LHC : Présent et Futur

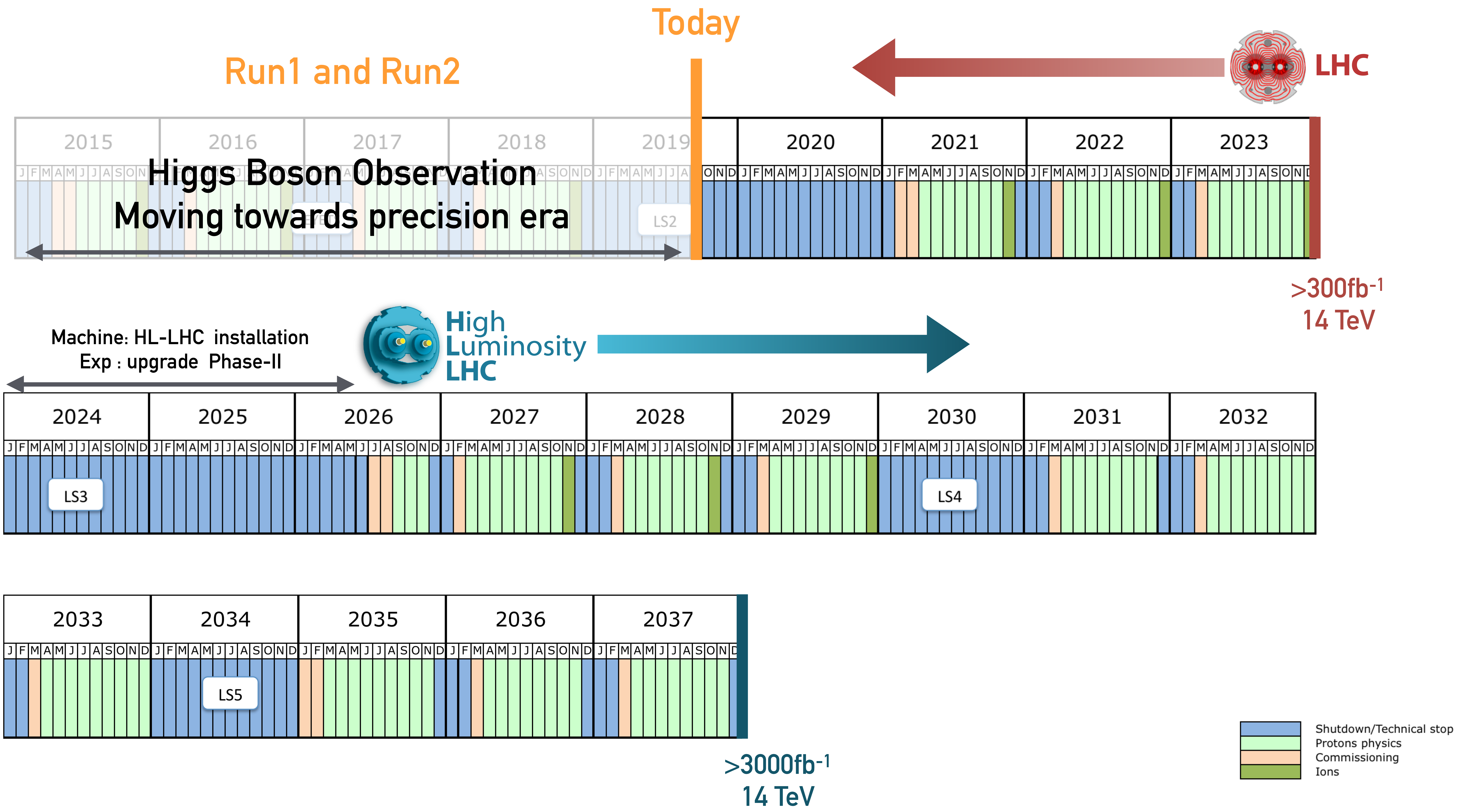
Perspectives au LHC et HL-LHC

Journées prospectives du LLR

Cité de l'espace TOULOUSE

Roberto Salerno
LLR CNRS/IN2P3 Ecole Polytechnique

LHC AND HL-LHC TIMELINE



FOREWORD

The Higgs boson is a fundamental scalar particle (spin 0) and its theory is unlike anything else we have seen in nature.

Its discovery have open a huge landscape at LHC and HL-LHC of possibilities in the study of Higgs boson properties, EWSB, SM, and new avenues in probing new physics beyond SM

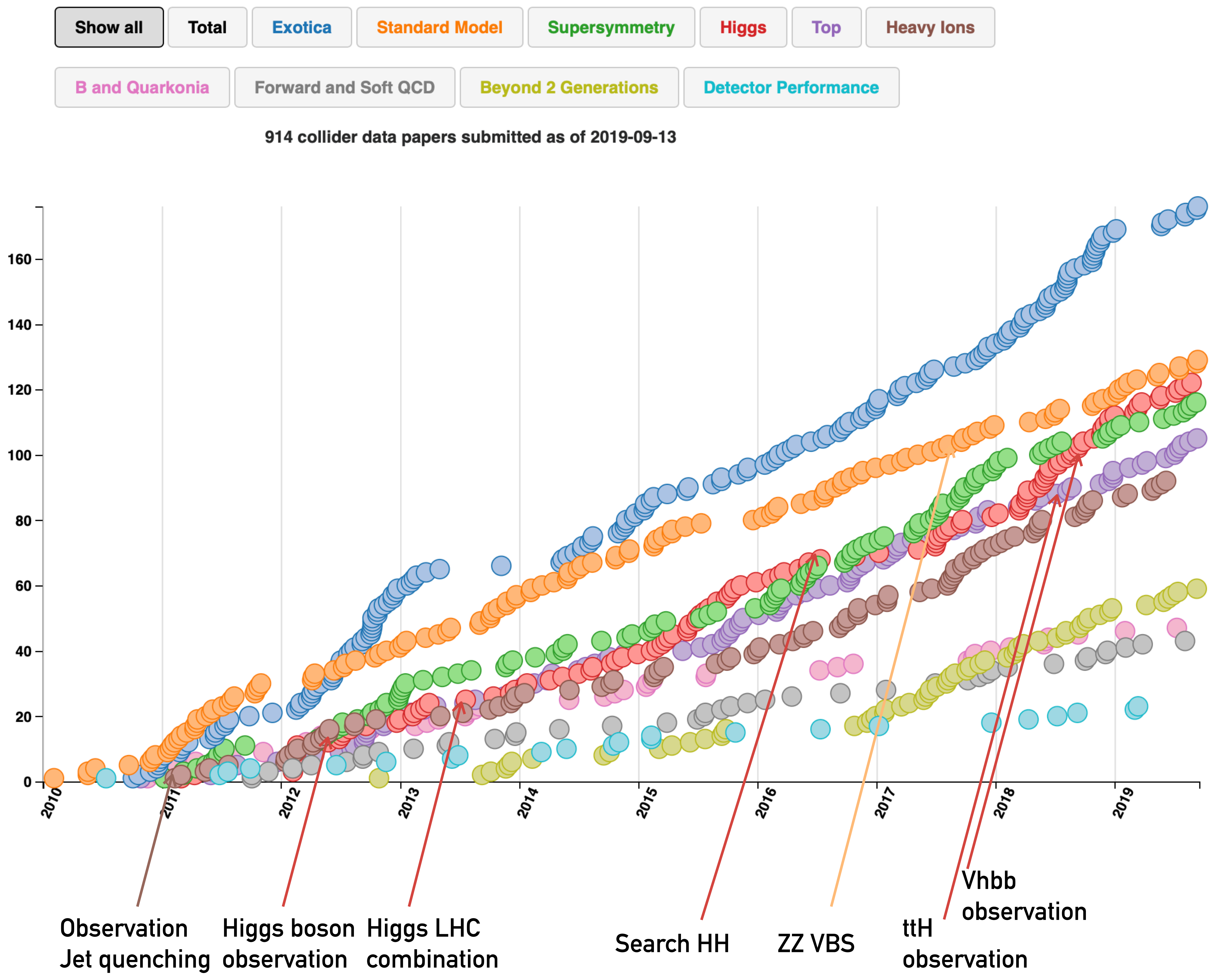
Outline

- ✓ QCD studies
- ✓ EW phenomena
- ✓ Flavour physics (aka top quark physics)
- ✓ Higgs boson properties
- ✓ Higgs boson as portal for New Physics
- ✓ Searches for New Physics at high mass

PUBLICATIONS

More than 900 LHC-collisions based paper already submitted by CMS for publication!

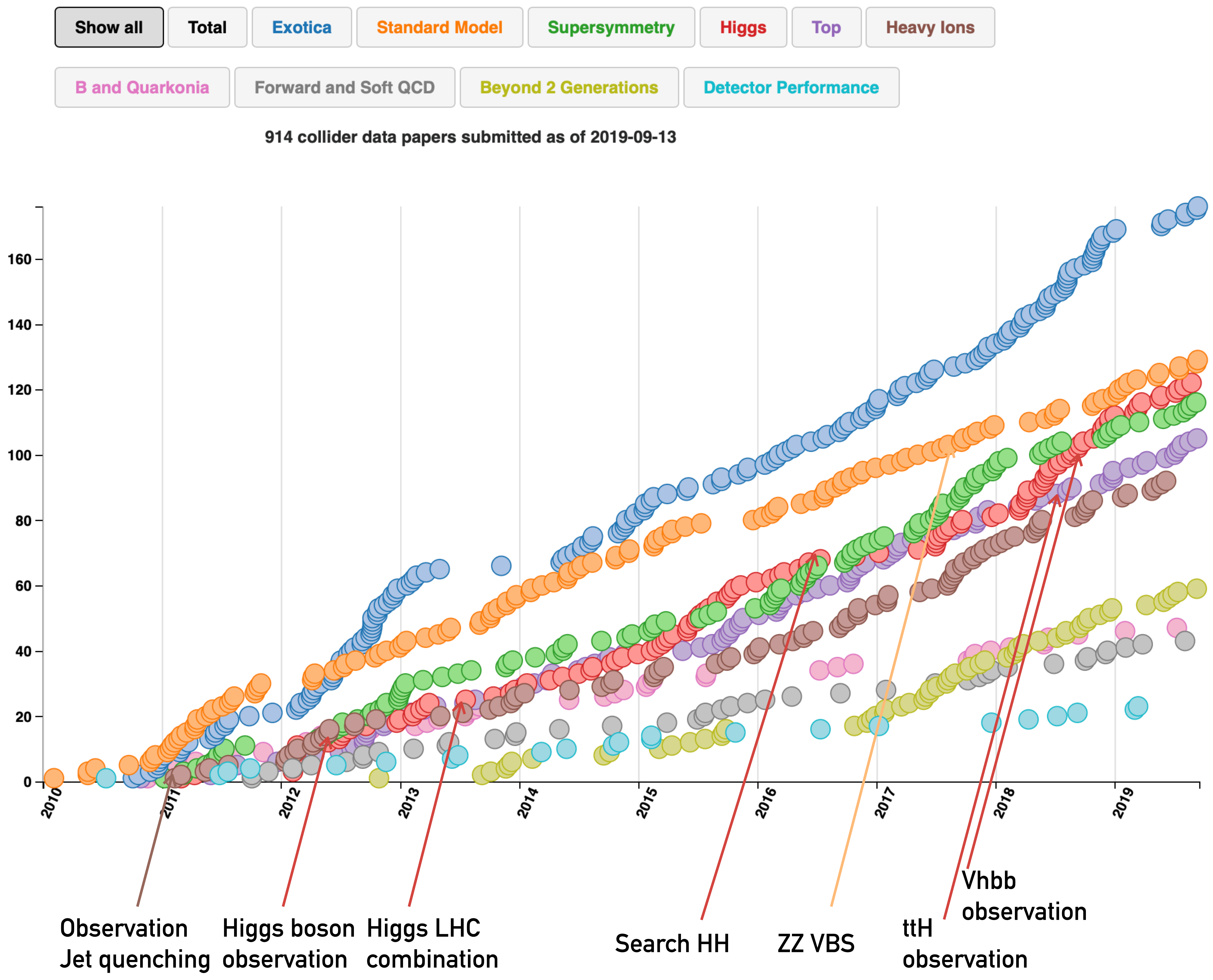
+ the same order by ATLAS



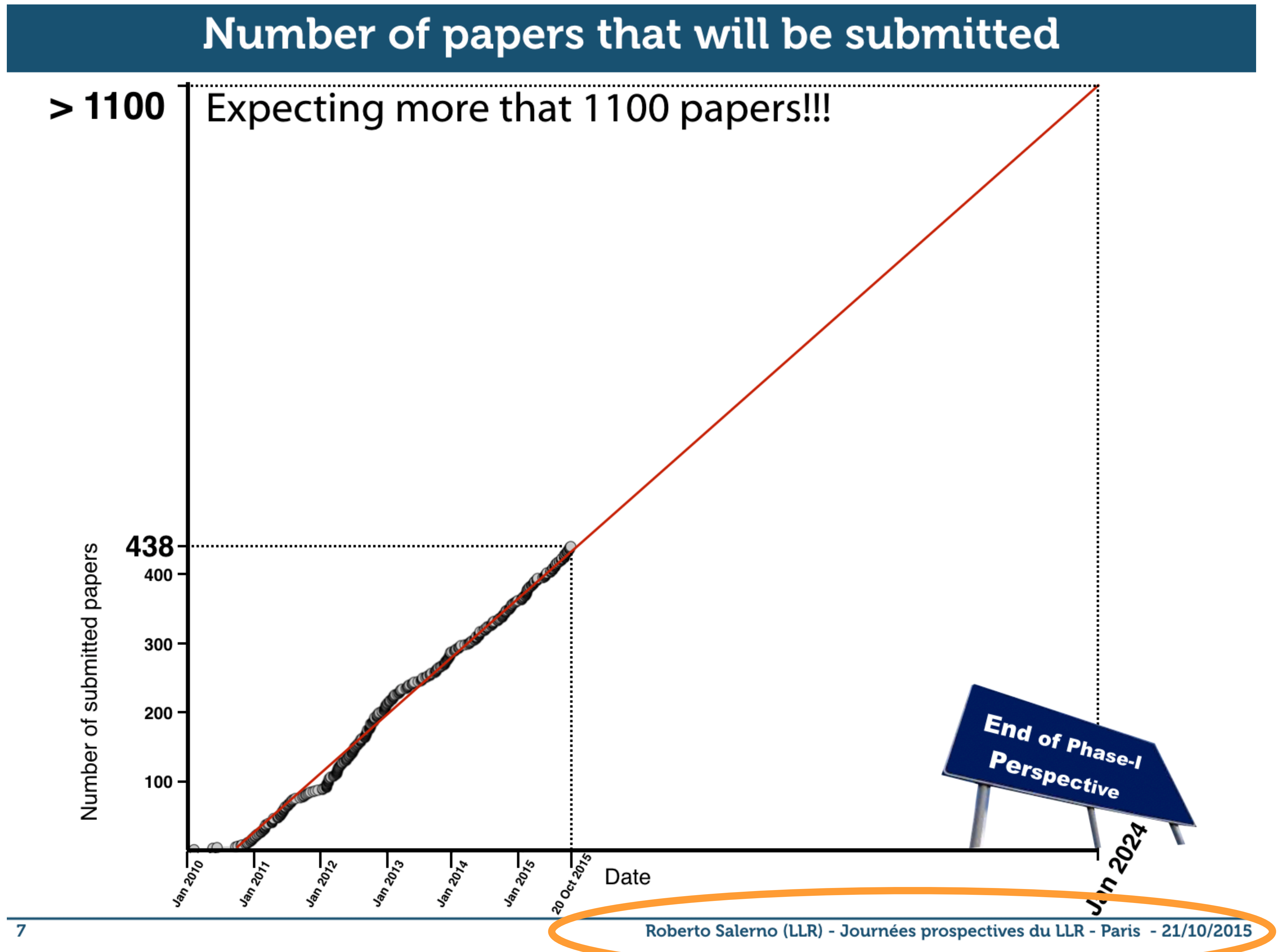
PUBLICATIONS

More than 900 LHC-collisions based paper already submitted by CMS for publication!

+ the same order by ATLAS



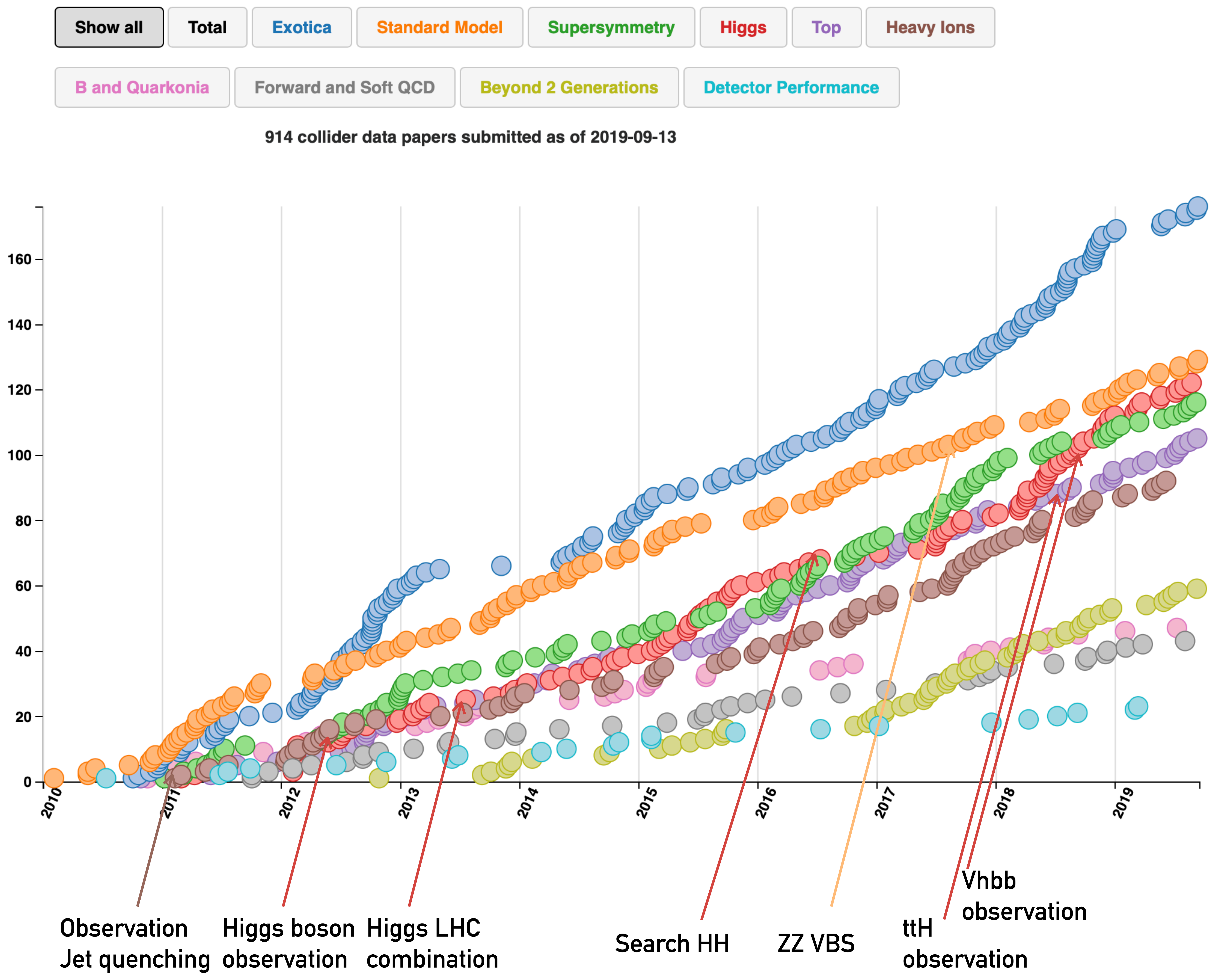
At the 2015 "Journées prospectives"



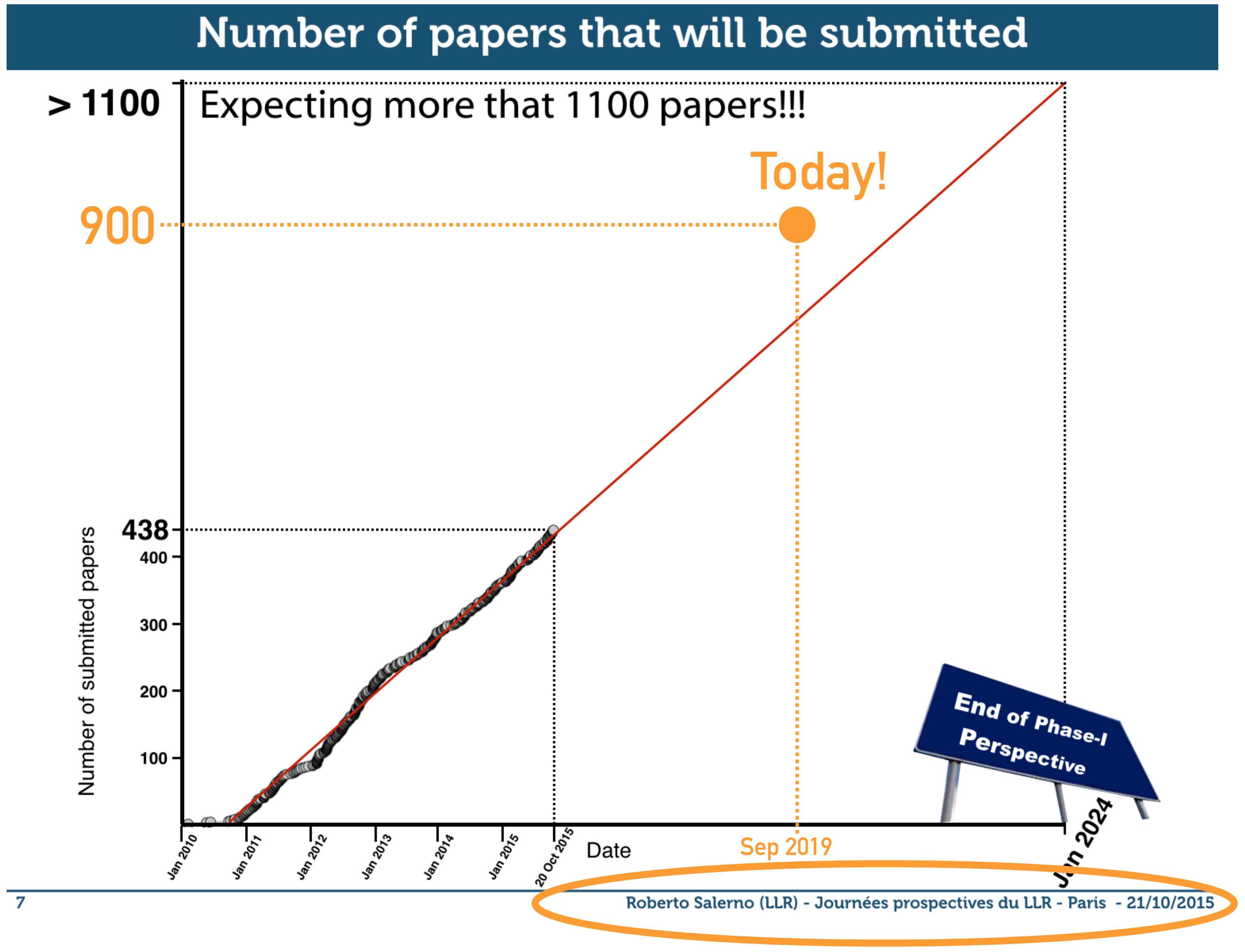
PUBLICATIONS

More than 900 LHC-collisions based paper already submitted by CMS for publication!

