Energy Frontier
Activities and Focus Questions

Snowmass Community Planning Meeting, Oct 5-8, 2020

Laura Reina (FSU)
Meenakshi Narain (Brown U.)
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DPF Core Principles and Community Guidelines (CP&CG)

- By participating in this meeting, you agree to adhere to the CP&CG
  - **Respect and support community members**
  - **Commit to constructive dialogue and take initiative**
  - Details of what this means, expectations for behavior, and accountability procedures are provided in the CP&CG document linked at: https://snowmass21.org/cpcg/start

- Everyone is invited to invoke the CP&CG as needed to encourage constructive and supportive collaboration

- The conveners of this meeting are your recommended first point of contact for reports of CP&CG violations occurring here
  - The conveners have received training in the CP&CG and how to handle reports
  - The CP&CG accountability procedure is designed to encourage early intervention and is flexible enough to appropriately address issues ranging from the discourteous to the egregious
  - Please do not hesitate to contact us! (EF and EF TG convenors)

- Snowmass is most successful when everyone's voice can be heard!

APS Code of Conduct

Slack and Q&A

- For **Discussions** related to topics presented in this session (*EF Intro*) and next EF session (*EF Planning, Wed Oct 7*) you are welcome to use the dedicated **Slack channels** – Slack channel name is also reported in session title
  - `#cpm_ef_intro` ← **THIS Session**
  - `#cpm_ef_planning` ← **Wed. Oct 7 '*EF Planning*' Session**

- For **Questions to speakers** in both sessions

  ➔ **use '*raise hand*' feature in Zoom**

Energy Frontier: exploring the TeV scale

Snowmass 2021: a very exciting time

- LHC **Run 2** is providing a wealth of new measurements.
- Entering the era of **precision Higgs physics**.
- The **HL-LHC is a reality**.
- **Updated scenario of proposed future colliders**.
- Exciting results from other frontiers: rare processes, cosmology, …

...and we have no preferred way beyond the SM:

$\Rightarrow$ Great time to **propose new ideas, new perspectives, new tools.**

Our vision for the future of the Energy Frontier

- **The future of the Energy Frontier in the U.S and internationally is up to us!**
- **Snowmass is a scientific study,** it provides *an opportunity for the entire particle physics community to define the most important questions* for our field and to *identify promising opportunities to address these questions in a global context*.
- **The Energy Frontier (EF) group at Snowmass will explore the TeV energy scale and beyond**, under different future accelerator scenarios, including lepton-lepton, hadron-hadron, and lepton-hadron colliders.
- **Sharp physics questions will bring focus to issues pertaining to EF future directions**
  - *Re-evaluate existing ideas* and emphasize how existing work can lead to new ideas (for example HL-LHC results may shape future colliders)
  - Identify *new ideas*
  - Highlight "*scientific merit*" of *various collider options* and *connections with other Frontiers*
  - Starting point for the Final Report (Summer 2021).

Big Picture Questions

- Why is physics at the energy frontier important?
- *How should the US be involved in near future and far future energy-frontier machines after the HL-LHC?*
- What could be the energy-frontier machines that follow the HL-LHC?
- *How can the US continue to play a leadership role in energy-frontier experiments?*
- *How can the Snowmass process help develop a plan* for the energy-frontier research and convince the community about our priorities?
- *Should we start entertaining the idea of a future collider in the US again?* If so, what are our goals, the benefits for the US and the international community, and how can we get there?
- etc...

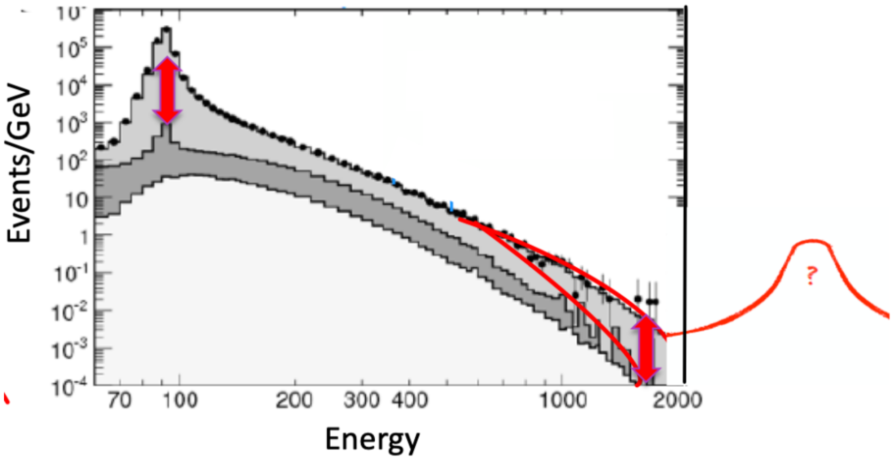
- These questions were discussed in the Panel: **"The importance of the Energy Frontier in the US HEP future planning"** at the "Energy Frontier Workshop - Open Questions and New Ideas", July 20-22, 2020
  - By Jorgen D'Hondt, Nima Arkani-Hamed, Sarah Eno, Vladimir Shiltsev, Xinchou Lou, Young-Kee Kim
  - See Zoom recording of Panel Discussion

Developing Focus Questions

- A plethora of studies for physics sensitivities for various future colliders exist in various CDRs and TDRs etc.
  - These studies serve as a baseline for us.
  - We want to focus on *“open questions”* which are identified by these studies.
- *New ideas* are welcome! We need to make the case stronger.
- *Defining baselines* is a guidance for where to start, and connect with the studies which already exist.
  - Accelerator baselines
  - Instrumentation baselines
  - Understand Computational needs
  - However, if the sensitivities for physics scenarios can improve considerably with some change in the machine parameter, or the detector design, we should consider them!
- **Snowmass is our time to innovate and set new directions without barriers and constraints set by our collaborations.**

Higgs, Top, Electroweak sectors

- What is the scale of New Physics that can be probed with precision measurements?
  - *Precision needed in SM Higgs measurements* to probe BSM physics scenarios?
  - *What theory calculations are needed* to enable the theory precision to match the projected experimental precision of future measurements?

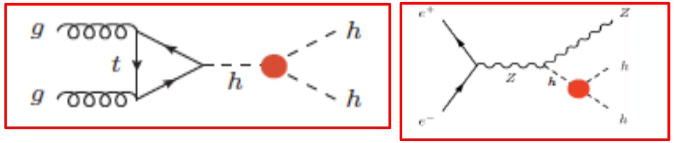


- Energy: direct access to new resonances
- Precision: indirect evidence of deviations at low and high energy.

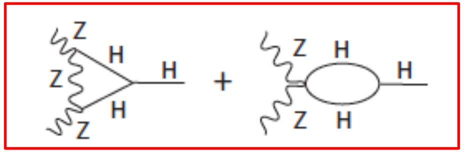
Higgs, Top, Electroweak sectors

- How can measurements in the Higgs sector be *combined with precision measurements in other sectors* to improve our understanding of high scale physics?
    - Higgs + EW + top precision fits
- Does the Higgs boson result from the *scalar potential of the Standard Model*?
- How to improve *double Higgs and single Higgs* production measurements to better probe the potential?
- What experiments allow Yukawa couplings, λ_3 and λ_4 measurements with greatest precision?

Double Higgs production



Single Higgs extraction via loop corrections



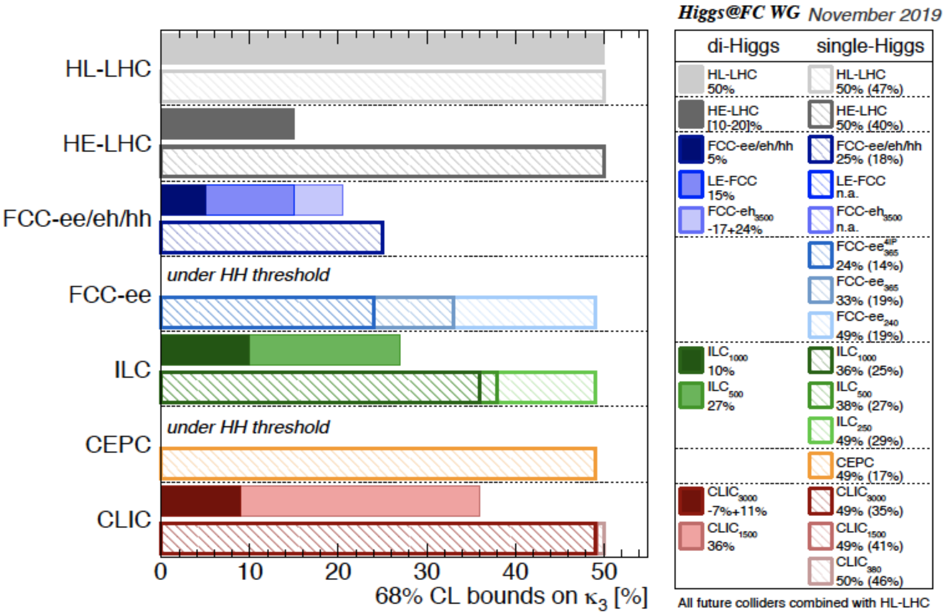
Precision Needed in Higgs Self-Coupling

ArXiv:1910.00012

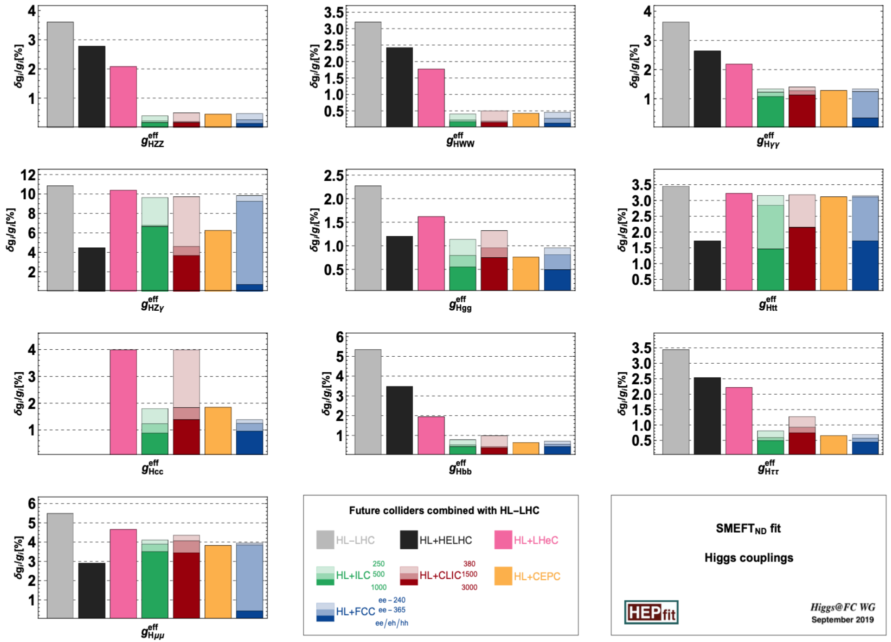
100%: sensitivity to models with largest new physics effects (few hundred GeV masses)
50%: establish that $\lambda_3 \neq 0$ at 95%CL *(expected HL-LHC reach)*
25-50%: sensitivity to mixing of Higgs boson with a heavy (1 TeV) scalar
1-10%: sensitivity to loop diagrams effects (e.g. light stop) and quantum corrections to Higgs potential

