Report from the Energy Frontier

Snowmass Community Planning Meeting
October 5-8, 2020

Meenakshi Narain (Brown U.)
Laura Reina (FSU)
Alessandro Tricoli (BNL)

Energy Frontier - at a glance

Exploring the TeV energy scale and beyond: detailed studies of **Electroweak (EW) physics, QCD and strong interactions, and Beyond-Standard-Model (BSM) physics** under different future accelerator scenarios, including lepton-lepton, hadron-hadron, and lepton-hadron 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 (UW-Madison)	Zhen Liu (U. Maryland)	Simone Griso (LBL)
EF10: BSM: Dark Matter at colliders	Caterina Doglioni (Lund)	LianTao Wang (Chicago)	

Energy Frontier: Liaisons with other Frontiers

Assure coordination among frontier activities on studies of common interest: important role leading up to the CPM and in particular the CPM Breakout Sessions.

- **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 (Desy)
- **Community Engagement Frontier:** Daniel Whiteson (UCI), Sergei Gleyzer (U. Alabama)

For more details see EF-only Breakout Sessions:

↪️ **Session #1**: "Energy Frontier: Activities and Focus Questions" (**Alessandro Tricoli**)

↪️ **Session #201**: "Energy Frontier: Activities and Planning" (**Meenakshi Narain**)

Energy Frontier: Planning towards CPM

- **Several EF-wide meetings** have been arranged in preparation for the *Community Planning Meeting*
  - EF Kick-off Meeting - May 21, 2020
  - Preparatory Joint TG Sessions - July 7-8, 2020
  - EF Workshop - July 20-22, 2020
  - Workshop on non-perturbative uncertainties (EF05)
  - Workshop on EIC physics (EF05-06-07)

- **Cross-Frontier Meetings**:
  - Jointly with AF: established colliders - June 24, 2020
  - Jointly with AF: novel colliders - July 1, 2020
  - Jointly with AF and RF: Dark Sector and Long-Lived Particles - July 15-16, 2020
  - More meetings planned after CPM
- **Monte Carlo Task Force** (Chair: John Stupak)**:**
  - Bi-weekly meeting: surveying Monte Carlo sample needs.
  - Tutorials on Monte Carlo/simulation frameworks for future colliders: Aug-Oct 2020

- **Ongoing bi-weekly meetings arranged by Topical Groups** since April: where plans are developed in a bottom-up approach, ideas and new studies are presented, etc.

Energy Frontier: Letters of Interest (LOIs)

- **Broad effort of LOI solicitation through dedicated TG meetings**
  - 376 received.
  - 268 have EF as primary.
  - Cross-frontier LOIs with: TF (21), AF (20), IF(17), RF (16), CF (14), NF (11), CompF (9).
  - All LOIs have been acknowledged (by conveners or TG conveners).

- **Frontier activities and LOIs have informed EF Breakout Sessions at CPM**
  - New ideas and focus points have emerged (main theme EF Workshop in July).
  - Cross-TG and cross-frontier connections have been established.
    - EF brings together theorists and experimentalists in each TG.
    - Cross-frontier interactions are mandatory (TF, AF, IF, …).
  - Contacts with current and future colliders collaborations have been established

- **Breakout Sessions: natural outcome of coordinated work**
  - Proposed by EF community: entirely **bottom-up process**
  - Covering the **leading themes and ideas that emerged in EF work so far**.

THANK YOU!

- **TOPICAL GROUP CONVENERS,**
- **LOI's AUTHORS,**
- **PROPOSERS and ORGANIZERS of BREAKOUT SESSIONS,**
- **ALL WHO CONTRIBUTED to EF ACTIVITIES in the last few months.**

Your participation has been crucial in shaping the physics program and vision of the Energy Frontier

We hope that many more will join after CPM!

CPM - EF Breakout Sessions

- **EF Specific**
    - *#1 - Introduction*
    - *#201 - EF Planning*
        - Early Career activities and plans.
        - MC task force: update and production plans.
        - Organization, timeline and steps towards final report, how to get involved, survey of EF participation.

- **Accelerator options**
    - *#129 - Higgs factories* (< 1TeV): Higgs properties projections and machine challenges.
    - *#183 - Intermediate-energy machines* (500 GeV-3 TeV): lepton colliders between 500 GeV and 3 TeV, e.g. upgrades of ILC/CLIC or plasma collider or muon collider.
    - *#26 - Discovery machines* (>3 TeV): 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*

CPM - EF Breakout Sessions

- **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 - Computational requirements:* challenges at HL-LHC and future colliders
  - *#132 - Data analysis strategies:* strategies, algorithms, triggering challenges, tools for data analysis
  - *#99 - Monte Carlo event generators and simulations:* new strategies and techniques for accurate and efficient event generation and detector simulation at colliders

CPM - EF Breakout Sessions

- **QCD and EW precision calculations, EFT, theoretical errors**
  - *#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 - Effective Field Theories:* theoretical development and use at future colliders, e.g. SMEFT fits.
  - *# 29 - Low energy precision experiments:* precision experiments relevant for global SM and SMEFT fits.
- **QCD and strong interactions**
  - *#40 - Hadron spectroscopy:* discussion of key topics
  - *# 92 - Non-perturbative QCD:* PDFs (at HL-LHC, EF 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.

CPM - EF Breakout Sessions

- **BSM physics**
  - *#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 dark matter:* complementarity between EF, cosmology and neutrino experiments for light DM searches.
  - *#136 - Heavier dark matter (>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

Energy Frontier: exploring the TeV scale

Snowmass 2013: in the wake of the Higgs discovery: a game changer!

Snowmass 2021: time to push new explorations!

- 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:

Great time to **propose new ideas, new perspectives, new tools**.

Key physics questions of the EF program

What is the origin of the electroweak scale?

The Higgs discovery has given us a unique handle on BSM physics and any future plan needs to make the most out of it.

- Can we uncover the nature of UV physics from **precision Higgs measurements** (mass, width, couplings)?
- 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**?
- Can constraints come from other effects of the **EW phase transition** (ex. gravitational waves)?

"How can we answer these questions?" has been the main focus of several EF meetings, Breakout Sessions, and LOIs.

Key physics questions of the EF program

These theory-motivated benchmarks should influence future directions in both theory and experiments at the EF. If reached, they can change our understanding of BSM physics.

