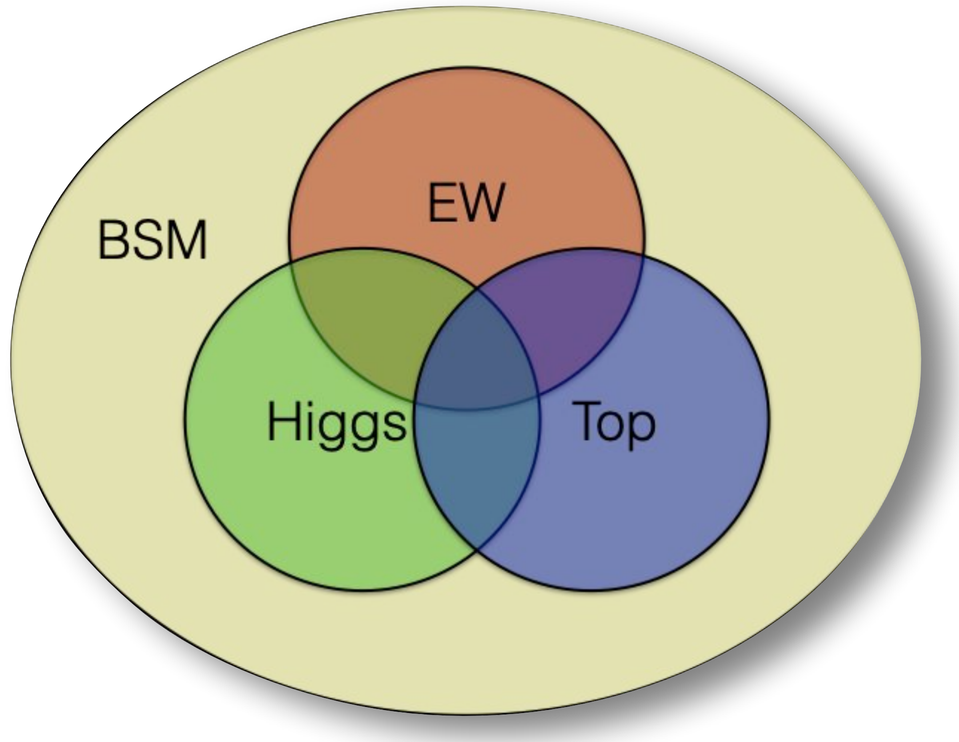
EF and RPF: Report from the Energy Frontier



Manuel Franco Sevilla

University of Maryland

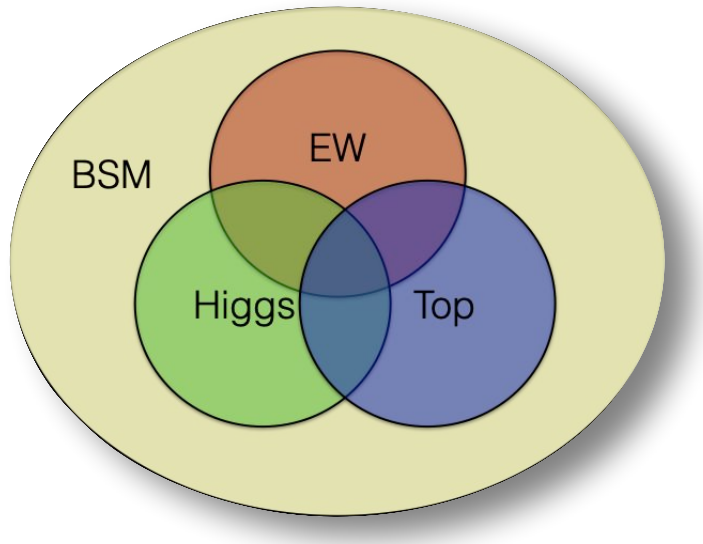
19th May 2022

Snowmass Rare and Precision Measurements Frontier Spring Meeting

Cincinnati, OH

Outline

1. **Overview** of the Energy frontier
2. **Highlights** and **connections to RPF**
   - ➡ **Electroweak scale precision physics**
     - ✦ Higgs boson
     - ✦ Top quark
     - ✦ Electroweak & global fits
   - ➡ **QCD & Heavy ions**
   - ➡ **BSM**



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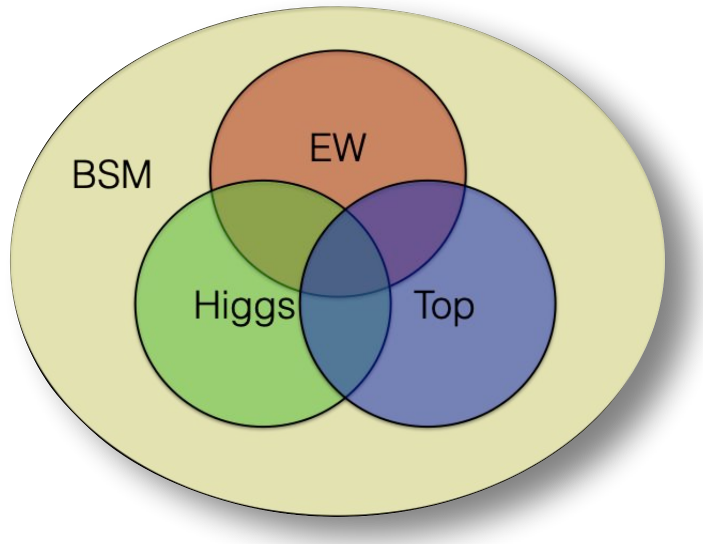

- A **large body of work**
  - Numerous topical group meetings
  - May 21, 2020 - EF kickoff workshop
  - July 7-8, 2020 - Preparatory Joint TG Sessions
  - July 20-22, 2020 - Open Questions and New Ideas
  - Aug 30-Sep 3, 2021 - EF restart workshop
  - **Mar 1-Apr 2 - EF workshop**
  - **139 white papers**

The Energy Frontier mandate

Explore the TeV scale and beyond

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- **Large part of EF** is about **precision measurements**, so more precisely

> *Precision measurements of the **Higgs** and **vector bosons**, **top quark**, and **QCD**, and exploration of the **TeV scale** and beyond*

The Energy Frontier mandate

Explore the TeV scale and beyond

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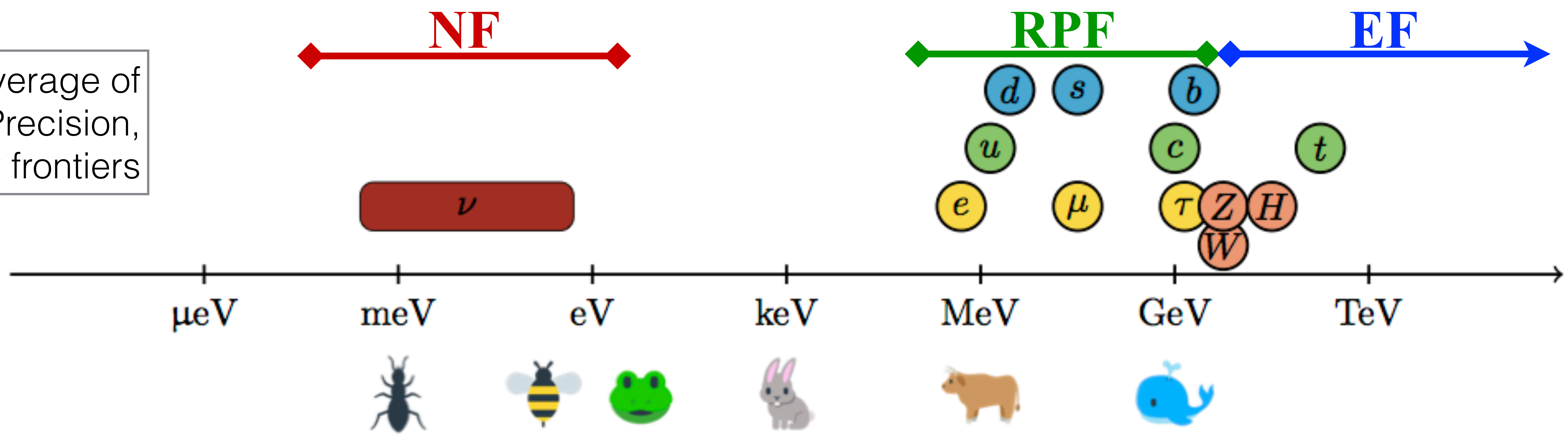
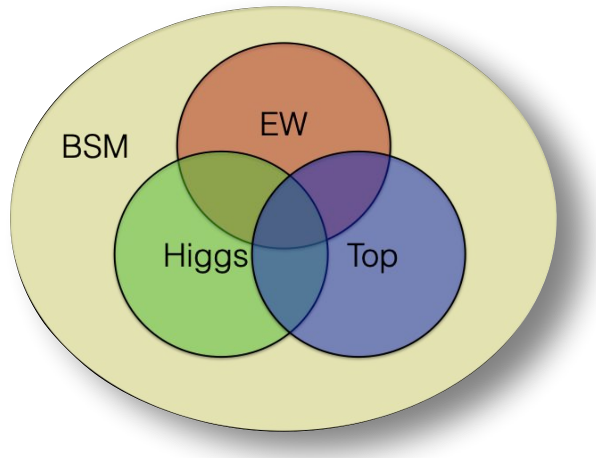
Rough energy coverage of Neutrino, Rare and Precision, and Energy frontiers



EF big questions

- What is the **origin of the EW scale**?
- What is the **nature of QCD**?
- How do we **best build the BSM program**?



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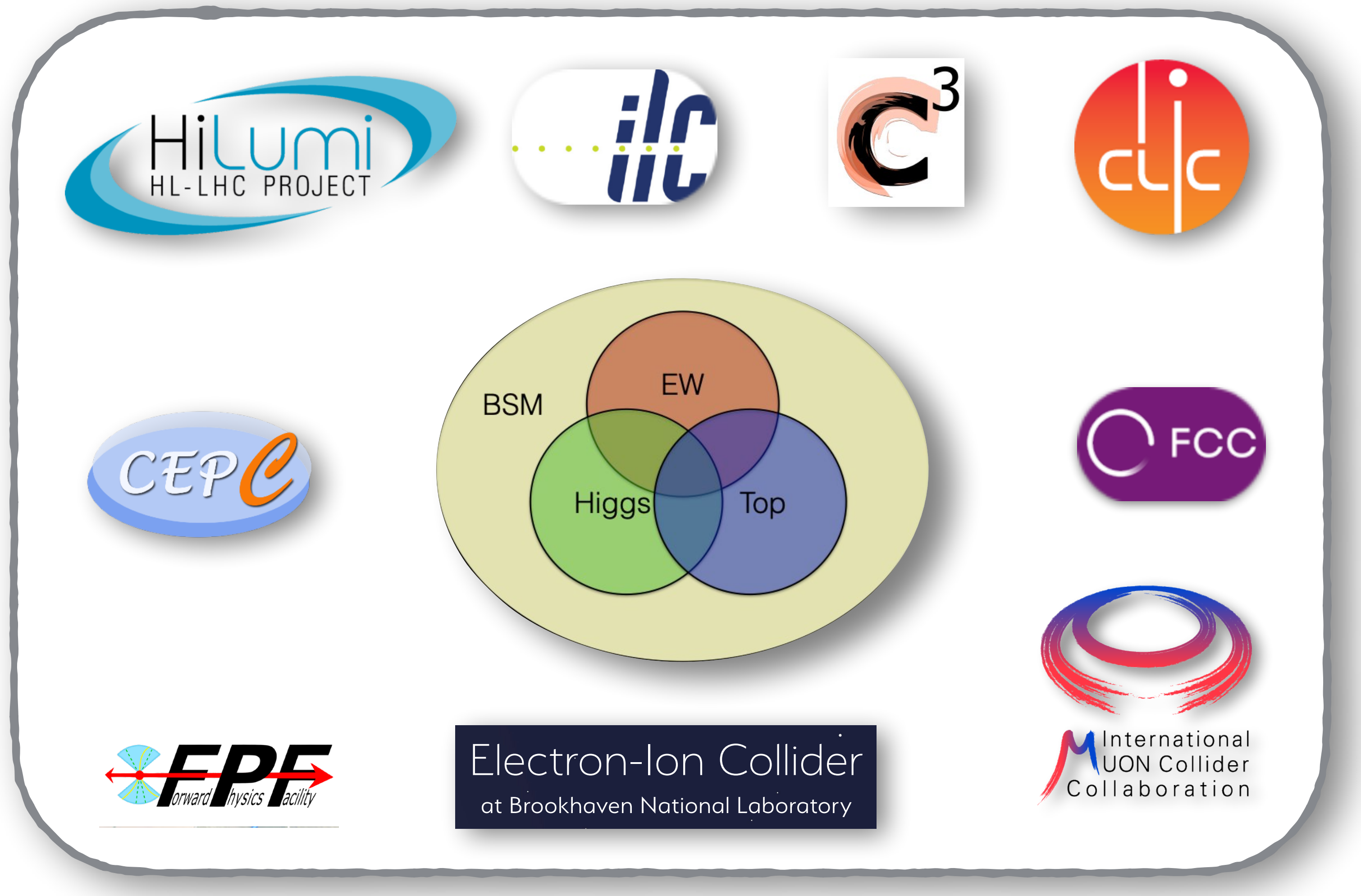

- What is the **origin of the EW scale**?
- What is the **nature of QCD**?
- How do we **best build the BSM program**?
- **How should the US be involved in near and far future energy-frontier machines** after the HL-LHC?
  - What could be the energy-frontier machines that follow the HL-LHC?
  - How can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

EF organization

Meenakshi Narain (Brown U)

Laura Reina (FSU)

Alessandro Tricoli (BNL)

Topical Group			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 Phys. & constraining new phys.	Alberto Belloni (Maryland)	Ayres Freitas (Pittsburgh)	Junping Tian (Tokyo)
EF05	QCD and Strong Interactions	Precision QCD	Michael Begel (BNL)	Stefan Hoeche (FNAL)	Michael Schmitt (NW)
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)	Elliott Lipeles (UPenn)	Nausheen Shah (Wayne State)
EF09	BSM	More general explorations	Tulika Bose (UW-Madison)	Zhen Liu (Minnesota)	Simone Griso (LBL)
EF10	BSM	Dark Matter at colliders	Caterina Doglioni (Lund)	LianTao Wang (Chicago)	Antonio Boveia (Ohio St.)

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

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Why I'm talking today

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139 white papers submitted

30 papers submitted to **"General" EF** (below), and **109** to the various **Topical Groups** (slides ahead)

Green: also submitted to RPF

Title	Authors	arXiv
The Forward Physics Facility: Sites, Experiments, and Physics Potential	**L. A. Anchordoqui, A. Ariga, T. Ariga, et al**	**2109.10905**
The Forward Physics Facility at the High-Luminosity LHC	**J. L. Feng, F. Kling, M. Hall Reno, et al**	**2203.05090**
The Future Circular Collider: a Summary for the US 2021 Snowmass Process	**G. Bernardi, E. Brost, D. Denisov, et al**	**2203.06520**
Software and Computing for Small HEP Experiments	**D. Casper, M. Elena Monzani, B. Nachman, et al**	**2203.07645**
Detector and Beamline Simulation for Next-Generation High Energy Physics Experiments	**S. Banerjee, D. N. Brown, D. N. Brown, et al**	**2203.07614**
The International Linear Collider	**A. Aryshev, T. Behnke, M. Berggren, et al**	**2203.07622**
Physics with the Phase-2 ATLAS and CMS Detectors	**The ATLAS and CMS Collaborations.**	**link**
In Search of Excellence and Equity in Physics	**E. Barzi, S. James Gates Jr., R. Springer.**	**2203.10393**
An Impartial Perspective for Superconducting Nb3Sn coated Copper RF Cavities for Future Accelerators	**E. Barzi, B. C. Barish, R. A. Rimmer, et al**	**2203.09718**
Japan's Strategy for Future Projects in High Energy Physics	**M. Endo, K. Hamaguchi, M. Ibe, et al**	**2203.13979**
High Energy & High Luminosity γγ Colliders	**E. Barzi, B. Barish, W. A. Barletta, et al**	**2203.08353**
C3:A 'Cool' Route to the Higgs Boson and Beyond	M. Bai, T. Barklow, R. Bartoldus, et al	2110.15800
The physics case of a 3 TeV muon collider stage	J. De Blas, D. Buttazzo, R. Capdevilla, et al	2203.07261
Muon Collider Physics Summary	C. Aimè, A. Apyan, M. Attia Mahmoud, et al	2203.07256
Enabling U.S. participation in Future Higgs Factories	K. Black, K. Bloom, J.E. Brau, et al	2203.06255
Strategies for Beam-Induced Background Reduction at Muon Colliders	D. Ally, L. Carpenter, T. Holmes, et al	2203.06773
Strategies for conformal REBCO windings	J. Rogers, P. McIntyre, T. Elliott, et al	2203.06800
Promising Technologies and R&D Directions for the Future Muon Collider Detectors	S. Jindariani, F. Meloni, N. Pastrone, et al	2203.07224
Future Collider Options for the US	P. C. Bhat, S. Jindariani, G. Ambrosio, et al	2203.08088
A Muon Collider Facility for Physics Discovery	D. Stratakis, N. Mokhov, M. Palmer, et al	2203.08033
Simulated Detector Performance at the Muon Collider	N. Bartosik, K. Krizka, S. Pagan Griso, et al	2203.07964
Hybrid conformal REBCO dipole for a next hadron collider	P. M McIntyre.	2203.08132
The Physics Case for a Neutrino Factory	A. Bogacz, V. Brdar, A. Bross, et al	2203.08094
Higgs-Energy LEptoN (HELEN) Collider based on advanced superconducting radio frequency technology	S. Belomestnykh, P.C. Bhat, A. Grassellino, et al	2203.08211
The CLIC project	O. Brunner, P. N. Burrows, S. Calatroni, et al	2203.09186
Event Generators for High-Energy Physics Experiments	J. M. Campbell, M. Diefenthaler, T. J. Hobbs, et al	2203.11110
Circular Electron Positron Collider (CEPC)	C. Accelerator Study Group.	2203.09451
Particle Flow Calorimetry	R. Ruchti, K. Kruger.	2203.15138
Physics at Future Colliders: the Interplay Between Energy and Luminosity	Z. Liu, L. Wang	2205.00031

Facilities are main connection to RPF

Snowmass 2021 Higgs Factory Study Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3 c.o.m almost similar	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	$\pm80/0$ $\pm80/0$ $\pm80/0$	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV $2\ M_{top}$		150 10 5 1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

- The **Higgs** and possible direct detection of **BSM physics** will **drive decision on next high-energy facility**
  - ➡ Probably a **good place for RPF** measurements too!

Snowmass 2021 EF Discovery Collider Scenarios

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

Effort to homogenize results according to these benchmark scenarios

139 white papers → 5 EF reports

Topical Group		
EF01	EW Physics	Higgs Boson properties and couplings
EF02		Higgs Boson as a portal to new physics
EF03		Heavy flavor and top quark physics
EF04		EW Precision Phys. & constraining new phys.
EF05	QCD and Strong Interactions	Precision QCD
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EF01+EF02: **Higgs boson**

EF03: **HF production & Top quark**

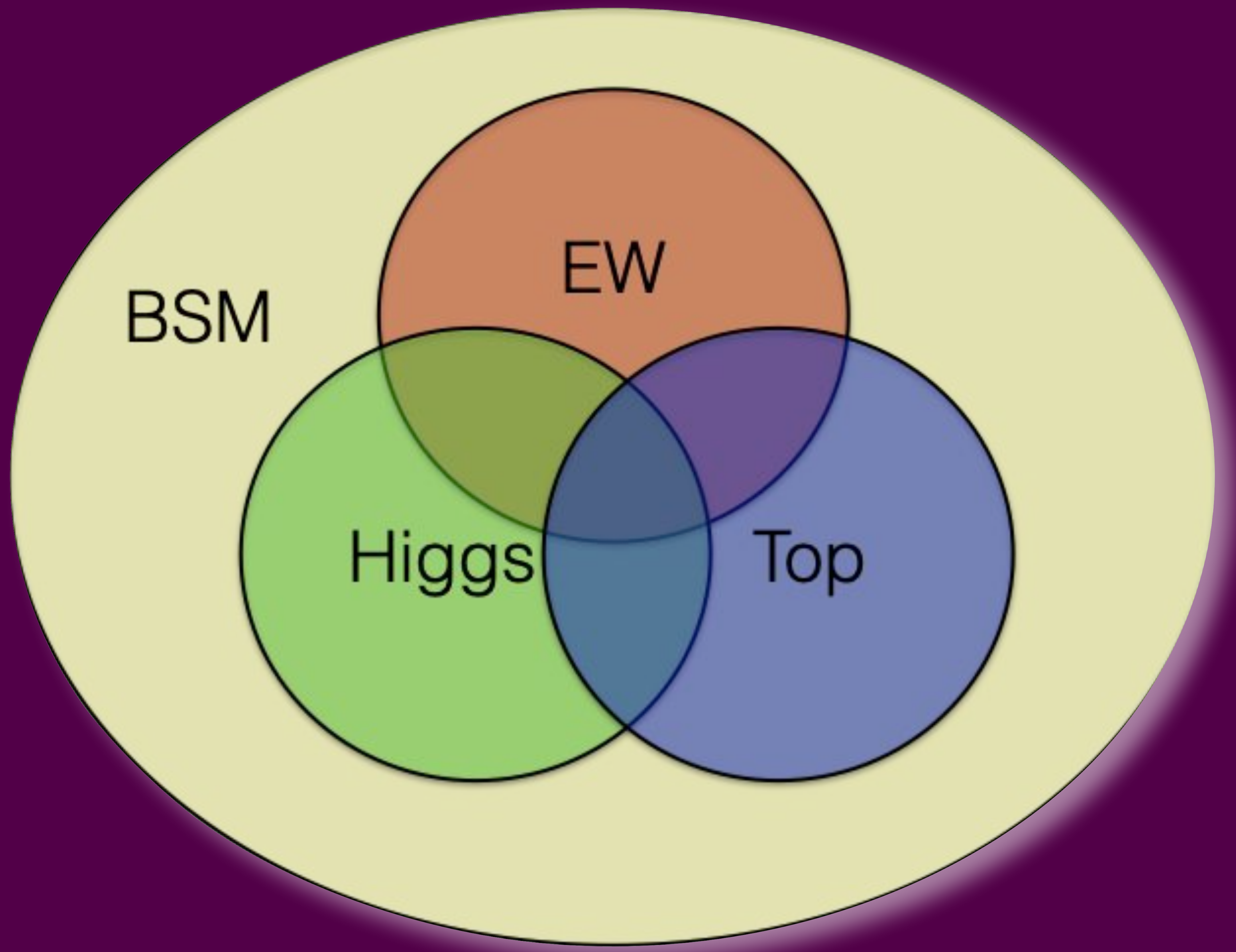
EF04: **Electroweak & Global fits**

EF05+EF06+EF07: **QCD & Heavy ions**

EF08+EF09+EF10: **BSM**

First drafts being reviewed internally, public drafts on May 31

Electroweak scale precision physics



Reports

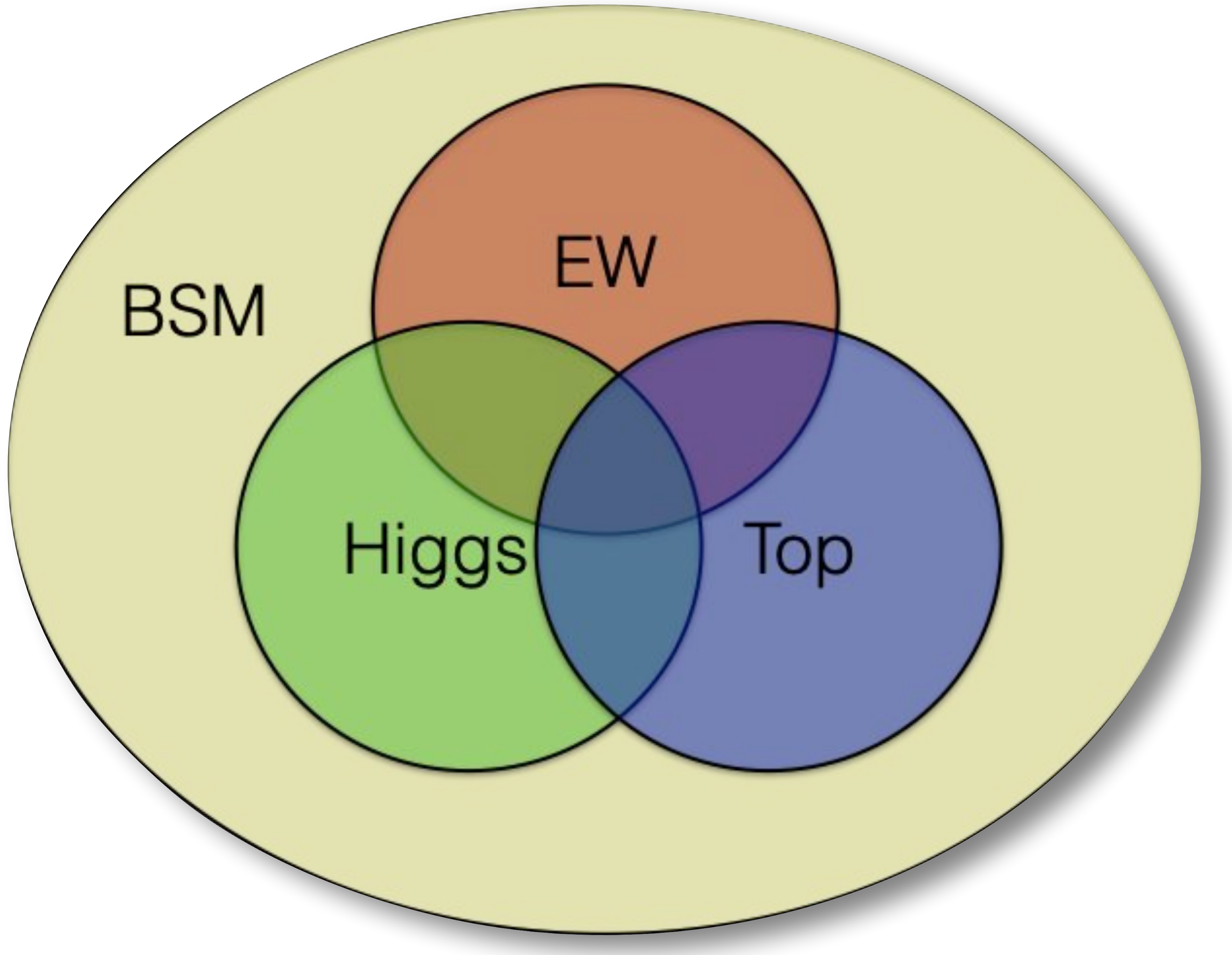
EF01+EF02: Higgs boson

EF03: HF production & Top quark

EF04: Electroweak & Global fits

Measuring the EW scale

- EW precision measurements **complement direct searches for NP**
  - Tool **similar to flavor, very powerful beyond energy reach**
- **Higgs boson most exciting discovery/confirmation** in this century
  - Traditionally, discovery of particles followed by collider to study particles
    - Eg, LEP following the discovery of W and Z at UA1/UA2
  - The Higgs boson **will be key in selecting next collider**
- **Evaluate the reach** of various options with **global fits to EW observables**
  - Inputs from **Higgs**, **top quark**, and **EW** measurements
  - Can help to first **detect BSM effects** and then **identify** the **model**



24 papers submitted to EF01+EF02

Green: also submitted to RPF

TG	Title	Authors	arXiv
EF01	***Ultrafast Inorganic Crystals with Mass Production Capability for Future High-Rate Experiments***	**C. Hu, L. Zhang, R. Zhu**	**2203.06788**
EF01	*Higgs Factory Considerations*	J. A. Bagger, B. C. Barish, S. Belomestnykh, et al	2203.06164
EF01	*Tree-level Interference in VBF production of Vh*	C. Paranjape, D. Stolarski, Y. Wu	2203.05729
EF01	*Study of the hγZ coupling at the ILC*	Y. Aoki, K. Fujii, J. Tian	2203.07202
EF01	*Measuring the CP properties of the Higgs sector at electron-positron colliders*	I. Božović-Jelisavucić, N. Vukausinović, D. Jeans	2203.06819
EF01	*Improving Di-Higgs Sensitivity at Future Colliders in Hadronic Final States with Machine Learning*	D. Diaz, J. Duarte, S. Ganguly, et al	2203.07353
EF01	*CERC - Circular e+e- Collider using Energy-Recovery Linac*	V. N Litvinenko, N. Bachhawat, M. Chamizo-Llatas, et al	2203.07358
EF01	*The ReLiC: Recycling Linear e+e− Collider*	V. N Litvinenko, N. Bachhawat, M. Chamizo-Llatas, et al	2203.06476
EF01	*Directly Probing the CP-structure of the Higgs-Top Yukawa at HL-LHC and Future Colliders*	R. Kumar Barman, M. E. Cassidy, Z. Dong, et al	2203.08127
EF01	*Complex Scalar Singlet Model Benchmarks for Snowmass*	S. Adhikari, S. D. Lane, I. M. Lewis, et al	2203.07455
EF01	*Strategy for Understanding the Higgs Physics: The Cool Copper Collider*	S. Dasu, E. A. Nanni, M. E. Peskin, et al	2203.07646
EF01	*Higgs Self Couplings Measurements at Future proton-proton Colliders*	A. Taliercio, P. Mastrapasqua, C. Caputo, et al	2203.08042
EF01	*Expected Sensitivity to Invisible Higgs Boson Decays at the ILC with the SiD Detector*	C. Potter, A. Steinhebel, J. Brau, et al	2203.08330
EF01	*Prospects for the Measurement of the Standard Model Higgs Pair Production at the Muon Colliders*	K. Black, T. Bose, S. Dasu, et al	2203.08874
EF01	*Strange quark as a probe for new physics in the Higgs sector*	A. Albert, M. J. Basso, S. K. Bright-Thonney, et al	2203.07535
EF01	*XCC: An X-ray FEL-based γγ Collider Higgs Factory*	T. Barklow, S. Dong, C. Emma, et al	2203.08484
EF01	*High Precision Higgs from High Energy Muon Colliders*	M. Forslund, P. Meade	2203.09425
EF01	*Higgs boson decay to charmonia via c-quark fragmentation*	T. Han, A. K. Leibovich, Y. Ma, et al	2202.08273
EF01	*Jet Flavour Tagging for Future Colliders with Fast Simulation*	F. Bedeschi, L. Gouskos, M. Selvaggi	2202.03285
EF02	*Good things to do with extra Higgs doublets*	H. Davoudiasl, I. M. Lewis, M. Sullivan	2203.01396
EF02	*A short overview on low mass scalars at future lepton colliders*	T. Robens	2203.08210
EF02	*Higgs Coupling Sensitivities and Model-Independent Bounds on the Scale of New Physics*	F. Abu-Ajamieh, S. Chang, M. Chen, et al	2203.09512
EF02	*Study of Electroweak Phase Transition in Exotic Higgs Decays at the CEPC*	Z. Wang, X. Zhu, E. E Khoda, et al	2203.10184
EF02	*Detection of Early-Universe Gravitational Wave Signatures and Fundamental Physics*	R. Caldwell, Y. Cui, H. Guo, et al	2203.07972

21 papers submitted to EF03+EF04

Green: also submitted to RPF

TG	Title	Authors	arXiv
EF03	*On the modeling uncertainties of ttbar W± multi-lepton signatures*	G. Bevilacqua, H.Y. Bi, F. Febres Cordero, et al	2109.15181
EF03	*Azimuthal angular correlation as a new boosted top jet substructure*	Z. Yu, C.-P. Yuan	2203.02760
EF03	*Higher-order corrections for t tbar production at high energies*	N. Kidonakis	2203.03698
EF03	*Optimising top-quark threshold scan at CLIC using genetic algorithm*	K. Nowak, A. Filip Zarnecki	2103.00522
EF03	*Probing heavy-flavor parton distribution functions at hadron colliders*	K. Xie, M. Guzzi, P. Nadolsky	2203.06207
EF03	*Top-quark mass extraction from t tbar j+X events at the LHC: theory predictions*	S. Alioli, J. Fuster, M. Vittoria Garzelli, et al	2203.07344
EF03	*Dependence of the top-quark mass measured in top-quark pair production on the parton distribution functions at the LHC*	J. Gombas, J. Fein, S. Sawford, et al	2203.08064
EF03	*Implications of Energy Peak for Collider Phenomenology: Top Quark Mass Determination and Beyond*	K. Agashe, S. Airen, R. Franceschini, et al	2204.02928
EF03	*Prospects for measurements of the bottom quark mass*	J. Aparisi, J. Fuster, A. Hoang, et al	2203.16994
EF03	*Prospects for the measurement of top-quark couplings*	G. Durieux, A. Gutiérrez Camacho, L. Mantani, et al	2205.02140
EF04	***Belle II physics reach and plans for the next decade and beyond***	**Belle II Collaboration**	**link**
EF04	***Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation***	**S. Banerjee, J. Michael Roney (for the US Belle II and polarization upgrade Groups)**	**link**
EF04	*Longitudinally polarized ZZ scattering at the Muon Collider*	T. Yang, S. Qian, Z. Guan, et al	2107.13581
EF04	*Vector Boson Scattering Processes: Status and Prospects*	D. Buarque Franzosi, M. Gallinaro, R. Ruiz, et al	2106.01393
EF04	*Vector boson fusion at multi-TeV muon colliders*	A. Costantini, F. De Lillo, F. Maltoni, et al	2005.10289
EF04	*The Effective Vector Boson Approximation in High-Energy Muon Collisions*	R. Ruiz, A. Costantini, F. Maltoni, et al	2111.02442
EF04	*Measurement of ALR using radiative return at ILC 250*	T. Mizuno, K. Fujii, J. Tian	2203.07944
EF04	*Anomalous quartic gauge couplings at a muon collider*	B. Abbott, A. Apyan, B. Azartash-Namin, et al	2203.08135
EF04	*Measuring the tau polarization at ILC*	K. Yumino, D. Jeans	2203.07668
EF04	*Sensitivity to longitudinal vector boson scattering in W±W±jj at future hadron colliders*	A. Apyan, C. Mwewa, L. Nedic, et al	2203.07994
EF04	*Electroweak fragmentation at high energies*	T. Han, Y. Ma, K. Xie	2203.11129
EF04	*SMEFT at the LHC and Beyond*	W. Shepherd	2203.07406
EF04	*RADiCAL: Precision-timing, Ultracompact, Radiation-hard Electromagnetic Calorimetry*	T. Anderson, T. Barbera, D. Blend, et al	2203.12806

Physics considerations of a Higgs factory

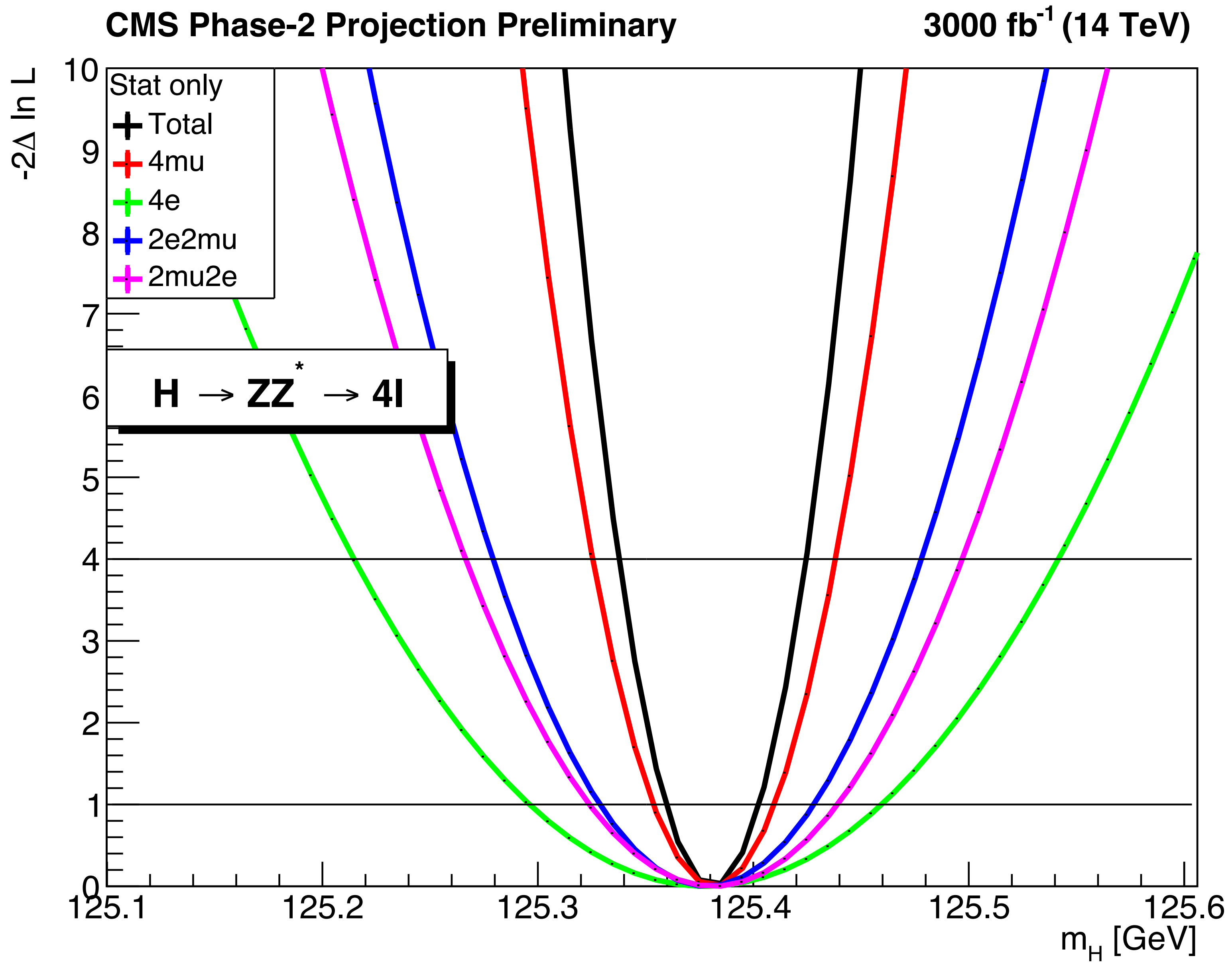
1. Precision measurement of **Higgs couplings to SM fermions** and **gauge bosons**
2. Measurement of **Higgs self-couplings**
3. Sensitivity to **rare or non-SM Higgs decays**
4. Discovery potential for **new non-SM physics**
5. Ability to directly measure **top electroweak and Yukawa couplings**
6. BSM sensitivity via precision **top/W masses, top width, Z-pole parameters**
7. Ability to improve precision of the **strong coupling constant**

Bagger, Barish, Belmestnykh, Bhat, et al, 2203.06164

Already have a Higgs factory approved: HL-LHC

CMS PAS FTR-21-007

- Updated HL-LHC mass/width projections for Snowmass



Higgs mass uncertainty (±stat ±syst)

(**±22 ±20**) MeV from $\boldsymbol{H \to ZZ \to 4\ell}$

(**±20 ±70**) MeV from $\boldsymbol{H \to \gamma\gamma}$

Detector upgrade improves 4μ resolution by 25% and 4ℓ yield by 17%

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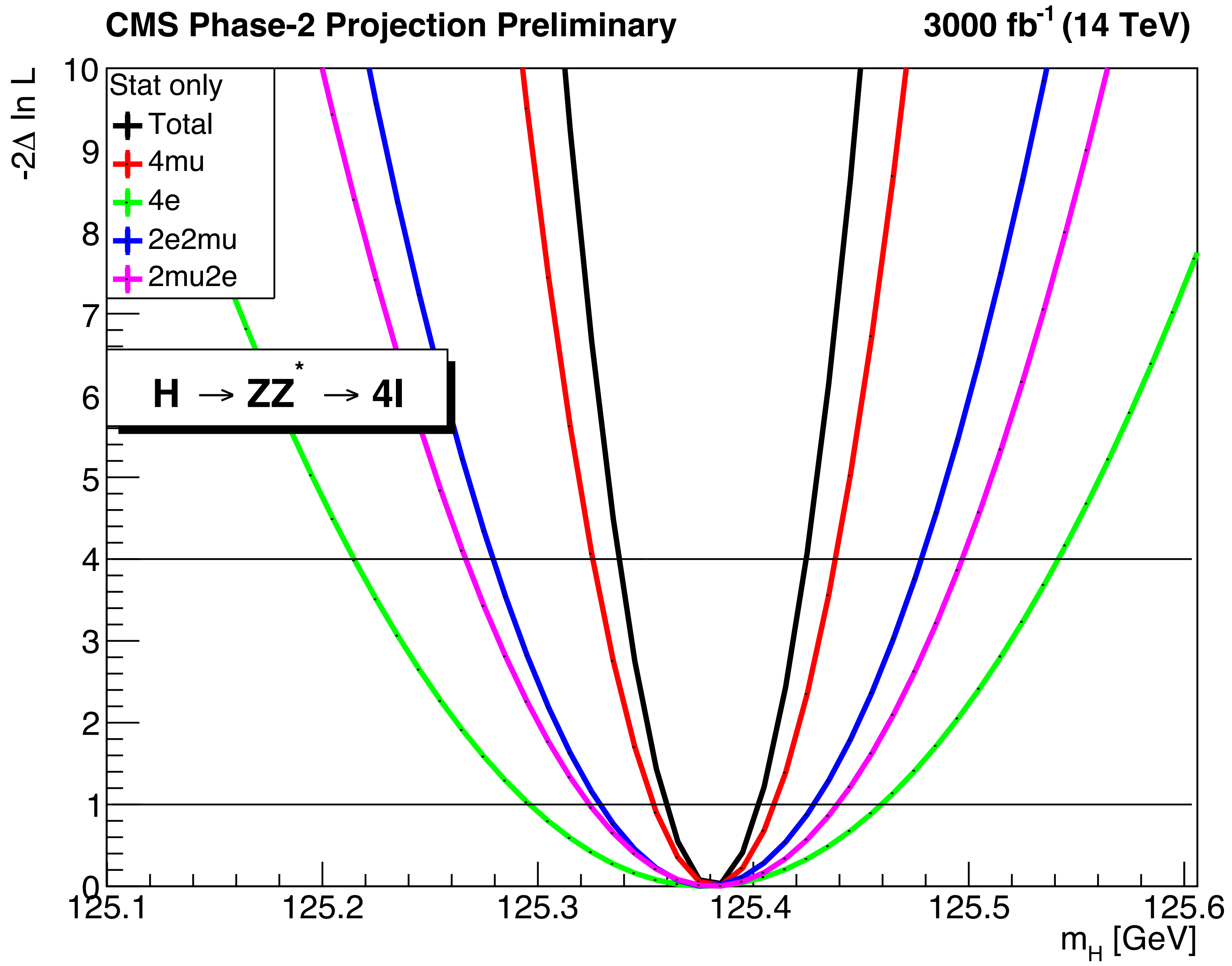

