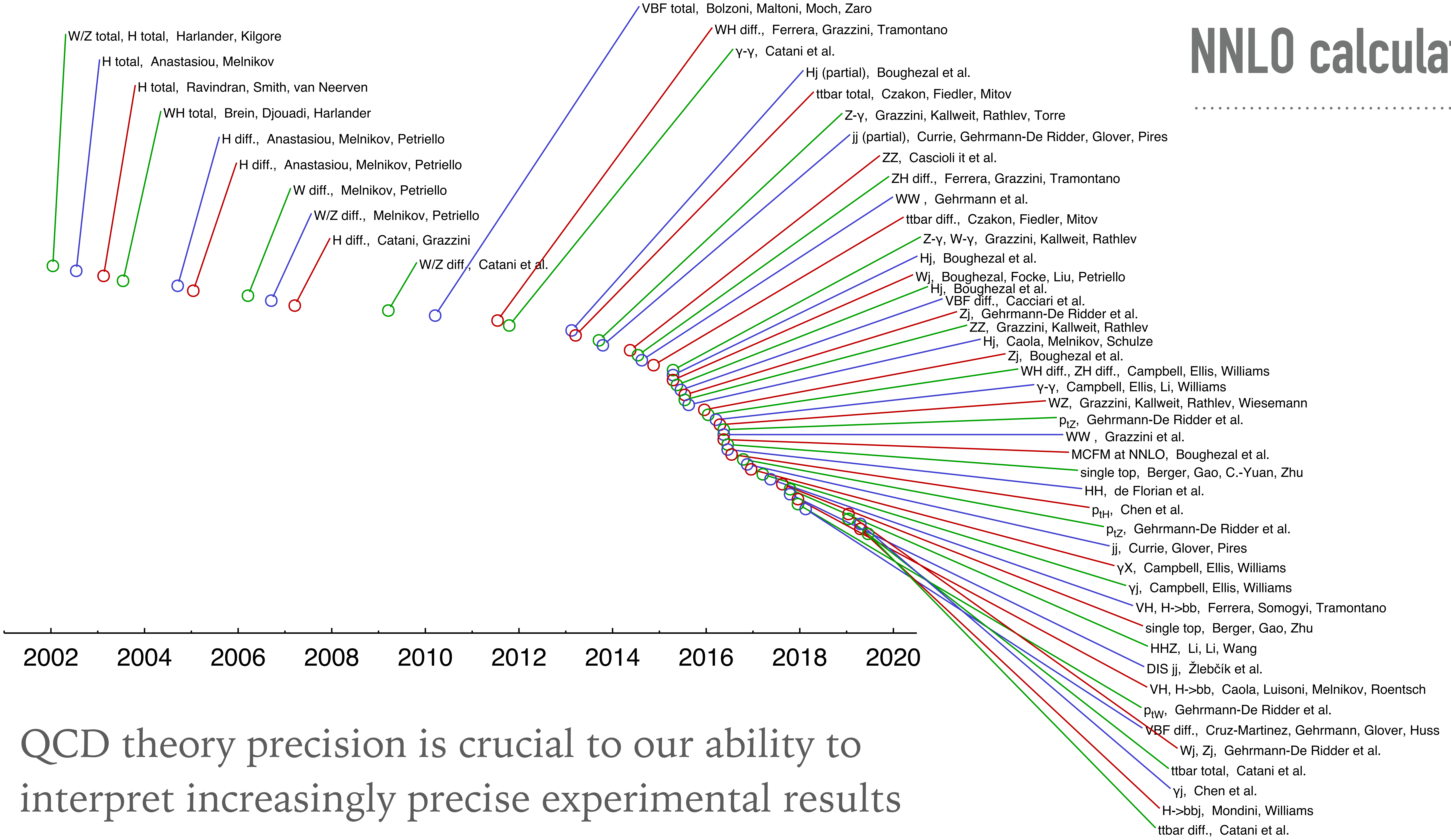


likely progress in PDFs



up to $\times 2$ reduction in uncertainty on partonic luminosities (e.g. # of quark-antiquark collisions)
relative to today's PDFs

