E I S A
European Institute for Sciences and Their Applications

Corfu2024 Workshop on Future Accelerators
19-26 May 2024

Summary and outlook

Michelangelo L. Mangano
TH Department
CERN


The future starts today, not tomorrow.
Pope John Paul II
BrainyQuote


The future starts
on July 4, 2012 ~~today~~, not
tomorrow.
Pope John Paul II
BrainyQuote

55 talks ~ 39 hrs ⇒

1 min of summary / 1 hr of talks

NB: Not a real conference summary, but a story build around the material that (I believe) I understood and that mostly resonated with my own perspective …

No time/expertise to present technical details, just a sort of collection of take-home messages …

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A possible thread to organize and decipher the ***overwhelming amount*** of material presented this week

- **Where we are => LHC status**
- **Where we know we're going => HL-LHC**
- **A diverse landscape**
- **Where we'd like to go next**
  - **The opportunities**
  - **The physics context:**
    - *guaranteed deliverables*
    - *exploration*
  - **The challenges:**
    - *accelerators*
    - *detectors*
    - *theory*
- **The strategic assessment**

Where we are => LHC status

Higgs Physics: current status and prospects from the experiment side, T.Qiu

Electroweak physics: current status and prospects from the experiment side, R. Bellan

QCD/top physics: current status and prospects from the experiment side, S. Kluth

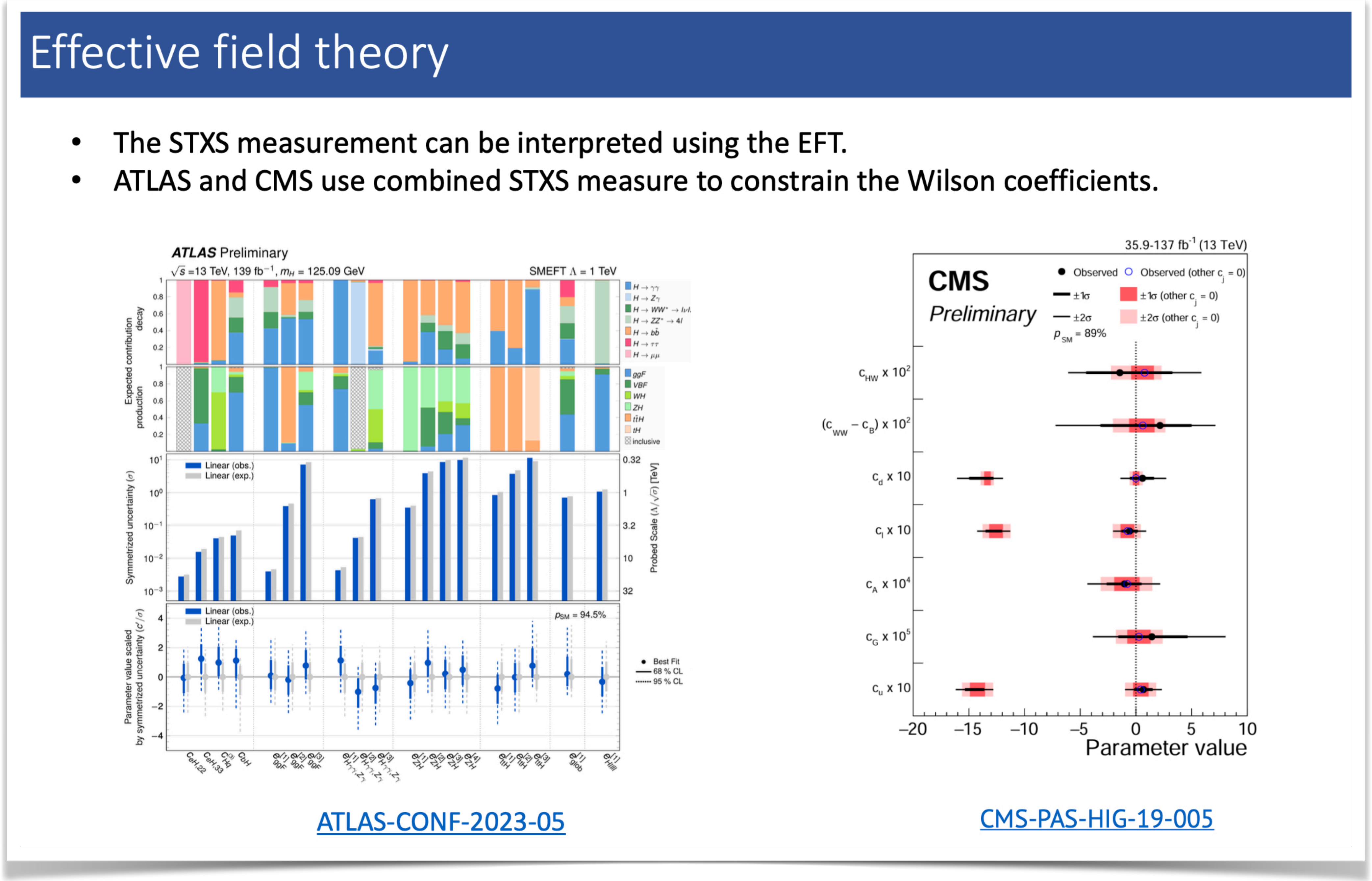
Status and prospects of the flavour physics experimental programme, M. Pepe-Altarelli

Highlights and future perspectives of LHC experiments, J.Jovicevic

Using collider systems to search for new physics, J. Pinfold

Heavy ion physics: current status and prospects at future accelerators, A. Soto Ontoso

Tong Qiu: Higgs physics

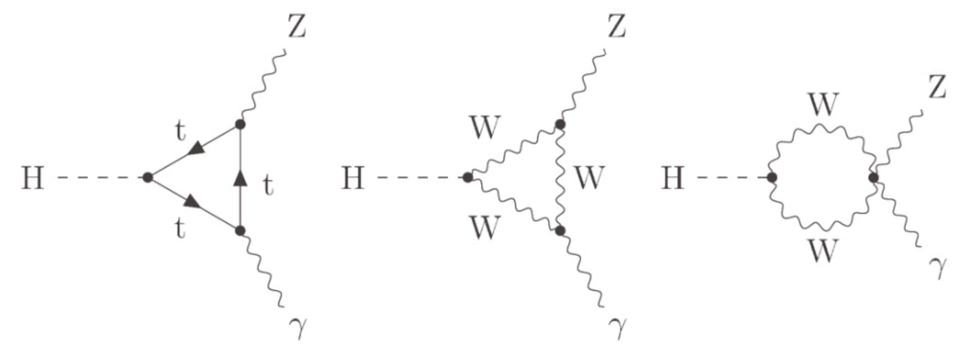


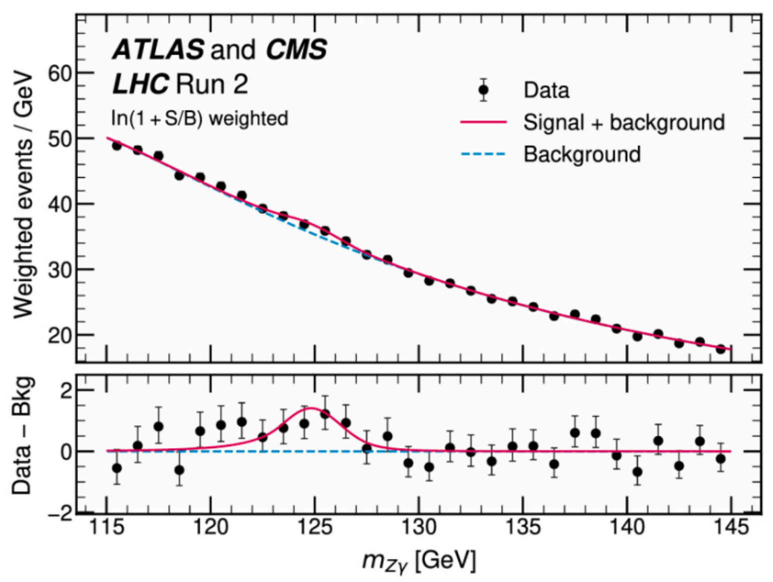
exploration of arbitrary SM deviations of Higgs behaviour: no anomalies to report

Tong Qiu: Higgs physics

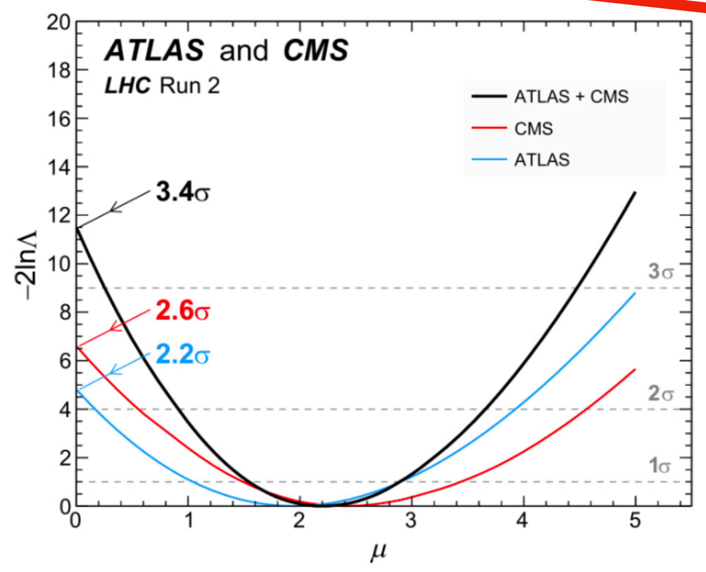
Higgs decays into $Z\gamma$

- $H \rightarrow Z\gamma$ decay has a small branching ratio (1.5×10^{-3}) in the Standard Model.
- Many BSM scenarios increase the branching ratio.
- ATLAS and CMS searched for $H \rightarrow Z\gamma$ where the Z decays into electrons or muons. Results combined.
  - observed event yield: 2.2 ± 0.7 times SM prediction
  - observed (expected) local significance: 3.4σ (1.6σ)





PhysRevLett.132.021803



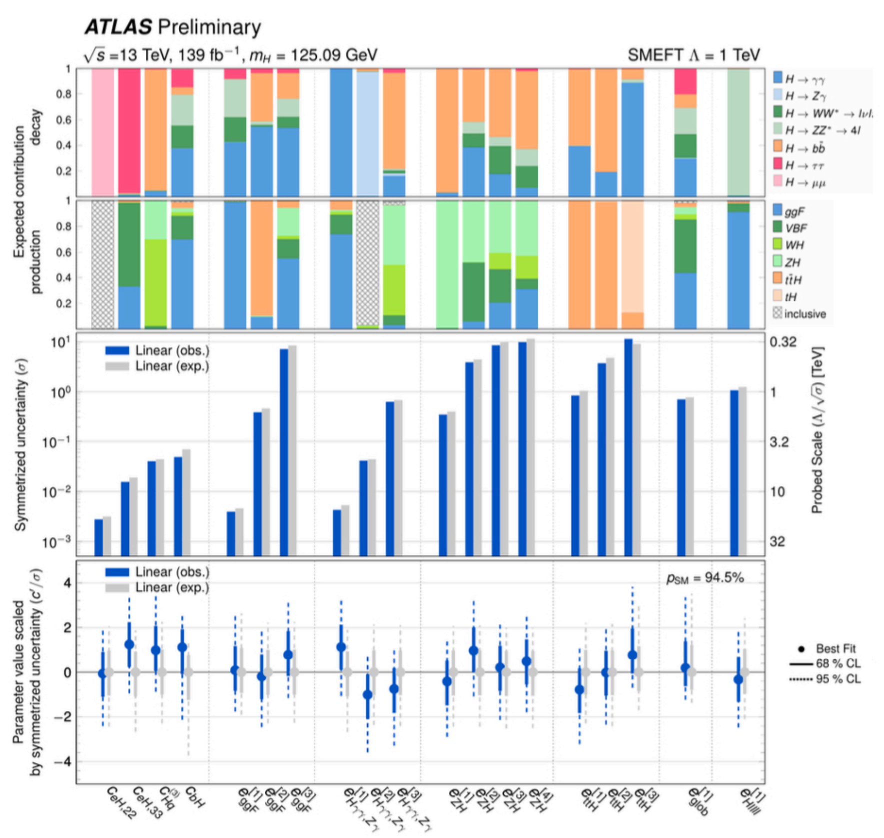
PhysRevLett.132.021803

21

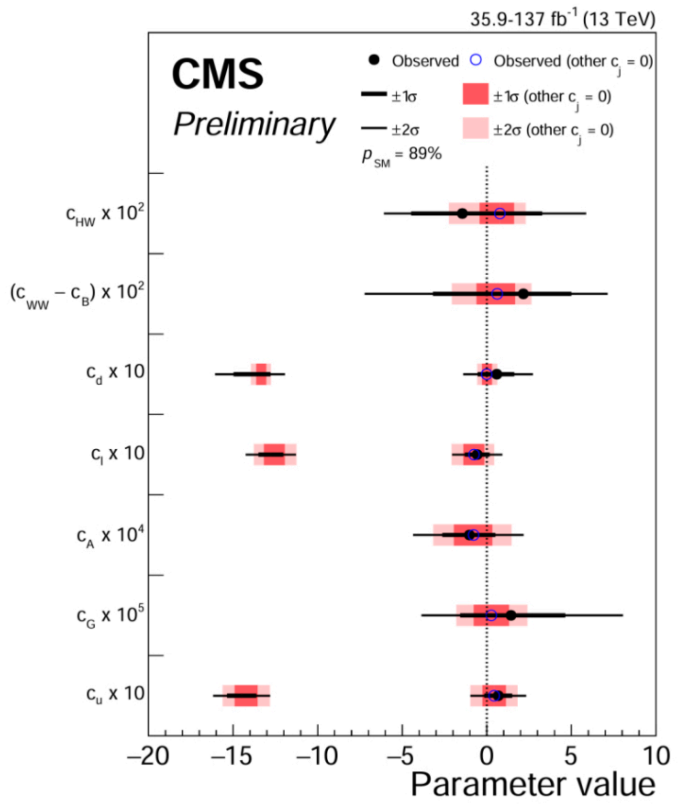
if this is real, HL-LHC will fully confirm it

Effective field theory

- The STXS measurement can be interpreted using the EFT.
- ATLAS and CMS use combined STXS measure to constrain the Wilson coefficients.



ATLAS-CONF-2023-05



[CMS-PAS-HIG-19-005](CMS-PAS-HIG-19-005)

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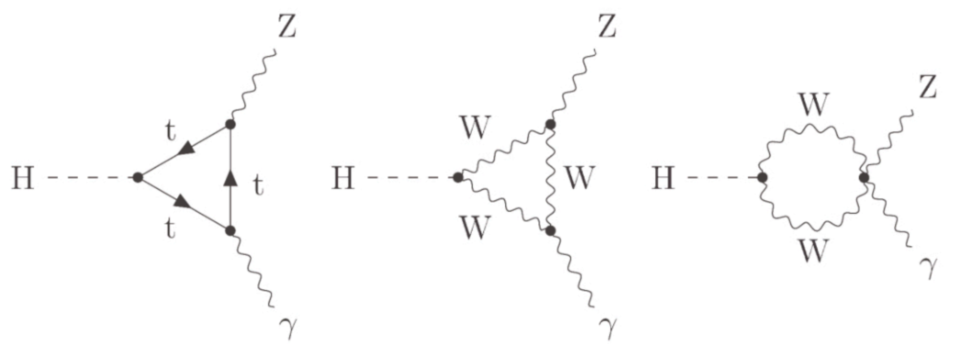

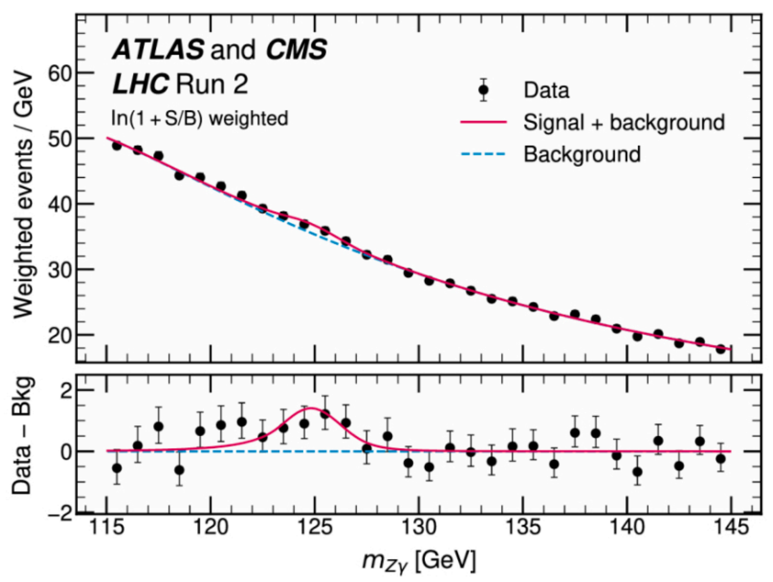

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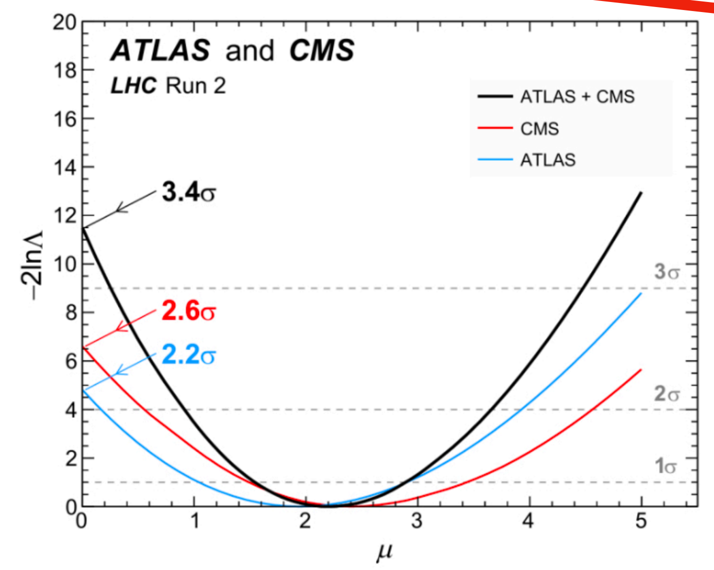

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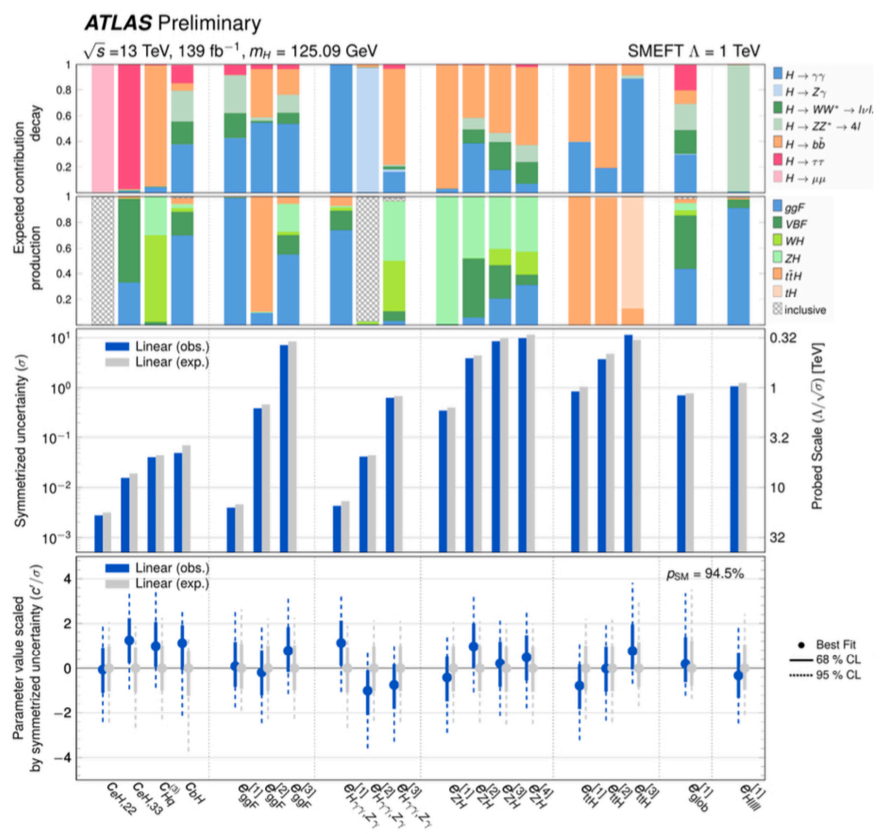
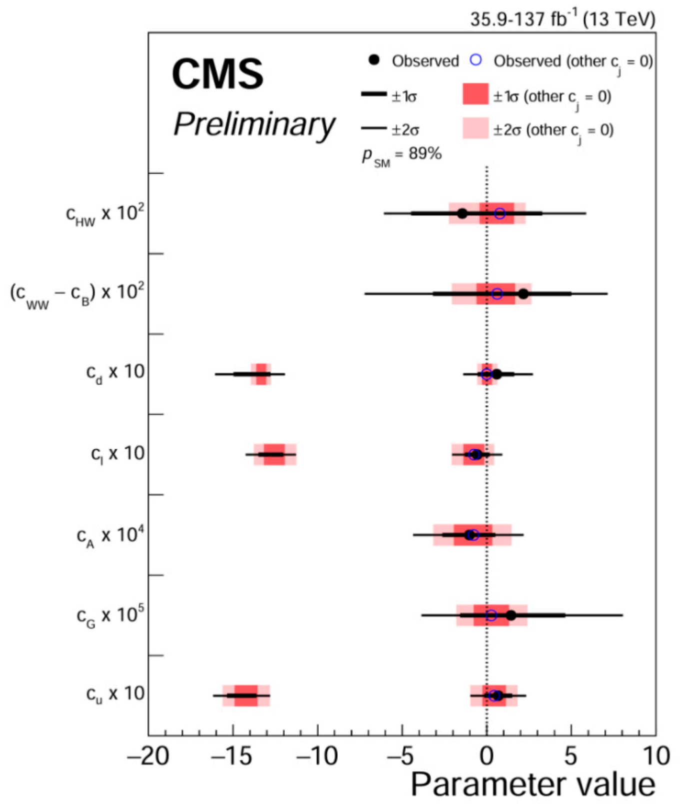


ATLAS-CONF-2023-05



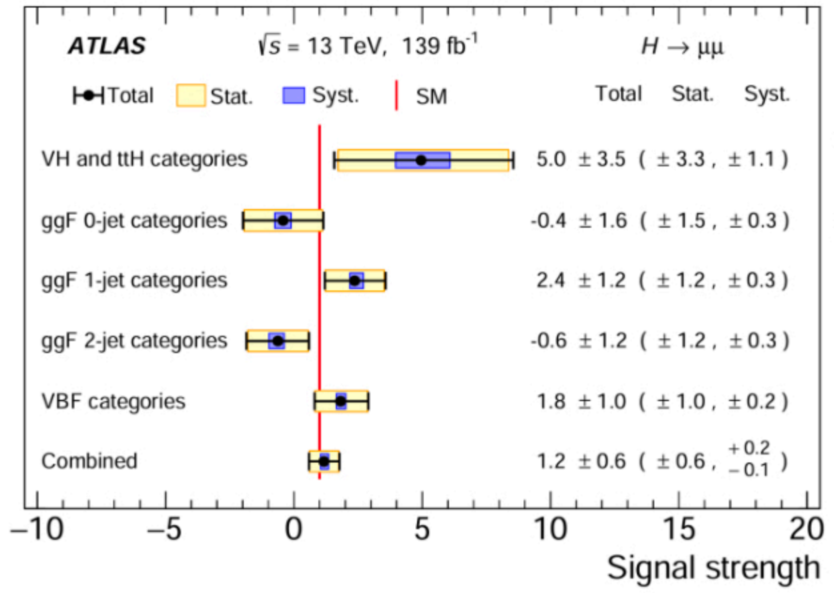
CMS-PAS-HIG-19-005

exploration of arbitrary SM deviations of Higgs behaviour: no anomalies to report

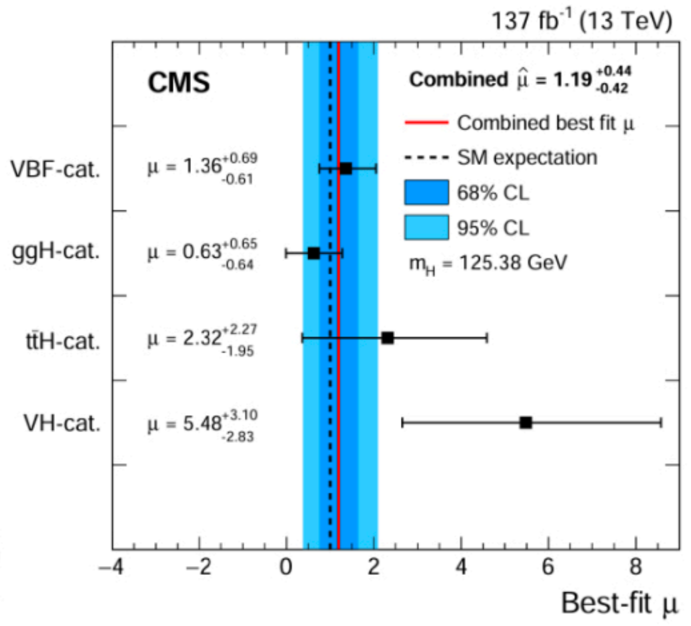
At what level does a "small" deviation in the Hμμ coupling become interesting from the model-building perspective?
Are there justified precision "targets"?

H → μμ searches

- Search for ggH, VBF, VH, ttH production.
- Observed (expected) significance
  - ATLAS: 2.0σ (1.7σ)
  - CMS: 3.0σ (2.5σ)



arXiv:2007.07830



arXiv:2009.04363

- Extensive and diverse research program from both ATLAS and CMS
- New taggers, triggers and techniques to improve sensitivity and constrain previously non-accessible parameter space

ATL-PHYS- PUB-2023-008

https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/

(not exhaustive) Overview of latest results!

* BSM H/A -> tt [ATLAS-CONF-2024-001]
* A-> ZH-> lltt [CMS-PAS-B2G-23-006]
* A-> ZH-> 4l+jj/MET [https://arxiv.org/abs/2401.04742]
* H/A -> 4top [ATLAS-CONF-2024-002]
* HNL via WW scattering in ee, eμ final states [EXOT-22-019]
* HNL in final states with e, μ, hadronic τ [EXOT-22-011]
* Search for heavy long-lived charged particles [CMS-PAS-EXO-18-002]
* light LLP with displaced vertices [2403.15332 **[hep-ex]**]
* LQ pair —> b mu b mu [CERN-EP-2023-301]
* 3rd gen. LQ pair production [CERN-EP-2023-288]
* Combination of heavy spin-1 resonances [EXOT-2022-38]
* High-mass reso —> τ+MET [EXOT-2018-37]
* Search for a resonance decaying to Wγ [PAS-EXO-21-017]
* Search for resonances decaying to HH [CERN-EP-2024-062]
* Mono-top [EXOT-2022-40]
* Search for mass-degenerate Higgsinos [2401.14046 [hep-ex]]
* Model-agnostic search with dijet resonances [CMS-PAS-EXO-22-026]

only one SUSY-related search! but an important one … more on this later …

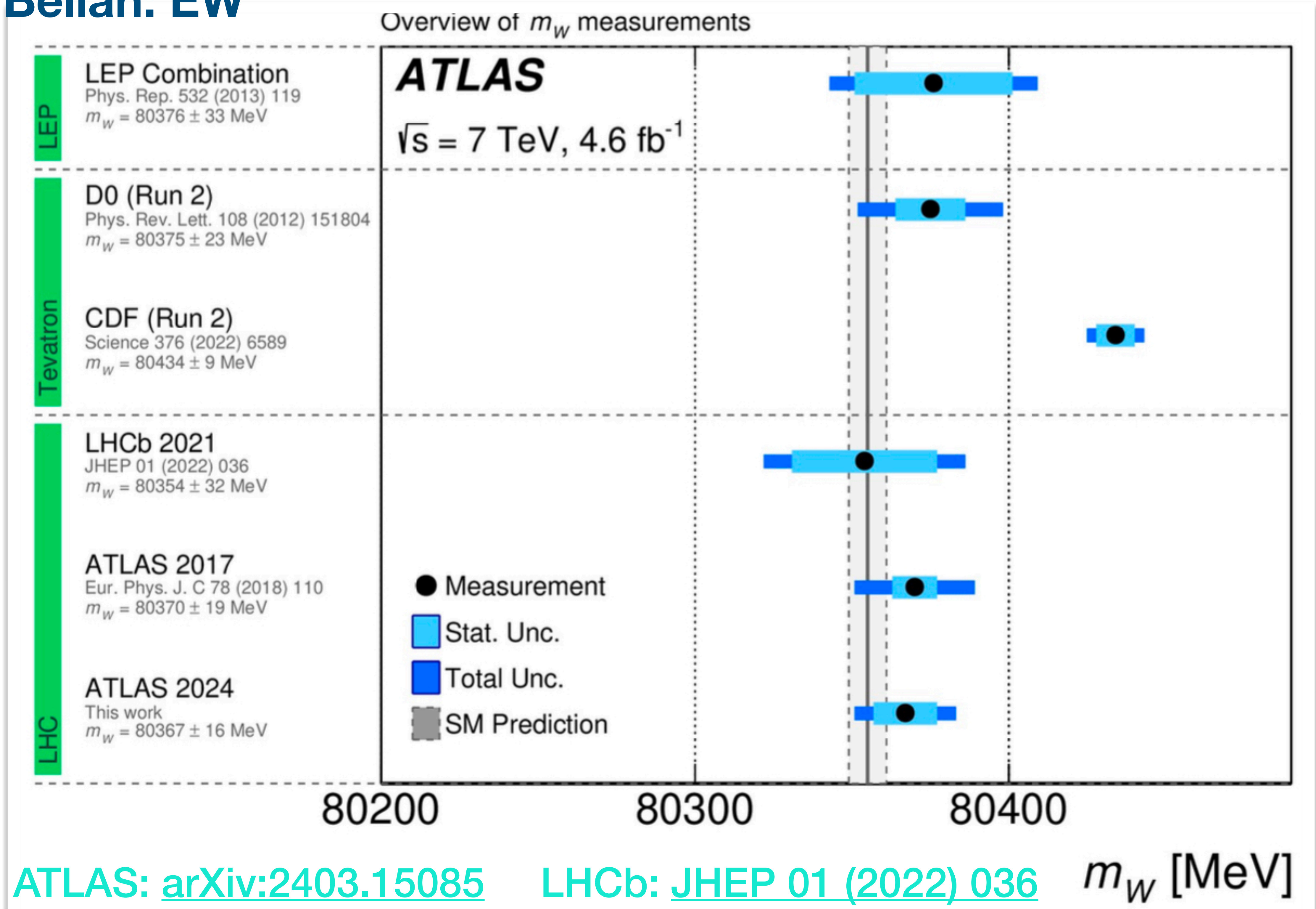
Message

- Innovation with detector upgrades, trigger evolution and analysis techniques can boost by large factors acceptance, efficiency and S/B for key searches ⇒ the growth from 300 to 3000 fb^{-1} can increase the statistical reach by much more than x10
- No evidence for saturation in the degree of ingenuity and range of opportunities for exotics searches: a continuously compelling and motivating research goal for young researchers

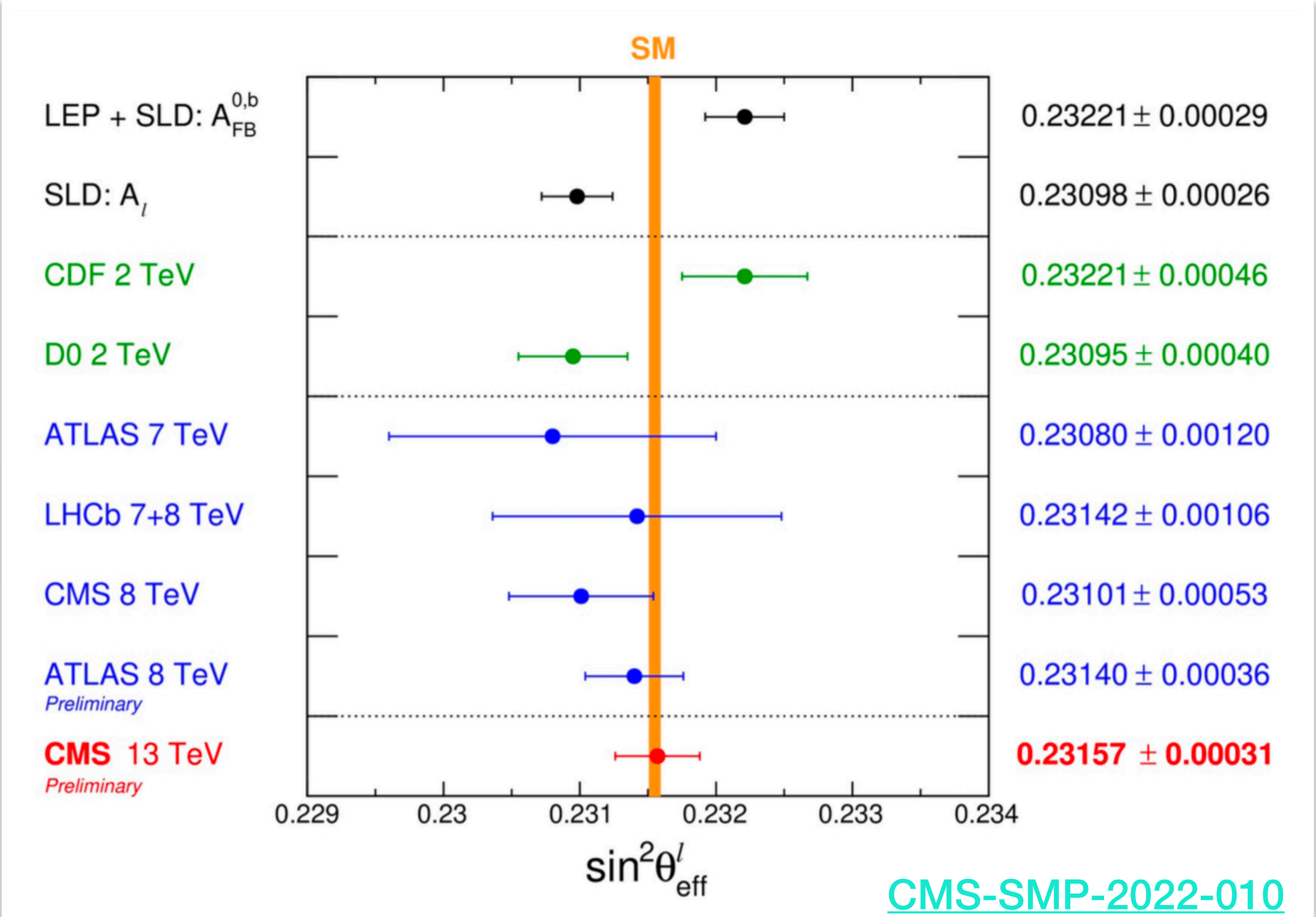
Overview of CMS HNL results

Summary tables like this one used to be enough to cover most exotica searches, from SUSY to new gauge bosons or compositness…. now it takes a full table just to summarize results of searches for heavy neutral leptons!

