Sfide per HL-LHC e fisica ai colliders futuri

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Frontiera in Energia e Intensità, Cosmologia, Astroparticelle e Nuove Technologie

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FÜR PHYSIK

Outline and Disclaimer

Goals of this talk

- Give a broad overview and challenges of the LHC physics program (with a focus on Higgs physics), emphasise its breadth and illustrate how it has now evolved to add precision to its already formidable physics and discovery potential!

- Discuss the possible scenarios for the next projects and how very important decisions that will decide the future of the field soon have to be made.

Fundamental Puzzles, Problems and Mysteries*

- What is the origin of the electroweak scale? What is the nature (elementary or composite) of the Higgs Boson! **The Gauge Hierarchy and Naturalness problem**
- What is the nature of Dark Energy*? **The cosmological constant problem**
- Why are fermions masses so different? What is the nature of the neutrino (Dirac or Majorana)? **Flavour Hierarchy problem**
- What is the origin of the asymmetry between matter and anti-matter in the universe? **CP Violation and EW transition**
- Why do electrons have precisely the same charge as the protons? **Grand Unification**
- Why is the electric dipole moment of the neutron so small? **The Strong CP problem**
- What are the properties of **Quark Confinement** ?
- What is the nature of **Dark Matter**?

All these fundamental questions (and many more) addressed by the LHC physics program (and to Higgs physics)!

Spoiler alert: None entirely answered but much progress has been made!

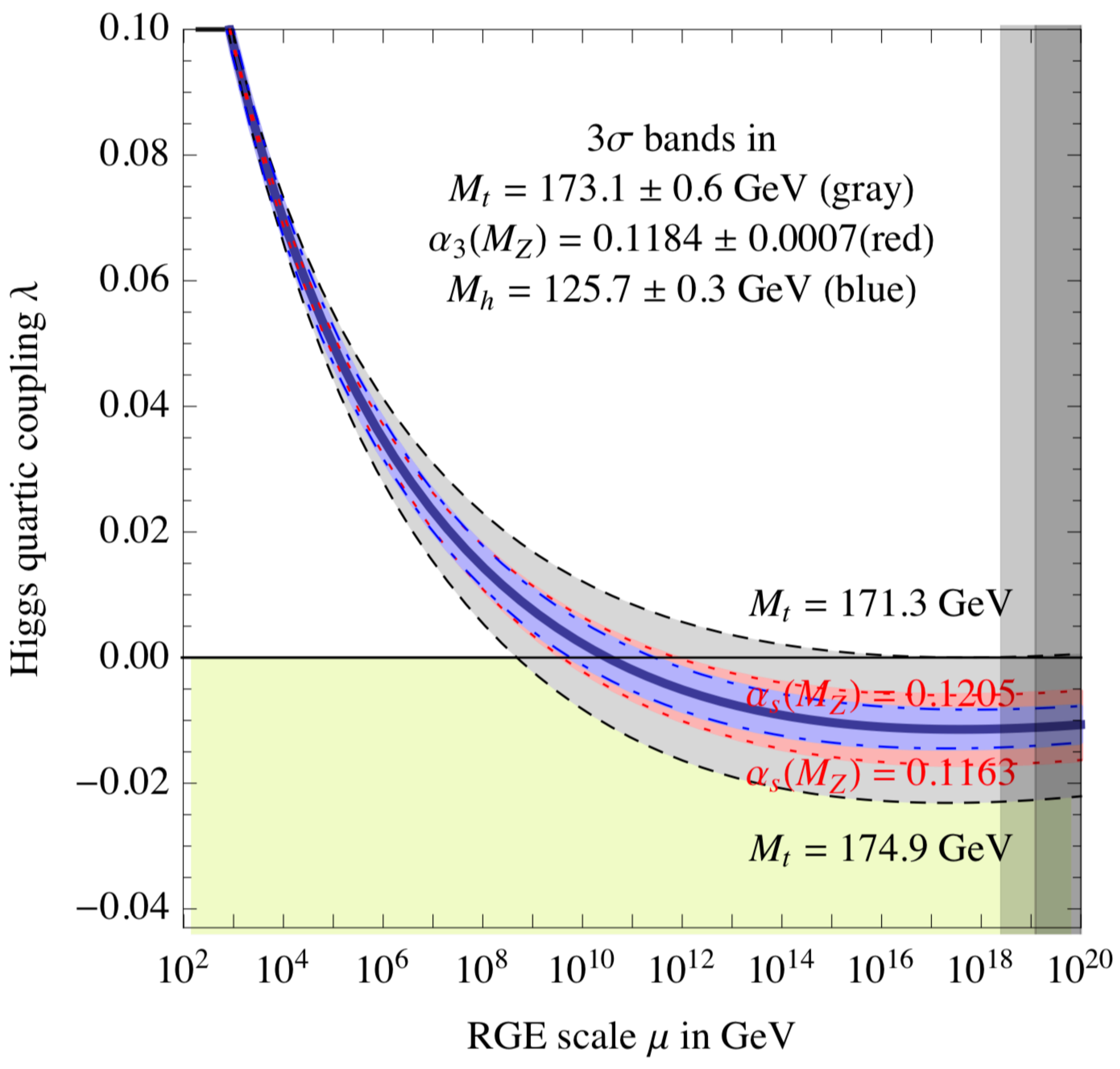
What have we learned?

Two main outcomes of the LHC: The discovery of the Higgs boson and nothing else (so far)

…and knowing the Higgs boson mass of 125 GeV

Vacuum (meta) stability

Running of the Higgs self coupling, **assuming SM** only at high scale

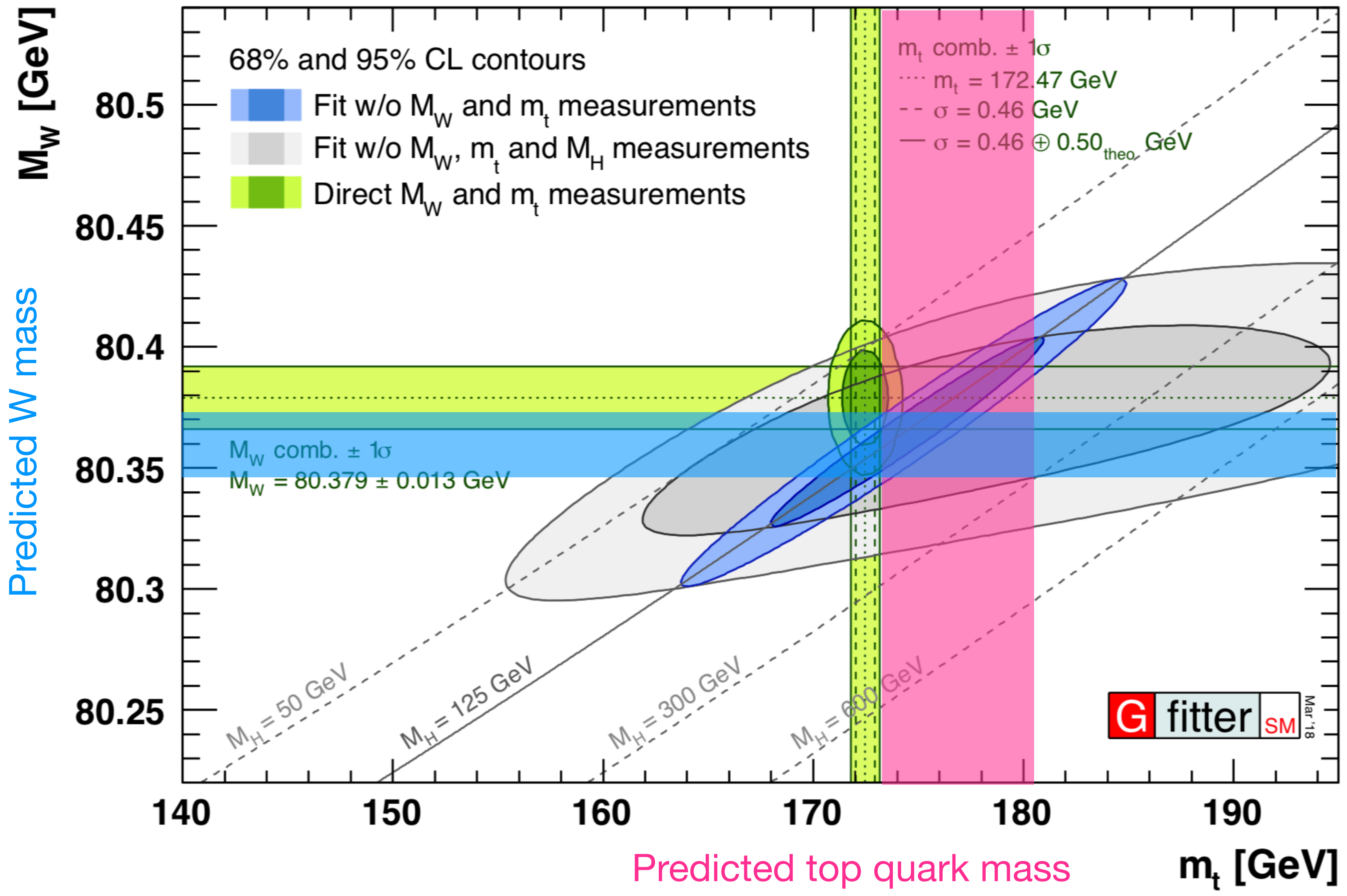


Near vanishing self coupling at the Planck scale

The SM is valid up to exponentially large scales!

The role of Precision

Electroweak Measurements consistent at quantum corrections level (**assuming SM**)



The Large Hadron Collider (LHC)

Unrivalled at Energy Frontier

13.6 TeV (COM energy)

Outstanding at Intensity Frontier

Record Luminosity* $2.26 \times 10^{34}\ cm^2 s^{-1}$

*Close to SuperKEKB at $4.71 \times 10^{34}\ cm^2 s^{-1}$

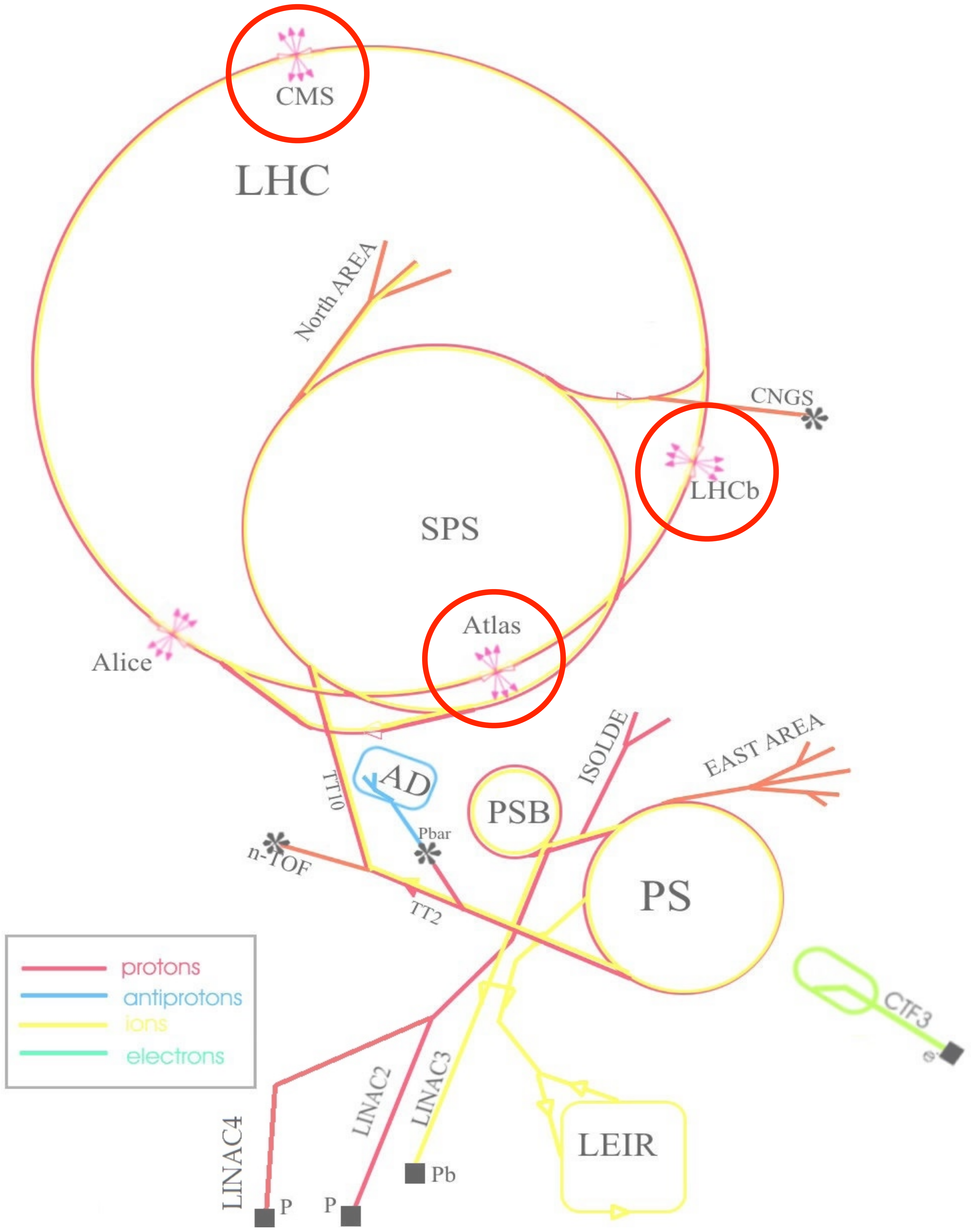
So far the LHC has delivered:

- 10 Million Higgs bosons produced
- 400 Million top quarks produced
- 10 Billion Z bosons with 300 Million per lepton flavour
- 40 Billion W bosons (3 billion per lepton flavour)
- 200 Trillion b quarks

Still 15 times more statistics expected at HL-LHC!

In comparison Future ee up to ~1-4 M Higgs, much cleaner and « usable » events

Focus on pp collisions, superb heavy Ions program, not covered in this talk!



The LHC a 70 Years Vision

Project

15 years bringing concepts together (since 1977 first discussions by CERN DG J. Adams)

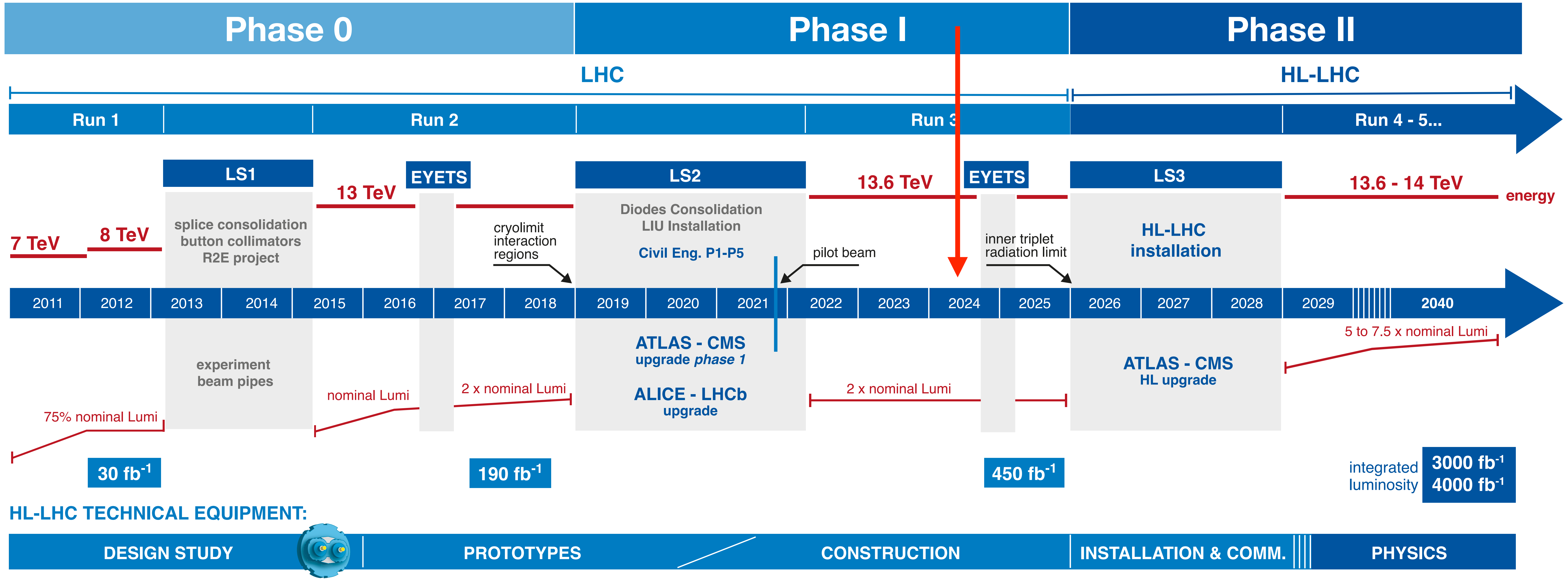
20 years of design, construction, integration and commissioning of the machine and detectors

Operations in 3 phases

15 years of operations (since 2009): Phase 0 and Phase I

15 years of future High Luminosity operations: Phase II

We are here!



Run 1 - 7 ,8 TeV
L~**30** $\mathbf{fb^{-1}}$ **(LHCb 3.2** $\mathbf{fb^{-1}}$**)**

Run 2 - 13 TeV
L ~**160** $\mathbf{fb^{-1}}$ **(LHCb 6** $\mathbf{fb^{-1}}$**)**

Run 3 - 13.6 TeV
L ~**60** $\mathbf{fb^{-1}}$ **(LHCb ~1** $\mathbf{fb^{-1}}$**)**

HL-LHC
14 TeV **3000** $\mathbf{fb^{-1}}$ PU ~140-200

Still **15 times luminosity** to be collected!

So far reached 60 fb^{-1} per year, would need ±40 years

Major machine (operating already for 15 years) and **detector upgrades** required, and **reconstruction** challenge (with **PU up to 200**)!

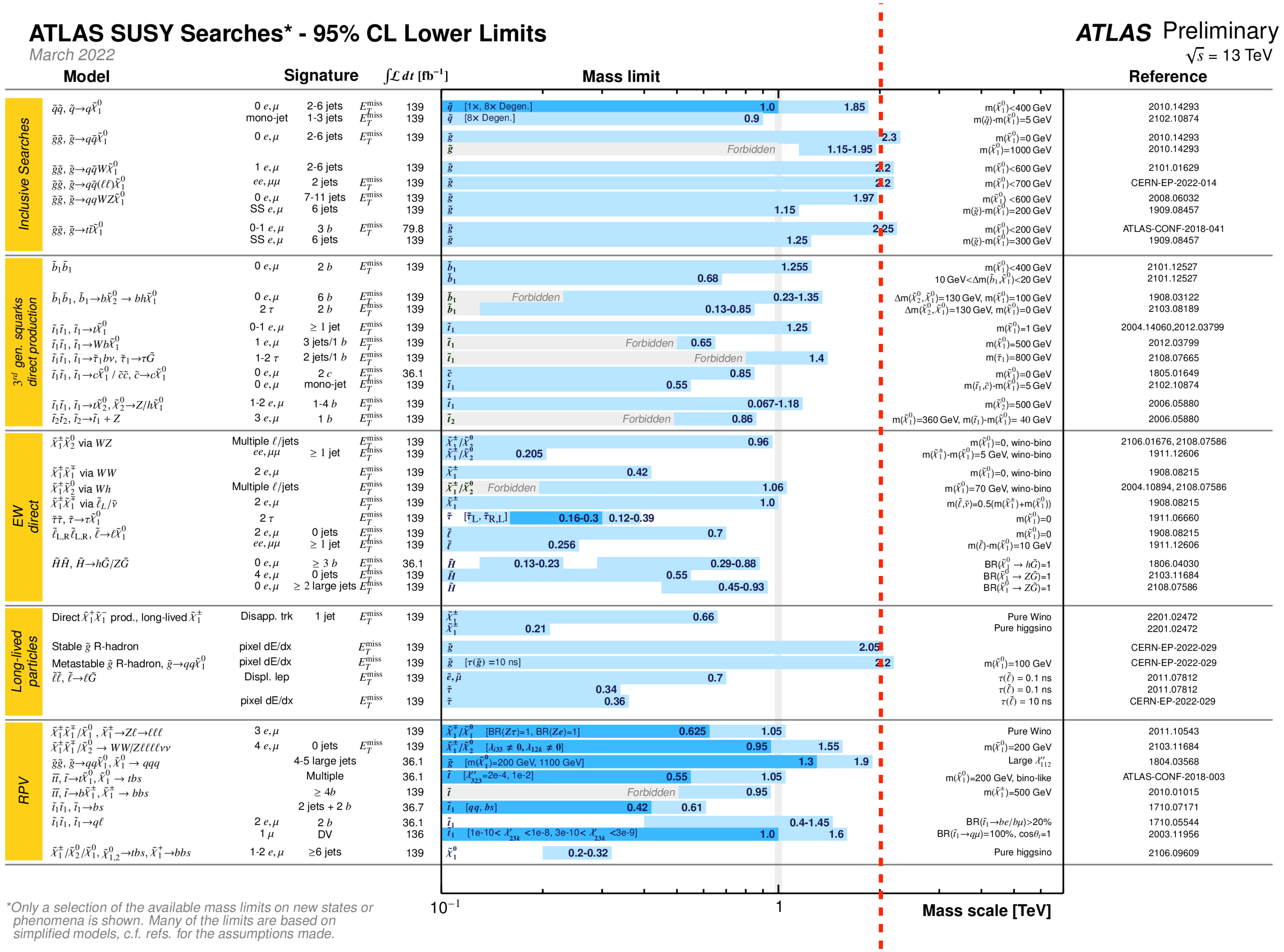
Only less than two years to completion of Run 3!

LS4 major upgrade(s) of LHCb (and ALICE) under consideration
(see CERN-LHCC-2018-027 and talk by V. Vagnoni here).

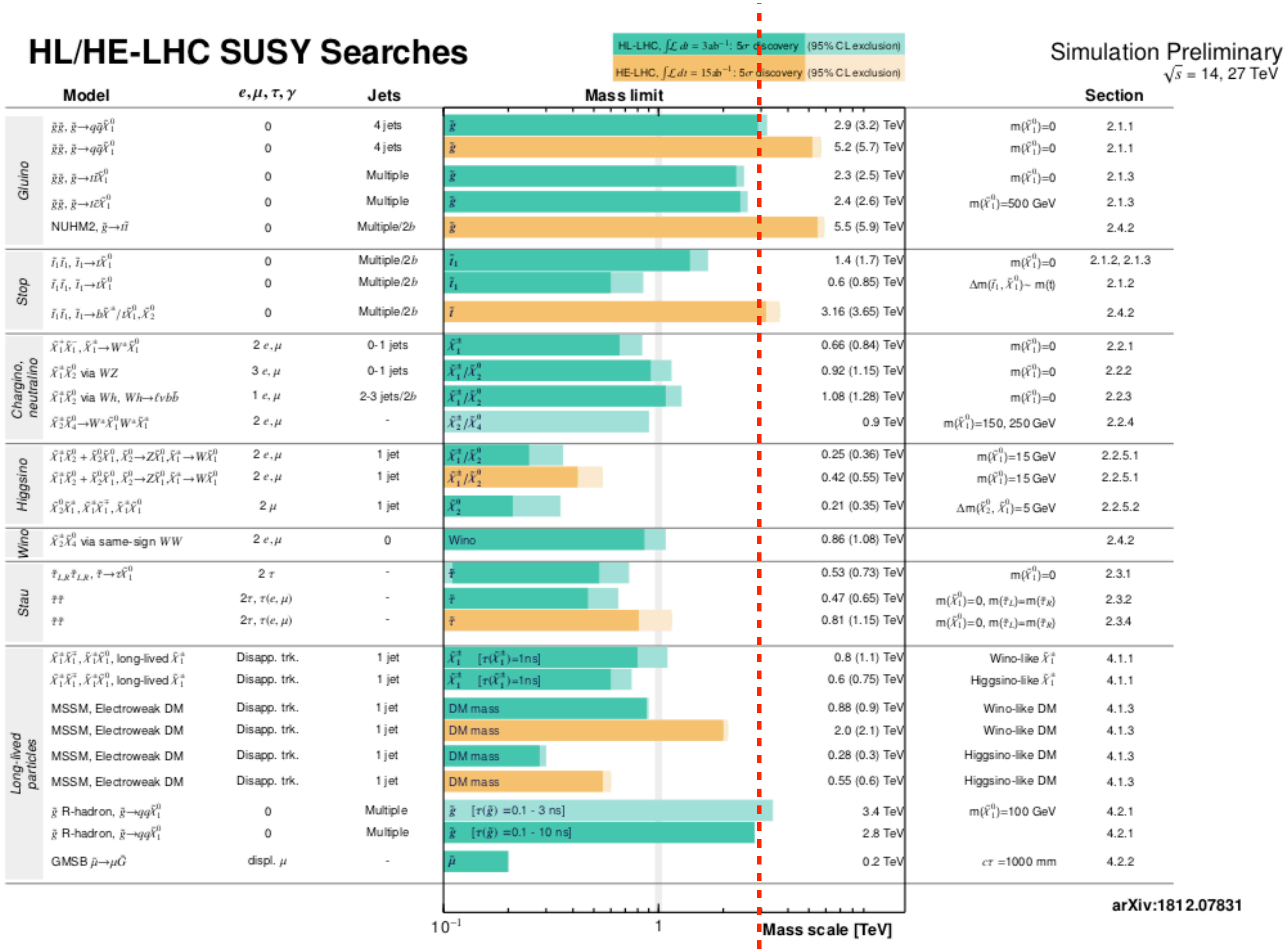
Very Large Number of SUSY Searches

(in large variety of topologies and models)

"""... and nothing else!" Not at all a trivial statement!!



2 TeV



3 TeV

Example from ATLAS (similar for CMS)

HL-LHC YR
1812.07831

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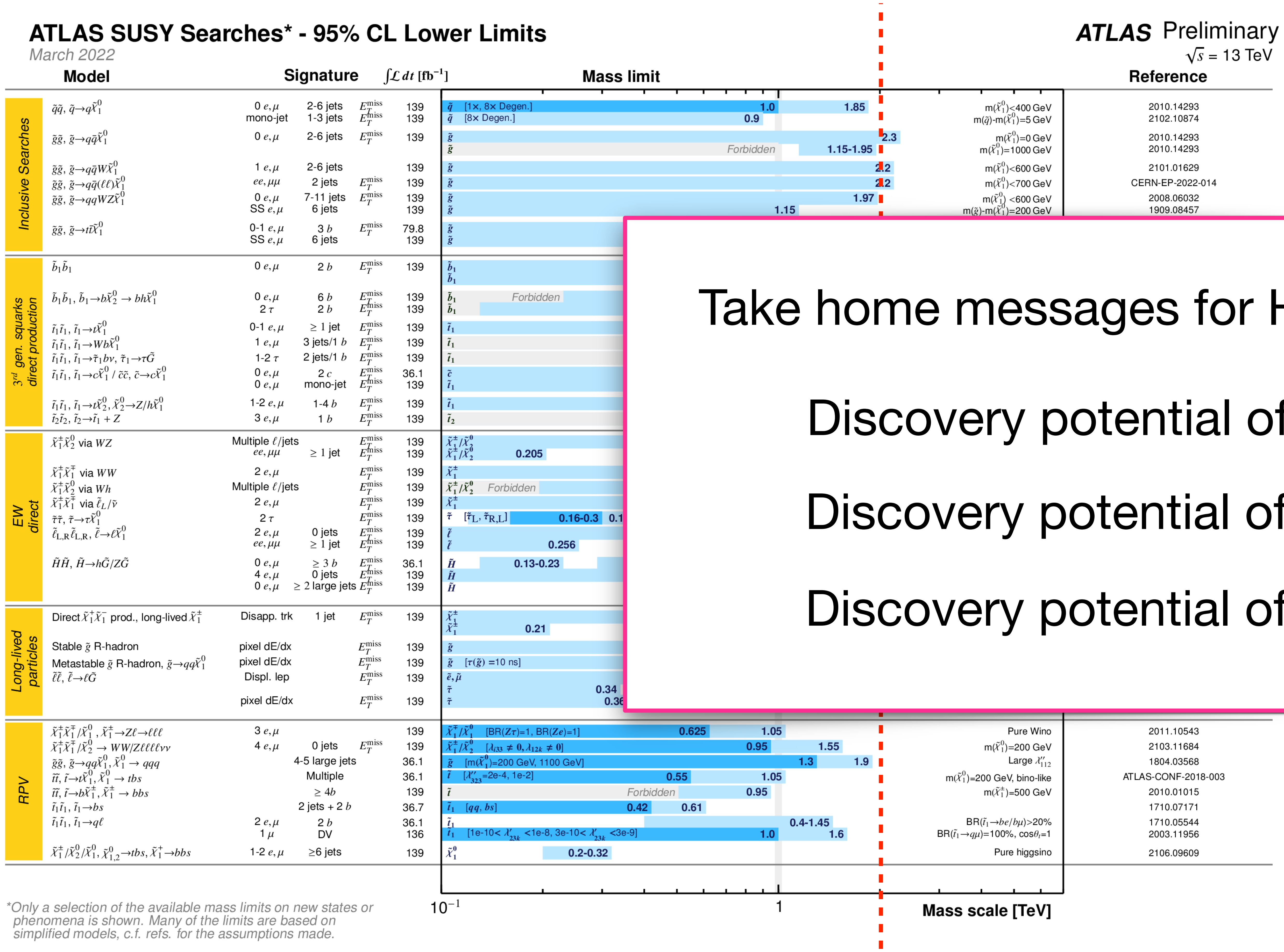


2 TeV

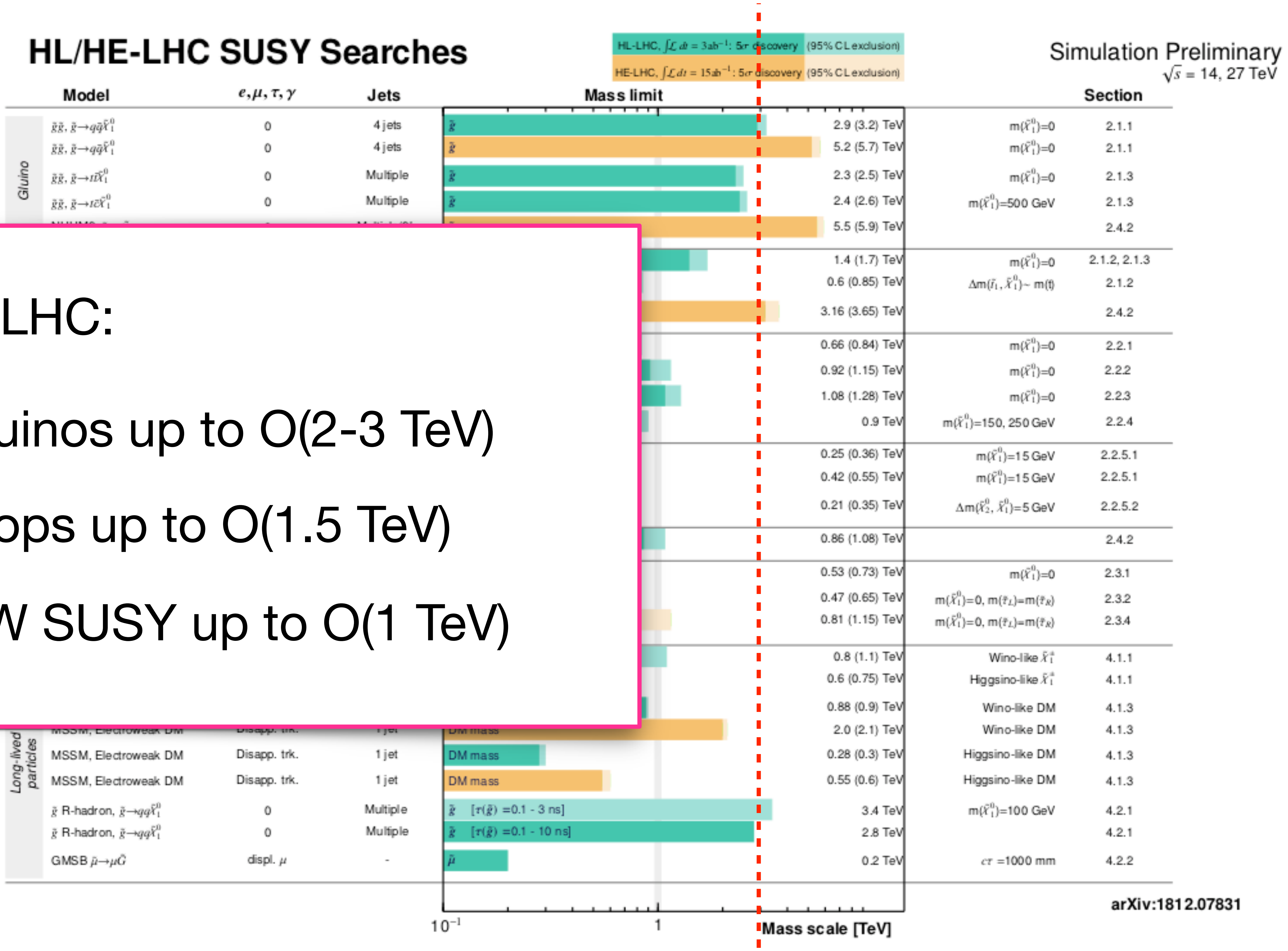
Example from ATLAS (similar for CMS)

Take home messages for HL-LHC:

Discovery potential of gluinos up to O(2-3 TeV)

Discovery potential of stops up to O(1.5 TeV)

Discovery potential of EW SUSY up to O(1 TeV)



3 TeV

HL-LHC YR
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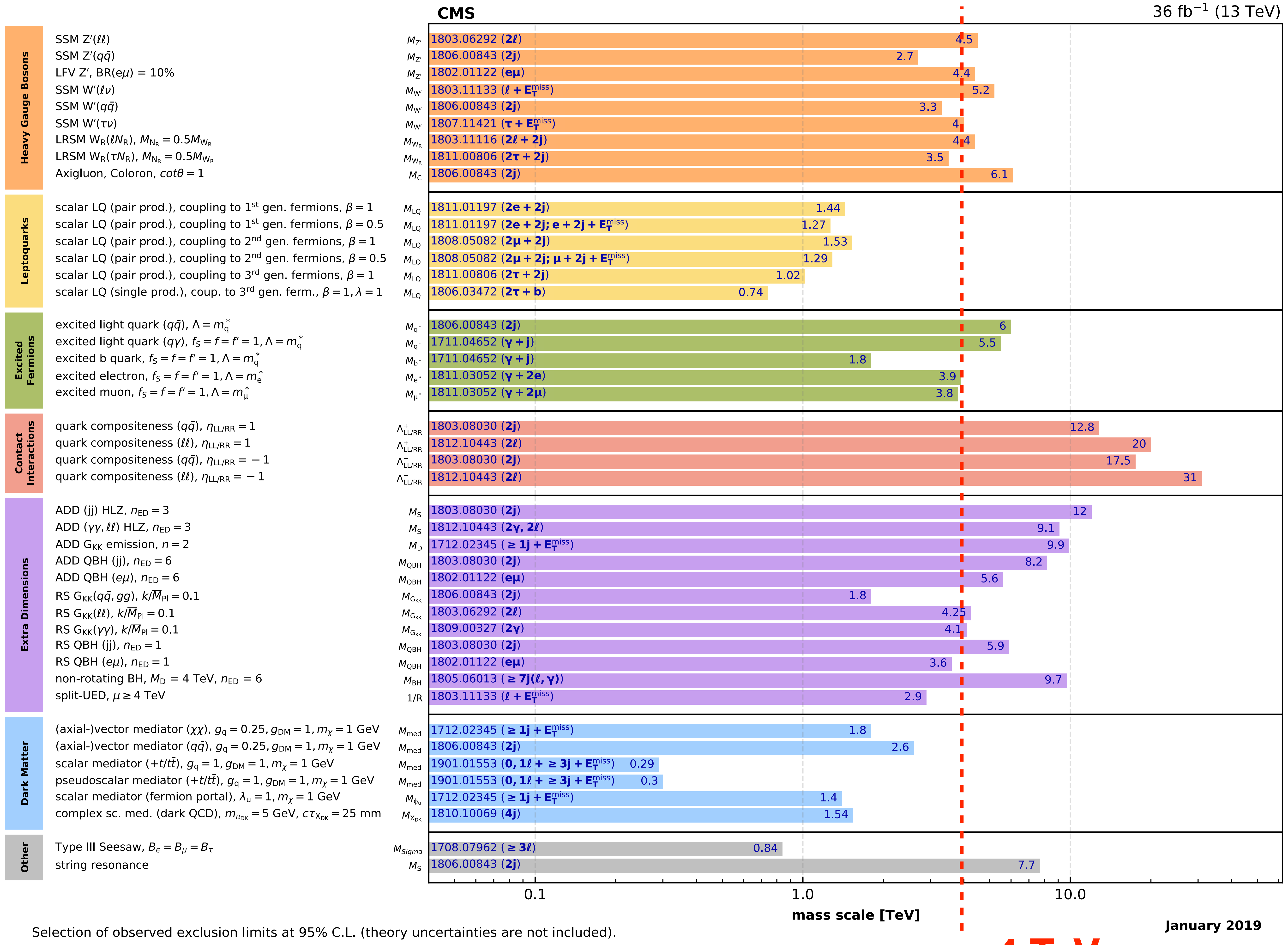
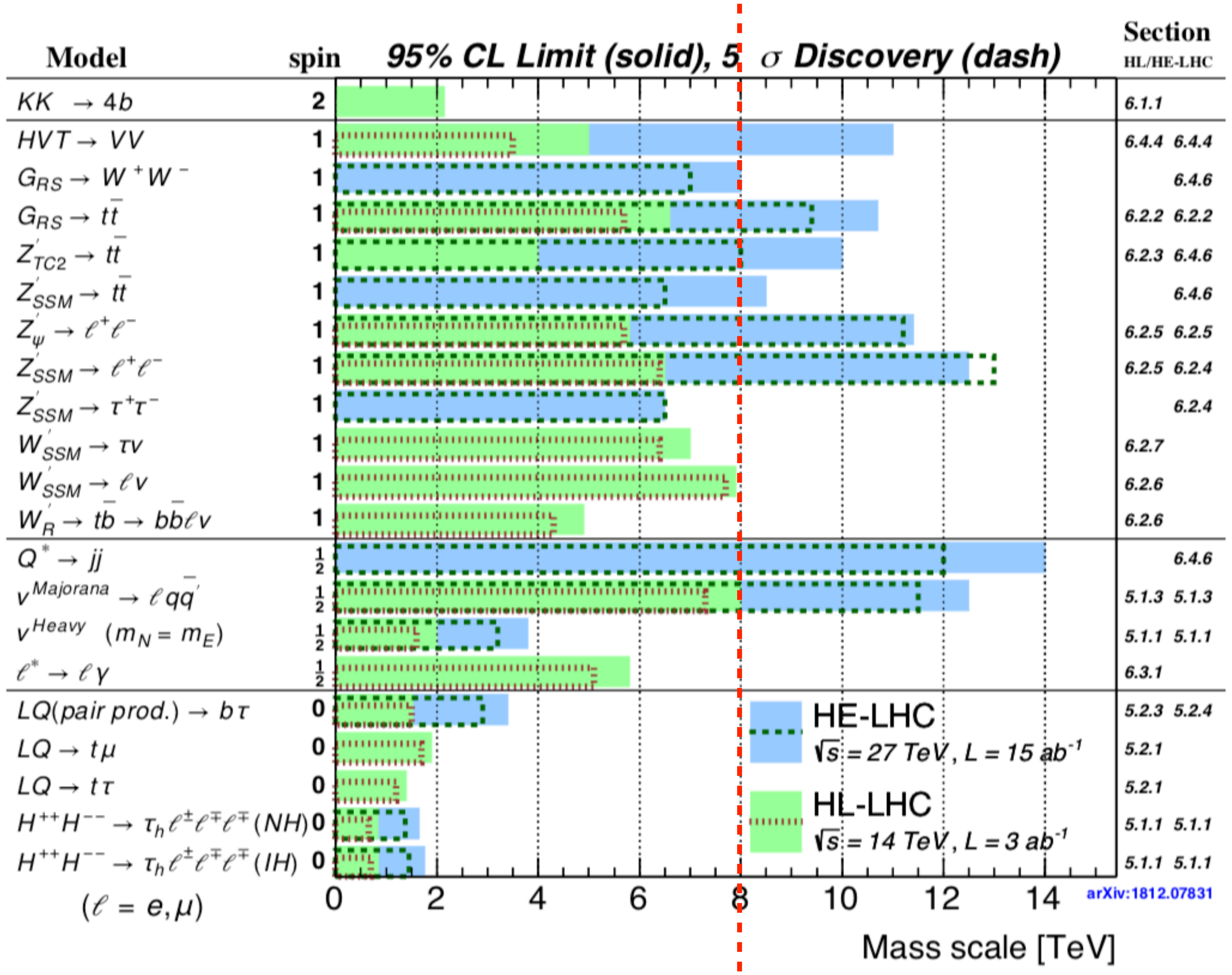
Very Large Number of Exotic NP Searches

(in large variety of topologies and models)

"“… and nothing else!” **Not at all a trivial statement!!**



4 TeV



8 TeV

HL-LHC YR
1812.07831

Example from CMS (similar for ATLAS) - latest plot in the backup!

Very Large Number of Exotic NP Searches

(in large variety of topologies and models)

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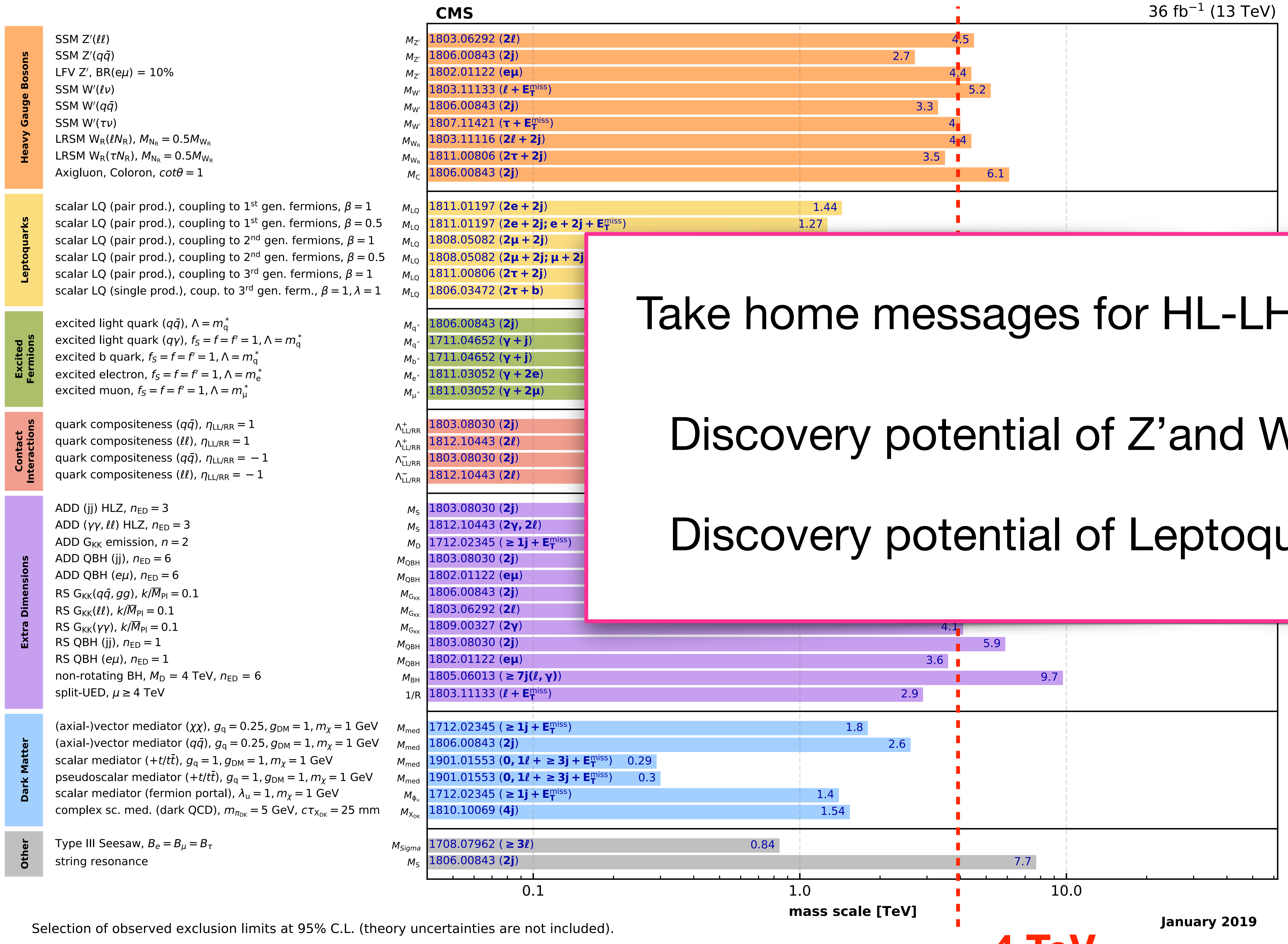
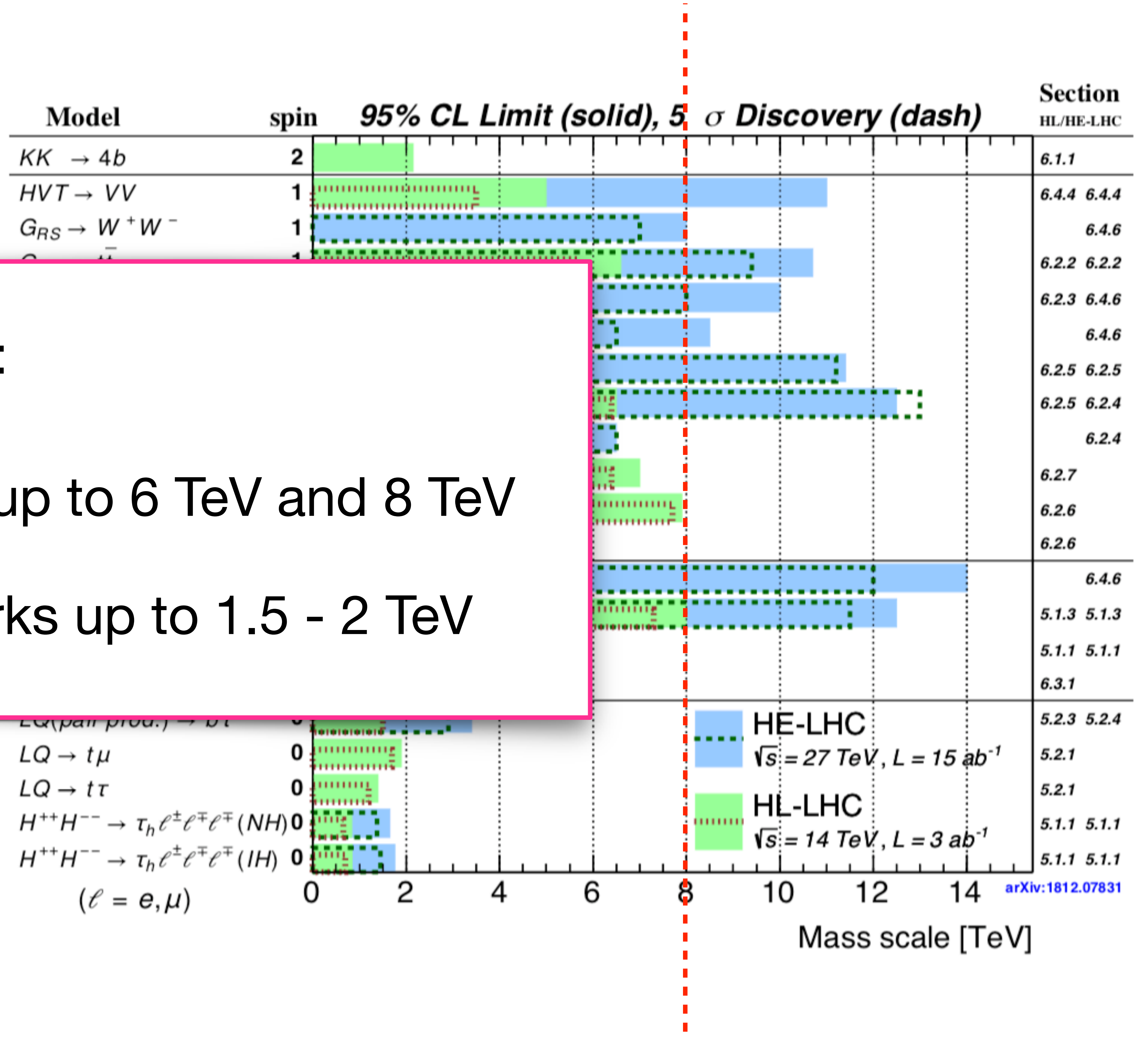


Example from CMS (similar for ATLAS)



Take home messages for HL-LHC:

Discovery potential of Z'and W' up to 6 TeV and 8 TeV

Discovery potential of Leptoquarks up to 1.5 - 2 TeV

HL-LHC YR
1812.07831

Leaving No Stone Unturned !

"“… and nothing else!” Not at all a trivial statement!!

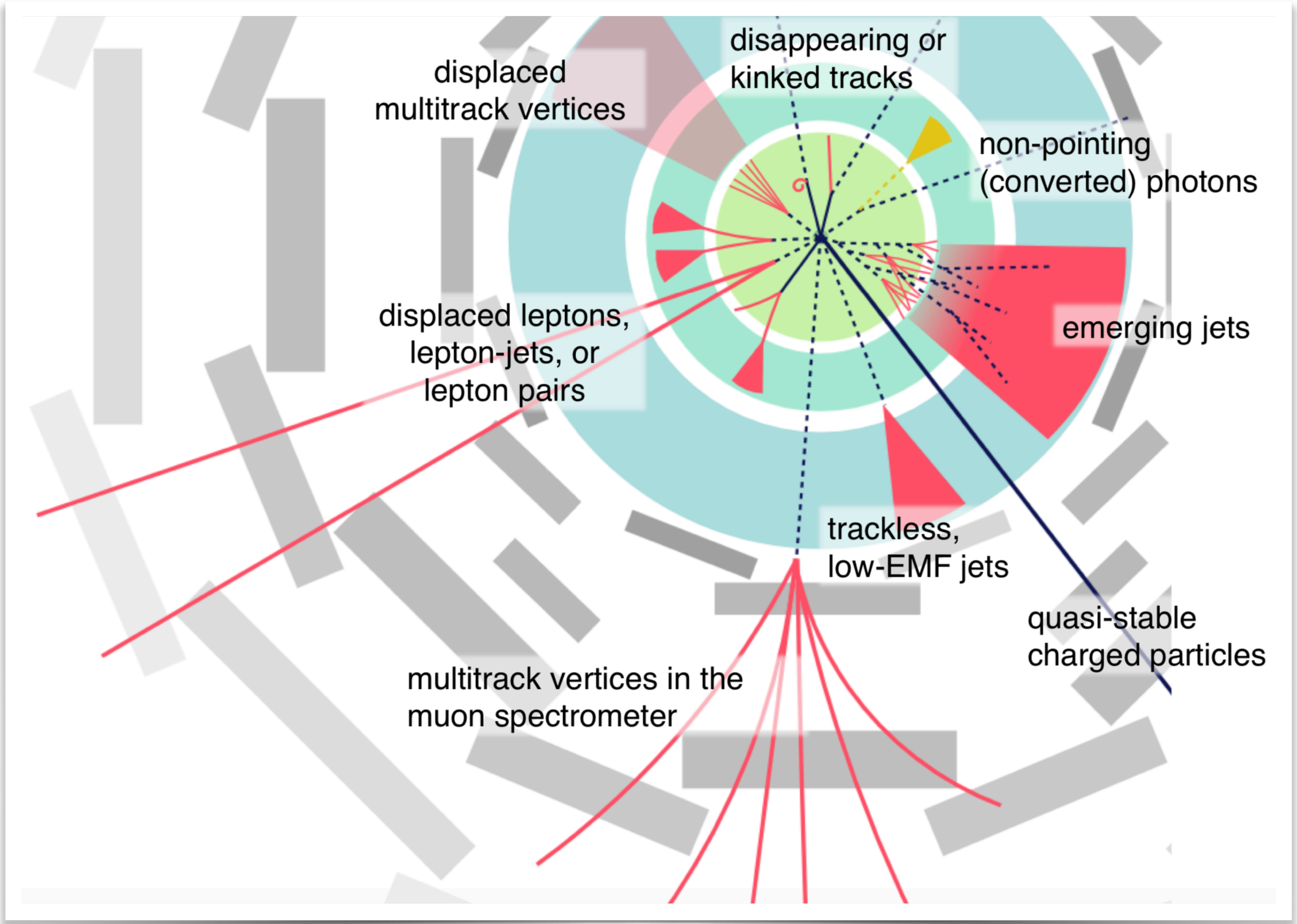
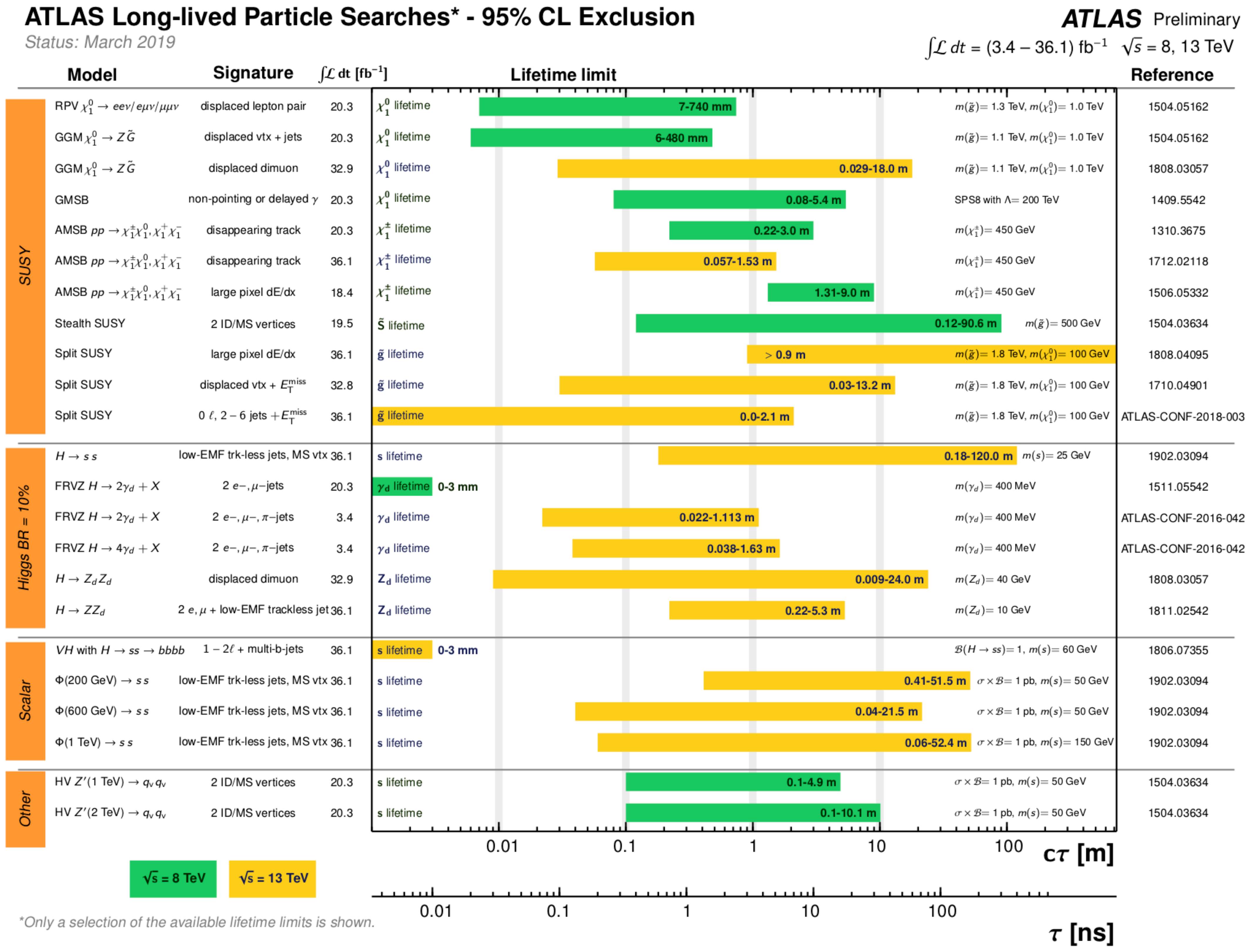


Image from H. Russel

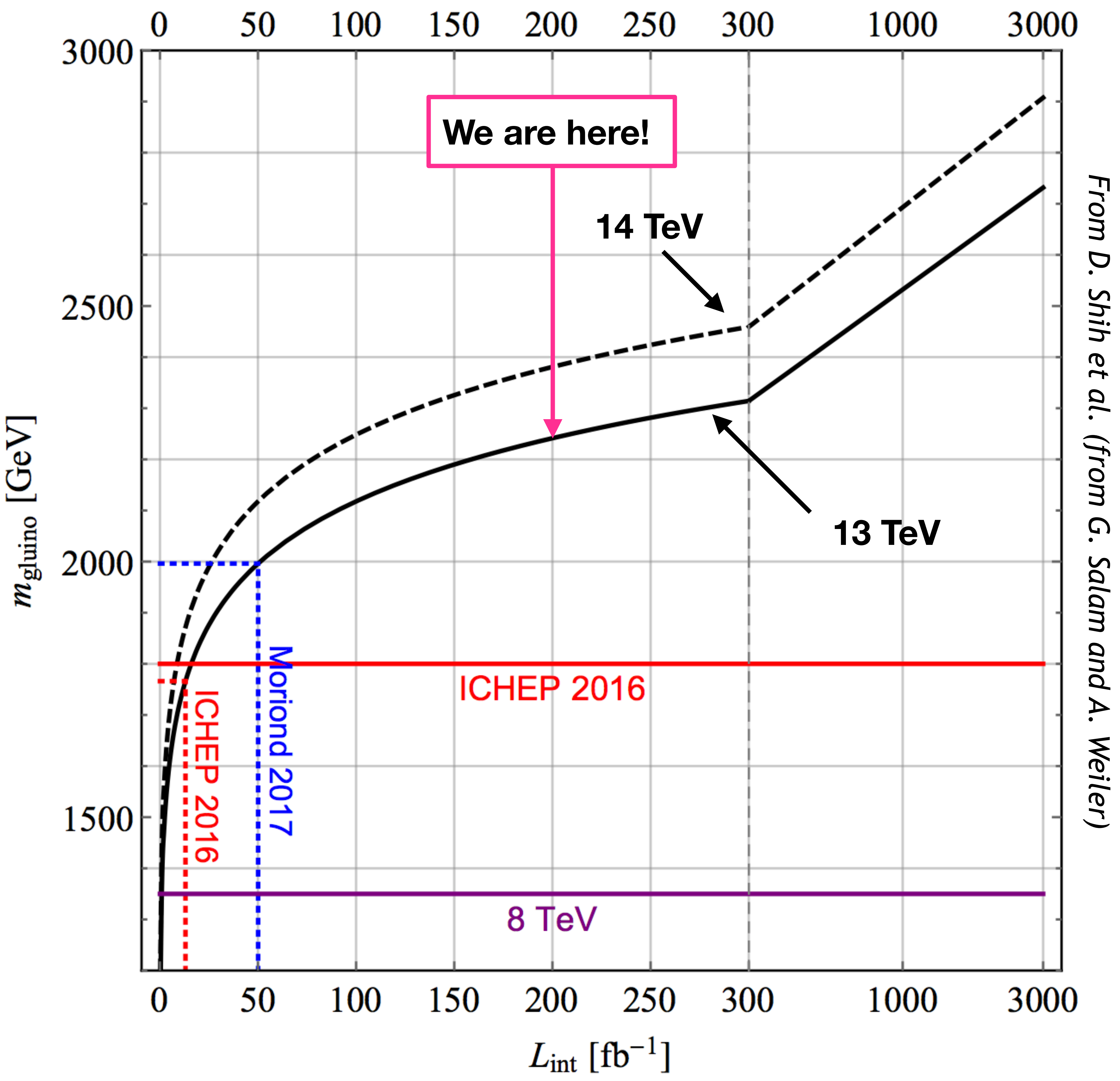


Sample for ATLAS (same for CMS)

Difficult signatures requiring specific complex reconstruction and trigger or specific detectors (MoEDAL - Monopole and Exotic Detector at the LHC, searches for Stable Highly Ionizing Particles) !

Still Room for Discoveries?

Evolution of **exclusion** search sensitivity for generic strongly interacting particle (e.g. **gluino**)

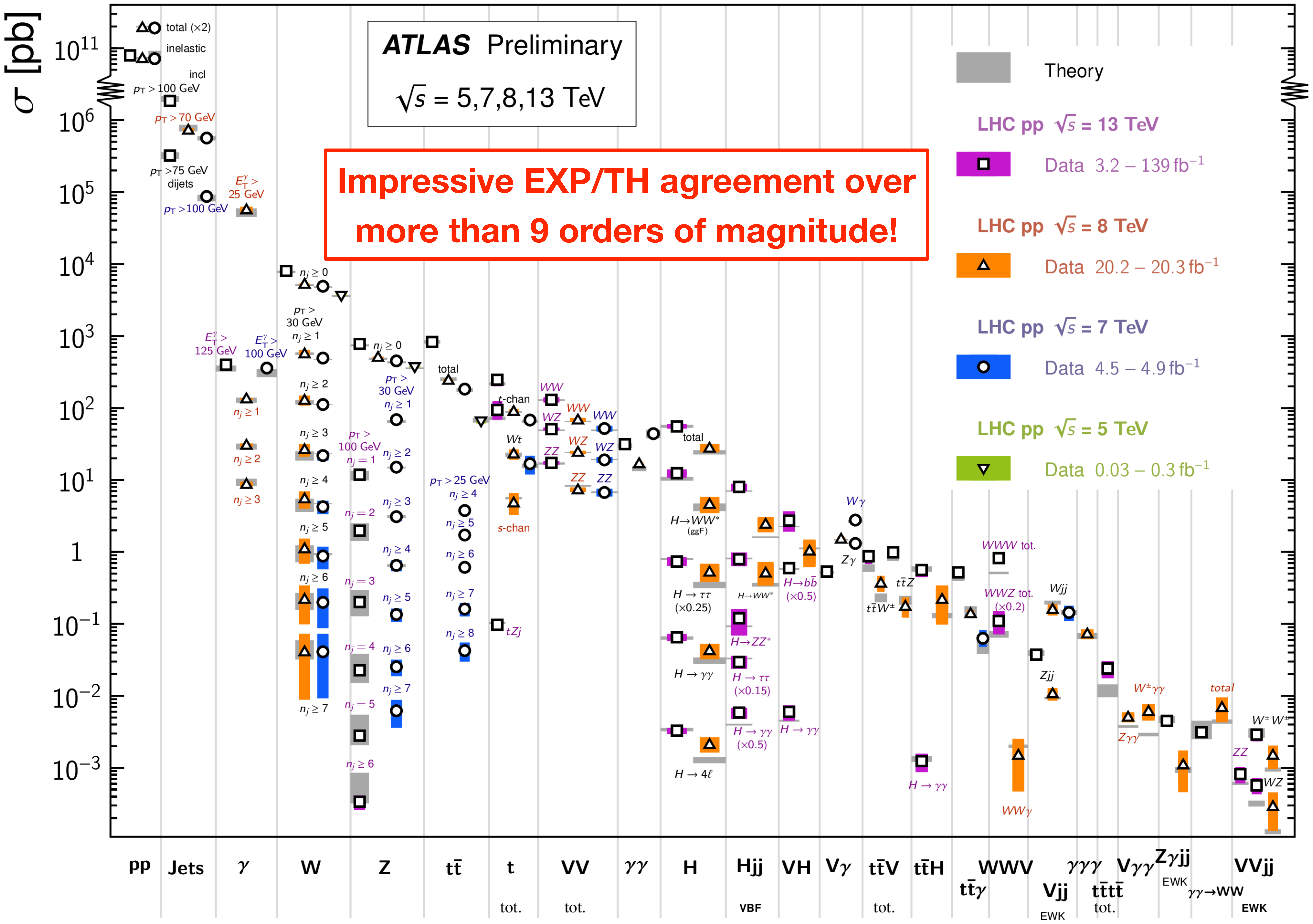


At HL-LHC still a **factor of 15** (effectively 20) in luminosity:

This plot does not take into account the improvement of reconstruction and analysis techniques and ancillary measurements!

- Still **room for discoveries!** (~1σ can become 5σ)
- Performance can be improved!
  - With new ideas and developments at all levels reconstruction and analysis (e.g. ML techniques).
  - **Improving precision and ancillary measurement!**
  - **Still nearly 1 TeV of Exploration!!**
- Discoveries will however take longer: **doubling time of the luminosity of several years**

Very Broad Physics Program!



Impressive EXP/TH agreement over more than 9 orders of magnitude!

- pp elastic scattering (down to the CNI regime), exclusive production, diffractive scattering
- Inclusive inelastic cross sections measurements
- QCD Jets, multi jets, photons and photons-jets
- DY (W,Z) and with (HF) jets, photons and Z Off mass shell, multi parton interactions
- Top pair production with (HF) jets or photons
- Diboson inclusive
- Single top Wt, t-channel and s-channel
- Tri-bosons
- Higgs production ggF-jets, VBF, HV, ttH
- Four tops, EWK dibosons…

Breadth of the Physics Program

- Broad program of different proton-Ion and **Ion-Ion collisions** configurations (not discussed in this talk), but used as diphoton collider for a measurement of the **tau g-2**!
- Detailed measurement of the total, inelastic and elastic cross sections in the Coulomb-Nuclear int. region, independent meas. of the luminosity and the pomeron exchange (possible discovery of the odderon exchange), with TOTEM (CMS) and ALFA (ATLAS).
- **Measurement neutral pion production in the forward region (with LHCf)!**
- Measurement of Central Exclusive Production processes with forward proton tagging with AFP and CT-PPS.
- **First observation of collider neutrinos (with FASER and SND)!**
- Study of fragmentation and hadronisation models through multi particle production kinematics and multiplicity.
- Study of QCD through jet production cross sections (measurements of α_S).
- Spectroscopy of new states **72 New Hadrons discovered** (among which 64 at LHCb) with 23 exotic hadrons (tetra quarks or pentaquark) - further understand models of quark confinement!
- Studies of **CP violation in heavy flavour b and c hadrons** (in particular at LHCb): with leading measurements better than B-factories (β and γ), measurements not possible at B factories.
- Stringent **probes of lepton universality** in B decays and (on-mass shell) in W decays.

Breadth of the Physics Program

- DY **precision** measurements (precision dominated by PDF uncertainties):
  - $\sin^2\theta_W$ measured at 0.15% only a factor of 2 larger than current LEP and SLC average
  - α_S from Sudakov Z peak at low transverse momentum, best measurement so far and precision at 0.9% on par with LQCD
  - W Mass precision at 16 MeV (experimental puzzle with the CDF measurement)

- Precise measurements of **di-boson production** and polarisation, improvements in analysis techniques led to possibility of **observing longitudinally polarised EW vector boson scattering at the HL-LHC!**

- Observation and measurements of tri-boson production in several channels!

- Detailed measurements of the production of single top and top pairs (inclusive, exclusive associated with jet, HF jets, vector bosons).

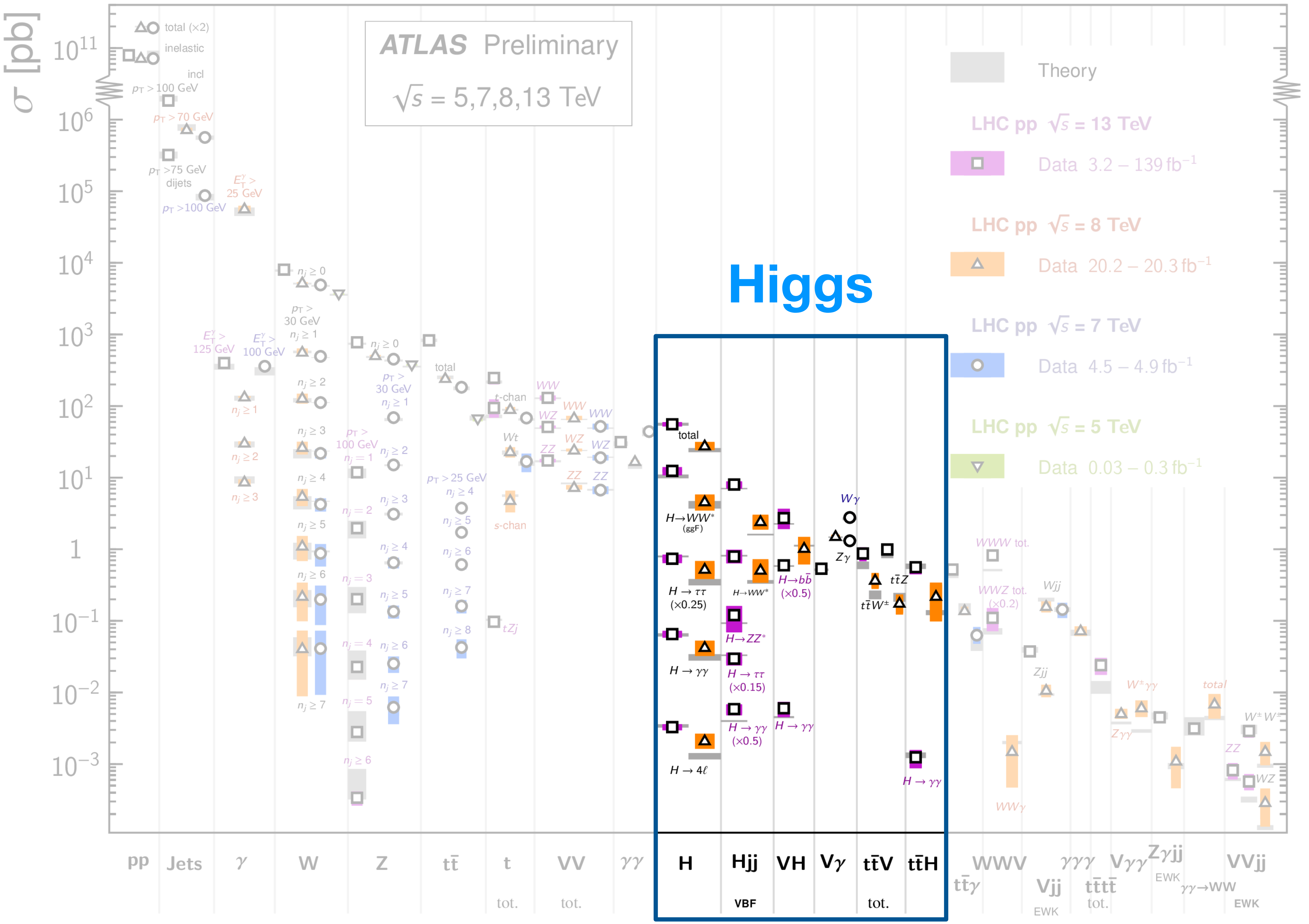
- Observation of **four top quark production!** Providing another way to probe top Yukawa coupling!

- Precision measurements of top production and properties: in particular precision on top mass with **statistical precision of 0.02%** (overall precision dominated by systematics of 0.2%).

- **Recent observation of quantum entanglement in top pair production!**

Huge breadth of results well beyond what was thought possible at the start of the LHC!

Very Broad Physics Program! Focus on Higgs Physics



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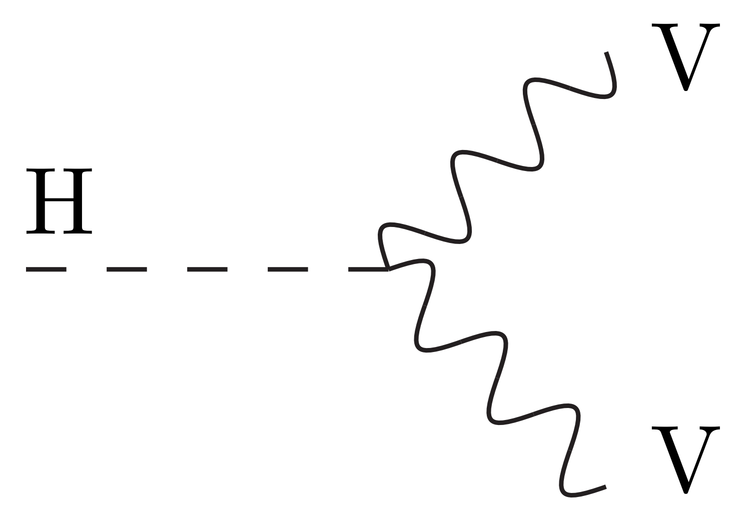
Pillars of Higgs Physics at Colliders

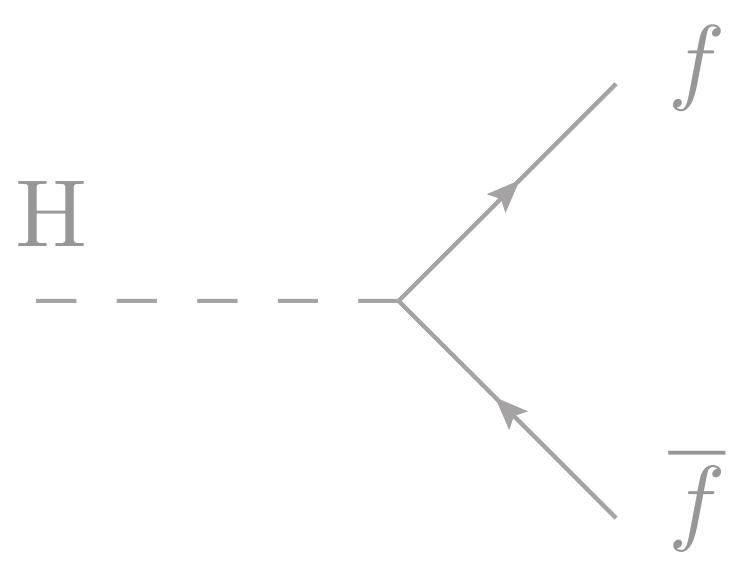
All the couplings of the Higgs boson to Standard Model particles (except itself) were known before the discovery of the Higgs boson! A very predictive model!



$$\frac{2m_V^2}{v}$$

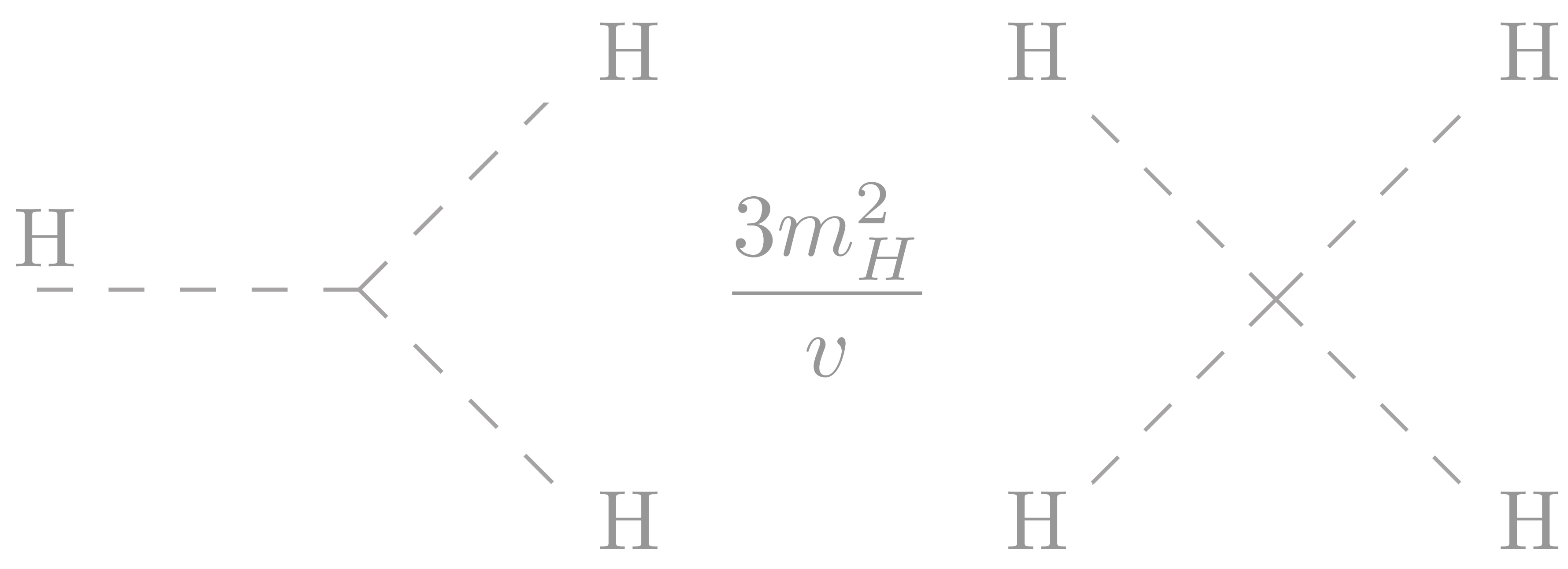
$$|D_\mu \phi|^2$$

This term could not exist without a vev



$$\frac{m_f}{v}$$

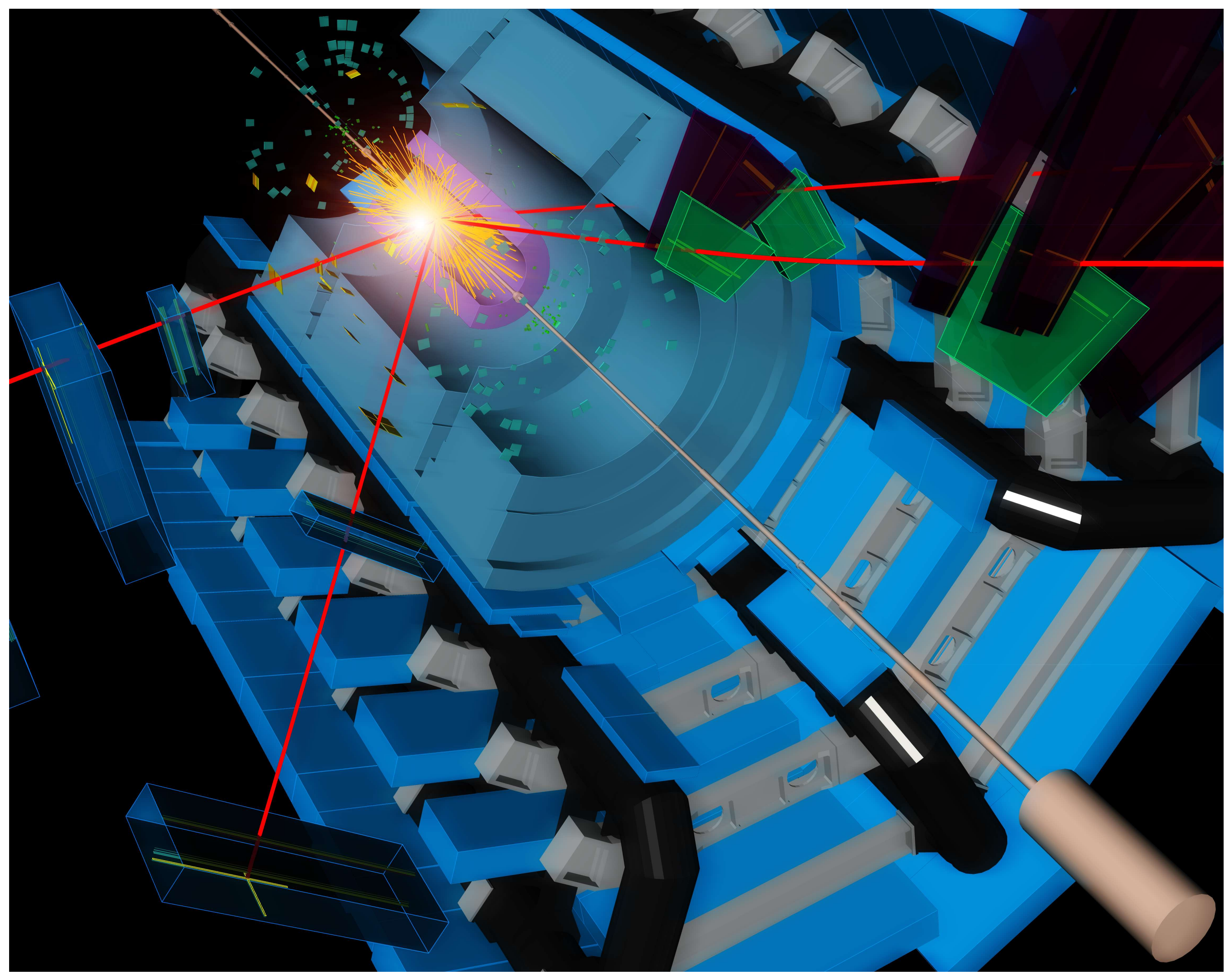
$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



$$\frac{3m_H^2}{v} \qquad \frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Four lepton events can have s/b of up to ~30!



Unambiguous proof of the existence of the Higgs condensate!

	Current	HL-LHC
$\kappa_{W,Z}$	6%	1.5%, 1.7 %

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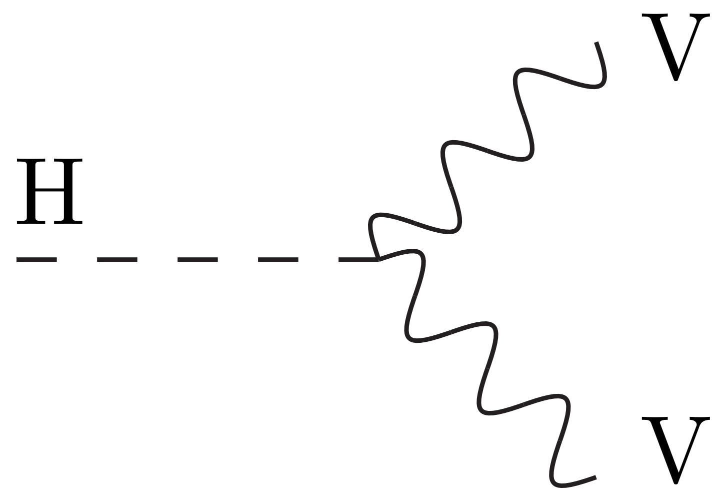

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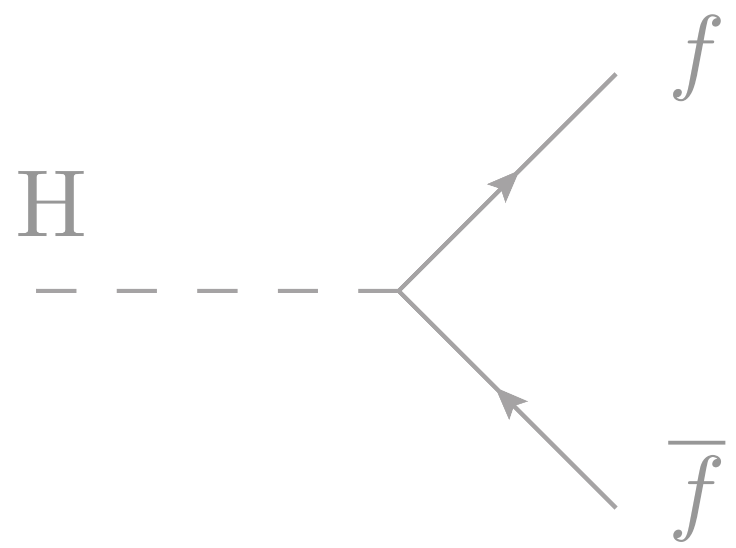

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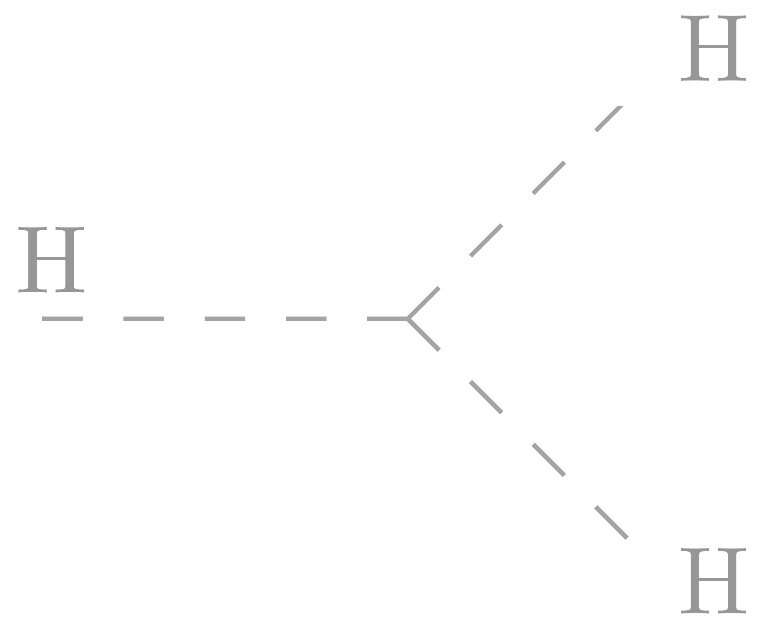
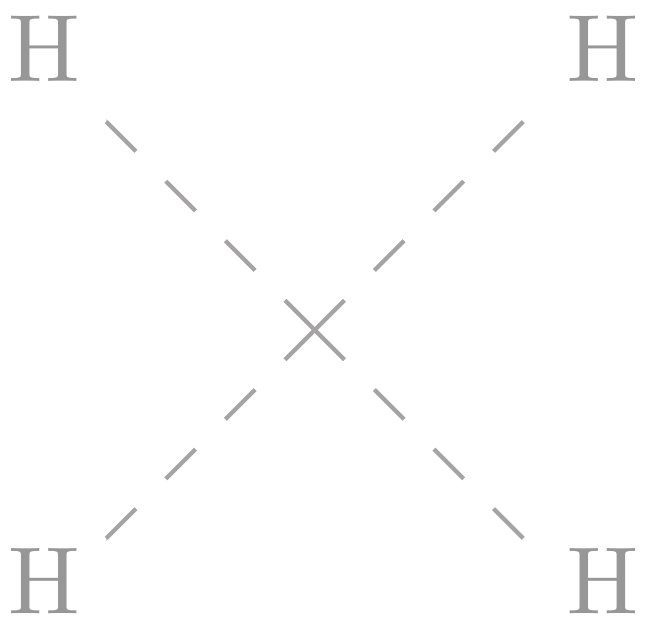


$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Most precisely known Higgs coupling tells us how elementary the Higgs boson is!

...or what its effective size is!

Comparing the Compton radius of the Higgs $1/m_H$ to its effective radius $1/\Lambda$ through the higher order operator:

$$\frac{c_H}{\Lambda^2} \cdot \frac{1}{2} \left(\partial_\mu |H|^2\right)^2 \to \left(\frac{2c_H v^2}{\Lambda^2}\right) \cdot \frac{1}{2} \left(\partial_\mu h\right)^2$$

(as comparing the mass of the pion to that of the ρ meson)

Current precision $\Lambda > 1$ TeV

The Higgs could well be a pNGB as the pion!

