STATUS OF SNOWMASS ENERGY FRONTIER PERSPECTIVE WITH RESPECT TO FUTURE COLLIDERS

Snowmass EF wiki: https://snowmass21.org/energy/start

Meenakshi Narain

(Brown University, USA)

at the FCC Week 2022

May 30 – June 3, 2022

DPF Community Planning Exercise - aka Snowmass

- The charge of the Snowmass Process:

  "define the most important questions in the field of particle physics and identify promising opportunities to address them."

- Timescale:
- Planning for 2025-2035 with a view toward 2050

- Sponsored by Division of Particles and Fields of the American Physical Society

The Range of Snowmass Discussion

- There are **ten** Snowmass Frontiers spanning
- **Five scientific areas** of particle physics addressing fundamental questions about the universe
  - Accelerator Frontier
  - Cosmic Frontier
  - Energy Frontier
  - Neutrino Frontier
  - Rare Processes and Precision
- **Four technical areas** which enable scientific work
  - Computational Frontier
  - Instrumentation Frontier
  - Theory Frontier
  - Undergrounds Facilities
- And Community Engagement Frontier addressing the community development needed to maintain a vibrant profession and to engage with society.

The Snowmass Questions

- Goals: What are the **important scientific questions** in each frontier of particle physics during this period?
- Goals: What **enabling tools, technologies, or facilities studied** by each frontier are needed to address the pressing scientific questions in particle physics during this period?
- Goals: **How can we ensure that the US particle physics community is vibrant, inclusive, diverse,** and capable of addressing the scientific questions identified, and of fulfilling our obligations to society during this period?
- Context: **What can be expected from ongoing, approved, planned, or proposed scientific, technical, or community programs** in addressing the issues identified by each frontier?

The Snowmass Questions

- Opportunities: What opportunities identified by each frontier are there **for new scientific, technical, or community activities to create transformative change** in particle physics, on what timescales could these occur, and what resources are required to realize these activities?
- Opportunities: What **investments need to be made during 2025-2035 for the continuing scientific, technical, or community progress** identified by your frontier in the decades beyond, on what timescales can these be implemented, and what resources would be required?
- Collaboration: What opportunities exist for cross-frontier, cross-disciplinary, or international collaboration and cooperation in the coming decade to enhance our ability to address the issues identified (including training or mentorship)? How do these collaborations affect the timescales or resources needed for these activities?

The Start of the Snowmass Process

- The APS/DPF in 1982 at Snowmass, Colorado provided a model for the community summer studies open to all active particle physicists in the United States, joined by representatives of the European physics community, the DOE, and the NSF.

"The 1982 DPF Summer Study was the first attempt in recent years to bring together physicists from the whole country to consider the future of our field from the point of view of the best overall national program.

- The avowed purpose of Snowmass 1982 was to "assess the future of elementary particle physics, to explore the limits of our technological capabilities, and to consider the nature of future major facilities for particle physics in the U.S."

From "How to Snowmass" by Chris Quigg

IMPORTANT NOTE:
THIS PRESENTATION IS THE ENERGY FRONTIER PERSPECTIVE WITH RESPECT TO FUTURE COLLIDERS

Energy Frontier at Snowmass 2021

- 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

- **Energy Frontier Conveners:**

Laura Reina (FSU, USA)

Alessandro Tricoli (BNL, USA)

Meenakshi Narain (Brown University, USA)

Energy Frontier Topical Groups

Ten Topical Groups focused on Electroweak, QCD, BSM physics

Topical Group	Co-Conveners		
EF01: EW Physics: Higgs Boson properties and couplings	Sally Dawson (BNL)	Andrey Korytov (U Florida)	Caterina Vernieri (SLAC)
EF02: EW Physics: Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook)	Isobel Ojalvo (Princeton)	
EF03: EW Physics: Heavy flavor and top quark physics	Reinhard Schwienhorst (MSU)	Doreen Wackeroth (Buffalo)	
EF04: EW Physics: EW Precision Physics and constraining new physics	Alberto Belloni (Maryland)	Ayres Freitas (Pittsburgh)	Junping Tian (Tokyo)
EF05: QCD and strong interactions: Precision QCD	Michael Begel (BNL)	Stefan Hoeche (FNAL)	Michael Schmitt (Northwestern)
EF06: QCD and strong interactions: Hadronic structure and forward QCD	Huey-Wen Lin (MSU)	Pavel Nadolsky (SMU)	Christophe Royon (Kansas)
EF07: QCD and strong interactions: Heavy Ions	Yen-Jie Lee (MIT)	Swagato Mukherjee (BNL)	
EF08: BSM: Model specific explorations	Jim Hirschauer (FNAL)	Elliot Lipeles (UPenn)	Nausheen Shah (Wayne State)
EF09: BSM: More general explorations	Tulika Bose (U Wisconsin-Madison)	Zhen Liu (Maryland)	Simone Griso (LBL)
EF10: BSM: Dark Matter at colliders	Caterina Doglioni (Lund)	LianTao Wang (Chicago)	Antonio Boveia (Ohio State)

Synergies: Energy Frontier Topical Groups & Other Frontiers

Accel. Frontier

Instrum. Frontier

Theory Frontier

Computational Frontier

Neutrino Frontier

Rare Processes and Precision Meas. Frontier

Cosmic Frontier

QCD and Strong Interactions (EF05-06-07)

- Accuracy of future MC event generators (with CompF)
- Forward Phys and Neutrinos (with NF)
- Hadron spectroscopy (with RF)

- EW physics in HI
- Jet substructure
- BSM Searches in HI

Electroweak (EF01-02-03-04)

- BSM Higgs
- EW measurements as inputs to reinterpretations

- H/Z/top/mesons rare decays etc. (with EW groups)
- BSM interplay with EFT
- H/Z/top/mesons rare decays etc.
- Complementarity of DM searches with fixed target, direct detection (with CF & RF)
- Projections for FASER/CODEX-b/Mathusla, etc. (with RF)

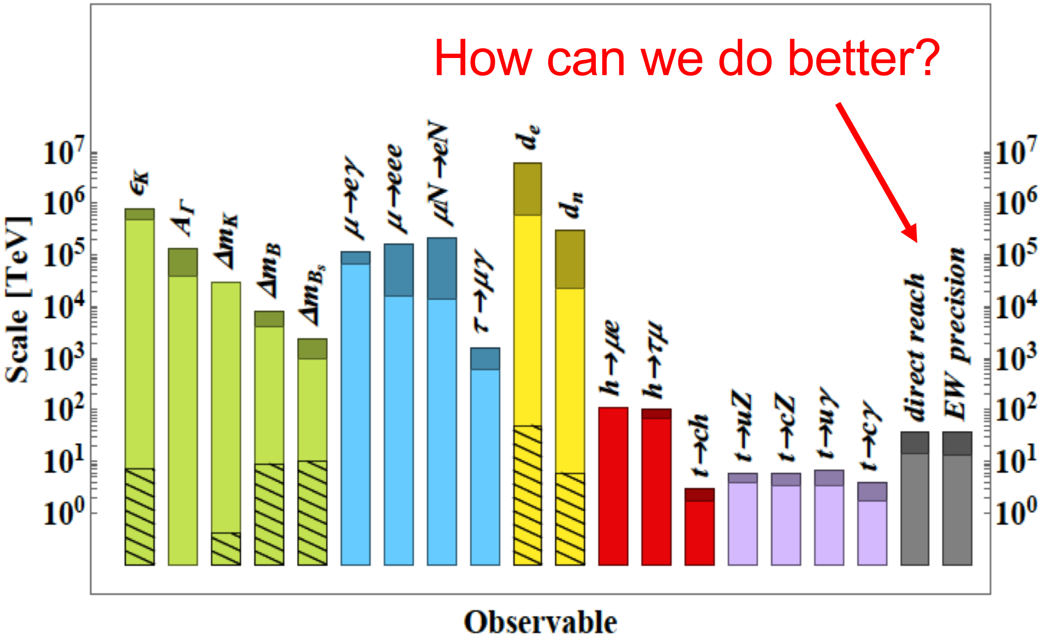
BSM (EF08-09-10)

Probing the energy scale for new physics

- Probing the energy scale for new physics

Complementarity with other Frontiers

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

Reach in new physics scale from both direct and indirect searches

Patrick Meade

Key physics questions of the Energy Frontier (EF) program

What is the origin of the electroweak scale?

- The Higgs discovery is a unique handle on BSM physics and we need to make the most out of it.
  - Can we uncover the nature of UV physics from **precision Higgs measurements** (mass, width, couplings)?
  - How does this improve the constraining power of global EW fits?
  - Can we measure the shape of the **Higgs potential**? Can the Higgs give us insight into **flavor** and vice versa?
  - What are the implications for **Naturalness**?

How to build a complete program of BSM searches via both model-specific and model independent explorations?

- Models connect the high-level unanswered questions in particle physics (dark matter, electroweak naturalness, CP violation, etc) to specific phenomena in a self-consistent way.
  - Allow the comparison of experimental reach between various approaches, e.g. direct searches vs precision. But …**Which models to consider? How to compare model spaces in a consistent way?**
  - How do we conduct searches in a more model-independent/agnostic way ?
  - How do we compare the results of different experiments in a more model-independent way to ensure complementarity and avoid big gaps in coverage?

Key physics questions of the EF program

What can we learn of the nature of strong interactions in different regimes?

- **Fundamental (theory + phenomenology):** ➢ Strong Interactions
  - What precision in αS can be reached by each future machine/experiment?
  - Define the direction of future high-precision QCD calculations
  - What is the evolution of jets as a function of energy at the EIC and at hadron colliders?
  - Are jets universal? If not, how do we deal with non-universality in our hadronization models?
  - Explore PDFs coming from lattice calculations – how to benchmark them using conventional PDFs?
- **Data and Computing:**
  - Find a better way to analyze and study multiple-parton interactions and the underlying event.
  - What can we learn about non-perturbative physics using minimum-bias events at the LHC?
  - Strengths and weaknesses of existing MC event generators – define what is needed for the future.