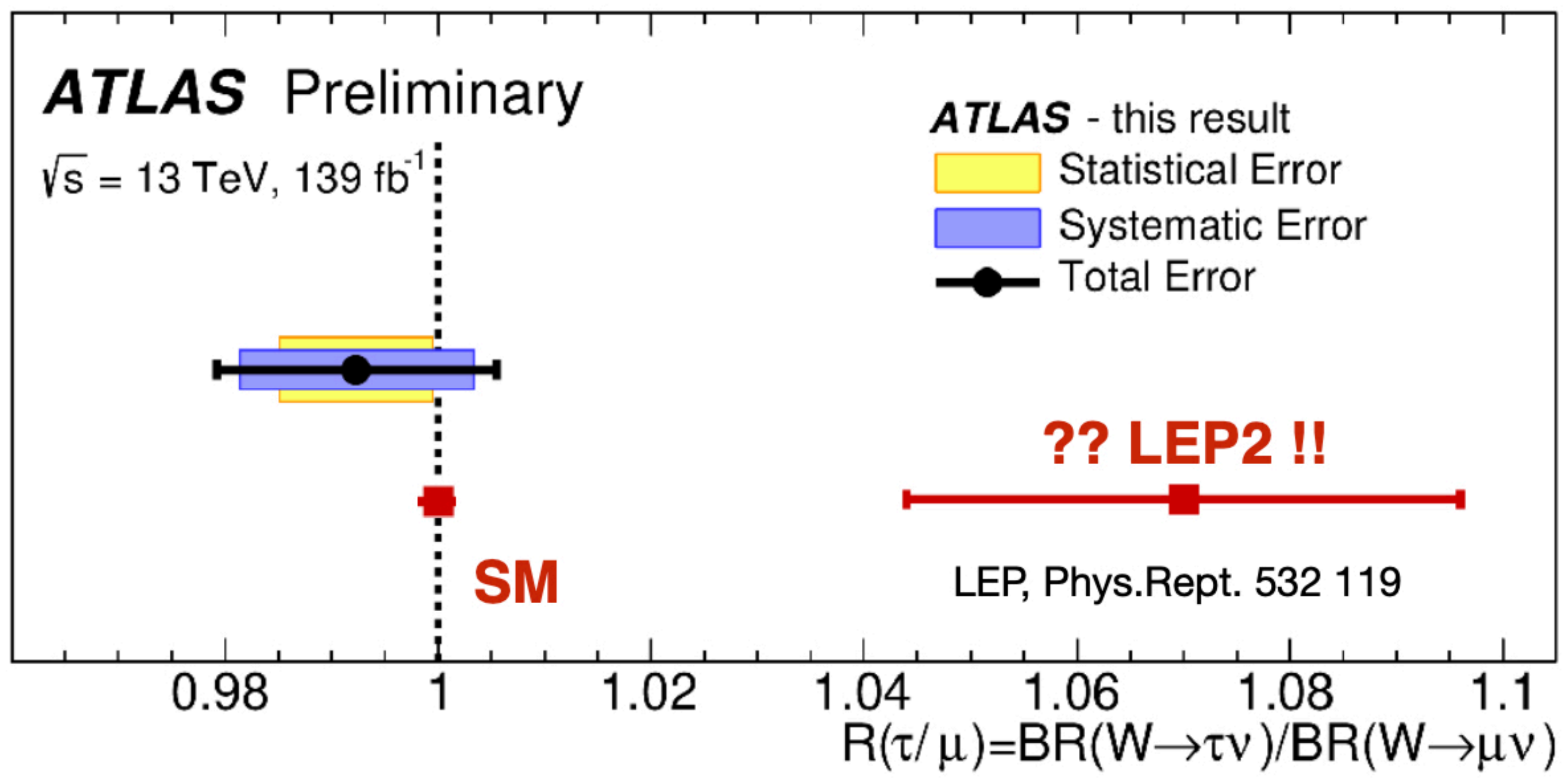
R. Bellan: EW



ATLAS: arXiv:2403.15085 LHCb: JHEP 01 (2022) 036

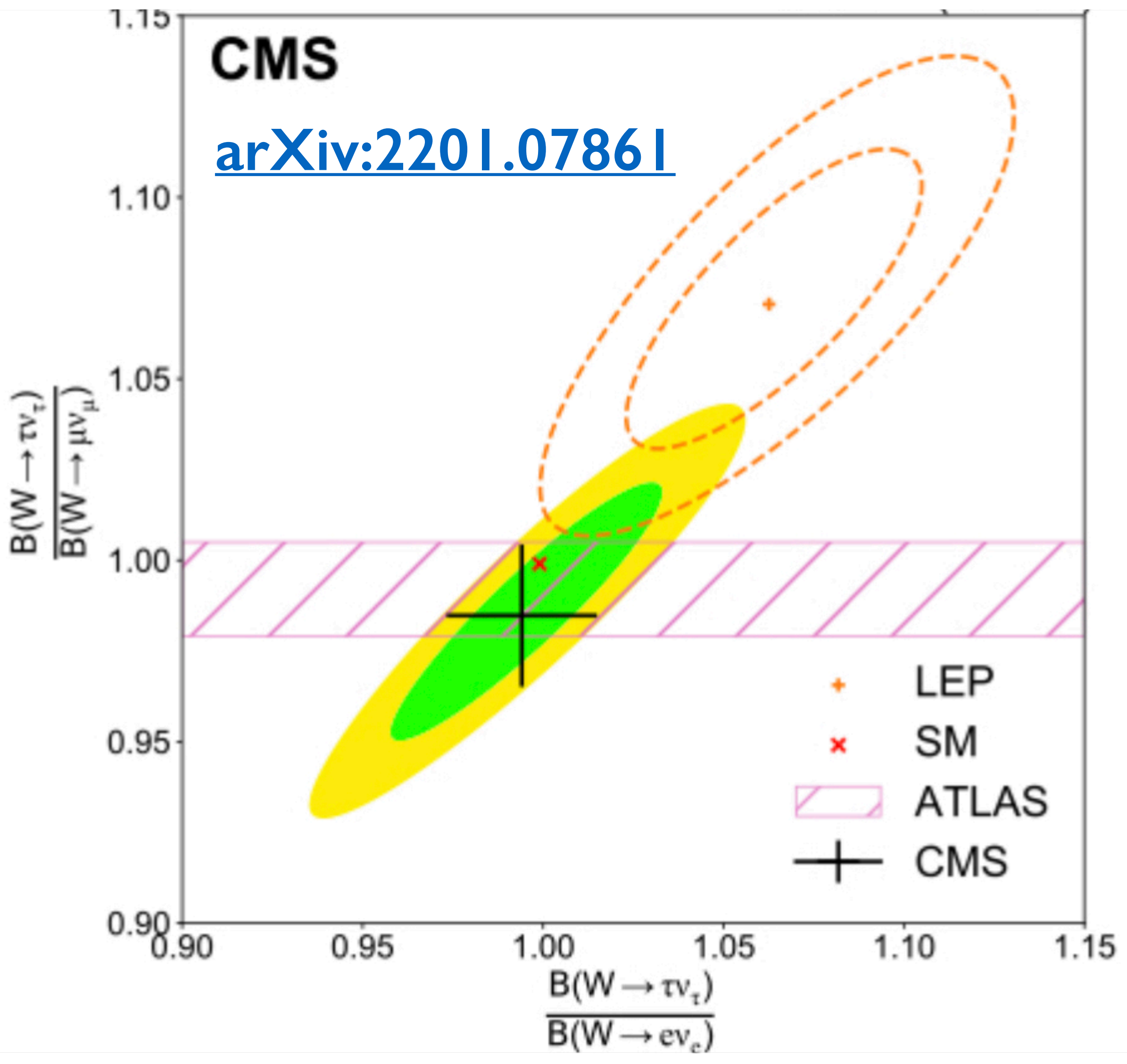


CMS-SMP-2022-010



LEP:
***BR*(W→τν)/*BR*(W→μν) = 1.066 ± 0.025**

ATLAS:
***BR*(W→τν)/*BR*(W→μν) = 0.992 ± 0.013**



Message:

- LHC's EW precision has by now surpassed LEP for all observables it has access to
- LHC has settled SM discrepancies left pending by LEP/SLD
- A rich programme of EW multiboson measurements is ongoing and still stat-limited in its reach: crucial input to EFT determinations in the EW-Higgs sector (see G. Durieux talk)

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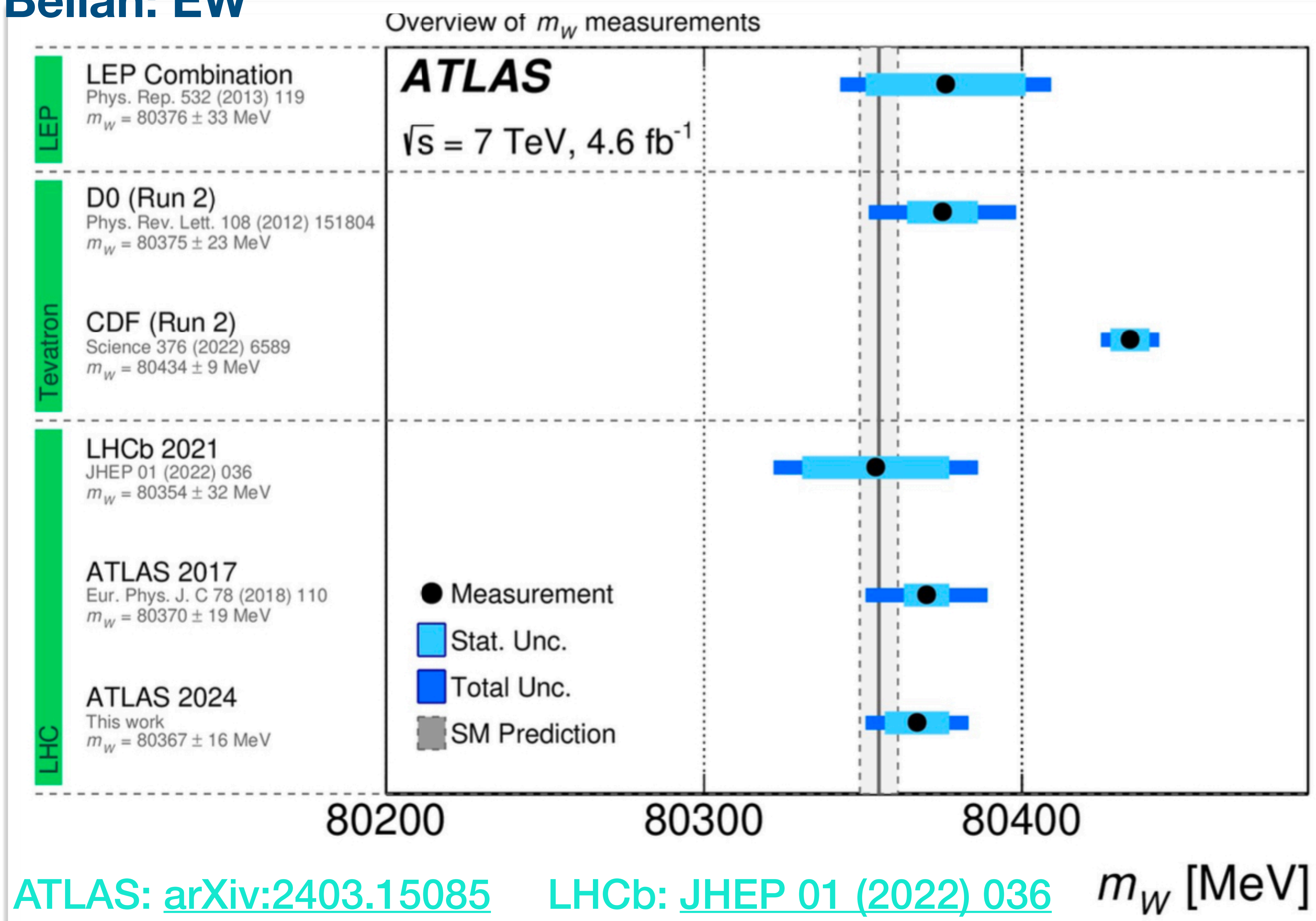

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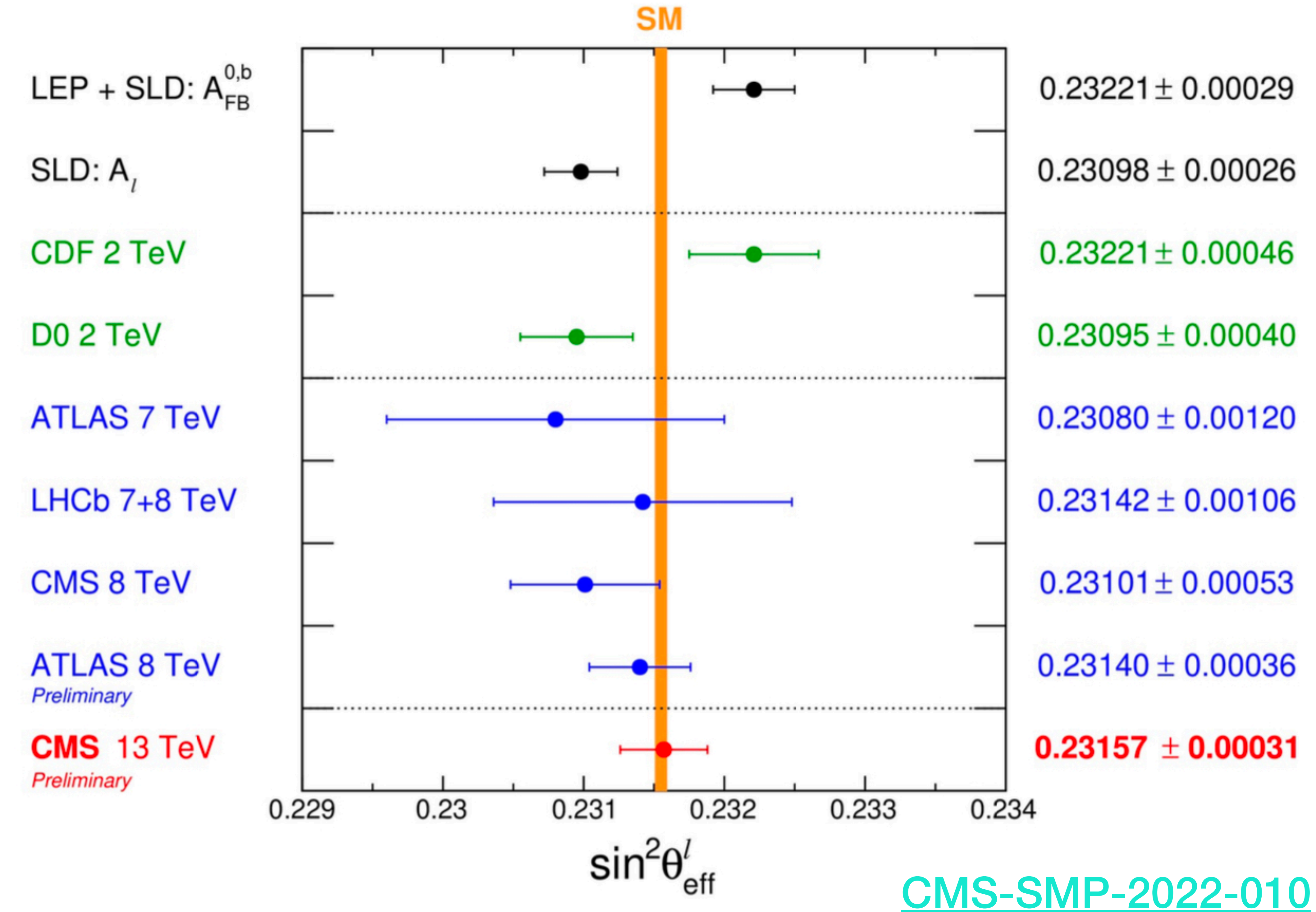
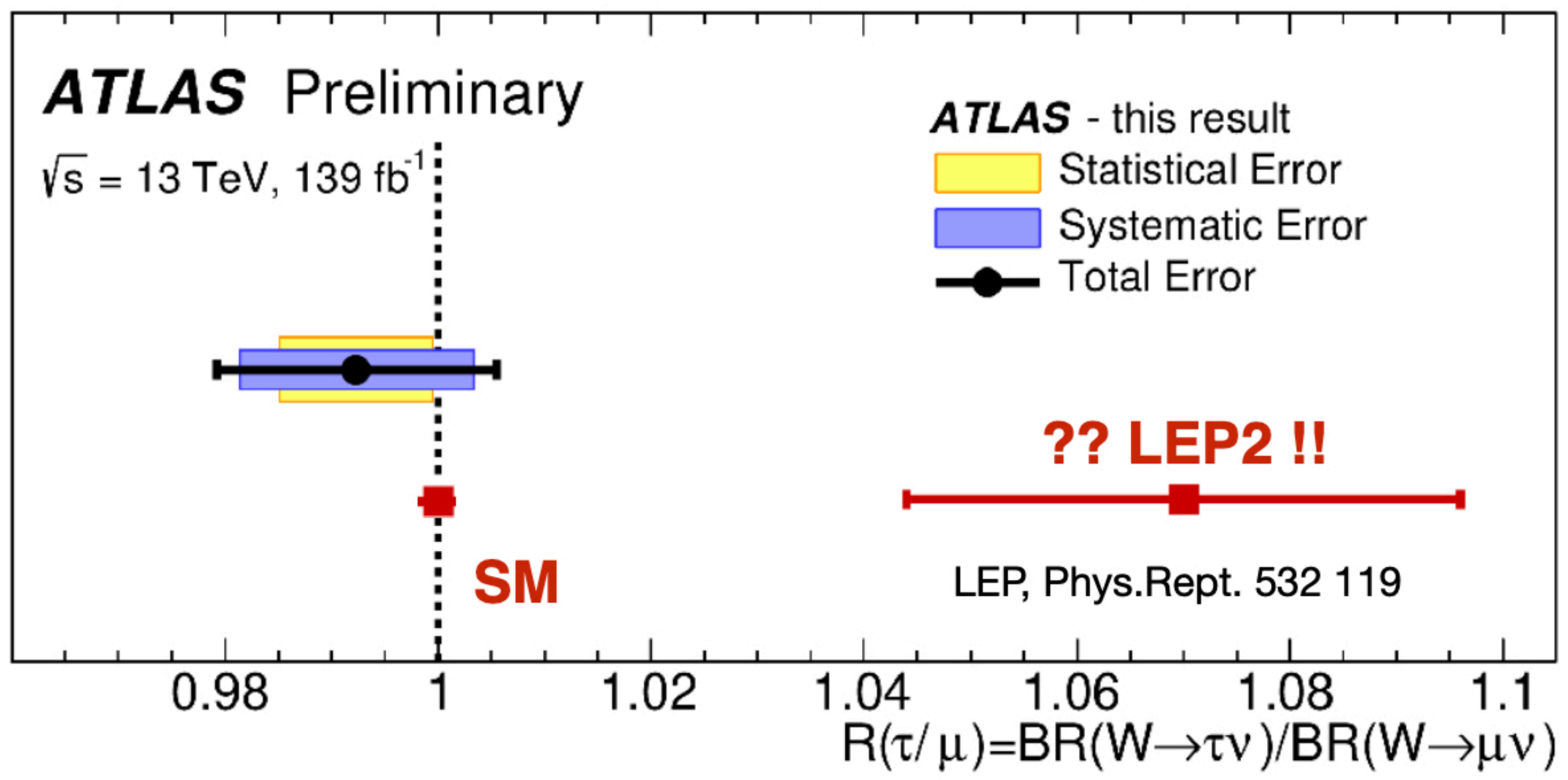


CMS-SMP-2022-010



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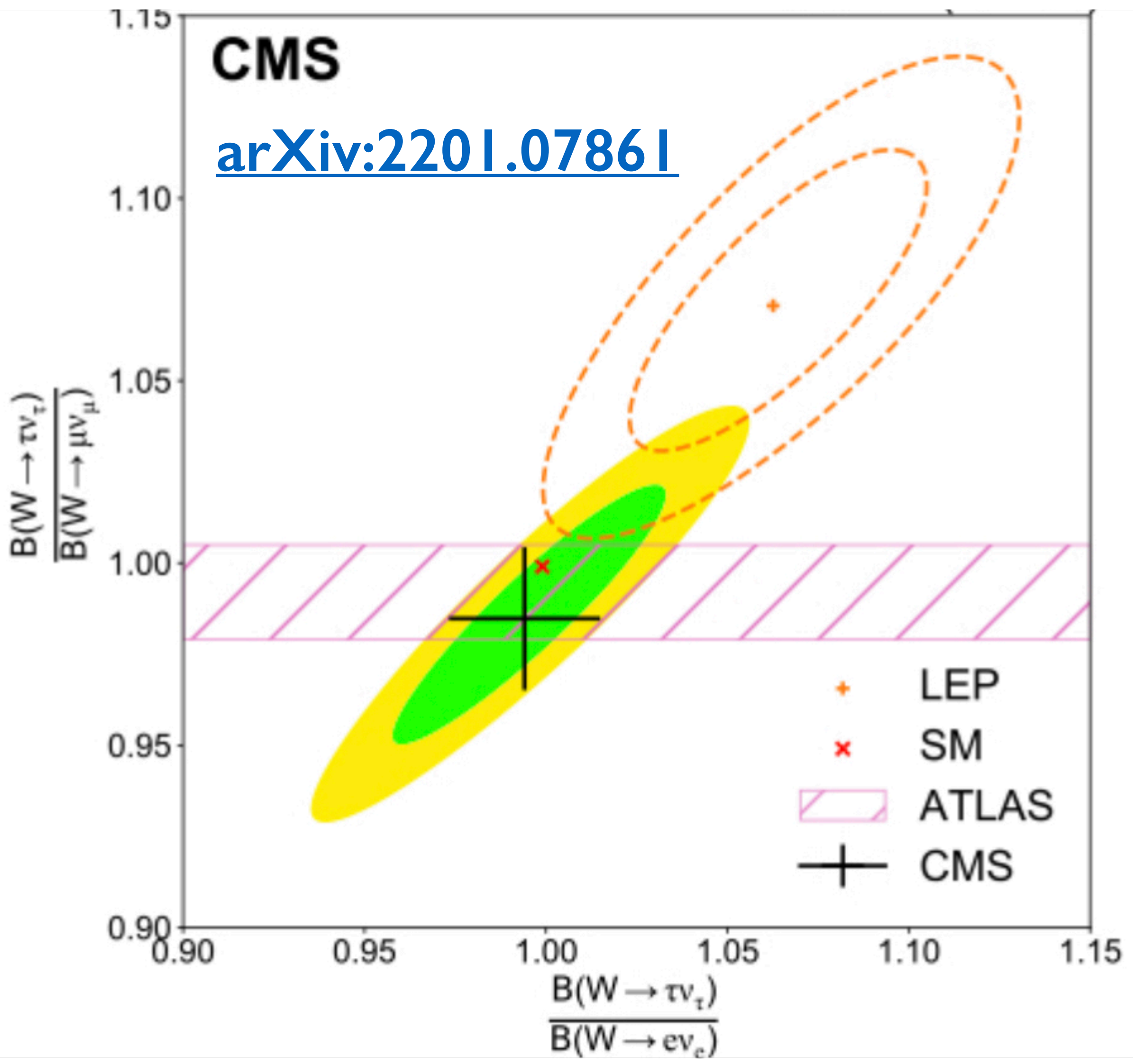

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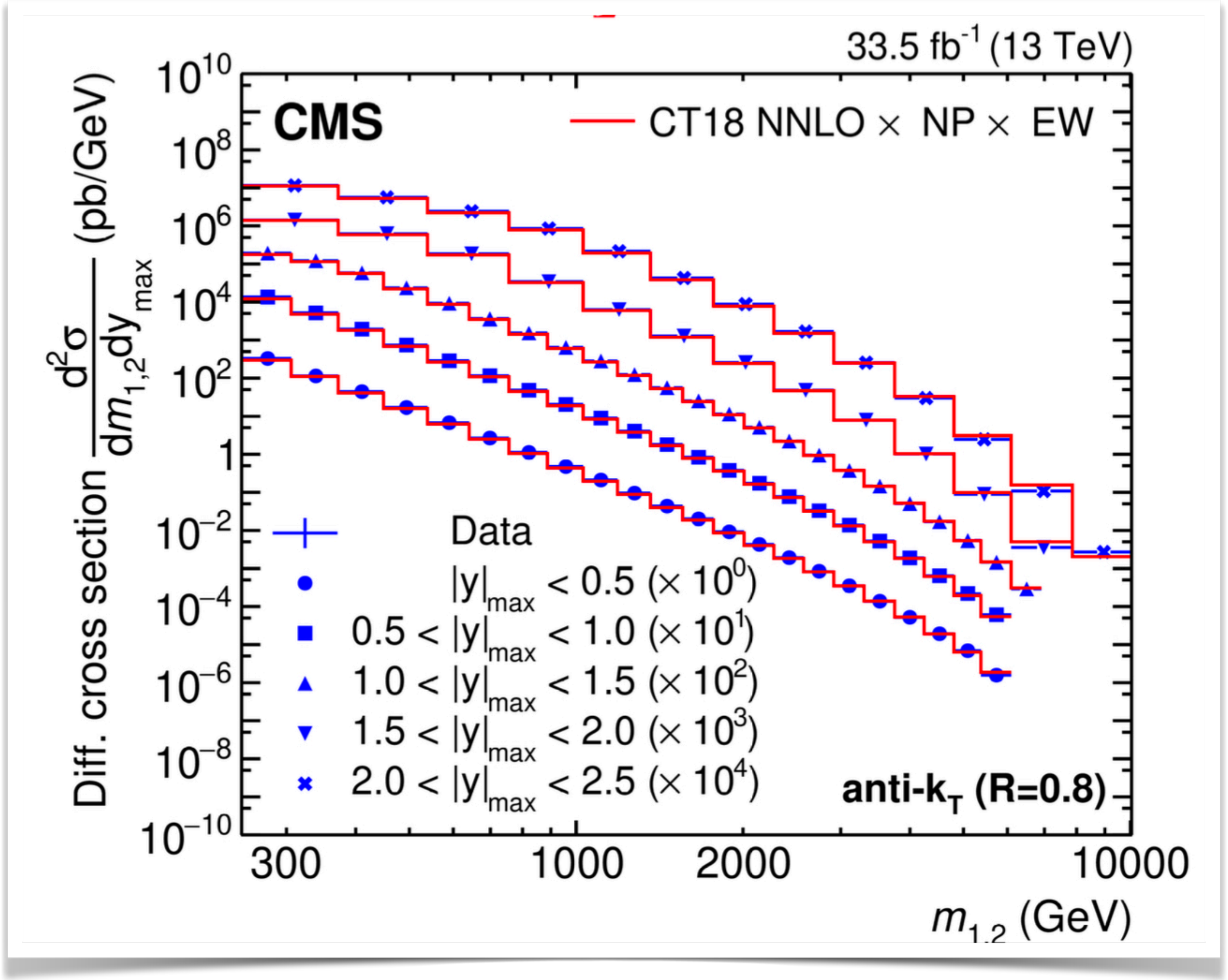
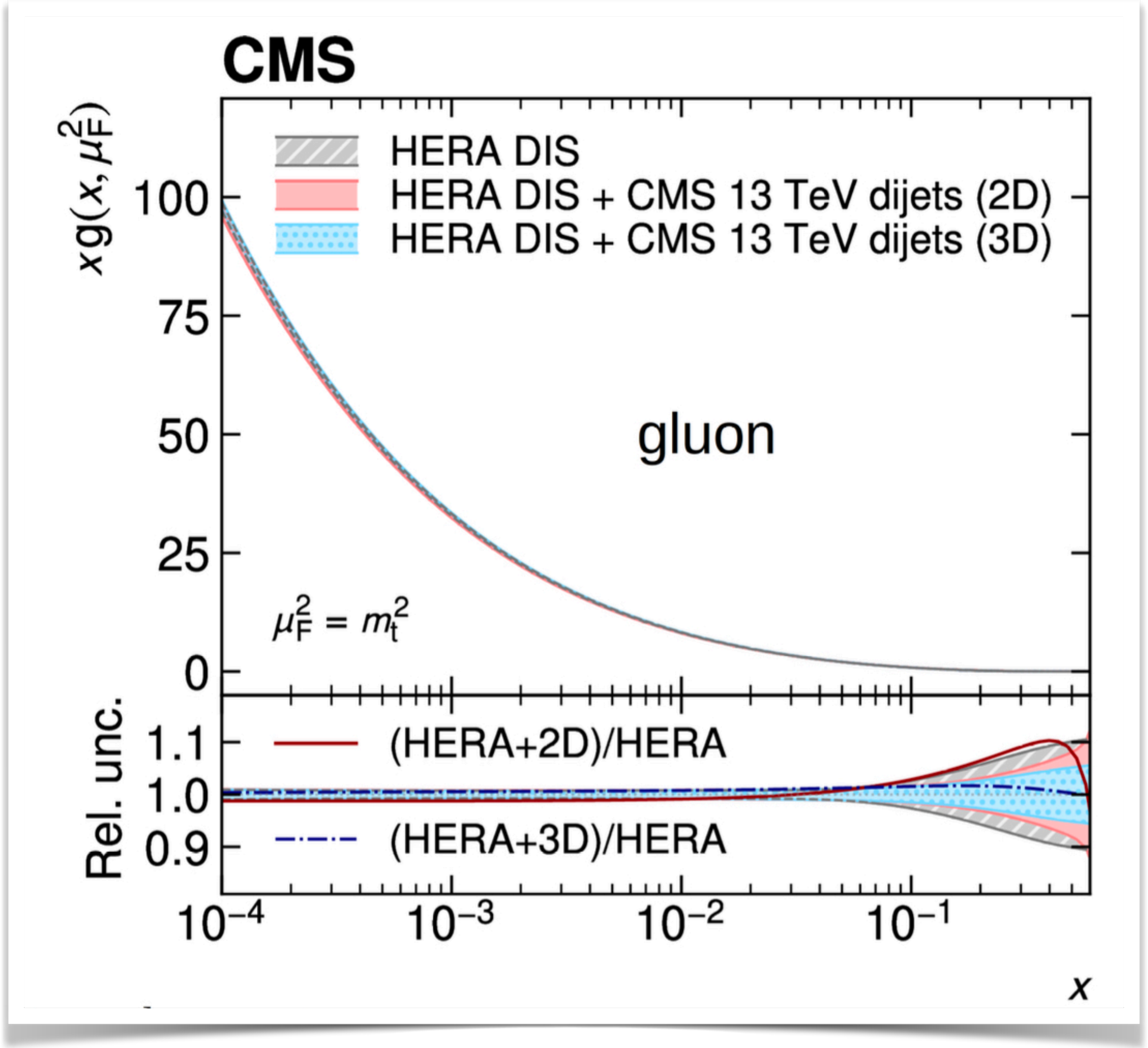
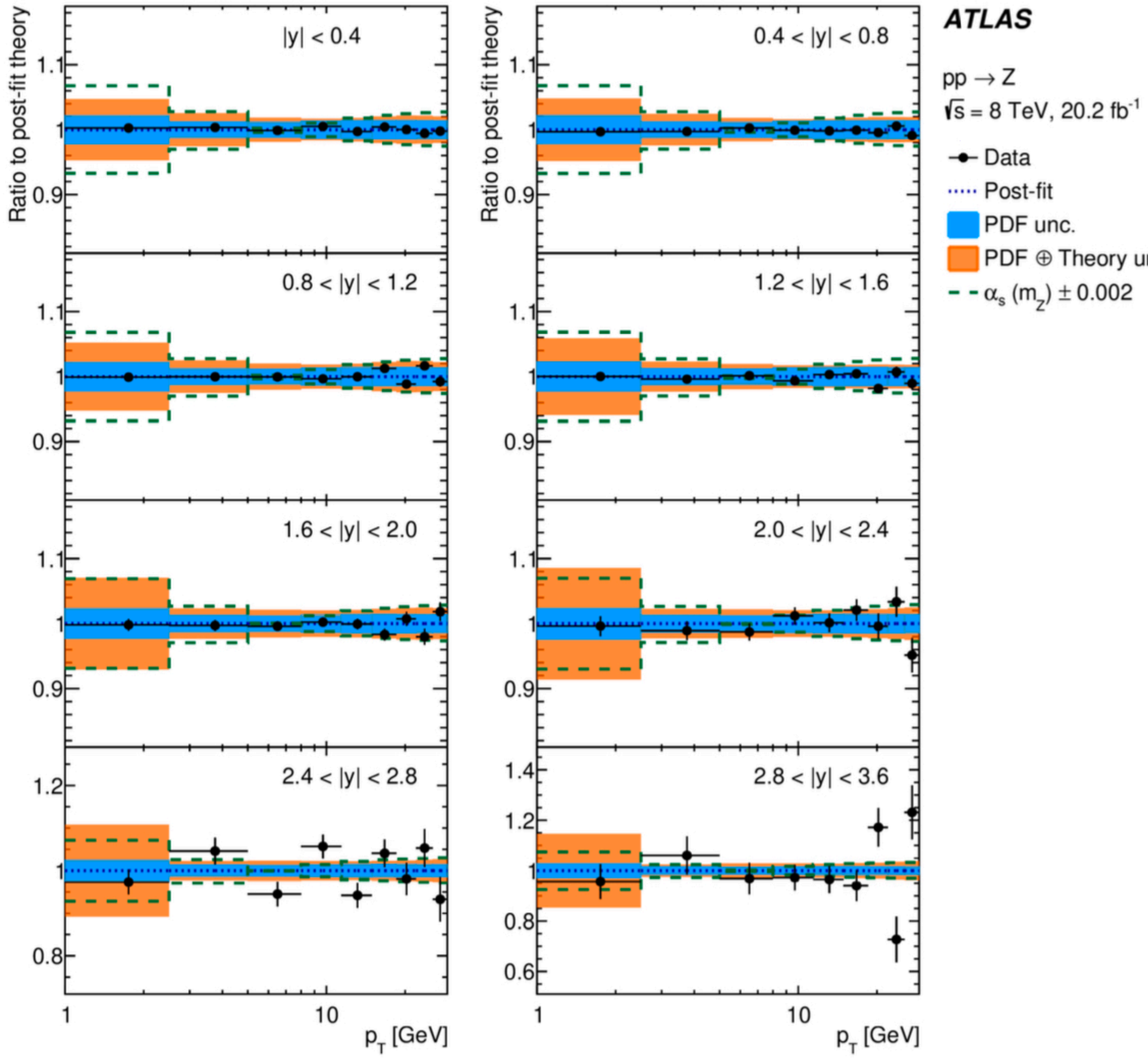


Precision below 10% over 10 orders of magnitude!



Impact on PDF determinations



[ATLAS-STDM-2023-01, arXiv: 2309.1298]

pt(Z) ⇒ α_S = 0.1178 ± 0.0009

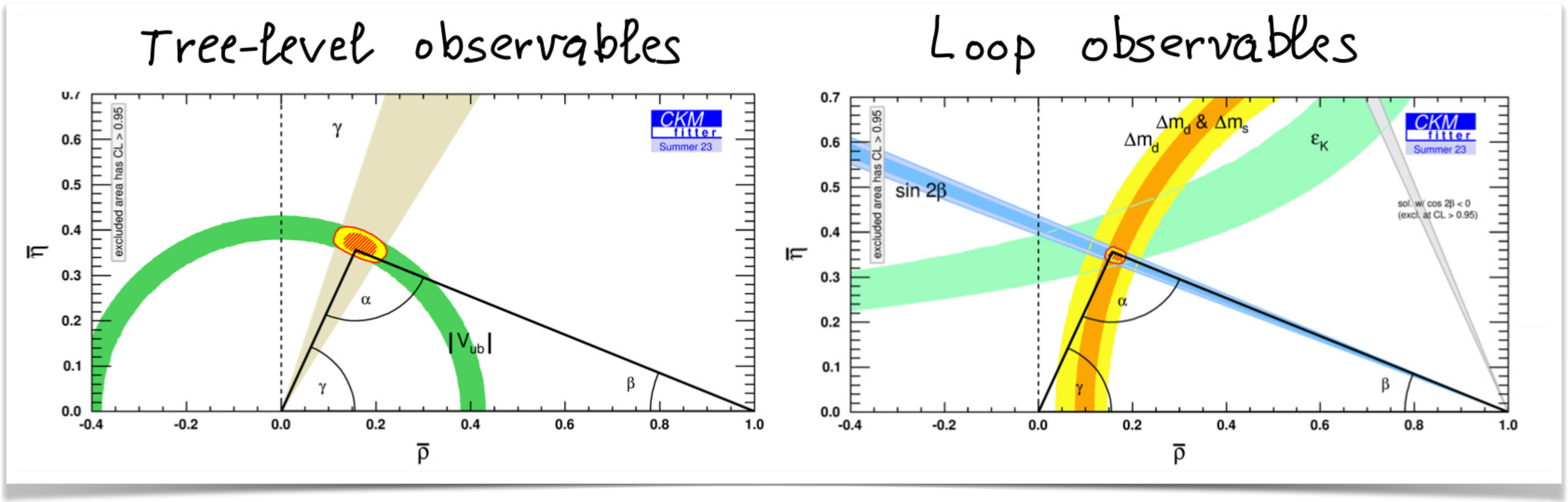
single most precise determination beyond LQCD

ATLAS + CMS m_{top} combination:

m(top) = 172.52 ± 0.33

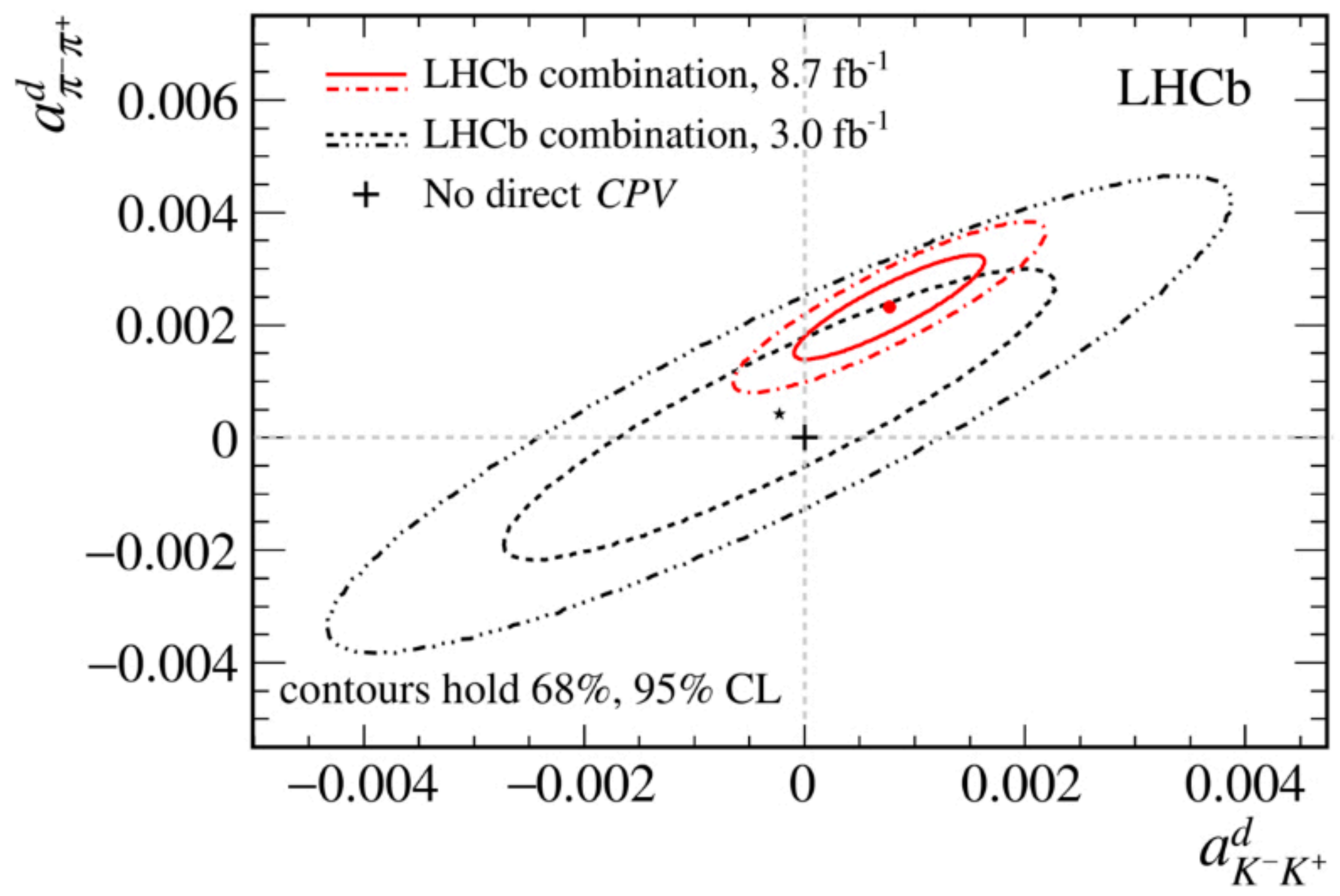
Message:

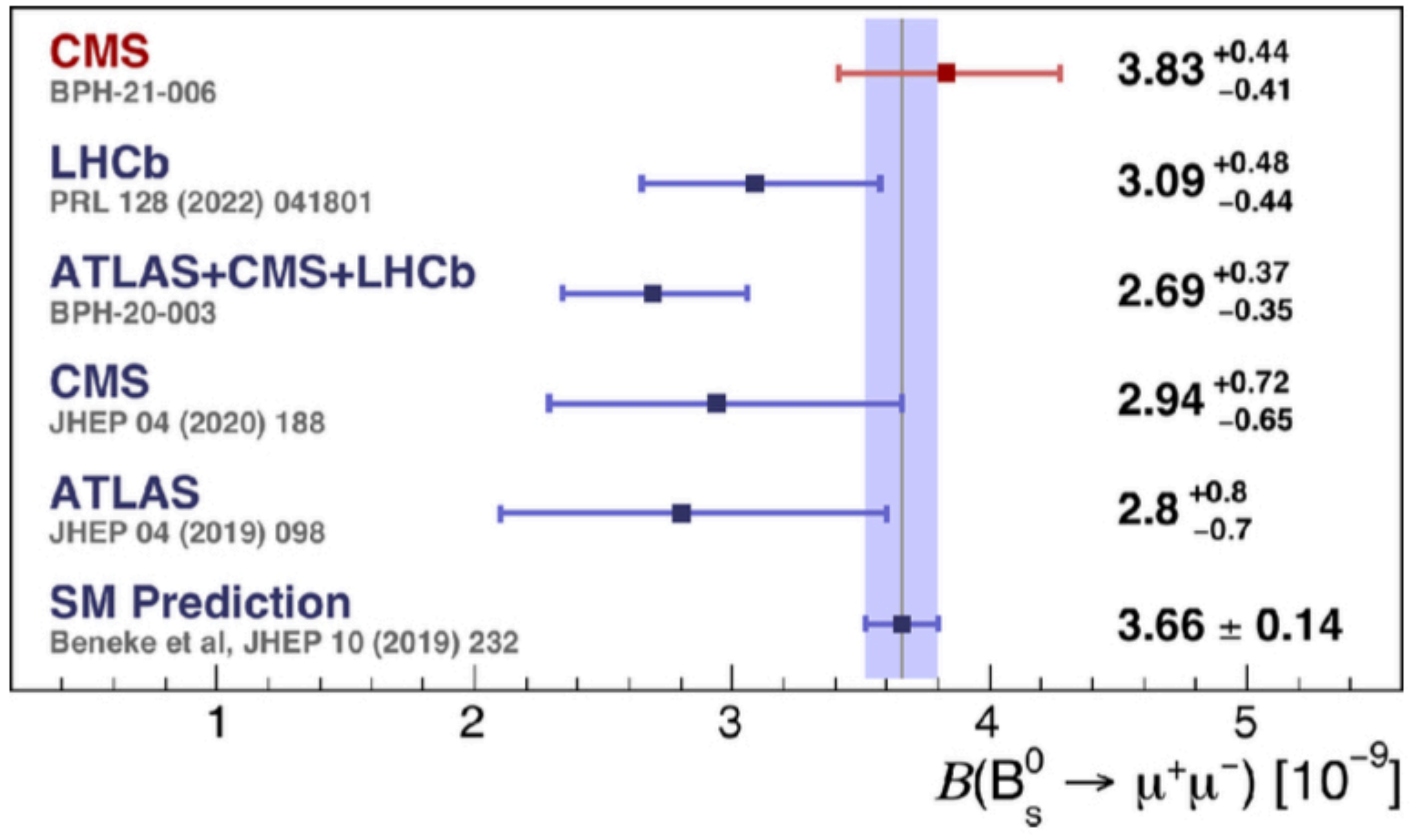
- **by and large bread and butter physics measurements, but achieving a reduction and a control of systematics beyond anything expected!**
- **Several exptl systematics still data driven (eg PDF, JES, bJES), room for further improvements or consolidation**
- **Critical role played by the astounding progress in TH calculations and reduction of TH systematics (see S.Forte and A.Mitov talks)**



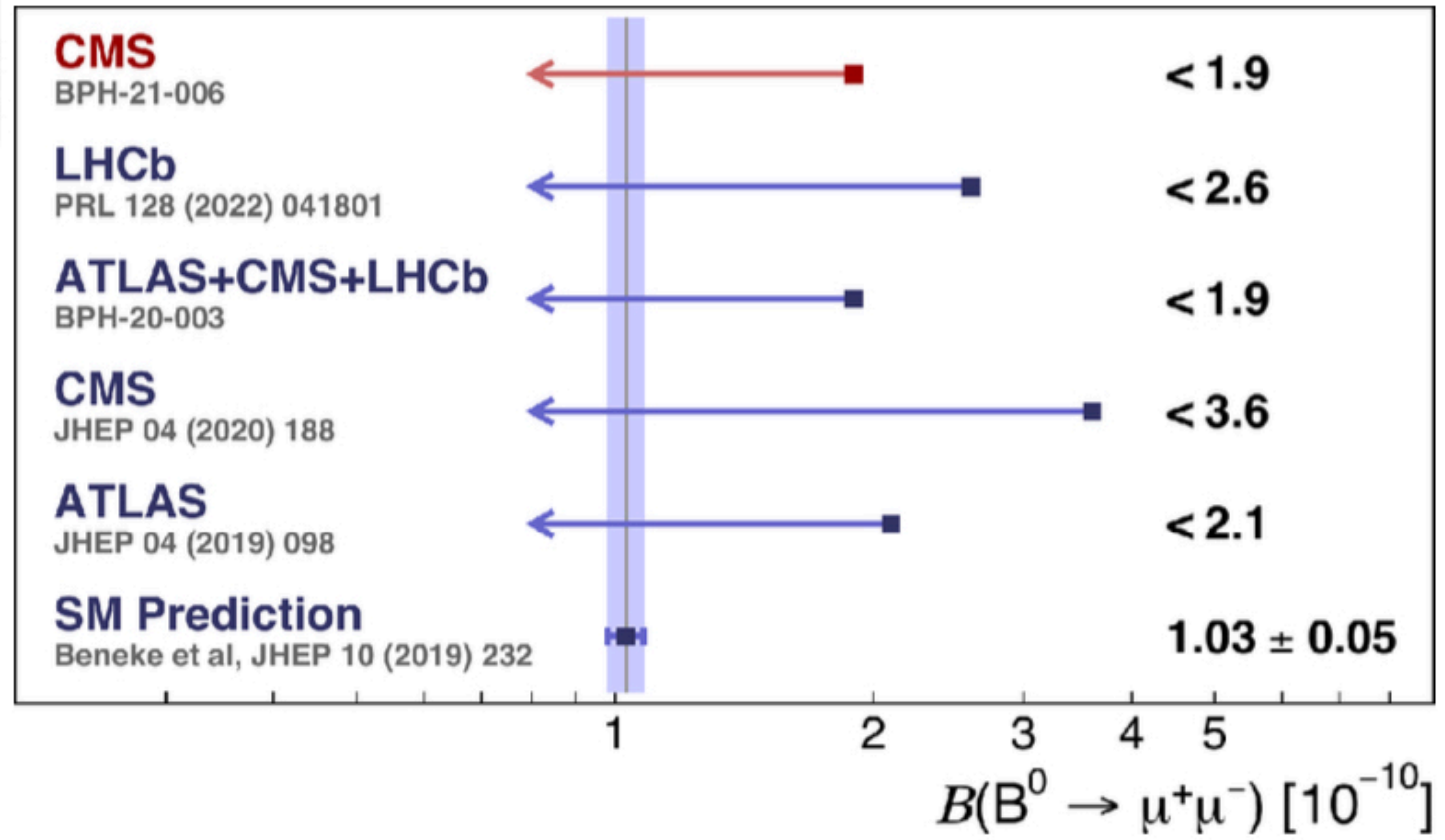
Full consistency of CKM fits to tree- and loop-level observables

Direct CPV for charm: done!

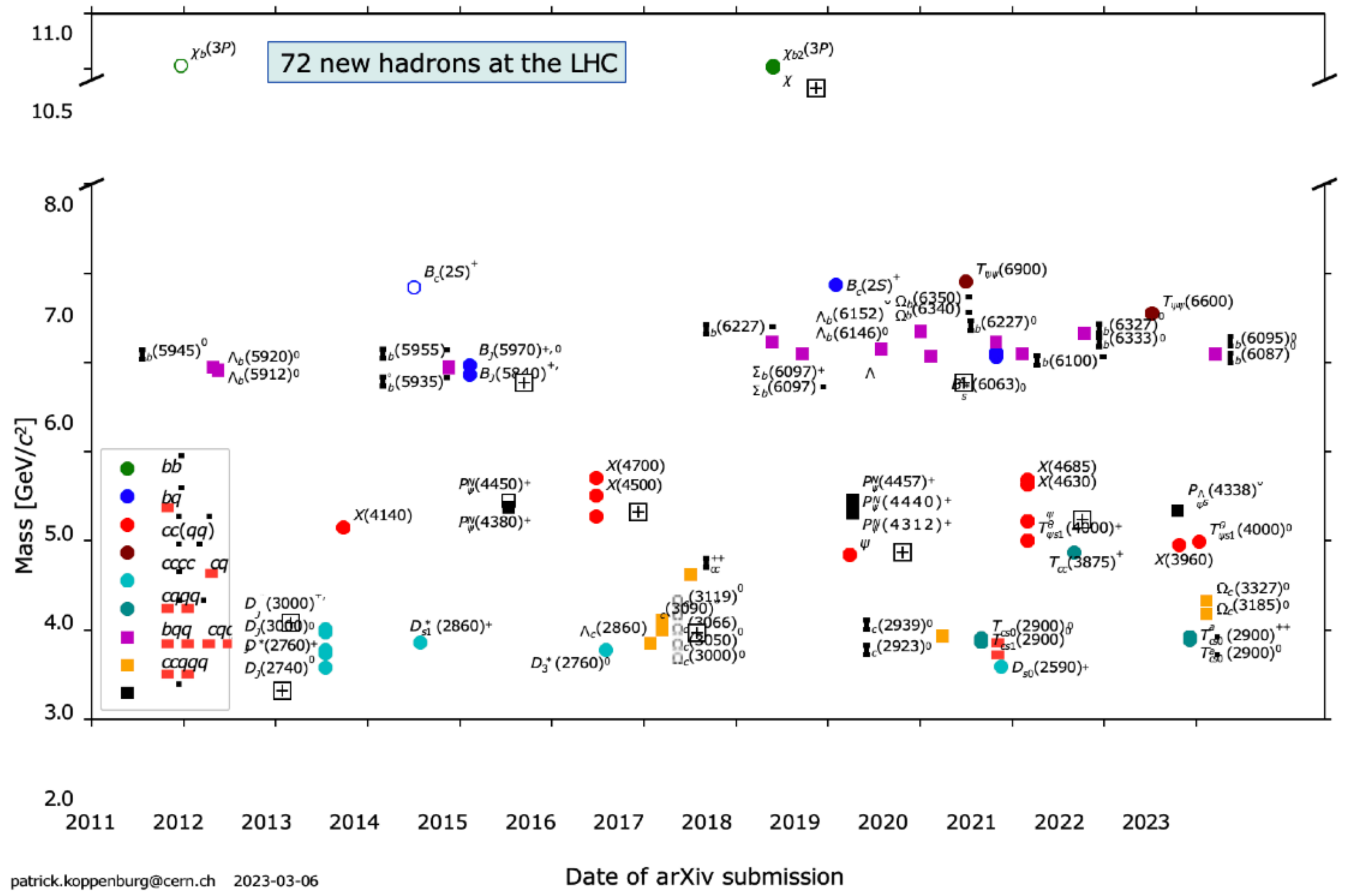




Not only LHCb! The power of data parking strategies by CMS

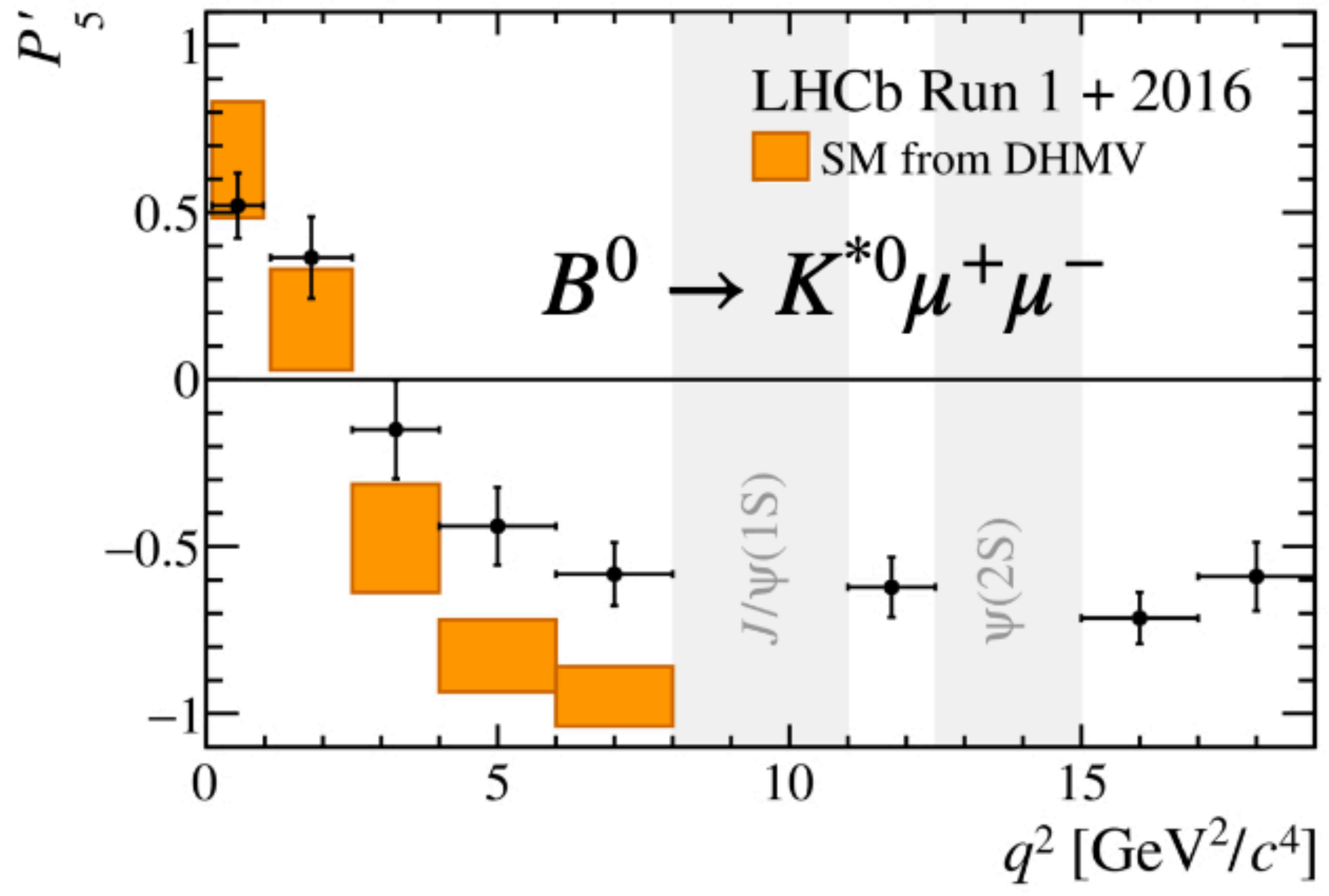


waiting for HL-LHC …

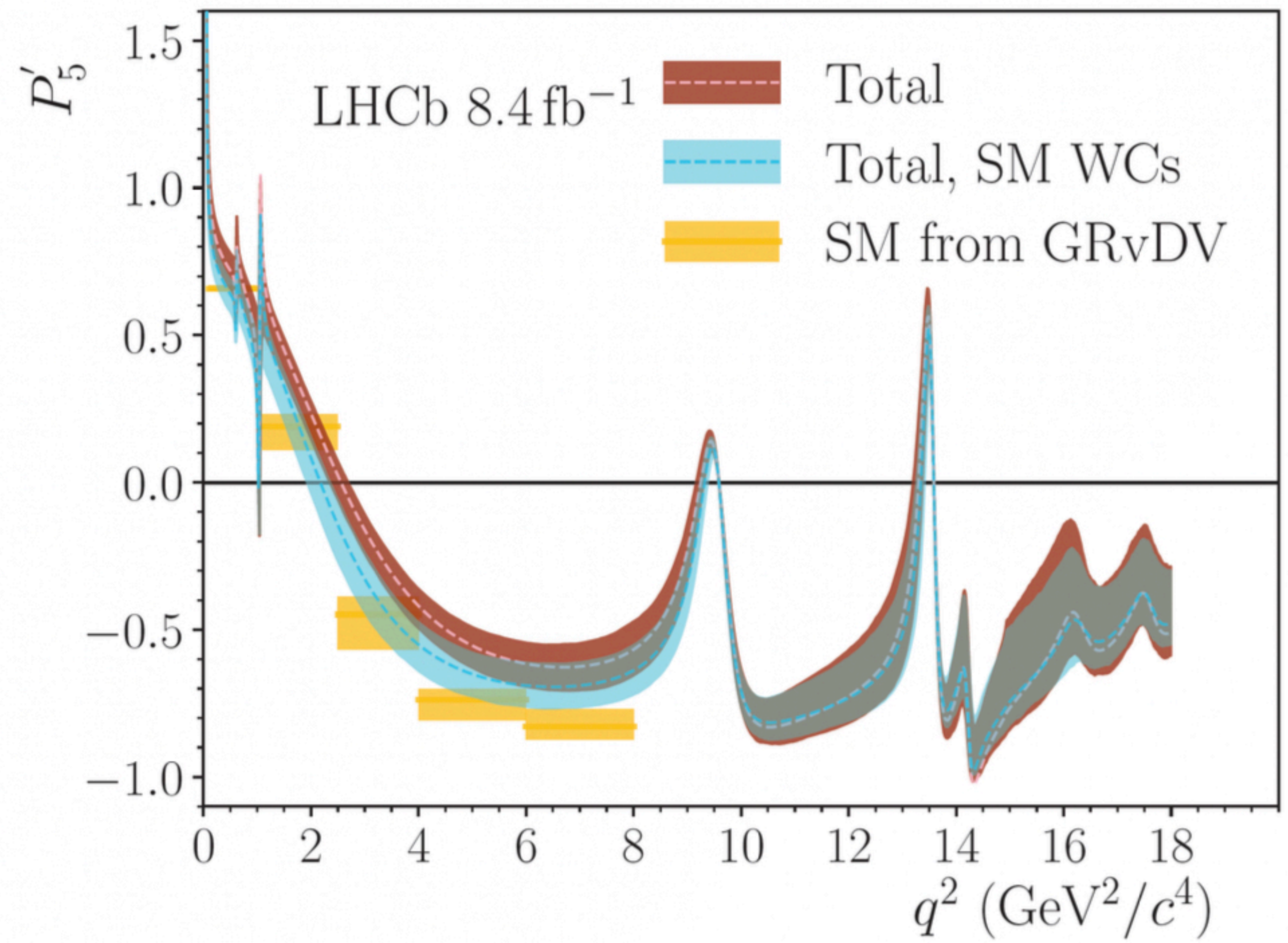


72 new hadrons discovered at LHC, opening a new era of studies of QCD exotic spectroscopy

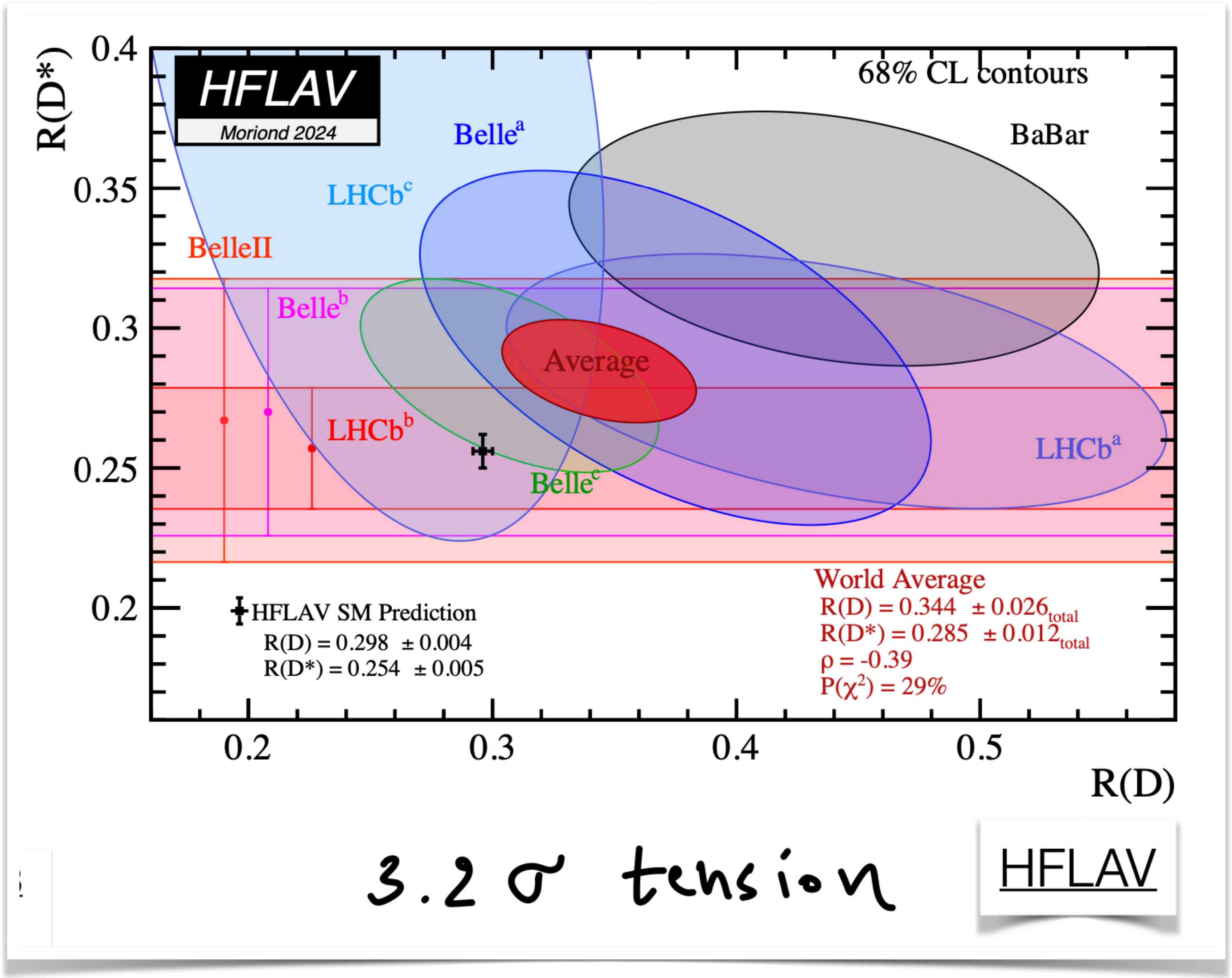
Hints of NP in the flavour sector



Anomaly in the $\mu^+\mu^-$ mass spectrum corroborated by further $b \to s\mu\mu$ channels such as $B_s \to \phi\mu\mu$



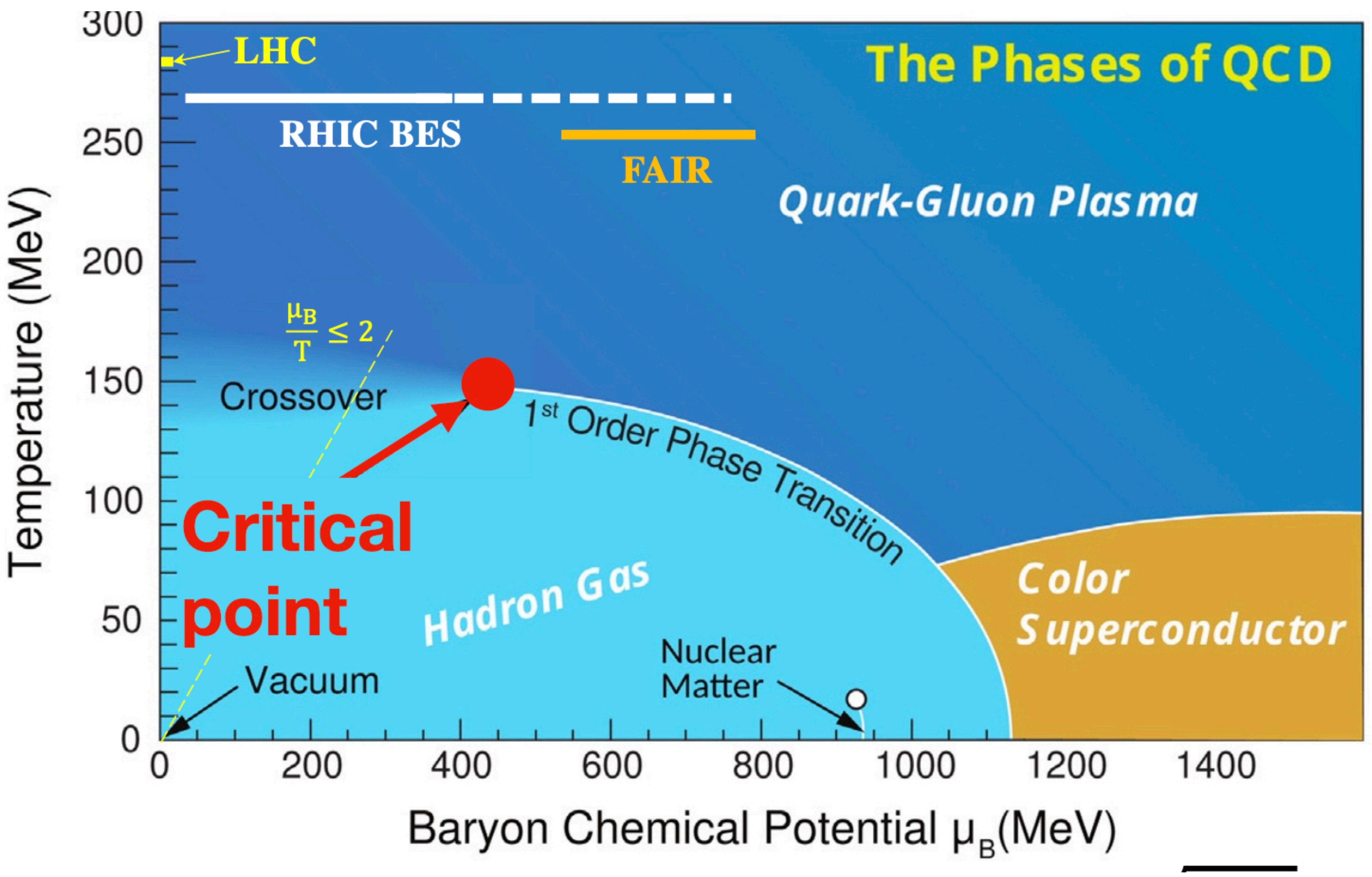
Data-driven evaluation of non-local (NP) effects in the region below the resonances, still leaving 1.5 σ tension with SM (2.1 σ in C9).
To be documented in: LHCb-Paper-2024-011



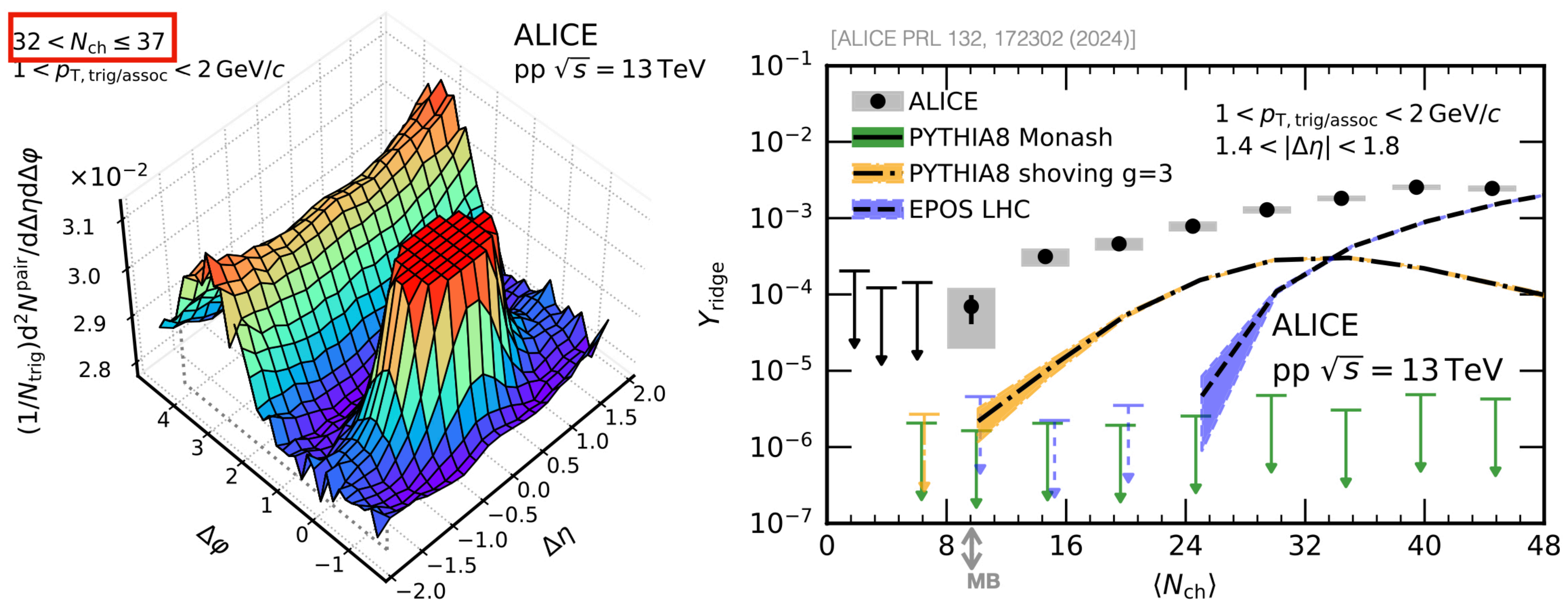
Message, from Monica's conclusions:

"The precision program in flavour physics over the next 10 ÷ 15 years is, in my view, the most promising direction to make discoveries before the next accelerator (assuming NP is on the horizon). "

A. Soto Ontoso: heavy ion physics

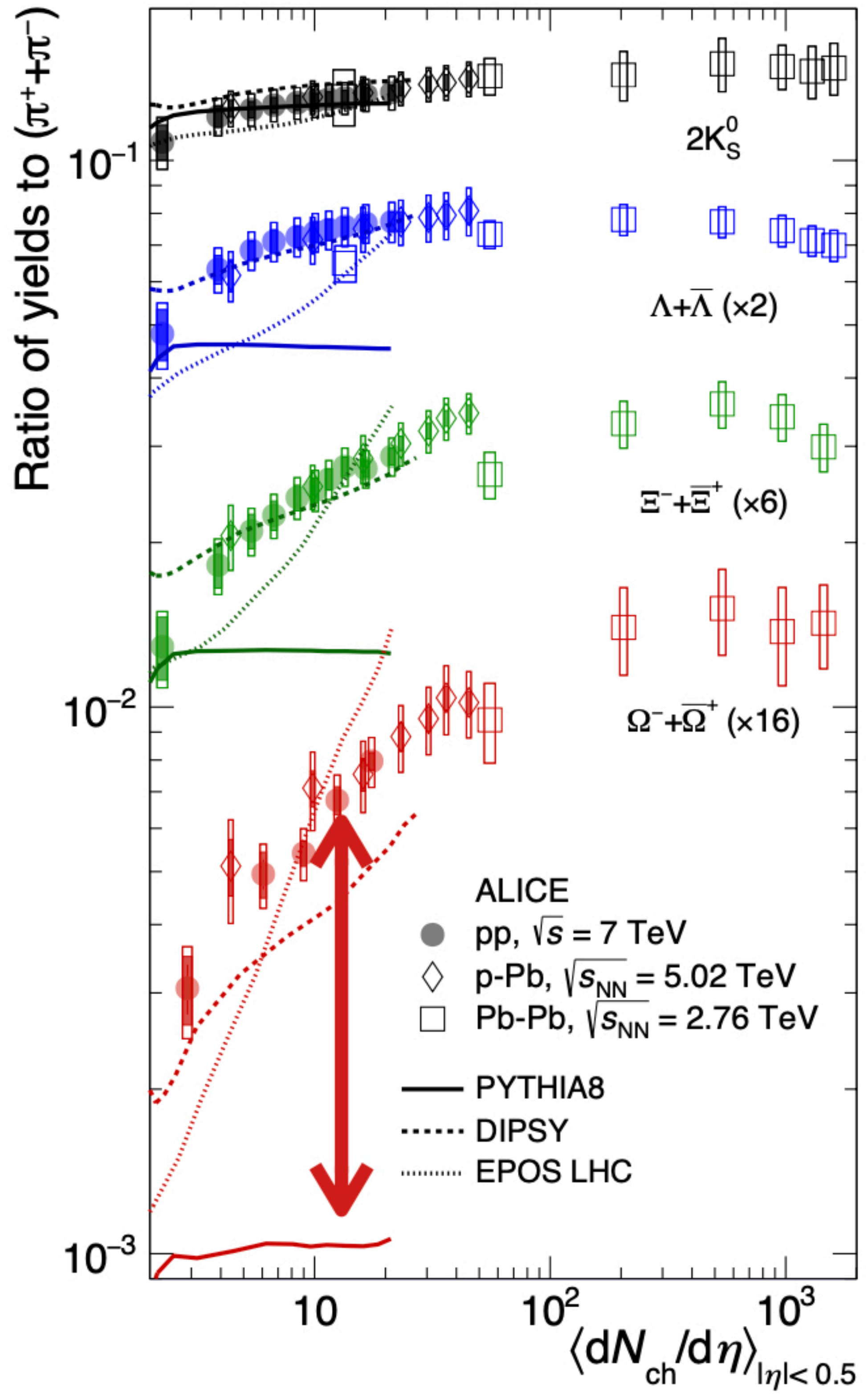


HIP meets high-energy particle physics at LHC: pp ridge



Multi-particle correlations appear for minimum bias collisions (?!)