"A case for future lepton colliders" N. Craig (See paper)

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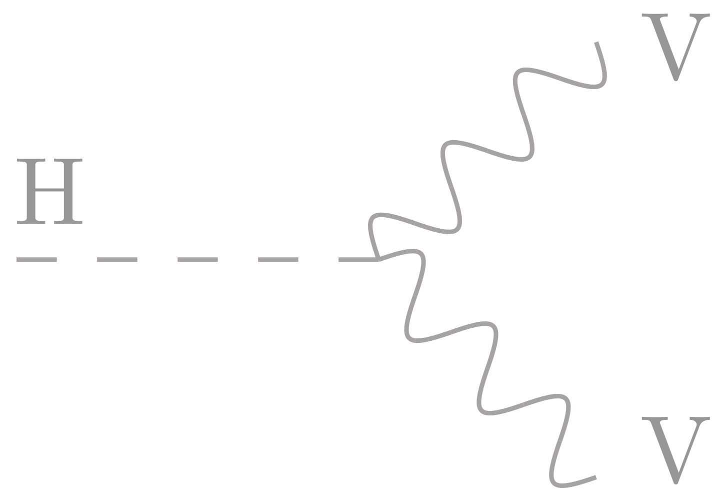

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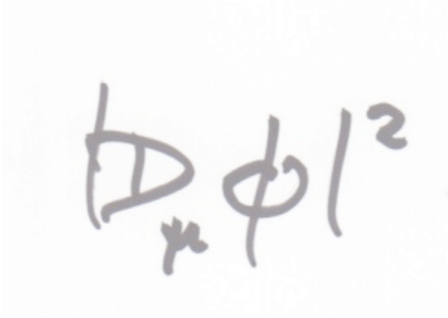

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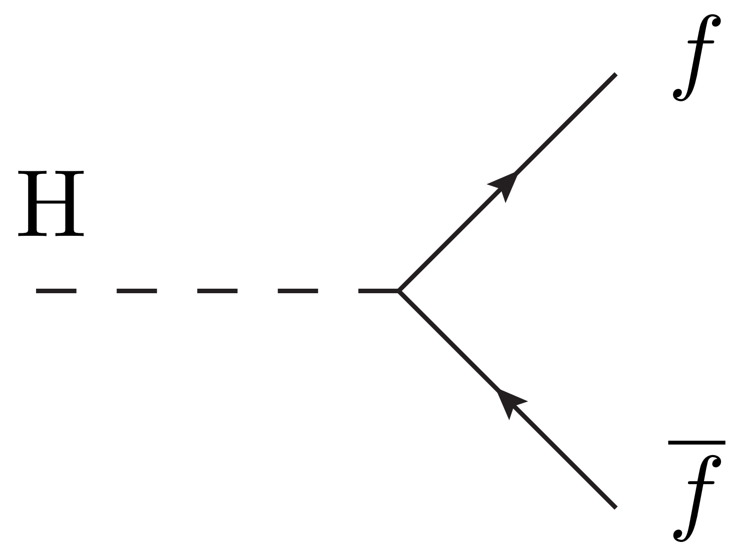

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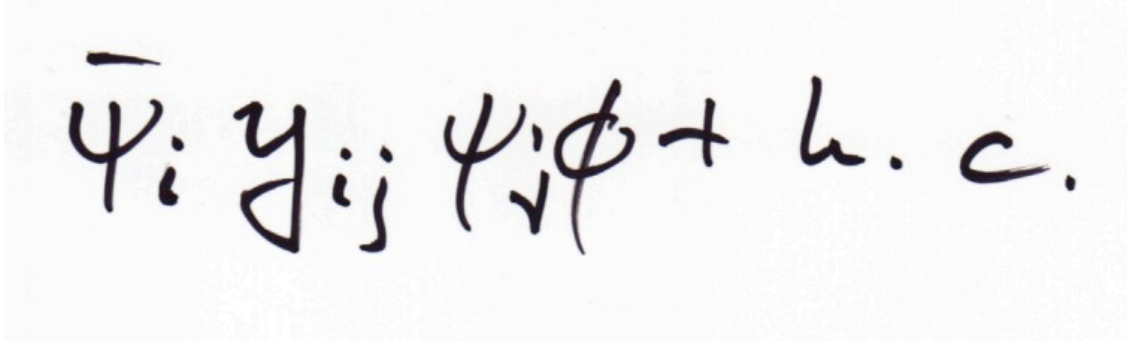

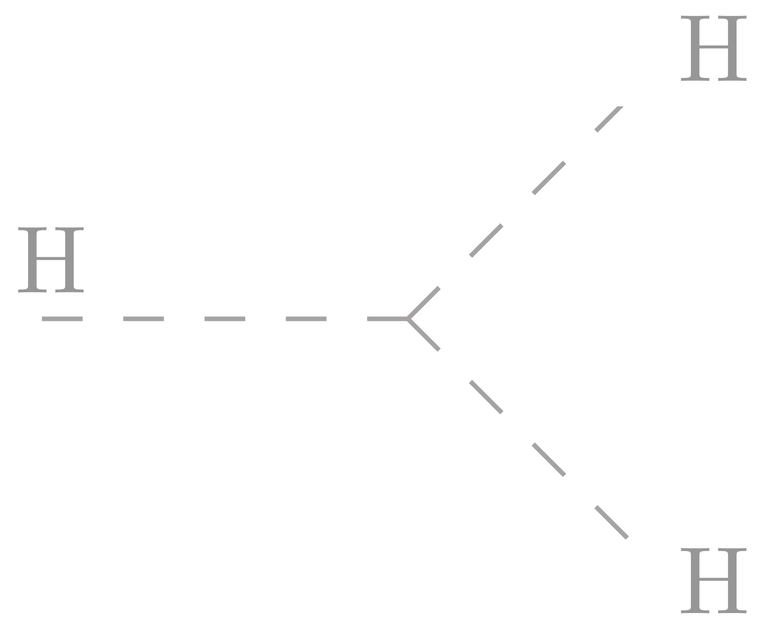

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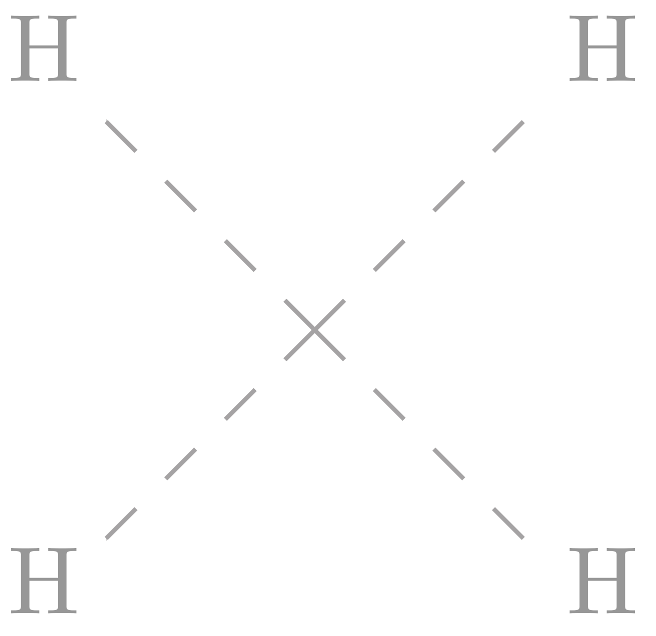

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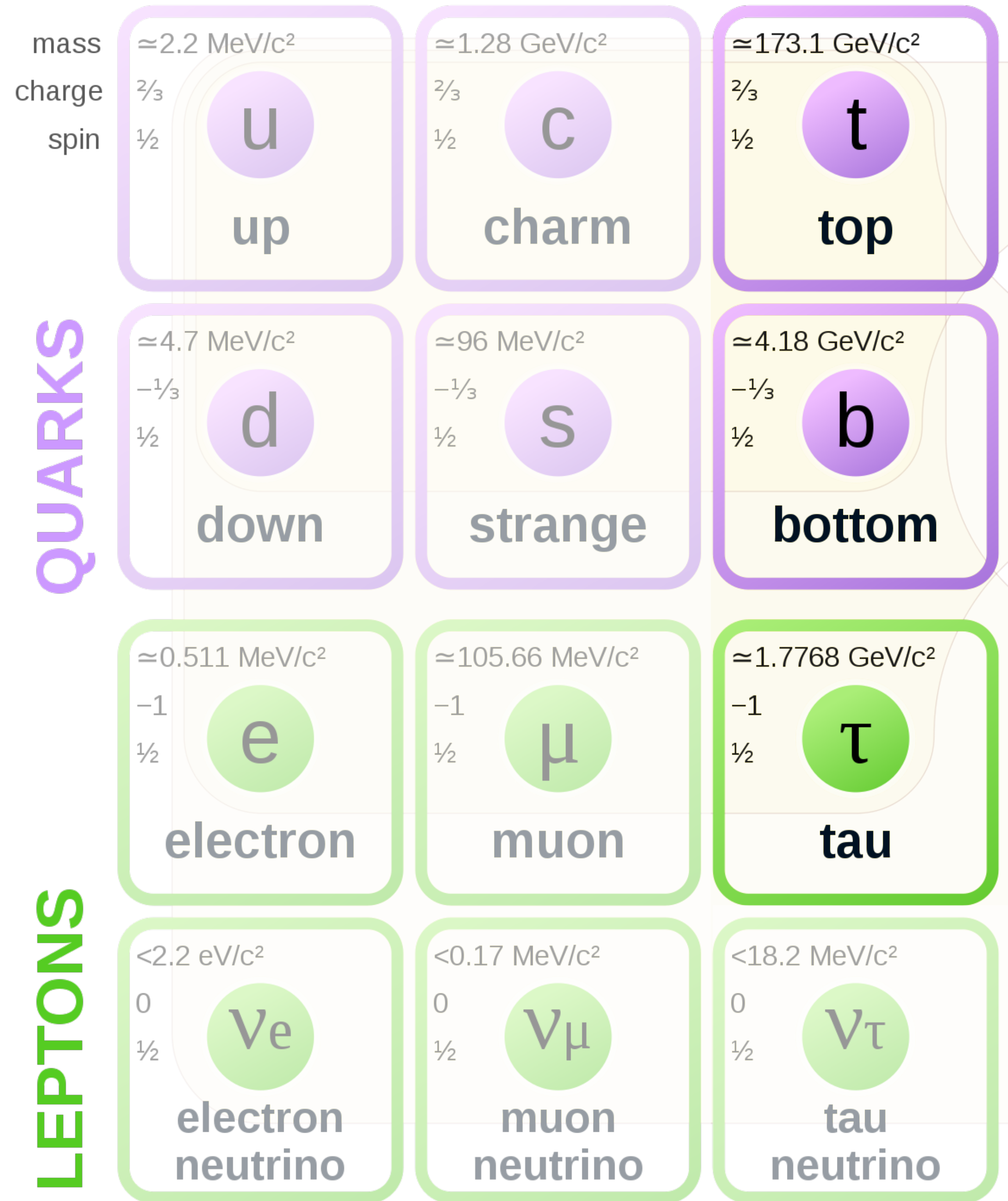

"We would not consider the theory of electromagnetism established if we had only verified the strength of electromagnetic forces to within 10% accuracy." (Salam, Wang, Zanderighi, Nature)

	Current	HL-LHC
κ_t	11%	3.4%
κ_b	11%	3.7%
κ_τ	8%	1.9%

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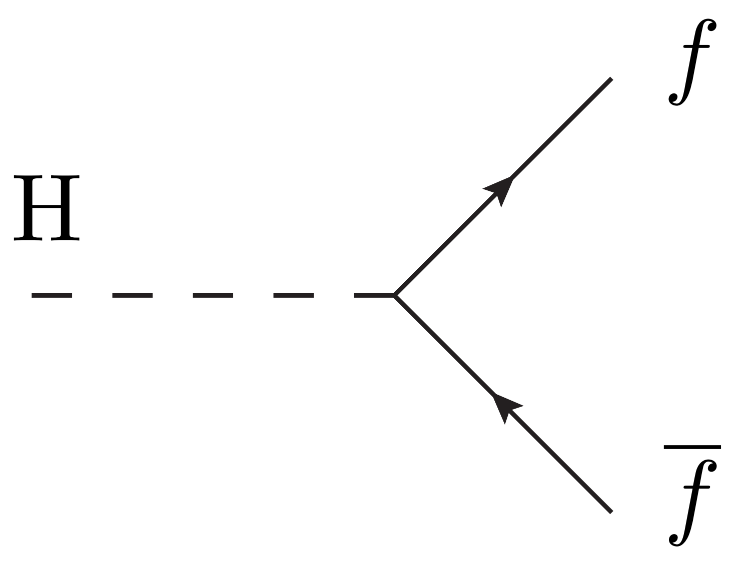

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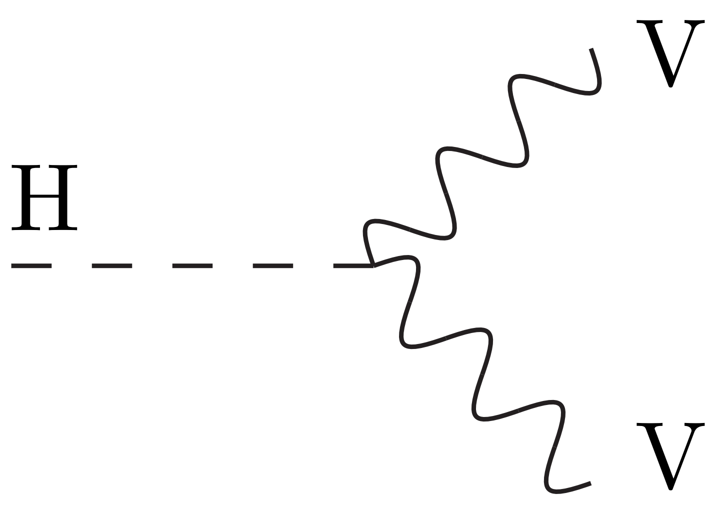

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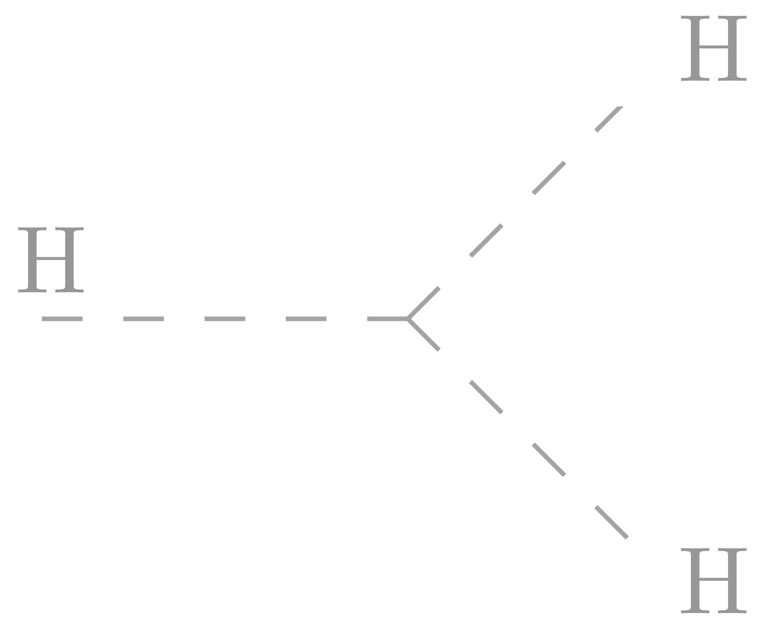

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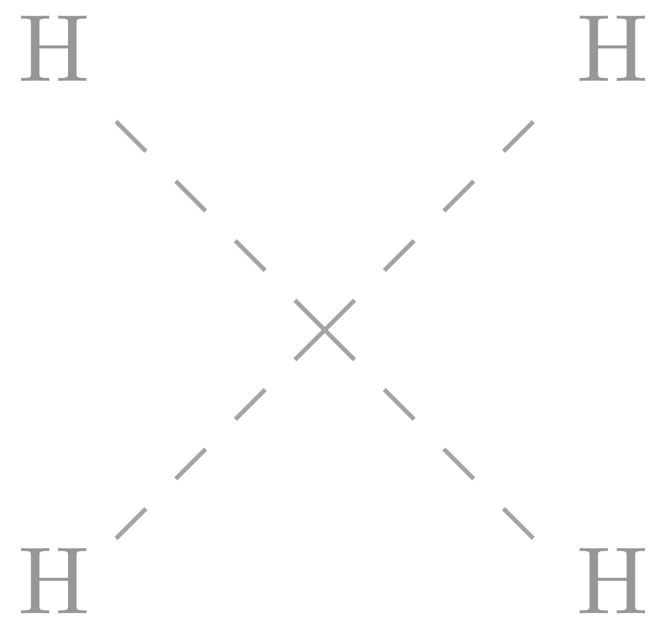
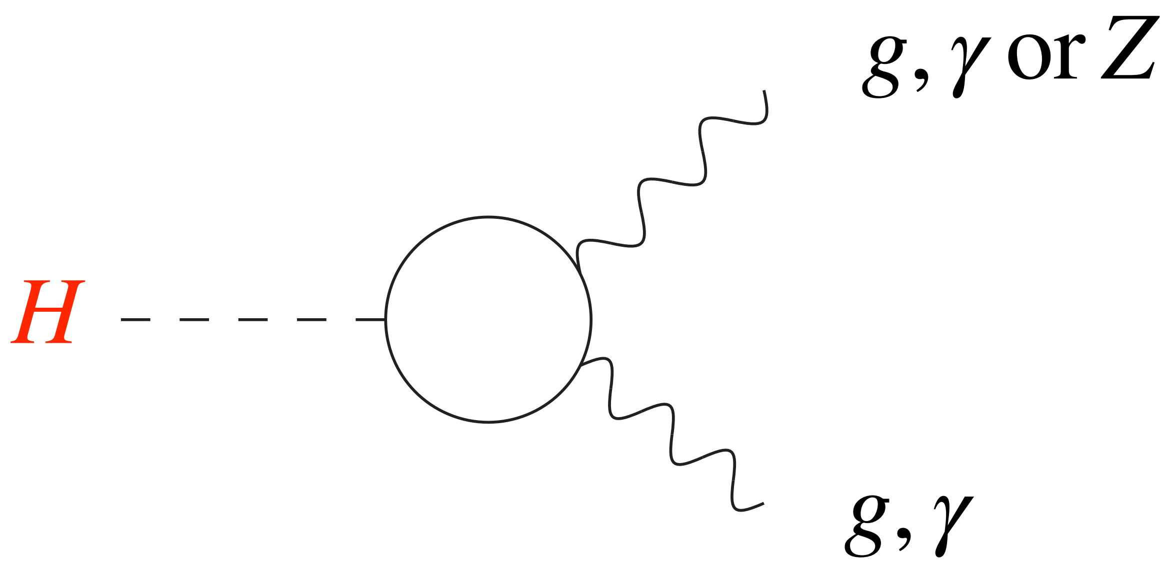


$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Probing new particles through loops in production and decays!



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κ_g	7%	2.5%

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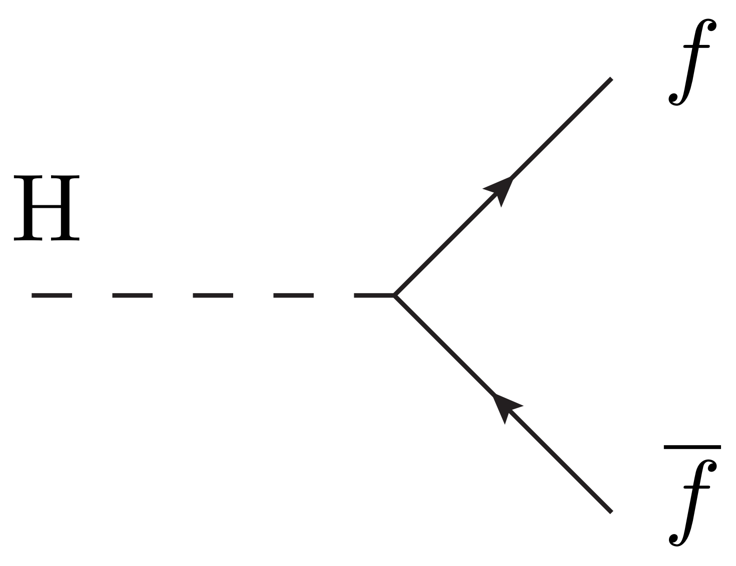

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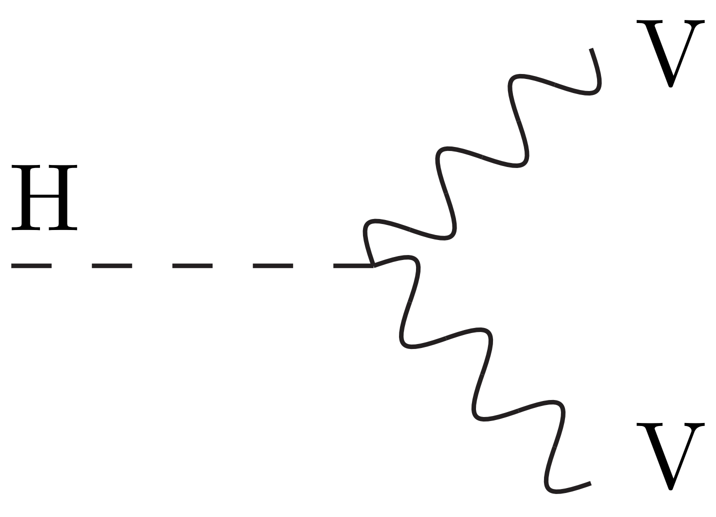
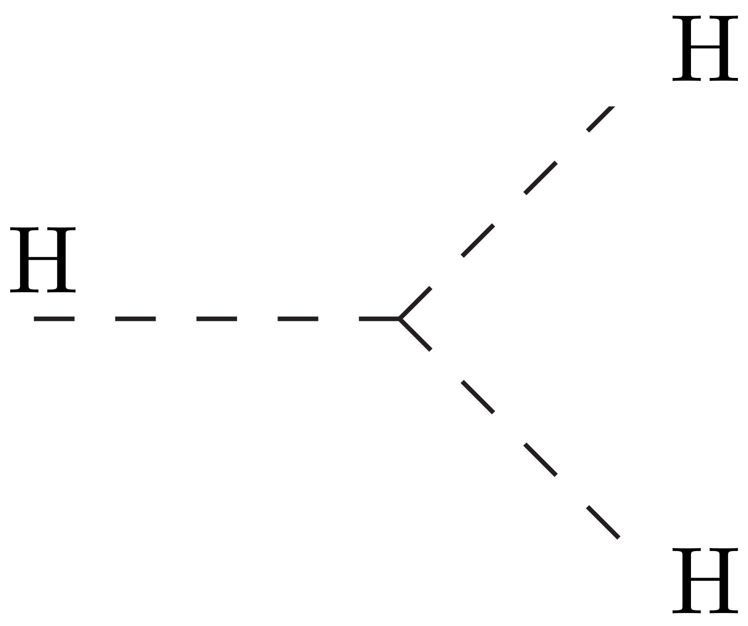


$$\frac{2m_V^2}{v}$$

$$|D_\mu \phi|^2$$

This term could not exist without a vev



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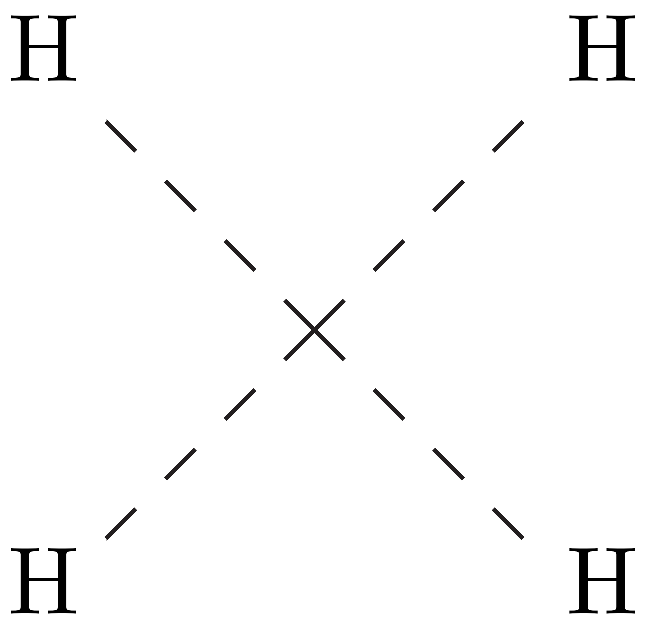
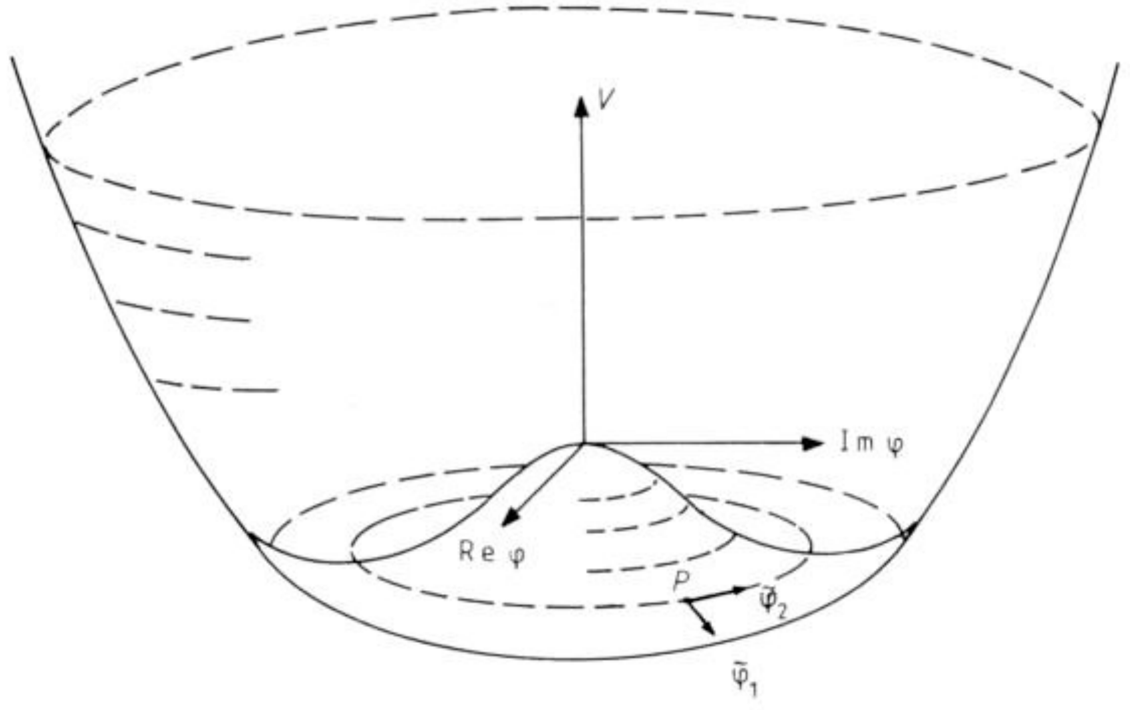


$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Spontaneous Symmetry Breaking

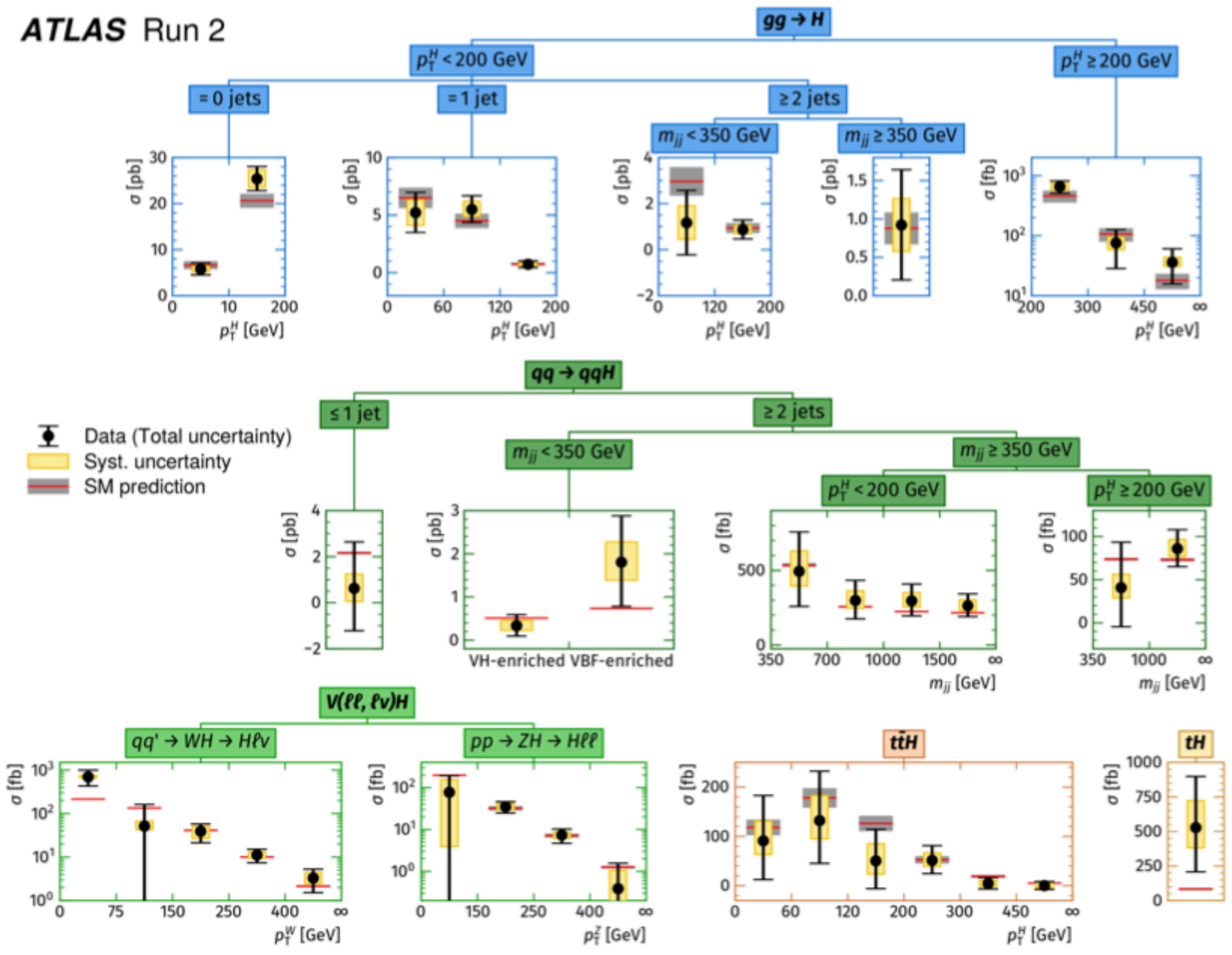


$$V(\phi) = \mu^2 \phi^* \phi + \lambda(\phi^* \phi)^2$$

In the SM EW transition is a cross over does not fulfil requirements for baryogengesis, studying the Higgs potential is an outstanding goal of the Higgs physics program

Exploring further with STXS and SMEFT Interpretations

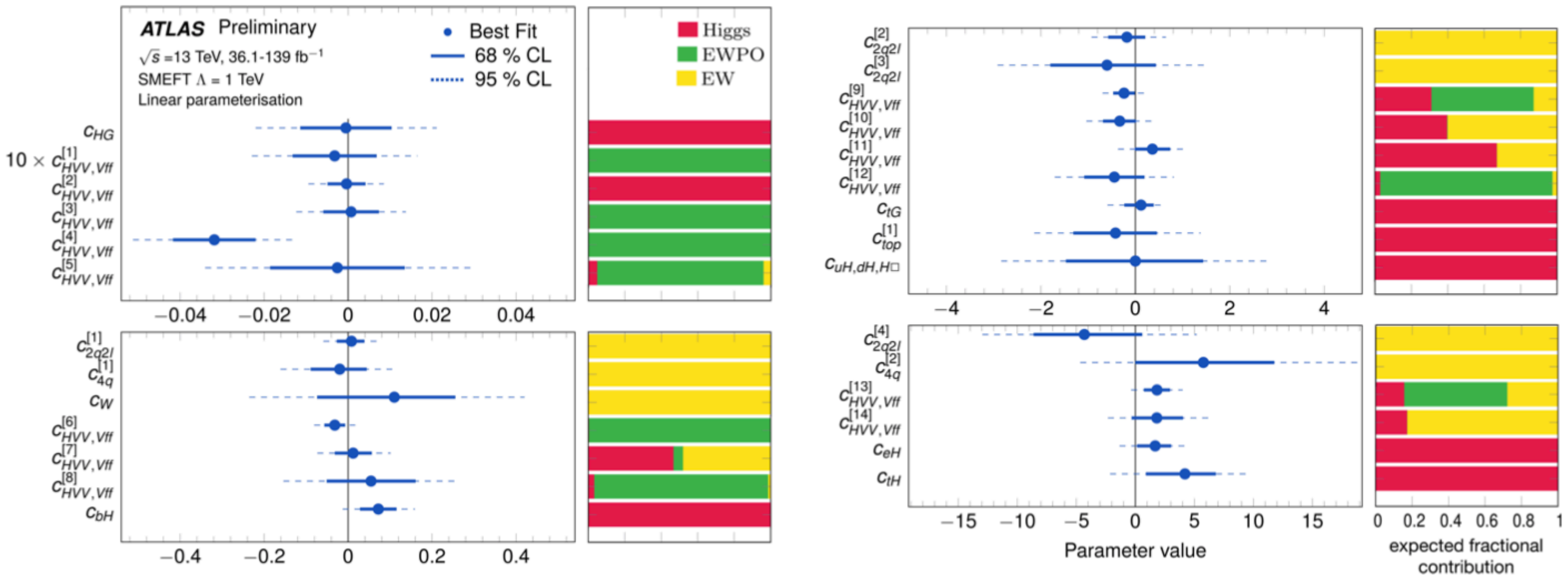
Simplified Template Cross Sections (STXS): Combined measurements of Higgs boson production and decay in exclusive kinematic regions of the production phase space (and different production processes).



Interpretation in **Standard Model** (only SM fields) **Effective Field Theory (SMEFT)**: Electroweak precision data on the Z resonance from LEP and SLC.

SMEFT is a coherent tools to interpret our data, it is key given that the no new physics has been directly found at the LHC.

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$



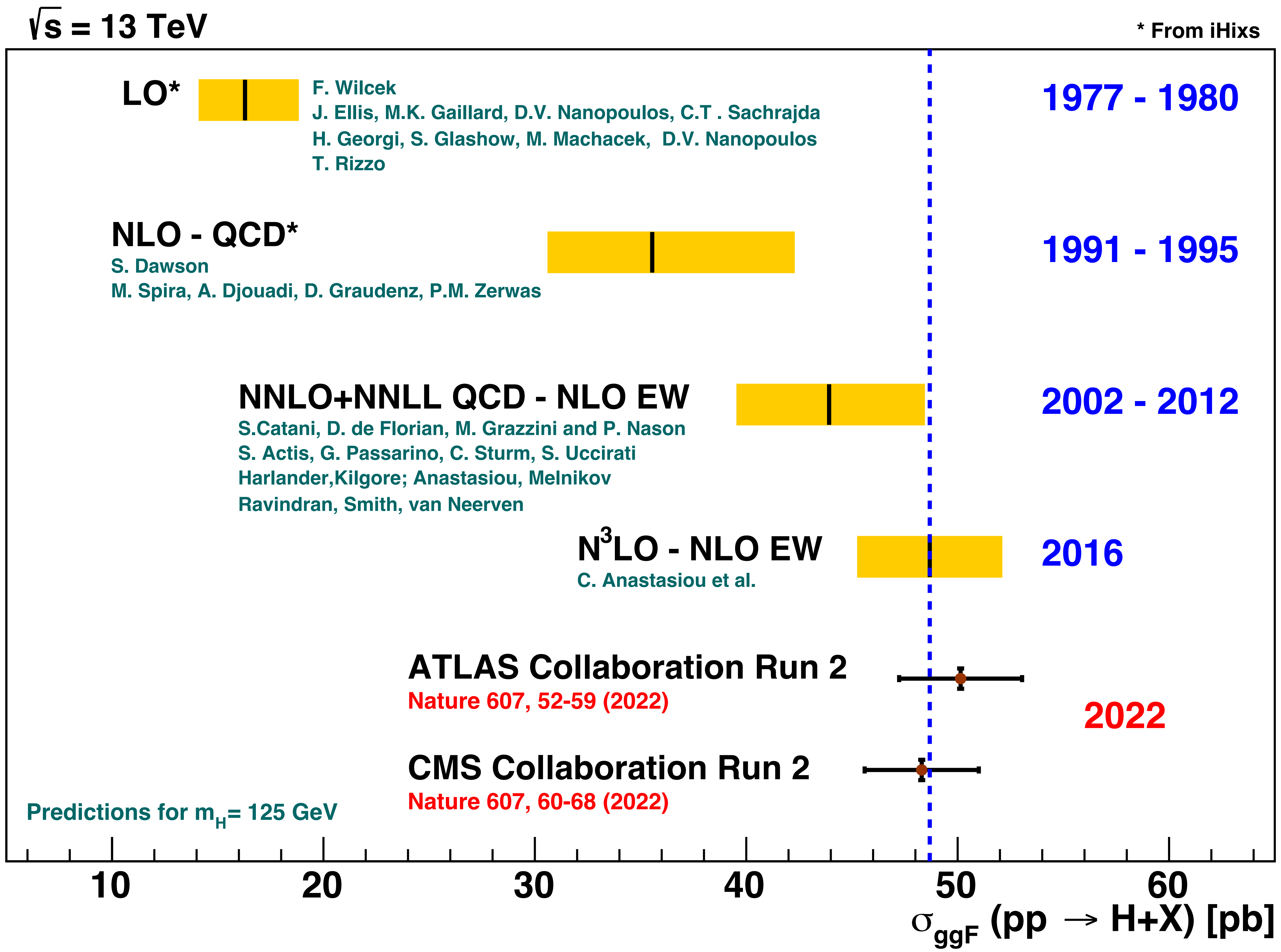
The Importance of Theory and Modelling

Predictions at hadron colliders are complex and require several levels of modelling and calculations (higher order hard processes, parton fragmentation, hadronization, parton distribution functions, etc…)

The interpretability of our results relies on our ability to compute accurate and precise predictions!

Precision at the LHC has become would not be possible without the efforts of precise TH and modelling.

Half a century of progress in Higgs production predictions



Achieving the Impossible in Higgs Physics!

- First evidence of the **Higgs off shell** contribution (as a propagator) and constraints on the **Higgs boson total width** with precision already at the 50-60% level, should reach better than **20% at HL-LHC**!

- Boosted and flavour tagging techniques (using Graph NN techniques) enabled unforeseen sensitivity:
  - Inclusive Higgs production and $H \to b\bar{b}$ in the high transverse momentum regime (above 250 GeV)
  - **Sensitivity to $H \to c\bar{c}$ with new flavour tagging techniques should reach ~40% precision at HL-LHC!!**

- Reconstruction of tau polarisation sensitive variables, allowed for the first measurement of CP odd couplings in $H \to \tau^+\tau^-$ (unlike other constraints on Higgs CP odd couplings, these constraints are competitive with indirect constraints from EDM measurements, in particular of the electron). **Precision on CP mixing angle of ~15° already better than what was foreseen in the 2020 European Strategy for HL-LHC!**

- Already **first evidence** at Run 2 of the coupling to second generation fermions in the $H \to \mu^+\mu^-$ **decay!**

- Already first evidence at Run 2 of the tensor coupling of the Higgs boson $|H|^2 W^a_{\mu\nu} W^{a\mu\nu}$ in the decay $H \to Z\gamma$ and first evidence of the $H \to \gamma\gamma^*$ (in the low $\gamma^* \to \ell^+\ell^-$ regime with novel reconstruction techniques).

Well beyond what was thought possible at the start of the LHC!

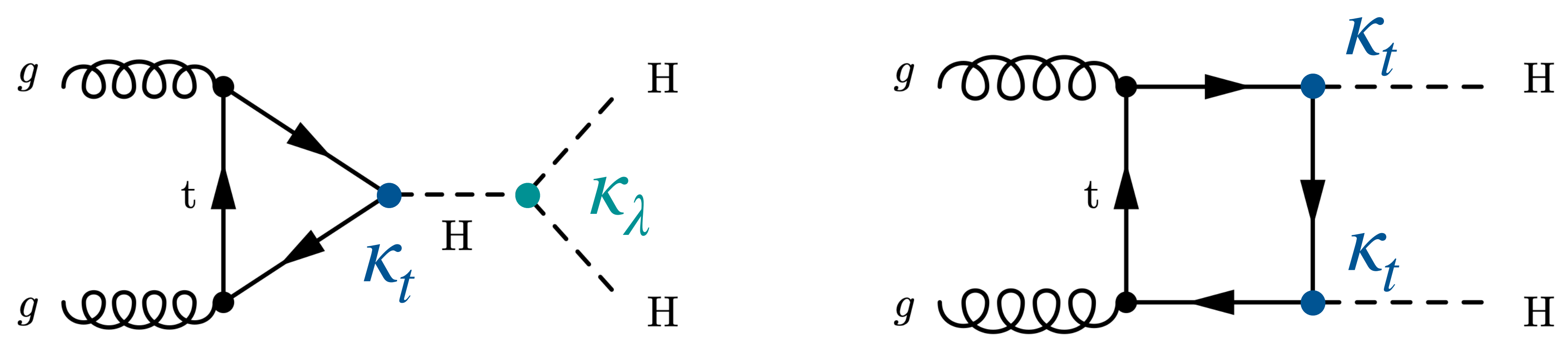
HH Production and Higgs Self coupling

Measuring the di-Higgs production provides a unique and direct probe of the Higgs boson self-coupling

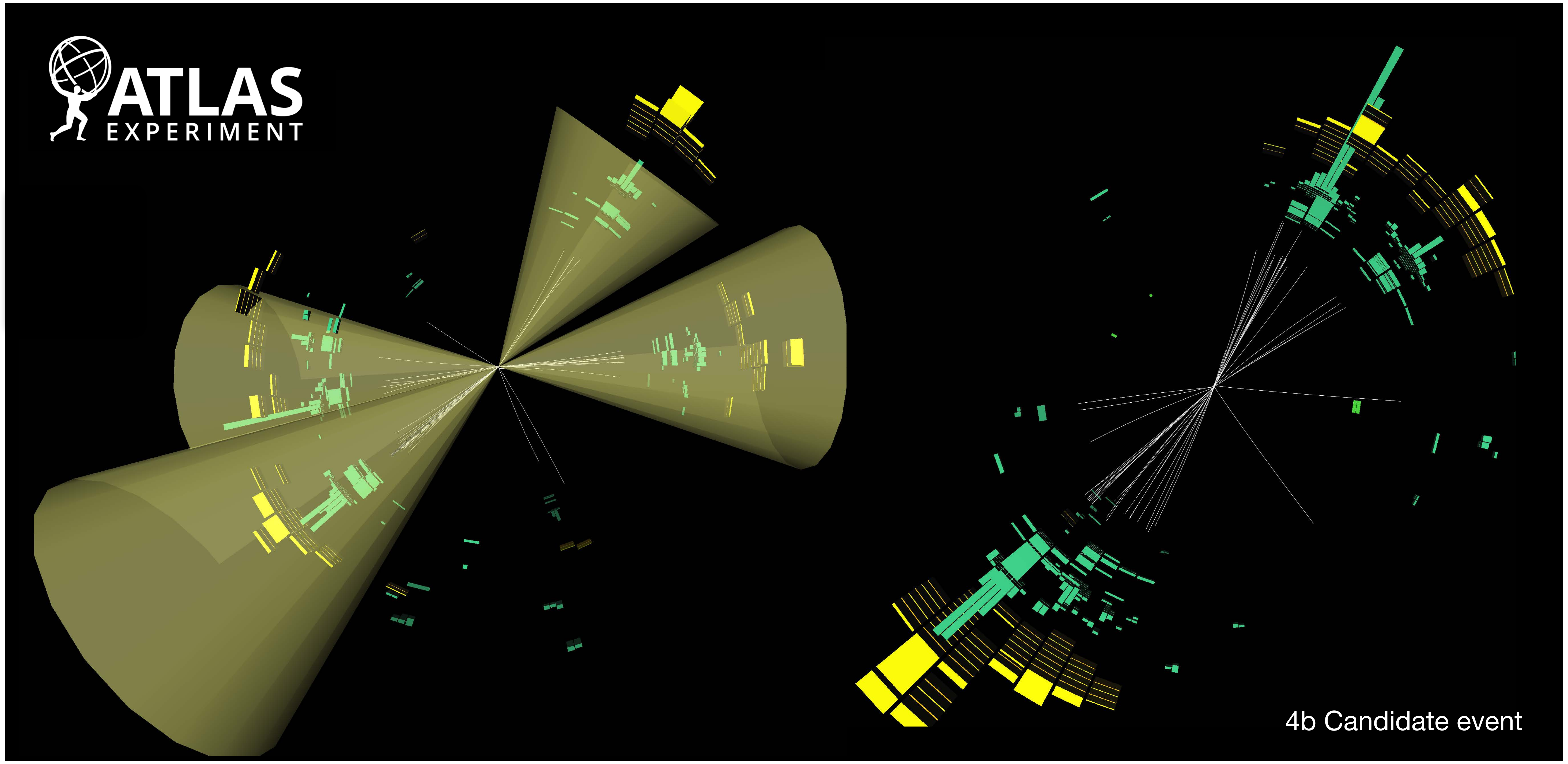
Very similar analysis as the Off-shell Higgs couplings!

Very small cross section ~1000 times smaller than Higgs production!

Huge challenge! but still more than 100k event will be produced at HL-LHC!



Multiple channels investigated: depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!

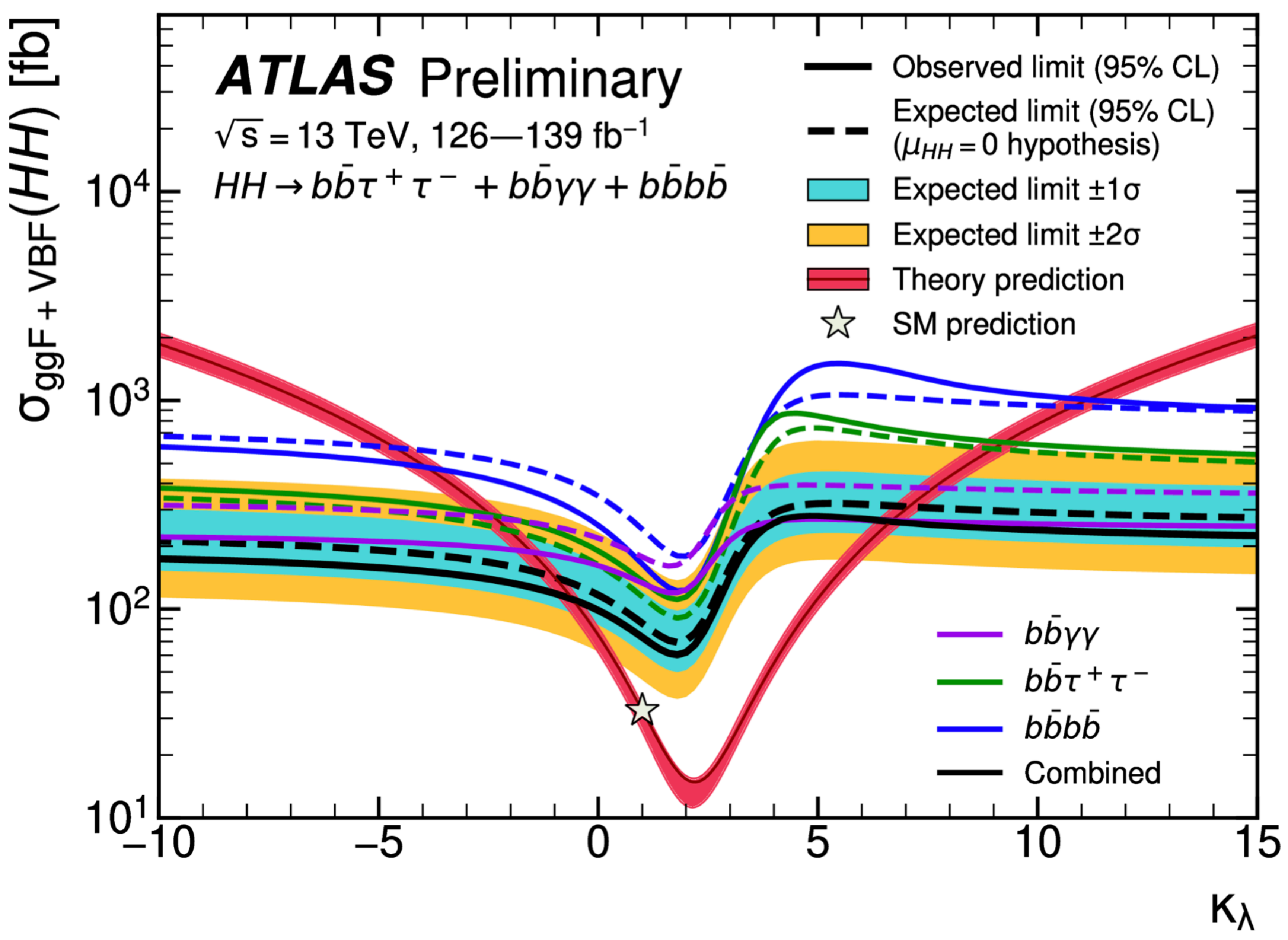


Reached a sensitivity to exclude at 95% CL di-Higgs production 2-3 times higher than expected in the SM!

Analyses performance improved by ~50% w.r.t. earlier the Run 2!

HH Production and Higgs Self coupling

Partial combination in ATLAS



Observed $-0.4 < \kappa_\lambda < 6.3$

Expected $-1.9 < \kappa_\lambda < 7.5$

HL-LHC observation of an HH signal at 5σ

50% level constraints on the Higgs boson self coupling!

At HL-LHC

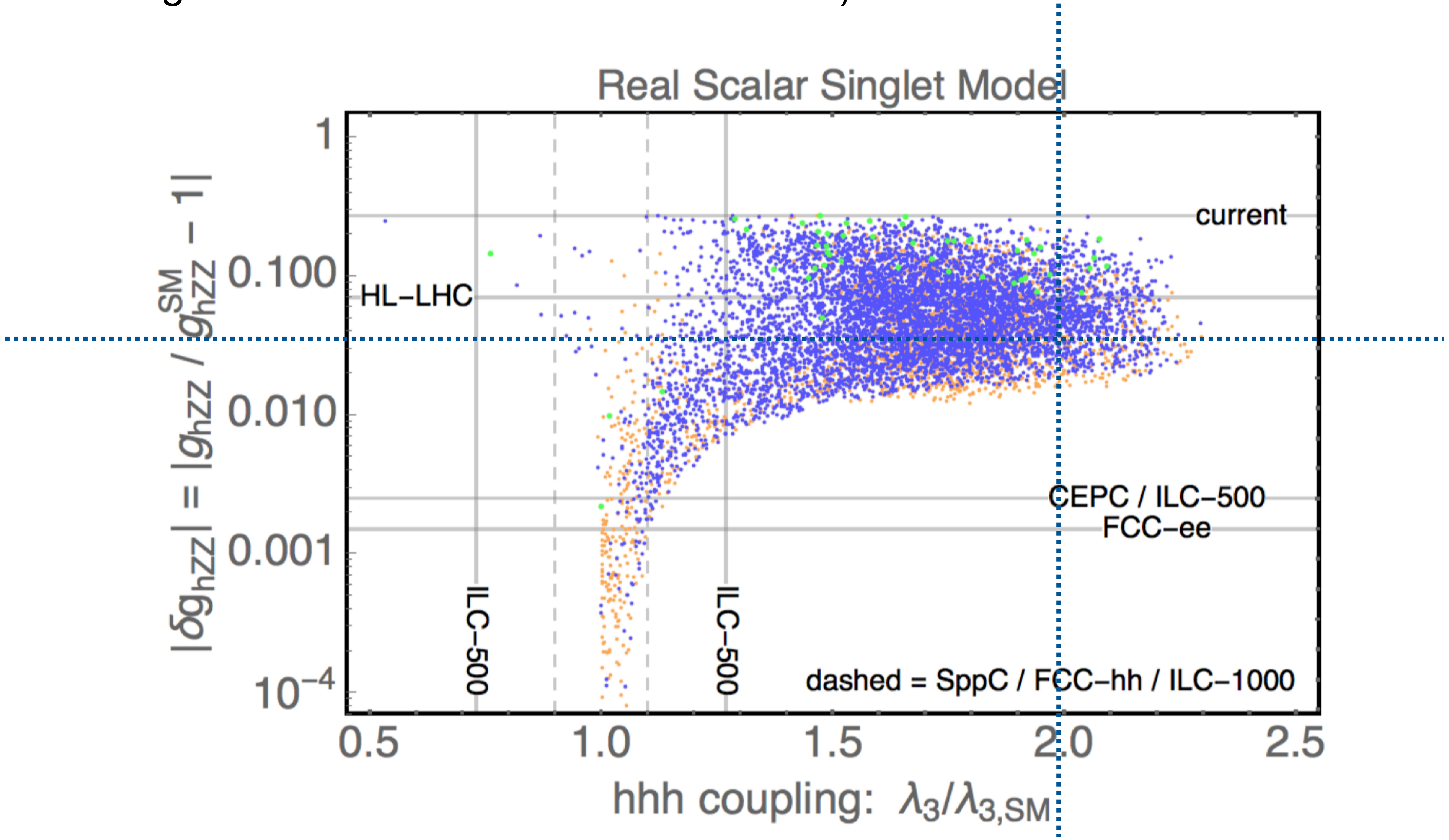
κ_λ **~50%**

From P. Huang, A. Long and L.-T. Wang

Probing 1st order phase transition and GW signals

The sensitivity of HL-LHC to the trilinear coupling could constrain models which would predict strongly first order EW phase transition!

In these cases, signals of stochastic background (e.g. collisions of bubbles) in the phase transition could potentially be detected by next generation interferometers like eLISA*)



*eLISA: evolved LISA

Challenges for HL-LHC

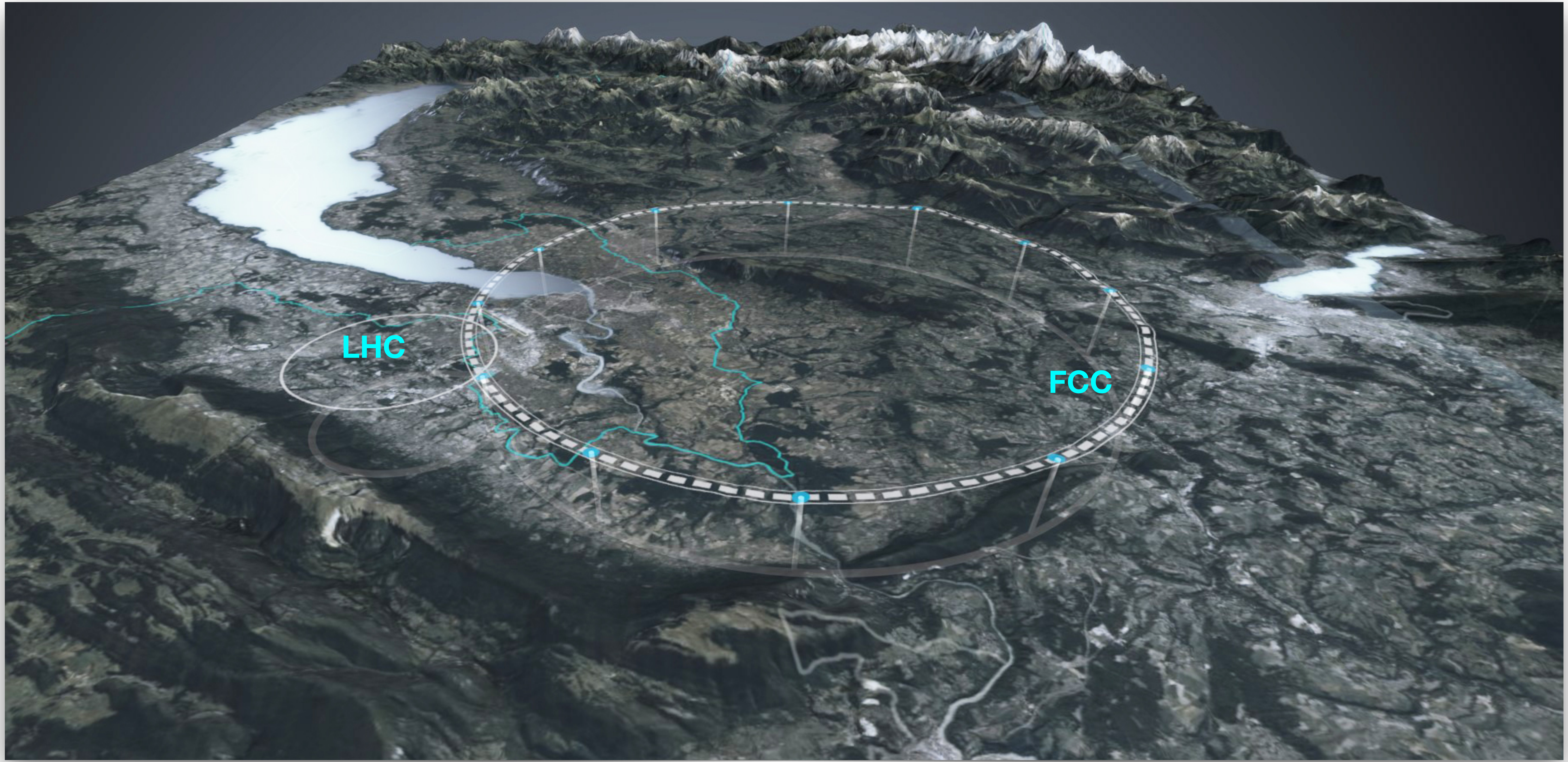
- **Critical period for the LHC machine and experiments** due to the convergence:
  - Installation, commissioning and operations of LS2 upgrades.
  - Production of upgrades and preparation of LS3
  - Operation of Run 3 to gather the LHC dataset for the next decade and produce new exciting results!

- The LHC has already achieved **landmark** results with **profound implications on our understanding of nature**

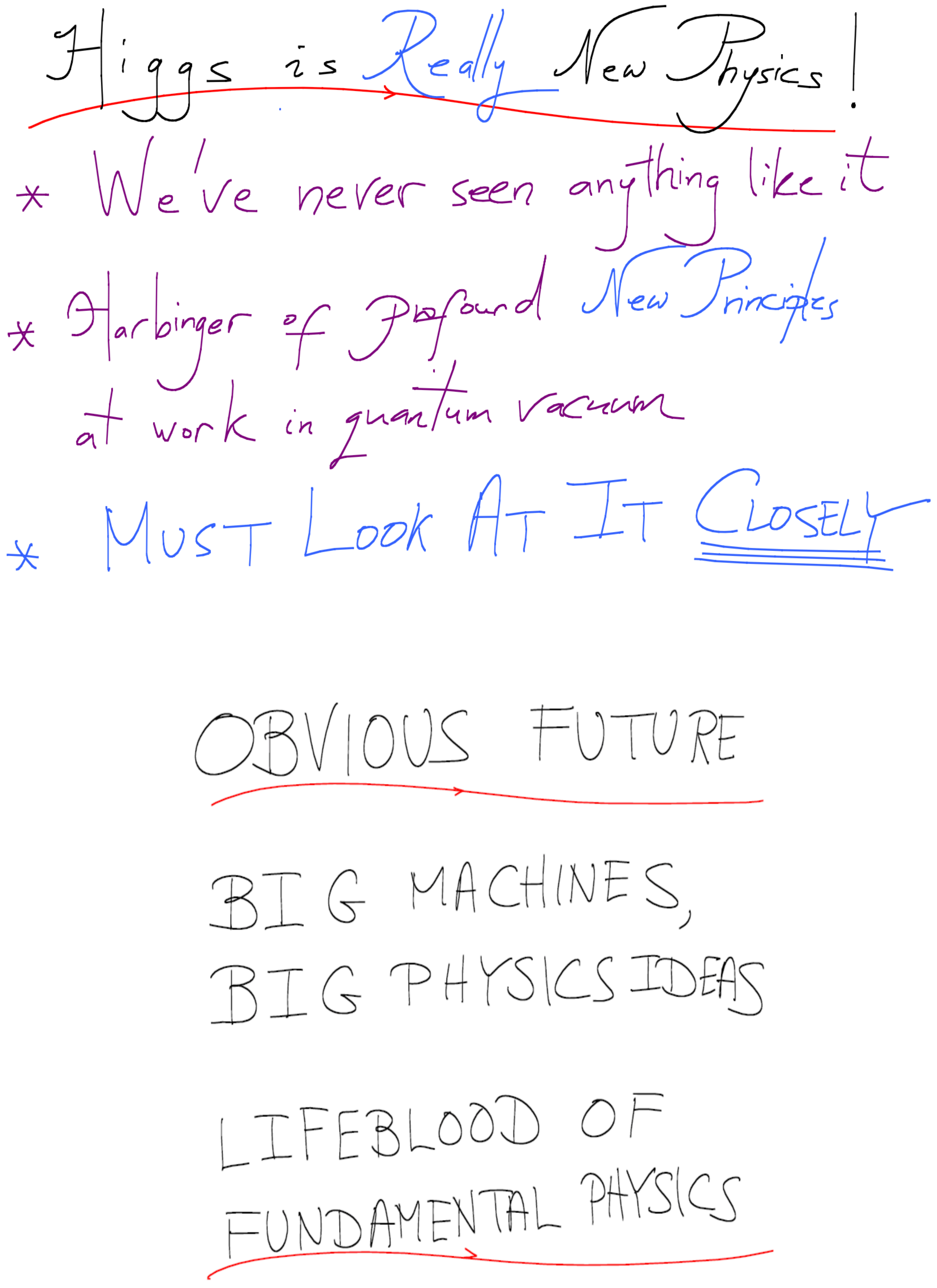
- The ingenuity of the entire community has expanded the range of possibilities **well beyond what was initially though possible!** The LHC has an **exciting, broad and diverse physics program ahead** (hopefully illustrated by selected **highlights**).

- The LHC has entered a **precision** era, this is a **joint TH and EXP effort**, which is key for both direct and indirect searches for new phenomena beyond the Standard Model. **Opening a vast range of exciting opportunities!**

Future Collider Projects



Opportunities at Future Colliders at the Energy Frontier



N. Arkani Hamed

Energy Frontier Vision in which the Higgs boson plays a very important role

- **Short term**: immediate priority is the success of the HL-LHC (construction, operations, computing and software, and physics program)

- **Medium term**: e^+e^- Higgs factory, either based on a linear (ILC, C3, CLIC) or circular collider (FCC-ee, CepC) to enable an **unprecedented precision investigation of the EW sector**.

- **Long term**: a 100-TeV or more proton-proton collider (FCC-hh, SppC), a 10-TeV muon collider to directly probe the order 10 TeV energy scale or high energy e^+e^- collider

Strategies and Guidelines : Feasibility is key!

European Strategy for Particle Physics in 2020

- “An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.”
- “Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.”
- “Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.
- “The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.”

Recommendations of the P5 Pannel 2024

- “In the area of colliders, the panel endorses an **off-shore Higgs factory**, located in either Europe or Japan, to advance studies of the Higgs boson following the HL-LHC
- “The panel recommends dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a **10 TeV parton center-of-mo- mentum (pCM) collider** to search for direct evidence and quantum imprints of new physics at unprecedented energies.”
- “This process will establish whether a proton, electron, or muon accelerator is the optimal path to our goal.”

Huge challenges: technical, cost effective and minimising environmental impact!

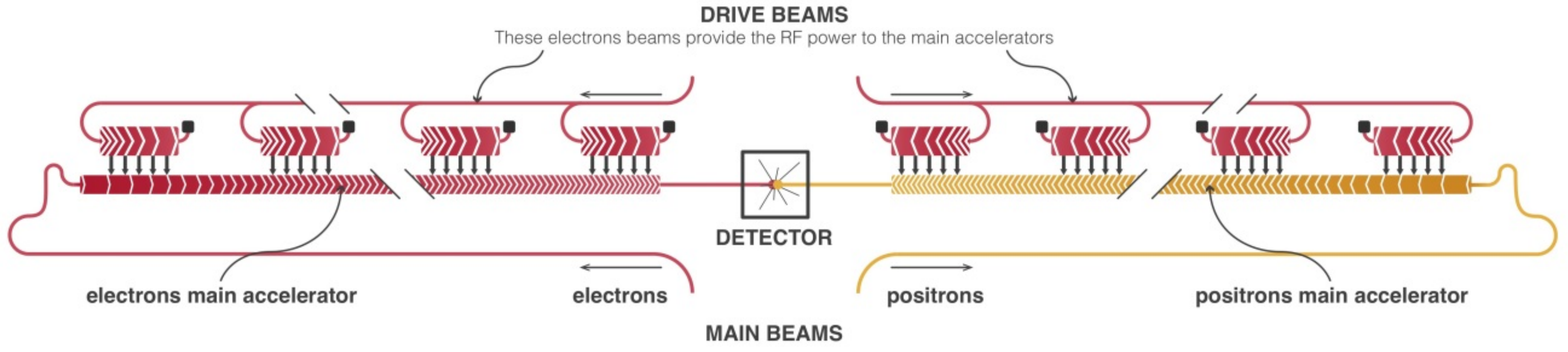
A Scientific Mission for the 21st Century

e^+e^- Collider Projects - Linear

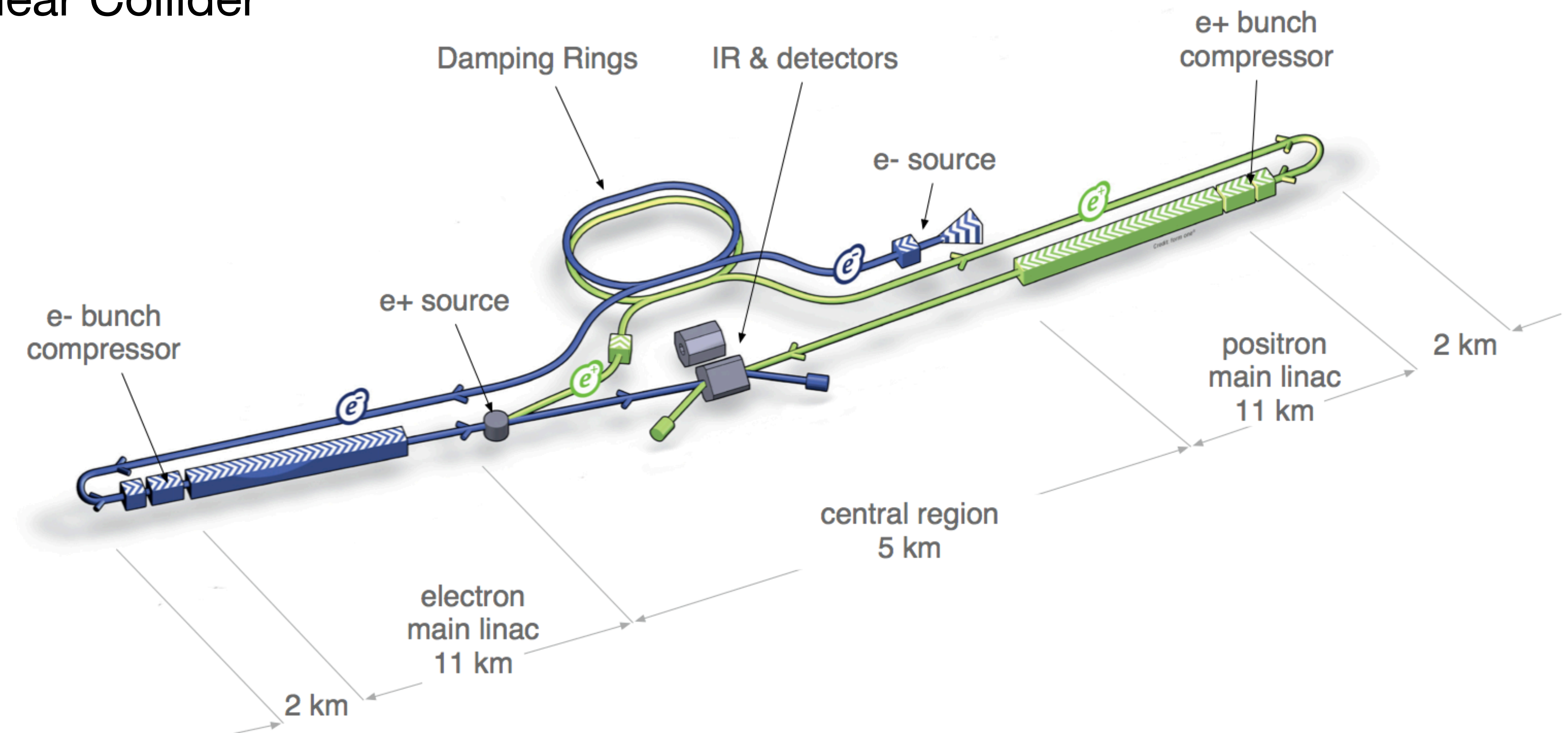
Project	ILC	CLIC	FCC-ee	CepC	C^3
Location	Kitakami - JP	CERN	CERN	China TBD	Japan - US?
Length	20.5 km	11-50 km	90-100 km	100 km	8 km
COM energy	250 GeV	0.38, 1.5, 3 TeV	90-365 GeV	90 -250 GeV	250-550 GeV
Lumi (10^{34} $cm^{-2}s^{-1}$)	1.35	1-2	7	4	1.3-2.4
Int. Lumi	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}	~2 ab^{-1}

CLIC Compact Linear Collider

RF power generated by decelerating drive beam

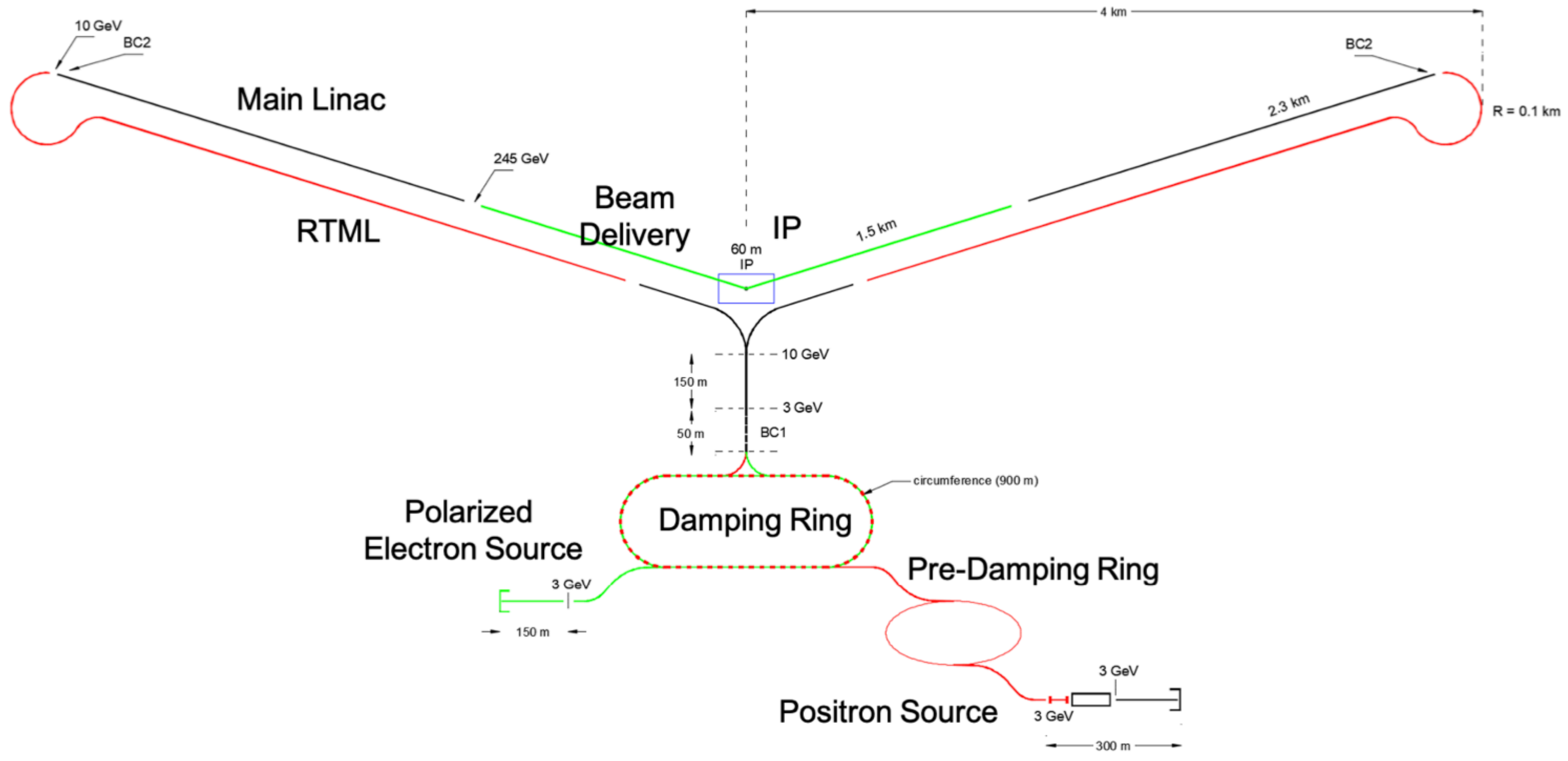


ILC International Linear Collider



C^3 Cool Copper Collider

High-gradient with cryogenic normal conducting cavities!



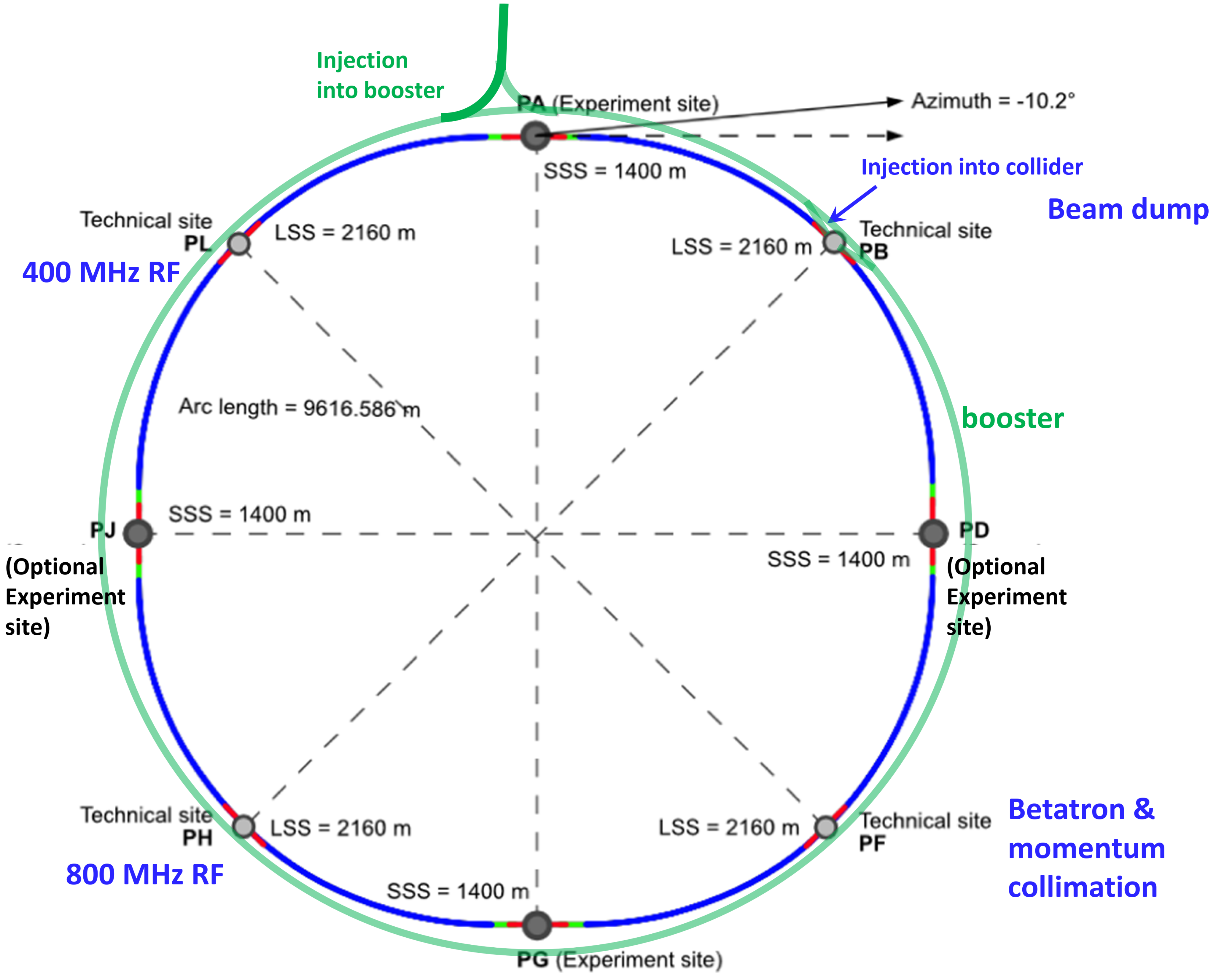
Different options available: GigaZ, ILC 500, and ILC 1000

e+e- Collider Projects - Circular

Project	ILC	CLIC	FCC-ee	CepC	C3
Location	Kitakami - JP	CERN	CERN	China TBD	Japan - US?
Length	20.5 km	11-50 km	90-100 km	100 km	8 km
COM energy	250 GeV	0.38, 1.5, 3 TeV	90-365 GeV	90 -250 GeV	250-550 GeV
Lumi (10^{34} $cm^{-2}s^{-1}$)	1.35	1-2	7	4	1.3-2.4
Int. Lumi	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}	~2 ab^{-1}

FCC-ee Future Circular Collider are CERN

~91 km Design with 4 interaction points



FCC-ee

Modern two-ring design (to reach amper currents): benchmark at ***KEK-B*** *and Super* ***KEK-B*** *with double-ring e+e– collider with multi-ampere stored currents with over than 1000 bunches, small* β_* *of down to 0.8mm, top-up injection as well as a 22 mrad crossing angle at the IP with crab crossing!*

CepC similar design (in China) see TDR

e^+e^- Collider Projects - Circular

Project	ILC	CLIC	FCC-ee	CepC	C^3
Location	Kitakami - JP	CERN	CERN	China TBD	Japan - US?
Length	20.5 km	11-50 km	90-100 km	100 km	8 km
COM energy	250 GeV	0.38, 1.5, 3 TeV	90-365 GeV	90 -250 GeV	250-550 GeV
Lumi (10^{34} $cm^{-2}s^{-1}$)	1.35	1-2	7	4	1.3-2.4
Int. Lumi	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}	~2 ab^{-1}

Large amount of extremely useful data in a very clean environment!

- 100 000 Z / second
- 10 000 W / hour
- 1 500 Higgs bosons / day
- 1 500 top quarks / day

Event statistics (4IP)

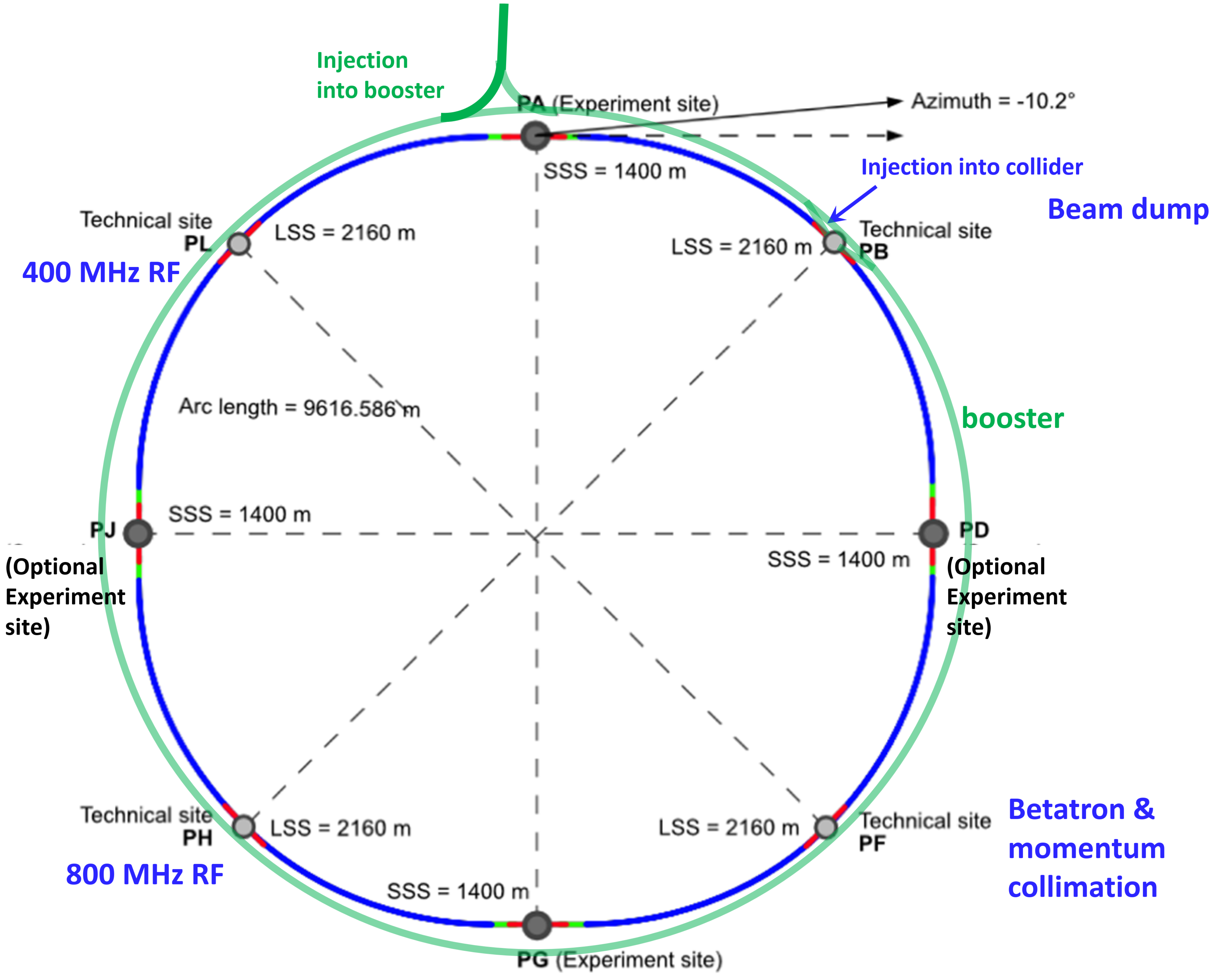
					E_{CM} errors	
Z peak	E_{cm} = 91 GeV	4yrs	6. 10^{12}	$e^+e^- \to Z$	<100 keV	**LEP x 3.10^5**
WW threshold	$E_{cm} \geq$ 157-161	2yrs	2. 10^8	$e^+e^- \to WW$	<300 keV	**LEP x 2.10^3**
ZH maximum	E_{cm} = 240 GeV	3yrs	1.5 10^6	$e^+e^- \to ZH$	1 MeV	**Never done**
s-channel H	$E_{cm} = m_H$	*(3yrs?)*	*O(5000)*	$e^+e^- \to H$	<< 1 MeV	**Never done**
Top production	E_{cm} = 340-365 GeV	5yrs	2. 10^6	$e^+e^- \to t\bar{t}$	2 MeV	**Never done**

*From A. Blondel

Precision on m_H of ~3 MeV

FCC-ee Future Circular Collider are CERN

~91 km Design with 4 interaction points



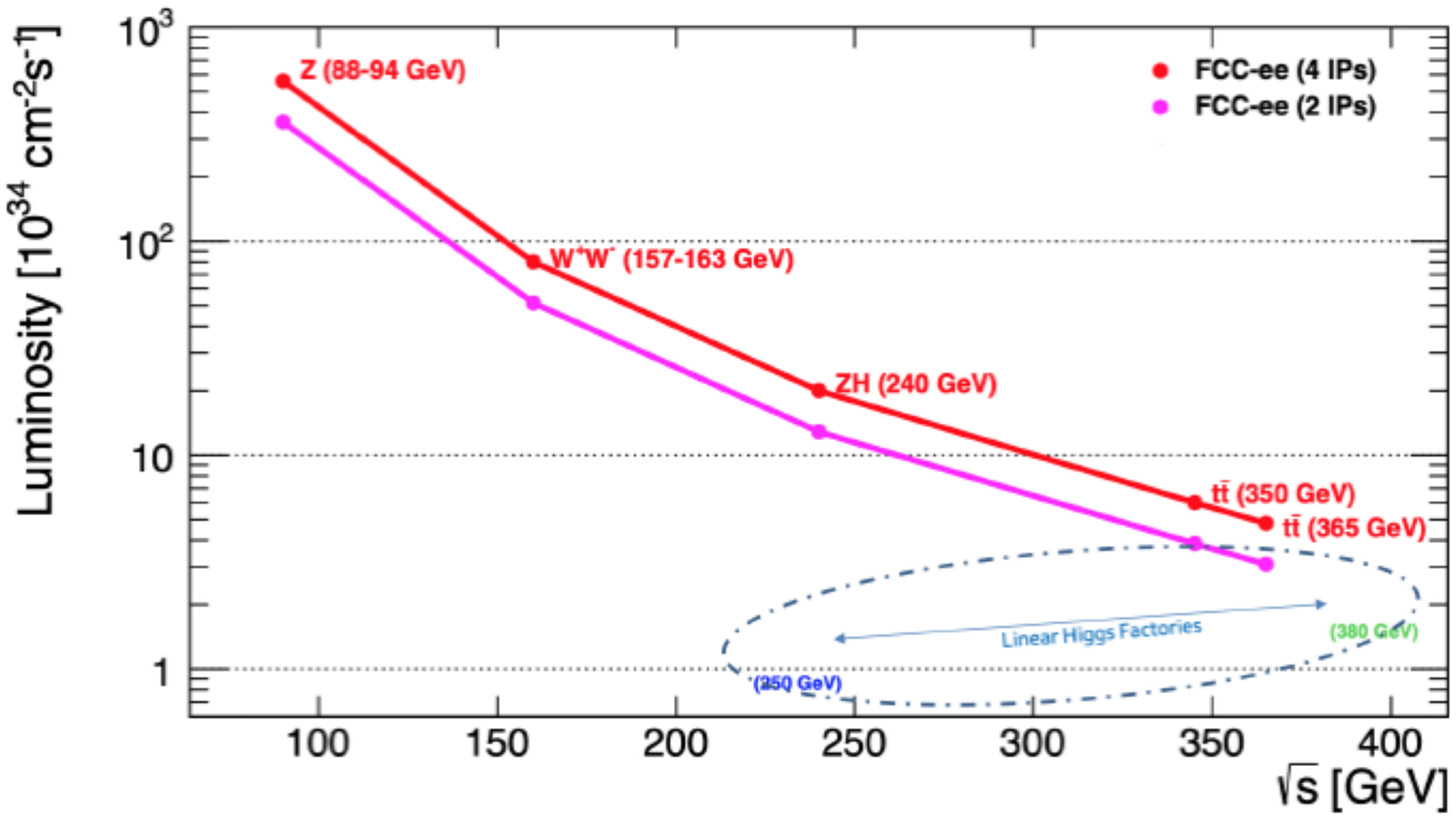
One LEP produced every 3 minutes!!

CepC similar design (in China) see TDR

e+e- Collider Projects

Future e+e- projects are complementary

- Circular colliders provide massive amount of data to address the Higgs and EW scale precision needs (1)
- Linear colliders could address specific questions more the need to explore higher energies (2)



Clear advantage of circular and 4 IP in terms of luminosity (but also on experimental diversity)!

Central to the precision program is the precision on the centre-of-mass energy reaches 100 keV (2.10^{-6}) using resonant depolarisation!

In comparison at ILC at the level of 10^{-4}

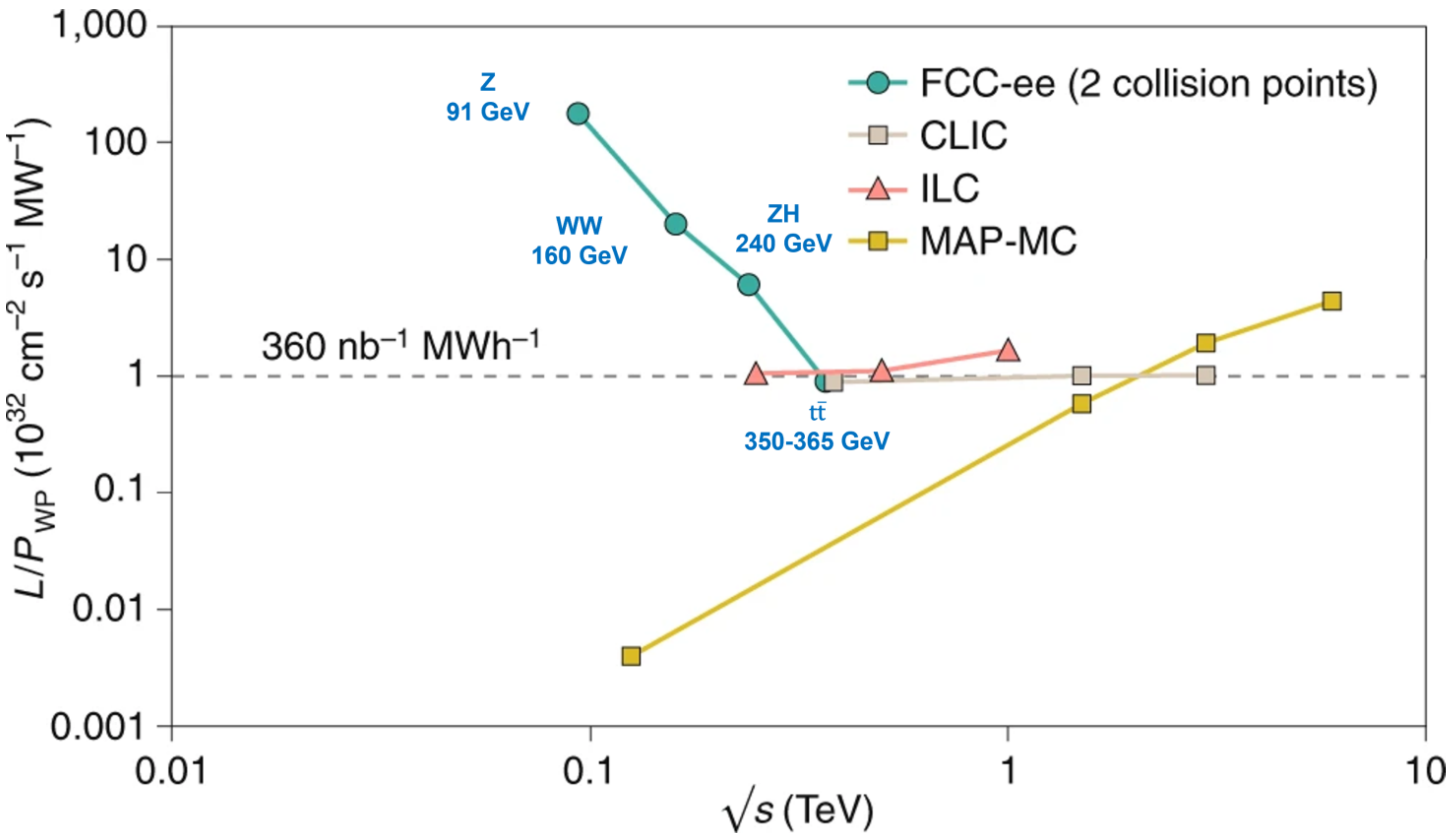
e+e- Collider Projects

Outstanding issues

- Timescales:
  - Projects outside CERN: ILC (2038) and CepC (2035)
  - Projects at CERN: FCC-ee and CLIC (2048)
- Sustainability, Energy and Power consumption are key parameters

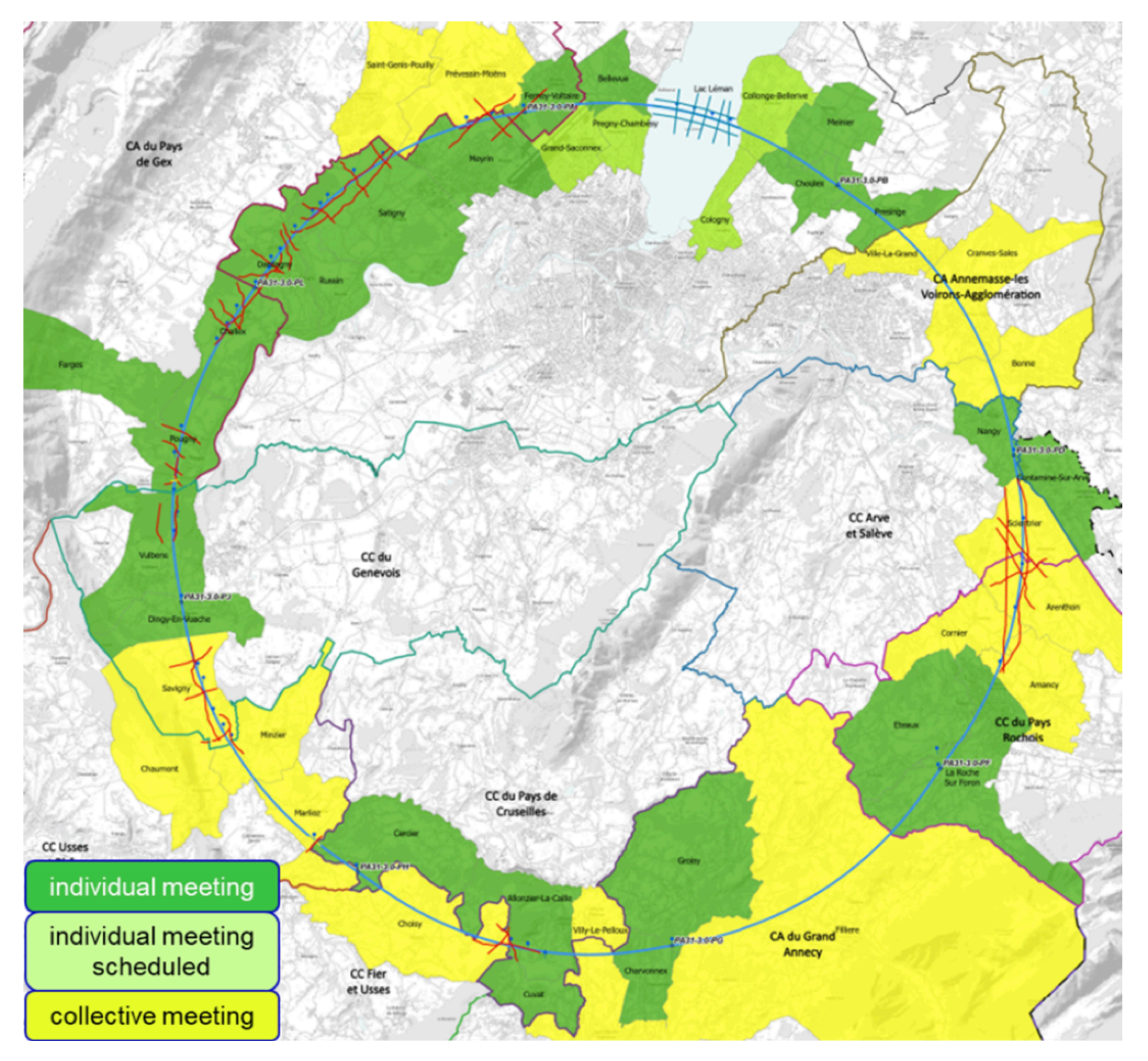
Challenging ideas to the FCC-ee

- An upgrade of e+e– collisions to higher energies, ~600 GeV or beyond, has been proposed through converting the FCC-ee into a few-pass ERL (Physics Letters B 804 (2020) 135394).
- Monochromatisation could give access to the s-channel Higgs production and thus the electron Yukawa! Understudy.



Large uncertainties see Snowmass white paper

Feasibility Studies

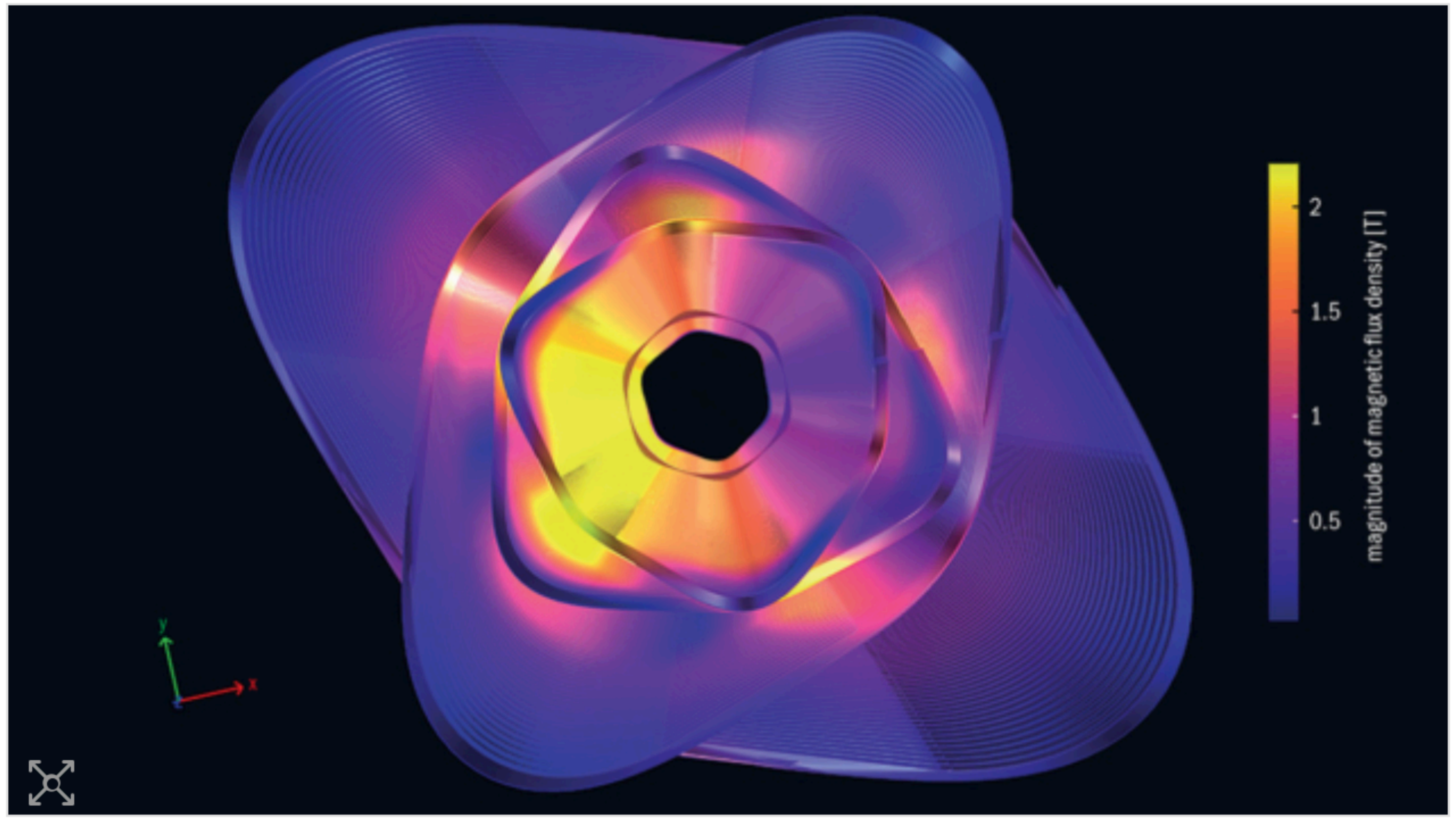


- Choice of baseline layout (90.7 km) - discussions with local authorities, environmental investigations and civil engineering designs well under way.
- In particular studies of possible injection schemes [article]

ACCELERATORS | NEWS

FCC-ee designers turn up the heat

7 November 2022



Innovative The magnetic flux density of a nested main sextupole–quadrupole system for FCC-ee, looking along the direction of the electron beam. Credit: M Koratzinos/RAT GUI

Power consumption

- 240 GeV the instantaneous power is 291 MW (compared to 140 MW for ILC and 110 MW for CLIC for less luminosity)
- Replace 5800 quadrupole and 4672 sextuple normal conducting magnets by HTS CCT magnets! [article]

e+e- Ultimate Precision Machine!!