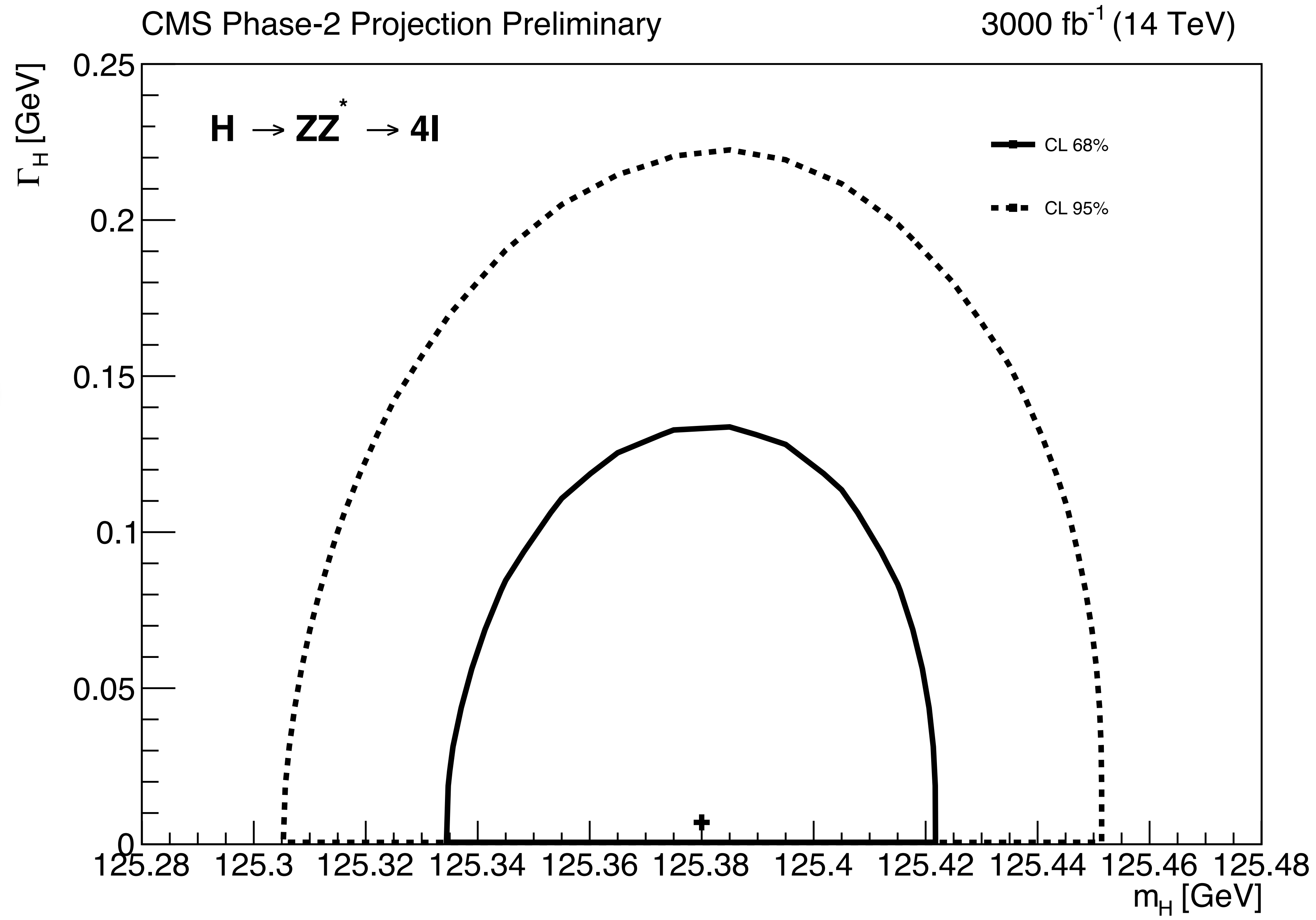

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Detector upgrade improves 4μ resolution by 25% and 4ℓ yield by 17%

Direct measurement Γ_H **< 177 MeV (95% CL)**, limited by lineshape resolution

Indirect measurement $\Gamma_H = 4.1^{+0.7}_{-0.8}$ **MeV** assuming SM offshell/onshell Higgs production

Higgs factory scenarios

Snowmass 2021 Higgs Factory Study Scenarios

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CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV 2 M_{top}		150 10 5 1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

~ High-luminosity e$^+$e$^-$ colliders proposed as **Higgs factories** can be **used to study EW scale** too

ILC, C^3:

- ✓ **Run at 250+ GeV**
- ✓ **Measure Z with $e^+e^- \to Z\gamma$**
- ✓ **Dedicated Z and WW runs possible with small modifications**
- ✓ **Up to 80%/30% polariz. of e^-/e^+**

CLIC:

- ✓ **Run at 350+ GeV**
- ✓ **Measure Z with $e^+e^- \to Z\gamma$**
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- ✓ **Up to 80%/0% polariz. of e^-/e^+**

Higgs factory scenarios

Snowmass 2021 Higgs Factory Study Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C[3] c.o.m almost similar	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	$\pm80/0$ $\pm80/0$ $\pm80/0$	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV $2\ M_{top}$		150 10 5 1.5
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~ High-luminosity e⁺e⁻ colliders proposed as **Higgs factories** can be **used to study EW scale** too

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- ✓ Up to 80%/0% polariz. of e^-/e^+

FCC:
- ✓ Runs at Z, WW, HZ, tt
- ✓ No polarization
- ✓ Largest Z sample

CEPC:
- ✓ Runs at Z, WW, HZ, tt
- ✓ No polarization
- ✓ Similar Z sample (100 ab^{-1})

Higgs factory scenarios

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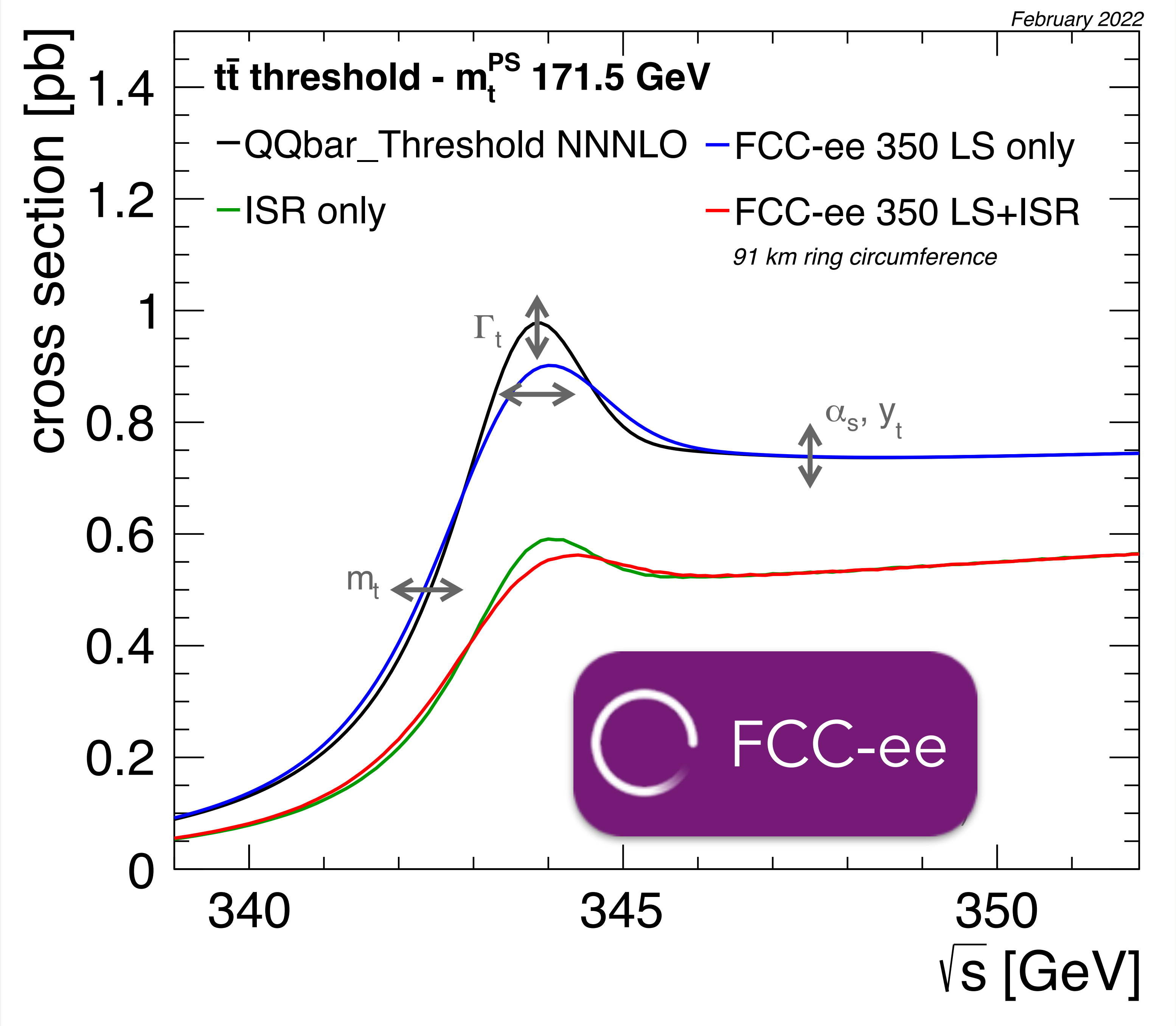
- ✓ **No polarization**
- ✓ **Largest Z sample**

CEPC

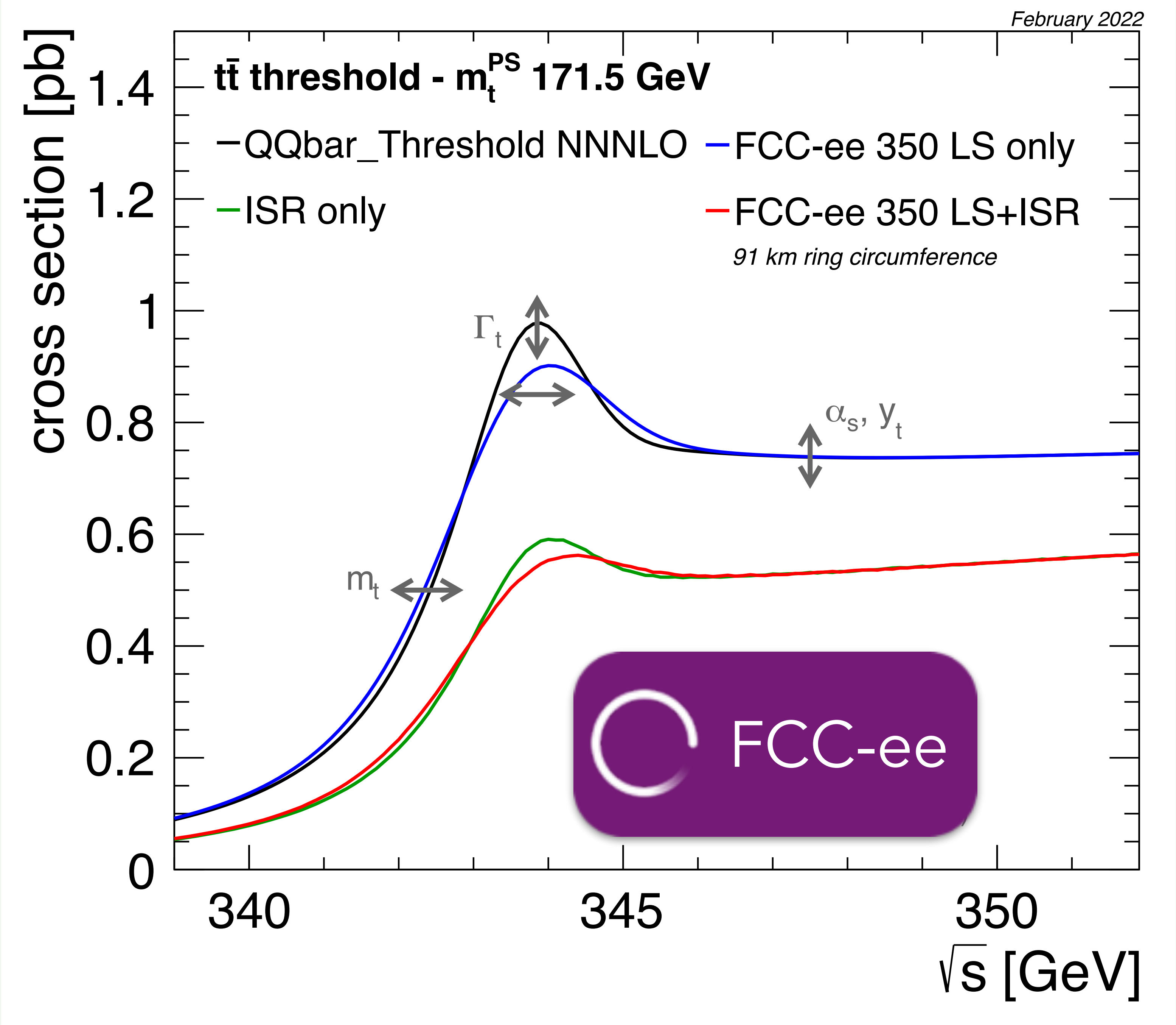
- ✓ **Runs at Z, WW, HZ, tt**
- ✓ **No polarization**
- ✓ **Similar Z sample (100 ab^{-1})**

Great flavor physics with **10^{12}+ Z bosons at circular colliders**



- With a 200 fb^{-1} $t\bar{t}$ scan
  - $\sigma_{stat}(m_t) < 9$ MeV when Γ_t and y_t assumed
  - $\sigma_{stat}(m_t) = 17$ MeV and $\sigma_{stat}(\Gamma_t) = 45$ MeV if both floated

Unprecedented precision and reach



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  - $\sigma_{stat}(m_t) < 9$ MeV when Γ_t and y_t assumed
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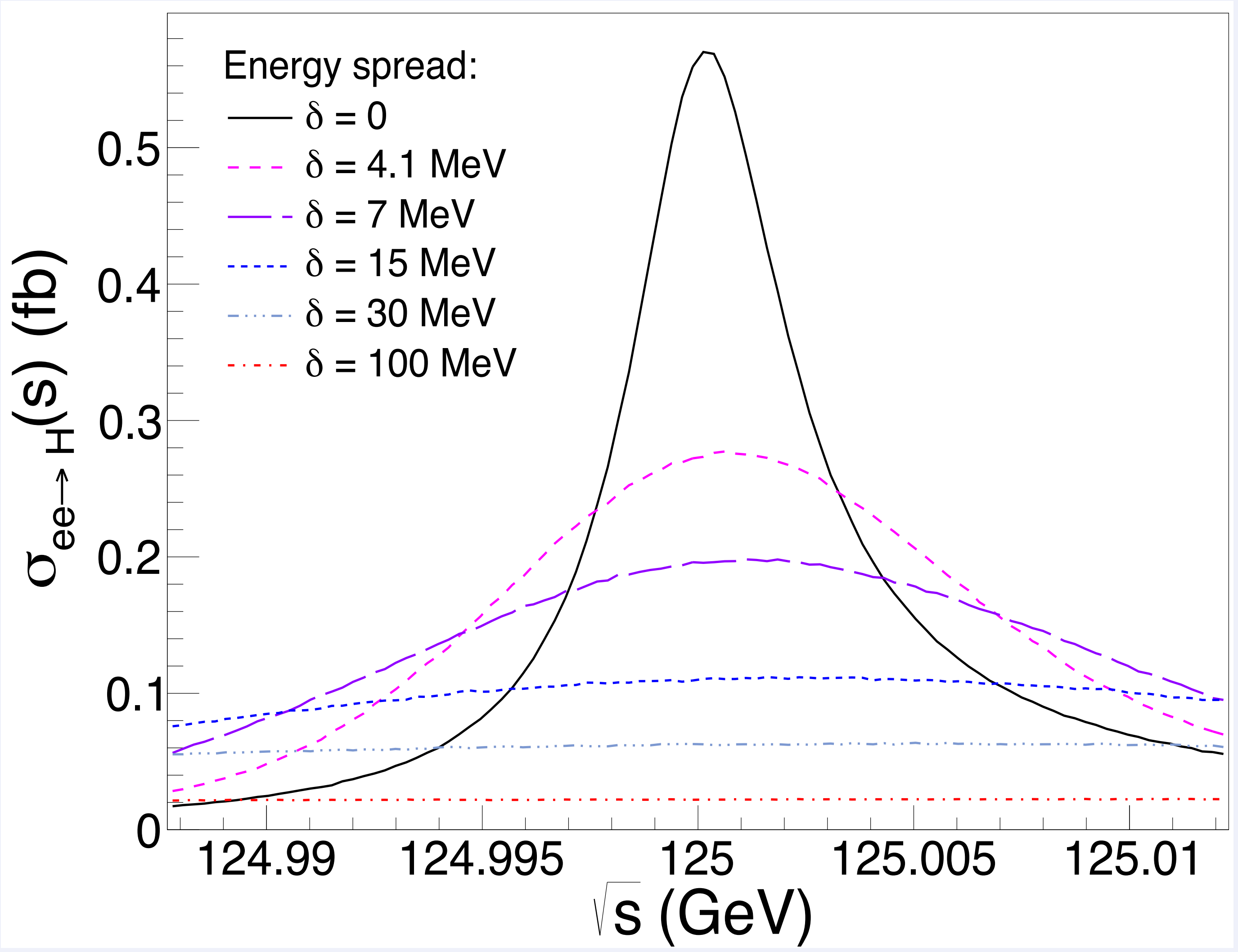
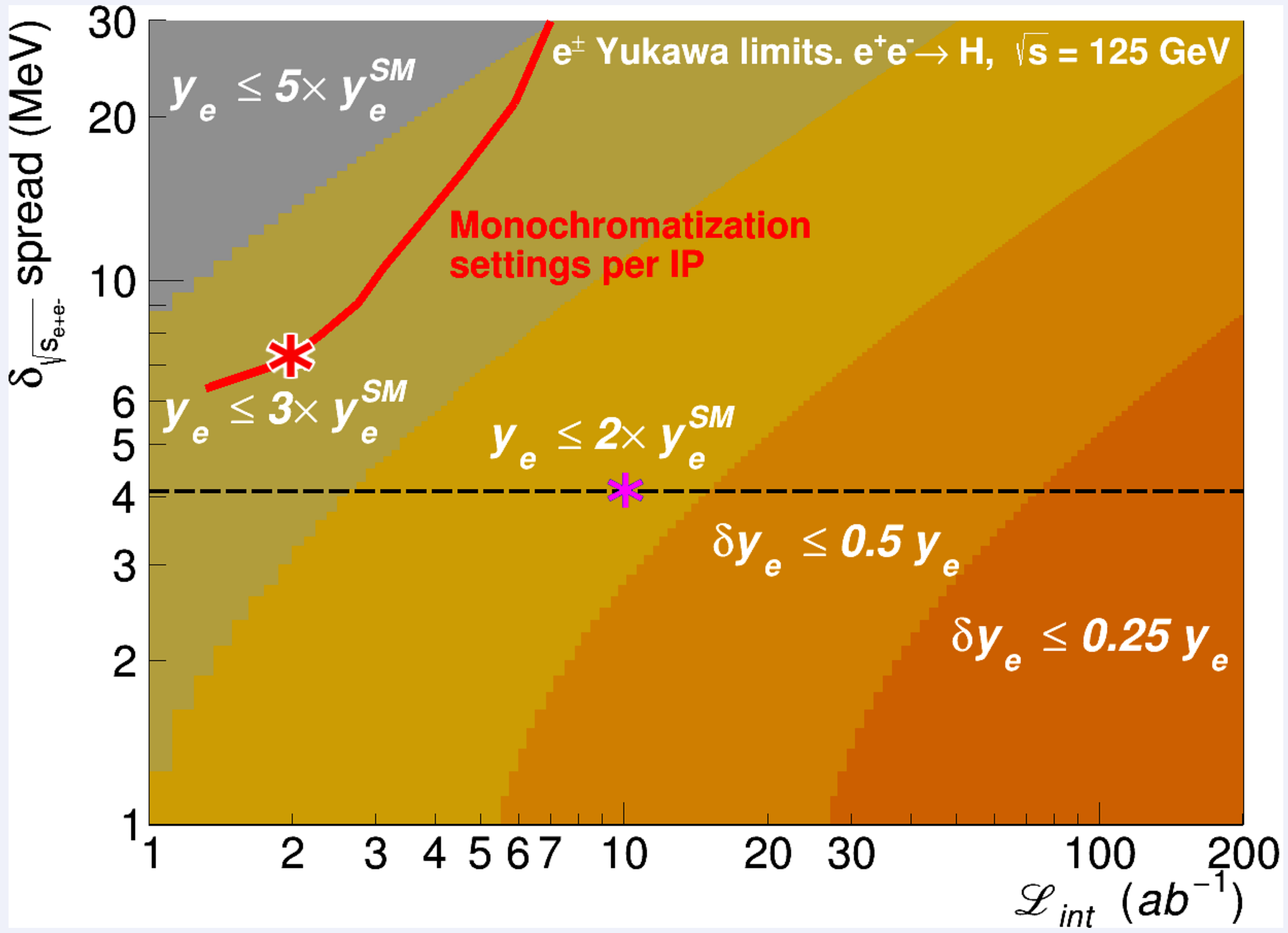
- Higgs electron Yukawa very challenging
  - $\sigma(ee \to H) = 0.57$ fb, highly dependent on beam monochromaticity, Higgs mass needed, bkg orders of magnitude larger
- Can reach $y_e \leq 1.6 y_e^{SM}$ with 2 years running at Higgs pole
  - 100 times better than HL-LHC

FCC-ee

2203.06520



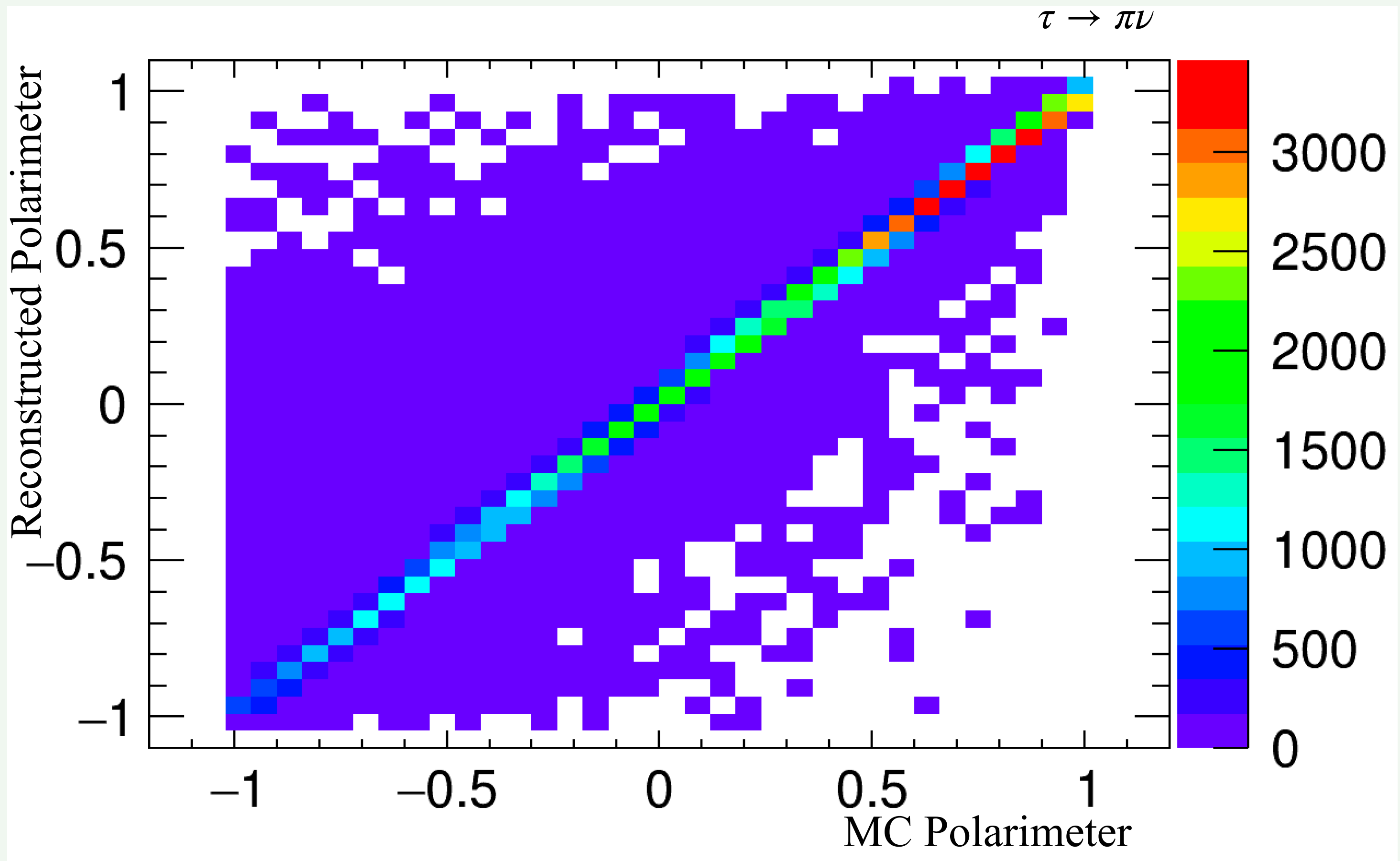


Polarization can play an important role

- Beam polarization allows for
  - Leveraging of xsection dependence on polarization
    - Cross section enhancements
    - Background reduction
    - Asymmetries
  - Control of systematic uncertainties

2203.07668

ilc



τ polarization tests **universality of the chiral interactions between lepton generations**

Method achieves 2% precision with 400 fb^{-1} of ILC500, seems to also have good precision at ILC250

When analyzing **Higgs couplings with SMEFT, 2 ab^{-1} of polarized** beams yield **similar precision as 5 ab^{-1} of unpolarized** beams

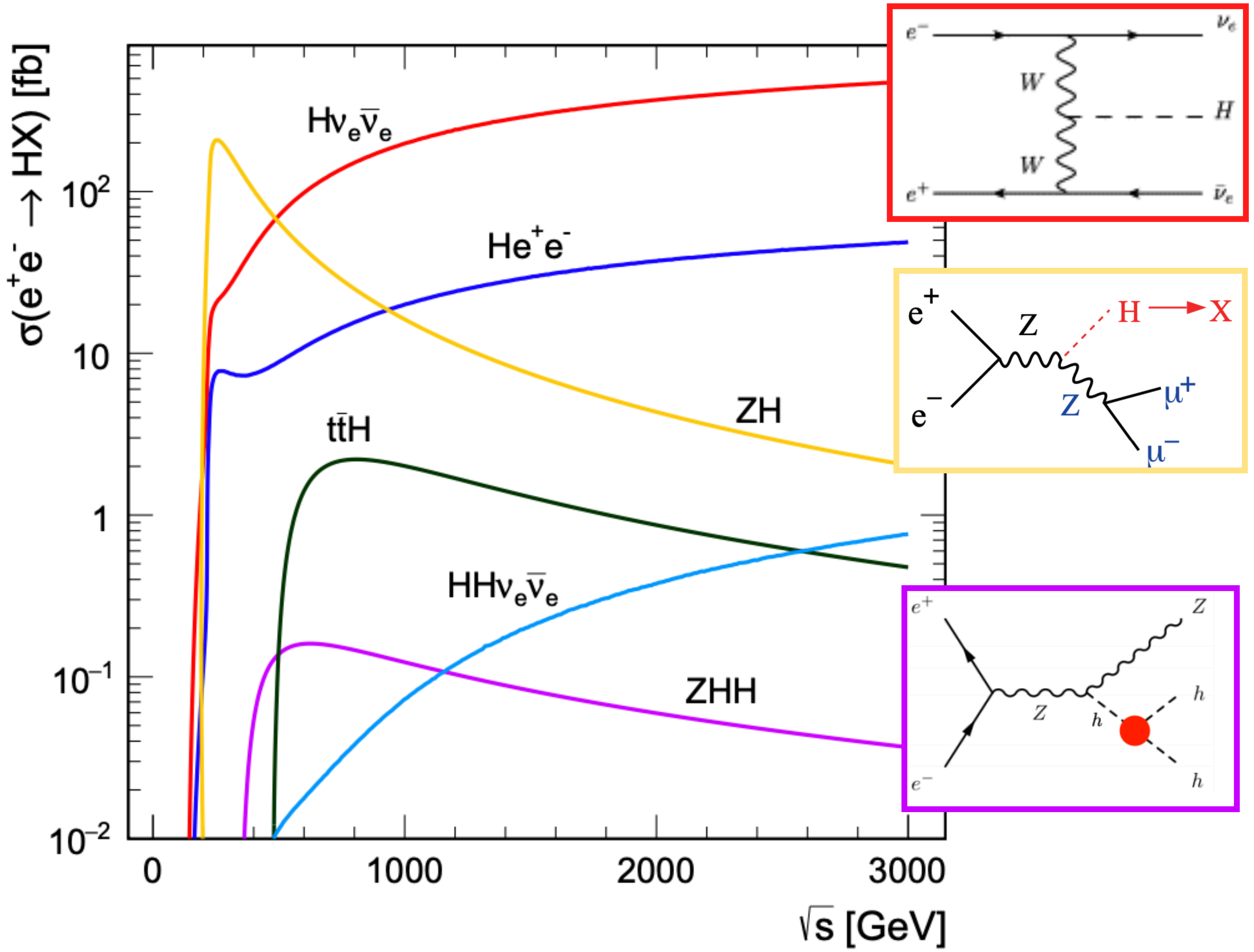
ilc

1801.02840
2203.07622
EF01/02 report

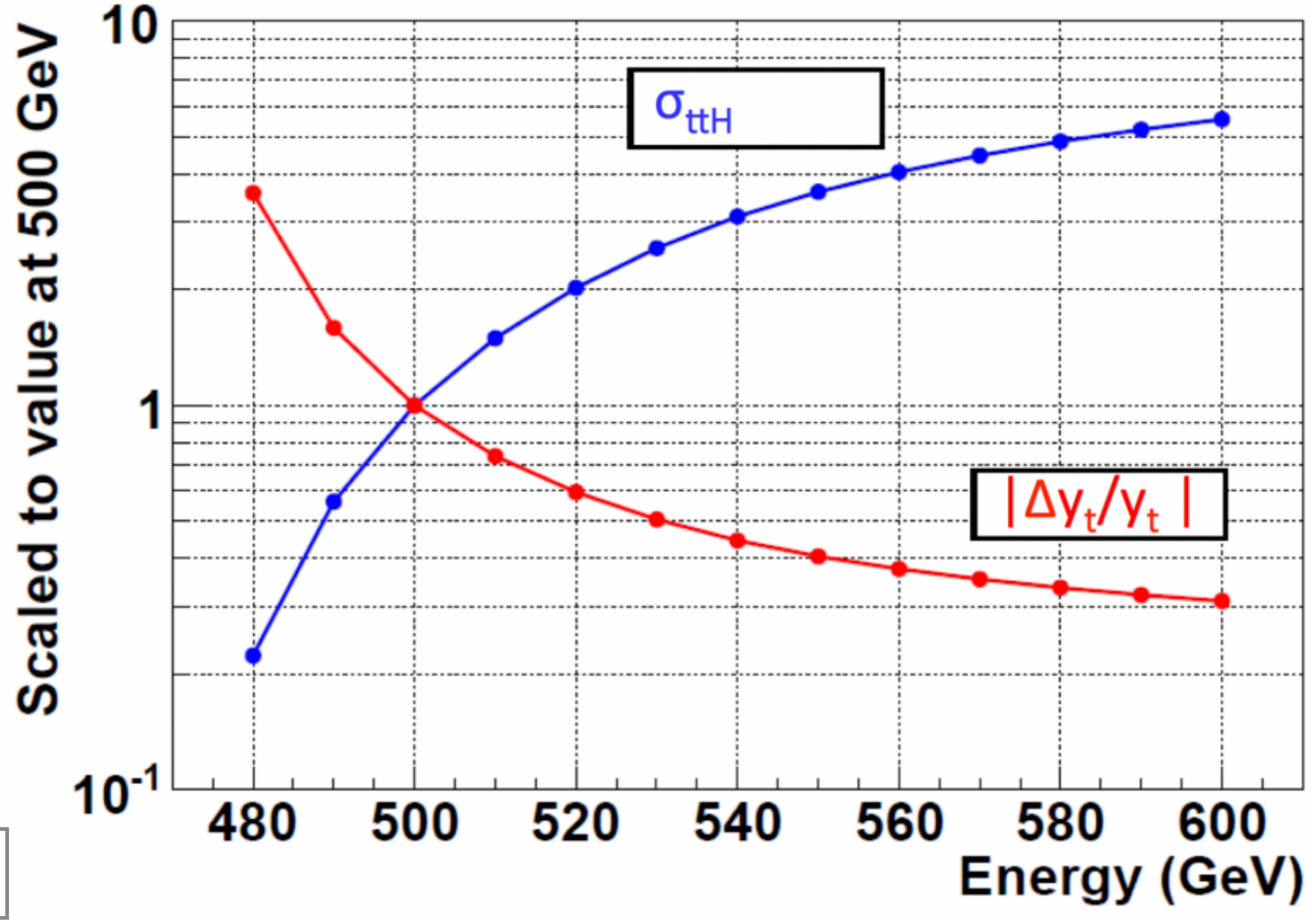
Electron polarization is key, positron's low impact

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

500+ GeV gives access to top Yukawa



- **Linear colliders** provide direct **access to top Yukawa via ttH**
- Now that we know Higgs mass, we should **optimize second stage energy**
  - ➡ eg, uncertainty on σ_{ttH} at 550 GeV is half that at 500 GeV!