A successful program will have to improve on

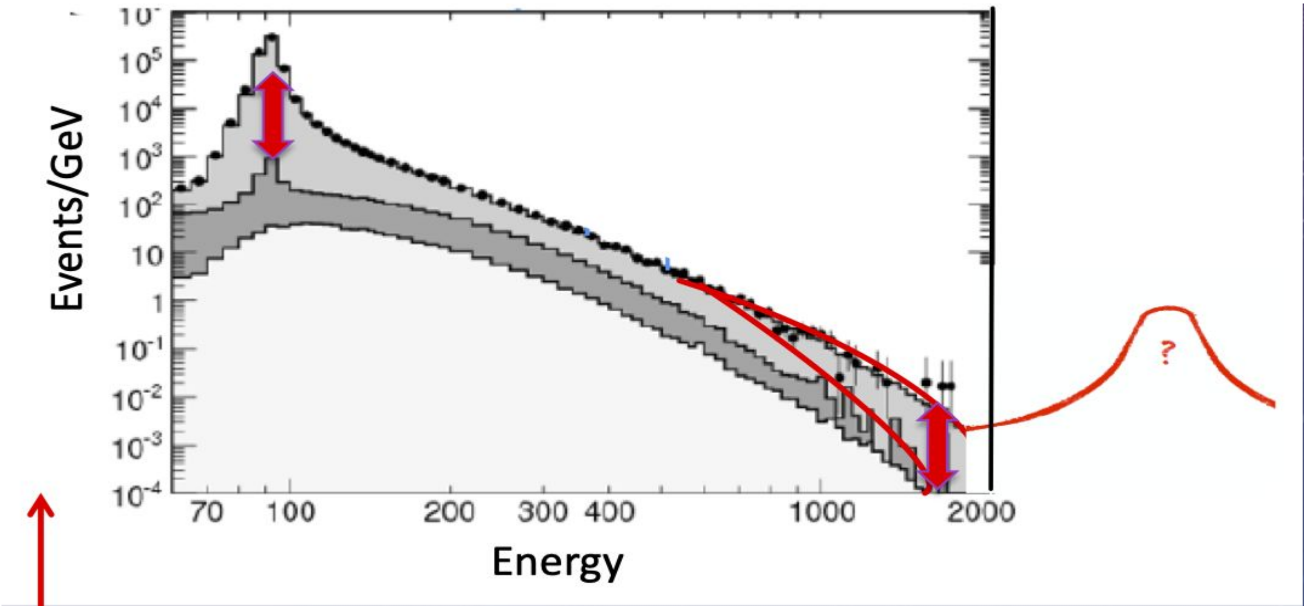
- Precision (crucial to allow for **indirect evidence of new physics**)
- Energy reach (enable **direct evidence of new physics**)
- Theoretical accuracy (affects both)

All three aspects have been at the core of many Breakout Sessions, in particular:

- Higgs factories (#129) , Discovery Machines (#26)
- Physics requirements for detectors (#131)
- Higgs as a probe of new physics (#101)
- Theoretical challenges (#28), From Amplitudes to precision physics (#128)
- EFT (#125) BSM (#126), and more.

Key physics questions of the EF program

Need both precision and energy

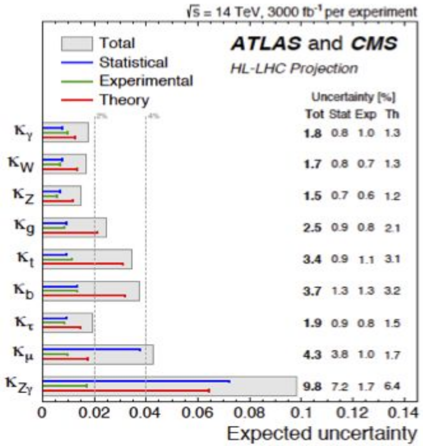


- Precision: indirect evidence of deviations at low and high energy.
- Energy: direct access to new resonances.

EF: 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



% 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

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

↪ Higher precision probes higher Λ

Challenge for future colliders: measure couplings to light fermions (c,s,u,d,e)!

EF: measuring the Higgs potential

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?

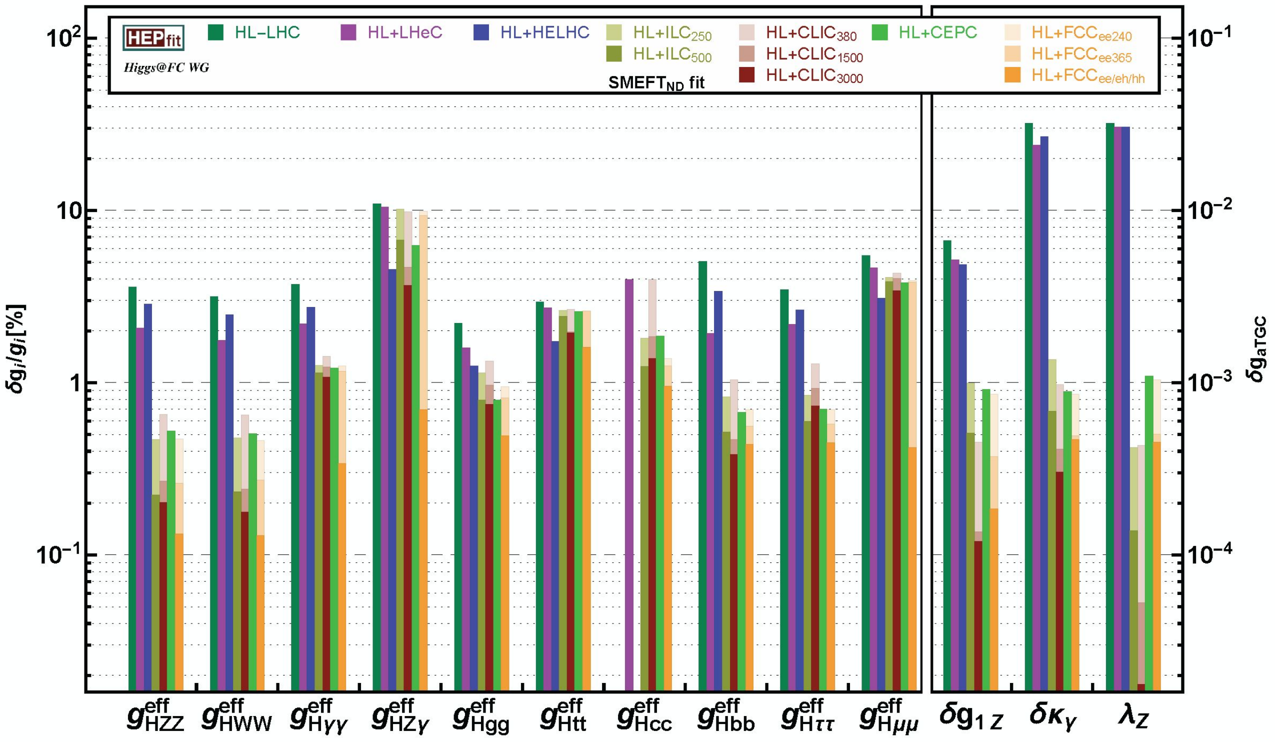
Can we measure both λ_3 and λ_4?

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.

