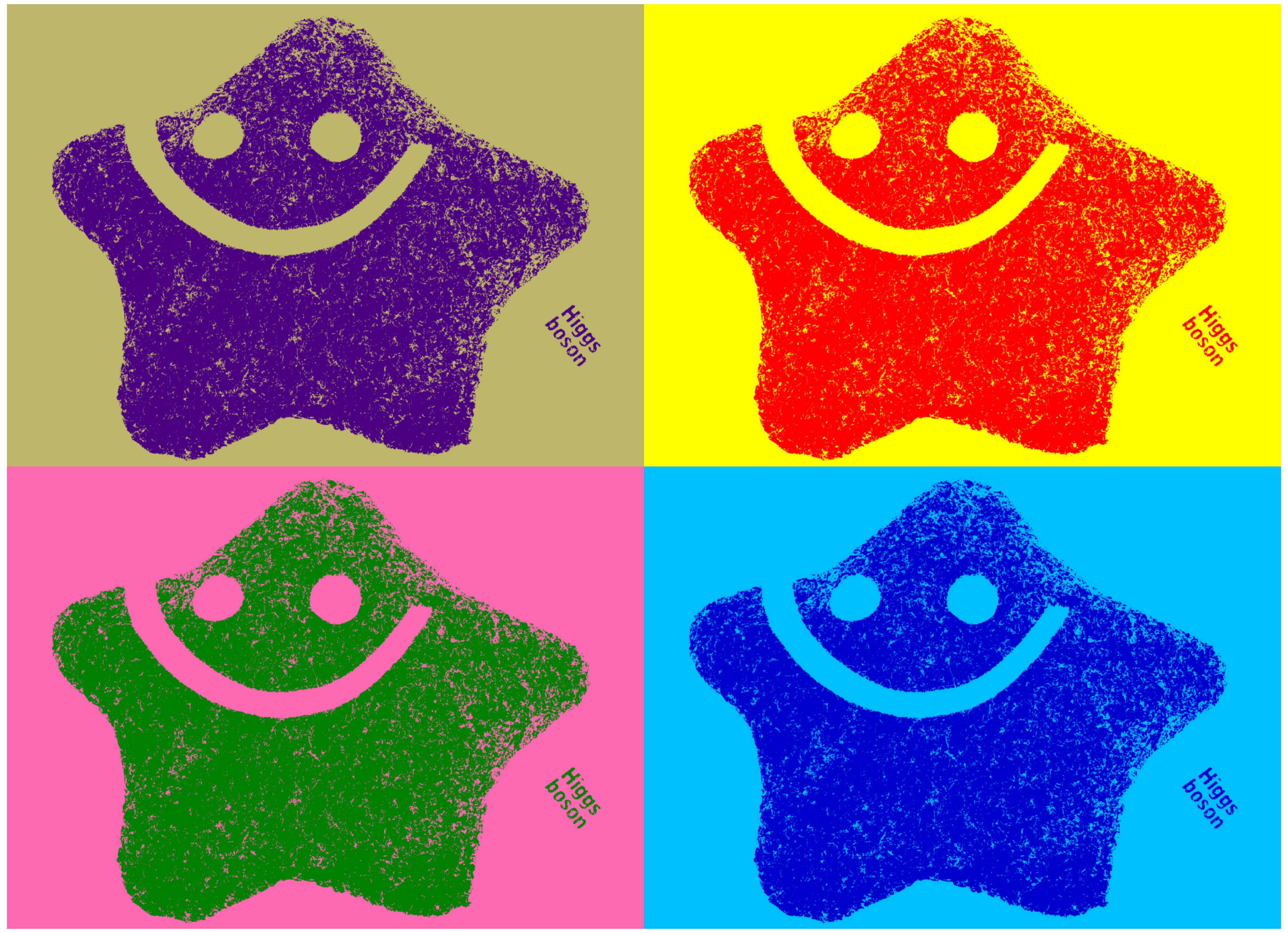
HL-LHC and Future Perspectives

Pheno 2022

University of Pittsburgh

May 9th 2022

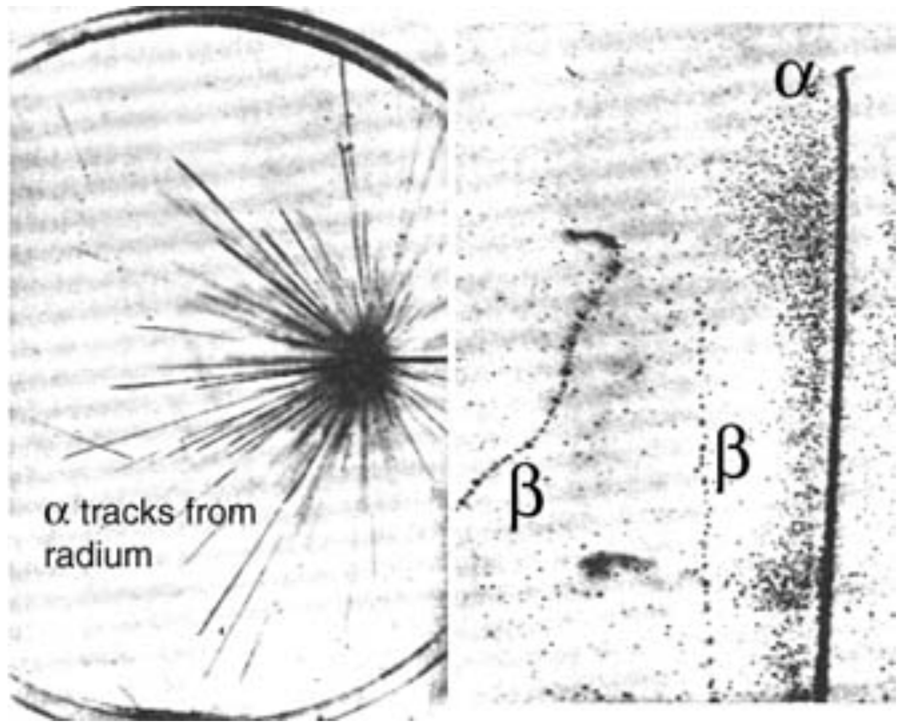


Isobel Ojalvo

ATLAS and CMS Collaborations

A HISTORY of Particle Physics

1897
Electron Discovered
by J.J. Thomson

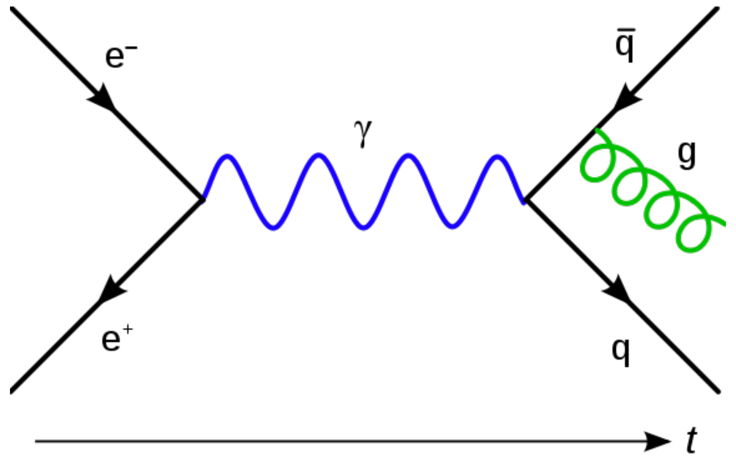


1912
Cloud Chambers Invented

1891
Electron Named/ Theorized
G. Stoney

1919
Proton Discovery
Rutherford

1930
Wolfgang Pauli proposes the neutrino



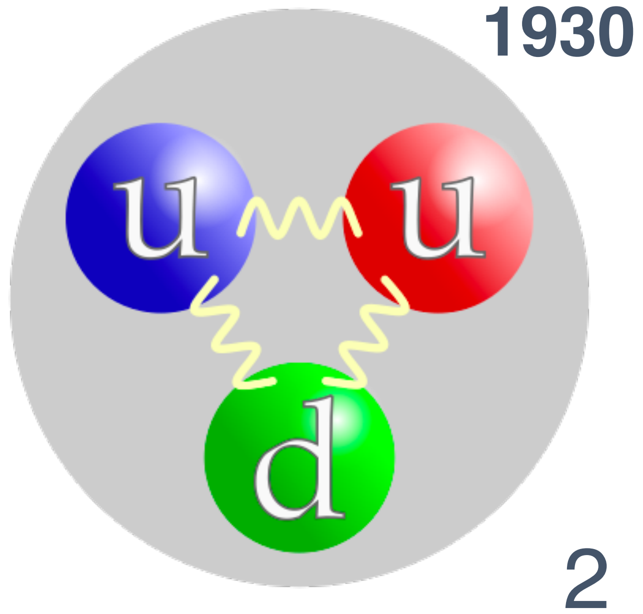
1948
Invention of the Feynman Diagram

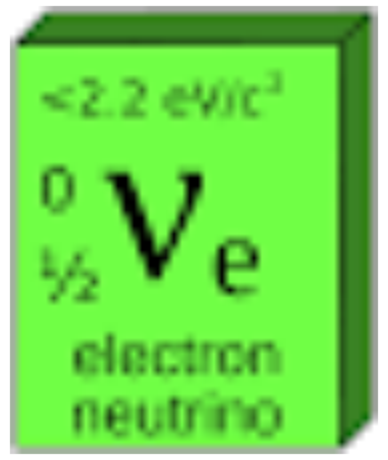
1937
Discovery of the Muon by J. C. Street and E. C. Stevenson

1954
Founding of CERN

1957
Discovery of the Electron Neutrino

1890 1910 1920 1930 1940 1950 1960



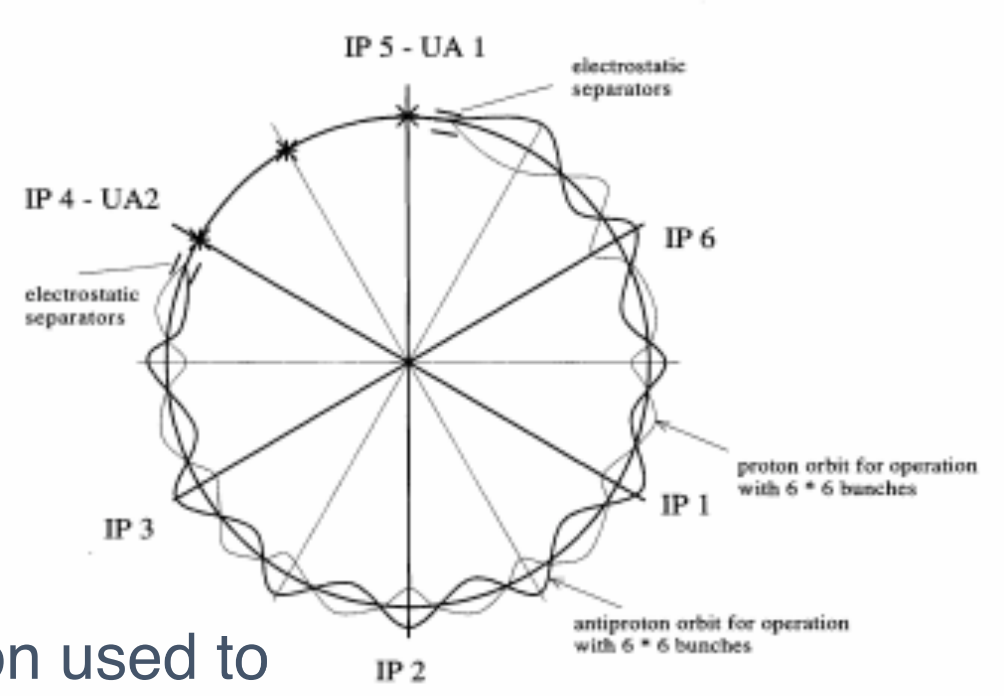


A HISTORY of Particle Physics

1961
Electroweak Theory

1964
Higgs Field Proposed

1968
Higgs Boson used to unify EM and Weak forces
FNAL Founded



1974
Tau Discovered

1979
SPS Proposal Submitted

1983
W&Z Bosons Discovered
LHC Proposed

1987
SSC Approved

1988
LEP Tunnel completed

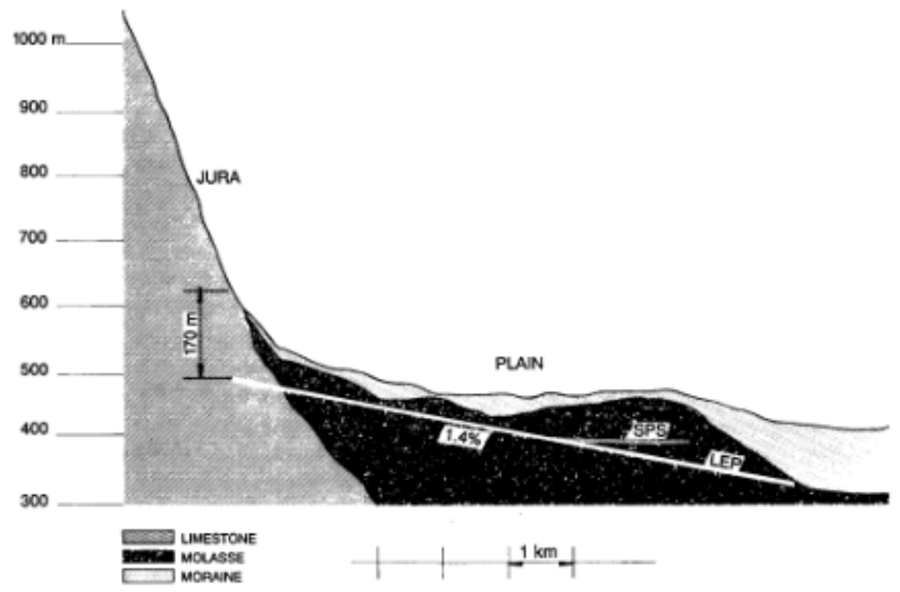


Fig. 2 Inclined plane of the tunnel

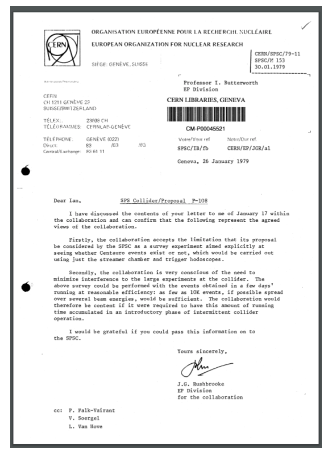
1993
SSC Scrapped

1994
LHC Approved
Top Quark Discovered

2008
LHC Begins Operation

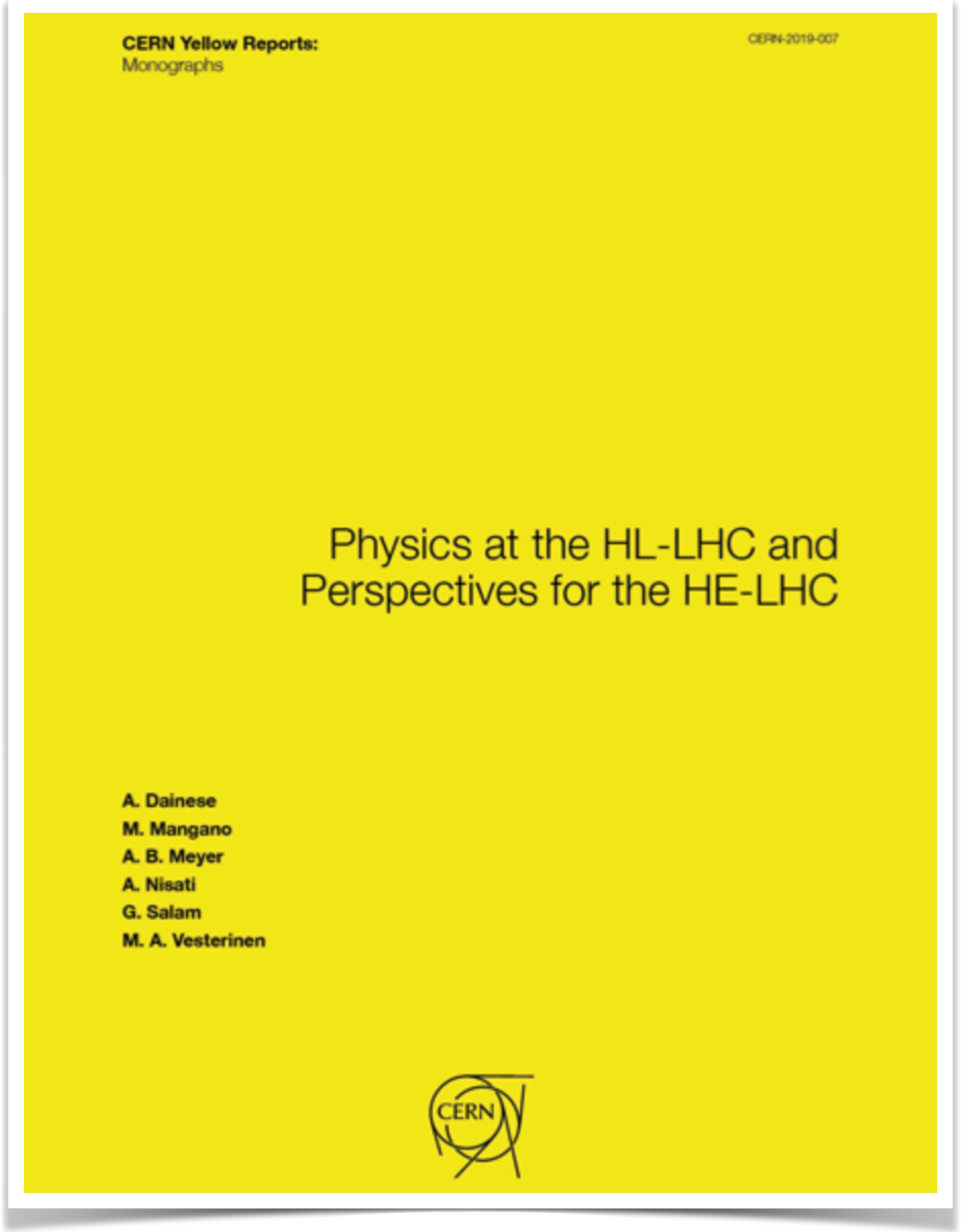
2012
Higgs Boson Discovered!!
H→ZZ
H→γγ
H→WW
H→ff
H→ττ
ttH
H→bb

1960 1970 1980 1990 2000 2010 2020
LHC Run 1 Run 2



Overview

- Snowmass White Paper Contribution released in March
    - Builds on the 2018 effort for the European strategy
- Projections extrapolate from Run 3 Results
    - Assume that Phase 2 detectors perform as well as the current ones but in harsher PU conditions



CERN Yellow Reports:
Monographs

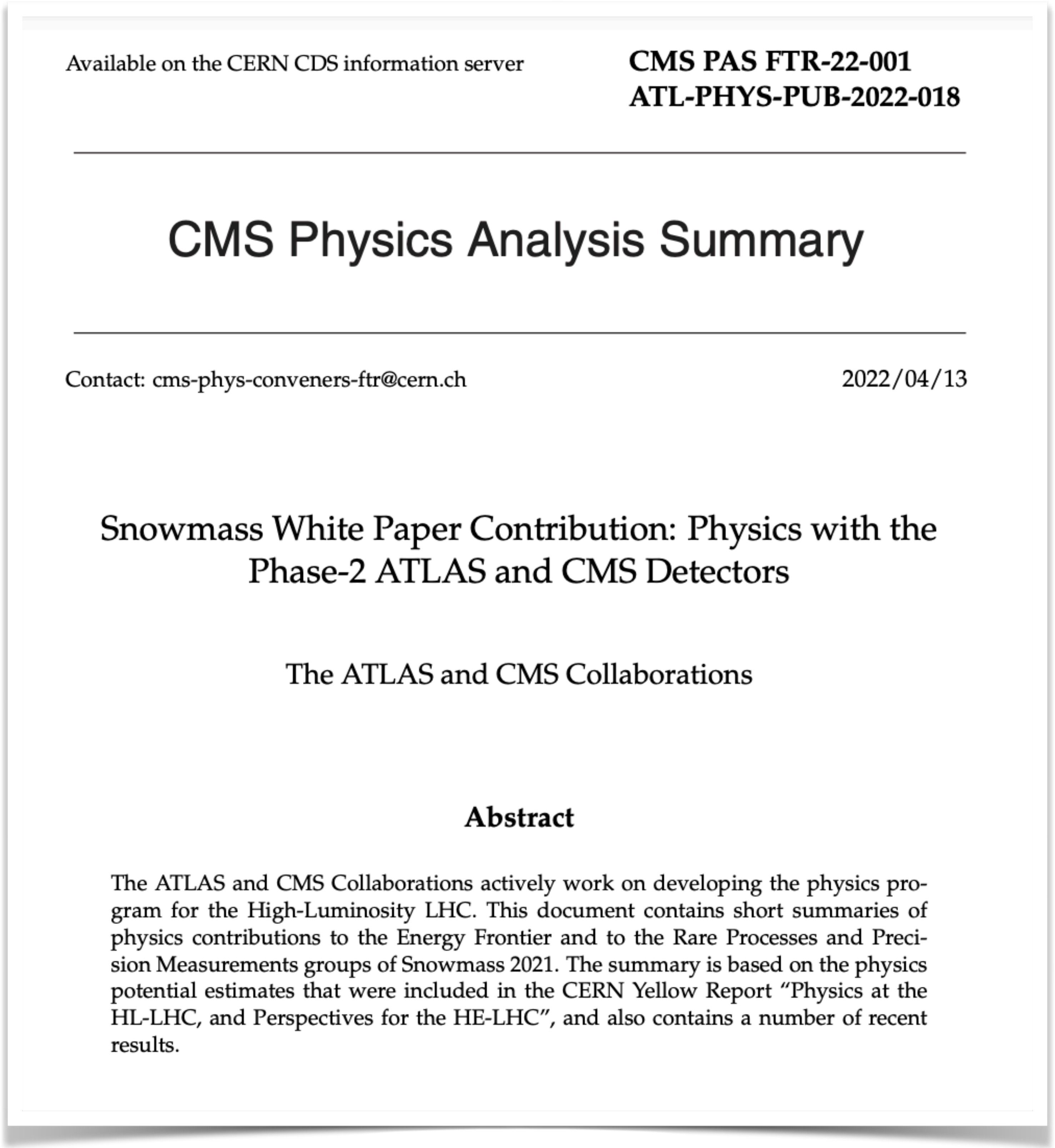
CERN-2019-007

Physics at the HL-LHC and
Perspectives for the HE-LHC

A. Dainese
M. Mangano
A. B. Meyer
A. Nisati
G. Salam
M. A. Vesterinen

CERN

2019 CERN Yellow Report



Available on the CERN CDS information server

CMS PAS FTR-22-001
ATL-PHYS-PUB-2022-018

CMS Physics Analysis Summary

Contact: cms-phys-conveners-ftr@cern.ch

2022/04/13

Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors

The ATLAS and CMS Collaborations

Abstract

The ATLAS and CMS Collaborations actively work on developing the physics program for the High-Luminosity LHC. This document contains short summaries of physics contributions to the Energy Frontier and to the Rare Processes and Precision Measurements groups of Snowmass 2021. The summary is based on the physics potential estimates that were included in the CERN Yellow Report "Physics at the HL-LHC, and Perspectives for the HE-LHC", and also contains a number of recent results.

Snowmass White Paper 2022

Overview

- Snowmass White Paper Contribution released in March
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  - Assume that Phase 2 detectors perform as well as the current ones but in harsher PU conditions

Snowmass White Paper 2022

Snowmass Projections	#New Results
Higgs Physics	14
Electroweak	2
QCD and Strong	1
Heavy Ions	1
BSM	5

Large number of results - choosing a few recent for this summary

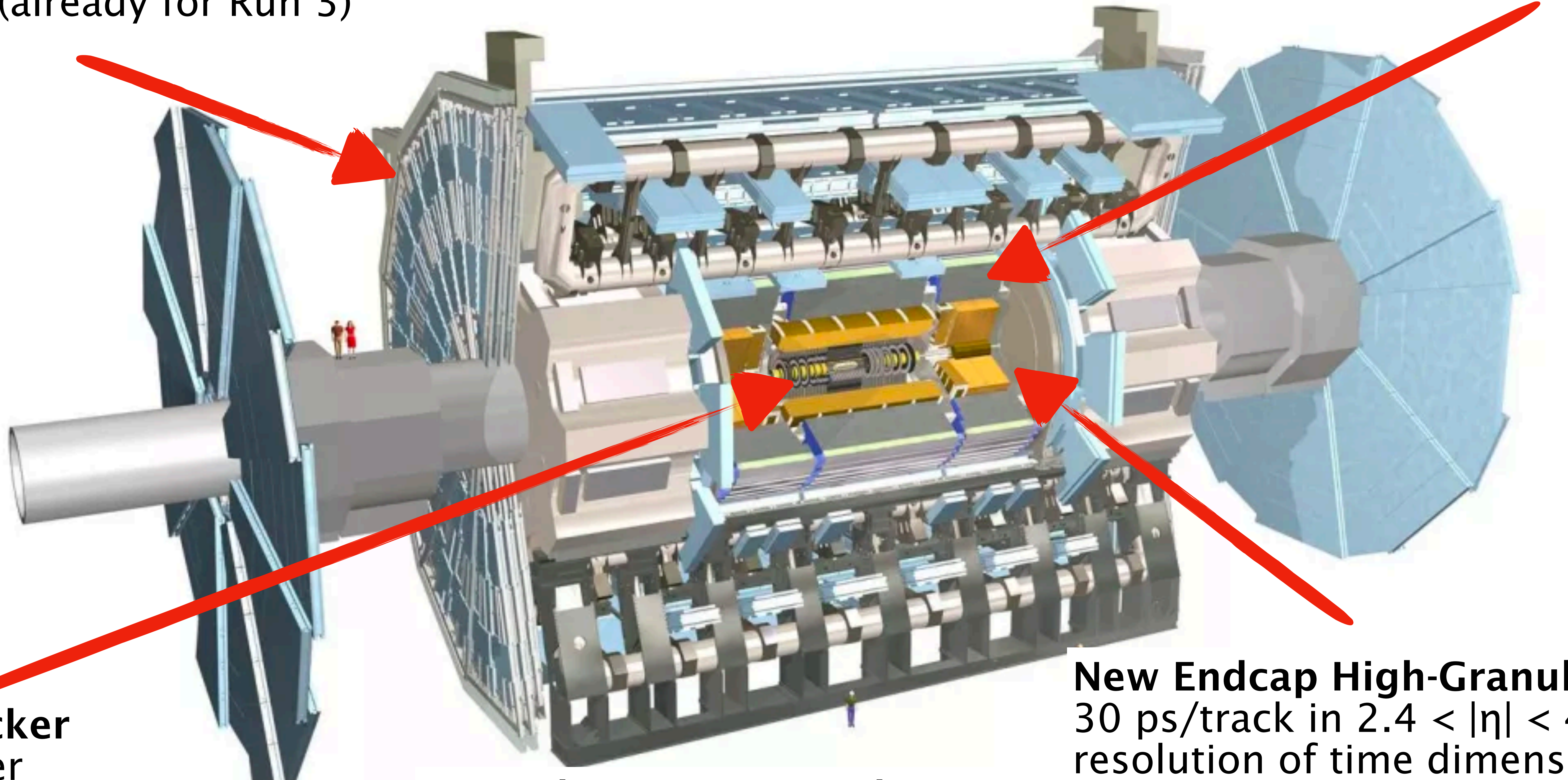
HL-LHC Updated Schedule

In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years

Upgraded Detectors at ATLAS

Improved Muon Coverage and Trigger
new RPCs in innermost layer
new MDT readout
new small wheels (already for Run 3)

Updates to calorimeter and trigger
new, higher granularity trigger
new Tile Cal readout



New Inner Tracker
all silicon tracker
5 layers of pixels
4 layers of strips
coverage to $|\eta| < 4$

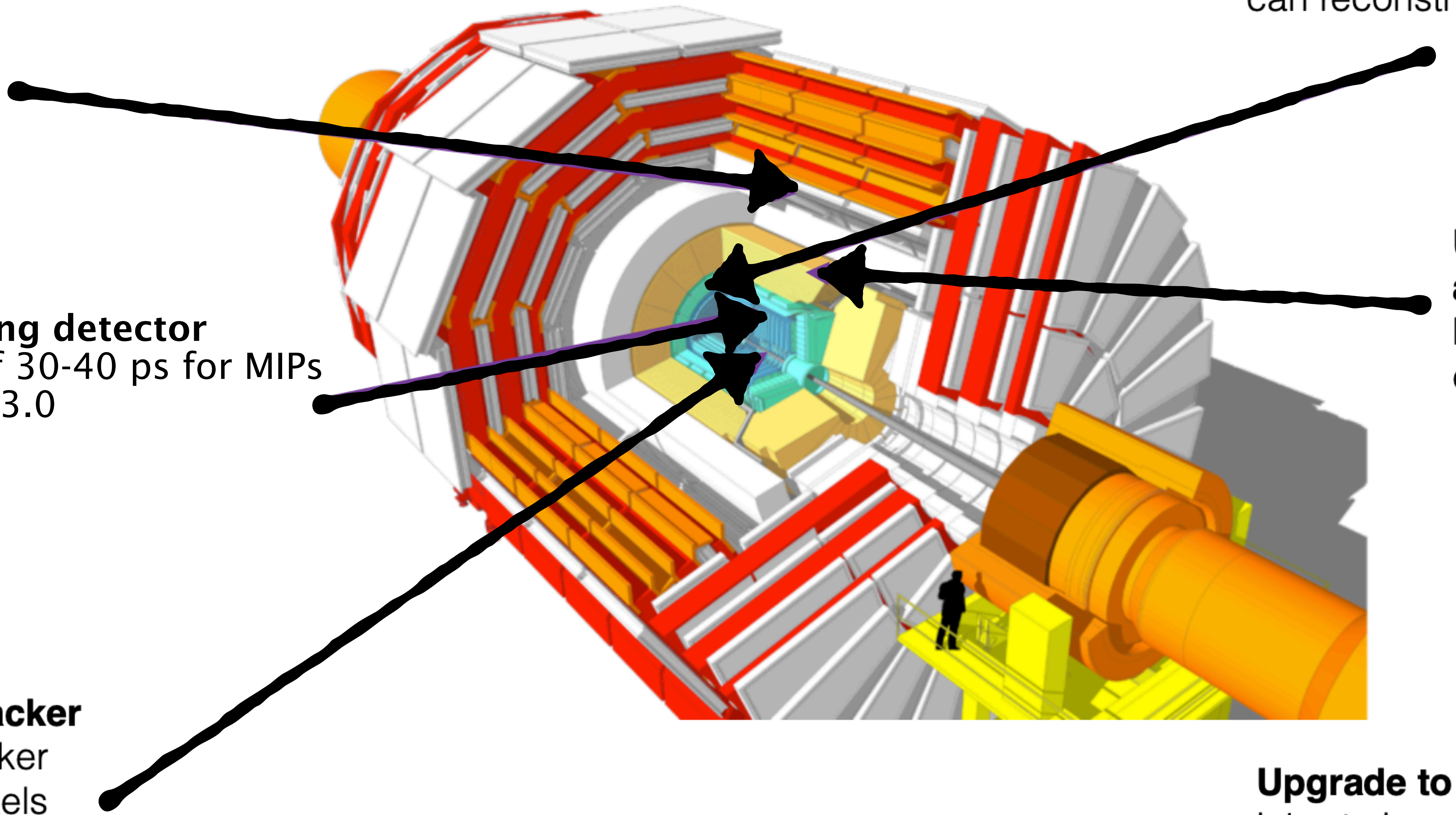
Upgrade to trigger and DAQ
L1 rate increased to 1 MHz
High Level Trigger rate to 10 kHz

New Endcap High-Granularity Timing Detector
30 ps/track in $2.4 < |\eta| < 4$
resolution of time dimension of beam spot

Upgraded Detectors at CMS

Improved muon coverage and trigger
increased RPC coverage (1.5 < |η| < 2.4)
new electronics

New endcap calorimeters
high granularity
can reconstruct showers in 3D



Updates to calorimeter and trigger
higher granularity
electronics for trigger

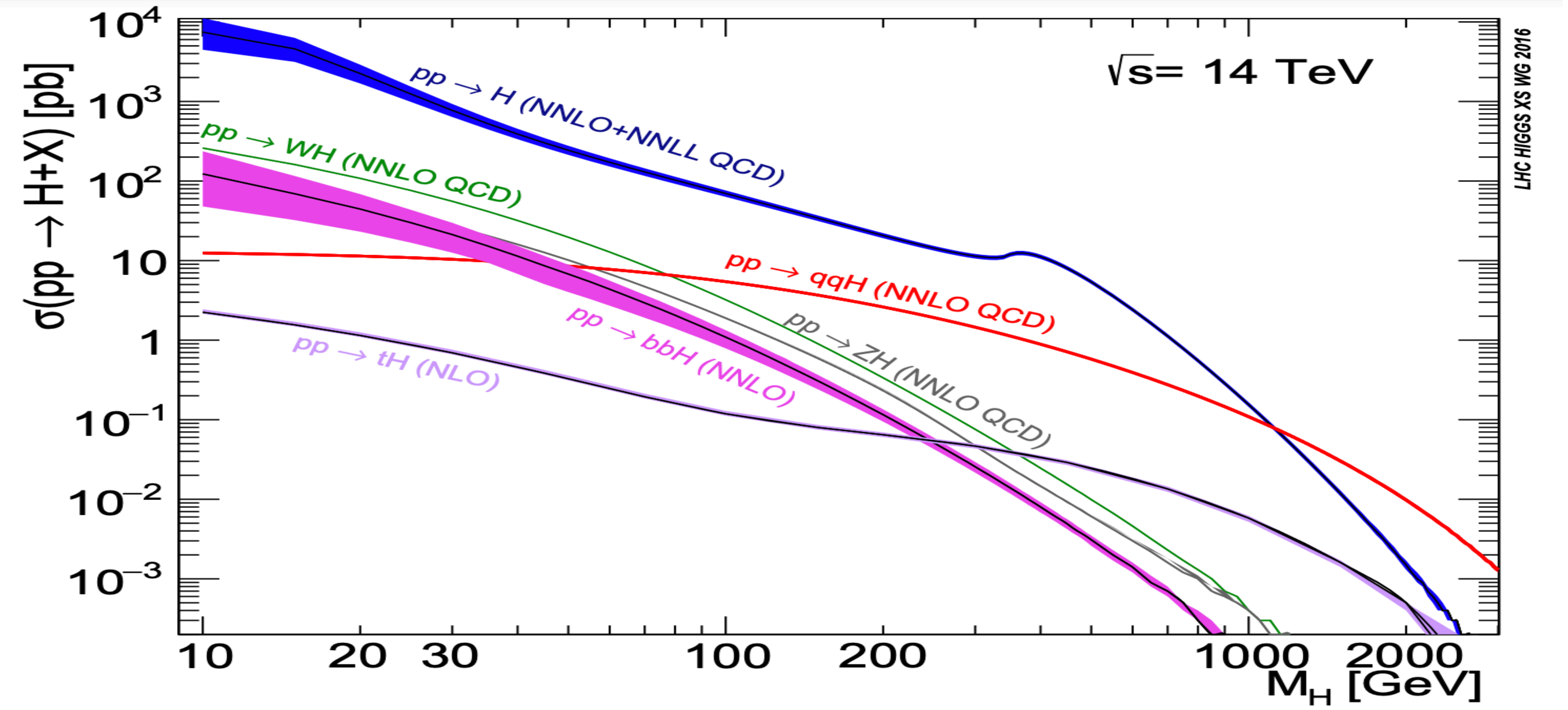
New precision timing detector
Timing resolution of 30-40 ps for MIPs
Full coverage of |η|<3.0

