Standard Model and Beyond at colliders

JUL. 5 2017

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Open Questions on the “big picture” on fundamental physics circa 2020

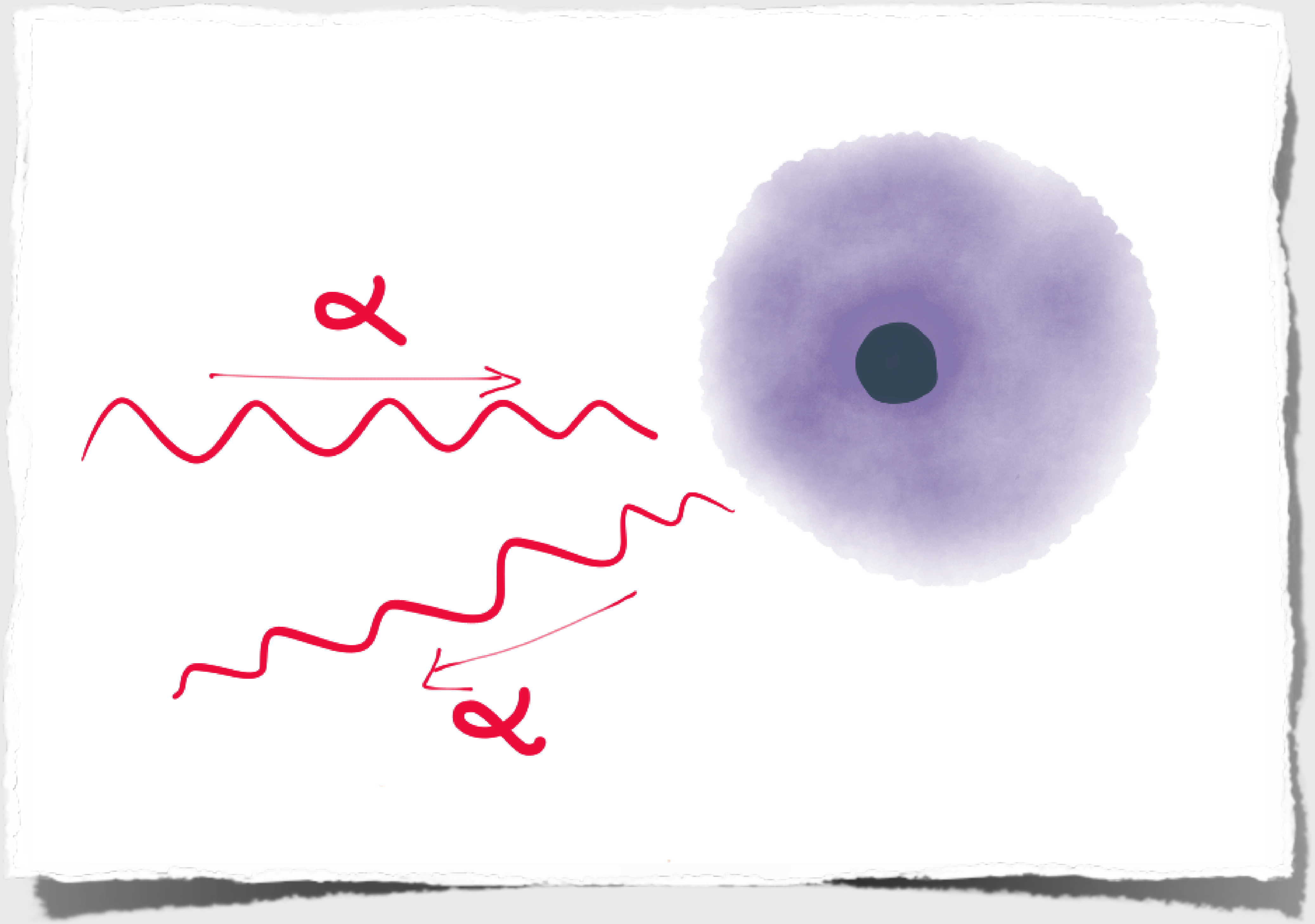
- why QCD does not violate CP?
- how have baryons originated in the early Universe?
- ? what is the dark matter in the Universe?
- what originates flavor mixing and fermions masses?
- what gives mass to neutrinos?
- ~~EFT~~ why gravity and weak interactions are so different?
- ~~EFT~~ what fixes the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

} end of “The Boltzmann Way”

How we got there

COLLISIONS

AS PROBES OF THE MICROSCOPIC CHARACTER OF NATURE



How we got there

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

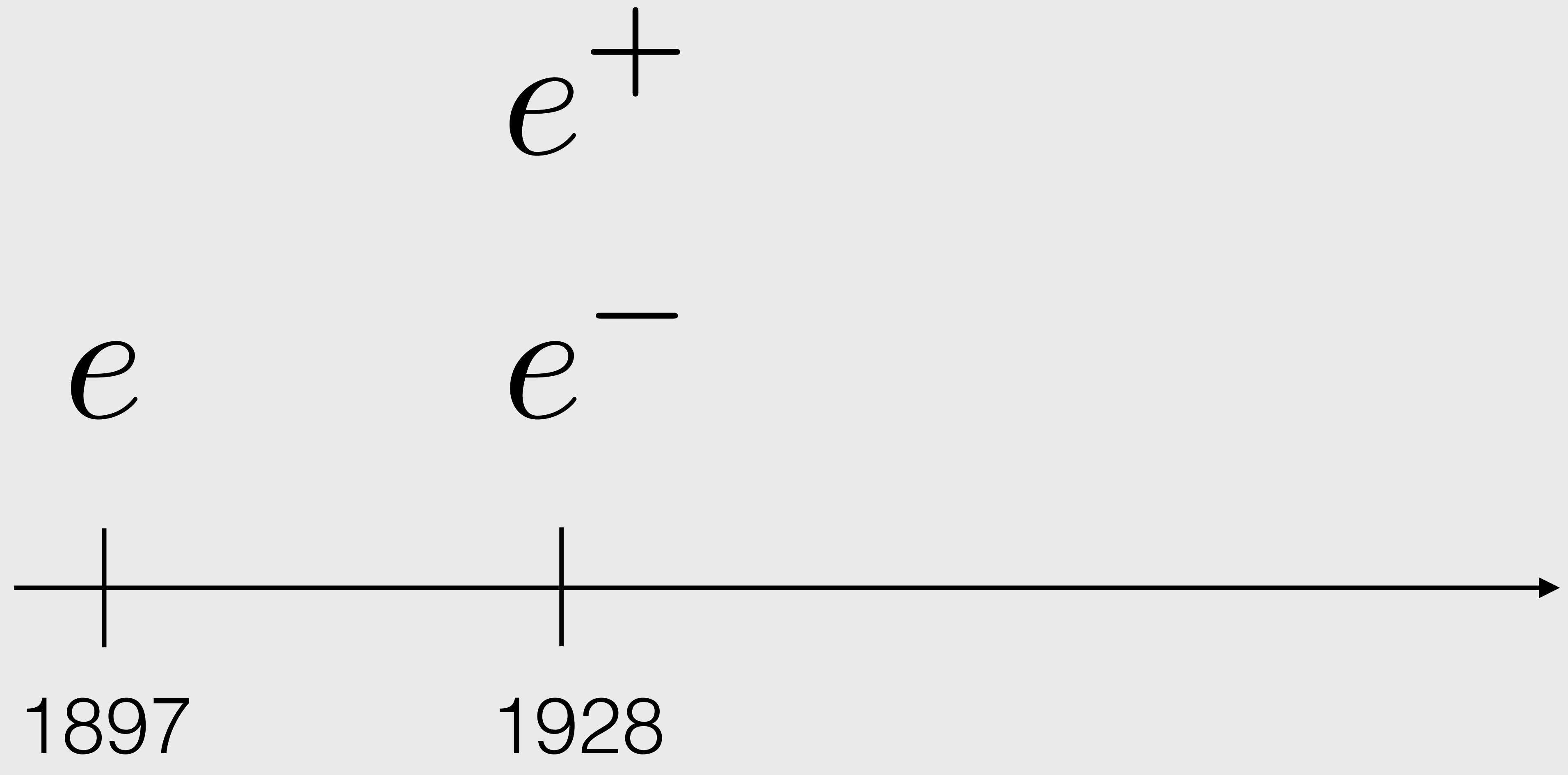
Symmetries and particles

How we got there

SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



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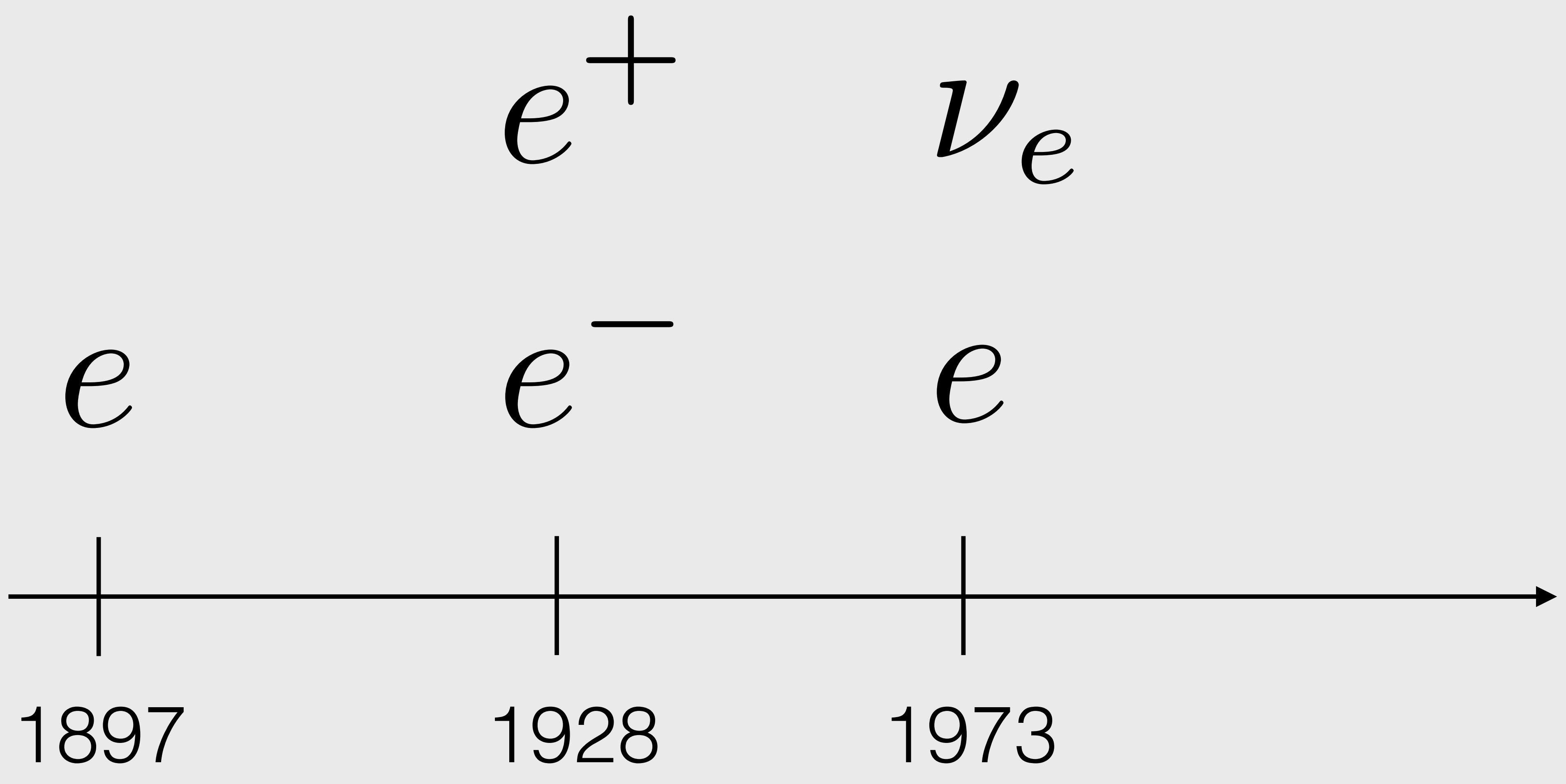

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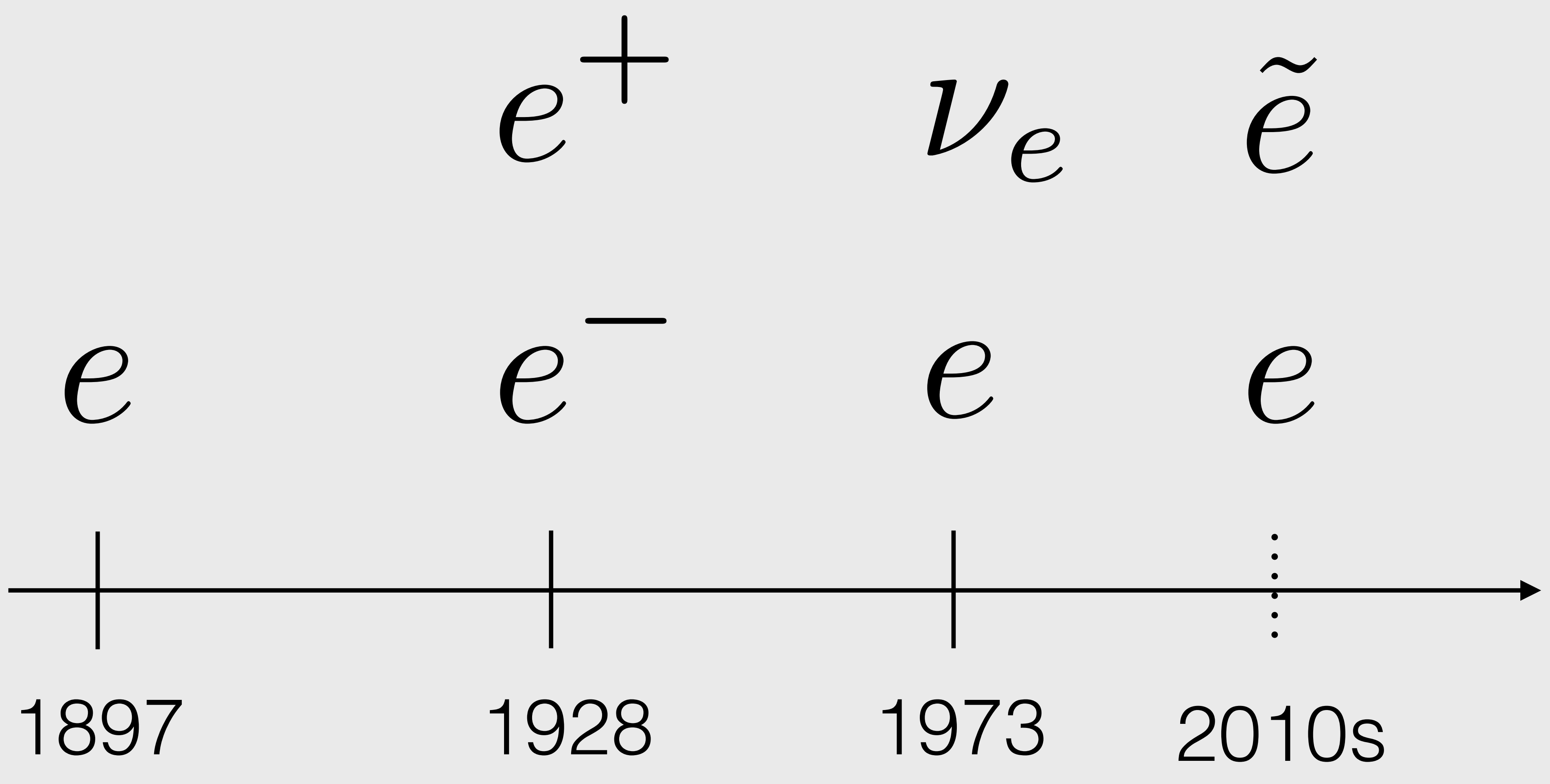


a symmetry that relates bosons and fermions, supersymmetry

How we got there

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles

	e^+	ν_e	$\tilde{e}$
e	e^-	e	e
1897	1928	1973	2010s

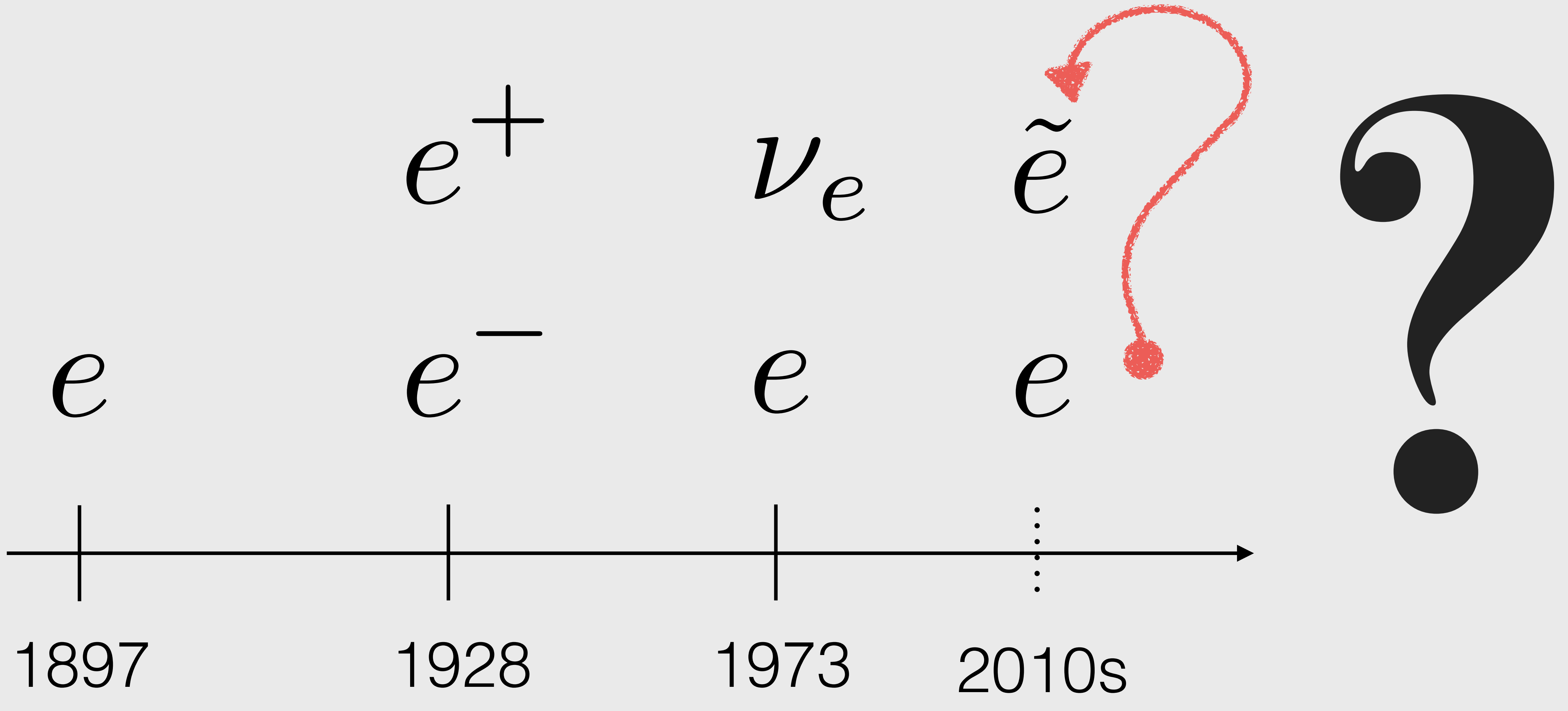
a symmetry that relates bosons and fermions, supersymmetry

How we got there

SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



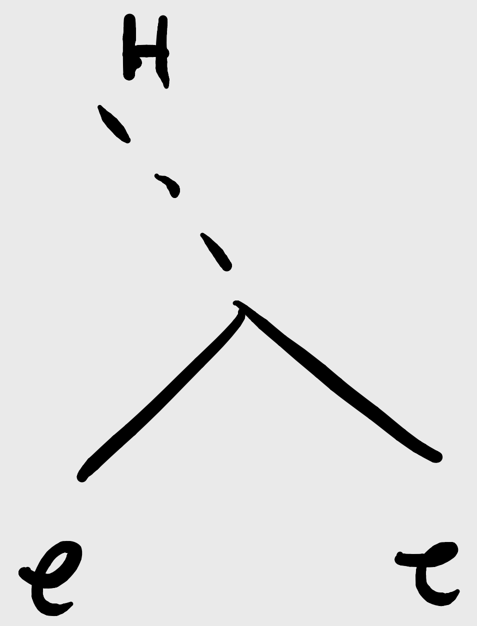
a symmetry that relates bosons and fermions, supersymmetry

How we got there

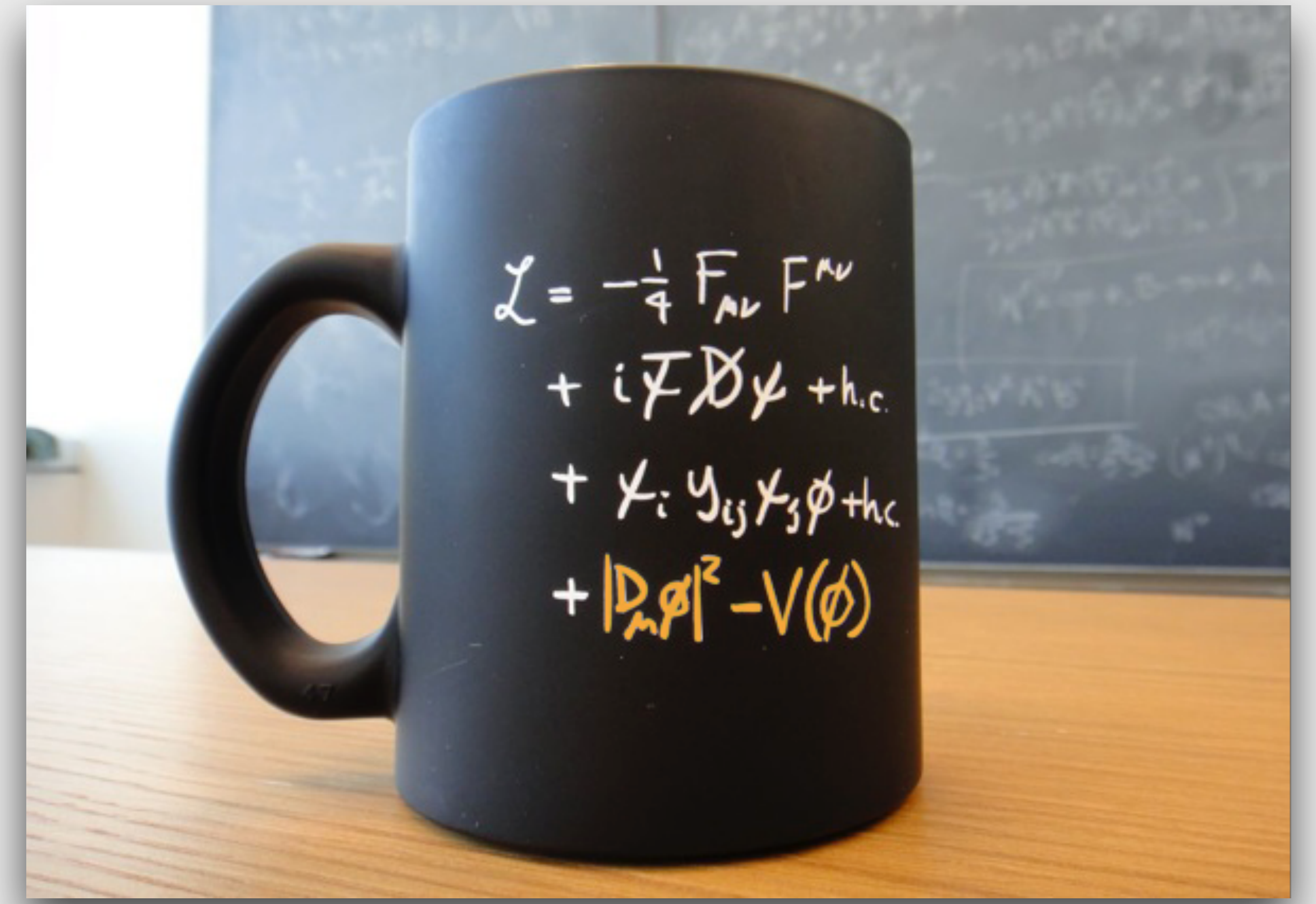
SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

$$\frac{\partial \psi}{\partial t} = H\psi \xrightarrow[\text{Schrödinger}]{\text{relativistic}} \bar{\psi}_e\left(i\cancel{\partial}_\mu + m + \cancel{A}_\mu\right)\psi_e$$

$$F = \begin{array}{cccc} \cdot & E_x & E_y & E_z \\ & \cdot & B_z & B_y \\ & & \cdot & B_x \\ & & & \cdot \end{array} \xrightarrow{\text{Maxwell's}} +\left(F_{\mu\nu}F^{\mu\nu}\right)$$

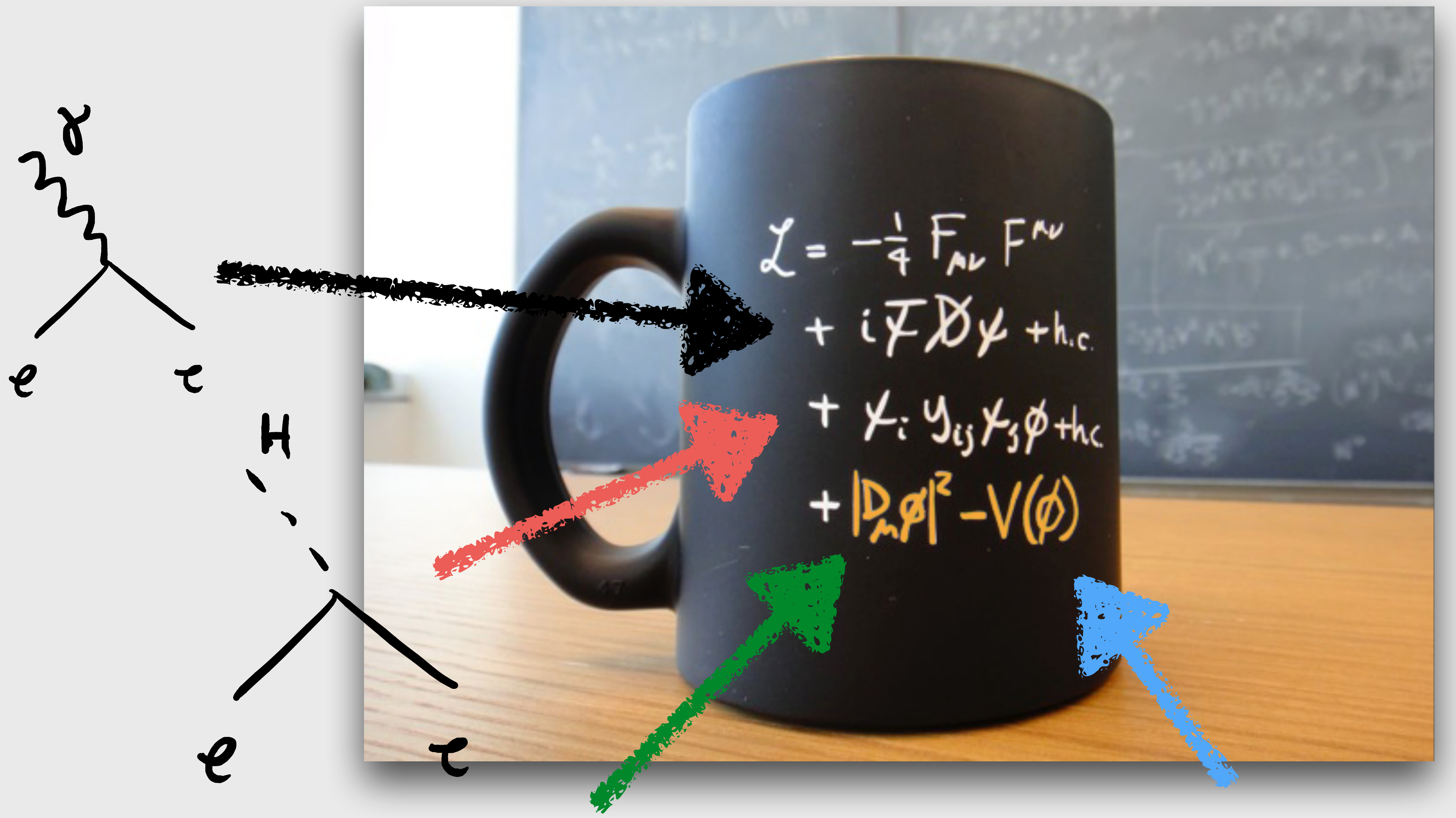


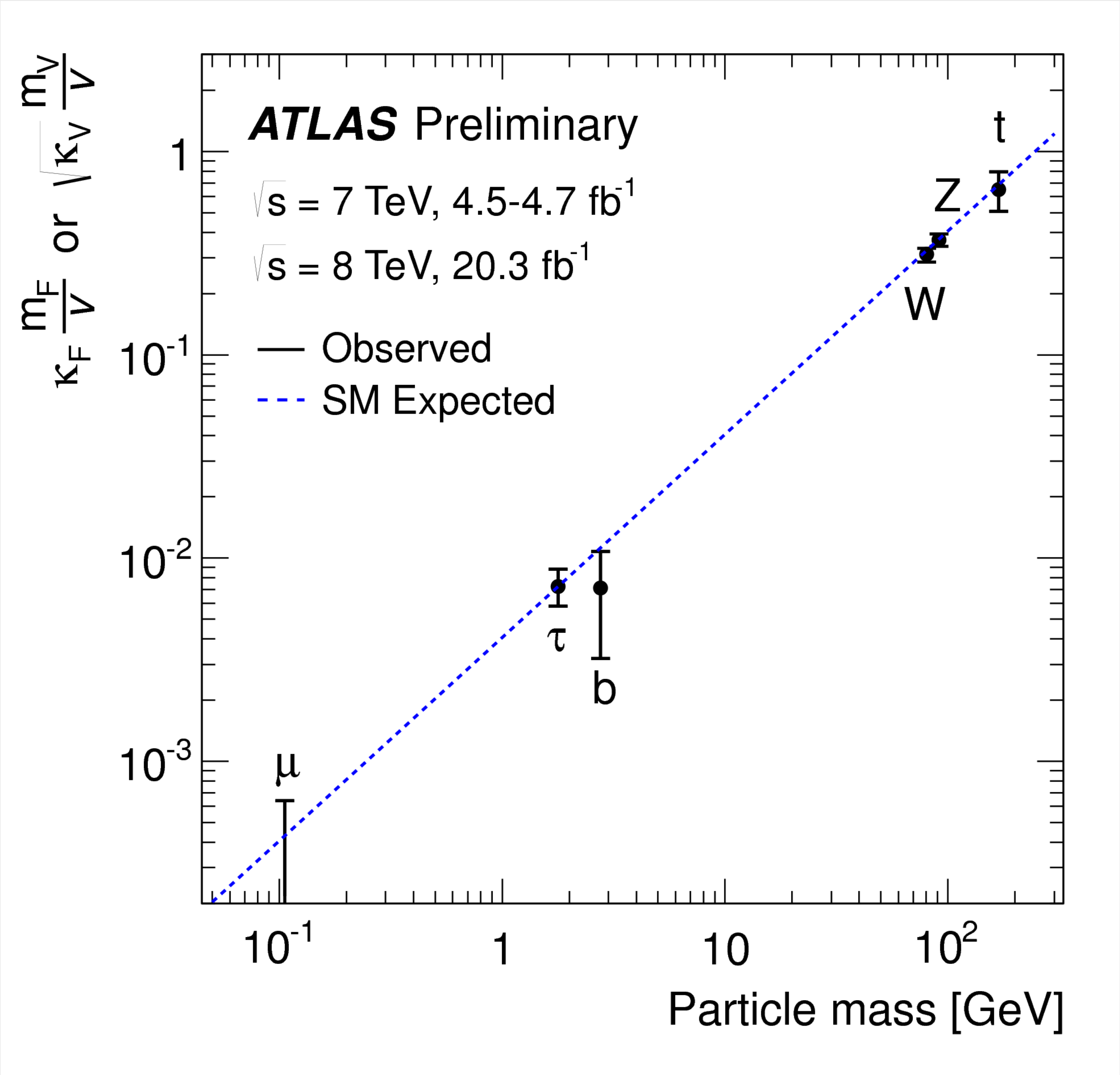
$\xrightarrow{\text{Mass!}}$ Brout, Englert, Higgs



How we got there

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????





