Snowmass physics: Energy Frontier & Future Collider

Joint Workshop of the CEPC Physics, Software and New Detector Concept

May 23 - 25, 2022

Meenakshi Narain
(Brown University)

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

Snowmass2021 Timeline

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

Contributions by CepC

- CEPC Accelerator Study Group. ”Circular Electron Positron Collider (CEPC)“, arXiv:2203.09451 [physics.acc-ph] (pdf). (also under AF03)

- Huajie Cheng, Wen Han Chiu, Yaquan Fang, Yu Gao, Jiayin Gu, Gang Li, Tianjun Li, et al. “The Physics potential of the CEPC”, arXiv:2205.08553 [hep-ph] (pdf). (also under TF0, AF0)

- Zhen Wang, Xuliang Zhu, Elham E Khoda, Shih-Chieh Hsu, Nikolaos Konstantinidis, et al. ”Study of Electroweak Phase Transition in Exotic Higgs Decays at the CEPC”, arXiv:2203.10184 [hep-ex] (pdf).

Energy Frontier at Snowmass 2021

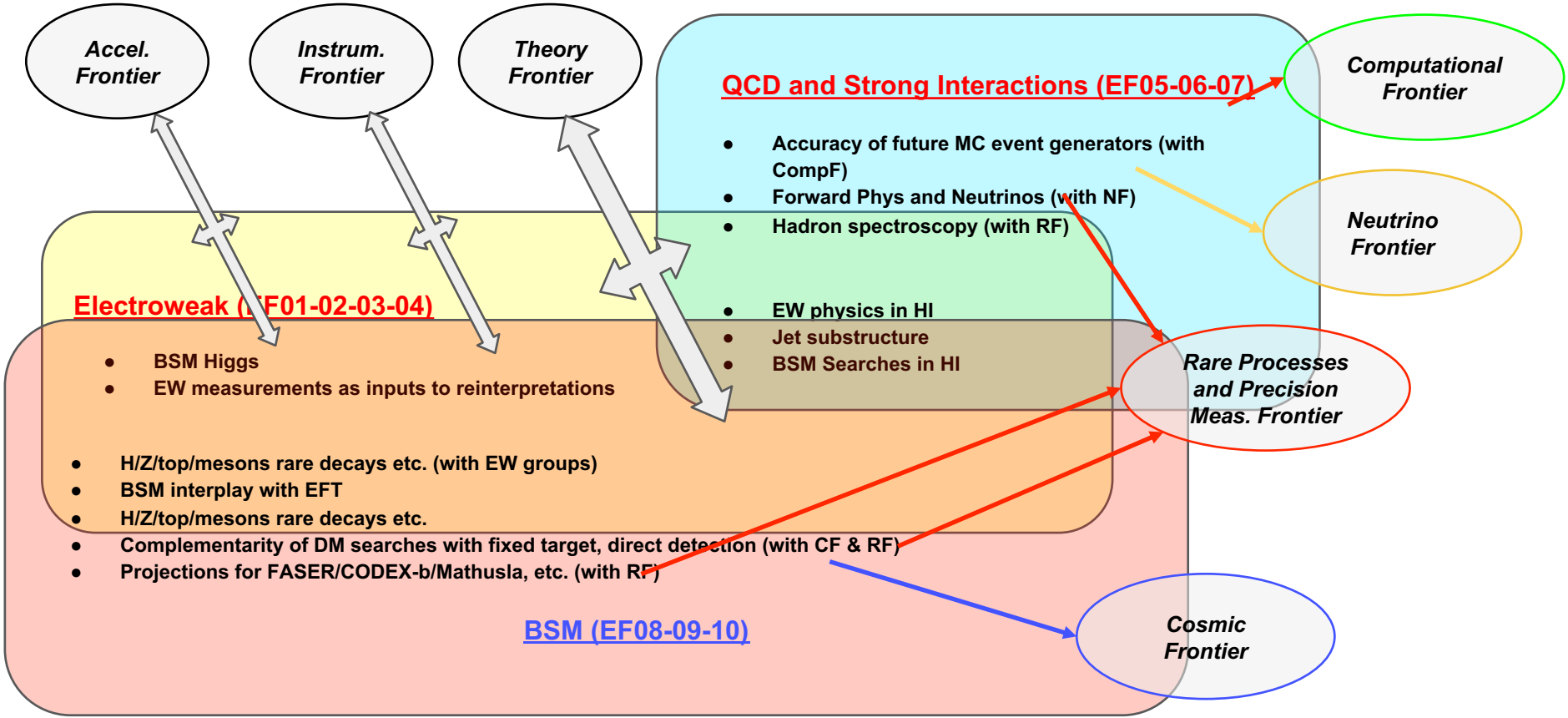
- Collider Physics is an opportunity to study a huge number of phenomena!!
  - Origin of EW Scale
  - Evolution of the Early Universe
  - New constituents of matter
  - Origin of Flavor
  - Additional Symmetries of Spacetime
  - Nature of Dark Matter
  - Origin of Neutrino Mass

Energy Frontier Topical Groups

Ten Topical Groups focused on Electroweak, QCD, BSM physics

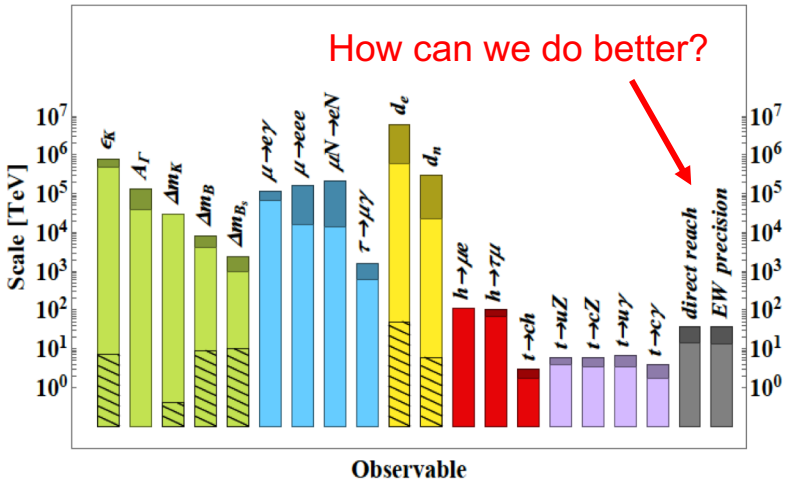
Topical Group	Co-Conveners		
EF01: EW Physics: Higgs Boson properties and couplings	Sally Dawson (BNL)	Andrey Korytov (U Florida)	Caterina Vernieri (SLAC)
EF02: EW Physics: Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook)	Isobel Ojalvo (Princeton)	
EF03: EW Physics: Heavy flavor and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

Synergies between EF TG and Other Frontiers



Probing the energy scale for new physics

Probing the energy scale for new physics



Reach in new physics scale from both direct and indirect searches

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

Key physics questions of the EF program

What is the origin of the electroweak scale?

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

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

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

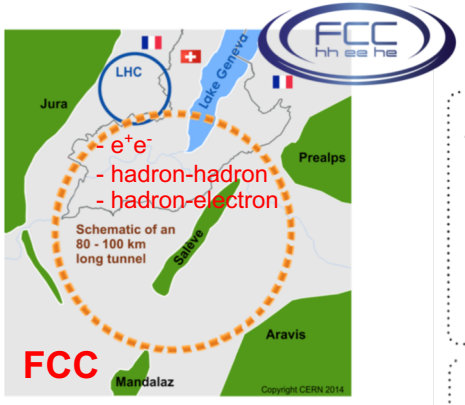
Key physics questions of the EF program

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

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

Finding answers generates more specific questions.