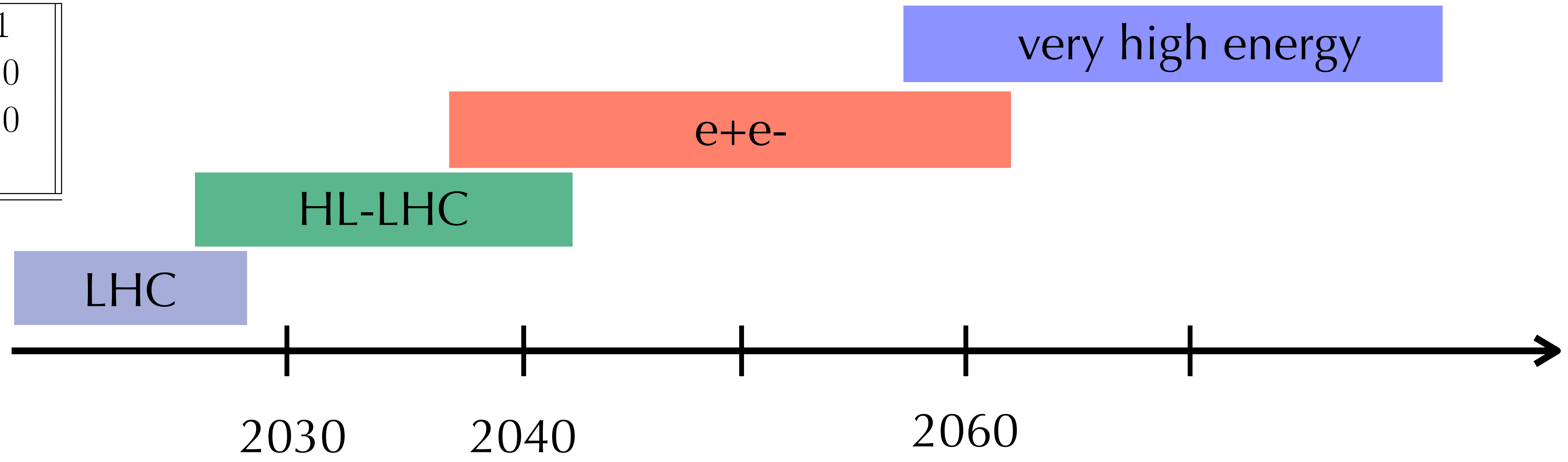
1506.07830

High energy machines also help precision

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

- "Discovery" machines can also achieve great precision, as the LHC has shown
  - ➡ Critical for multiboson production such as HH, WW, WWW, or ZZZ



H couplings to:	**O(5-15)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

Caterina Vernieri
EF01/02 report

Higgs self-coupling

- Observing HH is key to measure Higgs potential
  - ➡ Very sensitive to BSM physics

$$\mathcal{L}_h = \frac{1}{2} m_{\mathrm{H}}^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

$$\lambda_3^{SM} = m_H^2 / 2v$$

$$\lambda_4^{SM} = m_H^2 / 8v$$

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

1910.00012

- Observing HH is key to measure Higgs potential
  - ➡ Very sensitive to BSM physics

$$\mathcal{L}_h = \frac{1}{2} m_{\rm H}^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

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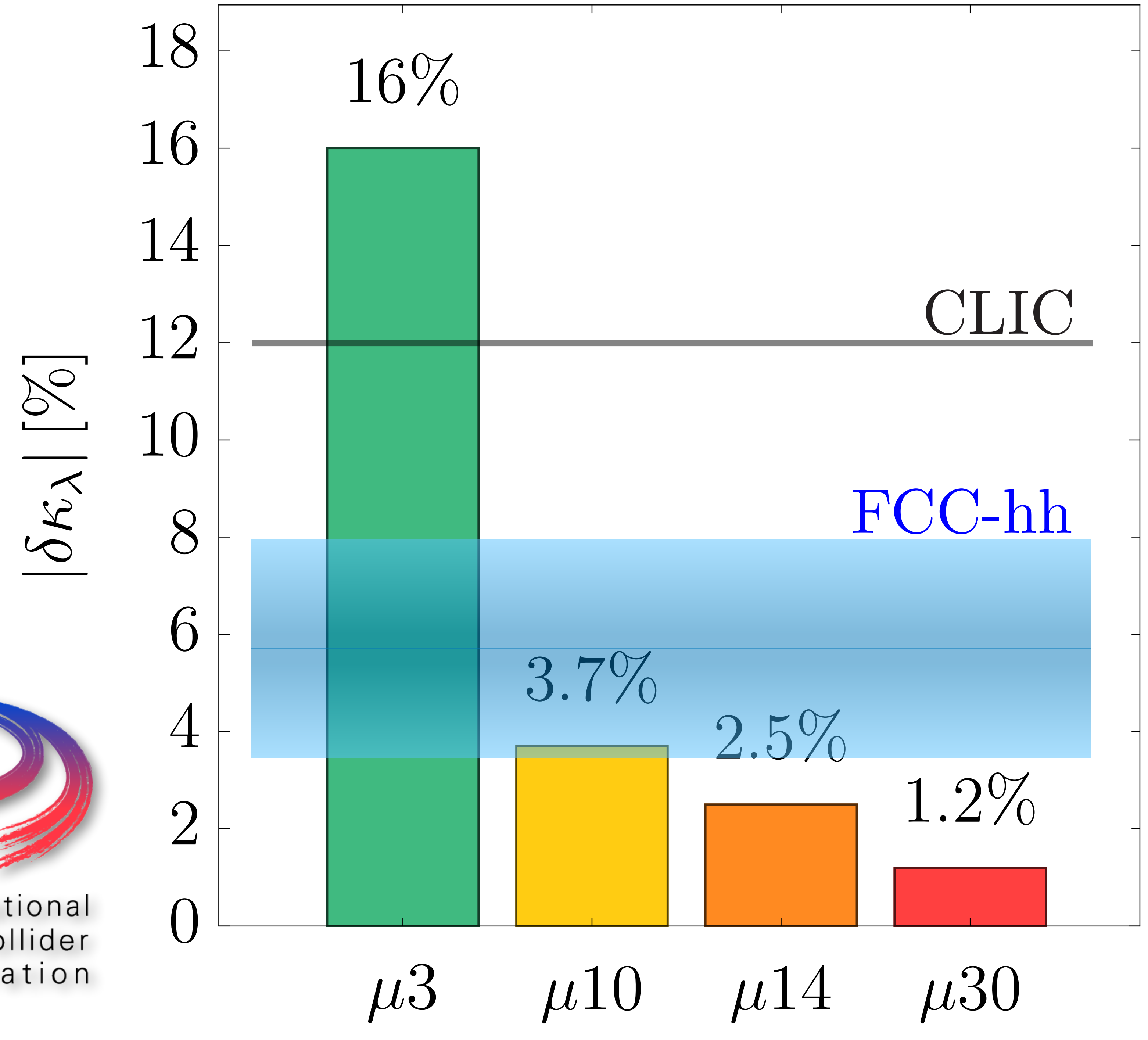
CLIC_{1500}	49%	36%	29%
CLIC_{3000}	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

1910.00012

2203.07256



Higher energy hadron or muon colliders are needed to measure self-coupling λ with good precision

CP-structure of Higgs couplings

~ In the SM, the Higgs is CP even ($\alpha^{SM} = 0°$)

$$\mathscr{L}_{ttH} \propto \bar{t}\left(\cos\alpha + i\gamma_5 \sin\alpha\right) tH$$

FCC-hh and muC can probe α in ttH with precision down to 3°

Bounds on α at 95% CL ($\kappa_t = 1$)	Channel	Collider	Luminosity
$\lvert\alpha\rvert \lesssim 36°$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 25°$ [2]	$t\bar{t}(h \to \gamma\gamma)$ combination	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 3°$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	100 TeV FCC	30 ab^{-1}
$\lvert\alpha\rvert \lesssim 9°$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	10 TeV $\mu^+\mu^-$	10 ab^{-1}
$\lvert\alpha\rvert \lesssim 3°$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	30 TeV $\mu^+\mu^-$	10 ab^{-1}

2203.08127

FCC-hh

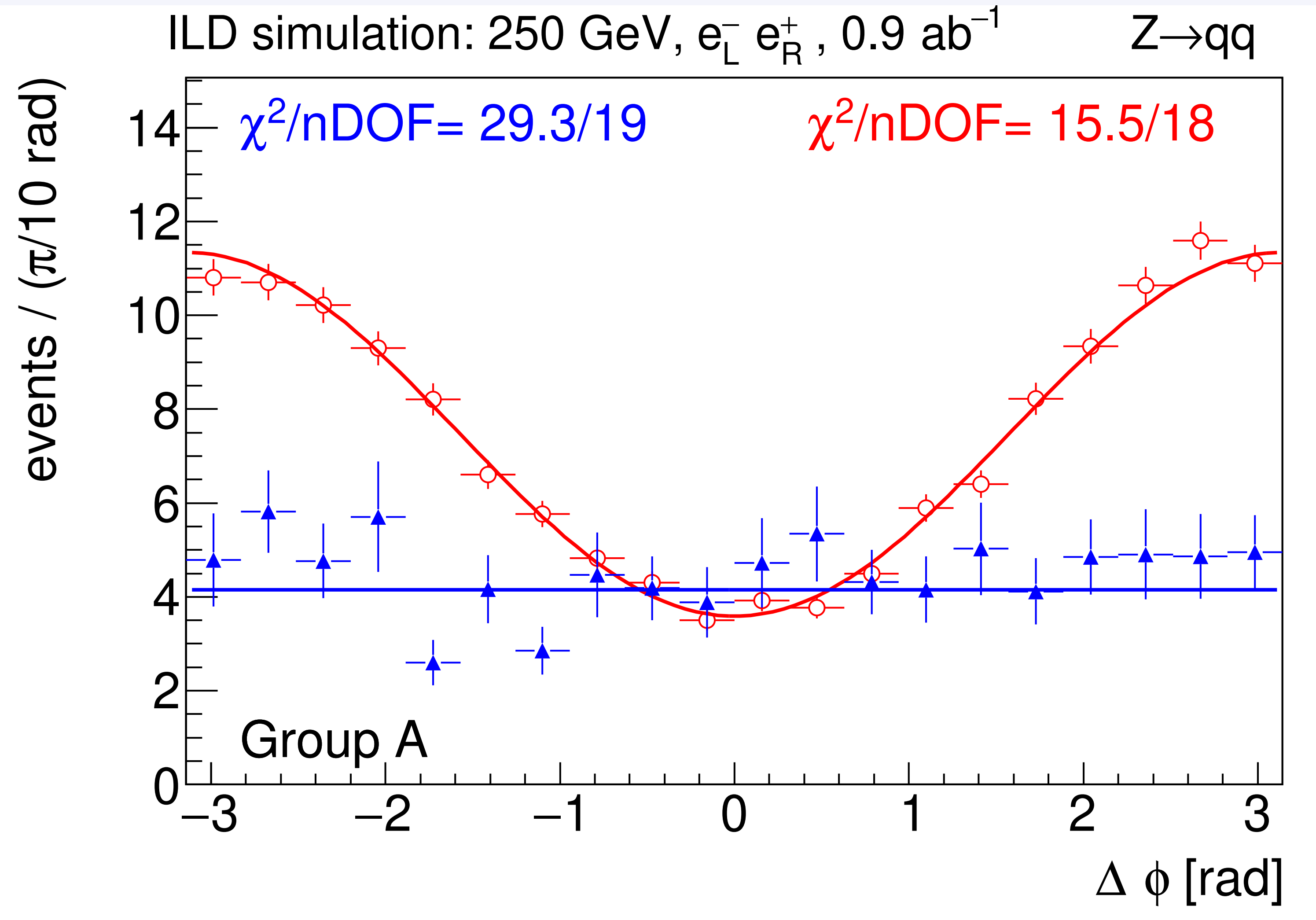
International MUON Collider Collaboration

$$\mathscr{L}_{\tau\tau H} \propto \bar{\tau}\left(\cos\psi + i\gamma_5 \sin\psi\right) \tau H$$

ILC can probe ψ in $H \to \tau\tau$ with precision down to 4.3°

ilc

2203.06819



Global fits

- Study various collider scenarios with SMEFT global fits
  - Place generic constraints on BSM physics, unify the assumptions about systematic errors
  - **Model-independent** if new physics scales are significantly higher than the EW scale
  - **Combine** large sets of **experimental data in a systematically** improvable **QFT approach**

de Blas, Du, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, *in preparation*

Quantity	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (**negl.?**)	64
ΔA_μ ($\times 10^5$)	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	400
ΔA_τ ($\times 10^5$)	86 (4.5)	3 (8)	0.5 (**20**)	1.2 (**6.9**)	570
ΔA_b ($\times 10^5$)	53 (35)	9 (50)	2.4 (21)	3 (21)	380
ΔA_c ($\times 10^5$)	140 (25)	20 (37)	20 (15)	6 (**30**)	200
$\Delta\sigma^0_{\text{had}}$ (pb)			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.7
δR_μ ($\times 10^3$)	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7
δR_τ ($\times 10^3$)	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6
δR_b ($\times 10^3$)	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.8
δR_c ($\times 10^3$)	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6

	1.5 ab^{-1} FCC-ee365		1.0 ab^{-1} CEPC360	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	0.9(0.84)	-	1.4(1.02)	-
$\sigma \times BR_{bb}$	0.5(0.71)	0.9(1.14)	0.90(0.86)	1.1(1.39)
$\sigma \times BR_{cc}$	6.5(5.0)	10(11.9)	8.8(6.1)	16(14.5)
$\sigma \times BR_{gg}$	3.5(3.8)	4.5(4.8)	3.4(4.7)	4.5(5.9)
$\sigma \times BR_{ZZ}$	12(11.4)	10(12.5)	20(13.9)	21(15.3)
$\sigma \times BR_{WW}$	2.6(2.55)	(3.6)	2.8(3.12)	4.4(4.4)
$\sigma \times BR_{\tau\tau}$	1.8(1.83)	8(10)	2.1(2.24)	4.2(12.2)
$\sigma \times BR_{\gamma\gamma}$	18(17.7)	22(28.1)	11(21.7)	16(34.4)
$\sigma \times BR_{\mu\mu}$	40(40)	(100)	41(48)	57(123)
$\sigma \times BR_{inv.}$	0.60(0.42)	-	(0.49)	-

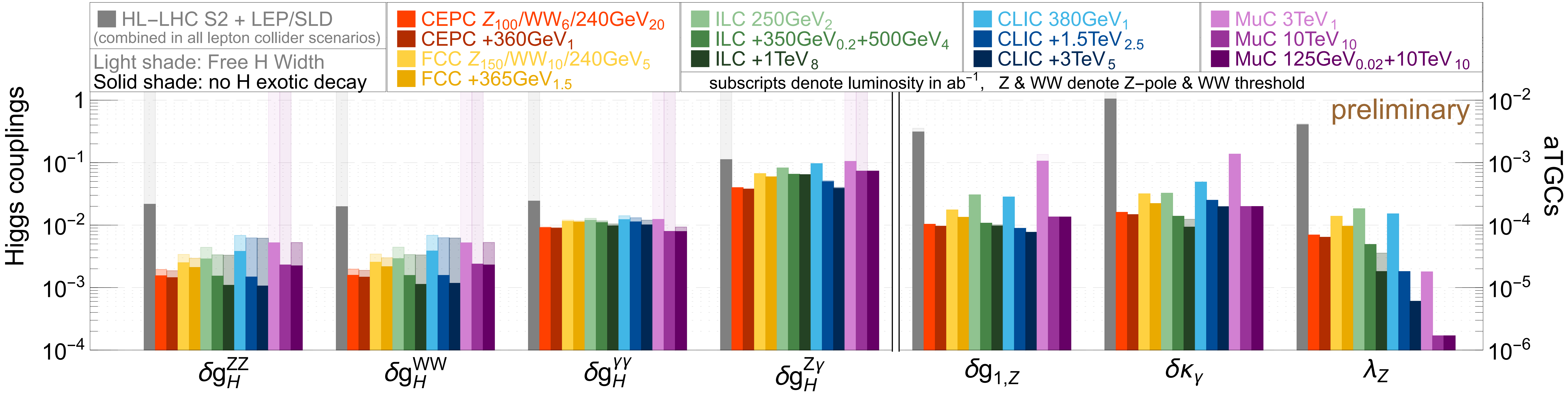
Also some low-energy observables

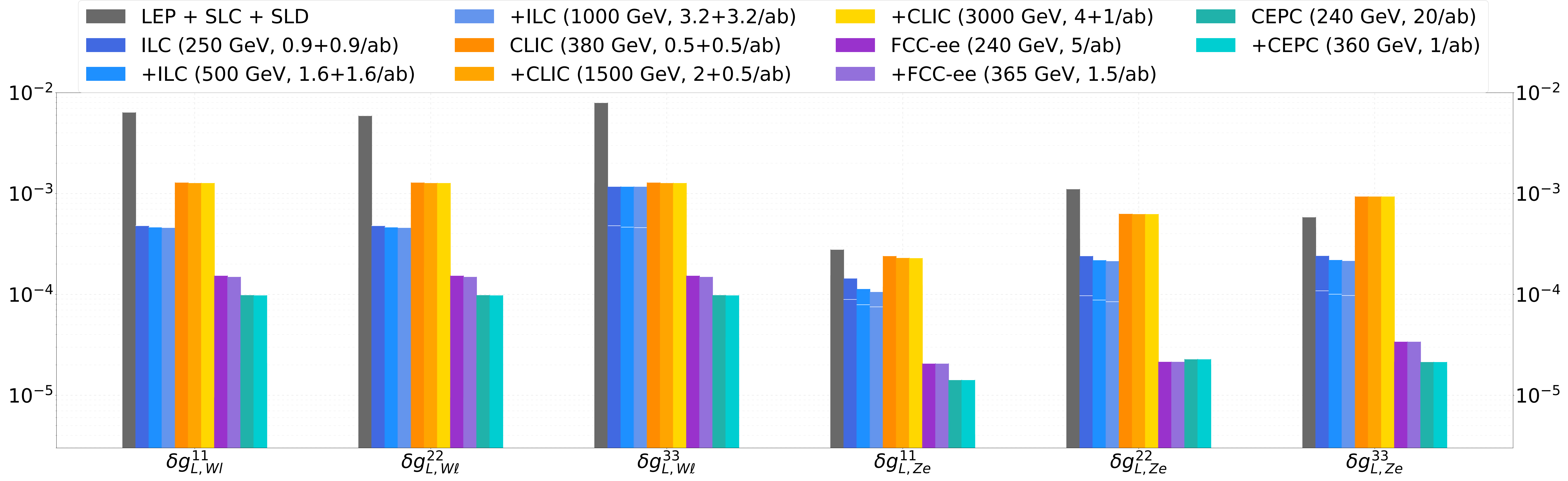
Process	Observable	Experimental value	Ref.	SM prediction
$\overset{(-)}{\nu}_\mu - e^-$ scattering	$g_{LV}^{\nu_\mu e}$	-0.035 ± 0.017	CHARM-II [24]	-0.0396 [25]
	$g_{LA}^{\nu_\mu e}$	-0.503 ± 0.017		-0.5064 [25]
τ decay	$\frac{G^2_{\tau e}}{G^2_F}$	1.0029 ± 0.0046	PDG2014 [26]	1
	$\frac{G^2_{\tau \mu}}{G^2_F}$	0.981 ± 0.018		
Neutrino scattering	R_{ν_μ}	0.3093 ± 0.0031	CHARM ($r = 0.456$) [27]	0.3156 [27]
	$R_{\bar{\nu}_\mu}$	0.390 ± 0.014		0.370 [27]
	R_{ν_μ}	0.3072 ± 0.0033	CDHS ($r = 0.393$) [28]	0.3091 [28]
	$R_{\bar{\nu}_\mu}$	0.382 ± 0.016		0.380 [28]
	κ	0.5820 ± 0.0041	CCFR [29]	0.5830 [29]
	$R_{\nu_e \bar{\nu}_e}$	$0.406^{+0.145}_{-0.135}$	CHARM [30]	0.33 [31]
Parity-violating scattering	$(s_w^2)^{\text{Møller}}$	0.2397 ± 0.0013	SLAC-E158 [32]	0.2381 ± 0.0006 [33]
	$Q_W^{\text{Cs}}(55, 78)$	-72.62 ± 0.43	PDG2016 [31]	-73.25 ± 0.02 [31]
	$Q_W^{\text{p}}(1, 0)$	0.064 ± 0.012	QWEAK [34]	0.0708 ± 0.0003 [31]
	A_1	$(-91.1 \pm 4.3) \times 10^{-6}$	PVIDS [35]	$(-87.7 \pm 0.7) \times 10^{-6}$ [35]
	A_2	$(-160.8 \pm 7.1) \times 10^{-6}$		$(-158.9 \pm 1.0) \times 10^{-6}$ [35]
	$g_{VA}^{eu} - g_{VA}^{ed}$	-0.042 ± 0.057	SAMPLE ($\sqrt{Q^2} = 200$ MeV) [36]	-0.0360 [31]
		-0.12 ± 0.074	SAMPLE ($\sqrt{Q^2} = 125$ MeV) [36]	0.0265 [31]
	b_{SPS}	$-(1.47 \pm 0.42) \times 10^{-4}\,\text{GeV}^{-2}$	SPS ($\lambda = 0.81$) [37]	$-1.56 \times 10^{-4}\,\text{GeV}^{-2}$ [37]
		$-(1.74 \pm 0.81) \times 10^{-4}\,\text{GeV}^{-2}$	SPS ($\lambda = 0.66$) [37]	$-1.57 \times 10^{-4}\,\text{GeV}^{-2}$ [37]
τ polarization	$\mathcal{P}_\tau$	0.012 ± 0.058	VENUS [38]	0.028 [38]
	$\mathcal{A}_\mathcal{P}$	0.029 ± 0.057		0.021 [38]
Neutrino trident production	$\frac{\sigma}{\sigma^{\text{SM}}}(\nu_\mu \gamma^* \to \nu_\mu \mu^+ \mu^-)$	0.82 ± 0.28	CCFR [39–41]	1

de Blas, Du, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, *in preparation*

Some preliminary results

precision reach on effective couplings from SMEFT global fit





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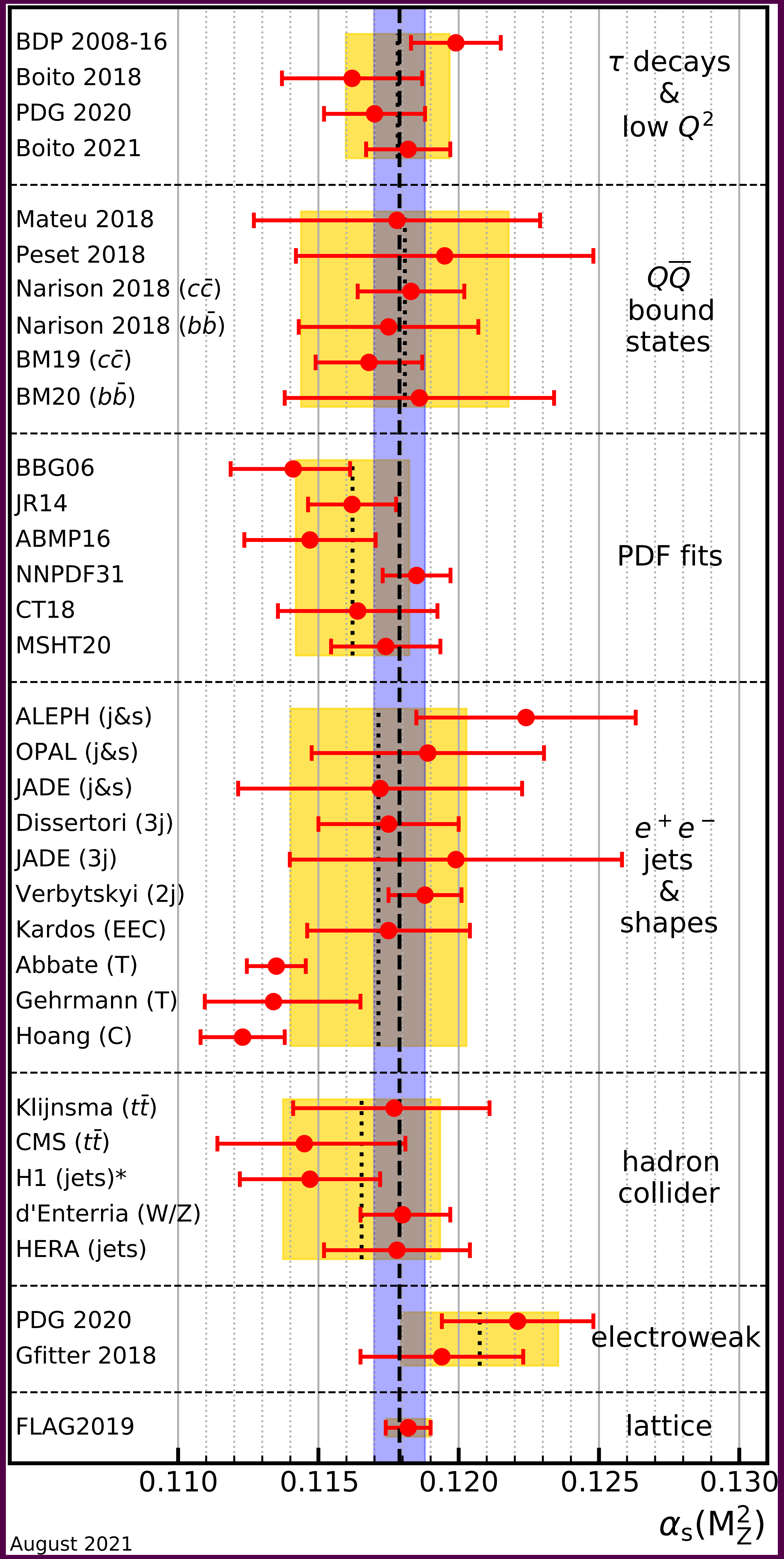

EF05+EF06+EF07: QCD & Heavy ions

Focus areas in QCD report

- What is the **ultimate precision for α_S**
- Which **precision QCD calculations are needed** to support measurements
- What are the **requirements for MC development**
- Guidance/support/developments in **jet substructure**
- New developments in (groomed) **event shapes** and **energy-energy correlators**
- Physics opportunities at **forward physics experiments**
- **Fragmentation functions** & modeling of **hadronization** transition from low to high energies
- Opportunities for precision tests of QCD at the **HL-LHC, EIC, FCC**

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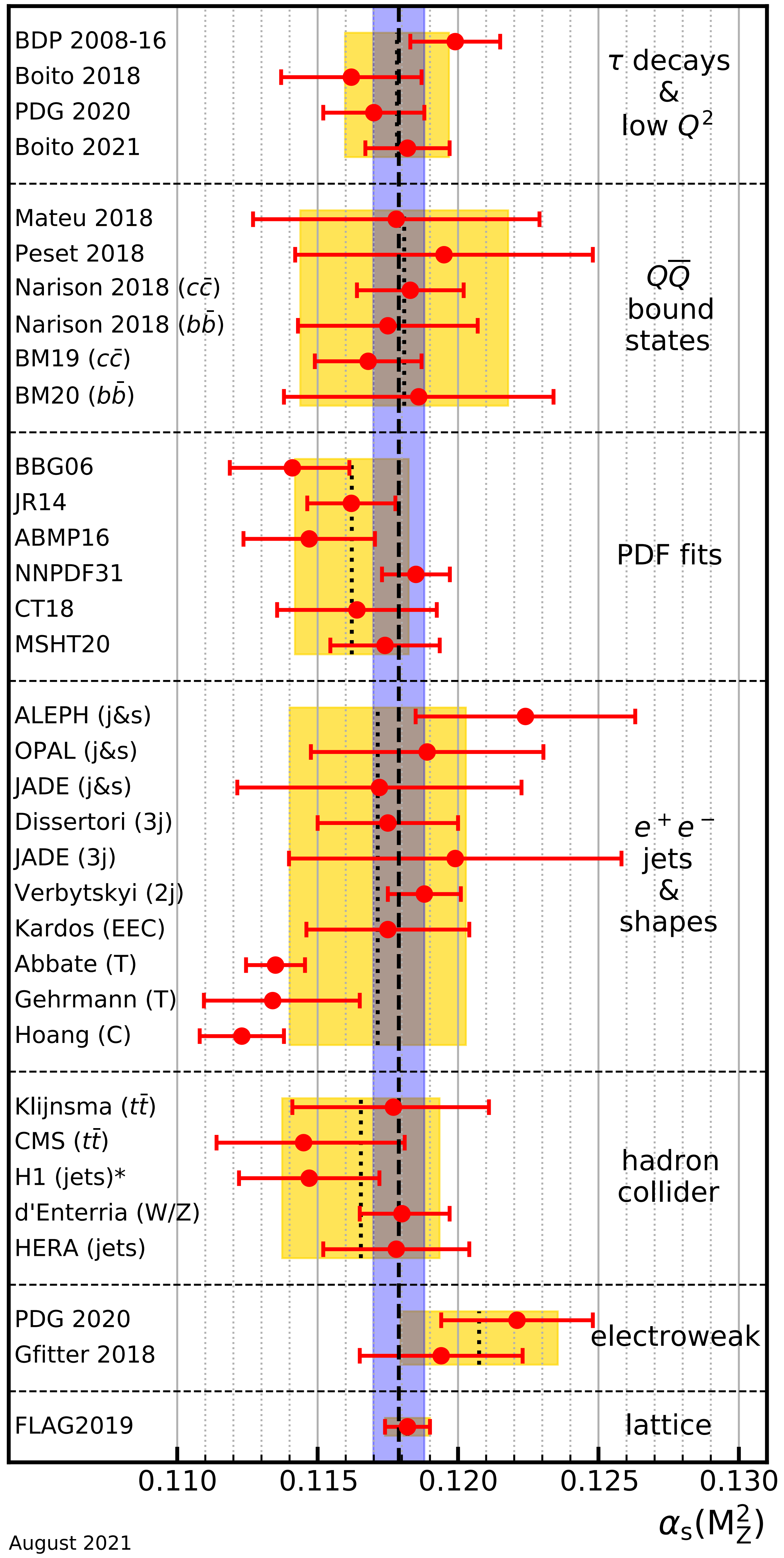
QCD not the **driving force for many future experiments**, but **crucial** for **understanding** them

13 papers submitted to EF05+EF06+EF07

Green: also submitted to RPF

TG	Title	Authors	arXiv
EF07	***Heavy Neutral Lepton Searches at the Electron-Ion Collider***	**B. Batell, T. Ghosh, K. Xie, et al**	**2203.06705**
EF05	*Jets and Jet Substructure at Future Colliders*	B. Nachman, S. Rappoccio, N. Tran, et al	2203.07462
EF05	*The strong coupling constant: State of the art and the decade ahead*	D. d'Enterria, S. Kluth, G. Zanderighi, et al	2203.08271
EF06	*Some aspects of the impact of the Electron Ion Collider on particle physics at the Energy Frontier*	S.V. Chekanov, S. Magill	2202.11529
EF06	*Lattice QCD Calculations of Parton Physics*	M. Constantinou, L. Del Debbio, X. Ji, et al	2202.07193
EF06	*Prompt electron and tau neutrinos and antineutrinos in the forward region at the LHC*	W. Bai, M. Vaman Diwan, M. Vittoria Garzelli, et al	2203.07212
EF06	*xFitter: An Open Source QCD Analysis Framework*	xFitter Developers Team	link
EF06	*The Potential of a TeV-Scale Muon-Ion Collider*	D. Acosta, E. Barberis, N. Hurley, et al	2203.06258
EF06	*Forward Physics, BFKL, Saturation Physics and Diffraction*	M. Hentschinski, C. Royon, M. Alcazar Peredo, et al	2203.08129
EF06	*Proton structure at the precision frontier*	S. Amoroso, A. Apyan, N. Armesto, et al	2203.13923
EF06	*Impact of lattice s(x)−sbar(x) data in the CTEQ-TEA global analysis*	T. Hou, H. Lin, M. Yan, et al	2204.07944
EF07	*Opportunities for new physics searches with heavy ions at colliders*	D. d'Enterria, M. Drewes, A. Giammanco, et al	2203.05939
EF07	*Electron Ion Collider for High Energy Physics*	R. Abdul Khalek, U. D'Alesio, M. Arratia, et al	2203.13199

Determination of α_S

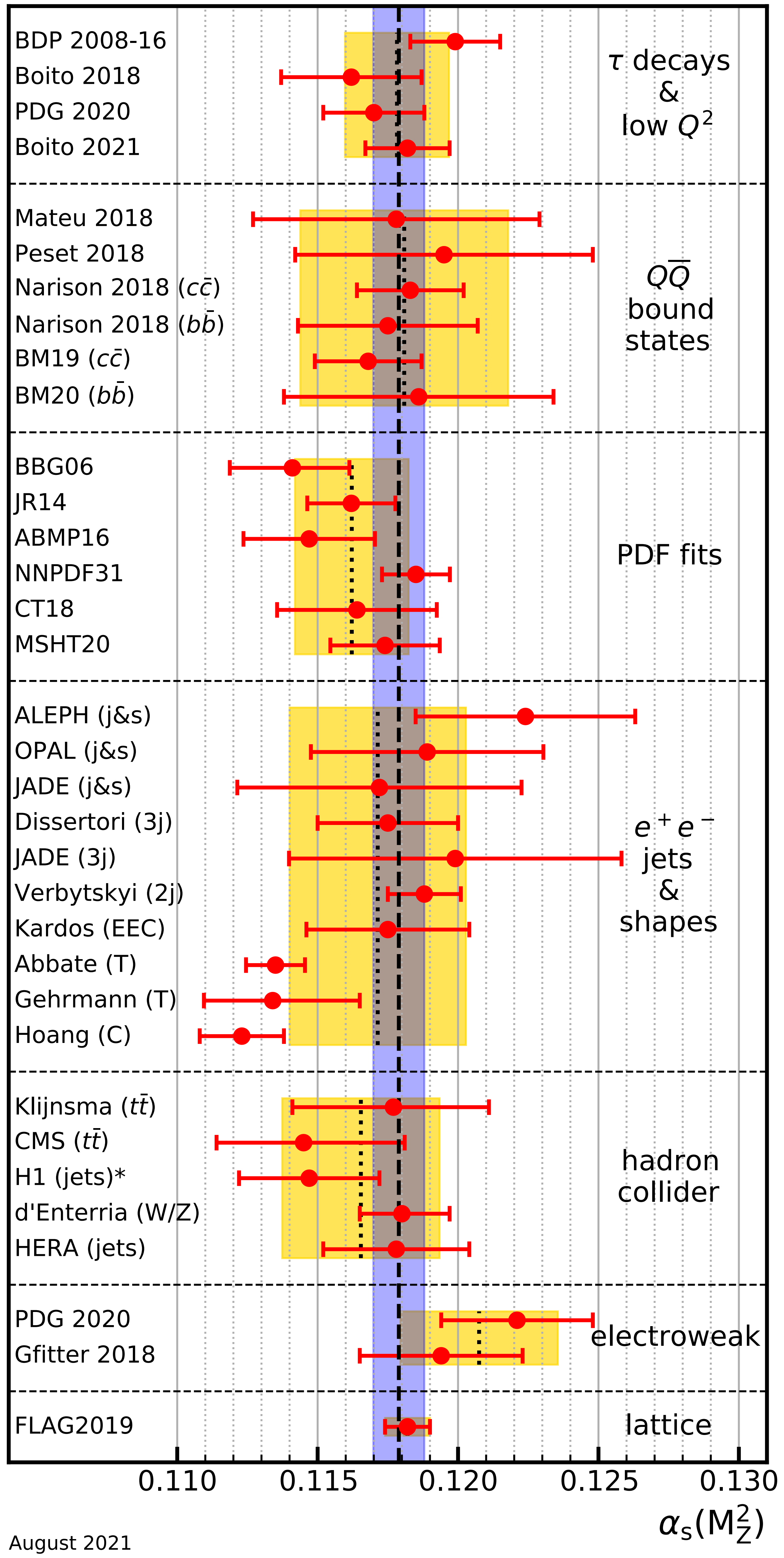


Determinations from all subfields agree very well

[2203.08271]

Method	Relative $\alpha_S(m_Z^2)$ uncertainty: Current — theory & exp. uncertainties sources	Near (long-term) future — theory & experimental progress
(1) Lattice	0.7% Finite lattice spacing & stats. $N^{2,3}$LO pQCD truncation	$\approx$ 0.3% (0.1%) Reduced latt. spacing. Add more observables Add $N^{3,4}$LO, active charm (QED effects) Higher renorm. scale via step-scaling to more observ.
(2) τ decays	1.6% N^3LO CIPT vs. FOPT diffs. Limited τ spectral data	$<$ 1.% Add N^4LO terms. Solve CIPT–FOPT diffs. Improved τ spectral functions at Belle II
(3) $Q\overline{Q}$ bound states	3.3% $N^{2,3}$LO pQCD truncation $m_{c,b}$ uncertainties	$\approx$ 1.5% Add $N^{3,4}$LO & more ($c\bar{c}$), ($b\bar{b}$) bound states Combined $m_{c,b} + \alpha_S$ fits
(4) DIS & PDF fits	1.7% $N^{2,(3)}$LO PDF (SF) fits Span of PDF-based results	$\approx$ 1% (0.2%) N^3LO fits. Add new SF fits: $F_2^{p,d}$, g_i (EIC) Better corr. matrices. More PDF data (LHeC/FCC-eh)
(5) e^+e^- jets & evt shapes	2.6% NNLO+$N^{(1,2,3)}$LL truncation Different NP analytical & PS corrs. Limited datasets w/ old detectors	$\approx$ 1.5% ($<$ 1%) Add $N^{2,3}$LO+N^3LL, power corrections Improved NP corrs. via: NNLL PS, grooming New improved data at B factories (FCC-ee)
(6) Electroweak fits	2.3% N^3LO truncation Small LEP+SLD datasets	($\approx$ 0.1%) N^4LO, reduced param. uncerts. ($m_{W,Z}$, α, CKM) Add W boson. Tera-Z, Oku-W datasets (FCC-ee)
(7) Hadron colliders	2.4% NNLO(+NNLL) truncation, PDF uncerts. Limited data sets ($t\bar{t}$, W, Z, e-p jets)	$\approx$ 1.5% N^3LO+NNLL (for color-singlets), improved PDFs Add more datasets: Z p_T, p-p jets, σ_i/σ_j ratios,...
World average	0.8%	$\approx$ 0.4% (0.1%)

Determination of α_S



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Lattice expected to keep leading, but will require sufficient computing and person power

2203.08271

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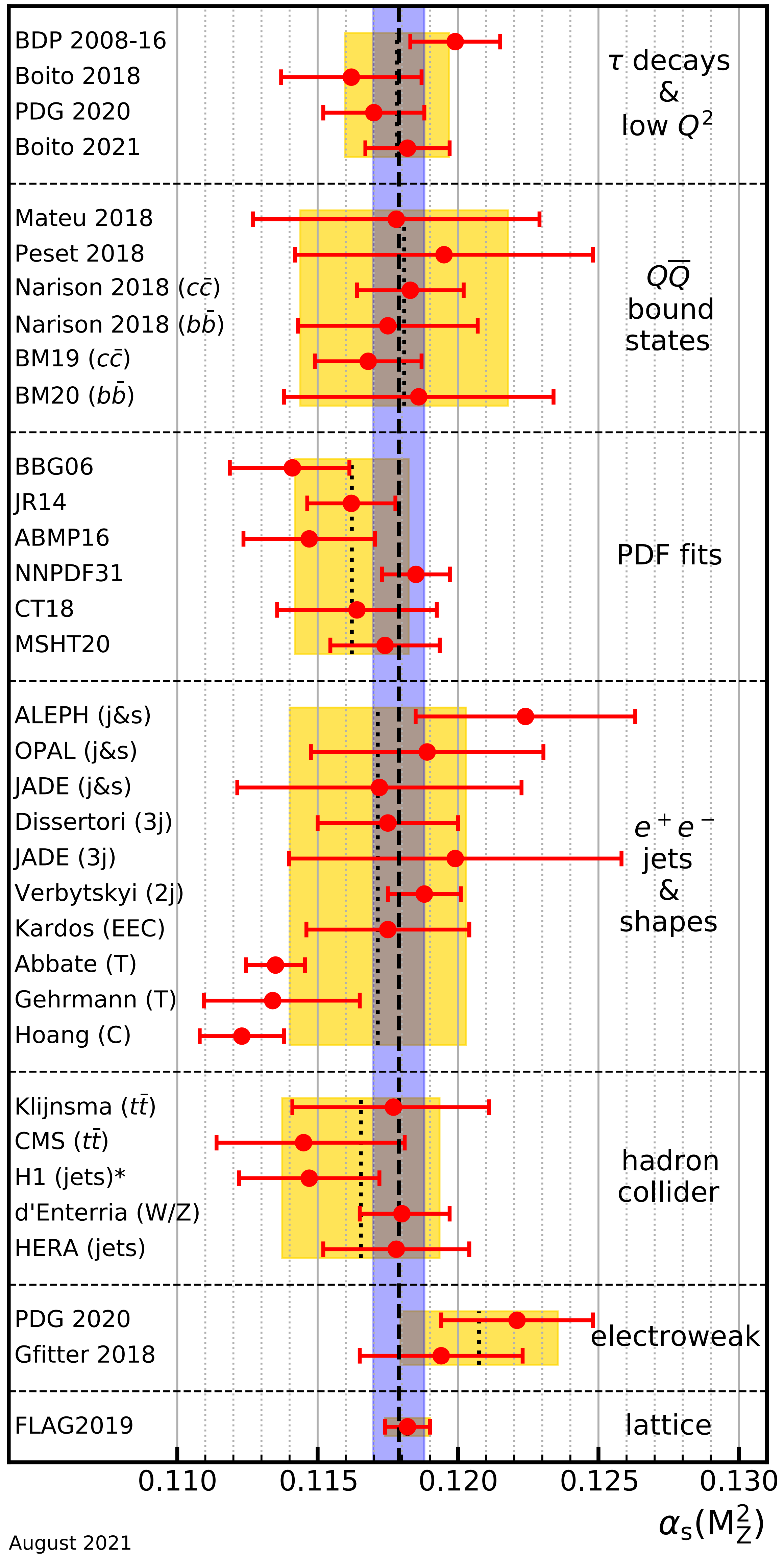

Determinations from all subfields agree very well

Lattice expected to keep leading, but **will require sufficient computing** and **person power**

Arguably, only way to reach **per mille purely experimentally** is through **Z,W → hadrons**

2203.08271

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PDFs outlook

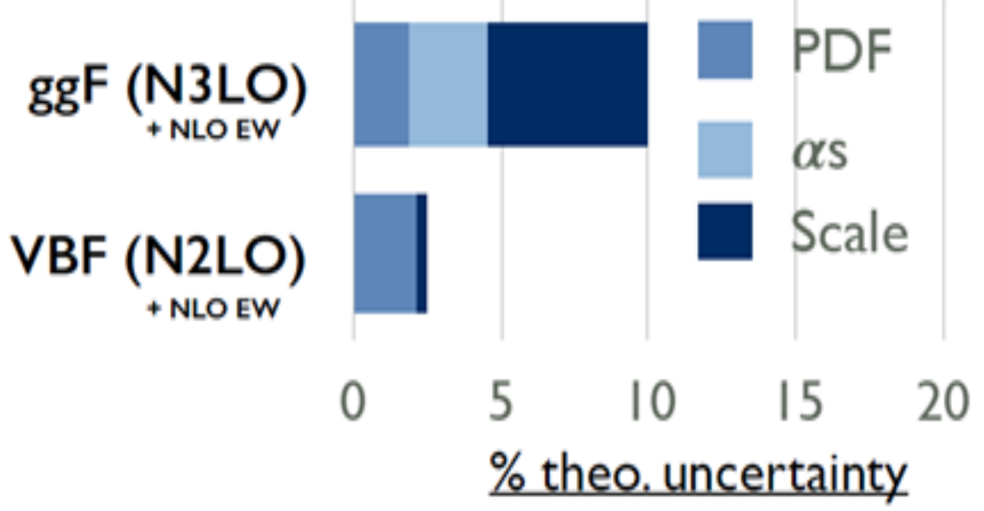
Topic	Status, 2013	Status, 2022
Achieved accuracy of PDFs	N2LO for evolution, DIS and vector boson produciton	N2LO for all key processes; N3LO for some processes
PDFs with NLO EW contributions	MSTW'04 QED, NNPDF2.3 QED	LuXQED and other photon PDFs from several groups; PDFs with leptons and massive bosons
PDFs with resummations	Small x (in progress)	Small-x and threshold resummations implemented in several PDF sets
Available LHC processes to determine nucleon PDFs	W/Z, single-incl. jet, high-p_T Z, $t\bar{t}$, $W+c$ production at 7 and 8 TeV	+ $t\bar{t}$, single-top, dijet, $\gamma/W/Z$ +jet, low-Q Drell Yan pairs, … at 7, 8, 13 TeV
Near-future experiments to probe PDFs	LHC Run-2 DIS: LHeC	LHC Run-3 DIS: EIC, LHeC, …
Benchmarking of PDFs for the LHC	PDF4LHC'2015 recommendation in preparation	PDF4LHC'21 recommendation issued
Precision analysis of specialized PDFs		Nuclear, meson, transverse-momentum dependent PDFs

NEW TASKS in the HL-LHC ERA:

Obtain complete N2LO and N3LO predictions for PDF-sensitive processes	Improve models for correlated systematic errors	Find ways to constrain large-x PDFs without relying on nuclear targets
Develop and benchmark fast N2LO interfaces	Estimate N2LO theory uncertainties	New methods to combine PDF ensembles, estimate PDF uncertainties, deliver PDFs for applications