EF: BSM via indirect constraints



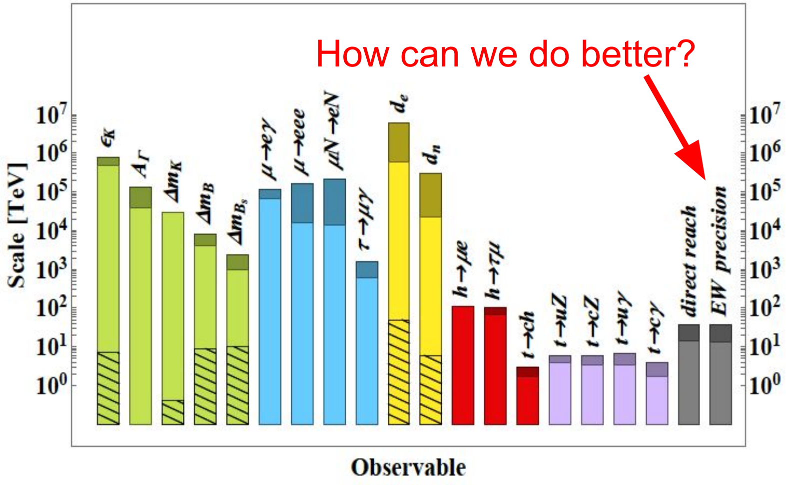
New opportunities of constraining new physics from improved global EFT fits

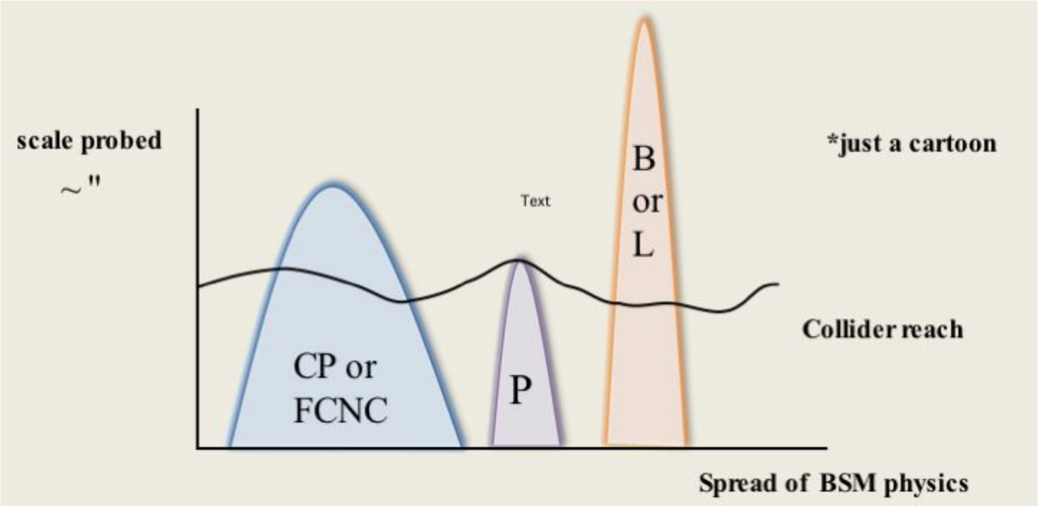
Can some of the assumptions be relaxed?

- Critical **assessment of systematic errors** on future EWPO
- Better understanding on **roles played by multi-boson processes**
- **Addressing theory errors & validity in EFT fits**

EF: BSM via indirect constraints

Probing the scale of new physics via **EW+top+Higgs+Flavor** ....





- **FCNC, CP, etc.** high reach but **target very specific sectors of BSM models**
- **Collider reach much broader**: needed to test models across the spectrum of all collider observables
- EW precision fits are a uniquely powerful tool.
- Very **unique complementarity** between EW precision fits and flavor observables.
- Matching effective interactions across energy thresholds (from flavor, to EW, to the UV) is the next step!

EF: BSM within specific models

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.

This allows the comparison of experimental reach between various approaches, e.g. direct searches vs precision.

Key Questions:

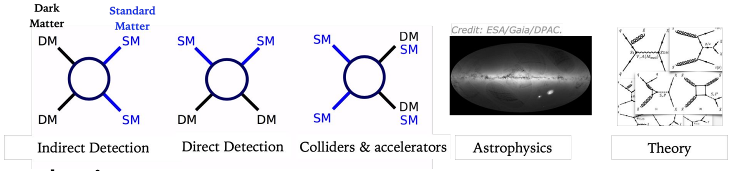
- **Which models to conside**r? Want a broad but achievable set of models (MSSM, Composite Higgs, ...)
- **How to compare broad model spaces in a concise and effective way**? For example, simplified models are often used but may not be representative of the full space
    - Compare inclusivity of leptons colliders vs reach of hadron collider
    - Compare direct searches vs indirect constraints from precision measurements
- **How is naturalness a guide t**o which measurements are most relevant for a particular model, and when that model becomes less attractive?
    - If we exclude parameter space XYZ how will the field be advanced?
    - How will the relative fine-tuning change before and after project XYZ?

EF: BSM via more general explorations

- Are there **new interactions or new particles around or above the electroweak scale**? To what extent can future experiments and colliders probe this ?
  - What's the interplay with precision measurements? (see session #126)
- **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?
  - Including interplay with DM (#108, #136)
  - Dedicated workshop on dark sector and light LLPs (also #127)
- How do we conduct **searches in a more model-independent/agnostic way** ?
  - Session #132
- How do we **compare the results of different experiments in a more model-independent way** to ensure complementarity and avoid big gaps in coverage?
- Is **lepton flavor/universality** violated ? What do we learn from high energy/p_T searches ?
  - See dedicated workshop here

EF: BSM and DM@Colliders - key questions

1. **How can we best test the WIMP paradigm?**
   - Simplest/minimal WIMP models (EW multiplets & extensions)
     i. *Mapping out full space of models, and optimizing searches.*
   - Simple mediator models
     i. *Work ongoing towards complementarity with non-EF experiments, involvement from SEC researchers*
   - Through the Higgs portal
     i. *LOI motivating and quantifying the impact of HL-LHC / FCC / Higgs factories, developed with EF02*
2. **How can we best explore beyond-WIMP scenarios?**
   - Using portals that privilege light dark sectors / dark matter: long-lived particles
   - Using less-explored *signatures* of dark sectors
     i. *Most numerous LOI category - working with EF09 / RF06 / AF02-5*
3. **How to best exploit synergies?**
   - In terms of different experiments / observations
     i. *Will plan topical workshops with CF/RF/NF*
   - In terms of detector, software, data acquisition and trigger design
     i. *Will join CompF/CommF/IF meetings for cross-talk LOIs*



Key physics questions of the EF program

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

Fundamental (theory + phenomenology):

- What precision in $alpha_S$ 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?** How can we tell? 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:

- 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?

Computing:

- Specify the strengths and weaknesses of existing MC event generators – define what is needed for the future.

Key physics questions of the EF program

Finding answers generates more specific questions.

- What **collider/detector properties** are necessary to probe the Higgs self interactions?
- **Explore a comprehensive range of future collider options** to understand what is needed from the collider and experimental communities.
- **Identify technologies** which will lead to discoveries (via the Higgs Portal and in general)

And also

- **What Theory calculations do we need to capitalize on**? (signals, backgrounds, EWPO, input parameters such as m_t or α_s, event generators, ...)
- **Where does theoretical accuracy matters most**? How to reduce theory systematics where needed?
- Where do **new approaches in searches or data analysis** matter most?

