Muon Collider
&
LLPs

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05/28/2021

Why LLPs at Muon Colliders?

LLPs at future colliders -- and future ideas: (muon colliders)

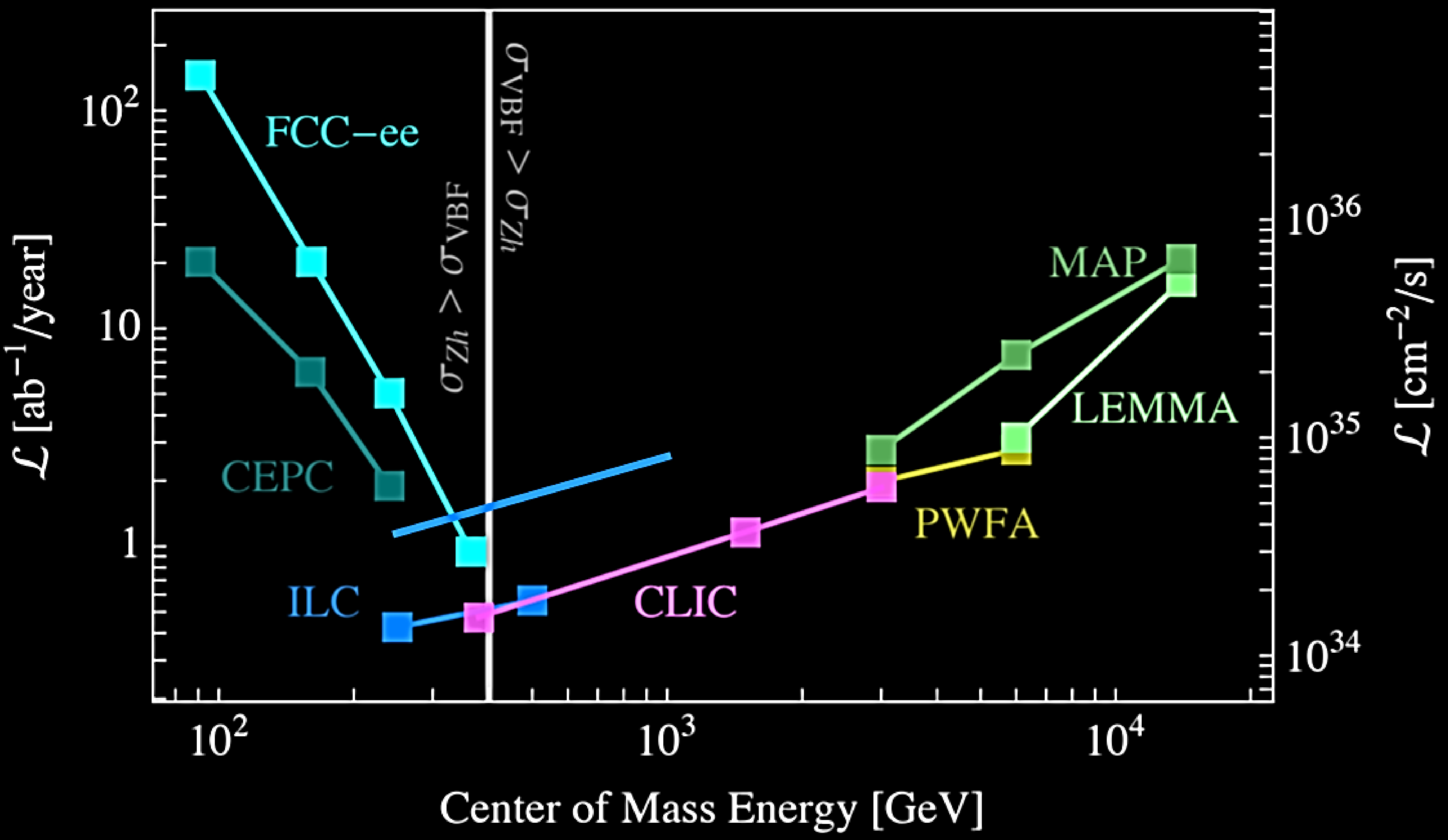
Conveners: Albert De Roeck (CERN), Carlos Vazquez Sierra (CERN), Sergo Jindariani

- 10:10 — **LLPs at a muon collider: Theory**
  Speaker: Zhen Liu (University of Minnesota)
- 10:25 — **Introduction to the muon collider**
  Speaker: Simone Pagan Griso (Lawrence Berkeley National Lab. (US))
- 10:40 — **LLPs at a muon collider: Experiment**
  Speaker: Federico Meloni (Deutsches Elektronen-Synchrotron (DE))

Why LLP? No need here.

Why Muon Collider? Quick answer.

The power of cleanness ⊕ power of high energy!



NO Brainer

*no (and no need for) a no-lose theorem (narrowly defined as discovering a new particle).

Around O(10) muon collider themed online meetings of various sizes (up to 350 participants) this year.

Current Status: US Snowmass & International

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

EF-TF collaboration!

Many LOIs

Recent theory developments

- **European Strategy Update & Overviews:** [Delahaye et al. 1901.06150; Franceschini & Greco 2104.05770]

The Muon Smasher's Guide

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Dario Buttazzo[3], Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[4], Nathaniel Craig[1], Majid Ekhterachian[5], JiJi Fan[6], Matthew Forslund[7], Isabel Garcia Garcia[8], Samuel Homiller[9], Seth Koren[10], Giacomo Koszegi[1], Zhen Liu[5,11], Qianshu Lu[9], Kun-Feng Lyu[12], Alberto Mariotti[13], Amara McCune[1], Patrick Meade[7], Isobel Ojalvo[14], Umut Oktem[1], Diego Redigolo[15,16], Matthew Reece[9], Filippo Sala[17], Raman Sundrum[5], Dave Sutherland[18], Andrea Tesi[16,19] Timothy Trott[1], Chris Tully[14], Lian-Tao Wang[10], and Menghang Wang[1]

2101.04956; Huang, Jana, Queiroz, Rodejohann 2103.01617; Asadi, Capdevilla, Cesarotti, Homiller 2104.05720]

International muon collider collaboration: https://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=MUONCOLLIDERDETECTOR-PHYSICS

Muon Collider Forum: SNOWMASS-MUON-COLLIDER-FORUM@FNAL.GOV at https://snowmass21.org/energy/start#communications.

A four-session muon collider symposium is organized in the recent APS April meeting: https://indico.fnal.gov/event/48798/

See Intro by Simone Pagan Griso

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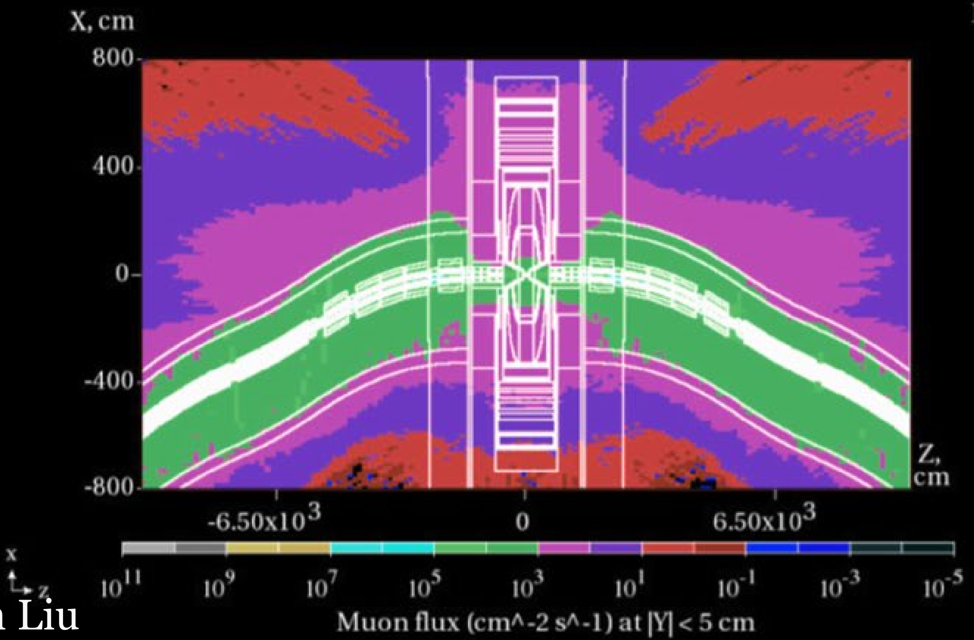
How to think about ~~Why~~ LLPs at Muon Colliders?

