Summary of EF09 Discussions

Samuel Homiller
Harvard University

For the EF09 Conveners:
Tulika Bose (UW-Madison), Zhen Liu (Minnesota), Simone Pagan Griso (LBL)

Energy Frontier Workshop, April 1, 2022

Goals of this talk:

Parallel Session on Wednesday reviewed all the EF09 submissions:

10:00 AM → 12:00 PM **Parallels: EF09 Parallel Session - BH Rm 190**

10:00 AM **Introduction** 10m
Speakers: Simone Pagan Griso (Lawrence Berkeley National Laboratory), Tulika Bose (University of Wisconsin-Madison), Zhen Liu (University of Minnesota)
BSM Snowmass re...

10:10 AM **New Bosons - summary and discussion of critical points** 15m
Speakers: Felix Yu (JGU Mainz), Felix Yu, Robert Harris (Fermilab)
EF09-220330-EFW... EF09-220330-EFW...

10:40 AM **New Fermions - summary and discussion of critical points** 15m
Speakers: Ian Lewis (University of Kansas), Julie Hogan (Bethel University), Julie Hogan (Bethel University), Julie Hogan (Bethel University)
EF09_HNL_Mar202...

11:10 AM **LLP - summary and discussion of critical points** 15m
Speakers: Juliette Alimena (CERN), Simon Knapen (Lawrence Berkeley National Lab and UC Berkeley)
LLPSnowmassSu...

11:40 AM **Other Exotica - summary and discussion of critical points** 10m
Speaker: Lingfeng Li (Brown U.)
EF09_Other_Exotic...

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10:40 AM **New Fermions - summary and discussion of critical points** 15m
Speakers: Ian Lewis (University of Kansas), Julie Hogan (Bethel University), Julie Hogan (Bethel University), Julie Hogan (Bethel University)

Today: quickly overview landscape of submissions, key directions

Summarize some of the main points of discussion, emphasis on overlaps with other topical groups

Heavy Bosons

(Summary from Robert Harris, Felix Yu)

New Fermions

(Summary from Julie Hogan, Ian M. Lewis)

Long-Lived Particles

(Summary from Juliette Alimena, Simon Knapen)

Other Exotica

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(Summary from Lingfeng Li)

Heavy Bosons

(Summary from Robert Harris, Felix Yu)

- Z': the "standard candle" of BSM physics
  - Generic models provide useful benchmark point for different collider options
  - Other Z's connected to Dark Sectors, LFV probes, …
- Numerous other models and channels
  - W-primes
  - Axion-like particles
  - Dijet resonances
  - …

Long-Lived Particles

(Summary from Juliette Alimena, Simon Knapen)

New Z-Primes: Standard Candles

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

Increasing Z' Sensitivity

"Minimal" models allow allow reach to be characterized in terms of only mass & coupling

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Increasing Z' Sensitivity

"Minimal" models allow allow reach to be characterized in terms of only mass & coupling

Discussion: best benchmark model?
(results for SSM — other universal models, e.g., $B - L$ more theoretically motivated, but may not have input / simulation)

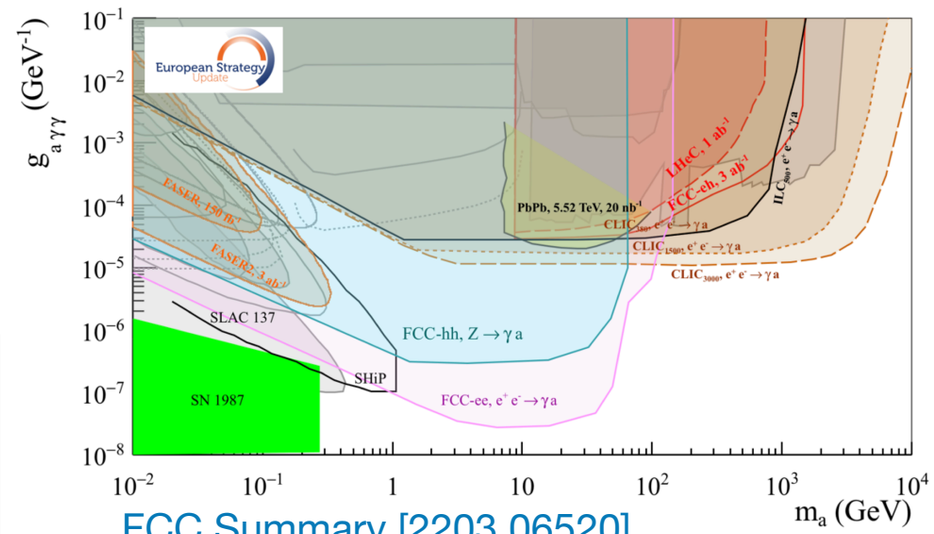
Other Heavy Bosons

- Other signatures discussed:
  W-primes, axion-like particles, dijet resonances, KK gluons, …

Dijet searches at hadron colliders:

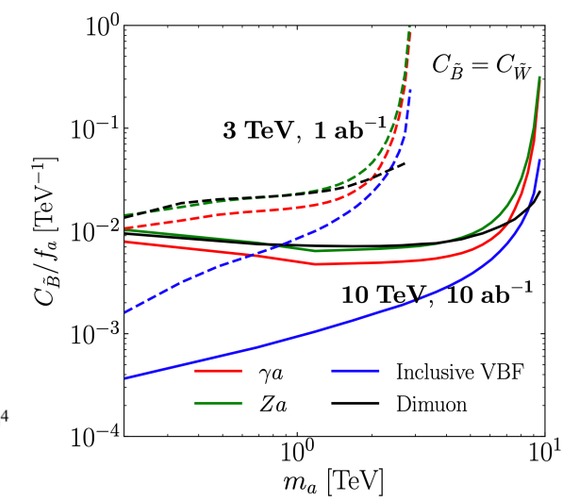
Snowmass 2021	HL-LHC		FNAL-SF		FCC-hh		VLHC		Collider in the Sea	
R. M. Harris	√s = 14 TeV, ∫Ldt = 3 ab^{-1}		√s = 27 TeV, ∫Ldt = 3 ab^{-1}		√s = 100 TeV, ∫Ldt = 30 ab^{-1}		√s = 300 TeV, ∫Ldt = 100 ab^{-1}		√s = 500 TeV, ∫Ldt = 100 ab^{-1}	
Model	**5σ** [TeV]	**95% CL** [TeV]	**5σ** [TeV]	**95% CL** [TeV]	**5σ** [TeV]	**95% CL** [TeV]	**5σ** [TeV]	**95% CL** [TeV]	**5σ** [TeV]	**95% CL** [TeV]
Strongly Produced Models of Dijet Resonances										
Diquark	8.7	9.4	16	17	57	63	160	180	249	284
Coloron	7.1	7.8	13	14	45	51	125	143	193	224
q*	7.0	7.9	12	14	44	50	121	140	184	217
Weakly Produced Models of Dijet Resonances										
W' (SSM)	4.8	5.6	8.2	9.9	29	36	79	99	117	150
Z' (SSM)	4.2	5.2	7.0	8.9	25	32	67	87	96	130
RS Grav.	3.5	4.4	5.8	7.5	21	27	56	73	81	109

Robert Harris, EF09 10/2021



FCC Summary [2203.06520]

[2203.05484, 2203.07261]



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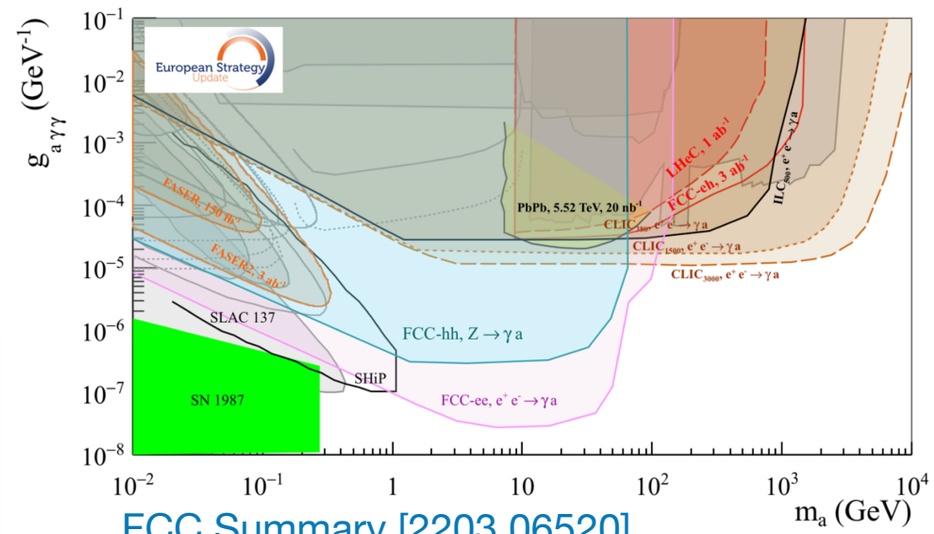

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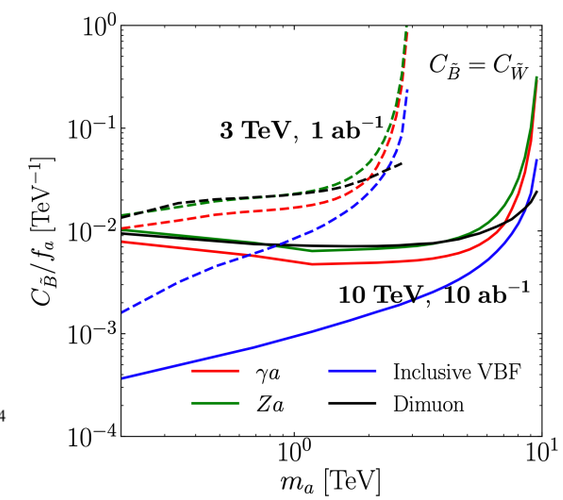

Discussion: Composite Higgs models lead to diboson signals (*WW, WZ, WH, ZH*) — important modes to cover, but also overlap with EF02/EF08?