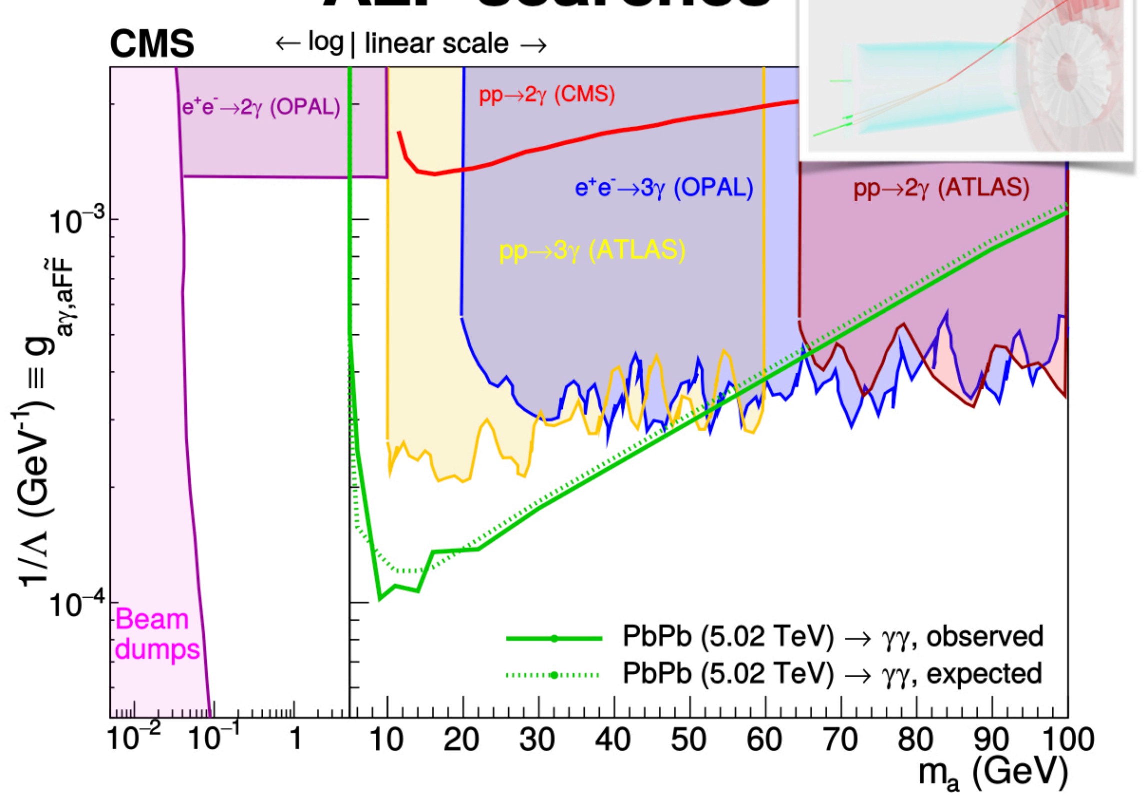
[ALICE Nature Phys. 13 (2017) 535-539]



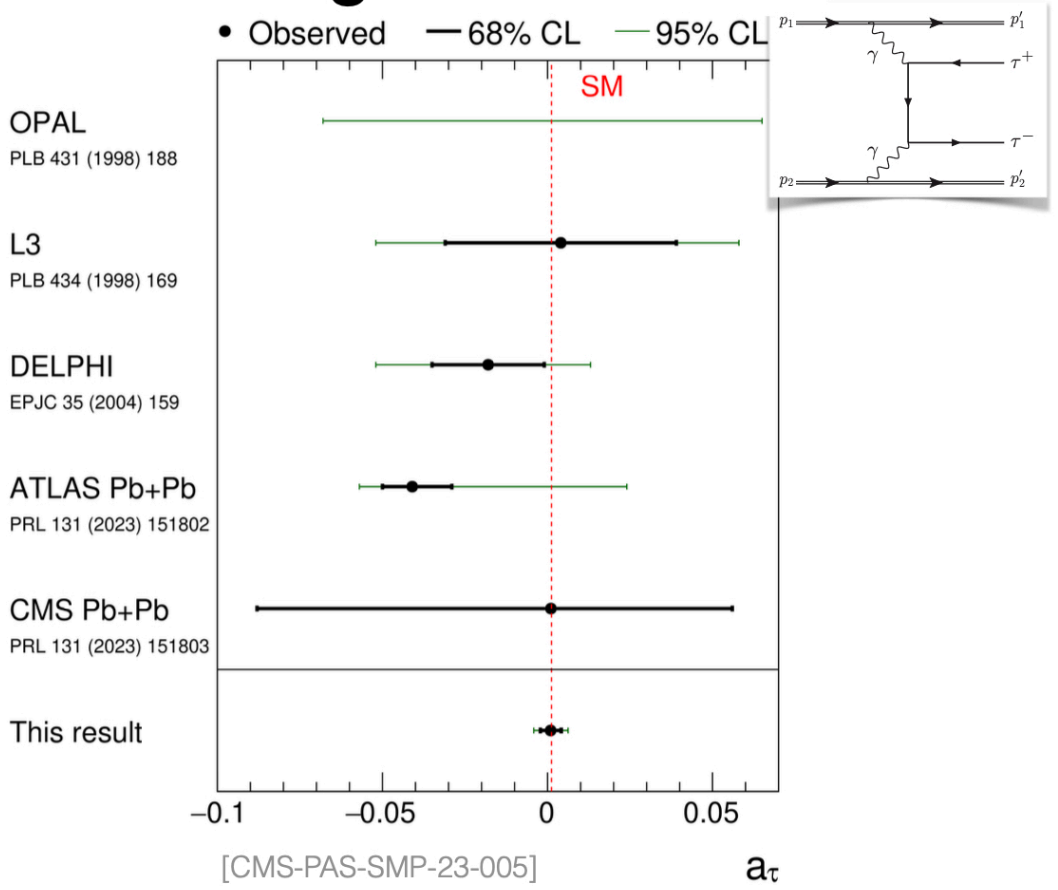
HIP meets high-energy particle physics: ultra-peripheral collisions

[CMS PLB 797 (2019) 134826]

ALP searches



τ magnetic moment



Exciting UPC program both for SM and BSM physics

23

Message:

It is fair to say that measurements stimulated by heavy ion collisions at the LHC led to the most remarkable and unexpected surprises and discoveries of the LHC programme, next to the Higgs discovery

Where we know we're going => HL-LHC

HL-LHC, Y. Papaphilippou

Upgrade of CMS calorimeters for the Phase-2 LHC, P. Milenovic

Technical challenges and performance of the new ATLAS LAr calorimeter trigger, C. Mwewa

The ATLAS ITk strip detector for the phase-II LHC upgrade, S. Ordek

Overview of the phase-2 upgrade of CMS detector, A. Purhoit

ATLAS ITk Pixel Detector Overview, E.A. Thompson

Highlights and future perspectives of LHC experiments, J.Jovicevic

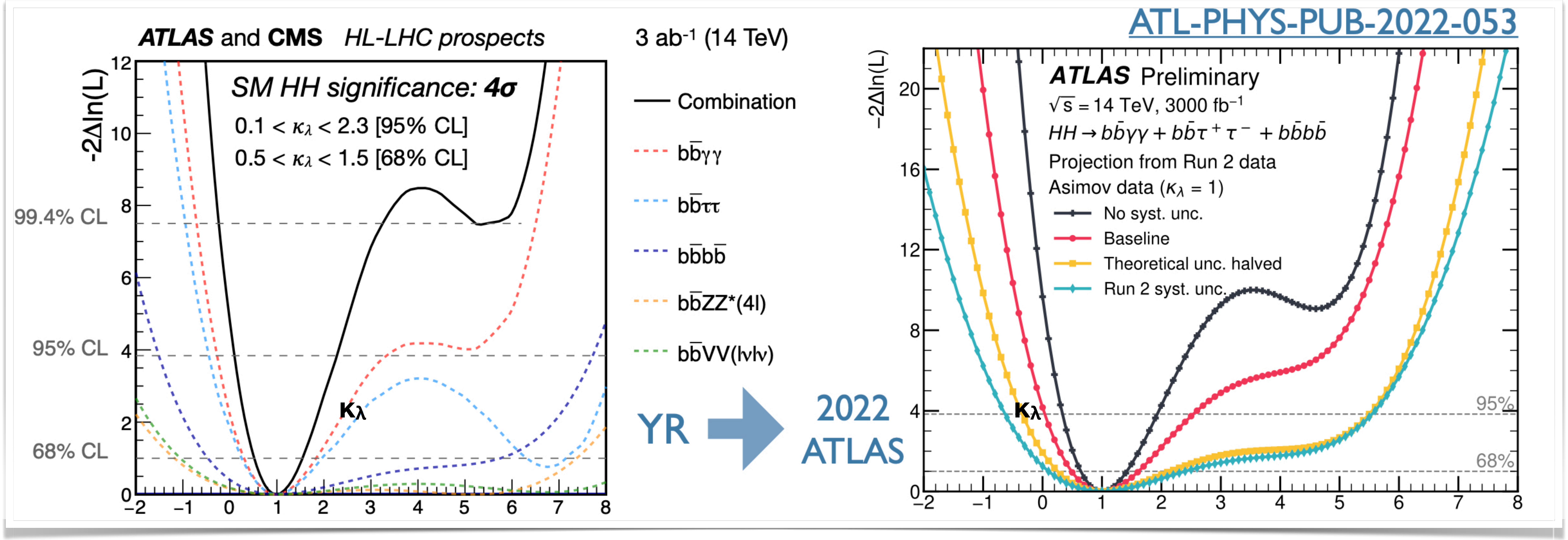
Computing for the HL-LHC, S. Crépé-Renaudin

Message

- Innovation with detector upgrades, trigger evolution and analysis techniques can boost by large factors acceptance, efficiency and S/B for key searches ⇒ the growth from 300 to 3000 fb^{-1} can increase the statistical reach by much more than x10
- The challenge to meet the computing demands for simulation is triggering new developments on the theory side, with efforts on the side of AI/ML to improve generation efficiency, and software engineering to accelerate execution. More effective computing opens new windows of opportunity for implementation of new TH algorithms (numerical vs analytical approaches), with direct impact on the feasibility of higher-order N^nLO calculations and the ultimate reduction of TH systematics

- Many anomalies or excesses from run 2, which could bloom at HL-LHC
- Many sensitivity and precision targets in need of the full HL-LHC statistics
- In general, a necessary training ground to prepare experiments detectors and theory for the challenging regimes of future (hadronic) colliders
- See the comprehensive review of ATLAS-CMS prospects in J.Jovicevic talk

Focus on a key deliverable of HL-LHC: the Higgs self-coupling



2019 ATL+CMS YR: CERN-2019-007

- 4.0σ w/ baseline systematics (4.5σ w/o syst.);
- 0.5 < κλ < 1.5 [68% CL].

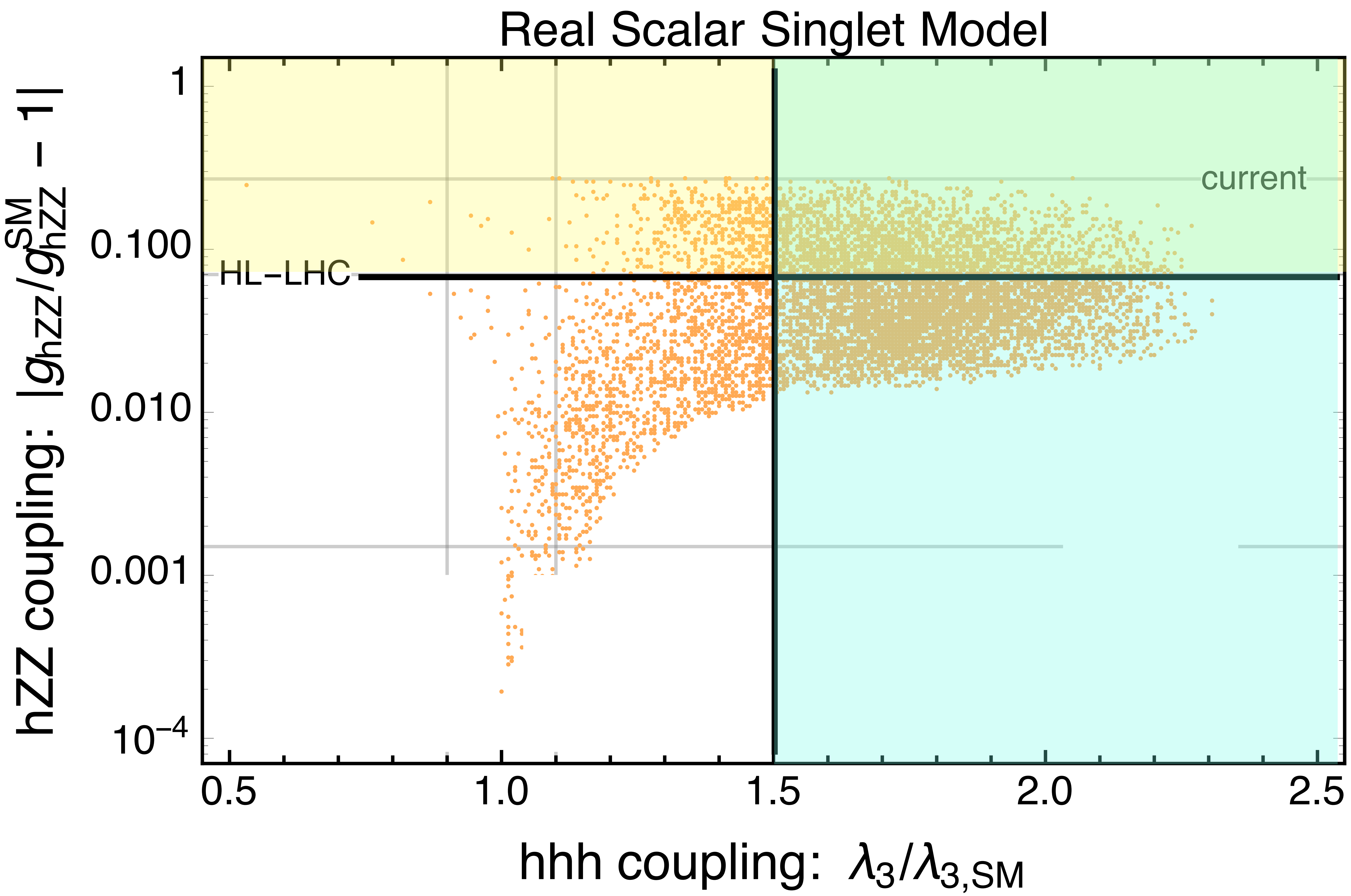
2022, ATLAS only ATL-PHYS-PUB-2022-053

- 3.4σ with baseline systematics (4.9σ w/o syst.)
- 0.5 < κλ < 1.6 [68% CL];

Is a 50% measurement of any interest, when H couplings to ZZ, WW, γγ will be at the few % level after HL-LHC? YES !!

see coverage and discussion of the TH impact of this measurement in several talks, eg by G. Weiglein, G.Durieux, …

Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

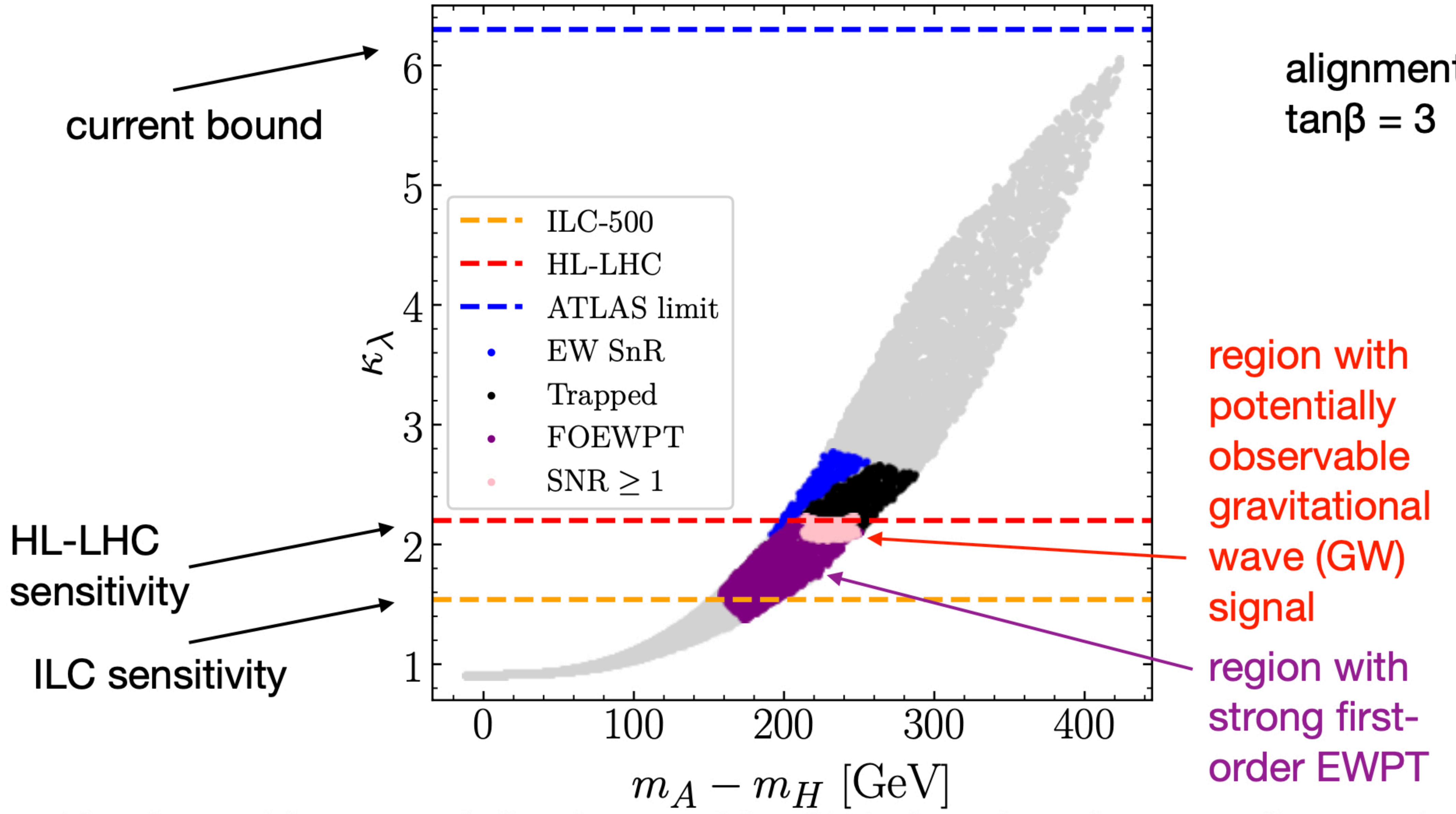


Message:
in the search for extended Higgs sectors with strong 1st order phase-transition, a 50% measurement of the Higgs self-coupling is more powerful than a few-% measurement of HZZ

Similar conclusions with other models for SFOEWPTG, see G.Weiglein talk …

Relation between trilinear Higgs coupling and strong first-order EWPT with potentially observable GW signal

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]



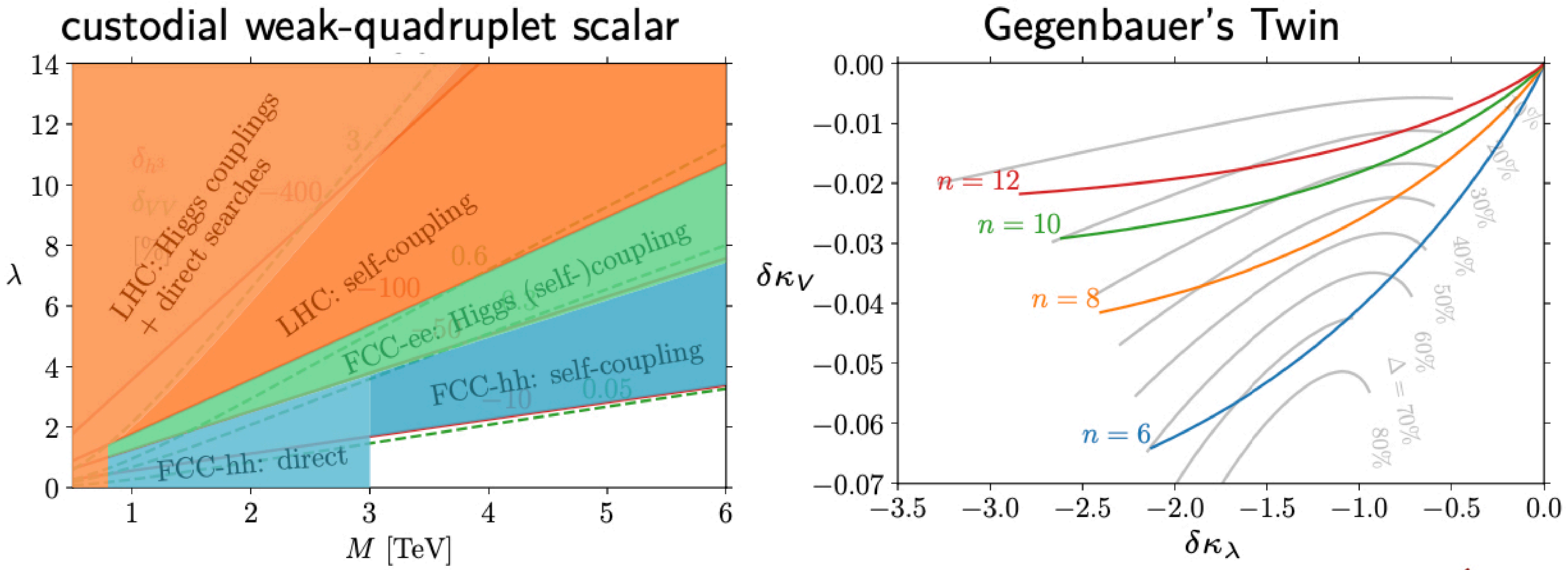
⇒ Region with potentially detectable GW signal and strong first-order EWPT is correlated with significant deviation of $\varkappa_\lambda$ from SM value

… and in specific model building scenarios, see G.Durieux talk

Structurally large $\delta\kappa_\lambda/\delta\kappa_V$ in BSM

[GD, McCullough, Salvioni '21, '22, '22]
see also: [Di Luzio, Gröber, Spannowsky '17]
[Gupta, Rzehak, Wells '13] [Falkowski, Rattazzi '19]
[Logan, Rentala '15] [Chala, Krause, Nardini '18] [etc.]

loop factor (or v^2/M_X^2) allowed dimensionally btw. H^6 and D^2H^4



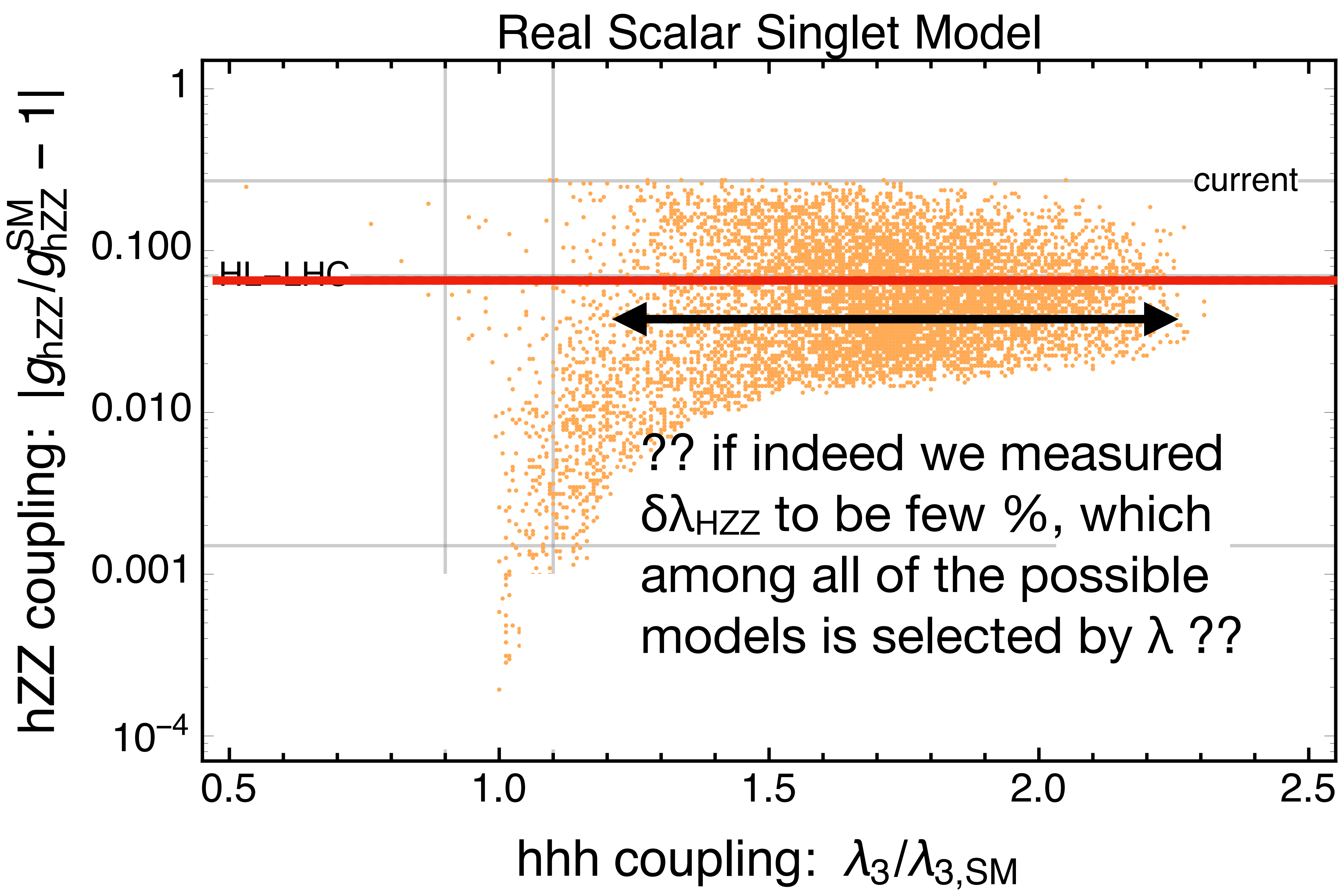
$$\lambda\, H^* H^* (\epsilon H)\Phi + \lambda \tfrac{1}{\sqrt{3}} H^* H^* H^* \widetilde{\Phi}$$

large representations!

- dim≫6 operators may be very relevant
- vacuum stability limiting the $\delta\kappa_\lambda/\delta\kappa_V$ ratio

Remark

- More in general: should HZZ deviate from the SM, λ_{HHH} is necessary to help break the degeneracy among all parameter sets leading to the same HZZ prediction



- The concept of *"which experiment sets a better constraint on a given parameter"* is a very limited comparison criterion, which looses value as we move from *"setting limits"* to *"diagnosing observed discrepancies"*
- Likewise, it's often said that some observable sets better limits than others: "all known model predict deviations in X larger than deviations in Y, so we better focus on X". But once X is observed to deviate, knowing the value of Y could be absolutely crucial ….
- Redundancy and complementarity of observables is of paramount importance

A diverse landscape

Heavy ion physics: current status and prospects at future accelerators, A. Soto Ontoso

Feebly-interacting particles at future colliders, S.Trojanowski

Neutrino physics: now and at future accelerators, V. Brdar

Neutrino Physics at future colliders, B. Dev

Using collider systems to search for new physics, J. Pinfold

Physics potential of beam dump experiments at future accelerators, D. Ueda

The storage ring proton EDM status and prospects, Y. Semertzidis

Gamma factory, W. Krasny

Integrated Photonic Circuit Accelerator for Dark Matter Search, R. Ischebeck

Future prospects for gravitational waves, D. Croon

The status of AI/ML in HEP and the vision towards future accelerators, T.Golling

Quantum developments and potential synergies with future colliders, M. Spannowski

Novel methods towards putting QFT on quantum computers, S. Abel

Simulating high-energy collision events with a quantum computer, S. Williams

DL Croon: Physics with GWs

Phenomenological opportunities

(not exhaustive!)

Compact object histories
Populations of black holes and neutron stars at high redshift

Cosmology
Independent probe of H_0

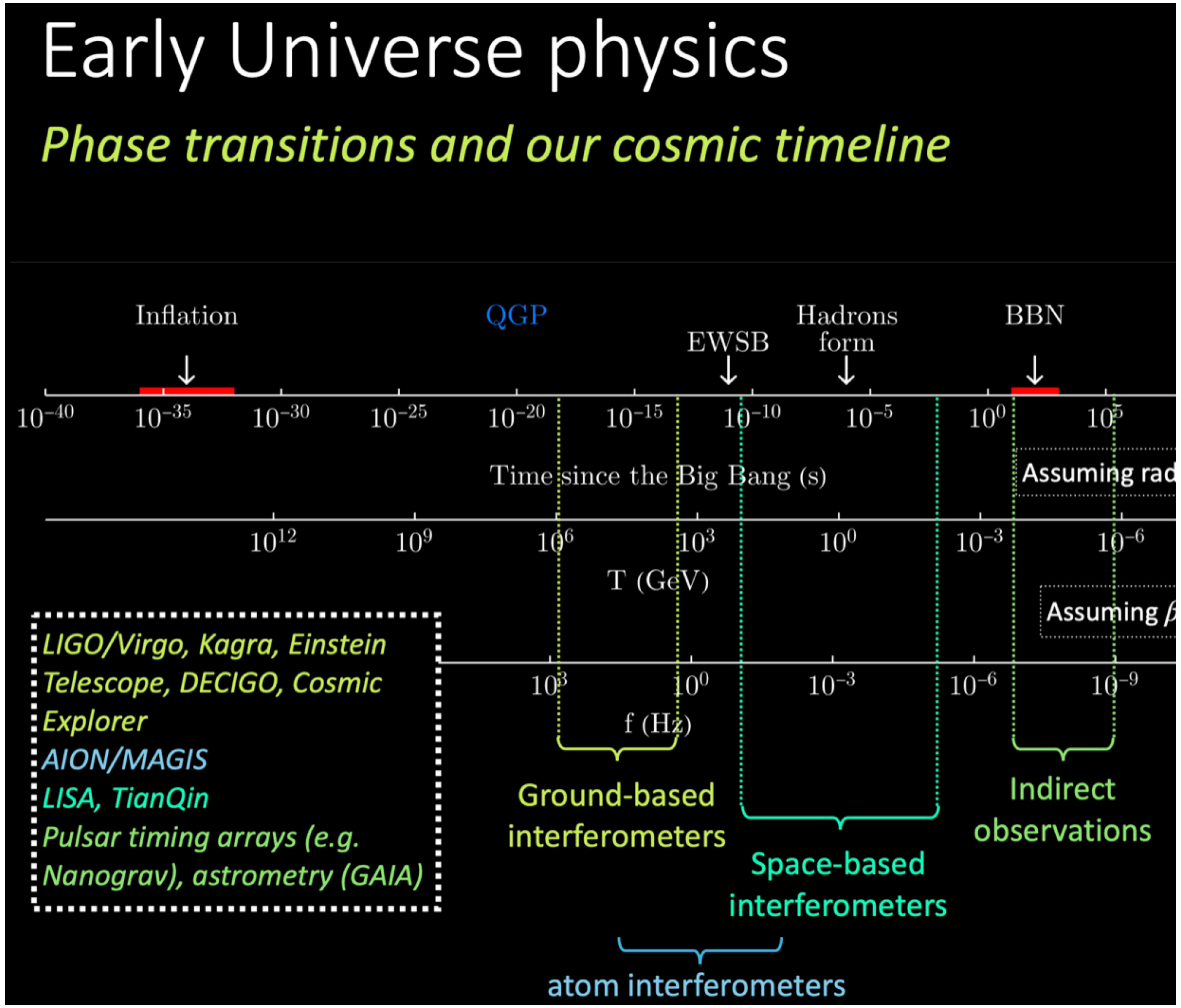
Tests of GR
Space-time near the horizon

Nuclear physics
The dynamics of dense matter
Multi-Messenger Astrophysics

Dark matter
Dark object binaries
Space-time near a black hole
Environmental effects
Early Universe signatures
Black hole superradiance
Direct searches for ultralight particles

Early Universe physics
Cosmological phase transitions
Cosmic strings

synergies w. accelerators

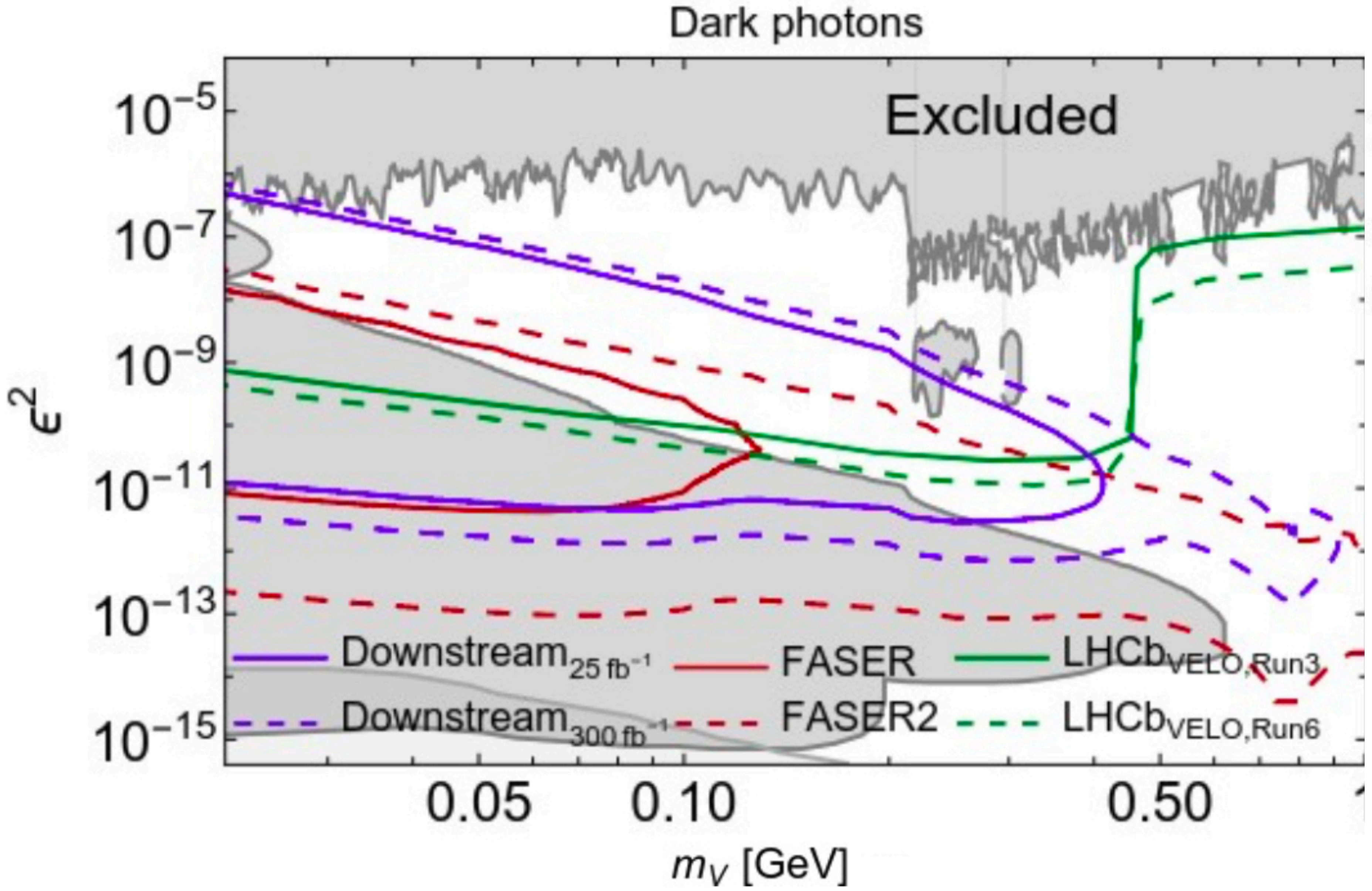


see previous discussion of Higgs selfcoupling as a probe of a strong 1st order EW phase transition (see also G. Weiglein talk)

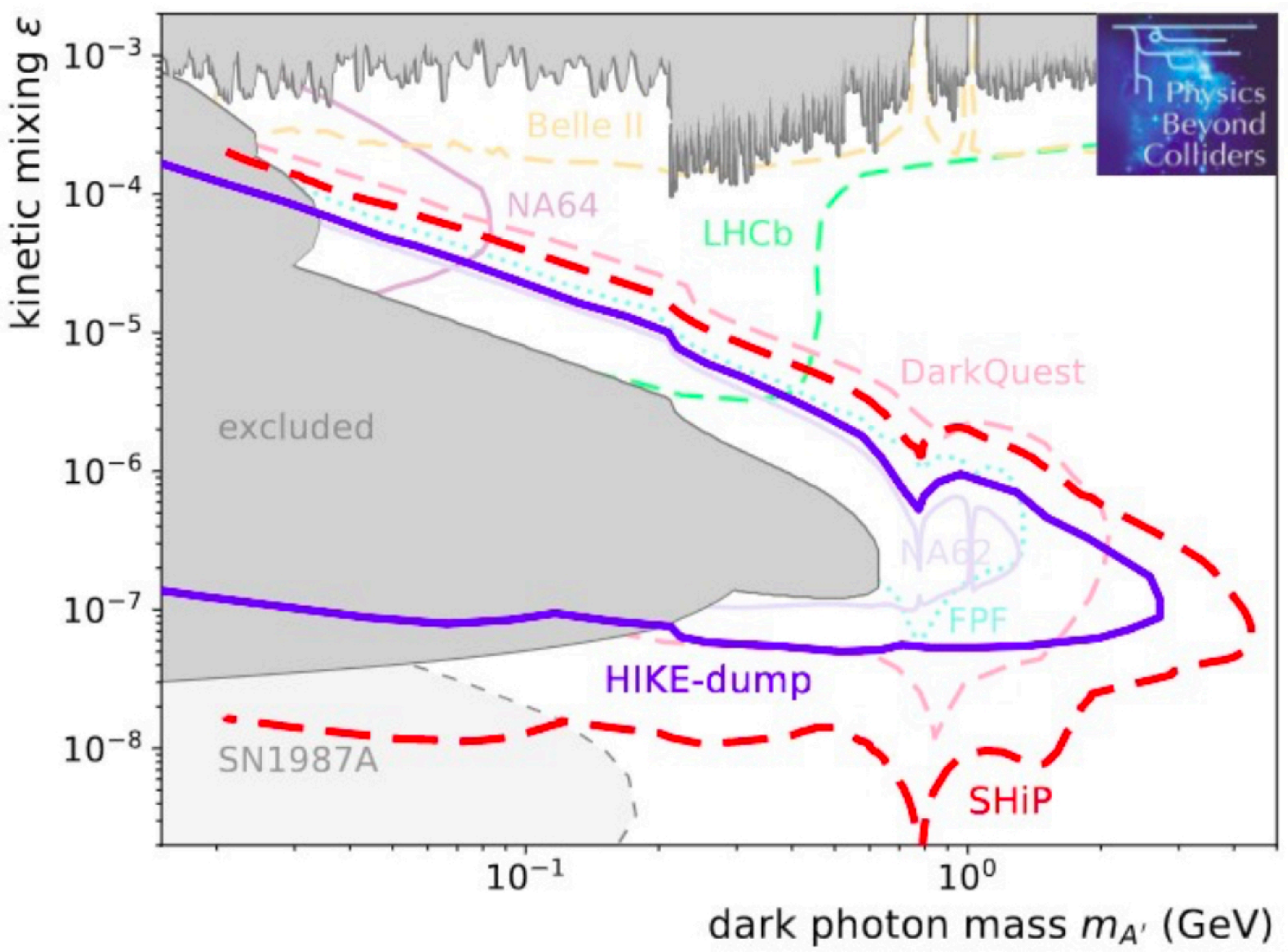
Feebly interacting particles, dark photons/Higgses, ALPs, relaxions, millicharged particles, magnetic monopoles, heavy neutral leptons, right-handed neutrinos, anomalous neutrino interactions, tau magnetic and electric dipole moments, cosmic ray interaction studies, etcetc:

this exploration goes well beyond the canonical ATLAS/CMS searches, including [dedicated current or future LHC experiments] (see talks by S.Trojanowski, B. Dev, J. Pinfold, …) **competing with or complementing the reach of other facilities** (see talks by P. Panci, V. Brdar, D. Ueda, Y. Semertzidis, R.Ischebeck, …)