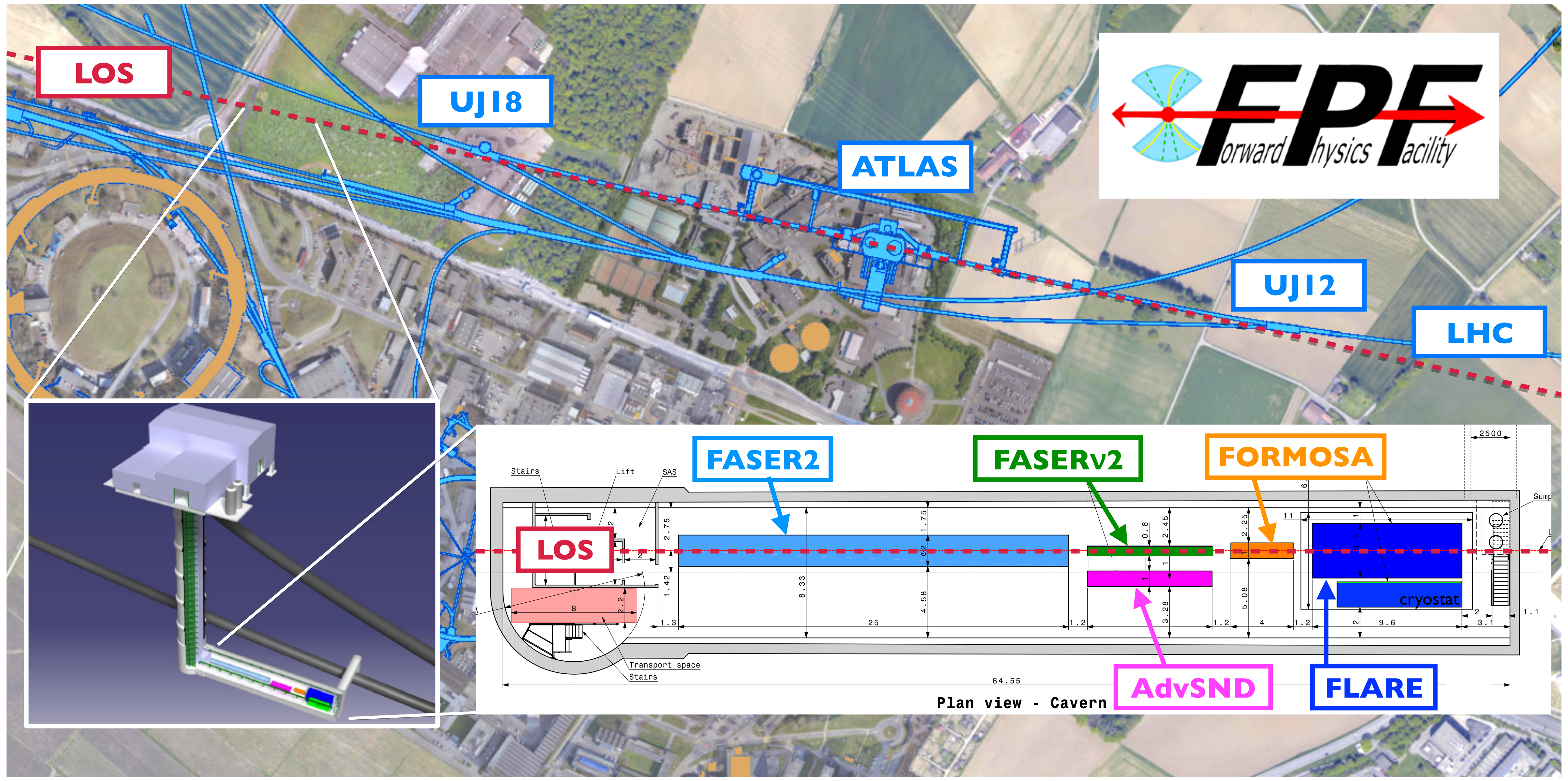
2203.13923

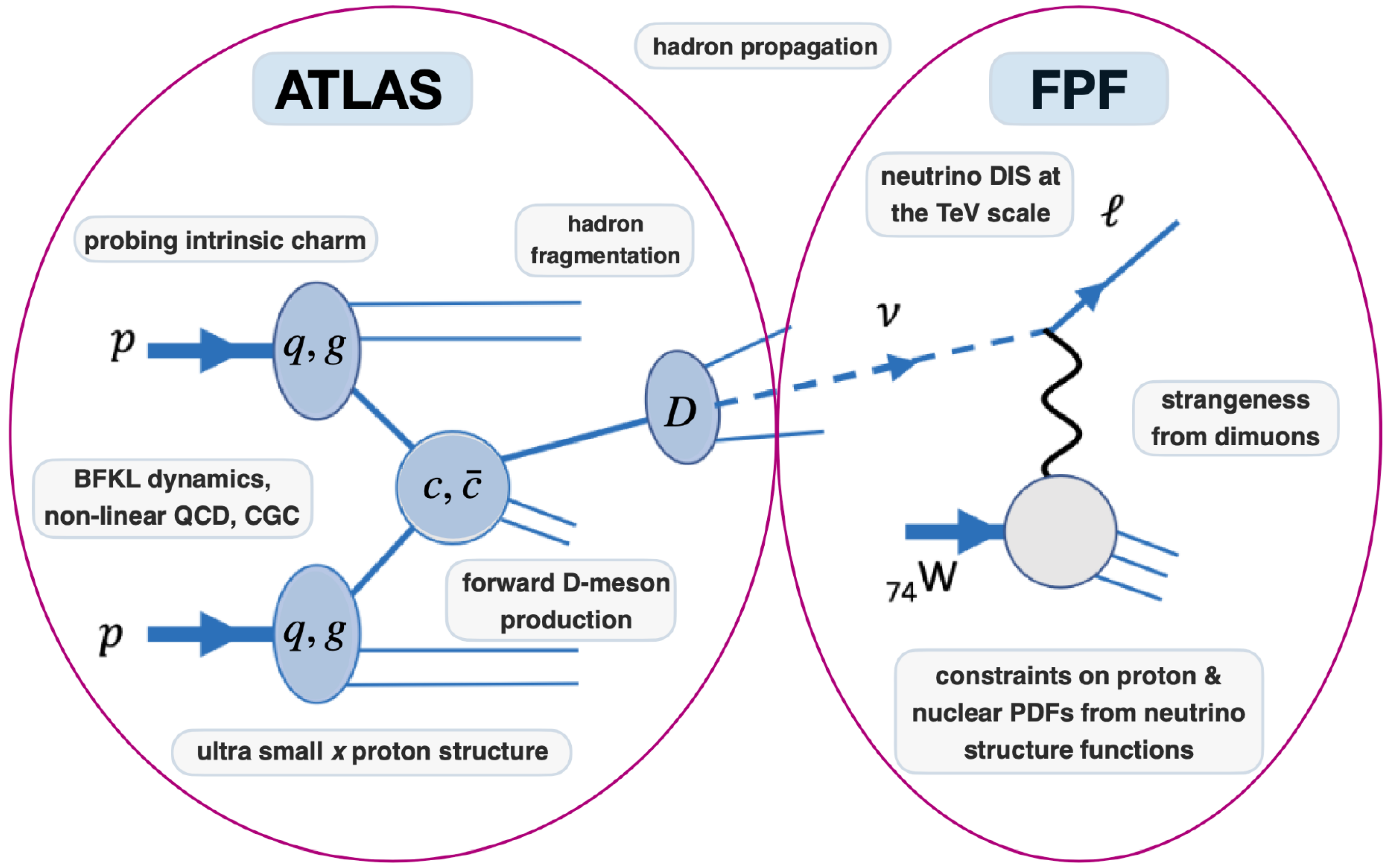
- Great progress since 2013
  - Similar will be needed for xsec in HL-LHC



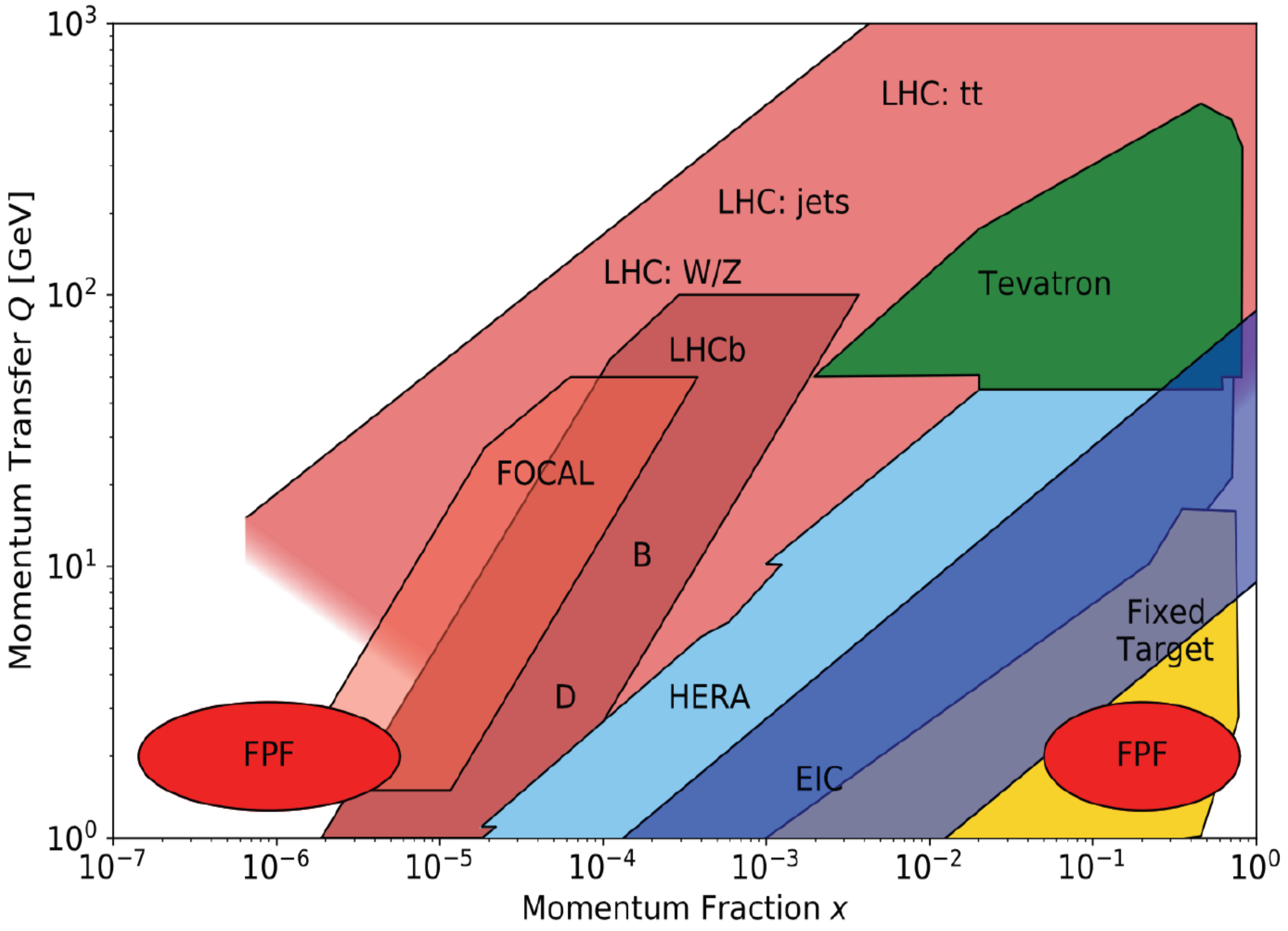
  - Also new kinematic regimes, eg low-x
  - Feasible strategy to obtain N3LO PDFs
- Nuclear, meson, transverse-momentum dependent PDFs with EIC and other facilities

Forward Physics Facility





[Jonathan Feng at EF workshop] and [2109.10905]



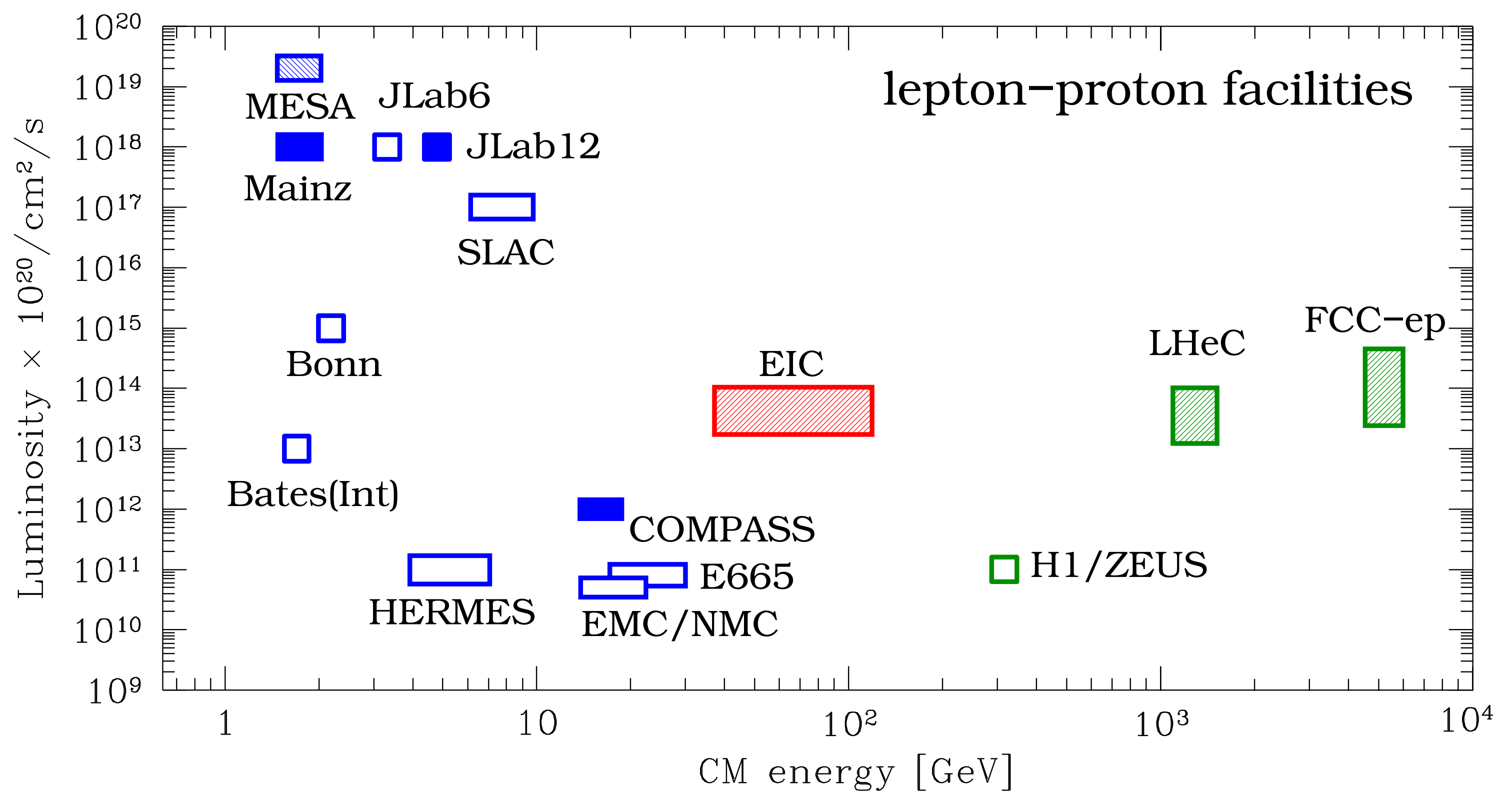
- Proposed underground facility ~620 m from ATLAS interaction point
- High energy neutrino fluxes for DIS
  - New regions of phase space in forward hadron production **probing both large-x and small-x**
  - Nuclear structure functions, PDF

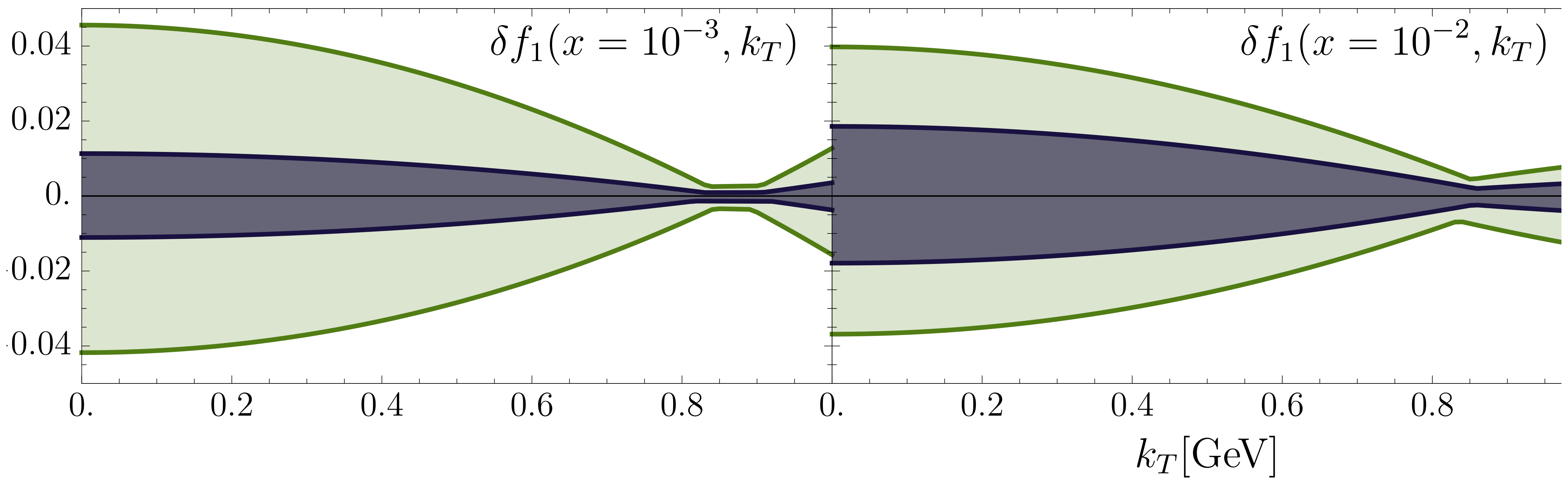
Electron-Ion Collider (EIC)

2203.13199

Electron-Ion Collider
at Brookhaven National Laboratory

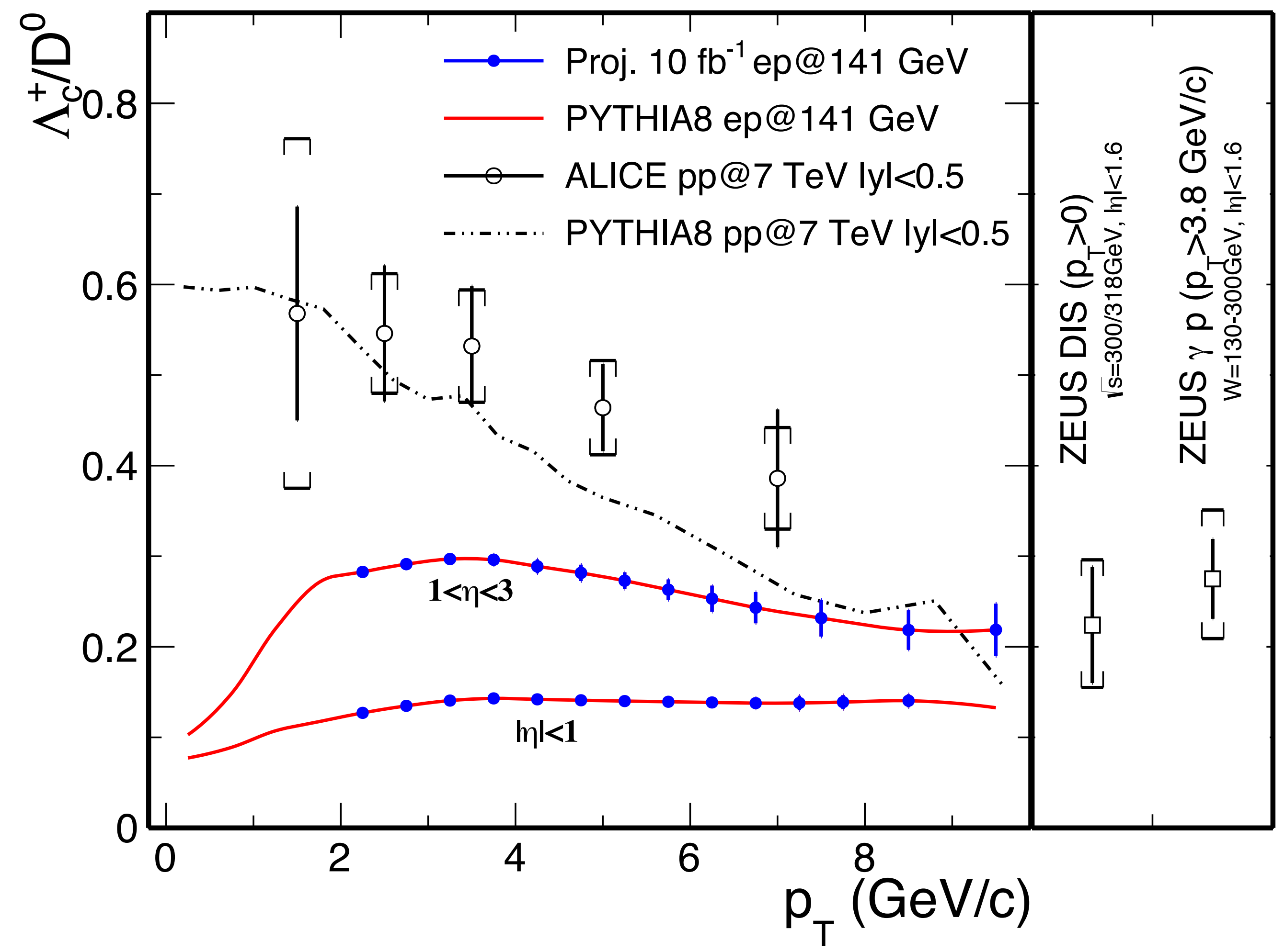
- The **only new large-scale accelerator** facility planned for construction **in US in the next few decades**
  - Polarized electrons with polarized beams of proton and light ions
- Will provide detailed information on
  - Nonperturbative distributions like nucleon and nuclear PDFs
  - Transverse-momentum dependent (TMD) distributions
  - Heavy flavor baryon production





eg, TMD PDFs one of the largest uncertainties for W mass

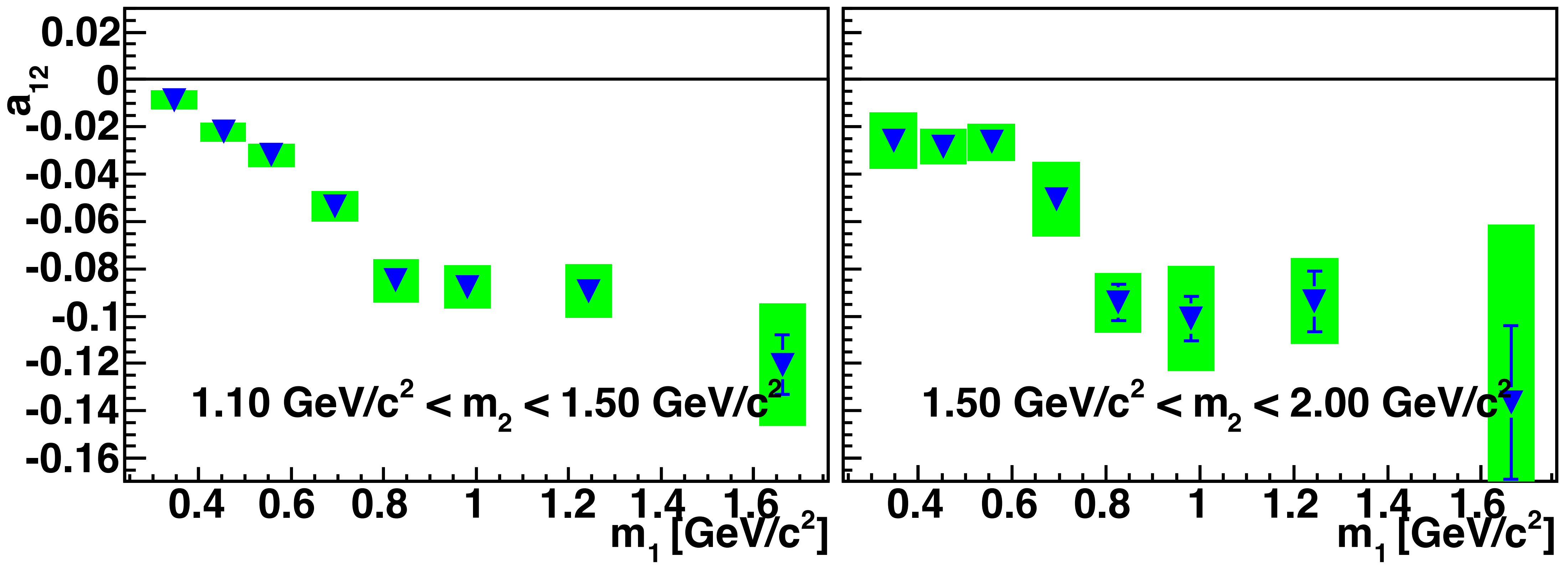
2103.05419



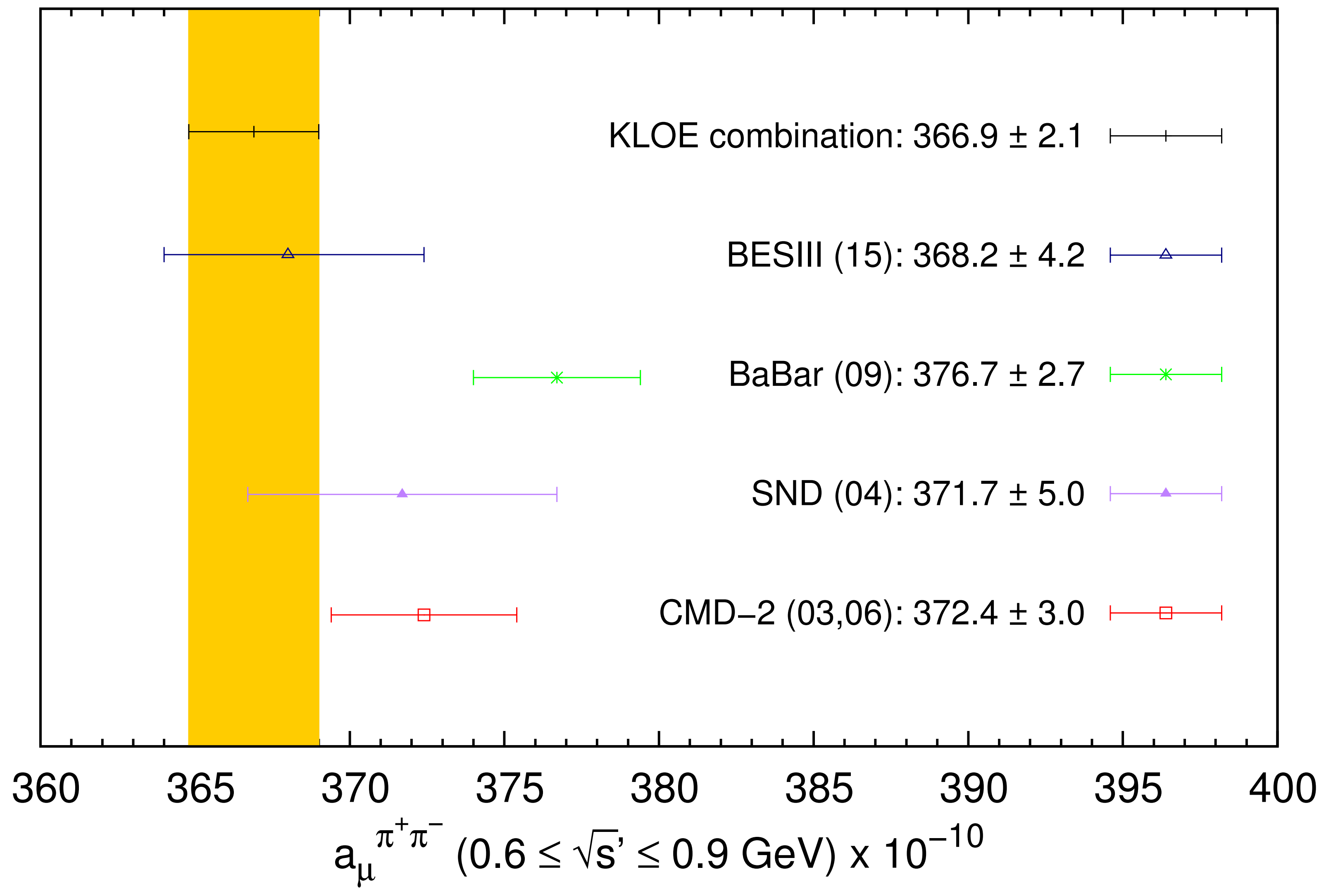
Will provide the strongest constraint on the heavy quark hadronization mechanism

Belle II QCD studies

- **Belle II** will provide **key inputs for TMD PDF measurements at EIC** on quark fragmentation
  - ➡ eg, transverse polarization of Λ hyperons, di-hadron correlations
- Will **constrain systematic uncertainties on** $g_\mu - 2$ determination
  - ➡ **Hadronic Vacuum Polarization** (HVP) large contributor to uncertainty
    - ✦ Belle II measurements can help reduce this with $e^+e^- \to \pi^+\pi^-(\gamma)$ and $\tau^- \to \pi^-\pi^0\nu_\tau$
  - ➡ Next uncertainty is **hadronic light-by-light** scattering (HLbL)
    - ✦ Constrained with $e^+e^- \to e^+e^-h$

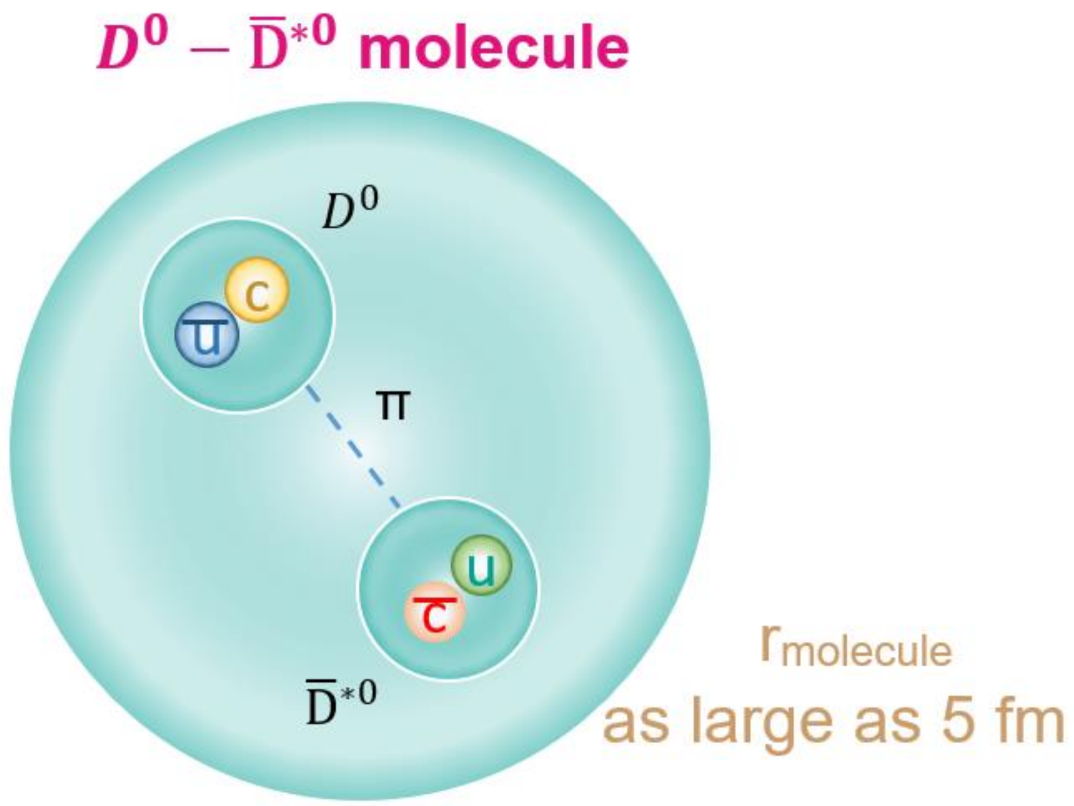


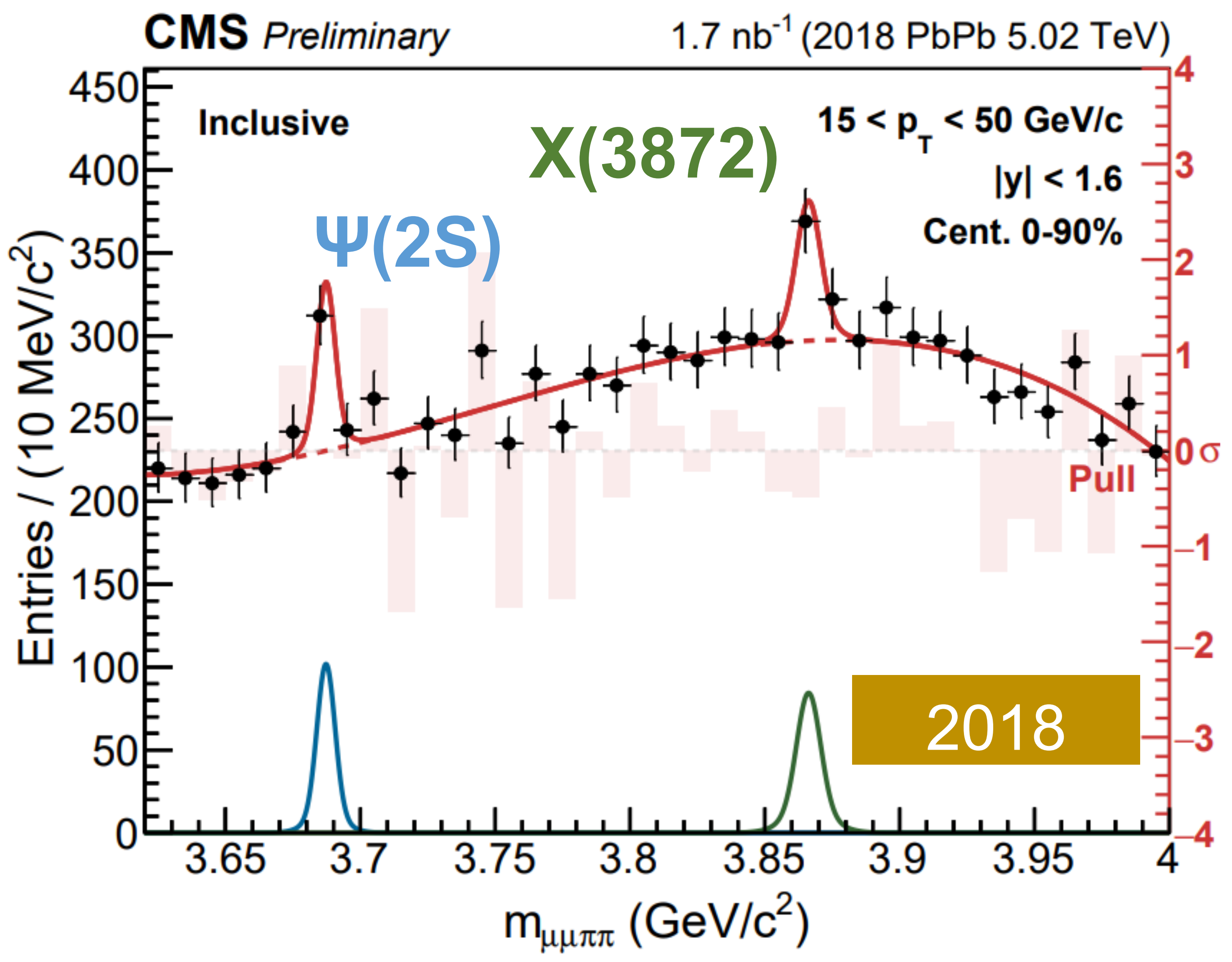
2204.02280



2203.05939

- Continuation of its exploration of QGP
- Contributions to **spectroscopy**
  - ➡ Observation of X(3872) in PbPb is expected (>5 σ) in Run3