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

EW Precision

Key measurements:

- $m_Z \sim 10^{-6}$, $m_W \sim 10^{-5}$, $m_{top} \sim 10^{-4}$
- $sin^2_{\theta_W} \sim 3.10^{-6}$, $\alpha_{QED}(m_Z^2) \sim 10^{-5}$, $\alpha_S \sim 10^{-4}$

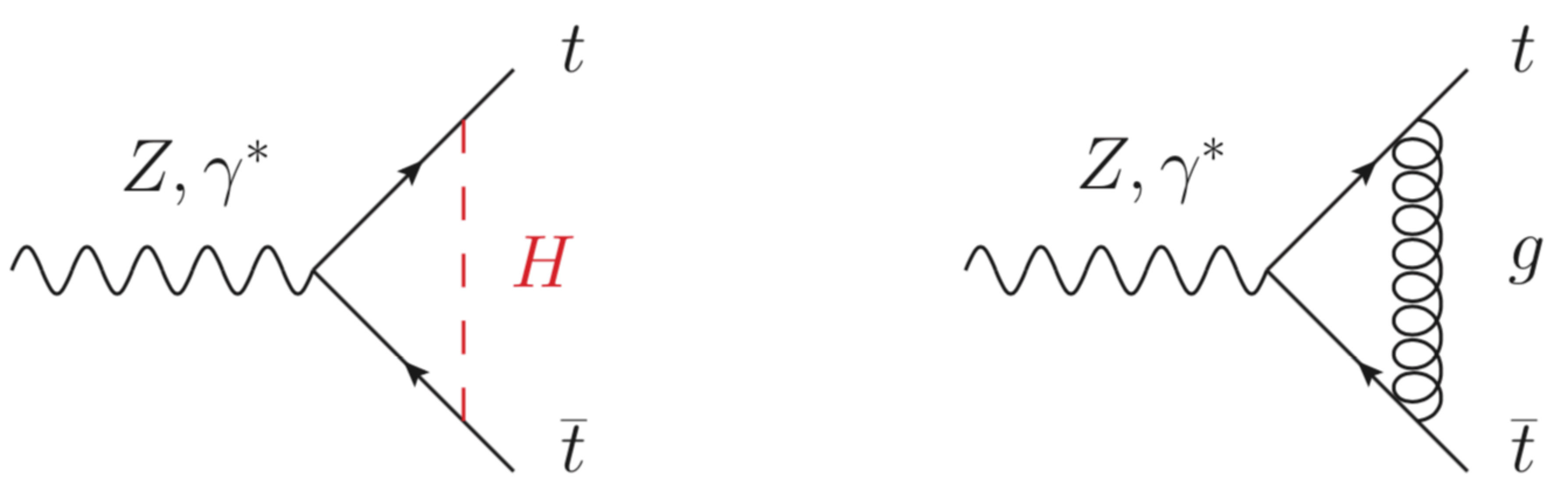
FCC-ee is much, much more than a Higgs factory!

Superb precision achieved and uncertainties are dominated by systematic uncertainties!

- x10-50 Improvement on all EW observables
- Up to x10 improvement on Higgs observables
- Indirect discovery **potential up to 70 TeV**
- **x10 improvement on Belle II stats for b, c and τ**
- Huge direct discovery potential for feebly interacting particles in the 5-100 GeV range

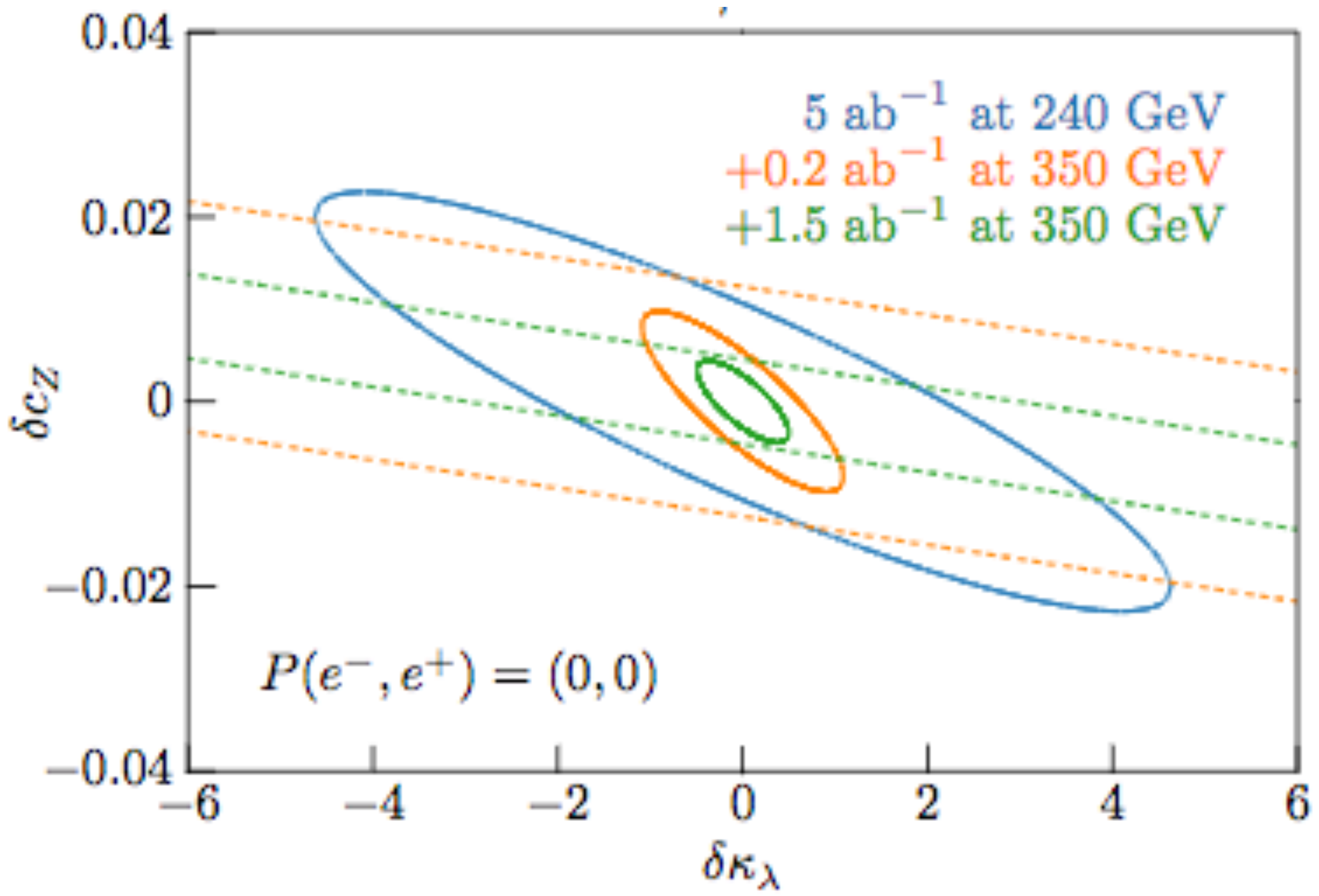
Model Dependent Measurements through Loops

Top pair cross section at threshold and above



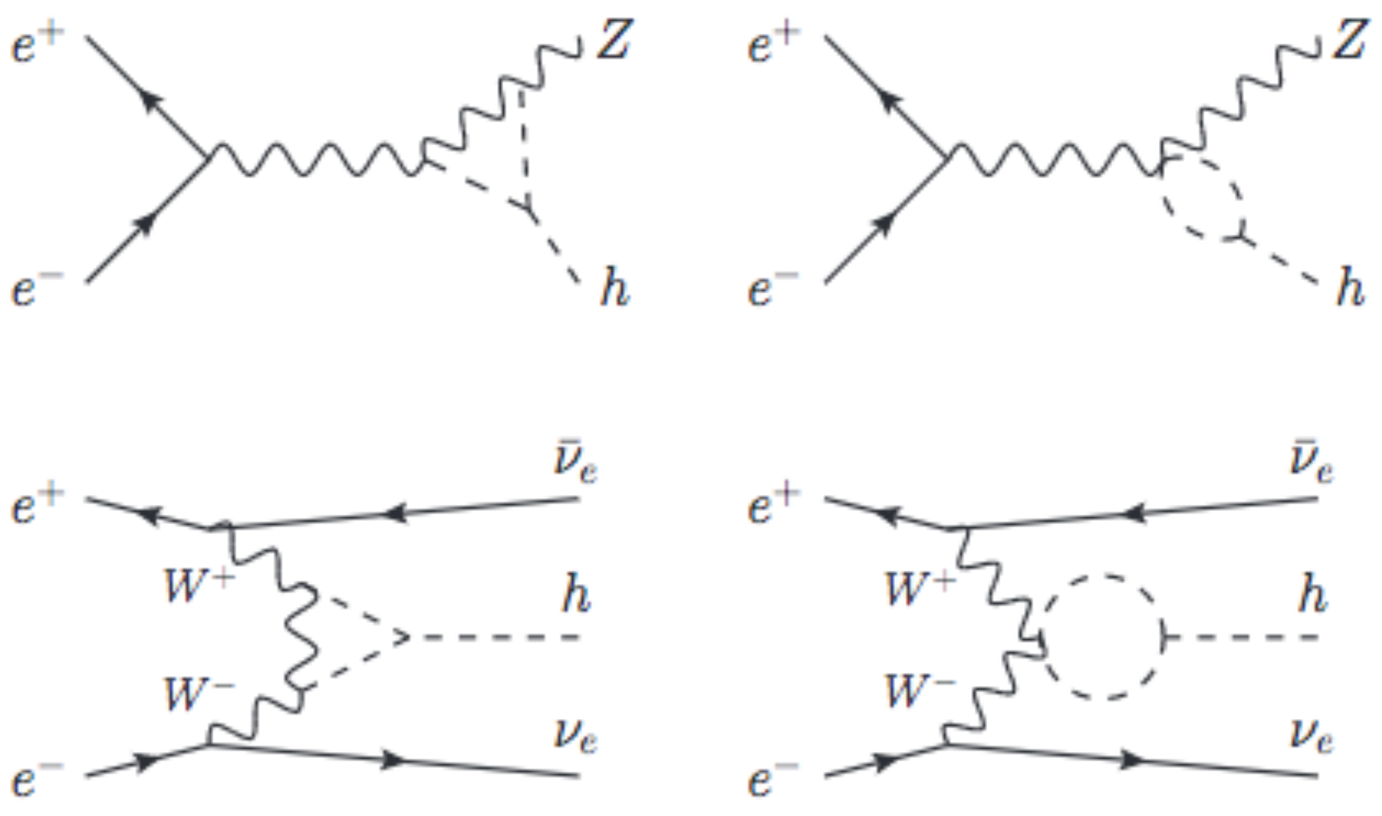
Precision on alphaS at FCC-ee will be important

Top Yukawa coupling precision from top pair cross section measurements **<10%**

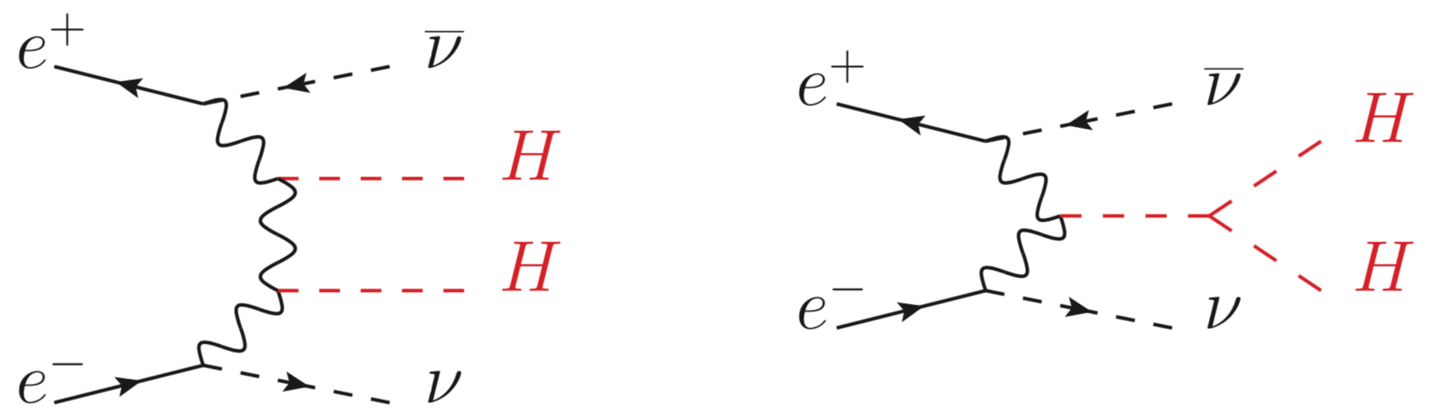


Higgs self coupling precision **~30%** - reduced to ~20% with kappaZ = 1 from SM

Higgs cross section at 240, 350, at 365 GeV



Similar precisions are obtained with double Higgs production at CLIC (√s = 1.4 and 3 TeV)

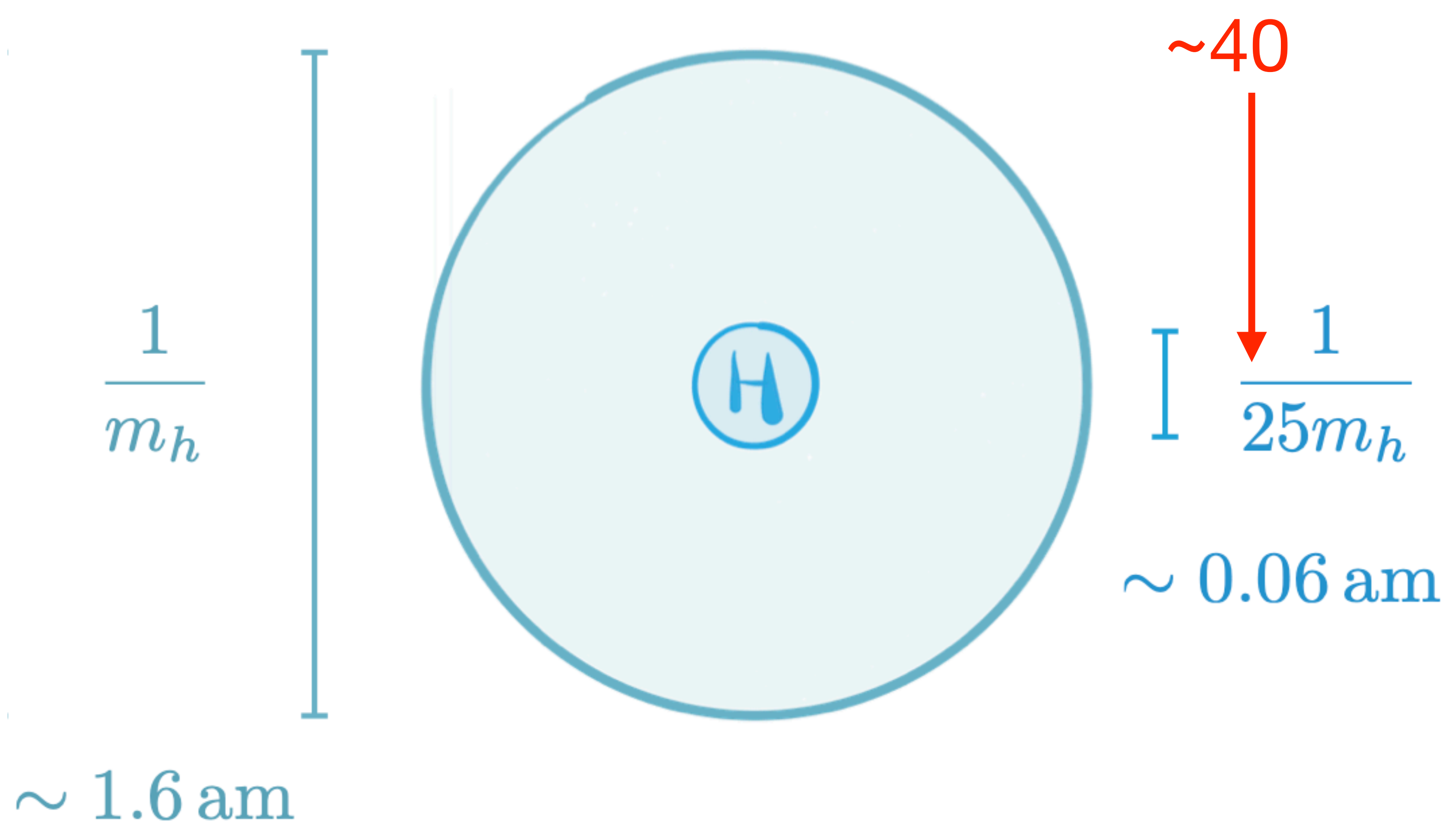


Precision Higgs Couplings Measurements

	ATLAS - CMS Run 1 combination	Current precision	HL-LHC	FCC-ee (only)
κ_γ	13%	6%	1.8%	3.9%*
κ_W	11%	6%	1.7%	0.4%
κ_Z	11%	6%	1.5%	0.2%
κ_g	14%	7%	2.5%	1%
κ_t	30%	11%	3.4%	-
κ_b	26%	11%	3.7%	0.7%
κ_c	-	-	40%	1.3%
κ_τ	15%	8%	1.9%	0.7%
κ_μ	-	20%	4.3%	8.9%*
$\kappa_{Z\gamma}$	-	30%	9.8%	-*
B_{inv}		11%	2.5%	0.2%

***Of course not competitive on rare decays.**

Far more stringent constraint on the size of the Higgs boson!



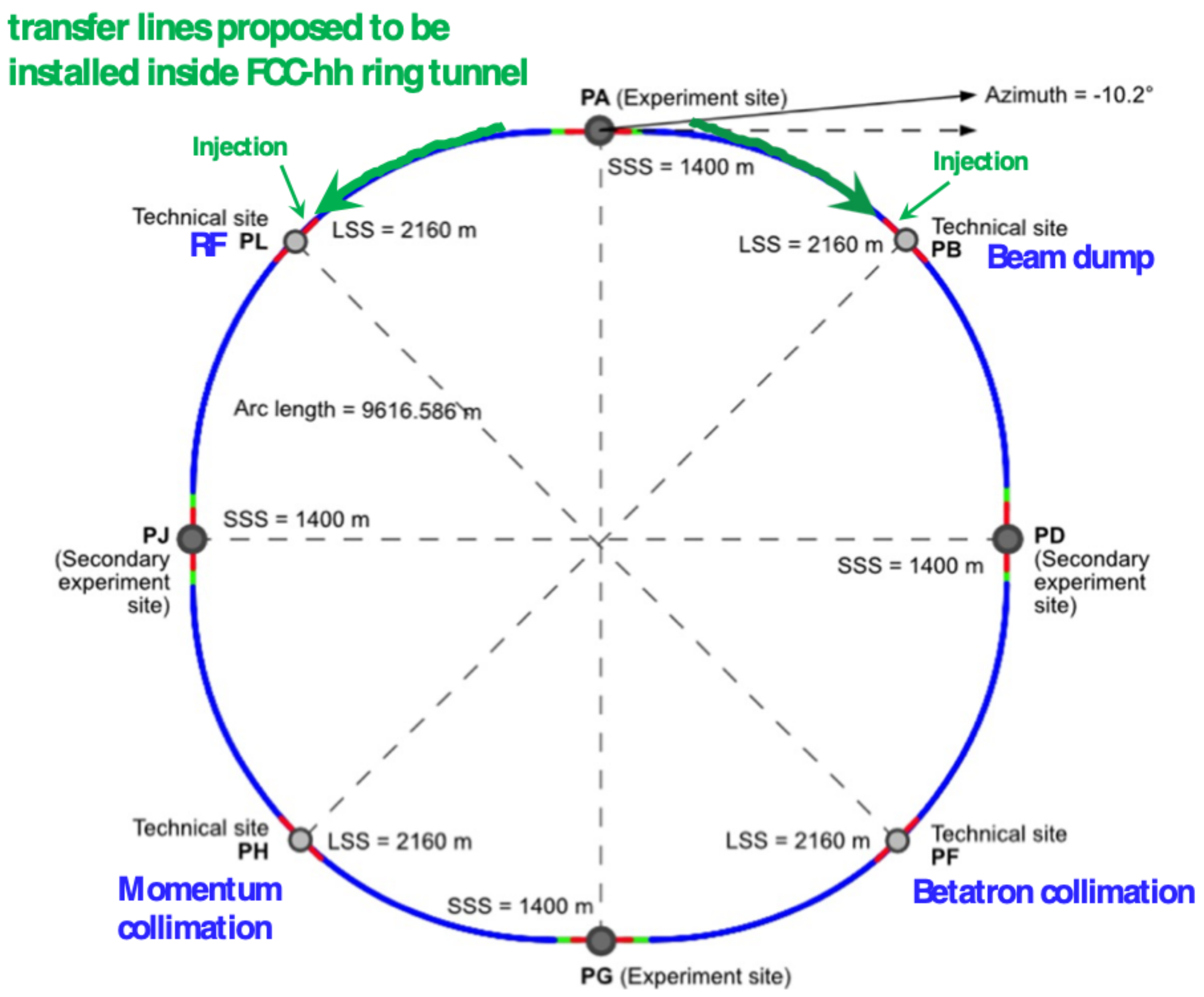
$$c_H \frac{v^2}{\Lambda^2} < 0.002$$

Taking $c_H = 1$ leads to $\Lambda > 5.5$ TeV

Hadron Collider Projects - Exploring the Multi-TeV scale

FCC-hh the second phase of the FCC program

Project	HL-LHC	FCC-hh	SppC
Location	CERN	CERN	China TBD
Circ.	27 km	90 km	55 - 100 km
COM energy	14 (15?) TeV	100 TeV	70 -140 TeV
Lum. (ab^{-1})	3	20-30	TBD
PU	200	1000	TBS
Field	8T	18T	20T



Key technological challenges

- **High field magnets**, need 16T to reach 50 TeV/beam - Nb3Sn (FCC-hh) or Nb3Sn with HTS inserts (SppC) - exploration of HTS magnets
- Machine protection 30 W/m synchrotron radiation and **8GJ per beam (equivalent to Boing 747 at cruising speed)**

SppC similar design

Hadron Collider Projects - Exploring the Multi-TeV scale

FCC-hh program

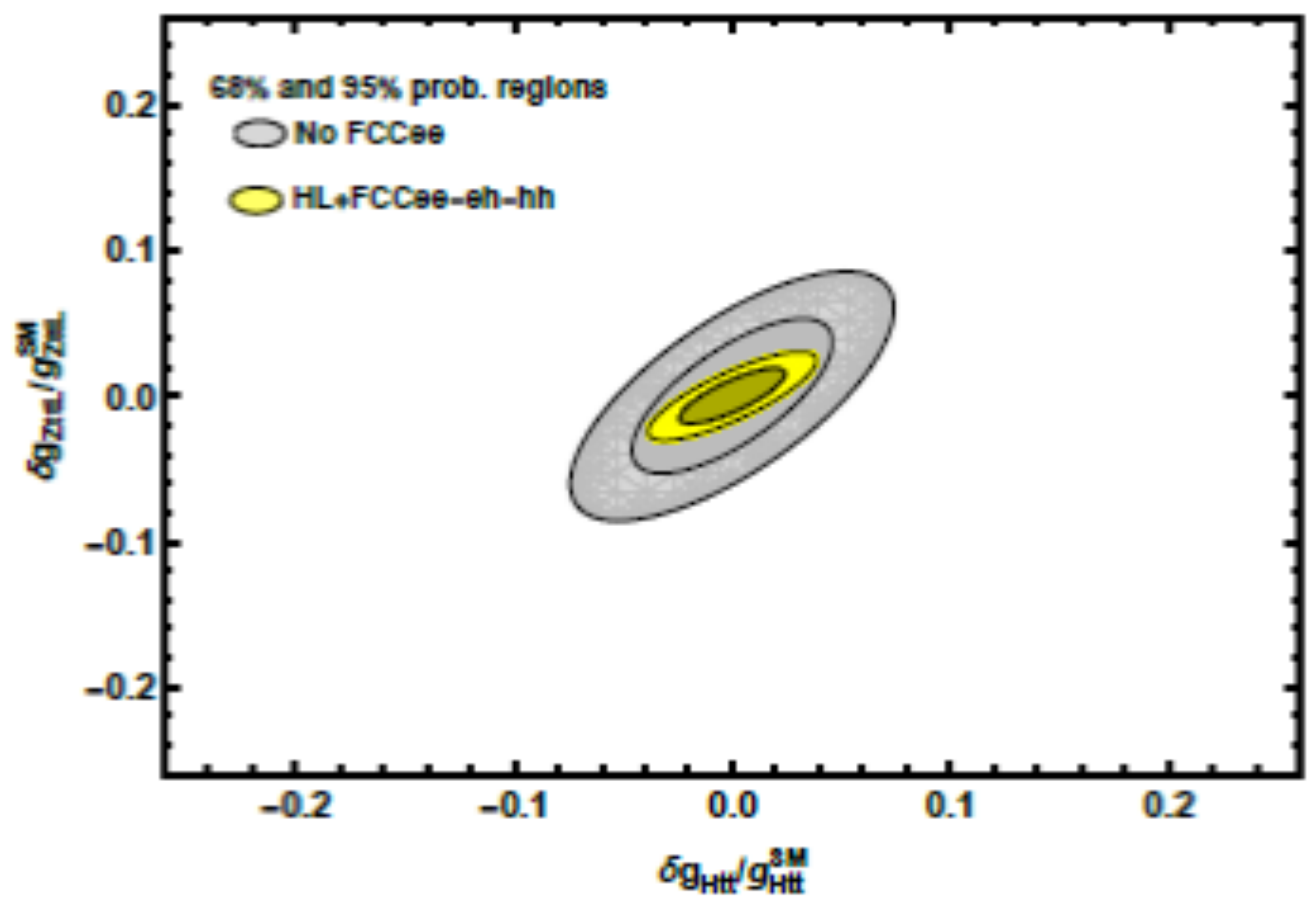
- **Primary goal is to explore the Multi-TeV scale with direct searches for new phenomena up to ~40 TeV!!**
- **Guaranteed deliverables**:
  - completion of the missing key pieces in Higgs precision κ_H and κ_t (model independence using complementarity from FCC-ee!)
  - Measurements of rare processes and in particular Higgs decays
  - Should give the final word on WIMP dark matte

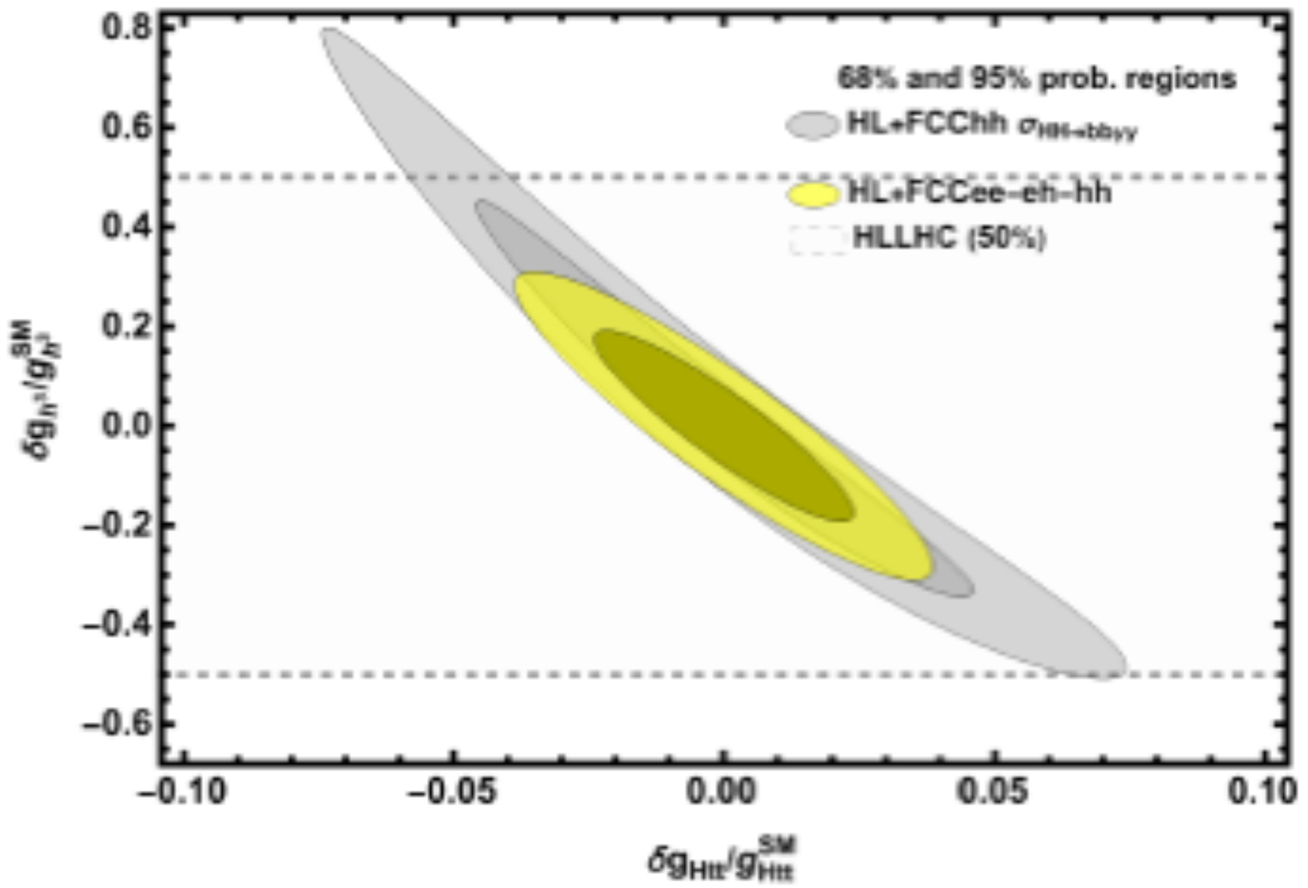
Ingredients

- FCC-ee measurement of the ttZ coupling ($e^+e^- \rightarrow t\bar{t}$ yields g_{ttZ})
- Measure the ratio ttH to ttZ at percent level!
- Then measure ratio HH to ttH

Essential complementarity with FCC-ee

- FCC-hh is a very intricate environment (up to 1000 PU events), event reconstruction at its limits and large TH uncertainites
- **Precision foreseen to be reached through ratios of cross sections.**
- Key precision deliverables: top Yukawa coupling and Higgs trilinear coupling! FCC-ee and FCC-hh together are 2-3 times better than FCC-hh alone.





	FCC	HL-LHC
κ_t	~1%	~3.5%
κ_λ	~5%	~50%

Muon Collider Project - Exploring the Multi-TeV scale

Best of all worlds?

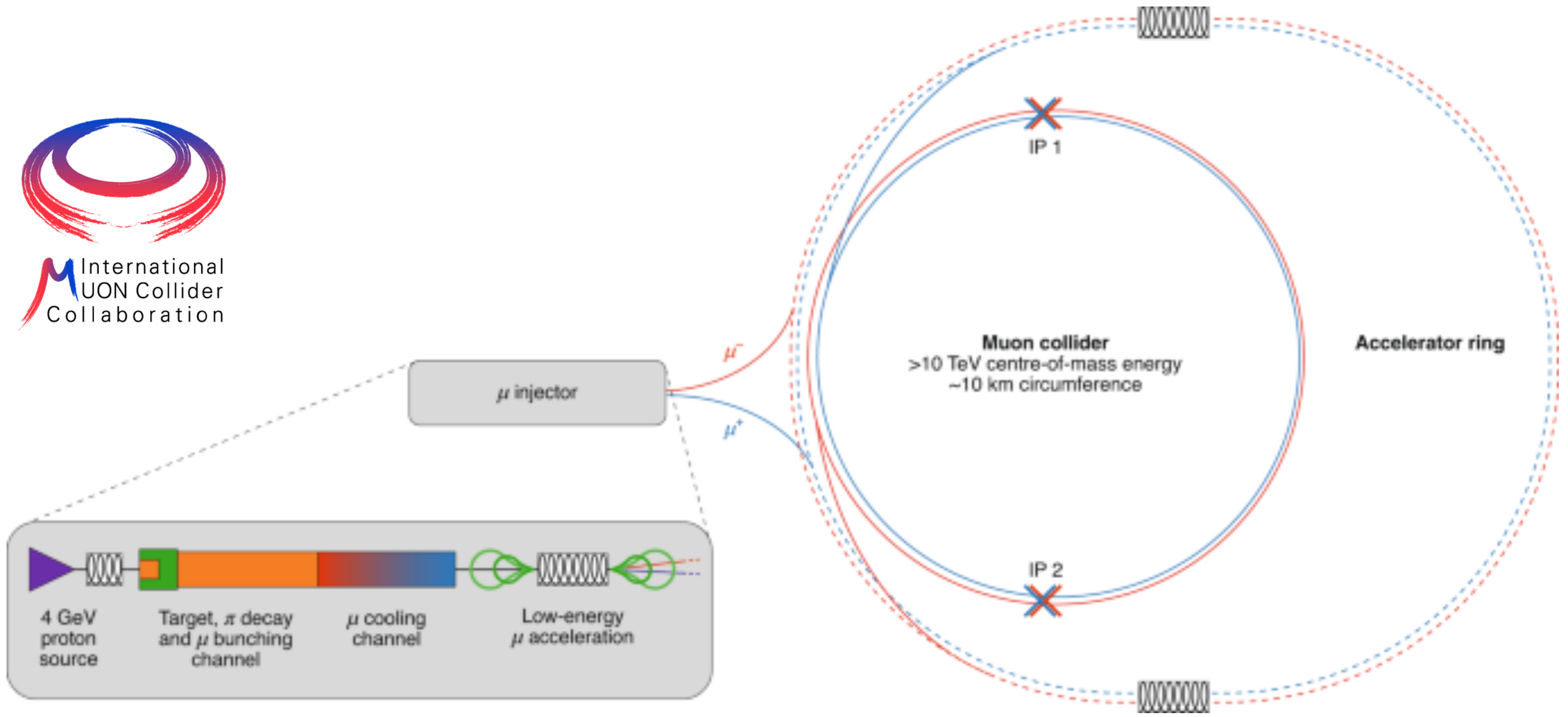
High energies, high luminosities with excellent lumi per MW ratio, (relatively) clean lepton collision events!

Mostly aimed at new physics searches in the Multi-TeV scale reach!

… incredibly challenging!

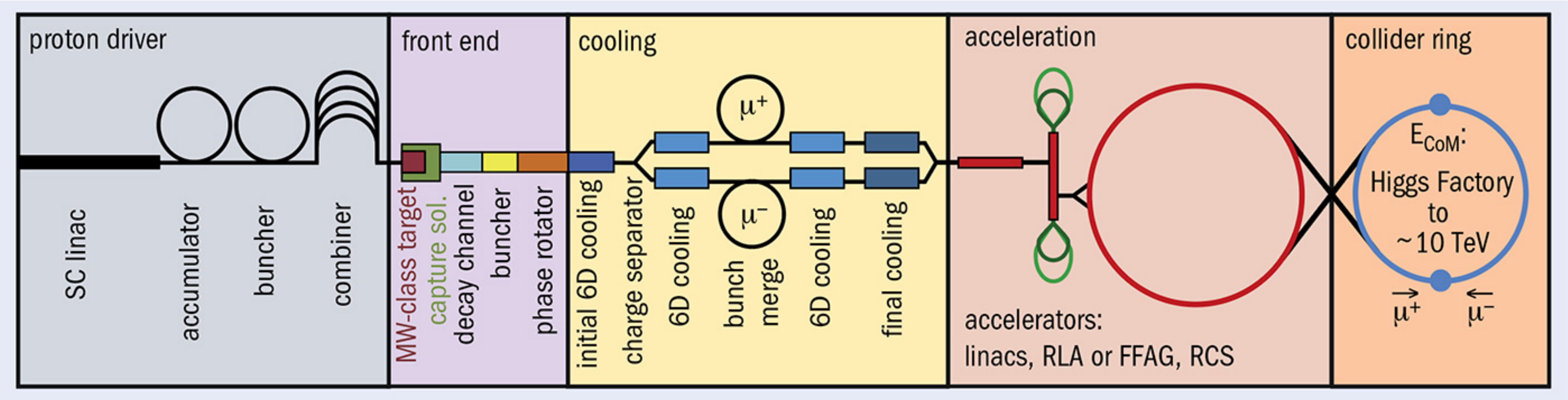
Initial targets for the integrated luminosities have been defined, namely 1, 10 and 20 ab−1 for 3, 10 and 14 TeV, **respectively**.

International MUON Collider Collaboration



MAP (Muon Accelerator Program)
Proton driven scheme

Reduction of the longitudinal and transverse emittance with a sequence of absorbers and RF cavities in a high magnetic field.



Muon Collider Project - Exploring the Multi-TeV scale

Muon collider as a Higgs Factory?

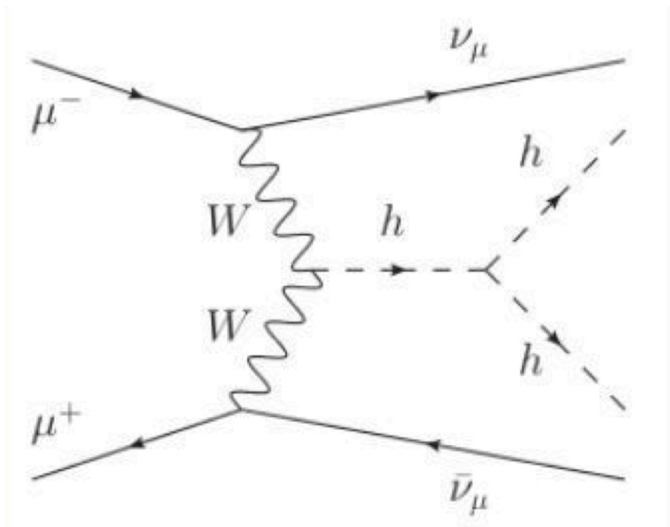
In principle could do everything as an e^+e^- collider with a much smaller ring! However the luminosity is estimated to be 2 orders of magnitude smaller at 240 GeV.

However at 125 GeV the s-channel production is 40,000 times larger (and a beam spread ~width).

Collider	μColl_{125}	$\text{FCC-ee}_{240\to365}$
Lumi (ab^{-1})	0.005	$5 + 0.2 + 1.5$
Years	6 to 10	$3 + 1 + 4$
g_{HZZ} (%)	SM	0.17
g_{HWW} (%)	3.9	0.43
g_{Hbb} (%)	3.8	0.61
g_{Hcc} (%)	SM	1.21
g_{Hgg} (%)	SM	1.01
$g_{\text{H}\tau\tau}$ (%)	6.2	0.74
$g_{\text{H}\mu\mu}$ (%)	3.6	9.0
$g_{\text{H}\gamma\gamma}$ (%)	SM	3.9
Γ_{H} (%)	6.1	1.3
m_{H} (MeV)	0.1	10.
BR_{inv} (%)	SM	0.19
BR_{EXO} (%)	SM	1.0

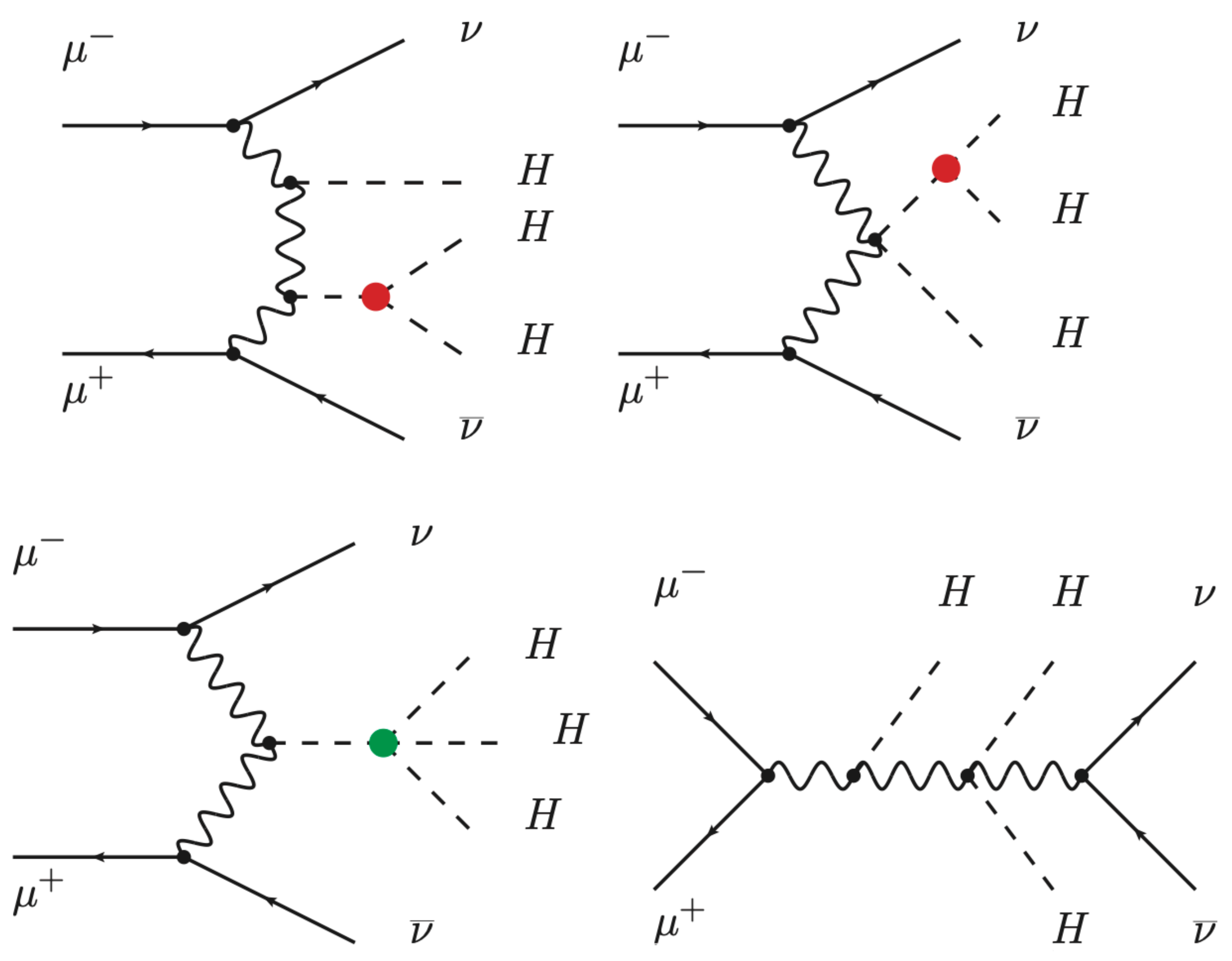
Muon Collider at 3 TeV

Notable result reach on trilinear coupling from di-Higgs production $\lambda_3 \sim 20\,\%$



Muon Collider at 14 TeV

Quartic couplings studies show (see paper)



Assuming $\lambda_3 = 1$ and $33\ ab^{-1}$ could reach **50%** precision of the Higgs boson quartic coupling.

Muon Collider Project - Exploring the Multi-TeV scale

Muon collider as a Higgs Factory?

In principle could do everything as an e^+e^- collider with a much smaller ring! However the luminosity is estimated to be 2 orders of magnitude smaller at 240 GeV.

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Collider	μColl$_{125}$	FCC-ee$_{240\to365}$
Lumi (ab^{-1})	0.005	$5 + 0.2 + 1.5$
Years	6 to 10	$3 + 1 + 4$
$g_{\rm HZZ}$ (%)	SM	0.17
$g_{\rm HWW}$ (%)	3.9	0.43
$g_{\rm Hbb}$ (%)	3.8	0.61
$g_{\rm Hcc}$ (%)	SM	1.21
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$g_{{\rm H}\gamma\gamma}$ (%)	SM	3.9
$\Gamma_{\rm H}$ (%)	6.1	1.3
$m_{\rm H}$ (MeV)	0.1	10.
BR$_{\rm inv}$ (%)	SM	0.19
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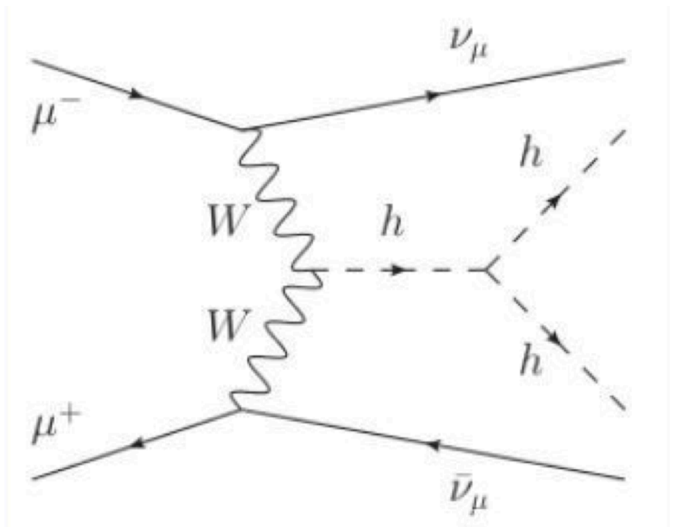
Muon Collider at 3 TeV

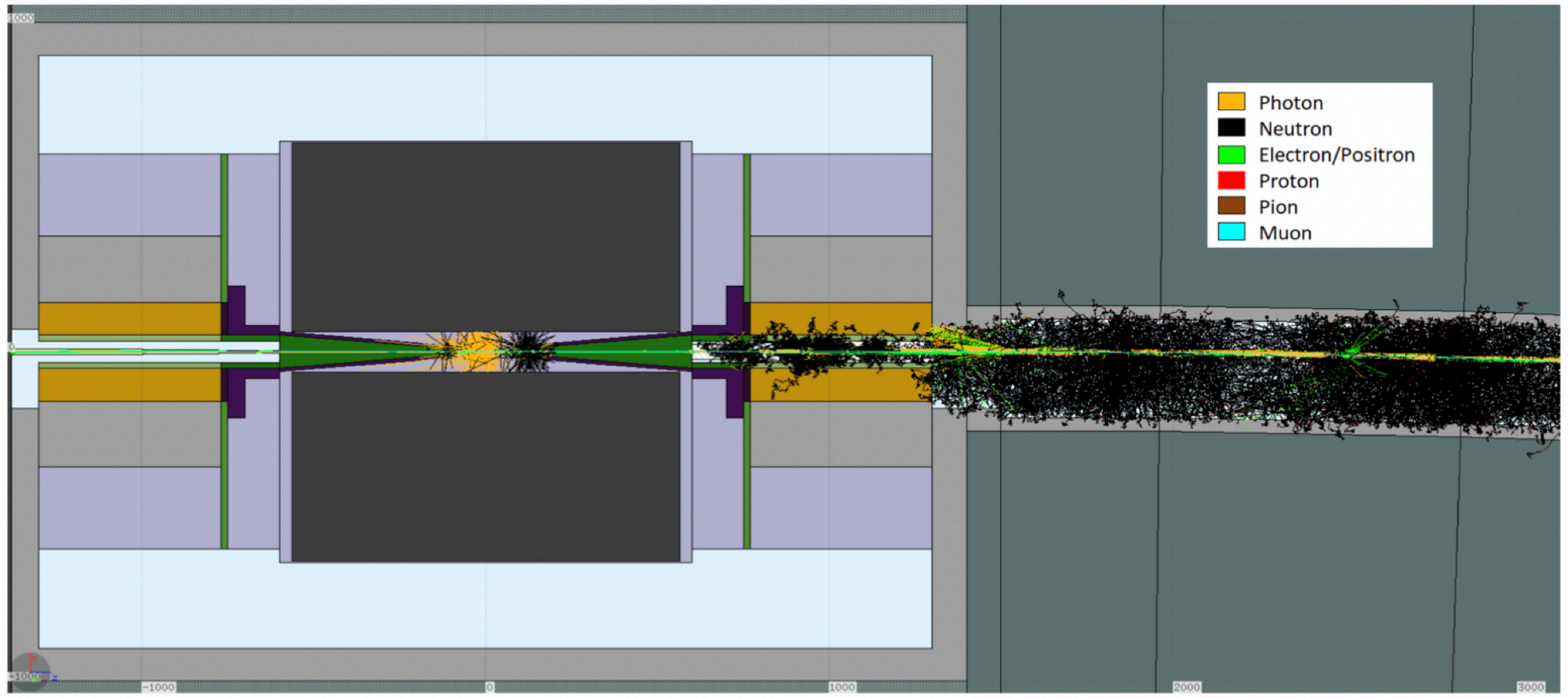
Notable result reach on trilinear coupling from di-Higgs production $\lambda_3 \sim 20\,\%$



Conceptual and design challenges

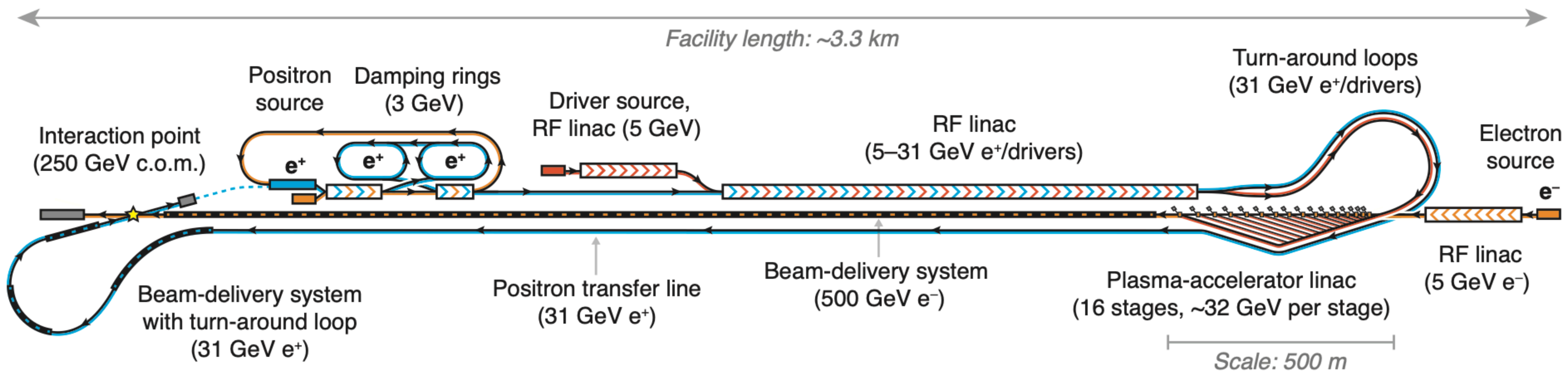
- High neutrino flux (requires mitigation above 3 TeV)
- Beam backgrounds challenge to detector design.
- Production, cooling and preservation of the muons!

Constant muon decays bring beam backgrounds, and radiation levels similar to LHC!

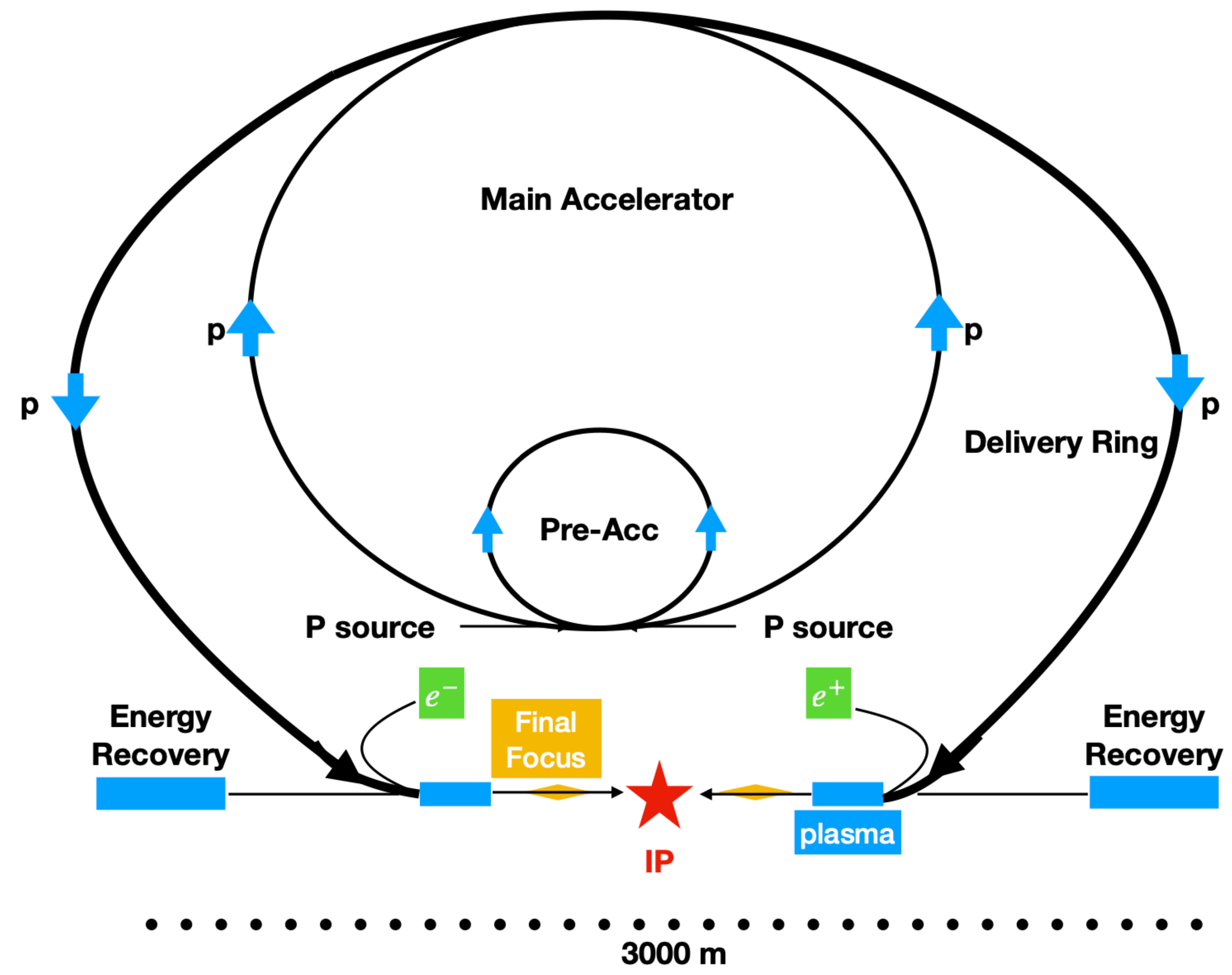


Other Projects

- Linear electron-positron colliders using **plasma wake field acceleration**, two proposals have been made (using beam driven PWFA)
  - Asymmetric (lower energy positron as their energy is a limiting factor) proposal based on electron bunch driven PWFA - see paper



  - Higgs factory proposal based on proton driven PWFA - see paper



- Photon collider - e.g. could be an option as an extension of linear e^+e^- colliders

- Electron-proton collider at the FCC (or the LHC) at 3.5 TeV with 60 GeV electron ERL - Part of the broad framework of the FCC project! (Side note the FCC could also be a formidable HI and electron-ion collider with up to 39 TeV and 2 TeV NN and eN COM energy!)

Outlook

The **LHC** has been already **extremely successful** and has a very broad and ambitious physics program, going well beyond what was initial foreseen through detector, computational, and theoretical breakthroughs. **The physics reach of LHC pushes the challenges of future projects!**

The community has been incredibly creative with proposals of future projects, that push the limits of what is feasible, and provide answers to any possible scenario of new physics appearing at the LHC.

With the LHC entering its HL phase and the LHC Run 2 results now established, a **timely decision for the next large scale project is needed!** In order to start as early as possible in the 2040's a decision is needed now.

Following the 2020 European Strategy, the community has made huge progress on the **feasibility study of the FCC project** which is foreseen to be completed by **March 2025**.

CERN has The council of March 2024 has decided to start immediately the European Strategy process and set the input submission at the date of the completion of the FCC feasibility study (essential element of the strategy).

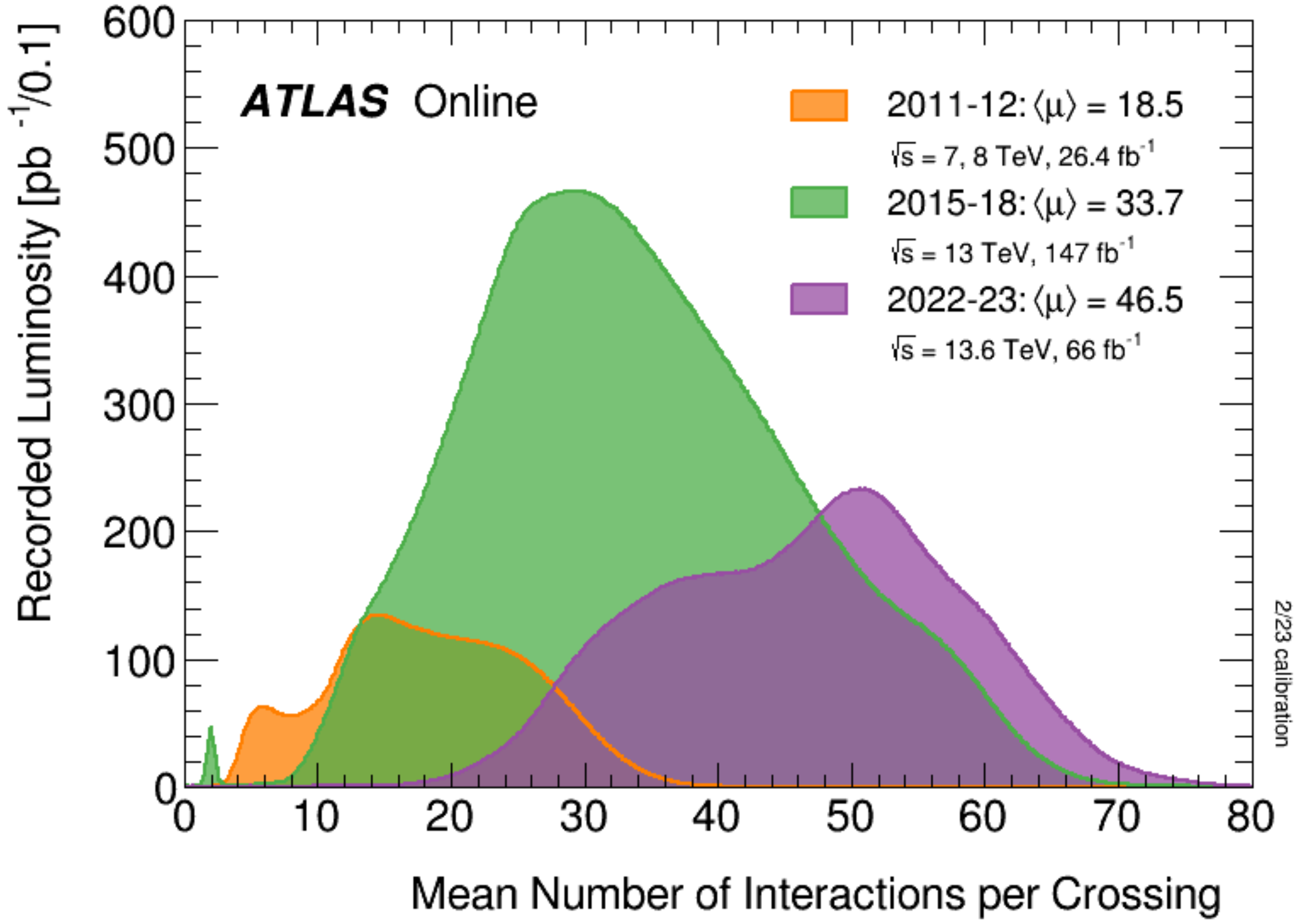
The physics possibilities are formidable! So are also the technical, economic, geopolitical and environmental challenges of these project.

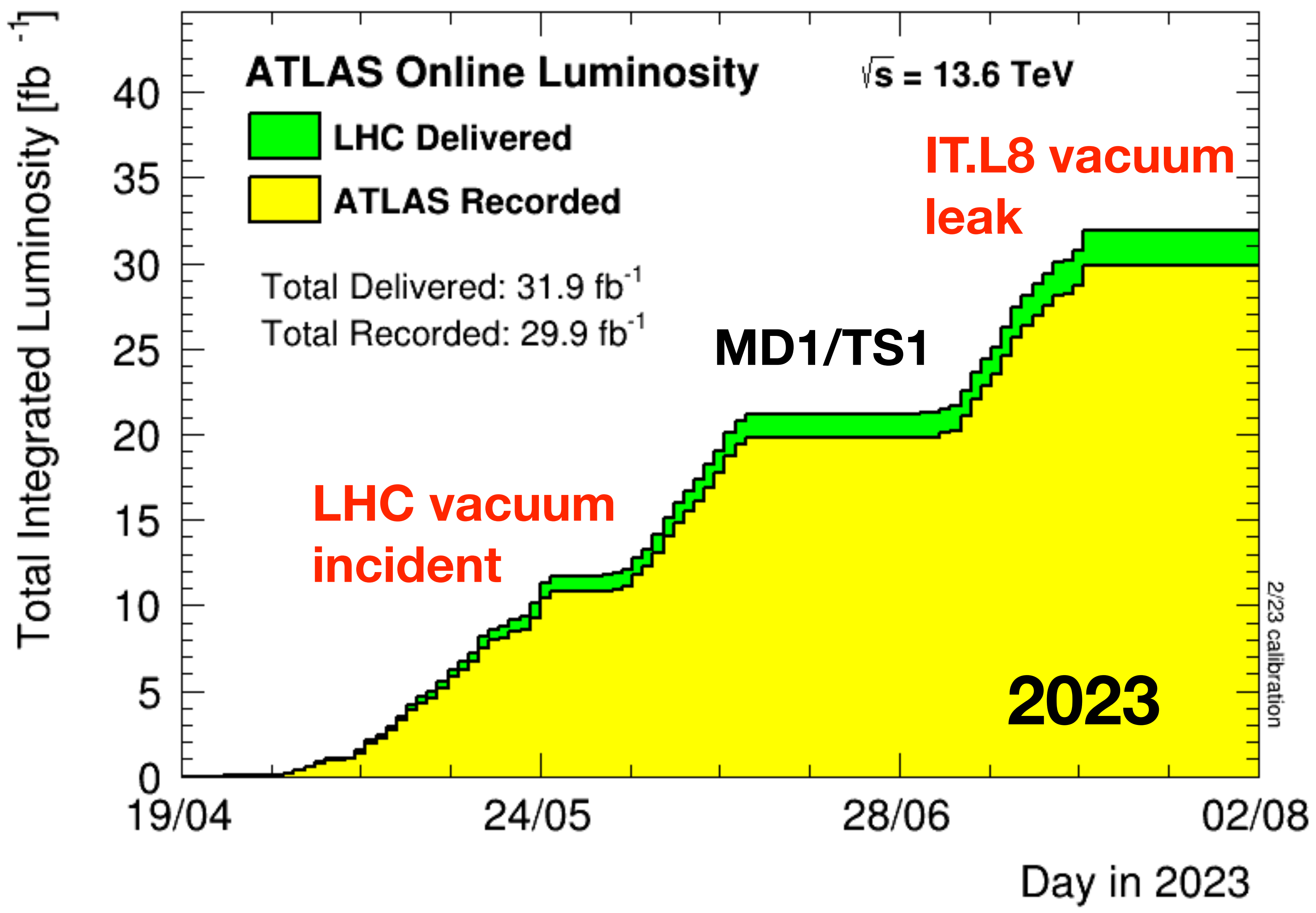
It is now time to decide what the next large scale project beyond the LHC!

Backup

The LHC, where do we stand?

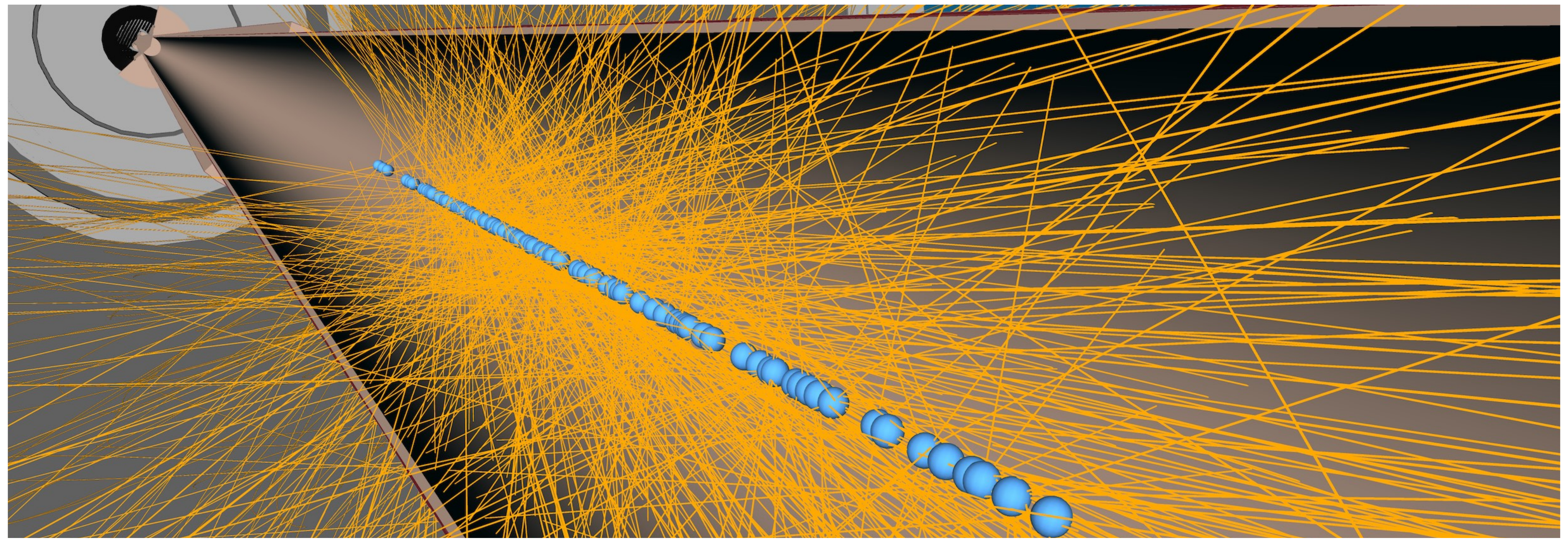
Similar numbers for CMS!





Typical data taking and data quality efficiency 90%

Huge number of lessons learned on how to mitigate PU - **Object reconstruction and trigger so far PU resilient!**



2023 operations: Excellent availability but unfortunate incident (in IT.L8) due to electric power glitch which provoked a vacuum leak (impact of 50 days) **Delivered 31.9 fb^{-1}**, target of 75 fb^{-1}

Experiment Briefing

Tags: luminosity, run 2

ATLAS delivers most precise luminosity measurement at LHC

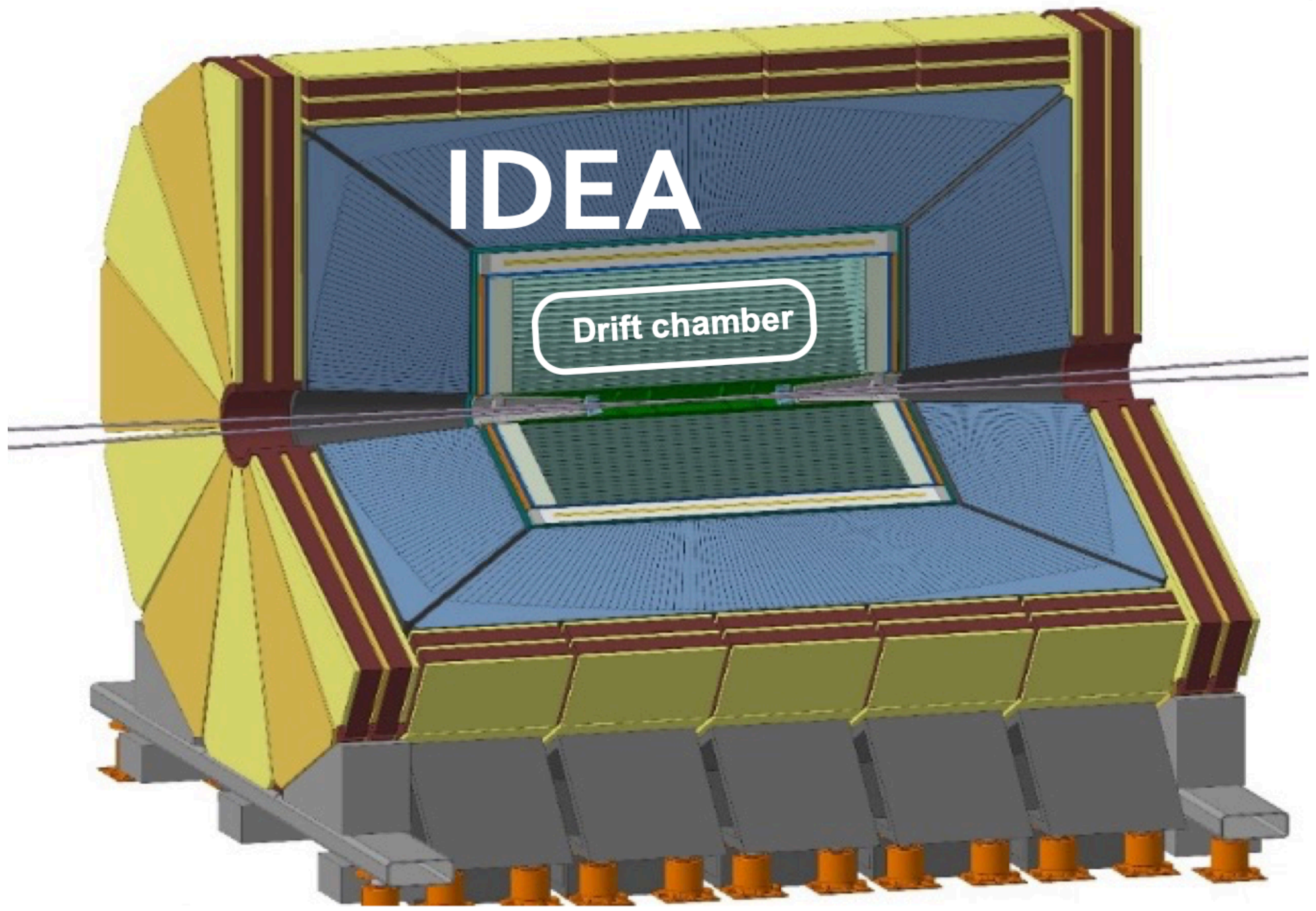
24 January 2023 | By ATLAS Collaboration

Precision of LHC experiments on the measurement of Luminosity now better than 1% (see briefing here)!

e^+e^- Ultimate Precision Machine!!

Ultimate precision machine requires ultimate precision detectors!

Analysis work is now strongly oriented **towards detector requirements to achieve the design precision**

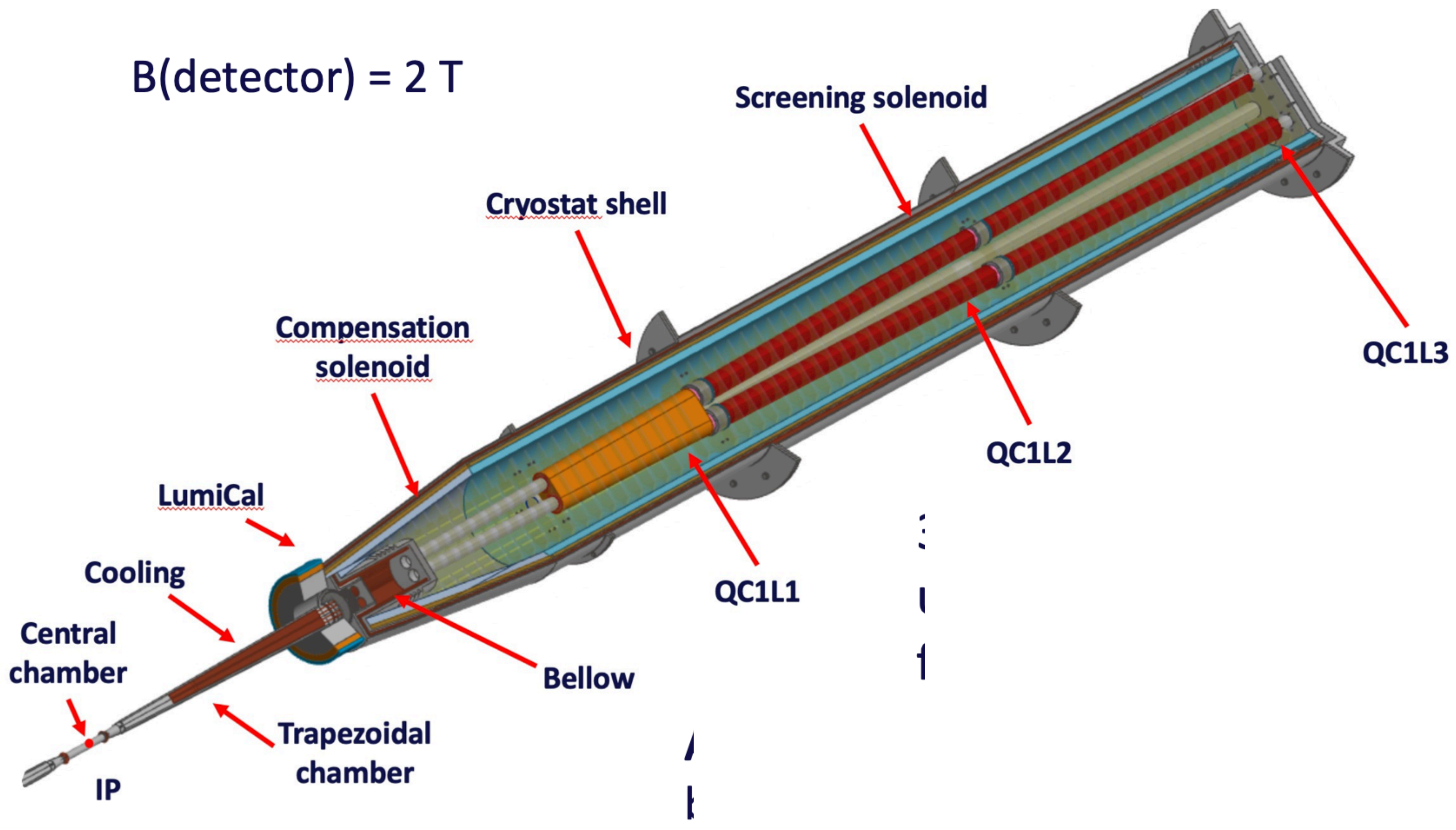


Several detector concepts: **CLD**, **IDEA** and **ALLEGRO** (Nobel Liquid concept)

Key aspects are very small amount of material in the inner detector region for precision track measurements and precise and highly granular calorimeter (numerous concepts)

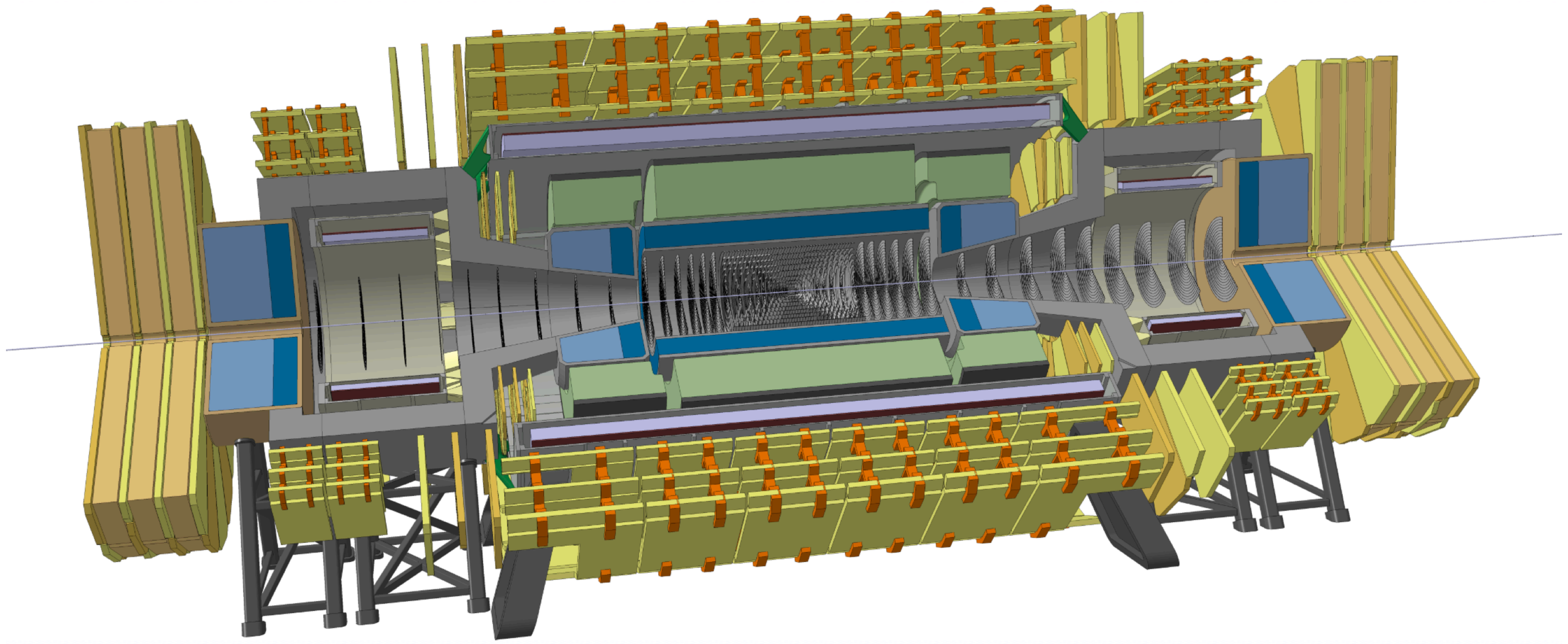
The FCC-ee interaction region and final focus!

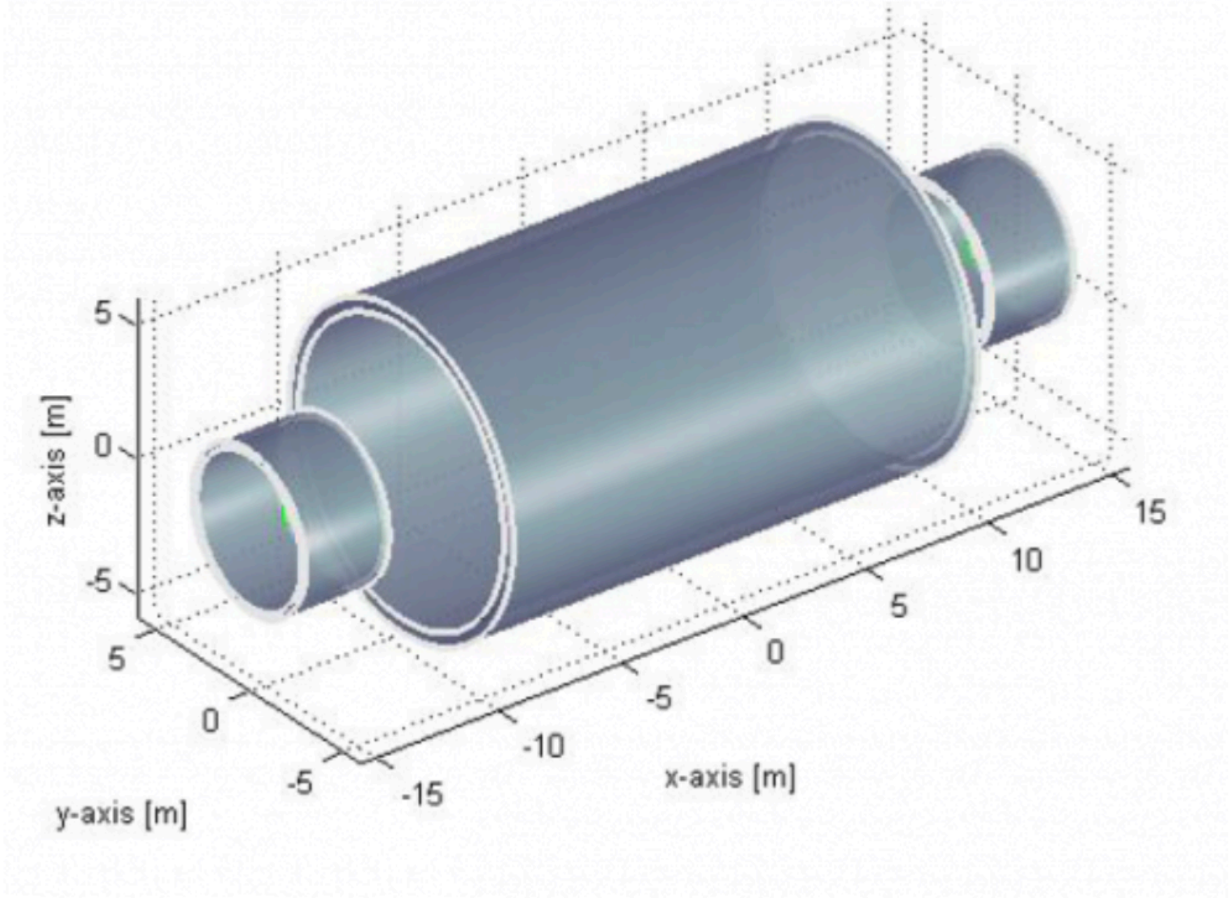
- Critical to reach highest possible luminosities
- Quadrupole magnets and final focus almost entirely inside the detector (at 8.4 m) - very strong requirements to reach **nano beams!**



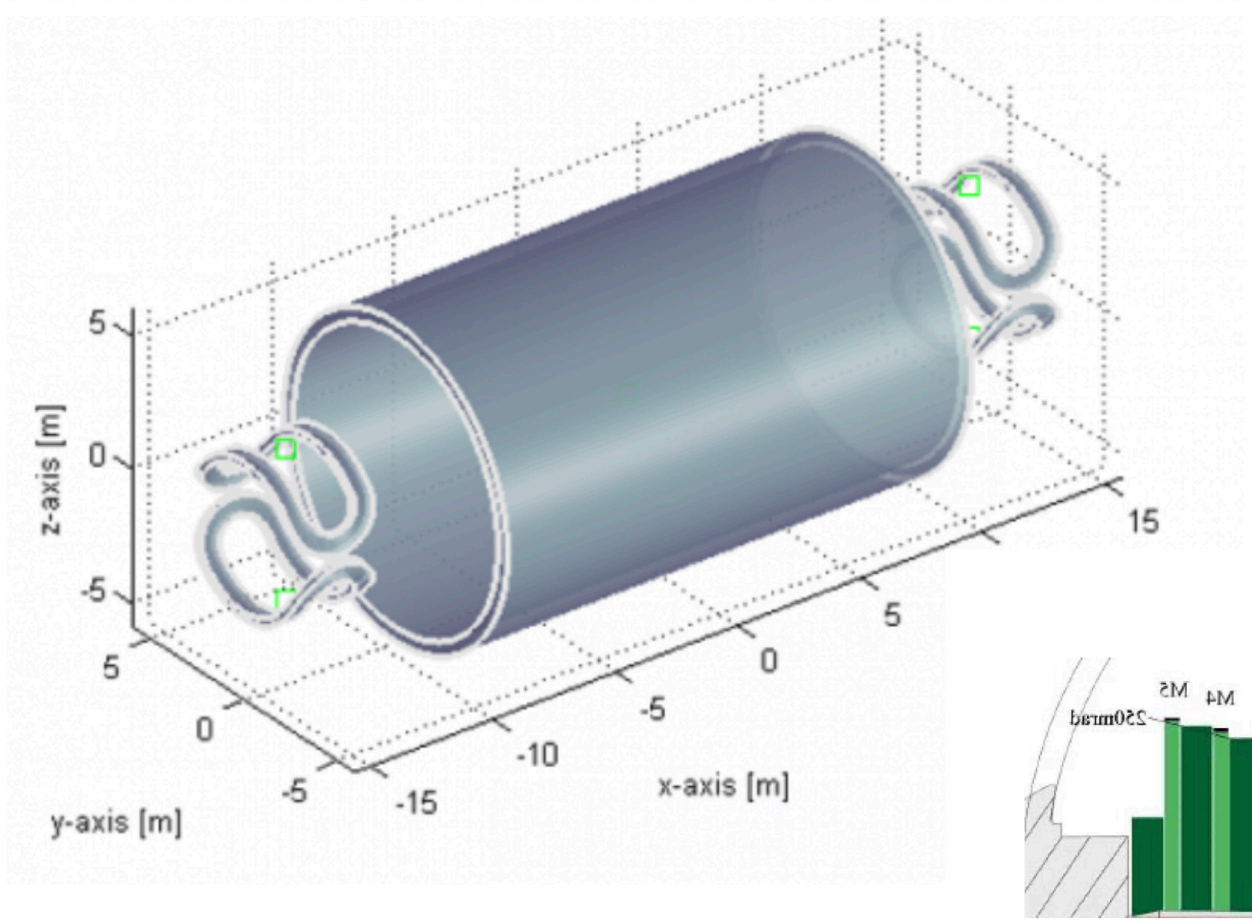
Hadron Collider Projects - Exploring the Multi-TeV scale

Dimensions commensurate (slightly larger) with current LHC experiments





Baseline



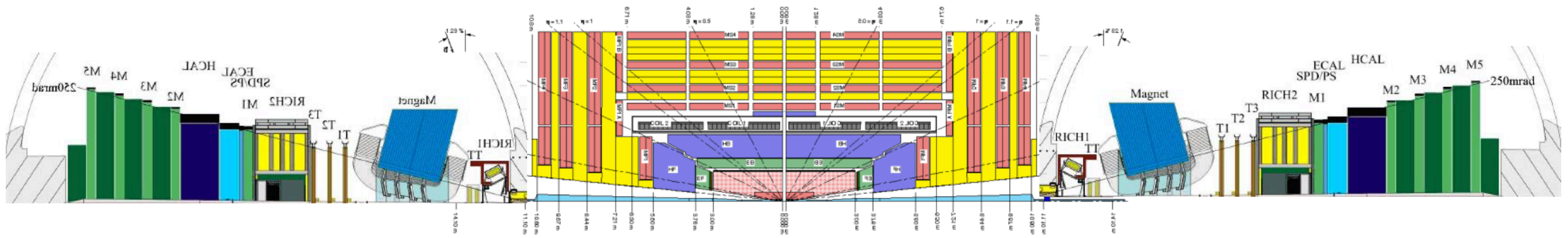
Alternative

FCC-hh key detector design challenges

- High luminosity - Extremely large PU, high occupancy and data rates, high trigger rates
- At FCC-hh Higgs produced up to rapidity of ~6.5 (up to 2.5 at LHC)
- Very high rates for triggering **Granularity** will be very important: decay product of a Z at 10 TeV separated by $\Delta R \sim 0.01$!!

Explore to improve on the resolution at high rapidity

Forward dipole magnet for high pseudo rapidity particles
Drawback: breaks the rotationally symmetric system…
Would be similar to a central CMS and two LHCbs in the forward directions!



Performance Achievements: Trigger

- Run 1 and Run 2: So far excellent trigger and object reconstruction performance in **increasing levels of PU**. Trigger Thresholds kept relatively stable throughout.

- The gain in acceptance and in performance with new detectors (to improve PU mitigation), new algorithms and new computing capabilities is expected to at least match current experimental performance.
  - Keeping Trigger thresholds at similar levels
  - Object reconstruction performance (efficiency vs rejection and energy scale and resolution) at stable levels.
  - Challenge to come: improve calibrations not only with more data to come but also improved strategies.

Menus at LHC and for HL-LHC

Signature	Run 1	Run 2	HL-LHC
Single e (isolated)	25	27	22 / 27
Single photon	120	140	120*
HT	700	700	375 / 350
MET	150	200	200

From A. Sfyrla LHCP 2018

- Increase readout rate 750-1000 kHz (currently 100 kHz).
- Increased latency and higher granularity.
- Enhanced data processing capabilities, storage rate up to 10 kHz (currently 1-2 kHz).