Higgs Couplings

Projected precision of λ_3 measurements



Coupling interpretations of precision Higgs measurements



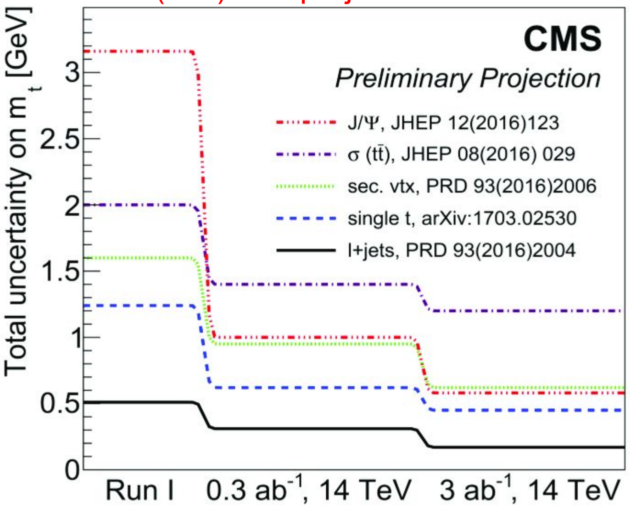
- Future colliders under consideration will improve the understanding of the Higgs boson couplings wrt HL-LHC - 0.5 - few% and λ_3 to the 5-10% level

Higgs, Top, Electroweak sectors

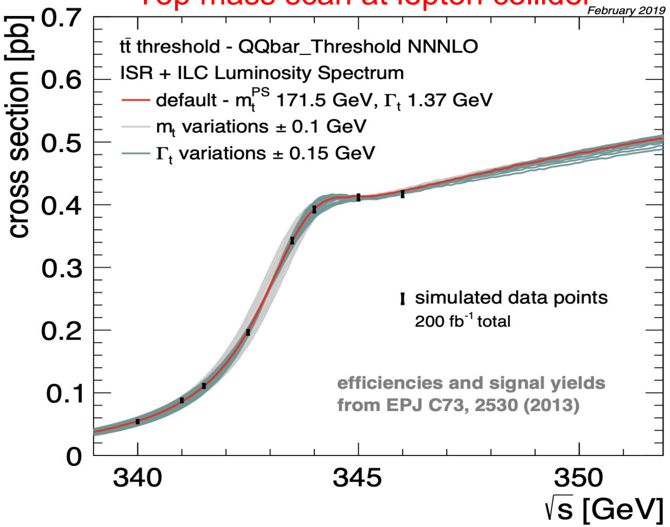
- How can the *top quark* help elucidate the *Higgs sector* and inform about possible BSM physics?
  - What is achievable/required precision for top-quark properties: m_{top} and *couplings*, *spin correlations*, *asymmetries*, *polarization* in new kinematic regimes
  - How much does it improve the reach of a *global EW precision fit*

(HL-)LHC projections

precision of ~200 MeV



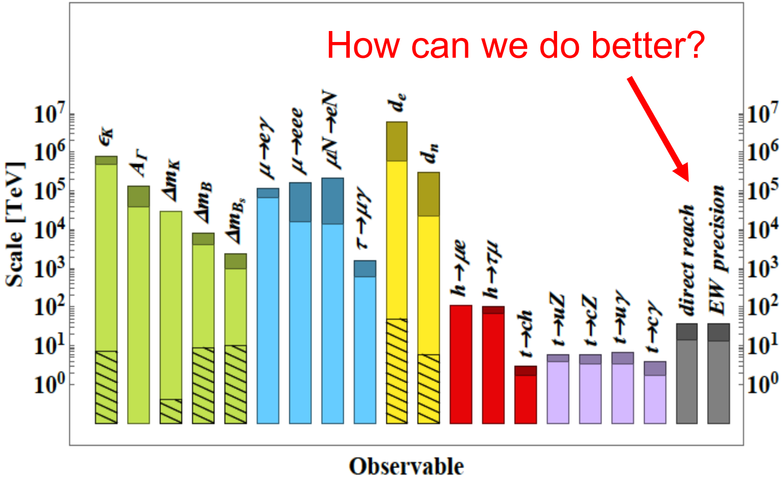
Top mass scan at lepton collider



precision of ~50 MeV

Probing the energy scale for new physics

Probing the energy scale for new physics



Reach in new physics scale from generic dimension 6 operators

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!

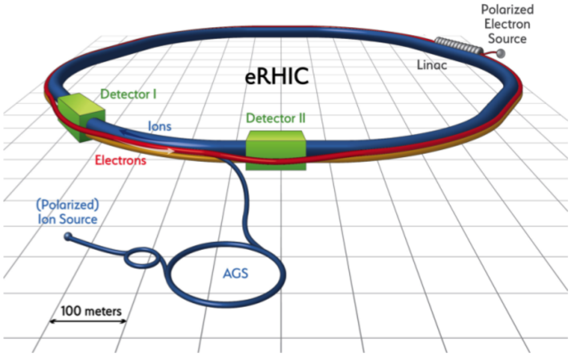
Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

Patrick Meade

QCD and Strong Interactions

- Precision QCD
  - What is the ultimate precision for α_s and how do we achieve it?
  - What theoretical developments are needed to support precision measurements of Higgs and top quark production and properties (including EW corrections, non-perturbative effects)?
  - Jet substructure observables

- Hadronic structure
  - What is the future of PDF determinations?
  - Synergies between EIC, proton PDF fits, and LHC pheno
    - What can the EIC do for proton PDFs?
  - How do *excited hadronic states* with two or more heavy quarks form and decay?
  - What are the *BSM connections for hadron spectroscopy* at future facilities?



QCD and Strong Interactions

- Forward Physics
  - *Prospects of running forward detectors* at the HL-LHC and at future hadron colliders?
  - What will be their *sensitivity to anomalous couplings between photon, W, Z bosons, top quarks*.

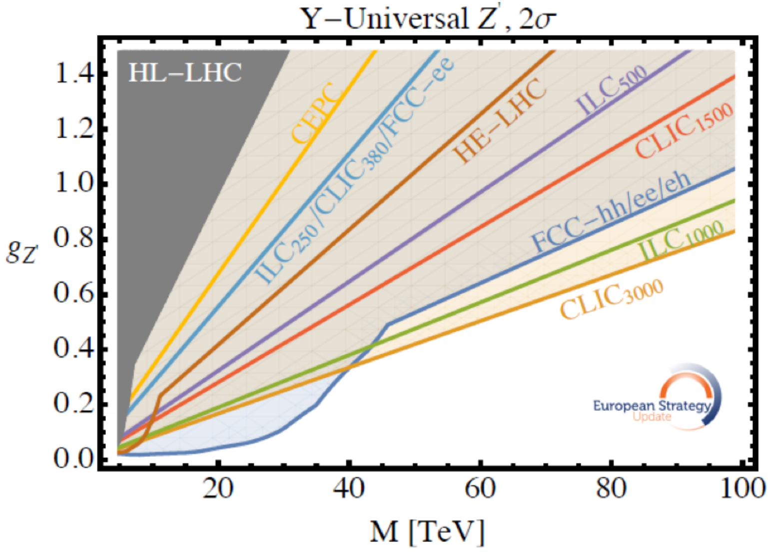
- Heavy Ions
  - What can we learn from *the jet and jet substructure* measurements about the nature of the *quark-gluon plasma*? How do we apply these techniques to studies of jets and the possible jet energy loss in EIC?
  - What is the best use of heavy-ion beams for the *search of new physics*?
  - What are the *heavy quark and quarkonia production mechanisms* in ee, eA, pp, pA and AA collisions?
  - How do we use heavy-ion beam to improve the understanding of *inclusive hadron and charm production*? connection to *new physics search at forward region and the studies of cosmic rays?*

BSM

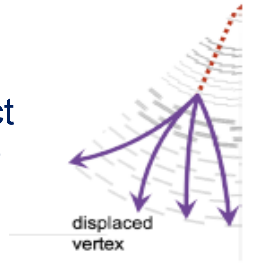
- How can future colliders address the puzzles of Nature to an extent that either *new physics* will appear or a new paradigm of thinking about the *naturalness problem* can emerge?
- What is the additional source of CP violation needed to explain the matter-antimatter asymmetry observed in our universe? How can we address the origin *of matter-antimatter asymmetry of our universe via future colliders*?
- Can the underlying explanation of the *flavor structure of the SM* be probed with existing or future machines?
- What are the best techniques to search for *lepton universality violation*? What do we learn from high energy searches?
- What is the *fundamental composition of Dark Matter*, what are the best ways to probe the composition of DM and whether it interacts weakly?