New inner tracker
all silicon tracker
4 layers of pixels
5 layers of strips
coverage to |η| < 4

Upgrade to trigger and DAQ
L1 rate increased to 750 kHz
High Level trigger rate to 7.5 kHz
Track information at L1

Physics at the HL-LHC

Higgs at the HL-LHC



Establish Decay and Production Mechanisms

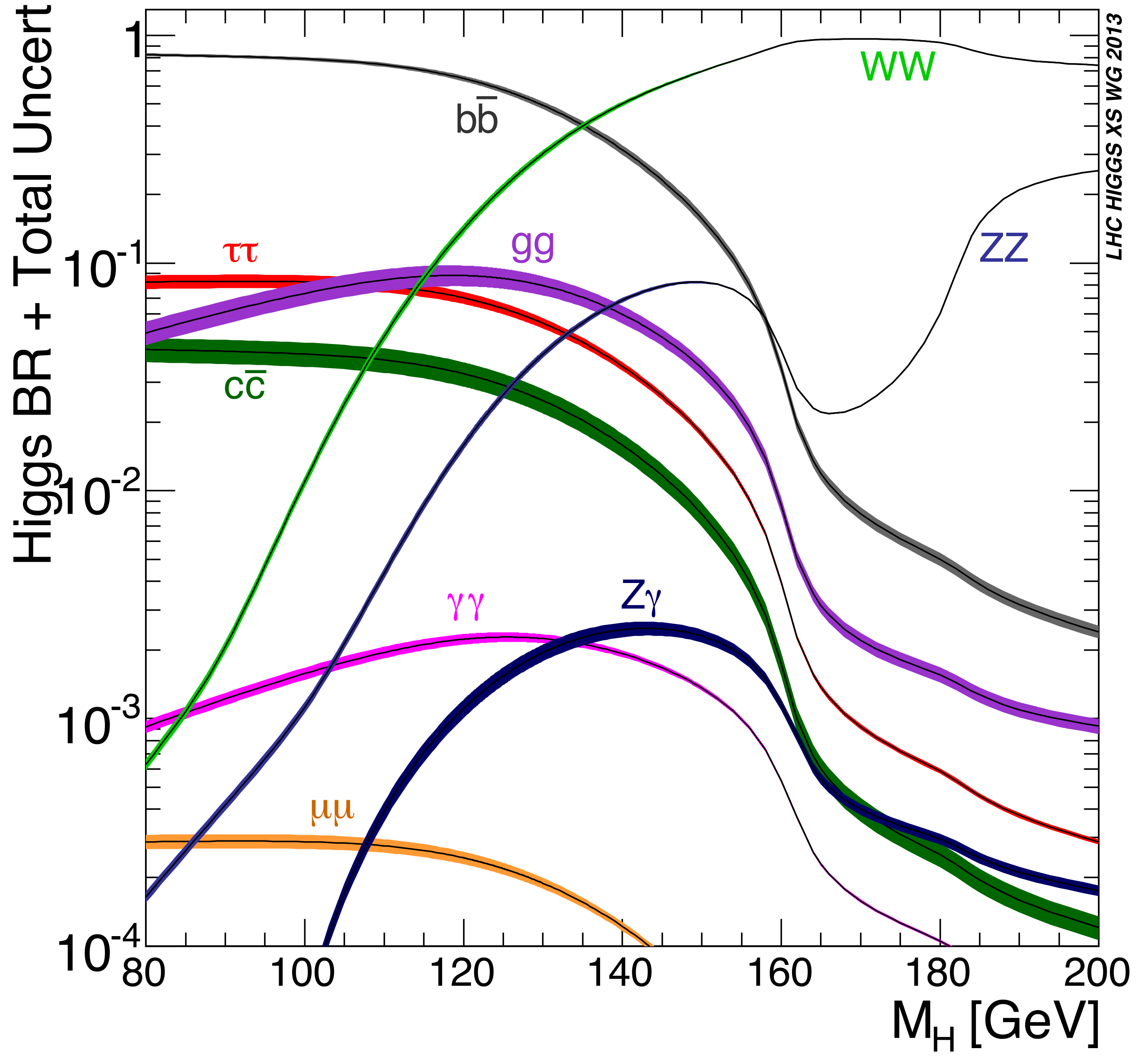
Measure mass, width, spin

Precision Measurements:

Differential, STXS, Global Fits

Search for Higgs Self-Coupling

Search for BSM Higgses



Δσ/σ [%]	ggF (+bbH)	VBF	VH: WH	VH: ZH	ttH	tH
γγ	2.5	7.9	9.9	13.2	5.9	54
ZZ	2.5	9.5	13		15.2	
WW	2.5	5.5	9.9	12.8	6.6	
ττ	4.5	3.9	10		10.7	
bb	19		8.3	4.6	10.2	
μμ	7					
cc			80			
Zγ	24	51.2				

YR result

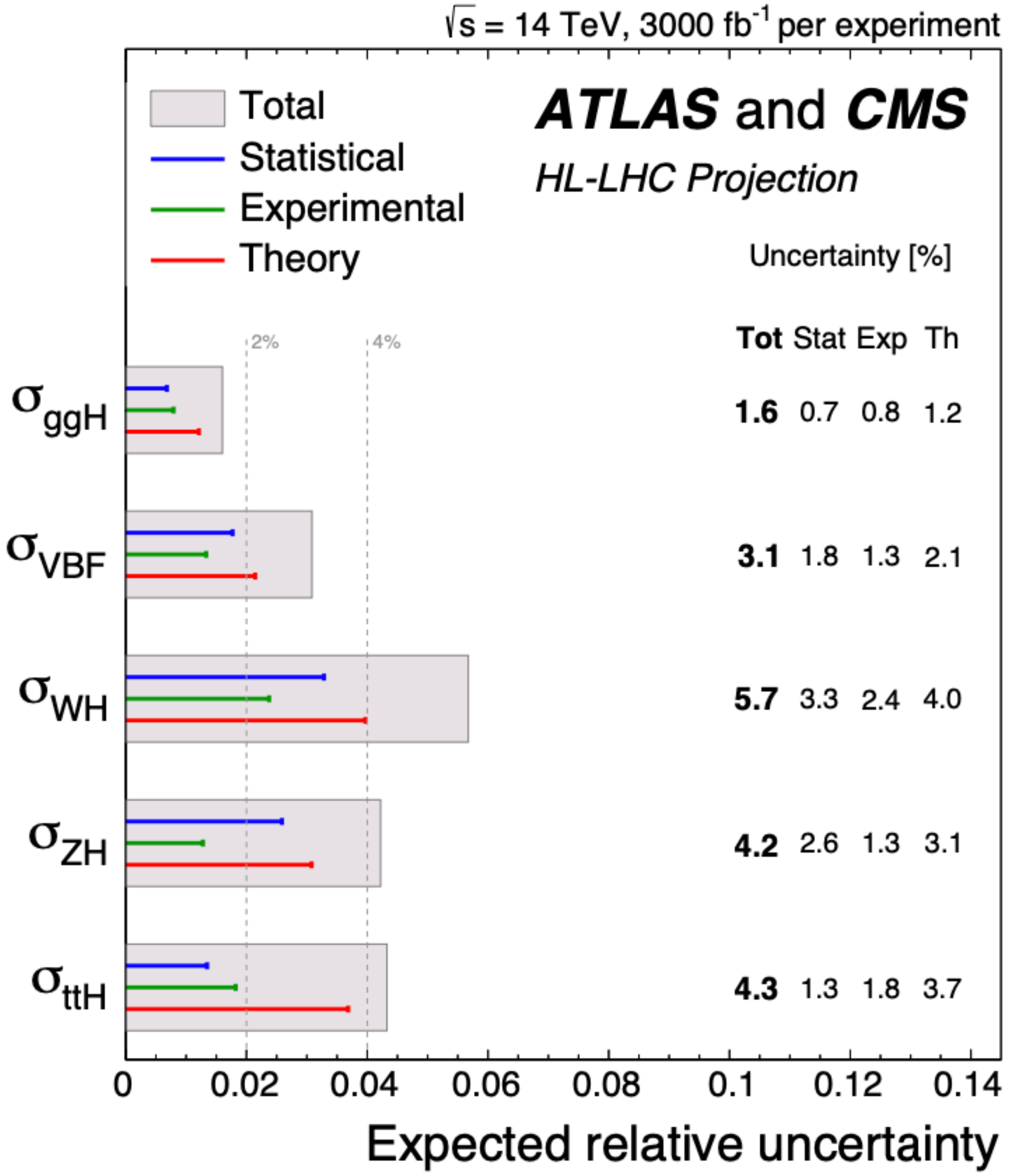
New for Snowmass

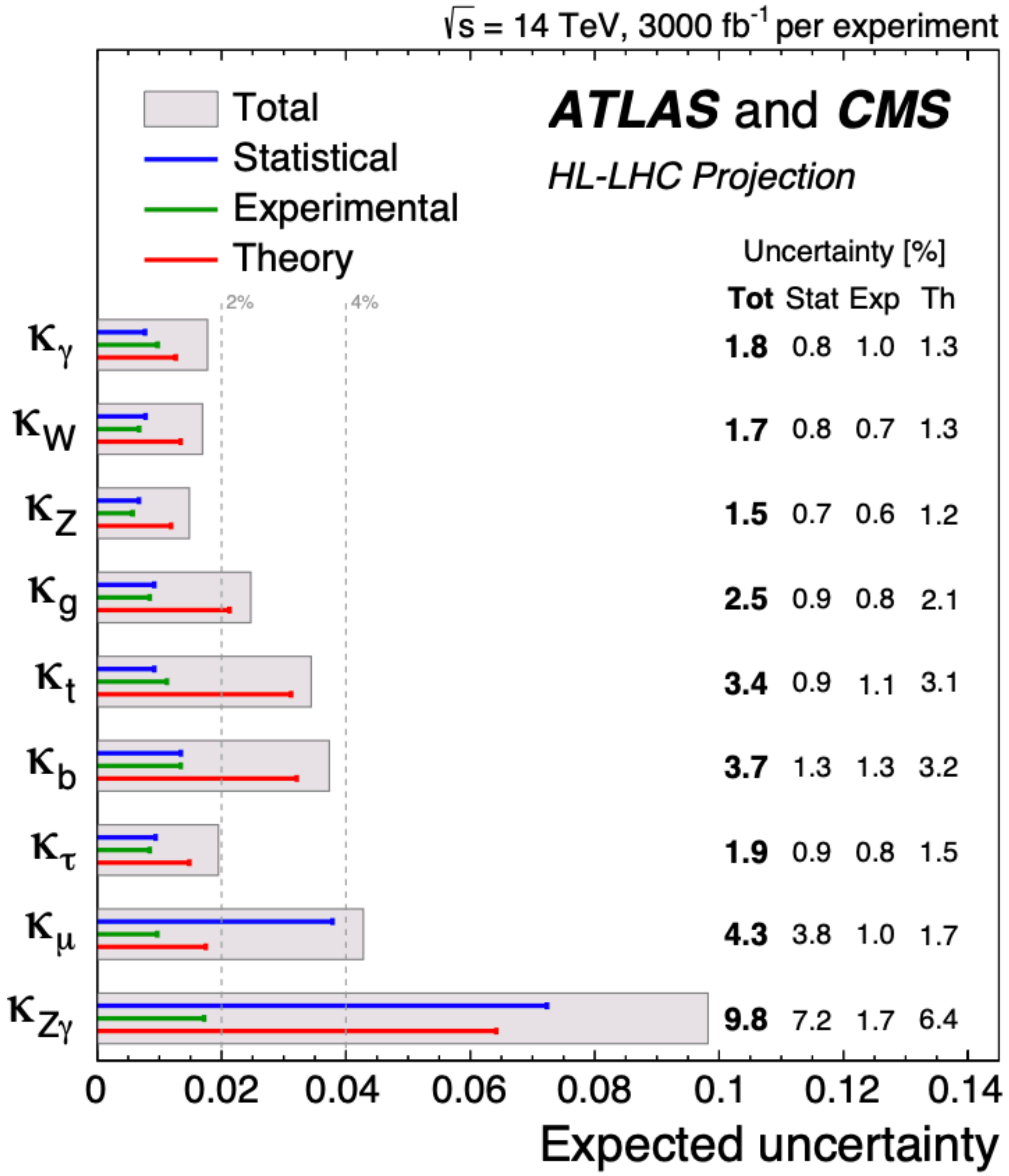
Run-2 result

Higgs Production and Couplings

Brief Review

- Study performed for the ESG
    - YR 18 uncertainties (S2 scenario)
- H→μμ and H→Zγ measurements still limited by size of the collected dataset
- Other couplings currently dominated by theoretical uncertainties
- Often experiments outperform expected projections for experimental uncertainties

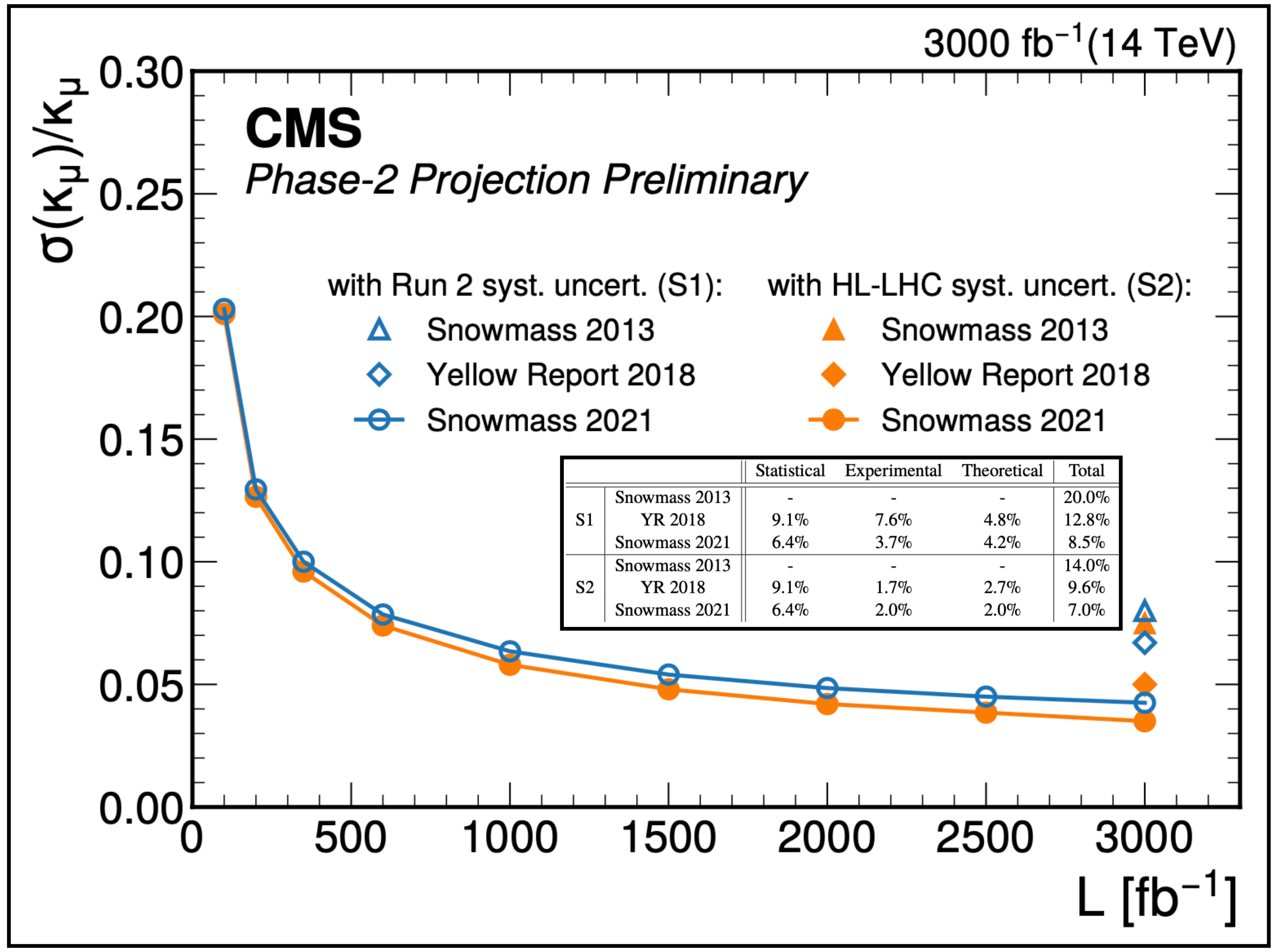




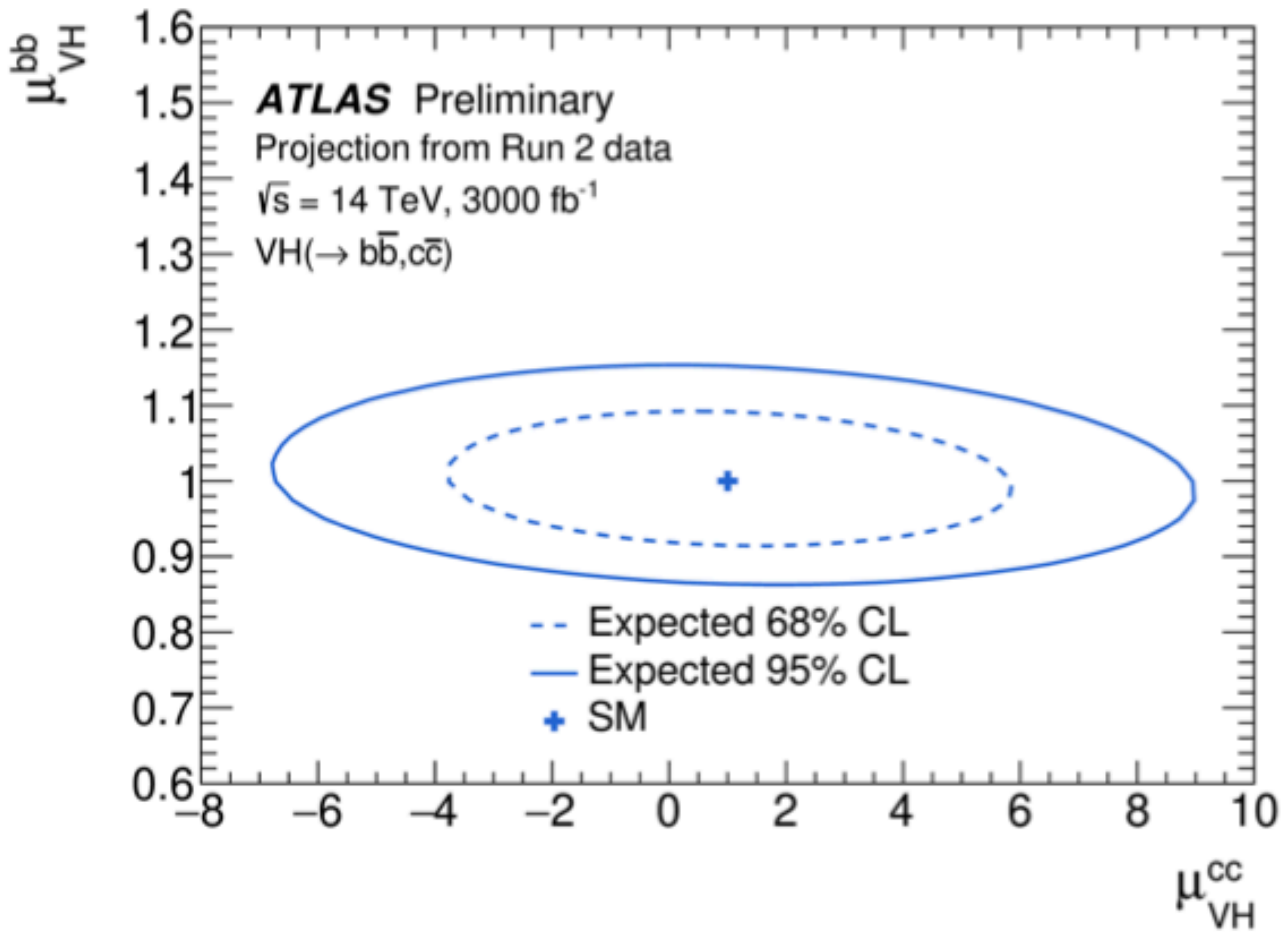
Higgs Couplings

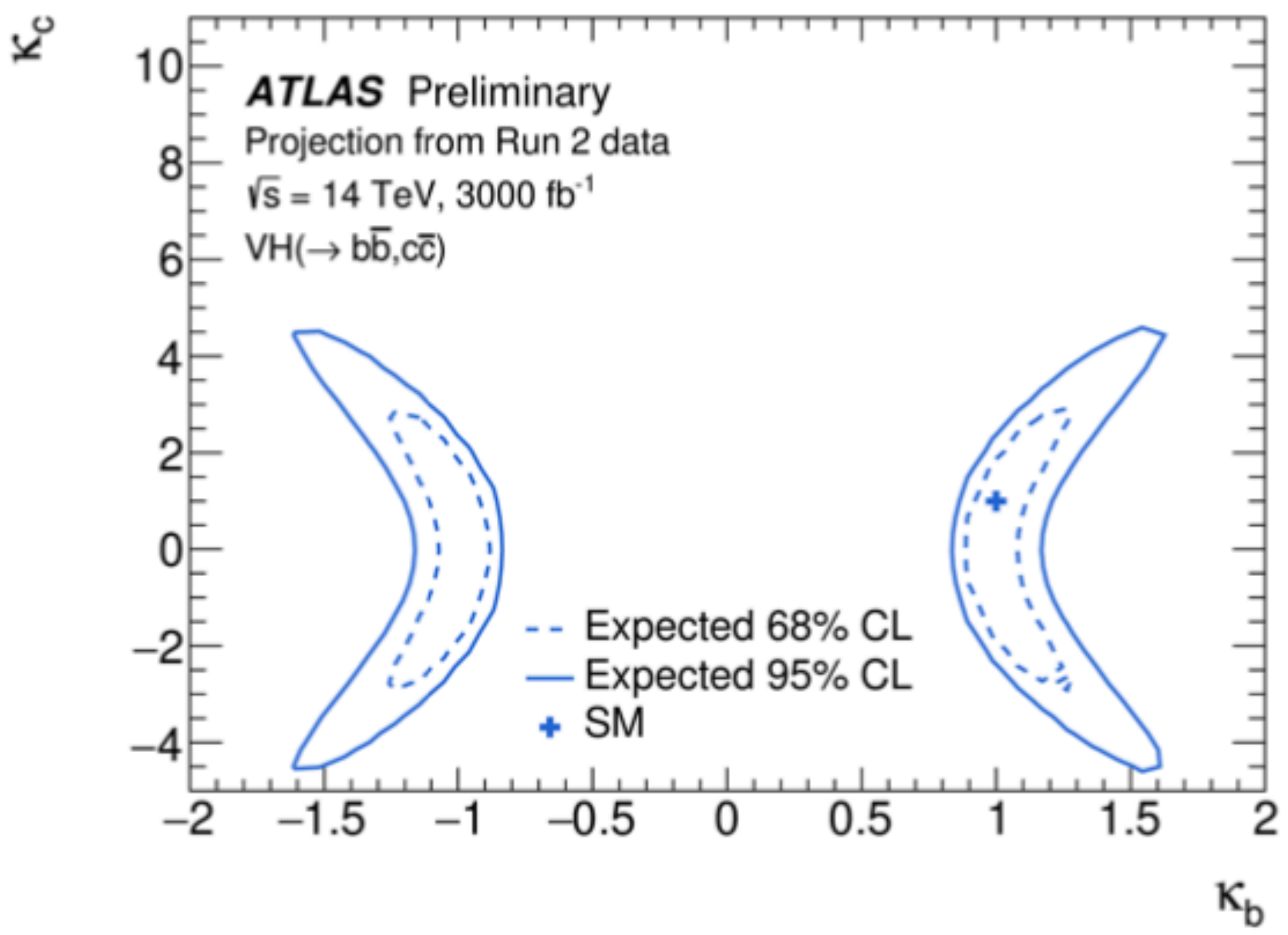
New Projections

- $H \to \mu\mu$
  - YR projections performed from partial Run2 dataset analyses Full Run2 measurements have improved beyond expectations
  - i.e. $H \to \tau\tau$ or $H \to bb$ improved as ~sqrt(L) despite being dominated by systematic uncertainties
- $H \to cc$
  - Projection based on recent updates from ATLAS and CMS using Run2 dataset
  - CMS' projection makes use of the powerful boosted analysis strategy
  - Merged-jet category for events with $p_T H > 300$ GeV
  - Direct measurement of the Higgs coupling to the charm is within reach at the HL-LHC!



		Statistical	Experimental	Theoretical	Total
S1	Snowmass 2013	-	-	-	20.0%
	YR 2018	9.1%	7.6%	4.8%	12.8%
	Snowmass 2021	6.4%	3.7%	4.2%	8.5%
S2	Snowmass 2013	-	-	-	14.0%
	YR 2018	9.1%	1.7%	2.7%	9.6%
	Snowmass 2021	6.4%	2.0%	2.0%	7.0%





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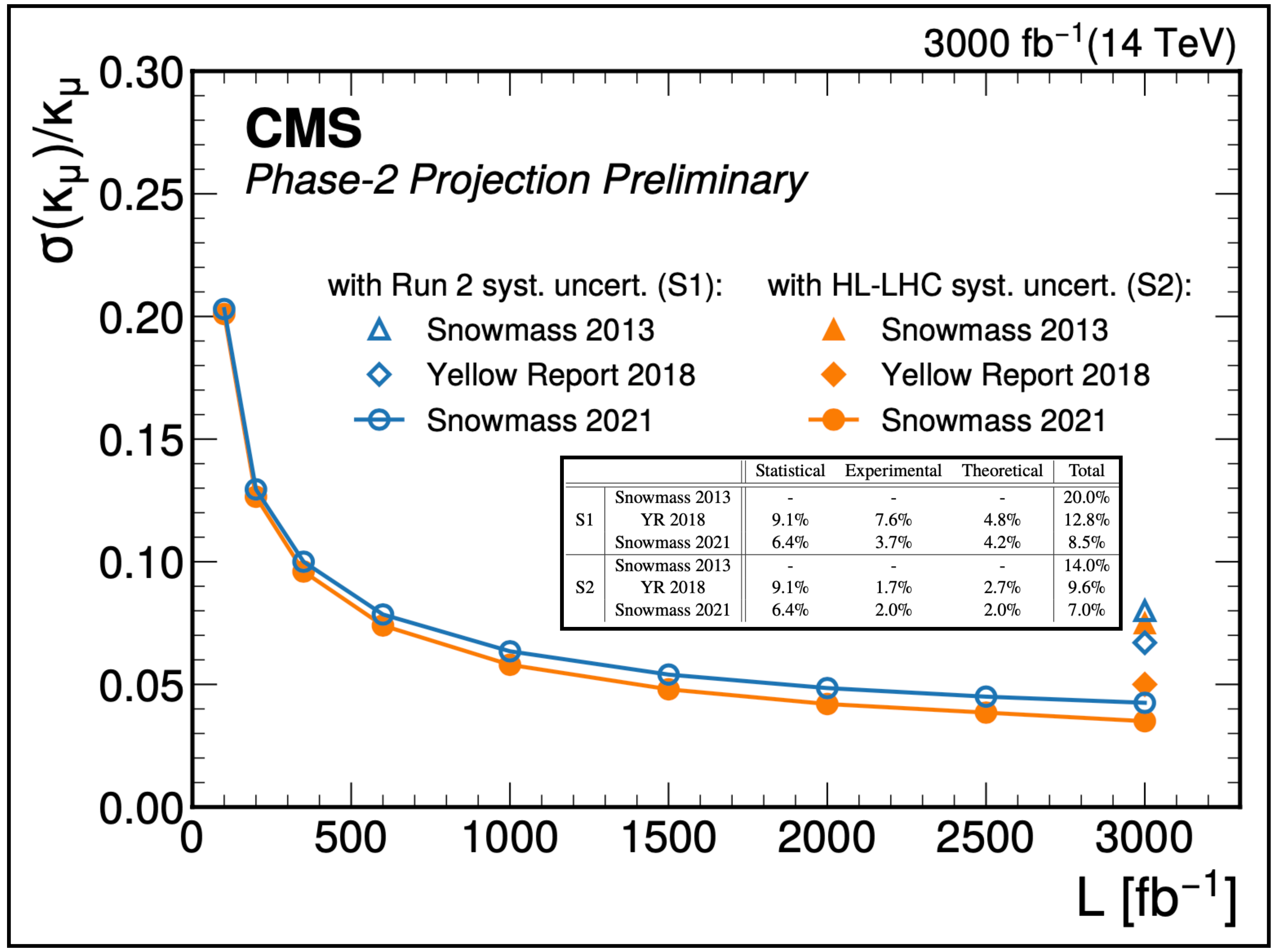