EF: Theory Challenges in Precision Measurements

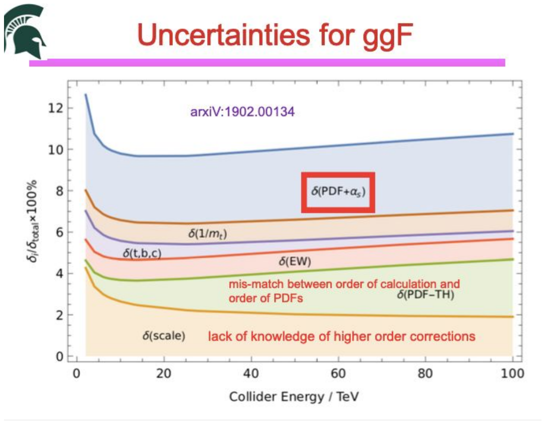
Lepton colliders (*Juergen Reuter*):

- Amazing experimental Higgs + EW precision program in *e+e−* collisions Most measurements allow per-cent down to (sub-) per mil level precision Hard theoretical work needed!
- *Z* / *WW* threshold: up to massive 2- and 3-loop 4-point functions needed Massive 3-loop diagrams: PDE, sector decomposition, Mellin methods etc.
- Higgs precision program: production processes NNLO, decays @ 3-loop
- Tools, tools, tools: community must value and support codes (loops, MC, fits)
- BSM models / SMEFT: precision needs to catch up; global fits ...
- Ultimate challenges for 10-50 TeV *e+e−* or $\mu+\mu-$ (EW PDFs, EW showers etc.)

From Breakout Session #28

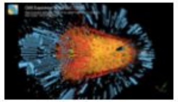
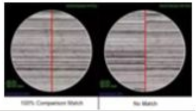
Hadron colliders (*Joey Huston*):

- Searches for new physics, as well as a better understanding of standard model physics, require an increasing level of precision, both for measurement and for theory
- On the theory side, an increase in precision also requires an increase in precision for the inputs to the calculations (i.e. PDFs, alphas(mZ)...)
- We will need to understand the impact of the new LHC data on the PDFs and their uncertainties



Theory Challenges in Precision Measurements

Hadron colliders (*Frank Krauss*):

CSI LHC: need precise & accurate tools for precision physics

This is a **massive challenge for the theory community**:

- develop new techniques (multi-loop, IR subtraction, ...)
- improve computational efficiency (HPC, GPU's, ...)
- understand & appreciate limiting factors
- necessitates **long-term investment**

(and possibly creation of new career & funding paths: "theory technicians")

Extrapolation to higher-orders in simulation:

NNLO will not be quite as simple - will need O(alphas^2) kernels (tricky, think about it as fully automated NNLO subtraction kernels)

opens parton shower for systematic uncertainty analysis

→ expect main effect in reduction of scale uncertainties

non-trivial impact of choices (kinematics) on log accuracy

- physics challenges:
  - physics challenge 1: sources of uncertainty
    (simple scale variations by a factor of two may not be sufficient: central scale in multi-scale processes? in addition: new sources of uncertainty. example: kinematics scheme in parton showers and impact on log accuracy)

    ⟶ community effort: agree on robust procedures
  - physics challenge 2: complexity & control
    (as the calculations become increasingly complex we need more and more independent – algorithmic, implementation, ... – checks. examples: two calculations for fixed order, two implementations of parton showers, etc.)

    ⟶ community effort: robust and open (cross-)validation procedures
  - physics challenge 3: input parameters as source of uncertainty
    (my favourite example: PDF's with different values for $\alpha_S(M_Z)$ and, yes, there's more: PDF's etc.)

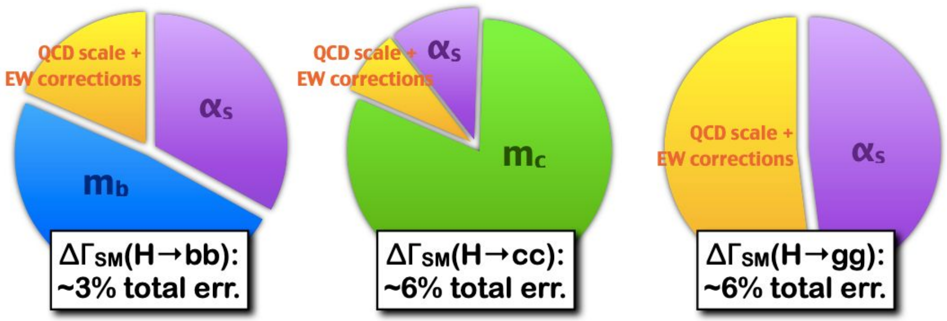
    ⟶ community effort: harvest "old data"

Theory Challenges in Precision Measurements

Lattice QCD for high-energy colliders (*Ruth van de Water*)

In next five years, finer lattice spacings and improved methods will roughly halve lattice errors on mc, mb , and alphas, at which point the precision will be adequate for ILC or other foreseeable future colliders.

- **Parametric errors from quark masses (m_c, m_b) & strong coupling constant (α_S) ar largest sources of uncertainty in SM Higgs partial widths** for many decay modes [LHCHXSWG-DRAFT-INT-2016-008]



Theory Challenges in Heavy Flavor Decays (*Benjamin Grinstein*)

Challenges are perturbative matching/running, hard non-perturbative MEs, non-systematic approaches sneak in by force of being accustomed and lore