Performance Achievements: Object Reconstruction

Electrons, photons and muons

- Multivariate methods used for identification (at many levels) and calibration
- In-situ calibration using Z, W, J/Psi and Upsilons

Jets/MET

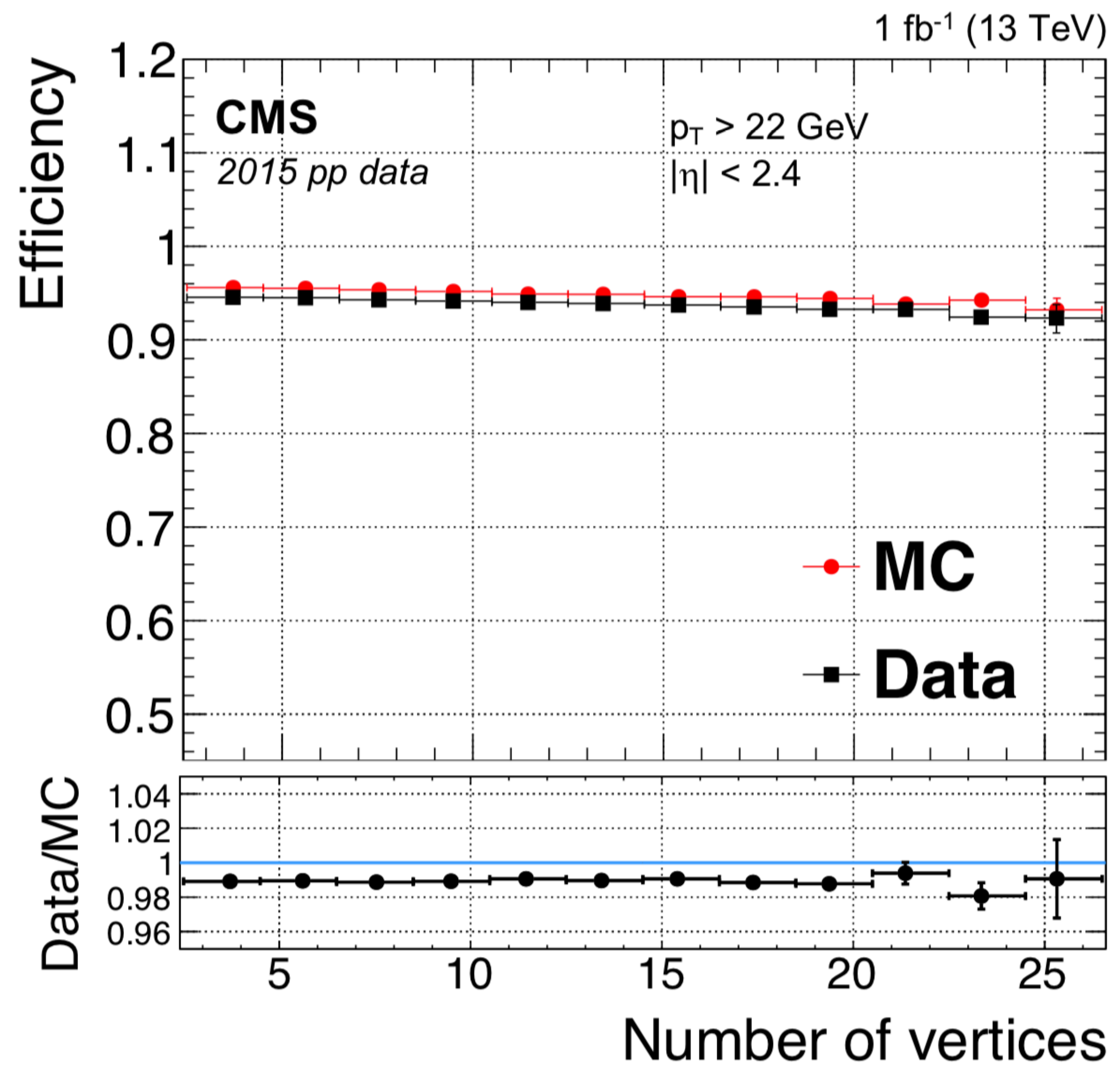
- JES *in situ* uncertainty reach ~1% level already (central and intermediate pT range) – using Z, γ and multi-jets.
- PU mitigation using associated tracks (jets and soft term in MET)

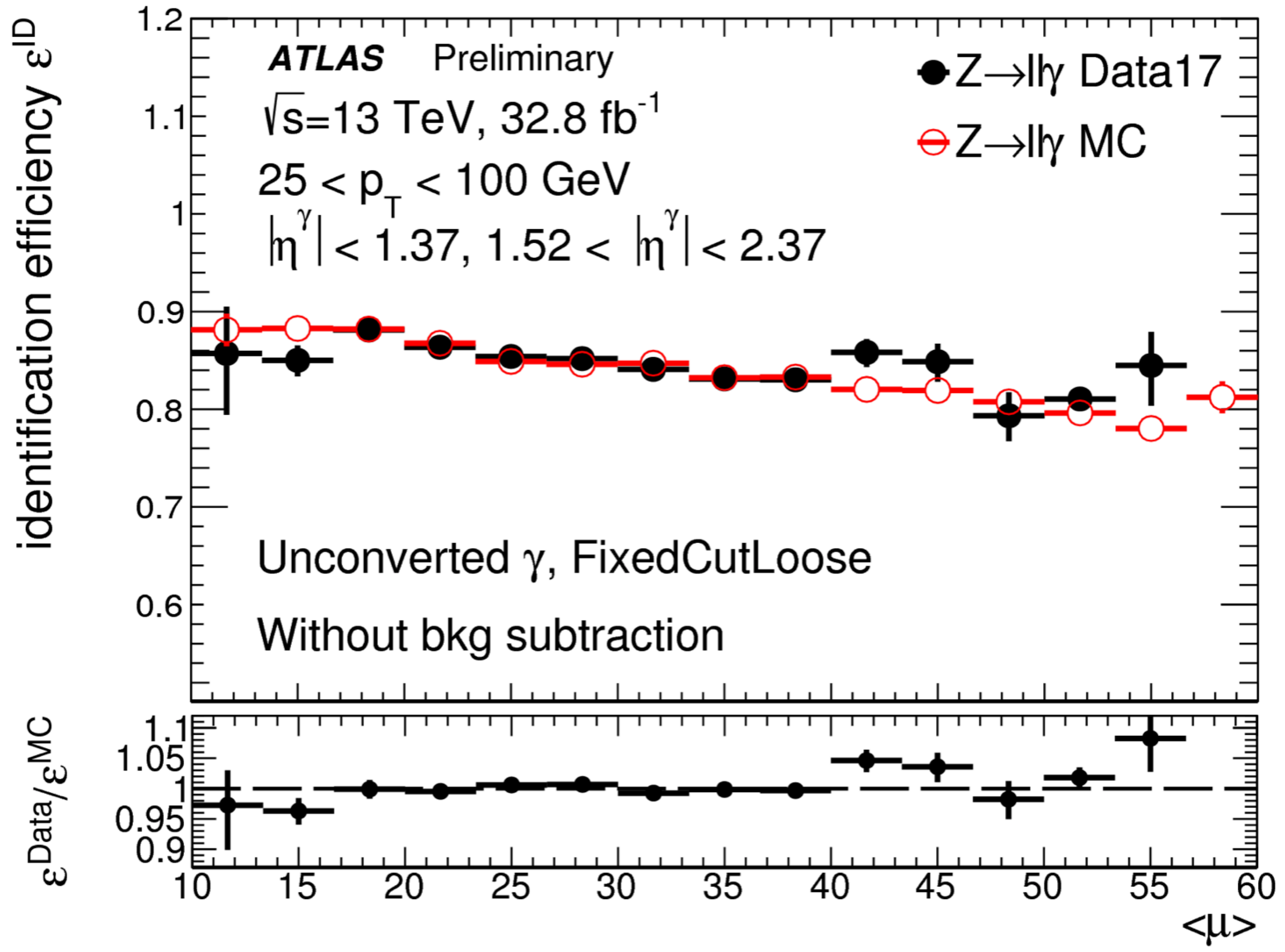
Taus

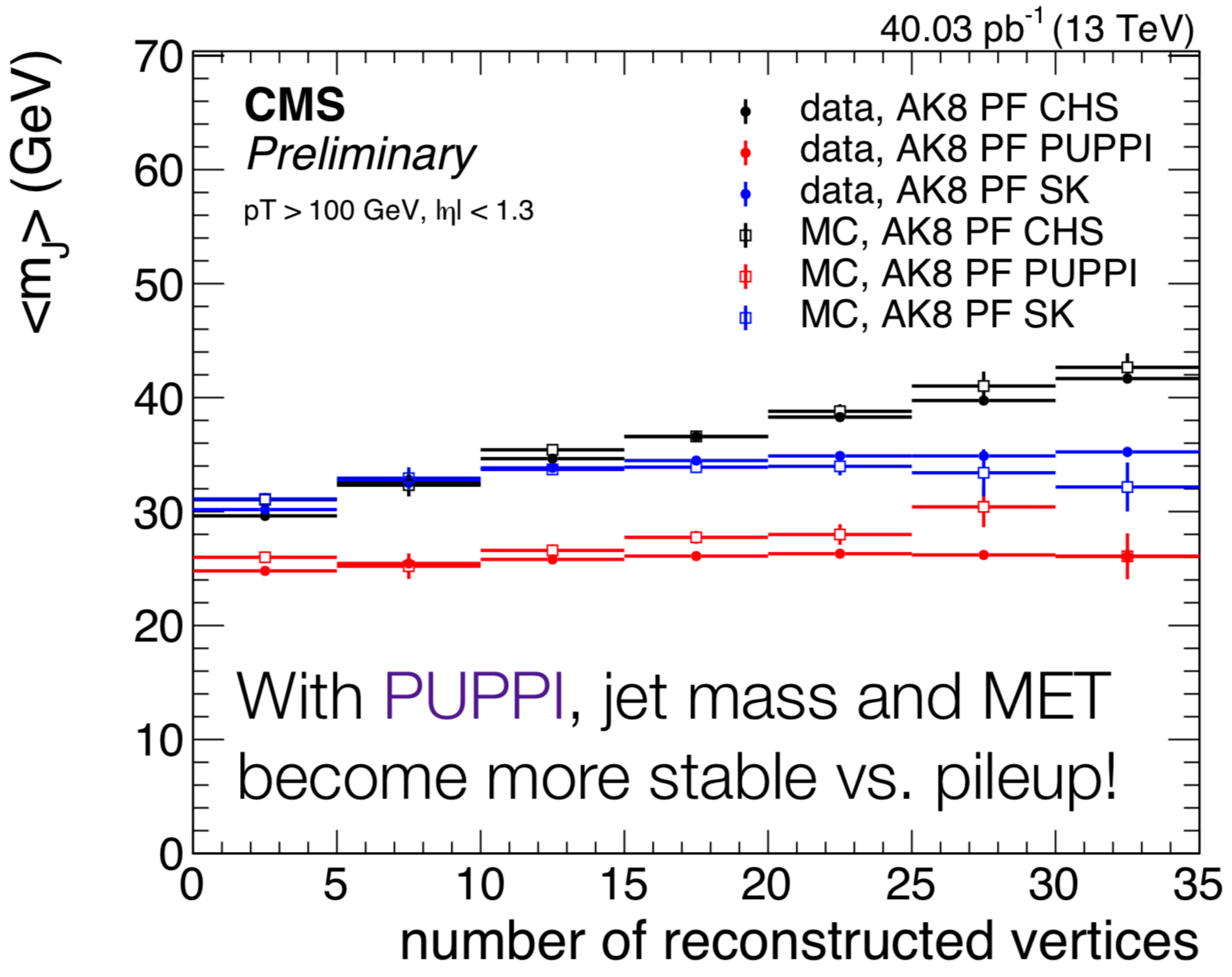
- BDT and RNN based identification (70% eff. and ~50 rej.)
- In-situ calibration based on Z events

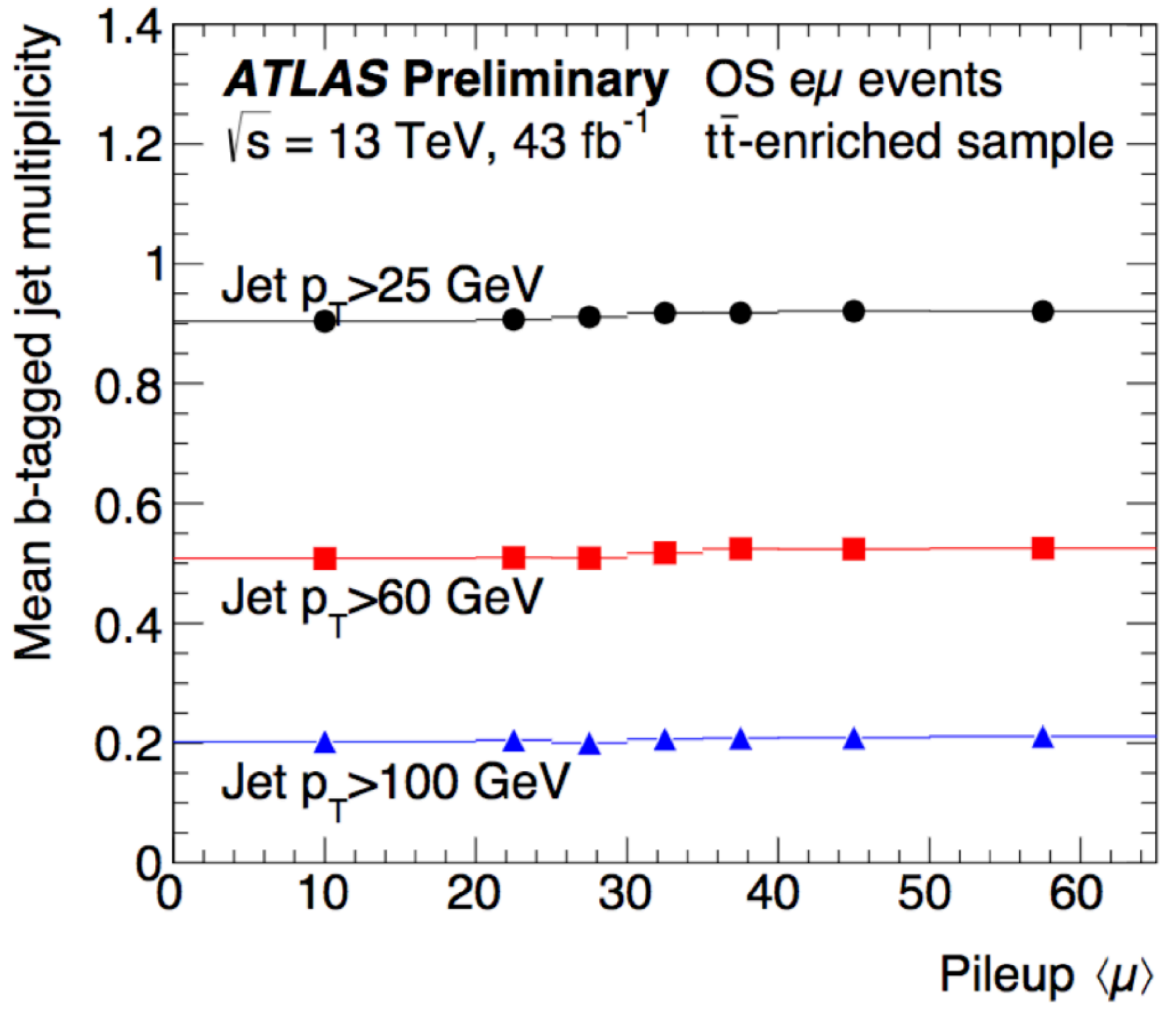
B- and C-jets

- In-situ calibration of b-tag efficiency (using top events and/or diet events)
- DL techniques from low level variables bring significant improvements









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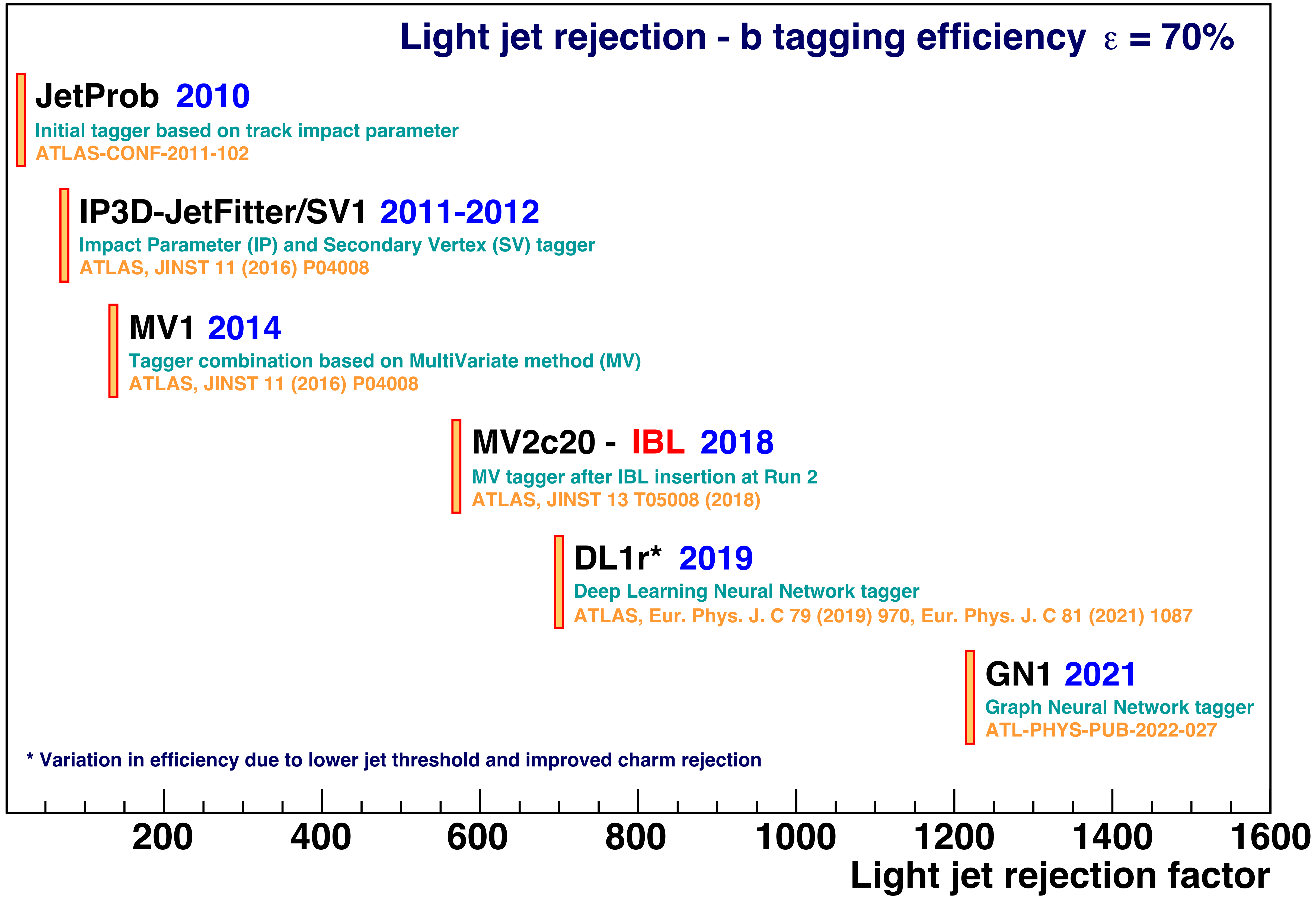

Reconstruction performance: Well calibrated, robust to PU and… well exceeding expectations!

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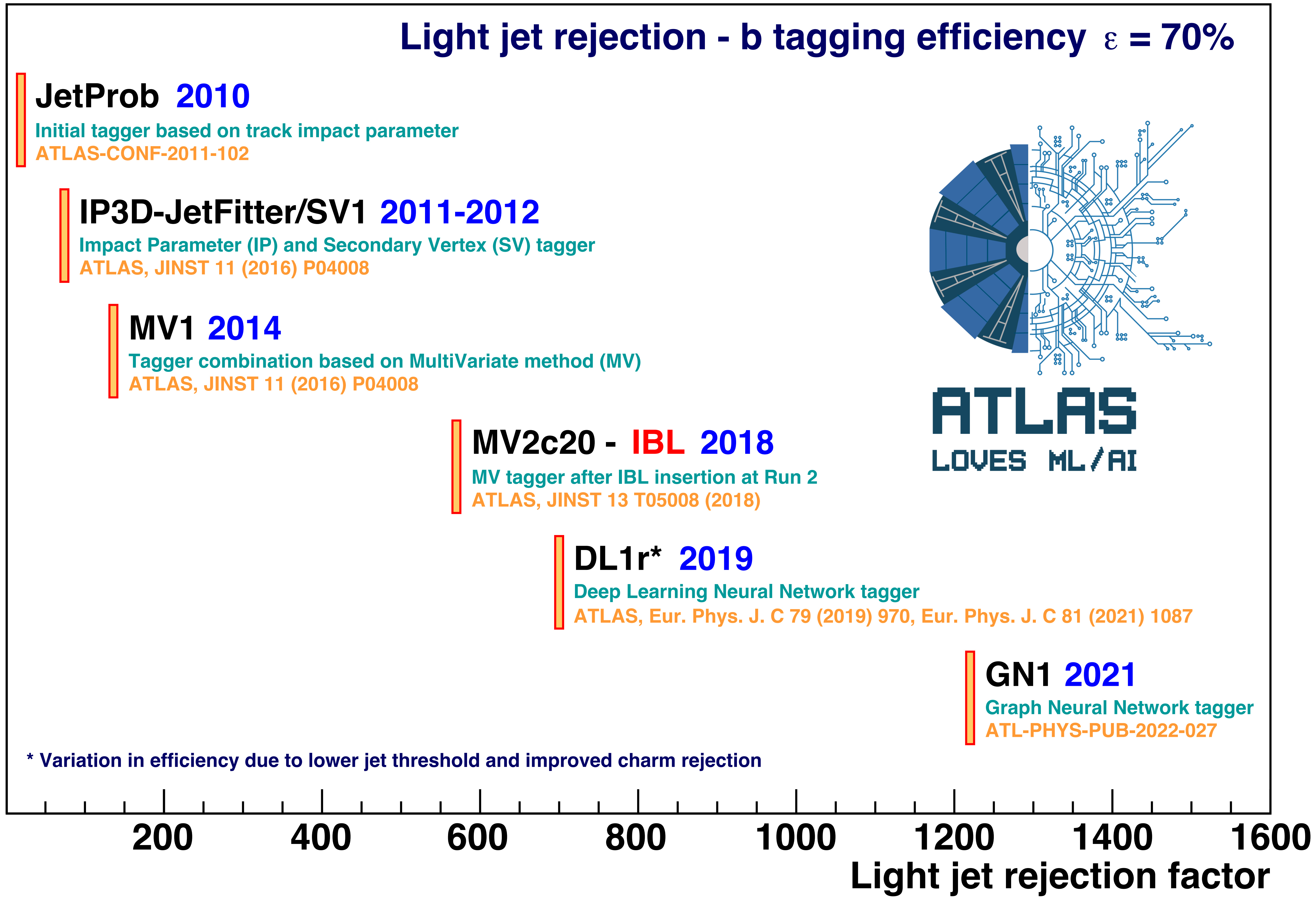

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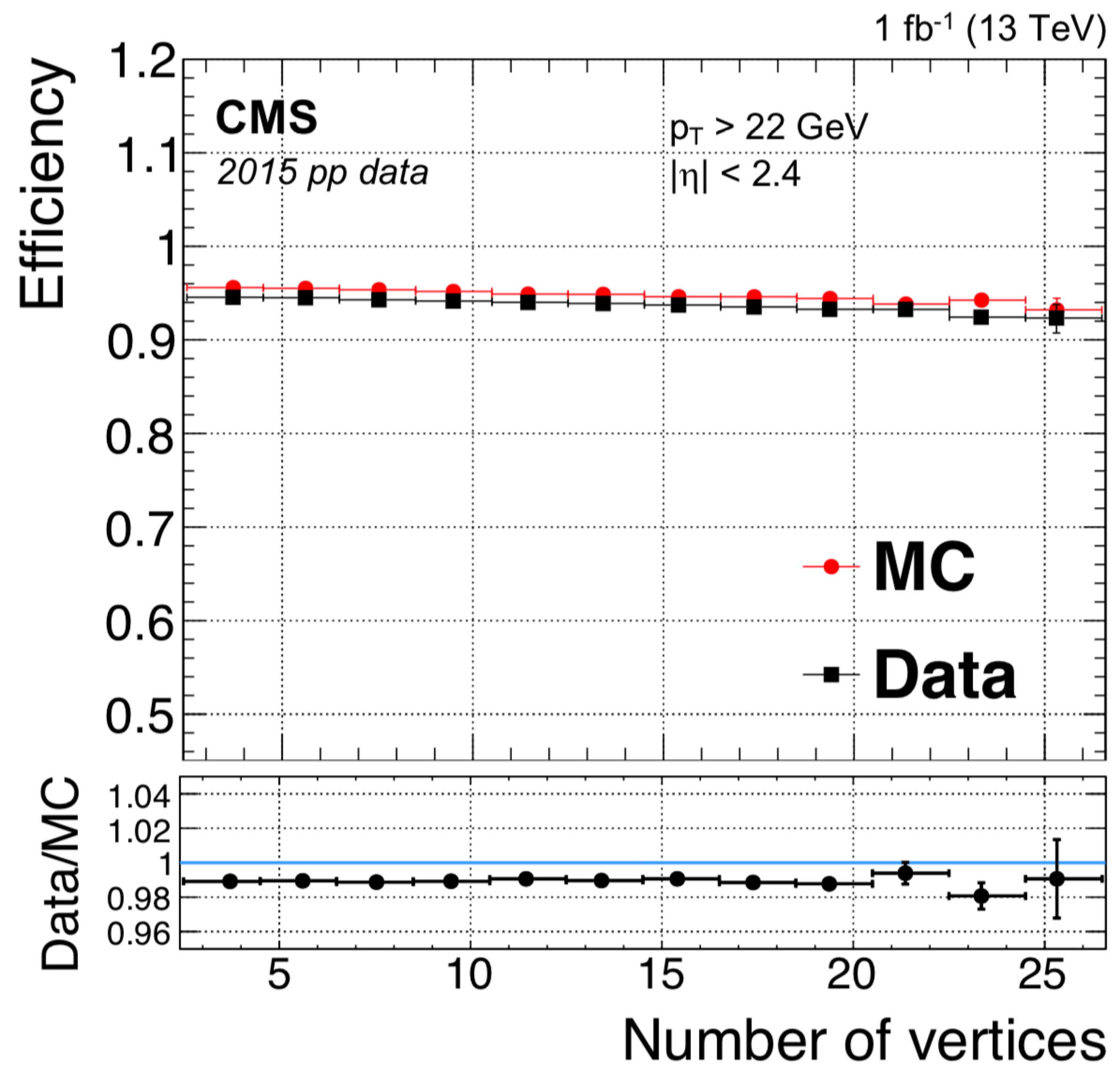
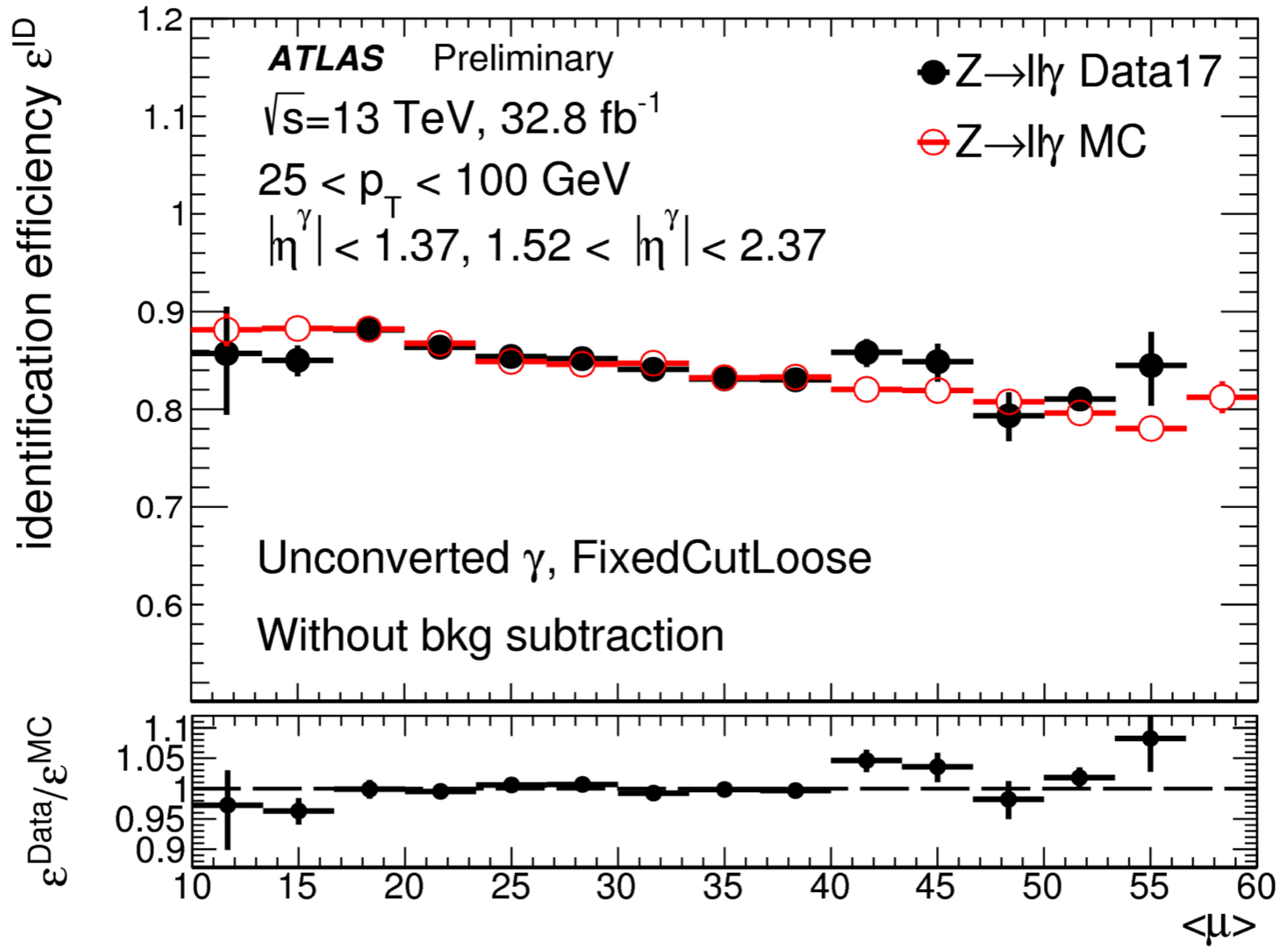
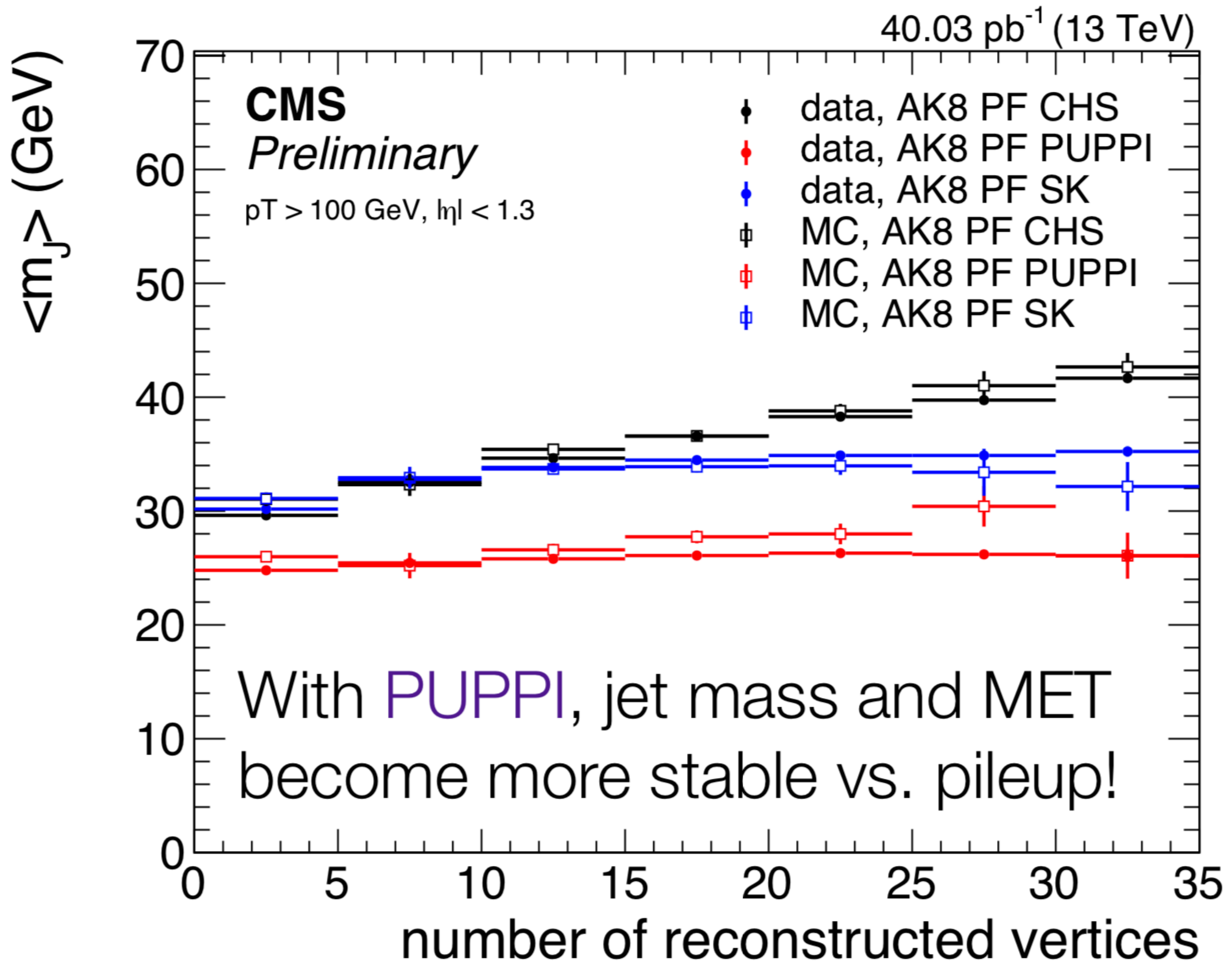
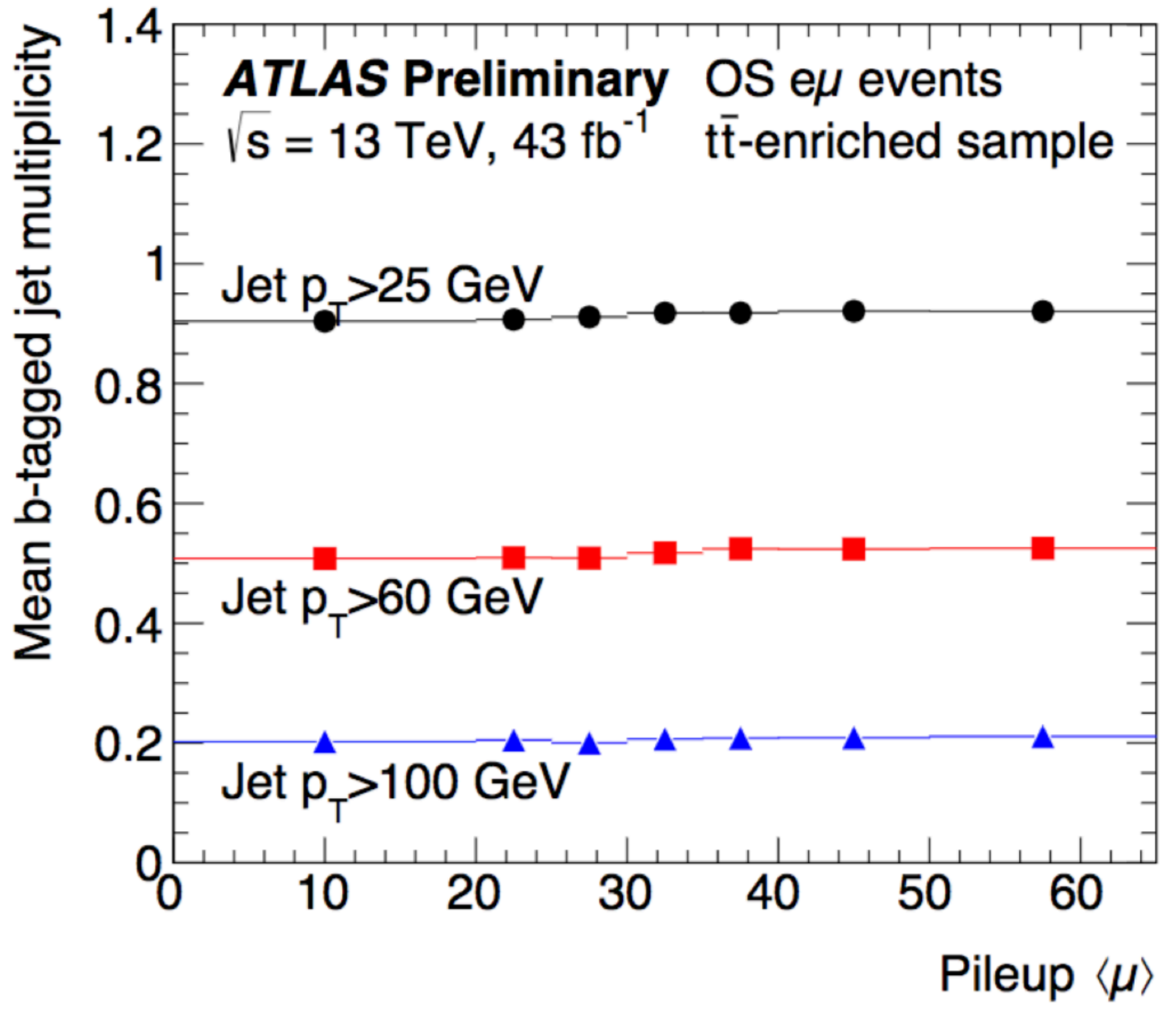
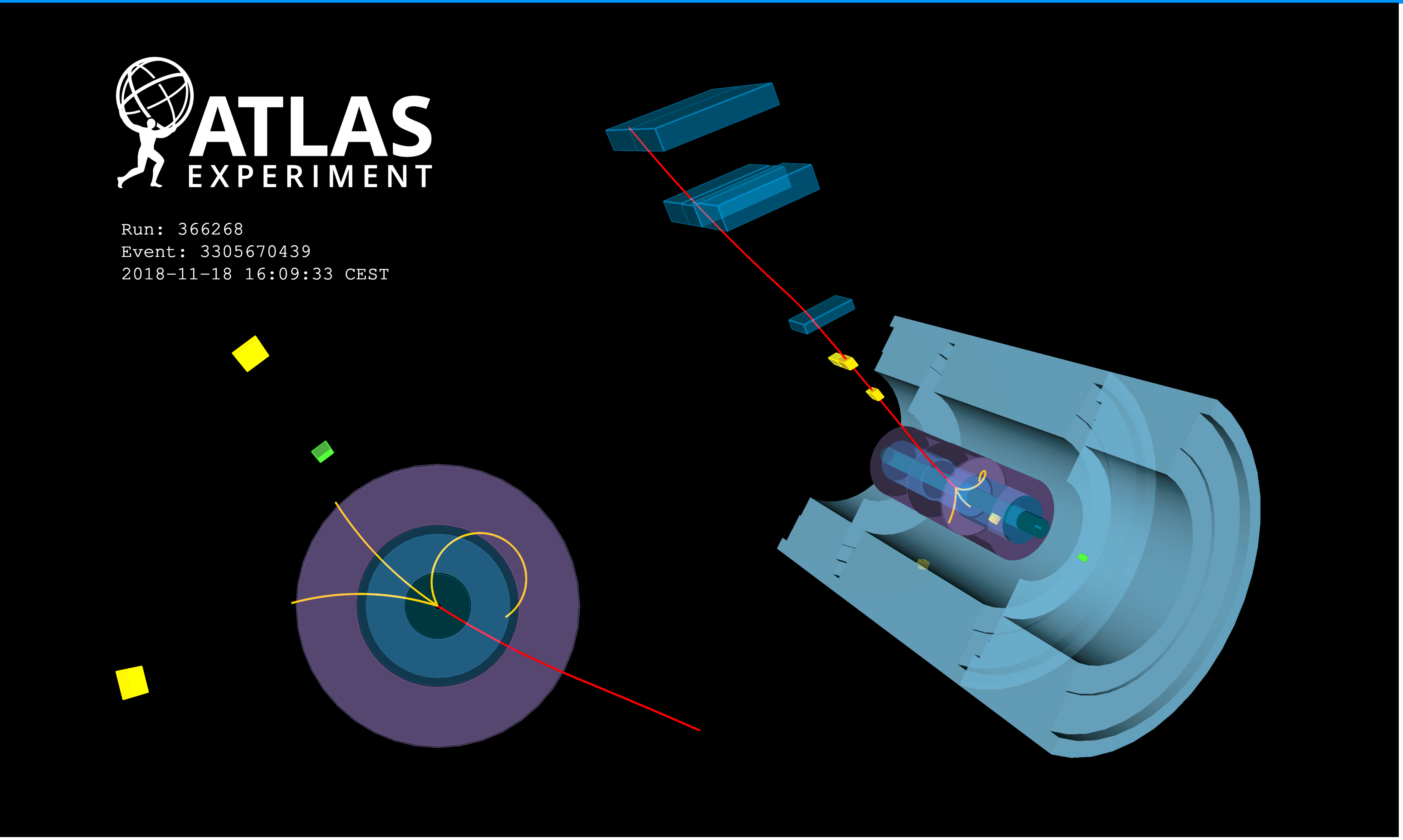


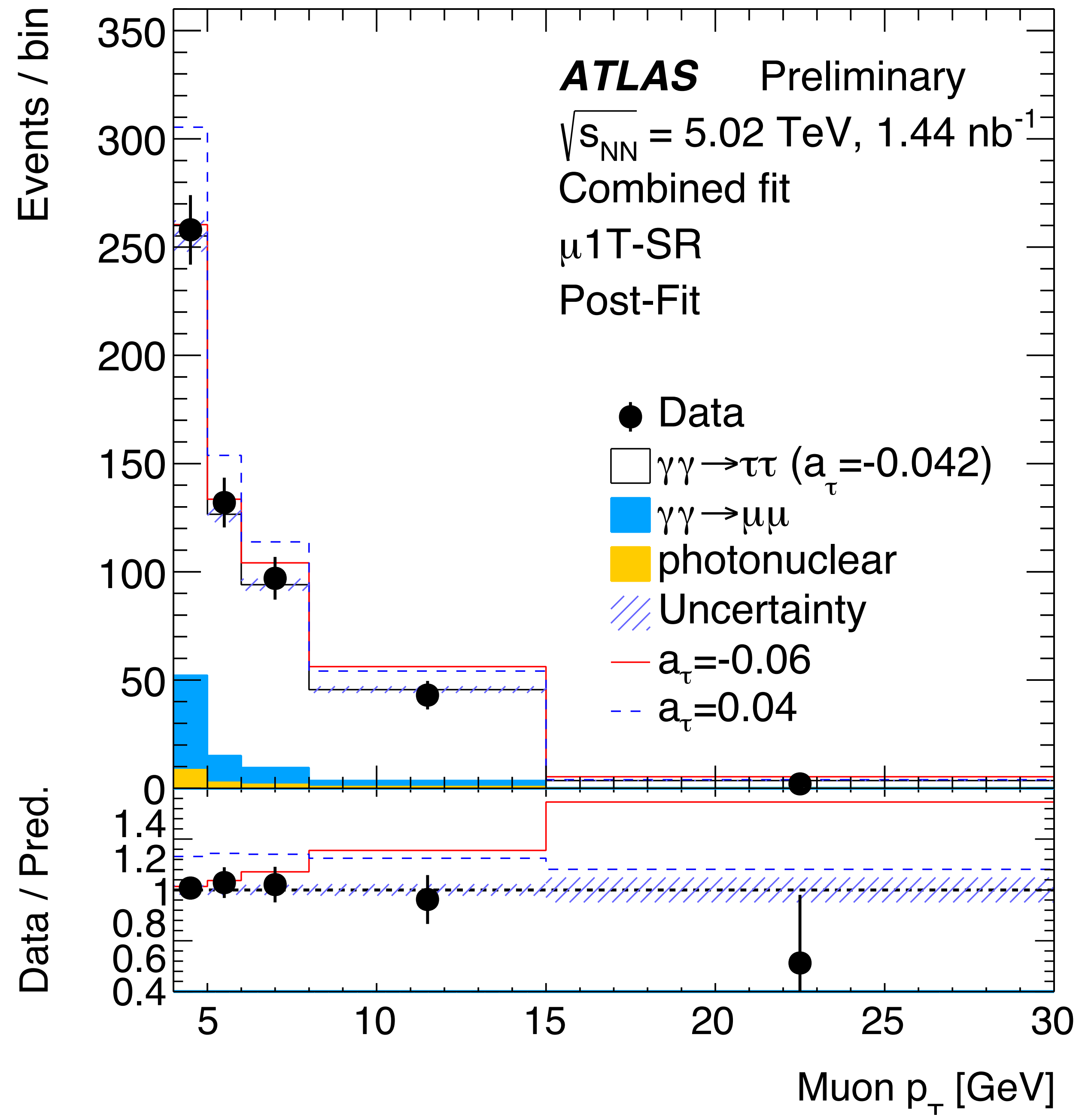


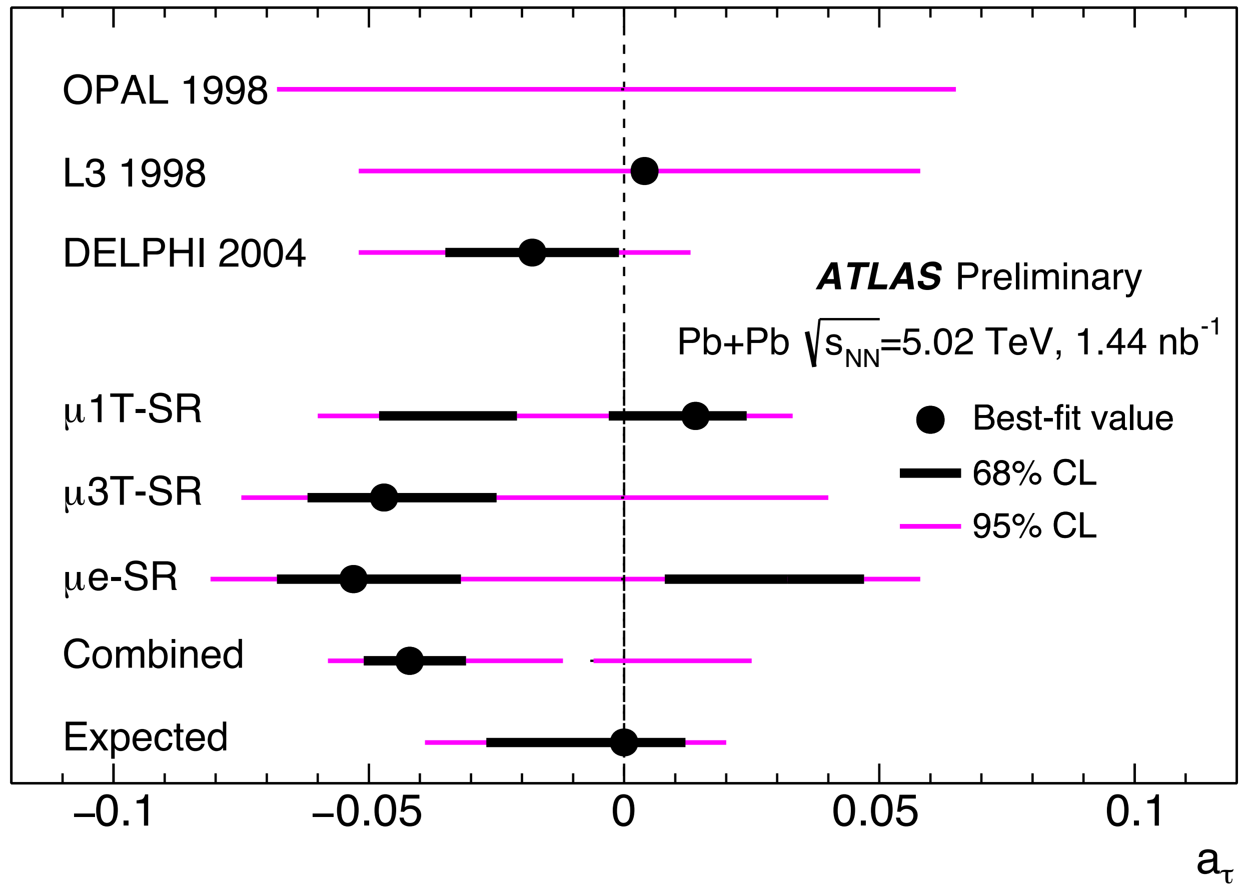




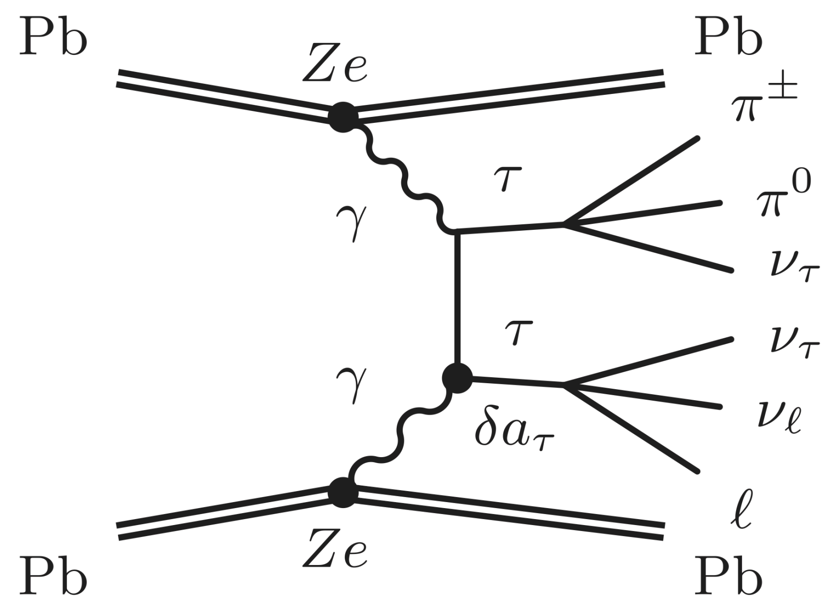
Tau magnetic moment and γγ → ττ Observation in PbPb



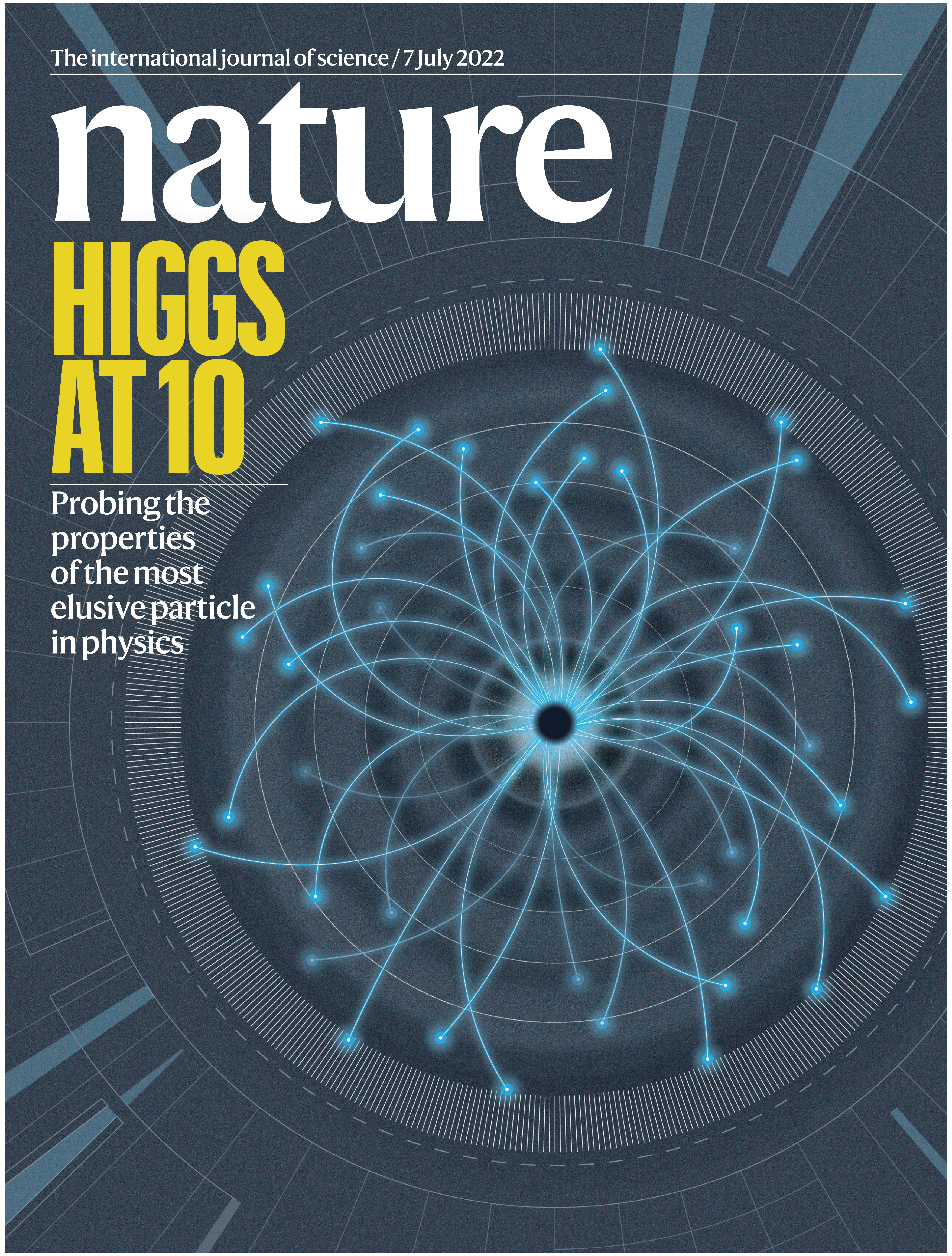




Observation of γγ → ττ in Pb-Pb collisions and constraint on tau anomalous magnetic moment



In case you missed it!



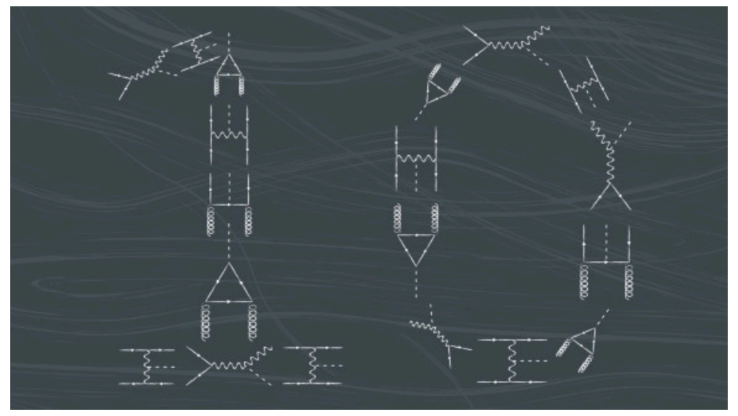
nature portfolio

nature > collection

Collection | **04 July 2022**

The Higgs boson discovery turns ten

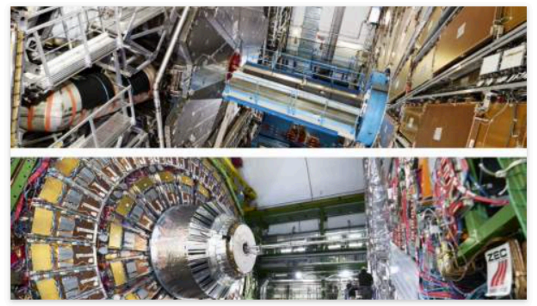
The discovery of the Higgs boson was announced ten years ago on the 4th of July 2012 — an event that substantially advanced our understanding of the origin of elementary particles' masses. In this collection of articles from *Nature, Nature Physics* and *Nature Reviews Physics* we celebrate this groundbreaking discovery and reflect on what we have learned about the Higgs boson over the intervening years.



CERN 10 years HIGGS boson discovery

Higgs 10 symposium at CERN

CERN news



ATLAS and CMS release results of most comprehensive studies yet of Higgs boson's properties

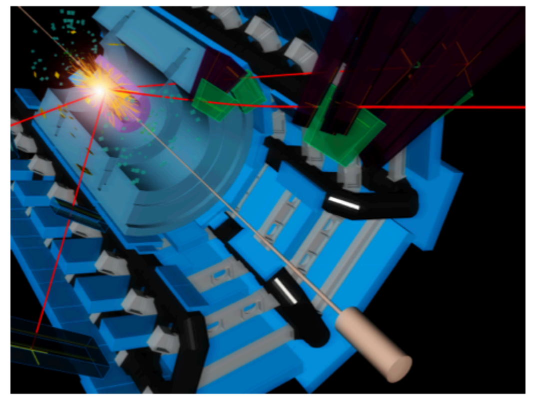
The collaborations have used the largest samples of proton–proton collision data recorded so far by the experiments to study the unique particle in unprecedented detail

News | Physics | 04 July, 2022

Higgs10: When spring 2012 turned to summer

It was just a few short weeks in mid-2012, but they were so intense that it felt like years. As 4 July drew near, the ATLAS and CMS experiments could sense that they were homing in on something big.

News | At CERN | 04 July, 2022



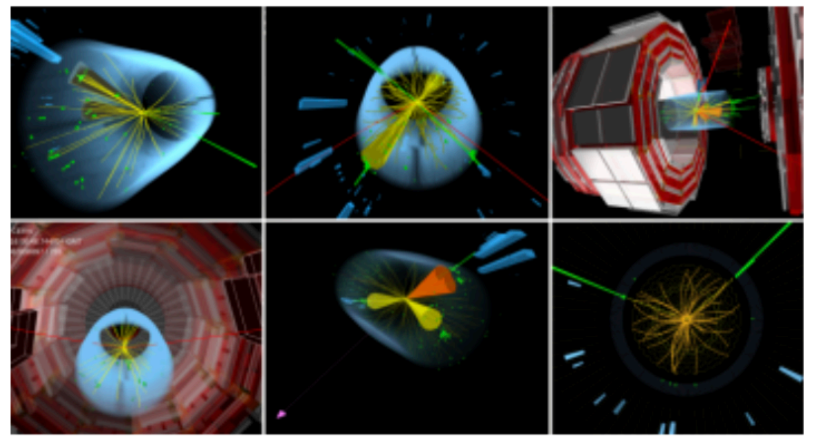
10 years of Higgs research

The ATLAS Collaboration at CERN has released its most comprehensive overview of the Higgs boson. The new paper, published in the journal Nature, comes exactly ten years after ATLAS announced the discovery of the Higgs boson. In celebration of this anniversary, a special all-day symposium on the Higgs boson is currently underway at CERN.

Press Statement | 4 July 2022

ATLAS news

CMS news

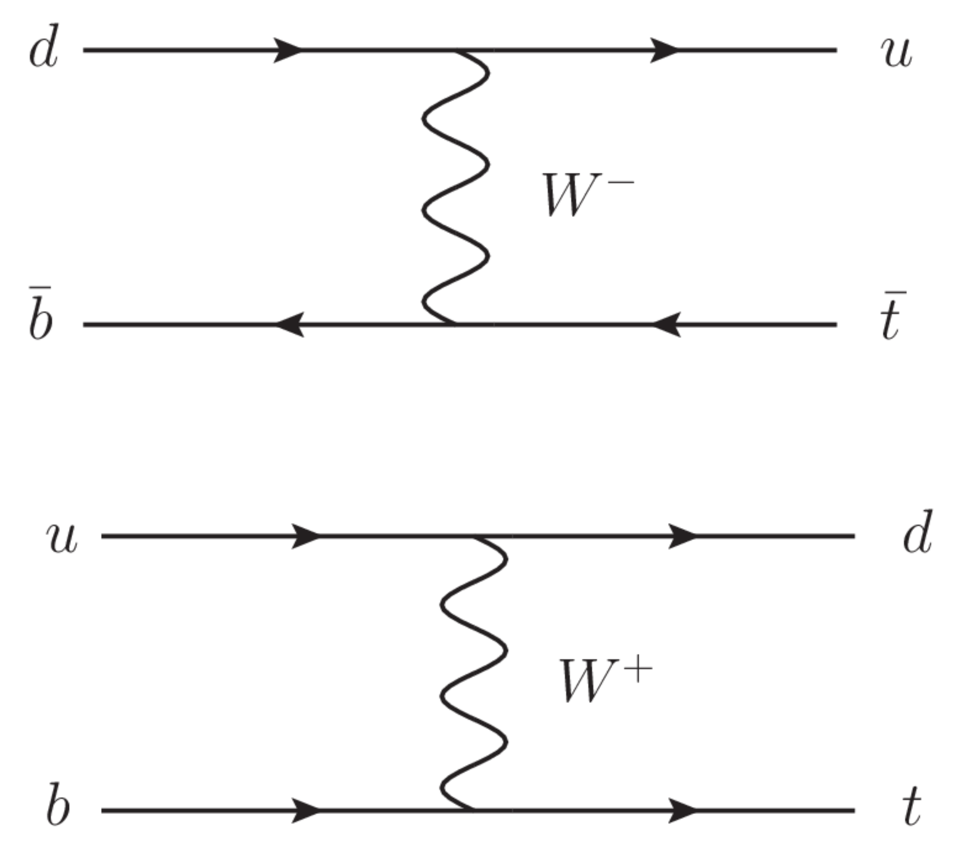


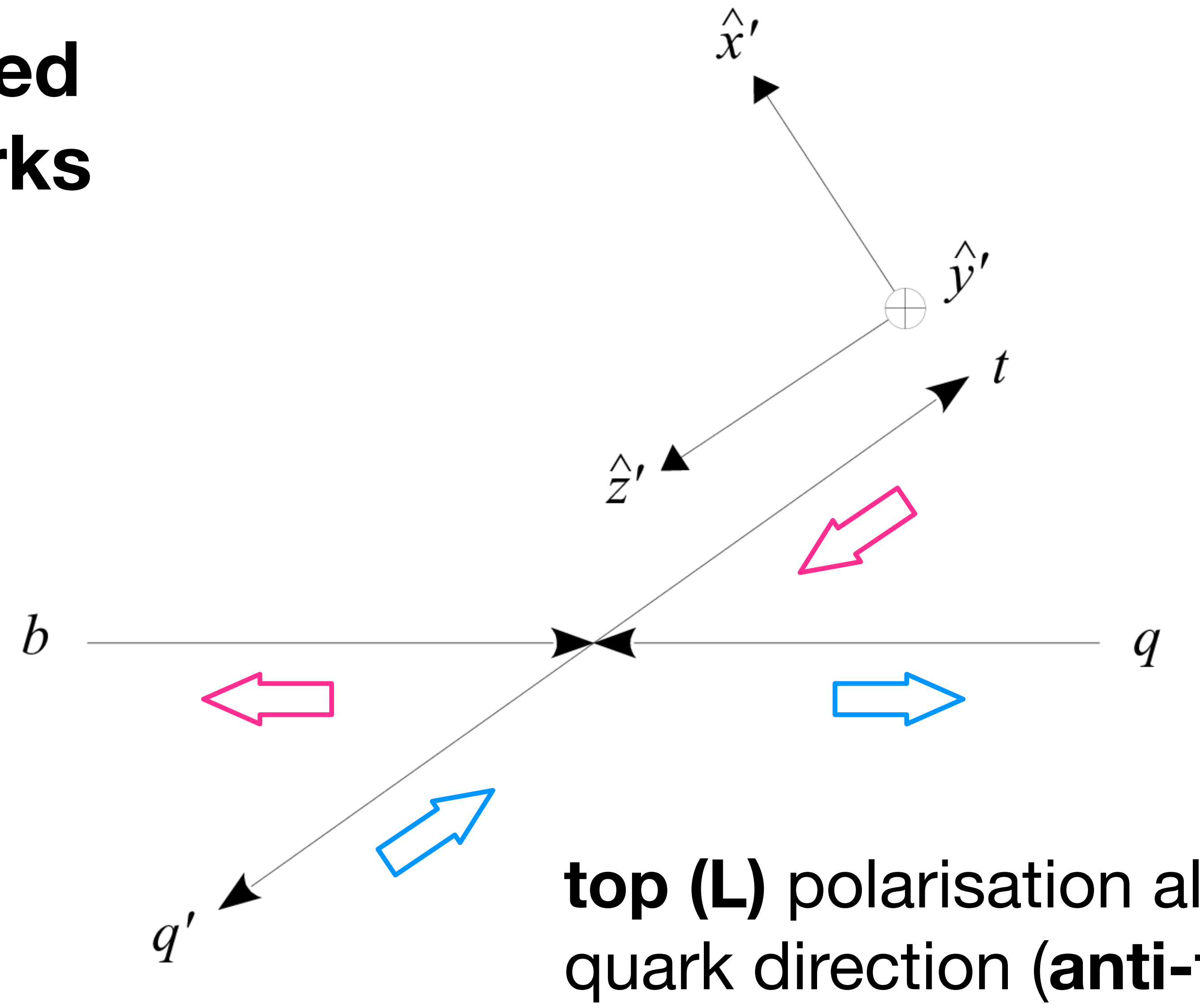
THE HIGGS BOSON TURNS 10: RESULTS FROM THE CMS EXPERIMENT

04 JUL 2022 | AJAFARI | PHYSICS

Single Top polarisation (t-channel)

V-A coupling induces polarised production of single top quarks

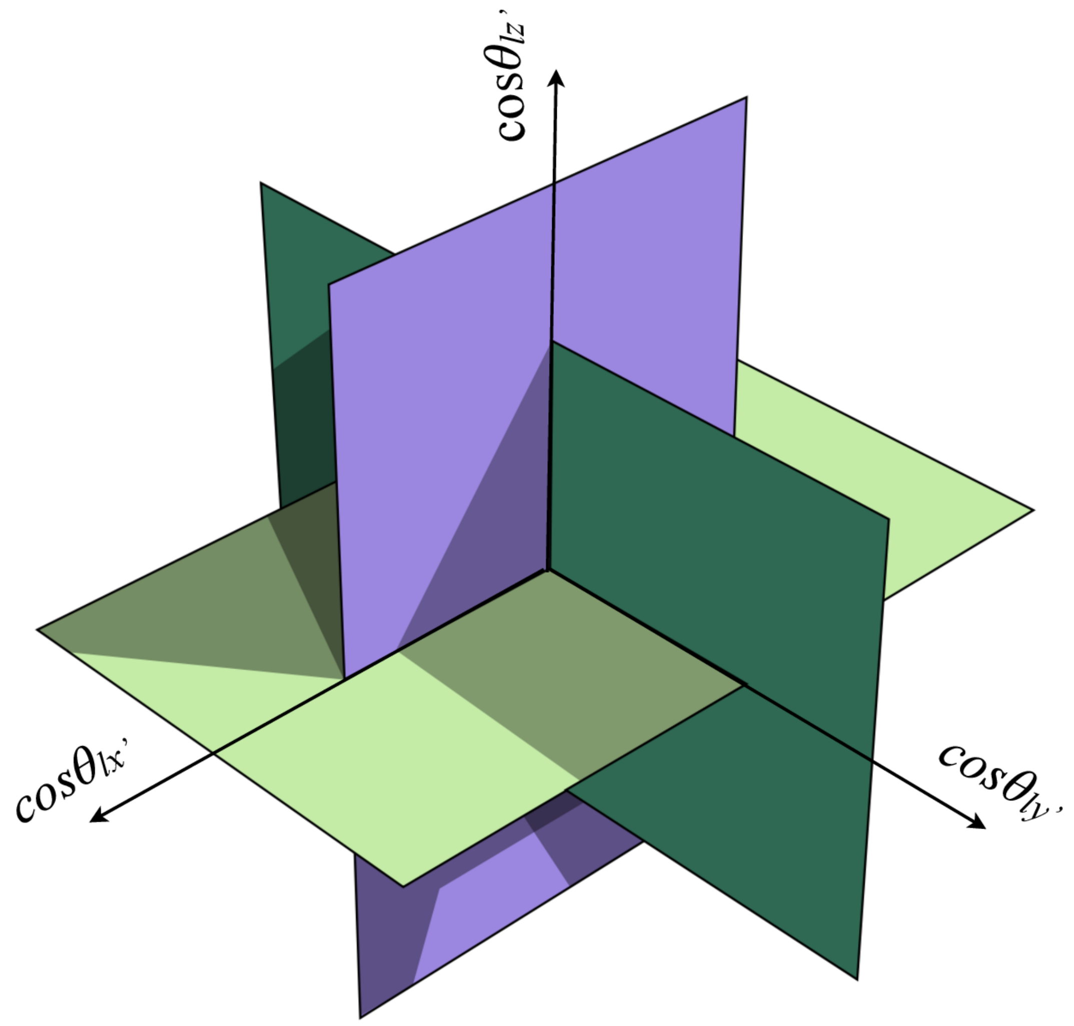


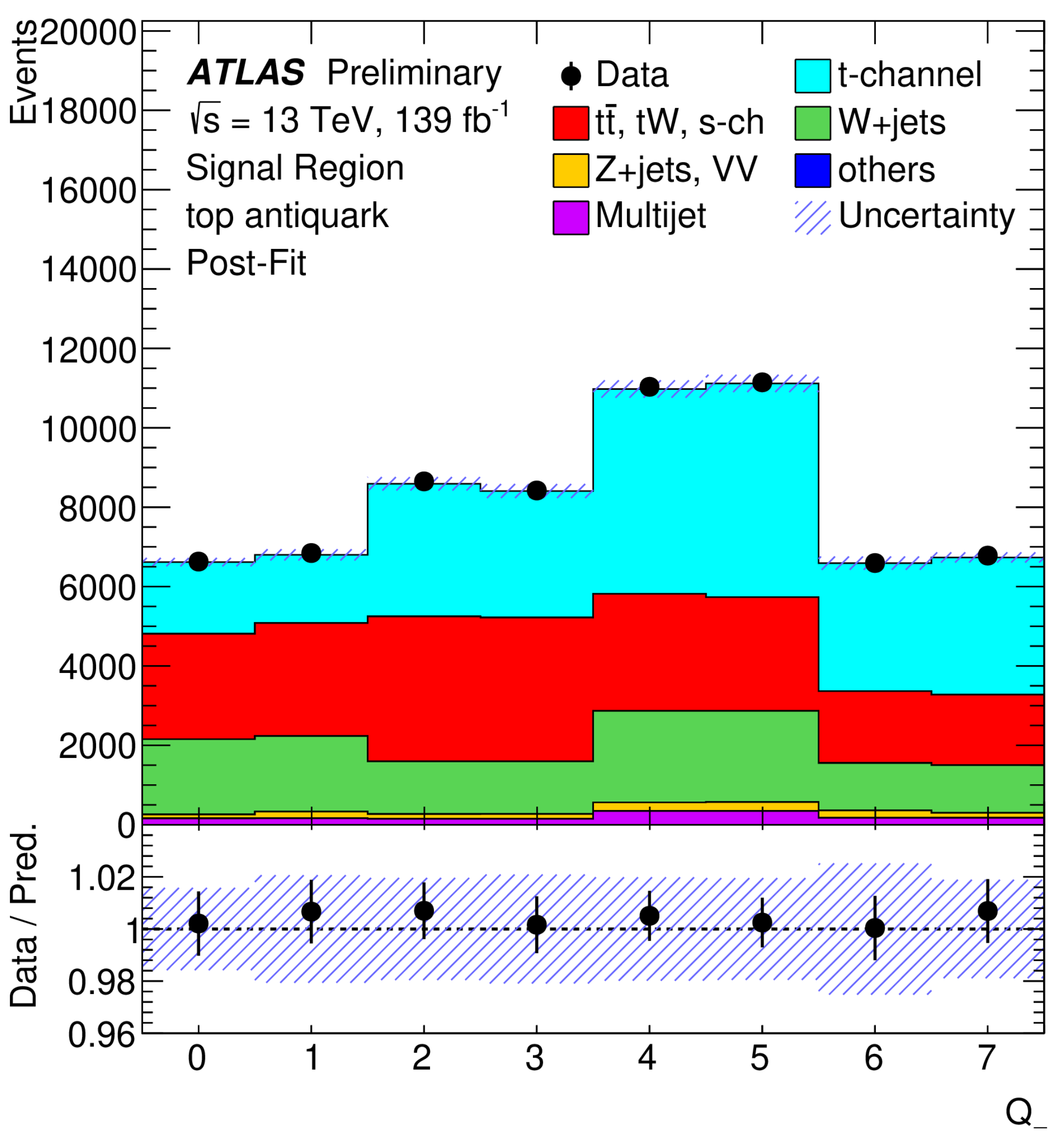


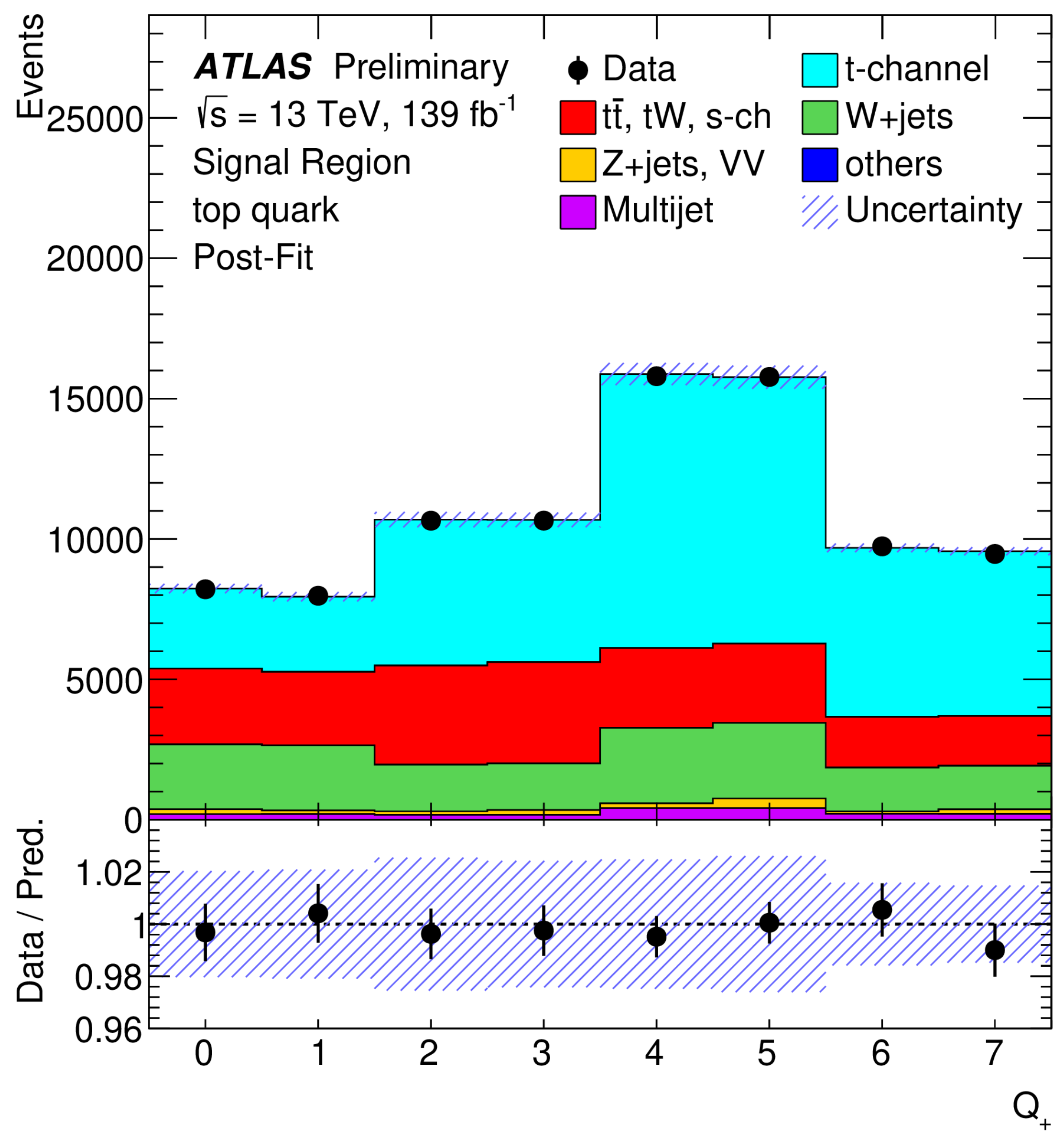
top (L) polarisation along spectator quark direction (**anti-top (R)** opposite)

Use semi-leptonic top decays!

Definition of a 3D discriminant based on the octant in which the lepton is produced!



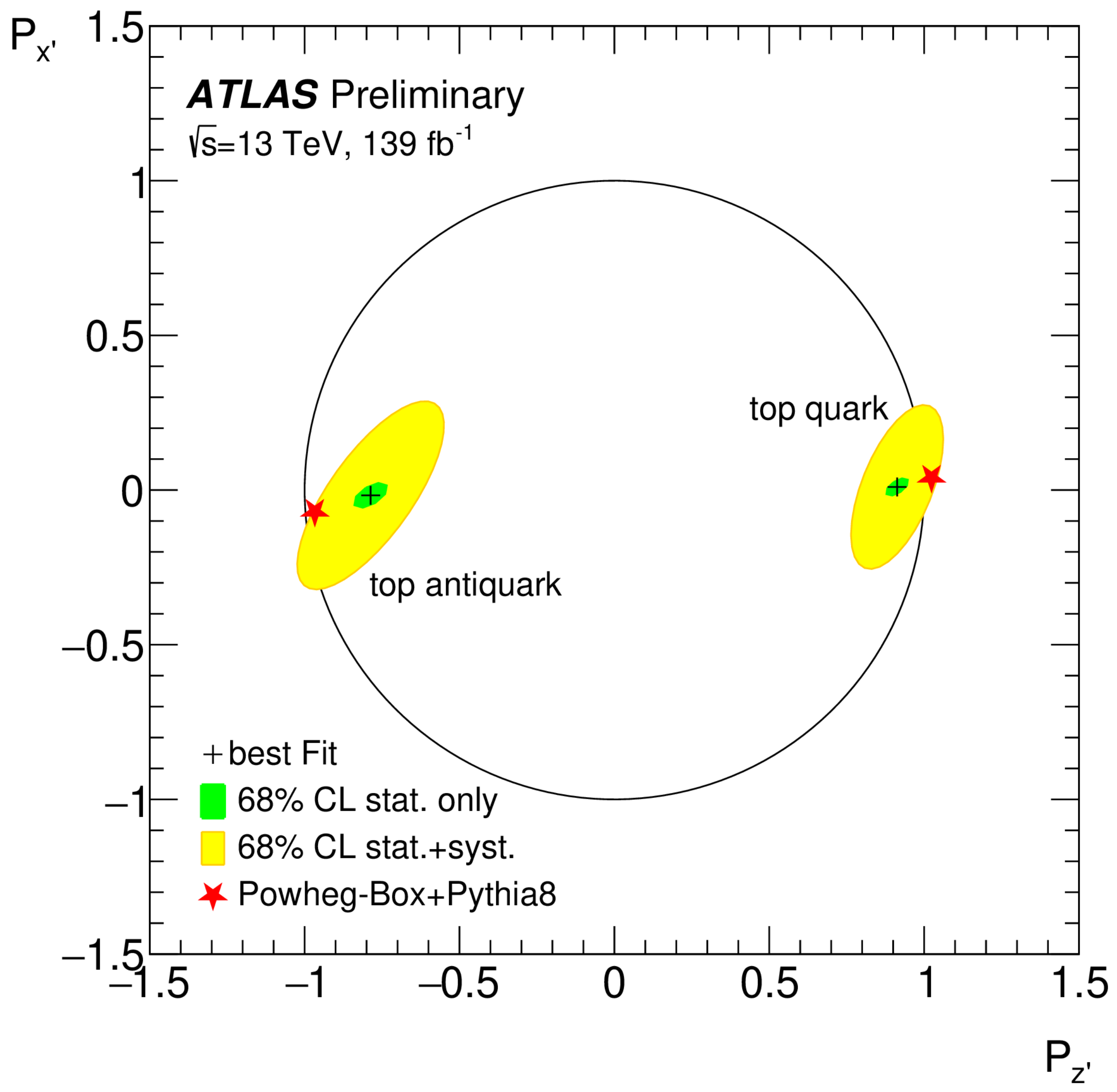




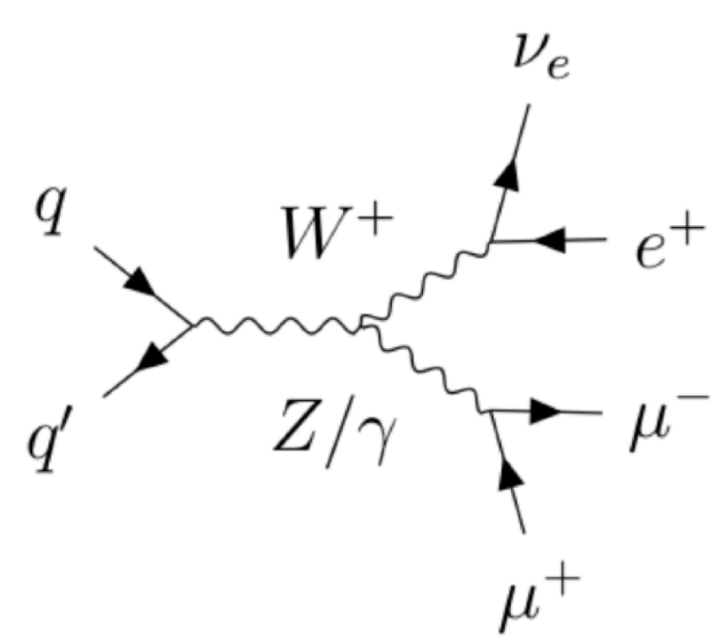
Fit to the polarisations Px, Py, Pz done using a parametrisation of this octant variable.

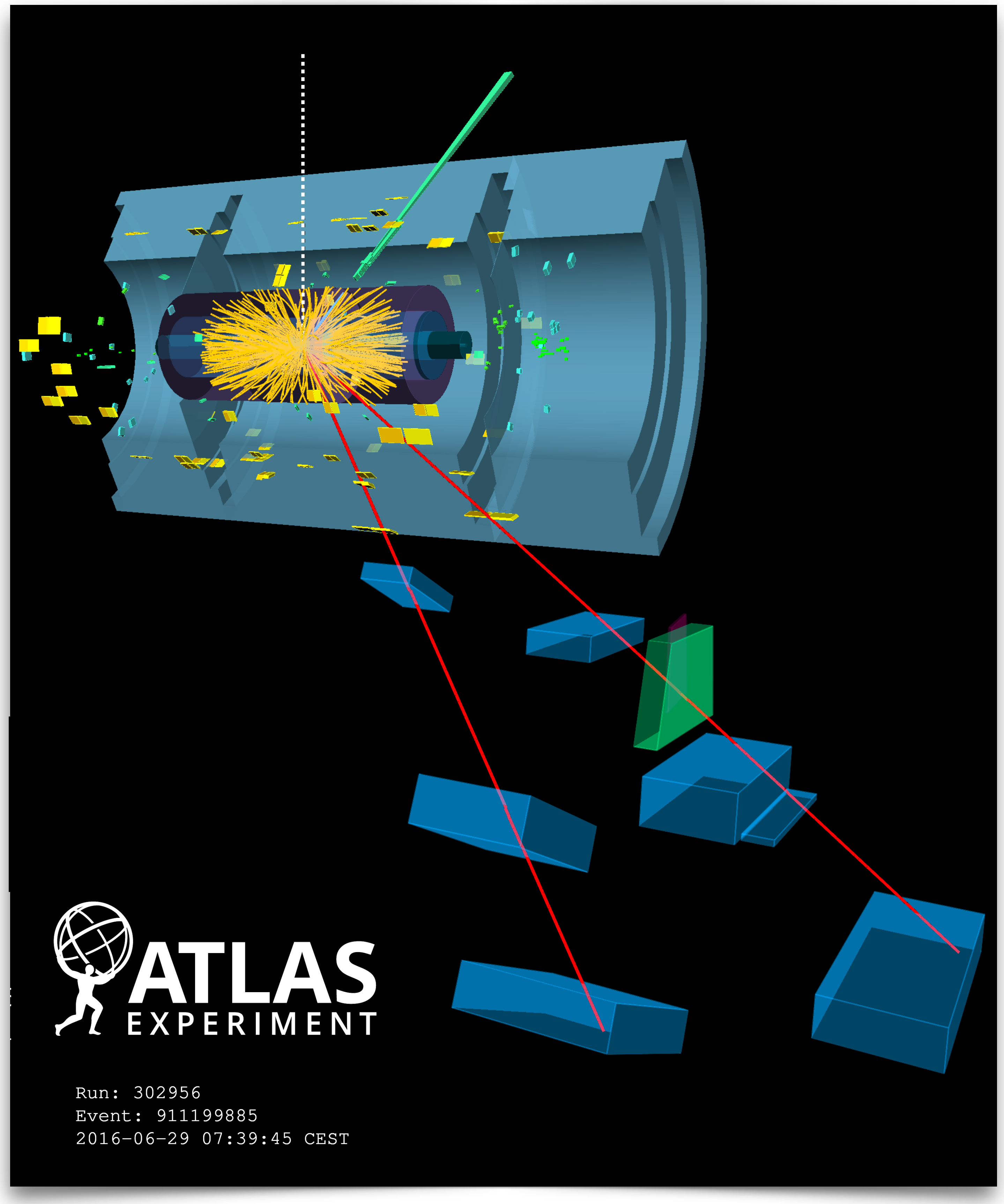
Py is sensitive to CP violating effects

Px is sensitive to NLO QCD effects



Di boson production

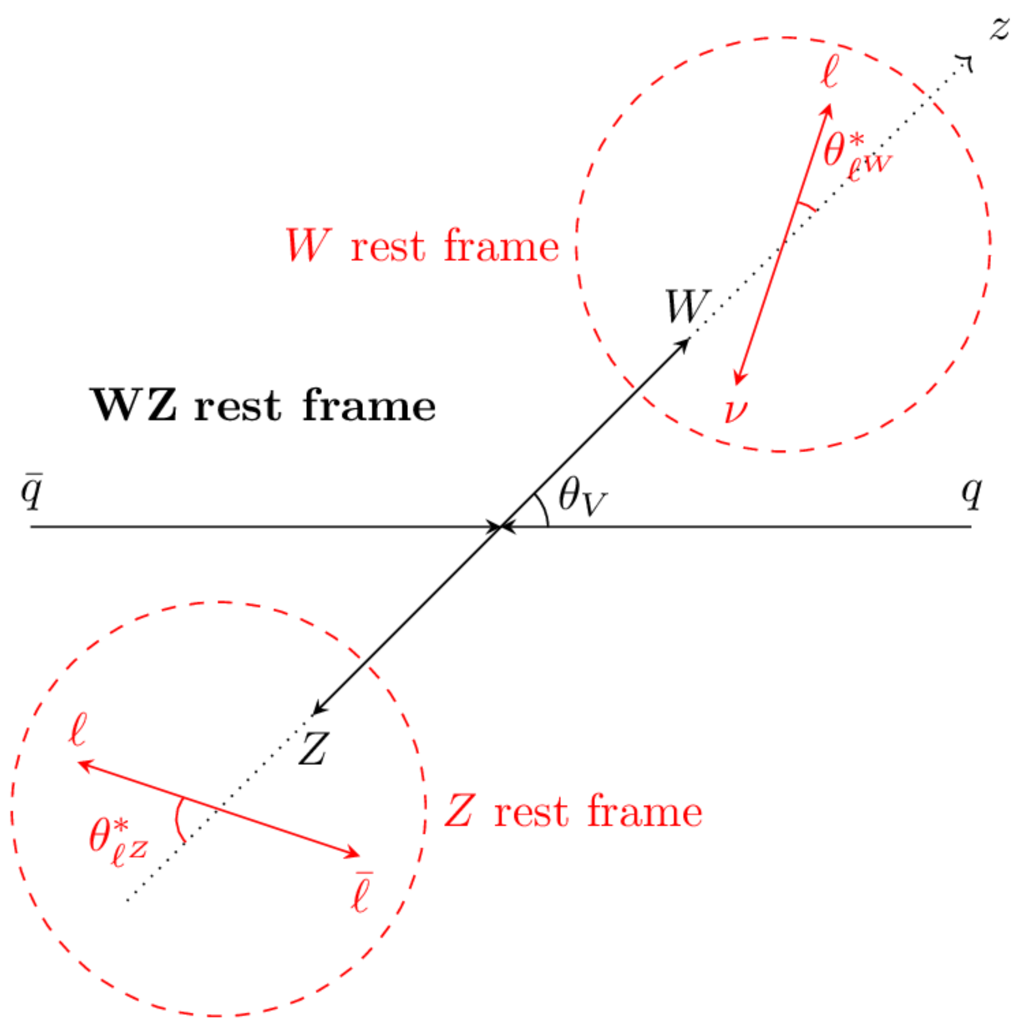


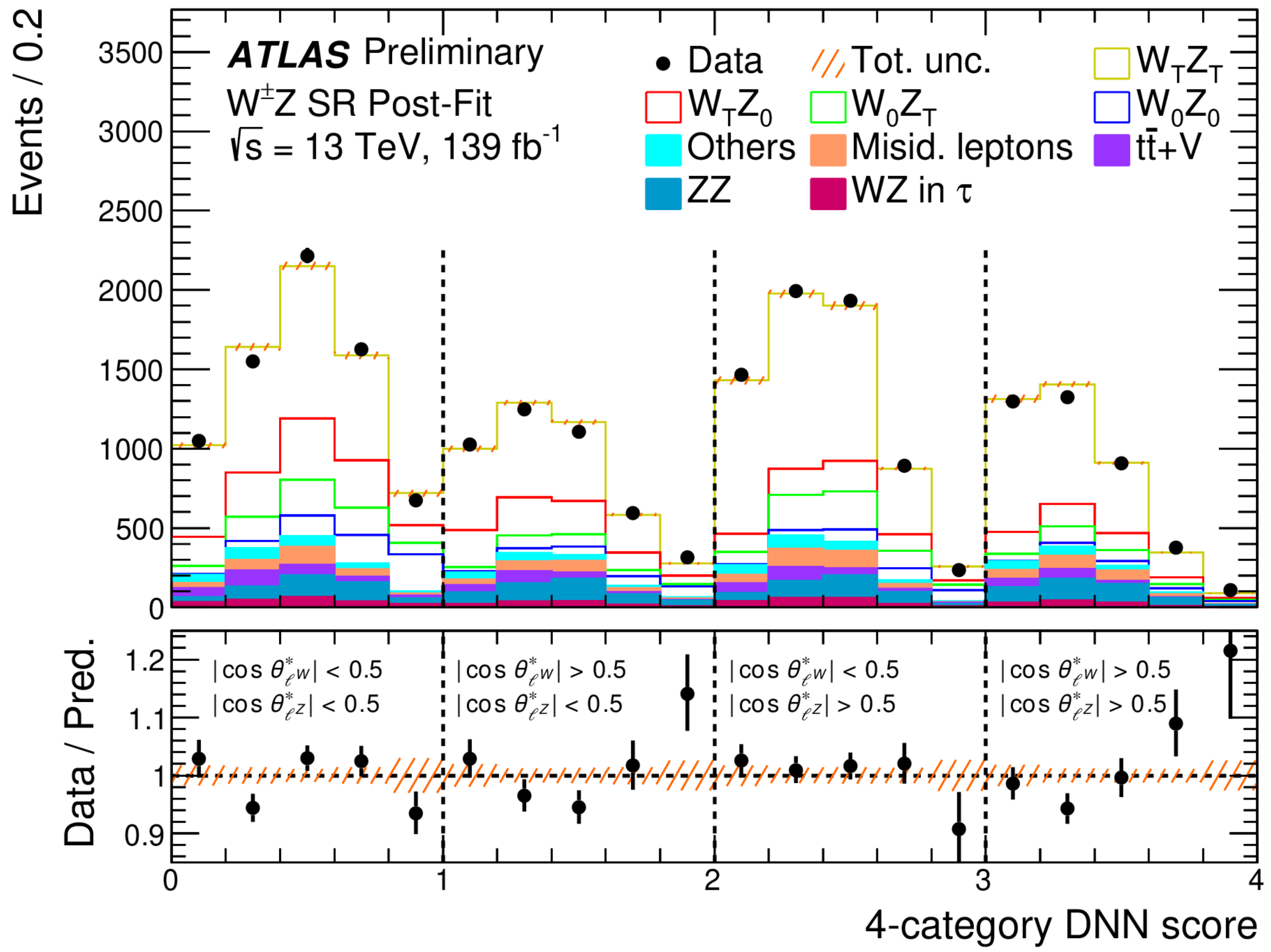


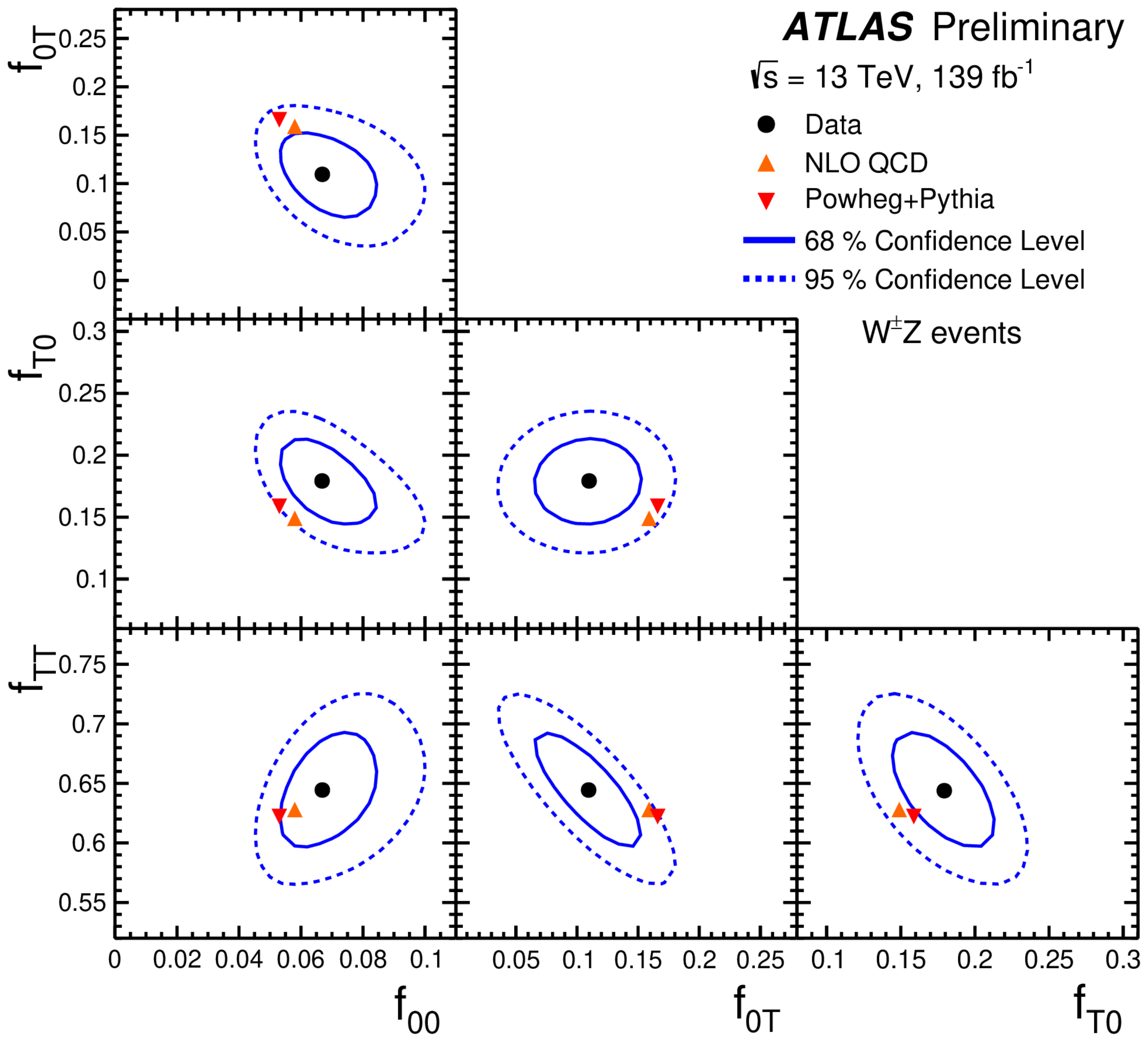
Measurement of vector boson polarisations in diboson inclusive production!

