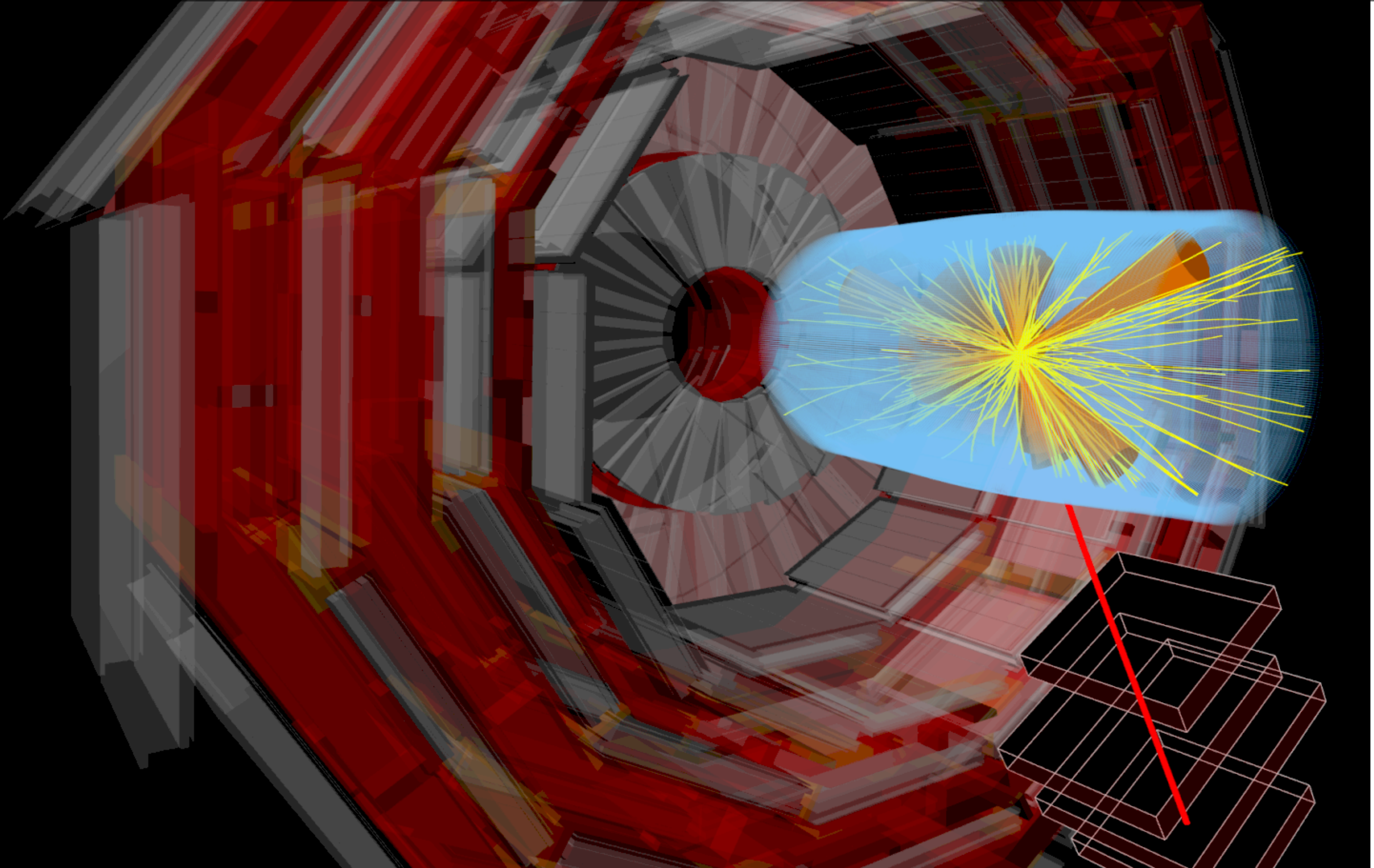
Direct Searches at Colliders Status and Perspectives



$$pp \to \tilde{t}\bar{\tilde{t}} \to t\chi\bar{t}\chi$$

Scuola Normale Superiore
Pisa

Gravity, Strings and Supersymmetry breaking
4 April 2025

MAX-PLANCK-INSTITUT FÜR PHYSIK

Marumi Kado

The Large Hadron Collider (LHC)

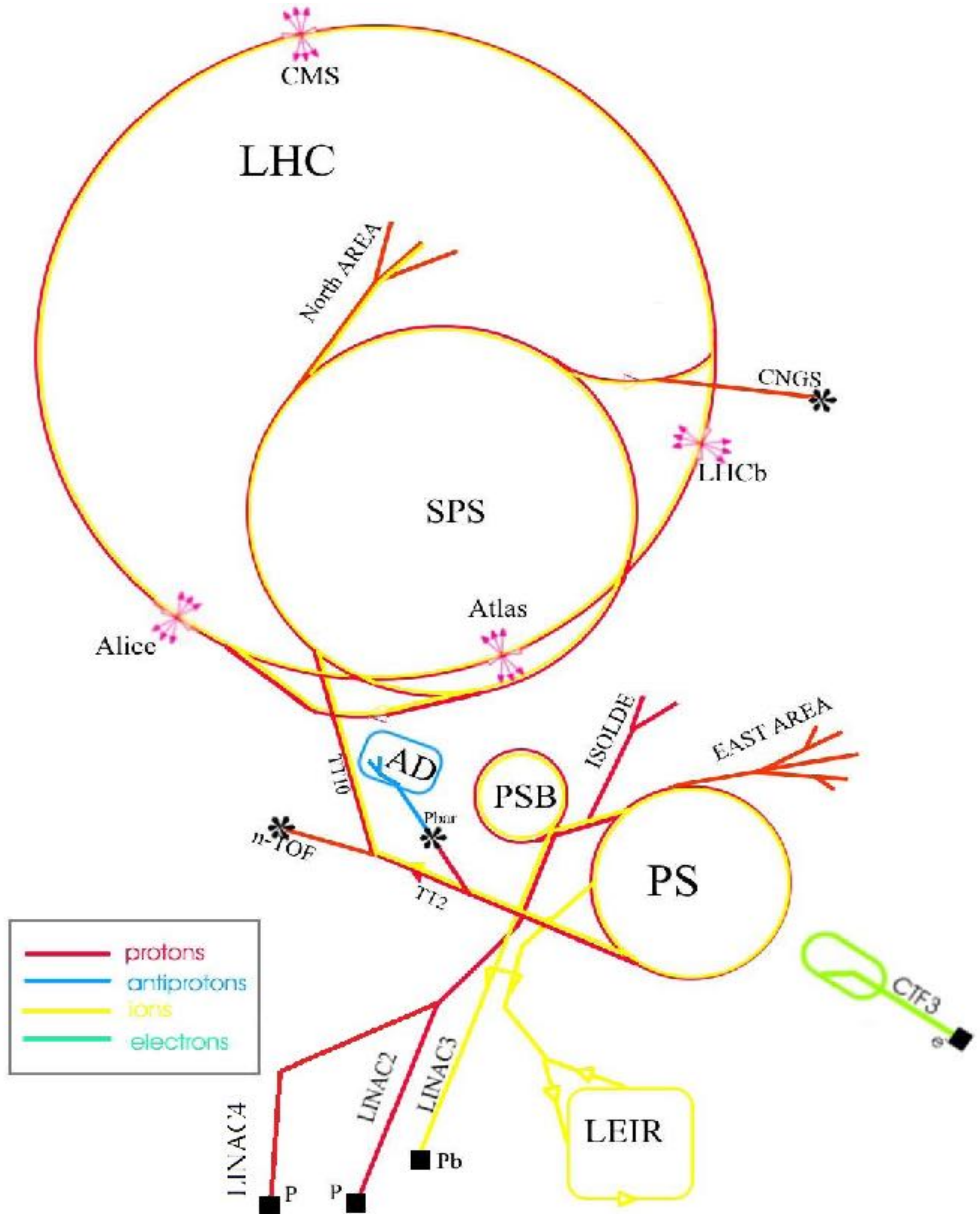
Unrivalled at Energy Frontier

13.6 TeV (COM energy)

Outstanding at Intensity Frontier

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

*Close to SuperKEKB at $5.1 \times 10^{34}\ cm^2 s^{-1}$



So far the LHC has delivered:

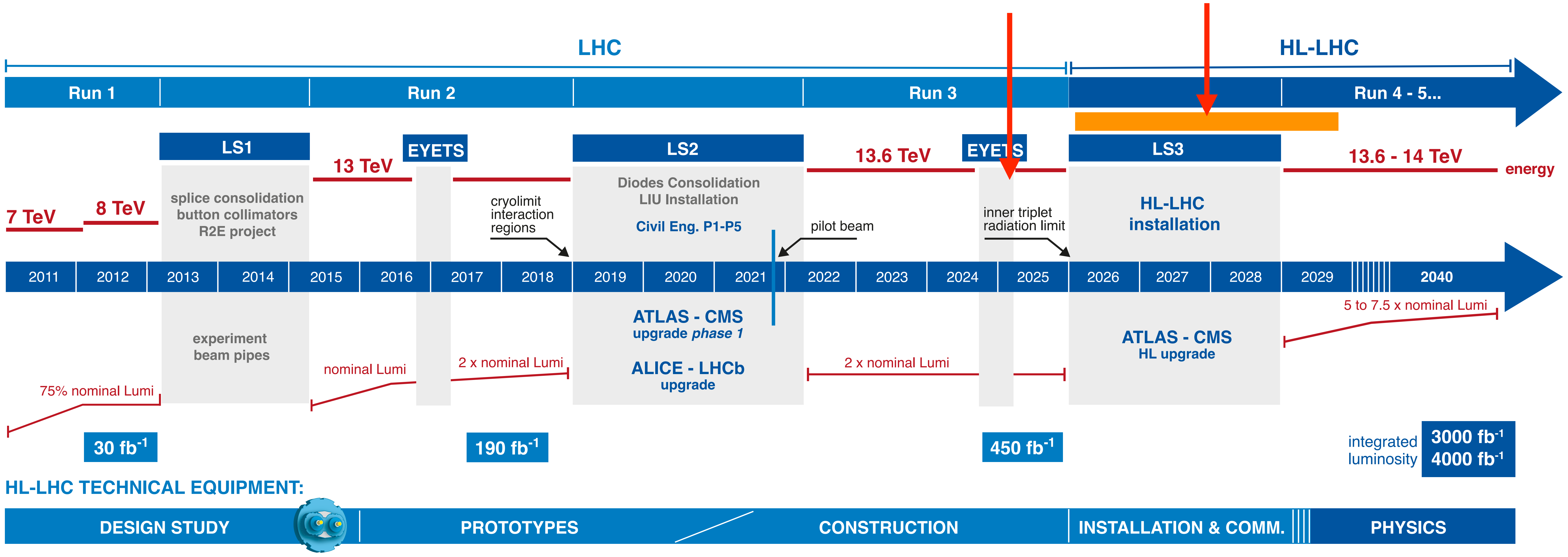
- 15 Million Higgs bosons produced
- 600 Million top quarks produced
- 15 Billion Z bosons with 300 Million per lepton flavour
- 60 Billion W bosons (3 billion per lepton flavour)
- 300 Trillion b quarks

Still 10 times more statistics expected at HL-LHC!

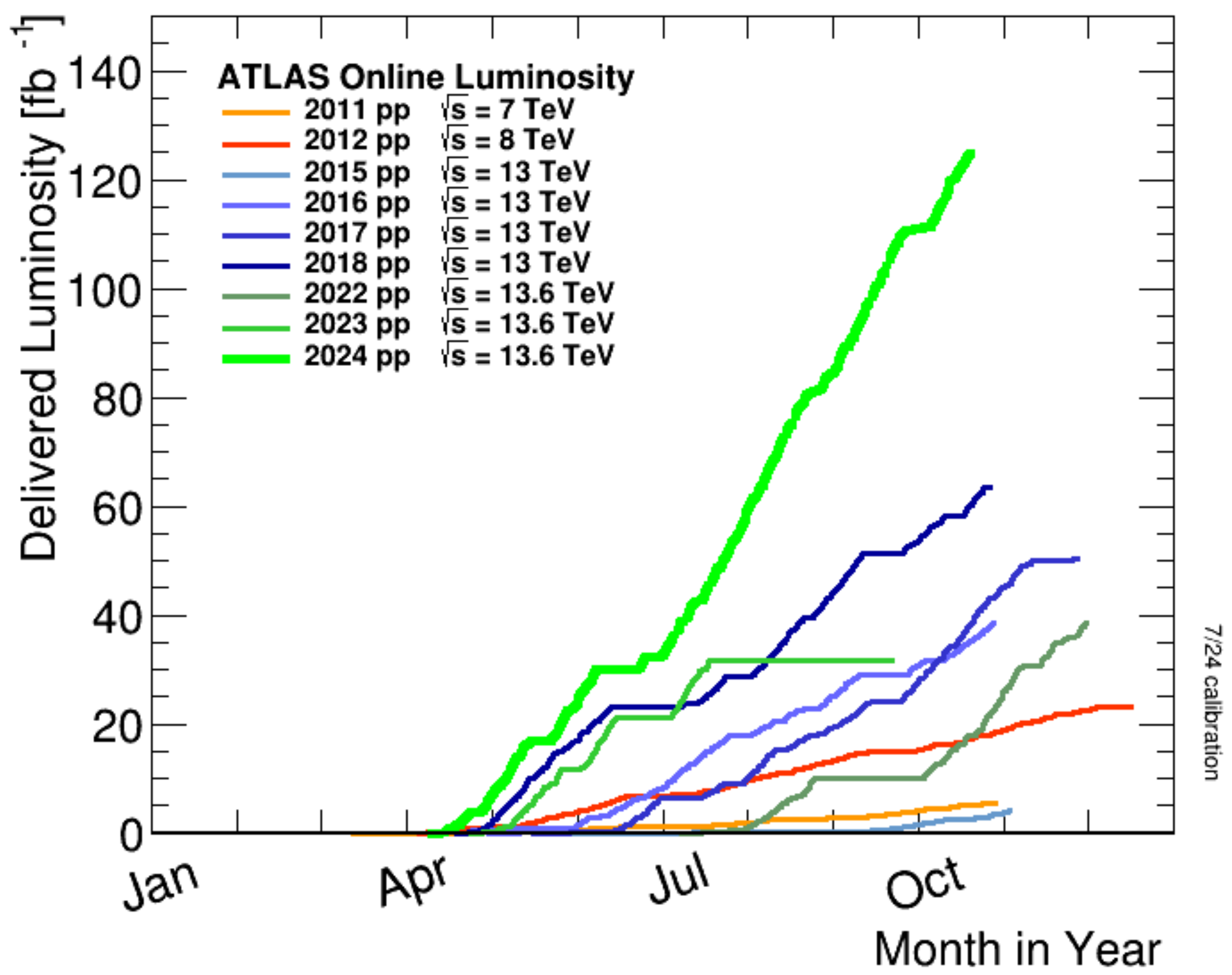
In comparison Future ee up to ~1-4 M Higgs, much cleaner and « usable » events

Extraordinary performance of the LHC accelerator complex

2024 - Best year ever! **We are here!** **New Schedule** (LS3 from Q3 2026 to Q2 2029)



2024 - High availability operation, Full mastery of considerable inherent operational risks



- The Run 3 has now surpassed the Run 2 dataset ~180 fb^{-1} at 13.6 TeV

- Approximately x10 Luminosity to be delivered **at HL-LHC** (in terms of results x20) in the same amount of time… **Major upgrades leading** to the High Luminosity during the third long shutdown now on the horizon! (See backup for more details).

Even with the record luminosity in 2024 need more than 20 running years to achieve HL-LHC luminosity!

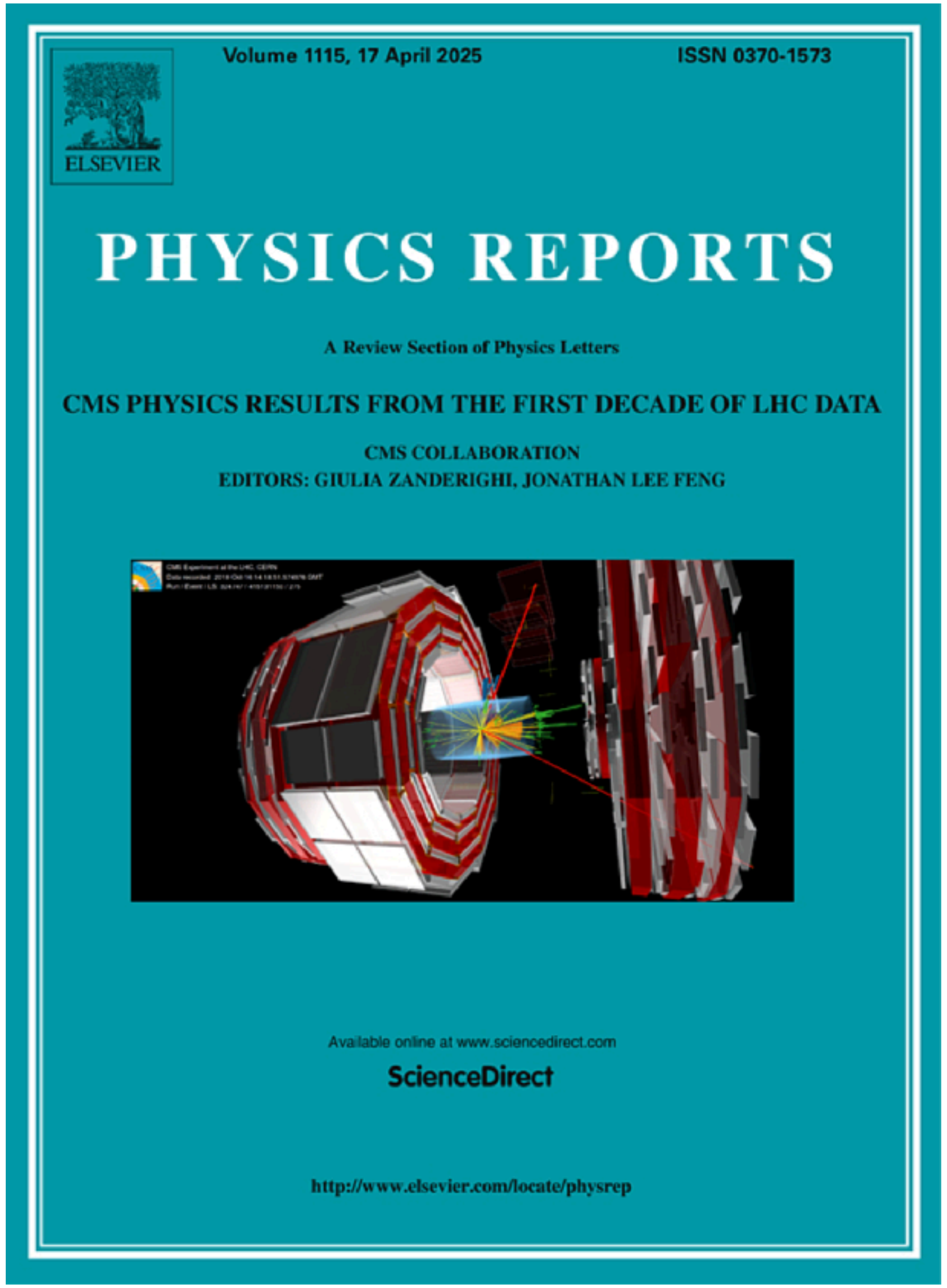
A Special Moment for LHC Physics Program

- The Run 1 dataset with only **of ~30** fb^{-1} at 7-8 TeV led to Discovery (and first measurements) of the Higgs boson!
- The Run 2 dataset surpassed the **initial goal** (in luminosity) of the LHC project and is a **clean and well calibrated dataset of ~140** fb^{-1} at 13 TeV
- The Run 3 aims at close to **~0.5** ab^{-1} **at 13.6 TeV** essential benchmark on the road to HL-LHC.

  - ATLAS and CMS have published approximately 1350 papers (each) since the start of operations.
  - Almost exclusively all papers have been published with data of up to Run 2 (only handful published with Run 3 data).
  - Approximately 50% of the ATLAS results are direct searches for new physics, 40% are measurements and 10% performance.
  - Among search papers 40% on SUSY and 60% on other BSM searches.

Each of these results would deserve an entire talk! Focus on the results and the guidelines (typically simplified models) used to identify the most interesting event topologies to investigate.

A Special Moment for the LHC Physics Program



ATLAS Outline

ATLAS Phys. Rep. Link

- Forward to the collection
- Climbing to the Top
- Electroweak, QCD and flavour physics
- Characterising the Hihggs boson
- Exotic Jungle Beyond the Standard Model
- Additional scalars and exotic decays
- The quest o discover supersymmetry

CMS Outline

CMS Phys. Rep. Link

- The Stairway to heaven
- Stairway to discovery: cross section measurements
- Review of top quark mass measurements
- High density QCD
- Searches for Higgs decays of heavy resonances
- Dark sector searches
- Vector like quarks, leptons and heavy neutral leptons
- Searches through data scouting

A collection of 14 Physics Reports - an overview of the LHC Run 2 results

Genesis of the LHC

First mention of the LHC in 1977 by sir John Adams (former CERN director) as an option of a superconducting hadron collider to be hosted in the LEP tunnel **(requesting that the LEP be made large enough to host a proton collider of at least 3 TeV beam energy)**.

15 years preparation period of the concept and project

15 years of construction

- 1984: CERN and ECFA workshop in Lausanne.
- 1988: LEP tunnel completed (Europe's largest civil engineering project prior to the channel tunnel).
- 1992: ATLAS and CMS letters of intent.
- **1994: Approval of the LHC** (1993 cancellation of 40 TeV SSC).
- 1995: LHC CDR published.
- 1997-98: ATLAS, CMS, LHCb and ALICE experiments approved.
- 2003-2005: Caverns completed installation started.
- 2007: LHC dipoles installed in LHC (after having been all individually checked at SM18).
- 2008: Experiments installed.
- 2008 September 10: Start of the LHC.
- 2008 September 19: Incident occurs between dipole and quadrupole.
- **2009** November: Beams are back in the LHC!

Since 2009: 16 years of successful operations and landmark results!

Strategy (Decision) Process

European Strategy Process well underway!
The principal goal of this strategy is to decide on the next **flagship CERN project**.

We are here!

Ongoing **feasibility study for the FCC** including costing and funding scenarios.

Community and national inputs submitted on Monday available since yesterday evening!

Strategy Documents Link

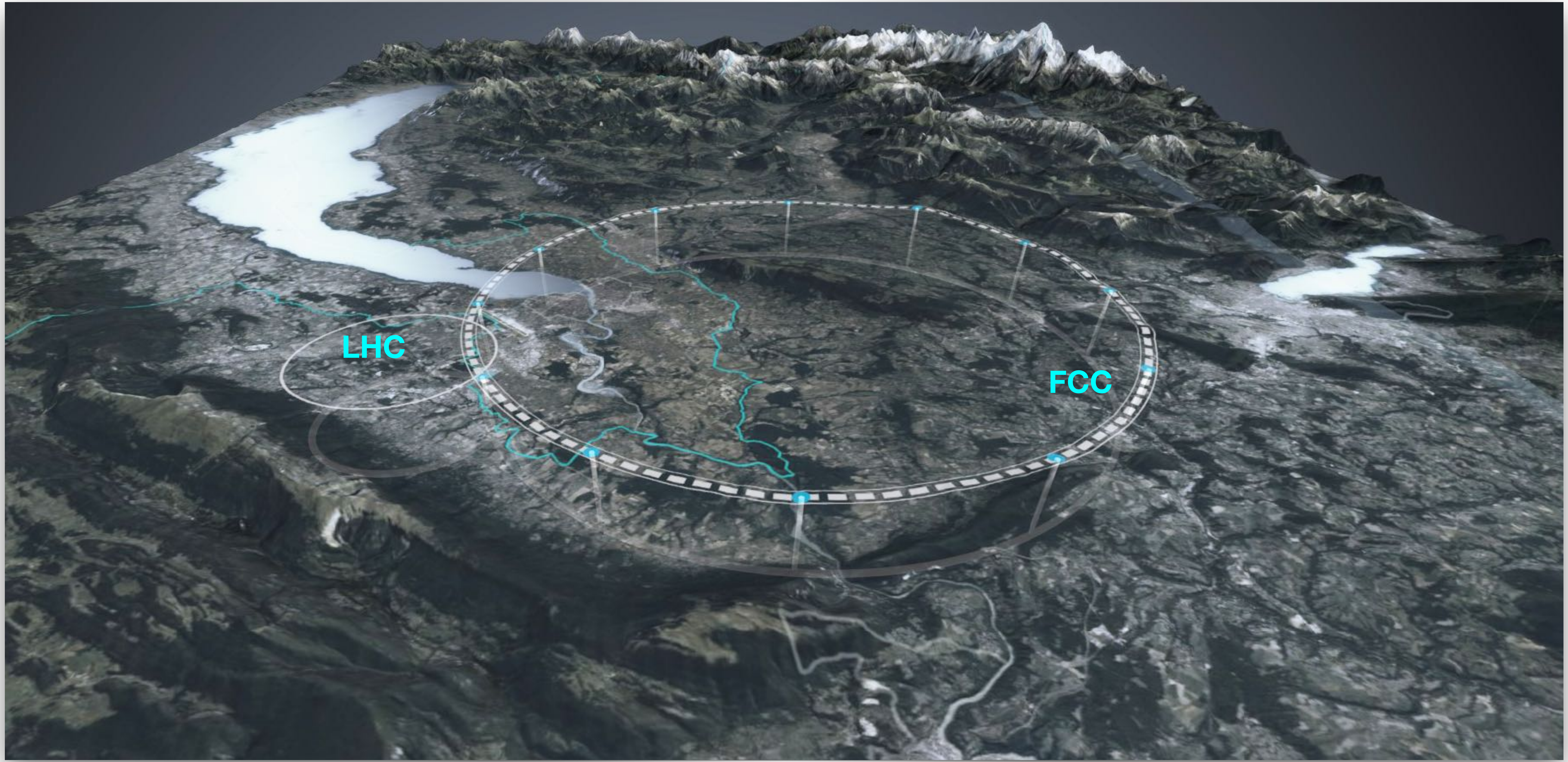
Crucial moment for particle physics:

A strategic decision on the next flagship project by the end of the year!

Aim at an approval by Council in 2028

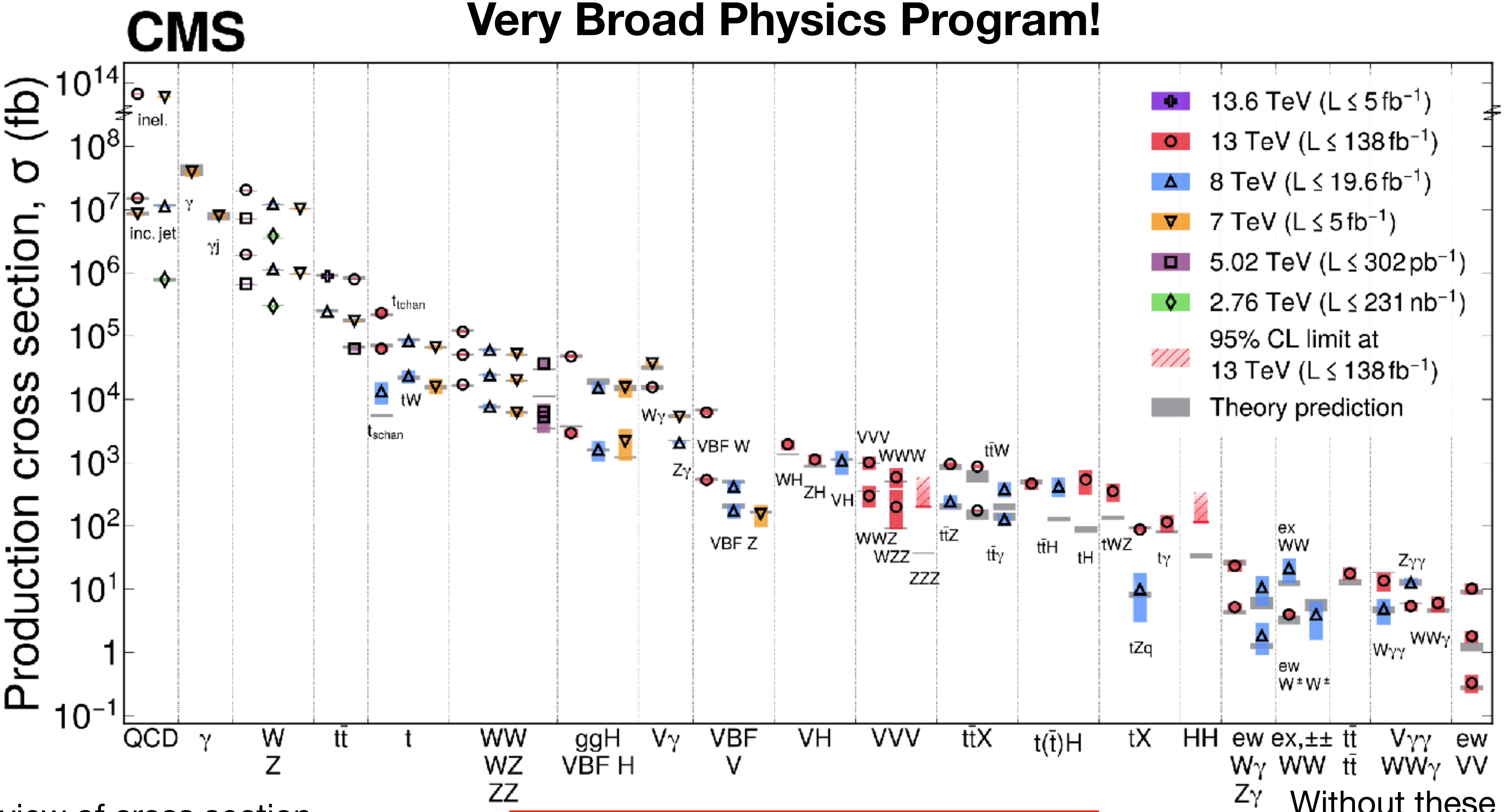
A Scientific Mission for the 21st Century

Future Collider Projects



Stairway to Discoveries

Very Broad Physics Program!



Broad view of cross section measurements compared to at least NLO in QCD predictions!

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

Without these precise predictions, a huge fraction of new physics searches would be impossible!

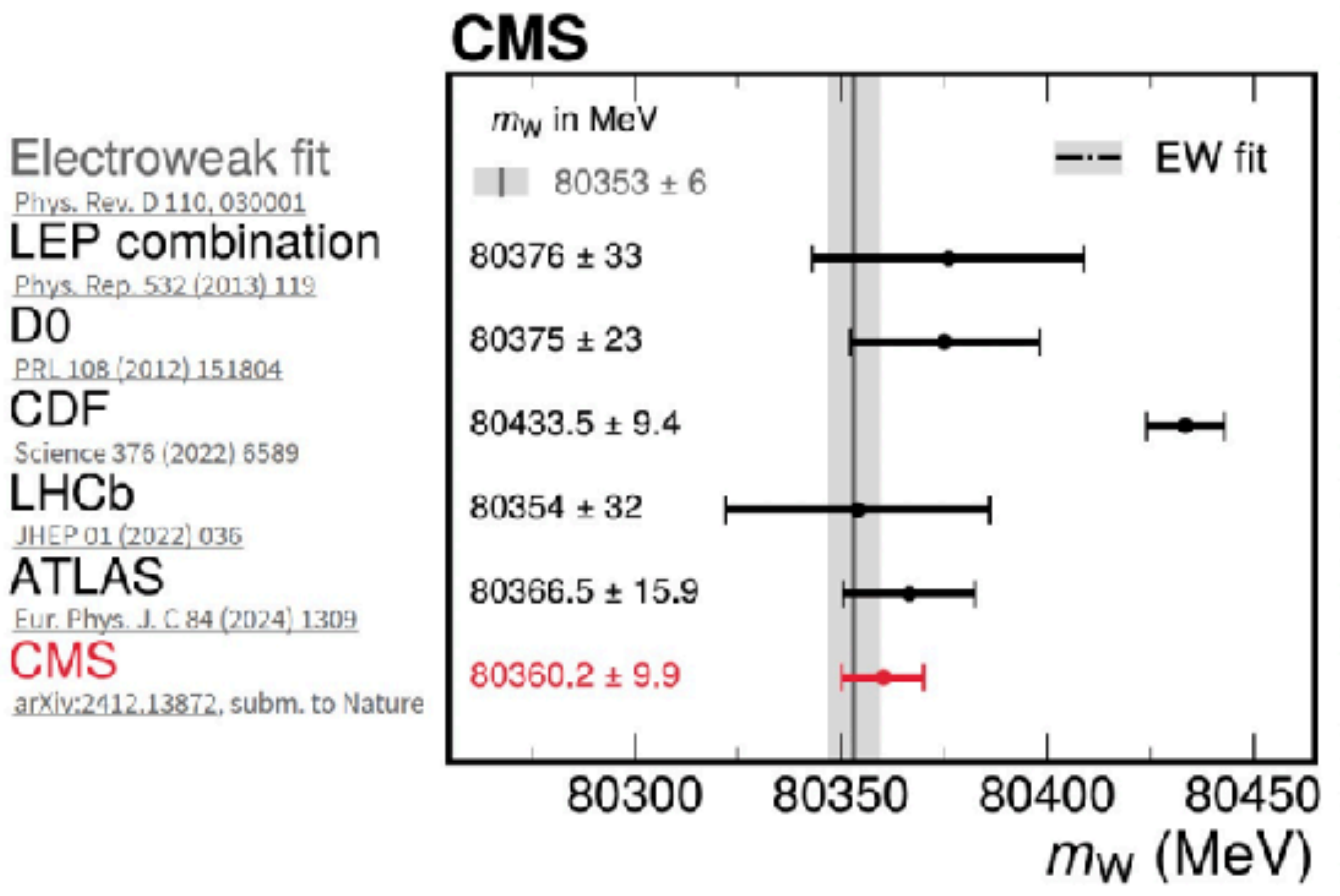
LHC Precision Measurements Highlights (I)

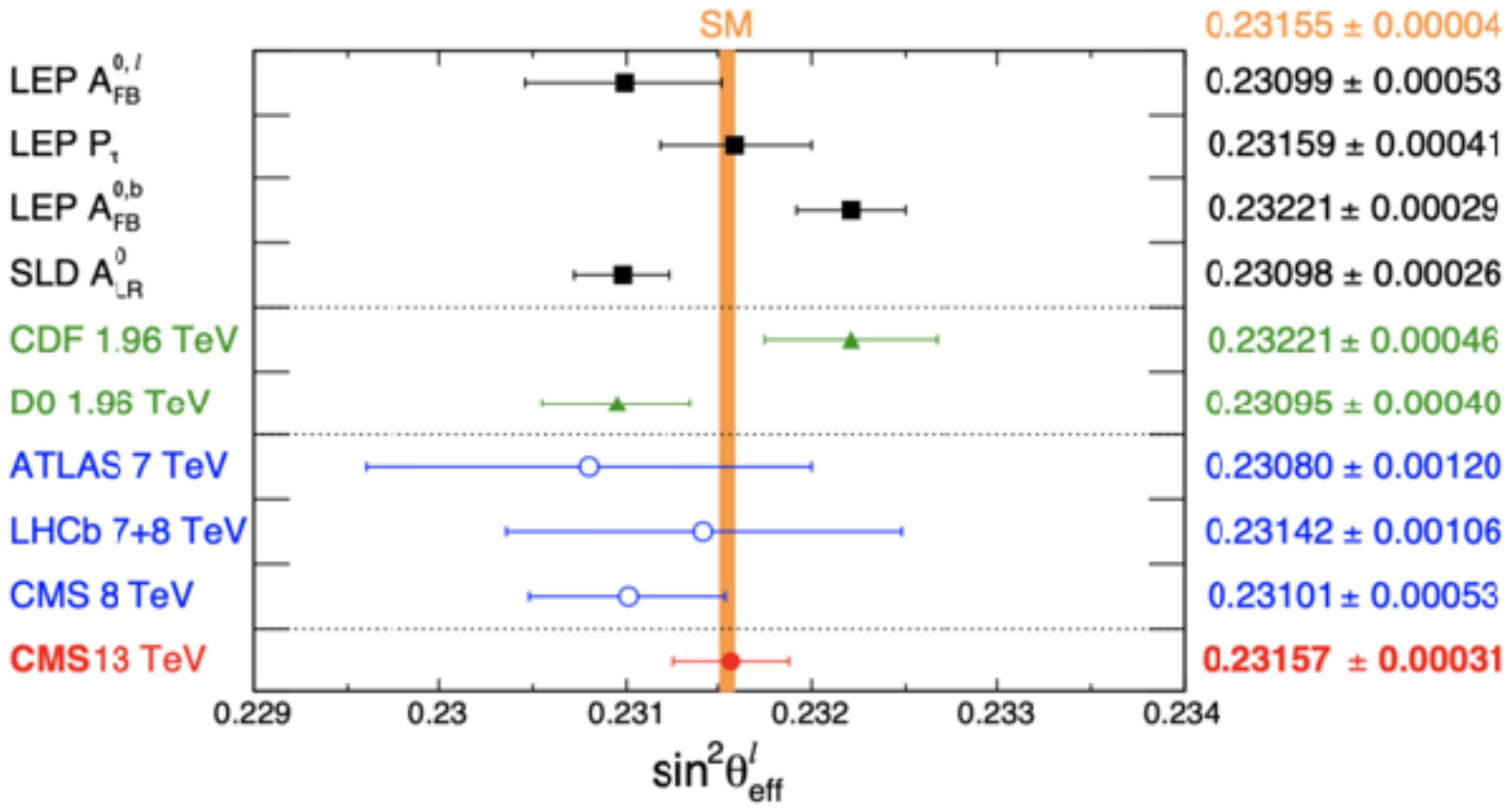
From precise Drell Yan (Z and W) measurements

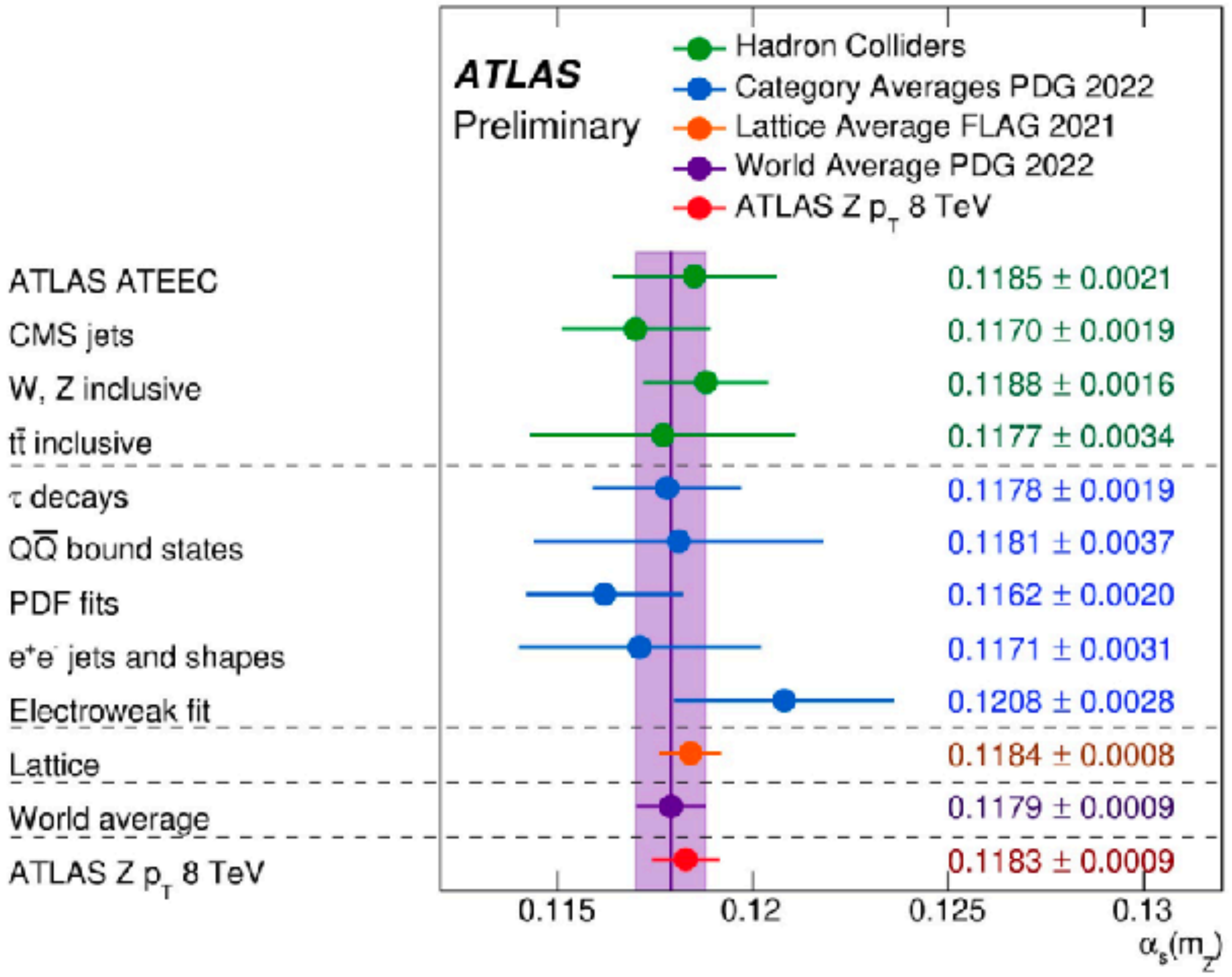
CMS W Mass precision at 10 MeV (experimental puzzle - **CDF measurement with outstanding 9 MeV precision but tension of 4σ with other experiments**)

$\sin^2\theta_W$ measured at 0.13% almost on par with best LEP and SLC measurements!!

α_S from Sudakov Z peak at low transverse momentum, best measurement so far and precision at 0.9%







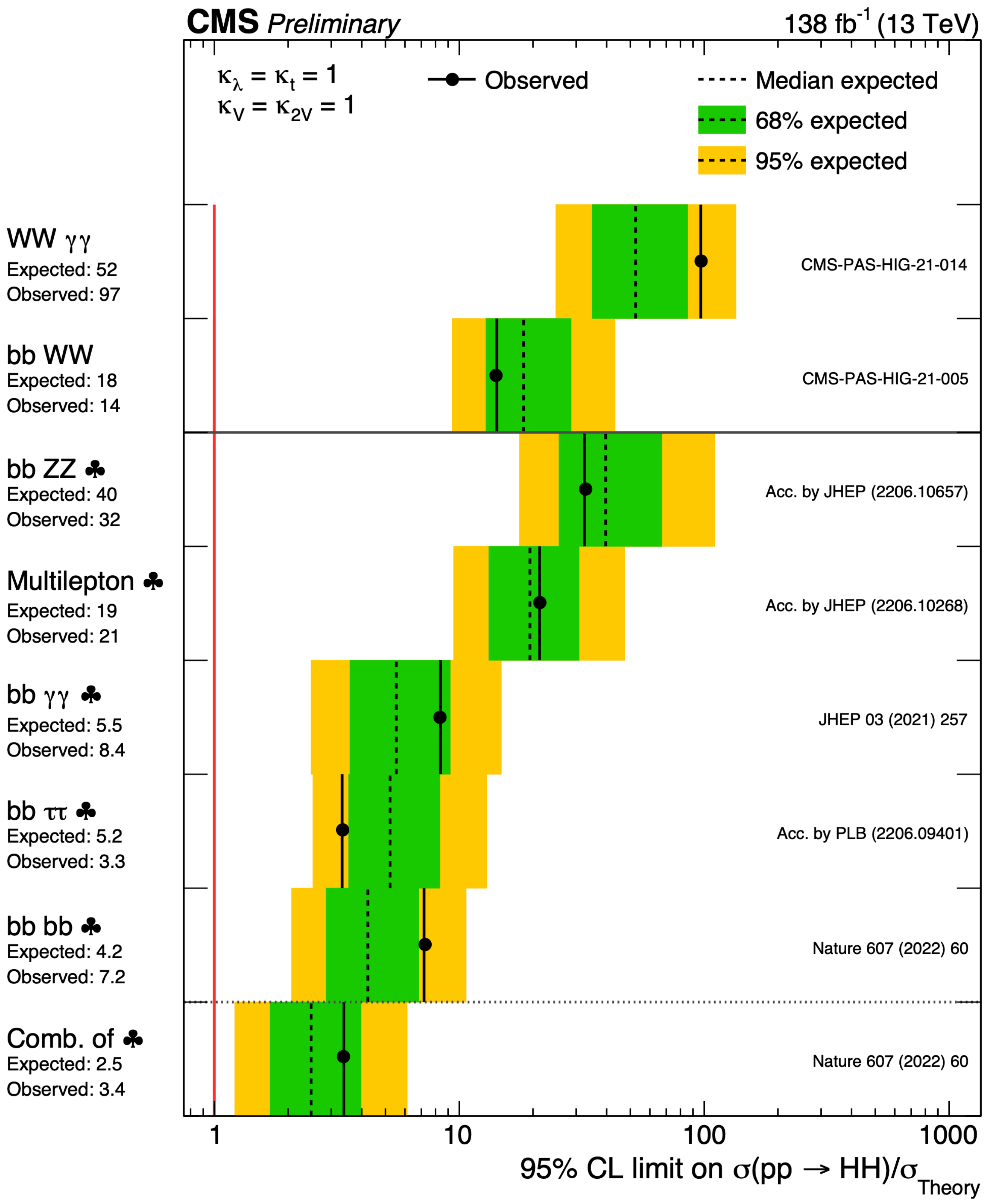
Significant evidence of measurement systematic bias!

Precision on par with lattice QCD and world average!

LHC Measurements Highlights (II)

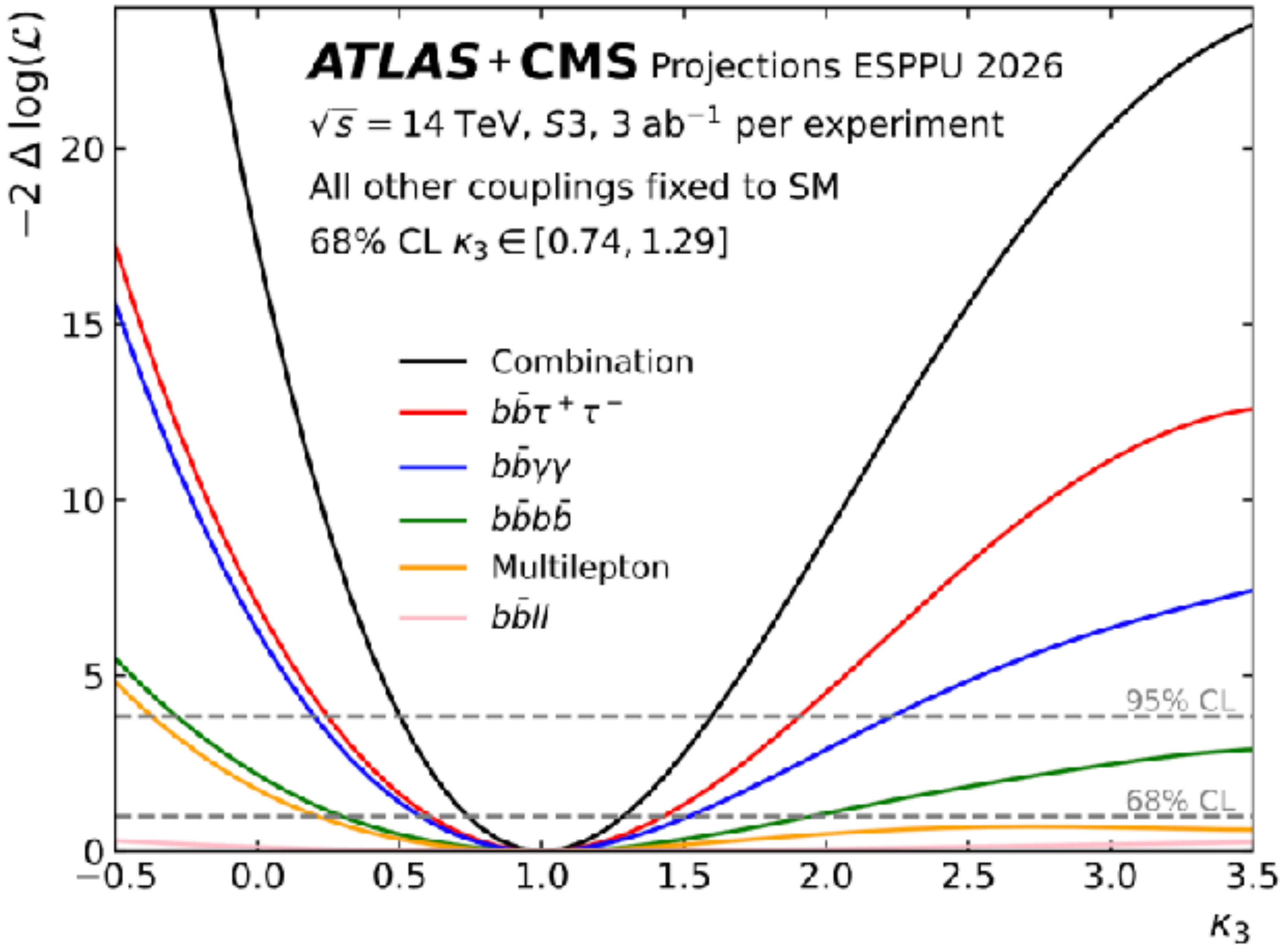
Di-Higgs production and Higgs (trilinear) self-coupling!

More channels and more performant analyses!



Both experiments have ~1σ sensitivity to a signal (Obs. ATLAS 0.4σ and CMS ~1σ) with Run 2!!

Naive comb. ATLAS-CMS sensitivity with Run 3 close 2.5 σ with improvements (and as much data as possible) **aim at 3σ**



Both experiments should reach ~5σ sensitivity at HL-LHC

A combined measurements precision of κ_λ of $^{+29\%}_{-26\%}$

IA Improvements at the LHC

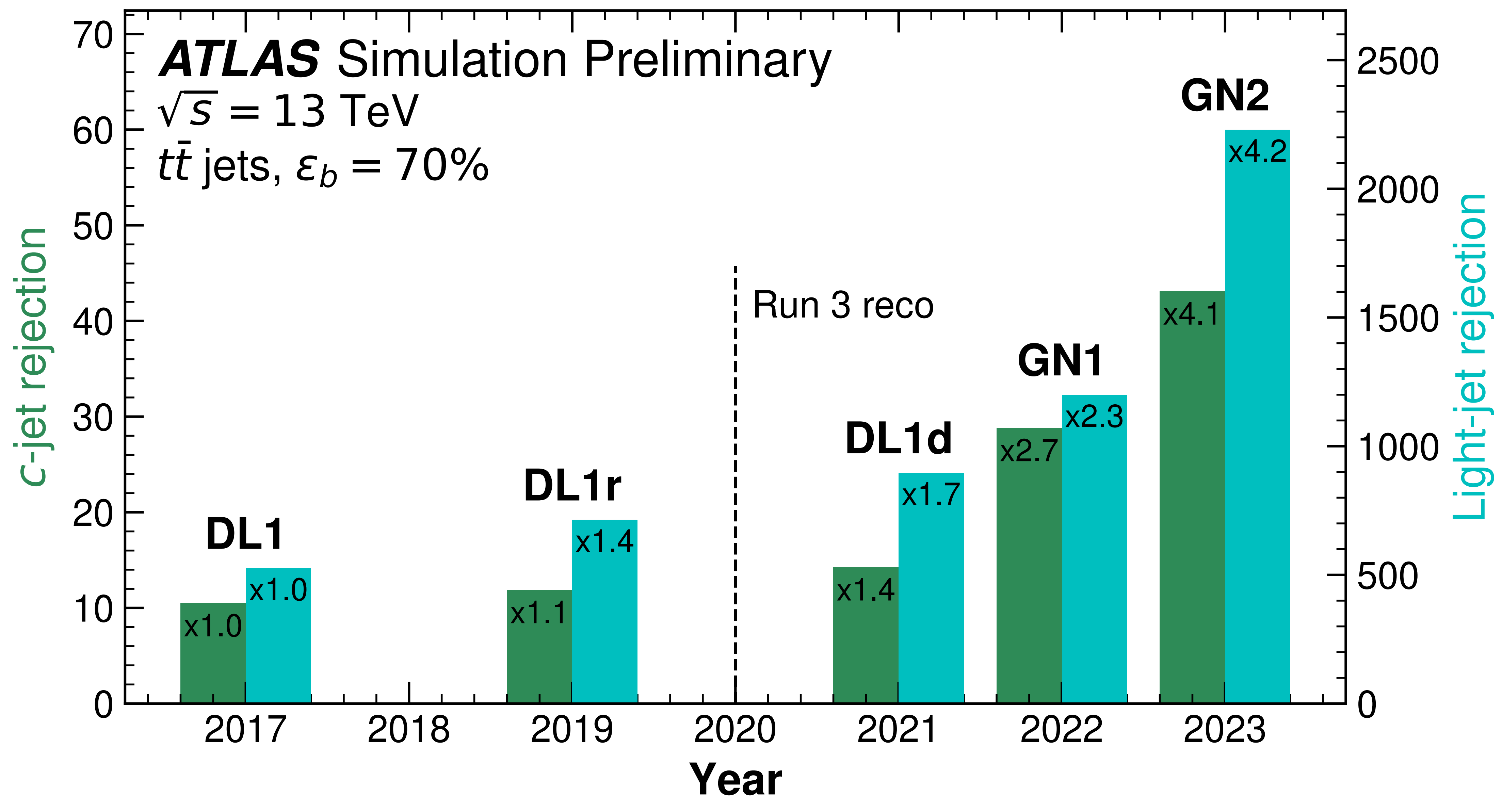
Flavour tagging progress with Deep Learning Techniques

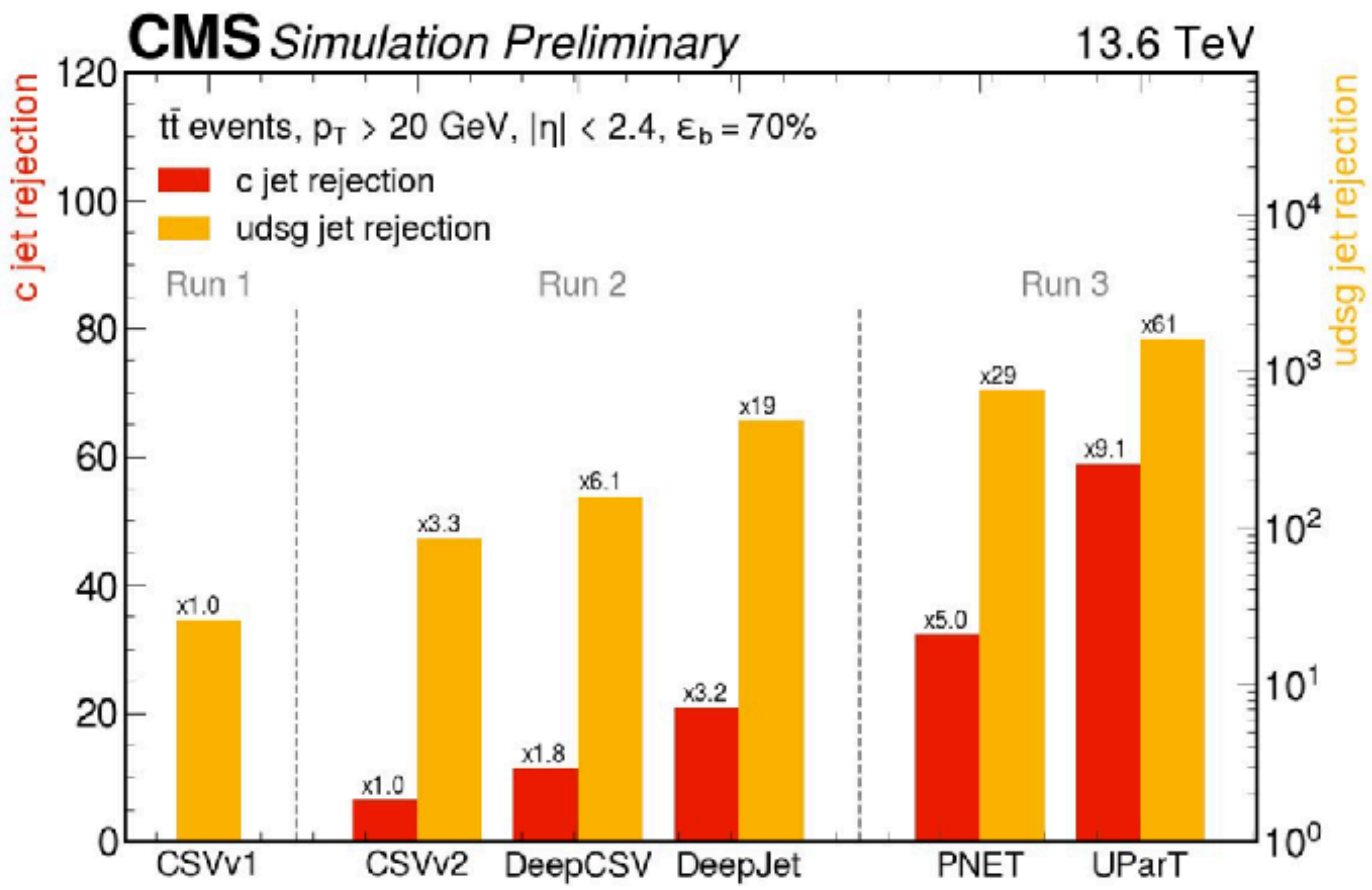
AI in HEP reconstruction has a significant impact!

Array of ML opportunities beyond classification and regression, in simulation, unfolding, anomaly detection, etc.

ATLAS LOVES ML/AI

New ideas also have to be concerned with **robustness and interpretability**





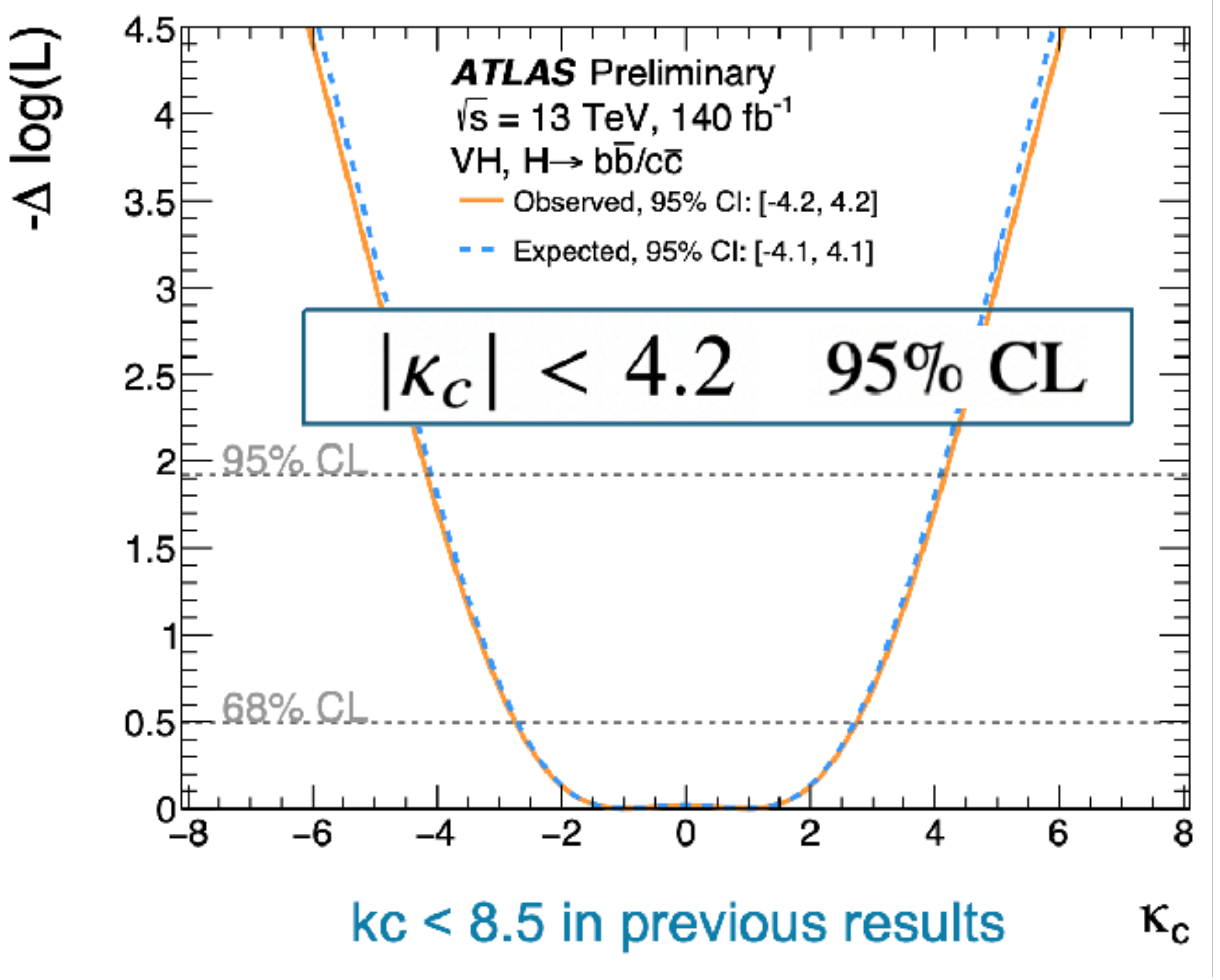
Still more improvements expected in flavour tagging techniques!

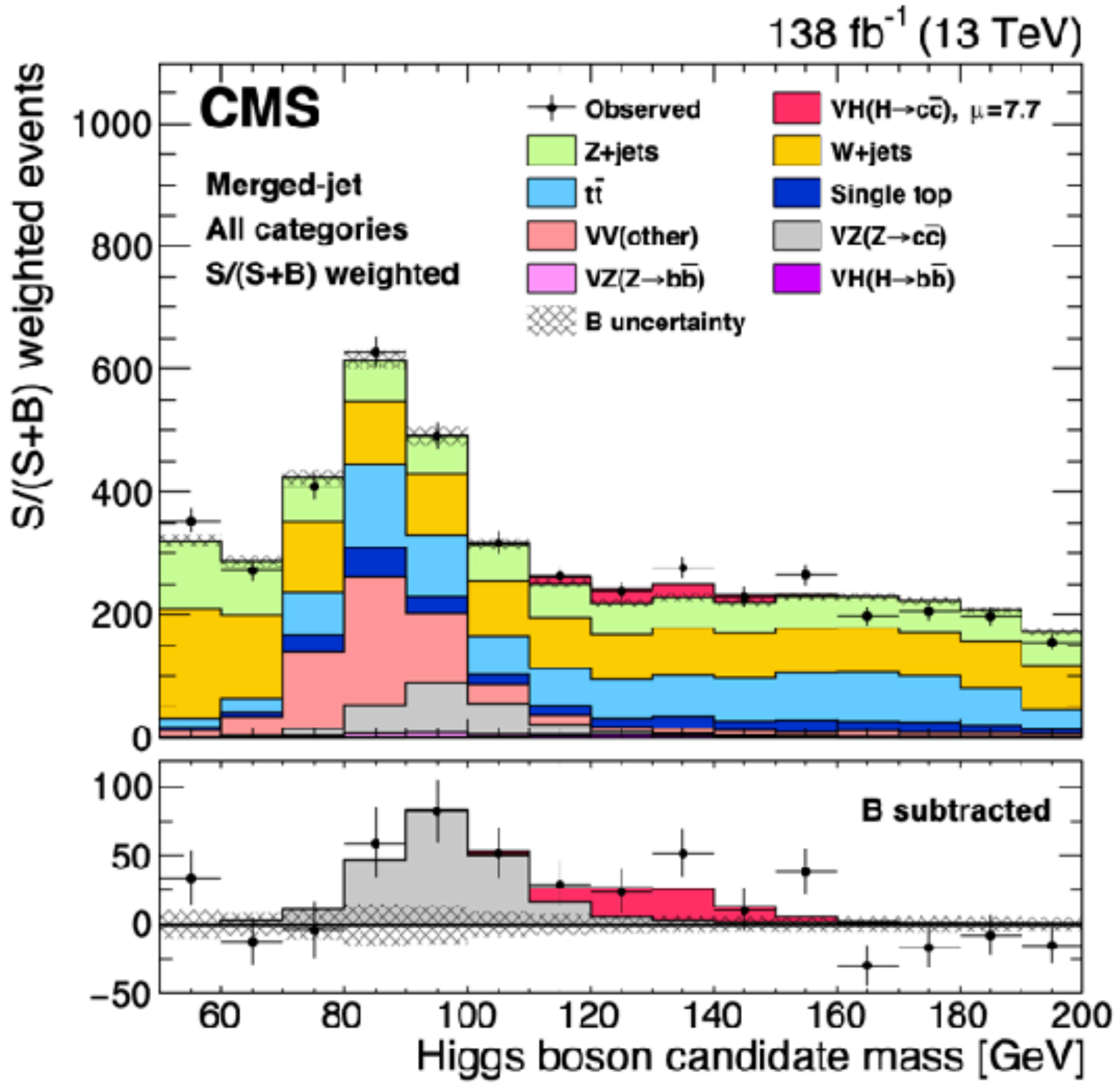
LHC Measurements Highlights (III)

Yukawa Coupling to Charm at the LHC

Refined analysis of Run 2 data with now Graph NN charm tagging!

Use of state-of-the-art ML techniques [Particle Net](#) uses Dynamic Graph CNN





$$\mu^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\,(\text{stat.})^{+3.6}_{-3.5}\,(\text{syst.}).$$

Improvement by a factor of 2 w.r.t. previous result

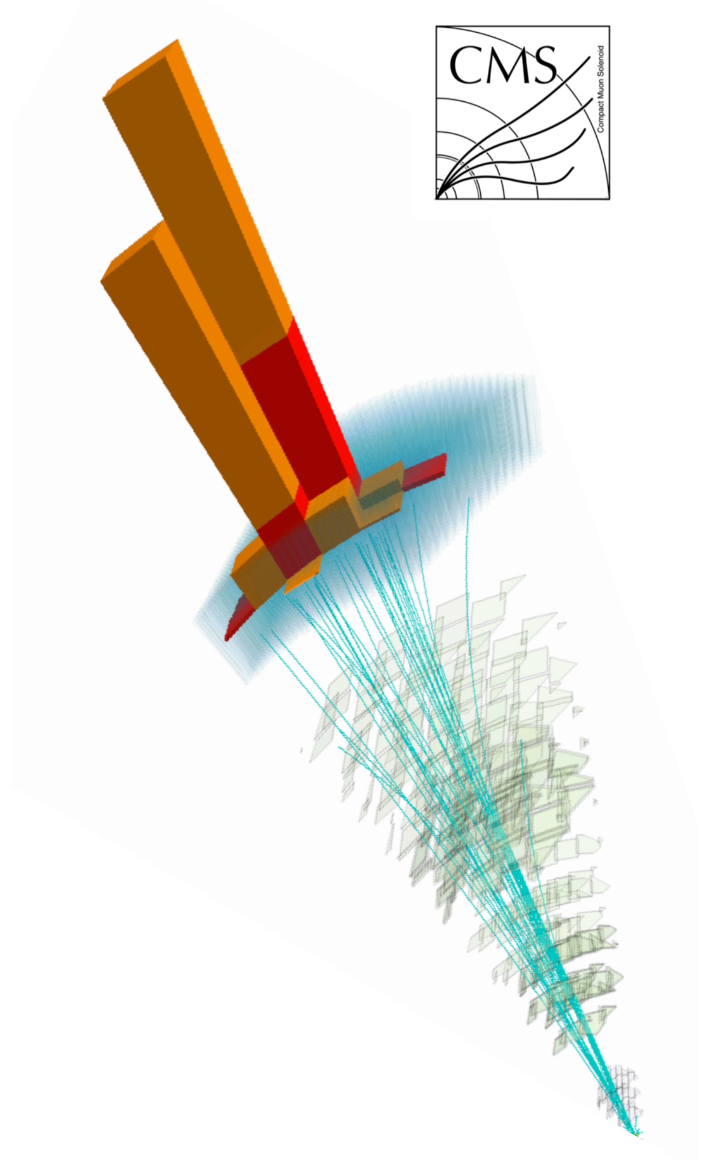
Constraints on charm Yukawa $1.1 < \kappa_c < 5.5$

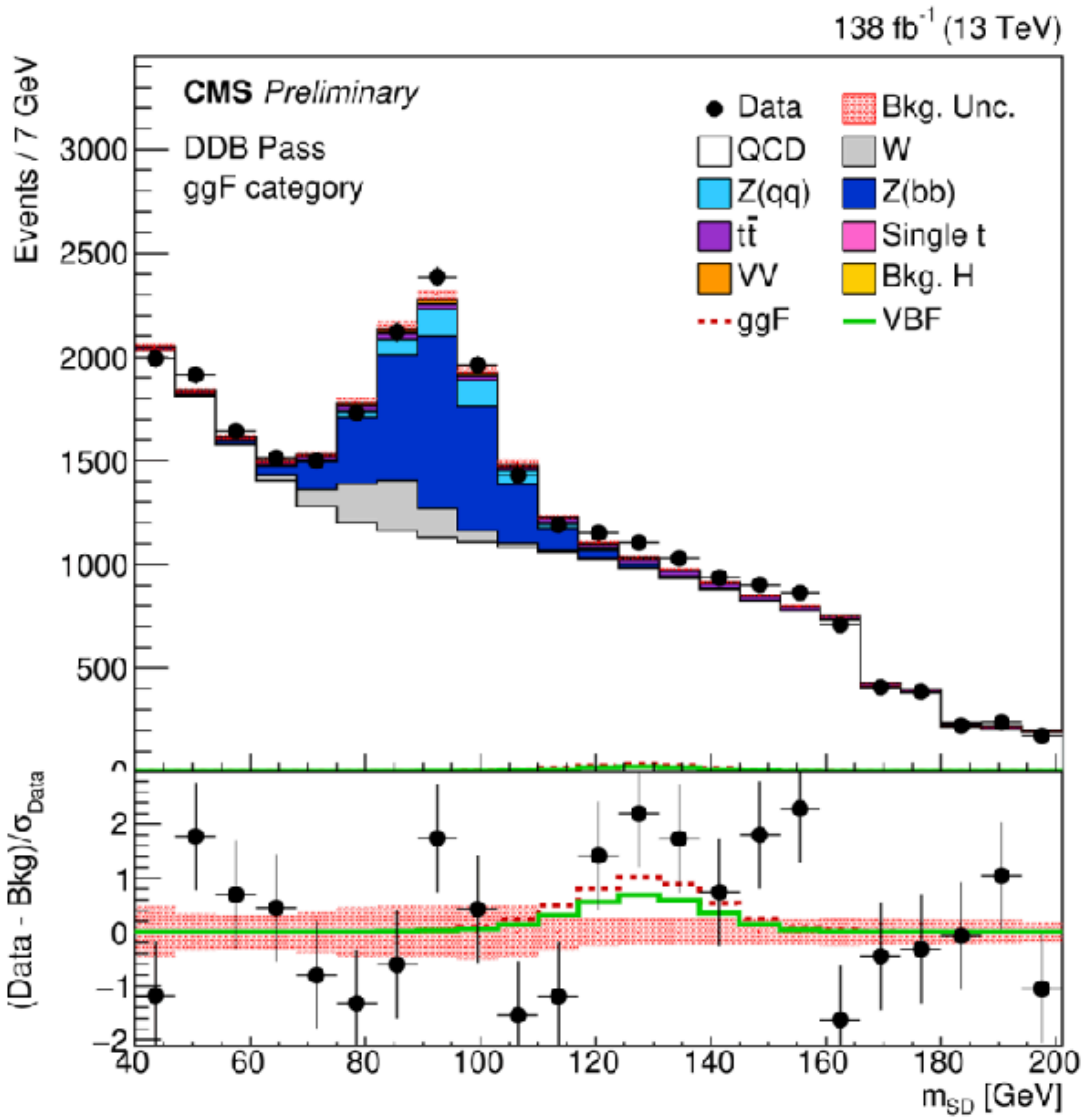
Yields a precision on κ_c of ~40% per experiment at HL-LHC

New perspective at the LHC!