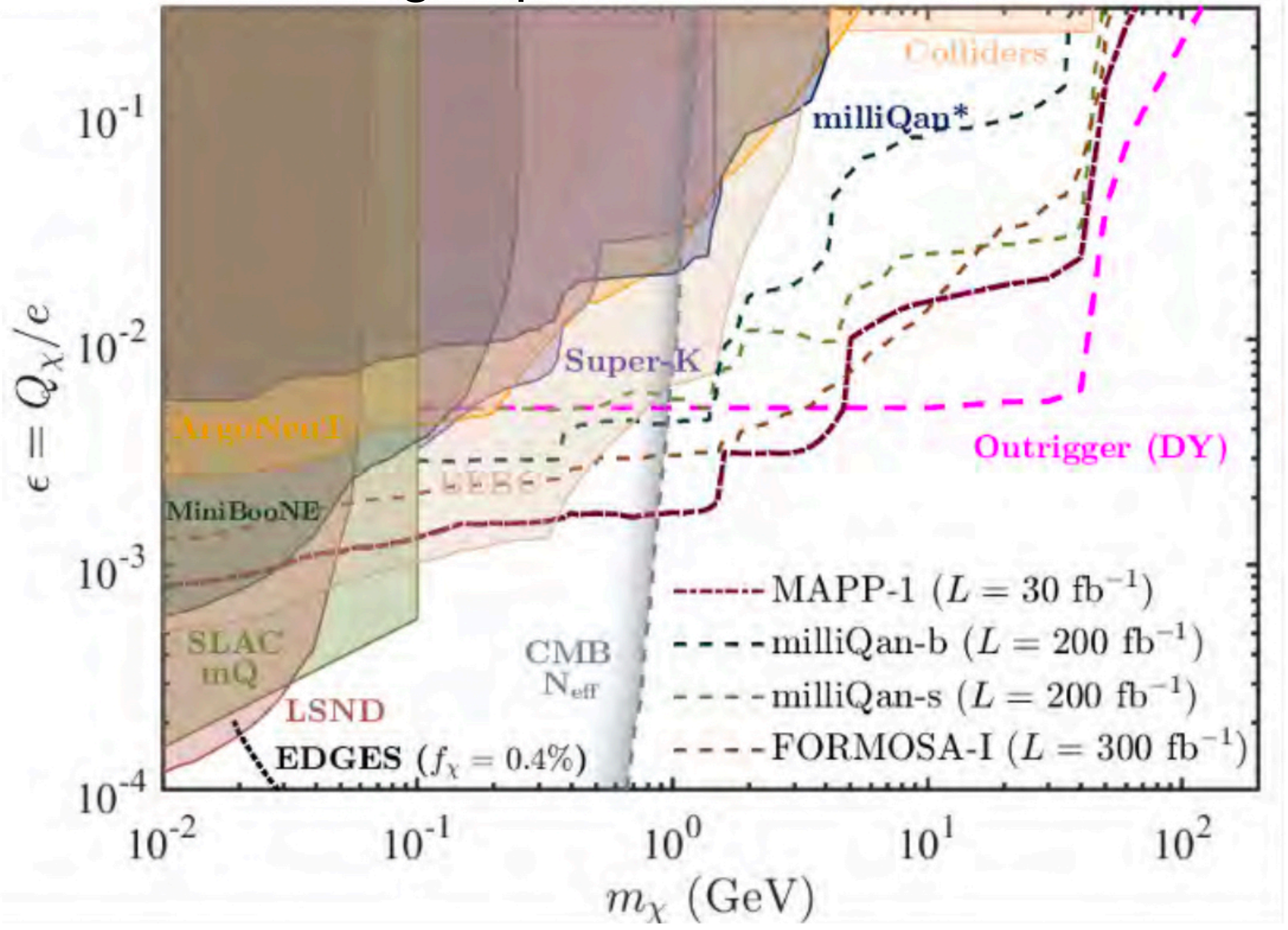
Operations with heavy ions contribute yet another dimension to the study of SM interactions in novel and extreme dynamical domains (see talk by A.Soto Ontoso)



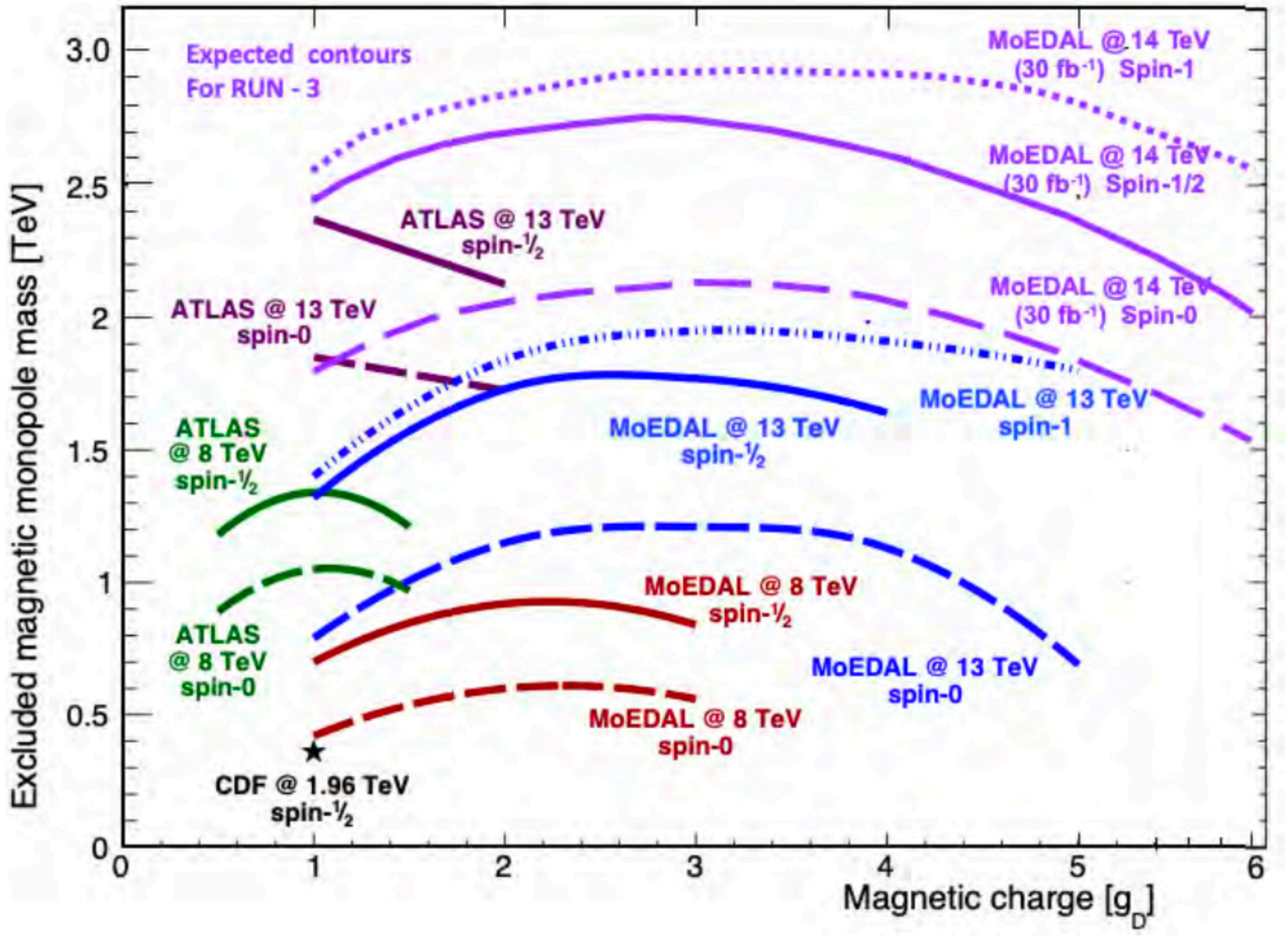
dark photons



millicharged particles



magnetic monopoles



The 9 LHC running experiments:

- **ALICE, ATLAS, CMS, FASER, LHCb, LHCf, MoEDAL/MAPP, SND@LHC, TOTEM (**absorbed in CMS as of run 3)
- **Over 4000 research published papers!**

- **The LHC, and more so HL-LHC, best embodies the spirit of cultivating diversity in the research programme of a single multipurpose facility**
- **There has never been in HEP history a more diverse physics programme carried out by a handful of synchronous experiments.**
- **LHC is continuously delivering measurements, including discoveries and surprises, of great impact on all areas of particle physics, from the dynamics of the fundamental interactions in the most extreme conditions of energy, density and temperature, to the exploration of the origin of fundamental puzzles such as the origin of EWSB, of DM, CPV, neutrino masses**

Where we’d like to go next:

future colliders

The opportunities

Higgs factories, A.Robson

FCC physics and FCC feasibility study, C.Grojean, E. Tsesmelis

Future e+ e- and muon colliders, P. Meade, N.Pastrone,

Key question for the future developments of HEP:
Why don’t we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**

- **Is the mass scale within LHC’s reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *precision* ⇒ *higher statistics, better detectors and dedicated experimental conditions*
- *sensitivity (to elusive signatures)* ⇒ *ditto*
- *extended energy/mass reach* ⇒ *higher energy*

Goals

precision

sensitivity to rare/elusive BSM up to Higgs mass scale

sensitivity to rare/elusive BSM between H and ~TeV mass scale

direct BSM reach beyond TeV mass scale

Facilities

Linear e+e–

FCC-ee + hh

muon collider

The discussion of future choices is all about the degree to which a facility meets the 4 goals, in the light of

- **technological feasibility, timescale and cost,**
- **our perception of how those goals have to be met (eg how much “precision” do we need?)…**
- **the role of diversity in the programme wrt the guaranteed deliverables part of the programme (eg value of heavy ions, dedicated experiments in the injector complex, ancillary detectors, etc.etc.**

see also remarks by P.Meade

… and don't forget G. Panico's message:

→ **energy helps accuracy!** [Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16]

✦ key point: deviations from SM typically **grow with energy**

$$\frac{\mathcal{A}_{\rm SM+BSM}}{\mathcal{A}_{\rm SM}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

→ LHC can match LEP sensitivity exploiting the **high energy** reach

$$0.1\ \% \quad \text{at} \quad 100\ \text{GeV} \longrightarrow 10\ \% \quad \text{at} \quad 1\ \text{TeV}$$

LEP energy *LHC energy*

The guiding principles

- The guaranteed deliverables
- The exploration and discovery potential
- Conclusive answers to important questions

The physics context: guaranteed deliverables

Prospects of QCD/top physics at future accelerators, S.Forte

QCD/top physics in the era of future accelerators, A. Mitov

Heavy ion physics: current status and prospects at future accelerators, A. Soto Ontoso

Electroweak physics at future accelerators, F. Piccinini

Higgs physics at future colliders, G.Weiglein

Flavor physics at future accelerators, Z. Ligeti

Status and future accelerator prospects of flavor physics, B.Stefanek

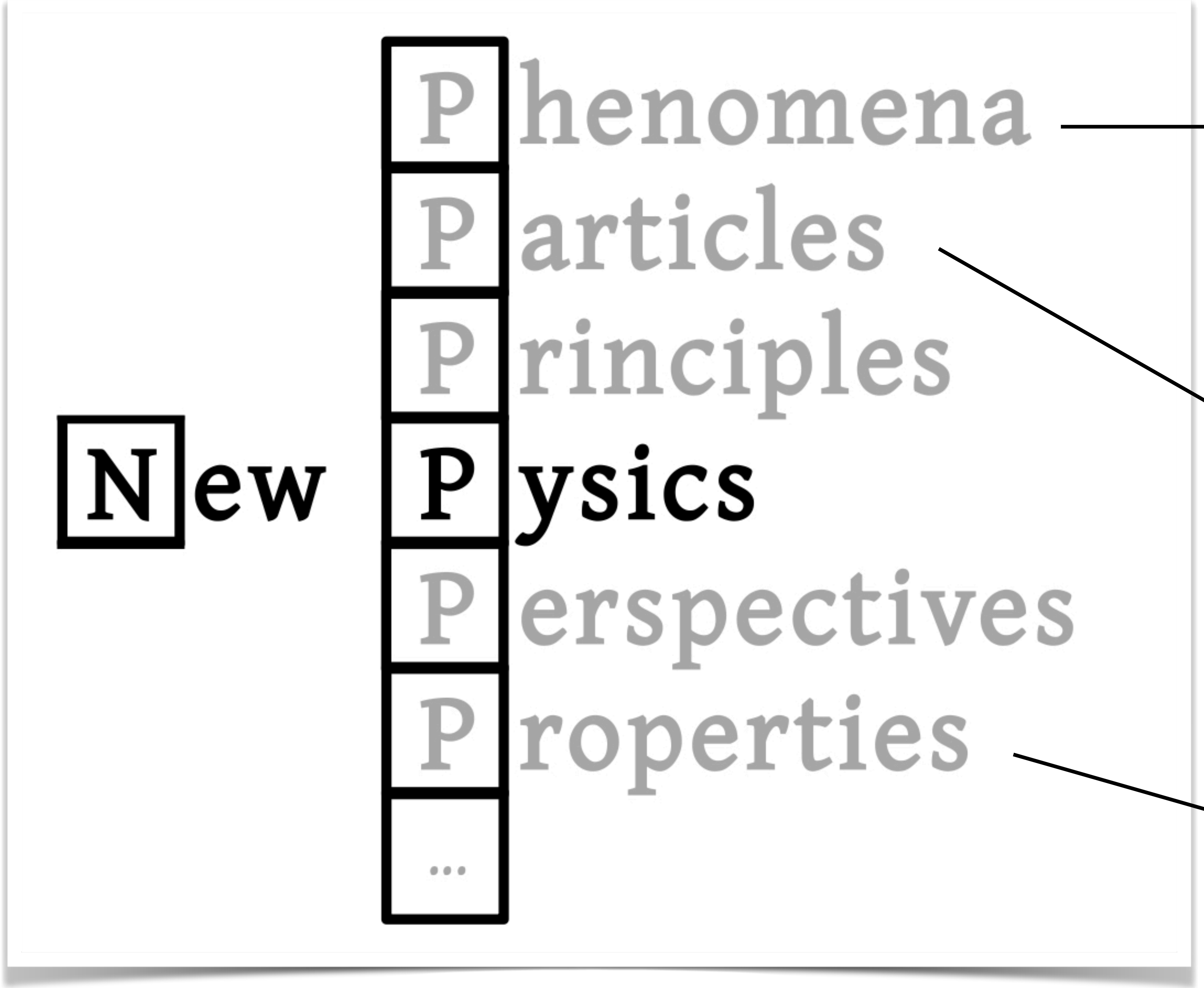
SMEFT at future colliders, G. Durieux

Prospects for precision measurements and SM physics well documented in these talks, in CDR/TDR of future facilities and in the ESPP2020/Snowmass21 literature

Guaranteed deliverables:

- improved *measurements* of fundamental constants and parameters
- deeper *exploration* of dynamics of SM interactions, eg
  - EW symmetry breaking and flavour phenomena
  - QCD non perturbative dynamics
- push further the boundary between established facts (*e.g. quarks* are pointlike at the scale of *(10 TeV)$^{-1}$*) and conjectures (*e.g. quarks* are *pointlike*)

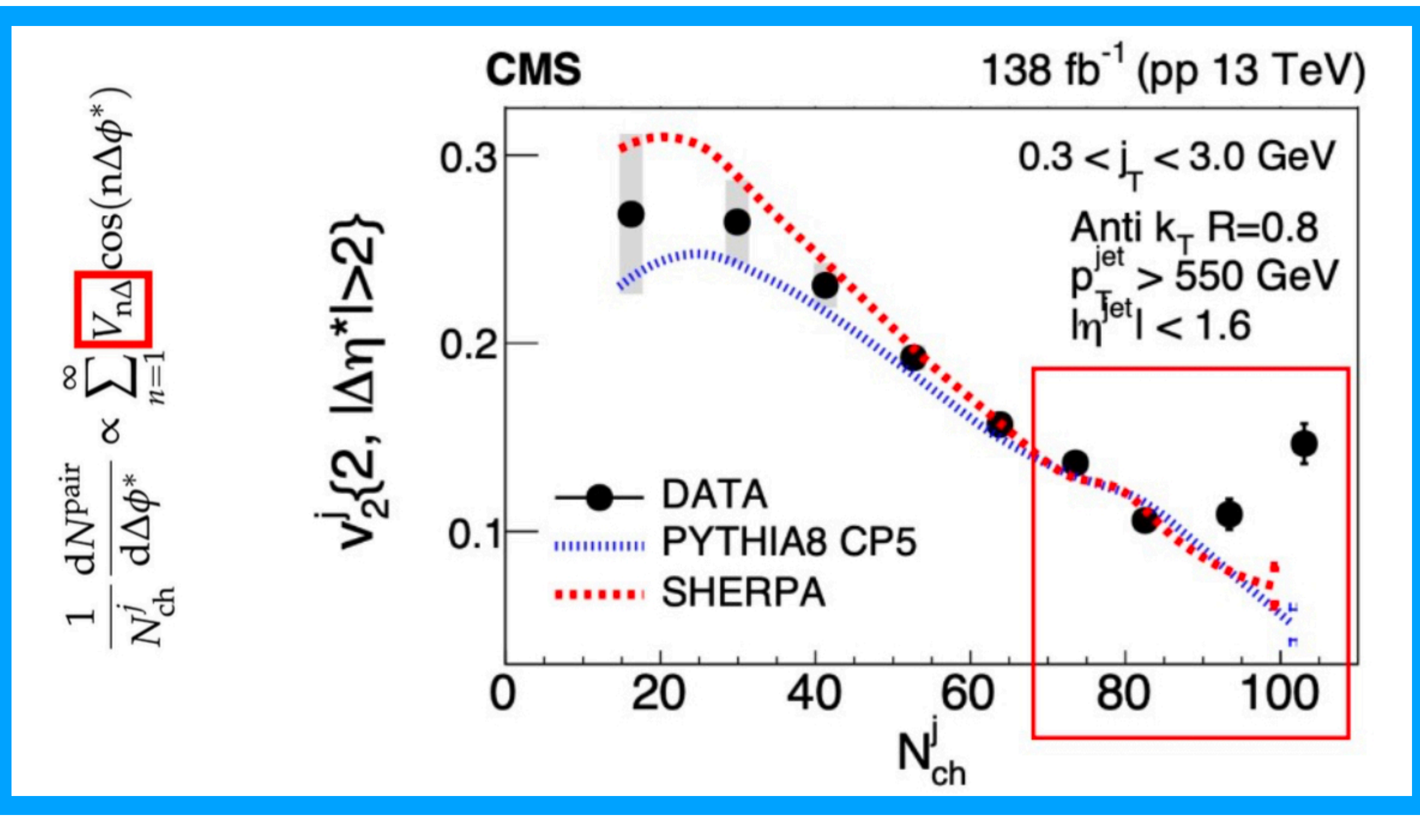
M. Riembau talk: "New physics is a multifaceted concept, it lies between the known and the unknown"



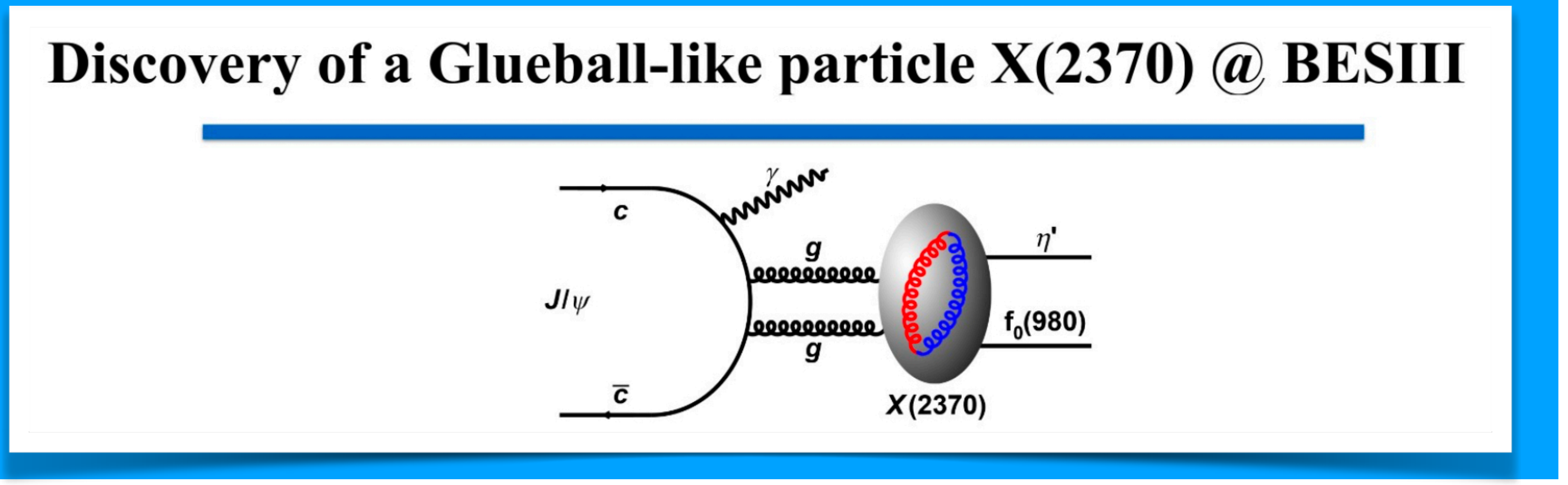
Collectivity?

Multiparton interactions?

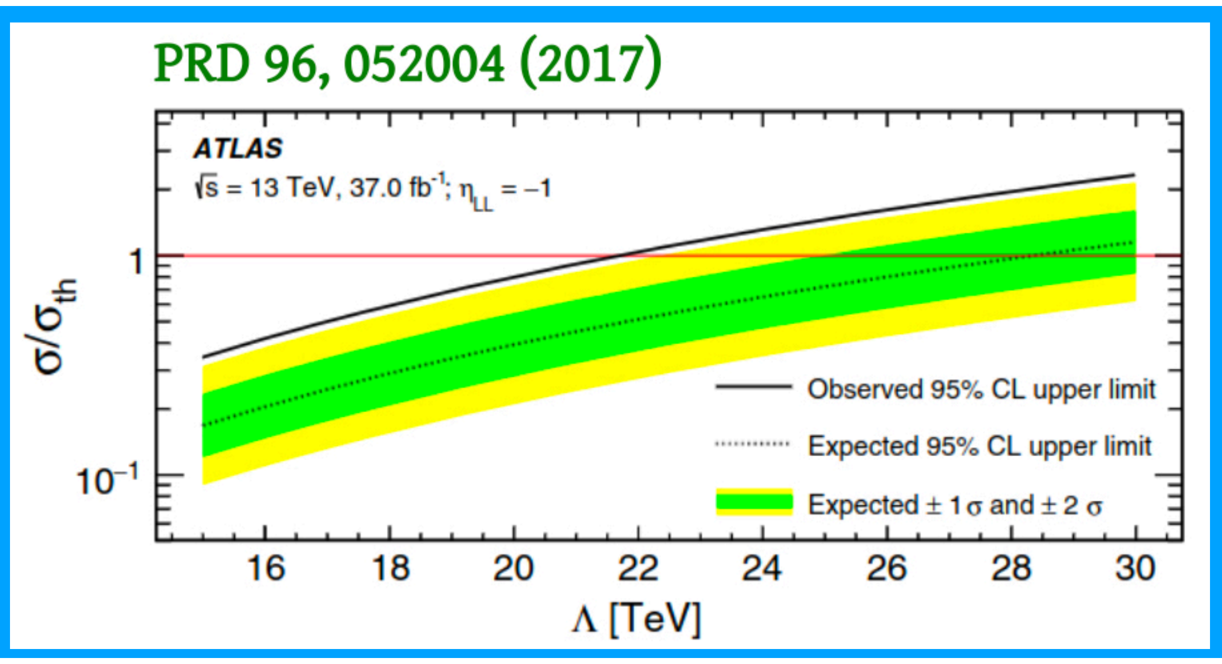
String dynamics?



new particles



limits to quark "pointlike-ness"



Flavour is still the least explored and documented, but possibly the most impactful, element of the "guaranteed deliverables" potential of FCC-ee at the Z pole: *should it be considered as a mandatory element of future facilities?*

statistics statistics statistics !!!

Z. Ligeti

Factors of a few be essential

ANNALS OF PHYSICS: 5, 156–181 (1958)

Long-lived Neutral K Mesons*

M. Bardon, K. Lande, and L. M. Lederman

Columbia University, New York, New York, and Brookhaven National Laboratories, Upton, New York

and

William Chinowsky

Brookhaven National Laboratories, Upton, New York

set an upper limit $<0.6\,\%$ on the reactions

$$K_2^0 \to \begin{cases} \mu^\pm + e^\mp \\ e^+ + e^- \\ \mu^+ + \mu^- \end{cases}$$

and on $K_2^0 \to \pi^+ + \pi^-$.

Volume 6, Number 10 PHYSICAL REVIEW LETTERS May 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov

Joint Institute of Nuclear Research, Moscow, U.S.S.R.

(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3 % for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our

"At that stage the search was terminated by administration of the Lab." [Okun, hep-ph/0112031]

Volume 13, Number 4 PHYSICAL REVIEW LETTERS 27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§

Princeton University, Princeton, New Jersey

(Received 10 July 1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As empha-

[Not what the goal of the experiment was!]

Particle production (10^9)	$B^0 + \bar{B}^0$	$B^\pm$	$B_s^0 + \bar{B}_s^0$	$\Lambda_b + \bar{\Lambda}_b$	$B_c^\pm$	$c\bar{c}$	$\tau^+\tau^-$
Belle II (50 ab^{-1})	27	27	—	—	—	65	45
tera-Z (5×10^{12} Z)	600	600	150	130	3	600	170

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	$\sim 2\,000$	~ 10	n/a (5)
LHCb Run I	150	-	~ 15 (–)
LHCb Upgrade	~ 5000	-	~ 500 (50)
FCC-ee	~ 200000	~ 1000	$\sim$1000 (100)

Impact of FCC-ee Tera-Z measurements like $b \to s\tau\tau$ and $B_c \to \tau\nu$ discussed in the context of current LHCb anomalies in the talk by B. Stefanek.
For impact of rare decays, flavour in the Higgs sector, and much more, see Z.Ligeti

The physics context: exploration and conclusive answers

Precision measurements at future colliders, G. Panico

Neutrino physics at future colliders, B.Dev

BSM phenomenology at future accelerators, H. Bahl

BSM theory in the era of future accelerators, M.Riembau

DM phenomenology: Brief status, P. Panci

Status and prospects of dark matter searches, R. Mahbubani

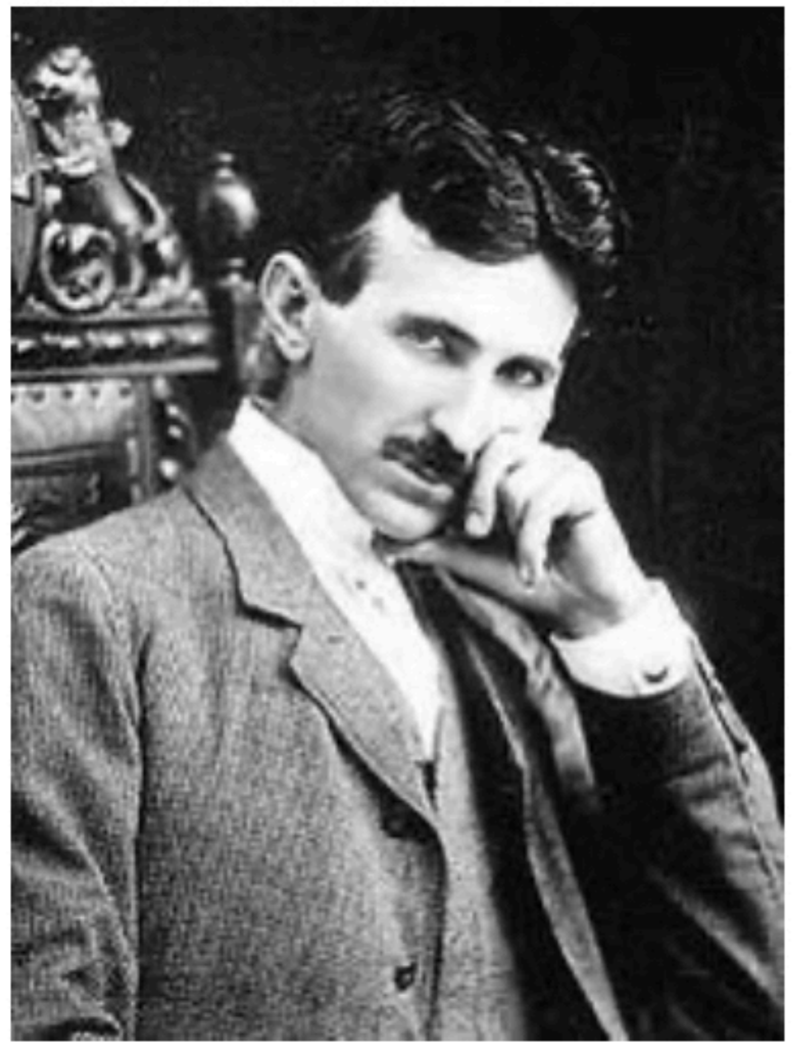
Feebly-interacting particles at future colliders, S.Trojanowski

Physics at a future muon collider, D. Buttazzo

From H. Bahl's talk

"We crave for new sensations but soon become indifferent to them. The wonders of yesterday are today common occurrences."

Nikola Tesla



→ So far no evidence for BSM physics…

But: motivation to search for BSM physics is still unbroken.

Nature of EWSB

Neutrino masses

Dark matter

Baryon asymmetry

Naturalness

Conclusive yes/no answers we should try to extract from a future facility — examples

- Is DM a thermal WIMP ?
- What was the nature of the EW phase transition ?
- Does the origin of neutrino masses lie at the TeV scale ?
- Are the Higgs potential and mass defined by physics at the few-TeV scale ?
- are there BSM sources of CPV below the few-TeV scale ?

R.Mahbubani, P.Panci

e.g. $\mathcal{L}_{\rm BSM} = i\bar{\chi}\not{D}\chi - M_\chi\bar{\chi}\chi + \ldots$ (Dirac fermion)

The original 'wimp miracle' $\sigma \sim \frac{\alpha_2^2}{M_{\rm weak}^2}$

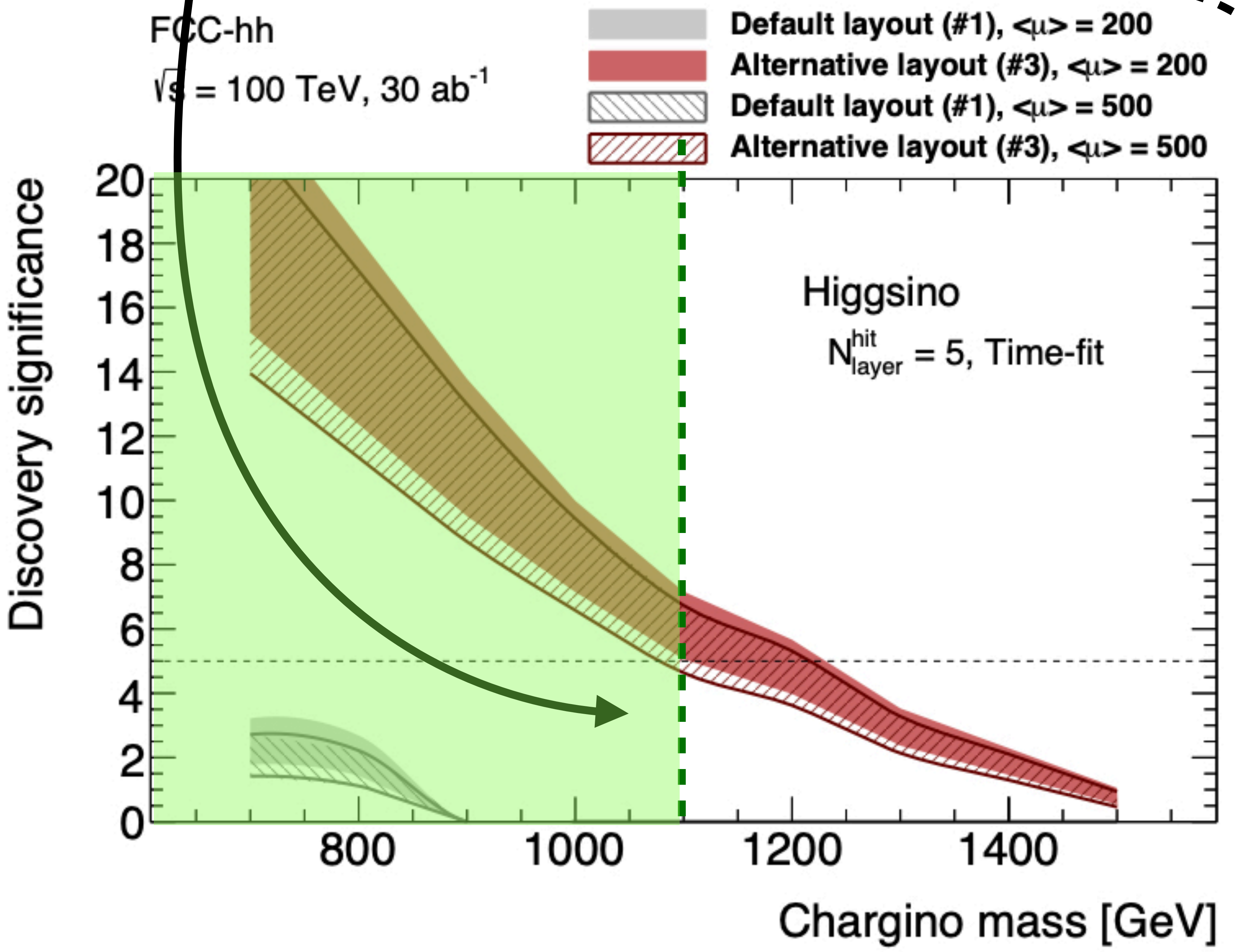
Saturating thermal relic abundance fixes mass

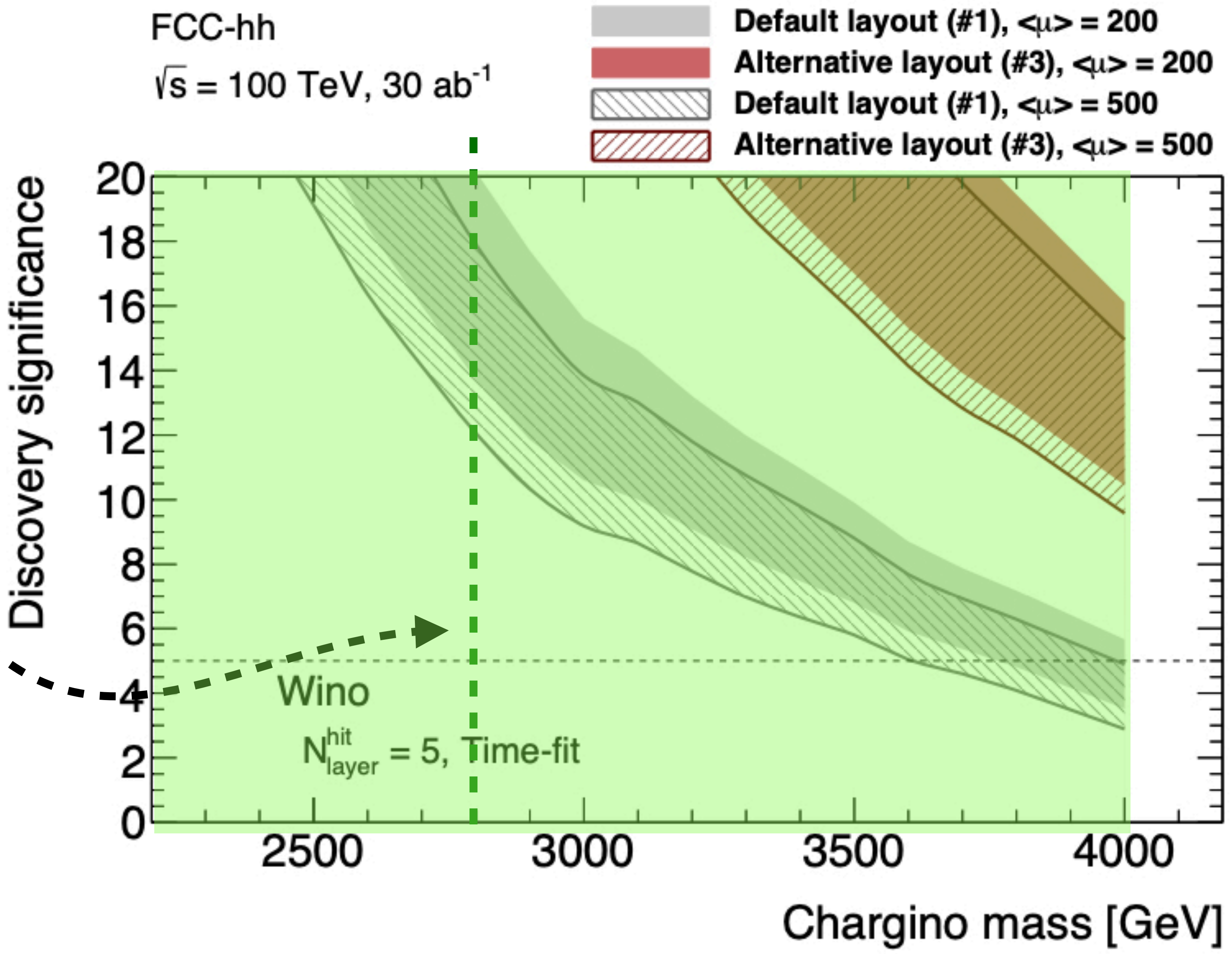
$$\Omega h^2 \approx 0.1 \times \left(\frac{3\times 10^{-26} cm^3 s^{-1}}{\langle\sigma v\rangle}\right)$$

M_χ =
- 1.1 TeV (Dirac (1, 2, -½) "higgsino")
- 2.8 TeV (Majorana (1, 3, 0) "wino")
- 14 TeV (Majorana (1, 5, 0) "quintuplet" fermion)

Cirelli et. al. hep-ph/0512090

Example: is DM a thermal WIMP?