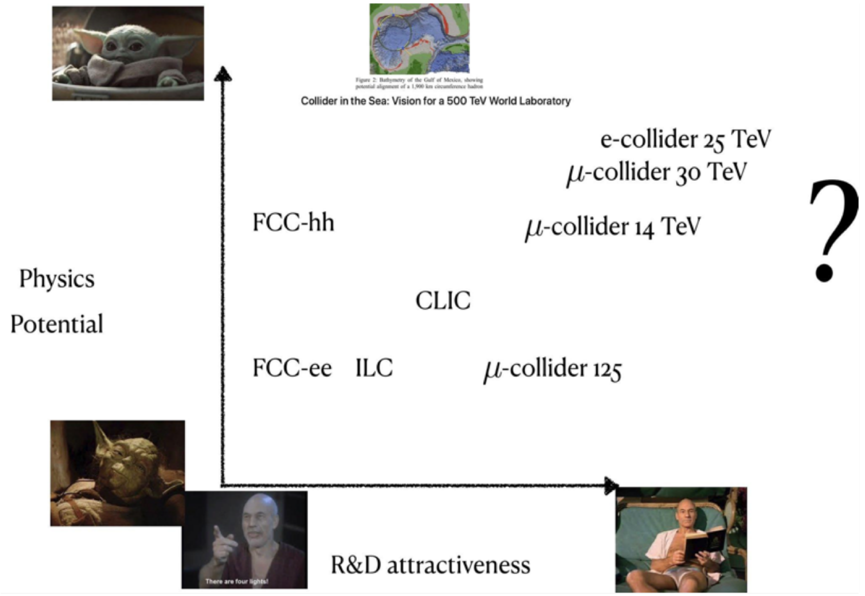
Finding answers generates more specific questions.

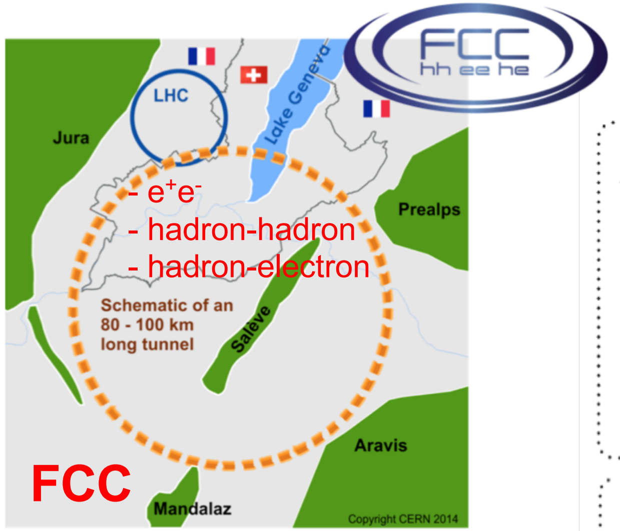
- What collider/detector properties are necessary to probe the Higgs self interactions?
- Identify technologies for discoveries; where do new approaches in searches or data analysis matter most?
- What Theory calculations do we need to capitalize on? (signals, backgrounds, EWPO, input parameters such as mt or αs, event generators, ...)? Where does theoretical accuracy matter most? How to reduce theory systematics?

➢ Dialogue among frontiers, between theory and experiments

Energy Fronter Machines

- Discoveries at the Energy Frontier are intricately linked to new accelerators and detector instrumentation.
- Proceed along two complementary directions
  - Study known phenomena at high energies
    - Factory of Higgs bosons (or other known particles)
    - Electroweak (EW) physics
    - QCD and Strong Interactions
  - Search for direct evidence of BSM physics
    - Next high energy frontier machine
- What are the most promising future colliders?





Hadrons

- large mass reach ⇒ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇒ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇒ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇒ EW couplings

Circular

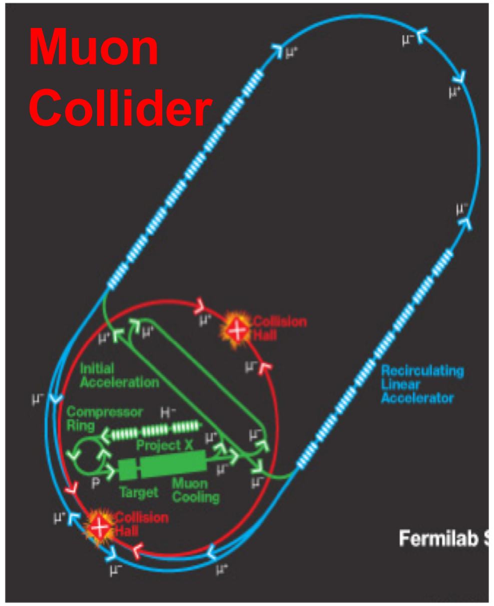
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

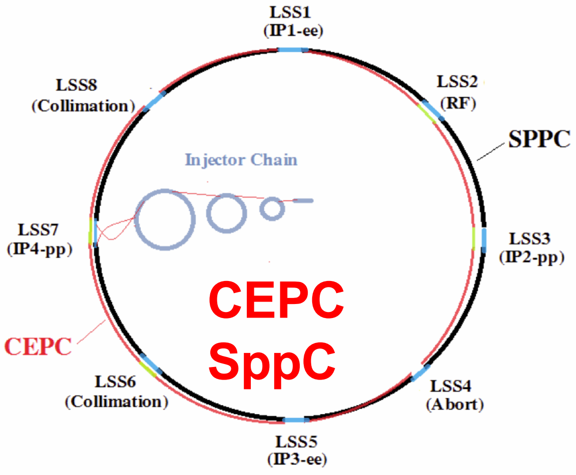
Linear

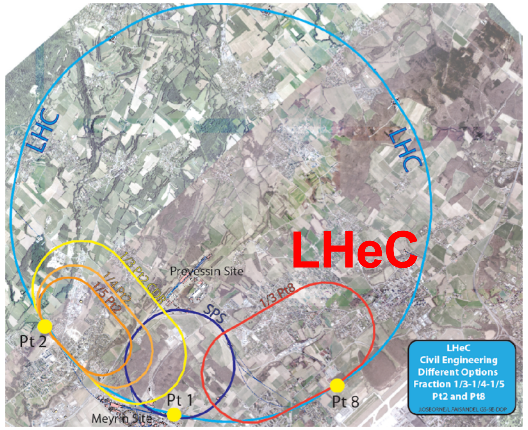
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

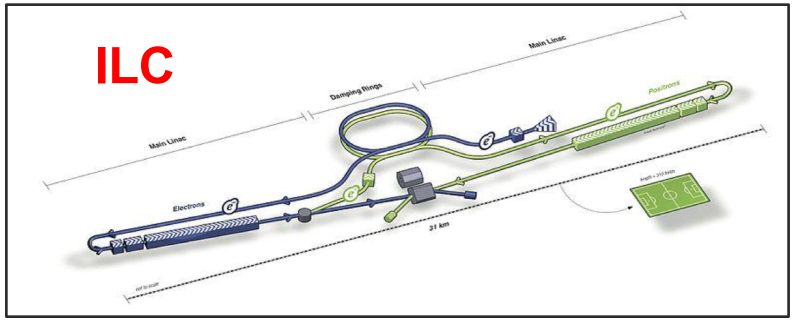
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

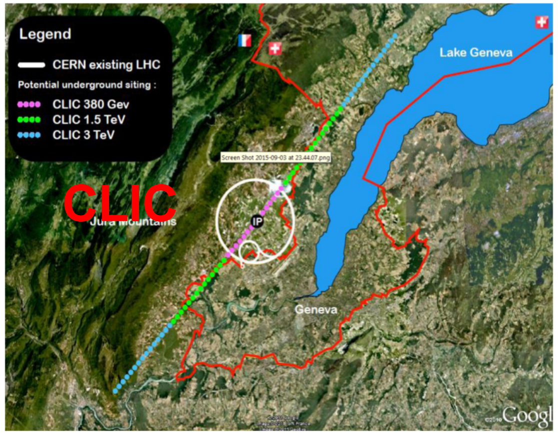
hristophe Grojean   Future Measurements   9   Inst. Pascal, Dec. 4, 2019











C^3, gamma-gamma?

Snowmass 2021: EF Benchmark Scenarios

Higgs Boson Factories

Snowmass 2021 Higgs Factory Study Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3 c.o.m almost similar	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
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

High Energy Machines

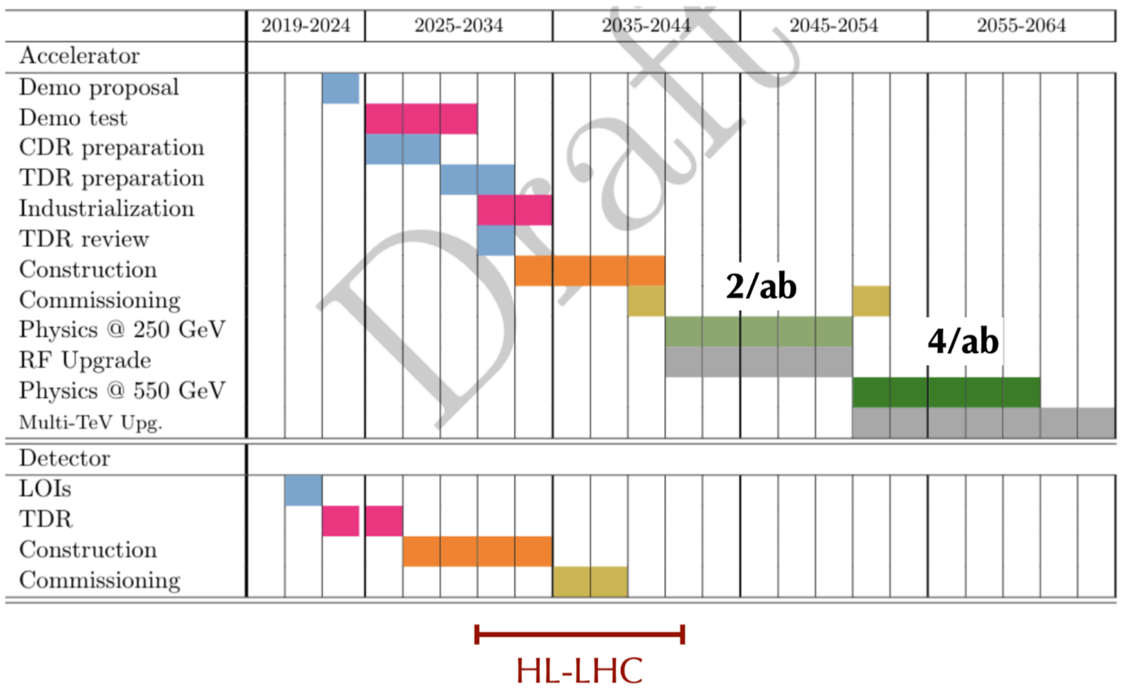
Snowmass 2021 EF Discovery Collider Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV	15
FCC-hh	pp	100 TeV	30
LHeC FCC-eh	ep ep	1.3 TeV 3.5 TeV	1 2
High energy muon-collider	$\mu\mu$	3 TeV 10 TeV 30 TeV	1 10 10