+ the same order by ATLAS

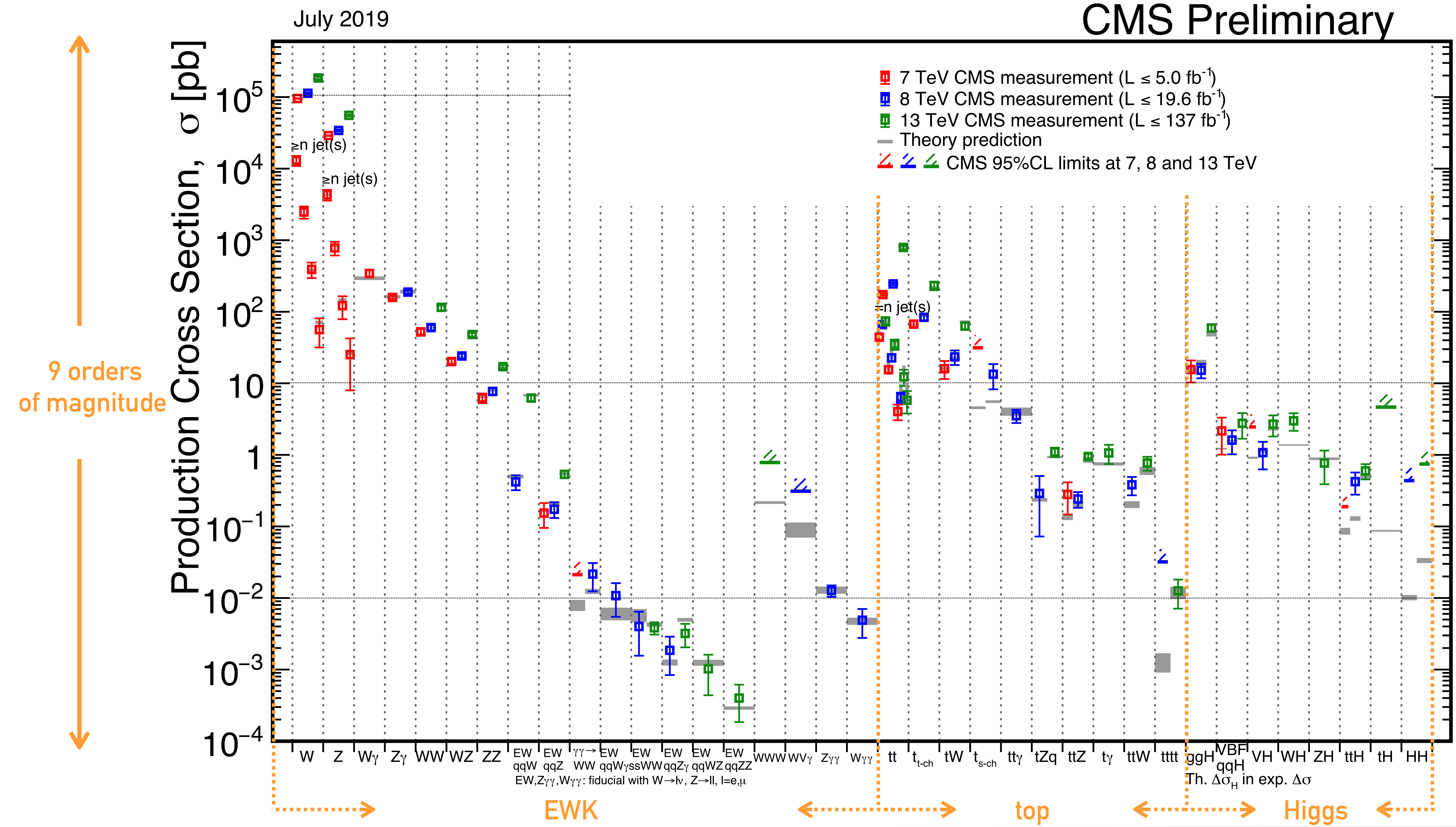


At the 2015 "Journées prospectives"



LHC projections usually are a bit conservative!

A Summary In A Single Plot



A Summary In A Single Plot

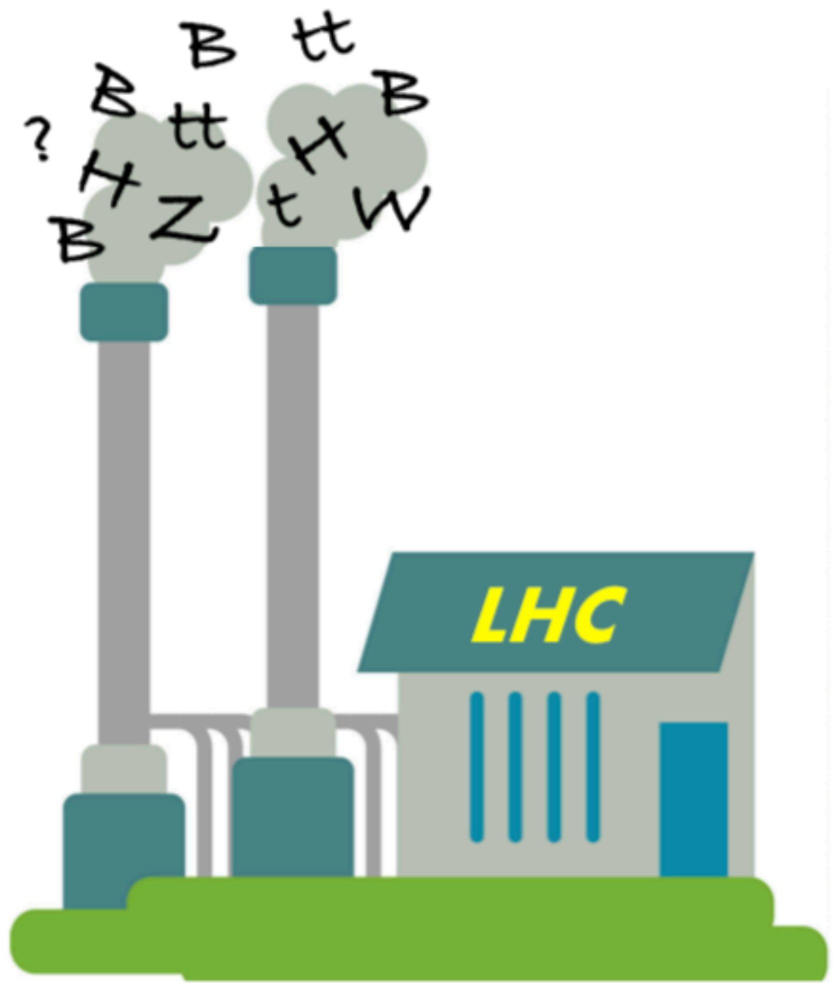
July 2019 CMS Preliminary

9 orders of magnitude

Production Cross Section, σ [pb]

The LHC is an **everything** factory

Particle	Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 million	
Top quark	275 million	
Z boson	2.8 billion	($\to \ell\ell$, 290 million)
W boson	12 billion	($\to \ell\nu$, 3.7 billion)
Bottom quark	~40 trillion	(significantly reduced by acceptance)

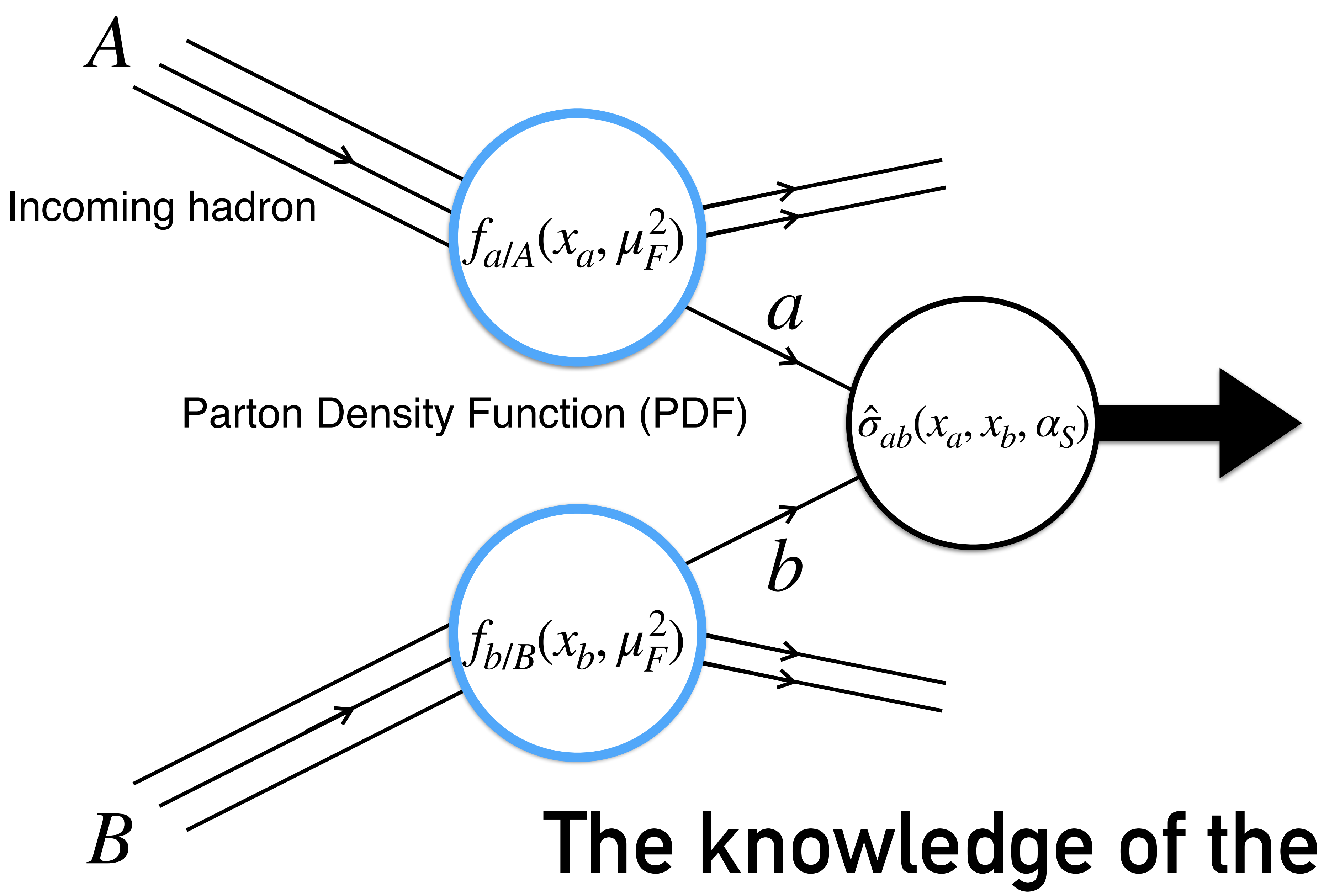


Broad physics potential by probing with high-precision Higgs and other Standard Model processes, detecting very rare processes, and exploring new physics via direct and indirect measurements

Andreas Hoecker EPS-HEP 2019

EWK top Higgs

ULTIMATE HL-LHC PDF



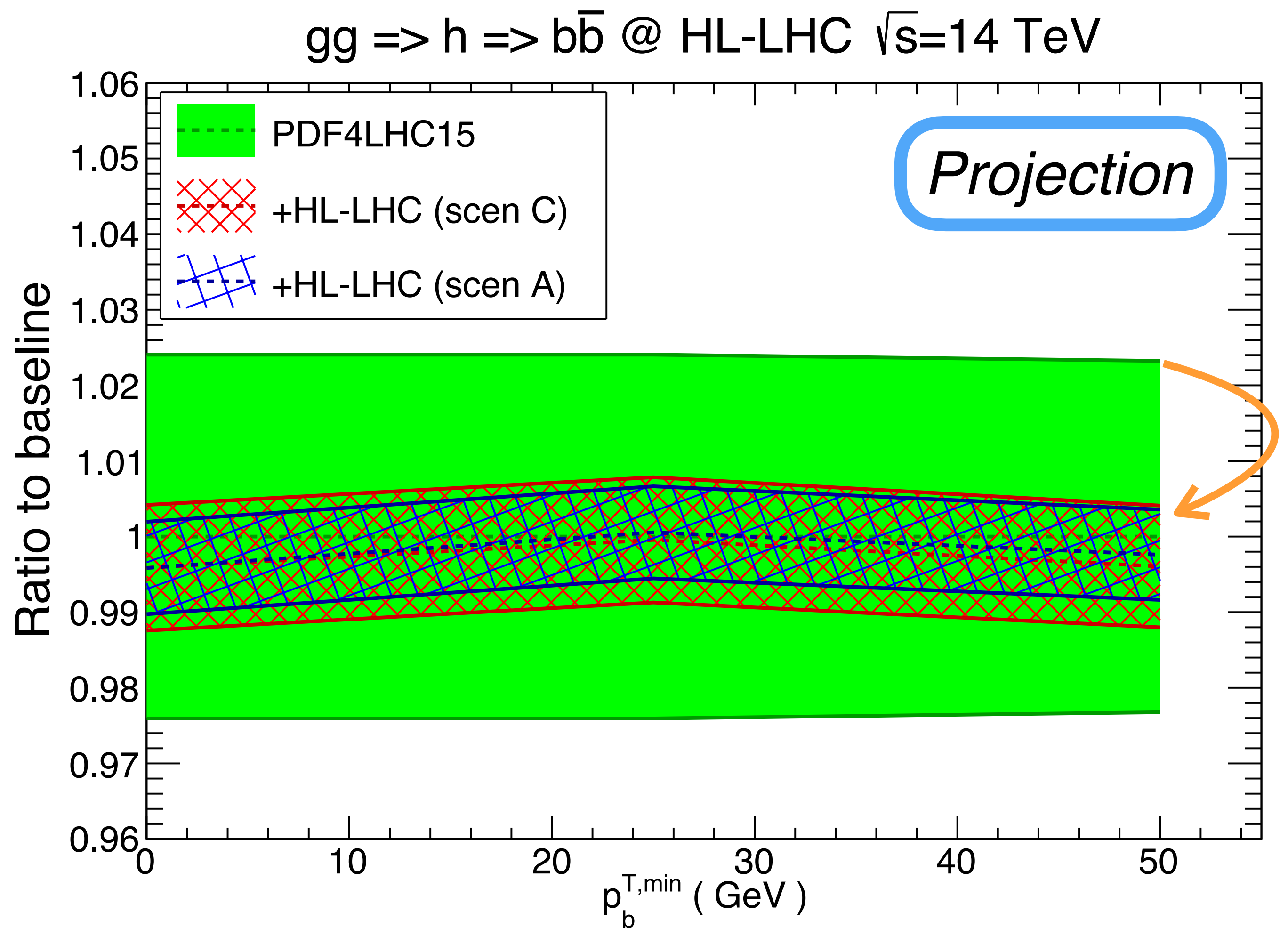
All hard production processes start from a partonic collision. Their rate is determined by the PDFs.
The PDFs functional form and uncertainty are not predicted by perturbative QCD and have to be measured experimentally.

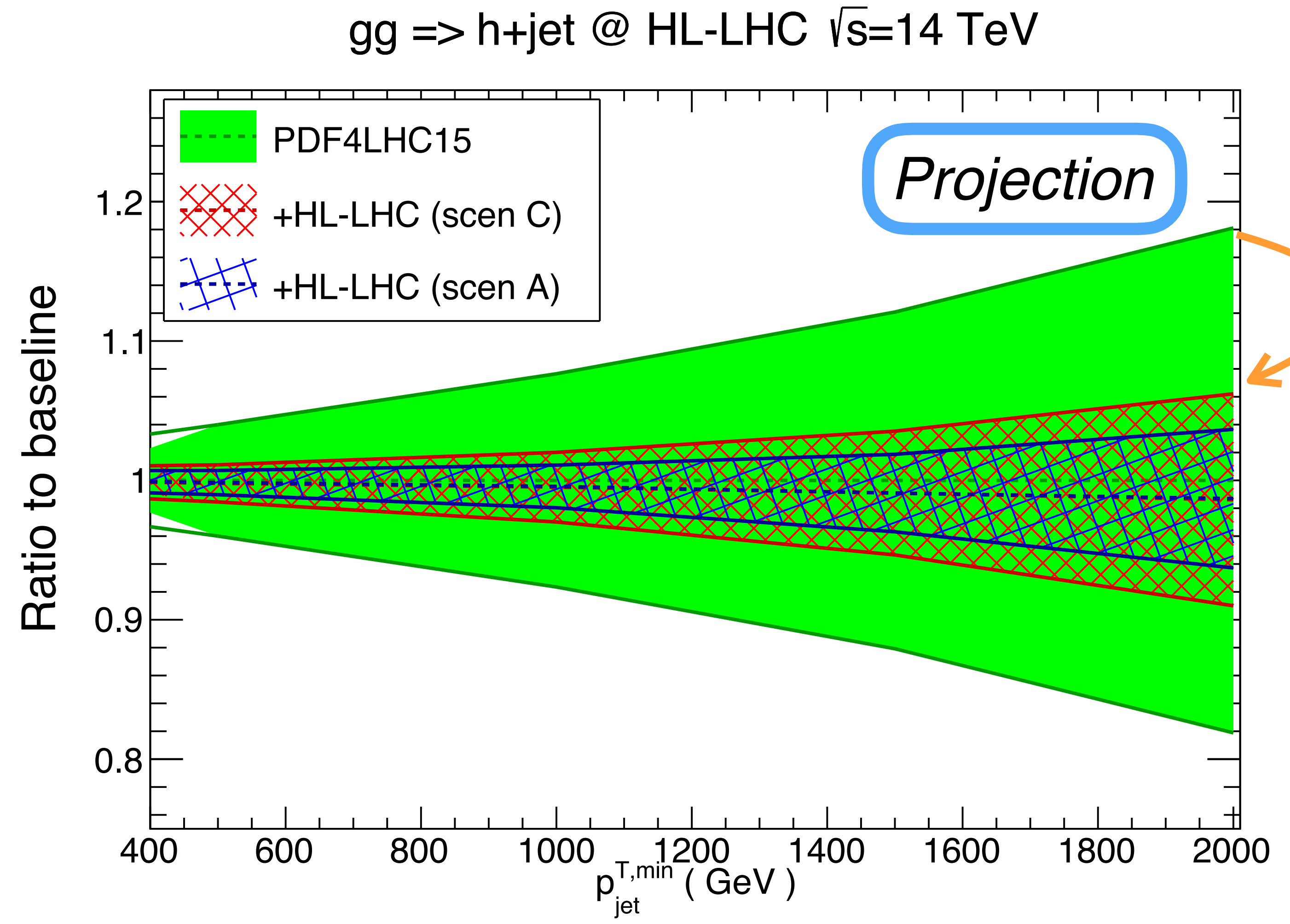
$$\sigma_{AB} = \sum_{a,b} \int dx_a dx_b \, f_{a/A}(x_a, \mu_F^2) \, f_{b/B}(x_b, \mu_F^2) \, \hat{\sigma}_{ab}(x_a, x_b, \alpha_S(\mu_R^2))$$

The knowledge of the PDFs is fundamental to extract couplings from cross-section measurements or from kinematical distributions

Quantify the precision of the PDF at the end of the HL-LHC running

pseudo-data generated for various inputs: top, Drell-Yan, photons, W+charm, W and Z in the forward region, inclusive jets…

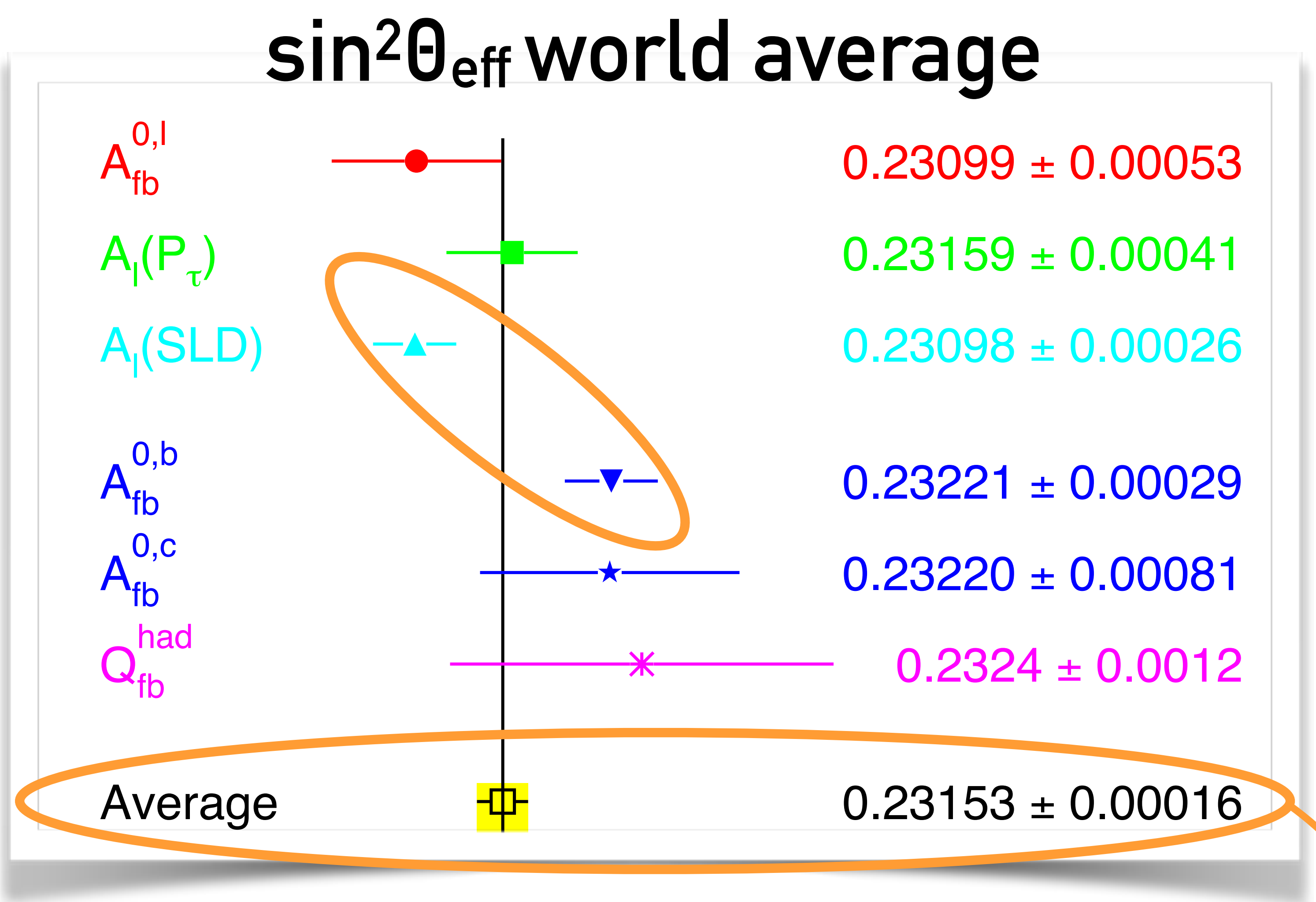




PDF uncertainties will improve by a factor 2 to 4

WEAK MIXING ANGLE

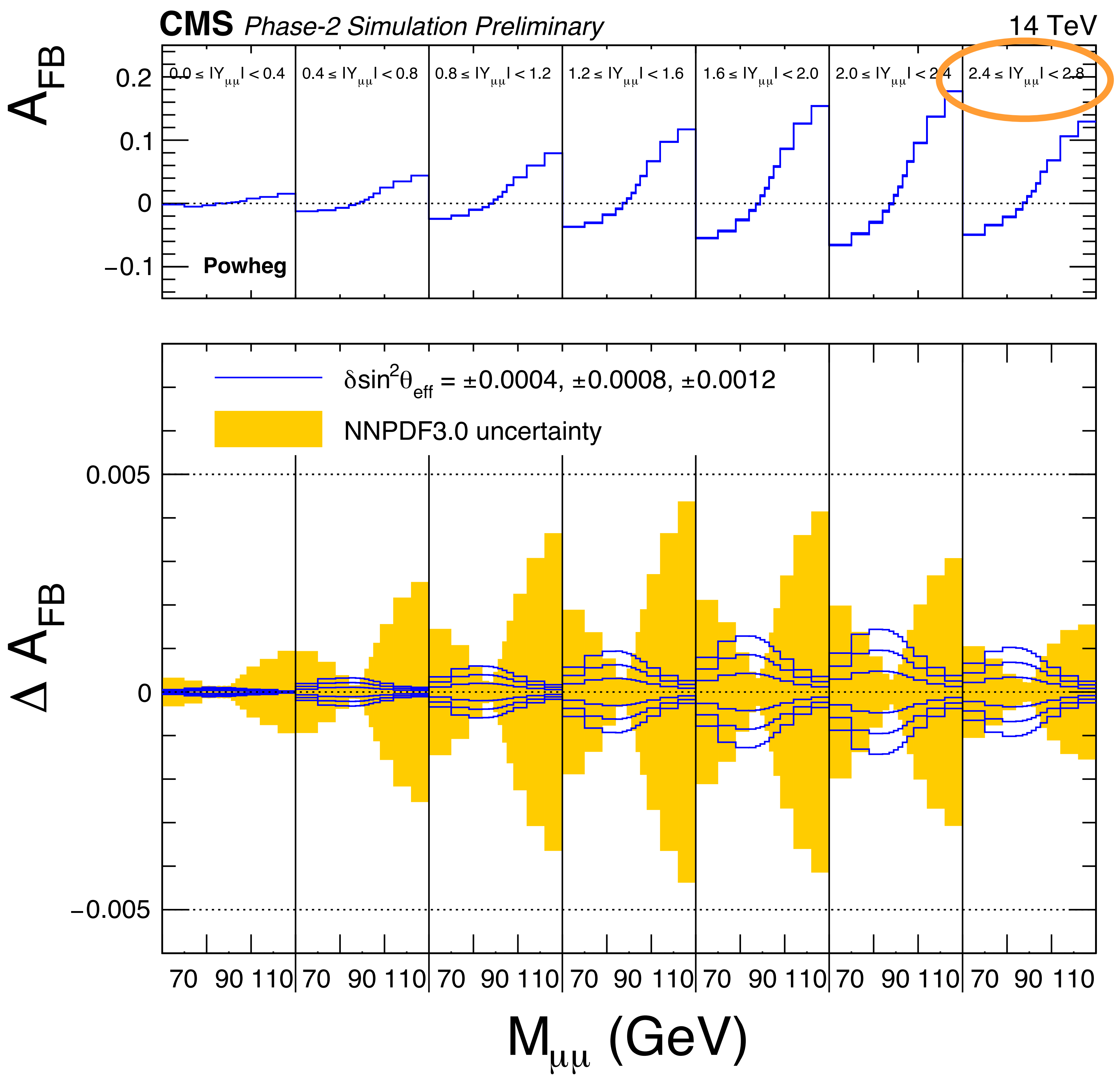
The world average of the weak mixing angle $\sin^2\theta_{eff}$ is dominated by determinations based on LEP and SLD data that differ of > 3σ.