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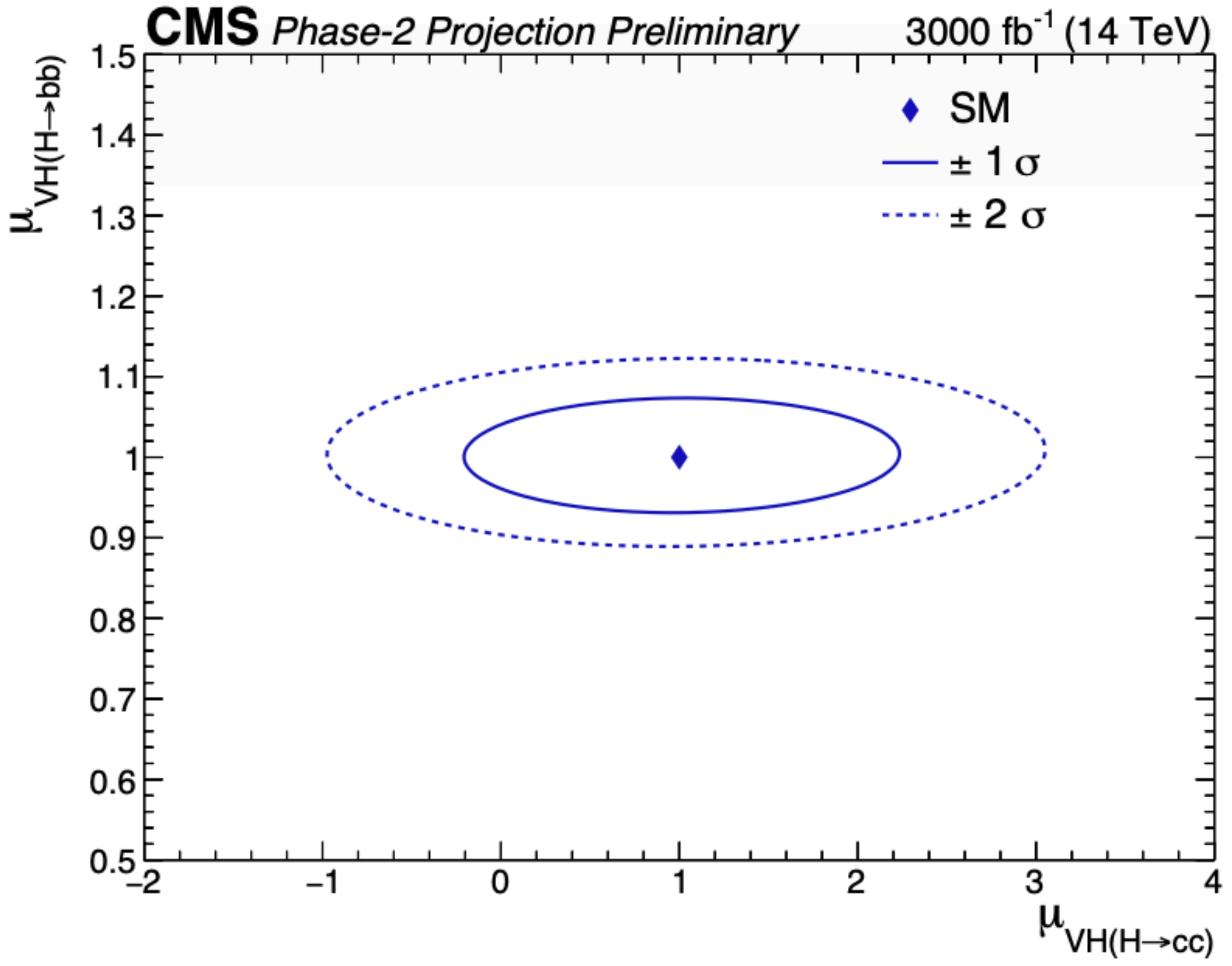
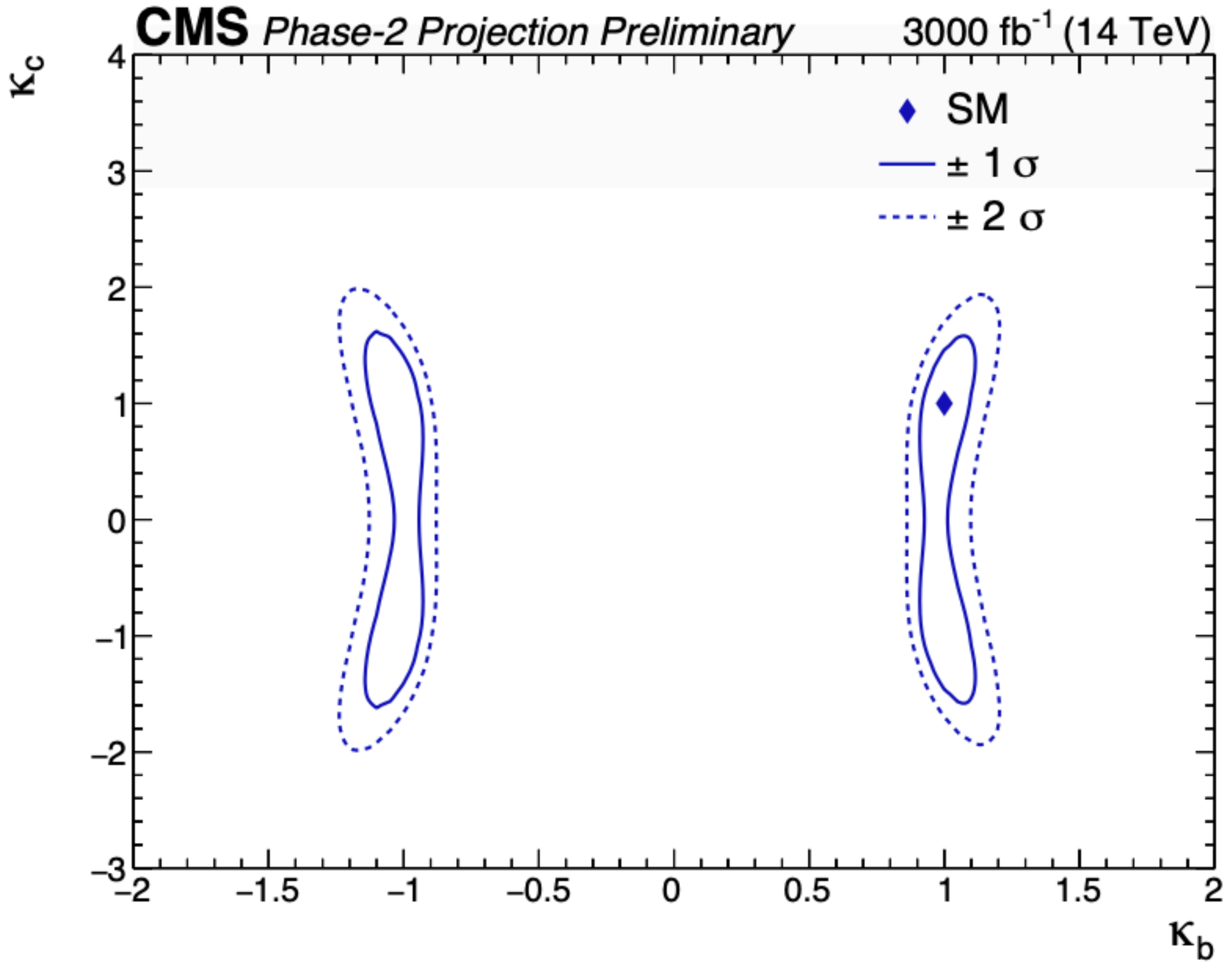
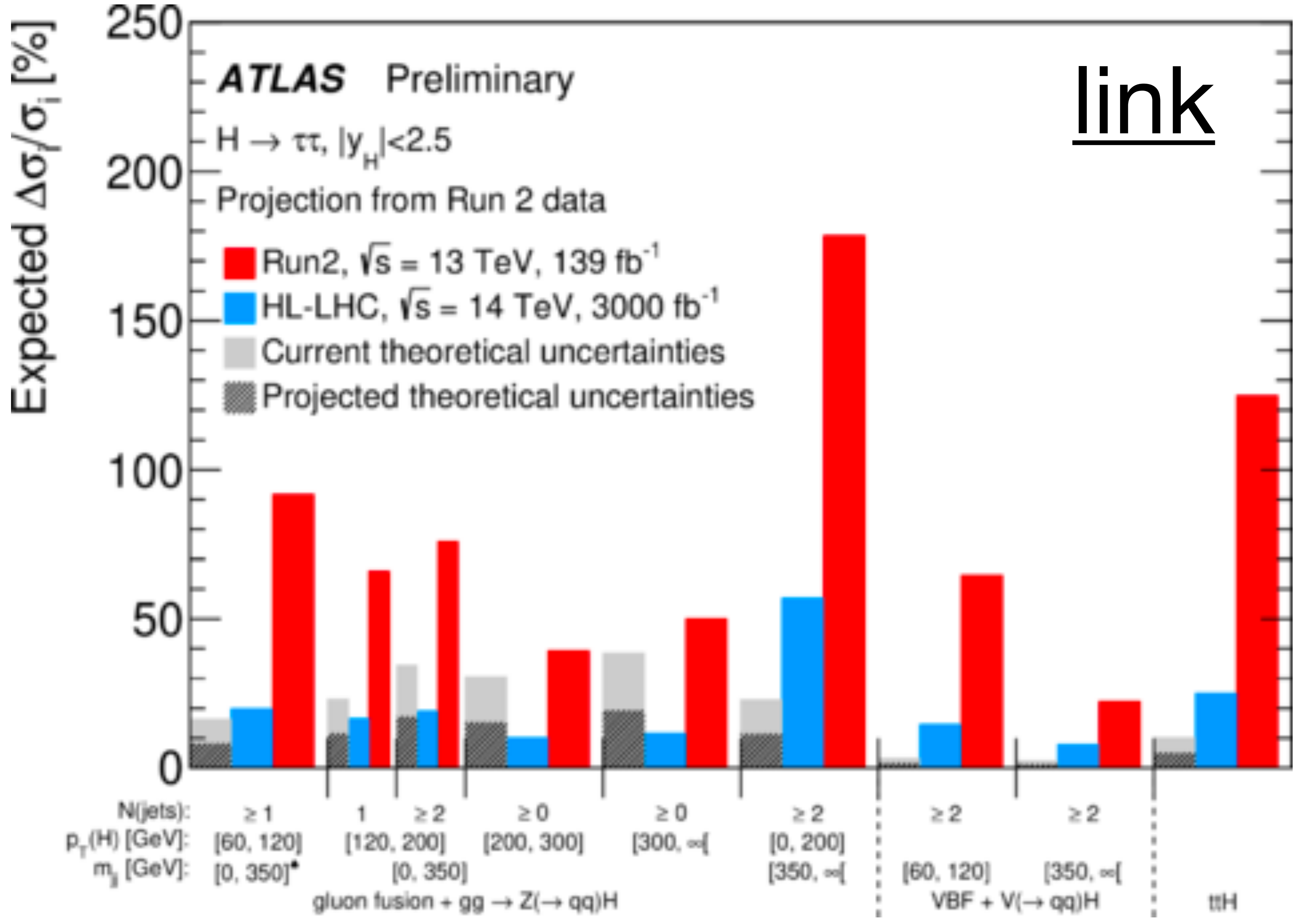


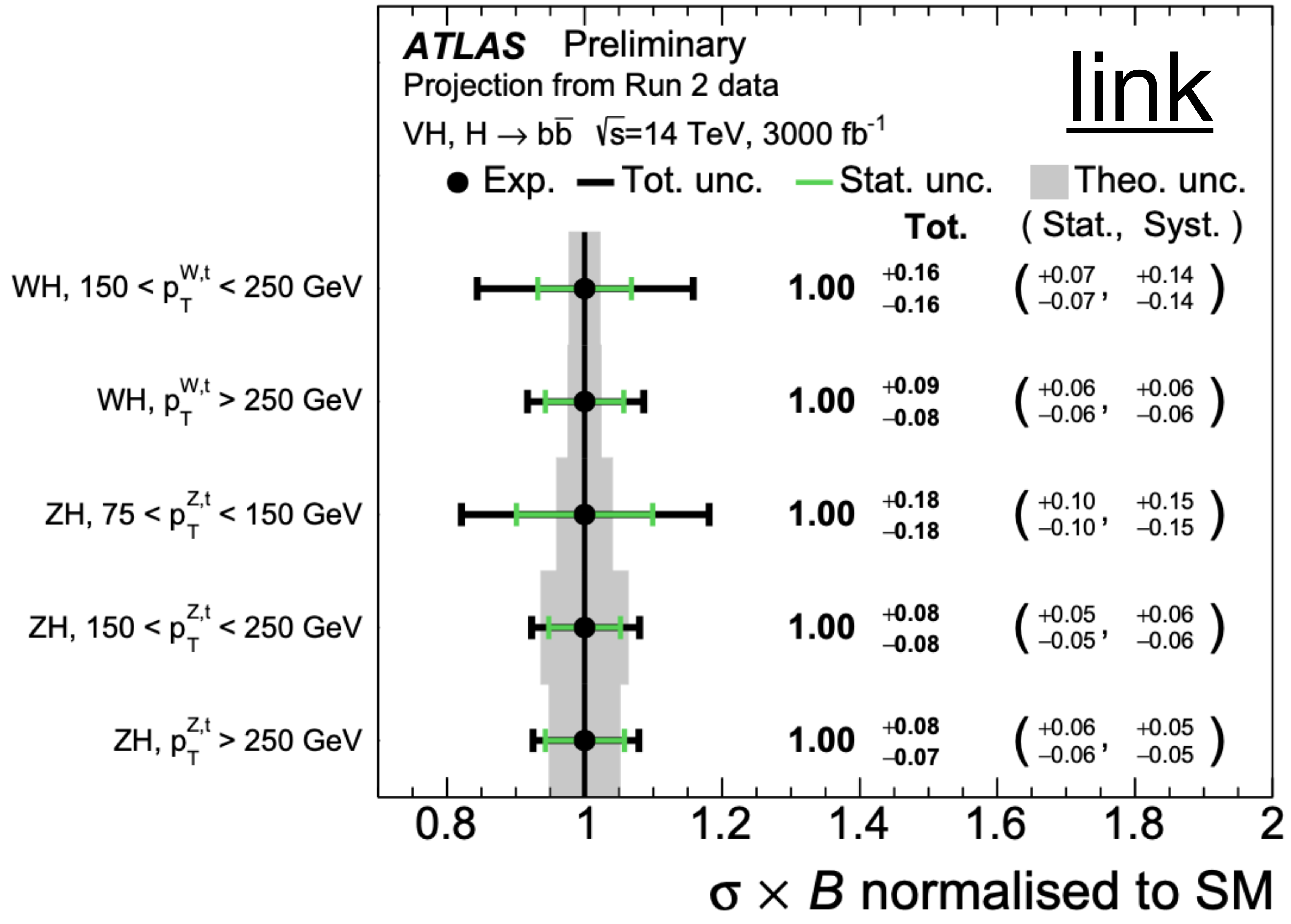


Differential Measurements

Higgs kinematics and Higgs associated production

- Measurement limited by systematic uncertainties (except at very high $p_T H$)
  Snowmass Update:
  ATLAS in H → ττ and VH → bb within the STXS framework





Differential Measurements

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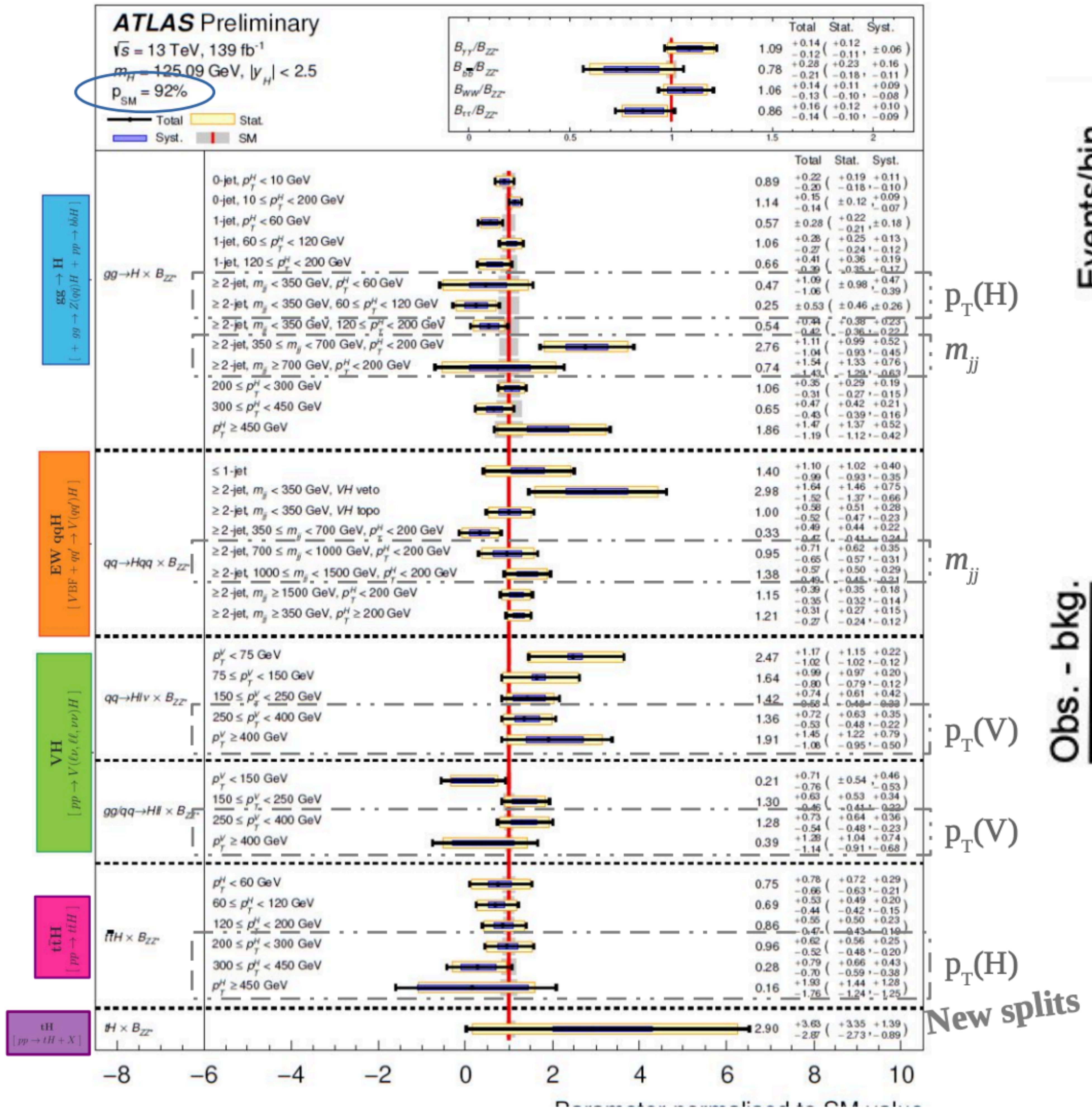
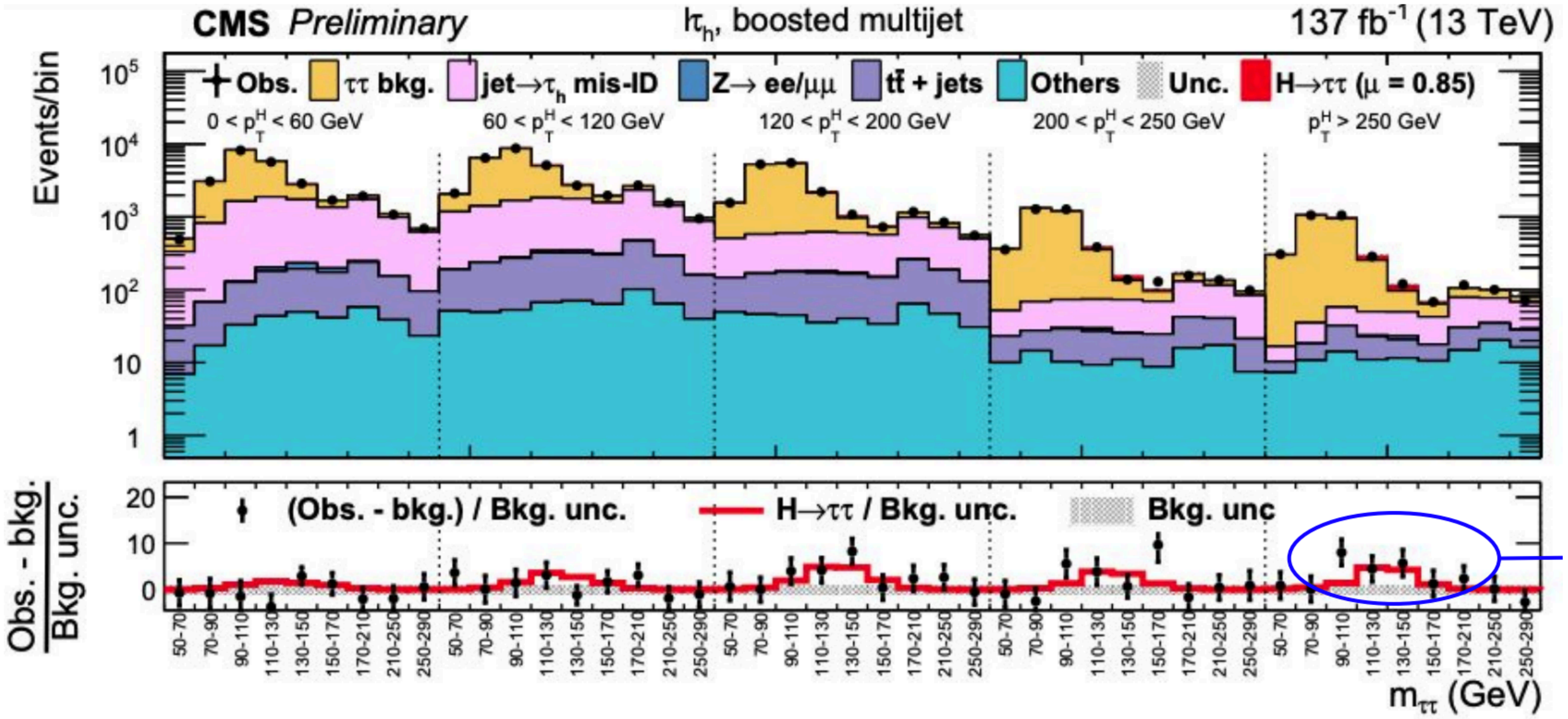
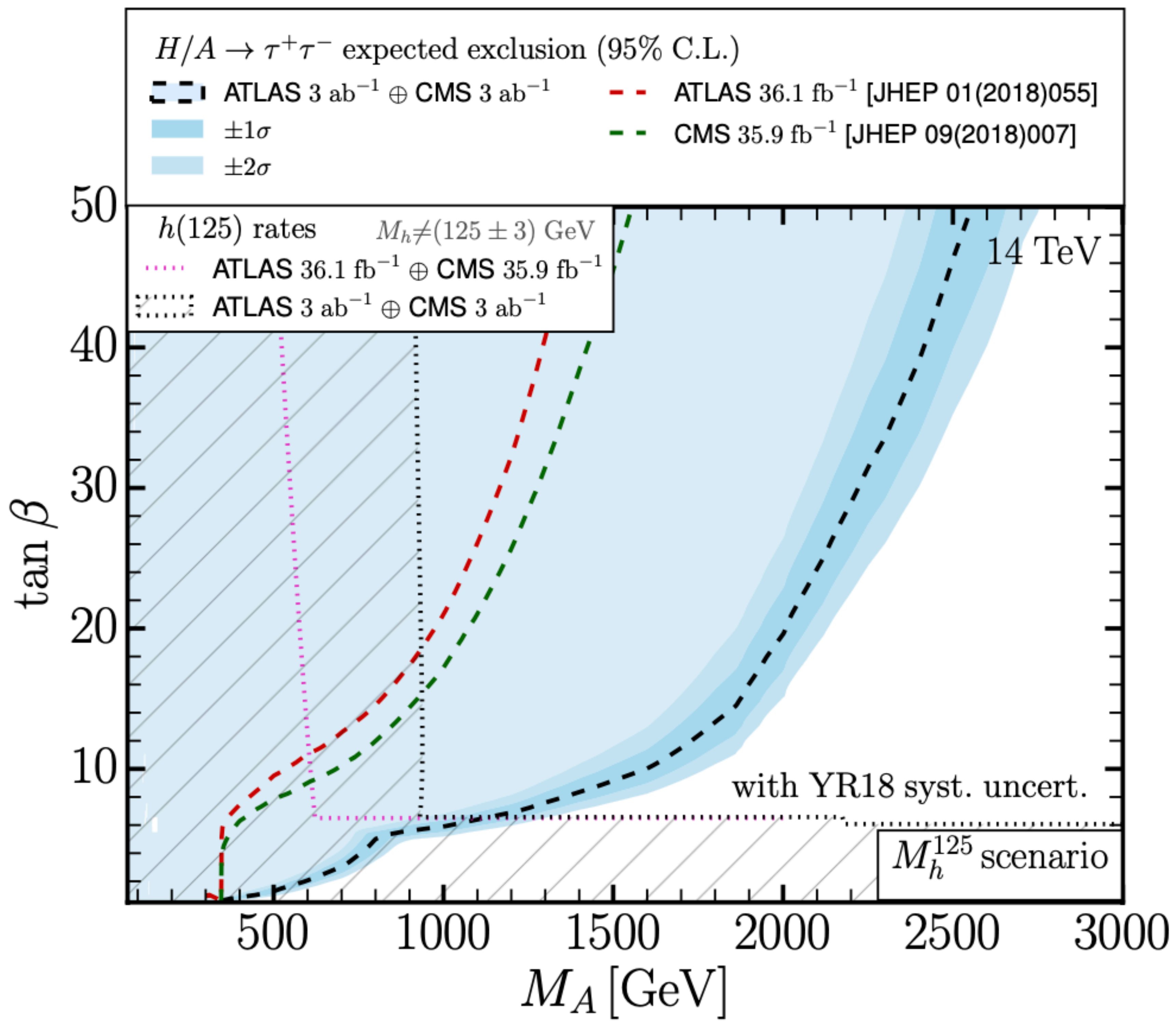




