High energy lepton colliders: Higgs, top and direct BSM

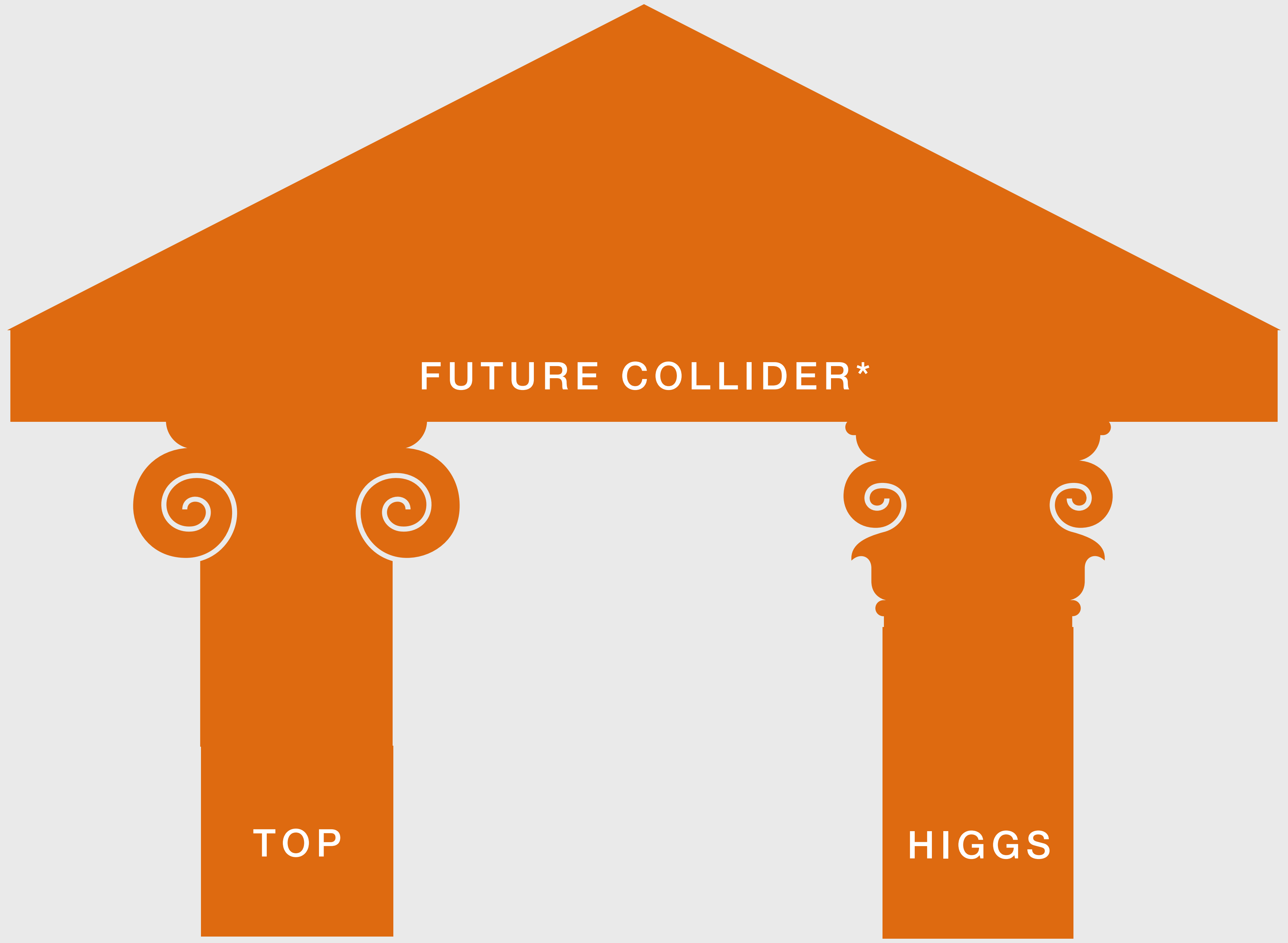
SEP. 13 2019

ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

How to move forward?

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

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?

- All projects under discussion are “slow” (decades to run them)
- All projects require different dedicated runs to achieve each of the several “goals”
- All the projects are somewhat similar to 20th century machines*
  … which is good and bad!

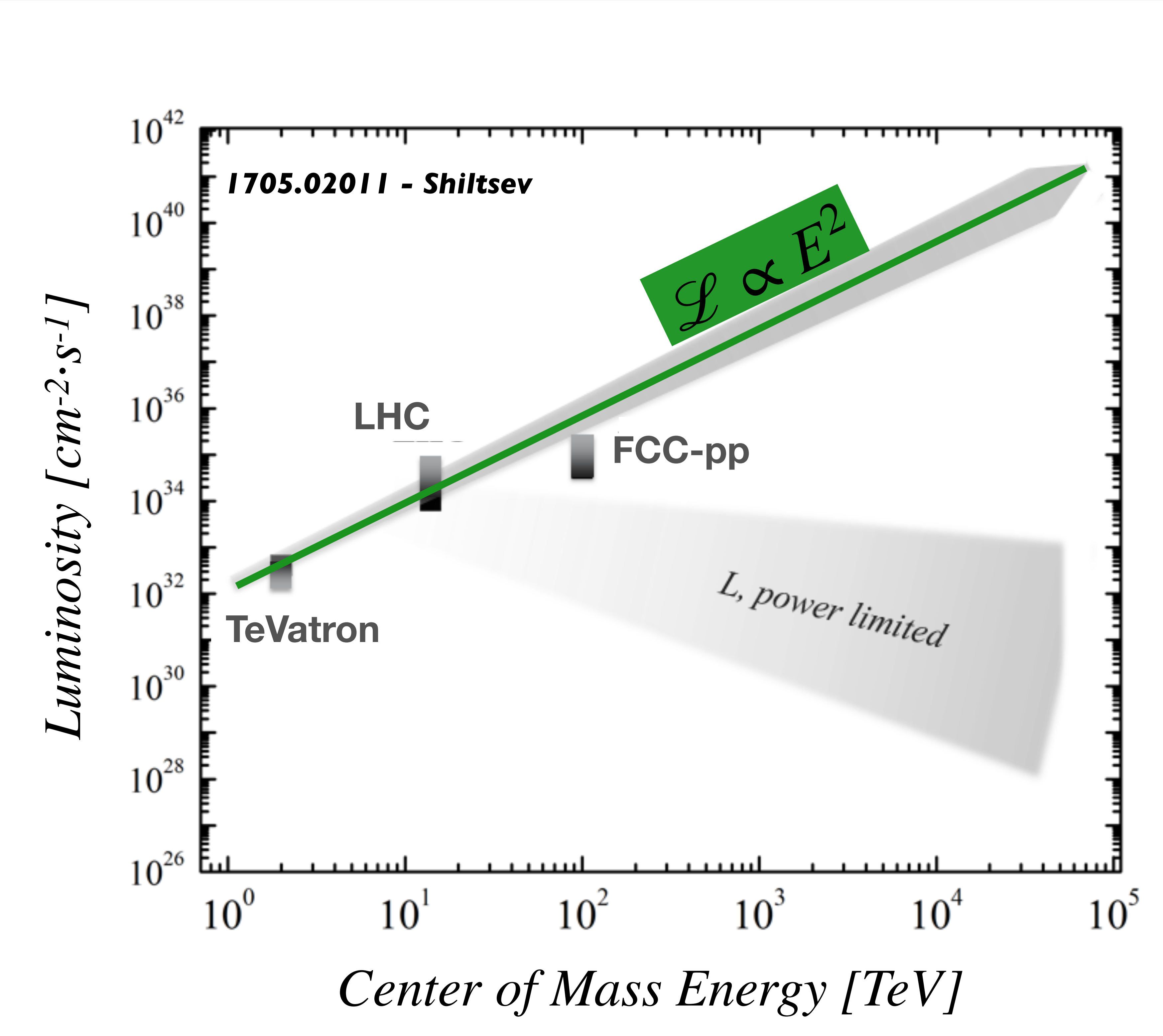
*except maybe CLIC and its drive-beam accelerator

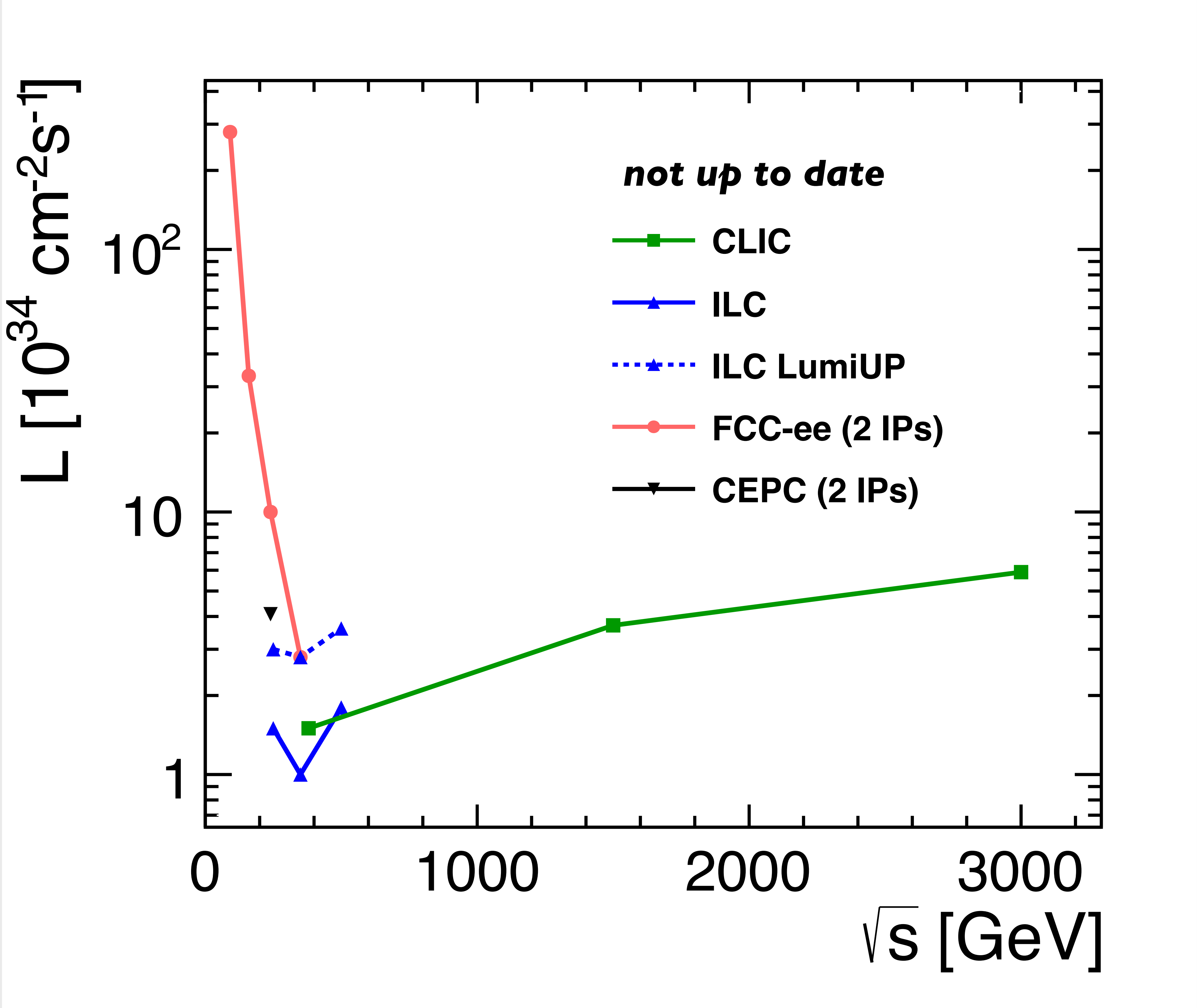
Challenges we can see already from here

TIME

$$\sigma(ab \to cd) \sim 1/E^2 \Rightarrow \text{you want } \mathscr{L} \sim E^2$$

$$\mathscr{L} \cdot \sigma(ab \to cd) \sim \text{const}$$





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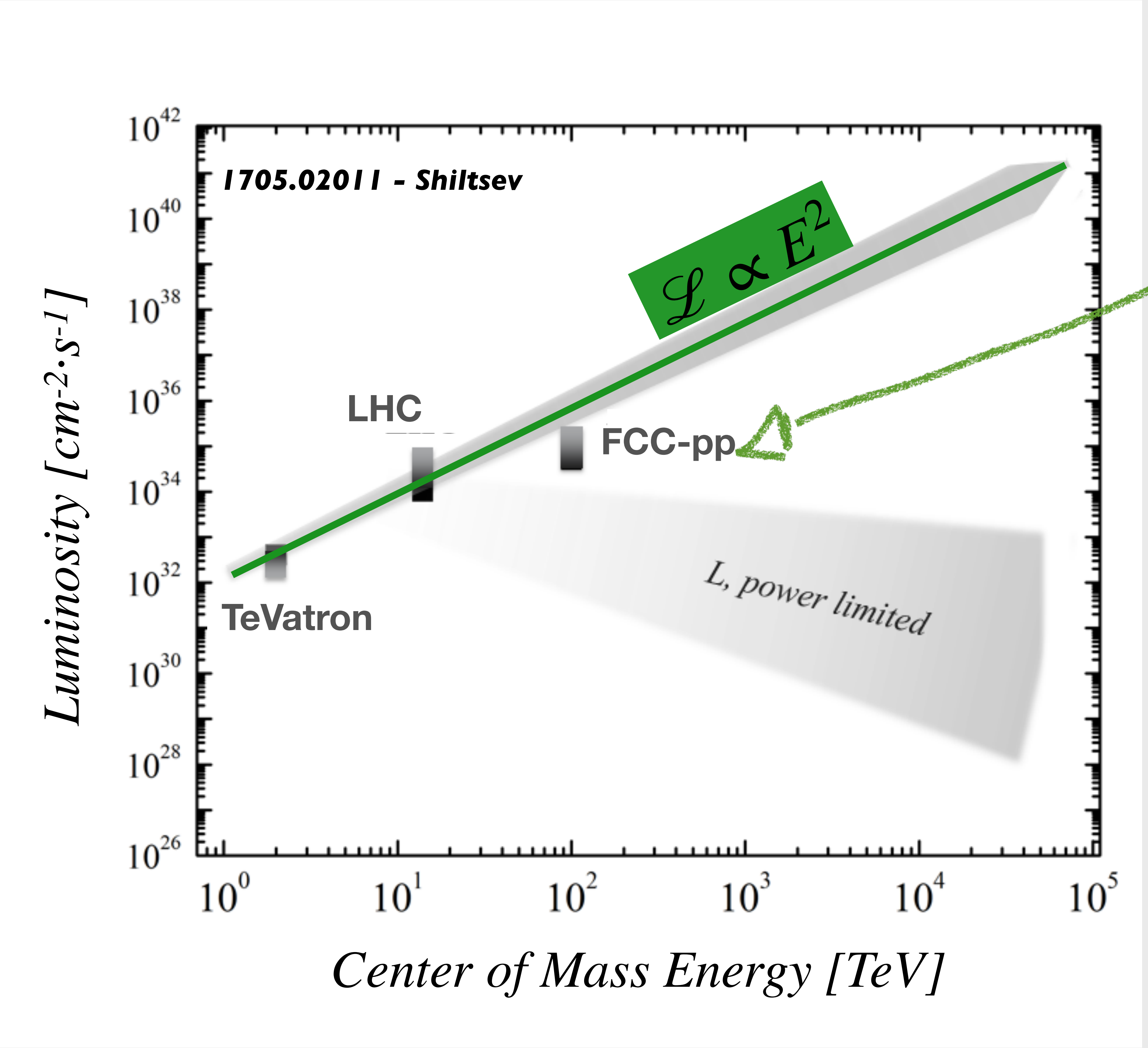
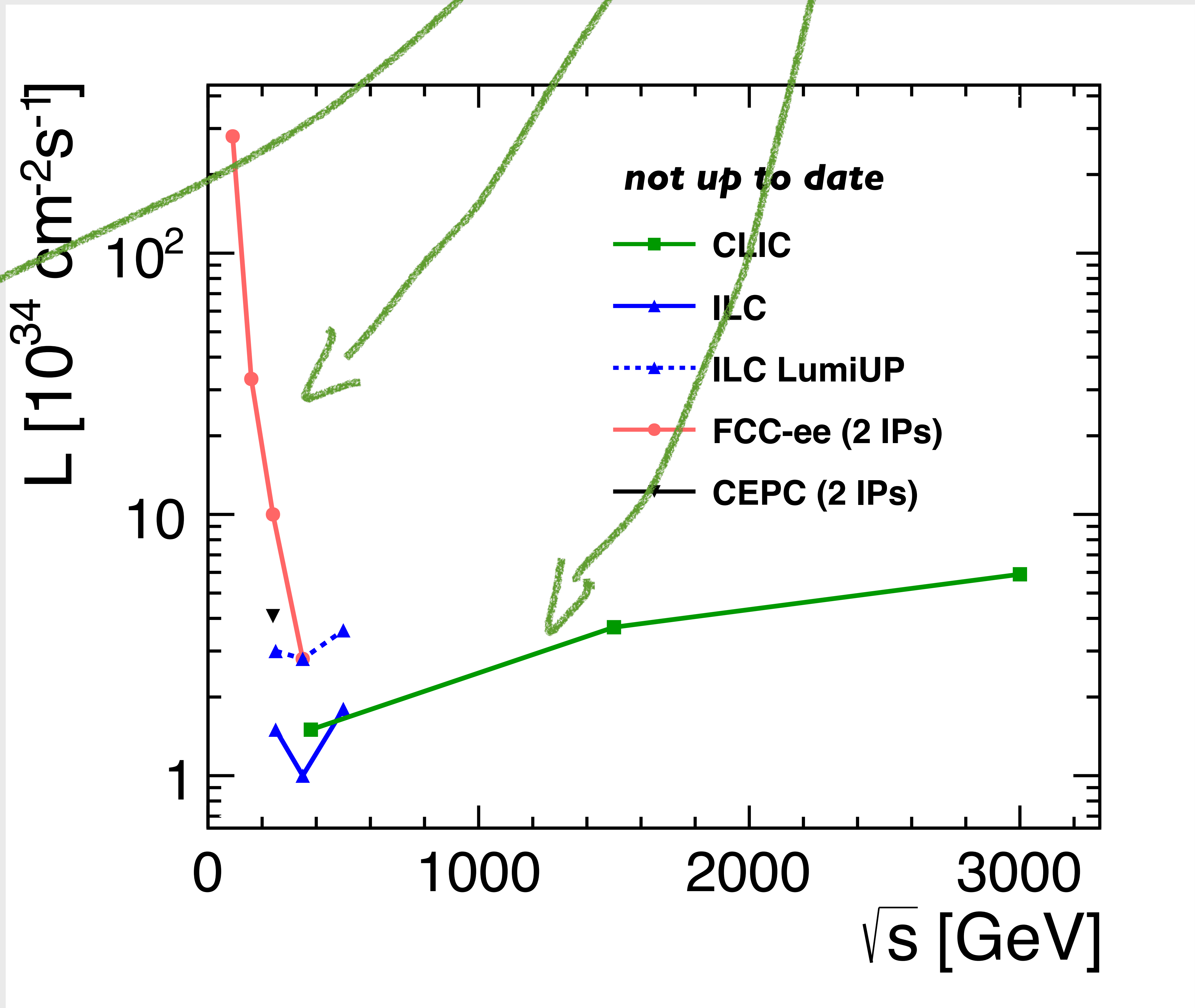
WE ARE
CLEARLY
FAILING





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Key issues

- Time
-

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"

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STRONG INTERACTIONS

WEAK INTERACTIONS

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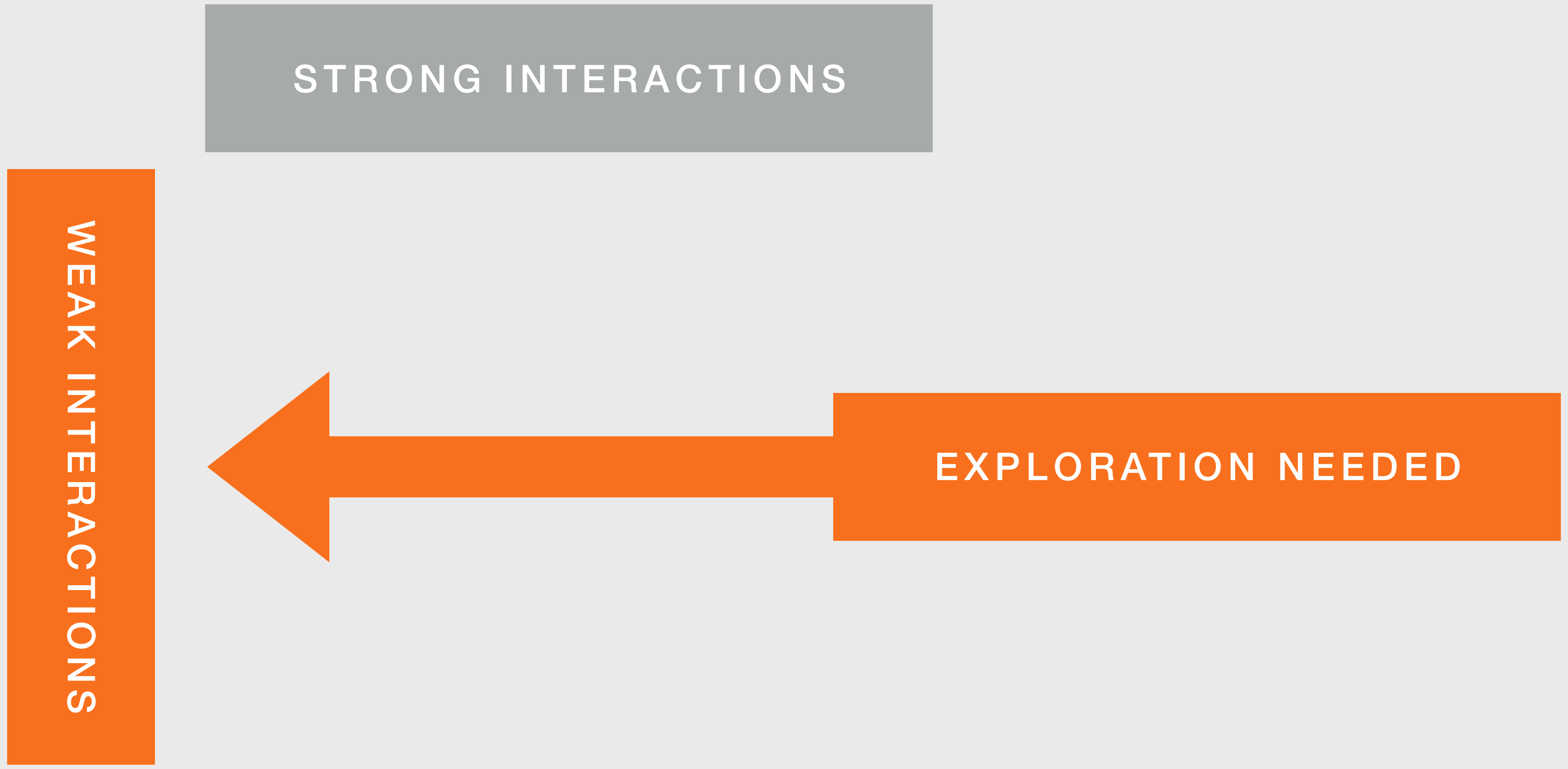


STRONG INTERACTIONS

WEAK INTERACTIONS

EXPLORATION NEEDED

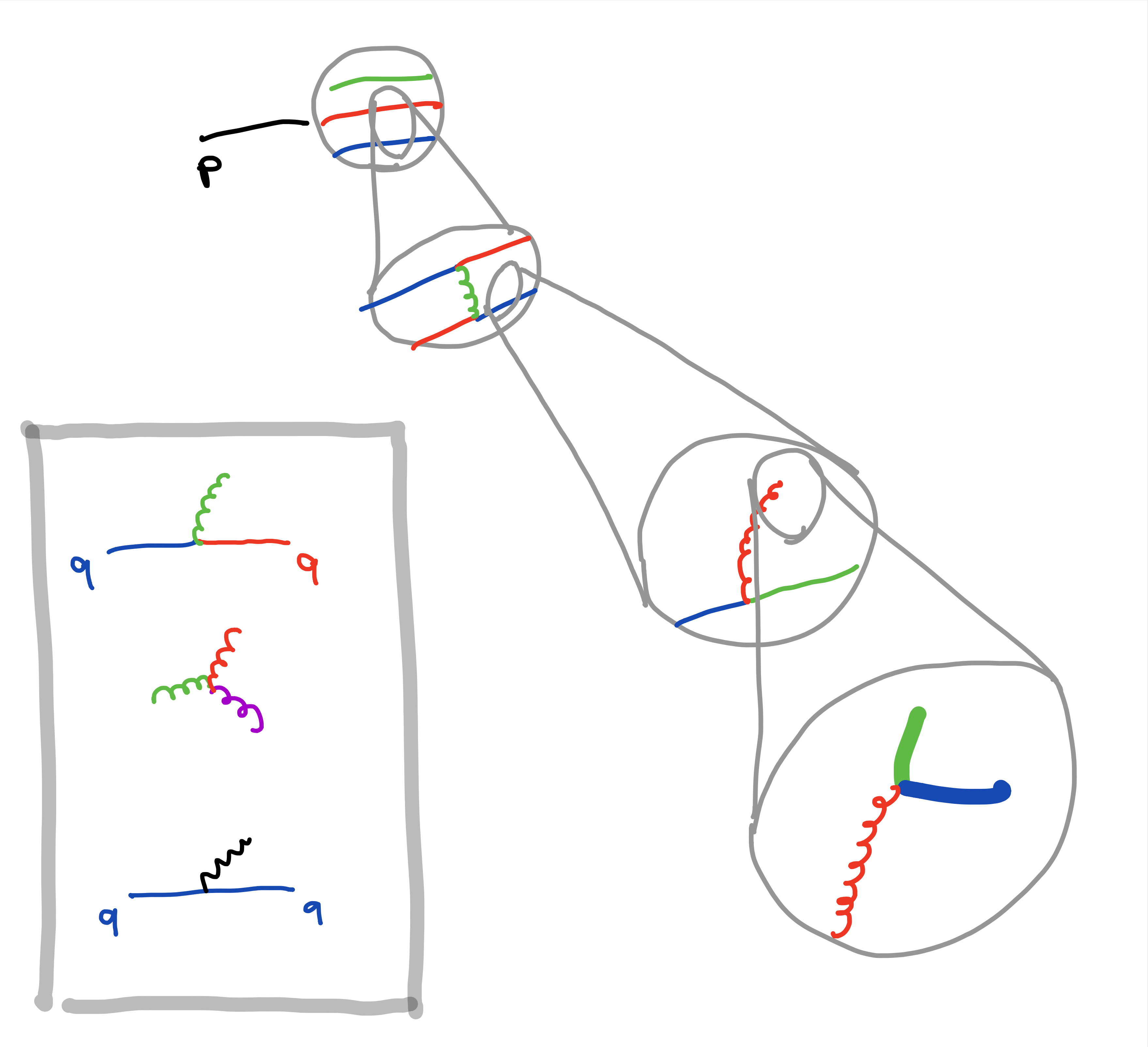
Key issues

- Time
- Need to understand the EW interactions

How to move forward?

p p

- quantum structure of the proton exposed at short time-scale
- anything appears in the beam at sufficiently large momentum transfer



- “**never**” collide at **full center-of-mass energy**
- “light” particles can be made very easily, e.g. **gg → h**

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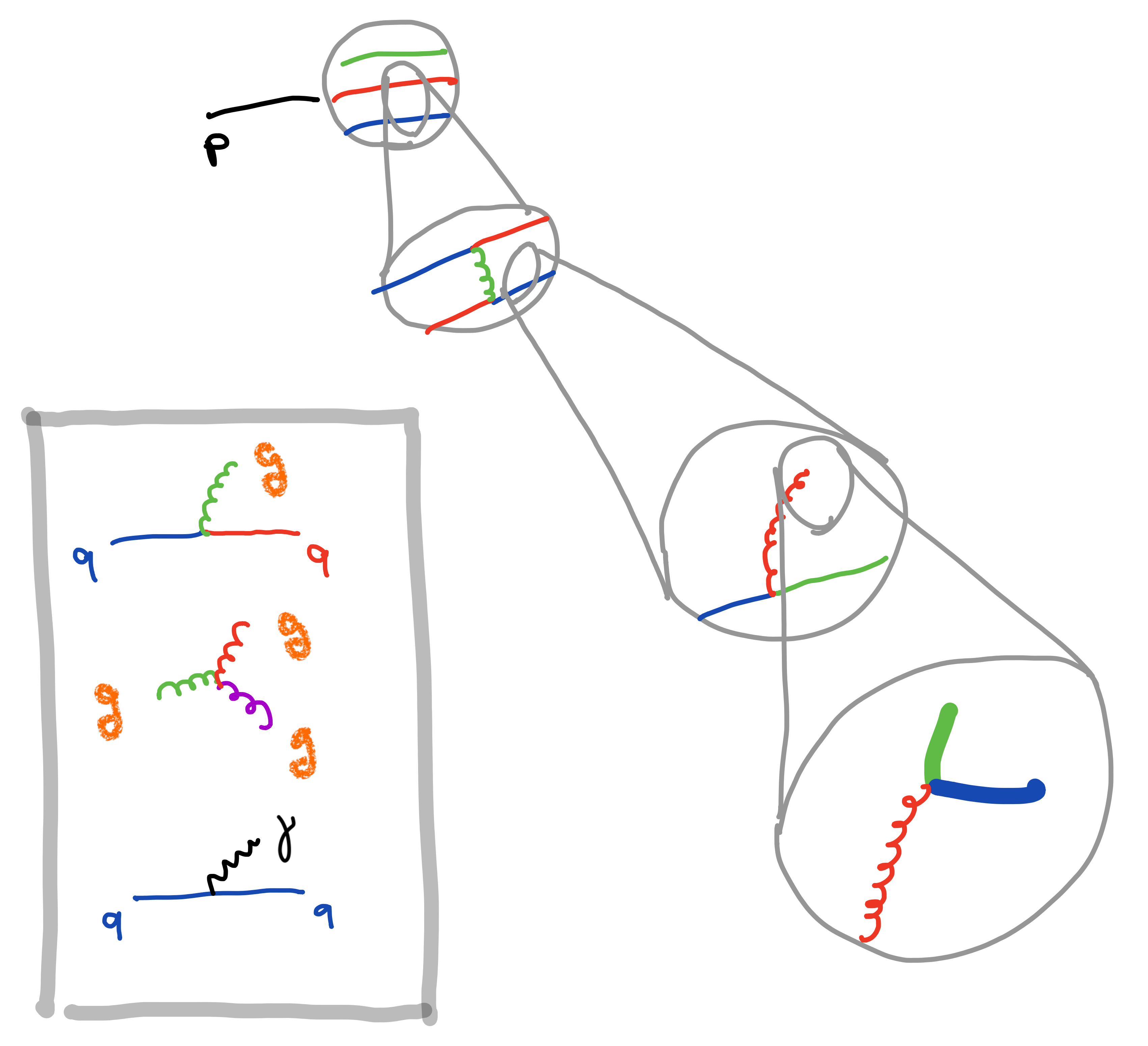

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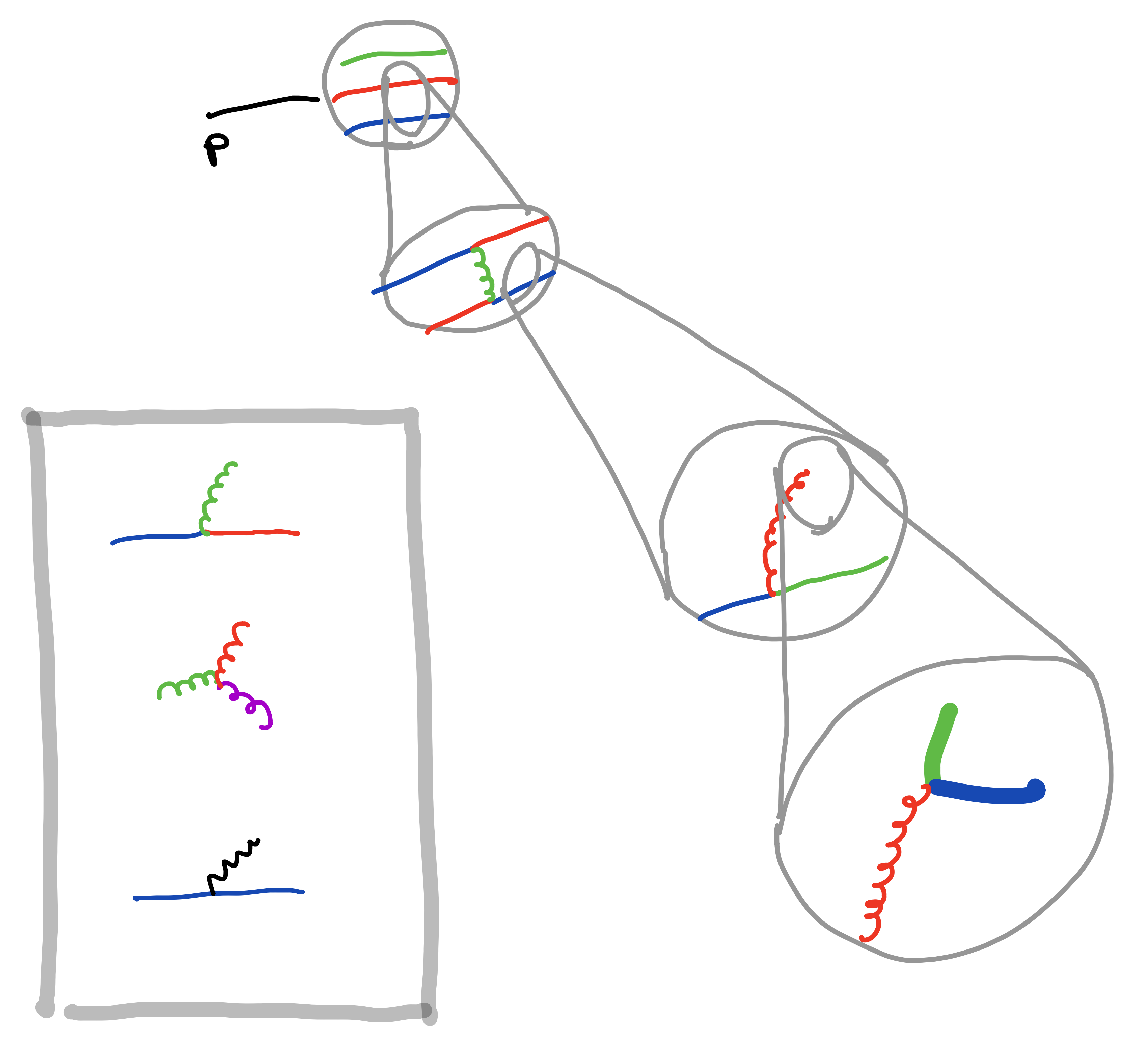

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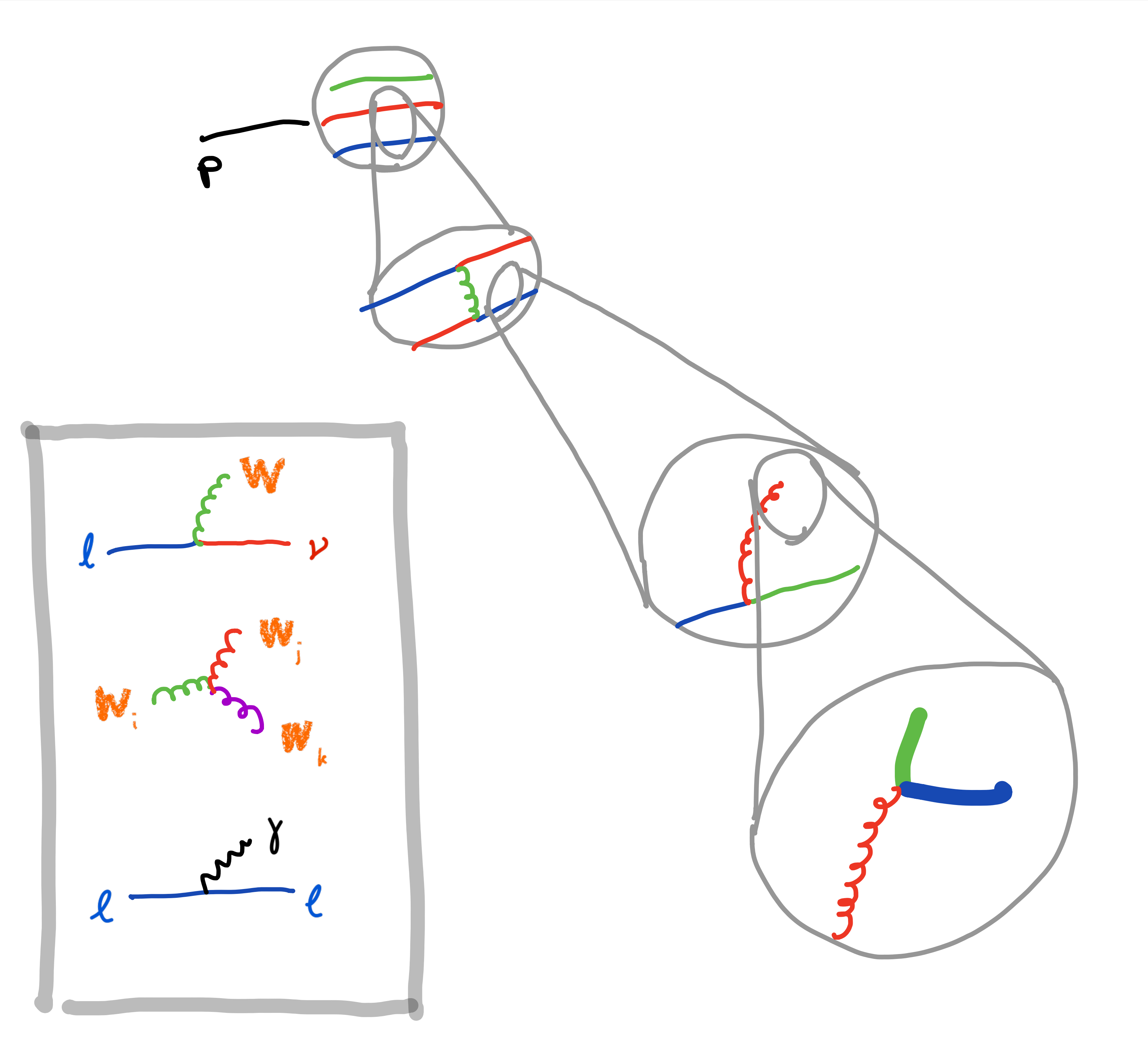

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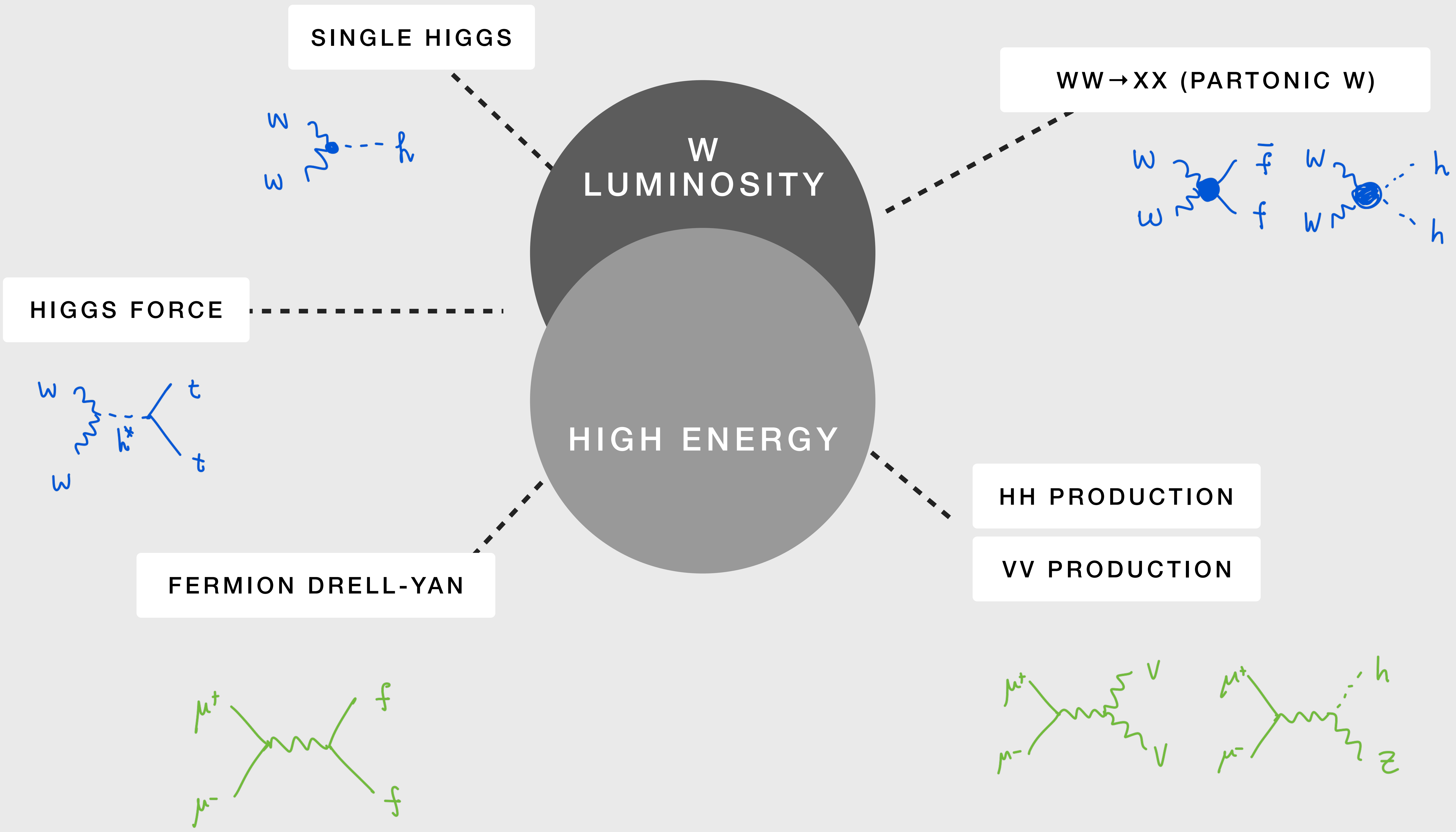
yet when we say e^+e^- we think LEP and Z-pole



