Theory Motivations for a Muon Collider

May 24th 2023 - Roberto Franceschini (Rome 3 U.)

ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Roma3

$\mu^+\mu^-$ collisions

New | Type of | Collider

- *all* the CoM energy can be used to produce SM or BSM states ($\mathcal{O}(10)$ larger mass scale can be explored w.r.t. to pp of same CoM energy)
- for CoM energy at or above 3 TeV $\mu \to W\nu$ is so "easy" that W and ν become "partons" in the muon beam (same role as gluon in LHC, with the advantage of being electroweak!)
- power-efficient (ISR beam loss ~ 10^{-9} w.r.t. e^+e^- of same CoM energy)
- fast lane to physics ($\mathcal{L}_{10\text{TeV}} = 10\,\text{ab}^{-1}$ in just about 10 years operation)
- small "footprint" (10 Km ring for 10 TeV collider)

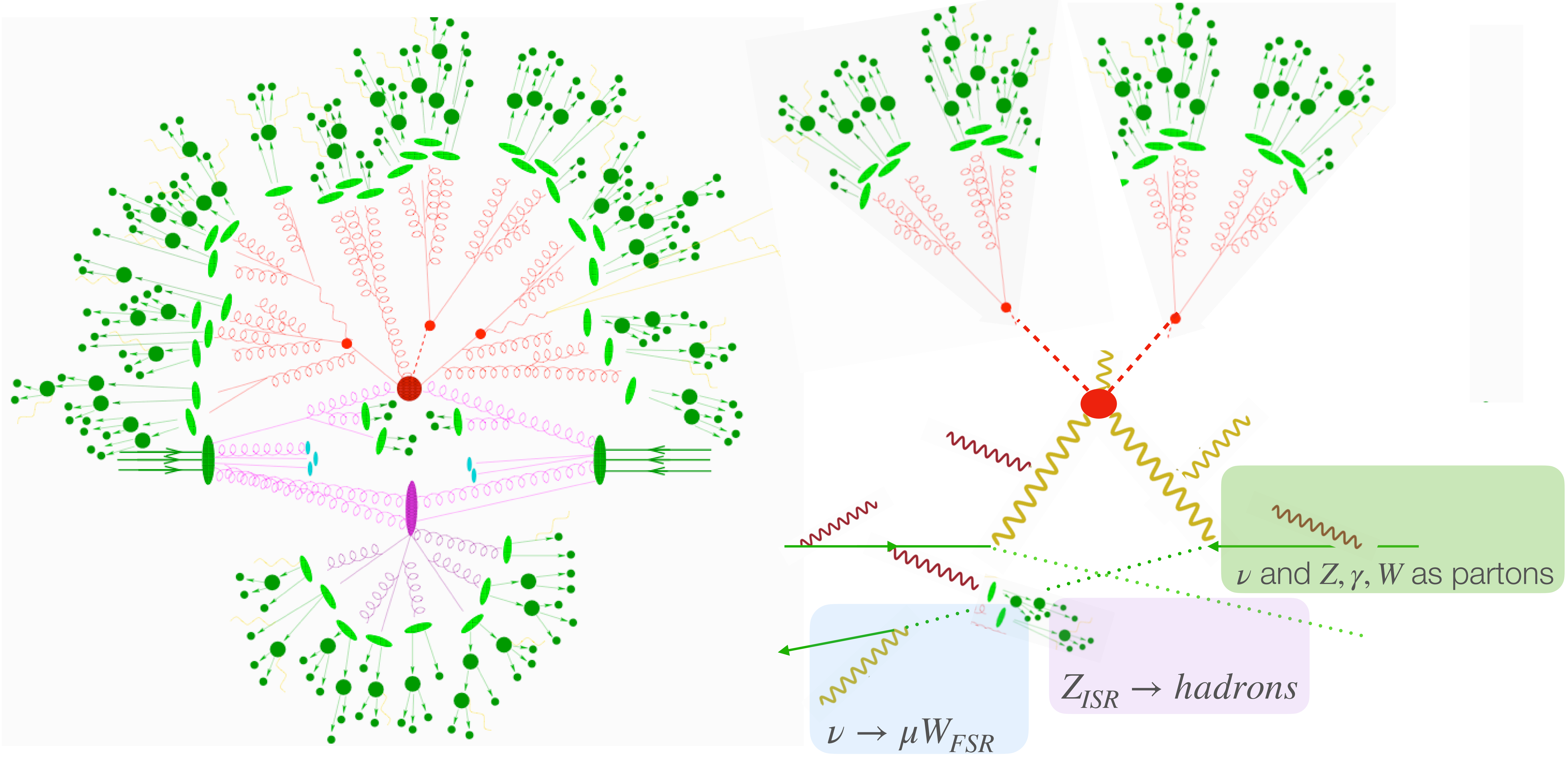
$\mu^+\mu^- \to$ all new business

Standard Model | "NEW PHYSICS"

$\mu^+\mu^- \rightarrow$ all new business

Standard Model | "NEW PHYSICS"

tth production at the LHC (Fully hadronic) HH→4b production at a multi-TeV muC (F. Maltoni)



NEW PHENOMENA AND NEW REGIMES IN pQFT

- weak corrections become "ordinary"
- weak "partons"
- large EW logarithms
- new regime of boosted SM objects (c, b, t, W, Z, h)

$\mu^+\mu^- \rightarrow$ beyond the Standard Model

	?	• what is the dark matter in the Universe?	✓		
		• why QCD does not violate CP?	✓	✓	
		• how have baryons originated in the early Universe?	✓		
		• what originates flavor mixing and fermions masses?	✓		
		• what gives mass to neutrinos?	✓		
~~EFT~~		• why gravity and weak interactions are so different?	✓		
~~EFT~~		• what fixes the cosmological constant?	✓		

WEAK INTERACTIONS

STRONG INTERACTIONS

Accelerators are excellent probes

$\mu^+\mu^- \rightarrow$ beyond the Standard Model

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WEAK INTERACTIONS

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ACCELERATORS

Accelerators are excellent probes

$\mu^+\mu^- \to$ beyond the Standard Model

$\mu^+\mu^-$ sensitivity to weak interactions

- ? • what is the dark matter in the Universe?
- • why QCD does not violate CP?
- • how have baryons originated in the early Universe?
- • what originates flavor mixing and fermions masses?
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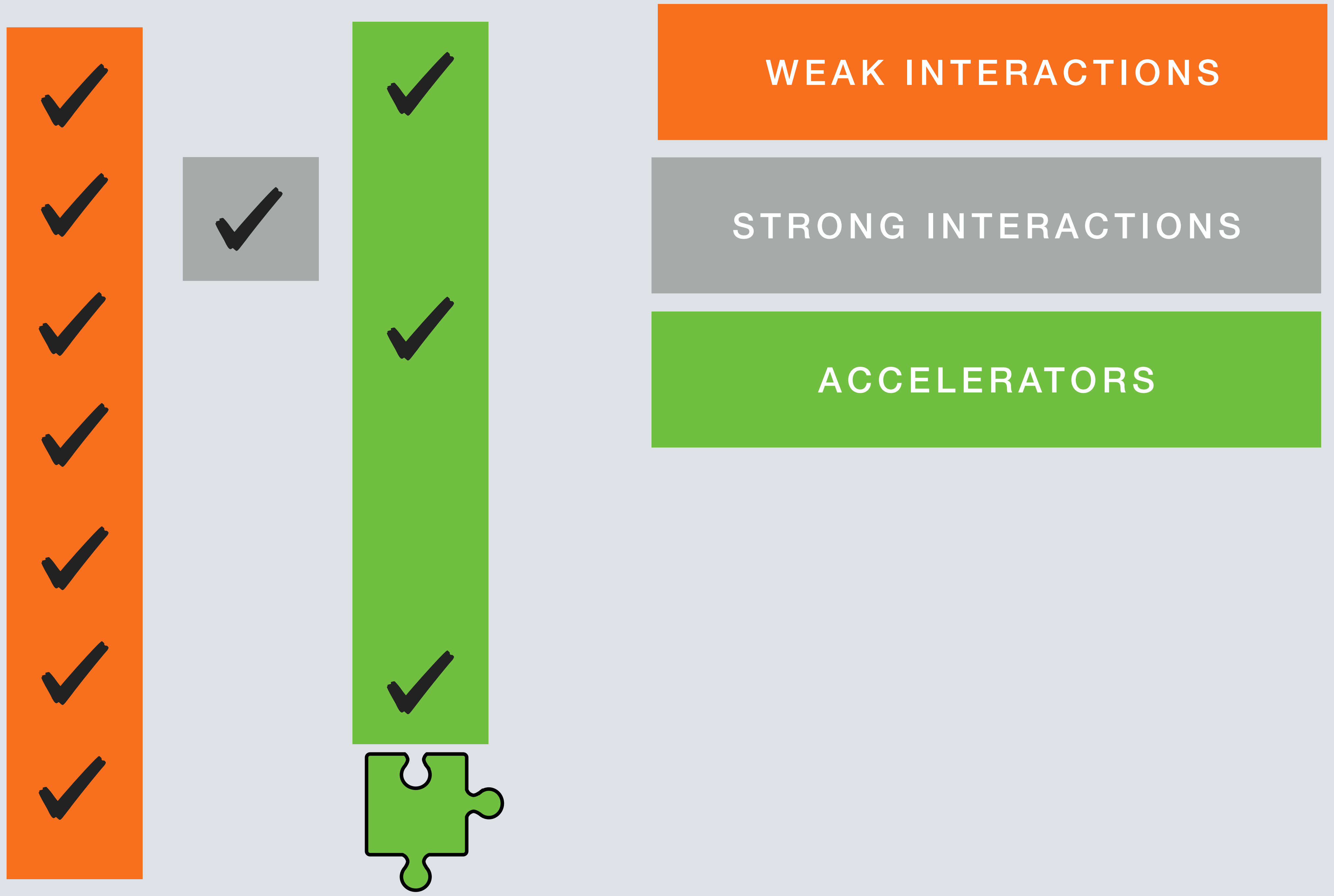
- EFT • why gravity and weak interactions are so different?
- EFT • what fixes the cosmological constant?



Accelerators are excellent probes

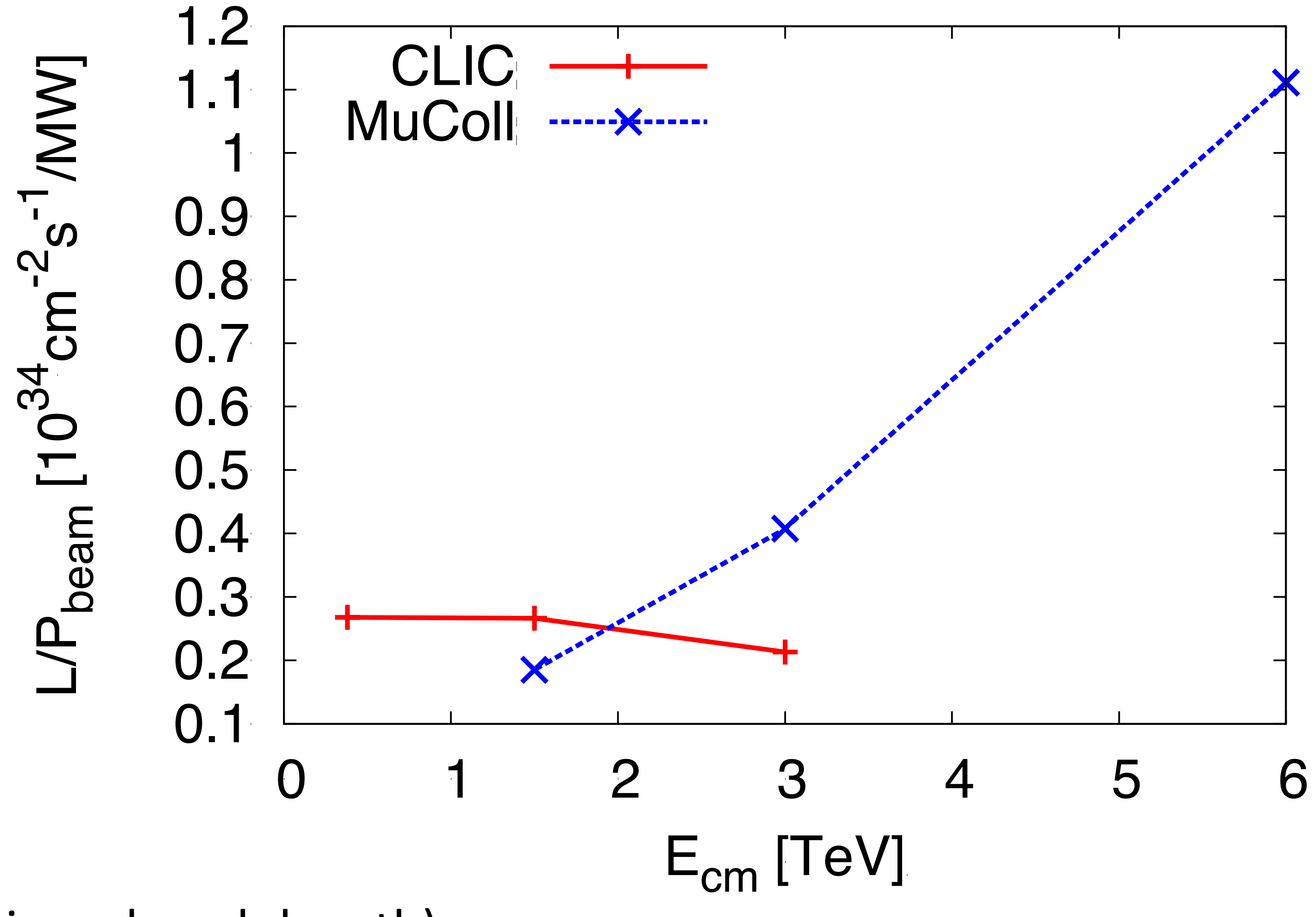
YOU $\rightarrow \mu^+\mu^-$

Highly efficient | high energy collider

Luminosity Comparison

The luminosity per beam power is about constant in linear colliders

It can increase in proton-based muon colliders

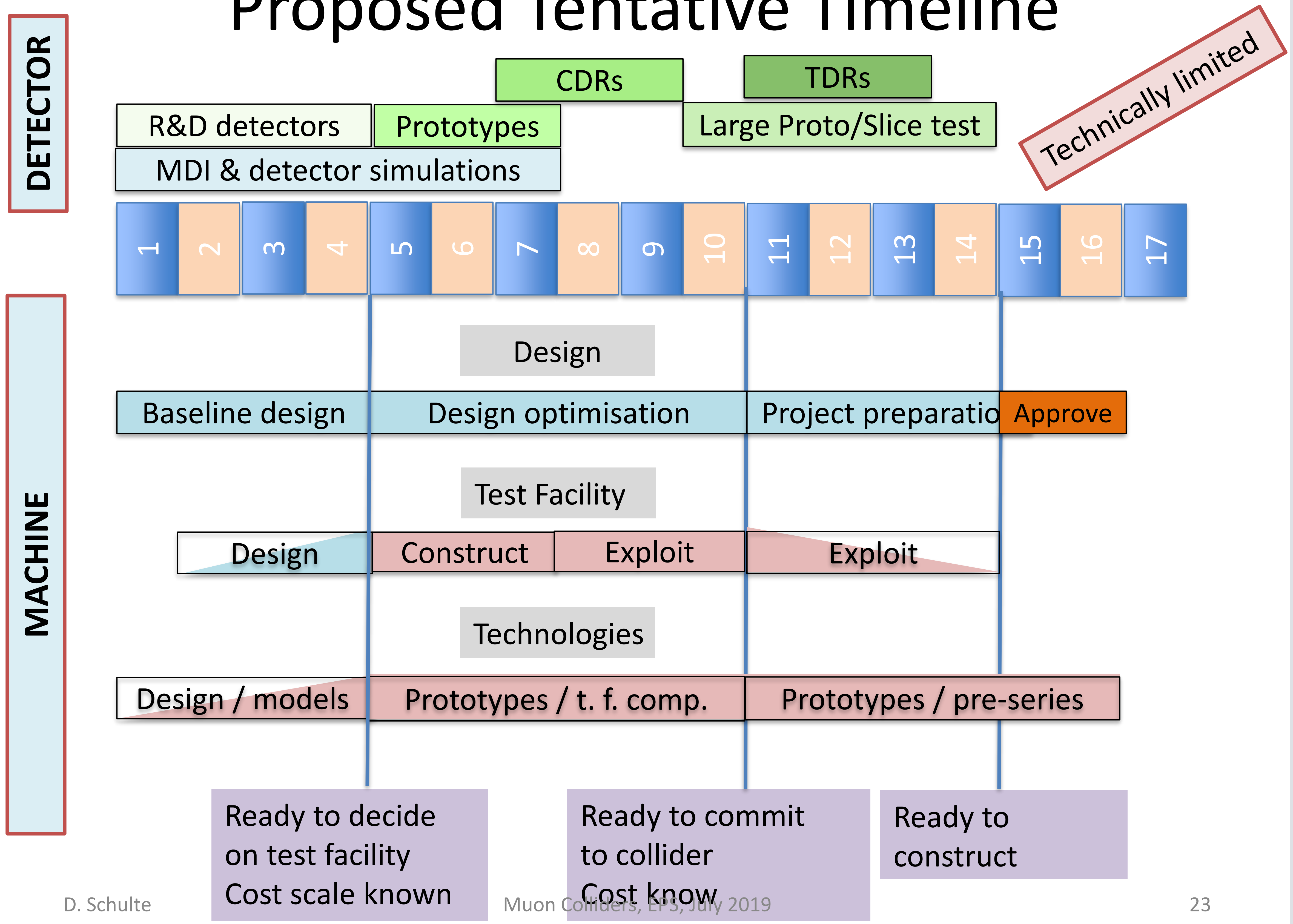


Strategy CLIC:
Keep all parameters at IP constant
(charge, norm. emittances, betafunctions, bunch length)
⇒ Linear increase of luminosity with energy (beam size reduction)

Strategy muon collider:
Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)

D. Schulte Muon Colliders, EPS, July 2019 7

Proposed Tentative Timeline



D. Schulte Muon Colliders, EPS, July 2019 23

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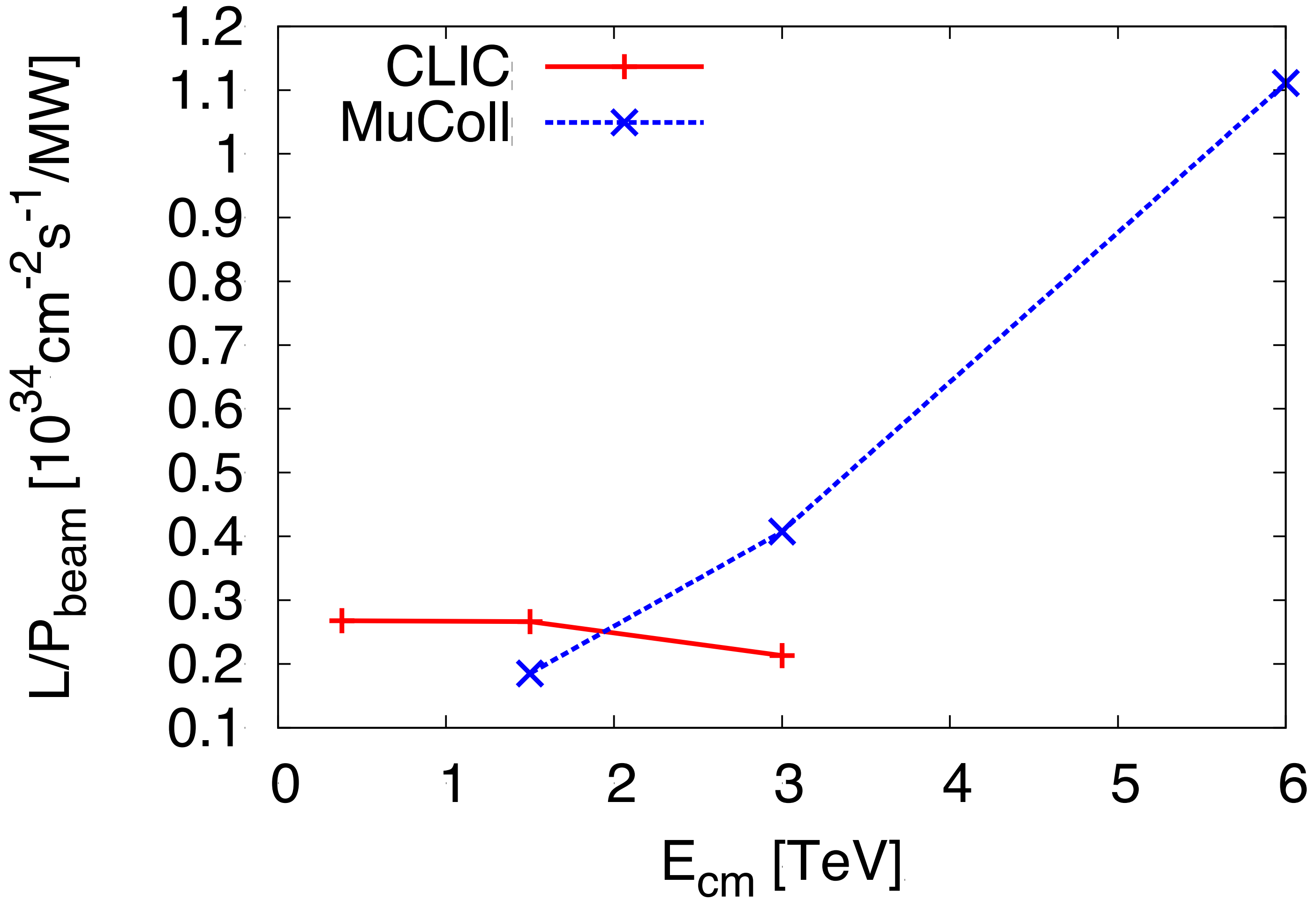

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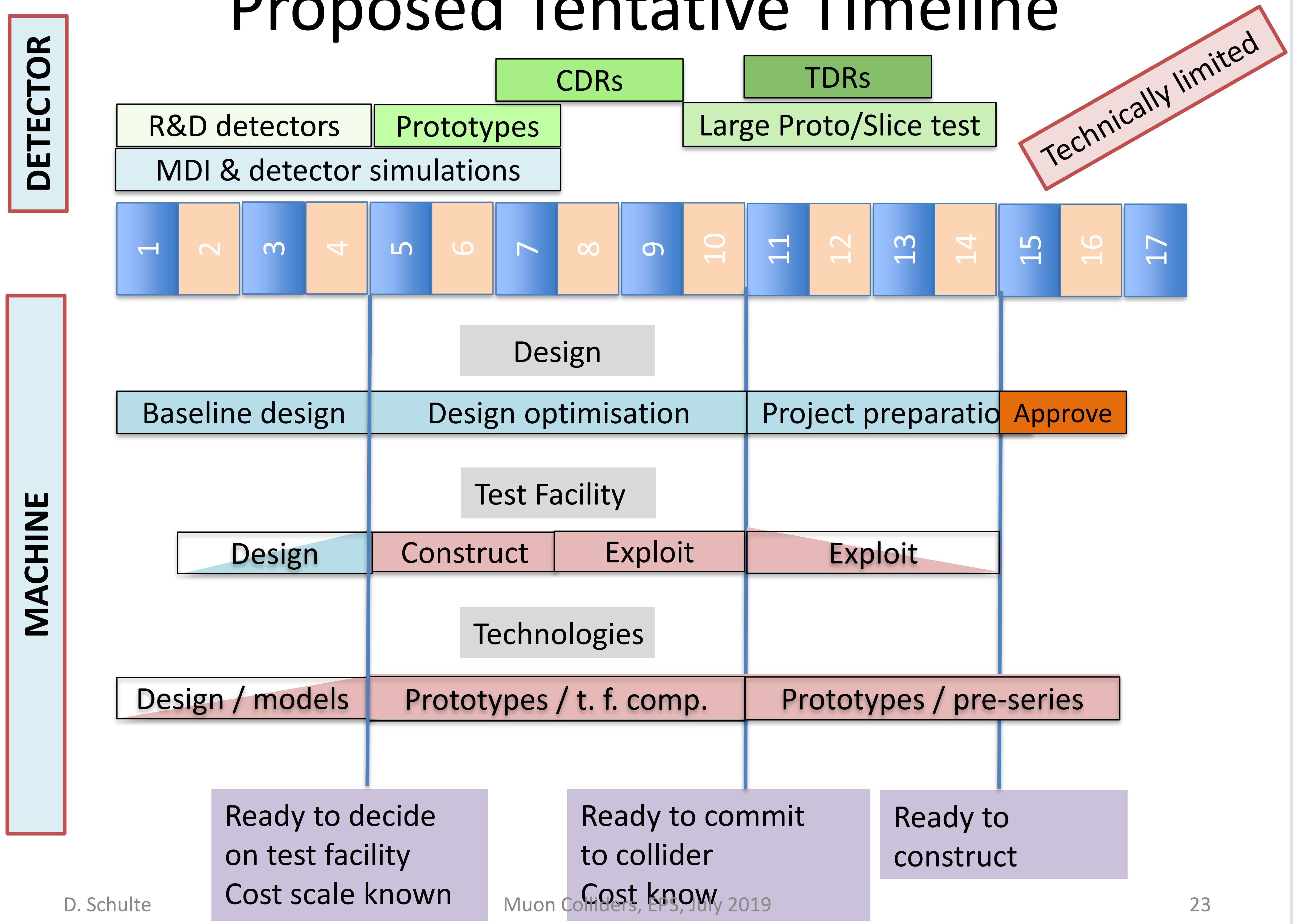