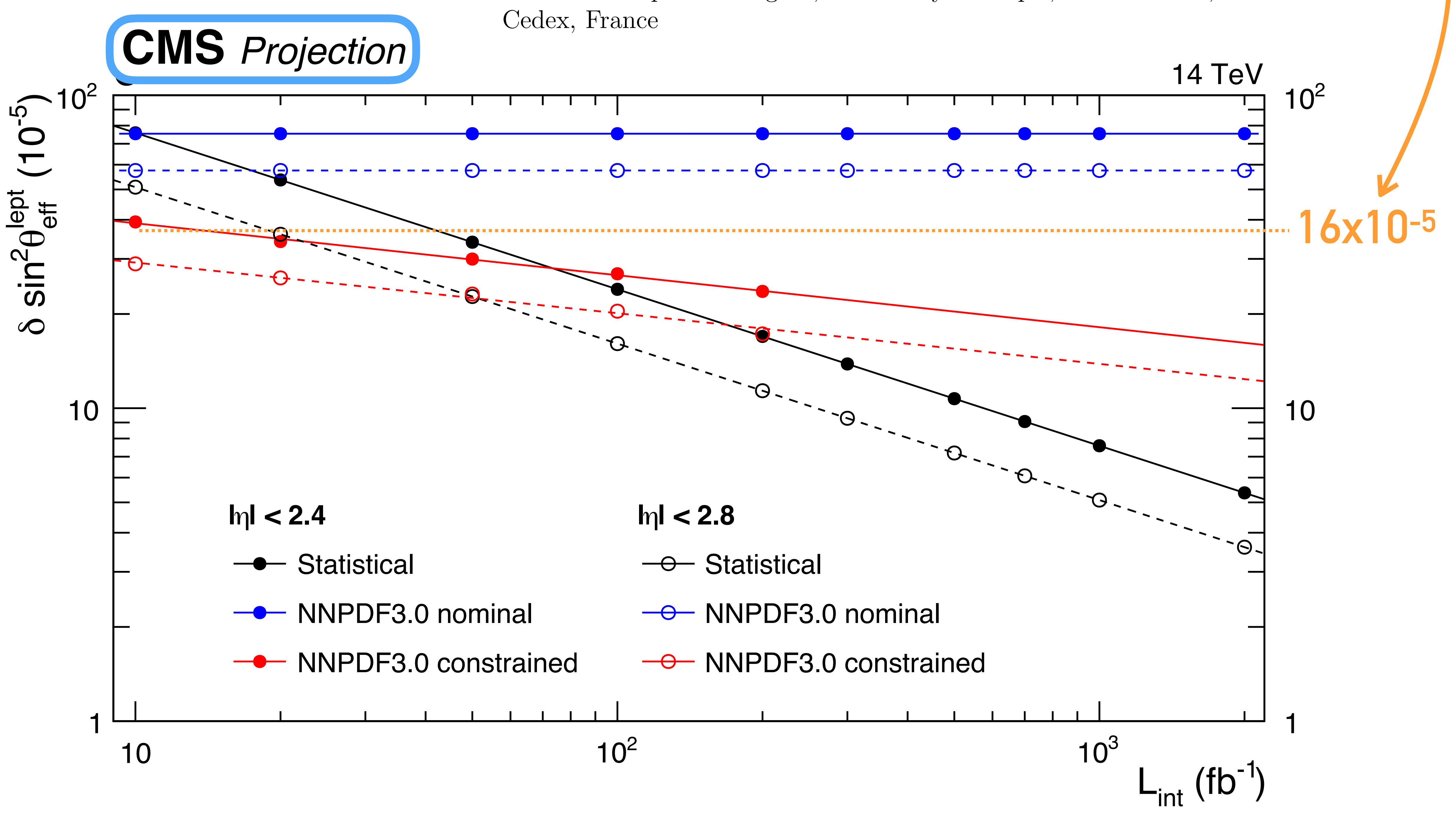


A. Blondel,[10,a12] G. Bonneaud,[10] J.-C. Brient,[10] F. Machefert,[10] A. Rougé,[10] M. Rumpf,[10] M. Swynghedauw,[10] R. Tanaka,[10] M. Verderi,[10] H. Videau,[10] V. Ciulli,[11] E. Focardi,[11] G. Parrini,[11]

[10] Laoratoire Leprince-Ringuet, Ecole Polytechnique, IN²P³-CNRS, F-91128 Palaiseau Cedex, France

Forward-backward asymmetry distribution

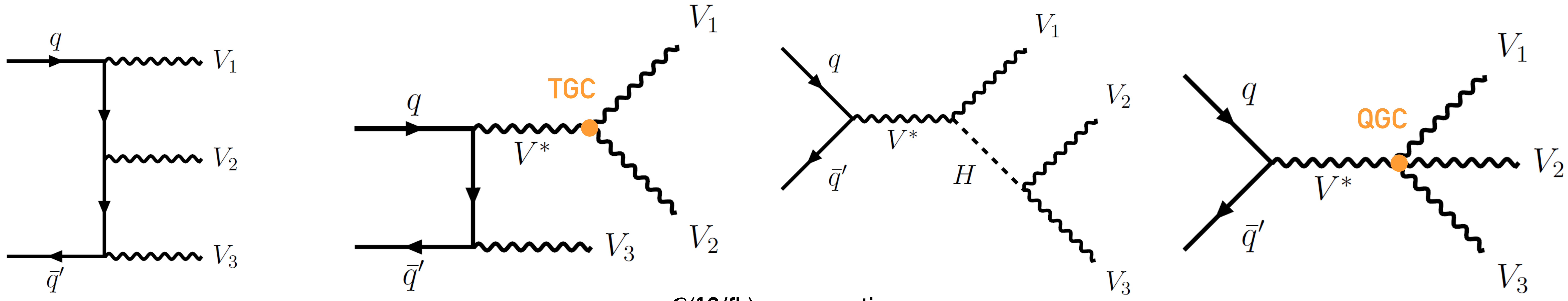




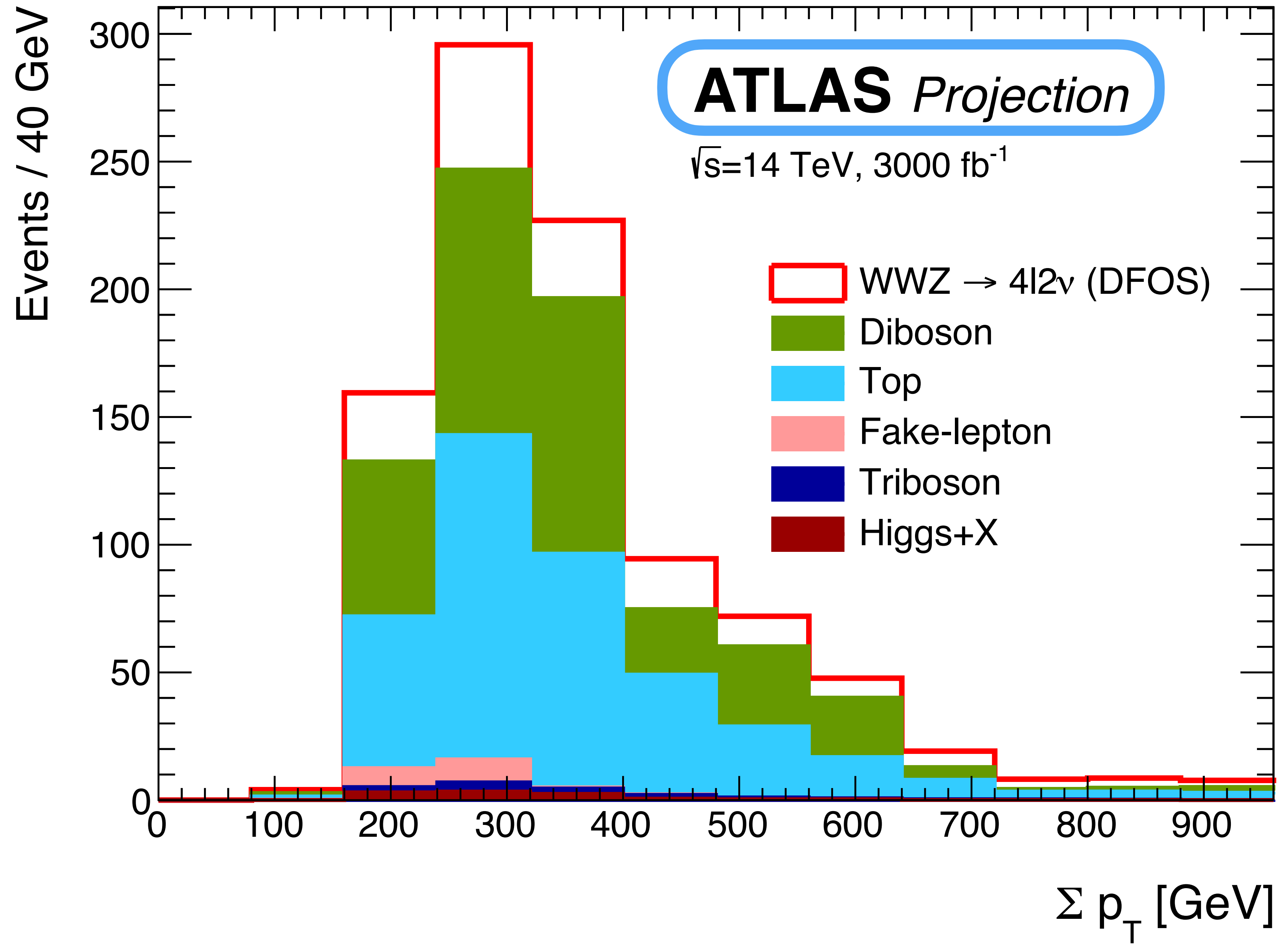
Increase forward detector acceptance is a key element !

Triboson Production

It can signal the presence of anomalous EW couplings (TGC/QGC), and of new physics at energy scales beyond the reach of direct resonance production



$\mathcal{O}$(10/fb) cross sections

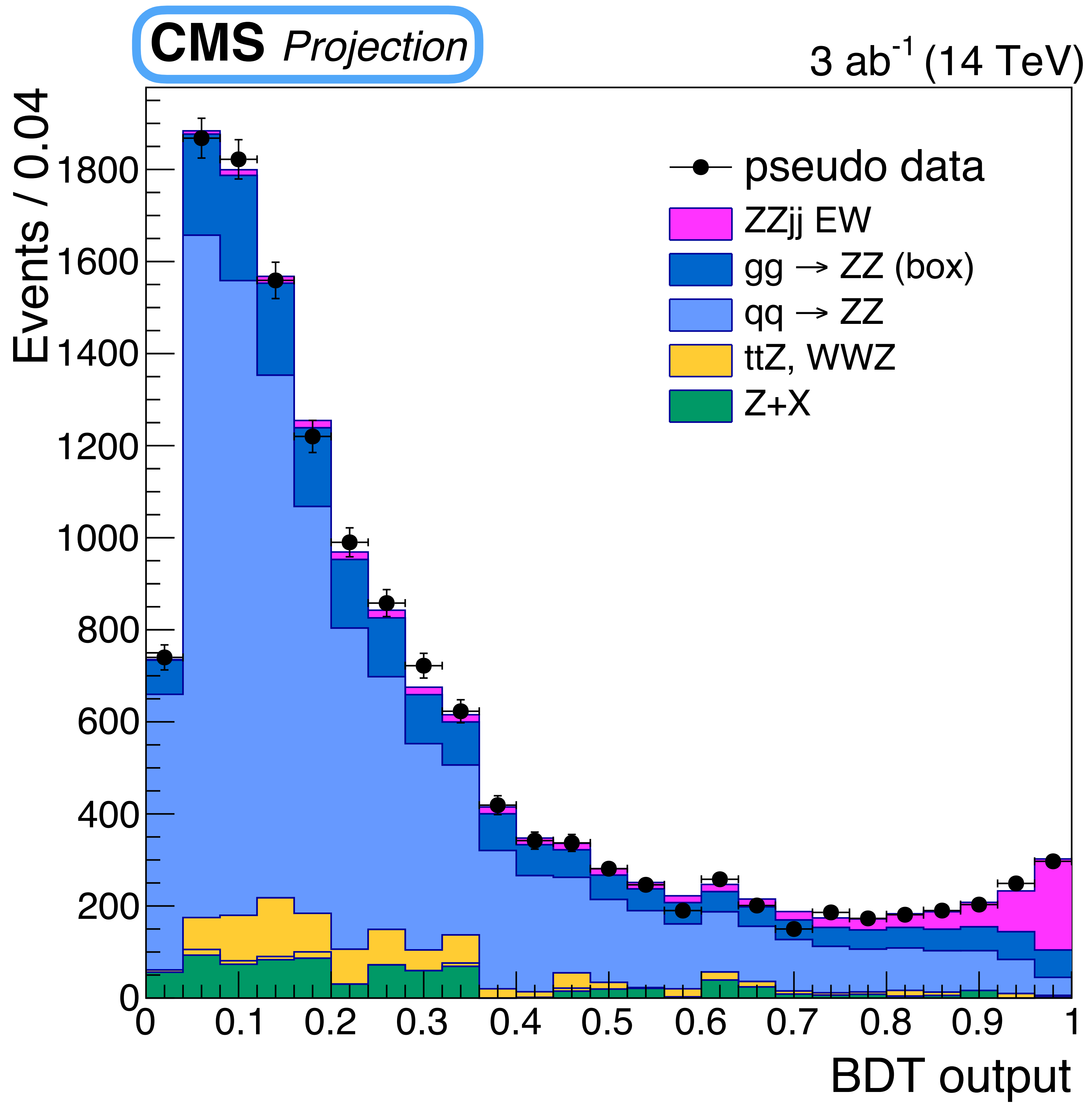


Channel	$\frac{\Delta\mu}{\mu}$ (3000 fb^{-1})	$\frac{\Delta\mu}{\mu}$ (4000 fb^{-1})
$WWW \to 3\ell\, 3\nu$ (0SFOS)	11%	10%
$WWZ \to 4\ell\, 2\nu$ (DFOS)	27%	25%
$WZZ \to 5\ell 1\nu$	36%	31%

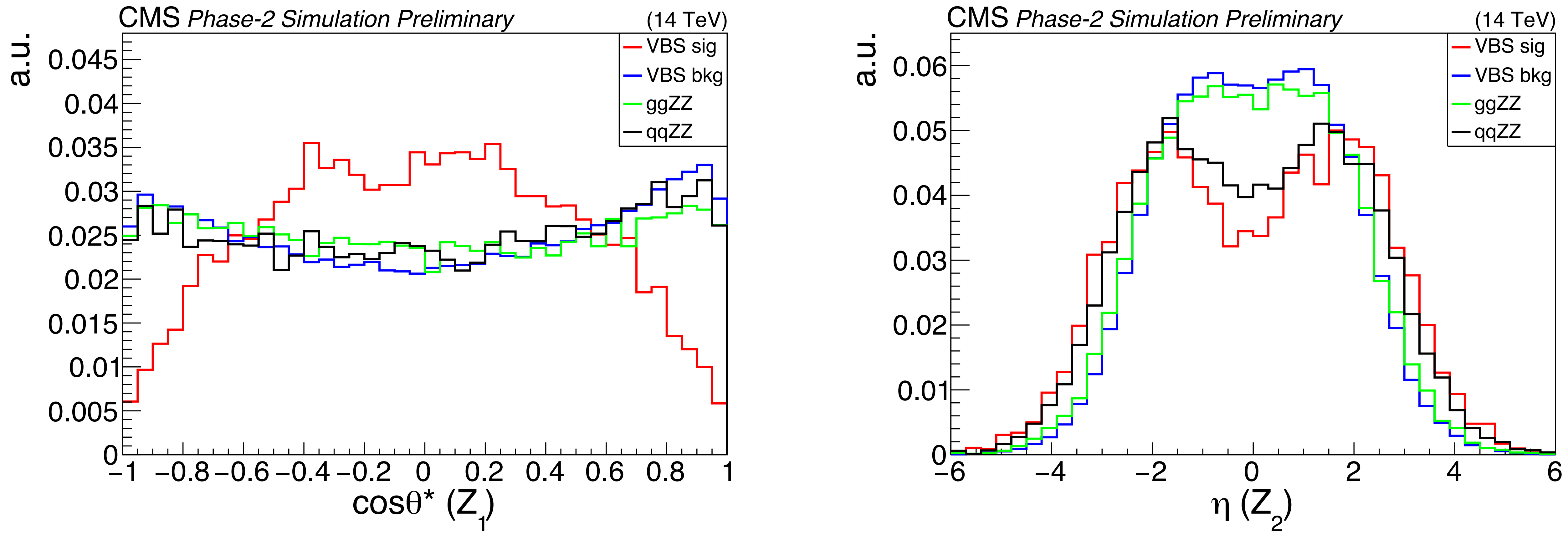
Expected precision on the signal strength measurement

Weak Vector Boson Scattering (VBS)

VBS provides a key opportunity to probe the nature of the electroweak symmetry breaking mechanism. Topology : two incoming quarks radiate bosons which interact, yielding a final state of two jets and two massive bosons



Discrimination between $Z_LZ_L \to Z_LZ_L$ (sig) and $Z_TZ_L \to Z_TZ_L$ or $Z_TZ_T \to Z_TZ_T$ (bck)



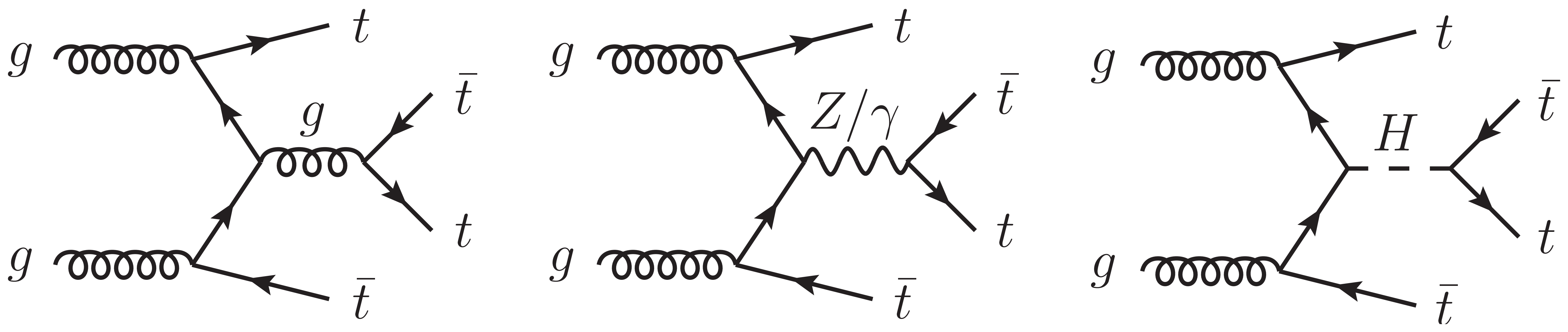
More coverage

η coverage	significance	VBS Z_LZ_L fraction uncertainty (%)
$\|\eta\| < 2.5(2.4)$	1.22σ	88
$\|\eta\| < 3.0(2.8)$	1.38σ	78
$\|\eta\| < 4.0(2.8)$	1.43σ	75

At HL-LHC first study of the longitudinal scattering of weak bosons ($Z_LZ_L \to Z_LZ_L$)

Four Top Quarks Production

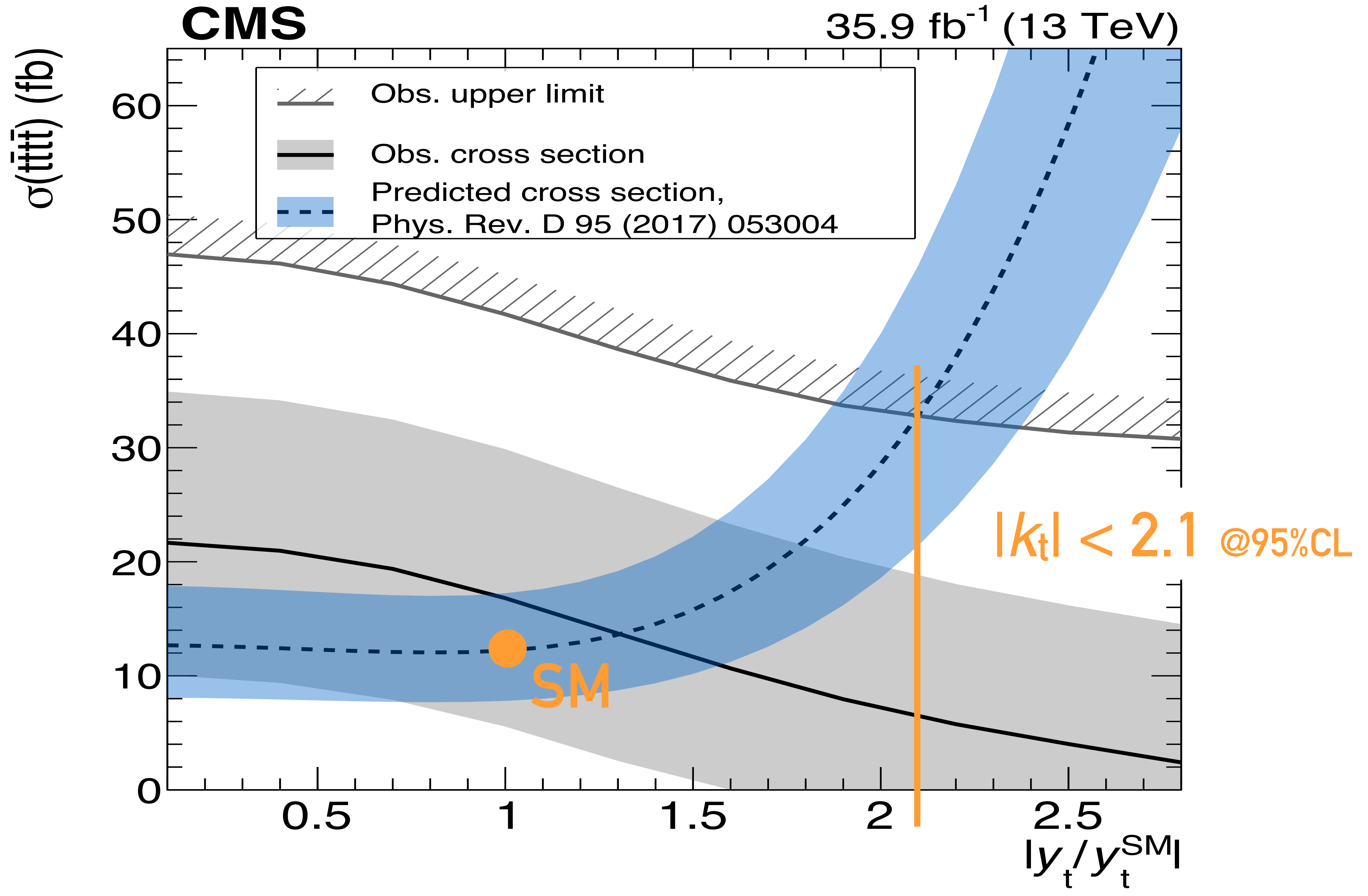
One of the rare SM processes that is expected to be discovered/studied by (HL-)LHC runs