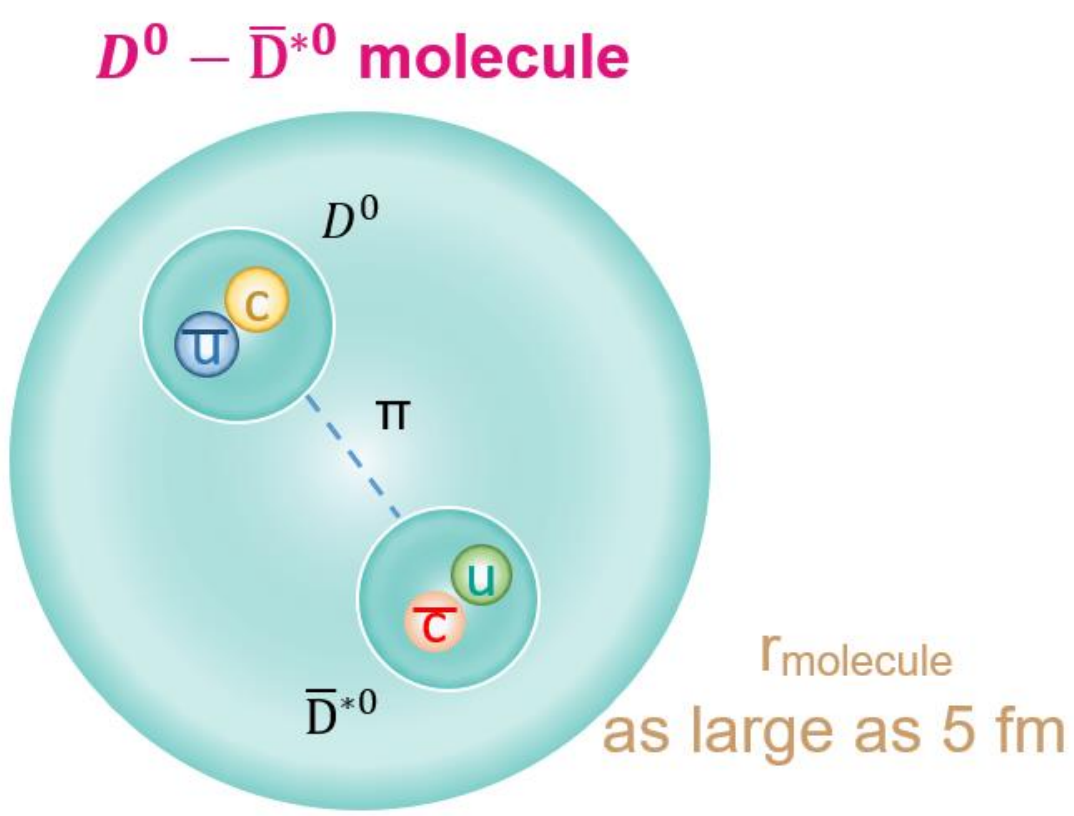


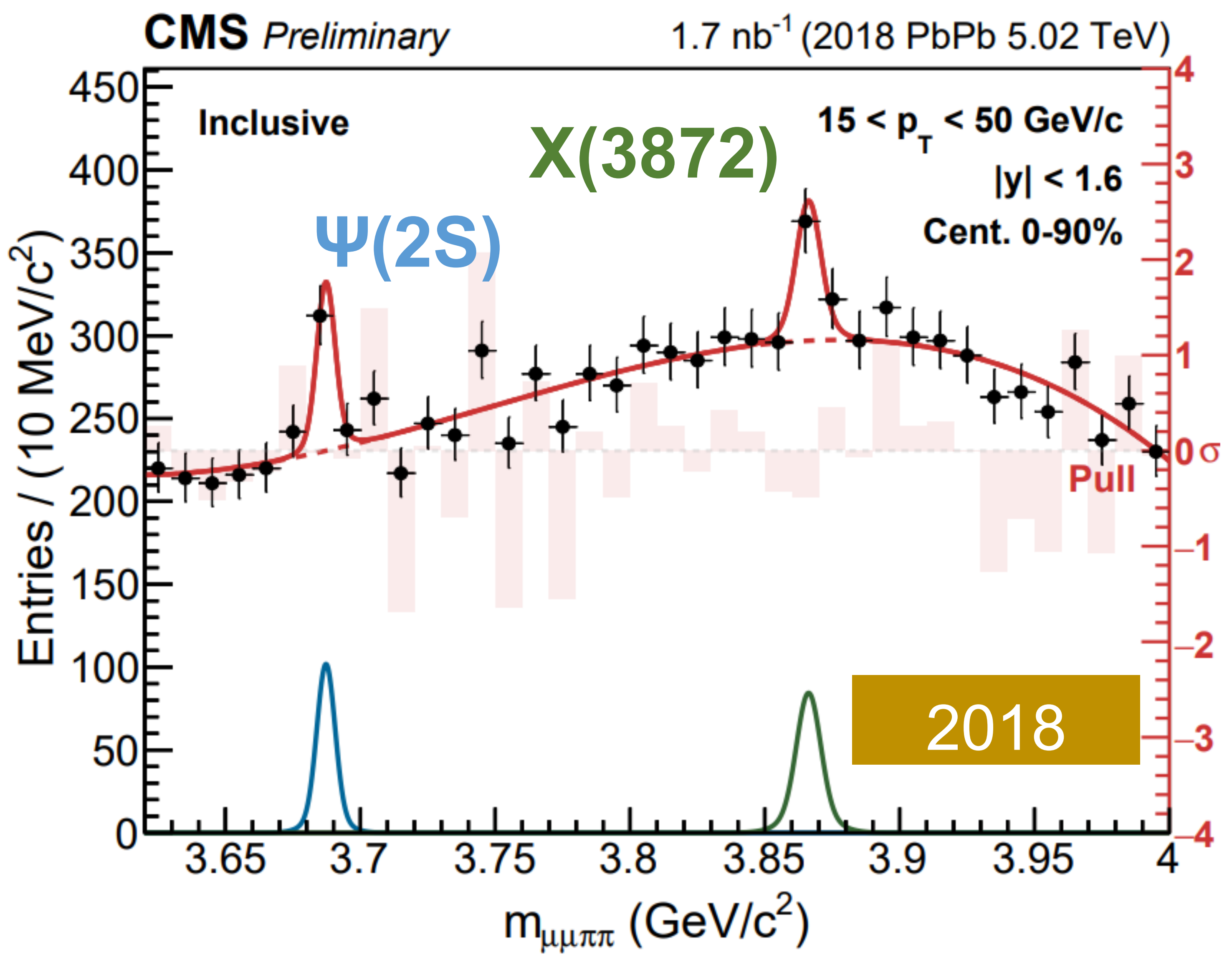


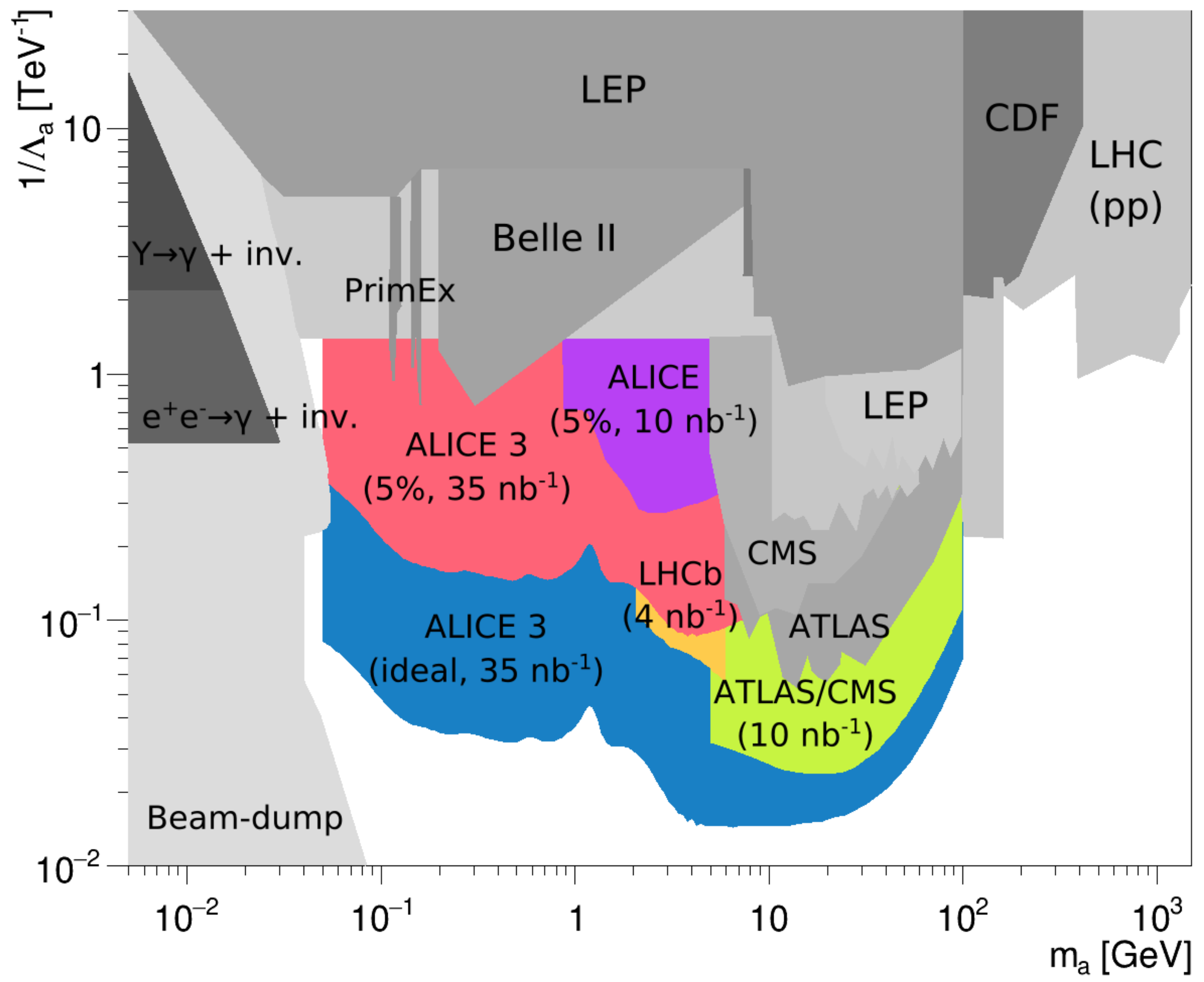
Heavy ions

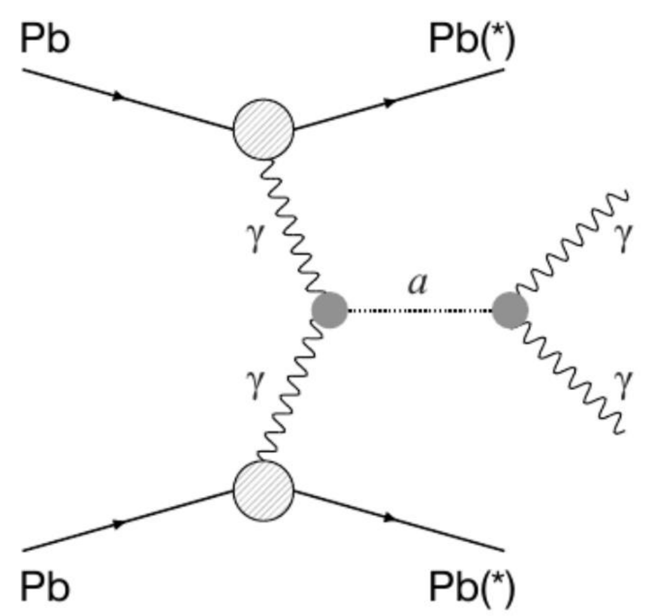
2203.05939

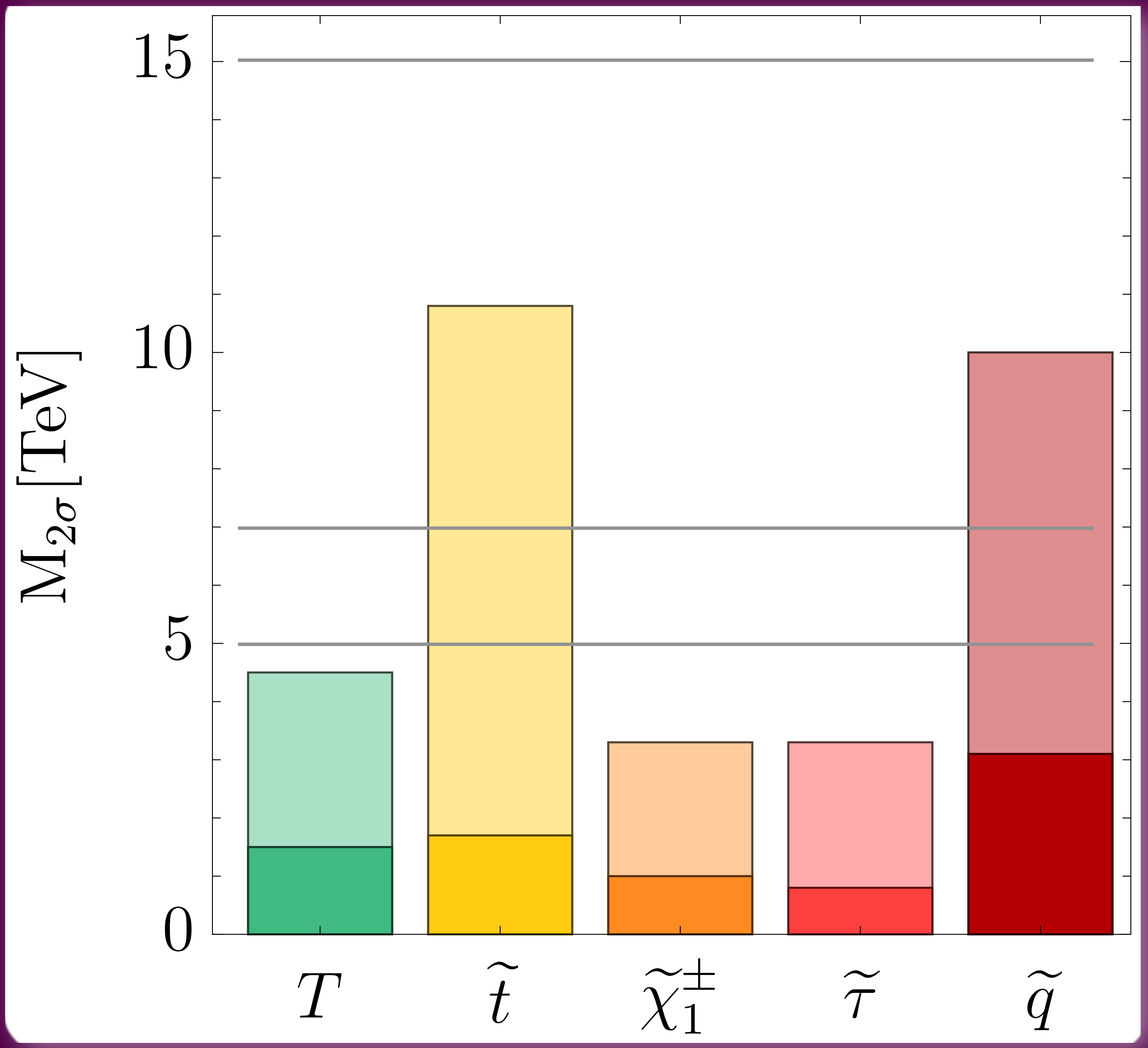
- Continuation of its exploration of QGP
- Contributions to **spectroscopy**
  - ➡ Observation of X(3872) in PbPb is expected (>5 σ) in Run3
- **ALP/Monopole searches**: rely on large EM field in HI collisions
  - ➡ ALICE 3 + CMS will push the ALP limit well below 1/TeV between 50 MeV and 100 GeV
  - ➡ Interesting because ALPs found in this range could potentially explain muon anomalous magnetic moment puzzle











EF08+EF09+EF10: BSM

Building the BSM program

EF08	BSM	Model specific explorations	Jim Hirschauer (FNAL)	Elliott Lipeles (UPenn)	Nausheen Shah (Wayne State)
EF09		More general explorations	Tulika Bose (UW-Madison)	Zhen Liu (Minnesota)	Simone Griso (LBL)
EF10		Dark Matter at colliders	Caterina Doglioni (Lund)	LianTao Wang (Chicago)	Antonio Boveia (Ohio St.)

- **Models connect the high-level unanswered questions** in particle physics **to specific phenomena** in a self-consistent way
  - Allow the comparison of experimental reach between various approaches
    - e.g. direct searches vs precision
  - Which models to consider? How to compare model spaces in a consistent way?
- How do we conduct **searches** in a **more model-independent way**?
  - e.g. long-lived and feebly-interacting particles, high-mass resonances
  - How do we compare the results of different experiments in a more model-independent way to ensure complementarity and avoid big gaps in coverage?

23 papers submitted to EF08+EF10

Green: also submitted to RPF

TG	Title	Authors	arXiv
EF08	***BSM Neutrino physics: complementarity across energies***	**T. Han, J. Liao, H. Liu, et al**	**2203.06131**
EF08	*Future searches for SUSY at the LHC post Fermilab (g−2)_μ*	A. Aboubrahim, M. Klasen, P. Nath, et al	2107.06021
EF08	*Comparison of SUSY spectra generators for natural SUSY and string landscape predictions*	H. Baer, V. Barger, D. Martinez	2111.03096
EF08	*Heavy neutrinos at future linear e+e− colliders*	K. Mękała, J. Reuter, A. Filip Żarnecki	2202.06703
EF08	*Angular cuts to reduce the tau taubar+jet background to the higgsino signal at the LHC*	H. Baer, V. Barger, D. Sengupta, et al	2203.03700
EF08	*Stau study at the ILC and its implication for the muon g-2 anomaly*	M. Endo, K. Hamaguchi, S. Iwamoto, et al	2203.07056
EF08	*Probing heavy Majorana neutrino pair production at ILC in a U(1)_{B−L} extension of the Standard Model*	J. Nakajima, A. Das, K. Fujii, et al	2203.06929
EF08	*Phenomenological aspects of composite Higgs scenarios: exotic scalars and vector-like quarks*	A. Banerjee, D. Buarque Franzosi, G. Cacciapaglia, et al	2203.07270
EF08	*Global fit of 2HDM with future collider results*	A. Beniwal, F. Rajec, M. Tobias Prim, et al	2203.07883
EF08	*Evaluating the ILC SUSY reach in the most challenging scenario: stau NLSP, low ΔM , lowest cross-section*	M. T. Núñez Pardo de Vera, M. Berggren, J. List	2203.15729
EF08	*Naturalness*	N. Craig	2205.05708
EF10	***LHCb future dark-sector sensitivity projections for Snowmass 2021***	**D. Craik, P. Ilten, D. Johnson, et al**	**2203.07048**
EF10	***Simplified dark matter models with charged mediators***	**T. Ghosh, C. Kelso, J. Kumar, et al**	**2203.08107**
EF10	*Higgs portal vector dark matter interpretation: review of Effective Field Theory approach and ultraviolet complete models*	M. Zaazoua, L. Truong, K. A. Assamagan, et al	2107.01252
EF10	*Event-level variables for semivisible jets using anomalous jet tagging*	H. Beauchesne, G. Grilli di Cortona	2111.12156
EF10	*Portal Matter and Dark Sector Phenomenology at Colliders*	T. G. Rizzo	2202.02222
EF10	*WIMP Dark Matter at High Energy Muon Colliders*	T. Han, Z. Liu, L. Wang, et al	2203.07351
EF10	*New approach to DM searches with mono-photon signature*	J. Kalinowski, W. Kotlarski, K. Mekala, et al	2203.06776
EF10	*New Physics with missing energy at future lepton colliders*	J. Kalinowski, T. Robens, A. Filip Zarnecki	2203.07913
EF10	*Prospects for searches for Higgs boson decays to dark photons at the ILC*	S. Snyder, C. Weber, D. Zhang	2203.08270
EF10	*Scalar-mediated dark matter model at colliders and gravitational wave detectors*	J. Liu, X. Wang, K. Xie	2203.10046
EF10	*Displaying dark matter constraints from colliders with varying simplified model parameters*	A. Albert, A. Boveia, O. Brandt, et al	2203.12035
EF10	*More is Different: Non-Minimal Dark Sectors and their Implications for Particle Physics, Astrophysics, and Cosmology – 13 Take-Away Lessons for Snowmass 2021*	K. R. Dienes, B. Thomas	2203.17258

26 papers submitted to EF09

Green: also submitted to RPF

TG	Title	Authors	arXiv
EF09	***The Road Ahead for CODEX-b***	**G. Aielli, J. Alimena, J. Beacham, et al**	**2203.07316**
EF09	***Theory Frontier: Theory Meets the Lab***	**R. Essig, Y. Kahn, S. Knapen, et al**	**2203.10089**
EF09	*Studies of granularity of a hadronic calorimeter for tens-of-TeV jets at a 100 TeV pp collider*	C.-H. Yeh, S.V. Chekanov, A.V. Kotwal, et al	1901.11146
EF09	*Physics potential of timing layers in future collider detectors*	S.V. Chekanov, A.V. Kotwal, C.-H. Yeh, et al	2005.05221
EF09	*A fast method for particle tracking and triggering using small-radius silicon detectors*	A.V. Kotwal	1910.14149
EF09	*The LHC Olympics 2020: A Community Challenge for Anomaly Detection in High Energy Physics*	G. Kasieczka, B. Nachman, D. Shih, et al	2101.08320
EF09	*Model-independent searches for new physics in multi-body invariant masses*	S.V. Chekanov, S. Darmora, W. Islam, et al	2103.10217
EF09	*Event-based anomaly detection for new physics searches at the LHC using machine learning*	S.V. Chekanov, W. Hopkins	2111.12119
EF09	*A note on blind technique for new physics searches in particle physics*	S.V. Chekanov	2112.09548
EF09	*Sensitivity to Dijet Resonances at Proton-Proton Colliders*	R. M. Harris, E. Gurpinar Guler, Y. Guler	2202.03389
EF09	*The Composite Higgs Signal at the Next Big Collider*	K. Lane	2203.03710
EF09	*Combined signatures of heavy Higgses and vectorlike fermions at the HL-LHC*	R. Dermisek, J. Kawamura, E. Lunghi, et al	2203.03852
EF09	*Axion-Like Particles at High Energy Muon Colliders*	T. Han, T. Li, X. Wang	2203.05484
EF09	*Searches for Long-Lived Particles at the Future FCC-ee*	C. B. Verhaaren, J. Alimena, M. Bauer, et al	2203.05502
EF09	*Displaced fat-jets and tracks to probe boosted right-handed neutrinos in the U(1)_{B−L} model*	R. Padhan, M. Mitra, S. Kulkarni, et al	2203.06114
EF09	*Two-fermion final states at International Linear Collider*	T. Suehara	2203.07272
EF09	*Track-Based Triggers for Exotic Signatures*	K. F. Di Petrillo, J. N. Farr, C. Guo, et al	2203.07314
EF09	*Strong CP Beyond Axion Direct Detection*	N. Blinov, N. Craig, M. J. Dolan, et al	2203.07218
EF09	*Tau Neutrinos in the Next Decade: from GeV to EeV*	R. Mammen Abraham, J. Alvarez-Muñiz, C. A. Argüelles, et	2203.05591
EF09	*Probing New Physics with mu+mu− → bs at a Muon Collider*	W. Altmannshofer, S. Aditya Gadam, S. Profumo	2203.07495
EF09	*Recent Progress and Next Steps for the MATHUSLA LLP Detector*	C. Alpigiani, J. Carlos Arteaga-Velázquez, A. Ball, et al	2203.08126
EF09	*Sensitivity to decays of long-lived dark photons at the ILC*	L. Jeanty, L. Nosler, C. Potter	2203.08347
EF09	*Probing the Electroweak Phase Transition with Exotic Higgs Decays*	M. Carena, J. Kozaczuk, Z. Liu, et al	2203.08206
EF09	*Theory, phenomenology, and experimental avenues for dark showers*	G. Albouy, J. Barron, H. Beauchesne, et al	2203.09503
EF09	*PetaVolts per meter Plasmonics*	A. A. Sahai, M. Golkowski, S. Gedney, et al	2203.11623
EF09	*Collider Physics Opportunities of Extended Warped Extra-Dimensional Models*	K. Agashe, J. H. Collins, P. Du, et al	2203.13305

Muon collider (muC)

$\sim e^+e^-$ colliders **lower energies** limit their direct detection potential

Muon collider (muC)

- e^+e^- colliders **lower energies** limit their direct detection potential
- **pp** has **great discovery potential**, but **loopholes** for exclusion

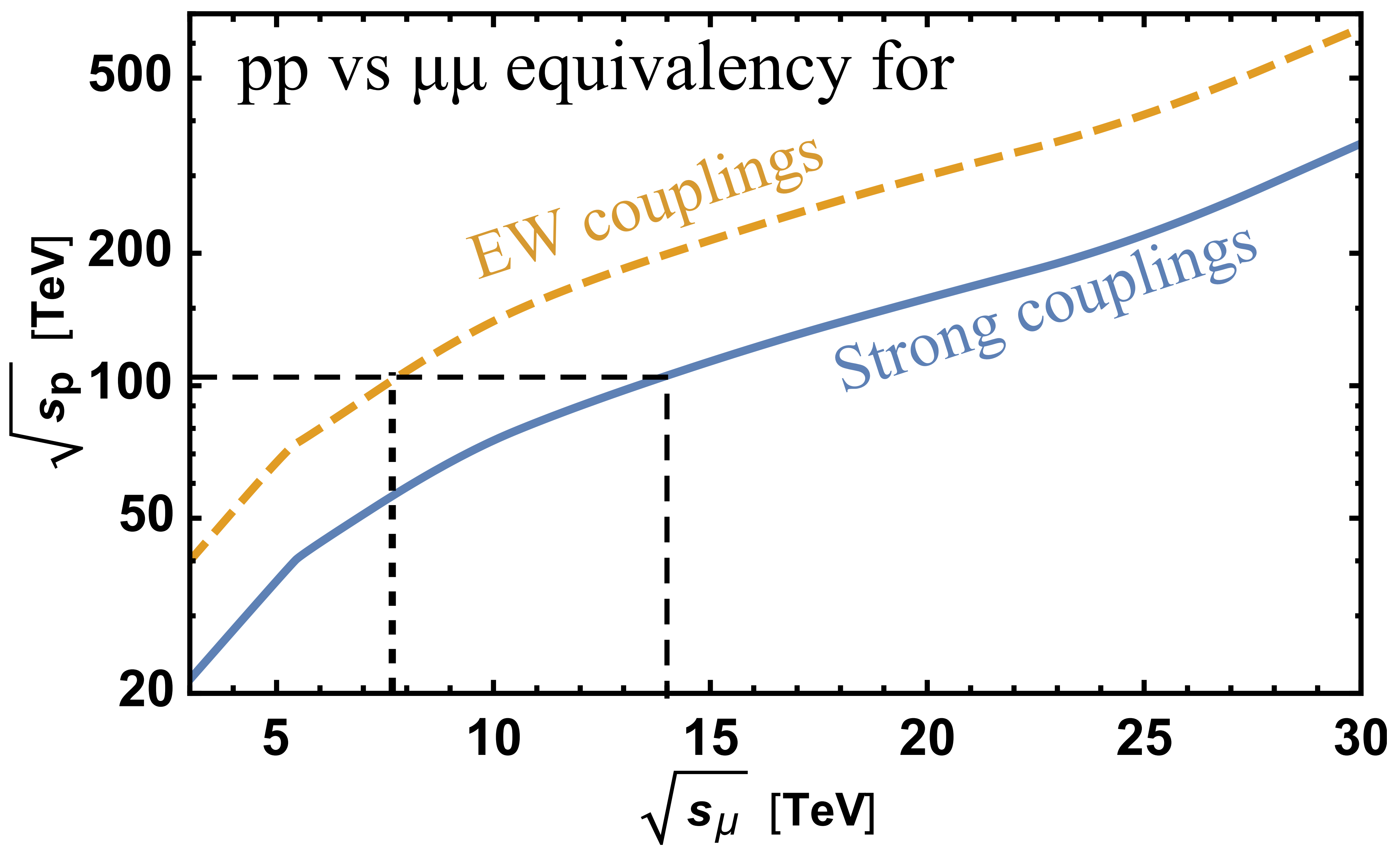
Muon collider (muC)

- e^+e^- colliders **lower energies** limit their direct detection potential
- **pp** has **great discovery potential**, but **loopholes** for exclusion
- **Muon collider** has the **best of both worlds**
  - A lot of progress recently
    - e.g. full simulations, understanding how to mitigate beam induced backgrounds

"The physics case of a 3 TeV muon collider stage", arXiv:2203.07261
"Muon Collider Physics Summary", arXiv:2203.07256
"Strategies for Beam-Induced Background Reduction at Muon Colliders", arXiv:2203.06773
"Promising Technologies and R&D Directions for the Future Muon Collider Detectors", arXiv:2203.07224
"A Muon Collider Facility for Physics Discovery", arXiv:2203.08033
"Simulated Detector Performance at the Muon Collider", arXiv:2203.07964
+ 7 white papers on specific physics analyses

Muon collider (muC)

- e^+e^- colliders **lower energies** limit their direct detection potential
- **pp** has **great discovery potential**, but **loopholes** for exclusion
- **Muon collider** has the **best of both worlds**
  - ➡ A lot of progress recently
    - ✦ e.g. full simulations, understanding how to mitigate beam induced backgrounds



[2203.07256]

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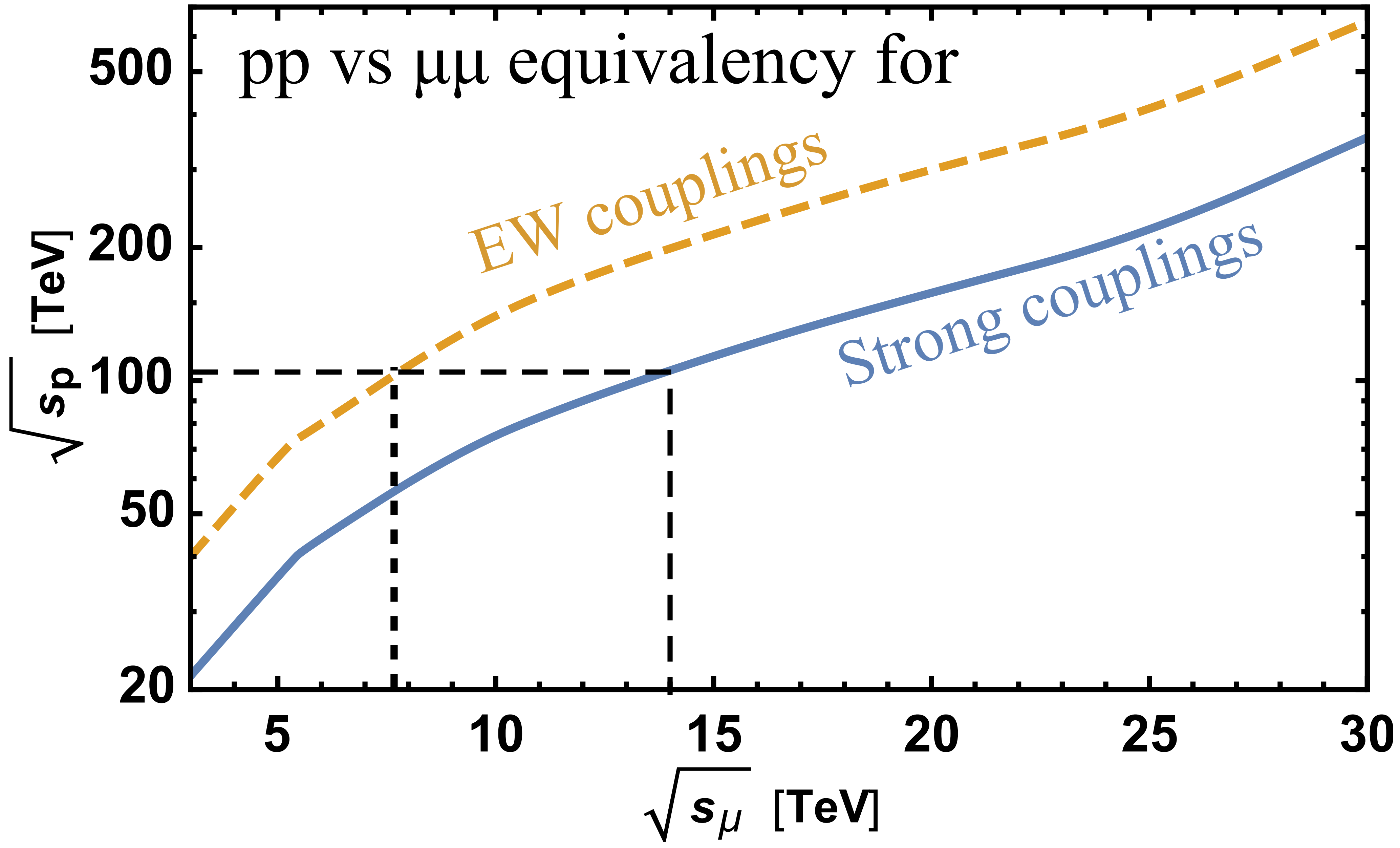
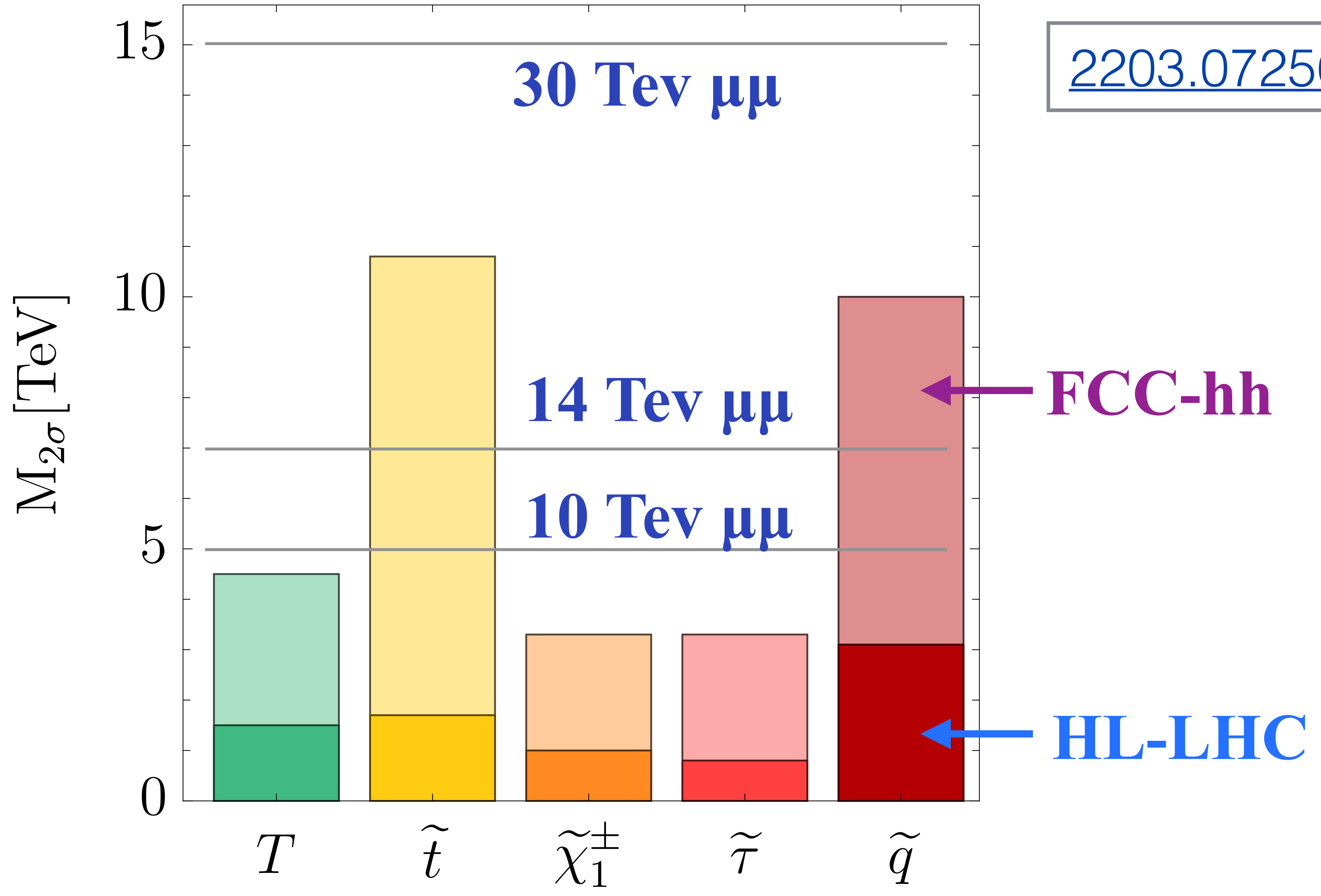
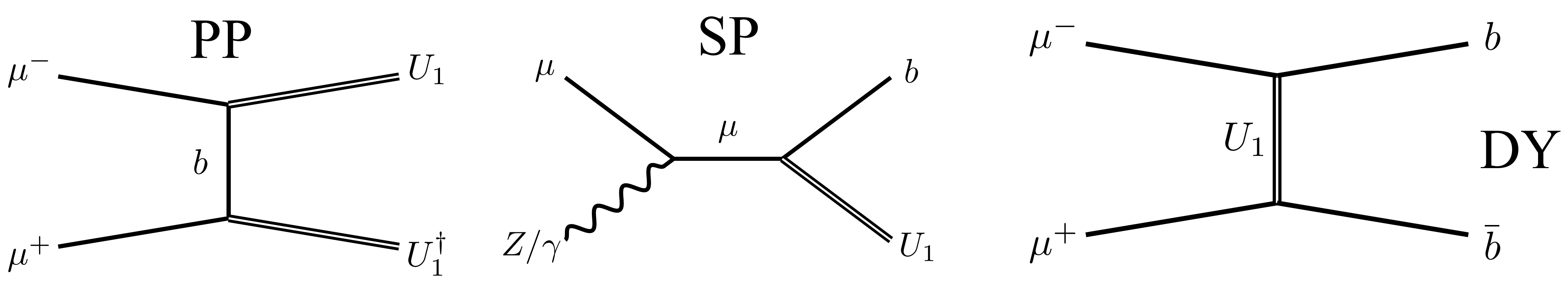


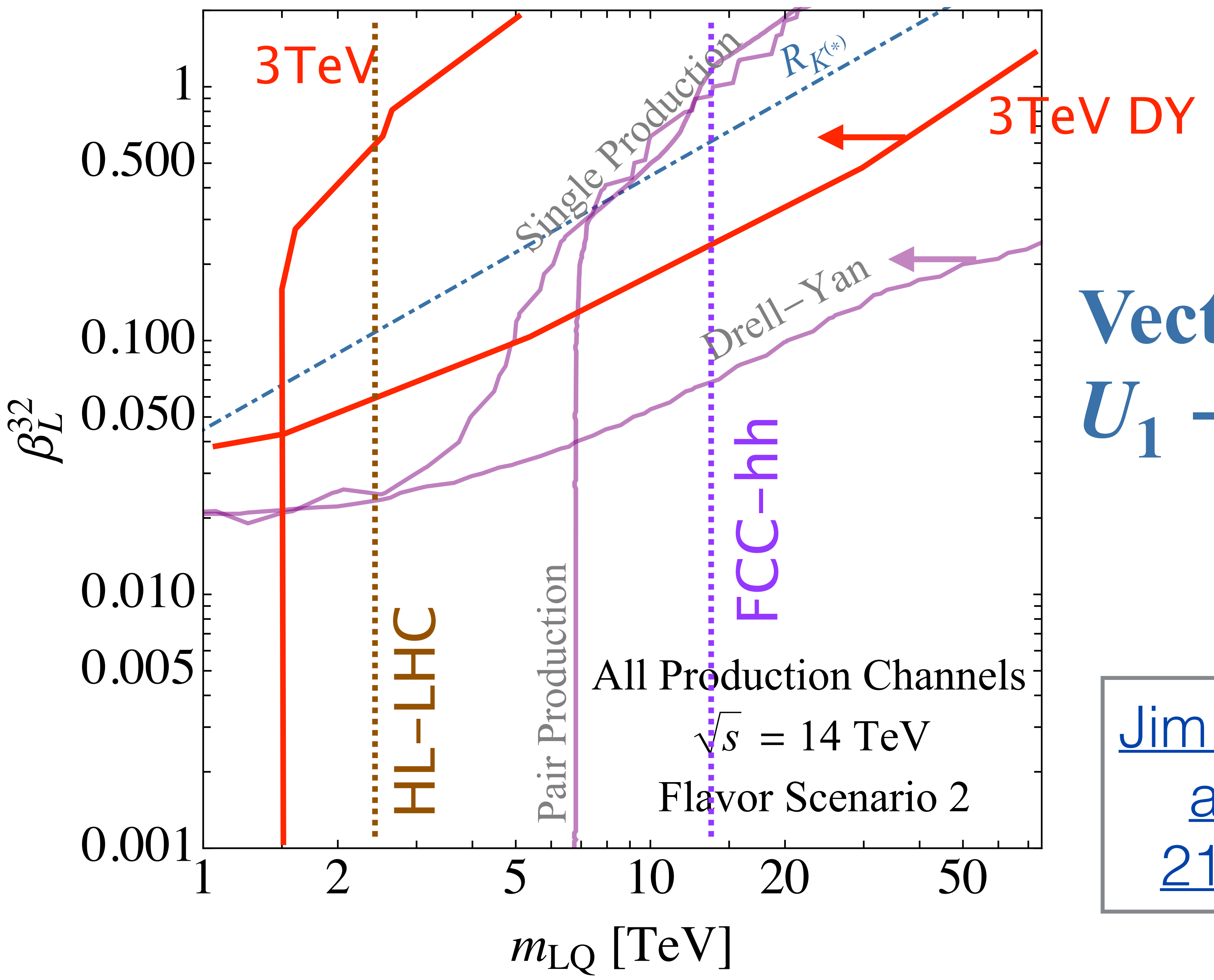


2203.07256

- $\mathscr{R}_{K^{(*)}}$ and $\mathscr{R}(D^{(*)})$ anomalies motivate searches for leptoquarks
- A **3 TeV muC already** provides **significant BSM opportunities**



International MUON Collider Collaboration



Vector LQ with
$U_1 \rightarrow \mu b$ coupling

[Jim Hirschauer at EF] and [2104.05720]

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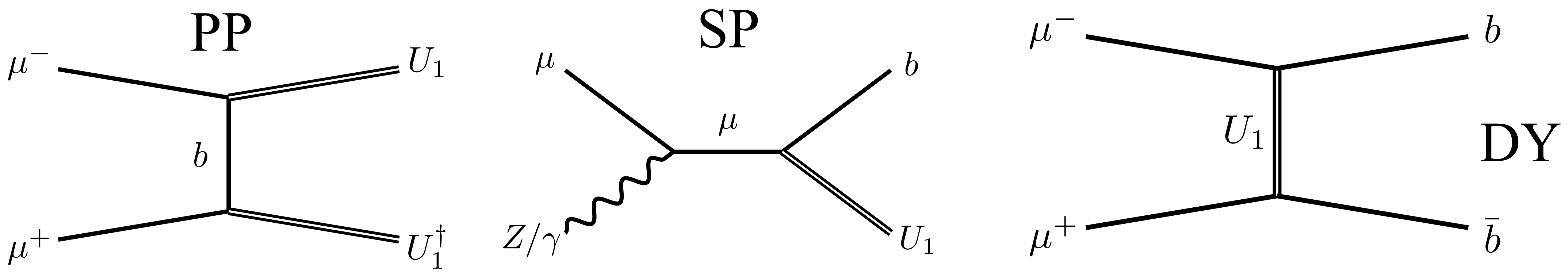