C3 - Cool Copper Collider

- Based on a new SLAC technology
- Two Key Technical Advances:
  - Distributed Coupling & Cryo-Copper RF
- Operation at cryogenic temperatures
  - (LN2 ~80K)
- Robust operations at high gradient:
  - 120~MeV/m

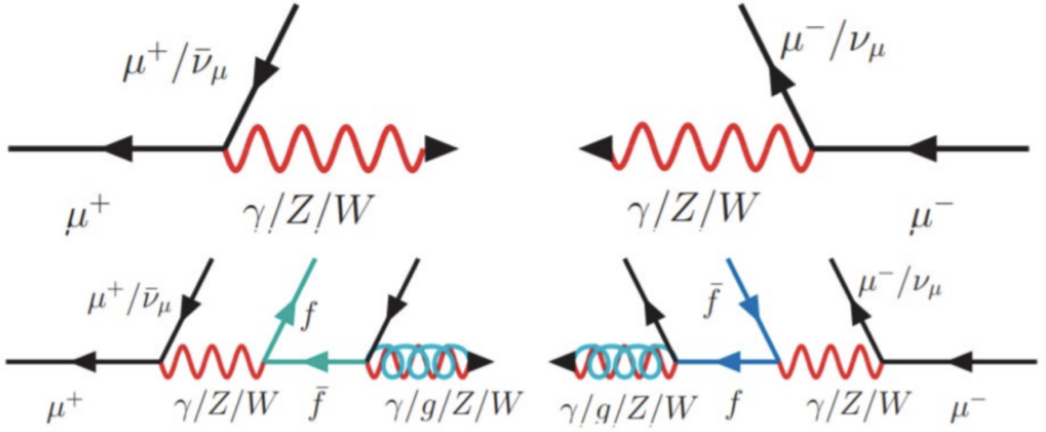
C³ timeline

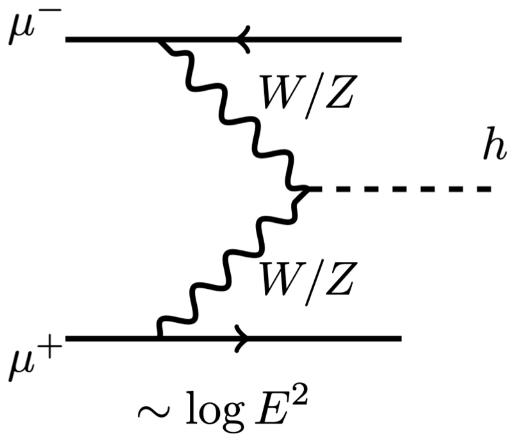


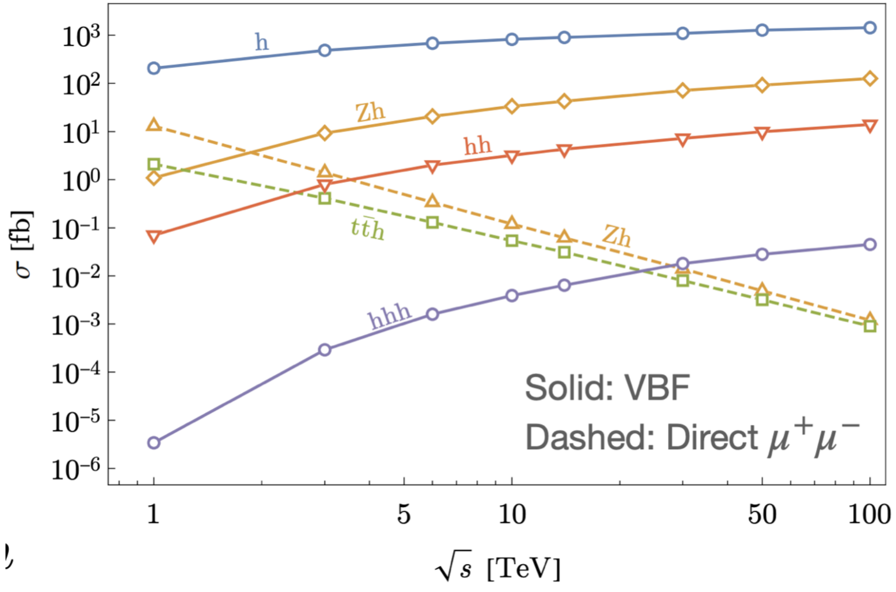
- Scalable to multi-TeV operation
- Operate at 250 and 550 GeV with possible commissioning at the Z pole

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 do 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 are actually EWK colliders with a mix of initial states







TIMELINES, DISCUSSIONS AND PAPERS

Energy Frontier Meetings

2020

- Energy Frontier **Kick-off Meeting**, May 21, 2020, see agenda
- **Energy Frontier Workshop "Open Questions and New Ideas"**, July 20-22, 2020,
- **Snowmass CPM Meeting**: **EF Report** (Oct. 2020): focus points and key questions.

2021

- **EF slowed down activities in 2021 until June**
  - Community continued to work collaboratively
  - Monte Carlo production activities continued to support the needs of EF
  - Occasional and informal Topical Group 'conversations' to assure scientific continuity and support of ongoing activities

- **EF Restart Workshop, Aug. 30-Sept. 3 2021:** https://indico.fnal.gov/event/49756/
  - Many interesting talks in plenary and parallel sessions
  - Joint parallel sessions with CompF and CF
  - Unstructured discussion sessions with CEF and AF

- **EF Workshop, March 28 - April 1st 2022: https://indico.fnal.gov/event/52465/**
  - Regroup after the submission of Contribute Papers (deadline: March 15)
  - Mostly plenary sessions, summaries of highlights from Topical Groups
  - **Sessions dedicated to highlights from TF**, CompF, IF
  - Discussion of outcomes from recent Snowmass *Agora on Future Colliders*
  - Discussion sessions to outline of Topical Group Reports
  - Discussion sessions to build and formulate EF vision towards final EF Report

Snowmass Agora on Future Colliders

- Series of events jointly organized by AF and EF, hosted by the Future Colliders initiative at Fermilab, to discuss both near and far future collider proposals, in different stages of development, synergistically grouped into five categories:
  - e+e- linear colliders (Dec. 15, 2021): https://indico.fnal.gov/event/52161/
  - e+e- circular colliders (Jan. 19, 2022) https://indico.fnal.gov/event/52534/
  - μ+μ- colliders (Feb. 16, 2022): https://indico.fnal.gov/event/53010/
  - circular pp and ep colliders (Mar 16, 2022) https://indico.fnal.gov/event/53473/
  - advanced colliders (April 13, 2022) https://indico.fnal.gov/event/53848/
- Critical discussions of physics reach, challenges and RD required, synergies with global context and local resources, timeframe, cost projection.

- Other specific dedicated meetings can be found on EF/AF Snowmass websites

Snowmass2021 Timeline

4/20-12/20	8/30-9/3/21	3/15/22	3/28-4/1/22	5/31/22	6/30/22	7/17-26/22	9/30/22	10/31/22
Snowmass Planning 1/21-7/21 Pause/ Slowdown	EF Restart Workshop	Contributed Paper Submission	EF Workshop (Brown U.)	Prelim. TG Reports	Prelim. Frontier Reports	**Community Summer Study (Seattle)**	Final Reports	Snowmass Book & ArXiv docs

Contributions by FCC listed on https://snowmass21.org/submissions/ef

Working Towards the Energy Frontier Report

- Physics: Many ideas, new studies, new directions.
  - Documented in the extensive reports from the Topical groups.
- Answering questions as listed on Slides 4 & 5

- Started the process of inviting the community to share their vision for the EF at the end of EF workshop March/April 2022
  - [you are welcome to add to the linked google doc]

- We are using this document and the contributed papers to answer the questions.
- We will share the reports
  - topical group reports – towards beginning of June with the community
  - and EF report – end of June

PHYSICS: MANY IDEAS, NEW STUDIES, NEW DIRECTIONS.

Caveats

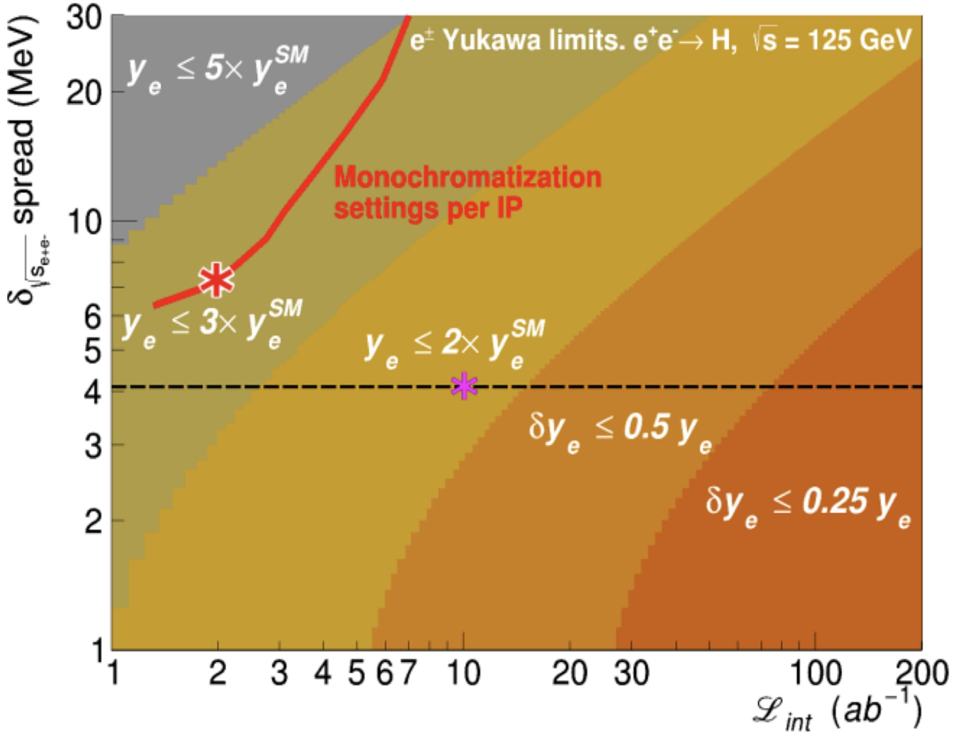
- There are many results which are new!
- **<u>We are still in the process of documenting</u>** and collating them in our topical group reports
- Hence, some of the plots, and/or results I may show may not be the latest, from the contributed papers.
  - This will change as soon the topical group reports appear [around beginning of June]

- There are 100+ contributed papers
  - I cannot summarize all, so I have made some personal choices.
  - This audience is familiar with the results from FCC Physics studies
  - I apologize in advance if this causes any concern, and your favorite study is not in these slides.