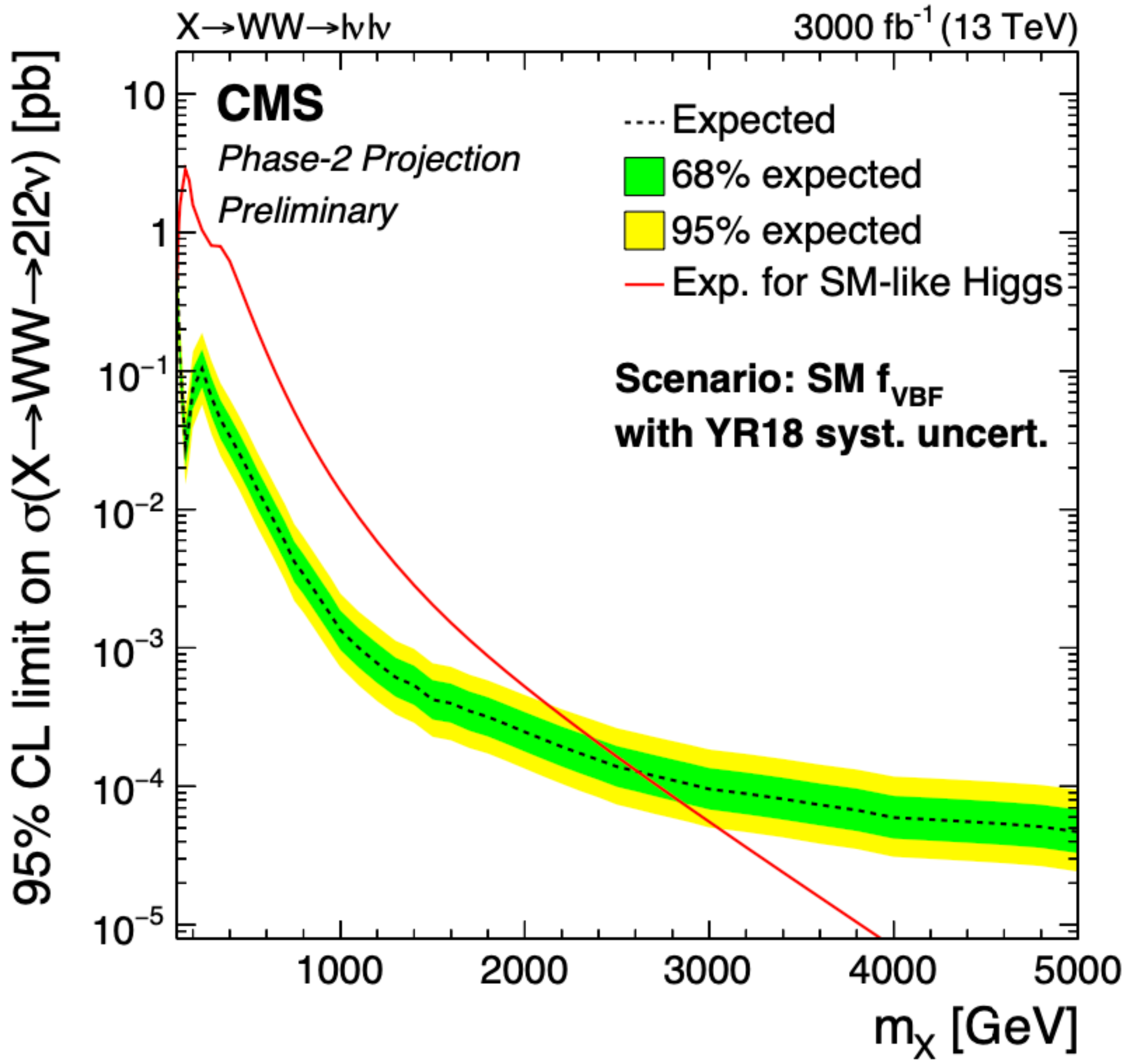
Run-2 Results as an Example

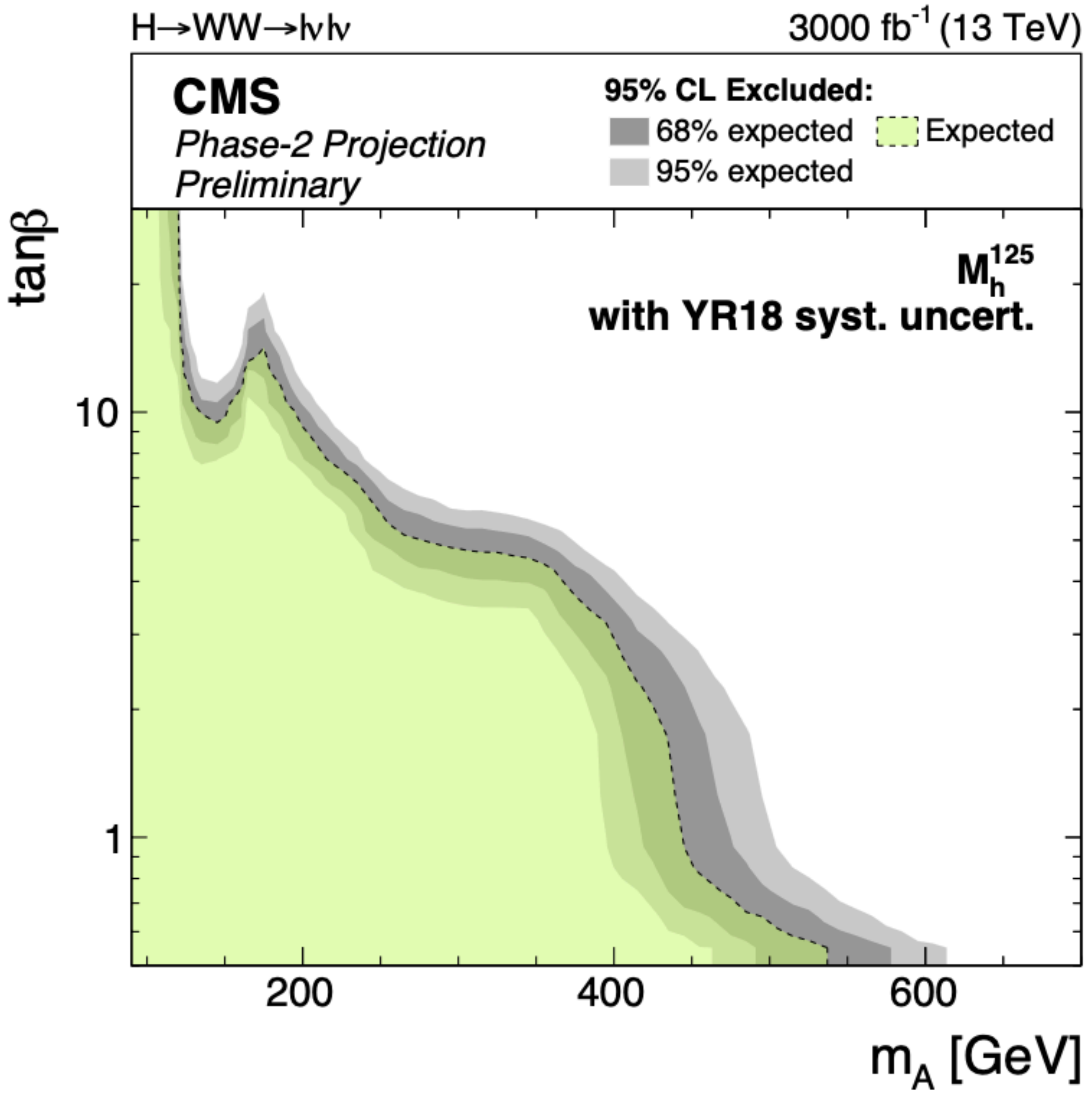
Higgs BSM

Selected 2HDM Results



YR18





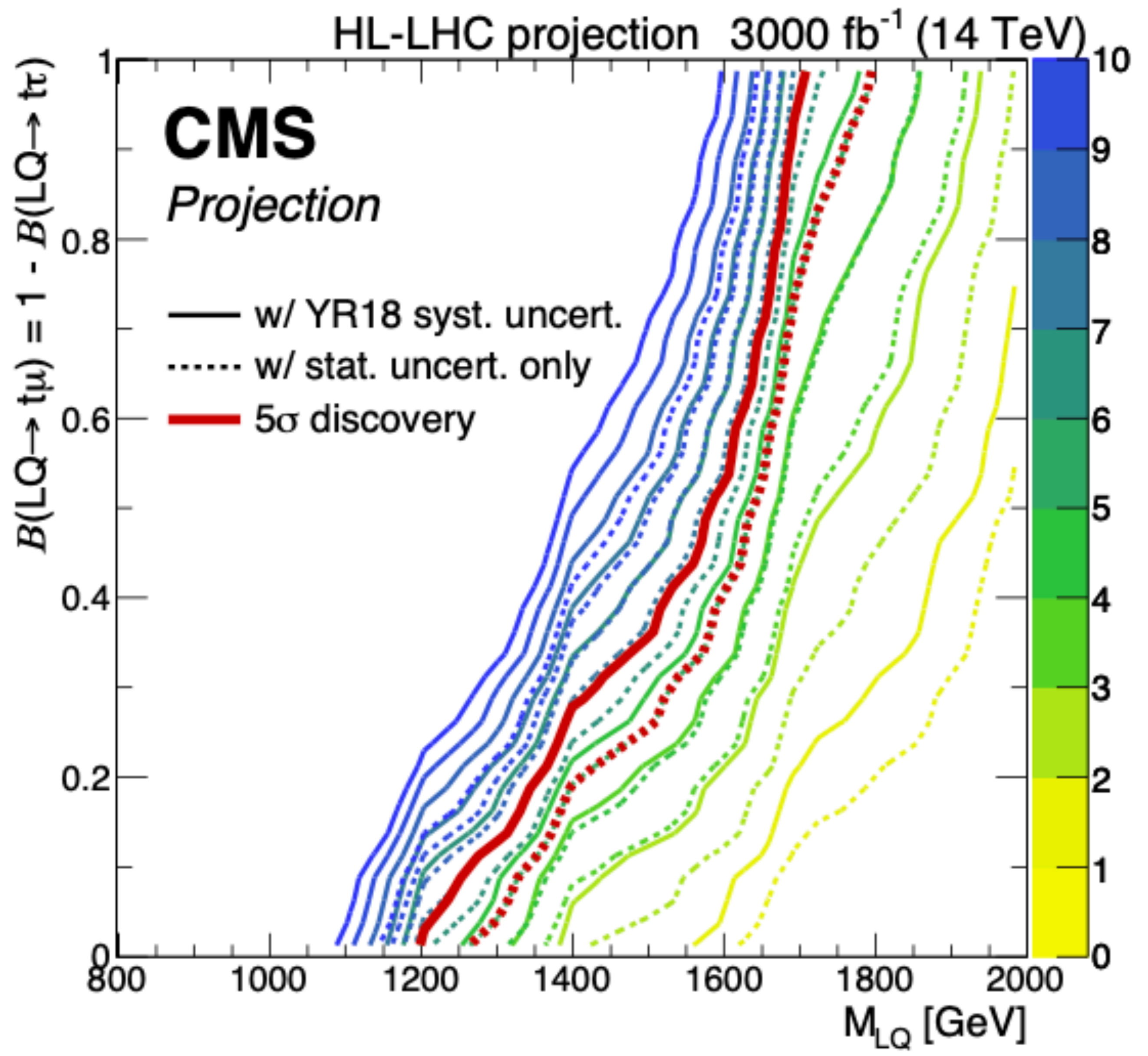
New for Snowmass

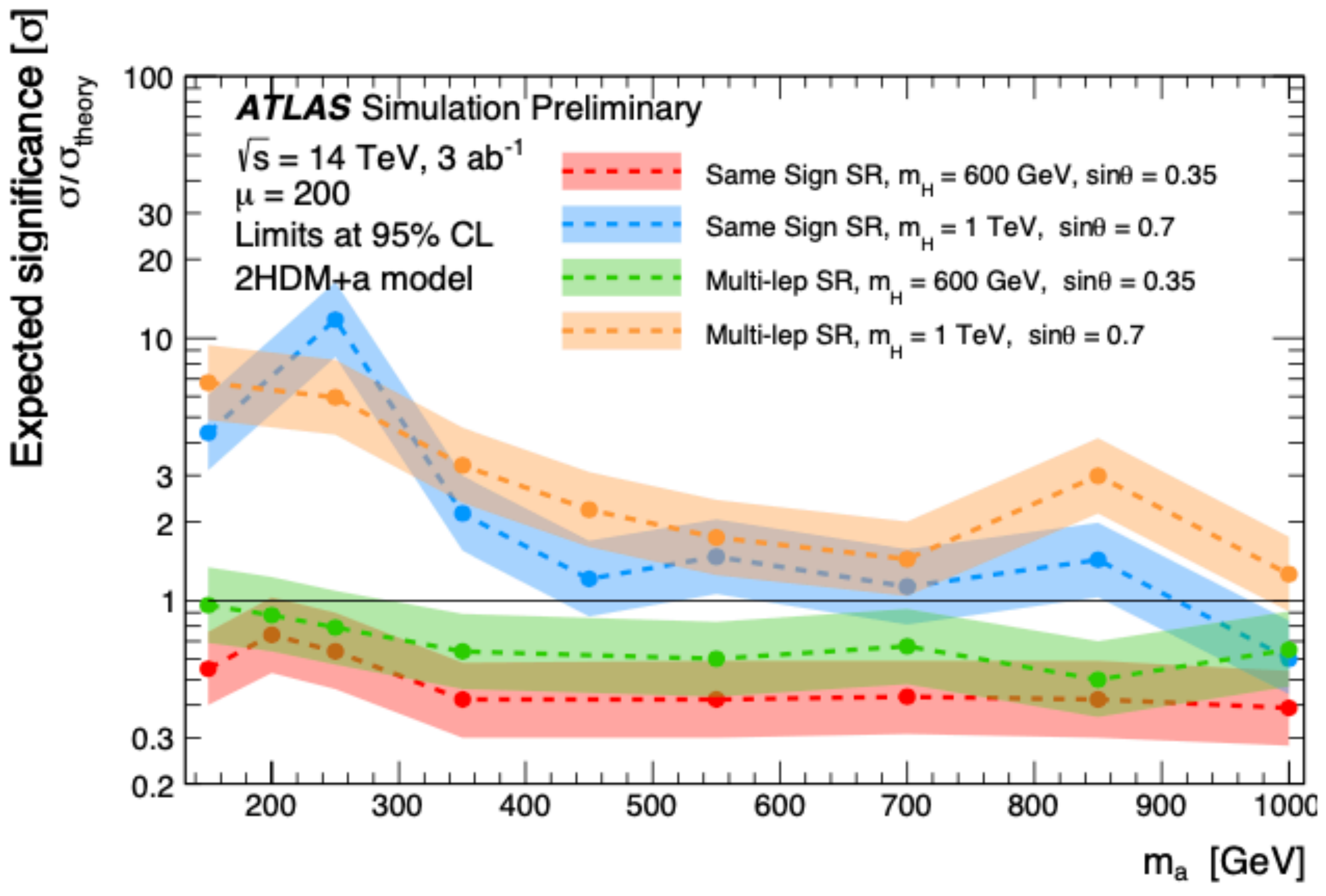
BSM at the HL-LHC

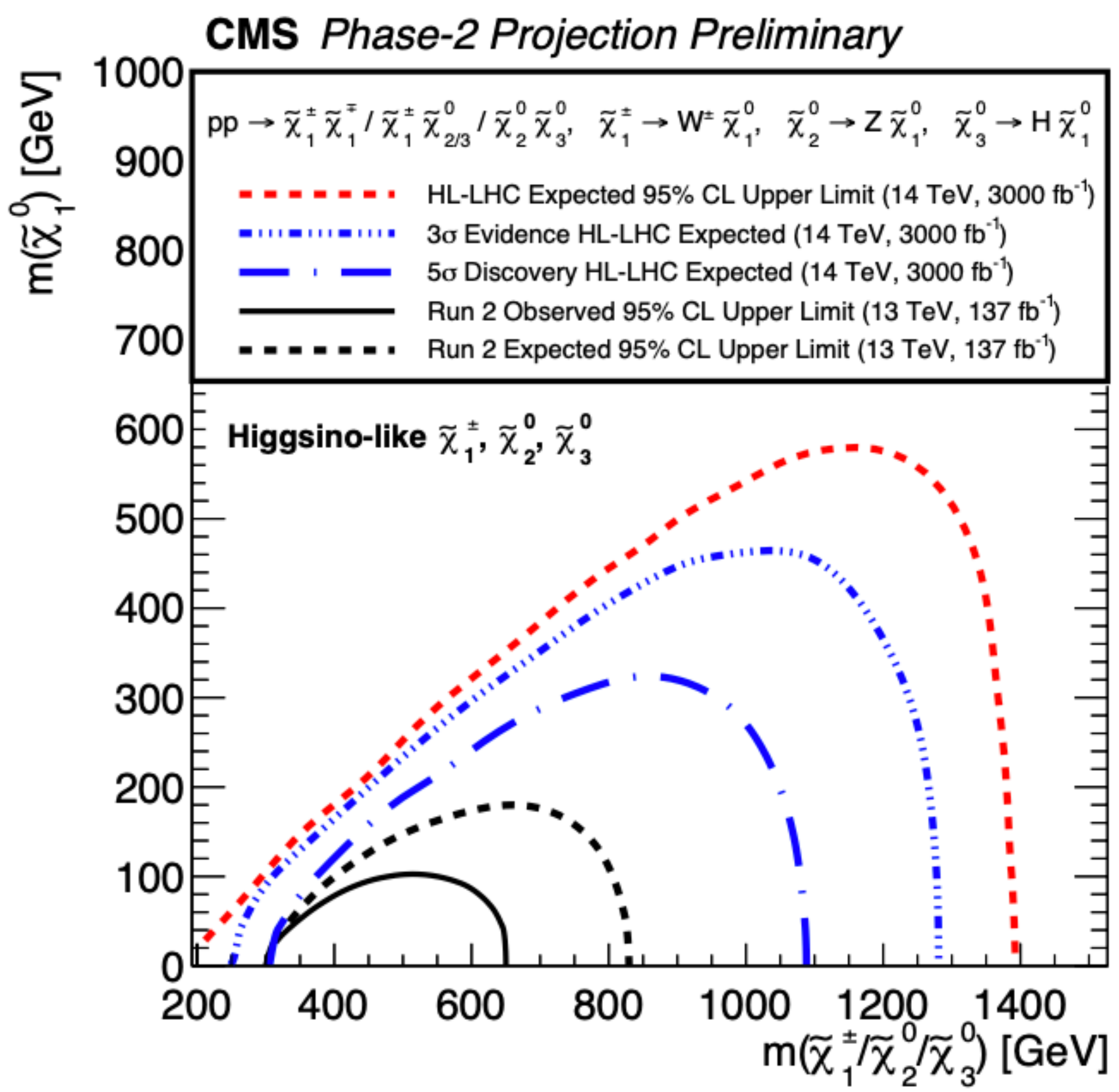
BSM

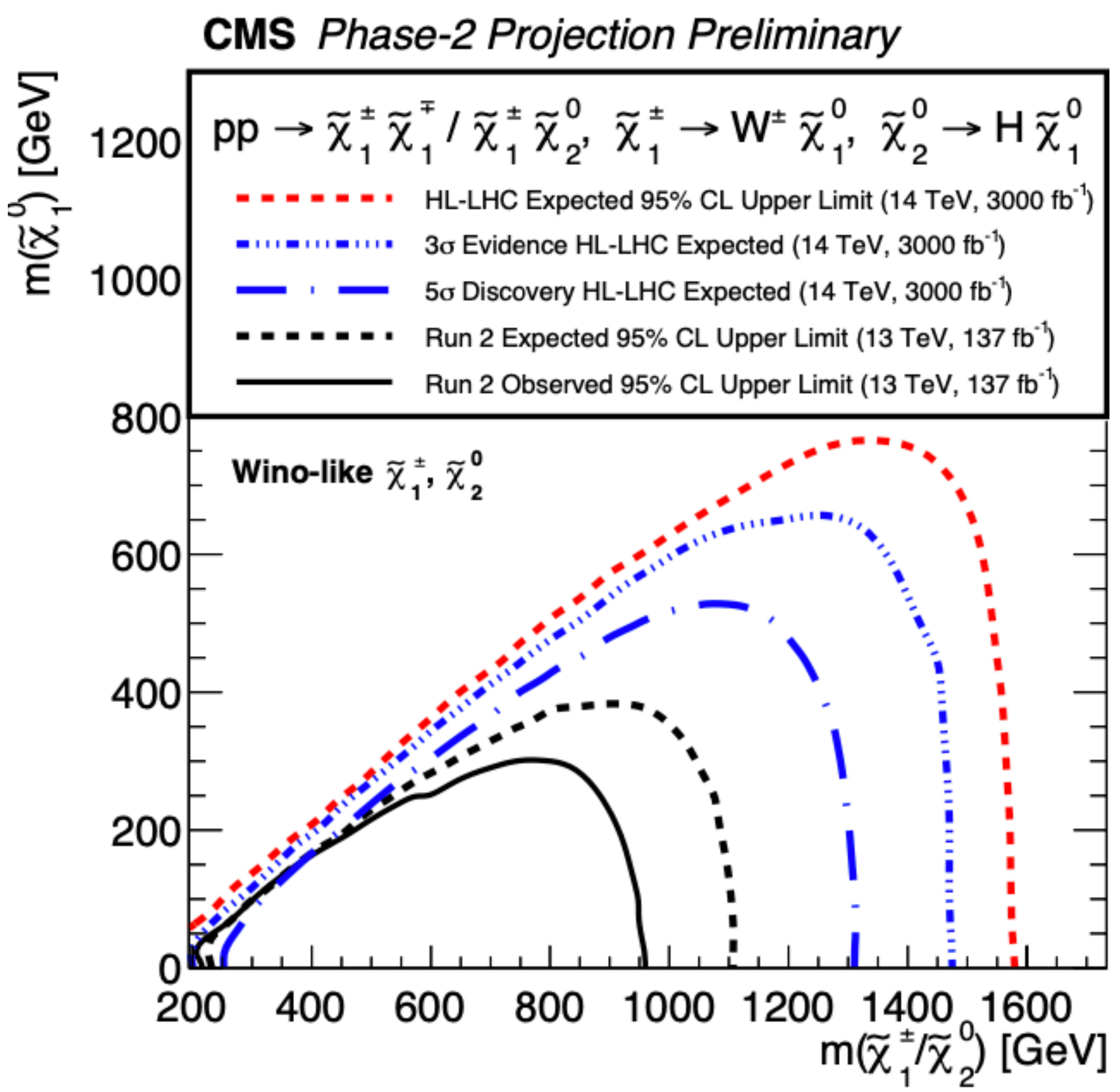
Selected Results

- Searches for Scalar leptoquarks at ATLAS and CMS
- Hadronic electroweak supersymmetry search with CMS at the HL-LHC
- Mass-degenerate higgsino-like and wino-like production





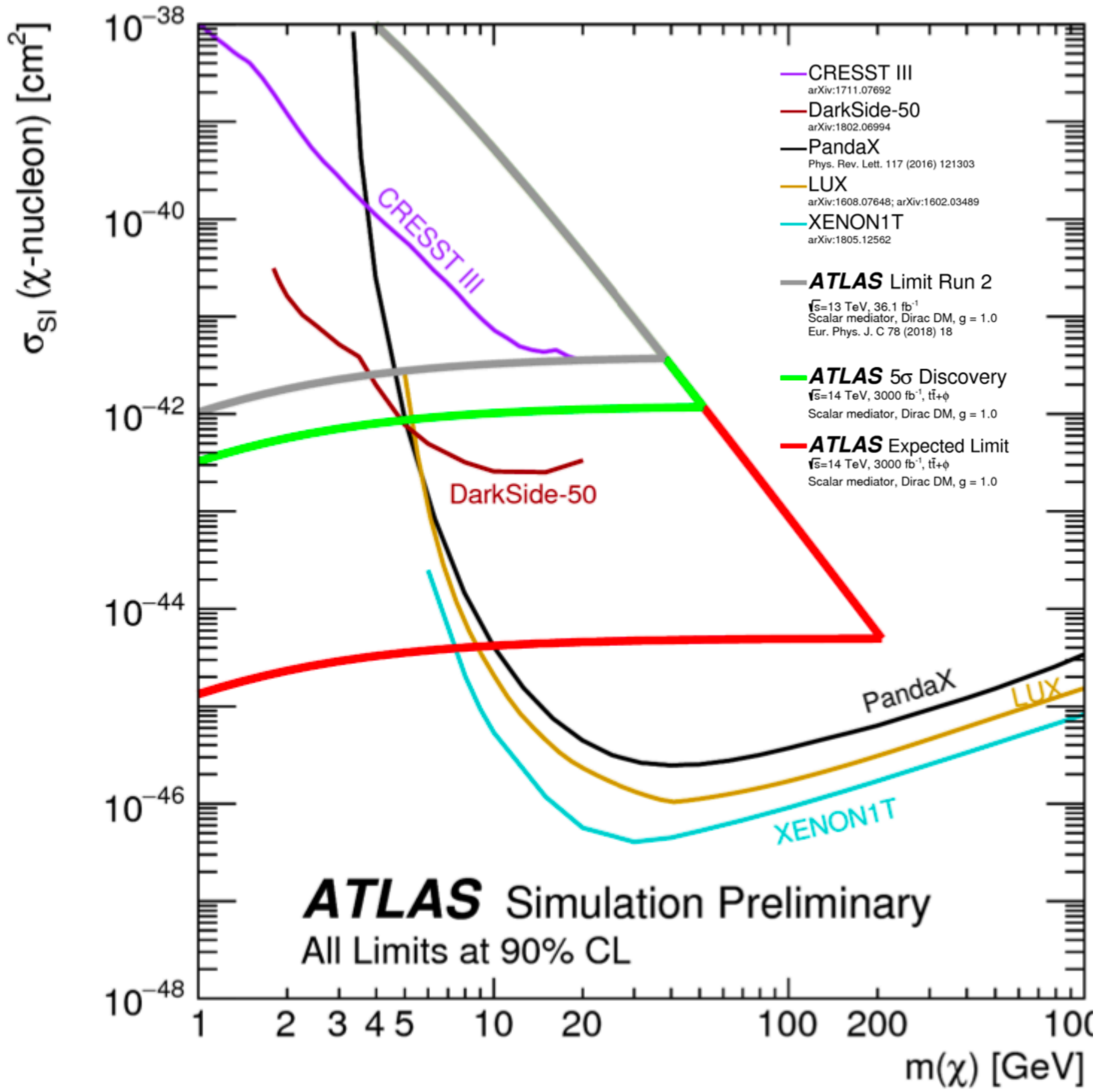


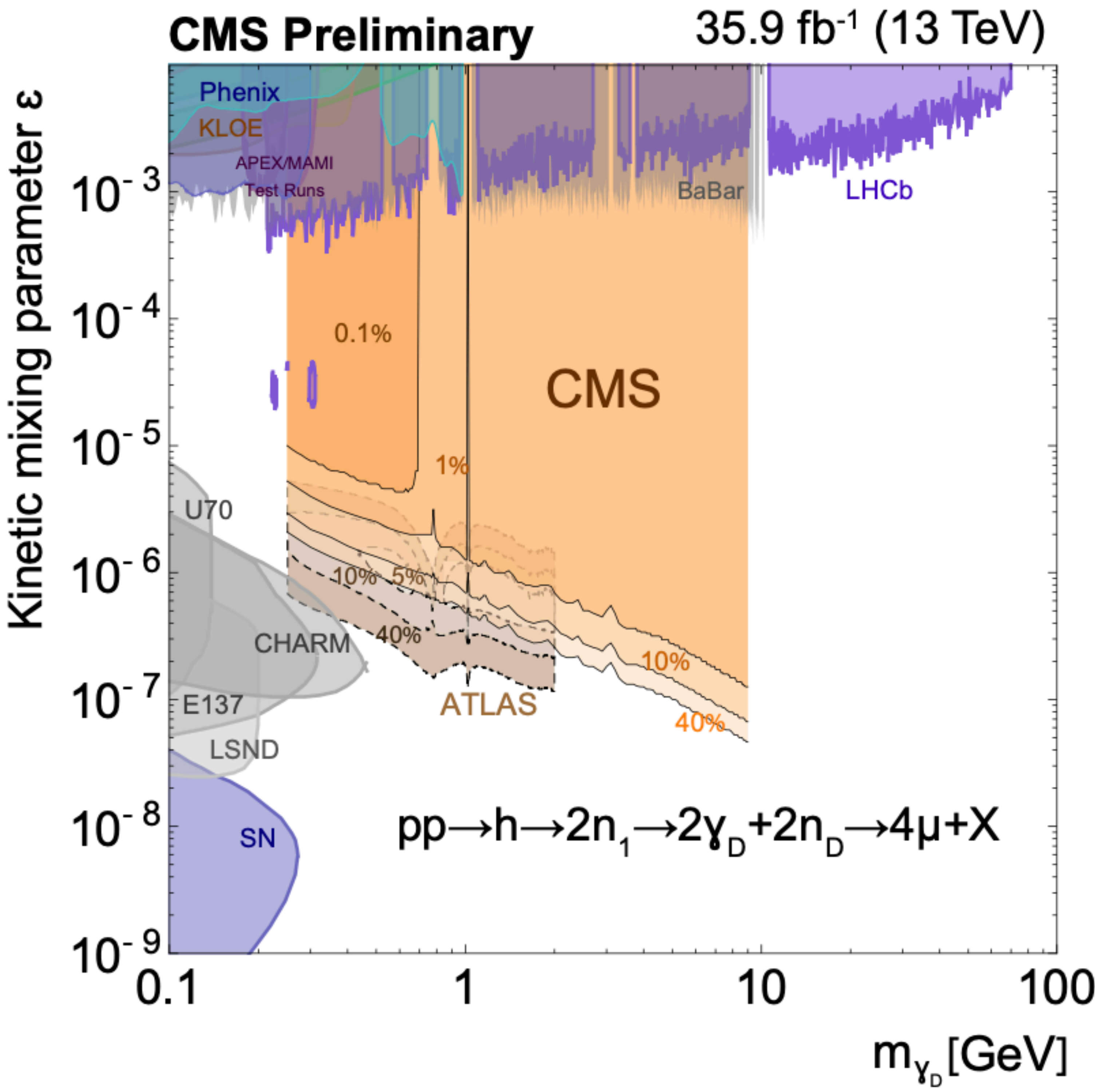


Dark Matter Searches at HL-LHC

Collider Complementarity

- ATLAS search for spin-independent DM-nucleon cross-section as a function of DM mass (left)
  - Top quarks in the final state
  - Color-neutral simplified model with scalar mediator
- CMS Search for dark photons decaying to displaced muons (right)
  - Dedicated displaced muon reconstruction algorithm



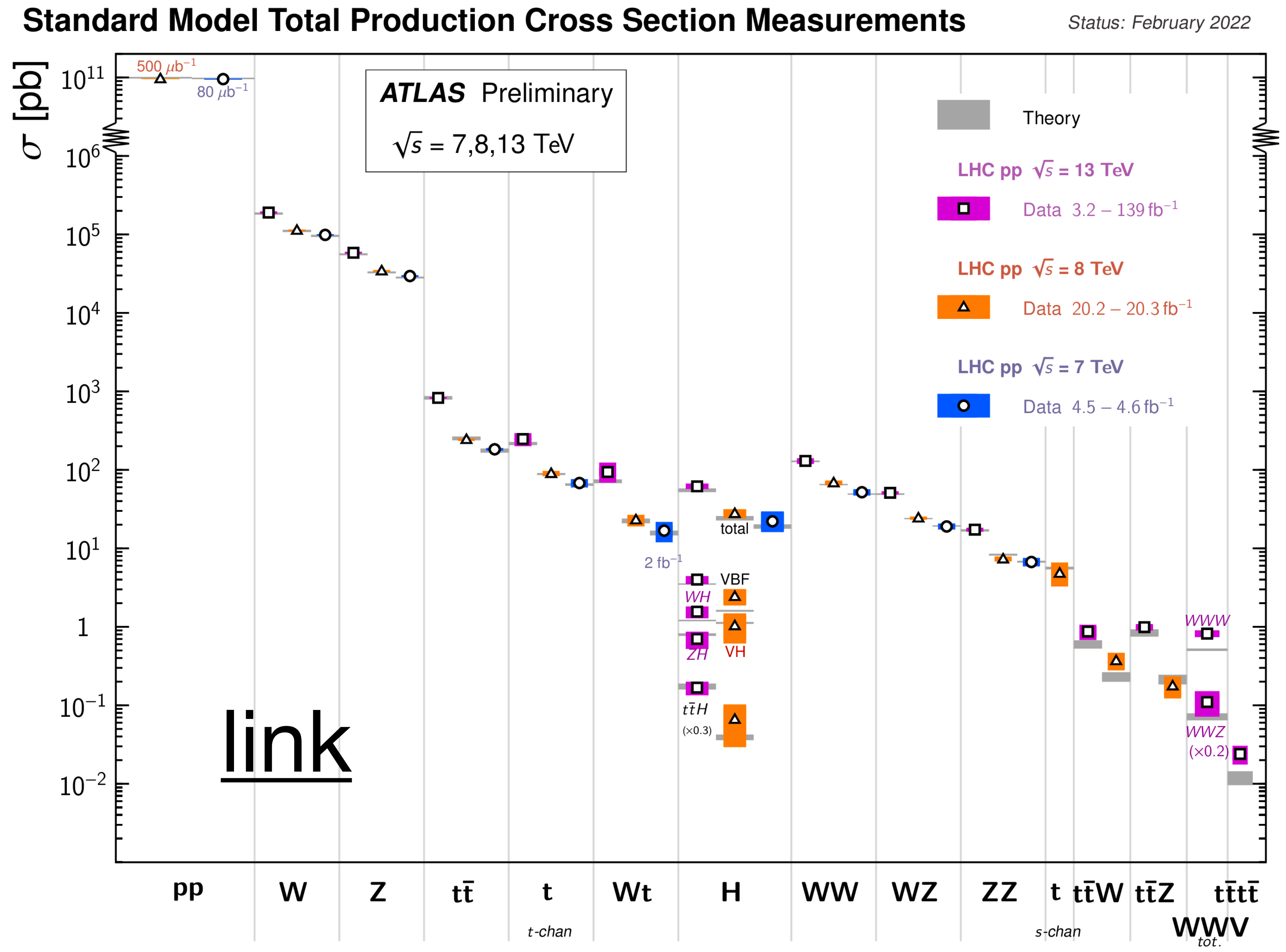


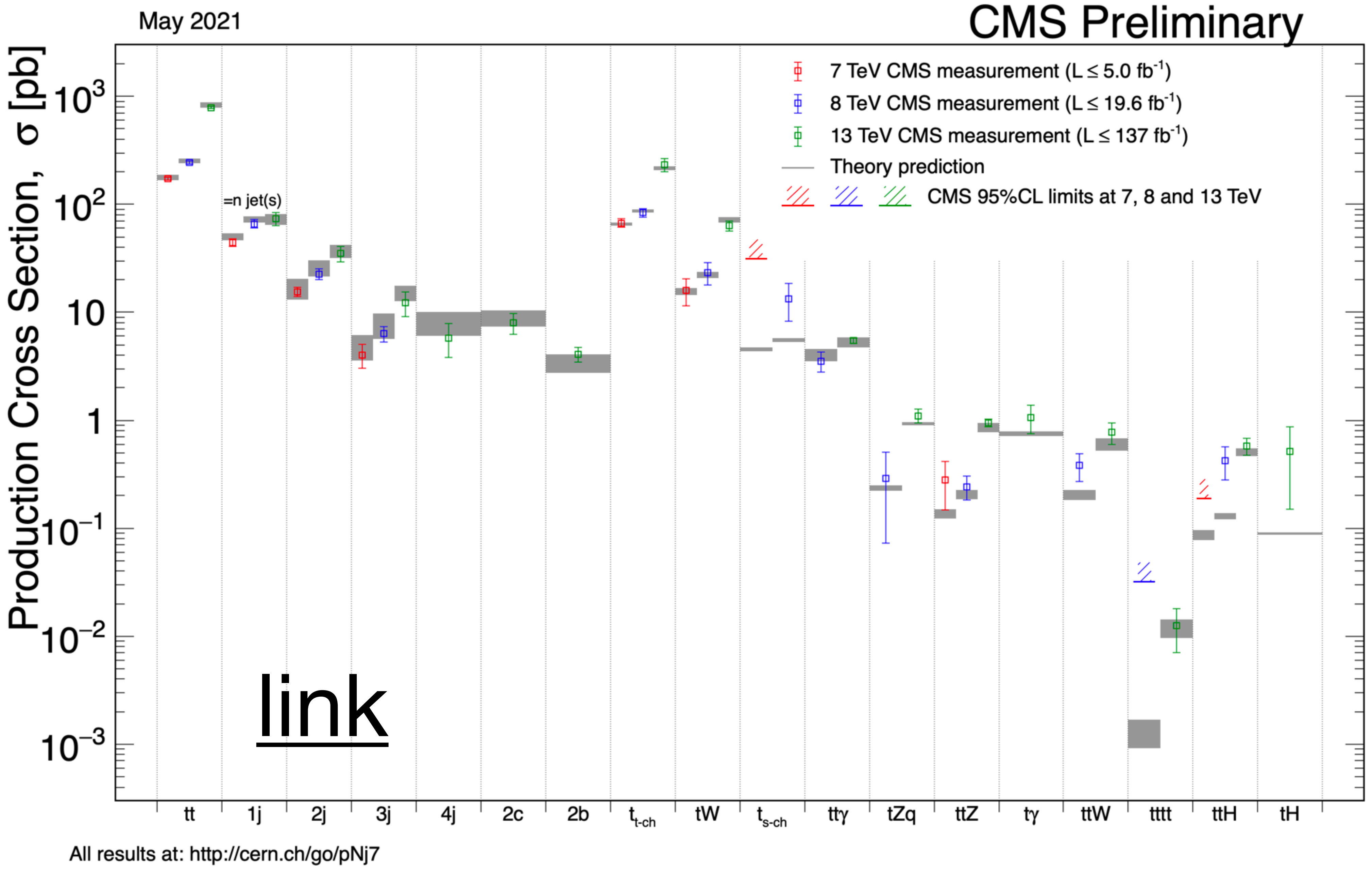
SM at the HL-LHC

SM Measurements

Current Status

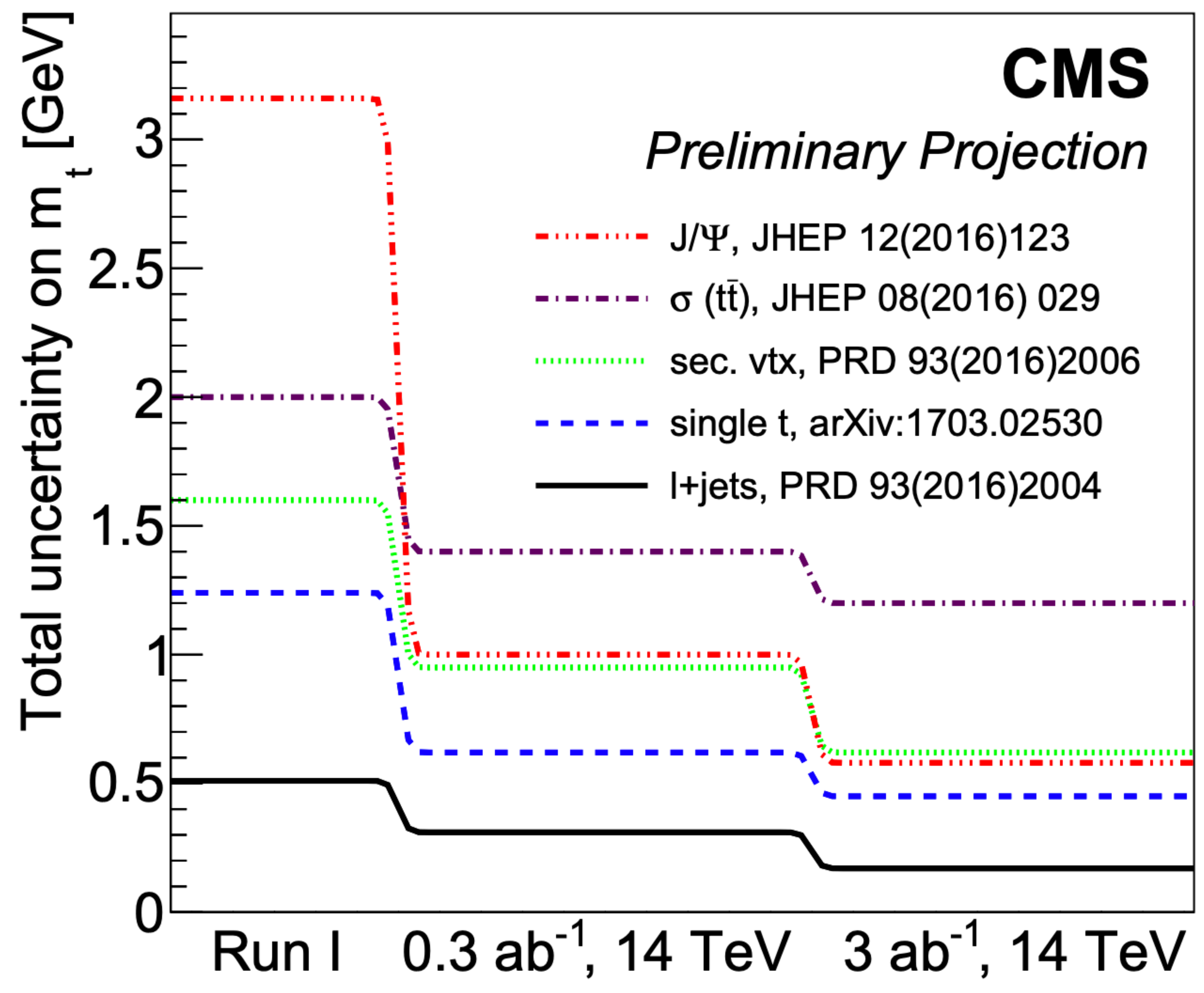
- Why continue studying the SM?
  - Improves our theoretical calculations, MC modelling, and understanding of CP calibrations and uncertainties
  - Important for constraining PDFs and understanding EWSB
  - Can uncover unexpected deviations from the SM
- HL-LHC will provide the opportunity for more precision

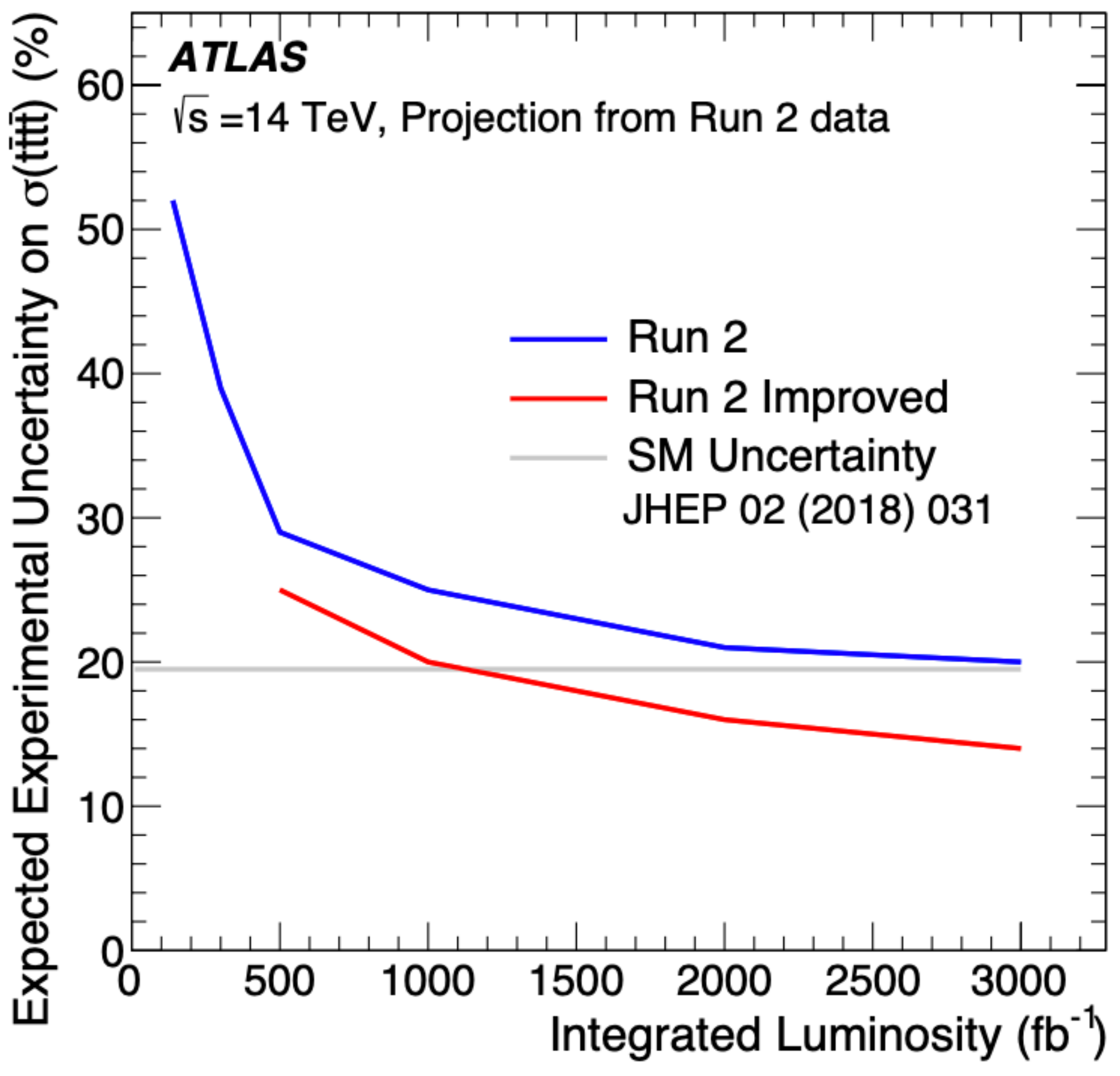


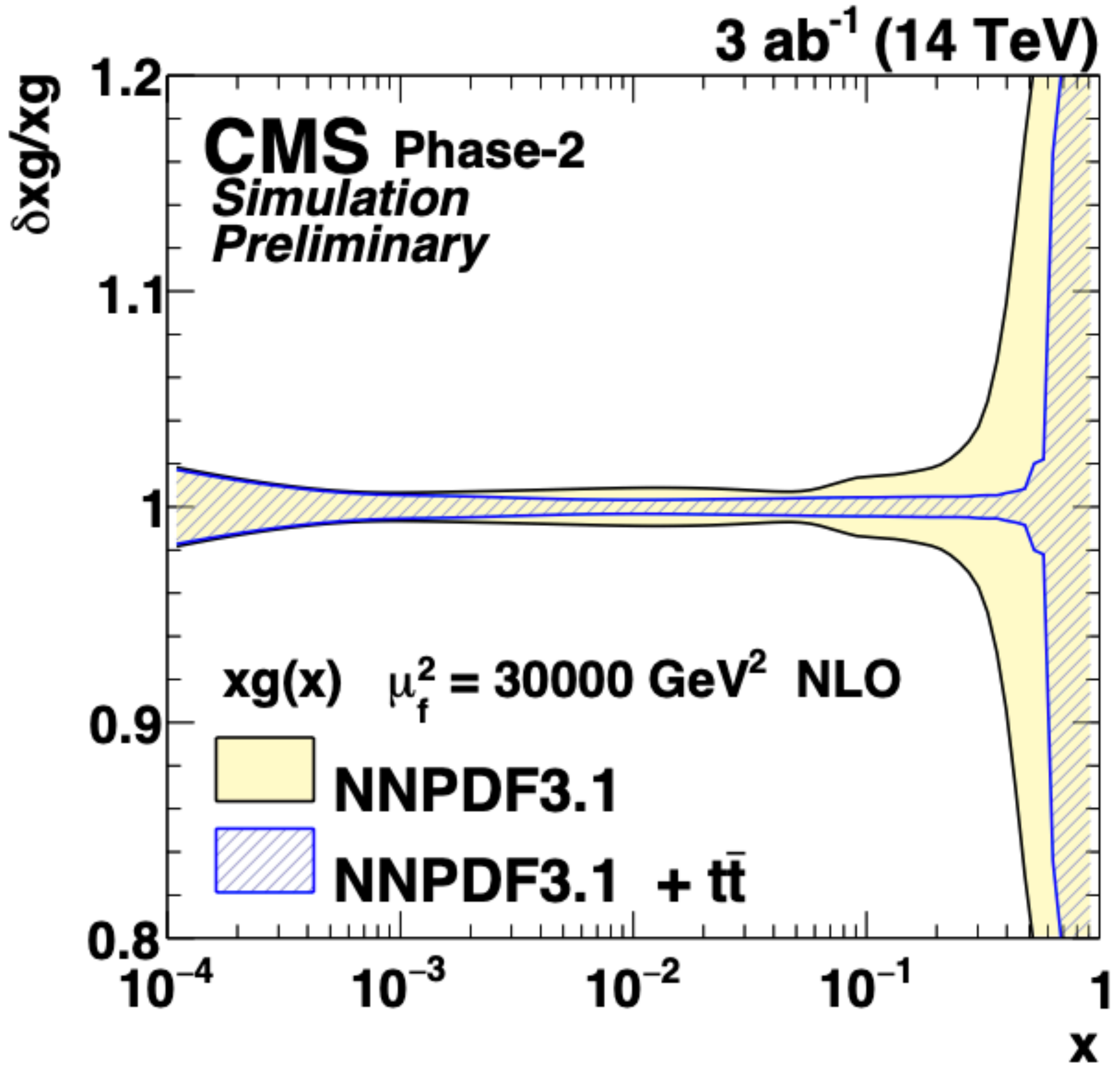


SM Measurements

Updated Results







- Top Mass and four-top measurements improve as experimentalists improve techniques
- PDF measurements (needed for many future measurements!)