Improving Reconstruction Techniques

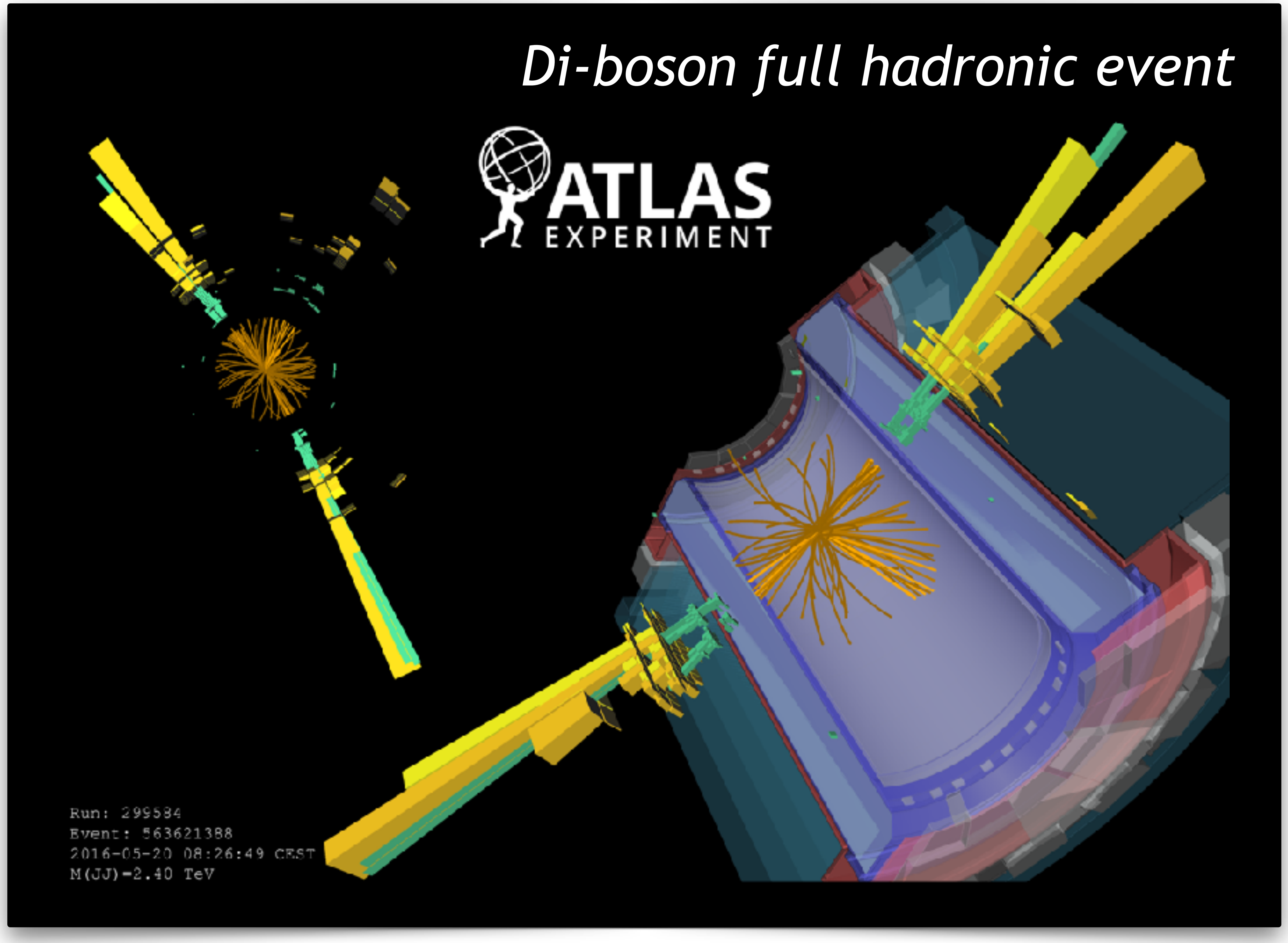
Jet substructure reconstruction improvements reconstructing a vector boson, a Higgs boson or a top quark.





Search for intermediate mass resonance as a single jet investigating its substructure (including b-tagging).

Searches for diboson in two boosted jets signatures

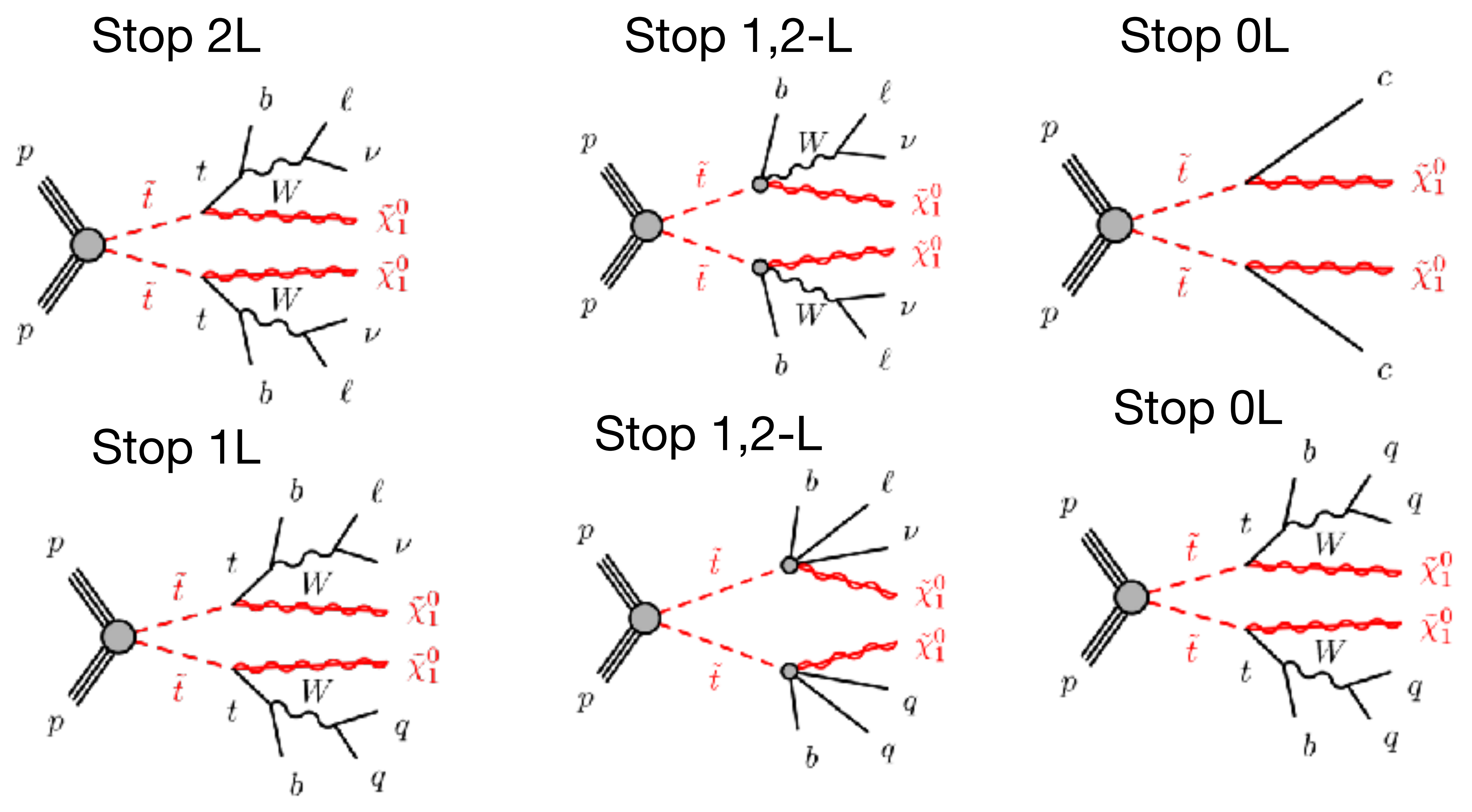


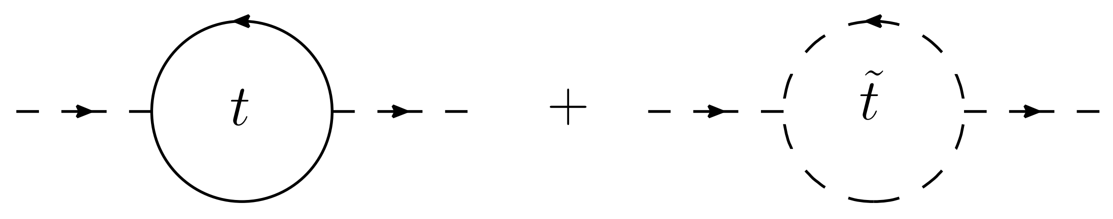
Di boson candidate event in a fully hadronic search, each jet has a mass compatible with a vector boson (W or Z).

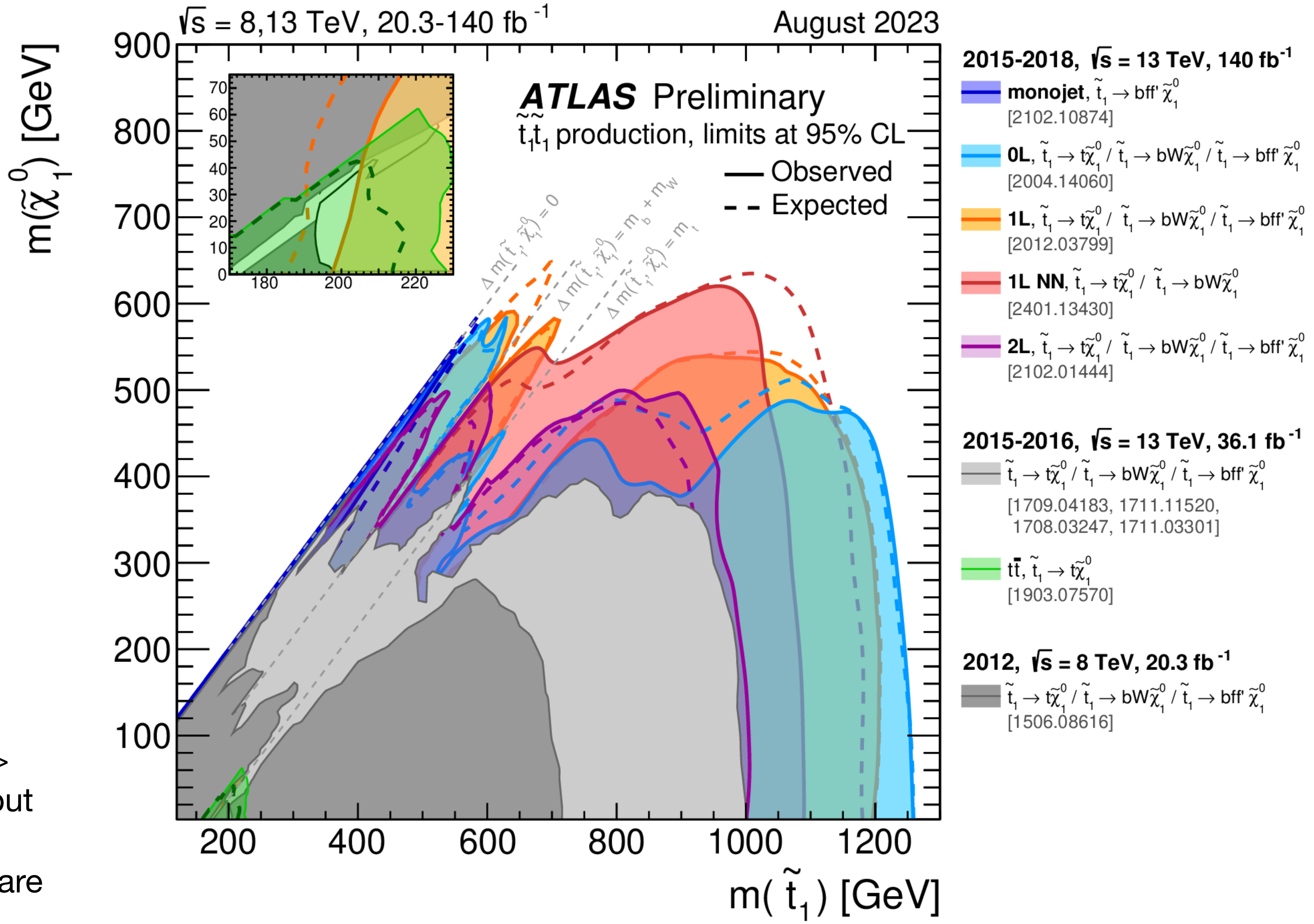
Supersymmetry

Constraining Strong Natural SUSY

Stop searches (main channels)



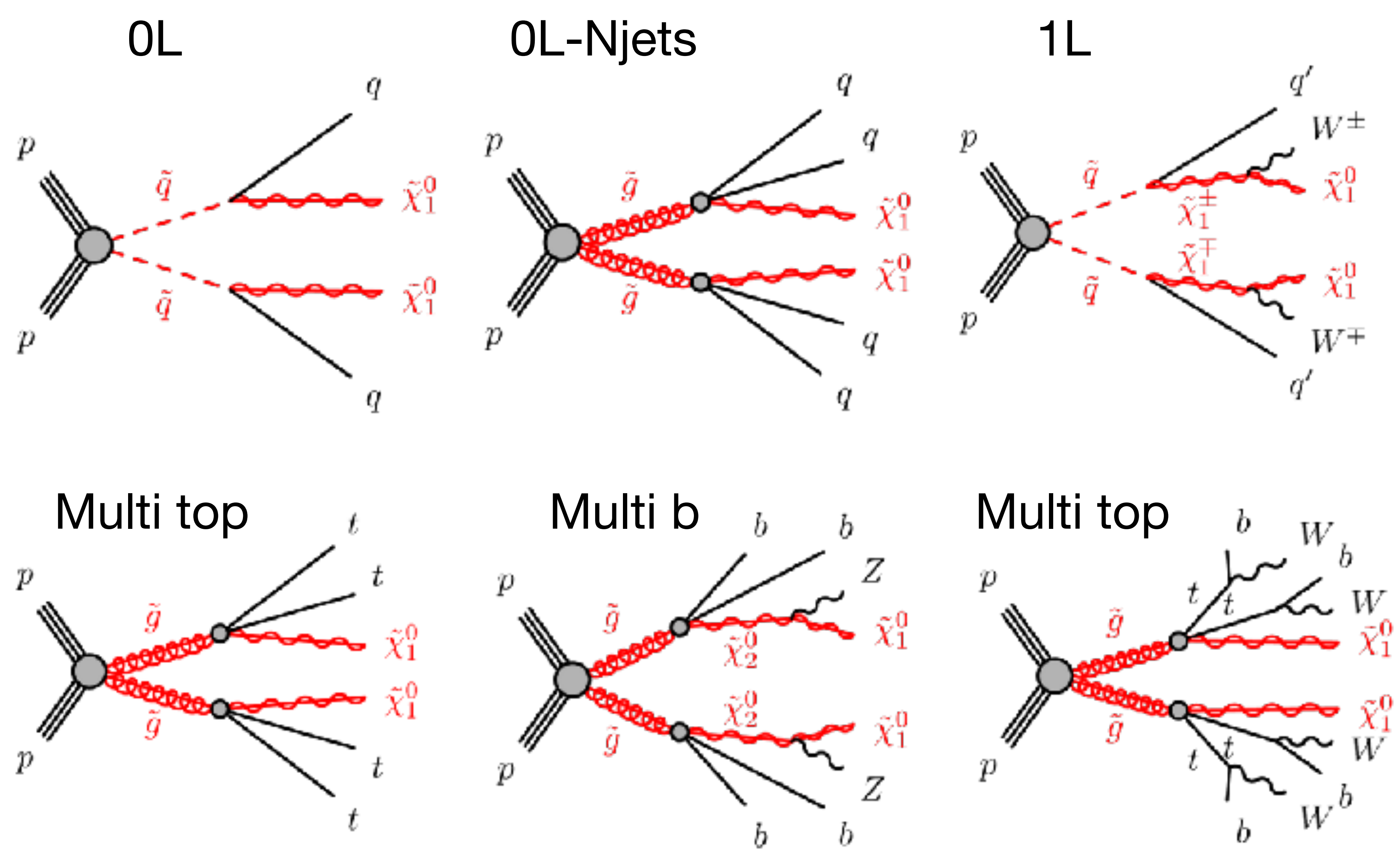




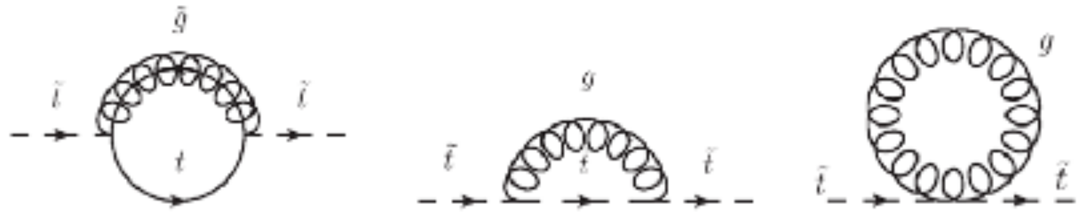
Not so natural SUSY: Stops > 1.2 TeV ~Tuning of factor **20**, but these exclusions are under specific conditions, and there are unexcluded corridors.

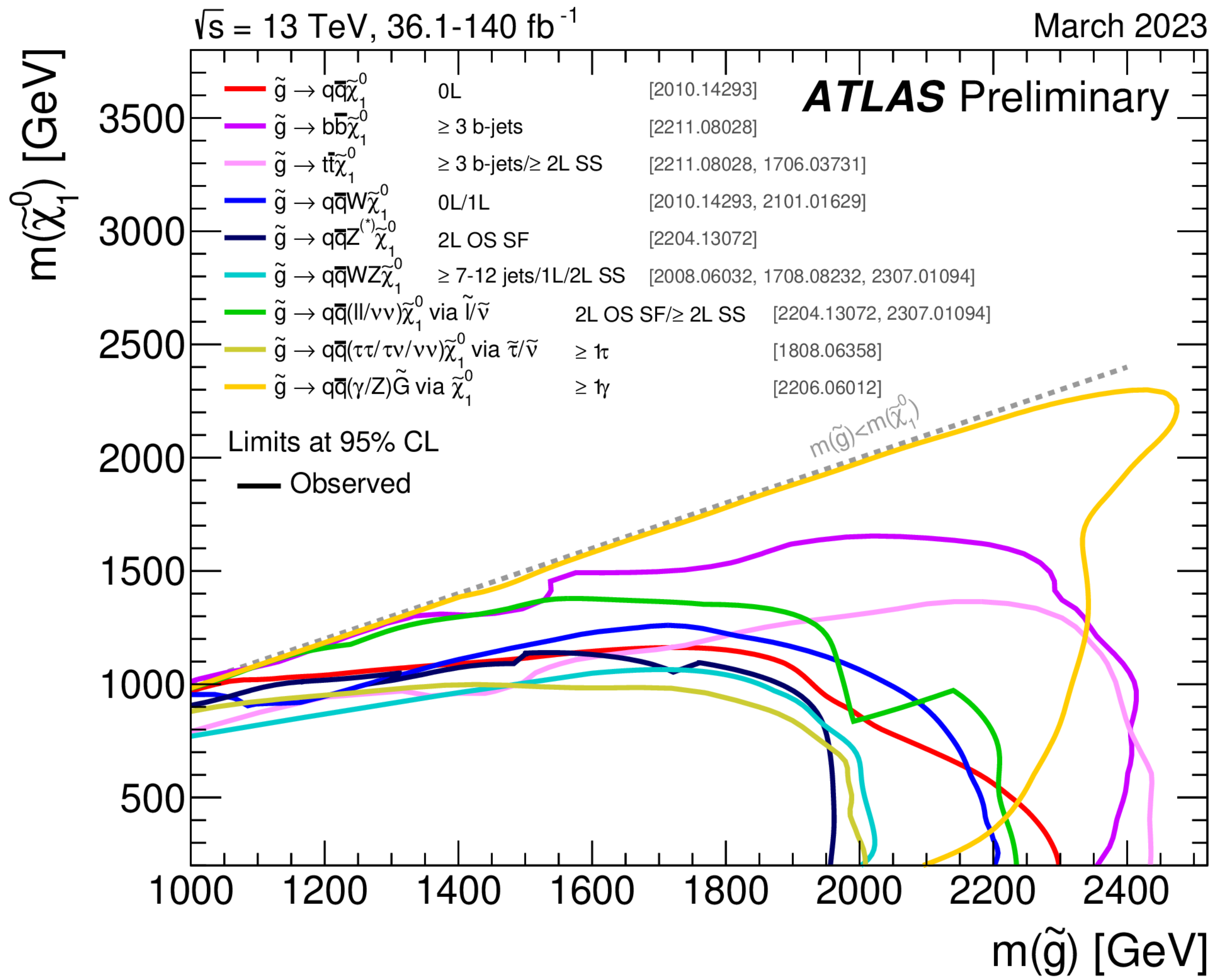
Constraining Strong Natural SUSY

Squarks and gluinos searches (main channels)



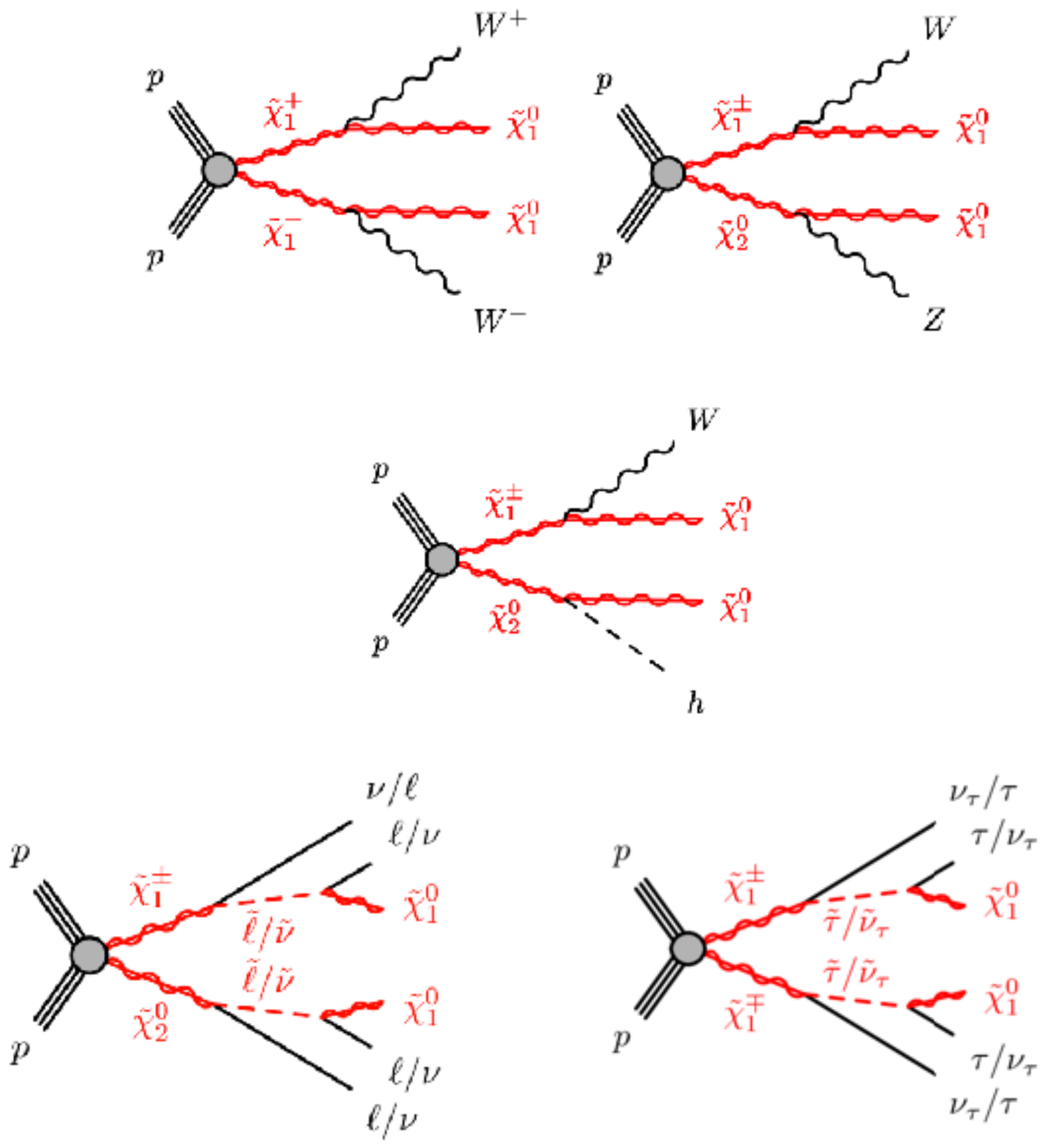
Stop also a scalar requires light gluinos to be light enough: for gluinos > 2.4 TeV ~tuning of Factor of **30**



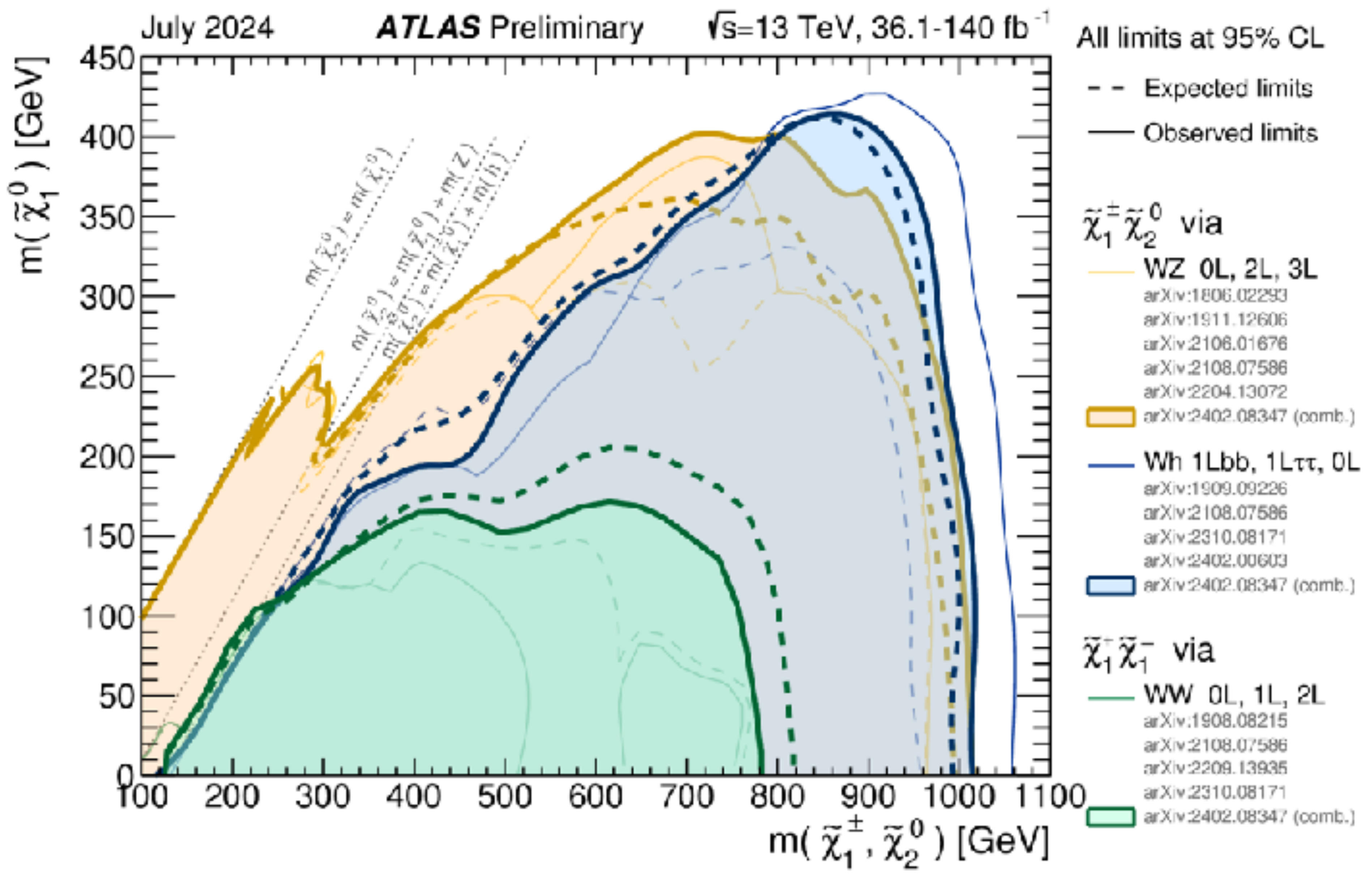


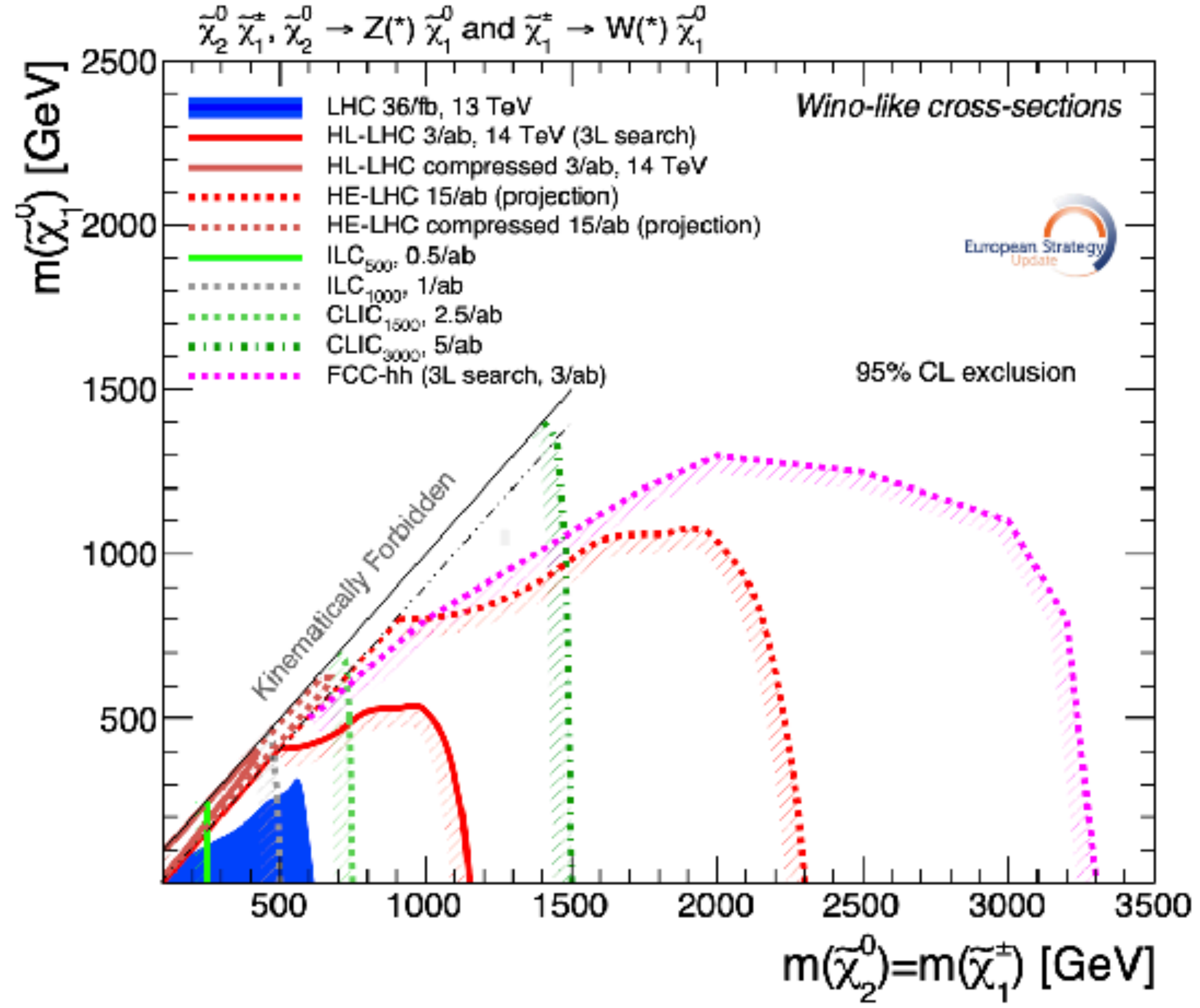
Constraining EW Natural SUSY

Weak production of charginos,
neutralinos and sleptons



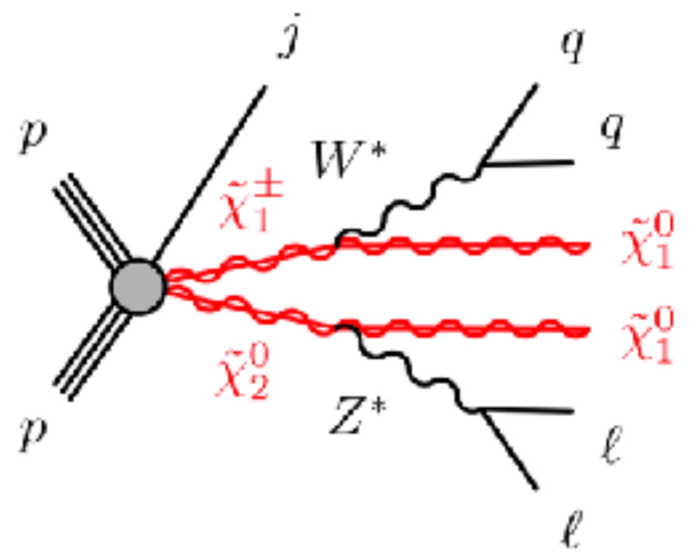
1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.



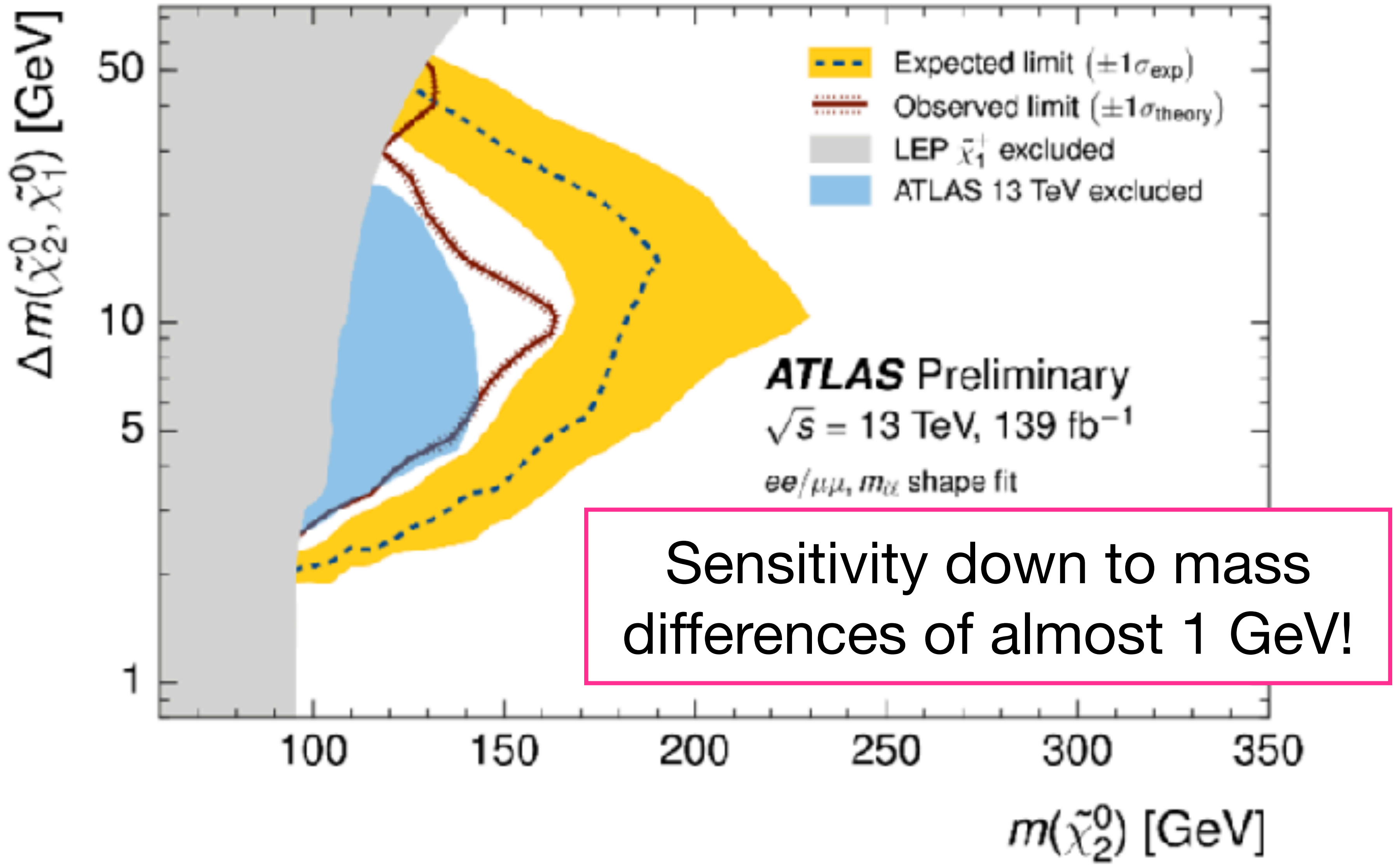


Searches for Charginos and Neutralinos (Examples)

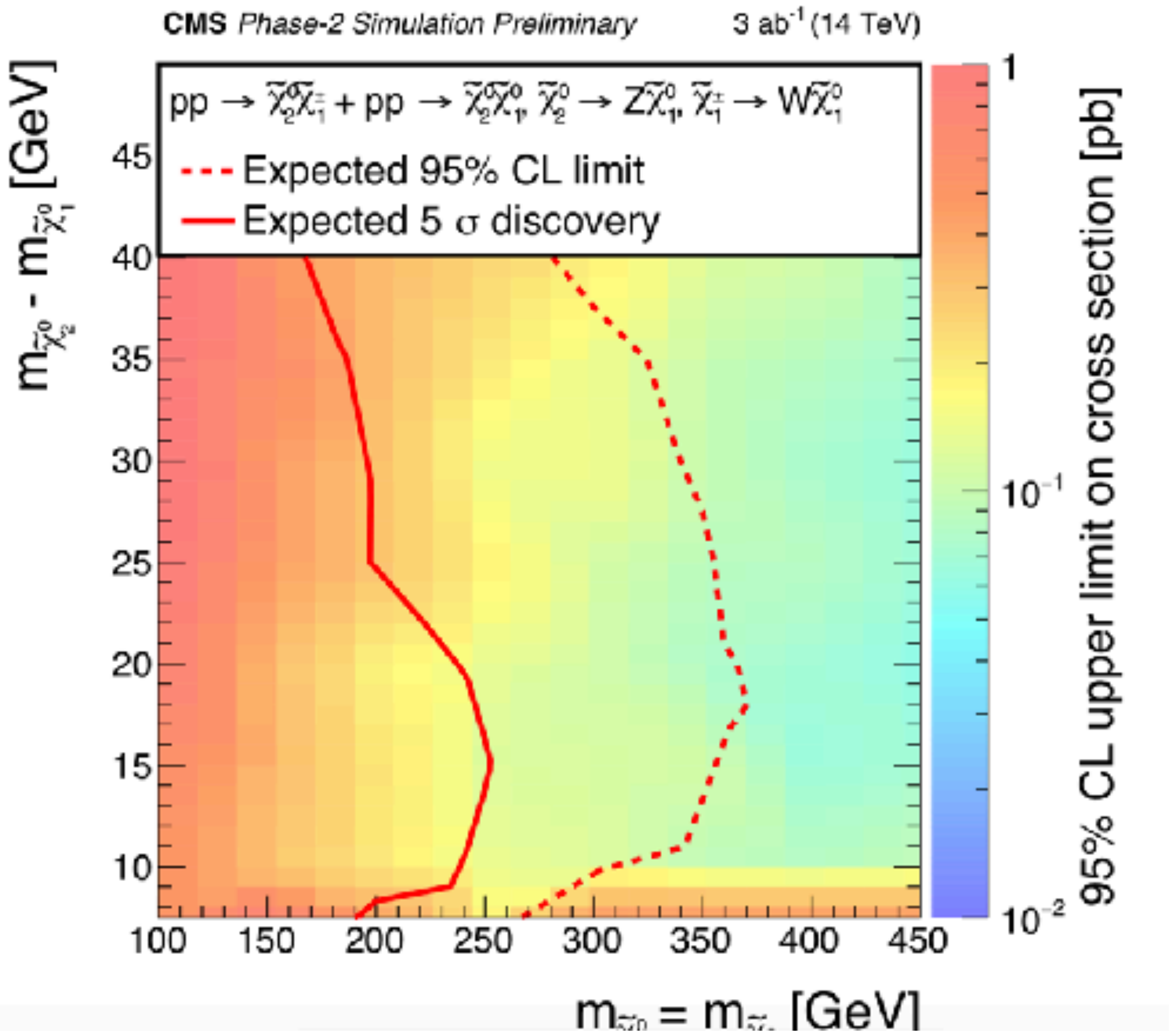
Weak production of charginos and neutralinos in compressed scenarios



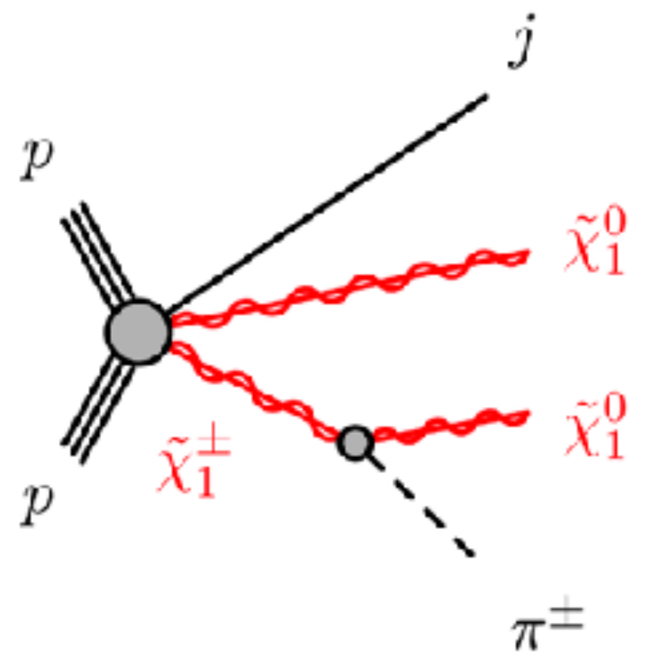
Example of boosting to find small mass differences.



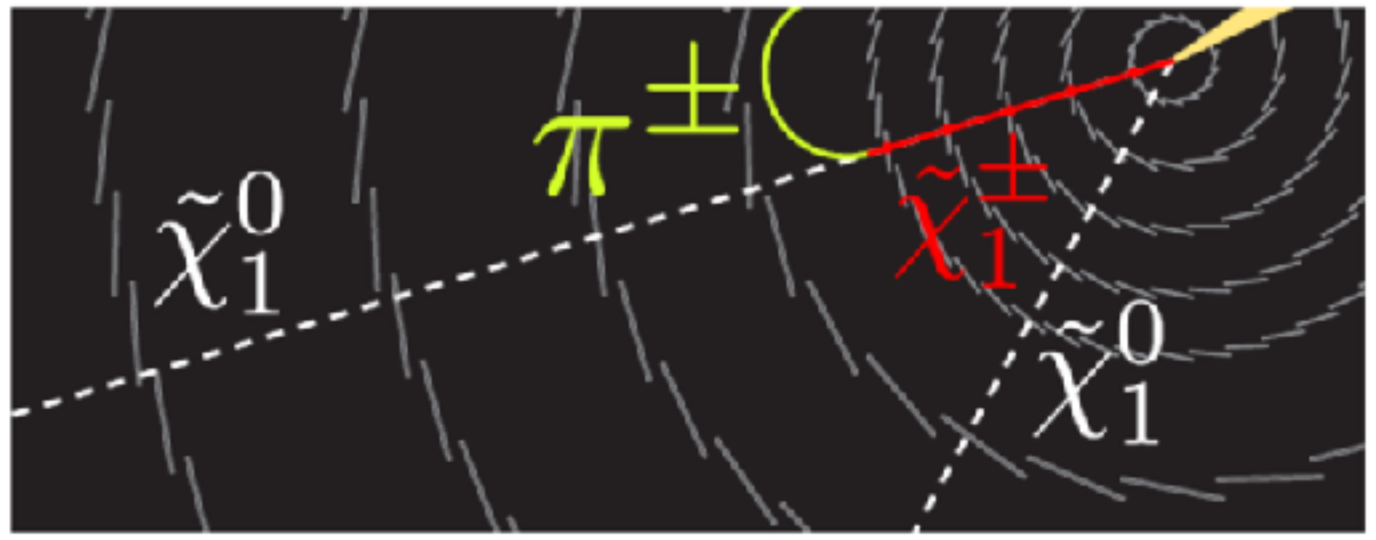
Sensitivity down to mass differences of almost 1 GeV!



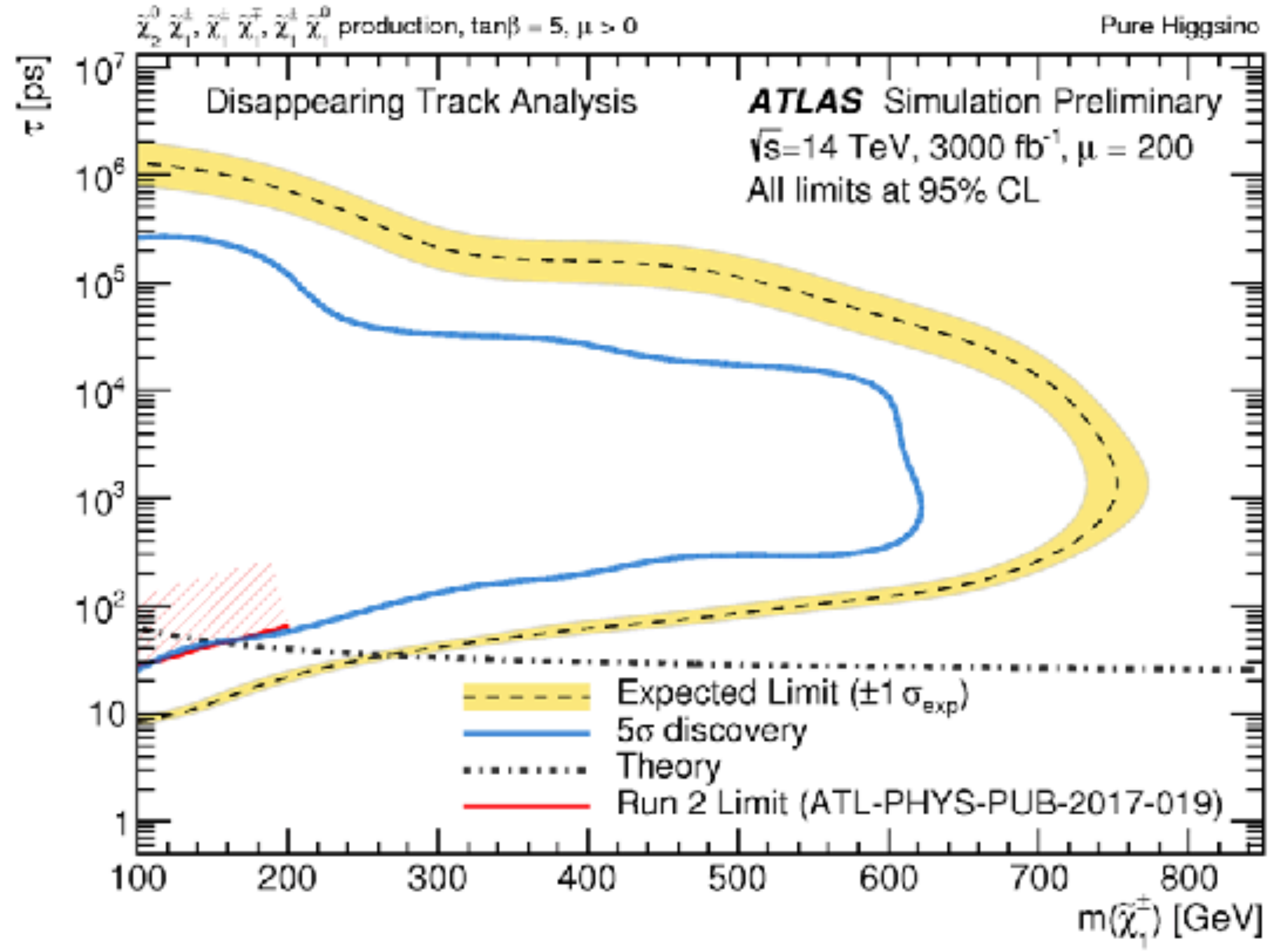
SUSY in highly compressed scenarios



Disappearing tracks topologies
(Uses MET Trigger - requires ISR jet)

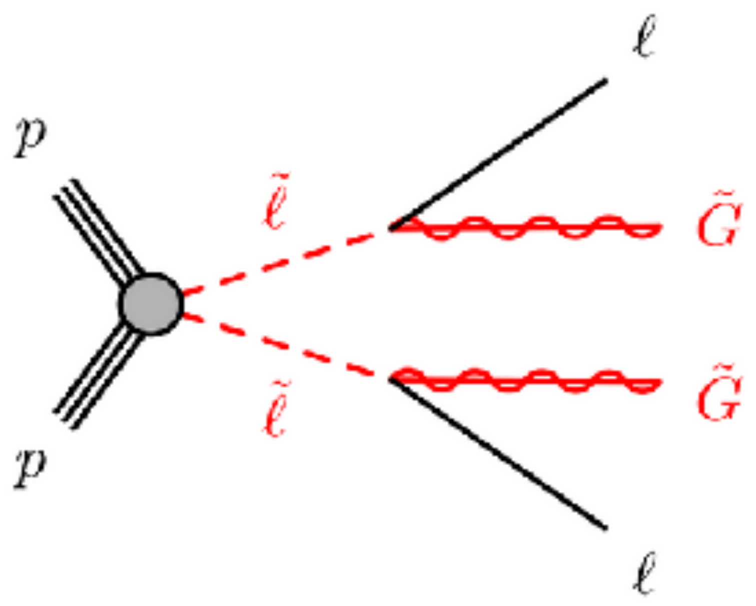


Scenario where the charginos and neutralinos are almost degenerate (chargino has significant lifetime and is seen in the first layers of the ID).

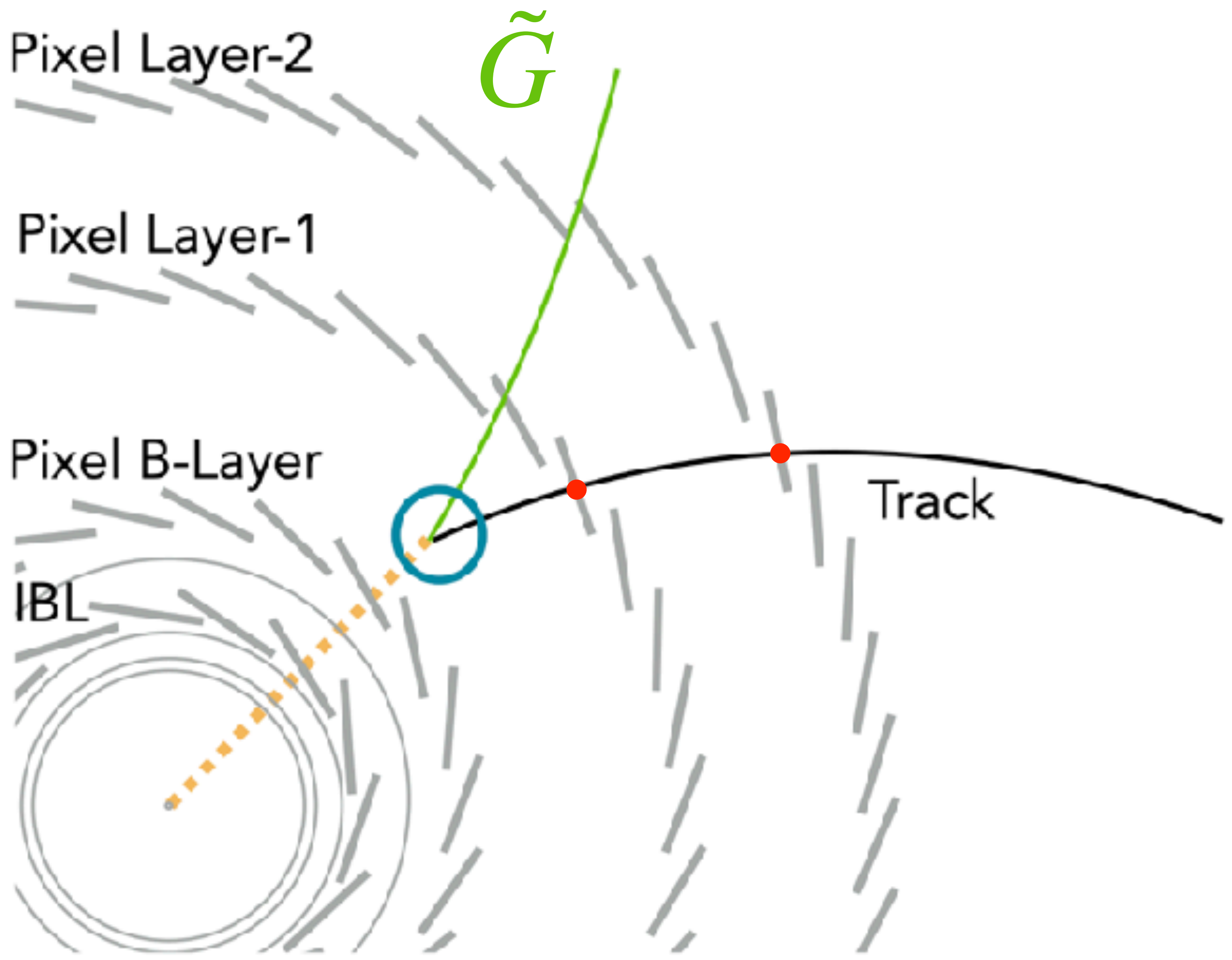


Unconventional Signatures at Colliders

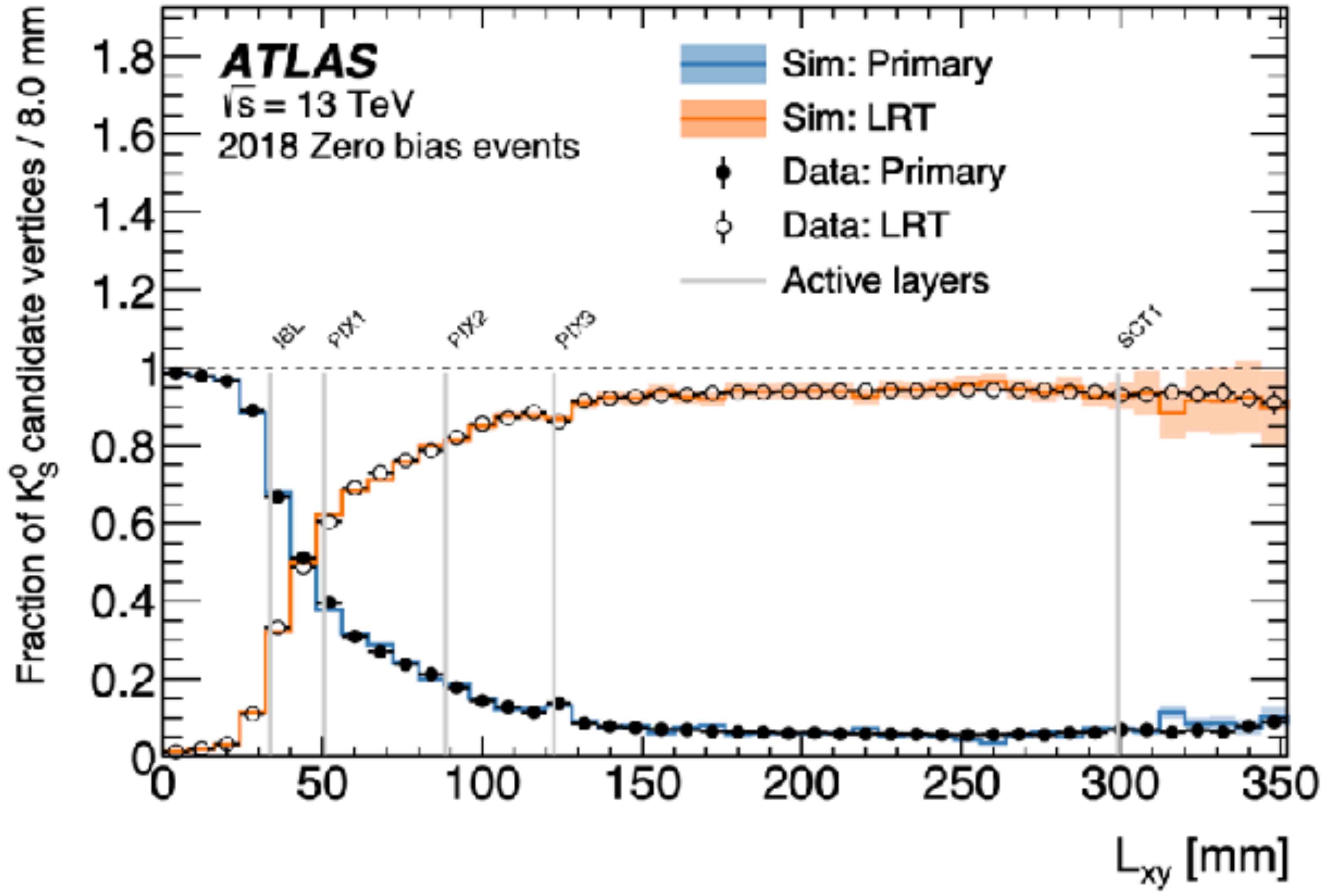
Another example of reconstruction improvements implemented for a Run 3 search! GMSB scenarios with low mass gravitino



Long lifetime due to the small coupling to the low mass gravitino!

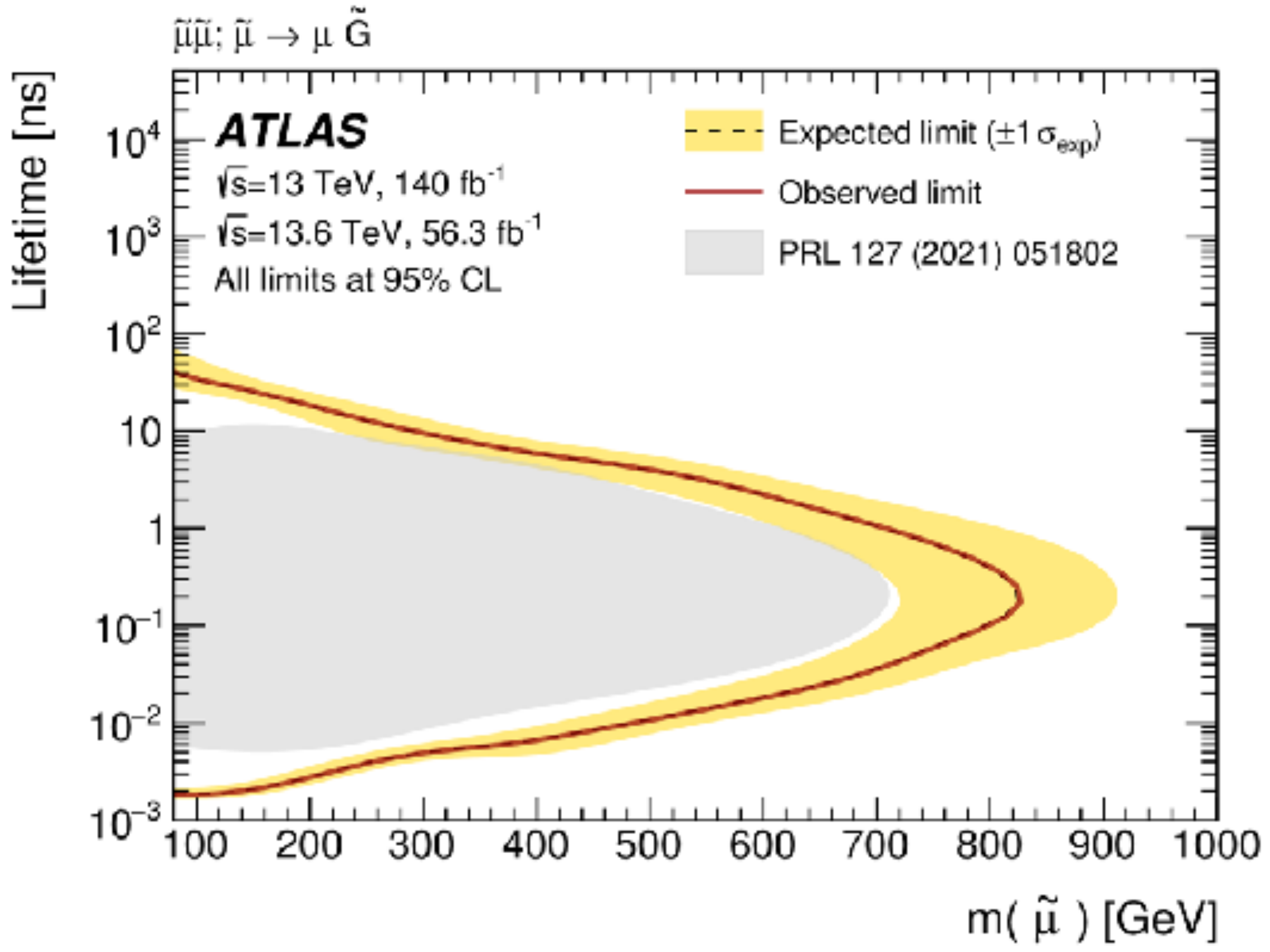


Improving reconstruction techniques e.g. ATLAS Large Radius Tracking at Run 3 and reprocessed Run 2!



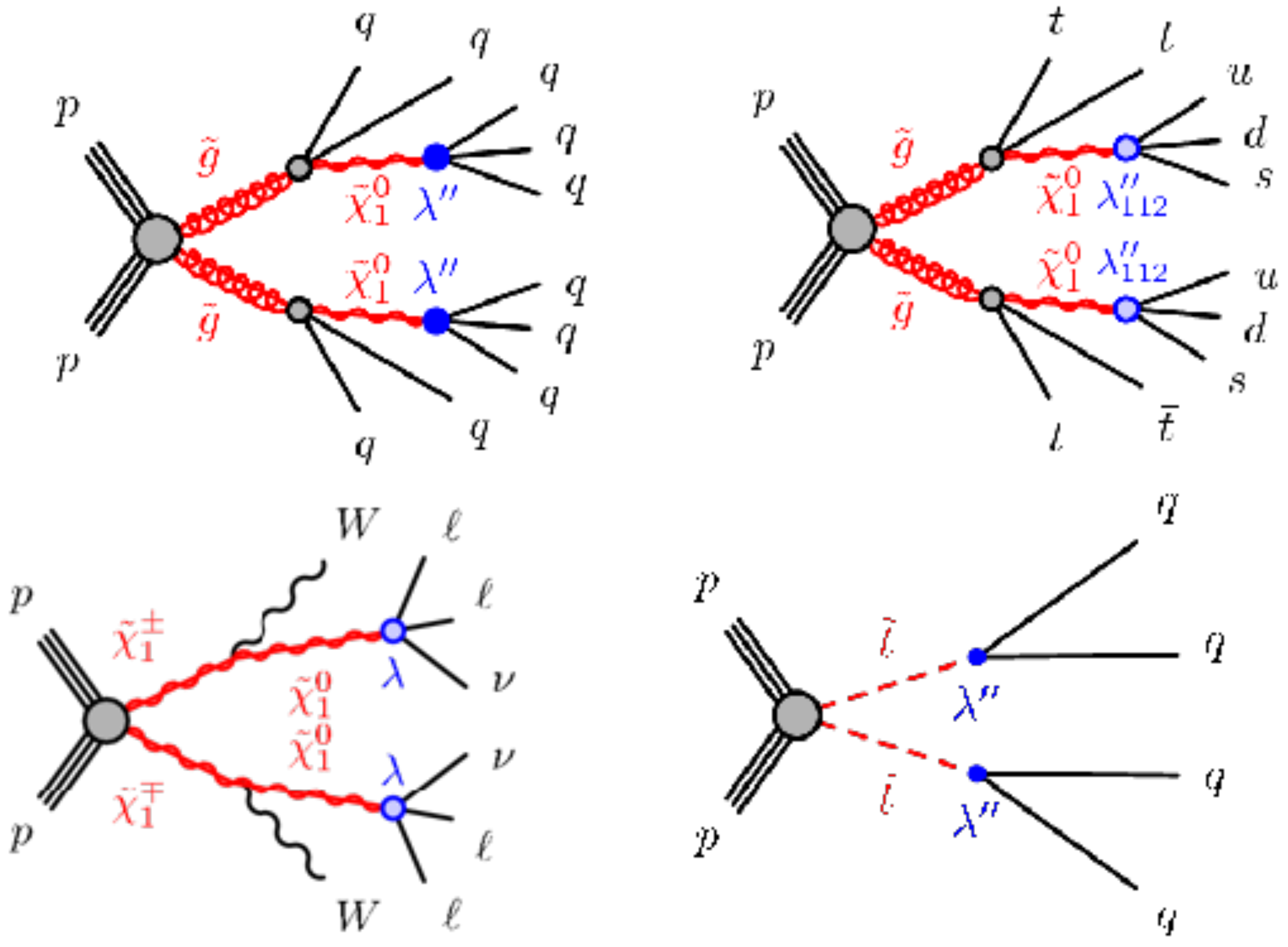
LRT performance tested with Ks reconstruction ([Paper](#))

Search done for smuons, selectron and staus.



When SUSY Comes Without MET

R-Parity violating SUSY



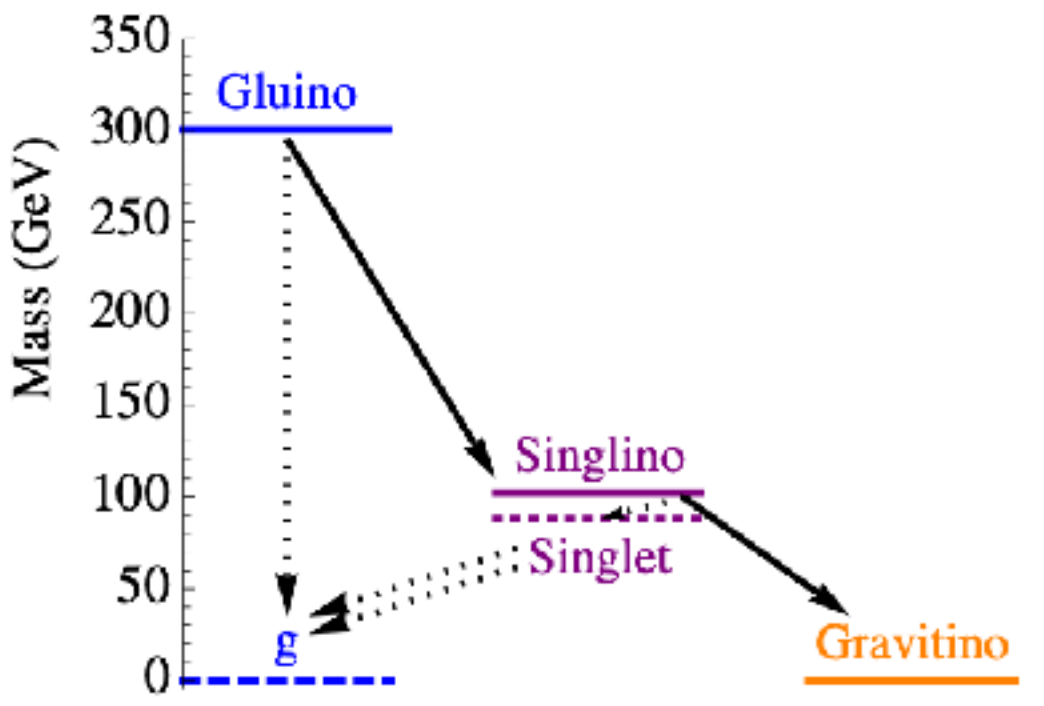
Resulting in topologies without LSP in the final state and therefore no MET.

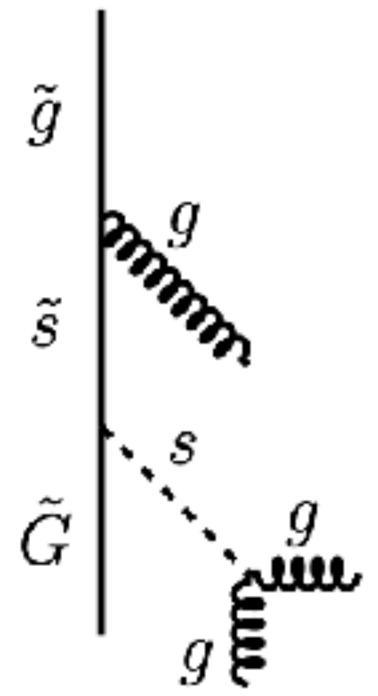
$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k$$
$$+\frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

RPV components of superpotential

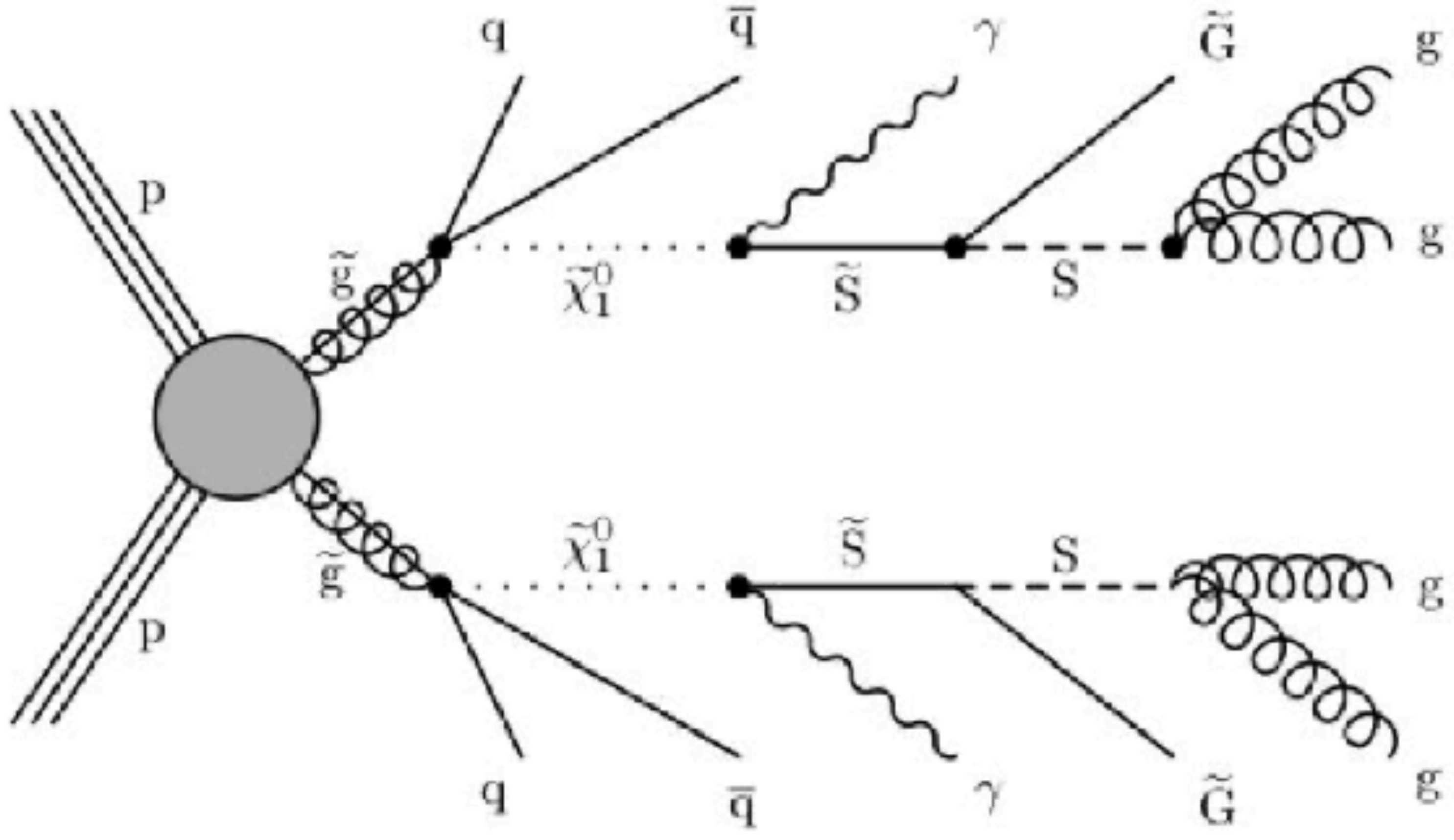
Stealth SUSY

R-Parity is preserved but “hidden” in the quasi degeneracy of Singlet and Singling with a nearly massless gravitino LSP.