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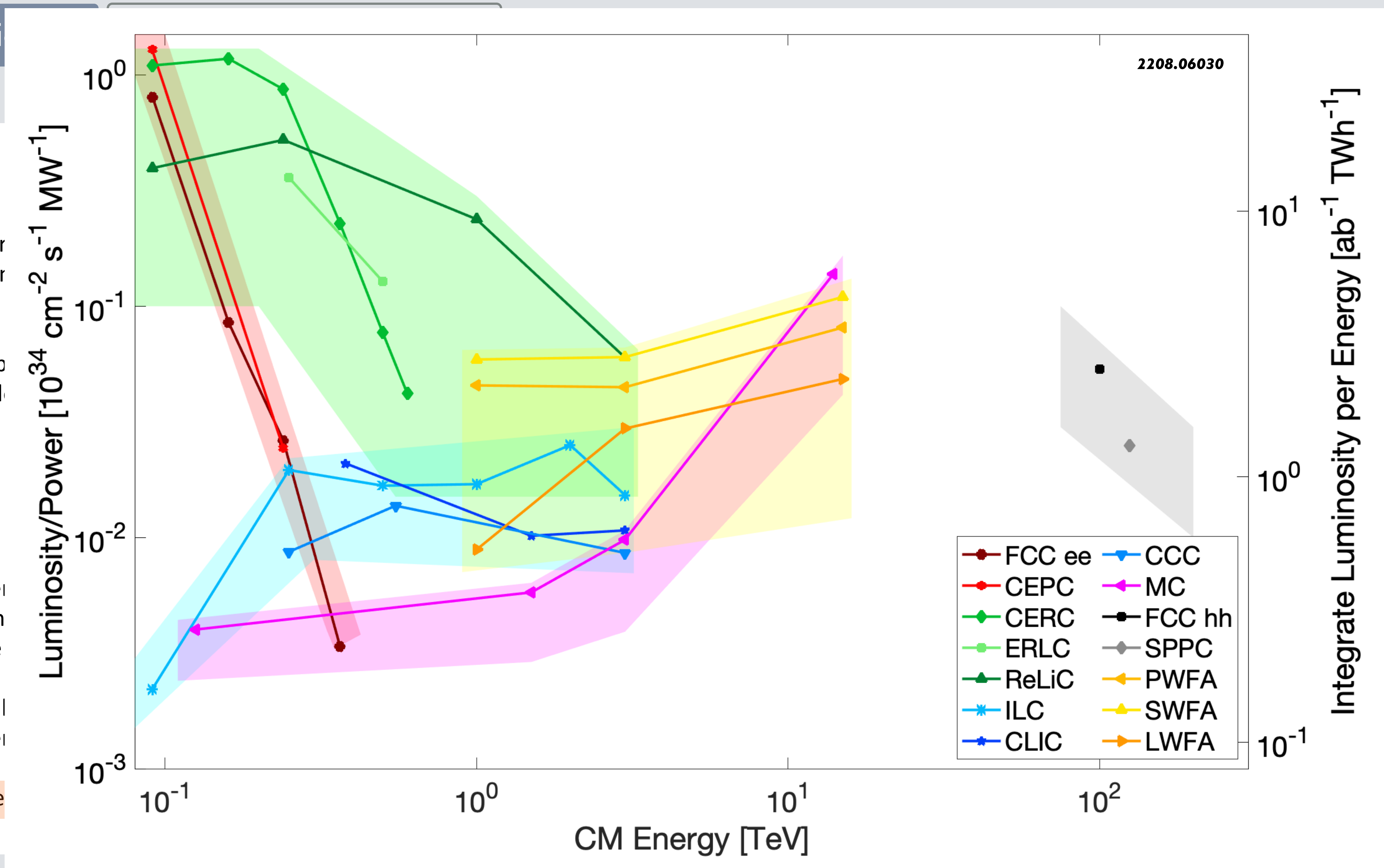
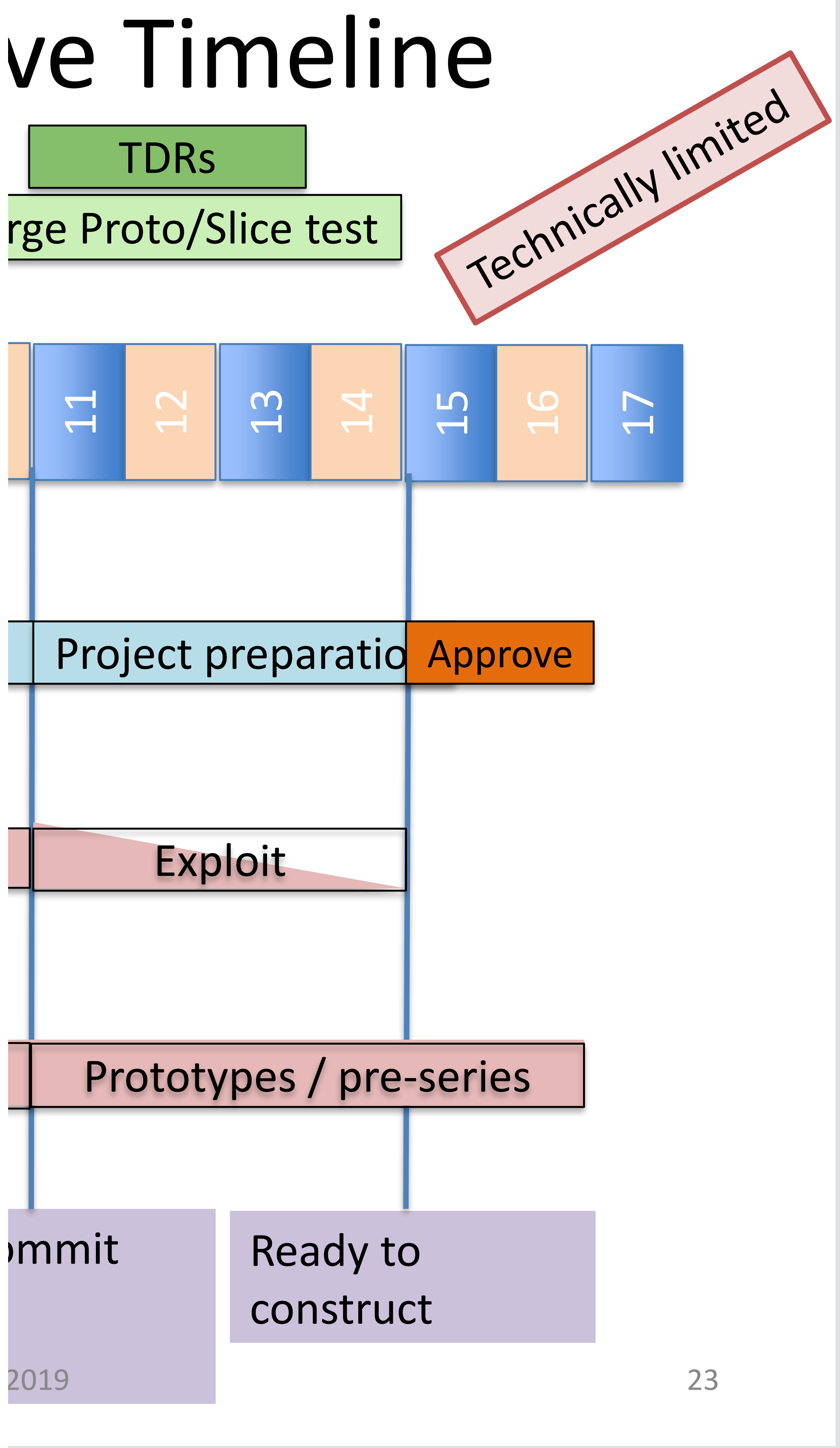
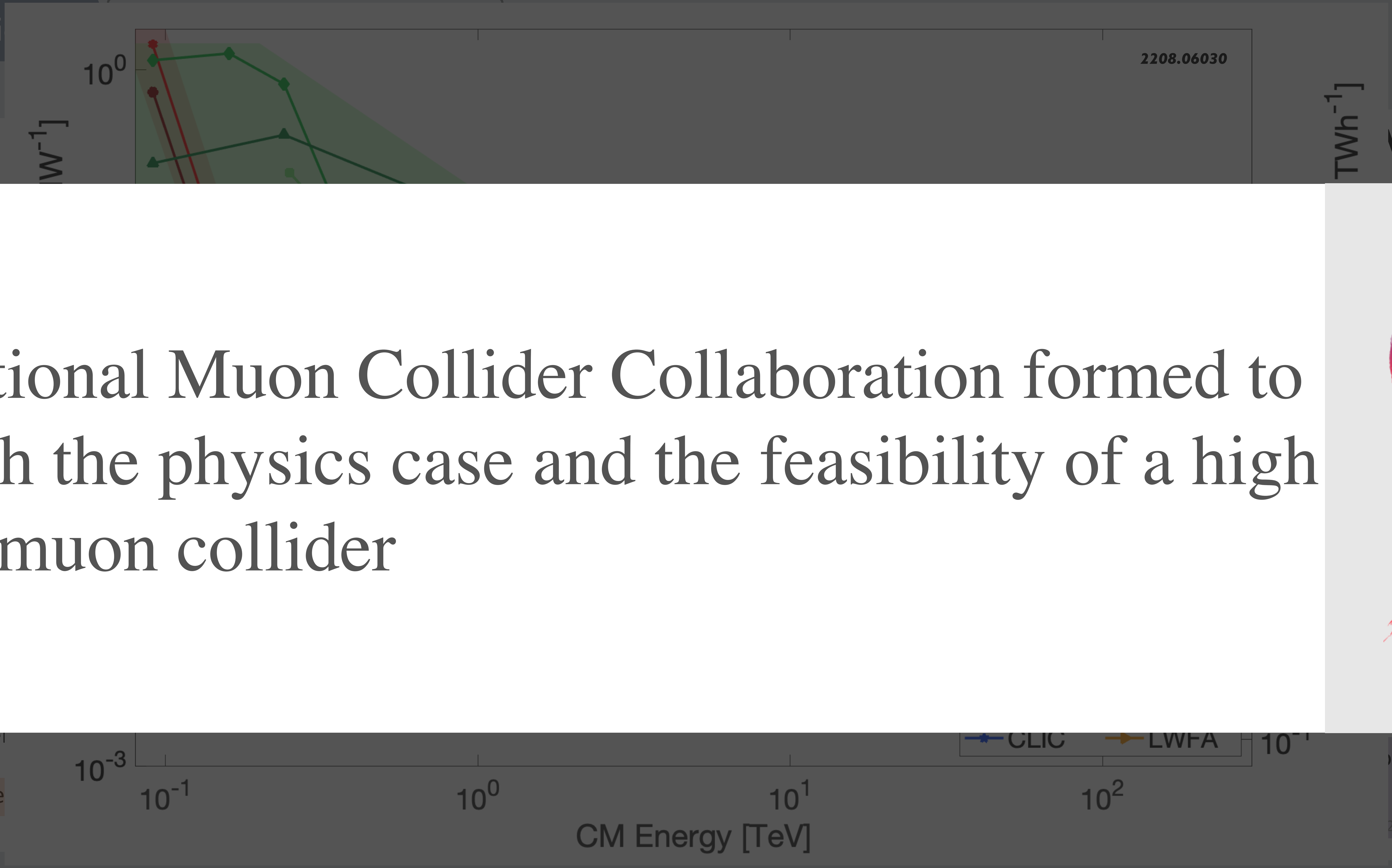
D. Schulte





YOU $\rightarrow \mu^{+}\mu^{-}$

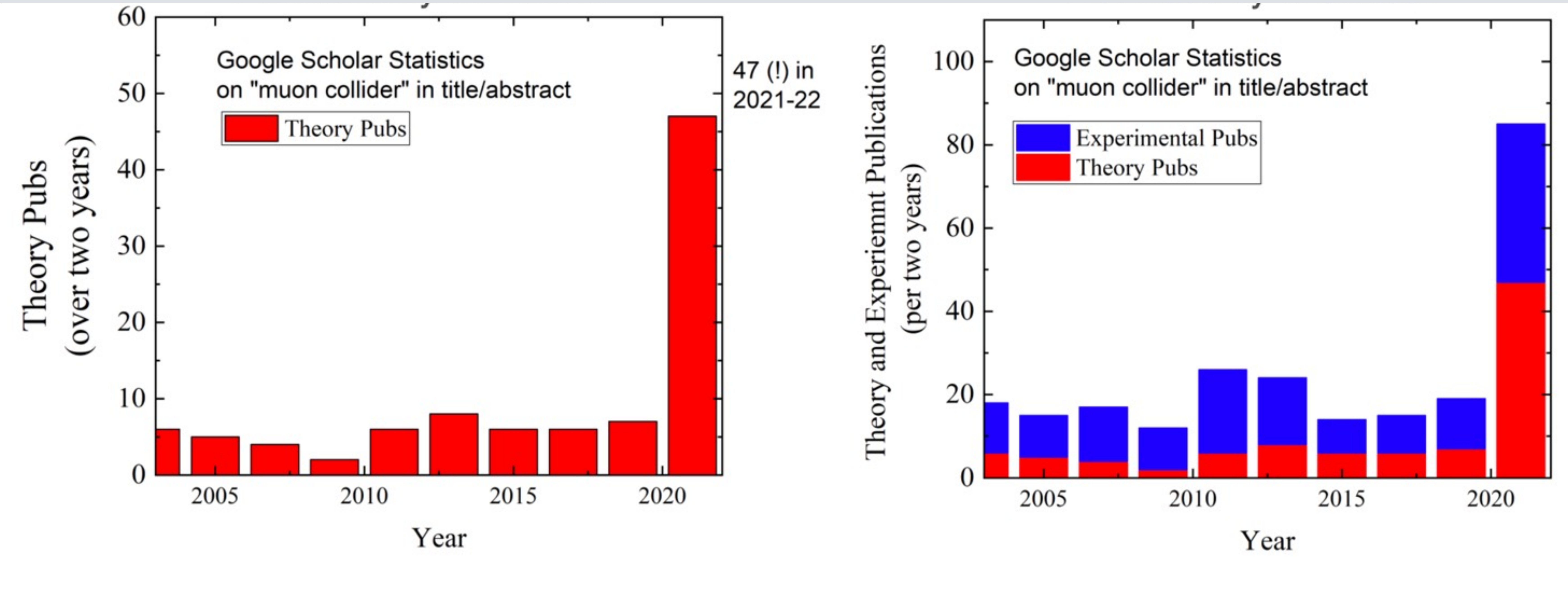


- International Muon Collider Collaboration formed to establish the physics case and the feasibility of a high energy muon collider

International MUON Collider Collaboration

“FUTURE” COLLIDER HAPPENS *NOW*

- Snowmass ’21 saw a huge surge of activity for muon collider machine, physics, detectors



- “The manual” 2303.08533 (submitted to EPJC)

- Crucial development of the machine, detectors, physics case in the years from now to the next European Strategy Update (2026^{2}_{0})

LOTS OF NOVELTIES WITH RESPECT TO pp OR e^+e^-

New challenges, new solution, often in uncharted territory ⇒ exciting work!

Nightmares for LHC (or pp in general) become easy physics targets:
new electroweak states searches are as easy as searches for colored ones.

⇒ unprecedented physics potential for key questions such as Dark Matter

Charged current hard scattering is largely suppressed at LEP (and e^+e^- in general),
The large E_{cm} of muon collider makes it almost as copious as neural current scattering.

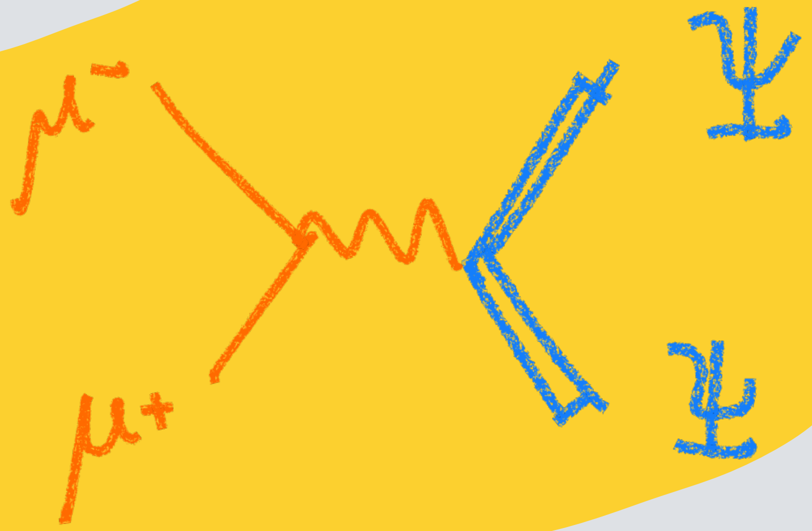
⇒ new search channels for new physics, new SM physics to be studied

Physics studies really require brand new thinking, and they need it now

$\mu^+\mu^-$ COLLISIONS TO PROBE FUNDAMENTAL PHYSICS

DIRECT SEARCHES

- production of SM and new physics in direct $\mu^+\mu^-$ annihilation

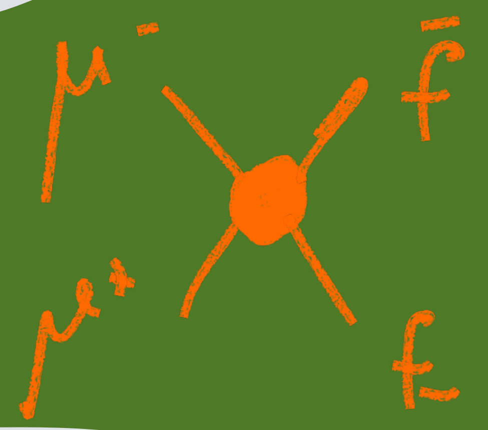


HIGH-INTENSITY PROBES

- production of SM and new physics using beam constituents (e.g. W bosons)

HIGH-ENERGY PROBES

- indirect probes of new physics in direct $\mu^+\mu^-$ annihilation



$\sqrt{s} \gtrsim 3$ TeV center of mass brings significant extension compared to HL-LHC

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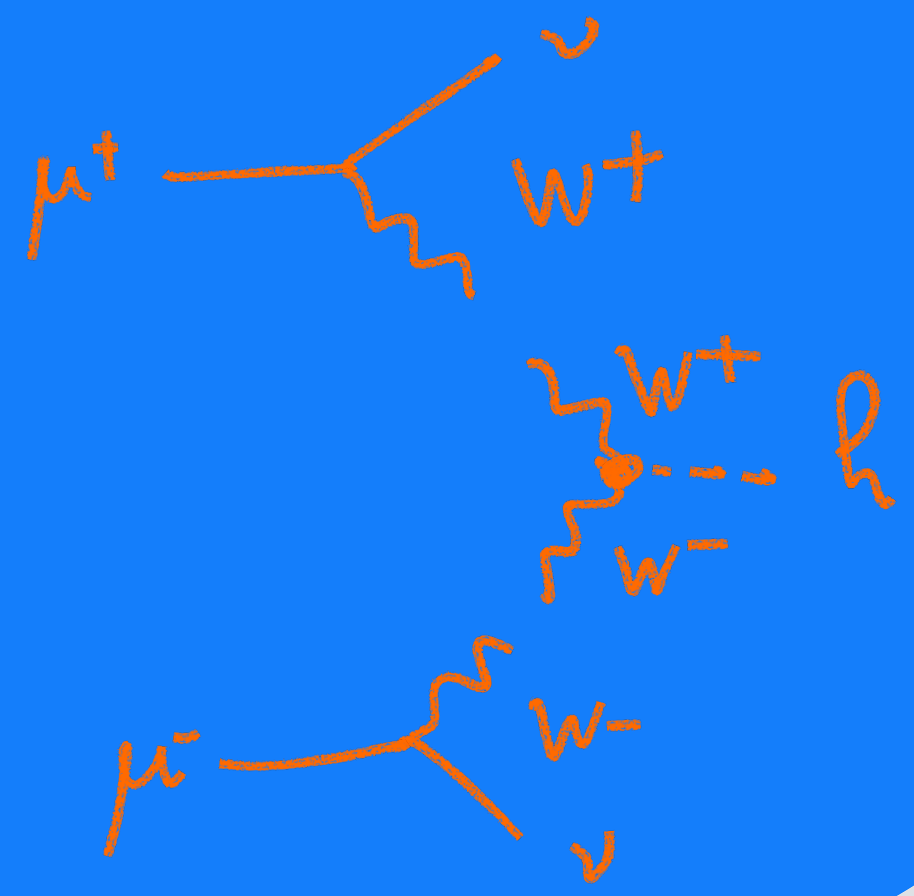

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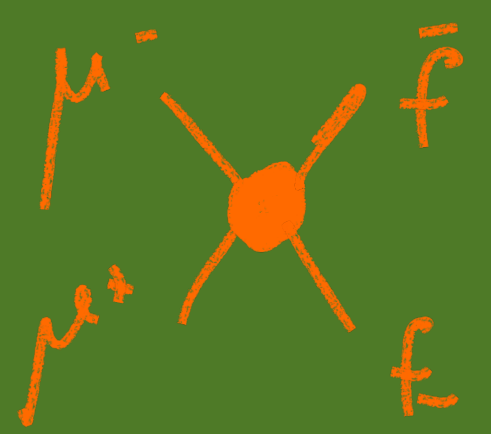

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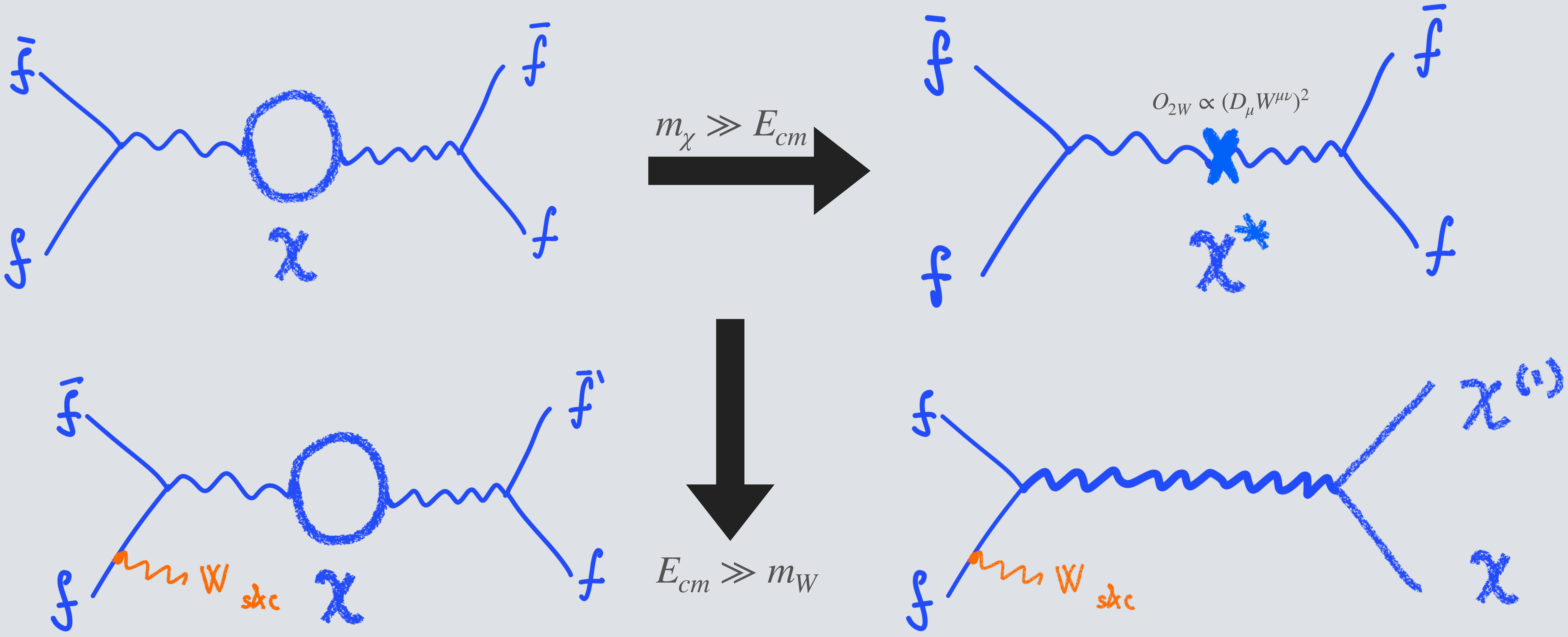
Still learning

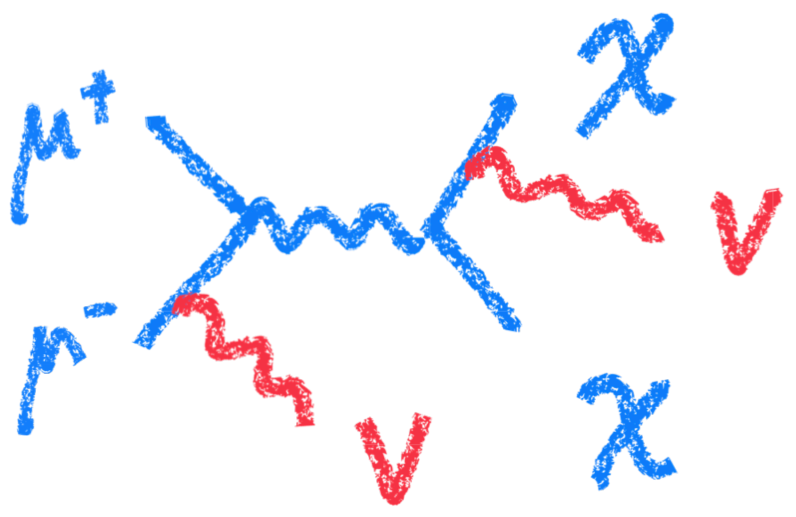
THE SYNERGIES FROM MULTIPLE STRATEGIES

THAT CAN BE PURSUED AT $\mu\mu$



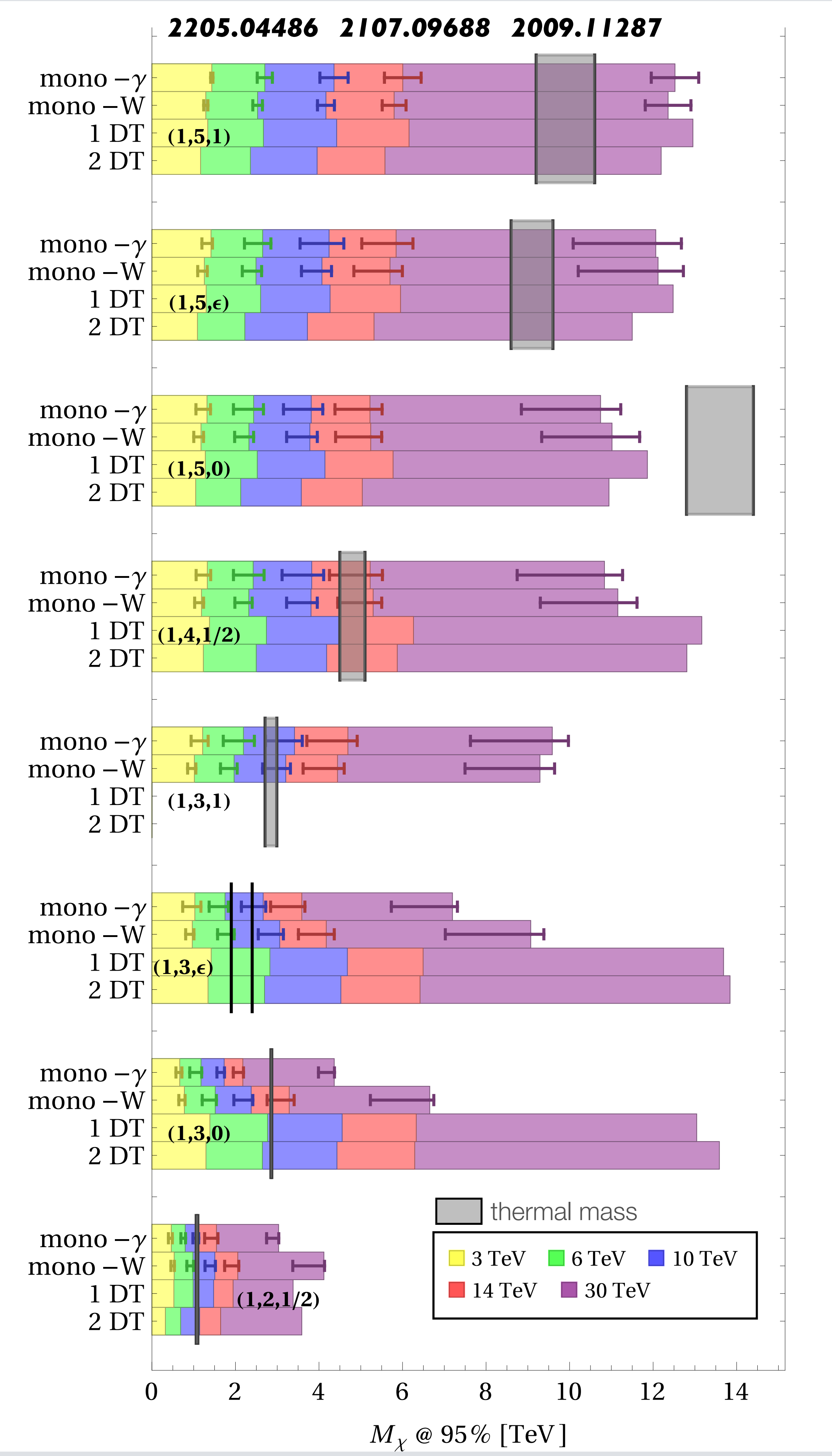
SEARCH FOR EW MATTER AT $\mu\mu$

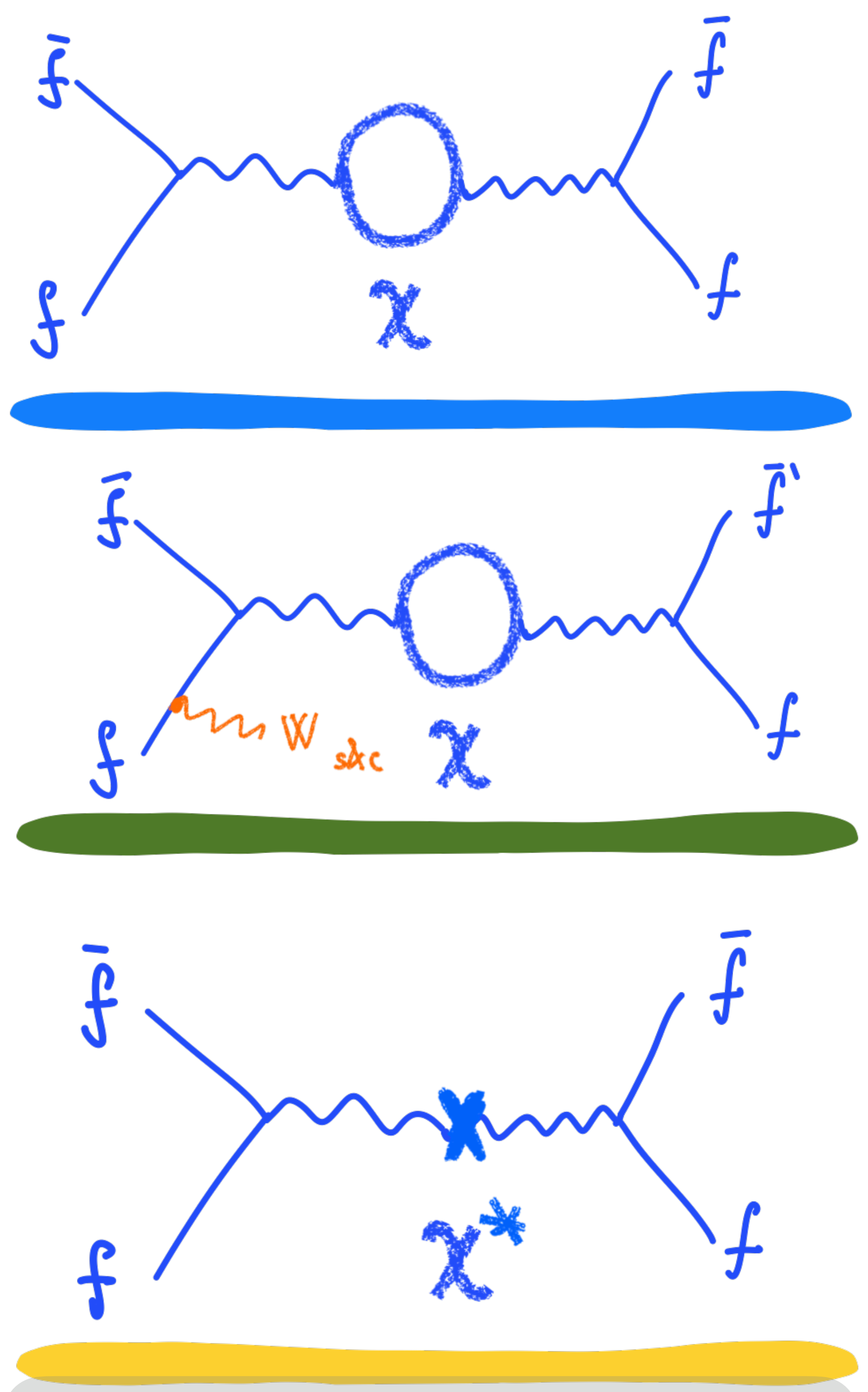
- Xe signal of heavy WIMP opens the chase from 1 TeV to fraction of PeV mass
- most solutions to open issues of the SM require new EW particles



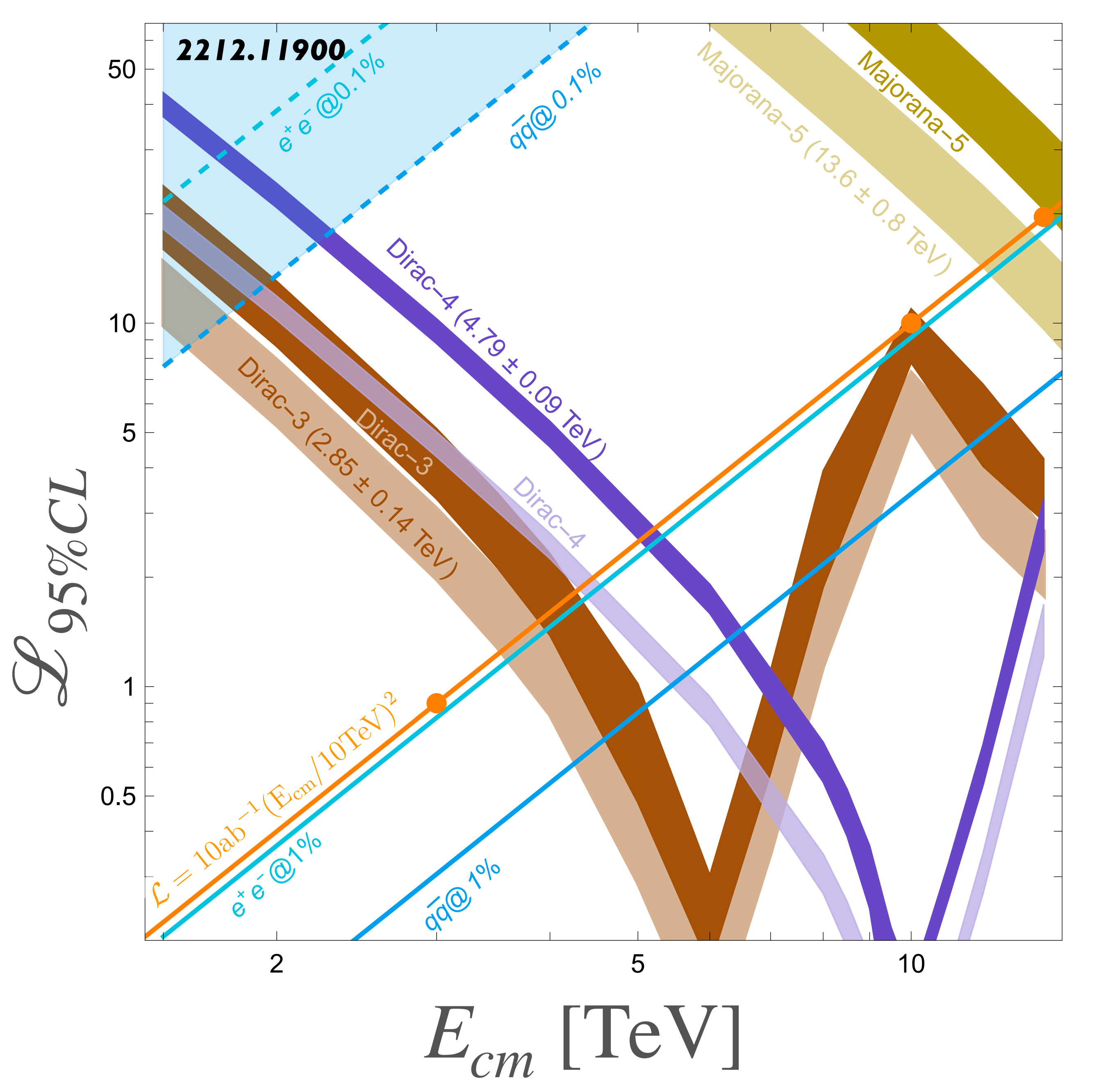
Large χ mass needs CoM energy!