Collider Physics is an opportunity to study a huge number of phenomena!!

- Origin of EW Scale
- Evolution of the Early Universe
- New constituents of matter
- Origin of Flavor
- Additional Symmetries of Spacetime
- Nature of Dark Matter
- Origin of Neutrino Mass

What don't we know about the Higgs?

Lots of room for improvement in all Higgs couplings, but two gaping holes:

$$-\mu^2 H^\dagger H + \lambda\left(H^\dagger H\right)^2$$

Higgs potential (self-coupling)

Extended scalar sectors
EW phase transition
Baryogenesis
Hierarchy Problem
...
...

$$\lambda^u_{ij} Q_i H \bar{u}_j - \lambda^d_{ij} Q_i H^c \bar{d}_j$$

Light flavor Yukawas

Flavor Puzzle
Strong CP Problem
Baryogenesis
Extended scalar sectors
...
...

Complementarity with other Frontiers

While slow at the start, the energy frontier is needed to ultimately "win the race"

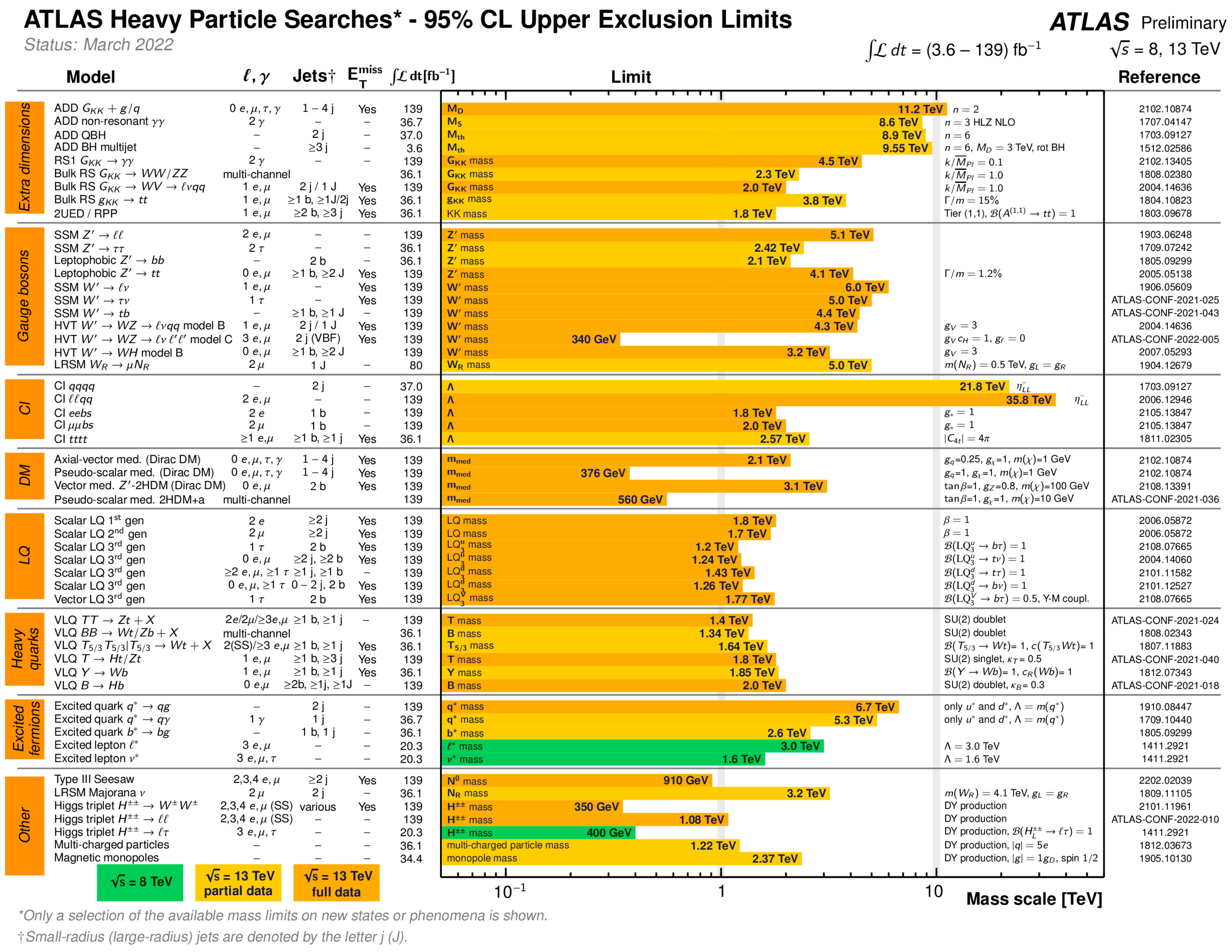
Nevertheless if we get indirect hints from existing

or planned experiments its important to know how to test them!

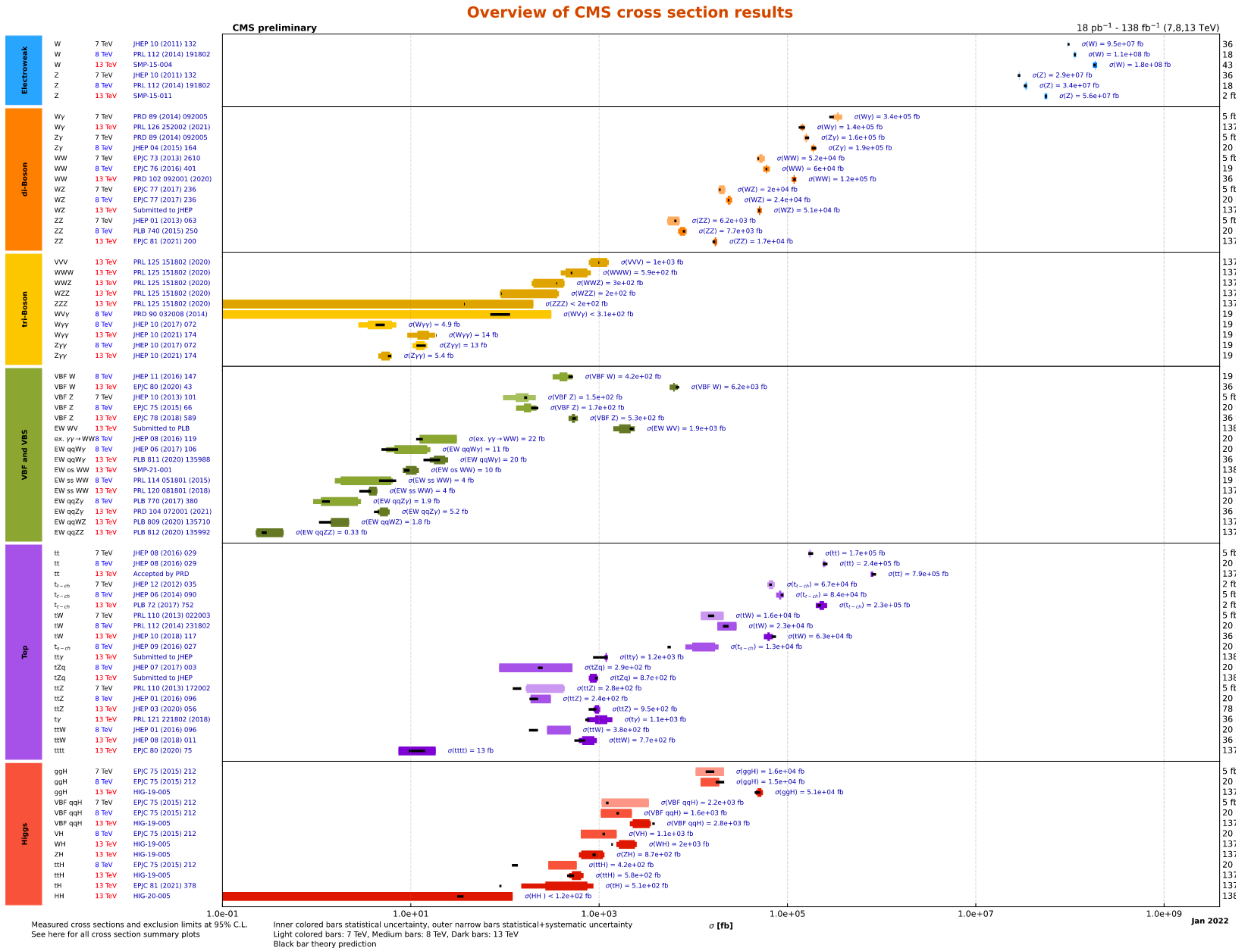
Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

Physics at Colliders

Colliders provide a RICH scientific environment



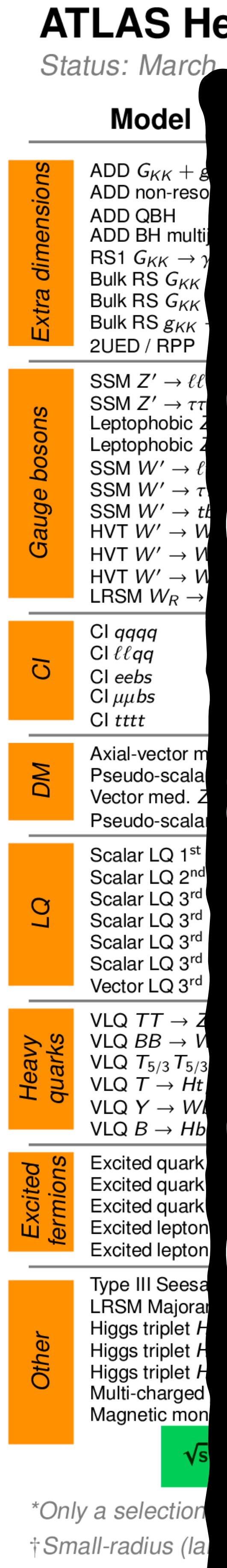
Heavy Particle Searches at ATLAS

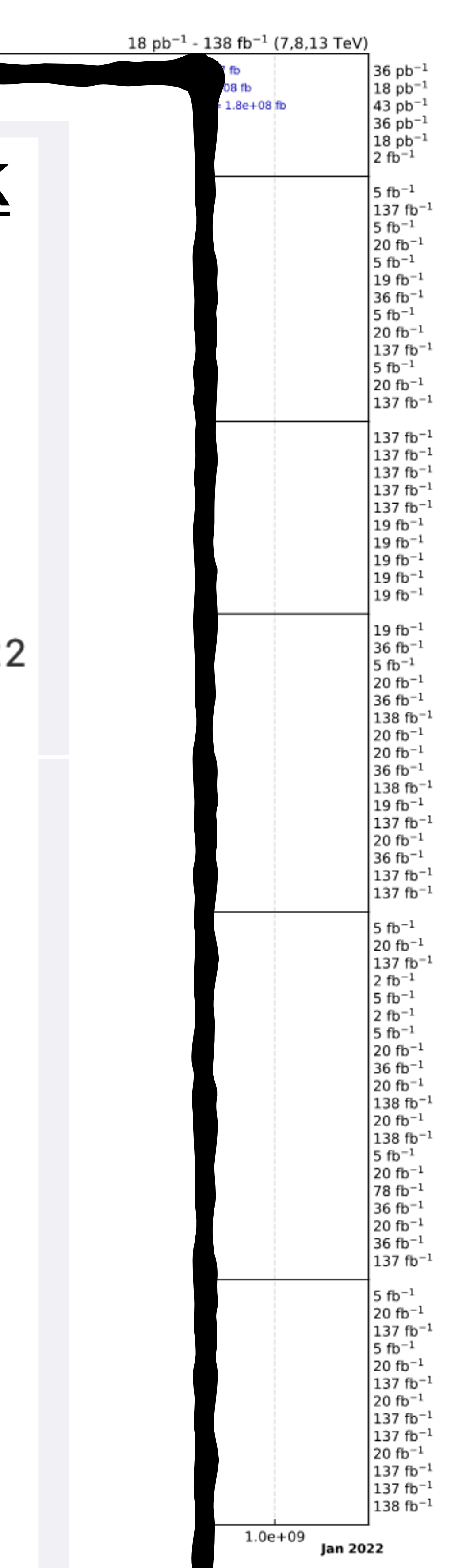


SM Measurements at CMS

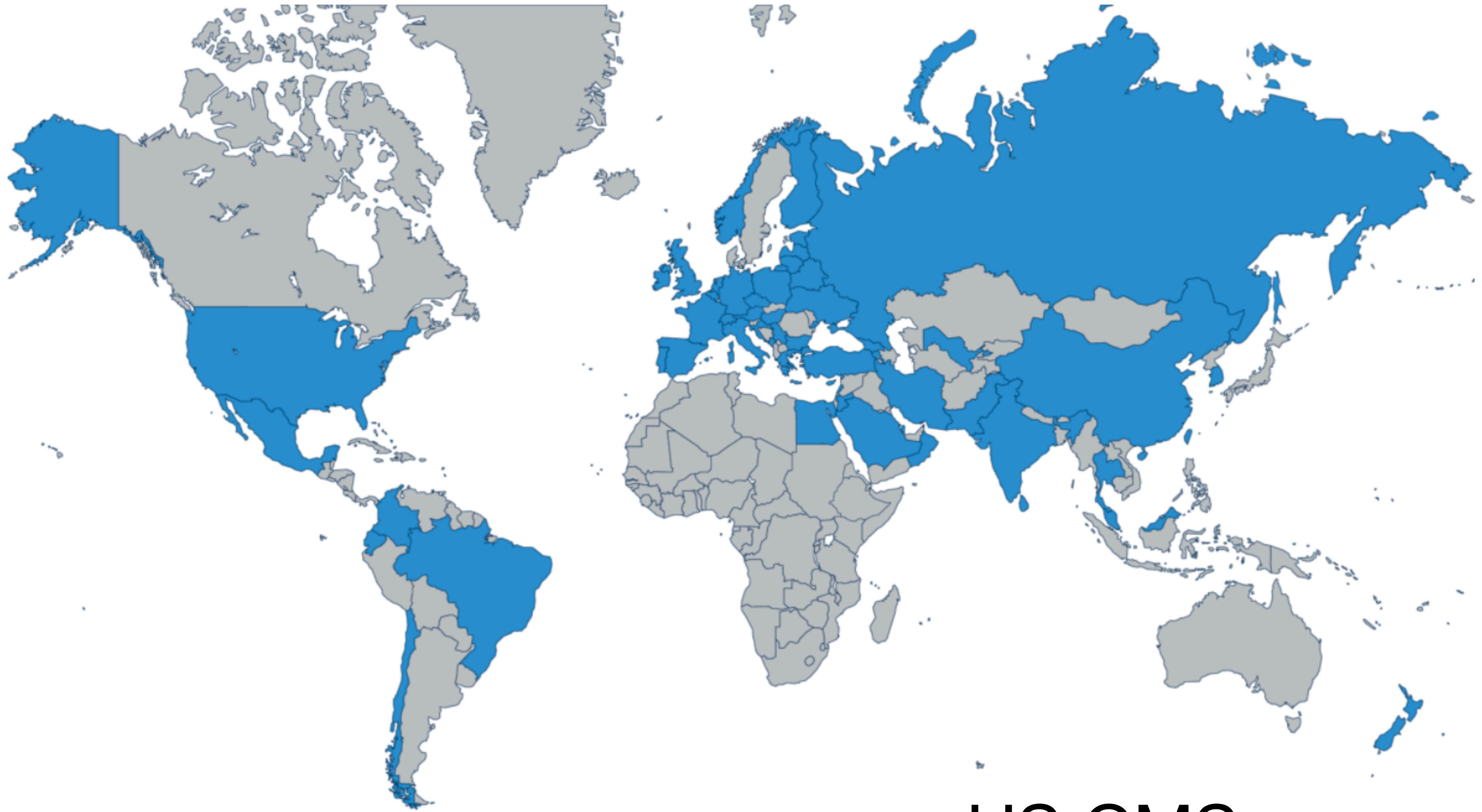
Physics at Colliders

Colliders provide a RICH scientific environment





CMS Experiment (as an example) link



The CMS collaboration has around:

5494
ACTIVE PEOPLE
(PHYSICISTS, ENGINEERS, TECHNICAL, ADMINISTRATIVE, STUDENTS, ETC.)

Of these members there are about:

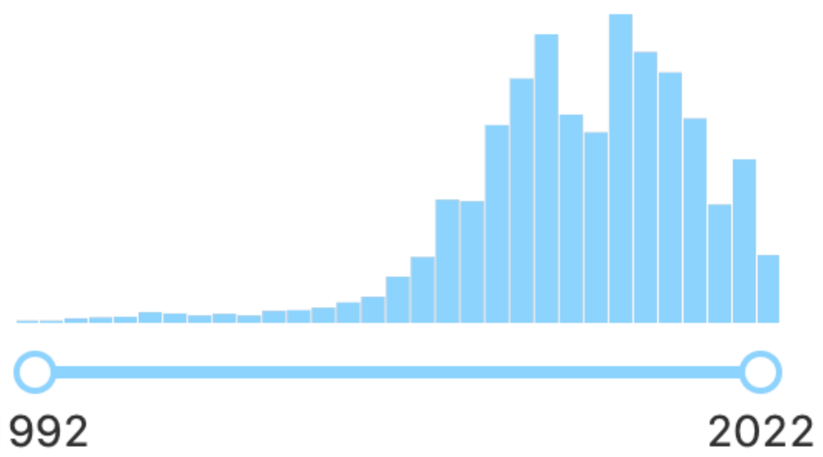
2053	1050	1031	978
PHD PHYSICISTS (1689 MEN, 364 WOMEN)	PHYSICS DOCTORAL STUDENTS (792 MEN, 258 WOMEN)	ENGINEERS (895 MEN, 136 WOMEN)	UNDERGRADUATES (708 MEN, 270 WOMEN)

US CMS
\>1000 participants
~50% PhD Students

link

spires link

Date of paper



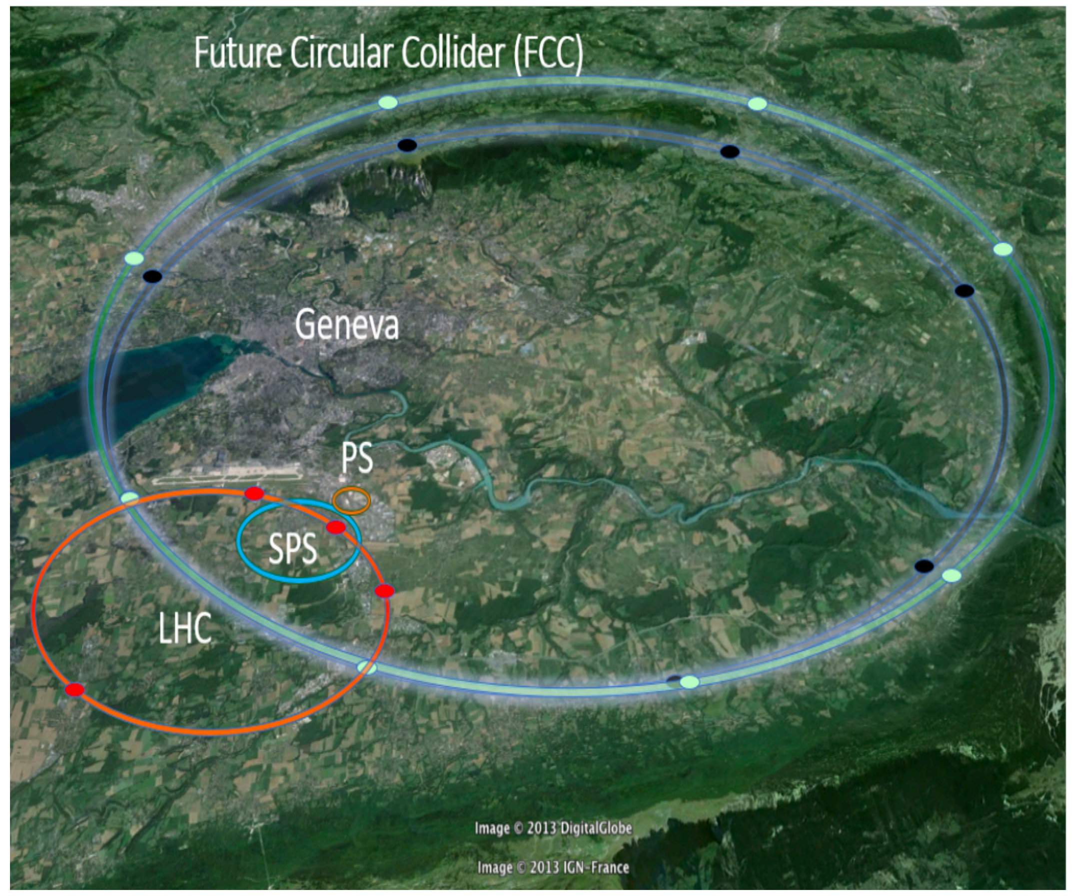
Document Type

conference paper	4,280
note	1,703
article	1,356
published	1,356
review	38
report	24
book chapter	12
book	2
introductory	2

CMS submitted its **1000th** paper in June 2020

Which Machines?

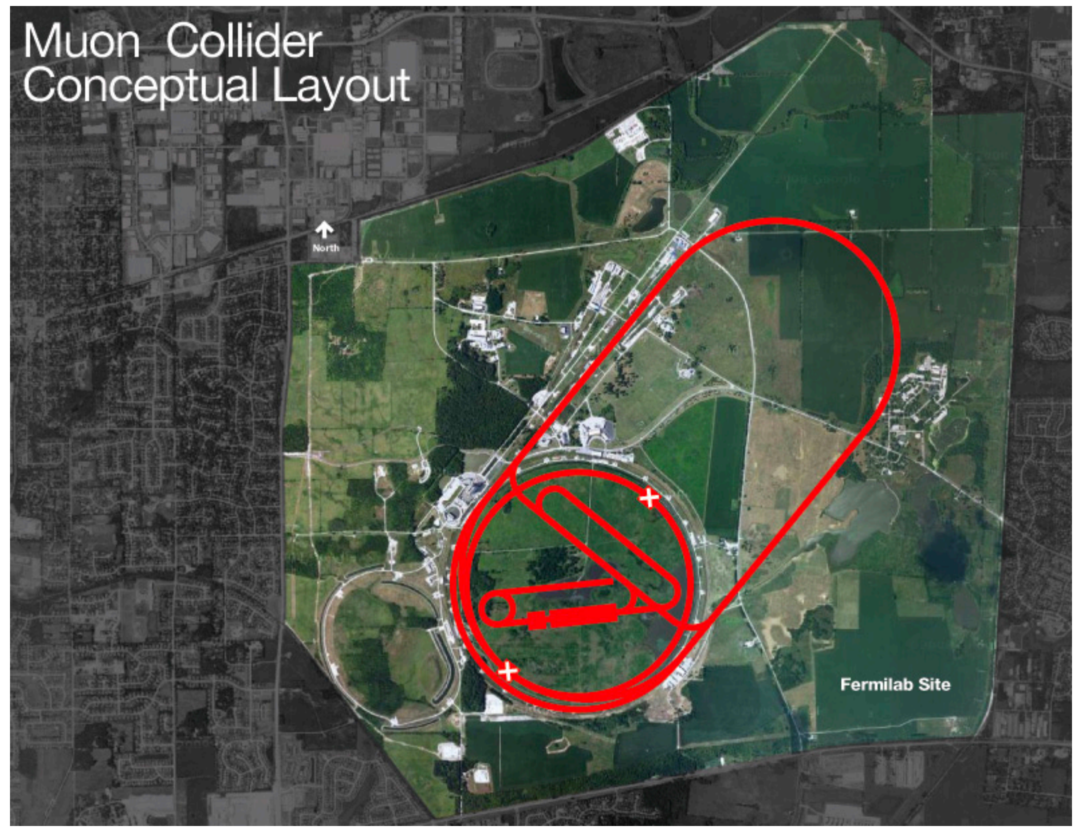
Hadrons



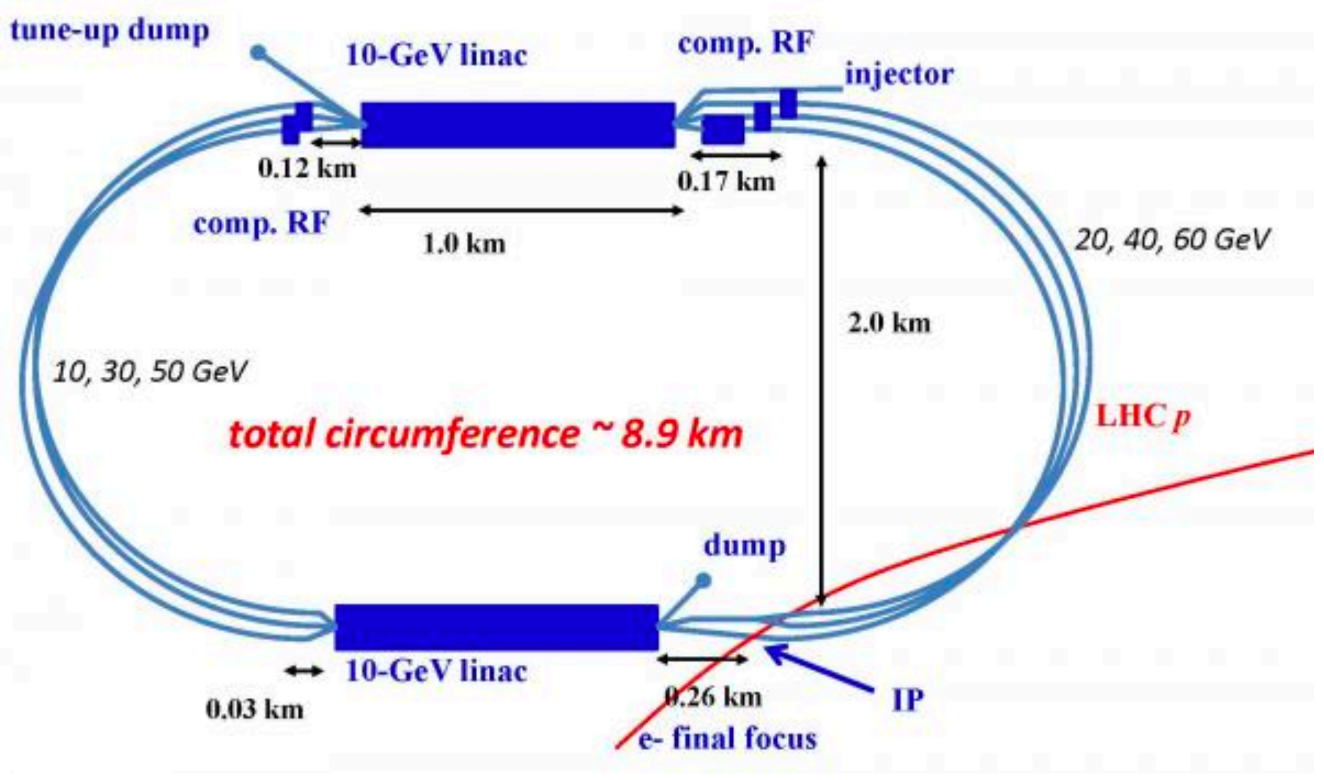
Discovery Machines
S/B ~10^{-10} w/o trigger
S/B ~0.1 with trigger
Divide CoM by partons
Stable particles
=> Quarks and Gluons

Leptons

Precision and Discovery
Large S/B
Polarized beams
EW couplings

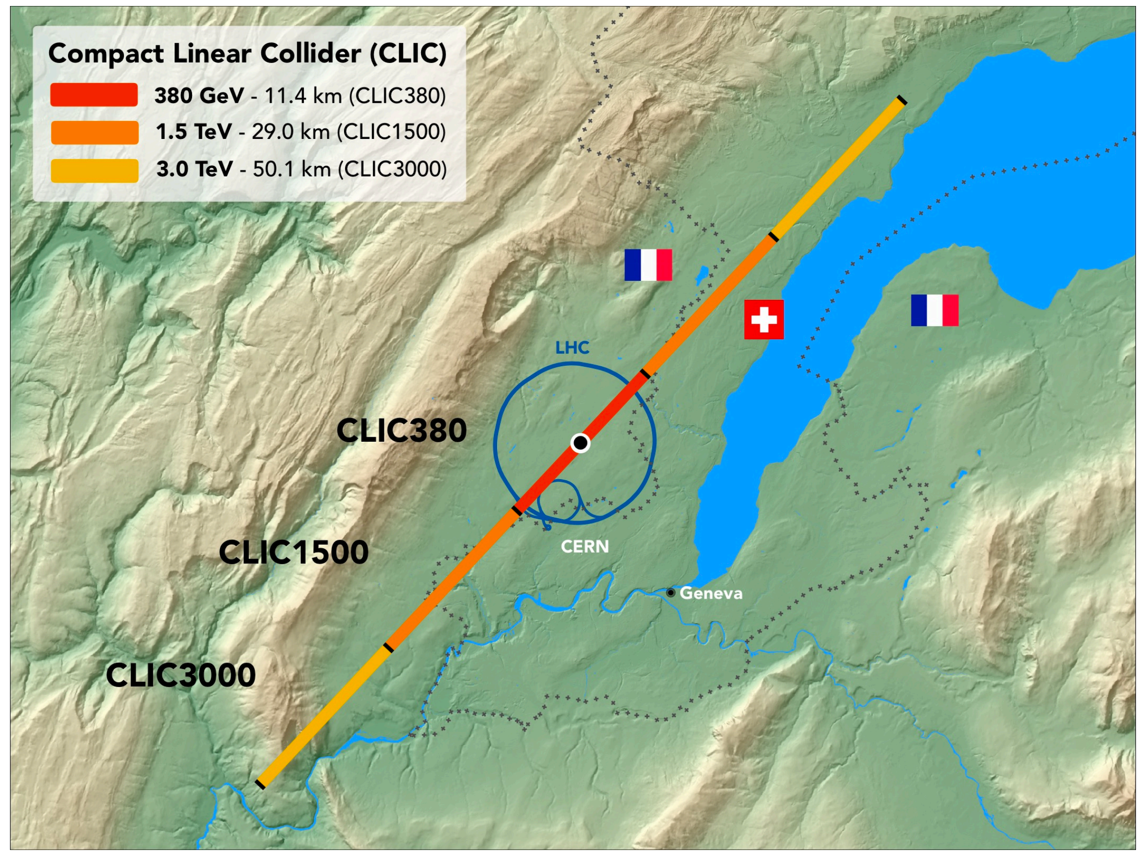


US Options discussed during Snowmass



Higher luminosities
Several interaction points
Limited by Synchroton radiation

Easier to polarize beams
One IP
Large Beamstrahlung



Circular

Linear

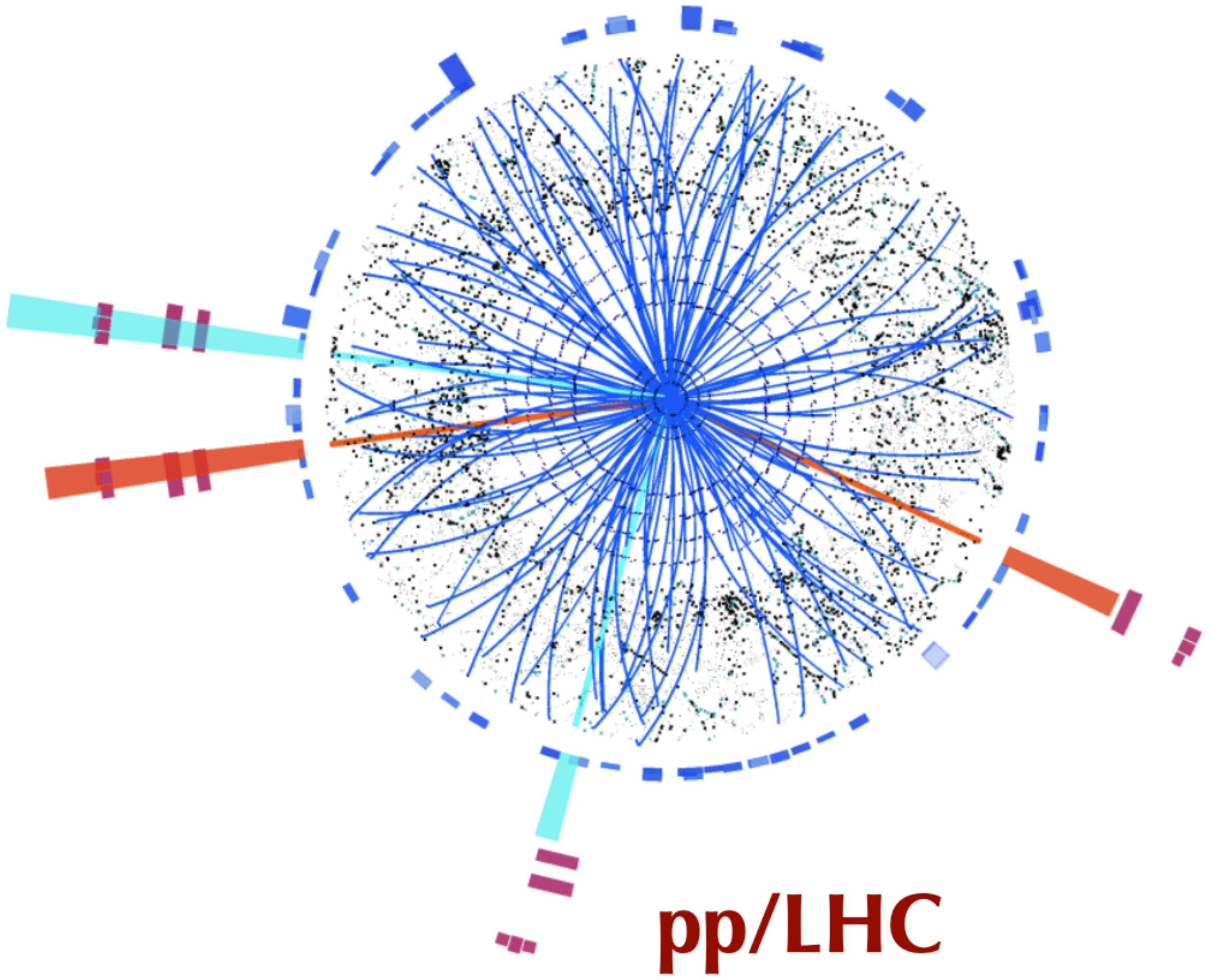
e+e- Colliders

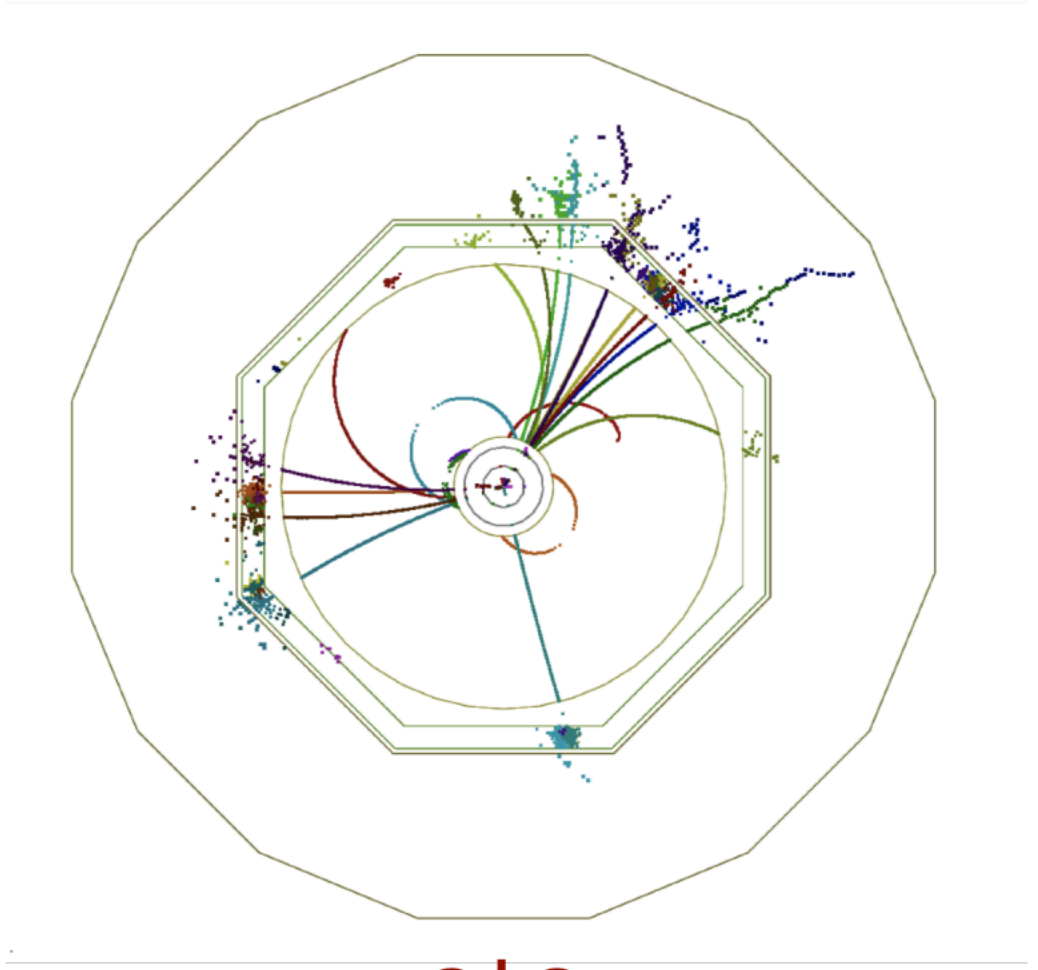
ZH is the dominant production mode above 250 GeV