SINGLE HIGGS

WW→XX (PARTONIC W)

W LUMINOSITY

HIGGS FORCE

HIGH ENERGY

HH PRODUCTION

VV PRODUCTION

FERMION DRELL-YAN

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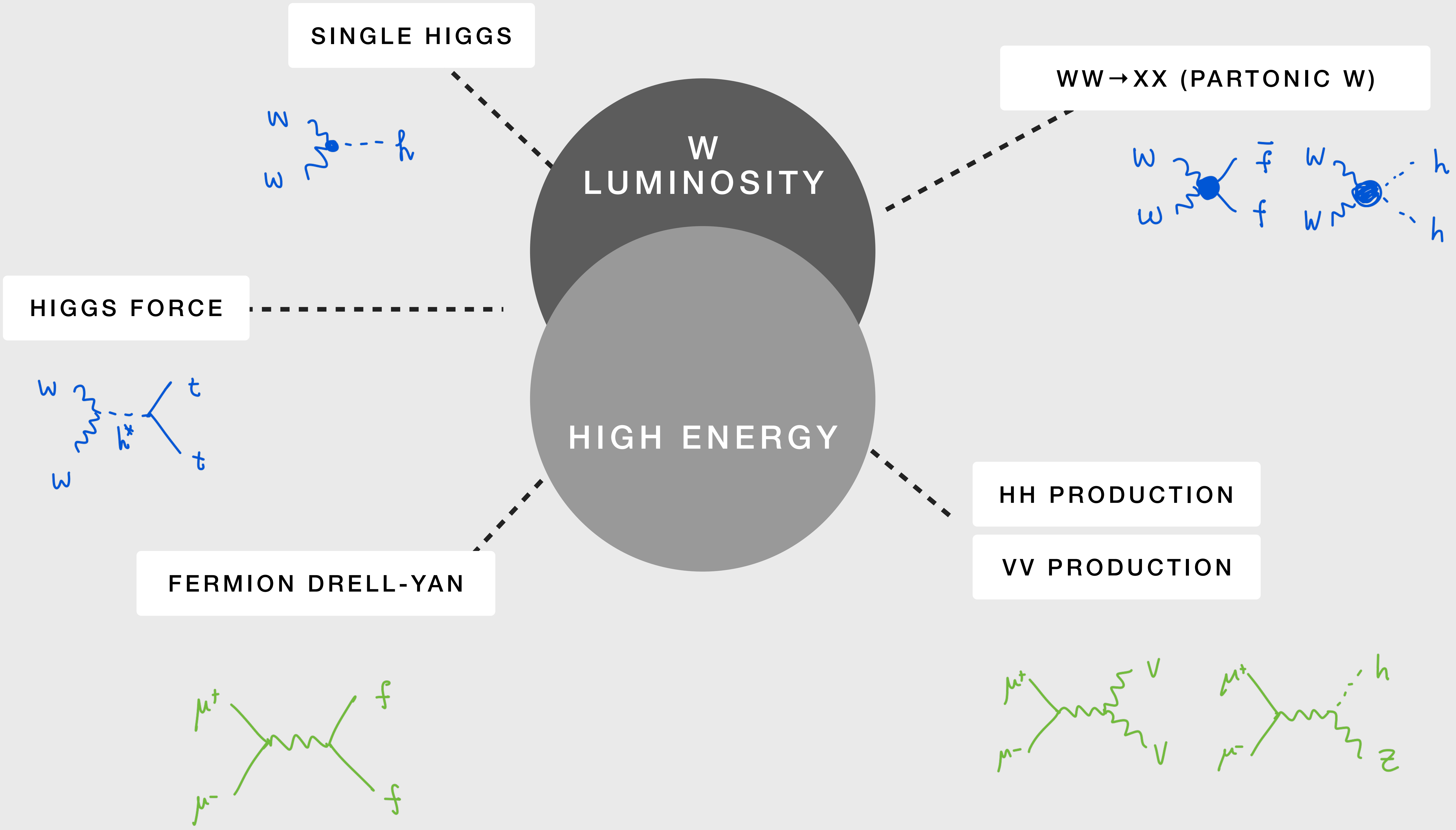
Indirect tests of BSM



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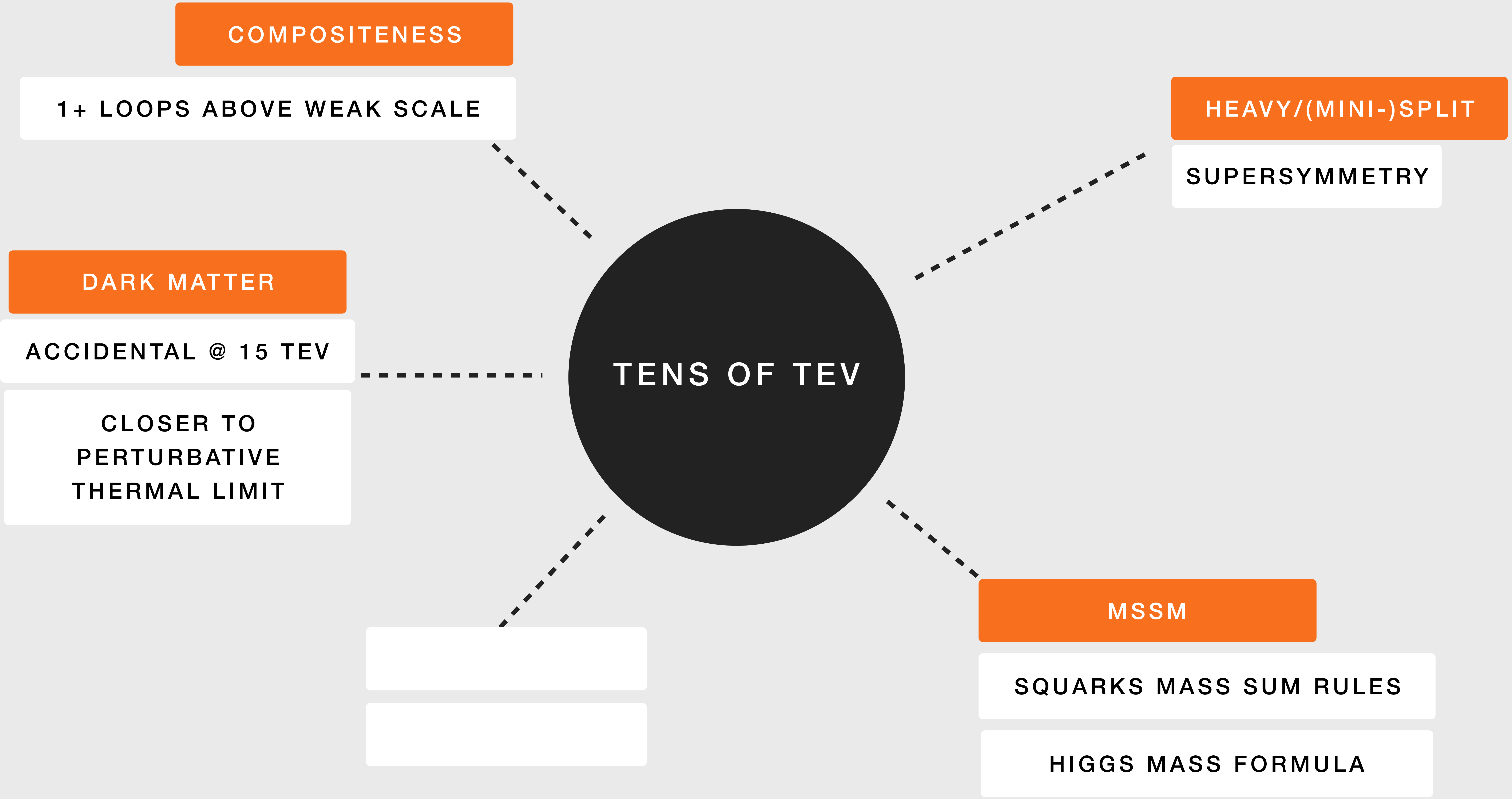


TENS OF TEV

COMPOSITENESS

1+ LOOPS ABOVE WEAK SCALE

HEAVY/(MINI-)SPLIT

SUPERSYMMETRY

DARK MATTER

ACCIDENTAL @ 15 TEV

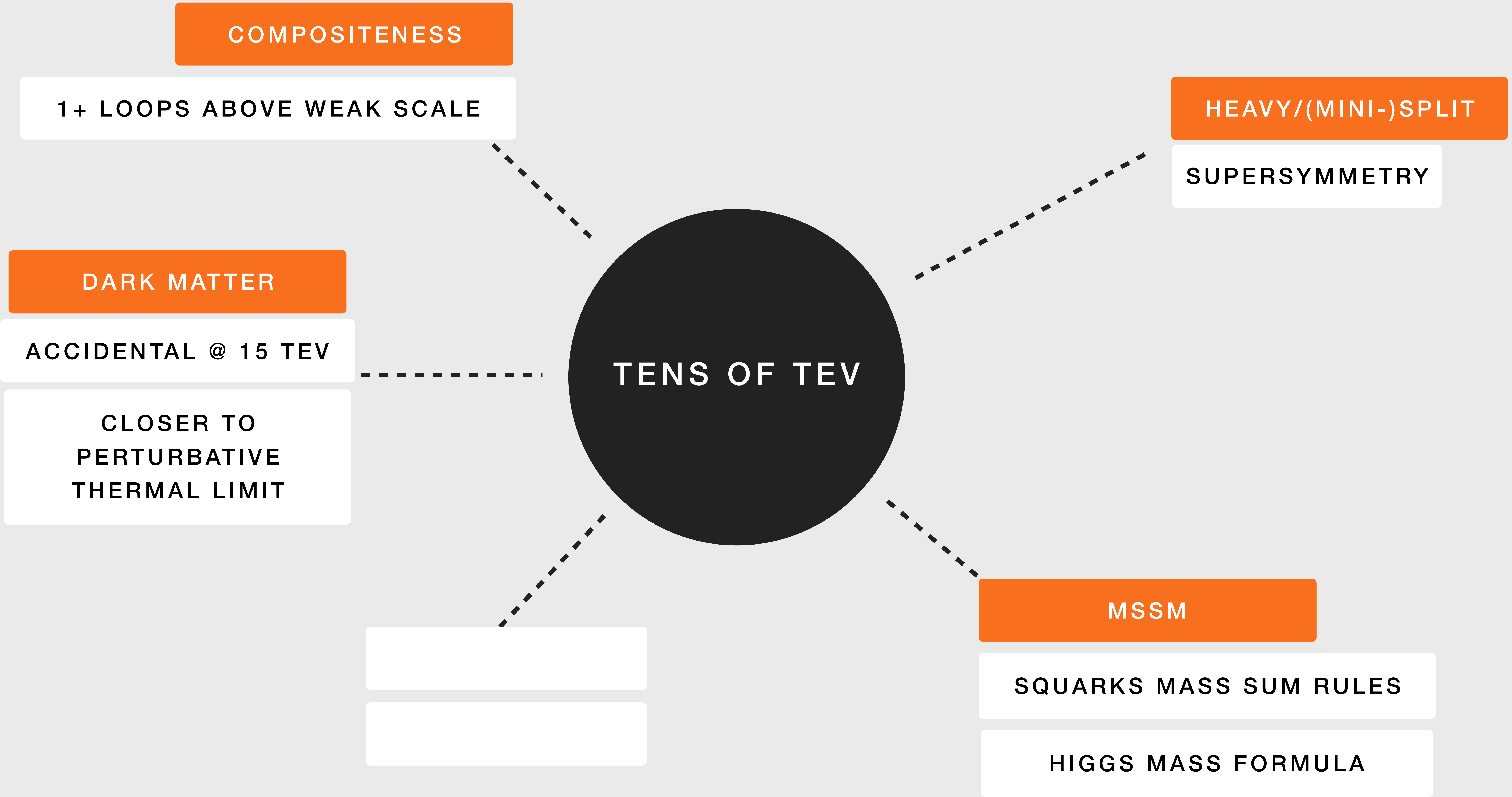
CLOSER TO PERTURBATIVE THERMAL LIMIT

MSSM

SQUARKS MASS SUM RULES

HIGGS MASS FORMULA

Direct Production



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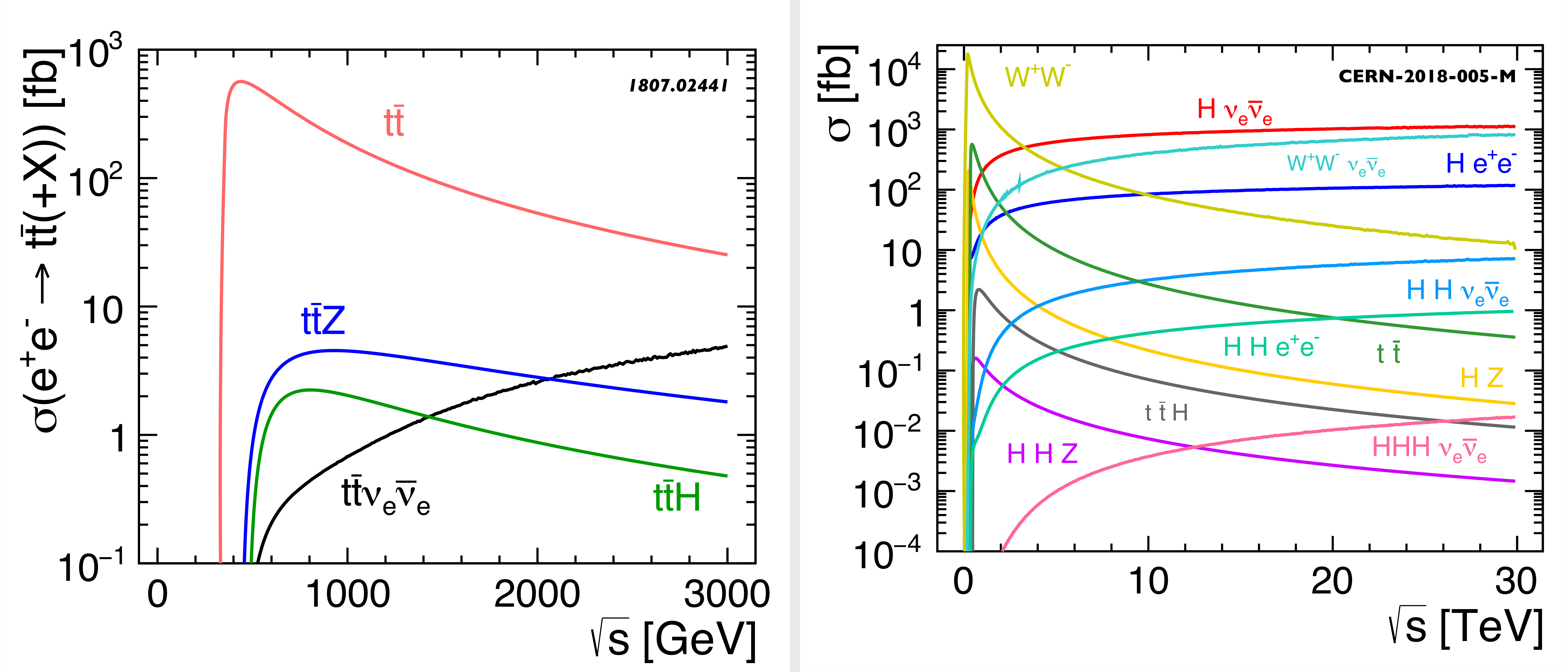
When does the transition happen?

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

$\ell^+\ell^-$ @TeV BEAM STRUCTURE EXPOSED



$\sqrt{s}$ > few TeV clearly makes W collisions "ordinary"

The luminosity challenge

HIGH-ENERGY

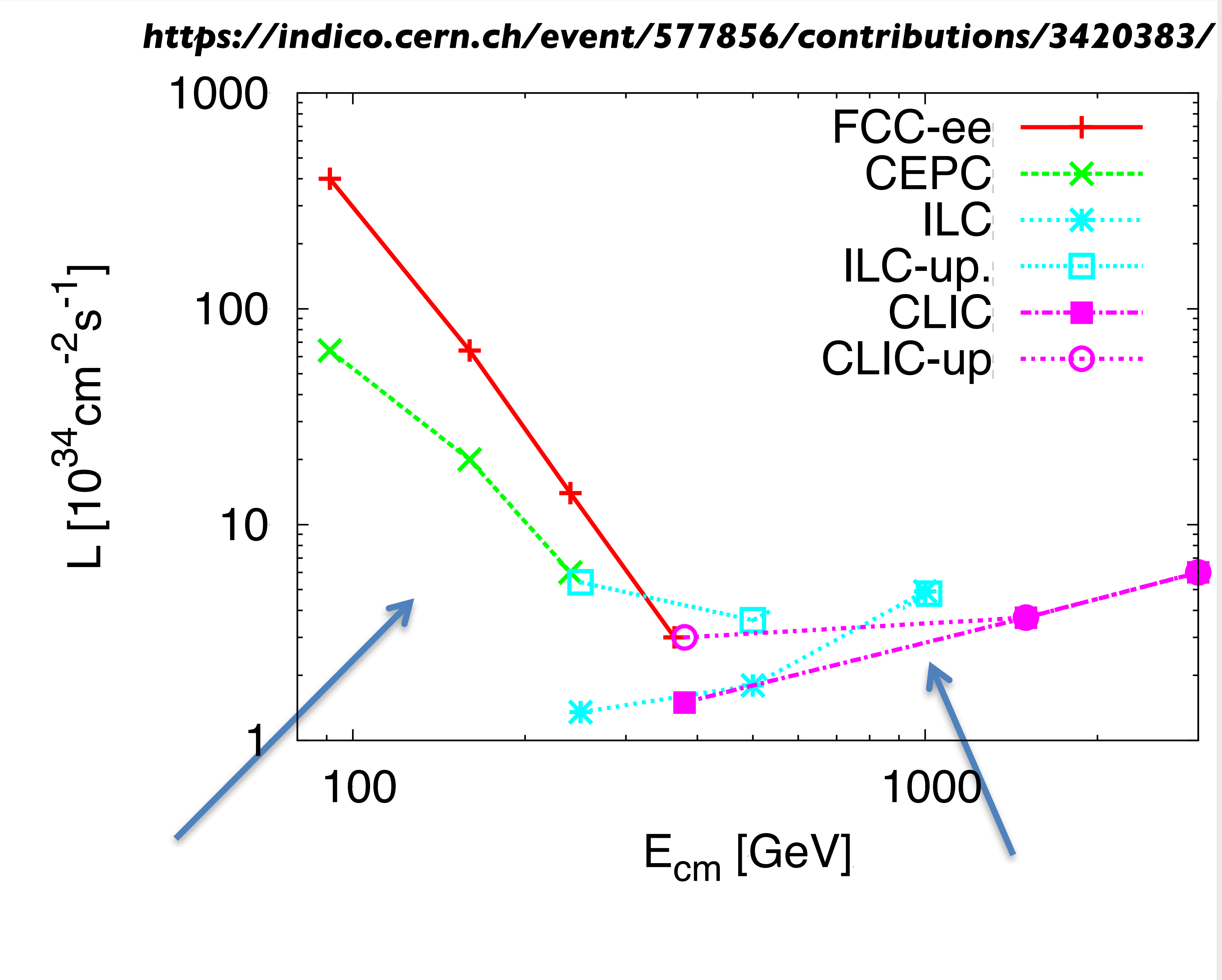
BLESSING AND CURSE

$$\sigma \propto 1/E^2 \qquad \mathscr{L} \propto \frac{N^2 f}{\sigma}$$

beam population

frequency of beam crossing

beam phase-space spread


https://indico.cern.ch/event/577856/contributions/3420383/

Number of events = $\mathscr{L} \cdot \sigma(ab \to cd)$ tends to decrease

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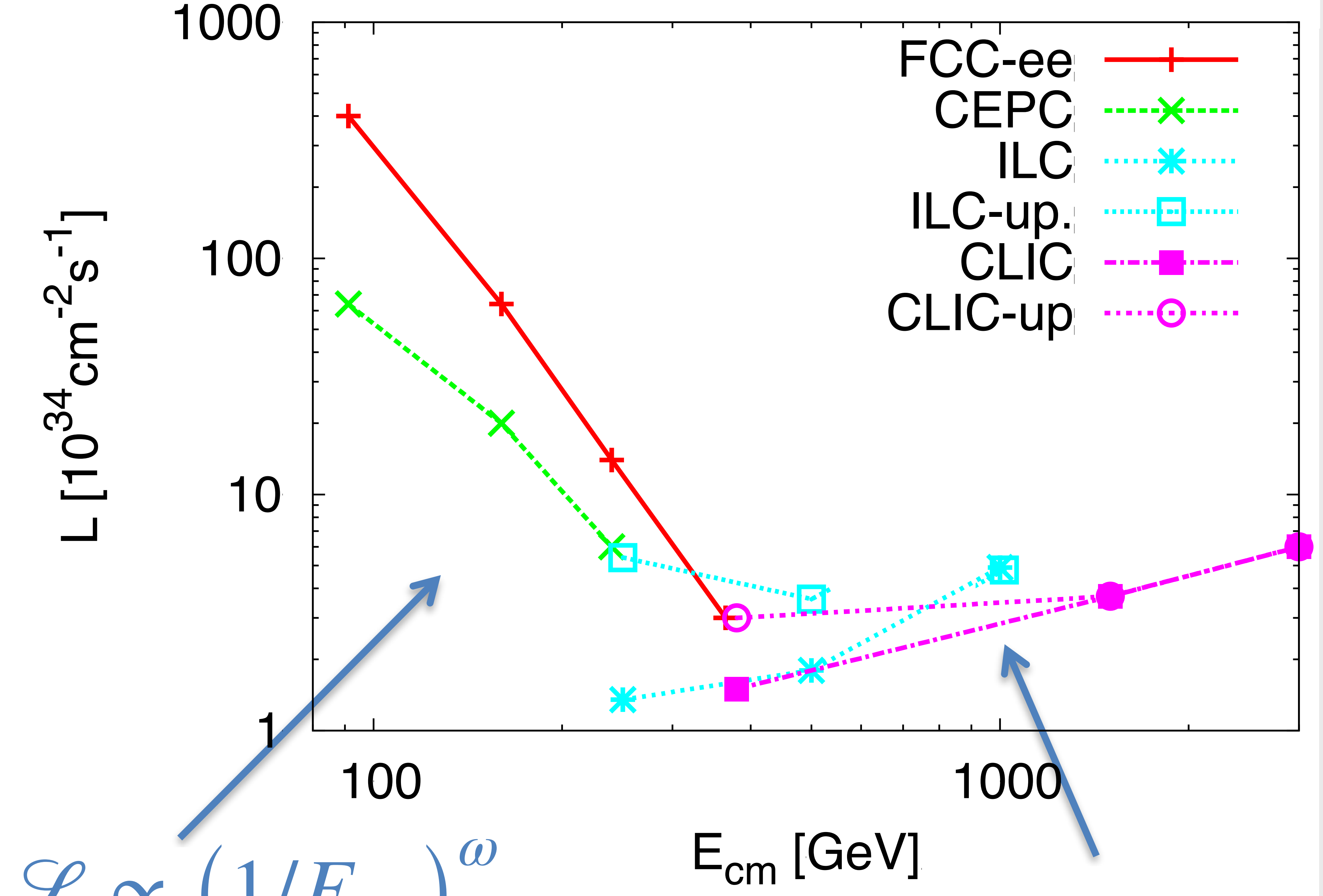

$$\mathscr{L} \propto \left(1/E_{cm}\right)^{\omega}$$

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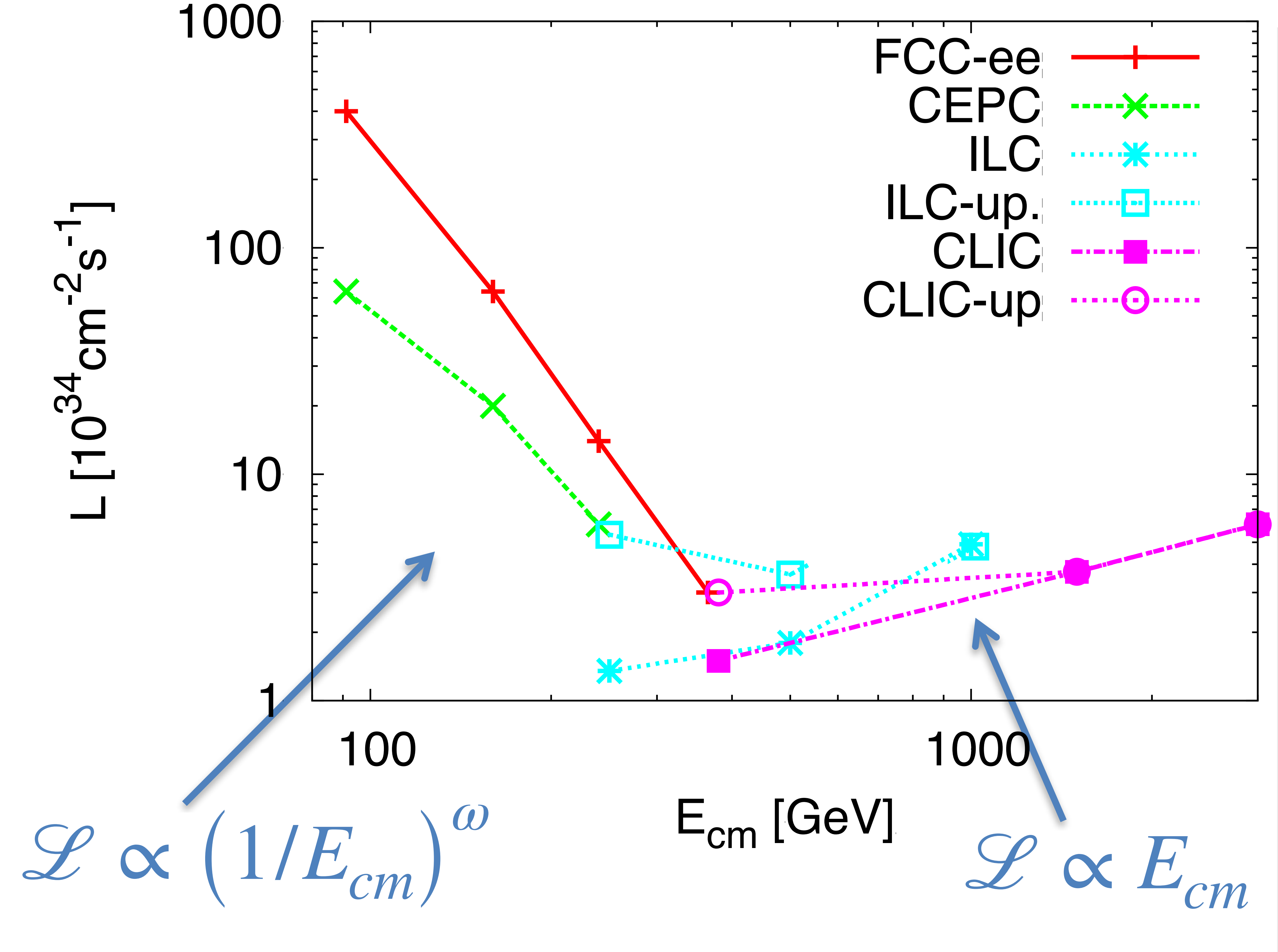

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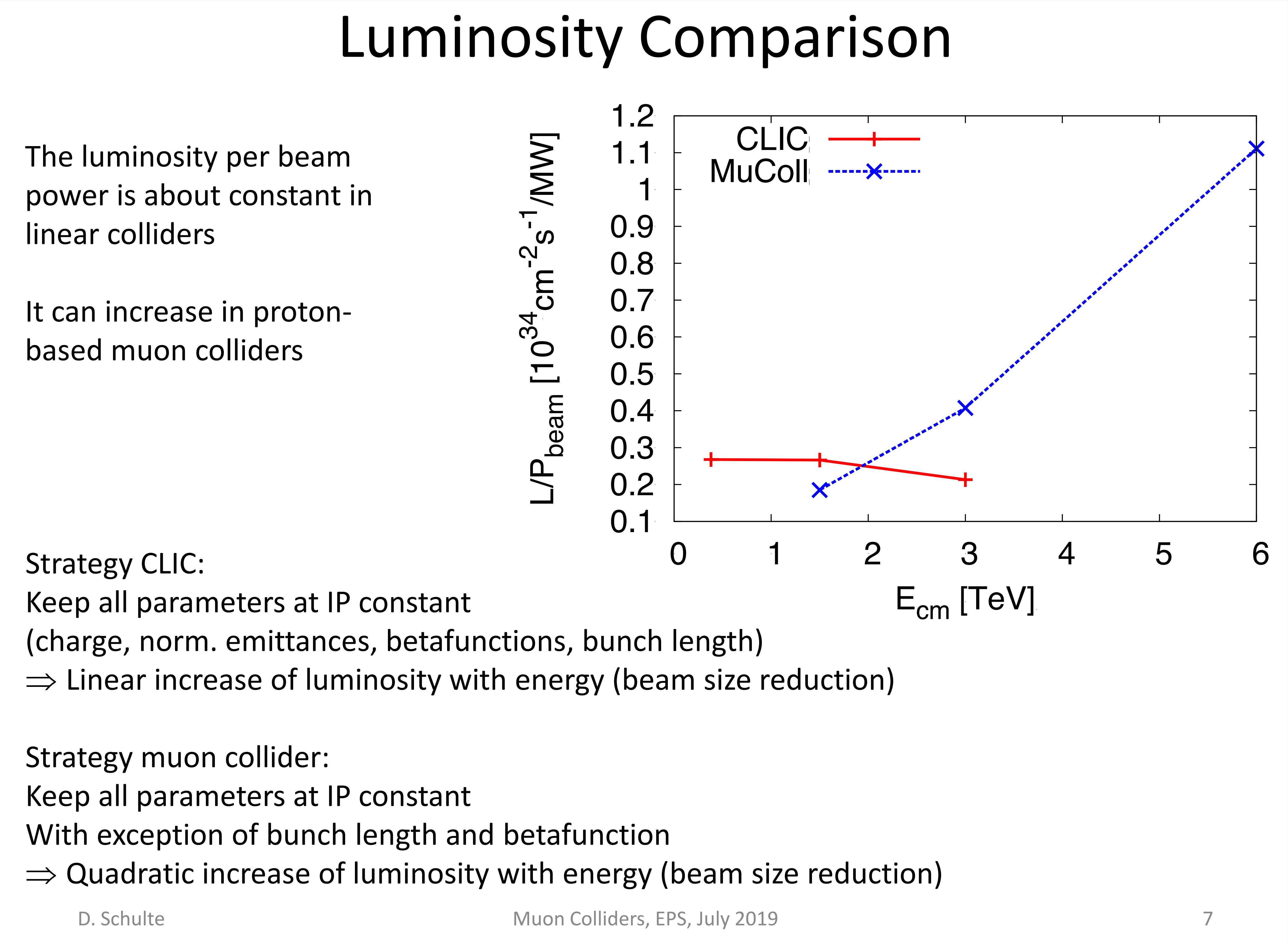
Muon colliders

MASS AND LIFETIME

BLESSING AND CURSE



Luminosity Comparison

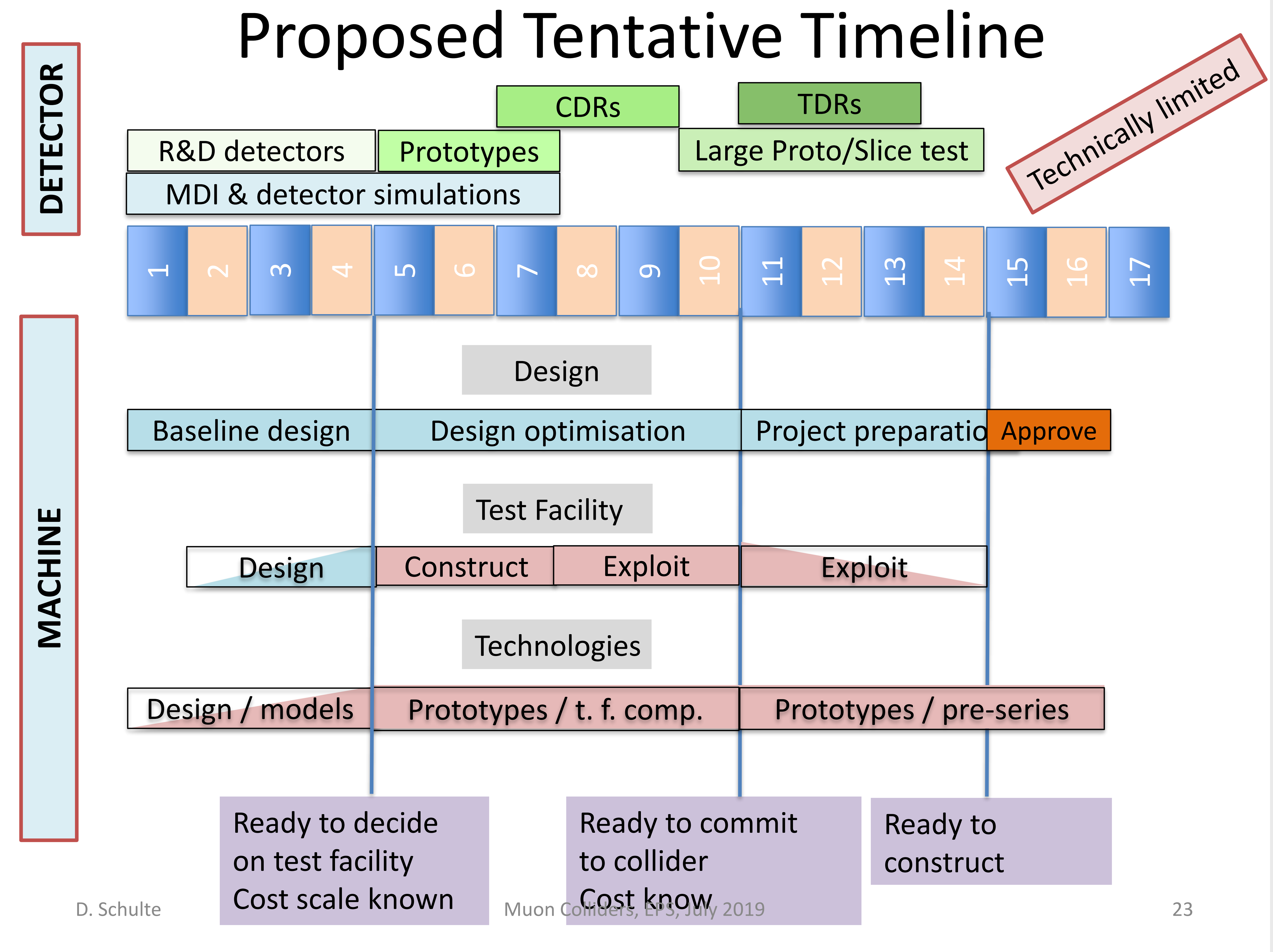
The luminosity per beam power is about constant in linear colliders

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

DETECTOR

CDRs
TDRs
R&D detectors
Prototypes
Large Proto/Slice test
MDI & detector simulations
Technically limited

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

MACHINE

Design
Baseline design
Design optimisation
Project preparatio
Approve

Test Facility
Design
Construct
Exploit
Exploit

Technologies
Design / models
Prototypes / t. f. comp.
Prototypes / pre-series

Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

D. Schulte Muon Colliders, EPS, July 2019 23

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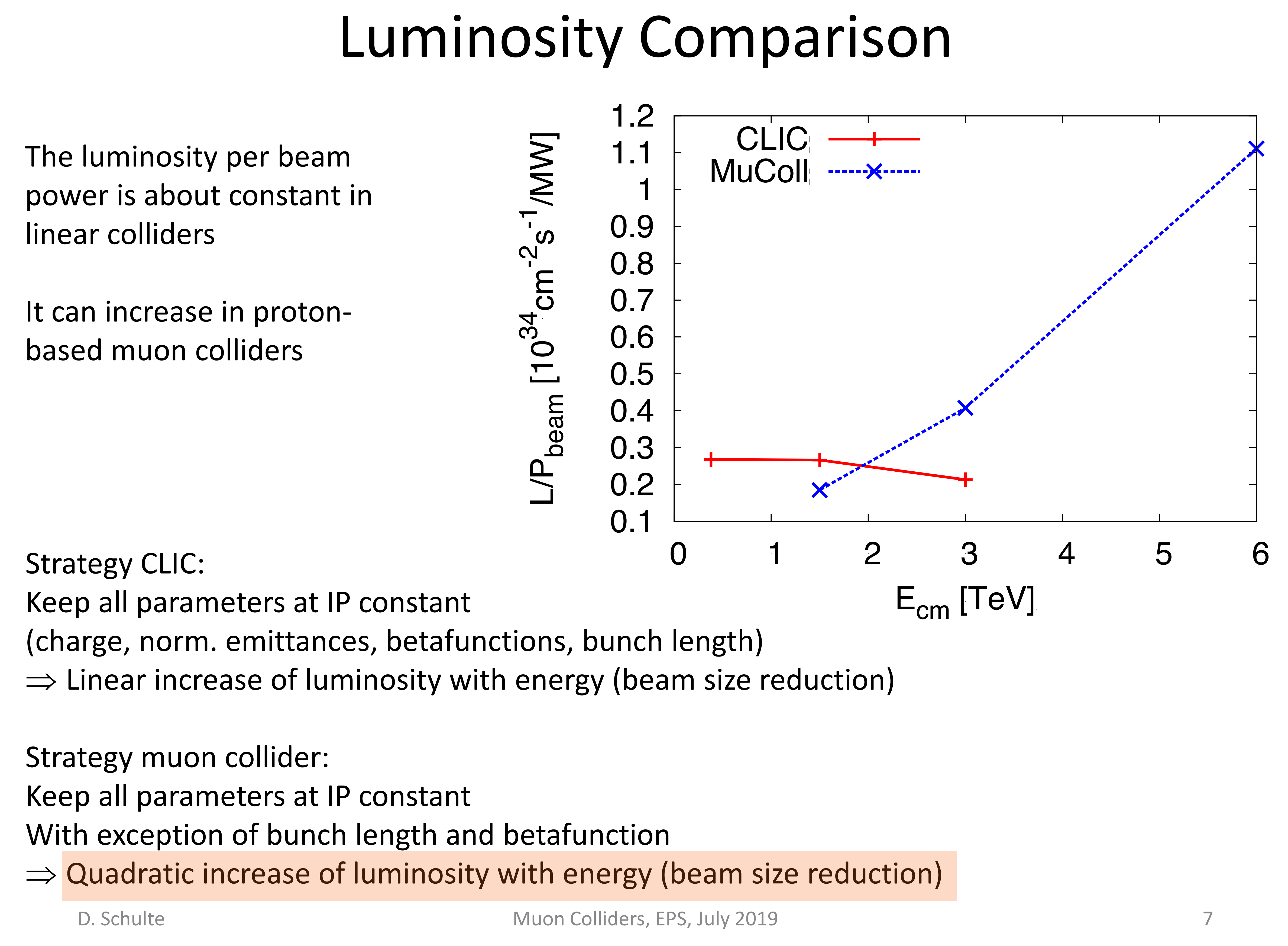

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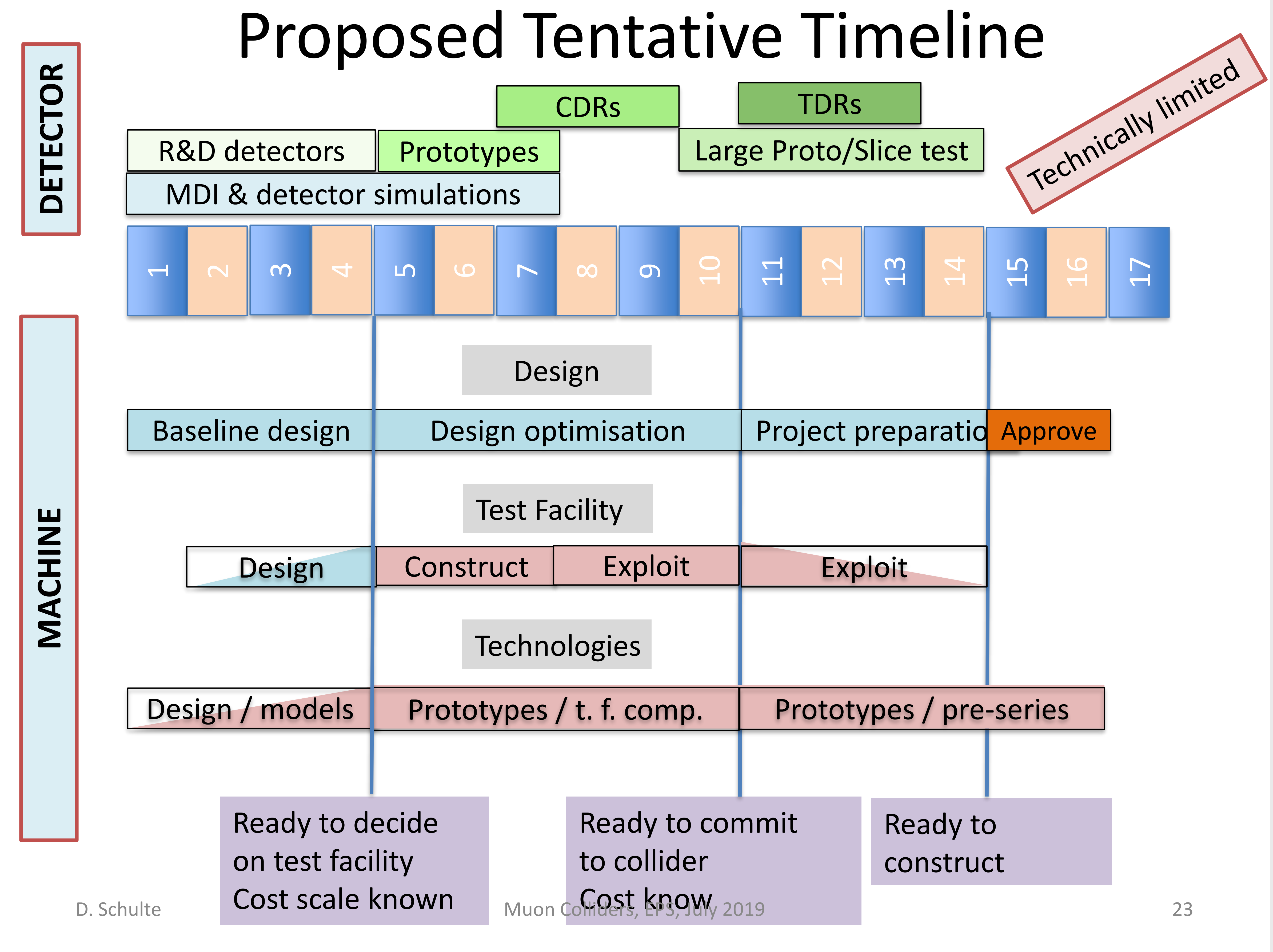

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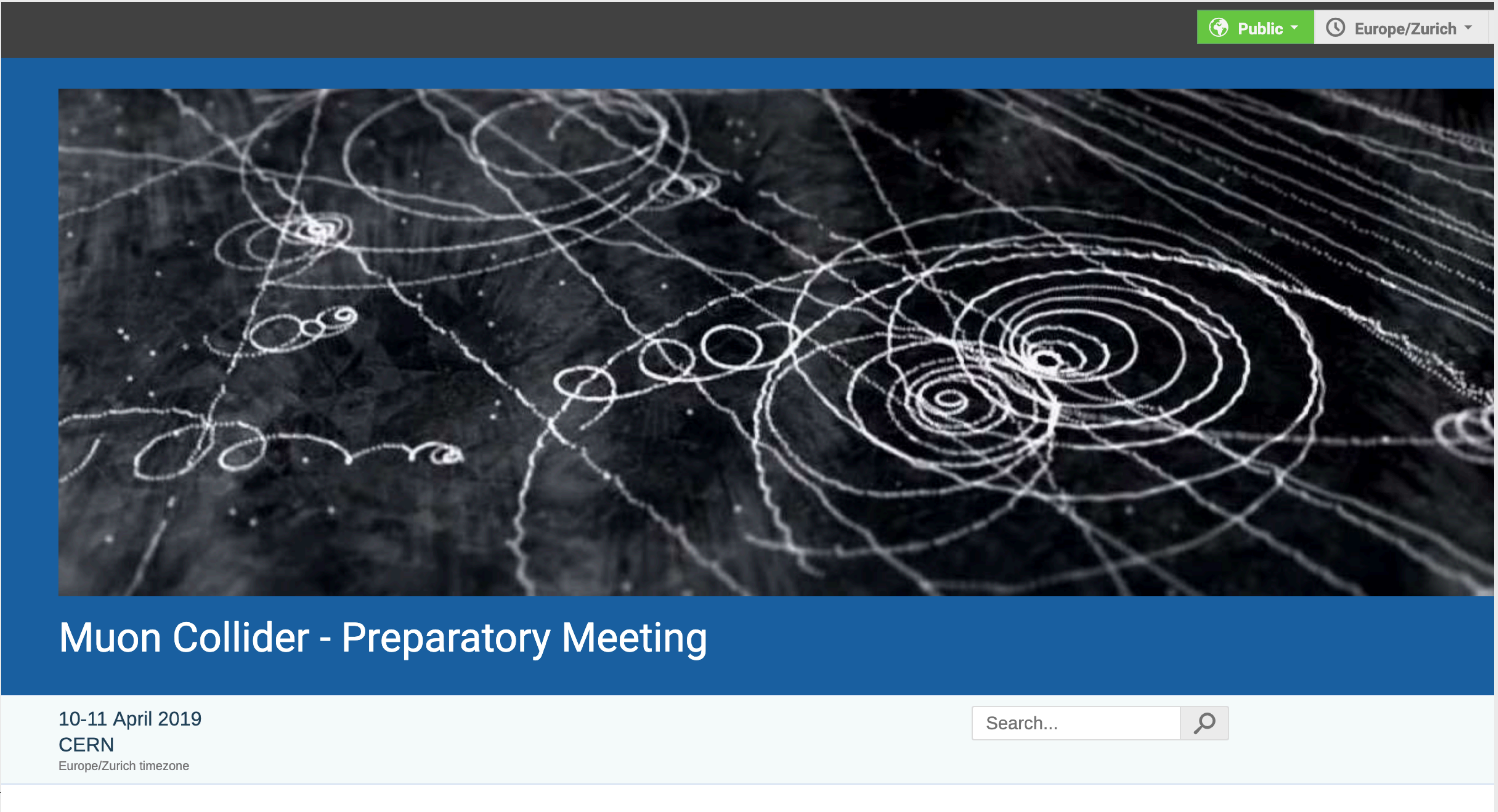
https://indico.cern.ch/event/801616/ https://indico.cern.ch/event/831718/

μμ→ new physics?