EF plan for Future Colliders Scenarios

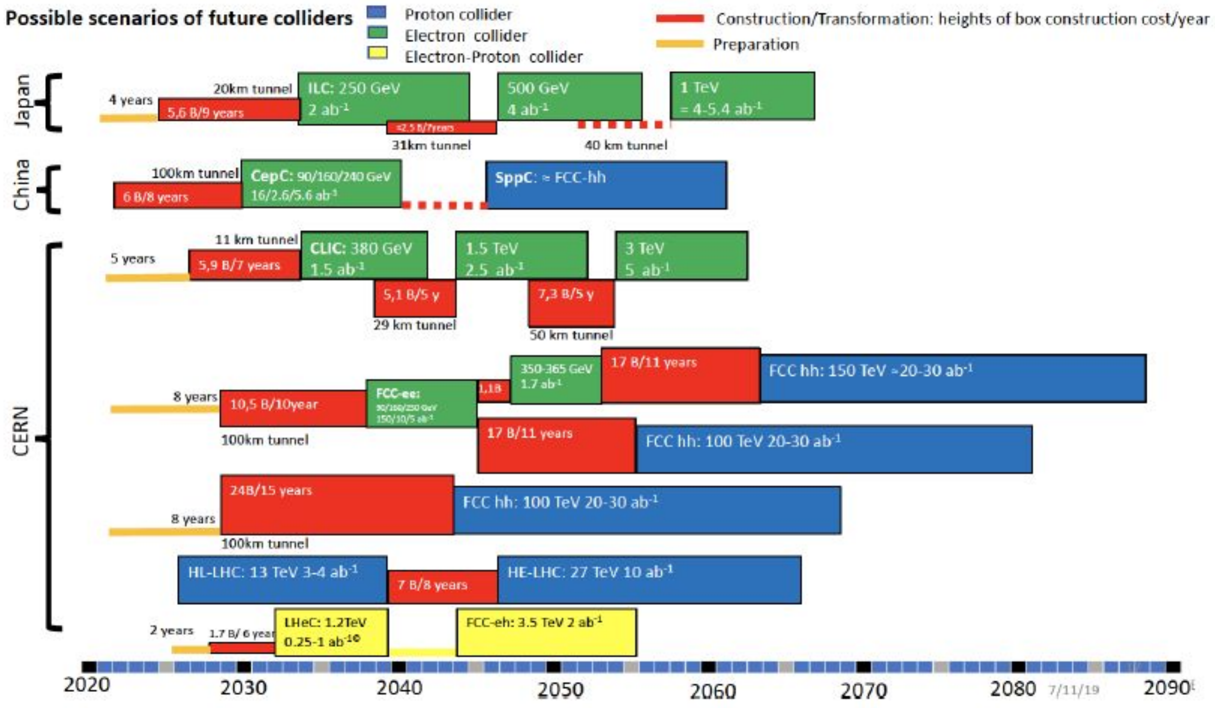
- ESG studies, comparing various options, are detailed in the briefing book

- We will **expand on these studies** and **add other collider scenarios**, e.g. Electron-Ion Collider, muon collider, γγ colliders, other c.o.m. ....

- Goals we set from the beginning of Snowmass 21:
  - Identify the “**Scientific Merits”** of the various collider options.
  - Develop a global picture and a future roadmap.
  - **Compile and complete existing studies** [start from ESG briefing book and confirm with AF].
  - **Add new studies** and information.
  - For pp future colliders, **HL-LHC will serve as a critical baseline.** HL-LHC results may be revisited if deemed necessary.

- Received LOIs from all current (LHC, HL-LHC) and future (ee,μμ,hh,eh) colliders collaborations.

Future Collider Scenarios & Timelines



Ursula Bassler @ Granada meeting

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

Snowmass 2021: EF Benchmark Scenarios

Snowmass 2021 Energy Frontier Collider Study Scenarios

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

Snowmass 2021 Energy Frontier Collider Study Scenarios

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

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

Other options to explore:

- Muon collider at a very high energy (>30 TeV?)[Need to consolidate growing list of c.o.m. energies]
- FCC pp >200 TeV? and ~75 TeV documenting sensitivity loss
- Very high energy e+e- collider
- gamma-gamma collider [need to understand energy/luminosity]

EF: Higgs Factories

Breakout Session #129
(Junping Tian)

proposals of future e+e- colliders

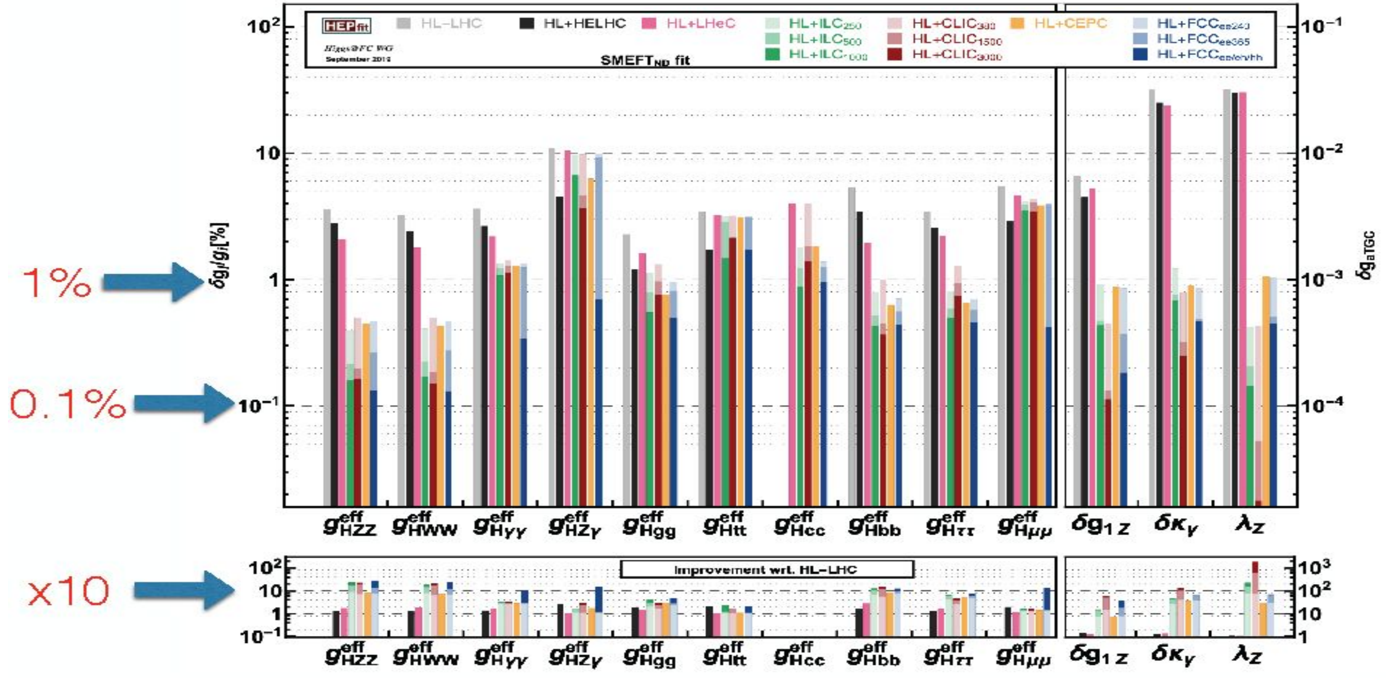
	$\sqrt{s}$	beam polarisation	$\int Ldt$ (baseline)	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2 ab^{-1} @ 250 GeV 0.2 ab^{-1} @ 350 GeV 4 ab-1 @ 500 GeV 8 ab-1 @ 1 TeV	TDR 2013
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	1 ab^{-1} @ 380 GeV 2.5 ab^{-1} @ 1.5 TeV 5 ab^{-1} @ 3 TeV	CDR 2012
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5.6 ab^{-1} @ 250 GeV 16 ab^{-1} @ M_Z 2.6 ab^{-1} @ $2M_W$	CDR 2018
FCC-ee	90 - 350 GeV	e-: 0% e+: 0%	150 ab^{-1} @ M_Z 10 ab^{-1} @ $2M_W$ 5 ab^{-1} @ 250 GeV 1.7 ab^{-1} @ 365 GeV	CDR 2018

common: Higgs factory with $O(10^6)$ Higgs events
differ in energy reach, luminosity, polarization, project readiness