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



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

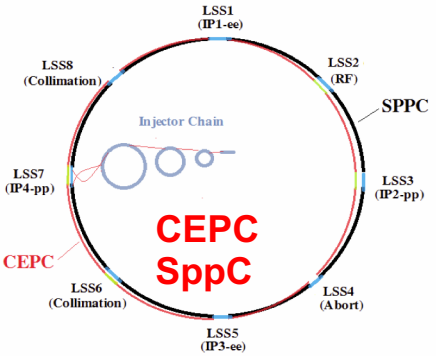
Circular

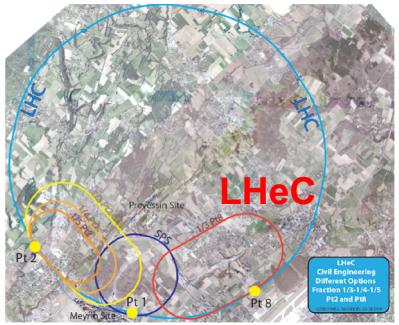
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
  - $\sqrt{s}$ limited by synchroton radiation

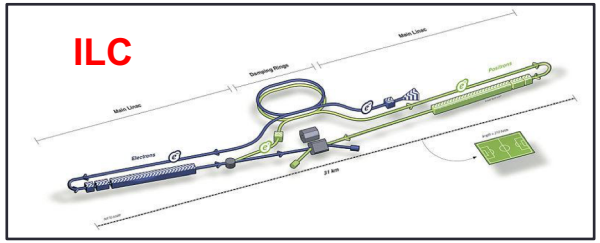
Linear

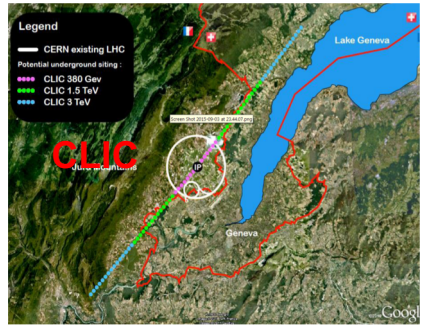
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
  - large beamsthralung
  - one IP only

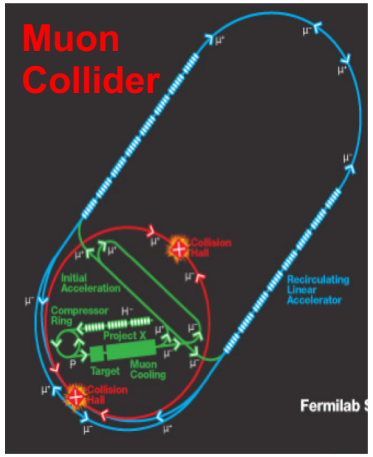
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders



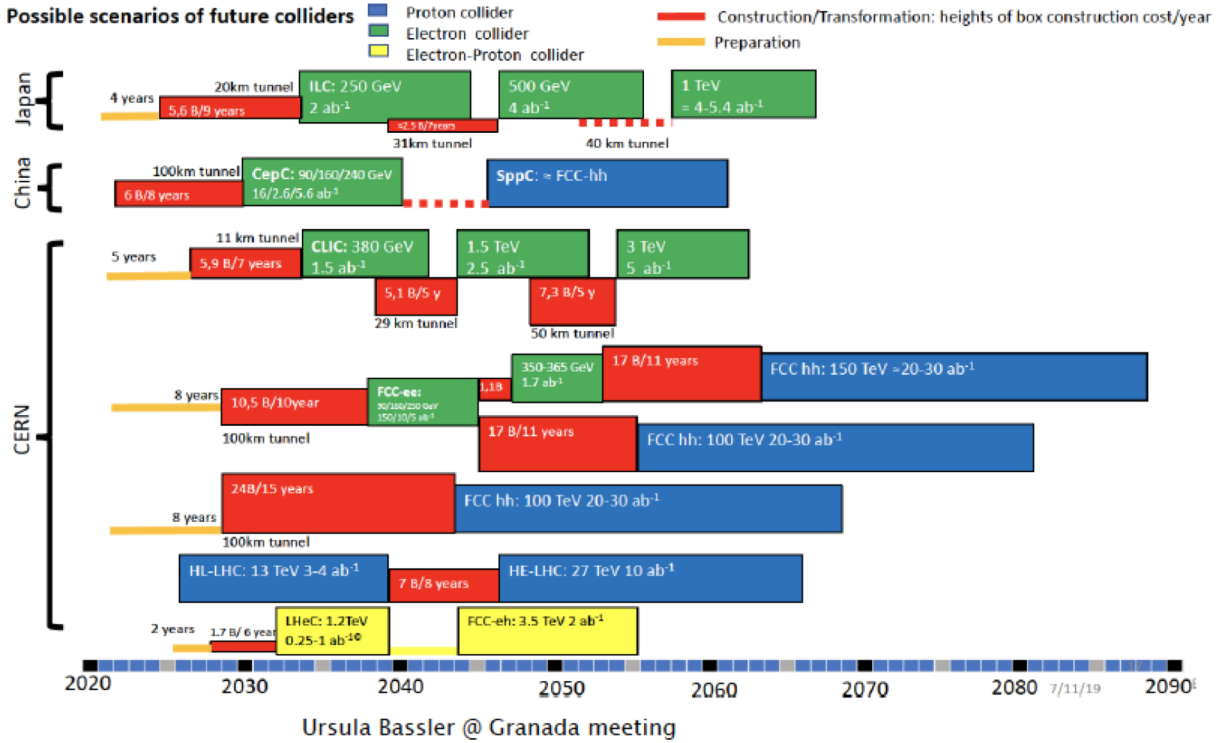








Future Collider Scenarios & Timelines



- Will add **EIC** and **Muon Collider** to this chart.
- Will consider **new proposals** that have come up during Snowmass 2021.
  - e.g. initiatives for C^3, gamma-gamma, plasma colliders etc.

Snowmass 2021 Higgs Factory Study Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3	ee	250 GeV	$\pm 80/\pm 30$	2
c.o.m almost		350 GeV	$\pm 80/\pm 30$	0.2
similar		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
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Snowmass 2021: EF Benchmark Scenarios

Snowmass 2021 EF Discovery Collider Scenarios

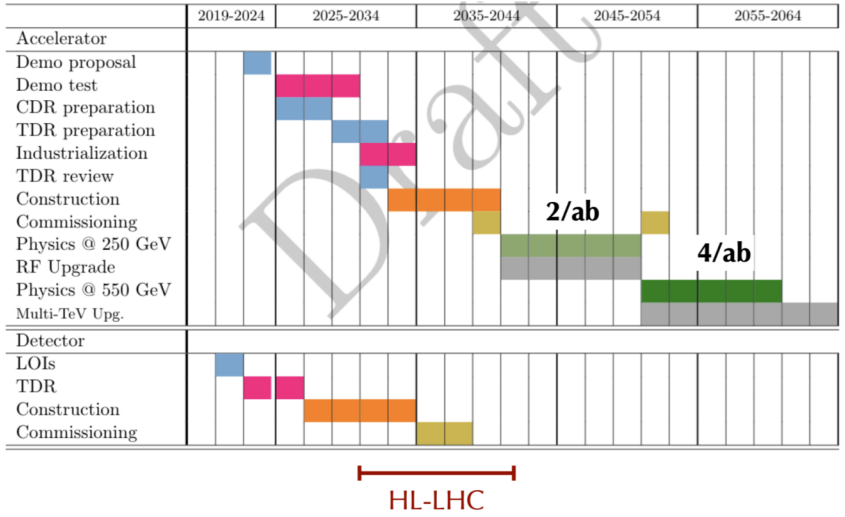
Collider	Type	$\sqrt{s}$	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV	15
FCC-hh	pp	100 TeV	30
LHeC	ep	1.3 TeV	1
FCC-eh	ep	3.5 TeV	2
High energy muon-collider	$\mu\mu$	3 TeV	1
		10 TeV	10
		30 TeV	10