MUON COLLIDER CHALLENGE



Muon Collider - Preparatory Meeting

10-11 April 2019
CERN
Europe/Zurich timezone

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

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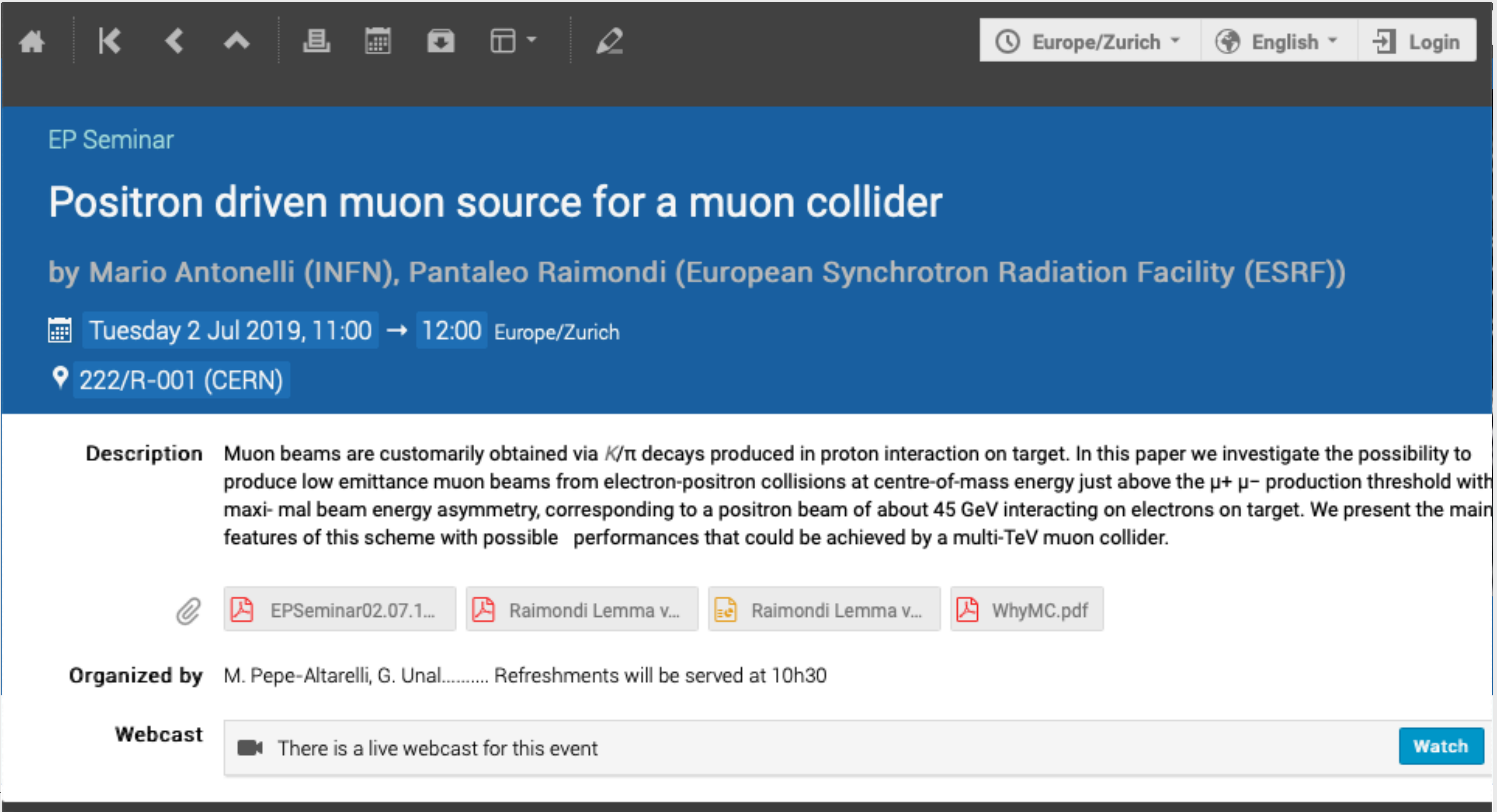


EP Seminar

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 μ+ μ− 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

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

$\mu\mu \rightarrow$ 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 > $10^{13}\mu$/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 $\approx 10^{11}$ μ/sec $N_\mu \approx 5\cdot10^9$/bunch **10-20Hz cycle**
- **by Gammas ($\gamma N \rightarrow \mu^+\mu^- N$): GeV-scale Compton γs** not discussed here
  production Rate $\approx 5\cdot10^{10}$ 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 ($e^-N \rightarrow \mu^+\mu^- e^- N$)

Straight section with targets at 360 phase advance for muons, 180 phase advance for positrons. Magnets strengths scaled to cope for positrons energy loss

1 bunch of μ every 135 accumulator turns (450 μs) or 135*n target interactions or 1 positron ring cycle.
10^{11-12} e^+ x 135 bunches x 100 targets x 7.4 10^{-8} (production rate) = 10^9 μ (neglecting muon lifetime)

Roberto Franceschini LFC19 ht

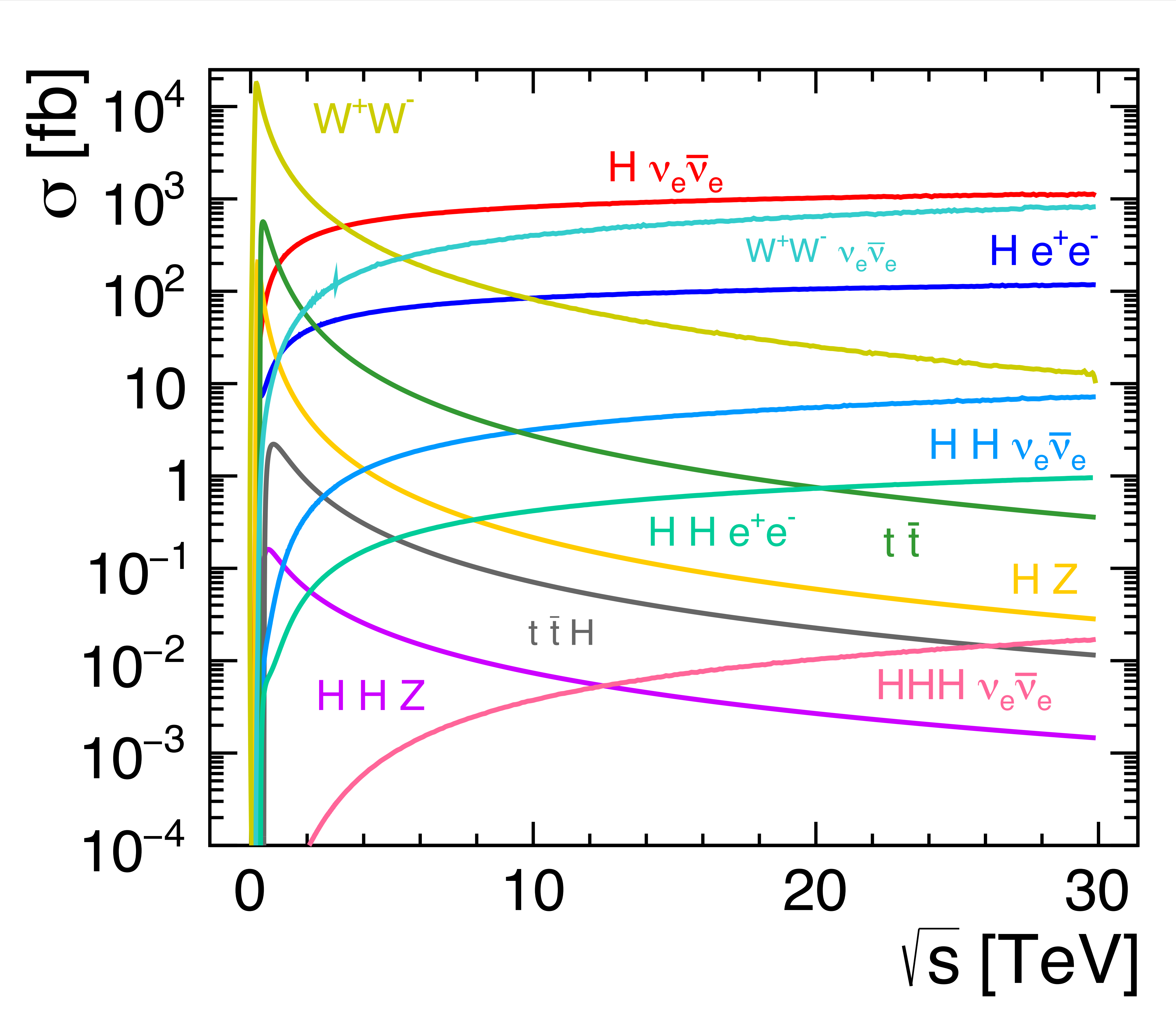
EWSB: Higgs Boson

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

10⁸ HIGGS BOSONS

100×MEGA-HIGGS FACTORY

$$\sigma \sim log(s) \simeq const \qquad \mathscr{L} \sim E^2$$



$$\sqrt{s} = 30\,\mathrm{TeV}$$

$$\sigma \cdot \mathscr{L} \Rightarrow 10^8\ \mathrm{h}$$

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

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

10⁸ HIGGS BOSONS

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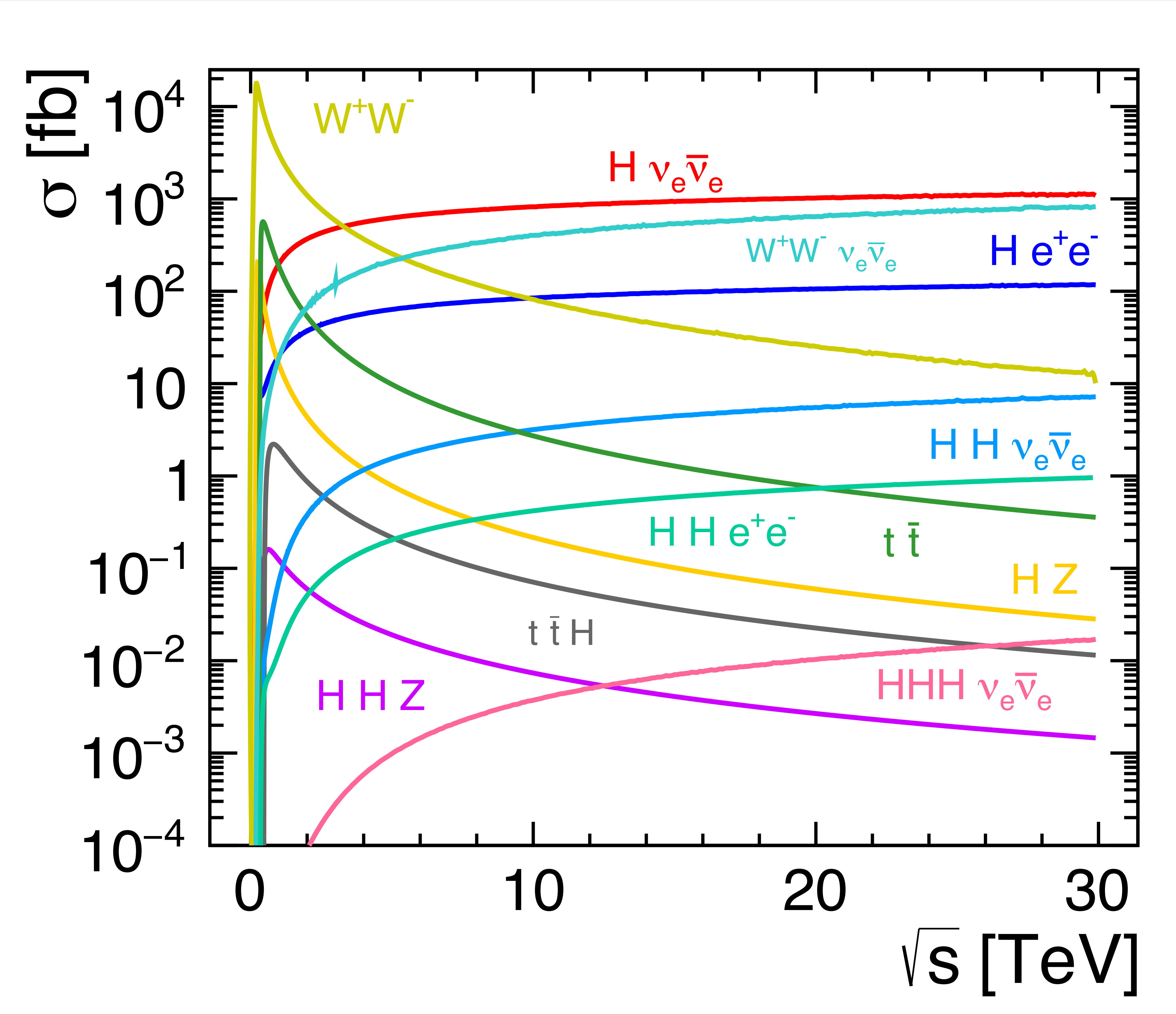
$$\mathscr{L} \sim 0.1\,\mathrm{ab}^{-1}\left(\frac{\sqrt{s}}{TeV}\right)^2$$



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Buttazzo, RF, Wulzer

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

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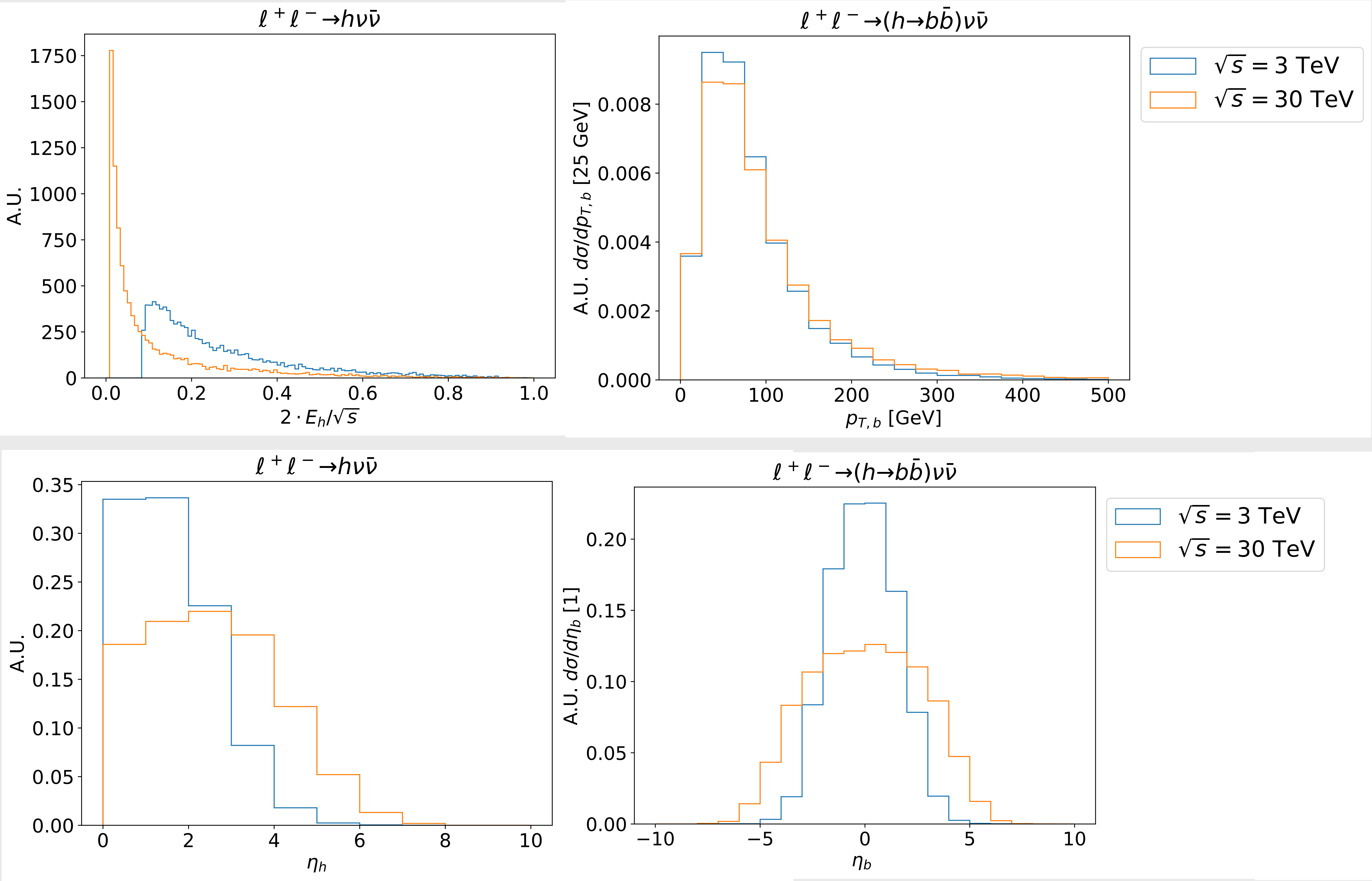


$$\mathscr{L} \simeq 90 \cdot \left(\frac{\sqrt{s}}{30\,\text{TeV}}\right)^2 \text{ab}^{-1}$$

$\sigma(\ell^+\ell^- \rightarrow \nu\nu(h \rightarrow bb)) = 1\,\text{pb}$ at 30 TeV

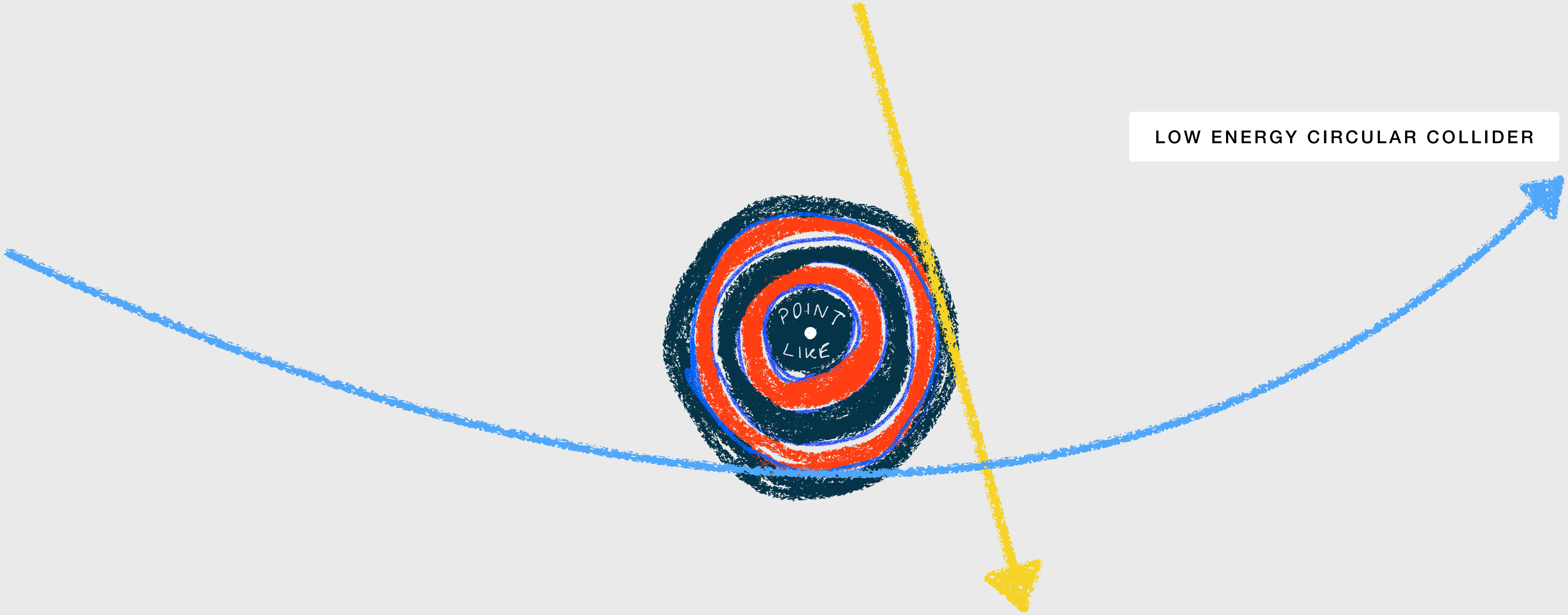
- most Higgs decays in acceptance
- O(10^4) H→$\mu^+\mu^-$ decays!
- clean decays where systematic may be small will be a key. E.g. 4ℓ, ℓℓ Z, γγ, Zγ

“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



LOW ENERGY CIRCULAR COLLIDER

LOW ENERGY LINEAR COLLIDER

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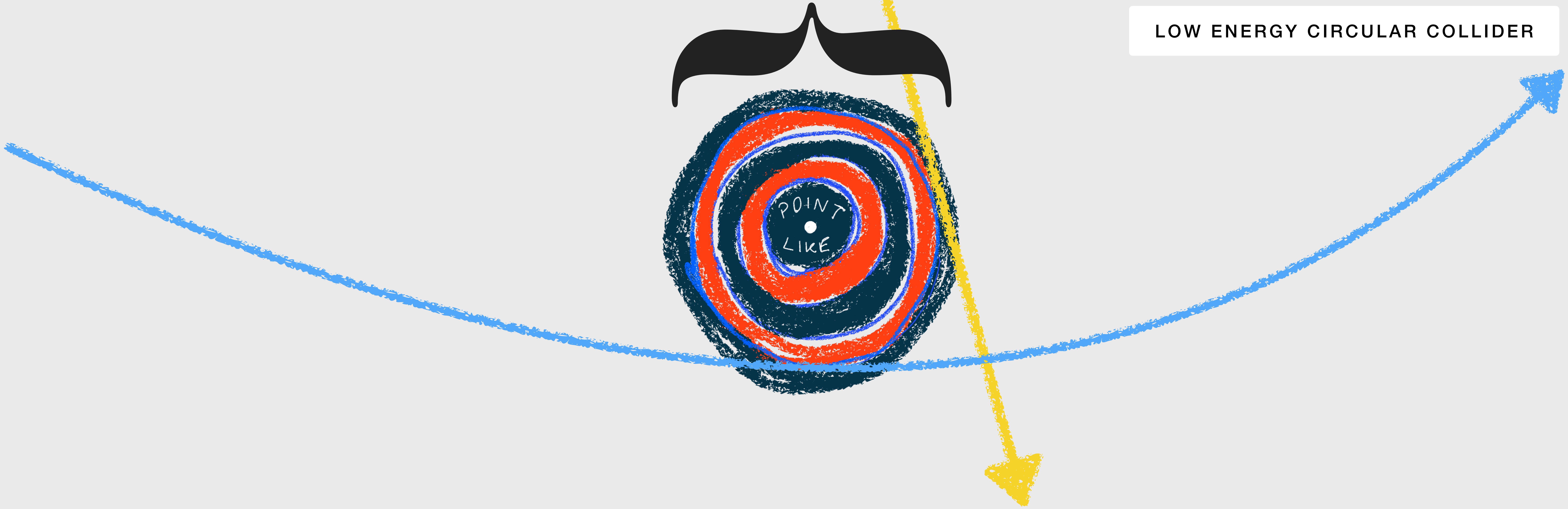
Looking ahead

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



LOW ENERGY CIRCULAR COLLIDER

LOW ENERGY LINEAR COLLIDER

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 νe⁻→νe⁻ 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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Lumi vs. Energy

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HIGH-LUMI PROBES

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measurements sensitive to a range of mass scales

- sensitive to a range of energy scales
- measurement of a spectrum (not so?!?) simple to grasp
- progress is easy to measure: bounds on new Fermi constants

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

$$
\begin{aligned}
\mathcal{L}^{d=6}_{universal} \quad = \quad & c_H \frac{g_*^2}{m_*^2} \mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2} \mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2} \mathcal{O}_6 + \frac{1}{m_*^2} \left[c_W \mathcal{O}_W + c_B \mathcal{O}_B \right] \\
+ \quad & \frac{g_*^2}{(4\pi)^2 m_*^2} \left[c_{HW} \mathcal{O}_{HW} + c_{HB} \mathcal{O}_{HB} \right] + \frac{y_t^2}{(4\pi)^2 m_*^2} \left[c_{BB} \mathcal{O}_{BB} + c_{GG} \mathcal{O}_{GG} \right] \\
+ \quad & \frac{1}{g_*^2 m_*^2} \left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B} \right] + c_{3W} \frac{3! g^2}{(4\pi)^2 m_*^2} \mathcal{O}_{3W} \\
+ \quad & c_{y_t} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_t} + c_{y_b} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_b}
\end{aligned}
$$

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

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

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

Effects of the size of the Higgs boson

h ~ π

STRONGLY INTERACTING LIGHT HIGGS

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

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

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

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

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

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

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

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

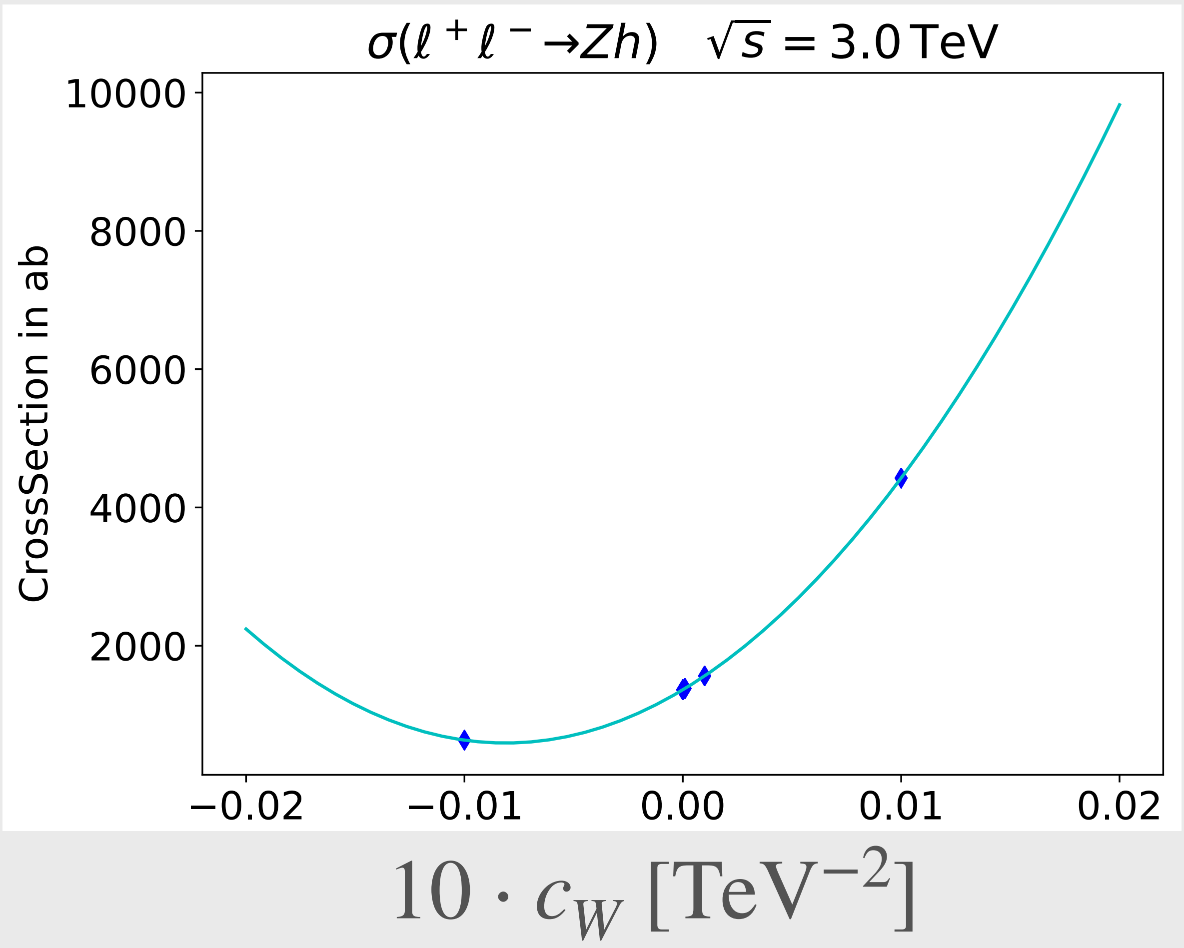
Roberto Franceschini LFC19 https://indico.ectstar.eu/event/55/

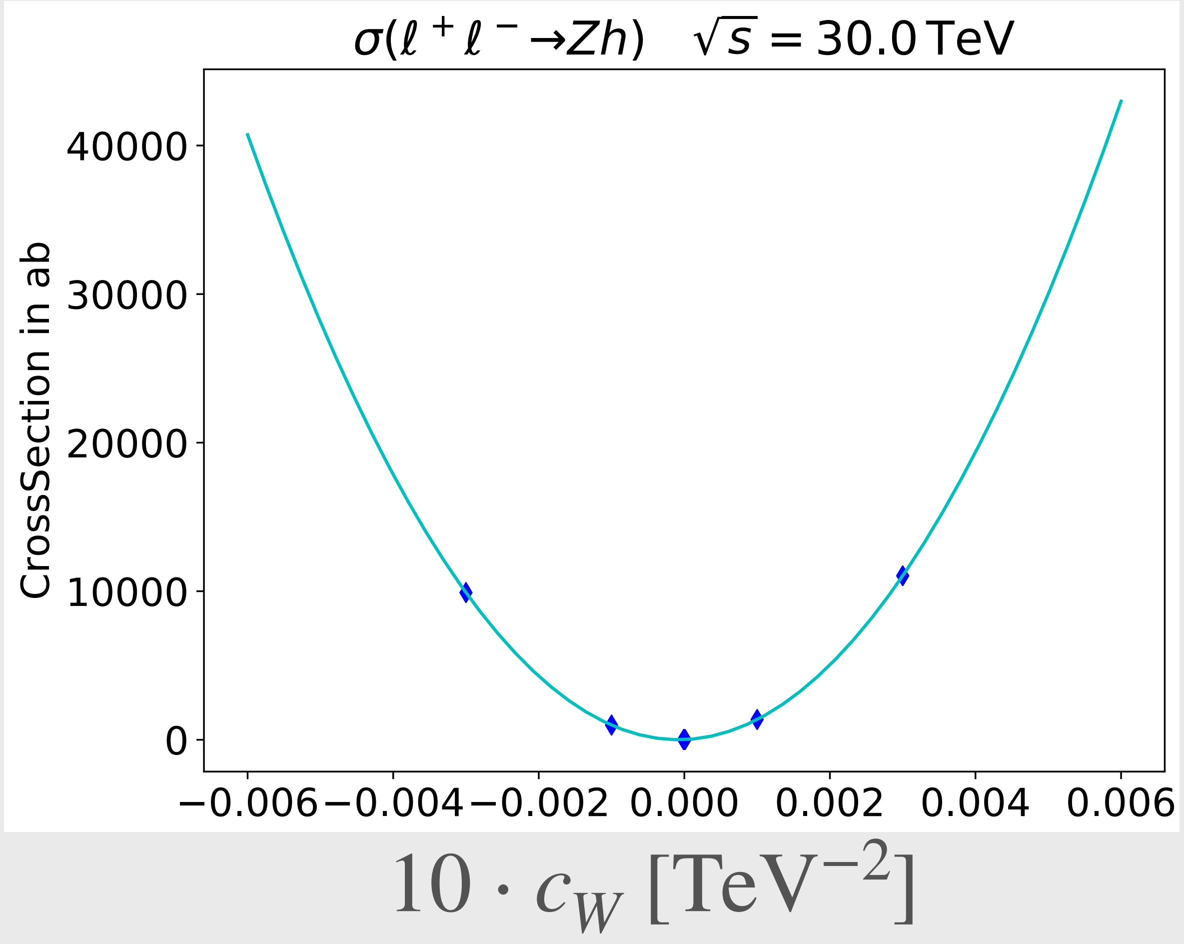
Buttazzo, RF, Wulzer

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

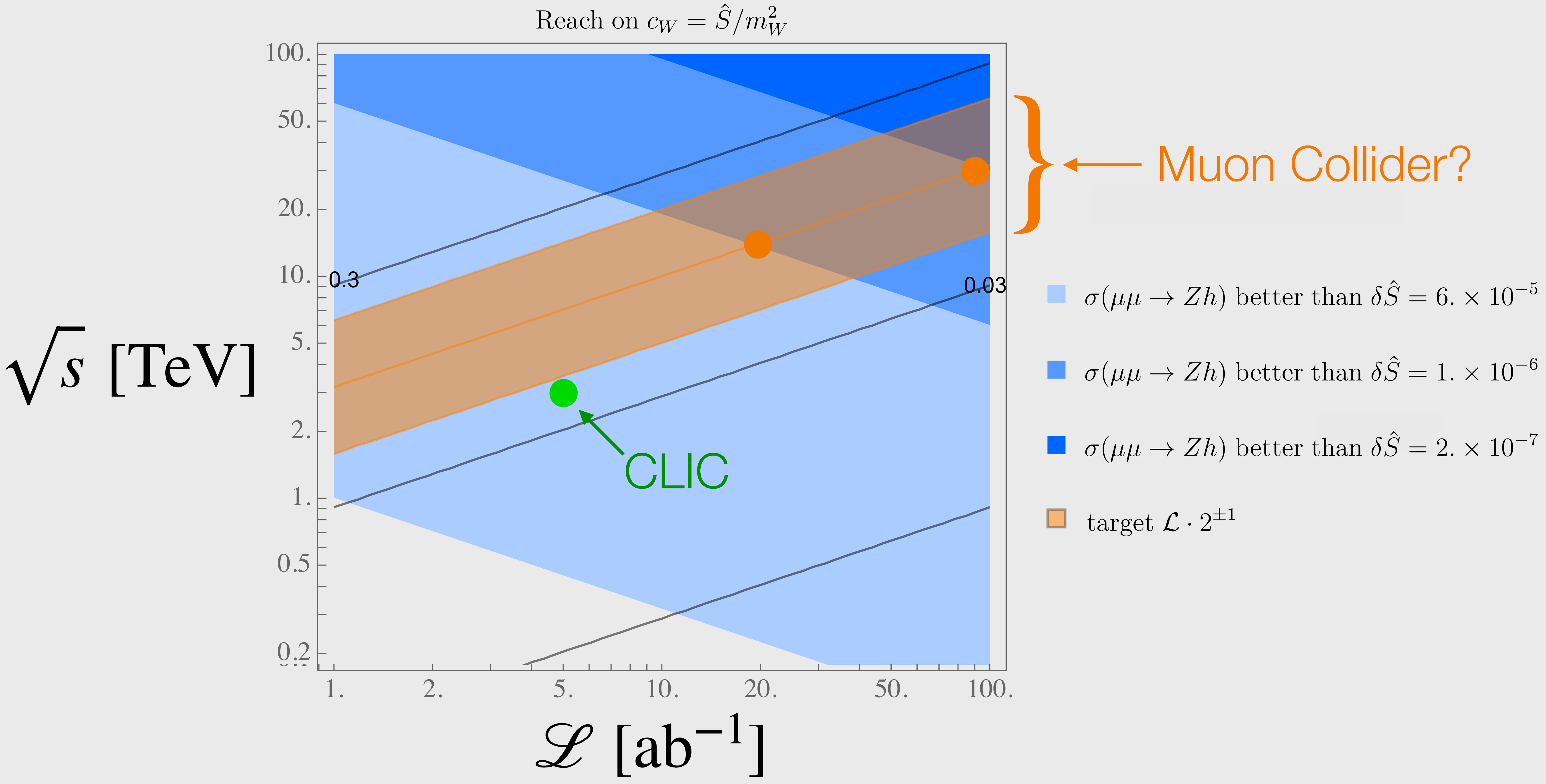
TOTAL RATE

$$\left|A_{SM}^{(00)}\right|^2 + A_{SM}^{00}\cdot A_{BSM}^{00} + \dots$$





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

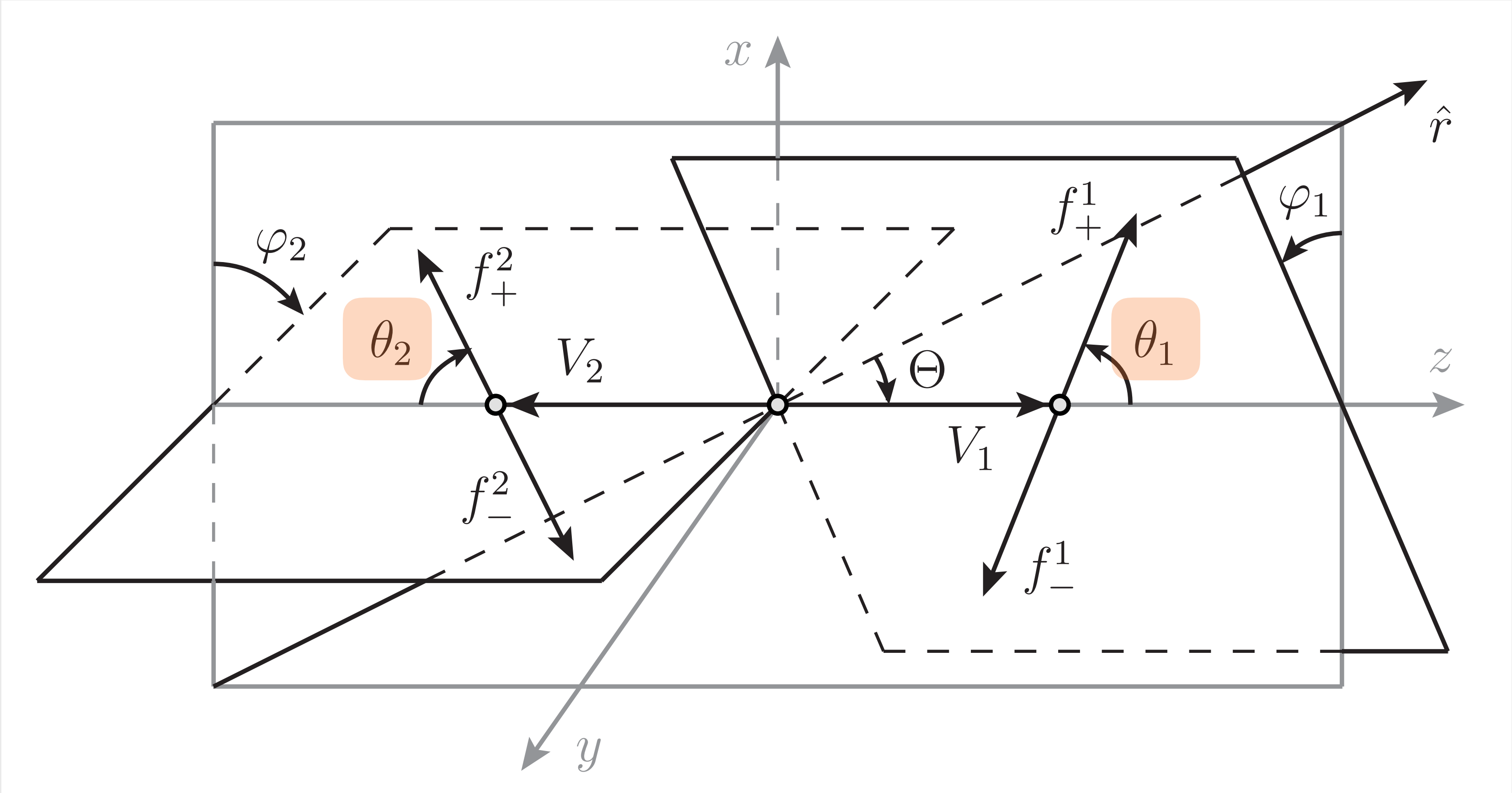
Roberto Franceschini LFC19 https://indico.ectstar.eu/event/55/