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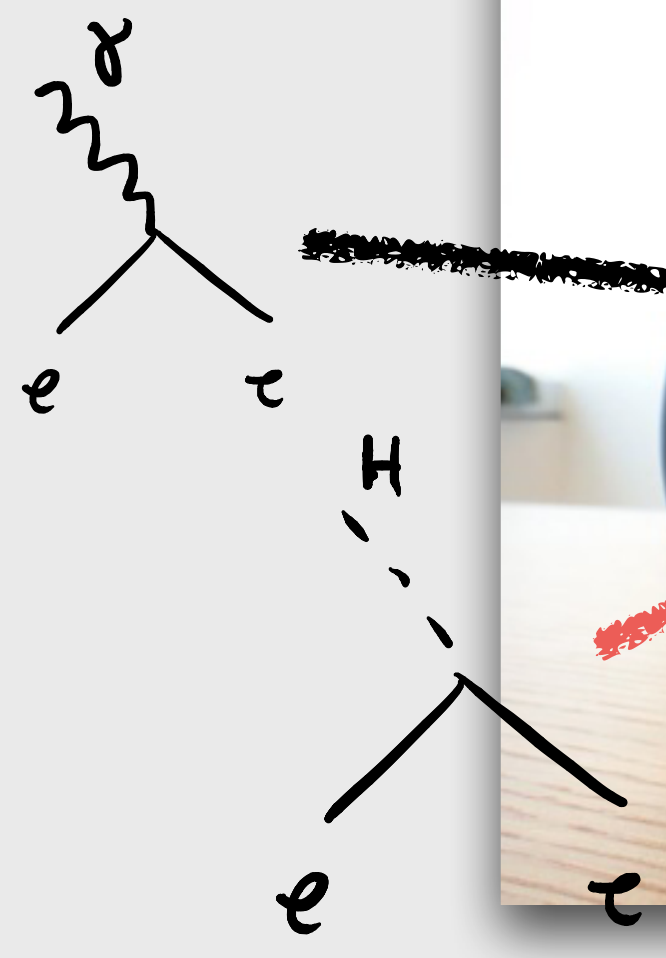
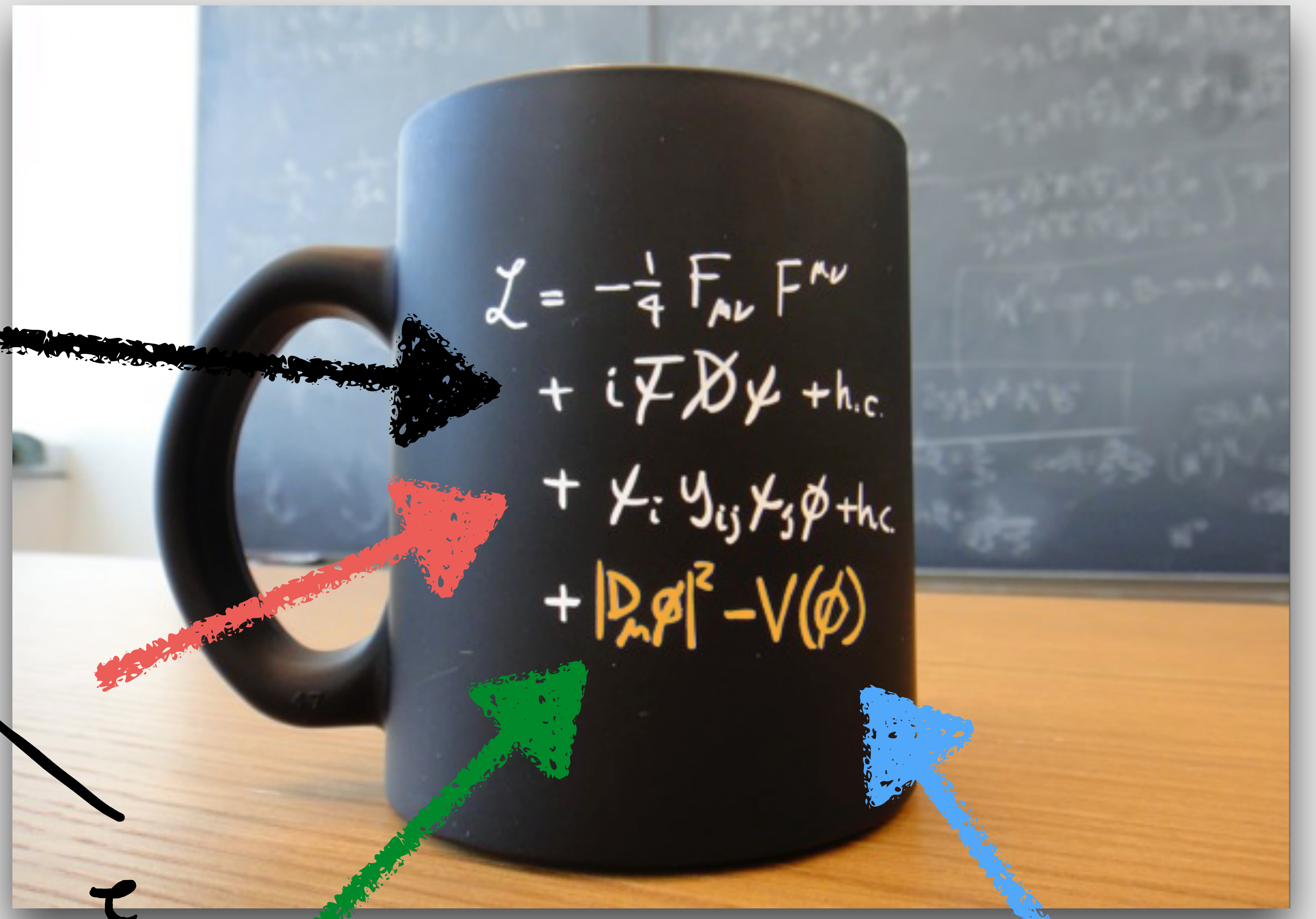
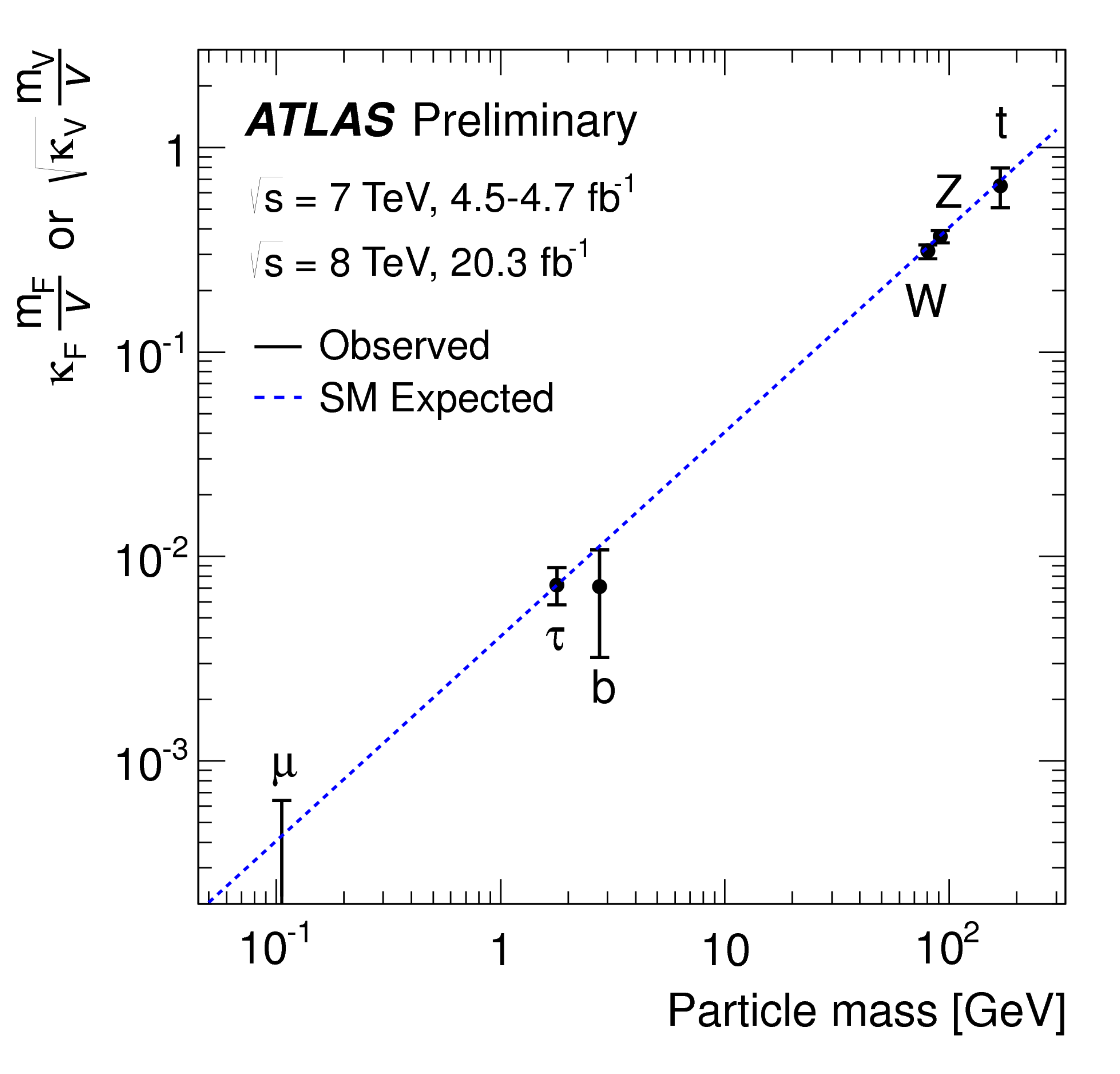




$|D\phi|^2$

$V(\phi)$



How we get out of there?

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????

Coincidences ?

$$\mathcal{L} = c + \mu^2 H^2 + \lambda H^4$$

Fermi constant
(periodic table)

Higgs boson mass
(meta-)stability of the Universe

Cosmological Constant
(galaxy formation)

Steven Weinberg Phys. Rev. Lett. 59, 2607 - If $c > 200\, c_{Misurato}$ galaxies would ne be able to form (matter-domination phase too short)

arXiv:hep-ph/9707380 Agrawal et al. - If $\mu > 5 \cdot \mu_{SM}$ periodic table disappears! (neutron decay too fast)

arXiv:1205.6497 - Degrassi et al. - If m_{Higgs} grew by 1%, Universe would be unstable (in the SM)

Rev. Mod. Phys. 68, 951 - Cahn, Robert N. - The eighteen arbitrary parameters of the standard model in your everyday life

How we get out of there?

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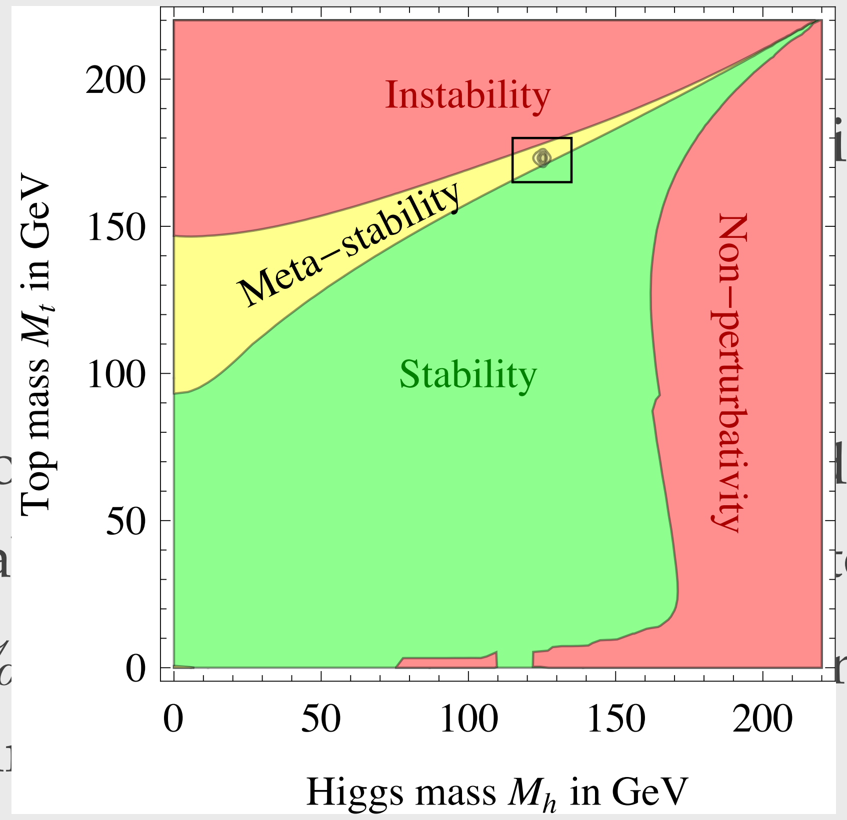
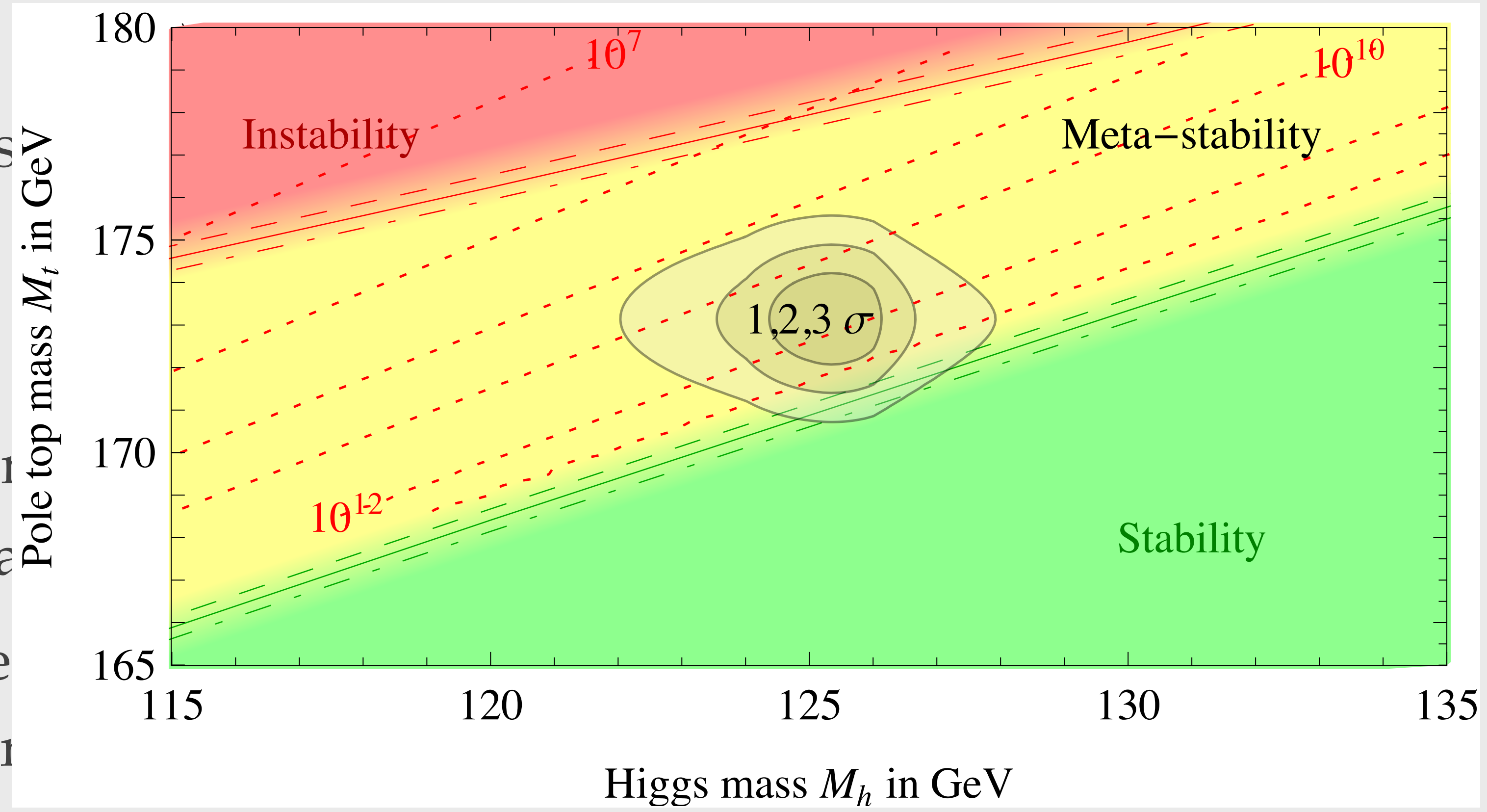
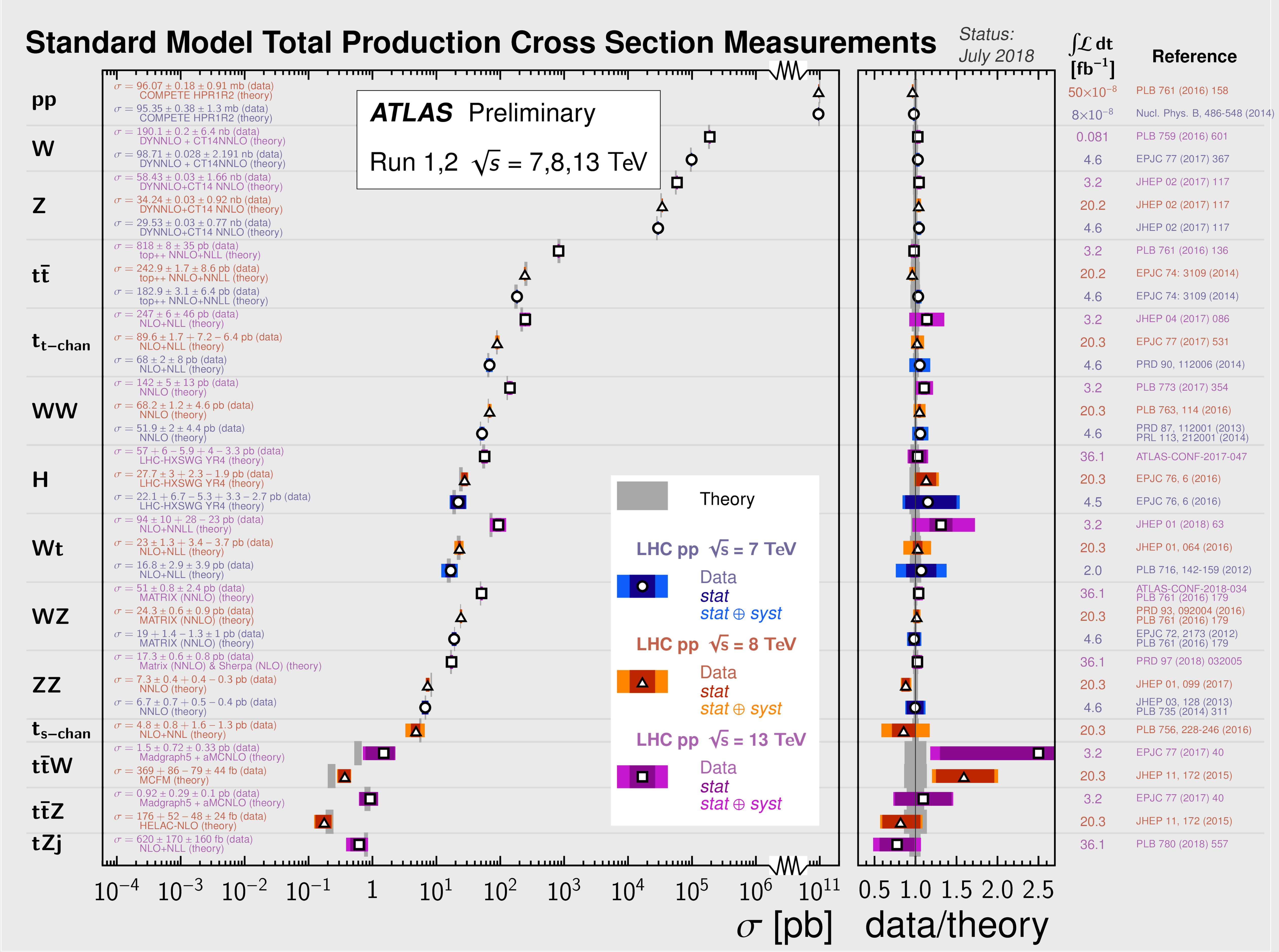




Beyond LO all the way

SYMMETRY CURSE OR BLESSING?



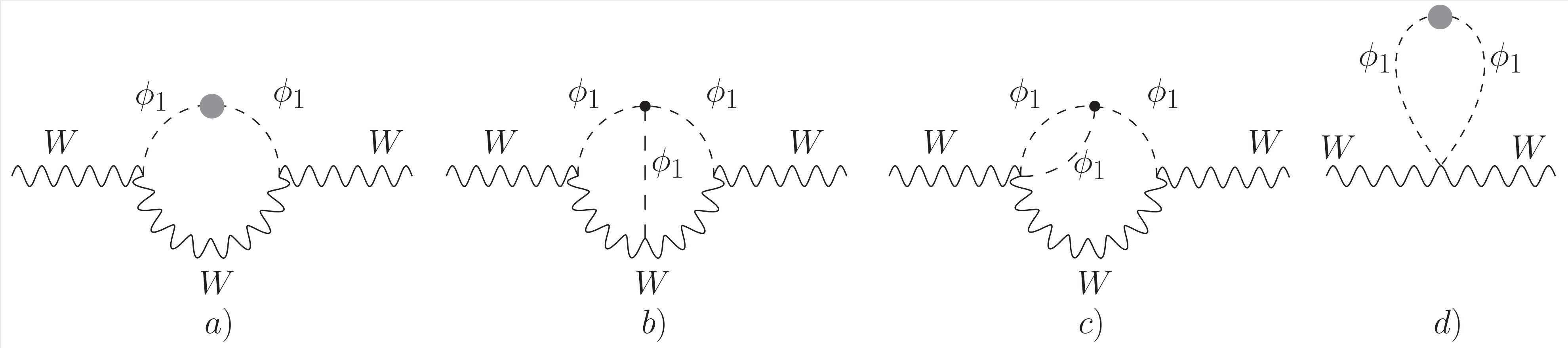
- Standard Model calculations have been improved beyond lowest order and can be automated in basically all cases at NLO (EW may still resist though).
- General agreement confirms SM in total rates
- Differential distributions may need NNLO, not easy but slowly coming
- In any event, amplitudes in a gauge theory beyond lowest order:
    - become too many
    - develop complicated divergences structure
- play with/remove gauge principle seems to help to simplify these issues (the "too many" problem for sure)

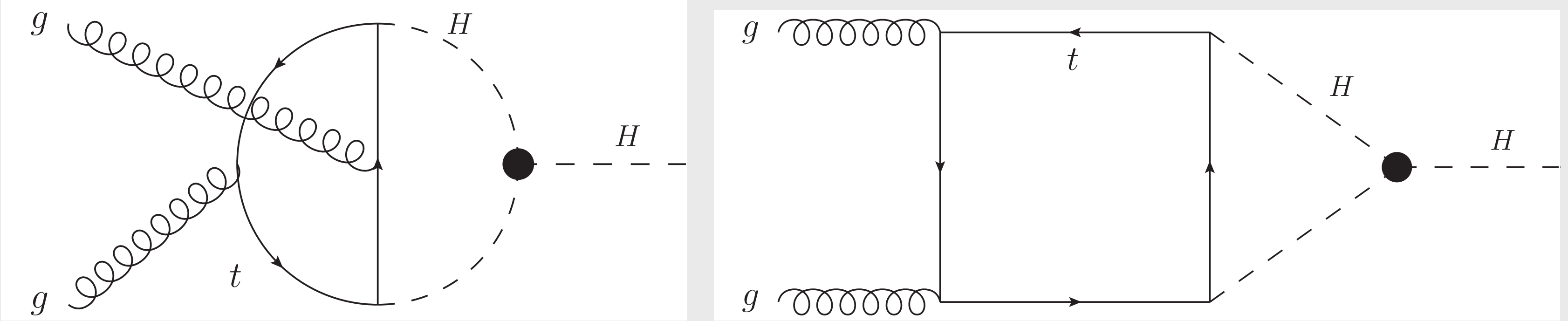
Beyond LO all the way

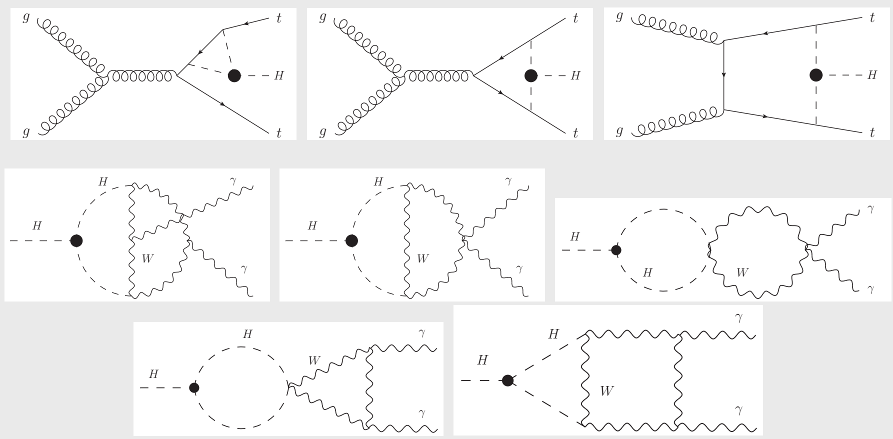
SELF-INTERACTION OF THE HIGGS BOSON

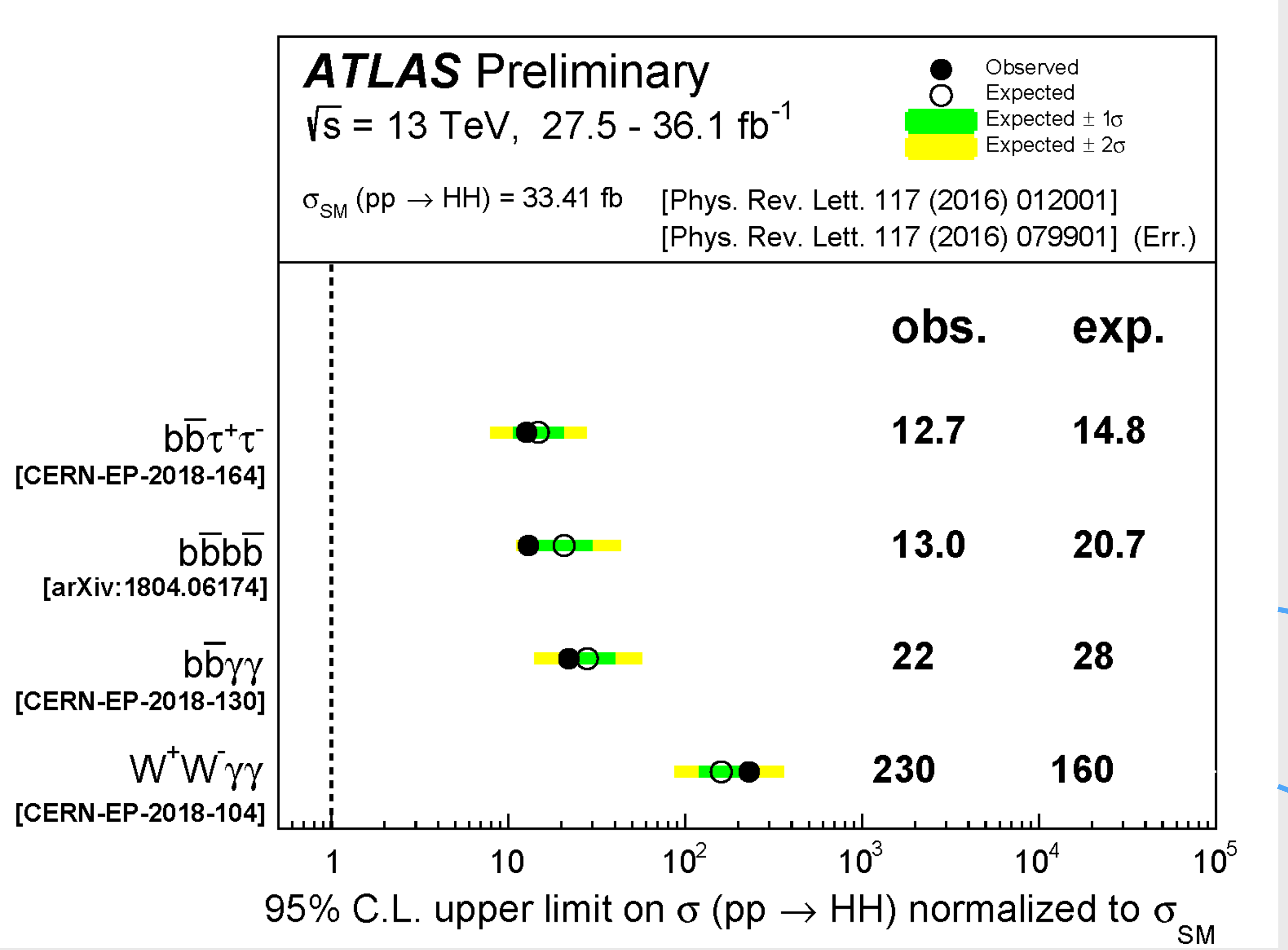
$$\mathscr{L}_{\lambda_3} \equiv \mathscr{L}_{SM} - \sum_{n=3}^{N} c_{2n} (\Phi^\dagger \Phi)^n ,$$

$$\mathscr{L}_{\lambda_3} : \kappa_\lambda = 1 + \frac{2\,v^2}{2\,m_H^2} \sum_{n=1}^{N} c_{2n}\, n(n-1)(n-2) \left(\frac{v^2}{2}\right)^{n-2}$$

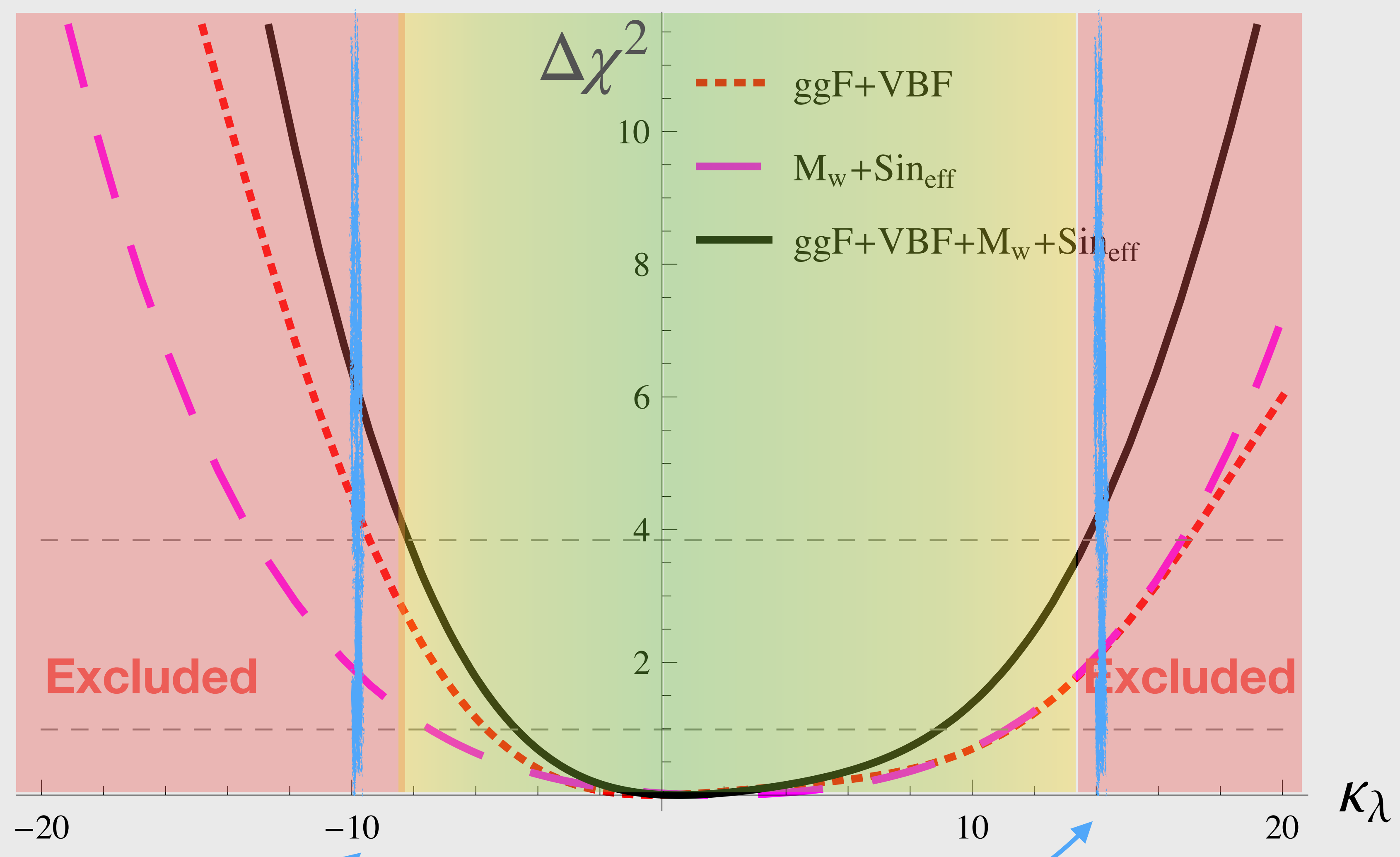








more reasonable BSM

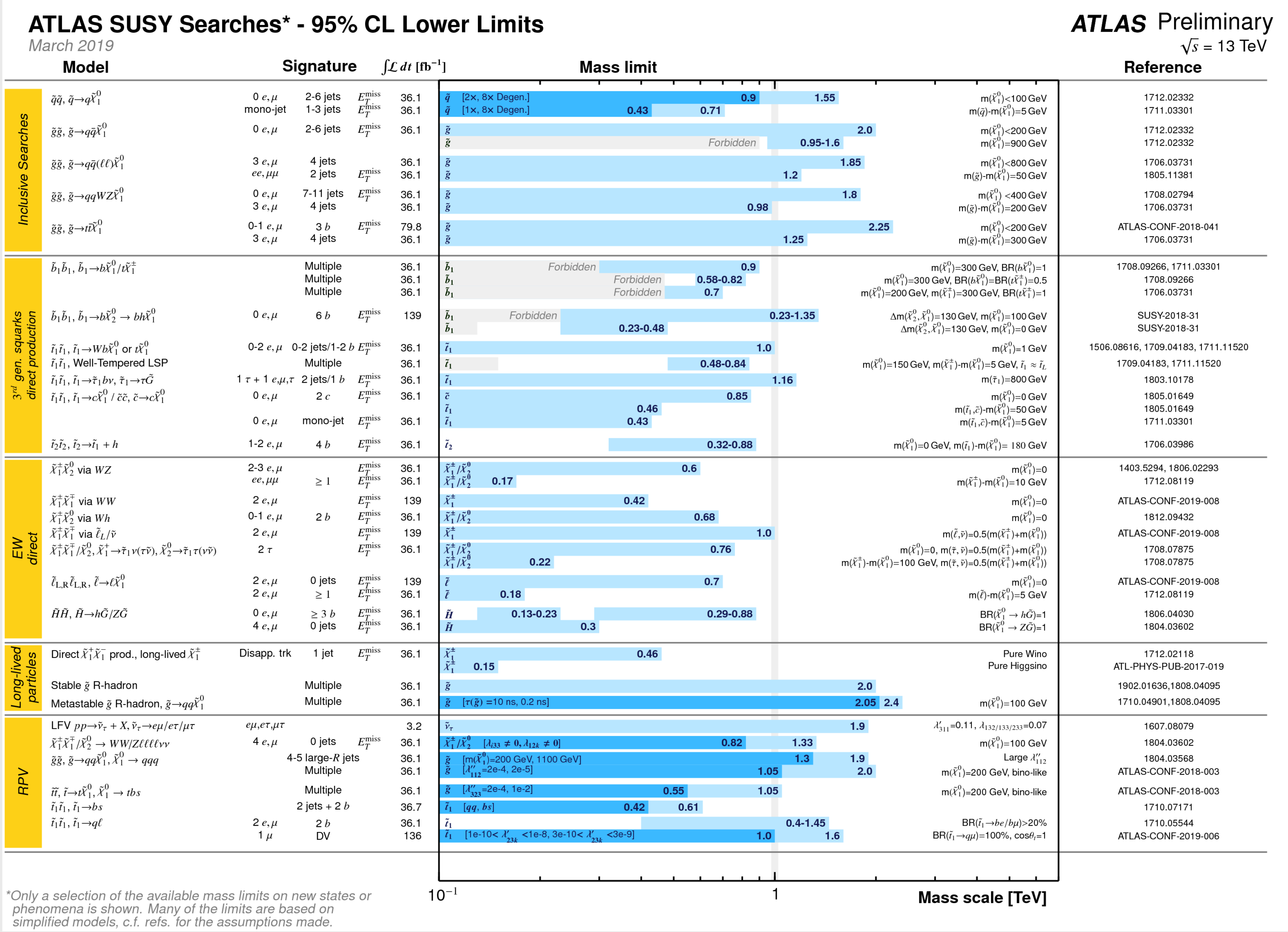


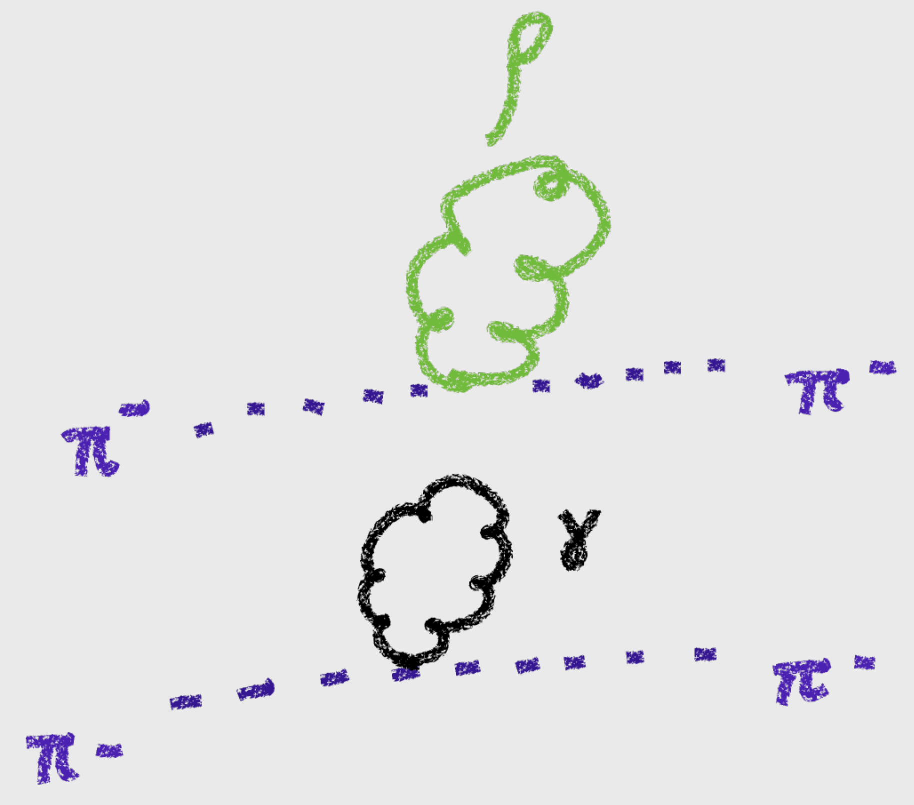
We conclude remarking that this range of κ_λ obtained using information coming from loop effects in single Higgs processes and precision physics is actually very competitive with the present bounds obtained from the direct searches of Higgs pair production.