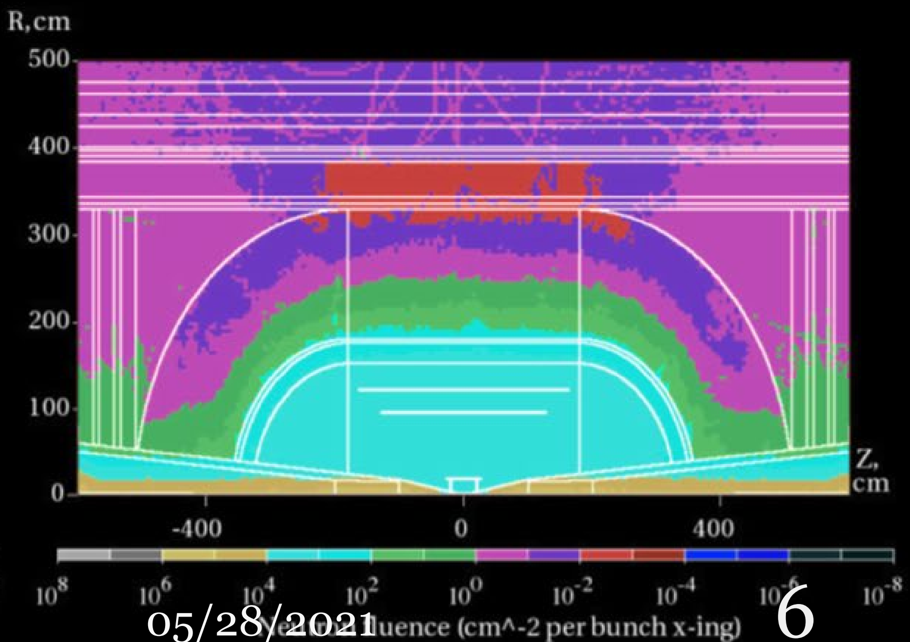
Signal & Background

- Background: a generically clean environment, QCD does not dominate.
  - Beam-induced background

See talk by Simone Pagan Griso
See talk by Federico Meloni

- Signal
  - Let's revisit our program





A cook book

- 9^{th} LLP workshop @ virtually, May. 2021
- 8^{th} LLP workshop @ virtually, Nov. 2020
- 7^{th} LLP workshop @ virtually, May. 2020
- Ghent 6^{th} L
- CERN 5^{th} L
- Online LLP
- Amsterdam
- LBNL LLP
- CERN 3^{rd} I
- Trieste 2^{nd}
- CERN 1^{st} Ll
- Umass Aml

… …

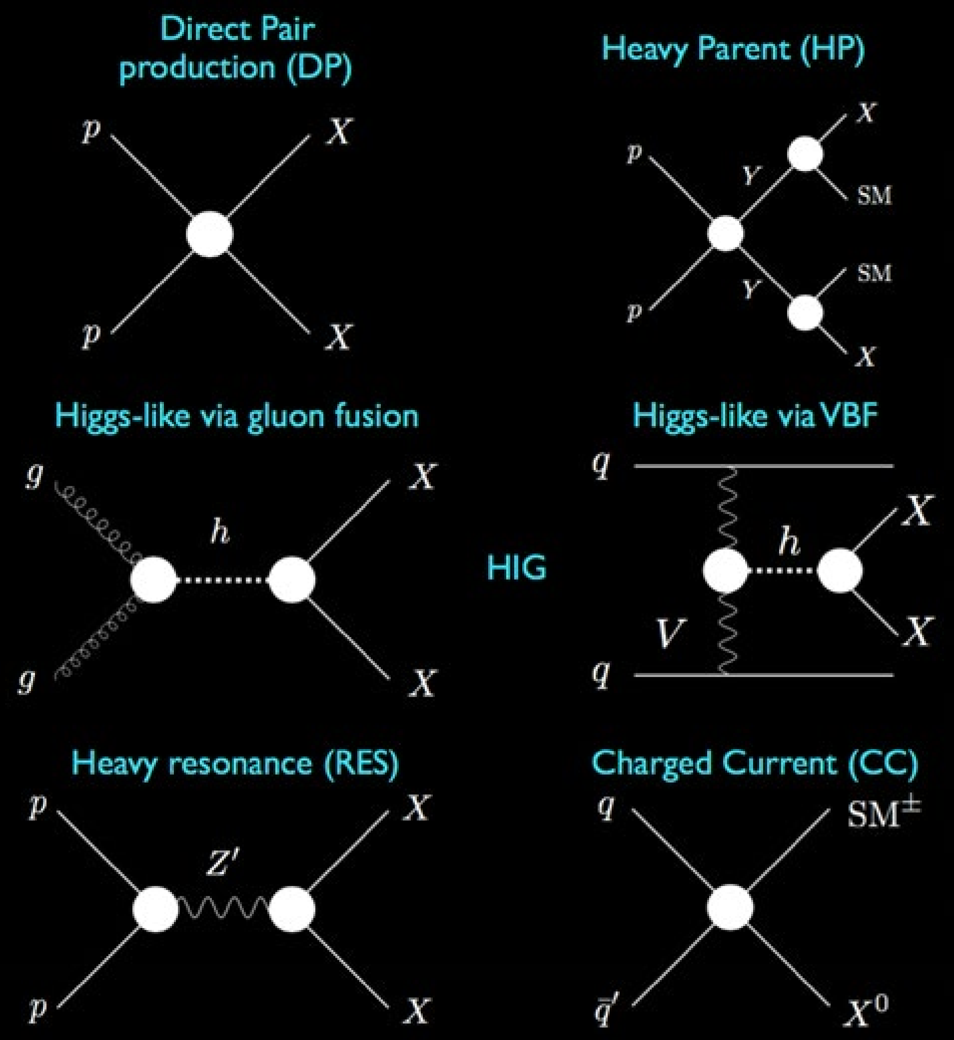
Searching for long-lived particles beyond the Standard Model
at the Large Hadron Collider 1903.04497

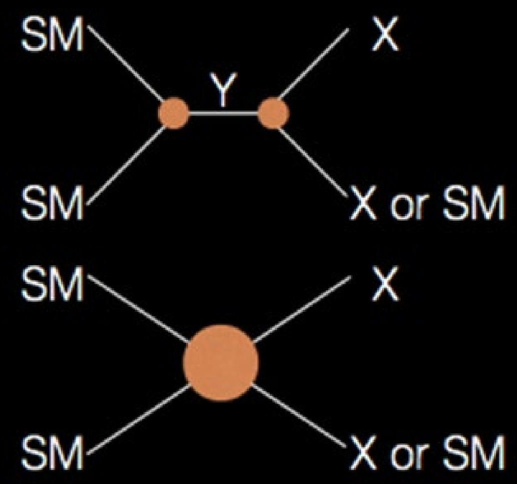
Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h \to X + \text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

Beacham[(2)] (Document
yang Cheng[(4)]
(Simplified Models,
ai[(8)] (Reinterpretations),
perimental Coverage),
lre Lessa[(13)] (Reinterpretations)
hlhase[(15)] (Backgrounds),
perimental Coverage),
cument Editor,
), Jose Zurita[(22,23)]

LLP community report 1903.04497
Also seen in Review by Lee, Ohm, Soffer, Yu 1810.12602

Classification: Production





- Factorize production and decay;
- Production affects kinematics of LLP and trigger consideration (except for LLP triggers, which are rare currently);
- Decay affects search strategy in picking up the LLPs, convoluting with lab frame geometries;

Another class of signals

Singly produced LLPs:

- HNL
- ALP
- Dark Photon
- Also, dark shower shall be very visible. See program yesterday.