BSM

Benchmark: simple sequential Z' mode



- Which *BSM models to consider*? What *benchmarks*?
- How to *compare broad model spaces* in a concise and effective way?
  - Simplified models are often used but may not be representative of the full space
  - Compare *inclusivity* of lepton colliders vs *reach* of hadron colliders
  - Compare *direct searches* vs *indirect constraints* from precision measurements
- How to conduct searches in a more *model-independent way*?
- How do we *compare results of different experiments* in a more model-independent way to ensure complementarity and avoid gaps in coverage?
- *Long-lived and feebly-interacting particles* represent an alternative paradigm with respect to traditional BSM searches. To what extent can future detectors and accelerators probe such particles?



Accelerators for Energy Frontier Studies

- EF science goals currently envision two types of future colliders
  - **Higgs** (and other known elementary particles) **factory**
  - **Next high energy frontier machine**
- Discoveries at the Energy Frontier are intricately linked to the progress in accelerators
  - *Iterative process* between AF and EF groups to identify most valuable options
- Tasks of EF group are to evaluate *trade-offs and narrow the range of collider options* to explore
- For physics studies, and to make a physics case, *machine parameters*, and estimates of *luminosity* and *backgrounds* are needed for the proposed options
- In addition to "readiness" other major features for classifications considered are:
  - for accelerator builders: *performance* (luminosity reach), *cost* and *power efficiency* (total power);
  - and for particle physicists – *physics reach* (energy) and *detectors* (backgrounds)

Two Joint AF-EF Meetings on Future Colliders.

Provided Tables with parameters, technical readiness/feasibility, cost, timeframes, for the various collider options (see Day 1 and Day 2)

Which machines?

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

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

Accelerator Benchmark 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	$\pm 80/\pm 30$	2
		350 GeV	$\pm 80/\pm 30$	0.2
		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
		1.5 TeV	$\pm 80/0$	2.5
		3.0 TeV	$\pm 80/0$	5
CEPC	ee	M_Z		16
		$2M_W$		2.6
		240 GeV		5.6
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		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	ep	1.3 TeV		1
FCC-eh	ep	3.5 TeV		2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10
		14 TeV		20
		30 TeV		90

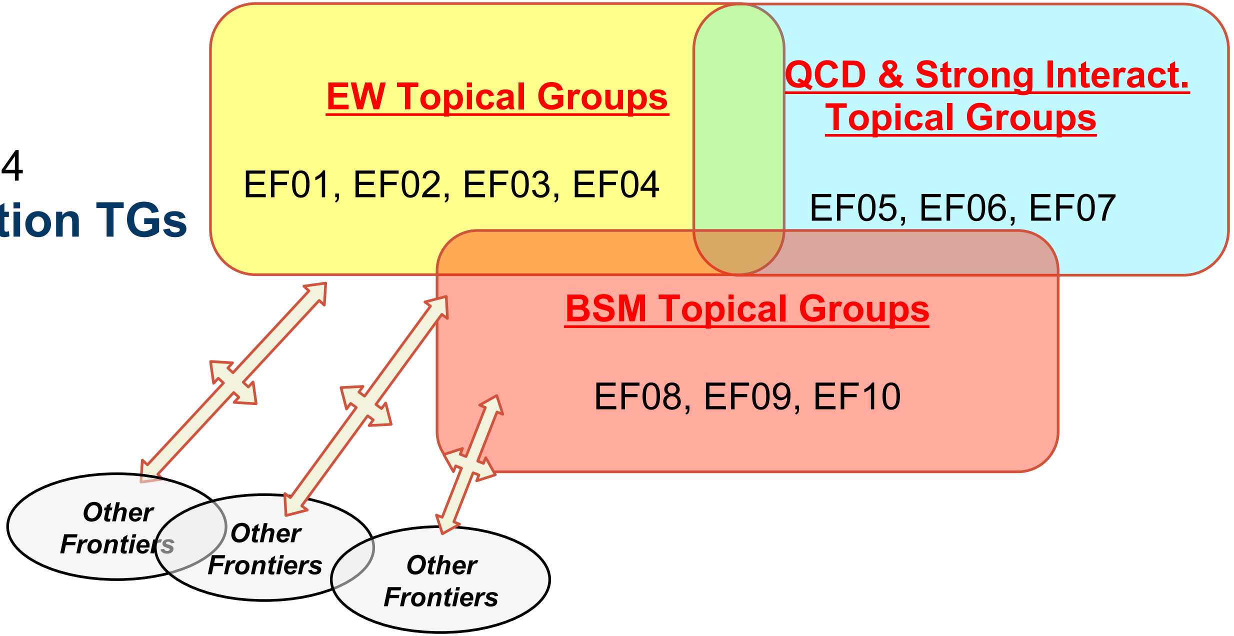
Note for muon-collider: It is important to note that the plan is not to run subsequently at the various c.o.m etc. These are reference points to explore and assess the physics potential and technology. The luminosity can be varied to determine how best to exploit the physics potential.

Other options to explore:

- Muon collider at a very high energy (>30 TeV?)
- FCC pp >150 TeV? and ~75 TeV documenting sensitivity loss
- Very high energy e+e- collider
- gamma-gamma collider

Topical Group Activities

- **Electroweak TGs**
  - EF01, EF02, EF03, EF04
- **QCD and Strong Interaction TGs**
  - EF05, EF06, EF07
- **BSM TGs**
  - EF08, EF09, EF10



Multiple Ongoing Activities

- See Wiki pages and indico meeting agendas for details of ongoing activities

The Energy Frontier Group

- **EF Convenors:** *Laura Reina (FSU), Meenakshi Narain (Brown U.), Alessandro Tricoli (BNL)*
- **Ten Topical Groups** study and compare the physics reach of future colliders.

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)	

Early Career members of the EF community

- The Snowmass process thrives on the participation of young people and offers an ideal environment for young people to get involved and promote their own initiatives.
- We strongly encourage young members of the community to get involved!
- **To all senior members: get your students and postdocs involved!**
- *See talk by Grace Cummings and Amber Roepe in Wednesday 'EF Planning' session*

Early Career EF Representatives

Liaisons between the EF management and EF Early Career members

- **Grace Cummings** (University of Virginia)
- **Amber Roepe** (University of Oklahoma)

MC Task Force and Production Plans

- Since Snowmass 2013, the landscape for simulations for future colliders has changed.
  - Both future e+e- colliders (FCC-ee, CepC, ILC, CLIC, etc.) and hh/eh colliders (FCC-hh/eh, SppC) have developed simulation and analysis frameworks, and generated MC samples for their studies.
  - **Software Tutorial have been arranged in EF for all accelerator concepts**
- **Two-step strategy** to address MC production for Snowmass 2021:

  1) Assess the MC needs for EF (exp+th) and formulate a plan. ⇒ a **"Task force"** has been formed

  2) Produce needed MC samples to carry out EF studies ⇒ a **"Production Team"** to be formed
- **MC Task Force mandate is coming to an end and we shall soon transition to the MC Production phase** *(see John Stupak's talk in Wednesday 'EF Planning' session)*

Members of the EF MC Task Force

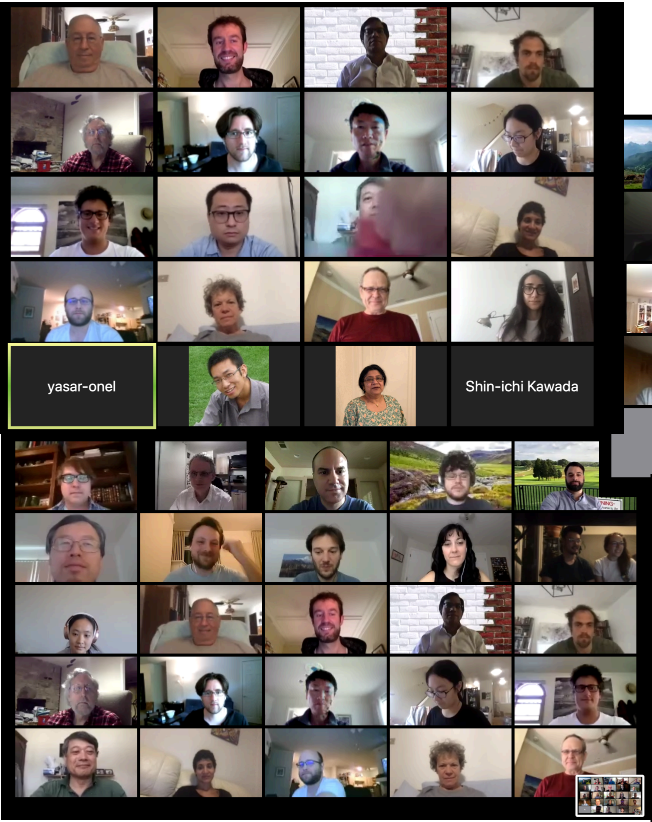
- **John Stupak** (Chair)
- EF TG conveners: **Isobel Ojalvo, Michael Schmitt, Simone Pagan Griso**
- MC authors: **Fabio Maltoni, Stefan Hoeche**
- OSG representative: **Robert Gardner**

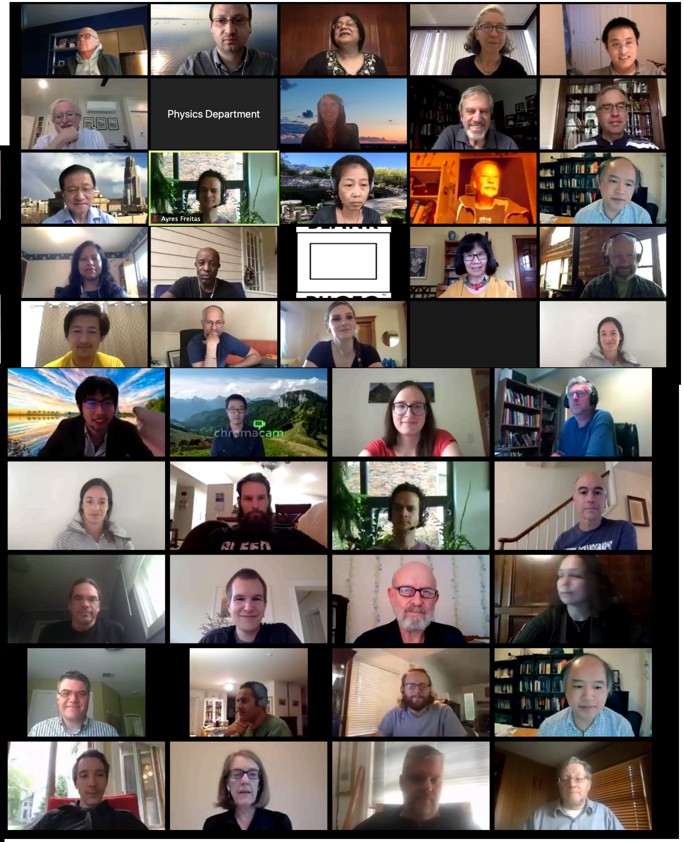
Liaisons among Frontiers

Liaisons provide high-level and bi-directional communication b/w Frontiers.