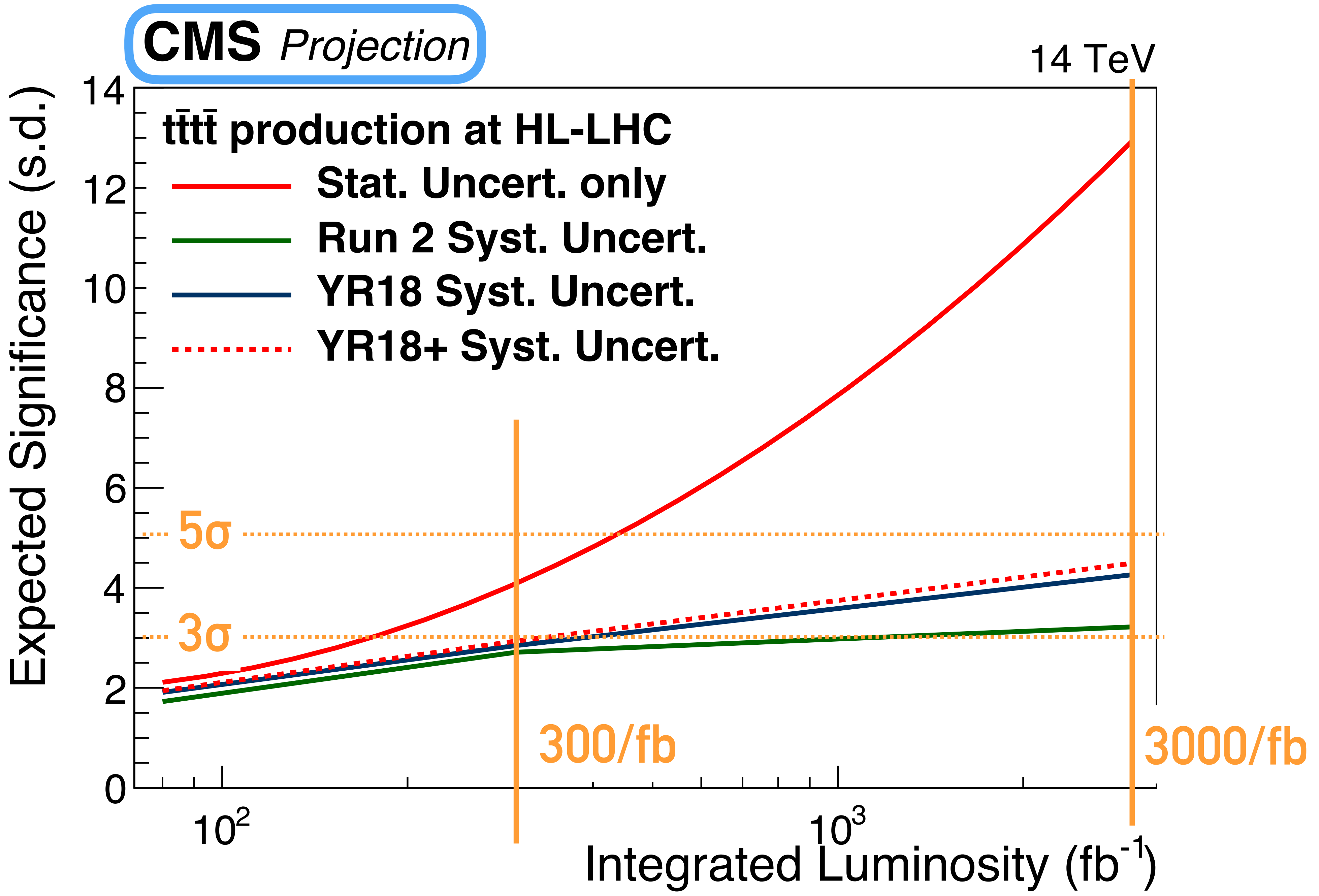


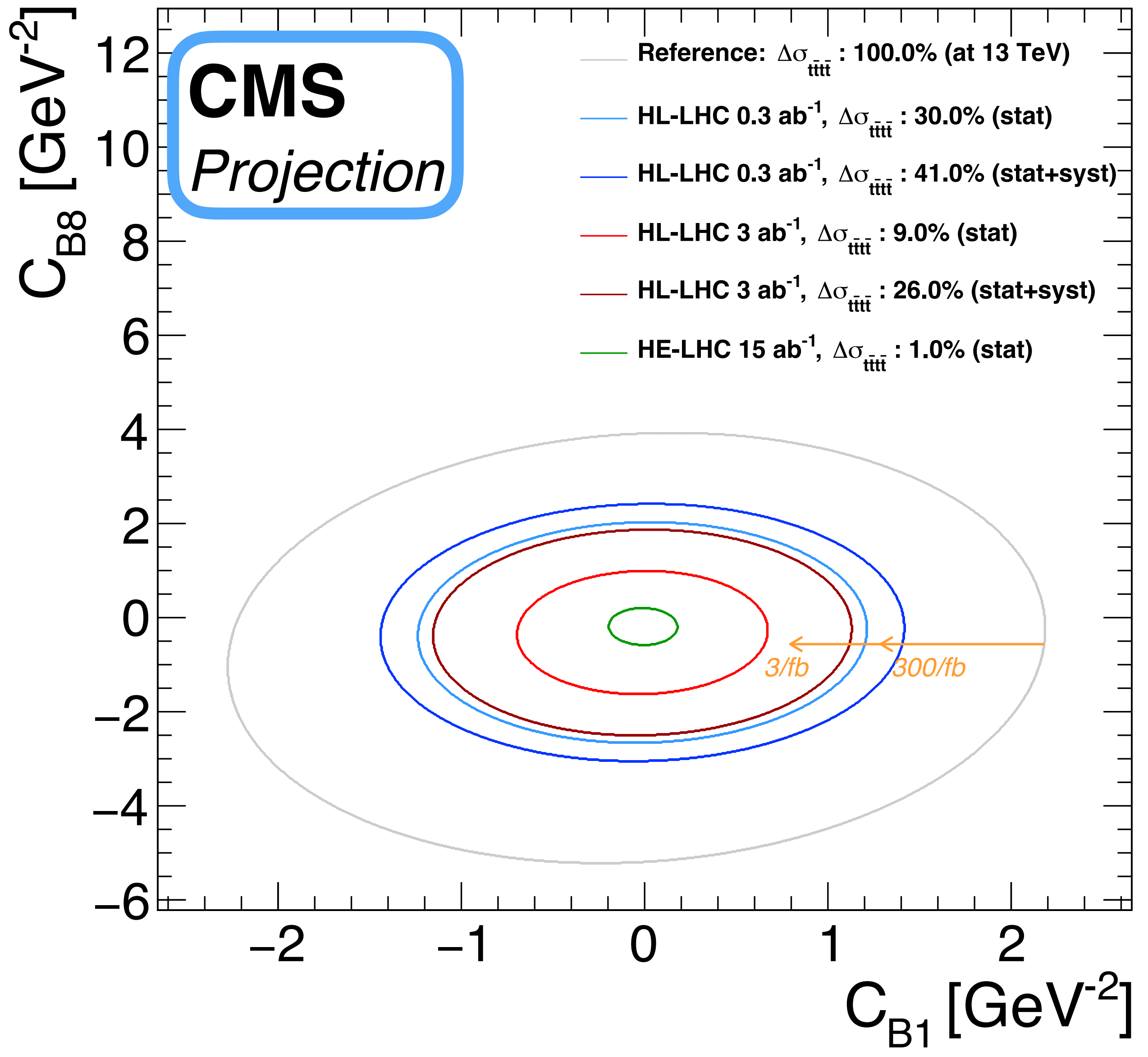
Higgs induced production
no depended of Γ_H

$$\sigma = \sigma_{g+Z/\gamma} + k_t^2\sigma_{int} + k_t^4\sigma_H = 12.0^{+2.1}_{-2.5}\ \text{fb @ 13TeV (where } k_t = y_t/y_t^{SM})$$

Increase of collision energy important, a 1.3 factor moving 13 TeV to 14 TeV

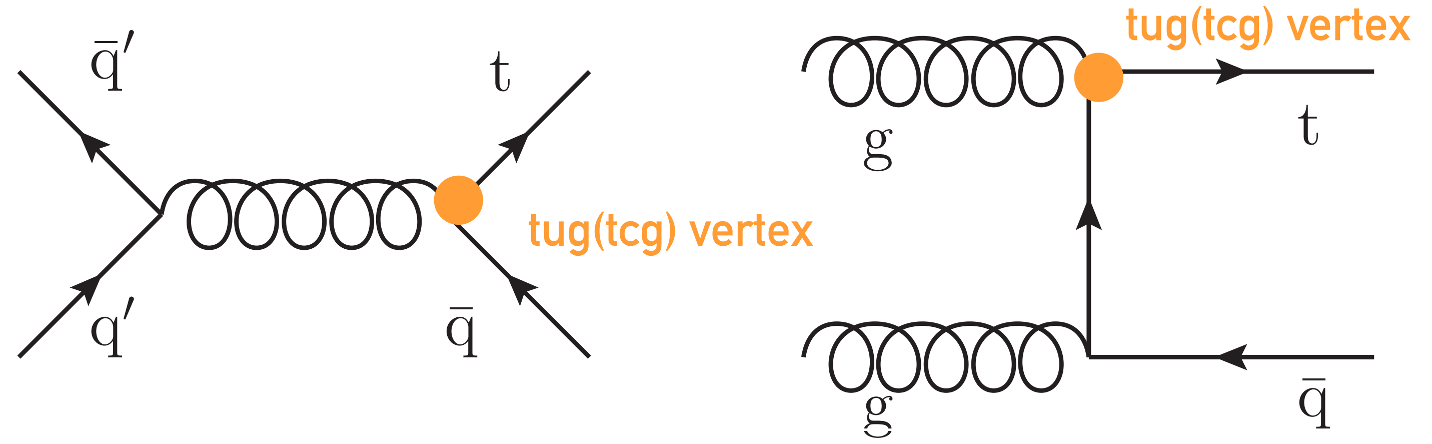






TOP FLAVOUR CHANGING NEUTRAL CURRENTS

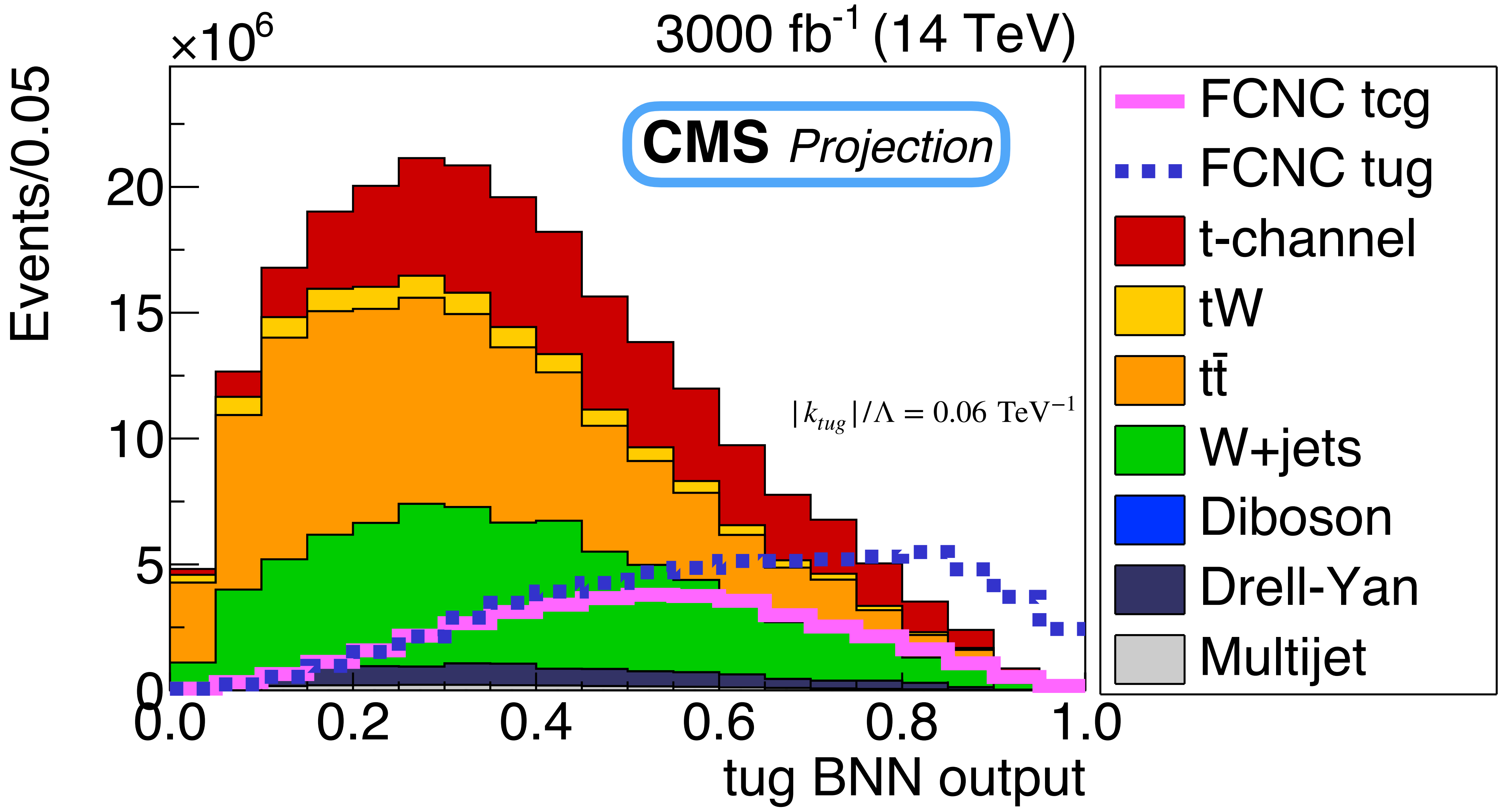
FCNC are forbidden at tree level, they occur only at one-loop level but are strongly suppressed by the GIM mechanism.

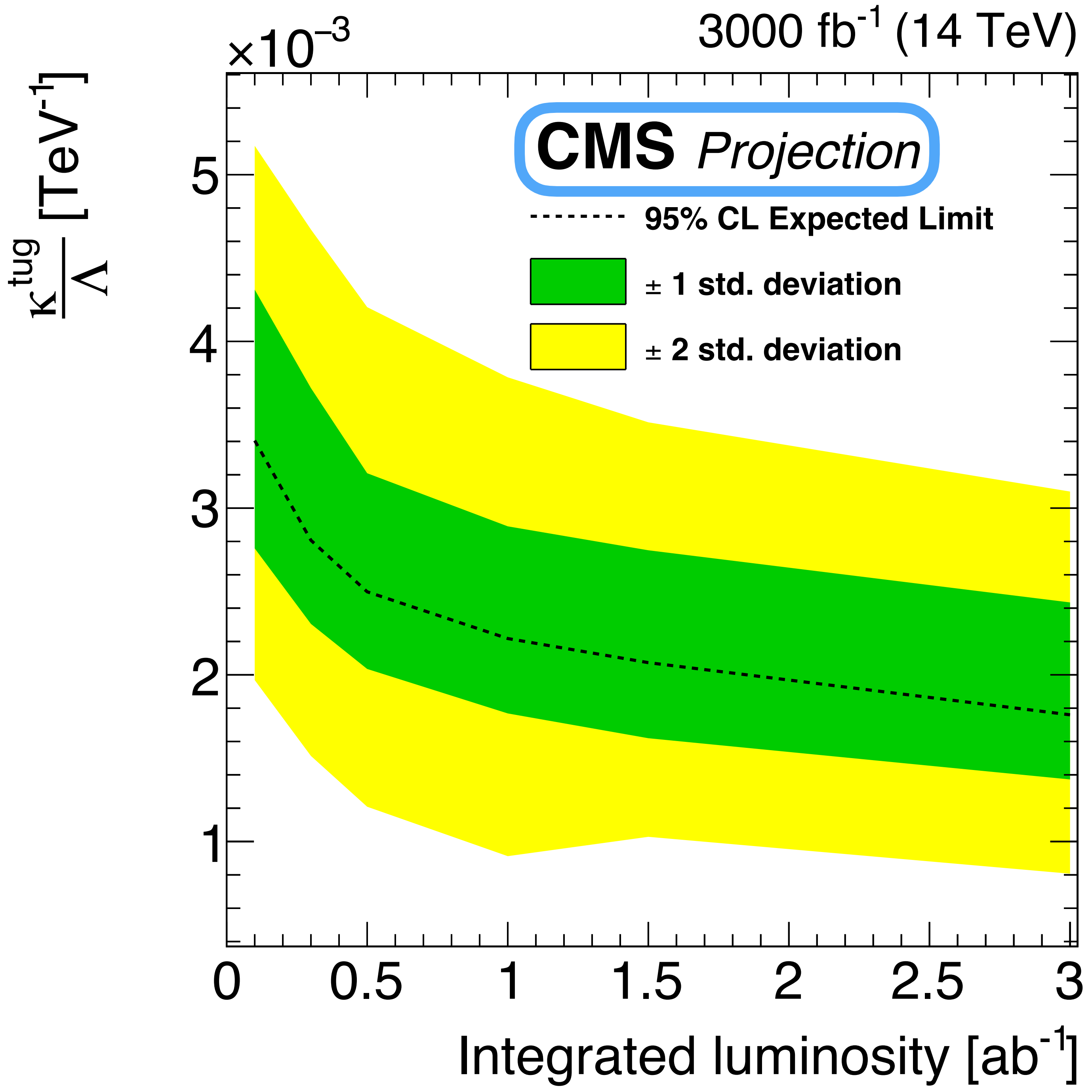


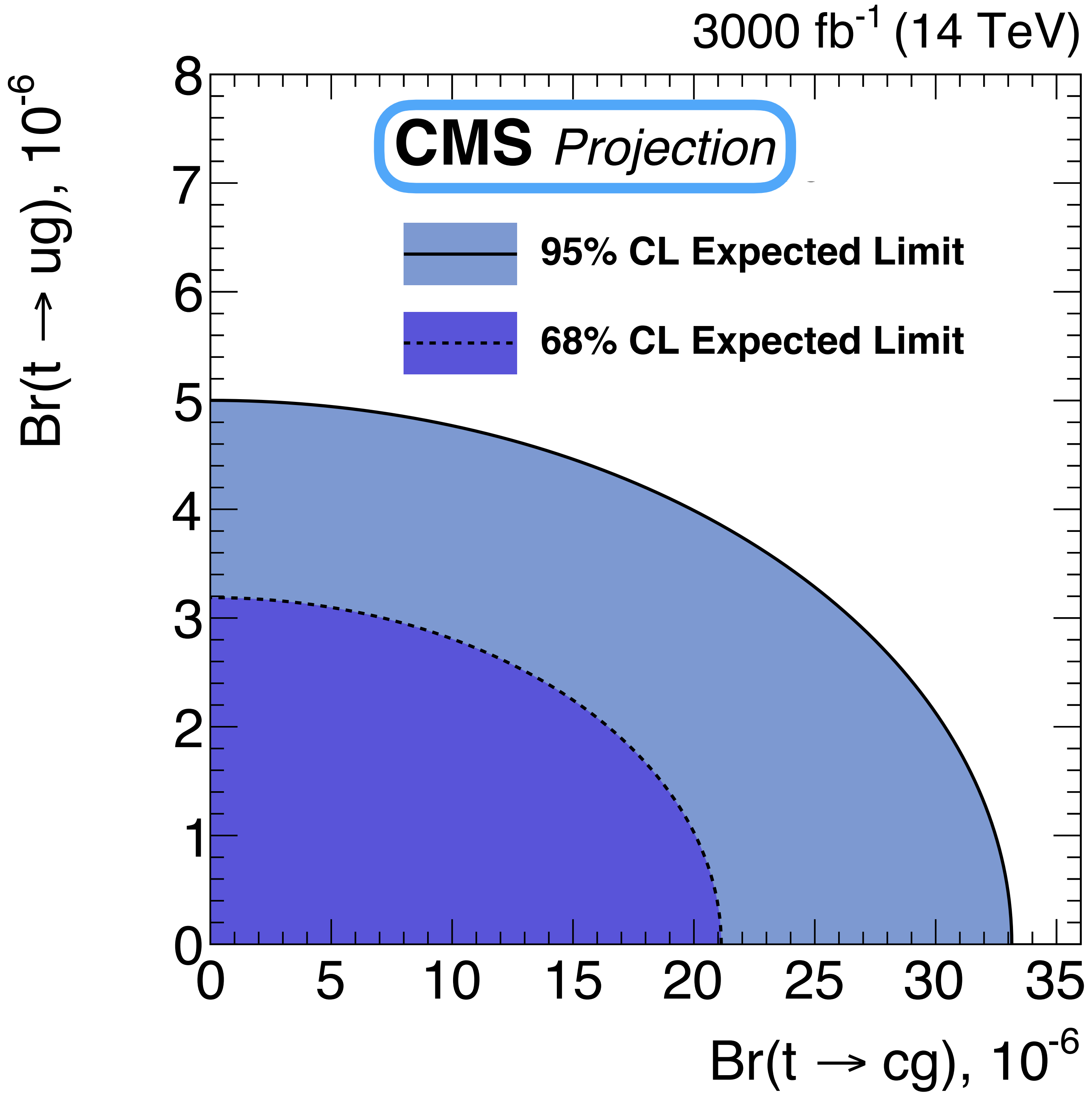
FCNC single top production processes

Model:	SM	QS	2HDM	FC 2HDM	MSSM	RPV SUSY	RS	EMF
$\mathcal{B}(t \to qZ)$:	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}	10^{-6}