BSM is missing

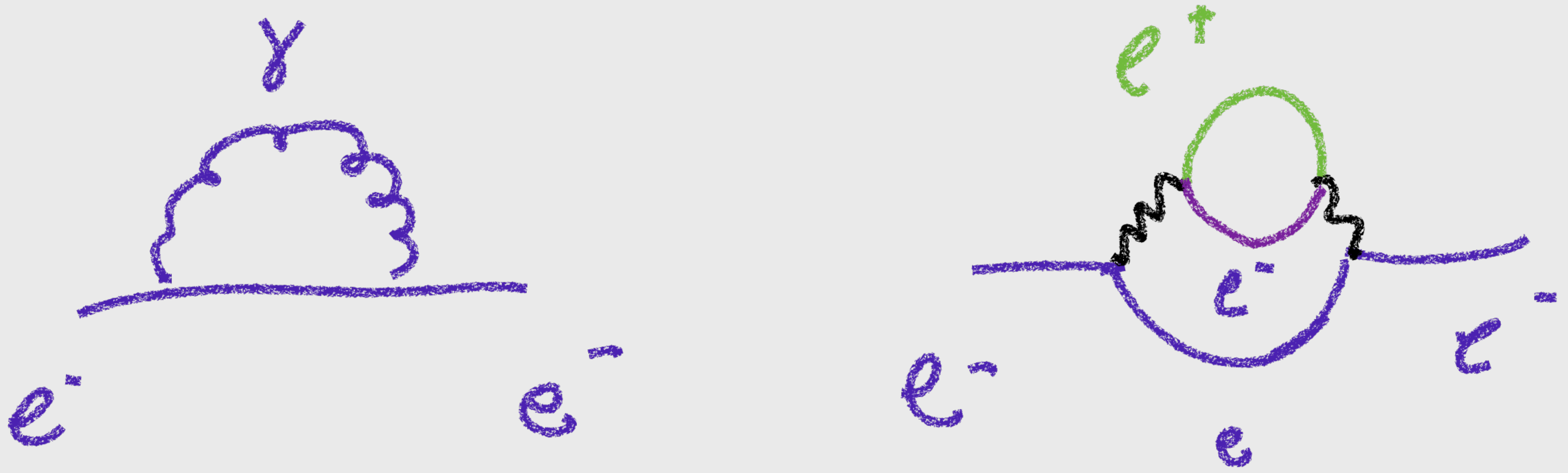
NEW SYMMETRY OR ENERGY SCALE

Tuning often quoted, but beware tuning is a plastic material shrinks under heat (unlike "normal" solid)





$m_{\pi^+} - m_{\pi^0}$



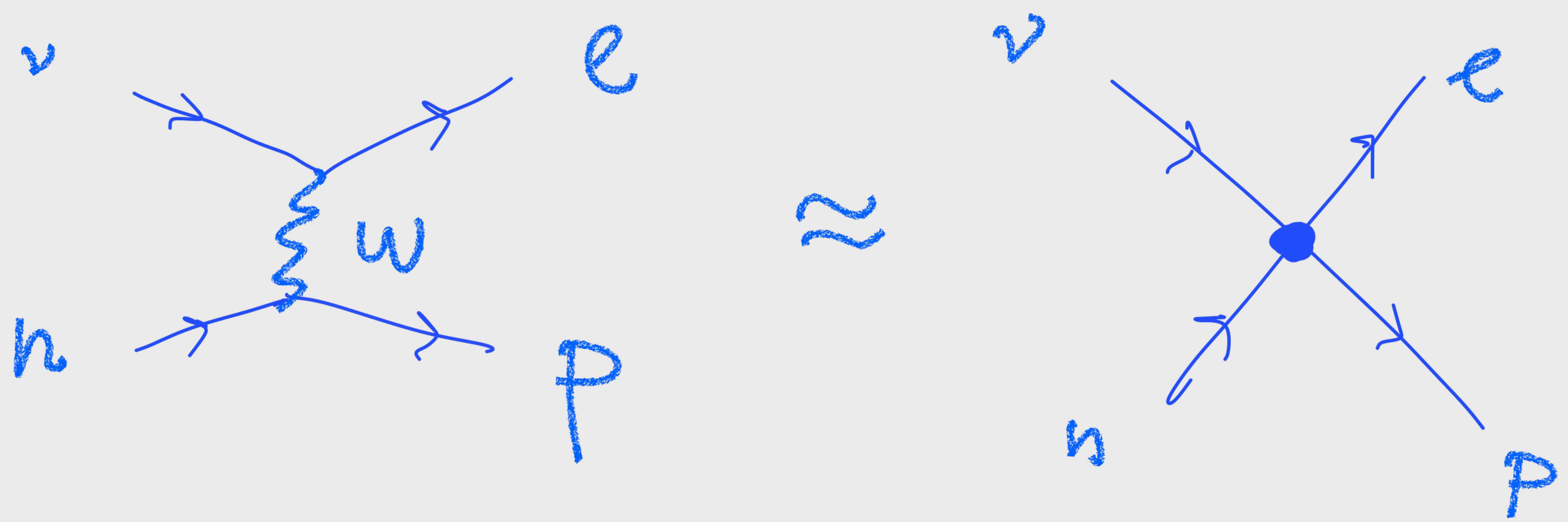
BSM must* be heavy

EFT from heavy new physics

XX CENTURY | EXAMPLE FROM WEAK INTERACTIONS

SHORT-DISTANCE THEORY

(which today we know)



EFFECTIVE 4-FERMION INTERACTION

$$\sigma \sim E^2 G_F^2 \sim \frac{E^2}{v^4}$$

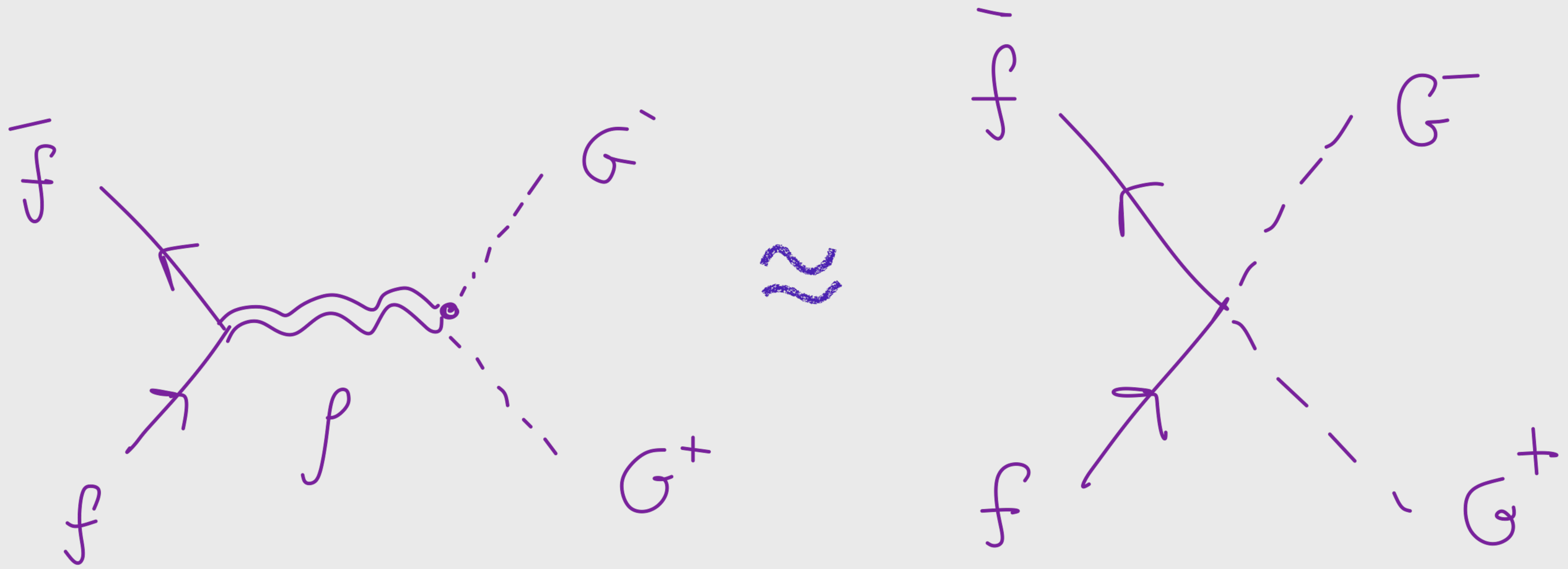
EFT from heavy new physics

XXI CENTURY

EXAMPLE FROM HIGGS&WEAK INTERACTIONS

SHORT-DISTANCE THEORY

(which today we DON'T know)



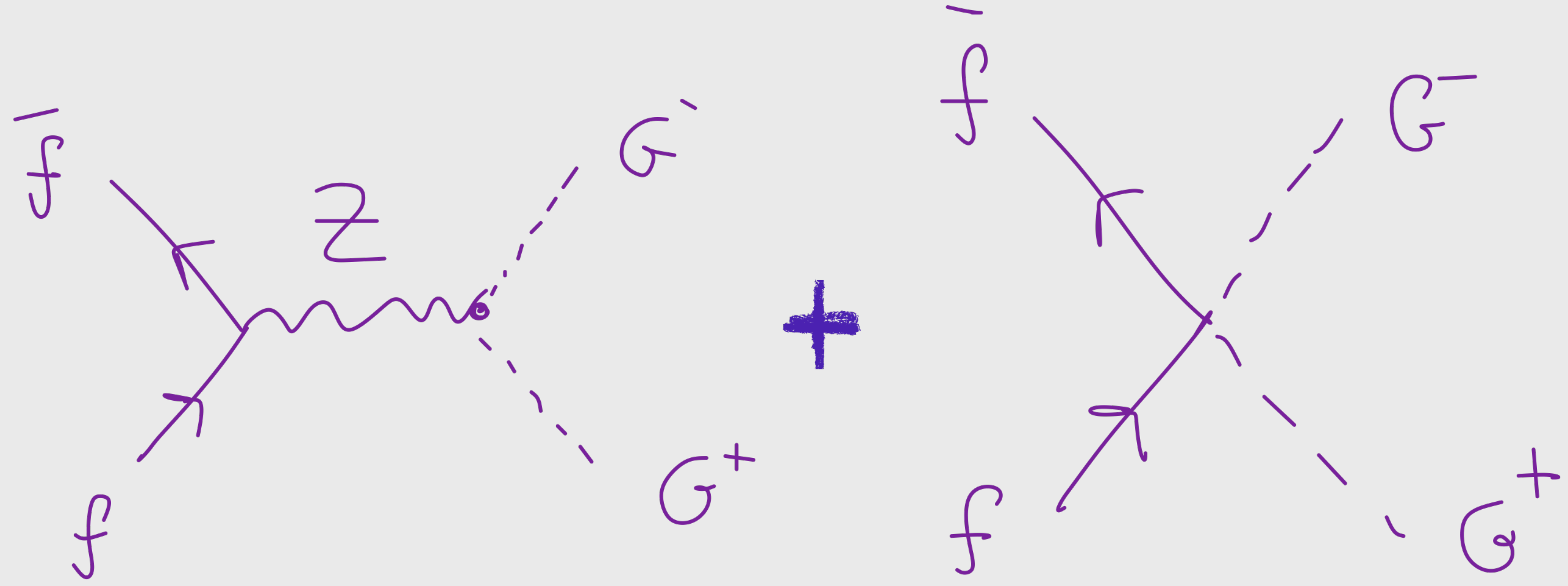
EFFECTIVE 4-PARTICLE INTERACTION

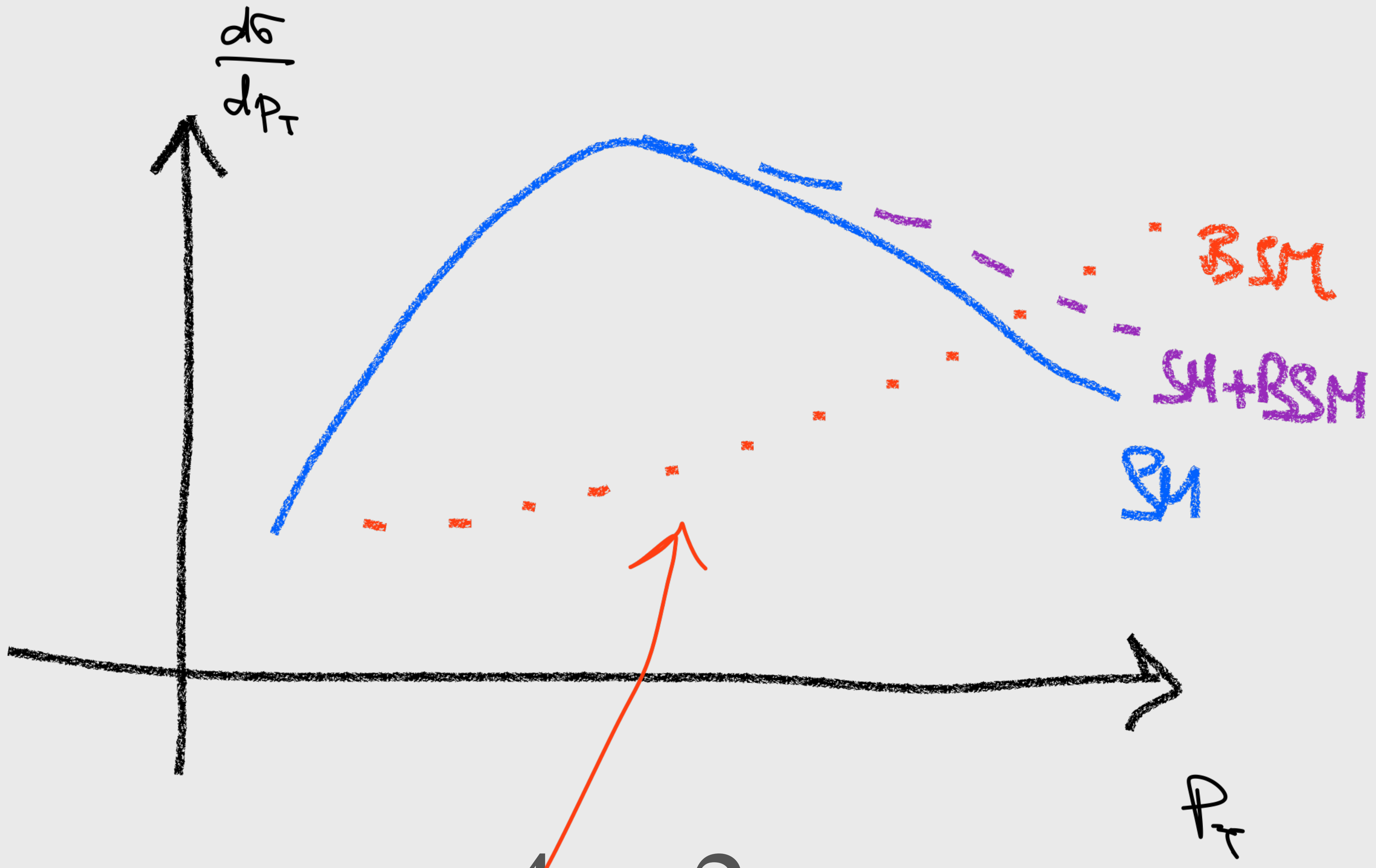
$$\sigma \sim E^2 G_{BSM}^2 \sim \frac{E^2}{f^4}$$

EFT from heavy new physics

XXI CENTURY

EXAMPLE FROM HIGGS&WEAK INTERACTIONS



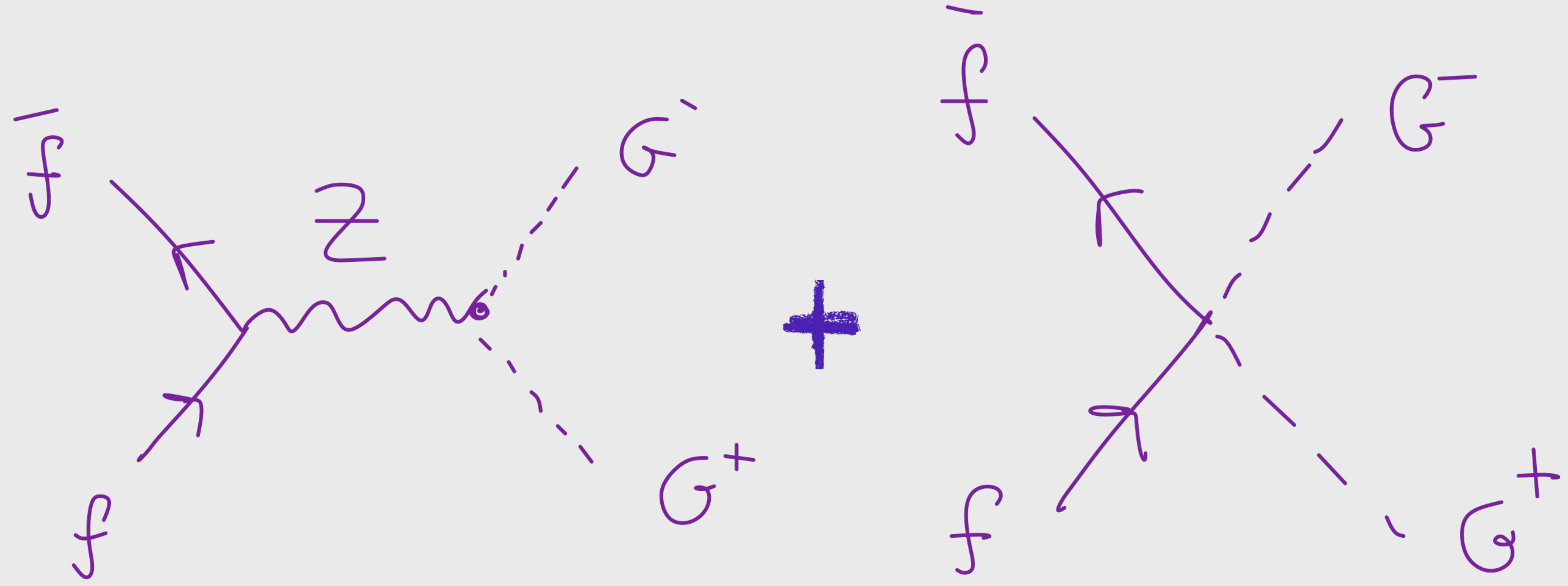


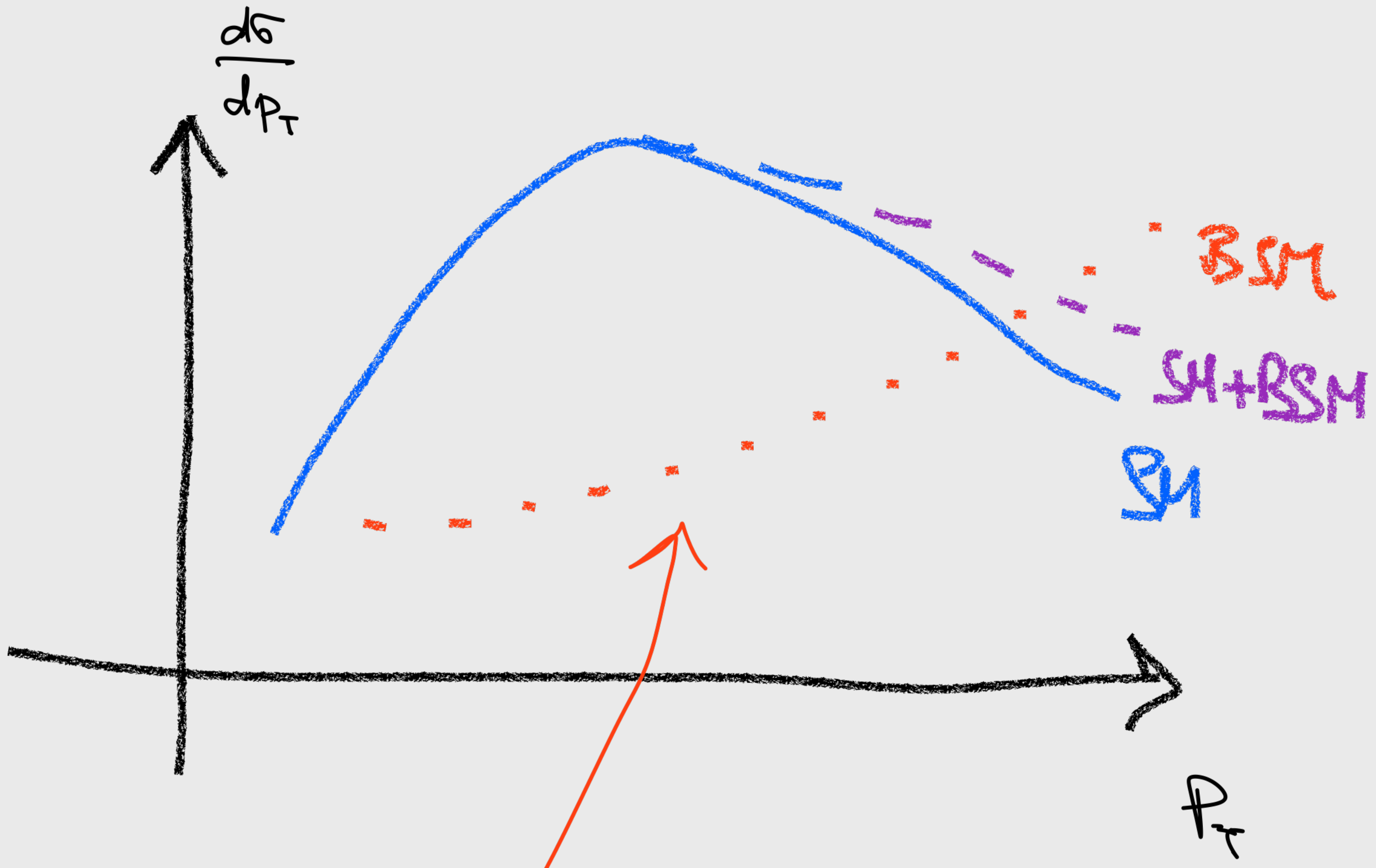
$$\sigma = \sigma_{SM} + \sigma_{BSM} \sim \sigma_{SM} \cdot (\underbrace{1 + E^2 G_{BSM}} + E^4 G^2_{BSM})$$

EFT from heavy new physics

XXI CENTURY

EXAMPLE FROM HIGGS&WEAK INTERACTIONS

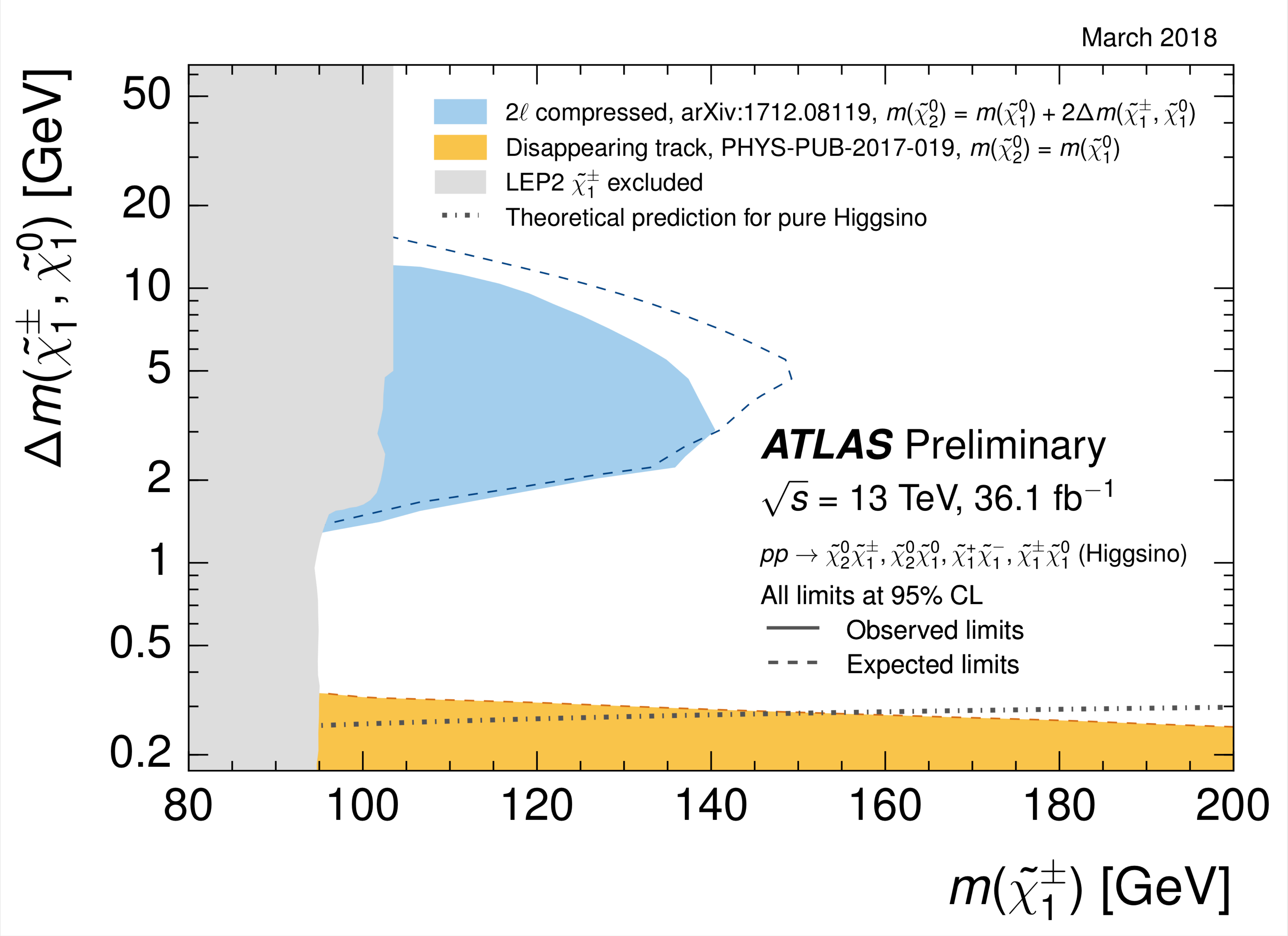


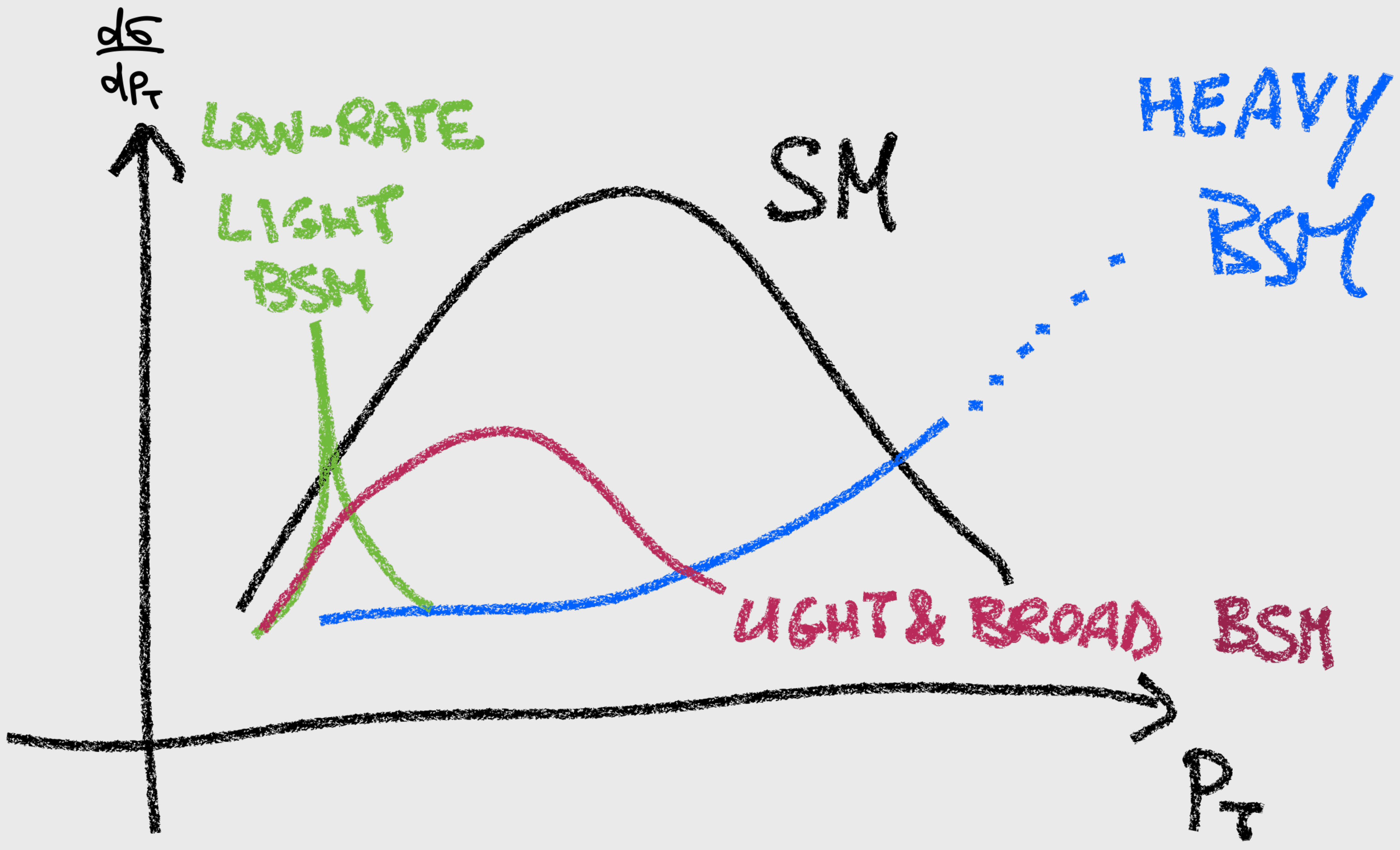


$$\sigma = \sigma_{SM} + \sigma_{BSM} \sim \sigma_{SM} \cdot \left(1 + \frac{E^2}{\Lambda_{BSM}^2} + \dots\right)$$

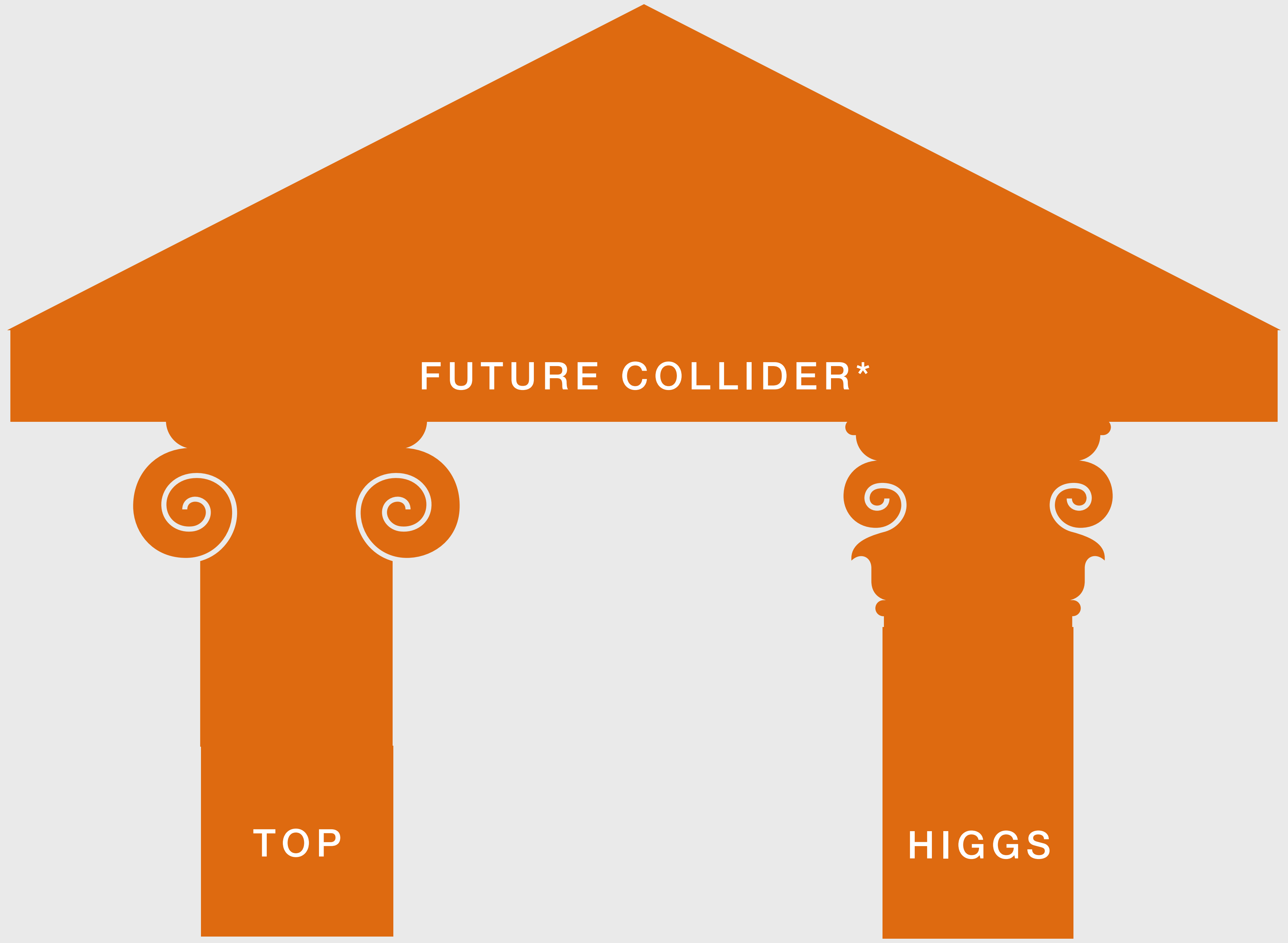
*Light exceptional cases

SYMMETRY AND ITS SUBTLE CONSEQUENCES





How to move forward?