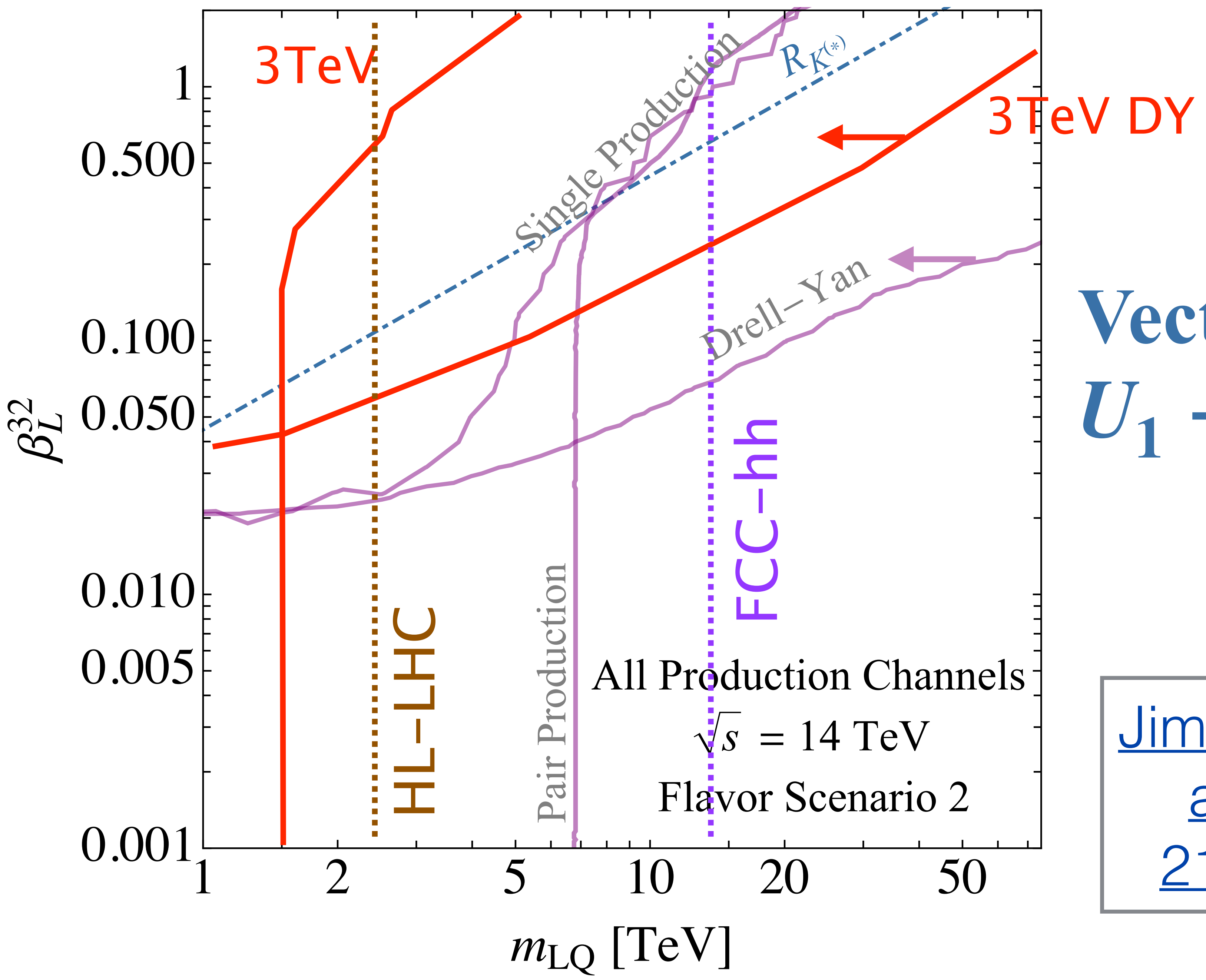

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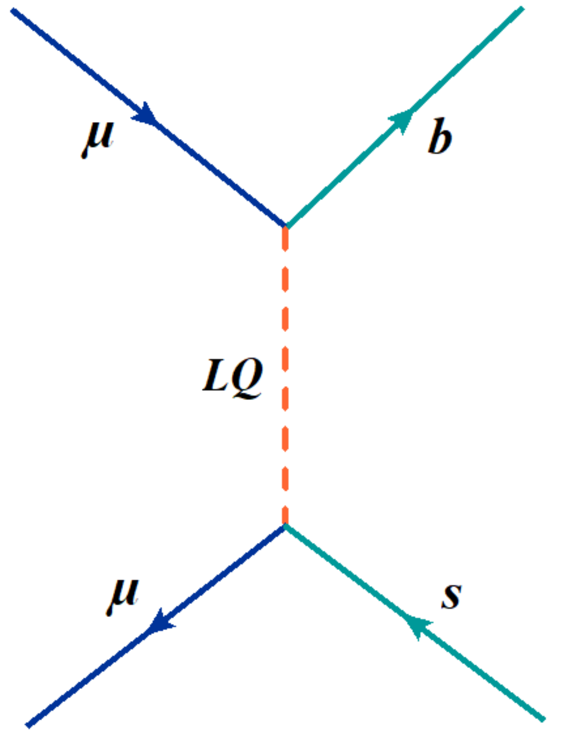
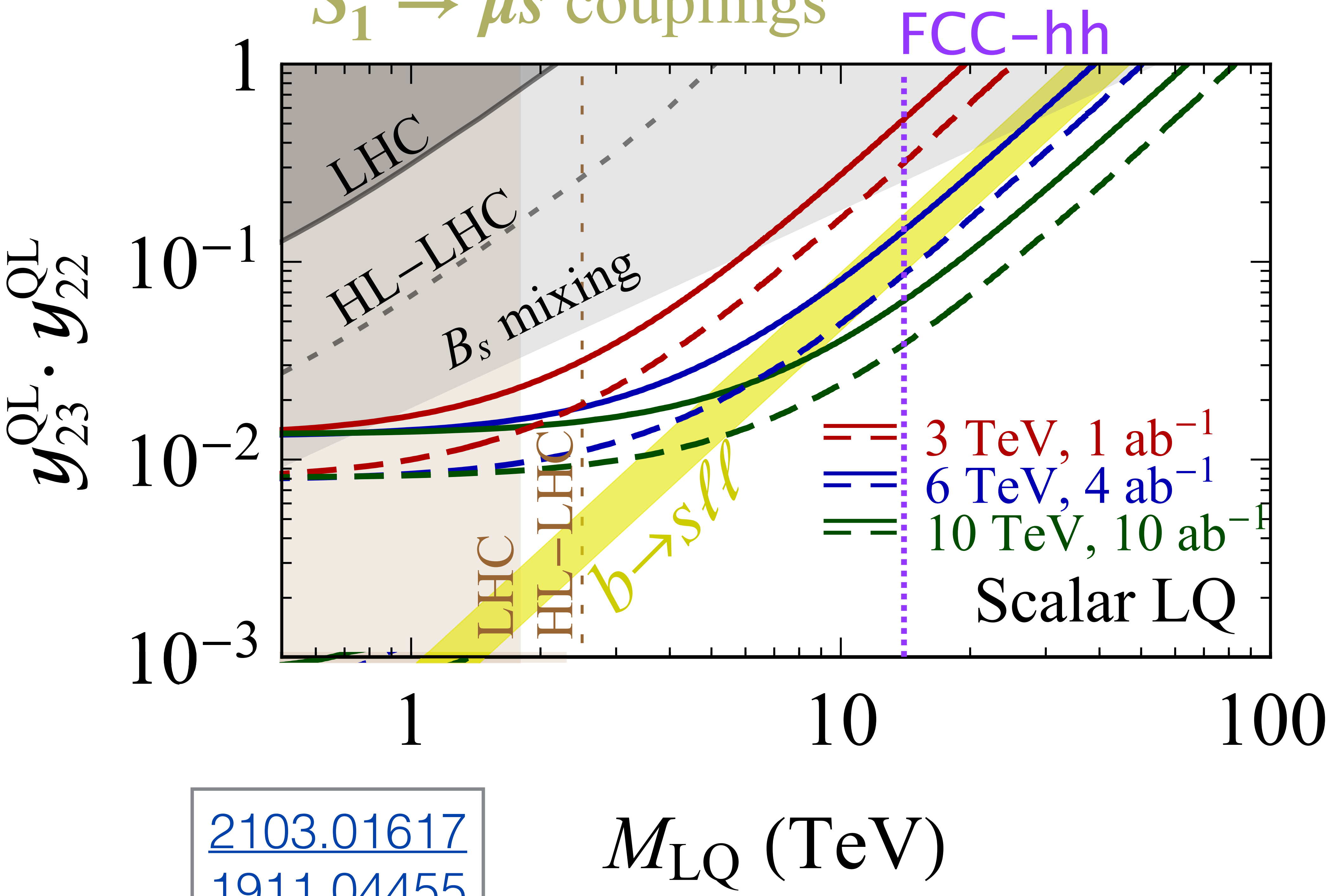


Scalar LQ with $S_1 \to \mu b$ and $S_1 \to \mu s$ couplings



2103.01617
1911.04455

Following the LFU anomalies

~ $\mathscr{R}_{K^{(*)}}$ and $\mathscr{R}(D^{(*)})$ anomalies motivate searches for Z' and leptoquarks

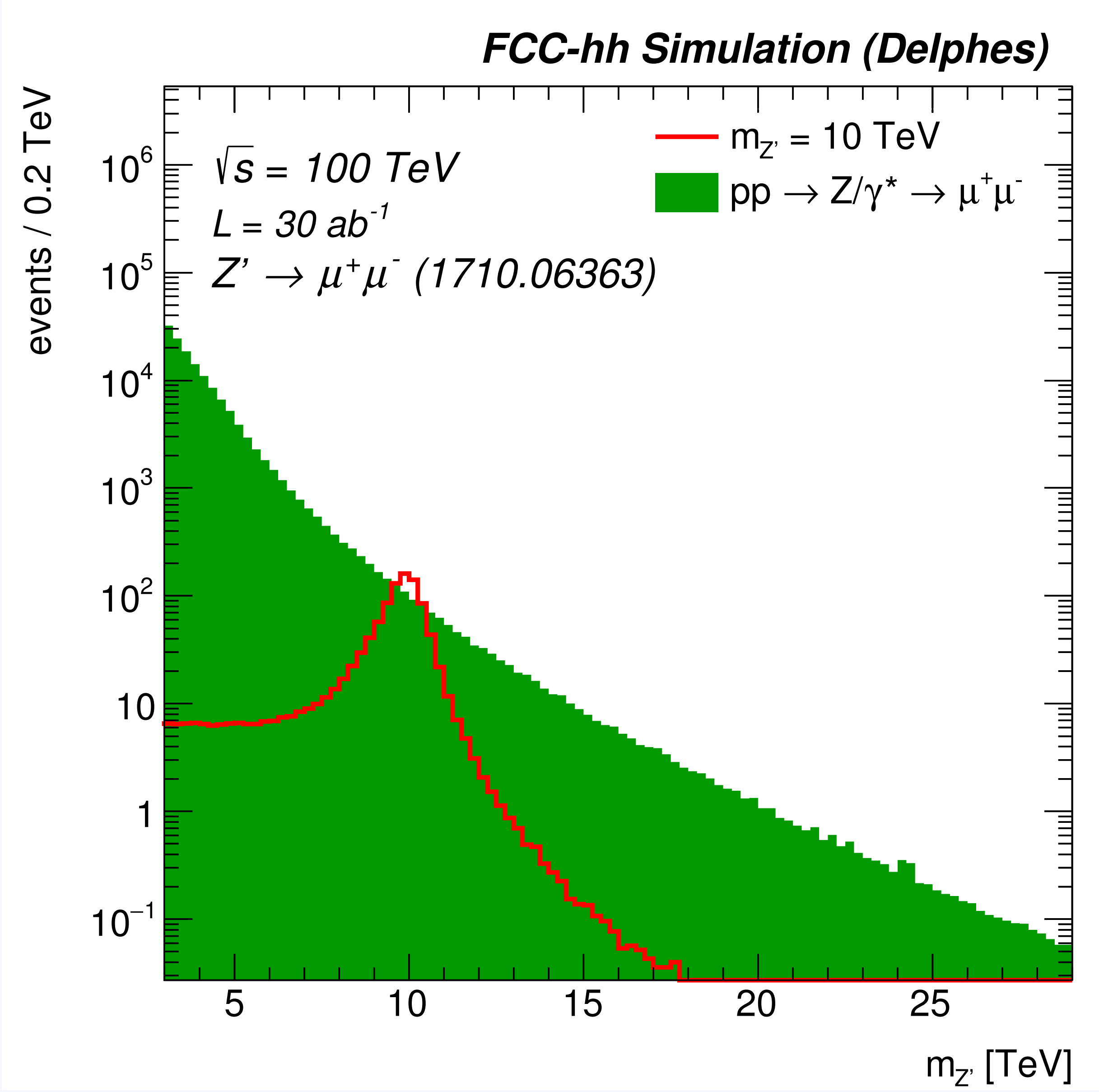
FCC-hh

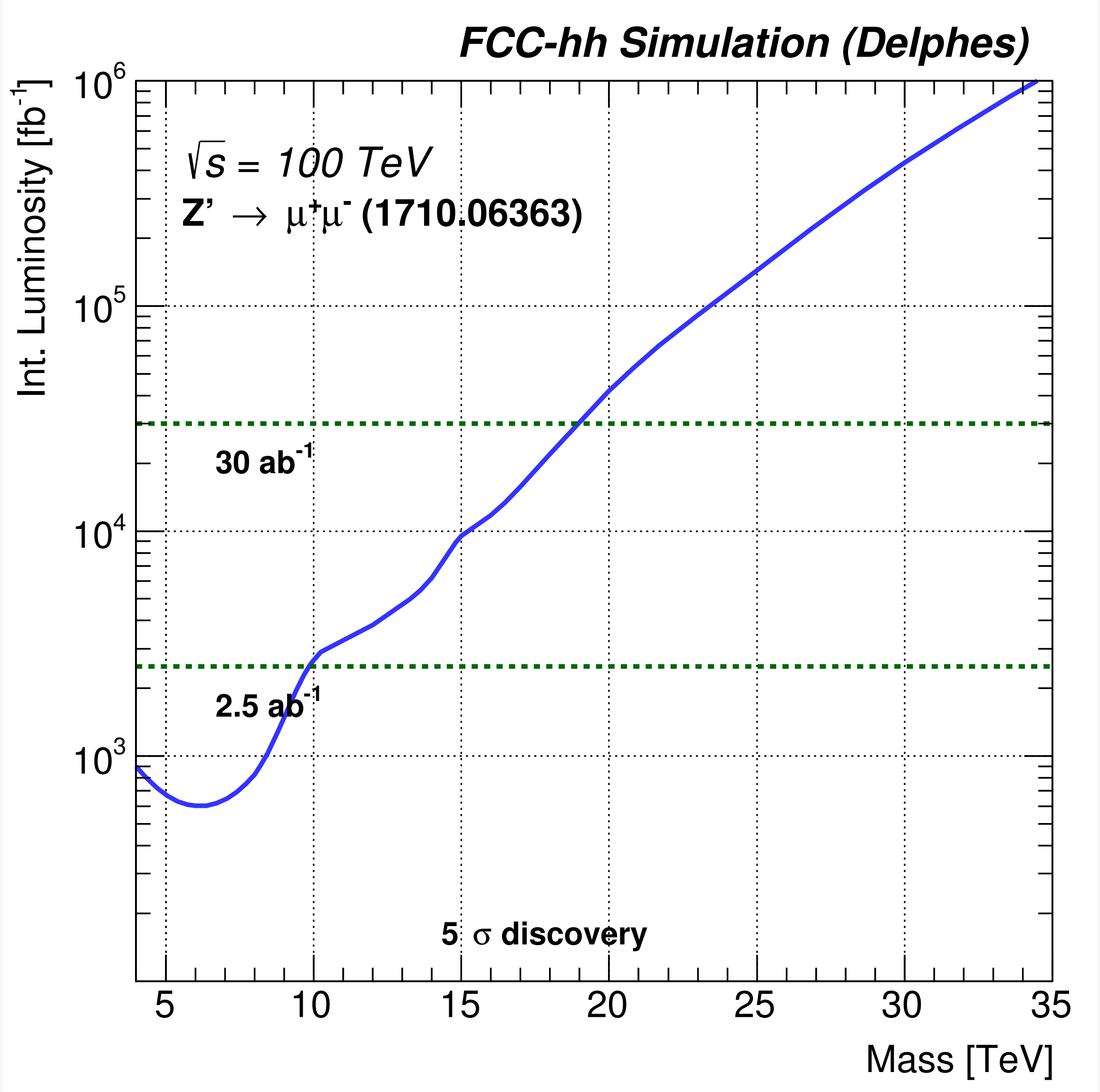
1902.11217

$Z' \to \mu\mu$ with couplings

$$g_{bs}\, g_{\mu\mu} \approx \frac{m_{Z'}^2}{(30\ \text{TeV})^2} \text{ from } \mathscr{R}_{K^{(*)}}$$

anomaly discovered up to 18 TeV





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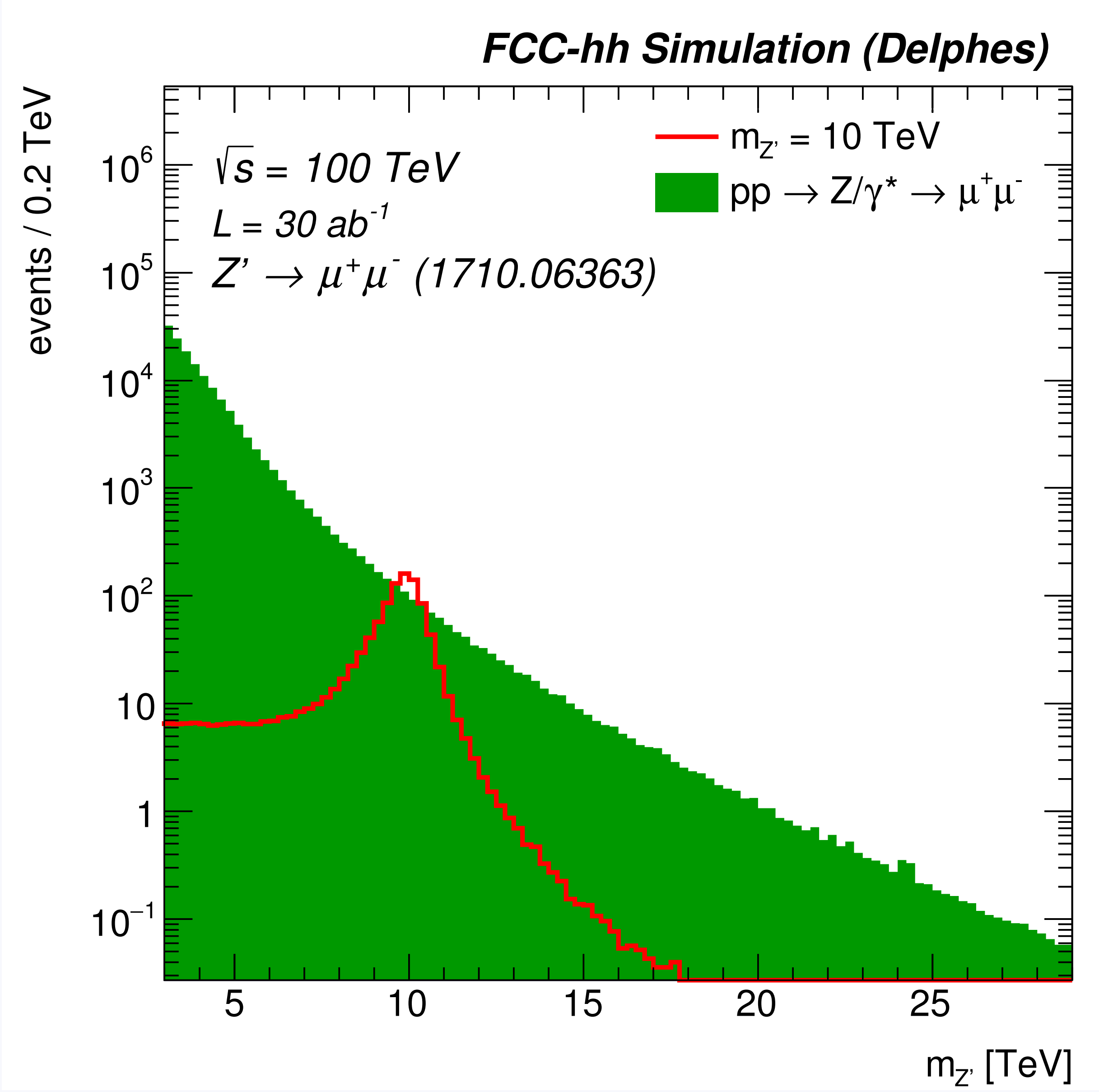
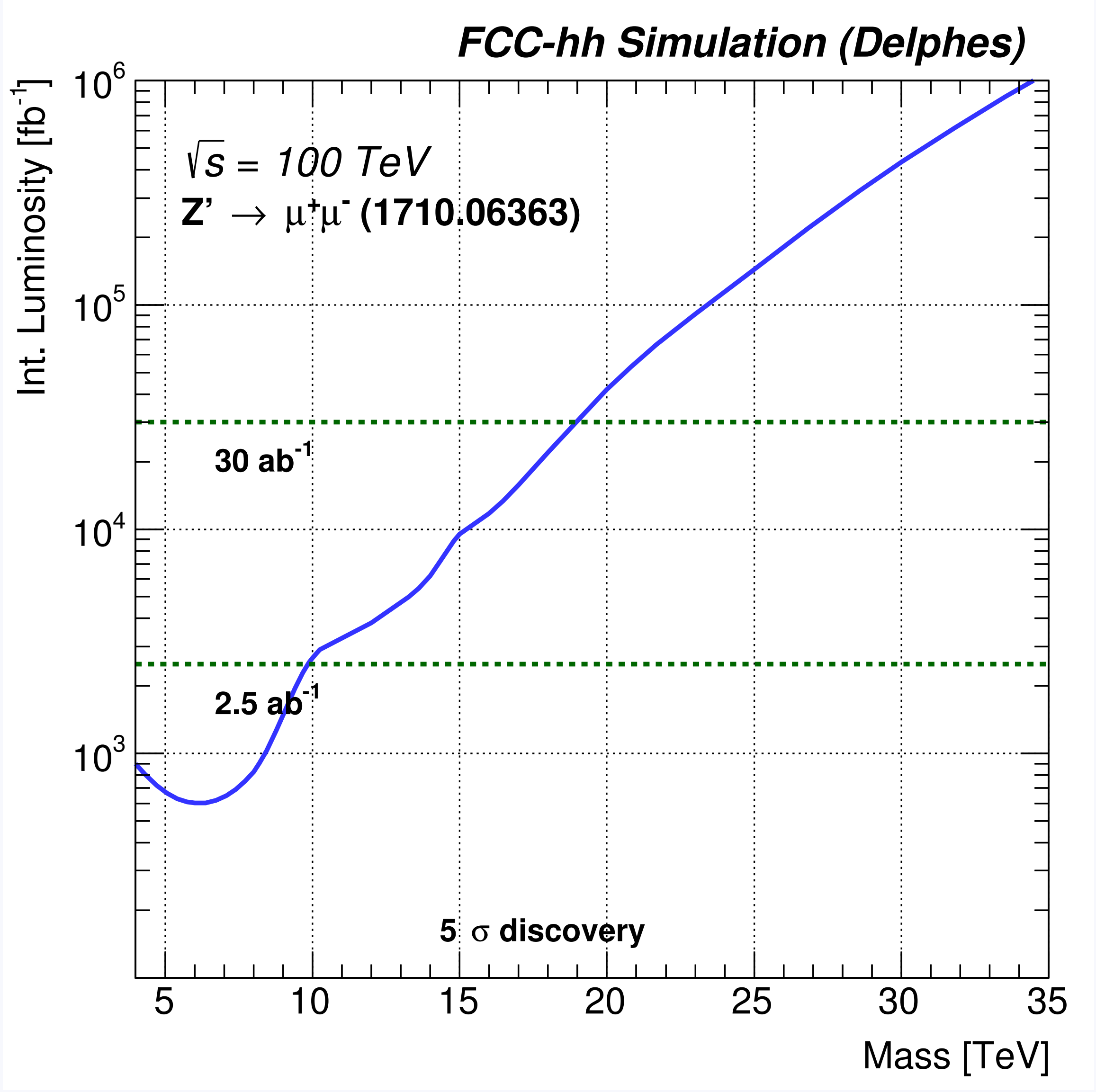
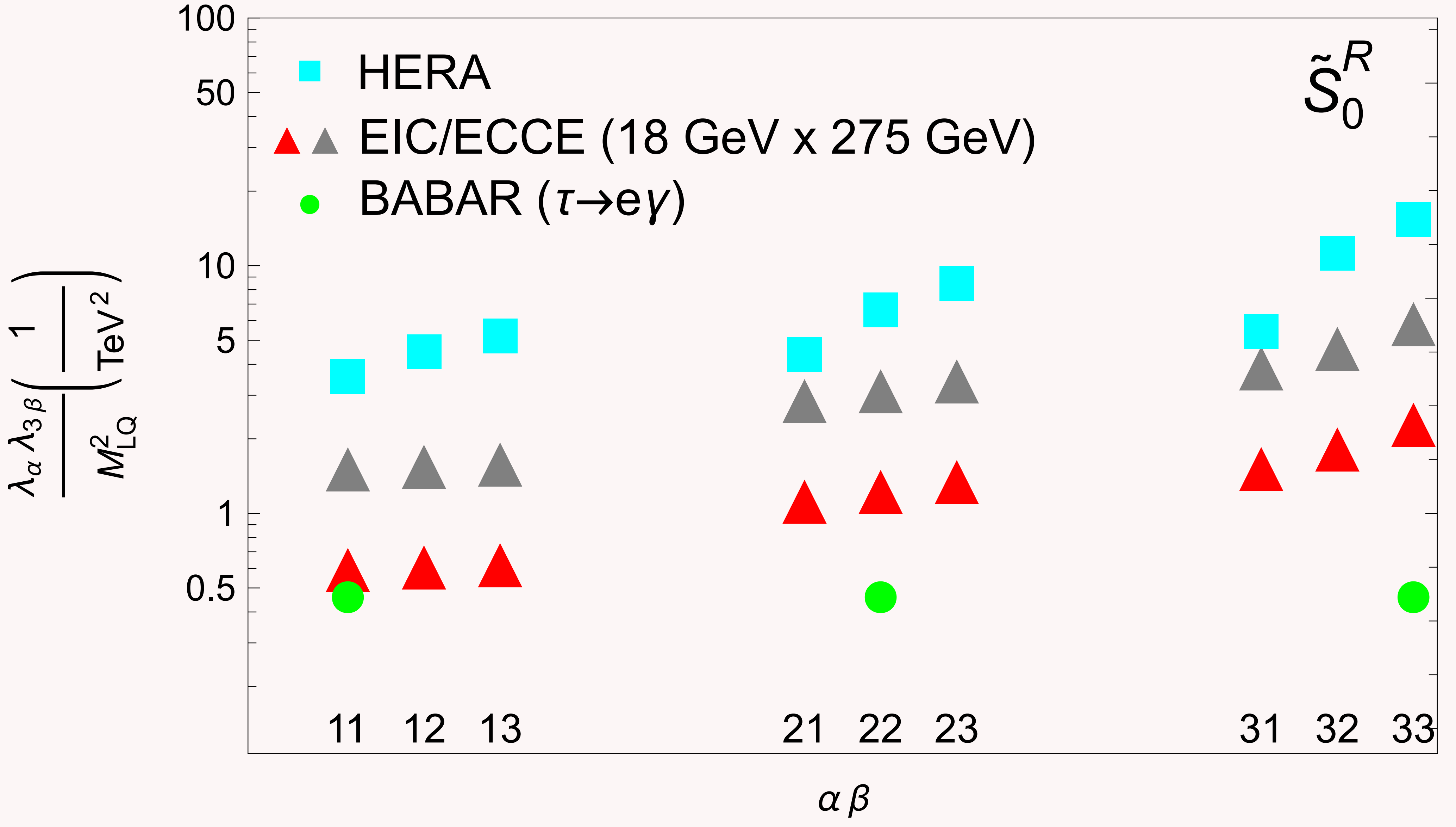




Scalar LQ mediated
ep → *τX* complement
B-factories

Electron-Ion Collider
at Brookhaven National Laboratory

2203.13199



Following $g_\mu - 2$

in preparation

Chakraborti, Heinemeyer, Saha :

The reinforced 4.2σ discrepancy between the experimental result for the anomalous magnetic moment of the muon, $(g-2)_\mu$, and its Standard Model (SM) prediction, can elegantly be explained by the contributions of the electroweak (EW) sector of the Minimal Supersymmetric Standard Model (MSSM), while being in agreement with all other experimental and theoretical constraints.

Following $g_\mu - 2$

2107.06021

Model	h^0	$\tilde{\ell}_L$	$\tilde{\ell}_R$	$\tilde{\nu}_L$	$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$	Ωh^2	$\Delta a_\mu (\times 10^{-9})$
(a)	123.0	508.1	762.0	502.3	331.9	324.2	404.3	0.004	2.11
(b)	123.4	305.0	463.0	295	251.7	237.4	237.6	0.002	2.33
(c)	123.7	346.8	511.9	338.0	240.3	205.6	205.8	0.001	2.67
(d)	125.3	422.8	763.8	415.7	370.4	337.3	337.6	0.003	2.14
(e)	124.5	628.7	402.2	623.6	338.3	326.8	998.4	0.082	1.94
(f)	123.4	722.8	262.9	718.2	206.5	195.5	1038.4	0.103	2.57
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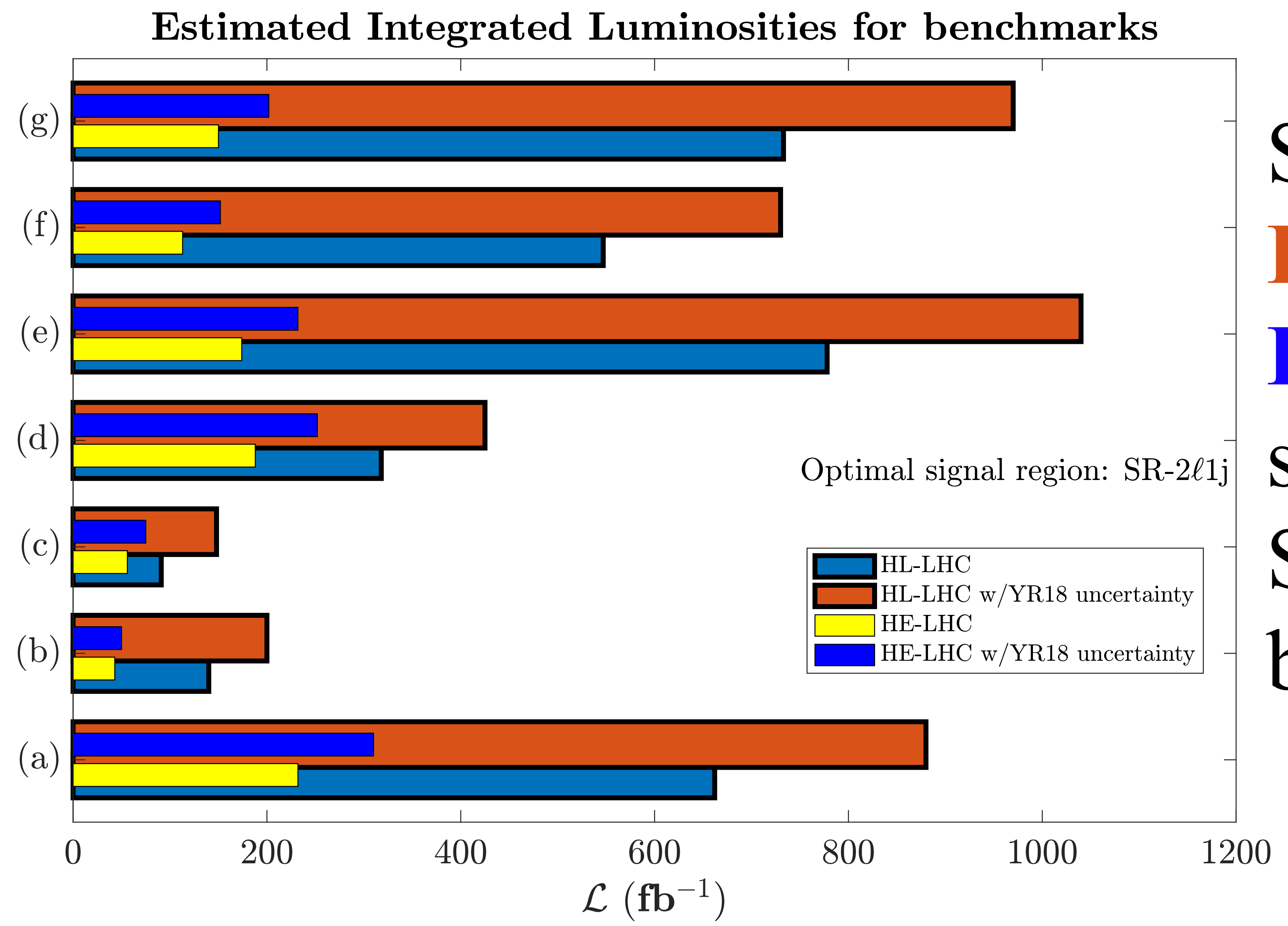

Sensitivity from **HL-LHC** and **HE-LHC** to many split-spectrum SUGRA benchmarks

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HiLumi HL-LHC PROJECT — 2107.06021

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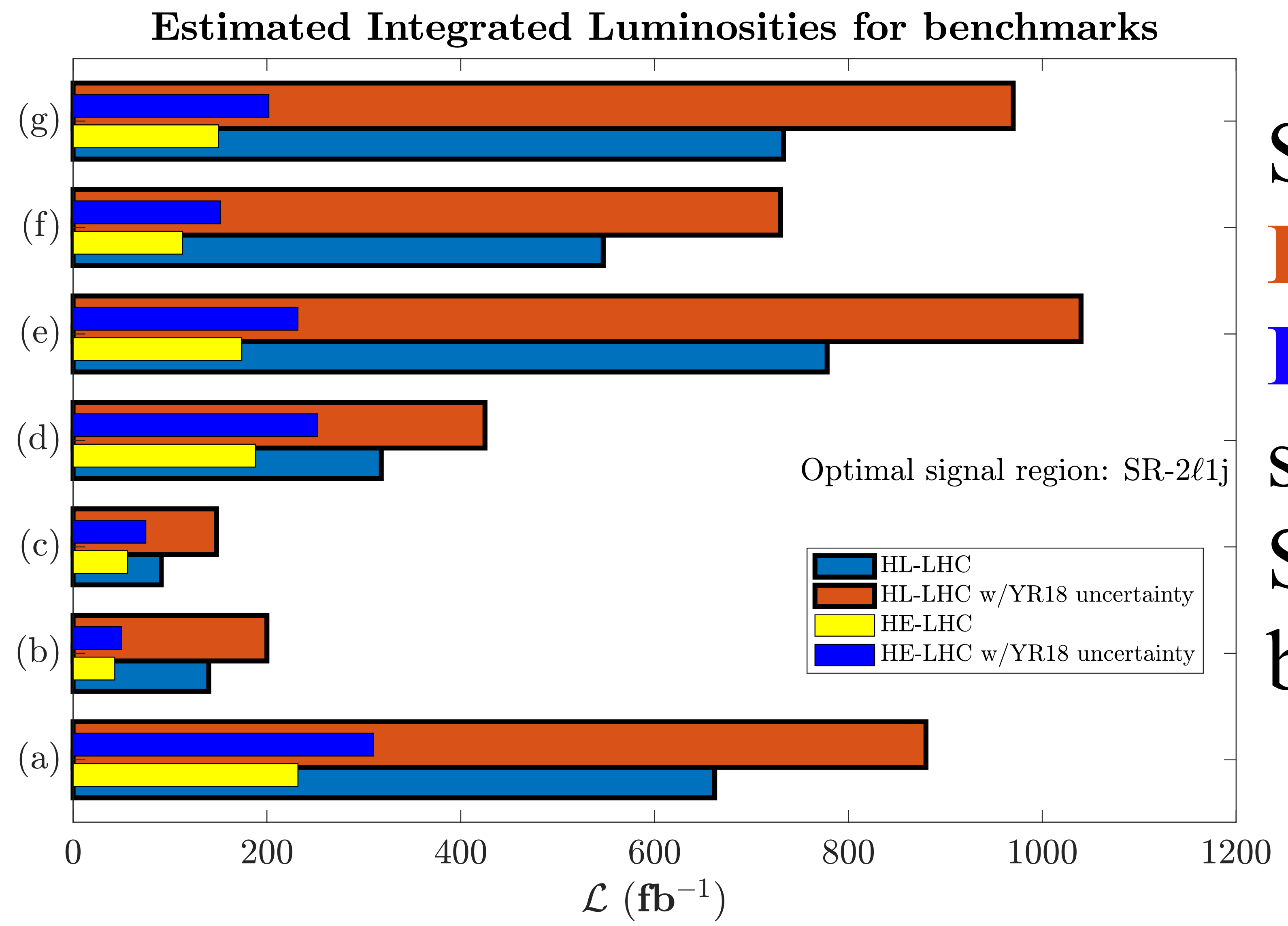
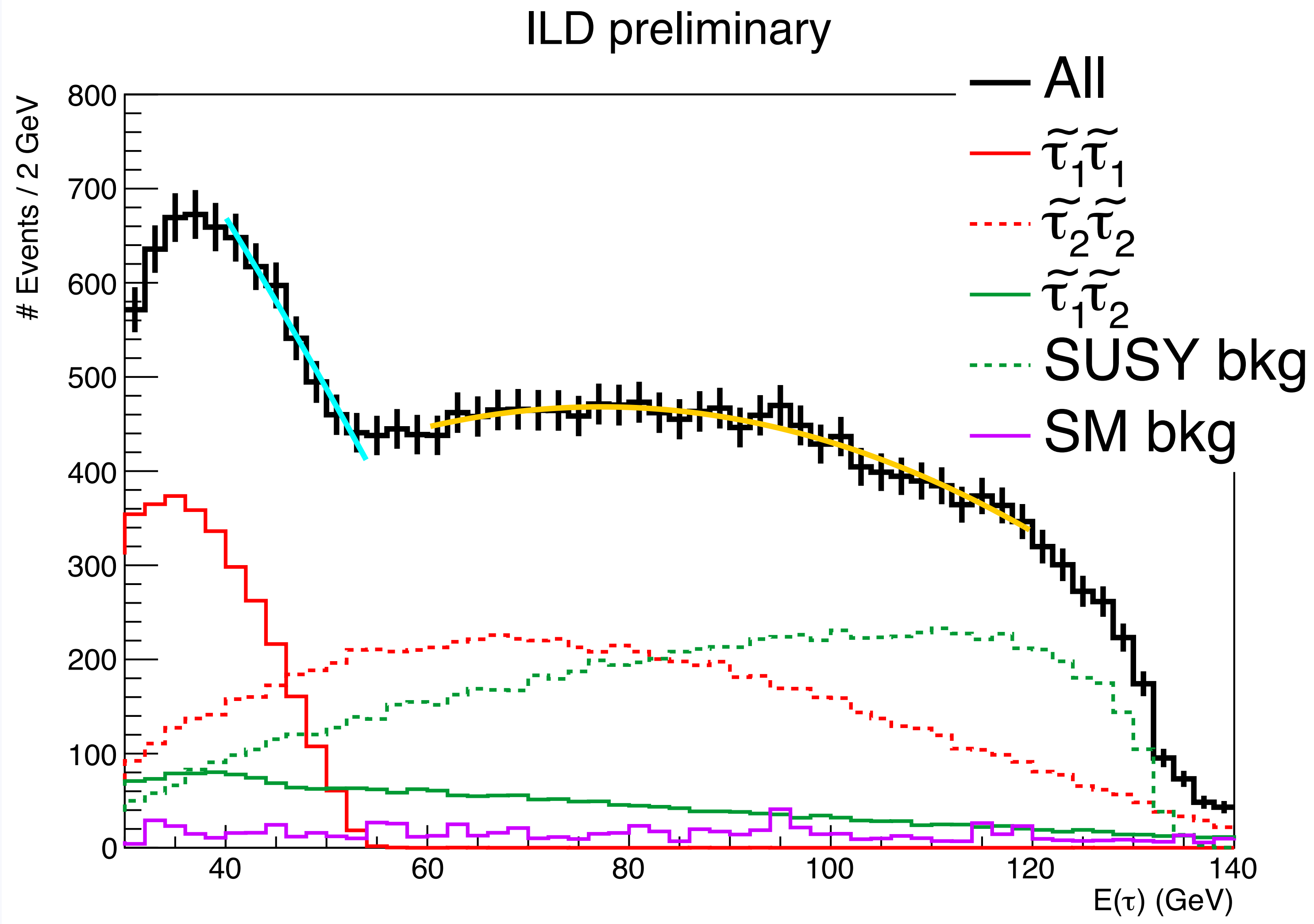


Sensitivity from **HL-LHC** and **HE-LHC** to many split-spectrum SUGRA benchmarks

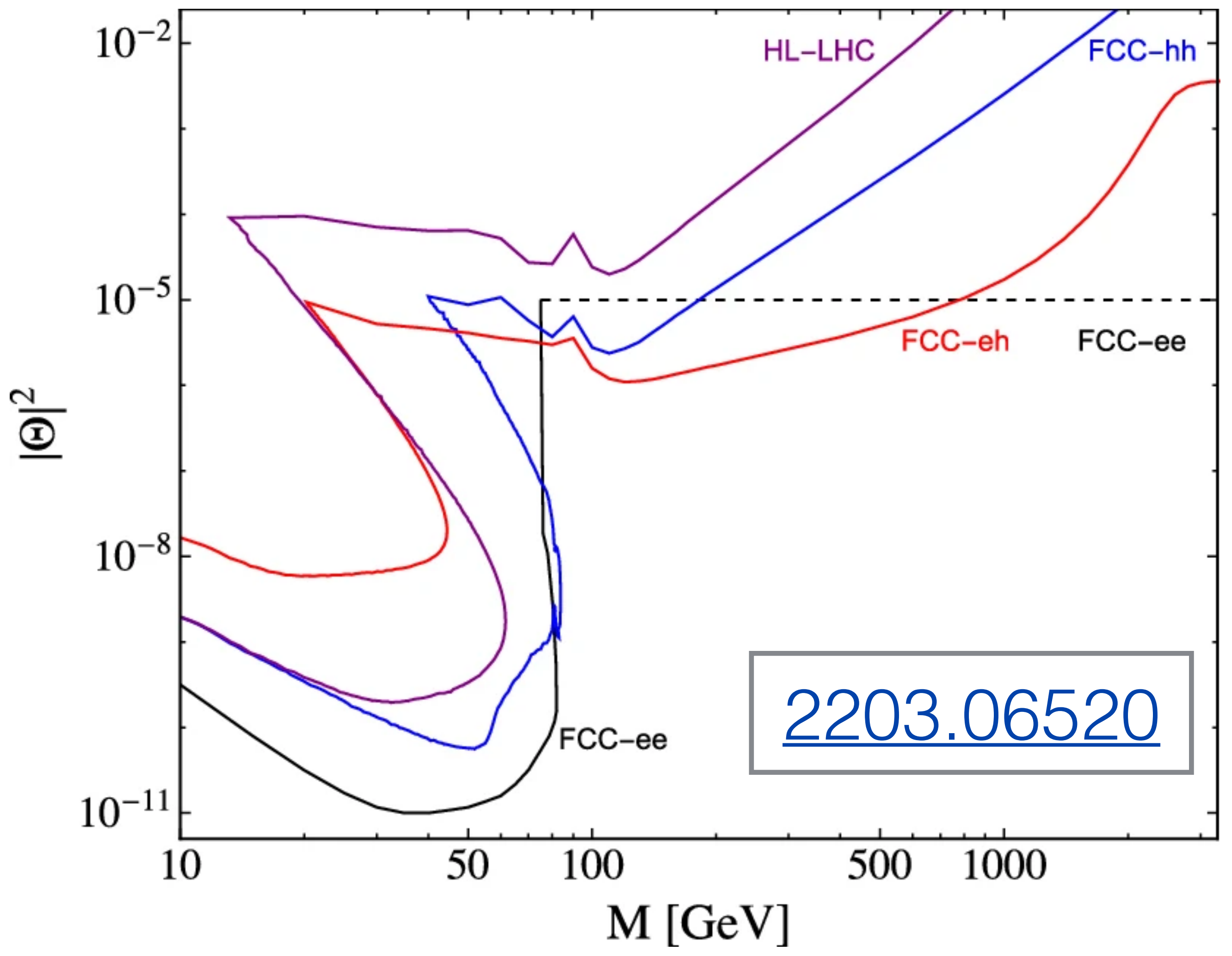
ilc — 2203.07056

$$e^+(P_{e^+})e^-(P_{e^-}) \to \tilde{\tau}_i^* \tilde{\tau}_j \to \tau^+\tau^- + 2\tilde{B} \quad (i,j=1,2)$$