C^3 - Cool Copper Collider

Based on a new SLAC technology

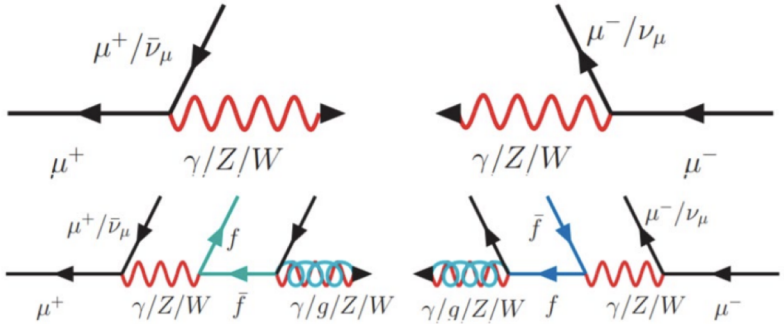
- Two Key Technical Advances:
  - Distributed Coupling & Cryo-Copper RF
- Operation at cryogenic temperatures (LN2 ~80K)
- Robust operations at high gradient: 120~MeV/m
- Scalable to multi-TeV operation
- Operate at 250 and 550 GeV with possible commissioning at the Z pole

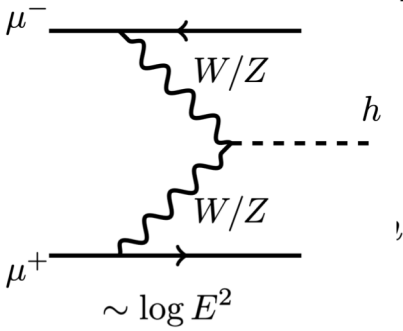
C^3 timeline

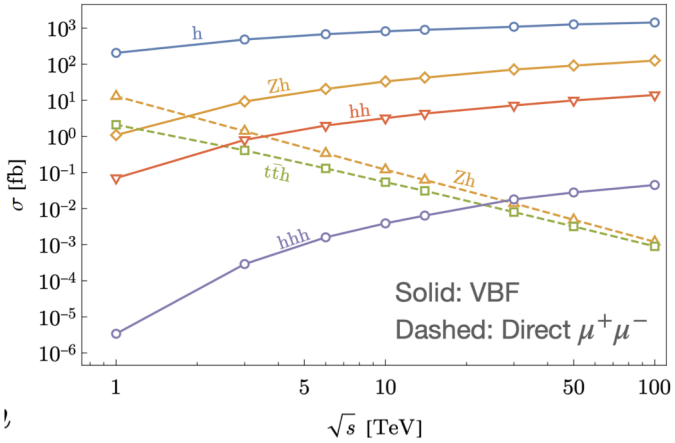


Muon Colliders

- First proposed more than 50 years ago, renewed interest in Muon Collider facilities in recent years, due to recent advances in technology!
- Muons do not suffer from energy loss due to Bremsstrahlung that makes e+e- circular machines difficult! But they do have a very short lifetime.
- Muon Colliders are actually EWK colliders with a mix of initial states







Snowmass Agora on Future Colliders

Series of events jointly organized by AF and EF, hosted by the Future Colliders initiative at Fermilab, to discuss both near and far future collider proposals, in different stages of development, synergistically grouped into five categories:

- e+e- linear colliders (Dec. 15, 2021): https://indico.fnal.gov/event/52161/
- e+e- circular colliders (Jan. 19, 2022) https://indico.fnal.gov/event/52534/
- μ+μ- colliders (Feb. 16, 2022): https://indico.fnal.gov/event/53010/
- circular pp and ep colliders (Mar 16, 2022)
- advanced colliders (April 13, 2022)

Critical discussions of physics reach, challenges and RD required, synergies with global context and local resources, timeframe, cost projection.

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

Will converge to dedicated discussion at the upcoming EF Workshop (March 28-April 1).

Caveats

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

- There are 100+ contributed papers
  - I cannot summarize all, so I have made personal choice.
  - As this audience may be already familiar with the results from CepC Physics studies, I choose to show majority of results which are non-CepC.
  - I apologize in advance if this causes any concern, and your favorite study is not in these slides.

Highlights from EW Topical Groups

EF02 - Higgs boson as a portal to new physics

- 1) Higgs as origin of EWSB, naturalness/fine-tuning portal to new physics, 2) Higgs and flavor, 3) Higgs and EW phase transition.
  a. BSM Higgs: 2HDM, SUSY Higgs (A→Zh, LFV, Charged Higgs etc.), extra scalars, exotic decays, mono-Higgs searches
  b. Composite Higgs (with BSM groups)
  c. Effect on Higgs couplings to fermions/bosons and Higgs width from extending the scalar sector
  d. Flavor violating Higgs production and decays
  e. H→ hh

- **Higgs rare decays**

EF01 - Higgs boson properties and couplings

- Higgs mass and width
- Higgs couplings to SM gauge bosons and fermions
- Higgs production modes: inclusive and diff.measurements (incl. ttH)
- HH production (includes resonant production)
- Higgs self-coupling
- **Anomalous couplings (including CP violation)**
- **Inputs to the Global Fit**

EF03 - Heavy flavor and top quark physics

- Heavy flavor production (top, bottom, and charm)
- Top-quark properties (mass, couplings) and diff. measurements
- New top-quark production modes and rare decays
- Detection algorithms for top-quark identification

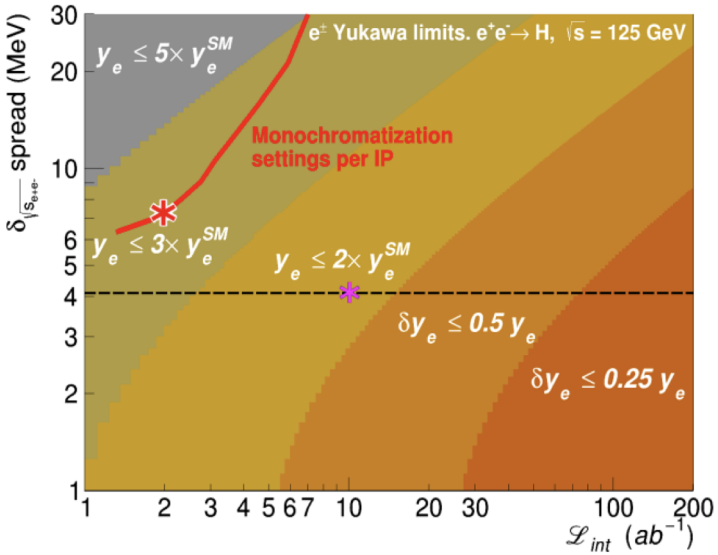
EF04 - Precision physics and constraining new phys.