**of any shape*

- the least well known
- the highest mass scale
- the most central to the origin of EW scale

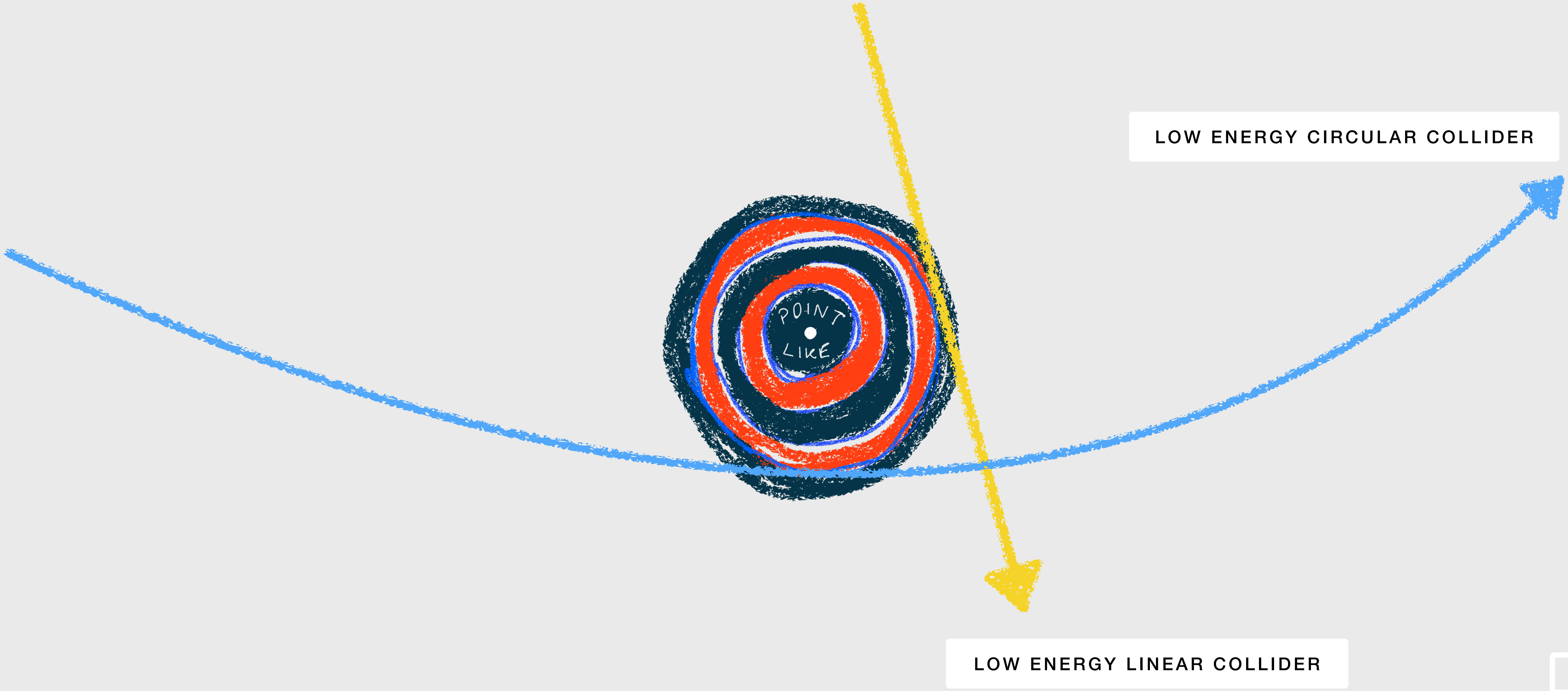
How to move forward?

“The size of the Higgs boson”

it matters because being “point-like” is the source of all the theoretical questions on the Higgs boson and weak scale

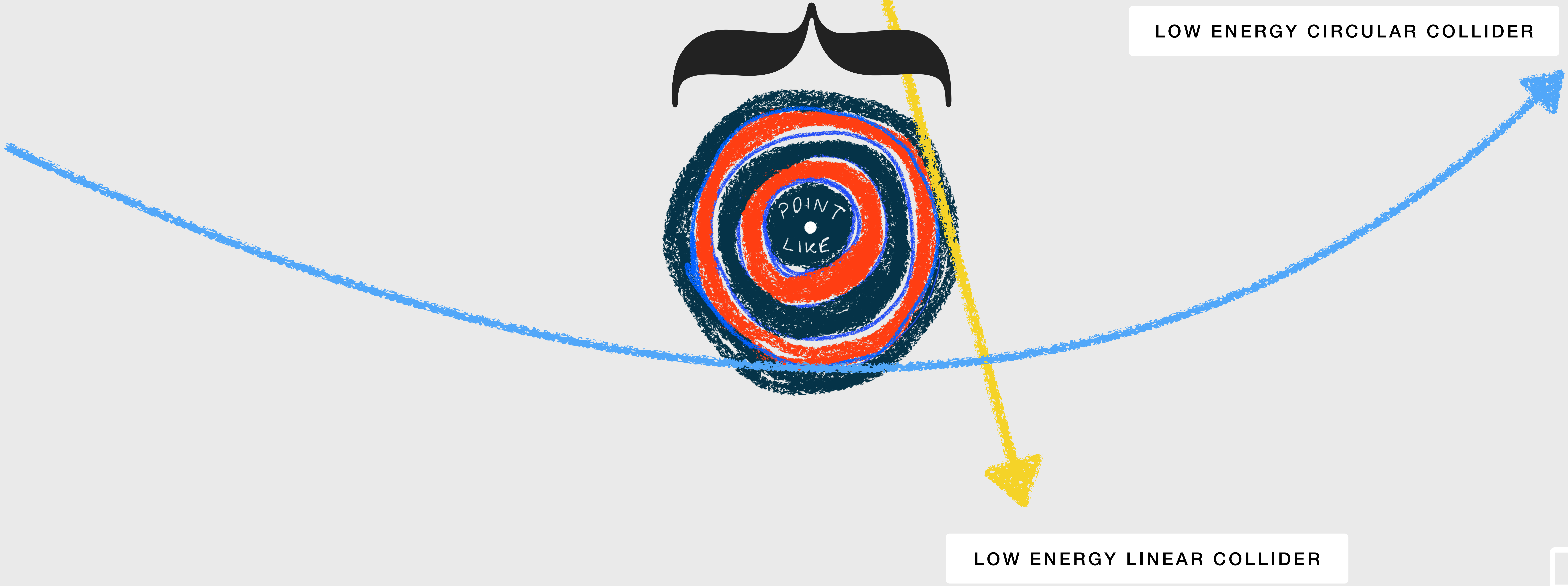
… and if it is not … well, that is physics beyond the Standard Model!

Looking ahead



Looking ahead

$$\ell_{Higgs} \sim f^{-1}$$



Lots of material from

Yellow Report

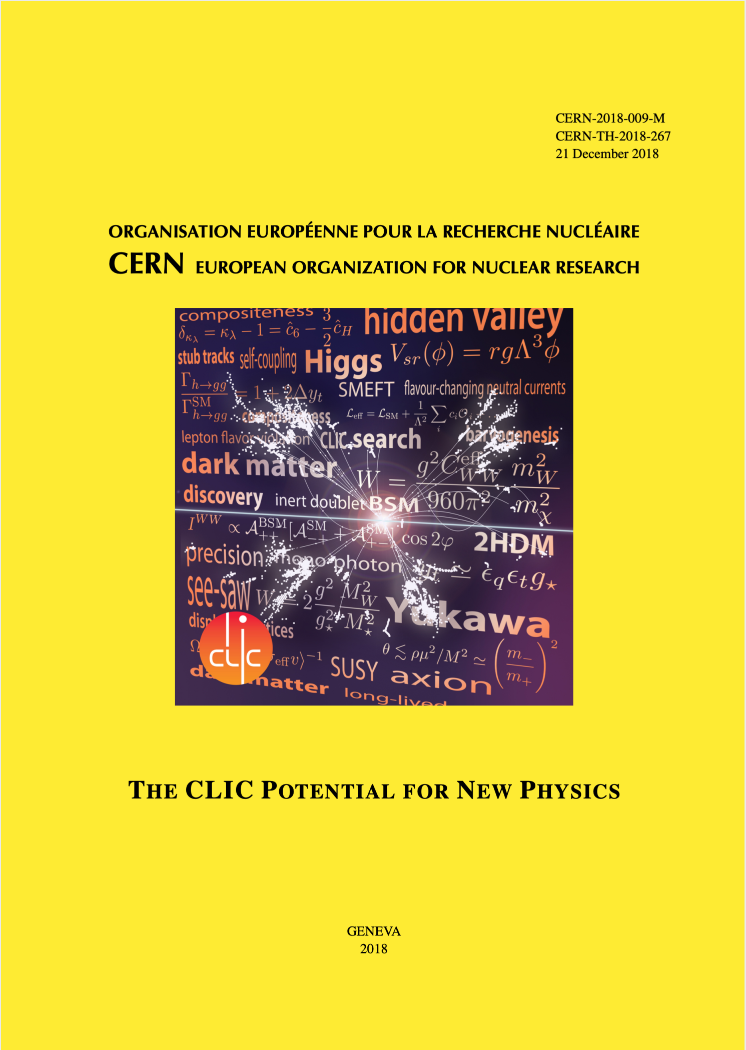
The CLIC Potential for New Physics

CLIC detector&physics + Theory community

Editors: J. De Blas, R. Franceschini, F. Riva, P. Roloff, U. Schnoor, M. Spannowsky, A. Wulzer, J. Wells, J. Zupan

http://clicdp.web.cern.ch/content/wg-physics-potential

Lots of material from



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1812.02093 - The CLIC potential for new physics - CERN Yellow Rep. Monogr. Vol. 3 (2018)

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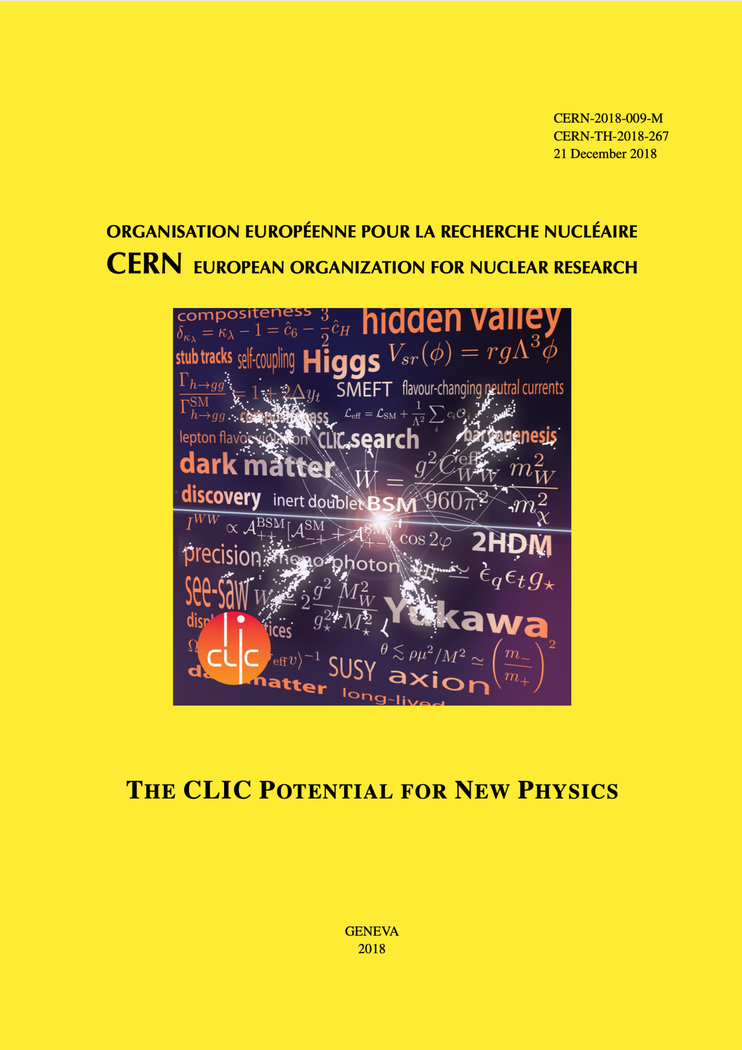
GM PRUNA



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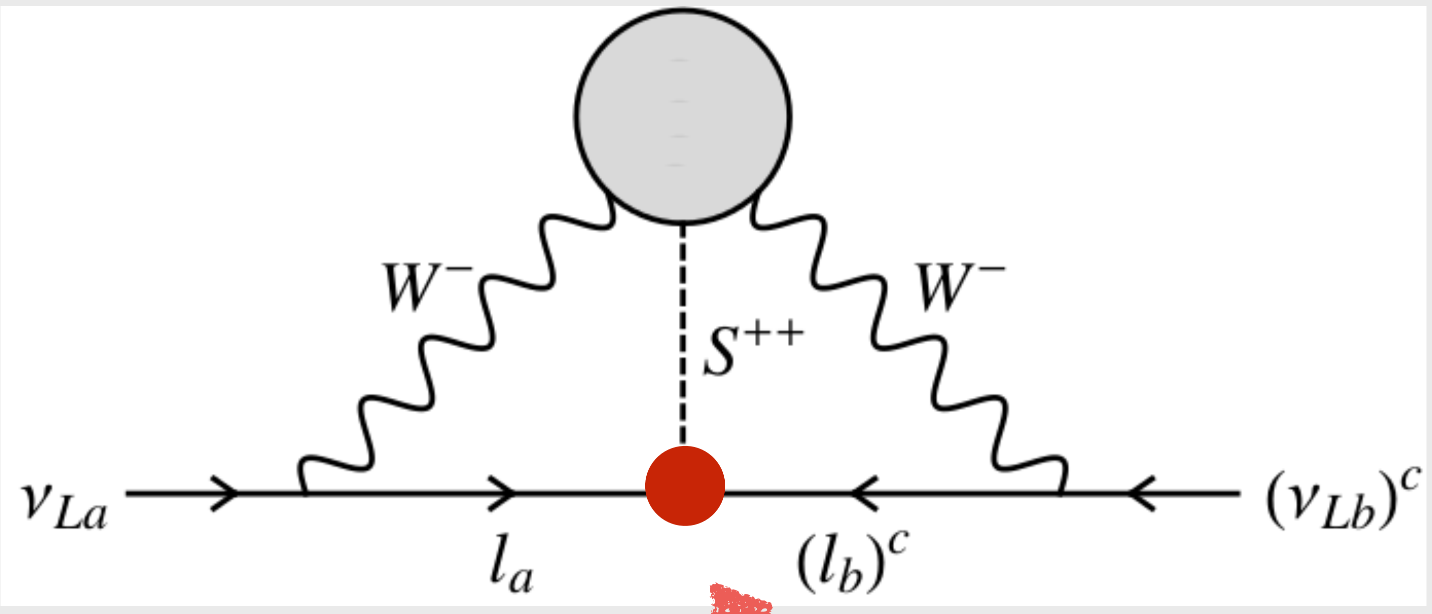
Mediator of Neutrino mass mechanism

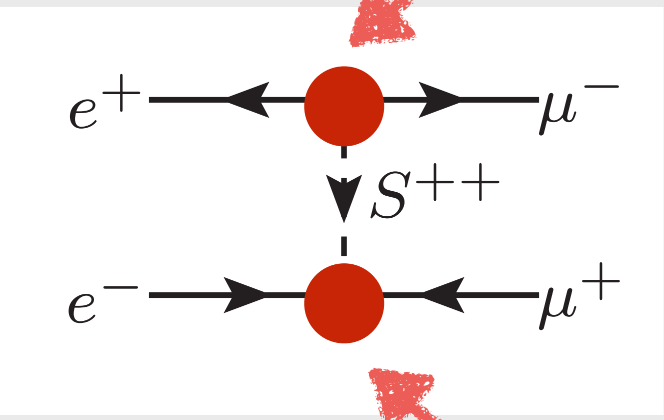
DOUBLY CHARGED

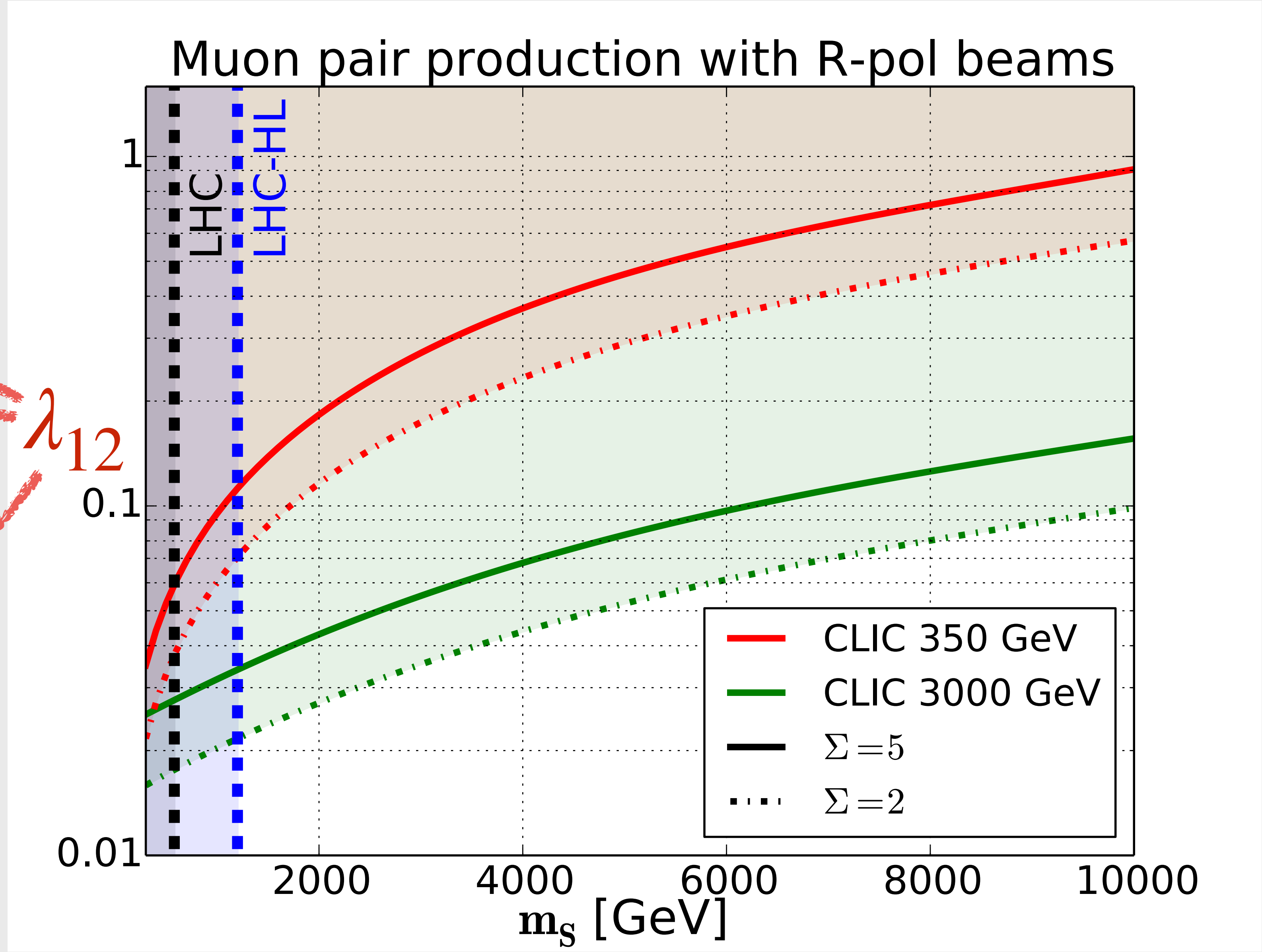
in total rate $e^+e^- \to \ell^+ \ell^-$

$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + \left(D_\mu S^{++}\right)^\dagger \left(D^\mu S^{++}\right) + \left(\lambda_{ab} \overline{(\ell_R)}^c_a (\ell_R)_b\, S^{++} + \text{h.c.}\right) +$$
$$+ \lambda_2 \left(H^\dagger H\right)\left(S^{--}S^{++}\right) + \lambda_4 \left(S^{--}S^{++}\right)^2 + [\ldots],$$



λ_{12}





Exclude Type-2 seesaw on the up to 10 TeV for triplet Yukawa ~0.1

Lumi vs. Energy

EFT EPOCH

LESSON FROM LHC

New Physics may fit well in a EFT (new contact interactions)

- effects grow at larger energies like $\nu e^- \to \nu e^-$ in Fermi Theory

$$m_W, m_Z, \sin\theta_W, A_{FB}^{whatever}, h \to Z\gamma, h \to ZZ, t \to b\tau\nu$$

measurements dominated by a single mass scale

- dominant energy scale is low
- measurement is simple to grasp
- progress is easy to measure (in)significant digits

$$\frac{d\sigma}{dp_T}$$

measurements sensitive to a range of mass scales

- sensitive to a range of energy scales
- measurement of a spectrum (not so?!?) simple to grasp
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HIGH-LUMI PROBES

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as NP effects may grow quadratically with energy

$$\Delta O = O_{NP} - O_{SM} \sim \left(\frac{E}{v}\right)^2$$

1% at m_Z is worse than 10% at 1 TeV

Effects of the size of the Higgs boson

h ~ π

STRONGLY INTERACTING LIGHT HIGGS

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

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

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

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

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

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

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

Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

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

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

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

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

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

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

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

$$\ell_{Higgs} \sim f^{-1} \sim g_\star/m_\star$$

EFT

COMPOSITE HIGGS

$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right] + \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$
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will consider a 3 TeV e+e- collider with L = few 1/*ab* as an ambitious but feasible option

complementary bounds from:

- Drell-Yan (high-pT probe)

$\frac{d\sigma}{d\cos\theta}$ of $e^+e^- \to f\bar{f}$

$$W = 2\frac{g^2}{g_\star^2}\frac{M_W^2}{M_\star^2}, \quad Y = 2\frac{g'^2}{g_\star^2}\frac{M_W^2}{M_\star^2}.$$

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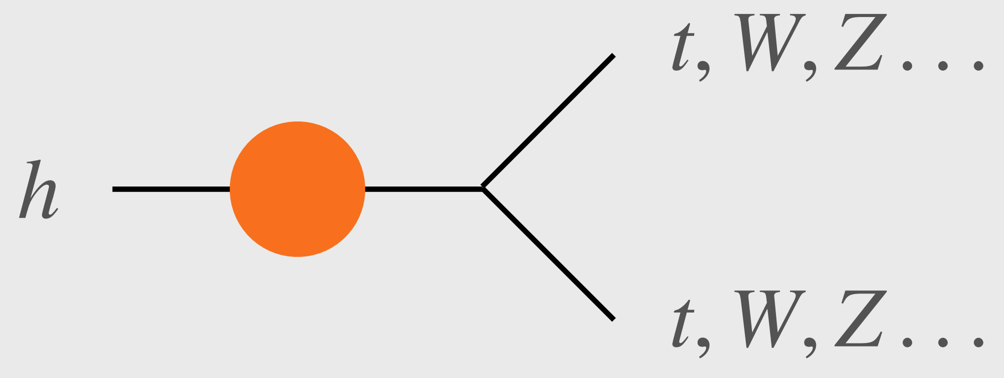
rate of
$e^+e^- \to h + \ldots \to XX + \ldots$



EFT

COMPOSITE HIGGS

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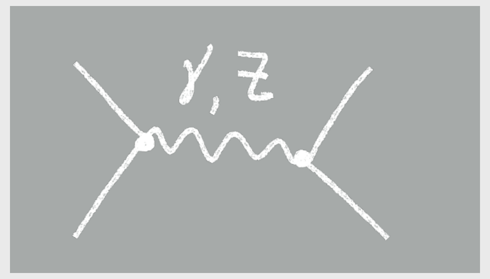

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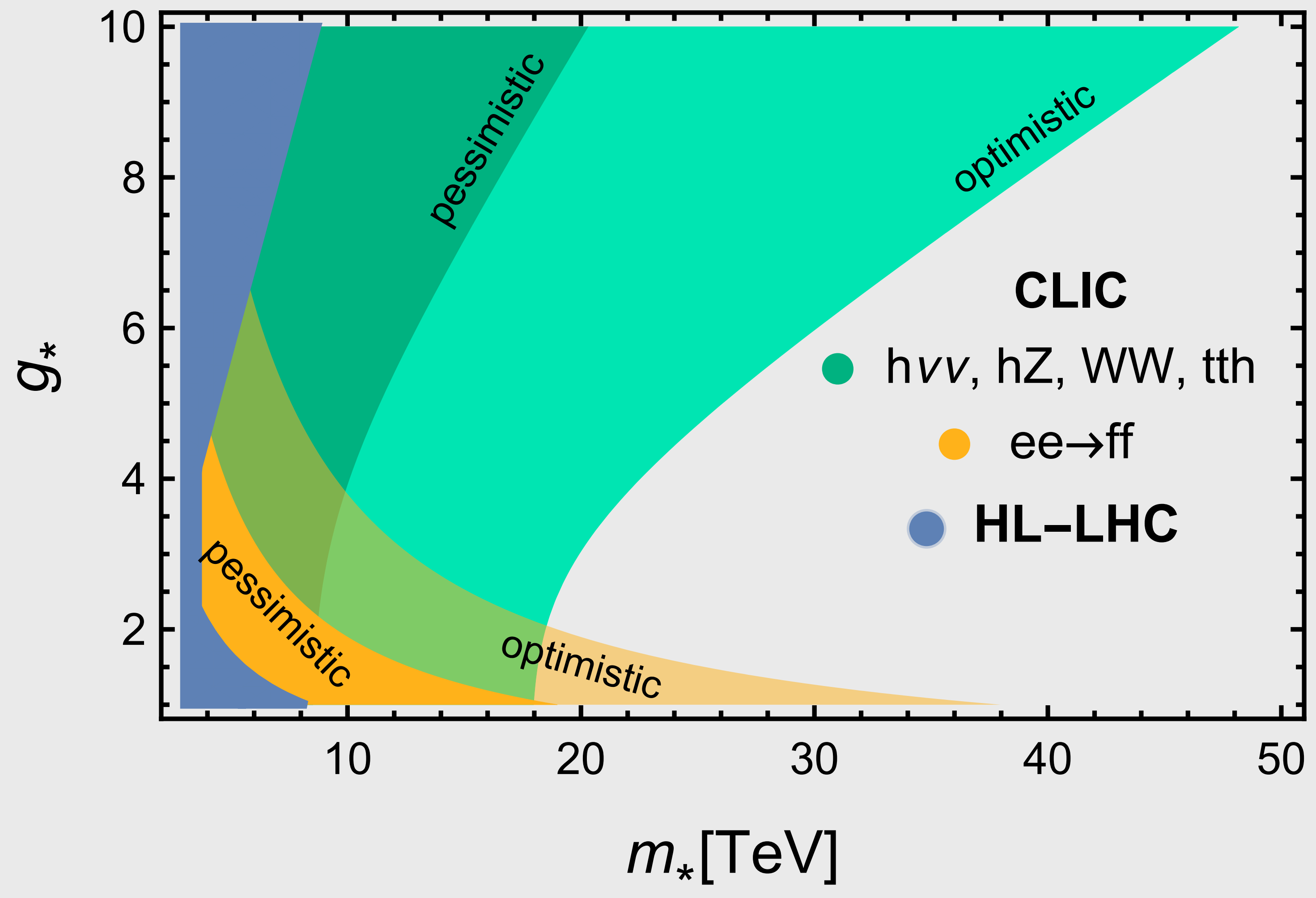

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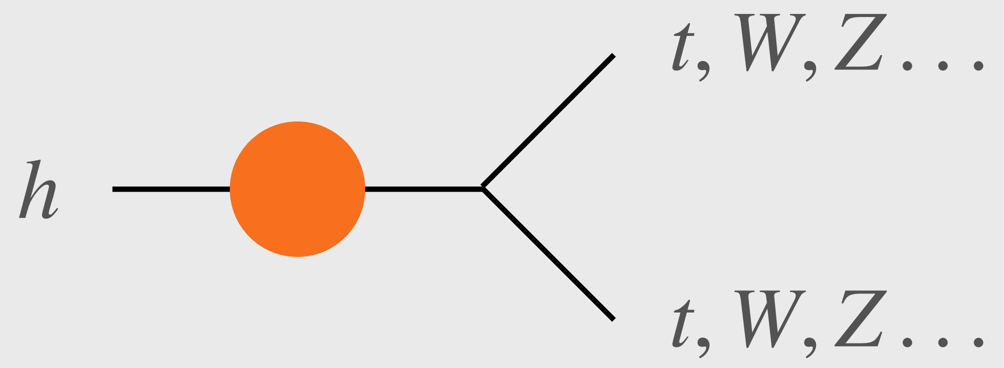

EFT

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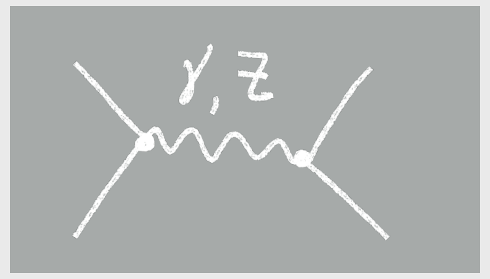

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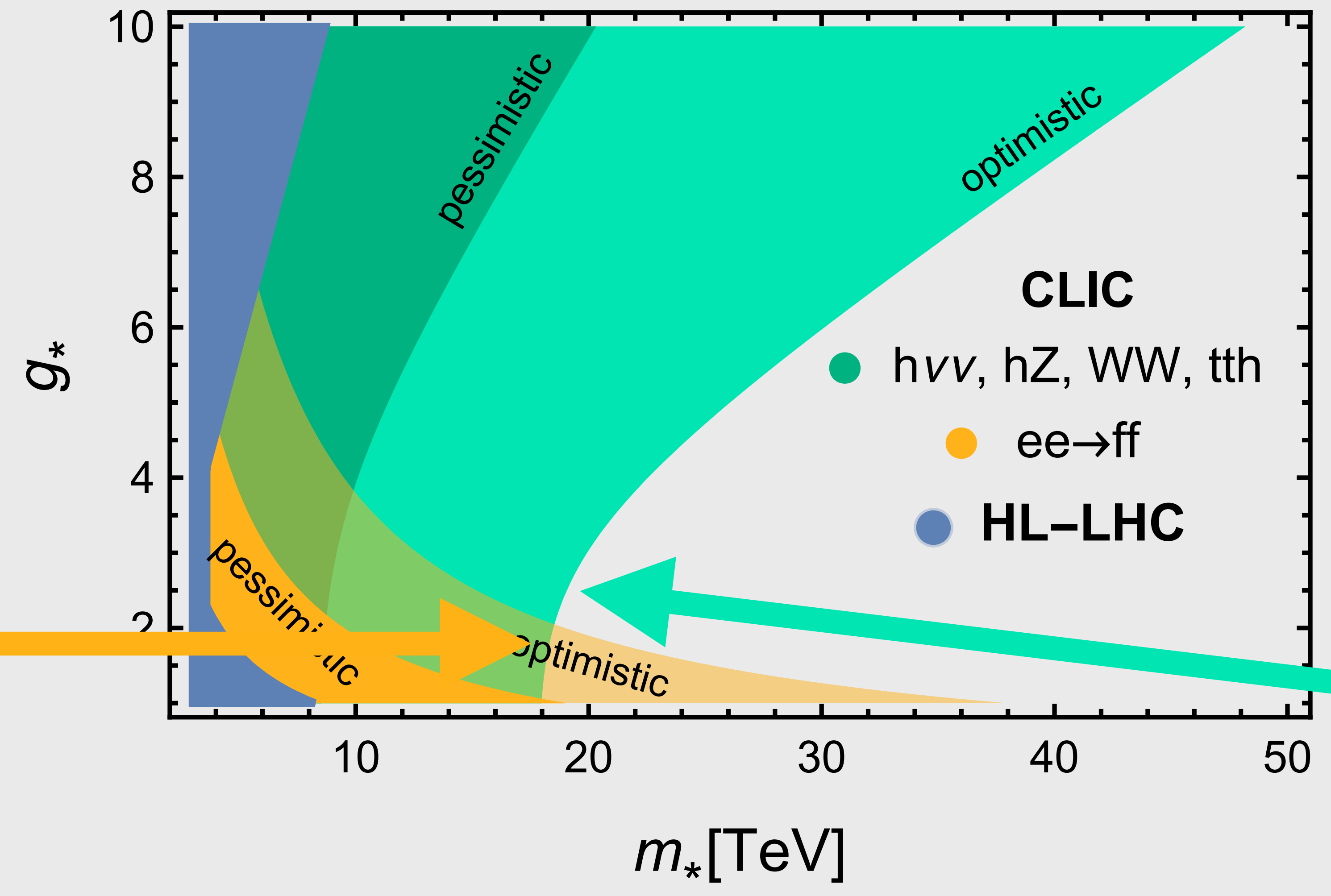