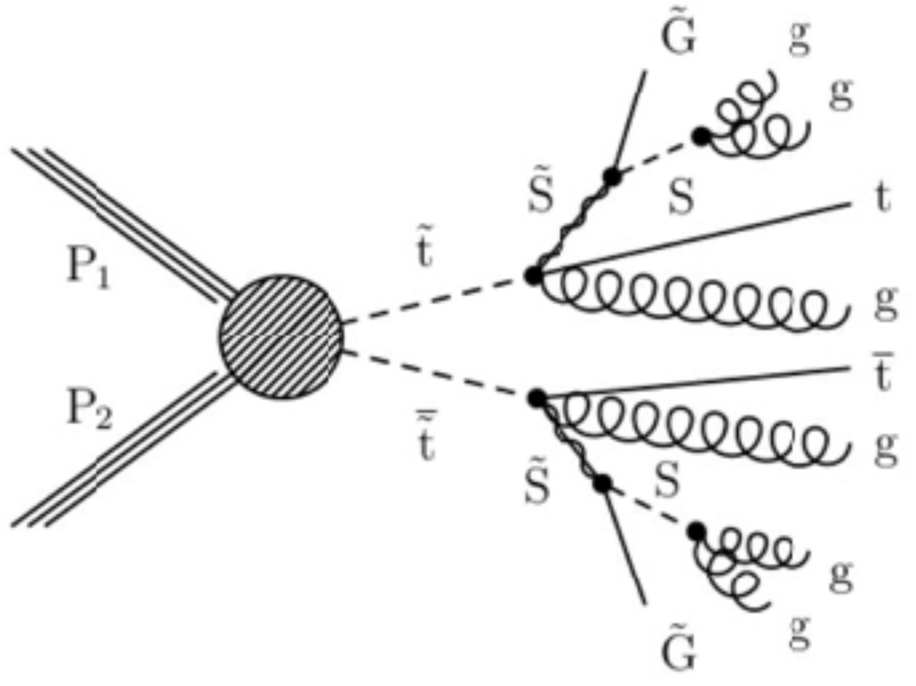


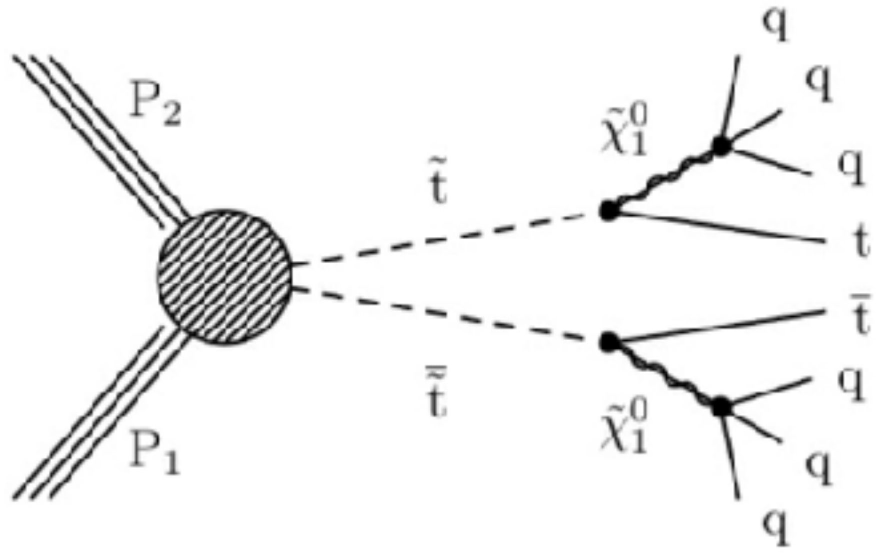


Searches e.g. in di-photon event topologies.



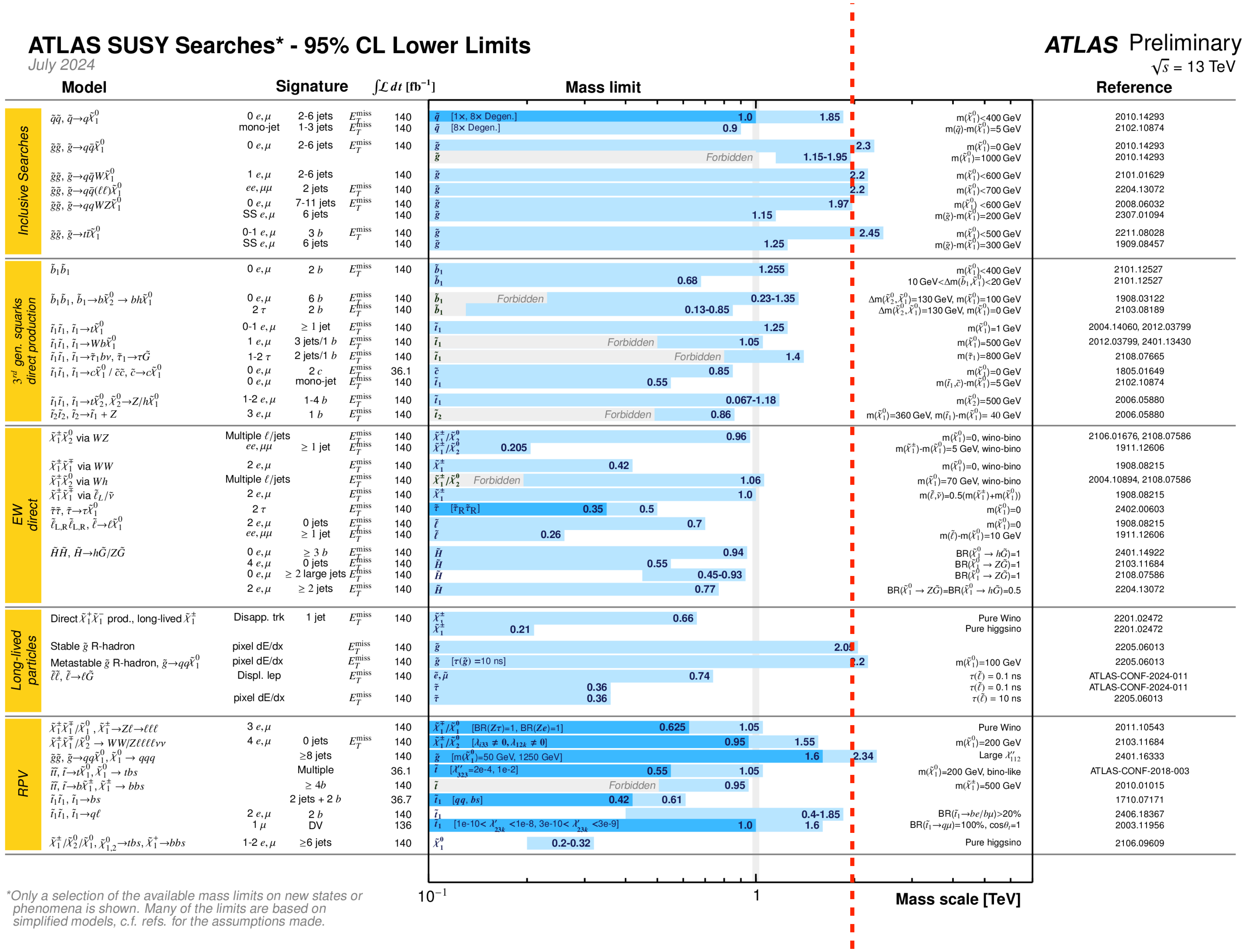
Some signatures are common to RPV andStealth scenarios!

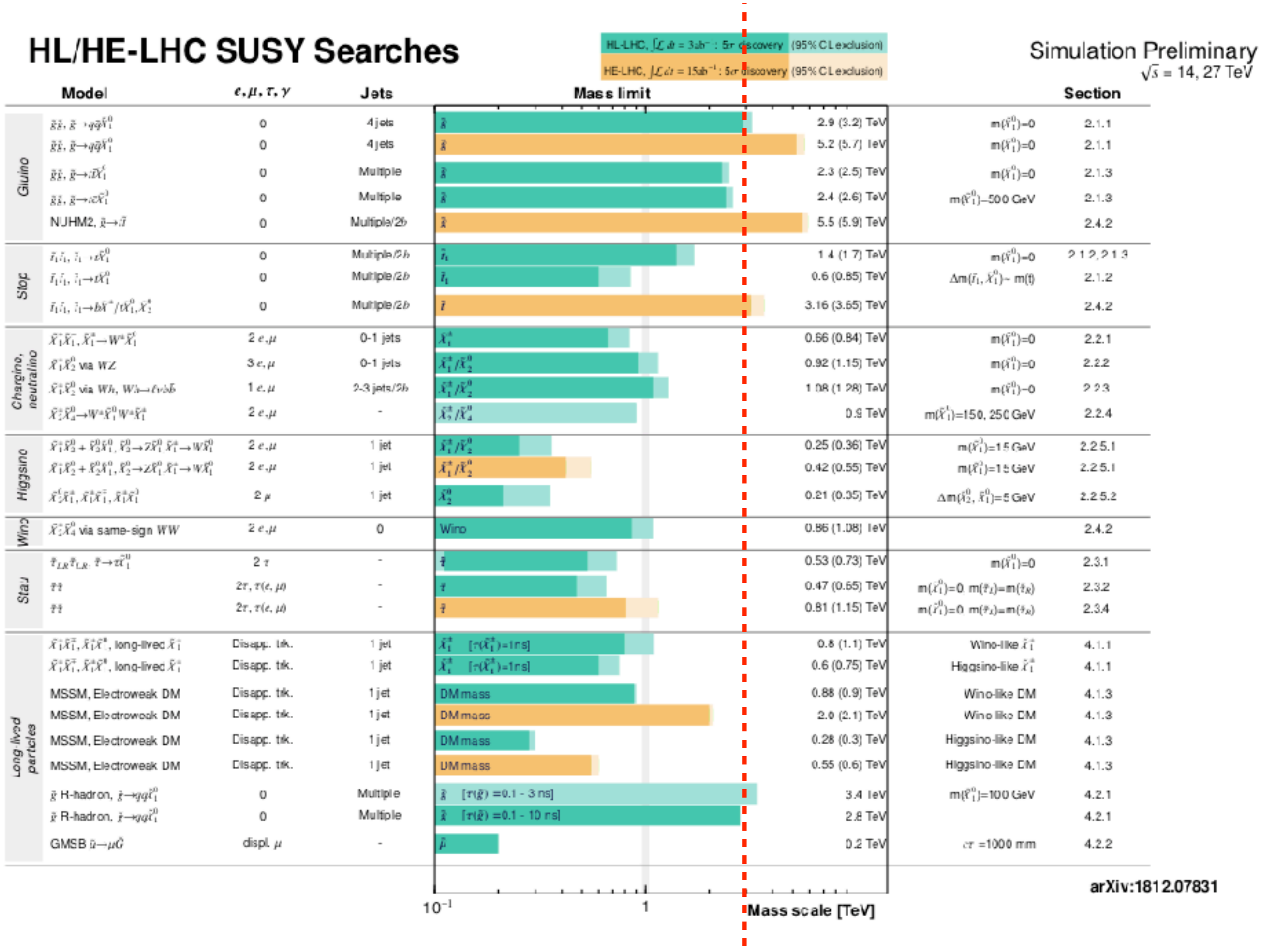




Very Large Number of SUSY Searches

(in large variety of topologies and models)





2 TeV

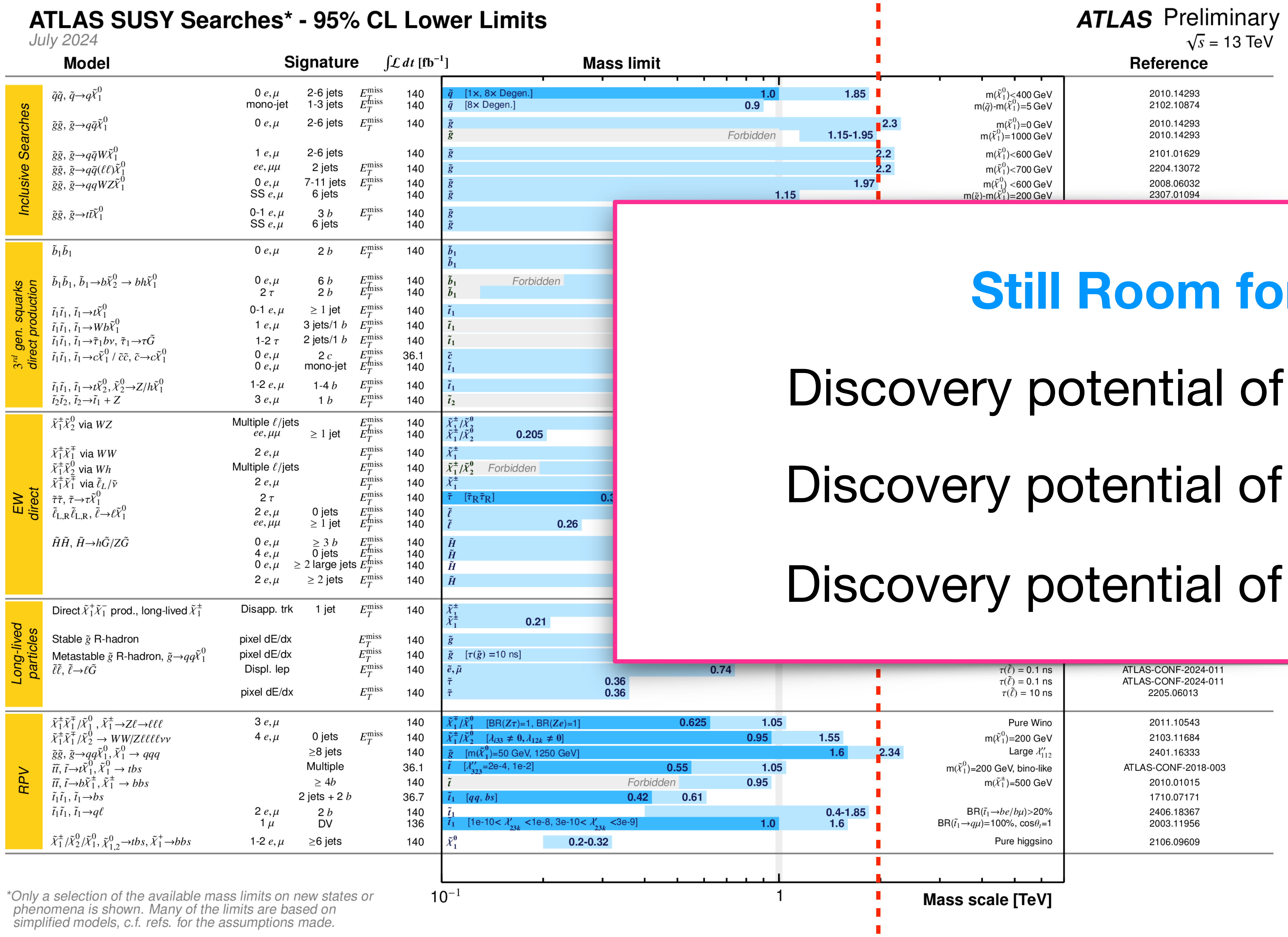
3 TeV

Example from ATLAS (similar for CMS)

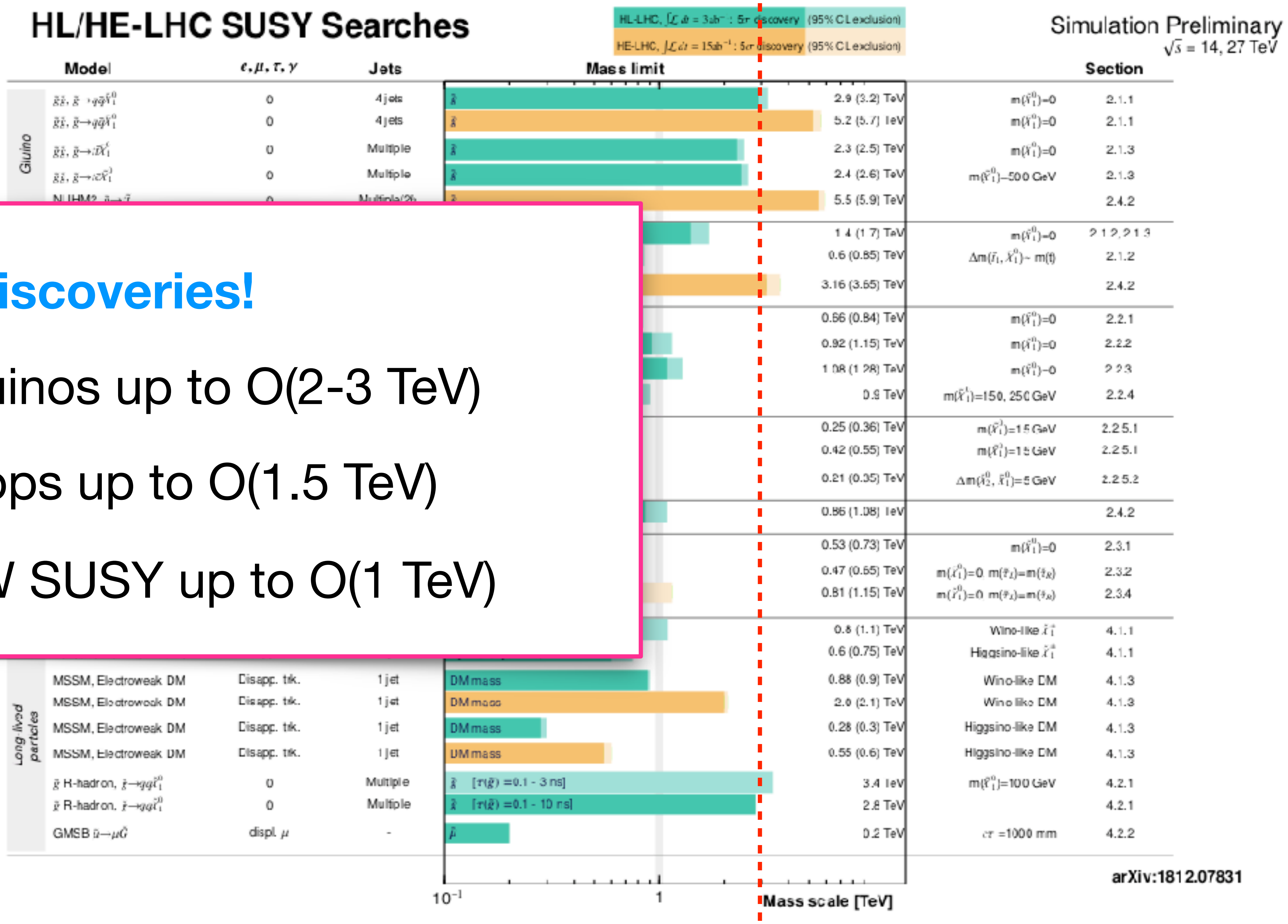
HL-LHC YR
1812.07831

Very Large Number of SUSY Searches

(in large variety of topologies and models)



Example from ATLAS (similar for CMS)



Still Room for Discoveries!

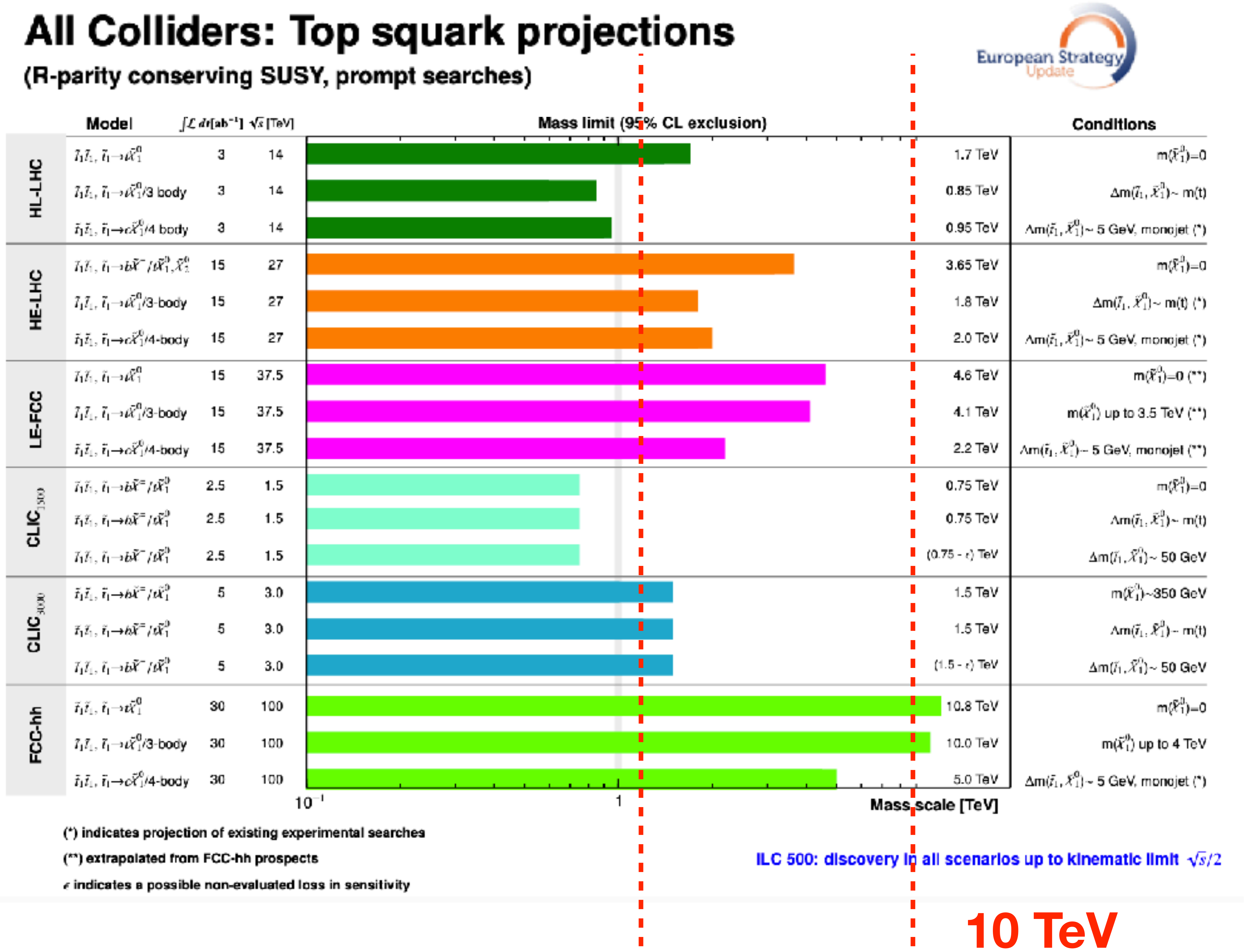
Discovery potential of gluinos up to O(2-3 TeV)

Discovery potential of stops up to O(1.5 TeV)

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

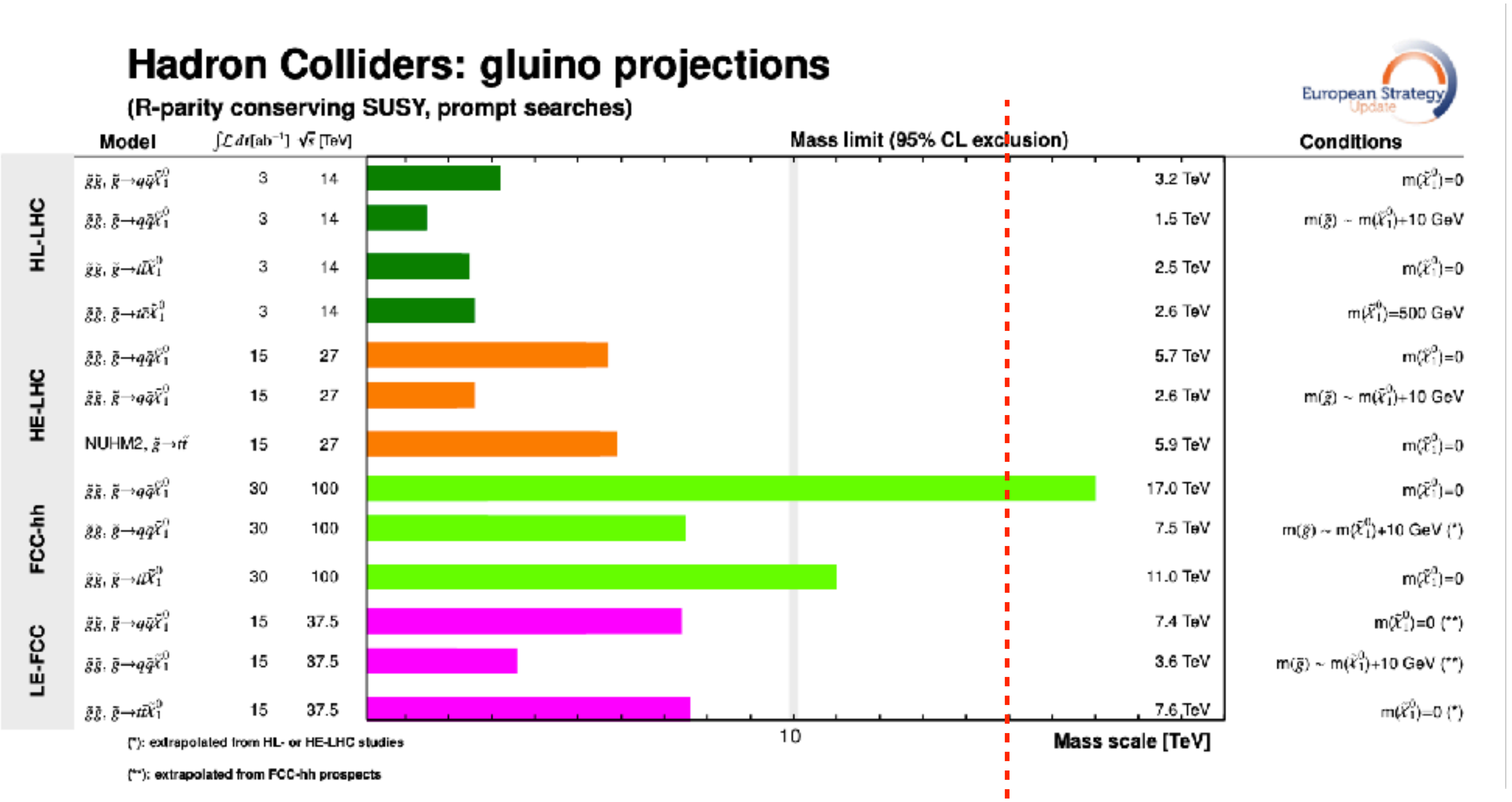
HL-LHC YR
1812.07831

Prjections at a Future Hadron Collider



10 TeV

CLIC - LHC

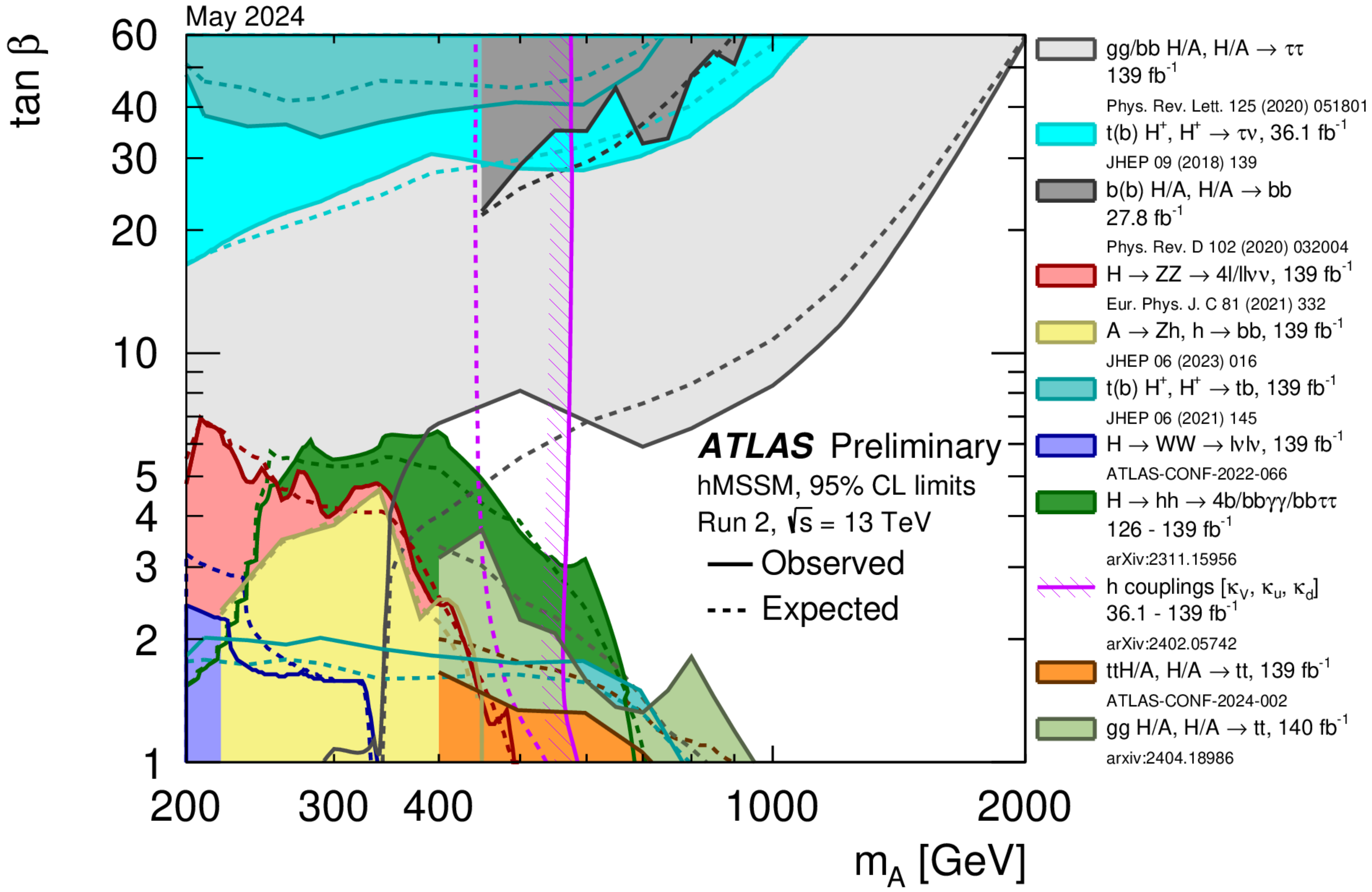


15 TeV

To go above the 10 TeV scale SUSY will require a future hadron collider (100 TeV) or a 10 TeV Parton COM energy machine.

Reaching SUSY from its extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).



hMSSM: trade the value Mh = 125 GeV against the radiative corrections where the Higgs mass is used as proxy for the leading stop sector corrections.
[Maiani, Polosa, Djouadi et al. link]

SUSY could modify the couplings of the Higgs

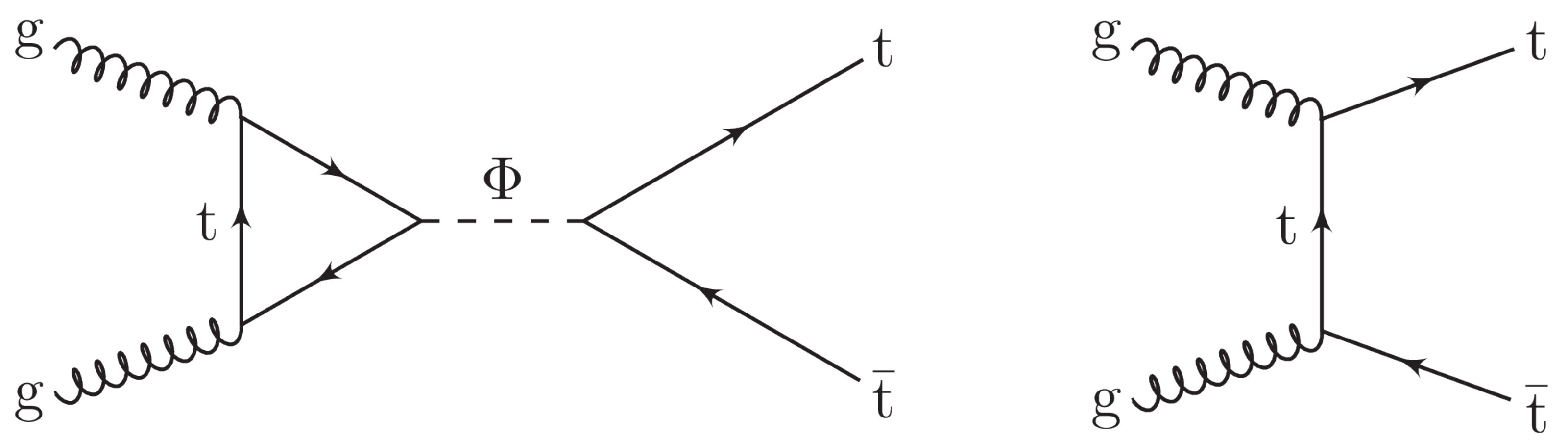
From the combination of all Higgs coupling measurements channels presented, mostly from constraints on up versus down Yukawa and coupling to vector bosons.

Direct searches for additional Higgs bosons (neutral and charged) have been performed:

- Neutral heavy Higgs to tau tau
- Charged Higgs to tau neutrino
- Heavy neutral Higgs to ZZ
- Charged Higgs to tb
- Heavy neutral Higgs to ZH
- Heavy Higgs boson to HH

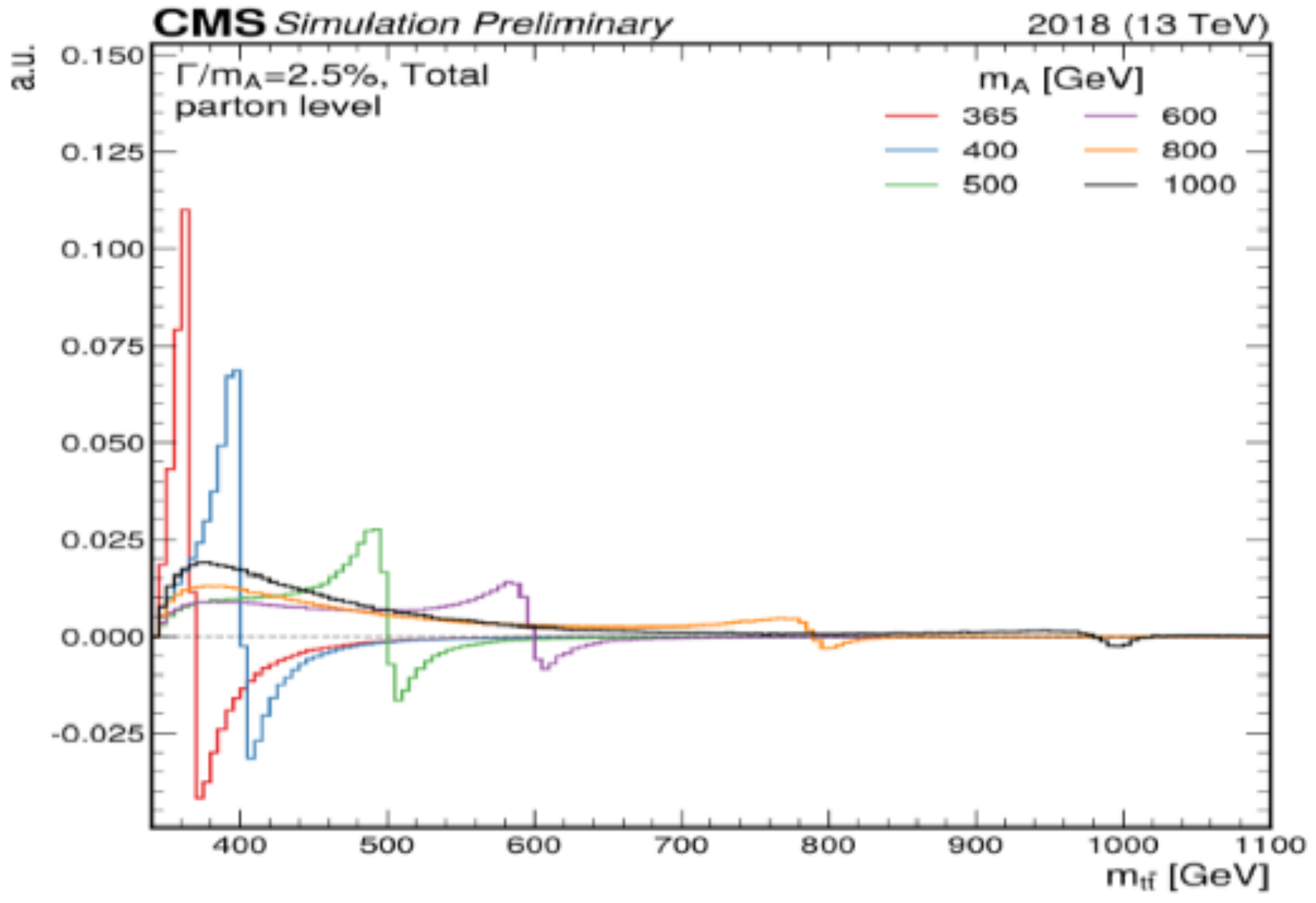
Search for a Top Quark Pair “Resonance”

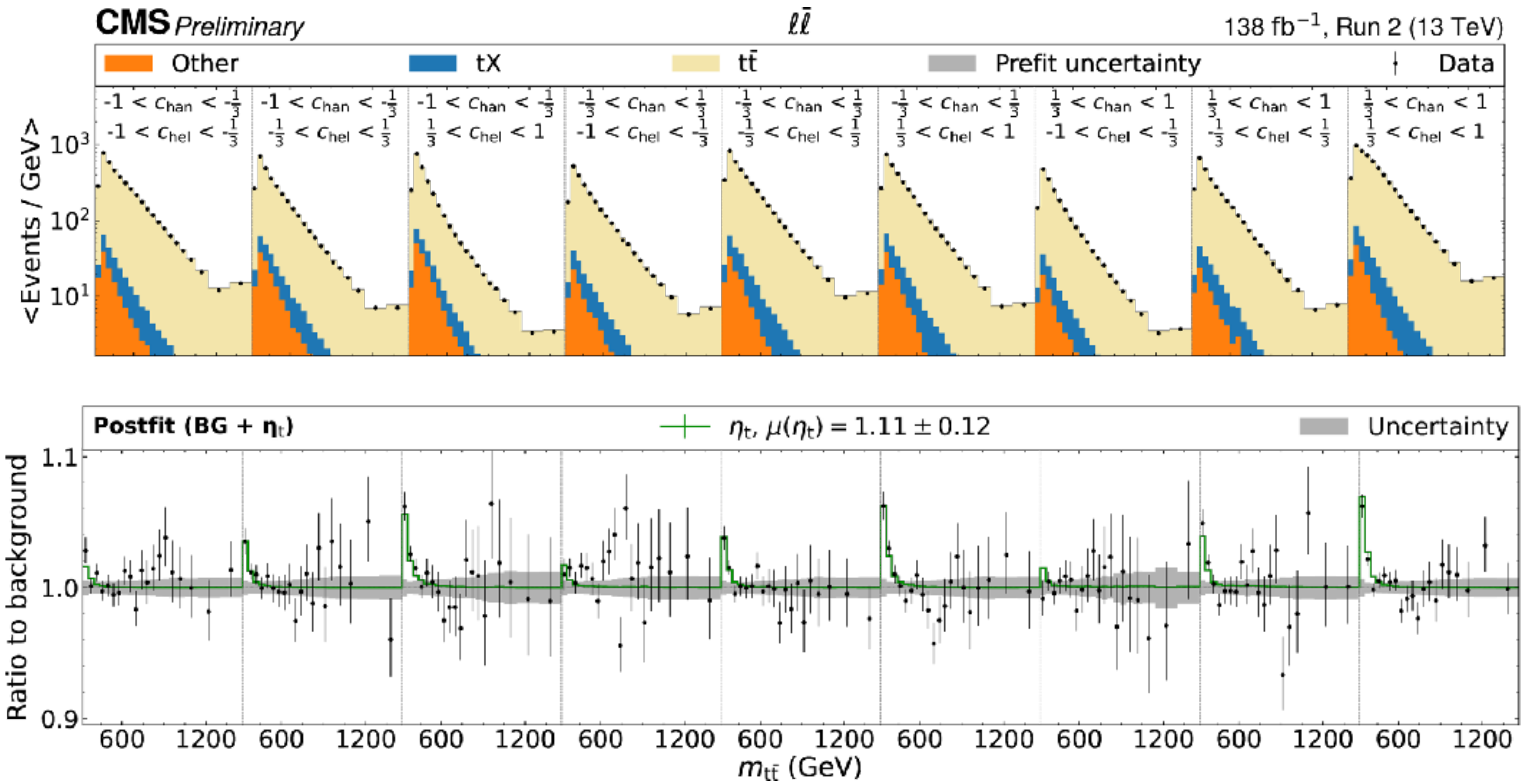
Search in three main channels di-lepton and single lepton channels!



Intricate search:

- look at peak-dip structure in the top pair mass spectrum
- Angular variable to distinguish spin-0 as well as scalar pseudo-scalar nature.





Interesting feature appears at threshold **(challenging for reconstruction)**

The behaviour of the feature w.r.t. angular distributions is strikingly in agreement with the production of a toponium state (also in rate).

A similar, less detailed (in angular distributions) analysis in ATLAS does not show this feature.

Top Entanglement Measured

In top pair production at the LHC, top quarks are **not produced polarised,** however a **spin correlation** exists.

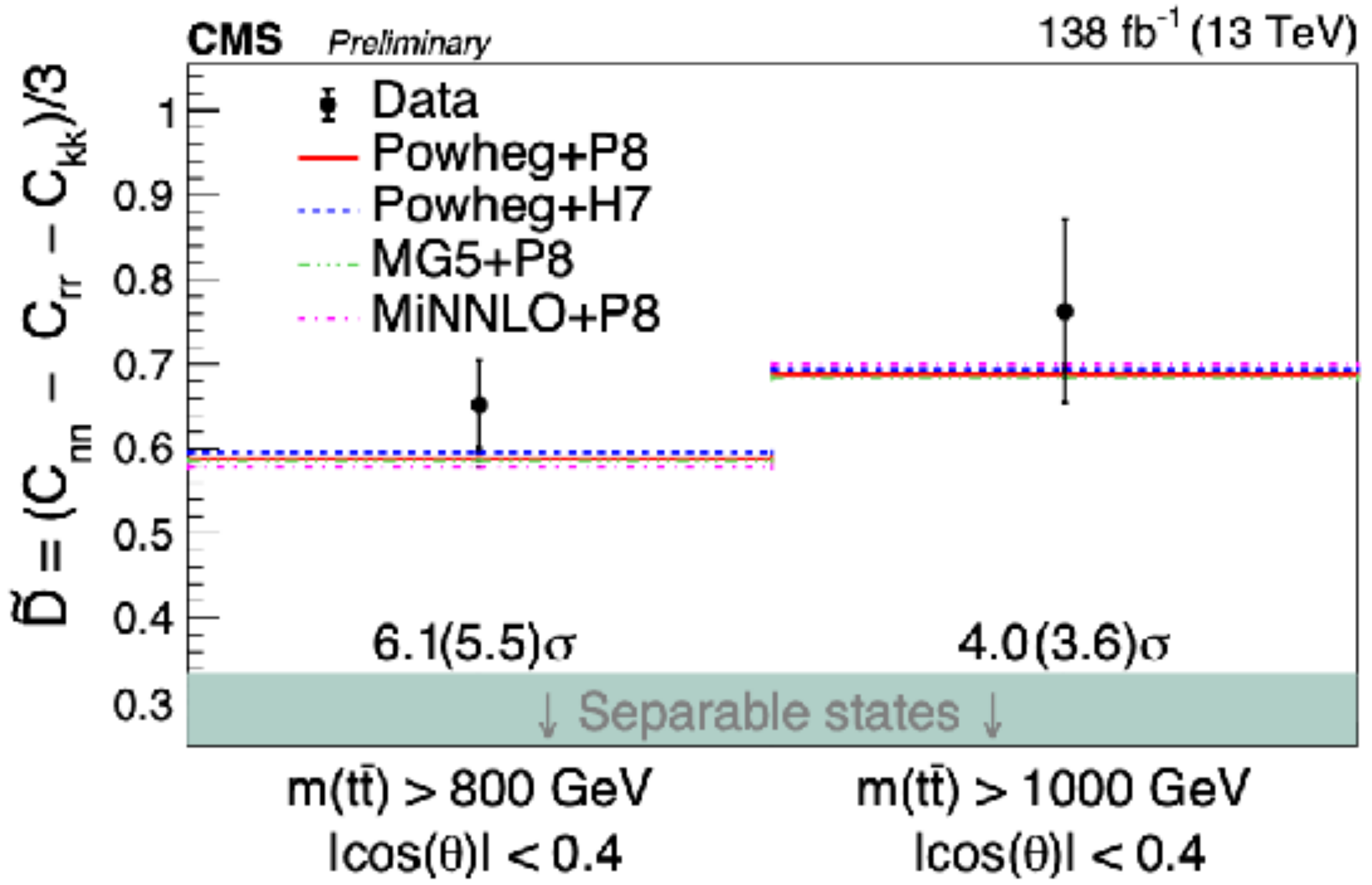
At threshold the $gg \rightarrow t\bar{t}$ production is dominated by the "singlet" spin configuration, **which is a pure, superposed and maximally entangled Bell state**:

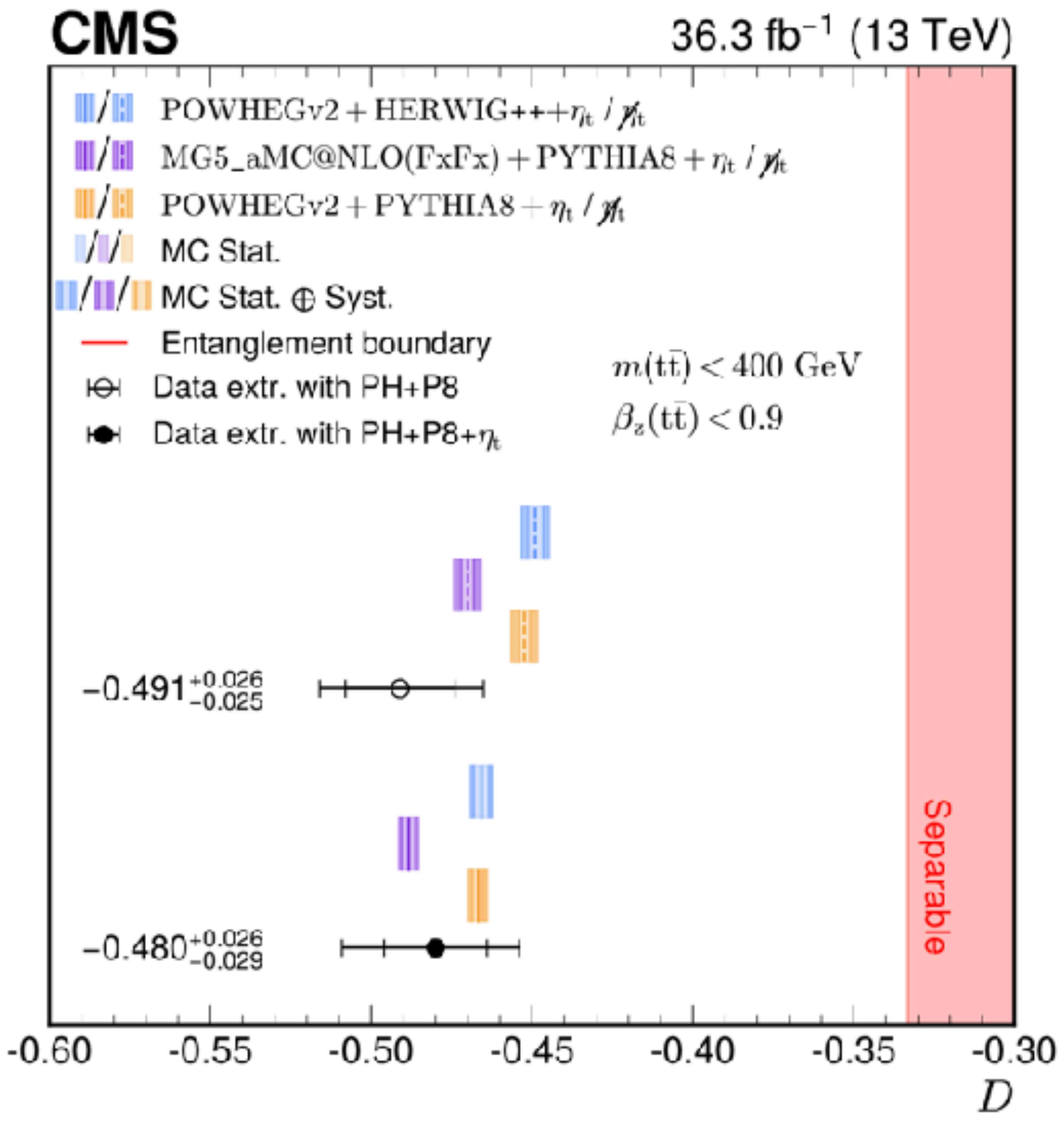
$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow> - |\downarrow\uparrow>)$$

From the measurement of the spin density matrice we can probe whether this correlation is of quantum nature or not!

Initially measured near threshold where it is easier! CMS went beyond with:

- At production threshold in $t\bar{t} \rightarrow b\ell\nu b\ell\nu$ events
- At high m_{tt} with $t\bar{t} \rightarrow b\ell\nu bq\bar{q}$ events, (phase space dominated 90% by space-like events)

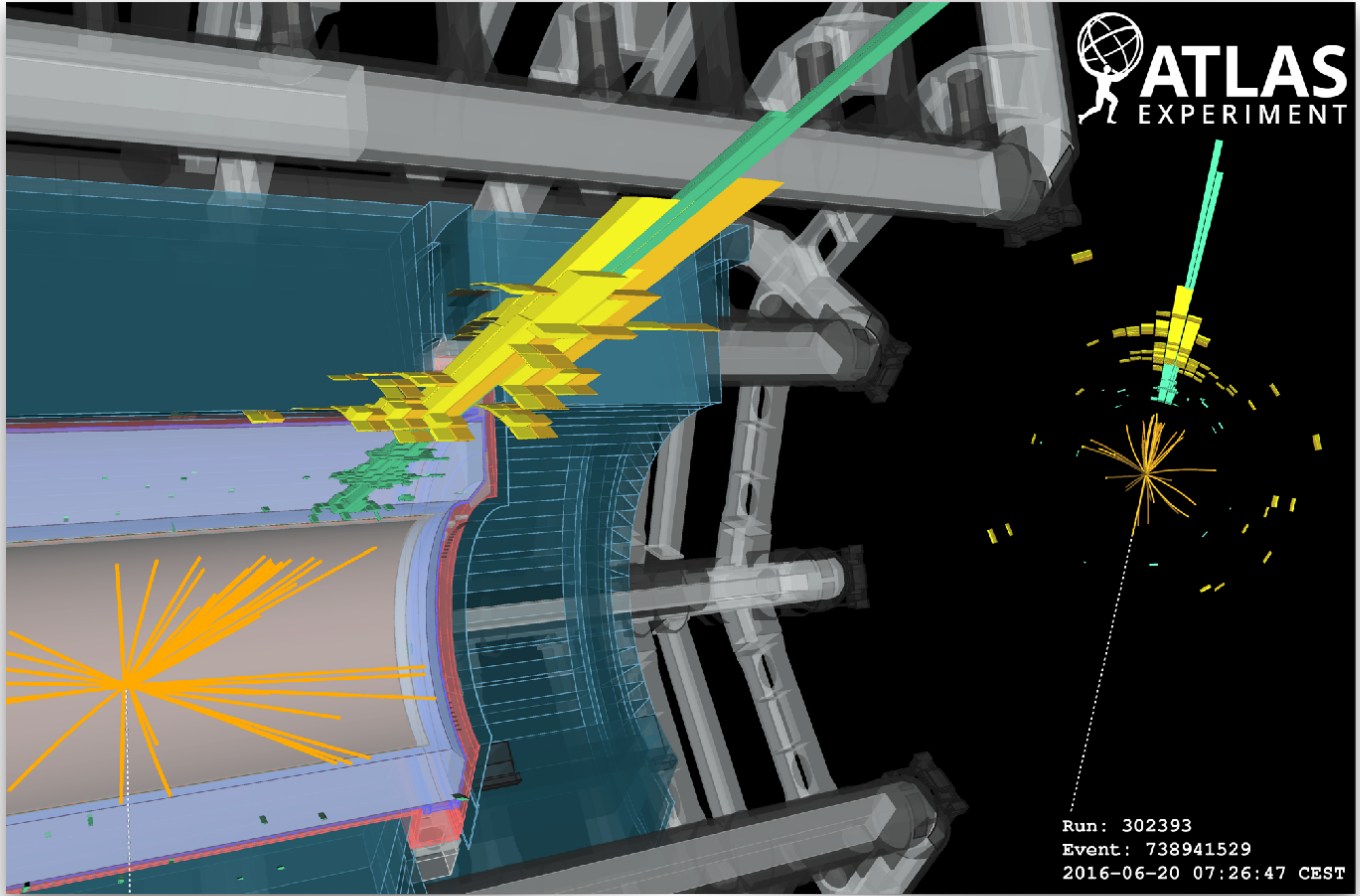




Interesting new observables in order to be sensitive to new physics scenarios, and further understand top production.

Dark Matter

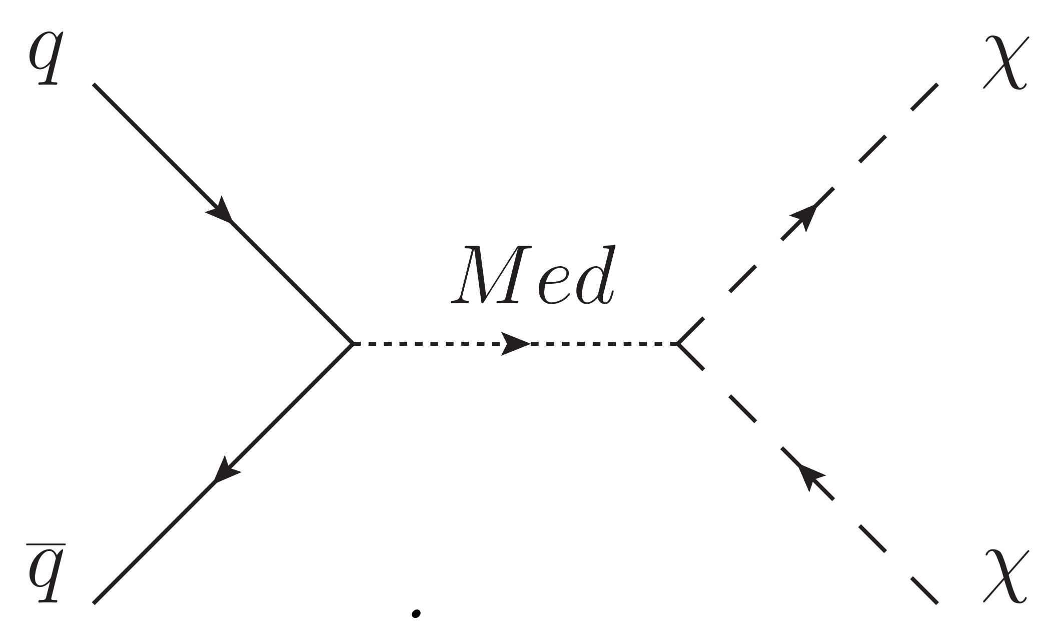
Generic Searches for Dark Matter



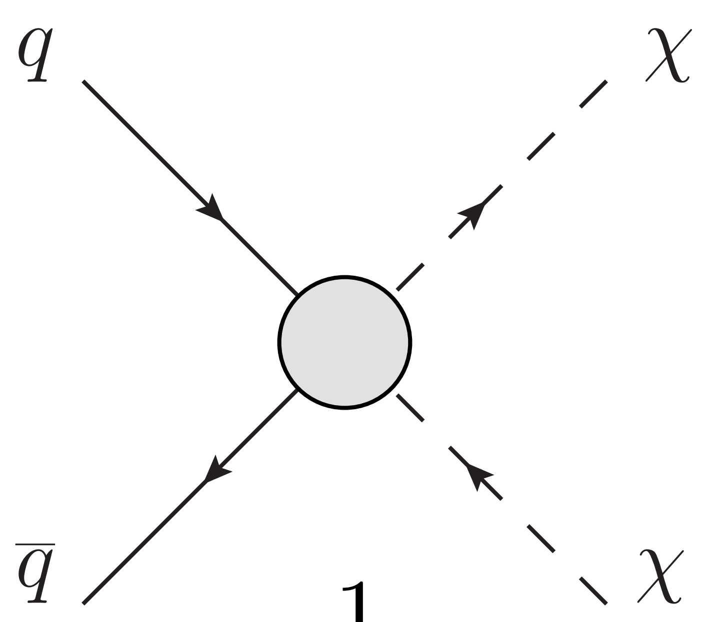
Jet with pT of 1707 GeV. The ETmiss of 1735 GeV is shown as the white dashed line. No additional jets with pT above 30 GeV is found.

Generic Searches for Dark Matter

At the LHC an EFT approach is limited to very heavy mediator masses, above O(few TeV)



$$\frac{i g_{DM} g_q}{q^2 - M_{Med}^2}$$



$$\frac{1}{M_*^2}$$

DM EFT valid in the
Heavy Mediator limit:

$$q^2 < M_{Med} \sim \frac{g_{DM} g_q}{M_*^2}$$

Simplified model approach: Overall assumption **Dark matter part. is a Dirac fermion** and s-channel production of DM particles.

Model parameters:

- Couplings g_{DM} g_q
- Masses of DM and the mediator
- Nature of mediator

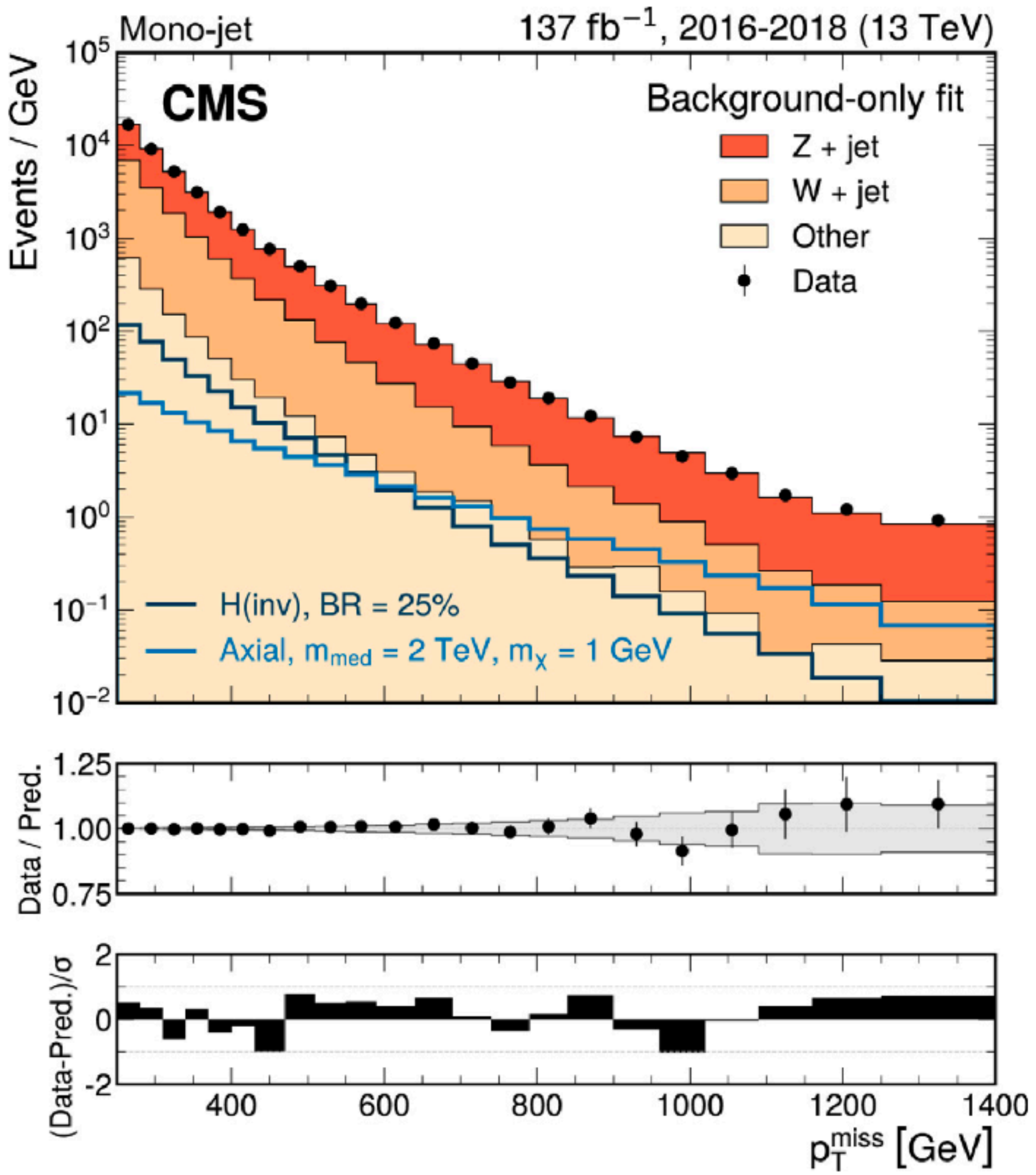
DM Forum benchmarks (LHC Exp. & TH) link

Generic Searches for Dark Matter

A wealth searches for DM at the LHC:

- Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top
- VBF-like signatures
- Associated production-like signatures
- Invisible Higgs searches

In all these channels, the background control as well as the resolution on the measurement of the MET are key!



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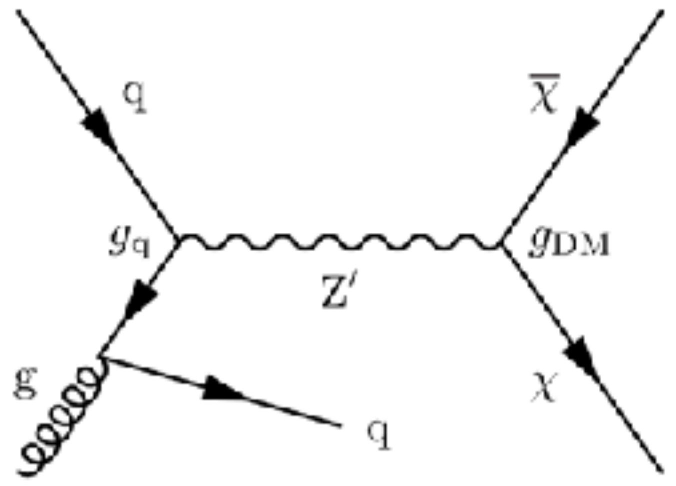
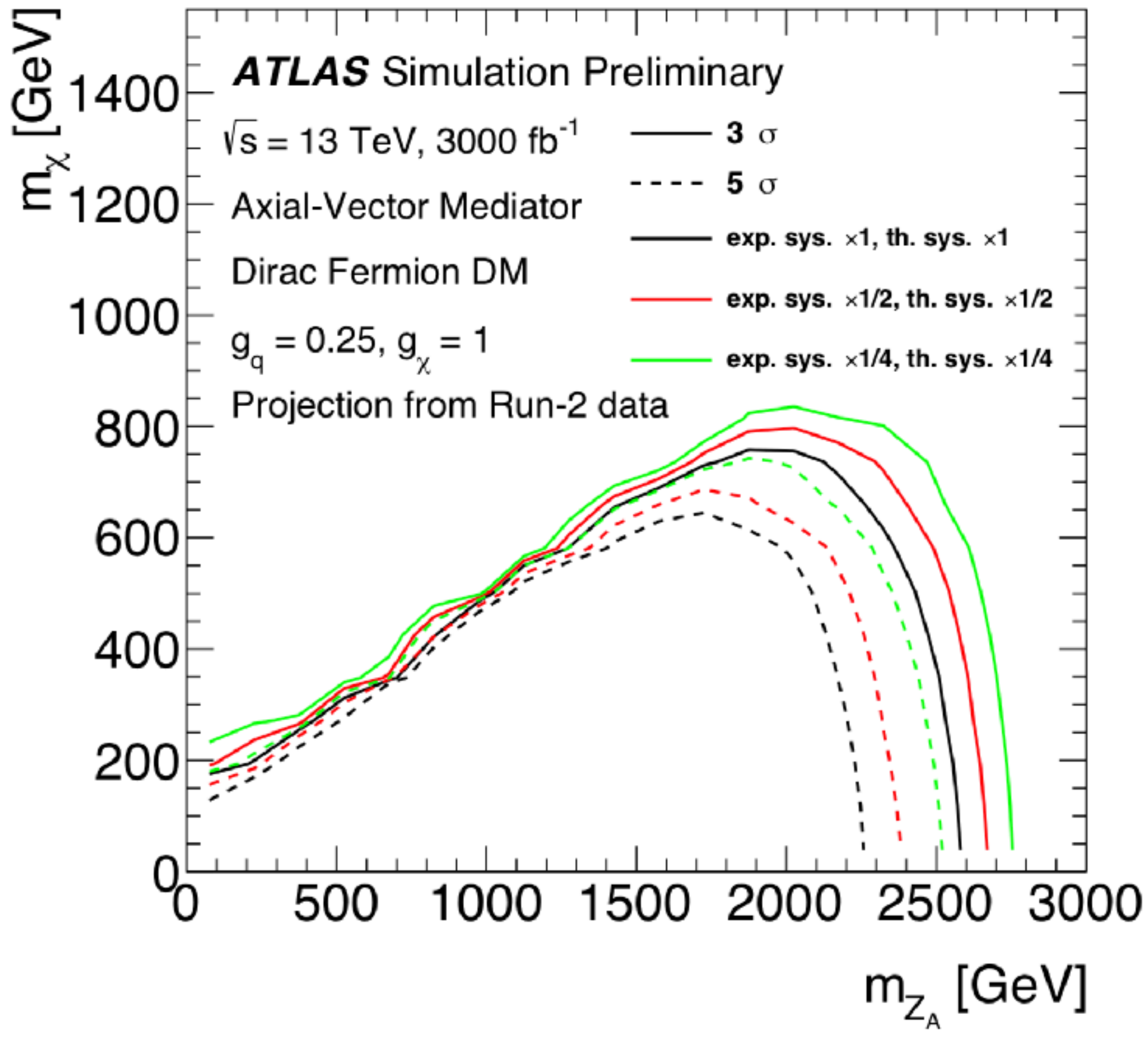
Example interpretation in Axial Vector Mediator

$$-Z'_\mu(g_{\rm DM}\bar{\chi}\gamma^\mu\gamma_5\chi + g_f\Sigma_f\bar{f}\gamma^\mu\gamma_5 f)$$

Interesting scenario limits impact of collider searches as the interaction in the non-relativistic limit is purely spin-dependent.