- Measurement of joint polarisation states in inclusive WZ production.
- Observation of longitudinal-longitudinal component at more than **7σ**

$$f_{00} = 0.067 \pm 0.010$$





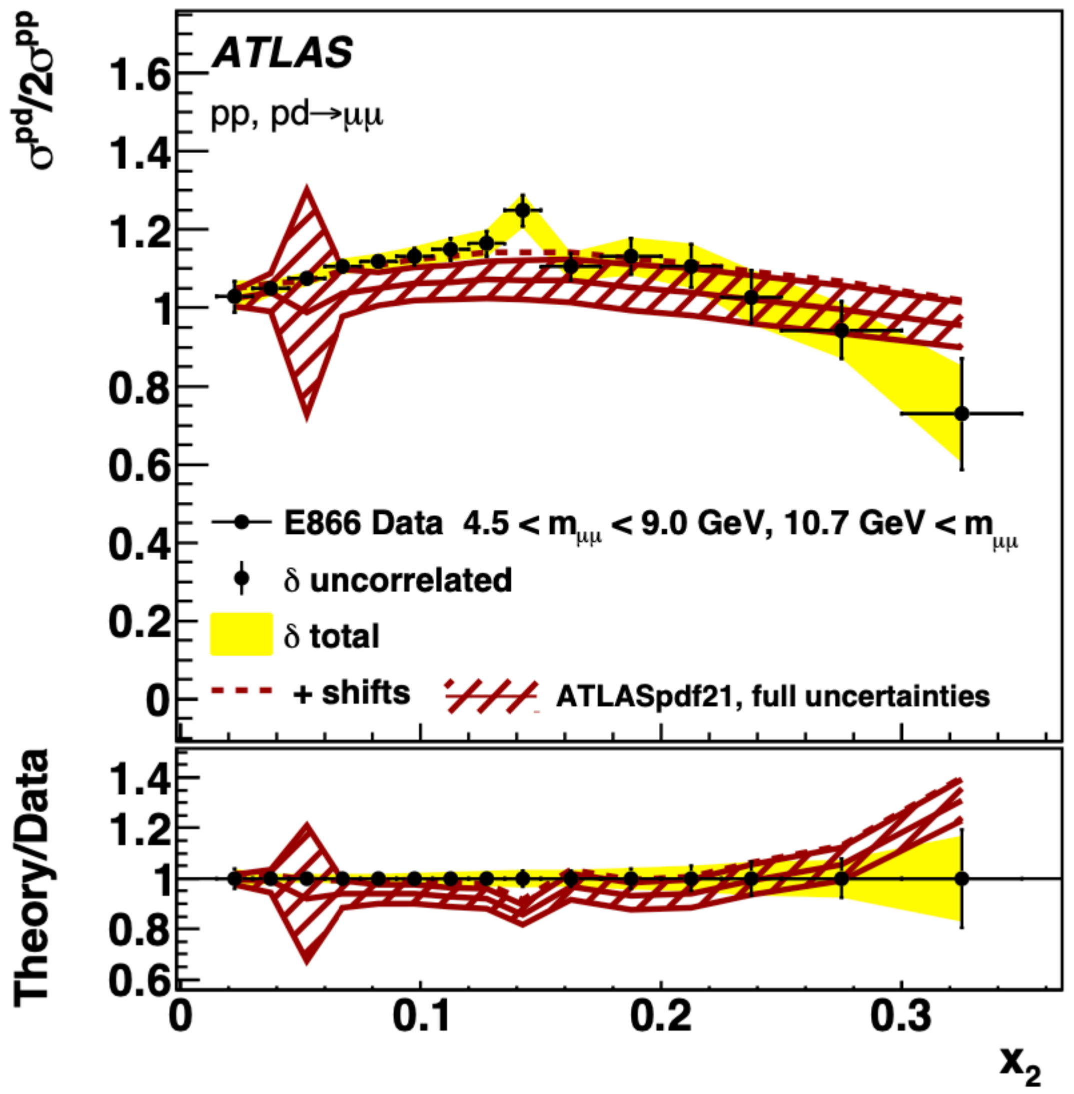


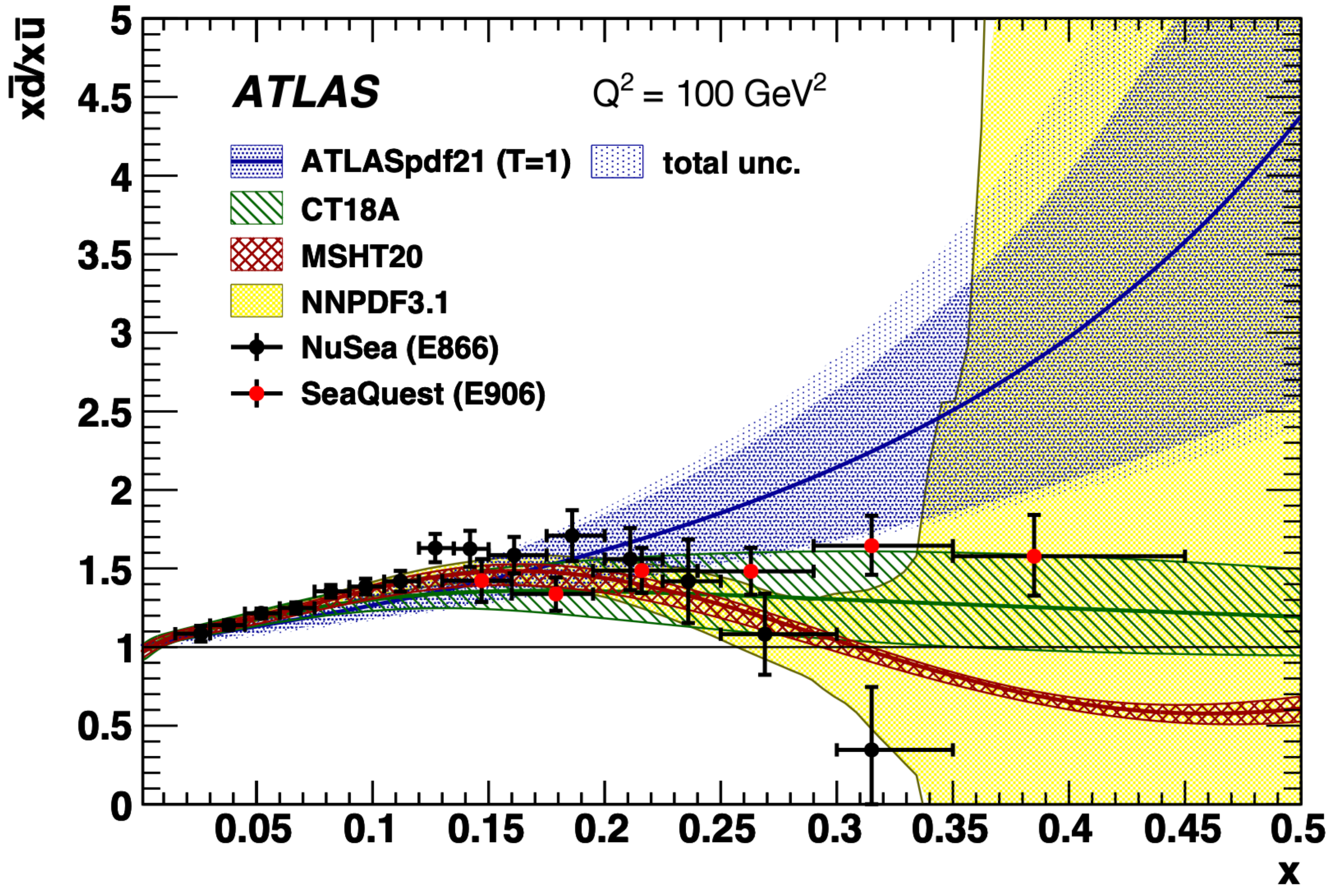
Global PDF Fits

PDF fit (ATLAS)

Using exclusively HERA ep data and ATLAS with the addition of W, Z (+jets), tt, jets, photon differential cross section measurements (fit done at NNLO in QCD, NLO in EW)

Light sea-quark contributions



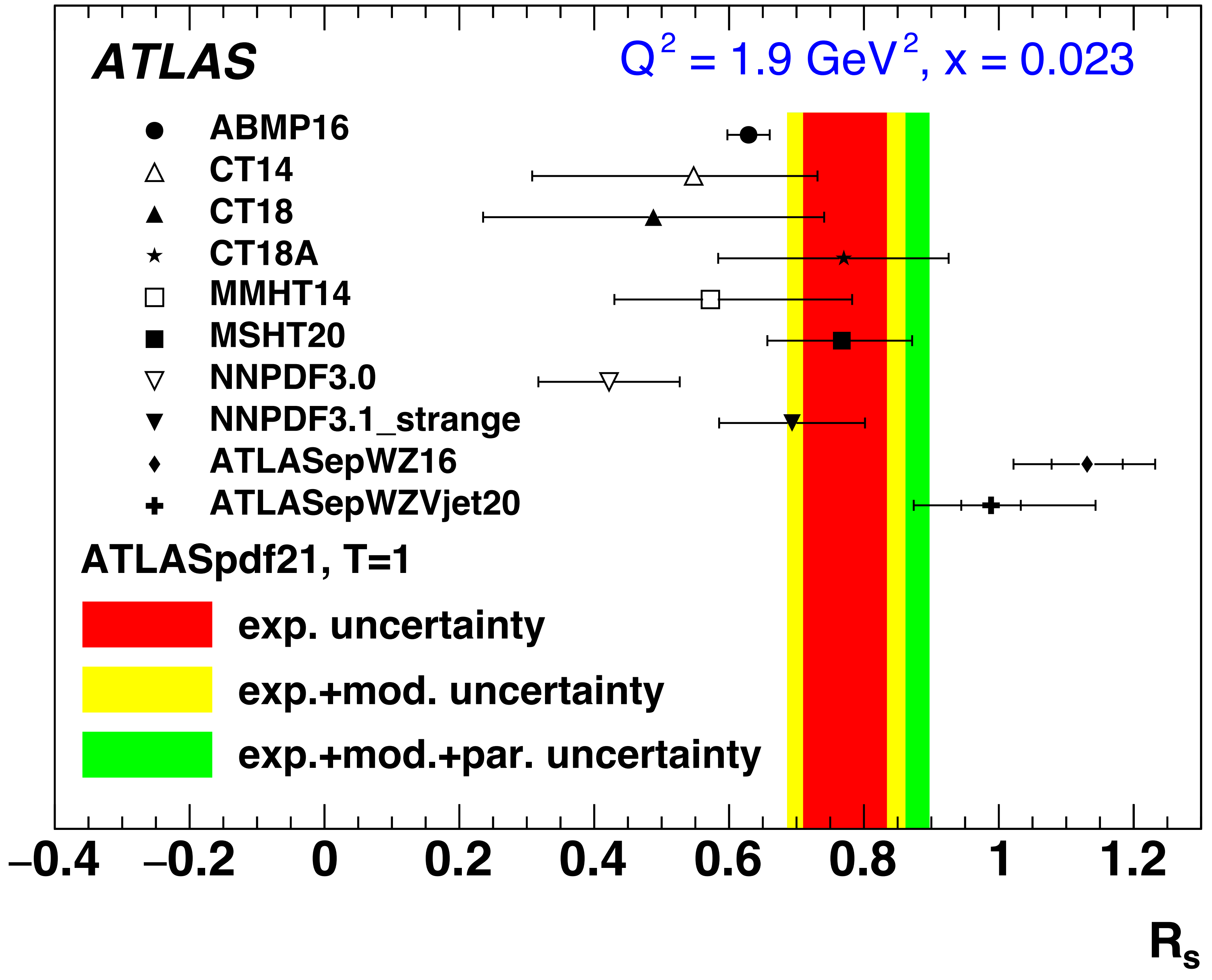


ATLAS data can be used to predict pD fixed target DY cross sections

Check relative densities of $\bar{u}$ and $\bar{d}$ sea contributions compatible with recent SeaQuest data E906 (at high x) rather than with NuSea (E866)

Strange quark composition

$$R_S = \frac{s+\bar{s}}{\bar{d}}$$



Improvement w.r.t. previous ATLAS PDFs

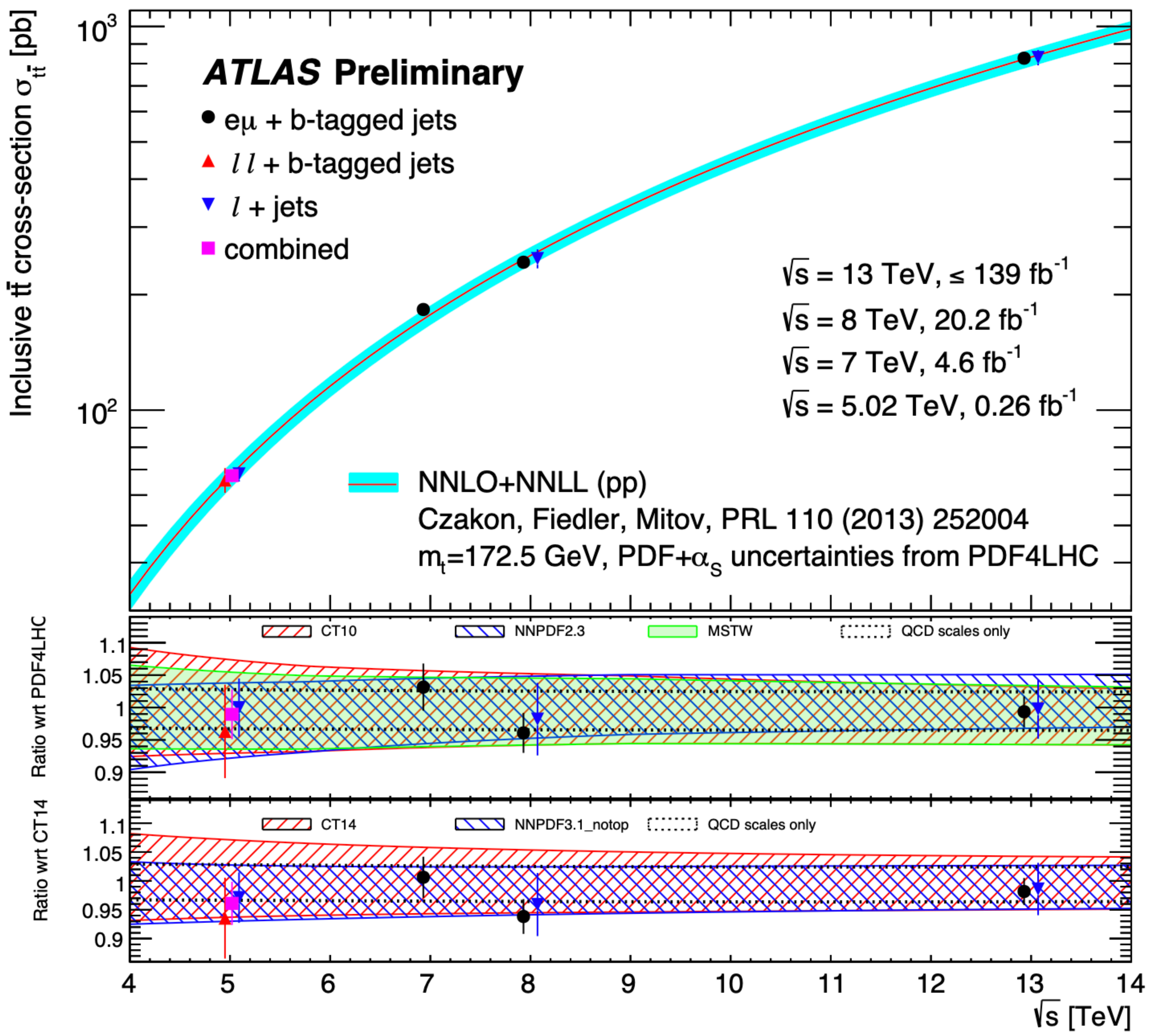
V+jets data suppresses R_s at high x (with effect on low x), as well as improved low-x parametrisation

Top Pair Production at 5.02 TeV

Top pair production cross section measurement at 5.02 TeV

New lepton-jets measurement and combination with earlier di-lepton channel in low PU runs at 5.02 TeV

Excellent precision reached with small dataset of 0.26 fb^{-1}

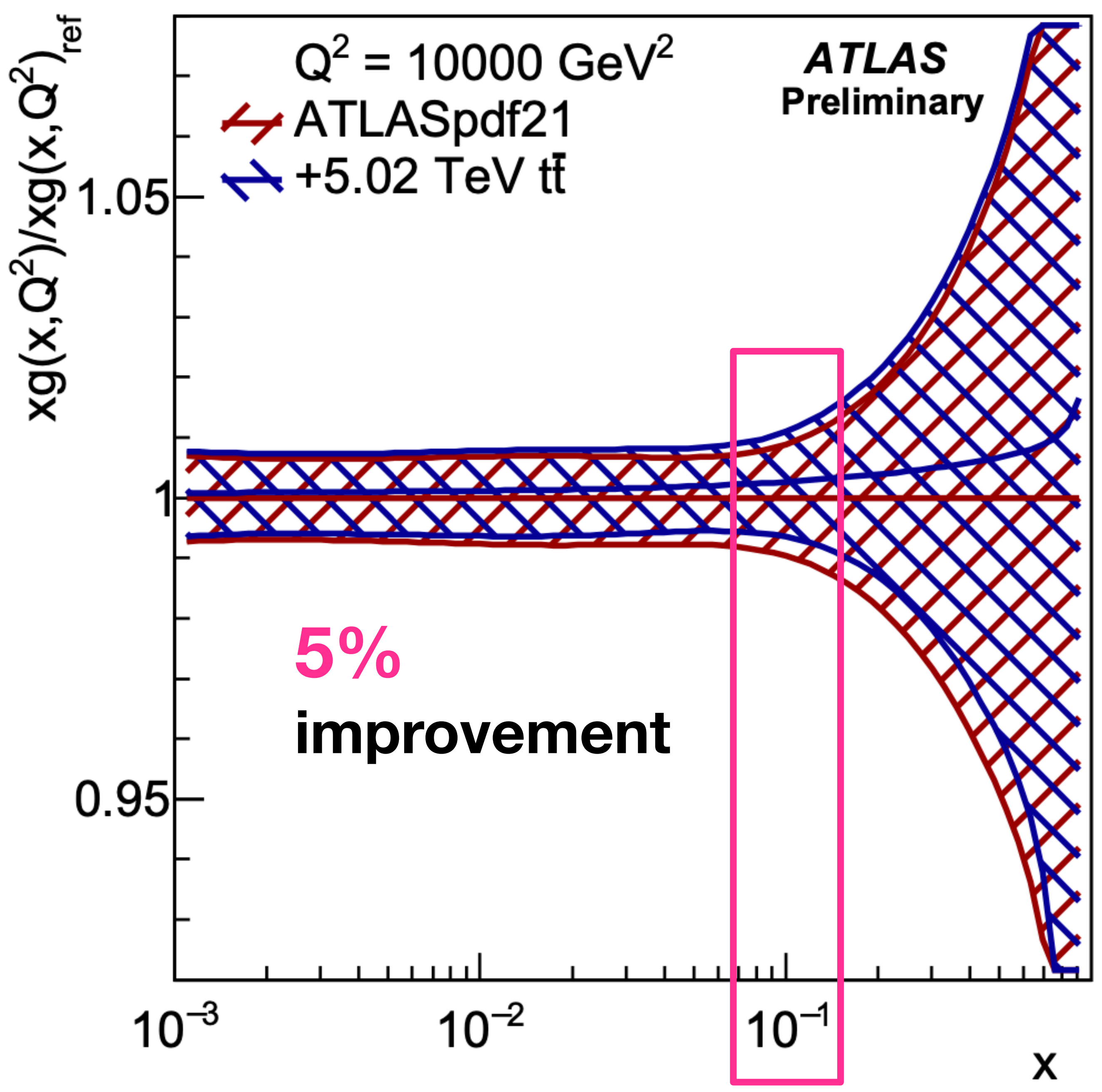


$$\sigma_{t\bar{t}} = 67.5 \pm 0.9\,(\text{stat.}) \pm 2.3\,(\text{syst.}) \pm 1.1\,(\text{lumi.}) \pm 0.2\,(\text{beam})\ \text{pb}$$

In excellent agreement with the NNLO-NNLL TOP++ prediction

$$68.2 \pm 4.8^{+1.9}_{-2.3}\ \text{pb}$$

Gluon PDF



Important feedback to improve Higgs precision measurements

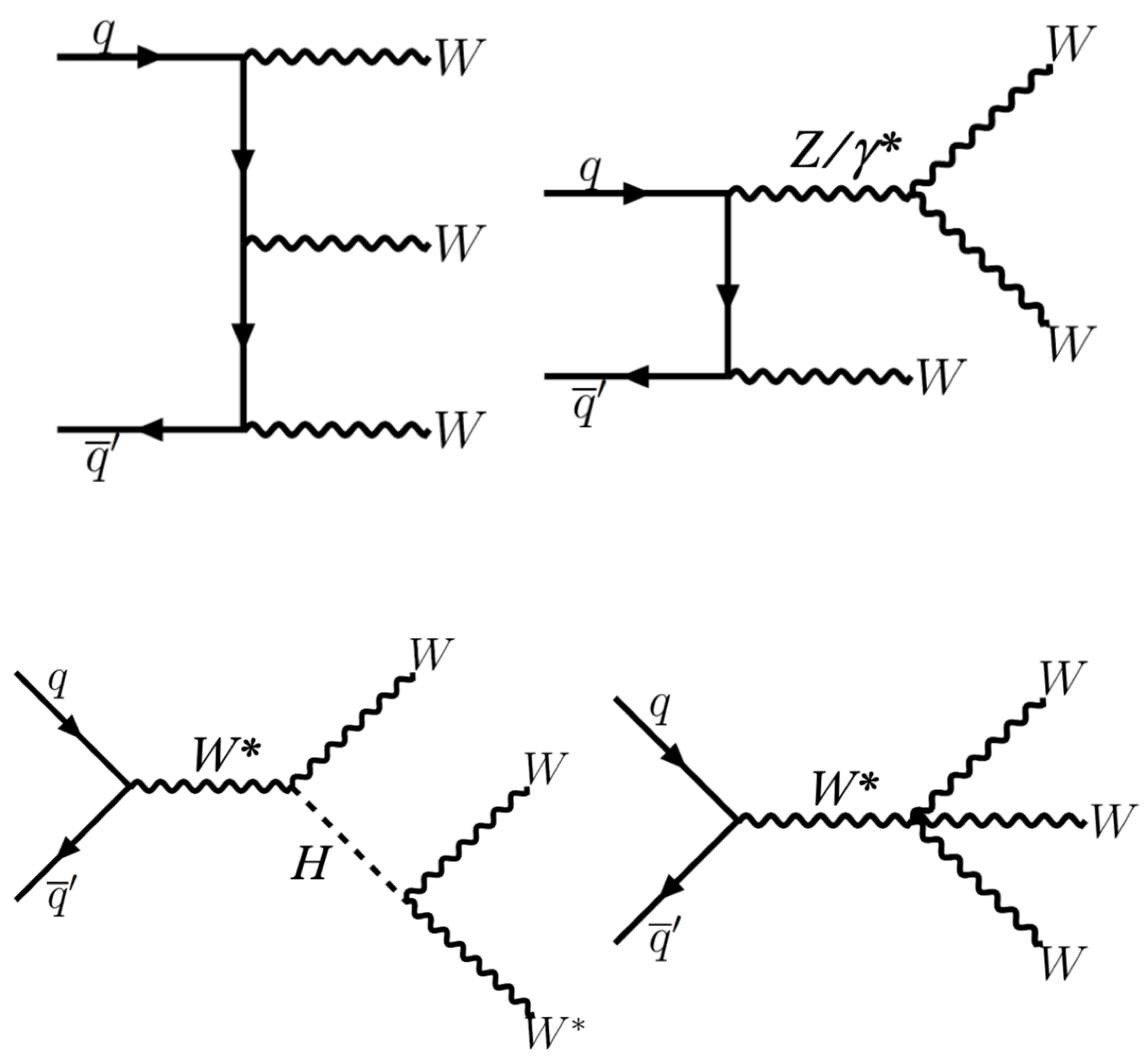
Multi-boson and Single top in Backup

e.g. tri-boson WWW observation

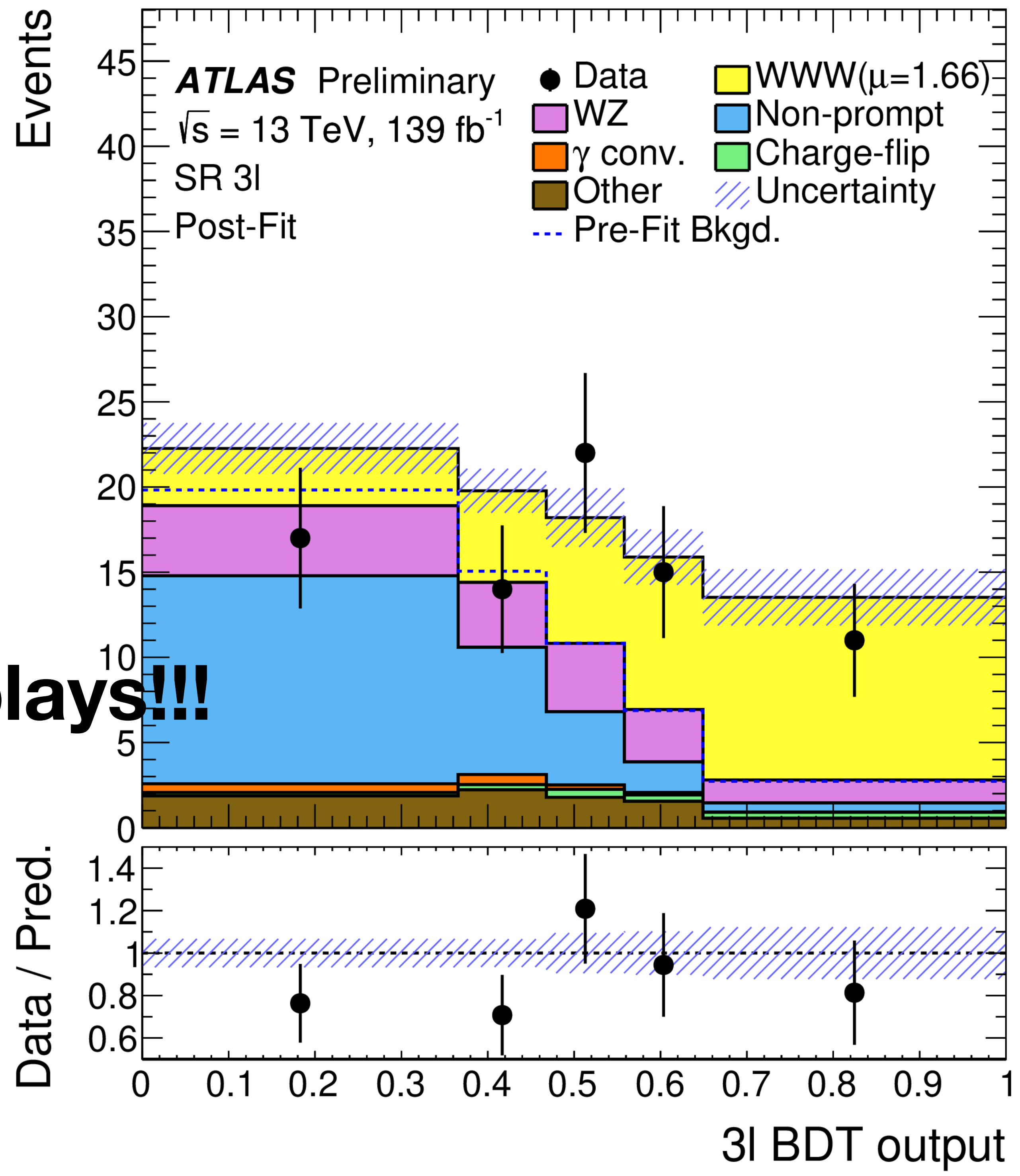
Boosted $ee\mu$ candidate event

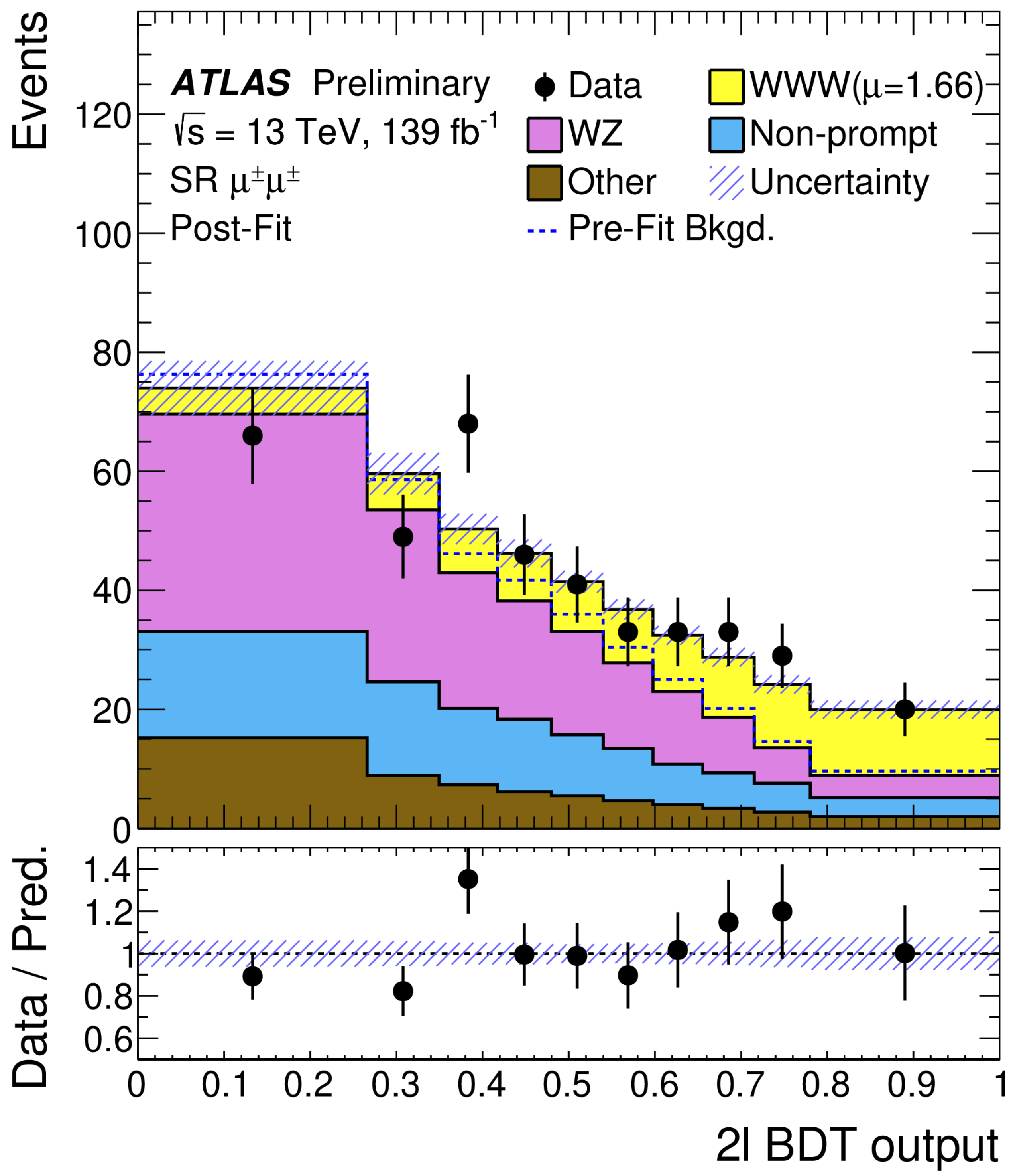
Triboson $W^{\pm}W^{\mp}W^{\mp}$ observation

Search for three W bosons production



Only Event Displays!!!





Same sign 2-lepton channel

$\ell^{\pm}\nu\ell^{\pm}\nu jj$

3-lepton channel

$\ell^{\pm}\ell^{\pm}jj$

First observation of $W^{\pm}W^{\mp}W^{\mp}$ at **8.2σ** (5.4σ expected)!

Measured cross section:

$$\sigma(pp \to WWW) = 820 \pm 100\,(\text{stat.}) \pm 80\,(\text{syst.})\ \text{fb}$$

Predictions:

511 ± 18 fb

$pp \to W^+W^-W^-$ $\quad 76\,^{+4}_{-3}\,(\text{scale}) \pm 2\,(\text{PDF})$ fb

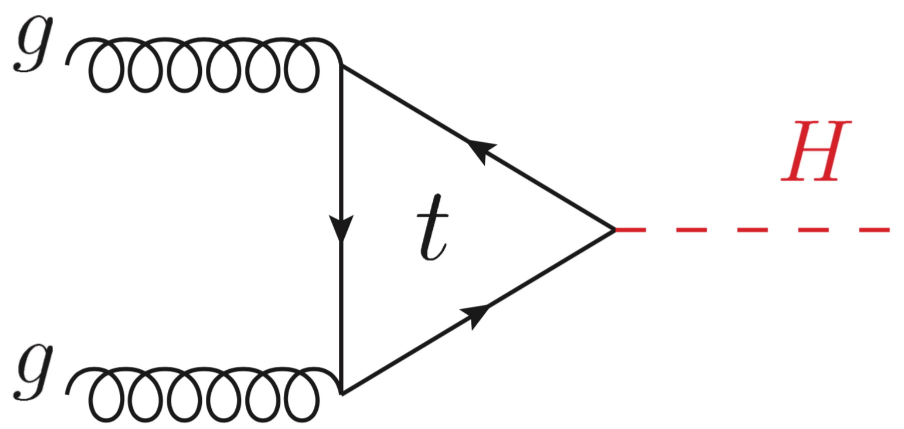
$pp \to W^-W^+W^+$ $\quad 136\,^{+6}_{-5}\,(\text{scale}) \pm 4\,(\text{PDF})$ fb

$pp \to WH \to WWW^*$ $\quad 293\,^{+1}_{-2}\,(\text{scale})\,^{+6}_{-5}\,(\text{PDF}) \pm 3\,(\alpha_s)$ fb

Compatibility 2.6σ

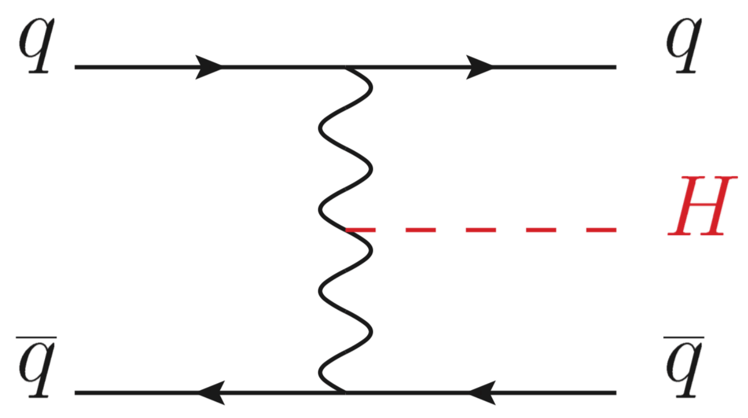
Signatures of the Higgs Boson

Production rates at Run 2 (13 TeV) for ~150 fb^{-1}



Gluon fusion process

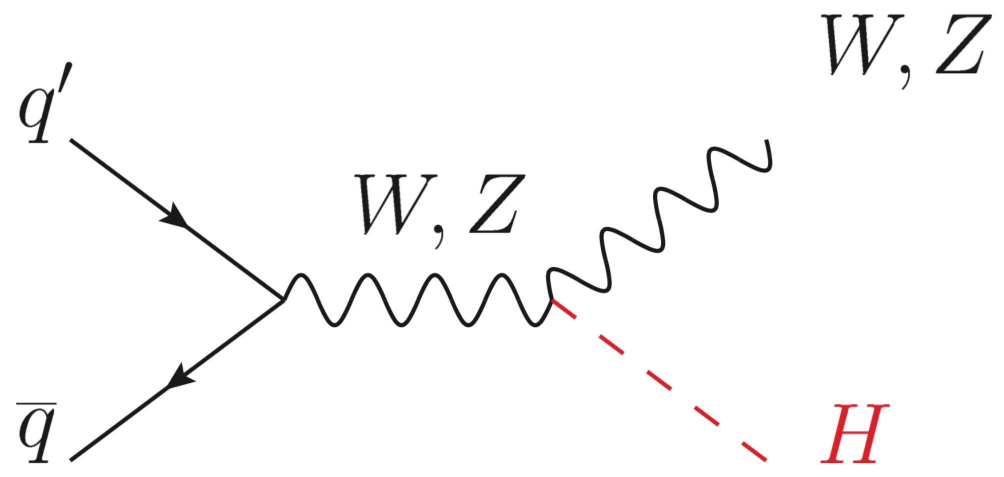
~8 M events produced



Vector Boson Fusion

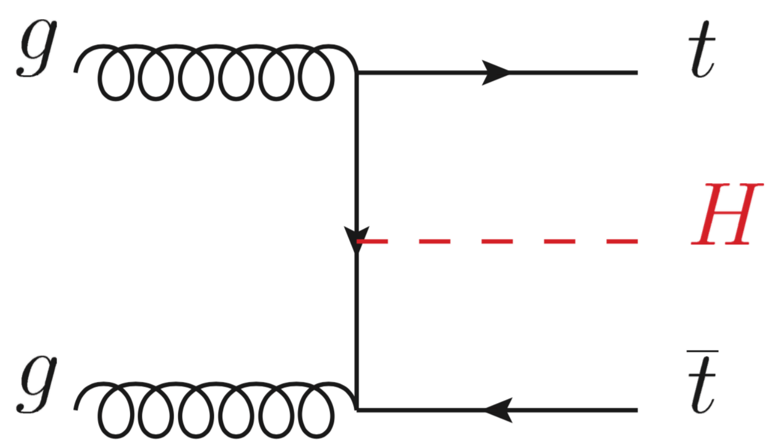
Two forward jets and a large rapidity gap

~600 k events produced



W and Z Associated Production

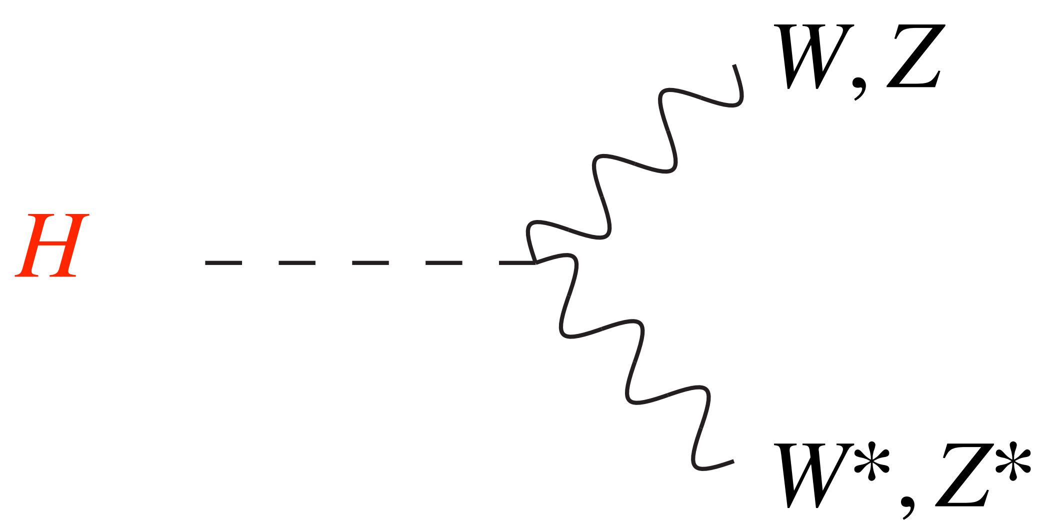
~400 k events produced



Top Assoc. Prod.

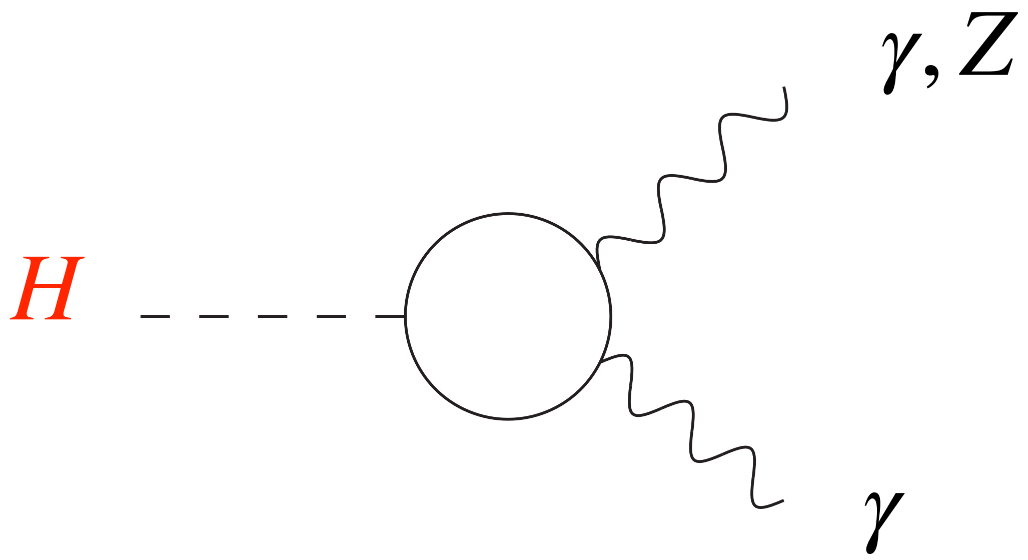
~80 k evts produced

Decay branching fractions



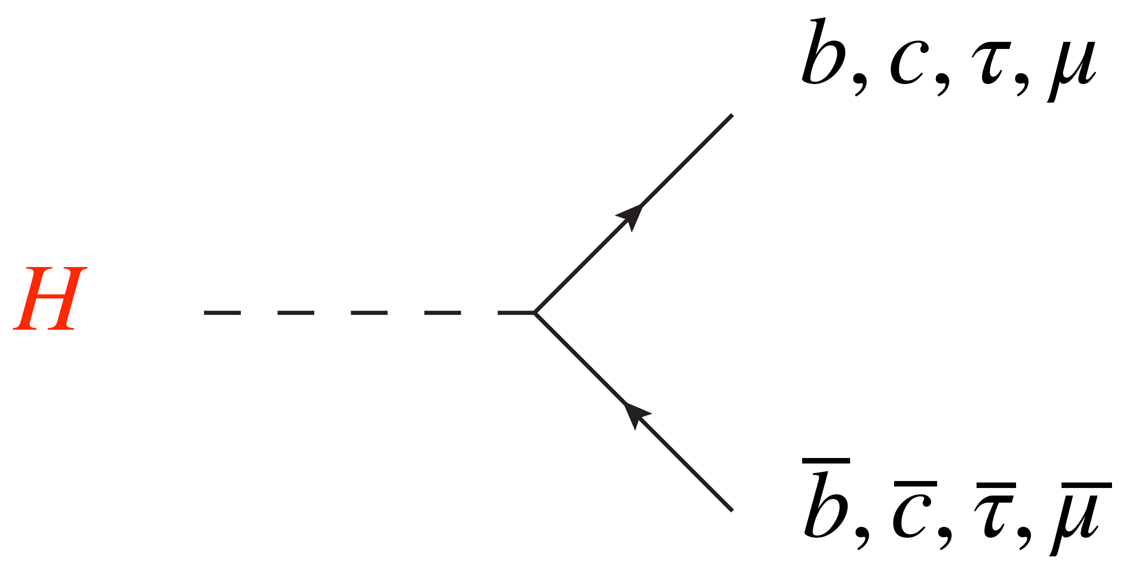
$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$



$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

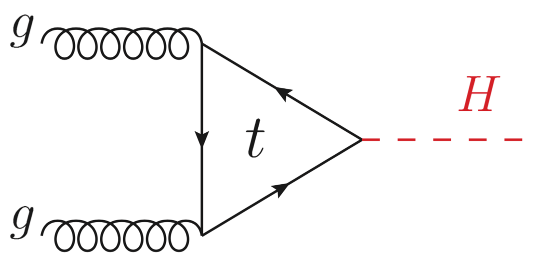
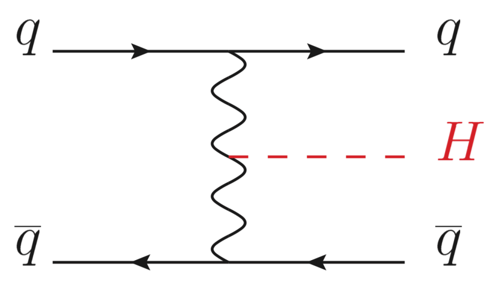
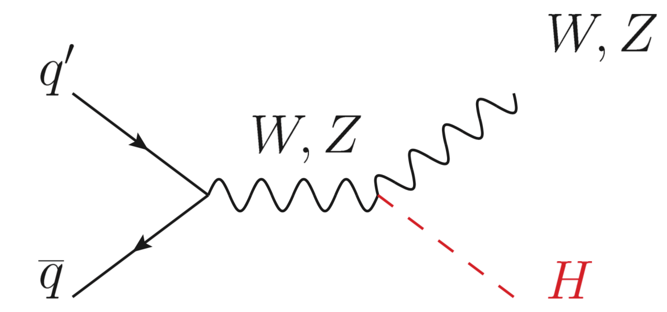
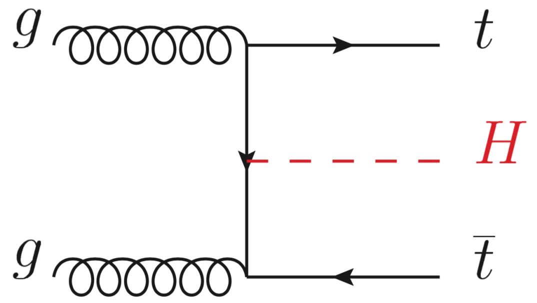
$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

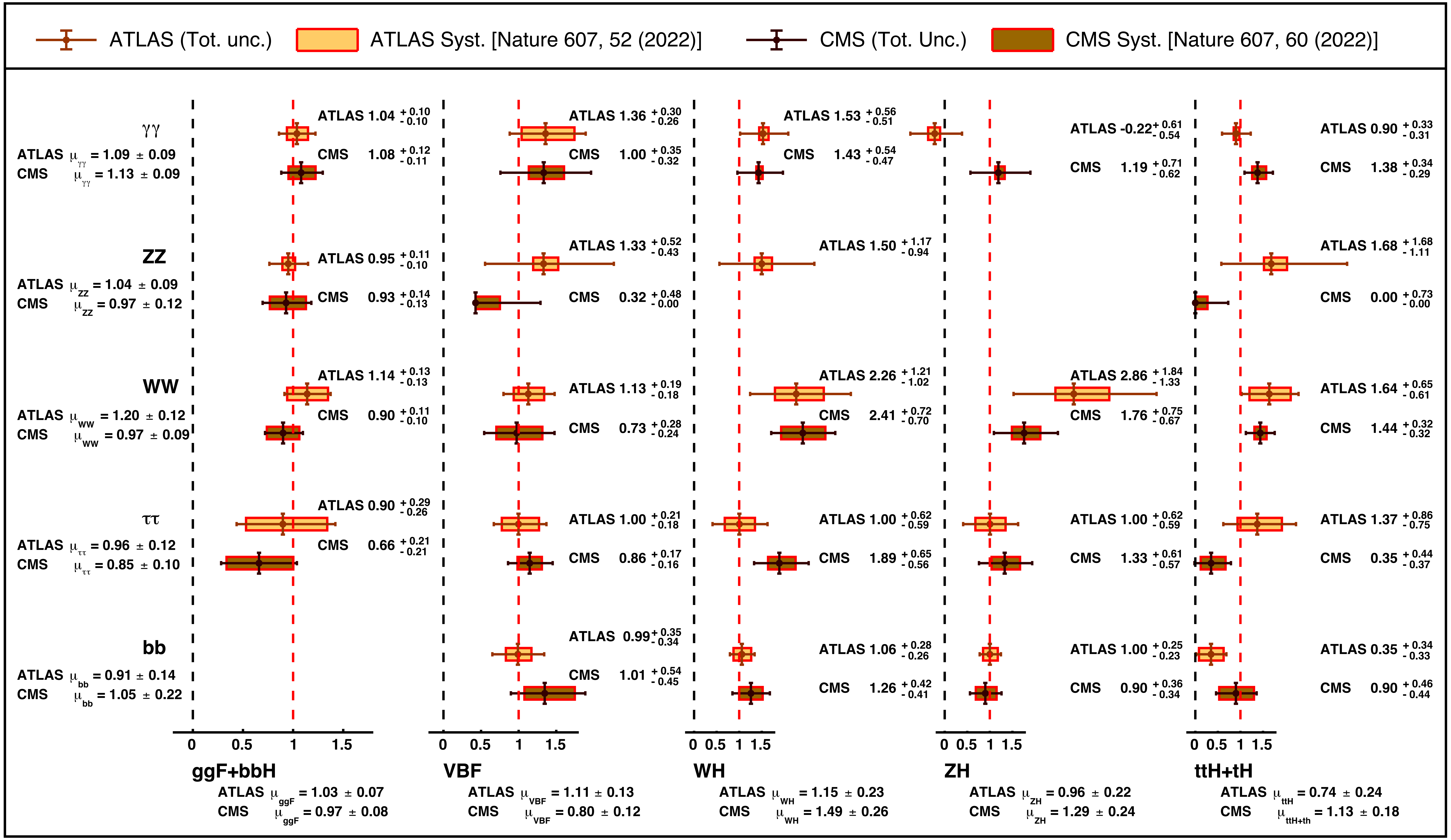
Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the Run 2 with only 5% (~150 fb-1) of full HL-LHC dataset!

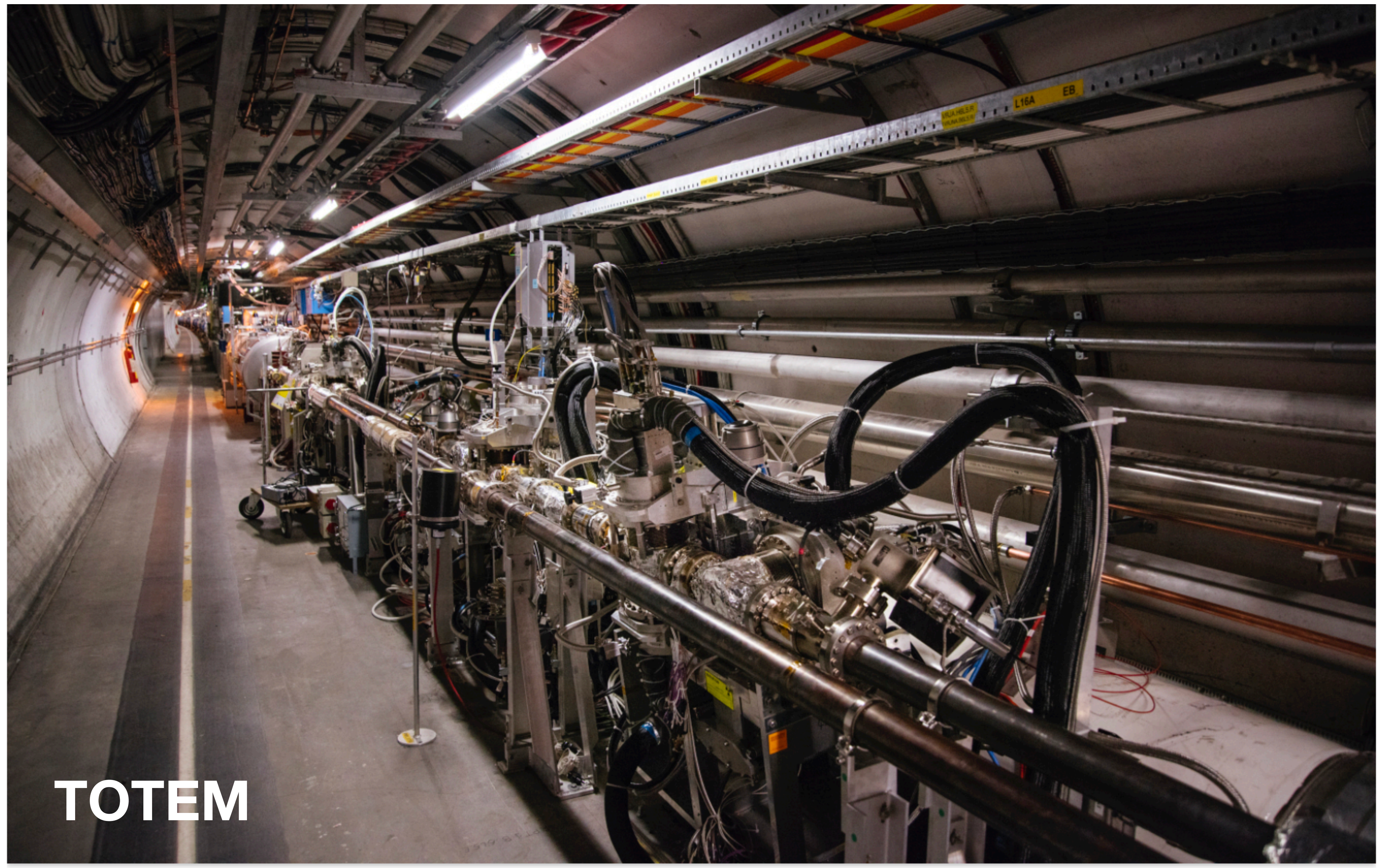
	Channel categories	Br	ggF  ~8 M vets produced	VBF  ~600 k vets produced	VH  ~400 k vets produced	ttH  ~80 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

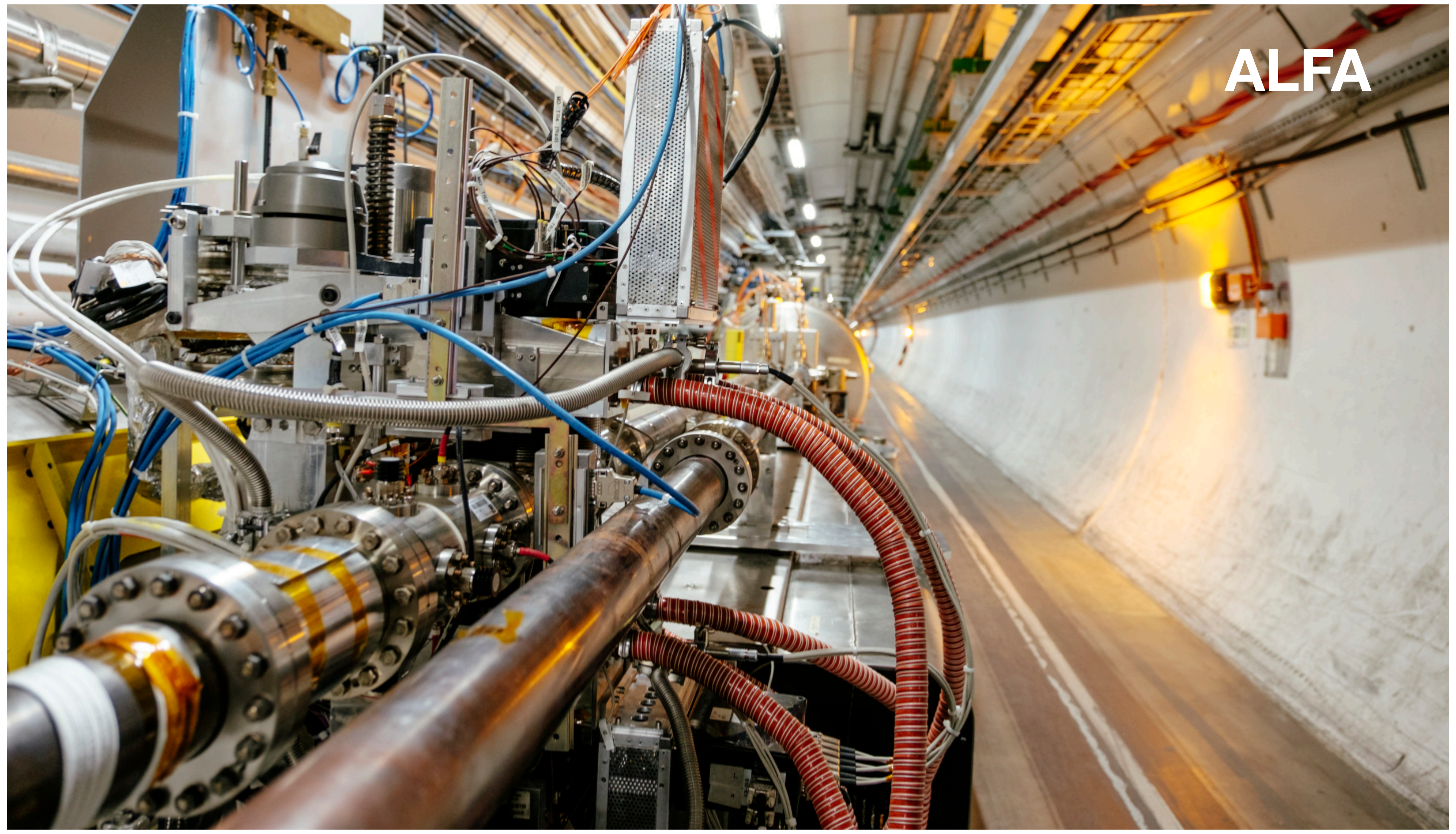
*N3LO

Very broad overview!



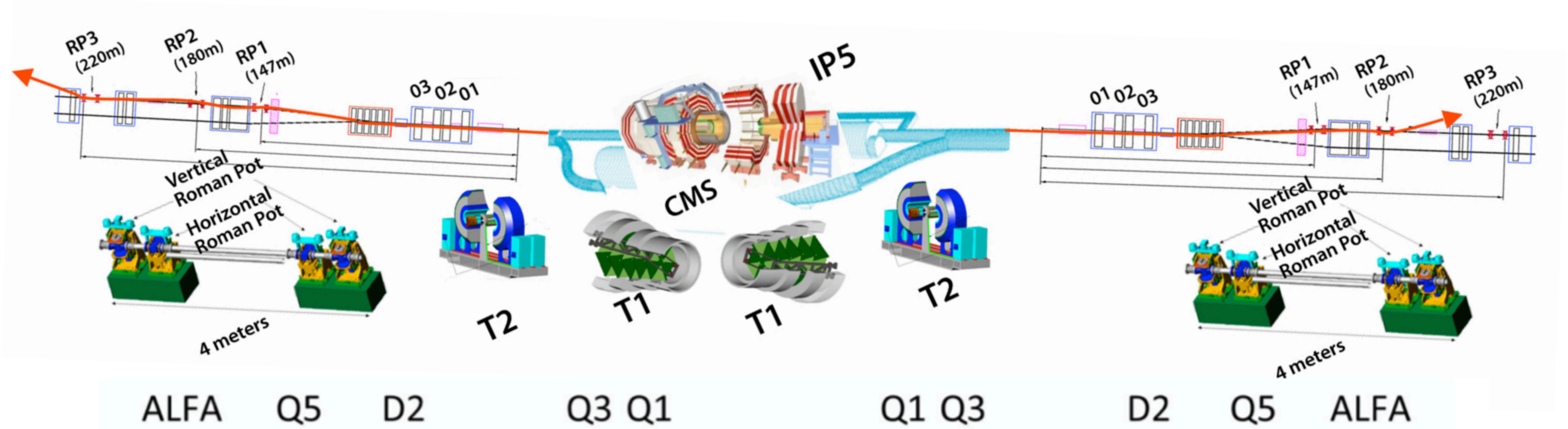
De-Squeezed Beams Measurements



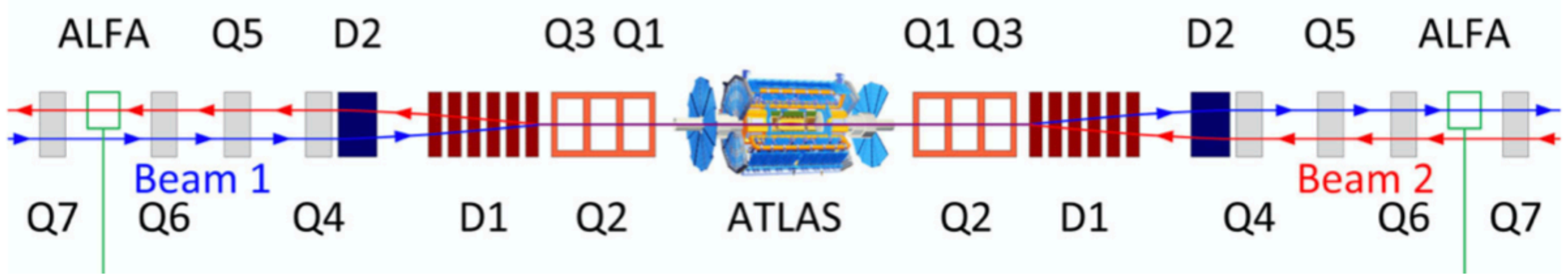


Measuring the elastic, total and Inelastic cross sections and more!

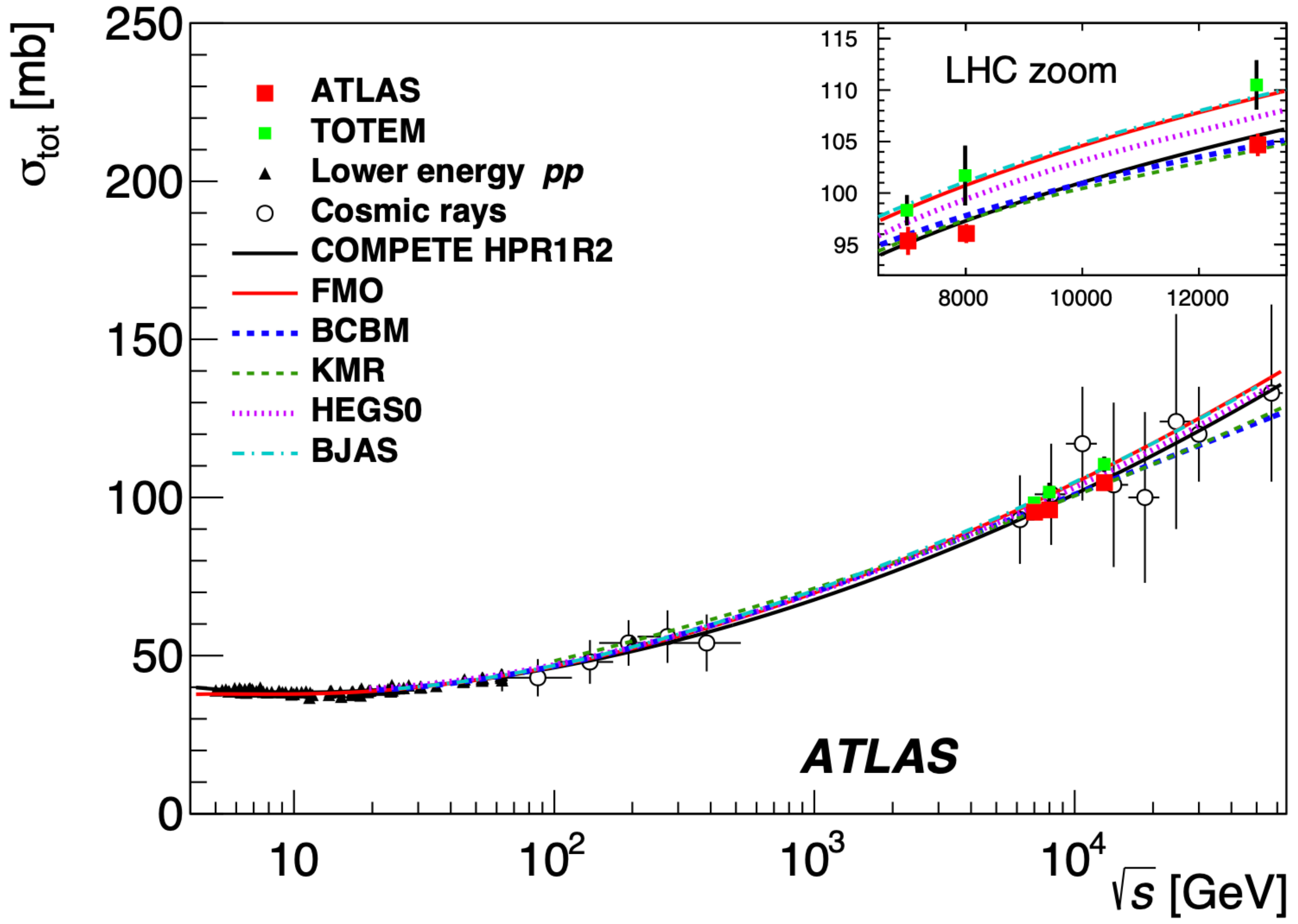
TOTEM



ALFA



Very special optics runs with beta* 2.5 km!



Use Opt. Theorem and simult. fit of total cross section and rho.

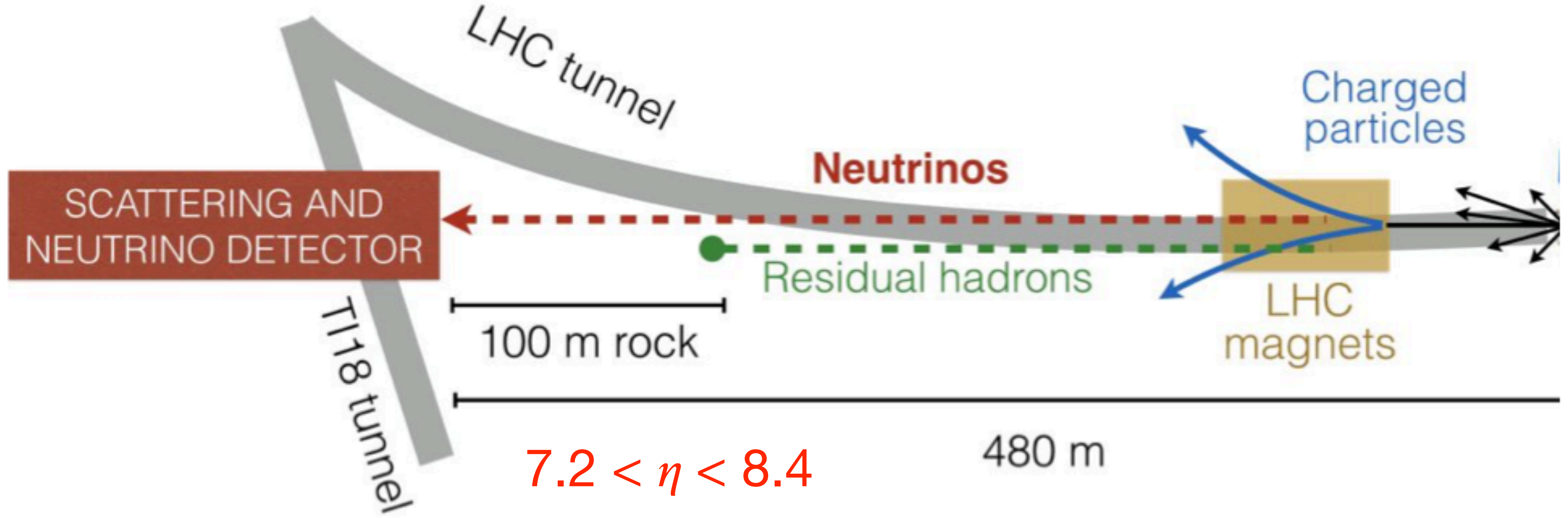
$$\rho = \frac{Re f_N(0)}{Im f_N(0)}$$

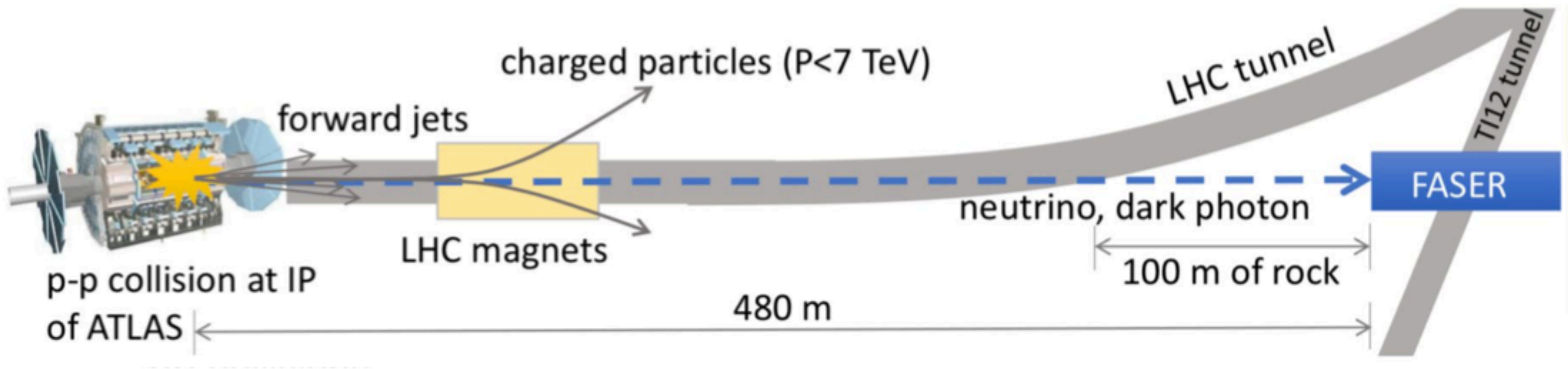
ρ = 0.098 ± 0.011

Smaller than predicted result indicates Odderon exchange or a slowdown of total cross section at high √s.

Forward detectors (TOTEM and AFP) also used for exclusive processes

The birth of Collider Neutrinos (at the LHC)





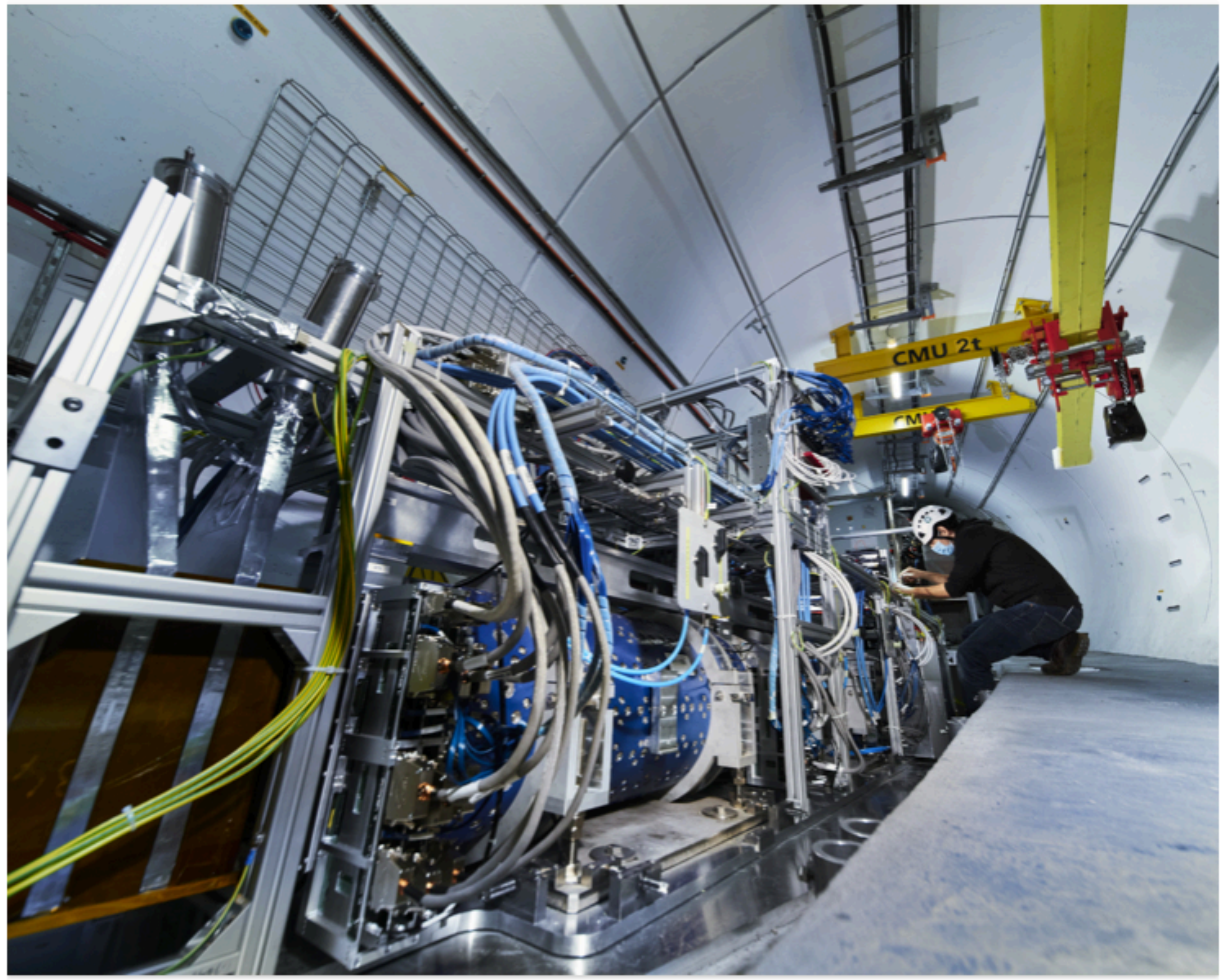
$7.2 < \eta < 8.4$

Off axis In TI18 unused LEP transfer tunnel

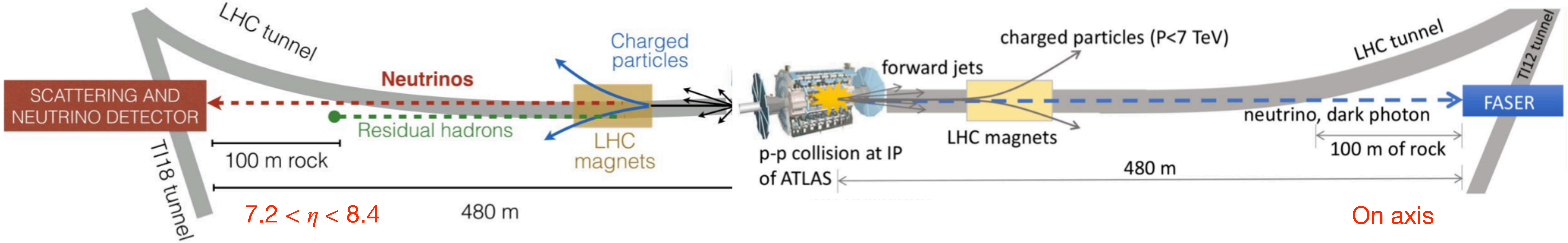
On axis In TI12 SPS - LHC transfer tunnel

SND

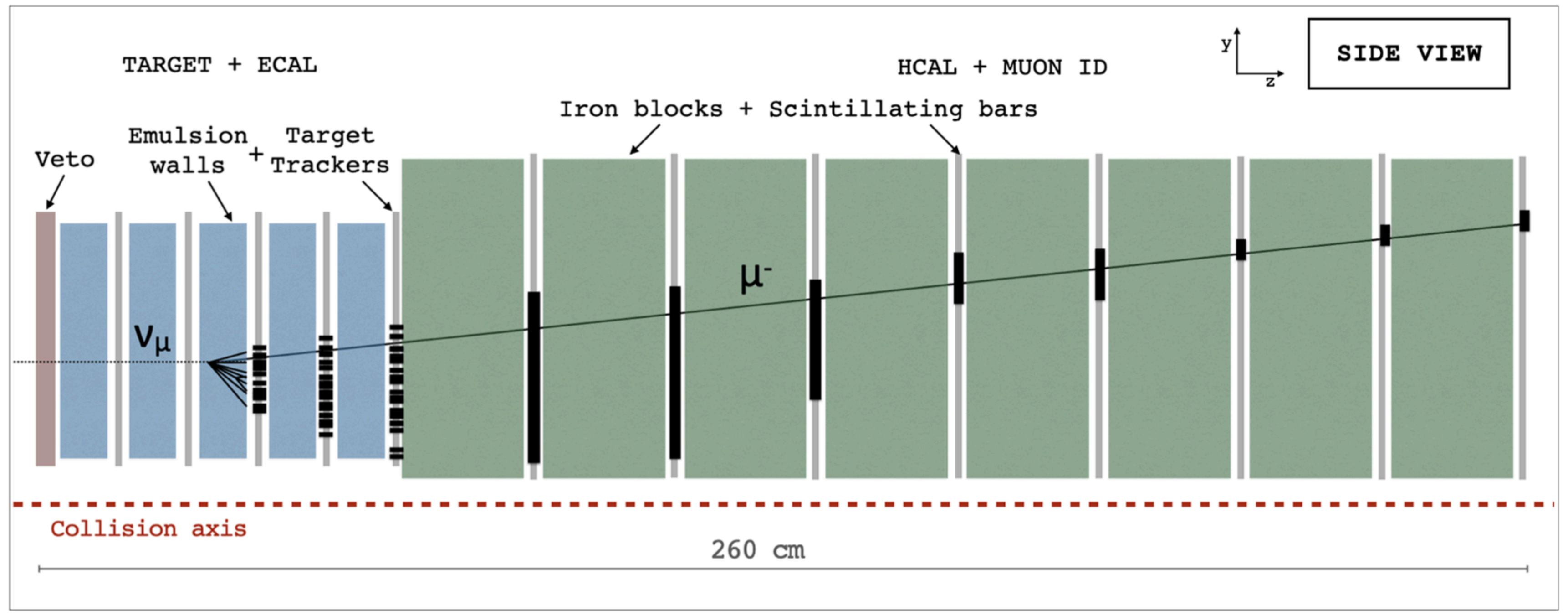
Faser-ν

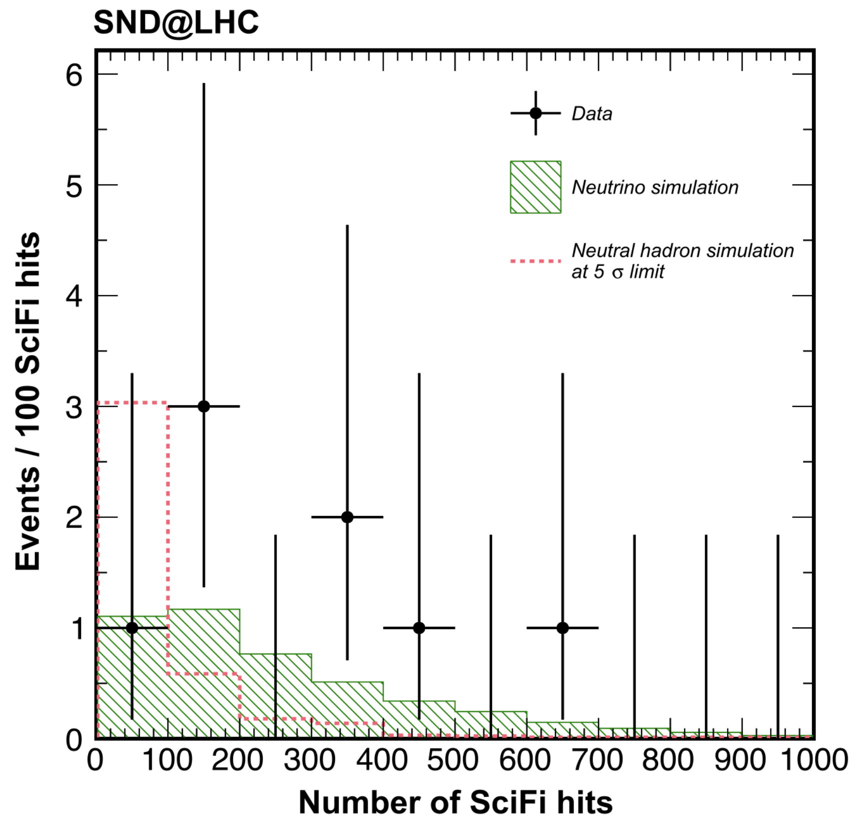


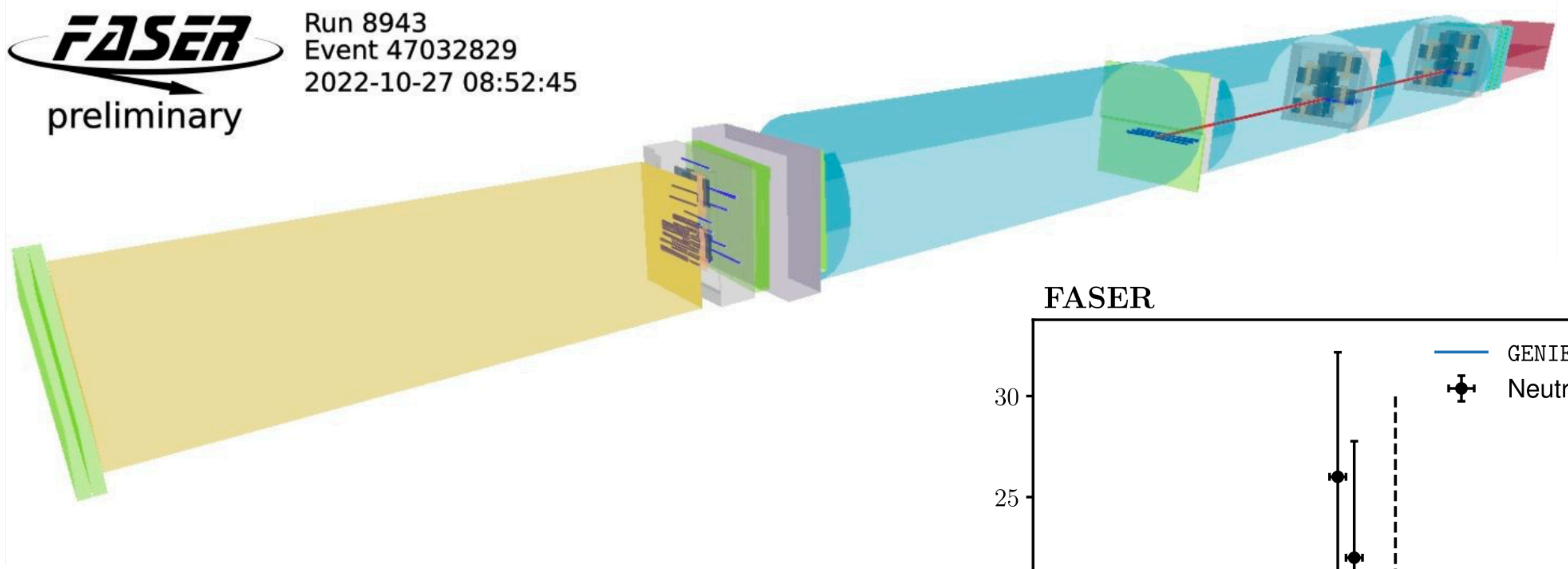
The birth of Collider Neutrinos (at the LHC)

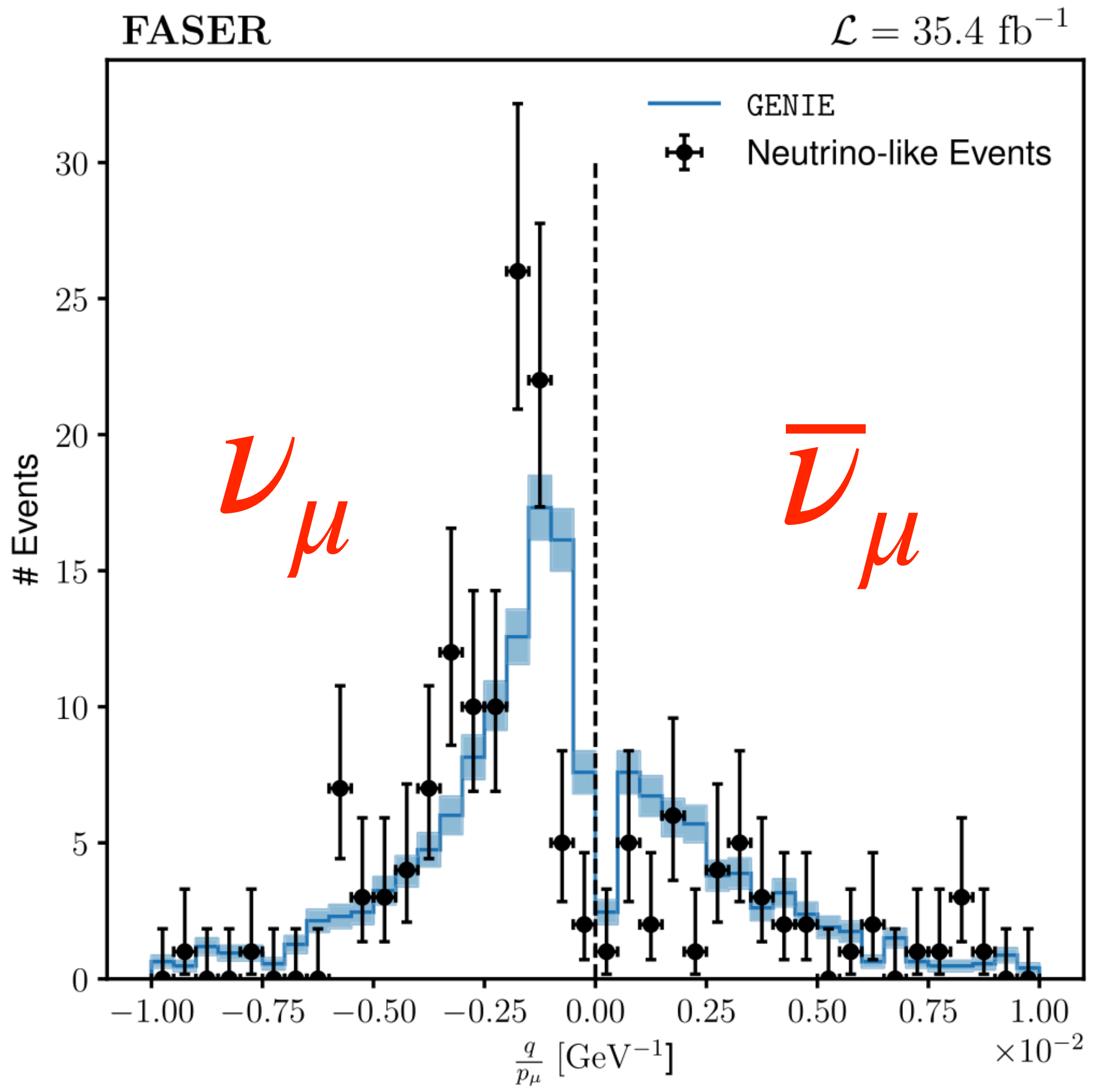


SND **First results from SciFi/Silicon tracking devices** **Faser-ν**









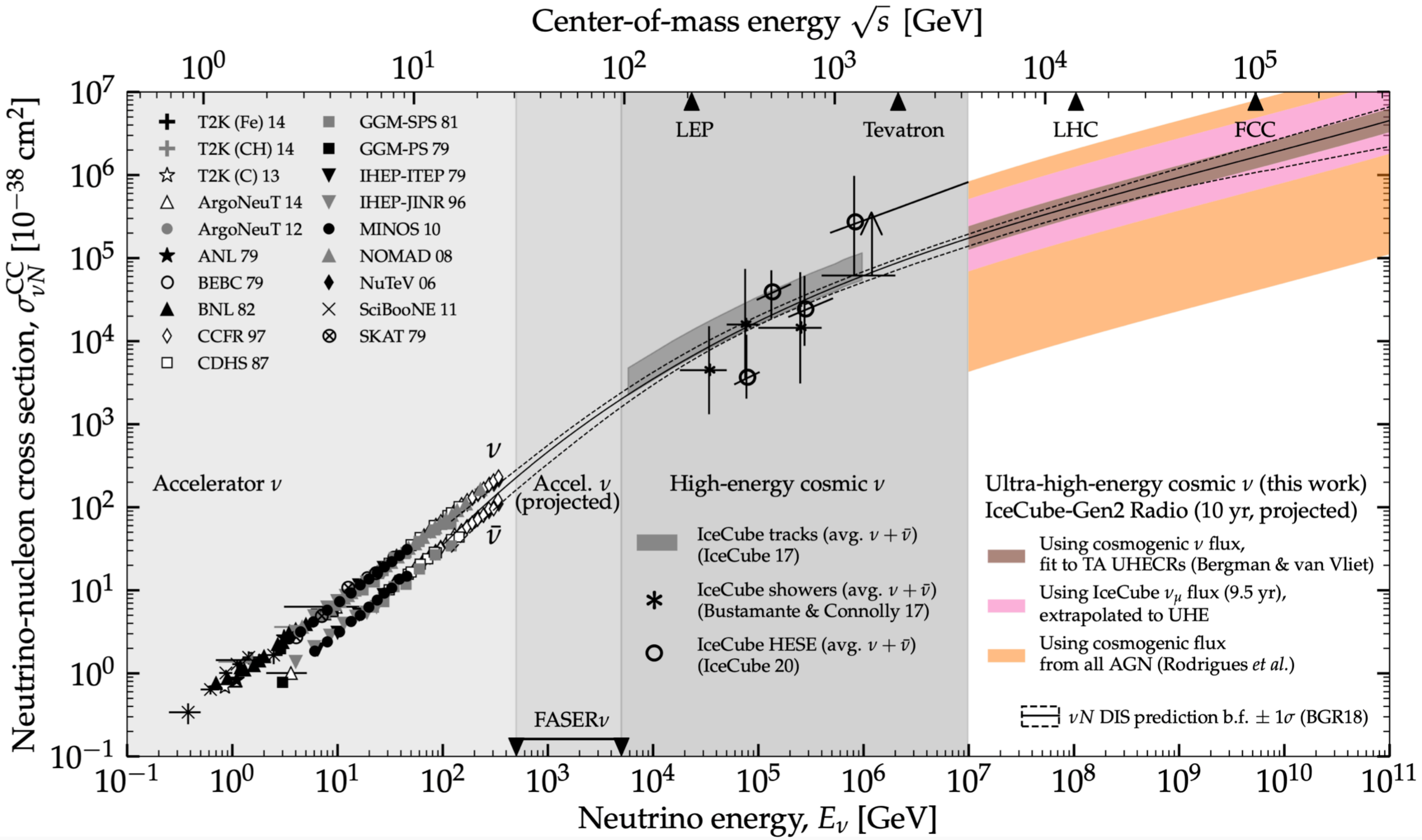
5 events expected and 8 observed (0.1 background)

6.8σ observation!

150 events expected and 153 observed (0.2 background!!)

16σ observation!

Filling the Gap Between Accelerator and Cosmic Neutrinos



Accelerator neutrinos, up to O(100 GeV)

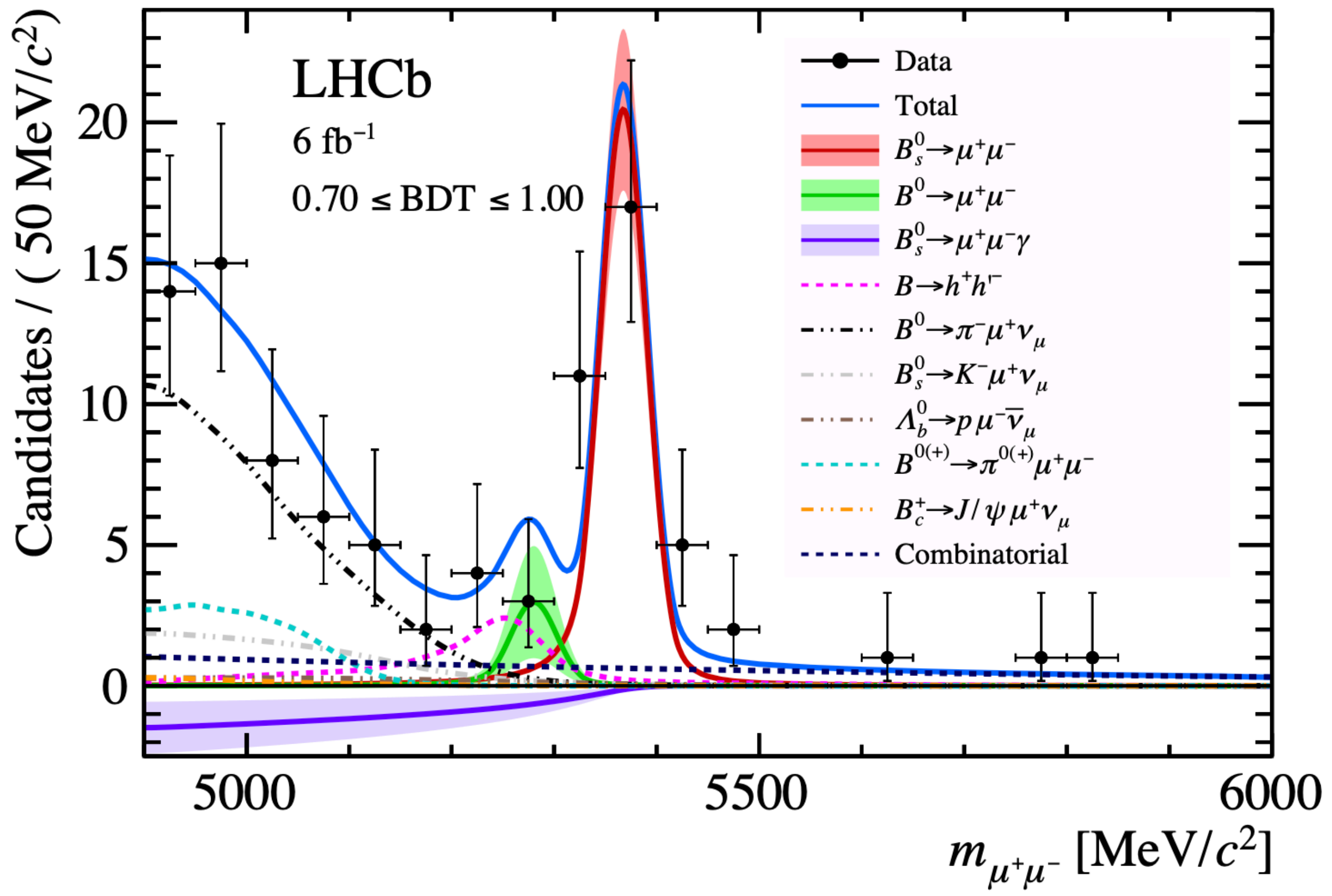
Cosmic neutrinos

Rare Decays

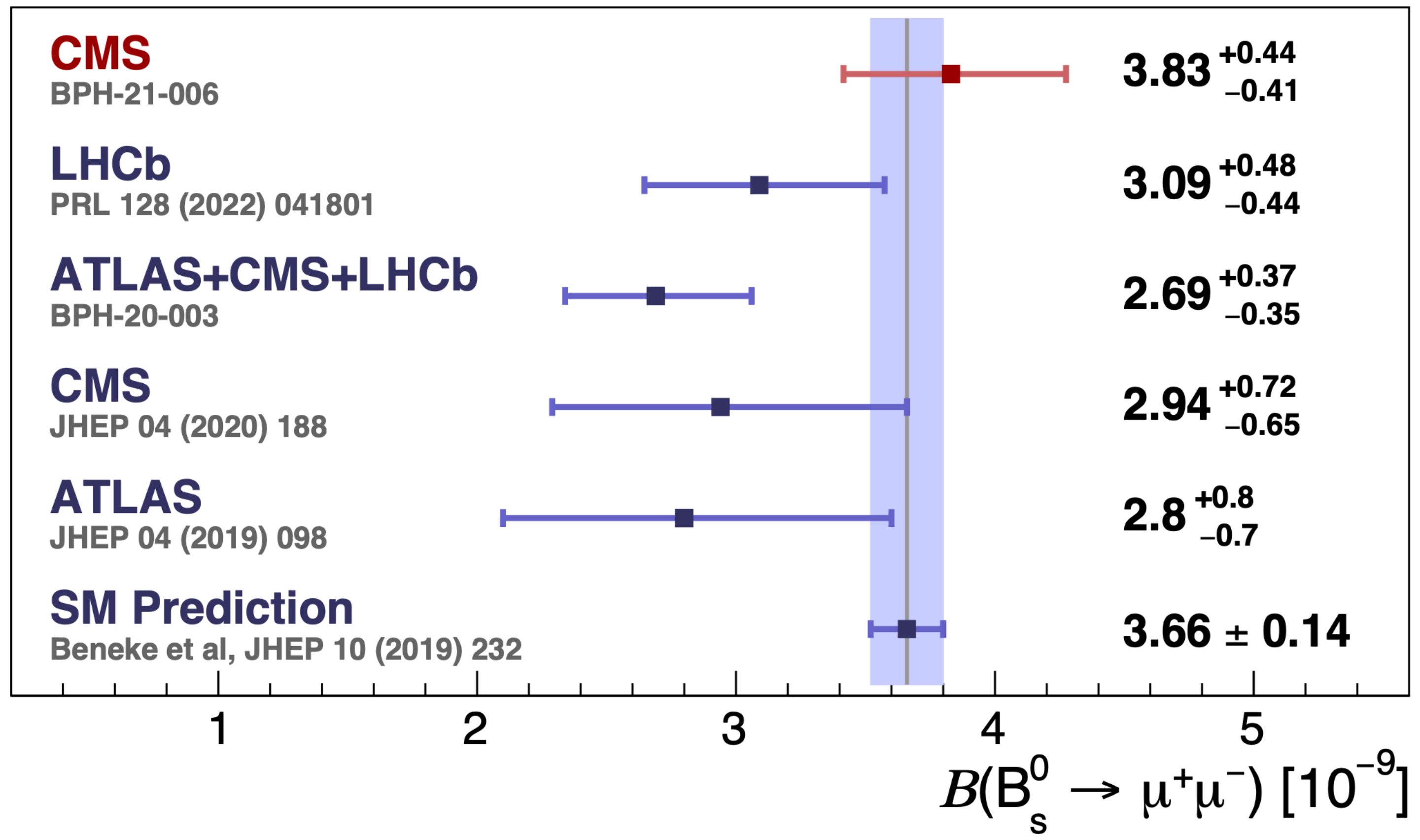
Very rare **Landmark** **FCNC and helicity suppressed $B_s \to \mu^+\mu^-$ decay!**

10^{-9}

Very sensitive to new physics!