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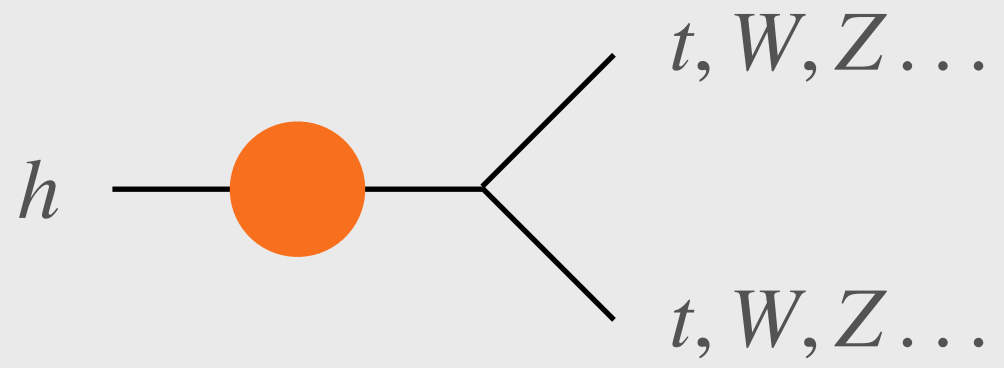

EFT

COMPOSITE HIGGS

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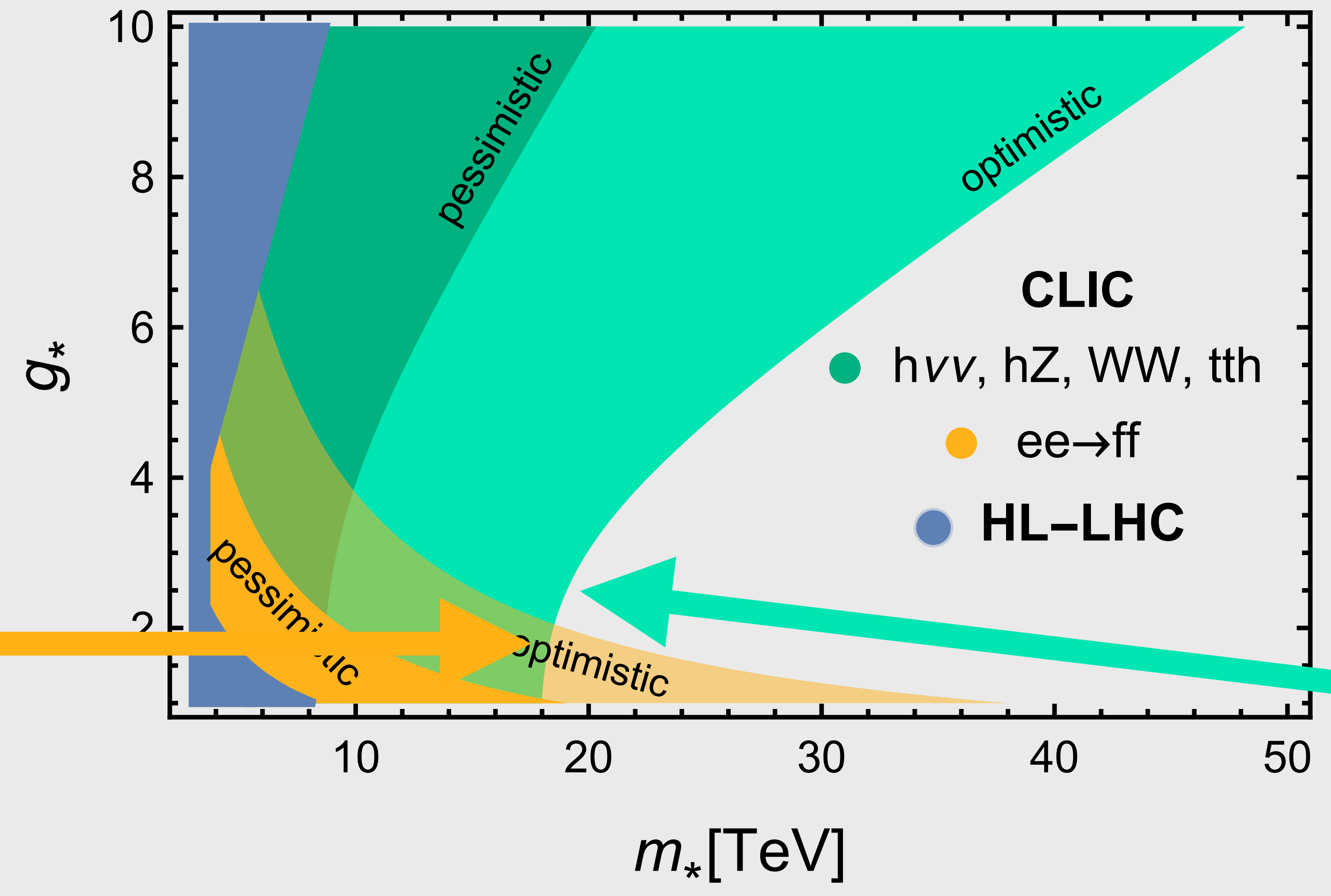

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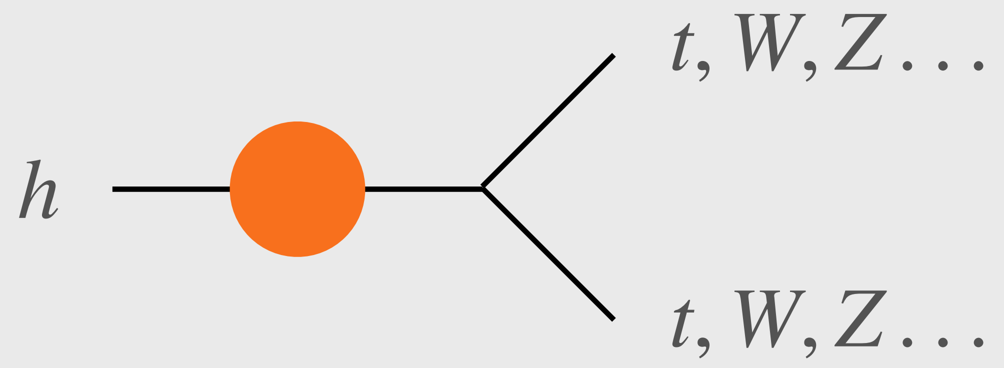


High energy lepton colliders can probe the large set of dim-6 operators

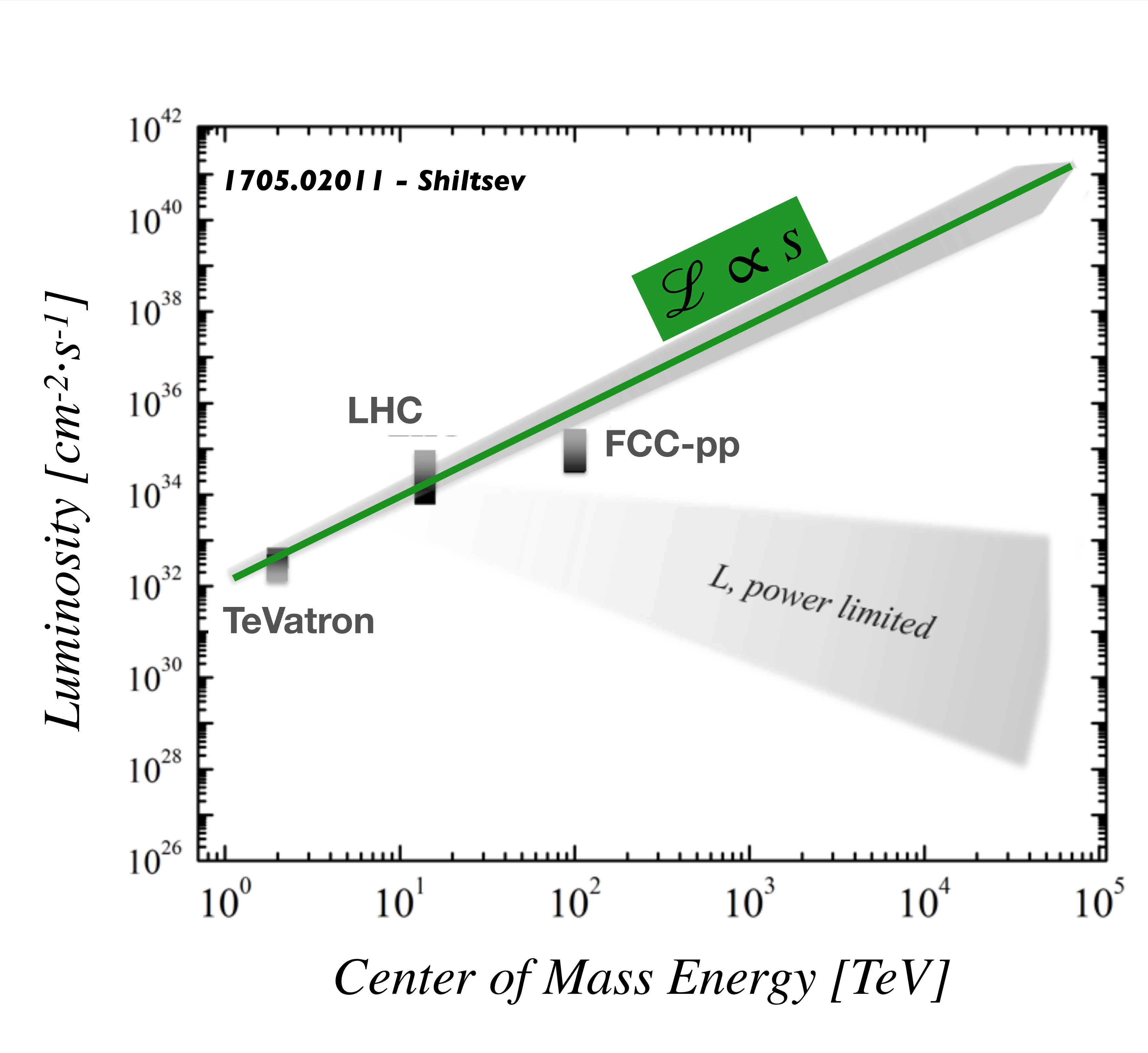
for universal theories (least flavor puzzling) bounds are improving one order or better w.r.t. HL-LHC

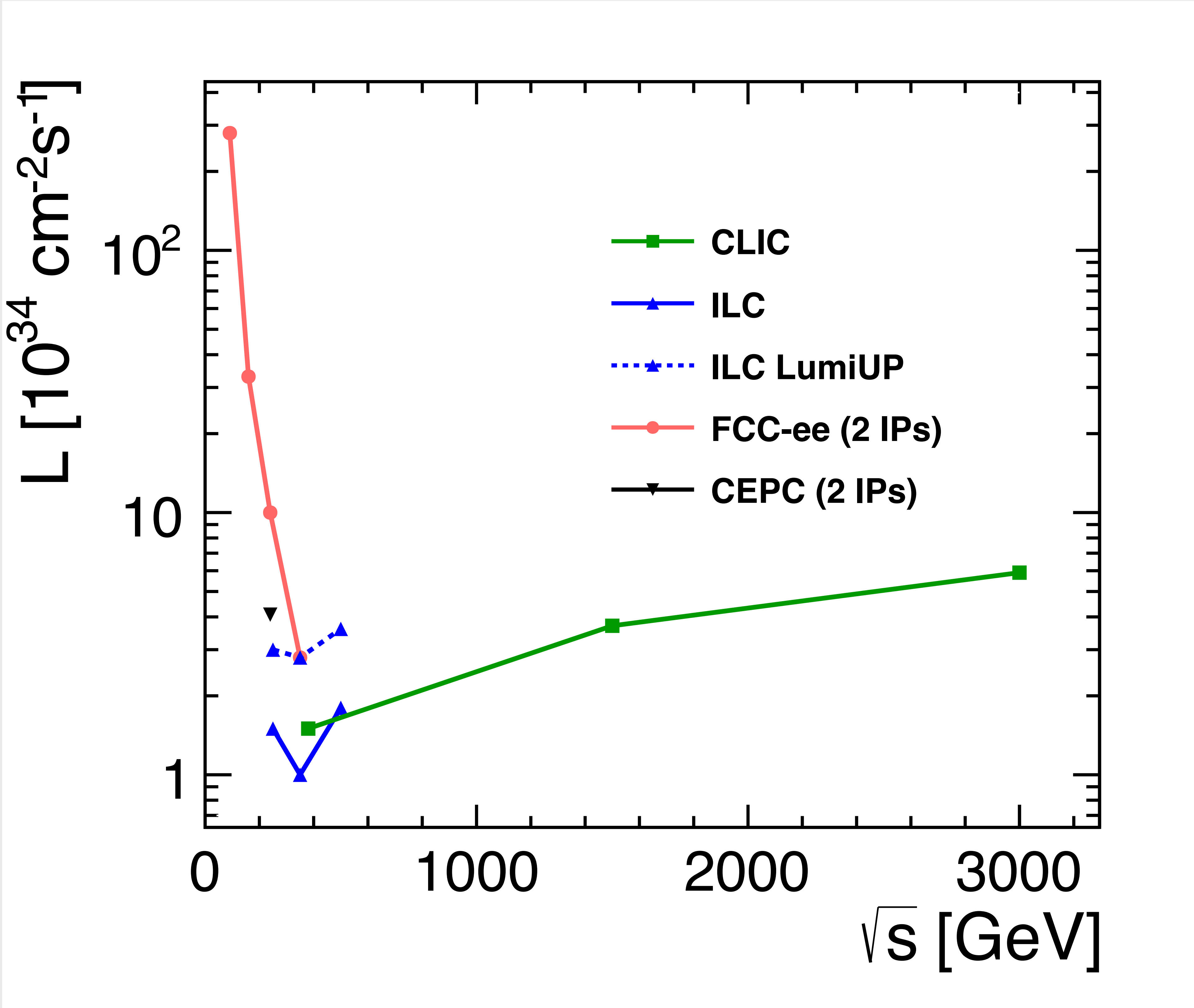
Unstable and weak: our future

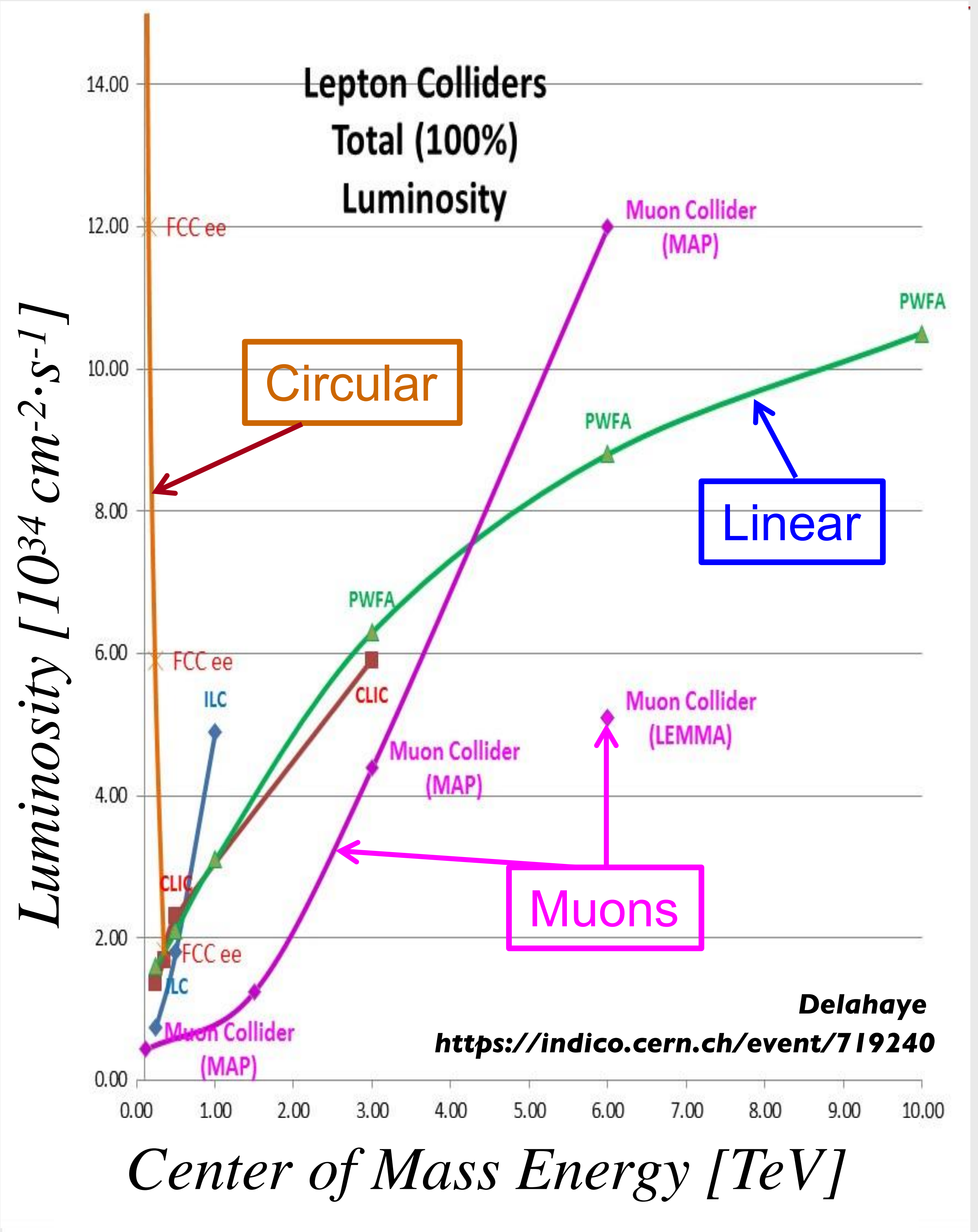
Unstable and weakly charged: our future beams

Challenges we can see already from here

A BALANCING PROBLEM



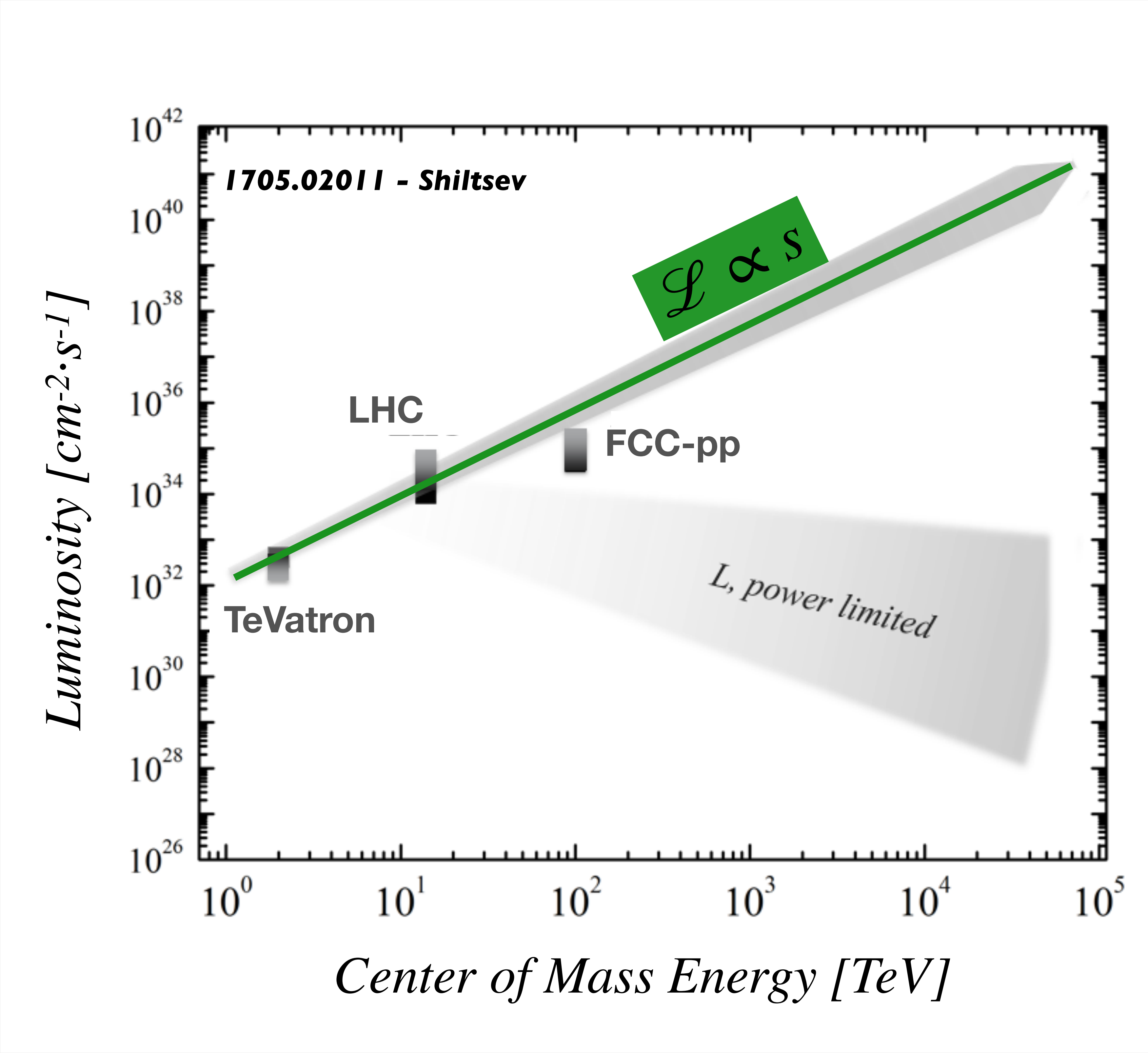


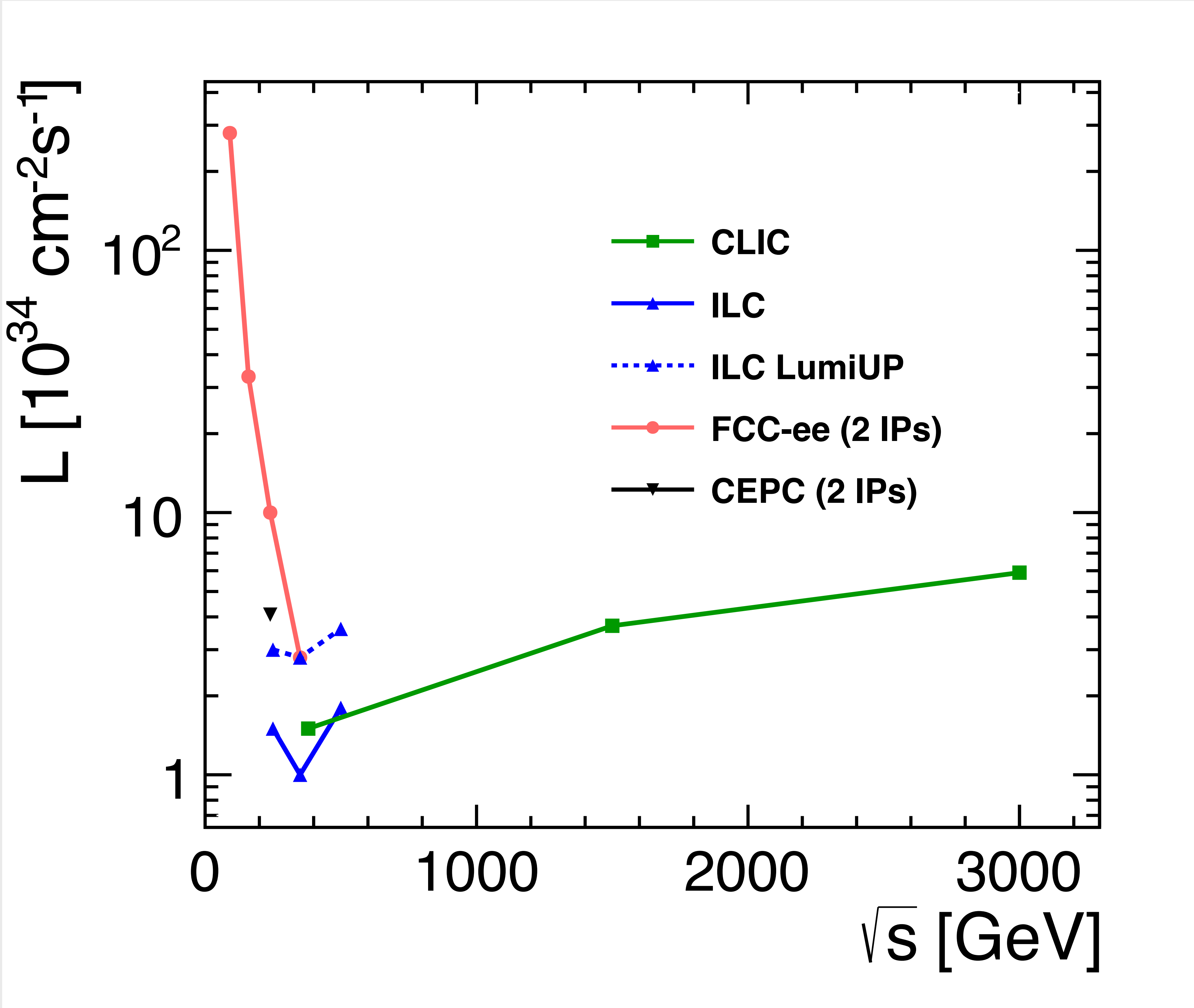


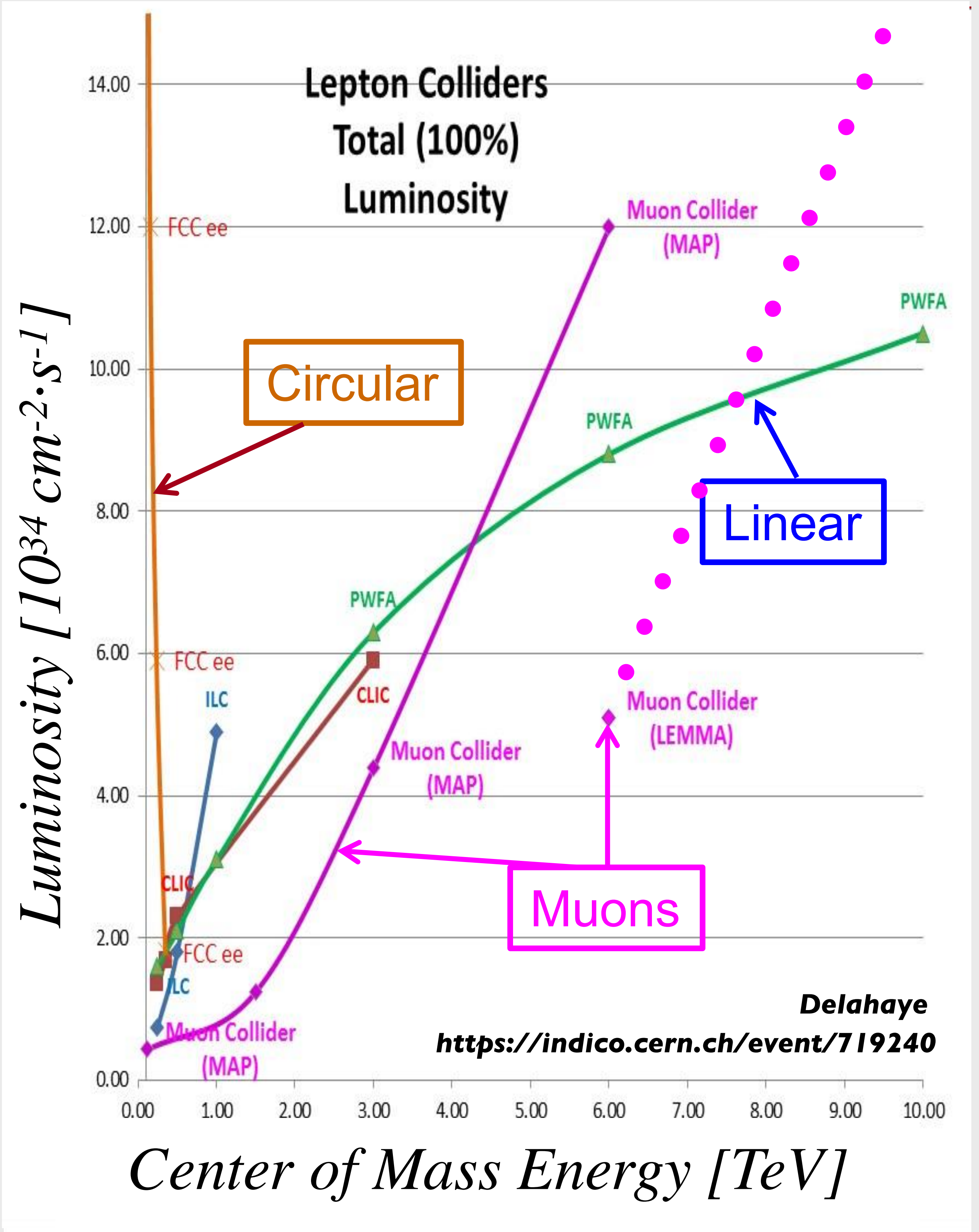
Challenges we can see already from here

A BALANCING PROBLEM

$\mathscr{L} \sim E^2$?