Other Frontier	Liaisons
Neutrino Physics Frontier	André de Gouvêa (Northwestern)
Rare Processes and Precision	Angelo di Canto (BNL)
Cosmic Frontier	Caterina Doglioni (Lund)
Theory Frontier	Laura Reina (FSU)
Accelerator Frontier	Dmitri Denisov (BNL), Meenakshi Narain (Brown)
Computational Frontier	Daniel Elvira (FNAL)
Instrumentation Frontier	Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay)
Community Engagement Frontier	Daniel Whiteson (UCI), Sergei Gleyzer (Alabama)

…and You!





Photos taken at EF Kick-off meeting May 21, 2020

…and Many More…

CPM Sessions

- CPM objectives of breakout sessions:
  - Focus *on inter-frontier discussions* and establish cross-working-group connections
  - Provide space for members across the field to talk to each other and to discuss, promote, and develop *new ideas*
  - *Identify gaps* and further input needed to achieve Snowmass goals
- CPM Sessions were developed based on the **380 LOIs** with EF as primary or secondary Frontier (**Big Thank You!**), informal expressions of interests and ongoing contributions.
- CPM is the occasion to develop plans across frontiers
  - Multiple breakout sessions joint with other Frontiers
  - Look here for a List of Suggested Breakout Sessions
- ***EF Timeline towards Report*** *will be presented by Meenakshi Narain in Wed. 'EF Planning' session*
- *See Laura Reina's talk on Thur. Plenary session for* ***highlights of CPM breakout sessions***

CPM Breakout Sessions

- Several sessions of generic interests (table below covers some of them)
  - **EF-specific**: ***#201 for EF Planning***
    - Early Career activities and plans
    - MC Task Force and Production plans
    - EF Timeline towards final reports, Identification of gaps in our research, Feedback from EF community
  - **Accelerator options:**
    - ***#129 - Higgs factories (<1 TeV):*** Higgs properties projections and machine challenges
    - ***#183 - Intermediate energy machines:*** lepton colliders between 500 GeV and 3 TeV, e.g. upgrades of ILC/CLIC or plasma collider or muon collider
    - ***#26: - Discovery machines****:* physics reach and technical challenges of very high energy pp colliders (100-200+ TeV), muon colliders (30 TeV?) etc.
    - ***#186 - High Field Physics with Intense Electron and Laser Beam***
  - **General interest: *#119 HEP Workforce, career and Training***

Breakout Session			Energy Frontier Topical Group										
#	Title	Date and Time (EST)	EF General	EF01	EF02	EF03	EF04	EF05	EF06	EF07	EF08	EF09	EF10
1	EF Intro	Oct 6, 2020, 12:00 PM	EF General										
201	EF Planning	Oct 7, 2020, 4:00 PM	EF General										
129	Higgs Factories	Oct 6, 2020, 12:30 PM	EF General	EF01	EF02								EF10
26	Energy Frontier discovery machines	Oct 7, 2020, 2:00 PM	EF General	EF01	EF02						EF08	EF09	EF10
183	Intermediate lepton collision energies between 500 GeV and 3 TeV	Oct 6, 2020, 4:00 PM	EF General										
186	High field (Schwinger limit) physics with intense electron and laser beams	Oct 7, 2020, 2:00 PM	EF General										
119	HEP Workforce, Careers, and Training	Oct 7, 2020, 2:00 PM	EF General										

CPM Breakout Sessions

- Several sessions of generic interests (table below covers some of them)
  - **Instrumentation:**
    - ***#131 - Physics requirements for detectors:*** physics and performance input to detector design
    - ***#130 - Low mass and fast-time detectors:*** picosecond timing for high precision studies of rare decays, new materials for massless detectors
  - **Computational requirements and data analysis strategy:**
    - ***#123 - Data Handling and ML, AI:*** prospects for AI/LM in particle physics, panel discussion
    - ***#80 - Computing requirements:*** bridging AI and Fundamental Interactions, programmable storage
    - ***#132 - Data Analysis Strategy:*** strategies, algorithms, triggering challenges, tools for data analysis
    - ***#99 - MC event generators and simulation:*** new strategies and techniques for accurate and efficient event generation and detector simulation at colliders

Breakout Session			Energy Frontier Topical Group											
#	Title	Date and Time (EST)	EF General	EF01	EF02	EF03	EF04	EF05	EF06	EF07	EF08	EF09	EF10
131	Physics requirements for HEP colliders	Oct 6, 2020, 1:30 PM	EF General										
130	Enabling technologies for low mass and ps timing detectors	Oct 6, 2020, 12:30 PM	EF General										
123	Data Handling and AI/ML	Oct 6, 2020, 4:00 PM	EF General										
80	Computing Requirements & Opportunities for the Energy Frontier	Oct 6, 2020, 3:30 PM	EF General										
132	Collider Data Analysis Strategies	Oct 6, 2020, 3:30 PM	EF General										
99	Advances in Event Generation and Detector Simulation	Oct 7, 2020, 2:00 PM	EF General					EF05	EF06				

CPM Breakout Sessions

- **Precision calculations and experiments in QCD and EW sectors:**
  - ***#28 - Theory Challenges:*** identifying main sources of theoretical systematics and estimating progress/impact on precision measurements (e.g. parton shower, heavy flavor decays, EW/Higgs physics)
  - ***#128 - From amplitudes to precision physics***: precision calculation techniques and needed progress to match precision benchmarks for future experiments (e.g. EW effects in parton showers, N3LO subtraction schemes, high order corrections)
  - ***#125 - EFT:*** theoretical development and use at future colliders, e.g. SMEFT fits
  - ***#29 Low-energy experiments:*** precision experiments relevant for global SM and SMEFT fits.

Breakout Session			Energy Frontier Topical Group										
#	Title	Date and Time (EST)	EF General	EF01	EF02	EF03	EF04	EF05	EF06	EF07	EF08	EF09	EF10
28	Theory Challenges in Precision Measurements	Oct 7, 2020, 2:00 PM		EF01		EF03	EF04		EF06				
128	From amplitudes to precision physics (Precision calculations and techniques)	Oct 6, 2020, 2:30 PM		EF01		EF03	EF04	EF05	EF06				
125	EFTs for new physics sensitivity studies	Oct 6, 2020, 12:30 PM		EF01	EF02	EF03	EF04						
29	Low-energy precision experiments	Oct 6, 2020, 4:00 PM					EF04						

CPM Breakout Sessions

- **Sessions on QCD and strong interactions**
  - ***#40 - Hadron Spectroscopy:*** discussion of key topics
  - ***#92 - Non-perturbative QCD:*** PDFs (at HL-LHC, Energy Frontier colliders, EIC), QCD at Forwards Physics Facility
  - ***#124 - Lattice QCD:*** impact of lattice QCD, new tools, goals, interpretations, panel discussion
  - ***#145 - Heavy Ion physics:*** Compact binaries as probes of dense matter and QCD phase transitions, nuclear astrophysics and neutron stars.

Breakout Session			Energy Frontier Topical Group										
#	**Title**	**Date and Time (EST)**	**EF General**	**EF01**	**EF02**	**EF03**	**EF04**	**EF05**	**EF06**	**EF07**	**EF08**	**EF09**	**EF10**
40	Exotic Hadron Spectroscopy and Interpretation	Oct 6, 2020, 4:00 PM							EF06				
92	Non-perturbative QCD dynamics at colliders	Oct 6, 2020, 12:30 PM				EF03		EF05	EF06	EF07			
145	QCD phase transitions and ultra-high density matter	Oct 6, 2020, 12:30 PM								EF07			
124	Lattice Gauge Theory for High Energy Physics	Oct 6, 2020, 2:00 PM						EF05	EF06	EF07			

CPM Breakout Sessions

- Several session on **Higgs and BSM**:
  - ***#101 - Higgs as a probe of New Physics:*** Higgs and Flavor, Higgs potential
  - ***#126 - BSM searches:*** flavor physics, naturalness and EWSB, EFT vs top-down
  - ***#127 - Dark Sector searches:*** direct detection > eV and < eV, and EF, RP, NF probes
  - ***#108 - Accelerator probes of light DM:*** complementarity between EF, cosmology and neutrino experiments for light DM searches
  - ***#136 - Heavier DM (>10 GeV):*** heavy DM searches, theory motivations and benchmarks in EF and CF
  - ***#138 - Astro-particle/Collider synergies:*** forward physics at colliders (FPF, Fraser, etc.), IceCube, ultra-high-energy cosmic ray etc.
  - ***#150 - DM complementarity:*** wave DM, cosmic and accelerator probes of DM, quantum sensors, high-energy neutrinos, searches for Dark Sector