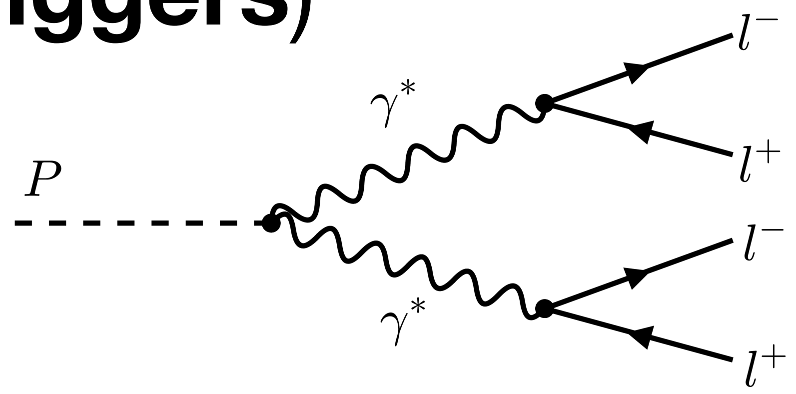


From D. Kovalskyi ICHEP tals



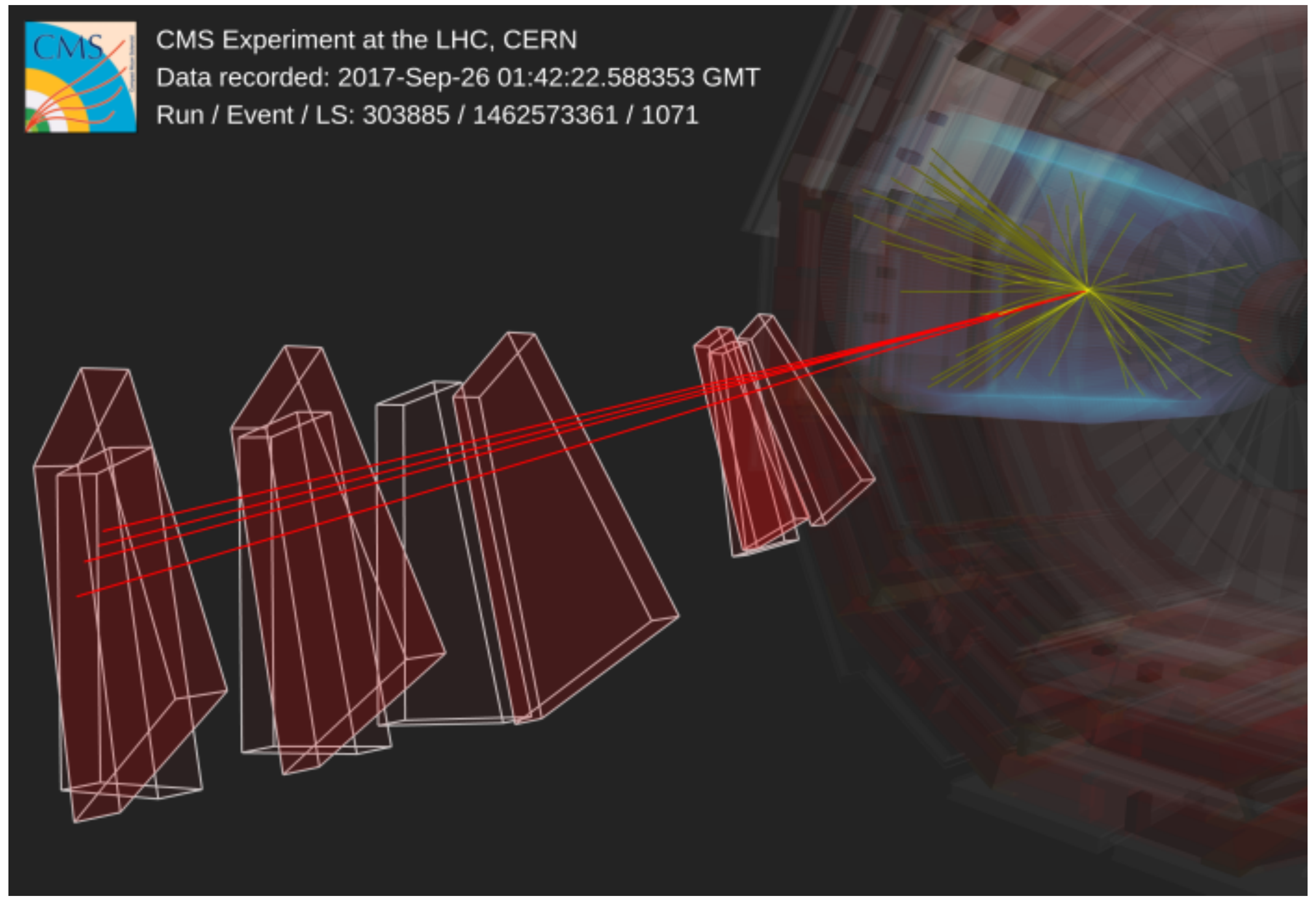
Observation of $\eta \to 4\mu$ narrow resonance Mass of **548 MeV** (using high rate **low threshold triggers**)

$$\eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

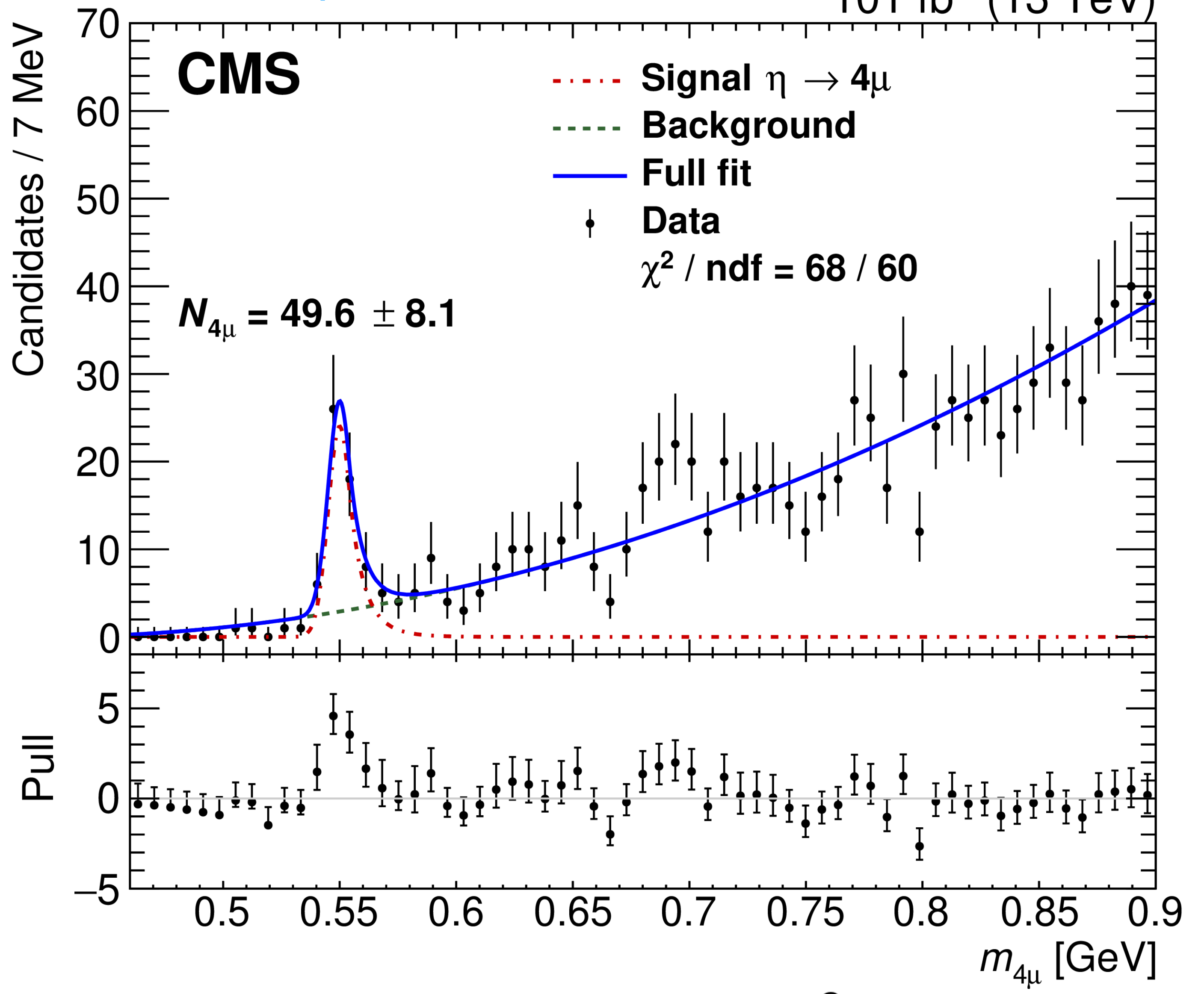


10^{-9}

CMS Briefing



CMS Paper



$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B})) \times 10^{-9}$$

In agreement with SM: $(3.98 \pm 0.15) \times 10^{-9}$

Impressive reconstruction capabilities!

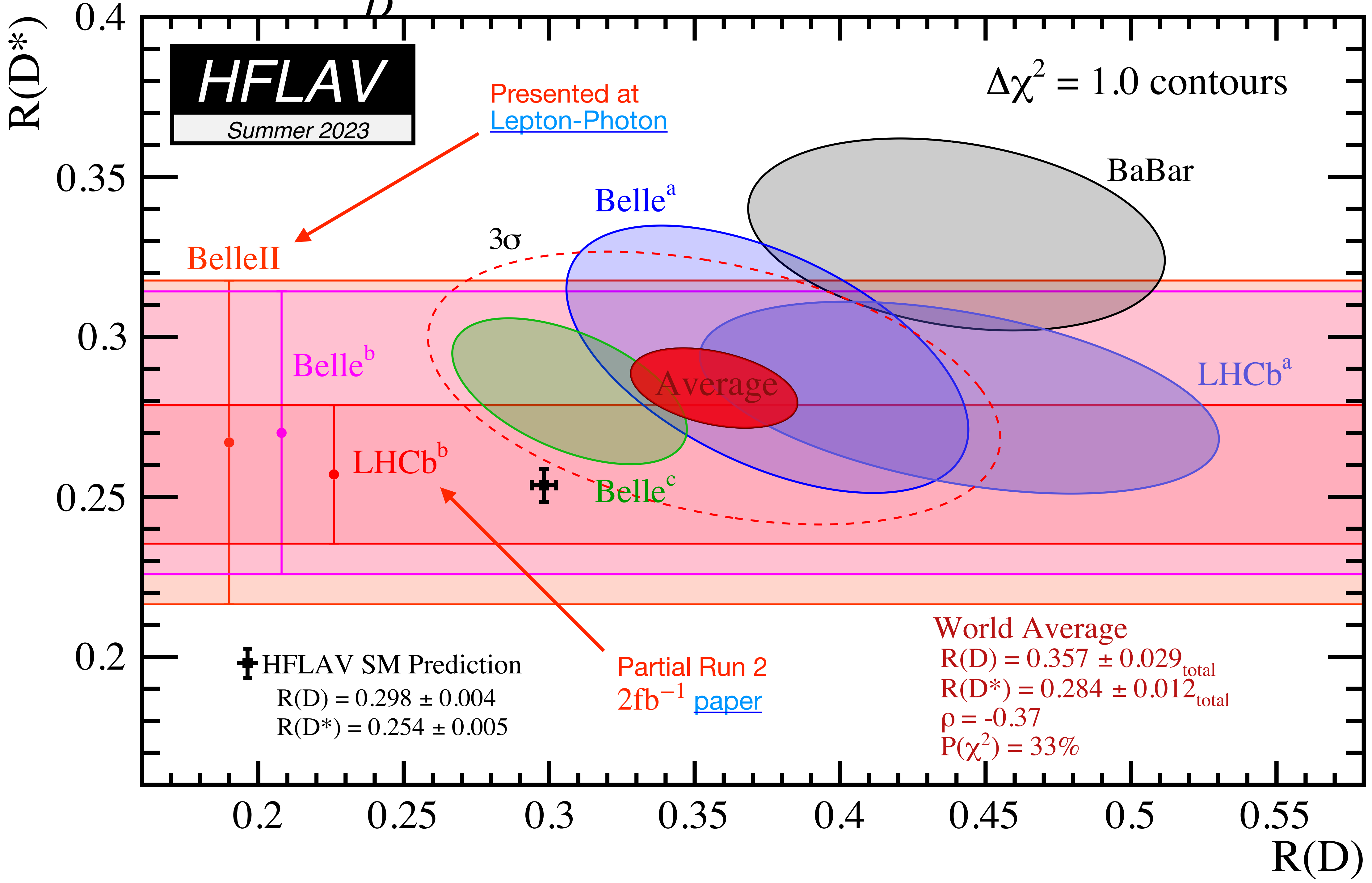
Lepton Flavour Universality

LHCb measurement of RD*

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}\left(B^0 \to D^{(*)-}\tau^+\nu_\tau\right)}{\mathcal{B}\left(B^0 \to D^{(*)-}\mu^+\nu_\mu\right)}$$

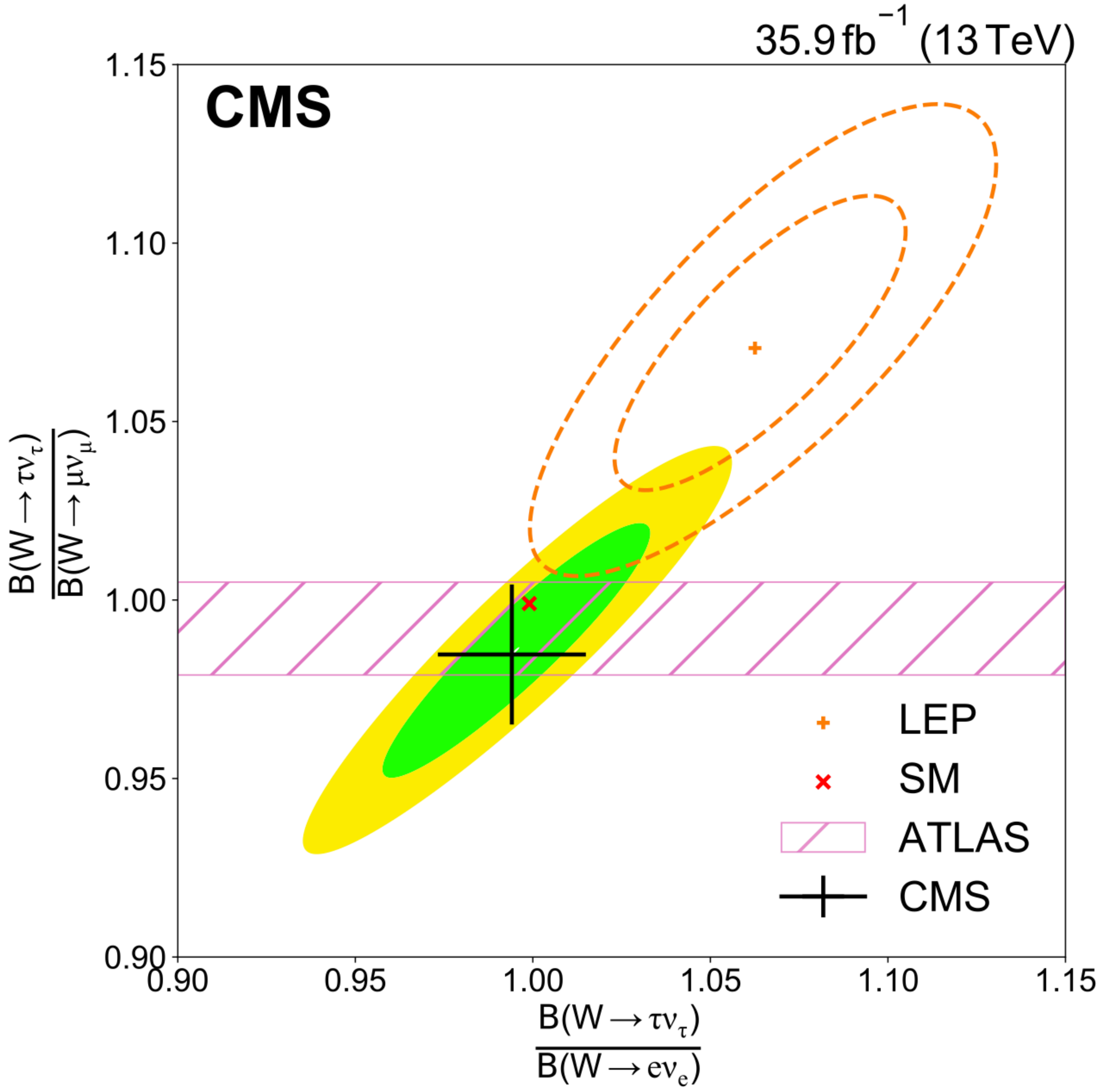
Both TH and EXP clean!

Recent R_D^* measurements from LHCb and Belle II



Tension with the SM of 3.3σ

Lepton universality measurements for "on-shell" W bosons at ATLAS and CMS:



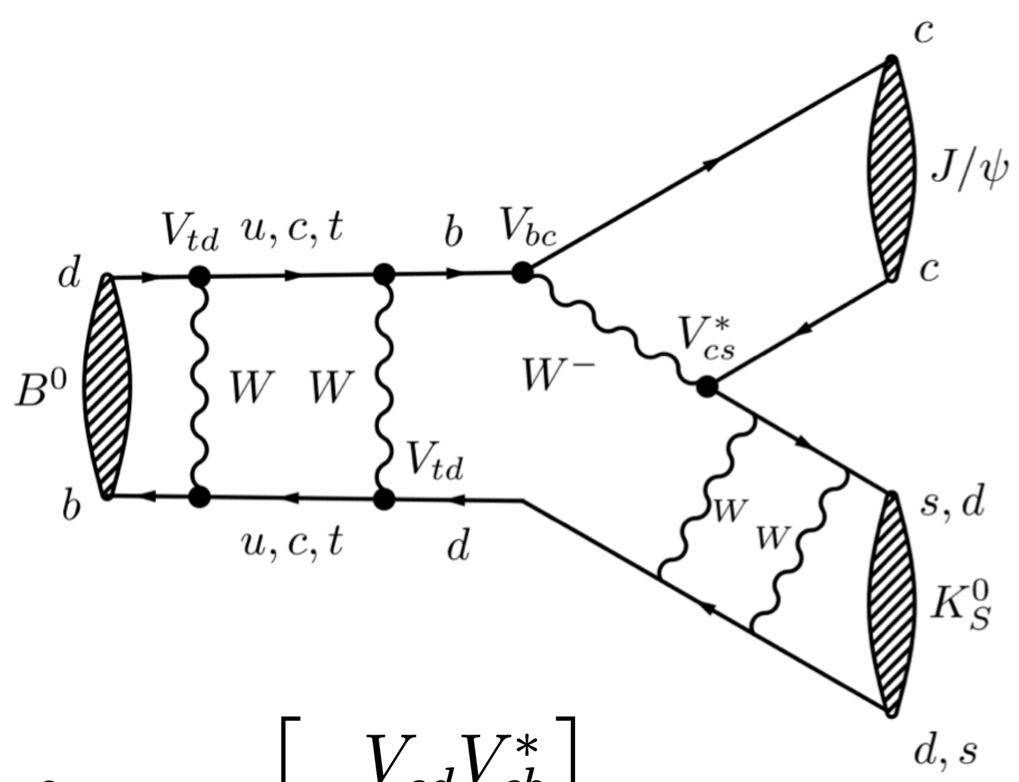
Initial **~2.6σ tension between LEP and the SM LFU prediction**, not confirmed by the more precise results obtained by both ATLAS and CMS!

Key Measurements of Matter–Antimatter Asymmetry*

*CERN Courier here.

The most precise measurement of the CKM angle β

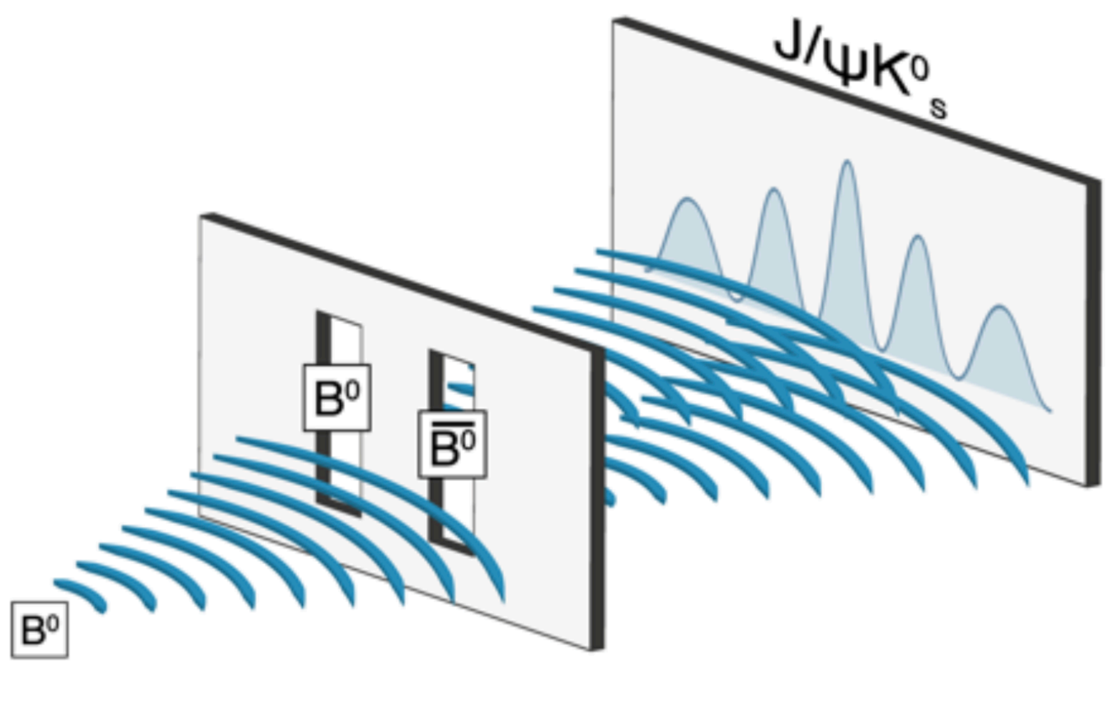
Interference between the amplitudes for the two decays B_0 or $\overline{B}_0$ results in a time-dependent asymmetry in the decays $B^0 \to J/\psi K_s, \psi(2s)K_s$



$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)}$$

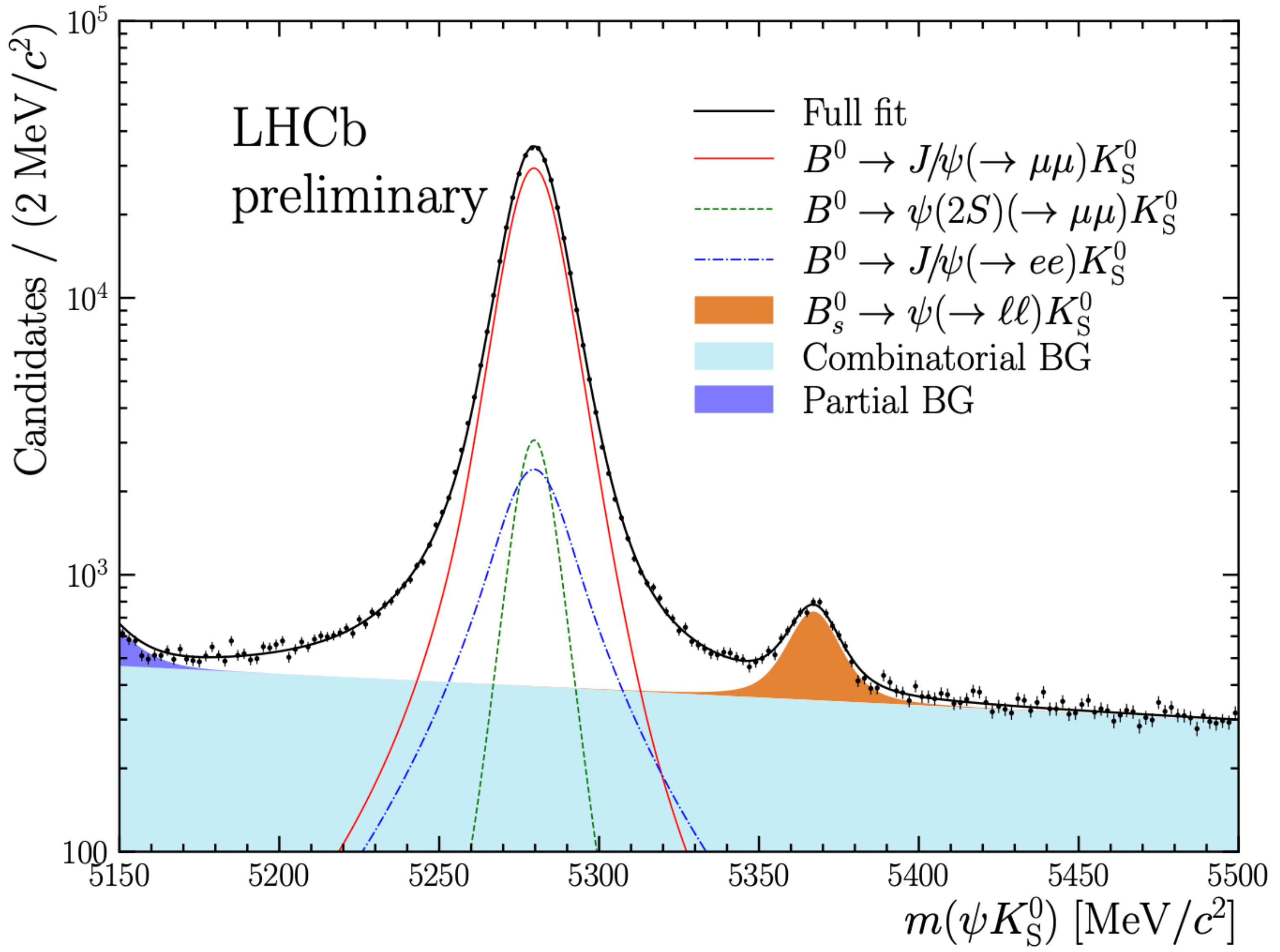
$$= \frac{S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

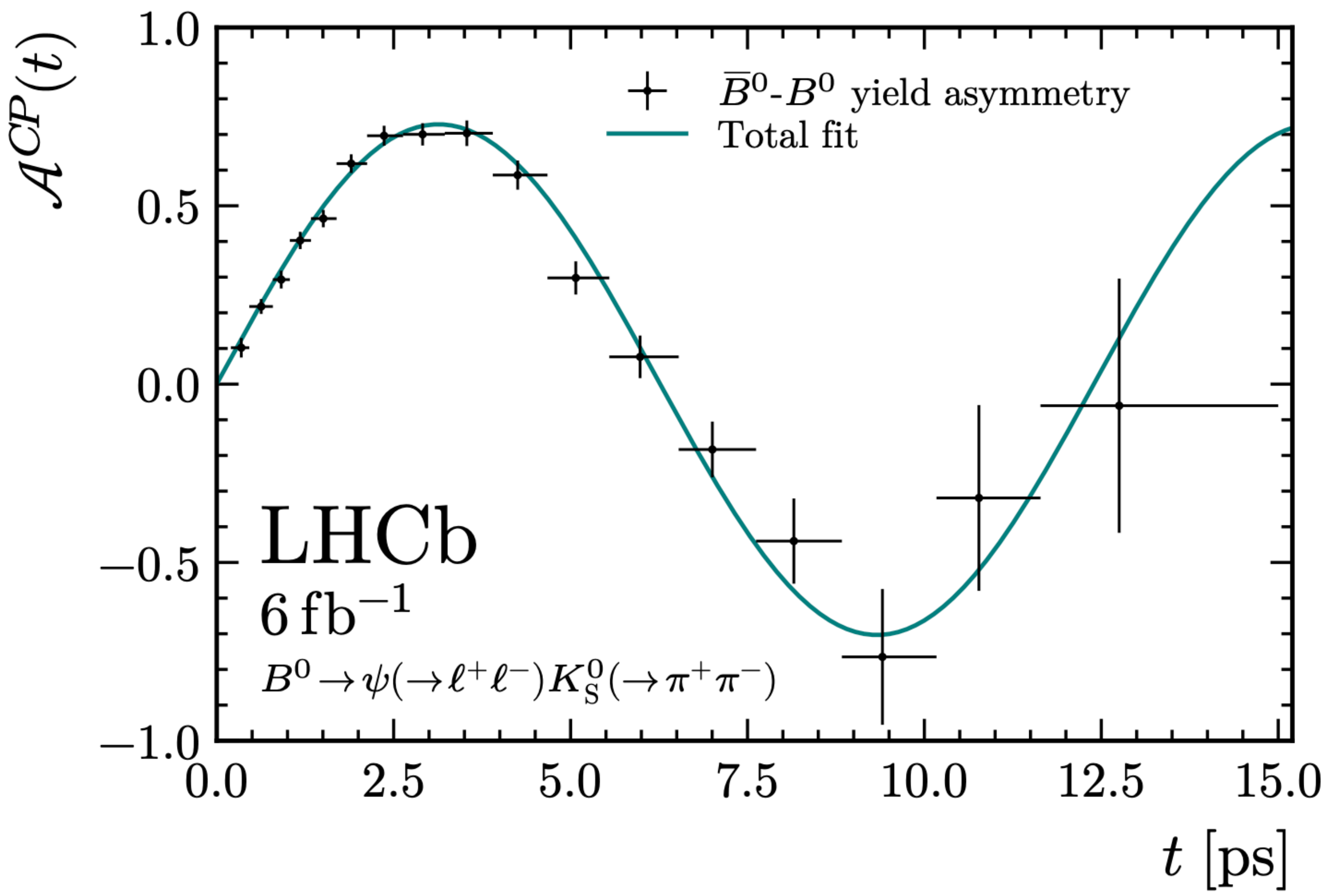
$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

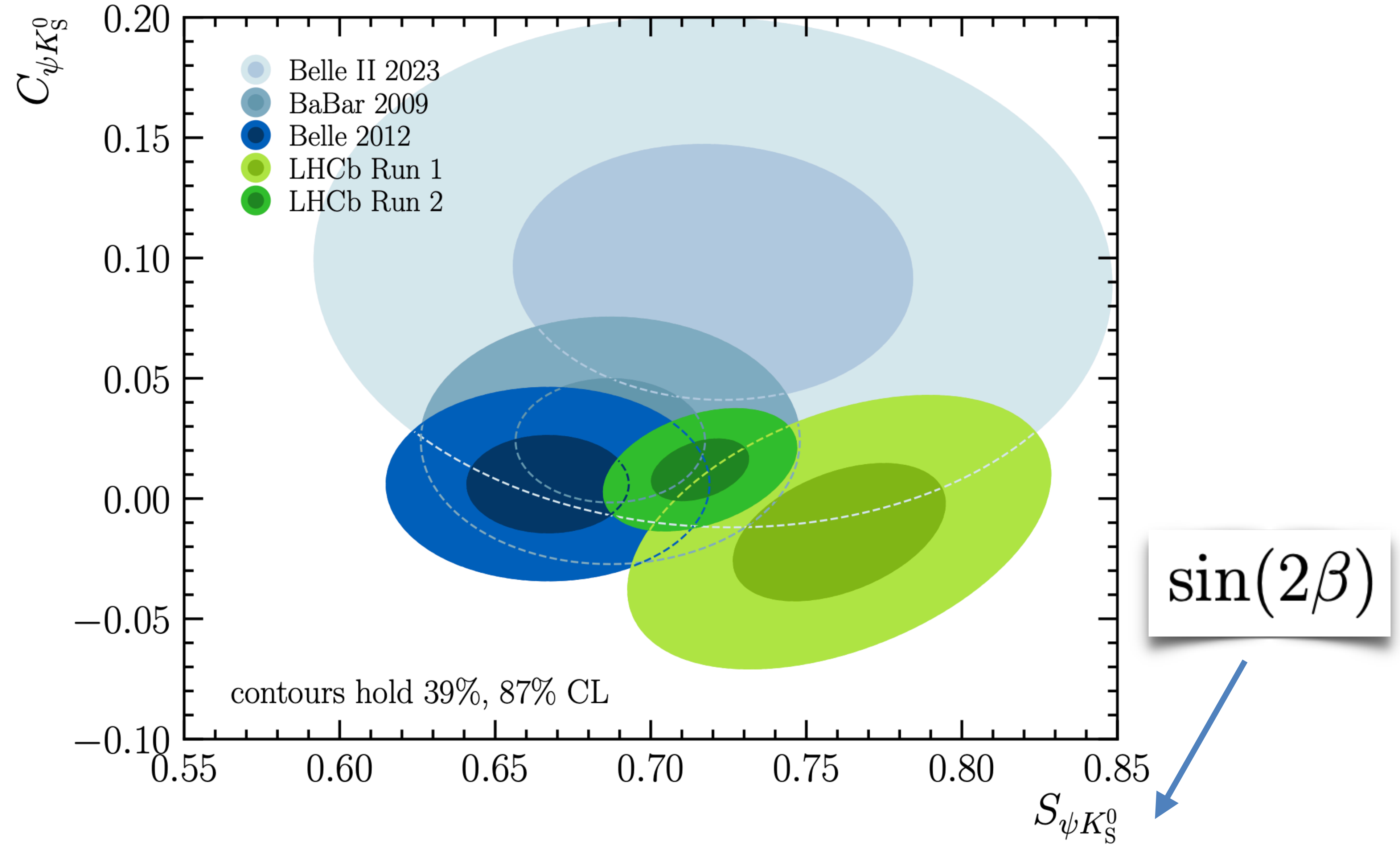


$(\phi_2, \phi_1, \phi_3) \equiv (\alpha, \beta, \gamma)$

Paper here and briefing!







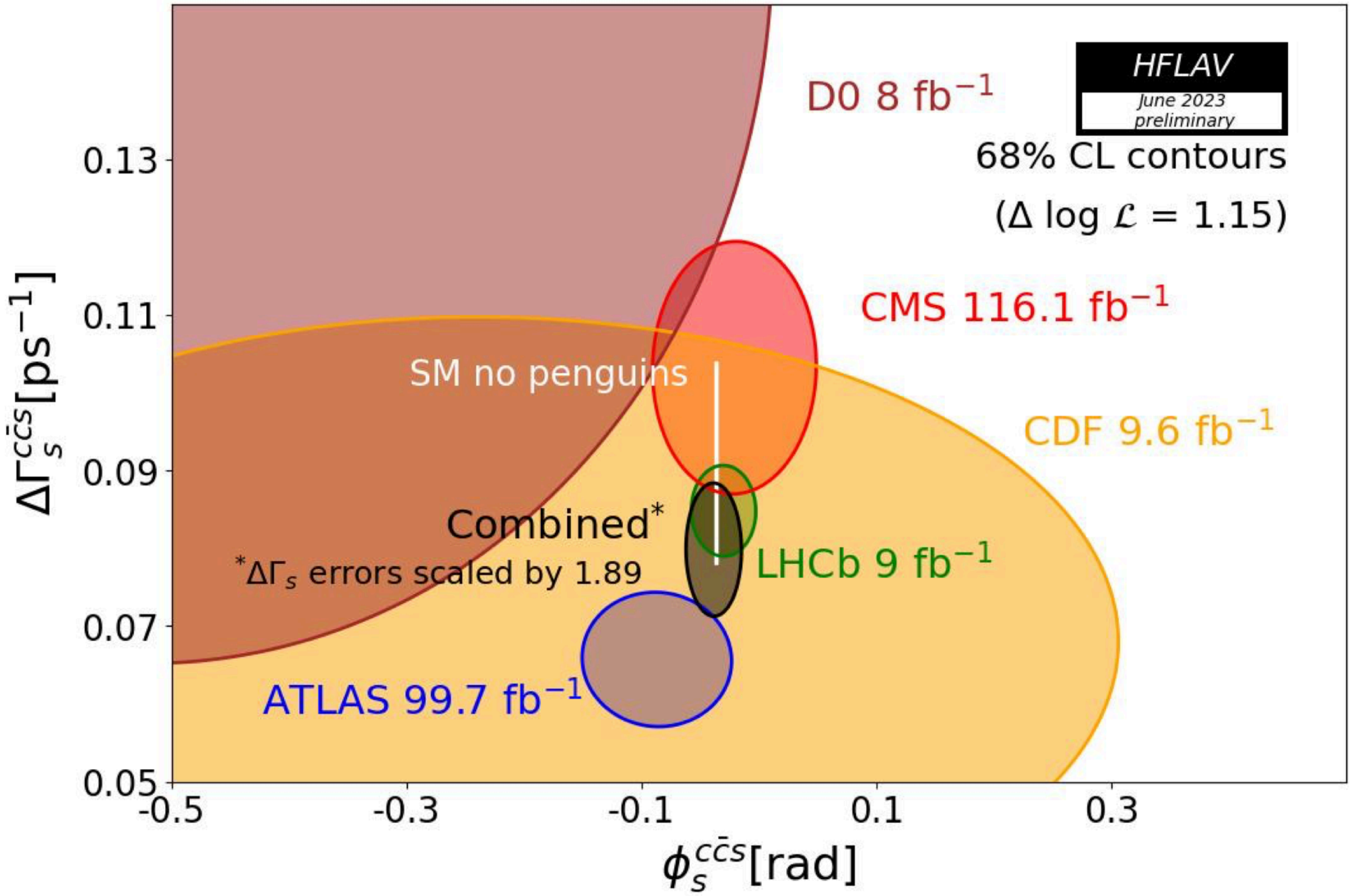
Results better than e^+e^- B factories (so far)

Key Measurements of Matter–Antimatter Asymmetry*

*CERN Courier here.

Best measurement of ϕ_s briefing

Time dependent time-dependent asymmetry in the decays $B_s^0 \to J/\psi\phi$ decays (i.e. in $b \to c\bar{c}s$ transition)



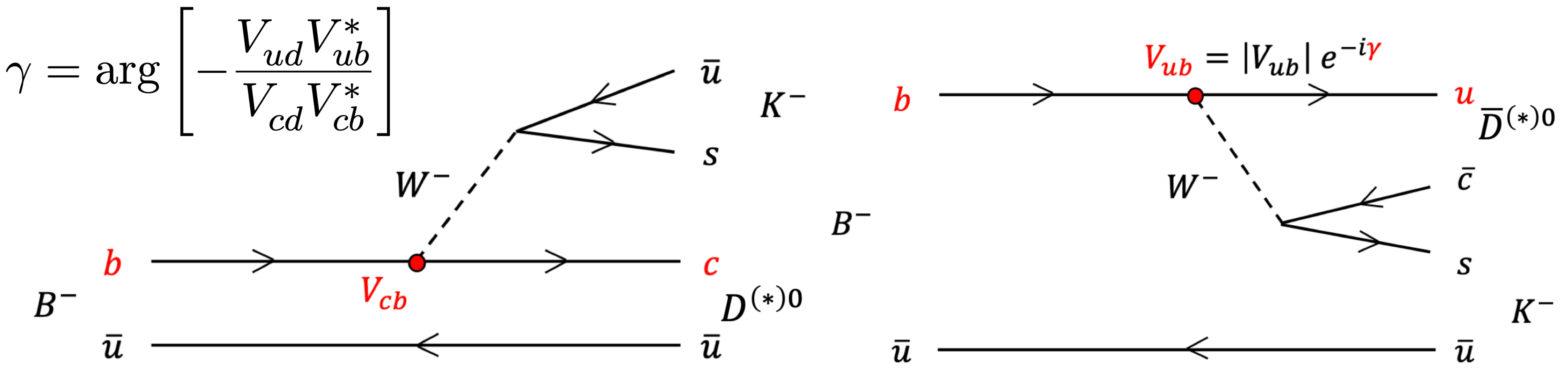
ϕ_s Very sensitive to New Phenomena

Many more measurements of CP violation effects as e.g. in Charm mesons…

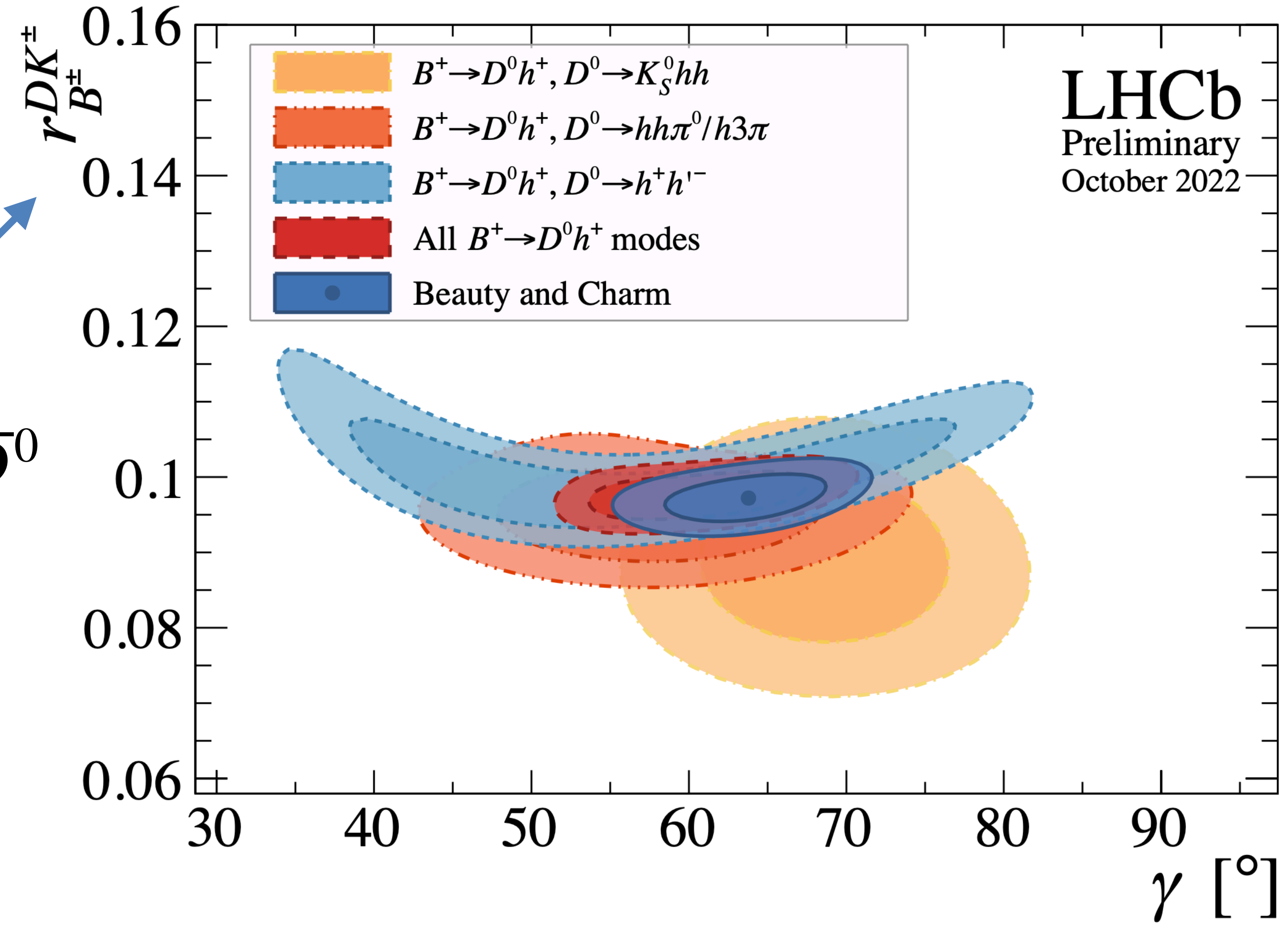
Most precise single experiment measurement of CKM angle γ

Time independent measurement in $B^\pm \to D^{(*)}h^\pm$ decay!

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



CKM and color suppression of $\bar{D}^0$



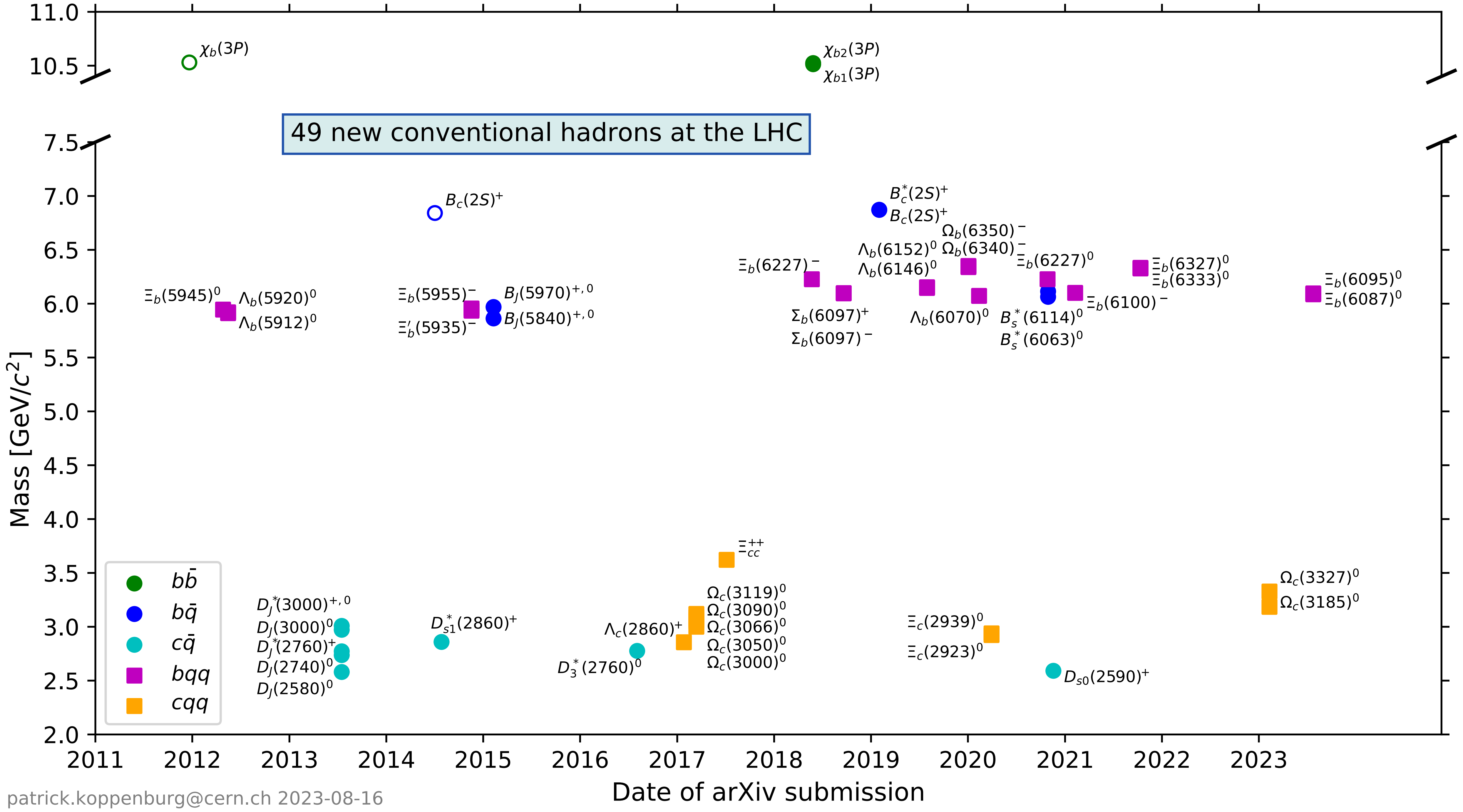
γ Measured from **interference between $b \to c$ and $b \to u$** processes

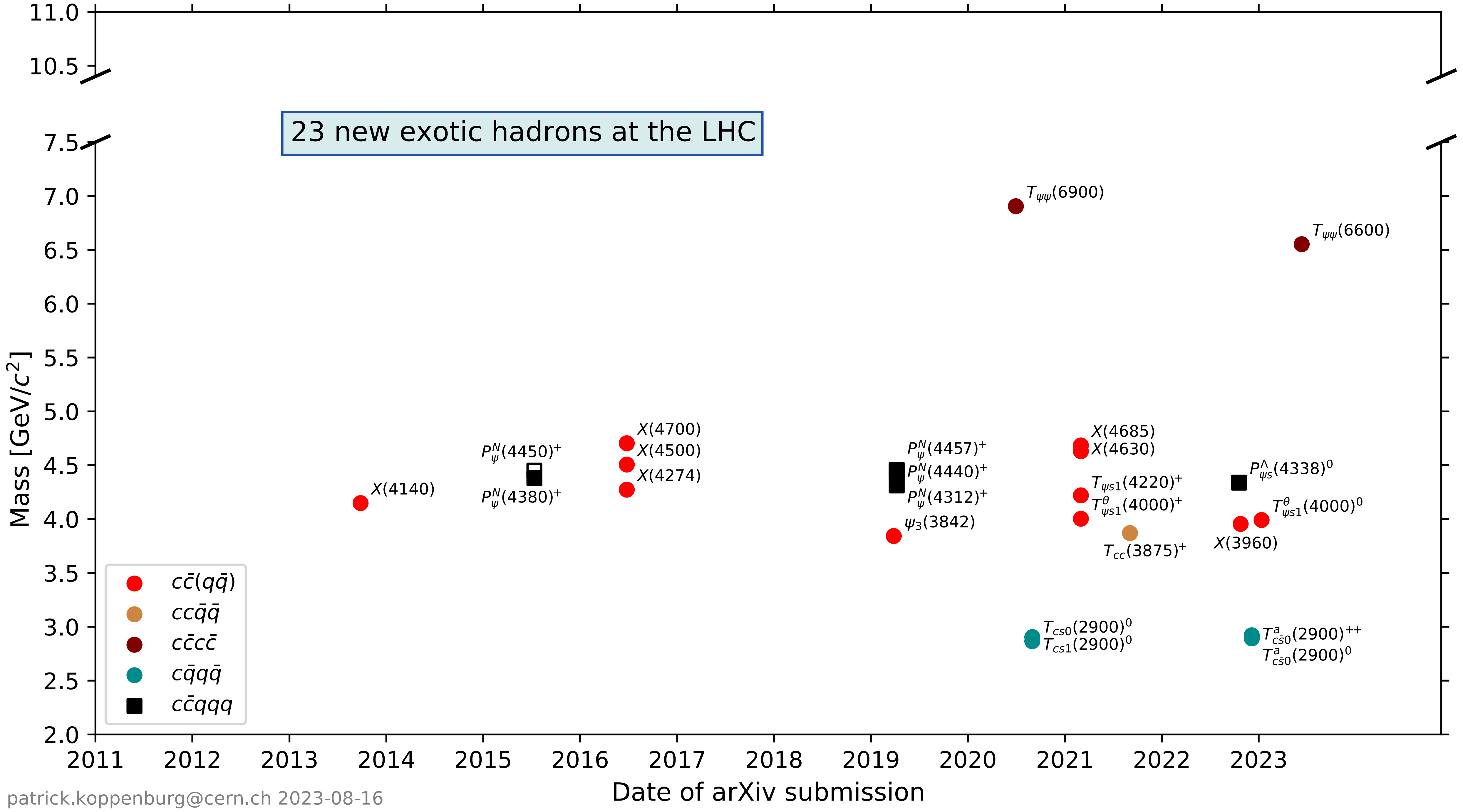
$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^\circ$$

$\gamma = \left(65.7^{+0.9}_{-2.7}\right)^\circ$ CKMfitter

$\gamma = (65.8 \pm 2.2)^\circ$ UTFit

Observation of New States





Further understanding and modelling quark confinement!

See nice summary page with all references from P. Koppenburg [here](#).

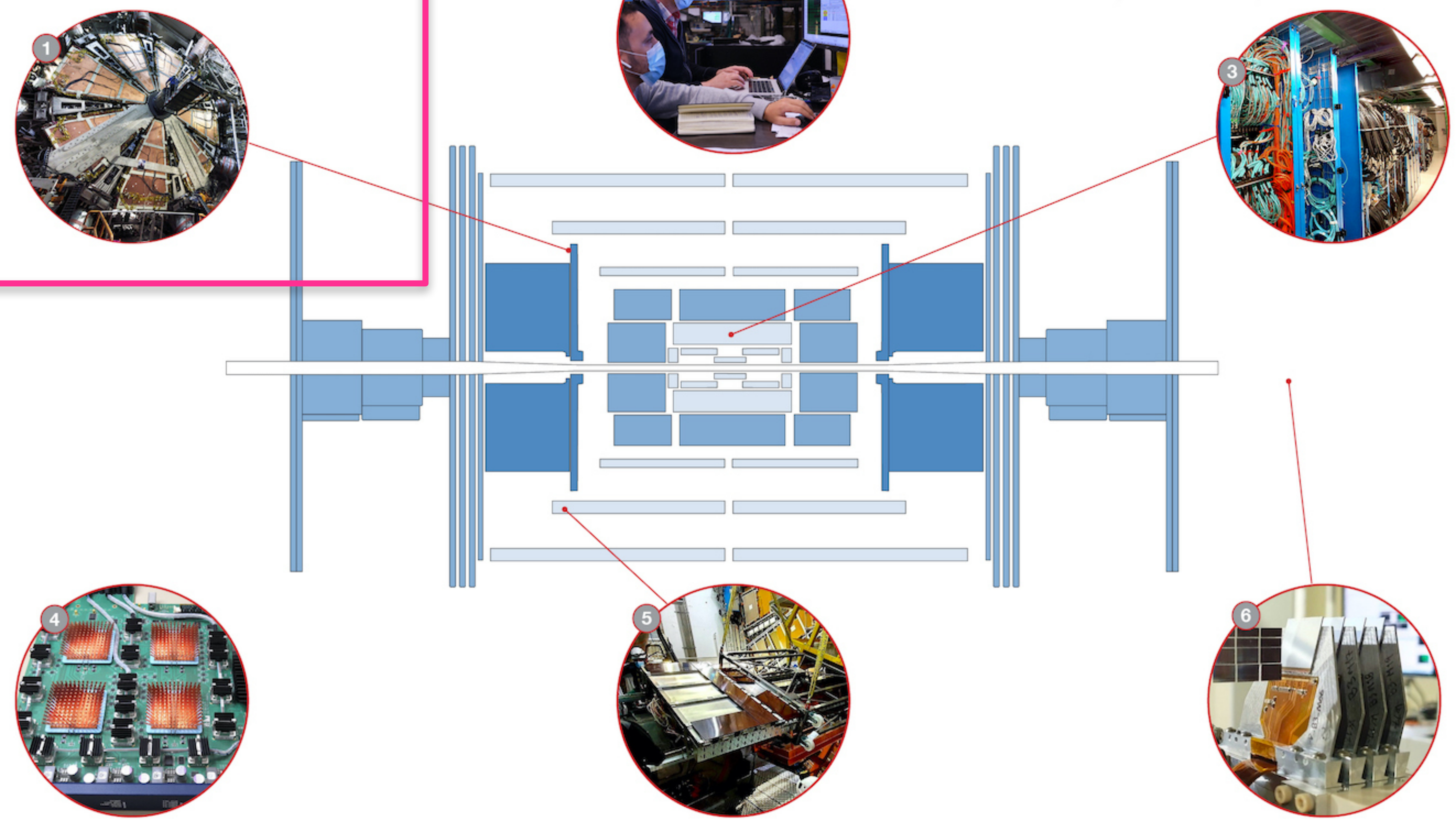
ATLAS Completed Commissioning of LS2 Upgrades

ATLAS Phase I (during LS2): New Small Wheels and more!

MUON NEW SMALL WHEELS (NSW)
Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.

NEW READOUT SYSTEM FOR THE NSWs
The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (sTGC) electronic readout channels.

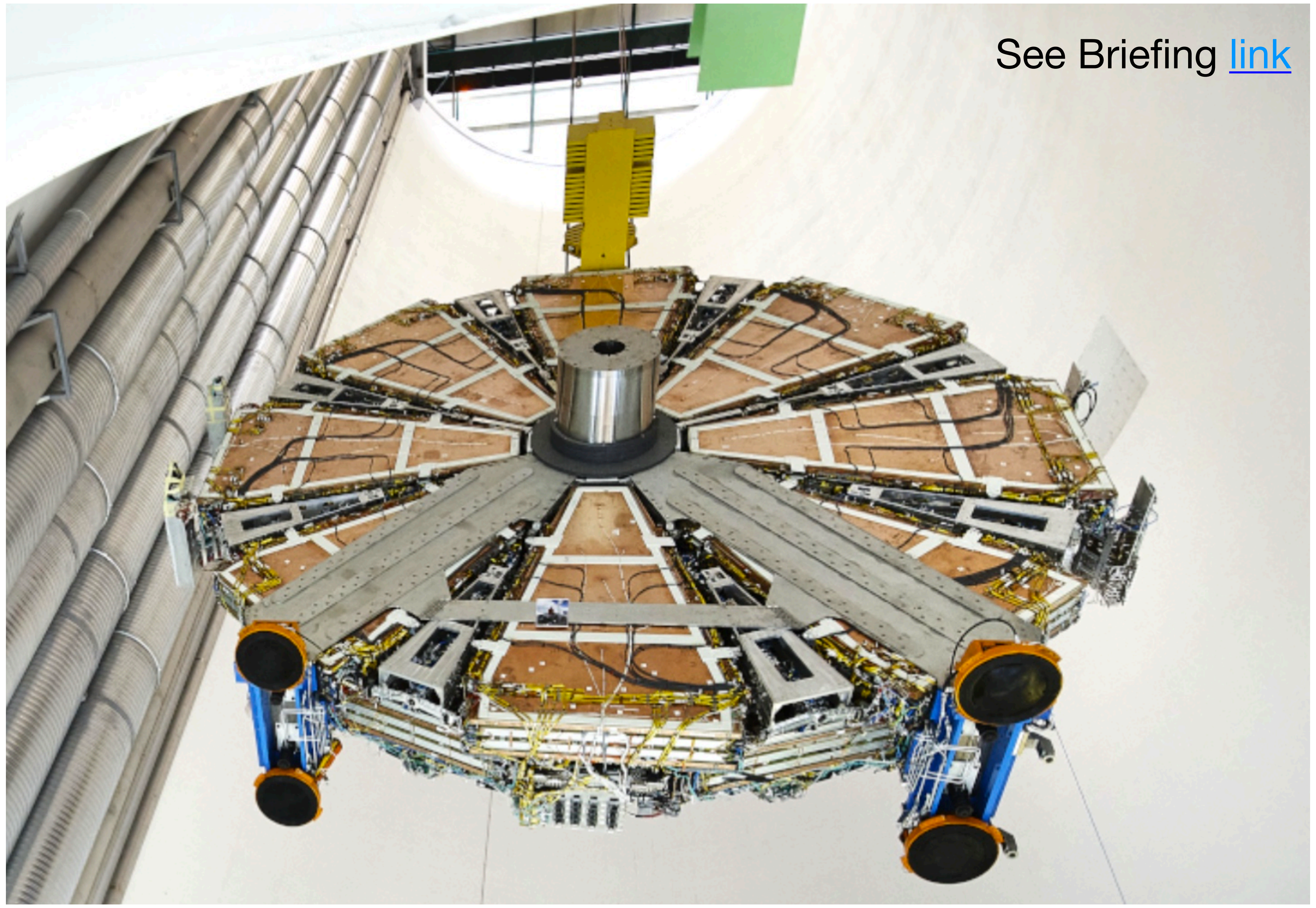
LIQUID ARGON CALORIMETER
New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.



TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)
Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.

NEW MUON CHAMBERS IN THE CENTRE OF ATLAS
Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.

ATLAS FORWARD PROTON (AFP)
Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new "out-of-vacuum" solution.

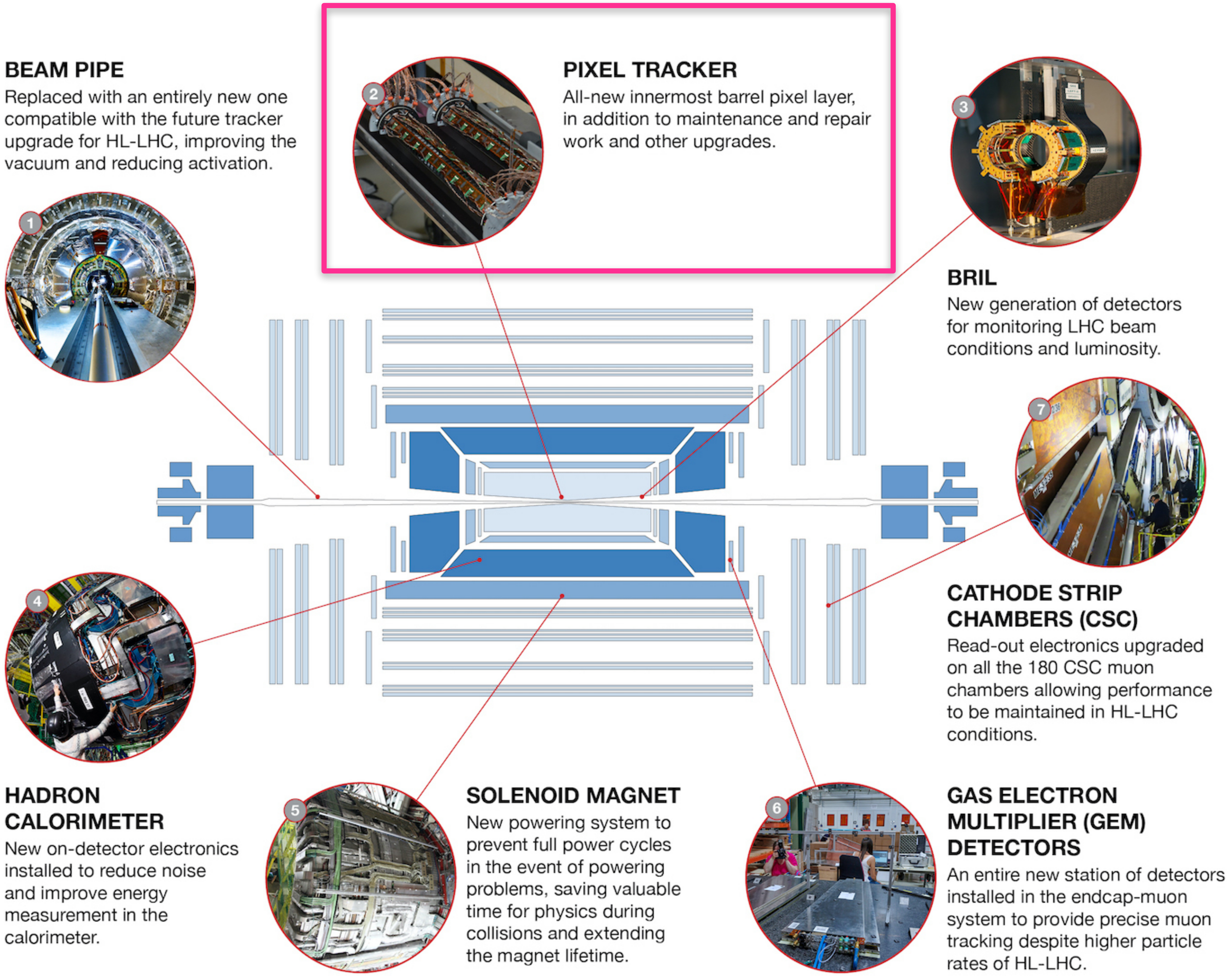


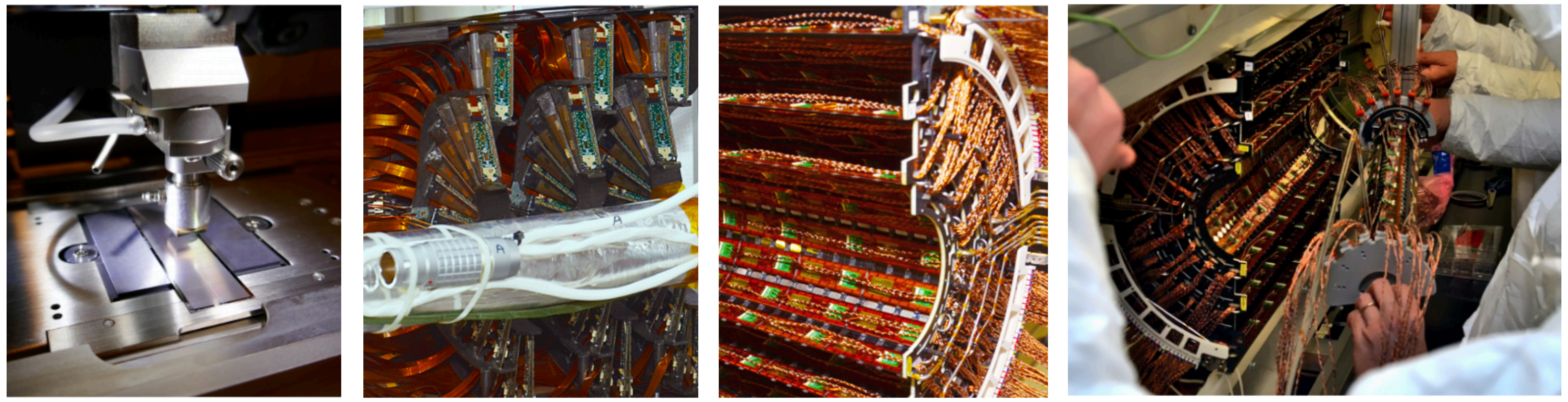
See Briefing link

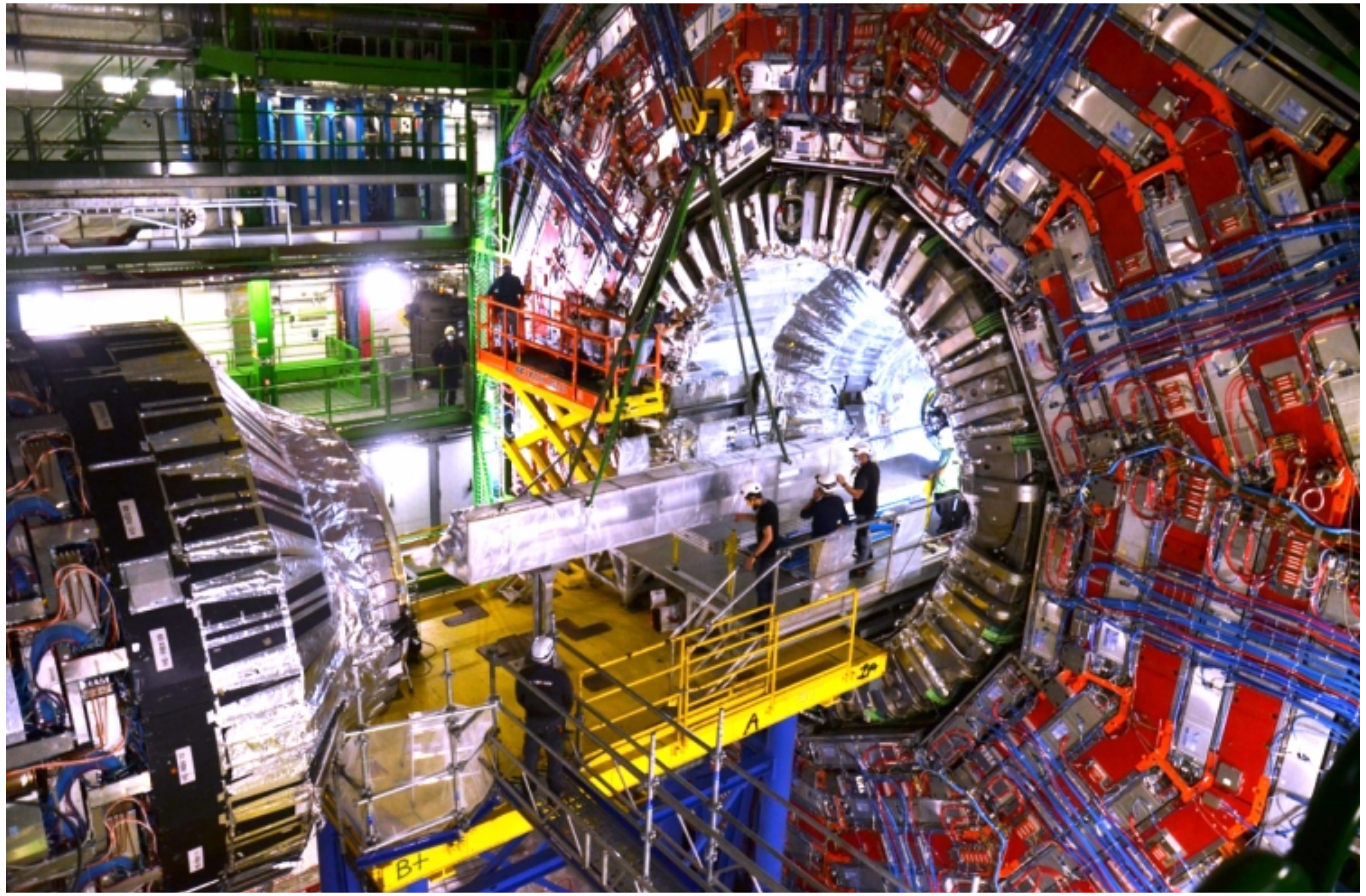
CMS Completed Commissioning of LS2 Upgrades

CMS Phase I (during LS2): New inner most pixel layer and more!

See EP News link







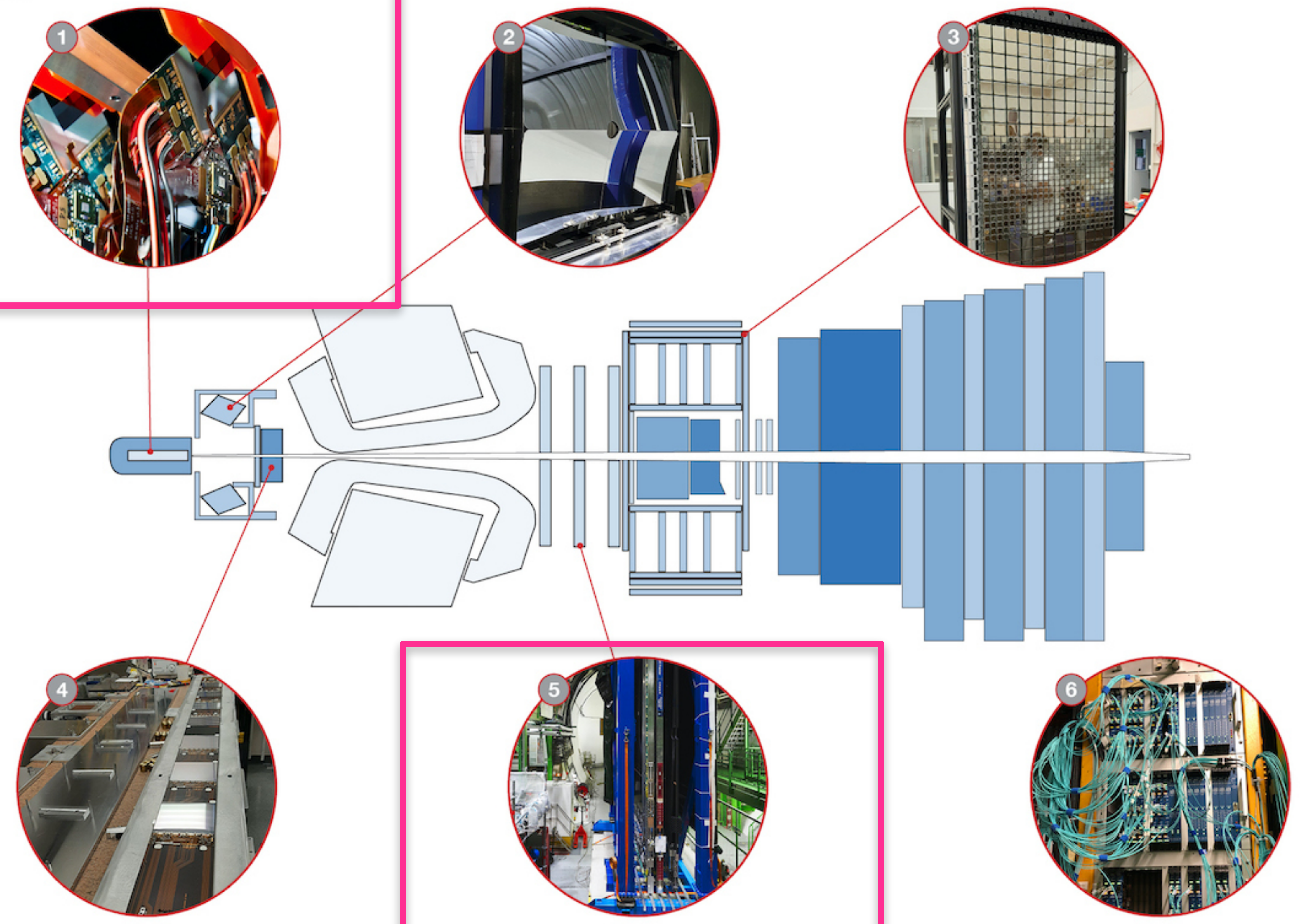
LHCb Major LS2 Upgrade

LHCb Upgrade I (during LS2): essentially a new detector!

VELO: NEW SILICON PIXEL DETECTOR
Vertex Locator (VELO) replaced by a new silicon pixel detector, installed as close as 5.1 mm to the proton beams.

RICH1
New optics of RICH1 mirrors, with larger curvature radius.

RICH2
New multi-anode photomultipliers replaced the hybrid photon detectors (HPD) in RICH1 and RICH2.



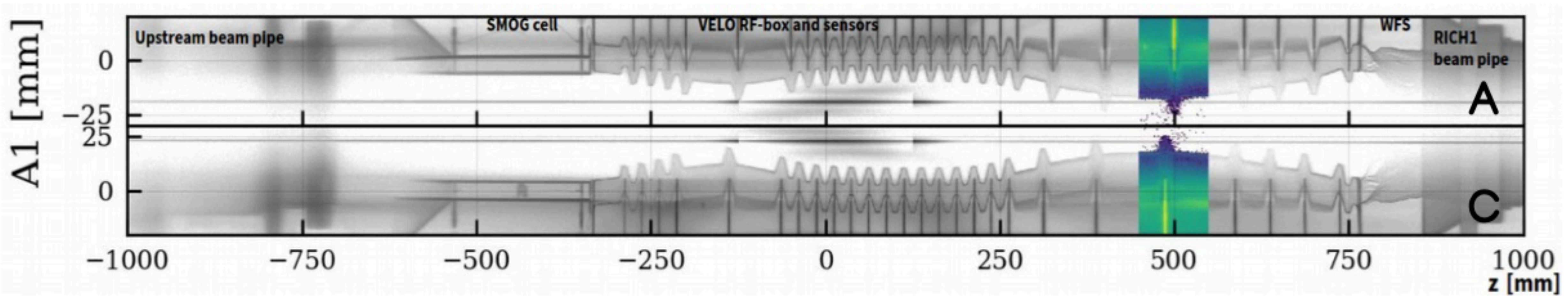
TRACKER: New UT
New high granularity silicon microstrip upstream tracker (UT).

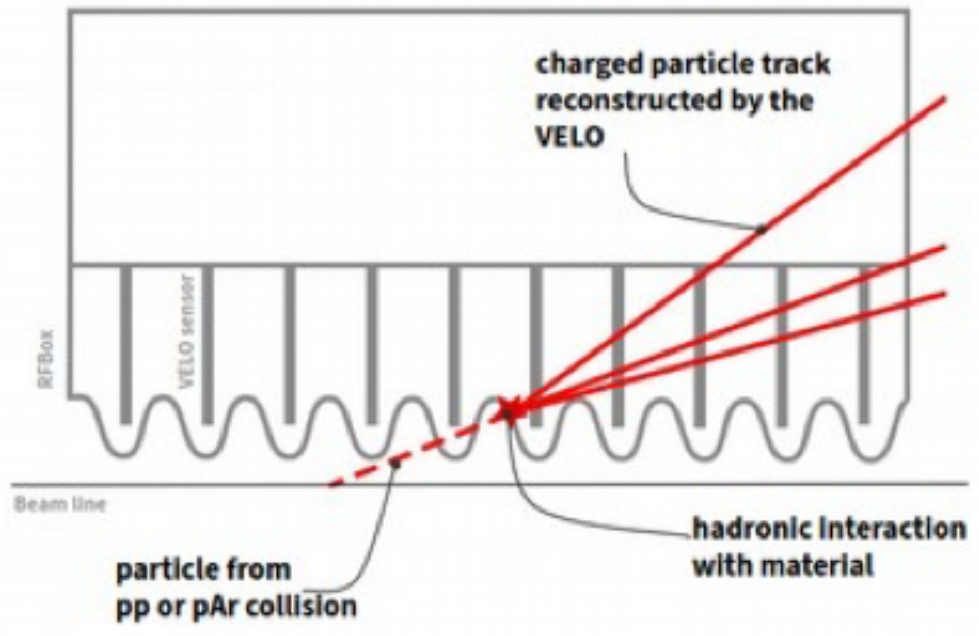
TRACKER: SCI-FI
Three new scintillating fibre tracker (Sci-Fi) stations.

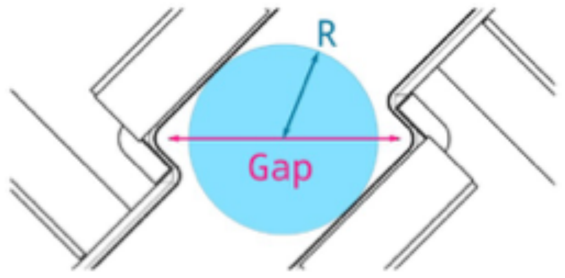
FRONT-END ELECTRONICS
All front-end electronics (i.e. those connected directly to the detectors) have been modified.

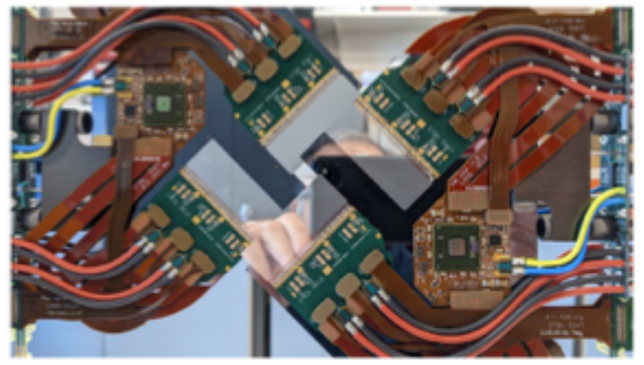
New VELO pixel detector and **SciFi-Tracker** with 11,000km of scintillating fibres!

Outstanding work during YETS: Replacement of RF foil* deformed in the vacuum incident in January 2023 implied Vertex Locator (VELO) with 49 mm gap operations ~16 weeks work program. [Done]!







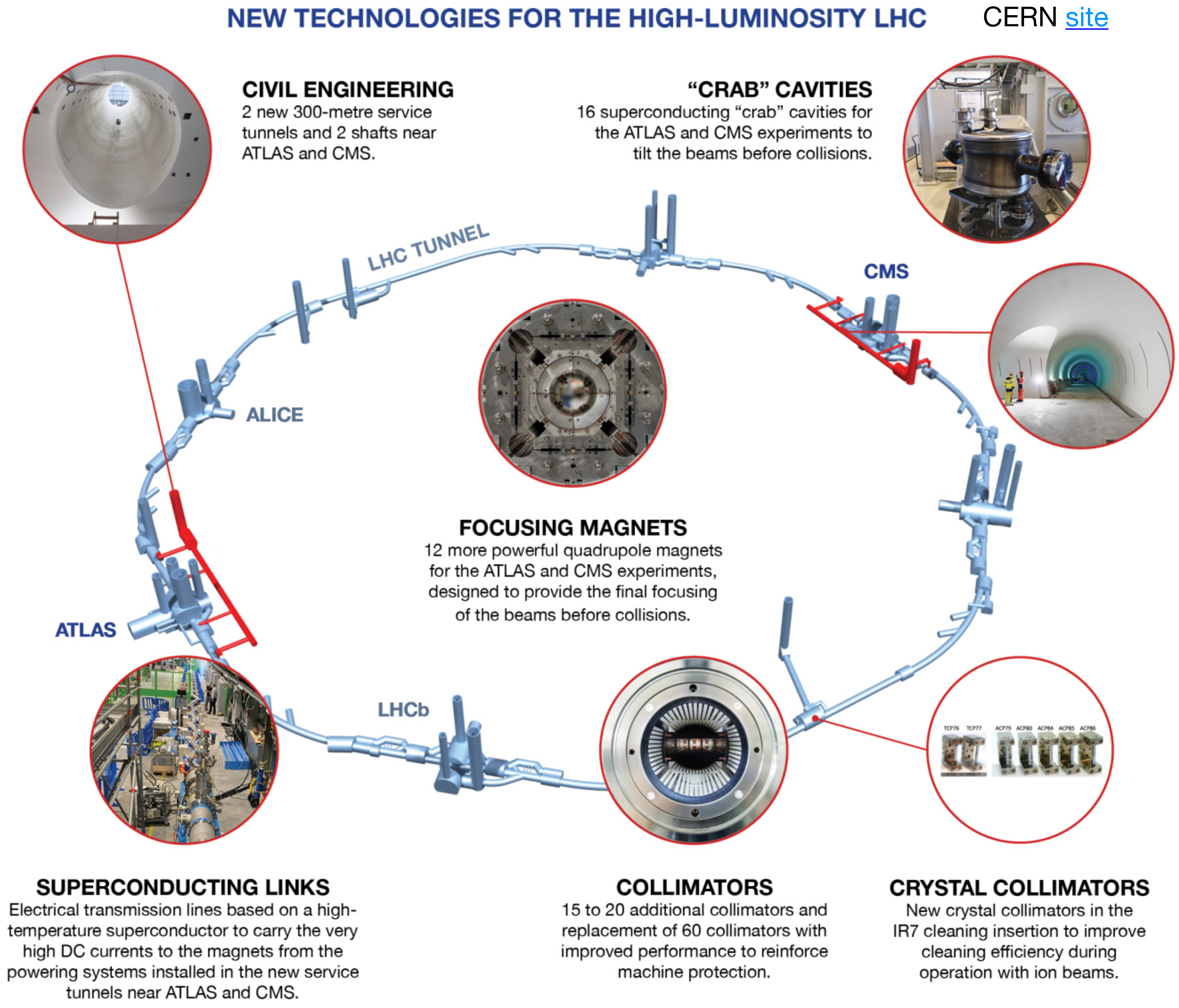


Replacement of the RF

*RF box protects VELO electronics agains RF interference from pulsed beams

LHC Machine Towards Major LS3 Upgrades

CERN site



Front page of the CERN Courier says it all!

LS3 installation fully on track!

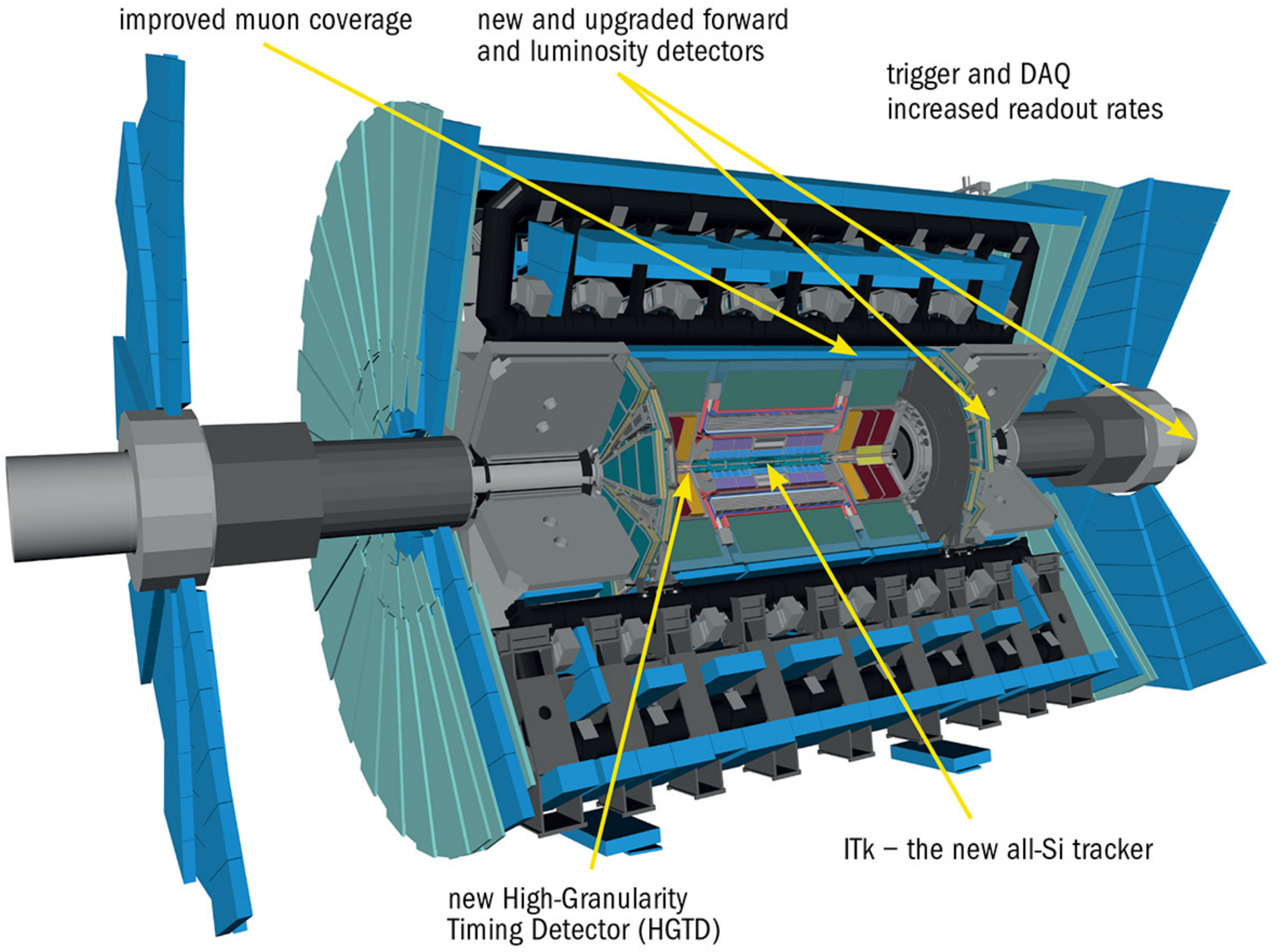
Nb3Sn series magnets manufactured at Fermilab arrived at CERN! See CERN News.