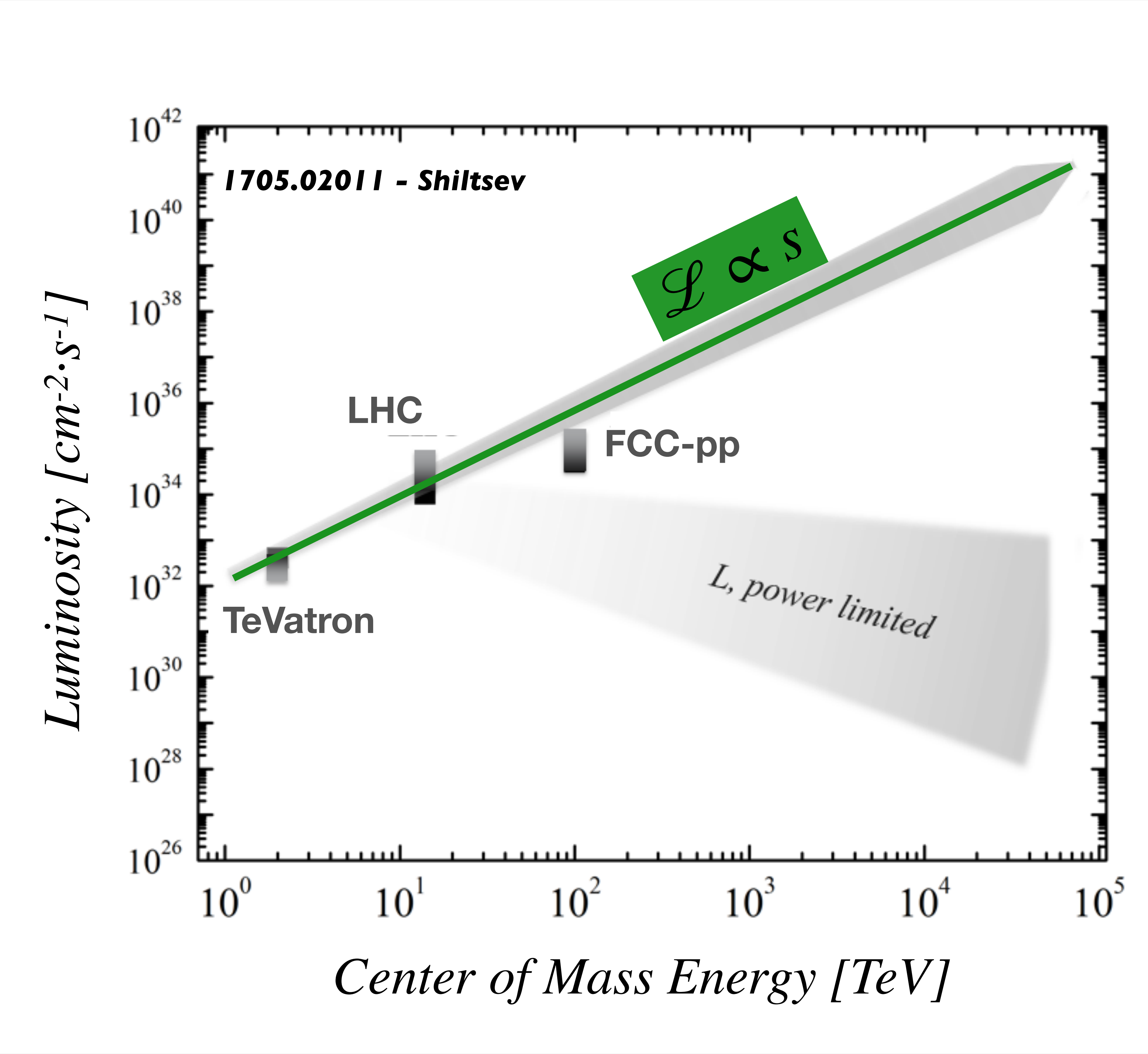


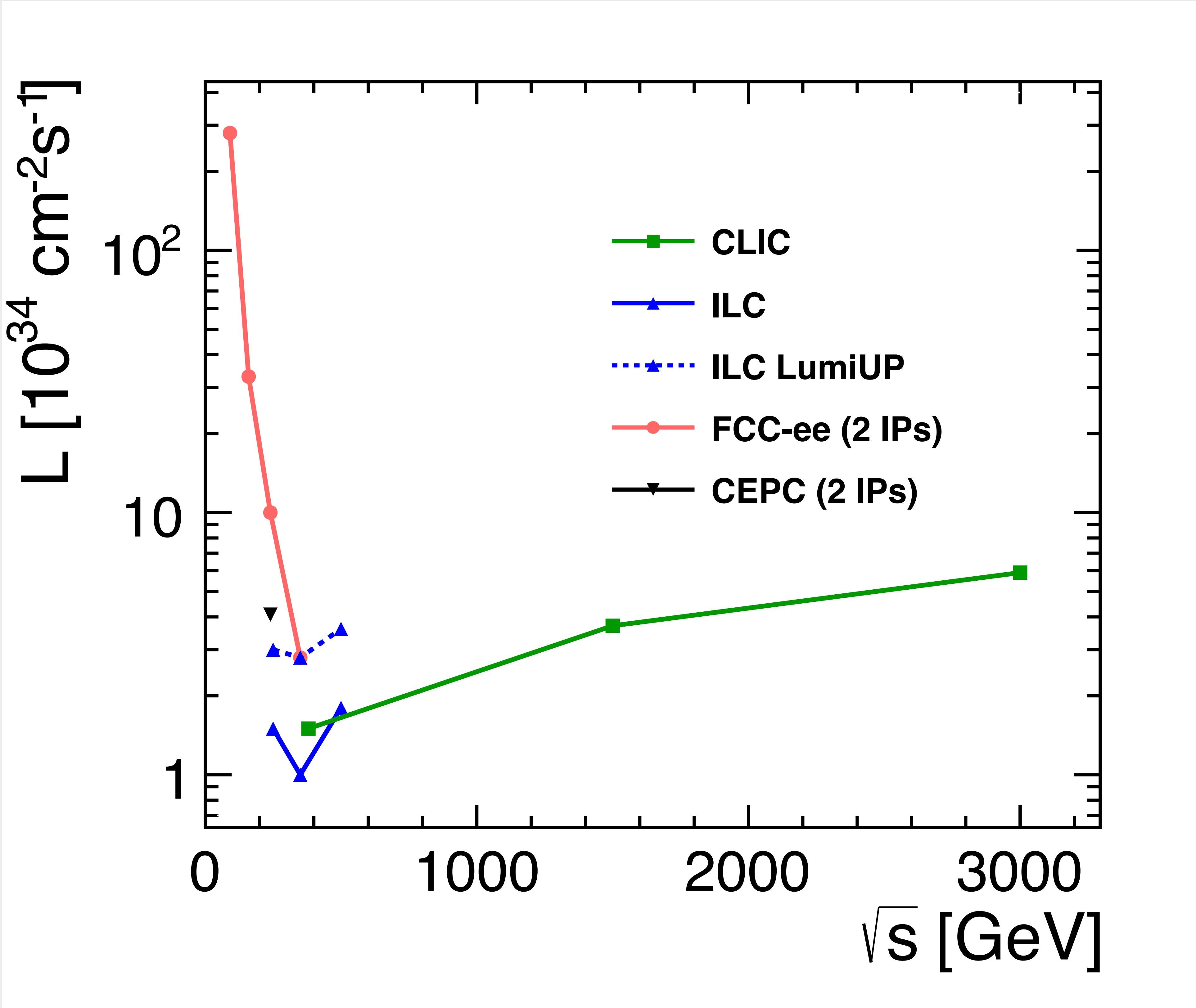
Challenges we can see already from here

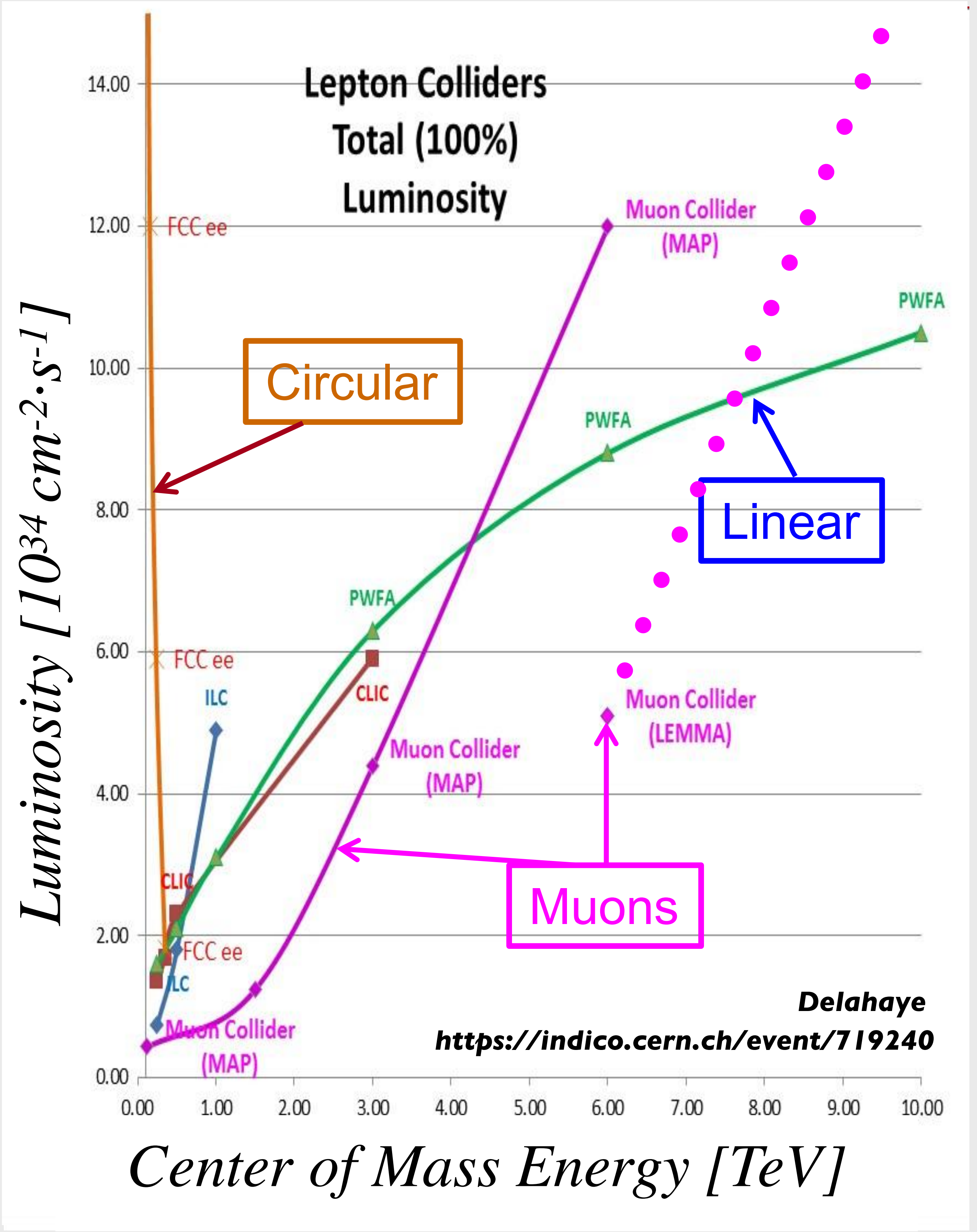
A BALANCING PROBLEM

$$\sigma(ab \to cd) \sim 1/E^2$$
$$\mathscr{L} \sim E^2$$
$$\mathscr{L} \cdot \sigma(ab \to cd) \sim \text{const}$$

?

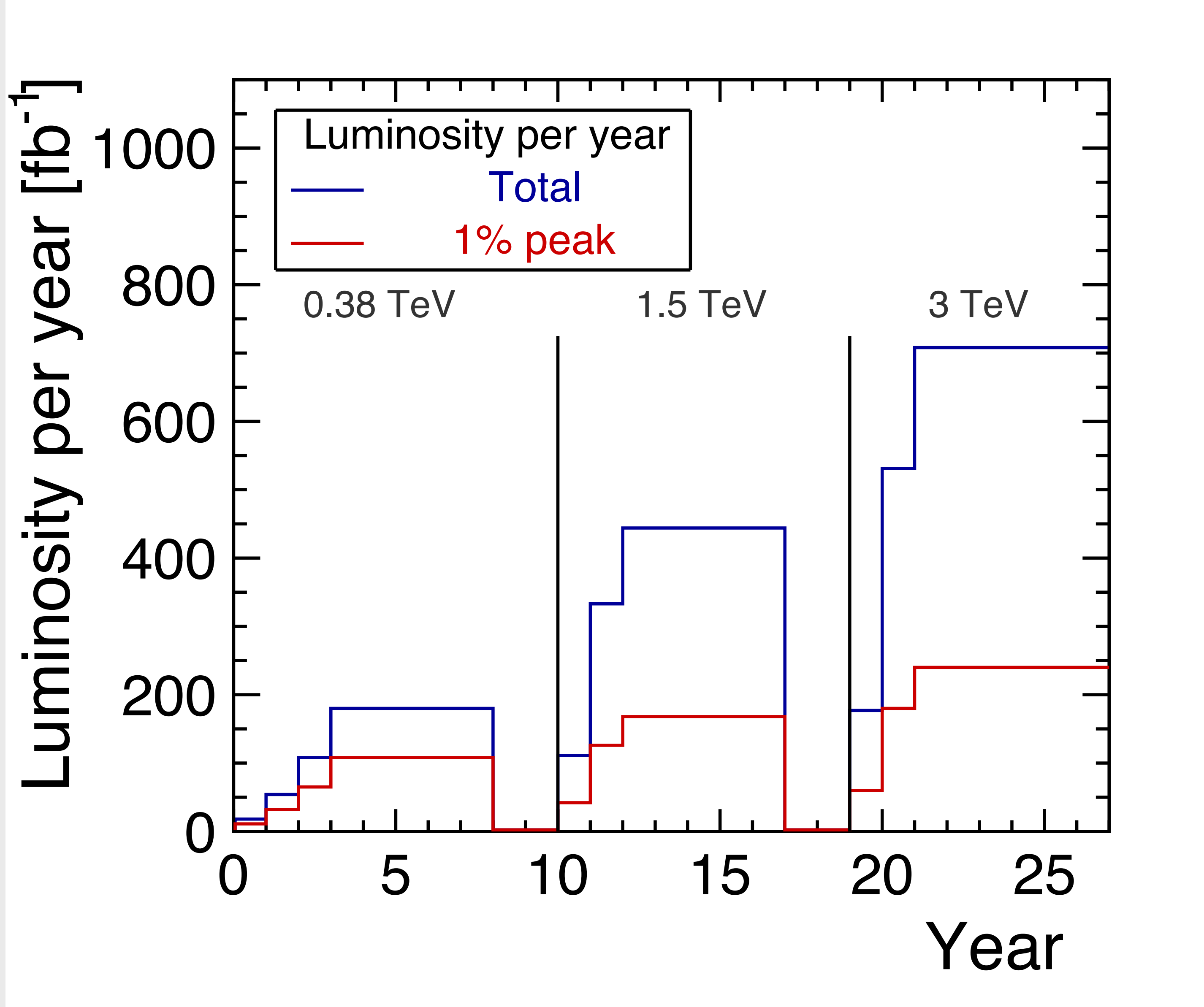


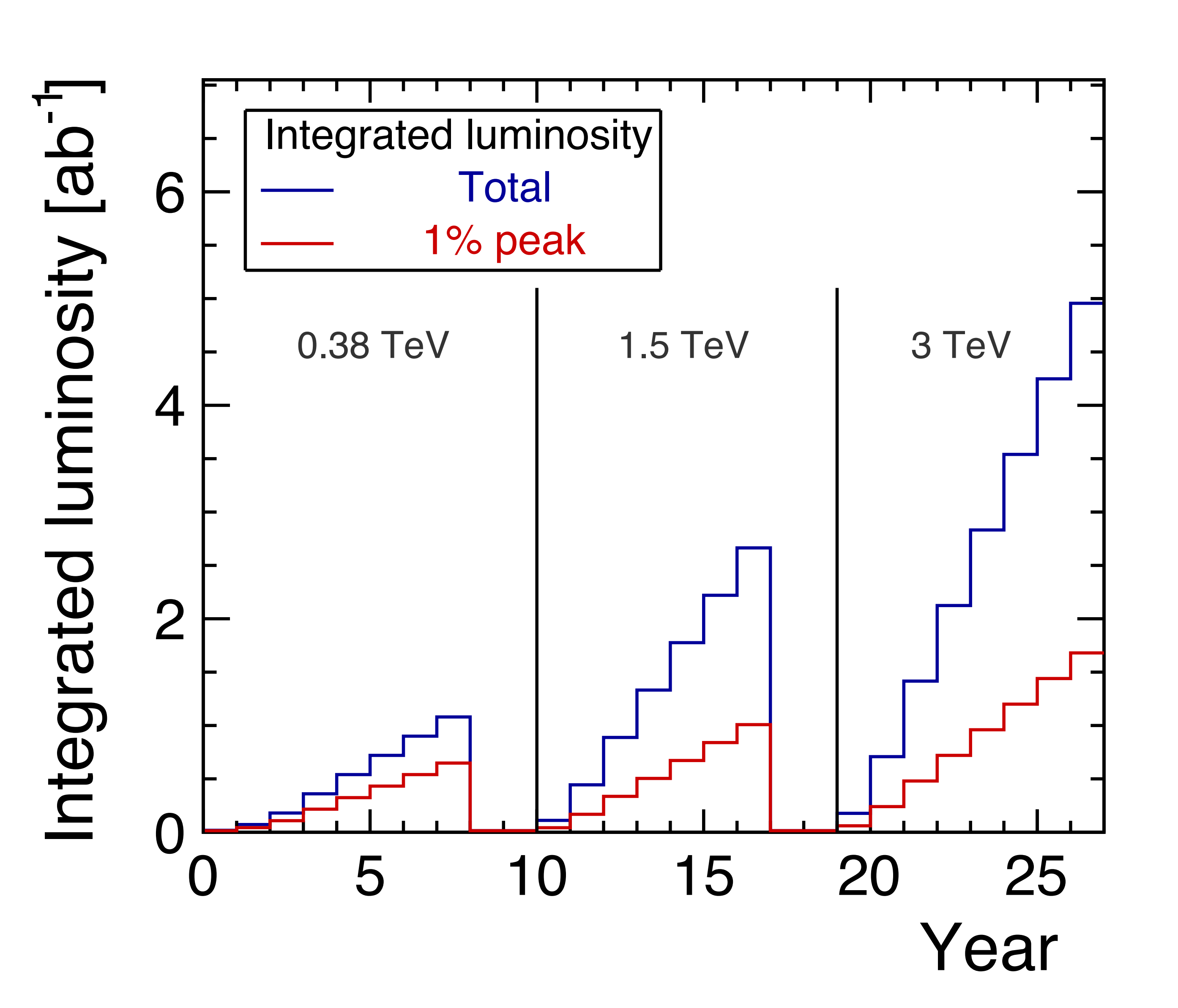


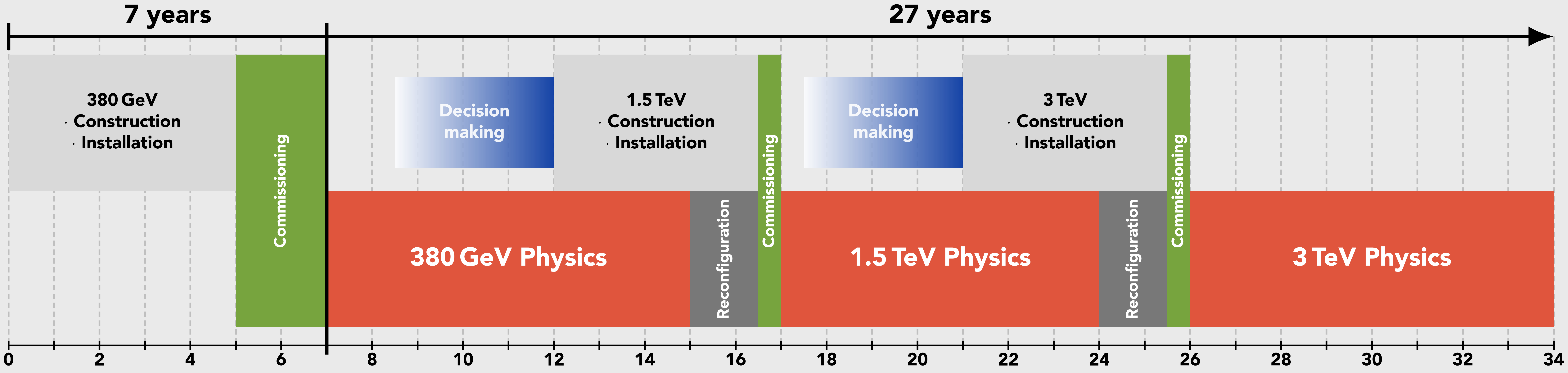


Time-scale

HOW LONG DOES IT TAKE TO GET THERE?







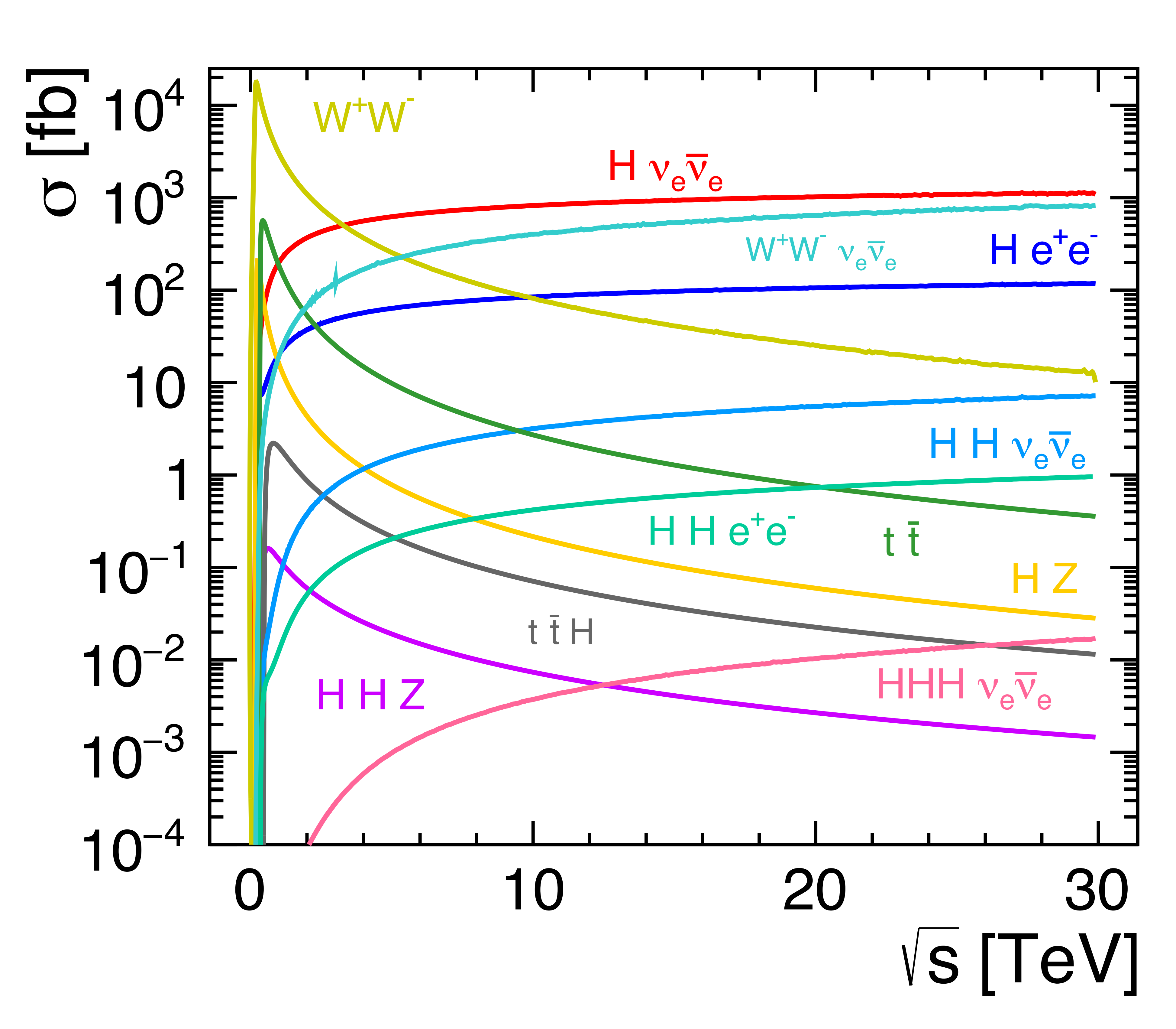
DOABLE WITHIN ONE GENERATION

Time-scale (time $\cdot 10^{\pm 1}$?)

FUTURE?

FUTURE COLLIDERS

- 1 billion Higgs bosons!
- High-energy probes at even higher energy!
- electroweak beam structure exposed
- WW scattering as a “ordinary” collision
- thoroughly explore weakly interacting physics one loop factor above weak scale
- WIMP in large SU(2) multiplets in reach
- directly access the scale of composite states or susy partners



https://indico.cern.ch/event/801616/ https://indico.cern.ch/event/831718/

μμ→ new physics?

MUON COLLIDER CHALLENGE

Public Europe/Zurich

Muon Collider - Preparatory Meeting

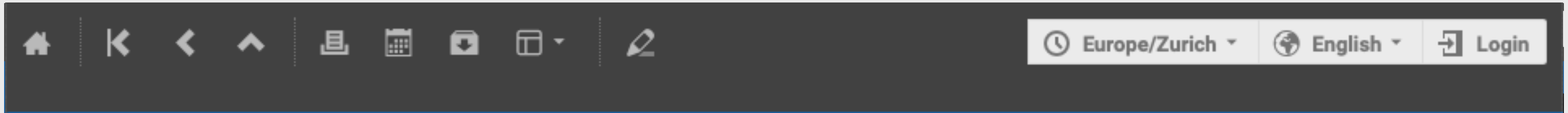
10-11 April 2019
CERN
Europe/Zurich timezone

Search...

https://indico.cern.ch/event/801616/ https://indico.cern.ch/event/831718/

μμ→ new physics?

MUON COLLIDER CHALLENGE


Europe/Zurich English Login

EP Seminar

Positron driven muon source for a muon collider

by Mario Antonelli (INFN), Pantaleo Raimondi (European Synchrotron Radiation Facility (ESRF))

Tuesday 2 Jul 2019, 11:00 → 12:00 Europe/Zurich

222/R-001 (CERN)

Description Muon beams are customarily obtained via K/π decays produced in proton interaction on target. In this paper we investigate the possibility to produce low emittance muon beams from electron-positron collisions at centre-of-mass energy just above the $\mu+\ \mu-$ production threshold with maxi- mal beam energy asymmetry, corresponding to a positron beam of about 45 GeV interacting on electrons on target. We present the main features of this scheme with possible performances that could be achieved by a multi-TeV muon collider.

EPSeminar02.07.1... Raimondi Lemma v... Raimondi Lemma v... WhyMC.pdf

Organized by M. Pepe-Altarelli, G. Unal.......... Refreshments will be served at 10h30

Webcast There is a live webcast for this event Watch

μμ→ new physics?

MUON COLLIDER CHALLENGE

Muon Source

Goals

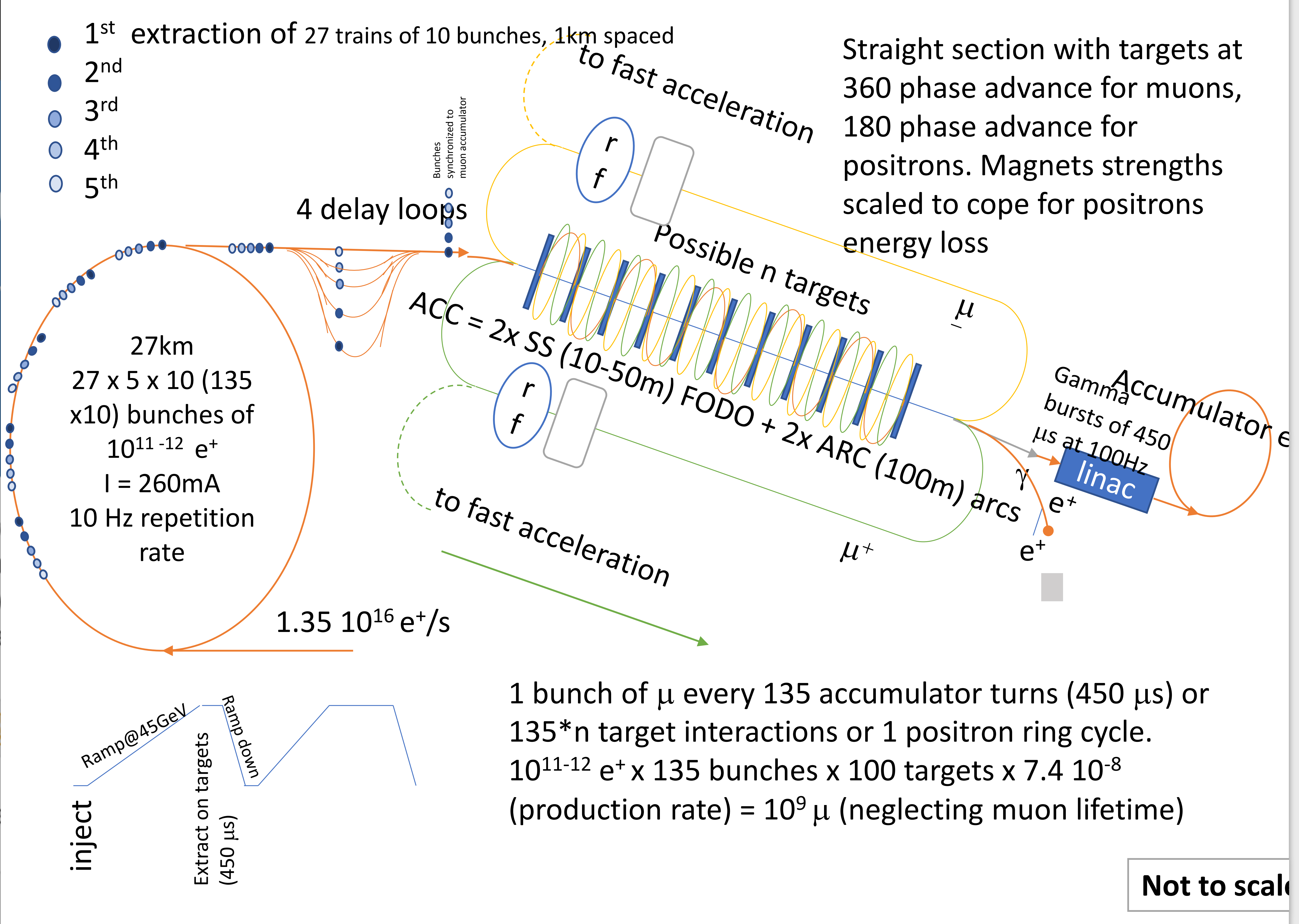
- **Neutrino Factories**: Rate > 10^{14} μ/sec within the acceptance of a μ ring
- **Muon Collider**: luminosities $>10^{34}$/cm^{-2}s^{-1} at TeV-scale ($\approx N_\mu^2\ 1/\varepsilon_\mu$)

Options

- Tertiary production through **proton on target:** cooling needed, baseline for Fermilab design study
  production Rate > 10^{13} μ/sec $N_\mu = 2\cdot10^{12}$/bunch (5 10^8 μ/sec today @PSI)

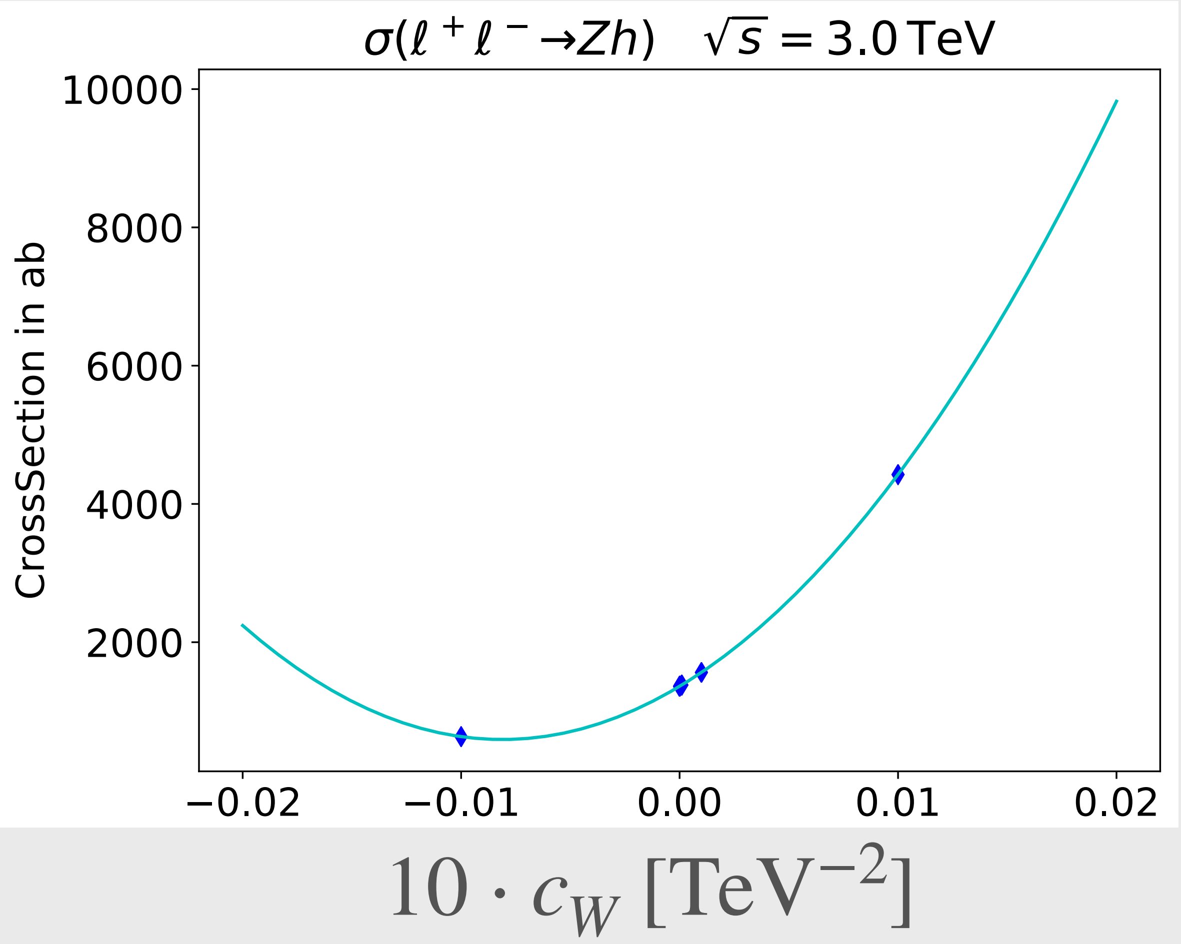
- **e^+e^- annihilation: positron beam on target**: very low emittance and no cooling needed, baseline for our proposal here
  production Rate ≈ 10^{11} μ/sec $N_\mu \approx 5\cdot10^9$/bunch **10-20Hz cycle**

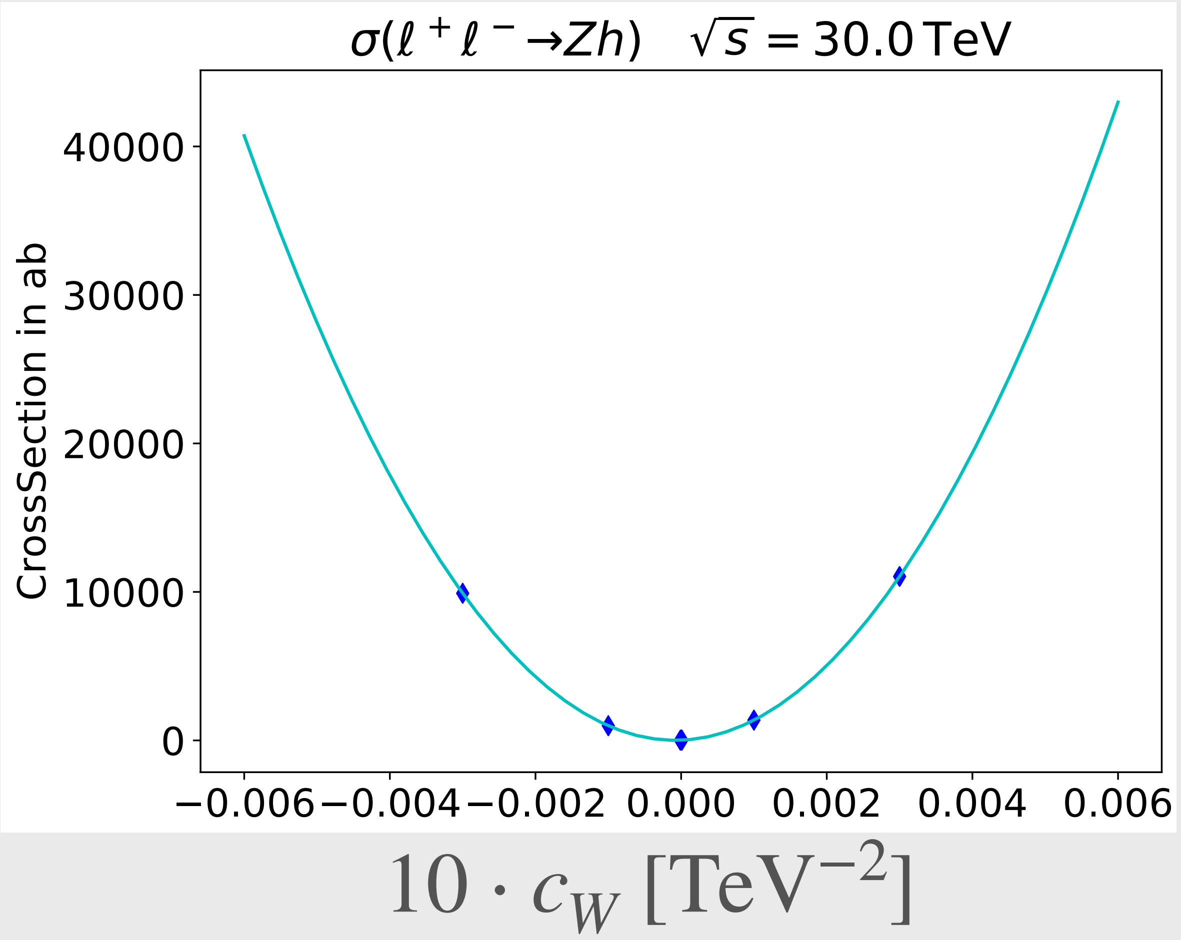
- **by Gammas ($\gamma N \to \mu^+\mu^- N$): GeV-scale Compton γs** not discussed here
  production Rate ≈ $5\cdot10^{10}$ μ/sec $N_\mu \approx 10^6$ (Pulsed Linac)
  production Rate $>10^{13}$ μ/sec $N_\mu \approx$ few$\cdot10^4$ (High Current ERL)
  see also: W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44 ($e^- N \to \mu^+\mu^- e^- N$)