Breakout Session			Energy Frontier Topical Group										
#	Title	Date and Time (EST)	EF General	EF01	EF02	EF03	EF04	EF05	EF06	EF07	EF08	EF09	EF10
101	Higgs as a probe of new physics	Oct 6, 2020, 4:00 PM		EF01	EF02						EF08	EF09	EF10
126	BSM: direct and indirect searches	Oct 6, 2020, 2:00 PM			EF02						EF08	EF09	EF10
127	Searches for dark sectors	Oct 6, 2020, 3:00 PM									EF08	EF09	EF10
108	Accelerator Probes of Light Dark Matter (keV-GeV)	Oct 6, 2020, 12:30 PM									EF08	EF09	EF10
136	Heavier particle dark matter >~ 10 GeV	Oct 6, 2020, 12:30 PM									EF08	EF09	EF10
138	Synergy of astro-particle physics and collider physics	Oct 7, 2020, 3:00 PM							EF06		EF08		EF10
150	Dark matter complementarity	Oct 7, 2020, 1:15 PM									EF08		EF10

Summary

- **EF activities have taken off**
  - Thanks to the numerous LOIs submitted to EF, expressions of interests, and ongoing contributions (Thank you all!)
  - Thanks to EF TG convenors for striving to make TG and CPM activities successful
- **CPM is a unique opportunity** to *clarify plans*, *connect with other frontiers and cross-fertilize*, discuss *new ideas* and identify *gaps*.
- Please join as many of the **breakout sessions** as you can**, contribute to the discussions**
  - Thanks to all sessions organizers!
  - A big thank to Laura Reina for the tremendous effort in shaping the CPM
- **Help build a strong EF community and define its strategy** towards the final report planned for the next summer.

Enjoy the rest of the CPM!

Backup

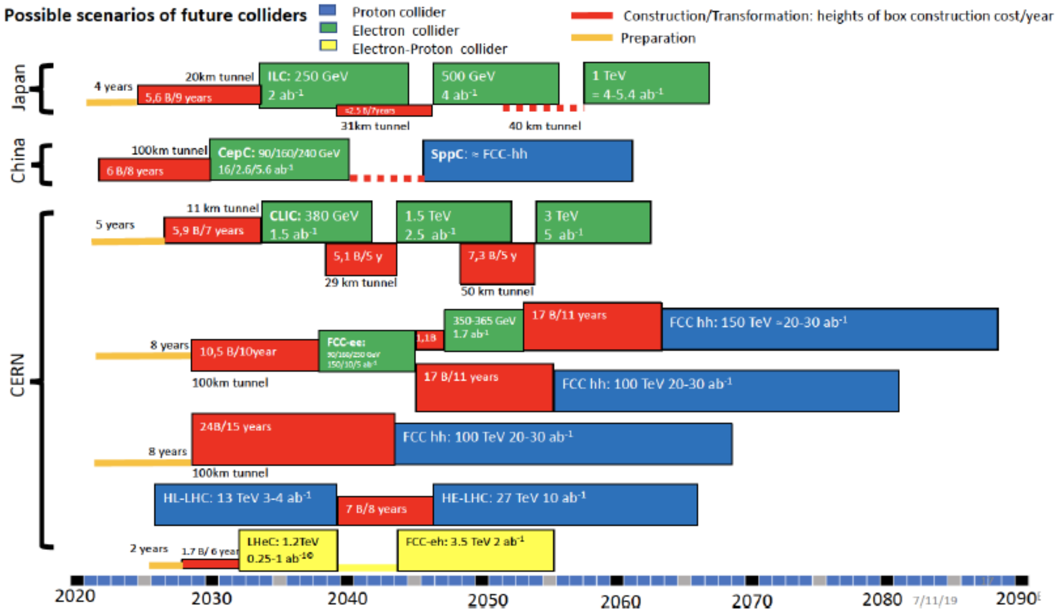
Energy Frontier Planning

- **Several EF-wide meetings** have been arranged in preparation for the *Community Planning Meeting*
  - EF Kick-off meeting on May 21, 2020
  - Preparatory Joint TG Sessions, July 7-8, 2020
  - EF workshop July 20-22, 2020!
  - Workshop on non-perturbative uncertainties
  - Workshop on EIC physics arranged by EF06-EF07

- **Cross-Frontier Meetings:**
  - Jointly with Accel. Frontier - established colliders (June 24, 2020)
  - Jointly with Accel. Frontier - novel colliders (July 1, 2020)
  - Jointly with Accel and Rare Proc. on Dark Sector and Light Long-Lived Particles (July 15-16, 2020)
  - **Continuing dialogue with other Frontiers through Liaisons**

- **Ongoing Biweekly meetings arranged by Topical Groups are where plans are developed in a bottom-up approach, new ideas are presented etc.**

Future Collider Scenarios & Timelines

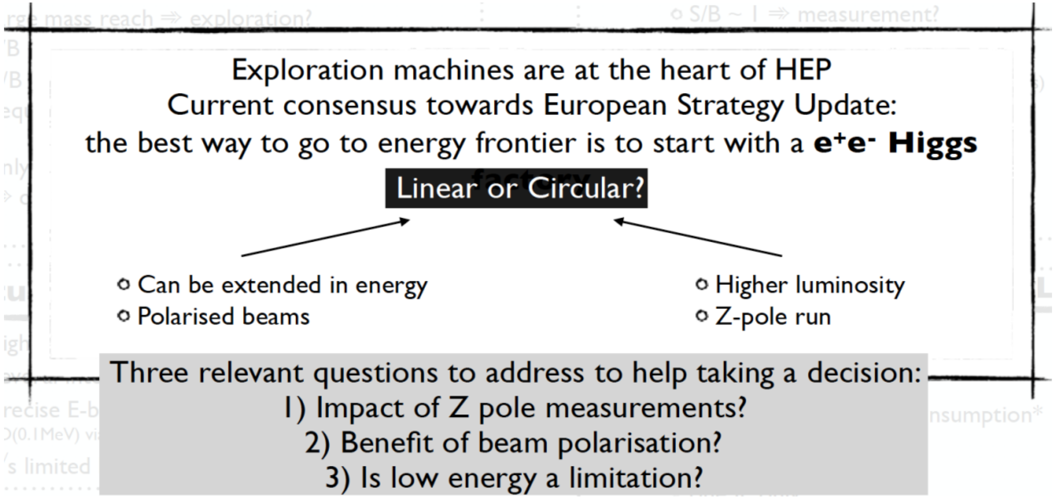


Ursula Bassler @ Granada meeting

- Will add **EIC** and **Muon Collider** to this chart.
- Will consider **new proposals** that may come up during Snowmass 2021.
  - e.g. initiatives for gamma-gamma and plasma colliders etc.

Which machines: e+e- Linear vs Circular?

- **Circular vs linear e^+e^- colliders** and complementarities
  - *Can we afford both?*
  - If we have to make a choice, then the decision will be driven by few main issues
    - Technical feasibility/maturity
    - Cost and timescale
    - And the *physics potentials*



- Continue the comparison of the *physics potentials* for the circular vs linear e+e- colliders
  - There are many studies available already in CDRs, ESG for the various proposals
  - There are *"open questions and new ideas"* which are being proposed to be studied by EF (see LOIs)

Far Future Collider Scenarios

I. EXISTING HIGH ENERGY PROPOSALS

beam type	$\sqrt{s}$ (TeV)	Lum. ($10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	Accelerator Tech/Notes	Reference
μ	.125	8×10^{-3}	MAP (0.3 km cir)	[1]
μ	3	4.4	MAP (4.5 km cir)	[2]
μ	6	12	MAP (6 km cir)	[1, 2]
μ	14	33	HE-LHC-$\mu\mu$ MAP[a]	[1, 3]
μ	10 - 30	20-100	pheno paper	[5]
μ	100	1-10	FCC-$\mu\mu$ LEMMA +GF	[6]
e	1	1	Laser-PWFA (.44 km)	[7]
e	3	10	Laser-PWFA (1.3 km)	[7]
e	30	10^3	Laser-PWFA (13 km)[b]	[7]
p	300	1	Eloisatron (300 km/10T)	[1]
p	500	50	Collider in the sea (1900 km cir/3.2T)	[1, 8]
p	5000(40 PeV?)	unknown	Fermi Globaltron (40000 km)	[1]

[a] These numbers are based on [3] which uses the LHC ring for acceleration and collisions, [4] has a tentative scaled up proposal using a 14 km tunnel collider ring (but would have to have an extensive accelerator complex), but similar luminosity.

[b] This clearly is amazing but they also say > 30 years for first step and > 30++ for final step since it's a staged program that reuses the laser.

TABLE I: Highest energy already proposed colliders for μ, e using advanced tech and futuristic hadron colliders.