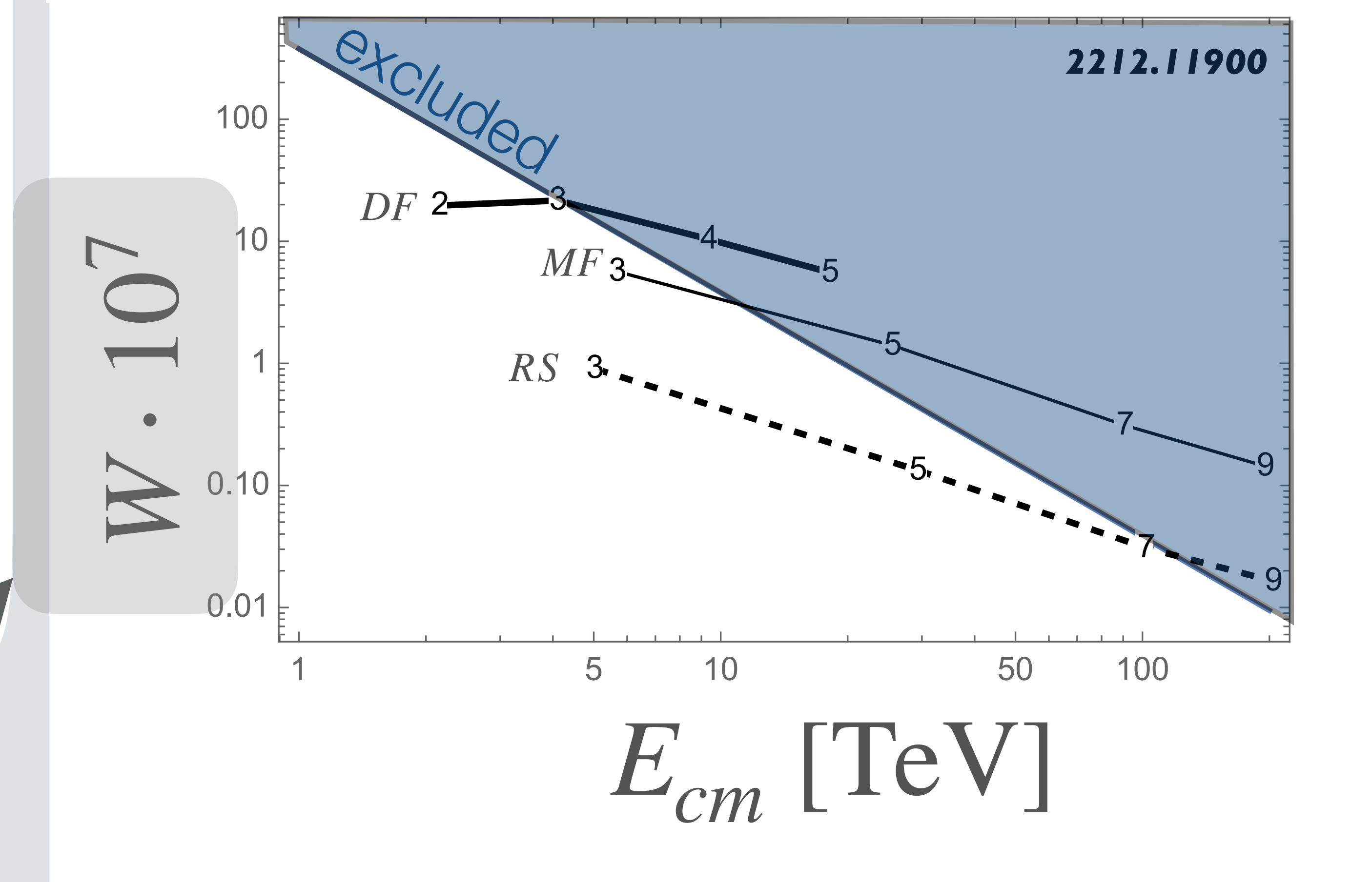
Weak radiation yield the most constraining channel "mono-W"





$O_{2W} \propto (D_\mu W^{\mu\nu})^2$





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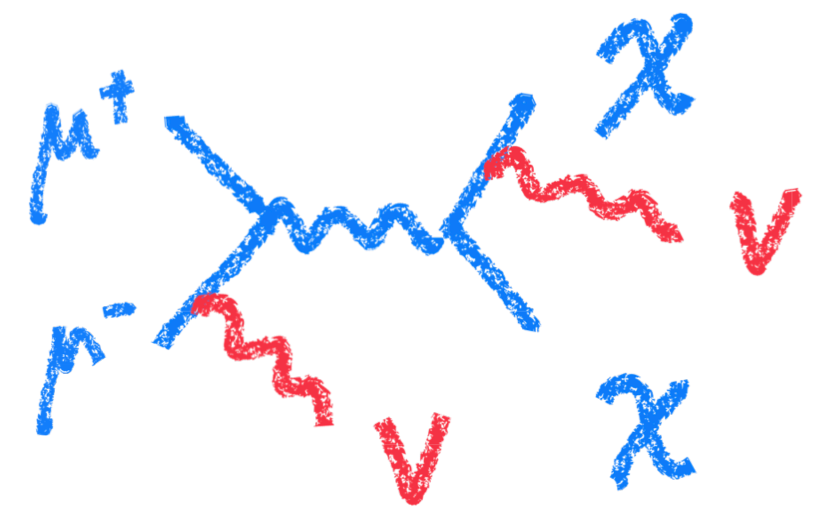

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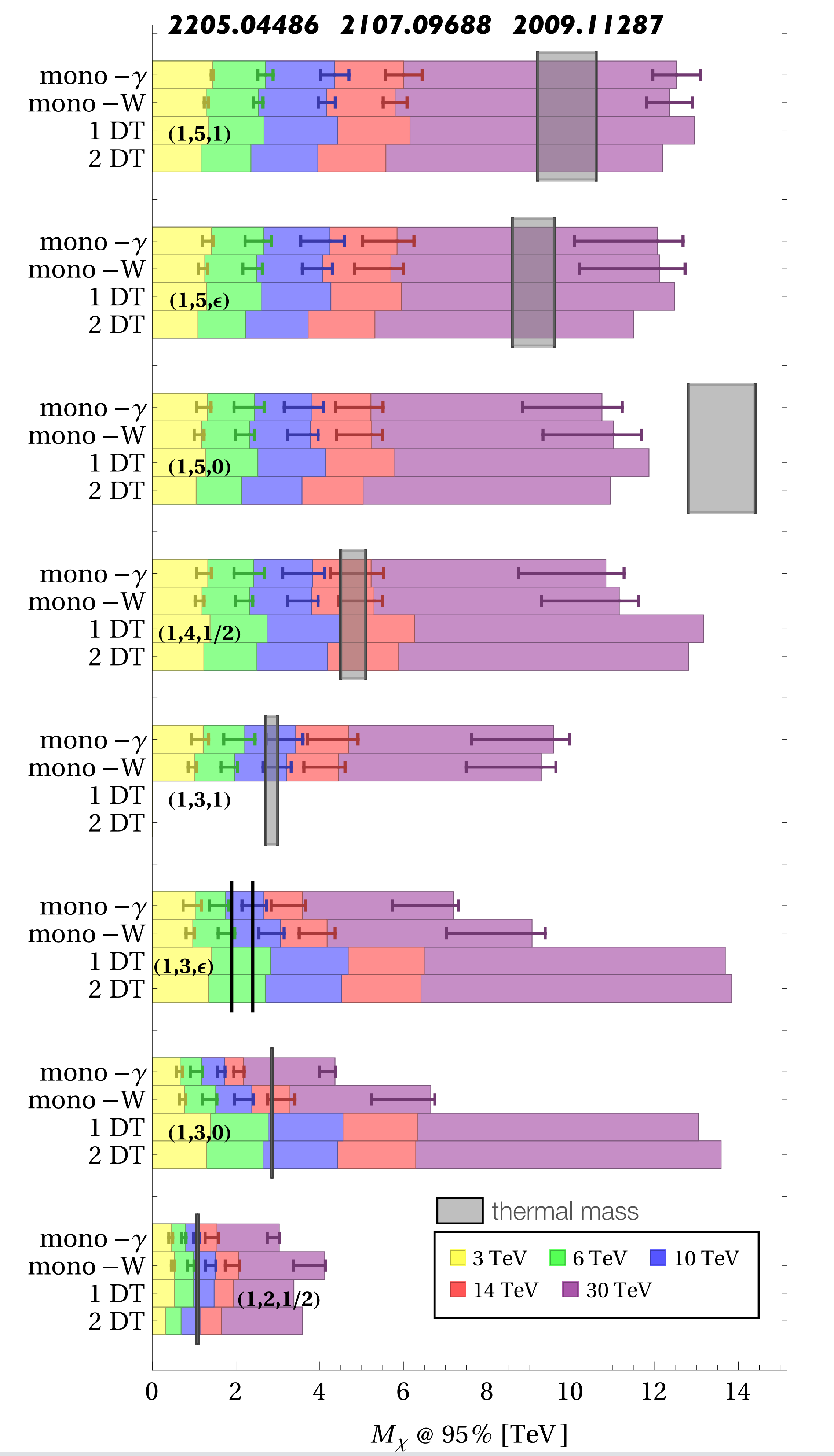

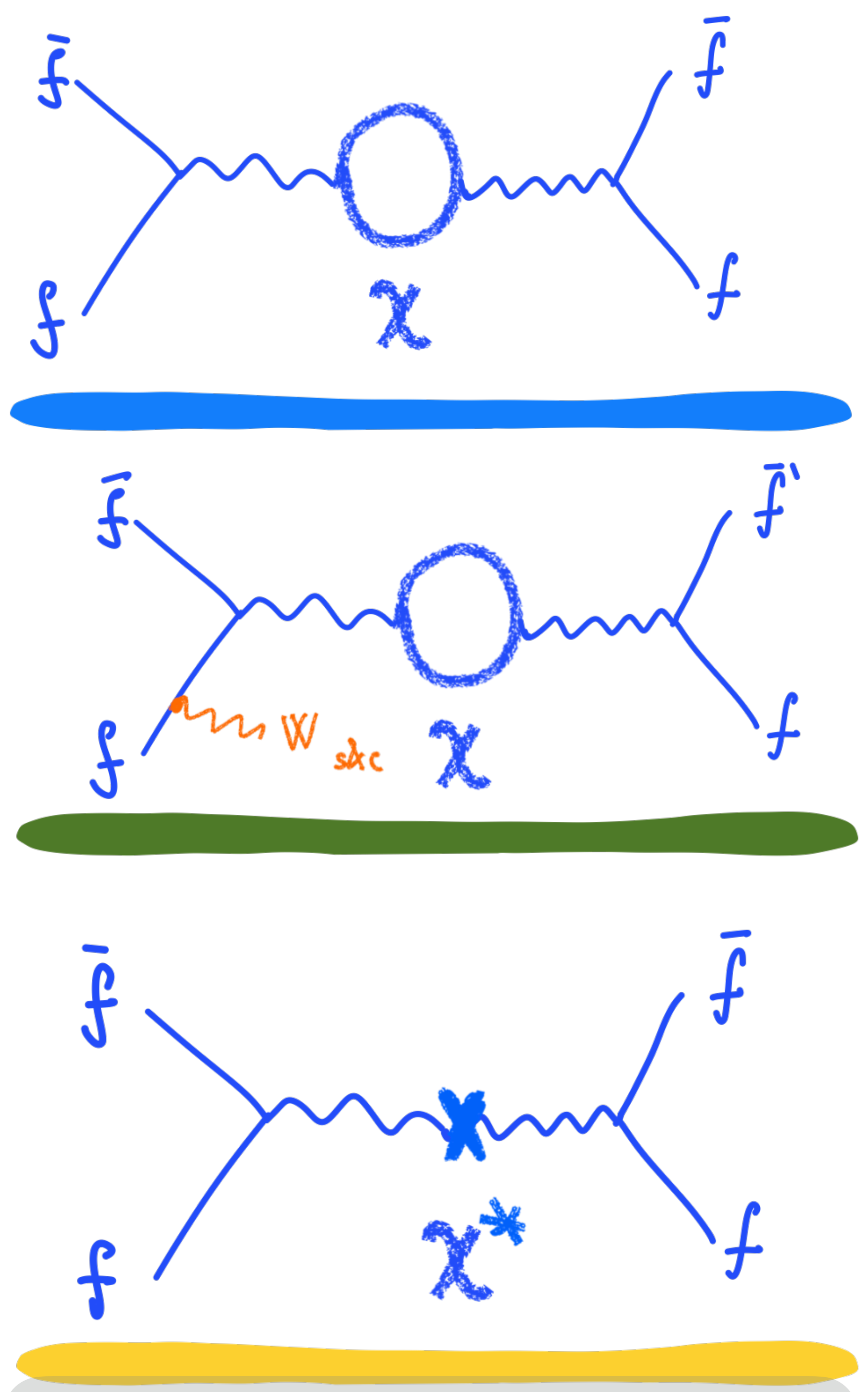

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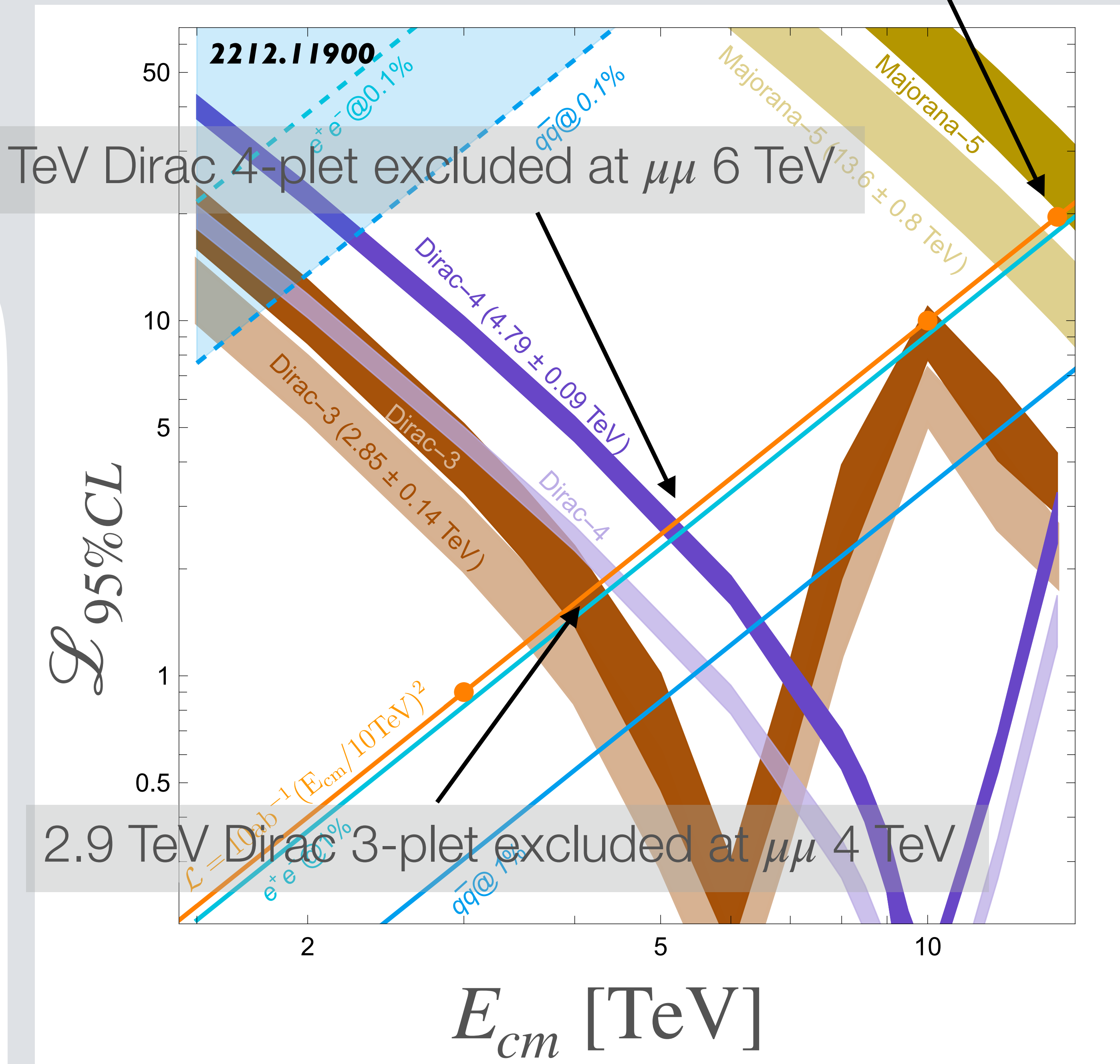
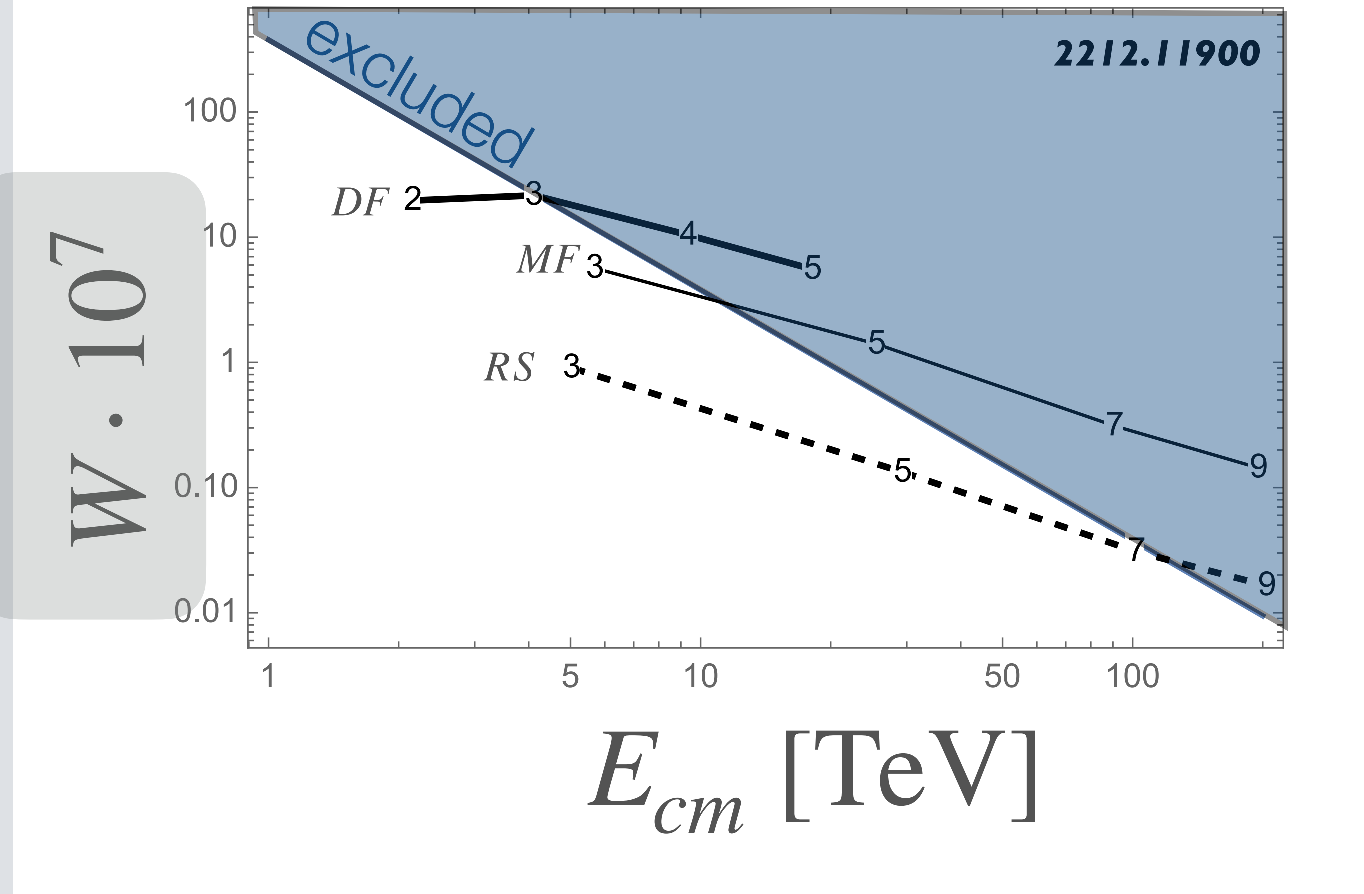
14 TeV Majorana 5-plet excluded at $\mu\mu$ 14 TeV

4.8 TeV Dirac 4-plet excluded at $\mu\mu$ 6 TeV

2.9 TeV Dirac 3-plet excluded at $\mu\mu$ 4 TeV

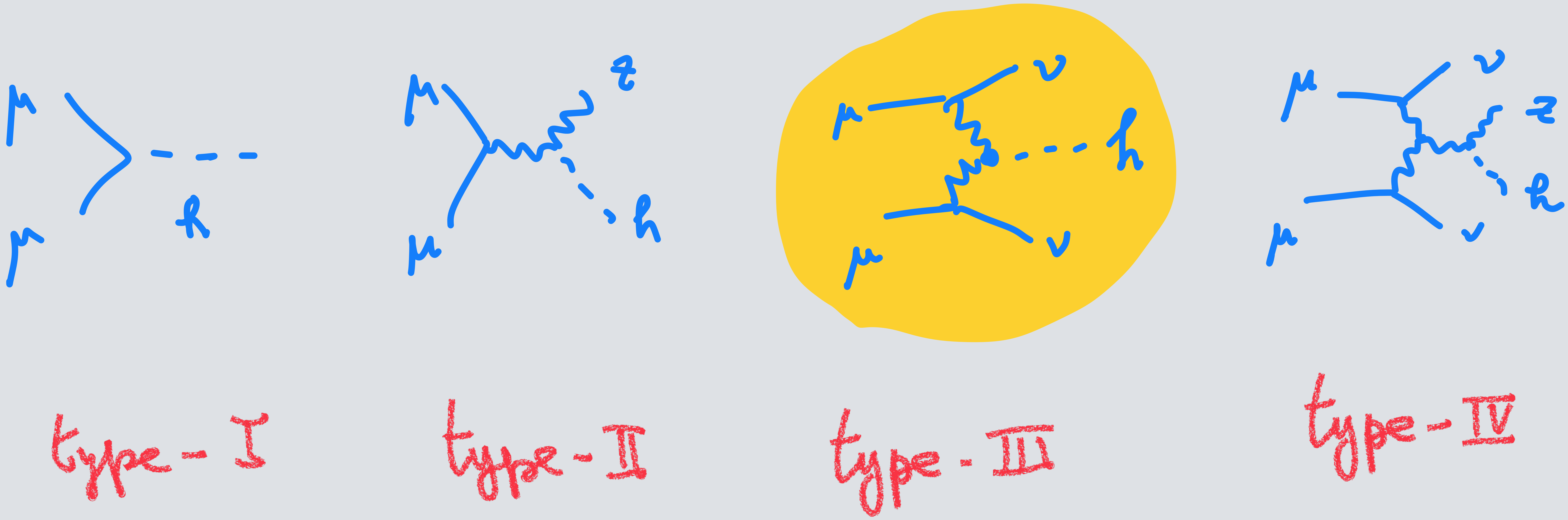




SYNERGIES AMONG STAGES

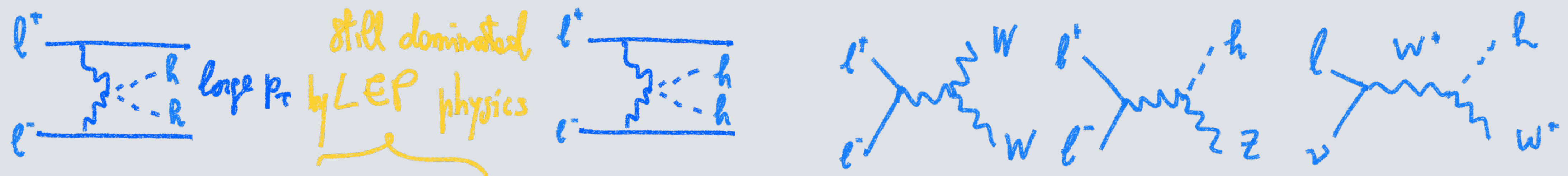
$WW \to h$ is the most abundant reaction for heavy SM production processes

Types of Higgs factories



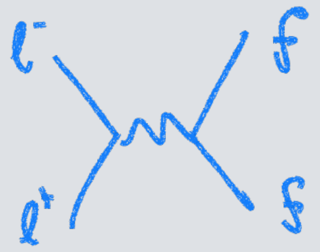
IS THE HIGGS BOSON POINT-LIKE?