- Precision fits of SM observables
- Multi-boson signatures, and VBF, VBS processes
- (SM)EFT analyses of EWPO, Higgs, and top observables
- Correlations among exp. and theory uncert.,
- Modeling of EW and QCD uncert., and their combination

Highlights from EF01 - Higgs boson properties and couplings

Conveners: Sally Dawson, Andrey Korytov, Caterina Vernieri

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



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

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

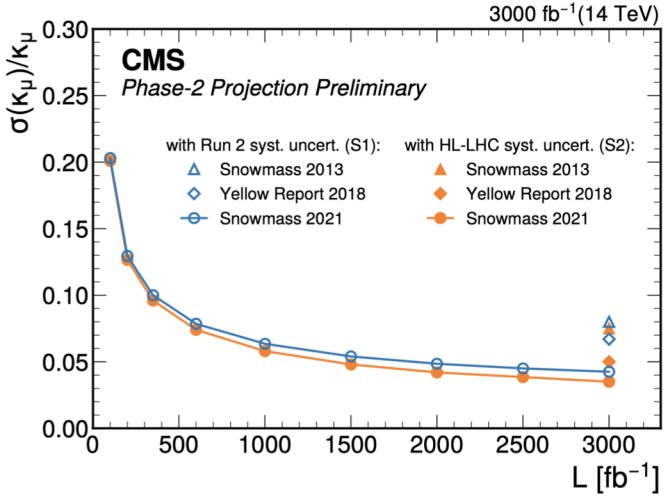
Higgs Couplings: HL-LHC New Projections

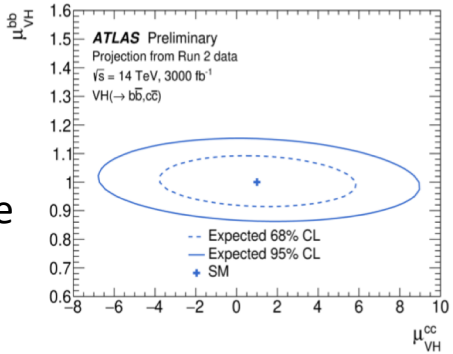
H→μμ

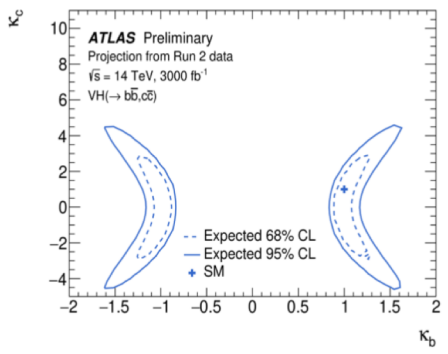
- YR projections performed from partial Run2 dataset analyses Full Run2 measurements have improved beyond expectations
- i.e. H→ττ or H→bb improved as ~sqrt(L) despite being dominated by systematic uncertainties

H→cc

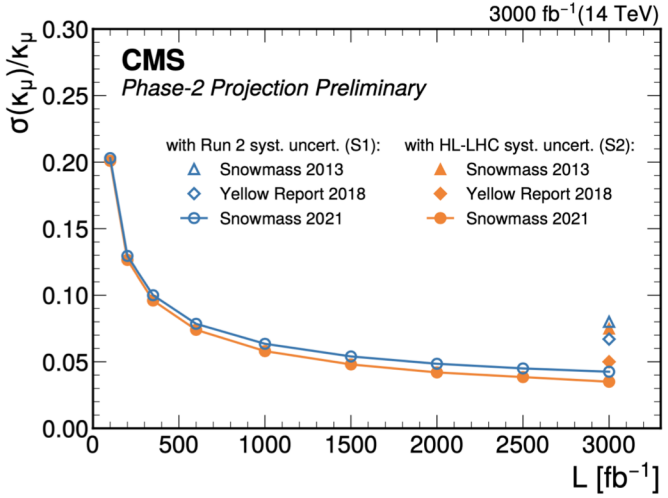
- Projection based on recent updates from ATLAS and CMS using Run2 dataset
- CMS' projection makes use of the powerful boosted analysis strategy
- Merged-jet category for events with pTH > 300 GeV
- Direct measurement of the Higgs coupling to the charm is within reach at the HL-LHC!







Higgs Couplings: HL-LHC New Projections

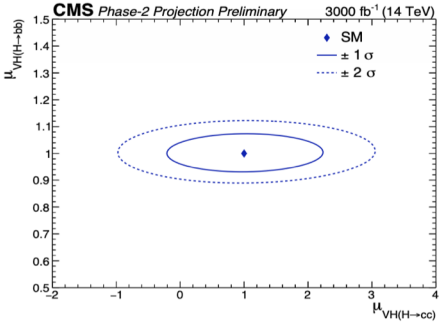


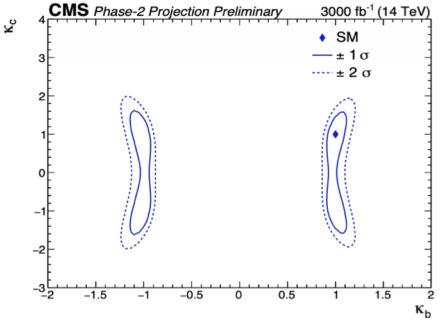
H→μμ

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

H→cc

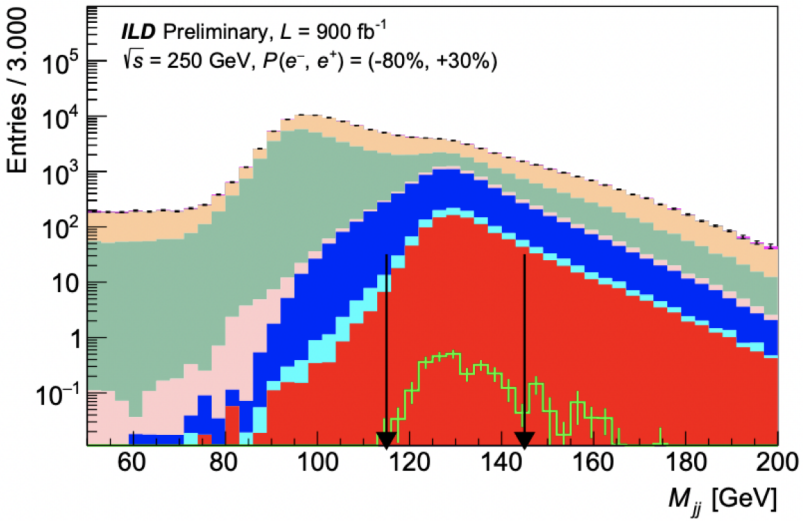
- Projection based on recent updates from ATLAS and CMS using Run2 dataset
- CMS' projection makes use of the powerful boosted analysis strategy
- Merged-jet category for events with pTH > 300 GeV
- Direct measurement of the Higgs coupling to the charm is within reach at the HL-LHC!

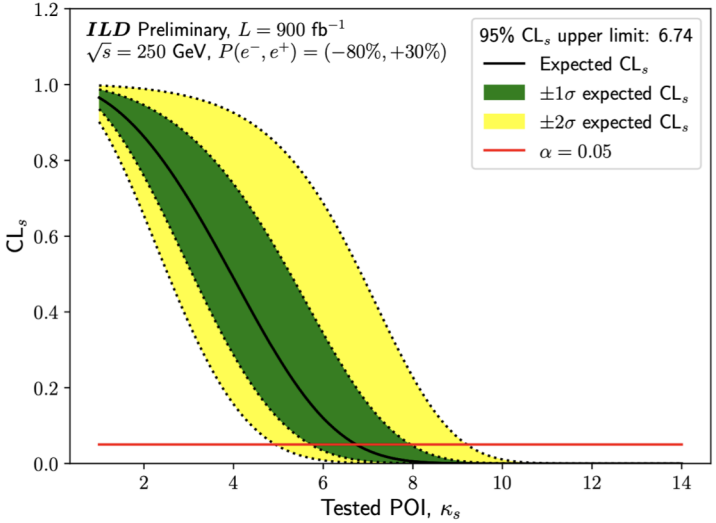




H to strange coupling

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

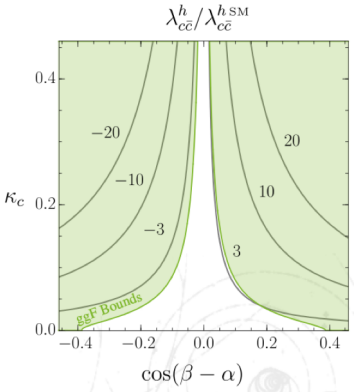




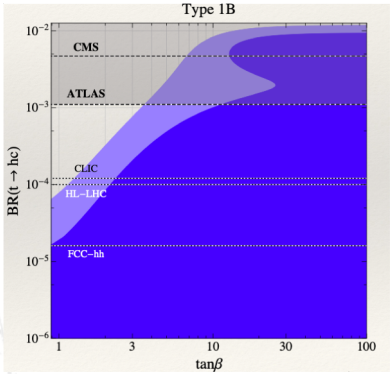
Highlights from EF02 - Higgs boson as a portal to new physics