Maximal FCNC decays predicted by some models







One order of magnitude improvement wrt existing LHC limits

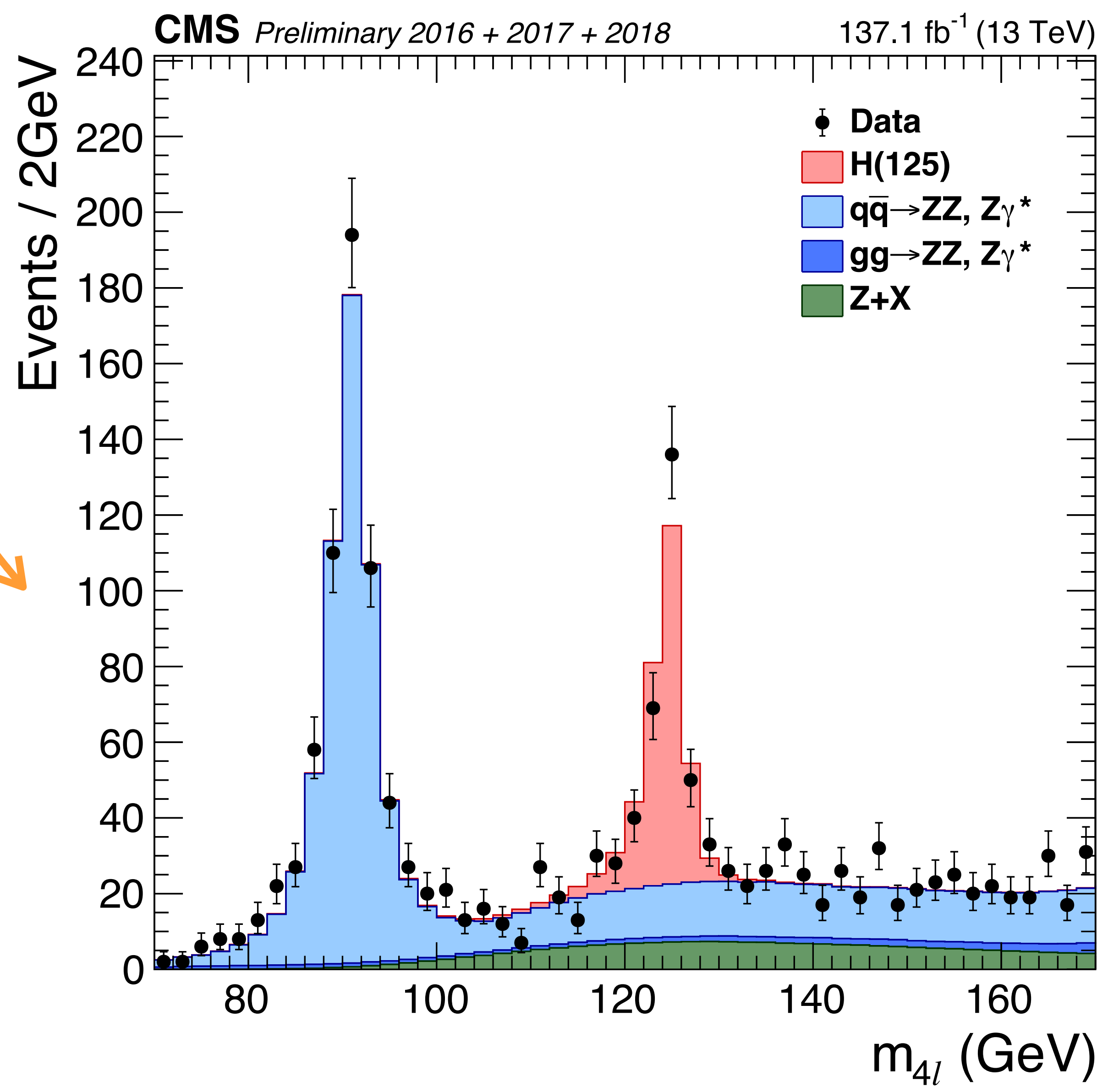
HIGGS BOSON TODAY

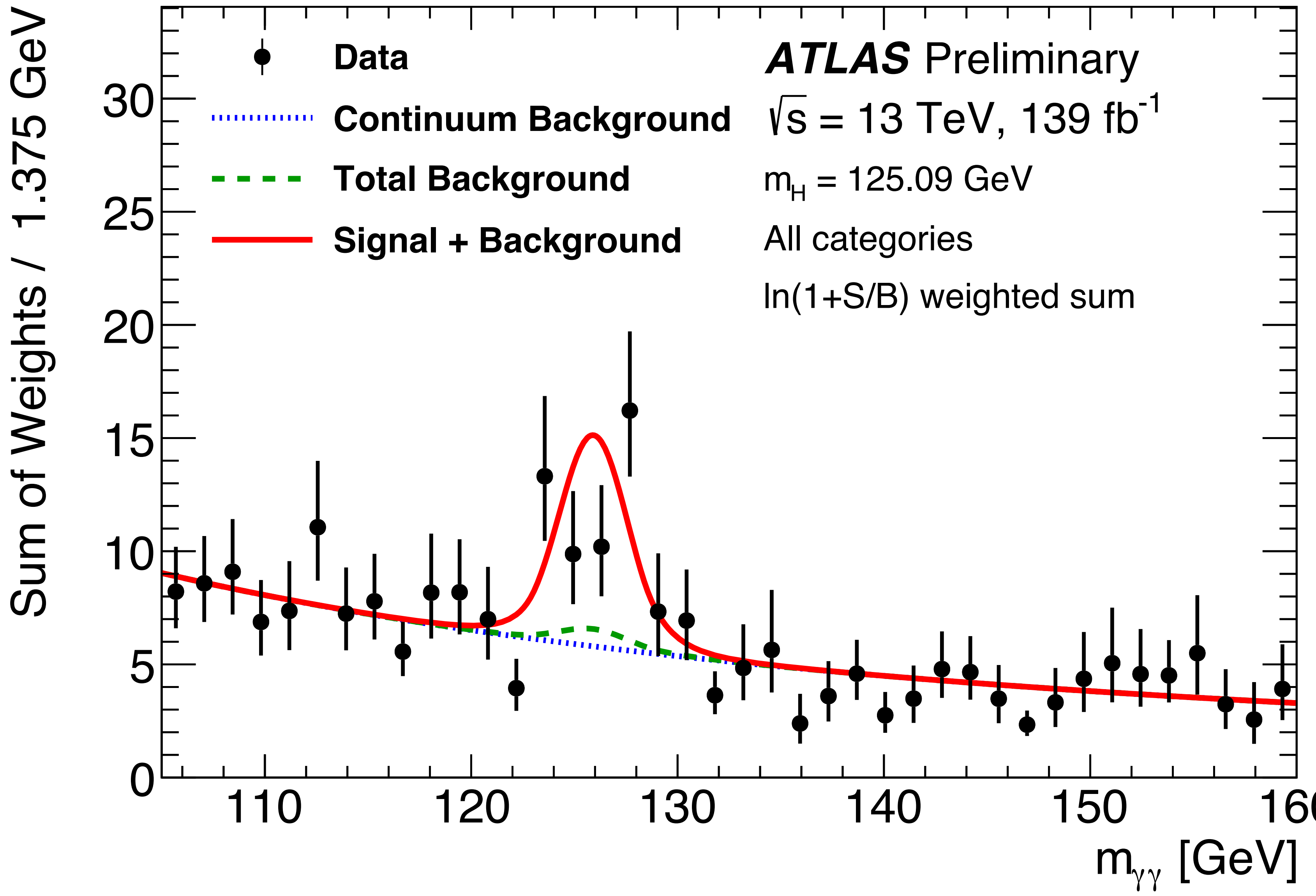
Using the LHC Run2 dataset (<5% of the final HL-LHC integrate luminosity)

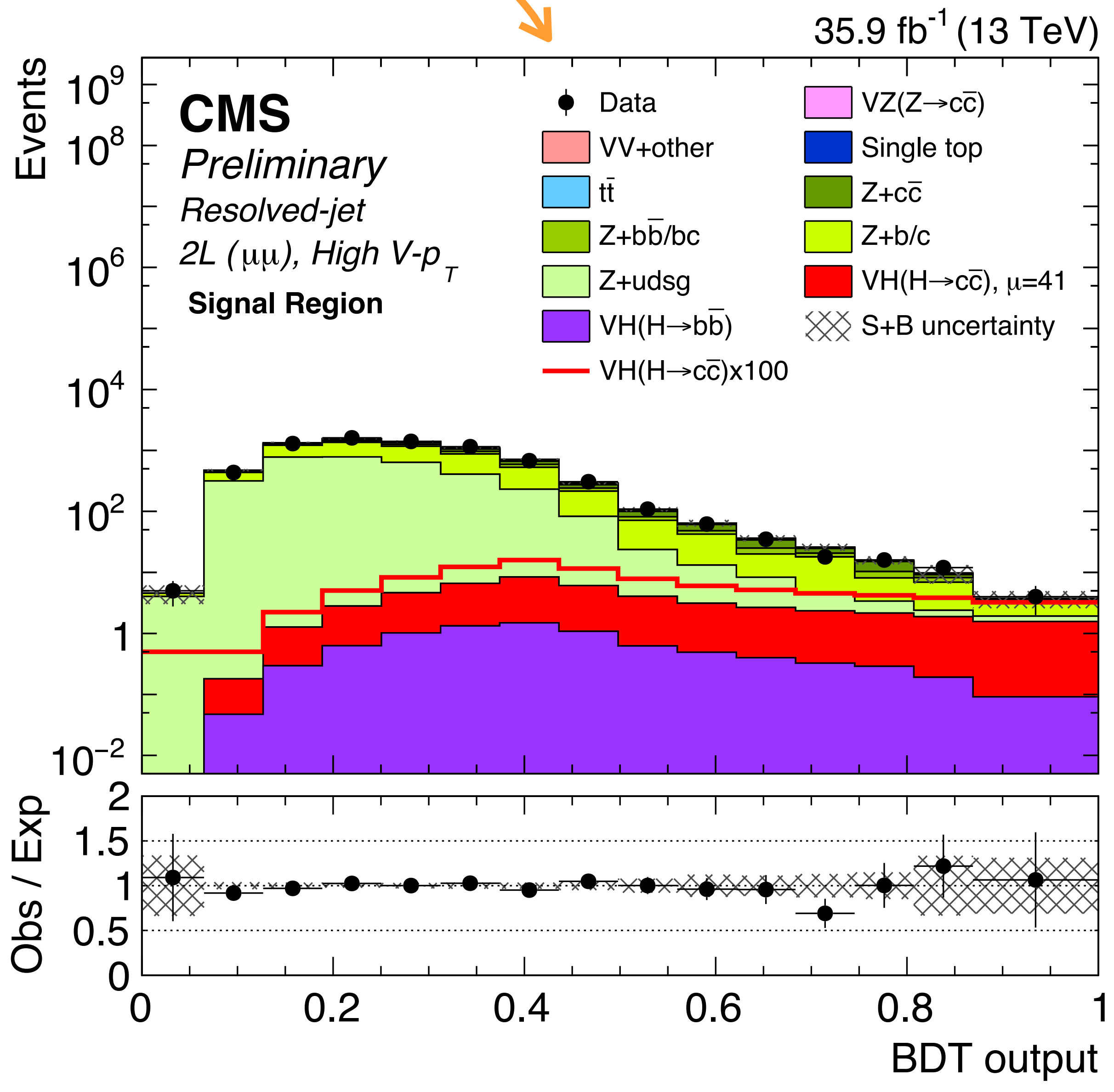
- Precision era in the gauge sector has started (towards <10% uncertainties)
- Switch from discovery to properties measurements using the 3rd-generation couplings
- Focus on rare processes

  evidence/observation of 2nd-generation coupling using LHC data

  probe charm-H interaction and Higgs self-coupling





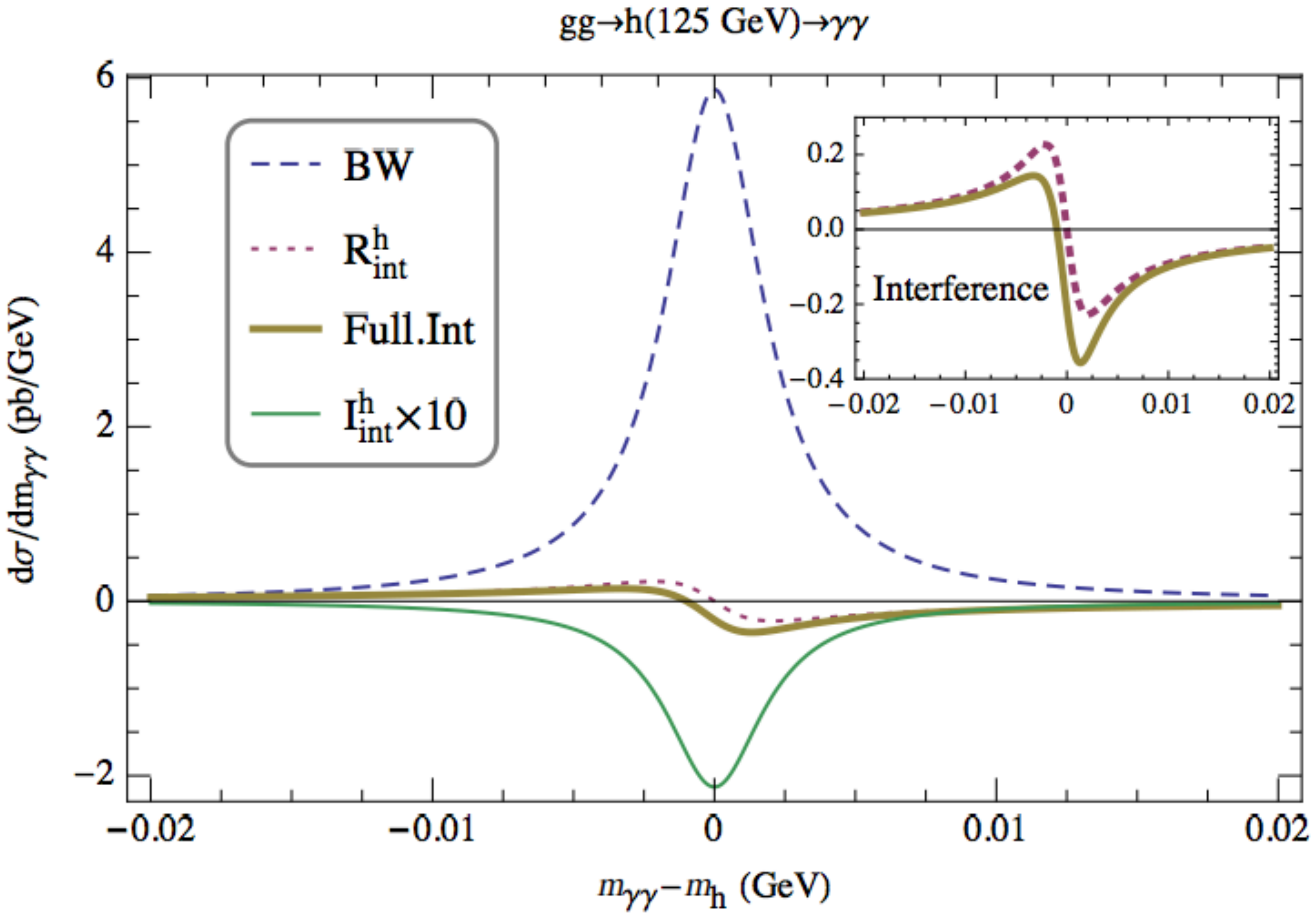


The determination of Higgs boson properties, and their connection to EWSB, is the primary target of the LHC/HL-LHC physics programmes

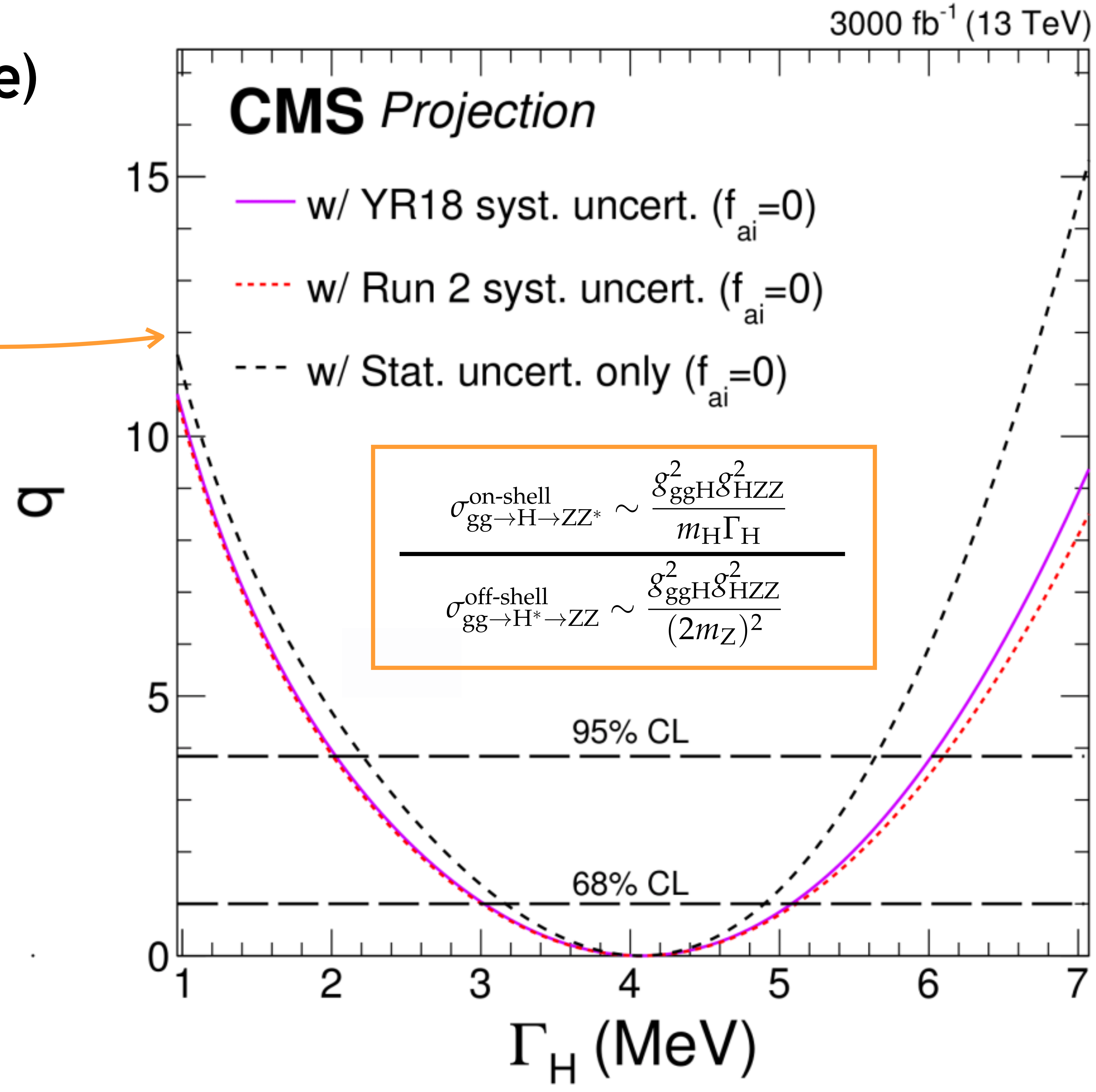
HIGGS BOSON WIDTH

A crucial parameter for BSM searches, in SM $c\tau_H = 48$ fm, small width $\Gamma_H = 4.1$ MeV

Direct measurements (on-shell line shape, lifetime) limited by detector resolutions, the way out are indirect measurements (off-shell production, interference, couplings)



Precision ~8-22xSM

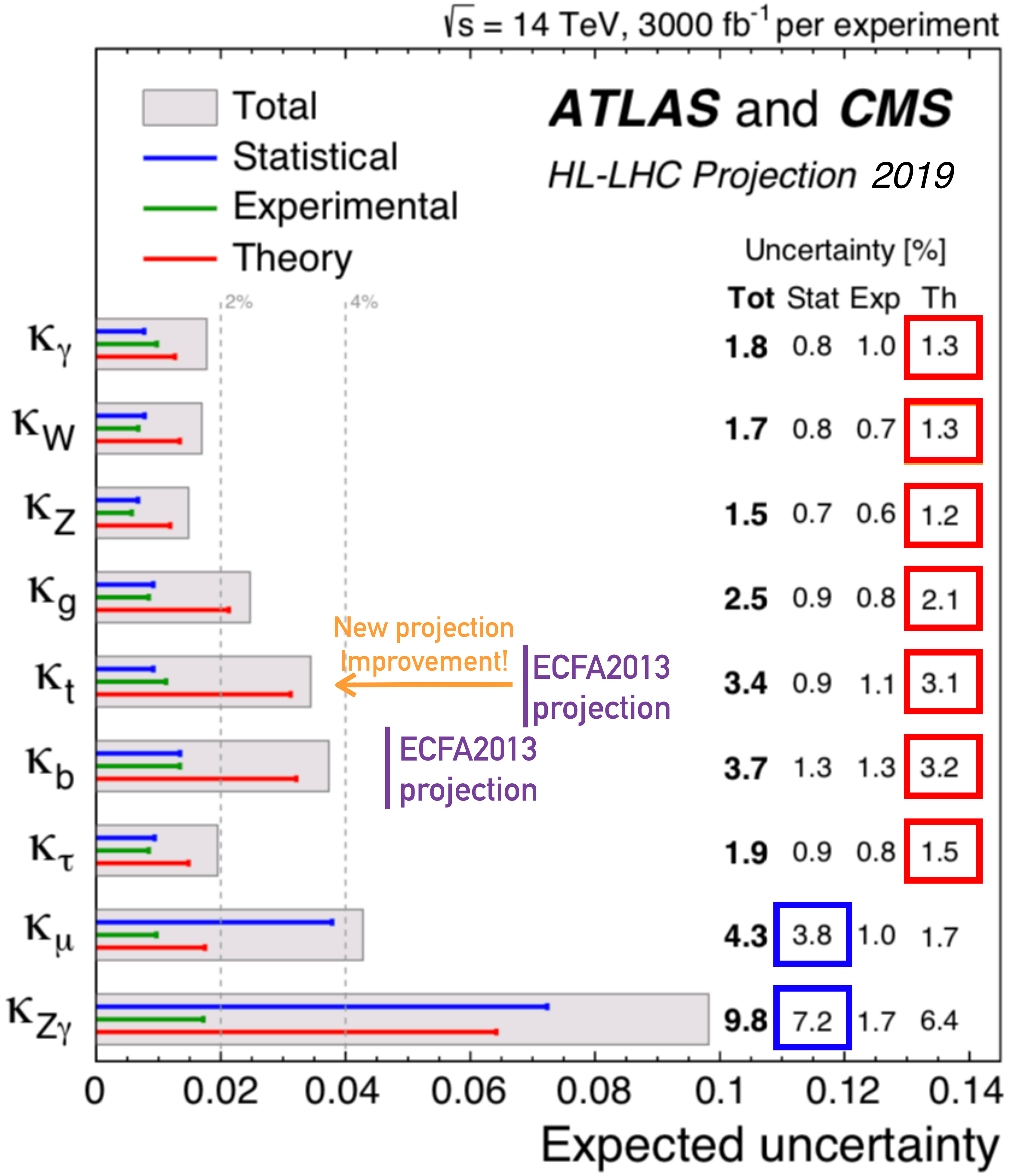


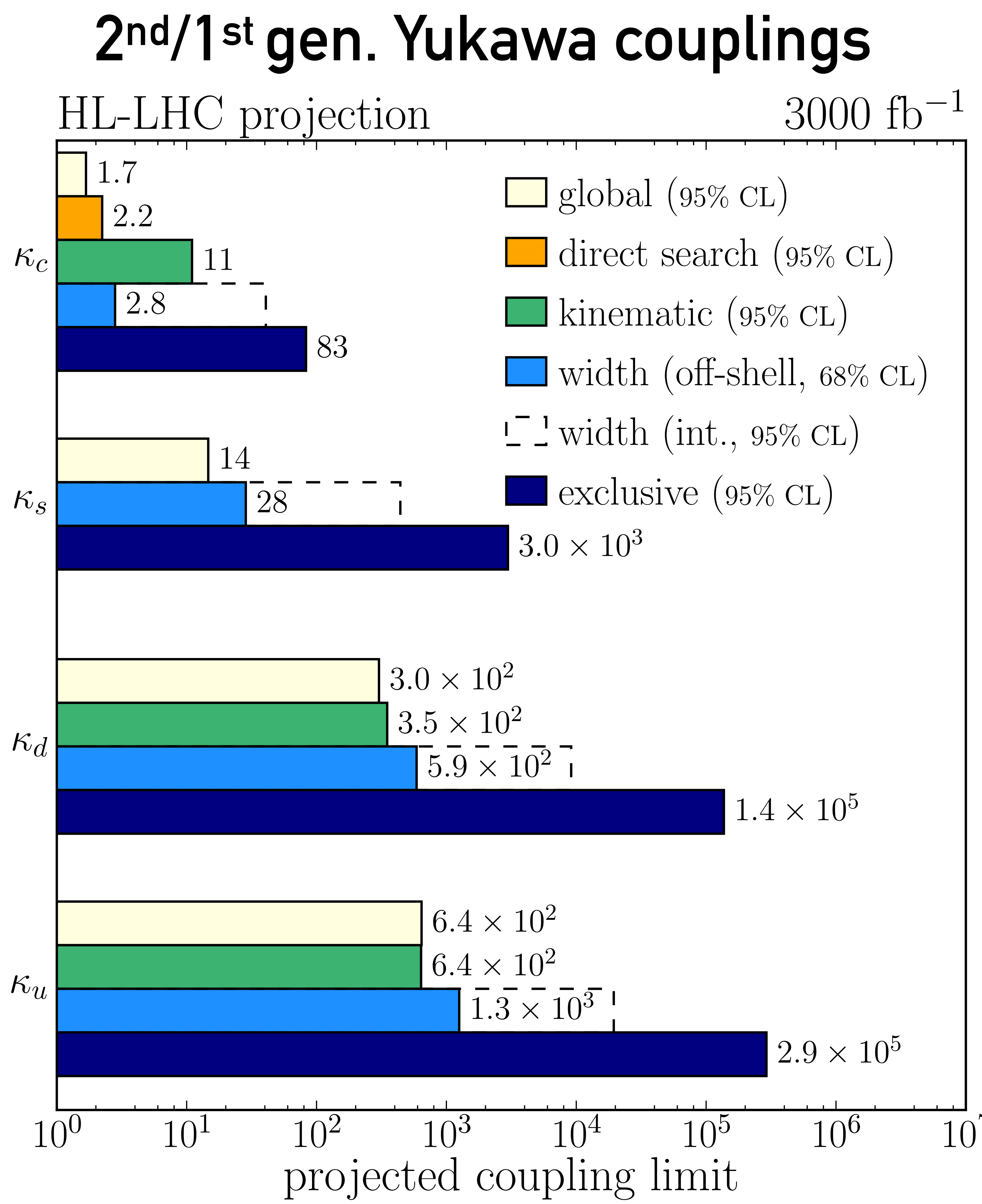
Precision ~25%

HIGGS BOSON COUPLINGS

Consider coupling modifiers $k_j^2 = \sigma_j/\sigma_{SM}$

Here: effective coupling modifiers (loops in γ, g and Zγ coupling not resolved)





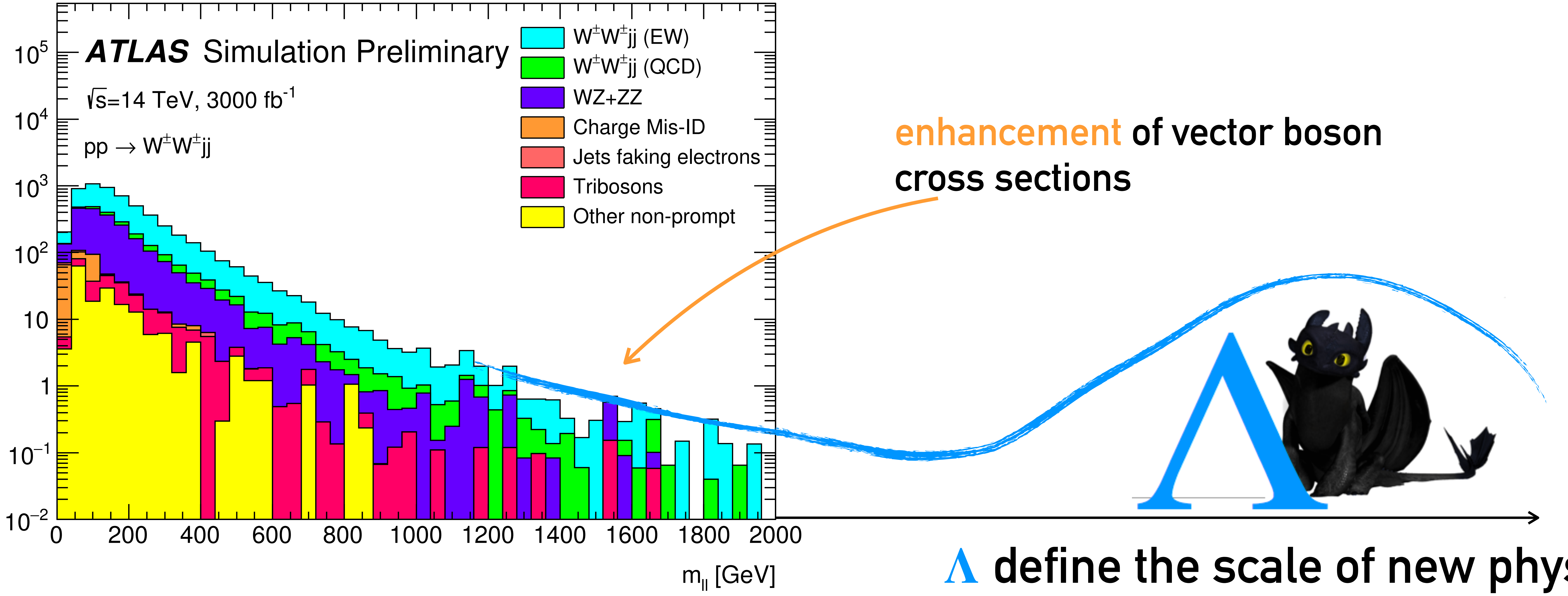
Per-cent level precision on most Higgs couplings, theory becomes the dominant systematics

HIGGS BOSON EFFECTIVE FIELD THEORY

Moving beyond kappas.