Strongly interacting higgs (and top)



$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$



$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

$1/f \sim g_\star/m_\star$

$1/(g_\star f) \sim 1/m_\star$

$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

$$\ell_{top} \sim 1/m_\star \sim \ell_{Higgs}$$

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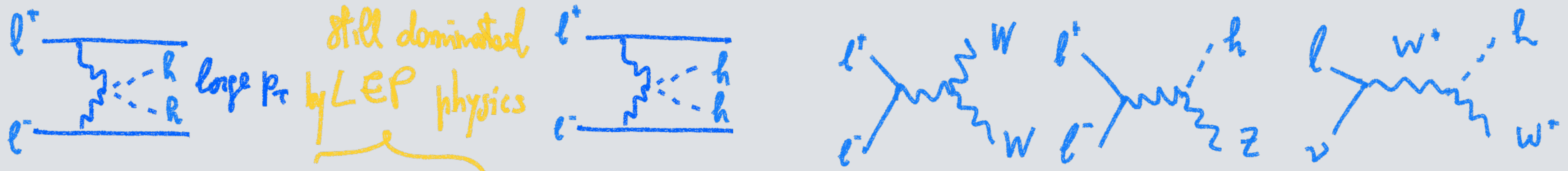

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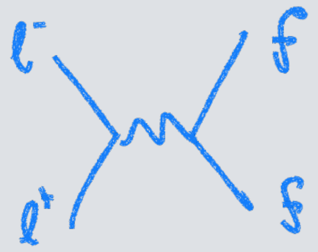

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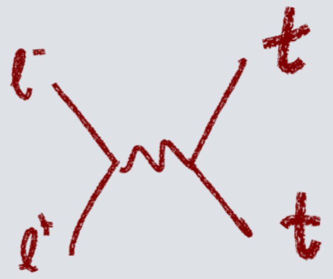

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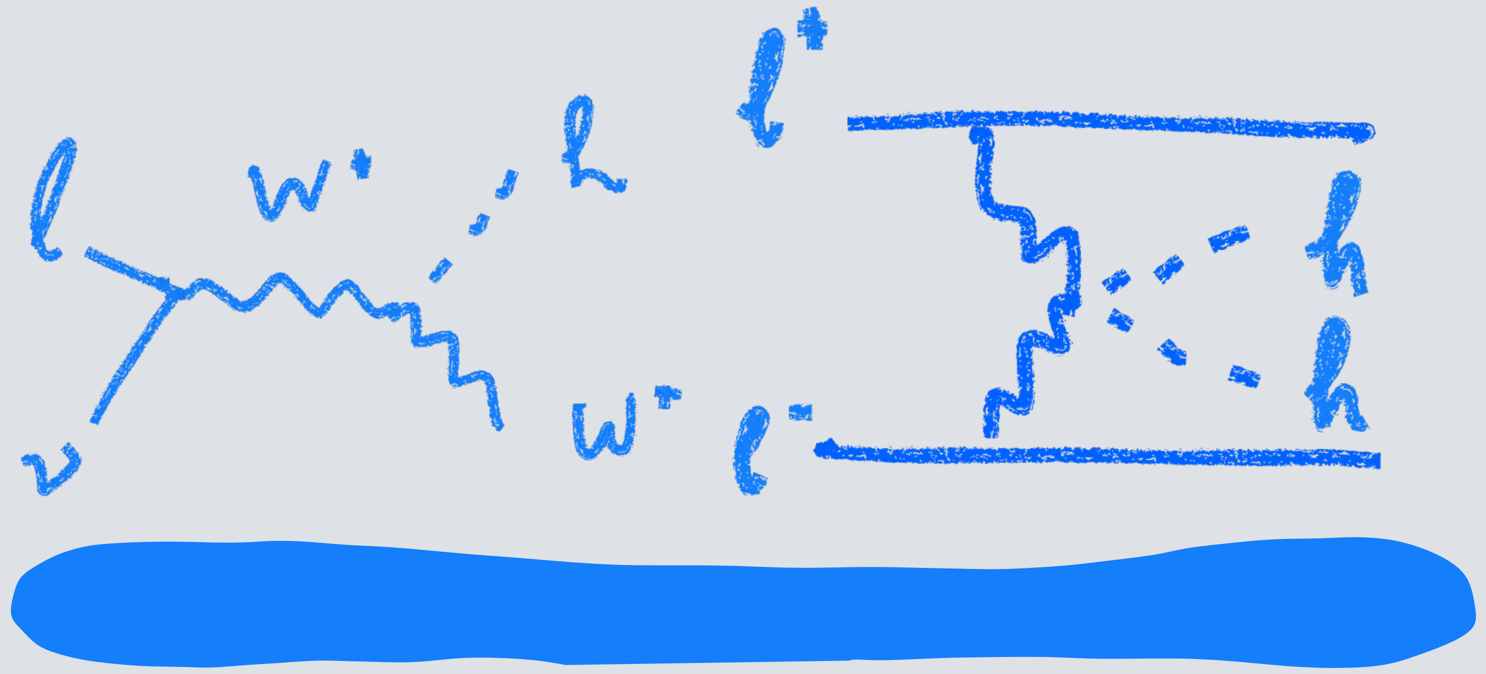
IS THE HIGGS BOSON POINT-LIKE?

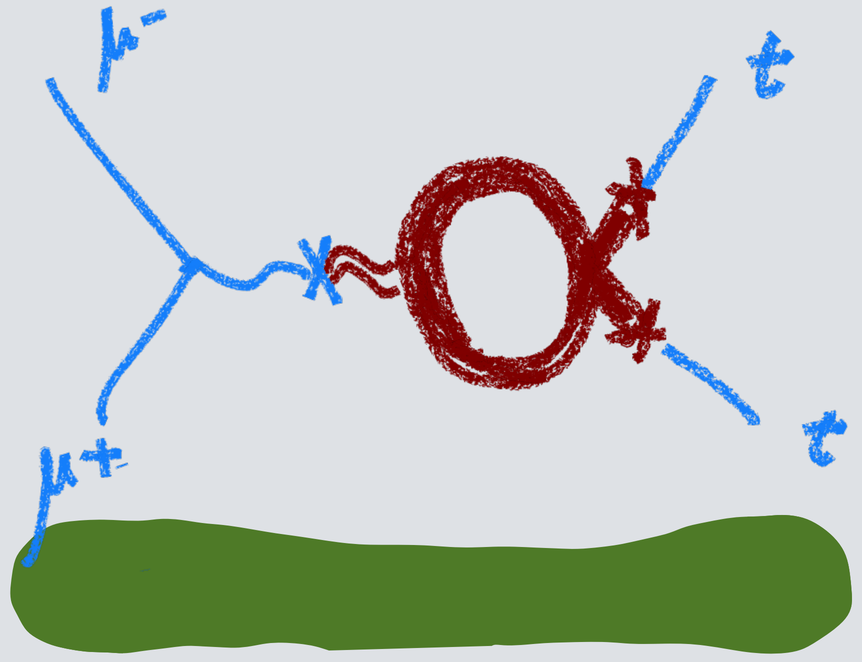
Strongly interacting higgs (and top)

point-like beams

"partons",radiative processes



contact interactions



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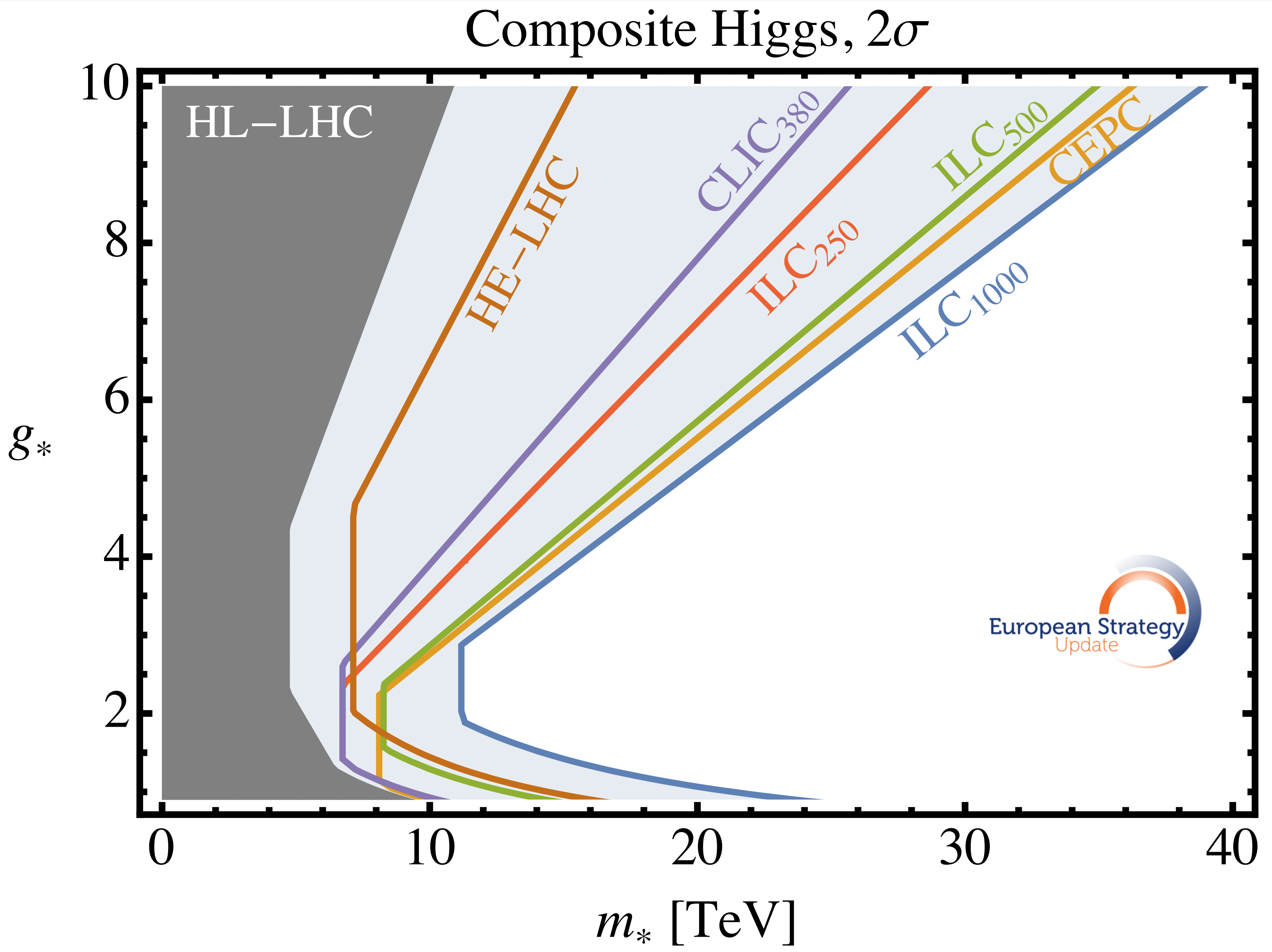
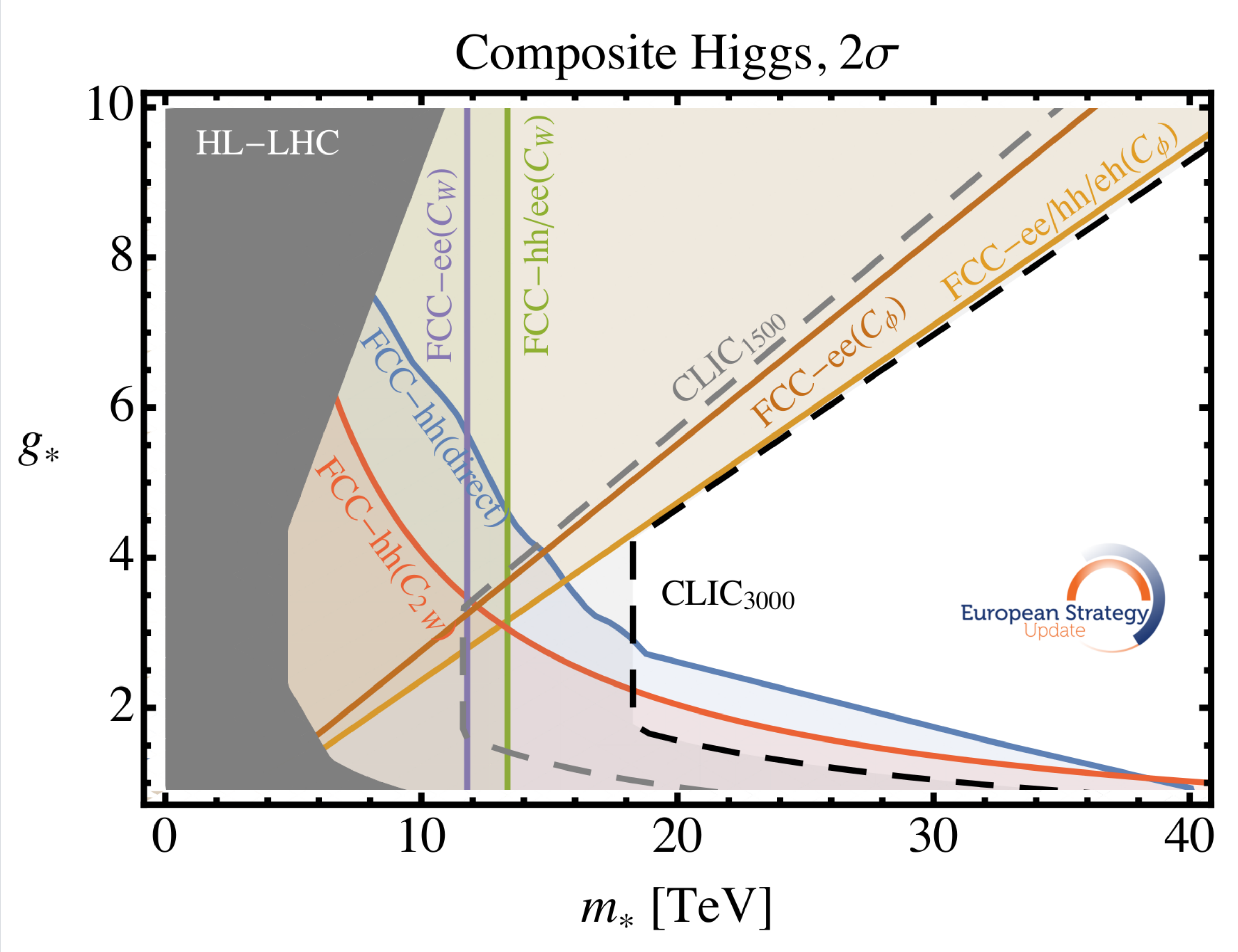




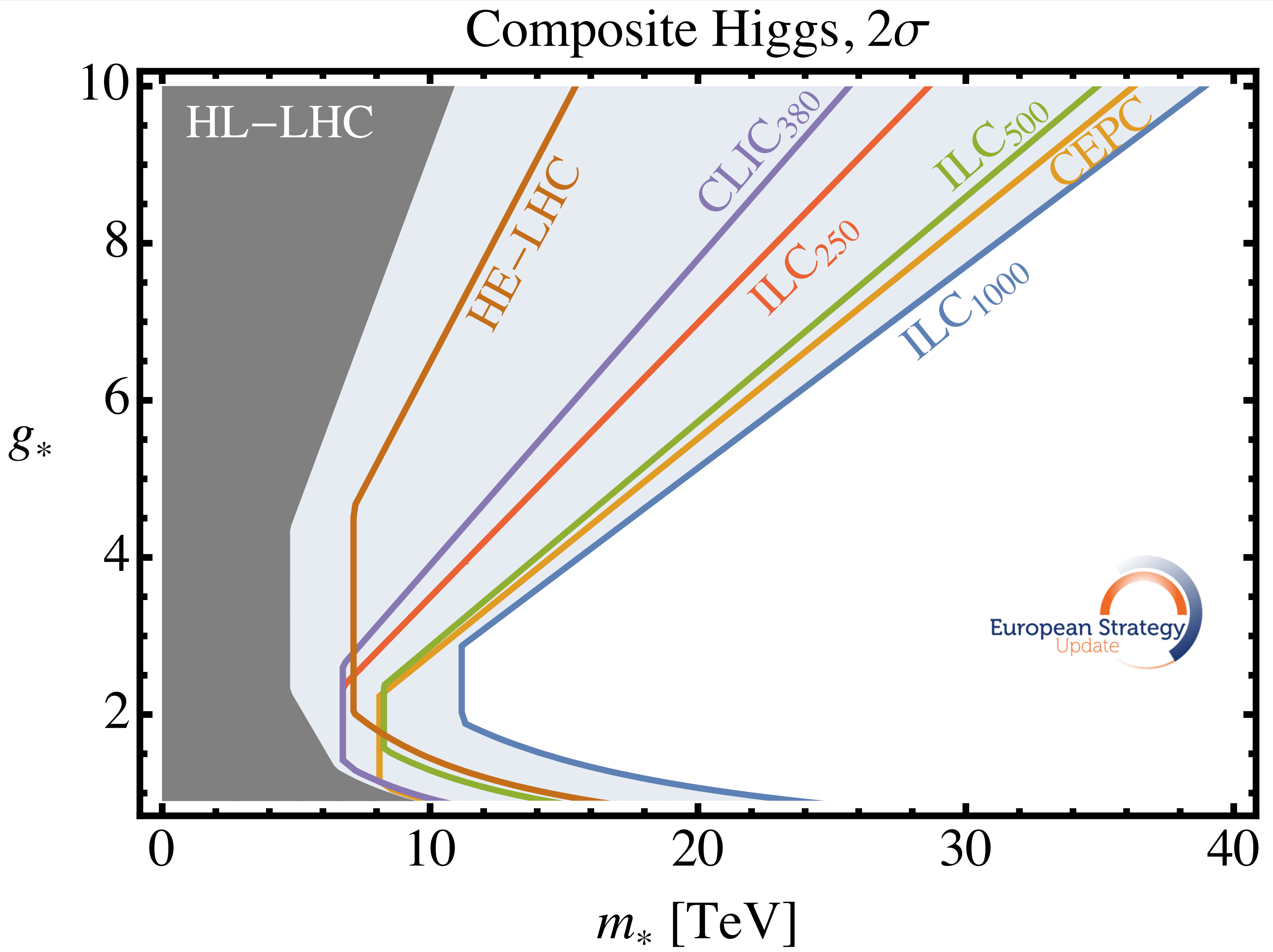
compositeness at few TeV @ HL-LHC

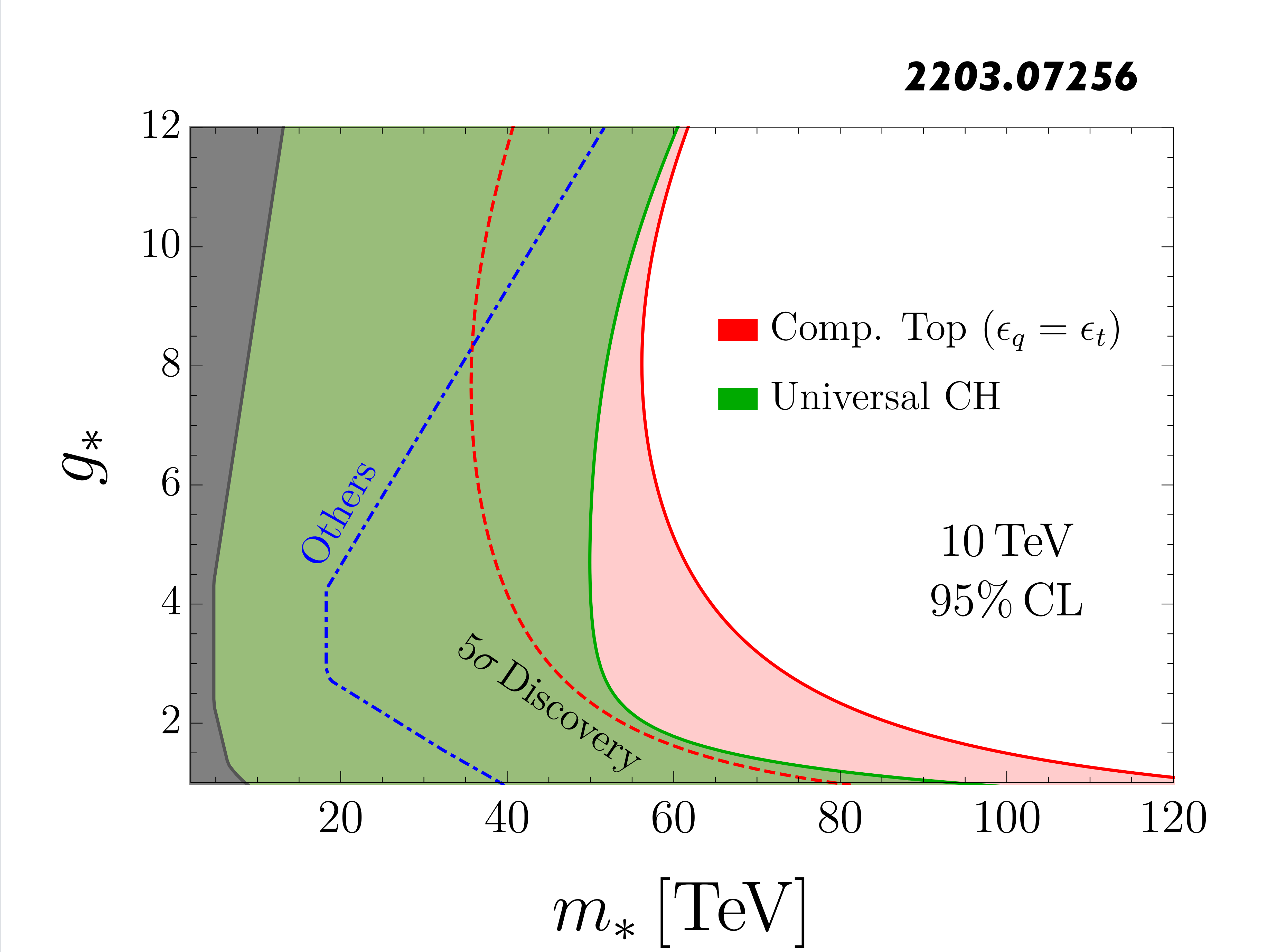
compositeness at few 10 TeV

IS THE HIGGS BOSON POINT-LIKE?

Strongly interacting higgs (and top)

Unique avenue to explore weak interactions
far offshore from the weak scale





compositeness at few TeV @ HL-LHC

compositeness at few 100 TeV

WHAT IS THE HIGGS BOSON POTENTIAL LIKE?

Origin of electroweak symmetry breaking (and of the matter of the Universe)

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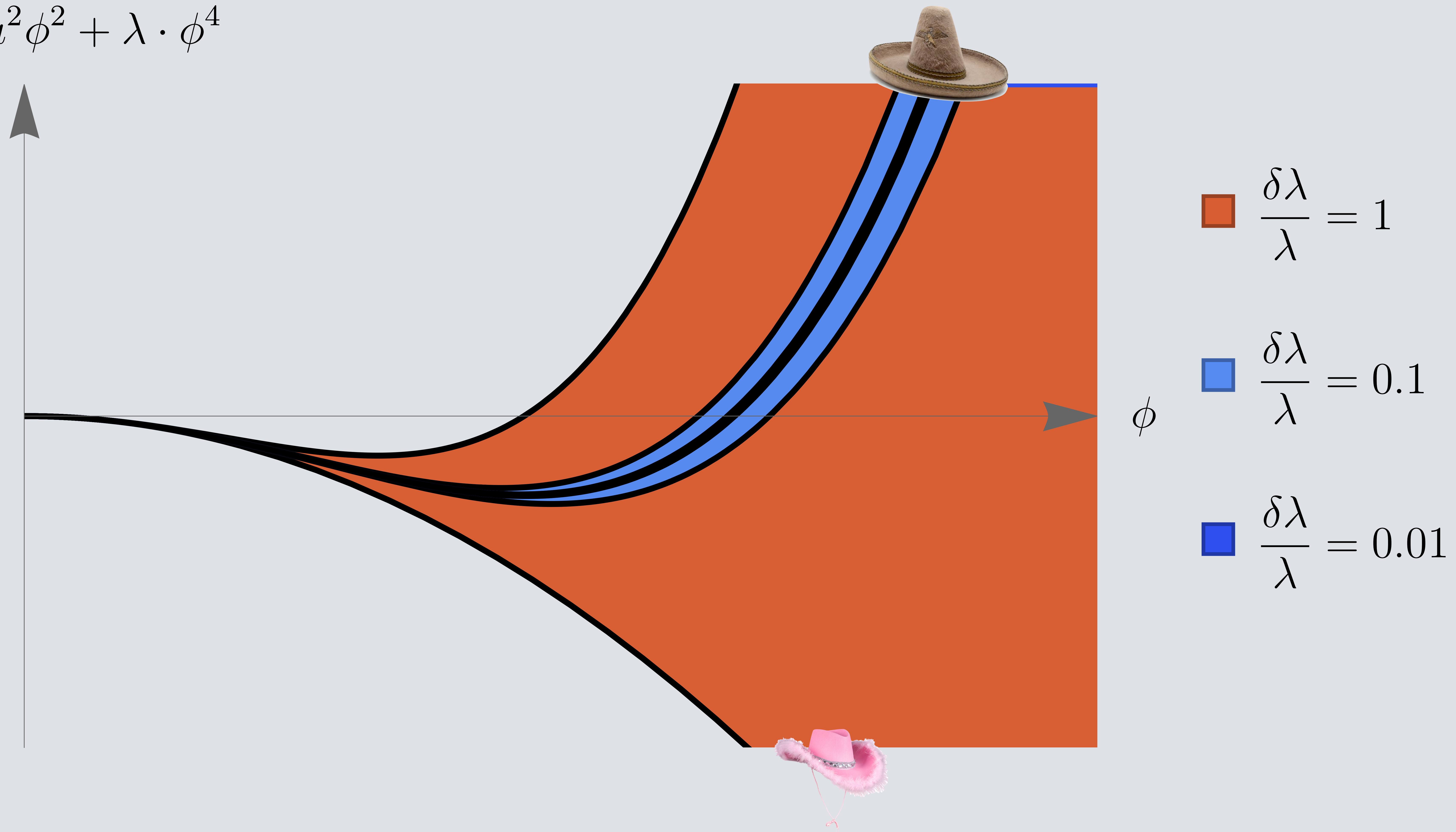
Origin of electroweak symmetry breaking (and of the matter of the Universe)

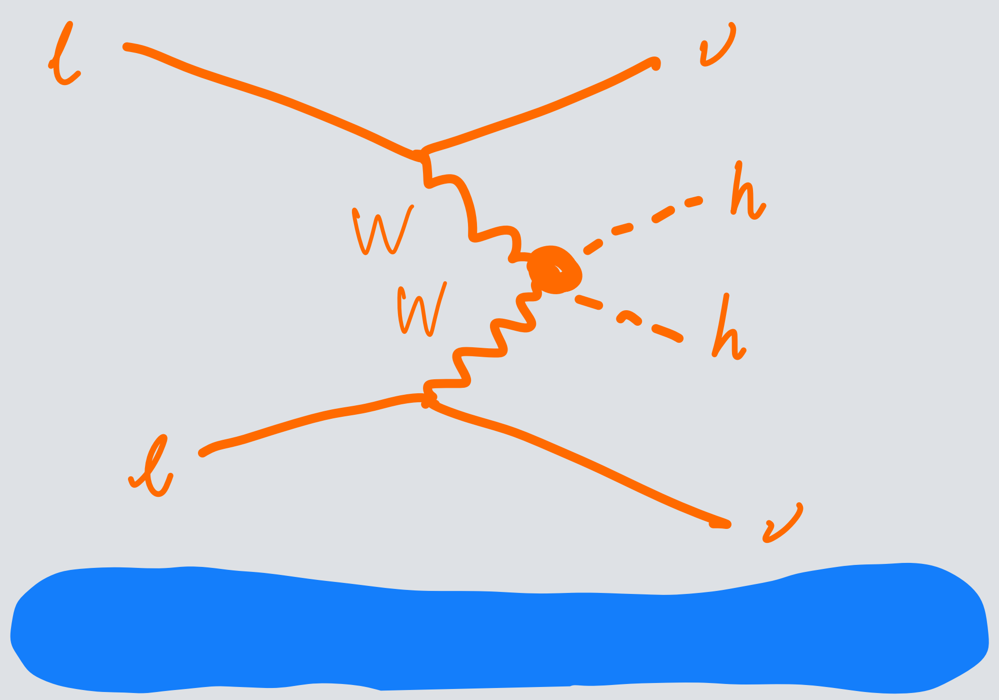
$$V(\phi) = \mu^2\phi^2 + \lambda \cdot \phi^4$$

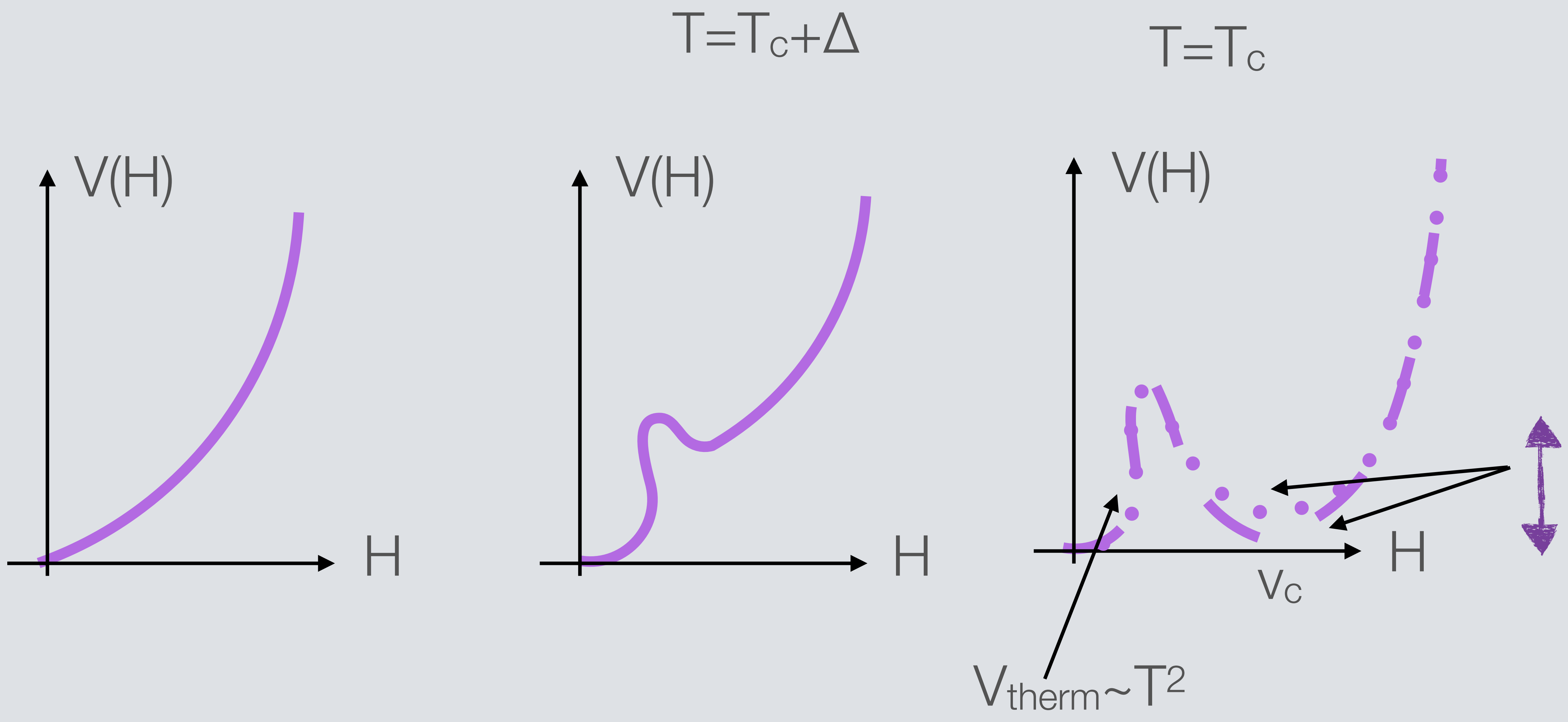


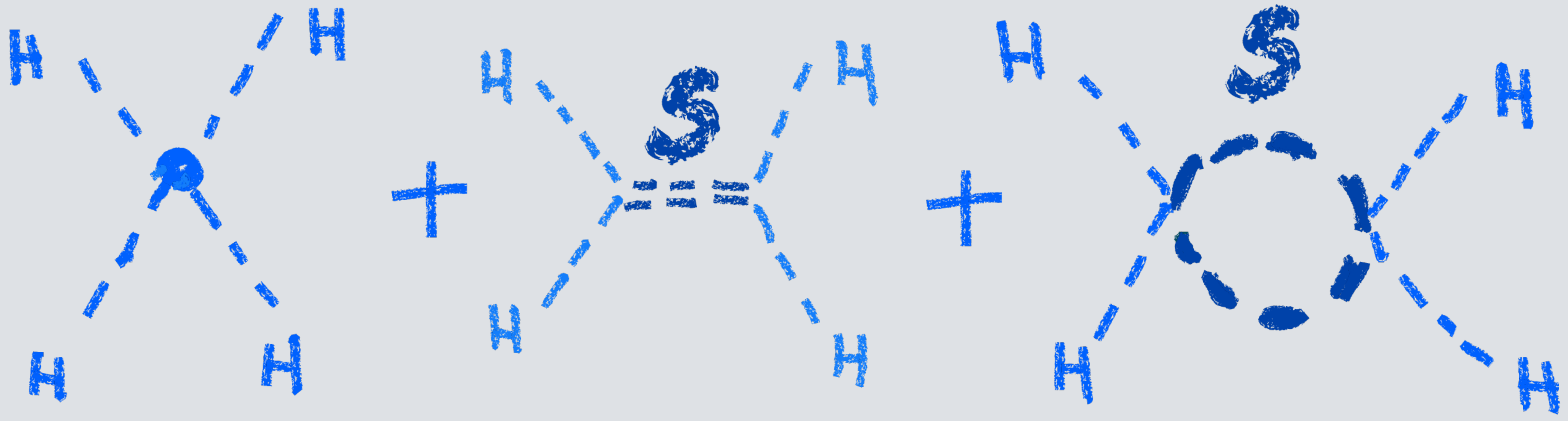
WHAT IS THE HIGGS BOSON POTENTIAL?