EF: Higgs Factories

Breakout Session #129
(Junping Tian)

expected Higgs coupling precisions @ future e+e-



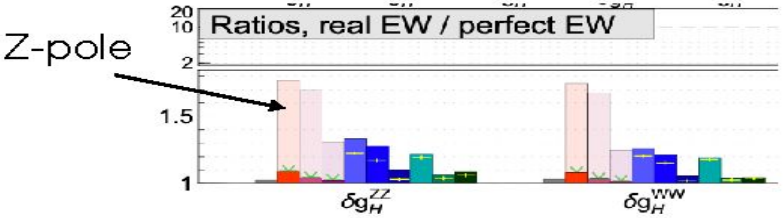
[global SMEFT fits by ESG]

EF: Higgs Factories

Breakout Session #129
(Junping Tian)

global perspective for Higgs meas. @ future e+e-

- the same new physics that modifies Higgs properties may show somewhere else as well
  - combined probe with EWPO, $e^+e^- \to$ WW / 2-fermion
- great synergies with (HL-)LHC measurements
  - Higgs rare decays; Top-quark EW couplings; TGC / QGC; etc
- CEPC / FCC-ee: important role by *Z-pole run*, ~x2 better δg_{HVV}
- ILC/ CLIC: important role by *beam polarizations*, made up $\int L$



[de Blas et al, arXiv:1907.04311]

[ESG] SMEFT$_{ND}$	ILC250	CLIC380	CEPC	FCC-ee240
$\int L$•ab	2	1	5.6	5
δg_{HZZ}	0.39%	0.5%	0.45%	0.47%
δg_{Hbb}	0.78%	0.99%	0.63%	0.71%
$\delta g_{H\tau\tau}$	0.81%	1.3%	0.66%	0.69

EF: Discovery Machines

See Breakout Session #26
(Meenakshi Narain, Summary talk)

- **Directions being pursued:**
  - **Hadron-hadron colliders**
    - Proposals for pp at 100 TeV (FCC-hh, SppC)
    - Some studies at 27 TeV and 33 TeV exist
    - Addition of other c.o.m. energies, 75 TeV?
  - **Lepton colliders**
    - Studies for muon colliders >=10 TeV,
      - international collaboration being formed
      - Large number of LOIs submitted!
      - Addition of other c.o.m. energies, 30, 100 TeV?
    - Gamma-gamma collider
      - 30 TeV? (discussed in session #186.)
- **Plans until CSS**
  - understand what "Energy and luminosity" would be best suited for a discovery machine
    - pp >> 100 TeV
    - High energy muon collider > 30 TeV
    - Very high energy e+e- collider

An example: muon collider

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[3], Nathaniel Craig[1], JiJi Fan[4], Isabel Garcia Garcia[5], Samuel Homiller[6], Seth Koren[7], Giacomo Koszegi[1], Zhen Liu[8], Qianshu Lu[6], Kunfeng Lyu[9], Amara McCune[1], Patrick Meade[10], Isobel Ojalvo[11], Umut Oktem[1], Matthew Reece[6], Raman Sundrum[8], Dave Sutherland[12], Timothy Trott[1], Chris Tully[11], Ken Van Tilburg[5], Lian-Tao Wang[7], and Menghang Wang[1]

- Illustrate:
  - Muon collider as an all-in-one machine - can achieve both precision and energy!
  - Muon collider as an electroweak boson collider

See P. Meade's talk, Session #26

- Attempt to quantify the integrated luminosity required at a given c.o.m. Energy to discover or constrain a given point in parameter space.
- For the purposes of forecasting two luminosity scalings are used -- “optimistic" scaling assumes integrated luminosity growing with “s” and, a more “conservative” scaling which follows the optimistic scaling up to c.o.m. E of 10 TeV, after which it remains at at 10 ab-1 for all subsequent energies.

$\sqrt{s}$ [TeV]	1	3	6	10	14	30	50	100
$\mathcal{L}_{\rm int}^{\rm opt}$ [ab^{-1}]	0.2	1	4	10	20	90	250	1000
$\mathcal{L}_{\rm int}^{\rm con}$ [ab^{-1}]	0.2	1	4	10	10	10	10	10

EF-TF collaboration!

EF activities towards Community Summer Study

- Moving ahead towards the CSS, EF Topica Groups will continue their regular meetings and workshops. ↪️See timeline in Back-up Slides.
- Time to **develop the studies planned before and during this meeting.**
- **EF is planning two all-frontier workshops:**
  - **Spring (April/May)**
    - To check the status of studies for the final Report.
    - To help coordinating the summaries of Contributed Papers.
  - **Late Spring/Early Summer (June)**
    - To review the inputs to the draft report.
- A **joint workshop with AF and TF** is being discussed.
- More cross-frontier workshops are being planned by individual EF Topical Groups.
- **We appreciate your feedback**: EF survey

Back-up slides

Preliminary Snowmass Timeline / Process

Starting point for discussion with the community during CPM

Meetings & Workshops (10 Frontiers & 80 Topical Groups) + Contributed Papers

Nov. 2020	Dec. 2020	Jan. 2021	Feb. 2021	Mar. 2021	Apr. 2021	May 2021	Jun. 2021	Jul. 2021	Aug. 2021	Sep. 2021	Oct. 2021
					Community Meeting (APS April Meeting)			Community Summer Study (CSS) July 11-20, 2021 + DPF 2021 (UW Seattle)			Snowmass Report

TGs: effort on consolidation, coordination & solicitation, leading to studies & Contributed Papers

TGs develop their key questions and opportunities

TGs produce outlines of their reports
(TGs: communication with authors of Contributed Papers)

Frontiers/TGs produce Preliminary Frontier Reports
Community feedback on Preliminary Frontier Reports

CSS

Build consensus on key questions / opportunities of particle physics, enabling technologies, and community engagement;
Formulate the content of the Snowmass Executive Summary

Frontiers/TGs produce Final Frontier Reports
Steering Group produces Preliminary Executive Summary
Community feedback on Prelim. Exec. Summary
Snowmass Draft Report and Review
Snowmass Final Report

Energy Frontier Specific
Preliminary Snowmass Timeline / Process

Starting point for discussion with the community during CPM

Meetings & Workshops (10 Frontiers & 80 Topical Groups) + Contributed Papers

Nov. 2020	Dec. 2020	Jan. 2021	Feb. 2021	Mar. 2021	Apr. 2021	May 2021	Jun. 2021	Jul. 2021	Aug. 2021	Sep. 2021	Oct. 2021

TGs: effort on consolidation, coordination & solicitation, leading to studies & Contributed Papers

TGs develop their key questions and opportunities

Community Meeting (APS April Meeting)

Community Summer Study (CSS) July 11-20, 2021 + DPF 2021 (UW Seattle)

Snowmass Report

- **This is an opportunity for EF participants to engage in the activities of the Topical Groups, and present /discuss their work**
- Topical Group and EF Conveners have been developing focus/key questions and preparing a summary of the existing physics landscape as a starting point of the report.
- The topical groups may need input from their community to include a brief description of proposed/ongoing work.
- This is also an opportunity to identify any gaps in physics topics and work on them.