Precision measurements to search for BSM dynamics that can still have an impact at smaller energies via virtual effects

→ Model independent EFT framework $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$

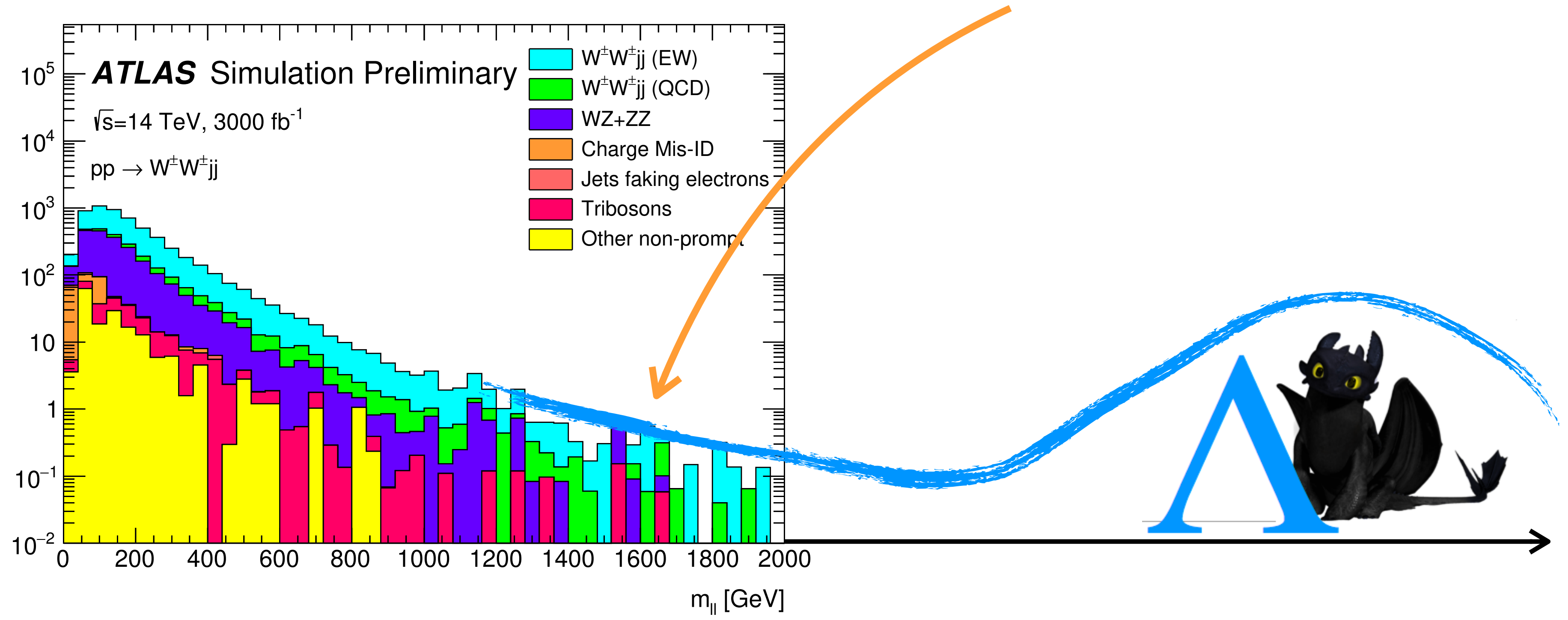


Λ define the scale of new physics

HIGGS BOSON EFFECTIVE FIELD THEORY

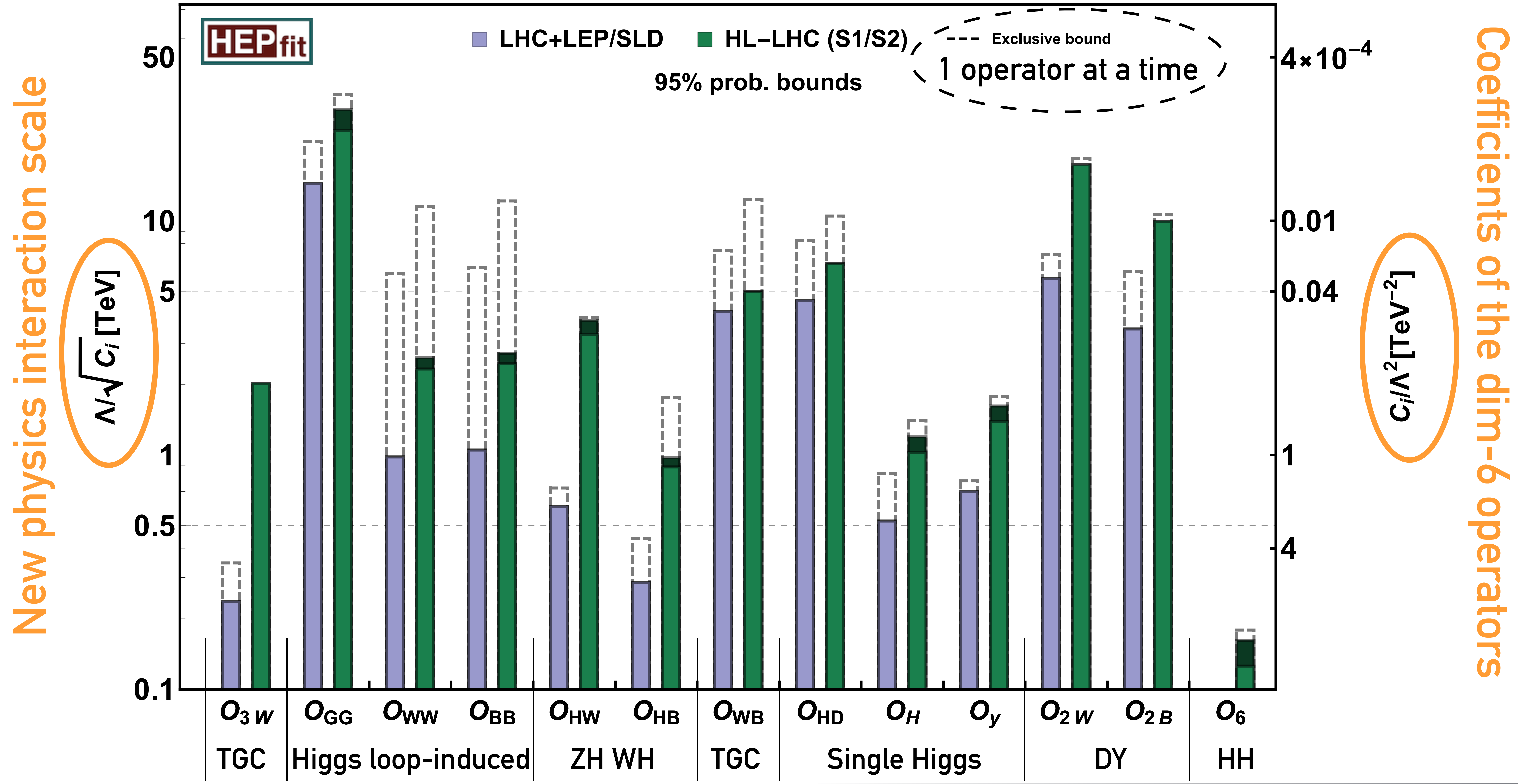
Moving beyond kappas.
Precision measurements to search for BSM dynamics that can still have an impact at smaller energies via virtual effects
→ Model independent EFT framework $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$

enhancement of vector boson cross sections

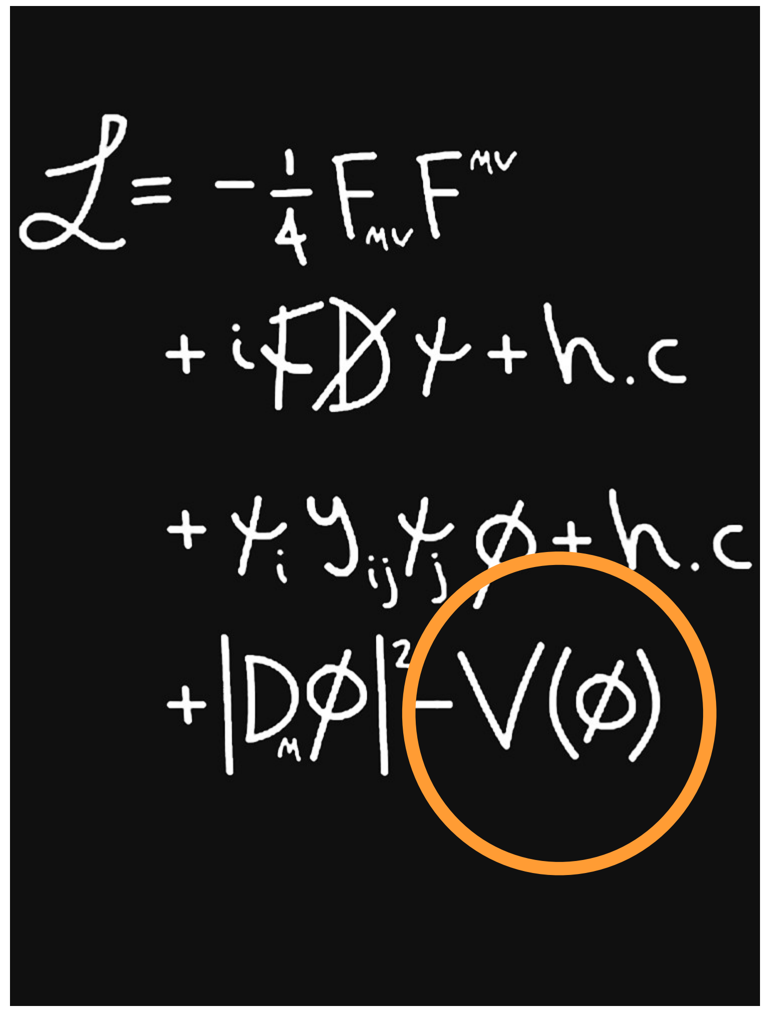


Λ define the scale of new physics

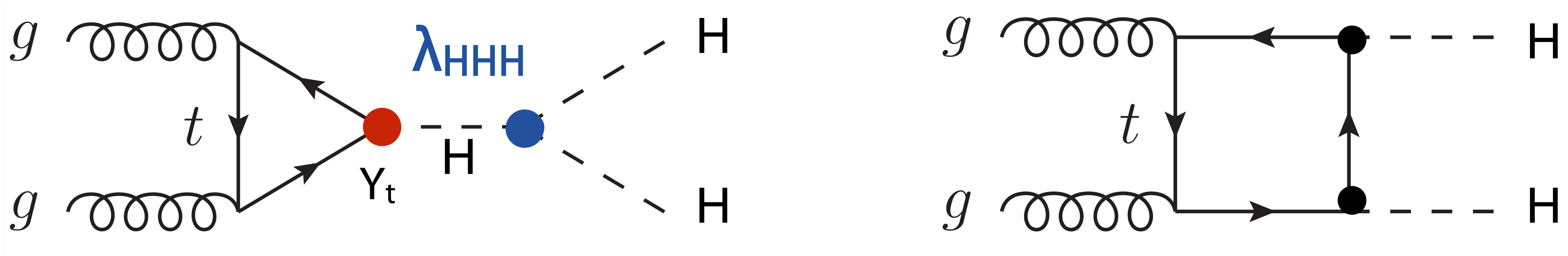
focus on the following non-redundant set of operators
$\{\mathcal{O}_H, \mathcal{O}_{HD}, \mathcal{O}_6, \mathcal{O}_{GG}, \mathcal{O}_{BB}, \mathcal{O}_{WW}, \mathcal{O}_{WB}, \mathcal{O}_{HB}, \mathcal{O}_{HW}, \mathcal{O}_{2B}, \mathcal{O}_{2W}, \mathcal{O}_{3W}, \mathcal{O}_y\}$



PROBING THE HIGGS BOSON SELF-COUPLING

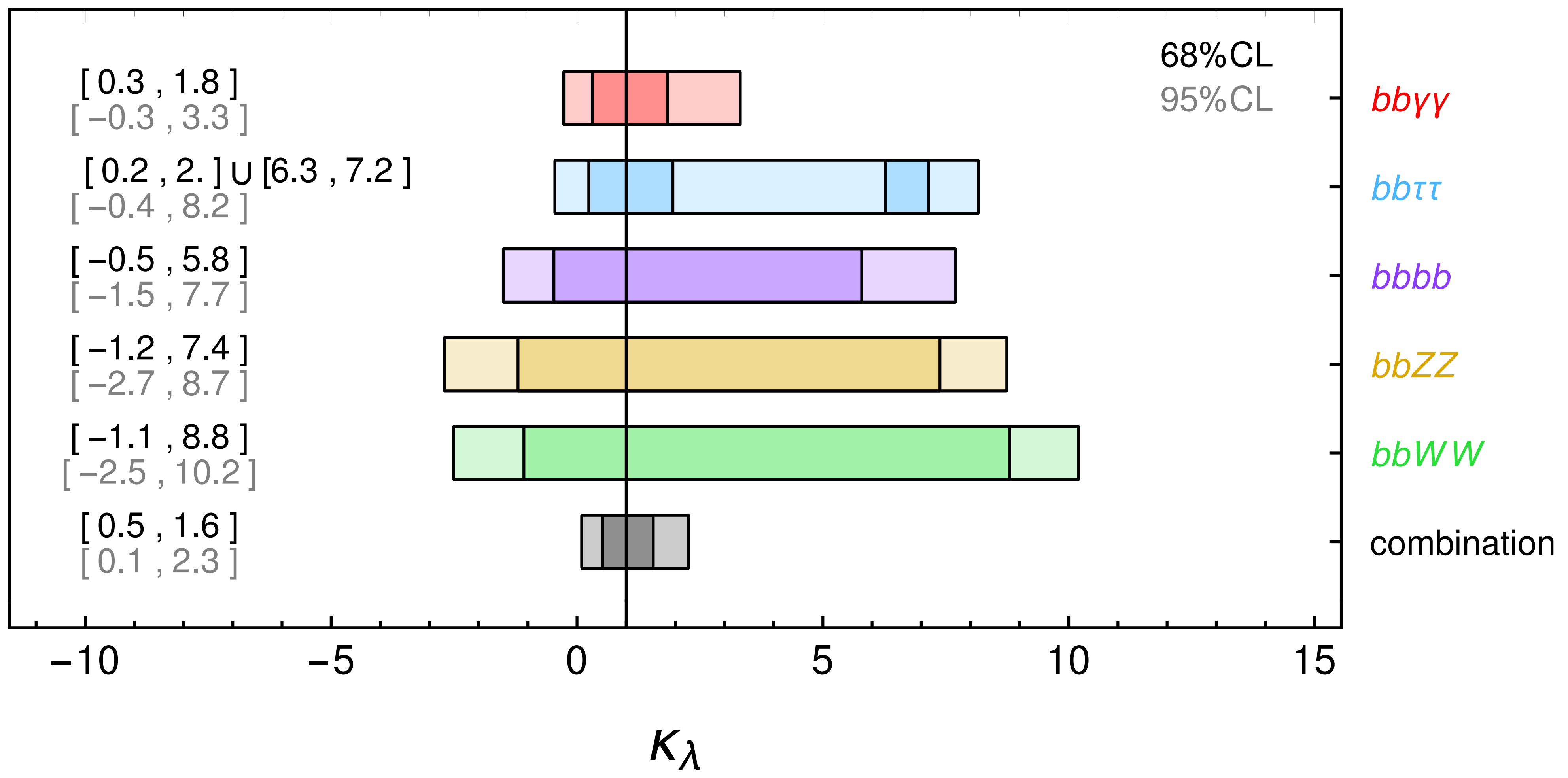


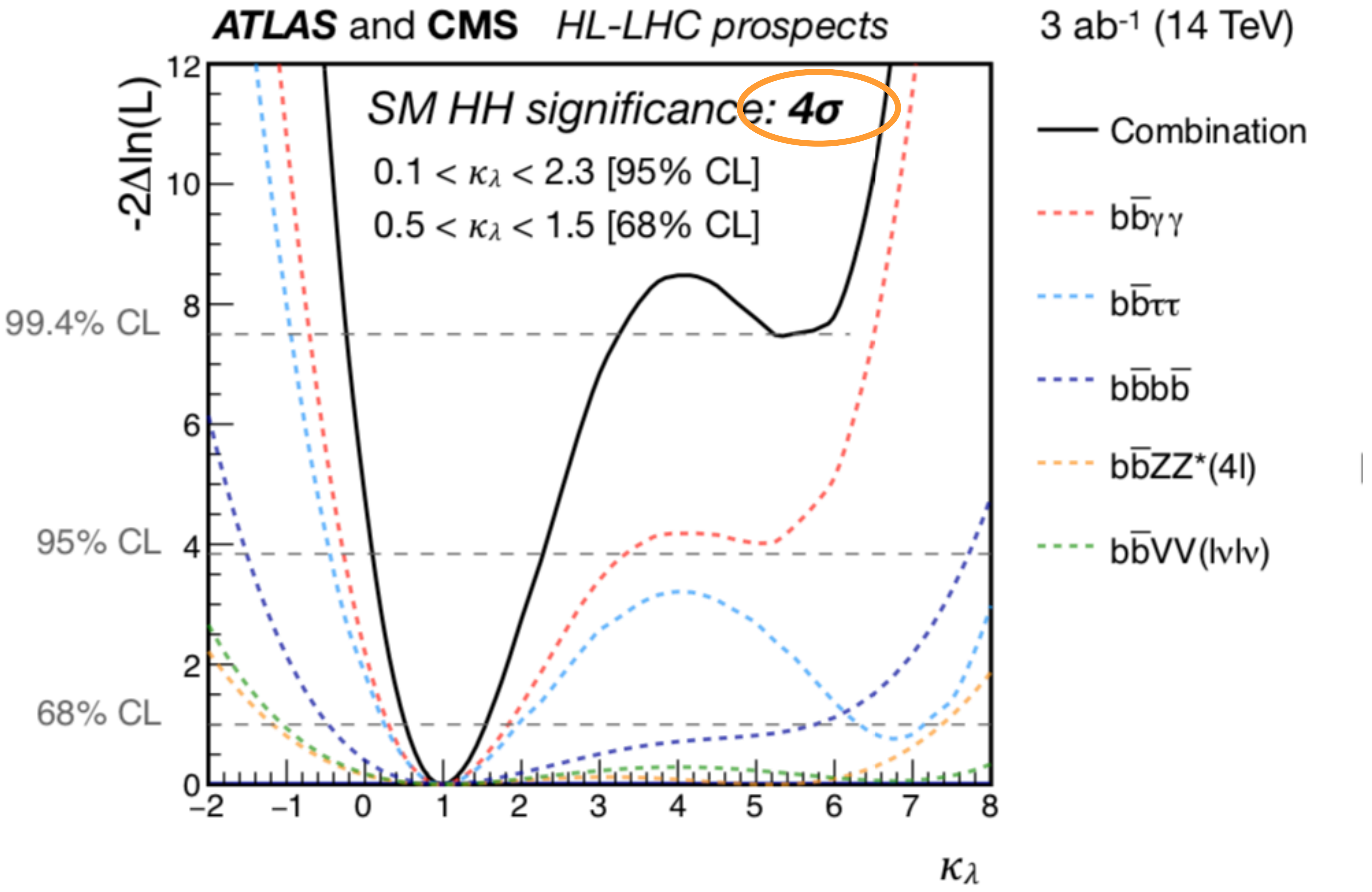
Essential in EWSB, need to measure the Higgs boson trilinear coupling (λ_{HHH})



σ(gg→HH) = 33.5 fb
[@13 TeV, NNLO + NNLL with top mass effects]

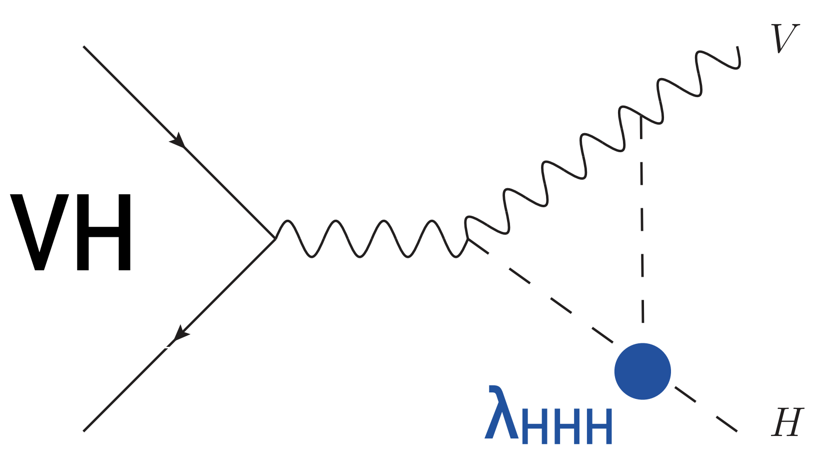
Expected constraints on the Higgs Boson self-coupling