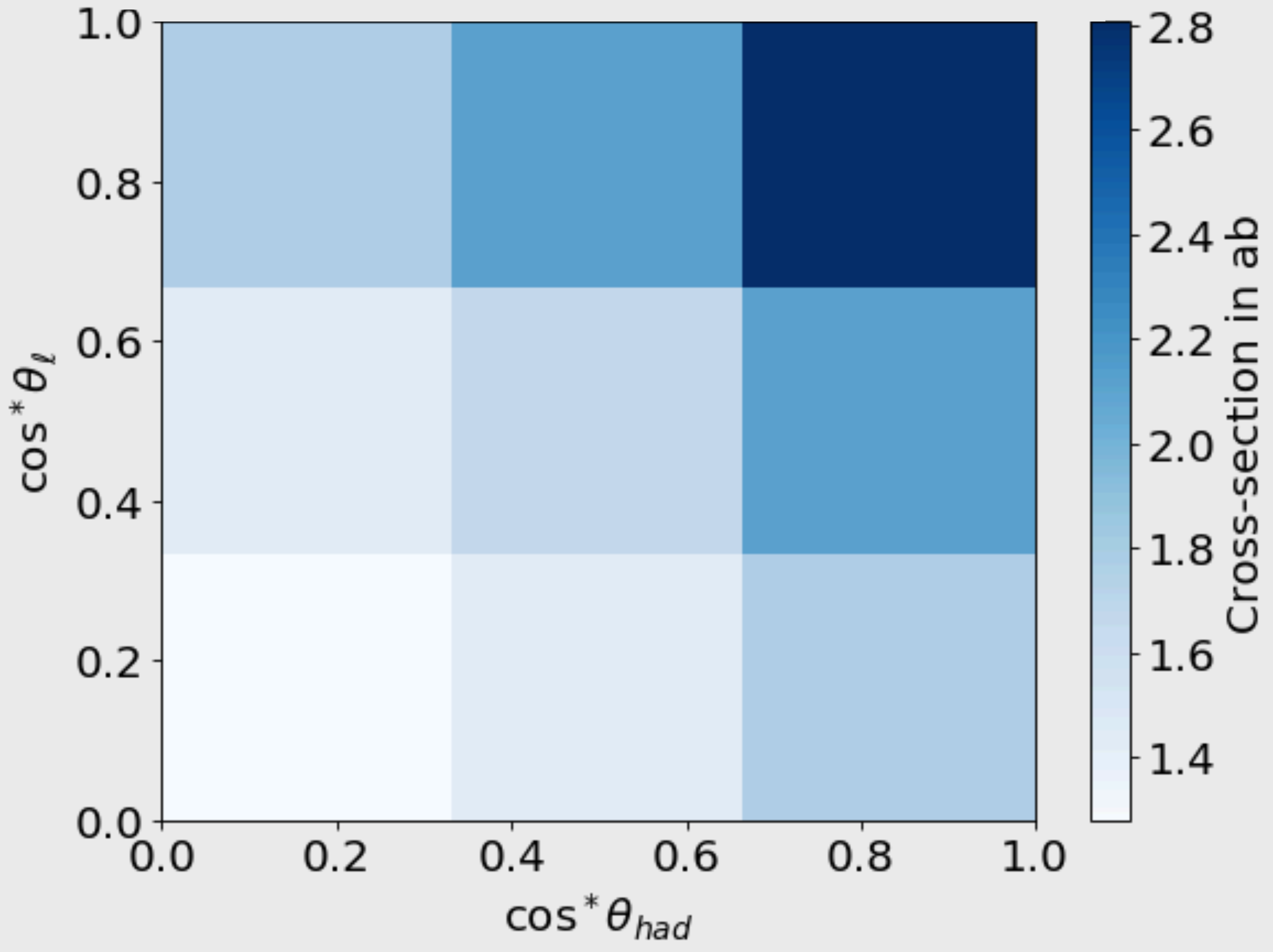
Buttazzo, RF, Wulzer

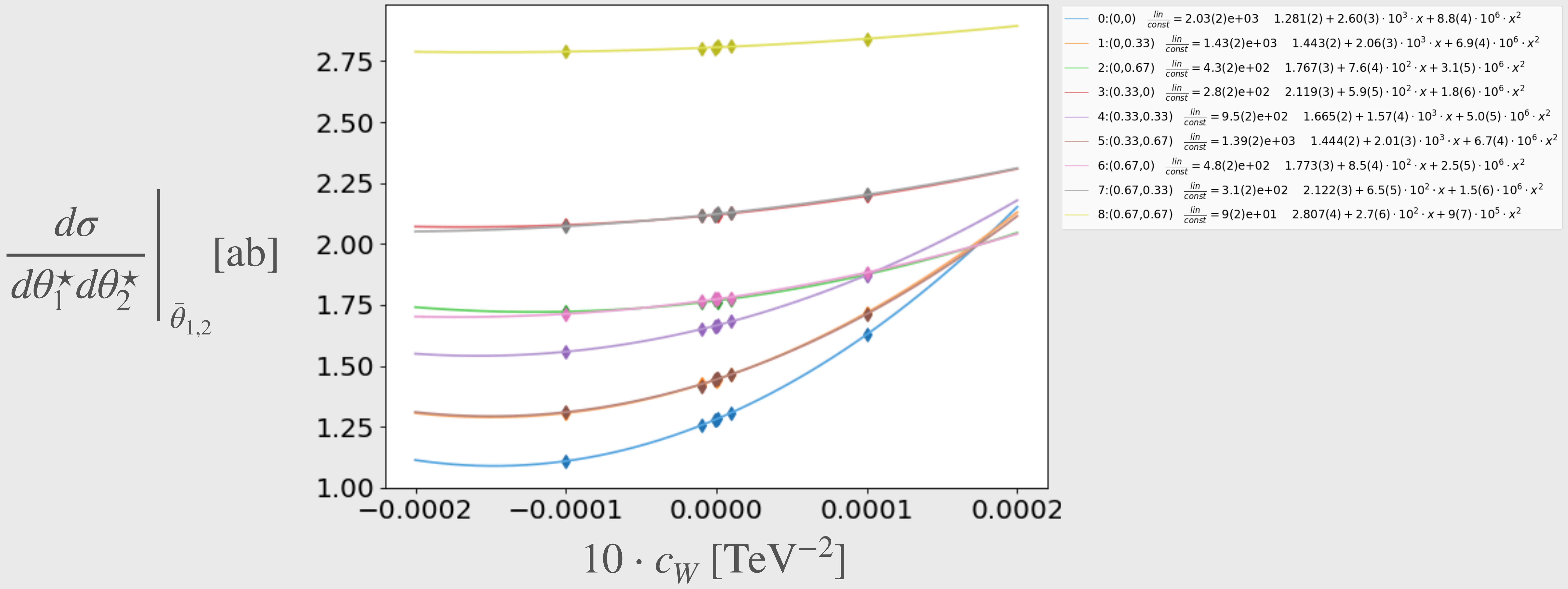
$\ell^+\ell^- \to \mathbf{W}^-\mathbf{W}^+$

POLAR ANGLE DISTRIBUTION

$$\left|A_{SM}^{(00)}\right|^2 + A_{SM}^{00}\cdot A_{BSM}^{00} + \ldots$$





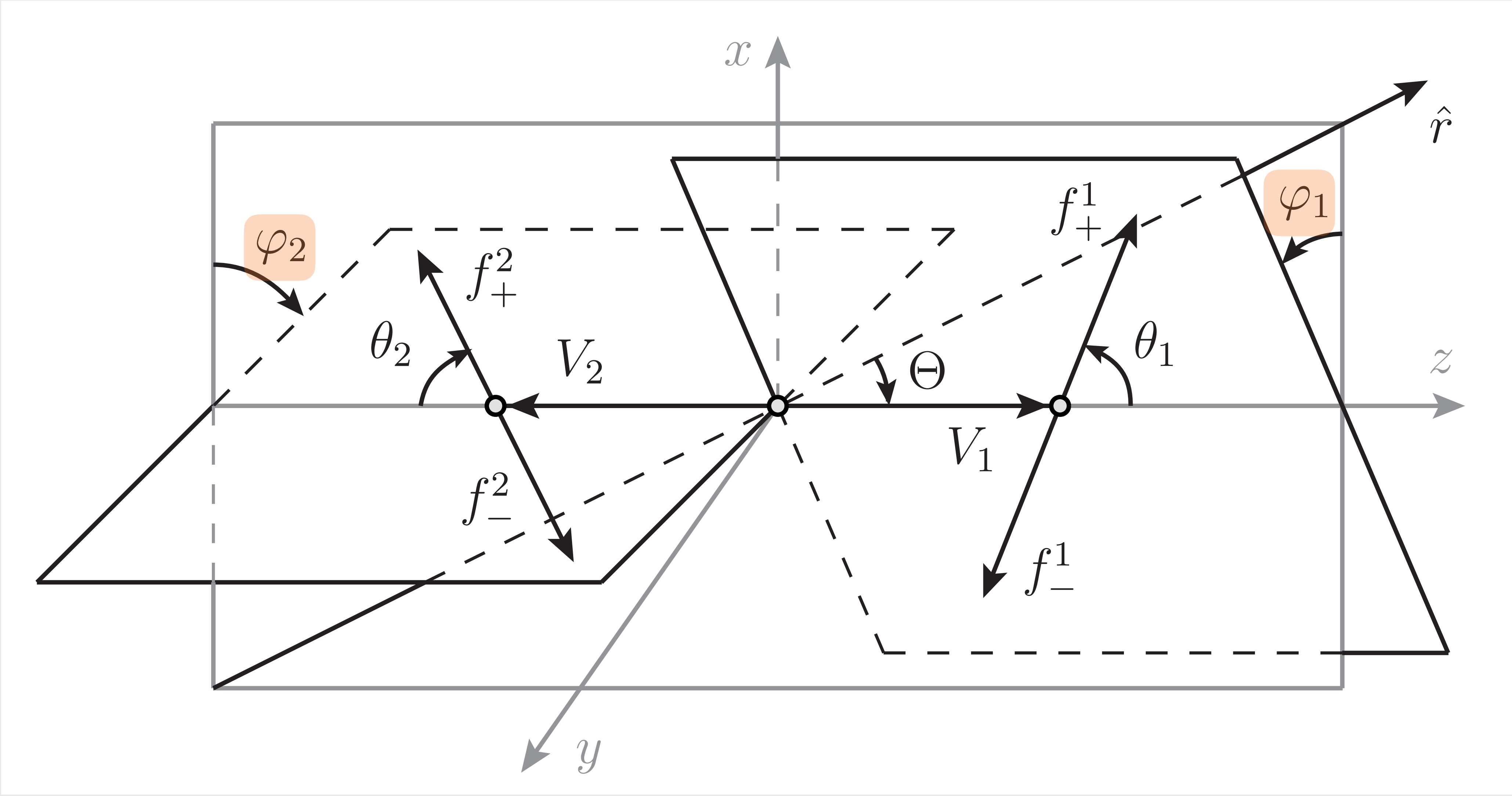


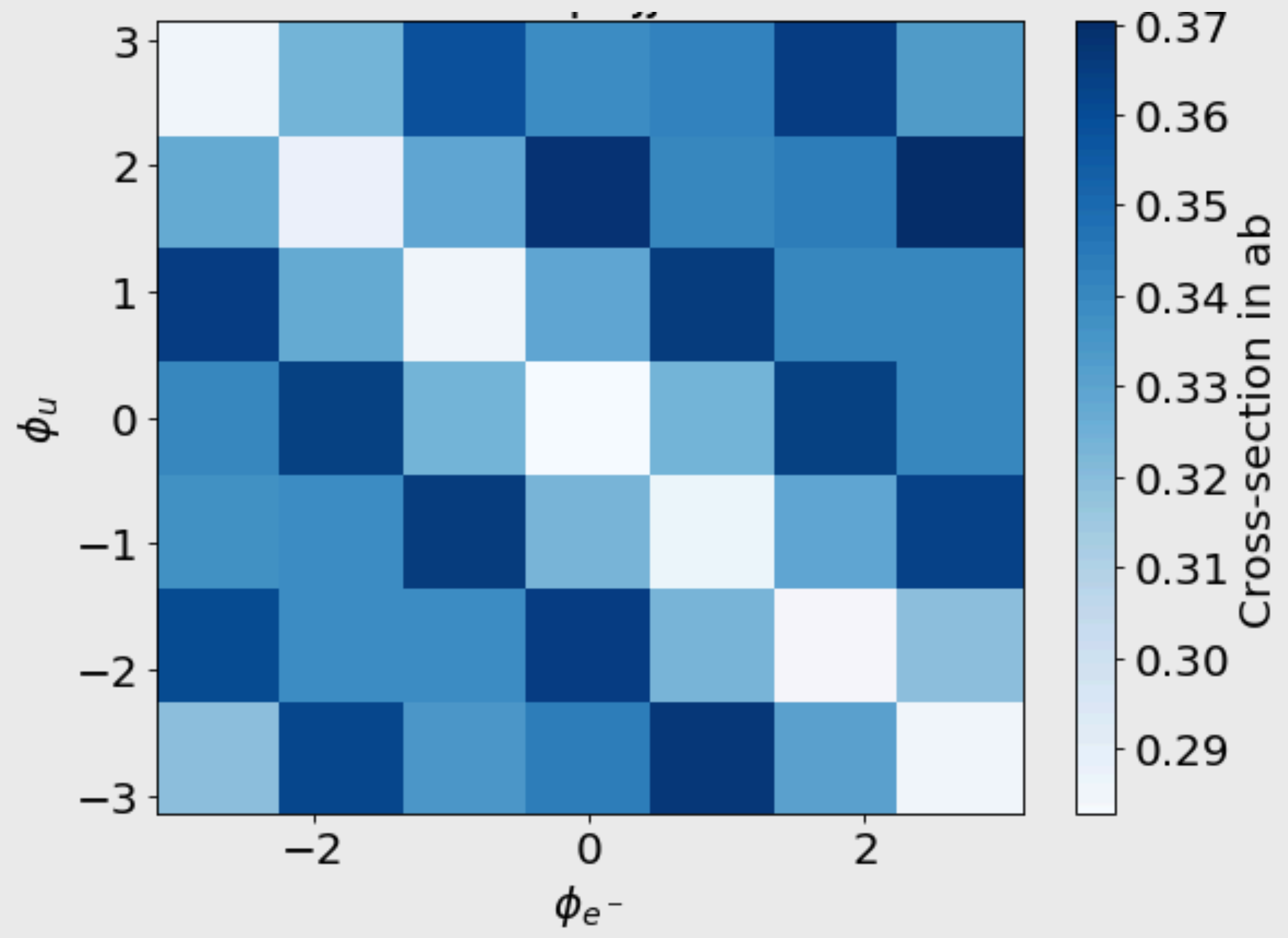
Buttazzo, RF, Wulzer

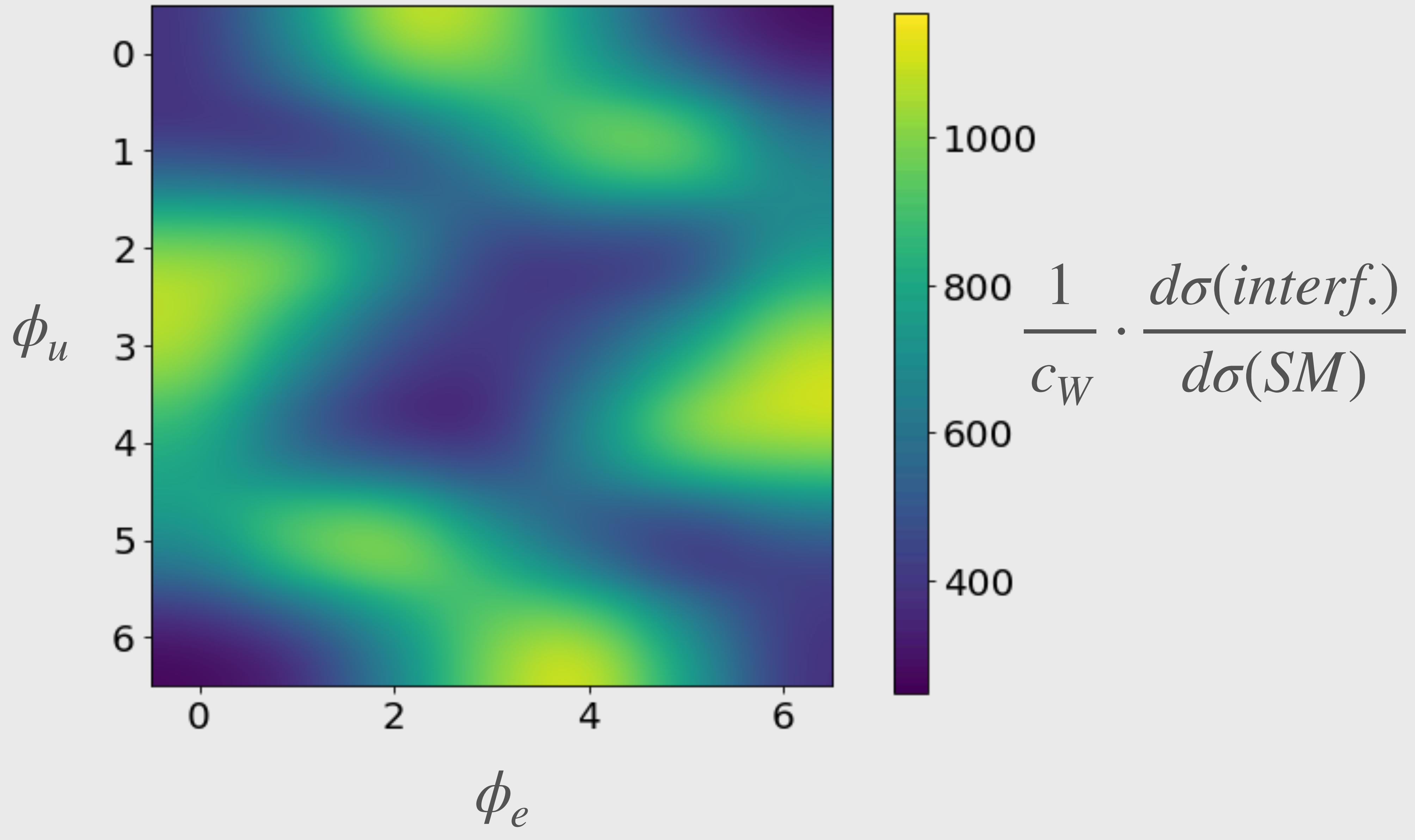
$\ell^+\ell^- \to W^-W^+$

AZIMUTHAL ANGLE DISTRIBUTION

$$\left|A_{SM}^{(TT)}\right|^2 + A_{SM}^{TT}\cdot A_{BSM}^{00} + \ldots$$





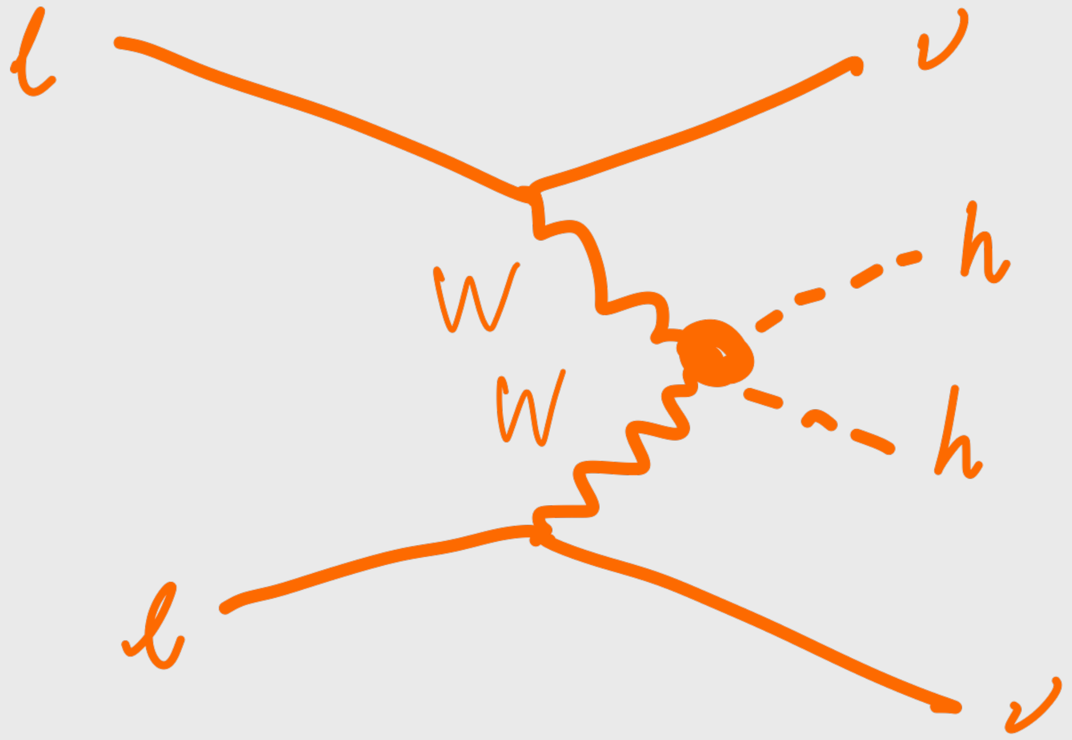


Buttazzo, RF, Wulzer

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

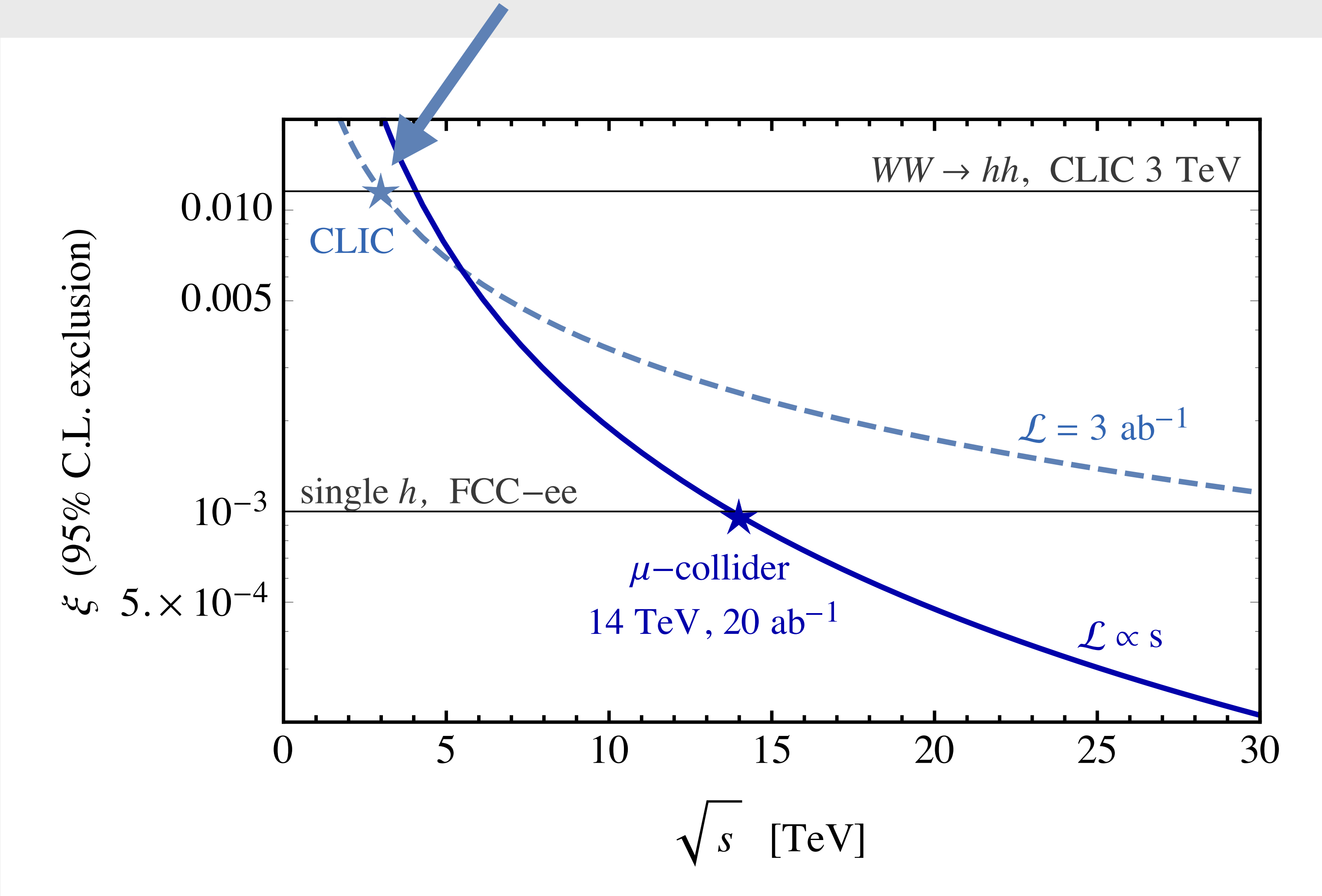
W BOSON **COLLIDER**

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. $\mathbf{O_H}$

1309.7038



need large p_T Higgs bosons

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

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

$$\downarrow$$

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

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

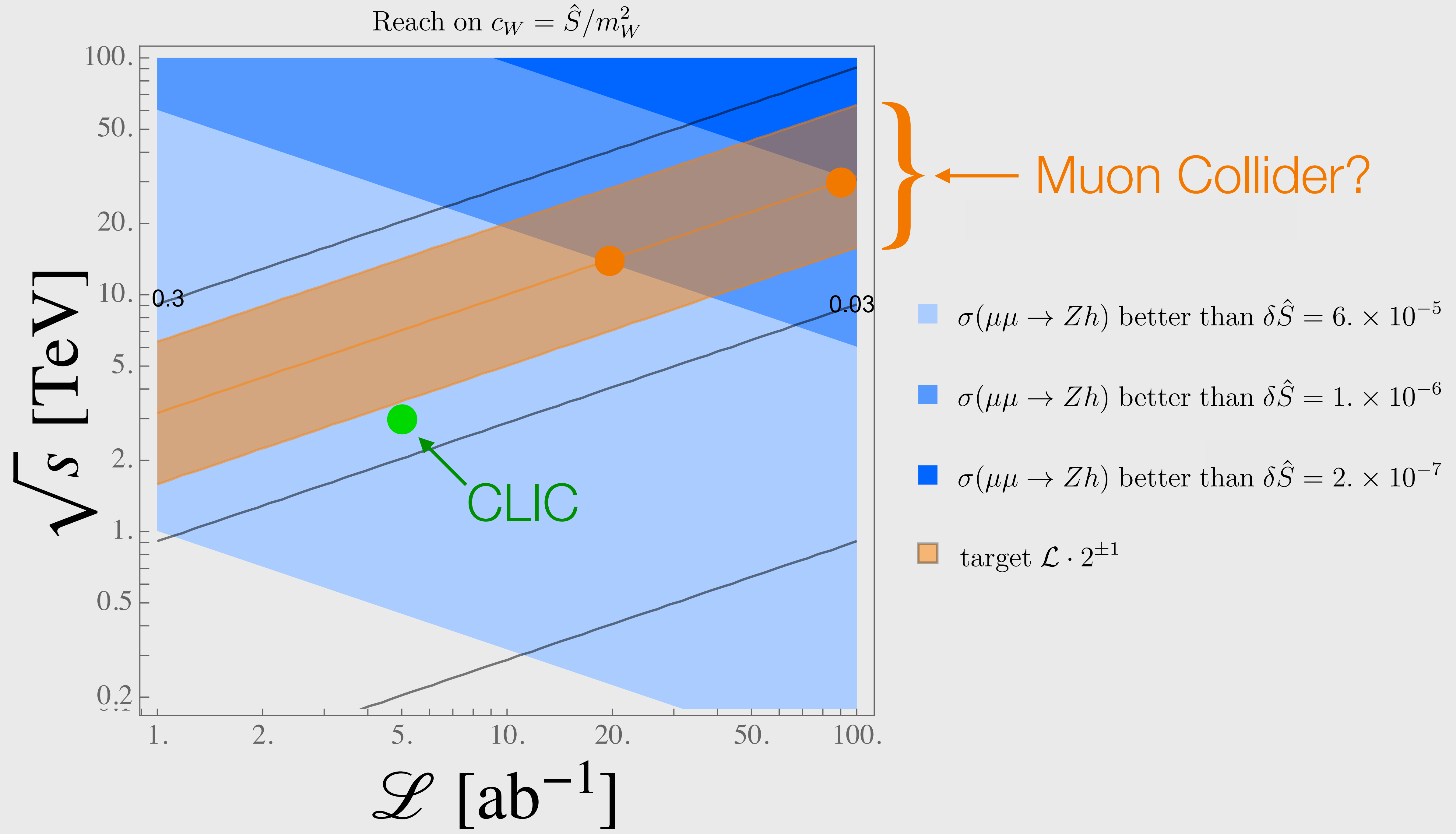
Buttazzo, RF, Wulzer

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

EFT EPOCH **LESSON FROM LHC**

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

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



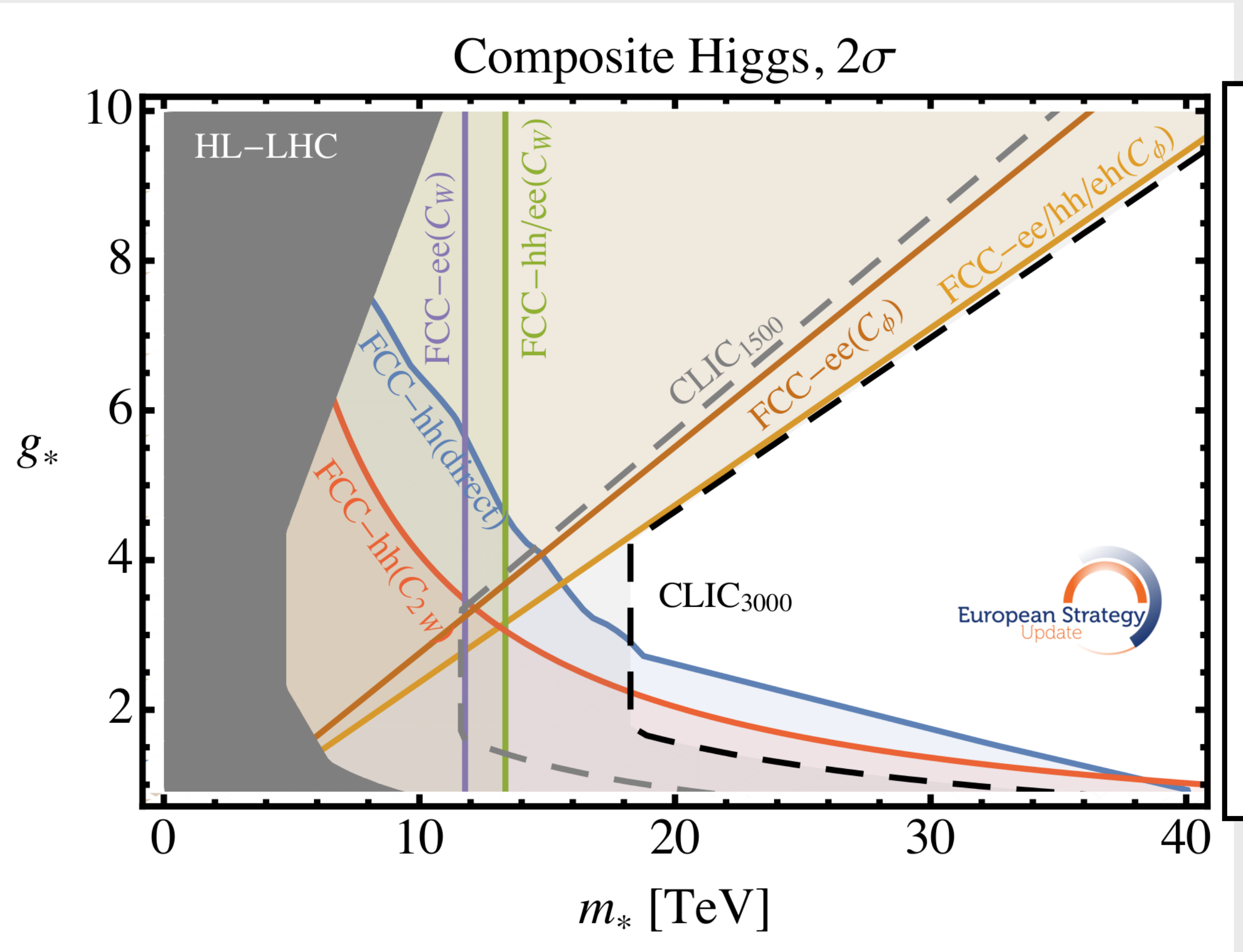
Order of magnitude improvement of the bunds on mass scale of new physics is possible

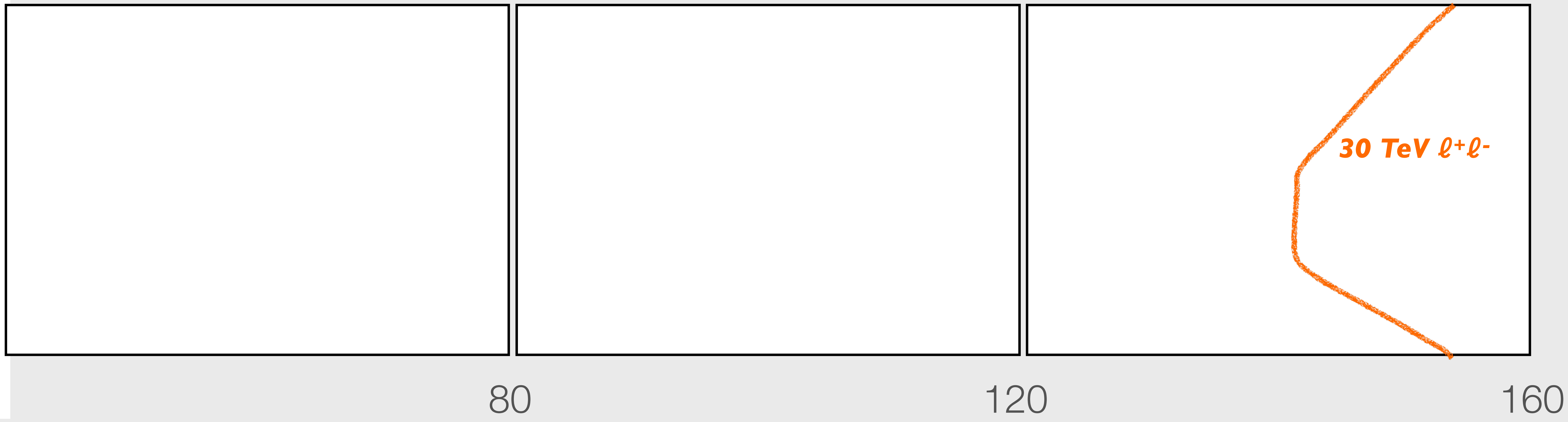
	Cross-Section @ 30 TeV	m* 95% CL	
HH	non trivial c&c analysis	60 TeV (g*/4)	$\mathcal{O}_H$
WW	pTW>7.5TeV: 180 ab	84 ⊕ 76 TeV ≃113 TeV	$a_q^{(3)}$
ZH	inclusive: 13 ab	120 TeV	$a_q^{(1)}$
ff	angular analysis	120 TeV (4/g*)	W,Y