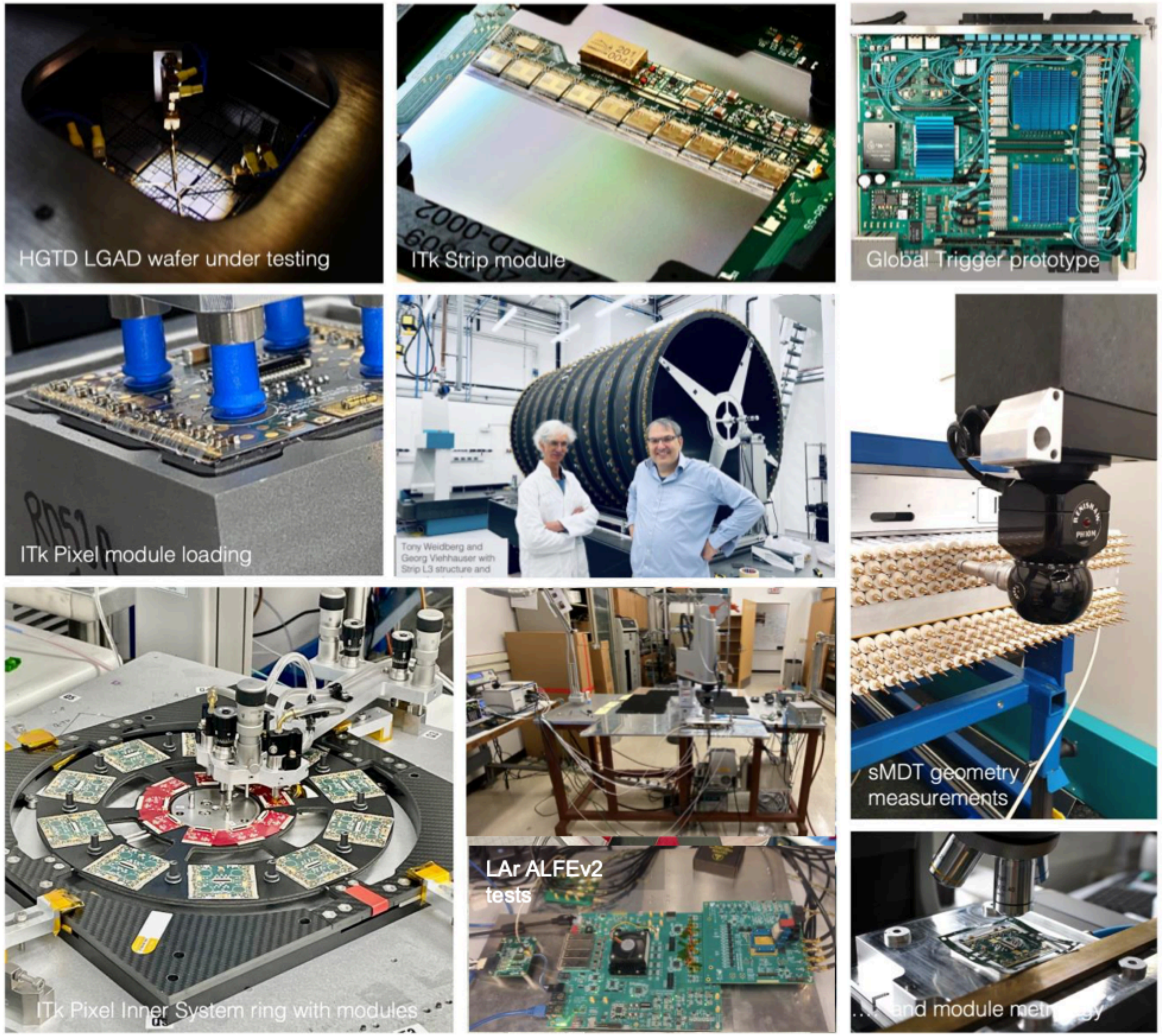
ATLAS Towards Major LS3 Upgrades

A new ATLAS for the high-luminosity era

18 January 2023 | By Stefan Guindon, Christian Ohm, Caterina Vernieri

Feature link





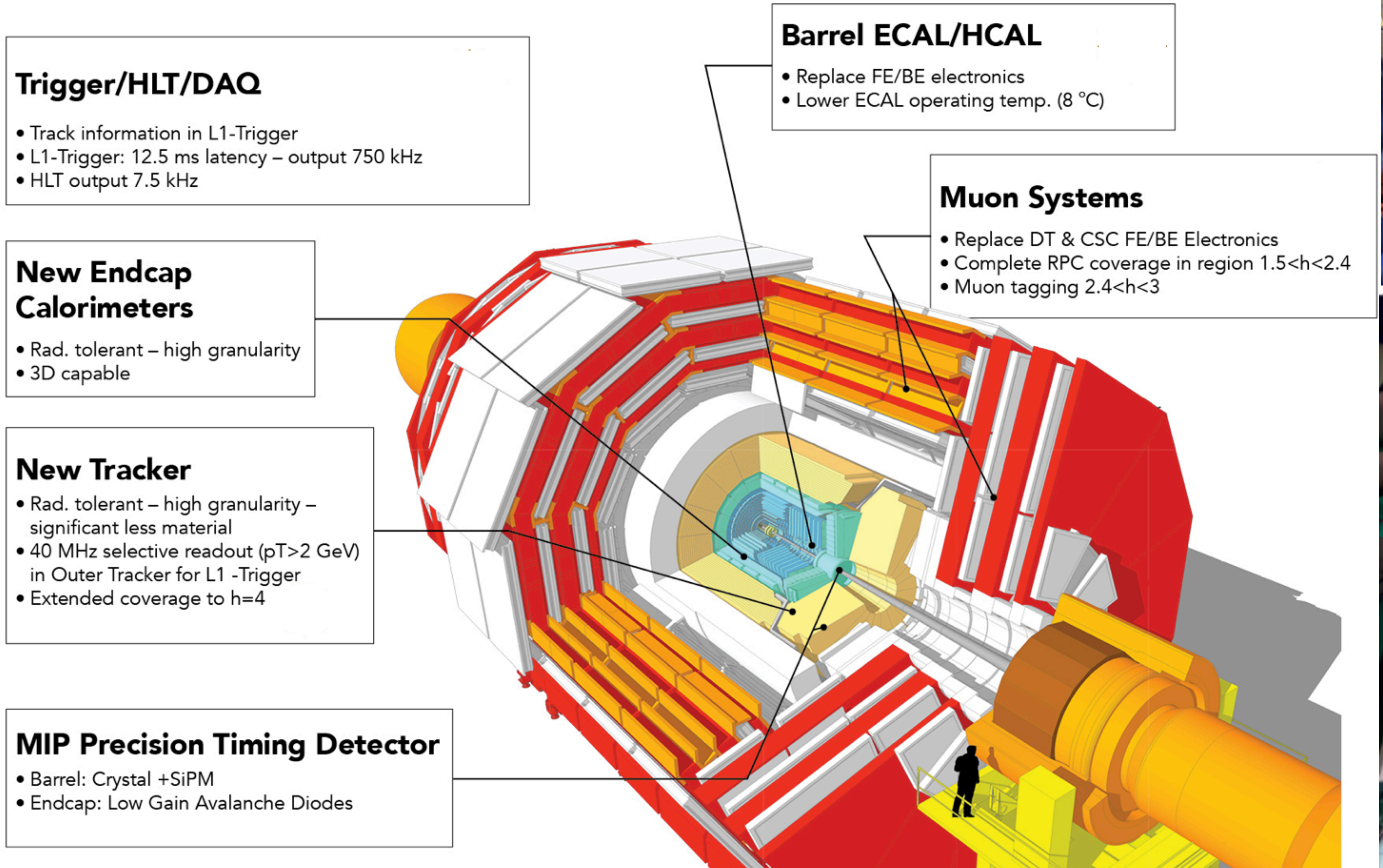
ATLAS Towards Major LS3 Upgrades

ACCELERATORS | FEATURE

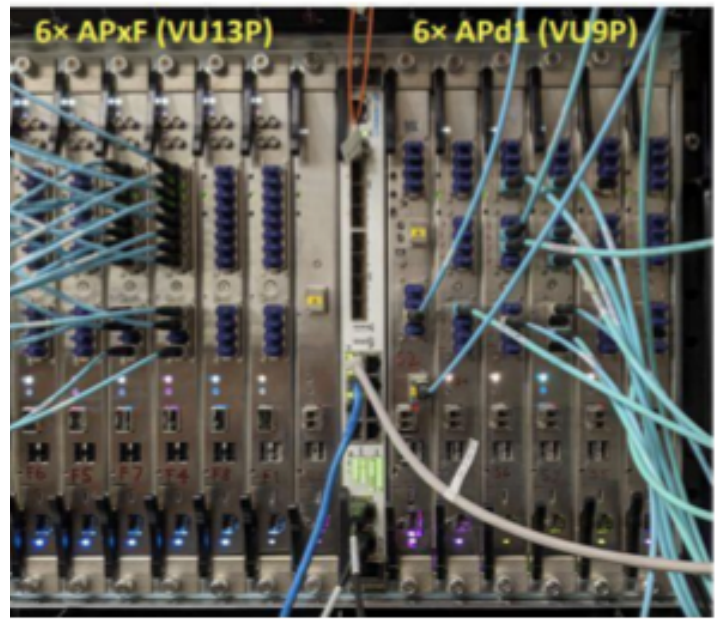
CMS prepares for Phase II

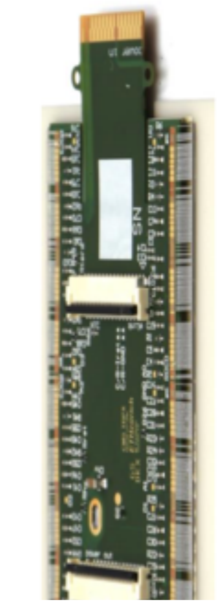
9 January 2023

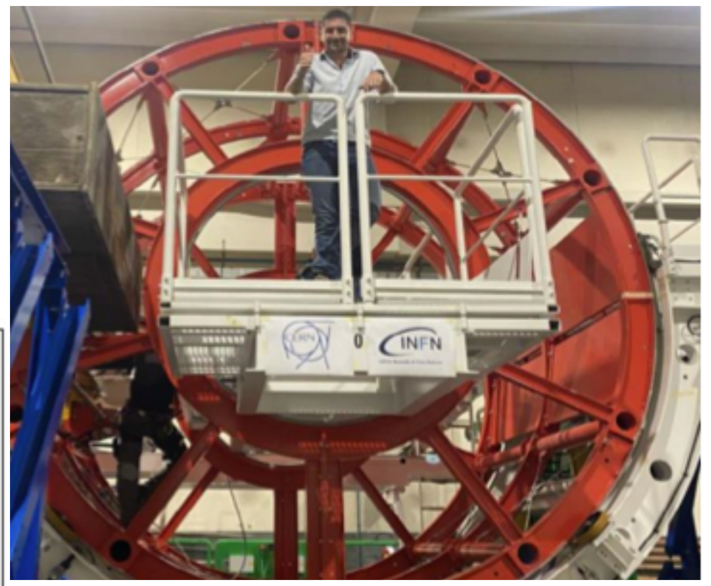
CERN Courier article link

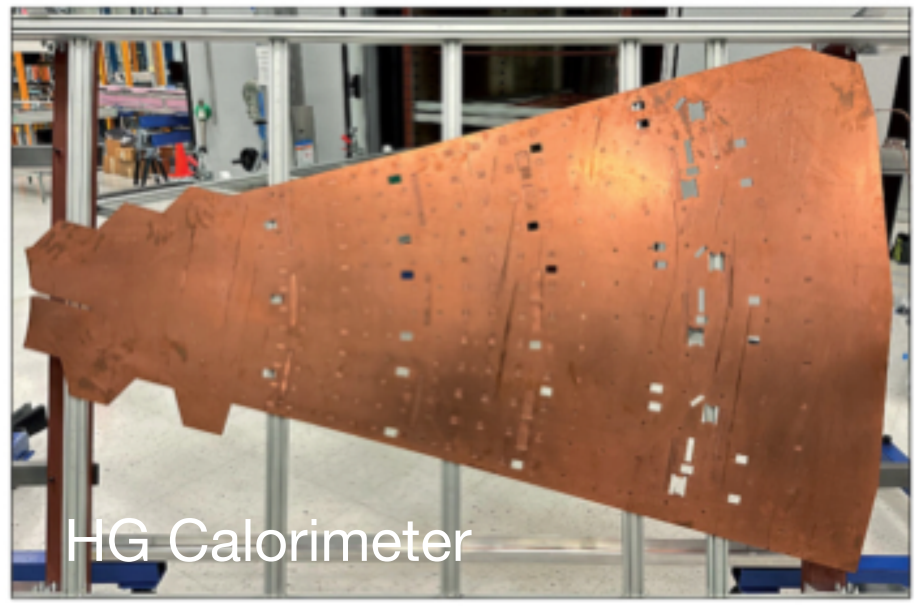


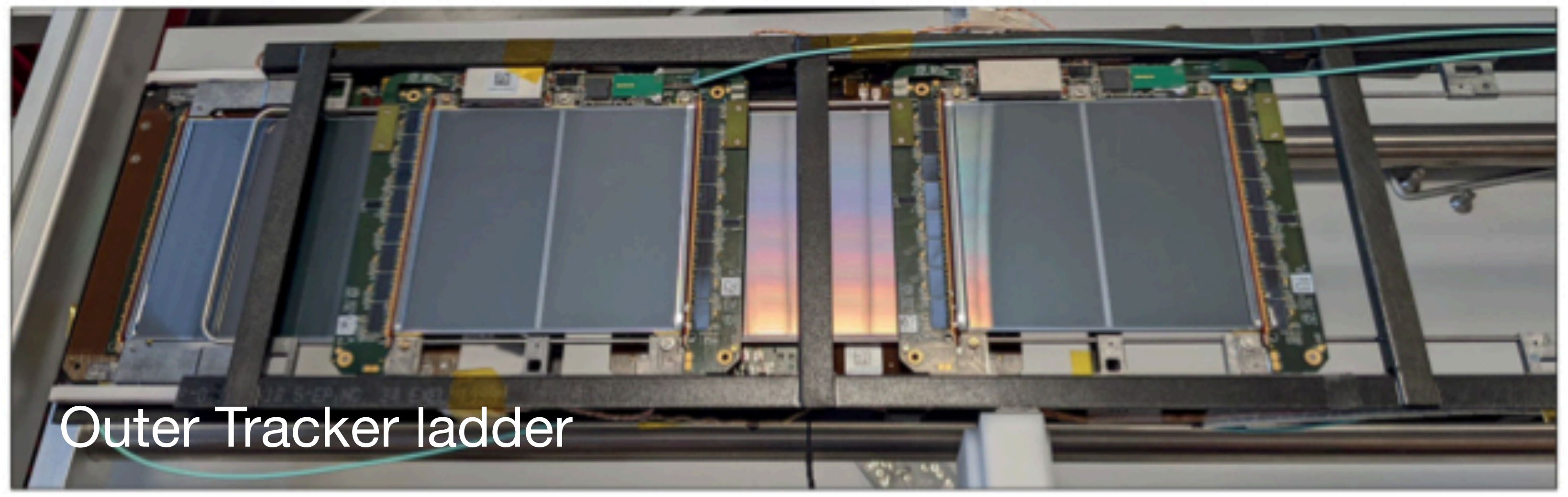
From CLASSE (Cornell)

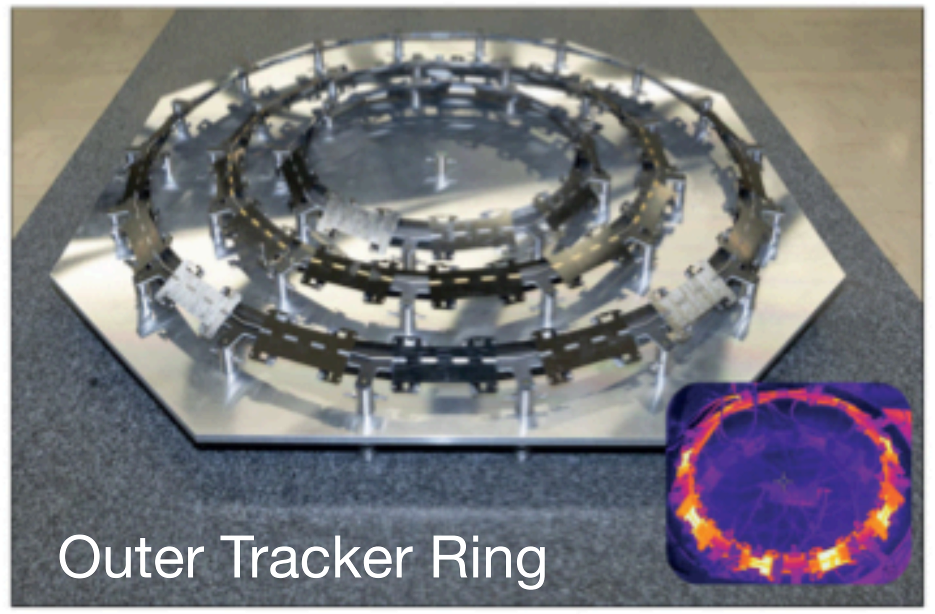




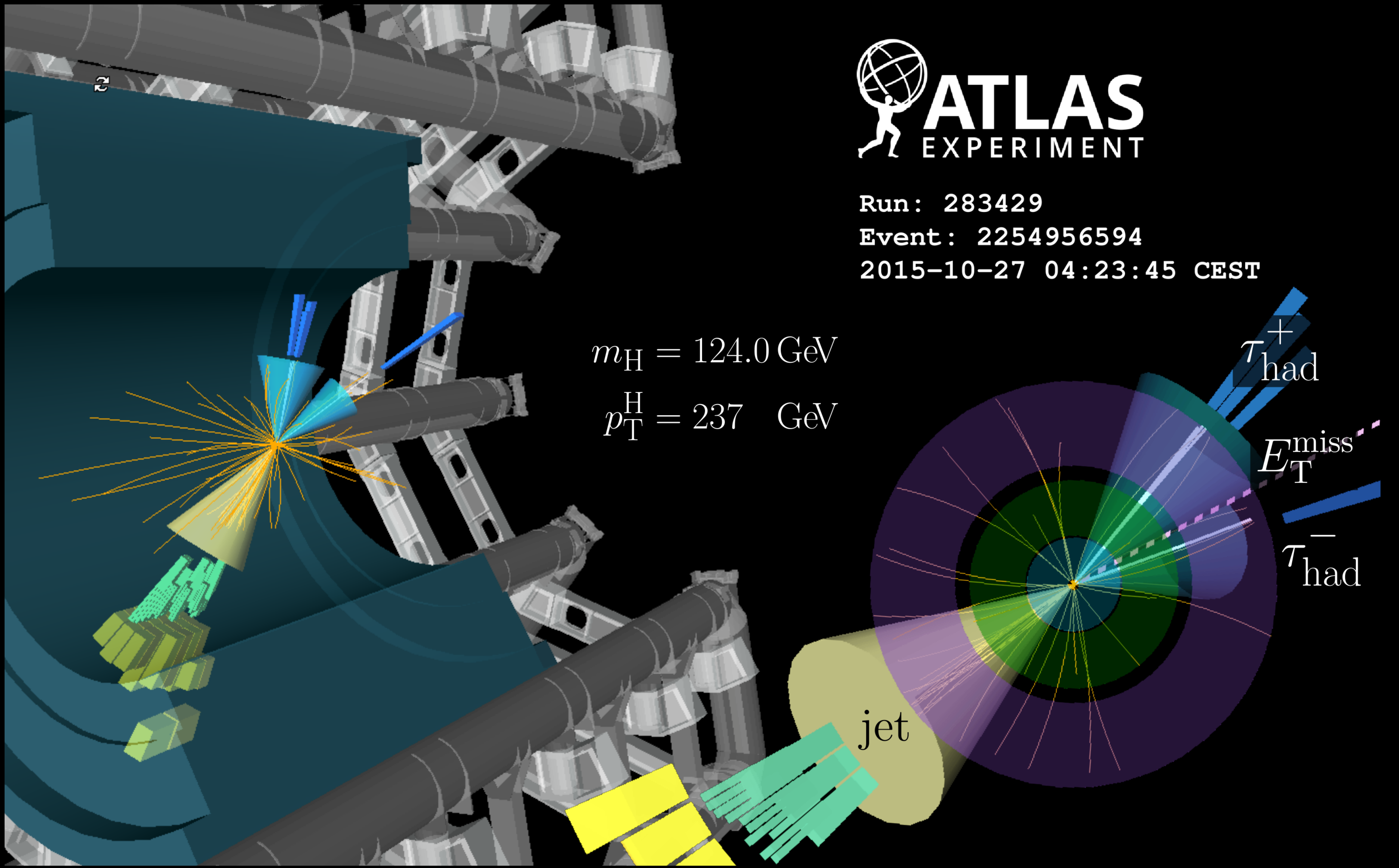








Higgs Yukawa to taus CP Properties



CP properties of the tau Yukawa through polarisation correlations in $H \to \tau^{+}\tau^{-}$ decay

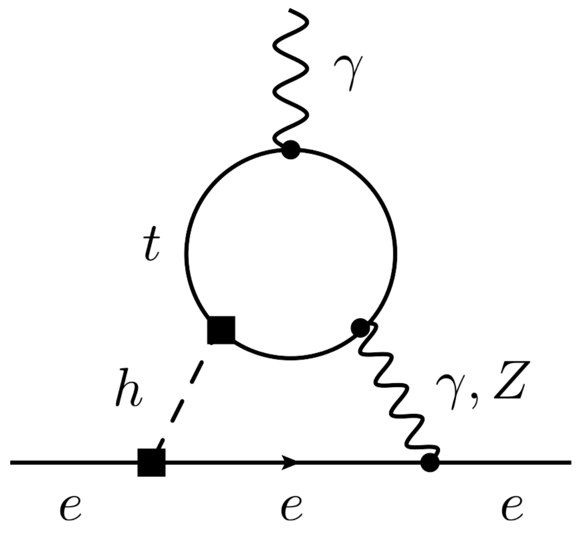
Boosted $H \to \tau^{+}\tau^{-}$ candidate event

Higgs Yukawa to taus CP Properties

$$\frac{\lambda_f}{\sqrt{2}}\left(\kappa_f h\overline{\psi}_f\psi_f + i\tilde{\kappa}_f h\overline{\psi}_f\gamma_5\psi_f\right)$$

Higgs boson couplings to fermions could be an important source of CP violation!

However **constrained through indirect probes** e.g. electron (and neutron) EDM very suppressed in the SM (where it arises at four loops)



From J. Brod., U. Haisch and J. Zupan 2013

$$\frac{d_e}{e} \propto G_F m_e\left[C_1\kappa_e\tilde{\kappa}_t + C_2\tilde{\kappa}_e\kappa_t\right]$$

$C_1 = f\left(\frac{m_t^2}{m_h^2}\right)$

ACME II limit: $\left|\frac{d_e}{e}\right| < 1.1\ 10^{-29}\ \mathrm{cm}$

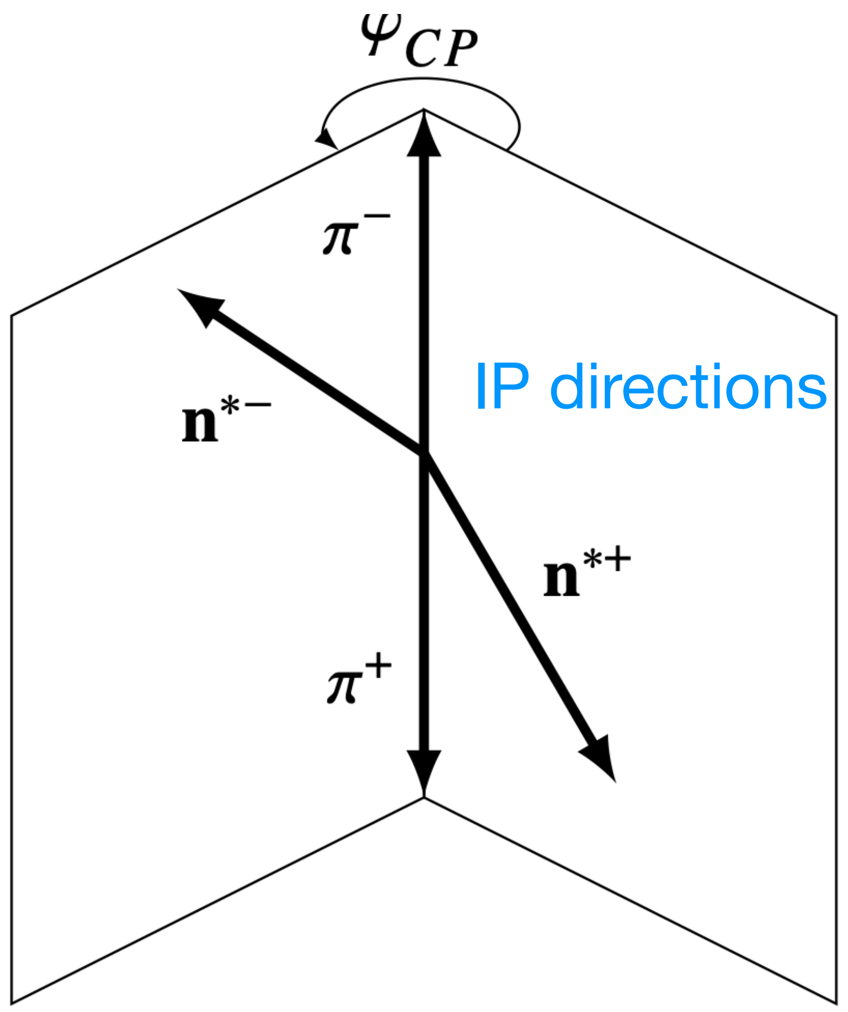
Assuming electron Yukawa SM $\tilde{\kappa}_t < 0.001$

The electron EDM constraint is weaker for taus $\tilde{\kappa}_\tau < 0.3$

Use tau polarisation variables in tau decays of the Higgs boson!

$$H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$$

Zero Momentum Frame



Tau transverse spin correlation sensitive variable

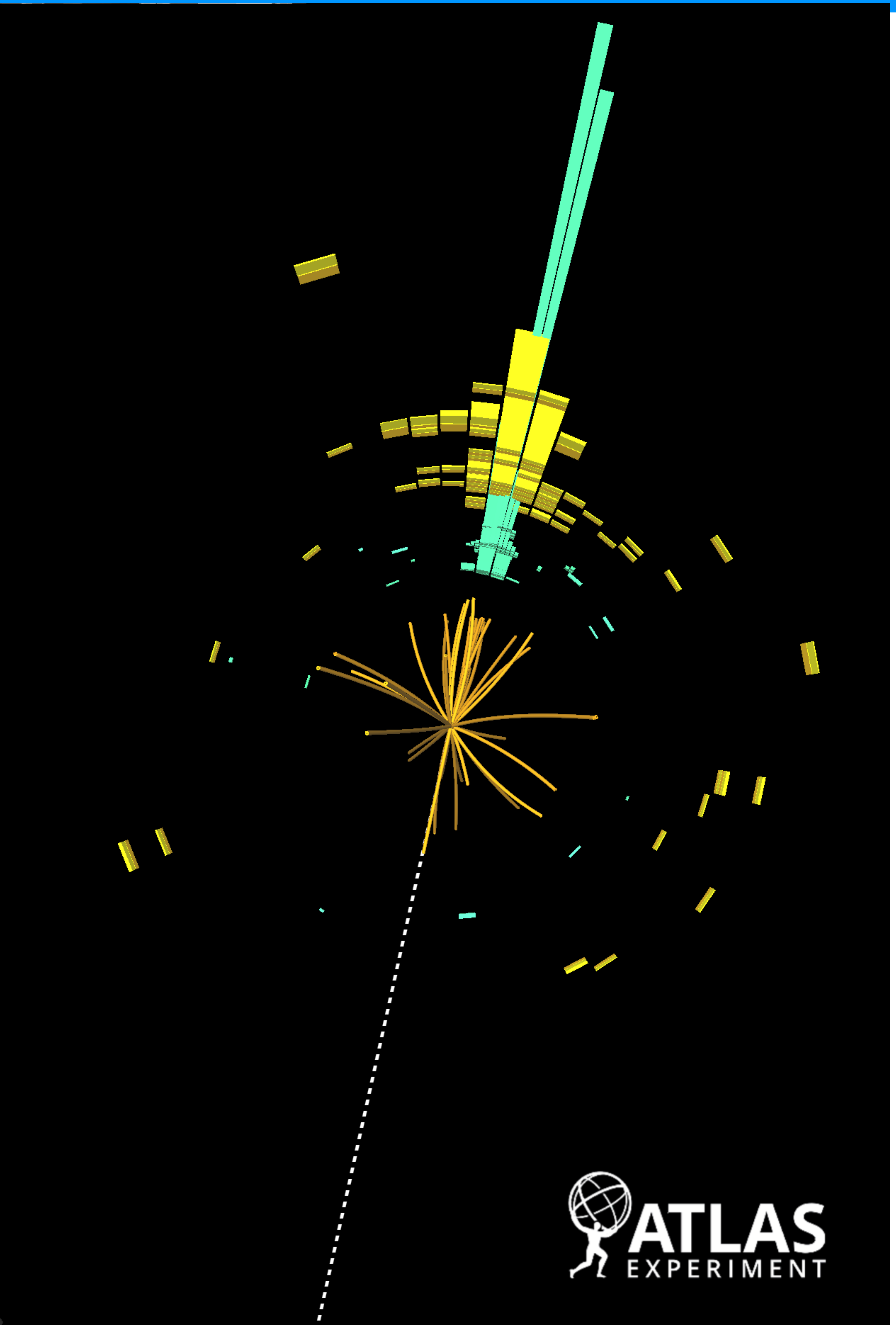
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

Fit the ϕ_τ parameter to the ϕ^*_{CP}

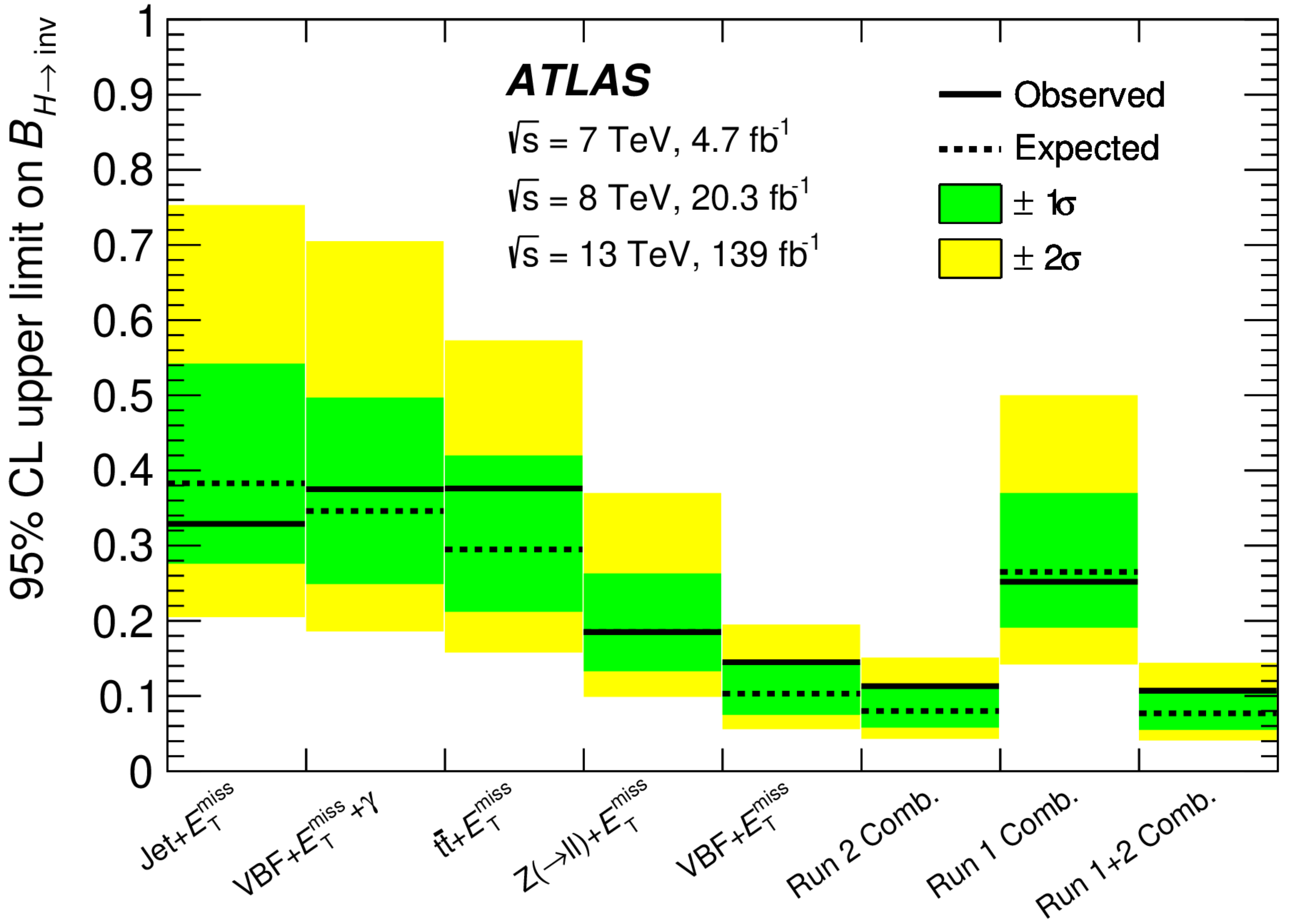
Pure CP-Odd hypothesis excluded at 3.4σ

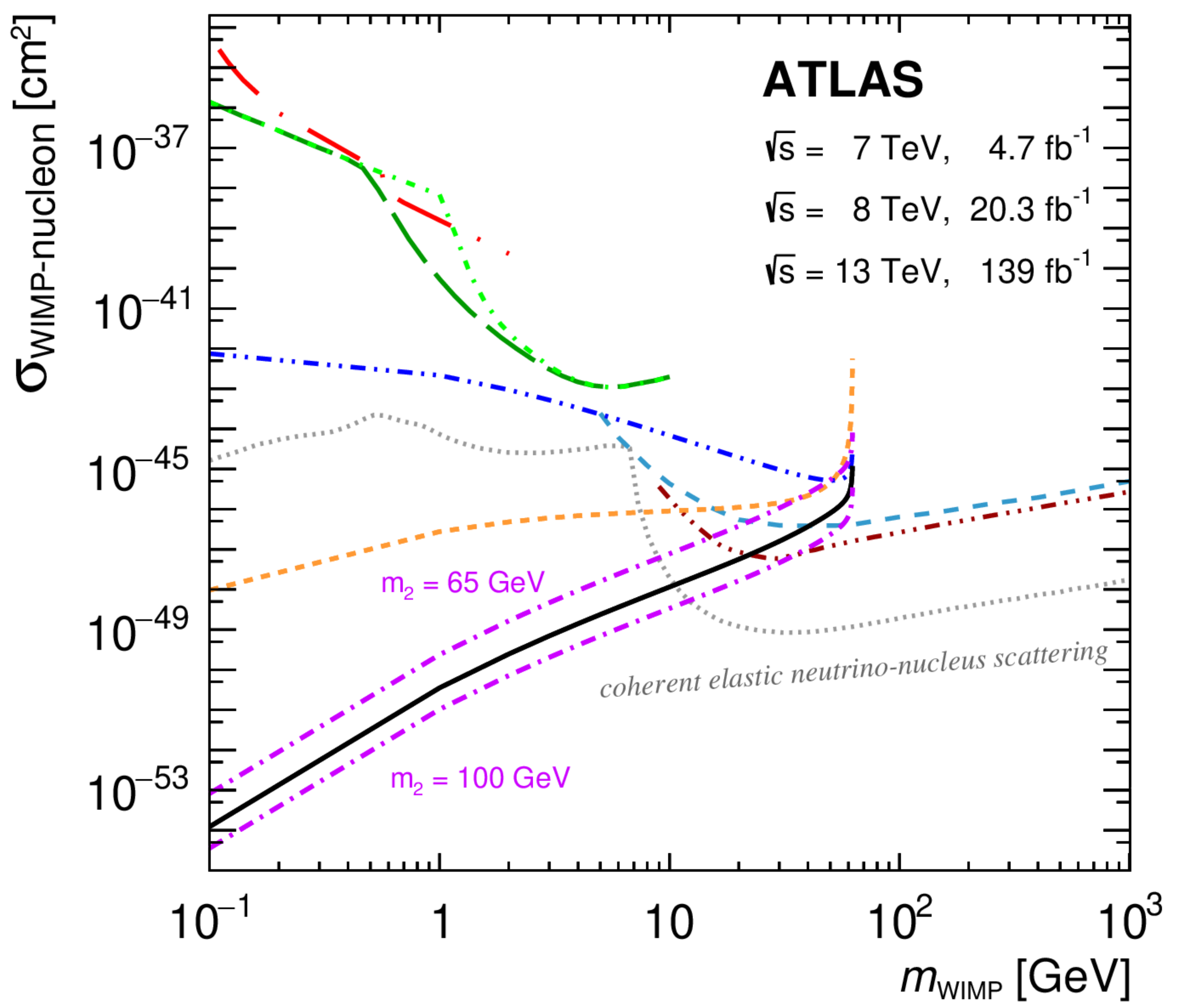
$$\phi_\tau = 9^o \pm 5^o\,(\mathrm{sys}) \pm 16^o\,(\mathrm{stat})$$

Invisible Higgs Decays



Searches for Dark Matter through Higgs Boson Decays!





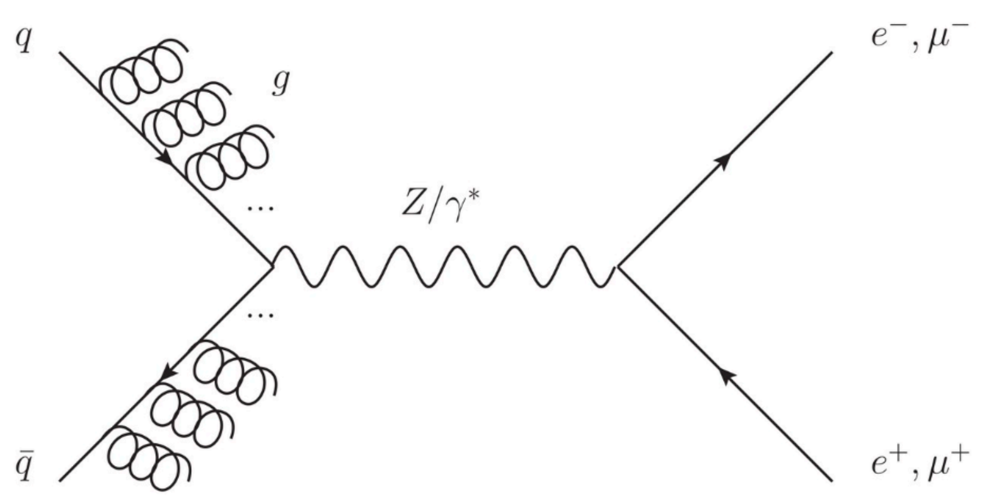
Upper limit on the H→invisible branching of **0.107** (0.077) at the 95% CL

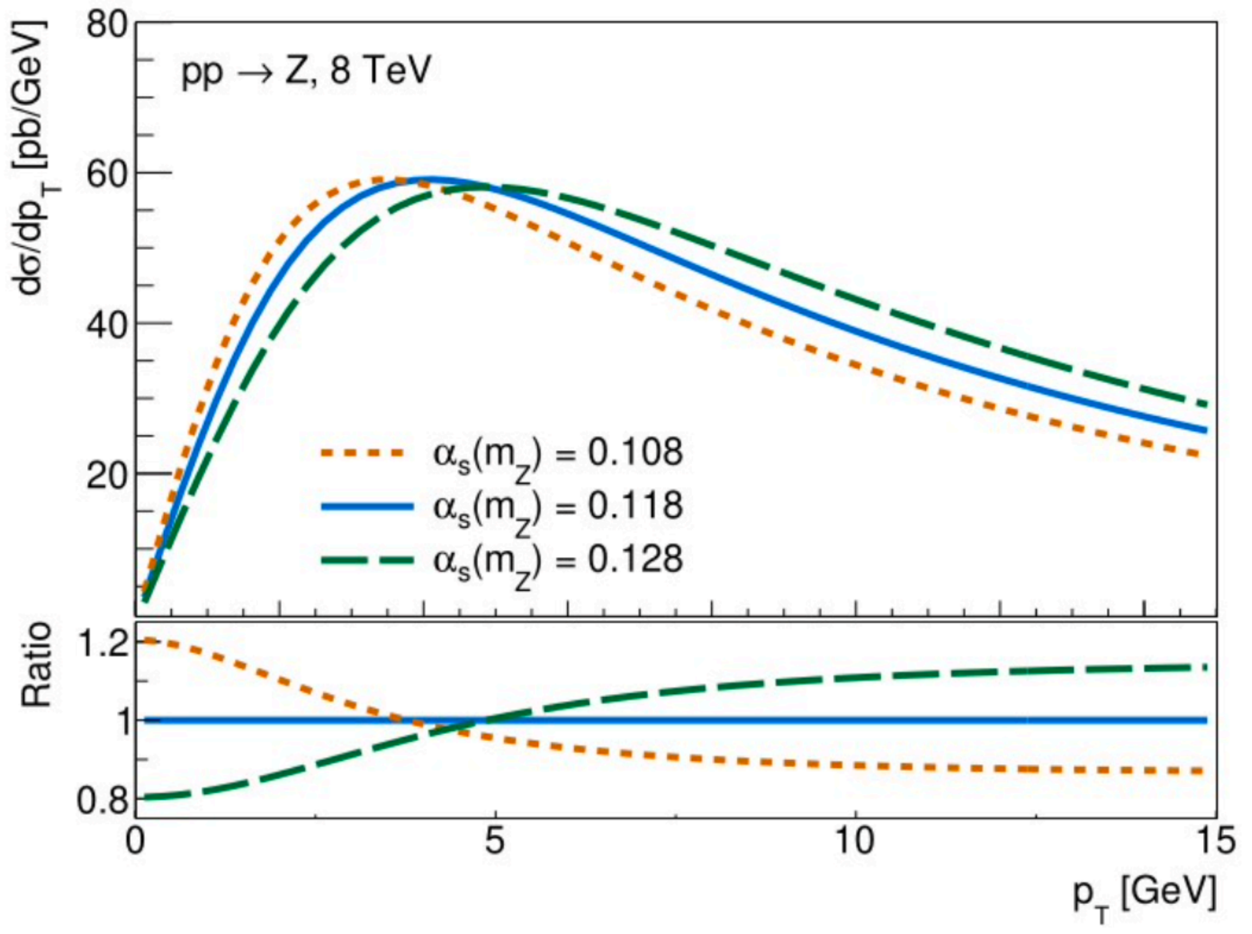
In the SM the H→invisible branching of **0.1%**

Should reach 2% level at HL-LHC! Major milestone for Run 3

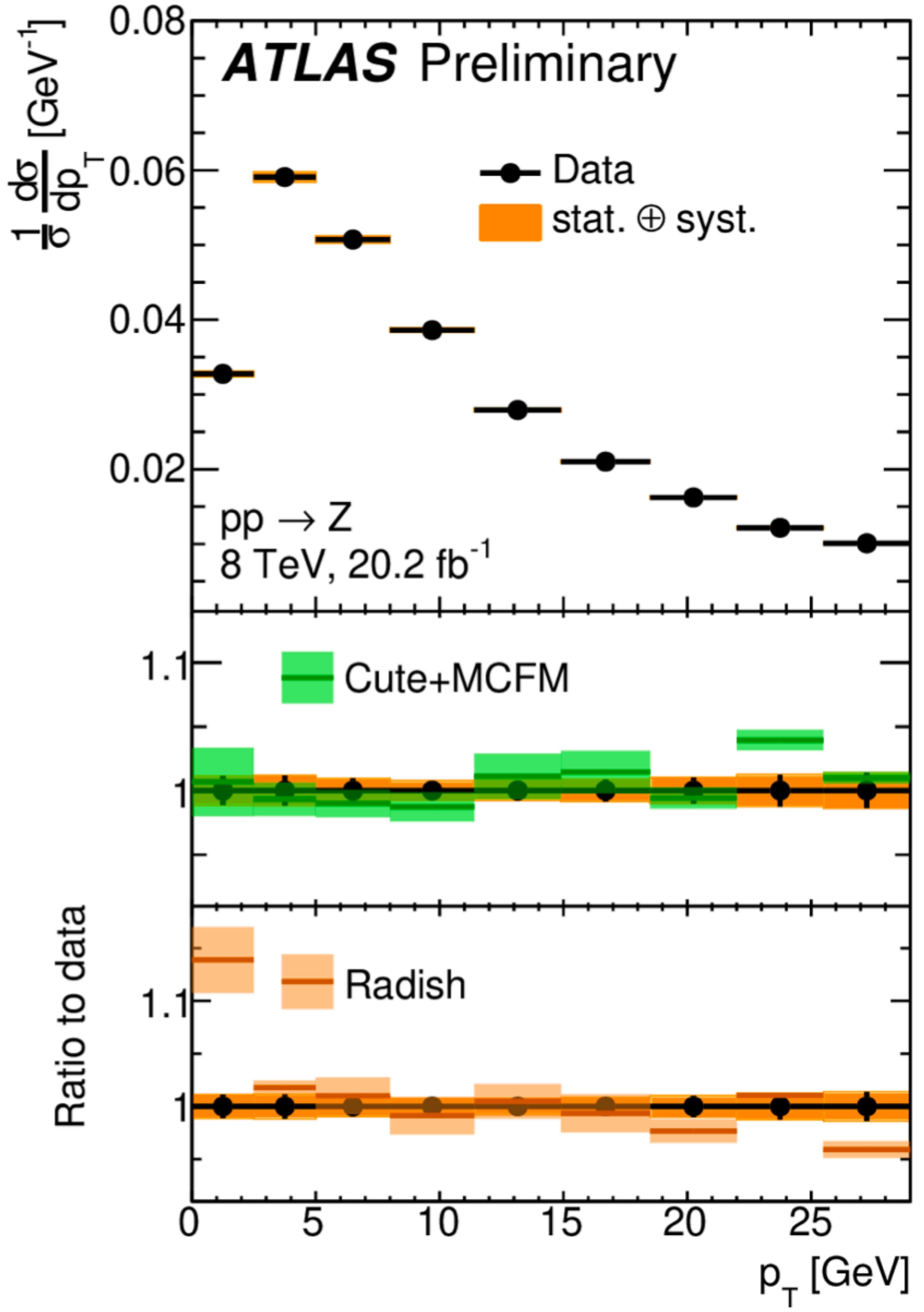
Precise Determination of α_S using $Z \to \ell^+\ell^-$

ATLAS measurement using on the **Sudakof peak in pT**, based on **resummed calculations**

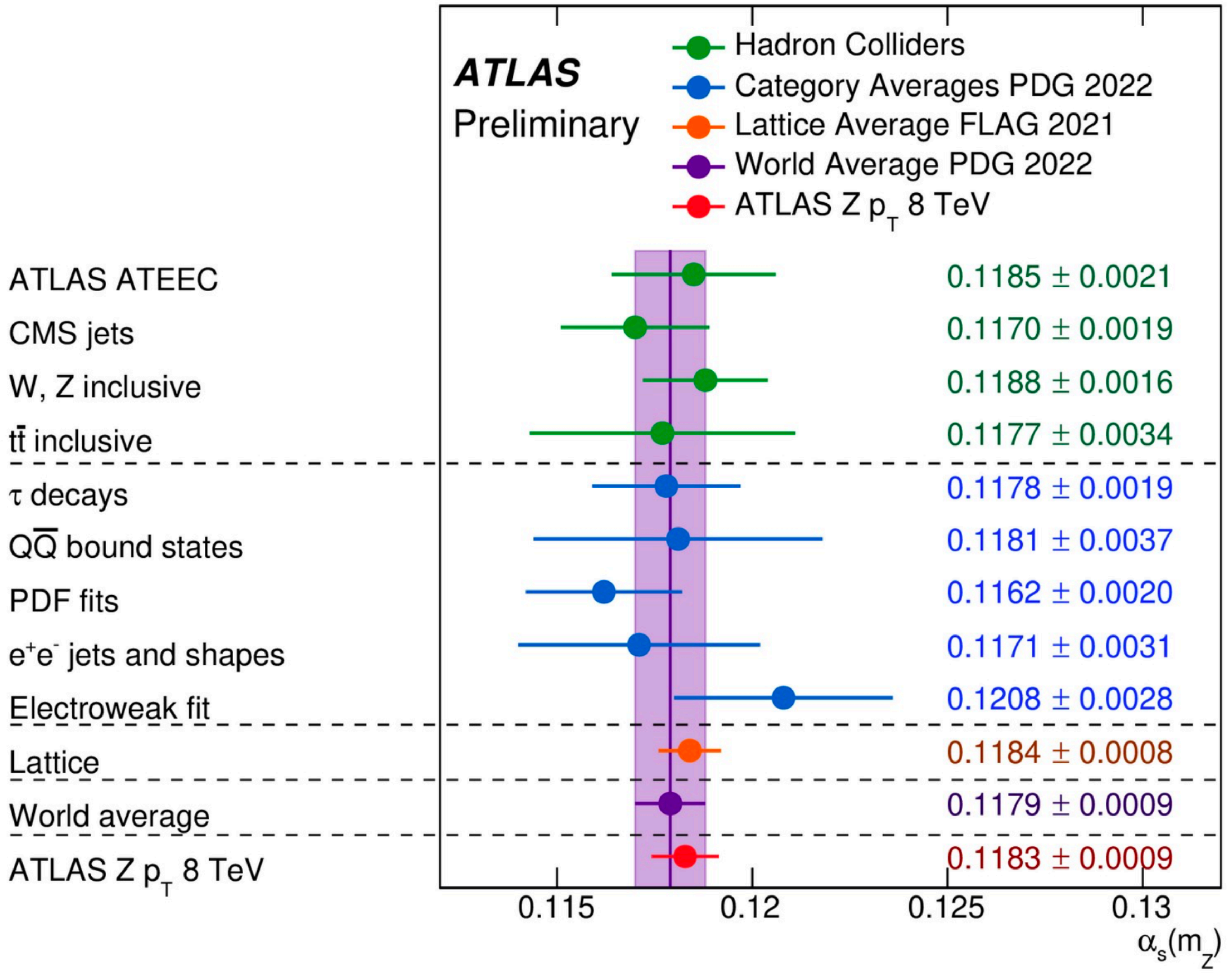




Measurement of the differential **full-lepton phase space** Z cross section!

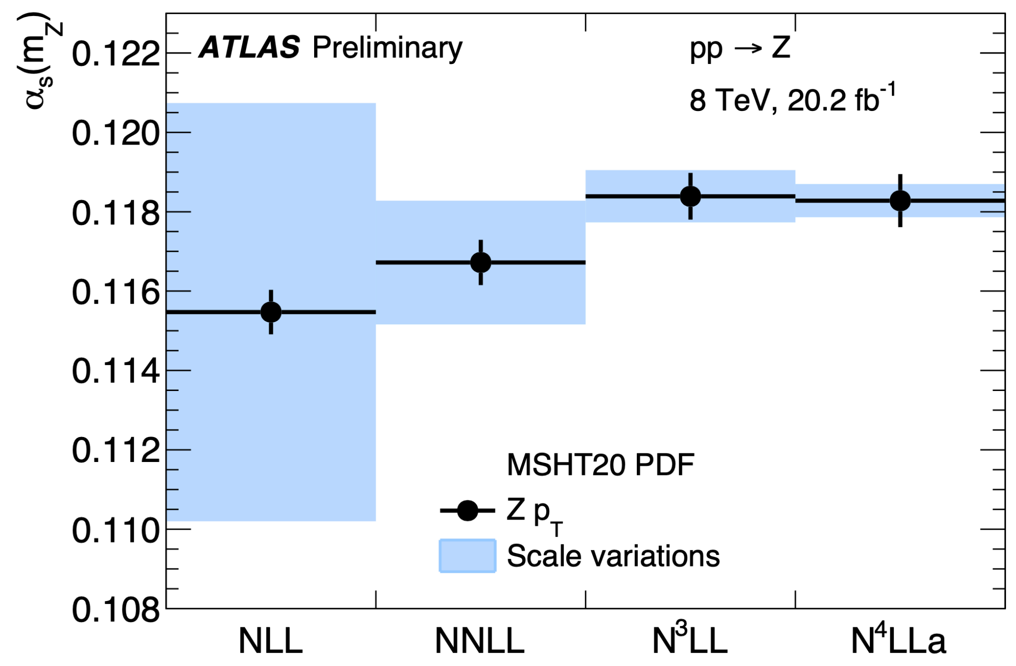


Comparisons done at N3LO-N4LL with N3LO PDFs !!!



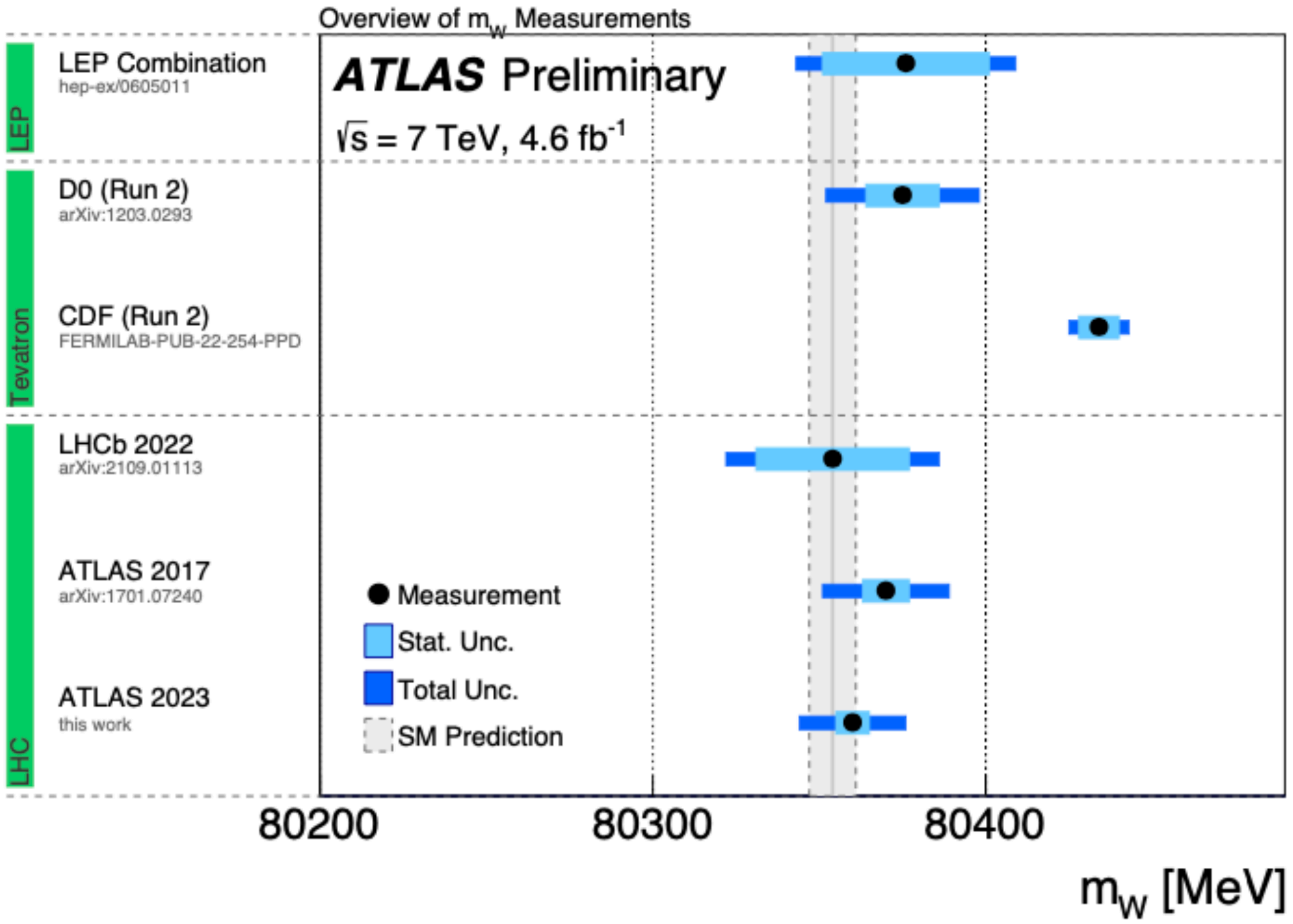
Precision on par with lattice QCD and world average!

Such precision would not be possible without precise TH predictions!



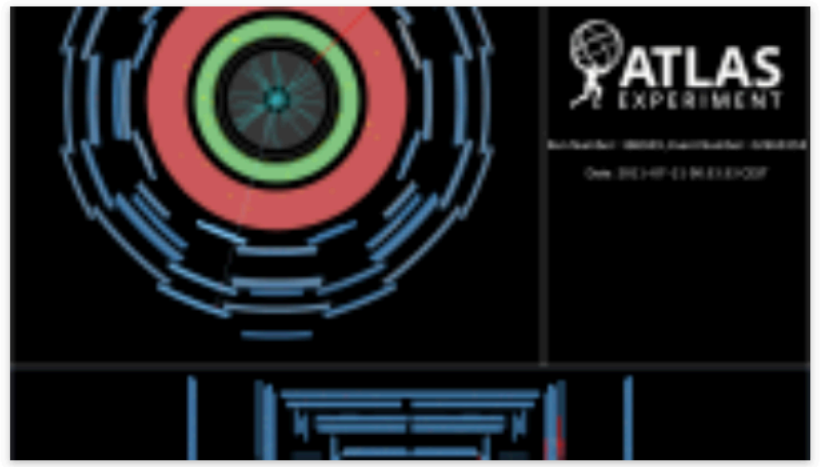
W Mass Puzzle

Measurements at LHC from ATLAS and LHCb



m_W = 80360±5(stat.) ±15(syst.) = 80360 ±16 MeV

m_W = 80370 ±19 MeV



Improved ATLAS result weighs in on W boson

An improved ATLAS measurement of the W boson mass is in line with the Standard Model of particle physics

Press release | Physics | 23 March, 2023

CERN press release

- Recent W mass update from ATLAS is agreeing even more with the SM prediction

  Several small improvements, but mostly relying on the huge analysis effort of the first 7 TeV

- **The tension with the CDF W mass is larger between ATLAS (only) and CDF 3.4σ now 4σ**

- (Tension of CDF measurement with the SM 7σ)

Where do we go from here?

Significant evidence of measurement systematic bias: **would need a collective effort to understand this puzzle!**

More measure precise measurements to come at the LHC!

Quantum Information at High Energies

In top pair production at the LHC, top quarks are **not produced polarised,** however in the gluon dominated production (90%) a **spin correlation** exists.

Spin correlations $pp \to t\bar{t}$ already measured, however could be used to demonstrate that the two tops are in a non separable state (i.e. entangled).

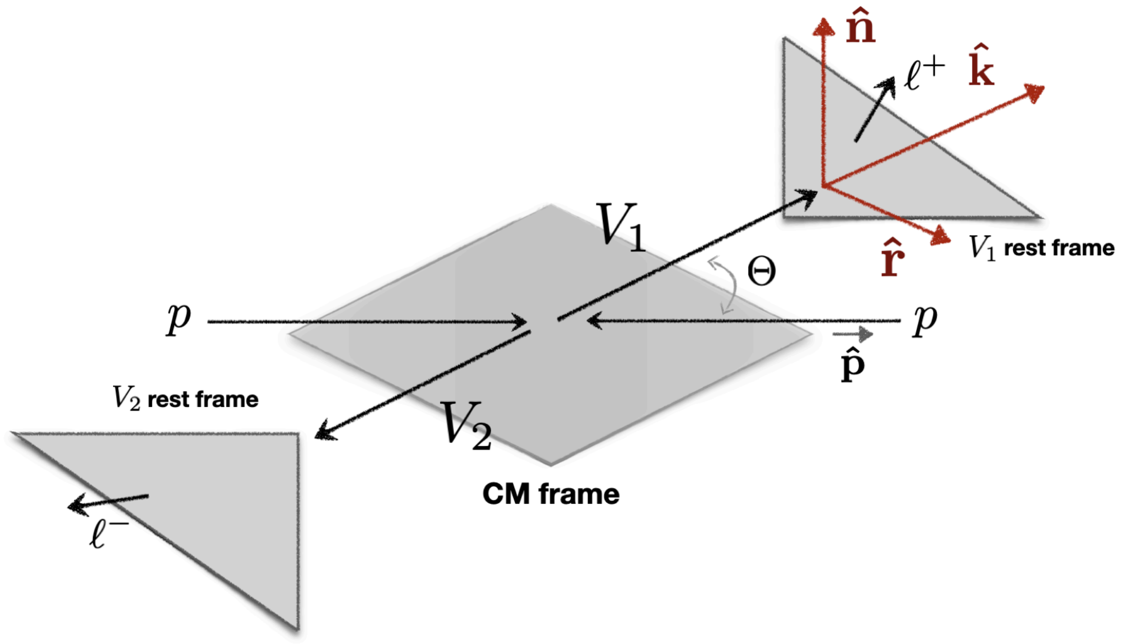
The lifetime of the top quark is shorter than the timescale for hadronisation (~10^{-23} s) and much shorter than the spin decorrelation time (~10^{-21} s) the spin information of the top quark is therefore

The spin configurations at threshold production i.e. $\beta_t \sim 0$ the $gg \to t\bar{t}$ is dominated by the "singlet" spin configuration, **which is a pure, superposed and maximally entangled Bell state**:

$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow> - |\downarrow\uparrow>\right)$$

Measure of entanglement level:
The trace of the three dimensional spin correlation matrix C (in the base illustrate here)

$$D = \mathrm{tr}[\mathbf{C}]/3 < -1/3$$

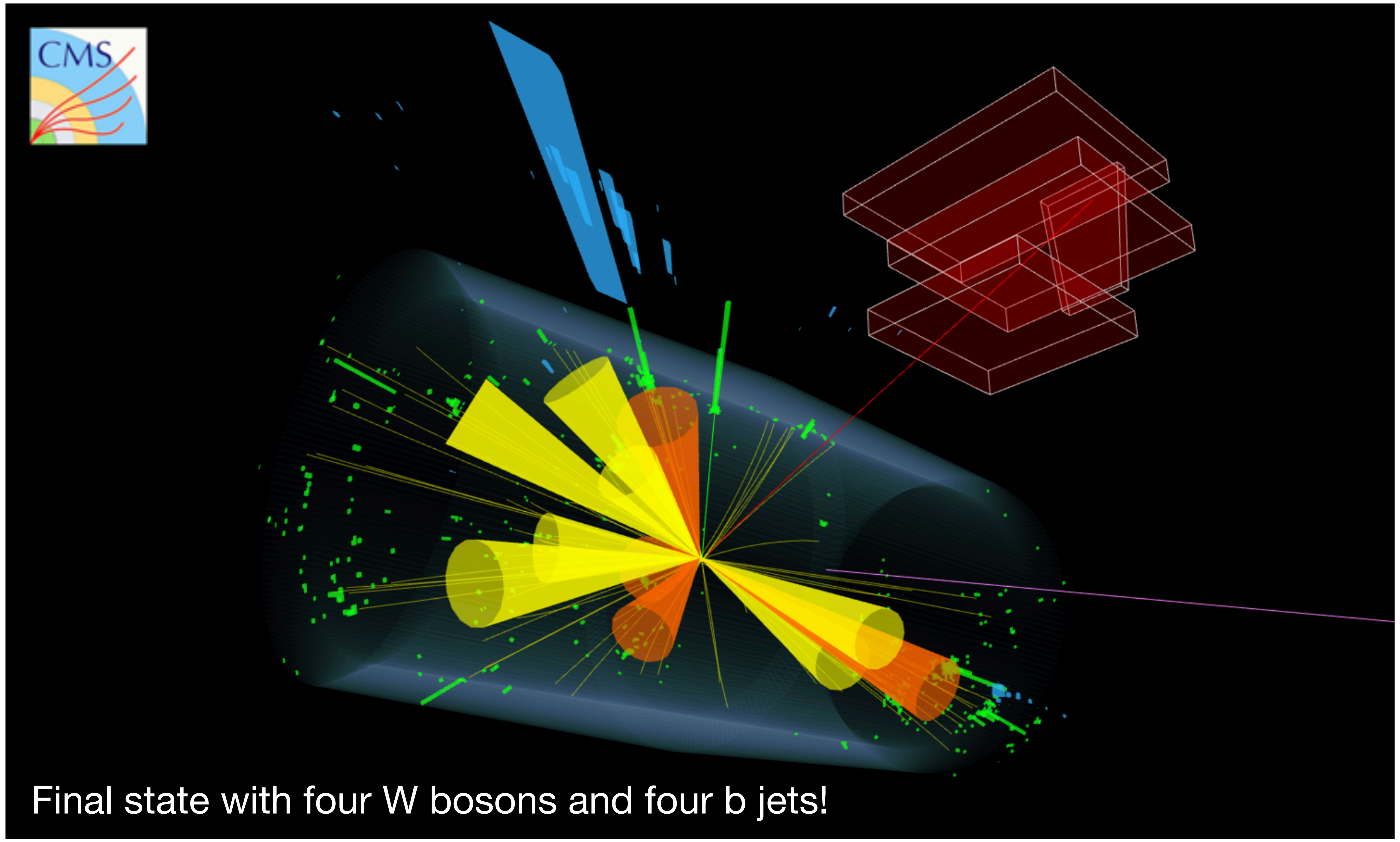


Analysis by ATLAS using fully leptonic electron/muon top pair events measuring D at the particle level in the near-threshold region [340, 380] GeV

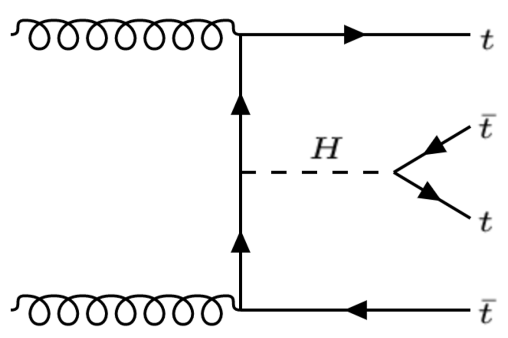
$$D = -0.547 \pm 0.002\ (\mathrm{stat}) \pm 0.021\ (\mathrm{syst})$$

Unambiguous observation of entanglement!

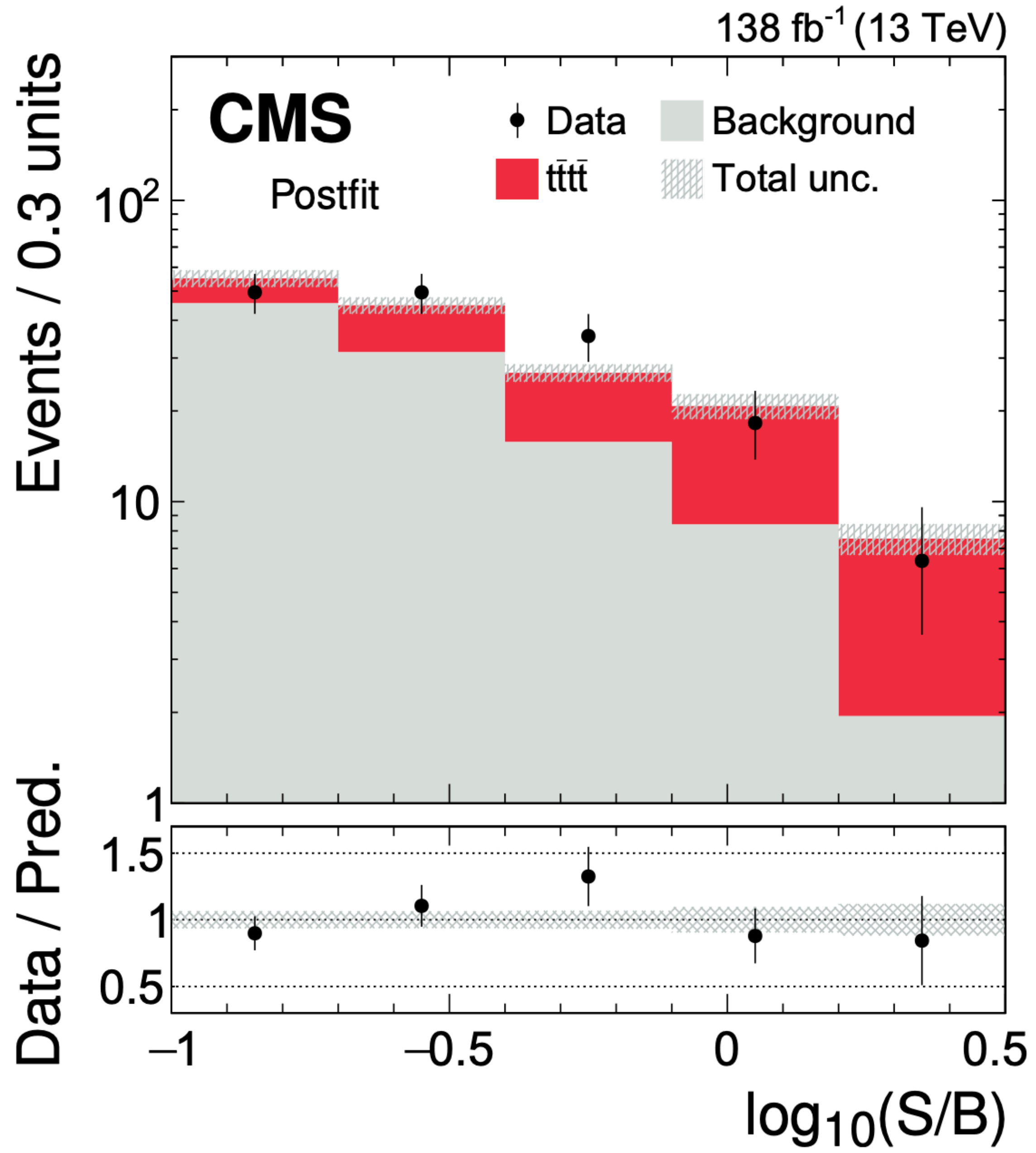
Four Top Quarks Production



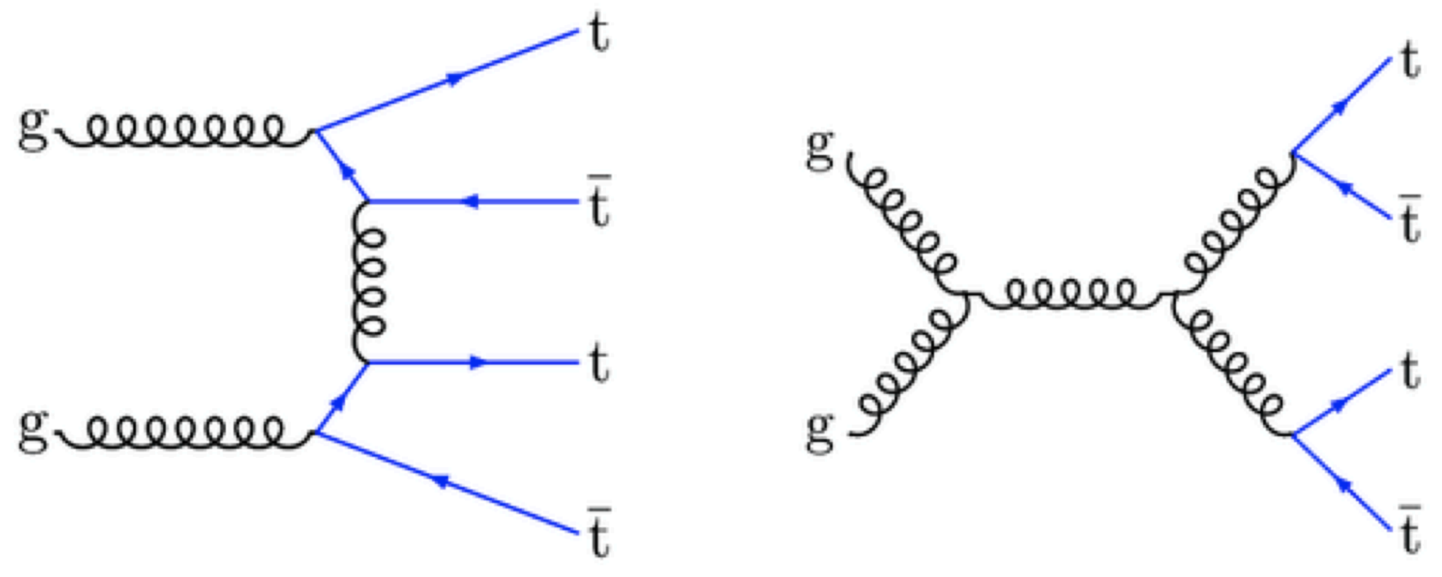
Clear observation with combined significance **5.6σ obs.** (4.9 exp.)



Also sensitive to Higgs contribution!



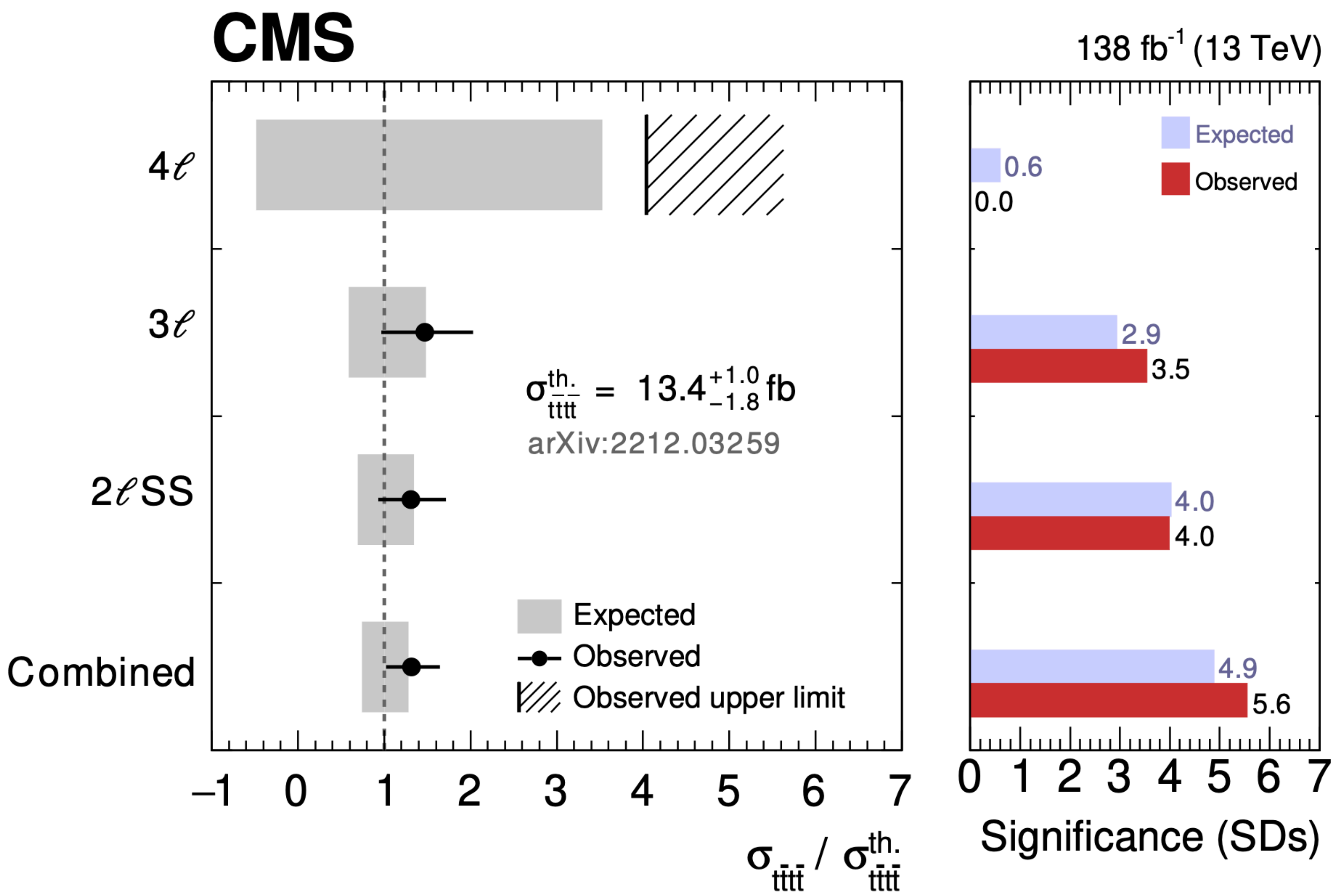
Four top production at LHC: Example of complexity revealed!



$\sigma^{SM}_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4$ fb

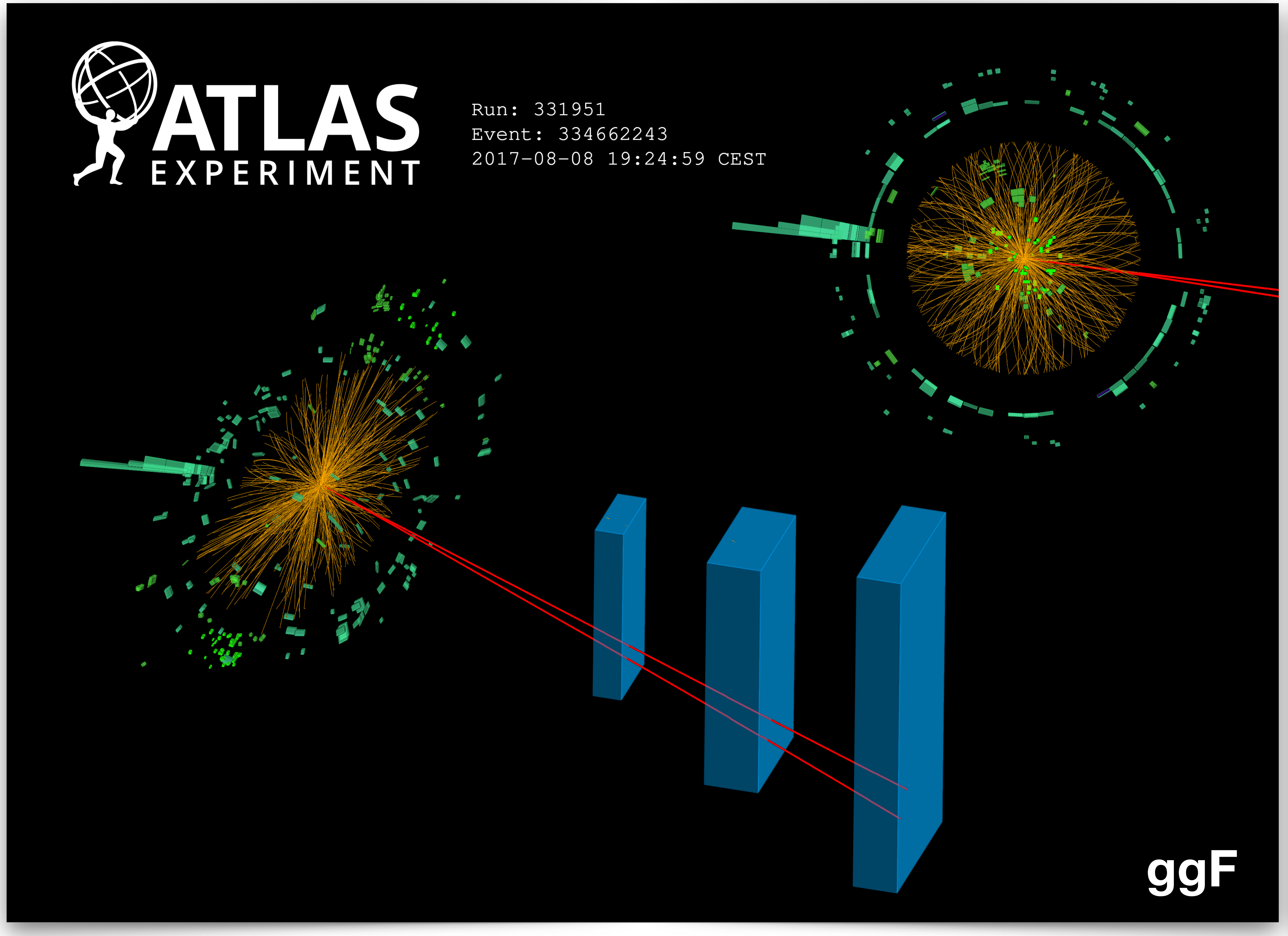
Very small cross section and very intricate final state!!

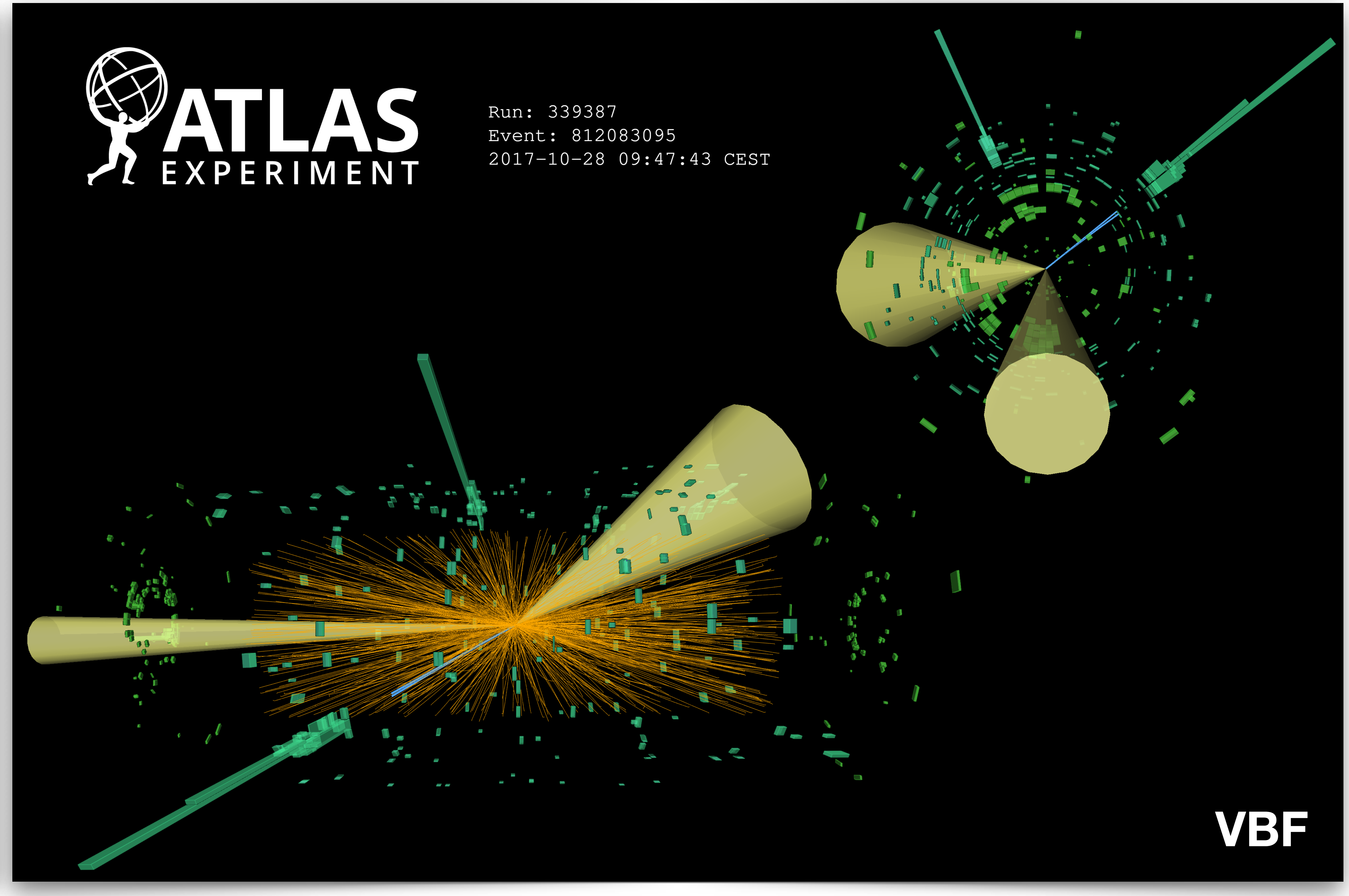
Searched for through its clea signature (muons and electrons) 4L, 3L and 2L-SS



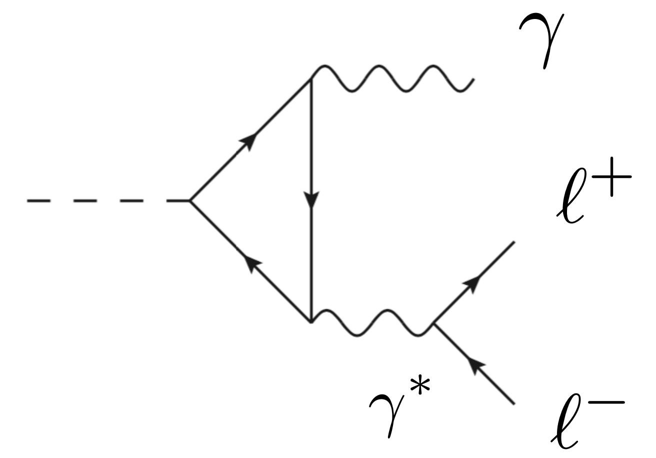
Measurements in agreement with SM!

Evidence for $H \to \gamma^* \ell^+ \ell^-$





Evidence for $H \to \gamma^* \ell^+ \ell^-$ and $H \to Z\gamma$



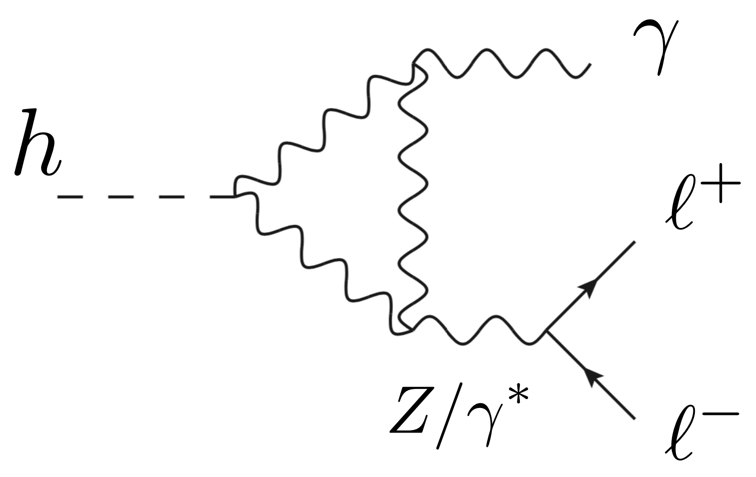
$m_{\ell^+\ell^-} < 50$ GeV

~ 1.7% of $Br(\gamma\gamma)$

Key experimental challenge: low dilepton mass! Required a **new reconstruction technique**

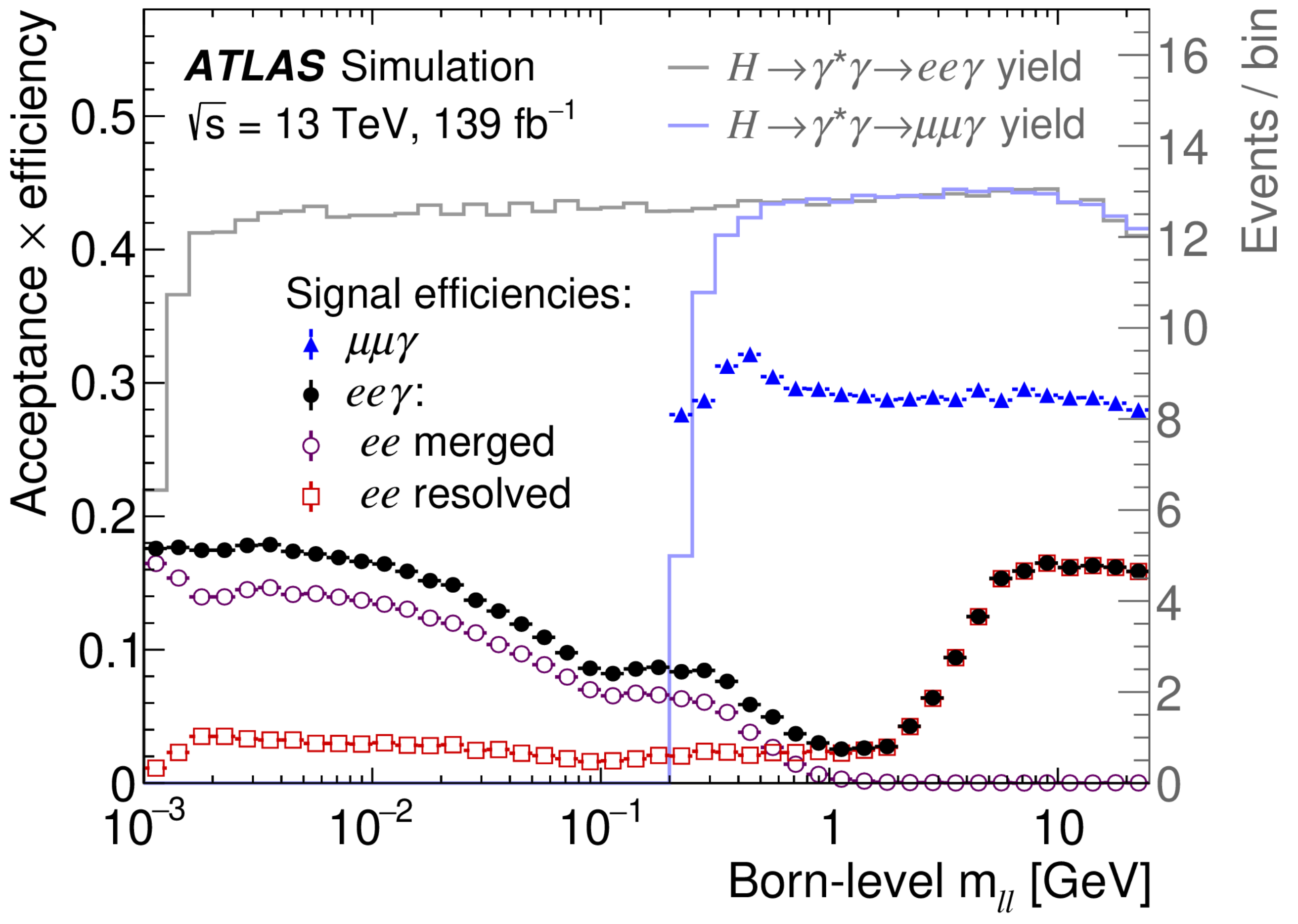
Z-photon $|H^2| W^a_{\mu\nu} W^{\mu\nu a}$

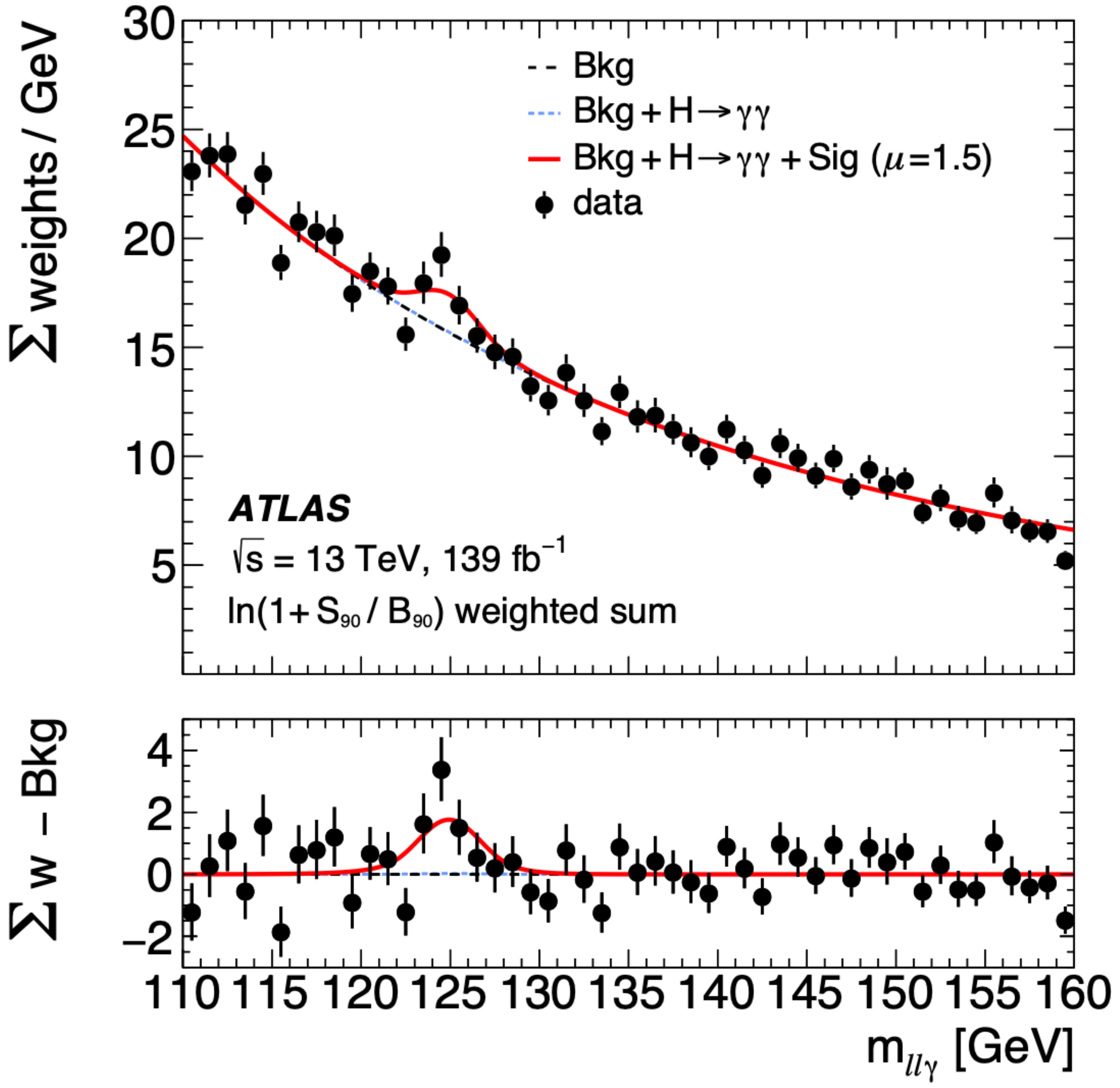
Field tensor coupling not measured yet!



~ 2.3% x $Br(\gamma\gamma)$

Merged electron reconstruction where a calorimeter (electron-like) cluster is associated to two tracks and conversions are carefully rejected!



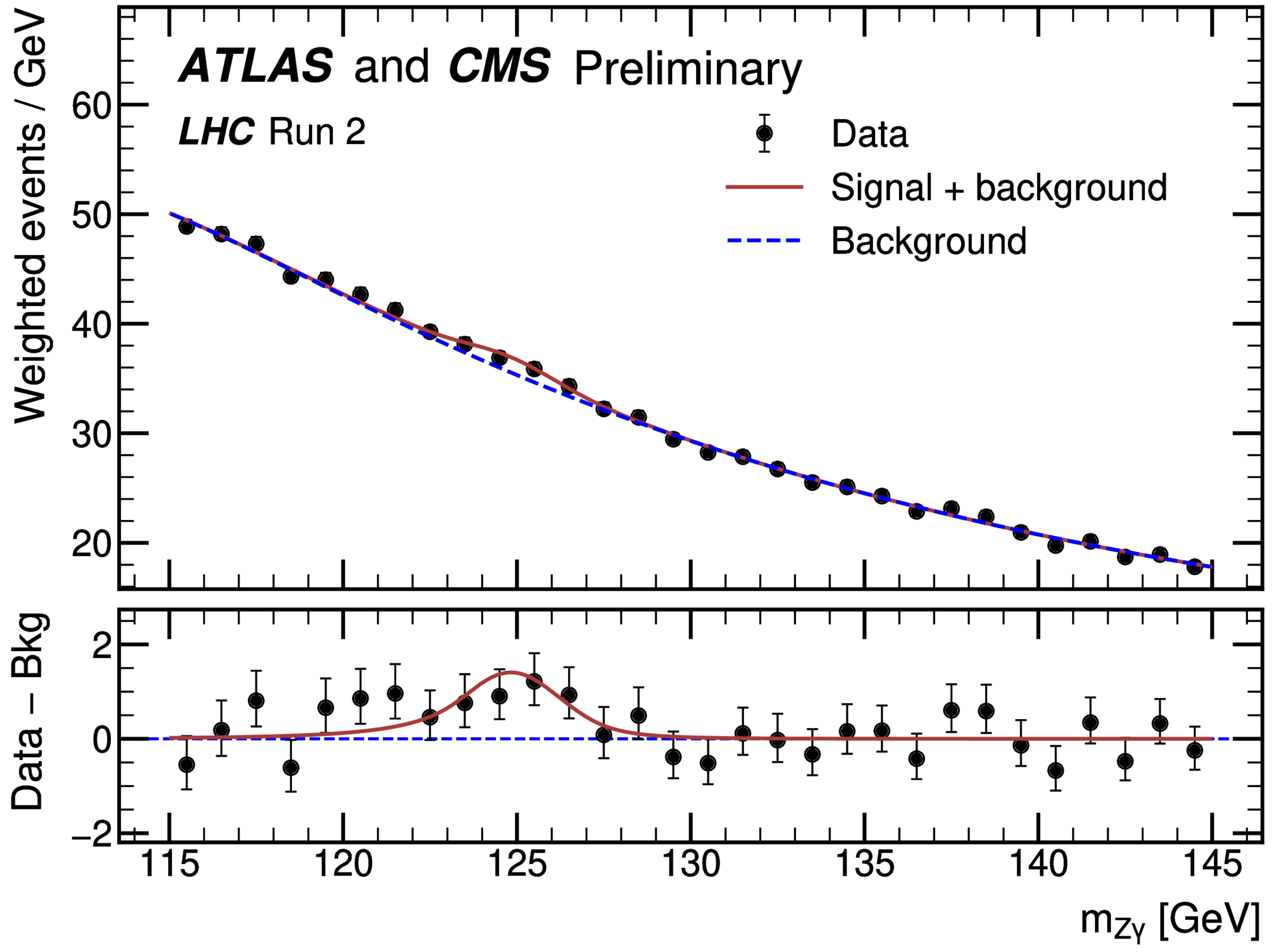


Phys. Lett. B 819 (2021) 136412

Expected 2.1σ

Observed 3.2σ

Combined ATLAS and CMS mass spectrum!