Higgs boson properties and couplings

- Progress on understanding light fermion Yukawa couplings
  - Electron Yukawa at FCC-ee with 4 years running, $Y_e < 1.6\ Y_e^{SM}$
  - Strange Yukawa?
  - Charm Yukawa limit, $|\kappa_c| < 8.5$ (CMS) motivates new studies
  - Searches for flavor violating H couplings motivated by LHC limits on H→μe, H→μτ and by B flavor anomalies
- Progress on the inverse problem
  - Planning for summary plots to map new physics phase space with constraints on EFT operators

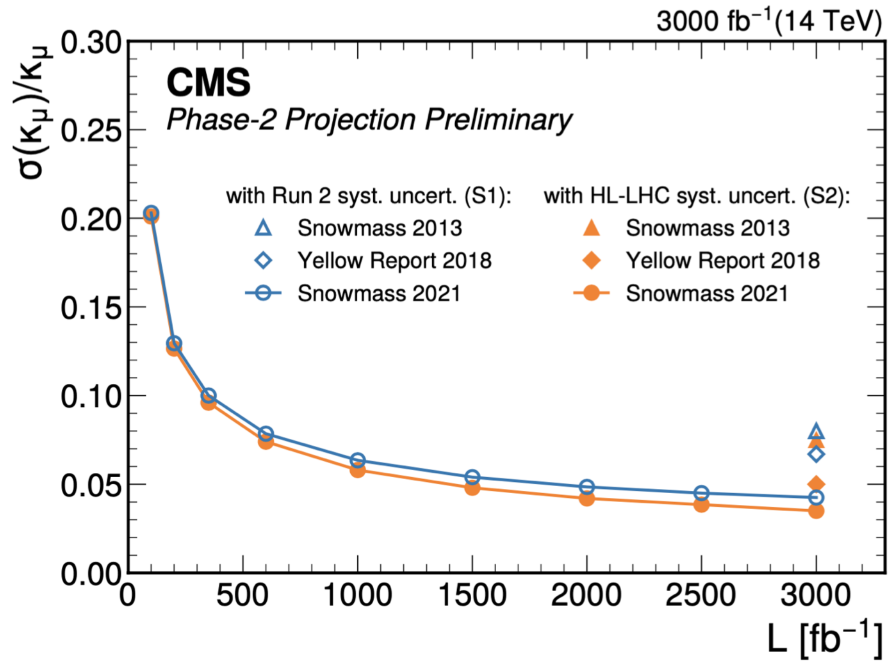
- HH production
  - HH is sensitive to a range of EFT operators, not just λ_3
    - Limits significantly degraded by inclusion of multiple EFT operators
  - New Projections are being evaluated
    - Including prospects at the muon collider
  - Discussions are ongoing to provide relevant benchmarks for BSM HH resonant and non-resonant interpretations
    - Dedicated discussions on the flavor assumptions



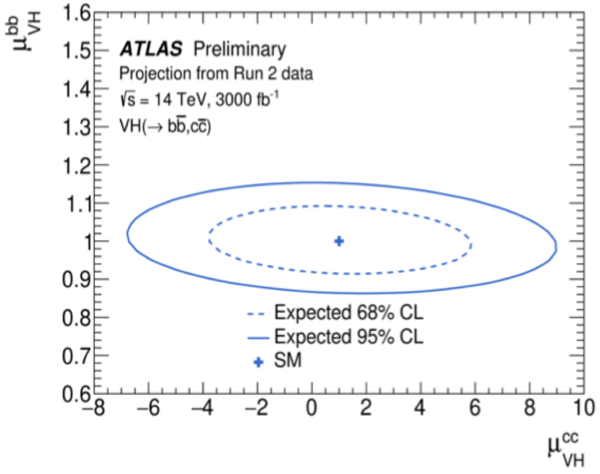
https://arxiv.org/pdf/2107.02686.pdf

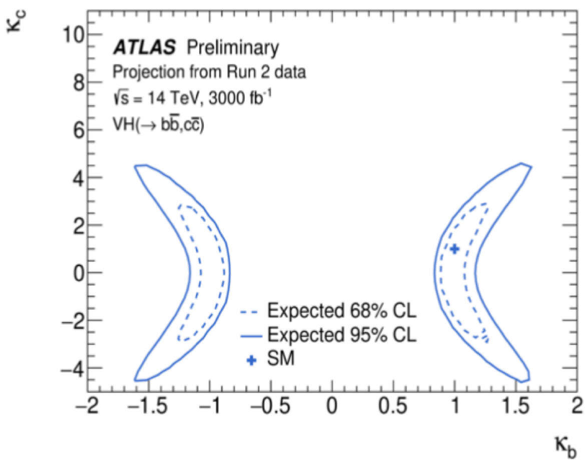
Higgs Couplings: HL-LHC New Projections

- H→μμ
  - YR projections performed from partial Run2 dataset analyses Full Run2 measurements have improved beyond expectations
  - i.e. H→ττ or H→bb improved as ~sqrt(L) despite being dominated by systematic uncertainties



- H→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_TH > 300 GeV
  - Direct measurement of the Higgs coupling to the charm is within reach at the HL-LHC!





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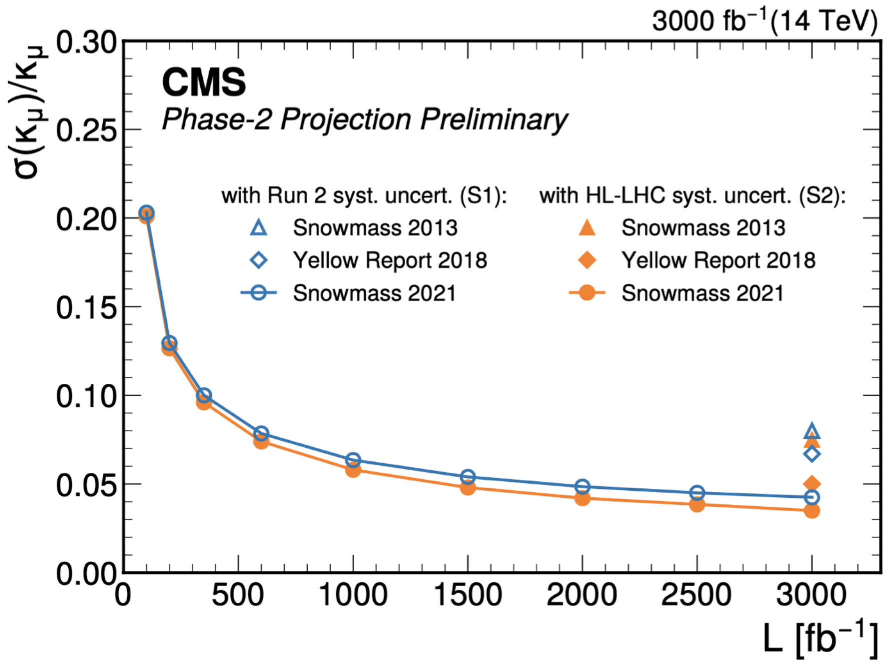

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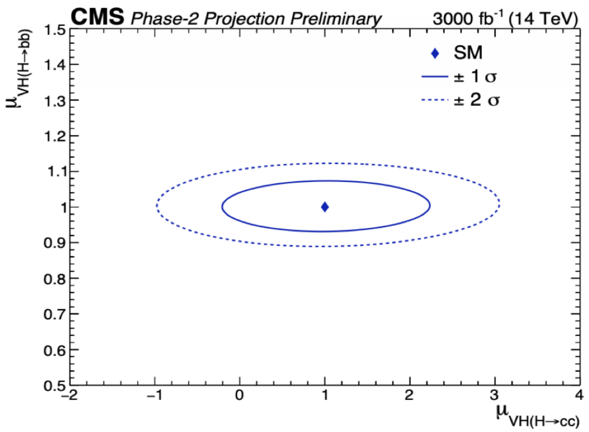
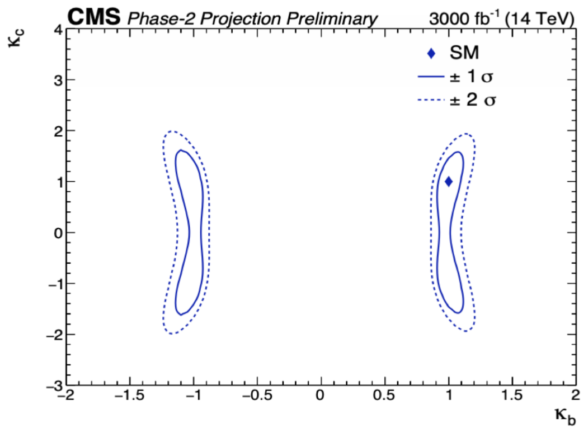
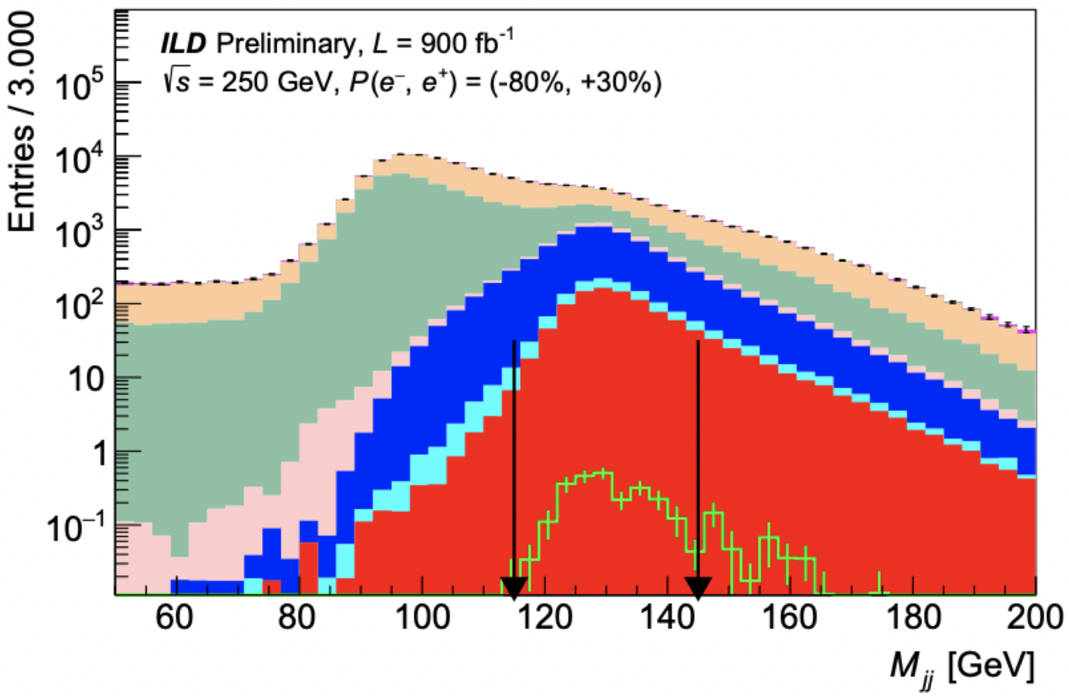
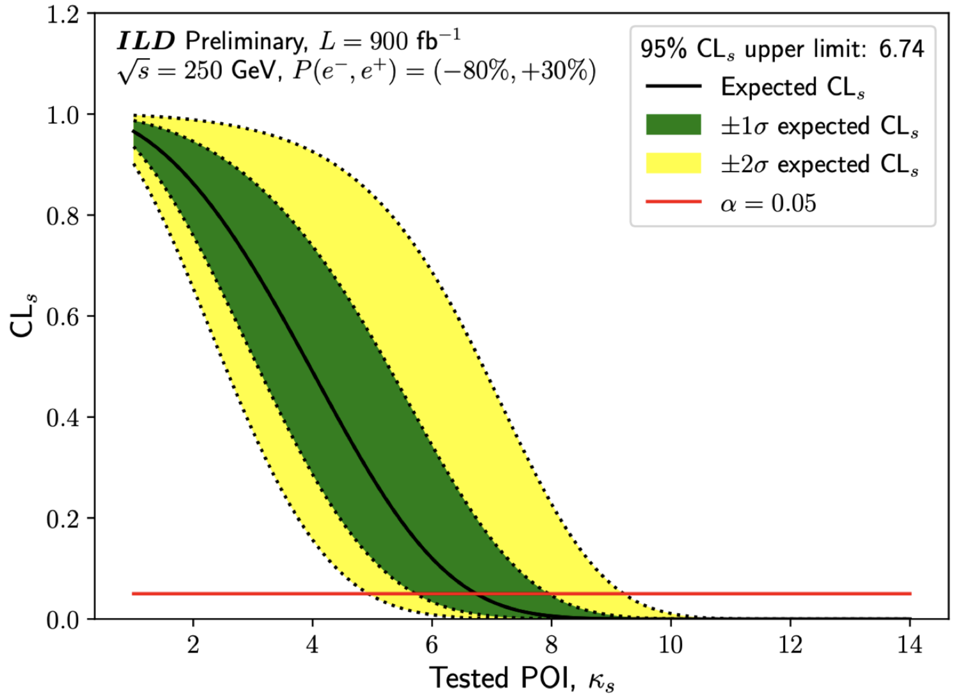