All-round progress up to m* ~ 10^3 m_{Higgs}

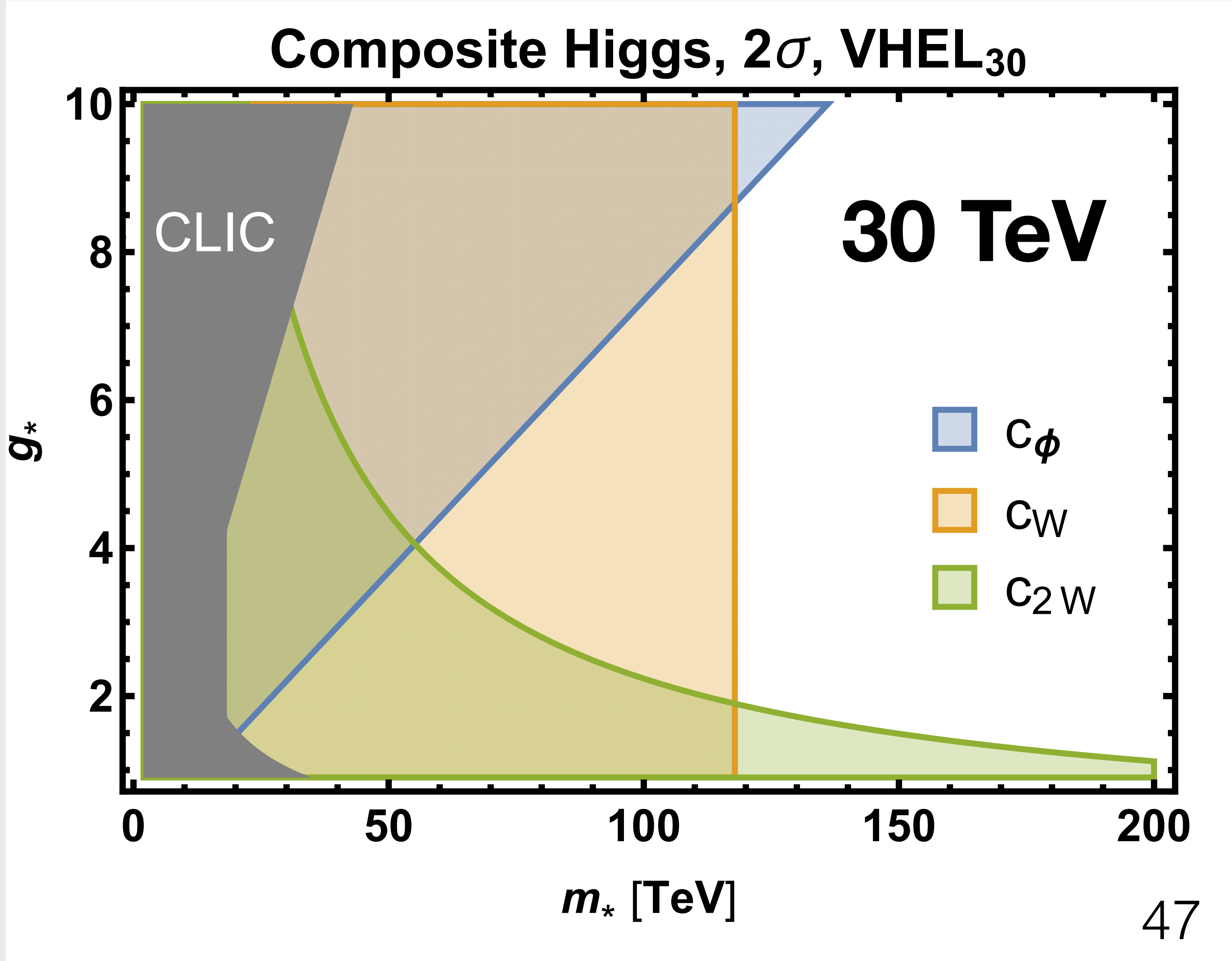
Looking ahead

https://indico.ectstar.eu/event/55/contributions/1354/

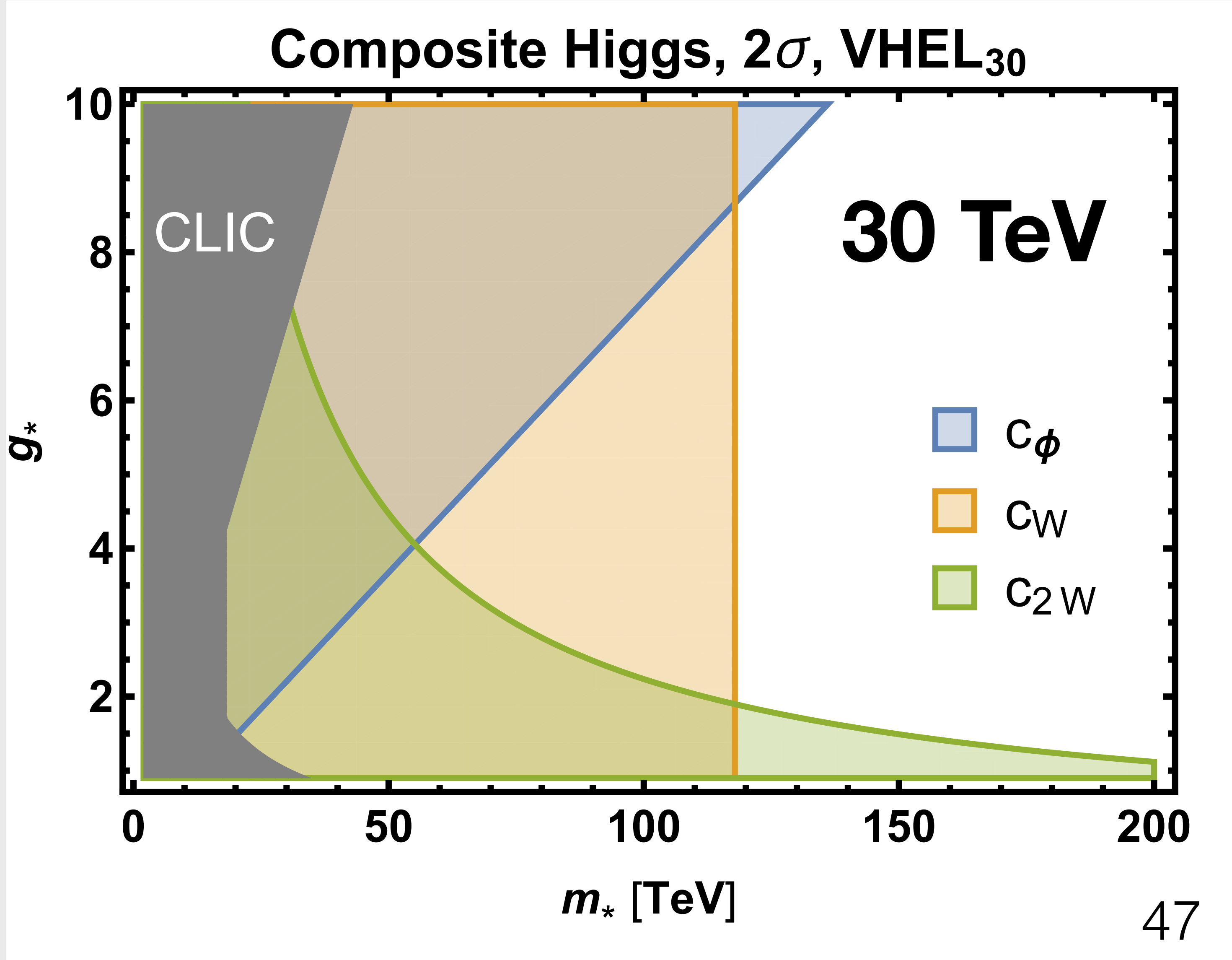


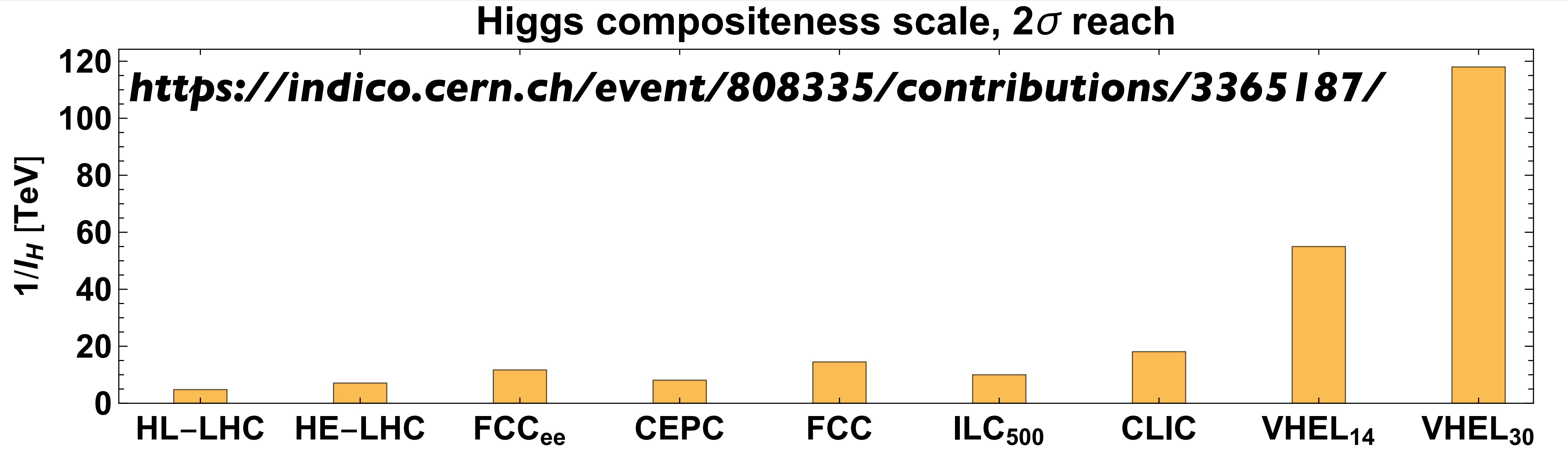


Looking ahead



Looking ahead



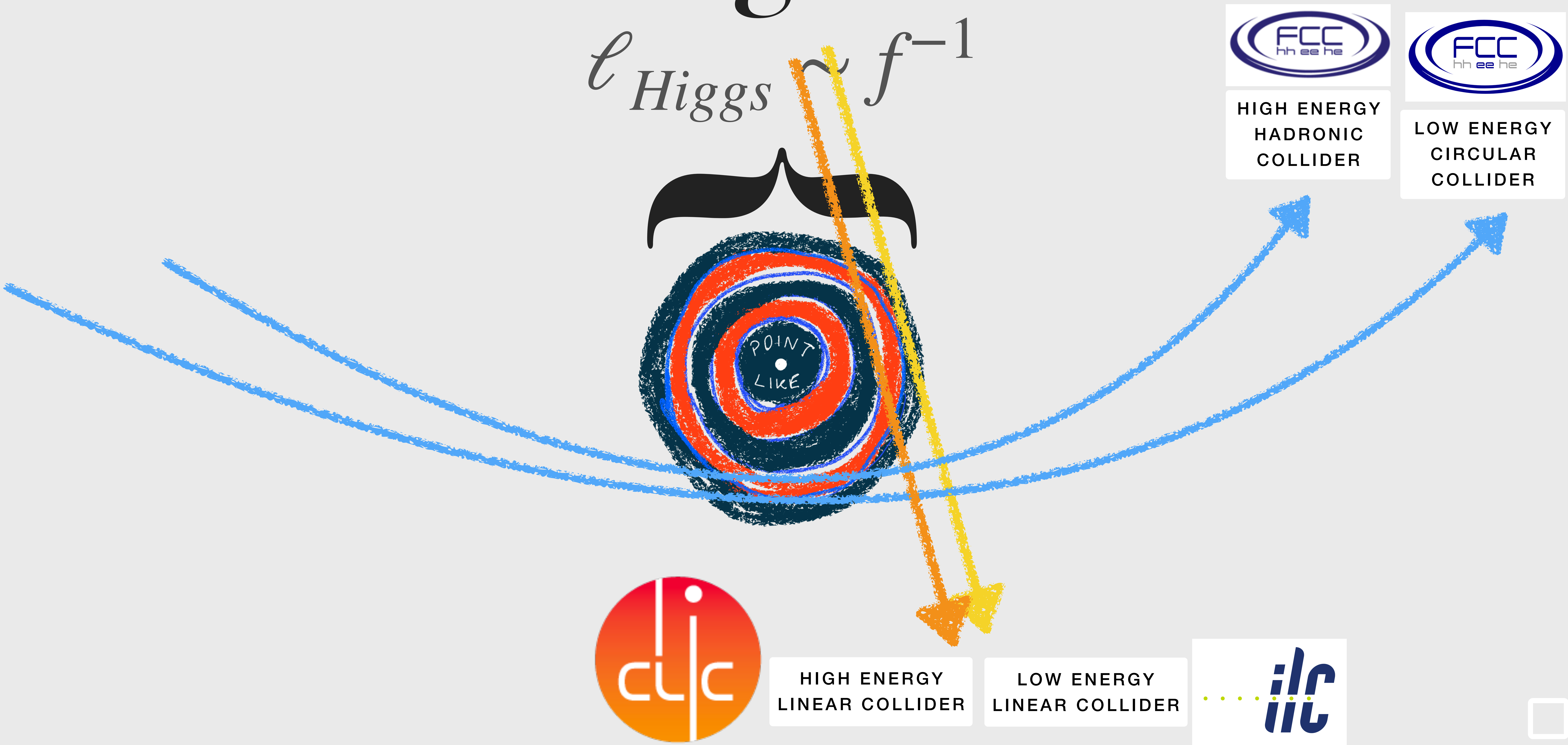


https://indico.cern.ch/event/808335/contributions/3365187/

Roberto Franceschini LFC19 https://indico.ectstar.eu/event/55/

Looking ahead

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



HIGH ENERGY HADRONIC COLLIDER

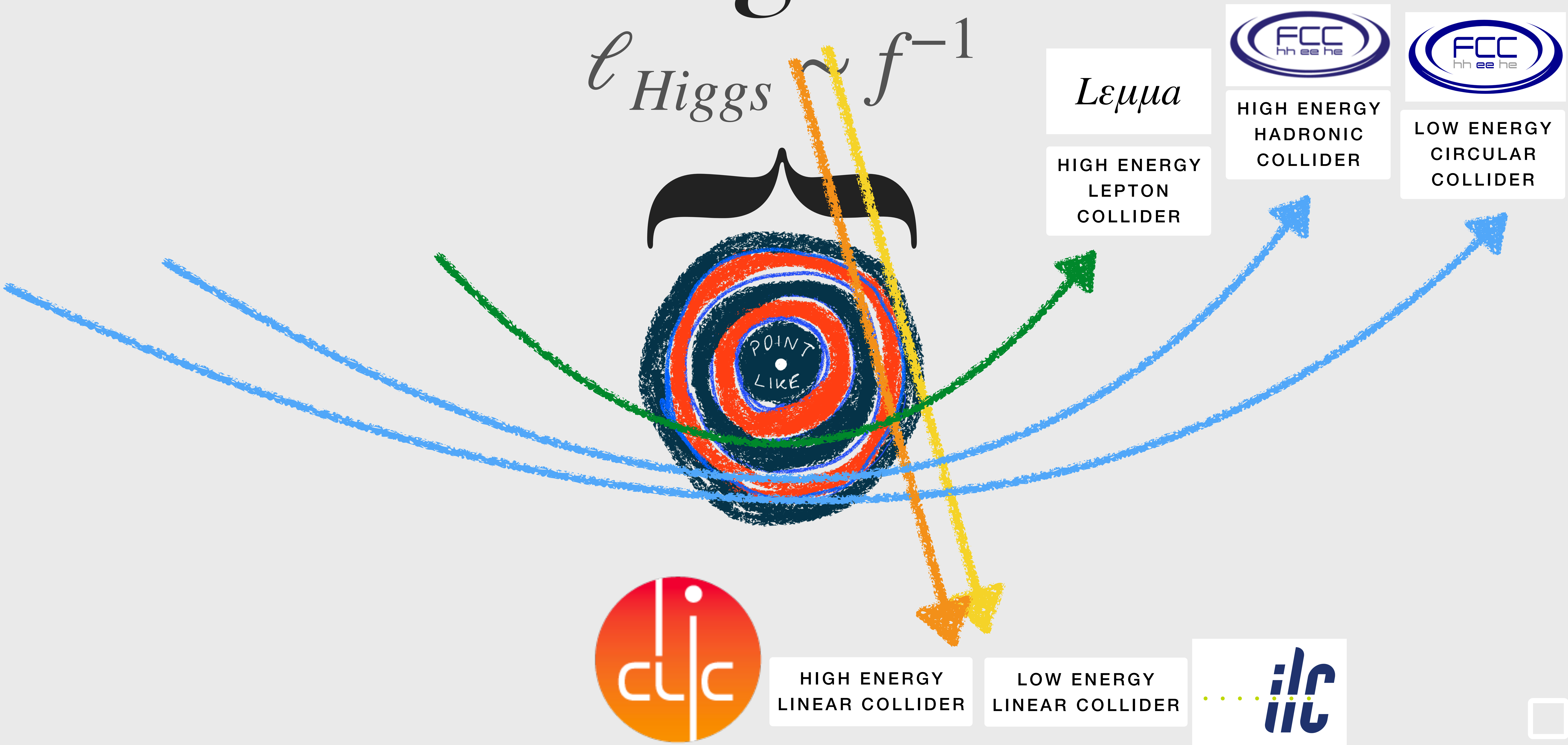
LOW ENERGY CIRCULAR COLLIDER

HIGH ENERGY LINEAR COLLIDER

LOW ENERGY LINEAR COLLIDER

Looking ahead

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



Lεμμα

HIGH ENERGY
LEPTON
COLLIDER

FCC hh ee he

HIGH ENERGY
HADRONIC
COLLIDER

FCC hh ee he

LOW ENERGY
CIRCULAR
COLLIDER

clic

HIGH ENERGY
LINEAR COLLIDER

LOW ENERGY
LINEAR COLLIDER

ilc

Top

Top quark production

ELECTRO-WEAK

HIGH AND LOW MOMENTUM TRANSFERRED

low momentum transfer

$\sqrt{s}$	$\sigma(\ell^+\ell^- \to t\bar{t})$	$\mathcal{L}$	$\sigma \cdot \mathcal{L}$	$\sqrt{s}$	$\sigma(\ell^+\ell^- \to \nu\nu t\bar{t})$	$\mathcal{L}$	$\sigma \cdot \mathcal{L}$
0.5 TeV	548 fb	4/ab	2.2M	0.5 TeV	0.23 fb	4/ab	0.9K
3 TeV	19 fb	2.5/ab	47K	3 TeV	5.4 fb	5/ab	27K
30 TeV	0.19 fb	90/ab	17K	30 TeV	31 fb	90/ab	2.7M

large momentum transfer

BOTH

- large number of top quarks for “pole precision” (e.g. mass, V_{tb}, rare decays, …)
- large enough number for “tail precision” (contact interactions)

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1 million top quarks

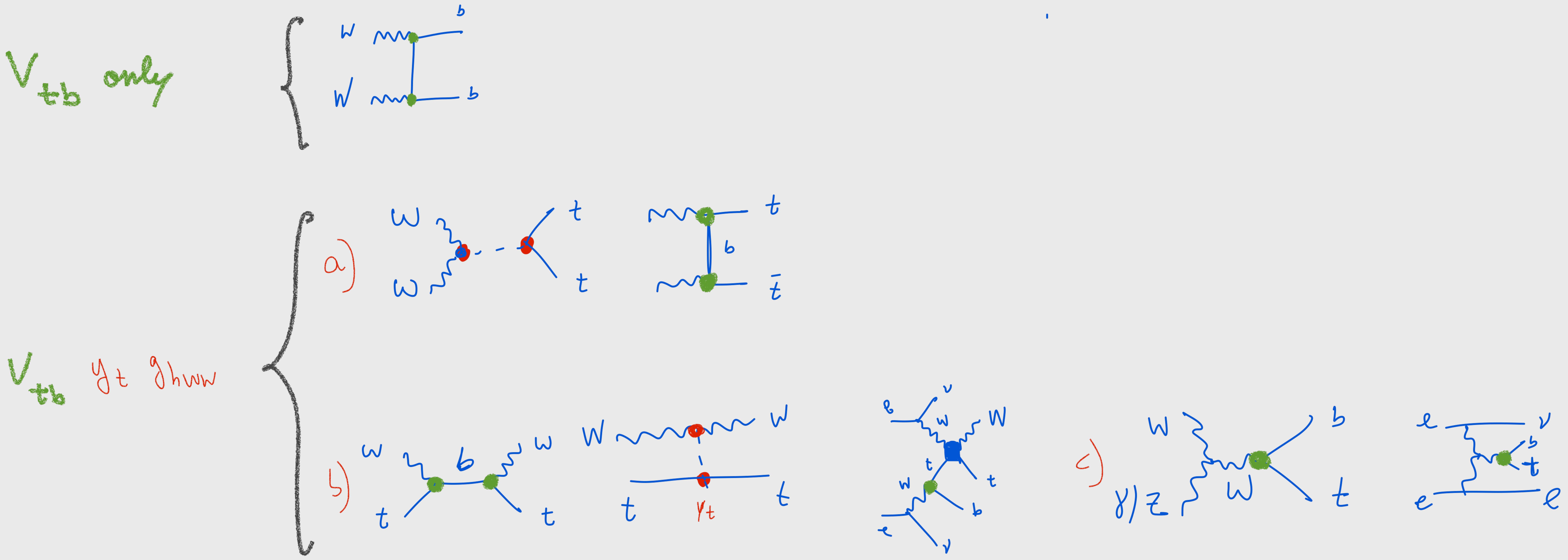
MEGA-TOP ILC-CLIC-FCC-LIKE TOP QUARK PROGRAM *e.g. 1807.02441, 1903.01629, CERN-ACC-2018-0056*

- top quark mass (off-threshold, reasonable target 100 MeV)
- rare production modes $\ell^+ \ell^- \to t\, c\, \nu\, \nu$
- rare decays e.g. $t \to H\, c$, $\phi\, c$, $\gamma\, c$
- contact interaction “intensity studies”

Each top is a “single top”

ELECTRO-WEAK PRODUCTION EVERYWHERE

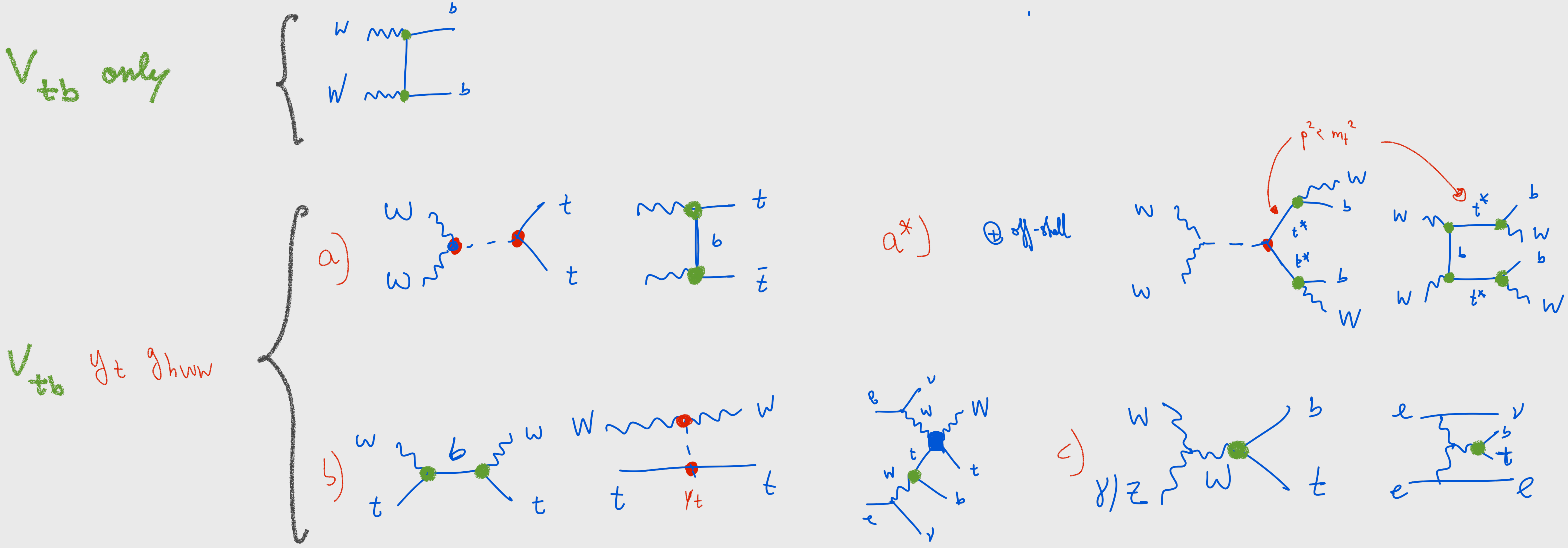
V_{tb} & g_{Ztt}, y_t, g_{hWW} intertwined in many processes



Each top is a “single top”

ELECTRO-WEAK **PRODUCTION EVERYWHERE**

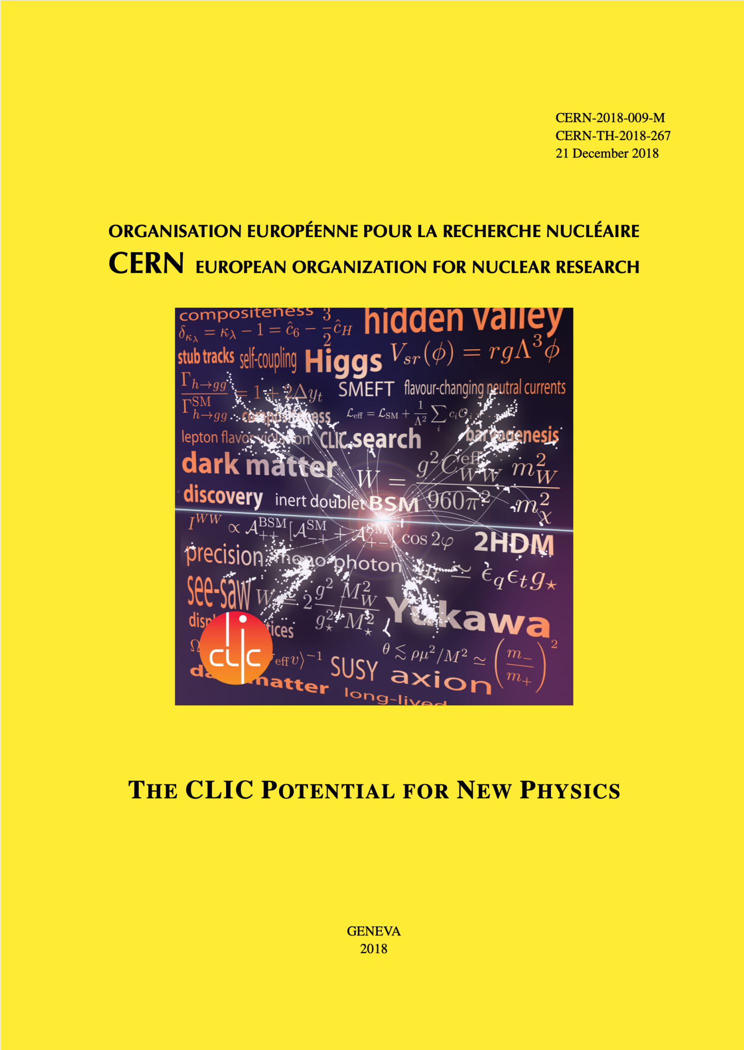
V_{tb} & g_{Ztt}, y_t, g_{hWW} intertwined in many processes



Direct

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

Lots of new studies!



CERN-2018-009-M
CERN-TH-2018-267
21 December 2018

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE CLIC POTENTIAL FOR NEW PHYSICS

GENEVA
2018

Contents

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

“Valence” Leptons

Buttazzo, RF, Wulzer

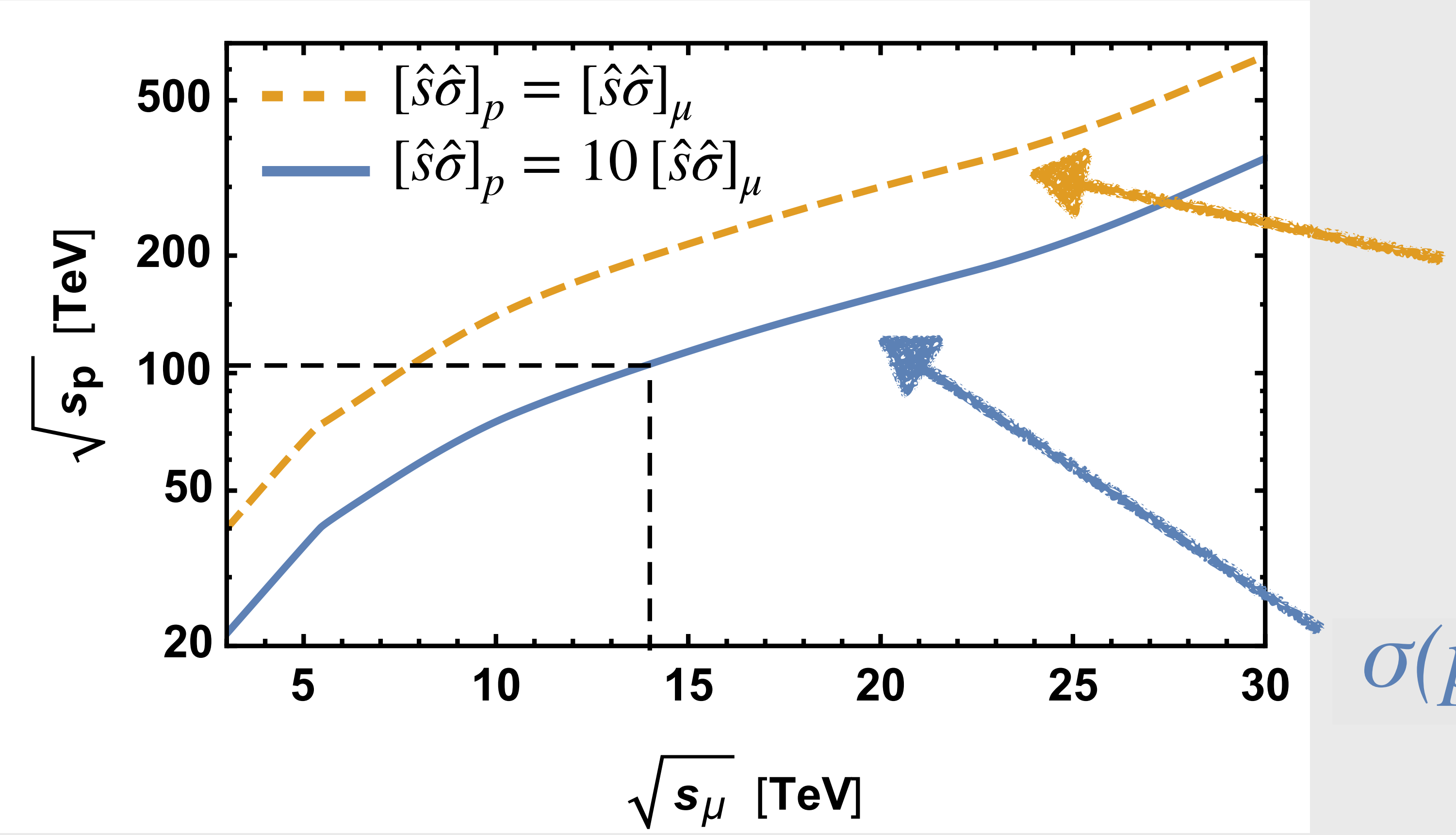
$\ell^+\ell^- \to$ new physics

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



$\sigma(pp)=\sigma(\mu\mu)$

$\sigma(pp)=0.1\sigma(\mu\mu)$

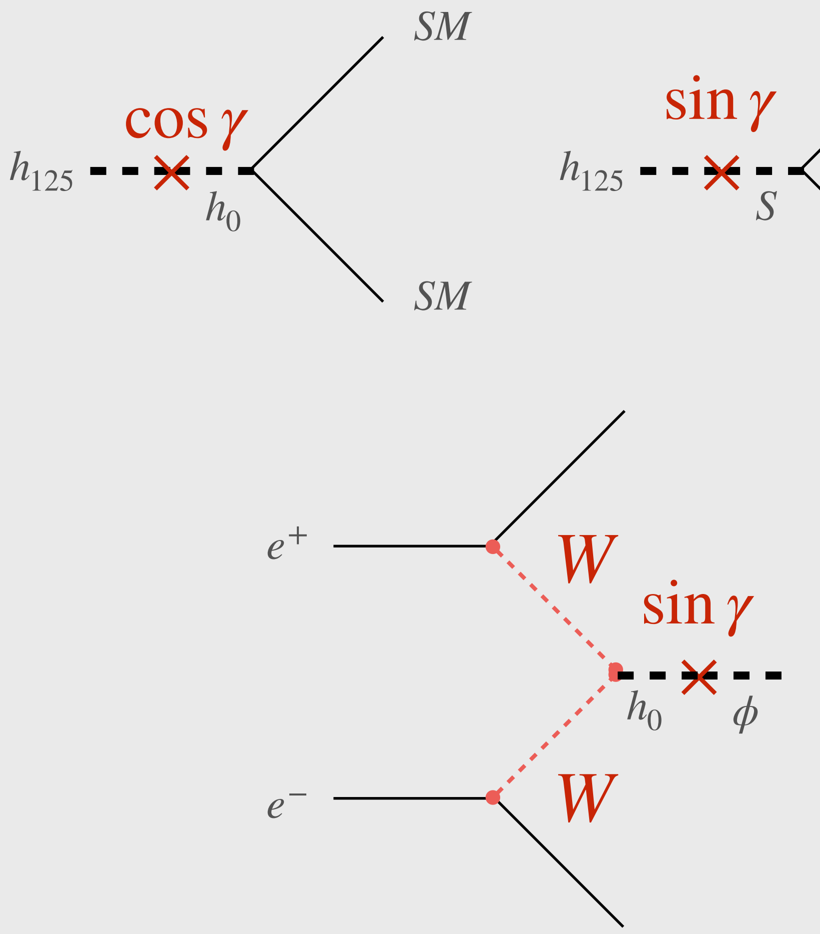
14 TeV μμ roughly equivalent to 100 TeV *pp*

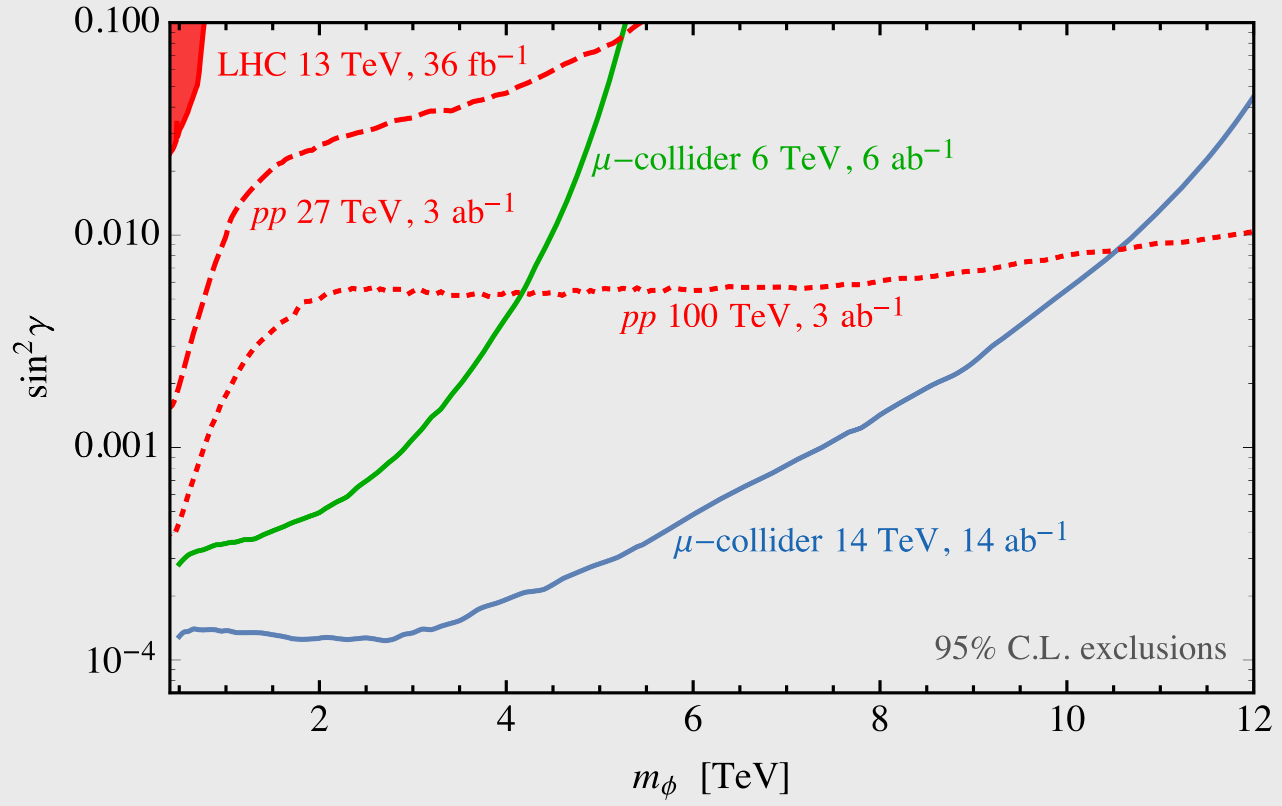
Reach on specific models

1807.04743 - Buttazzo, Redigolo, Sala, Tesi

Higgs + Heavy Singlet

MIXING VS. MASS | $e^+e^- \to \nu\nu\, S$ | $S \to h\, h \to 4b$

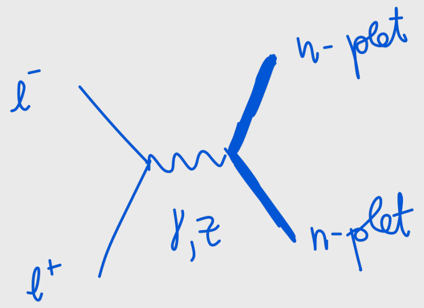




Degenerate EW multiplets

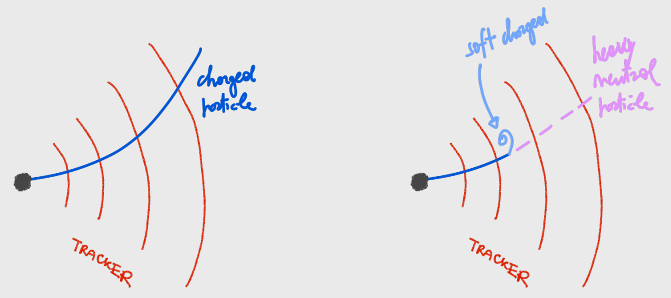
STUB-TRACKS | **EXTRAPOLATION FROM CLIC**

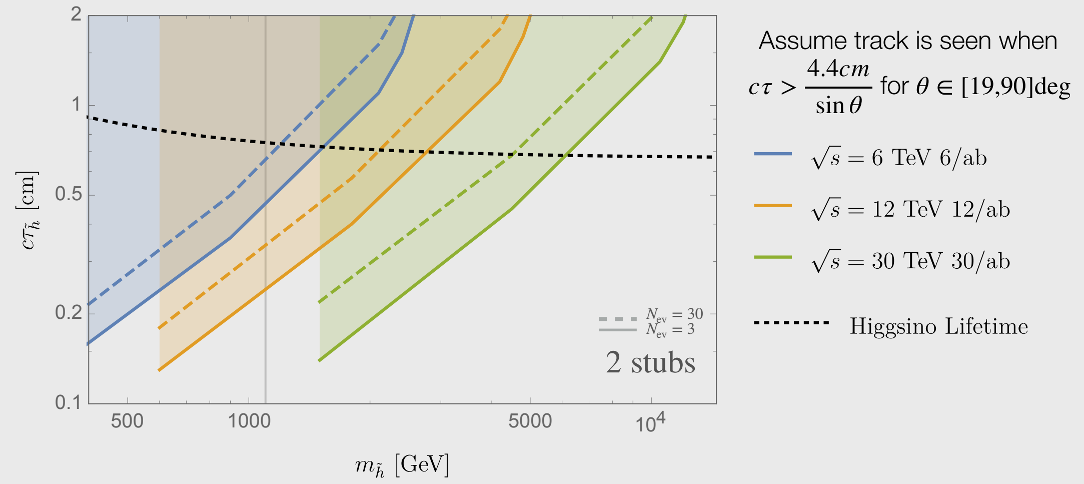
- Heavy n-plet of SU(2)
- Mass splitting ~ $\alpha_W\, m_W$ ~ 0.1 GeV - GeV



LARGE RATES, BUT NEEDS TO LIGHT UP THE DETECTOR IN A DISCERNIBLE WAY

- Heavily subject to detector design issues
- Even in CLIC needs full detector simulation



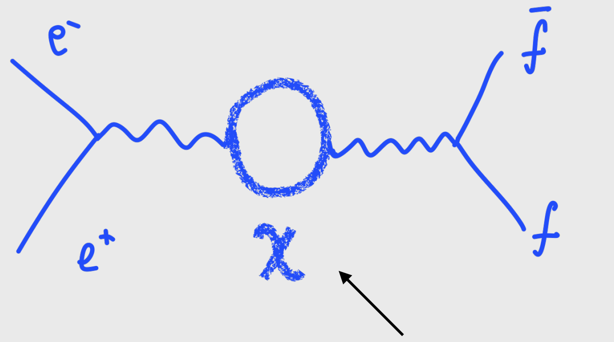


Assume track is seen when $c\tau > \frac{4.4cm}{\sin\theta}$ for $\theta \in [19,90]$deg

1810.10993 - Di Luzio, Grober, Panico

“Accidental” Dark Matter

PRECISION | **ANGULAR DISTRIBUTION**



χ is heavy/light new physics

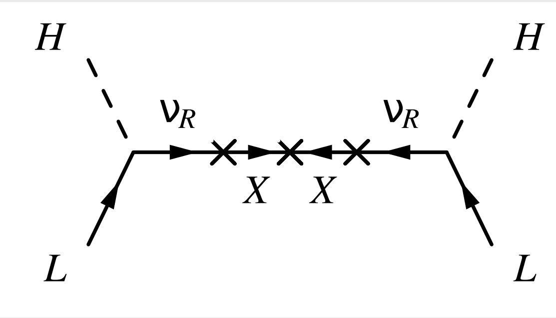
χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\rm DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\rm CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\rm DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\rm MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\rm CS}$	6.6	0.2	0.4	1.0	0.5 & [0.7,1.6]	1.6
$(1,5,\epsilon)_{\rm DF}$	6.6	1.5	2.8	7.1	3.9	11
$(1,5,0)_{\rm MF}$	14	0.9	1.8	4.4	2.9	3.5 & [5.1, 8.7]
$(1,7,\epsilon)_{\rm CS}$	16	0.6	1.3	3.2	2.4	2.5 & [3.5, 7.4]
$(1,7,\epsilon)_{\rm DF}$	16	2.1	4.0	11	6.4	18

1712.07621 - Baglio, Pascoli, Weiland

Mediator of Neutrino mass mechanism

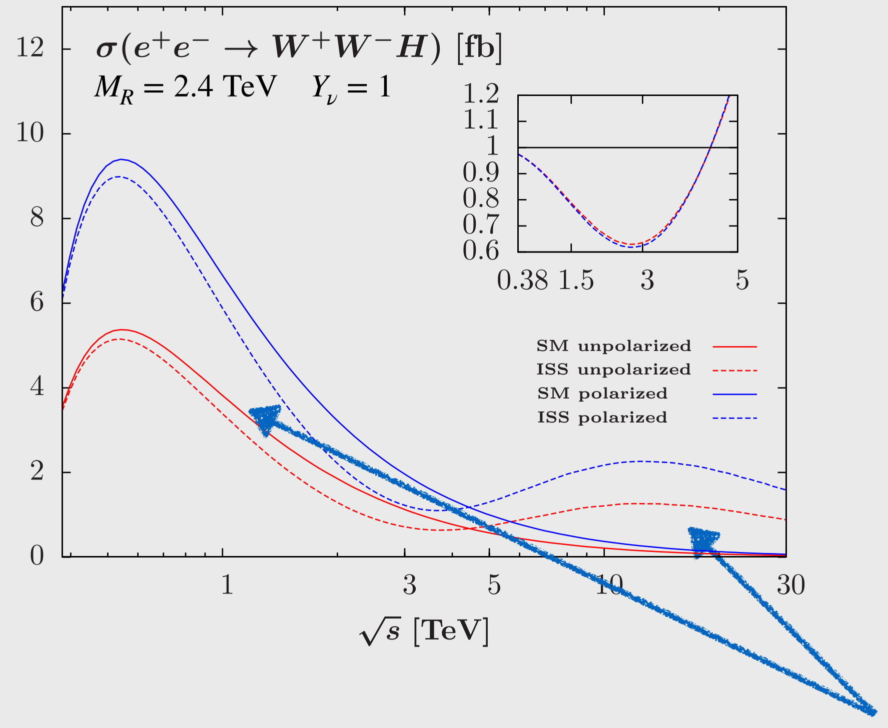
RIGHT-HANDED NEUTRINO | in total rate $e^+e^- \to W^+ W^- h$

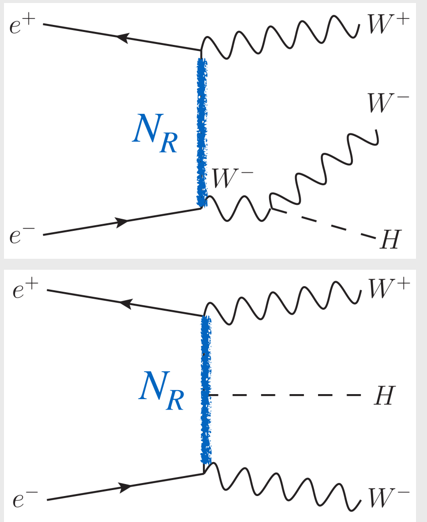
$$\mathcal{L}_{inverse} = -Y_\nu \bar{L}\tilde{\phi}\nu_R - M_R \overline{\nu_R^c} X - \frac{1}{2}\mu_X \overline{X^c} X + \text{h.c.}$$



$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$

$$m_\nu \approx \frac{m_D^2}{M_R^2}\mu_X$$





large deviations both at $\sqrt{s} \sim M_R$ and $\sqrt{s} > M_R$

Conclusions

About to flip page…

- The traditional paradigm where *pp* are discovery machines and $\ell^+\ell^-$ are measurement machines may be close to break down.
- Leptons beam structure enables *qualitatively new investigations* of the electroweak/Higgs sector
- CLIC definitively shows that technology is mature to consider seriously a machine above TeV center-of-mass energy
- If muon beams or plasmas can deliver even larger *energy and* keep the *luminosity* on track with $\mathscr{L} \propto E_{com}^2$ we can start probing fundamental interactions in novel and deeper ways.