Measurement of Bino contribution to $g_\mu - 2$ could be measured to 8%, $a_\mu^{(\tilde{B})} = 26.4^{+2.1}_{-1.7} \times 10^{-10}$



- A lot of growing interest in the recent years on **Long-lived particles (LLP)**
  - Many results from LHC, but also from b-factories and dedicated experiments
  - LLP searches are an attractive alternative (and complement) to mainstream new physics searches, but **challenge conventional reconstruction and trigger methods**



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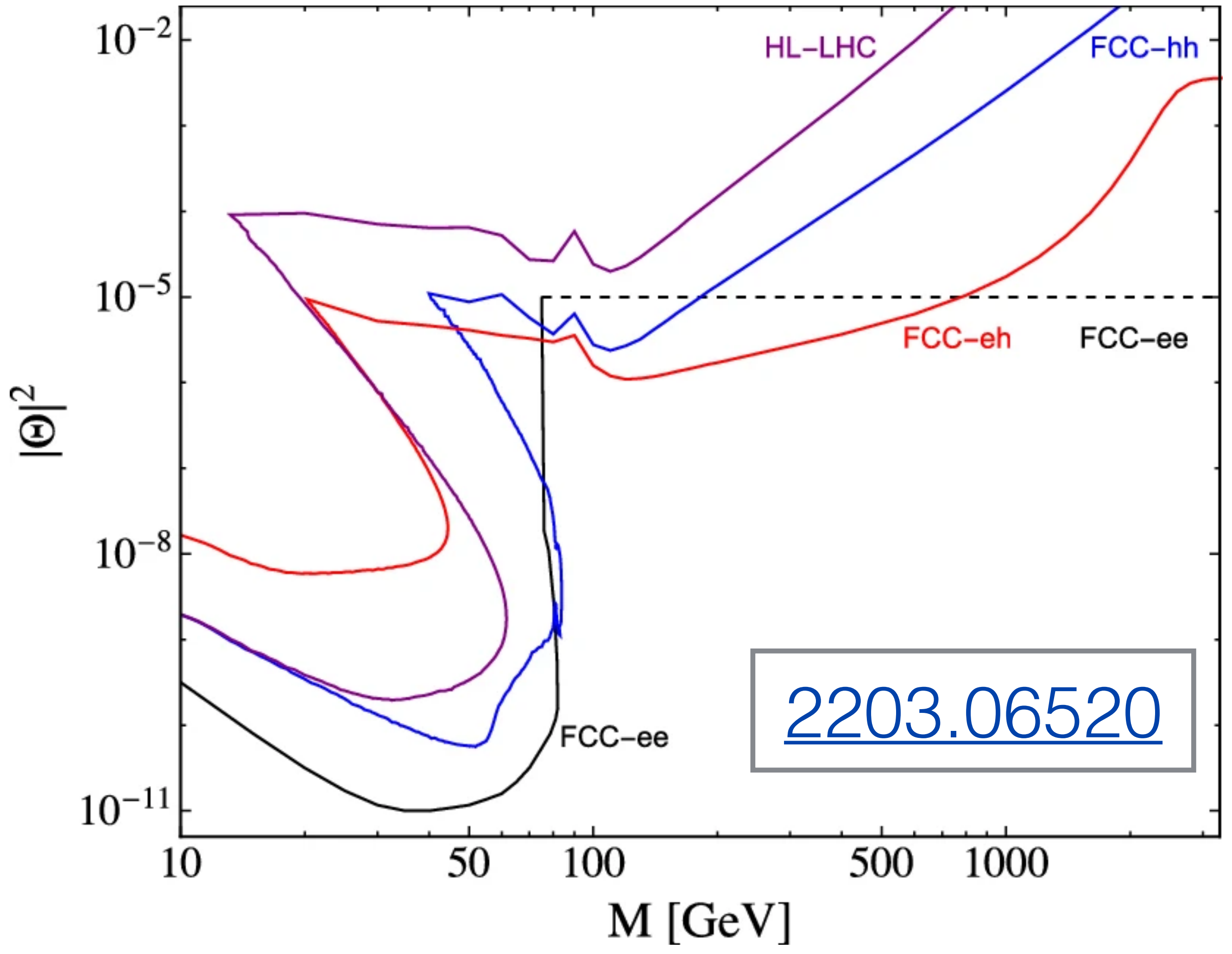

2203.06520

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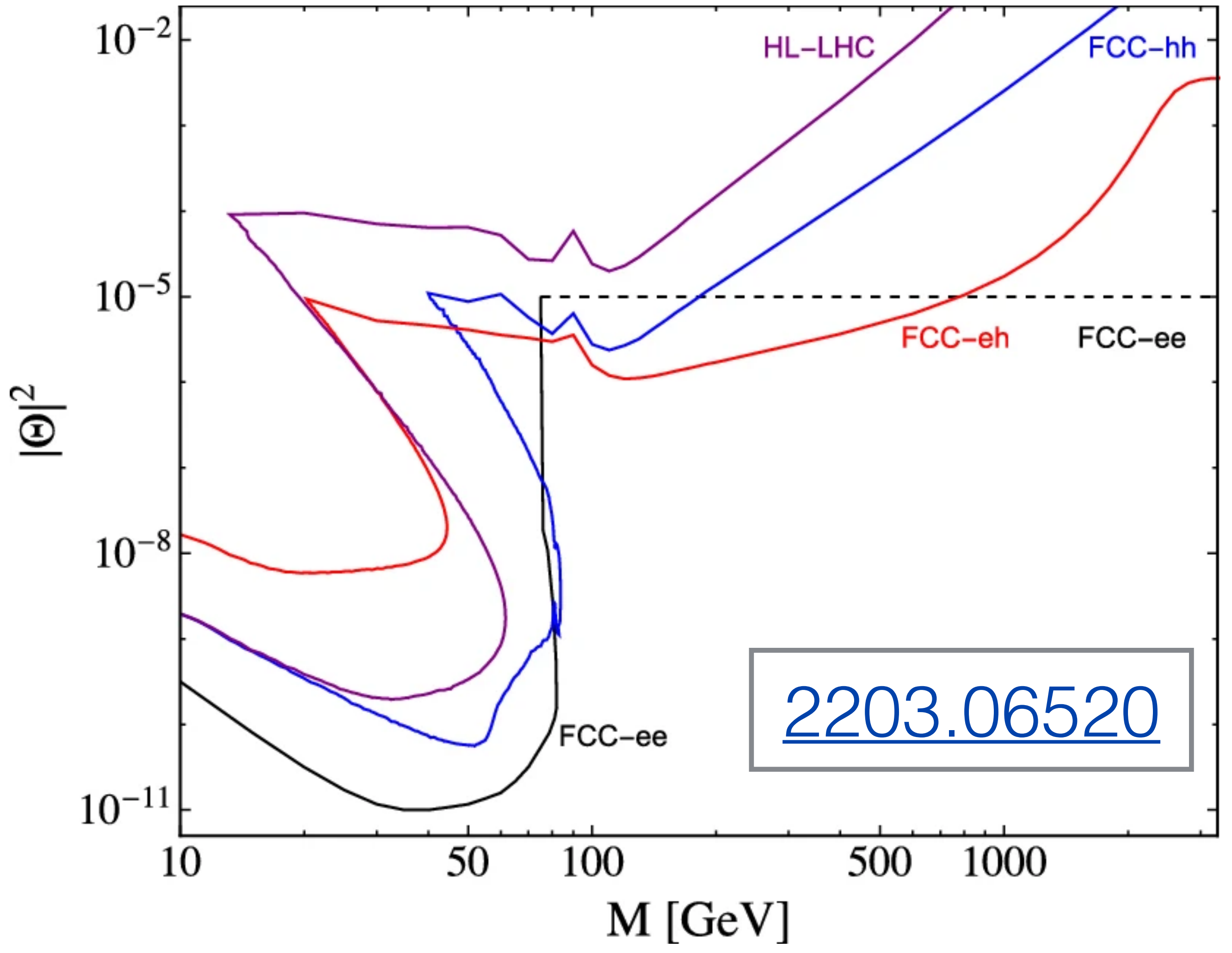
- **Lepton flavor violating** searches
  - Led by RPF, but high energy can contribute



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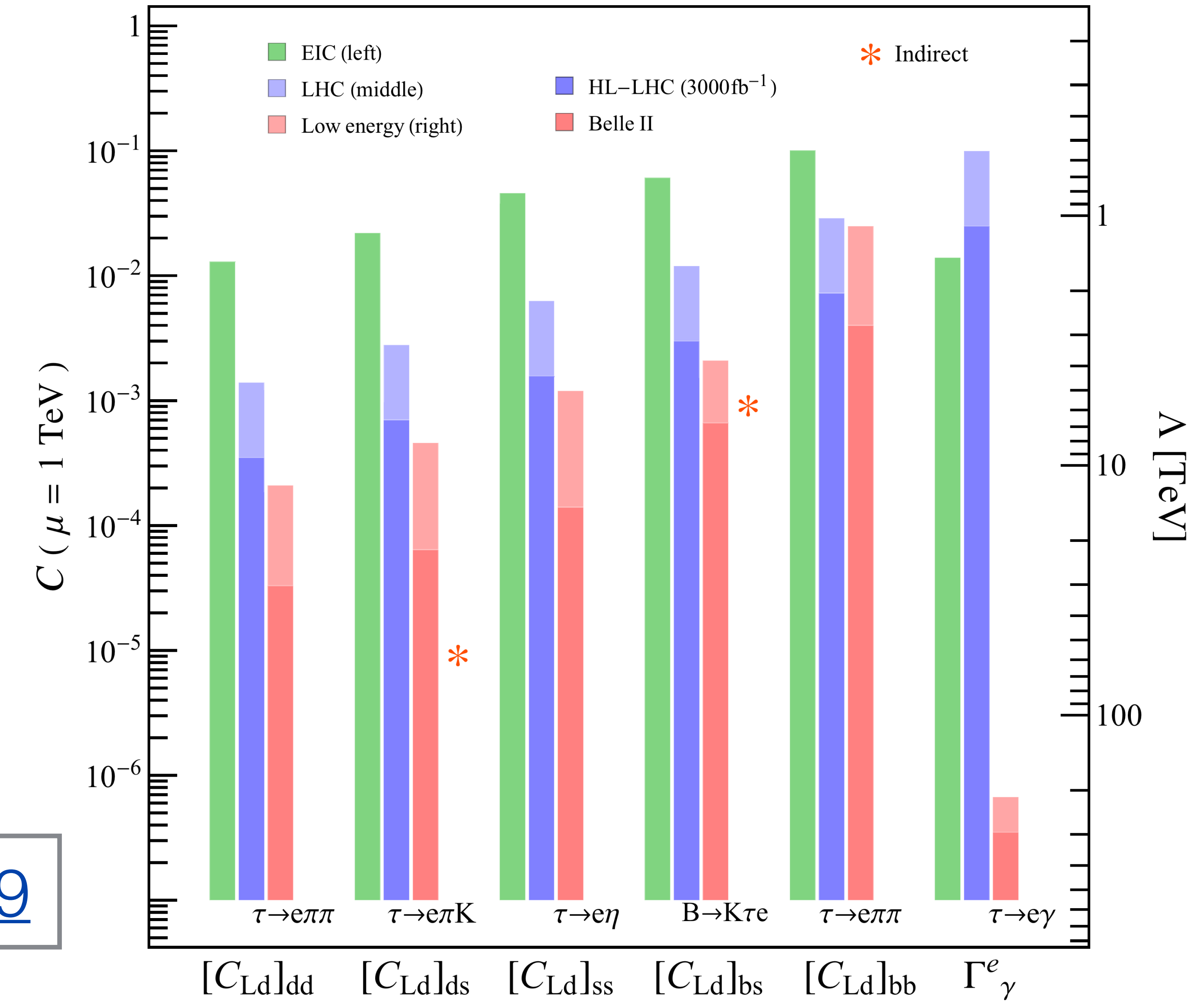

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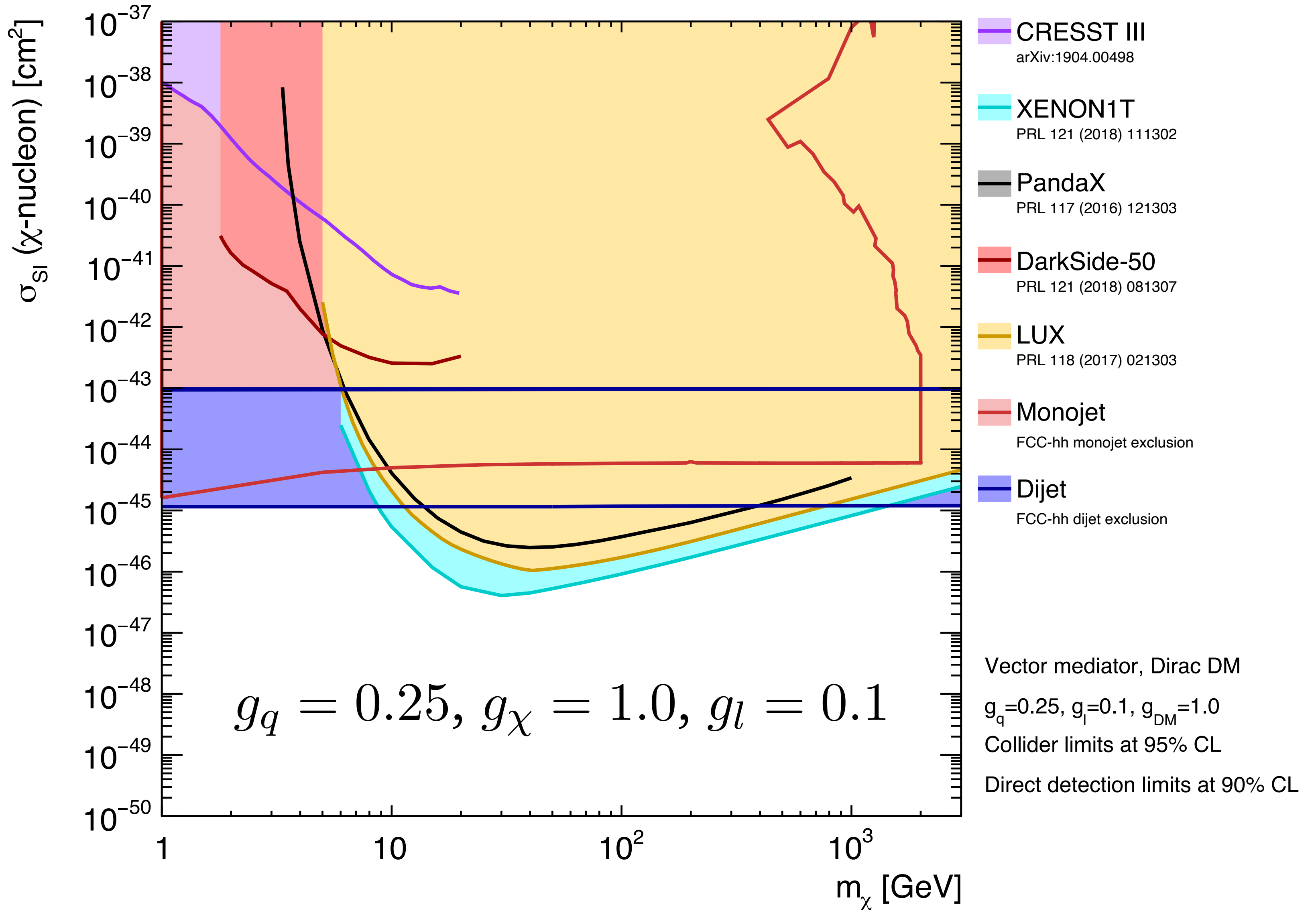
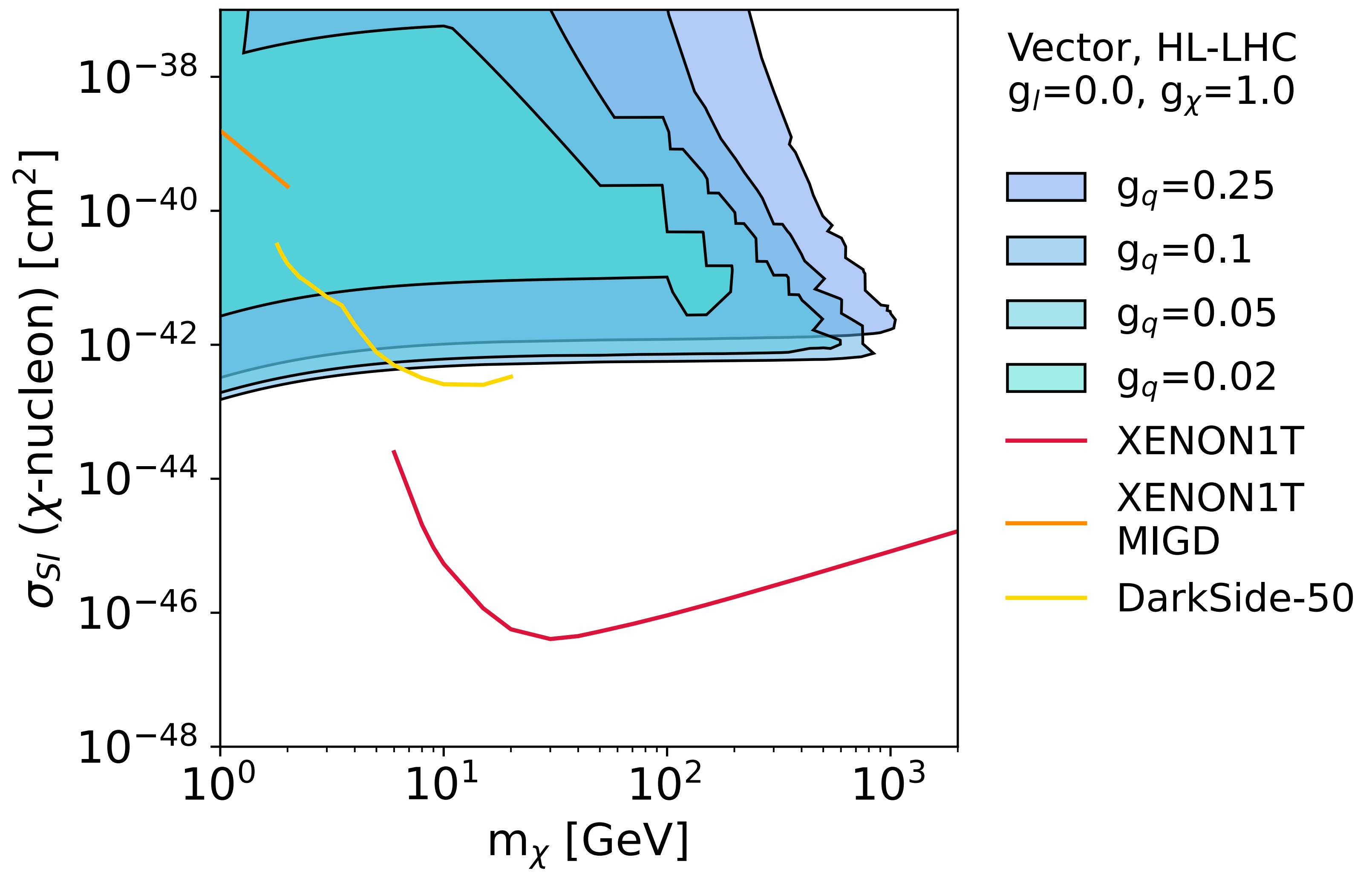
EF BSM report in preparation

- A future **hadron collider** has the **best reach for simple mediator models**
  - **If they have quark couplings**
  - Collider bounds are strongest in cases of TeV-scale mediator masses





Dark matter: the WIMP paradigm

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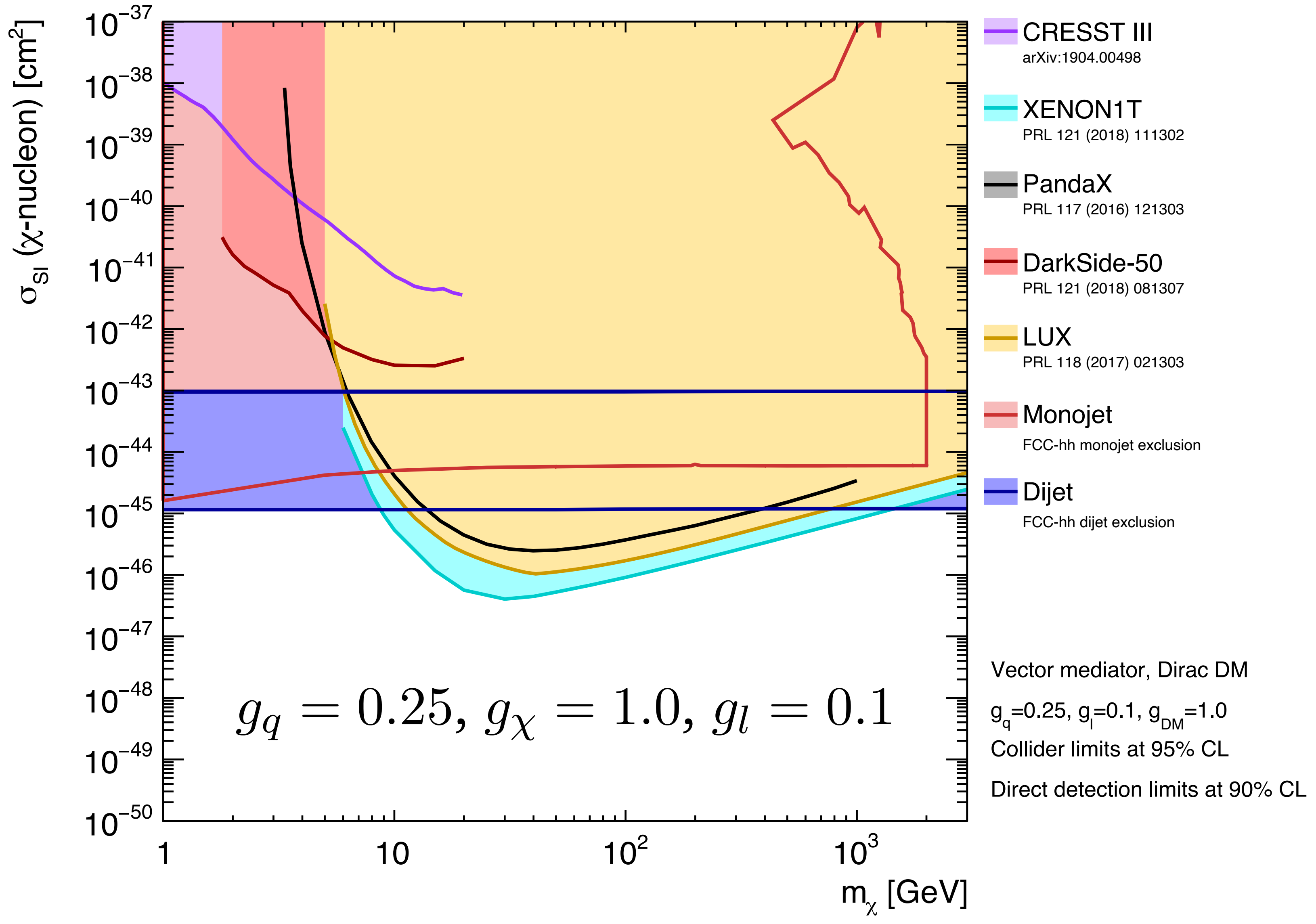

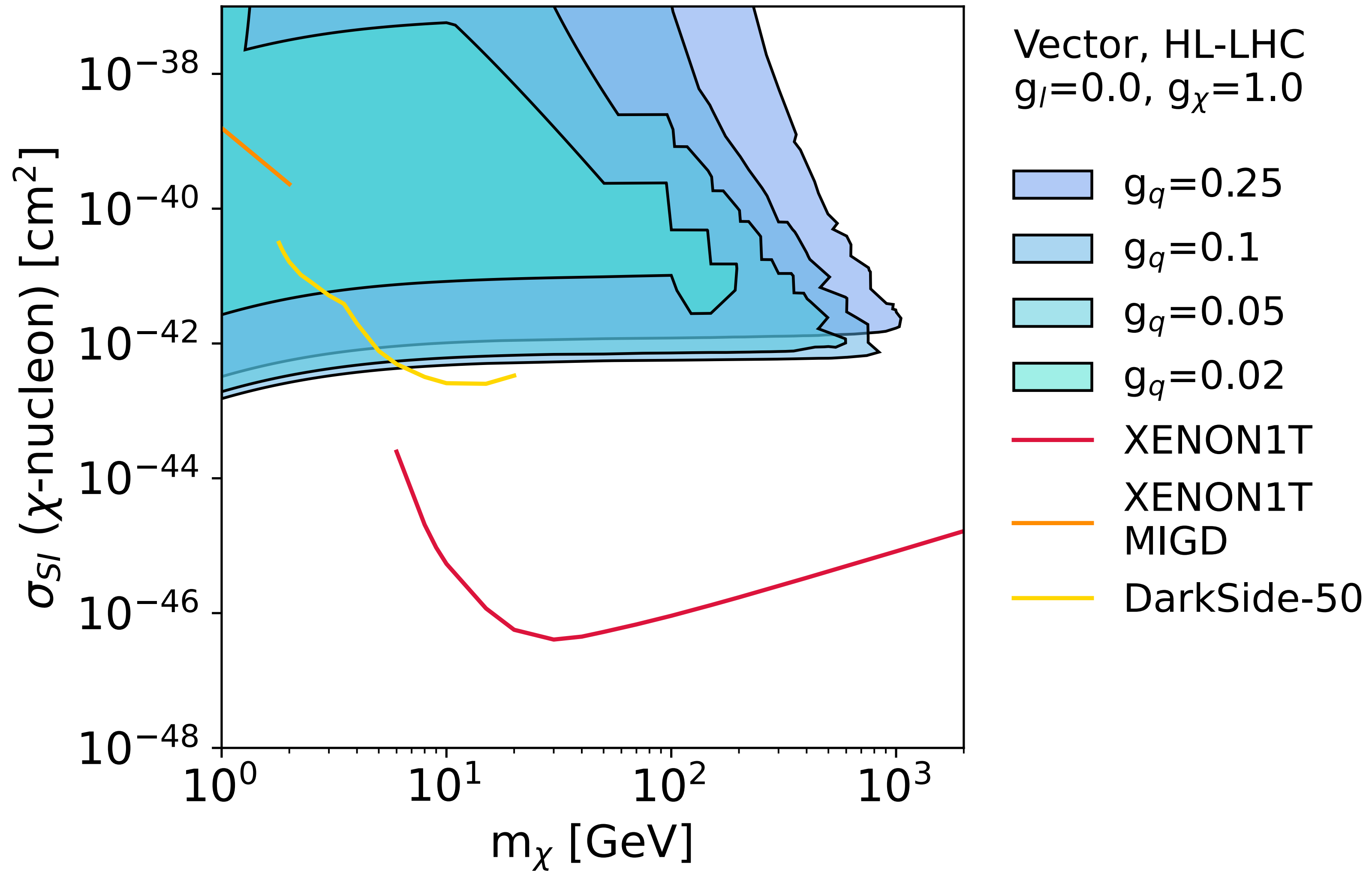

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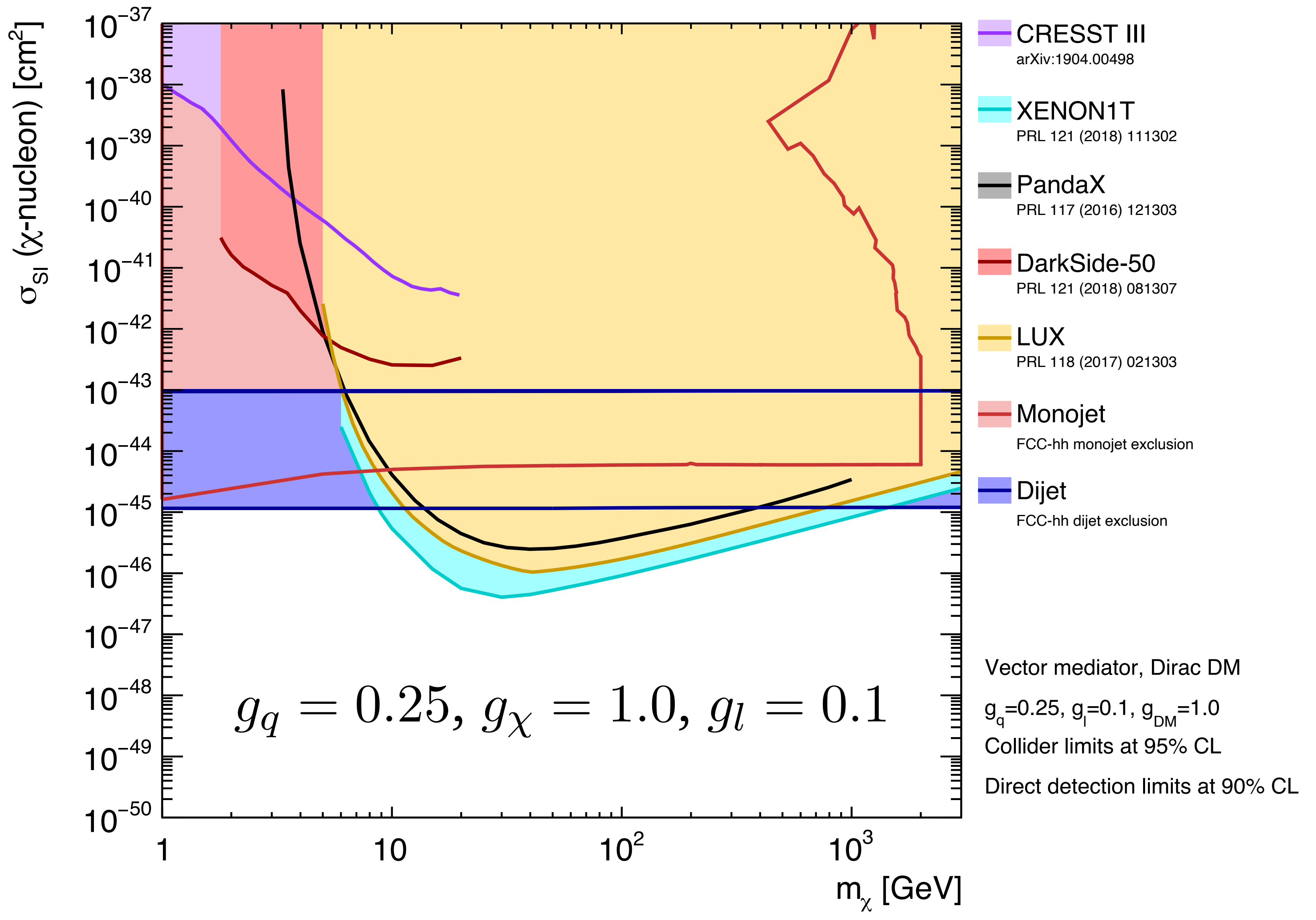
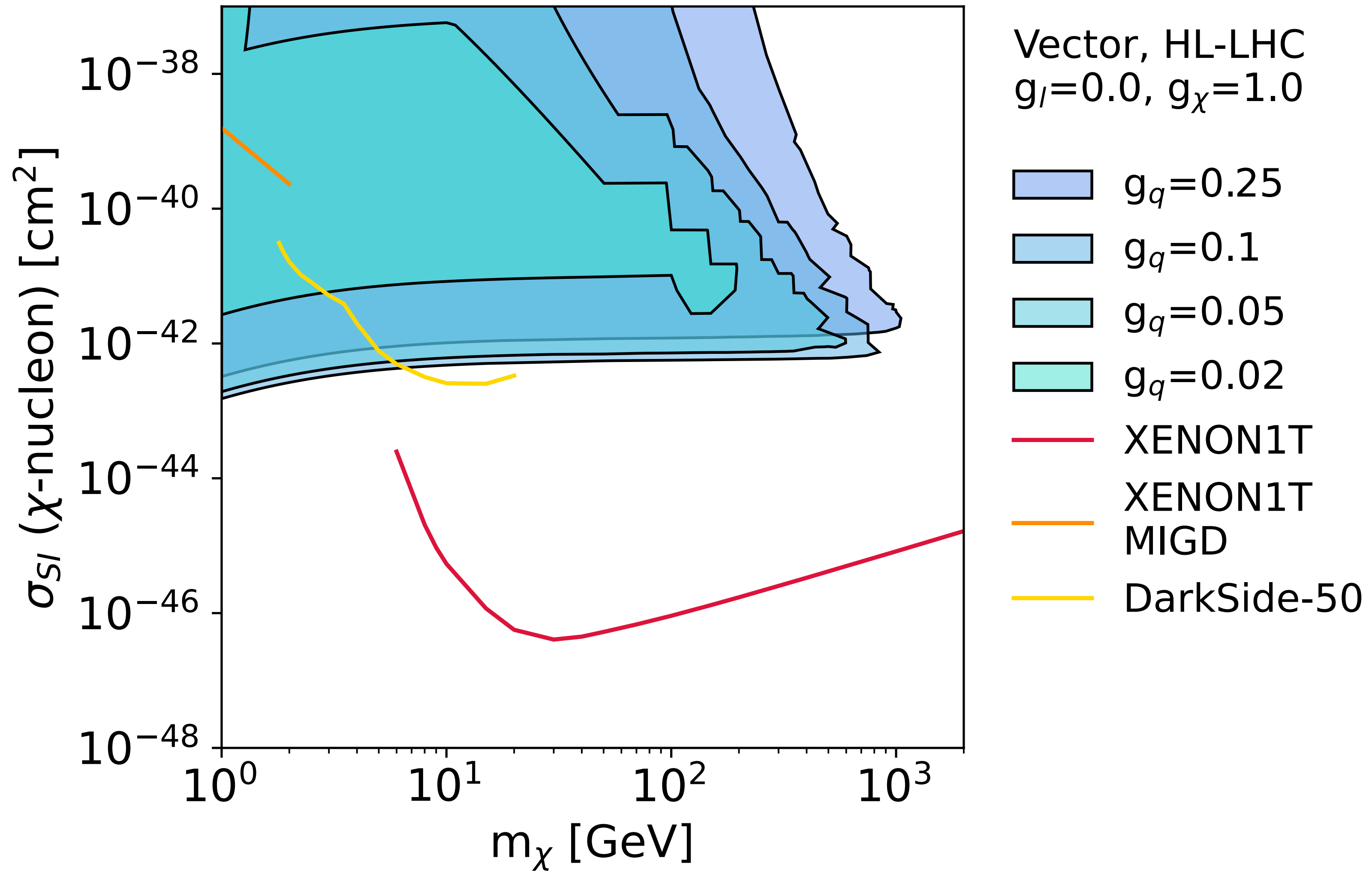
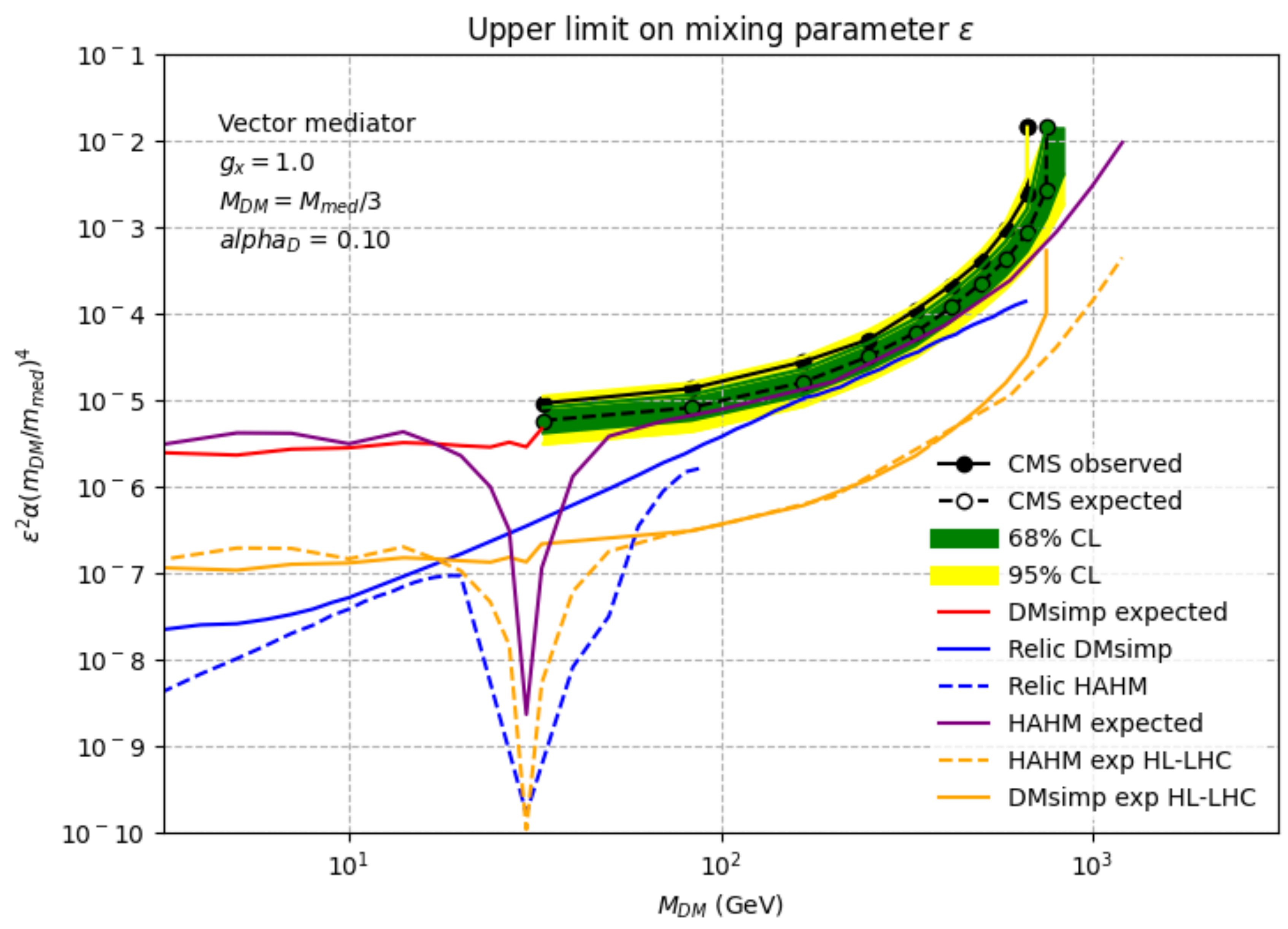
- **Electron colliders** play significant role in **models with lepton couplings** and **with mixing to Z/H/γ**
- **Complementary experiments are essential**
  - We'll need cosmological confirmation that what we discover is dark matter