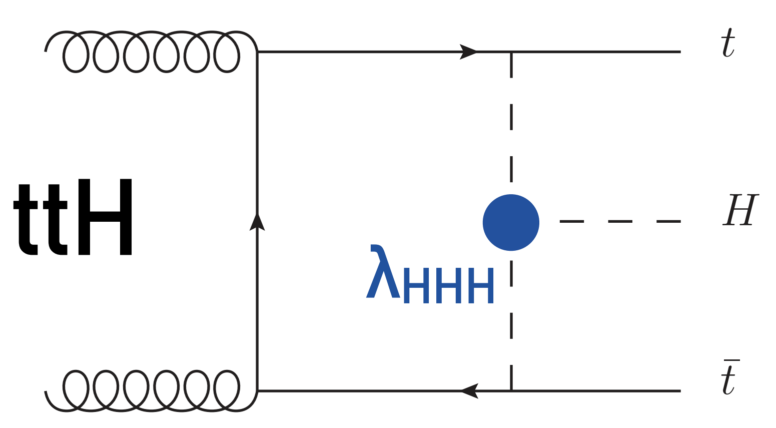


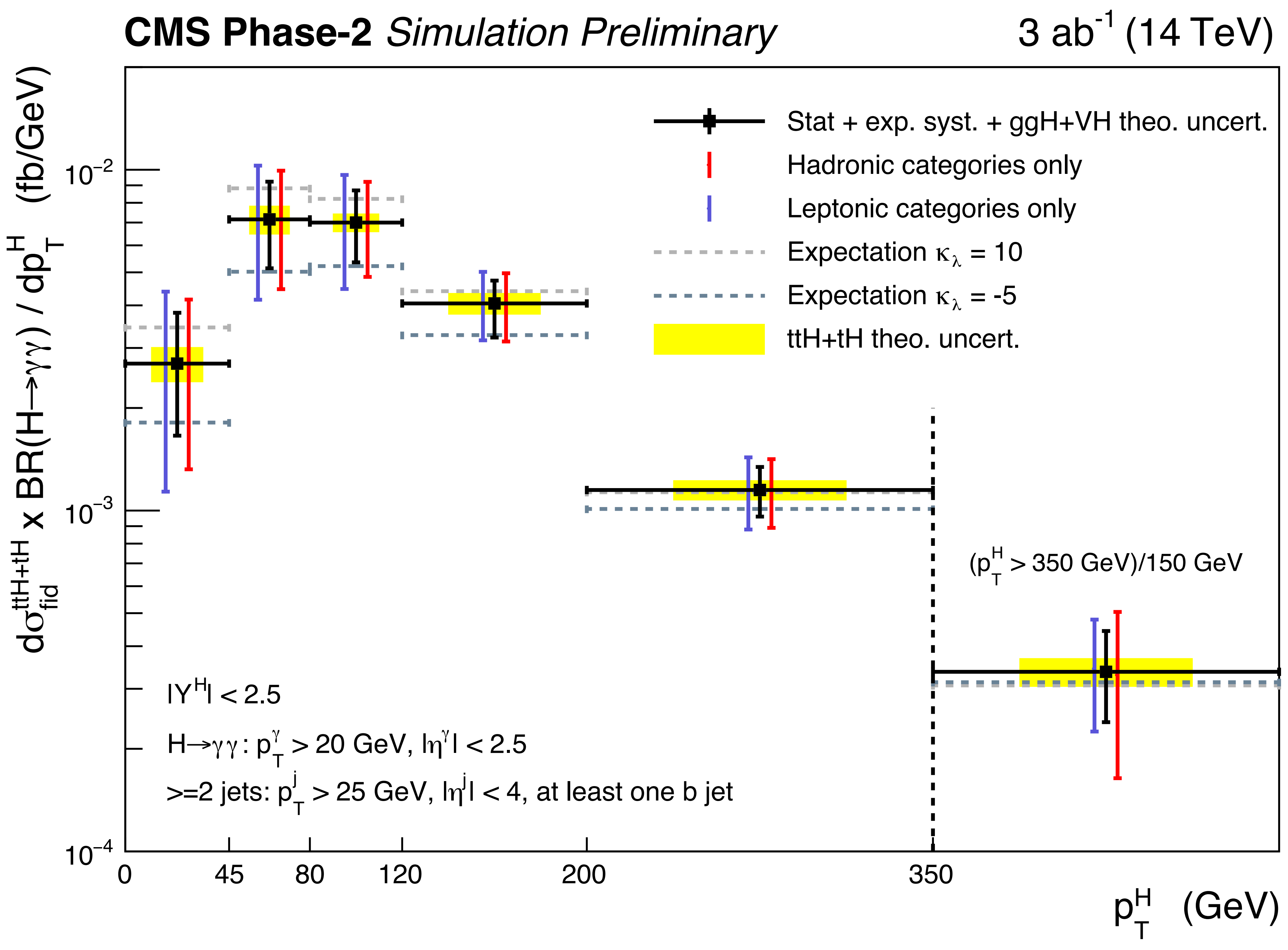


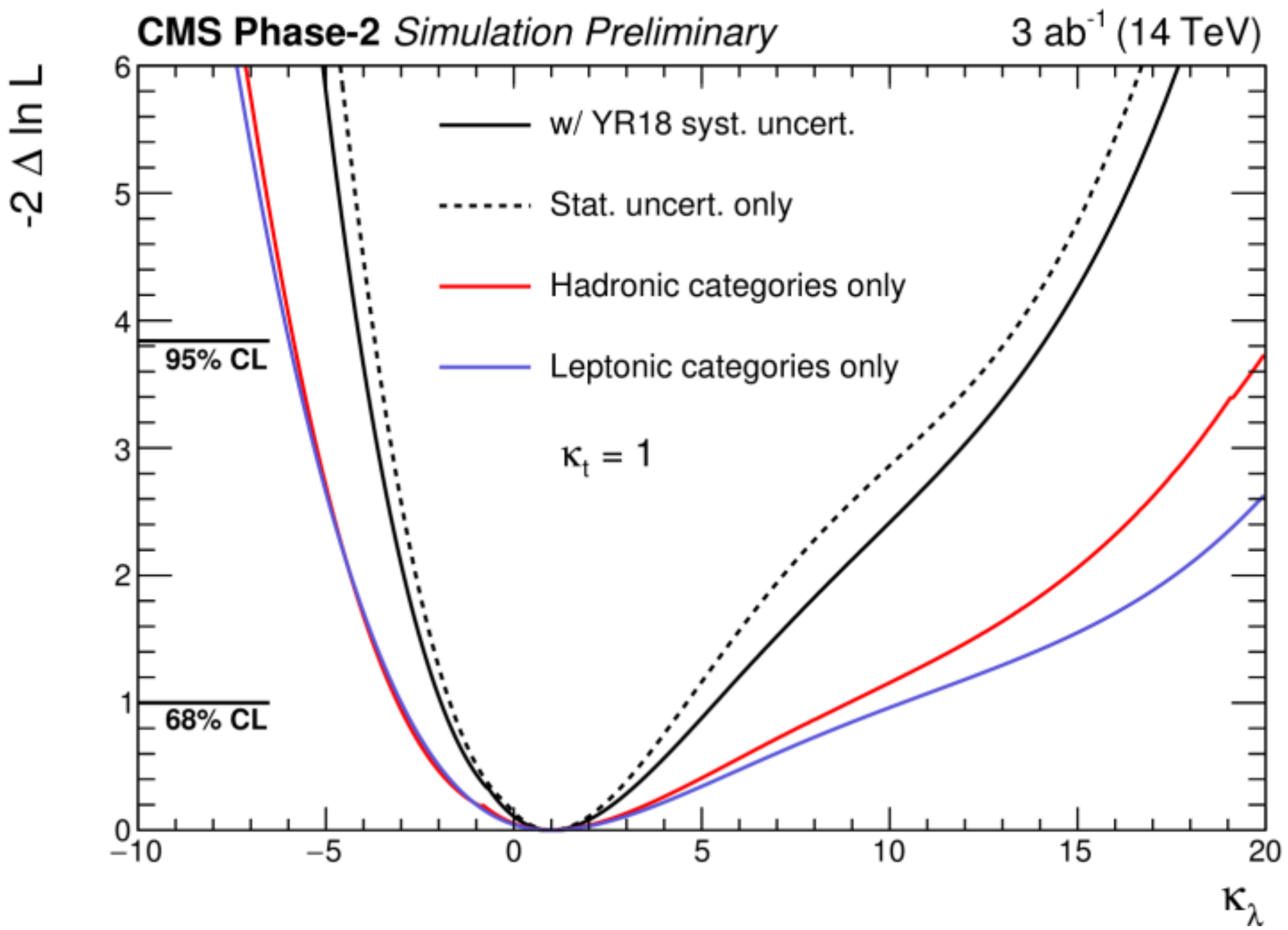
PROBING THE HIGGS BOSON SELF-COUPLING

Single Higgs boson productions, decays, and kinematics are sensitive to the self-coupling through EW corrections





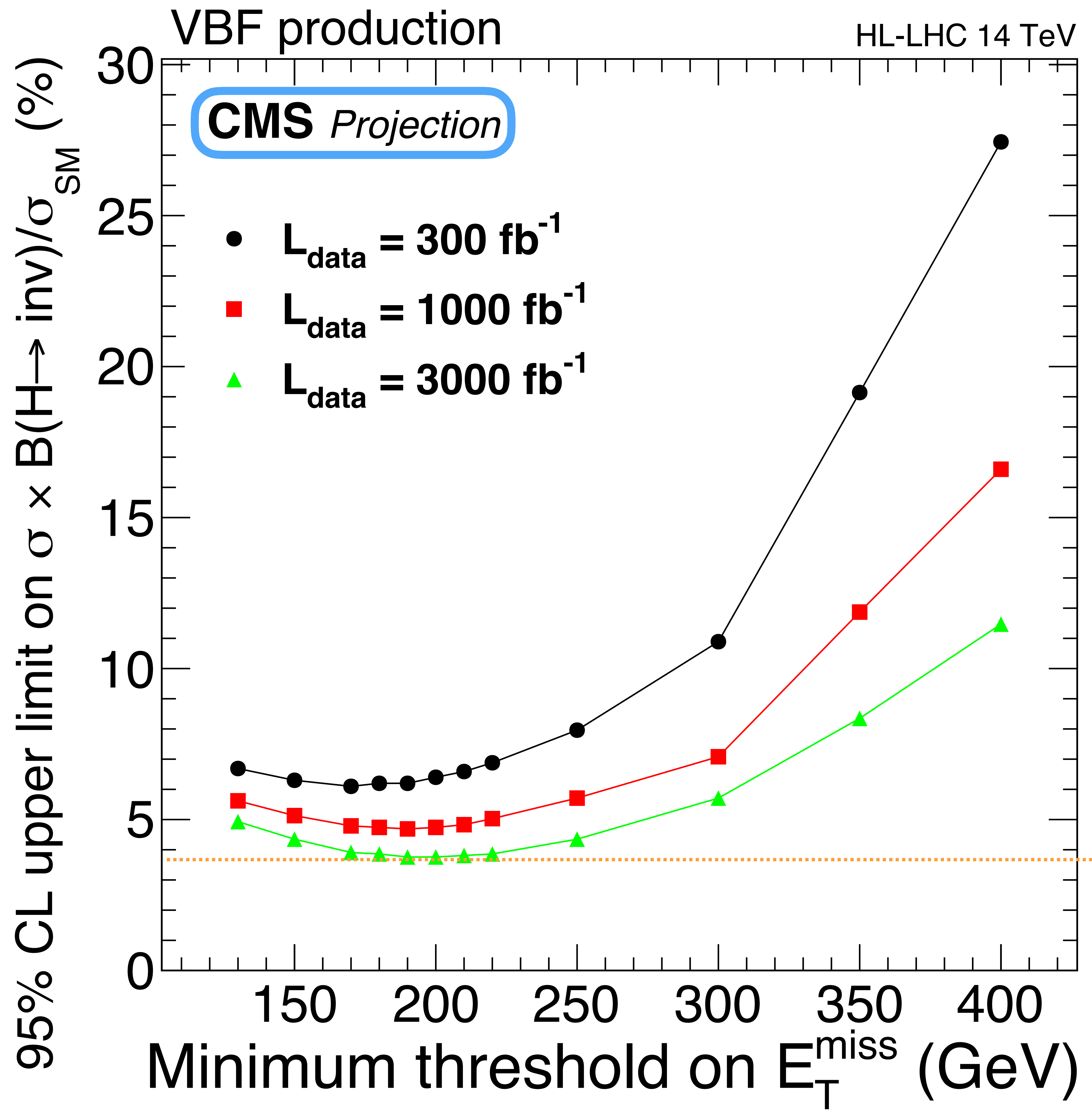




Complements direct determination from HH

Higgs Boson Invisible Decay

Invisible decays are a generic prediction of NP models with light dark matter. The invisible branching ratio in the SM is very small (0.1%) so any observable rate would be evidence for BSM



~4%

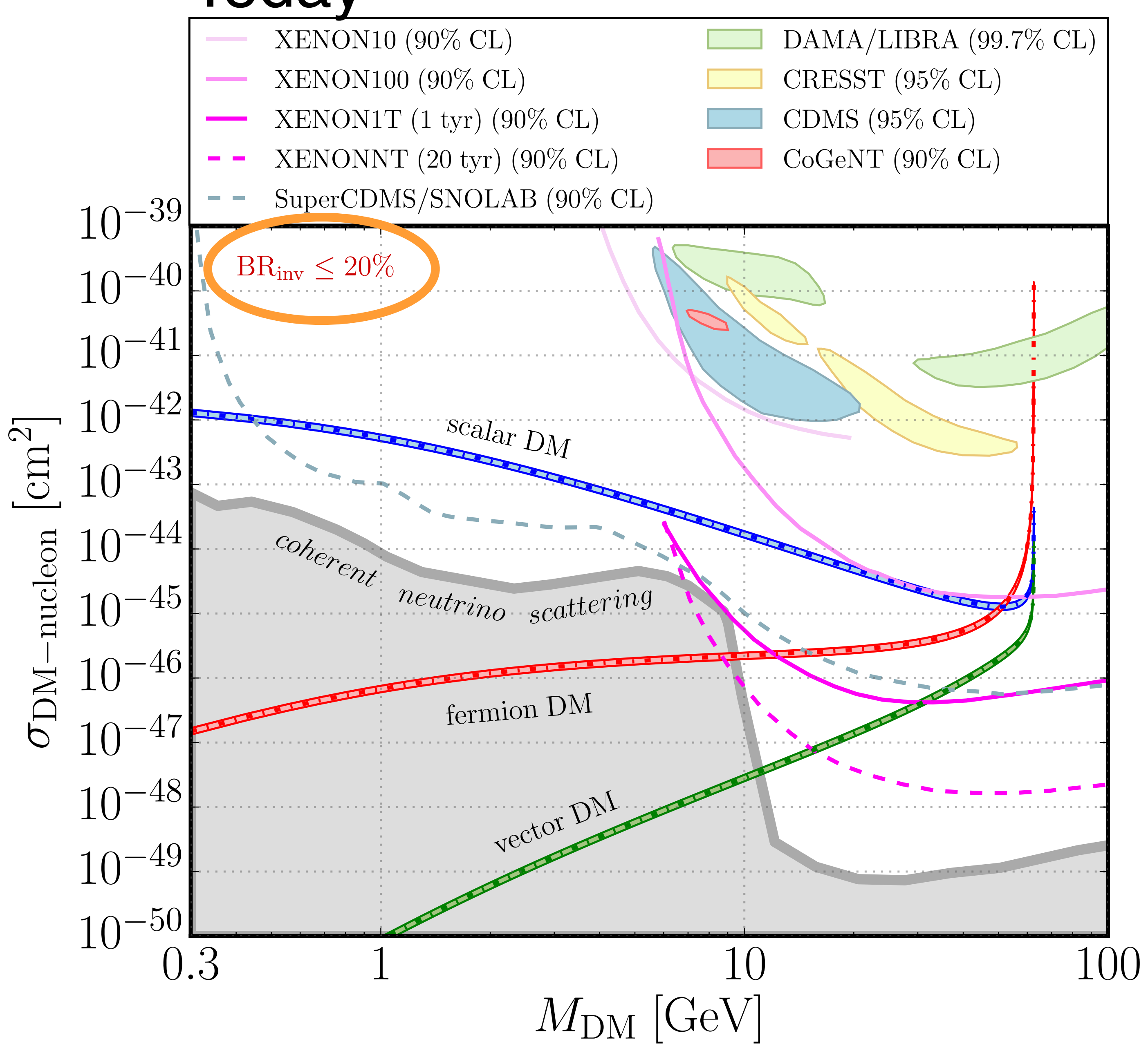
+ ATLAS projections for VH production ~8%

Assuming CMS/ATLAS perform equally well and neglecting correlations
$BR_{inv}^{HL-LHC} \leq 2.5\%$

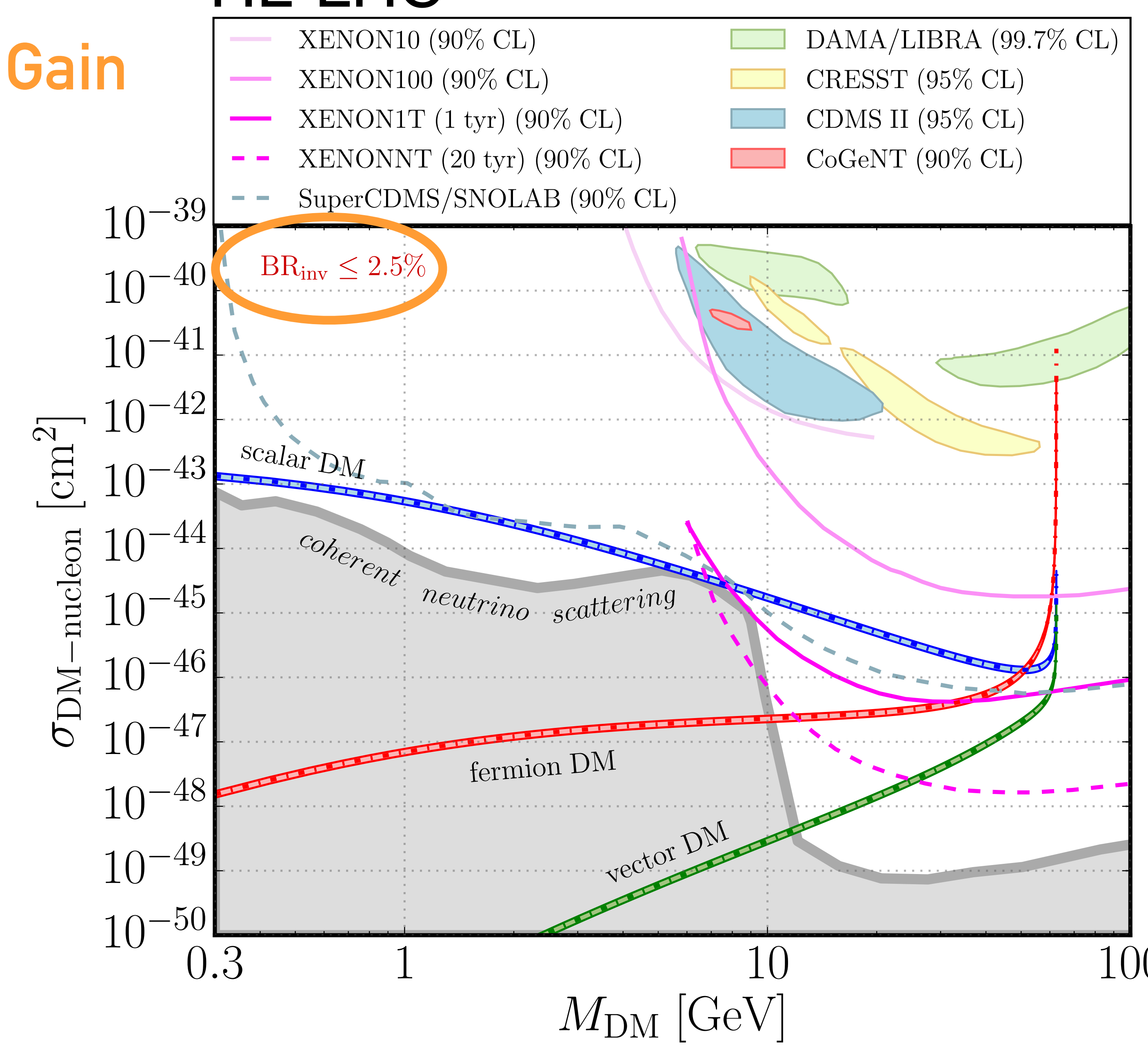
Interpreted in the minimal Higgs boson portal model

$$\mathcal{L} \supset -\frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \quad \text{(scalar DM)} \quad \text{or}$$
$$\mathcal{L} \supset +\frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu \quad \text{(vector DM)} \quad \text{or}$$
$$\mathcal{L} \supset -\frac{1}{4}\frac{\lambda_{h\chi\chi}}{\Lambda} H^\dagger H \bar{\chi}\chi \quad \text{(fermion DM)},$$