Conclusive 5σ discovery or exclusion up to the thermal limit

Similar reach obtained at 10 TeV μ collider

The open challenges: accelerators

Advanced accelerators for future particle physics experiments, J. Osterhoff

AWAKE: from proof-of-concept towards first particle-physics applications, J.Farmer

The path towards the Future Circular Collider at CERN, E. Tsesmelis

Positron sources for future lepton colliders, G. Moortgat-Pick

Not covered in detail at the conference, but critical for a global picture of the challenges ahead:

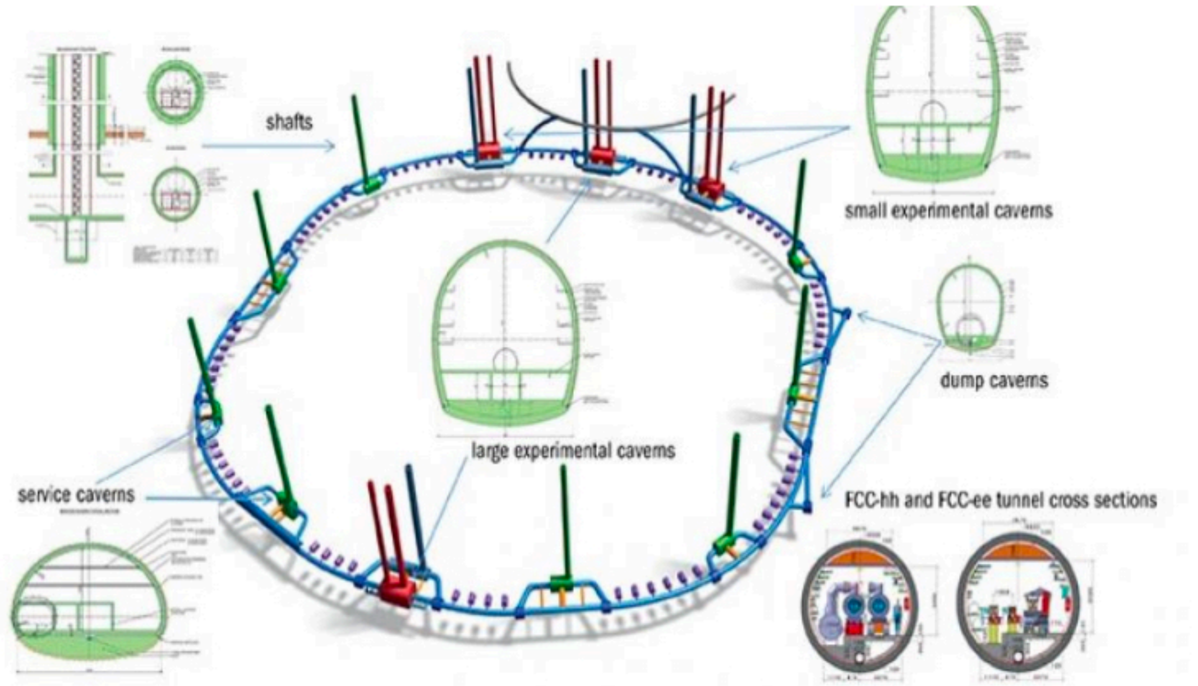
- **high-field magnet technology (for hadron and muon colliders)**
- **muon cooling demonstrator**

J. Osterhoff

10 TeV pCM technology must be developed, no concept ready

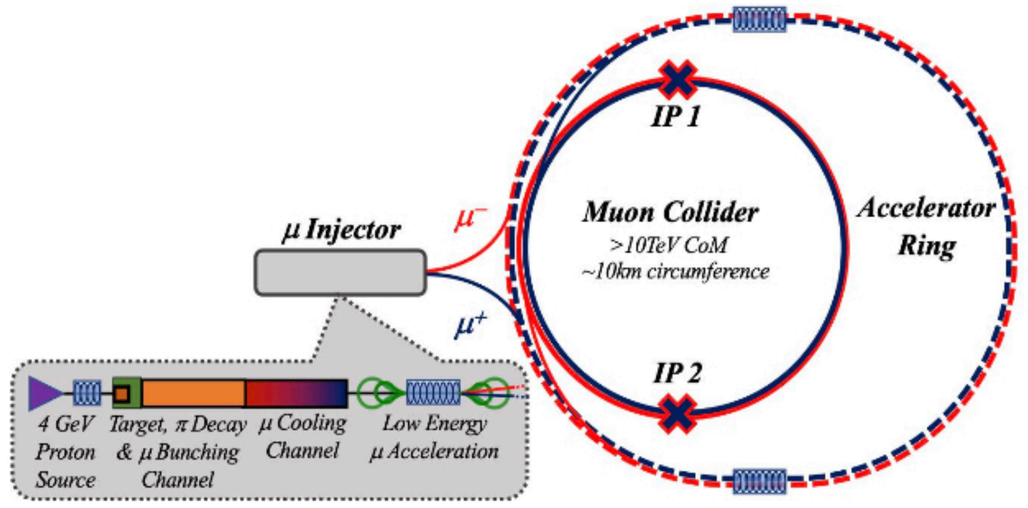
Proton collider

Key needs: high field magnets, detectors



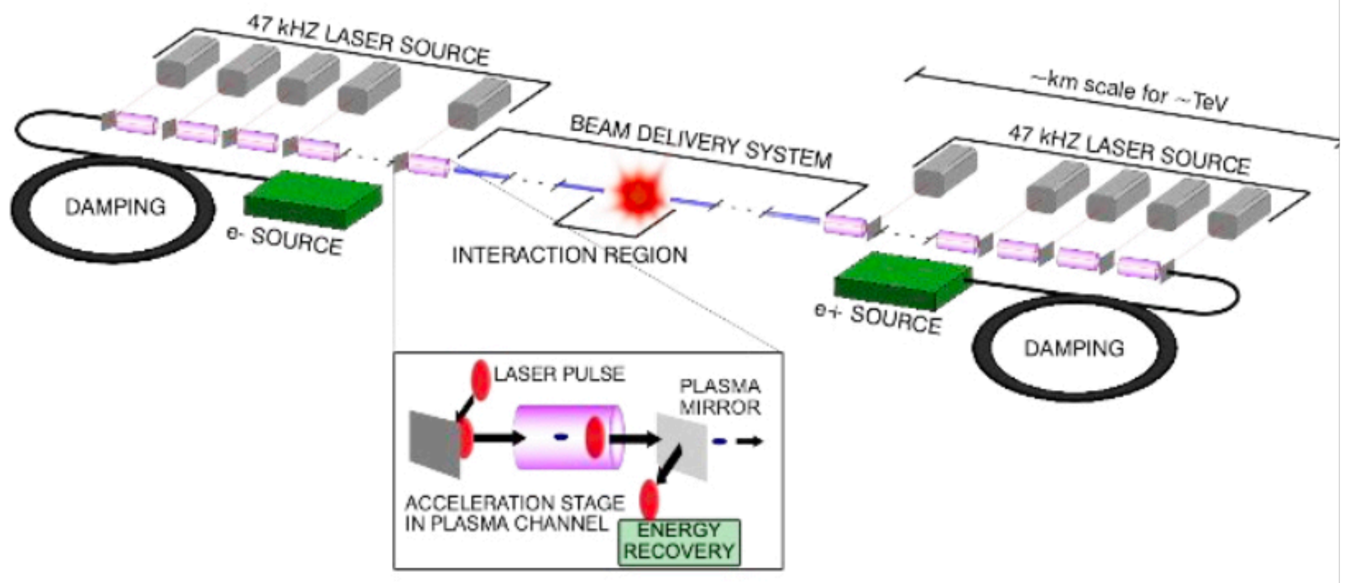
Muon collider

Key needs: targets, cooling



Linear wakefield lepton collider

Key needs: *see remainder of the presentation*



"All options for a 10 TeV pCM collider are new technologies under development and R&D is required before we can embark on building a new collider"

P5 Report (2023), p. 17

Challenges for all concepts: size, luminosity, power, detector

e^+e^- collisions offer similar physics to muons

- Potential advantage: relatively clean detector environment
- Conventionally too large and power hungry beyond few TeV

Advanced Accelerator Mission for Particle Physics

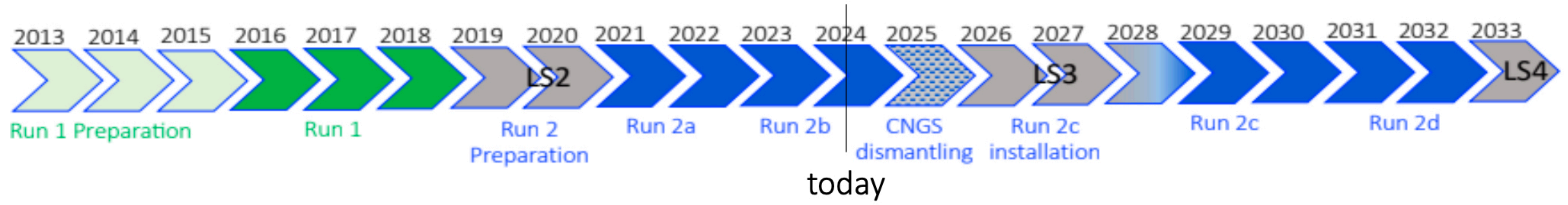
- **Reduce the size of future colliders**
- **Reduce the cost of future colliders**
- **Reduce the environmental impact of future colliders**

Summary and Conclusions

Advanced accelerators for future particle physics experiments

- Plasma wakefield accelerators are continuing to progress at a rapid pace, have demonstrated beam parameters for photon science applications
- Progress toward colliders encouraging — challenges remain: positrons, multi-staging, …
- New schemes, such as HALHF, demonstrate cost saving potential for plasma-based Higgs factory
- US P5 sets focus on a 10 TeV pCM collider, no technology ready, wakefields are a contender
- **We need intense R&D and test facilities to close the existing capability gaps for HALHF + 10 TeV collider**
- **We want to strongly engage the particle physics community to identify the most promising future avenues**

AWAKE Timeline



Particle physics

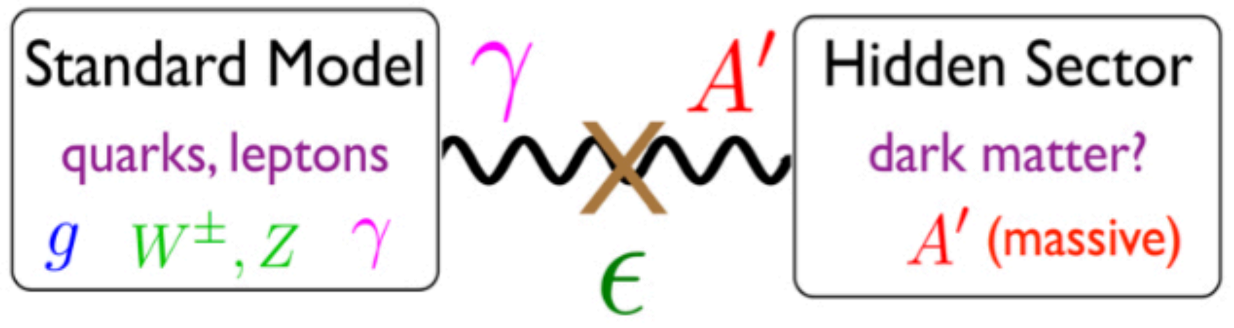
J. Farmer

Run 1 demonstrated self-modulation and first acceleration. **2013-15**
Run 2a demonstrated electron seeding. **’21-‘22**
Run 2b to demonstrate sustained wakefield amplitude. **’23-‘24**
Run 2c to demonstrate emittance control. **’29-‘30**
Run 2d to demonstrate extensible plasma sources. **’31-‘32**

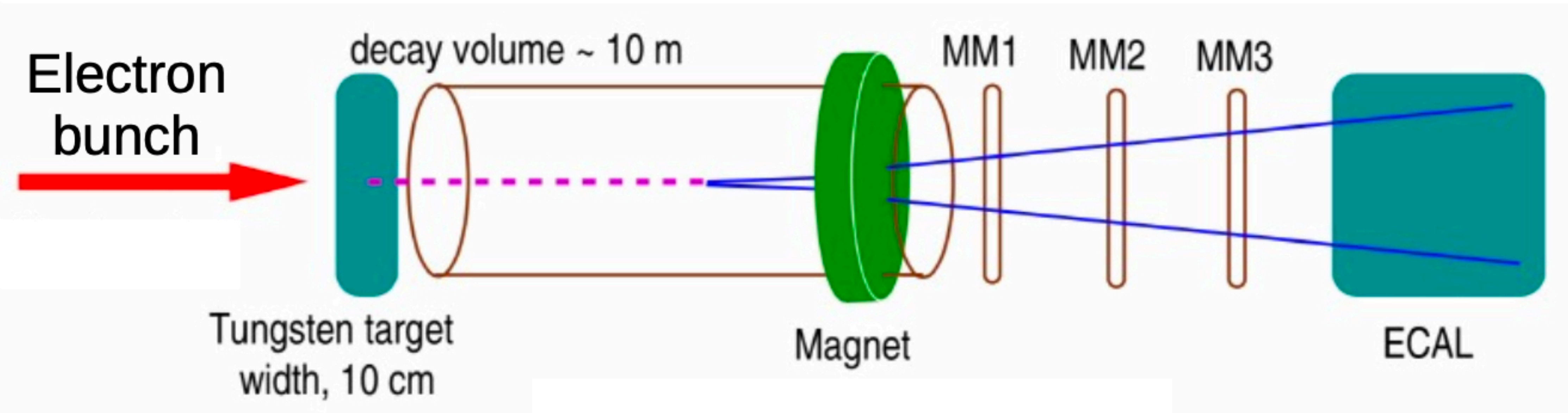
Passed successfully all milestones so far, proving excellent agreement between simulations and data

All technologies and beam parameters for a future particle physics experiment demonstrated by early 2030s.

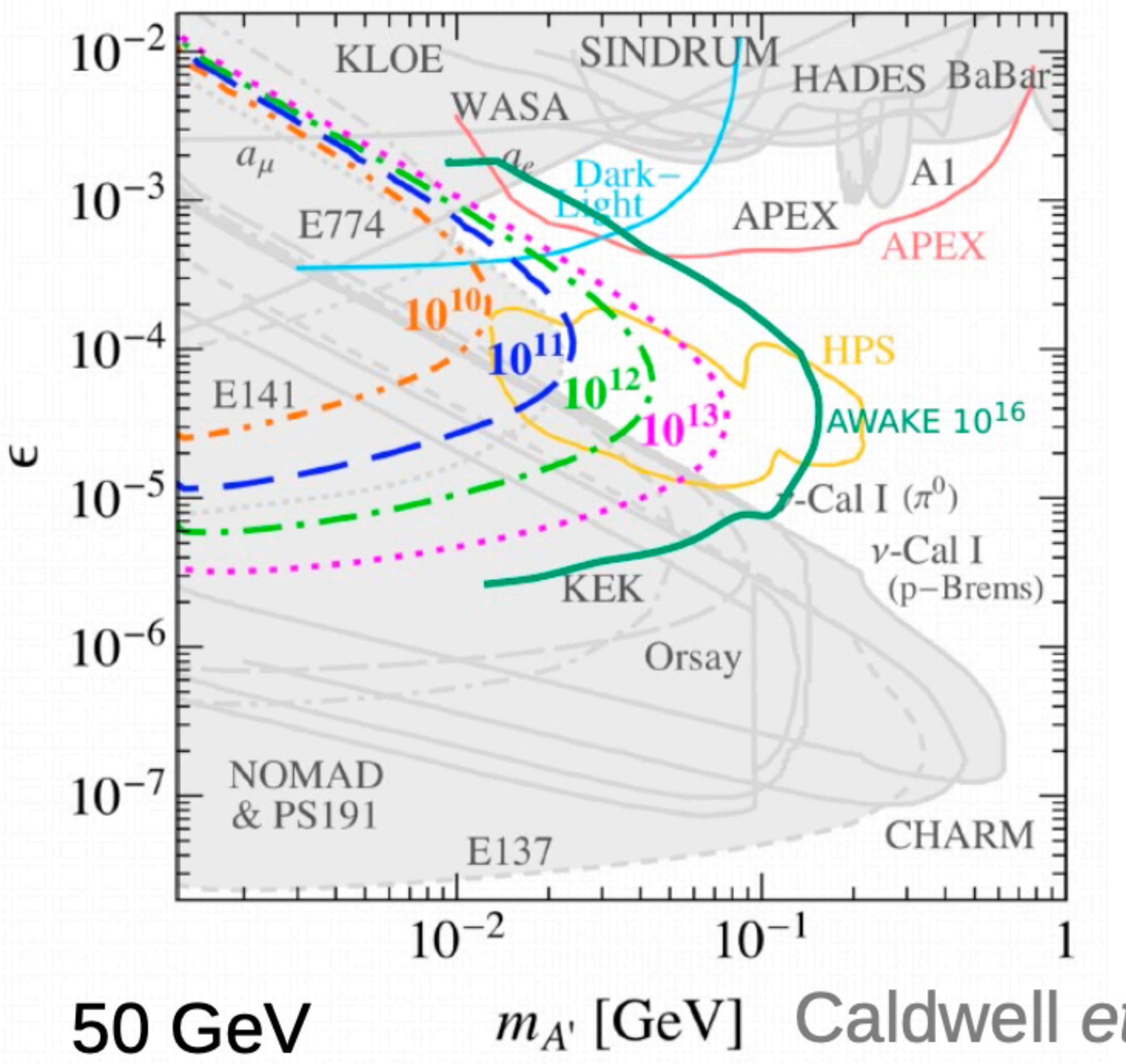
Example of possible first physics application by mid-30’s



- Decay of dark photon into visible particles (e.g. e+/e-)
- Energy and flux is important
- Relaxed parameters for emittance



Beam dump experiment, similar to NA64



50 GeV electrons

Caldwell *et al.*, 1812.11164

Key Challenges of the facility

Proton driver production
Baseline @ International Design Study

International
MUON Collider
Collaboration

10+ TeV
completely new
regime
to explore!

Beam induced background

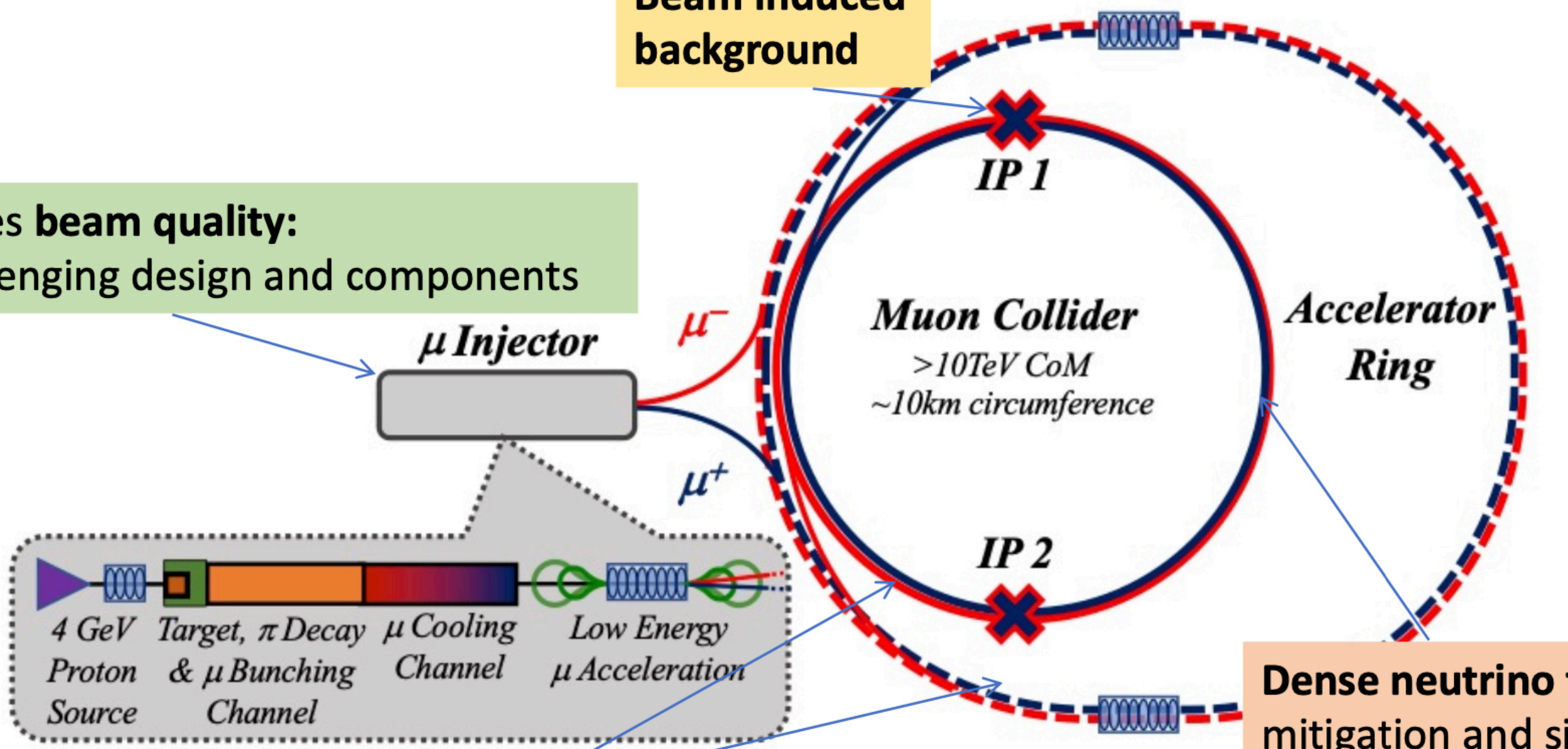
Drives **beam quality:**
challenging design and components

$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ \text{ab}^{-1}$

@ 3 TeV ~ 1 ab^{-1} 5 years

@ 10 TeV ~ 10 ab^{-1} 5 years

@ 14 TeV ~ 20 ab^{-1} 5 years



Dense neutrino flux
mitigation and site

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

Muon Collider Forum Report

8

New/recent coordinated initiatives

New US initiative to organize the community for an end-to-end 10 TeV pCM wakefield collider design

"Wakefield concepts for a collider are in the early stages of development. A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout."

P5 Report (2023), p. 85

- *Goal:* **end-to-end design concept** including sub-systems (detectors, beam delivery), cost estimates, **self-consistency**, **based on strong physics case**
- LBNL, SLAC, ANL launched 10 TeV wakefield collider initiative
  - Organizes the **US wakefield accelerator community** *(biweekly meetings; since January)*
  - Strong **links to particle physics incl. detectors** *(monthly meetings at LBNL, and with SLAC; since April)*
  - Strong **links to worldwide activities** emerging through ICFA ANA ALEGRO

Intl Muon Collider Collaboration

International Muon Collider Collaboration @ CERN

International MUON Collider Collaboration

High-priority future initiatives [..] **ESPPU recommendation in 19 June 2020:**

In addition to the high field magnets the **accelerator R&D roadmap** could contain: 10.17181/CERN.JSC6.W89E

[..] an **international design study** for a **muon collider**, as it represents a **unique opportunity** to achieve a ***multi-TeV energy domain*** *beyond the reach of* e^+e^- *colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider.
The **biggest challenge** remains to produce an intense beam of cooled muons….

Laboratory Directors Group (LDG) initiated the Muon Collider Collaboration July 2, 2020

Muon Collider Collaboration (IMCC) Objective:

Project Leader: *Daniel Schulte*

In time for the **next European Strategy for Particle Physics Update**, the **Design Study based at CERN** since 2020 aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified.**
It will **provide a baseline concept**, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.
It will also **identify an R&D path to demonstrate the feasibility.**

NEW ESPPU Input documents due by March 31 2025

Web page: http://muoncollider.web.cern.ch

5

tackling challenges beyond accelerator technology …

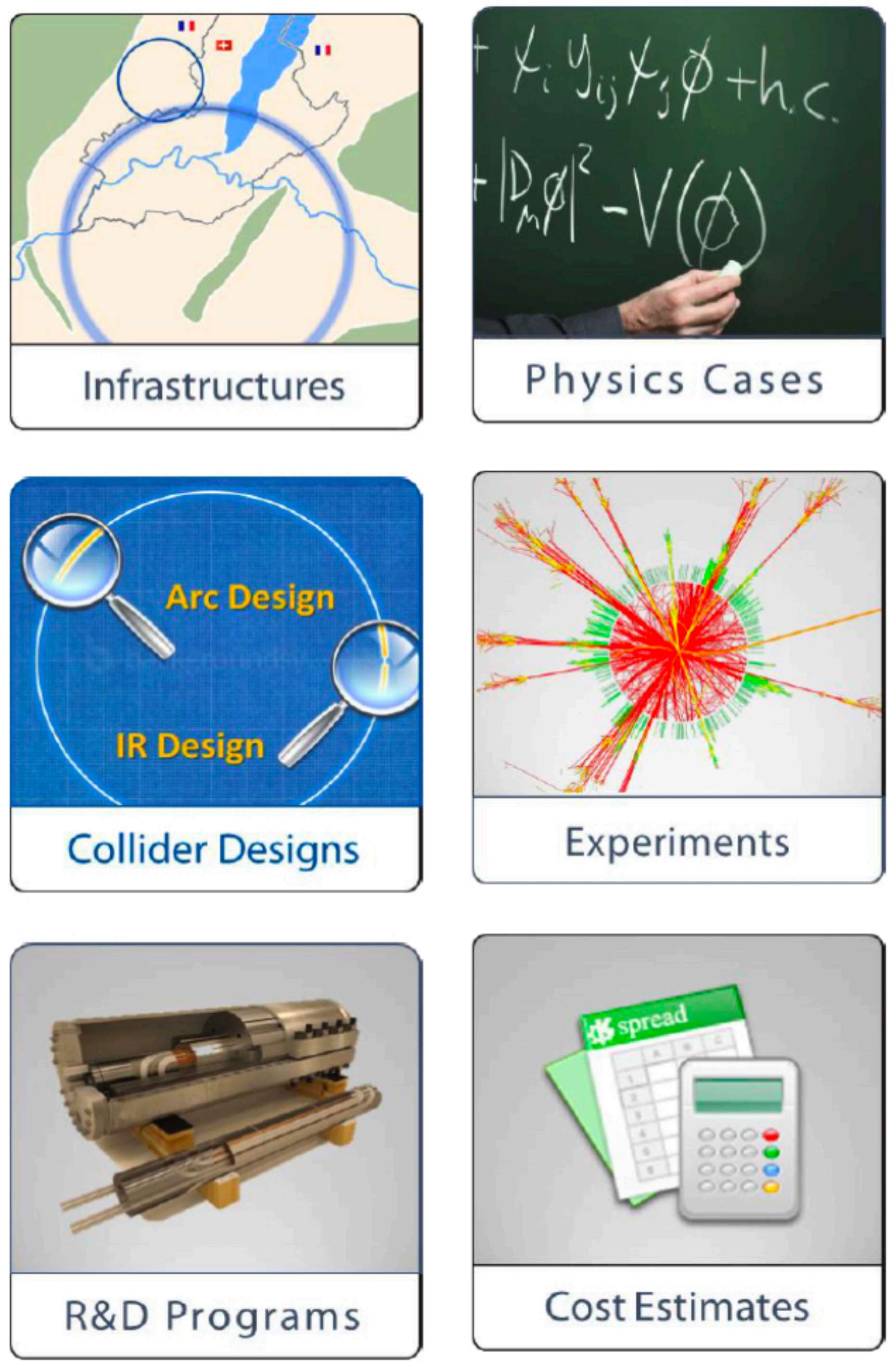
C. Grojean and E. Tsesmelis

FUTURE CIRCULAR COLLIDER

High-level Goals of Feasibility Study

High-level goals of Feasibility Study

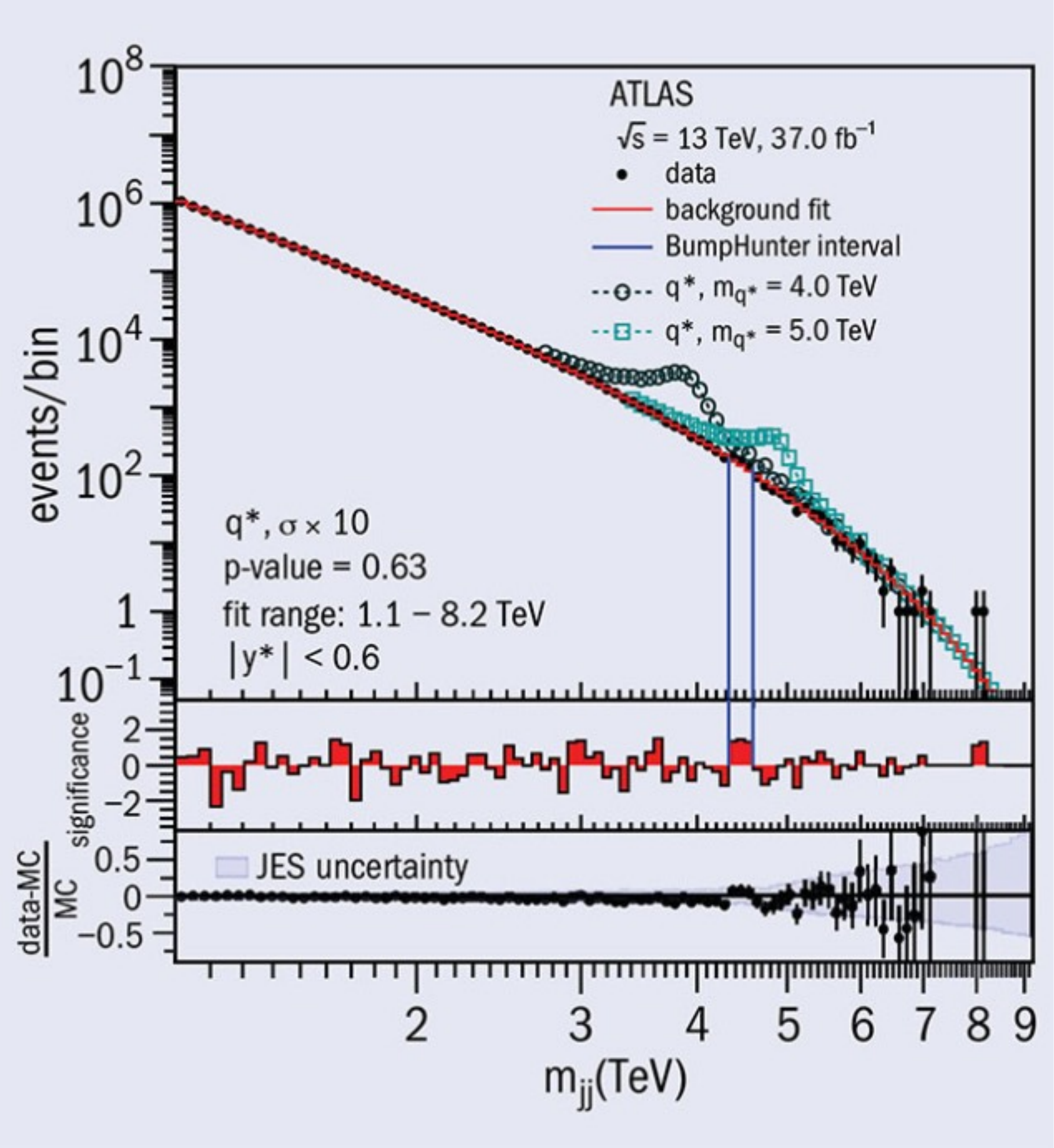
- optimisation of placement and layout of the ring and related infrastructure, and demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval, with a focus on identifying and surmounting possible showstoppers;
- optimisation of the design of the colliders and their injector chains, supported by targeted R&D to develop the needed key technologies;
- development and documentation of the main components of the technical infrastructure;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, environmental aspects and energy efficiency;
- identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project;
- consolidation of the physics case and detector concepts for both colliders.

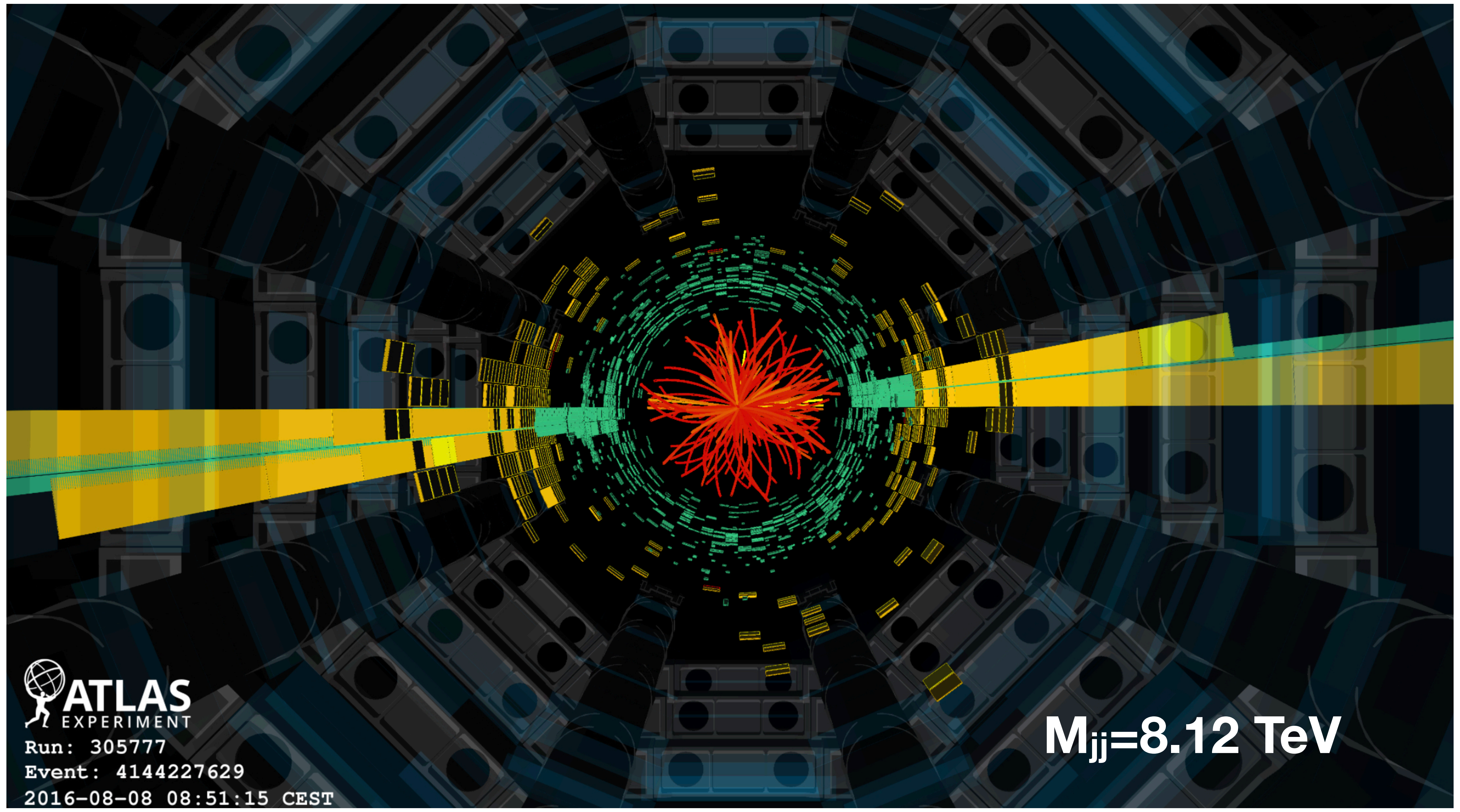


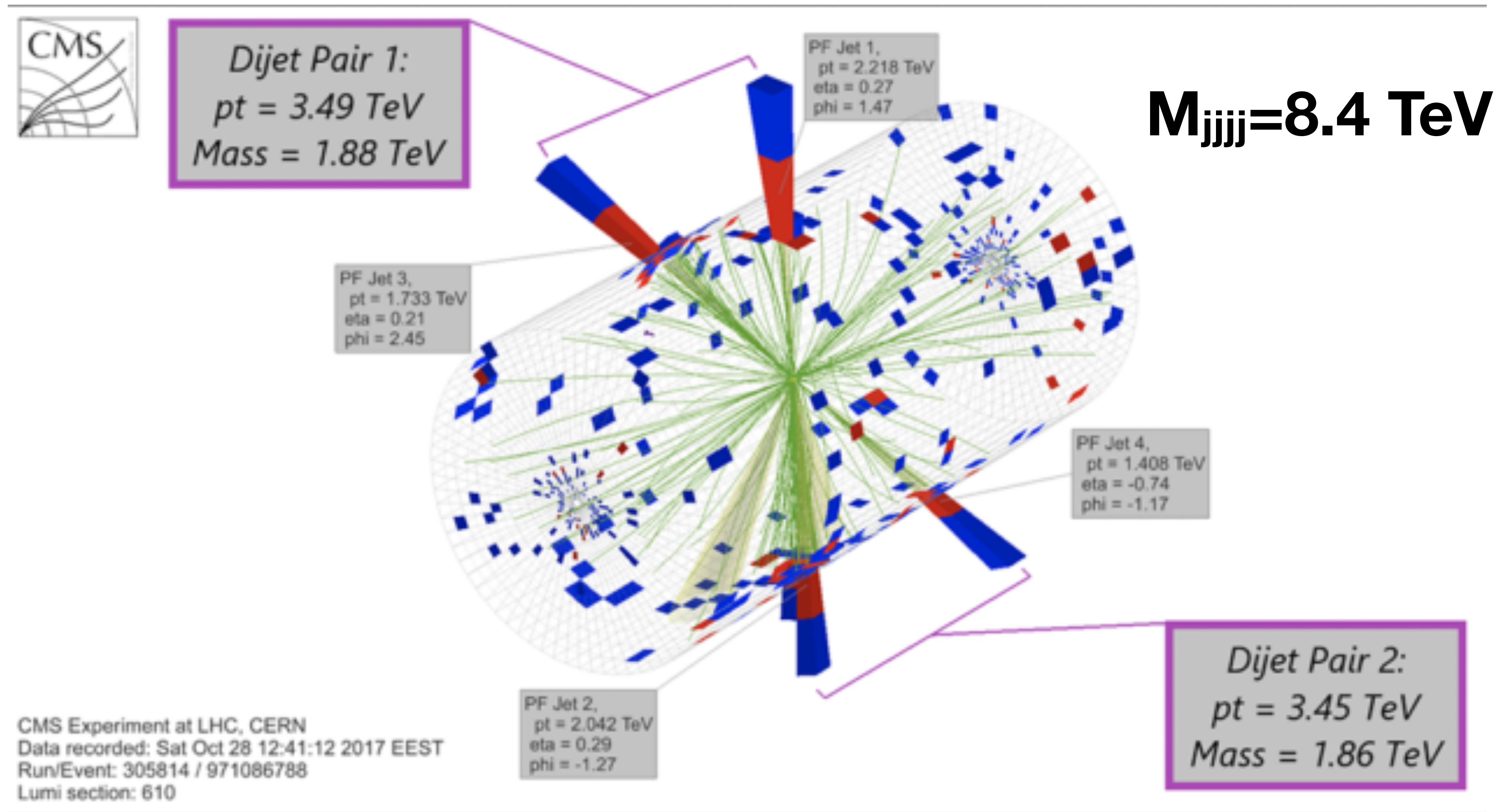
A remark …

> ***“All options for a 10 TeV pCM collider are new technologies under development and R&D is required before we can embark on building a new collider”***
>
> *P5 Report (2023), p. 17*