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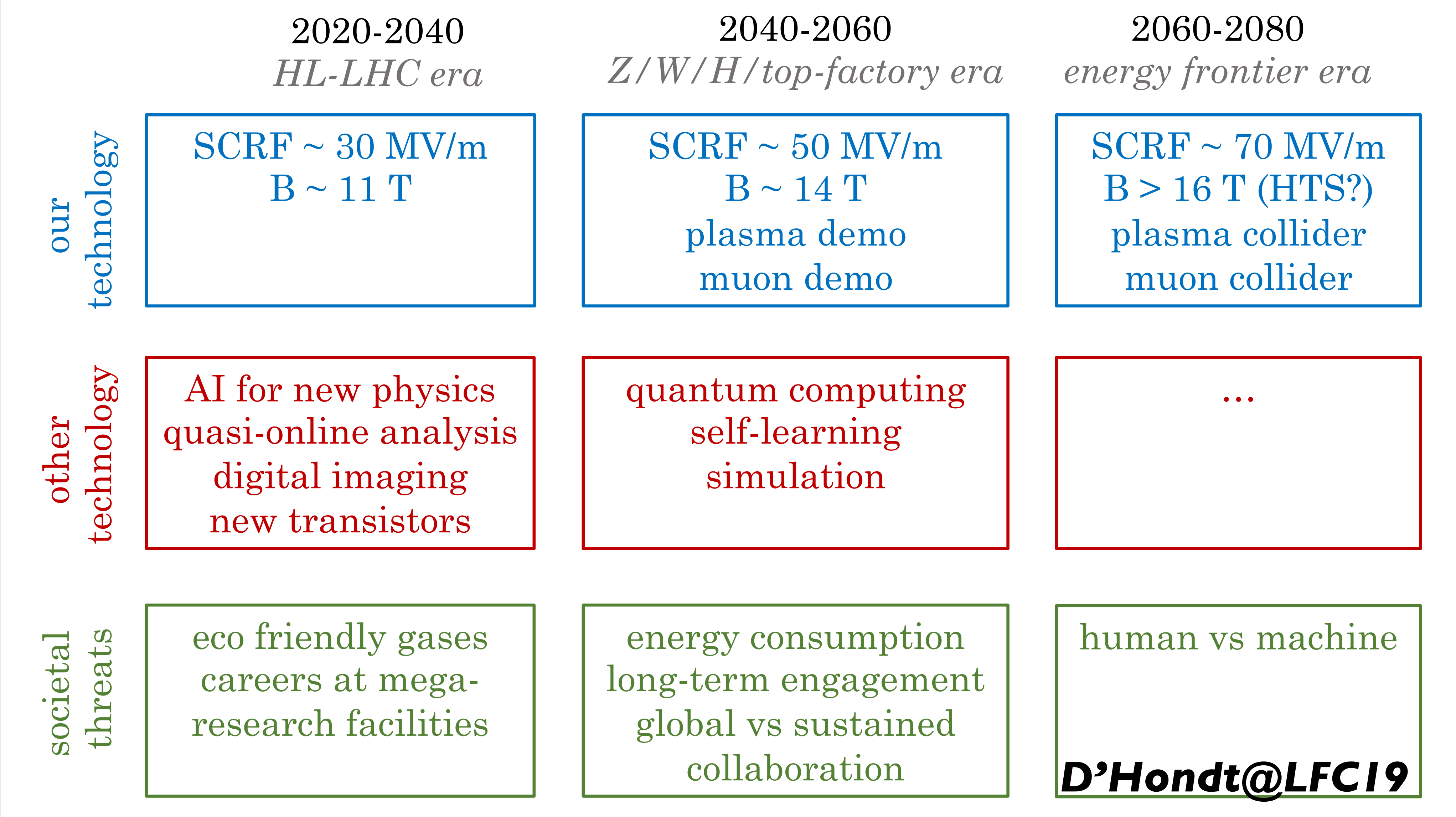
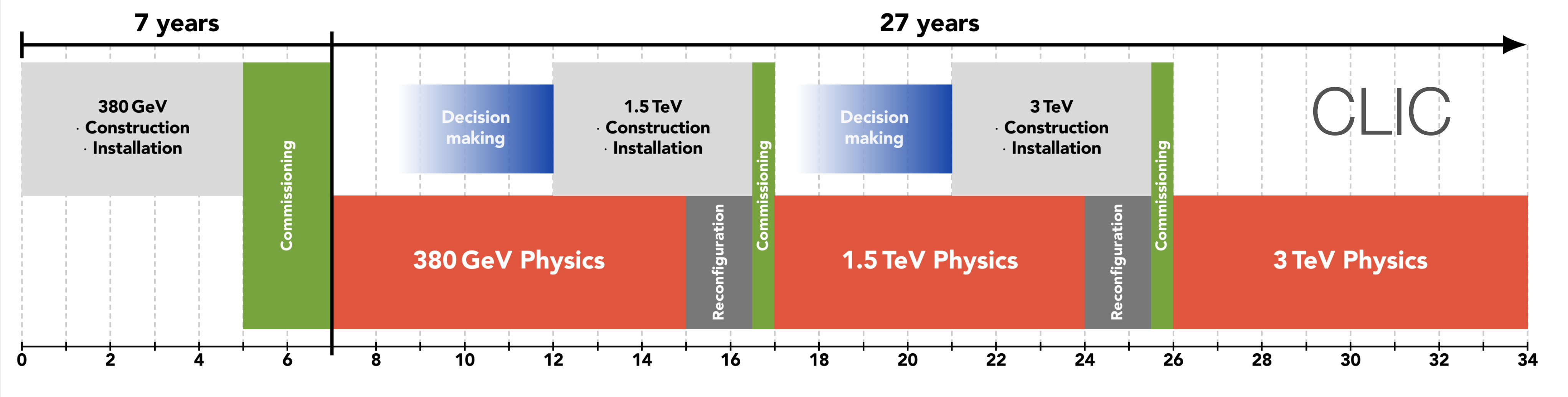
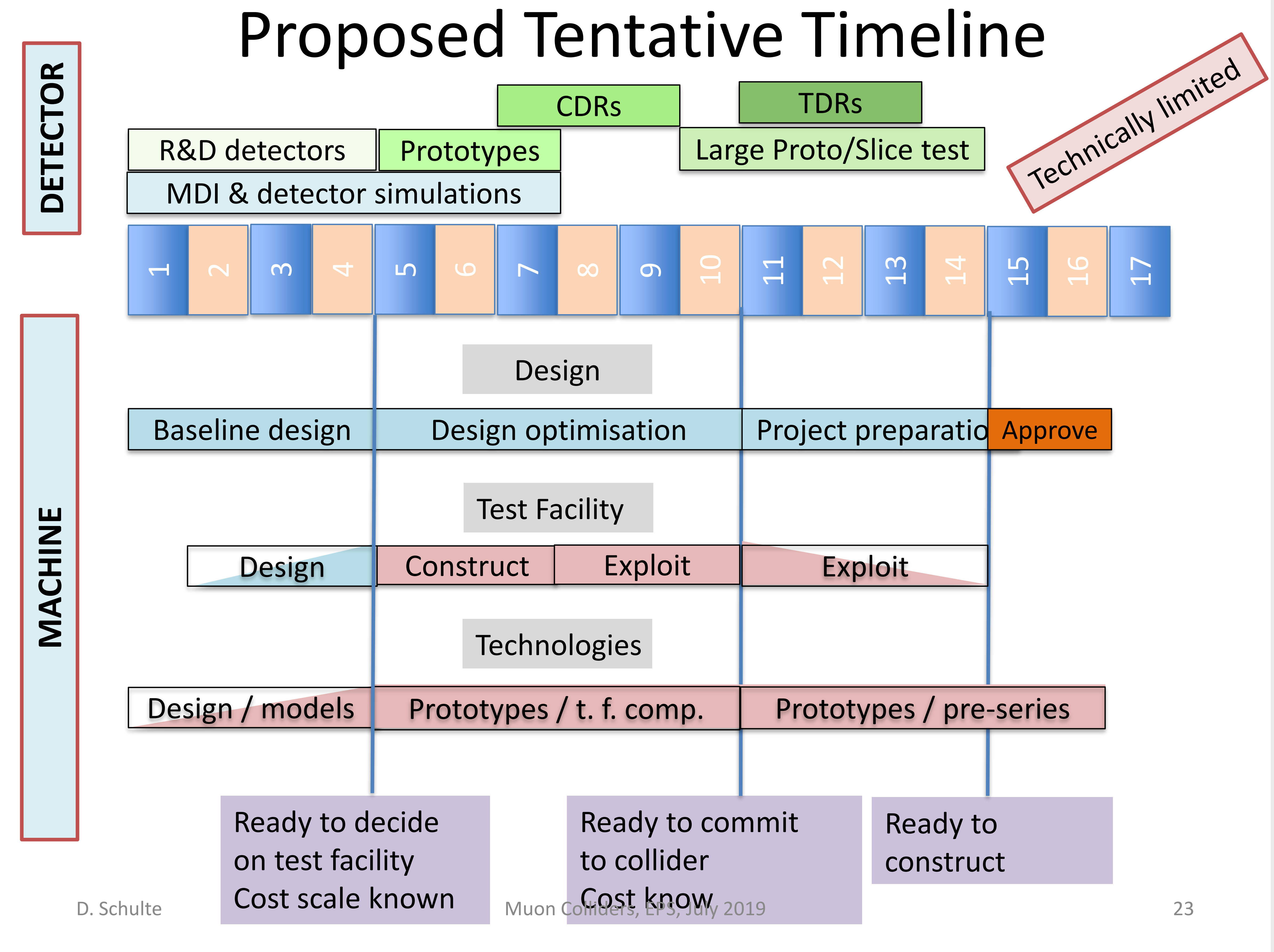
About to flip page…



	2020-2040 *HL-LHC era*	2040-2060 *Z/W/H/top-factory era*	2060-2080 *energy frontier era*
our technology	SCRF ~ 30 MV/m B ~ 11 T	SCRF ~ 50 MV/m B ~ 14 T plasma demo muon demo	SCRF ~ 70 MV/m B > 16 T (HTS?) plasma collider muon collider
other technology	AI for new physics quasi-online analysis digital imaging new transistors	quantum computing self-learning simulation	…
societal threats	eco friendly gases careers at mega-research facilities	energy consumption long-term engagement global vs sustained collaboration	human vs machine

D'Hondt@LFC19





Proposed Tentative Timeline

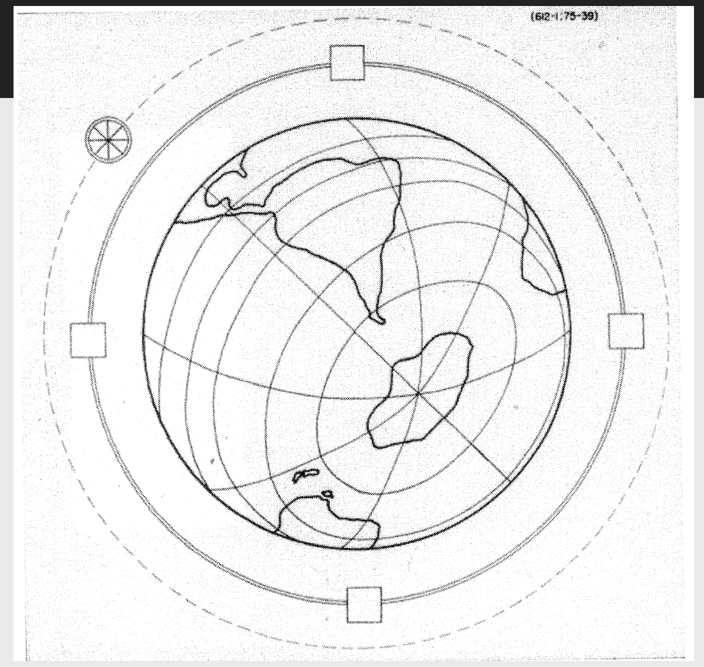
Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

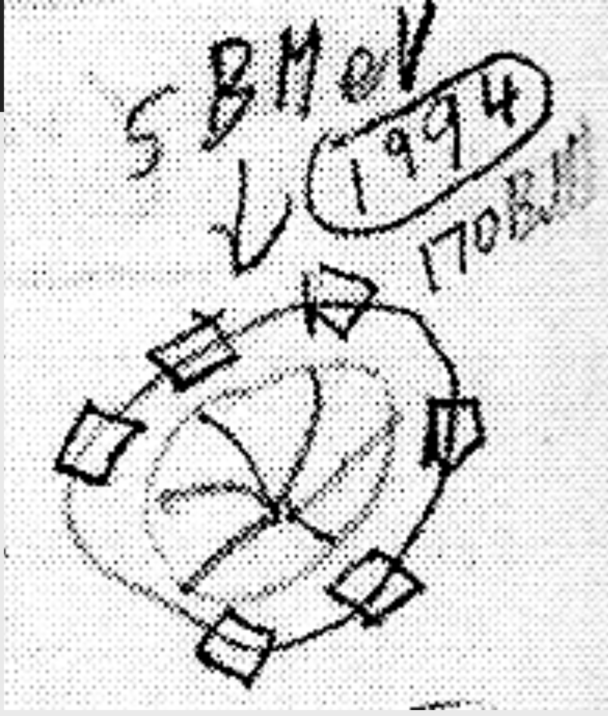
D. Schulte Muon Colliders, EPS, July 2019 23

Roberto Franceschini LFC19 https://indico.ectstar.eu/event/55/



Enrico Fermi (James W. Cronin (Editor)) - Fermi Remembered - Ch. 9 - What can we learn from high energy accelerators?

Circa 1954: B~2T, R~8000 Km
E(Beam)~1000 TeV, E(CoM)~3 TeV



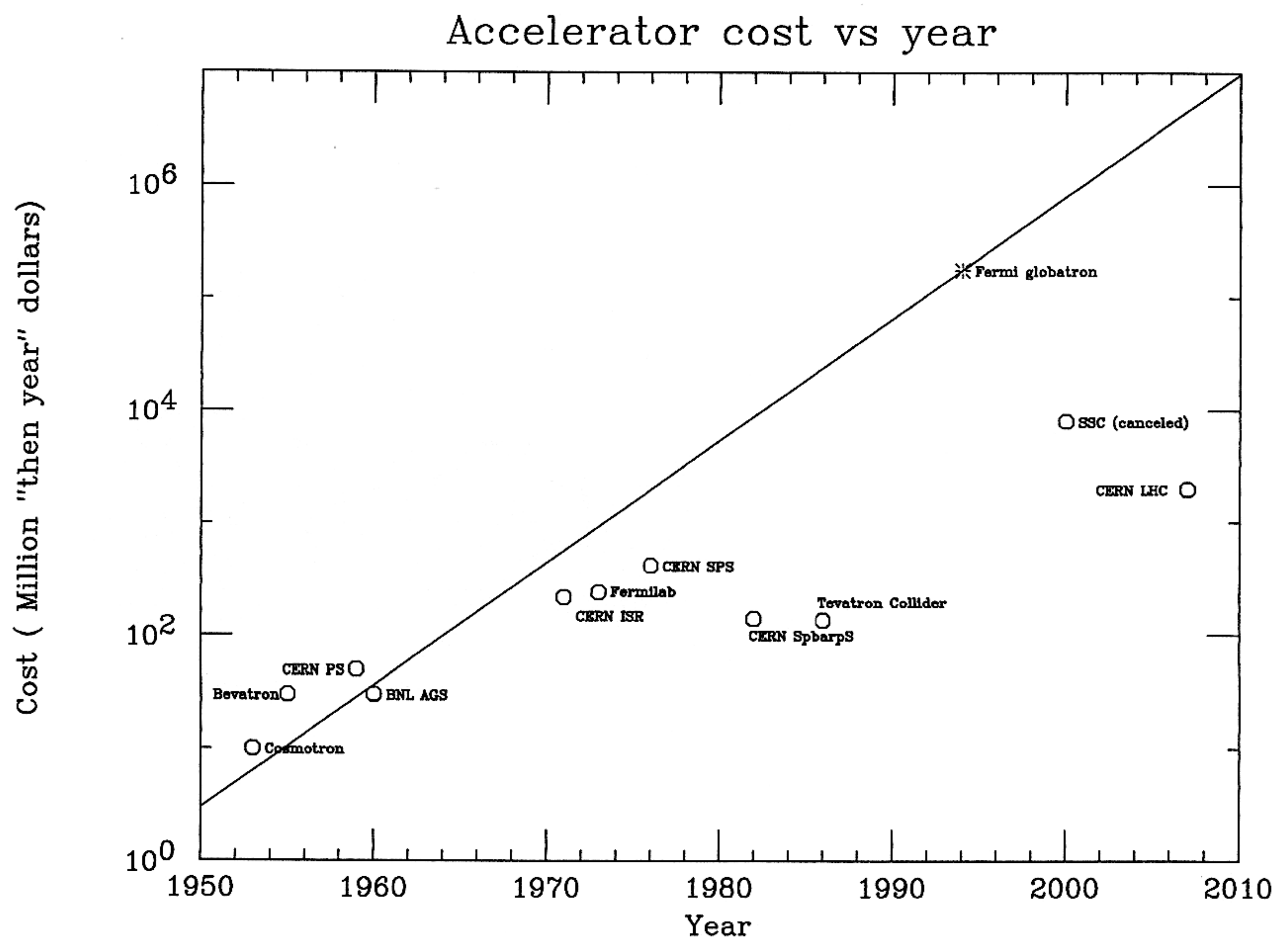


Figure 9.6 Approximate cost of actual accelerators versus time.

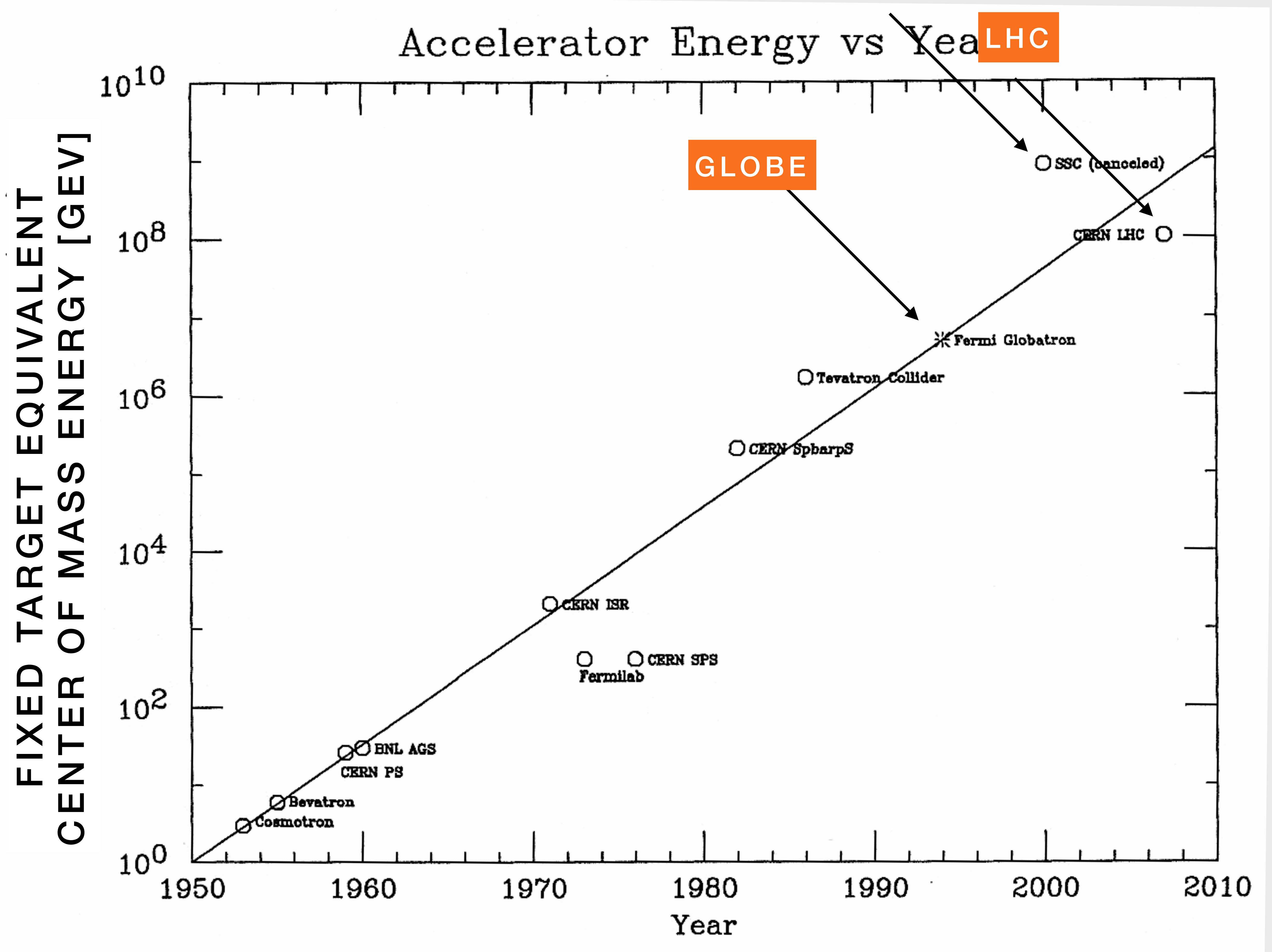


Figure 9.5 Energy versus time for actual accelerators.

Enrico Fermi (James W. Cronin (Editor)) - Fermi Remembered - Ch. 9 - What can we learn from high energy accelerators?

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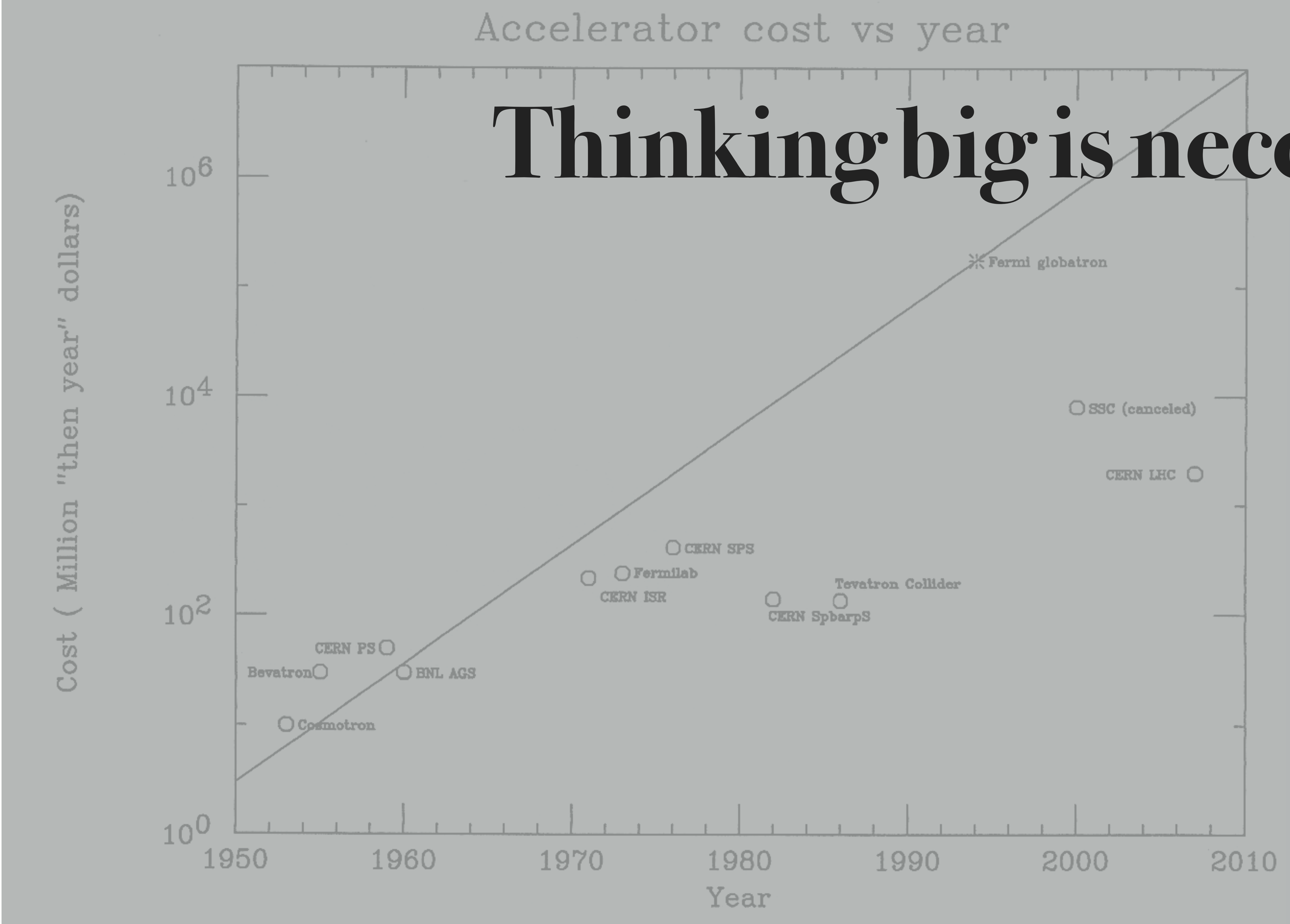
Thinking big is necessary, but not sufficient



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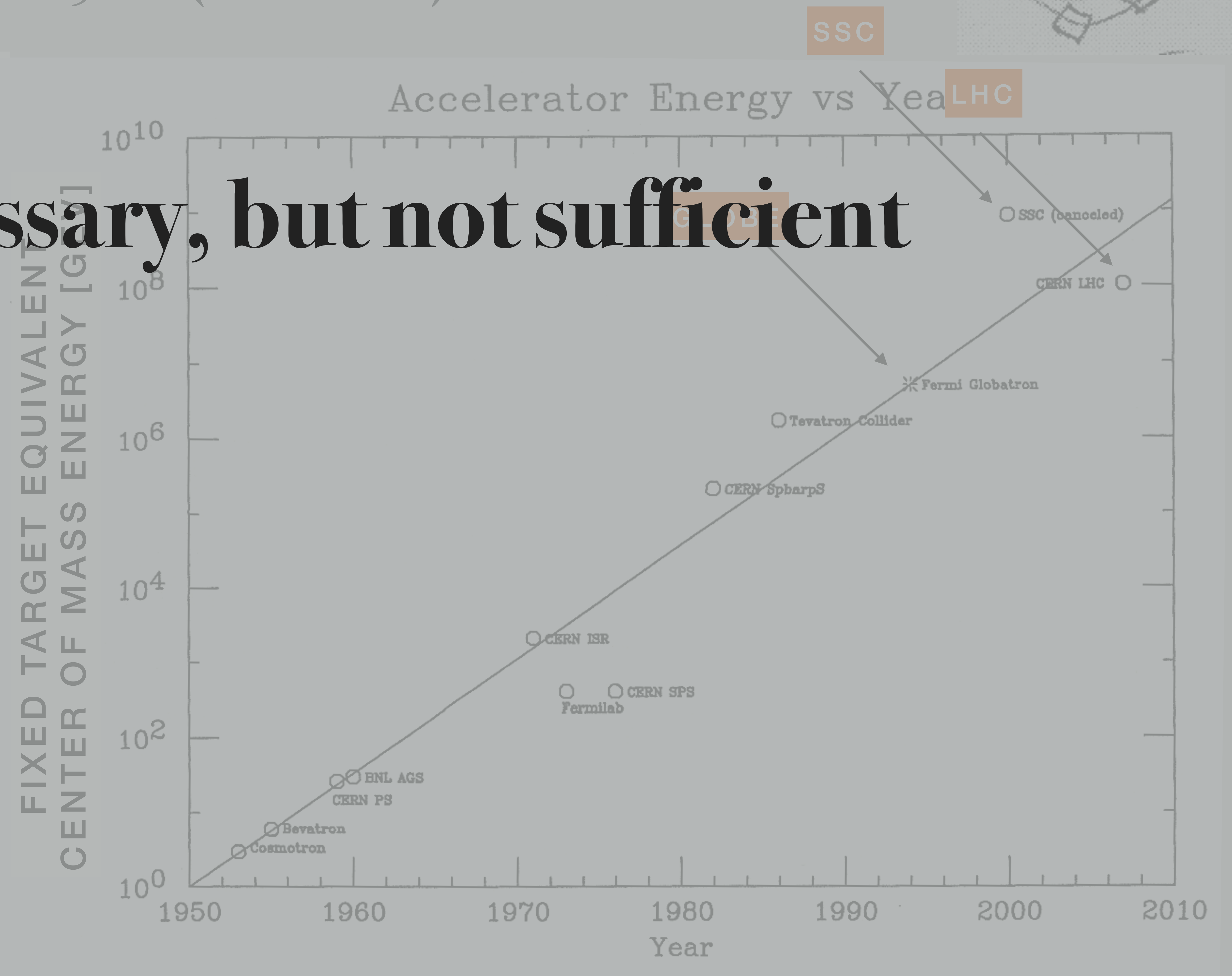

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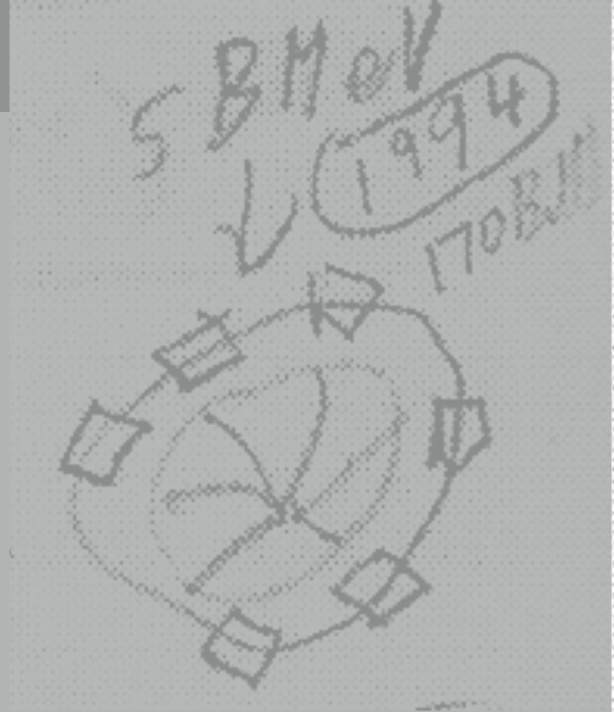
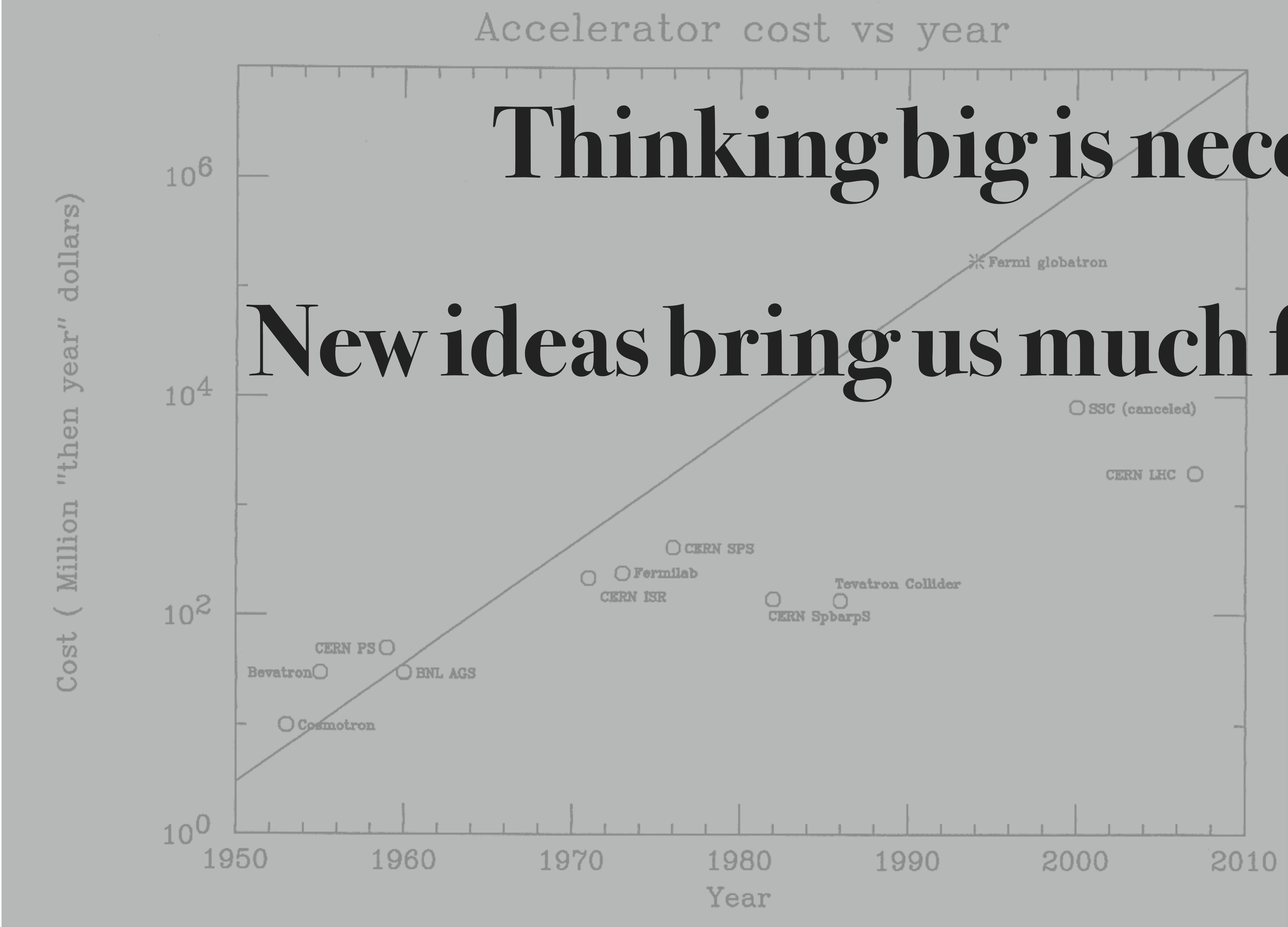
Enrico Fermi (James W. Cronin (Editor)) - Fermi Remembered - Ch. 9 - What can we learn from high energy accelerators?

Circa1954: B~2T, R~8000Km
E(Beam)~1000TeV, E(CoM)~3TeV


5 BMeV
1994
170B$

Thinking big is necessary, but not sufficient

New ideas bring us much farther (beam-beam, superconductors,...)



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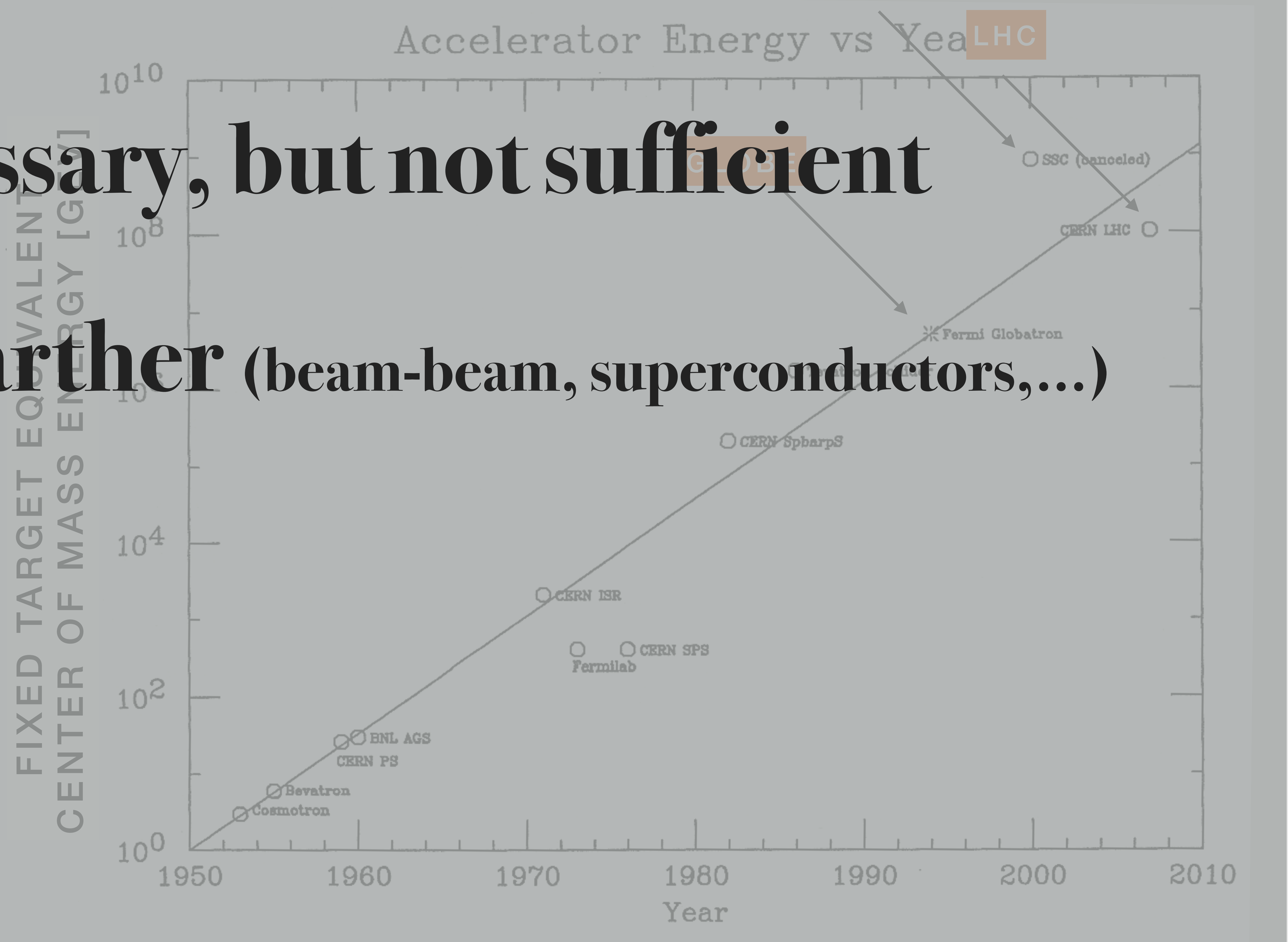

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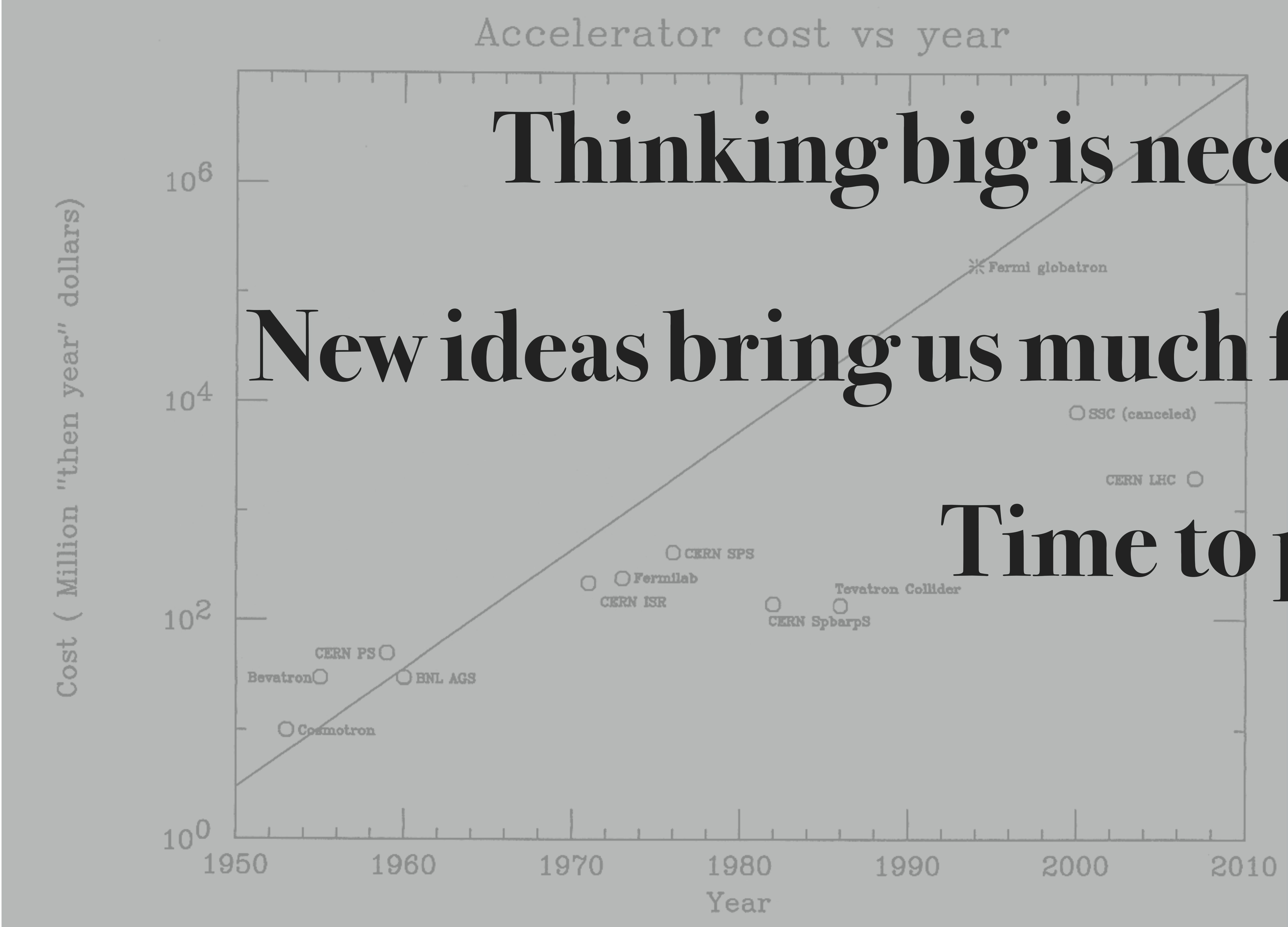

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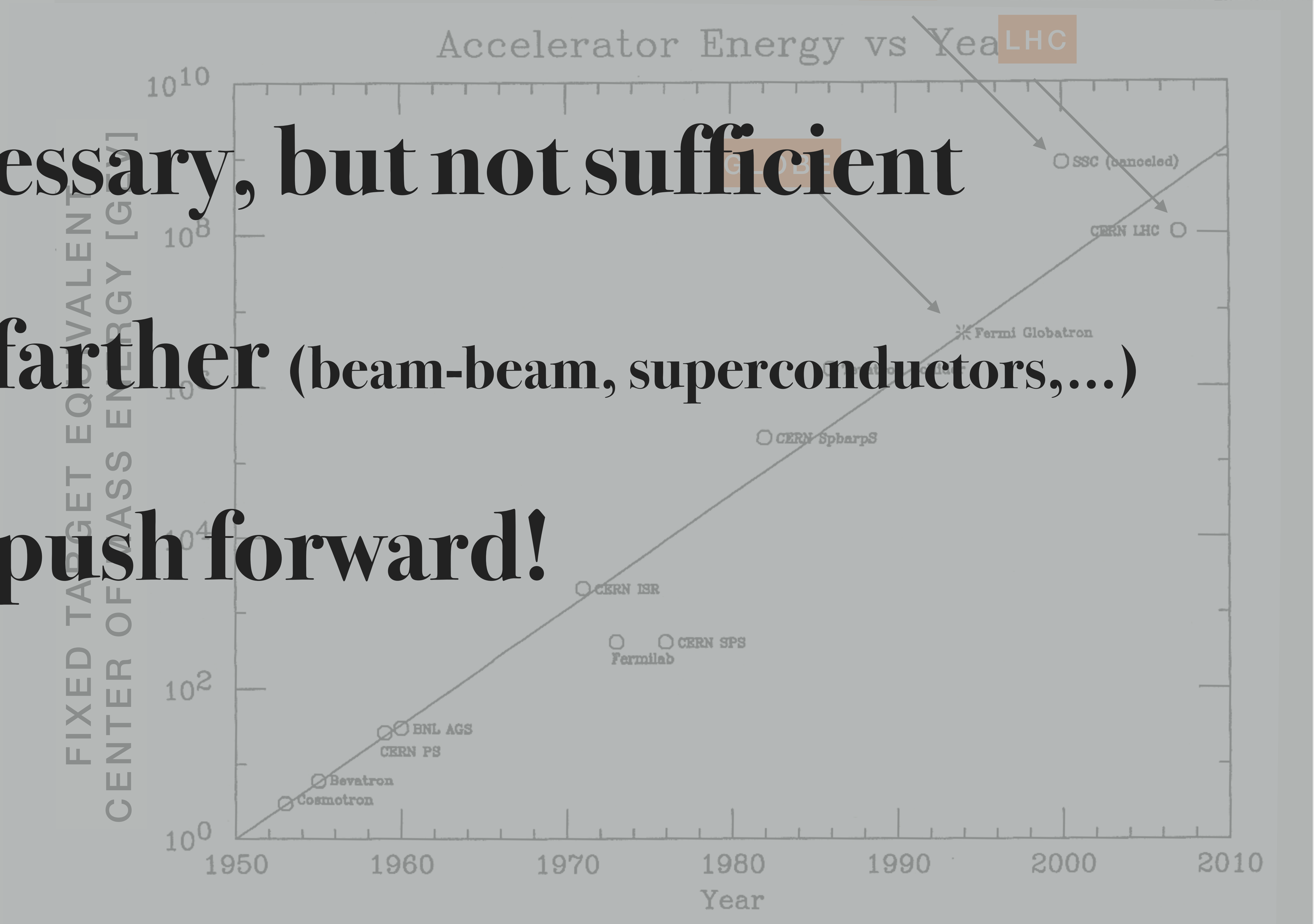

Figure 9.5 Energy versus time for actual accelerators.