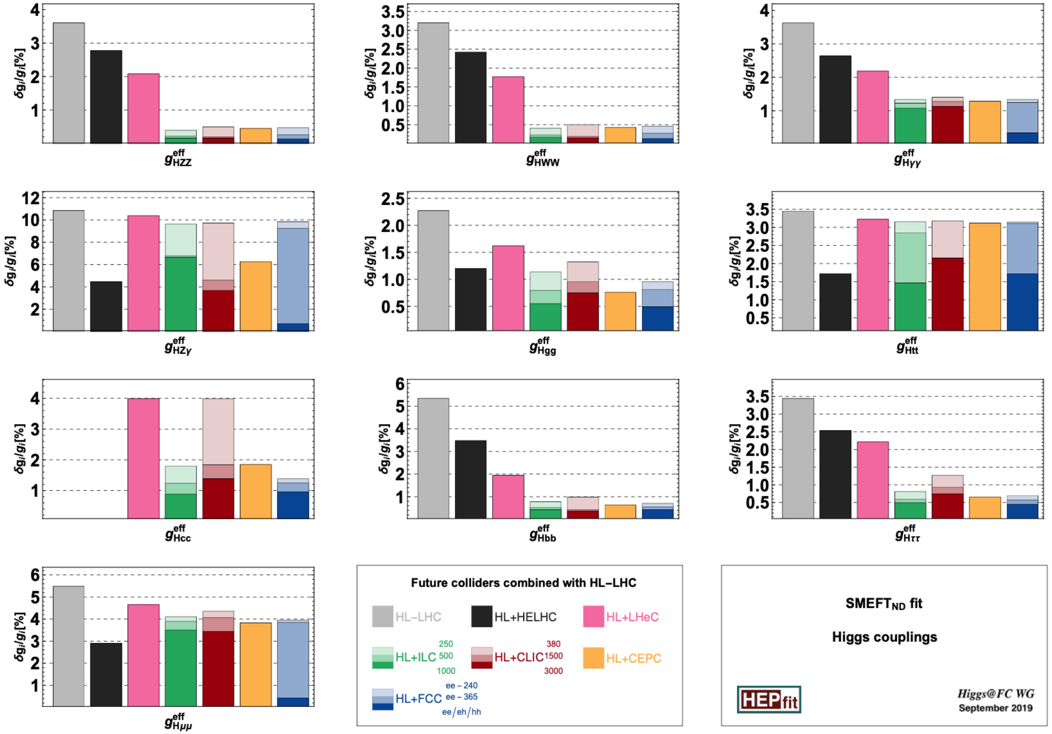
Note from P. Meade and I. Ojalvo

Some “Open Questions” from AF for EF

- Addition of other CoM options for very high energy pp collider? Currently studies use 100 TeV, shall we add an intermediate $\sqrt{s}$ e.g. 70 TeV and lower CoM ?
  - 100 TeV with 16T magnets would have long timeline and high cost.
  - 75 TeV with 12T magnets is feasible but still very expensive.
  - It was suggested to start with 6-7T Nb-Ti magnets. Is 40 TeV CoM of any interest?
- Muon Collider:
  - The $\sqrt{s}$ options presented were multi-TeV (3, 6, 10, 14 TeV)
  - Shall we also pursue muon-collider as a Higgs Factory?
  - Is there interest in $\sqrt{s}$ 30 and 100 TeV “dream” machines – big, very expensive and low(er) lumi
- Gamma-gamma Higgs factory is viable option from AF side [electron beams are used for photons scattering]. Is there a physics interest or a collaboration who is willing to do these studies?
- LHeC: another way to get to Higgs and up to ~1 TeV

Higgs, Top, EW

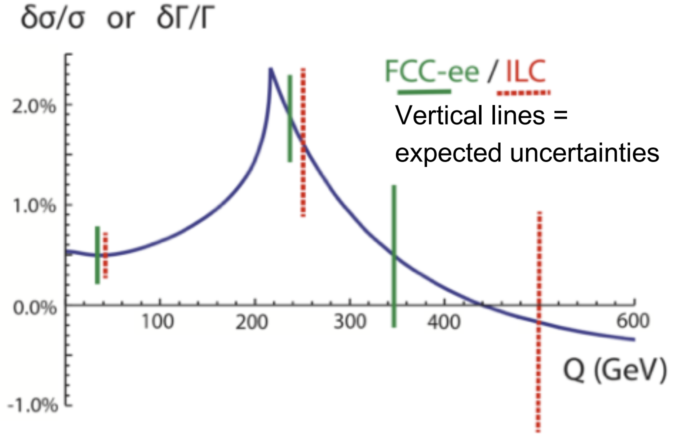
Coupling interpretations of precision Higgs measurements



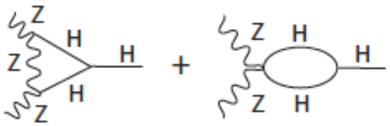
- Future colliders under consideration will improve the understanding of the Higgs boson couplings wrt HL-LHC - 0.5 - few%
    - At low energy top-Higgs coupling is not accessible at future colliders
    - HL-LHC does not probe Higgs-charm
    - Couplings to μ , Zγ benefit the most from the large dataset available at HL-LHC and not really improved at future colliders

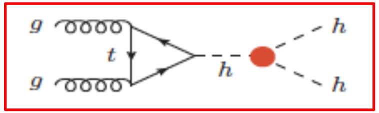
Higgs self coupling

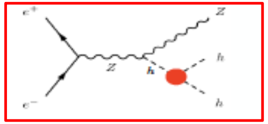
arXiv:1910.00012

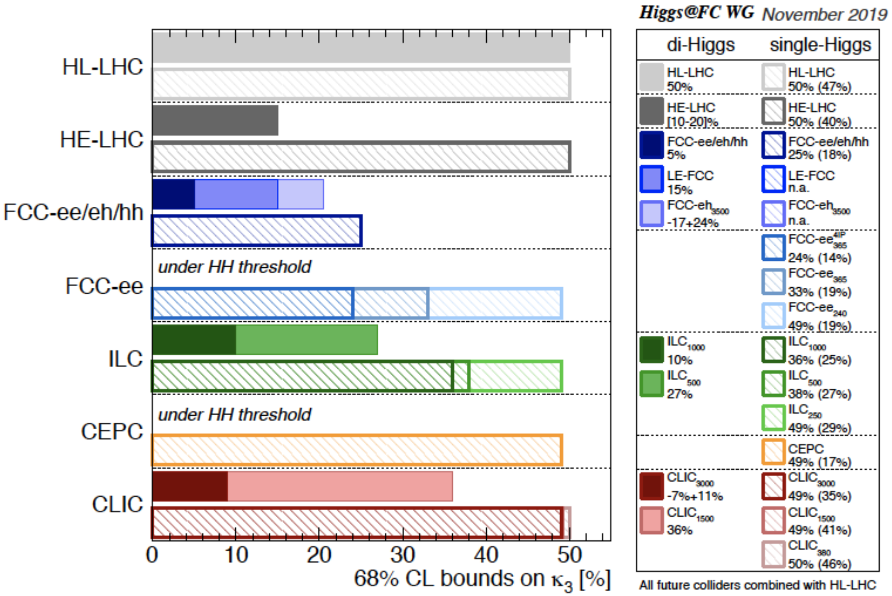


Single H extraction method: relative enhancement of the **σ(e^+e^- → ZH)** and the **Γ(h → W^+W^-)** partial width (in %) for k_λ=1, due small but momentum dependent radiative corrections:









Which precision on the self-coupling is needed?

arXiv:1910.00012

SLAC

BRONZE 100% | **SILVER 25-50%** | **GOLD 5-10%** | **PLATINUM 1%**

Sensitivity to models with the largest new physics effects, in which new particles of few hundred GeV mass appear in tree diagrams or as s-channel resonances

Sensitivity to mixing of the Higgs boson with a heavy scalar with a mass of order 1 TeV. Models of electroweak baryogenesis typically predict this level of deviation in the trilinear Higgs self-coupling.

Sensitivity to a broad class of loop diagram effects that might be created by any new particle with strong coupling to the H. This could possibly complement measurements on new particles that could be discovered at the HL-LHC.

Sensitivity to typical quantum corrections to the Higgs self-coupling generated by loop diagrams

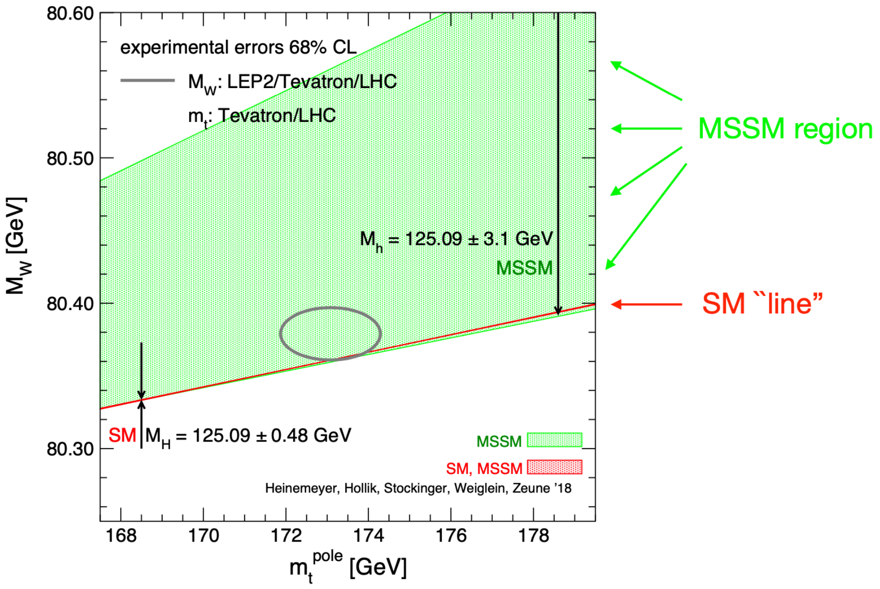
Higgs Self-Coupling

collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
$CEPC_{240}$	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

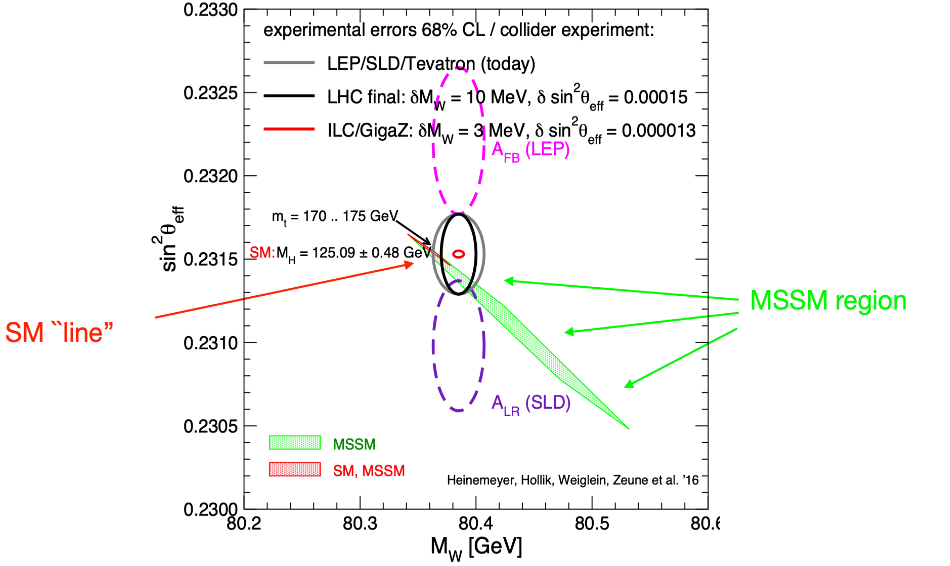
Sensitivity at 68% probability on the Higgs cubic self-coupling at various future colliders