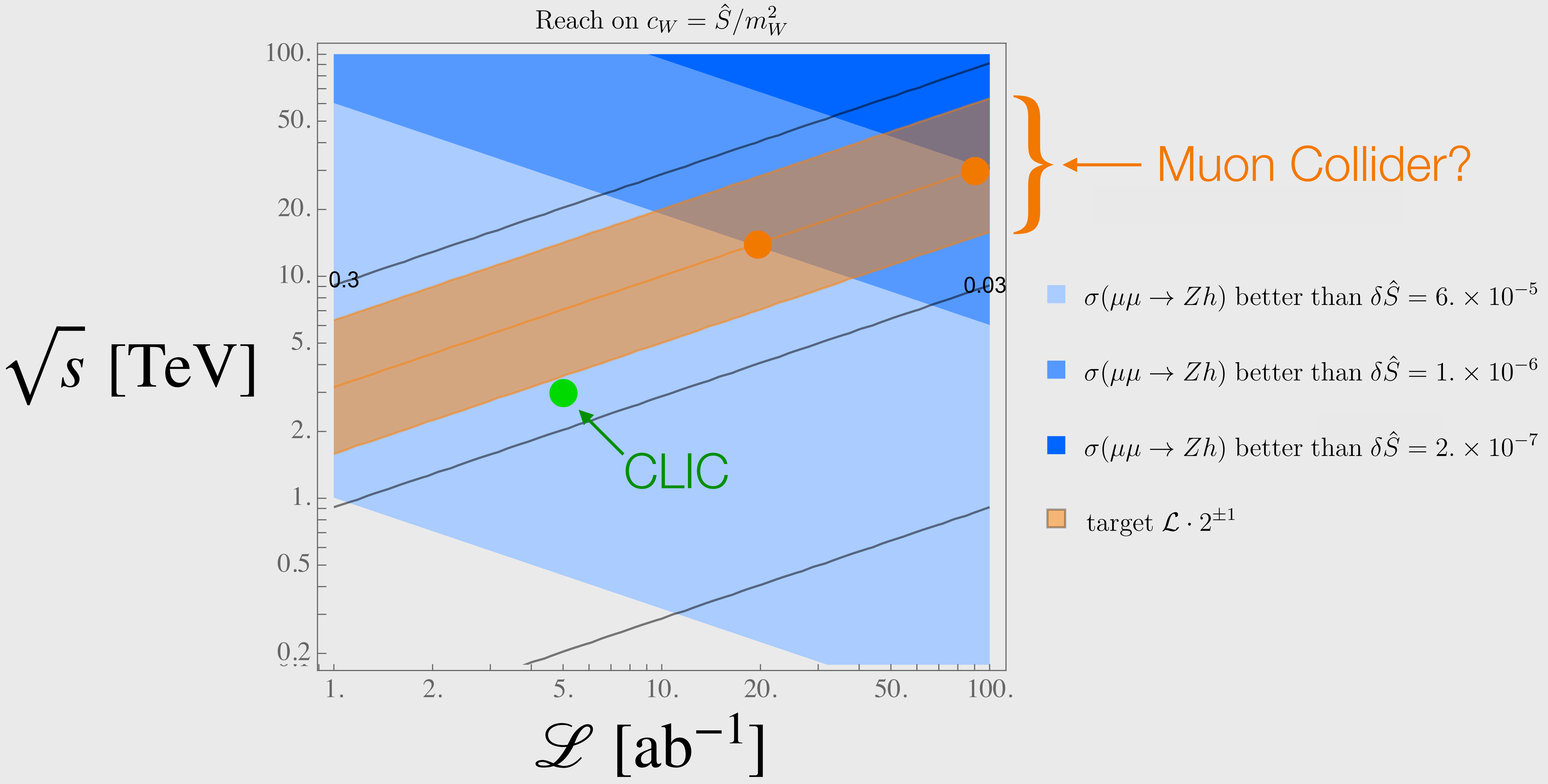
$\ell^+\ell^- \to Zh$

TOTAL RATE





Even higher energy colliders can exploit "precise" measurements at the 10% level

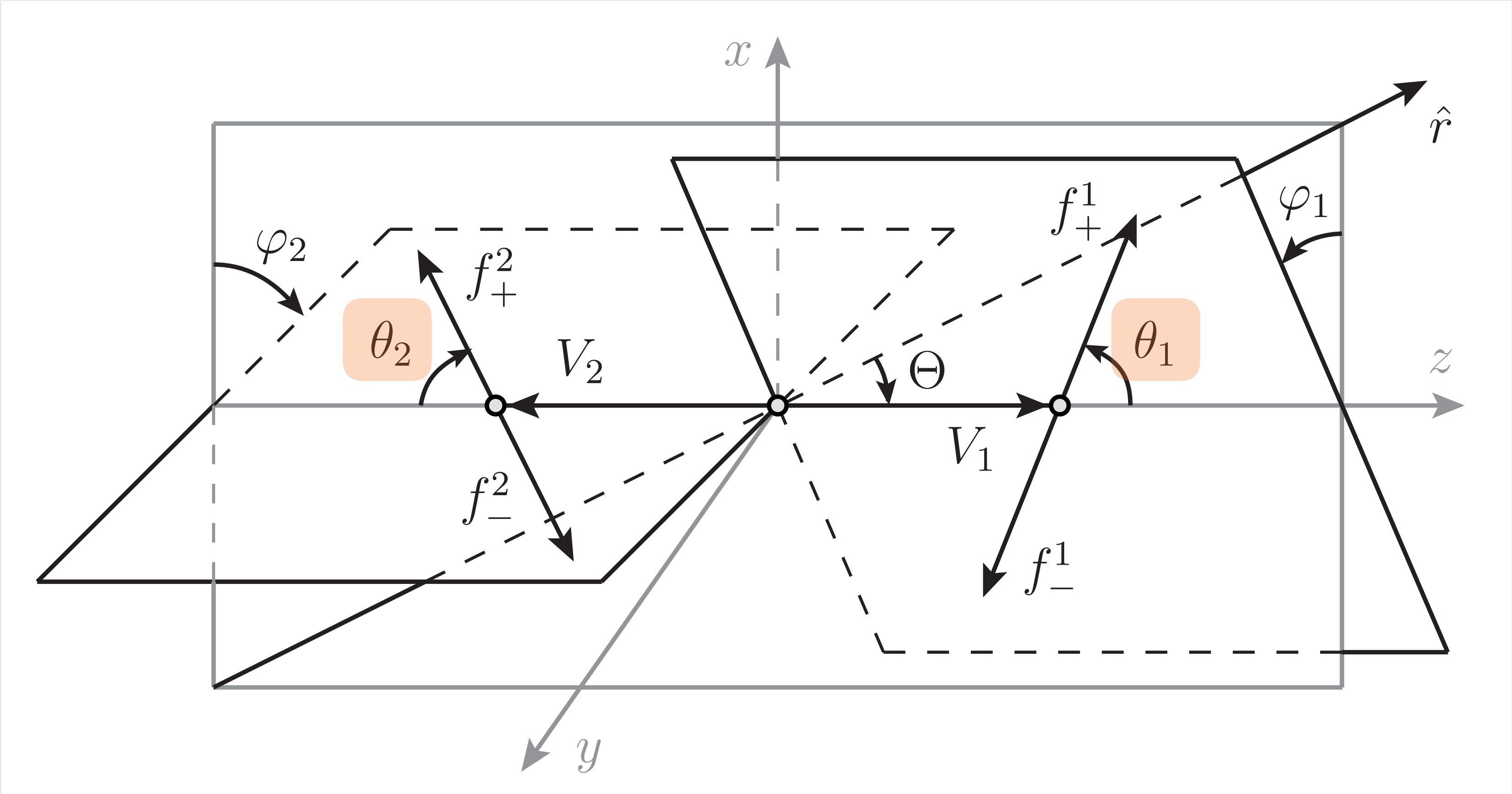


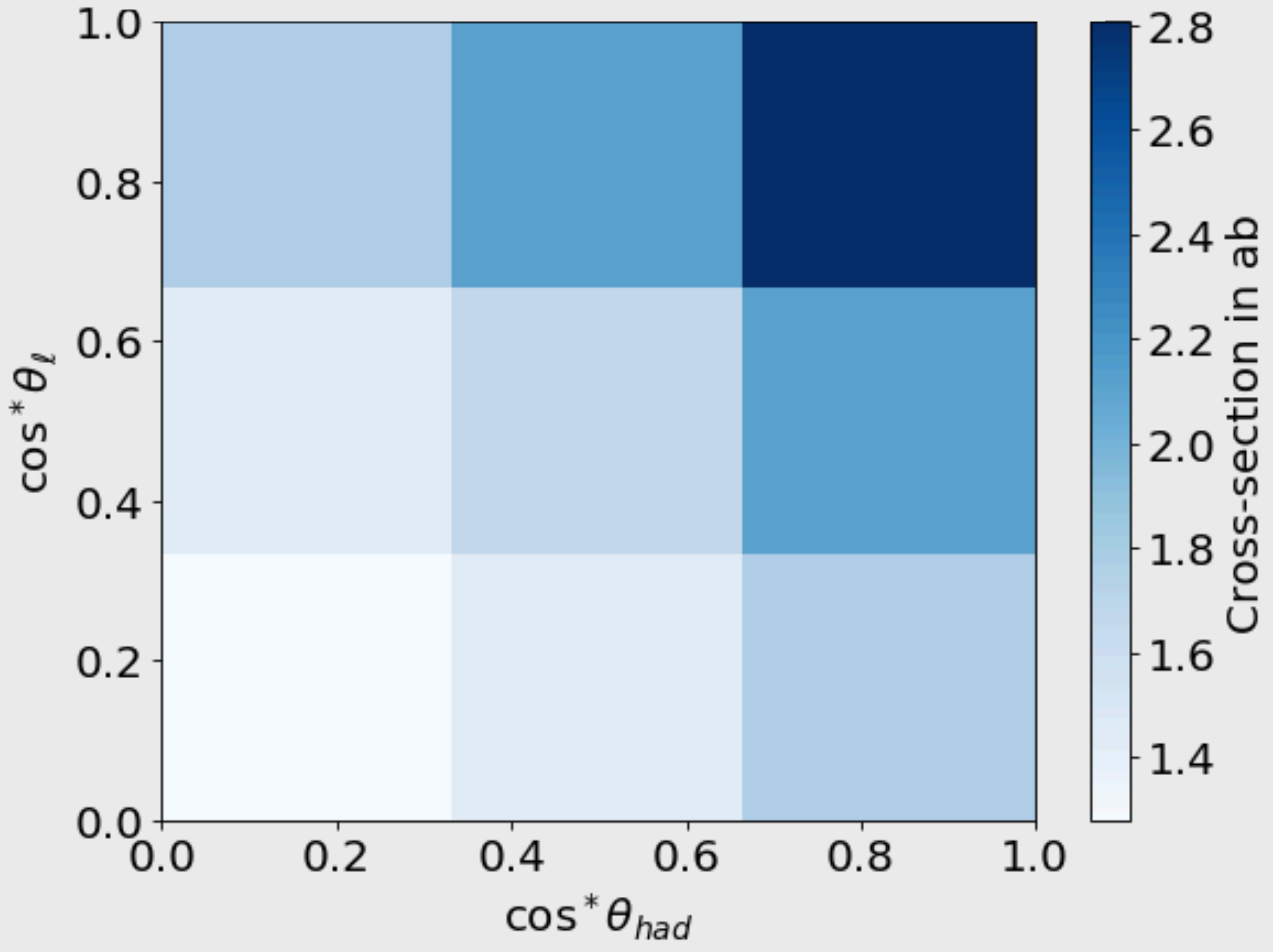
Order of magnitude improvement of the bunds on mass scale of new physics is possible

ZH	Cross-Section	m 95% CL
3 TeV	1362 ab	12 TeV
14 TeV	62 ab	57 TeV
30 TeV	13 ab	120 TeV

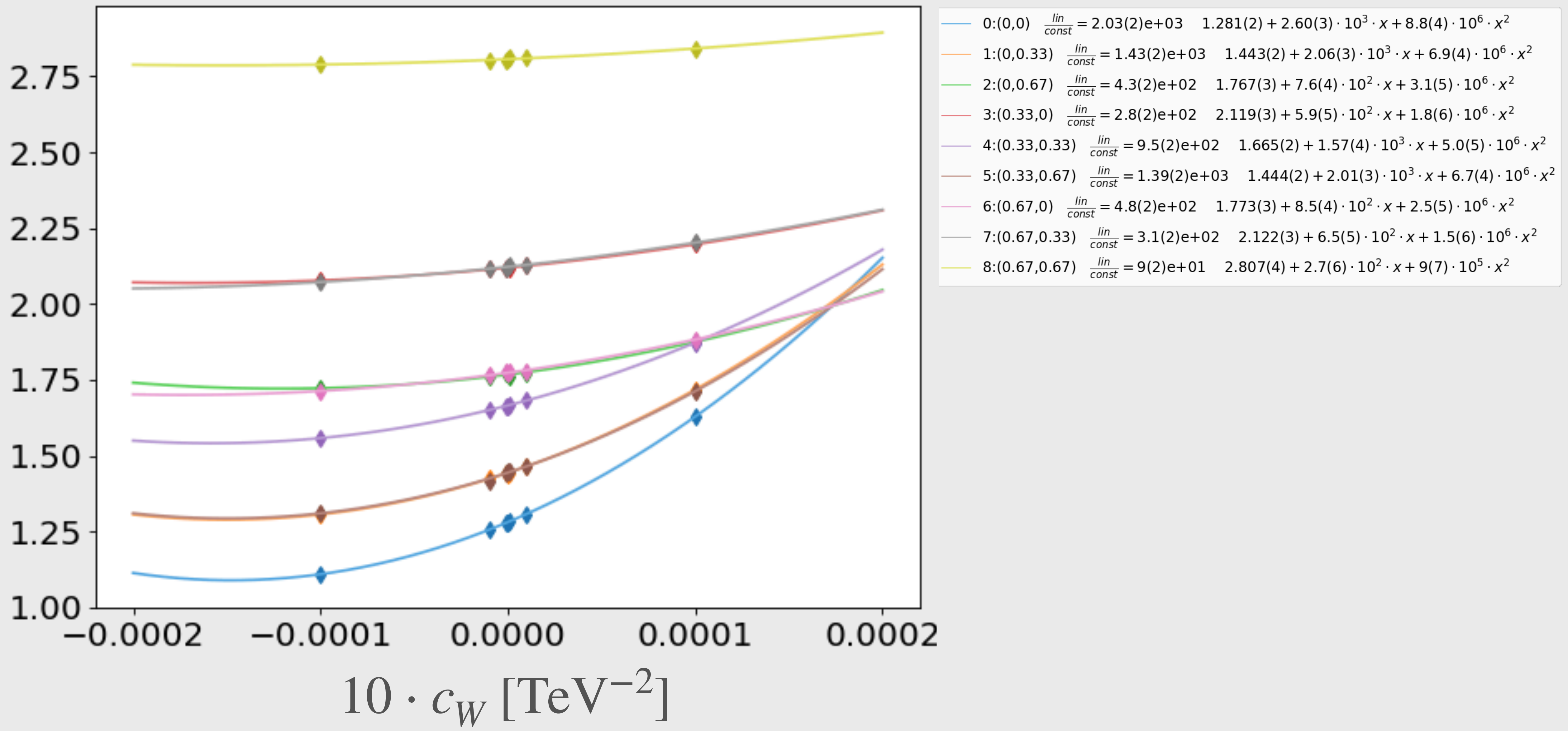
$\ell^+\ell^- \rightarrow \mathbf{W}^-\mathbf{W}^+$

POLAR ANGLE DISTRIBUTION



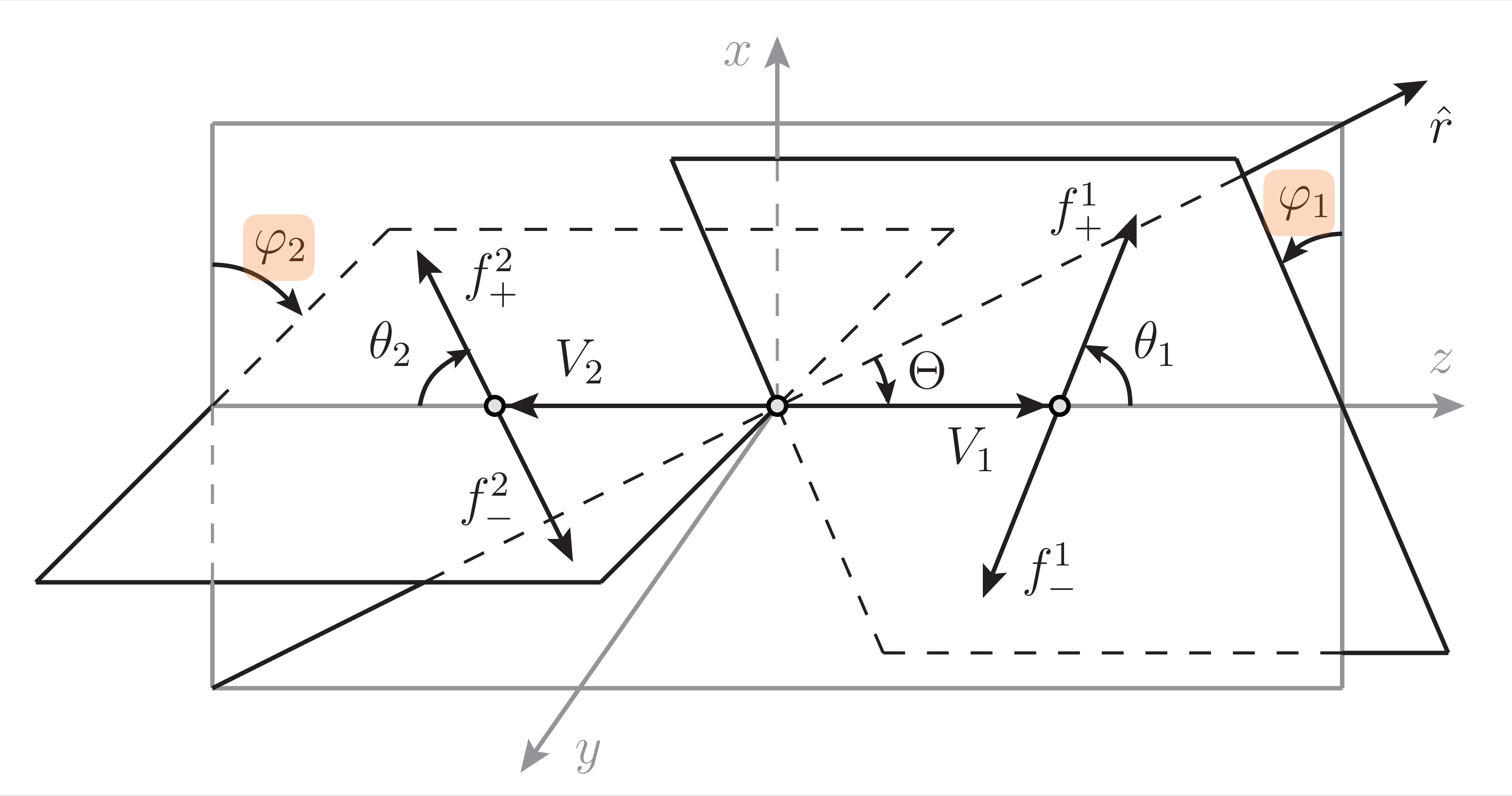


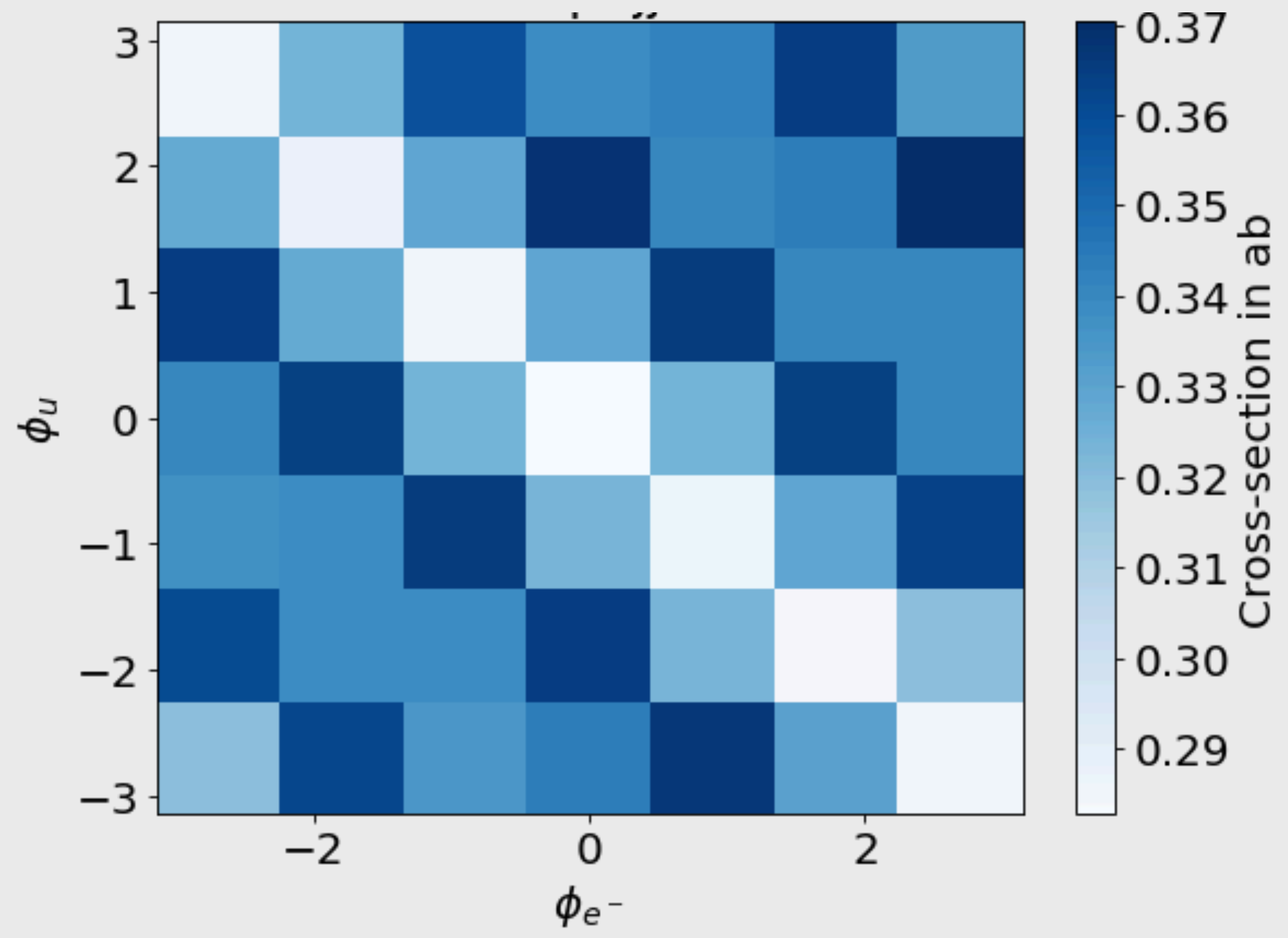
$$\left.\frac{d\sigma}{d\theta_1^\star d\theta_2^\star}\right|_{\bar{\theta}_{1,2}} \text{[ab]}$$

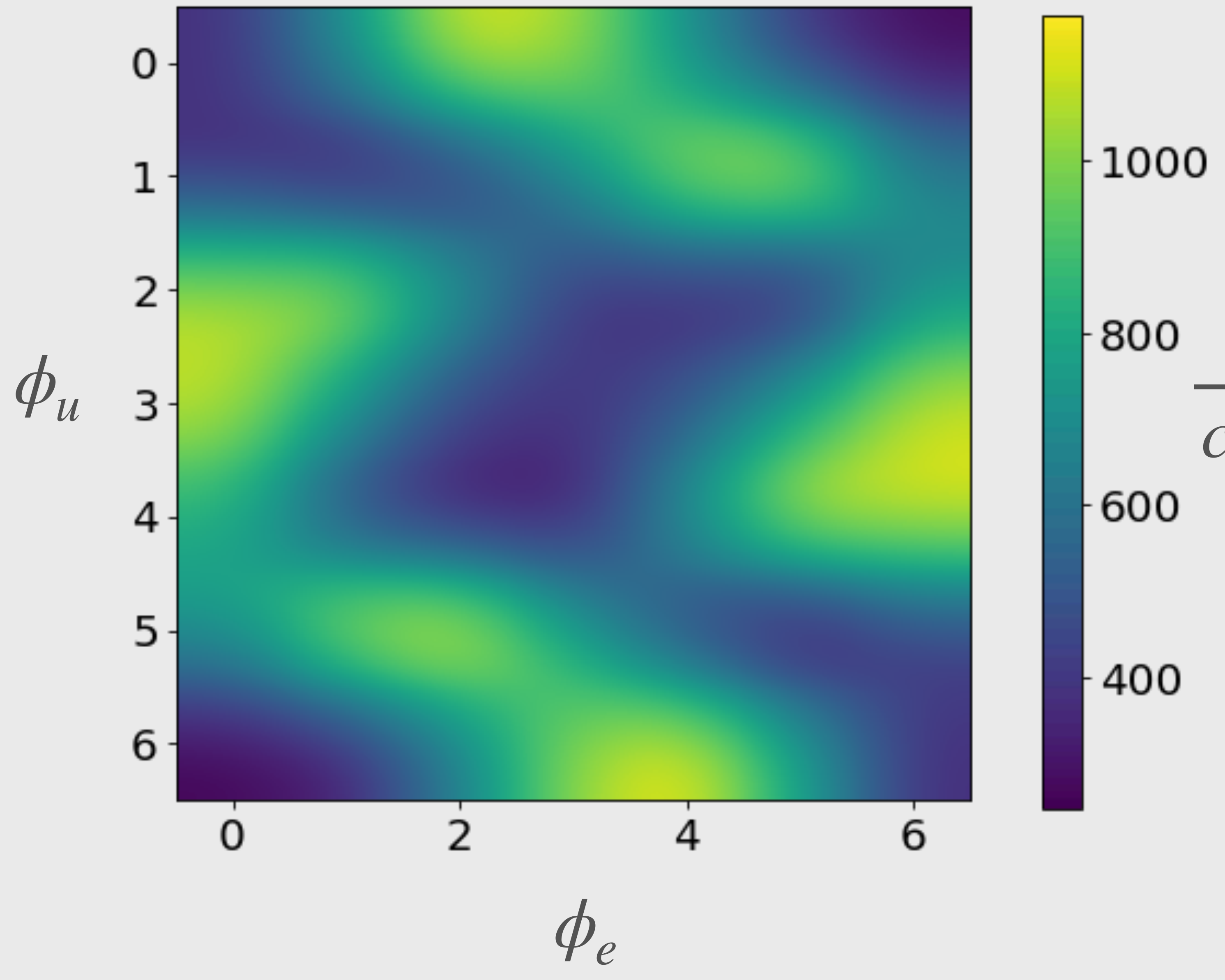


$\ell^+\ell^- \to W^-W^+$

AZIMUTHAL ANGLE DISTRIBUTION





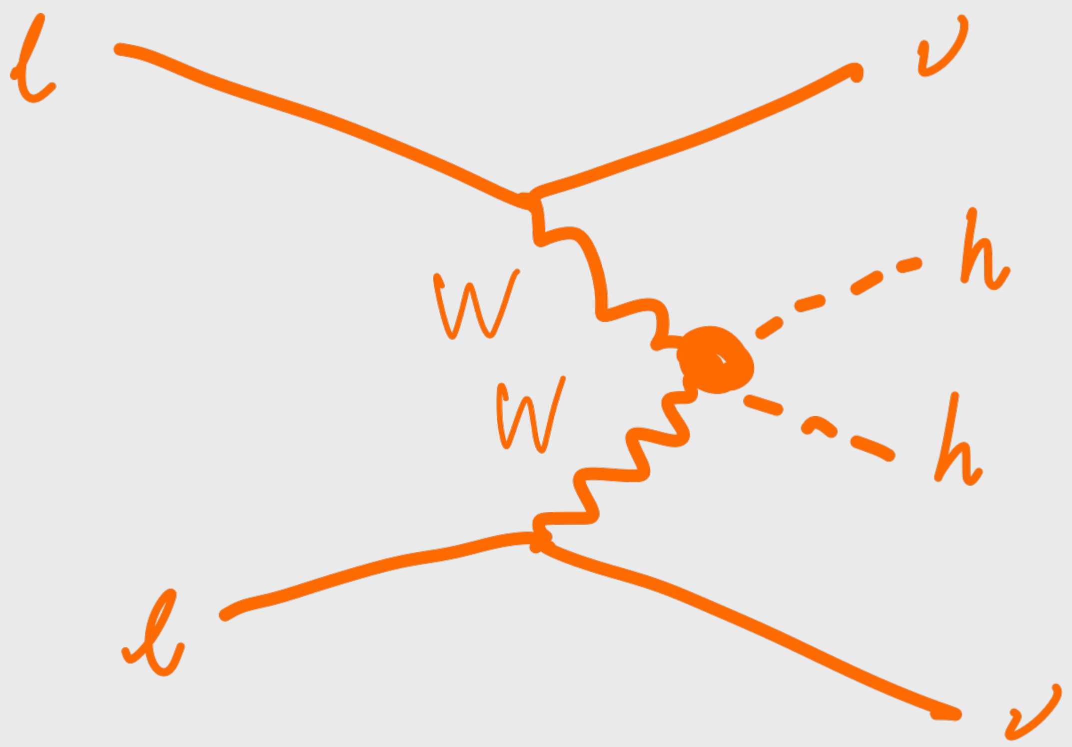


$$\frac{1}{c_W} \cdot \frac{d\sigma(interf.)}{d\sigma(SM)}$$

$\ell^+\ell^- \rightarrow \mathbf{hh}$

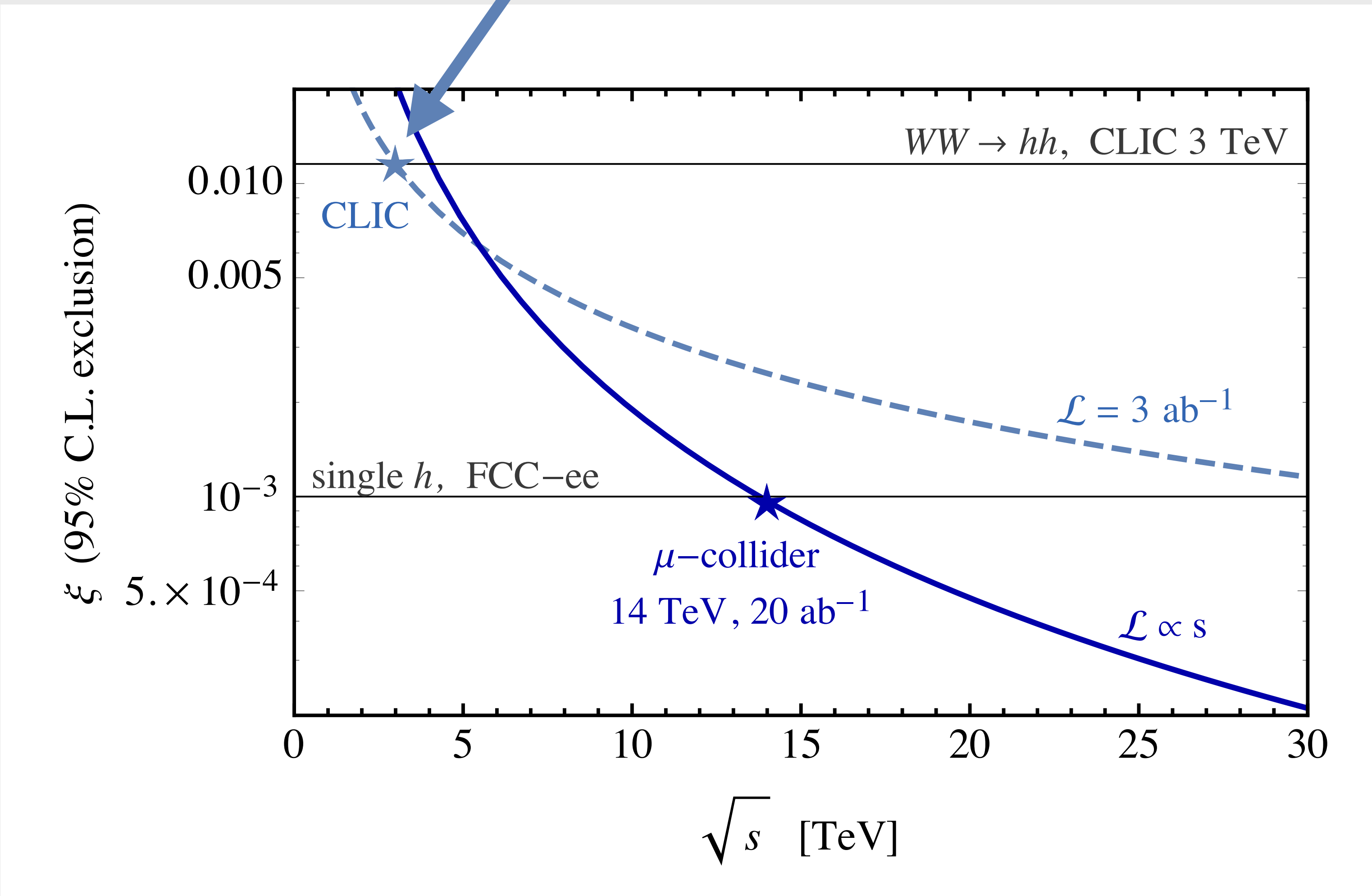
W BOSON **COLLIDER**

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



less powerful than Zh in general on m* but tests different operators, e.g. OH

1309.7038



need large p_T Higgs bosons

$$\Rightarrow \text{upper bound on } \xi \sim \frac{1}{E\sqrt{\mathscr{L}}}$$

$$\sqrt{s} = 3\ \text{TeV} \quad \mathscr{L} = 3\ \text{ab}^{-1} \quad \xi = \frac{v^2}{f^2} < 0.01$$

$$\downarrow$$

$$\xi < 2 \cdot 10^{-4} \text{ at } \sqrt{s} = 30\ \text{TeV}$$

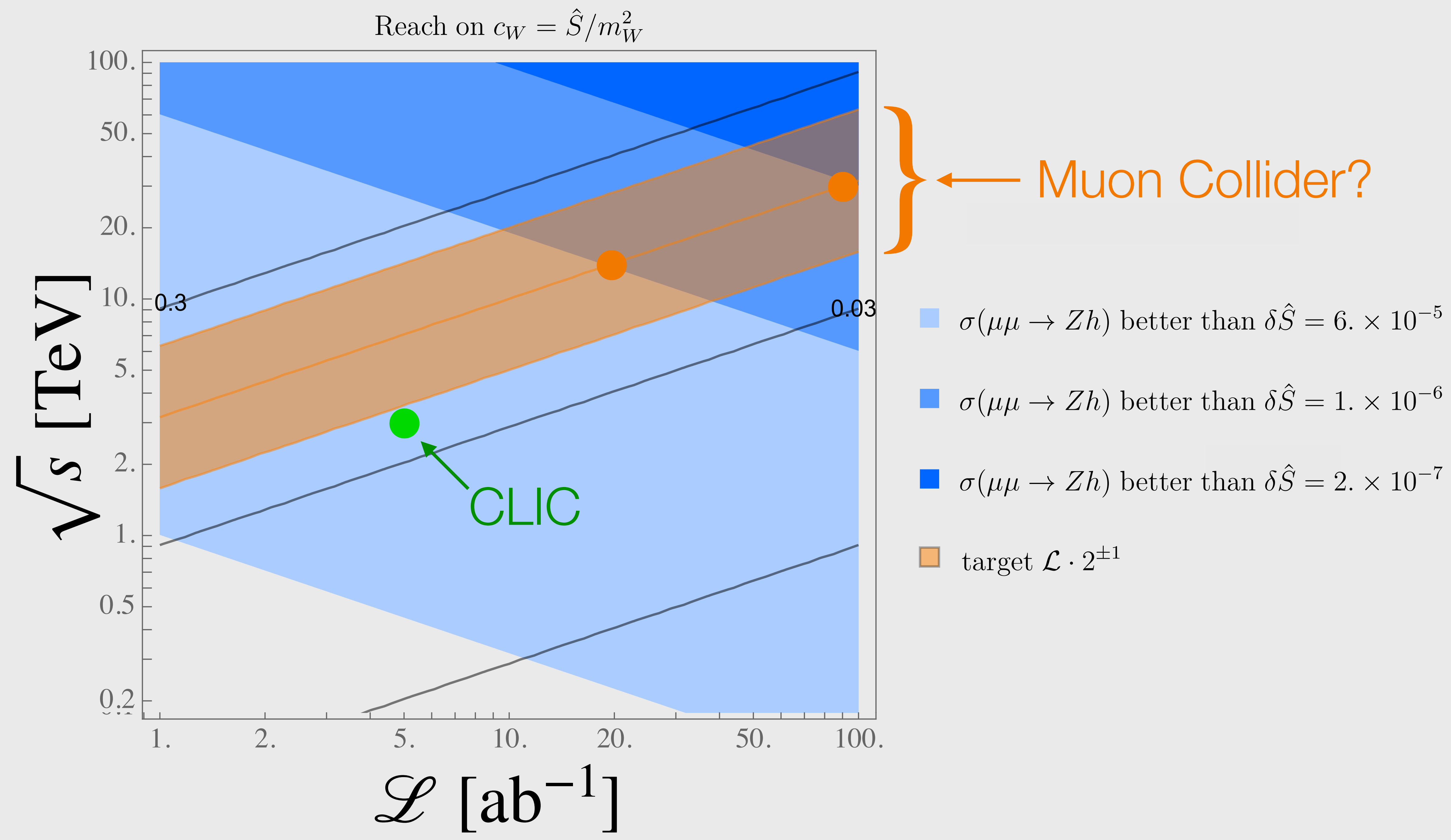
$$m_\star \gtrsim 14 \cdot g_\star\ \text{TeV}$$