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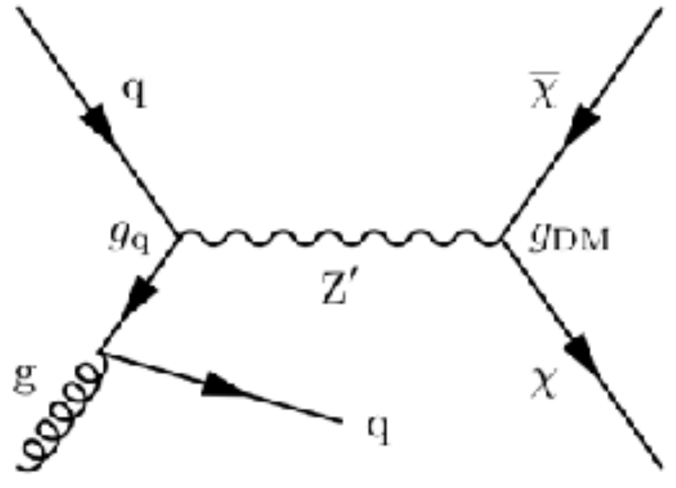

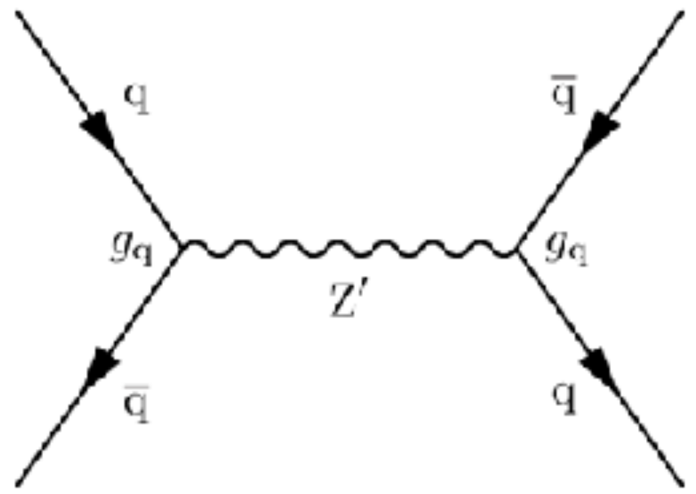

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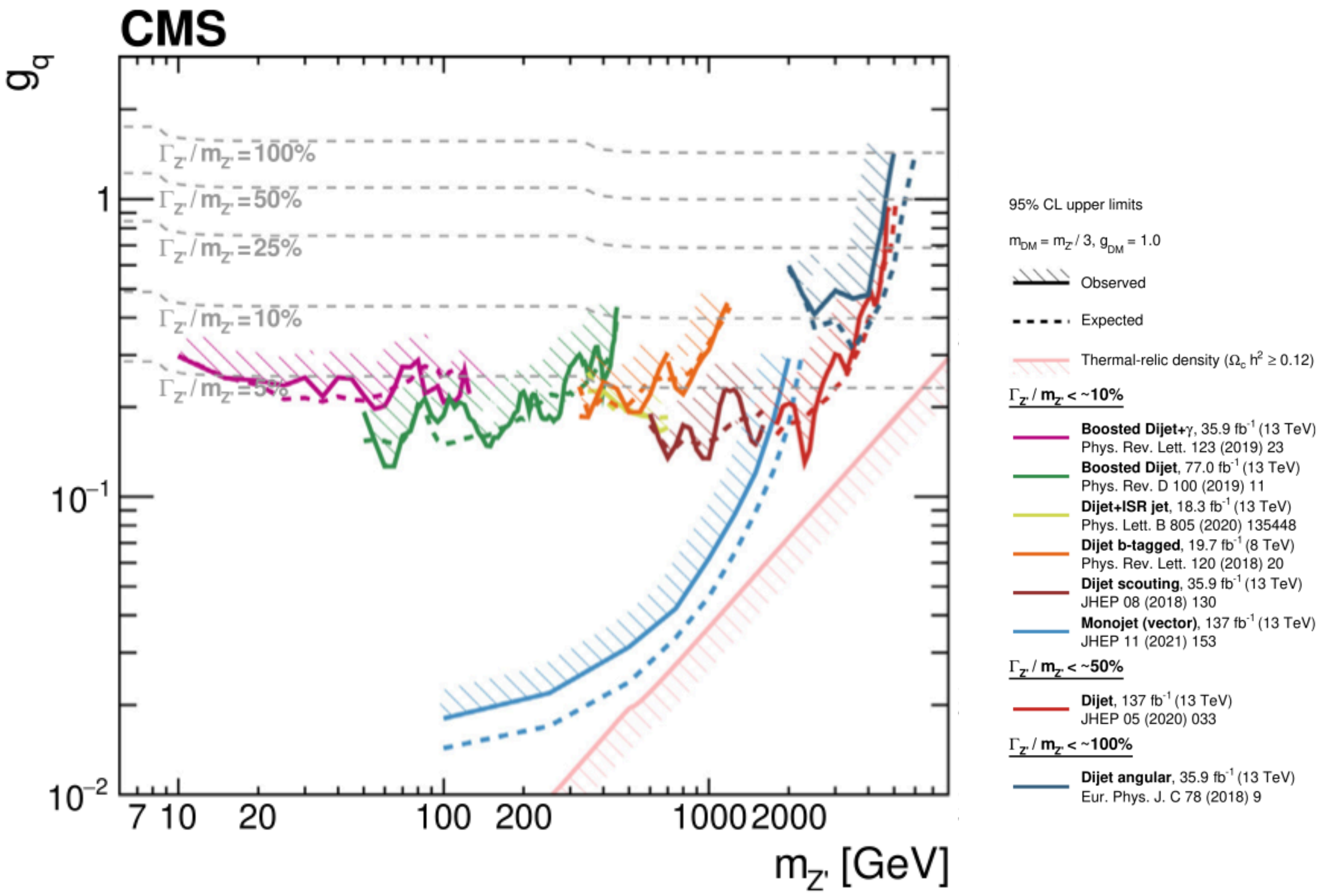

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$$-Z'_\mu \left(g_{\mathrm{DM}}\, \bar{\chi}\gamma^\mu \gamma_5 \chi + g_f \sum_f \bar{f}\gamma^\mu \gamma_5 f\right)$$

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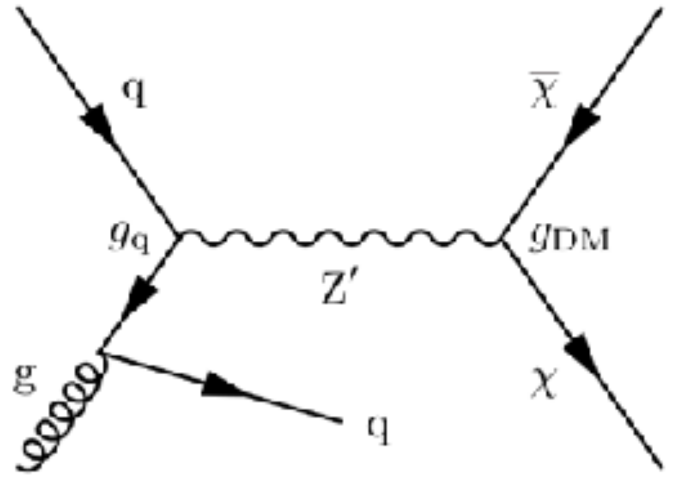
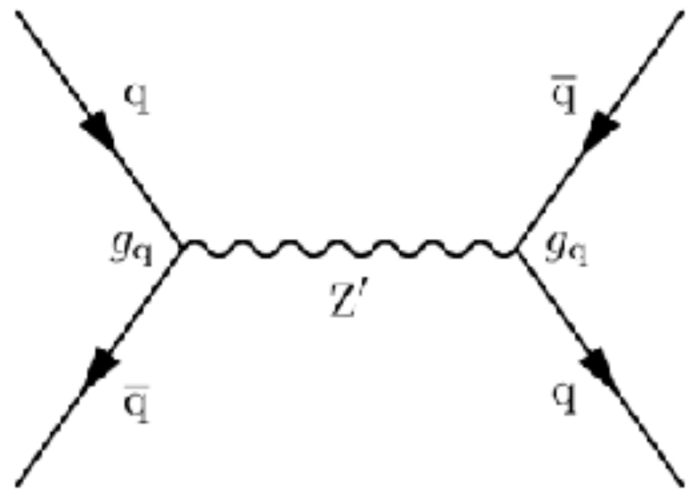
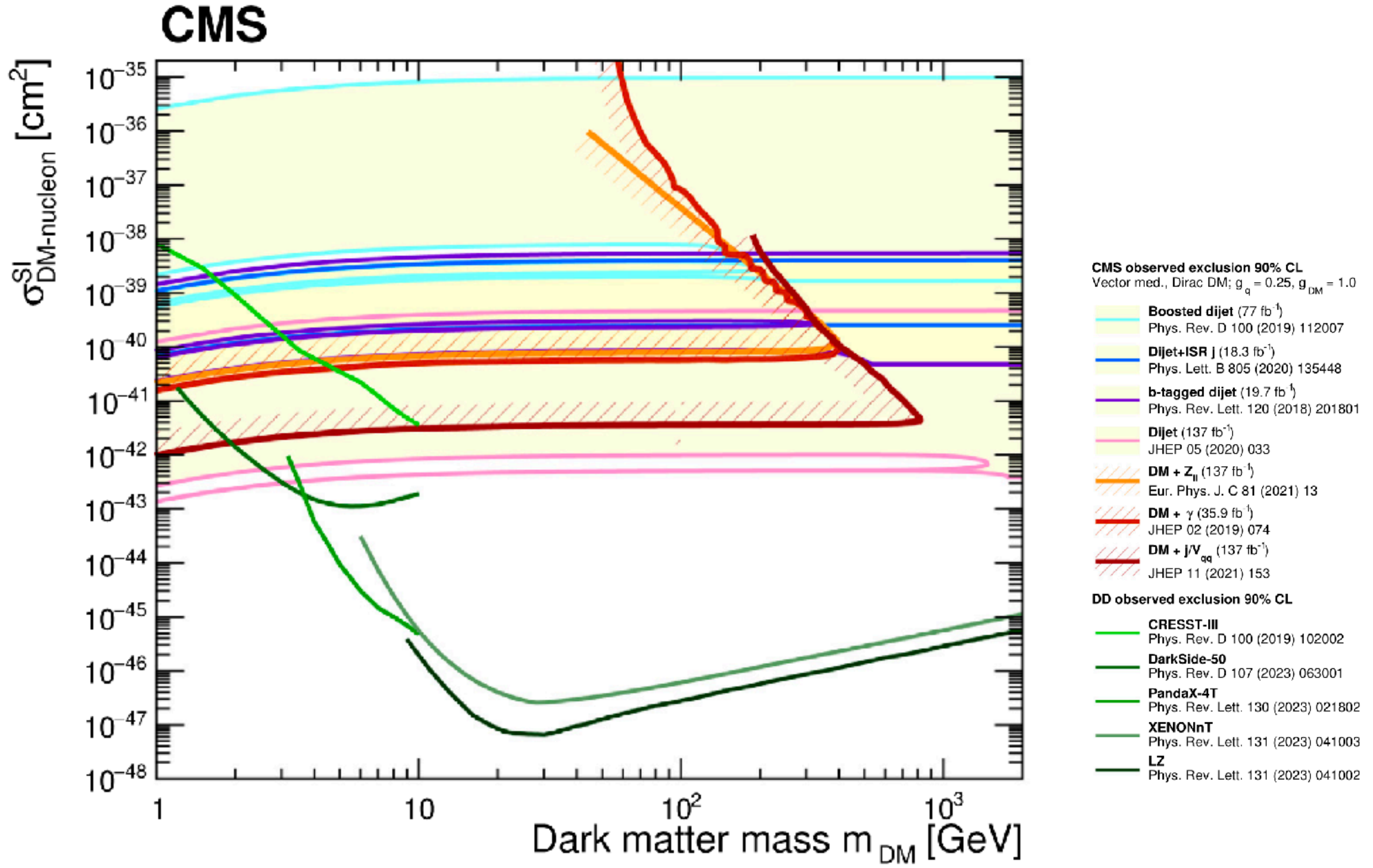






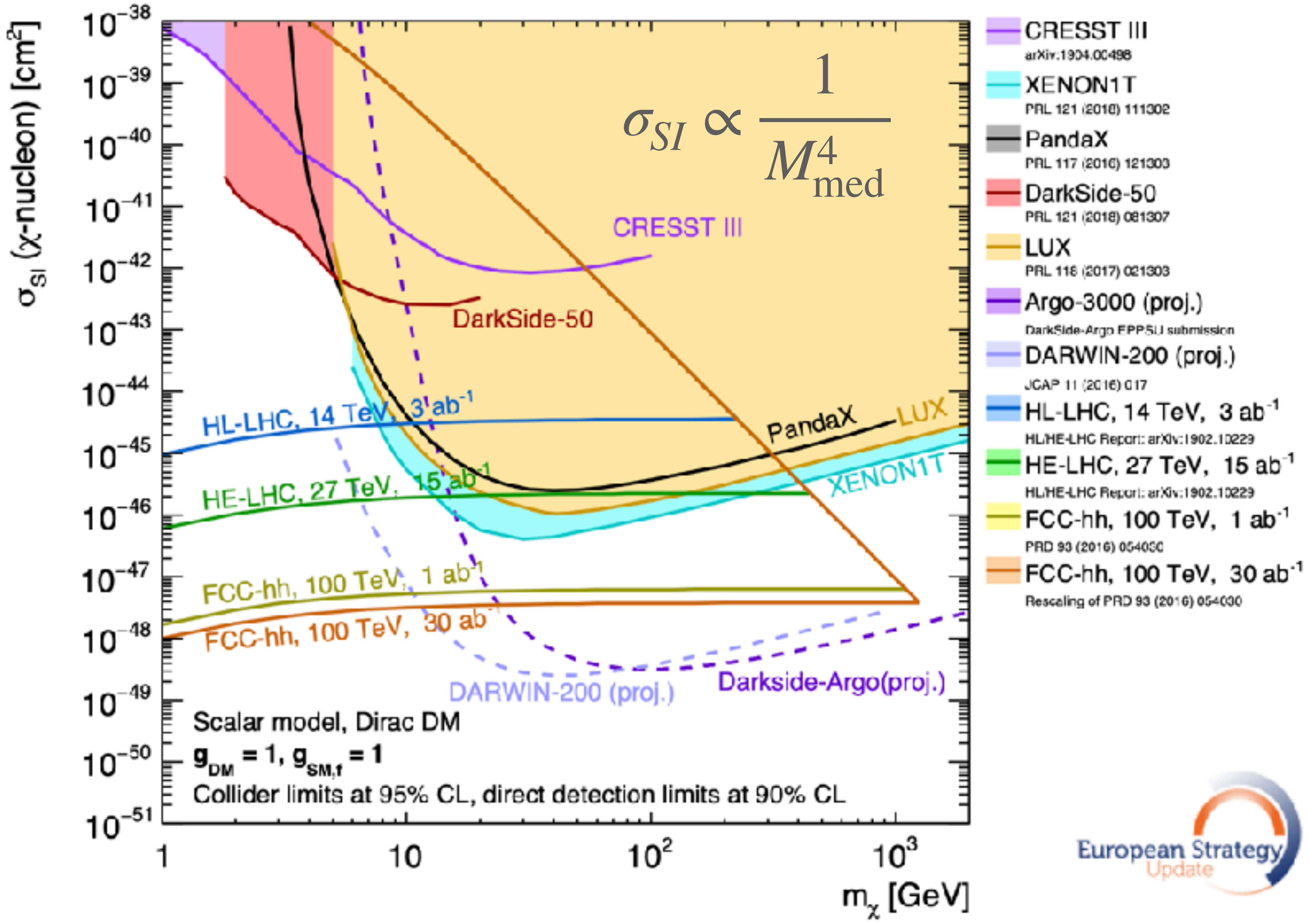
Generic Searches for Dark Matter

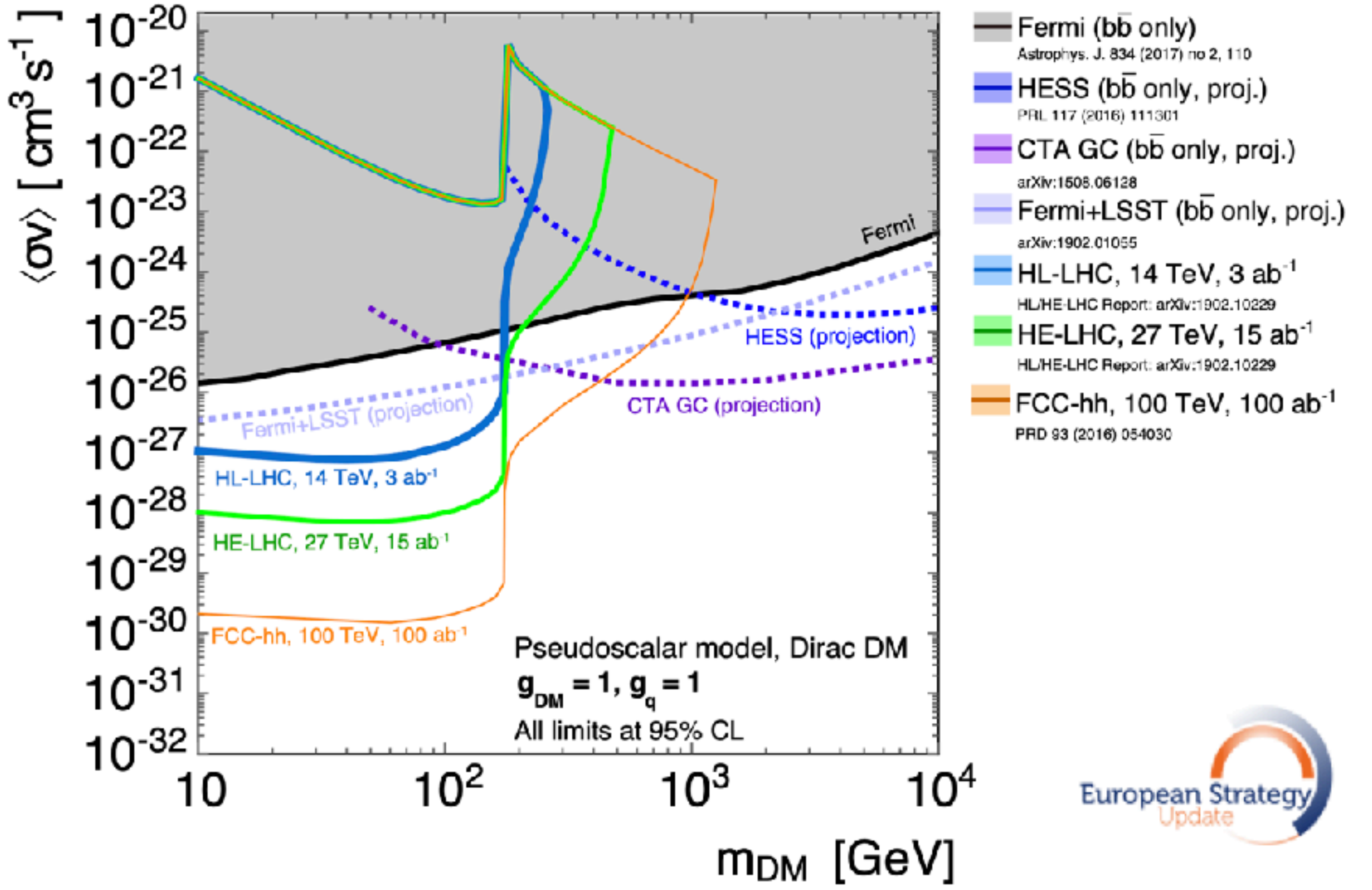
Scalar and Pseudo-Scalar scenarios more favourable and complementary to direct and indirect searches for DM!

Scalar $\phi(g_{DM}\bar{\chi}\chi - g_f \Sigma_f y_f \bar{f} f/\sqrt{2})$

Pseudo-scalar $-ig_{DM}\phi\bar{\chi}\gamma_5\chi - ig_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q$

For a pseudo-scalar mediator, the DD rate is suppressed it is not worth to compare w/ LHC results. Instead, can be compared against the limits from ID experiments in terms of annihilation XS.



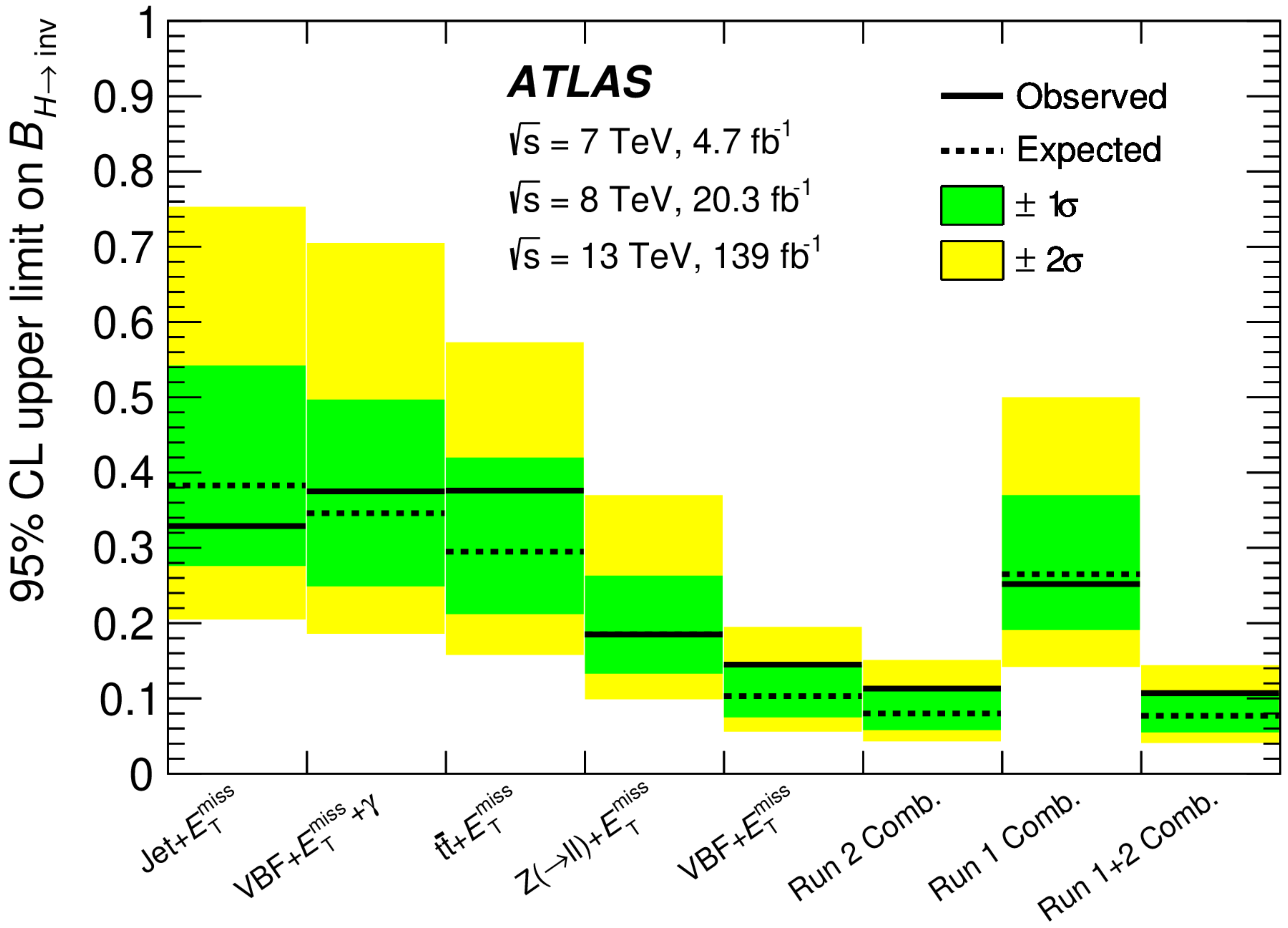


Nice Collider, DD and ID complementarity. Essential to understand nature of DM if discovered!

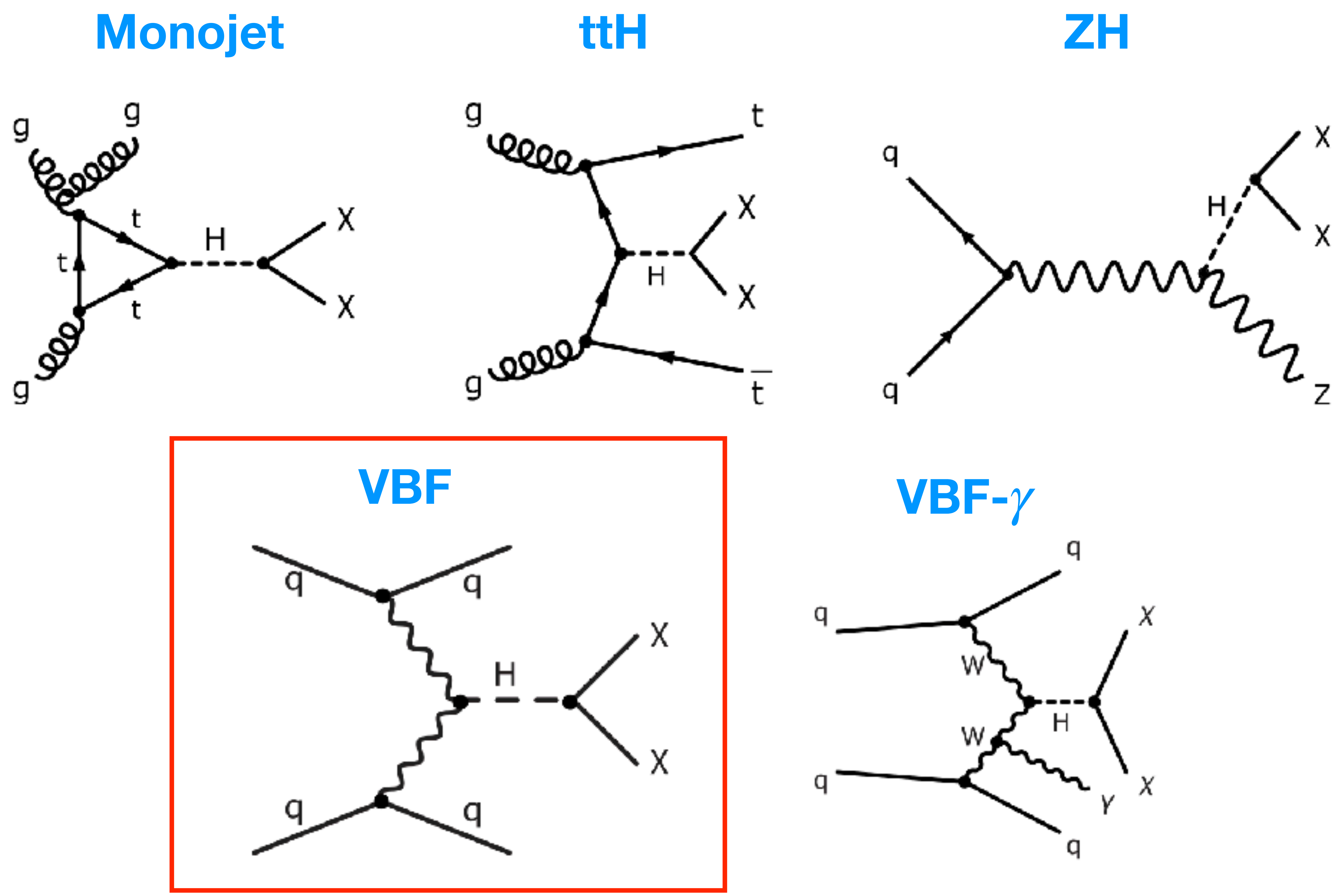
The Higgs portal and Invisible Higgs Decays

Searches for invisible decays of the Higgs boson in several channels!

To be precise: 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%**



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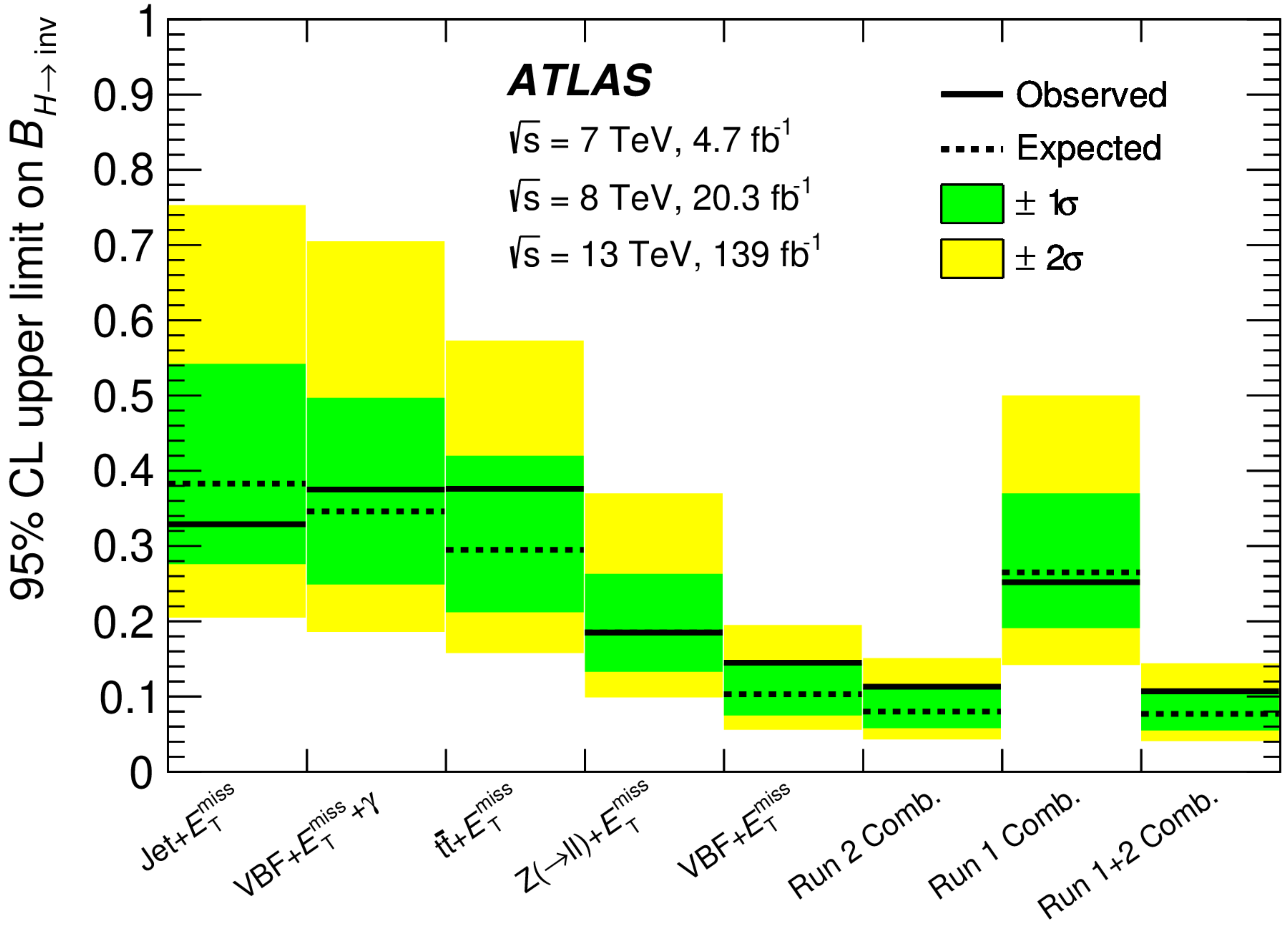
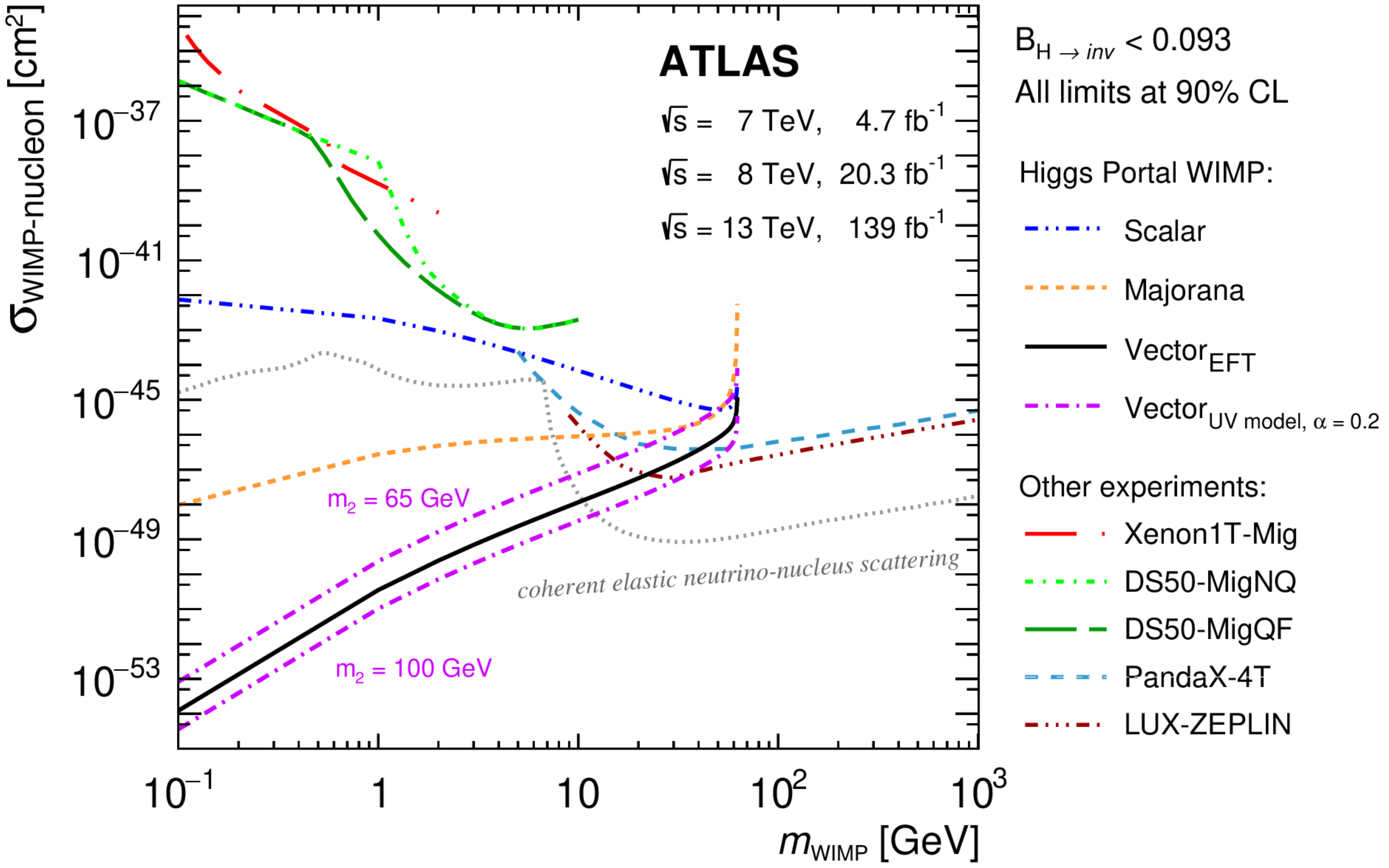


In the SM the H→invisible branching of **0.1%**

Current LHC limit 10% (90% CL)



Should reach 2% level at HL-LHC!

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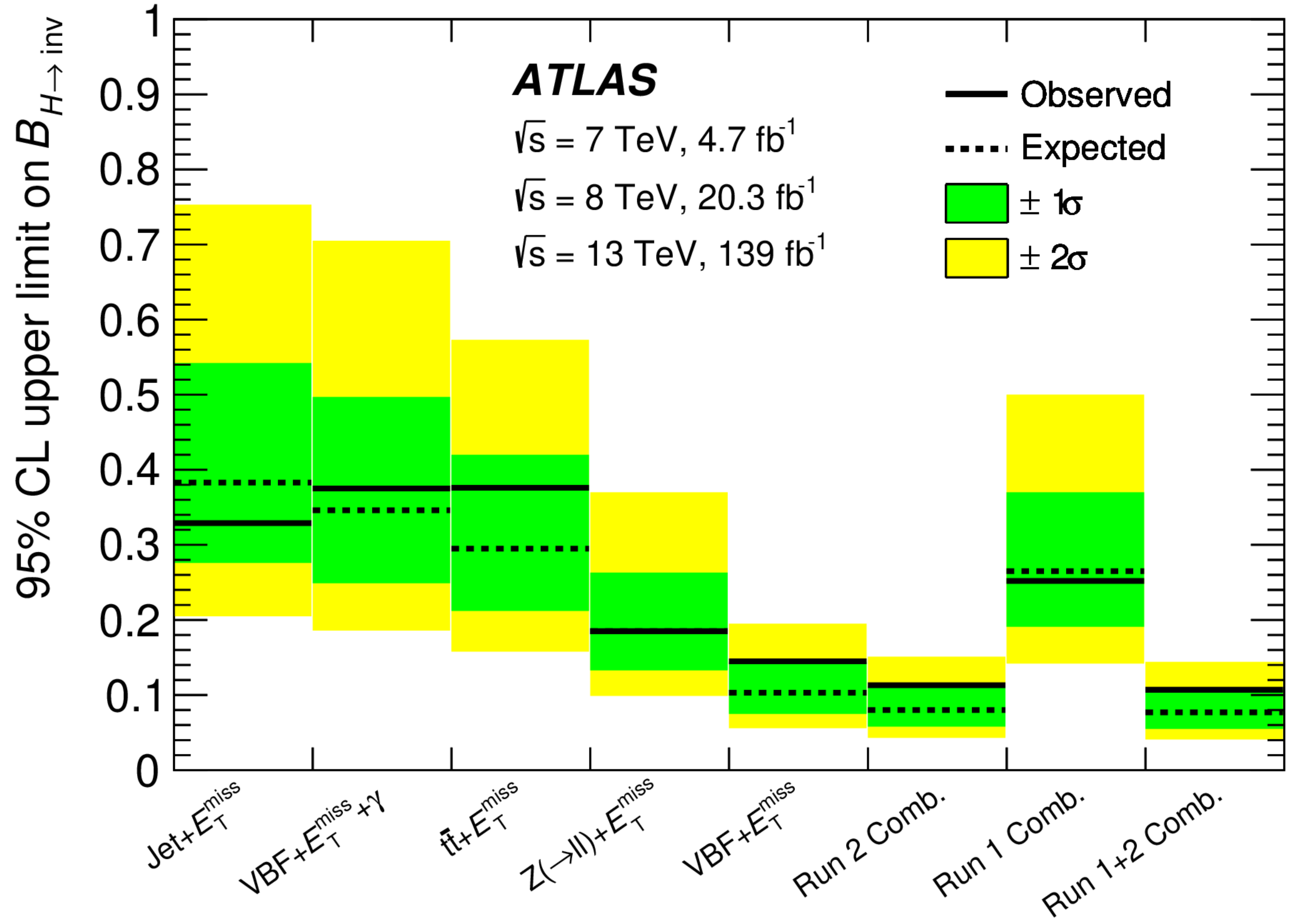

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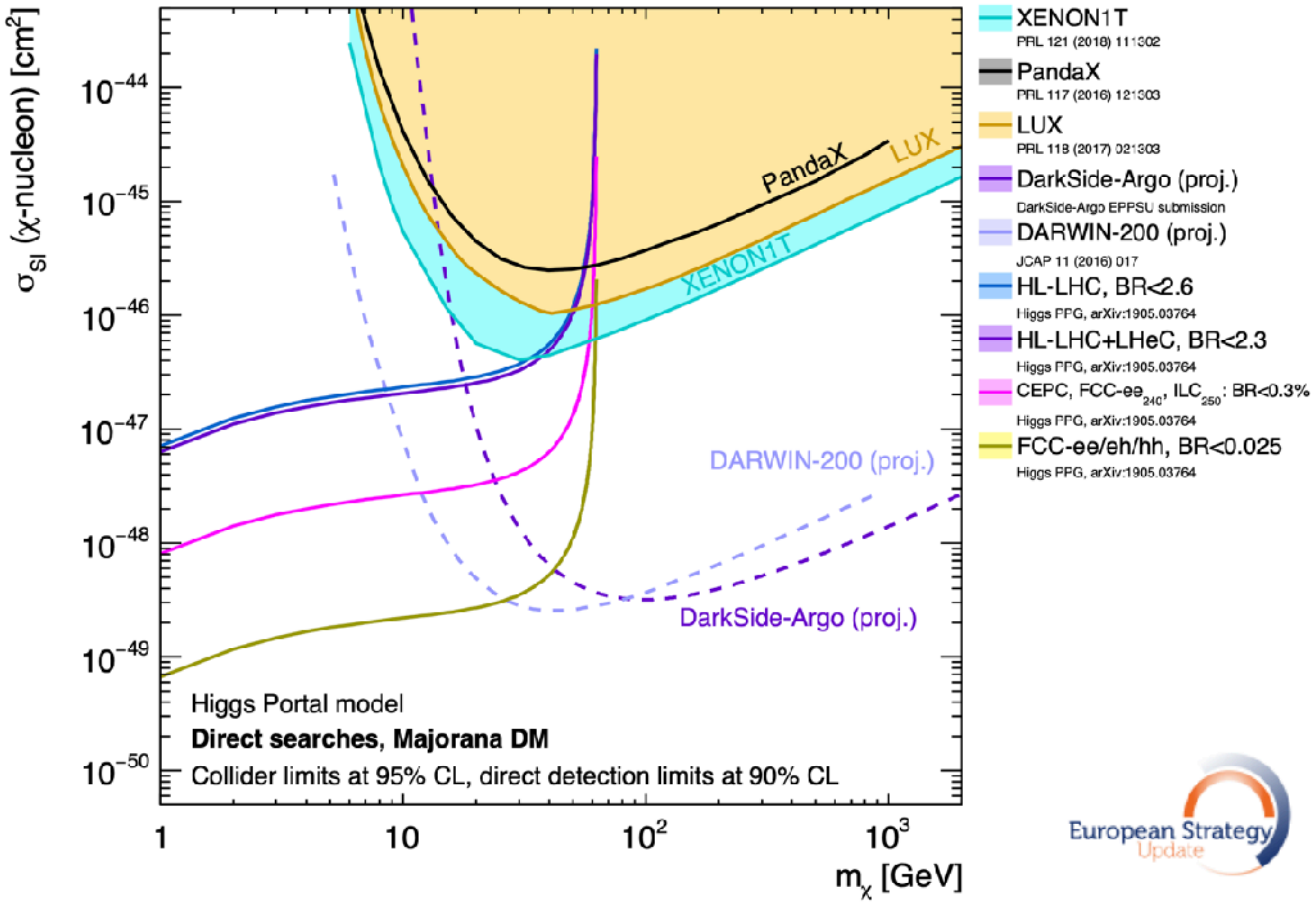


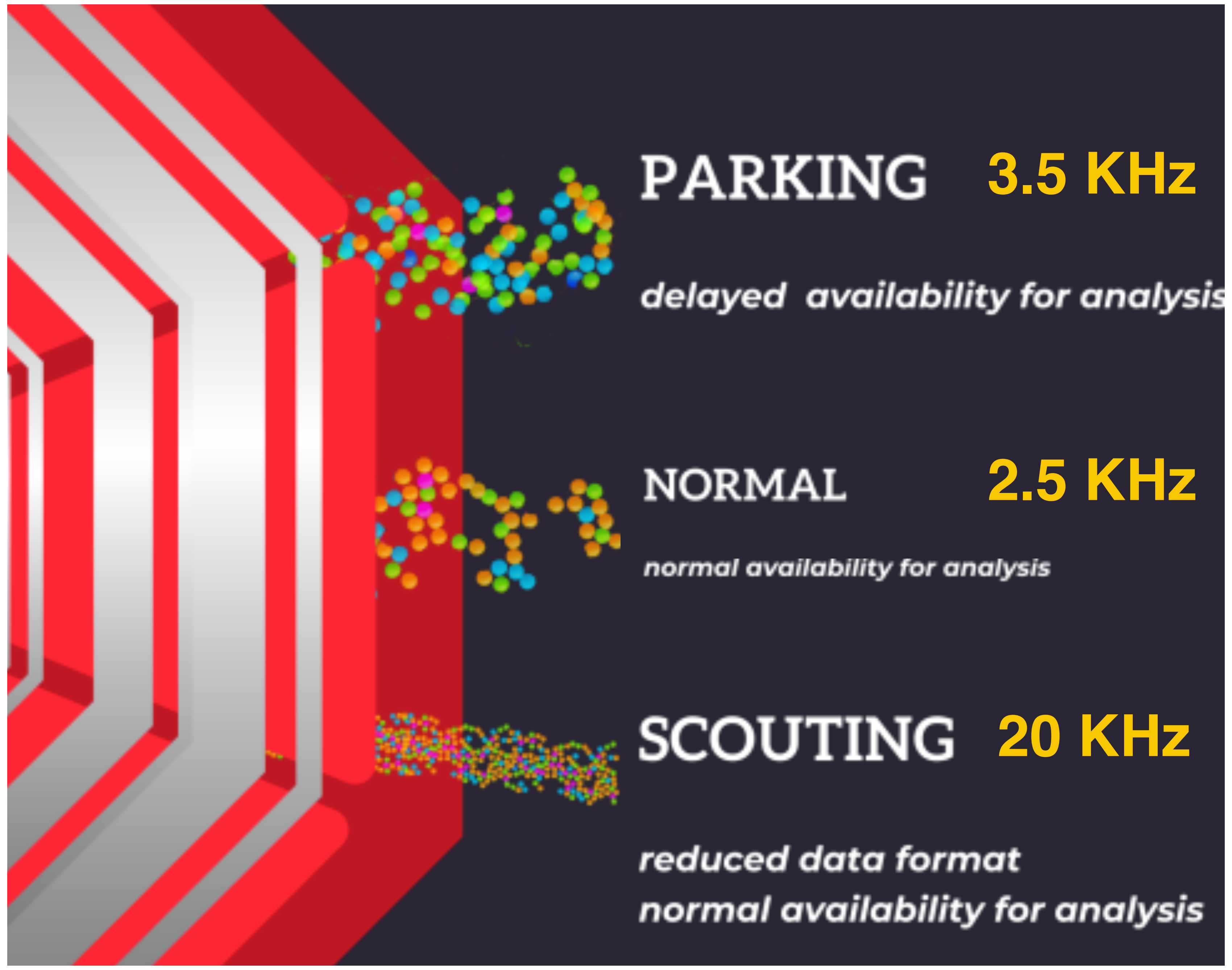
European Strategy Update

Should reach 0.3% level at FCC-ee and 0.02% with FCC-hh!

Searches Bellow the EW Scale Into Dark Sectors

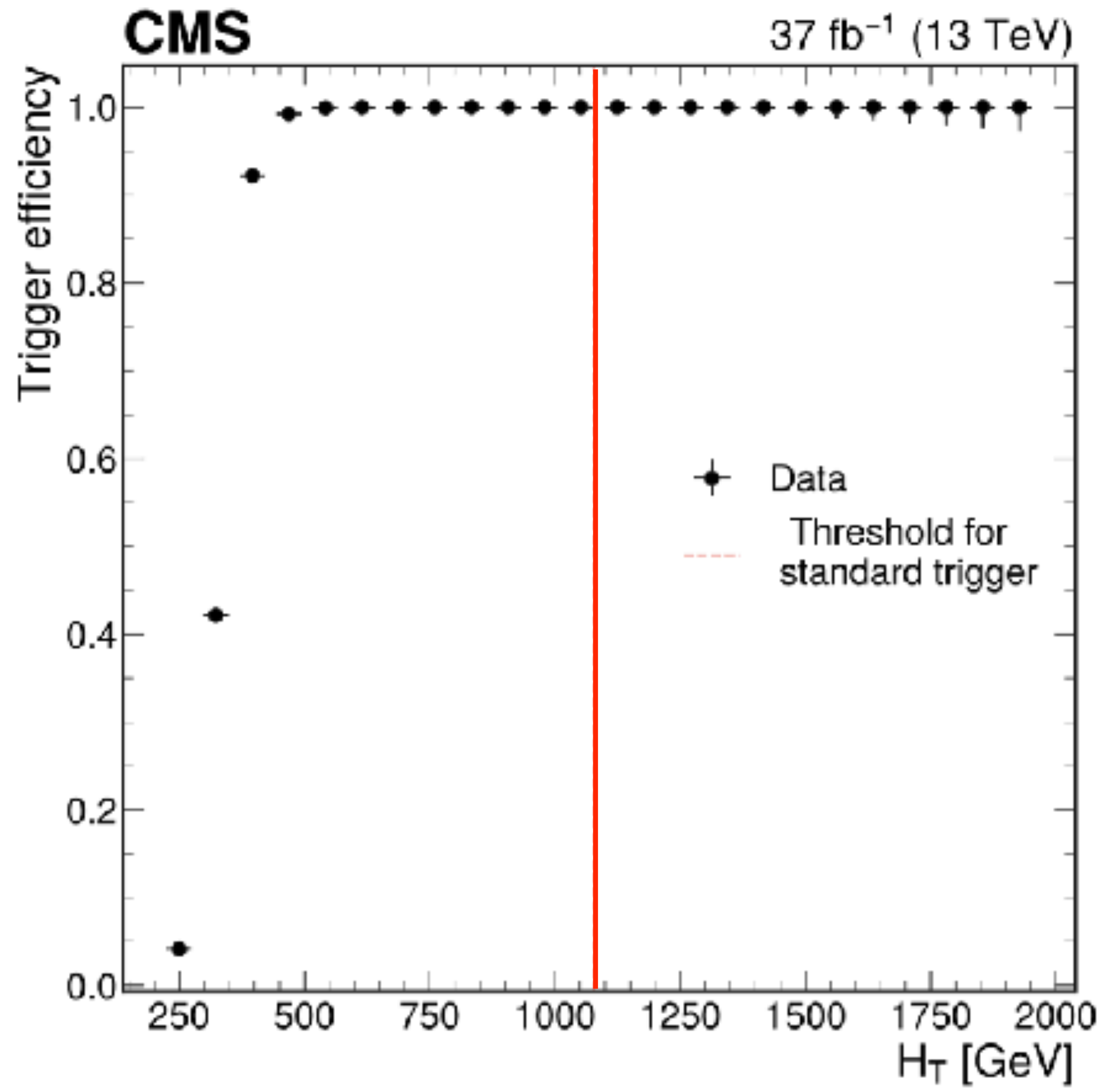
Portals are new dark-sector states (vector, scalar, pseudo-scalar and fermion) with the lowest dimension operators that mix with gauge-invariant combinations of SM fields.

Scouting, Parking and Trigger Improvements

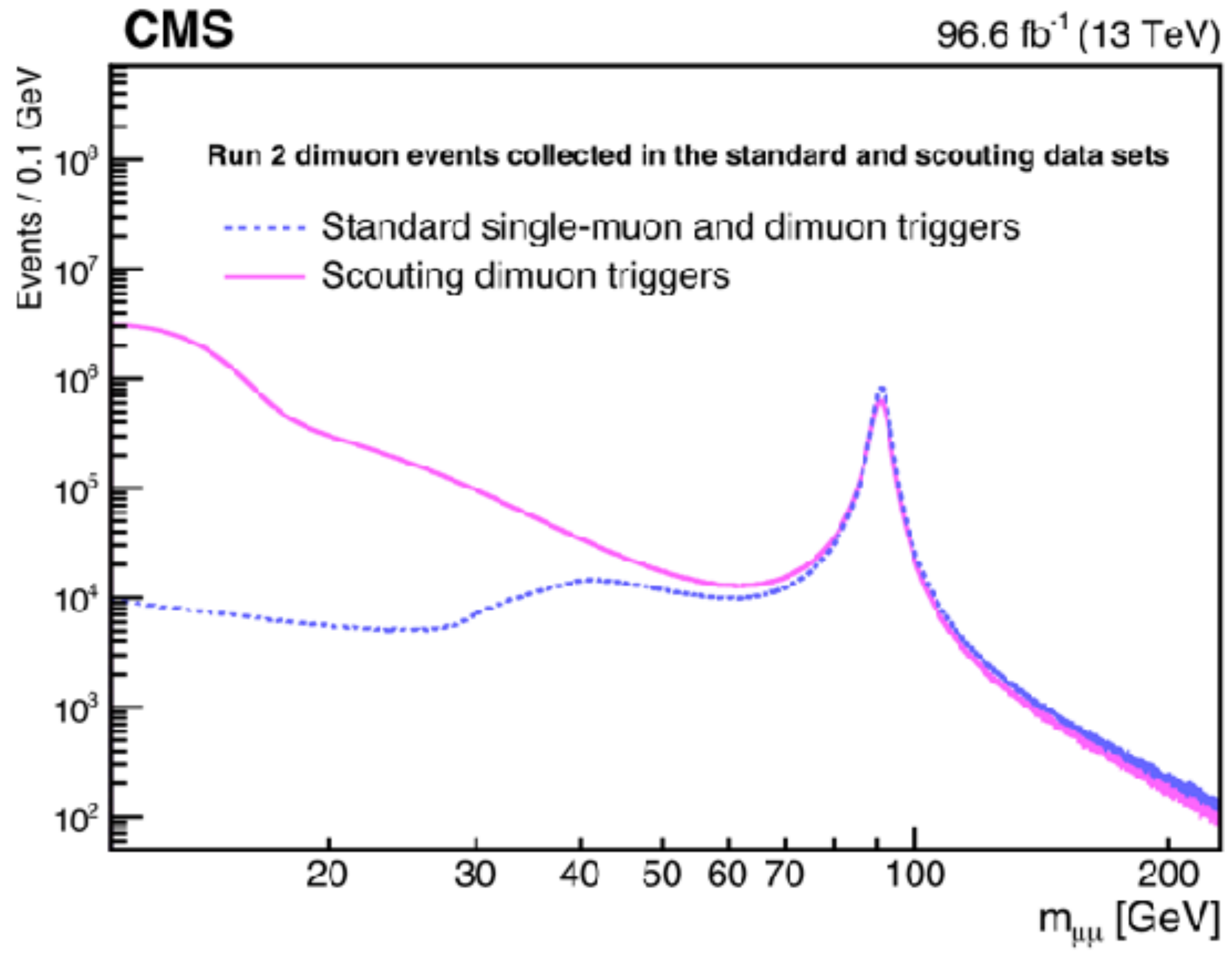


CMS-EXO-23-007

Reconstruction of **di-jets** with thresholds down to $p_T > 500\,\mathrm{GeV}$ instead of 1.1 TeV



Reconstruction of **muons** with thresholds down to $p_T > 3\,\mathrm{GeV}$

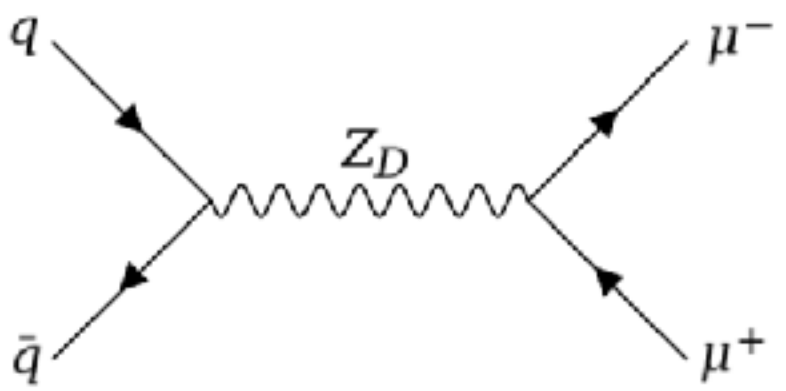


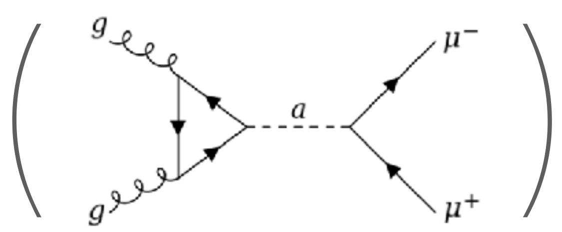
Scouting triggers: Selected L1 Triggers feed into stream with higher HLT rate and reduced content events for specific signatures (two streams: jets and muons).

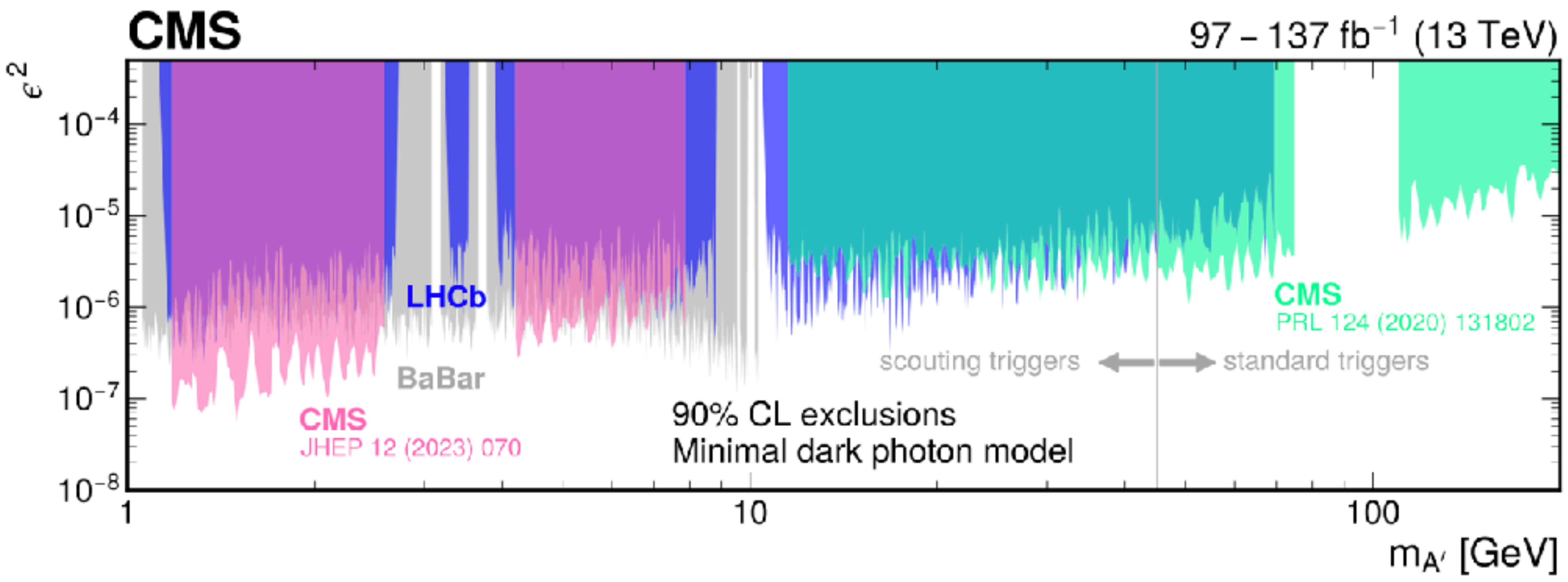
The Dark Photon Portal

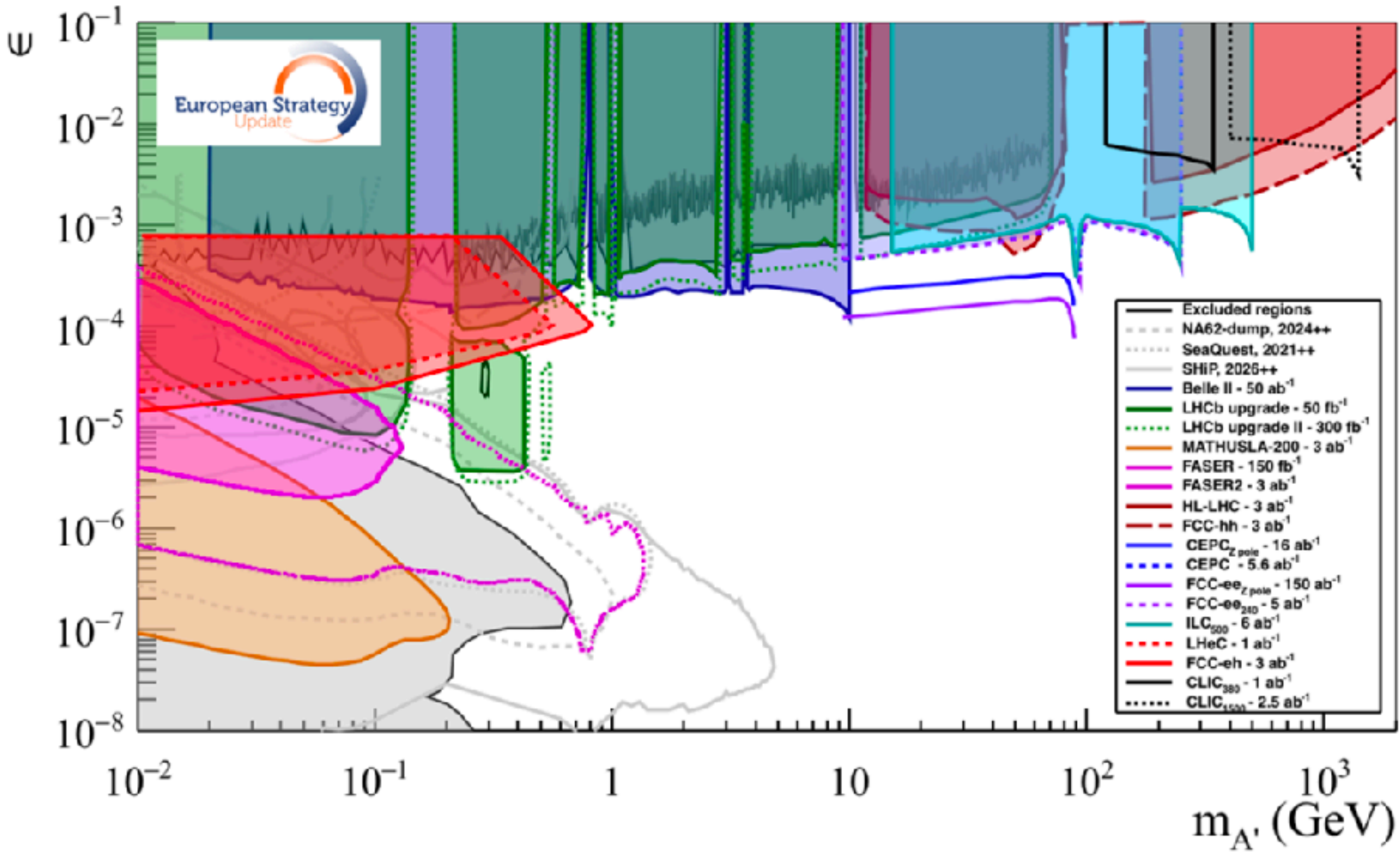
Searches for new **light vector particles** (Dark Photons) which mixes with the hypercharge field.

$$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$









With scouting triggers CMS competitive with LHCb in the low mass range.

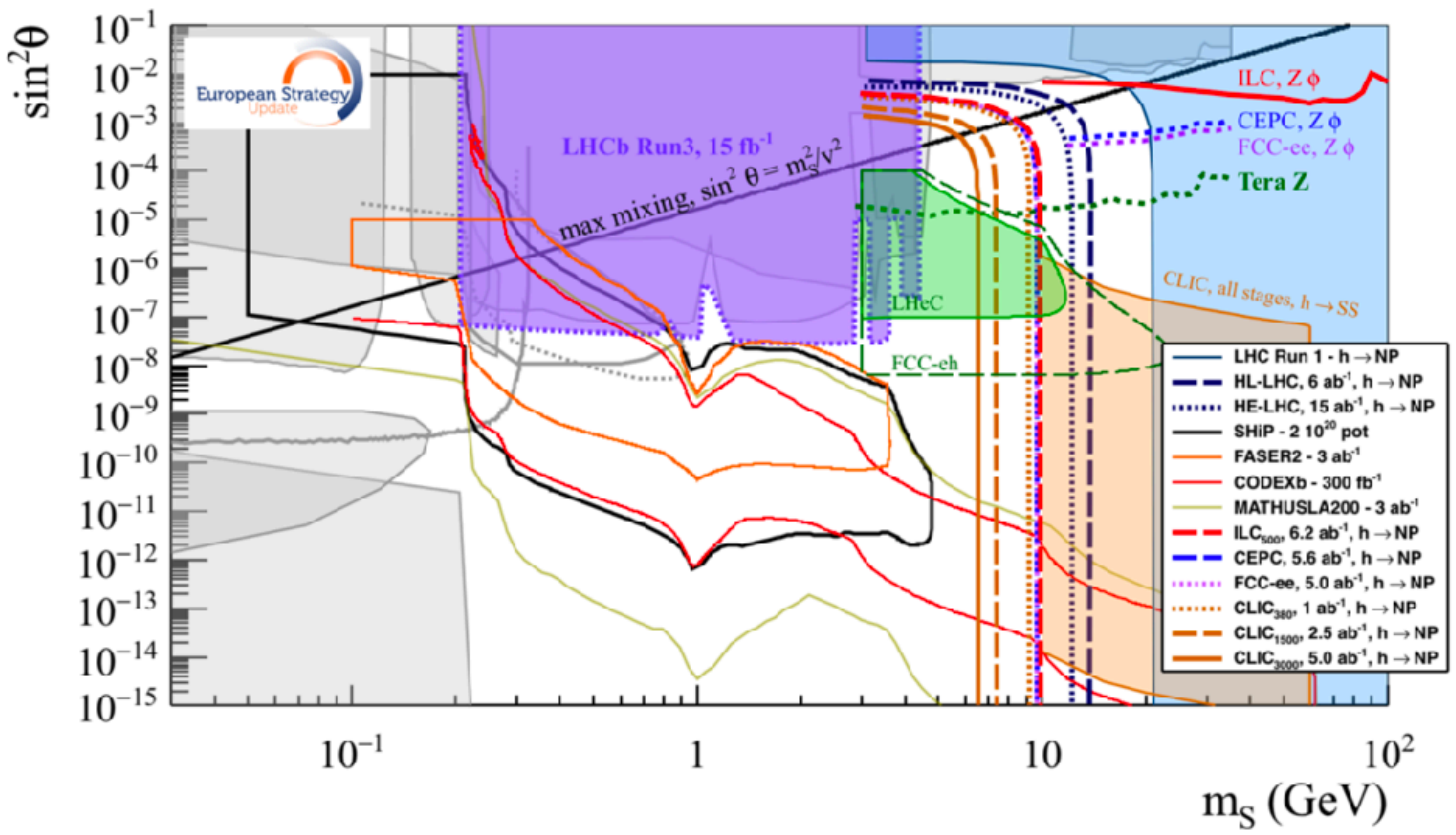
Scalar and HNL Portals

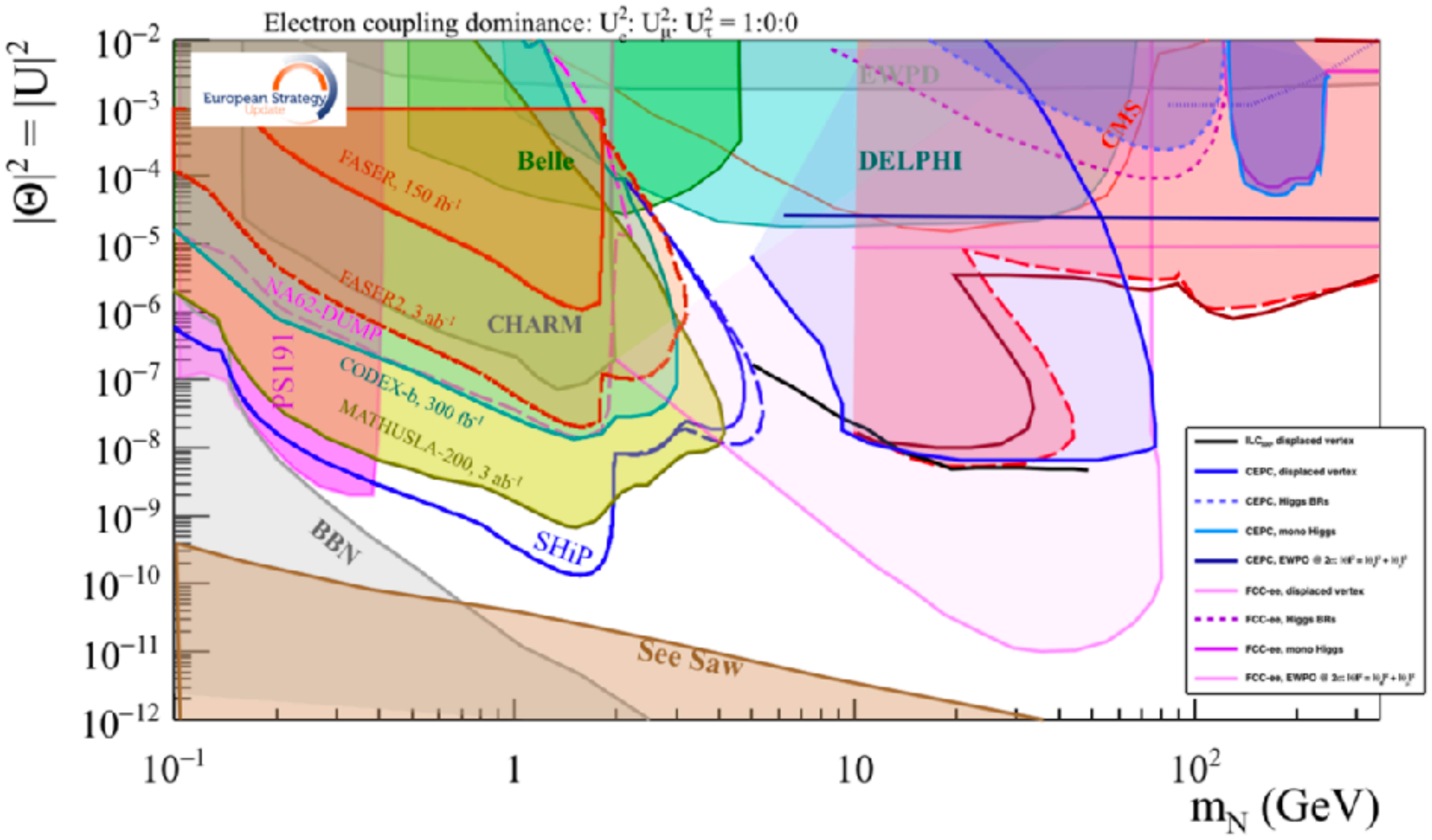
The scalar portal

$$(\mu S + \lambda_{HS} S^2) H^\dagger H$$

Searches for **new neutral fermions** (Heavy Neutral Leptons or Sterile Neutrinos) which mix with left handed SM fermions.