Conveners: Patrick Meade, Isobel Ojalvo

Higgs and Flavor

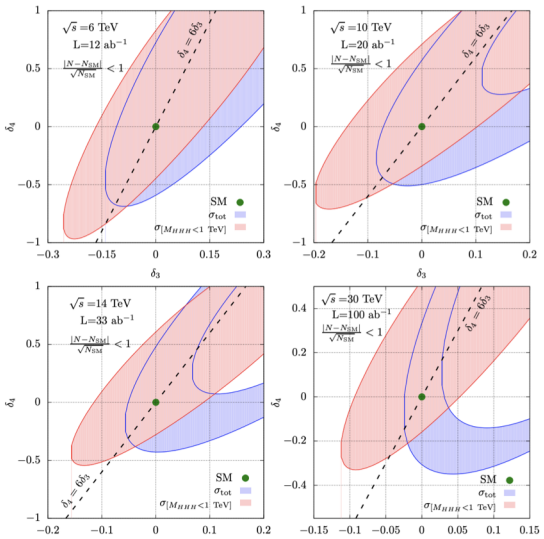


S. Hommiler



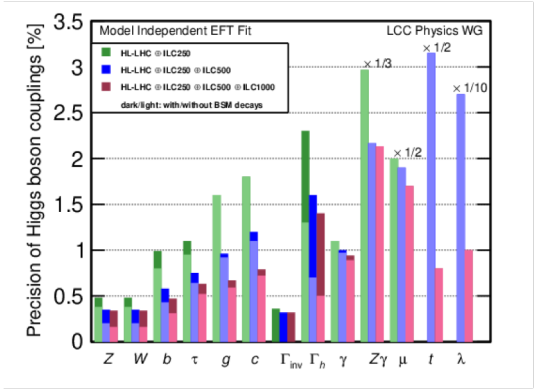
D. Tuckler

Higgs Quartic and Beyond



M. Chiesa, arXiv:2003.13628

Global Fits



arXiv:2004.14628

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

Lots of synergy between EF01 and EF02: similar need for new experimental techniques (e.g. strange tagging), but different focus for parameter space (EF02 more focused on models).

Highlights from EF03 - Top and Heavy Flavor Physics

Conveners: Reinhard Schwienhorst, Doreen Wackeroth

- **Prospects for precision measurements** (HL-LHC, FCC, ILC, muon collider,…):
  - top quark properties: mass, couplings
  - study of rare processes: single top, ttZ, ttW, tZq, tttt, FCNC, …
  - precision measurements of a wide variety of observables and in new kinematic regimes: spin correlations, boosted top, …
- **Joined studies**:
  - M_{top} in Global Electroweak fits (with EF04)
  - Top quark couplings and global EFT fits (with EF04)
  - Top and HF in PDF fits: extraction of gluon PDF, alphas, … (with EF06)
- **Prospects for HF physics (b,c) at future colliders**
  - Bottom quark couplings
- **Status of predictions and prospects for theory improvements**:
  - Interpretation of m_{top}, new ideas for m_{top} measurements
  - Higher order QCD and EW corrections

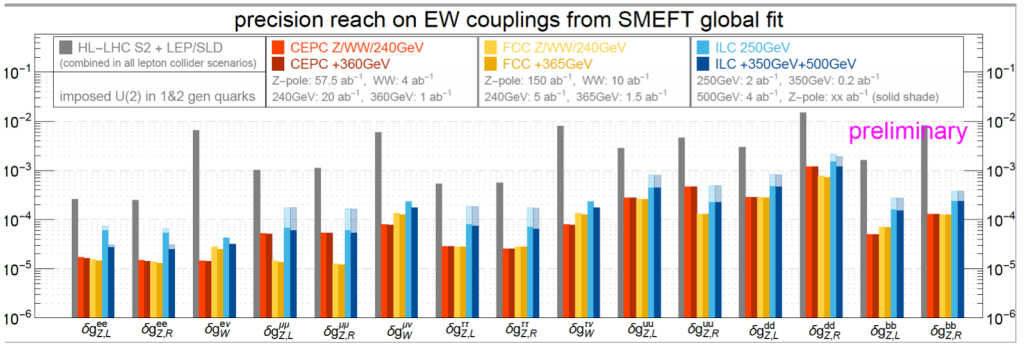
Highlights from EF04 - EW precision physics and constraining New Physics

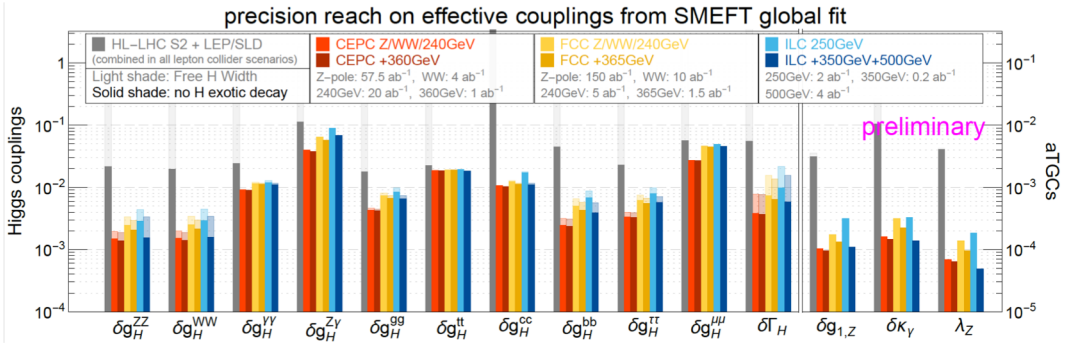
Conveners: Alberto Belloni, Ayres Freitas, Junping Tian

Global SMEFT Fit Team:

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

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





EF07 - Heavy Ions

- Physics of heavy ions (HI) and its impact on EF
- Physics at electron-ion colliders
  - **a.** BSM Searches in HI (with BSM groups)
  - b. EW physics in HI (with EW groups)
  - **c. Jets in HI**

EF05 - Precision QCD

- Jet and jet substructure
- Higher-order effects and impact on precision QCD physics
- Strong coupling constant and its running
- Quark masses
- W/Z(+jets) boson production
- Accuracy of future MC event generators
- **Impact of PDF fits and PDF-sensitive measurements**

EF06 - Hadronic structure and forward QCD

- PDF Fits and Generalized PDF
- Hadronic structure
- Forward and soft QCD
- **Hadron spectroscopy (with RF)**

Highlights from QCD Topical Groups

Highlights from EF05 - Precision QCD

Conveners: Michael Begel, Stefan Hoeche, Michael Schmitt

Strong Coupling

- precision α_s measurements at lepton colliders and in DIS, lattice-QCD determinations, ...

Precision observables

- Z lineshape at future e^+e^- colliders, Z & τ decay observables, energy-energy correlators, ...

Jet Physics

- jets and jet substructure at future colliders, azimuthal decorrelations, forward jets and dense systems, ...