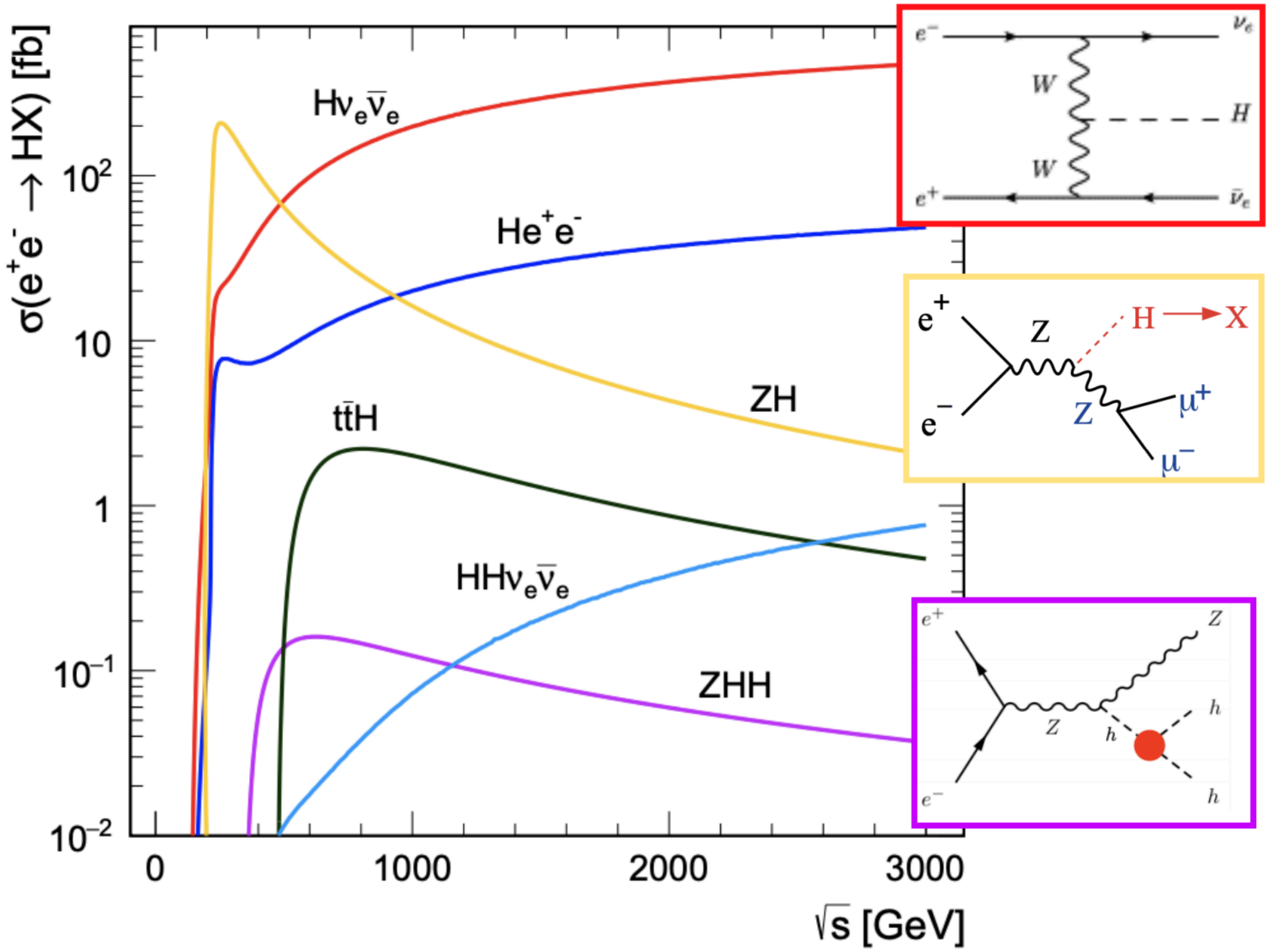
The well defined initial states allows to tag the Higgs boson without looking into its decay with “recoil” technique

- Measurement of the inclusive ZH cross section at 0.5-1%
- Recoil technique observes all final state, including all invisible and exotic decay modes

Clean environment for excellent b- and c-tagging (and beyond?) performance: bb/cc/gg separation



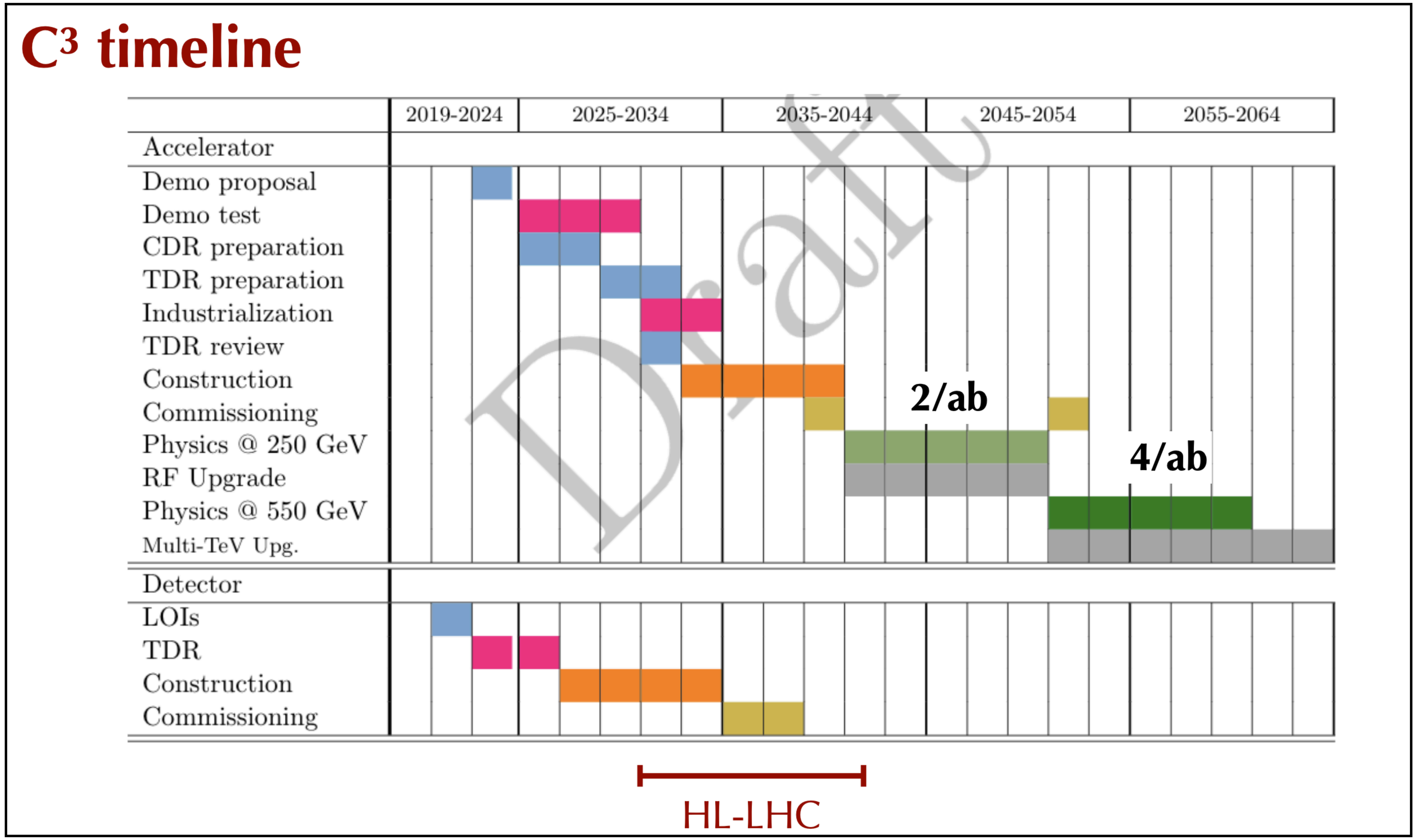




C³ - Cool Copper Collider

Based on a new SLAC technology

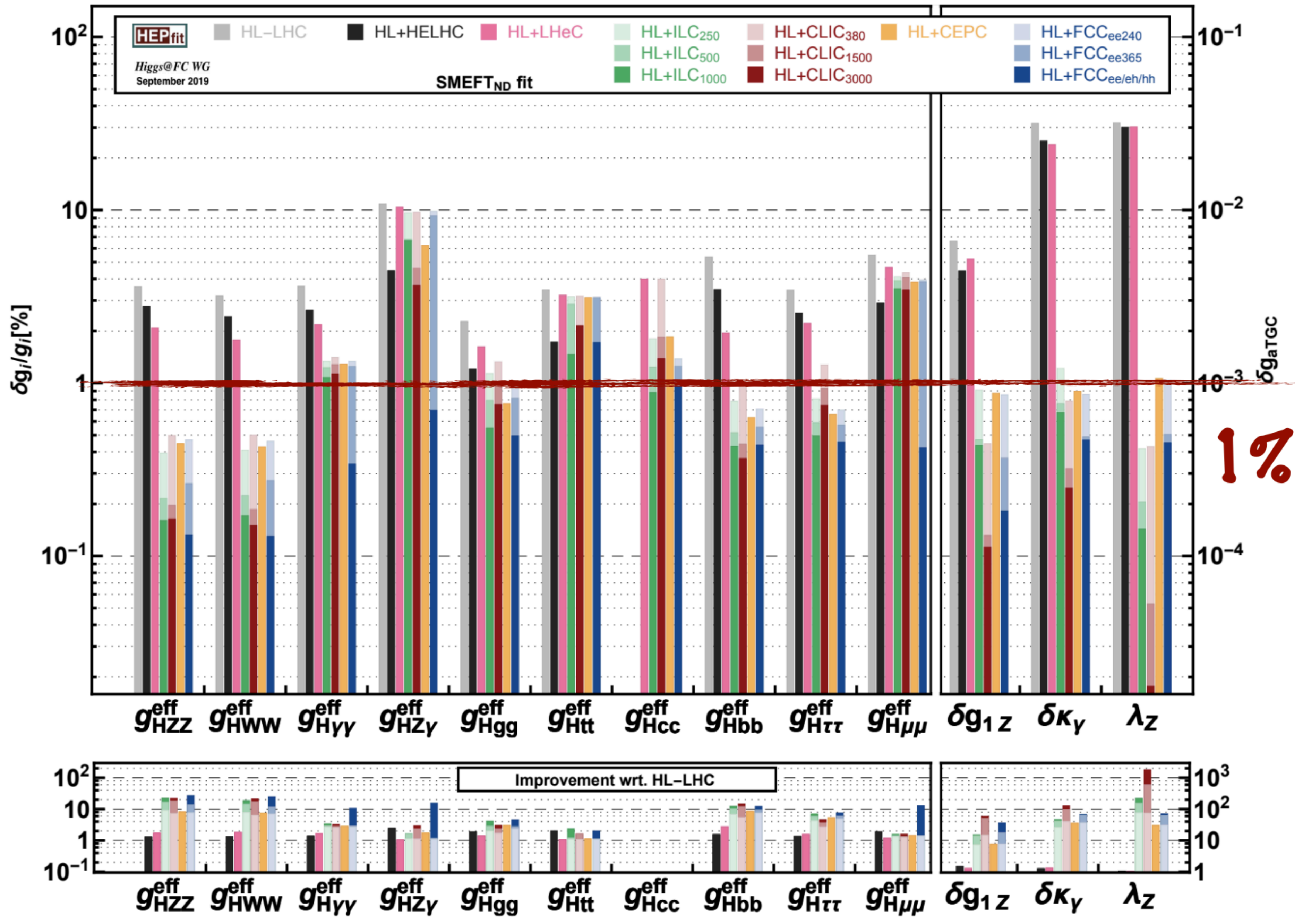
- Two Key Technical Advances: **Distributed Coupling** and **Cryo-Copper RF**
- Operation at cryogenic temperatures (LN2 ~80K)
- Robust operations at high gradient: 120~MeV/m
- Scalable to multi-TeV operation
- Operate at 250 and 550 GeV with possible commissioning at the Z pole

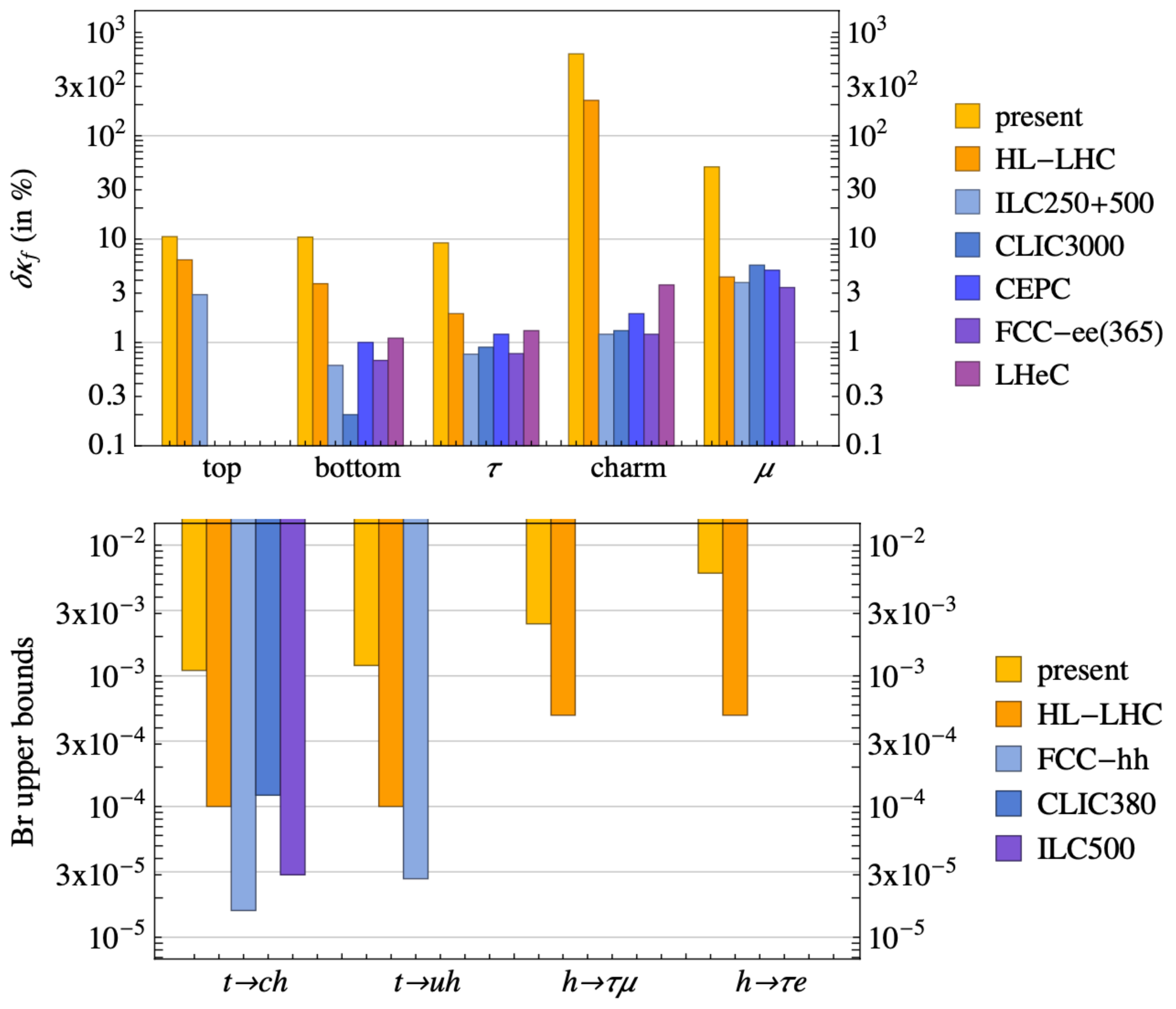


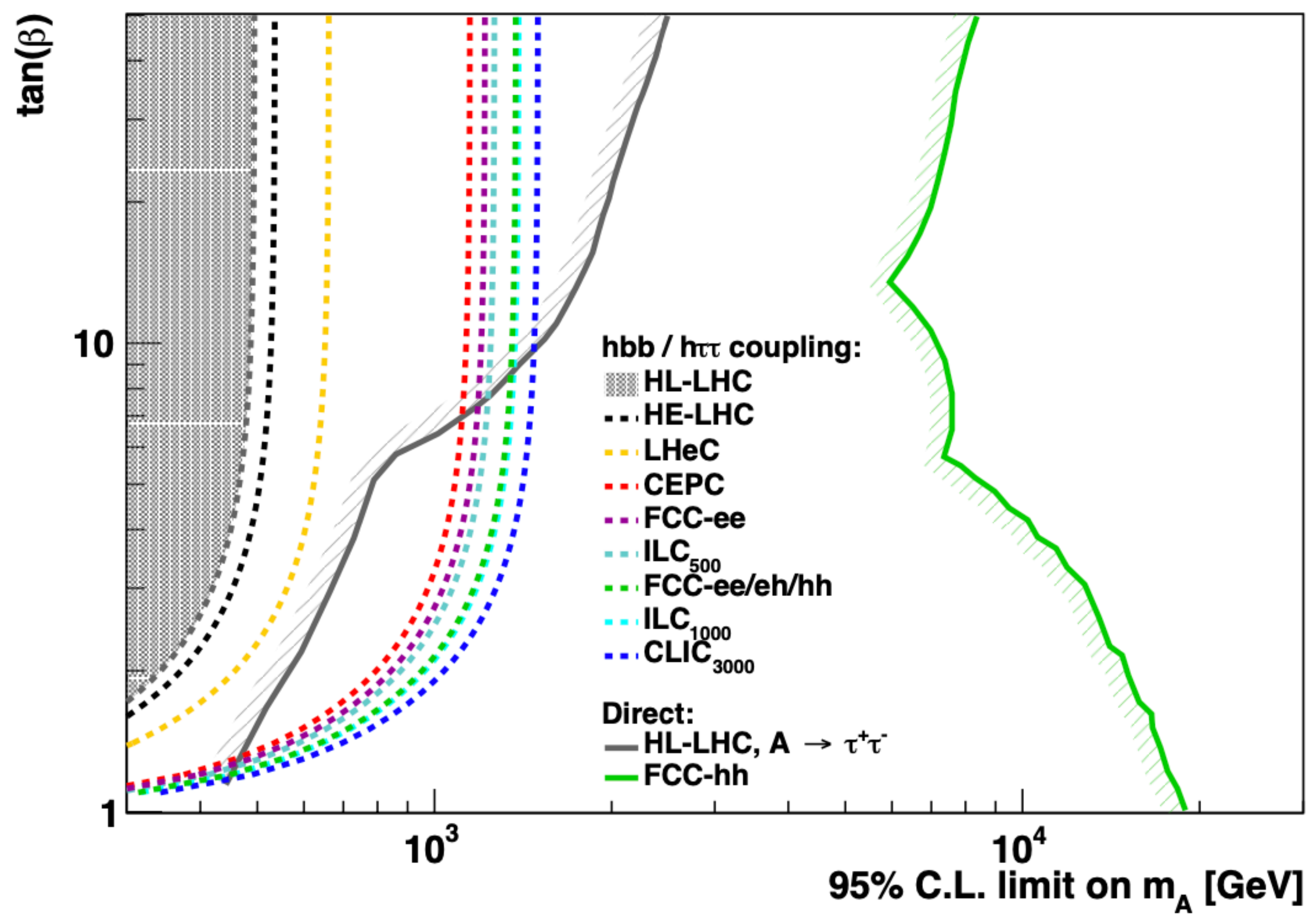
Possible US facility

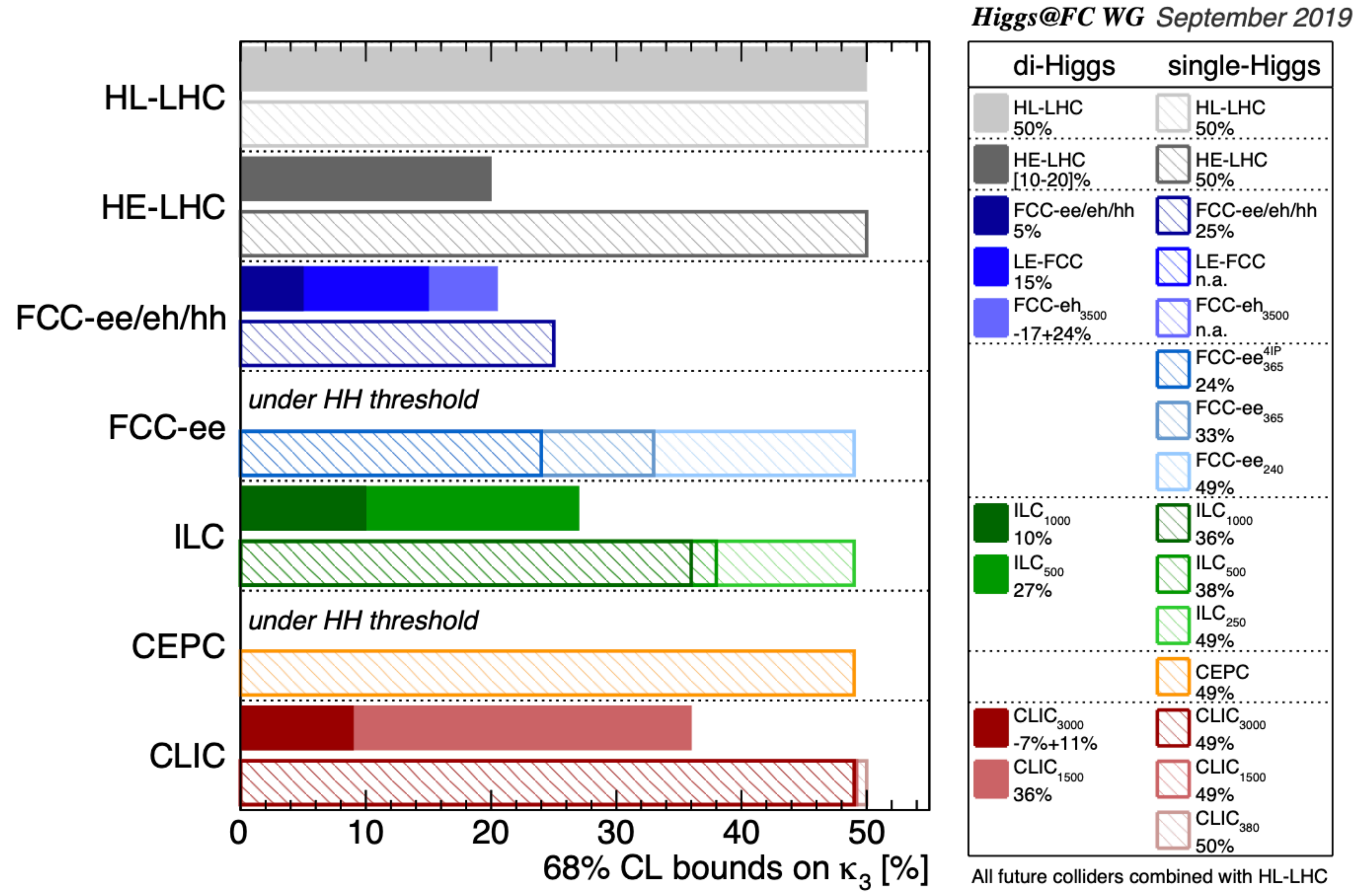
<u>E. Nanni</u>

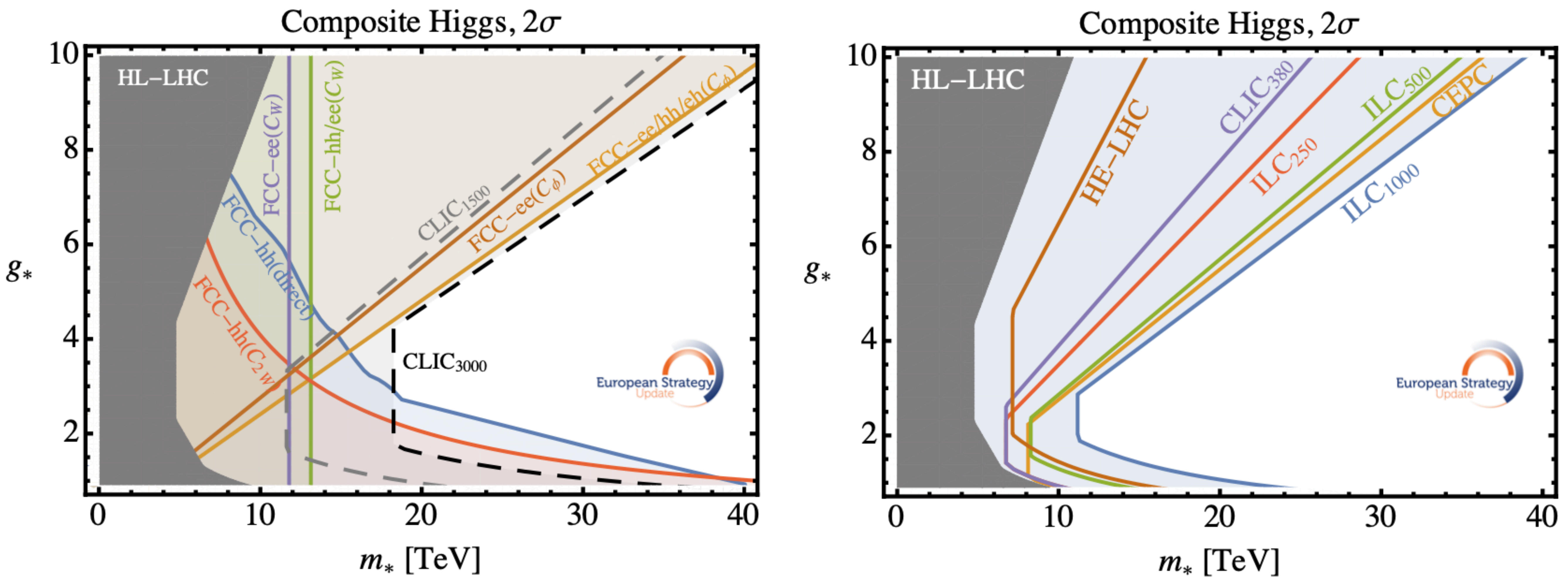
What do we expect at future e+e- facilities?









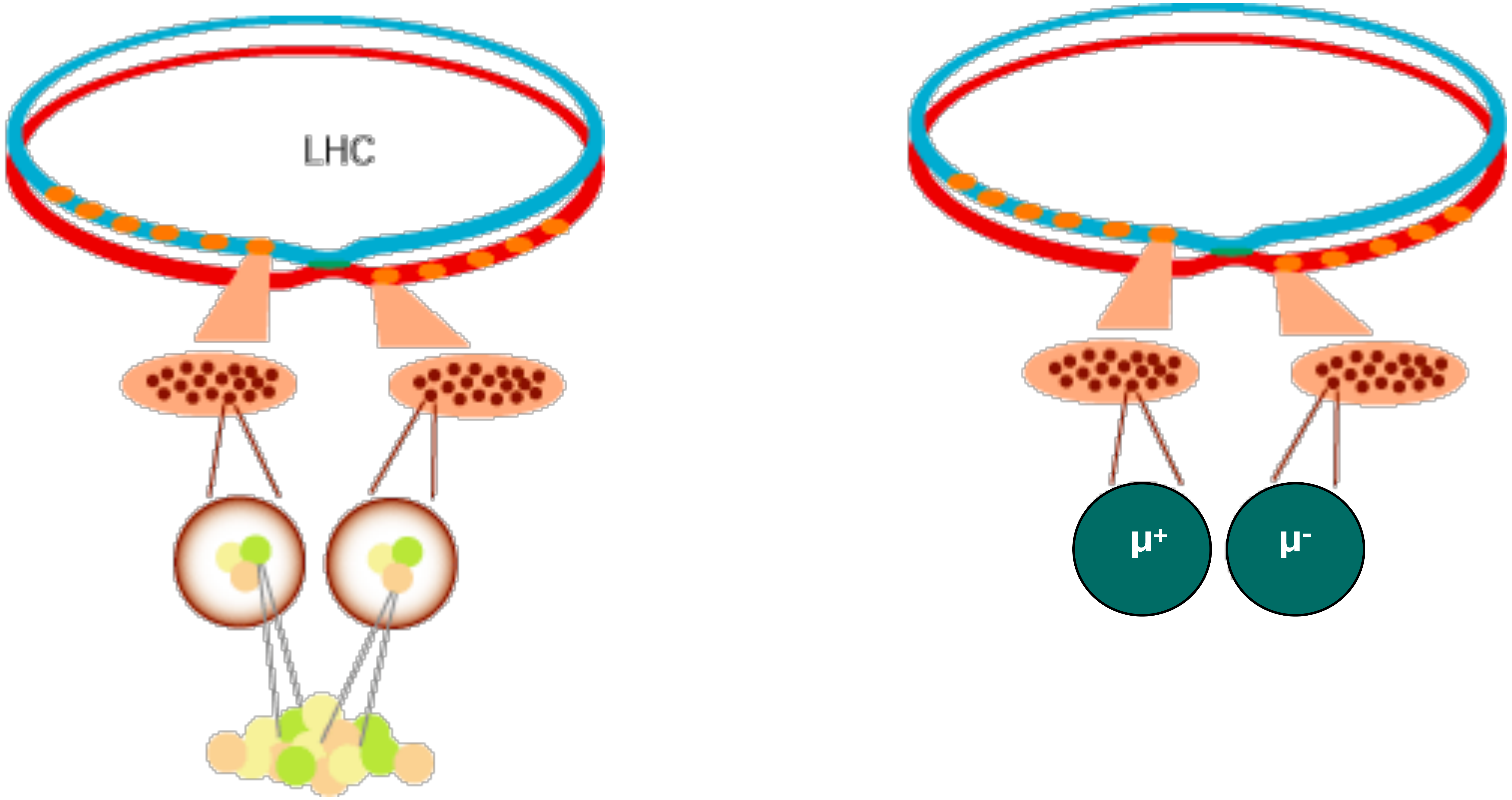


link Kirk McDonald

Muon Colliders

First proposed more than 50 years ago, renewed interest in Muon Collider facilities in recent years

Due to recent advances in technology!