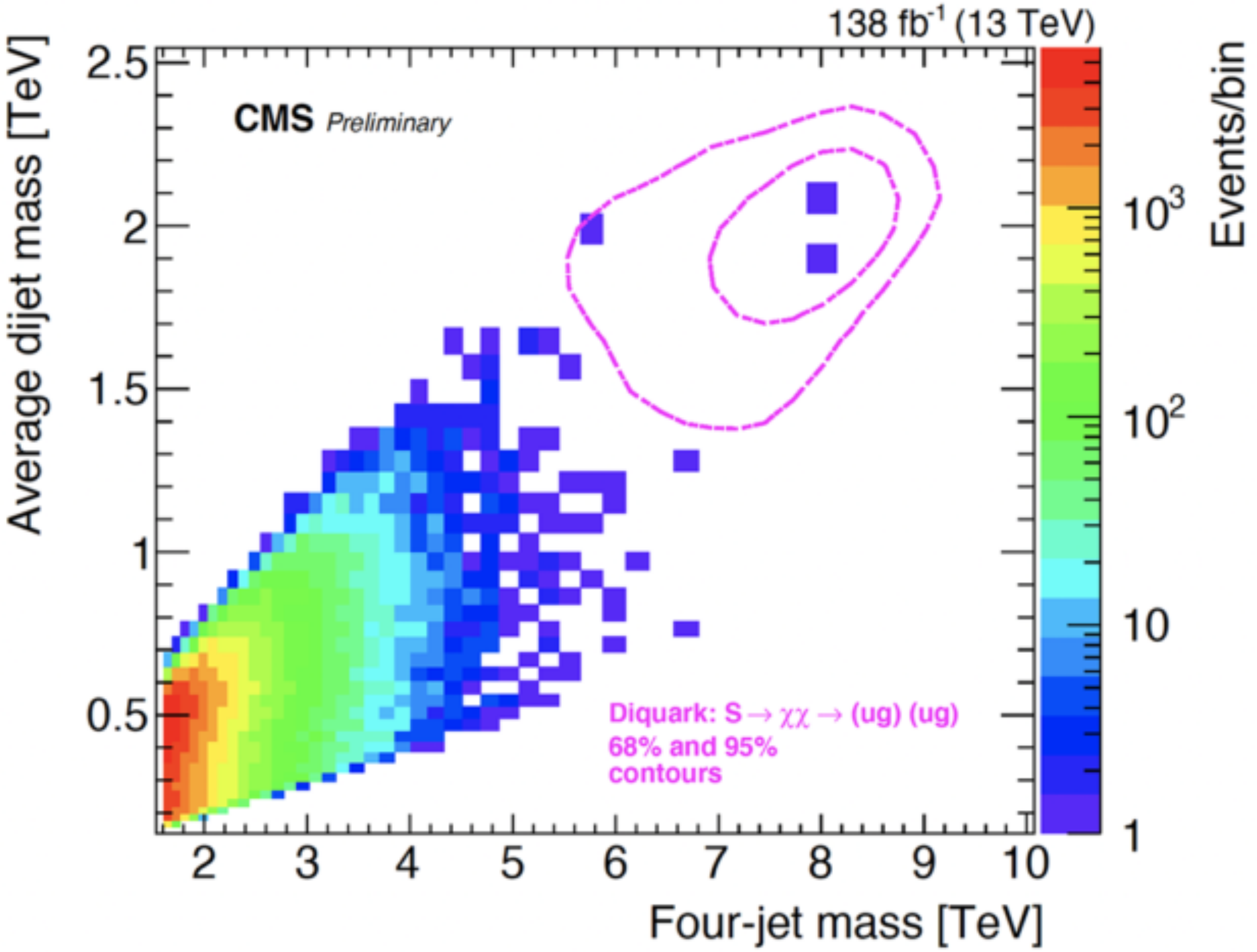
The 10 TeV pCM holy Grail: how far are we from it, really?
not much actually, already at the LHC



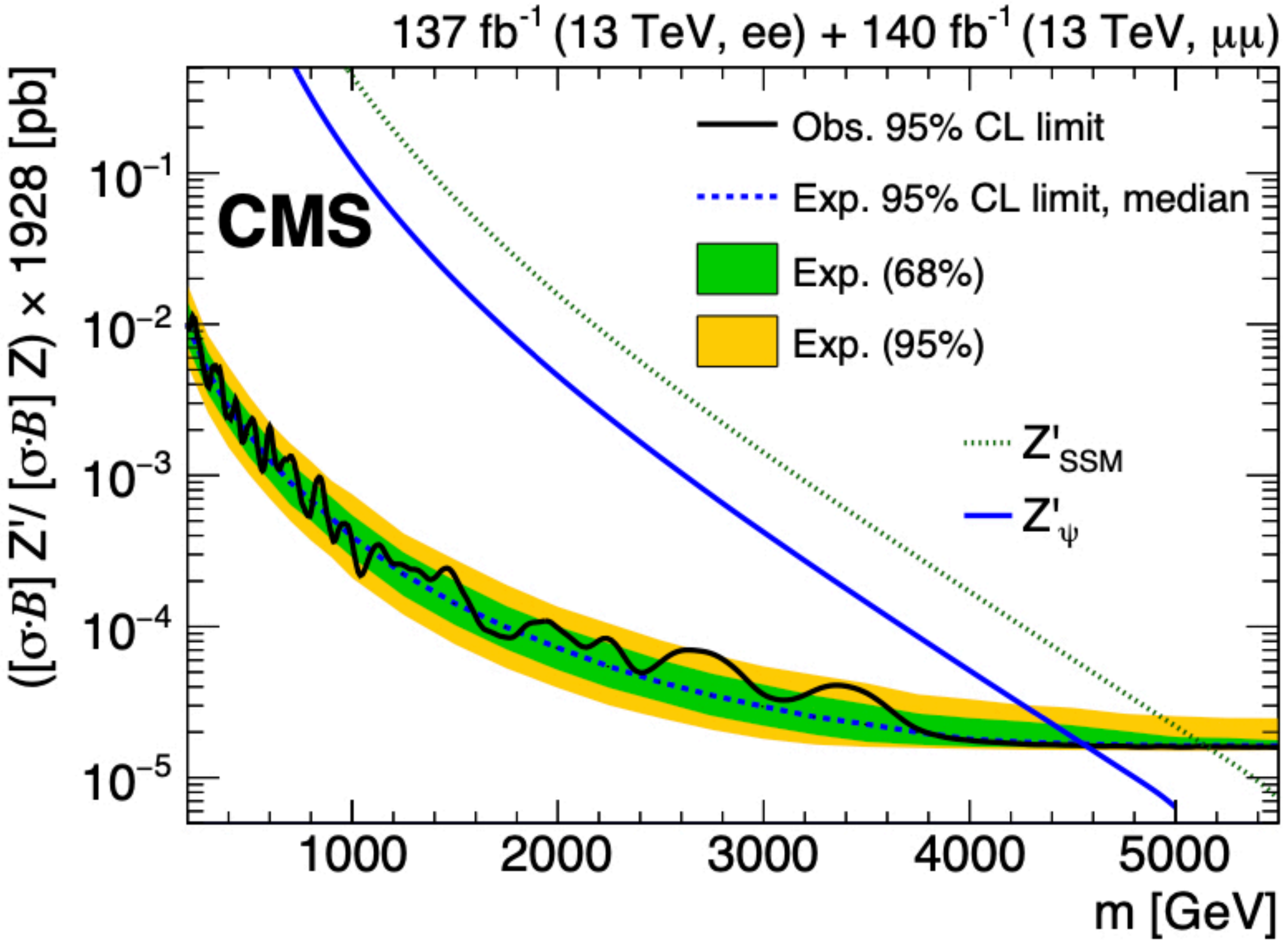




https://arxiv.org/abs/1911.03947



Multi-TeV direct search sensitivity also for weakly coupled objects

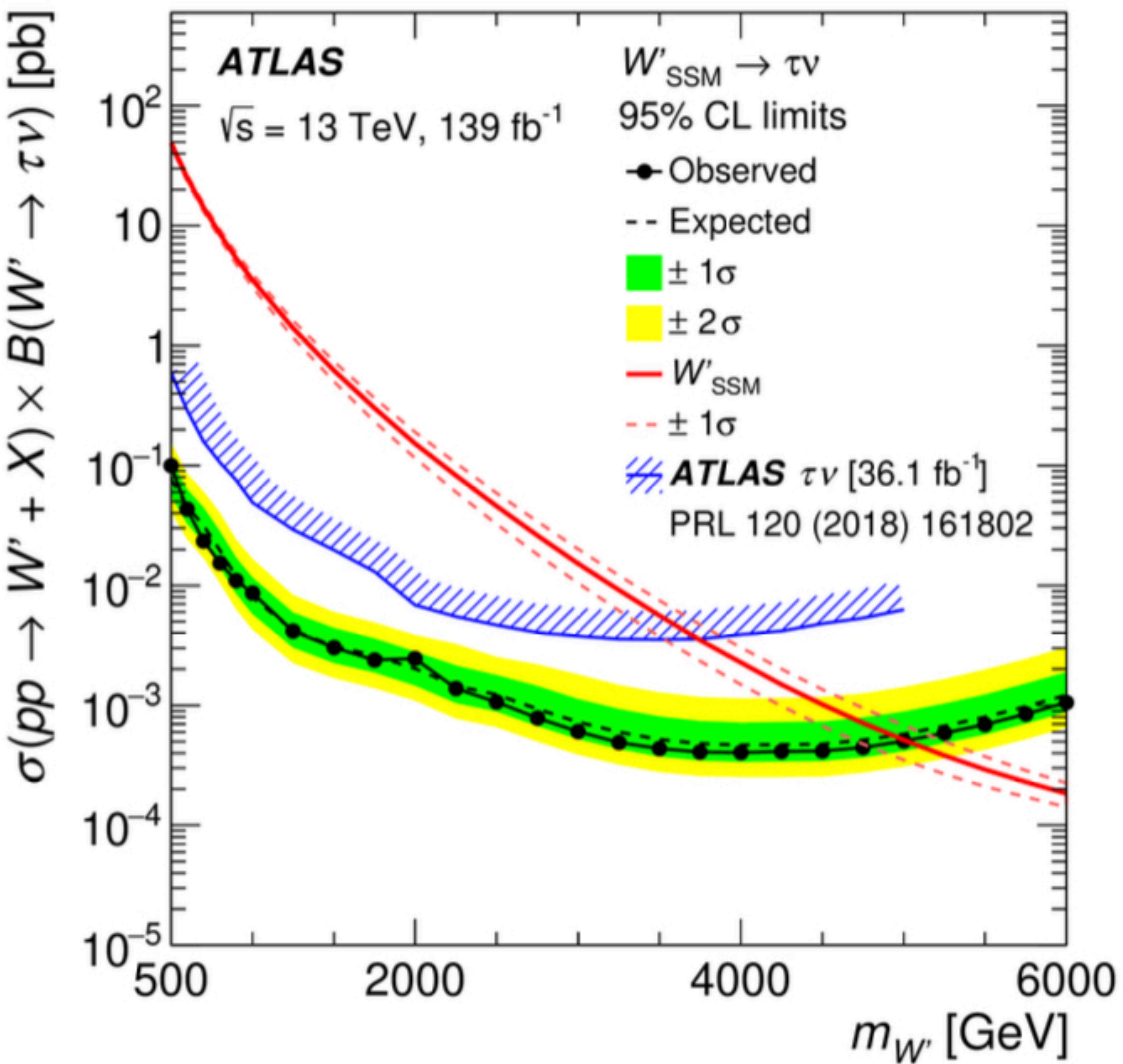


Remarks

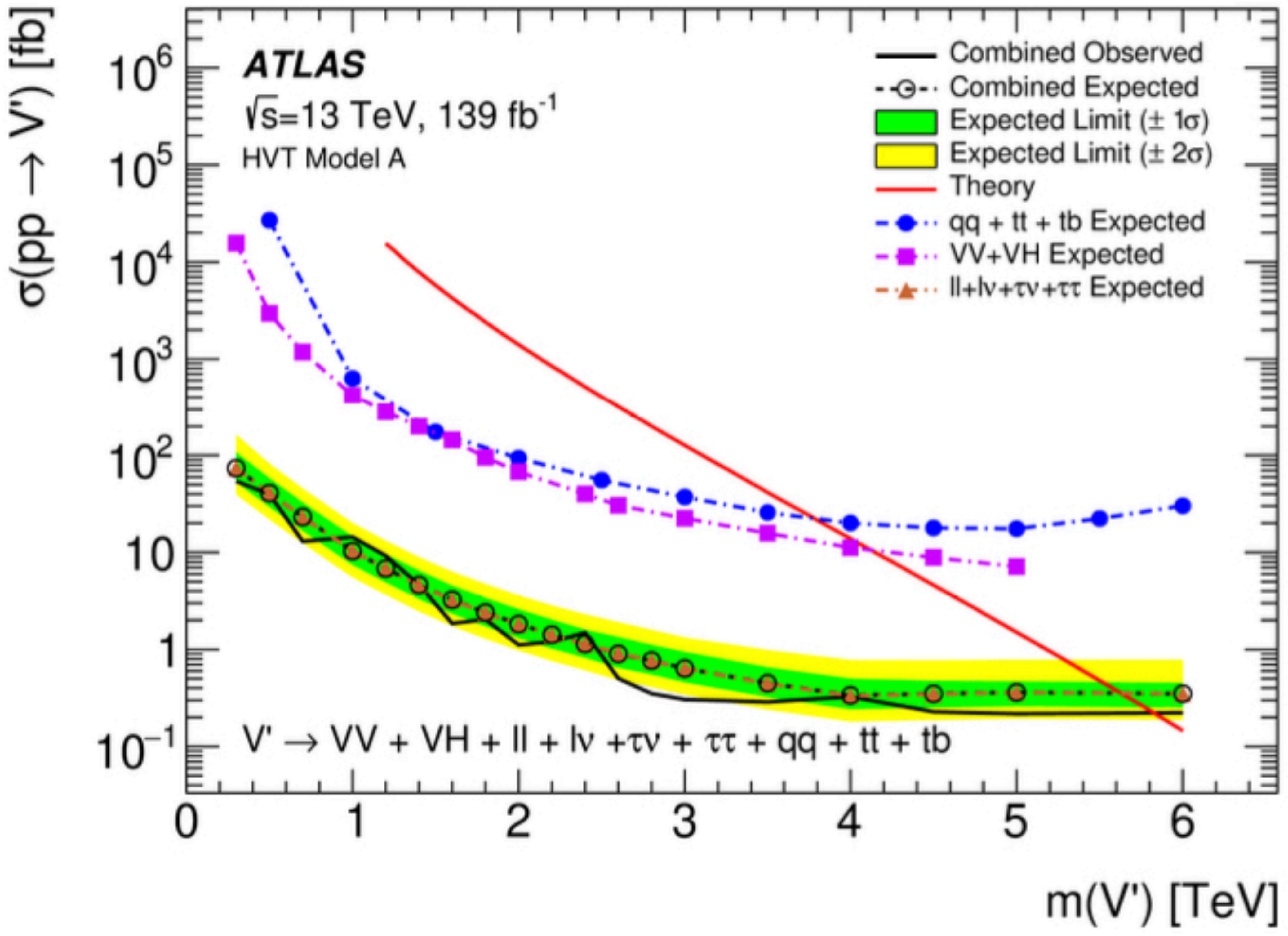
- These searches and constraints should not just be read to flag the largest excluded mass. Note that they also prove sensitivity to “lighter” resonances, up to x 100 times more weakly coupled wrt SM EW interactions

M. Franchini

W' → τν EXOT-2022-38



V' → VV, VH, ff EXOT-2018-37

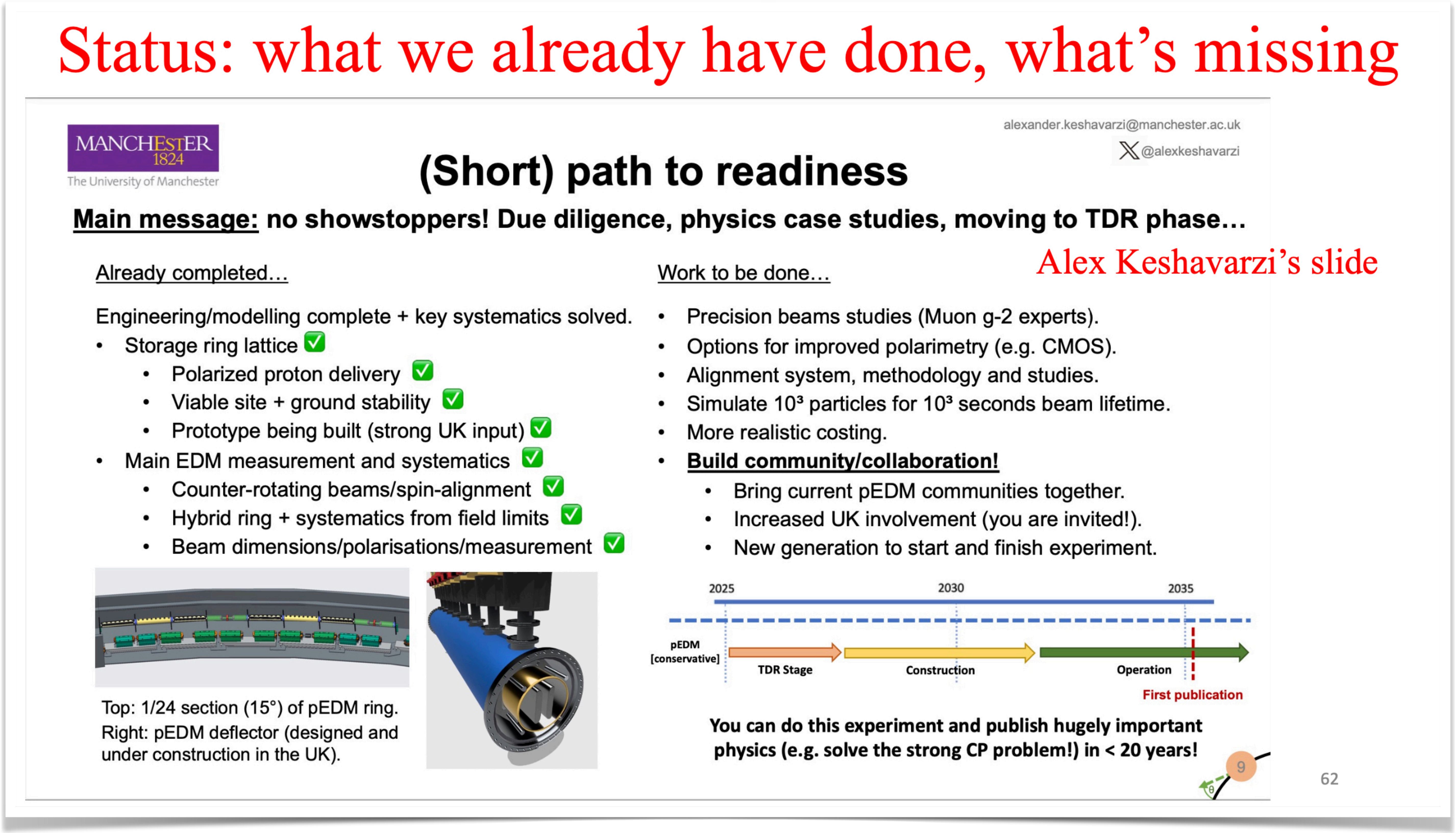


not just colliders …

The status and Future of the storage ring proton EDM experiment

Yannis K. Semertzidis, IBS/CAPP & KAIST

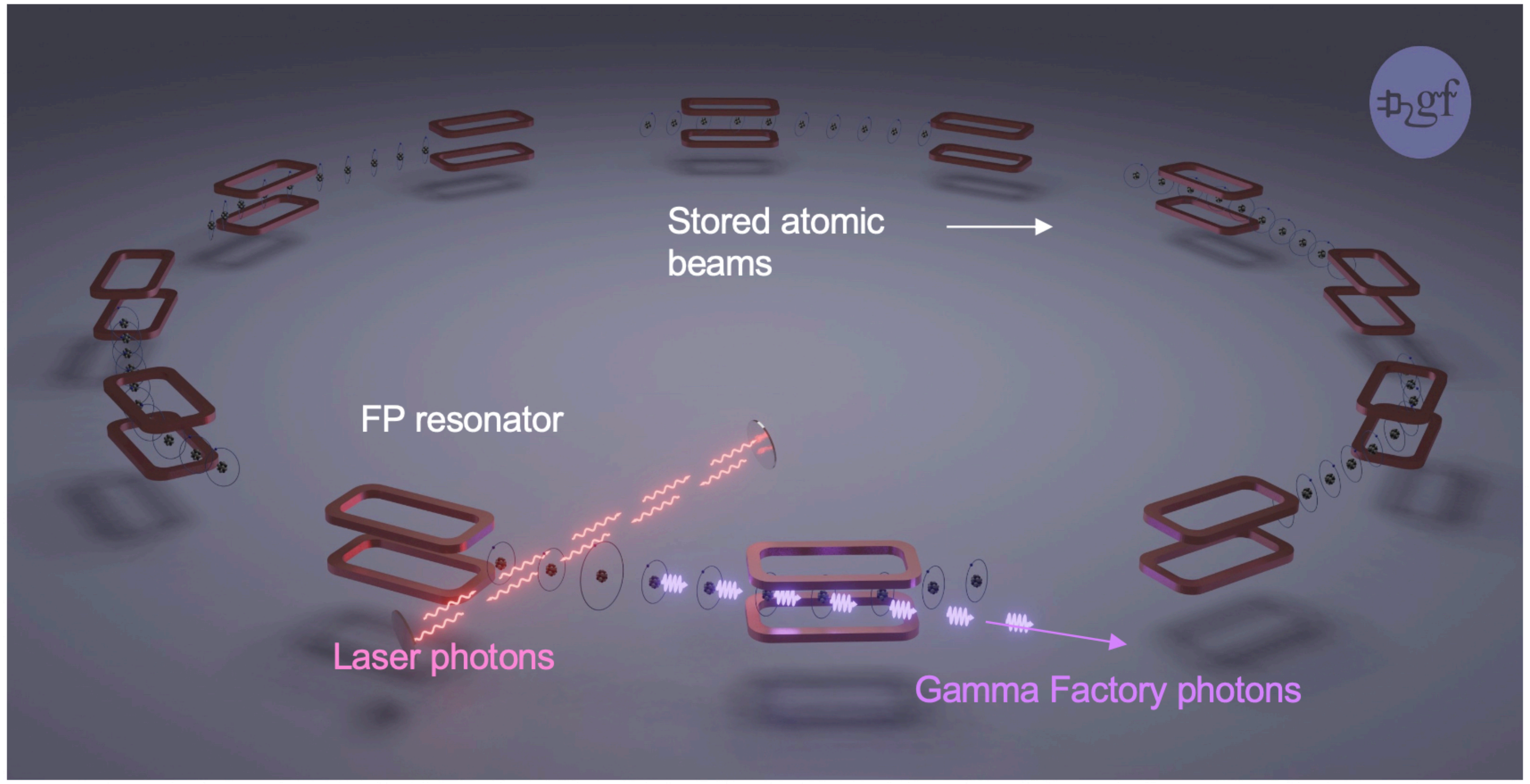
- Statistics for better than 10^{-29} e-cm for pEDM, ~10^3 TeV New-Physics reach
- Matching systematic error levels, greatly reduced using symmetries
- Getting ready to go (technically), need more community support to build



Gamma Factory

Mieczyslaw Witold Krasny (Gamma Factory group leader)
LPNHE, CNRS and University Paris Sorbonne and CERN, BE-ABP

- ***particle physics*** (precision QED and EW studies, vacuum birefringence, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, QCD-confinement studies, …);
- ***nuclear physics*** (nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear photo-physics, photo-fission research, gamma polarimetry, physics of rare radioactive nuclides,…);
- ***atomic physics*** (highly charged atoms, electronic and muonic atoms, pionic and kaonic atoms);
- ***astrophysics*** (dark matter searches, gravitational waves detection, gravitational effects of cold particle beams, $^{16}O(\gamma,\alpha)^{12}C$ reaction and S-factors…);
- ***fundamental physics*** (studies of the basic symmetries of the universe, atomic interferometry,…);
- ***accelerator physics*** (beam cooling techniques, low emittance hadronic beams, high intensity polarised positron and muon sources, beams of radioactive ions and neutrons, very narrow band, and flavour-tagged neutrino beams, …);
- ***applied physics*** (accelerator driven energy sources, fusion research, medical isotopes and isomers precision lithography).



Novel technology:
Resonant scattering of laser photons on ultra-relativistic atomic beam

What has been achieved?

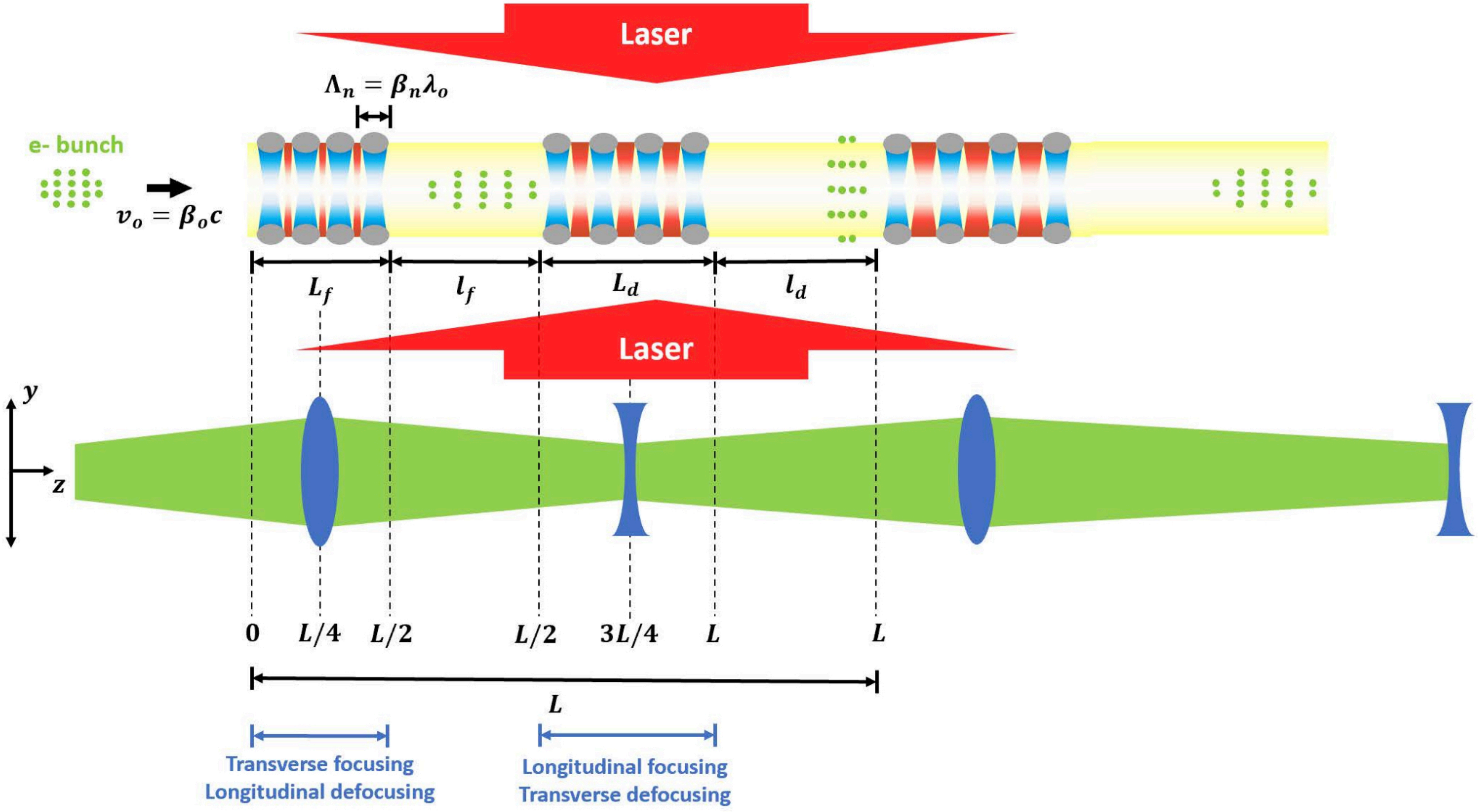
- *Demonstration of efficient production, storage and operation of the atomic beams n the SPS and LHC*
- *Demonstration of the stable, high power, laser photon beam storage in the Fabry-Perot cavity (world record of 500 kW stored power)*
- *Demonstration of the requisite precision of the beam steering in the collision point of laser pulses with atomic beam bunches*
- *Creation and benchmarking of the requisite software to simulate the production of the atomic beams, GF-photon beams and tertiary beams*

What remains to be done?

Proof of the stable remote operation of the laser + FP system incorporated to hadronic rings
→ Gamma Factory PoP experiment

- Direct laser acceleration in integrated photonic circuits
- also known as:
  - dielectric laser acceleration
  - accelerator-on-a-chip

ALTERNATING PHASE FOCUSING



DIRECT LASER ACCELERATION IN INTEGRATED PHOTONIC CIRCUITS

- Very low emittance beam
- High accelerating gradient ~ GV/m
- Staging of multiple structures
- Integrated focusing and beam control
- To be demonstrated:
  - Long structures (> 1 mm)
  - Energy efficiency
  - Repetition rate

The challenges: detectors

Calorimeter developments for future collider experiments, M-C. Fouz Iglesias

Detectors for Higgs factory, R. Ferrari

Prospects for particle identification at FCC with the IDEA detector, A. Coccaro

Detector concepts for future accelerators (like ILC, asymmetric Higgs factory), K. Buesser

Gaseous ionization detector developments for future collider experiments, M. Titov

The LDG working group on sustainability assessment of future accelerators, C.Bloise

Future of Solid State detectors within DRD3 collaboration, D. Varouchas

Detector challenges at a future muon collider, N. Pastrone

Future calorimeters front end electronics, C. De La Taille

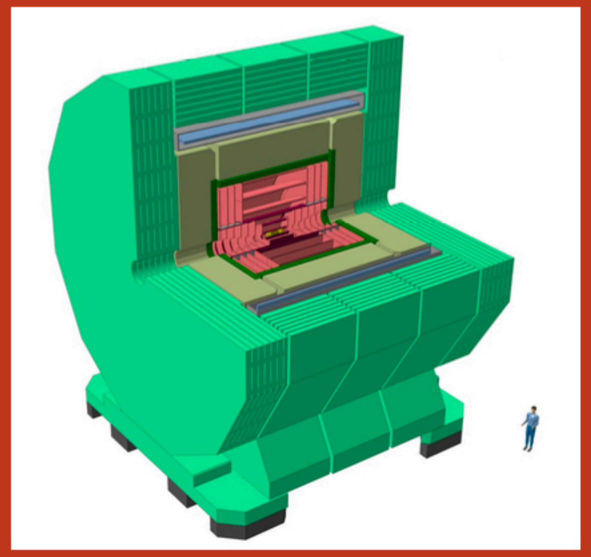
R.Ferrari

FCC-ee detectors

It's true that a LEP detector could do a lot of the FCC-ee physics …
but that's not good enough!

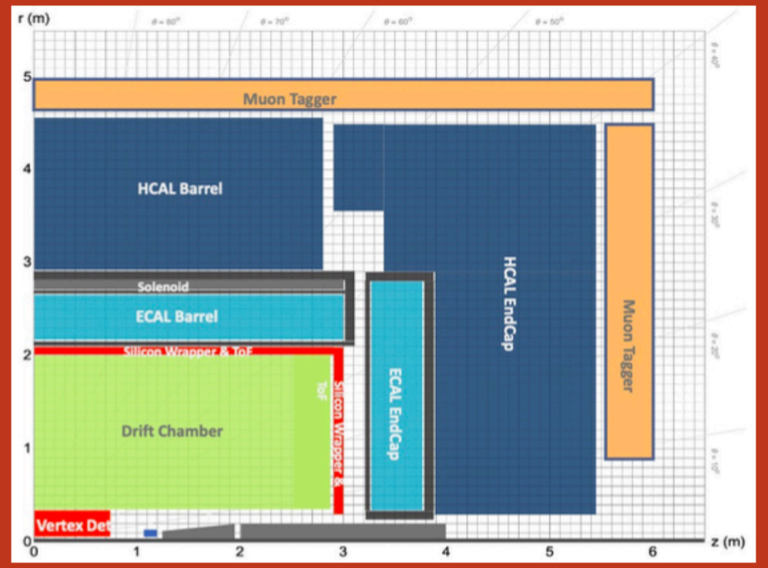
BSM: beyond the standard measurement technology …

CLD (CLIC-like Detector)



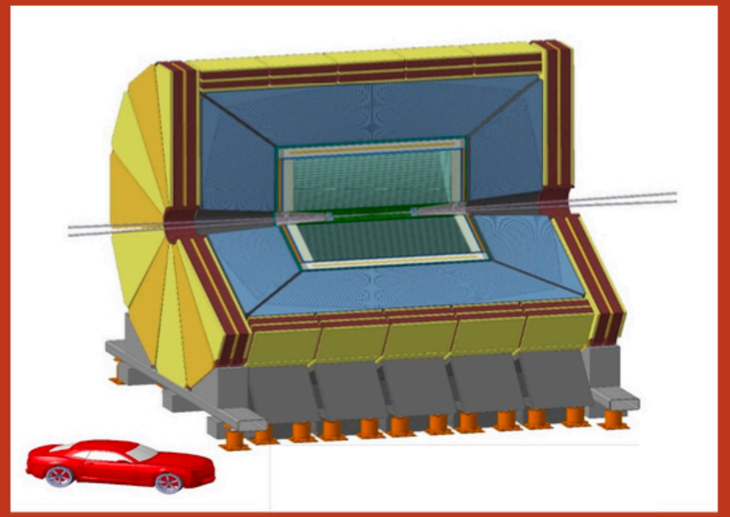
2 T solenoid **outside calo**
Full silicon tracker
SiW highly granular EM Calo
Sci-steel highly granular HAD Calo
RPC-based muon detector

ALLEGRO - A Noble-Liquid Ecal based



2 T solenoid **outside ECAL**
Tracking with ultra light drift chamber +
Si Wrapper (improved tracking + timing)
LAr EM Calo + Sci-steel HAD Calo

IDEA - Innovative DEtector for e+e- Accelerators

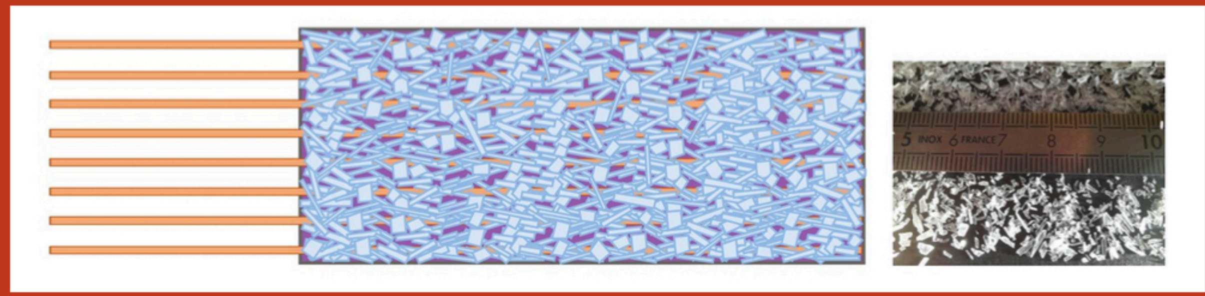


2 T thin solenoid within calo
Si vertex detector
Tracking with ultra light drift chamber
Dual-readout calorimeter + preshower
MPGD (μRwell) based muon detector

Recurrent key words:
- ultra-light
- granular
- timing
- …

Other ongoing R&D on calorimetry

GRAiNITA

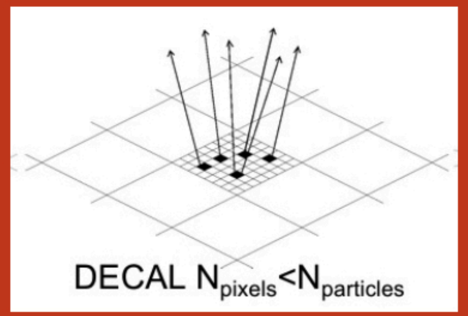


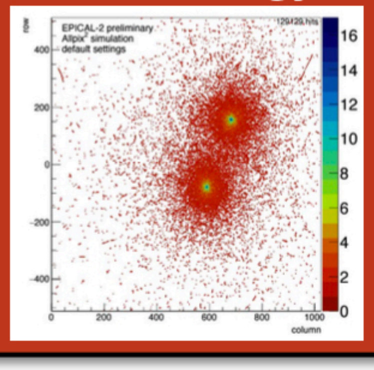
Scintillator grains and absorber suspended in liquid
Trapped light extracted with WLS fibres

High density EM calorimeter

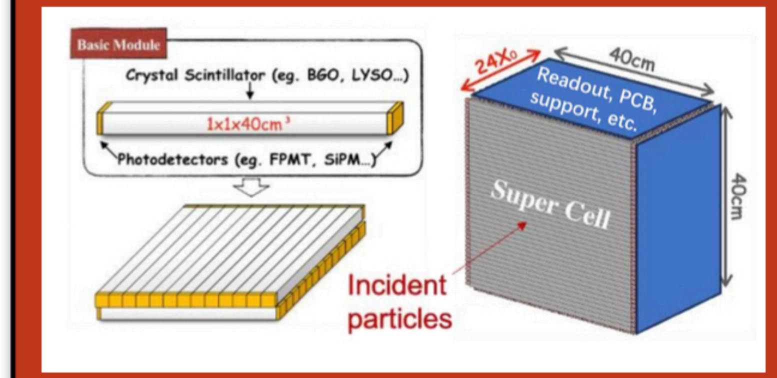
DECAL - Ultra-high granularity CMOS Ecal

High-density digital CMOS readout - count hits rather than measure energy





Crystal calorimeter for FCC-ee?