$\mu^+\mu^- \to hh$ and the electroweak phase-transition

- High-Energy lepton collider has large flux of "partonic" W bosons



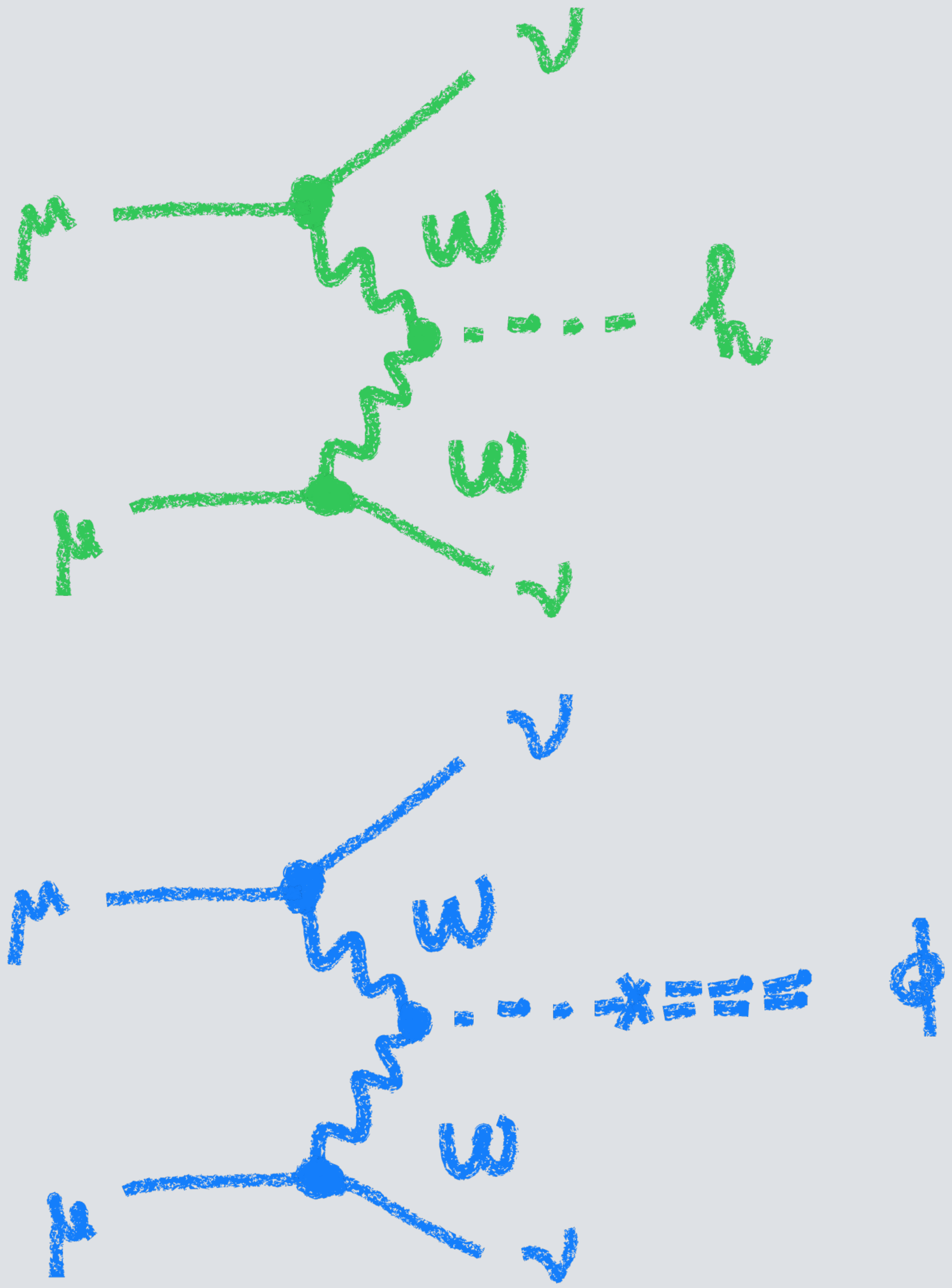


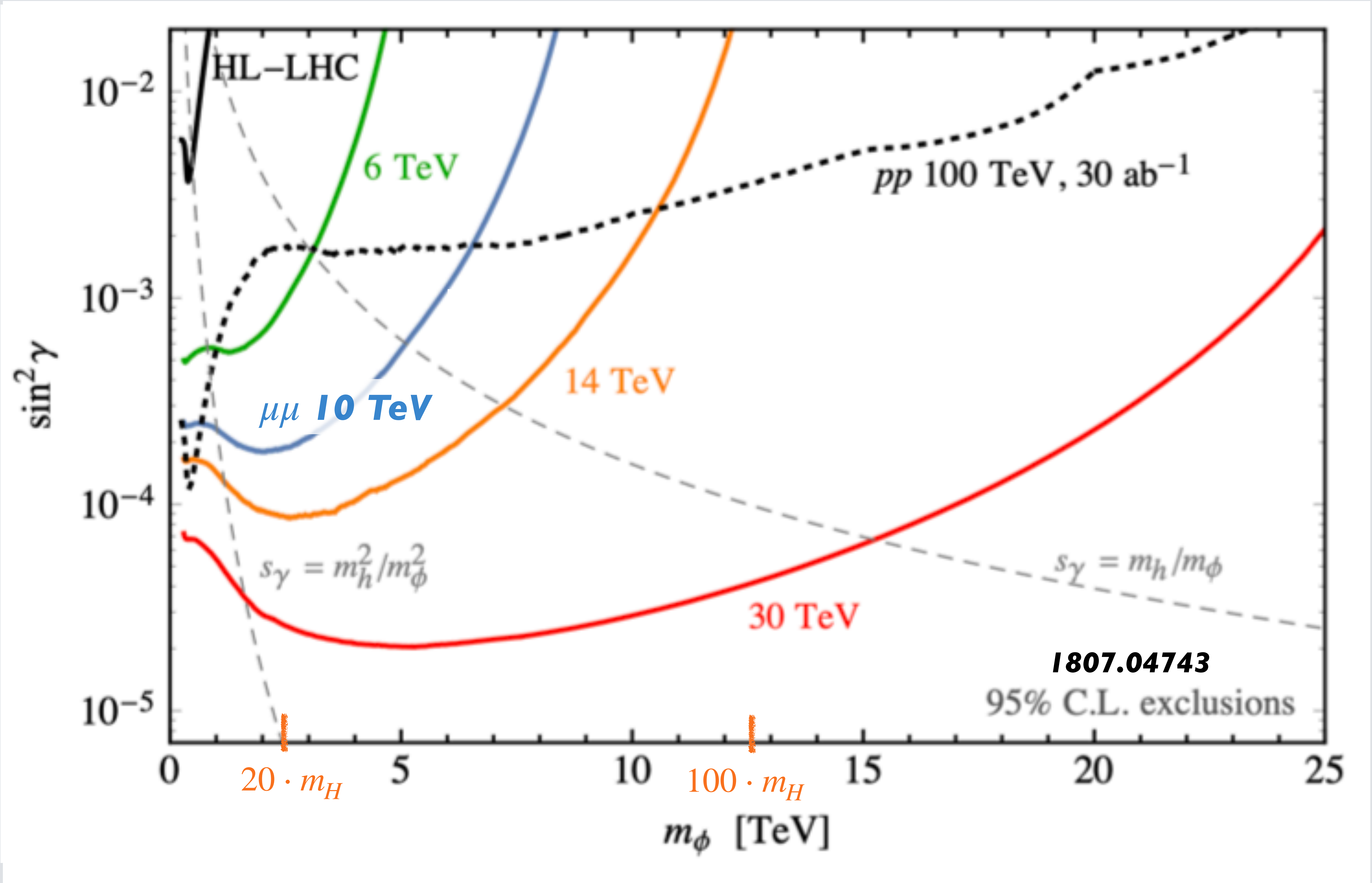


Singlet tree and loop makes V(0,v) deeper

WHAT MODIFIES THE HIGGS BOSON POTENTIAL?

$\mu^+\mu^- \to h\nu\nu$ and the electroweak phase-transition

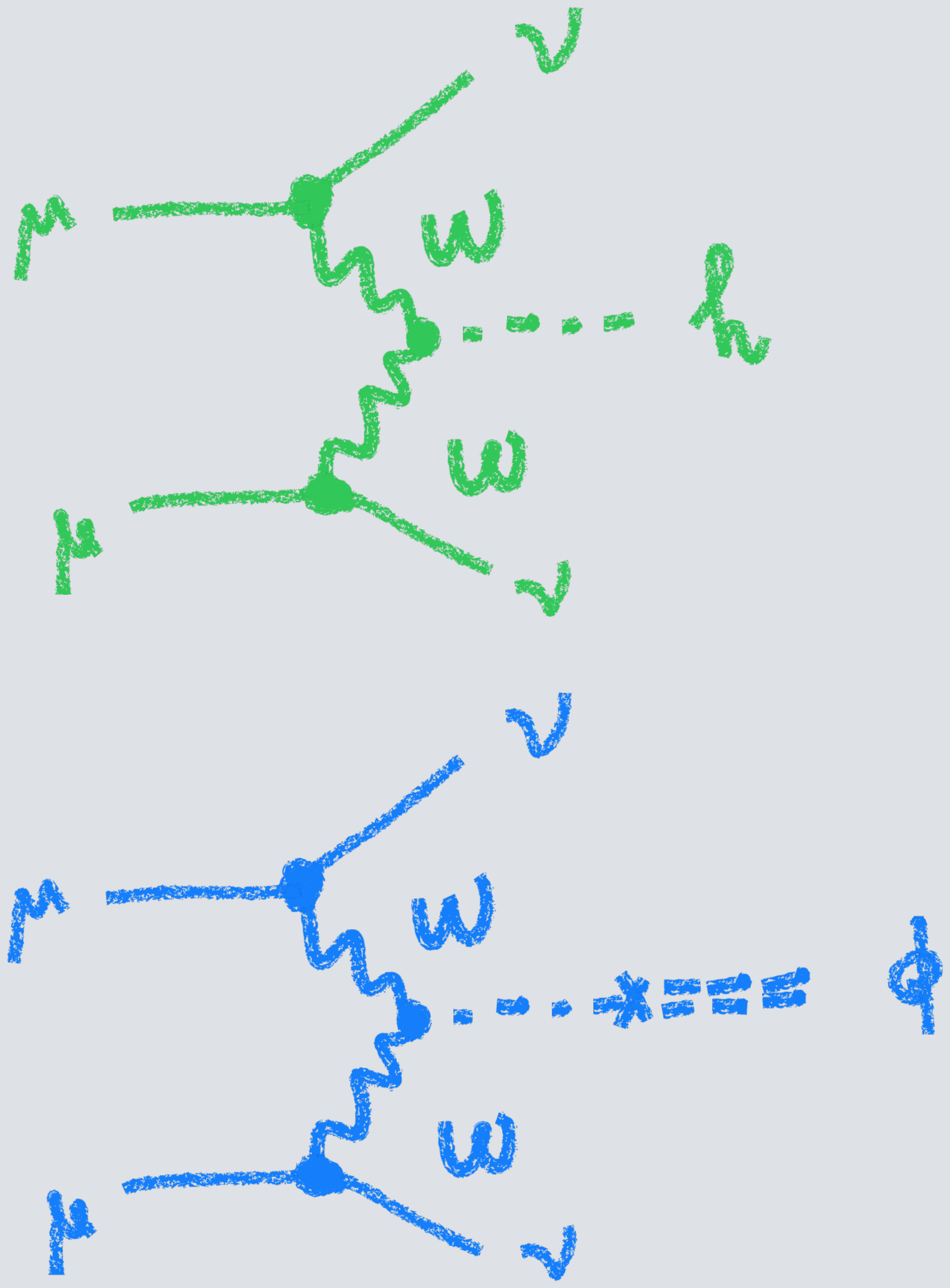


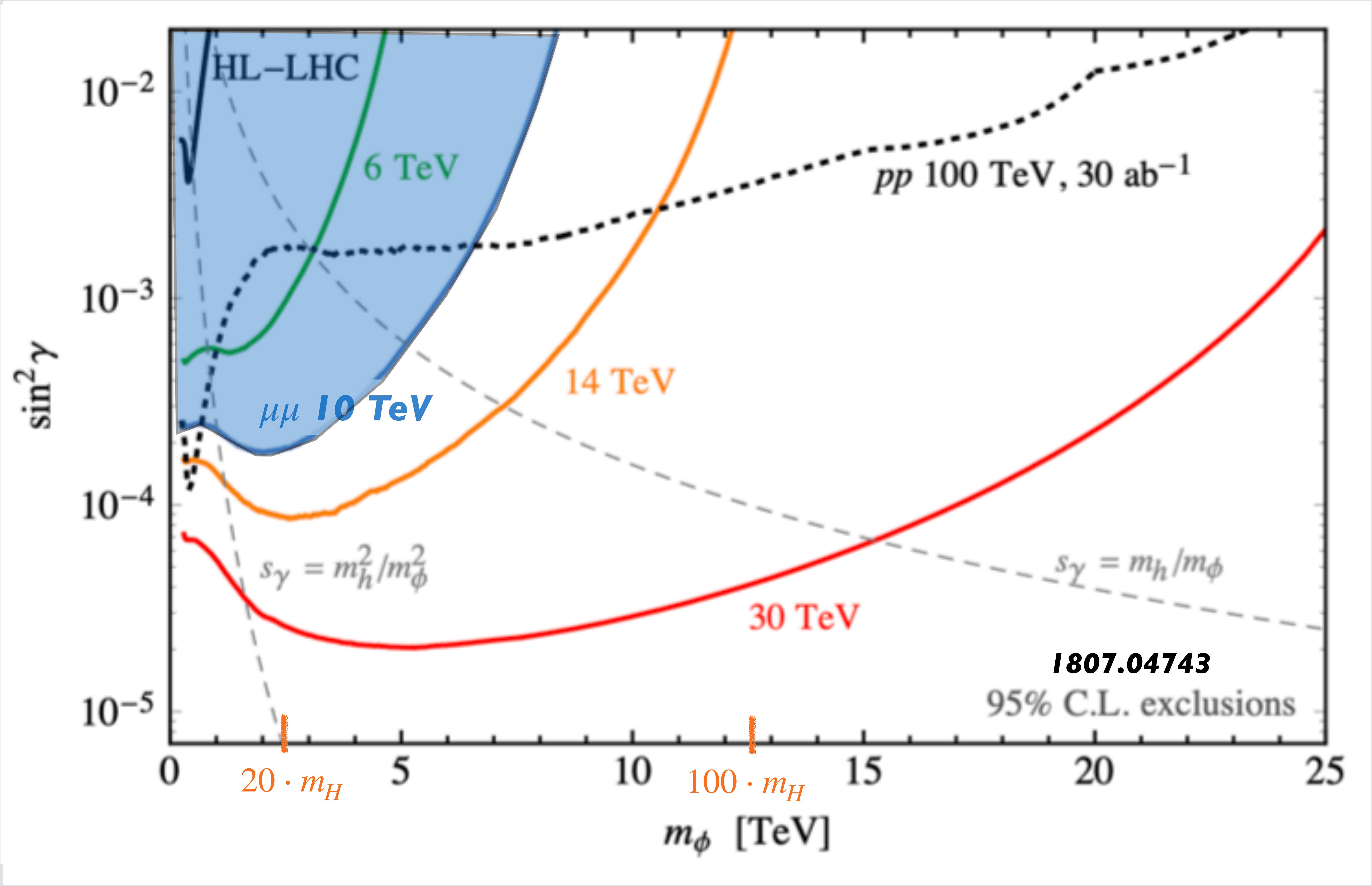


Usually we assume "previous machine" measures a "deviation" then "next machine " discovers what causes it. At $\mu\mu$ collider "next" and "previous" happen synchronously.

WHAT MODIFIES THE HIGGS BOSON POTENTIAL?

$\mu^+\mu^- \to h\nu\nu$ and the electroweak phase-transition





Usually we assume "previous machine" measures a "deviation" then "next machine " discovers what causes it. At $\mu\mu$ collider "next" and "previous" happen synchronously.

Roberto Franceschini - LHCP 2023 - https://indico.cern.ch/event/1198609/contributions/5368143/

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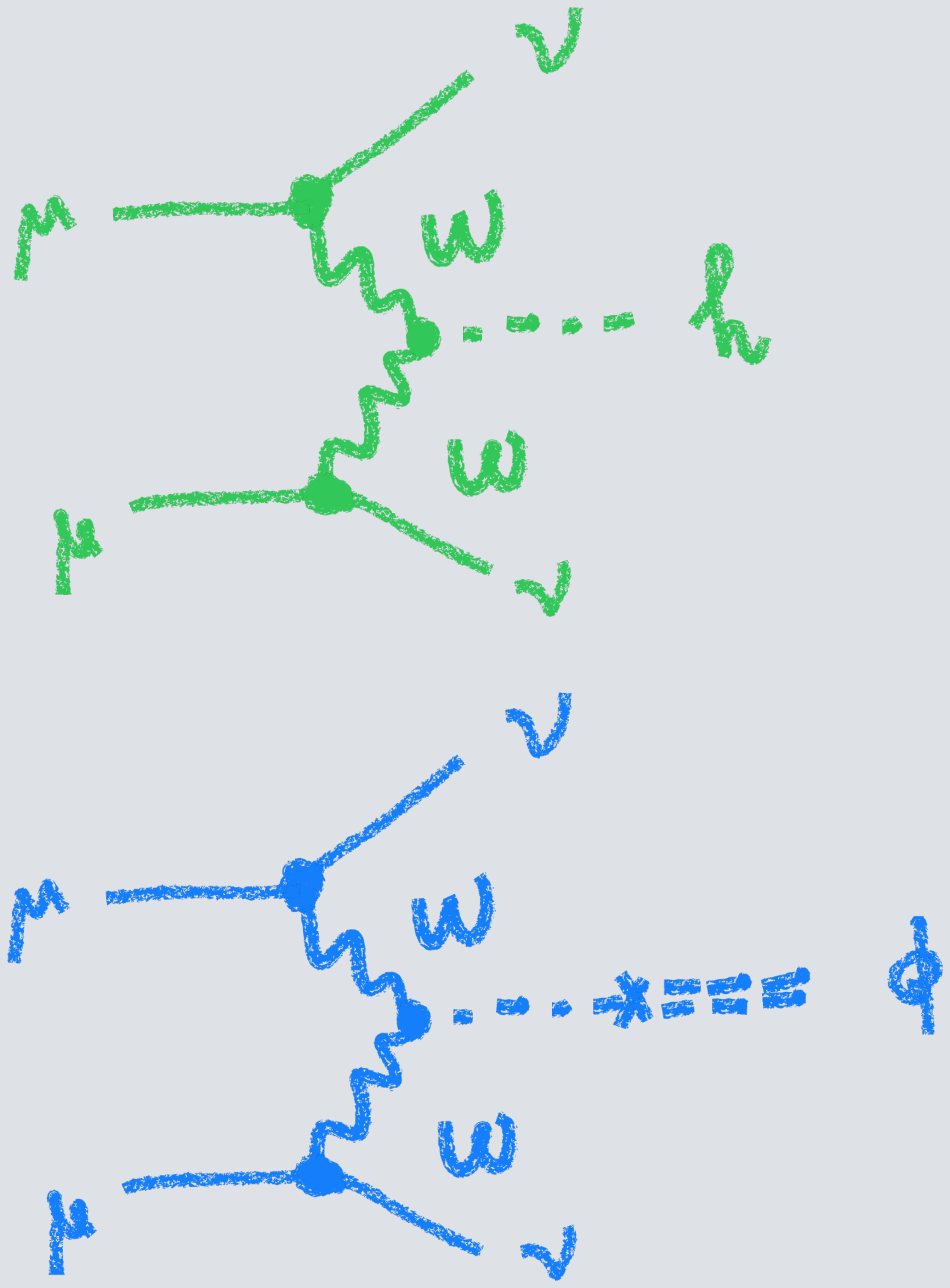

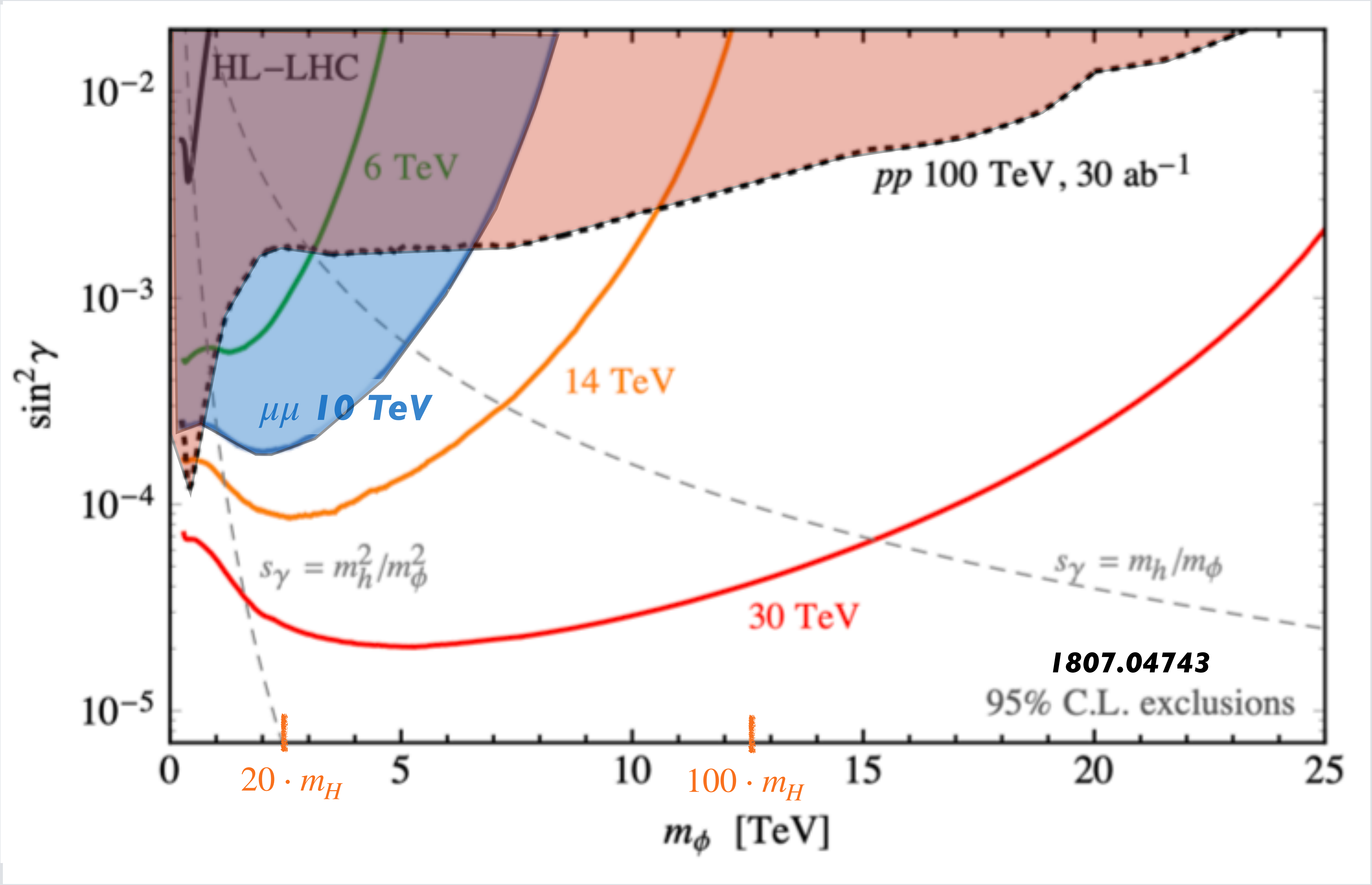

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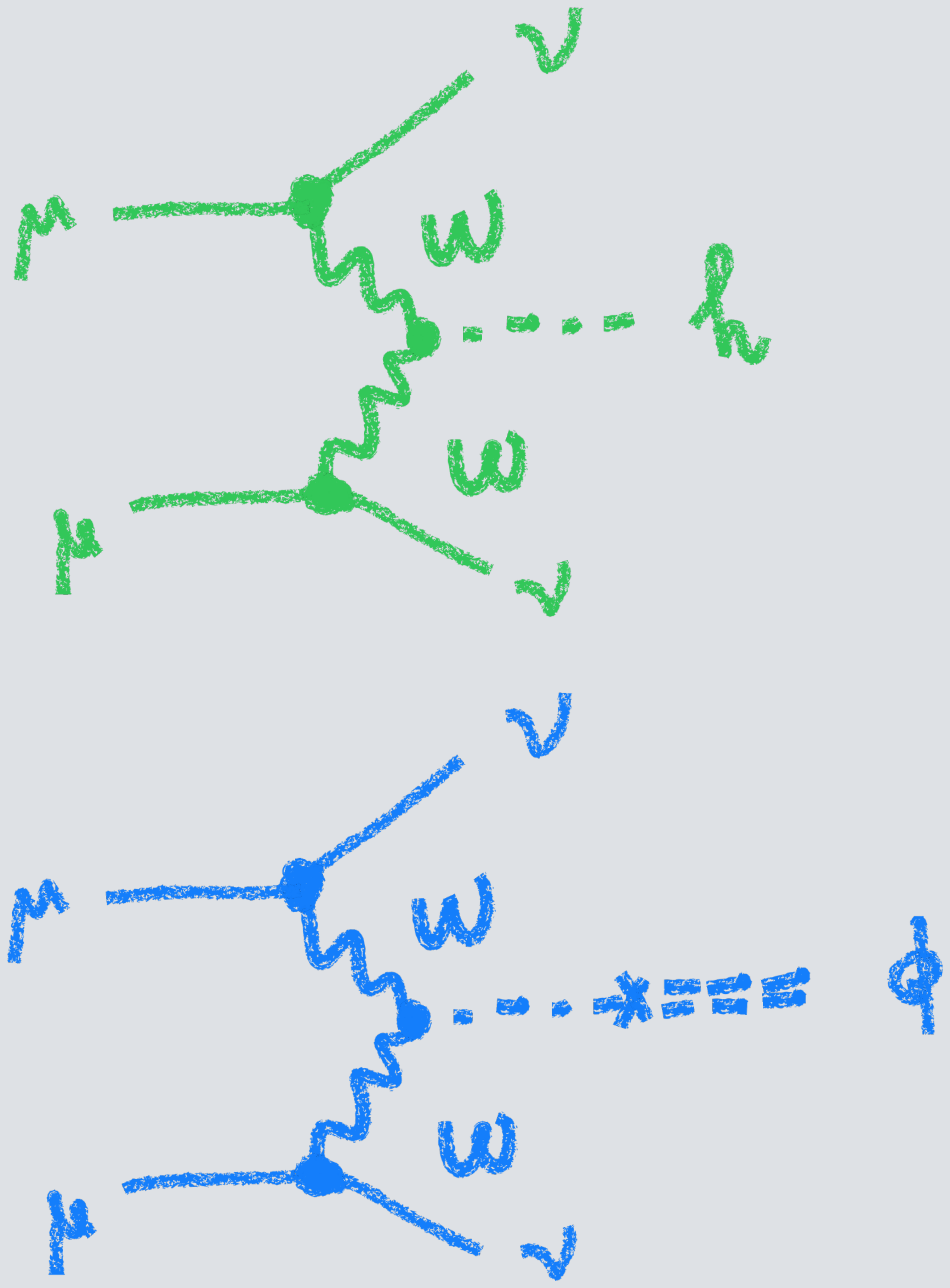