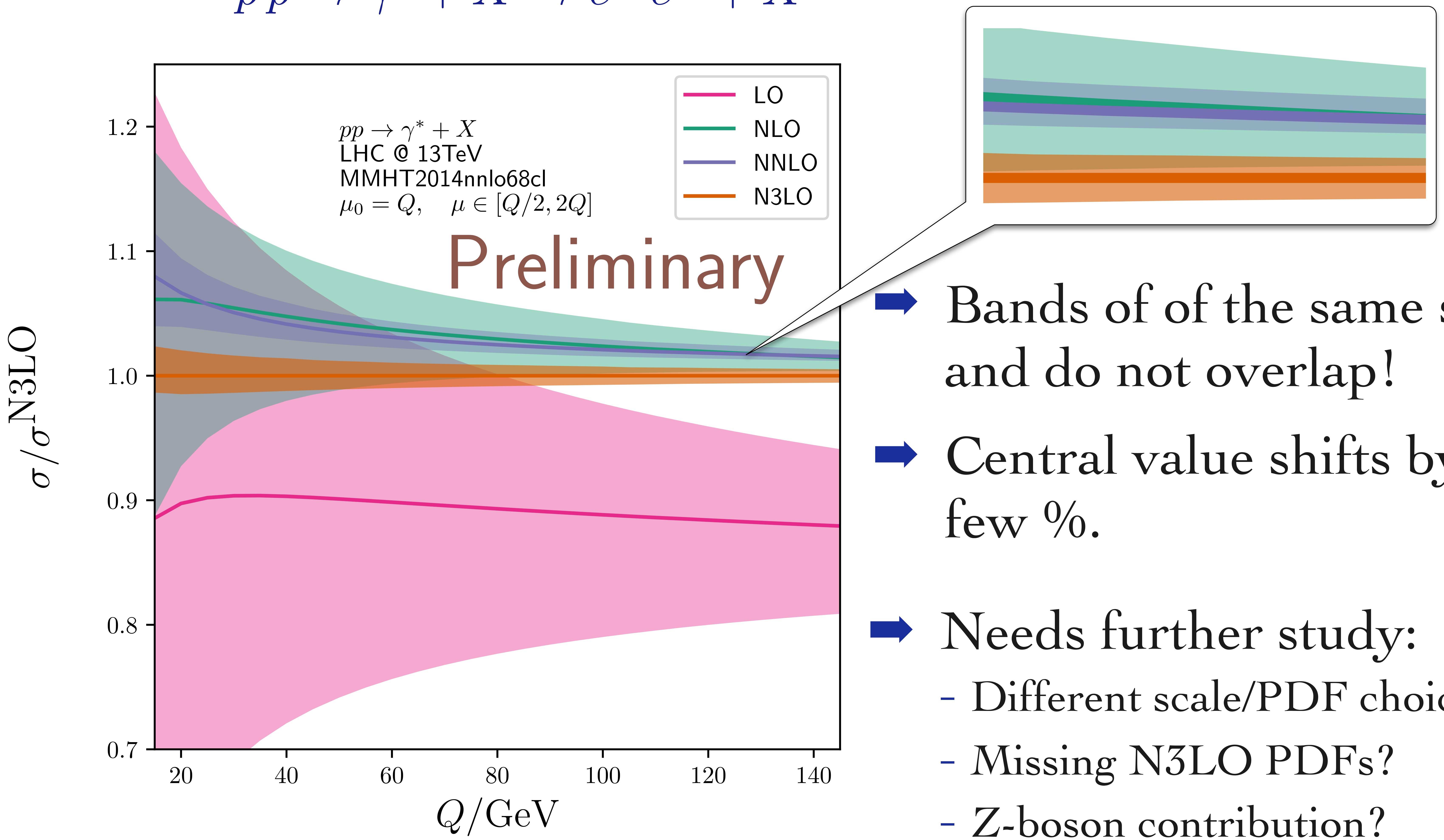
NNLO calculations



QCD theory precision is crucial to our ability to interpret increasingly precise experimental results