Heavy Bosons

(Summary from Robert Harris, Felix Yu)

New Fermions

(Summary from Julie Hogan, Ian M. Lewis)

Long-Lived Particles

(Summary from Juliette Alimena, Simon Knapen)

Other Exotica

(Summary from Lingfeng Li)

- Heavy Neutral Leptons
  - Prospects at HL-LHC, future colliders
  - Type-I, Type-II, Type-III Seesaw
- Heavy Vector-like Quarks / Leptons
  - Robust program for standard searches at LHC
  - Numerous non-standard channels can also be studied

(S)

New Fermions

(Summary from Julie Hogan, Ian M. Lewis)

Other Exotica

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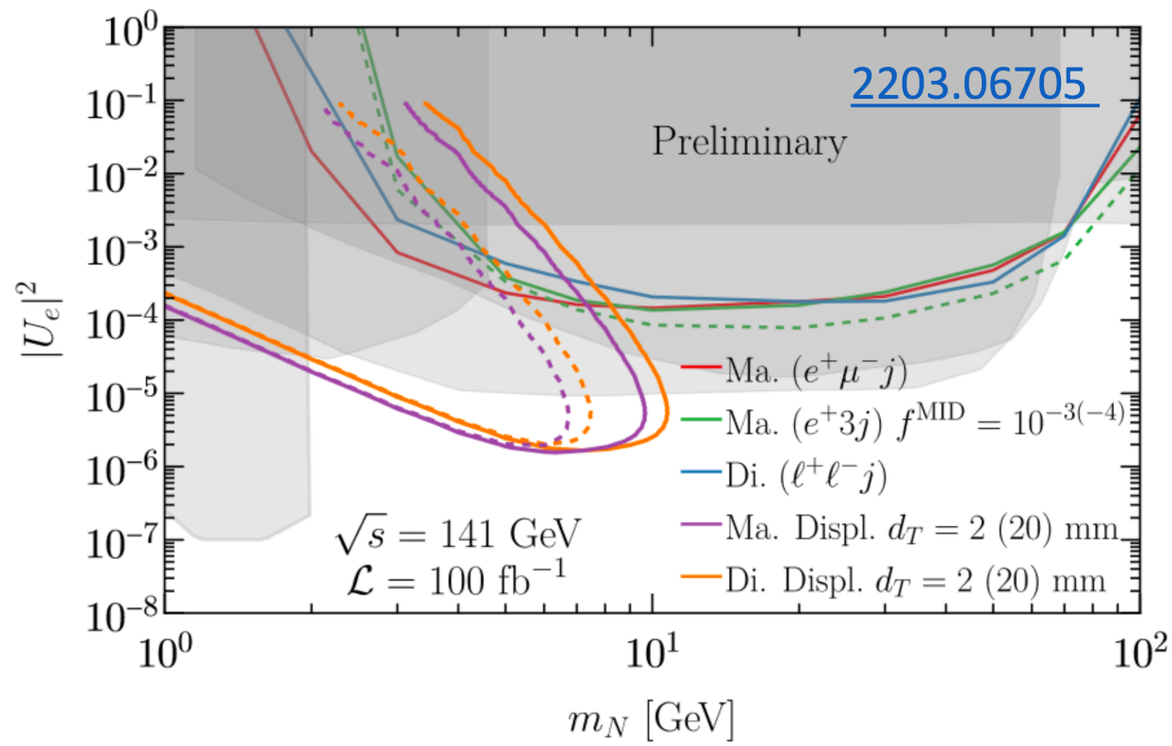
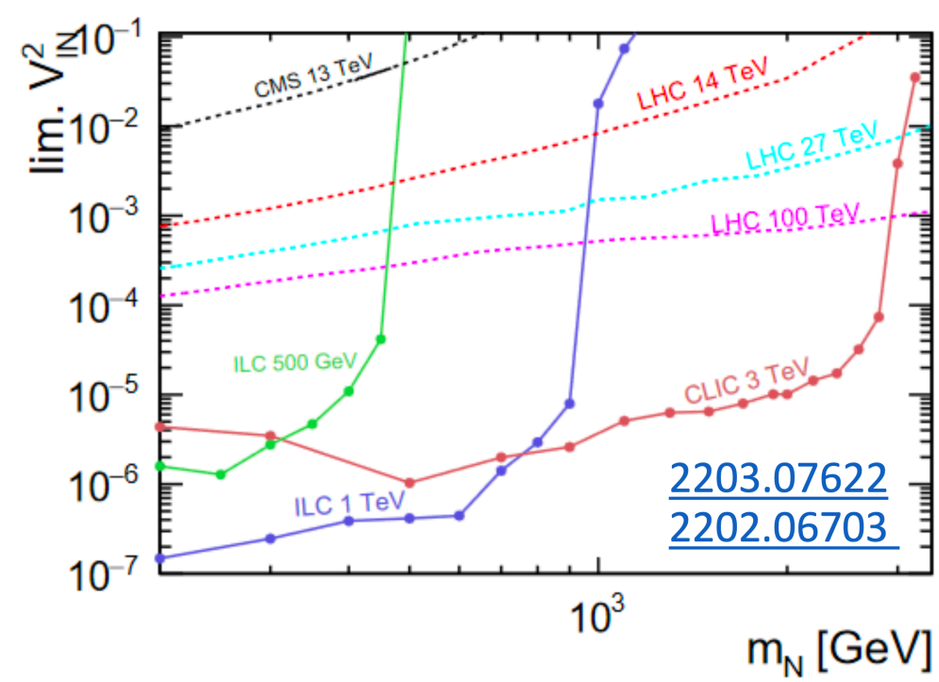
Heavy Neutral Leptons

Robust program at the LHC, and prospects at future electron-ion colliders, e^+e^- machines





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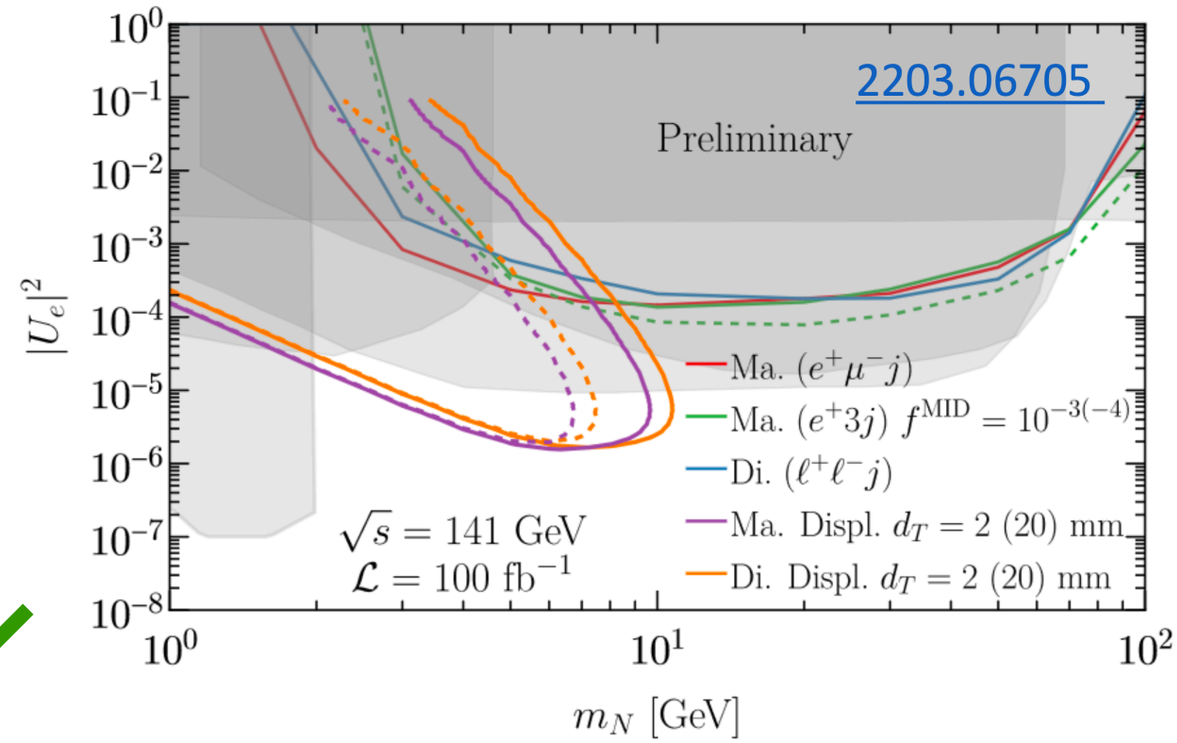
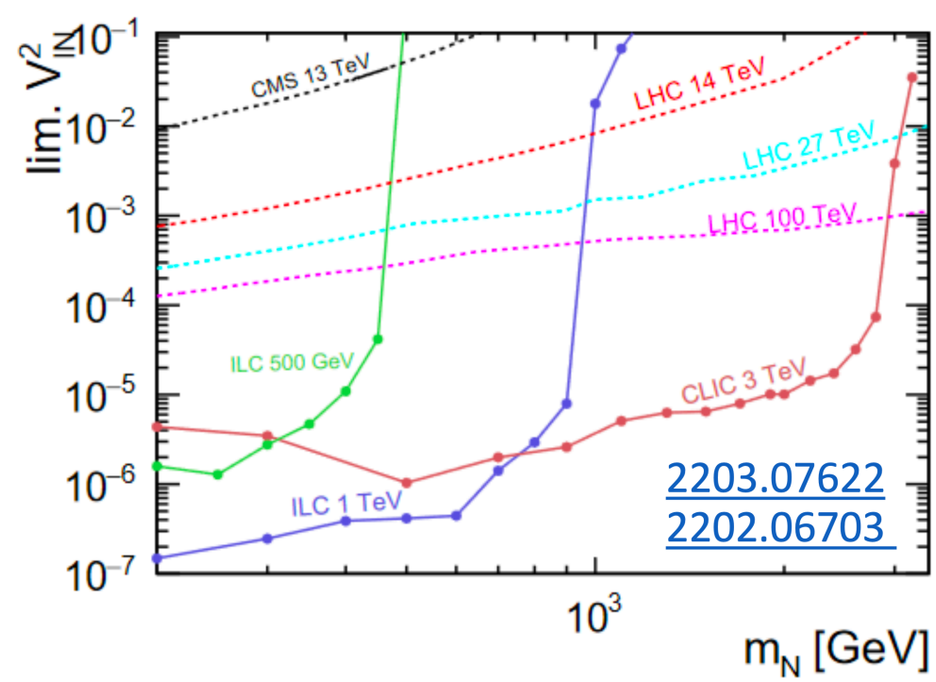
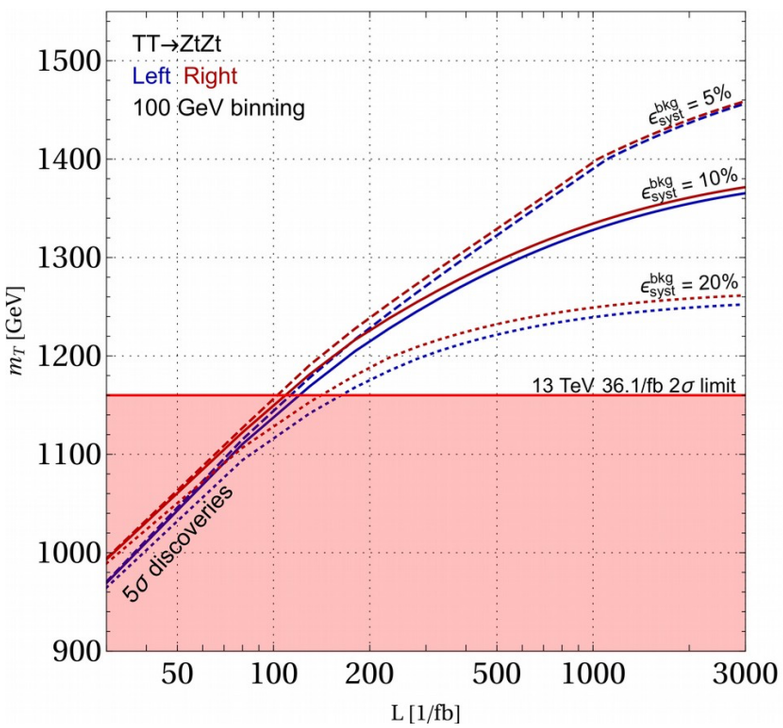