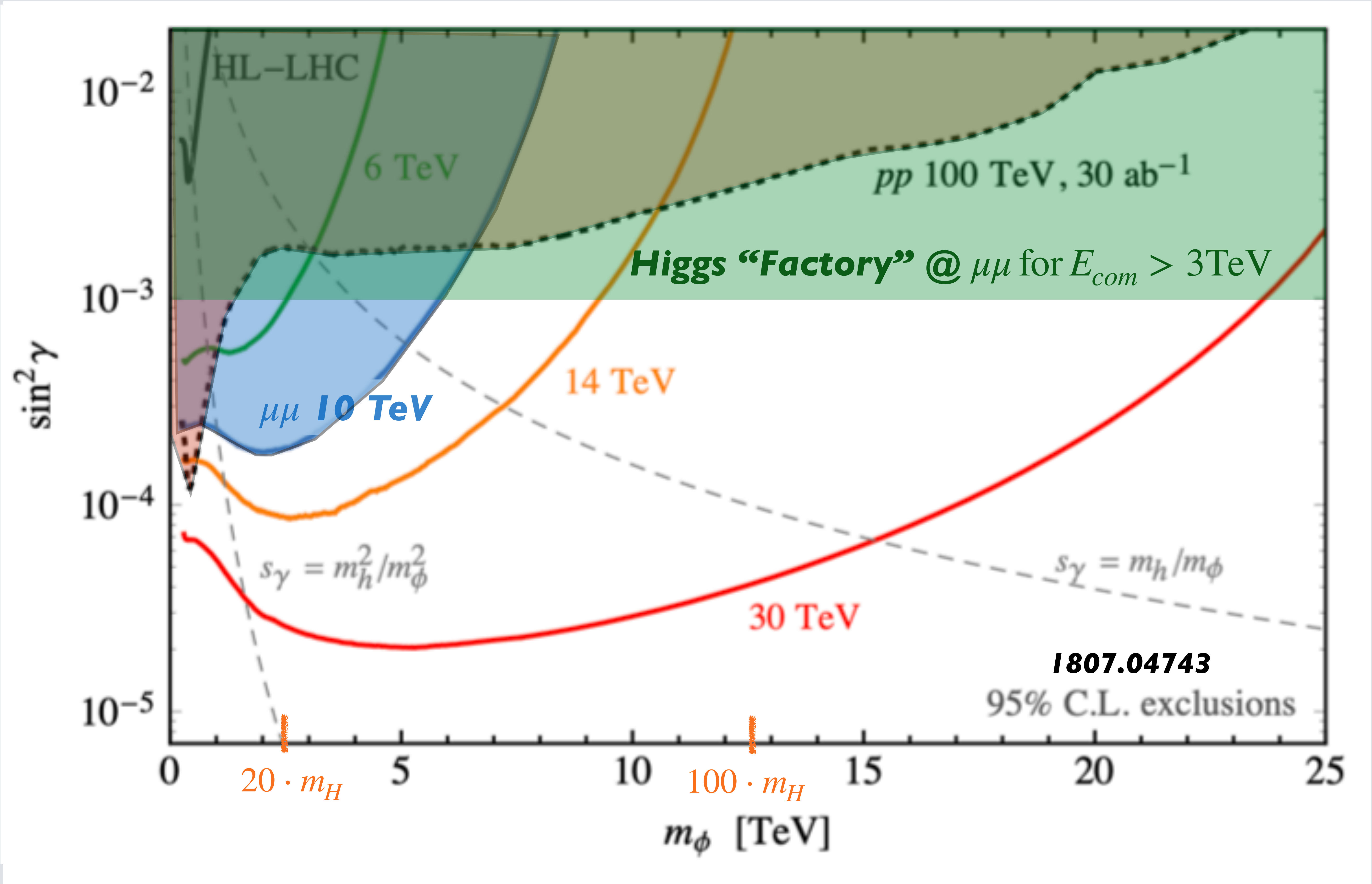

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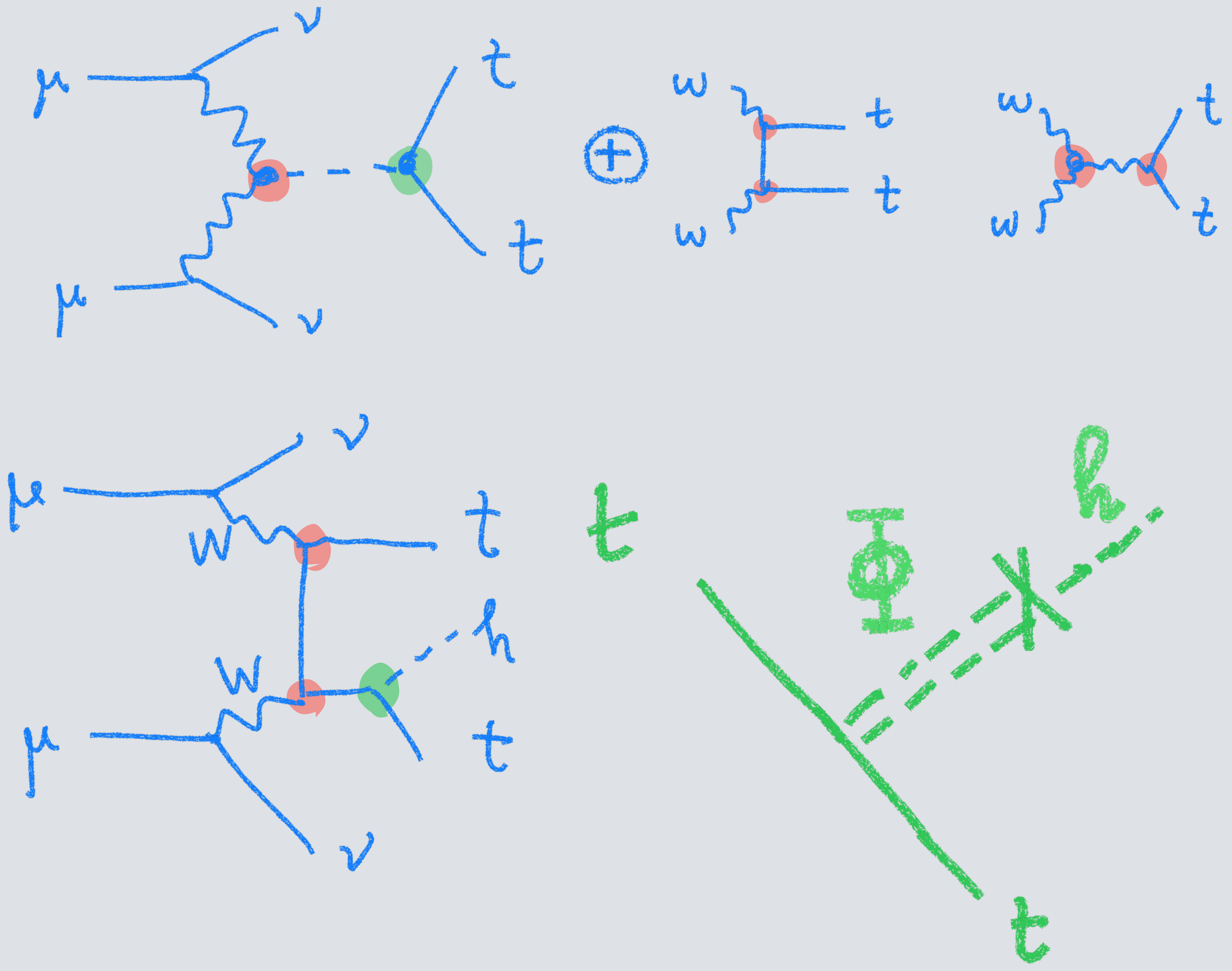
$\mu^+\mu^- \to tt\nu\nu$ and $\mu^+\mu^- \to tth$



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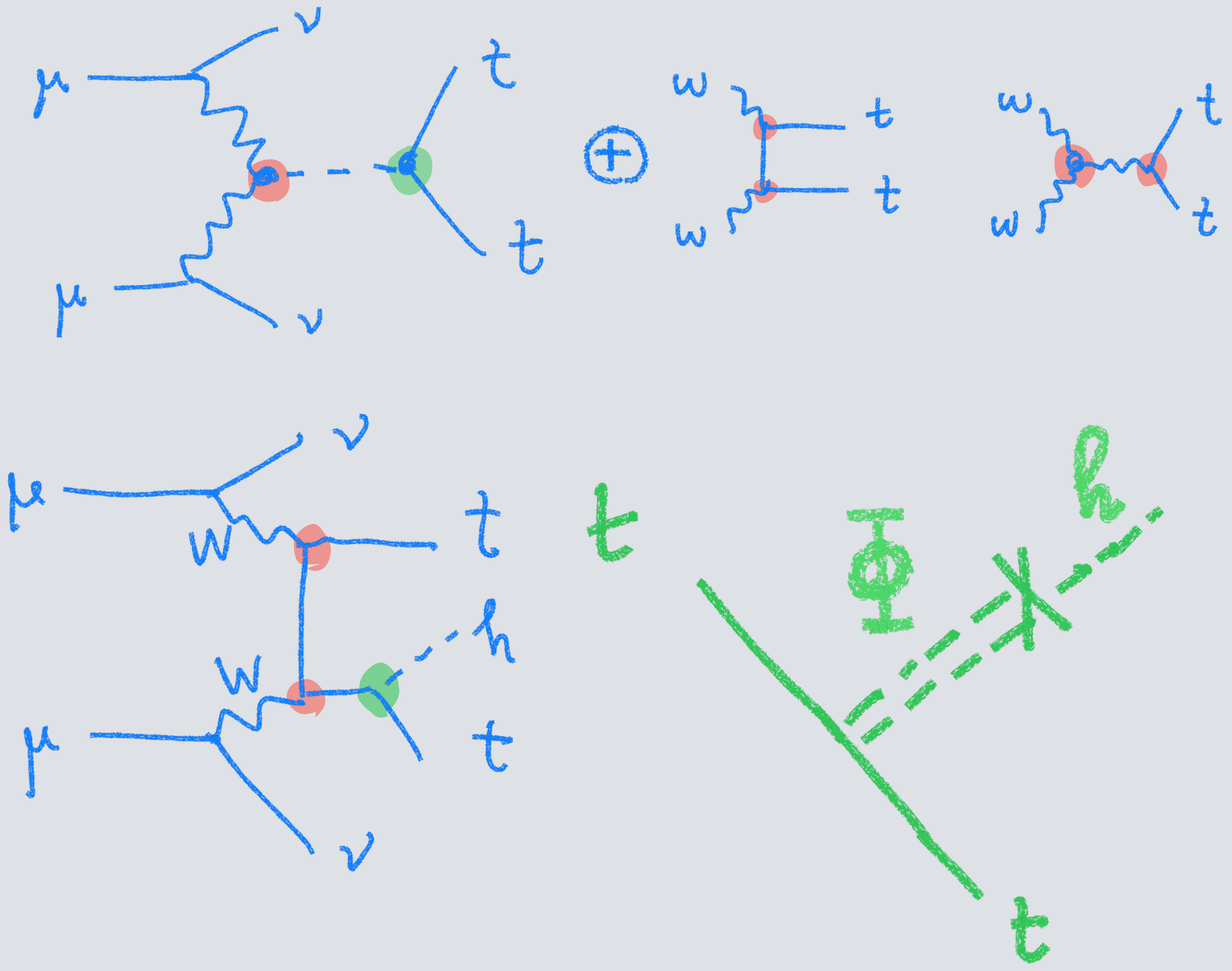

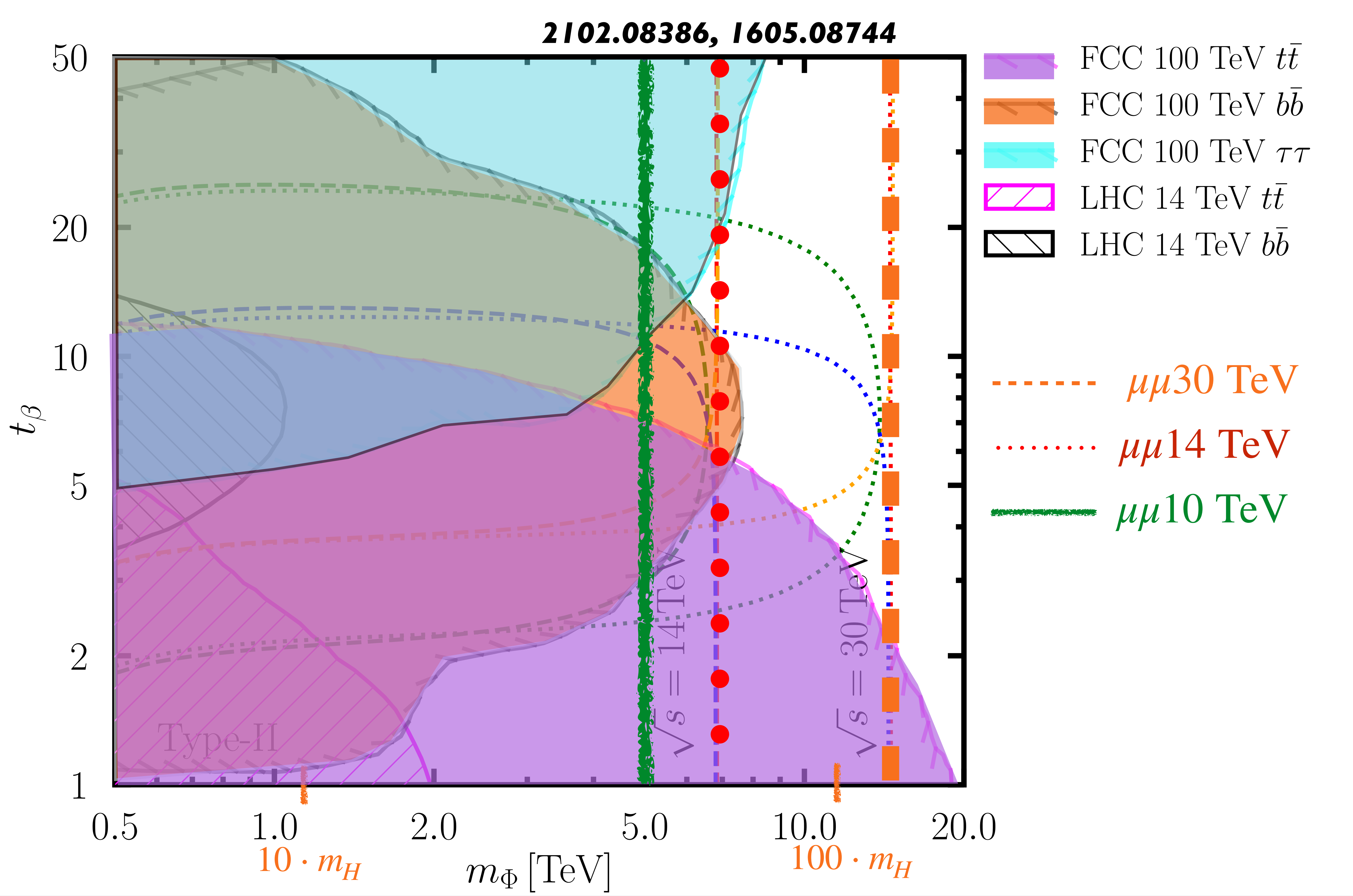

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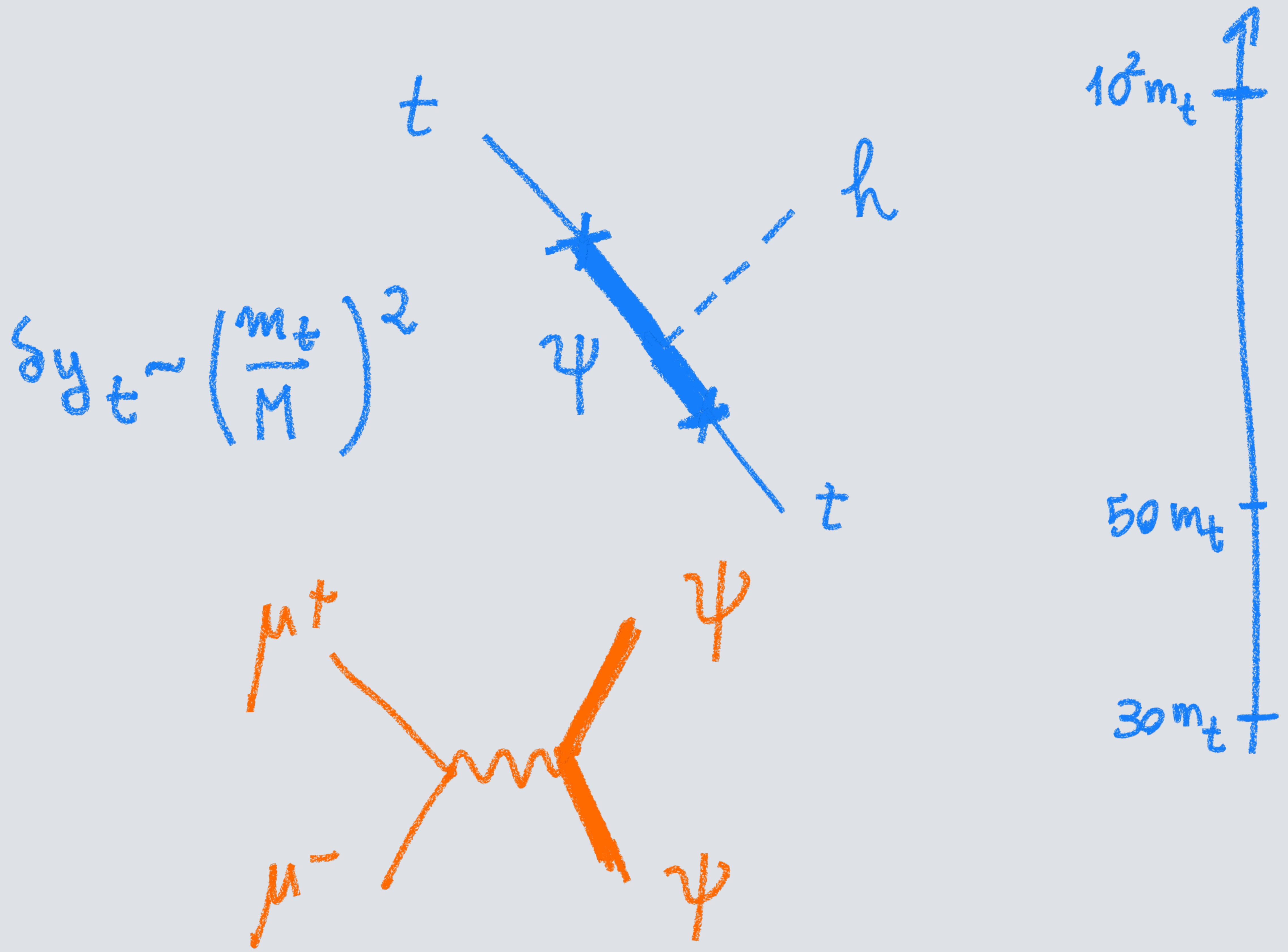

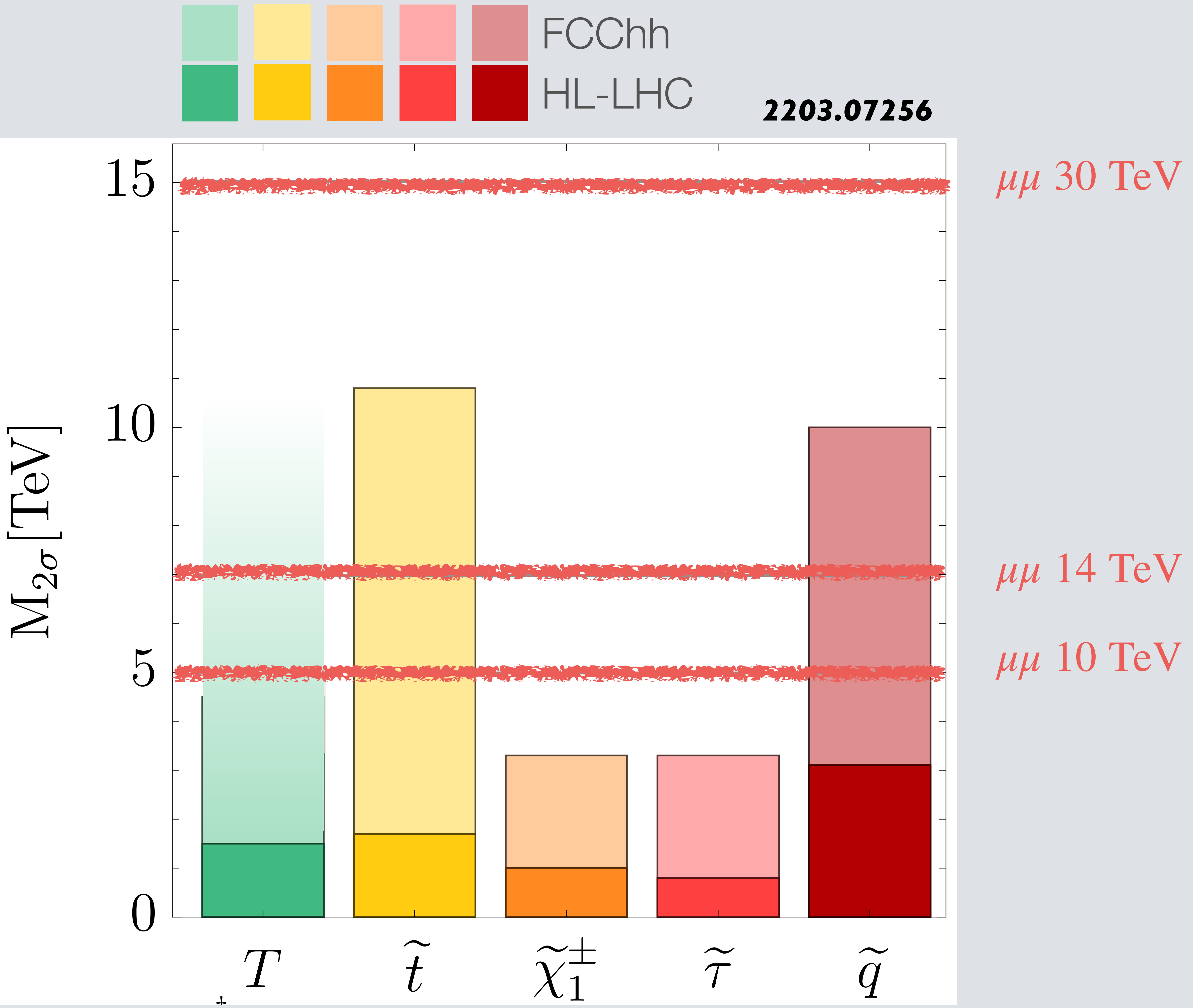

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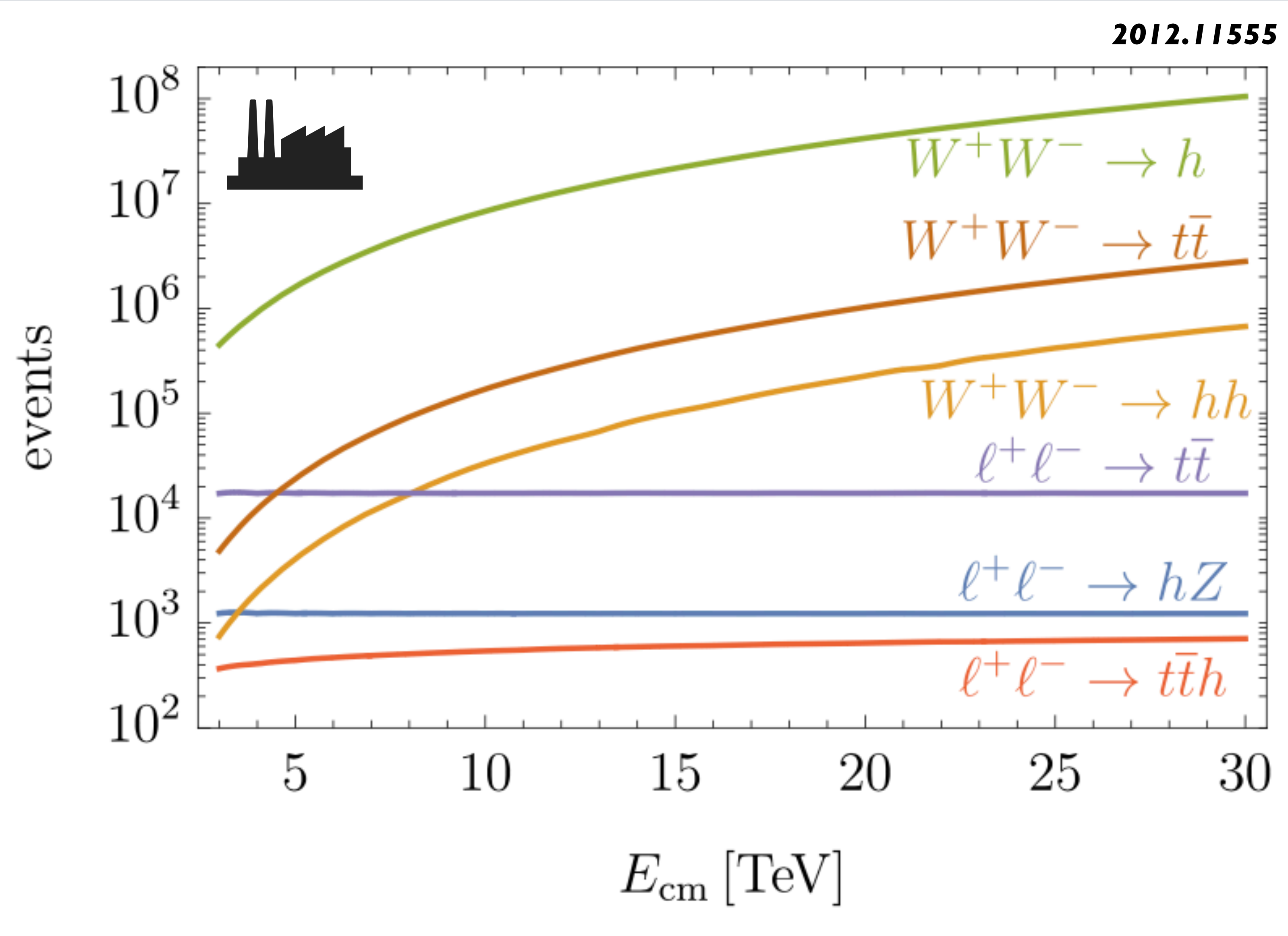
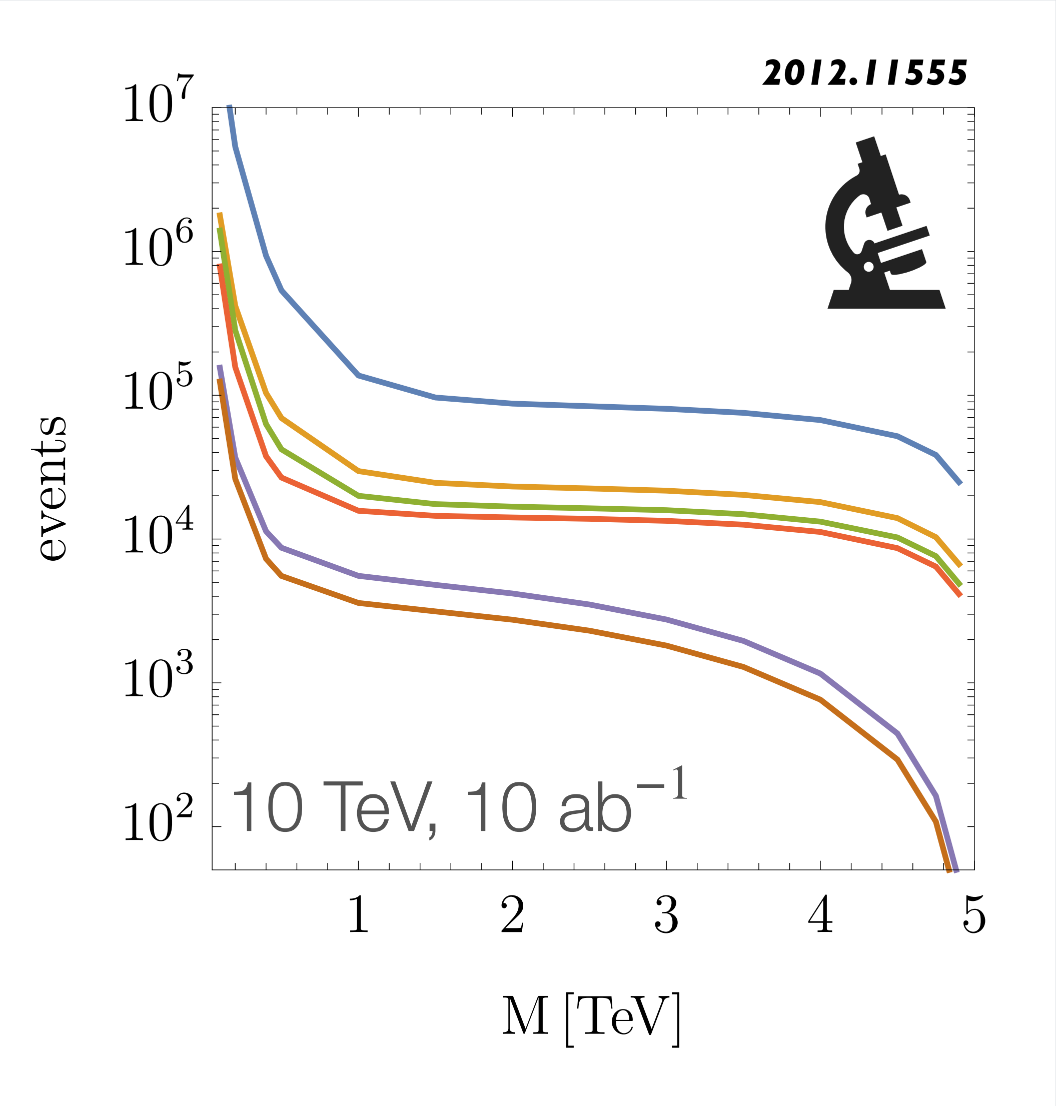
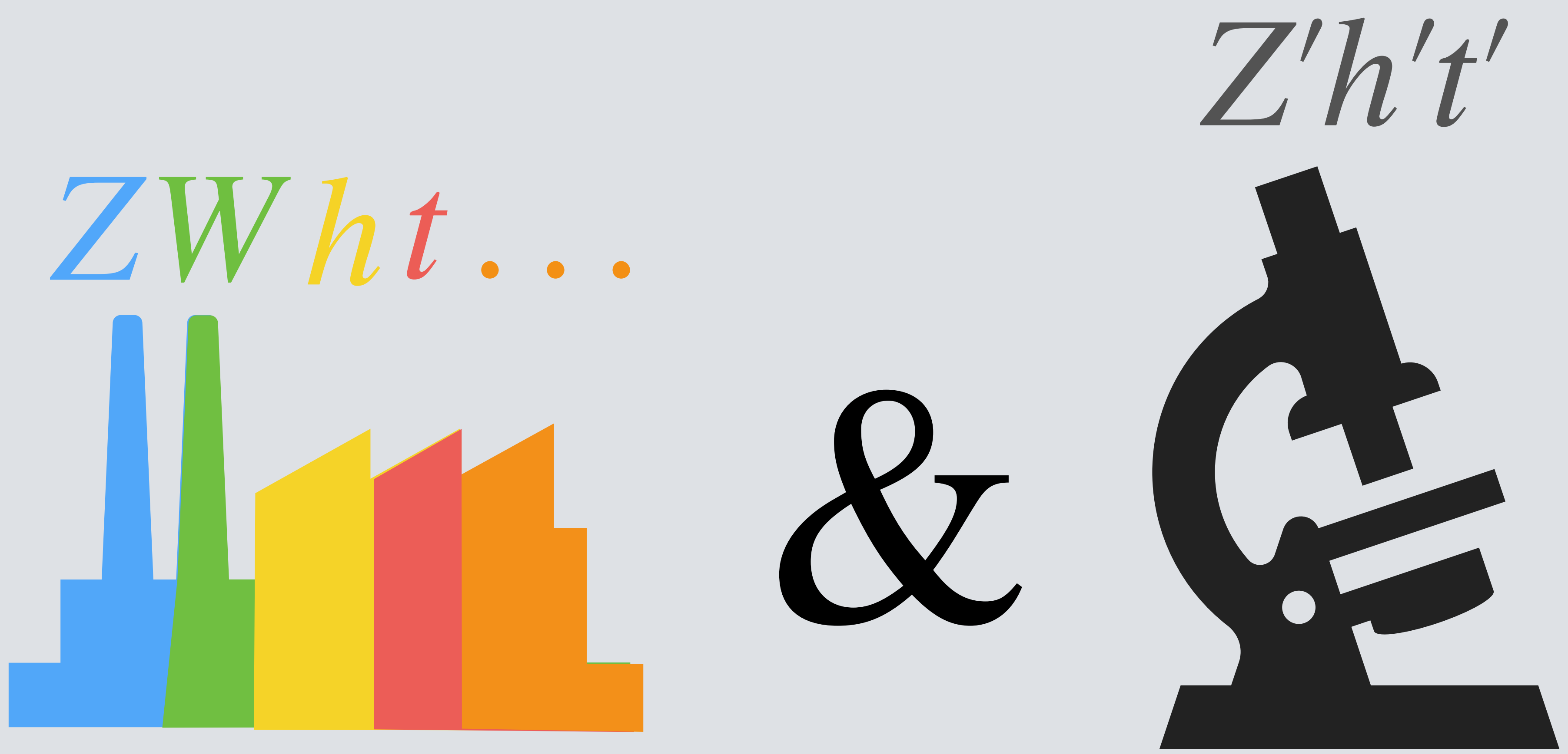
HUGE RATE FOR SM OBJECTS IN CLEAR ENVIRONMENT