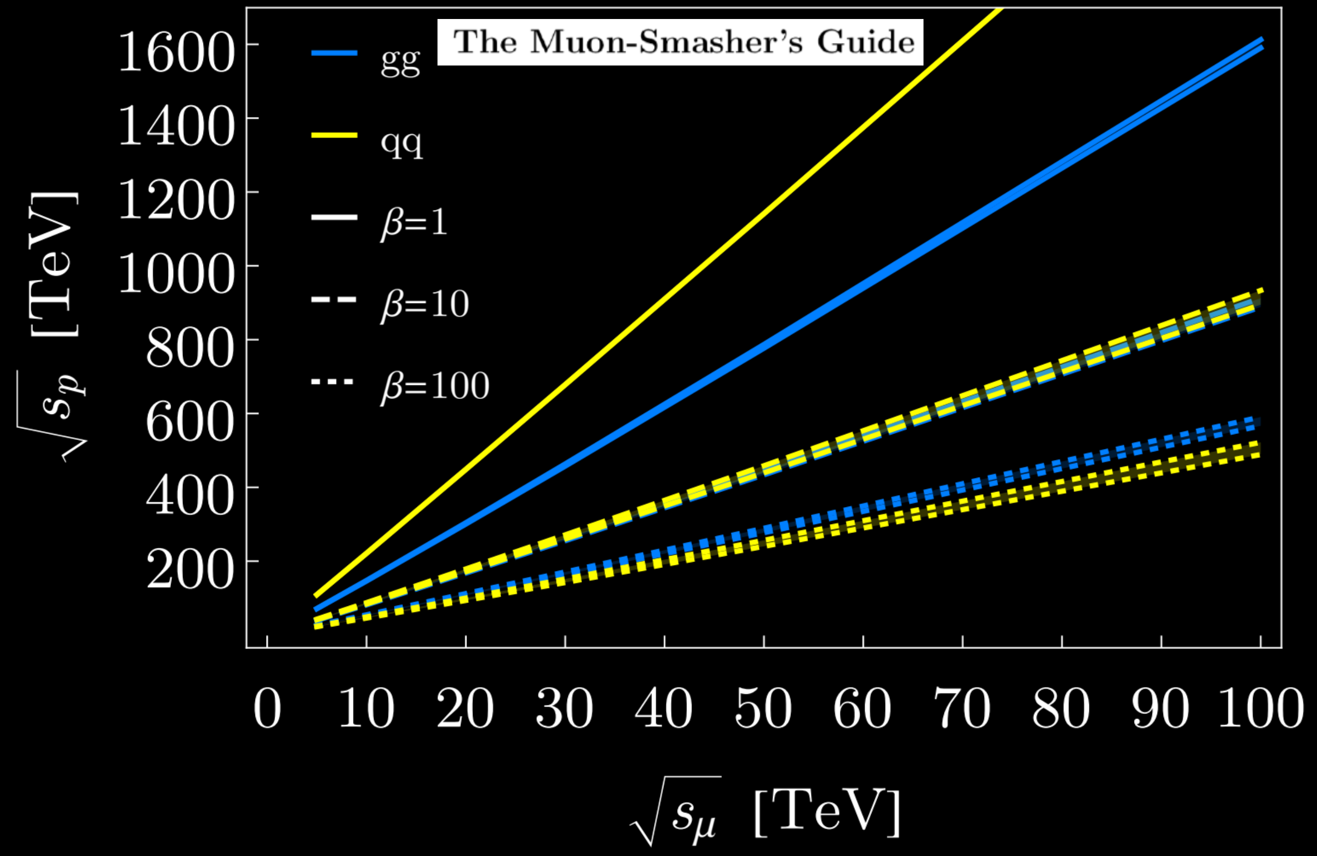
See theory talk by Maxim Pospelov

Long Lifetime = Low Production Rate

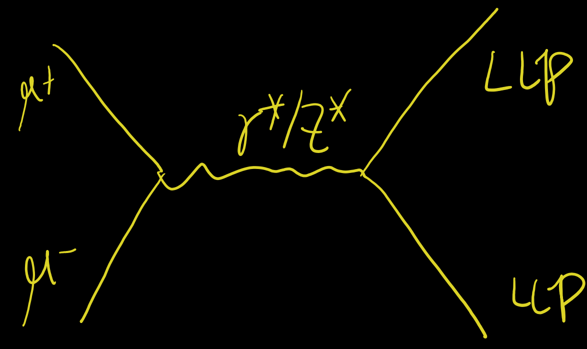
Hook, Kumar, ZL, Sundrum, 1911.12364

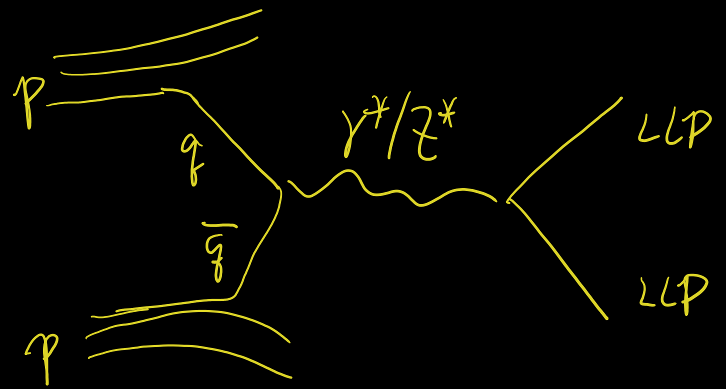
Clean environment (and technology advancements) may allow for triggerless data taking?
It will overcome one of the painful point of current searches.
Particularly critical for this class of rate limited processes.

A truly High Energy Machine



$\beta \equiv \sigma_{pp}/\sigma_{\mu\mu}$





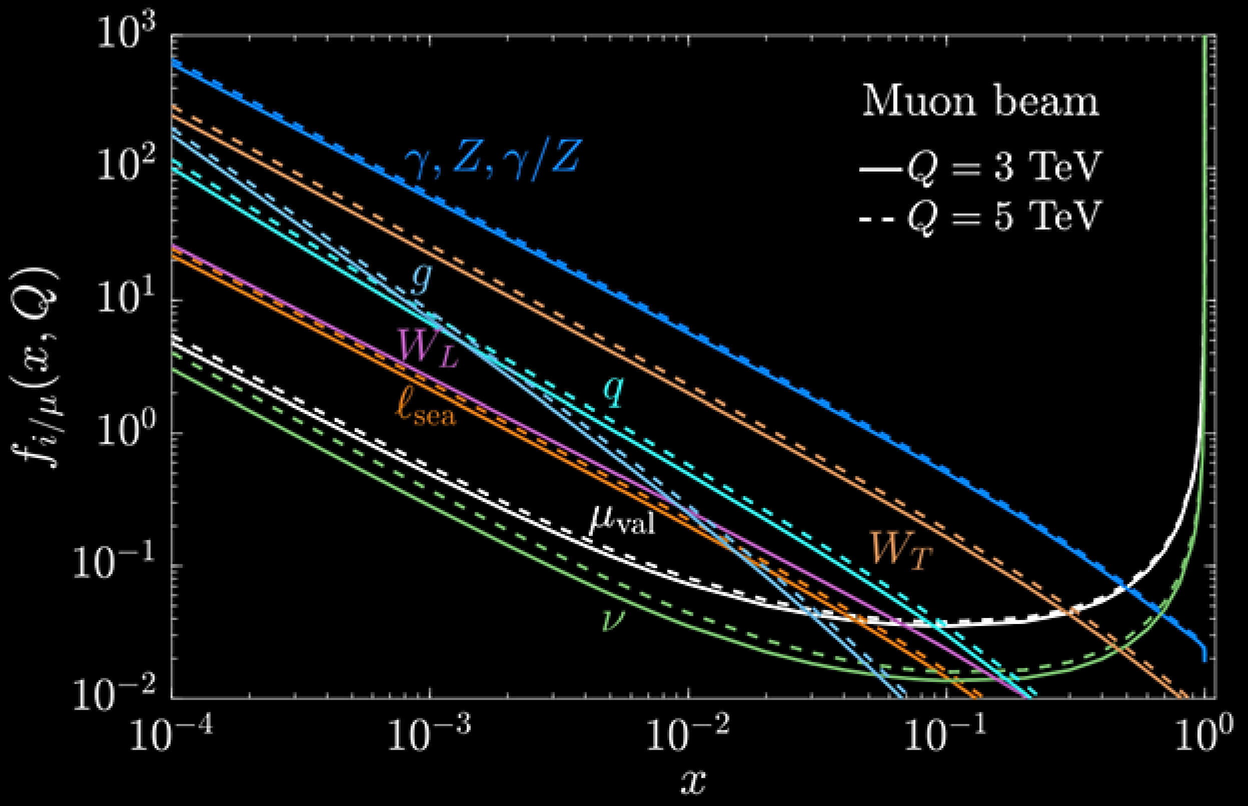
10+ TeV MuC outperforms 100 TeV collider in almost every aspect