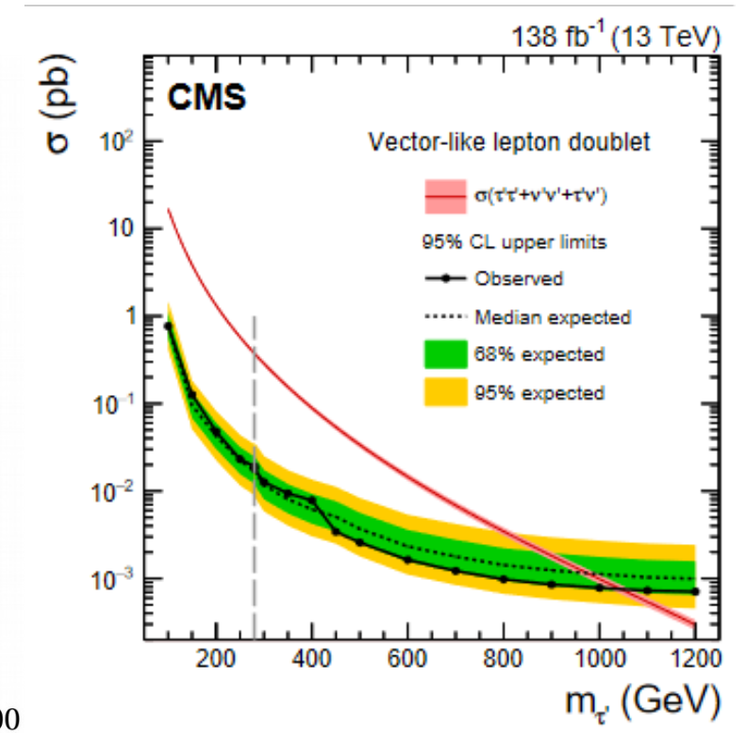
Discussion: lower mass end here naturally part of LLP program!



Heavy Vector-Like Fermions

Robust program for standard production / decay channels at the LHC — bounds will improve at HL





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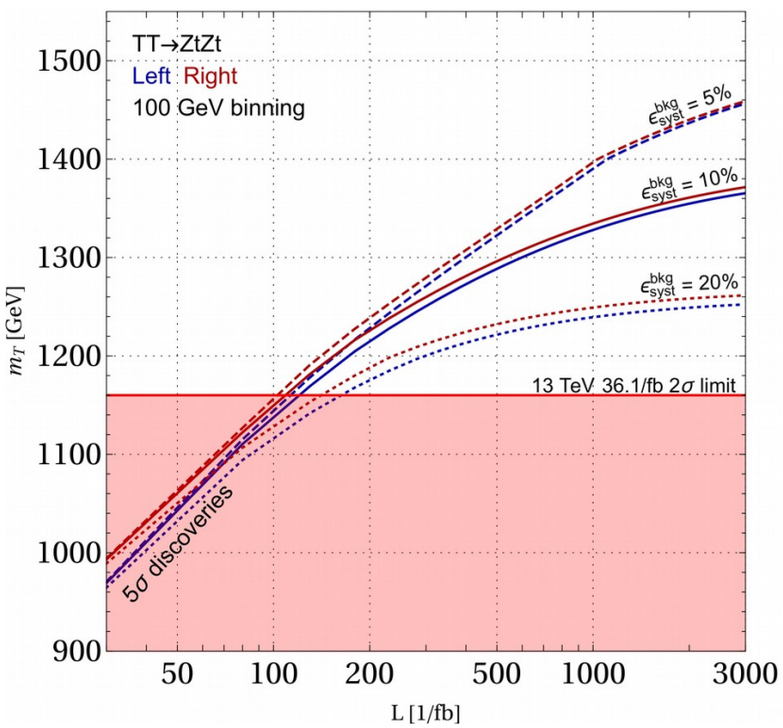
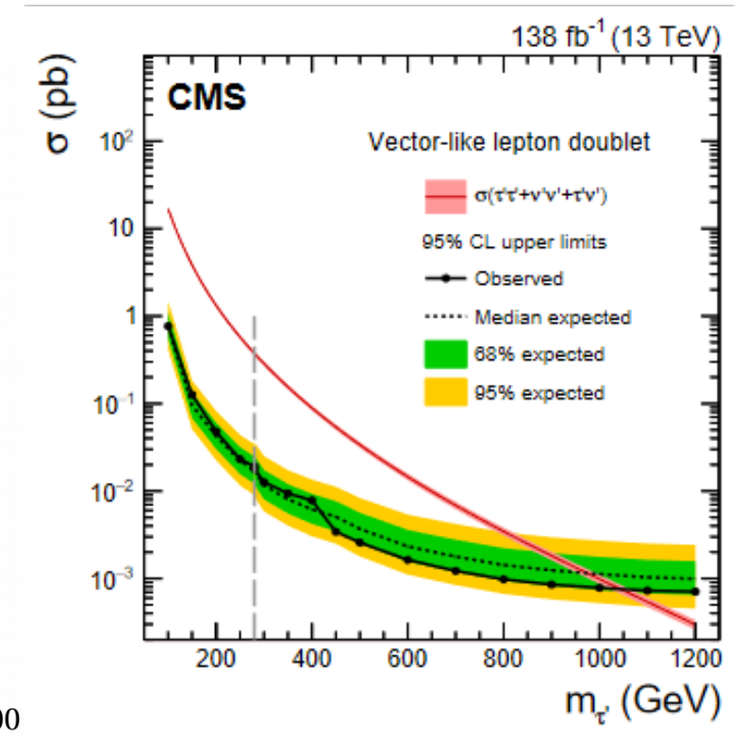
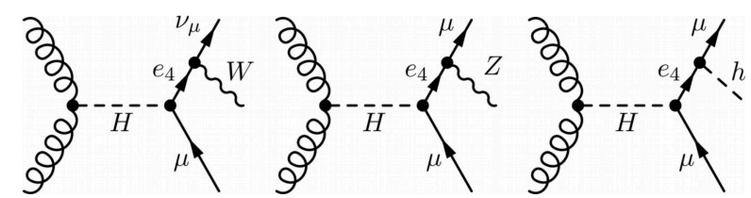
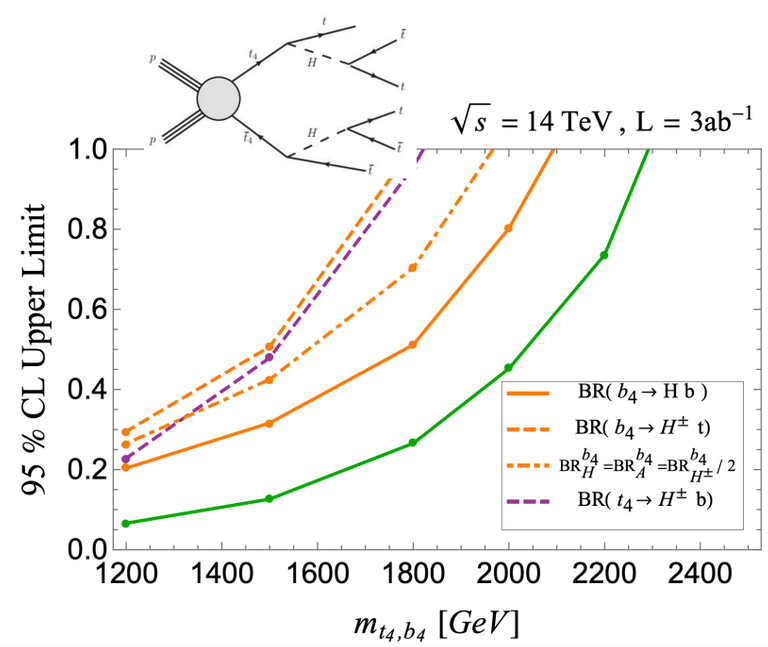
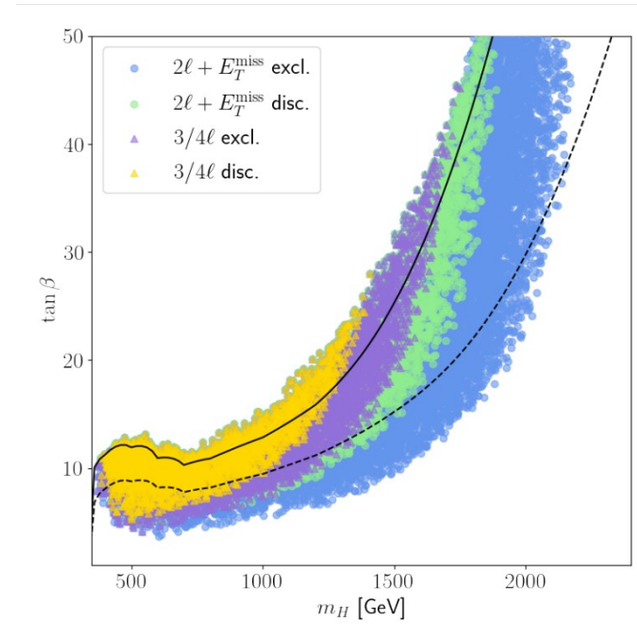