H to strange coupling

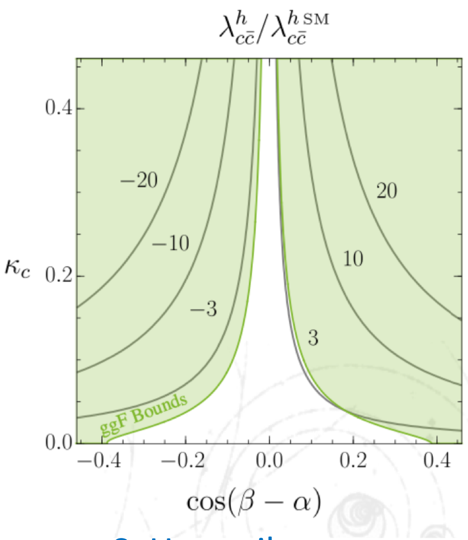
- Exploring ZH with Z going to leptons or neutrinos
- Combined limit of $\kappa_s < 6.74$ at 95% CL with 900/fb at 250 GeV (i.e. half dataset)



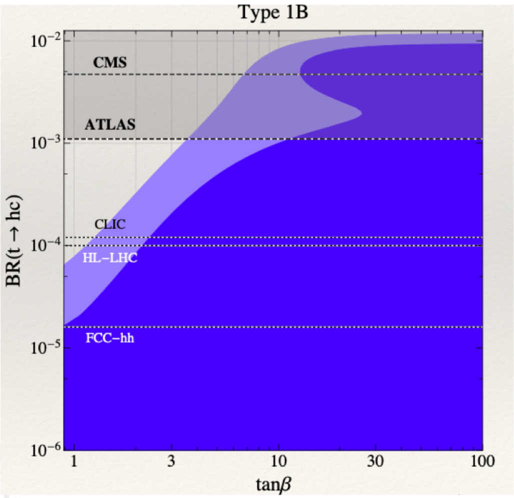


Higgs boson as a portal to new physics

Higgs and Flavor

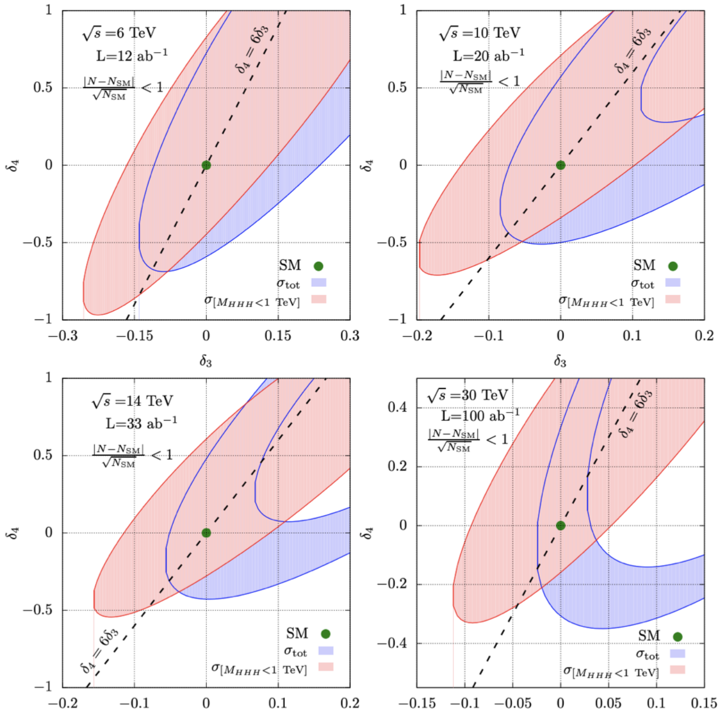


S. Hommiler



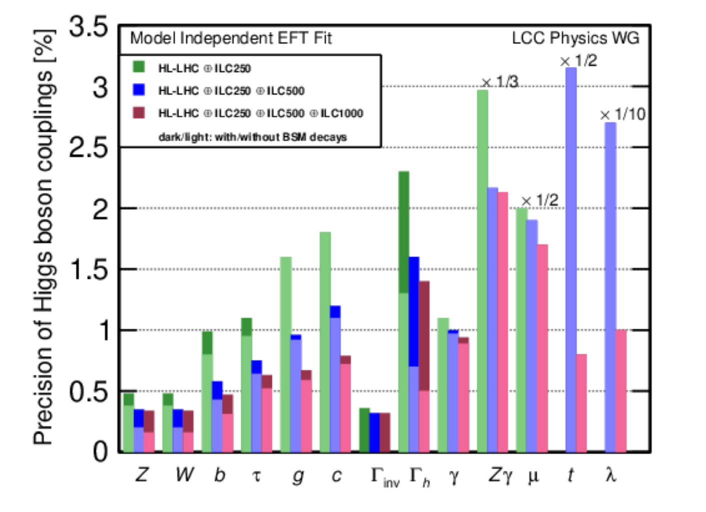
D. Tuckler

Higgs Quartic and Beyond



M. Chiesa, arXiv:2003.13628

Global Fits



arXiv:2004.14628

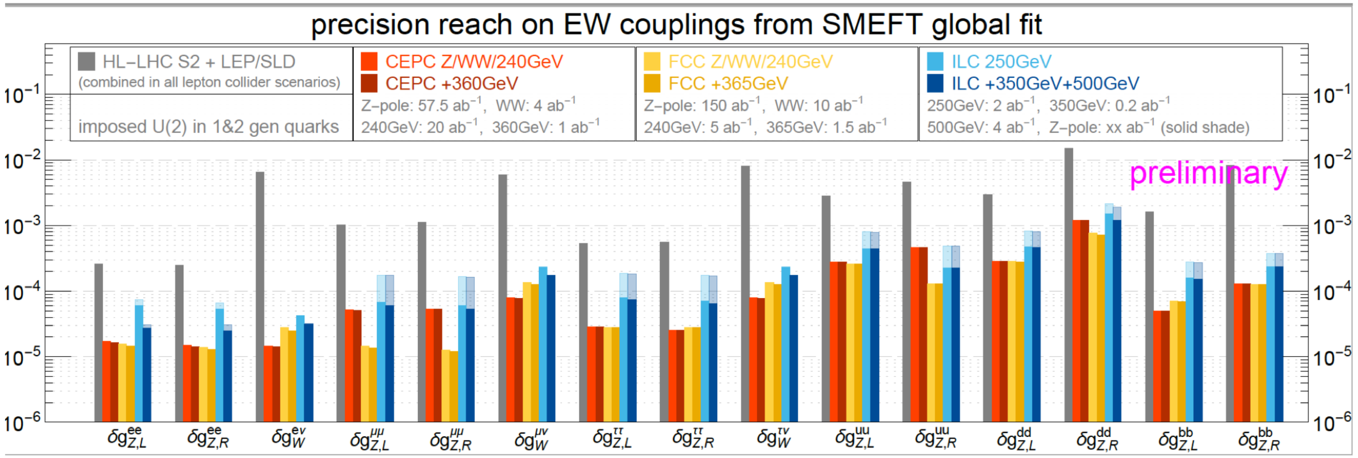
Recent Discussions: Higgs+X couplings, BSM Higgs complementarity with other frontiers.