$\ell^+\ell^- \to VV$

EFT EPOCH | LESSON FROM LHC

Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g^Z_{uL} - \delta g^Z_{dL})/g - c^2_{\theta_W}\delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{dL}/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{uL}/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g^Z_{fR}/g\right]$

Even higher energy colliders can exploit “precise” measurements at the 10% level

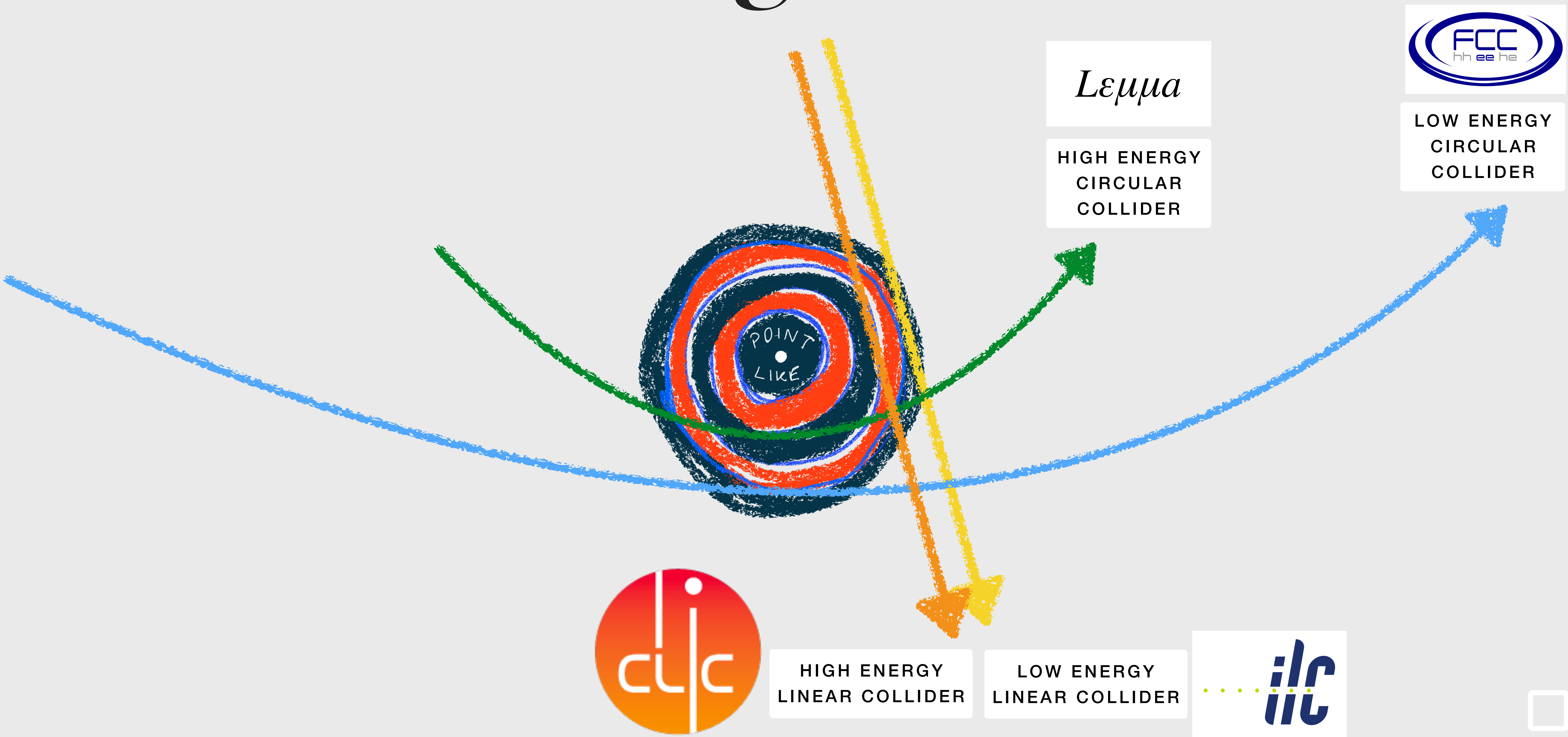


Order of magnitude improvement of the bunds on mass scale of new physics is possible

	Cross-Section @ 30 TeV	m* 95% CL	
HH	non trivial c&c analysis	60 TeV (g*/4)	$\mathcal{O}_H$
WW	pTW>7.5TeV: 180 ab	84 ⊕ 76 TeV ≃113 TeV	$a_q^{(3)}$
ZH	inclusive: 13 ab	120 TeV	$a_q^{(1)}$
ff	angular analysis	120 TeV (4/g*)	W,Y

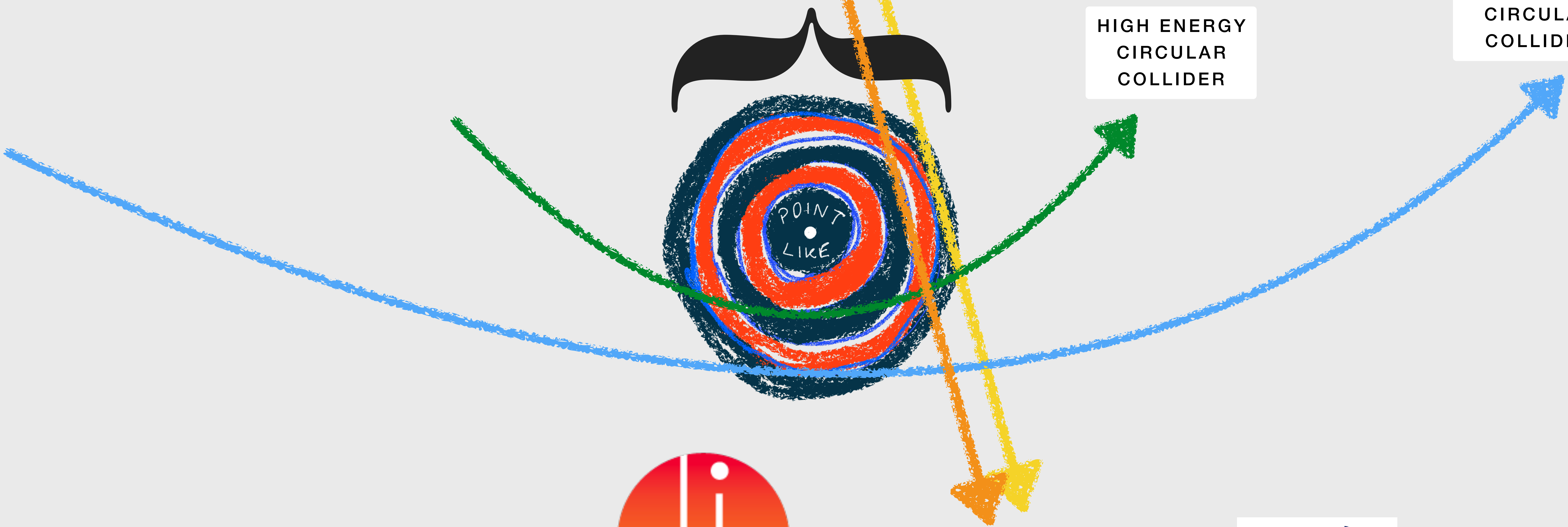
All-round progress up to m* ~ 10^2 m_{Higgs} (call it $16\pi^2$ m_{Higgs})

Looking ahead



Looking ahead

$$\ell_{Higgs} \sim f^{-1}$$



Lεμμα

HIGH ENERGY CIRCULAR COLLIDER

FCC hh ee he

LOW ENERGY CIRCULAR COLLIDER

CLIC

HIGH ENERGY LINEAR COLLIDER

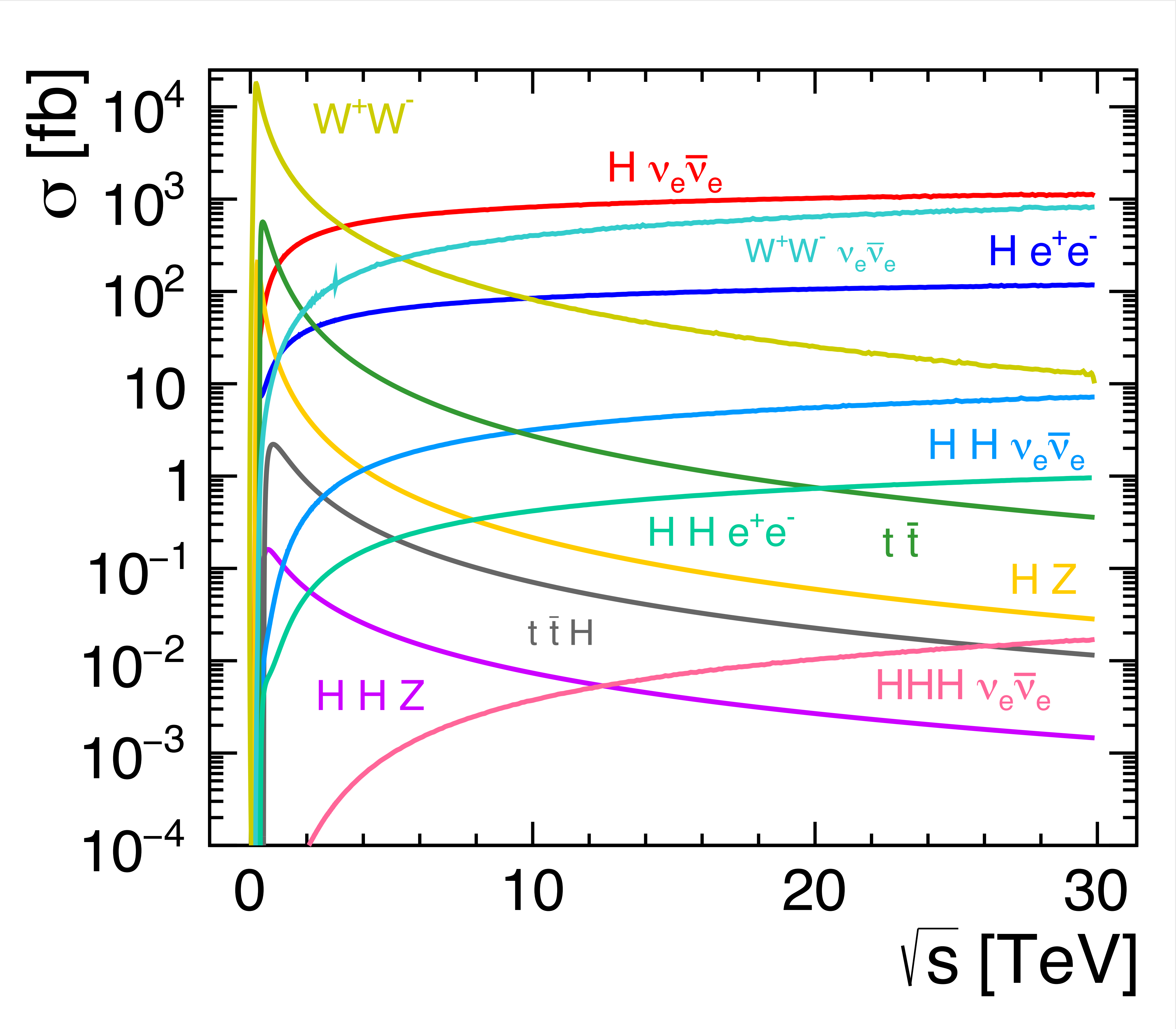
LOW ENERGY LINEAR COLLIDER

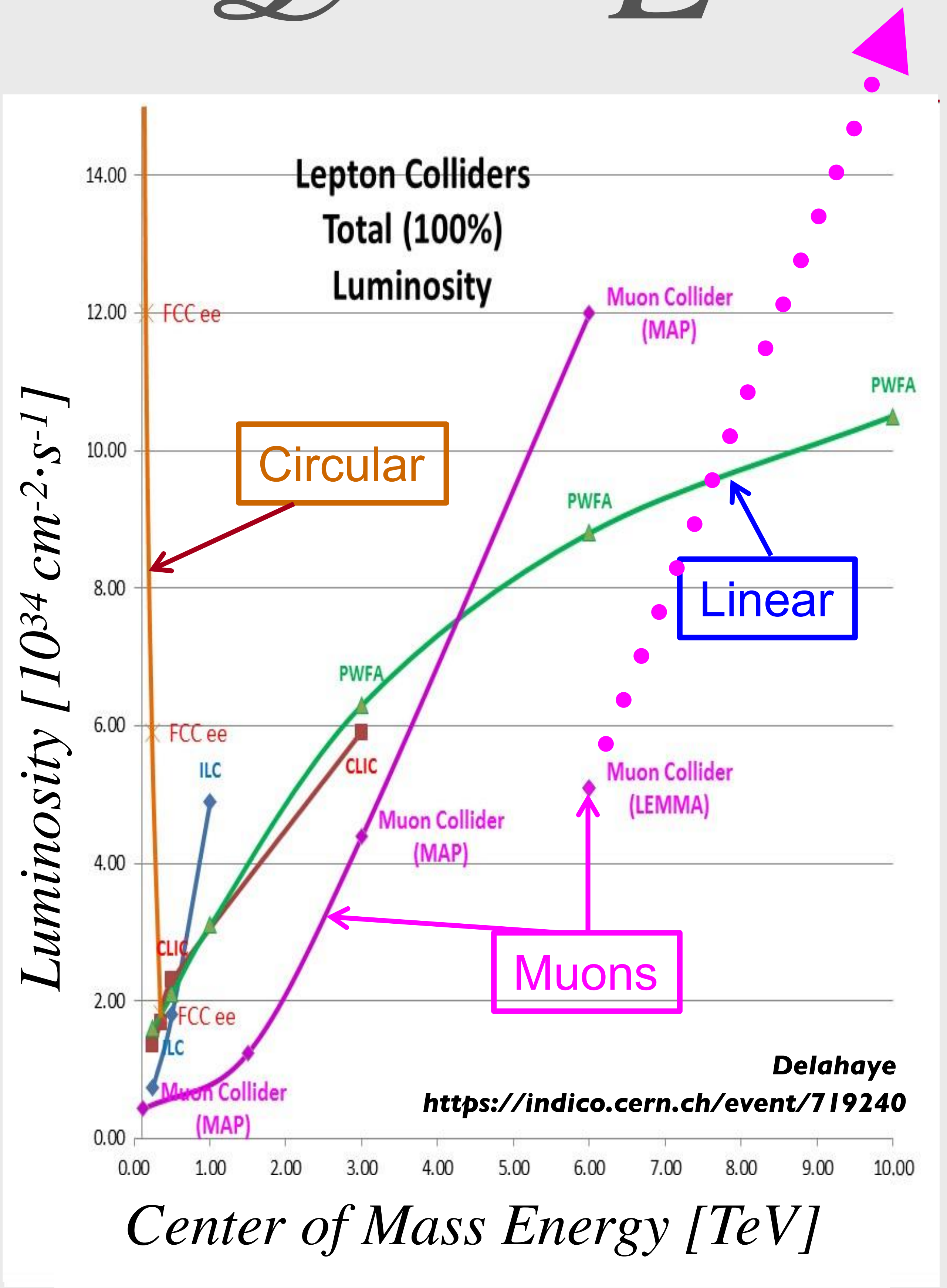
ilc

$\ell^+\ell^- \to h\nu\nu$

10⁹ HIGGS BOSONS | GIGA-HIGGS FACTORY

$$\sigma \sim log(s) \simeq const \qquad \mathscr{L} \sim E^2 \qquad \sigma \cdot \mathscr{L} \simeq 10^9 \text{ H}$$

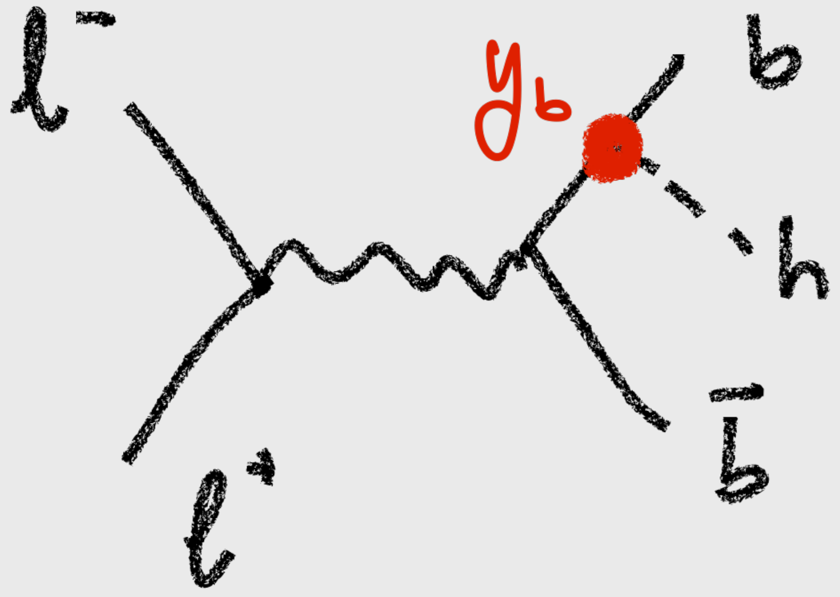


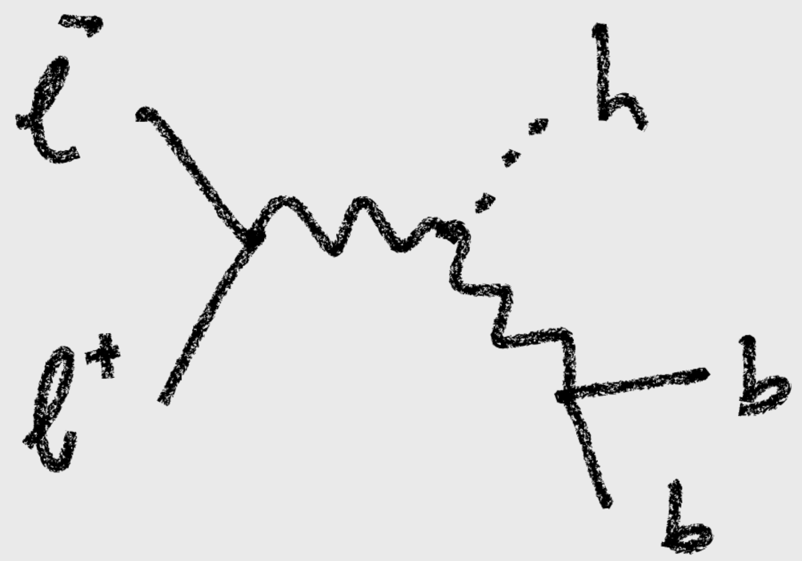


- ultra-rare Higgs decays
- differential distribution
- off-shell Higgs bosons
- rare production modes

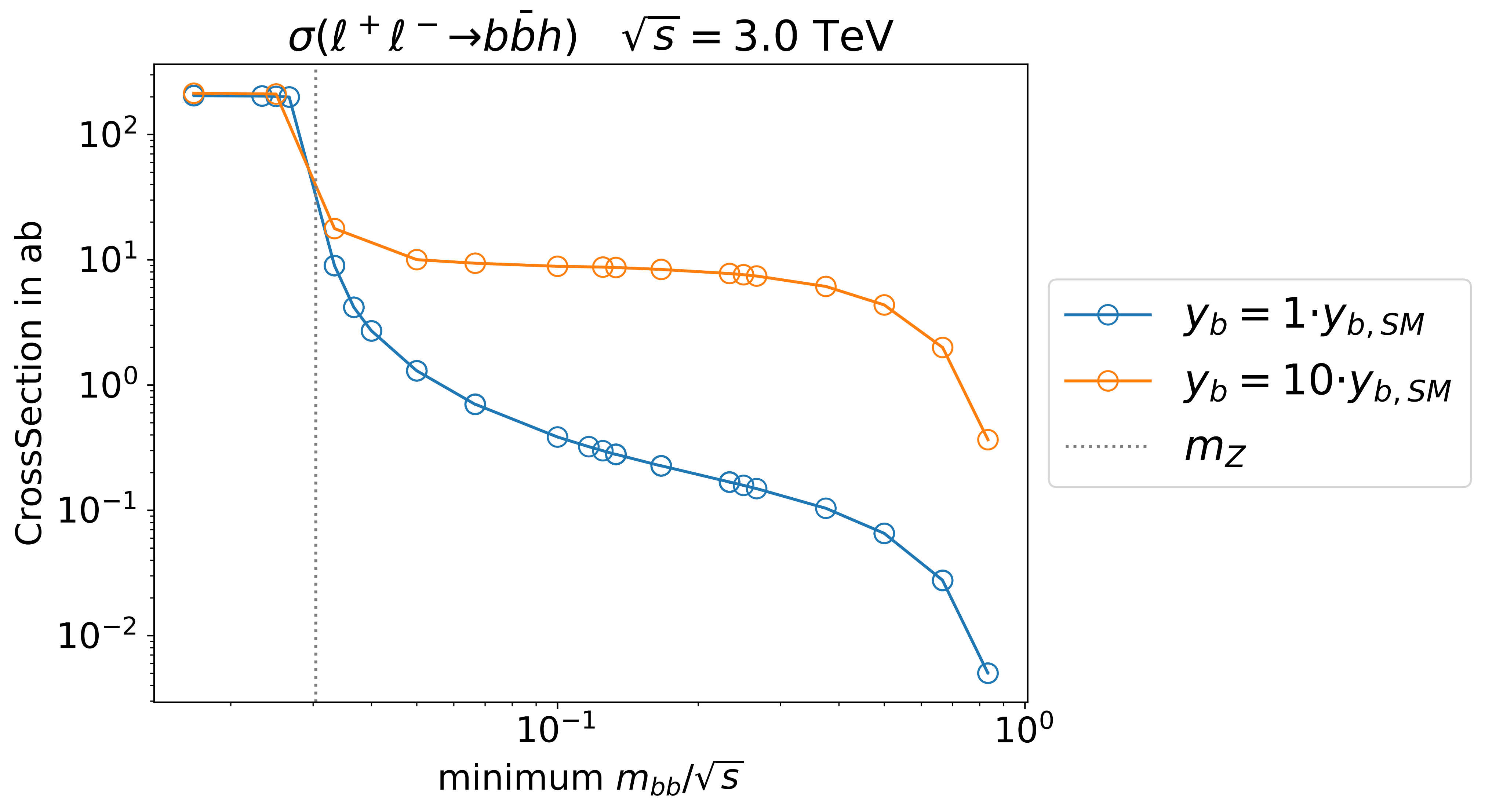
$\ell^+\ell^- \to b\bar{b}h$

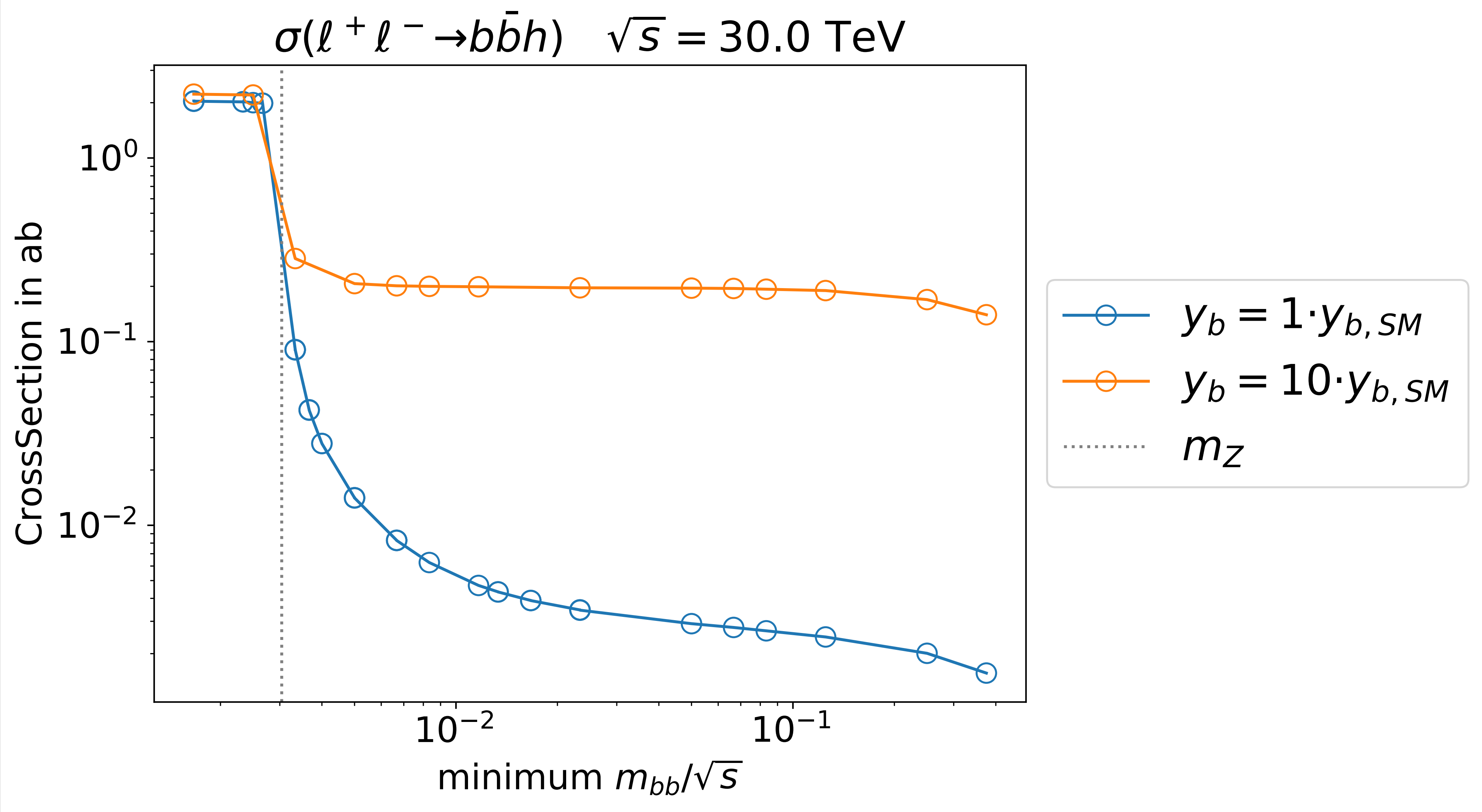
RARE | PRODUCTION MODES





Direct Measurement of Y_b



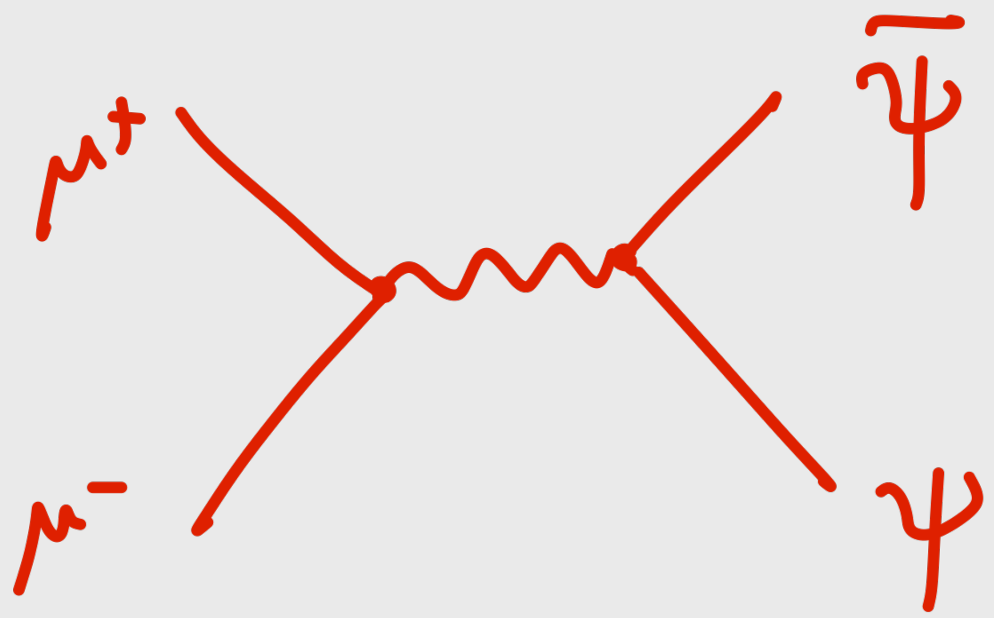


if $\mathcal{L} \sim 10^2 \mathcal{L}_{\text{baseline}} \to \delta y_b \sim 2\%$

$\ell^+\ell^- \to$ new physics

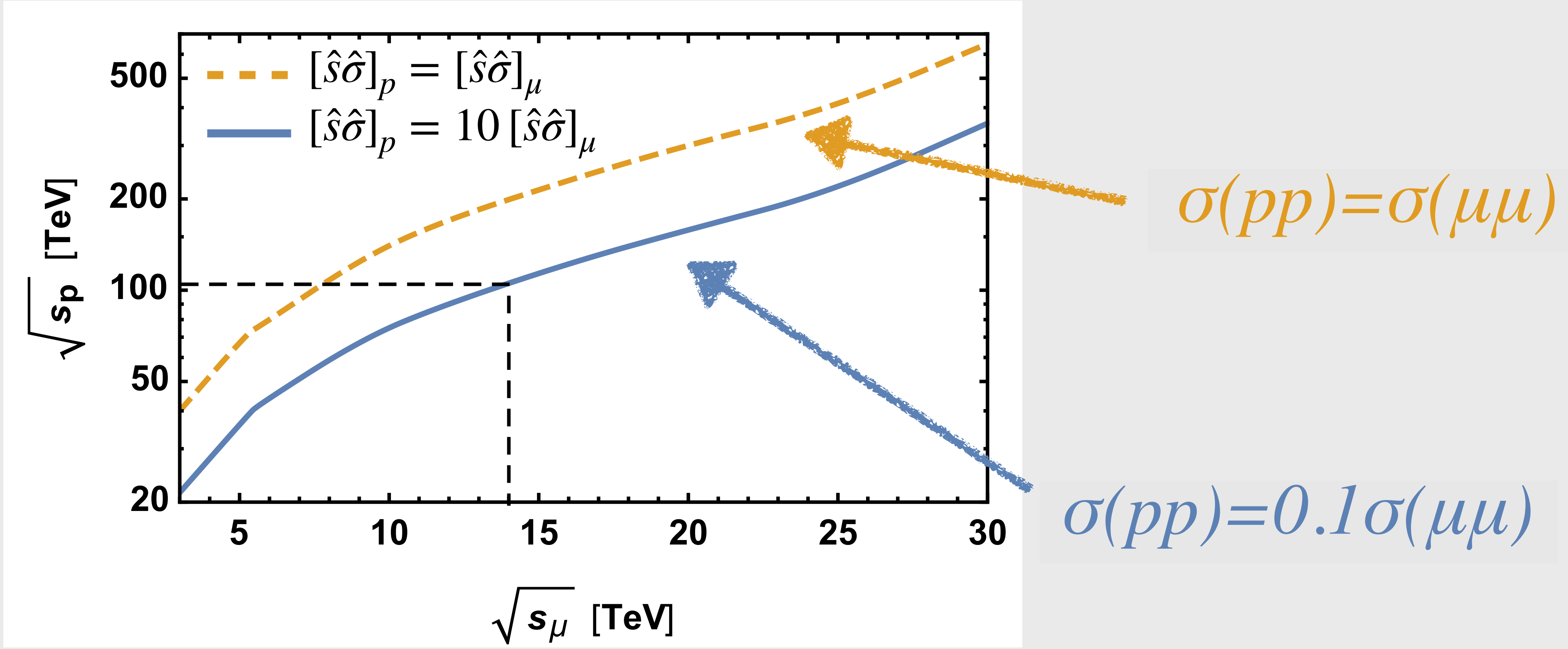
VALENCE LEPTONS

Can produce heavy new physics (colored or not)



in principle can probe directly new states at O(10) TeV scale!

Compares pretty well with a *pp* collider



$\boxed{\text{14 TeV } \mu\mu \text{ roughly equivalent to 100 TeV } pp}$

CONCLUSIONS

PRECISION AND MASS REACH

- Standard “targets” such as vanilla SUSY, compositeness of Higgs and other states, sub-TeV WIMPs are all being probed and are under a fair amount of pressure
- Motivations for new physics to be out there are stronger than ever

- Searches for new physics at colliders are shifting towards increasingly *heavier* and *subtler* signals (both direct and indirect)
- multi-TeV leptonic colliders can cope well with the ever subtler heavy and light new physics signals
- multi-TeV leptonic colliders, e.g. CLIC, can deliver high-energy and high-luminosity $\Rightarrow$ provide both *precision* and *mass reach* for BSM

- a multi-10-TeV muon collider appears as a fantastic chance to put high energy physics on a fast lane towards substantial advancement of our understanding of fundamental properties of constituents of matter and their interactions

Thank You!

20+X MIN.?

WITHIN 2:30PM - 3:00PM ???