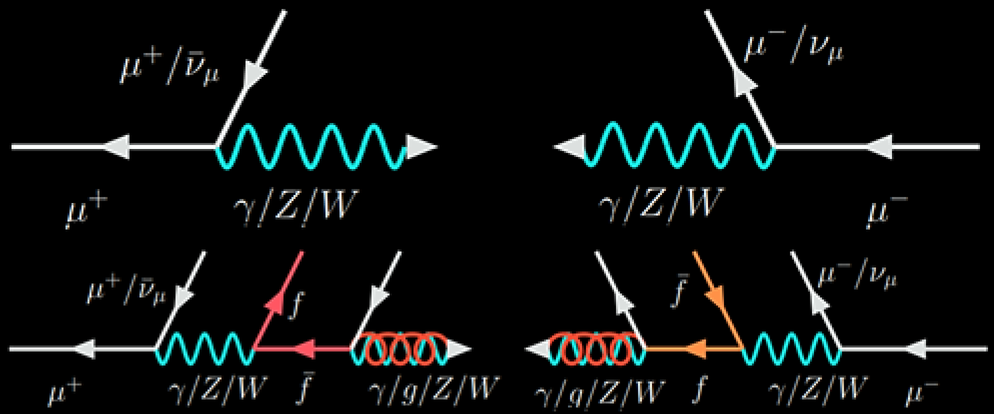
(except for dijet resonances; particles only color charged, no EW charges)

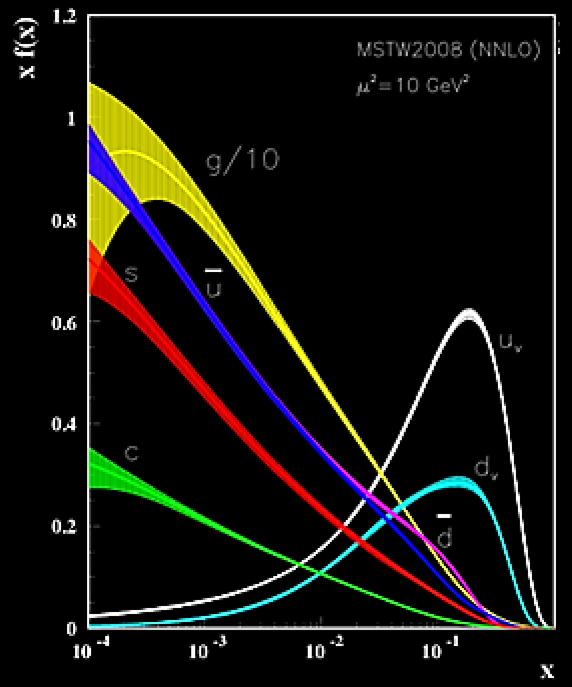
For electroweak states, already winning if MuC have 3+ TeV energy

Muon has (pseudo-) structure

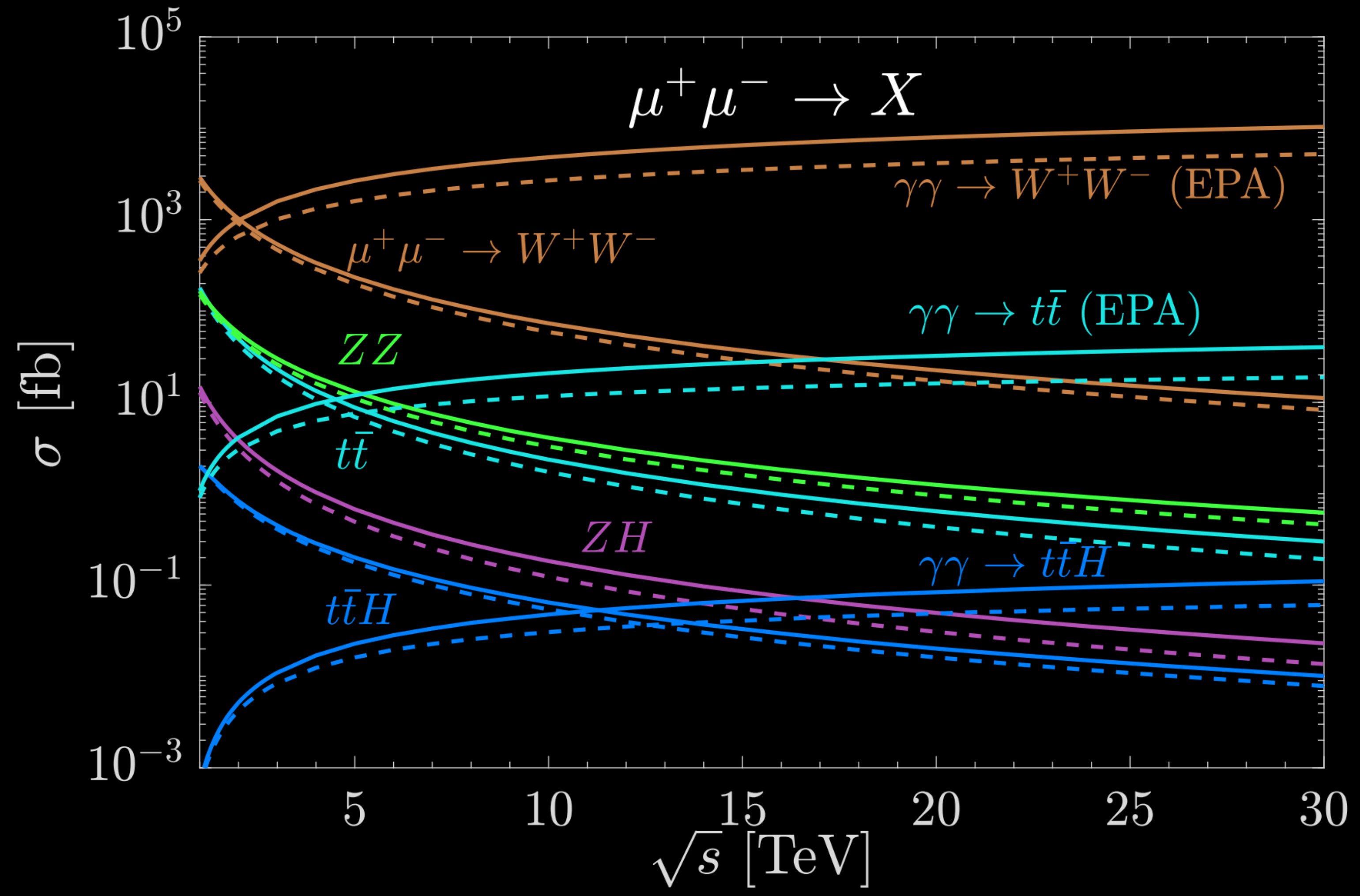
When colliding high energy leptons, we are colliding a bunch of electroweak states.





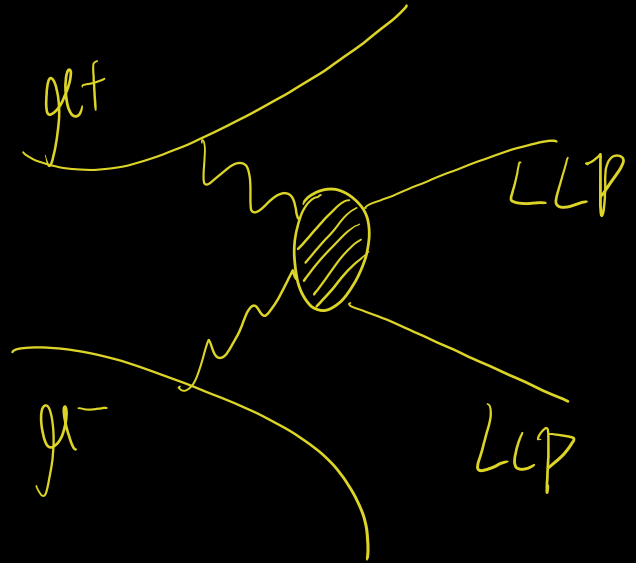


MuC is also a Vector Boson Machine



Han, Ma, Xie, 2007.14300

For light (<)(EW-charged) LLPs: VBF dominants the production. In particular, there is a logarithmic enhancement and longitudinal enhancement.