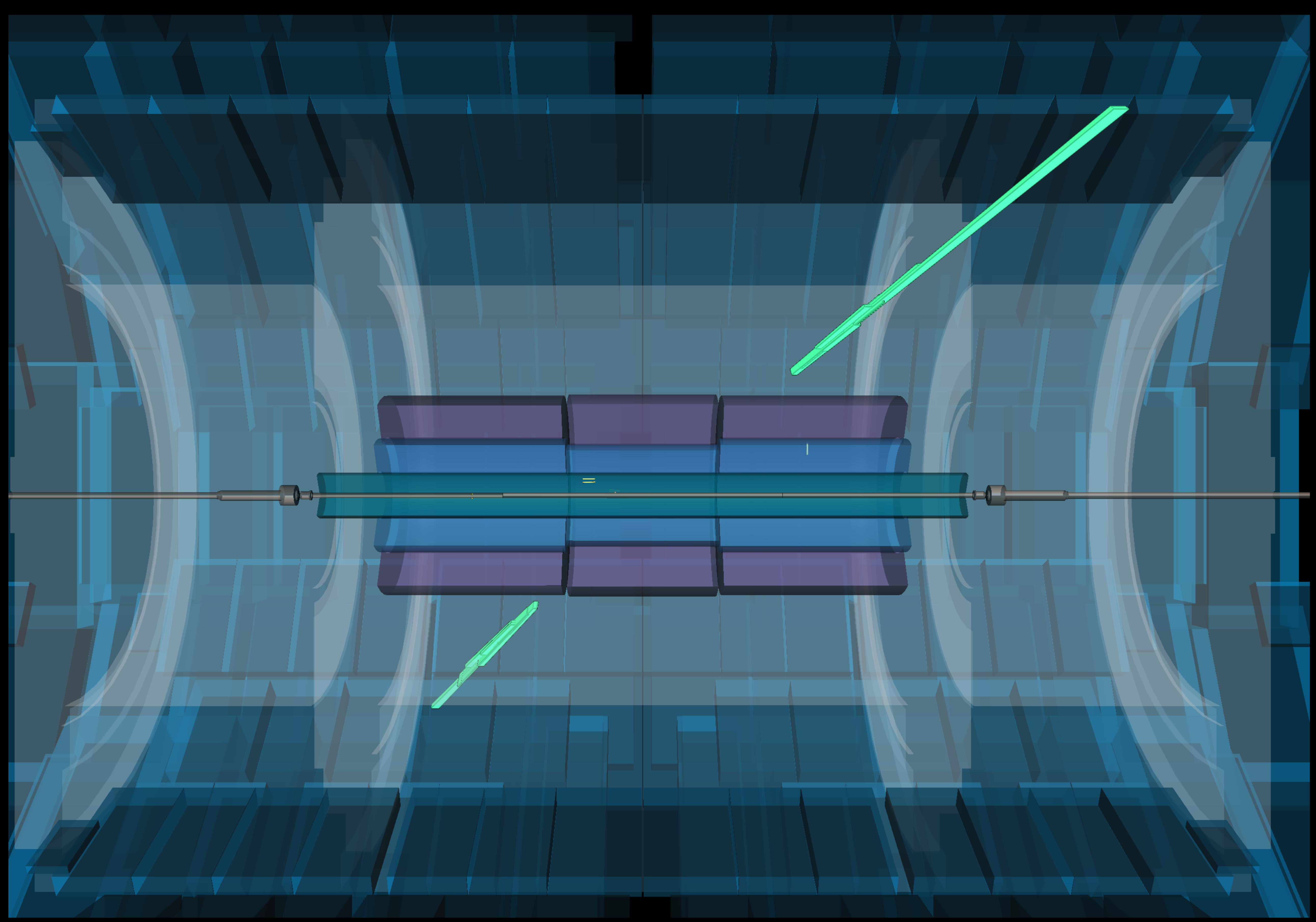
$$y_N L H N$$



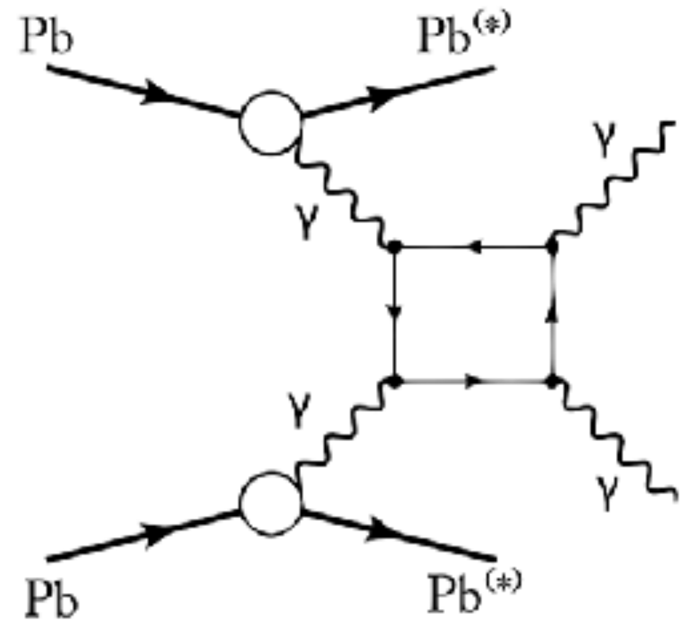


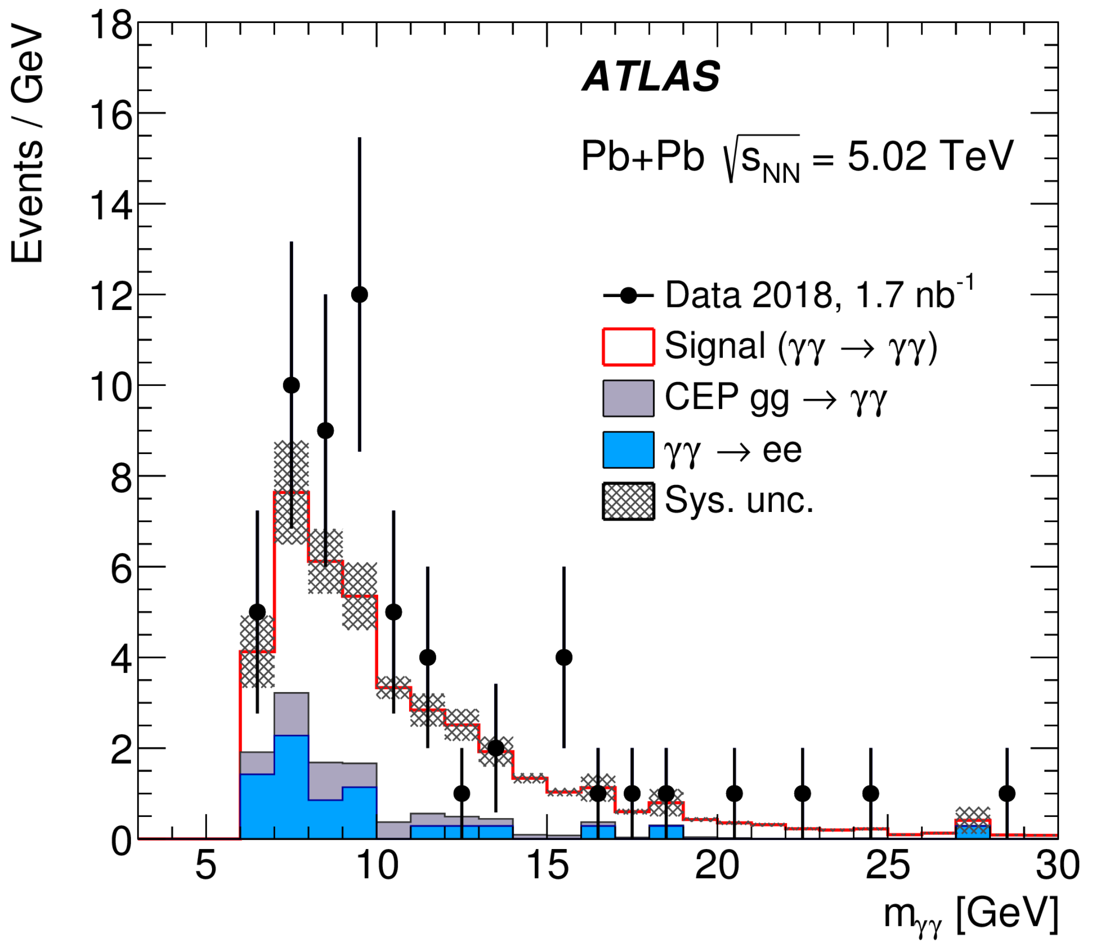
LHC covering higher mass range - FCC-ee high statistics covers lower masses.

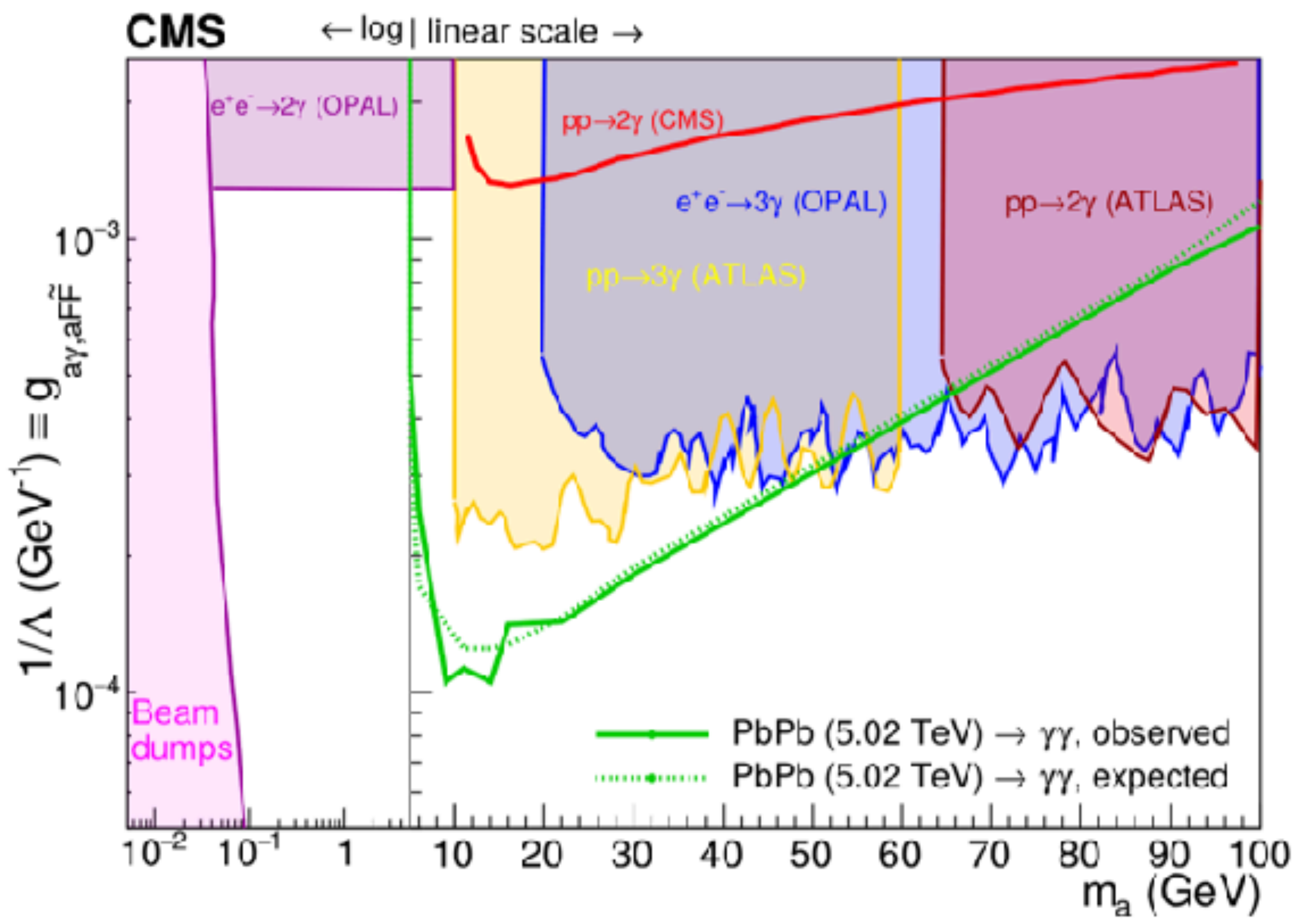
A Spectacular Heavy Ion Event



Observation of **Light-by-light scattering** (Central Exclusive Production)





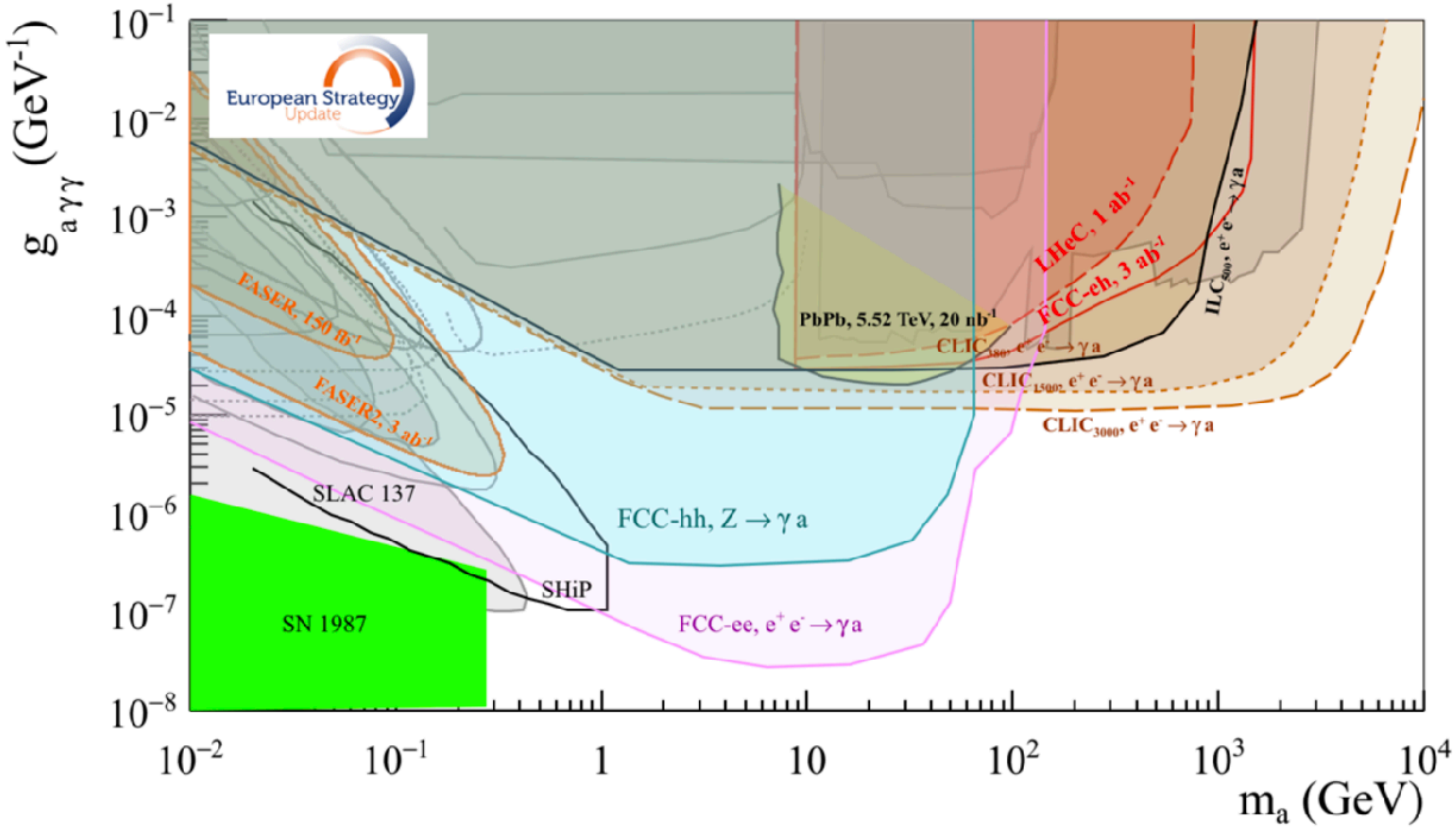


Constraints on ALP (Axion Like Particles) assuming sole coupling to photons.

Axion Like Particles

Searches for a light **pseudo-scalar particle (Axion or Axion like particle)** through Dimension-5 operators

$$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu},\ \frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu},\ \frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$$



A Sleuth of Searches in Unconventional Signatures

Many extensions of the Standard Model predict new particles that are long lived heavy (neutral and charged) and can decay after several cm or even meters.

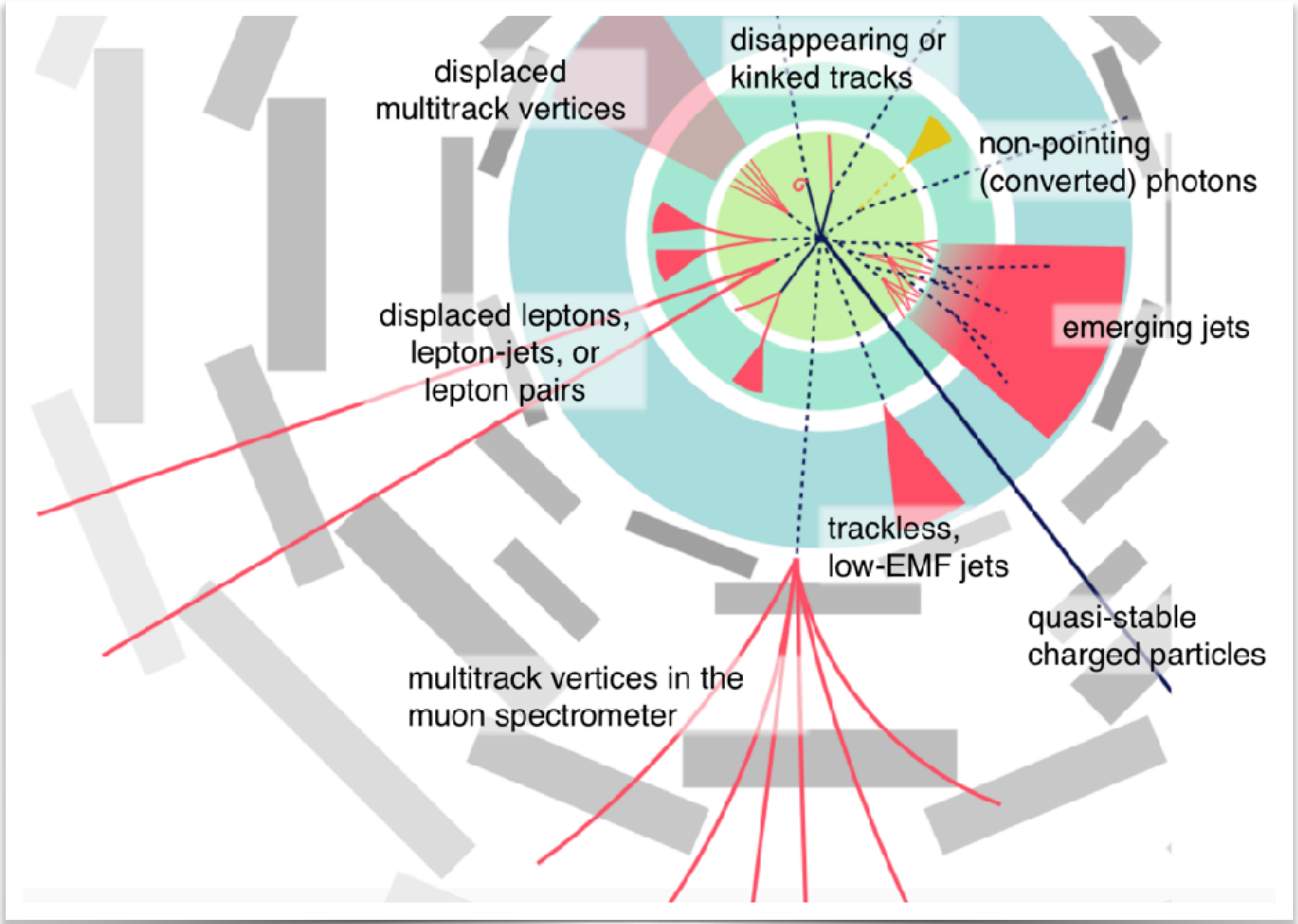
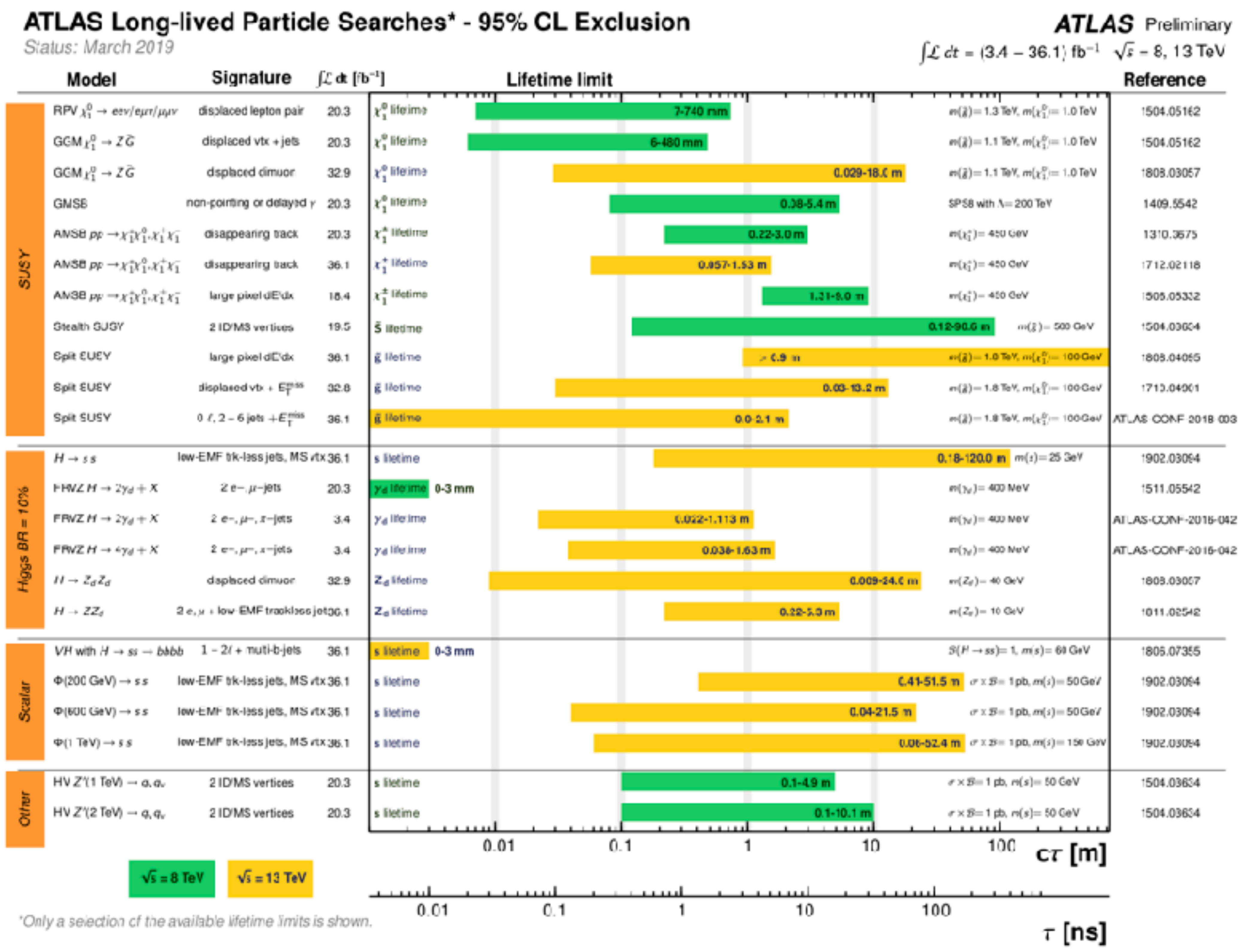


Image from H. Russel



Sample for ATLAS (same for CMS)

Difficult signatures requiring specific complex reconstruction and trigger!

“Conventional” Searches at the Energy Frontier

Panorama of Searches for Conventional Signatures

Searches for Vector Like Fermions

Simple additional chiral fermions are essentially ruled out by Higgs data.

Fermions that are not Chiral

- The L and R components transform the same way under SM symmetries.
- Interact with SM through mixing with SM quarks.
- Present in models where the Higgs is a pseudo Goldstone boson (e.g. in Composite Higgs and little Higgs models).
- Present in Warped Extra dimension models.

Large variety of possible states and complex channels

- Heavy quark partners with charges -1/3, 2/3, 4/3 and 5/3.
- Complex channels looking for T(2/3), B(1/3): Ht+X, Wt+X, Wb+X, Zb+X, Zt+X (Performed at Run 2) so far and T(5/3) 4tops final state.

And still many more !!

Searches for W'and Z'

High mass states motivated in many theories e.g. Grand Unified and additional gauge symmetries.

- electrons, muons, taus, jets, b-jets and tops.
- di-bosons including vector bosons and Higgs bosons

Searches for high mass states of spin 0 and 2

Motivated in Randall Sundrum models (Graviton and radion)

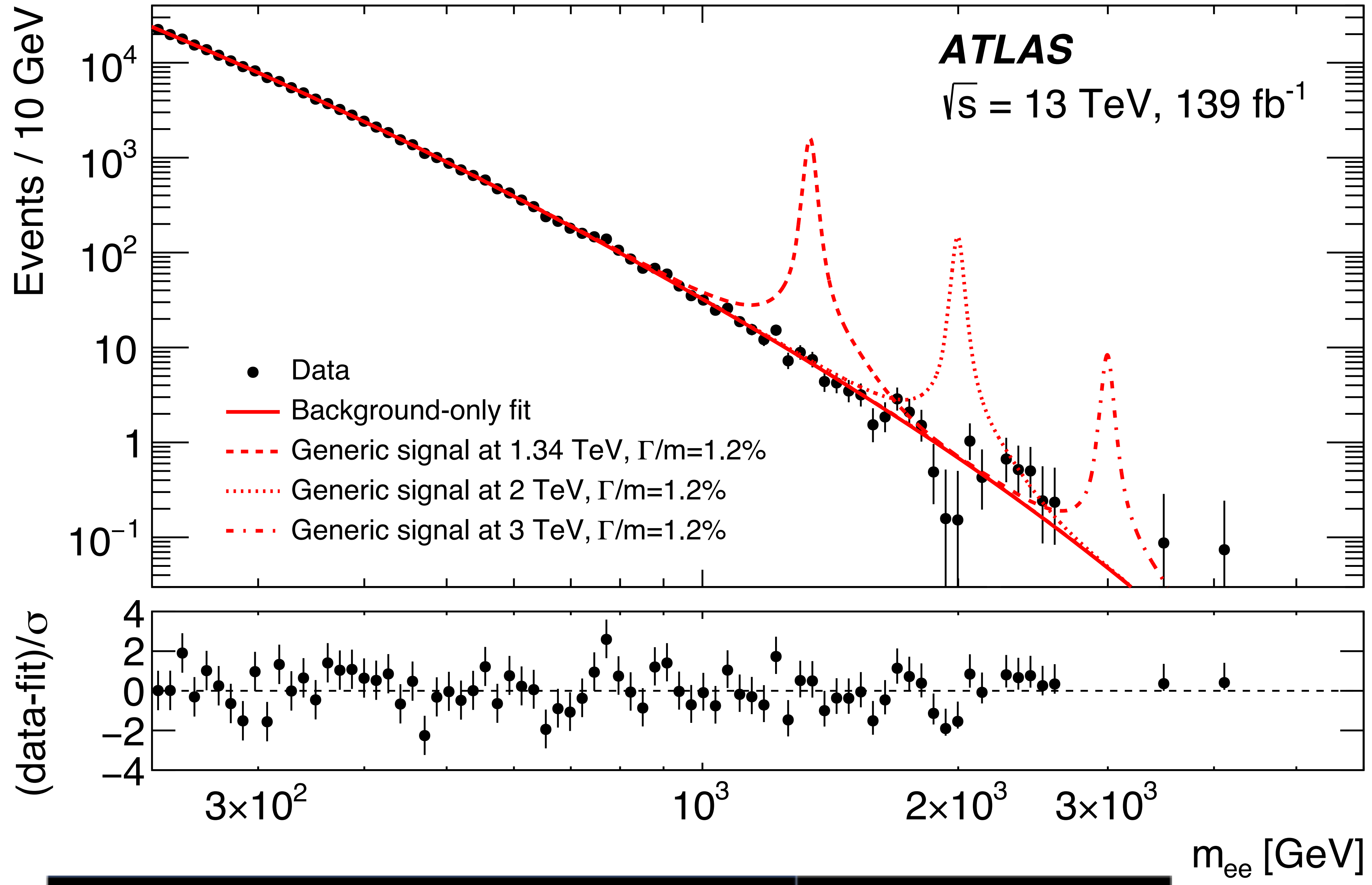
Searches in various channels dijet, diphoton and di-leptons

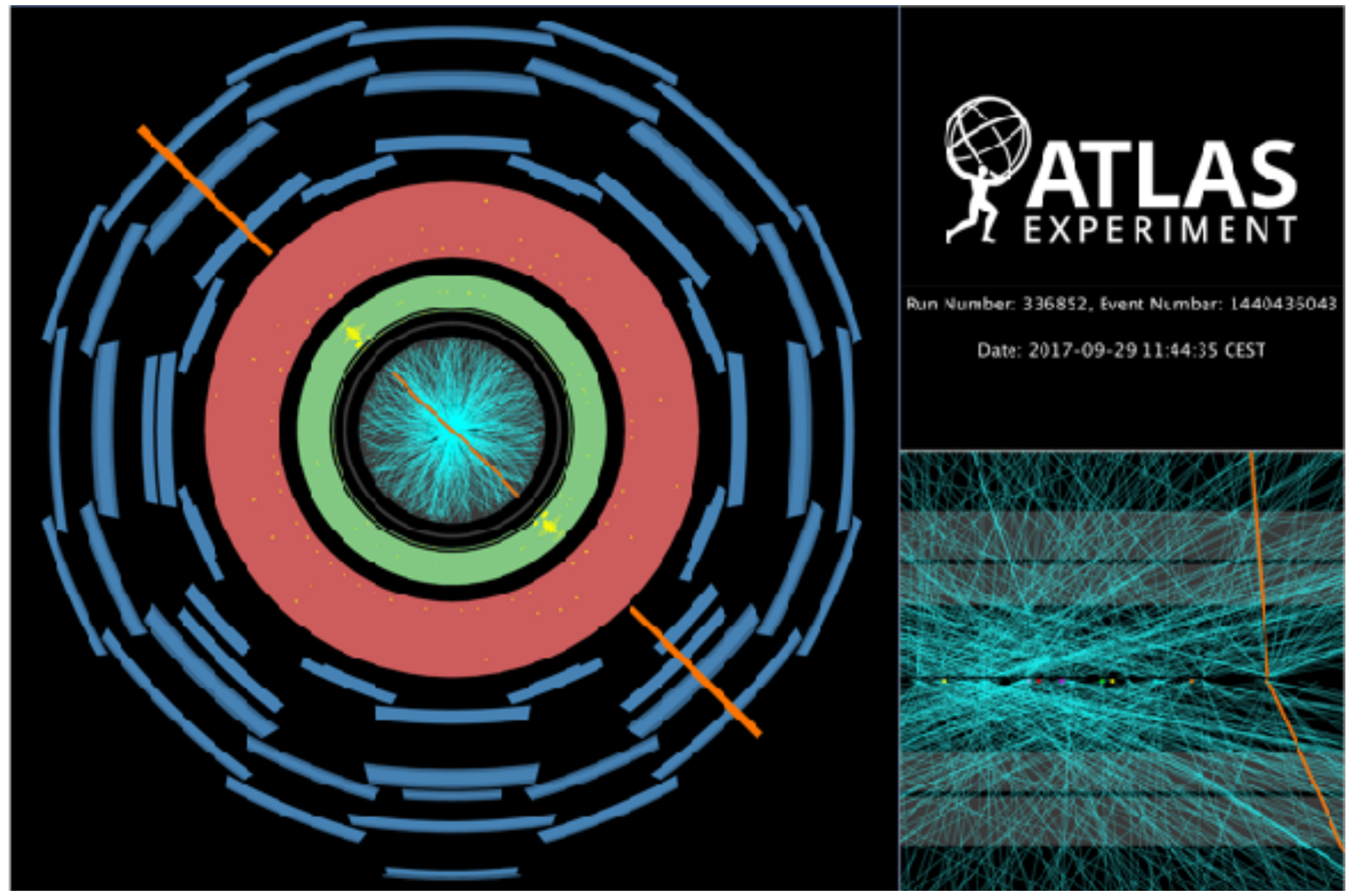
Any many more

- **Quark compositness**
- **Leptoquarks**: predicted in grand unified theories and interest raised by lepton flavor universality anomalies
- **Heavy neutrinos**: produced in theories for neutrino masses (e.g. Seesaw)
- **High mass and high activity events**: strong gravity (from extra dimension theories), mini black holes, quantum black holes…
- **Searches for low mass states.**

Searches for High Mass Resonances

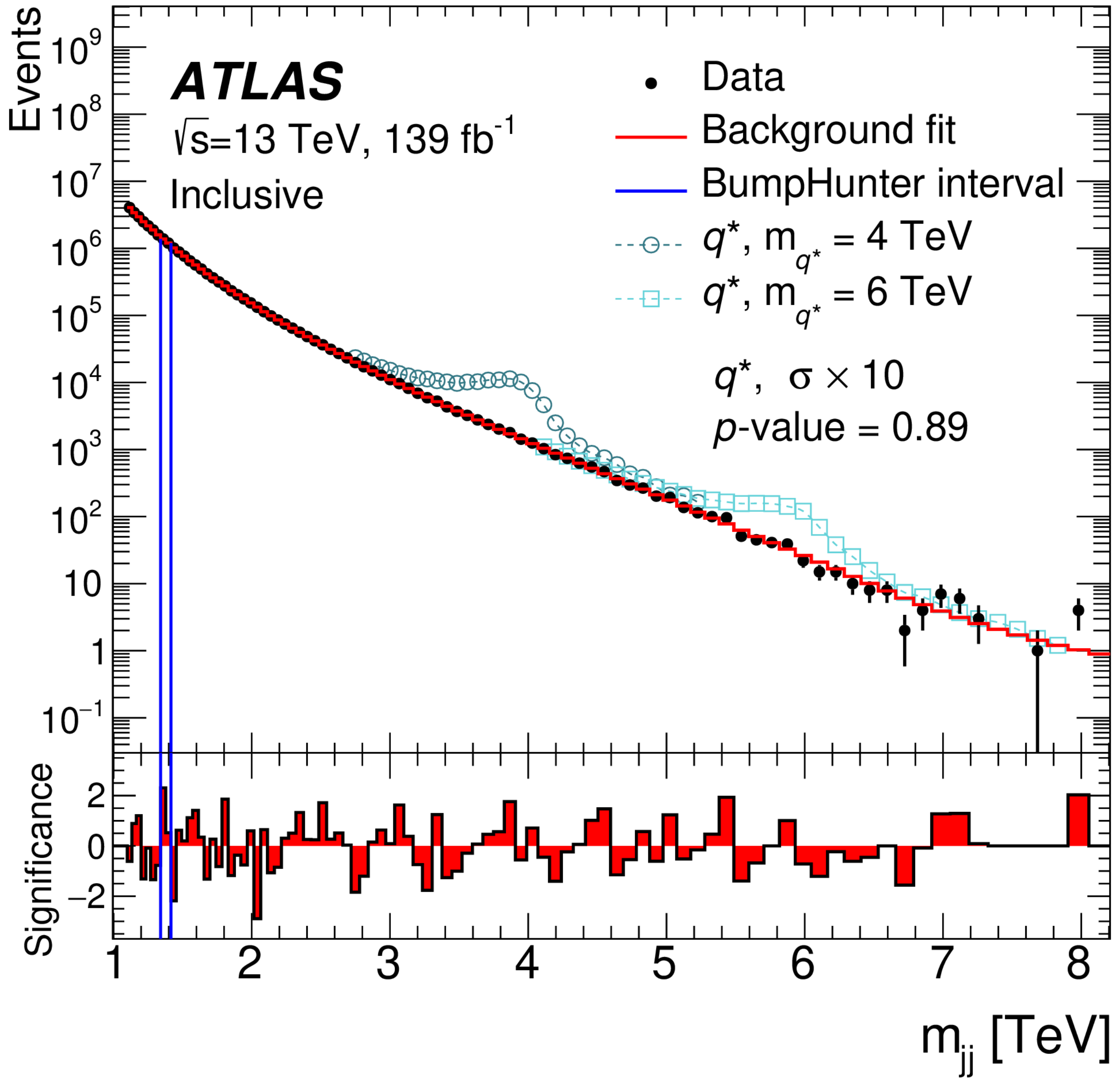
Di-electron search





Exclusions up to ~5 TeV

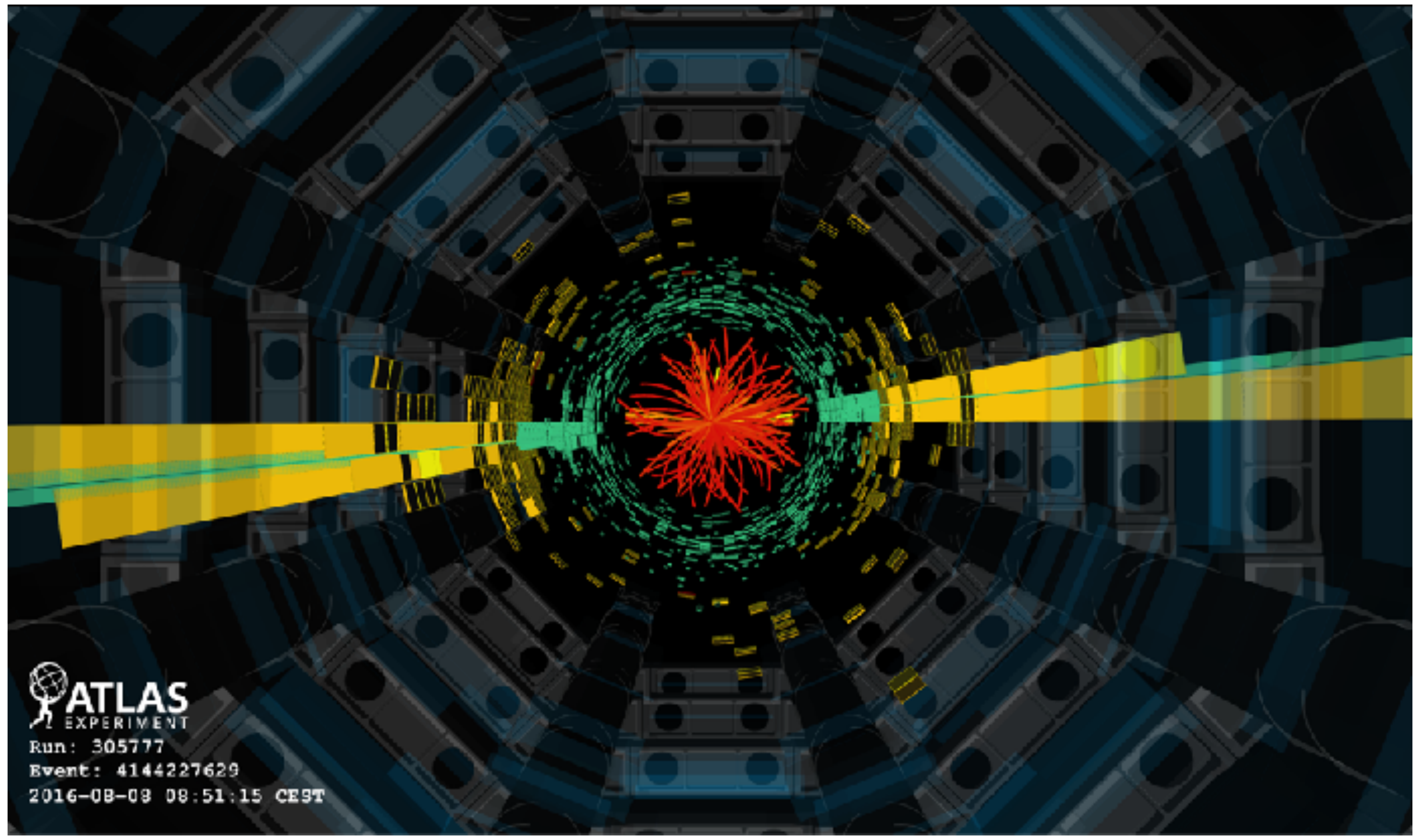
Highest mass di-electron event ~4 TeV



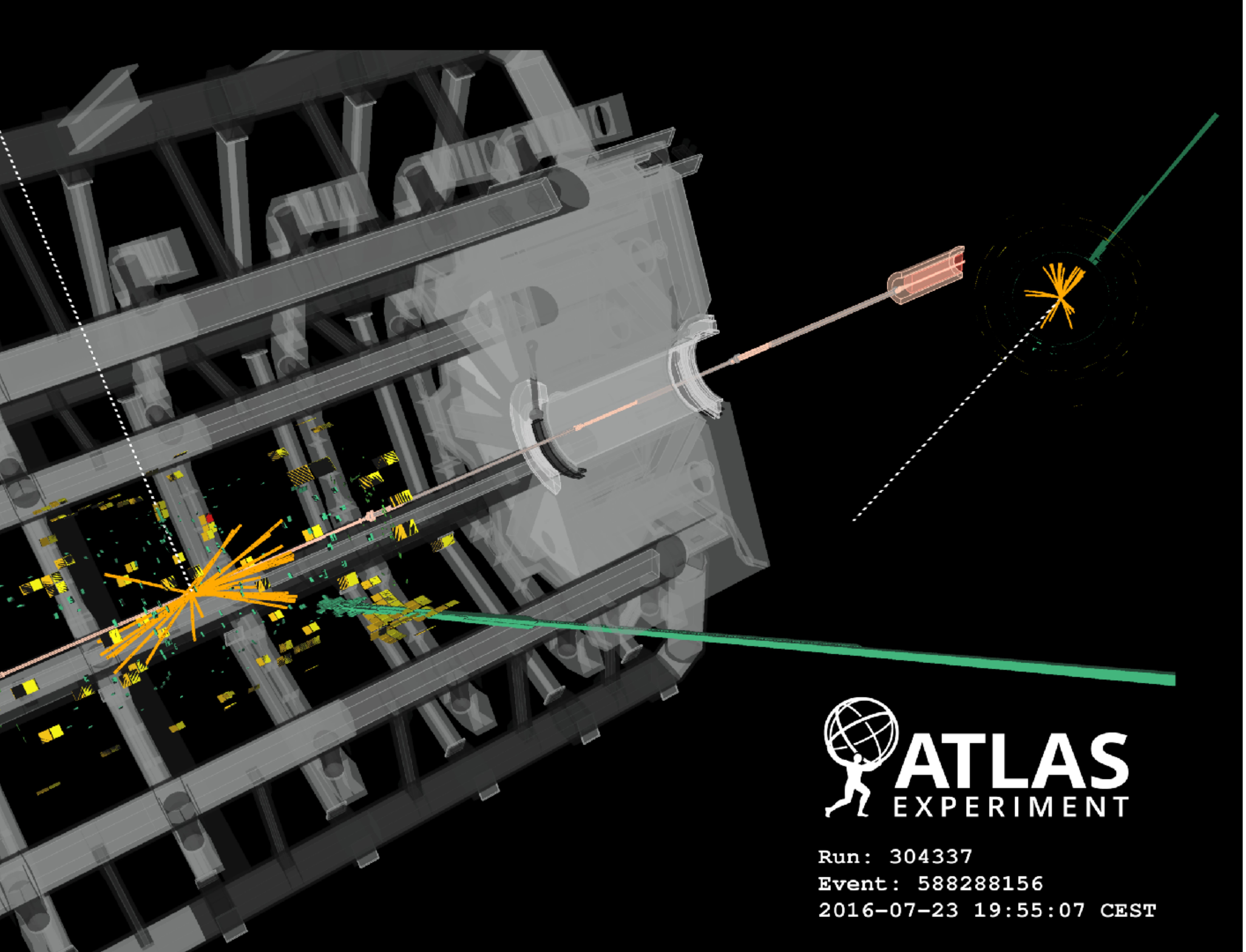
High mass Dijet search

Limits on excited quarks at 6.7 TeV

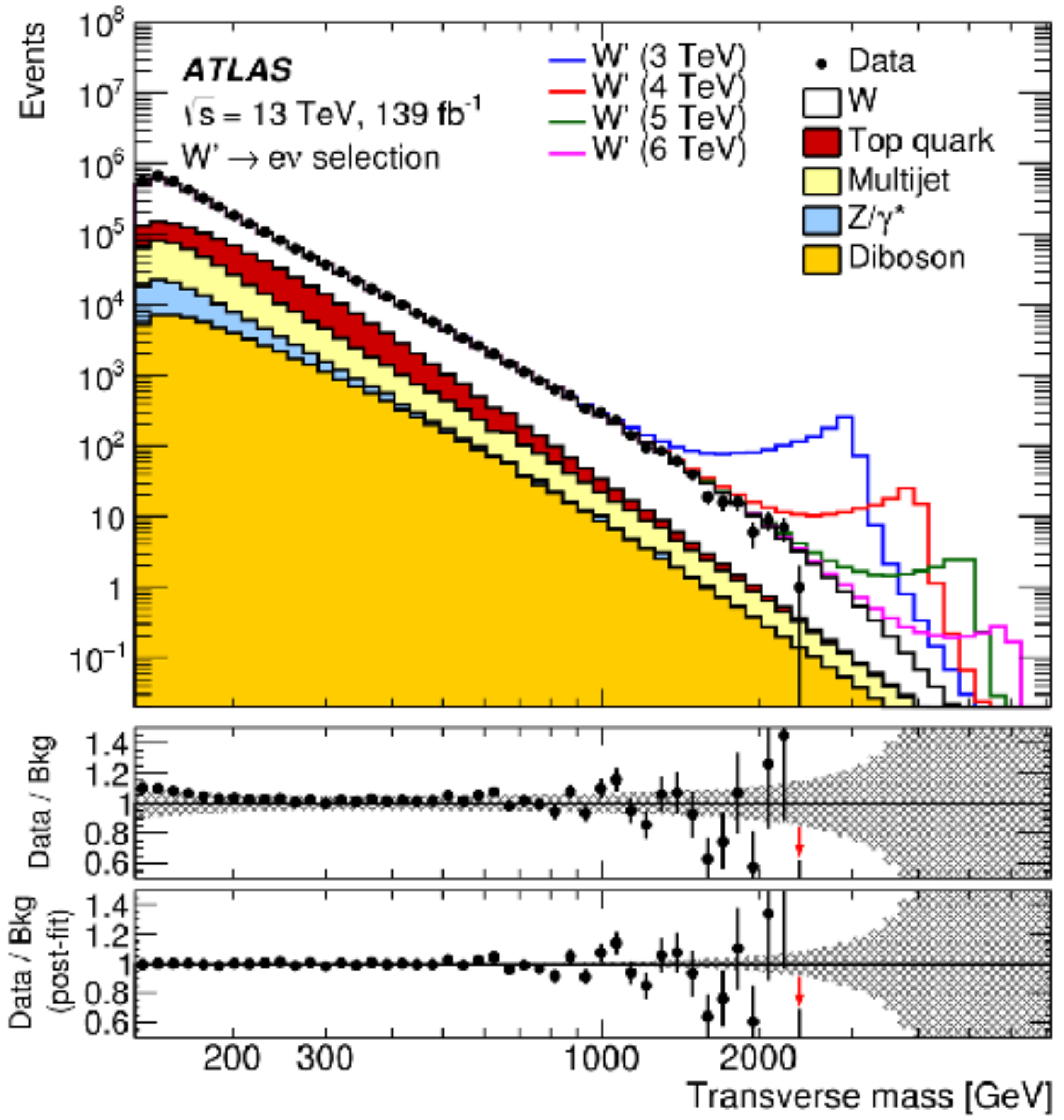
Also searches for ADD and RS gravitons and QBH



Highest mass (central) dijet event ~8 TeV



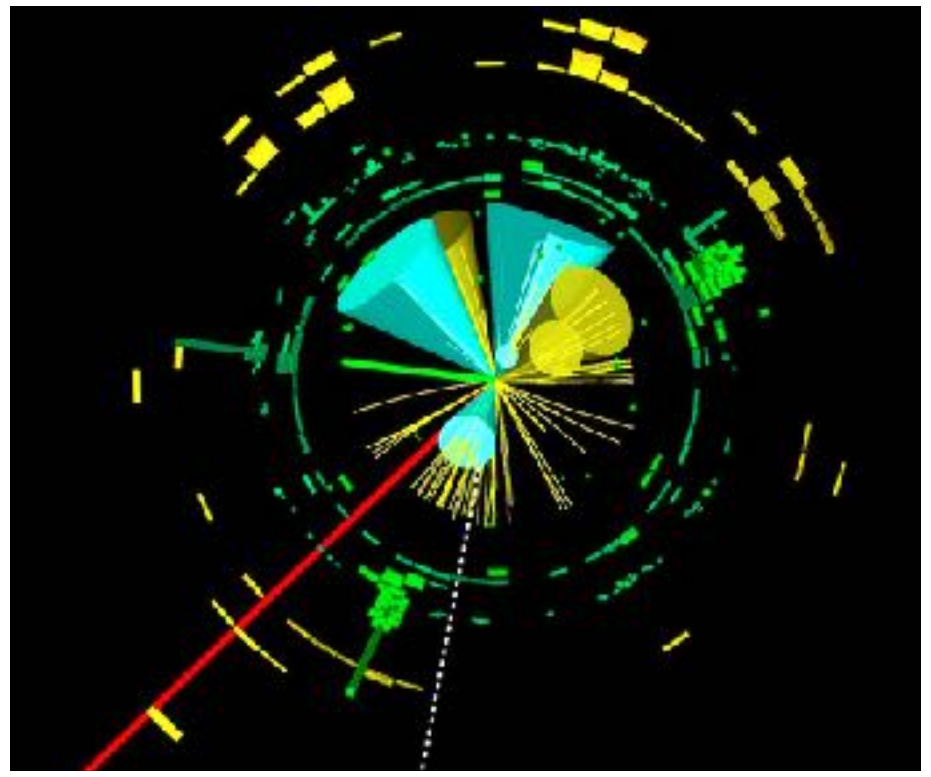
Transverse mass
(in lepton-MET search)



Drell Yan (and other processes) predictions and lepton calibration in the TeV energy range.

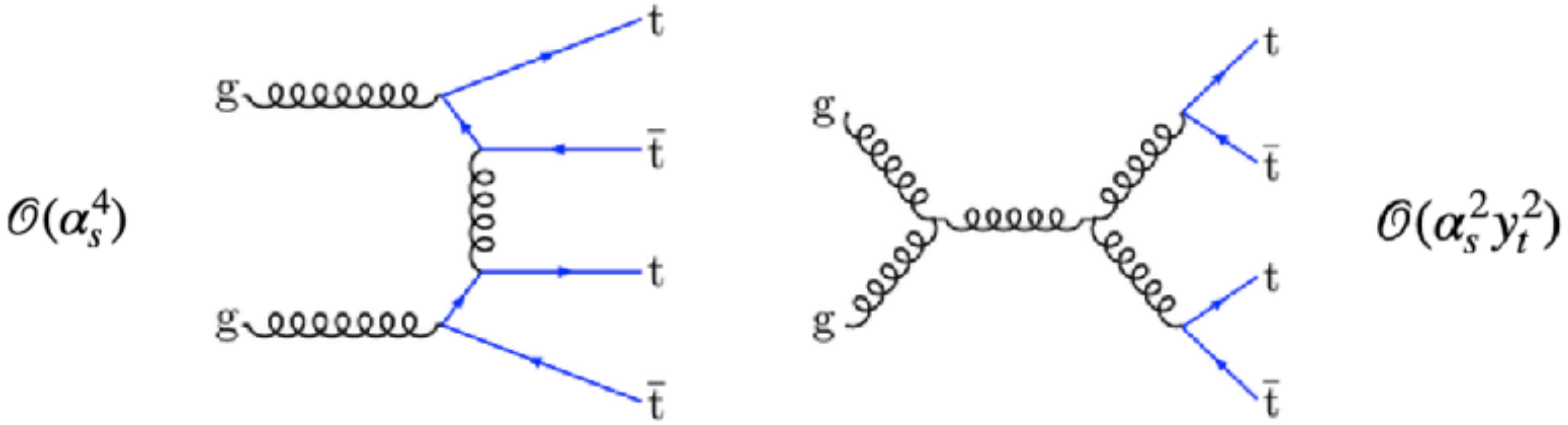
Electron pT = 1.1 TeV
MET = 1.16 TeV

LHC Measurements Highlights (IV)



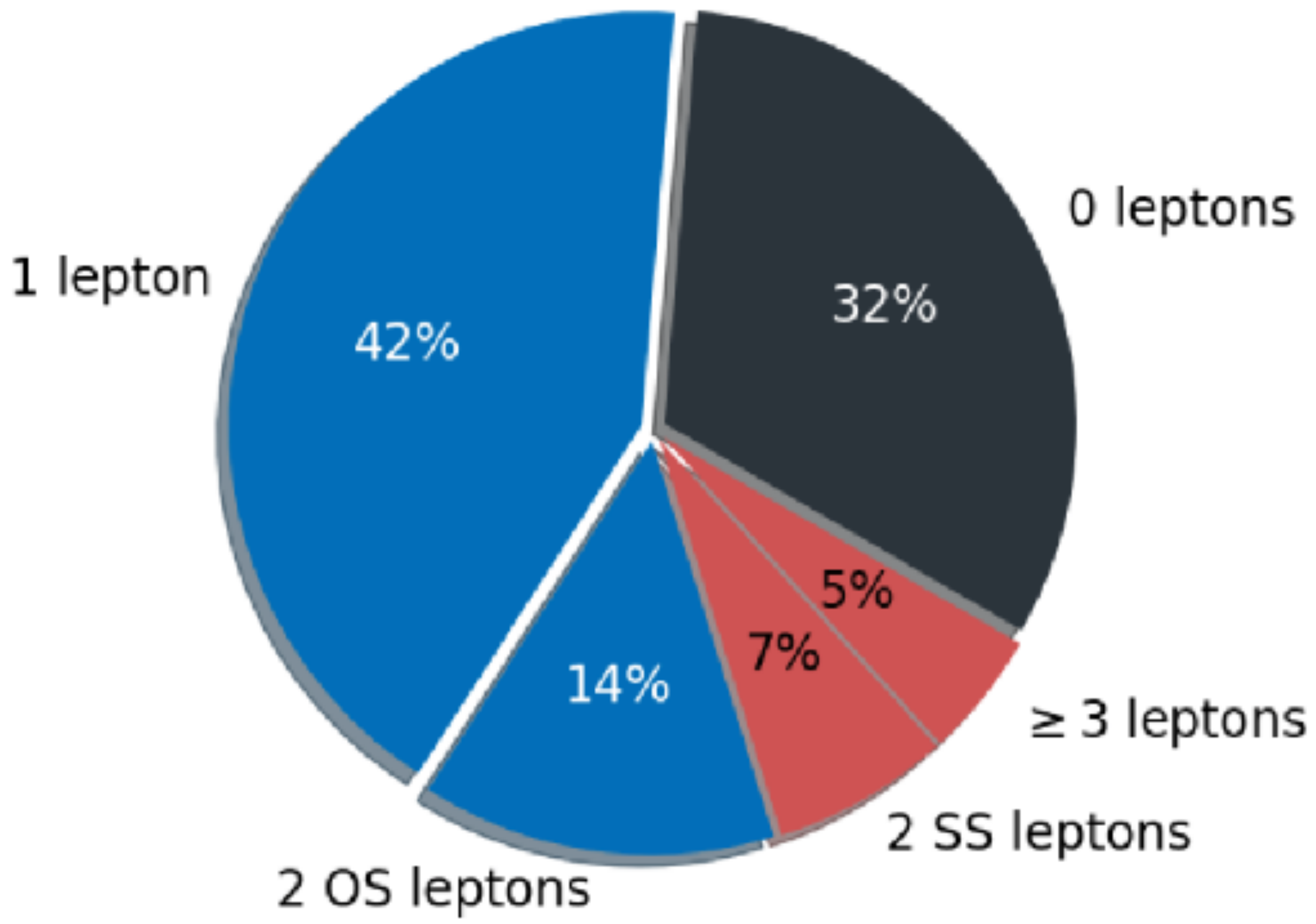
ATLAS and CMS observe simultaneous production of four top quarks

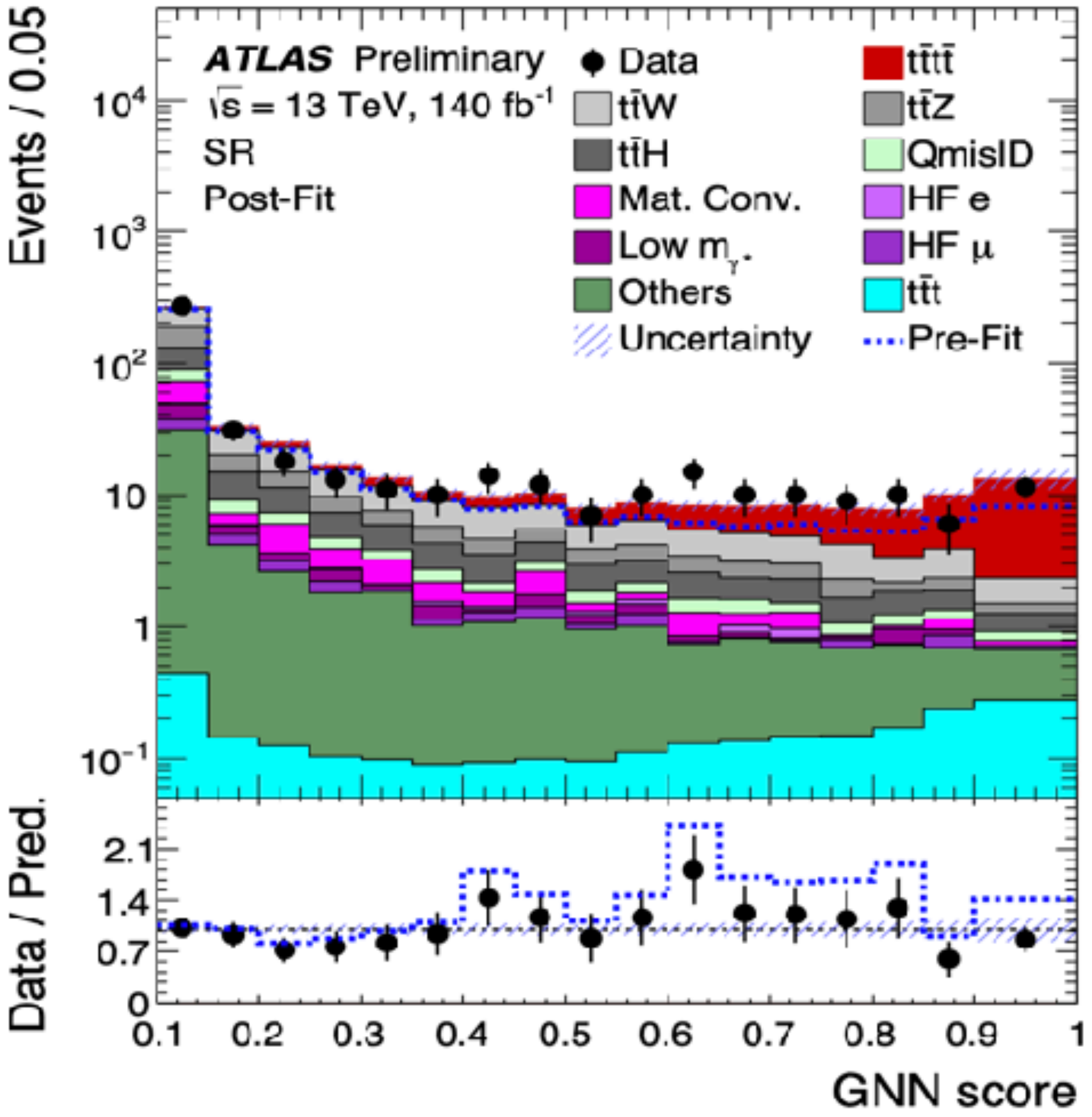
[Link](#) to CERN News

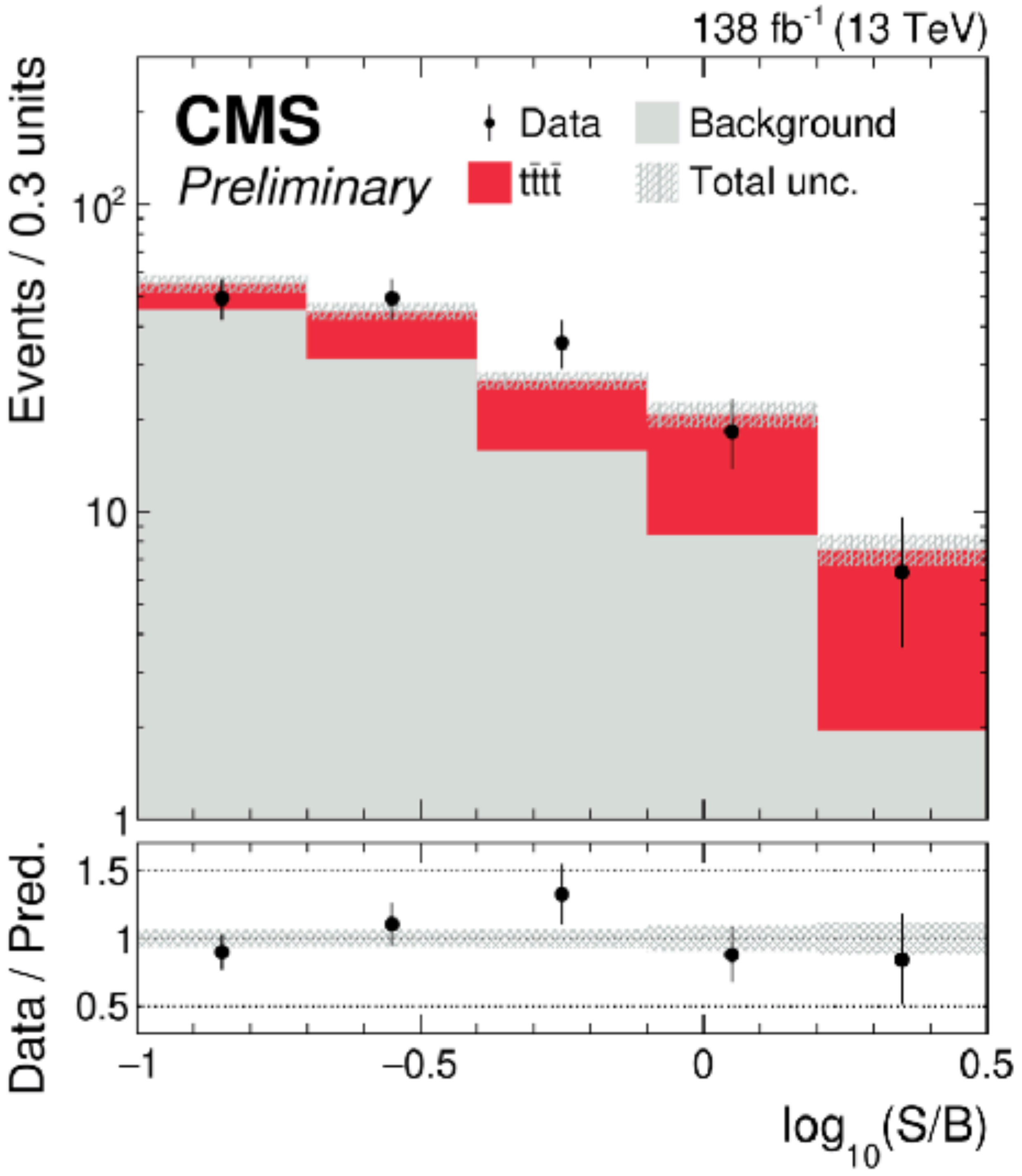


Final state with four W bosons and four b jets!

Numerous channels investigated!







(Independent) Observation by ATLAS and CMS of 4 top production!

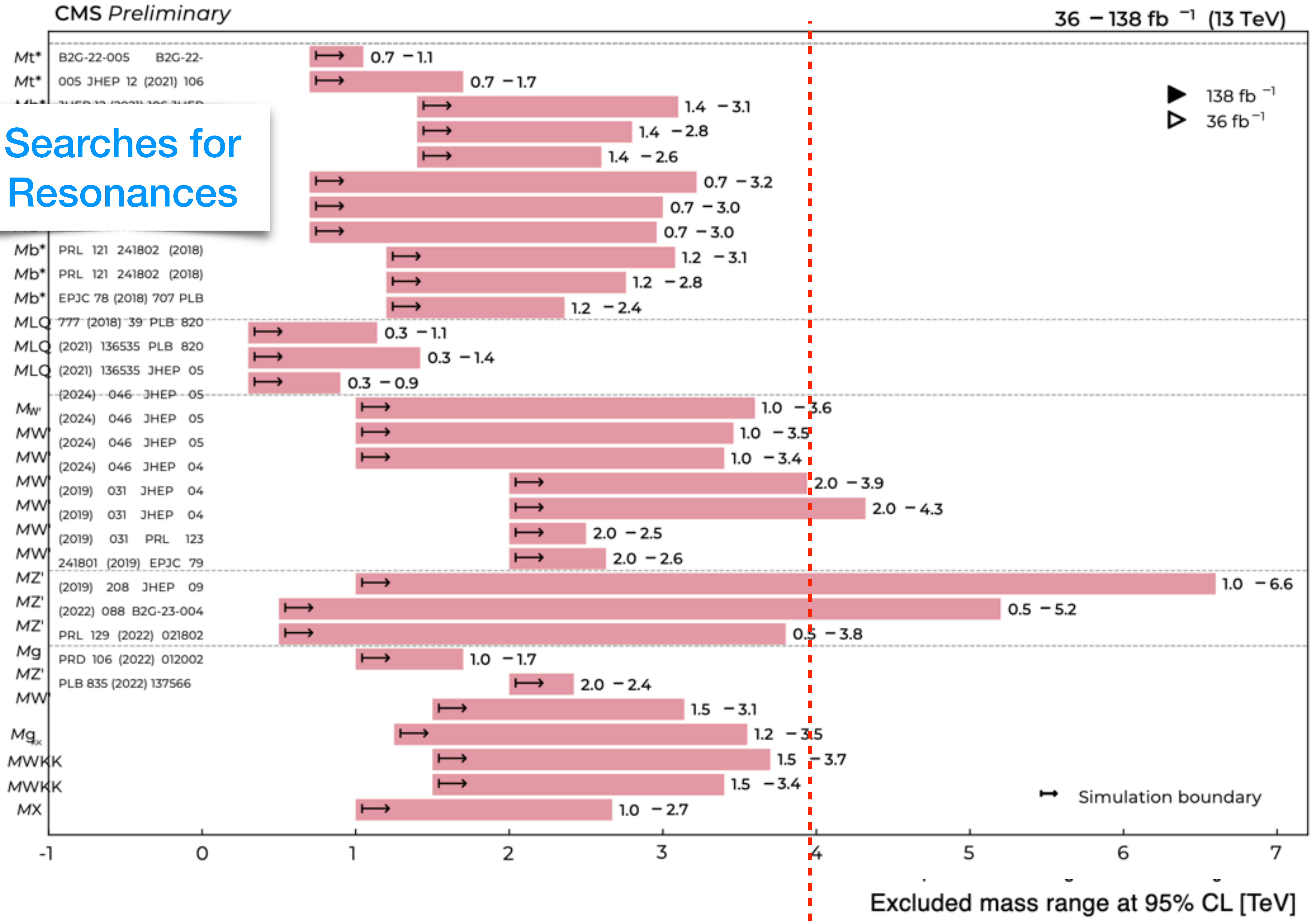
6.1 (4.3) σ observed (expected)

5.5 (4.9) σ observed (expected)

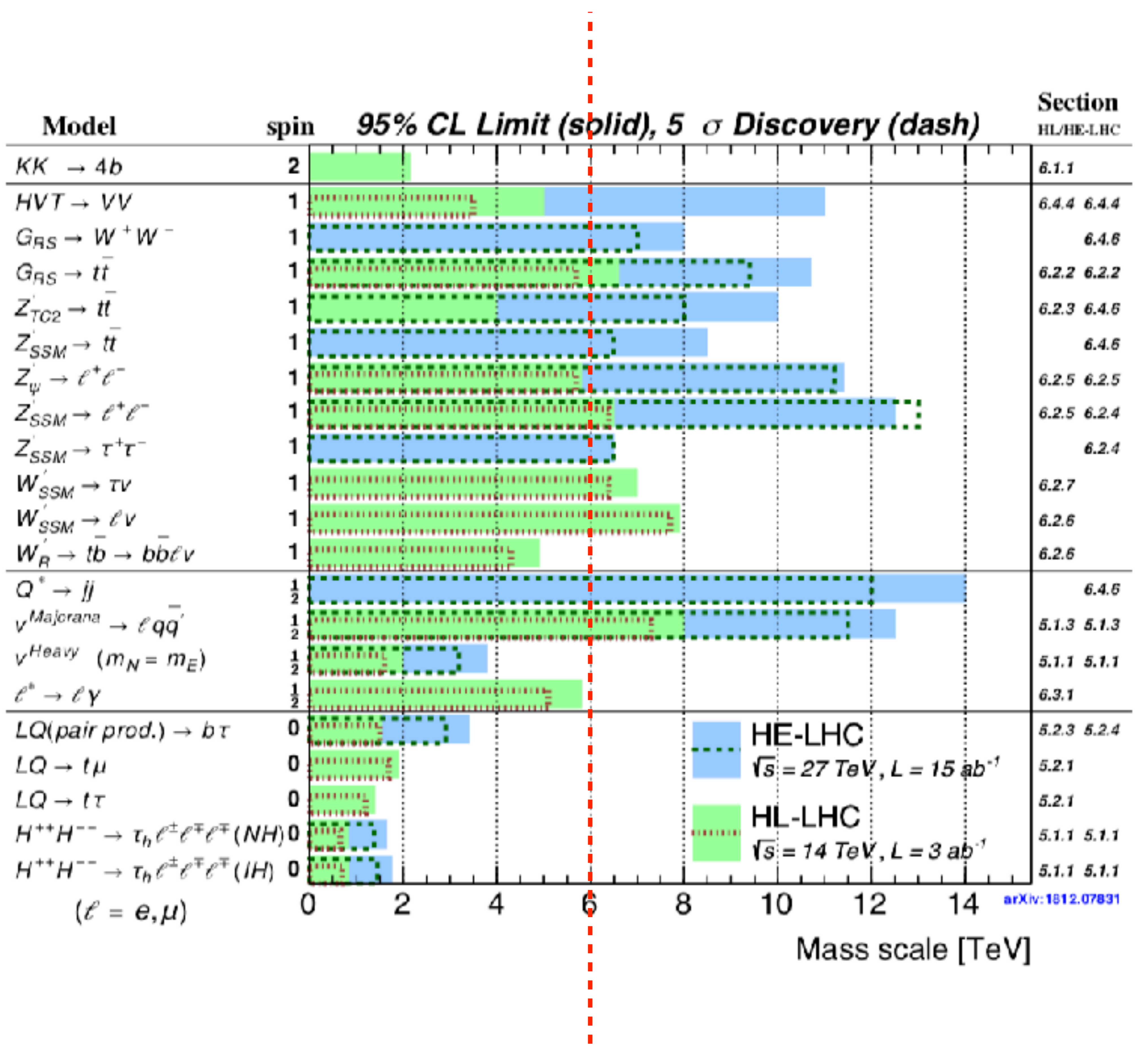
Very Large Number of Searches

(in large variety of topologies and models)

Searches for Resonances



4 TeV



6 TeV

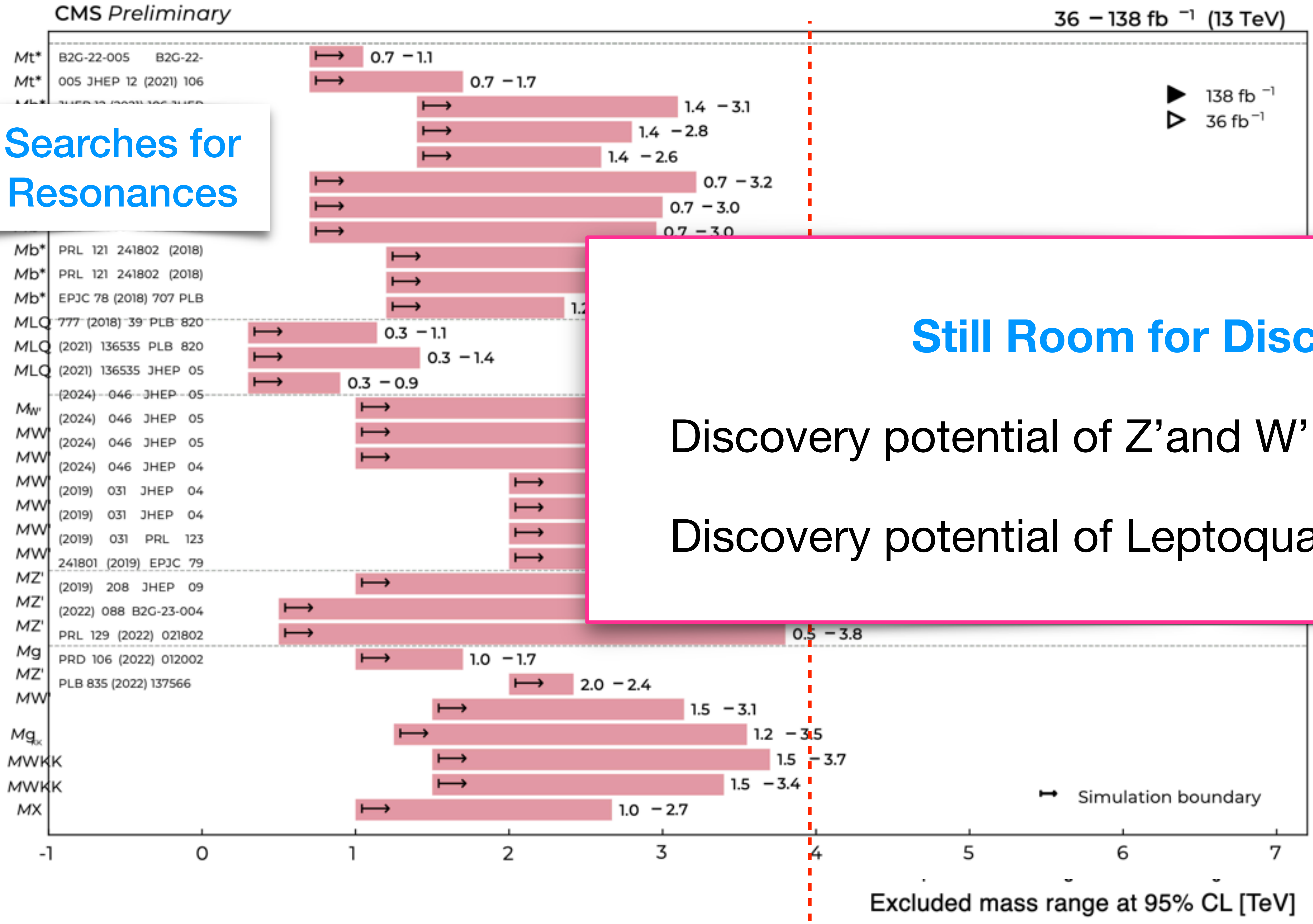
Example from CMS (similar for ATLAS) - latest plot in the backup!