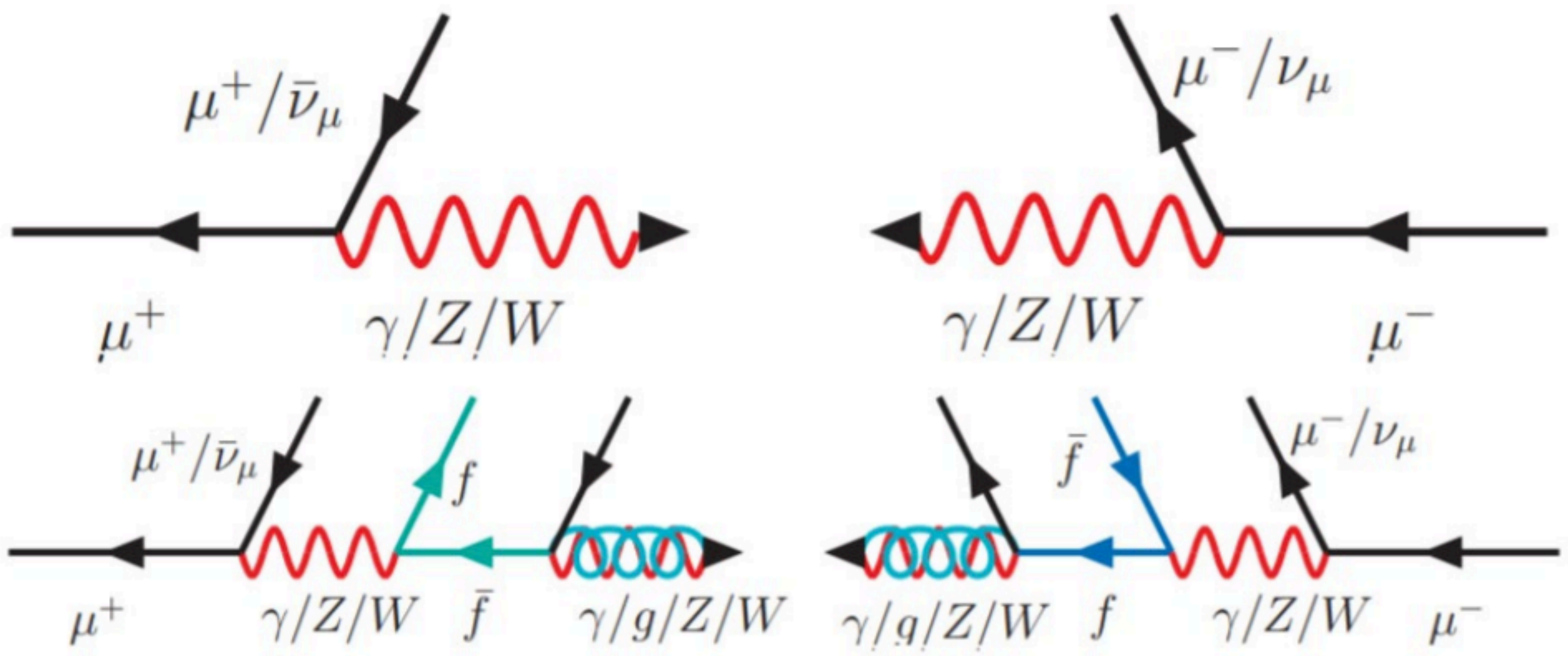


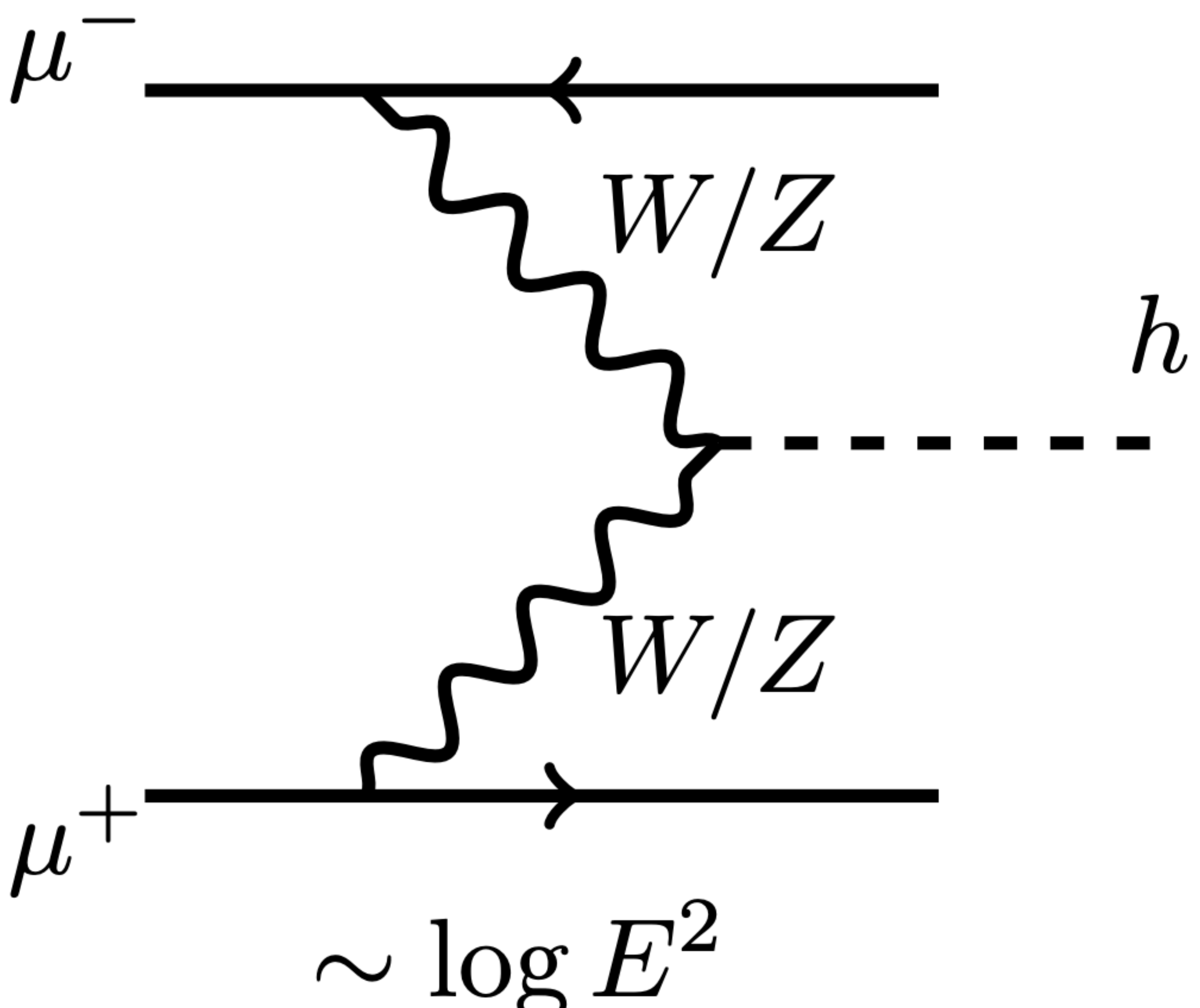
- Muons not suffer from energy loss due to Bremsstrahlung that makes e+e- circular machines difficult! But they do have a very short lifetime.

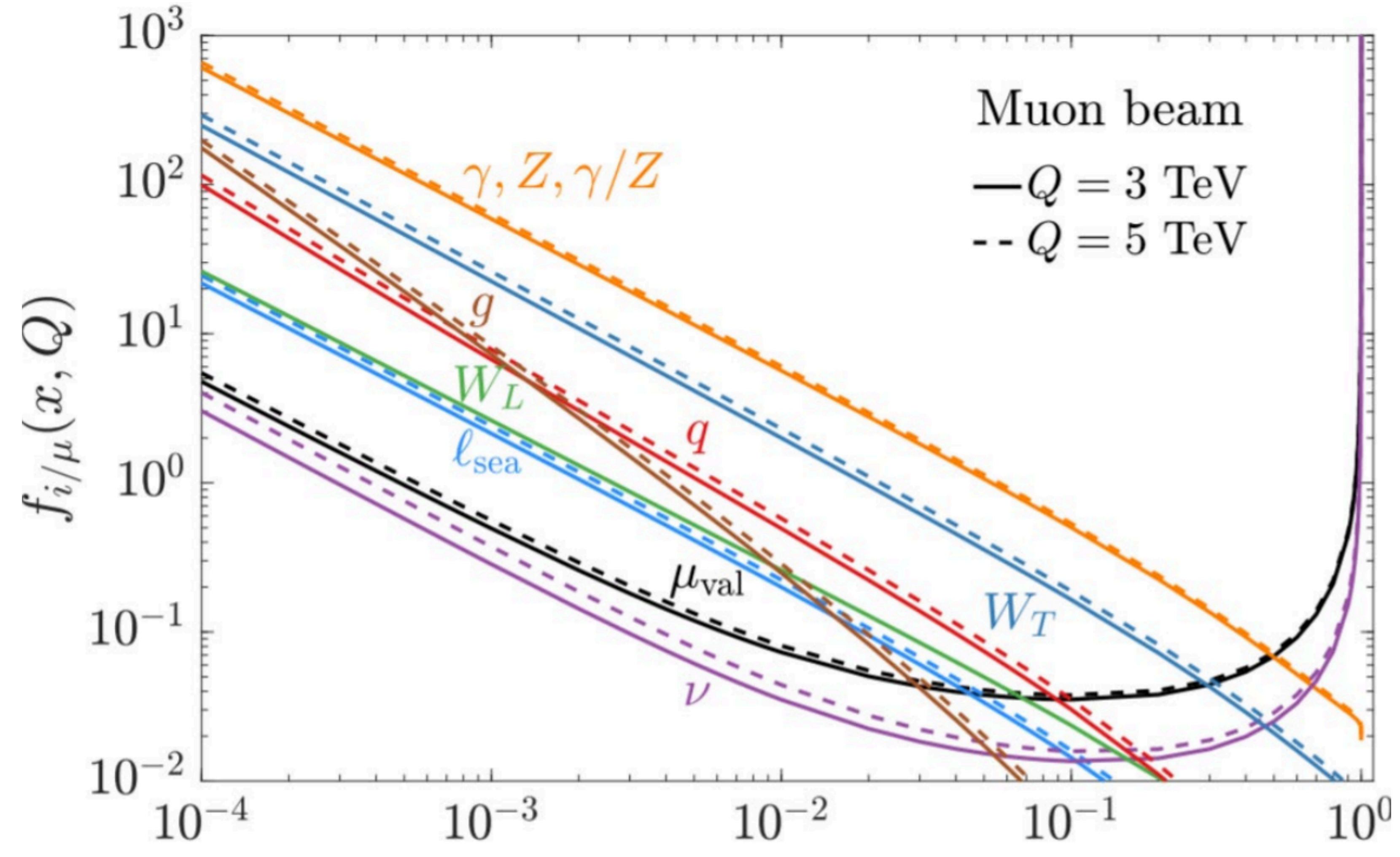
Muon Colliders: Production

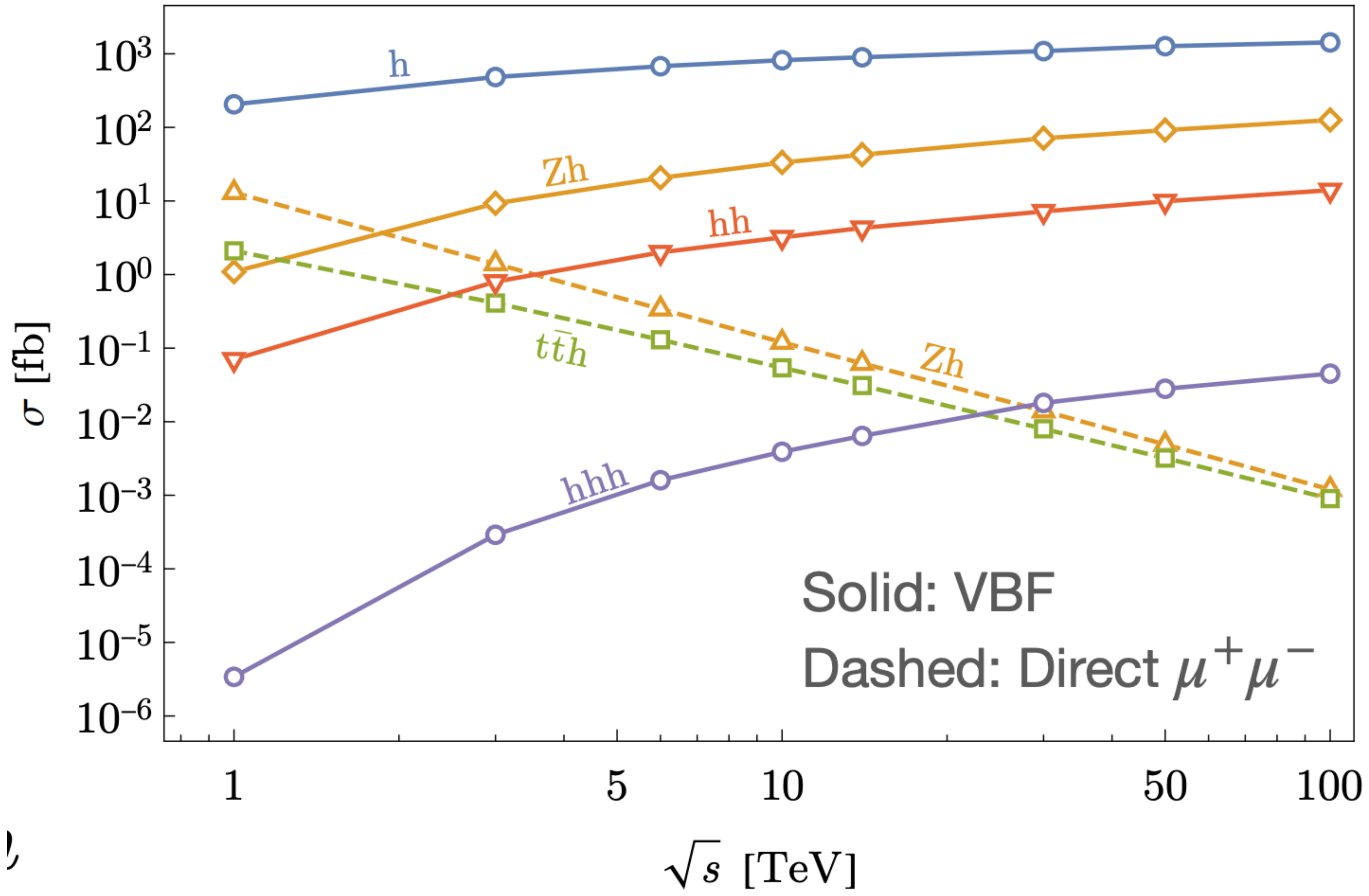
arXiv:1607.03210

Muon Colliders are actually EWK colliders with a mix of initial states



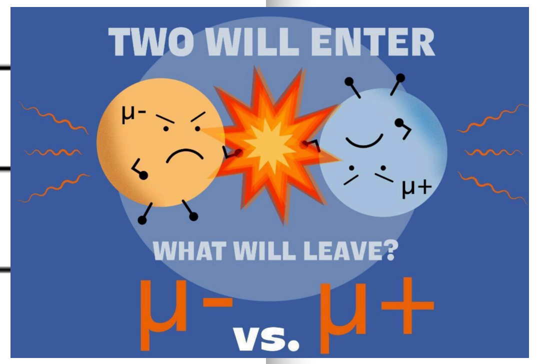


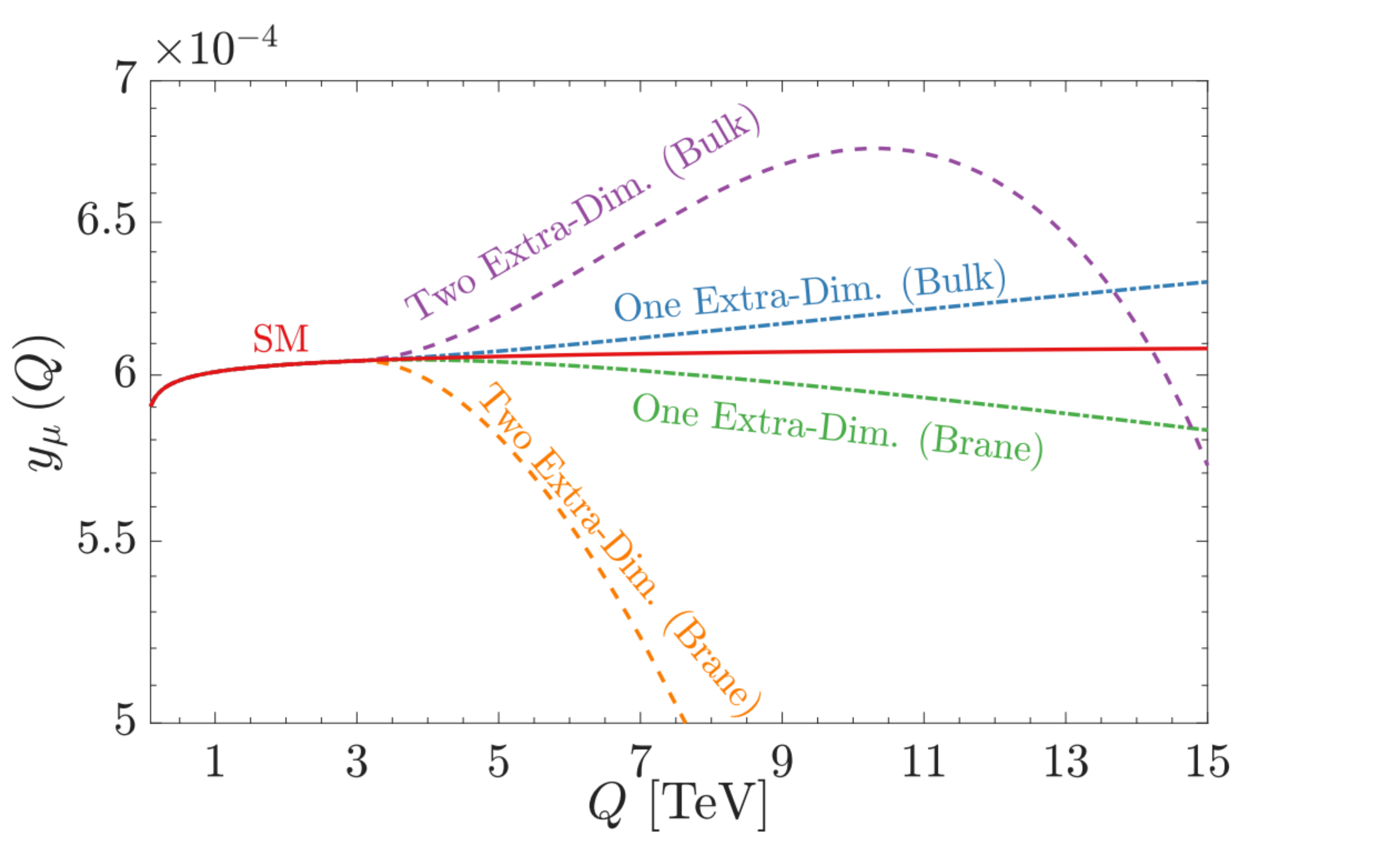




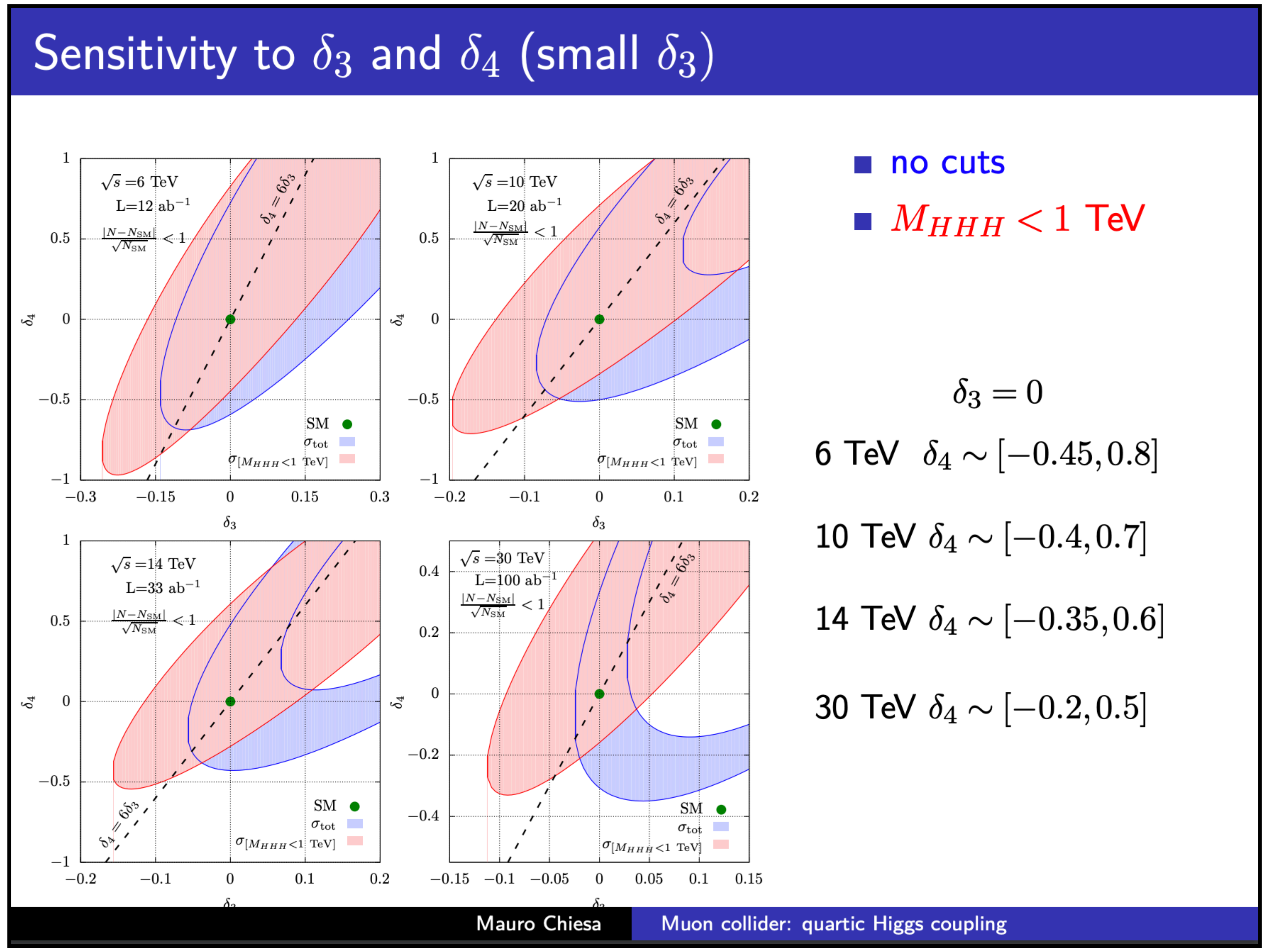
Muon Colliders: Physics Reach

	Fit Result [%]		
	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27





[We choose $1/R = 3$ TeV for illustration, Han et al. 2108.05362]