The dawn of N3LO

$$pp \to \gamma^* + X \to e^+ e^- + X$$



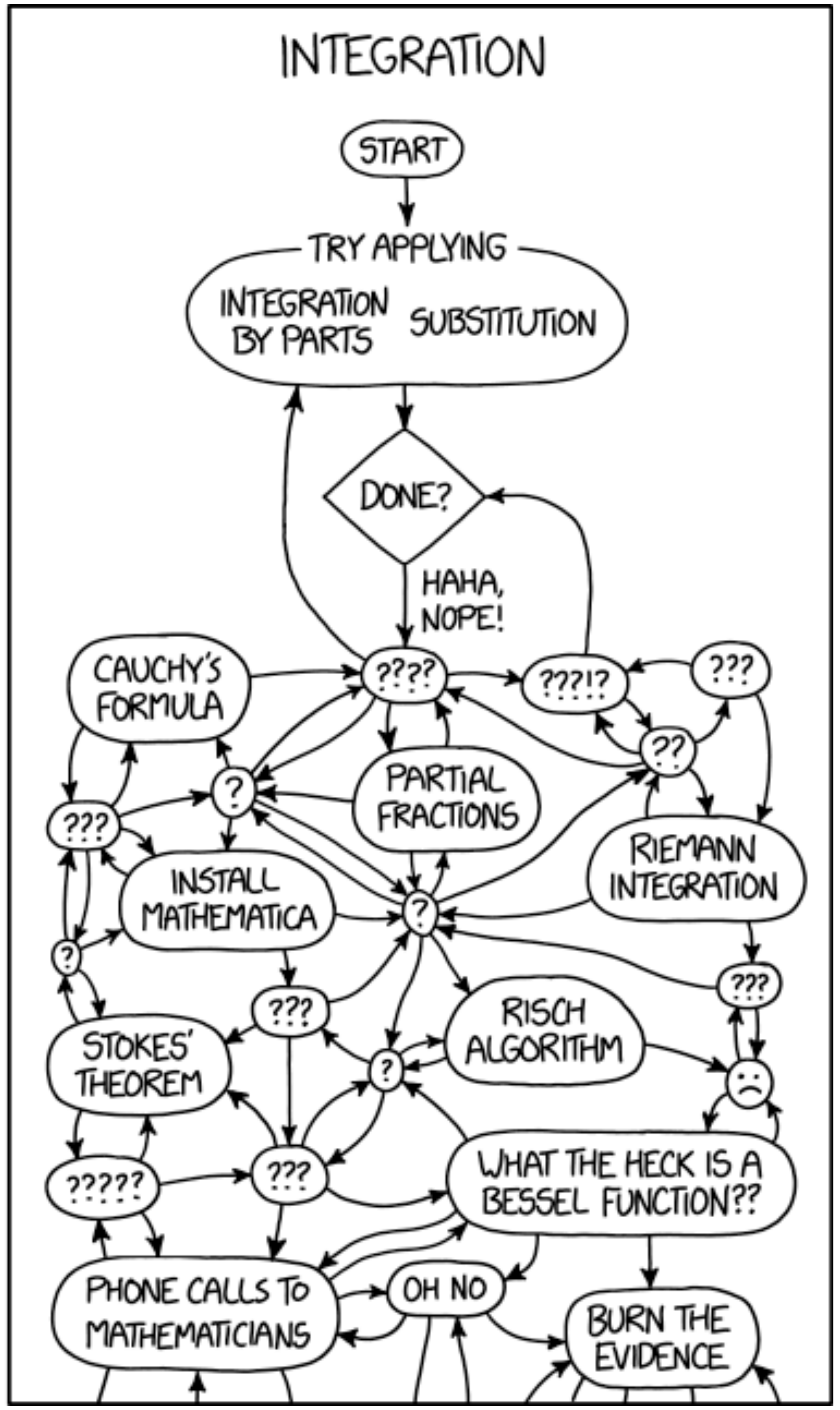
[CD, Dulat, Mistlberger (2019, to appear)]

➡ Bands of of the same size and do not overlap!

➡ Central value shifts by a few %.

➡ Needs further study:

- Different scale/PDF choices?
- Missing N3LO PDFs?
- Z-boson contribution?