Perturbative QCD calculations and MC simulations

- Les Houches higher-order wishlist, uncertainties in pQCD calculations and event generators, ...

Non-perturbative dynamics

- uncertainties in MC simulations of npQCD effects, QCD and hadronization studies at Belle II, ...

Close connection to EF06 / EF07:

- PDFs, forward physics & gluon saturation, EIC physics program, ...

Agendas and slides from presentations at : https://indico.fnal.gov/category/1139/

Highlights from EF06 - hadronic structure and forward QCD

Conveners: Huey-Wen Lin, Pavel Nadolsky, Christophe Royon

1.Hadron structure and Parton Distribution Functions

- In-depth tests of QCD -- the unique QFT accessible in both perturbative and nonperturbative regimes
- Essential input for EW precision and BSM studies in hadron scattering
- 3-dimensional hadron structure, new PDF types (TMD's, GPD's, polarized, nuclear,…)

2. QCD at small momentum fractions, saturation, diffraction

- Transition to the high-density regime of QCD
- Increasingly relevant at the HL-LHC, FCC-hh, LHeC
- Impact on the design of new detectors at FCC, etc.

3. Nonperturbative models of hadrons and hadron spectroscopy

- PDFs on the lattice
- New exotic hadronic states at the LHC, B-factories, …
  (overlaps with Rare Processes & Precision Measurements Frontier)
- …

Agendas and slides from presentations at https://indico.fnal.gov/category/1140/

Ongoing work on contributions on N3LO PDFs, EIC, LHC Forward Physics Facility, tests of QCD in forward production, lattice calculations of PDFs, …

Highlights from EF07 - Heavy Ions

Conveners: Yen-Jie Lee, Swagato Mukherjee

Kept steady pace during the pause due to EIC Yellow Report and the Nuclear Physics long-range planning process starting soon.

Focused on questions of direct interest to EF:

- What is the best use of heavy-ion beams for the search of new physics?
- How do we use heavy-ion beam to improve the understanding of inclusive hadron and charm production?
- Heavy Flavor Production in Heavy Ion Collisions
- Jet and Jet Substructure in Heavy Ion Collisions
- EW Physics in Heavy Ion Collisions and the Impact to nuclear PDF

Agendas and slides from presentations at: https://indico.fnal.gov/category/1141/

Highlights from BSM Topical Groups

EF08 - Model Specific explorations

- SUSY, Extra Dimensions, and Leptoquarks etc.
- Sensitivity, Reinterpretations of sensitivities (e.g. a long-lived particle as a Higgsino)
- Model parameter scans and comparisons with precision measurements (e.g. pMSSM scans)
    a. SUSY: Strong (inclusive searches / gluino / squark), 3rd gen (stop, sbottom), EWKino, singlino, “Pure” higgsino, R-parity violating SUSY
    b. Blackhole Mulitjets, RS Gravitons
    c. pMSSM or other scans
    d. Model-specific searches for excited fermions

EF10 - Dark Matter at colliders

- Dark Matter and Dark Sector searches at EF colliders
- WIMP models: ew multiplet, vector/scalar mediator simplified models, and Higgs portal
- Models targeting different DM masses and couplings wrt WIMP, and portals through dark photon and generic dark scalar/pseudoscalar
- DM interpretation of searches for visible decays of mediators
- **Complementarity with fixed target, direct detection (with CF & RF)**
- **Projections for FASER/CODEX-b/Mathusla, etc. (with RF)**
- **H/Z/top/mesons rare decays etc. (with EW groups)**
- **mono-X searches, MET Signatures**
    - **Long-live particle signatures**

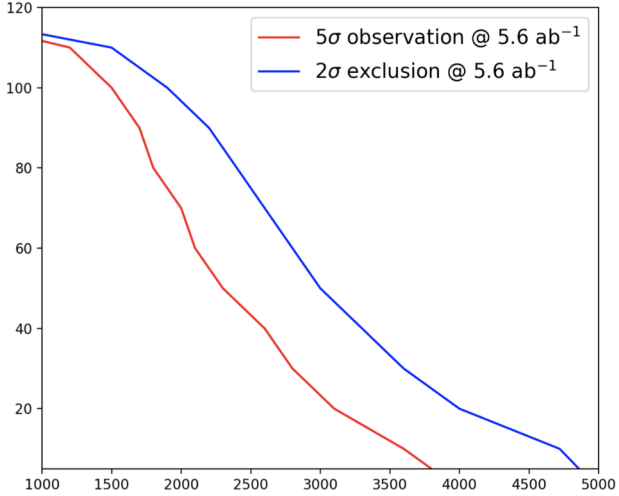
EF09 - More General explorations

- New Fermions (Top partners, Excited Quarks/Leptons, Sterile Neutrinos etc.)
- New Bosons (W', Z', diboson-resonances etc.)
- Dark/Hidden sectors (ALP, dark photons etc.)
- **BSM interplay with EFT (with EF04)**

Highlights from EF08 - BSM model-specific explorations

Conveners: Jim Hirschauer, Elliot Lipeles, Nausheen Shah

- **Goal:**
  - Search studies + summaries, including results from other groups, interpreting them in a model context.
- **Model list to include:**
  - Eg: SUSY, Compositeness/Extra Dimensions, Leptoquarks (Others?)
- **Work will include**
  - Search sensitivity estimates,
  - Reinterpretations of sensitivity estimates from other groups (e.g. long-lived particle as Higgsino),
  - Model parameter scans and comparisons with precision measurements (e.g. pMSSM scans).



limits on the m~e-m~B plane at a future lepton collider running with an integral luminosity 5.6 ab^{-1} and c.o.m. energy 240 GeV. @CepC

Light electroweakino and slepton searches @CepC

Highlights from EF09 - BSM general explorations

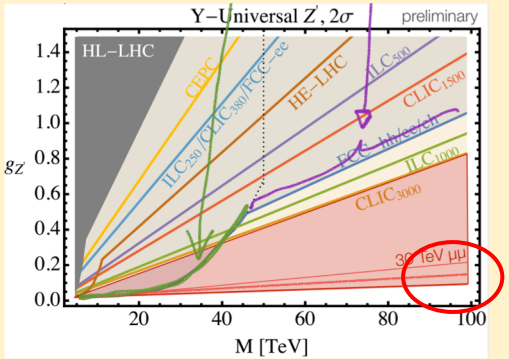
Conveners: Tulika Bose, Zhen Liu, Simone Pagan Griso

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

Heavy Bosons

Identified simplified models:

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



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

Resonance search and EFT searches are both needed.

Future Colliders ordered by Z' sensitivity

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

Highlights from EF09 - BSM general explorations

Long-Lived Signatures

Explore more the interplay of (carefully designed!) central detector and dedicated experiments

- Important for both HL-LHC as well as future colliders

Well-defined benchmarks to compare the reach

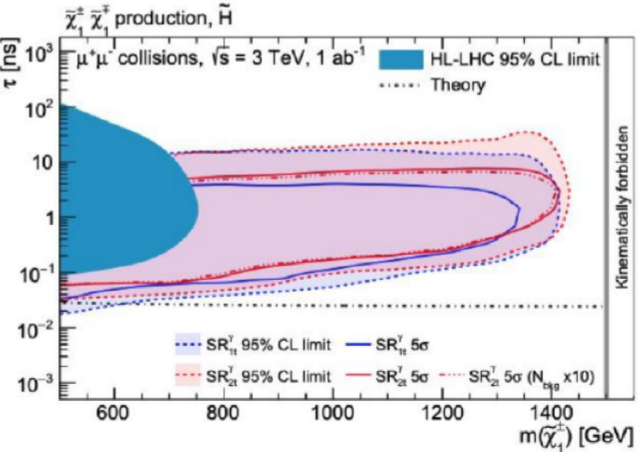
- Colored LLP: gluino, mini-split SUSY
- Non-colored LLP: Higgsino, GMSB
- Higgs portal : Higgs to LLPs, neutral naturalness
- Disappearing Track : Higgsino reach and Wino reach