Submissions emphasize the diversity of non-standard channels at HL-LHC and future colliders in extended scenarios





Heavy Bosons

(Summary from Robert Harris, Felix Yu)

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Long-Lived Particles

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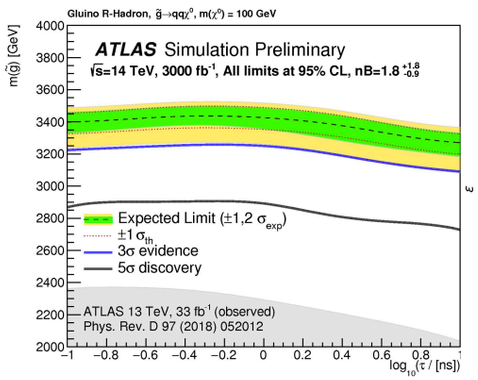
Long-Lived Particles

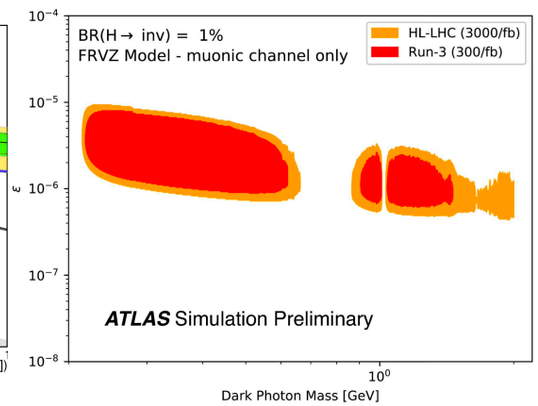
(Summary from Juliette Alimena, Simon Knapen)

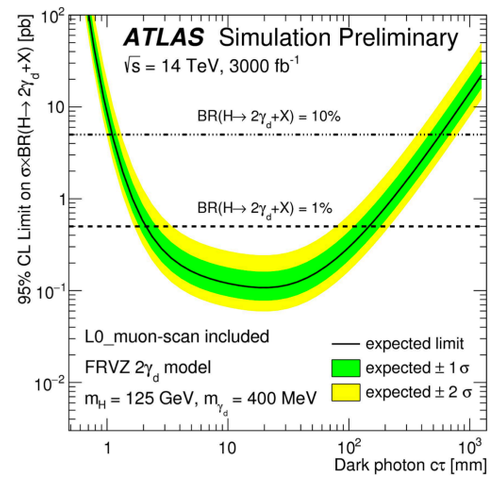
- Prospects at HL-LHC
  - Numerous LLP signatures identified, studied in Yellow report
- Prospects at auxiliary detectors
  - FASER2 (forward physics facility), MATHUSLA, CODEX-b, milliQan
  - Strong case for making progress in the coming decade!
- Prospects at future colliders?

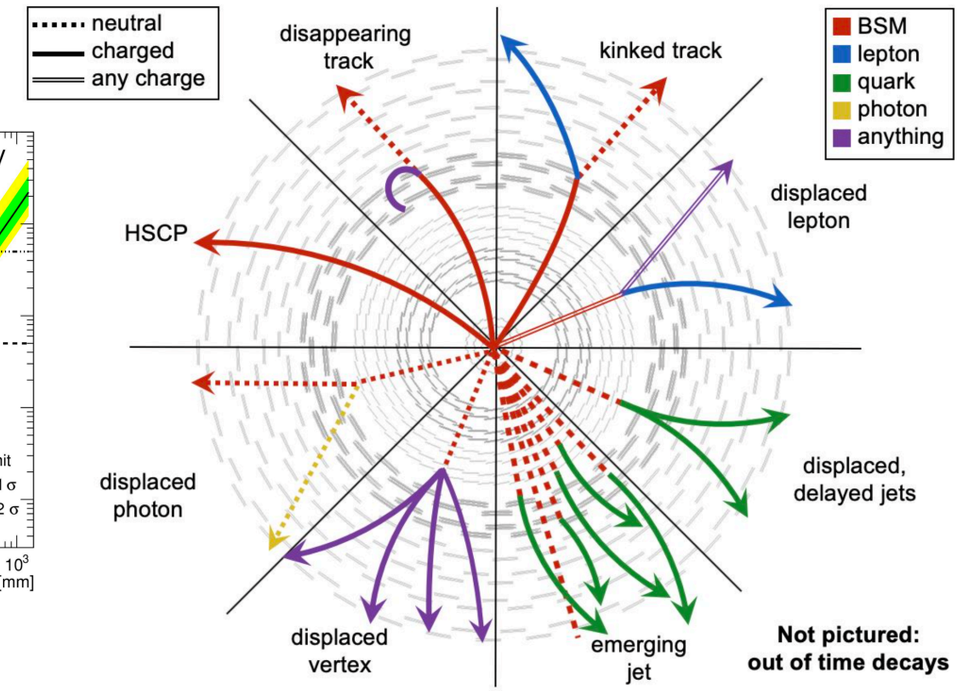
Prospects at HL-LHC / Future Colliders

HL-LHC prospects from Yellow Report summarized



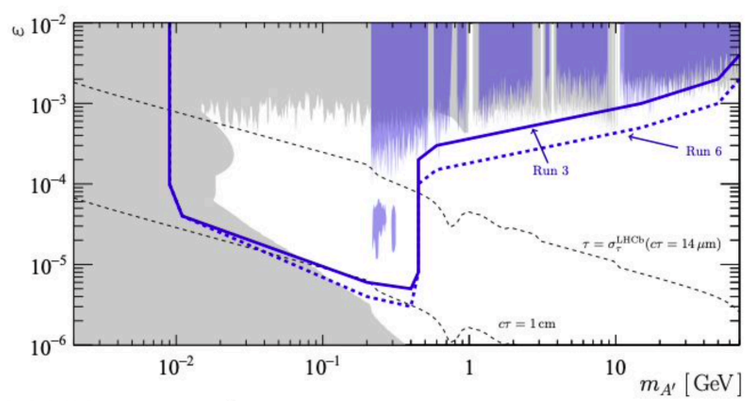




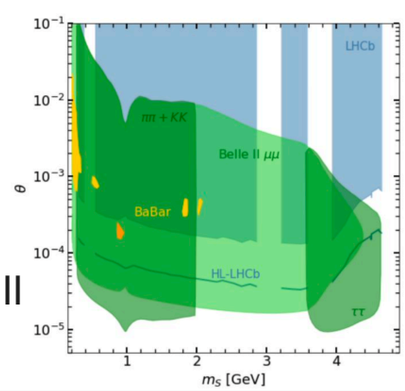


+ new exotic signatures studied at truth-level

B-factory prospects:

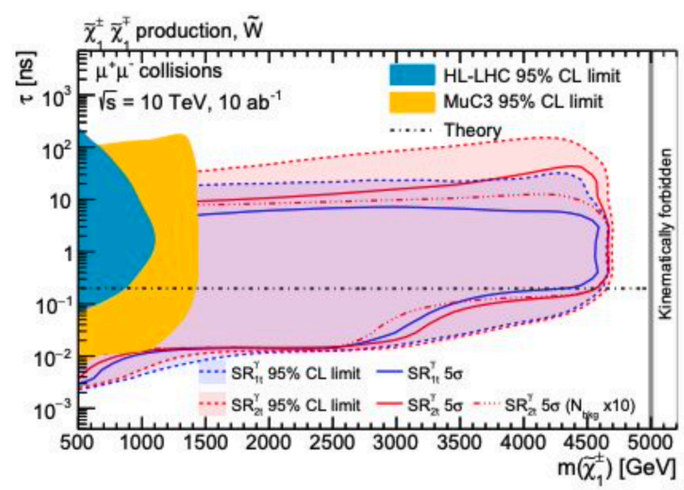


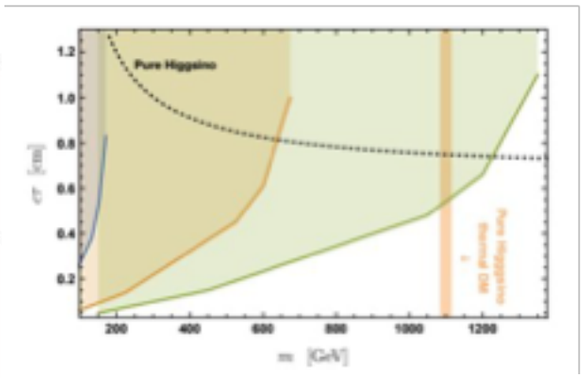
LHCb

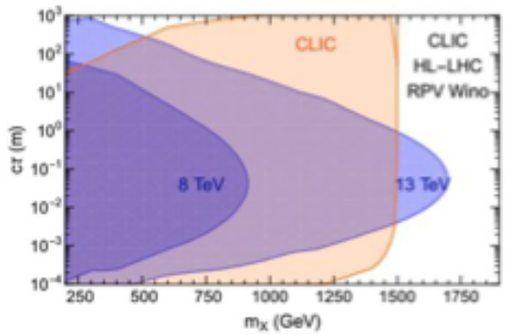


Belle II

Studies at future collider detectors:

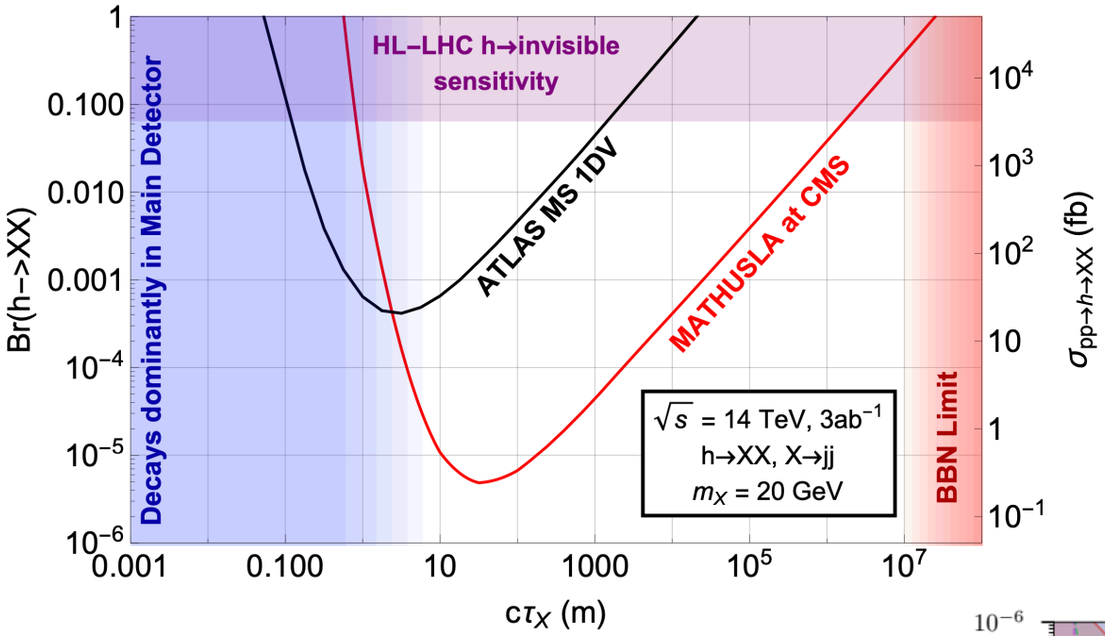




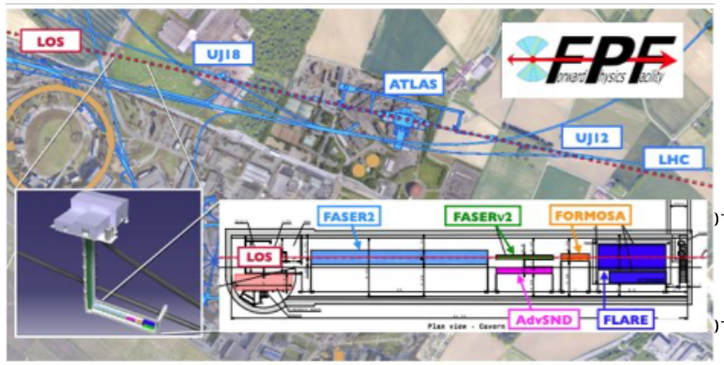


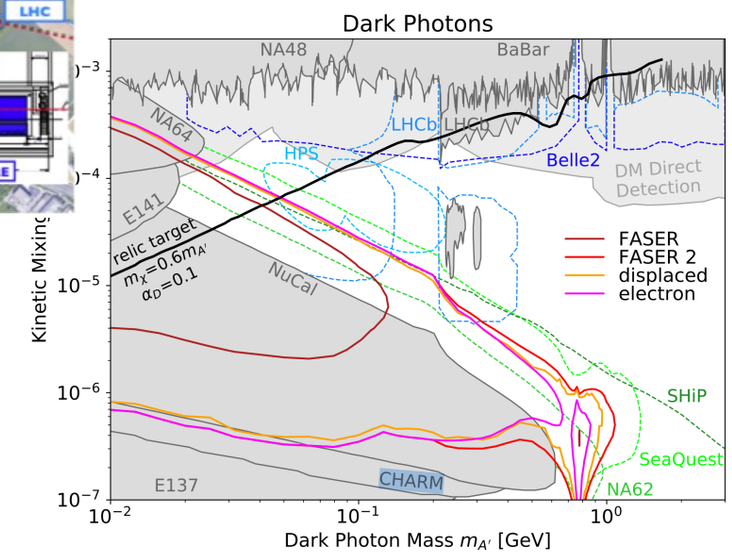
Prospects at New, Auxiliary Detectors

MATHUSLA [2203.08126]

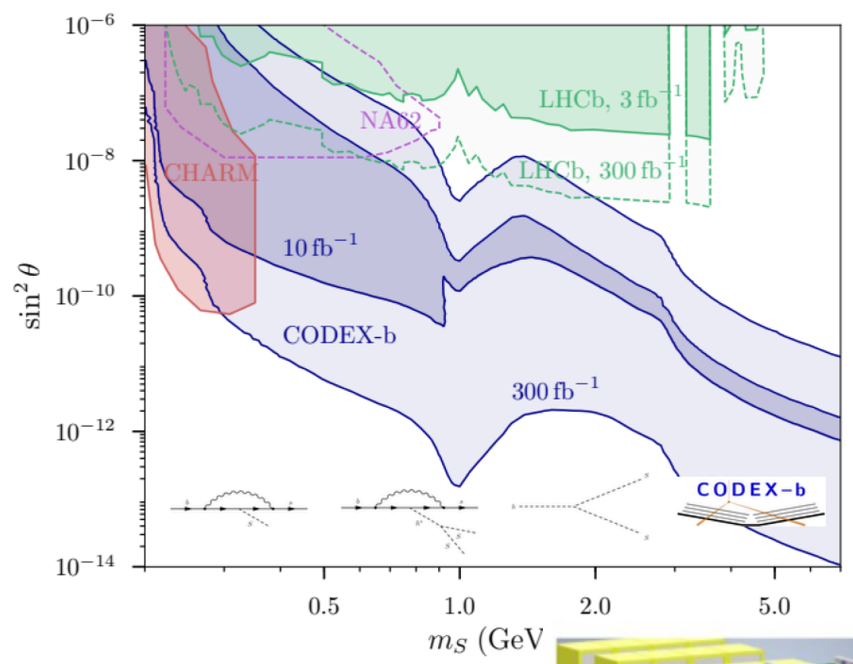


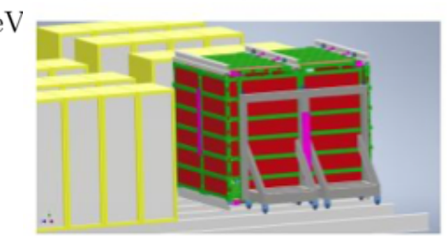
Forward Physics Facility [2109.10905, 2203.05090]



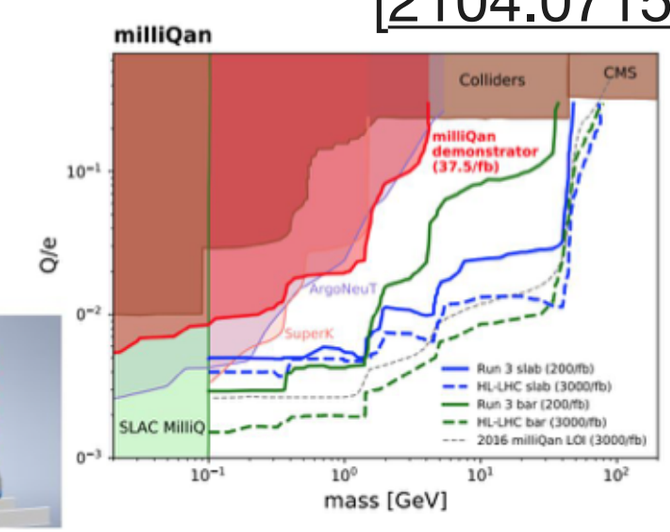


CODEX-b [2203.07316]



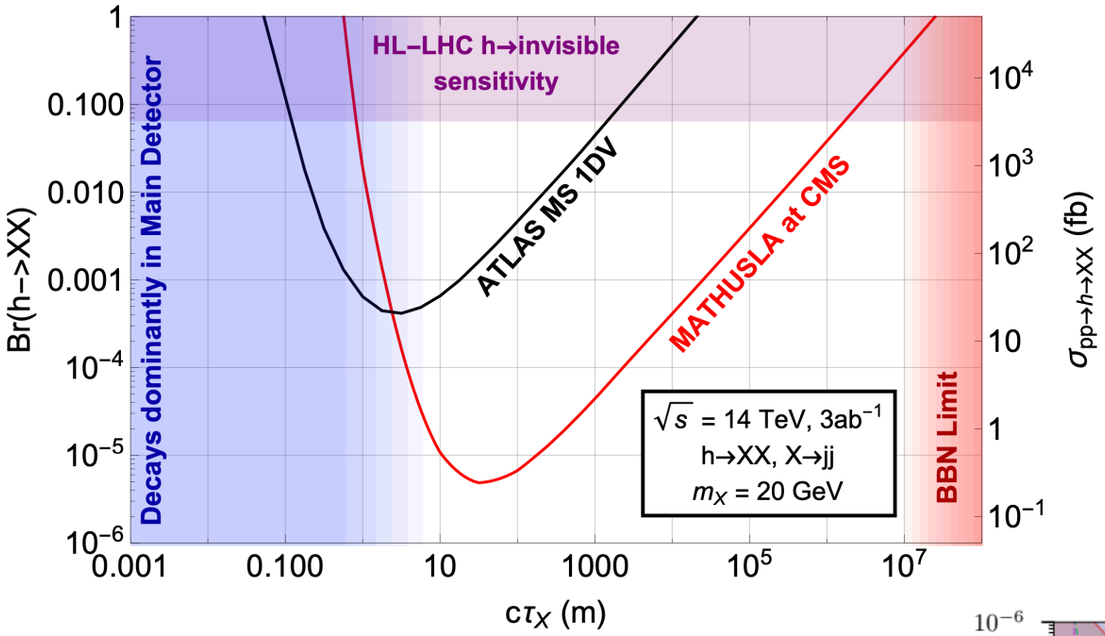


Millicharged particles [2104.07151]