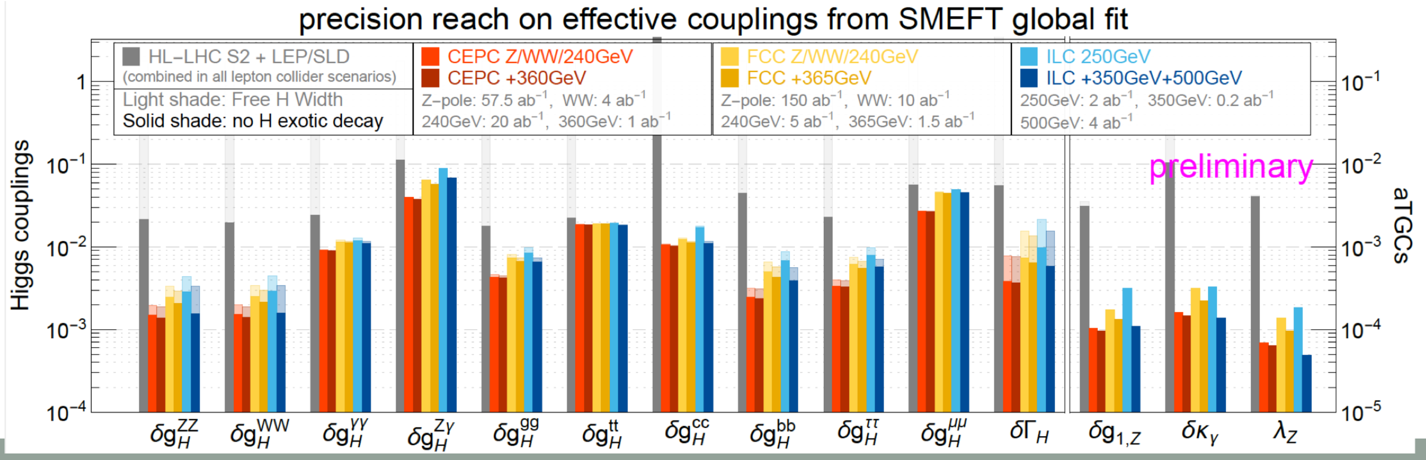
EW precision physics and constraining New Physics

Global SMEFT Fit Team:

New effort, with ultimate goal being a **concrete realization of global Higgs/EW/top fit**. For Snowmass 2021, the global EFT fit for ESG has been extended in a few directions:

- consistent implementation of full EFT treatment in e+e- → WW using optimal observables;
- new inclusion of a large set of 4-fermion operators;
- more complete set of operators that are related to top-quark.
- The projections of the uncertainties for various future e+e- colliders are made to be as consistent as possible, for instance: by applying common systematic errors; by extrapolating from one collider to another whenever there is any important missing input.





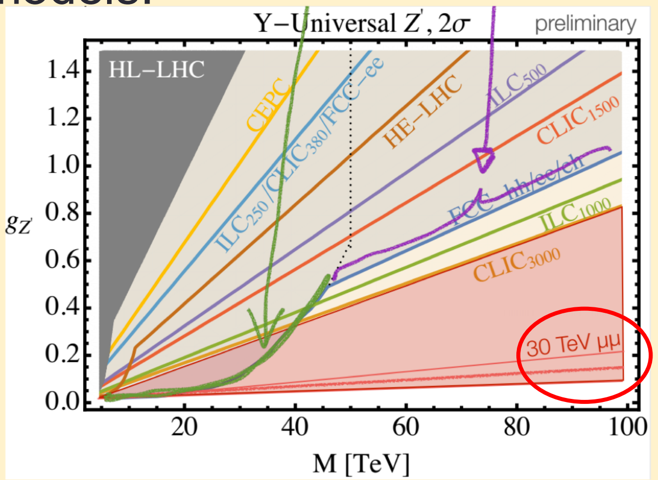
BSM general explorations

Identify important benchmarks, explore new collider options, focus on the physics messages

Heavy Bosons

Identified simplified models:

- Dilepton
- Dijets
- Diboson (VV, Vh, etc)
- Decays including Heavy Neutrinos



Layout the basic reach of future collider programs **comprehensively** in these simplified modes.

Resonance search and EFT searches are both needed.

Future Colliders ordered by Z' sensitivity

Machine	Type	√s (TeV)	∫L dt (ab⁻¹)	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \to$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \to l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \to l^+ l^-$	--	6.8
				EPPSU*	$Z'_{Univ}(g_{z}'=0.2)$	--	6
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \to f^+ f^-$	4.9	7.7
				EPPSU*	$Z'_{Univ}(g_{z}'=0.2)$	--	7
HE-LHC/ FNAL-SF	p p	27	15	EPPSU*	$Z'_{Univ}(g_{z}'=0.2)$	--	11
				ATLAS	$Z'_{SSM} \to e^+ e^-$	12.8	12.8
ILC	$e^+ e^-$	0.5	4	ILC	$Z'_{SSM} \to f^+ f^-$	8.3	13
				EPPSU*	$Z'_{Univ}(g_{z}'=0.2)$	--	13
CLIC	$e^+ e^-$	1.5	2.5	EPPSU*	$Z'_{Univ}(g_{z}'=0.2)$	--	19
Muon Collider	$\mu^+ \mu^-$	3	1	IMCC	$Z'_{Univ}(g_{z}'=0.2)$	10	20
ILC	$e^+ e^-$	1	8	ILC	$Z'_{SSM} \to f^+ f^-$	14	22
				EPPSU*	$Z'_{Univ}(g_{z}'=0.2)$	--	21
CLIC	$e^+ e^-$	3	5	EPPSU*	$Z'_{Univ}(g_{z}'=0.2)$	--	24
FCC-hh	p p	100	30	R.H.	$Z'_{SSM} \to$ dijet	25	32
				EPPSU*	$Z'_{Univ}(g_{z}'=0.2)$	--	35
				EPPSU	$Z'_{SSM} \to l^+ l^-$	43	43
Muon Collider	$\mu^+ \mu^-$	10	10	IMCC	$Z'_{Univ}(g_{z}'=0.2)$	42	70
VLHC	p p	300	100	R.H.	$Z'_{SSM} \to$ dijet	67	87
Coll. In the Sea	p p	500	100	R.H.	$Z'_{SSM} \to$ dijet	96	130

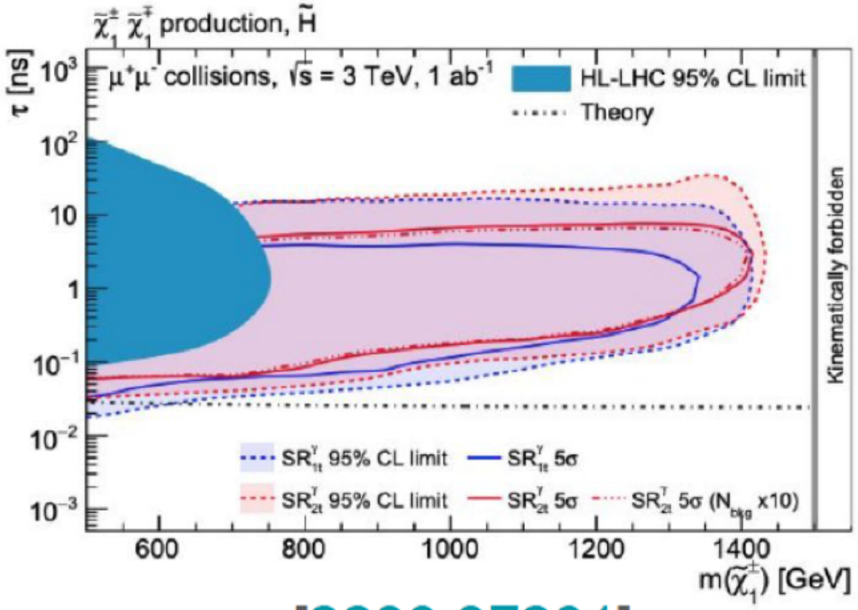
Increasing Z' Sensitivity

Future Colliders: Heavy Long Lived Particles

Strong community interest in LLPs, predicted by many BSM models, including Higgs Portals.

- Important for both HL-LHC as well as future colliders
- Well-defined benchmarks to compare the reach
    - Colored LLP: gluino, mini-split SUSY; Non-colored LLP: Higgsino, GMSB; Higgs portal : Higgs to LLPs, neutral naturalness; Disappearing Track : Higgsino reach and Wino reach
- Signature-driven arguments to highlight different environments and opportunities

Muon collider, Disappearing Track



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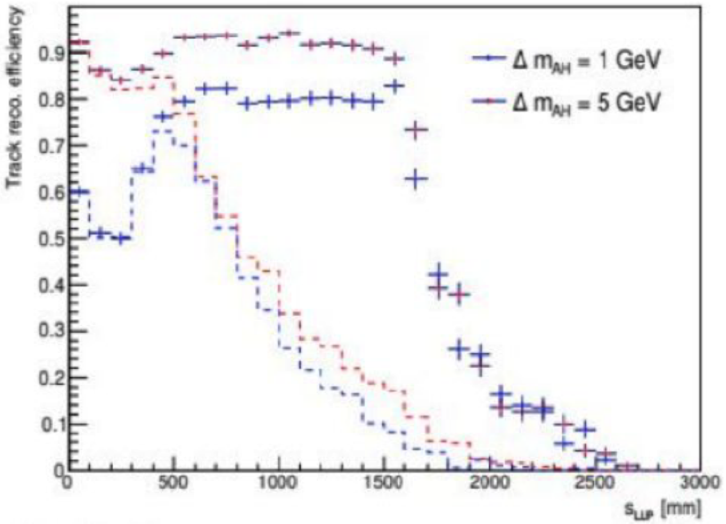
ILC, Heavy scalar decays



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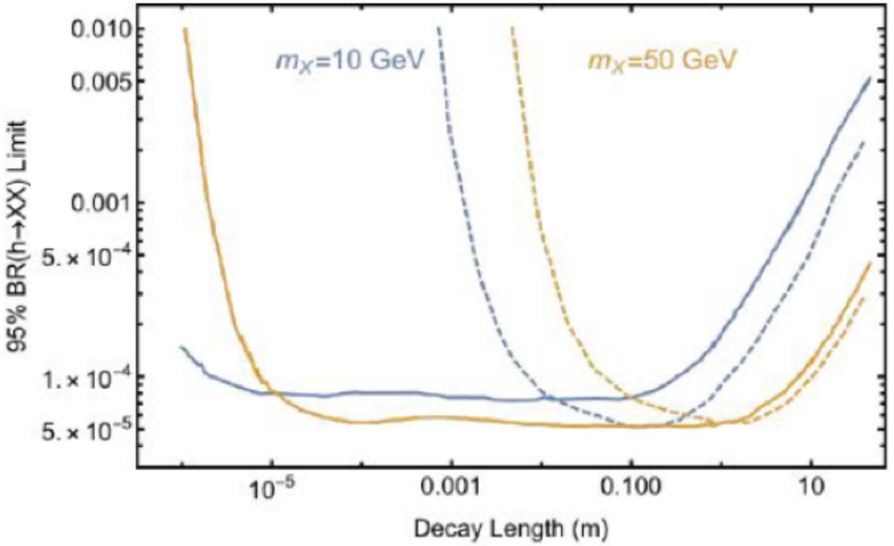
FCC-ee, Exotic Higgs decays