Signature-driven arguments to highlight different environments and opportunities

Future Colliders: Heavy Long Lived Particles

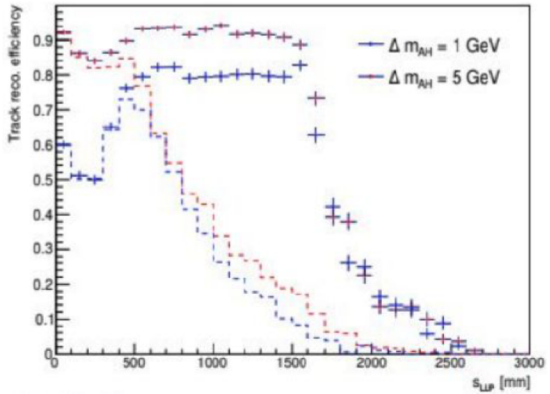
Strong community interest in Long Lived Particles, predicted by many BSM models, including Higgs Portals.

Muon collider, Disappearing Track



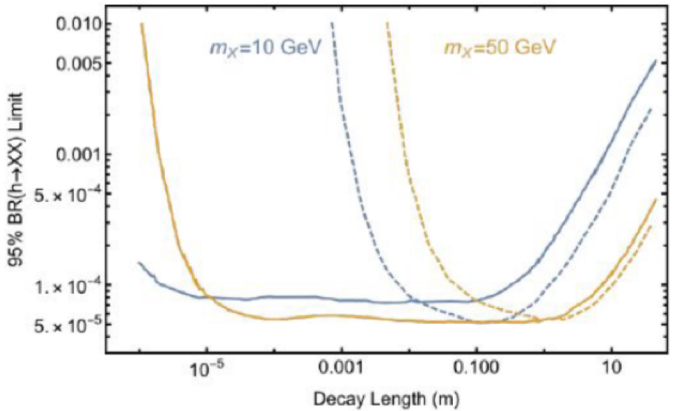
[2203.07261]

ILC, Heavy scalar decays



[2203.07622]

FCC-ee, Exotic Higgs decays



[2203.05502]

Highlights from EF09 - BSM general explorations

New Fermions

Discussed main benchmark models:

- Heavy Neutral Leptons
- Vector-like Quarks T, B, X5/3
- Leptoquarks, Top squark are covered through (EF08)

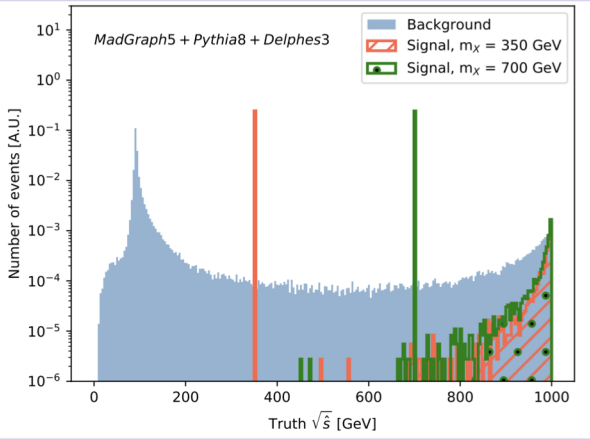
Some of these models not considered in the ES but would be extremely good to make statements on for Snowmass (e.g. Vector-like Quarks!)

Many new results, aim to identify gaps and call for contributions

Other exotica

Think ahead to ensure we don't miss unexpected new physics!

- Inclusive BSM searches
- AI-powered anomaly detection method
- ...



Highlights from EF10 - Dark Matter at colliders

Conveners: Caterina Doglioni, LianTao Wang

Most active areas:

- Snowmass **Dark Showers group** (joint with EF09)
  - Very general motivation: understand LHC signatures when varying theory parameters (Nc, flavor, etc.)
  - Organized a tutorial/workshop with experts during the Long Lived Particles Community Workshop
  - Contribute Paper in preparation (see outline here):

- **WIMPs at muon colliders**
  - There have been several studies on the search for WIMP dark matter (focusing on the so called Minimal Dark Matter scenario) at muon collider (with various energy and luminosity options), as well as a few more on-going work.
  - While it may not be as complete as the study for the 100 TeV pp collider for the briefing book, a set of basic results are available now to paint a big picture on this topic.

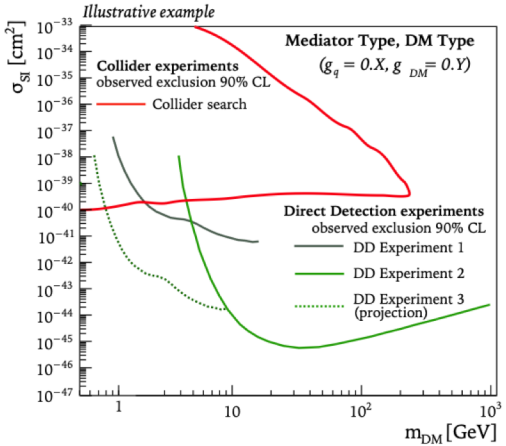
- **WIMPs and lighter DM at hadron/lepton colliders** → see also next slide
  - Some of our main contributors graduated, some are back as PhD students starting in September, some are new
  - One of the postdoc leaders of whitepaper also moving on to new jobs (!colliders) but want to keep contributing once Snowmass restarts
  - Organizers have been asked to give a talk in EF10 parallel session

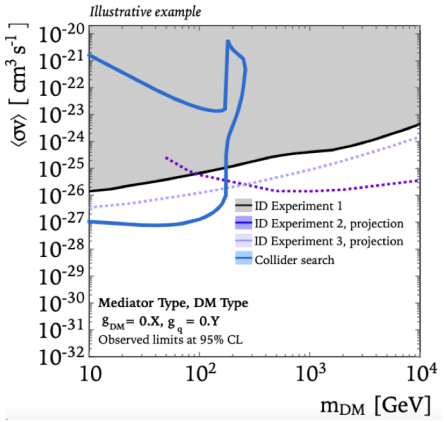
- New Wino/Higgsino studies with monojet signature ongoing

WIMPs and lighter DM at future colliders

Work done within EF10 towards whitepaper was written up in Boyu Gao's thesis (Undergraduate @ OSU → Graduate school @ Duke): Link to thesis: https://kb.osu.edu/handle/1811/92563

Contribution from SEC members (coordinated with Matt LeBlanc and Grace Cummings) to compile list of DM @ collider curves for summary plots and update European Strategy:

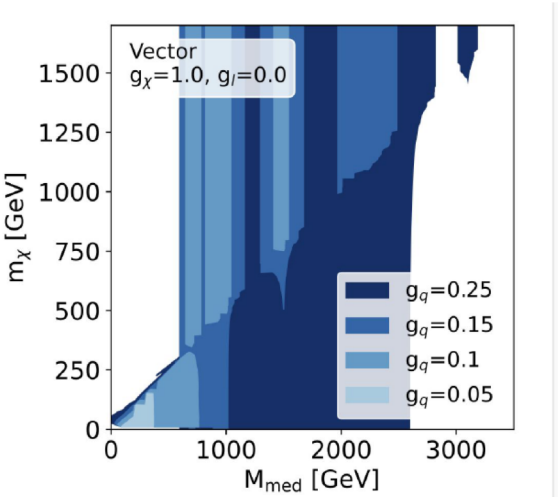




Work also will include the planned DMWG whitepaper (and discussion with other Frontiers) on lowering the couplings for the simplified models used by the LHC