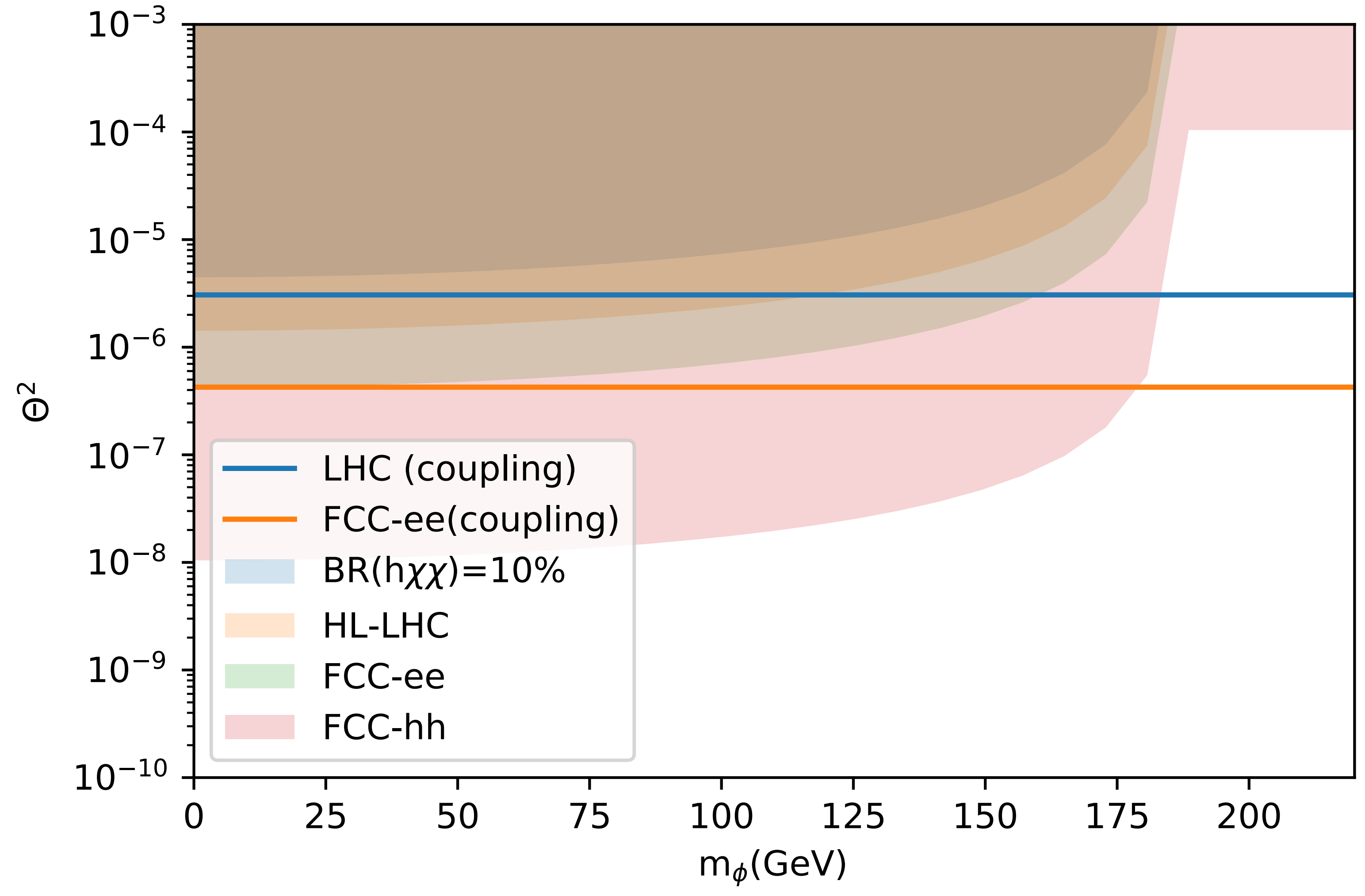




CMS EXO 20 004
WP in preparation

- **Many non-WIMP DM** models and **rich dark sectors accessible to colliders**
  - eg, vector (dark photon), scalar and axion portal
  - We shouldn't restrict/stop our searches even when the model is overproducing DM
    - Caveats to determine what coupling is needed to make up the entirety of the relic





Dark matter: beyond the WIMP

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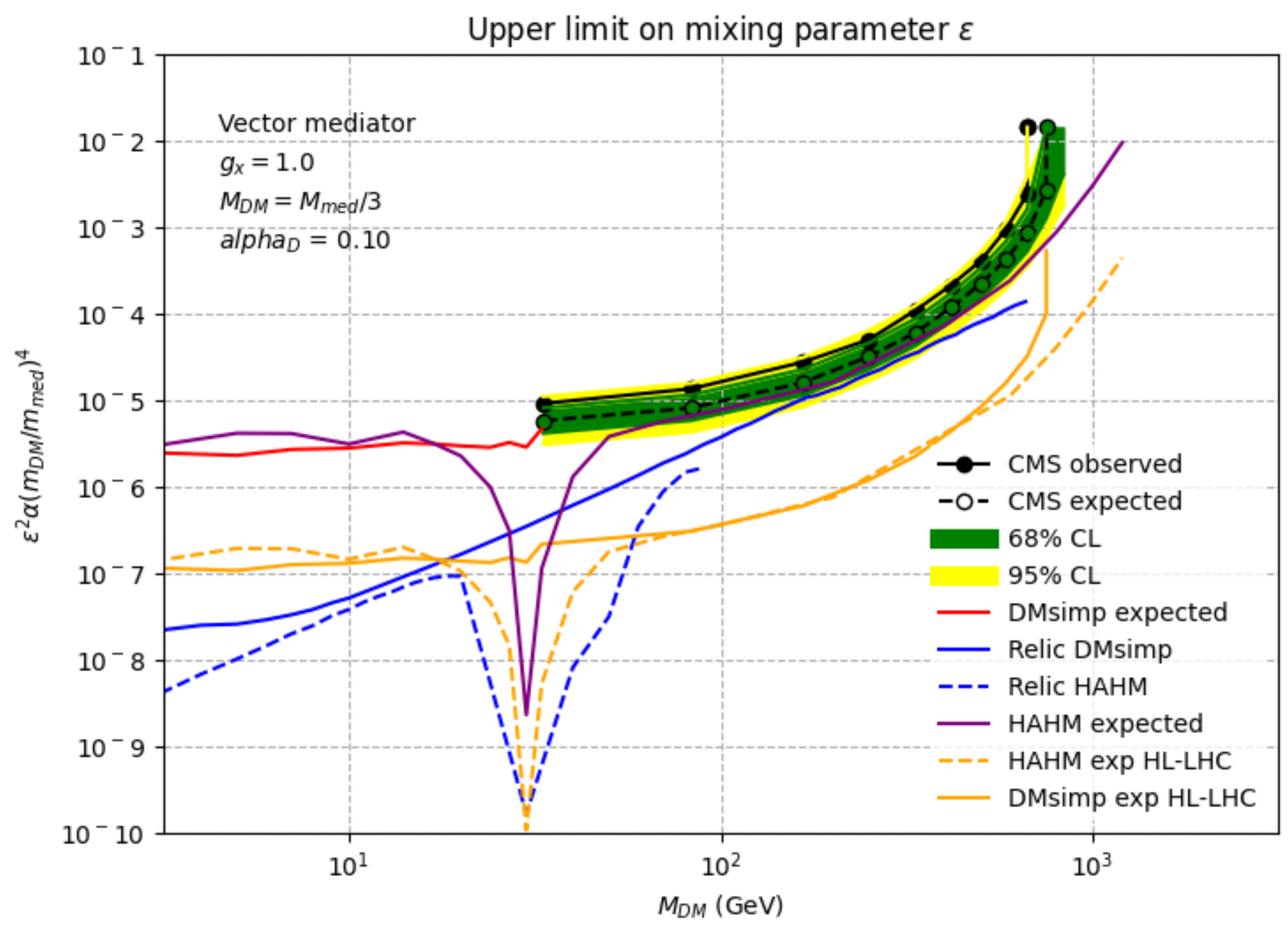
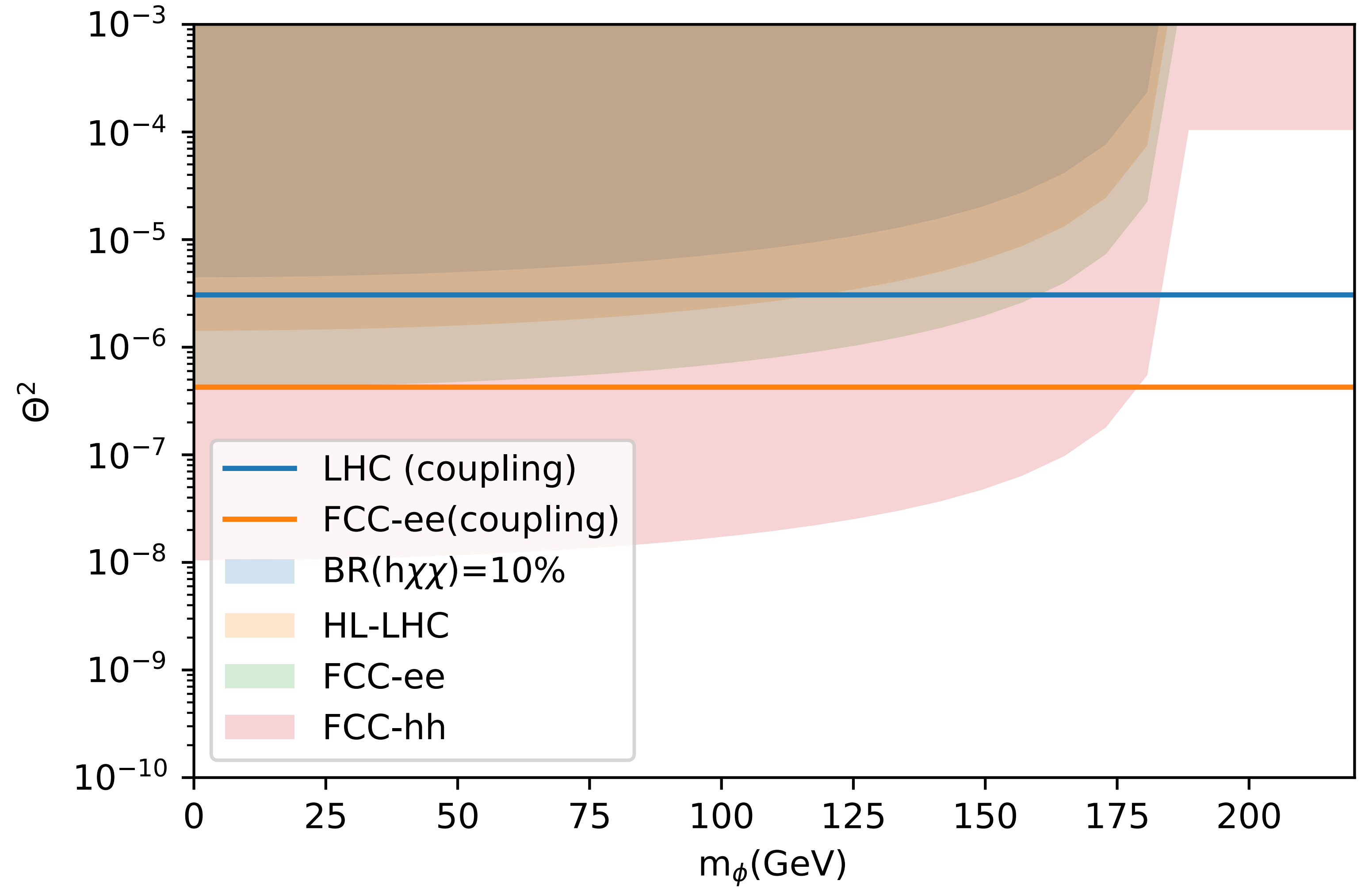
  - ➡ Can reinterpret RPF benchmarks too





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- Results from **"generic WIMP" searches often apply to non-WIMP**
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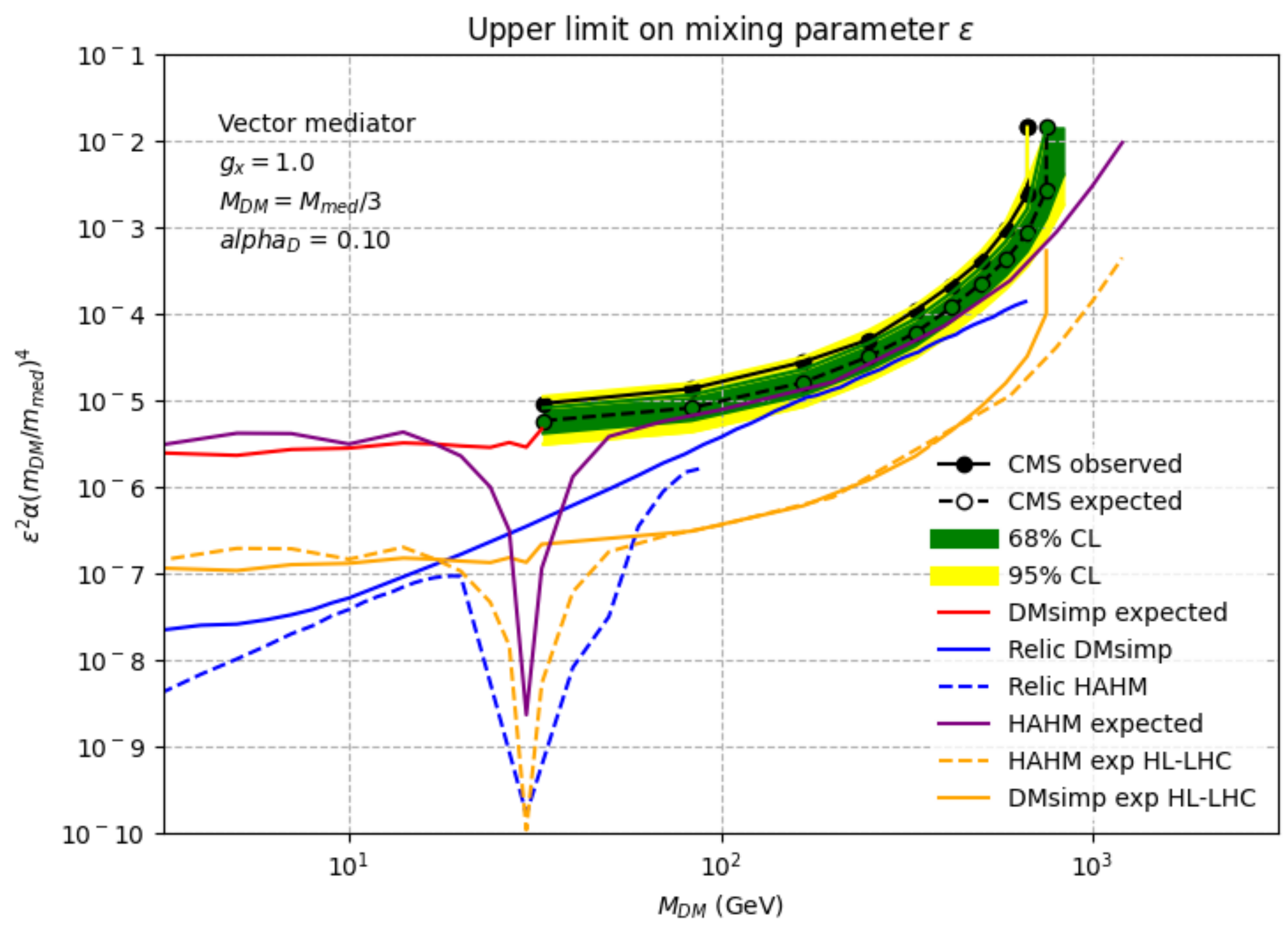
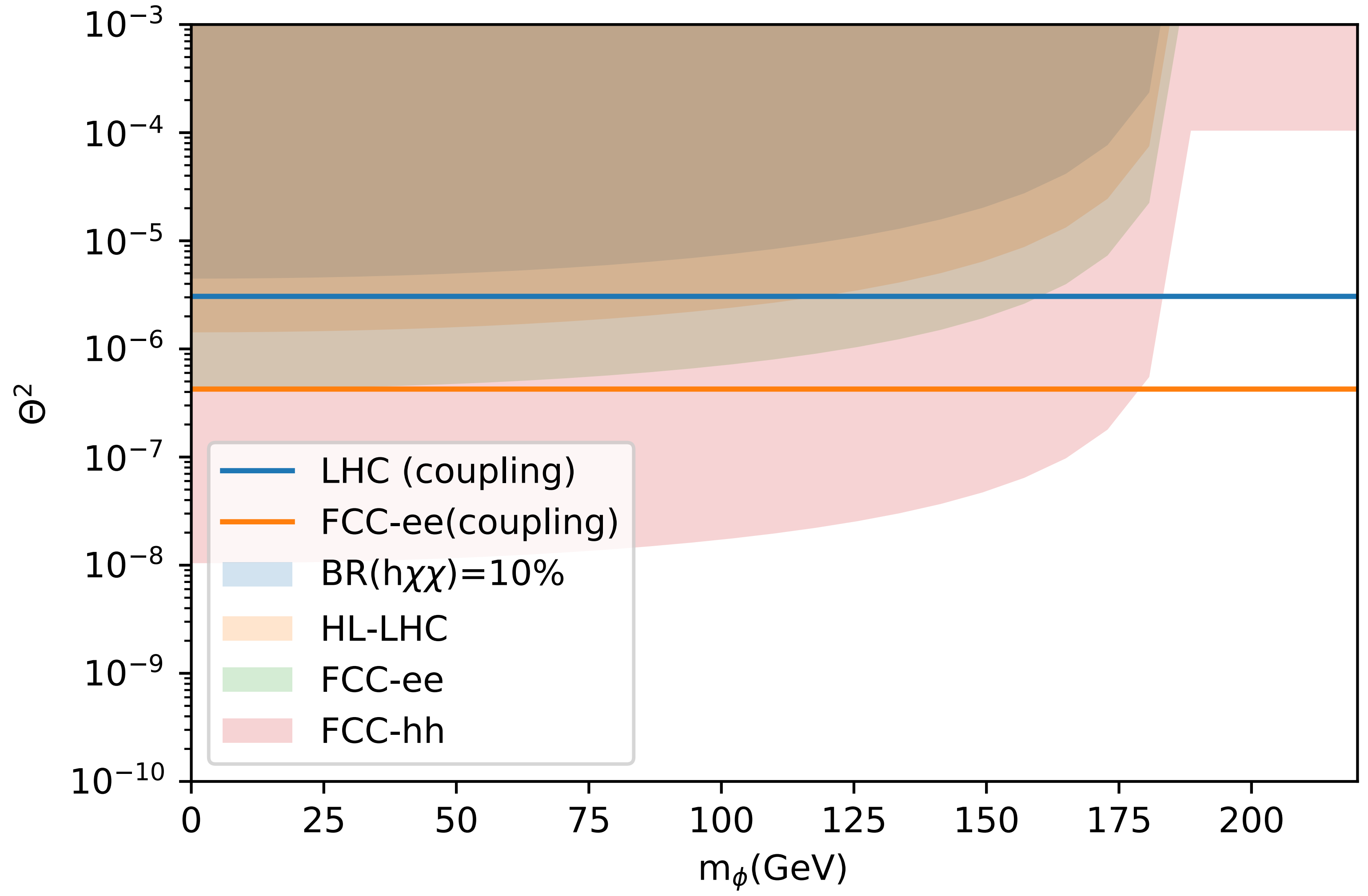
  - Can reinterpret RPF benchmarks too
- **Colliders** can **share infrastructure** for beyond-WIMP experimental facilities
  - eg, forward facilities





Dark matter complementarity in Snowmass

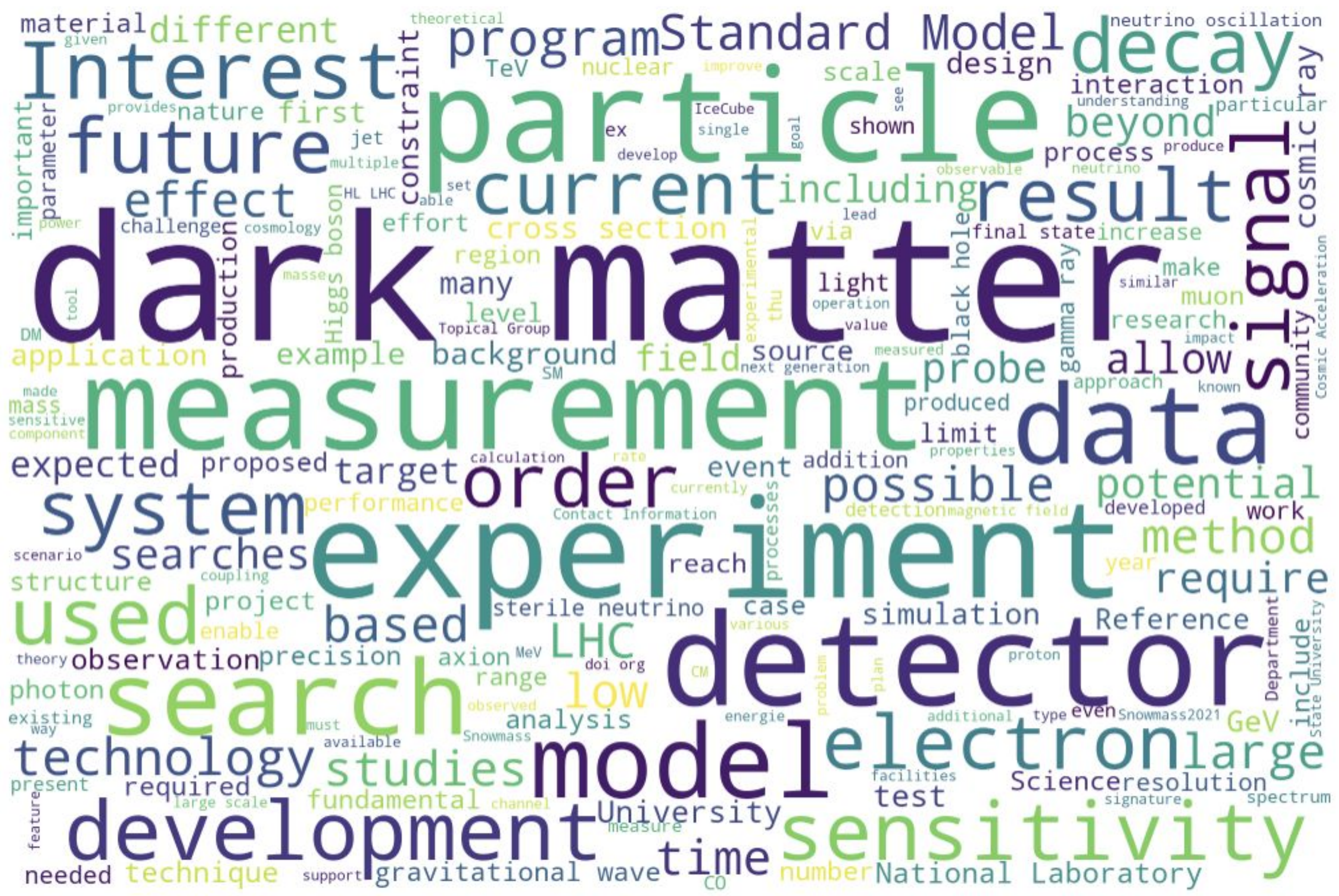
- **Dark matter** is a **central problem in Snowmass**
- **Next decade: exploratory phase** where new ideas can be implemented on short timescales operating **alongside longer-term projects on a diversity of project scales**
  - eg HL-LHC, FCC, Gen-3 direct detection, RPF accelerator experiments
- Ongoing Snowmass-wide, cross-frontier effort to **highlight dark matter complementarity**
  - This work builds from and contextualizes the work ongoing towards the white papers in the individual TGs and Frontiers
- **Cross-frontier whitepaper** expected in the near future, including key messages **from EF, CF, NF and RPF**, will be finalized in Seattle

https://gordonwatts.github.io/snowmass-loi-words

Word Clouds

Word clouds are made by looking at the word frequency in the LOI's. The more frequent the word, the larger the font-size in the word cloud.

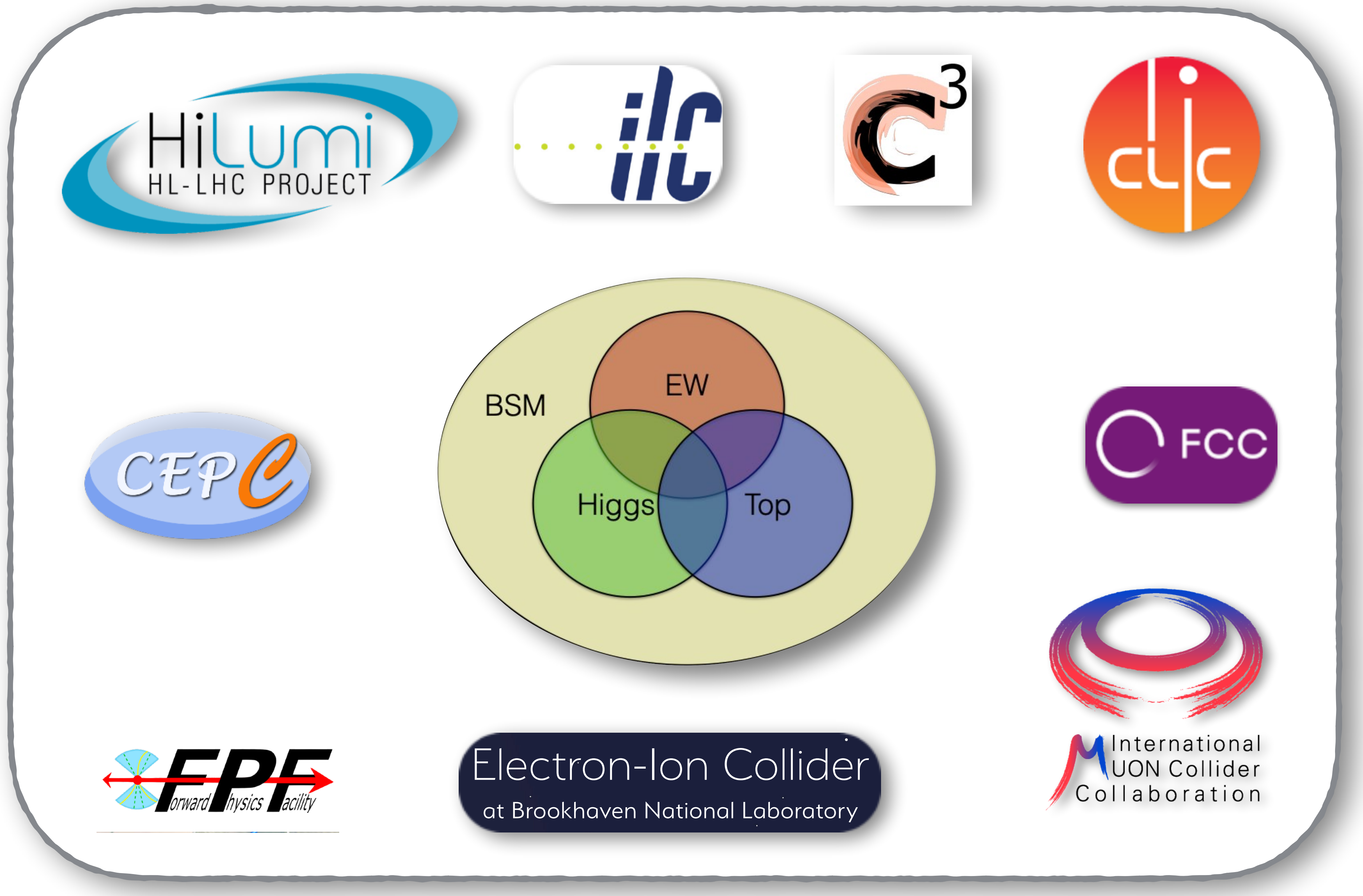
All LOI's



Credit C. Doglioni

Summary

- **Higgs boson most exciting** discovery/ confirmation in this century
  - ➡ Traditionally, discovery of particles followed by collider to study particles
  - ➡ The Higgs boson will be key in selecting next collider
- Proposals for **linear** and **circular** e^+e^- colliders would have **unprecedented reach** at precision physics at the **EW scale**
  - ➡ Hadron or muon colliders key for several precision measurements like HH



- Next years will **improve** our **understanding of QCD** significantly
  - ➡ EIC only new large-scale accelerator facility planned for construction in US *soon*
- **Comprehensive program** of **BSM** physics [model (in)dependent and DM @ colliders]
  - ➡ Muon collider could be great option for searches for BSM physics

Backup

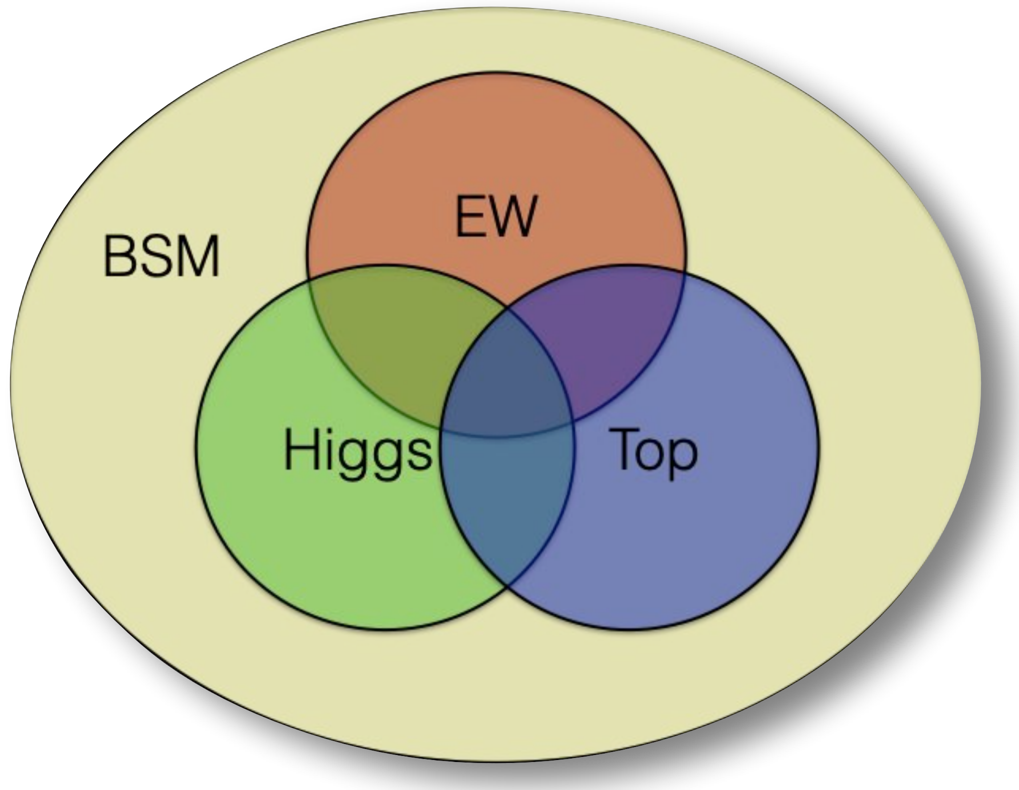
HiLumi HL-LHC PROJECT

ilc

C3

clic

CEPC



FCC

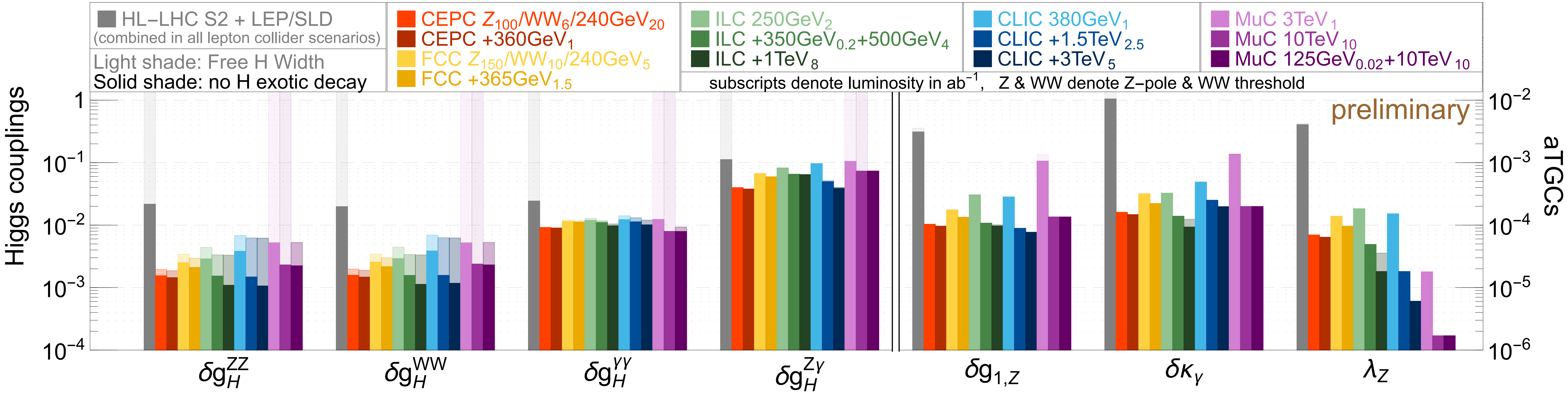
FPF Forward Physics Facility

Electron-Ion Collider at Brookhaven National Laboratory

International MUON Collider Collaboration

Some preliminary results

precision reach on effective couplings from SMEFT global fit



de Blas, Du, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, *in preparation*

- ➡ Z-pole and WW runs at circular e+e− colliders can help improve significantly the Higgs coupling precisions with respect to what can be obtained using only ZH runs;
- ➡ beam polarizations at linear e+e− colliders can play special roles that help lift degeneracies of different new physics effects, as a result of which similar Higgs coupling precisions can be achieved at linear e+e− with less integrated luminosity compared to circular e+e−.

Circular e^+e^- nominal running

FCC-ee

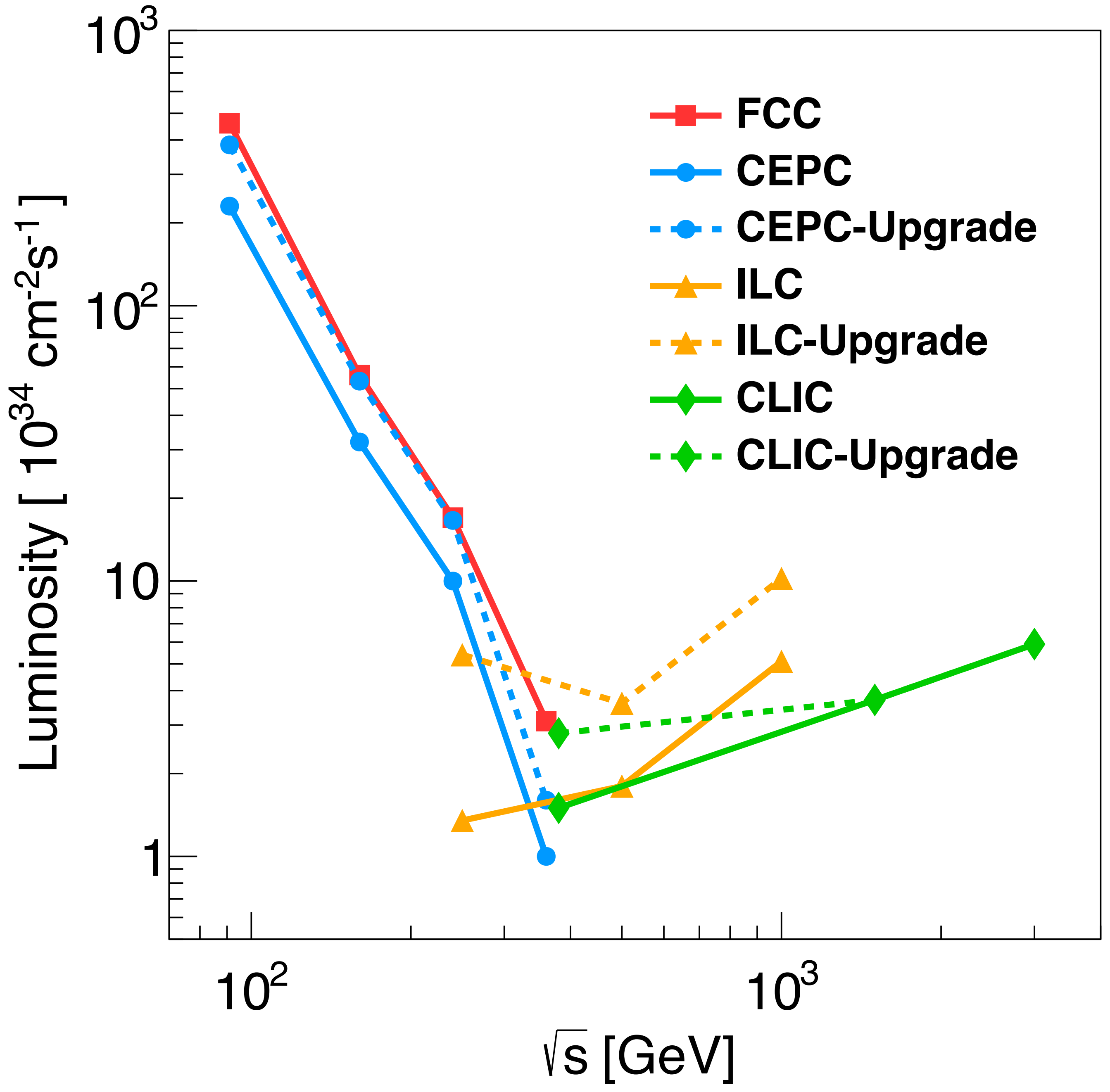
Working point	Z years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340–350	365	m_H
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\to$ H	10^6 $t\bar{t}$ +200k HZ +50k WW $\to$ H		(6000)

2203.06520

Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34} cm^{-2} s^{-1}$, per IP)	191.7	26.6	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6	20	1
Event yields	3×10^{12}	1×10^8	4×10^6	5×10^5

CEPC

2205.08553



CP violation in Higgs sector

$$f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{CP\,\text{odd}}}{\Gamma_{H\to X}^{CP\,\text{odd}} + \Gamma_{H\to X}^{CP\,\text{even}}}$$

2205.07715

TABLE I: List of expected precision (at 68% C.L.) of CP-sensitive measurements of the parameters f_{CP}^{HX} defined in Eq. (2). Numerical values are given where reliable estimates are provided, ✓ mark indicates that feasibility of such a measurement could be considered.

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	250	350	500	1,000	125	125	$\geq$ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000	250			
HZZ/HWW	$2\cdot10^{-4}$	$0.5\cdot10^{-4}$	$7\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	$\sim$1	–	–	–	–	–	–	–	$< 10^{-2}$
Hgg	0.20	0.06	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	–	–	0.29	0.08	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	0.01	0.01	0.02	0.06	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

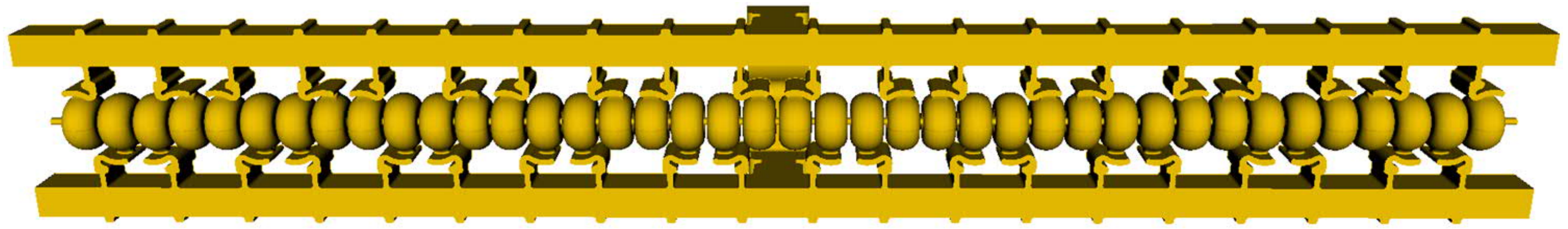
Cool Copper Collider (C^3)

The most important problem for operation of a normal-conducting cavity at high fields is electrical breakdown. Cavities optimized for efficiency, high accelerating gradient and low breakdown have small irises that prevent power flow at the fundamental frequency. Individual feeds to each cavity from a common RF manifold, all in the same copper block, solve this problem. Modern numerically controlled manufacturing techniques can build appropriate manifolds and individual cavity feeds in an extremely cost-effective way. We have also discovered that operation of these cavities at 80°K increases their material strength and conductivity, giving marked improvements in performance. These two innovations lead to the C^3 **concept, a new elevated baseline for normal-conducting electron accelerators**.

2110.15800

	Sub-Domain	%	%
Sources	Injectors	8	35
	Damping Rings	12	
	Beam Transport	15	
Main Linac	Cryomodule	10	33
	C-band Klystron	23	
BDS	Beam Delivery and Final Focus	8	13
	IR	5	
Support Infrastructure	Civil Engineer	5	19
	Common Facilities	11	
	Cryo-plant	3	
Total	3.7B$	100	100

Vacuum Space for Distributed Coupling Linac



Collider	NLC[28]	CLIC[29]	ILC[5]	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
σ_z [μm]	150	70	300	100	100
β_x [mm]	10	8.0	8.0	12	12
β_y [mm]	0.2	0.1	0.41	0.12	0.12
ϵ_x [nm-rad]	4000	900	500	900	900
ϵ_y [nm-rad]	110	20	35	20	20
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Beam Power [MW]	5.5	2.8	2.63	2	2.45
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Crab Angle	0.020/2	0.0165/2	0.014/2	0.014/2	0.014/2
Luminosity [x10^{34}]	0.6 (w/ IP dil.)	1.5 (max is 4)	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Shunt Impedance [MΩ/m]	98	95		300	300
Effective Shunt Impedance [MΩ/m]	50	39		300	300
Site Power [MW]	121	168	125	~150	~175
Length [km]	23.8	11.4	20.5 (31)	8	8
L* [m]	2	6	4.1	4.3	4.3