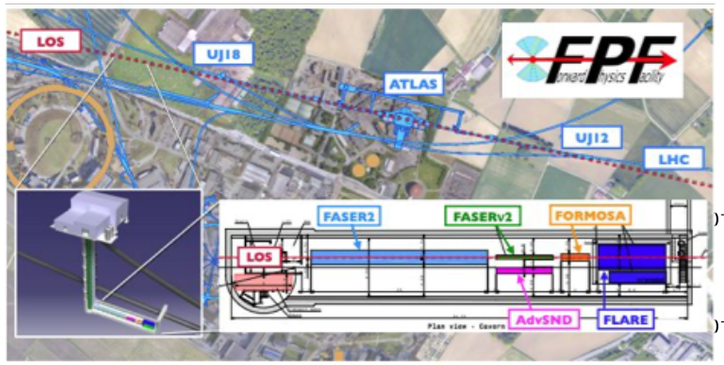


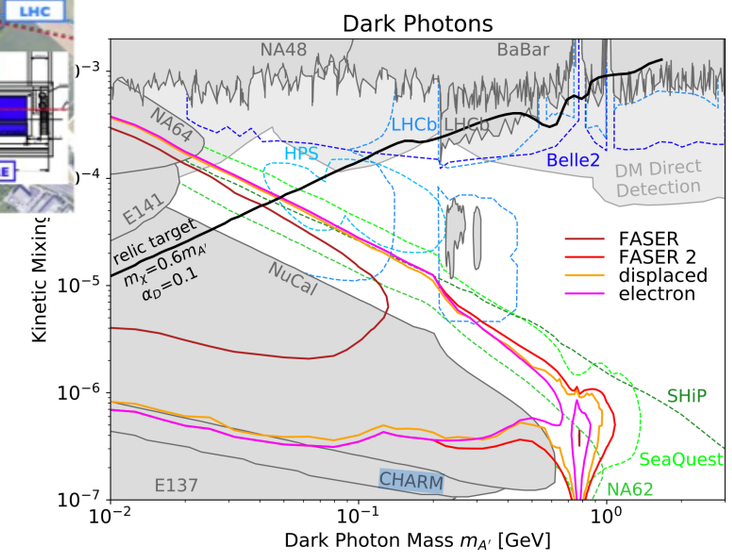
Prospects at New, Auxiliary Detectors

MATHUSLA [2203.08126]

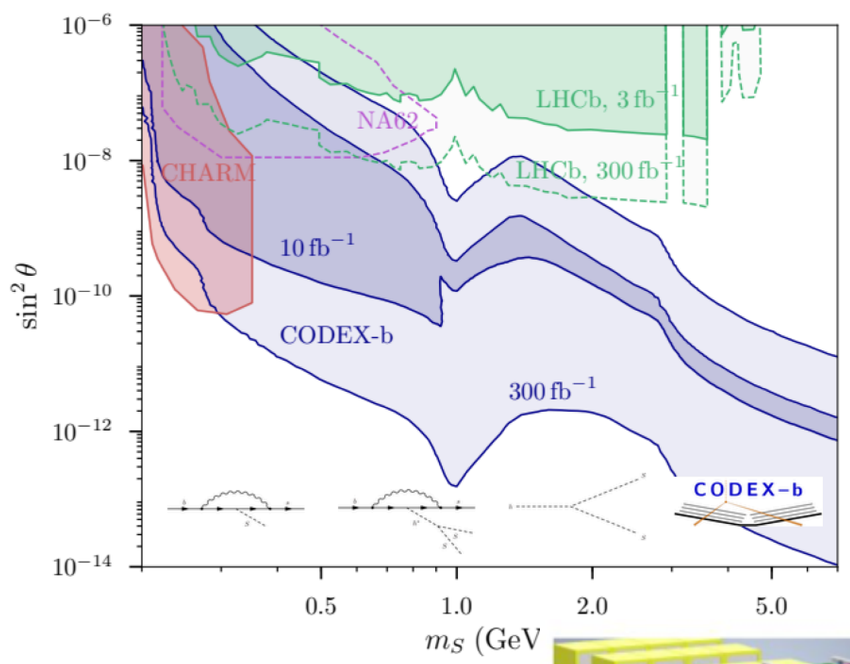


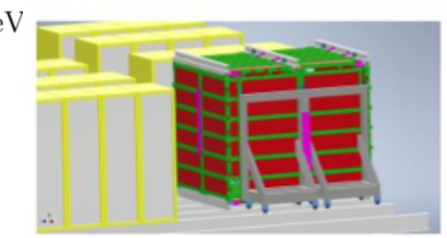
Forward Physics Facility [2109.10905, 2203.05090]



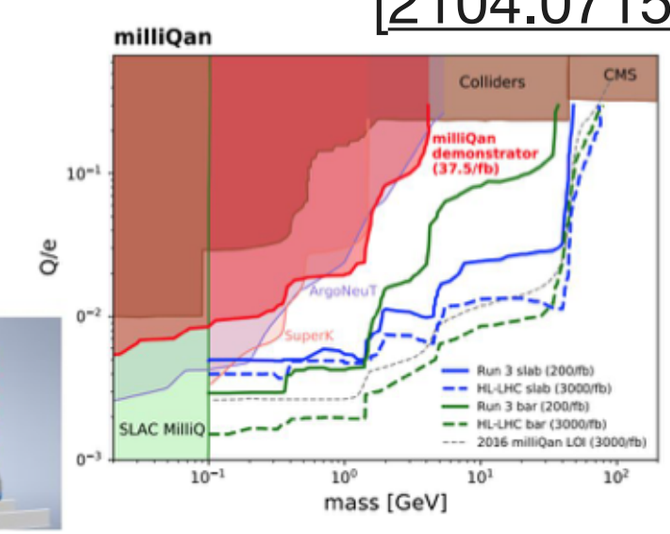


CODEX-b [2203.07316]





Millicharged particles [2104.07151]



Strong case for auxiliary detectors to make a big impact in the next ~decade!

Long-Lived Particles

LLP Matrix

Signature	HL-LHC	Higgs factories	High energy hadron colliders	Muon colliders
Neutral LLP (including Higgs)	• Track-Based Triggers for Exotic Signatures, arXiv:2203.07314 • The Present and Future Status of Heavy Neutral Leptons, arXiv:2203.08039 • Recent Progress and Next Steps for the MATHUSLA LLP Detector, arXiv:2203.08126 • Sensitivity to millicharged particles in future proton-proton collisions at the LHC, arXiv:2104.07151 • The road ahead for CODEX-b, arXiv:2203.07316 • The Forward Physics Facility, 2203.05090, 2109.10905 • Theory, phenomenology, and experimental avenues for dark showers, arxiv: 2203.09503 • Theory Meets the Lab, arxiv: 2203.10089 • LHCb future dark-sector sensitivity projections for Snowmass 2021, arxiv: 2203.07048 • Physics with the Phase-2 ATLAS and CMS Detectors	• Searches for Long-Lived Particles at the Future FCC-ee, arXiv:2203.05502 • The Future Circular Collider: a Summary for the US 2021 Snowmass Process, arXiv:2203.06520 • The Present and Future Status of Heavy Neutral Leptons, arXiv:2203.08039 • Physics potential of timing layers in future collider detectors, arxiv: 2005.05221 • Sensitivity to decays of long-lived dark photons at the ILC, arxiv: 2203.08347 • The International Linear Collider, arXiv:2203.07622 • Belle II physics reach and plans for the next decade and beyond	• The Present and Future Status of Heavy Neutral Leptons, arXiv:2203.08039 • Physics potential of timing layers in future collider detectors, arxiv: 2005.05221	• Axion-Like Particles at High Energy Muon Colliders, arXiv:2203.05484
Disappearing Tracks and HSCP	• Track-Based Triggers for Exotic Signatures, arXiv:2203.07314 • Physics with the Phase-2 ATLAS and CMS Detectors	• The International Linear Collider, arXiv:2203.07622		• The physics case of a 3 TeV muon collider stage, arXiv:2203.07261 • Hunting wino and higgsino dark matter at the muon collider with disappearing tracks, arXiv:2102.11292

Long-Lived Particles

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Can we look for LLPs at

- HL-LHC? Yes
- Higgs factory? Yes
- High energy hadron machine? Probably
- Muon collider? Yes

Discussion: difficult to project sensitivities at future machines without real detectors / data, but still useful for design studies!

Heavy Bosons

(Summary from Robert Harris, Felix Yu)

New Fermions

(Summary from Julie Hogan, Ian M. Lewis)

Long-Lived Particles

(Summary from Juliette Alimena, Simon Knapen)

Other Exotica

(Summary from Lingfeng Li)

- “Model-independent” Effective Interactions
  - Specific signatures, related to flavor anomalies?
- Models with exotic dynamics / signatures
- Anomaly Detection Techniques
  - Stress importance of being ready for unexpected signals!