Energy Frontier Specific
Preliminary Snowmass Timeline / Process

Starting point for discussion with the community during CPM

Meetings & Workshops (10 Frontiers & 80 Topical Groups) + Contributed Papers

Nov. 2020	Dec. 2020	Jan. 2021	Feb. 2021	Mar. 2021	Apr. 2021	May 2021	Jun. 2021	Jul. 2021	Aug. 2021	Sep. 2021	Oct. 2021
					Community Meeting (APS April Meeting)			Community Summer Study (CSS) July 11-20, 2021 + DPF 2021 (UW Seattle)			Snowmass Report

Contributed Papers Deadline: July 31, 2021
Contributed papers : "... *may include documents on specific scientific areas, technical articles presenting new results on relevant physics topics, and reasoned expressions of physics priorities, including those related to community involvement.* "

TGs produce outlines of their reports
(TGs: communication with authors of Contributed Papers)

Frontiers/TGs produce Preliminary Frontier Reports
Community feedback on Preliminary Frontier Reports

- **This is an opportunity for EF participants to make sure their work is reflected in the report.**
- **During Spring, the EF will announce the mechanism for collection of summaries of results to be included in the report by May 2021.**
- The TG conveners will assemble the report until July workshop. The TG conveners will start from the input provided by contributors, and edit the input to match the style and length of the report.
- We will solicit feedback on this preliminary report from the community to verify that their work has been summarized correctly.

Energy Frontier Specific
Preliminary Snowmass Timeline / Process

Starting point for discussion with the community during CPM

Meetings & Workshops (10 Frontiers & 80 Topical Groups) + Contributed Papers

Nov. 2020	Dec. 2020	Jan. 2021	Feb. 2021	Mar. 2021	Apr. 2021	May 2021	Jun. 2021	Jul. 2021	Aug. 2021	Sep. 2021	Oct. 2021
					Community Meeting (APS April Meeting)			Community Summer Study (CSS) July 11-20, 2021 + DPF 2021 (UW Seattle)			Snowmass Report

CSS

Build consensus on key questions / opportunities of particle physics, enabling technologies, and community engagement;
Formulate the content of the Snowmass Executive Summary

Frontiers/TGs produce Final Frontier Reports
Steering Group produces Preliminary Executive Summary
Community feedback on Prelim. Exec. Summary
Snowmass Draft Report and Review
Snowmass Final Report

Preliminary Snowmass Report Structure

Starting point for discussion with the community during CPM

Preliminary
Report Structure:
Adopting Snowmass 2013

Executive Summary
(~50 pages)
Introduction
A few pages from each Frontier

Frontier Report

Frontier Summary
(20~50 pages)

Topical Group Reports
(20~50 pages per TG)

Contributed Papers as References

Snowmass 2013

Intensity Frontier

Chapter 2: Intensity Frontier
Conveners: J.L. Hewett and H. Weerts

Working Group Summary (arXiv:1401.6077)

Subgroup Reports:

12. Neutrinos 1310.4340
13. Baryon Number Violation 1311.5285
14. Charged Leptons 1311.5278
15. Quark Flavor Physics 1311.1076
16. Nucleons, Nuclei, and Atoms 1312.5416
17. New Light Weakly Coupled Particles 1311.0029

Contributed Papers:

General:

001	K. Lesko	Why the US Needs a Deep Domestic Research Facility: Owning rather than Renting the Education Benefits, Technology Advances, and Scientific Leadership of Underground Physics	1304.0402 (PD
019	S. Holmes, *et al.*	Project X: A Flexible High Power Proton Facility	1305.3809 (PI
021	S. Glashow	Particle Physics in the United States: A Personal View	1305.5482 (PI
024	V.Shiltsev, *et al.*	Issues and R&D Required for the Intensity Frontier Accelerators	1305.6917 (PI
055	A. Kronfeld, *et al.*	Project X: Physics Opportunities	1306.5009 (PI
056	S. Holmes, *et al.*	Project X: Accelerator Reference Design	1306.5022 (PI

EF01: Higgs properties - Focus Questions

- **How well can Higgs interactions be measured at future colliders?**
  - Can we uncover the nature of UV physics from precision Higgs measurements?
  - Can the Higgs give us insight into flavor?
  - What do measurements of the Higgs mass, width, invisible decays tell us?
  - Capitalize on the complementarity with HL-LHC
- **What collider/detector properties are necessary to probe the Higgs self interactions?**
  - Can we devise benchmark models?
- **What theory calculations do we need to capitalize on Higgs measurements?**

EF02: Higgs as portal to new physics - Key ideas

Standard Approach:
Given a specific collider, what can we do?

Our Approach:
Determine what are some of the theory questions we would like to address

- Focus on aspirational targets which are theory driven!
  Formation of a "BSM Wishlist"

- Explore a comprehensive range of future collider options to understand what is needed from the collider and experimental communities

- Identify technologies which will lead to discoveries (via the Higgs Portal)

- Collaborate with EF01 to determine what level of precision is needed

- **Past Meetings:**
  2HDMs, Triple Higgs Couplings and Beyond, Higgs and Flavor, HH benchmarks, LOI Review
- **Future Meetings**:
  Naturalness, Exotic Decays, Naturalness… and more!

EF03: Heavy Flavor and Top Quark Physics – Some key questions

- How can the full exploration of the top quark, the heaviest known elementary particle, help elucidate the Higgs sector and inform about possible physics beyond the SM?
- What is the ultimate precision that can be reached for the measurement of a well-defined top quark mass and how much does it improve the reach of a global EW precision fit? What else can be learned (e.g, vacuum stability)? And if we want to push for the highest possible precision what is needed to reduce the theoretical uncertainties at the required level?
- What is the potential for discovery and studies of rare top-quark production processes, such as multiple top production and top in association with other heavy SM particles, and what is their impact on a global EFT fit and direct BSM searches?
- What can be learned from measurements of top quark properties other than the top quark mass and couplings such as spin correlations, asymmetries, polarization in new kinematic regimes, and what is the achievable/required precision?
- What are the optimal top quark observables for constraining EW top quark couplings in EFT fits? What can we learn from these constraints about specific BSM models?
- What is the potential of multi-differential cross sections in top quark production processes to simultaneously extract α_s, m_{top}, and the gluon PDF?
- What is the potential of heavy-quark production cross sections (also in association with EW gauge bosons) to probe heavy-quark PDFs, and could this improve the achievable precision of Higgs+heavy quark production processes?
- What can be learned from precision measurements of heavy-quark pair production at lepton colliders, and are systematic uncertainties from theory under control, especially higher-order electroweak corrections?