Today

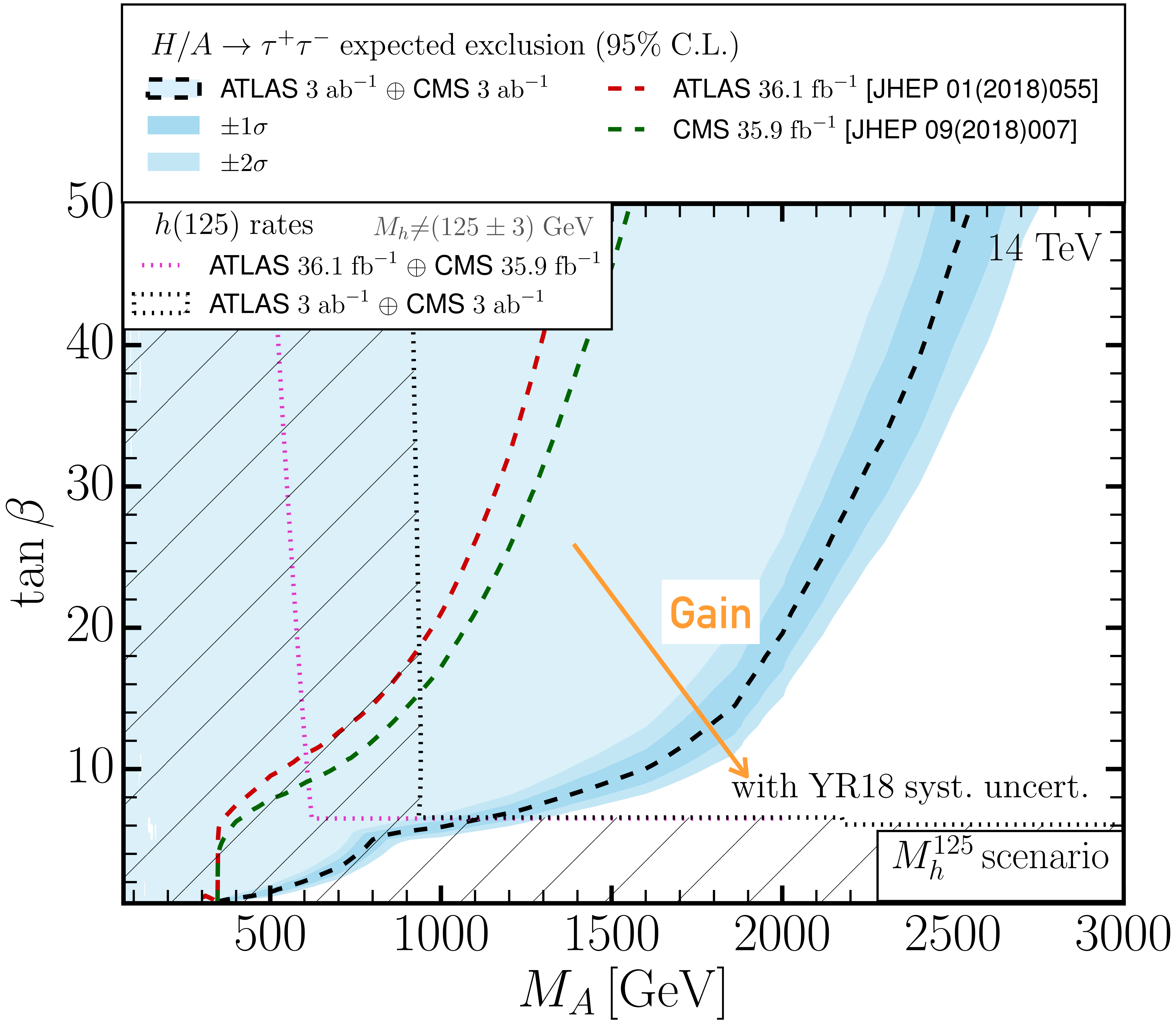


Gain → HL-LHC



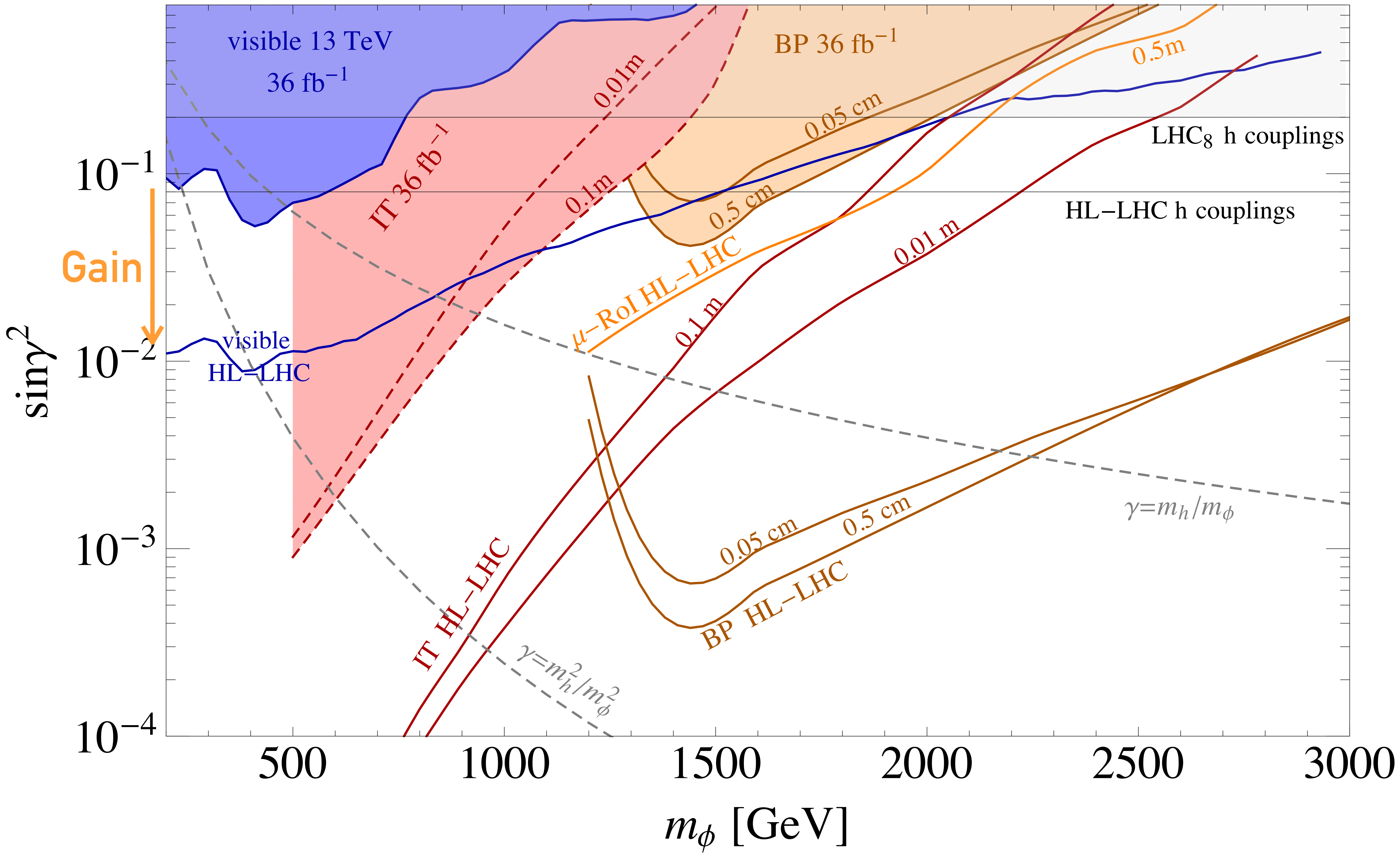
HIGGS BOSON BSM

The expected exclusion limit for H/A→ττ



Twin Higgs boson

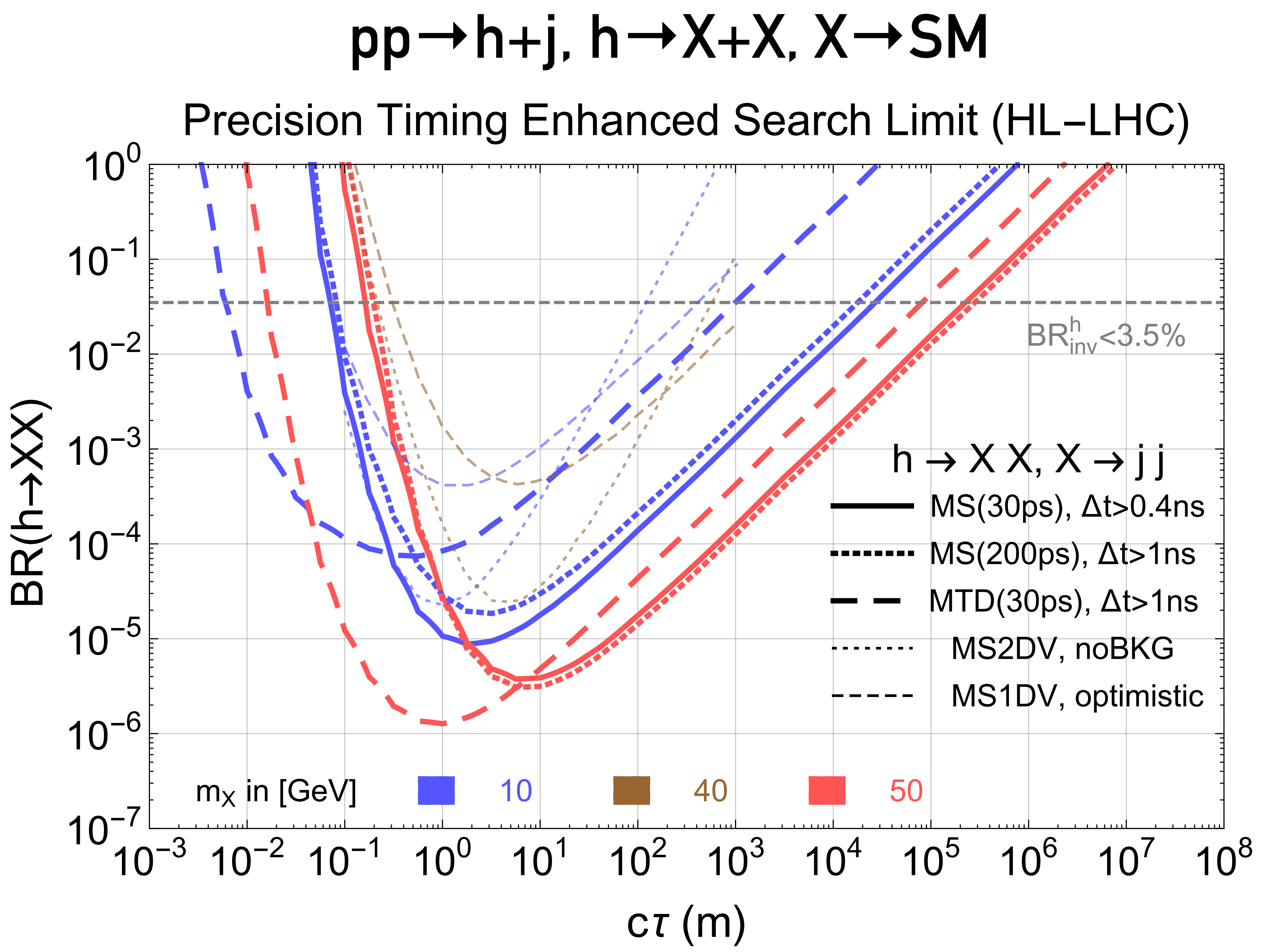
Second Higgs boson which is a singlet of the SM gauge group



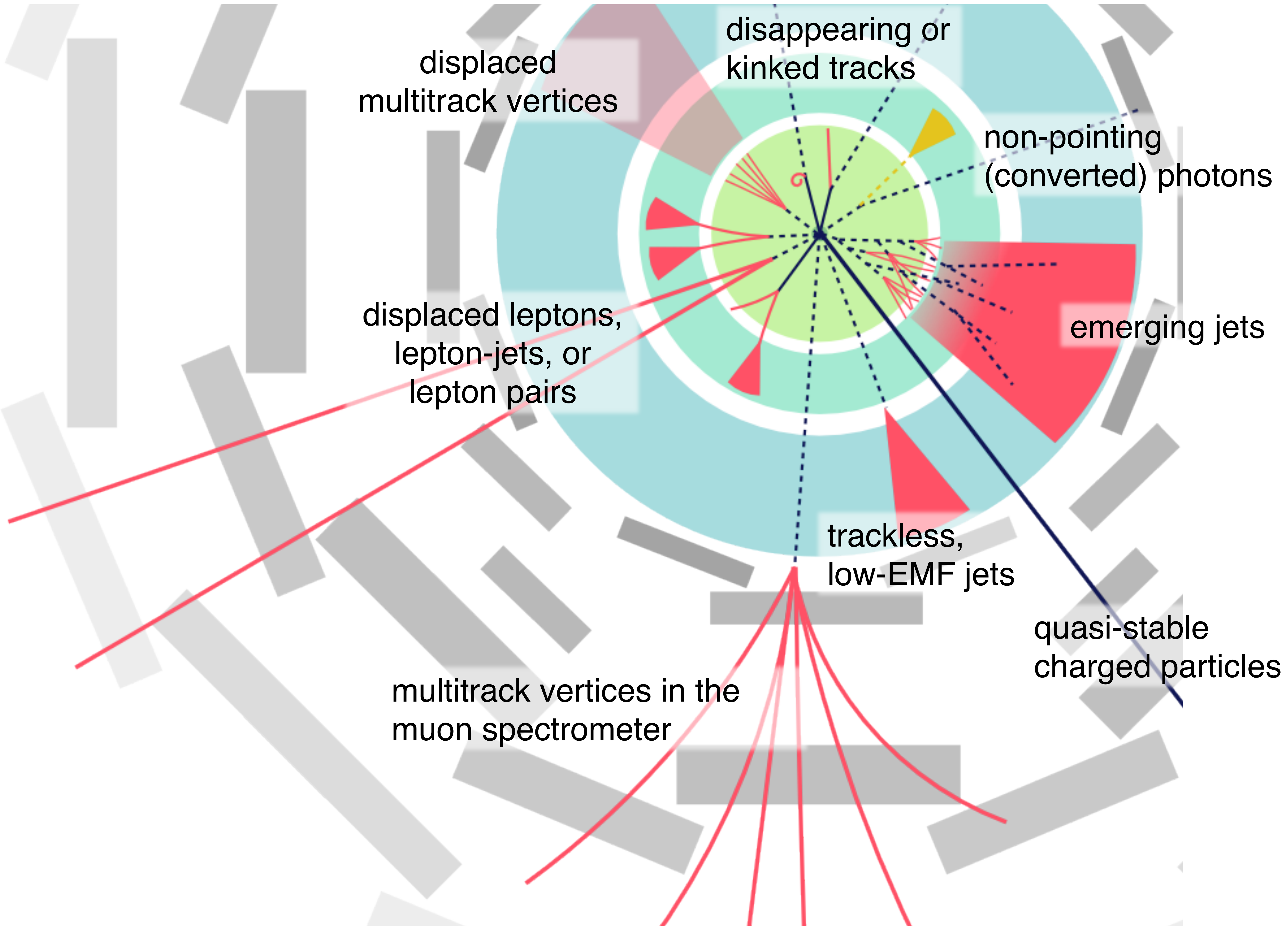
Interplay between direct searches for new Higgs bosons and 125 GeV Higgs boson coupling measurements to probe

LONG LIVED PARTICLE

In addition to the significant expansion of expected luminosity, new detector upgrades will enable searches in the long-lived particle regime.



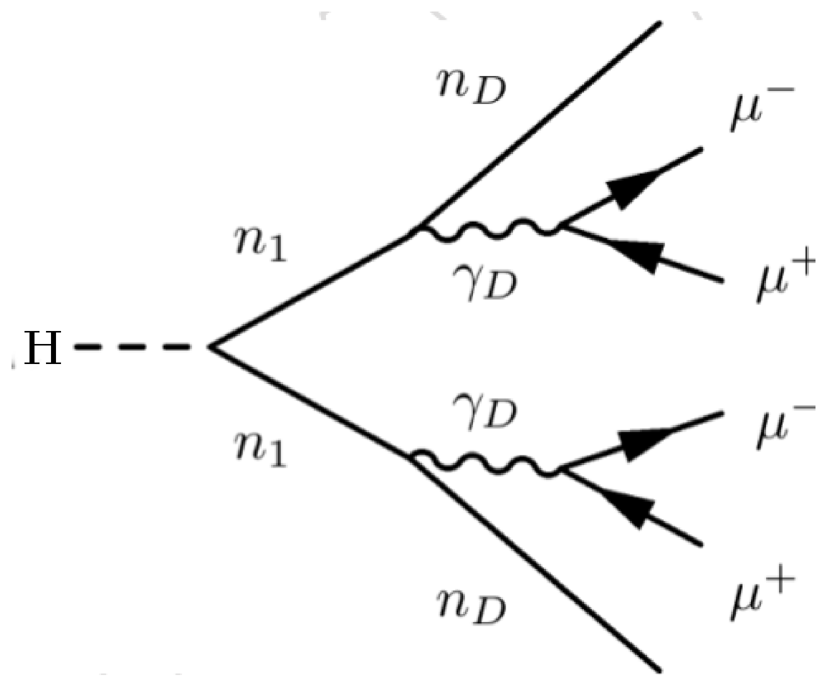
LLPs physiology

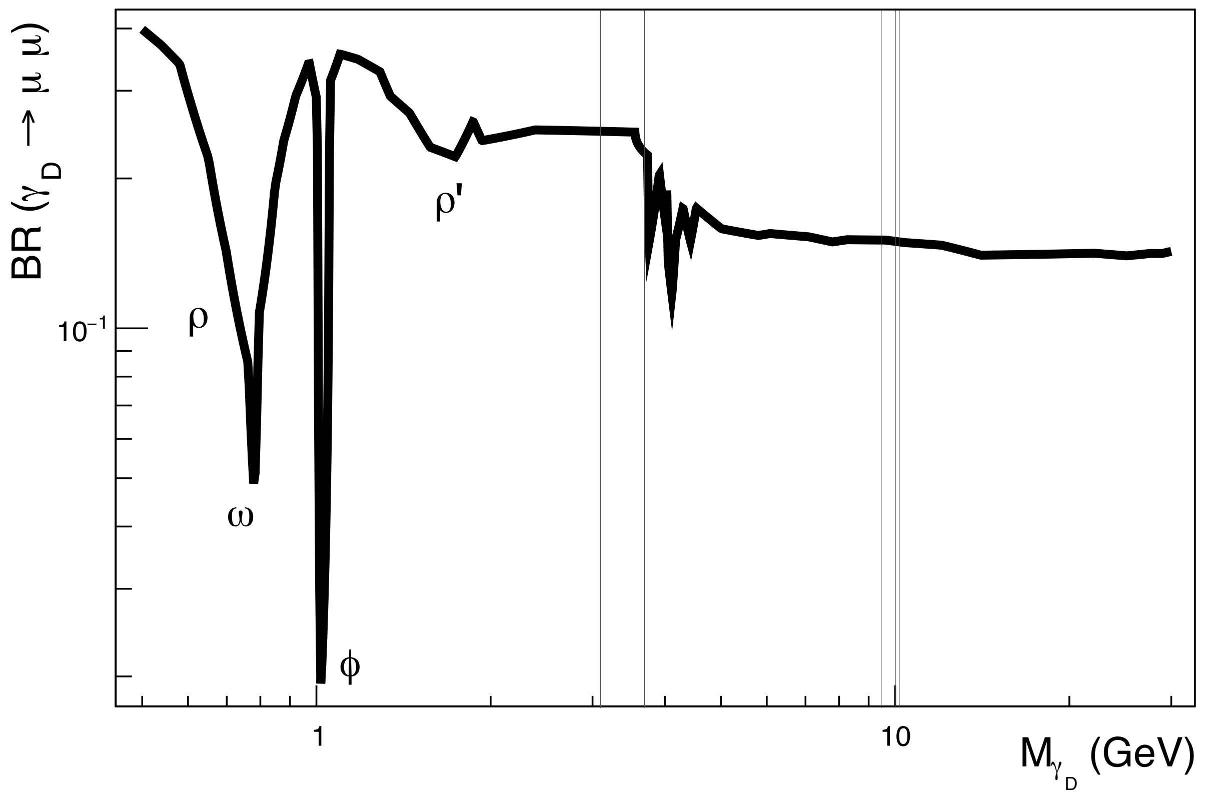


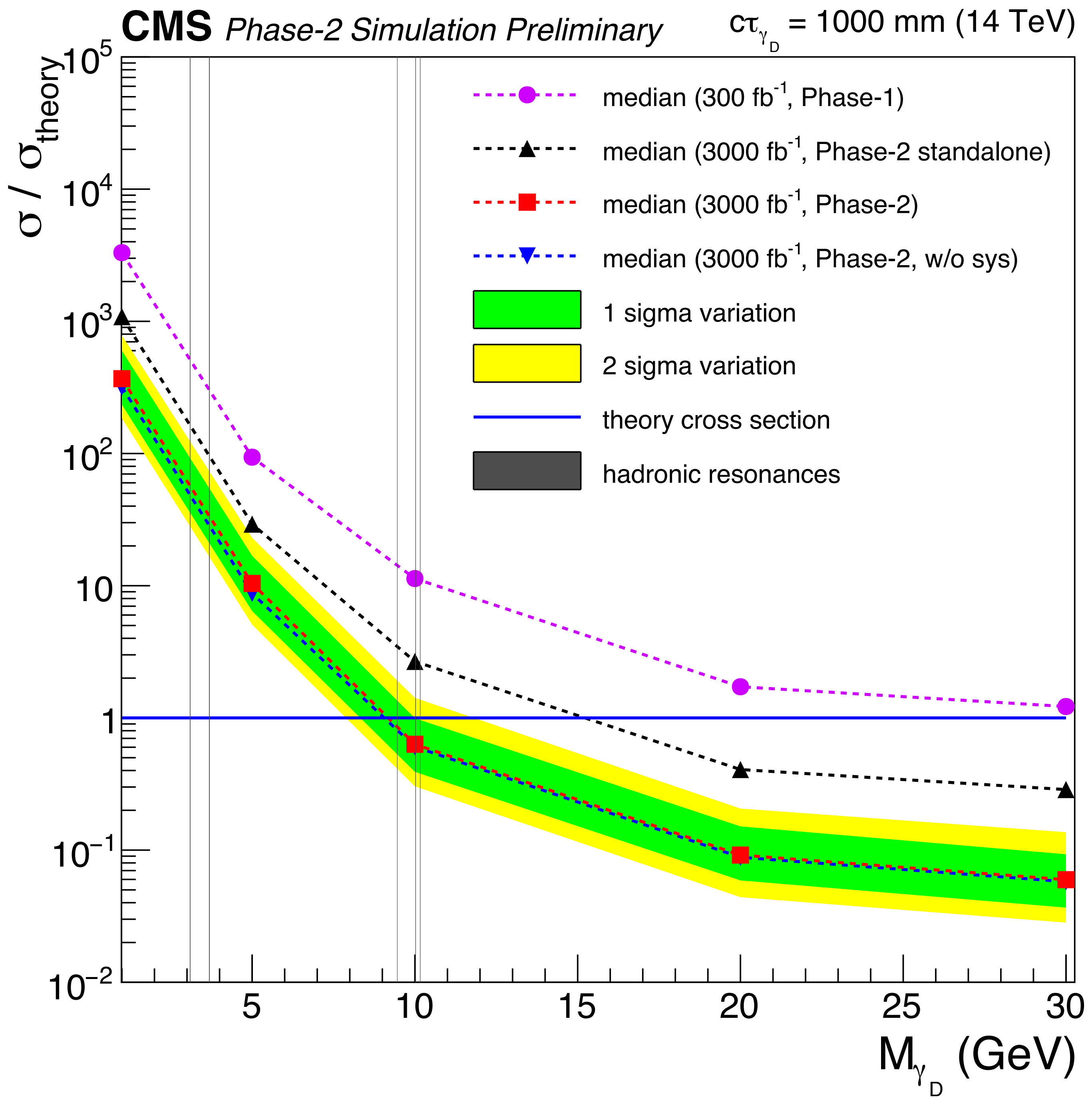
THE DARK SECTOR

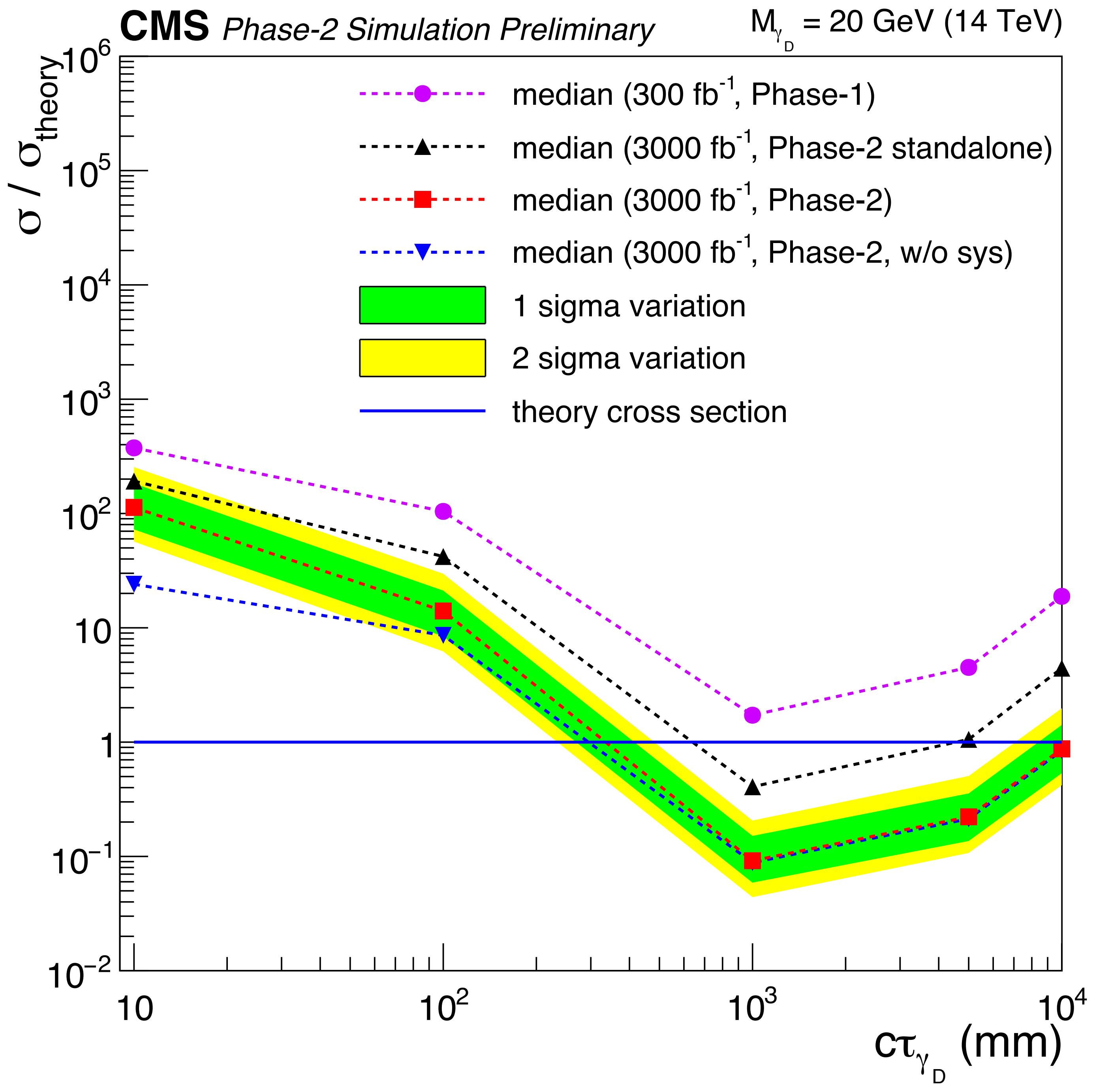
In our world, a Dark Sector could allow for long-range forces among its matter constituents

Search for long-lived dark photons (γ_D) that are produced in cascade decays of the SM Higgs boson









Outlook and Conclusions

The analysis of the LHC Run1 and Run2 datasets (<5% of the final HL-LHC integrate luminosity) confirmed the immense physics potential of LHC.

The LHC and HL-LHC potentials will push the reach for precision and sensitivity well beyond what was originally assumed possible.
A broad physics program is planned and the Higgs boson, that is 'really" new physics, is the star of such program.

We will have access to the rarest phenomena leading to measurements of hitherto unanticipated precision.