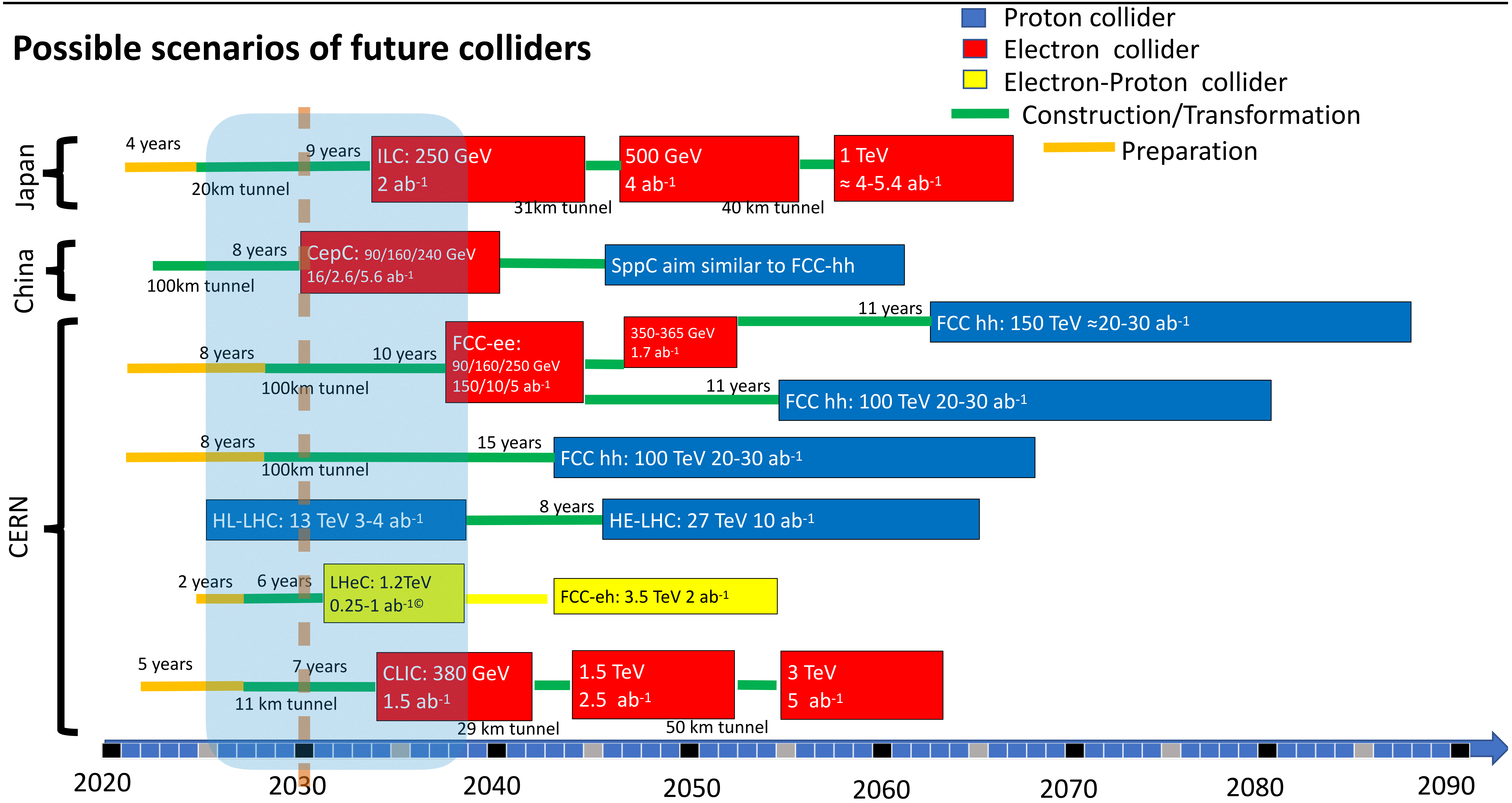


[© xkcd.com]

Looking beyond the 2020s

the decisions of the next years may well set the course for our field for the next few decades

Possible scenarios of future colliders



Granada, Open Symposium - Update of the European Strategy for Particle Physics (S. Bethke) 13/05/2019 UB arXiv:1909.04437

Future High Energy Circular e^+e^- Collider using Energy-Recovery Linacs

Vladimir N Litvinenko[1,2], Thomas Roser[2] and Maria Chamizo Llatas[3]

[1] Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA

[2] Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY, USA

[2] Nuclear and Particle Physics Directorate, Brookhaven National Laboratory, Upton, NY, USA

In this paper we present alternative approach for Future Circular electron-positron Collider. Current 100 km circumference design with the top CM energy of 365 GeV (182.5 GeV beam energy) is based on two storage rings to circulate colliding beams [1-2]. One of the ring-ring design shortcomings is enormous power consumption needed to compensate for 100 MW of the beam energy losses for synchrotron radiation. We propose to use energy recovery linac located in the same tunnel to mitigate this drawback. We show in this paper that our approach would allow a significant – up to an order of magnitude – reduction of the beam energy losses while maintaining high luminosity in this collider at high energies. Furthermore, our approach would allow to extend CM energy to 500 GeV (or above), which is sufficient for double-Higgs production.

how do we balance the need to settle long-term plans with the potential for new ideas to change the landscape of options?

Conclusions

"

I personally expect supersymmetry to be discovered at the LHC

-a Nobel prize-winning theorist [2008]

What can we hope to know by the end of 2020's

- fate of anomalies: flavour & muon g-2
- neutrinos: much more complete picture including mass hierarchy
- Higgs
  - below 5% for inclusive Higgs → we'll see how we're doing with systematics…
  - $H \to \mu\mu$ @ 4σ
  - high-p_T Higgs
- direct new-physics reach → **increased especially for more weakly coupled states**
- innovative small experiments, e.g. for axion searches
- continued "encroachment" of LHC experiments on each other's territory (including heavy-ion collisions) & the transition of LHC to a precision machine
- We will have a picture of the future landscape of HEP (we must settle our differences…)

Scope for surprises?

- The LHC experiments probably cover O(1000) different channels (cf. the 704 of the general search) with O(30 $\times$) more data
- Probably O(100) additional channels / regions covered by other experiments

We're giving ourselves a good chance of gaining direct clues about the big "unanswered" questions.

But whether or not we discover "new physics", we are making advances. Knowledge of the SM's range of validity & confidence in our understanding of its fundamental interactions is a legacy in its own right.