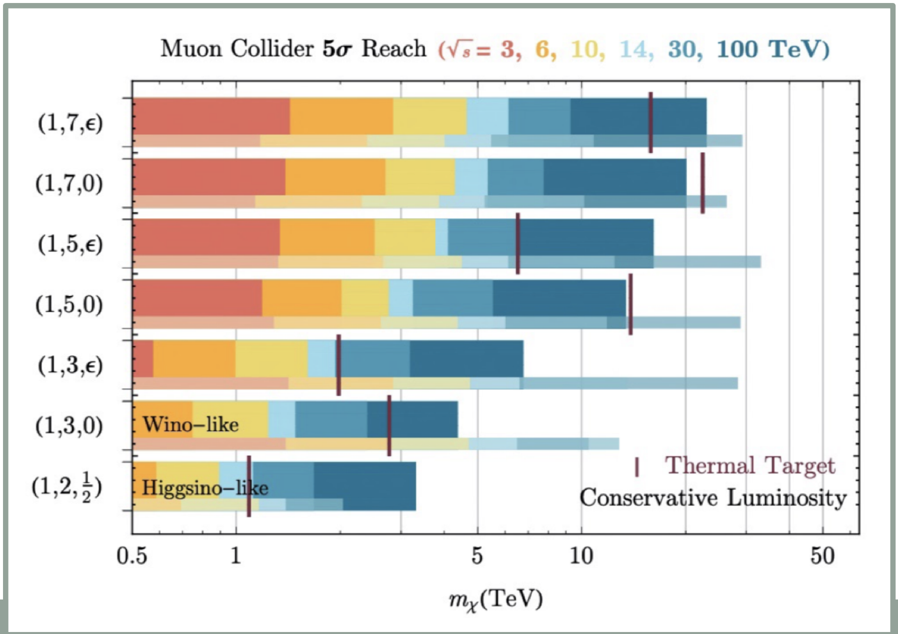
[2203.05502]

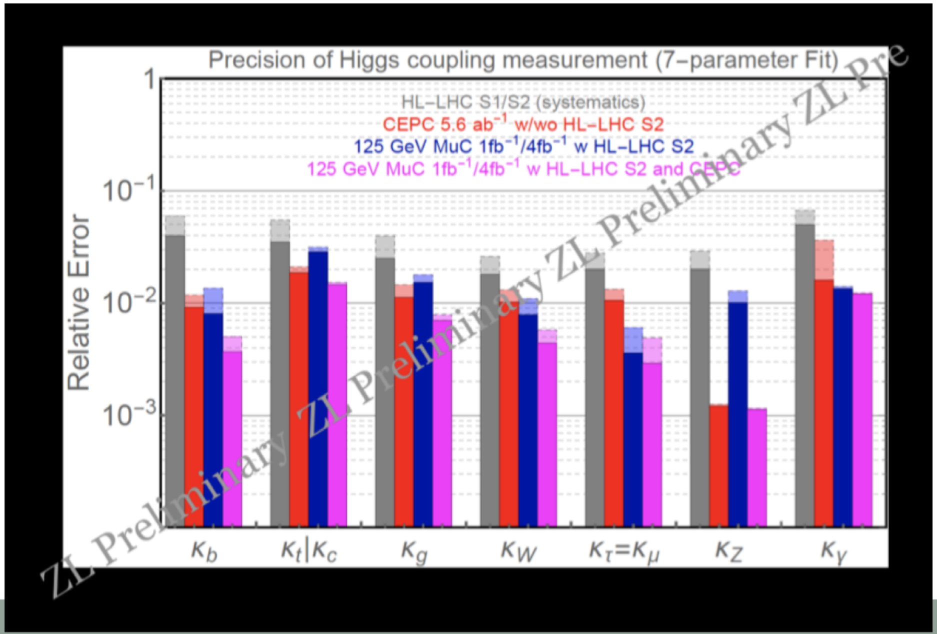
Dark Matter at colliders

- Most active areas:
- Snowmass Dark Showers group (joint with EF09)
  - Very general motivation: understand LHC signatures when varying theory parameters (Nc, flavor, etc.)
  - Organized a tutorial/workshop with experts during the Long Lived Particles Community Workshop
  - Contribute Paper in preparation (see outline here):
- WIMPs at muon colliders
  - There have been several studies on the search for WIMP dark matter (focusing on the so called Minimal Dark Matter scenario) at muon collider (with various energy and luminosity options), as well as a few more on-going work.
  - While it may not be as complete as the study for the 100 TeV pp collider for the briefing book, a set of basic results are available now to paint a big picture on this topic.
- WIMPs and lighter DM at hadron/lepton colliders → see also next slide
  - Some of our main contributors graduated, some are back as PhD students starting in September, some are new
  - One of the postdoc leaders of whitepaper also moving on to new jobs (!colliders) but want to keep contributing once Snowmass restarts
  - Organizers have been asked to give a talk in EF10 parallel session
- New Wino/Higgsino studies with monojet signature ongoing

Muon Colliders: Physics Highlights

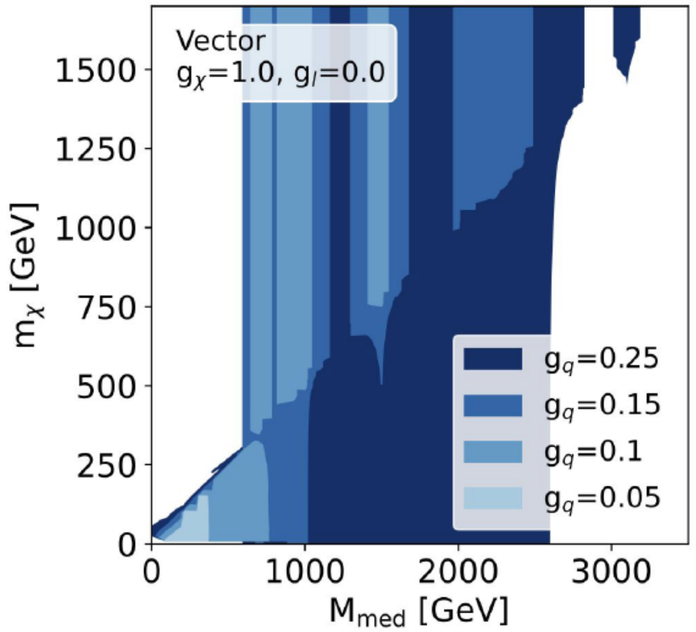
- High energy muon collider (6-10 TeV and above) has an incredible physics reach:
  - Precision Standard Model studies (including detailed exploration of the Higgs boson)
  - Access to trilinear and quartic (at higher energies) Higgs couplings
  - Searches for BSM with sensitivity way beyond what is achievable at the LHC and similar to FCC-hh
- Does 125 GeV Higgs Factory make sense as a staging option?
  - Improved luminosity projections with new technology advancements → translates into better physics
  - Small footprint and modest cost (tbd), physics while the multi-TeV ring is being built, reuse the injection complex





Simplified Model Coupling Scan

- Coupling scan necessary to extend current benchmarks for DM simplified models used for e.g. European Strategy (& ATLAS+CMS), where DM simplified models have couplings o(1)
- Goal: explore coupling scenarios systematically and efficiently to connect to other experiments / show effect of varying couplings
  - Efficiently: analytical rescaling of existing constraints rather than generate more MCs for different couplings
- Focus of Snowmass whitepaper:
  - A reference document defining the rescaling method for dijet / monojet + possible refinements (e.g. PDF weights, complex modelling of propagators…)
  - Cover different topologies, monojet, dijet, dilepton searches
  - Provide Python code for different users with summary plots as a final goal



Dijet + monophoton constraints from LHC data as example

COMMUNITY INPUT TO THE ENERGY FRONTIER REPORT

Started the process of inviting the community to share their vision for the EF at the end of EF workshop March/April 2022

[you are welcome to add to the linked google doc]

Energy Frontier Vision – the ultimate goal

- The discovery of the Higgs boson has made the standard model as "complete" as it is going to get - a tremendous achievement
- However, this also brings into focus that there are many questions that the standard model does not answer
  - Gravity
  - Dark energy
  - Dark matter
  - Matter – antimatter uncertainty
  - Hierarchy/naturalness problem

- Our vision must keep its focus on these big questions.
- Whatever the details of the vision are, it must enable us to continue to attack these questions from as many angles as possible
- Ultimately, this means that we must find a way to carry out experiments at energy scales far beyond those achievable today – 10 TeV, 100 TeV, more

Energy Frontier Vision – the immediate future

- The EF currently has a vigorous top notch program with the LHC at CERN.
- We are looking forward to Run 3 of the LHC. It will double the integrated luminosity collected at 13+ TeV by the LHC experiments.
- The high-luminosity LHC is scheduled to start operation in 2026+ and increase the integrated luminosity by another factor if 5 over the following decade. It will set the basis for any vision of the future of the EF program.
- The US is heavily involved in ATLAS and CMS (and LHCb, Alice) and contributes to aspects of the LHC accelerator infrastructure.
  - *More than half of the US HEP community are involved in LHC. Over the last years, US institutions have graduated ~100 PhDs/year based on research carried out based on LHC data.*

- Our highest immediate priority therefore has to be the HL-LHC, the successful completion of the upgrades, data taking and analysis.

Energy Frontier Vision – the intermediate future

- **What comes after the LHC?**
- The LHC has given us the Higgs boson, an obvious lamppost that must be examined closer
- Studying the Higgs boson, measuring its properties with the highest possible precision, may give us hints how we need to extend the standard model to explain some of these big questions.
- WW scattering, the top threshold, the W mass are other possible ways to improve the precision of our understanding of the standard model
- Such a program is possible essentially with today's technology

- e+e- colliders are the vehicle that will enable a program of ewk measurements that will increase the precision of our measurements by orders of magnitude.

Energy Frontier Vision – enabling the far future

- We do not have the technology today to reach our ultimate goal
- We therefore have to set aside sufficient funding to enable a vigorous R&D program into all the technologies that may allow us to do so, including hadron and muon colliders.
- This R&D program has to also enable instrumentation research that goes beyond current projects so that the detector technology will be available to make use of these high energy colliders once they can be built

- This R&D has to start now and run in parallel of the HL-LHC and any e+e- precision ewk program.

DRAFT Community input

Energy Frontier Vision – it has to be broad based

- CERN as host of the LHC has been the focus of EF activities for the past couple of decades
- Our vision for the EF can only be realized as a world wide program. In order for scientists from all over the world to buy into the program, it has to be sited all over the world.
- **Continue to work with international community on detector designs and develop extensive R&D programs, including the FCC program.**
  - *To realize this, we need DOE and NSF to fund R&D program focused on participation of the US community in future collider efforts as partners [currently this is severely lagging behind].*
- The community also aspires the possibility to bring a future experimental EF facility to the US.
  - for example linear e+e- if Japan or CERN do not pursue it.
  - i.e. be prepared to site a future linear e+e- collider in US in case other sites decided not to host an e+e- collider option, or muon collider in a long run, or a small scale circular e+e- (FNAL site filler) on a short time scale.
- Proceeding in multiple parallel prongs may allow us to build the next machine sooner.
- The community feels that there is potential to raise funds and get government buy-in for a future collider project located in the US.
- It will inspire more young people from the US
- Therefore there are requests to also cost include the siting of various e+e- options in the US, as a backup plan.