EF04: EW precision physics - Highlights

- **EF04 Mandate**: constraining new physics by precision fits of SM observables
- **Main theme topics appearing in EF04**
  - Global EFT fits
  - EWPO at future colliders
  - Multi-boson processes at LHC & high energy lepton colliders
- **Inputs from community**
  - Big questions of EF04 relevance collected in twiki page
  - Sixty LOIs submitted to EF04 attention
- **EF04 wishlist & possible advances for Snowmass 2021** (incomplete)
  - Critical assessment of systematic errors on future EWPO
  - Better understanding on roles by multi-boson processes
  - Addressing theory errors & validity in EFT fits
  - New opportunities of constraining new physics from improved global EFT fits
- **Challenges**
  - Many inter-TG and inter-frontier interactions; significant organizational challenge

EF05 Precision QCD – Focus Questions

Fundamental (theory + phenomenology):

- What precision in $alpha_S$ 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? How can we tell? 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?

Uncertainties:

- more precise and robust systematic uncertainties – try to develop a better formulation – disentangle theory & experiment
- What *is* a theoretical uncertainty (e.g. renormalization and factorization scales)?
- "Les Houches" accord on a realistic assessment of parton shower uncertainties (and correlations).

Data:

- Promote the analysis of Belle data to provide crucial information on non-perturbative QCD
- 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?
- What information (if any) can be extracted from neutrino data - i.e., data used to calibrate beam fluxes?

Computing:

- Specify the strengths and weaknesses of existing MC event generators – define what is needed for the future.

EF05 & EF06: major overlap on PDFs. **EF05 & EF07: major overlap on EIC-related topics**

EF08 BSM: Model dependent 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. This allows the comparison of experimental reach between various approaches, e.g. direct searches vs precision. This group focuses on evaluating the reach of EF experiments in the framework of a few critical models (selection being discussed).

The key questions for the group are:

- Which models to consider? Want a broad but achievable set of models
- What are the appropriate benchmarks/summary plots? Examples…
- How to compare broad model spaces in a concise and effective way? For example, 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 is naturalness a guide to which measurements are most relevant for a particular model, and when that model becomes less attractive? And then ultimately how does that feed into comparisons of experiment plans and their expected results.
    - If we exclude parameter space XYZ how will the field be advanced?
    - How will the relative fine-tuning change before and after project XYZ?

Forming small working groups to coordinate these investigations Please join!

EF09: BSM General Explorations Focus Questions

representative, not comprehensive

- Are there new interactions or new particles around or above the electroweak scale? To what extent can future experiments and colliders probe this ?
  - What's the interplay with precision measurements? (see session #126)

- 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?
  - Including interplay with DM (#108, #136)
  - Dedicated workshop on dark sector and light LLPs (also #127)

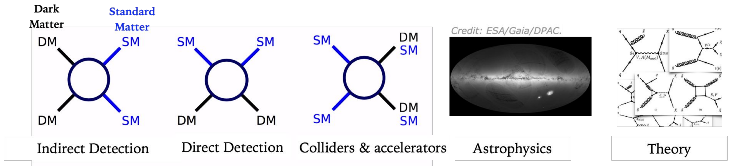
- How do we conduct searches in a more model-independent/agnostic way ?
  - Session #132

- How do we compare the results of different experiments in a more model-independent way to ensure complementarity and avoid big gaps in coverage?

- Is lepton flavor/universality violated ? What do we learn from high energy/p_T searches ?
  - See dedicated workshop here

DM@Colliders (EF10) focus questions & highlights

1. **How can we best test the WIMP paradigm?**
   - Simplest/minimal WIMP models (EW multiplets & extensions)
     i. *Mapping out full space of models, and optimizing searches.*
   - Simple mediator models
     i. *Work ongoing towards complementarity with non-EF experiments, involvement from SEC researchers*
   - Through the Higgs portal
     i. *LOI motivating and quantifying the impact of HL-LHC / FCC / Higgs factories, developed with EF02*
2. **How can we best explore beyond-WIMP scenarios?**
   - Using portals that privilege light dark sectors / dark matter: long-lived particles
   - Using less-explored *signatures* of dark sectors
     i. *Most numerous LOI category - working with EF09 / RF06 / AF02-5*
3. **How to best exploit synergies?**
   - In terms of different experiments / observations
     i. *Will plan topical workshops with CF/RF/NF*
   - In terms of detector, software, data acquisition and trigger design
     i. *Will join CompF/CommF/IF meetings for cross-talk LOIs*



Full list of EF10 LOIs & recordings [here]

CPM EF10 Session highlights.

EF10 involved in the following sessions:

#108 (Tue-11:30) - Accelerator Probes of Light Dark Matter (keV-GeV)

- *Energy frontier experiments can produce very boosted light dark matter → potential of future EF facilities*
- *Synergies with rare & precision frontier, neutrino and low-mass DM direct detection*

#127 (Tue-14:00) - Searches for Dark Sectors (focused on mediators)

- *Extremely active theory & experiment community, breadth of signatures and inter-frontier connections*
- *Work on DM (& more) benchmark is underway from the RF - see this summary slide by S. Gori / N. Toro*

#136 (Tue-11:30) - Heavier particle dark matter >~ 10 GeV

- *Theoretical && experimental motivation still strong for WIMPs*
  - *Generation-2 direct detection experiments + (HL-)LHC can probe some of the remaining phase space*
  - *Future colliders / indirect detection needed for TeV-scale WIMPs and above*
- *Randomized breakout sessions led to 30' of productive cross-frontier discussions, summarized in #150 and here*

#150 (Wed-12:15) - Dark matter complementarity

- *Great turn-out of ideas / sessions / participants → much work ahead*
- *Plan to write one or more "complementarity" contributed papers to be cited by TG reports*

B.S. #131: Physics requirements for detectors of future colliders
(C. Vernieri and A. Korytov)

Some key points

* Most inputs from BRN (position and timing precision, momentum and IP resolution). From LoIs, additional info in radiation length from 0.1%-1%. Additional requirements may come from LLP/dense jet requirements as wells as additional charm, strange, tau-tagging requirements may come from LoI.

* Beam-induced backgrounds can affect LLP search sensitivity. Important to consider bunch spacing and trigger/DAQ/reconstruction throughput, latter also between bunches, to catch LLP decays. Requirements on granularity and particle ID from LLP searches (e.g. use of dE/dx ⇒ analog readout in tracker and calorimeter). Worth exploring the feasibility of TPC tracking systems for LLP searches. Interest in not throwing out out-of-time signals. Interest in building experimental halls with future LLP detector extensions in mind. Snowmass goal: understand how LLP requirements are already covered by, or extend, requirements conceived by BRN study.

* Strong interest in MIP timing from jet reconstruction/substructure. Worth exploring (K/p/n)-pi separation with time of flight. O(10-20 ps) requirement for a MIP timing layer just in front of the EM calorimeter. Worth exploring intrinsic SiPM time resolution, though requirements may not be strong given natural time development of showers and resolution on clock distribution. For 100 TeV collider: need to consider deep (12 lambda_I) HCAL with small (3%) constant term for TeV jets and high transverse granularity for highly boosted particles, but longitudinal granularity requirement still unknown. Worth exploring jet resolution and substructure performance in dual readout calorimeter design.