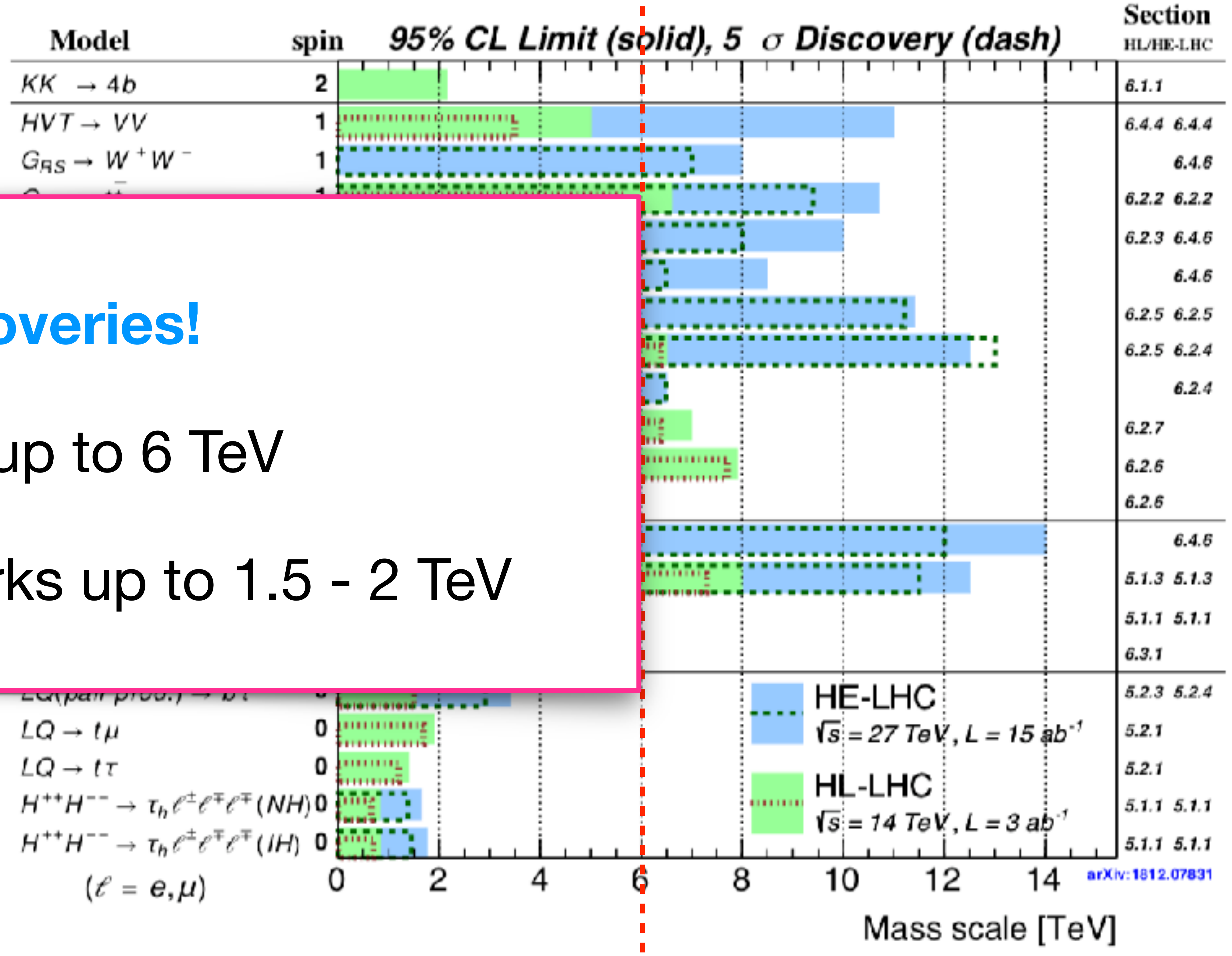
HL-LHC YR
1812.07831

Very Large Number of Searches

(in large variety of topologies and models)

Searches for Resonances





Still Room for Discoveries!

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

Discovery potential of Leptoquarks up to 1.5 - 2 TeV

4 TeV

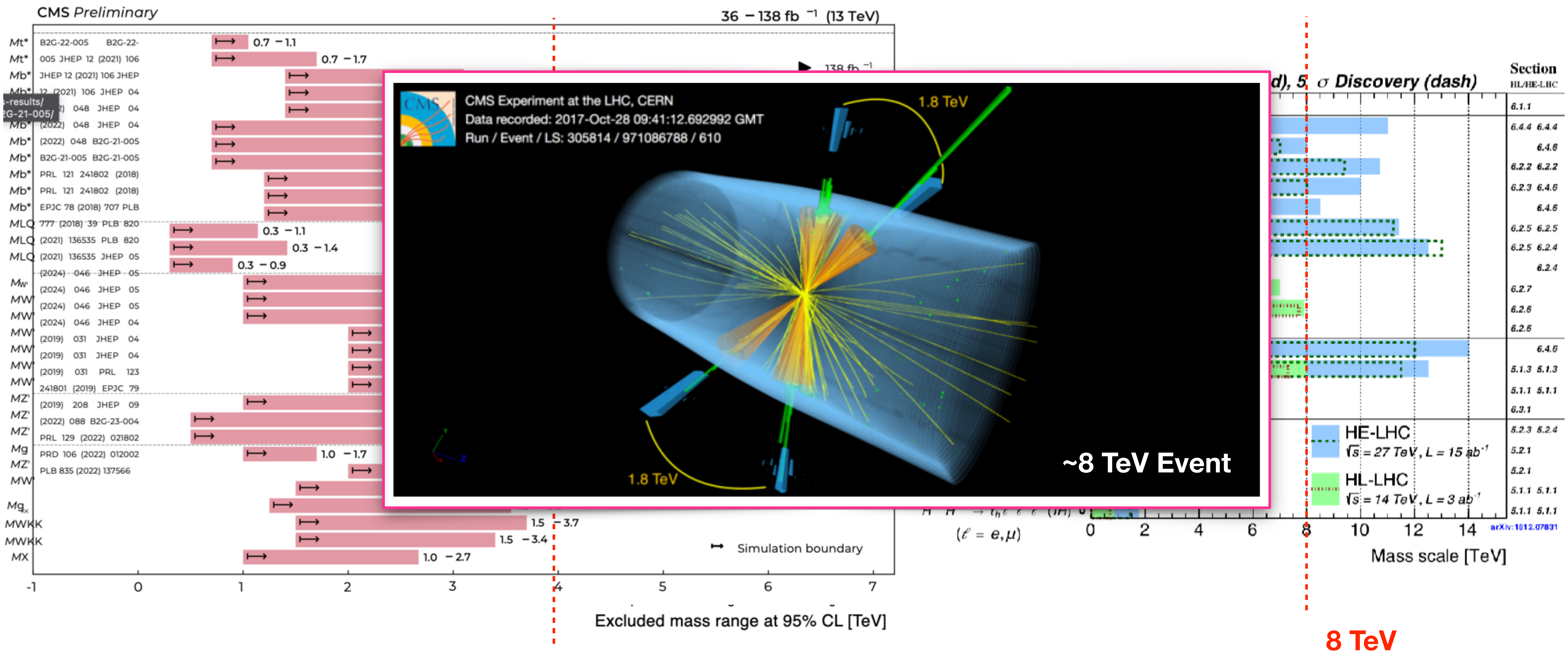
6 TeV

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

HL-LHC YR 1812.07831

Very Large Number of Searches

(in large variety of topologies and models)

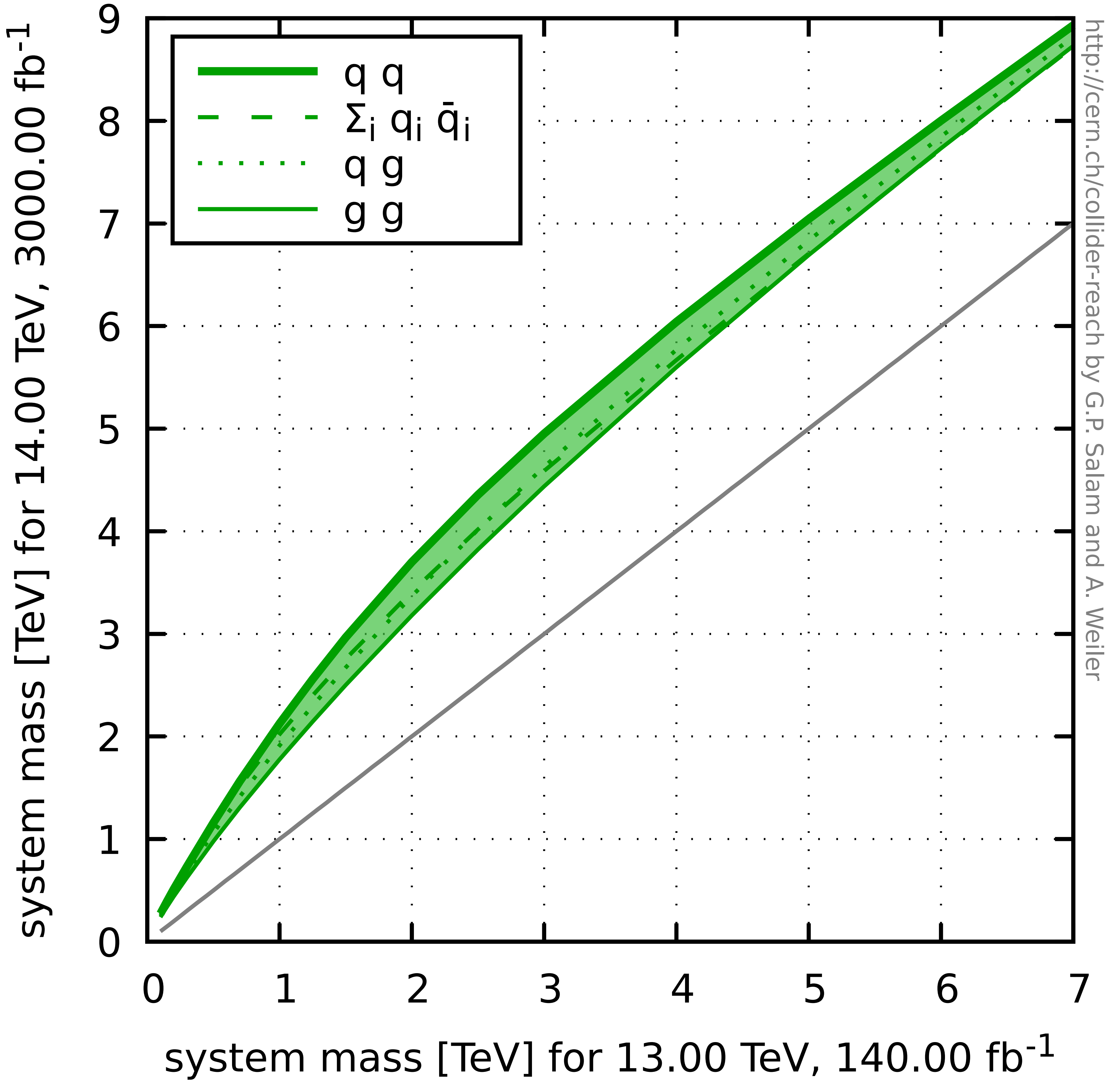


Example from CMS (similar for ATLAS) - latest plot in the backup!

HL-LHC YR
1812.07831

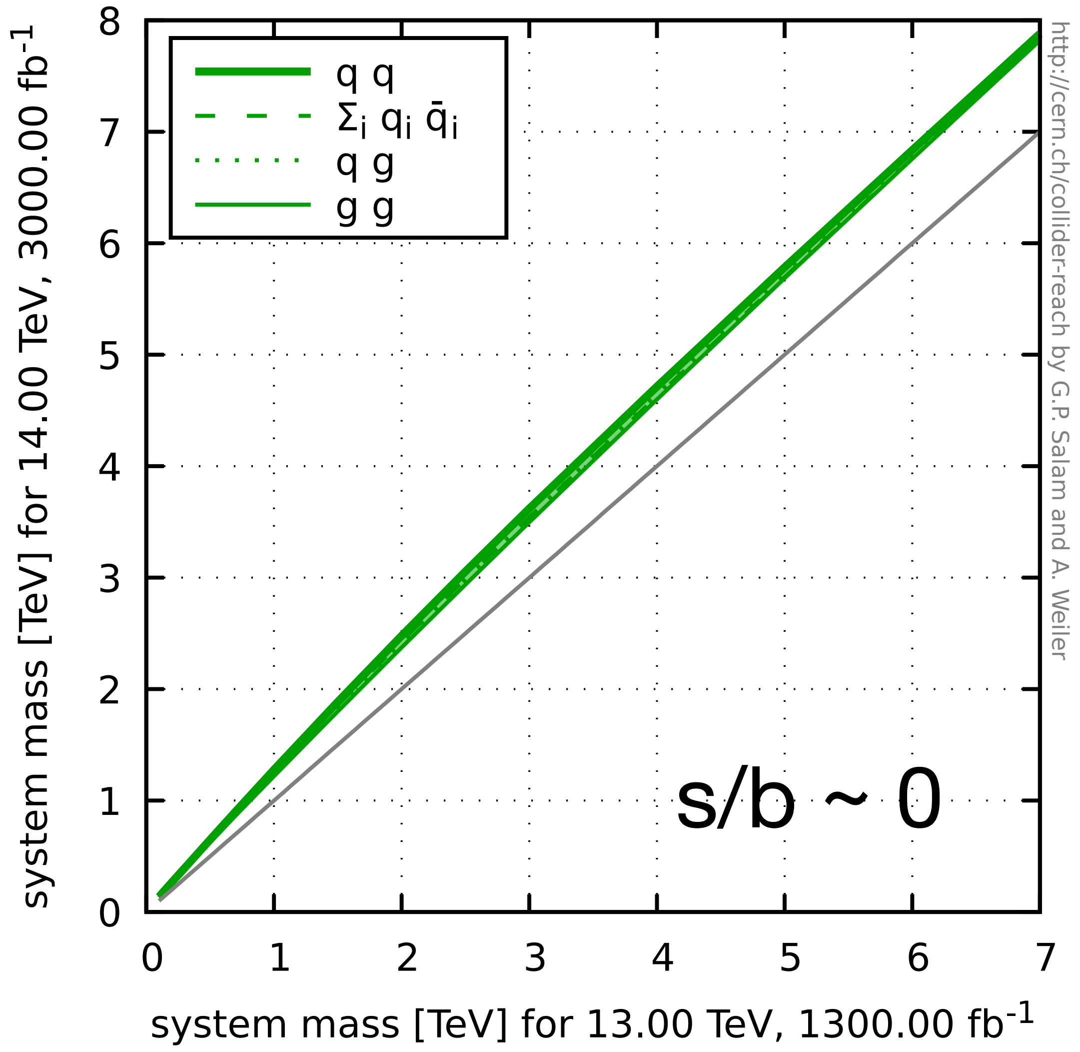
Outlook and Conclusions

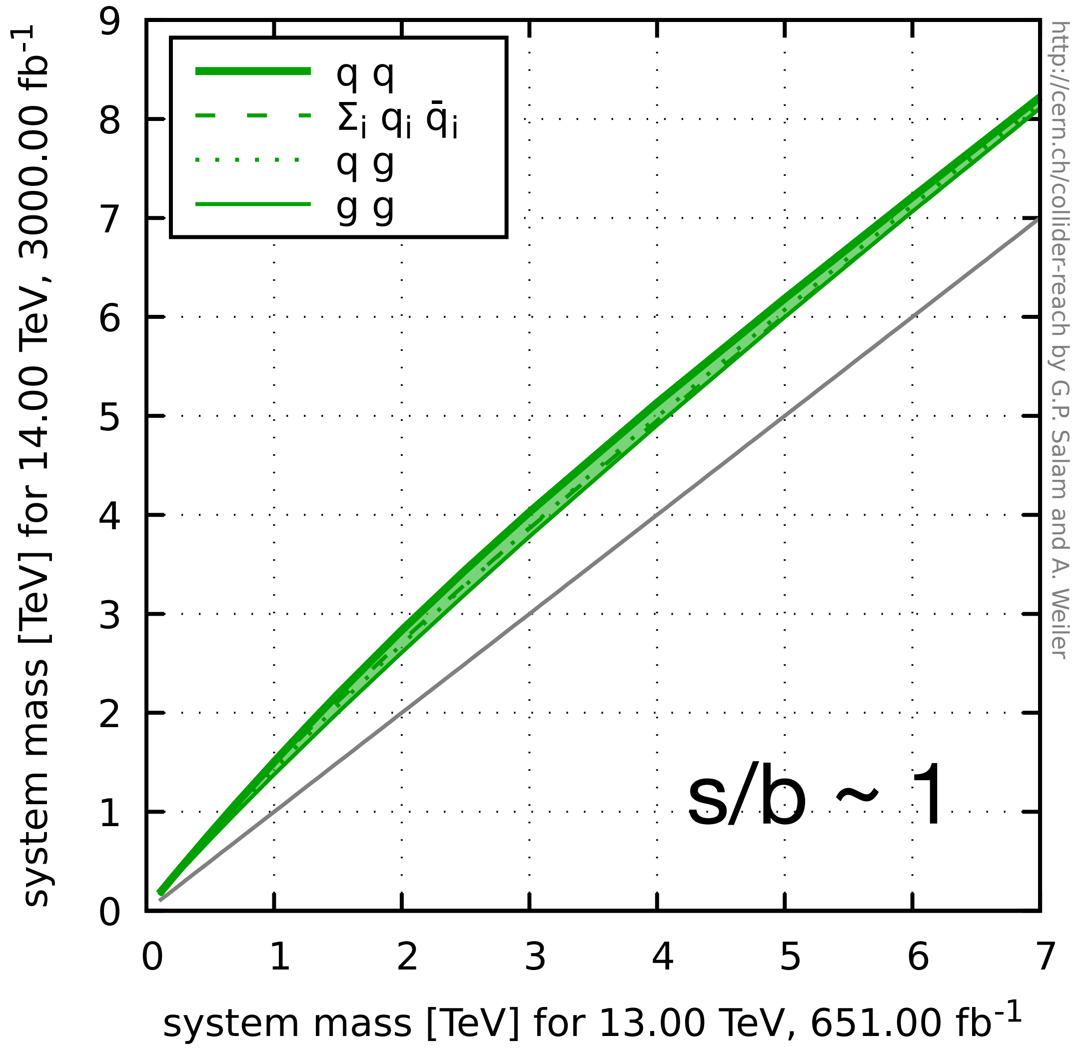
Still Room for Discoveries?



At HL-LHC still a factor of 10 (**effectively 20**) in luminosity

- Still **nearly up to 2 TeV of Exploration (exclusion)!!**
- Still **room for discoveries?** Depends on analysis purity (s/b)





Up to ~500 GeV improvement

Up to ~1 TeV improvement

Performance can be improved!

- New ideas and developments (e.g. ML techniques).
- **Improving precision and ancillary measurement!**

Conclusions

This was just a limited overview focussing on searches, the **LHC physics program is extremely rich and**

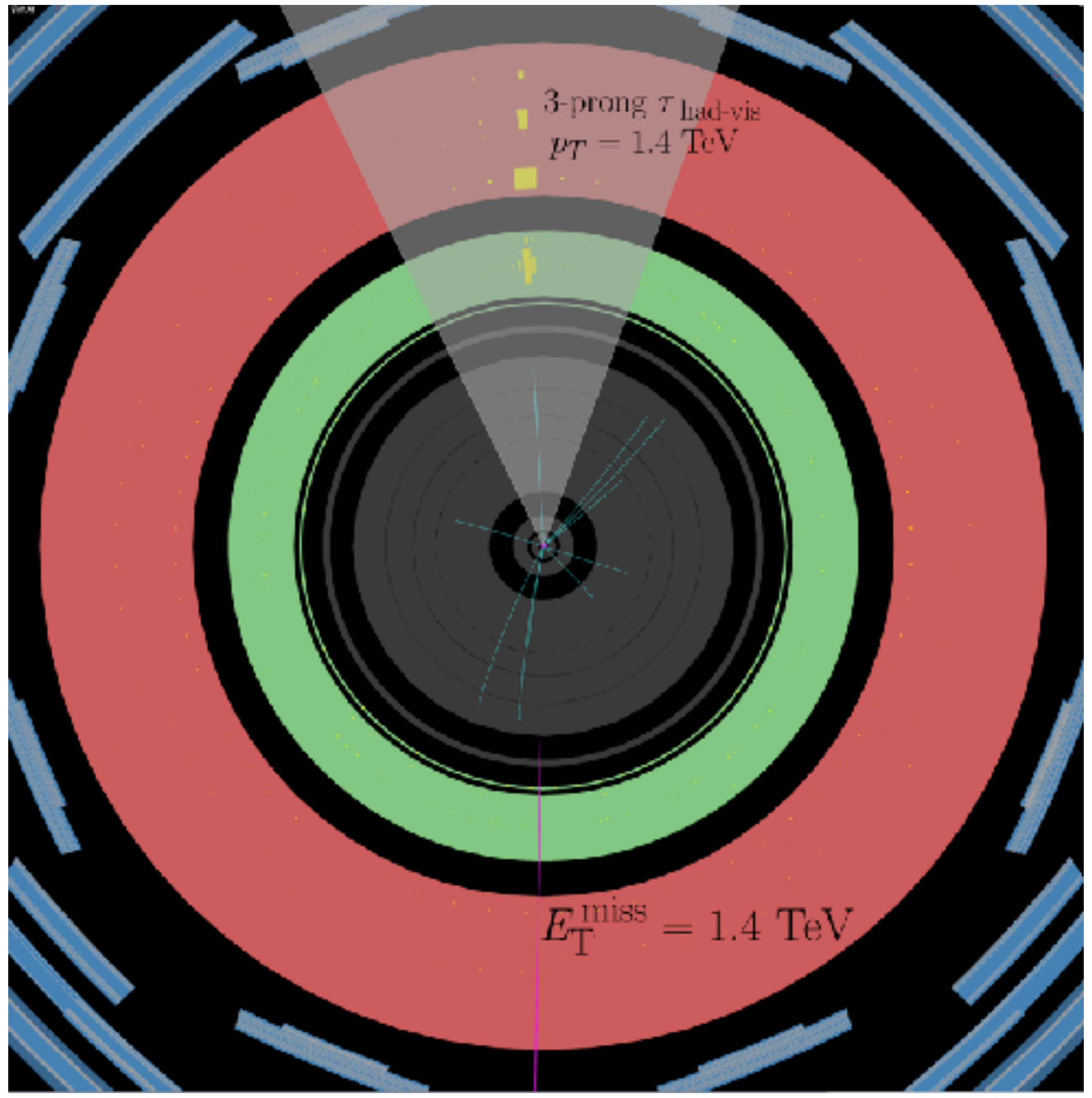
The LHC has surpassed its initial design luminosity and in all areas of its program **has delivered way more than the original expectations**!

Now is a pivotal moment for the future of High Energy Collider Physics, all invited to come to Venice in June at the open symposium to decide on the next **flagship project at CERN**!

Open Symposium on the European Strategy for Particle Physics

Backup

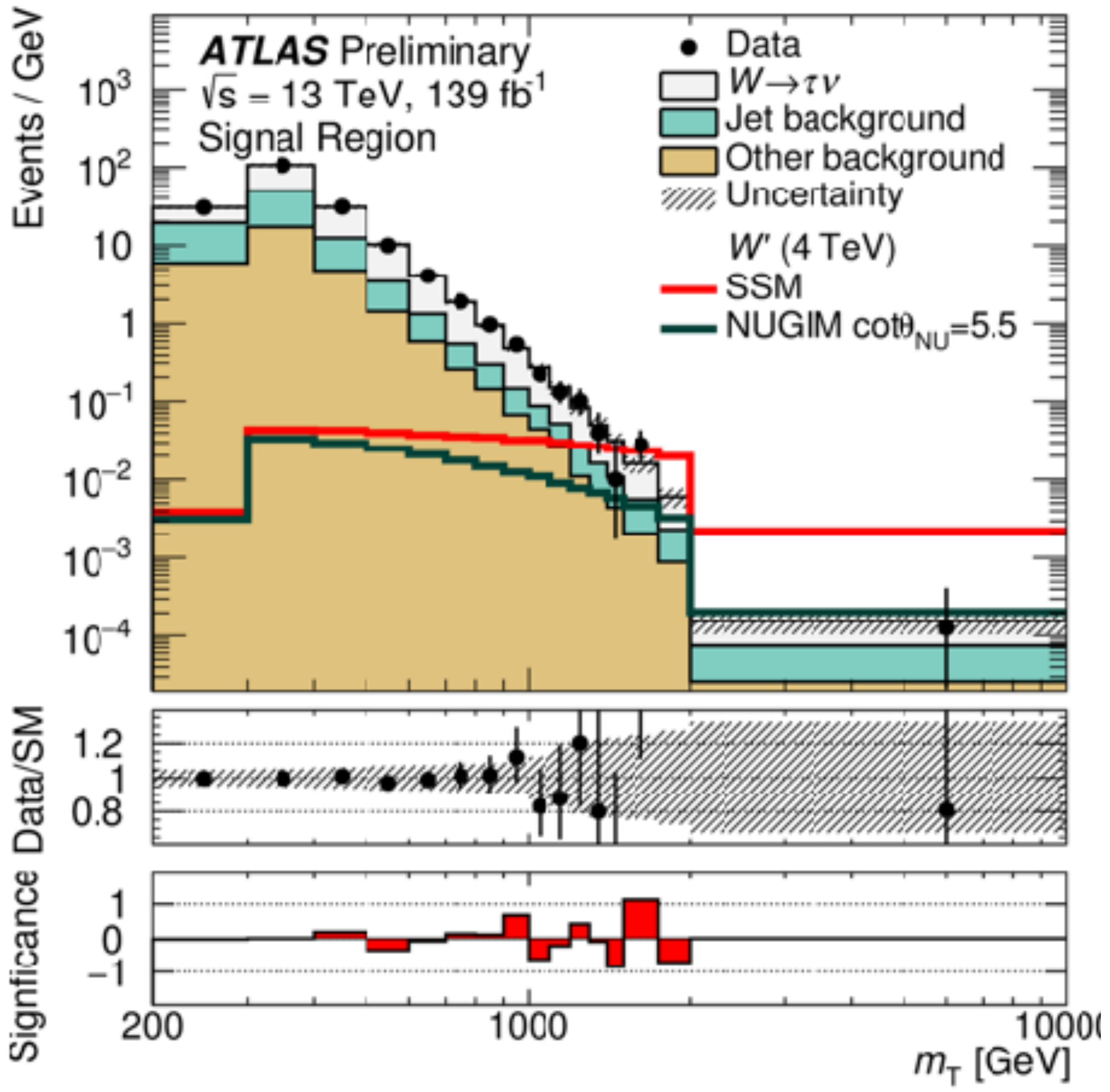
High energy phenomena with taus and b's

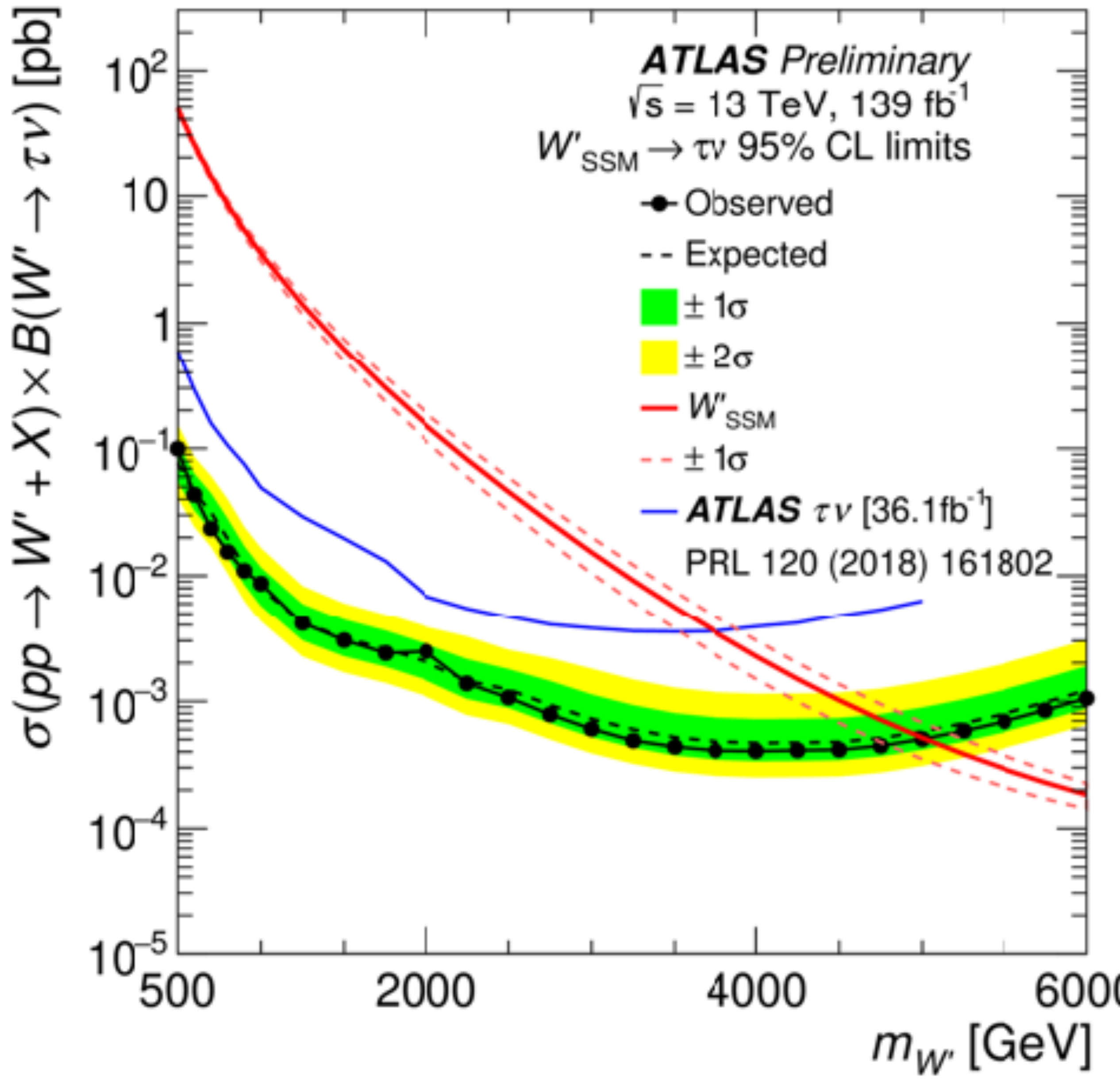


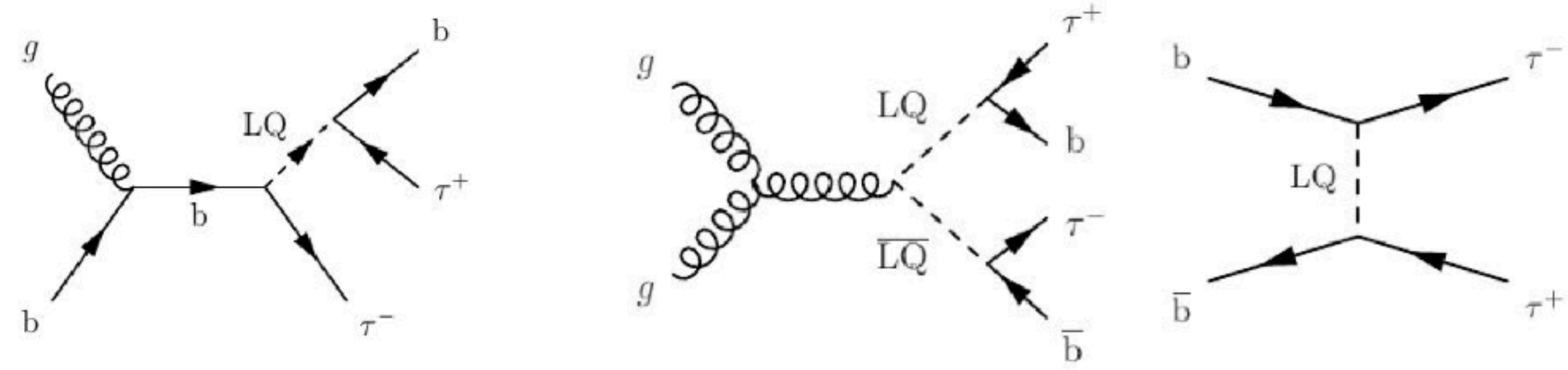
Search for $W' \rightarrow \tau\nu$

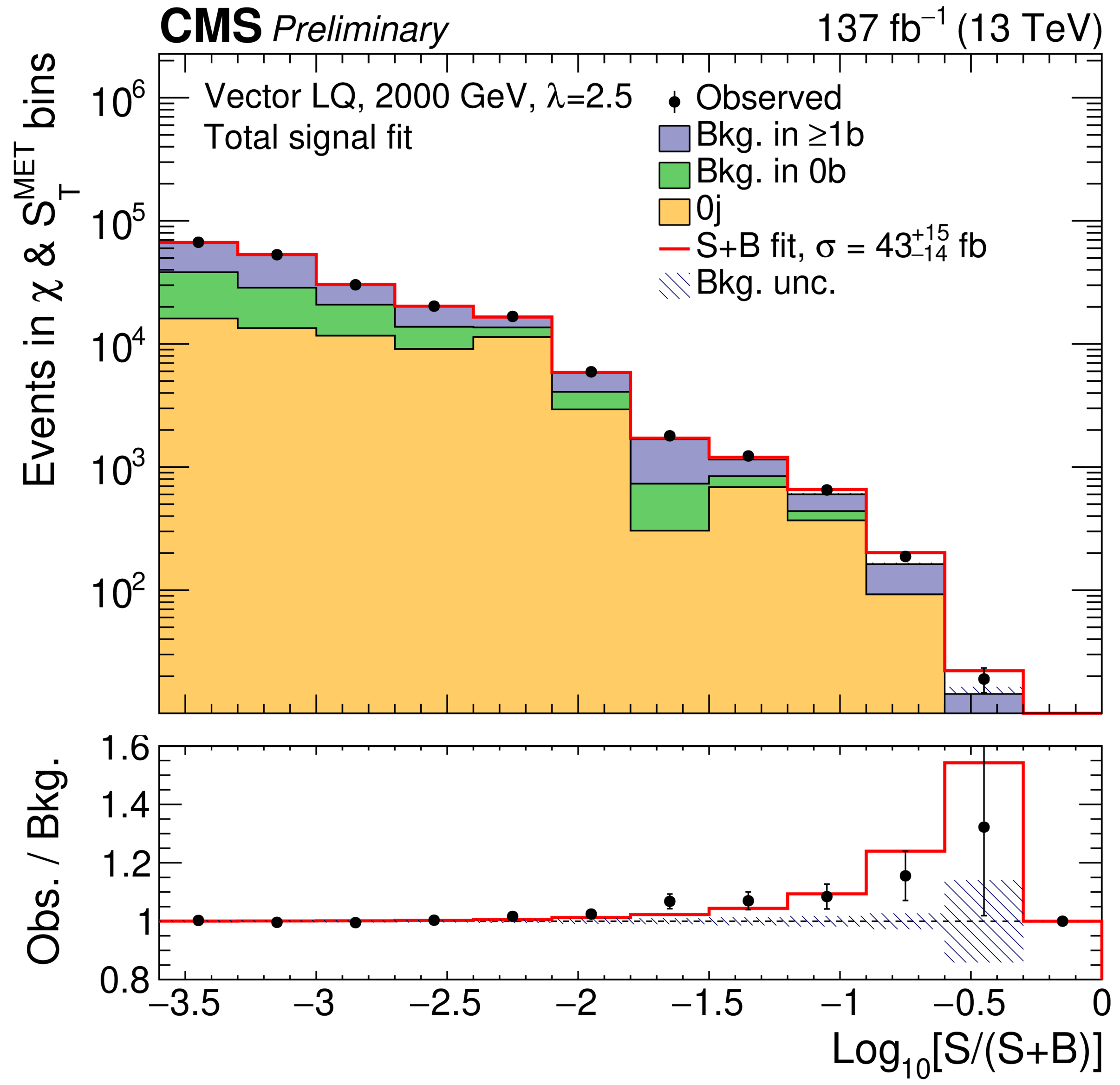
Excellent agreement between data and MC predictions!

Highest transverse mass candidate (see above event display is at **mT ~2.8 TeV**)

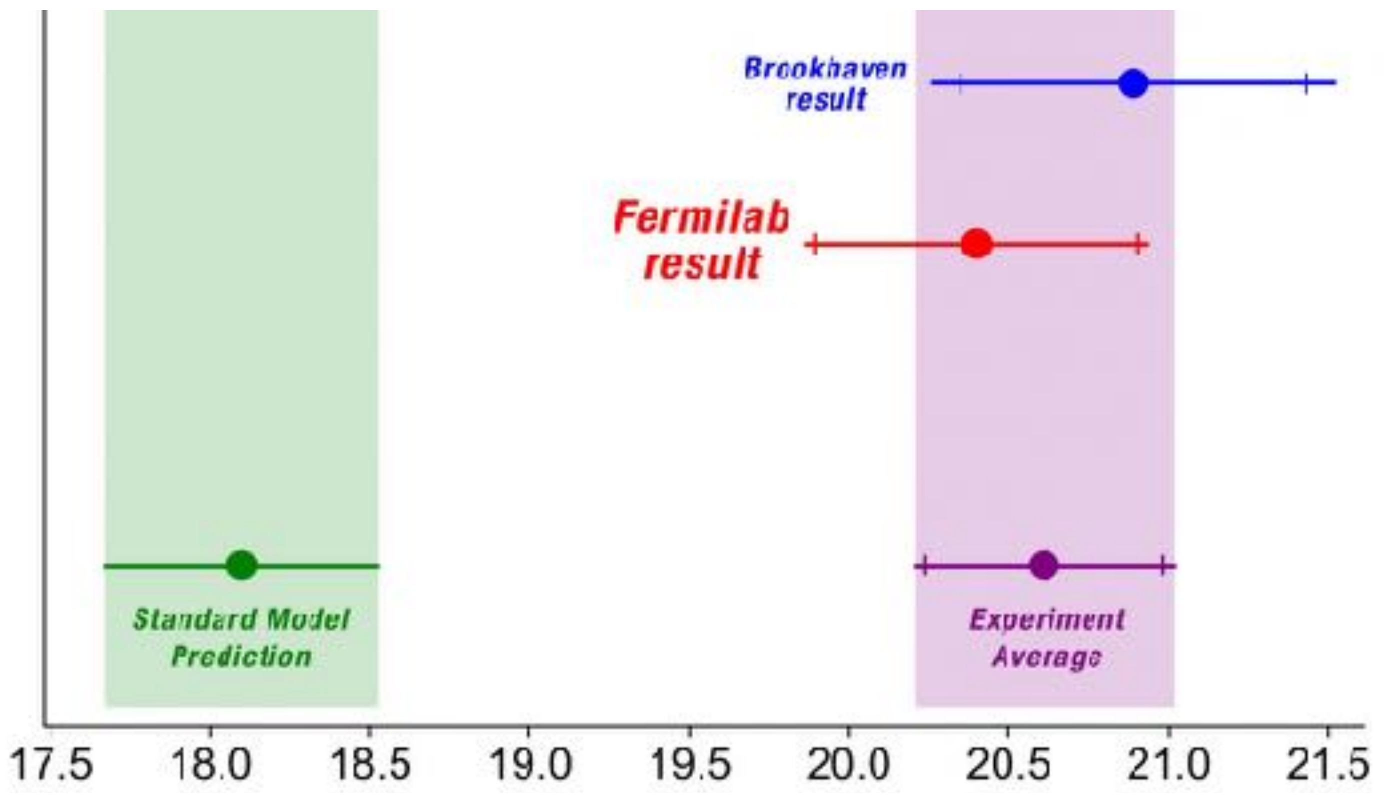




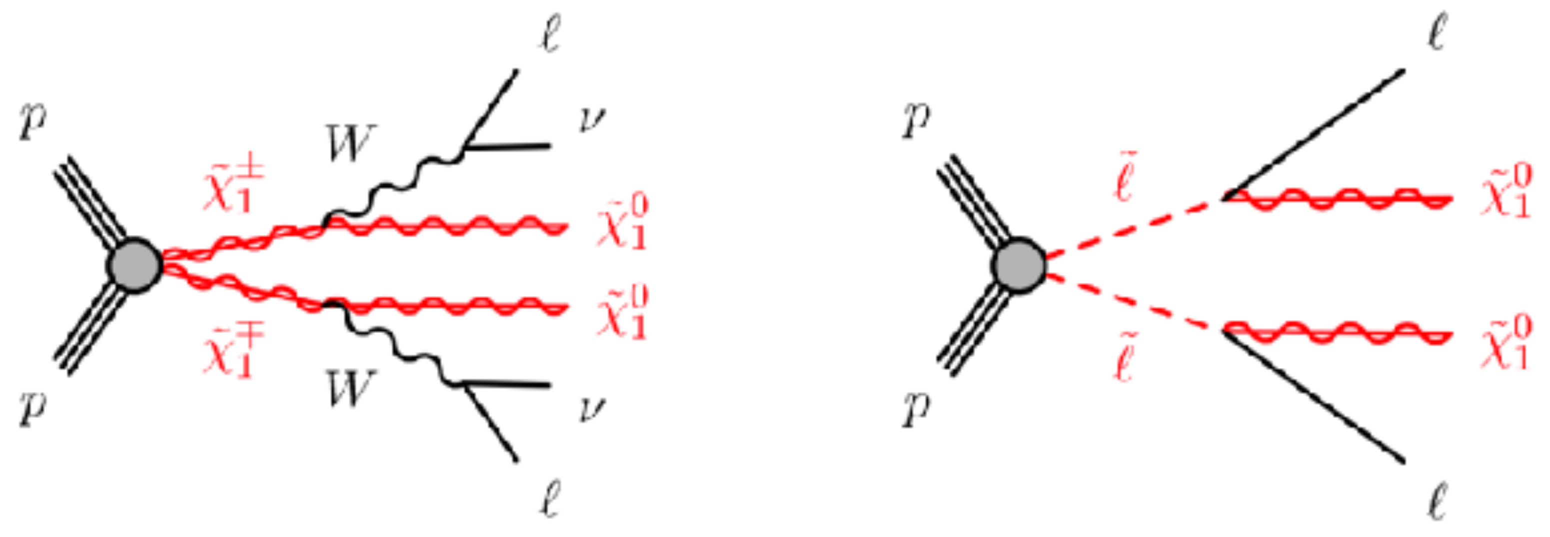




Search for third generation leptoquarks (LQ) in events with taus and bs…



Recent muon (g-2) result from Fermilab reinforces the long standing tension with SM prediction

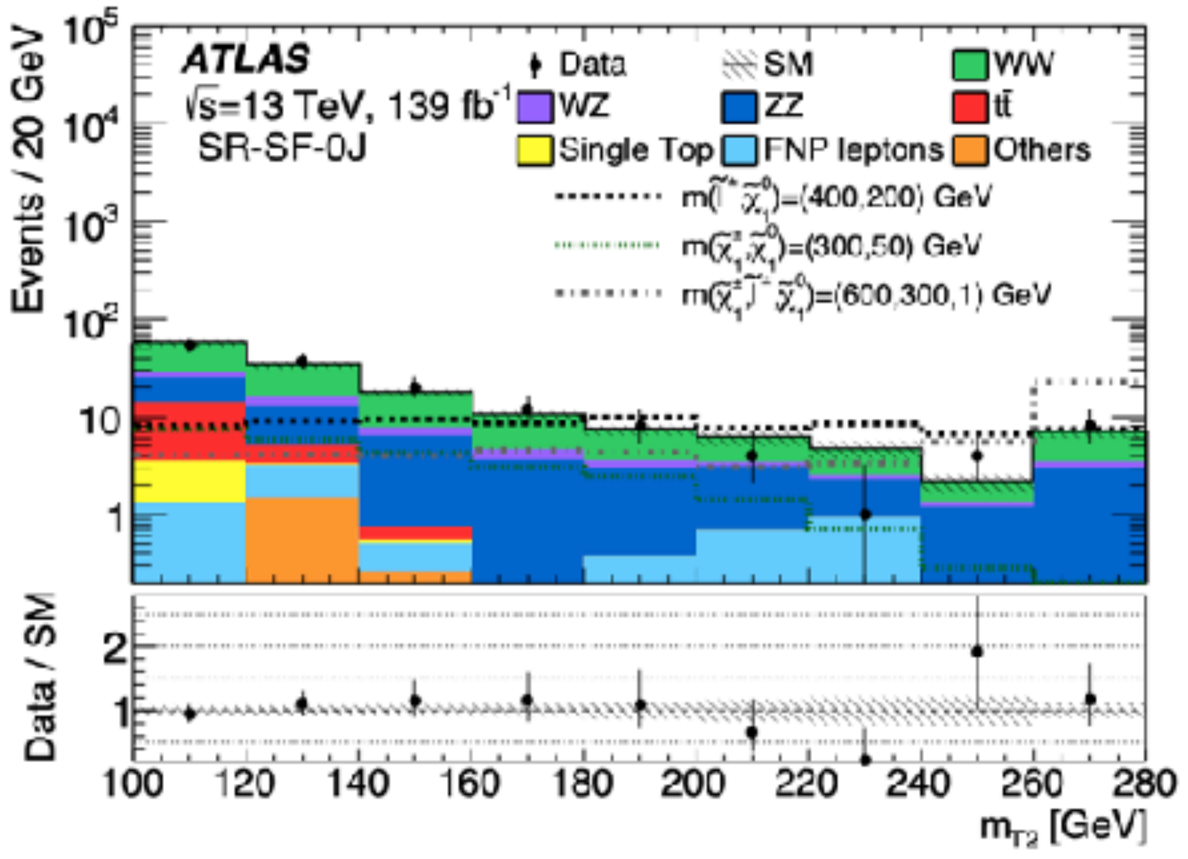


Search in scenarios with two leptons and MET

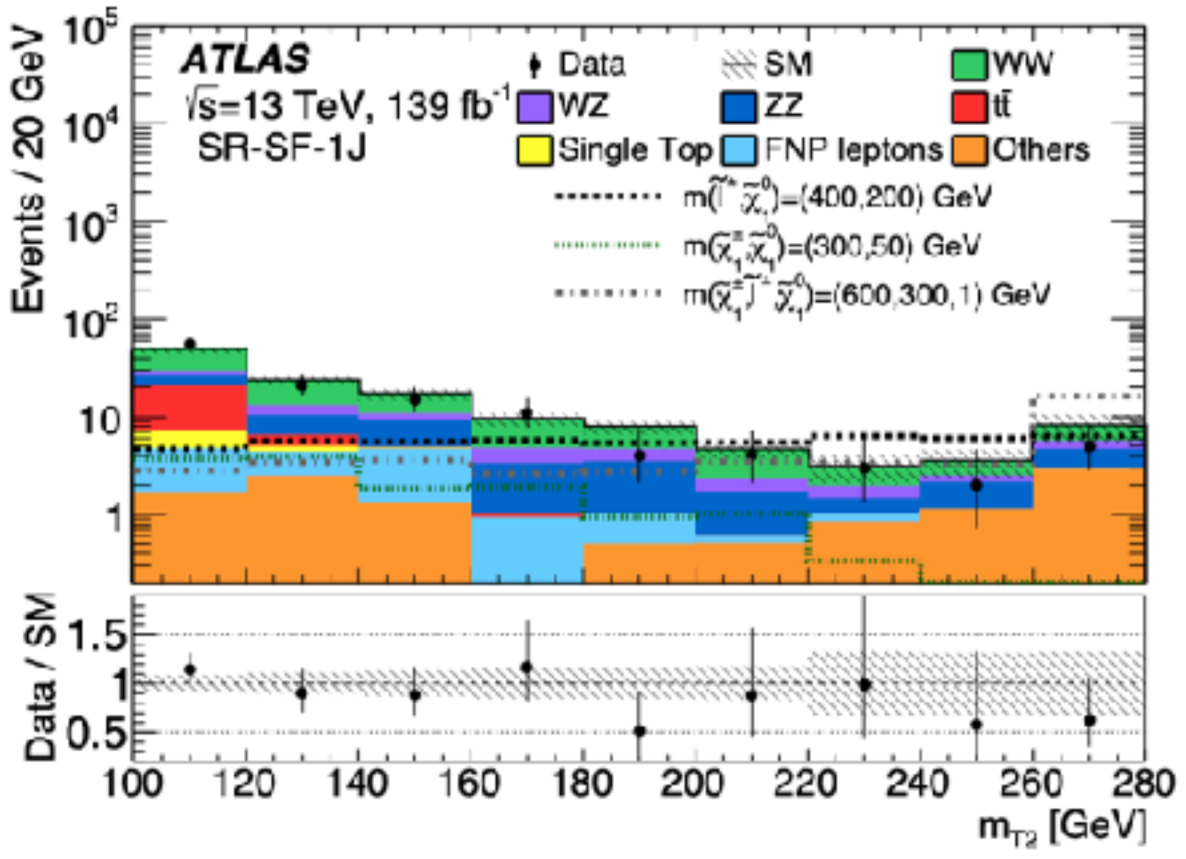
Muon (g-2) anomaly motivates searches for **smuons**

Using the s-transverse mass (estimated varying hypotheses of individual MET components)

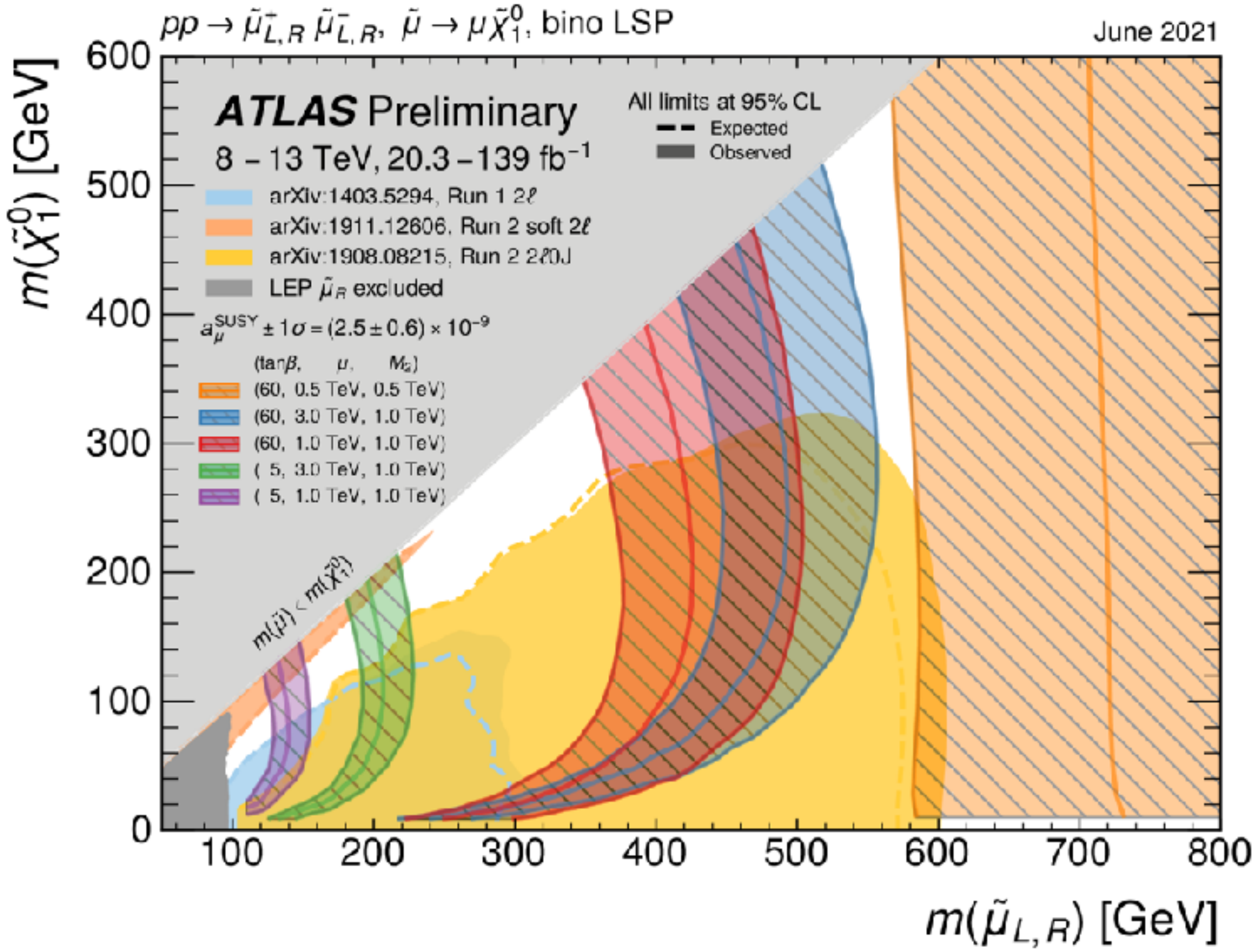
$$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{p}_T^{miss}} \{\max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2})\,]\}$$



m_{T2} distribution in SR-SF-0J



m_{T2} distribution in SR-SF-1J



Searching with Precision and High energy Phenomena

Measurement of SM processes in the high energy domain

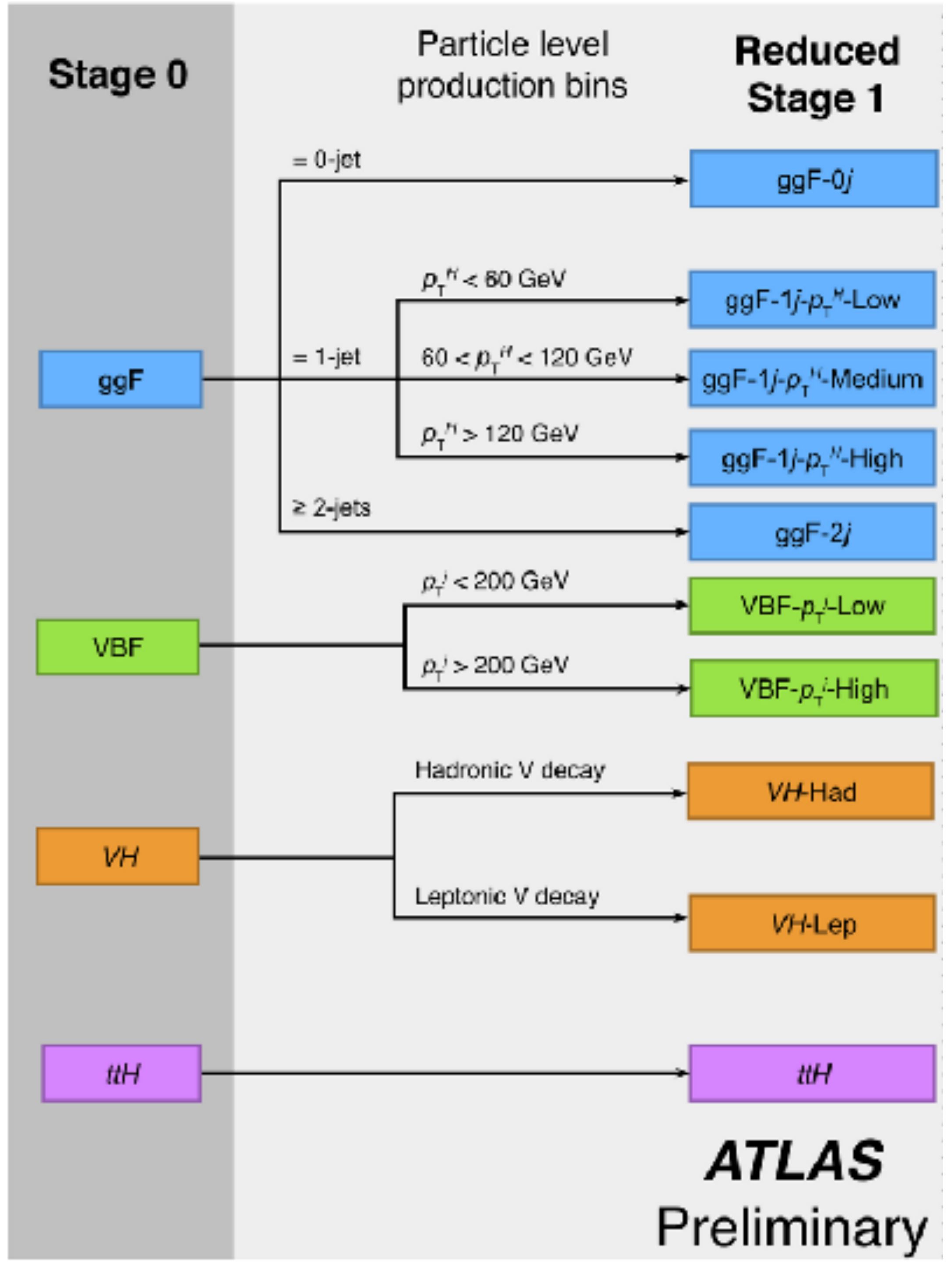
Effective field theory and measurements of non resonant processes at higher energy

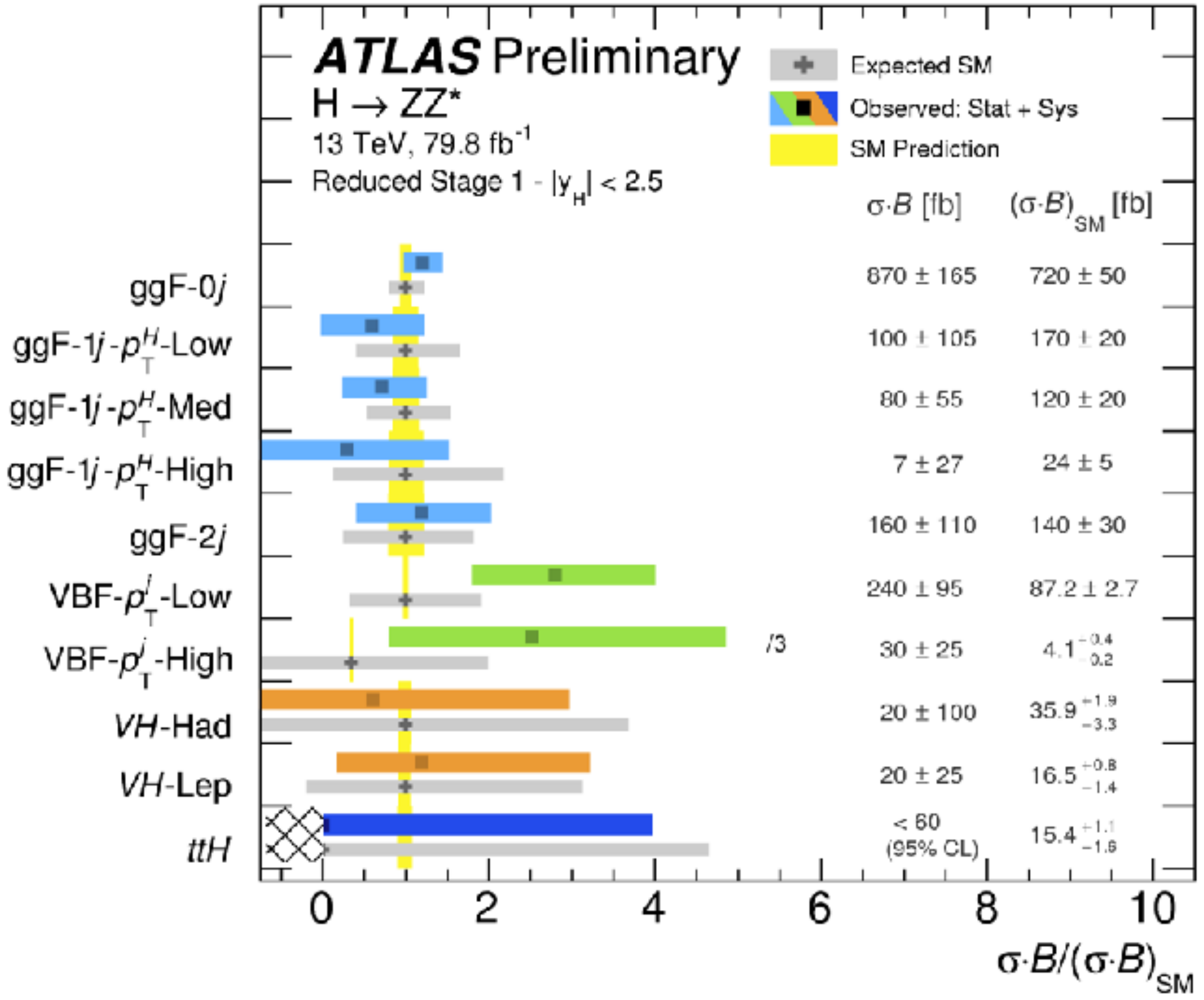
Higgs couplings at low energies

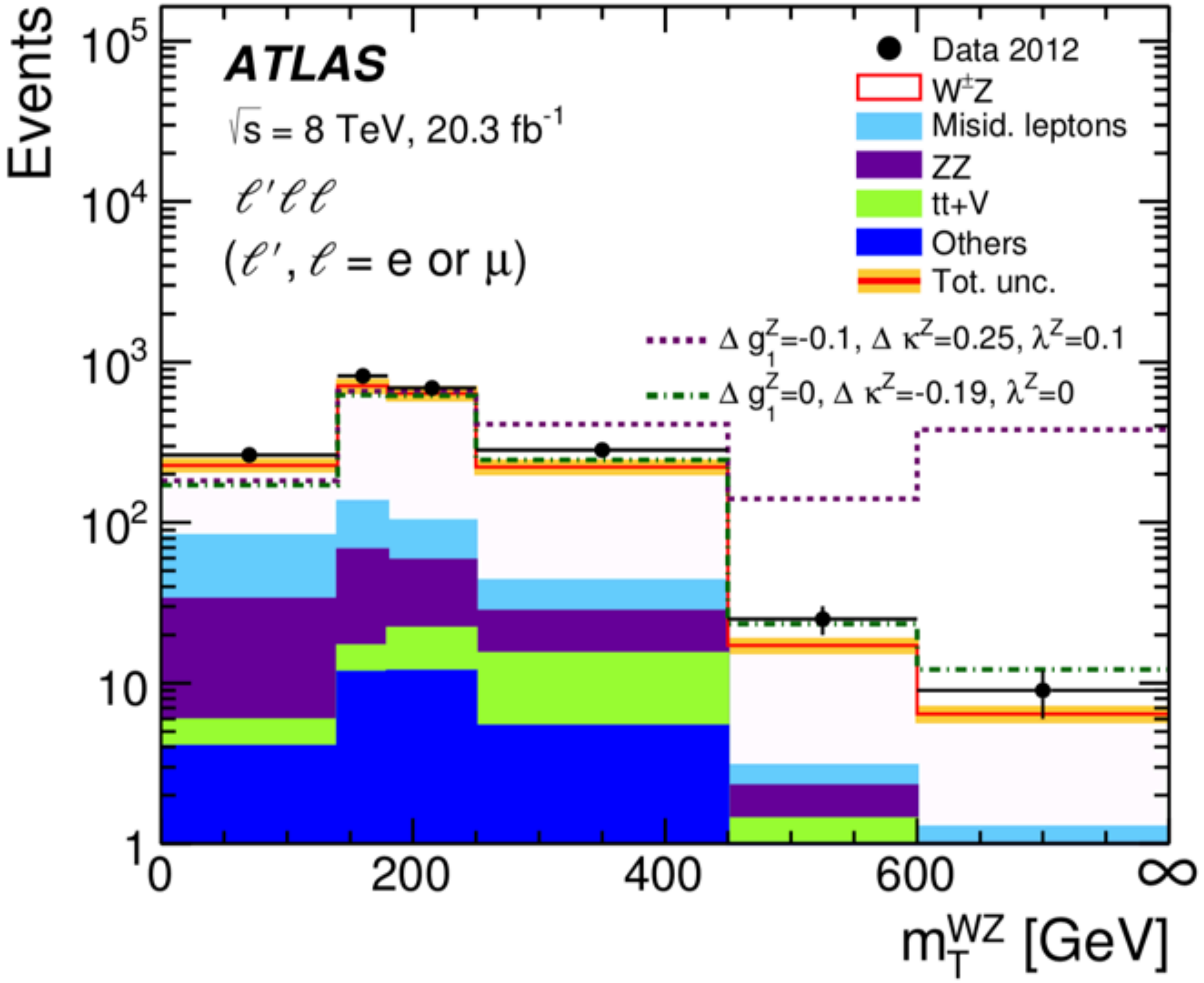
$$\frac{\delta c}{c} \sim \frac{g_*^2}{g_{SM}^2} \frac{m_h^2}{\Lambda^2}$$

Higher energy phenomena
(e.g. VV scattering)

$$\frac{\delta \mathcal{A}}{\mathcal{A}} \sim \frac{g_*^2}{g_{SM}^2} \frac{E^2}{\Lambda^2}$$





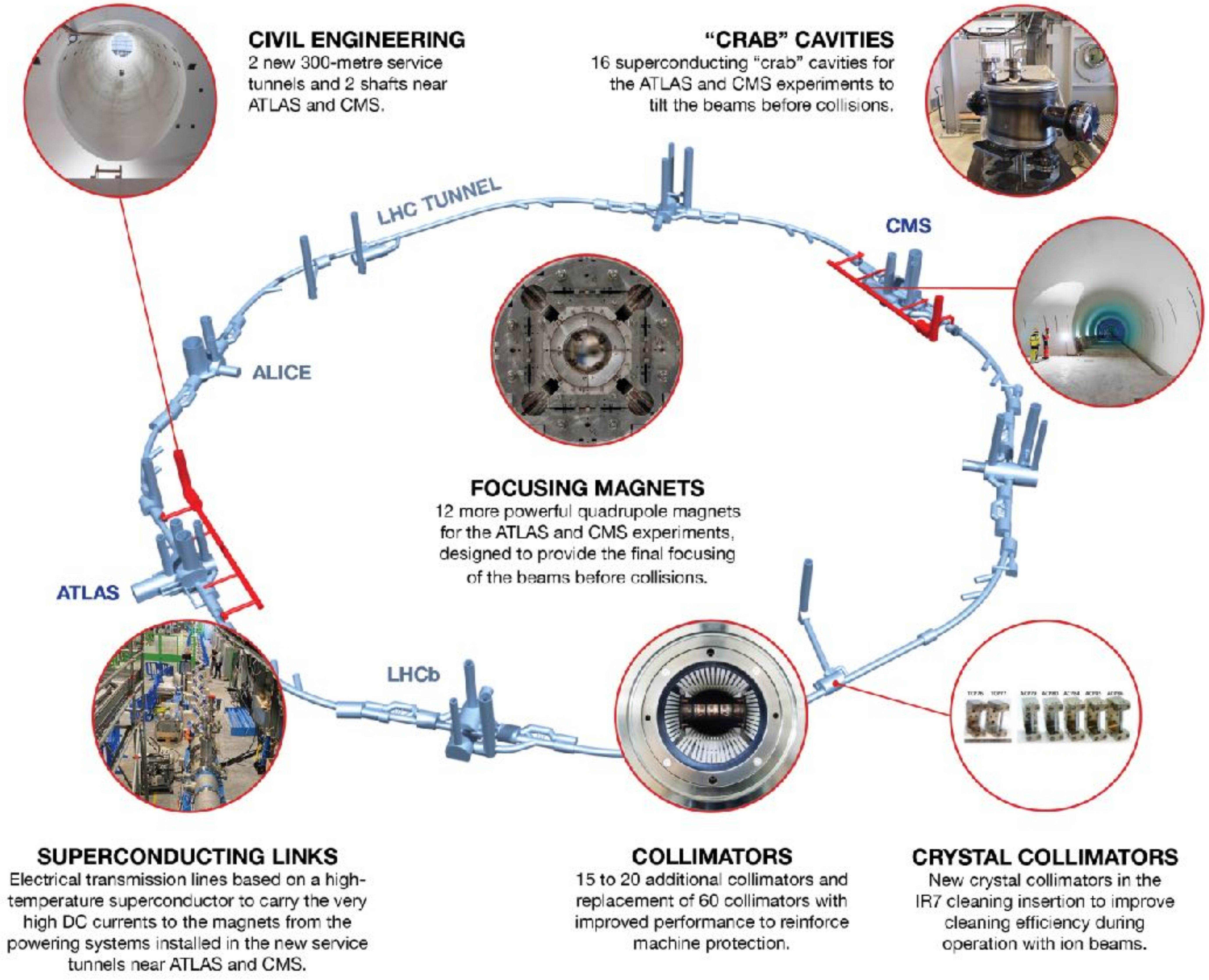


Measurement of Higgs production cross sections in high transverse momentum regime

Measurement of di-boson in the high mass regime

LHC Machine Towards Major LS3 Upgrades

NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC CERN site



Front page of the CERN Courier says it all!

LS3 installation fully on track!

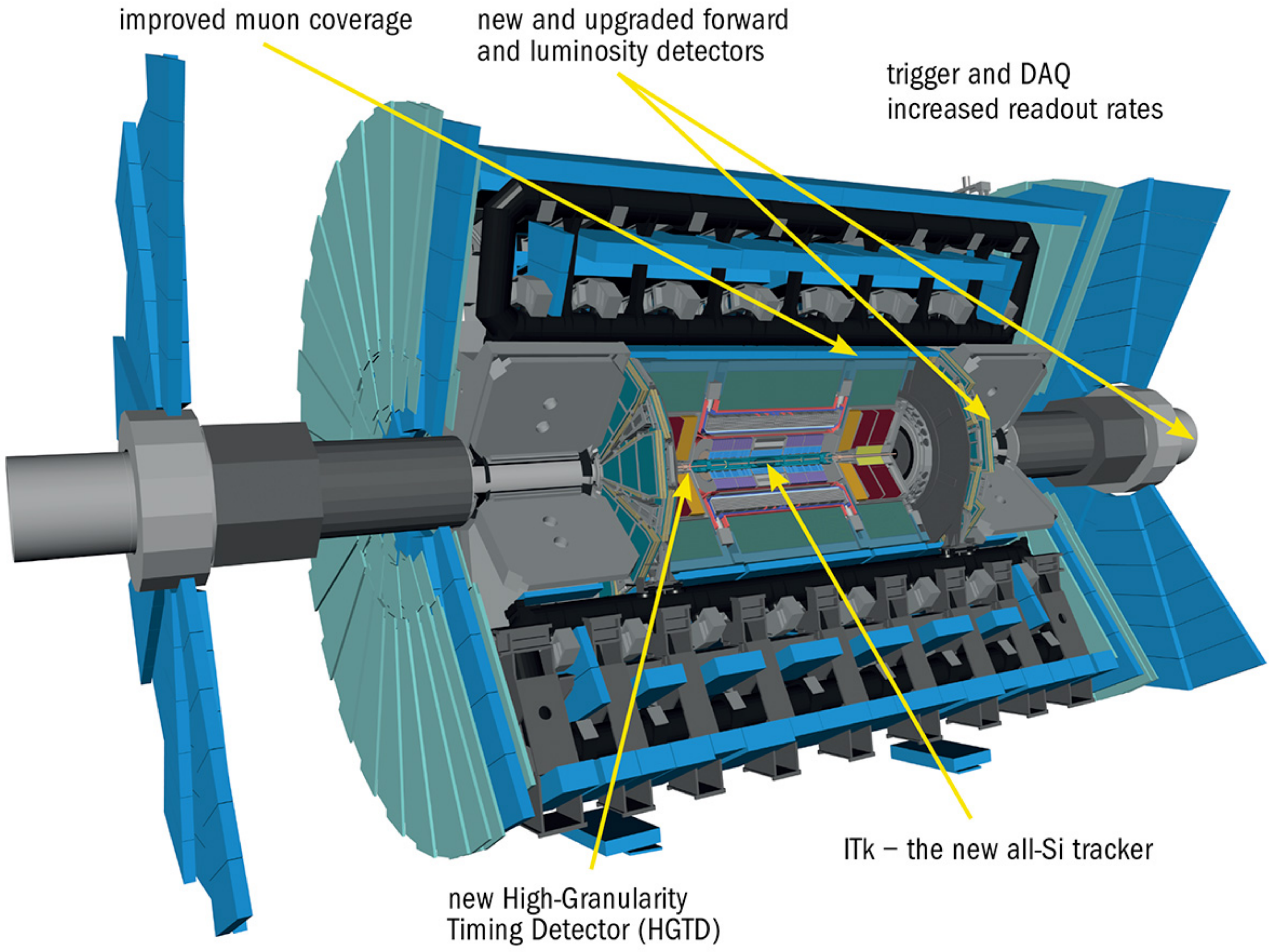
Nb3Sn series magnets manufactured at Fermilab arrived at CERN! See CERN News.