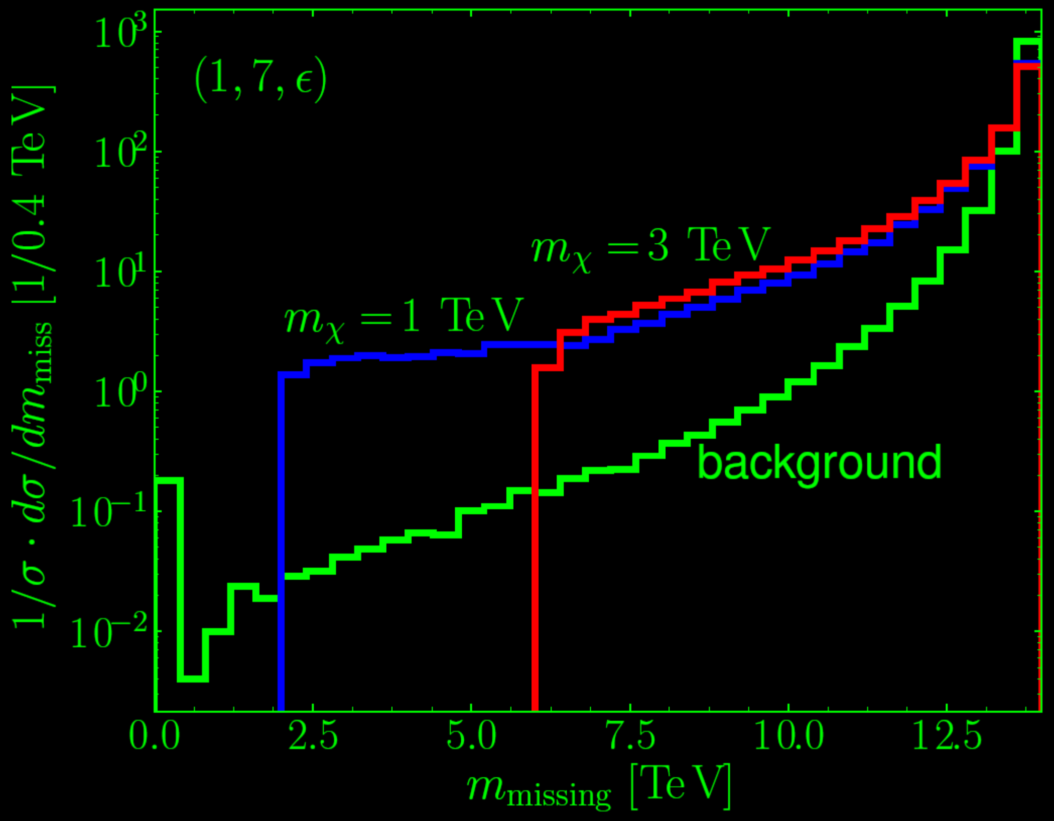
Han, ZL, Wang, Wang, 2009.11287

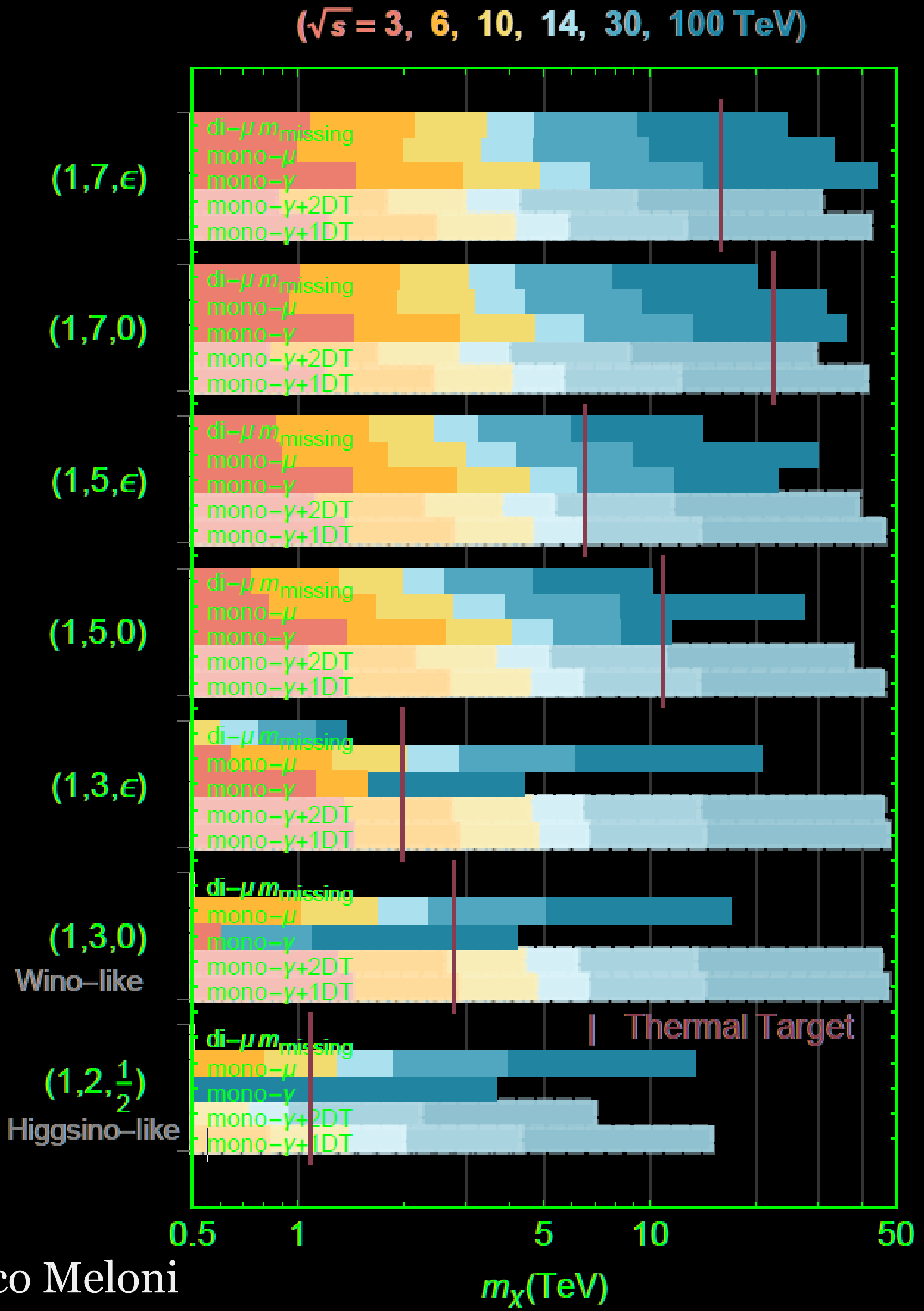
An upgrade of observables

Missing ET→

Missing ET, Missing Pz, and Missing Mass

$$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$$



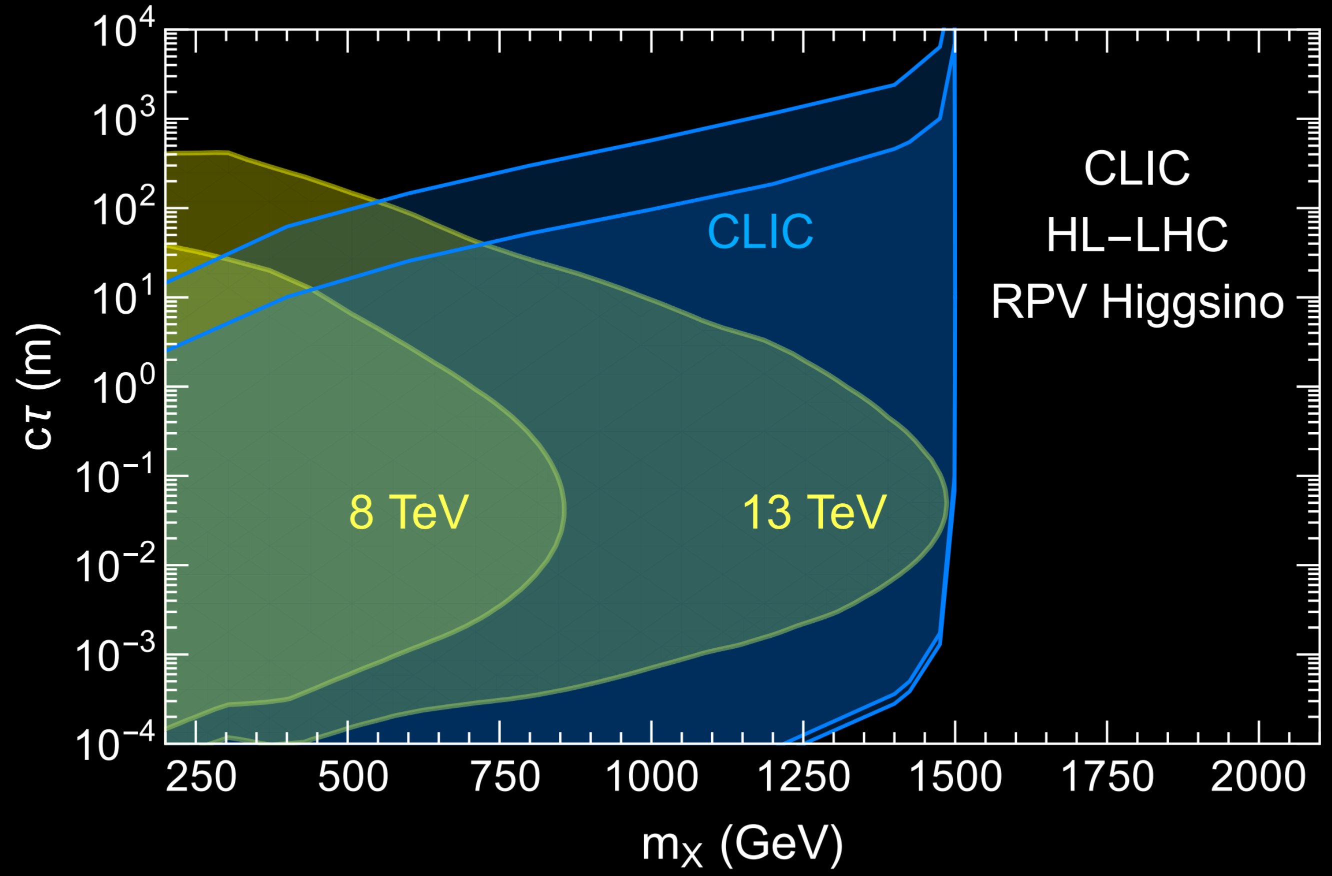