Thinking big is necessary, but not sufficient

New ideas bring us much farther **(beam-beam, superconductors,...)**

Time to push forward!

Unstable and weak: our future

- Pole Higgs physics statistics about 100 times a dedicated Higgs factory (10^8 Higgs)
- Pole Top quark physics comparable to dedicated top factory (order 10^6 Tops)
- Top, Higgs and NP collecting data during the *same "stage"*

- Probes at high momentum transfer hugely enhanced by large available energy: e.g. Higgs compositeness at hundreds of TeV (similar advantage for any EFT)
- Direct reach for "anything" with electroweak charge or coupled to the Higgs boson in the kinematic reach

Unstable and weakly charged: our future beams

- Pole Higgs physics statistics about 100 times a dedicated Higgs factory (10^8 Higgs)
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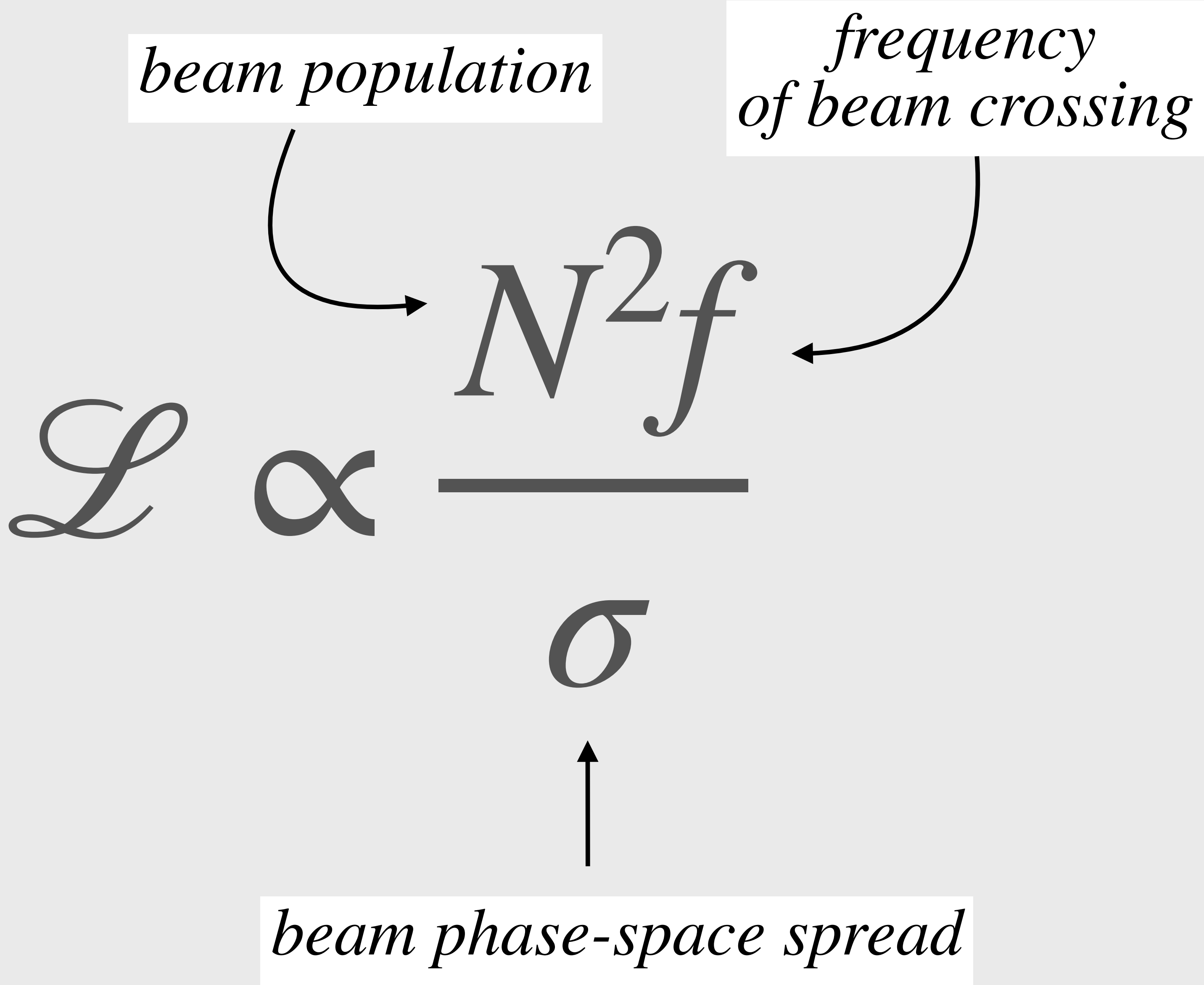
Thank you!

How to make a muon collider

Muon sources

BALANCE NUMBER AND SPREAD



beam population

frequency of beam crossing

$$\mathscr{L} \propto \frac{N^2 f}{\sigma}$$

beam phase-space spread

MAP

$$p\mathcal{N} \to \pi^\pm + X \to \mu^\pm + \ldots$$

- large cross-section
- large spread of muon velocity

LEMMA

$$e^+e^- \to \mu^+\mu^-$$

- small cross-section
- small spread of muon velocity

Muon sou

BALANCE

NUMBER AND SPREAD

MAP

$$p\mathcal{N} \to \pi^{\pm} + X \to \mu^{\pm} + \ldots$$

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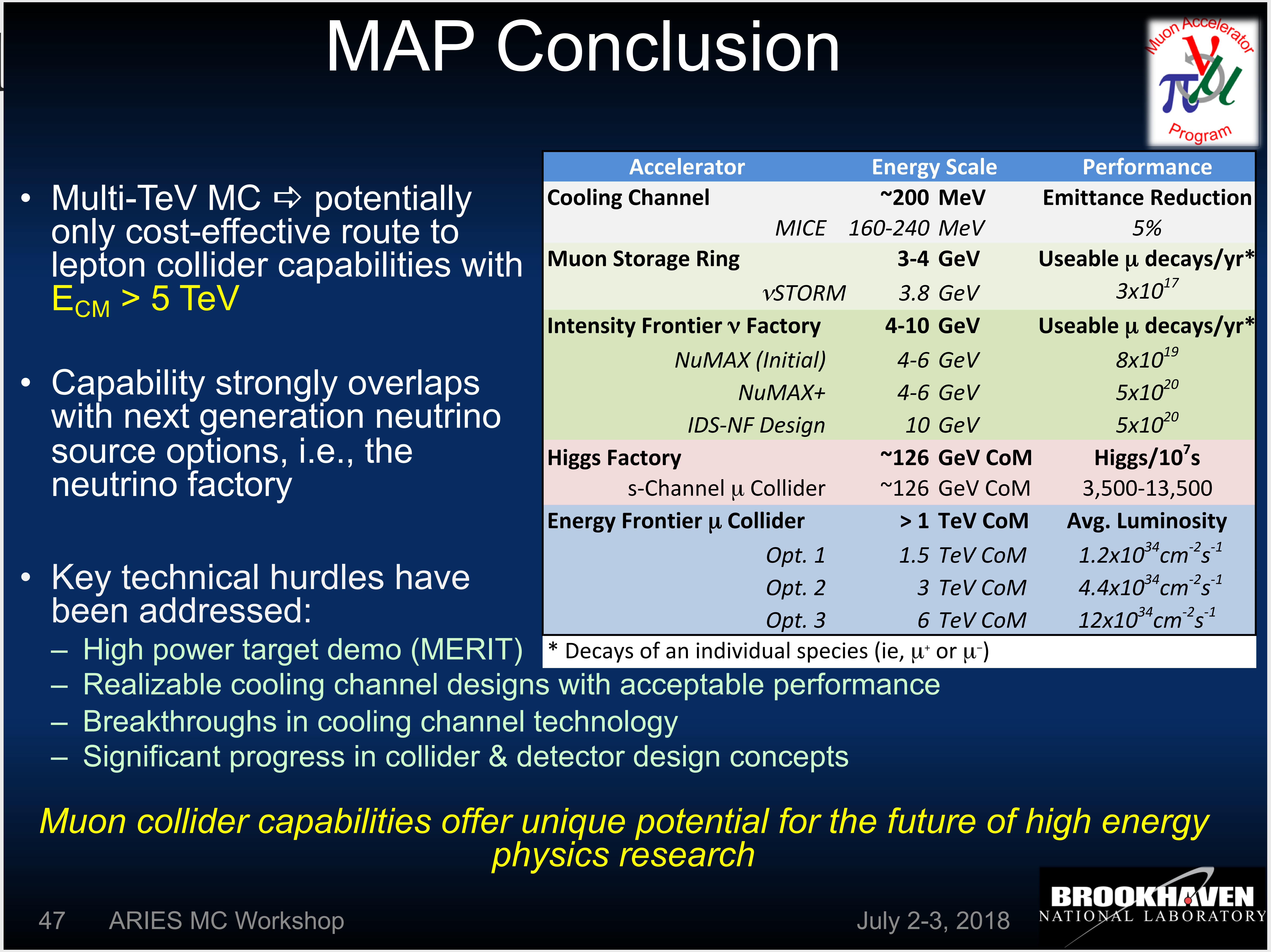


MAP Conclusion

- Multi-TeV MC ⇨ potentially only cost-effective route to lepton collider capabilities with E_{CM} > 5 TeV
- Capability strongly overlaps with next generation neutrino source options, i.e., the neutrino factory
- Key technical hurdles have been addressed:
  - High power target demo (MERIT)
  - Realizable cooling channel designs with acceptable performance
  - Breakthroughs in cooling channel technology
  - Significant progress in collider & detector design concepts

Accelerator	Energy Scale	Performance
Cooling Channel	**~200 MeV**	**Emittance Reduction**
MICE	*160-240 MeV*	*5%*
Muon Storage Ring	**3-4 GeV**	**Useable μ decays/yr***
νSTORM	*3.8 GeV*	*$3x10^{17}$*
Intensity Frontier ν Factory	**4-10 GeV**	**Useable μ decays/yr***
NuMAX (Initial)	*4-6 GeV*	*$8x10^{19}$*
NuMAX+	*4-6 GeV*	*$5x10^{20}$*
IDS-NF Design	*10 GeV*	*$5x10^{20}$*
Higgs Factory	**~126 GeV CoM**	**Higgs/10^7s**
s-Channel μ Collider	~126 GeV CoM	3,500-13,500
Energy Frontier μ Collider	**> 1 TeV CoM**	**Avg. Luminosity**
Opt. 1	*1.5 TeV CoM*	*$1.2x10^{34}cm^{-2}s^{-1}$*
Opt. 2	*3 TeV CoM*	*$4.4x10^{34}cm^{-2}s^{-1}$*
Opt. 3	*6 TeV CoM*	*$12x10^{34}cm^{-2}s^{-1}$*

* Decays of an individual species (ie, μ^+ or μ^-)

Muon collider capabilities offer unique potential for the future of high energy physics research

47 ARIES MC Workshop July 2-3, 2018

BROOKHAVEN NATIONAL LABORATORY

Roberto Franceschini LFC19 https://indico.ectstar.eu/event/55/

Muon sou

BALANCE NUMBER AND SPREAD

MAP

$p\mathcal{N} \to \pi^{\pm} + X \to \mu^{\pm} + \ldots$

- large cross-section
- large spread of muon velocity

Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

TIS-RP/IR/98-34 (1998) (updated by M.Antonelli)

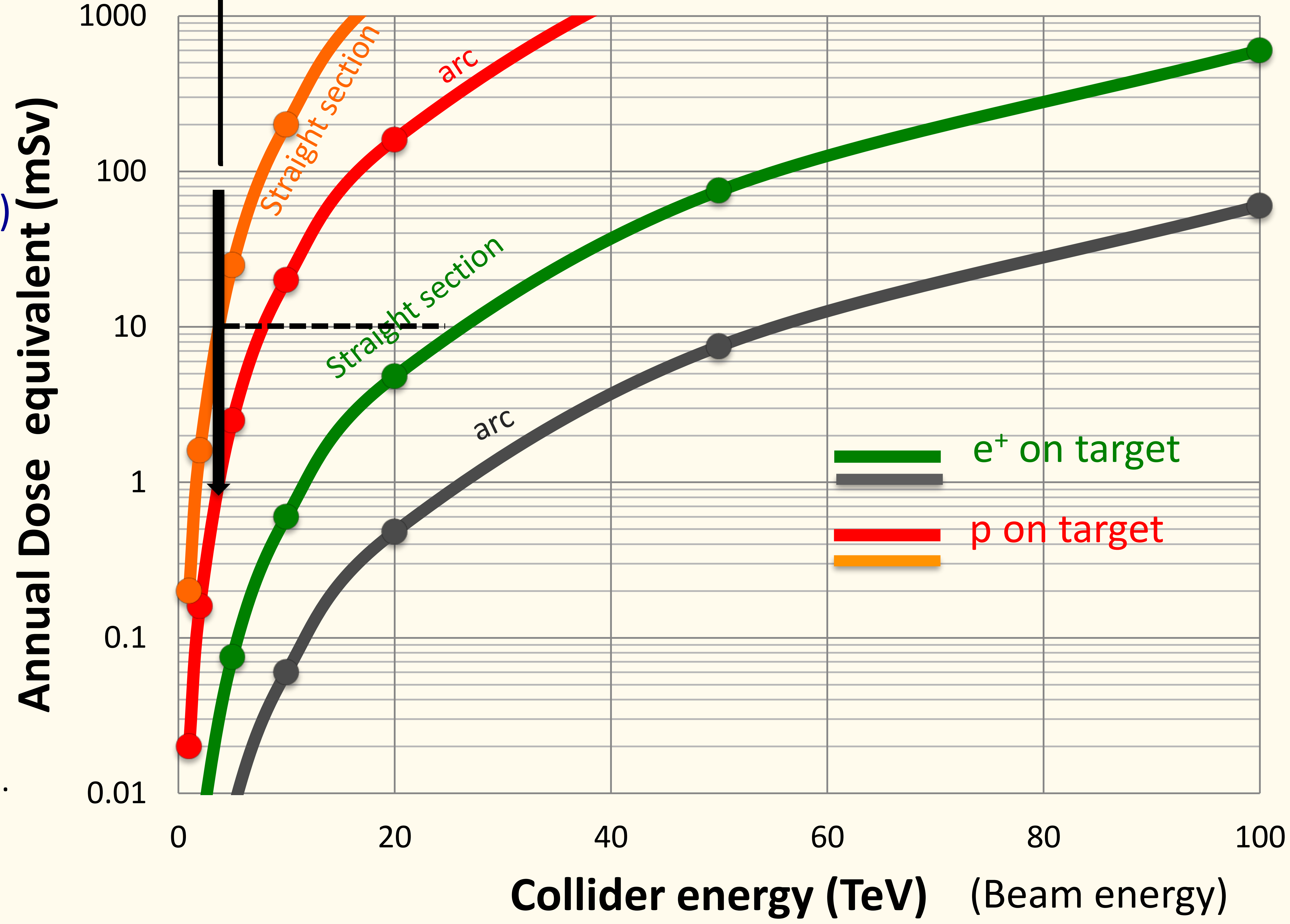
MAP design for a 6 TeV MC
(500 m depth)

Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

muon rate:
p on target option
3×10^{13} μ/s
e+ on target option
9×10^{10} μ/s

neutrino dose equivalent/fluence

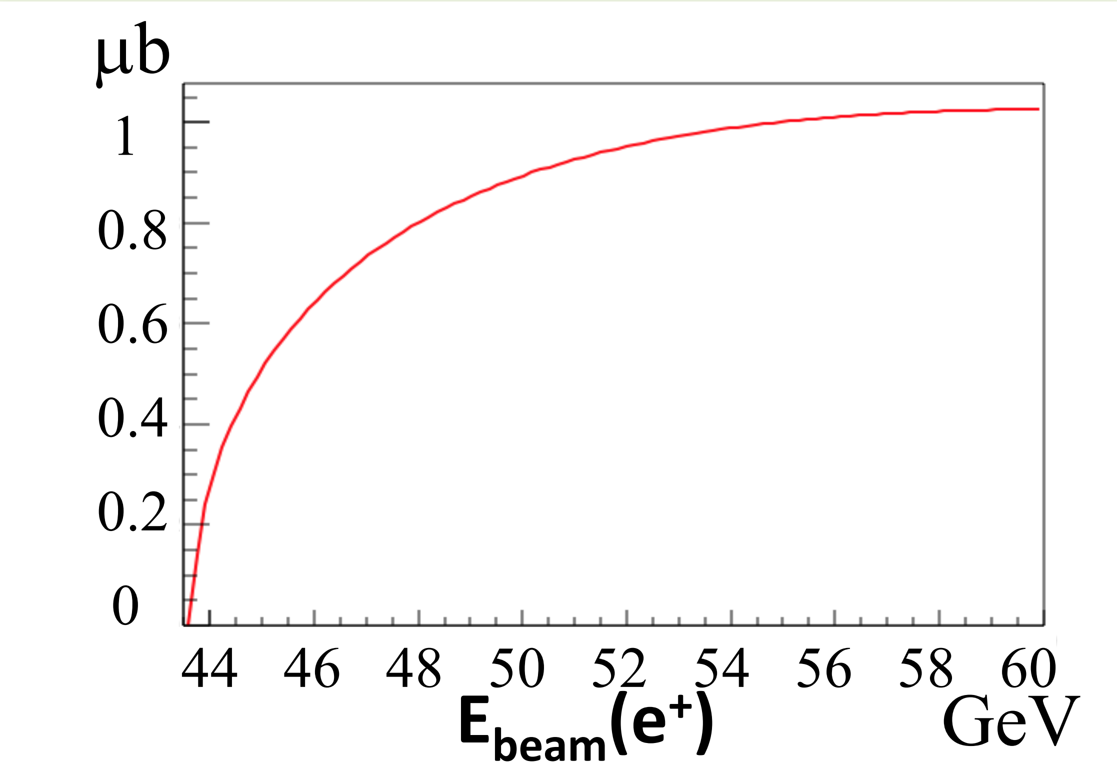
[J.D. Cossairt, N.L. Grossman and E.T . Marshall, Health Phys. 73 (1997), 894-898.]

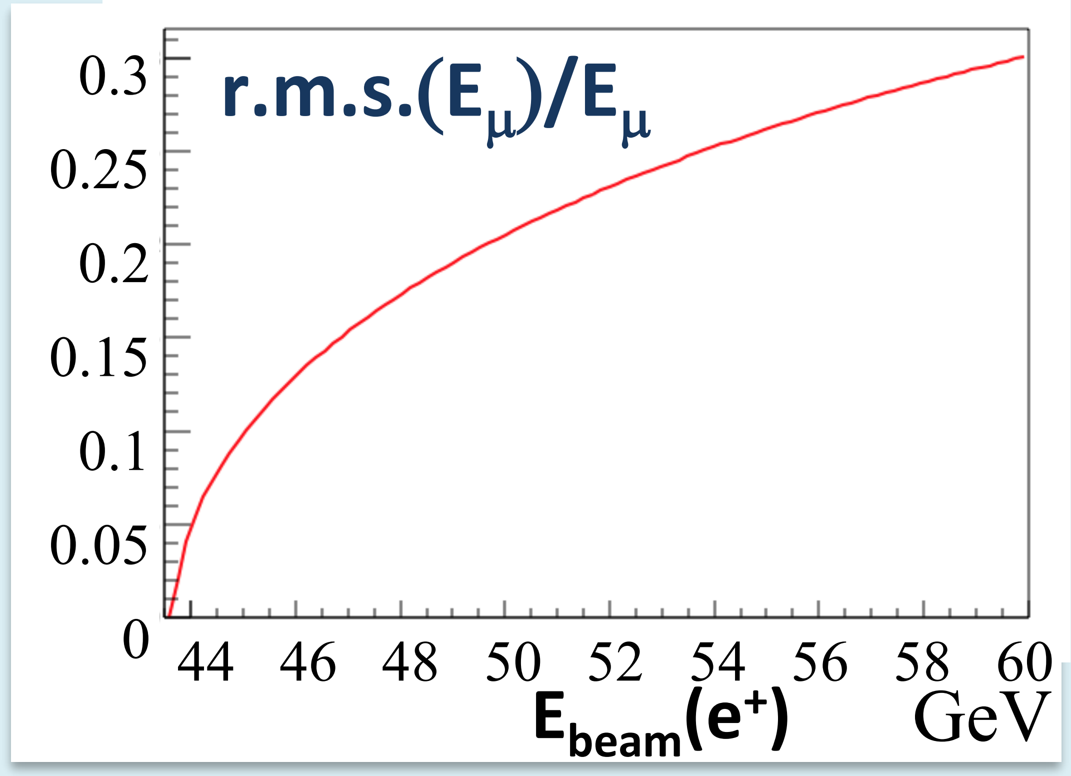


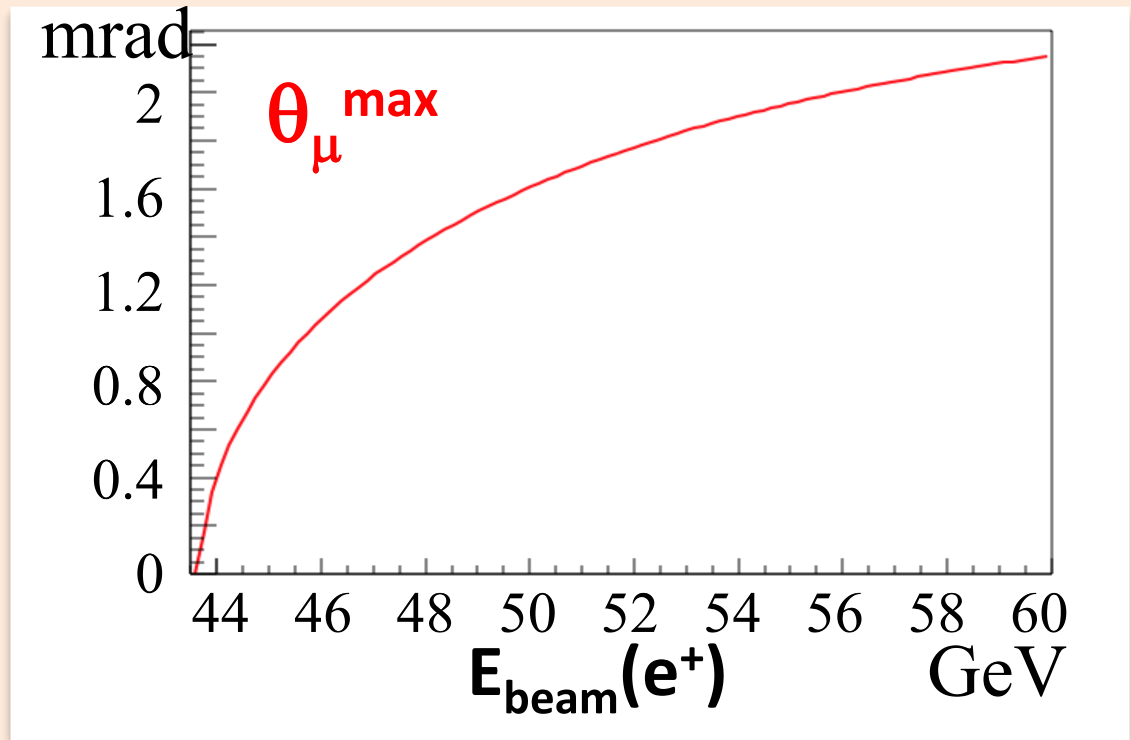
M. Boscolo, Padova, 2 July 2018

Muon sources

BALANCE **NUMBER AND SPREAD**







LEMMA

$e^+e^- \to \mu^+\mu^-$

- small cross-section
- small spread of muon velocity

$$\boxed{\begin{gathered} n_{\mu\mu} \simeq 10^{-5} n_{e+} \\ n_{e+} \simeq 25 \cdot n_{e+,ILC} \end{gathered}}$$

Muon sources

BALANCE NUMBER AND SPREAD

$$n_{\mu\mu} \simeq 10^{-5} n_{e^+}$$

$$n_{e^+} \simeq 25 \cdot n_{e^+,ILC}$$

LEMMA

$e^+e^- \to \mu^+\mu^-$

- small cross-section
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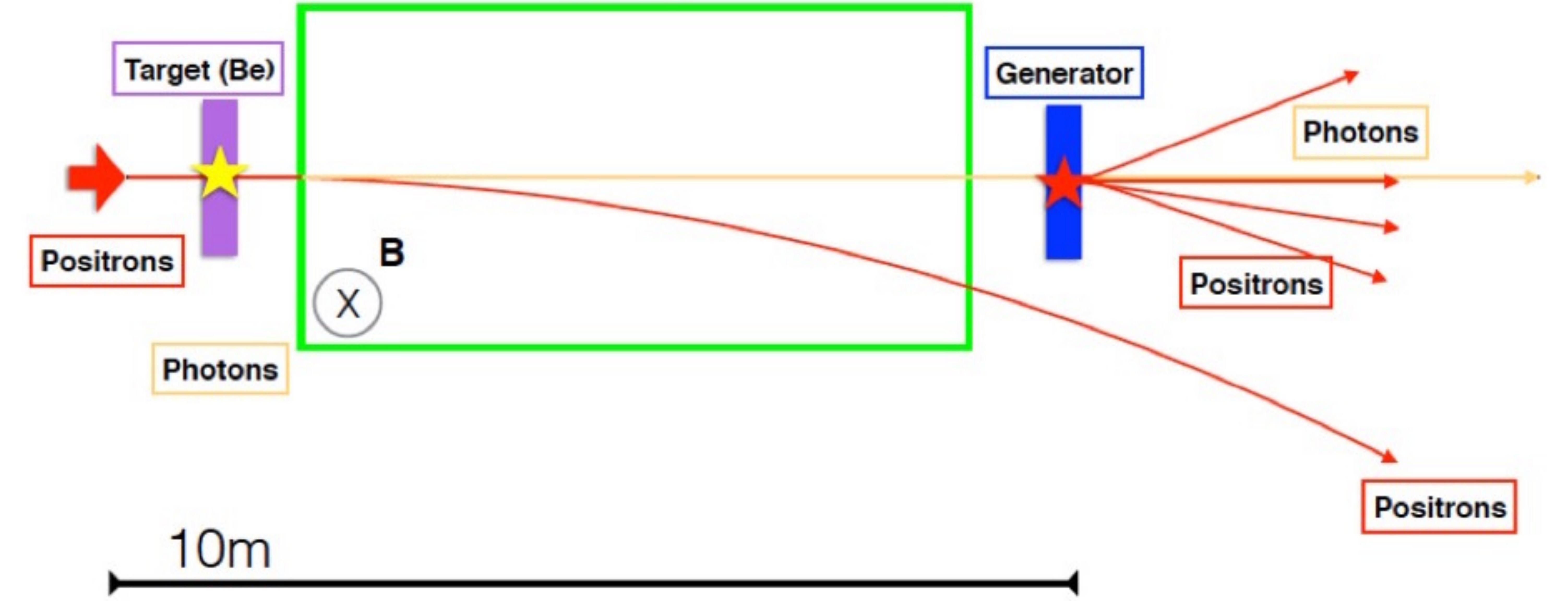
EMBEDDED POSITRON SOURCE



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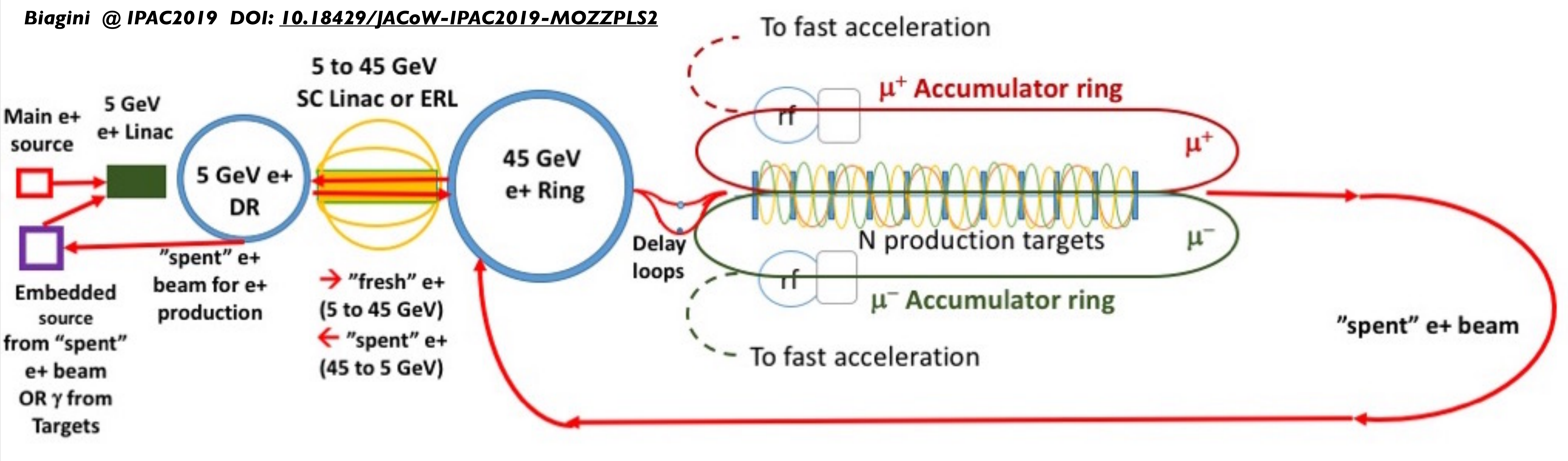
A possible design

MUON SOURCE

WORK IN PROGRESS


Biagini @ IPAC2019 DOI: 10.18429/JACoW-IPAC2019-MOZZPLS2

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A possible design

MUON SOURCE WORK IN PROGRESS

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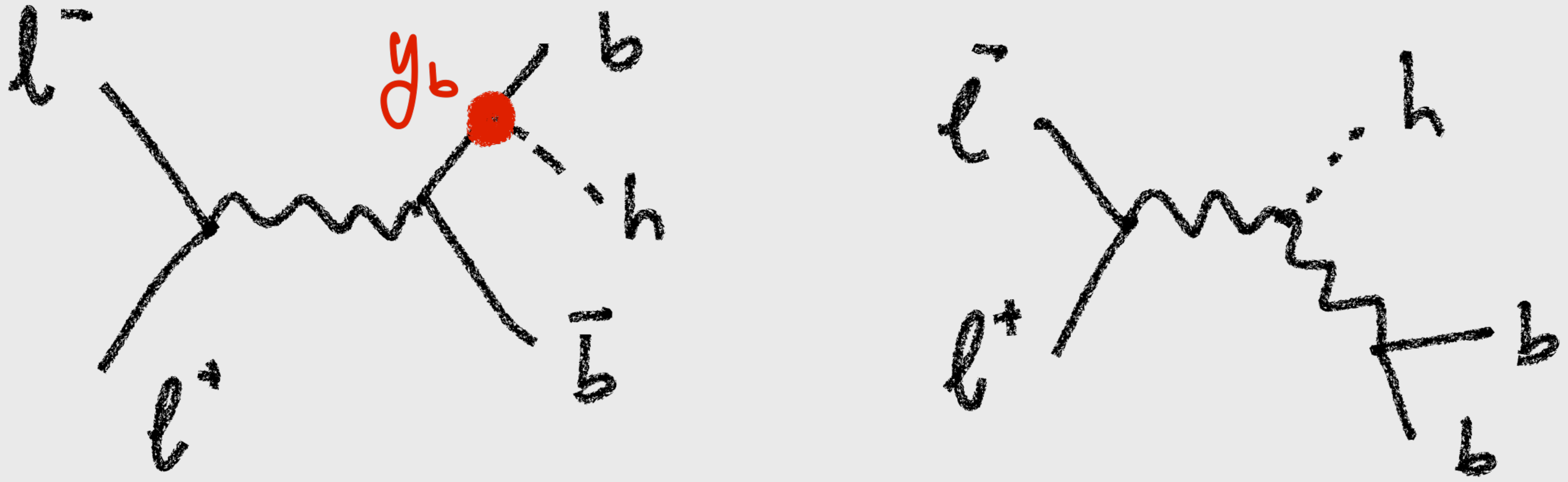
High Lumi

Buttazzo, RF, Wulzer

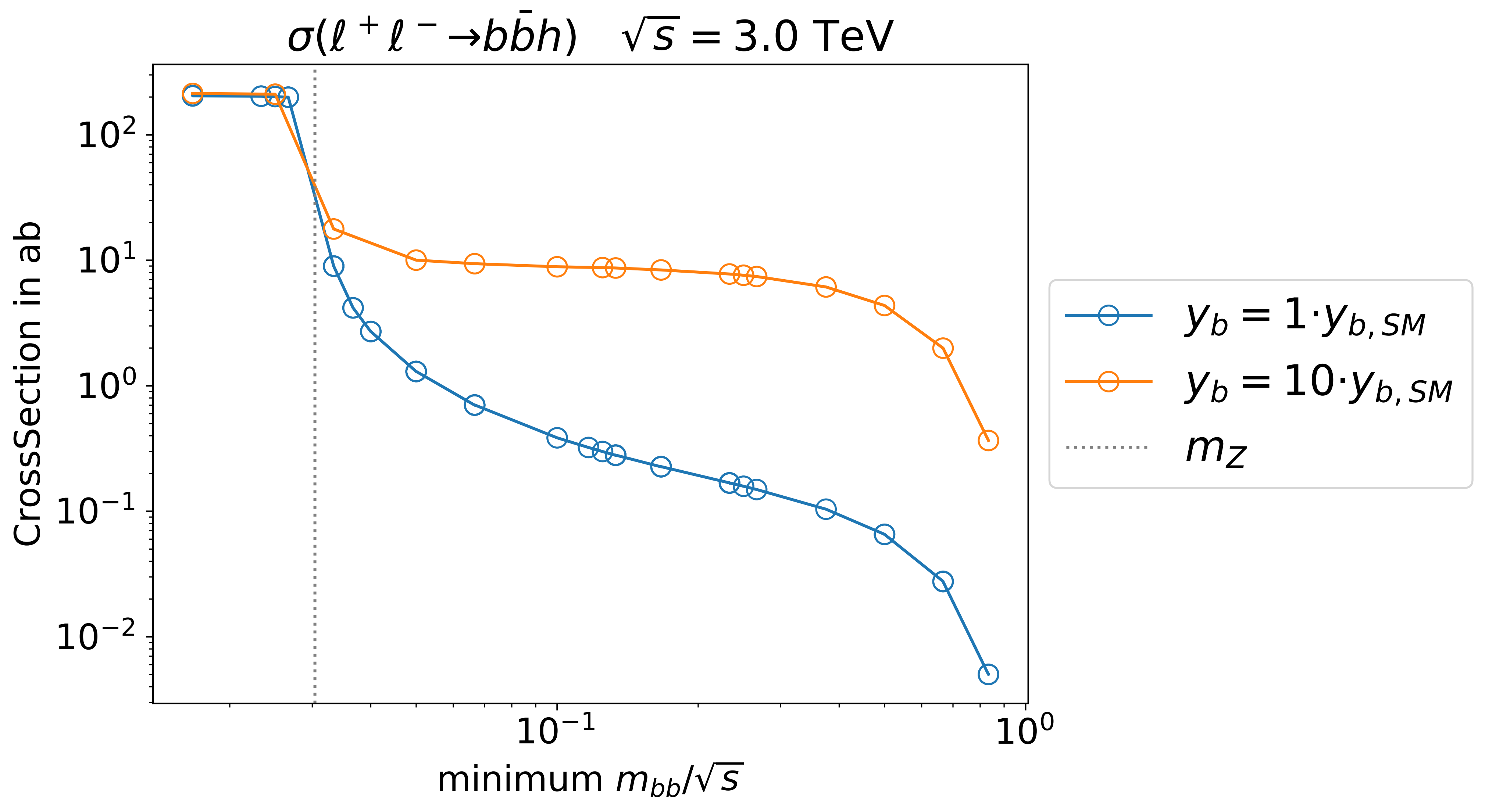
$\ell^+\ell^- \to b\bar{b}h$

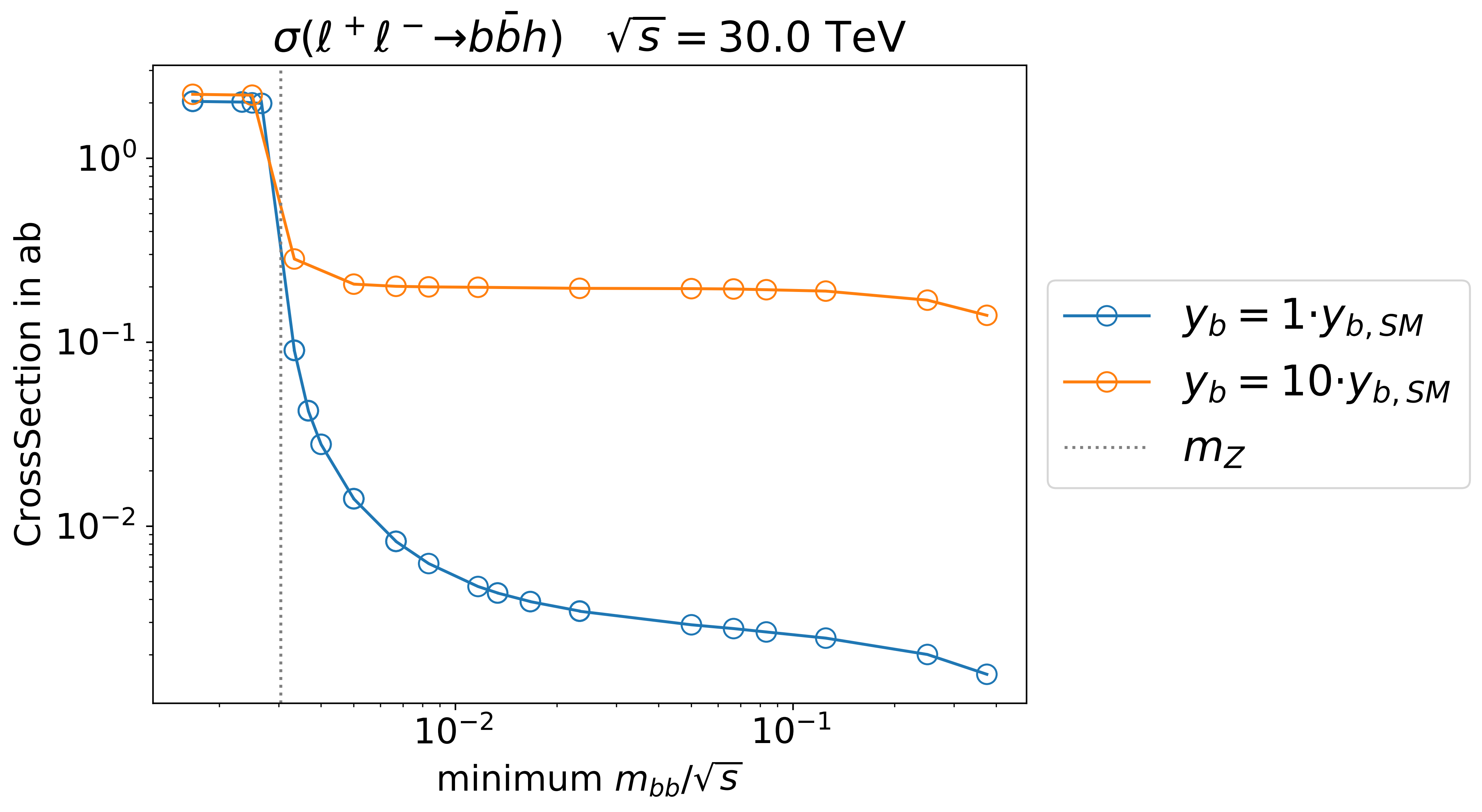
RARE

PRODUCTION MODES



Direct Measurement of Y_b





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

Gotchas

Not as usual

- Muons radiate EW
- Most $c\tau_0 \sim \mu m$ live for fractions of meter in the lab (b, c, τ …)

b	c	τ
40 cm	20 cm	74 cm

- Calo: $\delta E / E \sim \sim 1/\sqrt{E}$
- Tracker: $\delta p/p \sim c$

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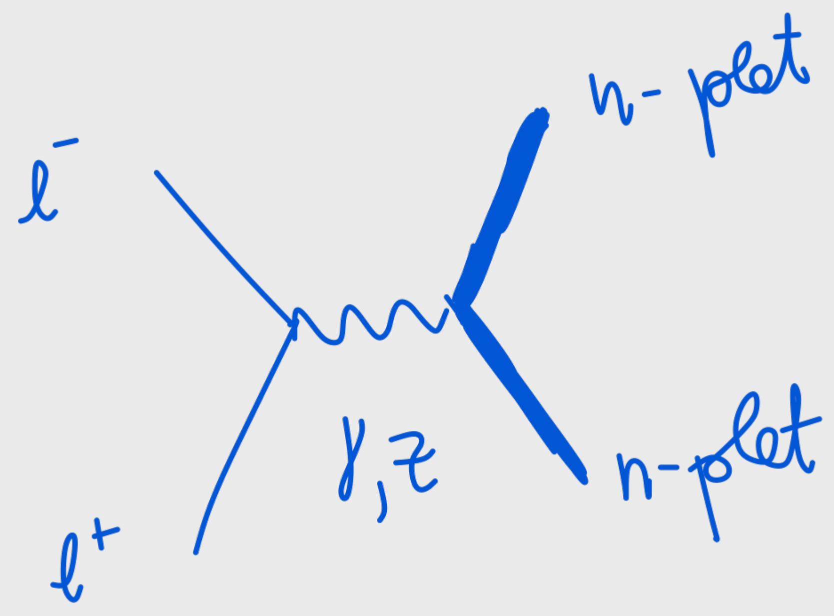
DarkMatter