- Stages at several TeV: e.g. 3 TeV and 10 TeV
- possibility to foresee higher energy runs, e.g. 30 TeV
- $$\mathscr{L} = 10\text{ab}^{-1}\left(\frac{E_{cm}}{10\text{ TeV}}\right)^2$$
- tens of thousands of new physics states
- **millions** of top quarks and Higgs bosons, **billions** of vector bosons, … ("multiplex" factory)



2209.07510

SUMMARY: HIGGS@FC (BY COUPLINGS)

all couplings floated independently | highly model-agnostic

0.1% coupling precision, sensitivity to new physics at $10\ \mathrm{TeV} \simeq 100 \cdot m_h$

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2209.07510

SUMMARY: HIGGS@FC (BY COUPLINGS)

all couplings floated independently | highly model-agnostic

precision reach on effective Higgs couplings from SMEFT global fit

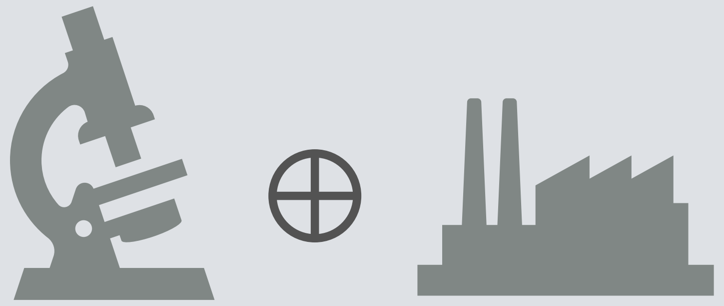
HL–LHC S2 + LEP/SLD (combined in all lepton collider scenarios) | CEPC $Z_{100}/WW_6/240GeV_{20}$ | ILC/C^3 $250GeV_2$ | $CLIC$ $380GeV_1$ | MuC $3TeV_1$

- Higgs factory at 3 TeV
- $10\times$ Higgs factory at 10 TeV
- $100\times$ Higgs factory at 30 TeV

International
UON Collider
Collaboration

0.1% coupling precision, sensitivity to new physics at $10\ \mathrm{TeV} \simeq 100\cdot m_h$

CONCLUSIONS



- Clear targets in the exploration of fundamental physics aheads of us: sharpen the picture of the Higgs boson, figure out electroweak symmetry breaking, figure out Dark Matter, …
- Colliders can contribute unique bits to the solution of the puzzle!
- Muon Collider can bring new knowledge in a short timescale operating at the same time as "*microscope*" and "*factory*"
- Many open issues await *your contribution*: theory of weak radiation, boosted SM objects, detector challenges, beam cooling, …
- HL-LHC will start the job. Muon collider at $3 \div 10$ TeV will bring huge gains on all fronts.
- Crucial time now to work and investigate performances and feasibility for a Muon Collider to go online soon after HL-LHC

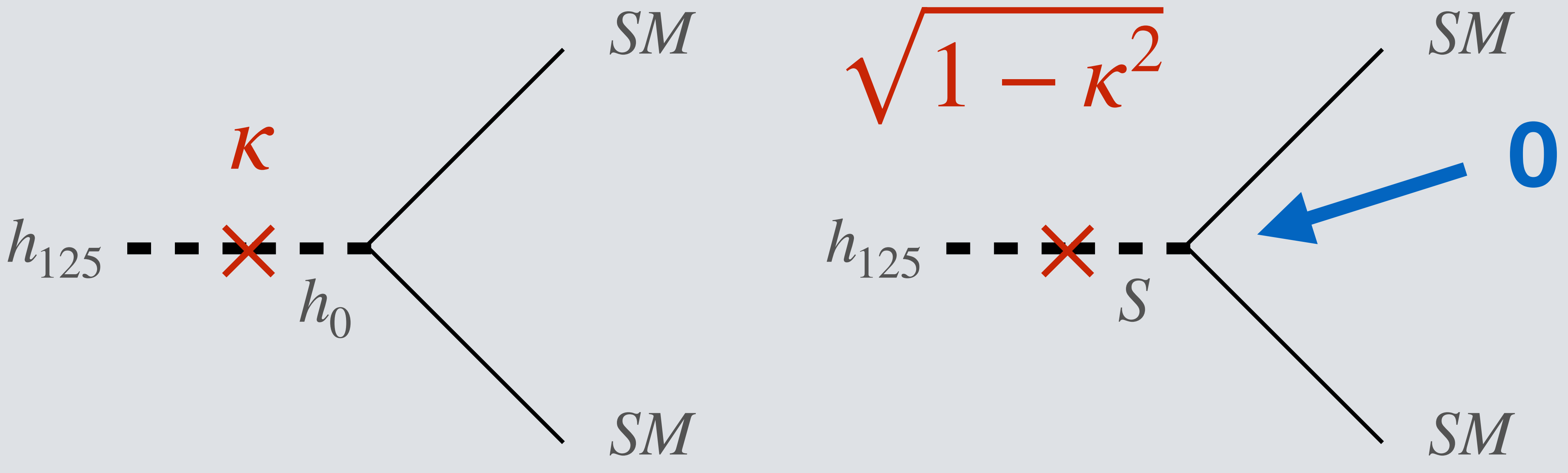
Thank you!

Please subscribe at the CERN e-group “muoncollider”:
MUONCOLLIDER-DETECTOR-PHYSICS MUST-phydet@cern.ch
MUONCOLLIDER-FACILITY MUST-mac@cern.ch

SUMMARY: HIGGS@FC (BY COUPLINGS)

new scalar | SM+heavy singlet

$$h_{125} = h_0 \cdot \kappa + S \cdot \sqrt{1-\kappa^2}$$



1812.02093

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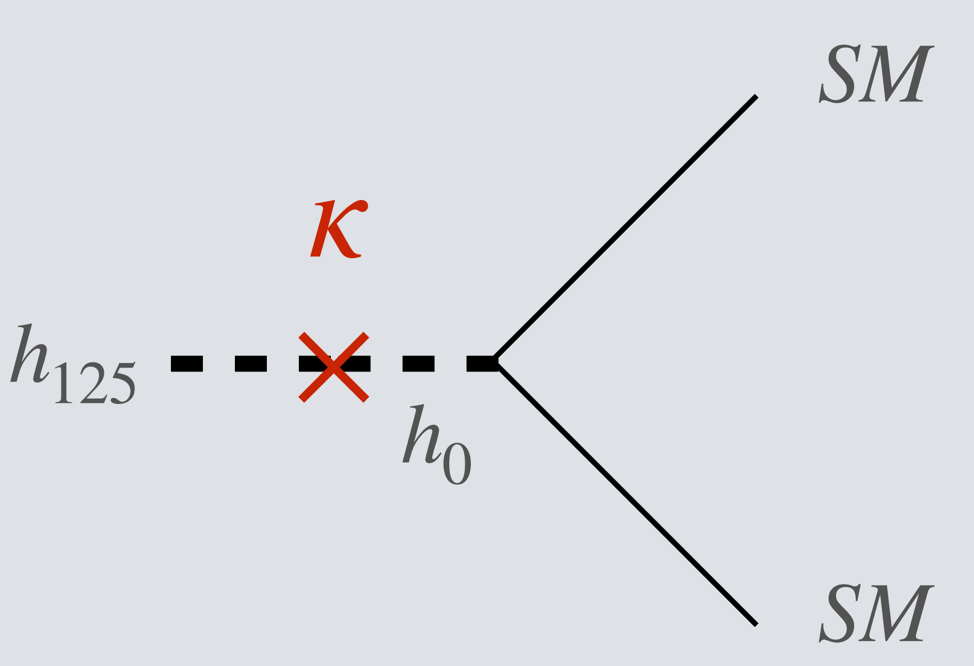
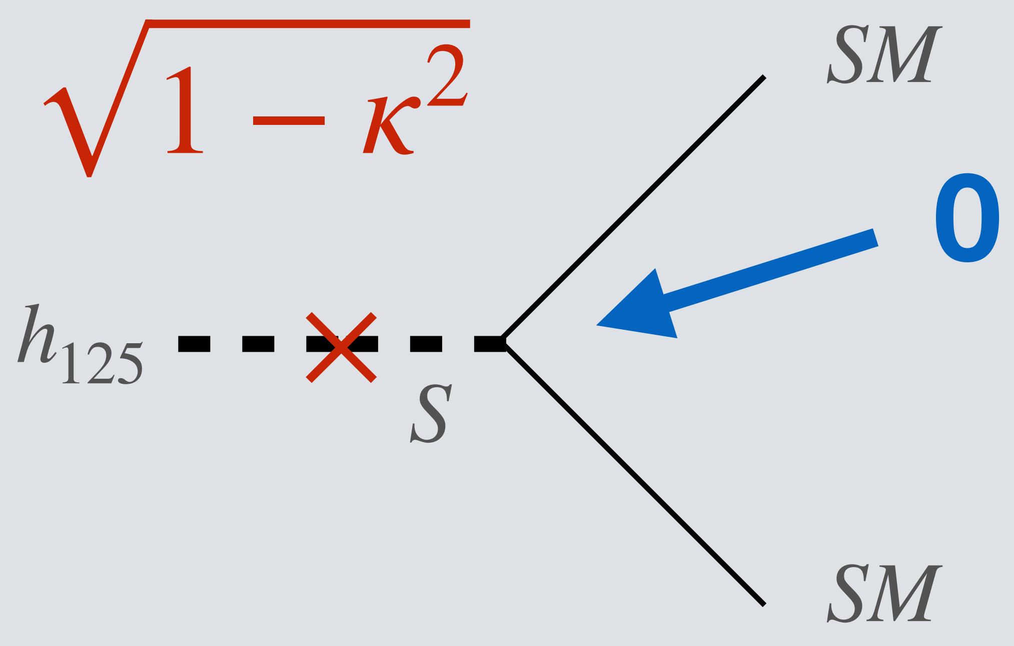
new scalar | SM+heavy singlet

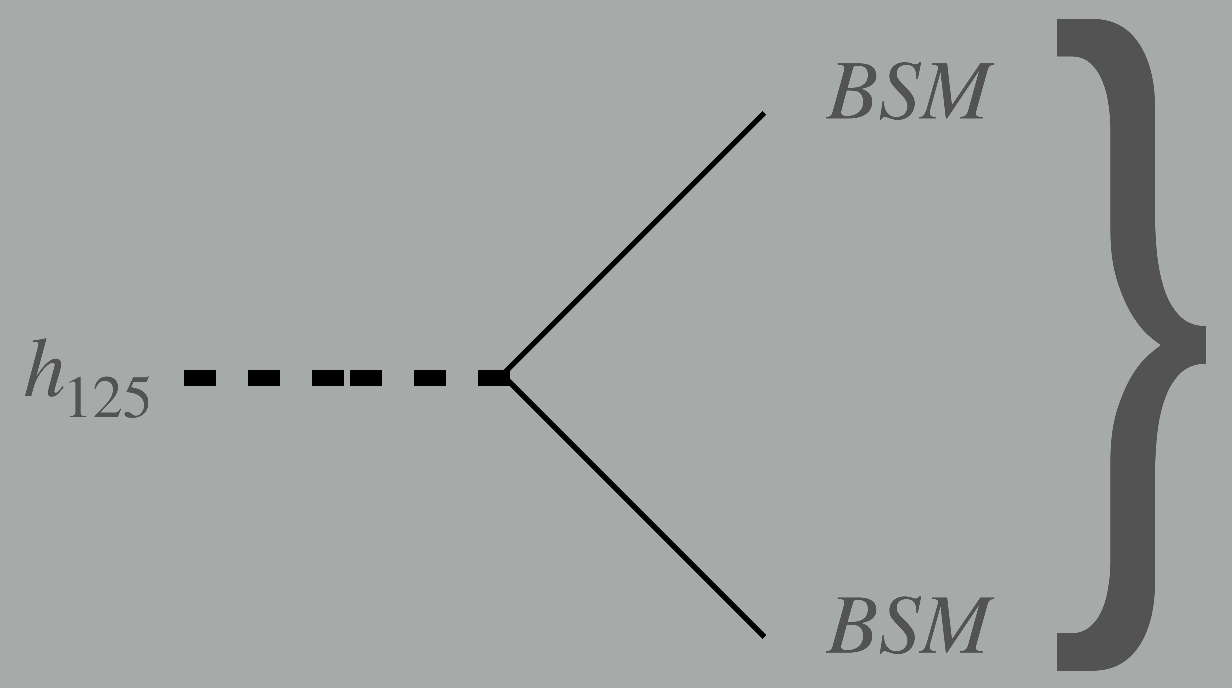
$$h_{125} = h_0 \cdot \kappa + S \cdot \sqrt{1-\kappa^2}$$





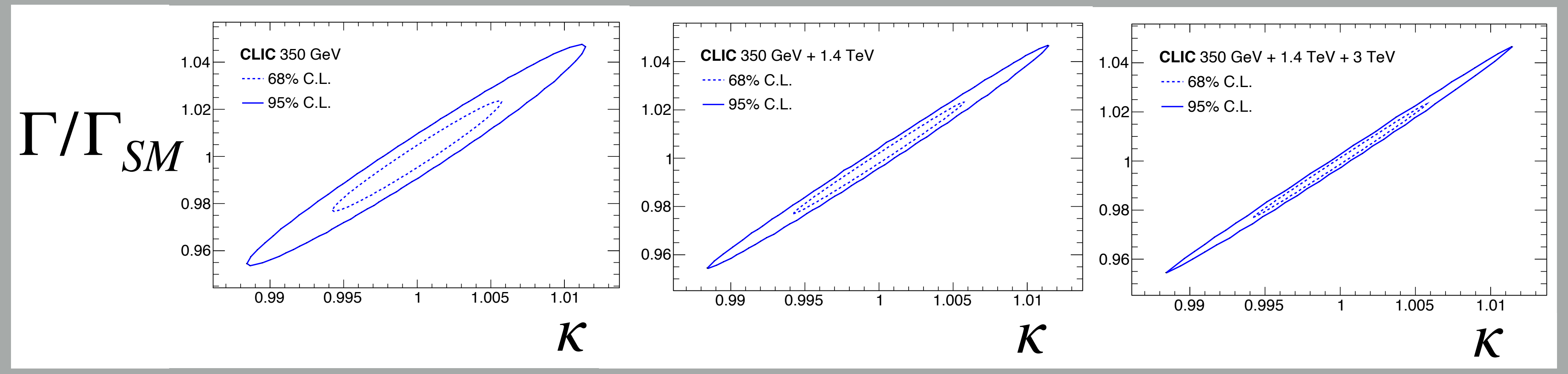
$h \to BSM$

$$\Gamma_H = k^2 \Gamma_{SM} + \Gamma_{BSM}$$



can it be observed?

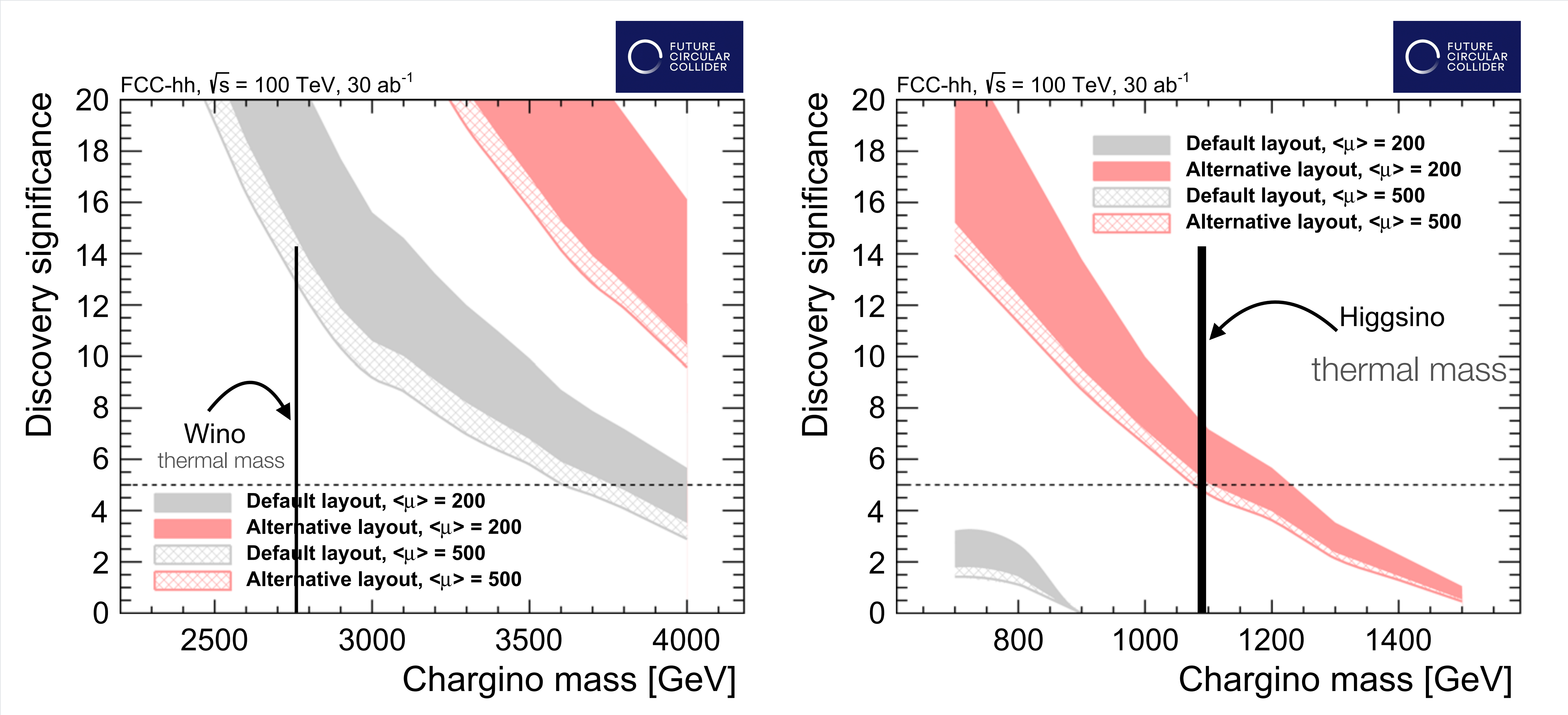
1812.02093

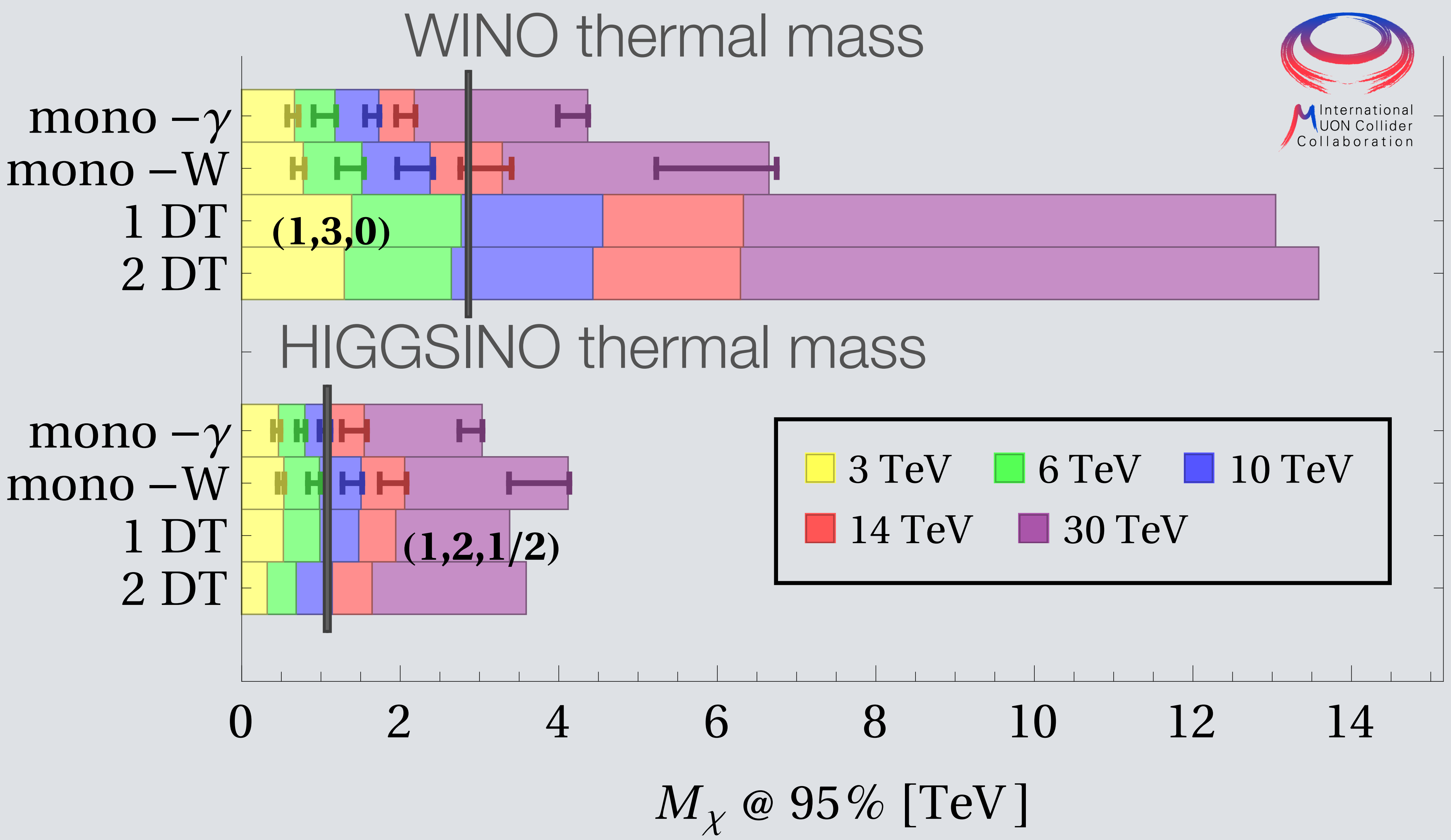


	Δg	$\Delta\Gamma_H$
Stage 1	0.58%	2.3%
Stage 1+2	0.57%	2.3%
Stage 1+2+3	0.57%	2.3%

	$\Delta\Gamma_H$
Stage 1	0.47%
Stage 1+2	0.20%
Stage 1+2+3	0.13%

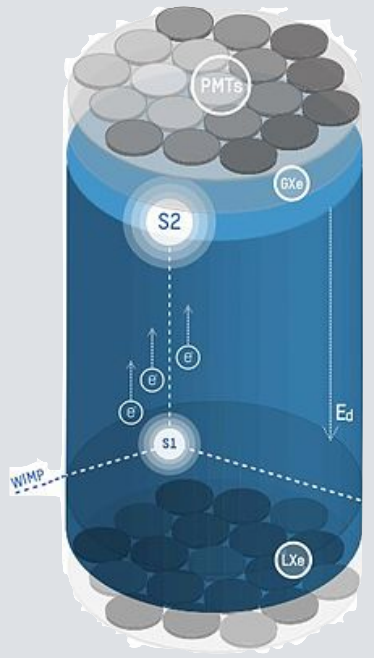
SIGHTING DARK MATTER

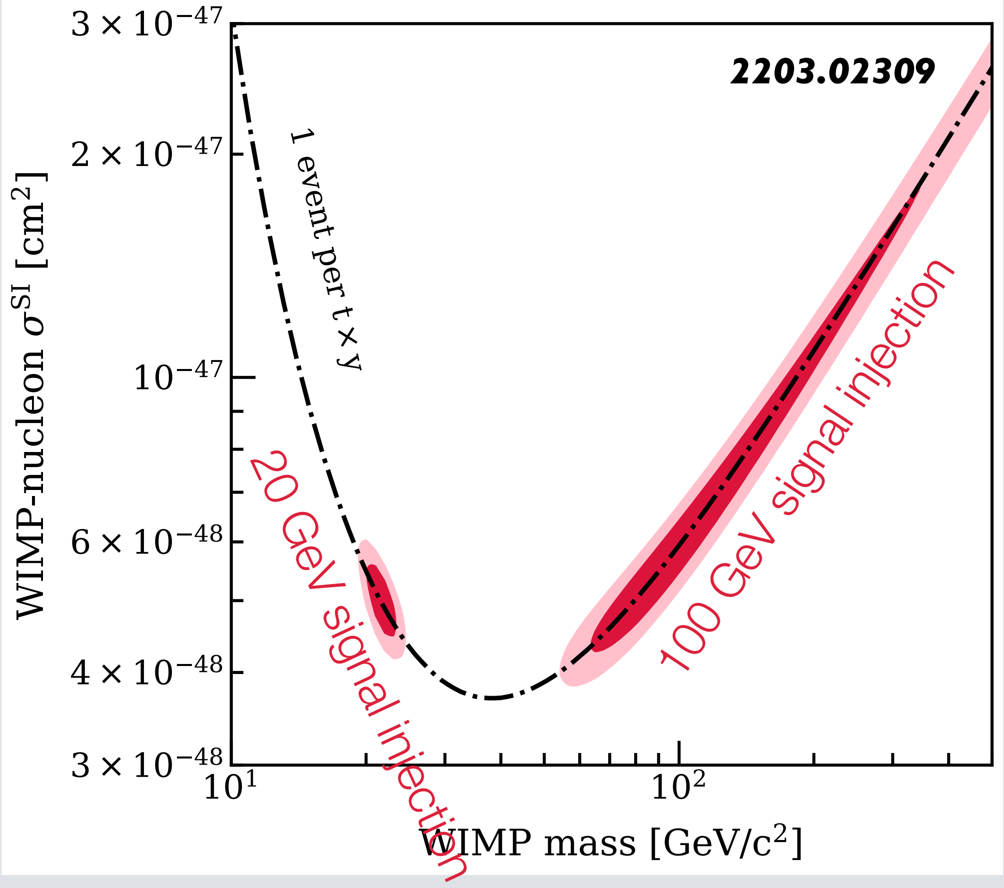




S1: no hints of WIMPs at Xenon, might be Higgsino

S2: hints of WIMPs at Xenon! little hints on its mass





URGENT NEED FOR A HIGH-ENERGY MACHINE BOTH IN S1 AND S2

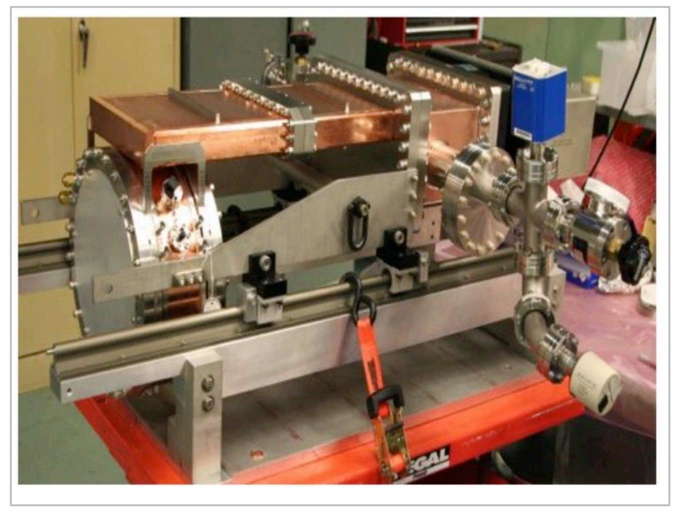
- Absence of Xe signals would require a 100 TeV pp or 6-10 TeV $\mu\mu$ to conclusively probe WIMPs by testing Higgsino
- Xe signal of heavy WIMP opens the chase from 1 TeV to fraction of PeV mass