Energy Frontier Vision – it has to be inspiring

- Realizing our ultimate goal will require significant funding and government support

- However, funding is not all that is needed – we also need a program that inspires the next generation of high energy physicists and that entices the next generation of graduate students to choose high energy physics as their field

- Bold “new” projects such as a muon collider will offer the next generation some challenges to rise to

Energy Frontier Vision – Summary

- Immediate future → successful implementation of the HL-LHC program
- Intermediate future → precision ewk program
  - Based on e+e- colliders
  - Work with international sites on detector designs and develop extensive R&D programs.
    - In addition, be prepared to site in US as a backup option.
- Far future → Collider to directly
  - access energies of 100 TeV or higher, high energy lepton colliders, muon colliders
  - Fund vigorous R&D program towards the technology to reach much higher energies
  - Pursue inspiring new ideas to reach our ultimate goal

Snowmass Community Summer Study Workshop

- Please join us !
- July 17-26, 2022 at the University of Washington, Seattle
- http://seattlesnowmass2021.net/
- Registration: http://seattlesnowmass2021.net/registration/

Day (times)	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7	Session 8	Session 9	Session 10	Session 11	Session 12	Session 13	Session 14
7-18 8am – 11:30am	AF AF2-5 (19G) (30 ppl)	AF AFx Internal (19H) (20 ppl)	Discussion (18I) / Discussion (18P) / Discussion (18S) / Discussion (18T)	CompF Experimental Algorithm Parallelization (20G) (20 ppl) / CompF CompF2 Theoretical Calculations and SImulation (20V) (20 ppl)	EF Higgs and BSM I (18K) (HUB 332 - 100 ppl)	EF Strong Interactions I (18L) (KNE 220 - 100 ppl)	IF IF1 (23H) (20 ppl)	IF IF2 (23G) (20 ppl)	IF IF5 (23D) (20 ppl)	NF All-Frontier (18N) (KNE 130 - 300 ppl)	XF CEF-EF-NF-RF-CF-TF-AF-IF-CompF-UF CEF Feedback (18A) (HUB 340 - 70 ppl)			
7-19 7:30am – 11:30am	AF AAF6 and AF1 Internal (19E) (30 ppl)	AF AF3 and AF4 Internal (19F) (20 ppl)	CEF Frontier Discussion (21D) (KNE 210 - 50 ppl)	CF CF3 Discussion (18H) / CF CF6 Discussion (18O) / Discussion (18R) / CF CF4 CF5 CF6 CF7 Dark Energy Complementarity	CompF CompF3 Machine Learning (20F) (20 ppl) / CompF CompF4 Storage and Processing Resource Areas (20U) (20 ppl)	IF IF10 (23E) (20 ppl)	IF IF3 (23F) (20 ppl)	IF IF4 (23E) (20 ppl)	IF IF6 (23C) (20 ppl)	NF DUNE FS Strategy (Oscillation Physics) (20N) (KNE 130 - 150 ppl) / NF DUNE FS Strategy (BSM Physics) (20X) (KNE 110 - 150 ppl)	RF RF1 Discussions (20C) (40 ppl) / RF RF2 Discussions (20S) (40 ppl)	UF UF2 (19B) (25 ppl) / XF UF-NF-RF 0nuBB from Natural Sources (19A) (JHN 102 - 50 ppl)	XF CF-EF-RF-TF CF1 CF2 CF3 CF7 DM Complementarity (20L) (KNE 220 - 150 ppl)	XF TF-EF Energy Frontier Theory (19J) (JHN 175 - 50 ppl)
7-20 7:30am – 11:30am	AF AF2 and AF5 Internal (19D) (20 ppl)	AF AF7 (19C) (30 ppl)	CF Report Discussion (23Q) (KNE 130 - 300 ppl)	CompF CompF5 End User Analysis (20E) (20 ppl) / CompF CompF6 Quantum Computing (20T) (20 ppl)	EF BSM II - non DM (19O) (KNE 210 - 100 ppl) / NF DUNE FS Strategy (Expanded Physics Scope in Phase II) (20Y)	EF EWK I (19N) (KNE 120 - 100 ppl)	EF TOP I (19M) (KNE 220 - 100 ppl)	IF Workshop Plans (HUB 250 - 100 ppl)	NF DUNE FS Strategy (Detector Technology) (20O) (JHN 102 - 150 ppl) / RF RF7 Exp and Theory Overview - Hadron Spectroscopy (20R) (40 ppl)	RF RF6 5 Big Idea + 1 Experimental Summary White Papers (20B) (40 / XF NF-AF Accelerator neutrino sources/cross-cutting issues (40	TF TF9-TF11 (18C) (HUB 337 - 50 ppl)	UF UF1 (18B) (25 ppl) / XF UF-NF Long Baseline (18Q) (40 ppl)		
7-21 7:30am – 11:30am	AF AF2 and AF5 Reports (24L) (JHN 102 - 100 ppl)	AF AF7 Internal (24K) (JHN 175 - 70 ppl)	CF Report Discussion (24M) (KNE 120 - 200 ppl)	EF EWK II (21P) (KNE 210 - 100 ppl)	IF IF7 (24G) (20 ppl)	NF Beyond neutrino mass physics reach of precision beta-decay experiments (21K) (20 ppl)	NF Blue Sky/Very Long Term ideas (21M) (30 ppl)	TF TF2-TF5 (18D) (JHN 111 - 50 ppl)	XF EF-CompF EF Centric Discussions (18X) (40 ppl) / EF DM Discussion (21N) (KNE 110 - 100 ppl)	XF IF-EF-AF-IF Detectors and MDI and Plots (21I) (40 ppl)	XF RF-EF-TF RF1 Flavor anomalies and exotics at colliders (22A) / XF IF-RF-EF Focus on timing and more generally tracking detectors (21J) (HUB 340	XF UF-IF QIS (22F) (HUB 337 - 50 ppl) / XF RF-CF RF1 large-volume data analysis and simulation and usage of HPC in	XF RF-EF-AF RF5 to discuss CLFV and heavy states (24O) (HUB 340 - 50 ppl)	
7-22 7:30am – 11:30am	AF AFx Internal (24H) (JHN 111 - 50 ppl)	AF AFx Internal (24I) (HUB 250 - 70 ppl)	AF P5 Strategy accel for neutrinos and PBC (24J) (HUB 332 - 70 ppl)	CompF Report Discussion (200 ppl) / CompF CompF7 Reinterpretation and long-term preservation of data and code	EF BSM IV (23N) (JHN 102 - 100 ppl) / RF RF5 Discussions (21R) (40 ppl)	EF Top II (23O) (KNE 210 - 100 ppl)	IF IF8 (24F) (20 ppl)	IF IF9 (24E) (20 ppl)	NF Optimizing Among Funding Agencies (21L) (30 ppl) / UF UF5 UF3 (22Q) (25 ppl)	RF RF3 Discussions (21B) (40 ppl) / XF EF-AF combined EF/AF report discussion (21V) (30 ppl)	TF TF4b-TF6-TF7 (18F) (HUB 337 - 50 ppl)	XF AF-EF Accelerator R&D Overseas (22G) (40 ppl) / XF RF-EF-TF RF7 EF6-EF7 hadrons as production probes; production	XF NF-EF Cross-cutting issues (22H) (30 ppl) / CompF Industry Session (JHN 175 - 50 ppl)	
7-23 7:30am – 11:30am	AF AF7 Reports (24C) (JHN 175 - 70 ppl)	AF AFx Internal (18M) (KNE 110 - 150 ppl) / IF Report (KNE 110 - 100 ppl)	EF Discussion and Summaries (24N) (KNE 130 - 300 ppl)	NF Early Career Presentations (Topic 1) (20I) (30 ppl)	NF Early Career Presentations (Topic 2) (20K) (JHN 102 - 60 ppl)	RF All-Frontier Discussions (23Y) (KNE 220 - 140 ppl)	TF TF1-TF3-TF4a (18G) (30 ppl)	TF TF8-TF10 (18E) (JHN 111 - 50 ppl)	XF IF-CF-CompF Instrumentation for Cosmic Frontier (21H) (30 ppl)	XF IF-CompF readout and AI/ML (21E) (JHN 175 - 40 ppl) / UF UF4 (21C) (25 ppl)	XF IF-NF Instrumentation for Neutrino Experiments (21G) (30 ppl)	XF IF-UF Cross-cutting Facilities (21F) (30 ppl) / XF NF-TF Neutrino theory network (22K) (KNE 110 - 50 ppl)	XF NF-CF-IF Dark matter detector (22J) (KNE 210 - 50 ppl)	XF TF-CF Cosmic Frontier Theory (19K) (KNE 120 - 50 ppl)
7-24 10am – 11:30am	AF AF1 Report (KNE 120 - 150 ppl)	AF Success Stories from AF (22D) (30 ppl)	IF Report (24D) (JHN 102 - 100 ppl)	NF Community Engagement Success Stories (22I) (20 ppl)	NF Early Career Presentations (Topic 3) (20H) (30 ppl)	NF Early Career Presentations (Topic 4) (20J) (JHN 175 - 60 ppl)	TF Discussion and frontier reports (19P) (KNE 220 - 175 ppl)	UF UF6 (23B) (25 ppl)	XF AF-CompF Cross-cutting issues (22E) (JHN 075 - 70 ppl)	XF AF-RF cross-cutting issues (22B) (40 ppl)	XF NF-CF Neutrino mass scale with beta decay kinematics (22C) (30 ppl)	XF NF-CF-TF high energy and ultrahigh energy astrophysical neutrino (22N)	XF RF-IF RF1 Discuss picosecond detectors - fast timing in tracking	XF RF-NF RF5 to discuss CLFV and neutrinos - mu2e and facilities (24A) (30 ppl)

DRAFT SCHEDULE
For CSS@Seattle
For mornings!

Pink boxes=EF
Blue boxes = AF
White boxes = XF

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 is to facilitate a comprehensive international program for US participation in future colliders that welcomes all with know-how and interest, and at all levels of innovation and R&D

- Give us input on your Vision for the EF in the document
  - Please note that the intent of this document is to understand collectively the interests of the community, and not the priorities for various projects [which is the task of P5].