Simplified Model Coupling Scan

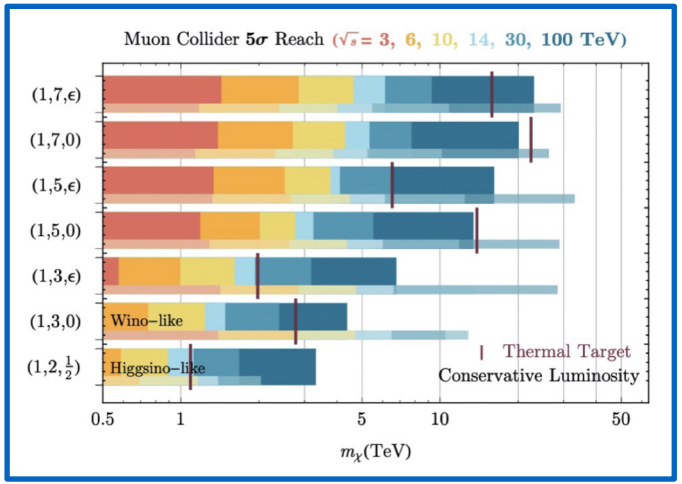
- Coupling scan necessary to extend current benchmarks for DM simplified models used for e.g. European Strategy (& ATLAS+CMS), where DM simplified models have couplings o(1)
- Goal: explore coupling scenarios systematically and efficiently to connect to other experiments / show effect of varying couplings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

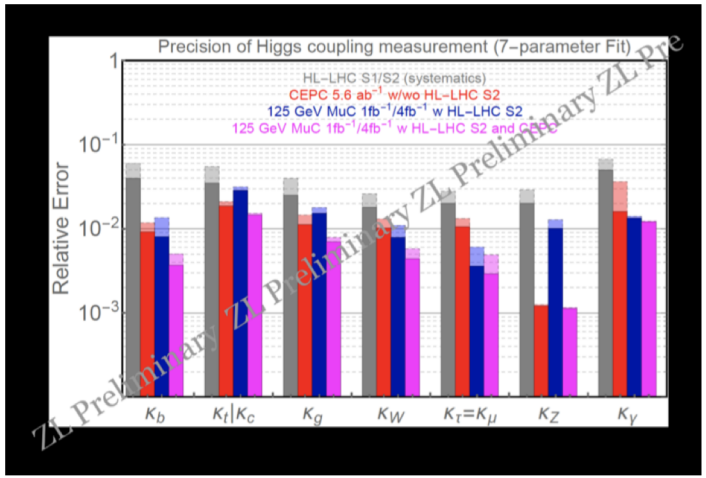


Dijet + monophoton constraints from LHC data as example

Muon Collider Forum: Physics Highlights

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

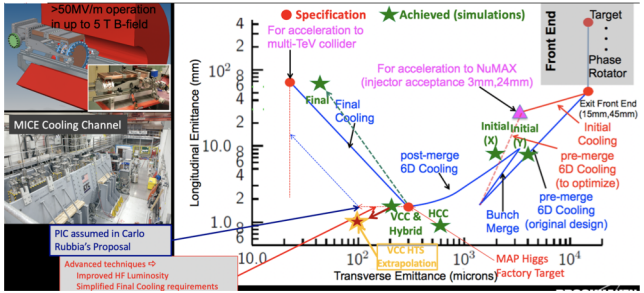




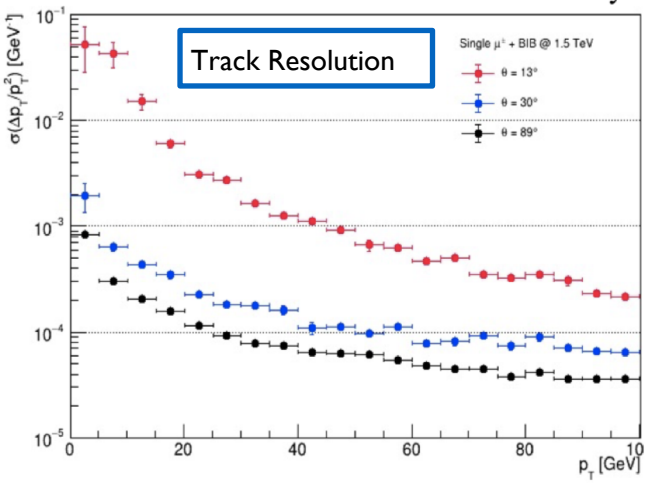
Muon Collider: Accelerator and Detector Highlights

- R&D areas in both accelerator and detector technologies are being identified
- Accelerator:
  - High power targets (synergies with future neutrino and muon experiments?)
  - High field magnets
  - High gradient normal conducting RF (NCRF) cavity for muon cooling
  - Demonstration and improvements to the muon cooling scheme ⇨ better luminosity performance
- Detectors
  - Many novel ideas to mitigate effects of the Beam Induced Background
  - 4D smart trackers, PF Calorimetry, novel reconstruction strategies
  - Preliminary evaluation of readout strategies and data rates
  - Baseline reconstruction performance demonstrated; improvements ongoing

Performance of different muon cooling schemes



Preliminary



Working Towards the EF Report

Many ideas, new studies, new directions.

In all of them, the role of theory has been crucial and maintaining a close contact among EF and TF in this final phase will be very important to build good physics cases and highlight the role of theory in building them.

Summary

The next 5-40 years will be an exciting time in Collider Physics!

- Snowmass process is marching on
  - Finalize studies and make worthwhile comparisons
  - Advocate to our scientific colleagues
  - Advocate to the public, our funding agencies and governments
- Our goal is to create a comprehensive international program that welcomes all with know-how and interest
- Give us input on your Vision for the EF in the document
  - Please note that the intent of this document is to understand collectively the interests of the community, and not the priorities for various projects [which is the task of P5].

Back-up slides

Energy Frontier Meetings

2020

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

2021

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

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

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

Please complete **Pre-registration Survey**

Liaisons, task forces, cross-frontier fora

Other Frontier	Liaisons
Neutrino Physics Frontier	André de Gouvêa (Northwestern)
Rare Processes and Precision	Manuel Franco Sevilla (Maryland)
Cosmic Frontier	Caterina Doglioni (Lund), Antonio Boveia (Ohio State)
Theory Frontier	Laura Reina (FSU)
Accelerator Frontier	Dmitri Denisov (BNL), Meenakshi Narain (Brown)
Computational Frontier	Peter Onyisi (U.Texas)
Instrumentation Frontier	Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay)
Community Engagement Frontier	Daniel Whiteson (UCI), Sergei Gleyzer (Alabama)

Early Career Representative

- **Grace Cumming** (U.Virginia)
- **Matt Le Blanc** (U.Arizona)

Muon Collider Forum Coordinators

EF: **Kevin Black** (U. Wisconsin-Madison), **Sergo Jindariani** (Fermilab)
AF: **Derun Li** (LBNL), **Diktys Stratakis** (Fermilab)
TF: **Patrick Meade** (Stony Brook U.), **Fabio Maltoni** (Louvain U., Bologna)

e+e- Collider Forum Coordinators

EF: **Maria Chamizo Llatas** (BNL), **Sridhara Dasu** (Wisconsin)
AF: **Emilio Nanni** (SLAC), **John Power** (ANL)
IF: **Ulrich Heintz** (Brown), **Steve Wagner** (Colorado)

Monte Carlo task force and production team

Coordinated by **John Stupak** (U. Oklahoma)
1) Assess the MC needs ⇒ **"Task force"**
2) Produce MC samples ⇒ **"Production Team"**