RESERVE

NEXT STEPS FOR THE FEASIBILITY

Cooling Cell design and integration

MuCol



MuCool @ FNAL
demonstrated cavity
with >50 MV/m in 5 T solenoid
- H2-filled copper cavities
- Cavities with Be end caps

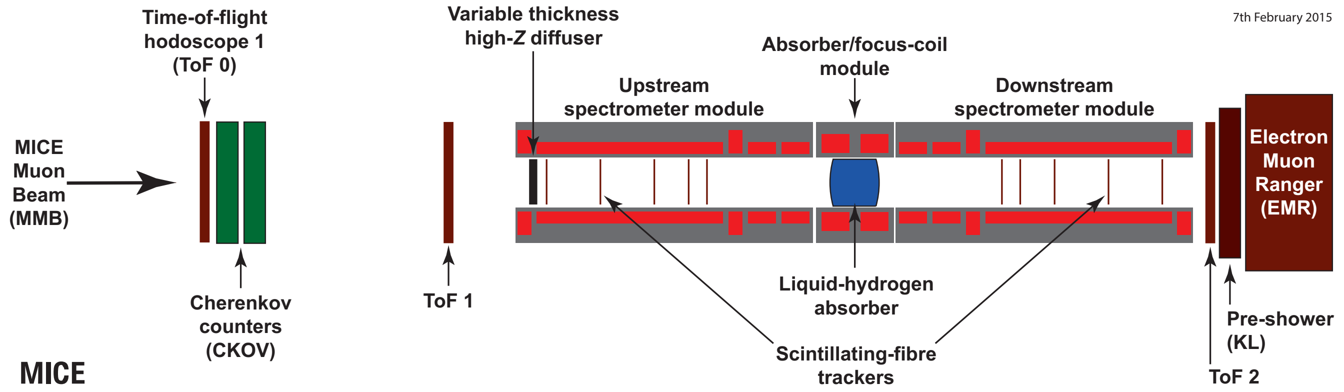
WP 6
WP 7
WP 8

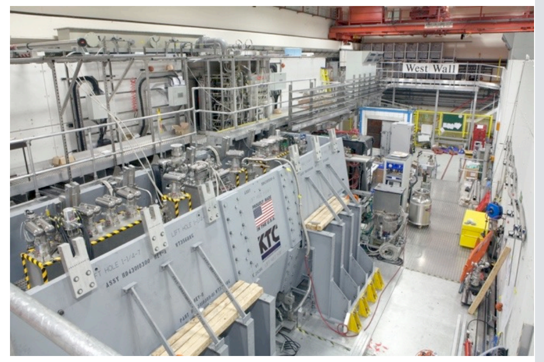
MI-LASA
LNS
LNL
NA
TO

Technology requirements for ionizing cooling:

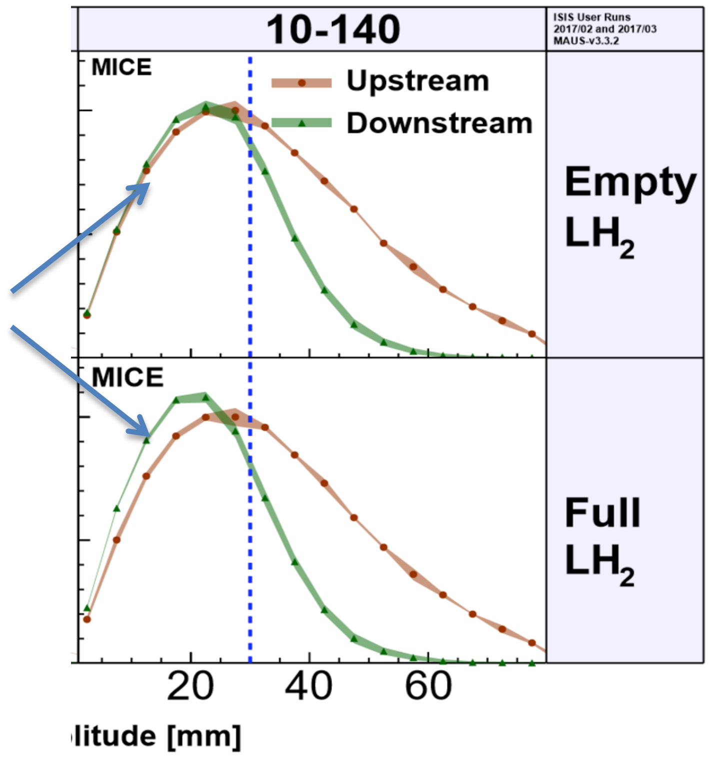
- Large bore solenoidal magnets: from 2 T (500 mm IR), to 14 T (50 mm IR)
- Normal conducting RF that can provide high-gradients within a multi-T fields
- Absorbers that can tolerate large muon intensities
- Integration: Solenoids coupled to each other, near high power RF & absorbers
- **Tight integration** of solenoids, RF, absorbers, instrumentation, cooling, vacuum, alignment, …

MICE experiment (RAL – UK)





More particles at smaller amplitude after absorber is put in place



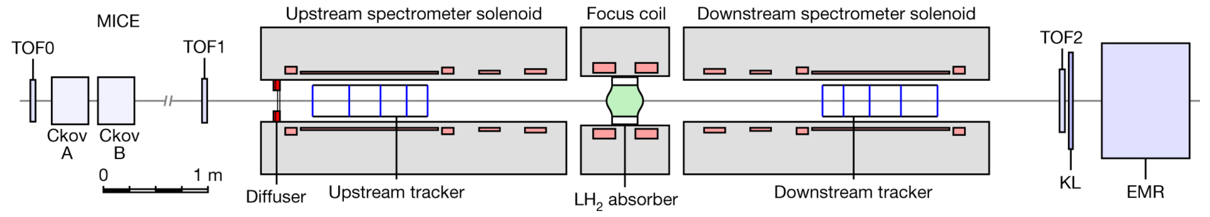
Transverse cooling at high emittance

Principle of ionisation cooling has been demonstrated in 4D

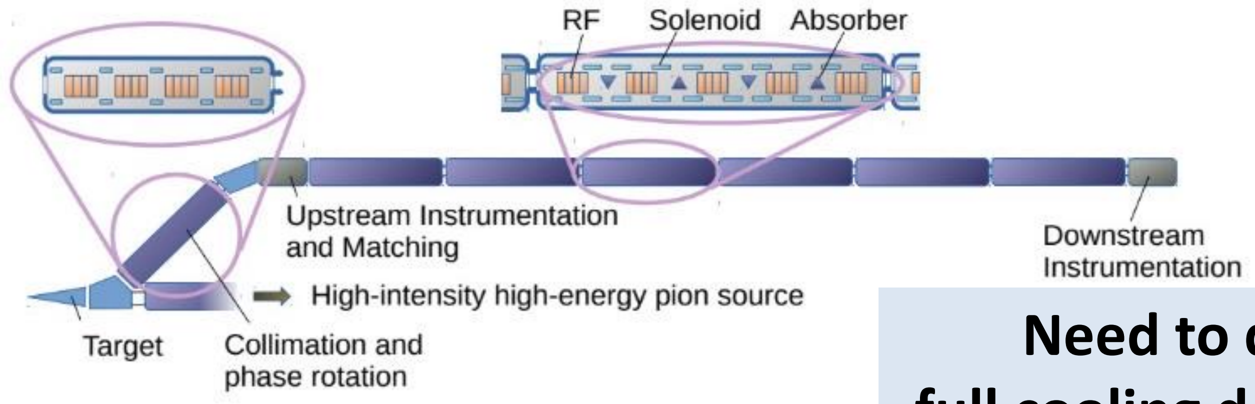
More complete experiment with higher statistics, more than one stage required

MICE collaboration. *Nature* **578**, 53–59 (2020)

Proposed cooling demonstrator vs MICE



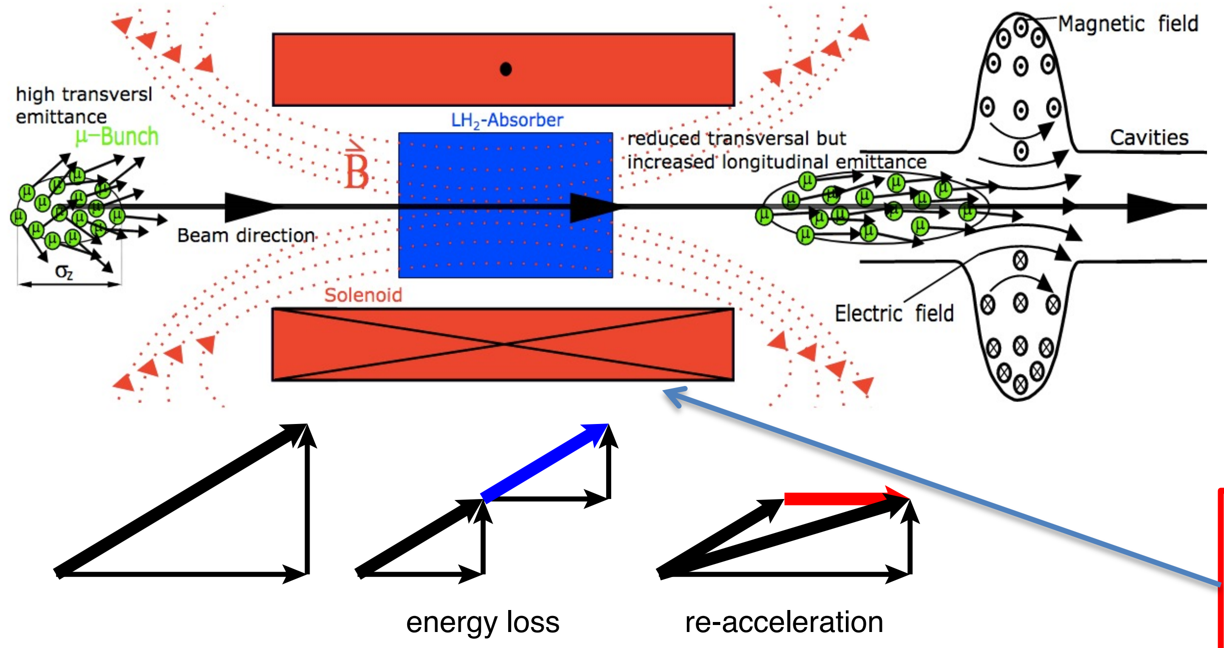
IMPORTANT to deliver a realistic end-to-end 6D design

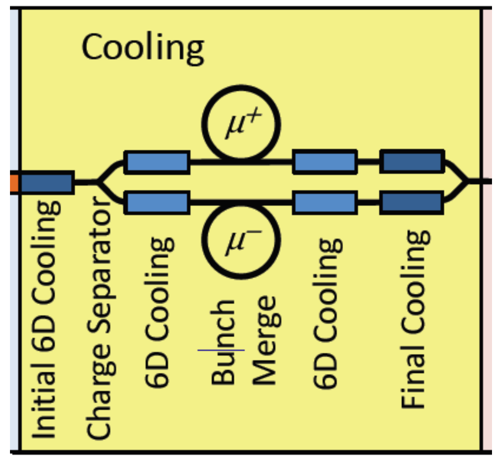


Need to develop full cooling demonstrator

	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style

Final Cooling Challenge





High field solenoids minimise beta-function and impact of multiple scattering

Energy loss = cooling

Multiple scattering = heating

$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

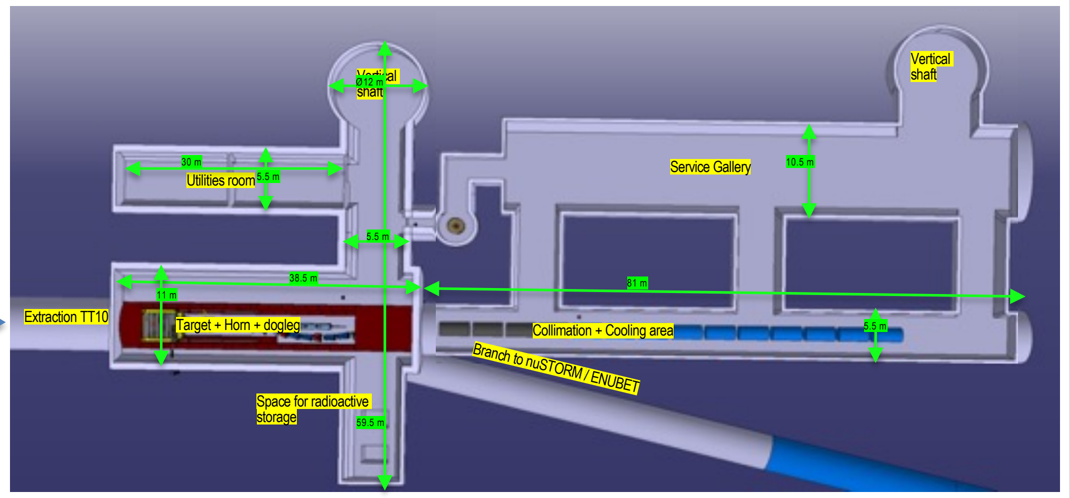
Mitigate with low-Z materials

Demonstrator and test facilities

(Muon production) and Cooling Demonstrator @ CERN

Strong synergies with nuSTORM and ENUBET

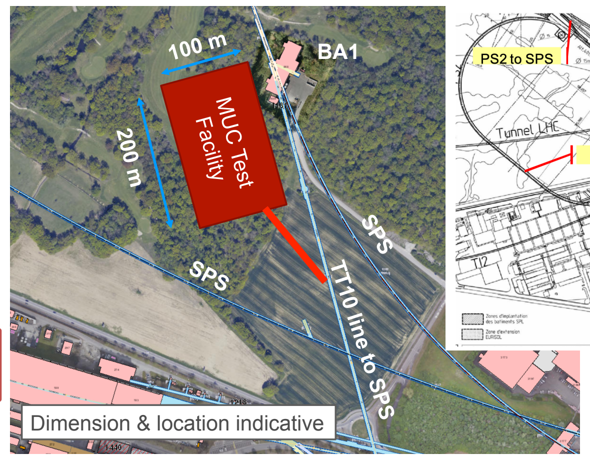
First attempt to design a site
Great opportunity to contribute

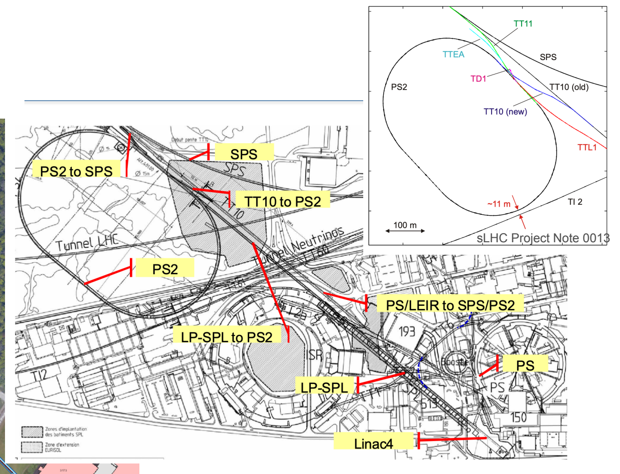


It could be close to TT10, and inject beam from PS
It would be on molasse,
no radiation to ground water

Test facilities for enabling tecnologies:
RF, Magnets, Target materials…..

Strong synergies with other future projects

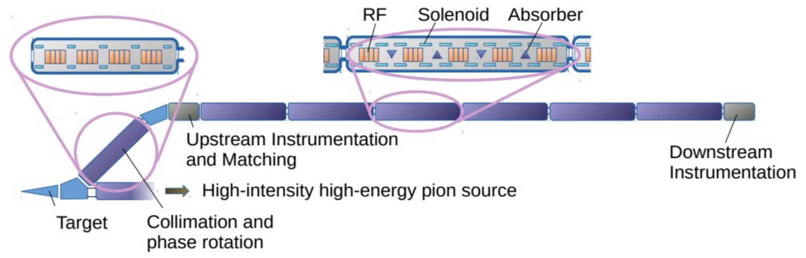


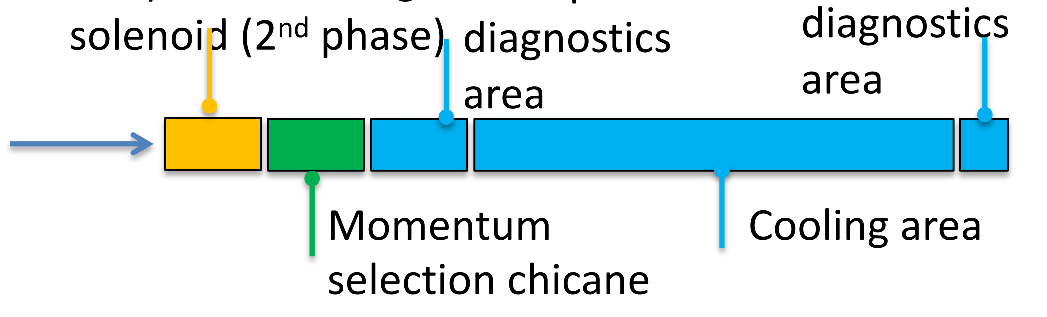


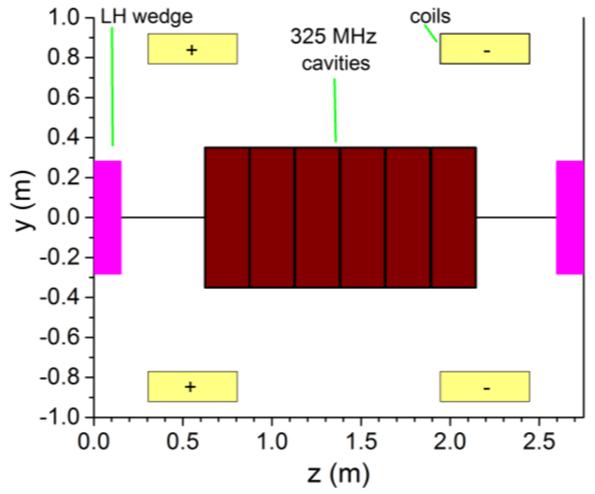
M. Benedikt, LHC Performance Workshop, Chamonix 2010
CERN-AB-2007-061

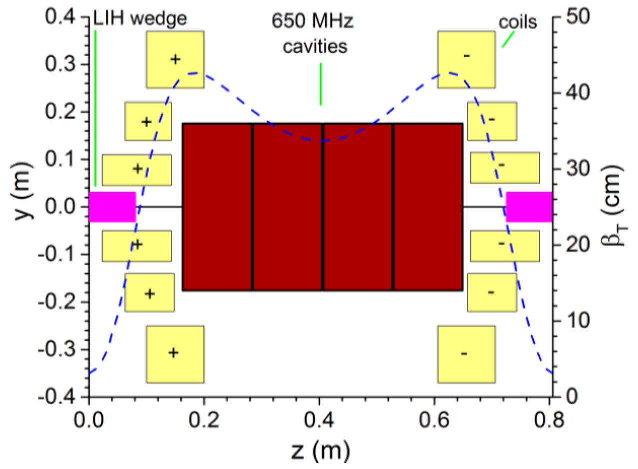
N. Pastrone

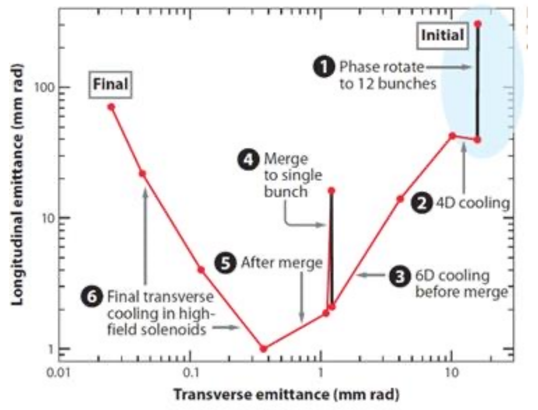
Towards a demonstrator





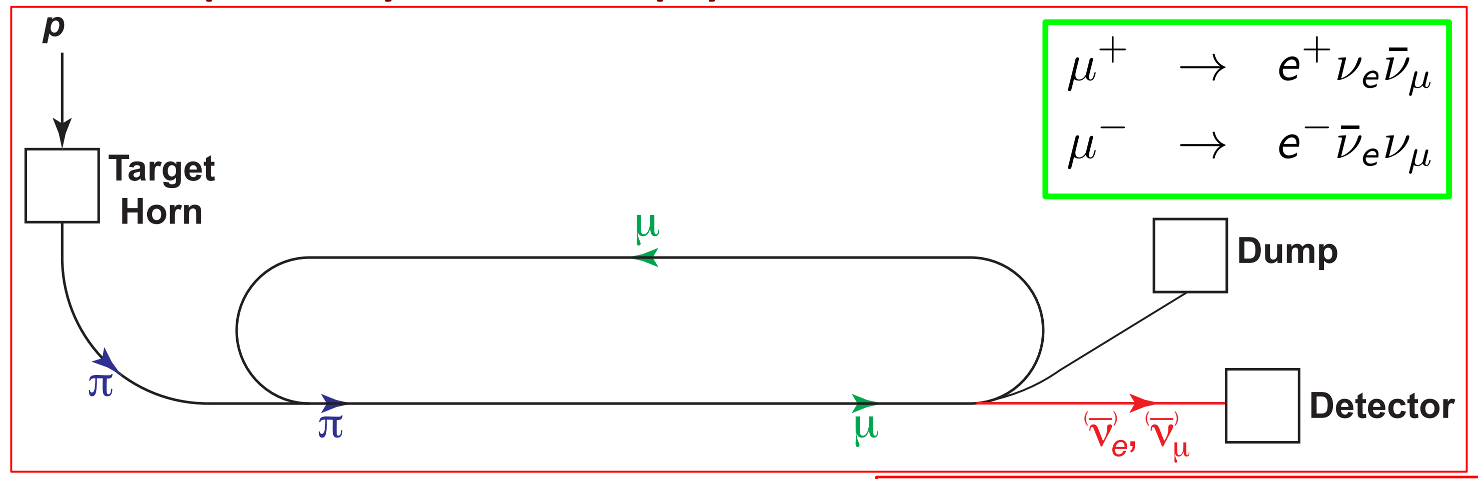






nuSTORM: neutrino from stored muons

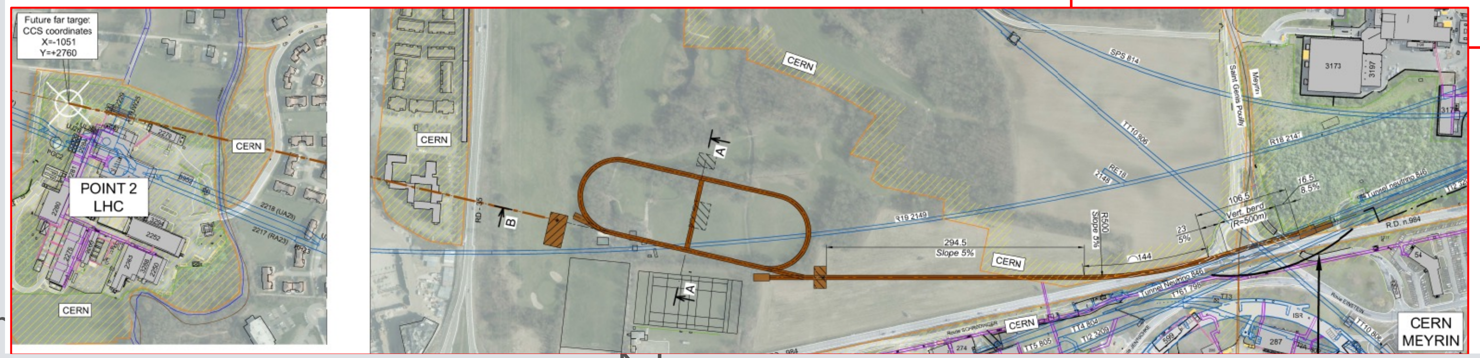
a unique facility for neutrino physics and muon-collider test bed



$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

- **Scientific objectives**:
  1. %-level ($\nu_e N$) cross sections
     - Double differential
  2. Sterile-neutrino/BSM search
     - Beyond Fermilab SBN

- **Precise neutrino flux:**
  - **Normalisation: < 1%**
  - **Energy (and flavour) precise**
- **$\pi \to \mu$ injection pass:**
  - **"Flash" of muon neutrinos**



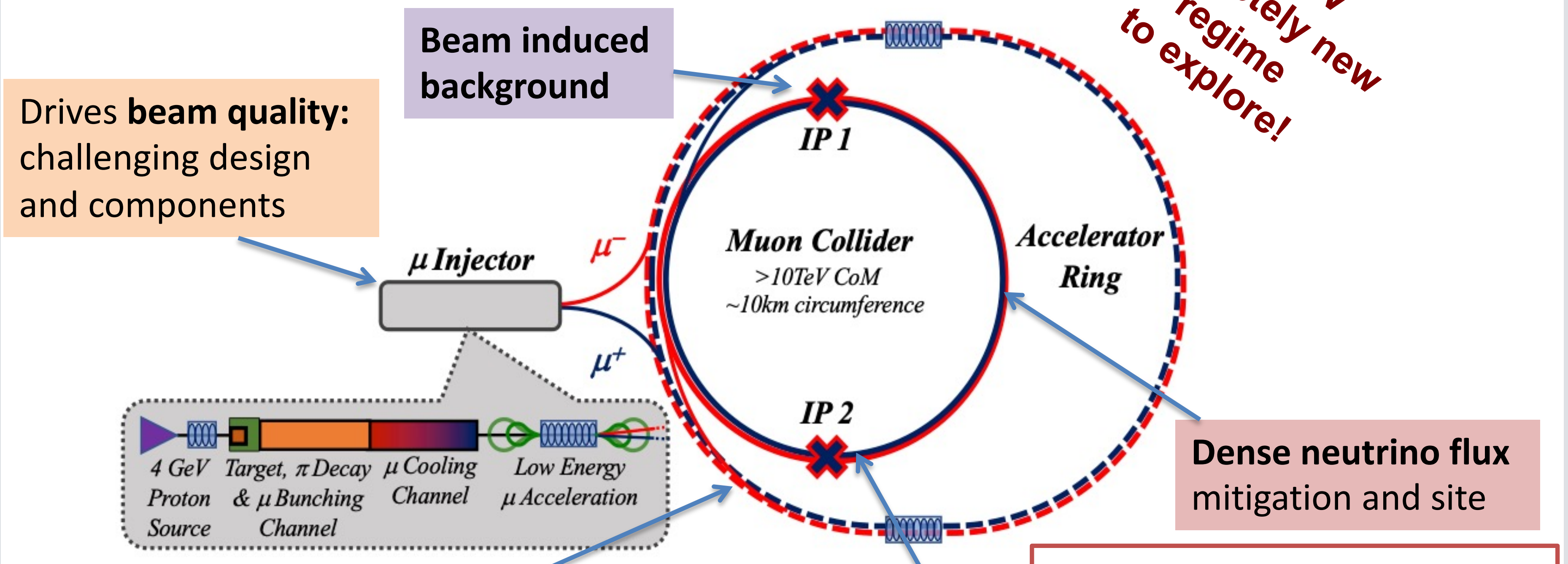
International Design Study facility

Proton driver production as baseline

- **Focus on two energy ranges:**

3 TeV technology ready for construction in 10-20 years
10+ TeV with more advanced technology

10+ TeV completely new regime to explore!



Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ \text{ab}^{-1}$

@ 3 TeV ~ 1 ab^{-1} 5 years

@ 10 TeV ~ 10 ab^{-1} 5 years

LARGELY UNEXPLORED YET

(my ignorance is probably speaking here)

- can there be a flavor program? (B and g-2 anomalies proved that if something comes up the machine can probe interesting models)
- reaction to a measurement that can happen in the next decade or so (electron EDM, dark matter "evidence" somewhere underground or in the sky, sharpening of the m_W puzzle, …)
- …
- What good use for the neutrinos from the beam?