Higgs, Top, EW

[S. Heinemeyer, W. Hollik, G. W., L. Zeune '18]



[S. Heinemeyer, W. Hollik, G. W., L. Zeune '16]



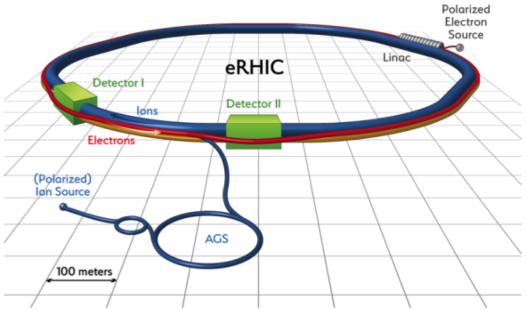
QCD and Strong Interactions

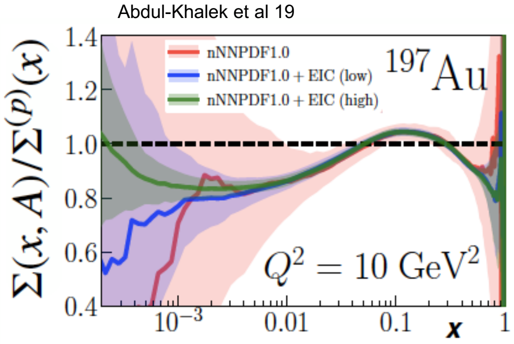
- Precision QCD
  - What is the *ultimate precision for* α_s and *how do we achieve it*? From the LHC, future pp, future e+e-, DIS (ep and eA), particle decays (tau, hadrons), and lattice QCD.
  - What *theoretical developments* are needed to support precision measurements of Higgs and top quark production and properties (including electroweak corrections, non-perturbative threshold effects)?
  - Evaluation and *interplay of uncertainties from theory and from experiment*.
    - Theory correlations in experimental measurements
    - Theoretical scales impact on PDF extraction
    - Non-perturbative effects → cross-cutting effort between lattice QCD and MC community
    - Parton shower development: EW emission, color flow, multi-parton interactions, scale choices.
    - Inclusion of higher-order calculations in MC event generators (NNLO QCD, NLO QCD+EW)
  - Jet substructure observables.

QCD and Strong Interactions

- Hadronic structure
  - What is the future of PDF determinations?
    - What is the potential of *new deep inelastic scattering facilities* (EIC, LHeC & FCC-eh) for probing the hadronic and nuclear structure in the regions relevant for HEP experiments?
    - How can the experience of the HEP community be transferred *to enhance the potential of the EIC* and LHeC studies?
    - What is the best approach to *reduce systematic uncertainties in LHC measurements* to achieve the accuracy of PDFs envisioned by electroweak precision studies at the future hadron colliders?
    - What is a feasible strategy for obtaining accurate *PDFs for N^3LO QCD* computations? Which theoretical advances and computational tools will be necessary?
  - How does the knowledge of hadron structure affect measurements of α_s in various processes?
  - How can LHC, LHeC, and FCC improve our knowledge of the 3-dimensional structure of nucleons and nuclei?
  - How do *excited hadronic states* with two or more heavy quarks form and decay?
  - What are the *BSM connections for hadron spectroscopy* at future facilities?

Nuclear/nucleon structure at the Electron-Ion Collider





Pinning down nuclear PDFs at small-x: onset of gluon-dominated matter?

- Synergies between EIC, proton PDF fits, and LHC pheno deserve attention
  - EIC likely the only lepton - nucleon collider operating in near future!
  - Assess impact on proton PDFs of simulated EIC pseudo-data
- What can the EIC do for proton PDFs?
  - *Replace the old fixed target DIS data*
  - Improved, cleaner coverage of *large-x region*
  - Robust large-x sea quarks from deuteron projectiles
  - New probes of the gluon from jets ….
  - *lots of unexplored potential!*

QCD and Strong Interactions

- Forward Physics
  - What are the *prospects of running forward proton detectors* at the HL-LHC and at future hadron colliders?
  - Which detectors (including acceptance/resolution) will be needed at the LHC and the EIC to perform the best possible measurements of energy, particle production in the very forward region?
  - What will be their *sensitivity to anomalous couplings between photon, W, Z bosons, top quarks*.
  - How to observe *saturation effects* or *high-gluon density* regimes at the LHC and the EIC?
- Heavy Ions
  - What can we learn from *the jet and jet substructure* measurements about the nature of the quark-gluon plasma? How do we apply the techniques to the studies of jets and the possible jet energy loss in EIC?
  - What is the best use of heavy-ion beams for the *search of new physics*?
  - What are the *heavy quark and quarkonia production mechanisms* in ee, eA, pp, pA and AA collisions? What is the relevance of co-moving matter effects and recombination for the classical observables e.g charm and beauty jet?
  - How do we use heavy-ion beam to improve the understanding of inclusive hadron and charm production? connection to the *new physics search at forward region and the studies of cosmic rays?*

BSM

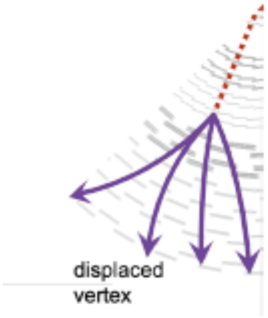
- *Long-lived and feebly-interacting particles* represent an alternative paradigm with respect to traditional BSM searches. To what extent can future detectors and accelerators probe such particles?
- Which *BSM models to consider*? What are the appropriate benchmarks?
    - What higgsino masses will still be allowed if we build XYZ
    - What scale of SUSY (RPC/RPV) or RS/Composite Higgs can be probed
- How to *compare broad model spaces* in a concise and effective way?
    - Simplified models are often used but may not be representative of the full space
    - Compare inclusivity of leptons colliders vs reach of hadron colliders
    - Compare direct searches vs indirect constraints from precision measurements
- How do we conduct searches in a more *model-independent way*?
- How do we *compare the results of different experiments* in a more model-independent way to ensure complementarity and avoid gaps in coverage?

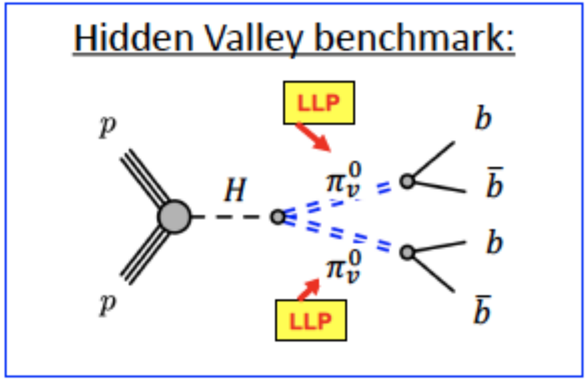
Long Lived Particles

Explore LLPs at both future hadron colliders, and lepton colliders (CLIC, FCC-ee)

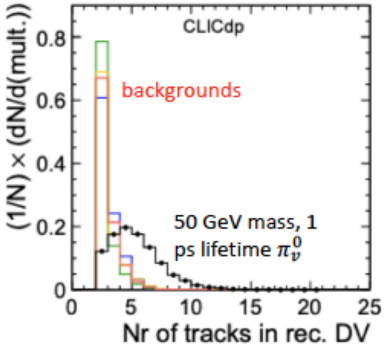
- *Lepton colliders* have a cleaner collision environment than hadron colliders
  - CLIC: possibility of readout without a trigger
  - First layers of pixels could be closer to the interaction point
- Search for *Higgs bosons that decay to long-lived particles that decay to b quarks* with a signature of displaced, multi-track vertices
  - Results with full CLIC_ILD detector simulation
  - Use BDT to separate signal from background

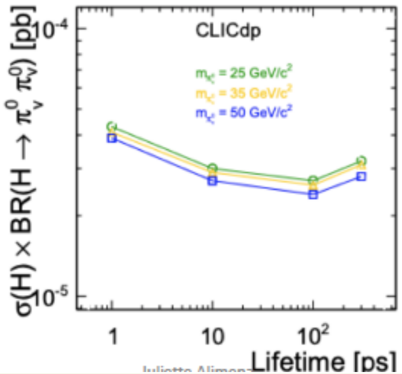
Good sensitivity to long-lived Higgs bosons in clean environment at CLIC





An input variable to the BDT:



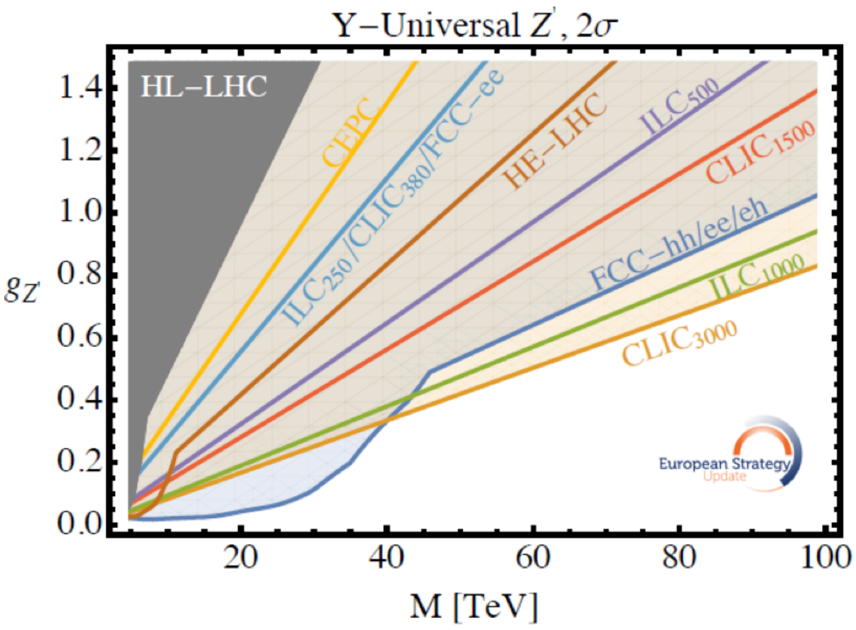


New Resonances

Future colliders extend significantly the reach for heavy resonances

- Includes *characterization of the resonances* and the ability to differentiate between models
- *Hadron and lepton machines are complementary*

Benchmark: simple sequential Z' mode



Open questions to address including how to:

- fully *exploit boosted topologies* (e.g. VLQ topologies not much studied at 100 TeV)
- develop state-of-the-art W/top/Higgs *taggers*
- Study impact of *detector choices*: e.g. calorimeter granularity, tracking
- Improve *high p_T b-jet tagging* (also boosted b-jet tagging)
- Better optimize/study *tau final states*
- Better estimation of systematic effects, broader set of models w/ diff couplings to generations, lepton/quark…

Instrumentation

- Understand the impact of detector designs on physics
  - Conversely comment on the improvement of physics sensitivity as function of a detector parameters
  - The detectors must maintain excellent precision and efficiency for all basic signatures
  - This performance has to be maintain over an immense range of momentum and angle because the detectors must excel at measuring both the relatively low energy decay products of the Higgs boson and the highest energy particles ever produced at an accelerator
  - For example: the 100 TeV pp collider will produce particles with momenta ranging between a few GeV and 20 TeV over $0<|\eta|<6$.
    - **These momentum and angular ranges are ten times and twice those achieved at the LHC!**
- The proposed collision energies and data rates of the next generation of EF colliders impose unprecedented requirements on detector technology.
- A few examples motivated by Higgs physics at future colliders, which were considered for the DOE Basic Research Needs (BRN) exercise for future instrumentation
  - Low-mass, high-granularity, radiation-hard, tracking detectors with picosecond timing
  - High-granularity, radiation hard, imaging calorimeters with picosecond timing
  - Integrated high-bandwidth, low-latency, ML-ready trigger and readout

Example: Requirements for detectors from Higgs Physics

- Technical requirements mostly from existing detector proposals.
- Technical requirements drive technology development
- We should develop further the technical requirements from Physics assessments
  - Is the physics sensitivity limited by a given detector parameter?
  - Work with Instrumentation Frontier to understand the constraints and future technology directions which may improve on the detector performance parameters.

Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2\times10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\mathrm{GeV}] \sin^{\frac{3}{2}}\theta)^{-1}\ \mu$m TR 1.1.3: Granularity : $25\times50\ \mu\mathrm{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	**18**, **19**, **20**, **23**
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8\times10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	**16**, **17**, **18**, **19**, **20**, **23**, **26**
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of $0.5\times0.5\ \mathrm{cm}^2$, hadronic cells of $1\times1\ \mathrm{cm}^2$ TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	**1**, **3**, **7**, **10**, **11**, **23**
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and $3\times10^{16}\ (5\times10^{18})\ \mathrm{n_{eq}/cm^2}$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	**1**, **2**, **3**, **7**, **9**, **10**, **11**, **16**, **17**, **23**, **26**
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8\times10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	**16**, **17**, **21**, **26**

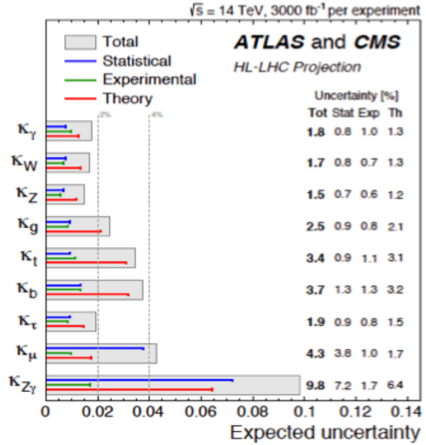
from DOE Instrumentation BRN

Energy Frontier: exploring the TeV scale

Stress-testing the Higgs sector

κ=(measured coupling)/(SM coupling)

	CMS	ATLAS
k_Z	$.99^{+.11}_{-.12}$	$1.10^{+.08}_{-.08}$
k_W	$1.10^{+.12}_{-.17}$	$1.05^{+.08}_{-.08}$
k_t	$1.11^{+.12}_{-.10}$	$1.02^{+.11}_{-.10}$
k_b	$-1.10^{+.33}_{-.23}$	$1.06^{+.19}_{--.18}$
k_τ	$1.01^{+.16}_{-.20}$	$1.07^{+.15}_{-.15}$
k_μ	$.79^{+.58}_{-.79}$	<1.51 at 95% cl



$\Delta\kappa \sim v^2/\Lambda^2$ → sensitive to scale of NP

↪ Higher precision probes higher Λ

% uncertainties with 2 ab^{-1}

	ILC250	ILC500
κ_γ	1.1	1.0
κ_W	1.8	0.4
κ_Z	.38	0.3
κ_g	2.2	0.97
κ_b	1.8	0.60
κ_τ	1.9	0.80

CLIC, % uncertainties

	350 GeV, 1 ab^{-1}	3 TeV, 5 ab^{-1}
κ_γ	-	2.3
κ_W	0.8	0.1
κ_Z	0.4	0.2
κ_g	2.1	0.9
κ_b	1.3	0.2
κ_τ	2.7	0.9

Energy Frontier: exploring the TeV scale

Difficult measurement: Higgs self-coupling ↔ EWSB

Collider	Accuracy on κ_λ	Running Years
HL-LHC	50%	12
HE-LHC	10-20%	20
ILC(500)	27%	21
CLIC(1500)	36%	15
CLIC(3000)	+11%, -7%	23
FCC(hh)	5%	13

Double vs single H production?

Indirect measurement?

Other options?

Deviations can be more subtle: not just a rescaling → explore effective interactions

Is that it? Are there more scalars? → direct searches

We still know very little, but we have very powerful constraints to guide us.

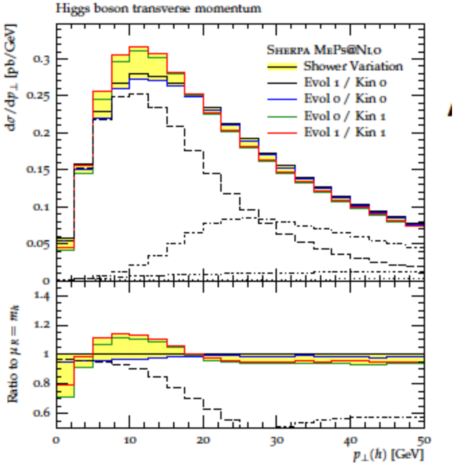
BSM Wish List

Observable/ Physics Driver/ Complementary Frontier Experiments	Scale or Precision Needed
EW Phase Transition	$\delta\lambda_3 \ll 1\%$
Higgs and Flavor	$\delta(y_u, y_d, y_s, y_e) \lesssim \mathcal{O}(1)$
Compositeness- Mesotuning	KK scale 10-100 TeV
Supersymmetry/Dark Matter- Mini Split SUSY	Nail the simplest WIMP 3 TeV Wino WIMP DM Mini-split implies 30 TeV gluino
Neutral Naturalness	Probe SM charged partner states at 20 TeV (naively implying 300 TeV pp collider)
Gravitational Waves/Phase Transitions	1-10 PeV LIGO 100 GeV-Tev LISA
Electron EDM rapid improvement 2-3 orders of mag in next decade or so	1 PeV - electron flavored 50 TeV - Higgs or EW Barr-Zee
Charged Lepton Flavor Violation 4 orders of mag in mu to e by 2035	50 TeV 1 loop CLVF

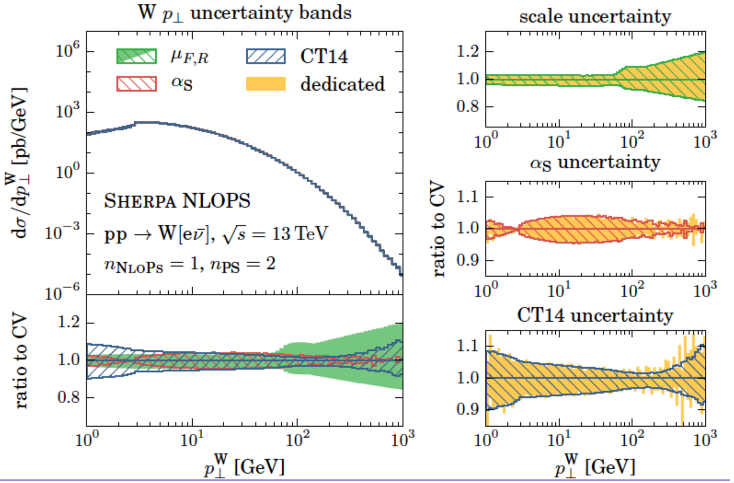
Uncertainties in Monte Carlo Event Generation

- Factorize into event stages according to characteristic scales
  - Use relevant approximation in each regime: Hard scattering, Parton evolution, Multiple interactions, Hadronization, Hadron decays, QED corrections
- Broadly categorized into Parametric, Perturbative, Algorithmic and Modelling uncertainties

Algorithmic:
diff choices of Parton Shower evolution and recoil schemes



Parametric:
Uncertainty in model parameters, non perturbative inputs



Modeling:
Heavy Flavor