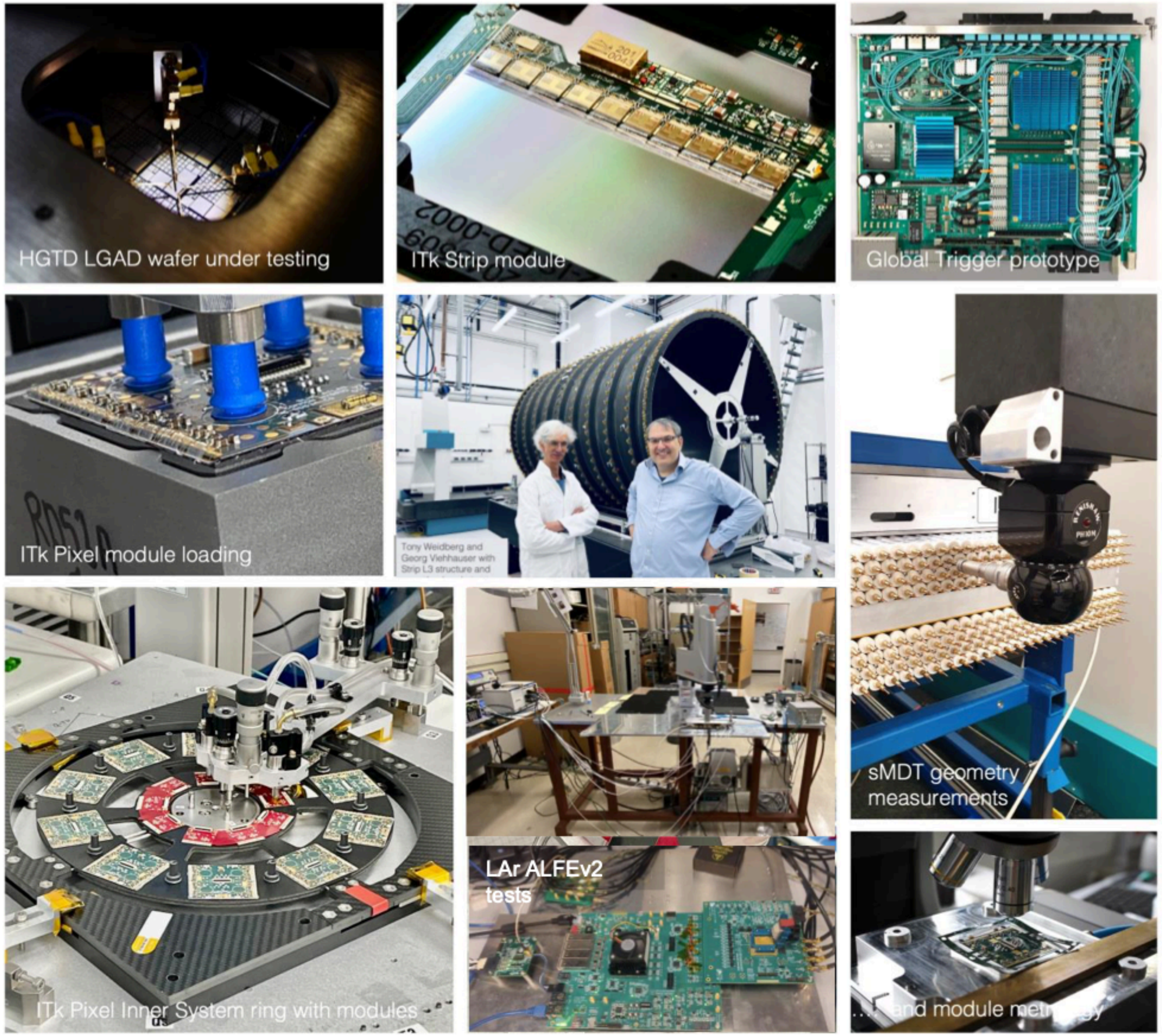
ATLAS Towards Major LS3 Upgrades

A new ATLAS for the high-luminosity era

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

Feature link





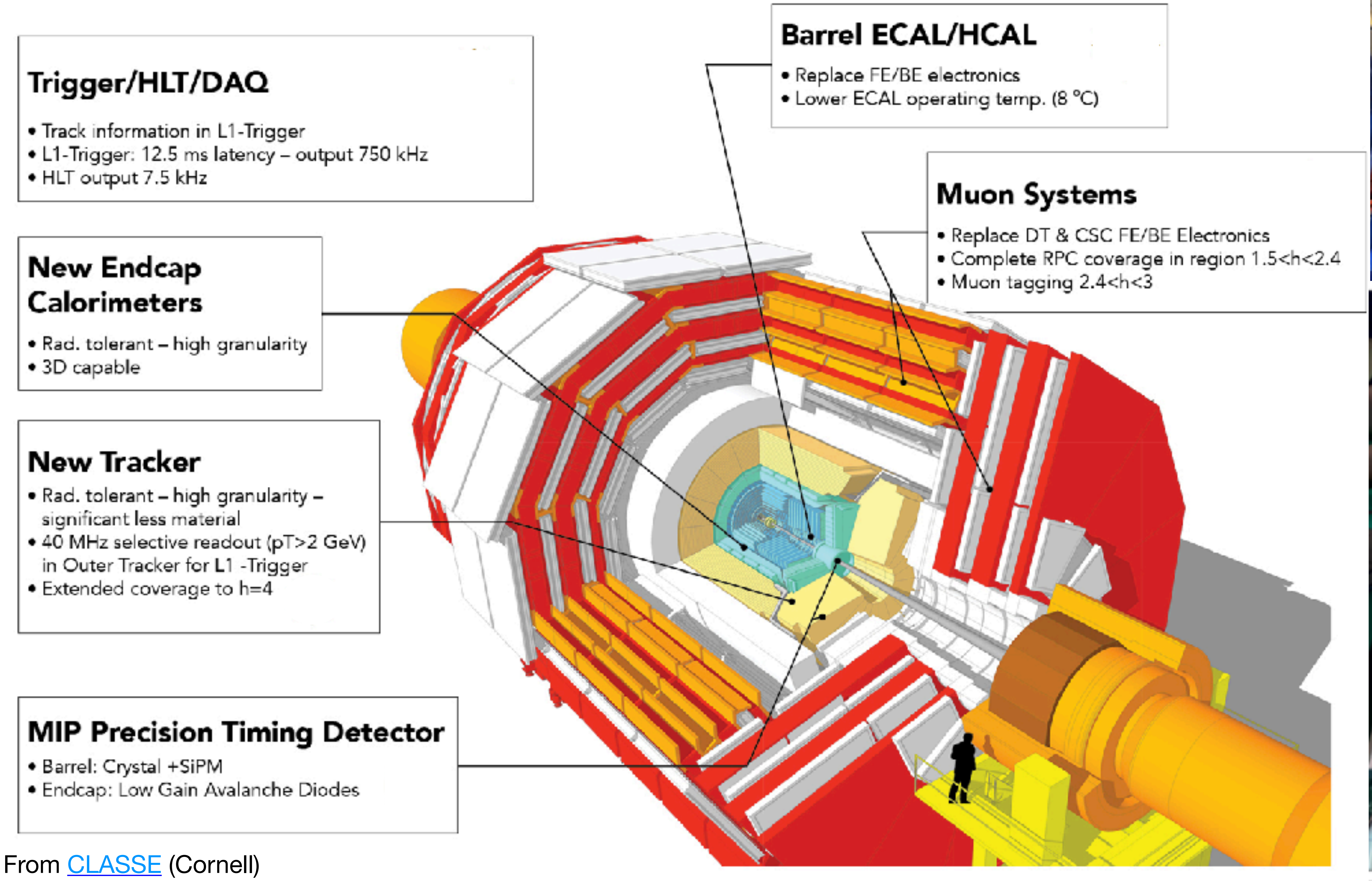
ATLAS Towards Major LS3 Upgrades

ACCELERATORS | FEATURE

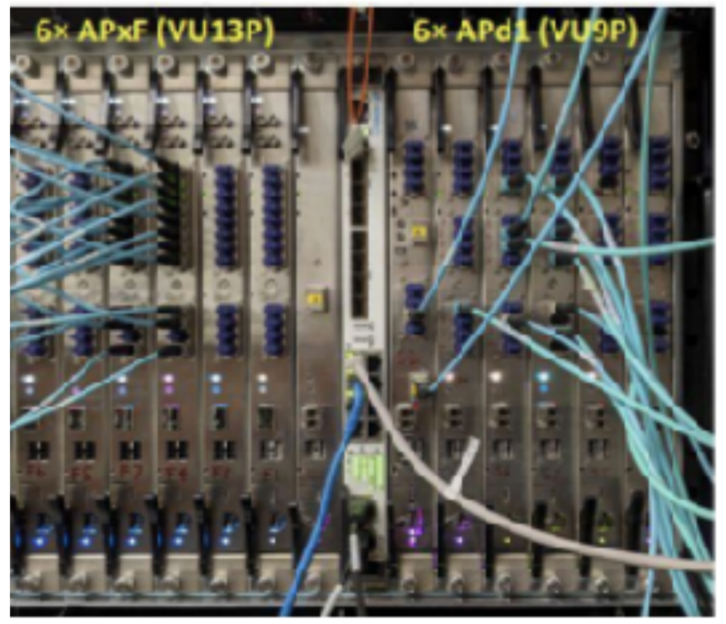
CMS prepares for Phase II

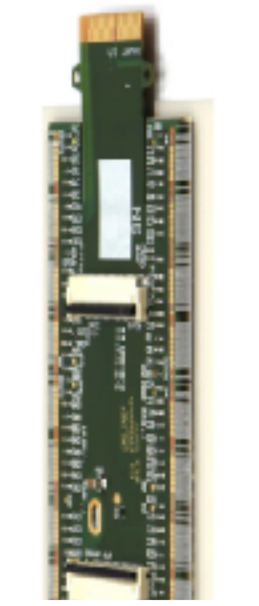
9 January 2023

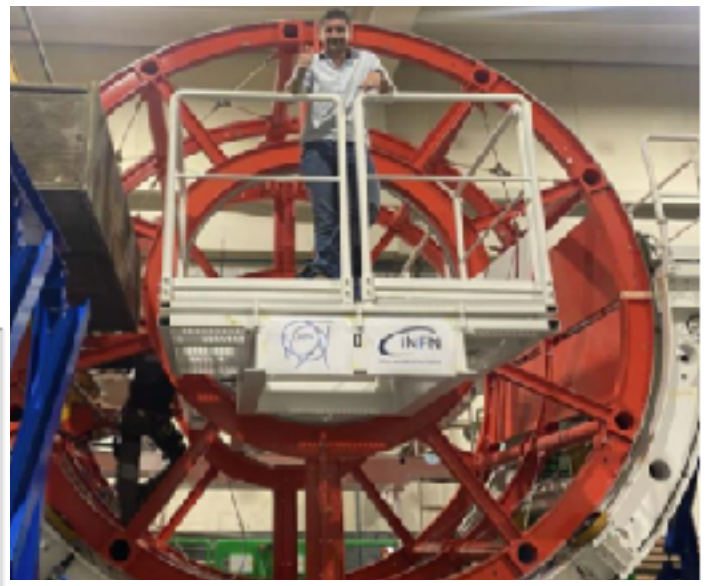
CERN Courier article link

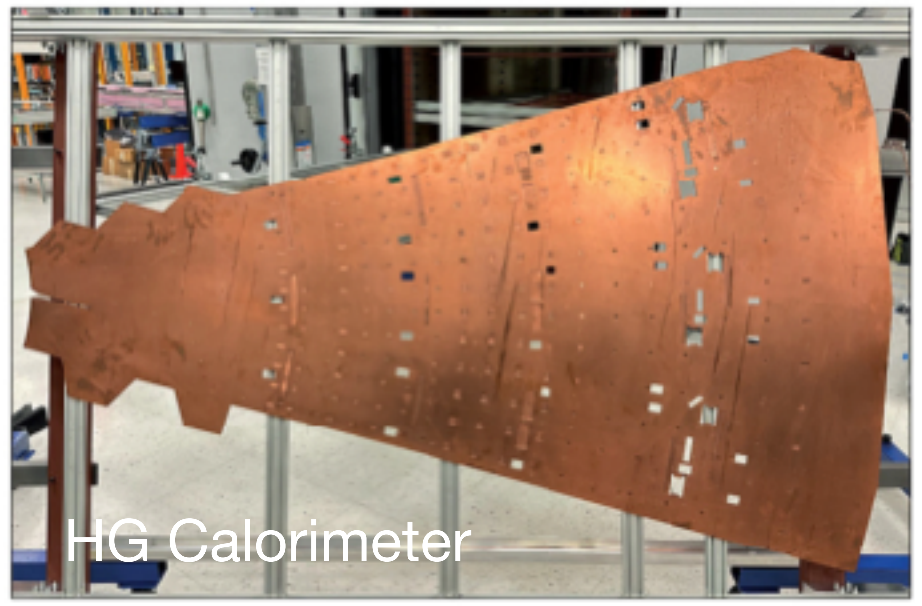


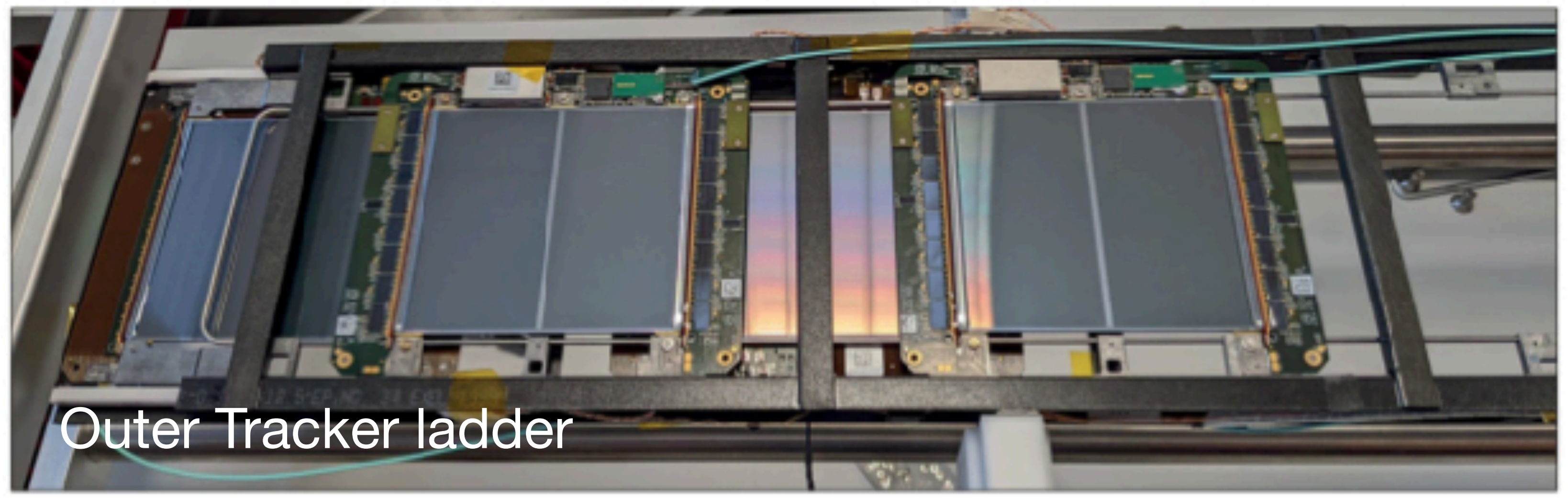
From CLASSE (Cornell)

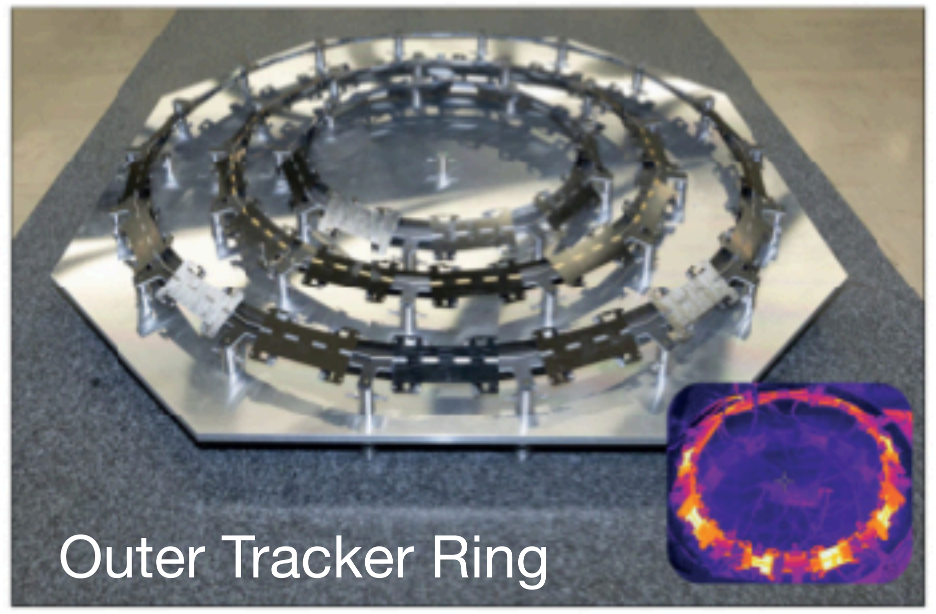








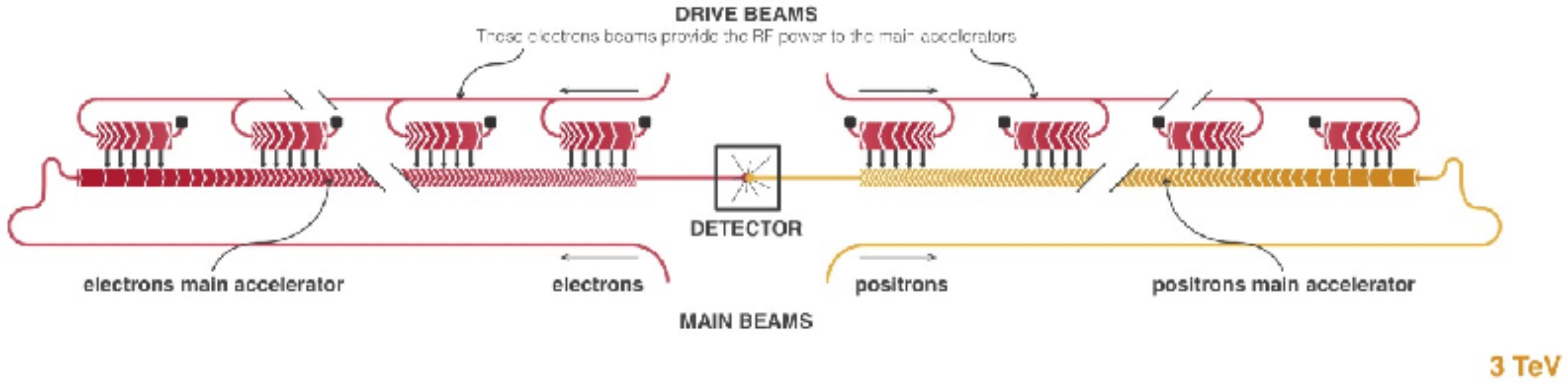




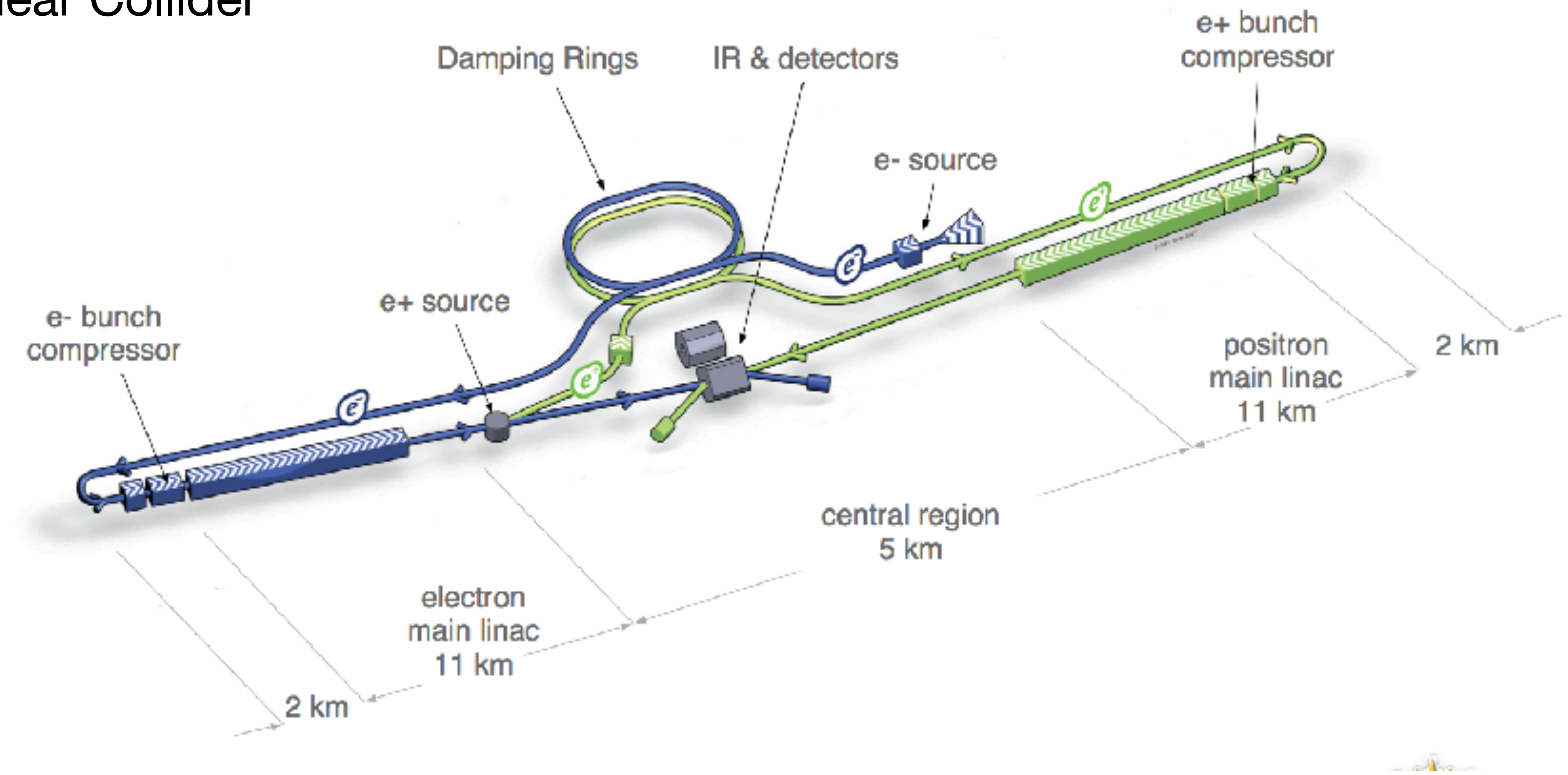
e^+e^- Collider Projects - Linear

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}

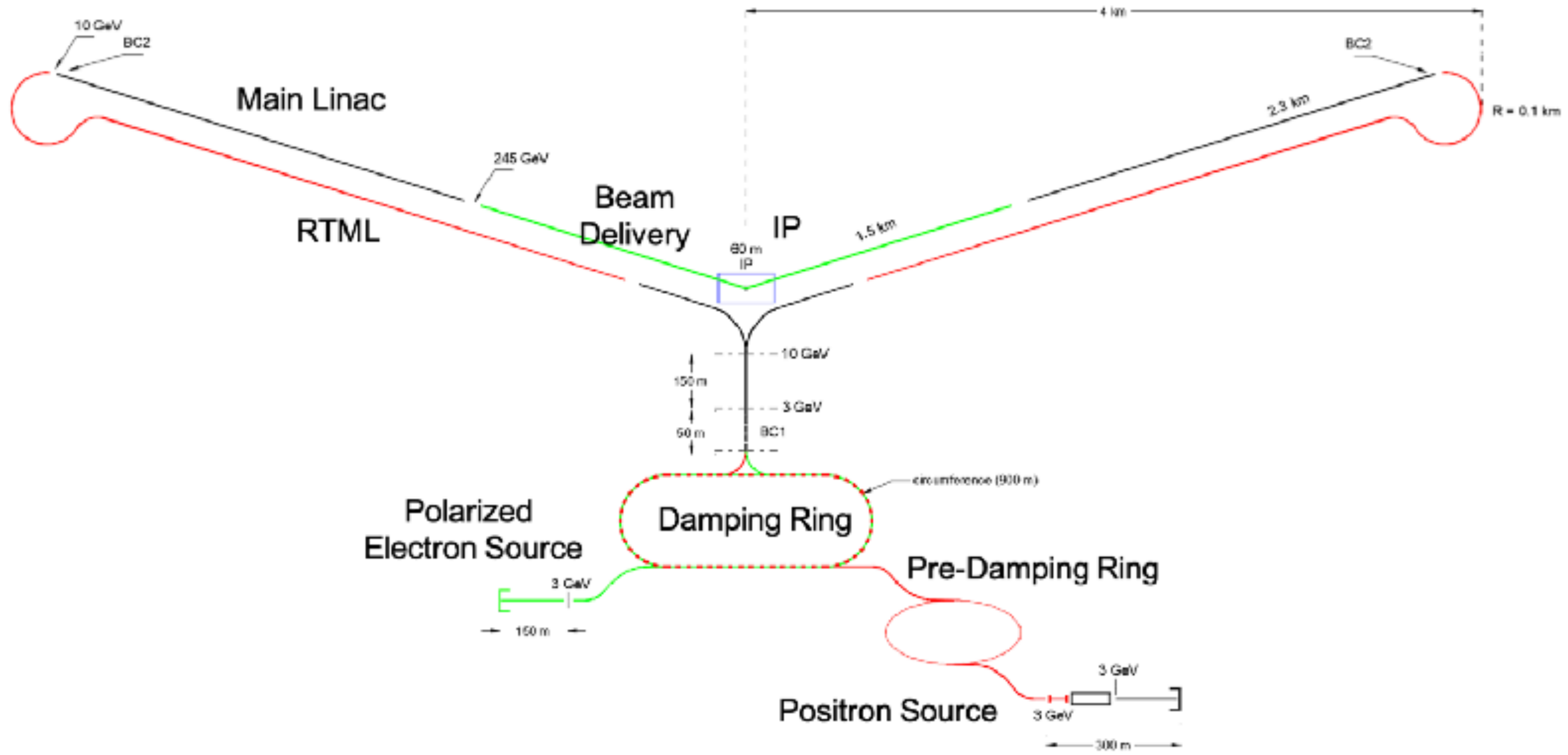
CLIC Compact Linear Collider



ILC International Linear Collider



C^3
Cool Copper Collider



e^+e^- Collider Projects - Circular

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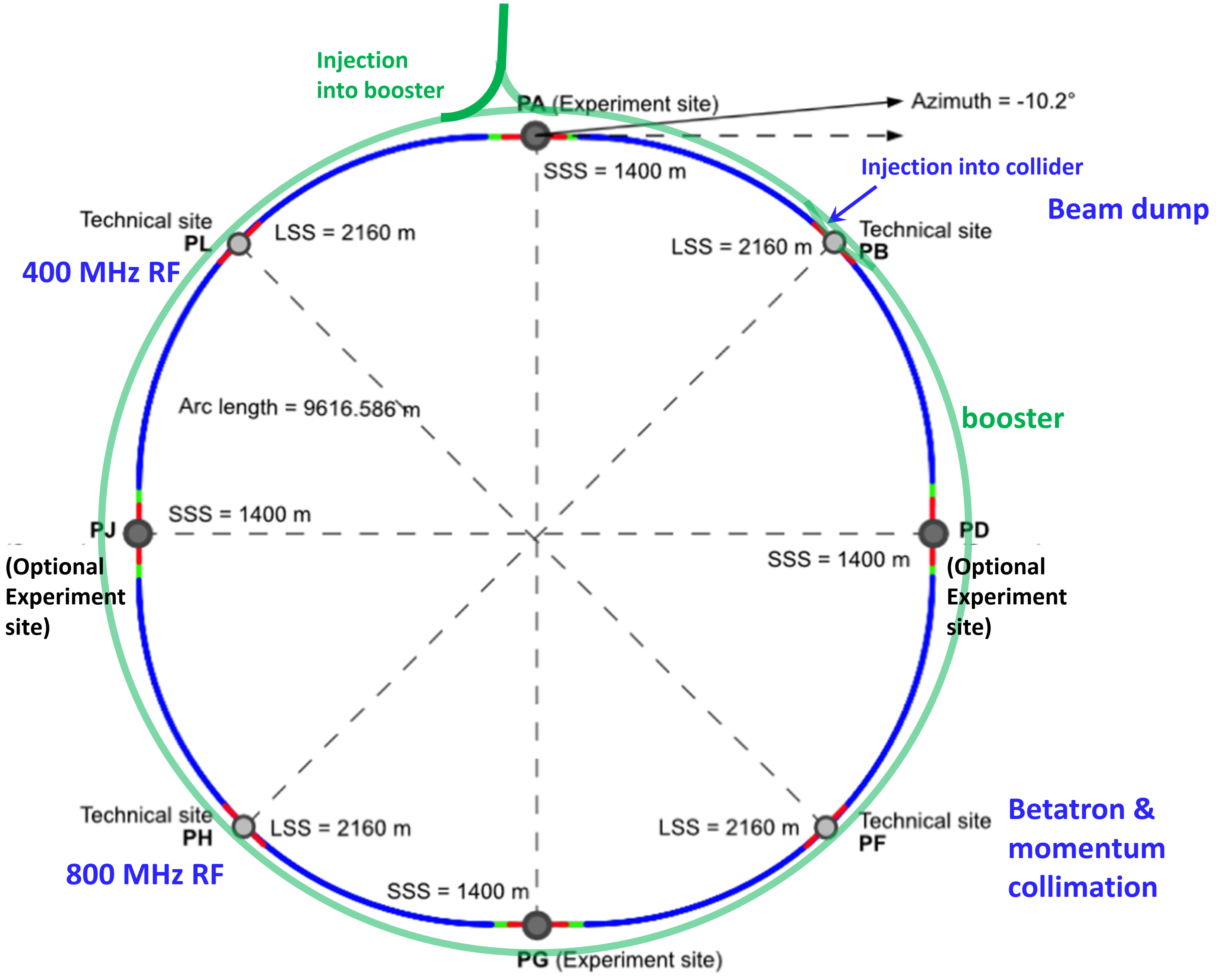
FCC-ee Future Circular Collider are CERN

~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)

e^+e^- Collider Projects - Circular

Project	ILC	CLIC	FCC-ee	CepC	C^3
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FCC-ee Future Circular Collider are CERN

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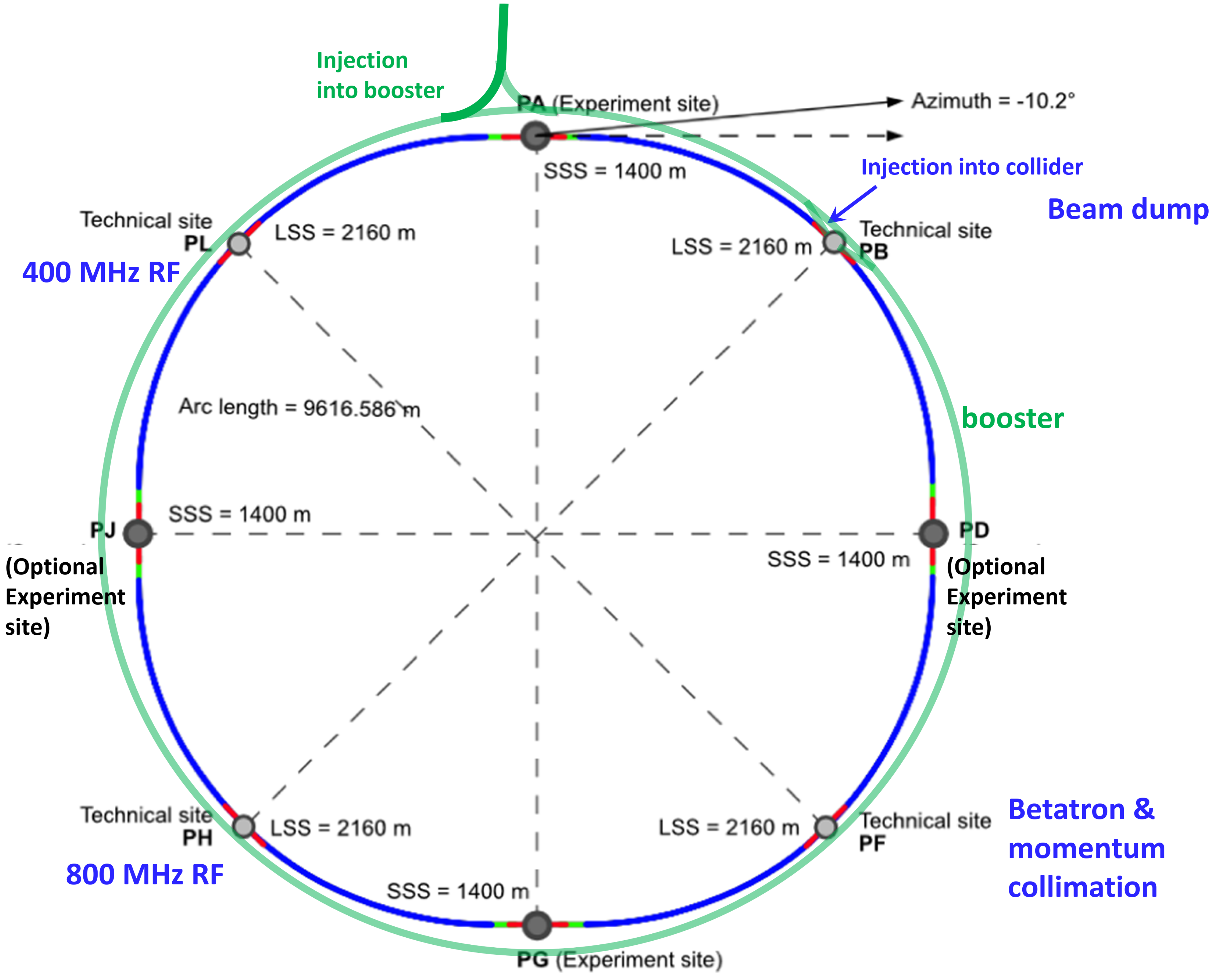


Large amount of extremely useful data in a very clean environment!

- 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

One LEP produced every 3 minutes!!

CepC similar design (in China)

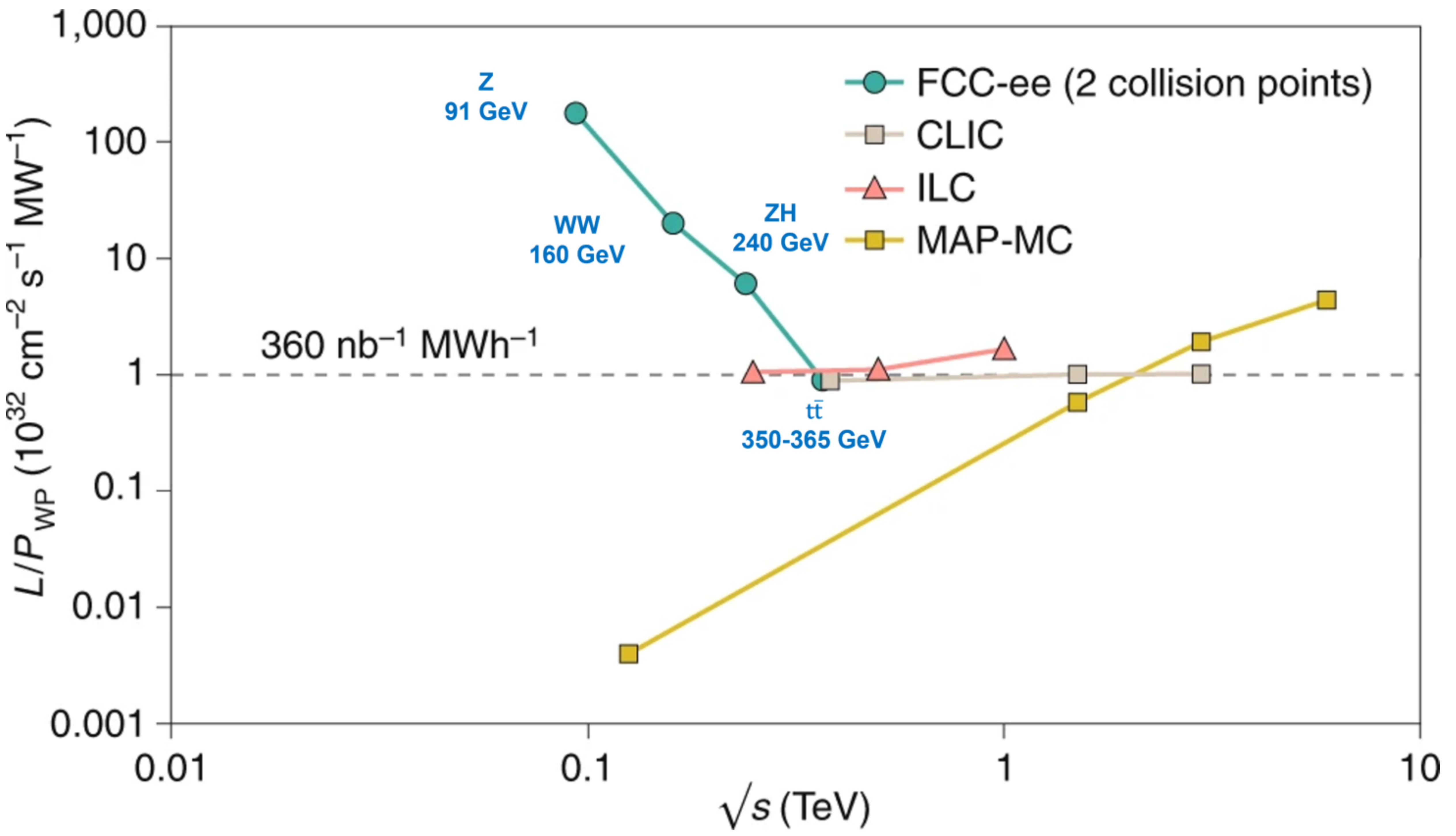
e+e- Collider Projects

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

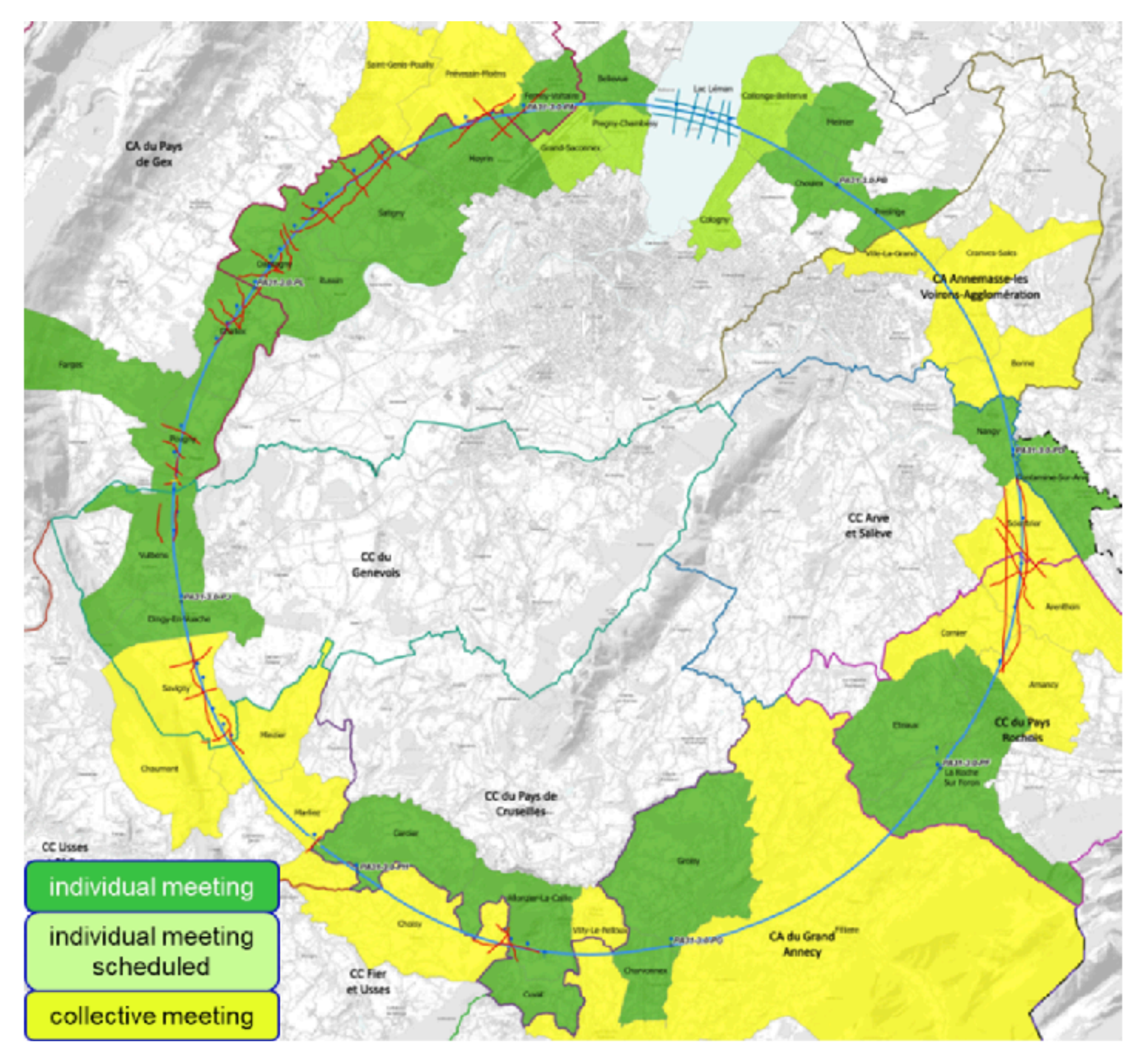
Challenging ideas to the FCC-ee

- 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

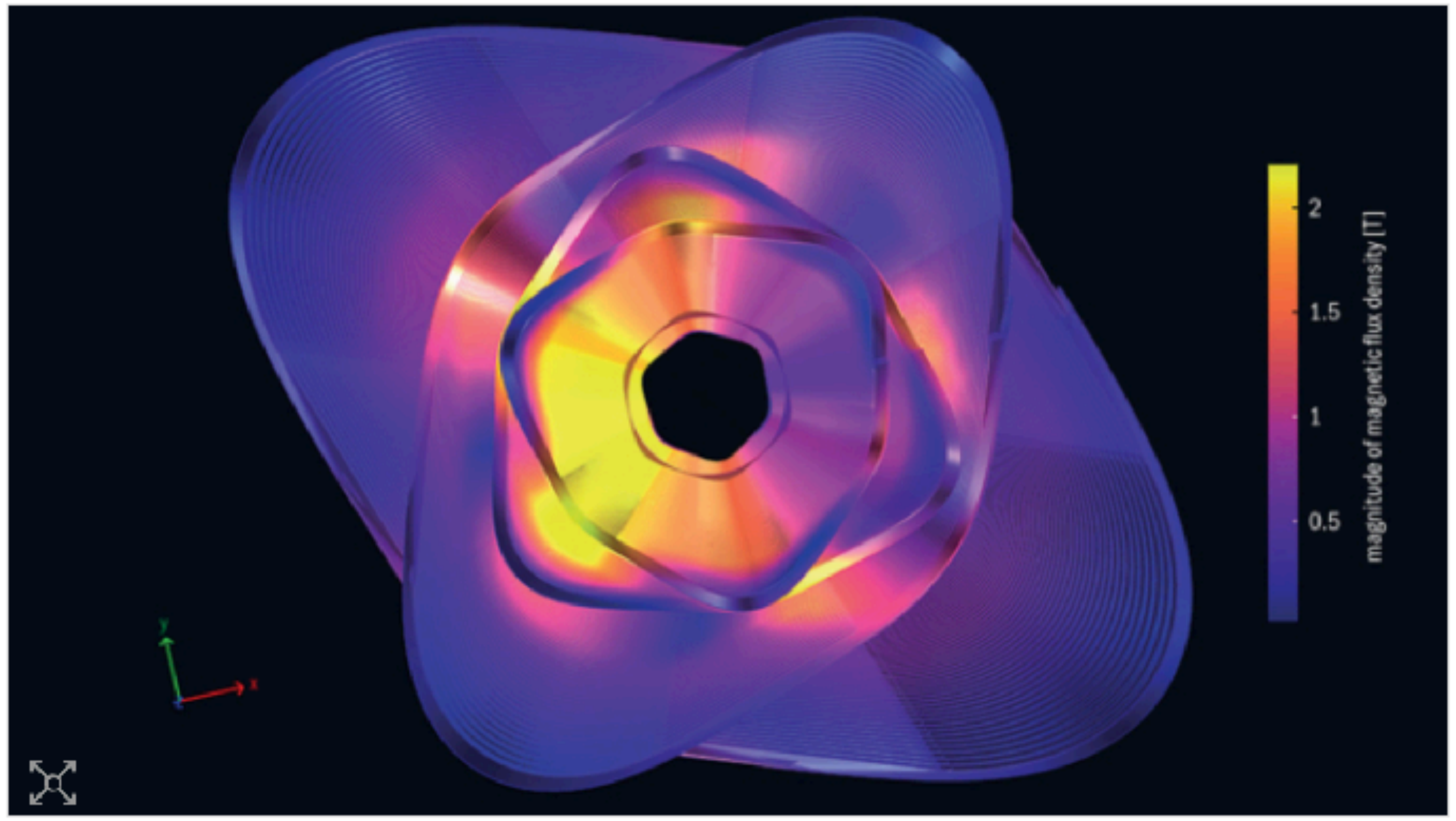


- Choice of baseline layout (90.7 km) - discussions with local authorities, environmental investigations and civil engineering designs well under way.
- In particular studies of possible injection schemes [article](#)

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

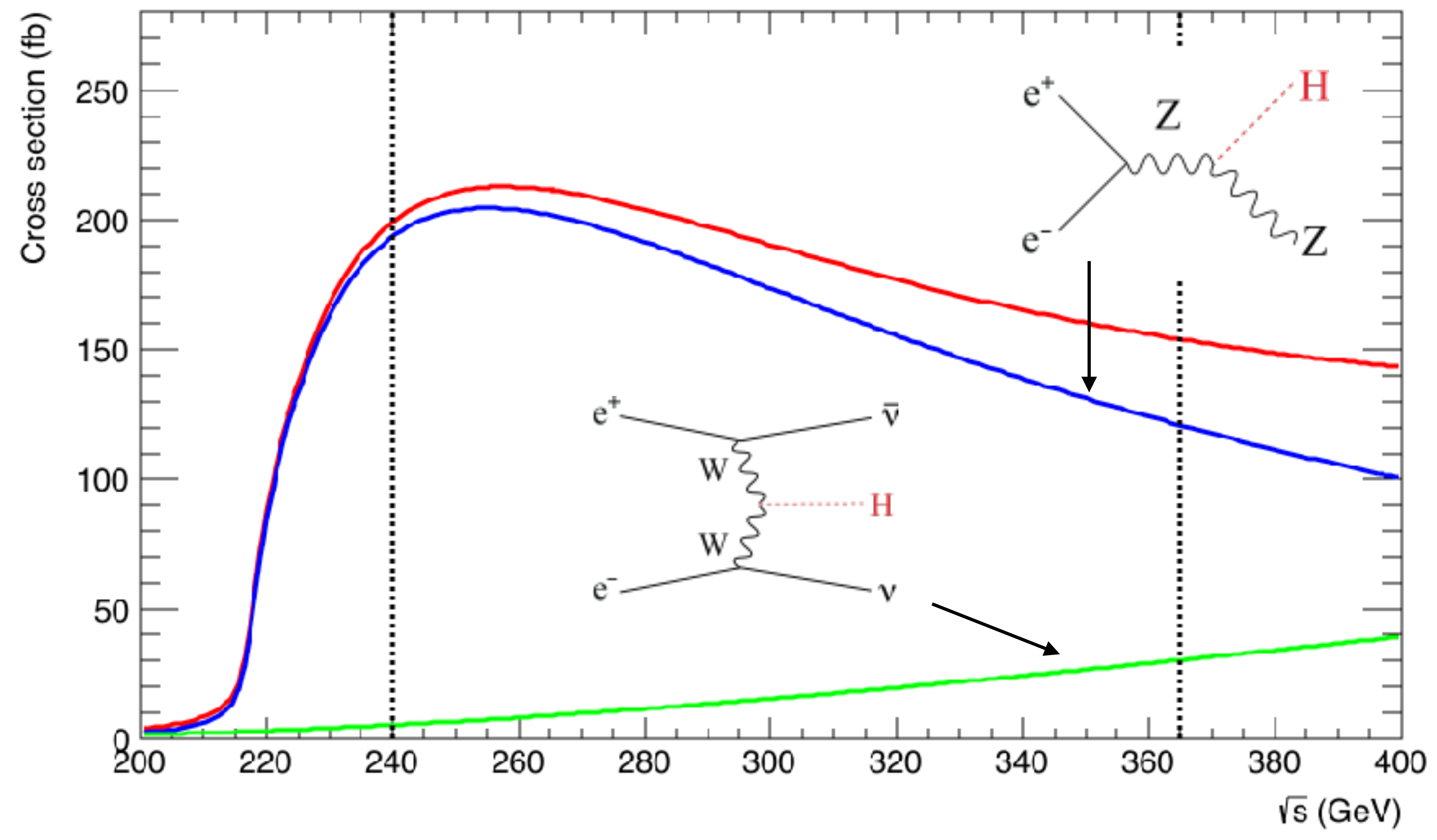
Power consumption

- 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](#)

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

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.

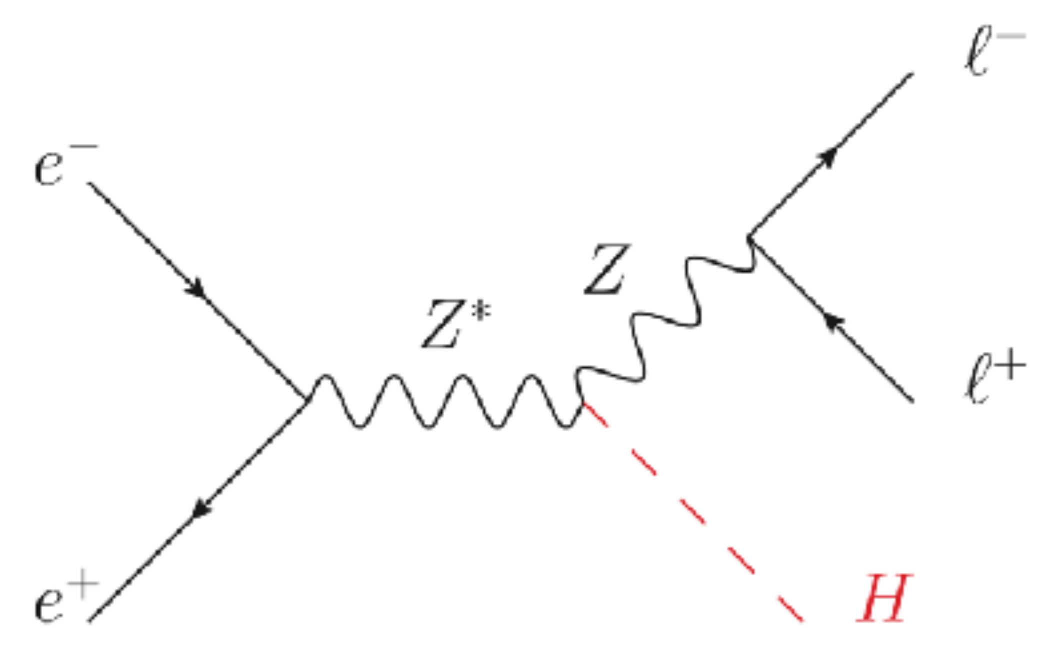
Additional 200k events at 350-365 GeV with approximately 30% from WW fusion which is interesting for the width measurement

- 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

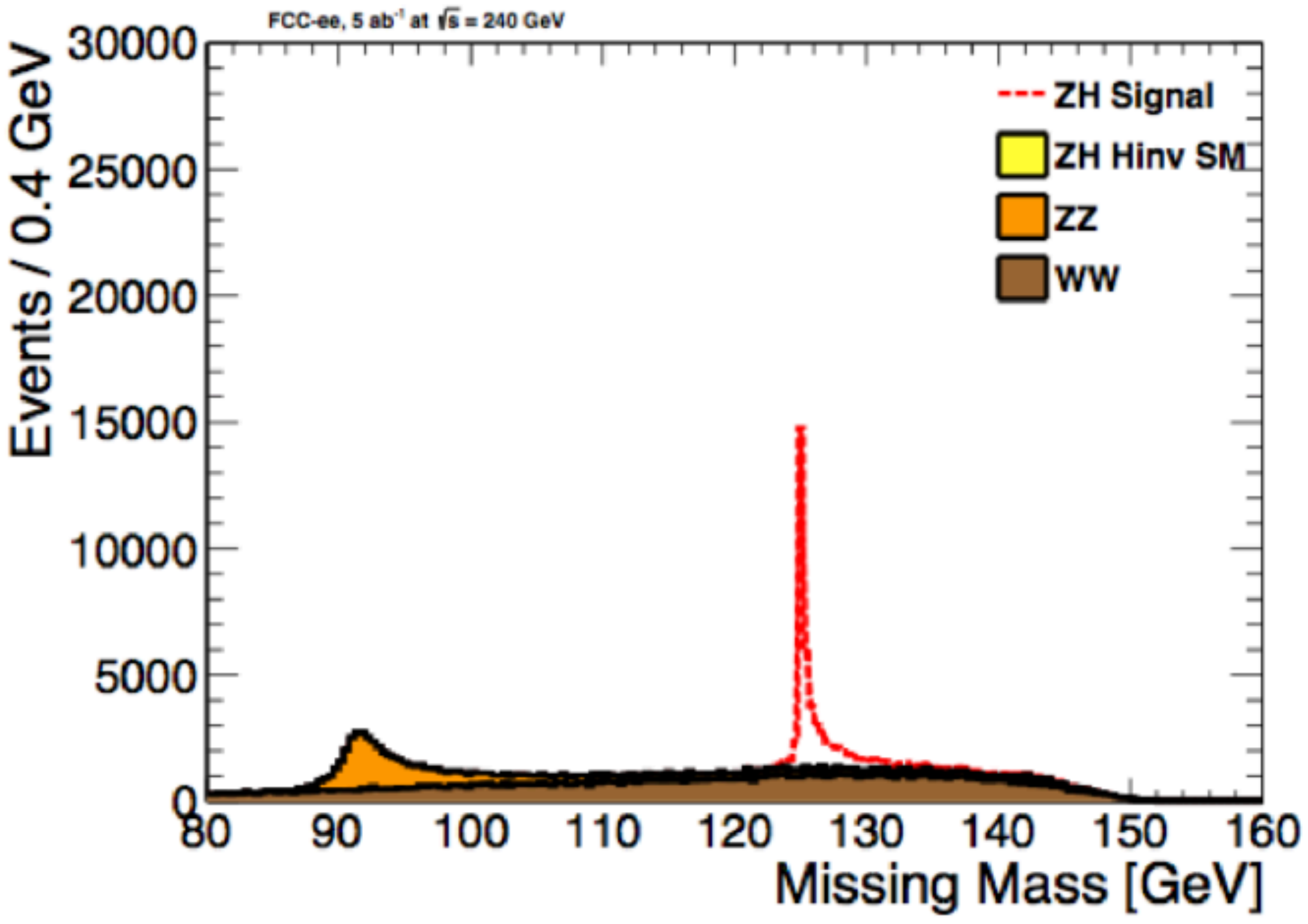
Threshold production of HZ provides a unique opportunity to measure the total HZ cross section through the recoil method



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

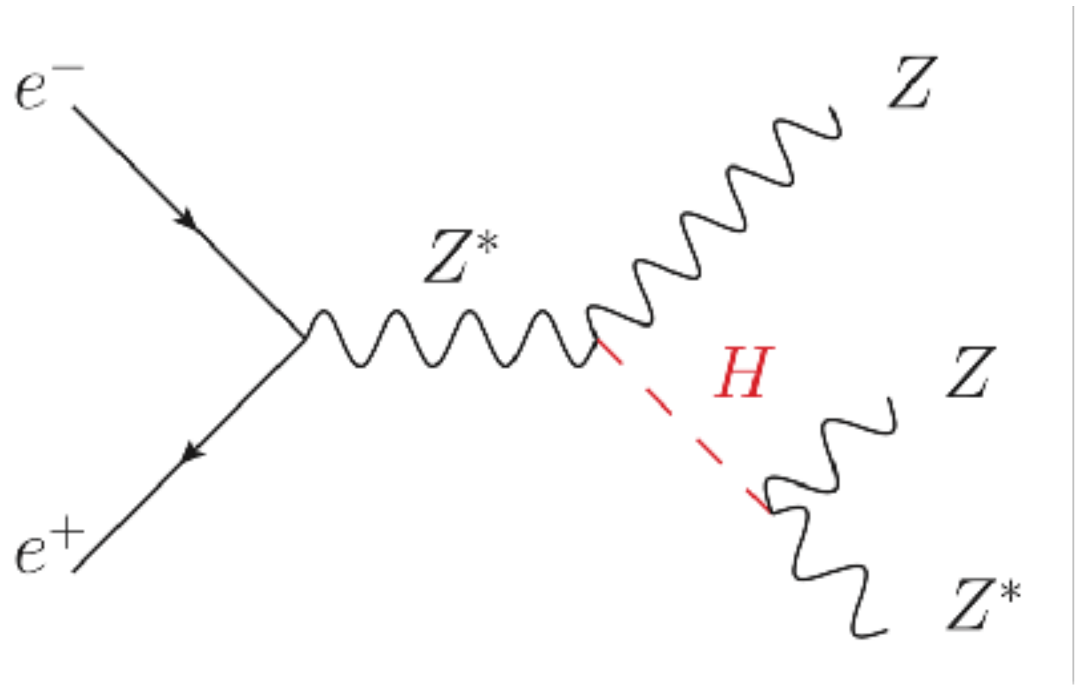
From conservation of energy and momentum, the energy and momentum of the Higgs is known from the Z without measuring the Higgs boson!

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



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*:

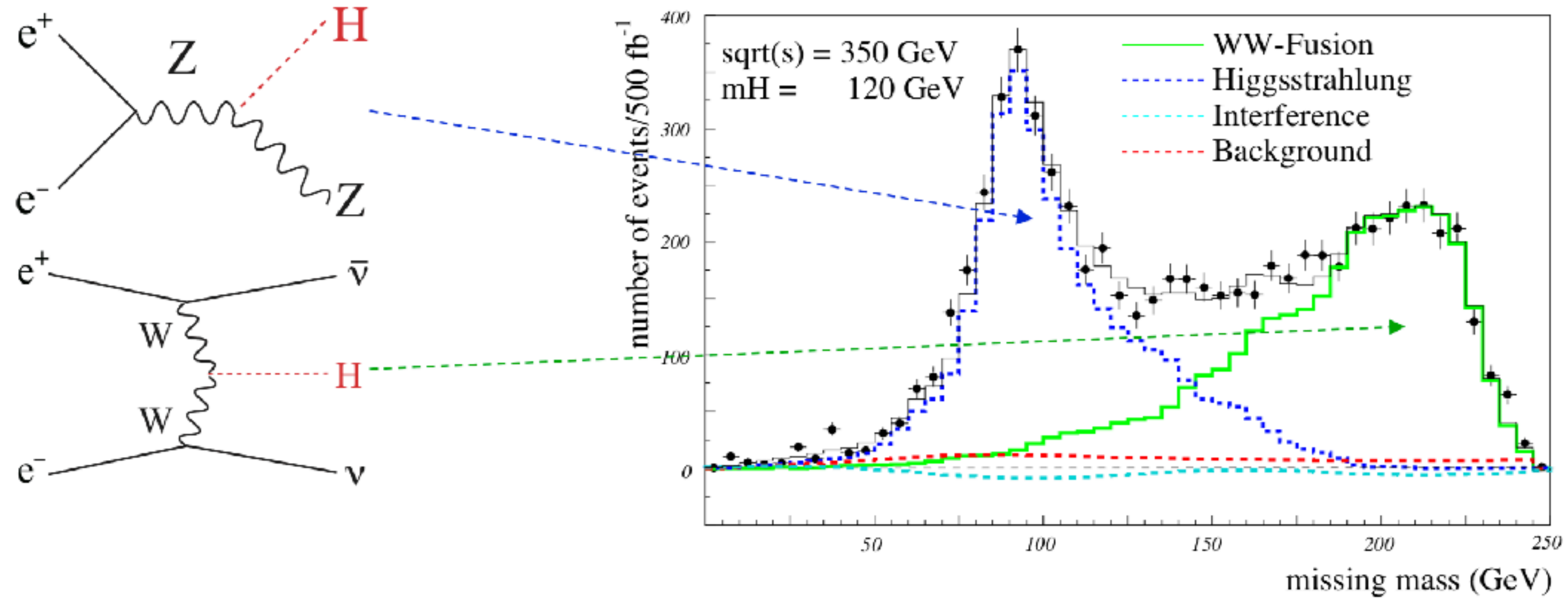


$$\sigma(e^+e^- \to HZ) \times B(H \to ZZ^*) \propto \frac{\kappa_Z^4}{\Gamma_H}$$

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

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)!

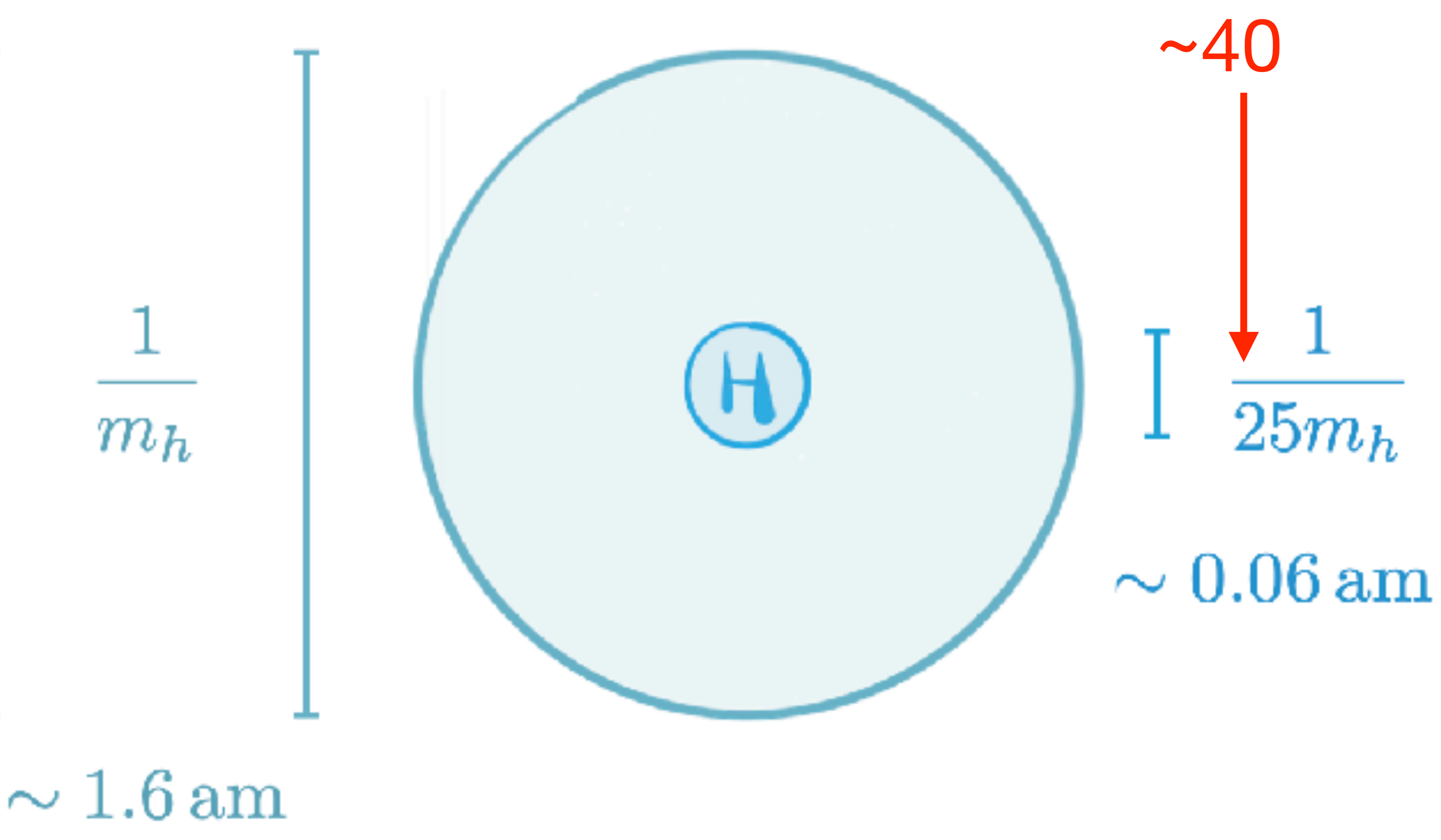
Precision on Γ_H of 1.1%

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%			
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

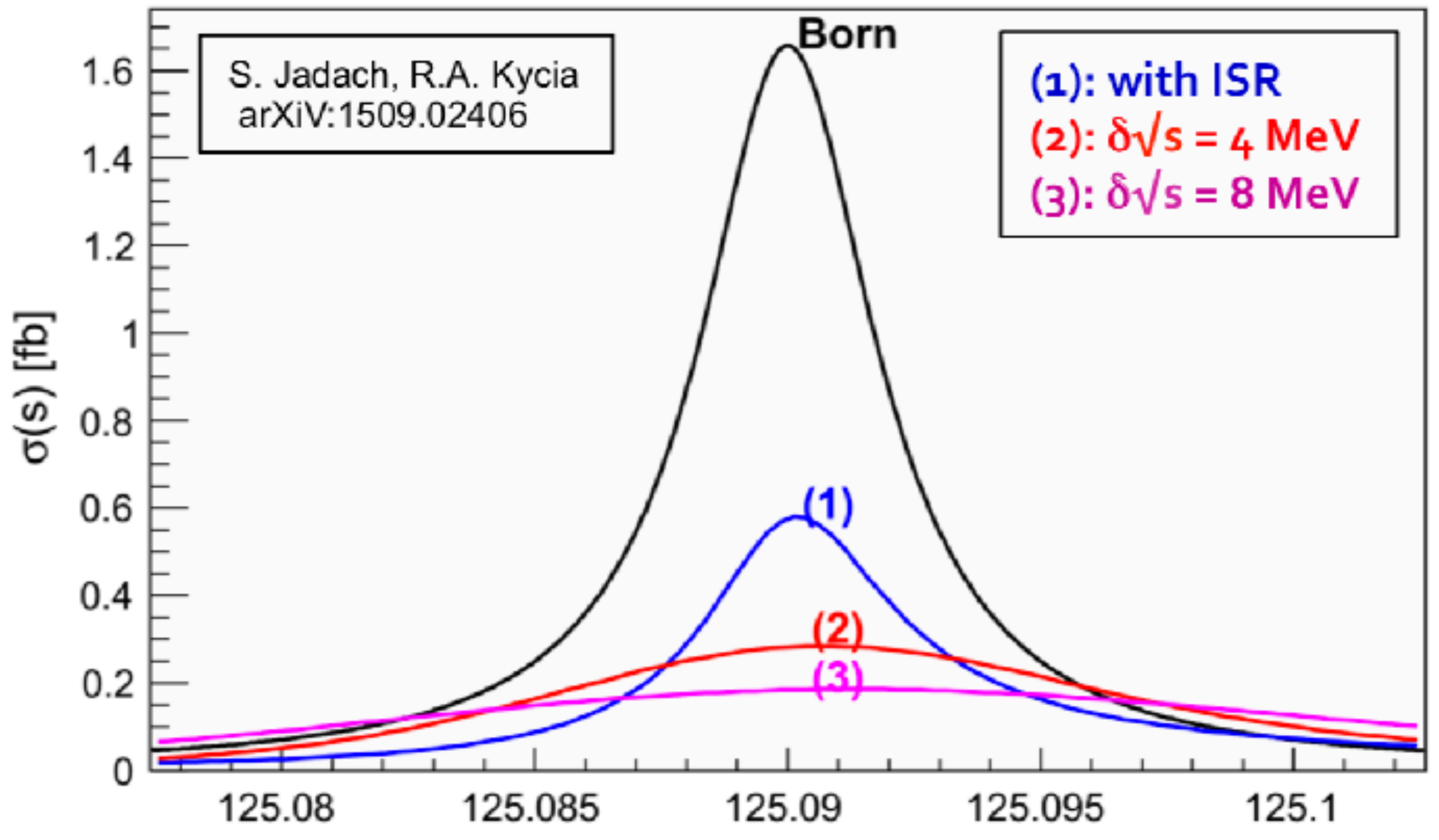
s-Channel Higgs production and e-Yukawa

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.



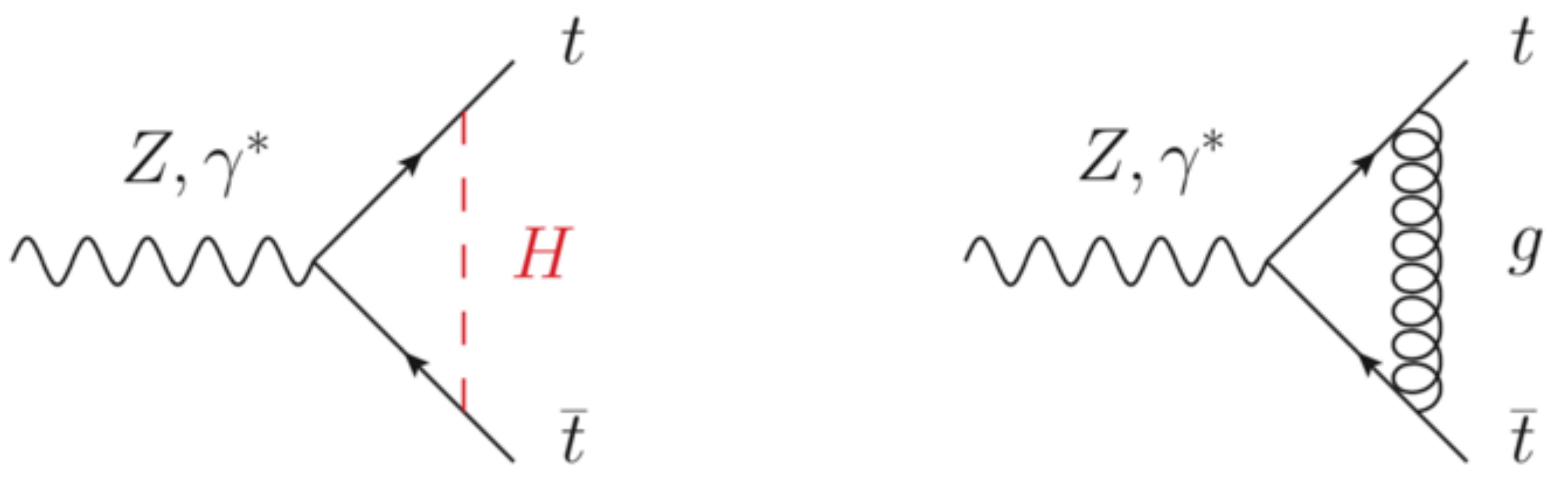
First studies indicate a sensitivity of 0.4σ per year and per detector (spread of ~6 MeV)

Monochromatization already considered but never used

Monochromatization uses opposite correlation between spatial position and energy.