New Fermions

(Summary from Julie Hogan, Ian M. Lewis)

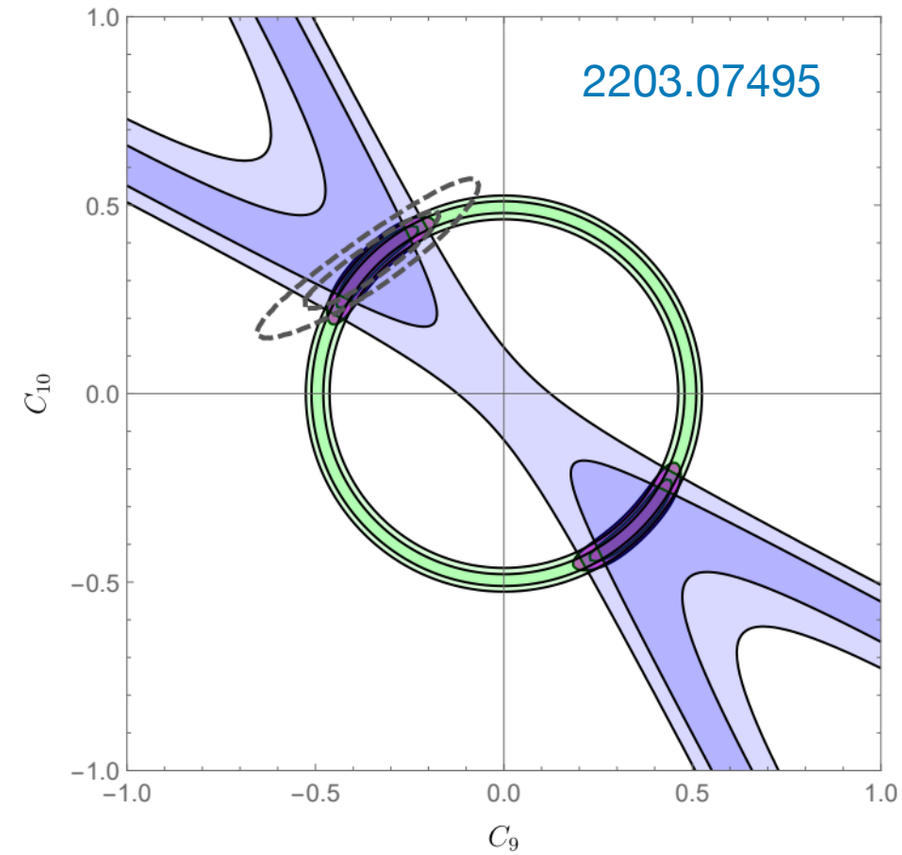
Other Exotica

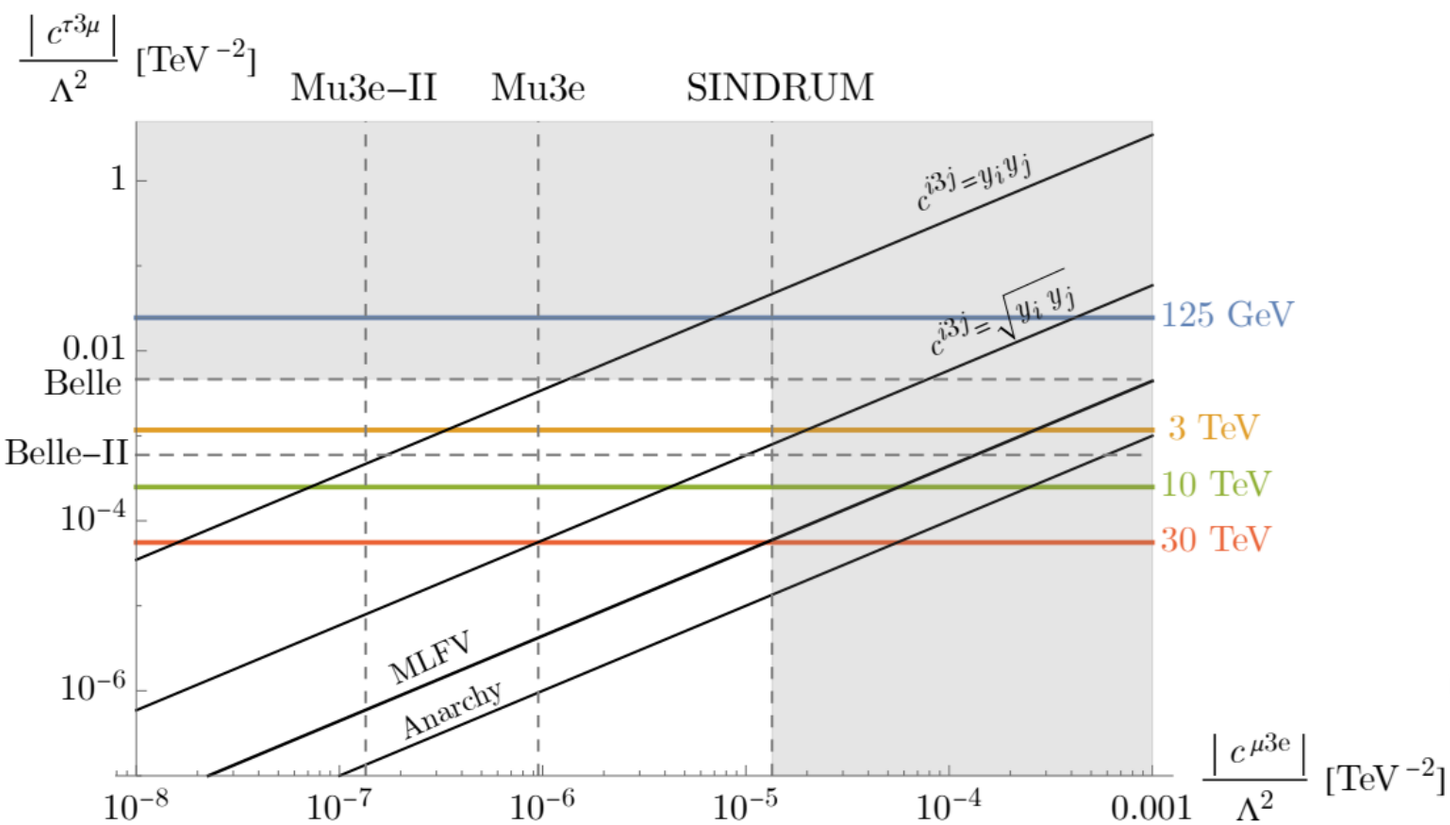
(Summary from Lingfeng Li)

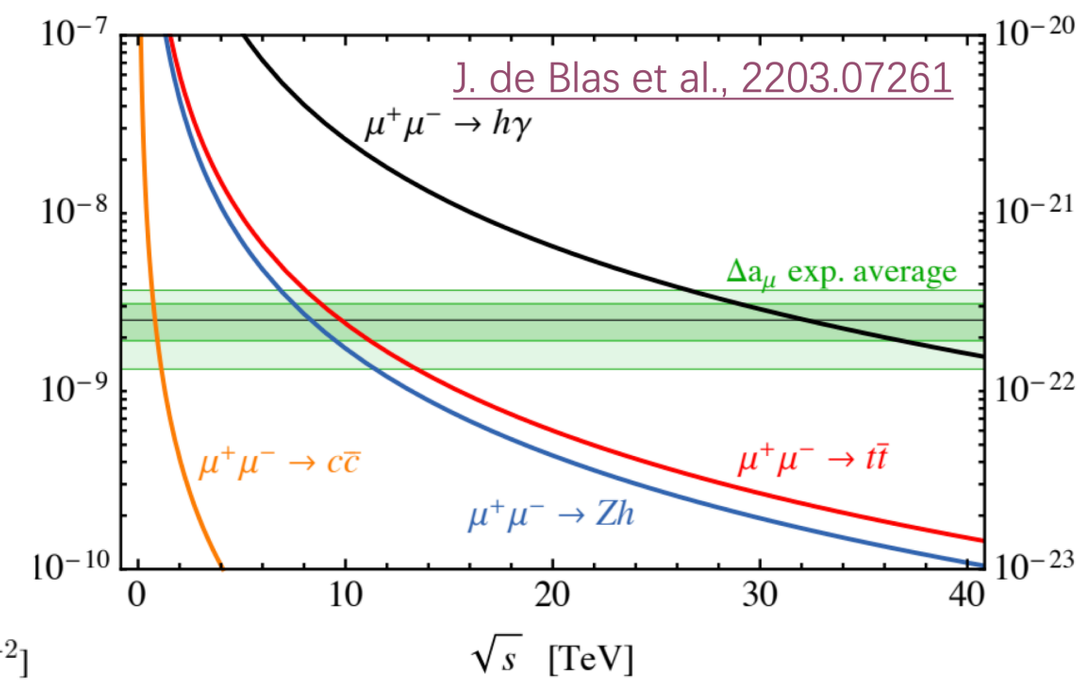
Effective Interactions

Projections for sensitivity to effective operators (especially flavor-violating ones)