DT search see talk by Federico Meloni

A typical reach

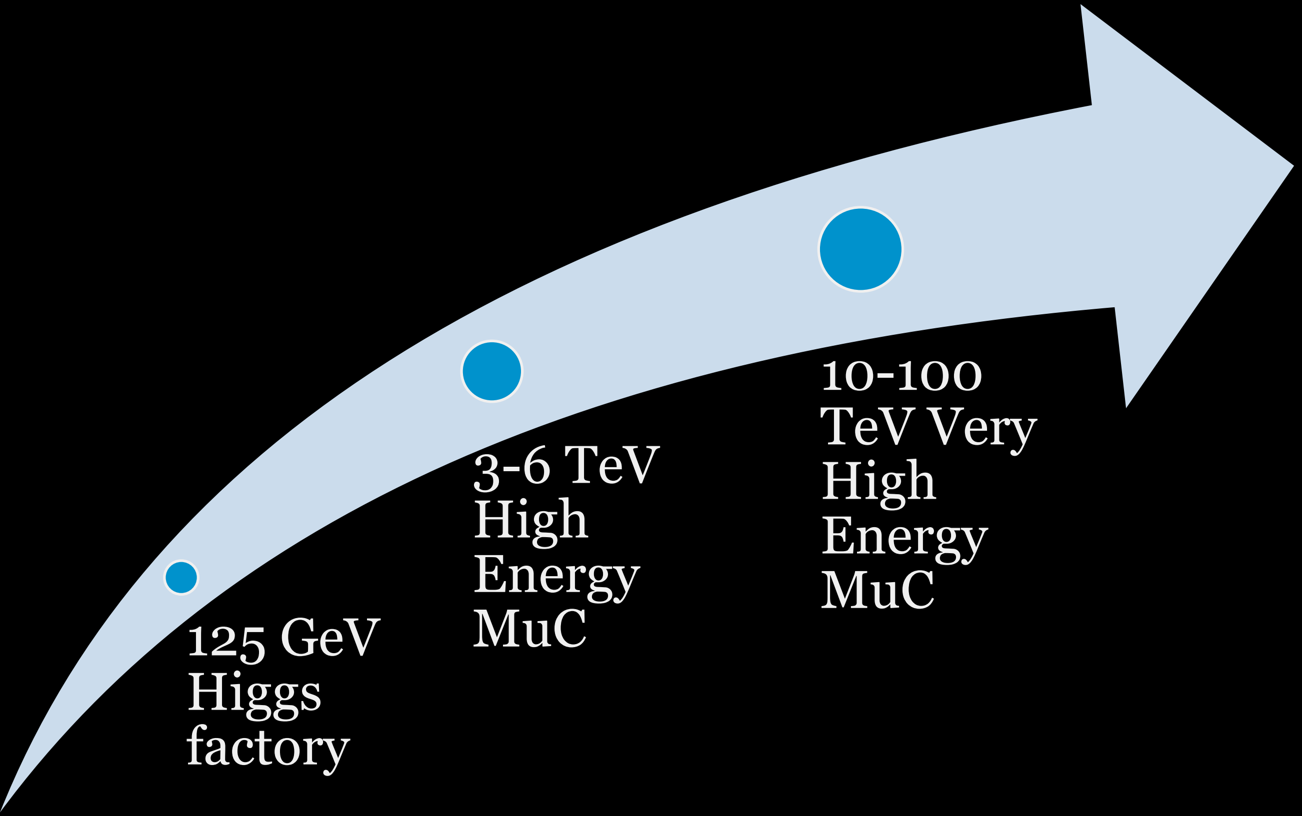
A typical high E lepton collider reach:

- Pair production sensitivity directly to the threshold (so long decays being visible);
- High mass region with low boost can reach long lifetime easily;