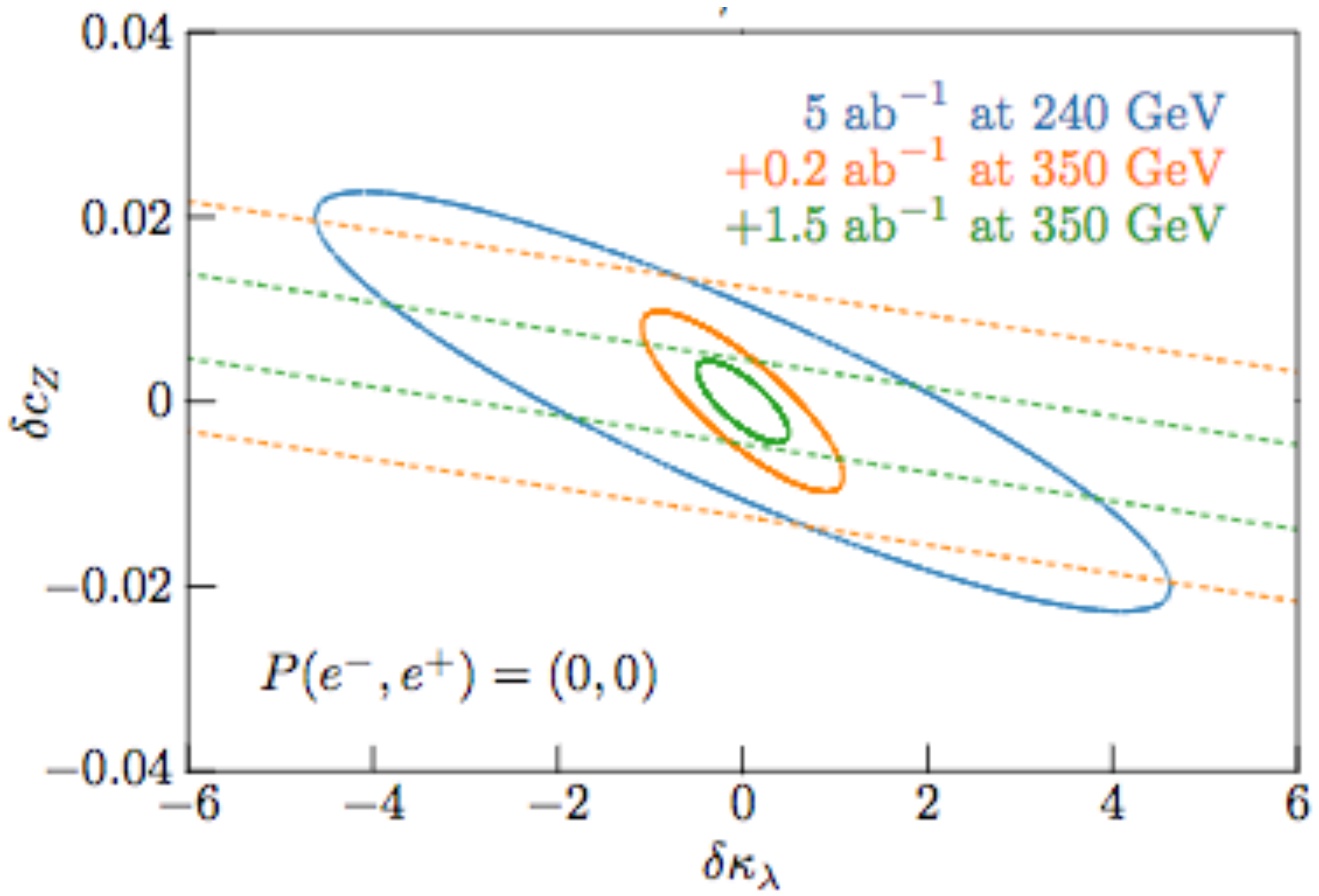
Model Dependent Measurements through Loops

Top pair cross section at threshold and above



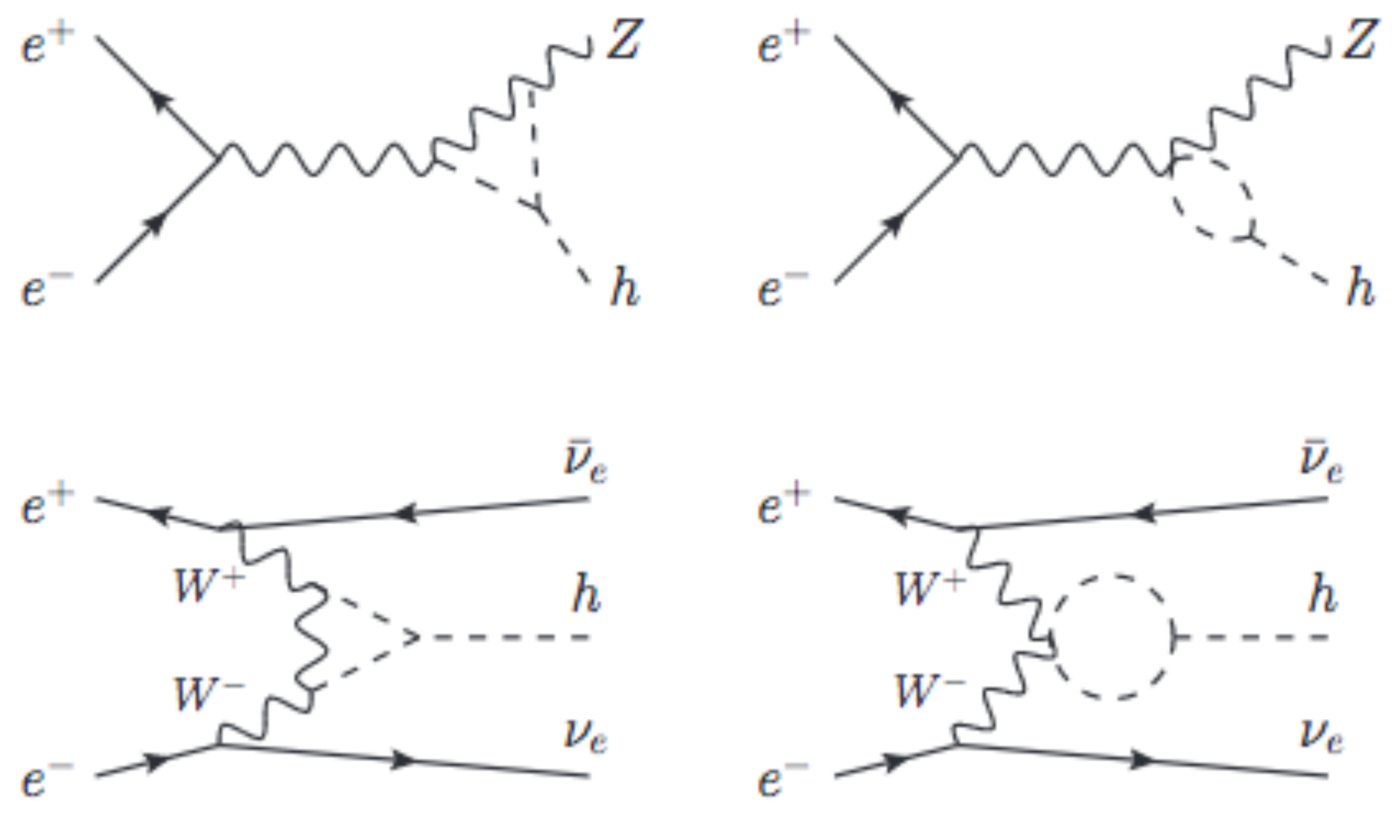
Precision on alphaS at FCC-ee will be important

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

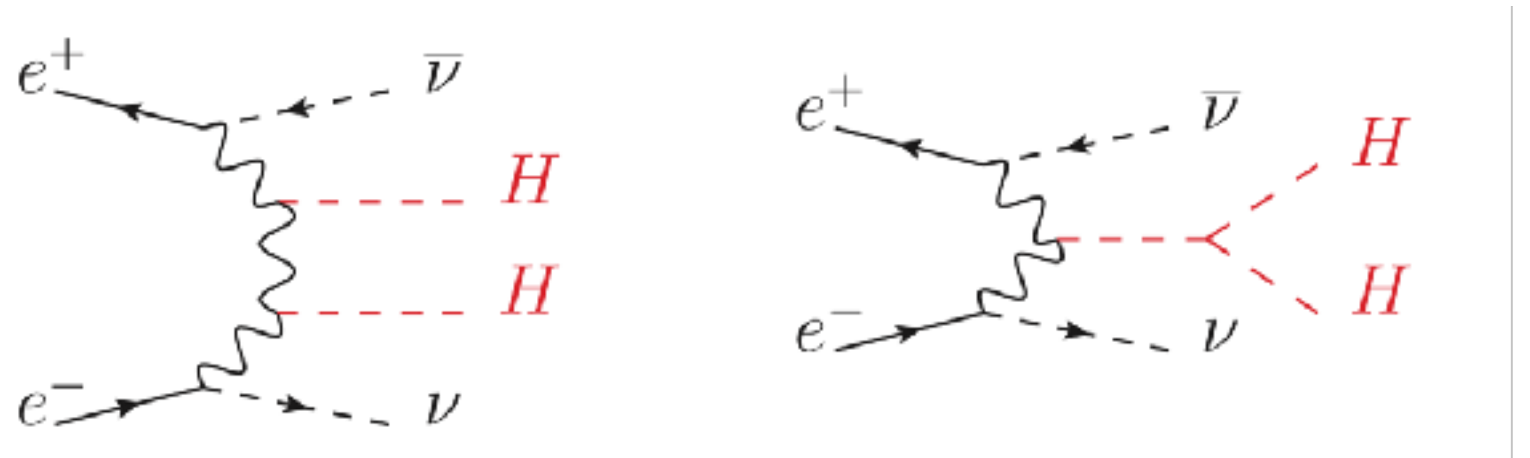


Higgs self coupling precision ~30% - reduced to ~20% with kappaZ = 1 from SM

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)



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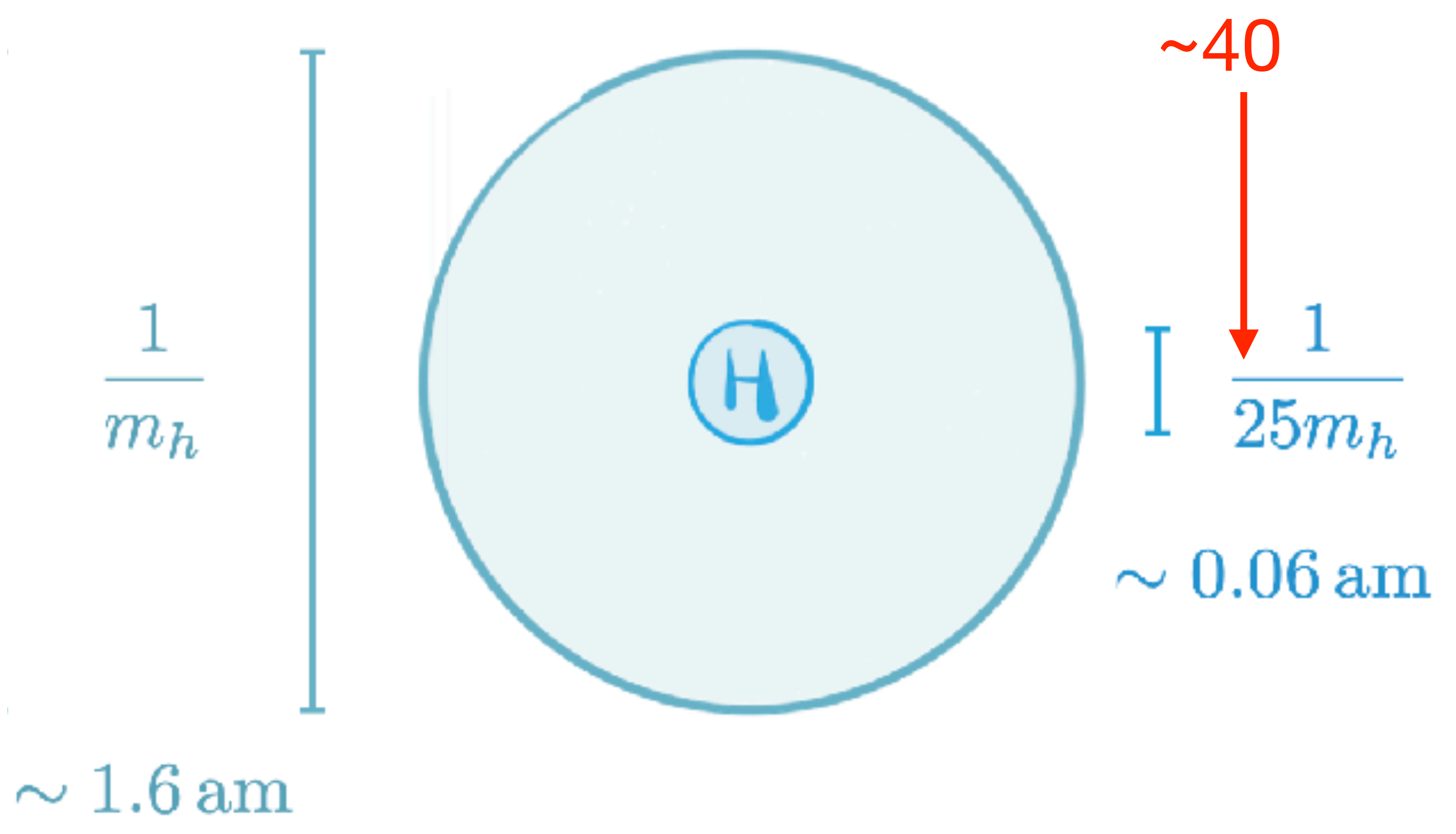
κ_μ	-	20%	4.3%	8.9%
$\kappa_{Z\gamma}$	-	30%	9.8%	-
B_{inv}	-	11%	2.5%	0.2%
κ_λ	-	-	50%	27%*

***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

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!

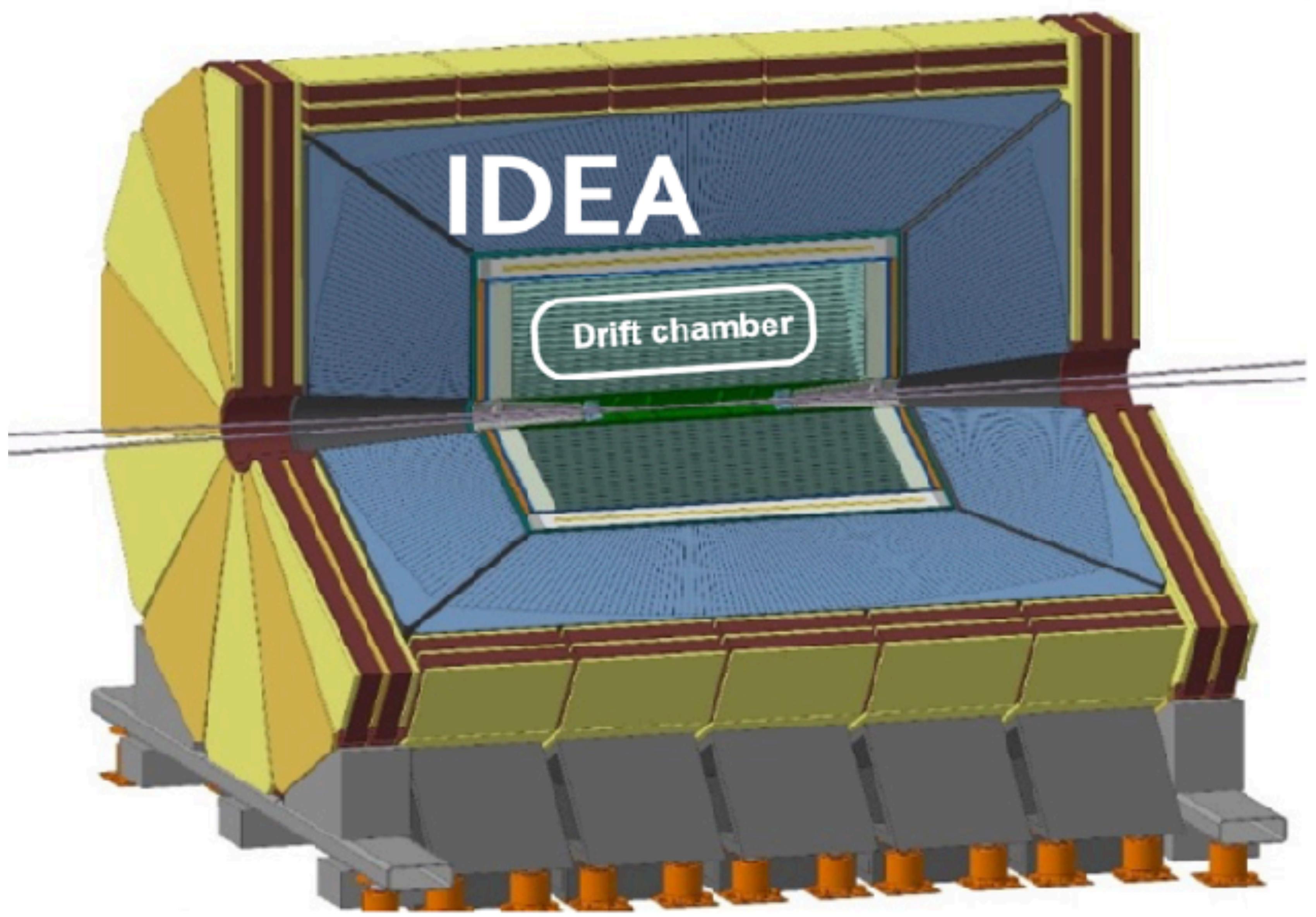
Superb precision achieved and uncertainties are dominated by systematic uncertainties!

- x10-50 Improvement on all EW observables
- Up to x10 improvement on Higgs observables
- Indirect discovery **potential up to 70 TeV**

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**



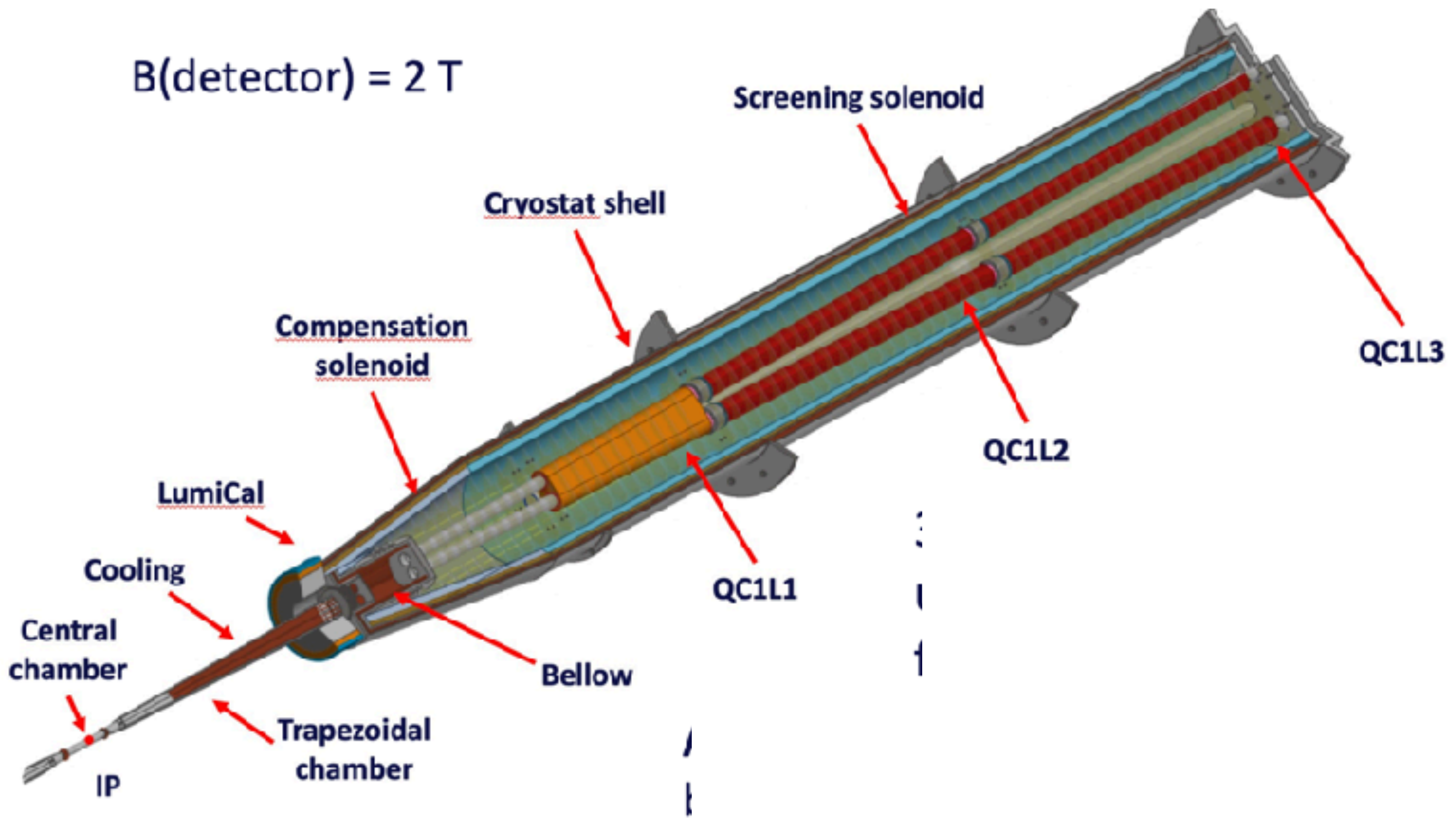
Several detector concepts: **CLD**, **IDEA** and **ALLEGRO** (Nobel Liquid concept)

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)

See talk by Magnus Mager on MAPS!

The FCC-ee interaction region and final focus!

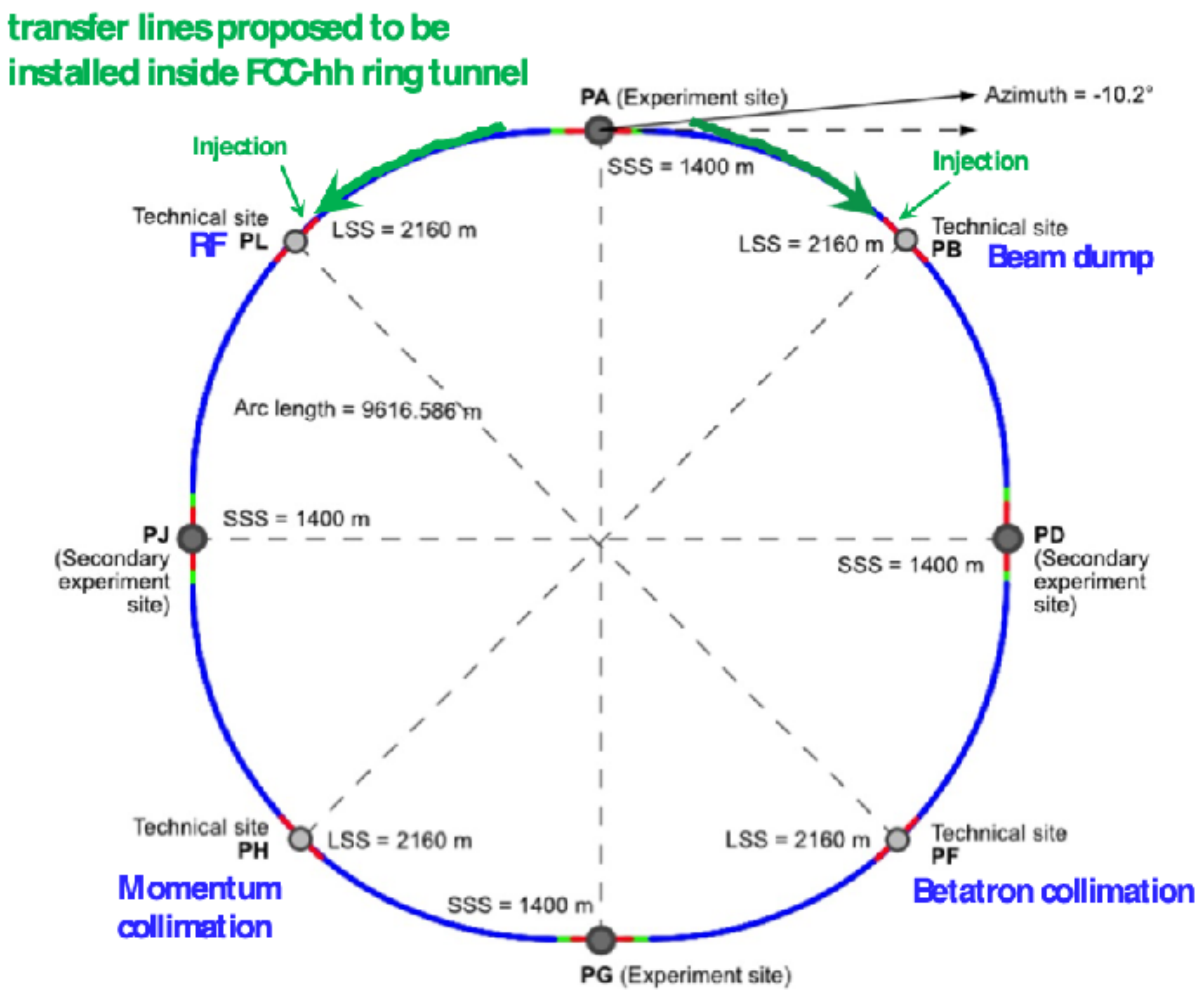
- Critical to reach highest possible luminosities
- Quadrupole magnets and final focus almost entirely inside the detector (at 8.4 m) - very strong requirements to reach **nano beams!**



Hadron Collider Projects - Exploring the Multi-TeV scale

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



SppC similar design

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)**

Hadron Collider Projects - Exploring the Multi-TeV scale

FCC-hh program

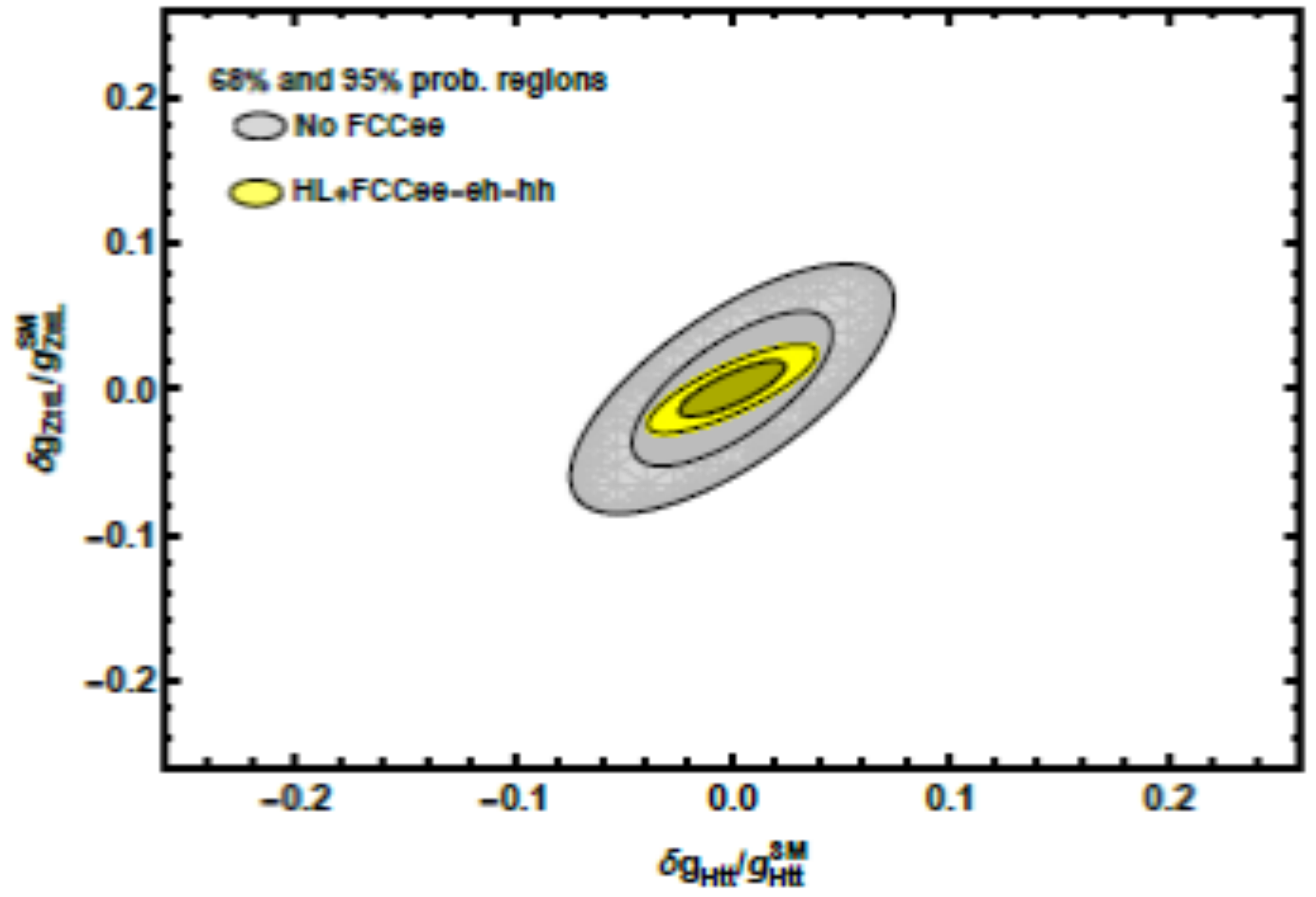
- **Primary goal is to explore the Multi-TeV scale with direct searches for new phenomena.**
- **Guaranteed deliverables**: completion of the missing key pieces in Higgs precision κ_H and κ_t

Essential complementarity with FCC-ee

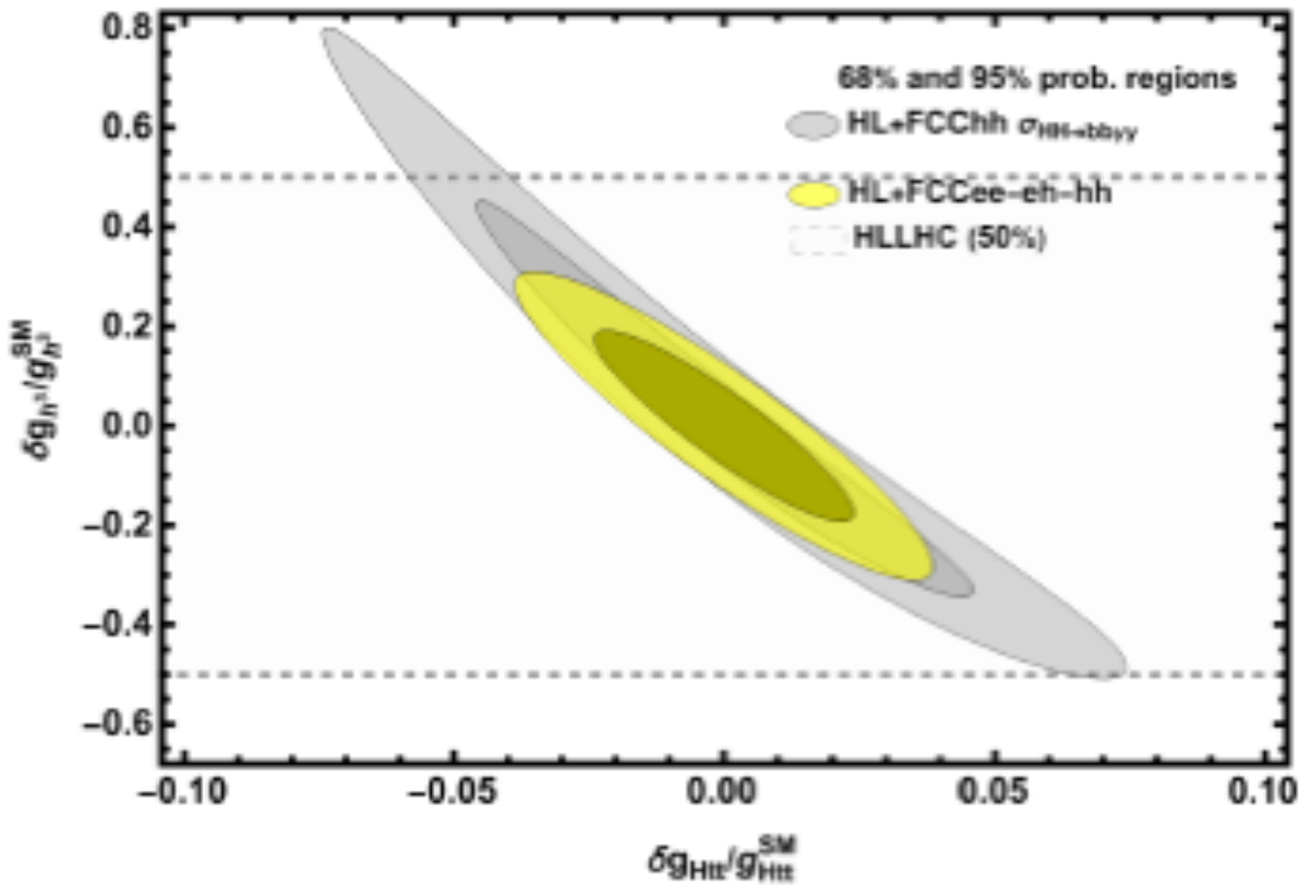
- FCC-hh is a very intricate environment (up to 1000 PU events), event reconstruction at its limits and large TH uncertainites
- Precision foreseen to be reached through ratios of cross sections.
- Key precision deliverables: top Yukawa coupling and Higgs trilinear coupling! FCC-ee and FCC-hh together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

Ingredients

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



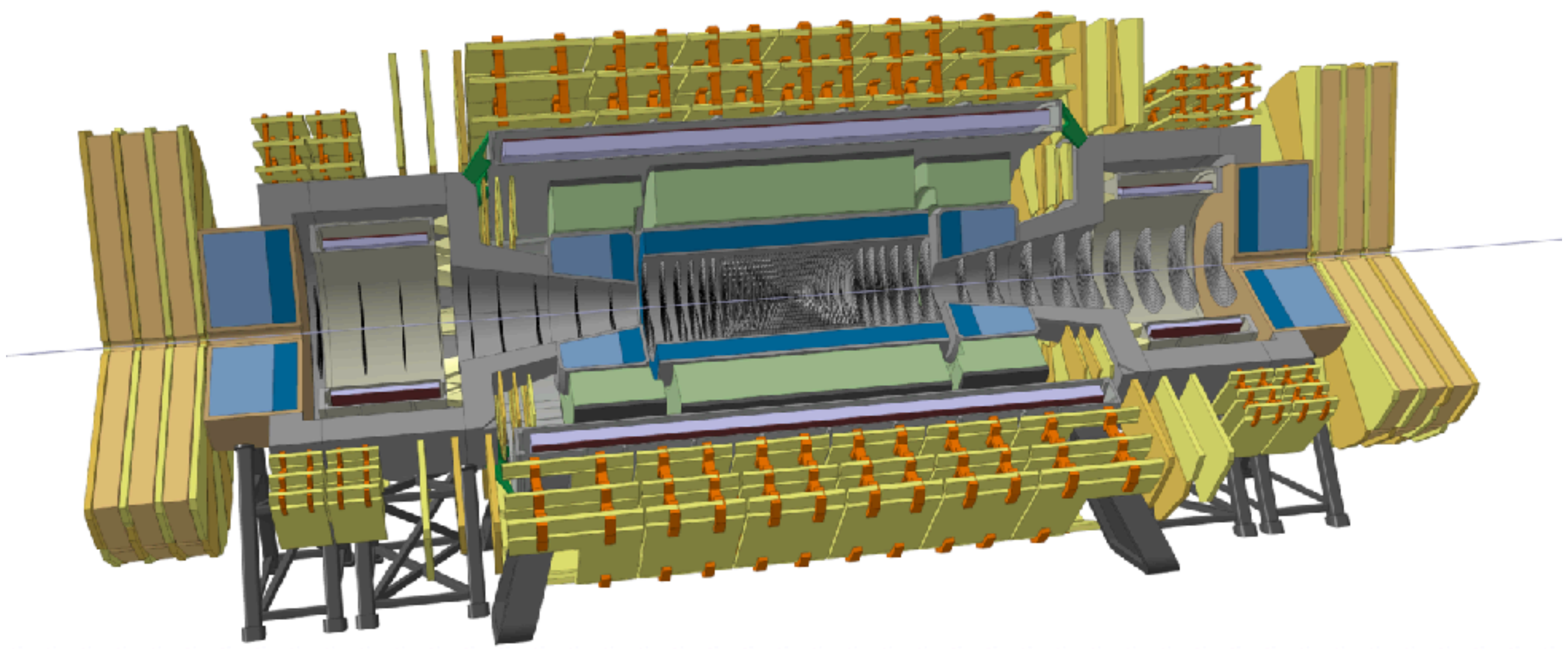
κ_t

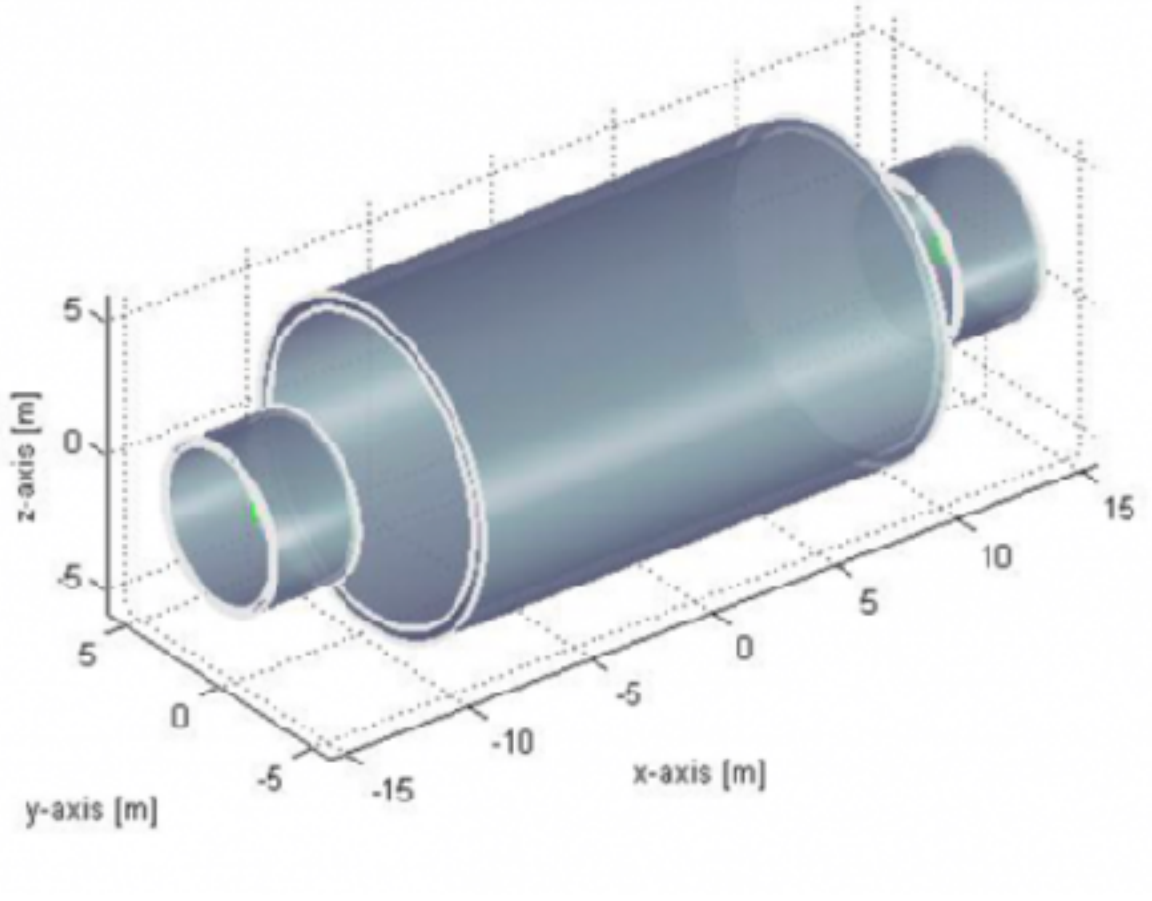


κ_λ ~5%

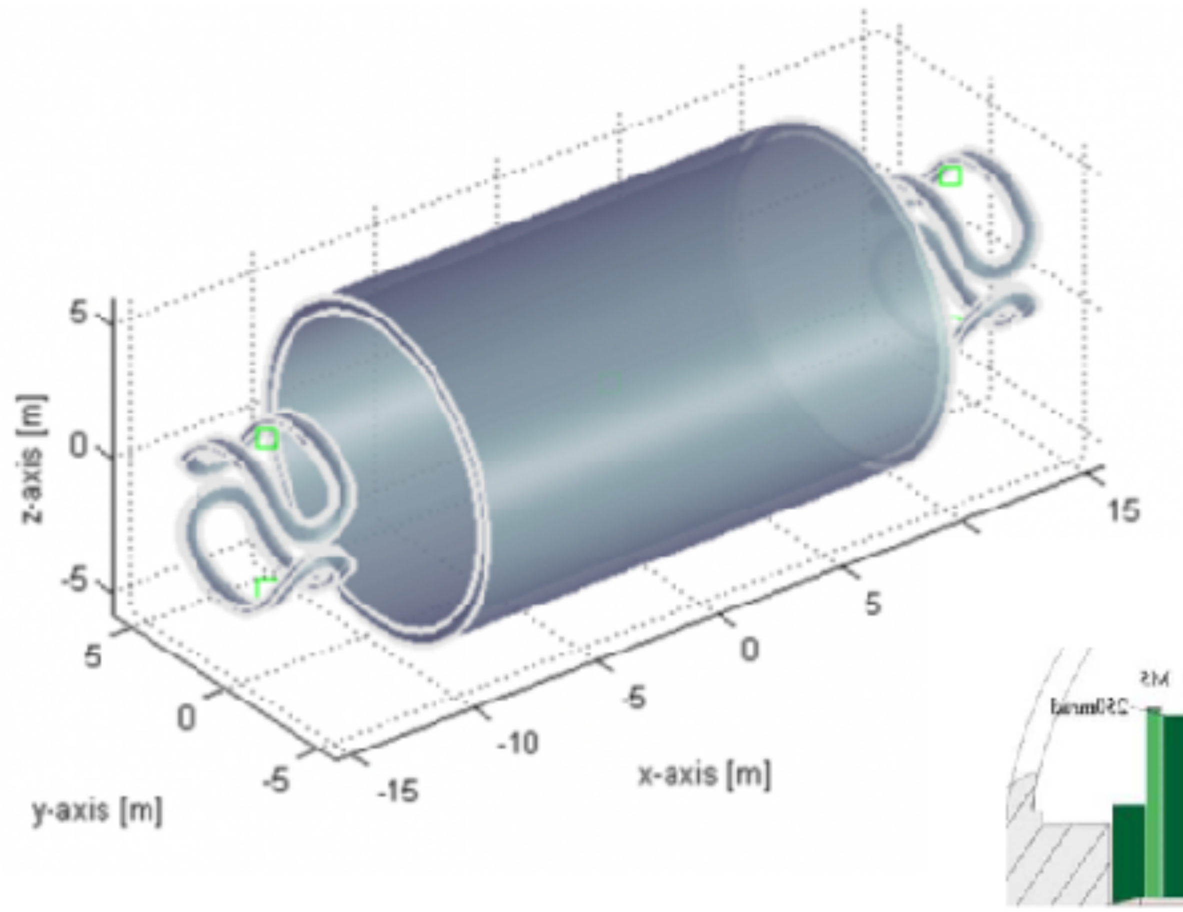
Hadron Collider Projects - Exploring the Multi-TeV scale

Dimensions commensurate (slightly larger) with current LHC experiments





Baseline



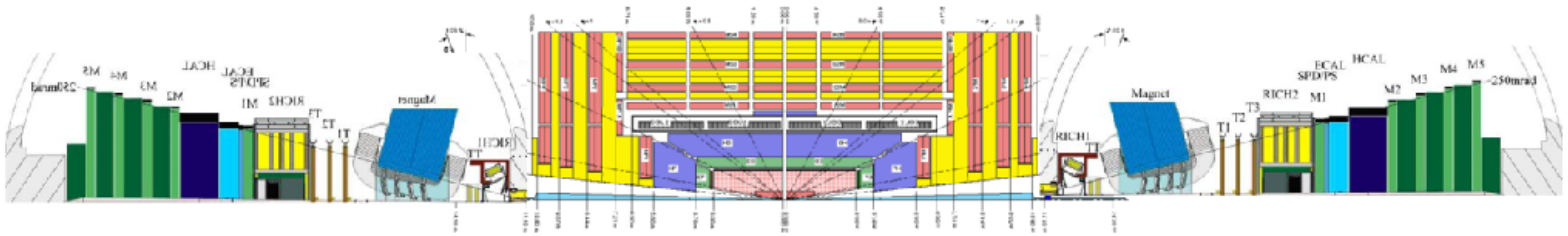
Alternative

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!



Muon Collider Project - Exploring the Multi-TeV scale

Best of all worlds?

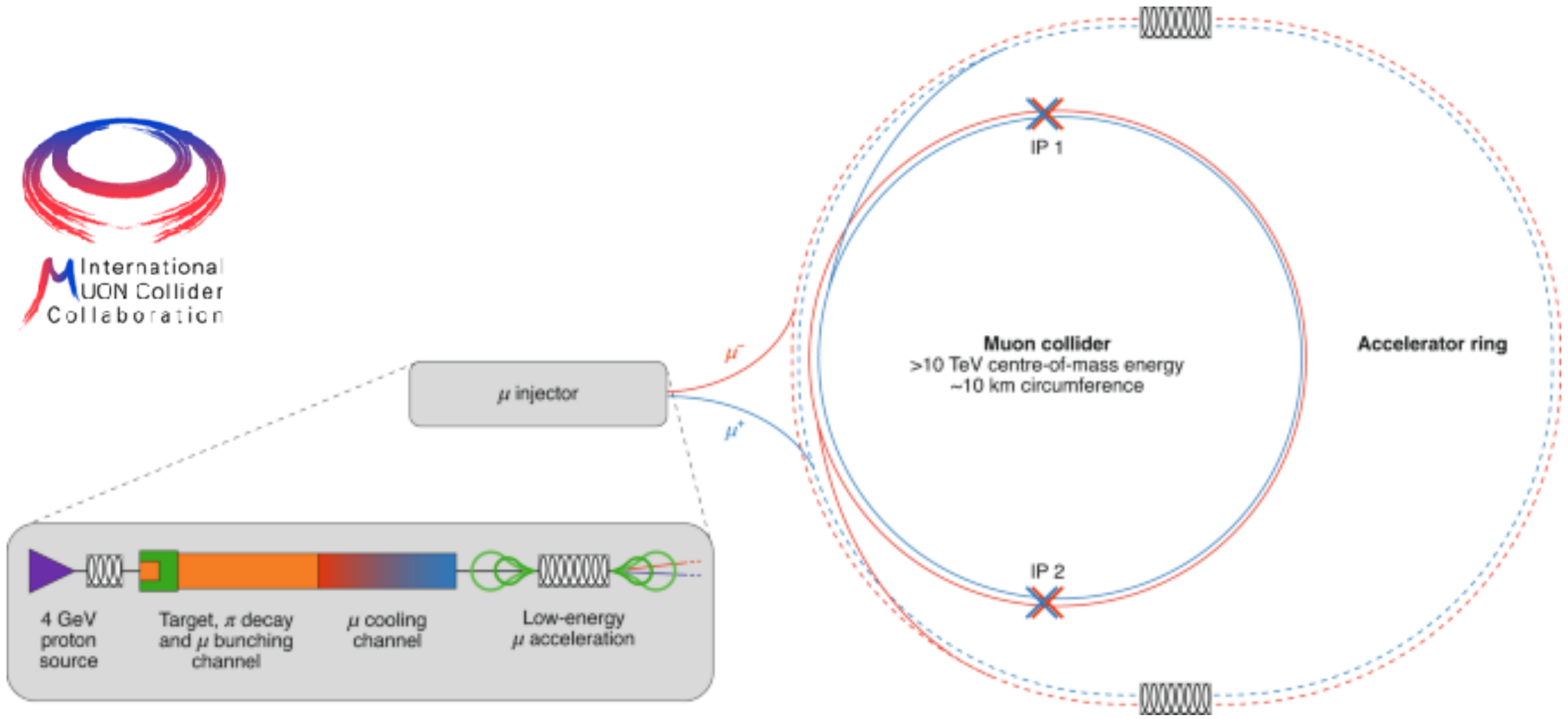
High energies, high luminosities with excellent lumi per MW ratio, (relatively) clean lepton collision events!

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

… incredibly challenging!

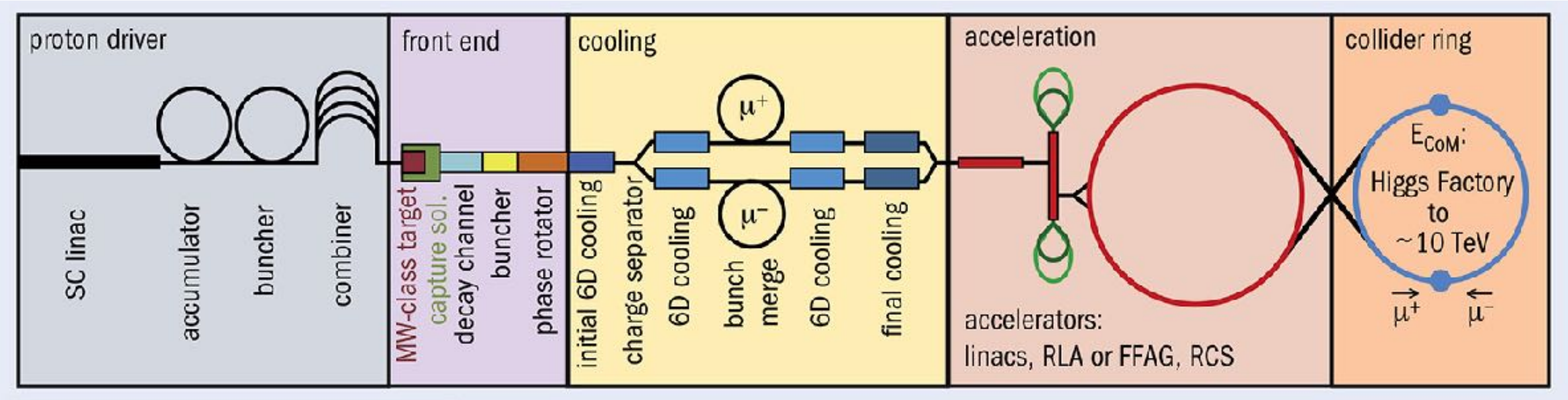
Initial targets for the integrated luminosities have been defined, namely 1, 10 and 20 ab−1 for 3, 10 and 14 TeV, **respectively**.

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?

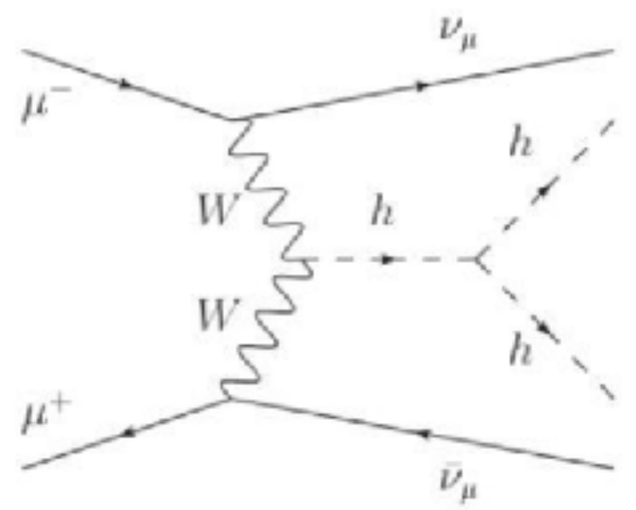
In principle could do everything as an e^+e^- collider with a much smaller ring! However the luminosity is estimated to be 2 orders of magnitude smaller at 240 GeV.

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

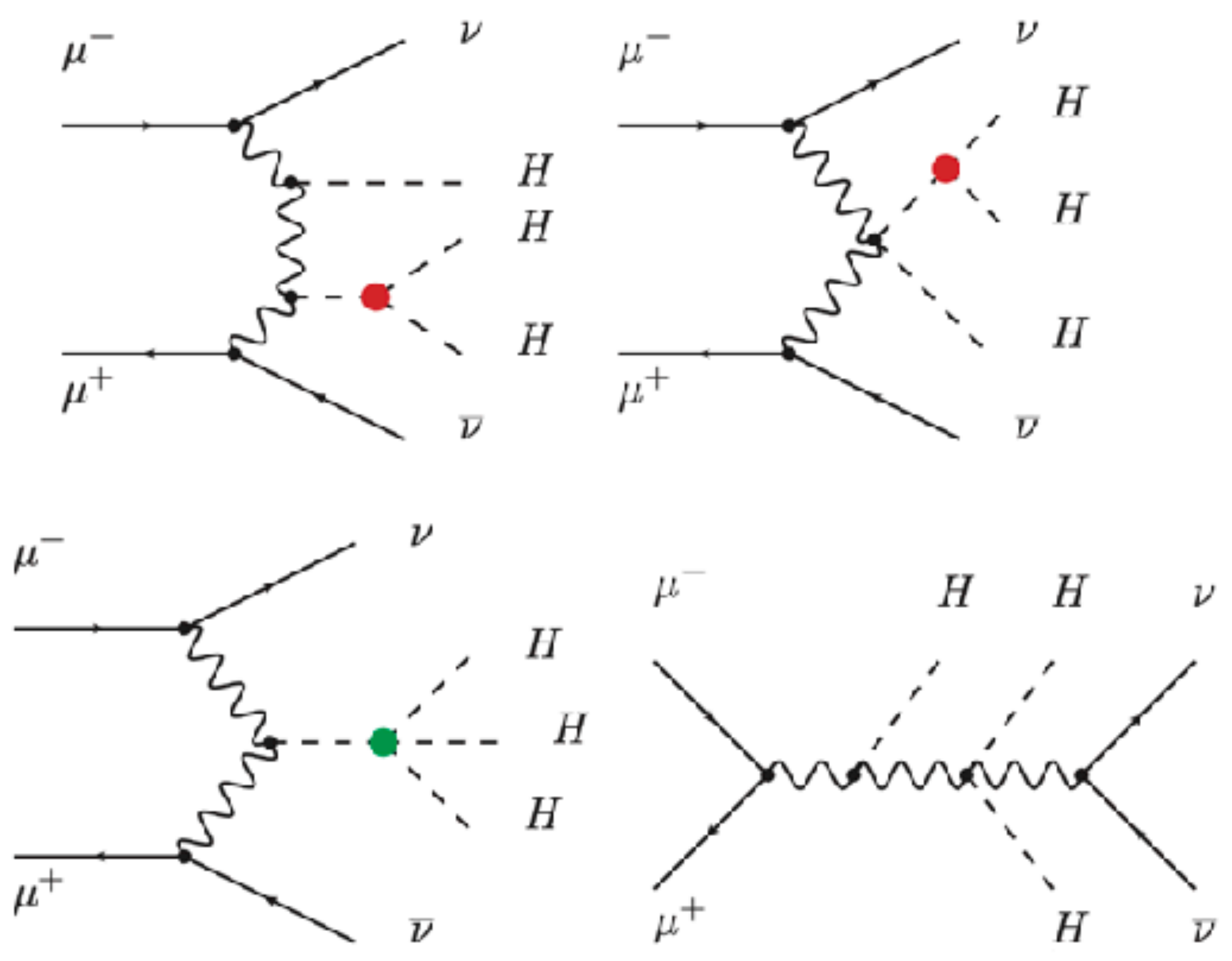
Muon Collider at 3 TeV

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

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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
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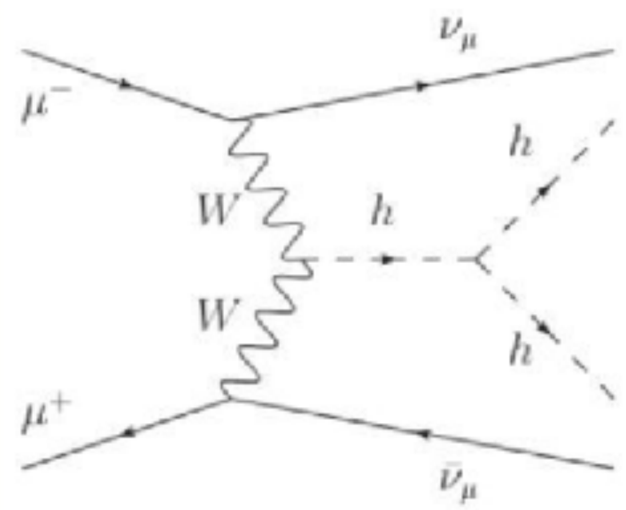
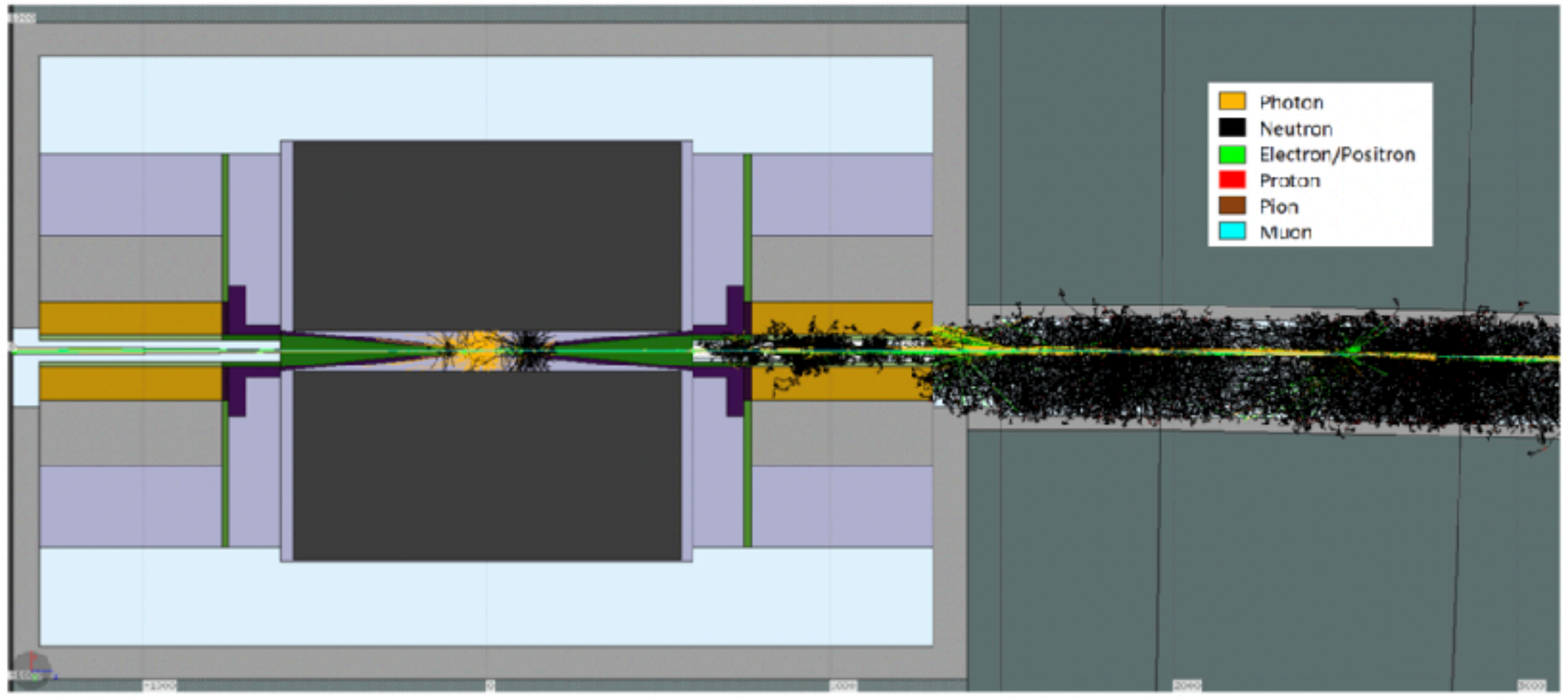


Conceptual and design challenges

- 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!



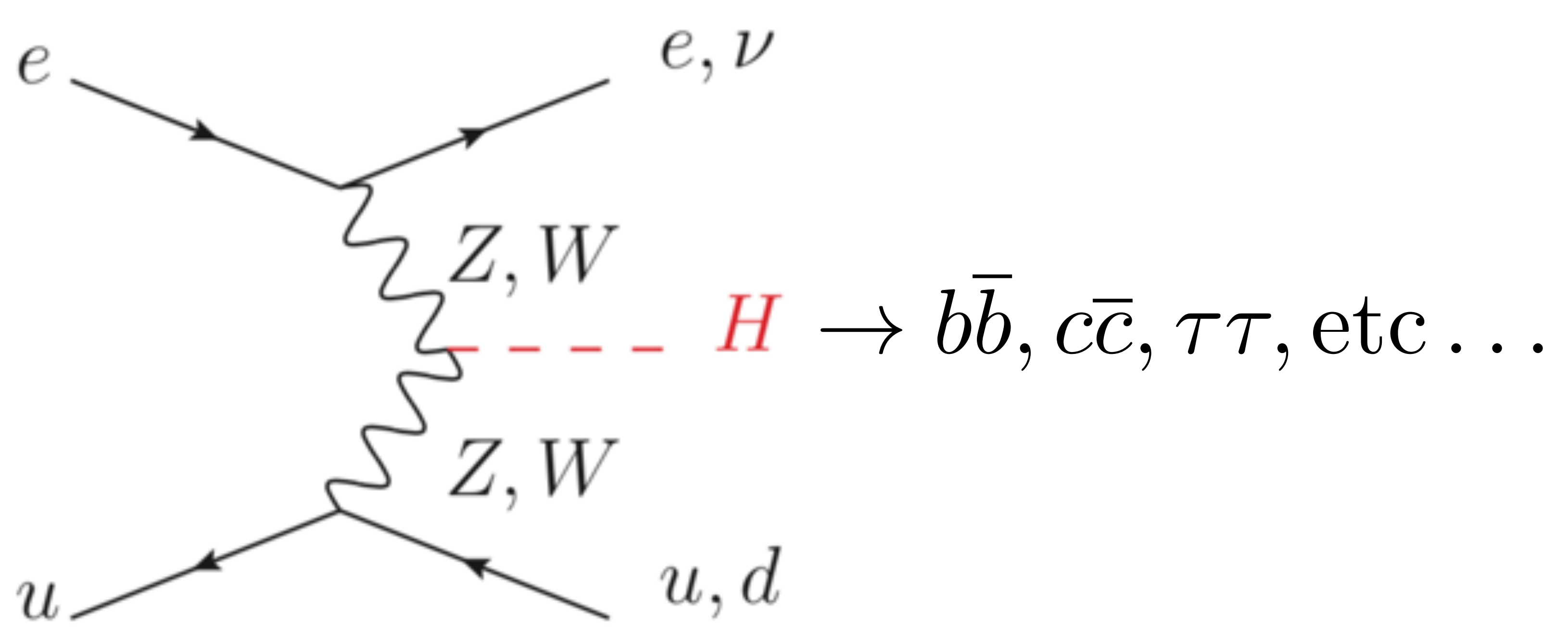
High Energy electron-proton Projects

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} $cm^{-2}s^{-1}$

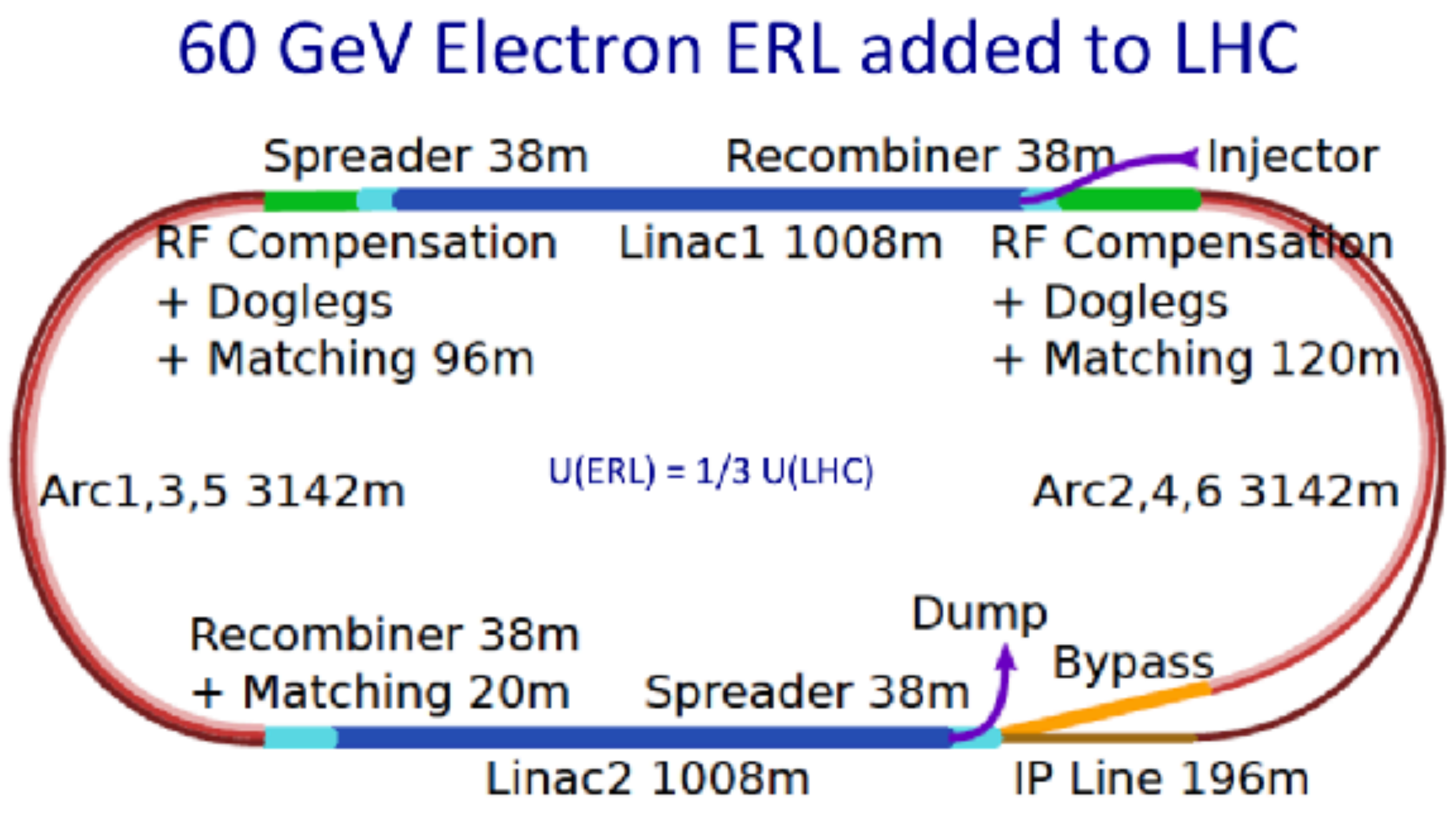
Primary program to measure proton PDFs, but also nice additional potential in Higgs physics

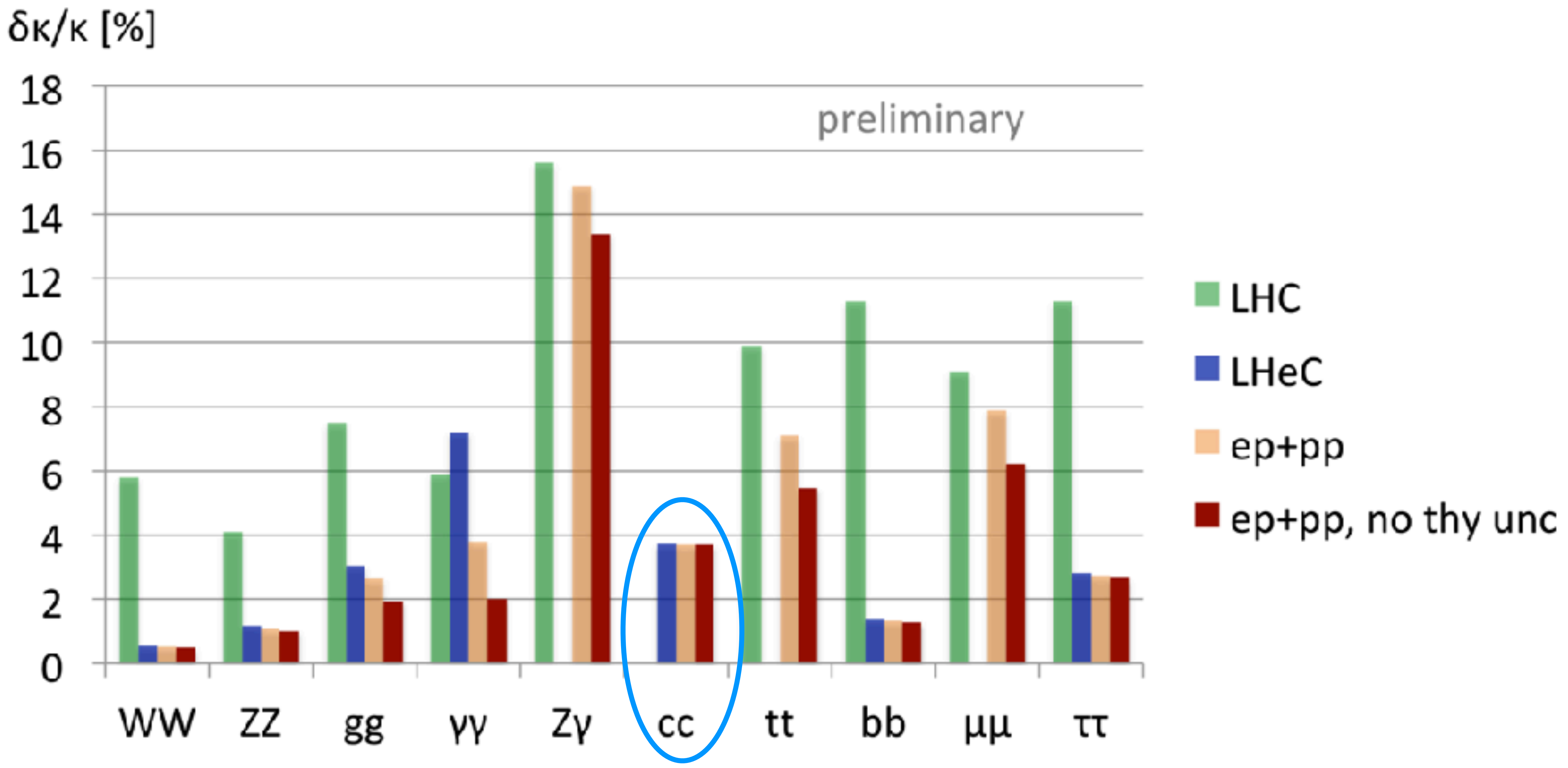
Main production process through vector boson fusion



Much cleaner environment than pure hadron!

Good reach in the WW channel.





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