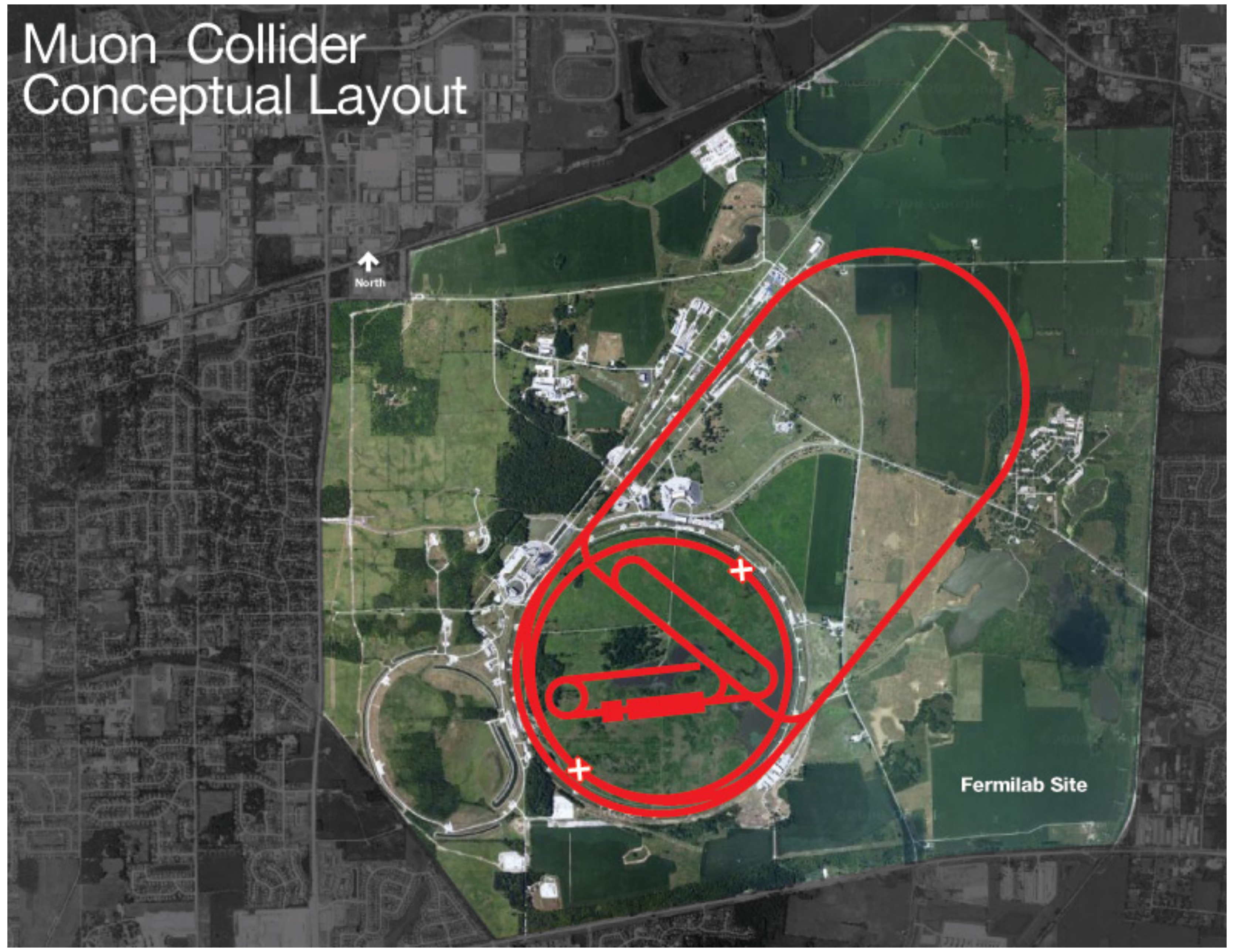


Muon Colliders

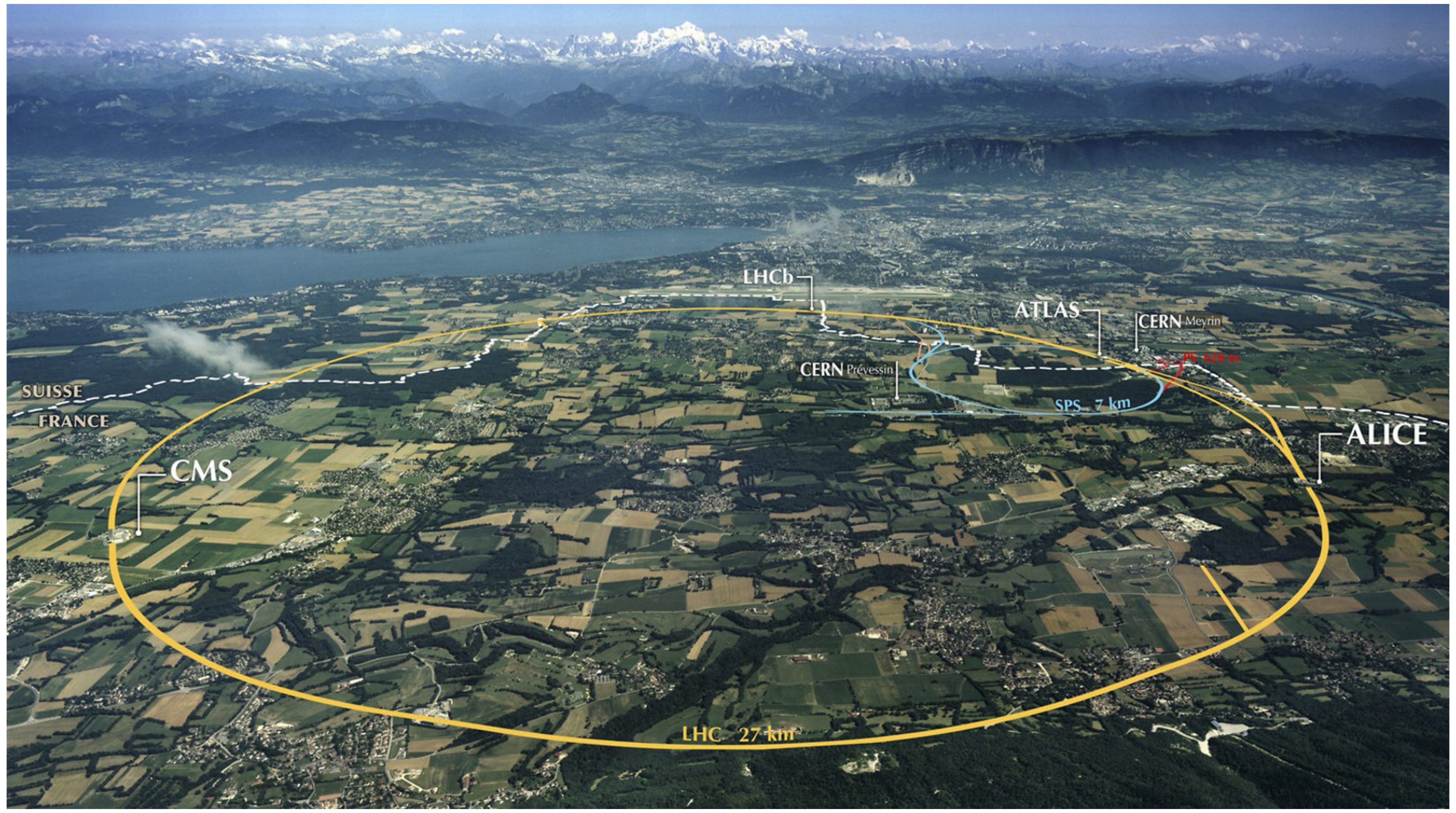
arXiv:1901:06150

An international effort

Possible US facility

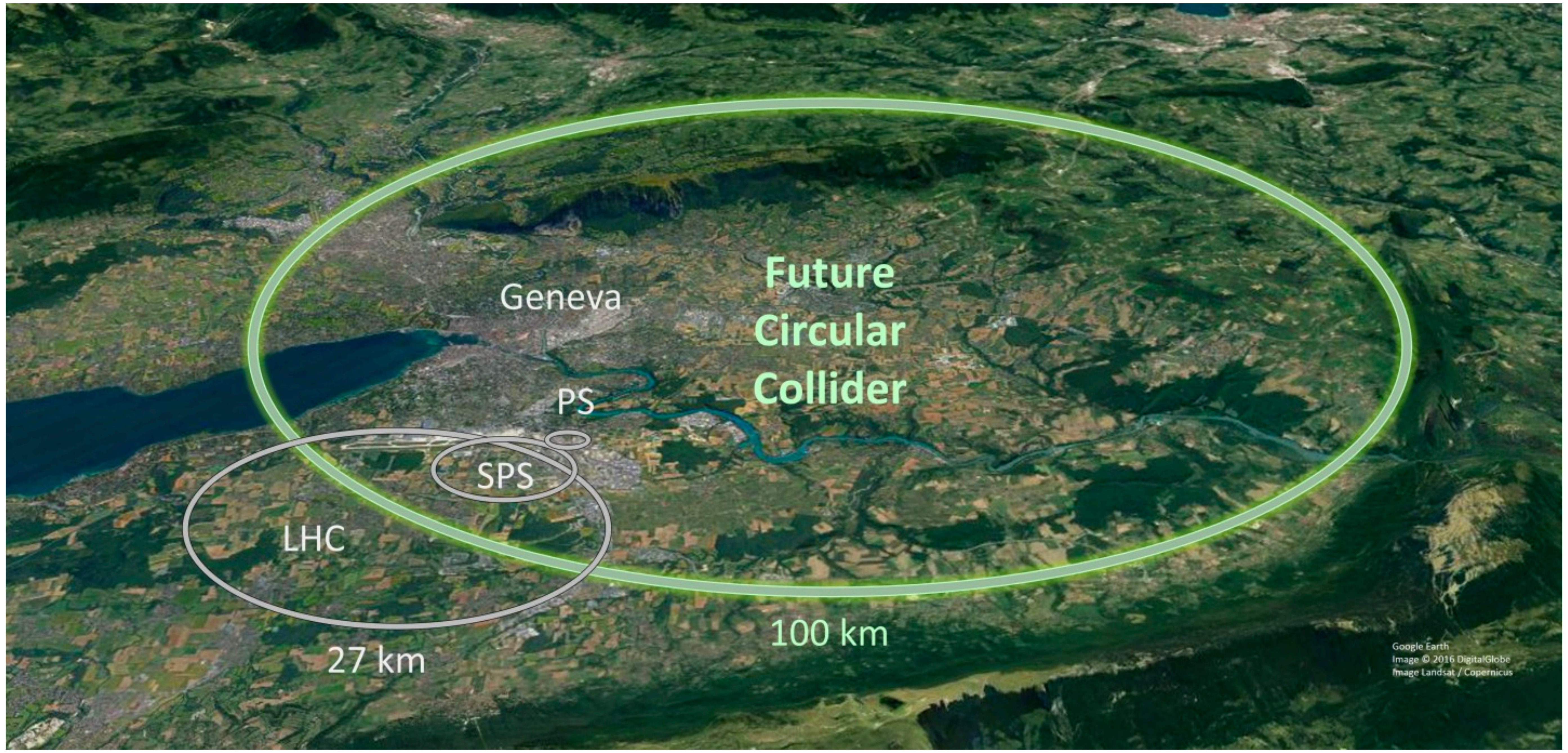


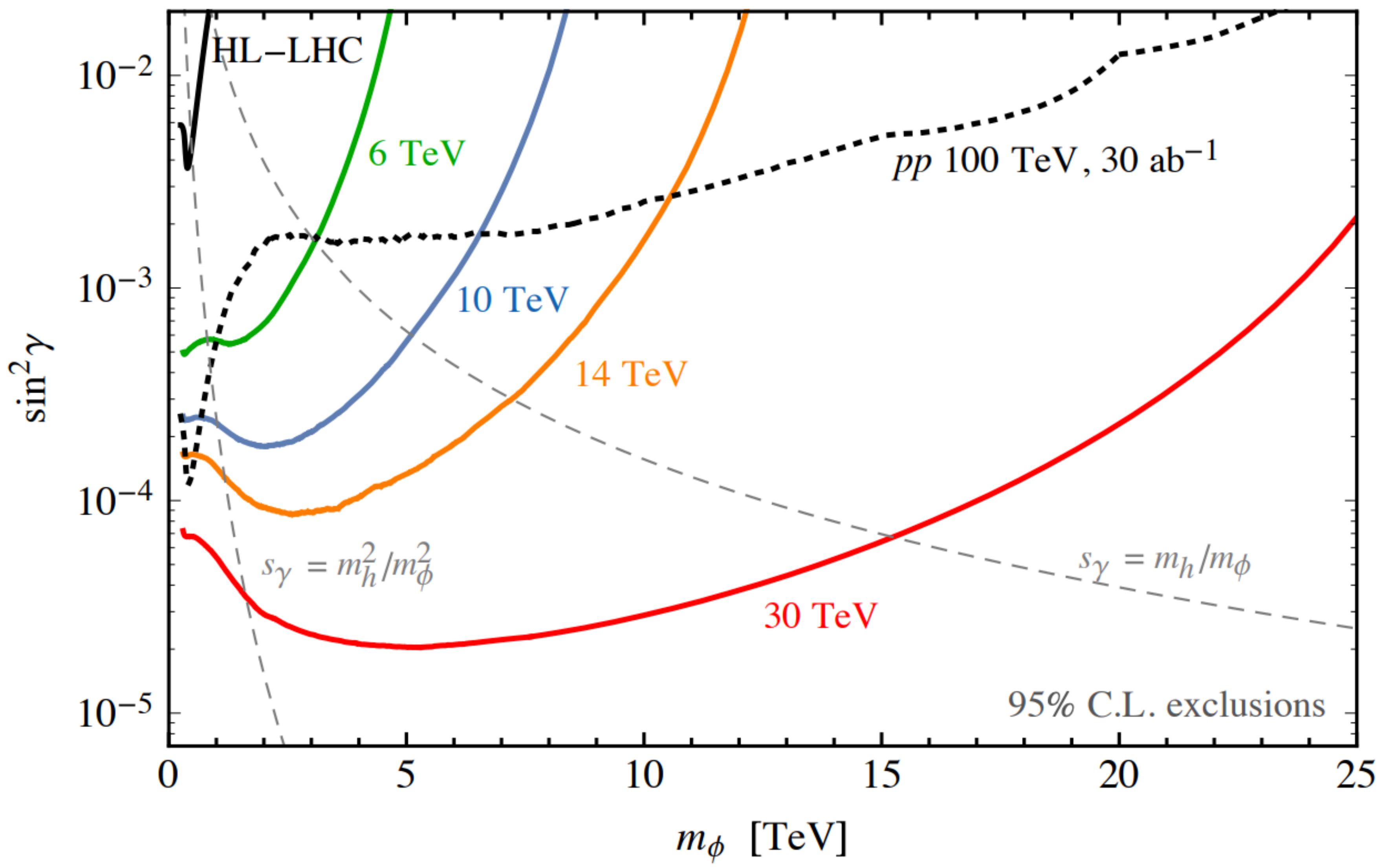
6-10 TeV could fit on FNAL site

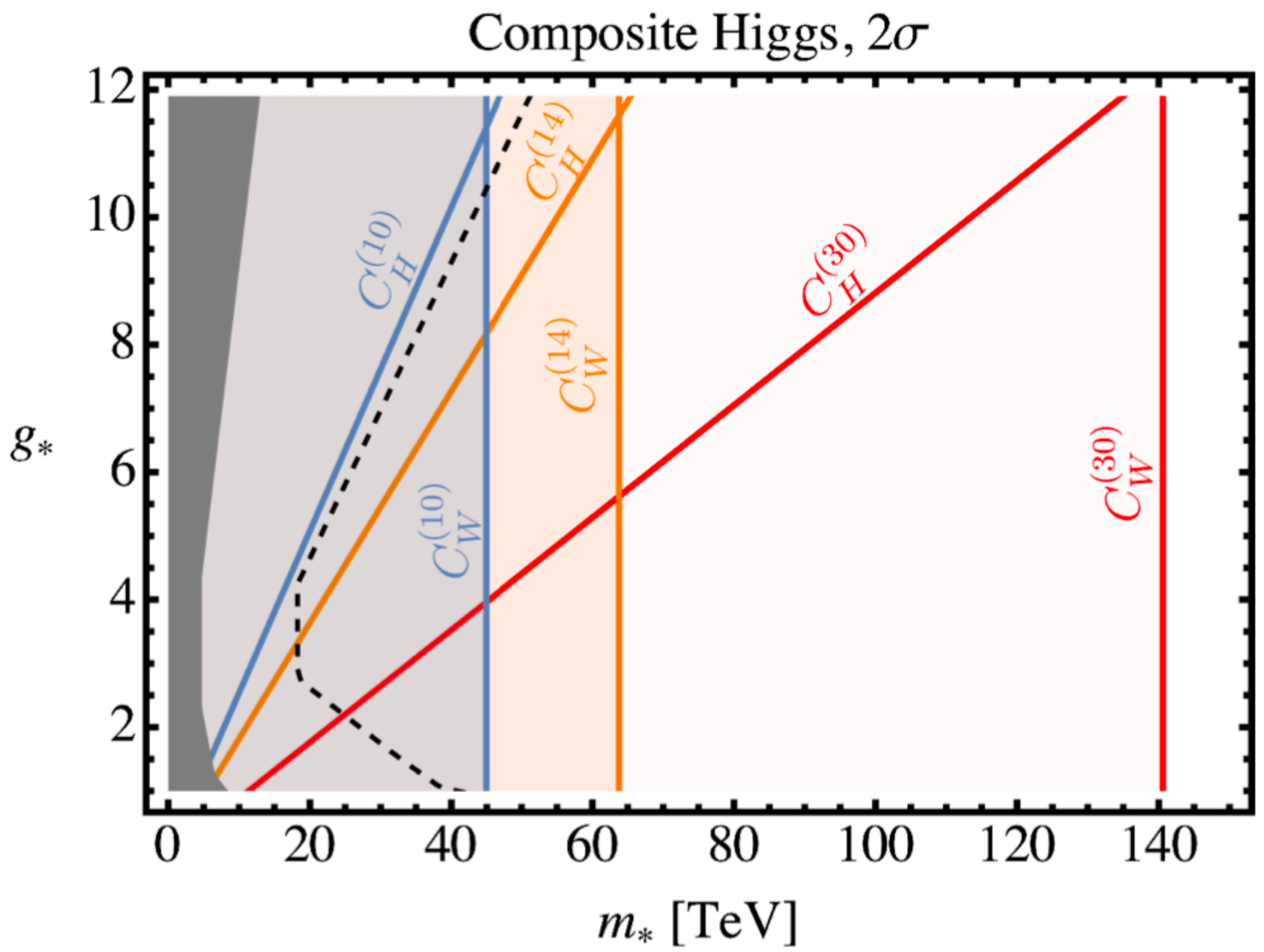


15 TeV could fit in the LHC Tunnel
- Funded IMCC effort at CERN

Discovery Machines: 100 TeV FCC hh and 30 TeV Muon Collider







- The R&D efforts made today will be the groundwork towards discovering new physics tomorrow!!

Snowmass Process

Snowmass Process: *

APS Division of Particles and Fields
Particle Physics Community Planning Exercise
Snowmass 2013
P5 (Particle Physics Project Prioritization Panel)
Takes the scientific input and develop a Strategic plan for the US - executed over 10 year timescale in the context of a "**20-year vision for the field**"

Final Products:

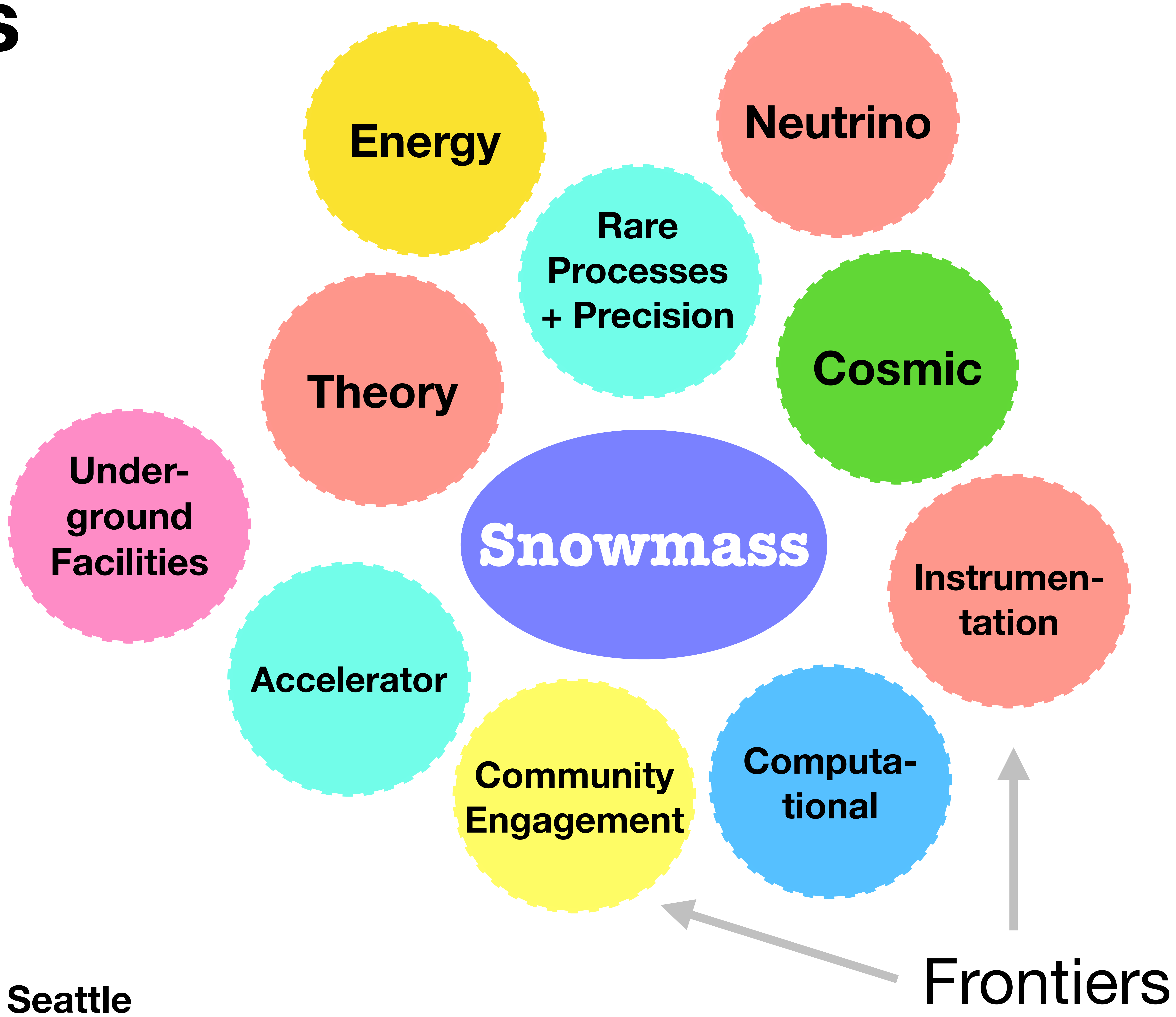
Snowmass report
Higgs/Higgs BSM working groups
- Outline the Big Questions
- Create Summary plots

Timeline:

(More on next slide)
Higgs, Higgs BSM working group meetings
Wednesday 12-2pm Indico

Pause due to Covid Pandemic
January 2021 - September 2021

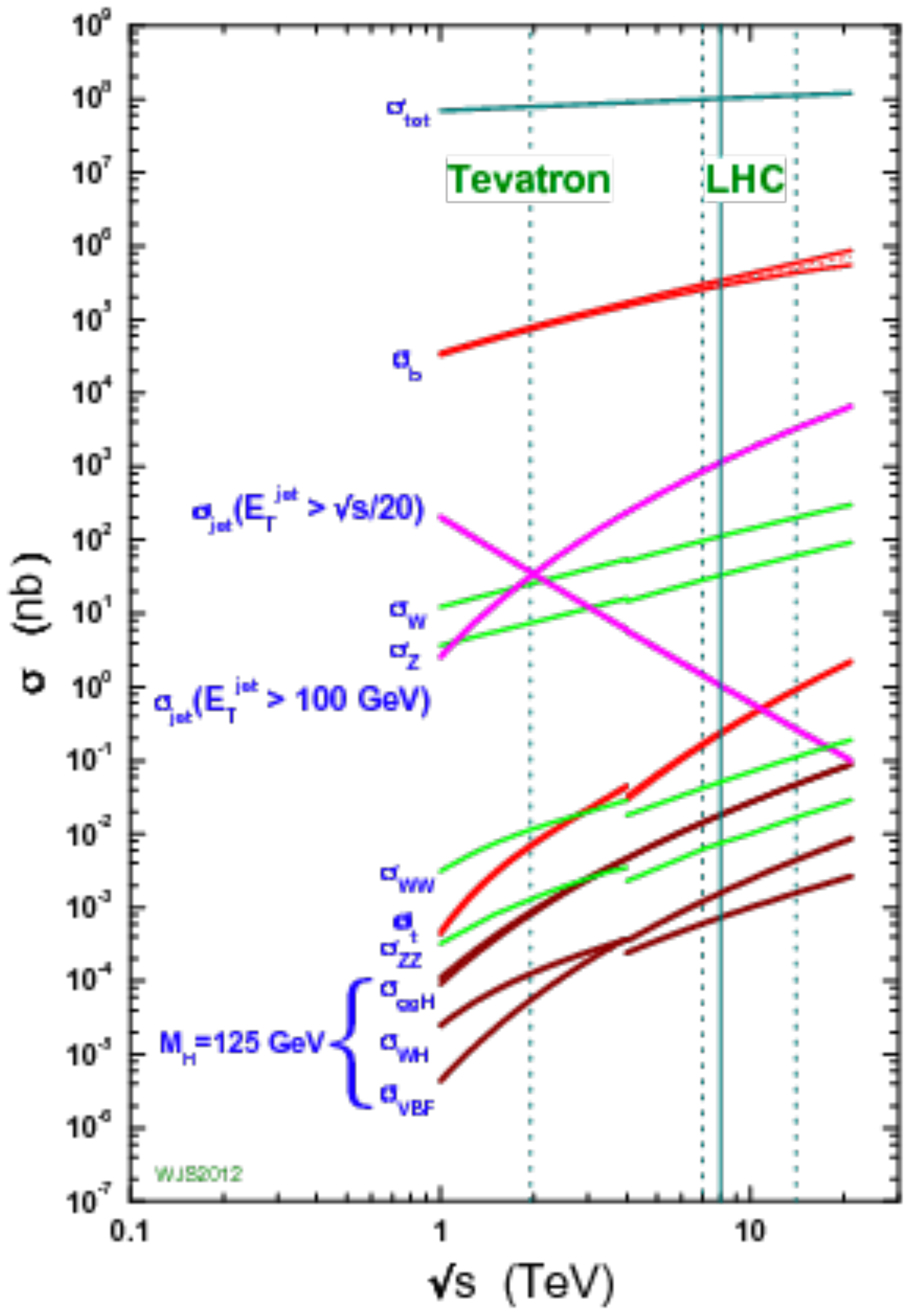
Snowmass Summer Study - July 2022 UW Seattle

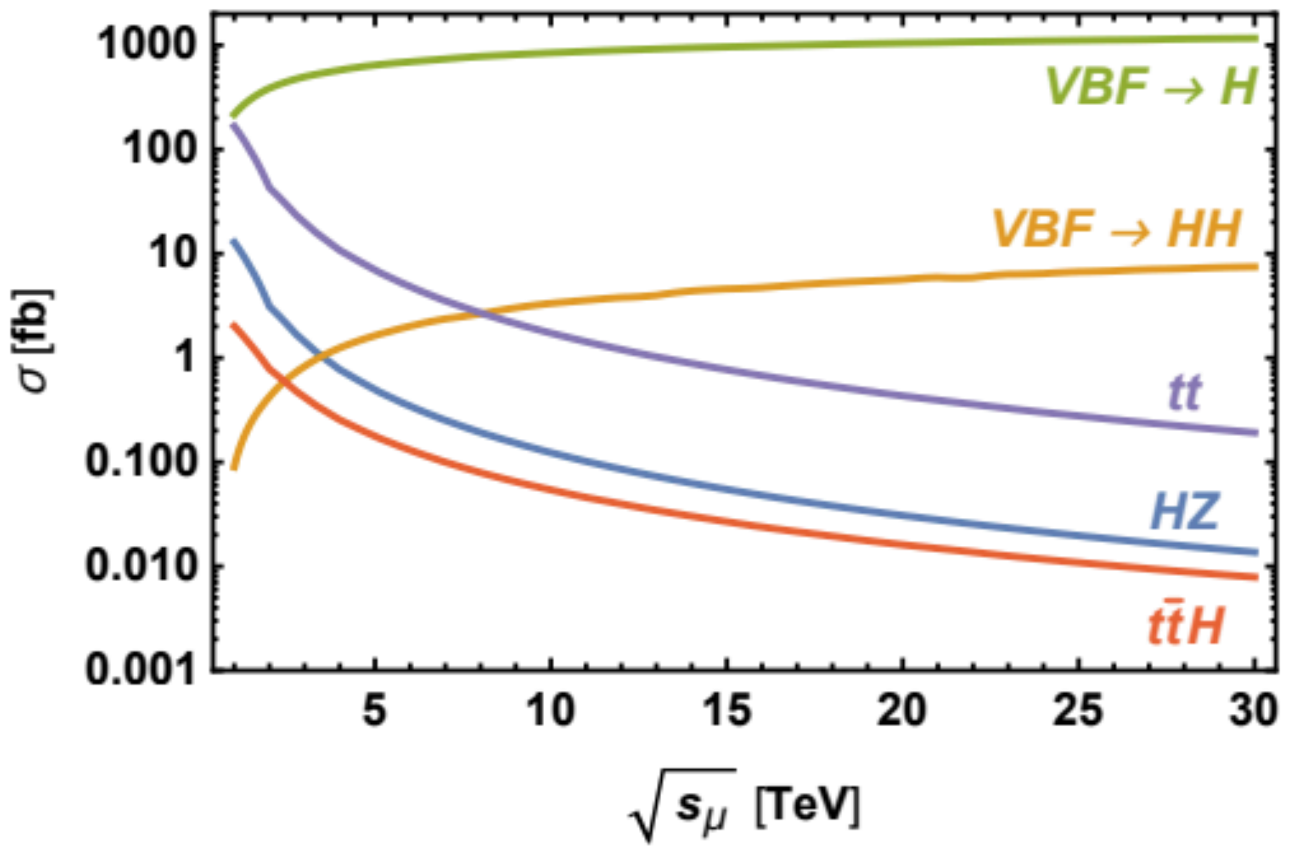


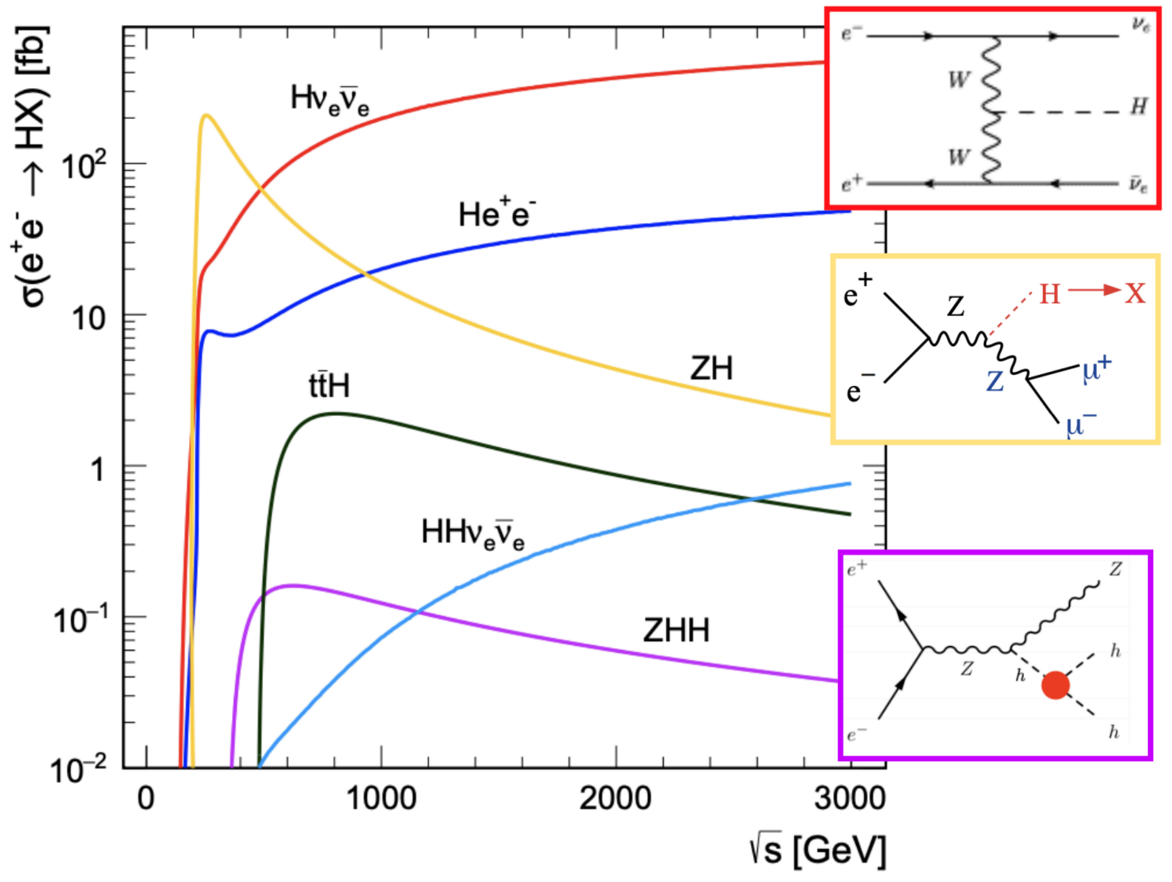
Summary

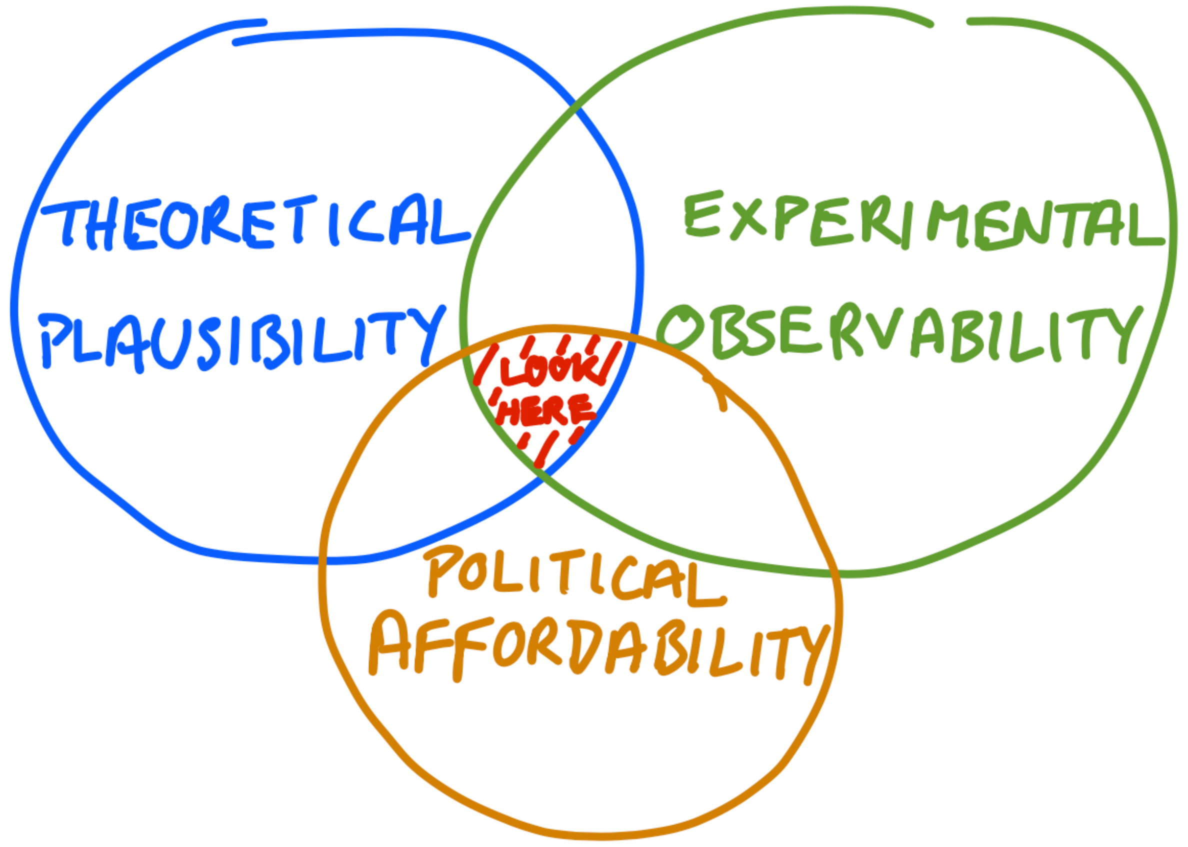
- The next 5-40 years will be an exciting time in Collider Physics!
- Snowmass process is marching on

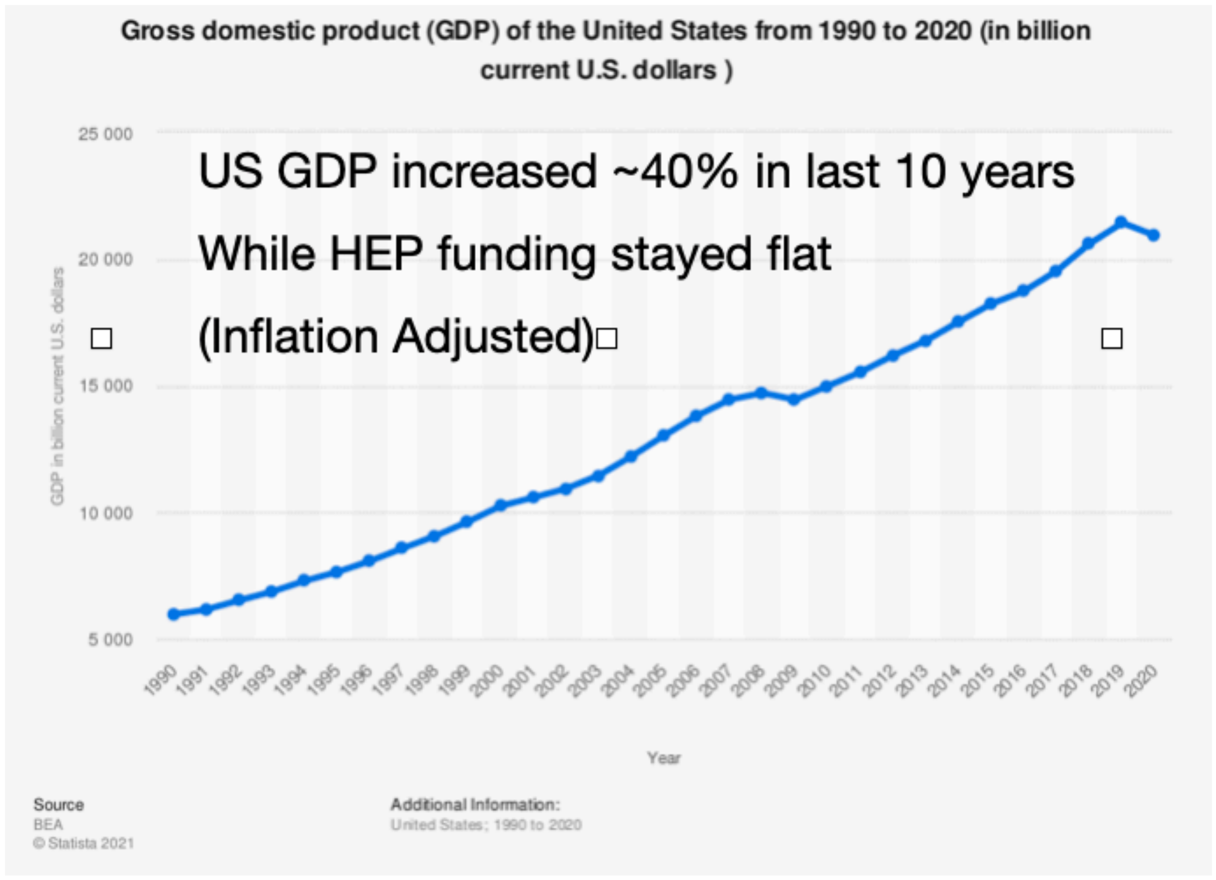
    - Finalize studies and make worthwhile comparisons
    - Advocate to our scientific colleagues
    - Advocate to the public, our funding agencies and governments
- Our goal should be to create a comprehensive international program that welcomes all with know-how and interest
- Come join the effort!!



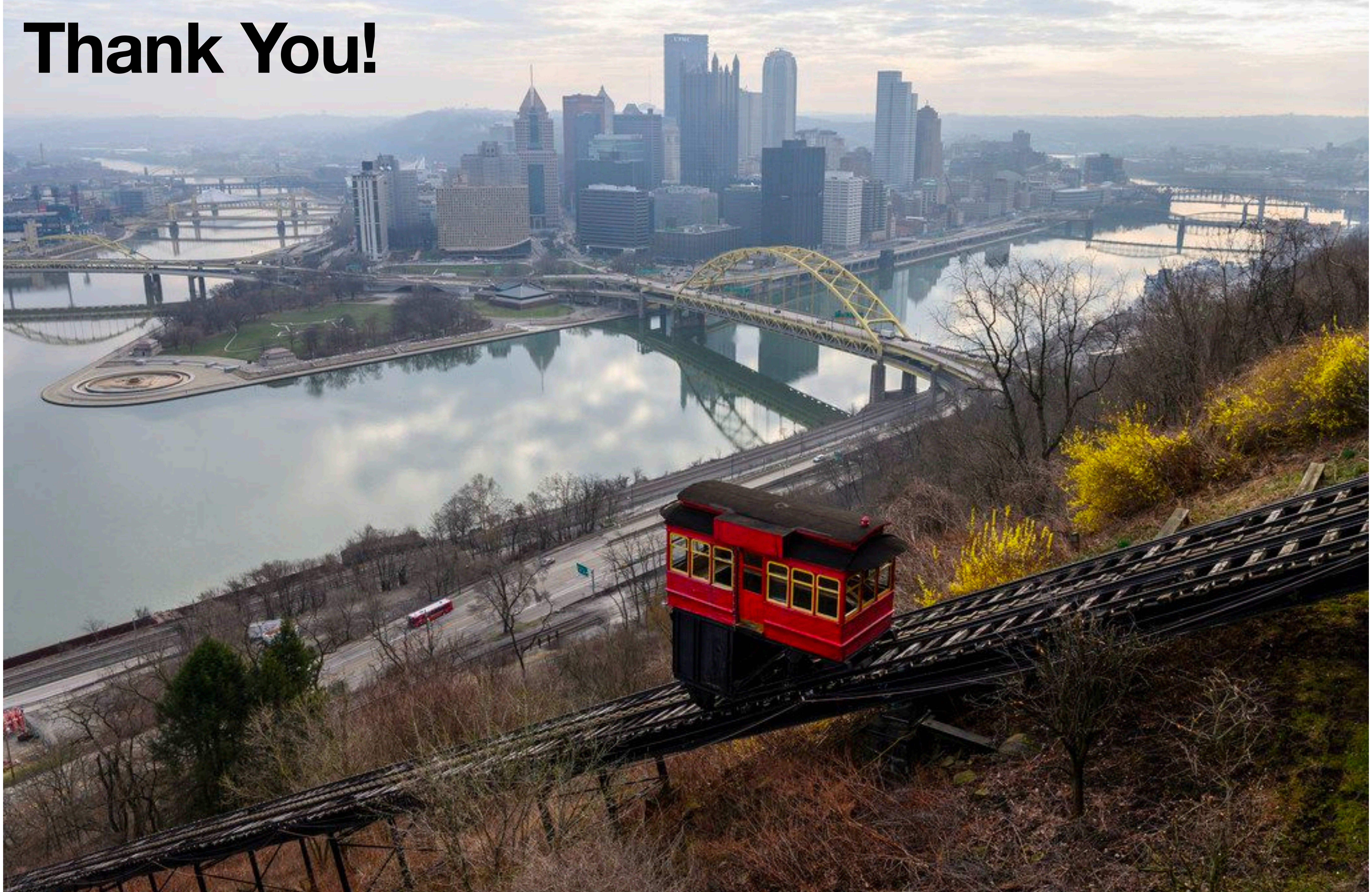








Thank You!



Snowmass Timeline

1/21-6/21	6/30/21	7/12/21	8/30/21	9/24/21	3/15/22	5/31/22	6/30/22	7/22	9/30/22	10/31/22
Activity Slowdown	Restart of Activities	DPF Meeting + Snowmass Townhall	Now, EF restart Workshop	Snowmass day	Deadline Contributed Paper Submission	Prelim. TG Reports	Prelim. Frontier Reports	Community Summer Study (UW-Seattle)	Final Reports	Snowmass Book & ArXiv docs

- **Sept. 24, 2021: Snowmass Day,** https://indico.fnal.gov/event/50538/
  - Plenary session 12:00-2:00pm (eastern time) with short talks from all frontiers
  - EF parallel session 2:30pm-5:00pm (eastern time) with highlights by topical group
  - Early Career (EC) will be chosen as speakers: they will provide their own perspective and highlight EC studies
- **Winter 2021-2022: few one-day virtual EF workshops by topic (SM, Higgs, BSM, Colliders,…)**
  - Check progress towards March deadline for contributed papers
  - Discuss overlap with other frontiers
- **Spring 2022: EF workshop to review contributed papers**
  - Focus on main themes and messages by contributed papers, towards May deadline for TG reports.
  - Converge on summary plots and other contributions involving multiple TGs or multiple frontiers
- **March-July 2022: circulations of preliminary TG and EF reports, then public readings**

Covid-19 has slowed this process down…

Snowmass Timeline

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Covid-19 has slowed this process down…
but now we record nearly everything!

Snowmass Parameters

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	$\pm80/0$ $\pm80/0$ $\pm80/0$	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV $2\ M_{top}$		150 10 5 1.5

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
FCC-hh	pp	100 TeV		30
LHeC FCC-eh	ep ep	1.3 TeV 3.5 TeV		1 2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV 10 TeV 14 TeV 30 TeV		1 10 20 90

Note for muon-collider: It is important to note that the plan is not to run subsequently at the various c.o.m etc. These are reference points to explore and assess the physics potential and technology. The luminosity can be varied to determine how best to exploit the physics potential.

Other options to explore:

- Muon collider at a very high energy (>30 TeV?)[Need to consolidate growing list of c.o.m. energies]
- FCC pp >200 TeV? and ~75 TeV documenting sensitivity loss
- Very high energy e+e- collider
- Other emerging ideas:, e.g. γ-γ collider, and the C^3 e^+e^- collider [C^3=Cool Copper Collider]

Common working points to evaluate collider scenarios discussed with Theory, Energy and Accelerator Frontiers

Looking Forward