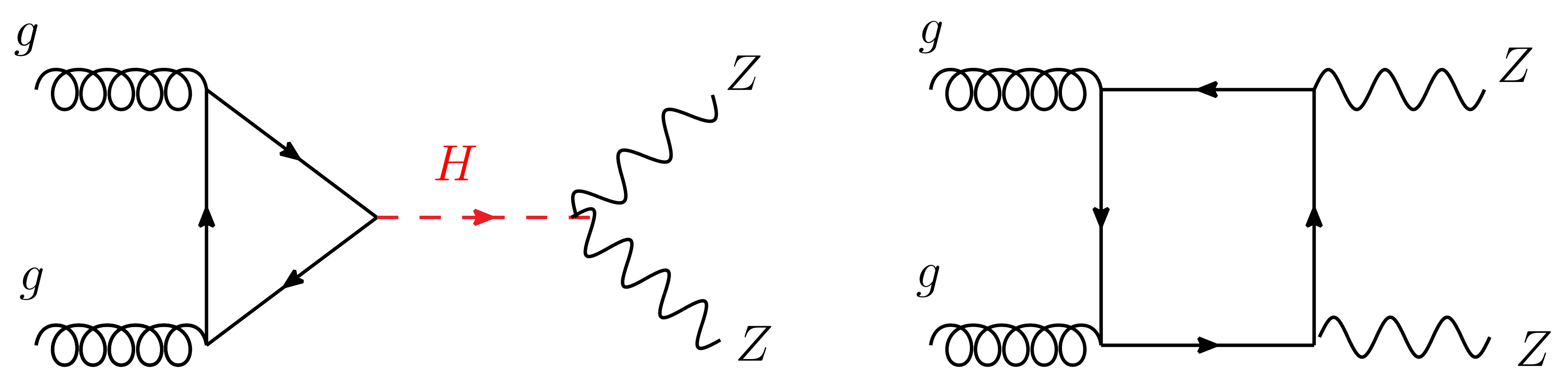


Combined search yields 3.4σ observed and 1.6σ expected (consistent with the SM expectation at the 1.9σ): First evidence!

HL-LHC ~10%

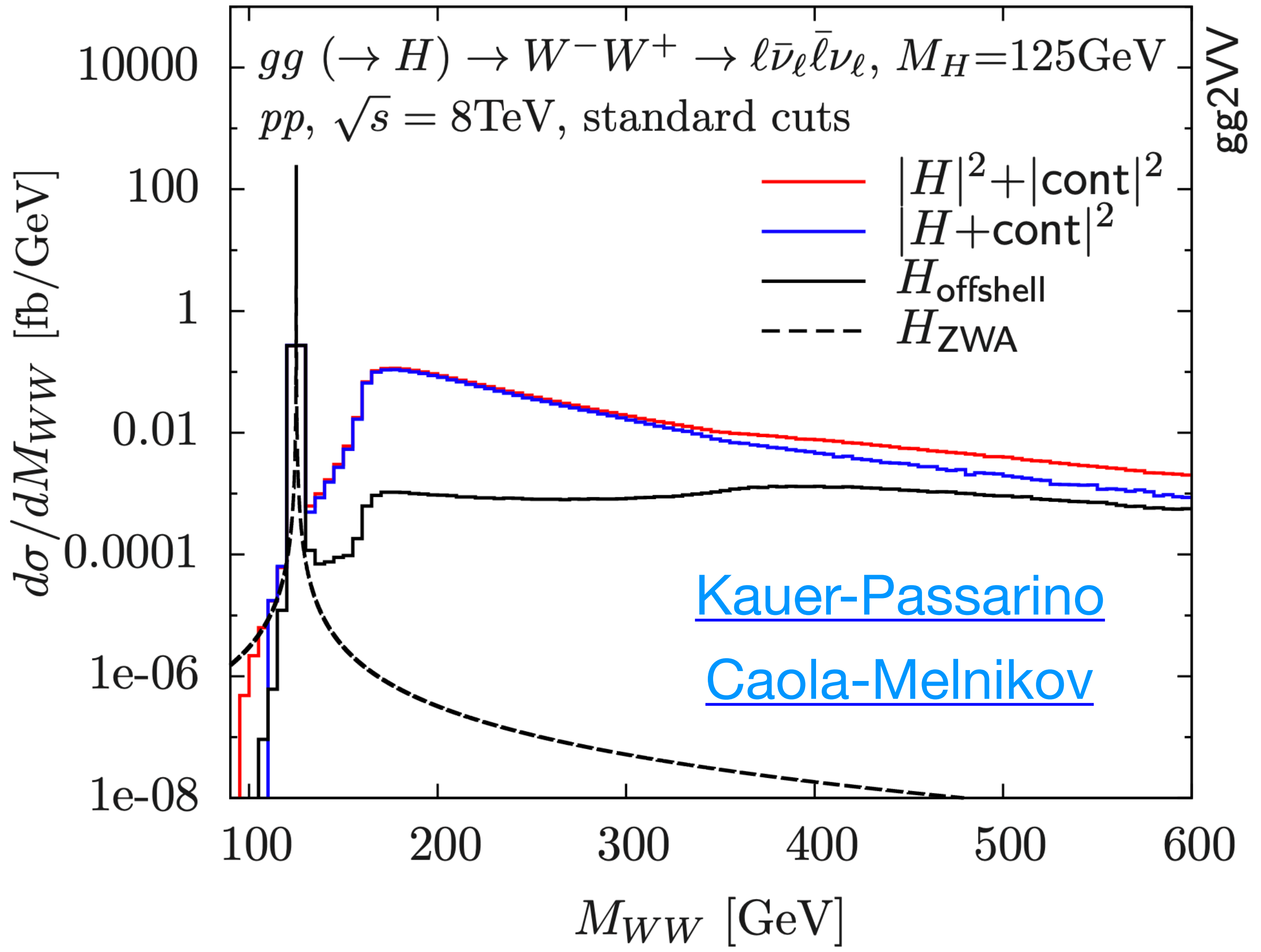
Off Shell HVV Couplings and Width

Off Shell Higgs boson to VV couplings



Study the 4-leptons spectrum in the high mass regime where the Higgs boson acts as a **propagator**

Negative interference between s-channel Higgs and di-boson production through gluon fusion…



Higgs Boson width

Thought to be impossible at the LHC!

Assumption of Standard Model and comparison to on shell allows for a measurement of the width of the Higgs boson!

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM} \qquad (\kappa_t^2\kappa_V^2)_{on\ shell} = (\kappa_t^2\kappa_V^2)_{off\ shell}$$

Yielding measurements of the Higgs width (CMS PRD 99):

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

Evidence for Off-Shell production at 3.6σ

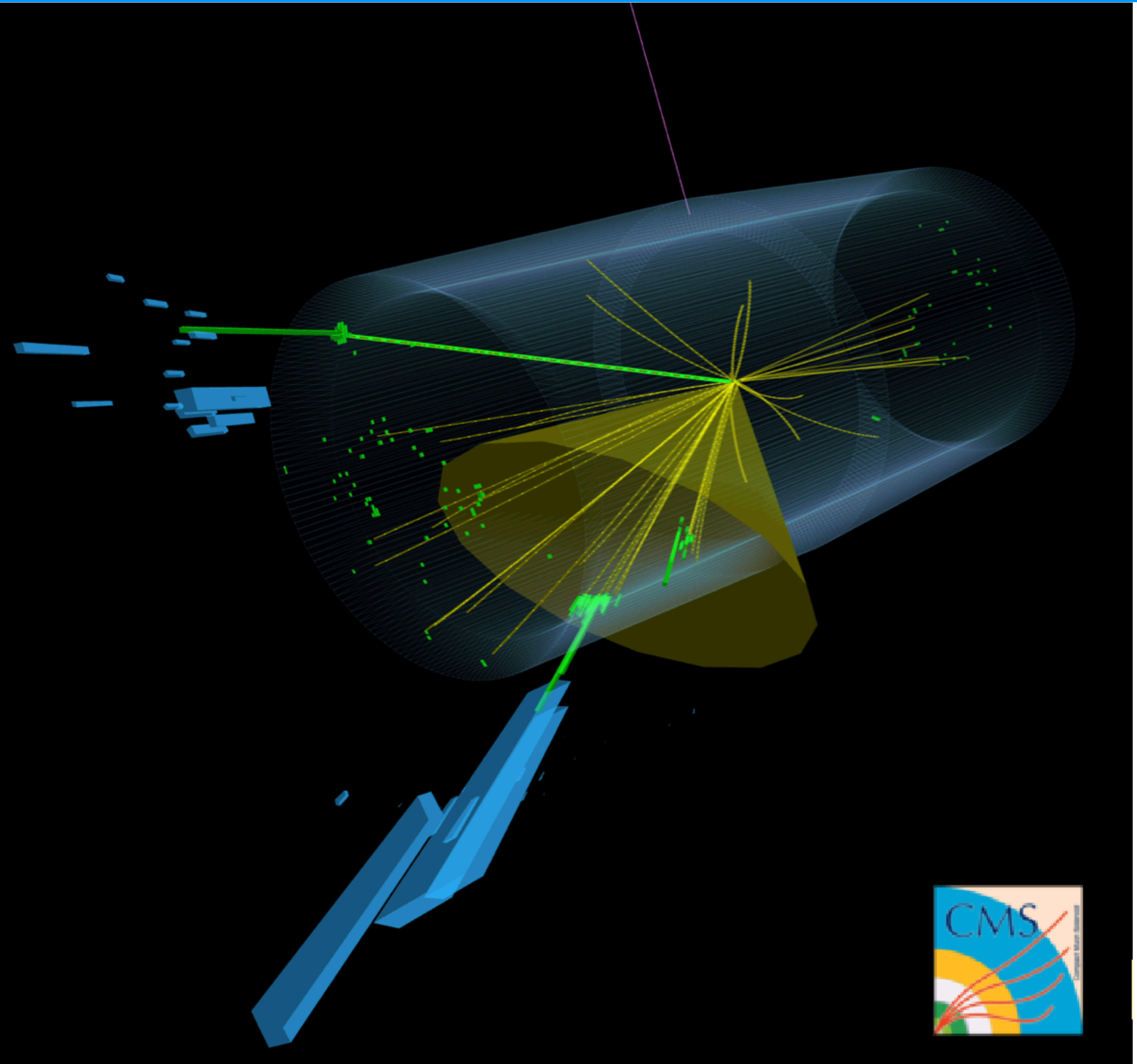
at HL-LHC:

$$\Gamma_H = 4.1^{+1.0}_{-1.1}$$

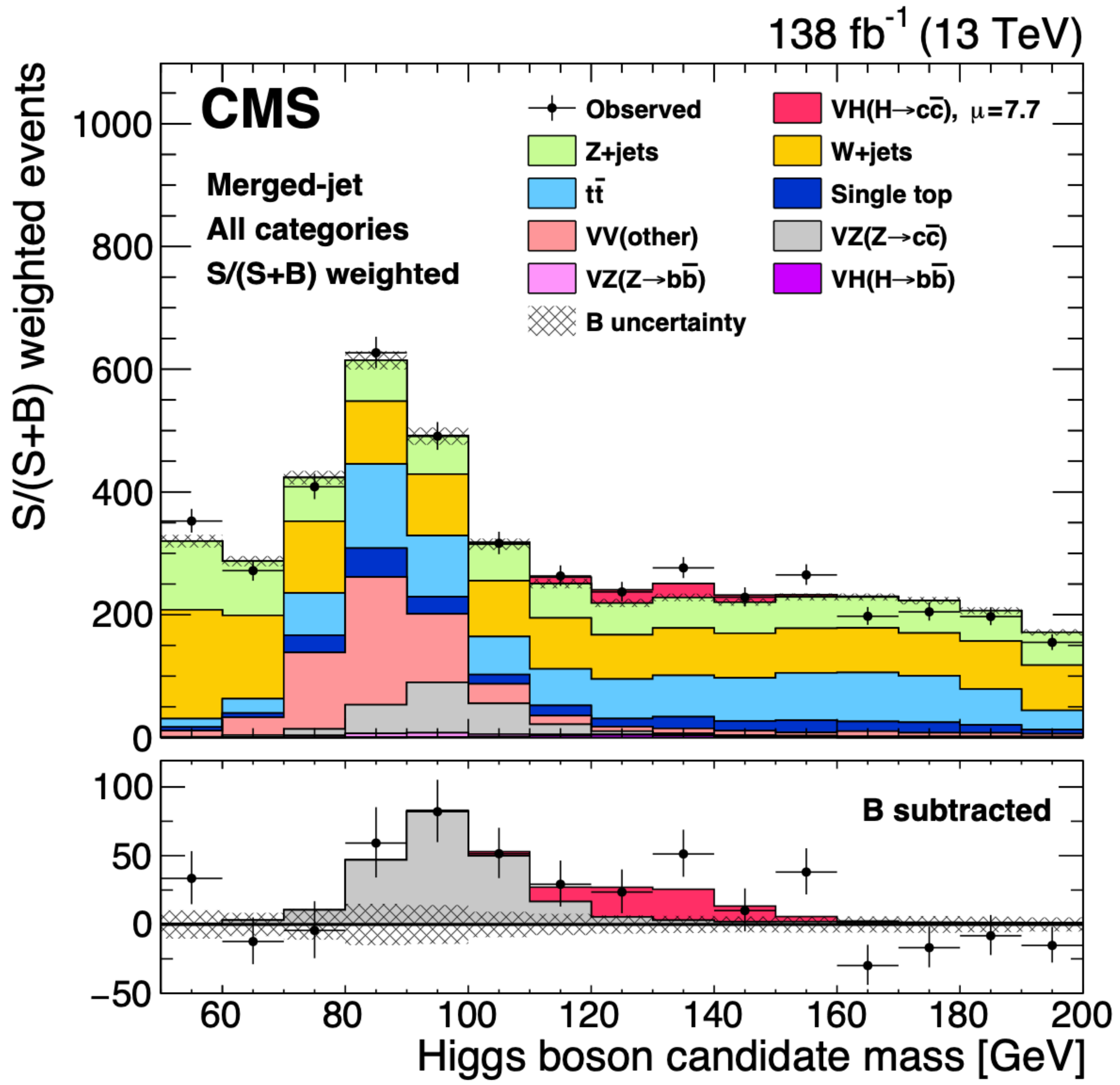
Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab^{-1}

Remarkable result to follow closely at Run 3!
How much better can be done at HL-LHC?

The Yukawa coupling to charm



Use of state-of-the-art ML techniques Particle Net uses Dynamic Graph CNN

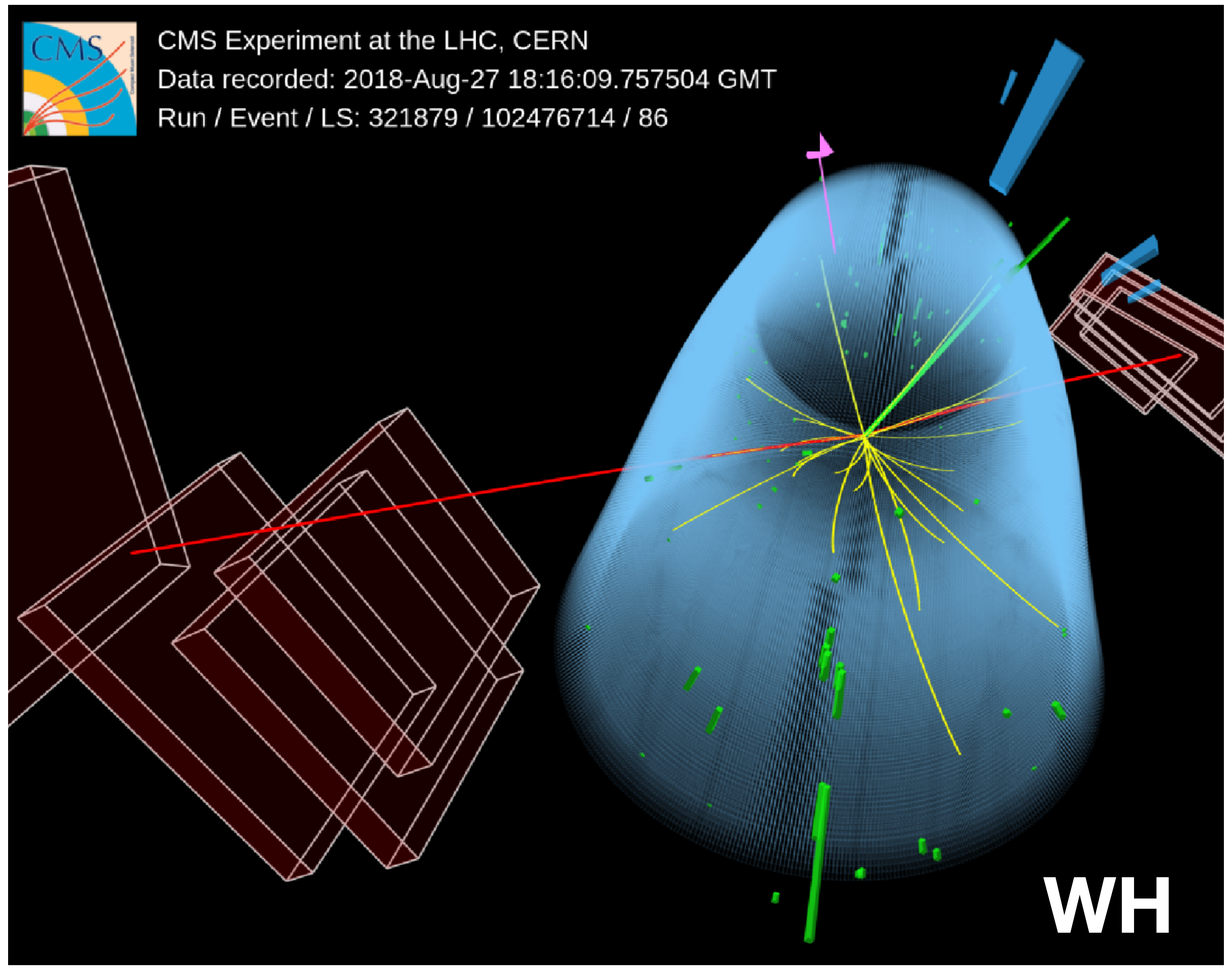


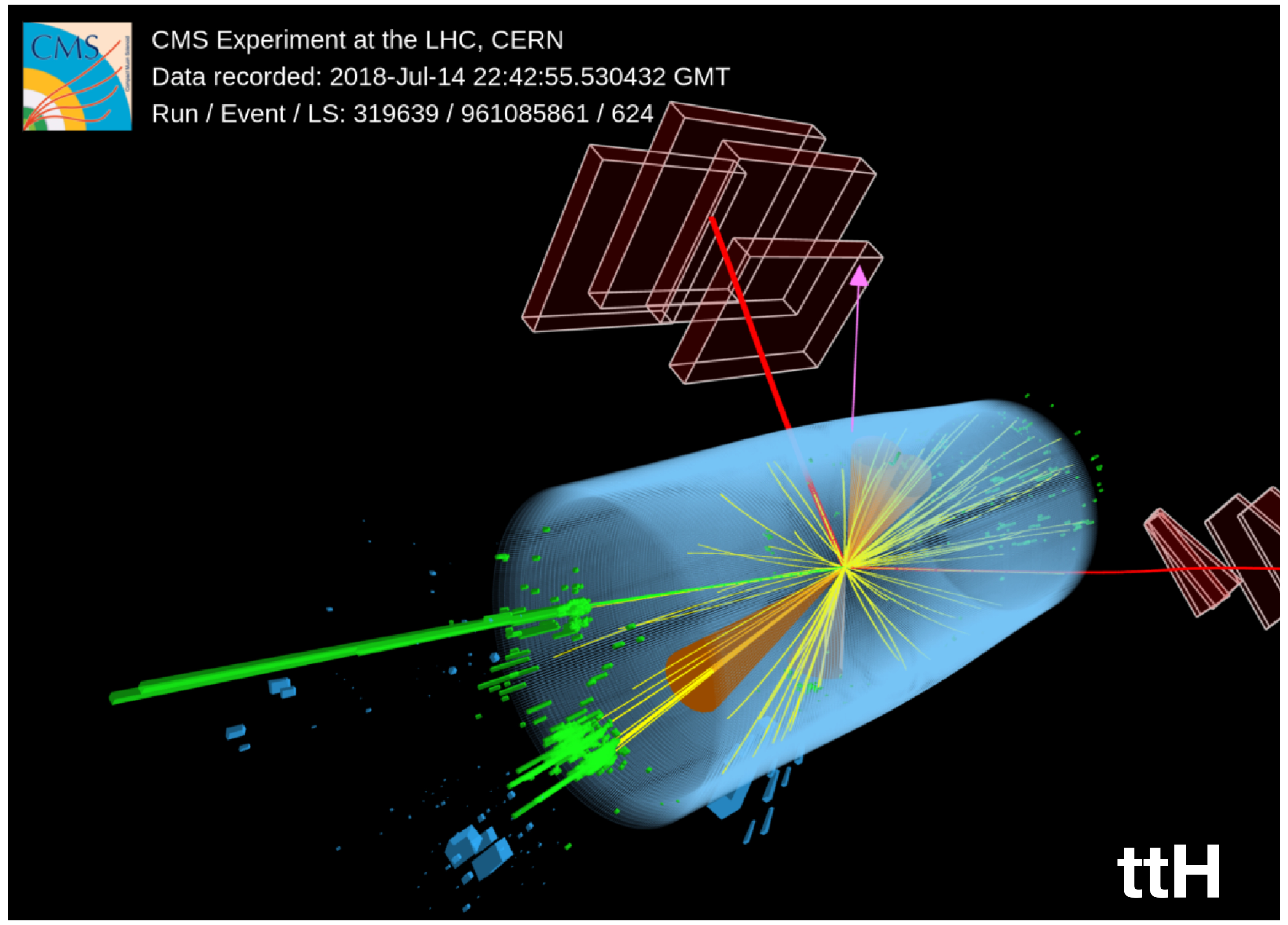
Constraints on charm Yukawa $1.1 < \kappa_c < 5.5$

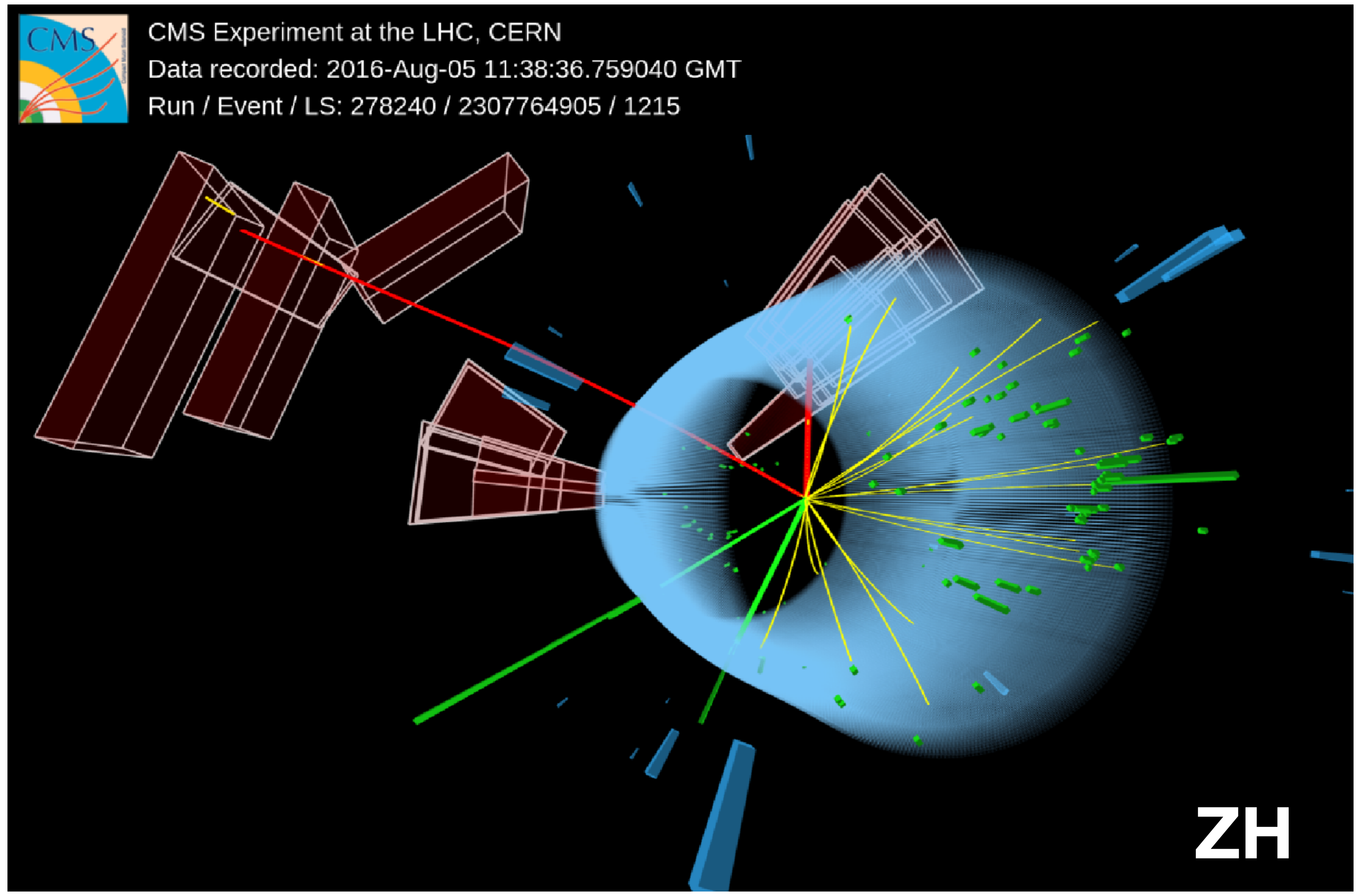
Yields a precision on κ_c of ~40% per experiment at HL-LHC

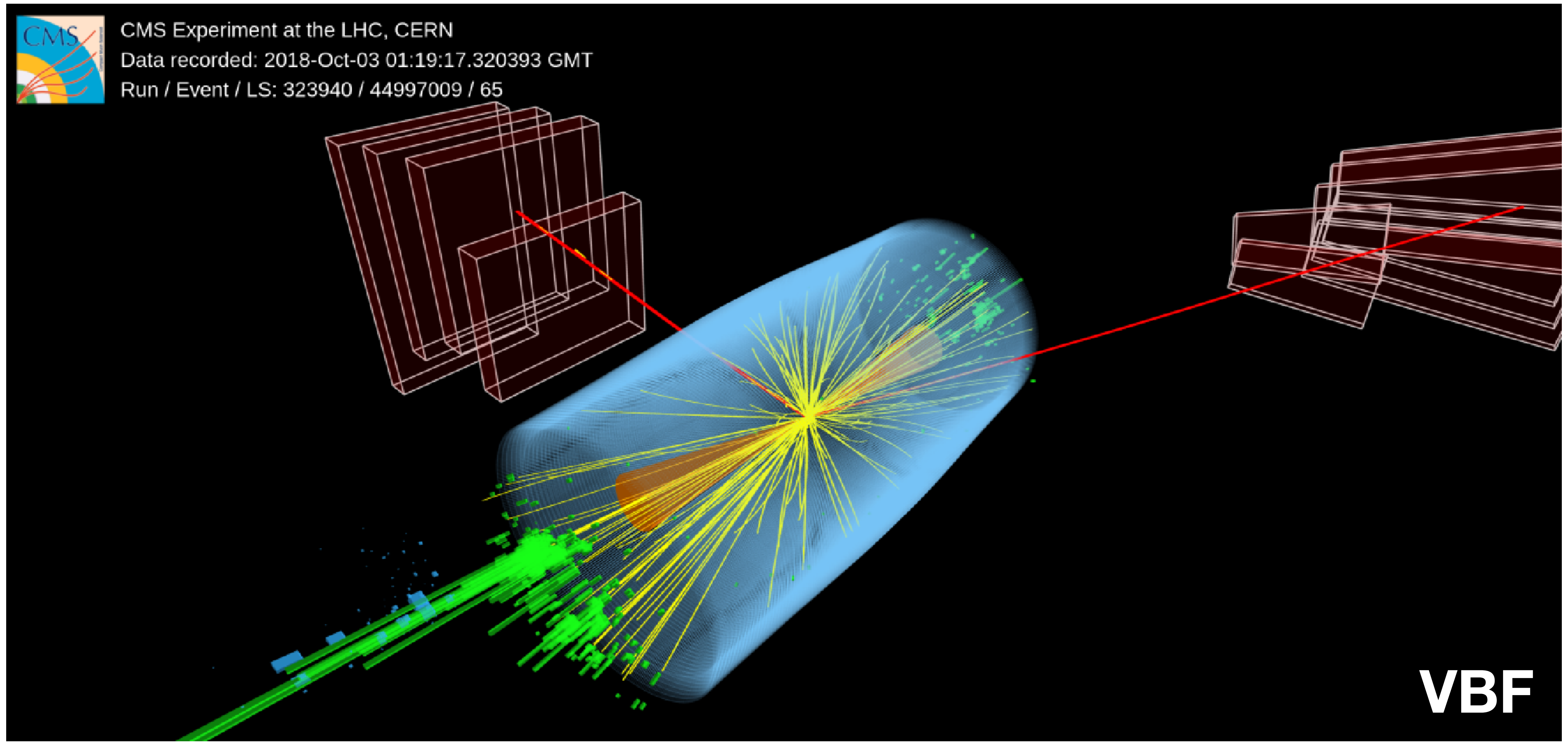
New perspective at the LHC!

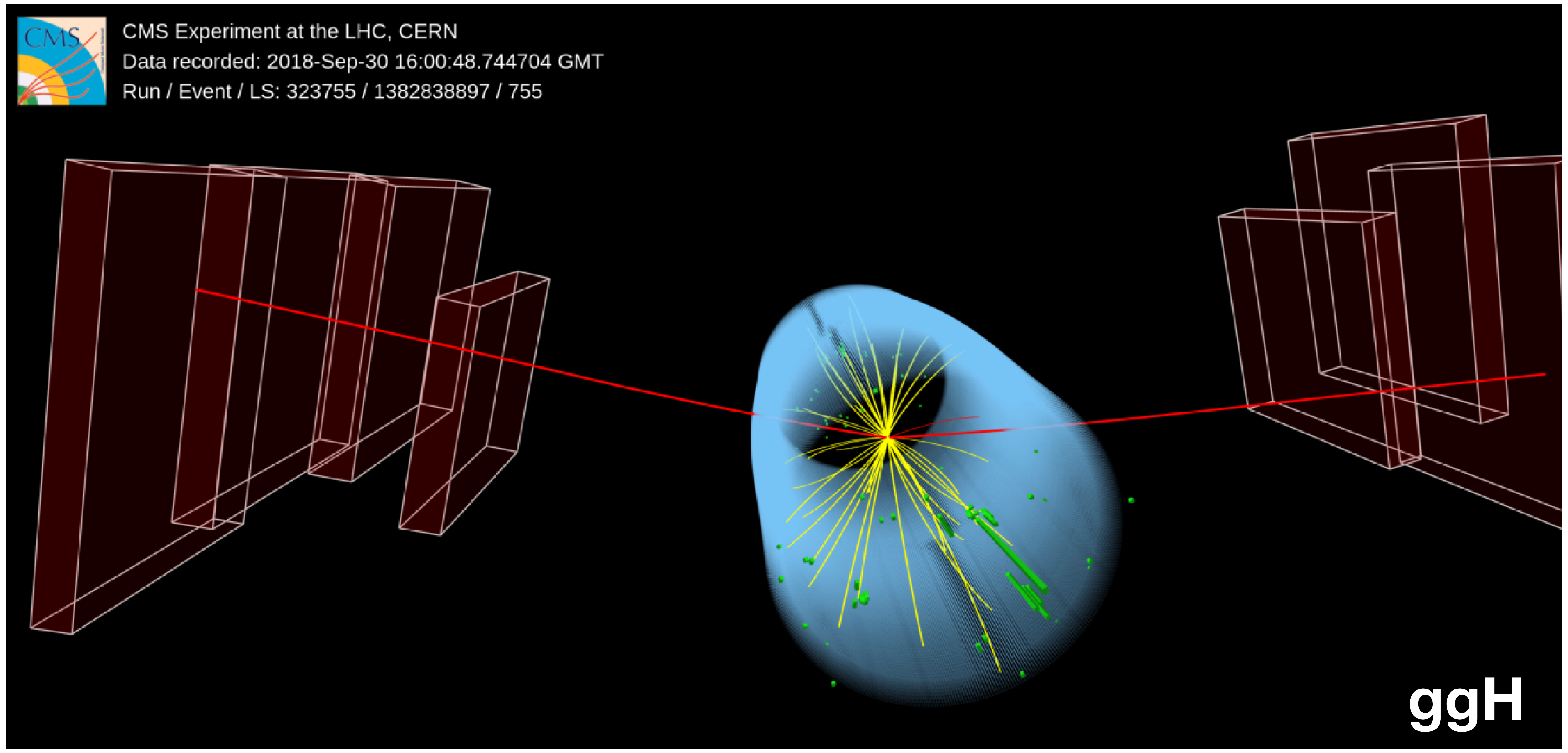
Evidence for $H \to \mu^+\mu^-$











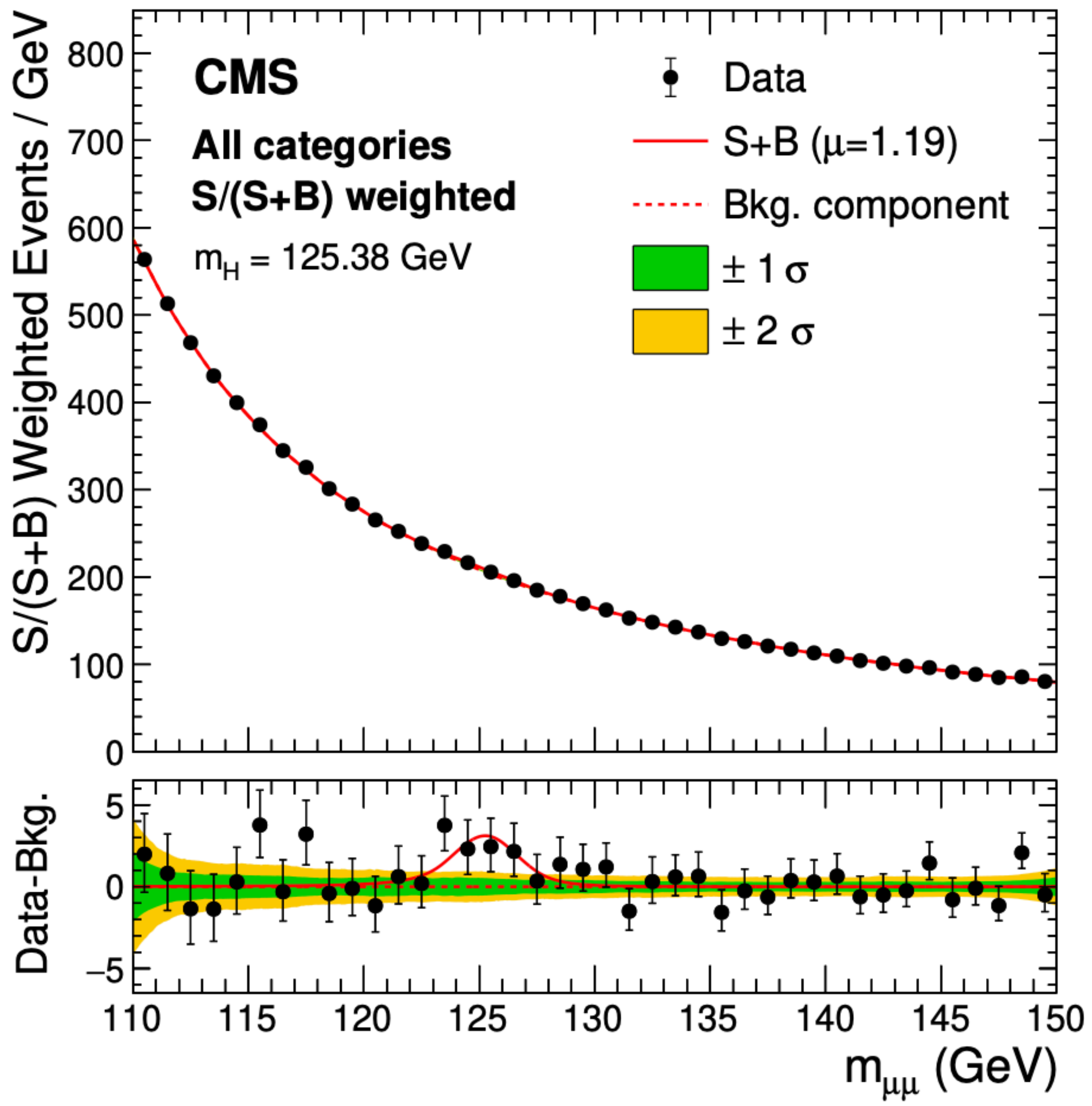
Evidence for Second Generation Yukawa Coupling

Very challenging channel!

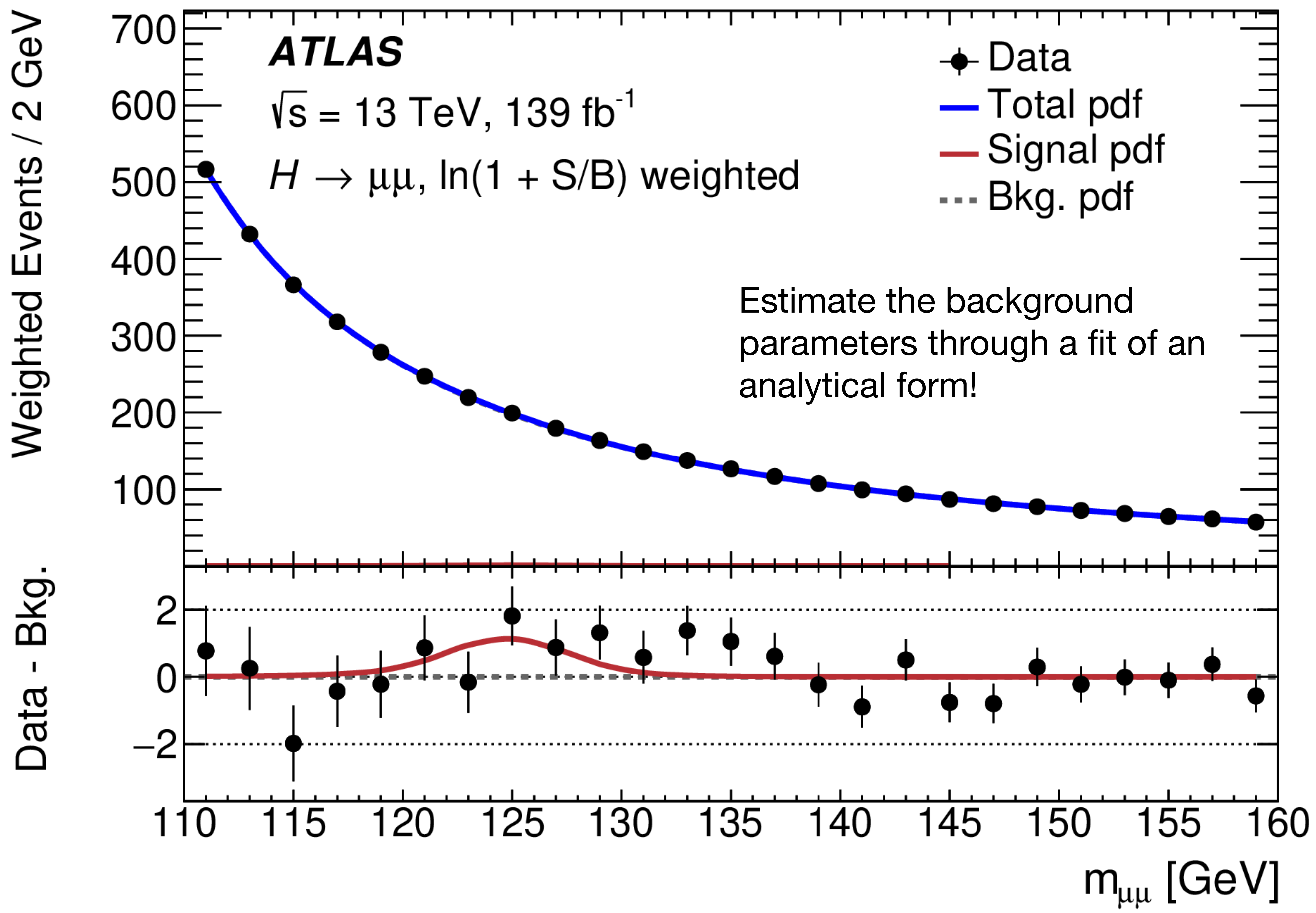
- Approximately 2k events produced but very small signal-to-noise
- Requires a very accurate description of the backgrounds.
- Gain in sensitivity mass resolution through Brem recovery and exclusively production modes!!

Summary of all categories

JHEP 01 (2021) 148 137 fb^{-1} (13 TeV)



PLB 812



CMS Result

Expected 2.5σ

Observed 3.0σ

$\mu = 1.19 \pm 0.43$

ATLAS Result

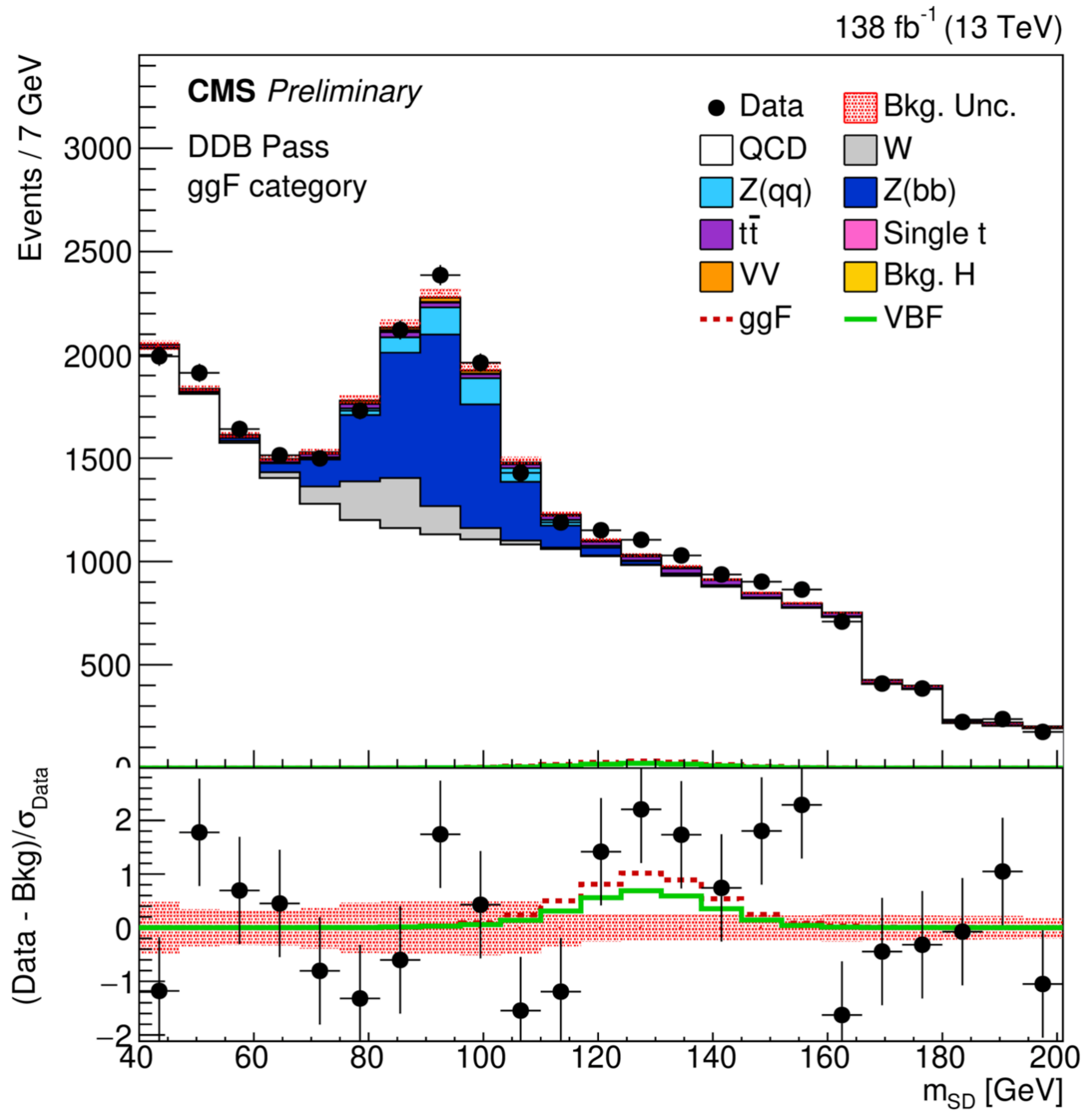
Expected 1.7σ

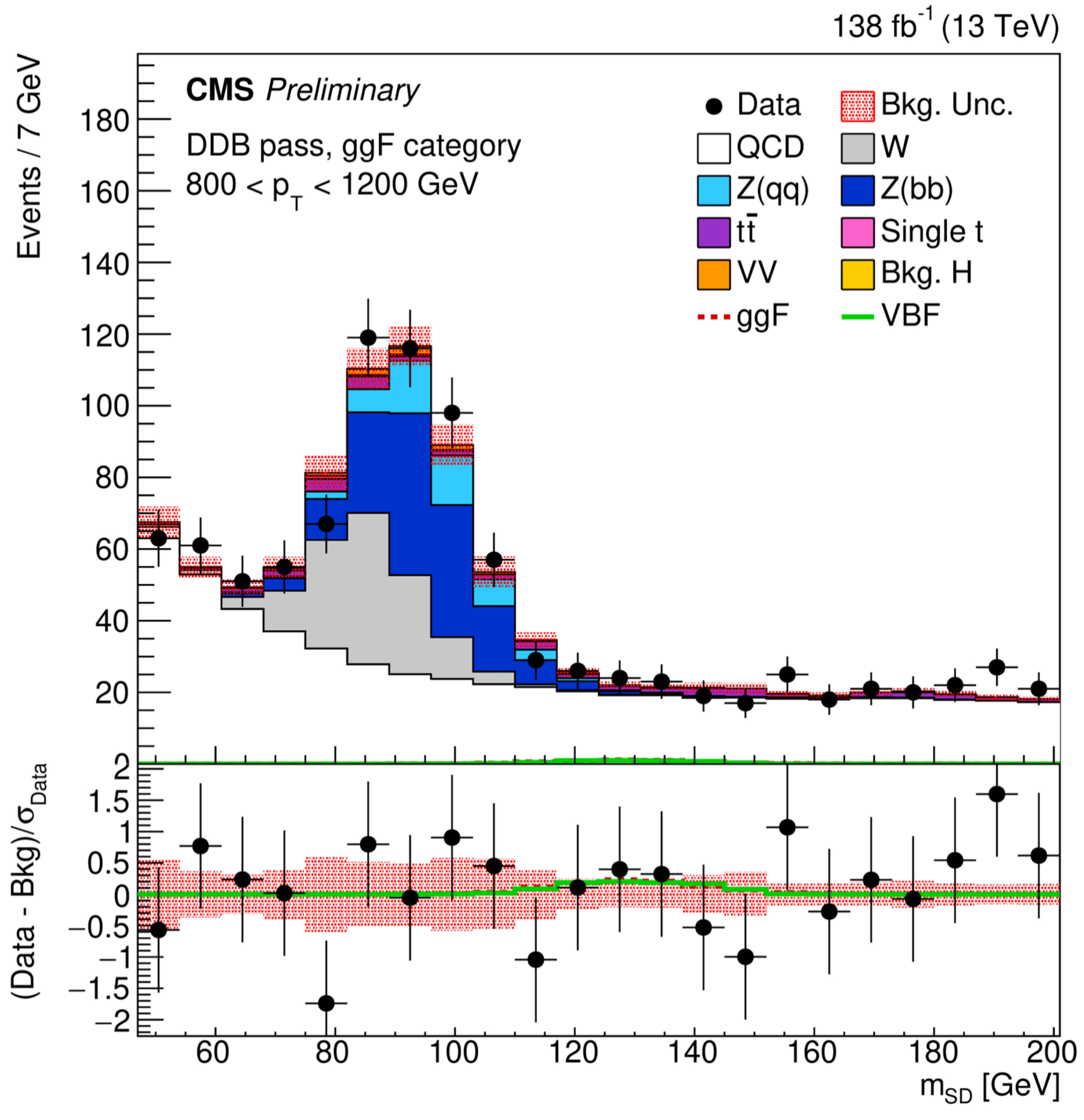
Observed 2.0σ

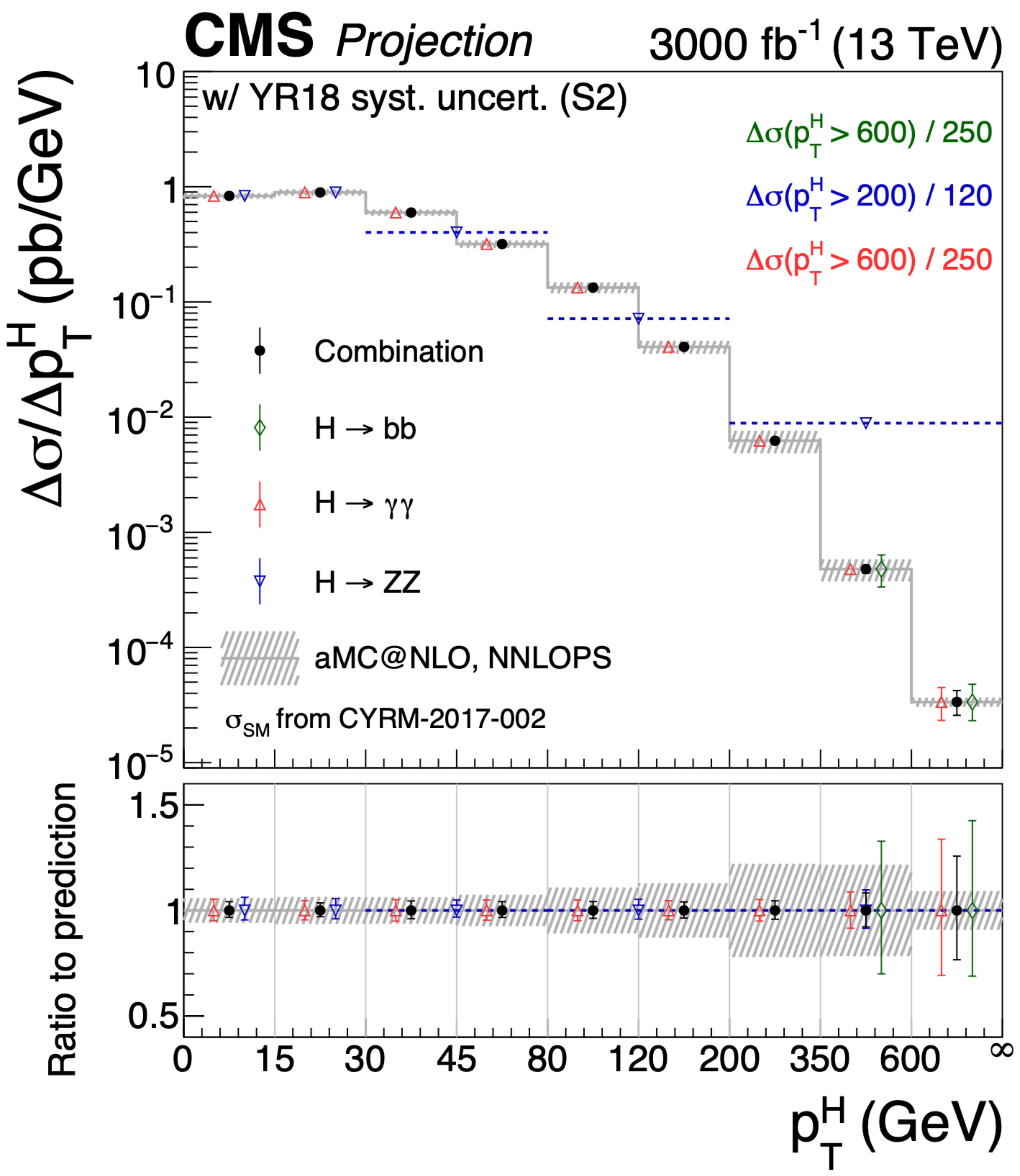
$\mu = 1.2 \pm 0.6$

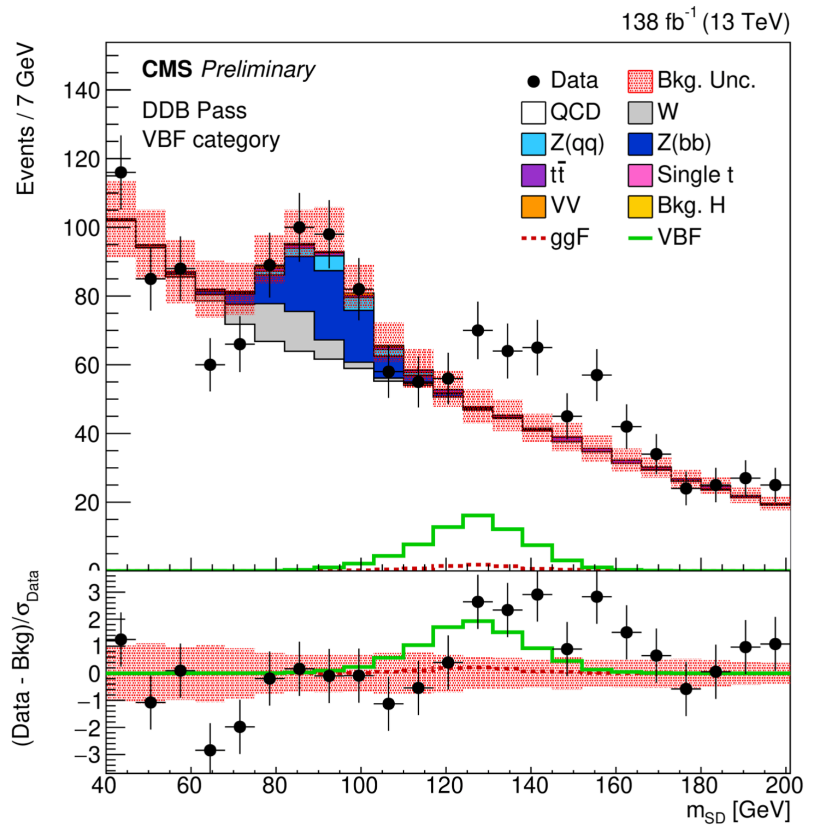
Example of impact of thorough analysis improvements!

Also of Reconstruction: e.g. Boosted Techniques!









Was thought to be completely impossible!

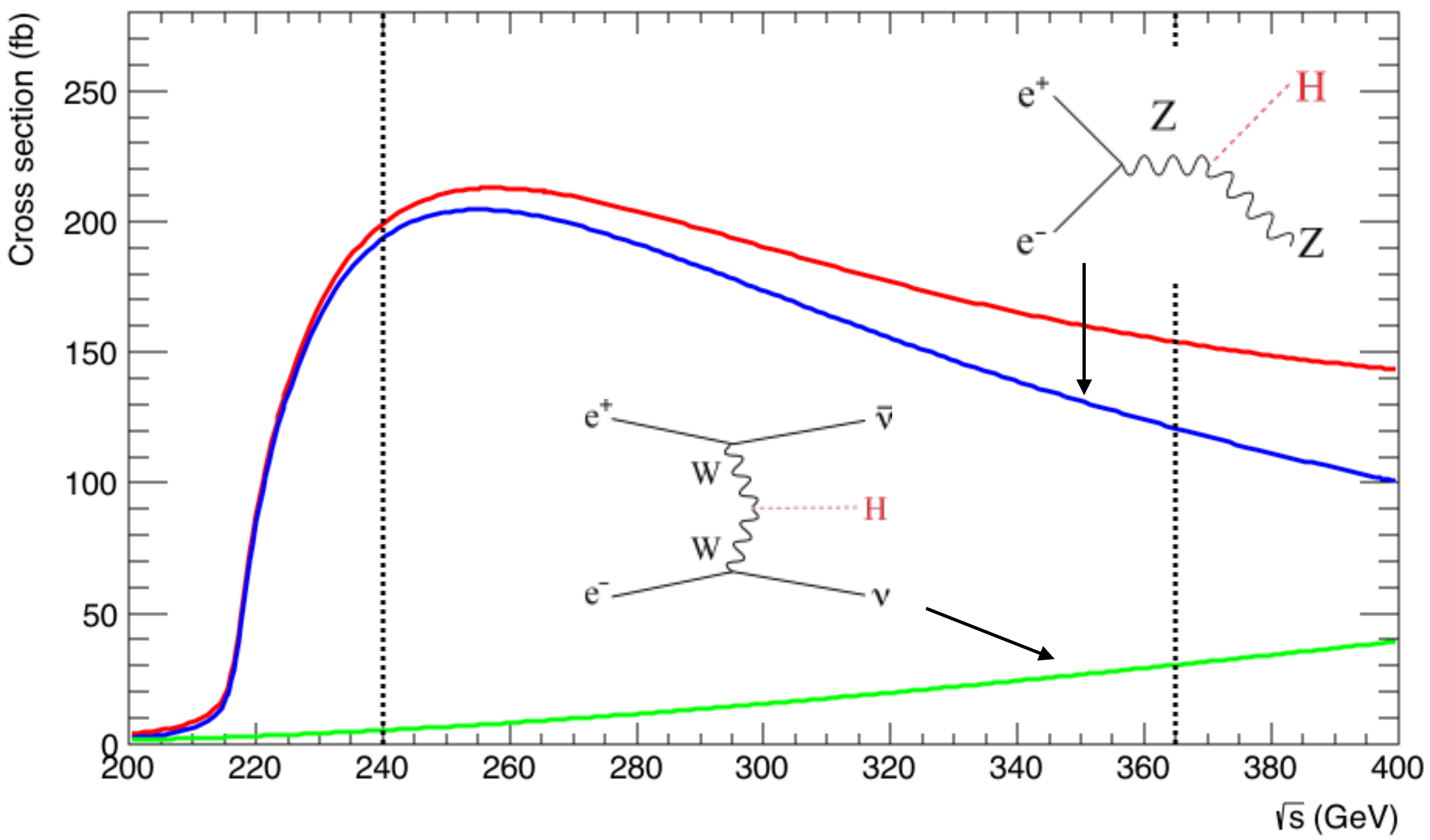
VBF significance is 3.0 σ (0.9 σ)

ggF significance of 1.2 σ (0.9 σ)

It can play an important role in the measurements of the inclusive production at high transverse momentum!

Extremely interesting for indirect NP constraints!

Higgs Physics at e^+e^- Colliders



1.5M per IP very clean ZH events produced at threshold

Approximately 1/3 of the number of ZH events at HL-LHC but in a much cleaner environment!

All final states can be very cleanly reconstructed.

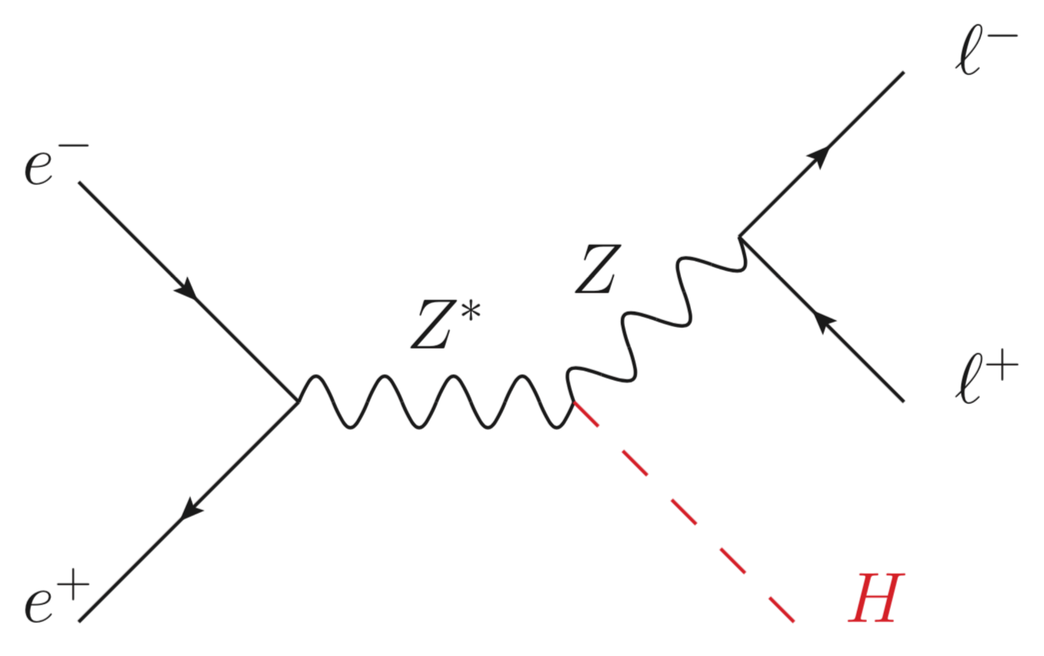
Additional 200k events at 350-365 GeV with approximately 30% from WW fusion which is interesting for the width measurement

- Measure $\sigma(e^+e^- \rightarrow HZ) \times Br(H \rightarrow bb, cc, gg, WW, \tau\tau, \gamma\gamma, \mu\mu, Z\gamma, \ldots)$ from each individual final state.
- Can also measure invisible decays from the reconstructed Z boson.

Fundamental difference with the LHC (and other hadron colliders): the width can be measured from the total HZ cross section! **Coupling measurements are less model dependent!**

Higgs Physics at e^+e^- Collider

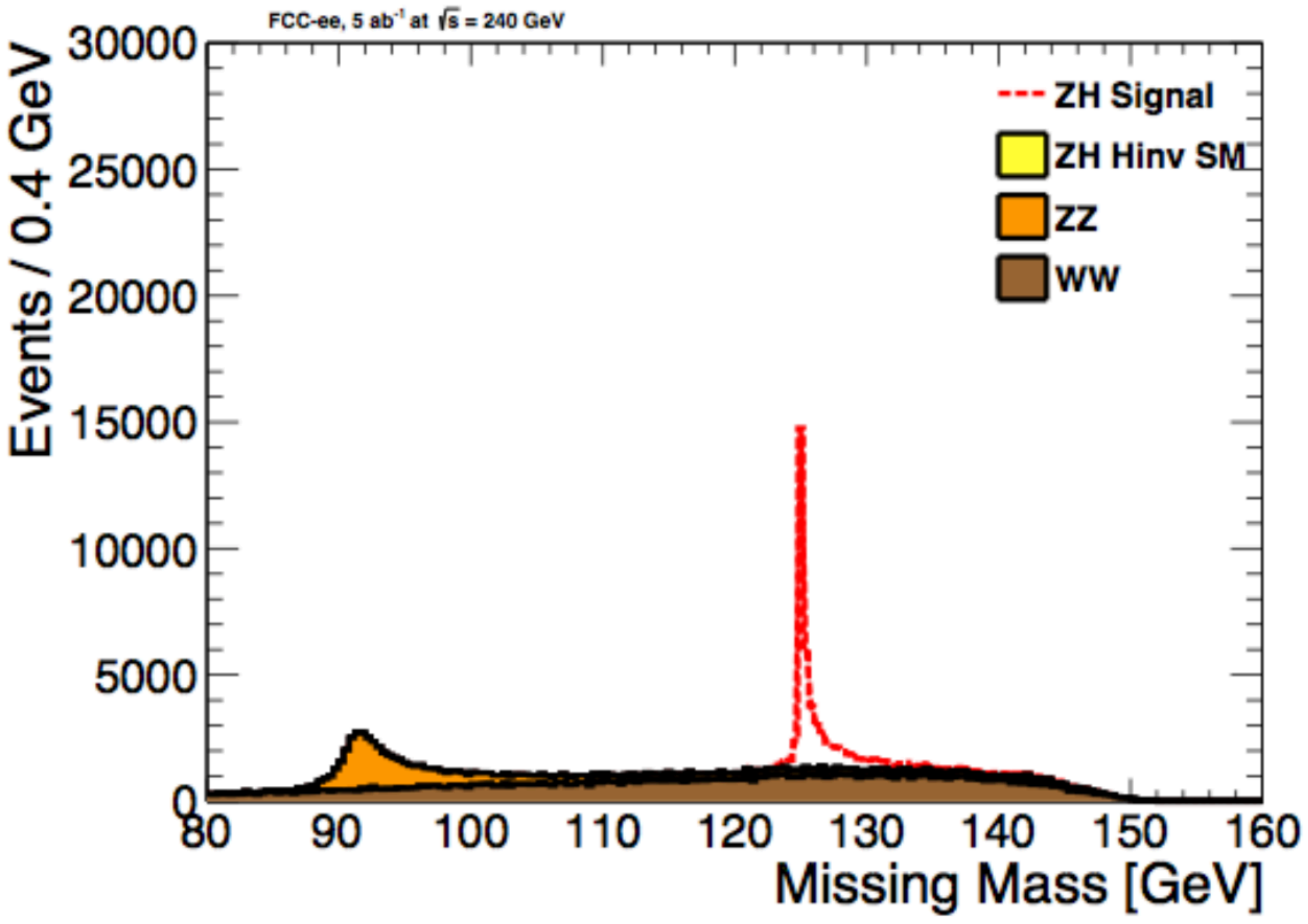
Threshold production of HZ provides a unique opportunity to measure the total HZ cross section through the recoil method



$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |p_{\ell\ell}|^2$$

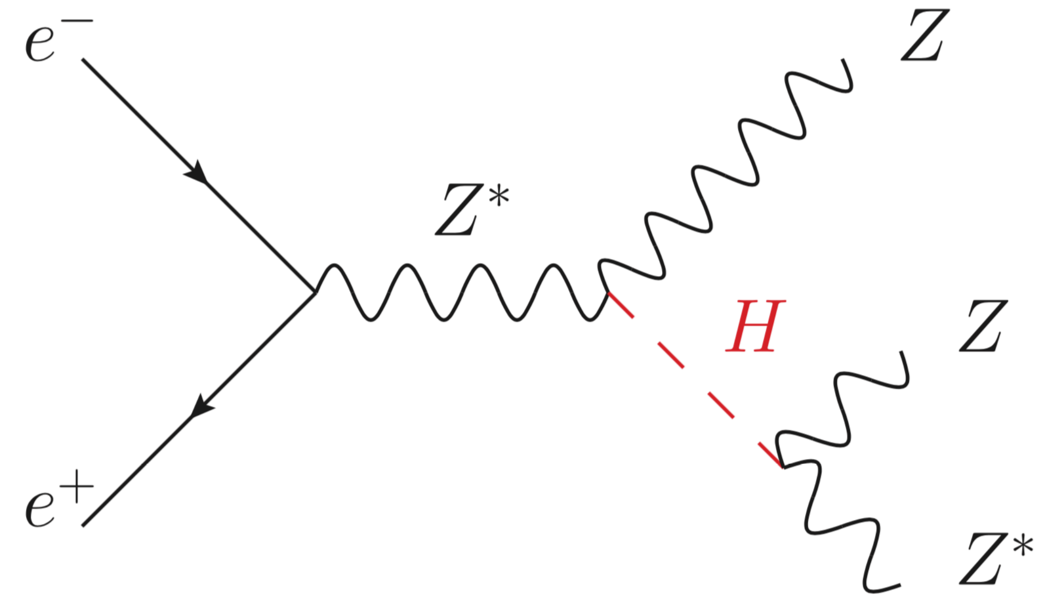
From conservation of energy and momentum, the energy and momentum of the Higgs is known from the Z without measuring the Higgs boson!

$$\sigma(e^+e^- \to HZ) \propto \kappa_Z^2$$



Measurement of the cross section at 240 GeV at 0.5% precision (0.9% at 365 GeV).

Then using the measurement of HZ with the Higgs to ZZ*:

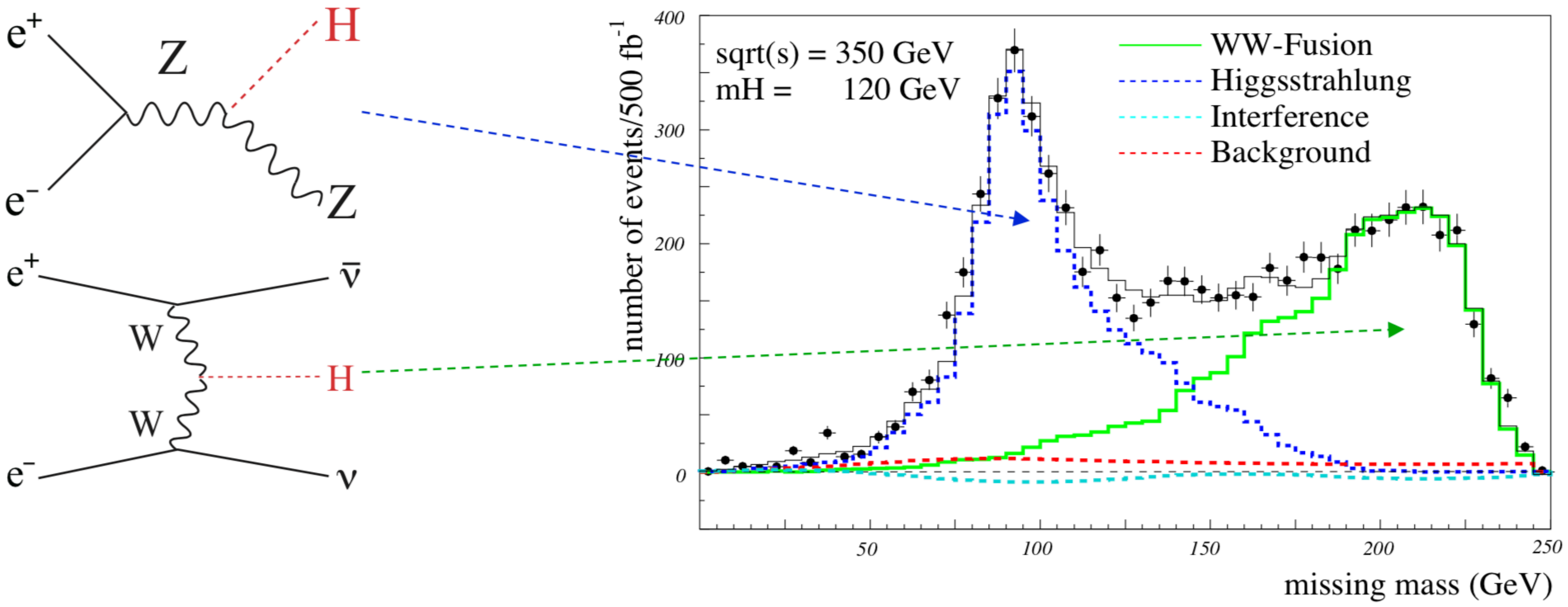


The total width of the Higgs can be measured at **~2.5%** level with FCC-ee (240) alone.

$$\sigma(e^+e^- \to HZ) \times B(H \to ZZ^*) \propto \frac{\kappa_Z^4}{\Gamma_H}$$

Higgs Physics at e+e- Collider

Further measurements of the width can be obtained using the WW fusion process as follows:



The WW fusion can be disentangled from the HZ process from the missing mass (which will not be peaked at the Z, but in this case at sqrt(s)-mH.

Then from the ratio of the following three measurements:

$$\frac{[\sigma(ZH)\times B(H\to WW)]\times[\sigma(ZH)\times B(H\to bb)]}{\sigma(\nu\nu H)\times B(H\to bb)}$$

Use different energy scale assumptions!

$$\propto \frac{\kappa_Z^2\kappa_W^2}{\Gamma_H}\times\frac{\kappa_Z^2\kappa_b^2}{\Gamma_H}\times\frac{\Gamma_H}{\kappa_W^2\kappa_b^2}=\frac{\kappa_Z^4}{\Gamma_H}$$

Substantial gain in sensitivity to the total width, using higher COM energies and adding FCC-ee (365)!

Precision on Γ_H of 1.1%

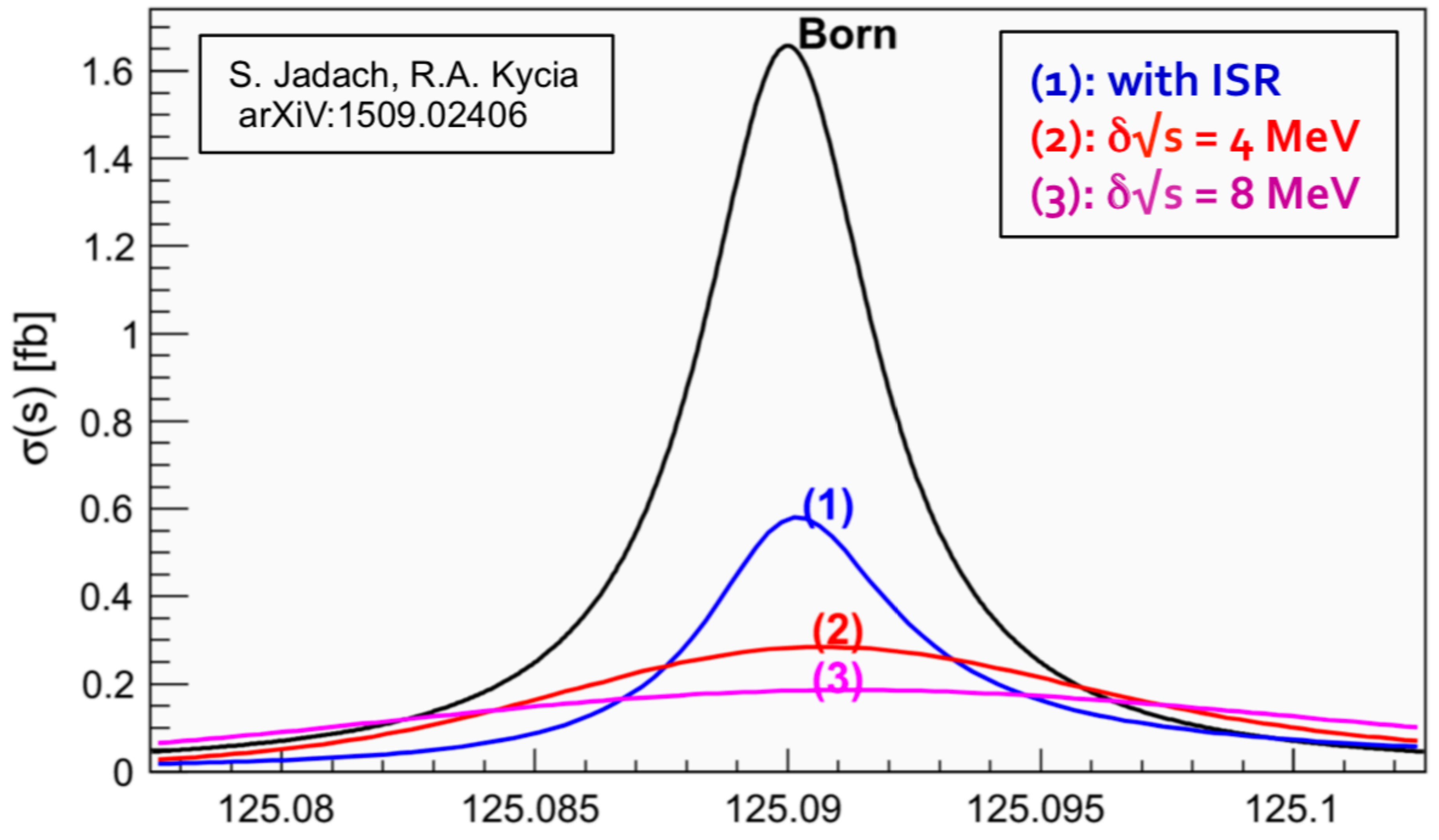
s-Channel Higgs production and e-Yukawa

Extremely challenging for several reasons:

1.- The production cross section is $\sigma(ee \to H) = 1.6 \text{ fb}$ will require extremely large luminosities

2.- Given the Higgs width of 4.2 MeV, and extremely small energy spread is necessary - require monochromatization.

- Default beam spread has delta ~ 100 MeV (no visible resonance)
- Requires beam monochromatisation
- Requires a prior knowledge of the Higgs boson mass of ~couple of MeV at most!
- Would require huge luminosity and therefore 4IPs.



First studies indicate a sensitivity of 0.4σ per year and per detector (spread of ~6 MeV)

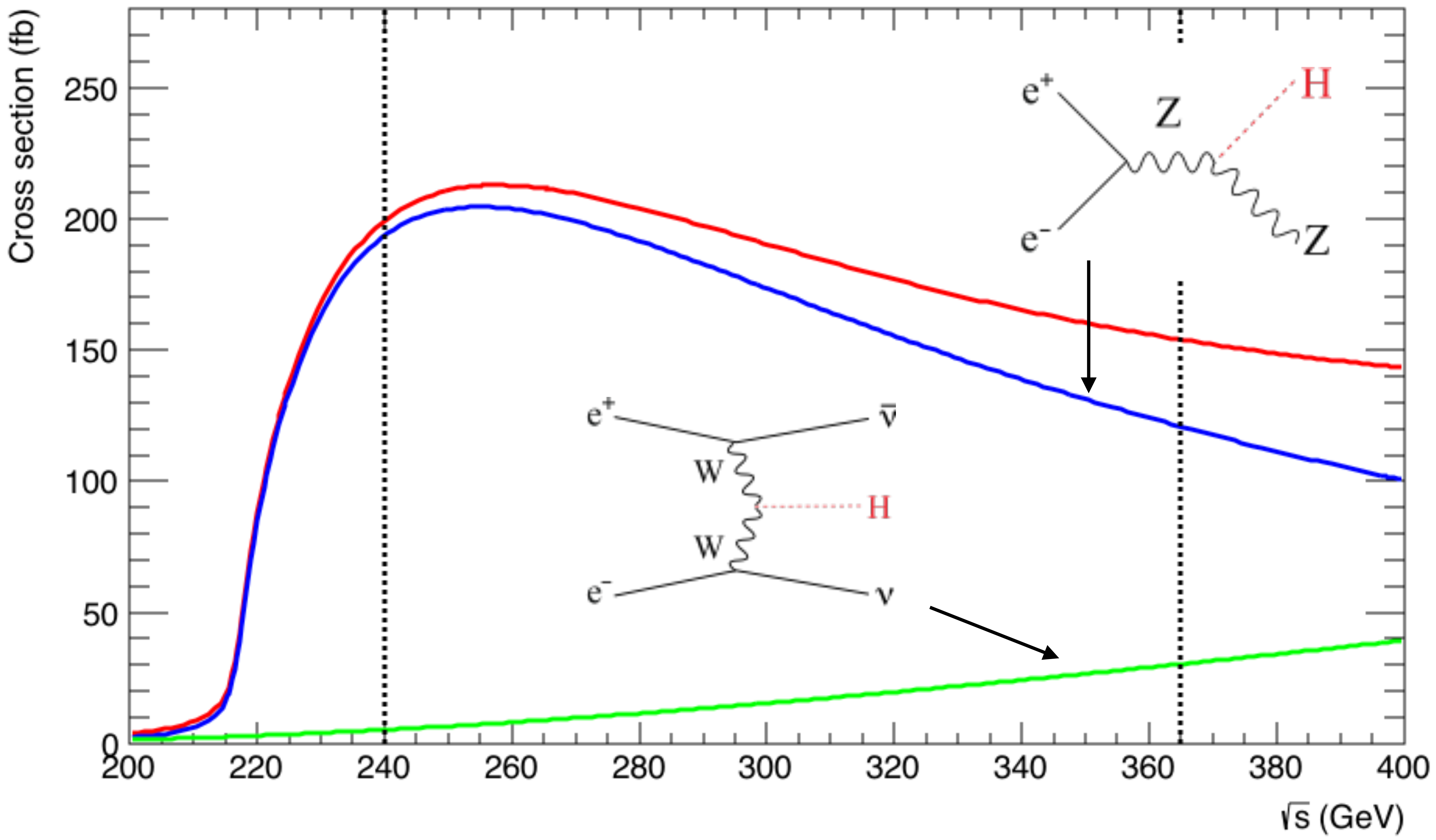
Monochromatization already considered but never used

Monochromatization uses opposite correlation between spatial position and energy.

Machine Parameters

Running mode	Z		W	ZH	$t\bar{t}$
Number of IPs	2	4	4	4	4
Beam energy (GeV)	45.6		80	120	182.5
Bunches/beam	12000	15880	688	260	40
Beam current [mA]	1270	1270	134	26.7	4.94
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	180	140	21.4	6.9	1.2
Energy loss / turn [GeV]	0.039	0.039	0.37	1.89	10.1
Synchr. Rad. Power [MW]			100		
RF Voltage 400/800 MHz [GV]	0.08/0	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	5.60	3.55	2.50	1.67
Rms bunch length (+BS) [mm]	13.1	12.7	7.02	4.45	2.54
Rms hor. emittance $\varepsilon_{x,y}$ [nm]	0.71	0.71	2.16	0.67	1.55
Rms vert. emittance $\varepsilon_{x,y}$ [pm]	1.42	1.42	4.32	1.34	3.10
Longit. damping time [turns]	1158	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	110	200	300	1000
Vertical IP beta β_y^* [mm]	0.7	0.7	1.0	1.0	1.6
Beam lifetime (q+BS+lattice) [min.]	50	250	—	<28	<70
Beam lifetime (lum.) [min.]	35	22	16	10	13
	4 years		2 yrs	3 yrs	5 yrs

FCC Physics Case



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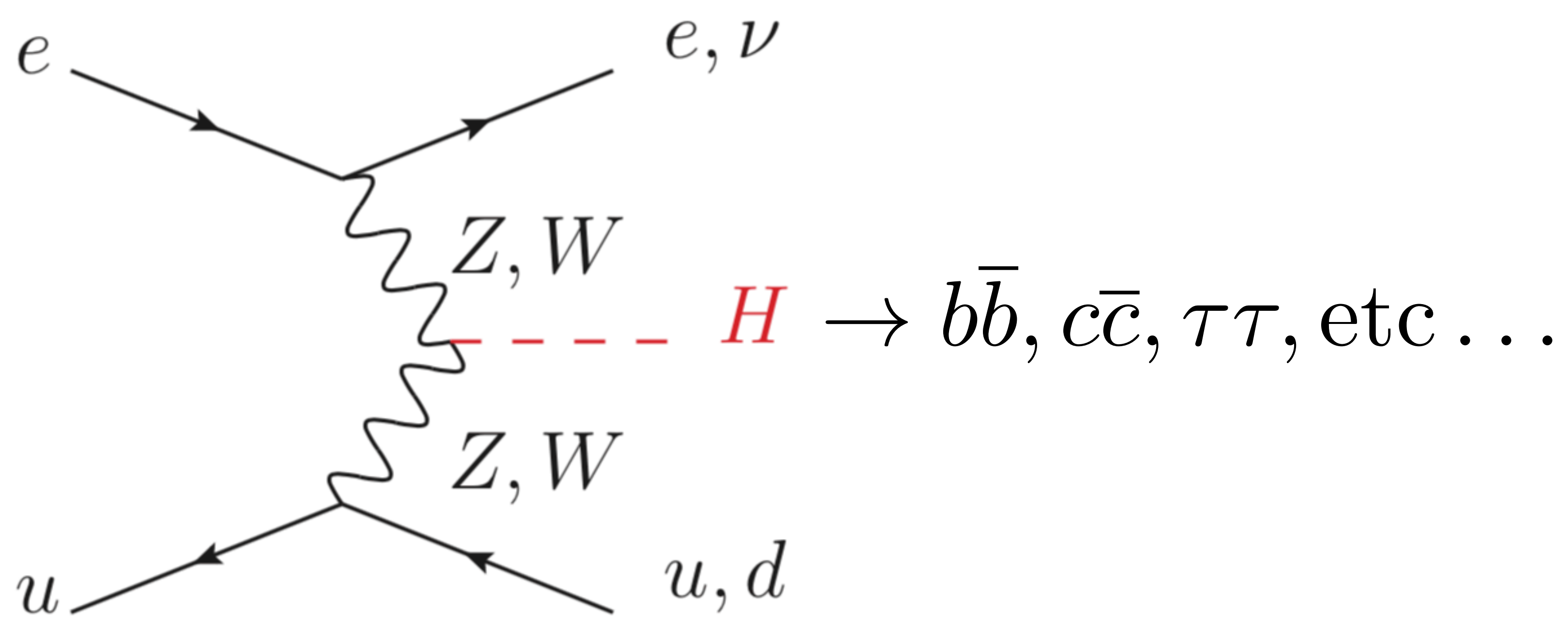
High Energy electron-proton Projects

The eh candidate machines

Project	LHeC	FCC-eh
Location	CERN	CERN
e energy	60 GeV	60 GeV
p energy	7 TeV	50 TeV
Lumi.	0.8 10^{34} $cm^{-2}s^{-1}$	1.5 10^{34} $cm^{-2}s^{-1}$

Primary program to measure proton PDFs, but also nice additional potential in Higgs physics

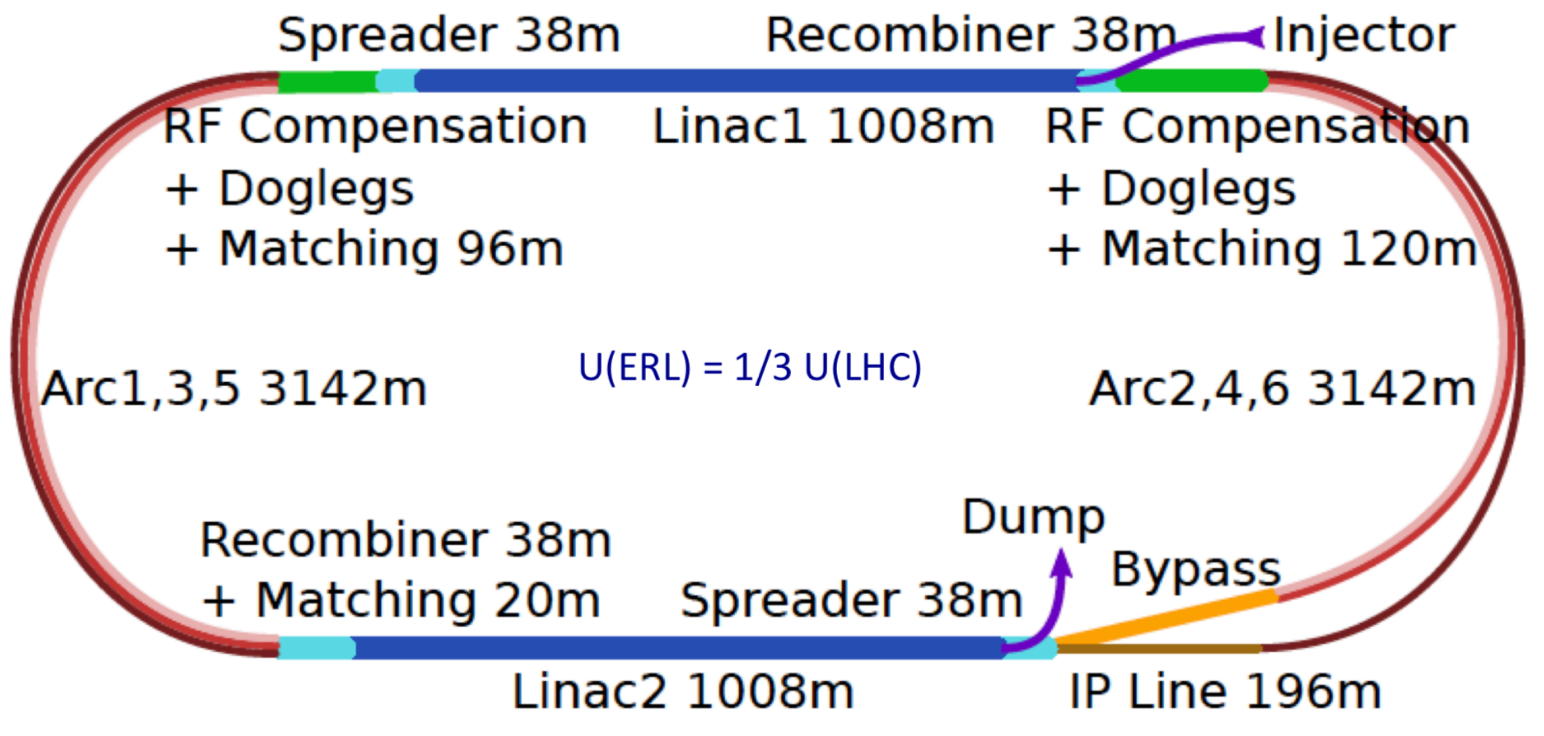
Main production process through vector boson fusion

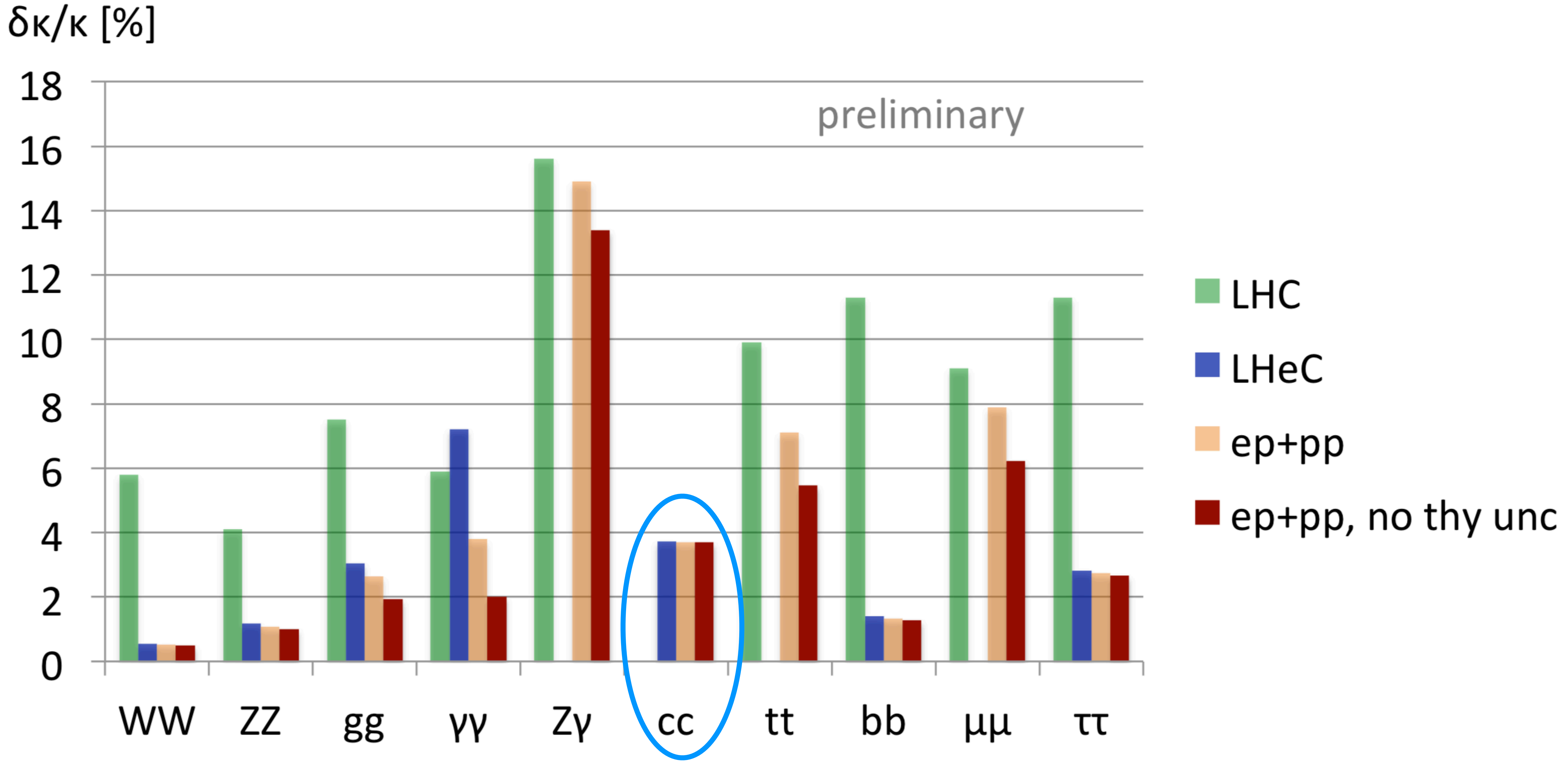


Much cleaner environment than pure hadron!

Good reach in the WW channel.

60 GeV Electron ERL added to LHC





Clean enough to make charm Yukawa at good precision and improvement in the b Yukawa as well w.r.t. HL-LHC.

Where do we Stand at the Energy Frontier?

Two main outcomes of the LHC: The discovery of the Higgs boson and nothing else (so far)

Triumph of the Standard Model?

The SM Lagrangian contains the information about the dynamics of the considered system.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

Beauty: simplicity of these expressions, and interactions governed by gauge symmetries only 3 (EW) and 2 (QCD) parameters!

The Higgs Mechanism… postulates the **Higgs field**!

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Ugliness: number of free parameters (26 altogether) not governed by symmetries

It cannot be the end of the story (does not include gravity), many important parts are not (or still poorly) established yet and fundamental questions remain…