Connections to outstanding flavor-anomalies $\Longrightarrow$



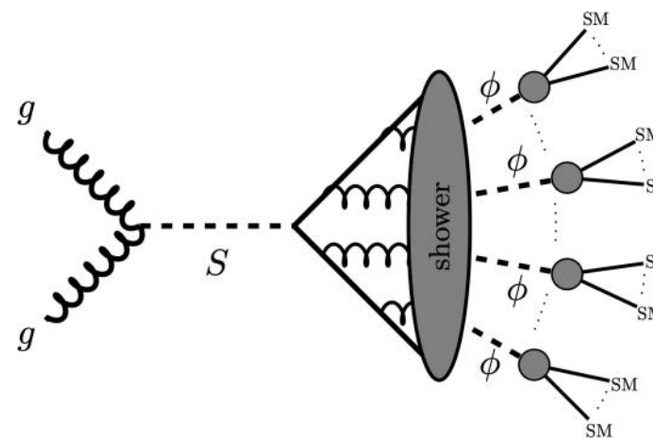


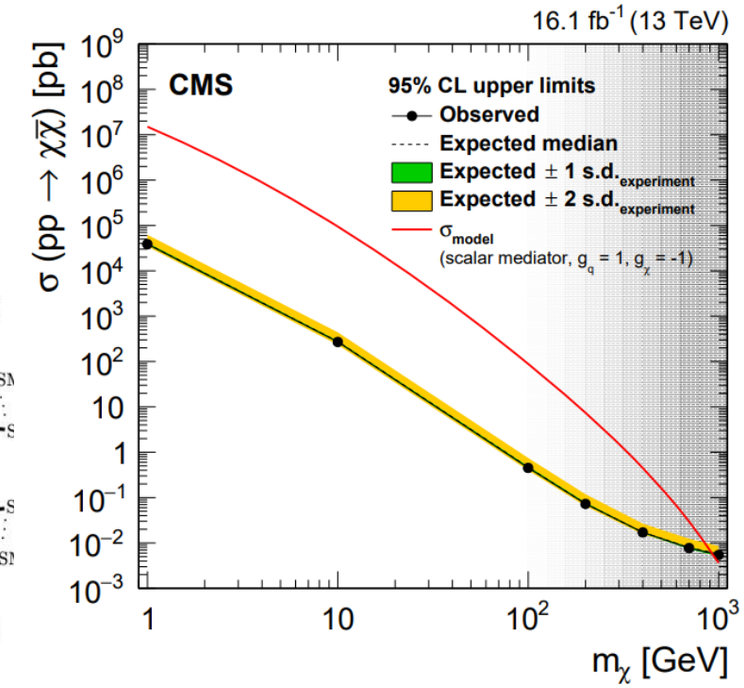


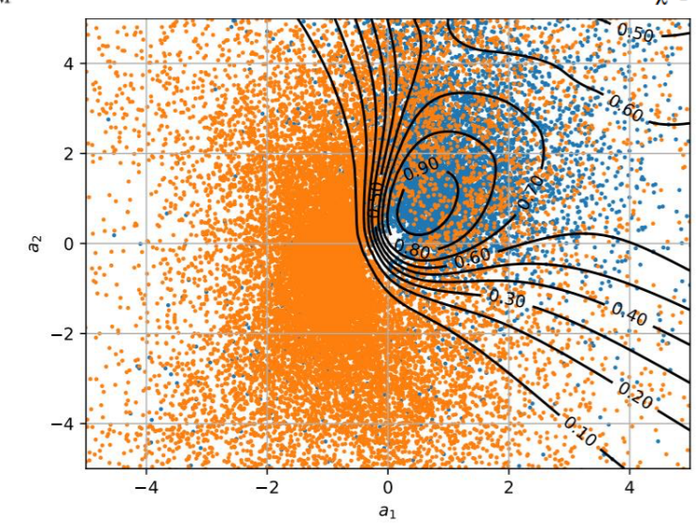
Exotic Dynamics

Examples of situations with exotic dynamics / decays / signatures:

- Dark showers
- SUEPs / soft bombs
- Trackless / semi-visible jets, …
- Quirks







These require new analysis techniques, identifying triggers, sophisticated observables…

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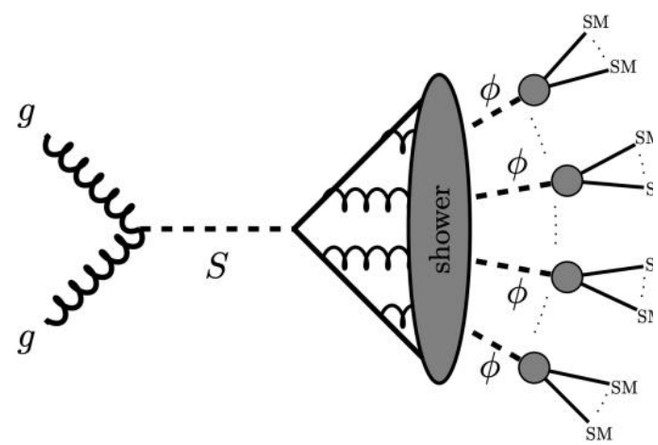
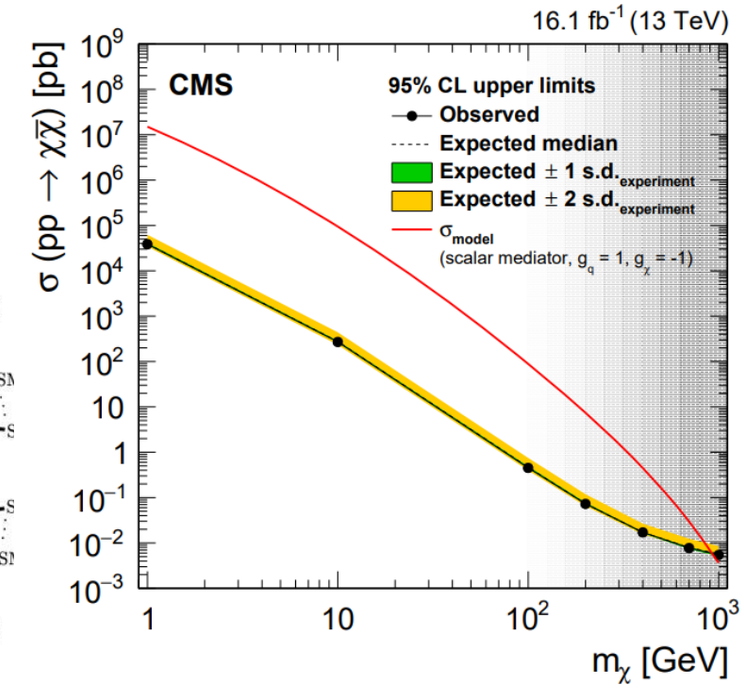
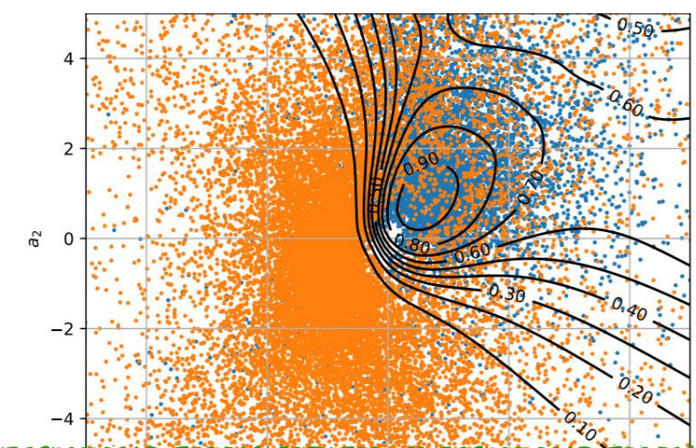




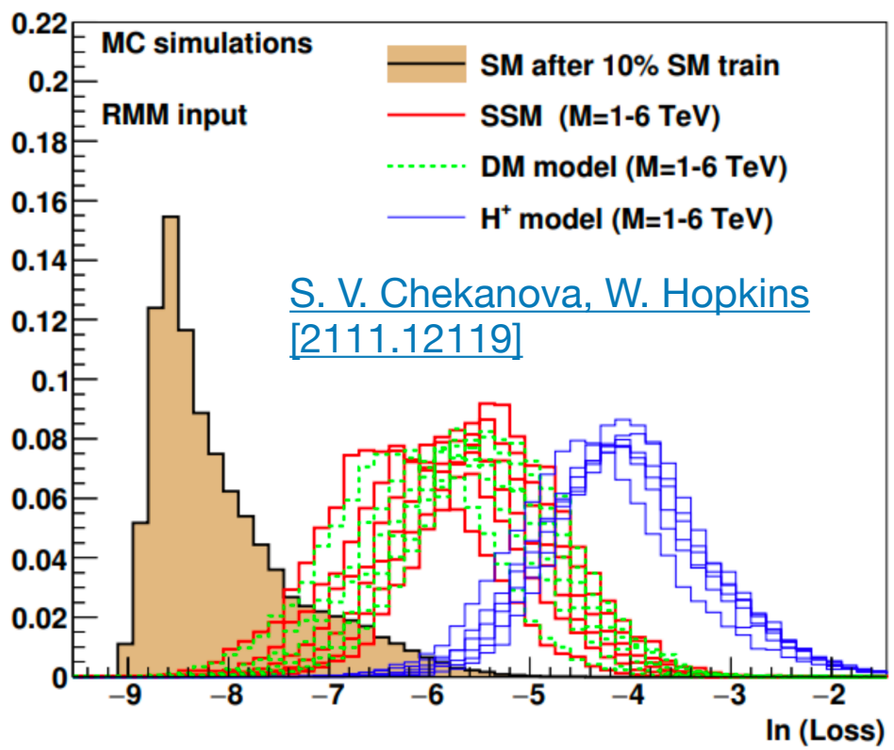


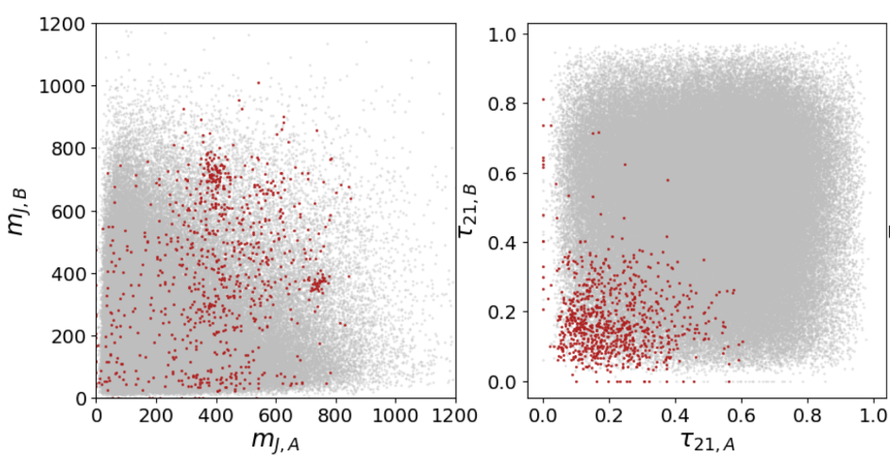
These require new analysis techniques, identifying triggers, sophisticated observables…

Discussion: important to consider these opportunities in early stages, so we don't miss them in detector designs!

Anomaly/Novelty Detection

Lots of recent interest in new techniques to search for anomalies without specifying new physics using machine-learning techniques





Many examples in LHC Olympics
[2101.08320]

Discussion: important to consider these opportunities in early stages, so we don't miss them in detector designs!

Summary

- Broad scope of models/signatures covered in EF09 submissions
  - Some signals (e.g., Z') are ideal standards to compare different machines
  - Others highlight unique opportunities (flavor-violating operators, color-charged resonances, …)
- Lots of studies focusing on interesting non-standard signatures — do we have all the “standard” channels covered?
- LLP studies offer good opportunity to showcase potential of HL-LHC (+ auxiliary experiments) in the next 10-20 years
- Lots of cross-talk with other groups/frontiers (composite Higgs models in EF02, LLPs in RF5, …)