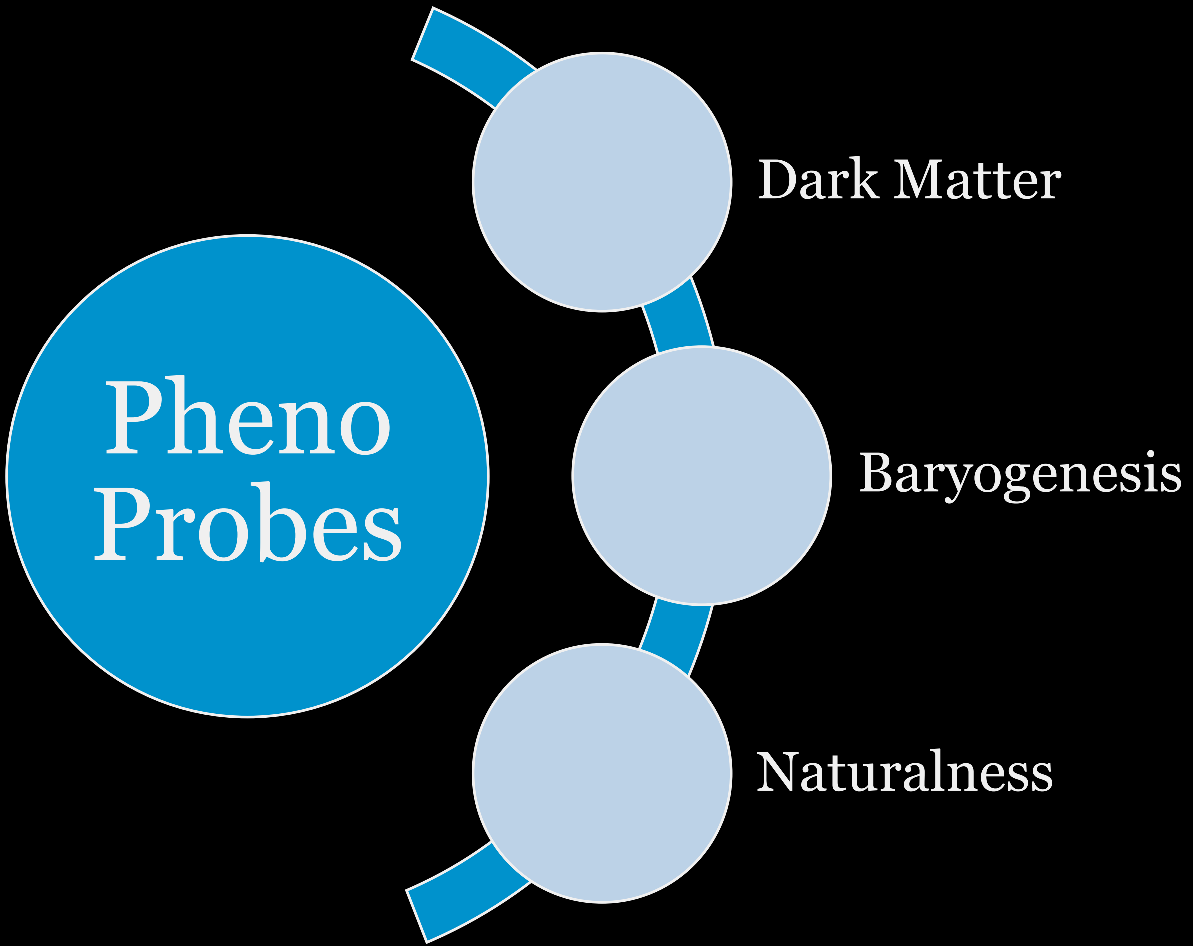


Cui, Joglekar, ZL, Shuve, to CLIC physics book, 1812.02093

The Dream Machine



Physics Driver

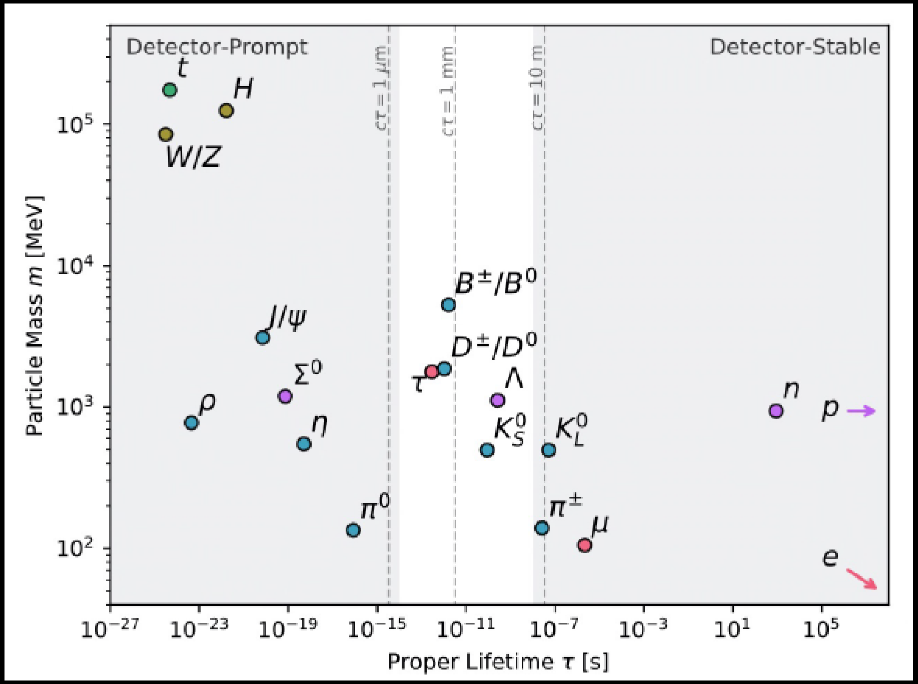


International muon collider collaboration: https://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=MUONCOLLIDERDETECTOR-PHYSICS
Muon Collider Forum: SNOWMASS-MUON-COLLIDER-FORUM@FNAL.GOV at https://snowmass21.org/energy/start#communications.

Thank you!

High Energy Rules

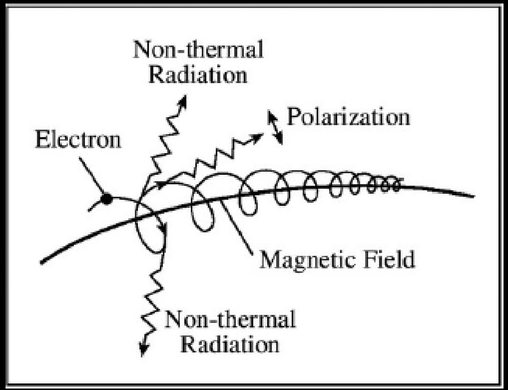
What to collide?