Traditionally achieve superb EM resolution but w/ limited granularity

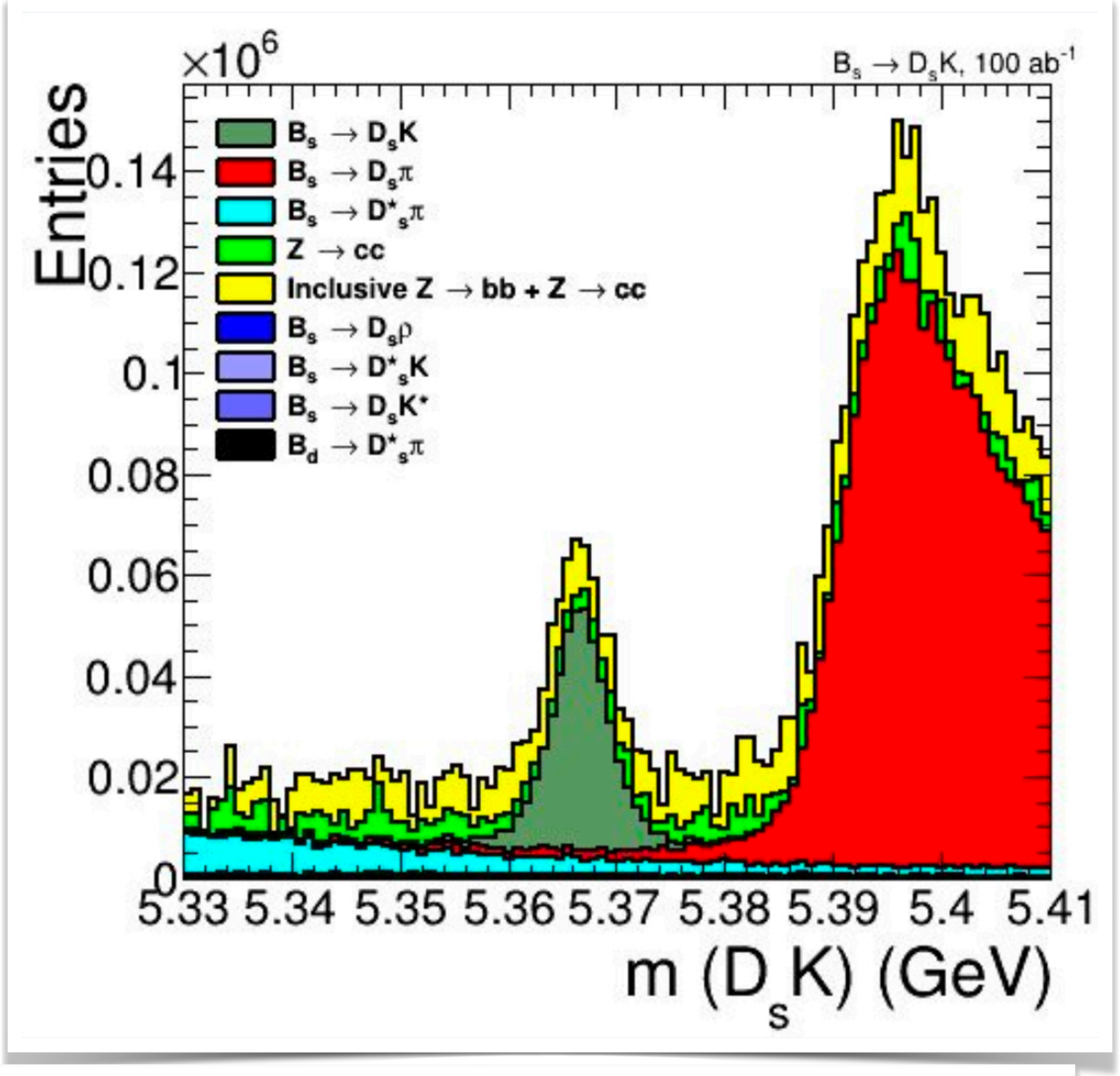
Recent R&D shows potential for particle flow

Crystal fibers for high granularity

On the electronics side (C. de La Taille)
Evolution of embedded calorimeter readout chips
- Further reduction in power dissipation
- Auto-trigger and data-driven readout
- More SiPM readout

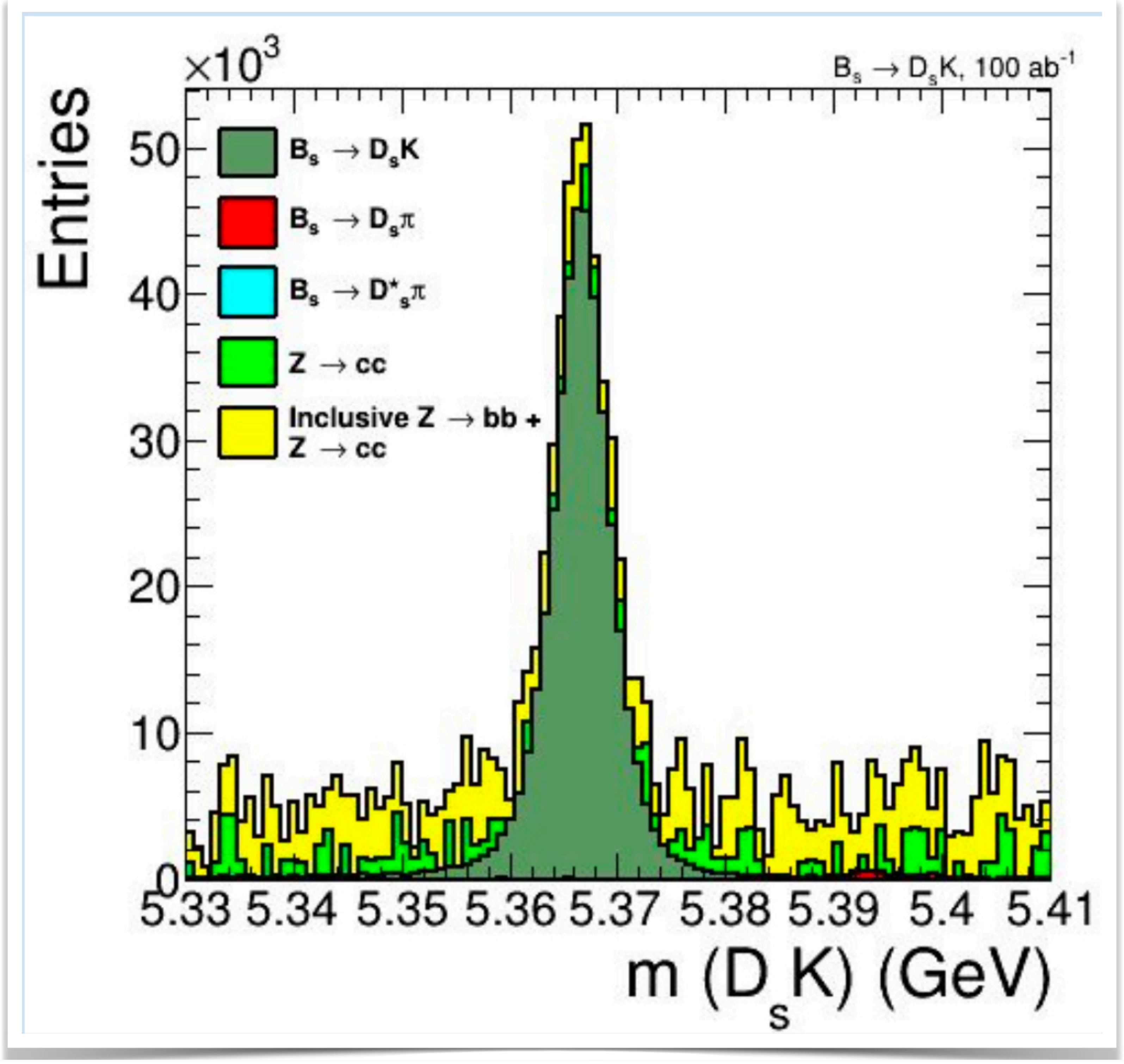
A.Coccaro

Detector performance improvements to meet requirements from flavour physics benefit other elements of the physics programme, eg H→ss searches

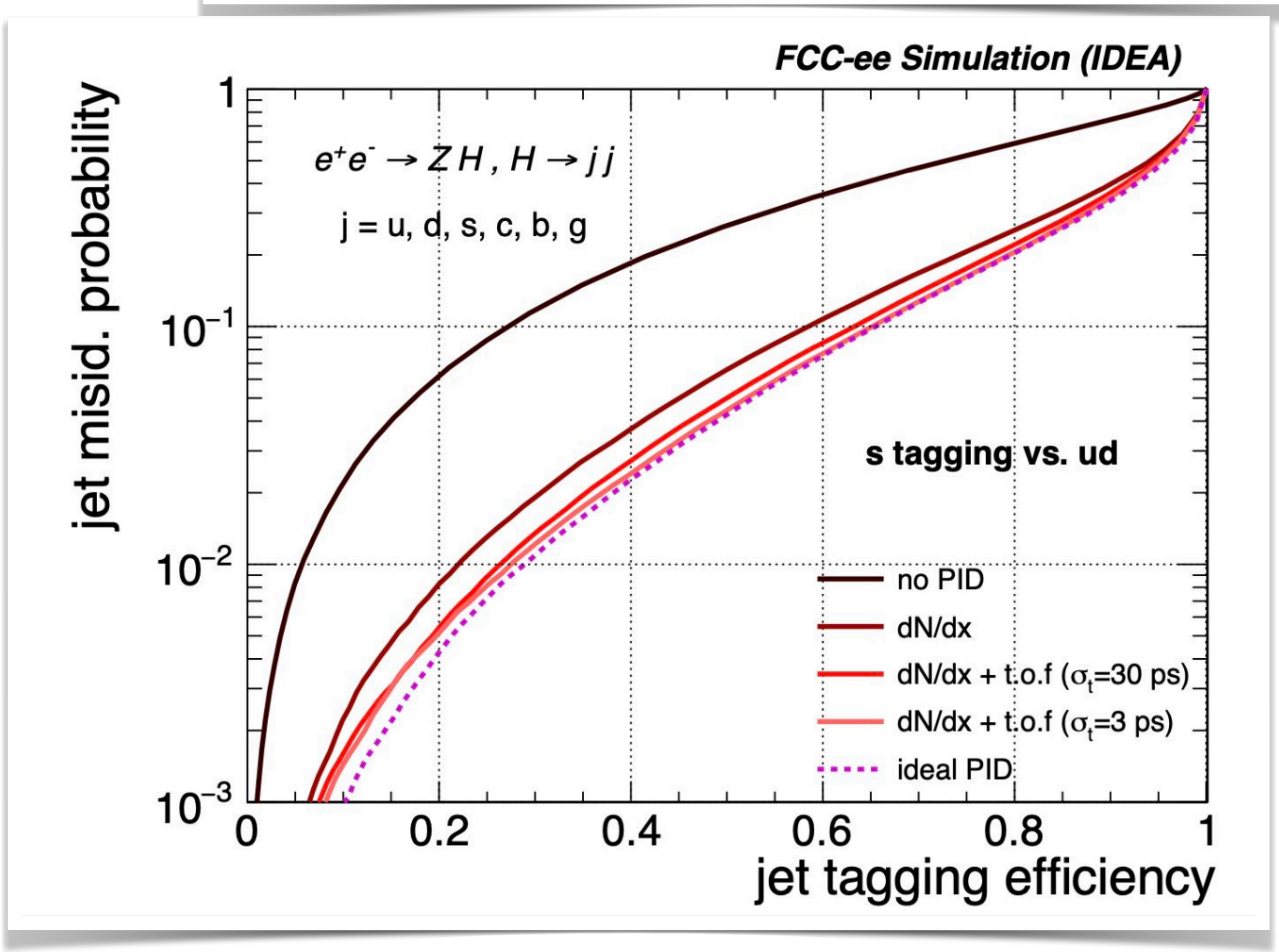


$B_S \to D_SK$

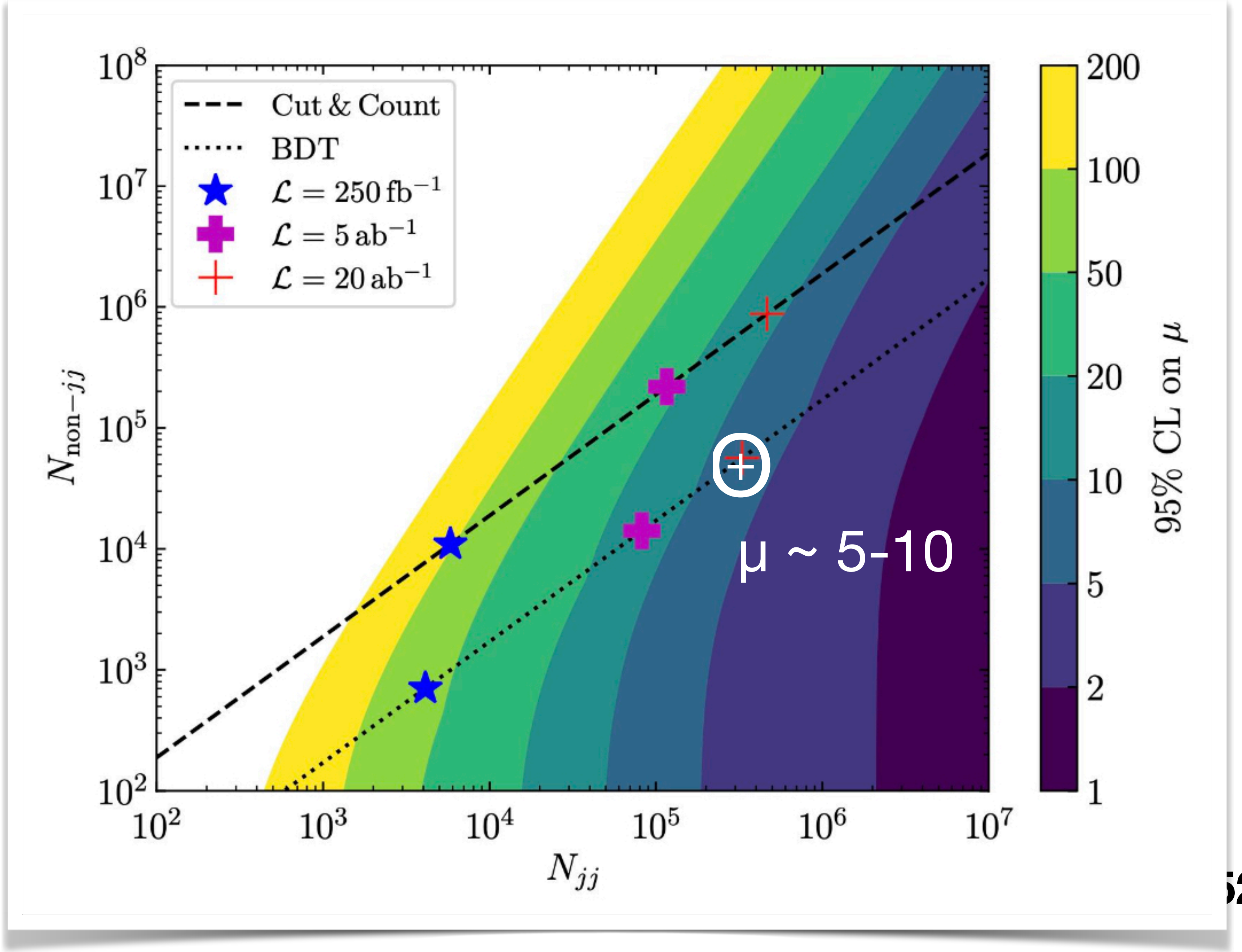
before/after PID



s tagging vs jet mis-ID, with PID



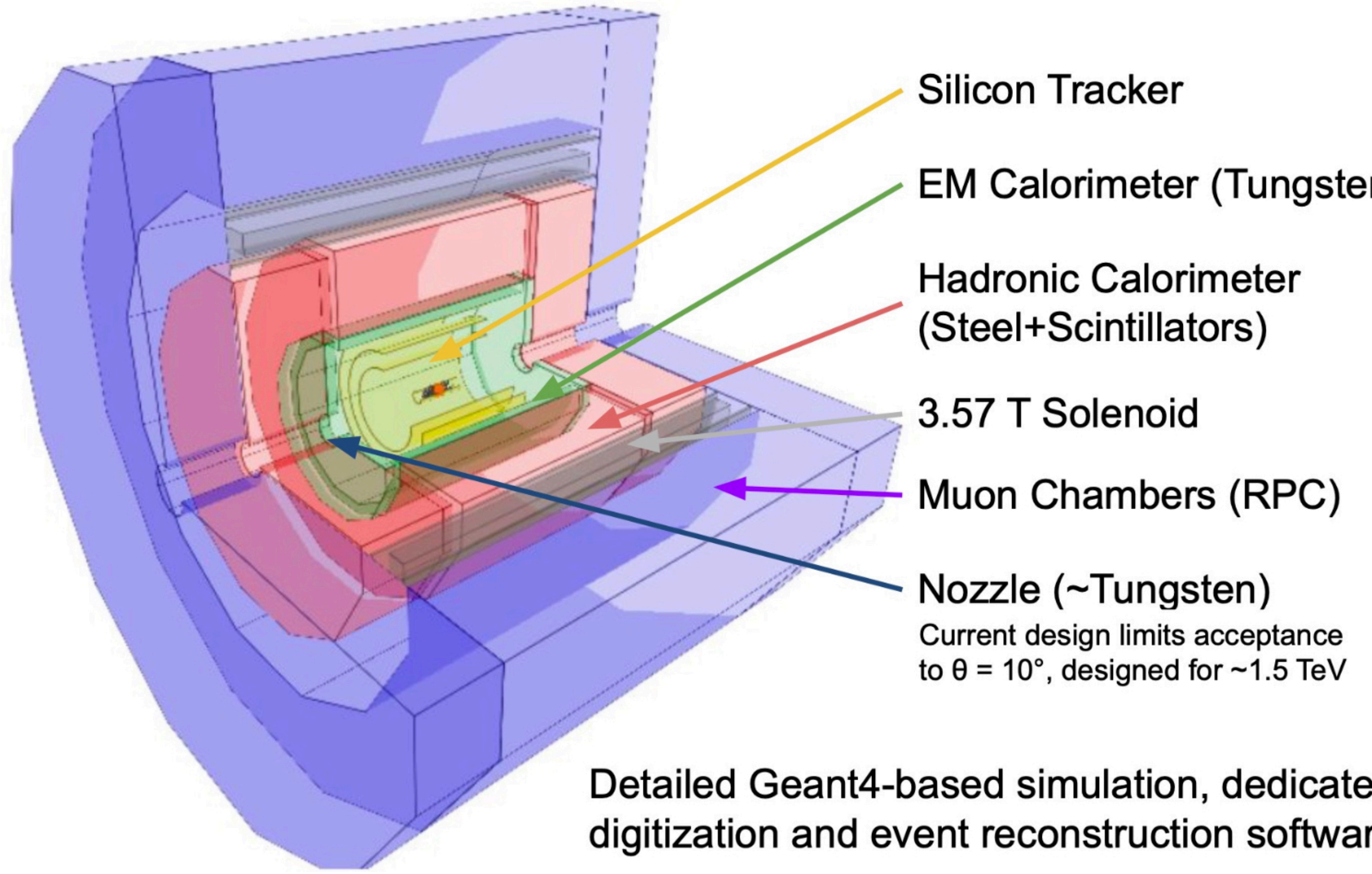
Colour contours: best limit on signal strength μ for the process H → ss, after PID with IDEA



Muon collider detectors

Final states of $\mu^+\mu^-$ collisions are not much different than those of e^+e^- collisions …

Multi-purpose detector that targets very broad physics goals.
- many components still inherited from CLIC design and can be further optimized



Detailed Geant4-based simulation, dedicated digitization and event reconstruction software.

… but the environment and the energies are closer to those of a pp collider!

N. Pastrone

Muon collider detectors

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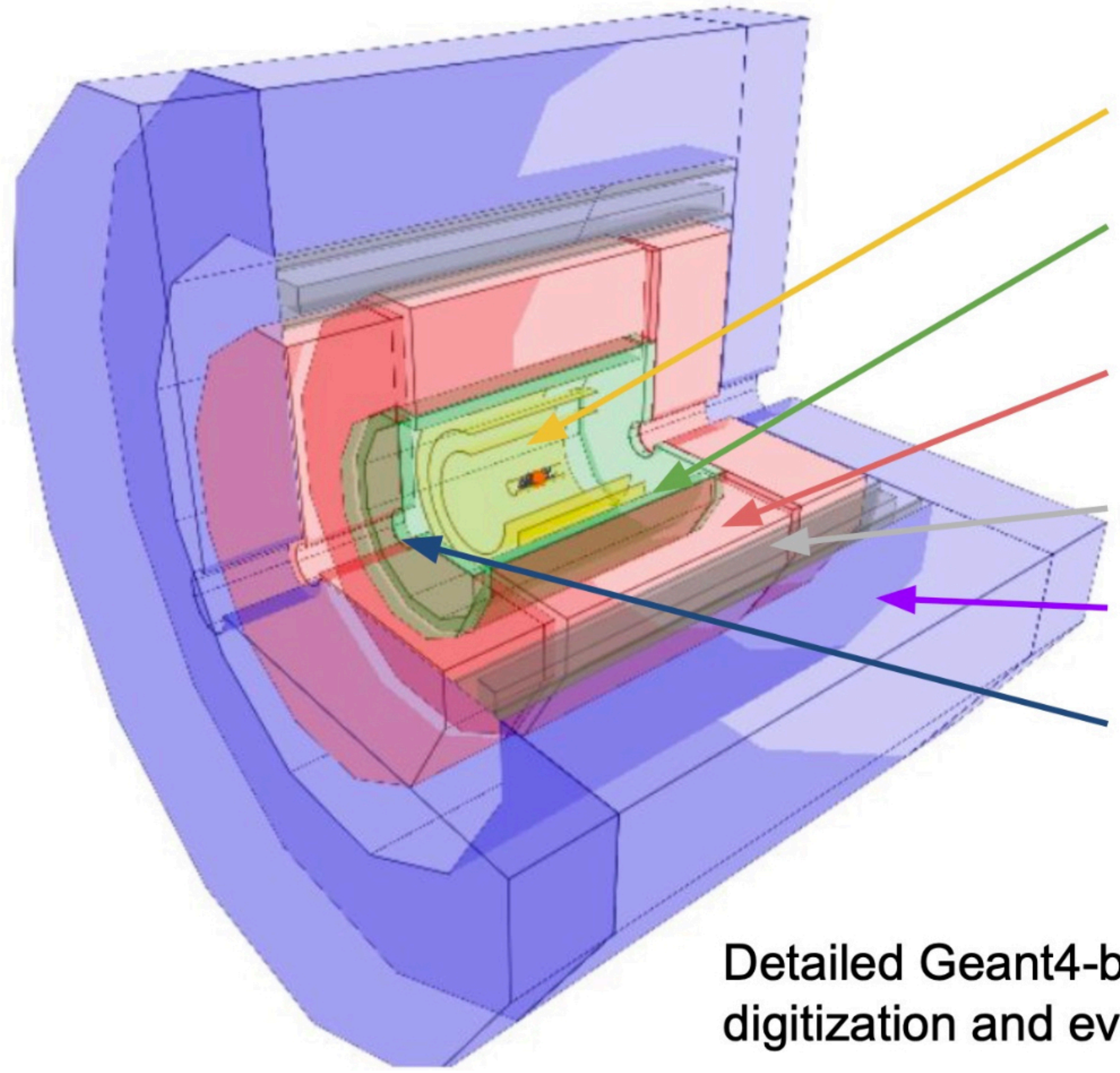

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… but the environment and the energies are closer to those of a pp collider!

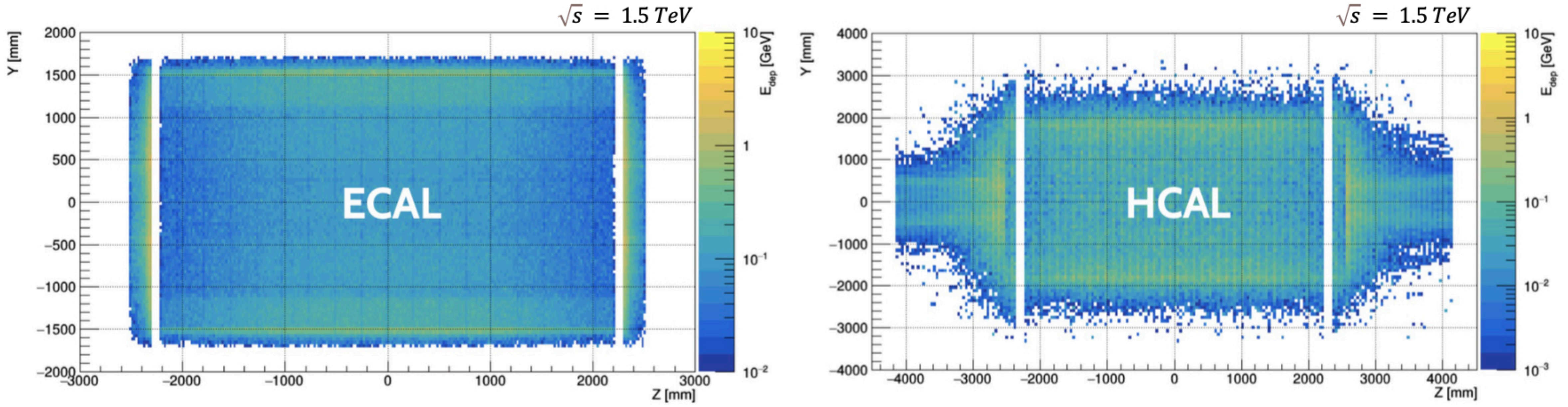
Beam Induced bkg impact on tracking….

Detector Reference	Hit Density [mm^{-2}] MCD	ATLAS ITk	ALICE ITS3
Pixel Layer 0	3.68	0.643	0.85
Pixel Layer 1	0.51	0.022	0.51

Higher hit occupancies than at HL-LHC detectors are expected, but the crossing rate at the muon collider is ~30-70 kHz vs 40 MHz at LHC

… and on calorimetry

BIB energy in the electromagnetic calorimeter **BIB energy in the hadronic calorimeter**



Expected an approximately uniform deposition of energy by BIB particles

Timing and longitudinal measurements play a key role in the BIB suppression

BIB mitigation is the key challenge driving design and technologies

The challenges: theory

Prospects of QCD/top physics at future accelerators, S.Forte

QCD/top physics in the era of future accelerators, A. Mitov

Electroweak physics at future accelerators, F. Piccinini

- **Extend all calculations by at least one more order (loop)**
  - to achieve similar progress in the past, timescale for various processes has been 10-20 yrs
  - recent acceleration observed, thanks to new conceptual developments and access to existing advanced mathematical infrastructure. Not clear as yet which complexities will arise at the next step
  - impact on selection of analytical vs numerical approaches
- **Automation essential for practical use by experiments:**
  - done for NLO
  - in progress, but far from accomplished, for NNLO
- **Adoption of ML-inspired tools to enable, facilitate, accelerate, improve efficiency, of complex calculations**
- **Control systematics other than higher-order unknowns:**
  - precision of parton-shower evolution, control of non-perturbative effects
- **Progress needed with parametric inputs (eg α_S, m_W, PDFs, ...):**
  - this will go hand in hand with exptl progress.
  - reliance on data and precise calculations themselves to extract parametric inputs leads to correlations that must be accounted for in the systemics (eg PDF constraints from datasets used for m_W measurement, non-PT modeling from datasets used for α_S measurement, etc)

Towards a strategy

From Aidan's talk

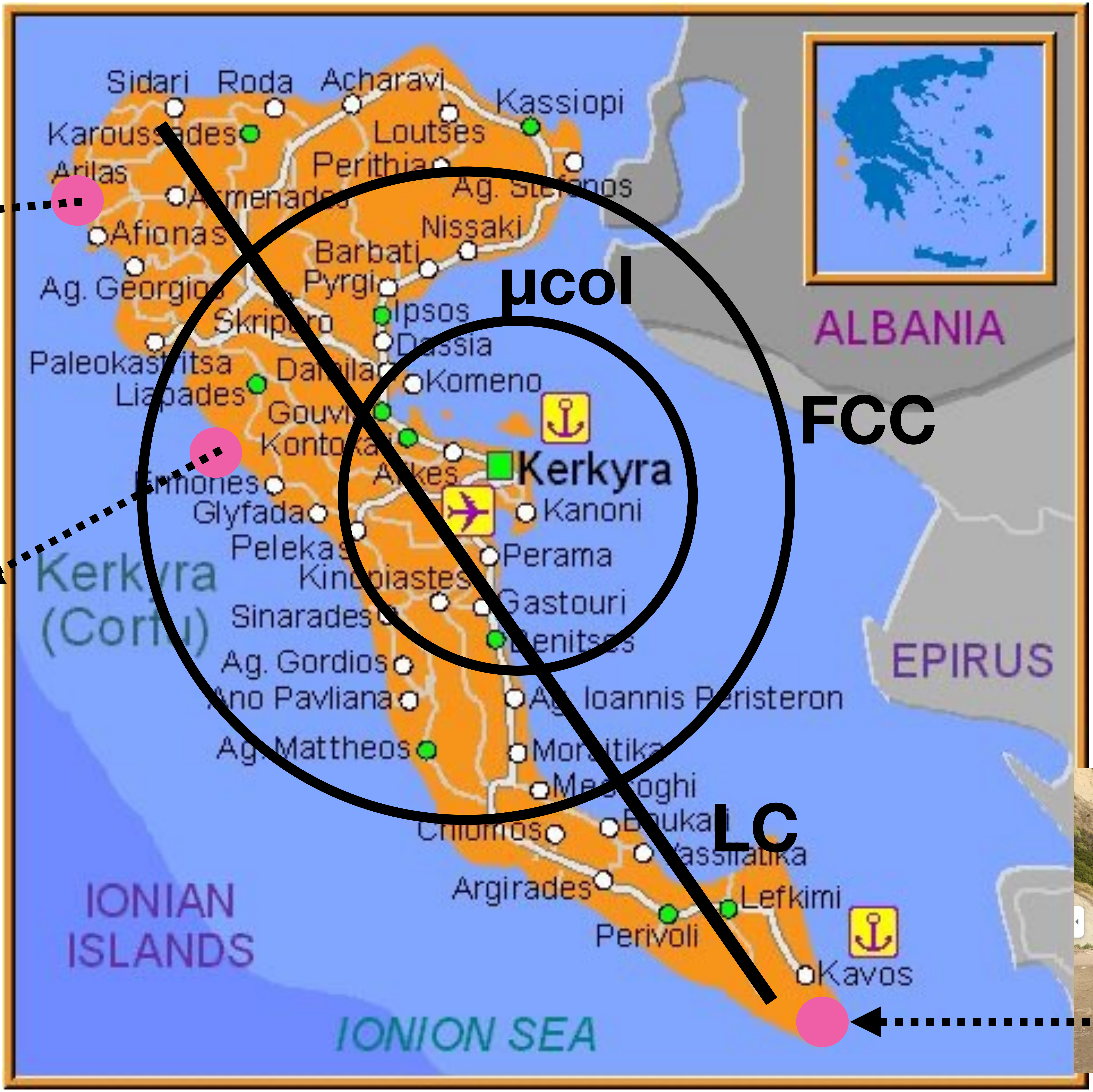
- **Strategic question 1:**
  – how much of the programme should be done with the next machine (e^+e^-) ?
- **Strategic question 2:**
  – how long are we prepared to wait for aspects of the physics programme?
- **Strategic question 3:**
  – when/how to fold in environmental considerations?
- **Strategic question 4:**
  – how concrete is the plan / how important is flexibility?
- **Strategic question 5:**
  – when/how to fold in cost considerations?
- **Strategic question 6:**
  – how to we wish to see the (collider) particle physics community evolving?
- **Strategic question 7:**
  – what should Europe do in the case that CEPC goes ahead?

My proposal for the next facility

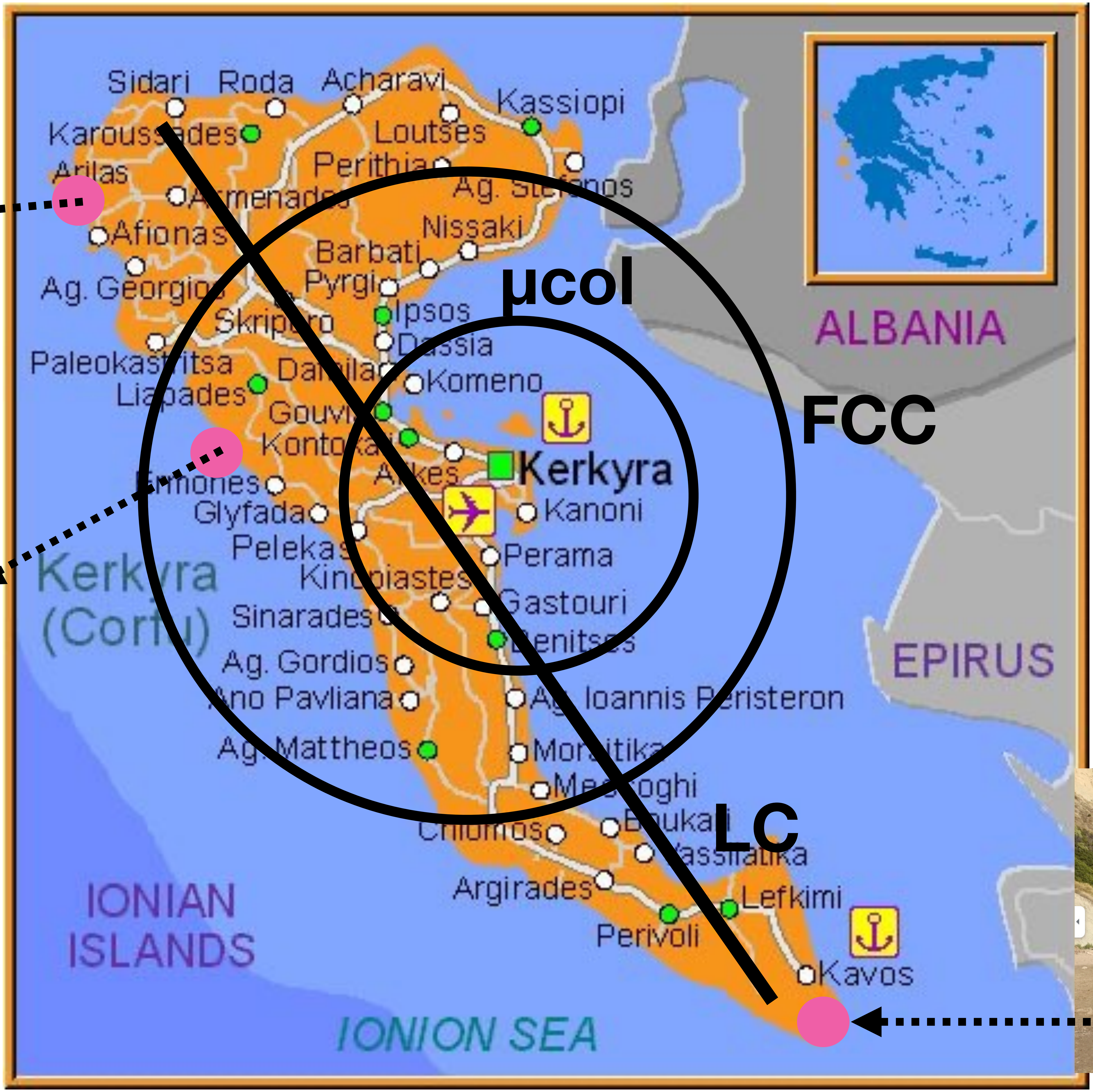
(inspired by Alba’s concluding remarks)


Porto Timoni


Giali Beach


µcol
FCC
LC
Sidari
Roda
Acharavi
Kassiopi
Loutses
Perithia
Arilas
Afionas
Nissaki
Barbati
Pyrgi
Ag. Georgios
Ipsos
Paleokastritsa
Komeno
Kerkyra
Kanoni
Glyfada
Perama
Gastouri
Sinarades
Ag. Gordios
Ano Pavliana
Argirades
Lefkimi
Perivoli
Kavos
Kerkyra
(Corfu)
ALBANIA
EPIRUS
IONIAN
ISLANDS
IONION SEA


Arkudias beach



… at least this will solve the problem of keeping young students excited during construction …

On behalf of all of us,

thanks to George, Jan and their team for the fantastic, warm hospitality

PS coffee, water, cookies and fruits 24/7 is really brilliant!

An Ad from the organizers …

Proposal details

Proposal "PI": Riccardo Torre (INFN - Genova)

- Need to build a valid and "credible" network, including leading centers for Future Collider studies and leading centers for AI/Quantum Computing
- Future Accelerator Corfu Workshop worked well in the last two years and will act as prototype of the central proposed activity
- If you are interested in participating, please reach us out!
  - riccardo.torre@ge.infn.it
  - george.zoupanos@cern.ch
  - kostas.kordas@cern.ch
  - kalino@fuw.edu.pl
  - tevong.you@cern.ch
  - frank.simon@kit.edu
  - oliver.kortner@cern.ch

AI and Quantum Computing for Future Colliders

- Favour interactions among communities of theorists and experimentalists studying Future Colliders and physicists looking at new "computing technologies"
- Favour interactions between different generations of scientists supporting continuity of the field
- Corfu Future Accelerators workshop a central event for the action
- Corfu Summer Schools on Future Colliders physics and on new techniques also desirable