Slide from T. Cohen's talk

- Charged

- Heavier is better

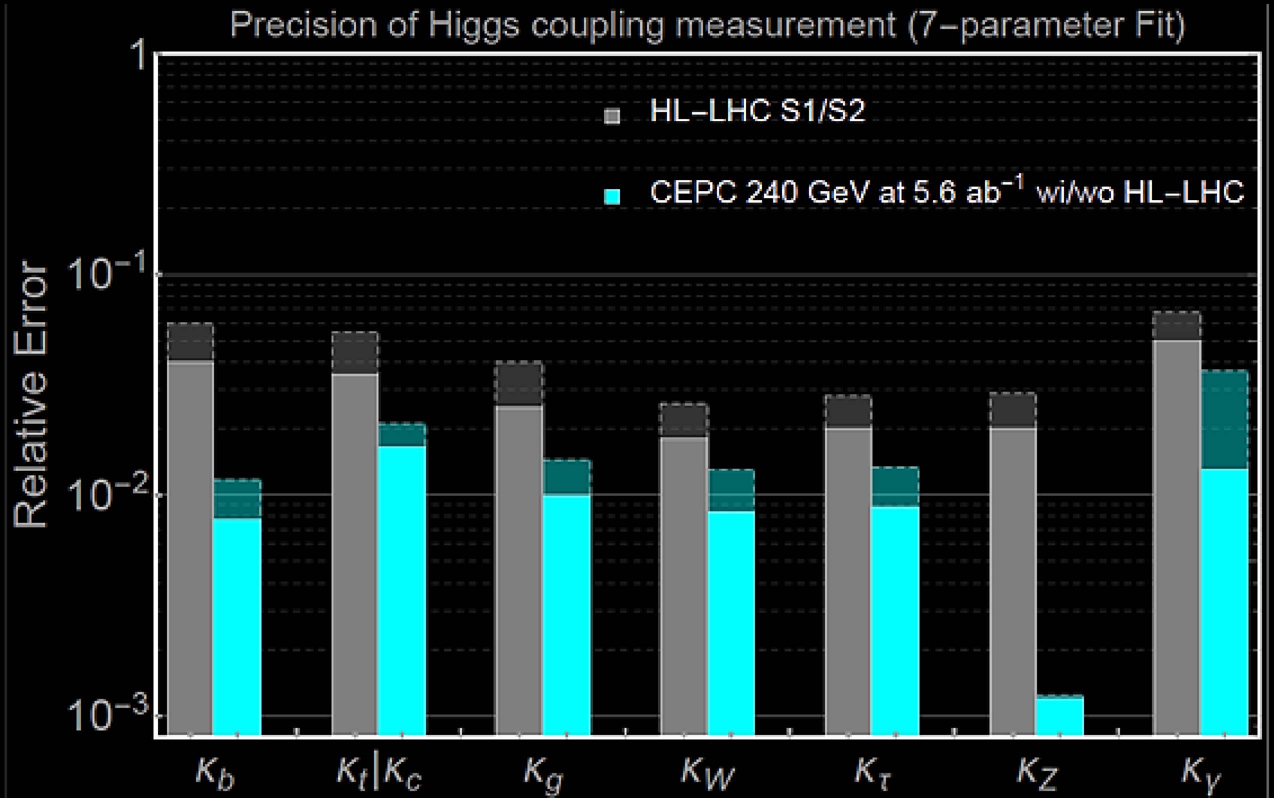


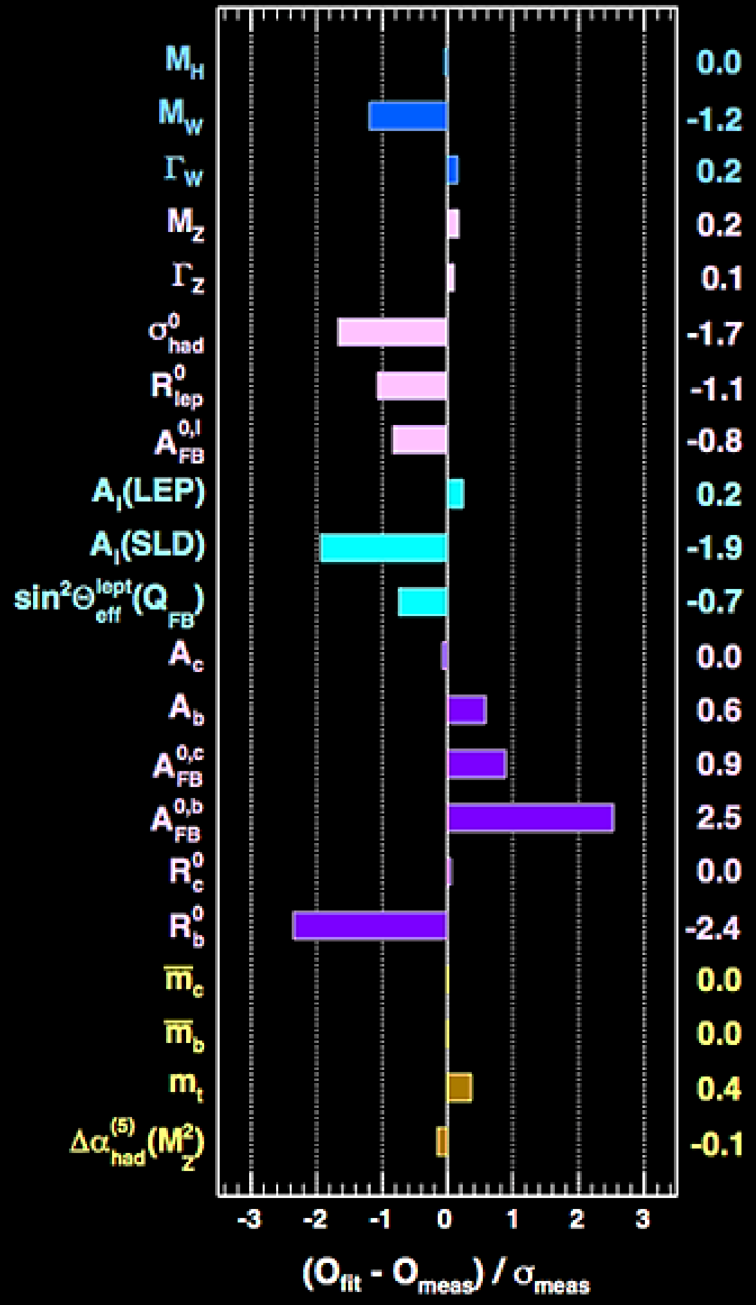
$P_{sync} \sim \frac{1}{m^4}$

- Stable(ish)

The power of cleanness

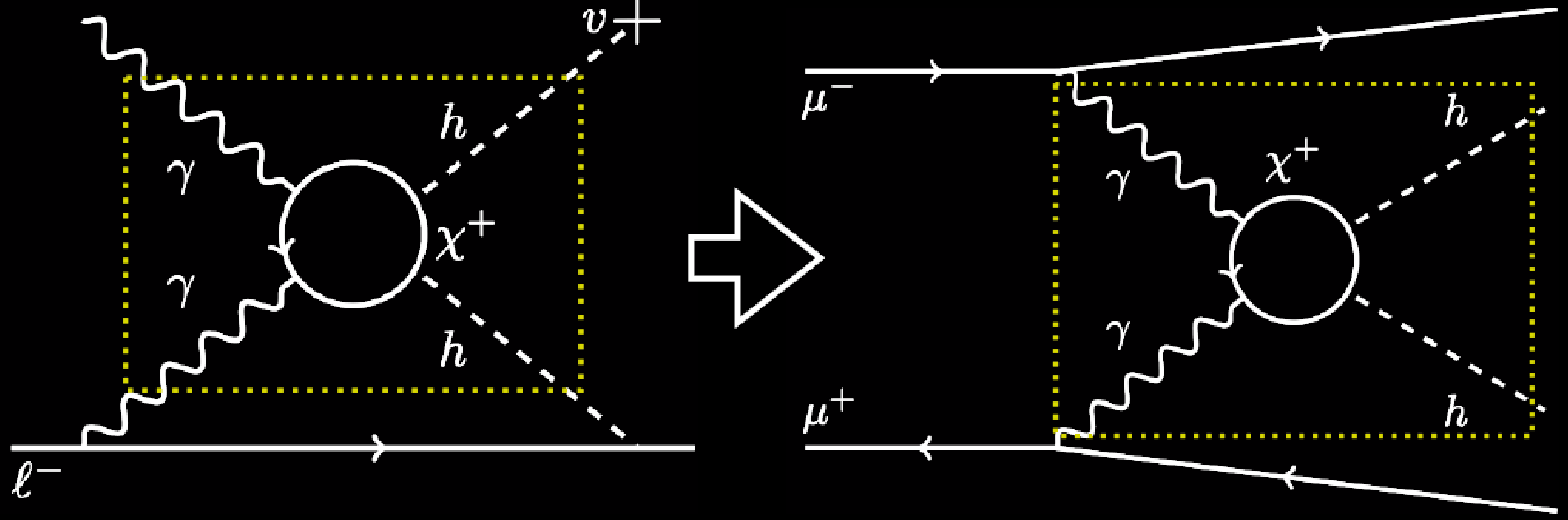
- LEP still is a headache/treasure of theorists
- 1M Higgs Higgs factory v.s. 0.5B Higgs HL-LHC



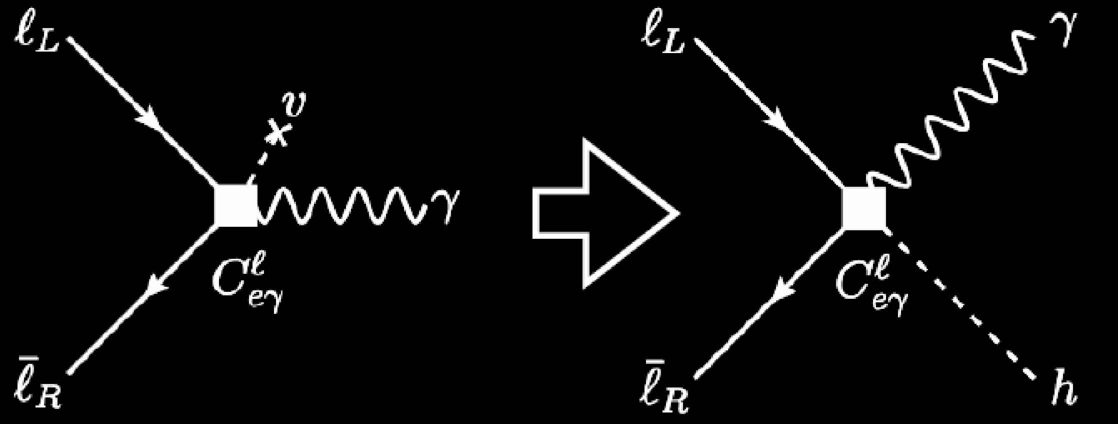


Complimenarity

E.g. next-gen. **electron EDM** experiments sensitive to ~20 TeV particles in Barr-Zee diagrams; same diagram probed in muon colliders



Any new physics contributions to **Muon g-2** efficiently probed at muon colliders [Capdevilla, Curtin, Kahn, Krnjaic, 2006.16277; Buttazzo & Paradisi, 2012.02769; Capdevilla, Curtin, Kahn, Krnjaic, 2101.10334; Chen, Wang, Yao 2102.05619; Yin, Yamaguchi 2012.03928]



[Buttazzo & Paradisi, 2012.02769]

A side note

MAP (US program) is an extremely valuable contribution to the field.

Increasing interests from international efforts, new LEMMA scheme

95'→00'→10'→20'→??

The muon quartet: Gunion, Barger, Berger , Han hep-ph/9504330

Overall physics evaluation: physics/9901022

Establishment of the MICE & **MAP** program

Discontinued funding for MAP

Higgs Discovery & much improved understanding of the physics of Higgs muon factory
Han & ZL, Eichten et al

MuC meeting, many institutions (globally) expressed interests, more than 250 participants

You will always hear two leading "criticism" (excuse of not thinking) on muon colliders:

- Where is the beam? (cooling and luminosity)
  - Solution: participate, understand, appreciate the muon cooling researches (as well as LEMMA), and be optimistic
- Background from muons decaying in flight
  - Solution: try to estimate and convince yourself it won't be a problem.