Degenerate EW multiplets

STUB-TRACKS

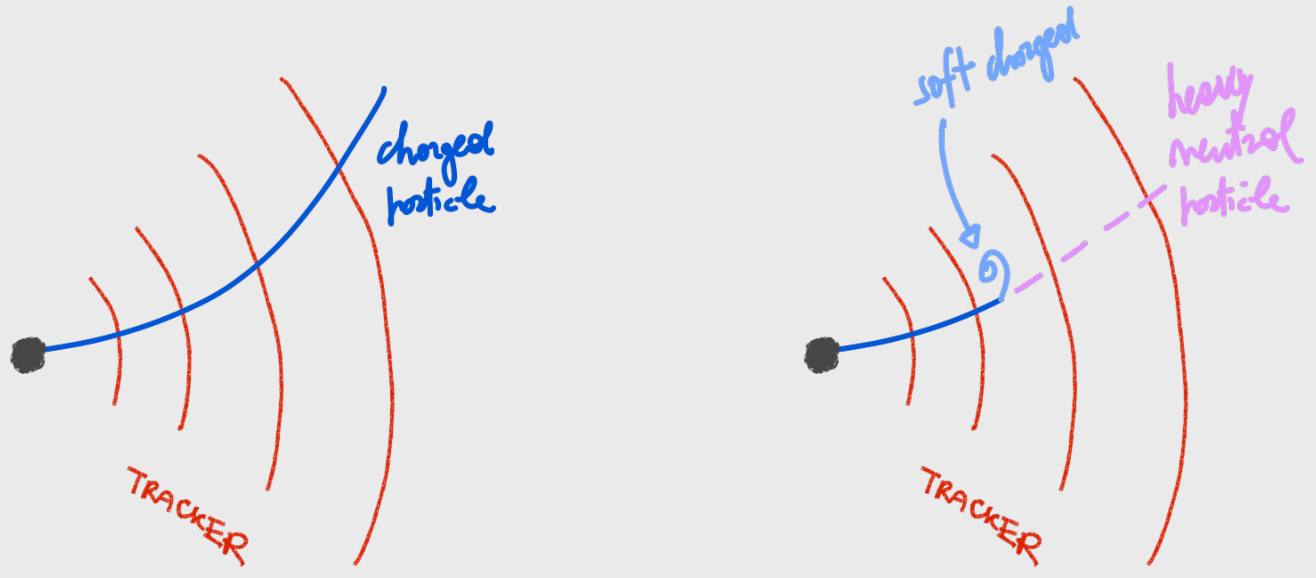
EXTRAPOLATION FROM CLIC

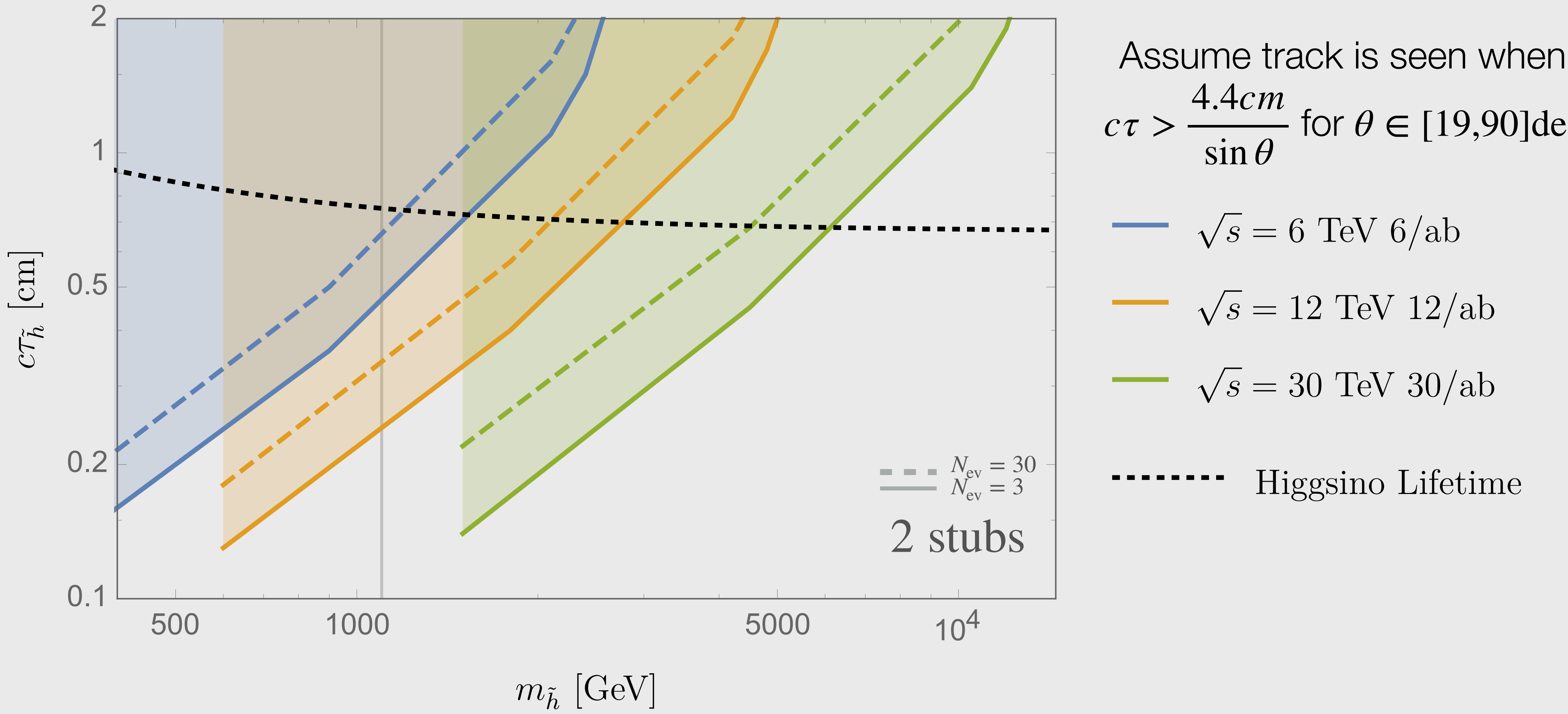
- Heavy n-plet of SU(2)
- Mass splitting ~ $\alpha_W m_W$ ~ 0.1 GeV - GeV



LARGE RATES, BUT NEEDS TO LIGHT UP THE DETECTOR IN A DISCERNIBLE WAY

- Heavily subject to detector design issues
- Even in CLIC needs full detector simulation





Assume track is seen when

$c\tau > \frac{4.4cm}{\sin\theta}$ for $\theta \in [19,90]$deg

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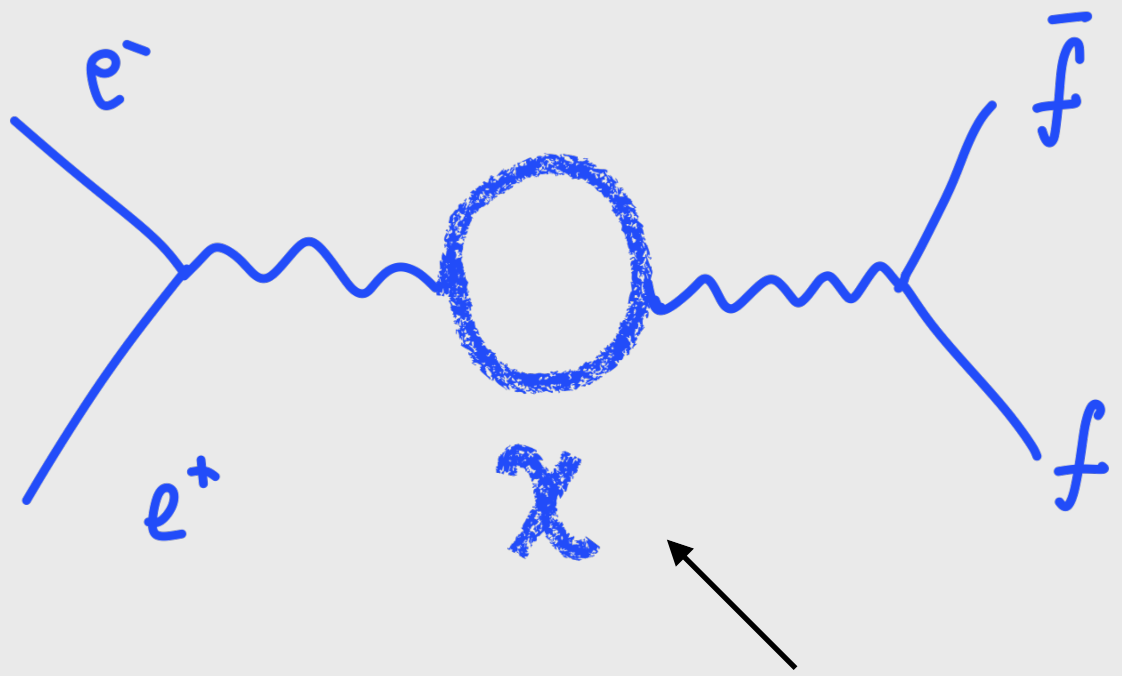
1810.10993 - Di Luzio, Grober, Panico

“Accidental” Dark Matter

PRECISION

ANGULAR DISTRIBUTION



χ is heavy/light new physics

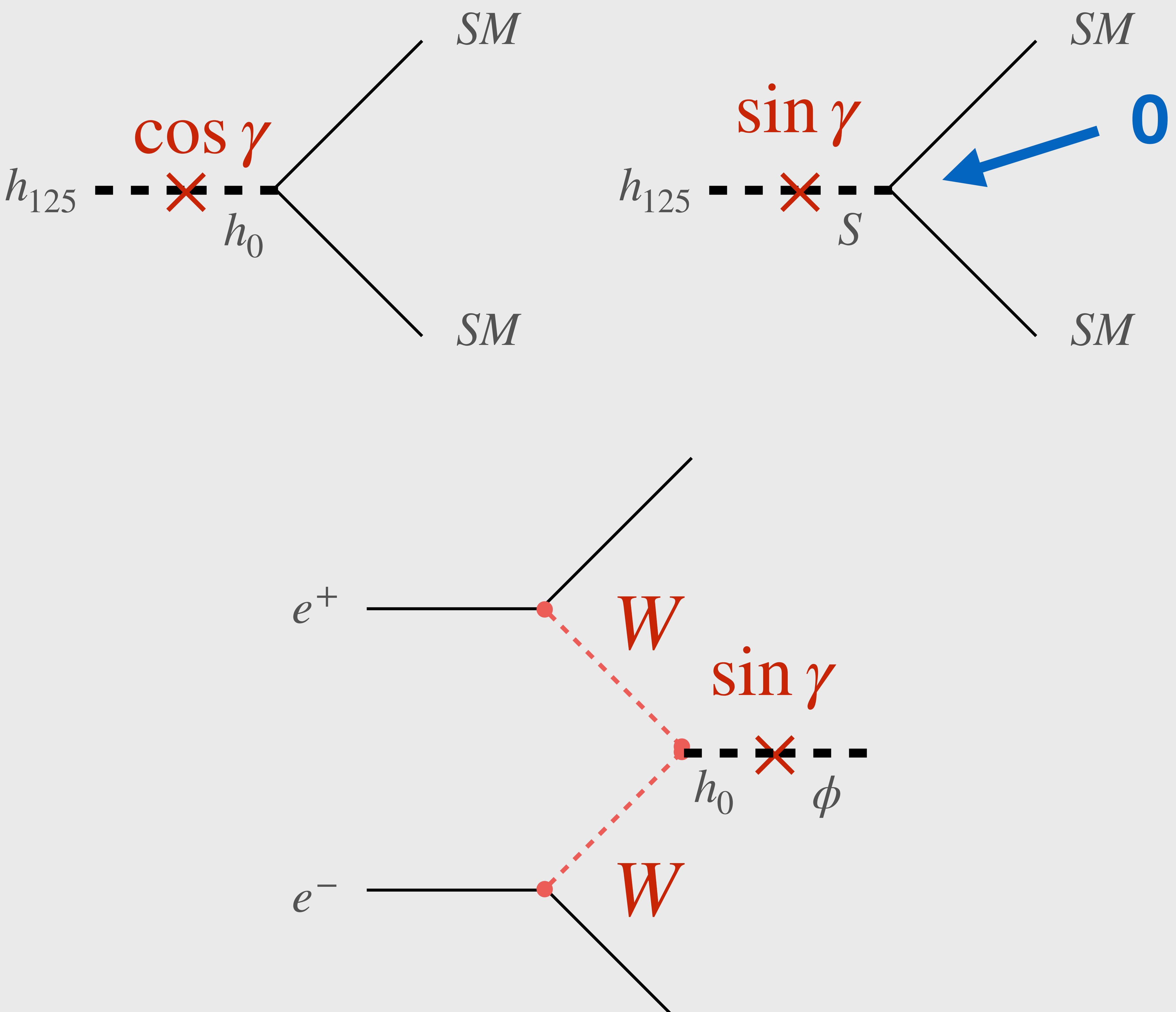
χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\mathrm{DF}}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\mathrm{CS}}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\mathrm{MF}}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\mathrm{CS}}$	6.6	0.2	0.4	1.0	0.5 & [0.7,1.6]	1.6
$(1,5,\epsilon)_{\mathrm{DF}}$	6.6	1.5	2.8	7.1	3.9	11
$(1,5,0)_{\mathrm{MF}}$	14	0.9	1.8	4.4	2.9	3.5 & [5.1, 8.7]
$(1,7,\epsilon)_{\mathrm{CS}}$	16	0.6	1.3	3.2	2.4	2.5 & [3.5, 7.4]
$(1,7,\epsilon)_{\mathrm{DF}}$	16	2.1	4.0	11	6.4	18

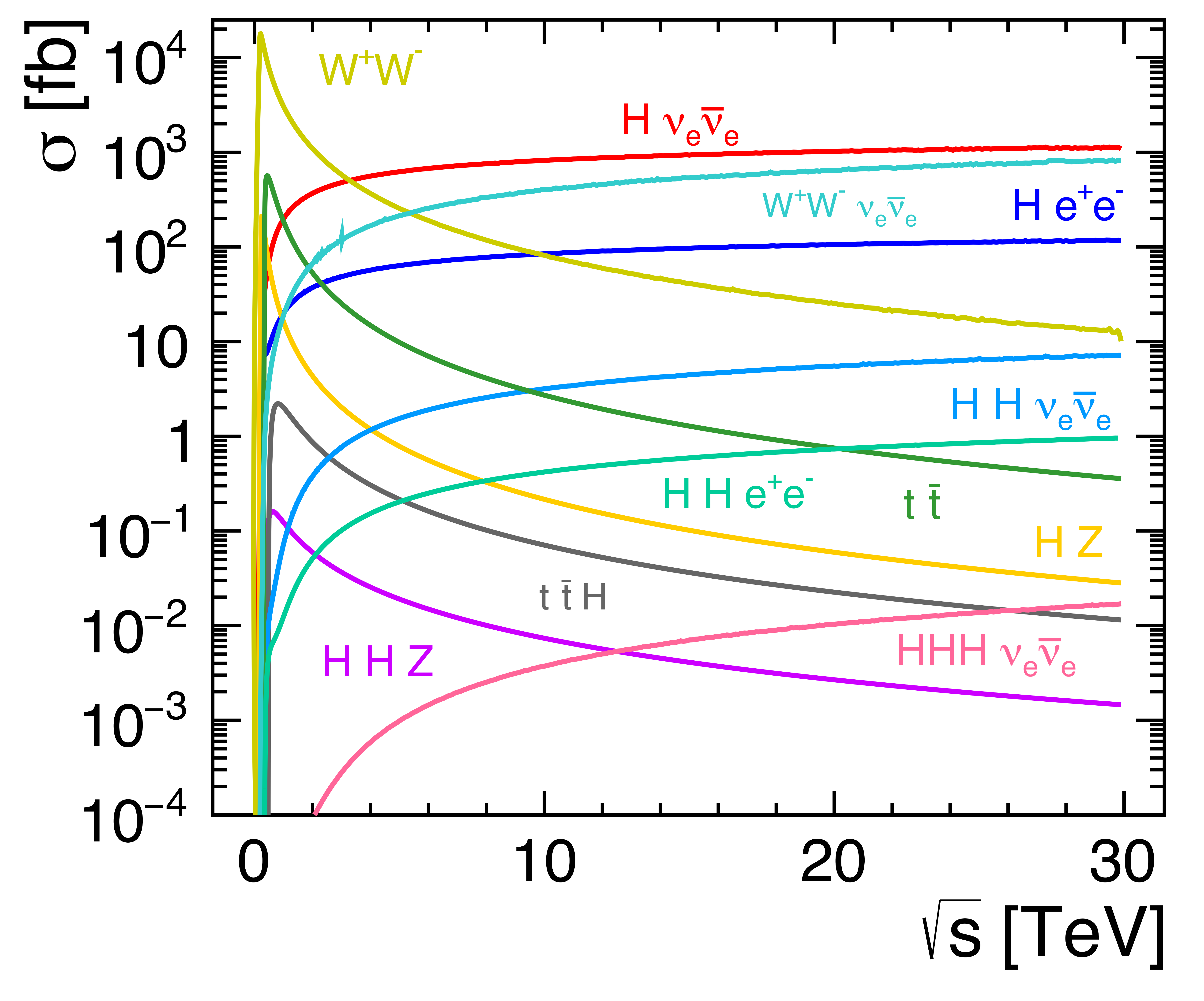
New Higgs bosons

1807.04743 - Buttazzo, Redigolo, Sala, Tesi

Higgs + Heavy Singlet

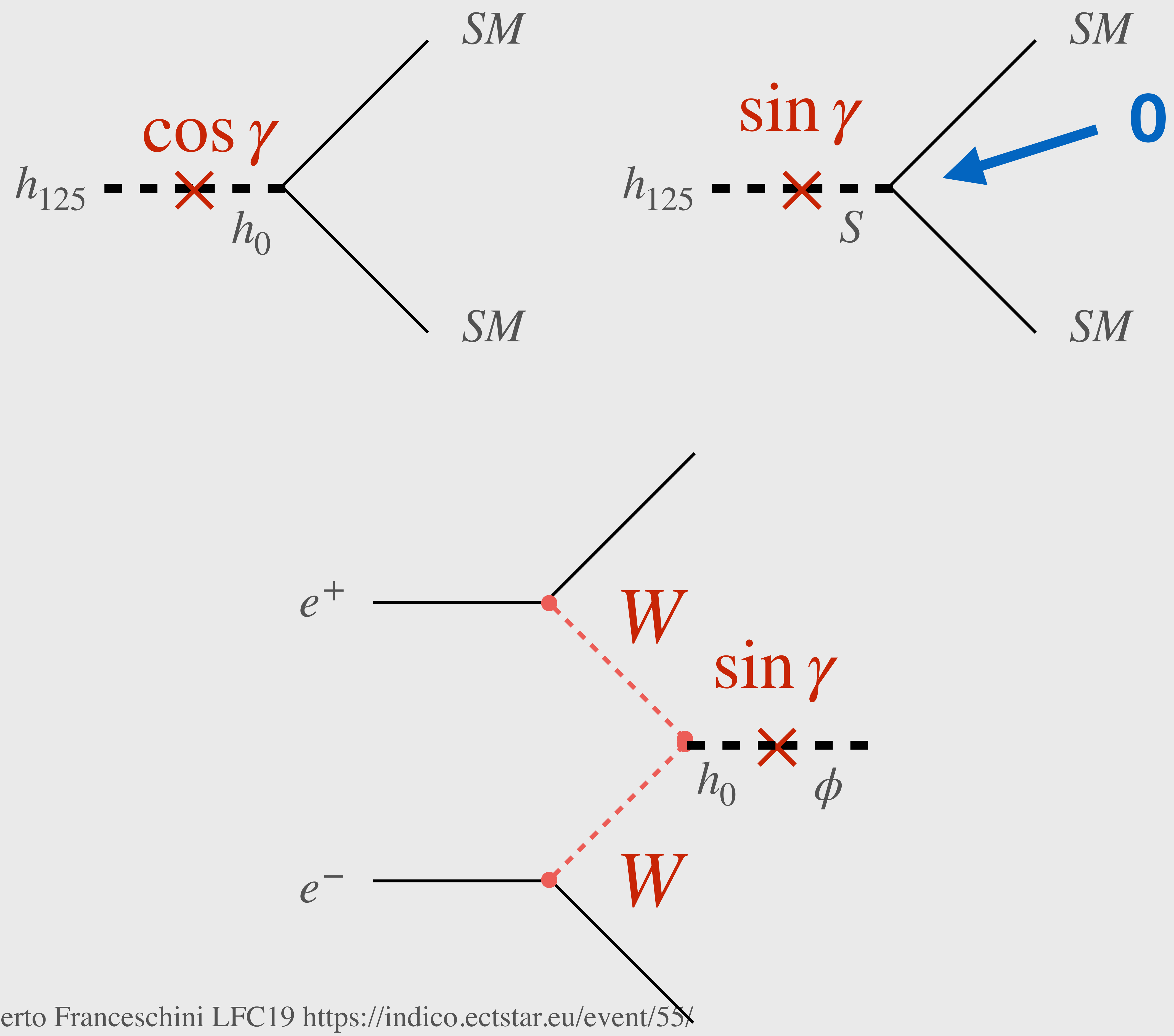
MIXING VS. MASS | $e^+e^- \to \nu\nu\, S$ | $S \to h\, h \to 4b$

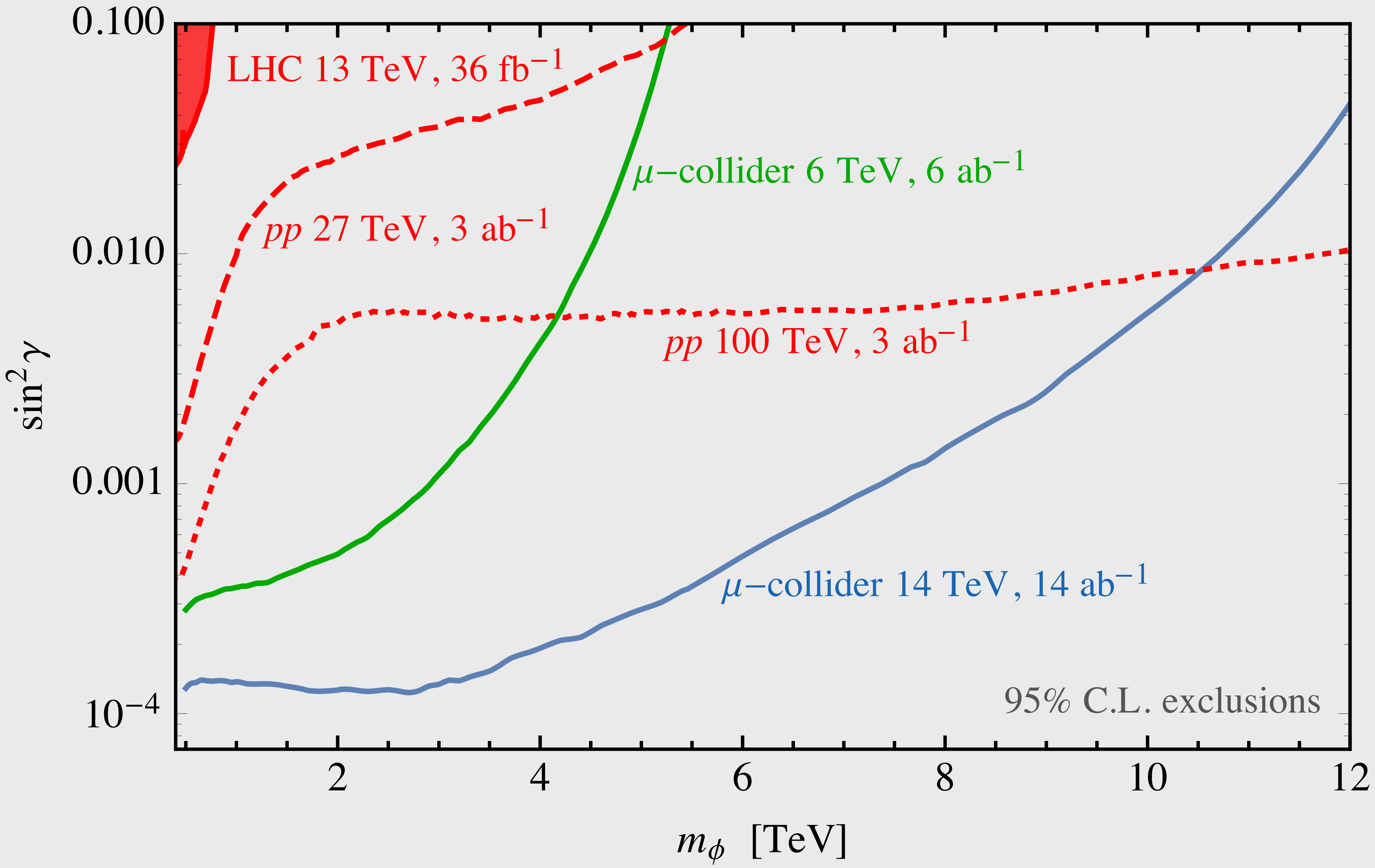




Higgs + Heavy Singlet

MIXING VS. MASS $e^+e^- \to \nu\nu\, S$ $S \to h\, h \to 4b$





Neutrinos, See-saw

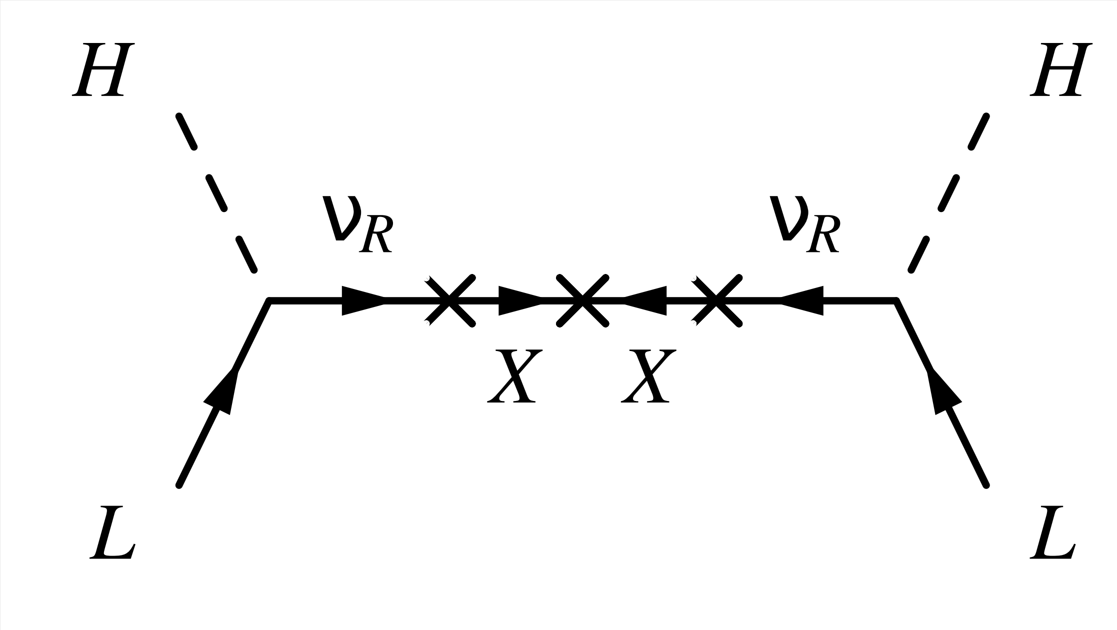
1712.07621 - Baglio, Pascoli, Weiland

Mediator of Neutrino mass mechanism

RIGHT-HANDED NEUTRINO

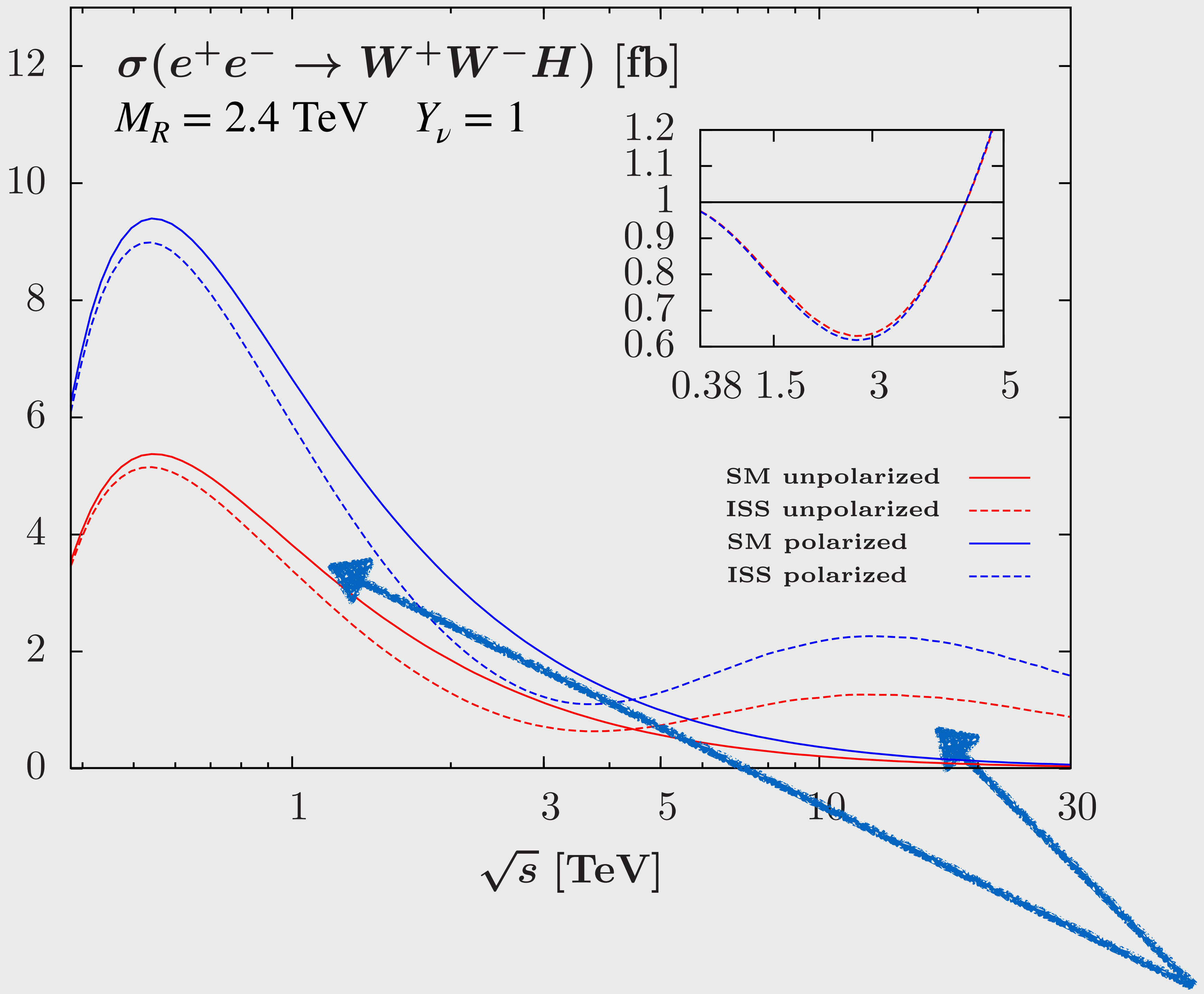
in total rate $e^+e^- \to W^+ W^- h$

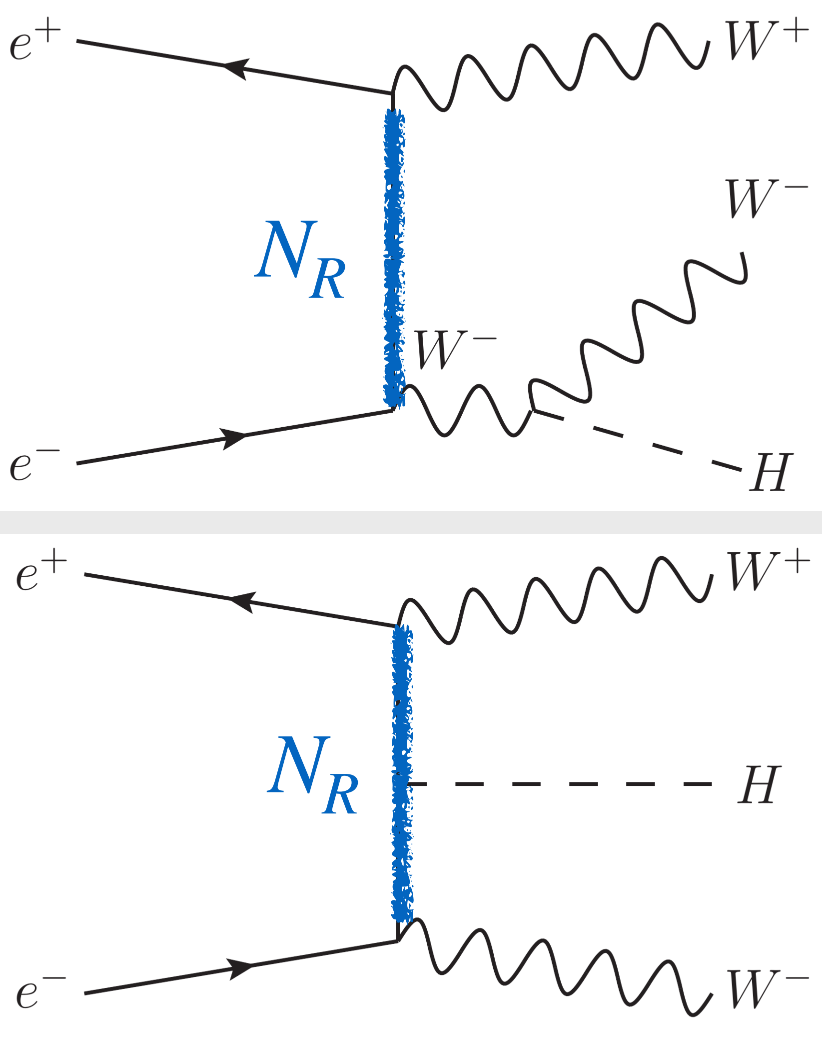
$$\mathcal{L}_{inverse} = -Y_\nu \overline{L}\tilde{\phi}\nu_R - M_R \overline{\nu_R^c} X - \frac{1}{2}\mu_X \overline{X^c} X + \text{h.c.}$$



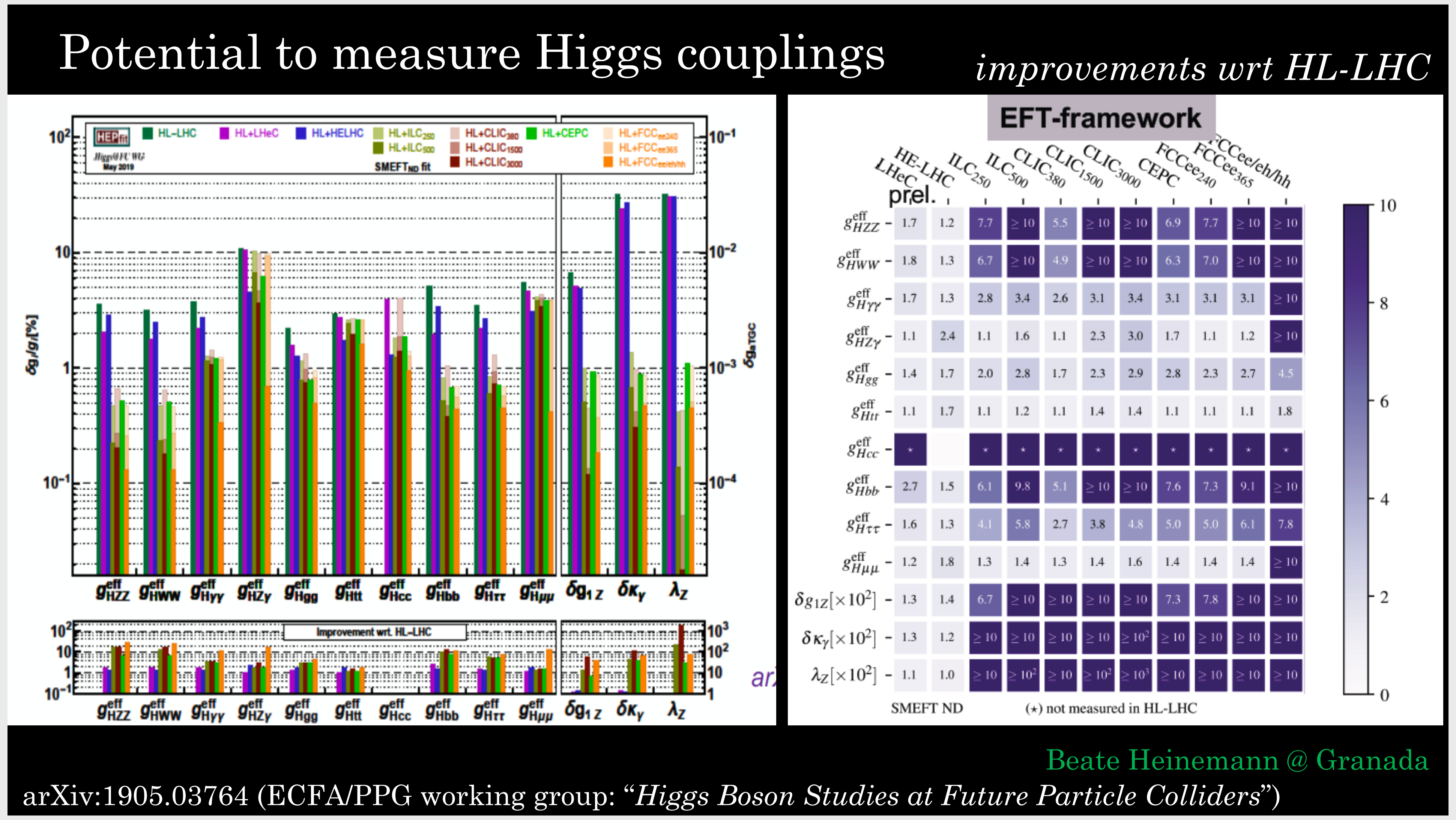
$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$

$$m_\nu \approx \frac{m_D^2}{M_R^2}\mu_X$$





large deviations both at $\sqrt{s} \sim M_R$ and $\sqrt{s} > M_R$



Potential to measure Higgs couplings

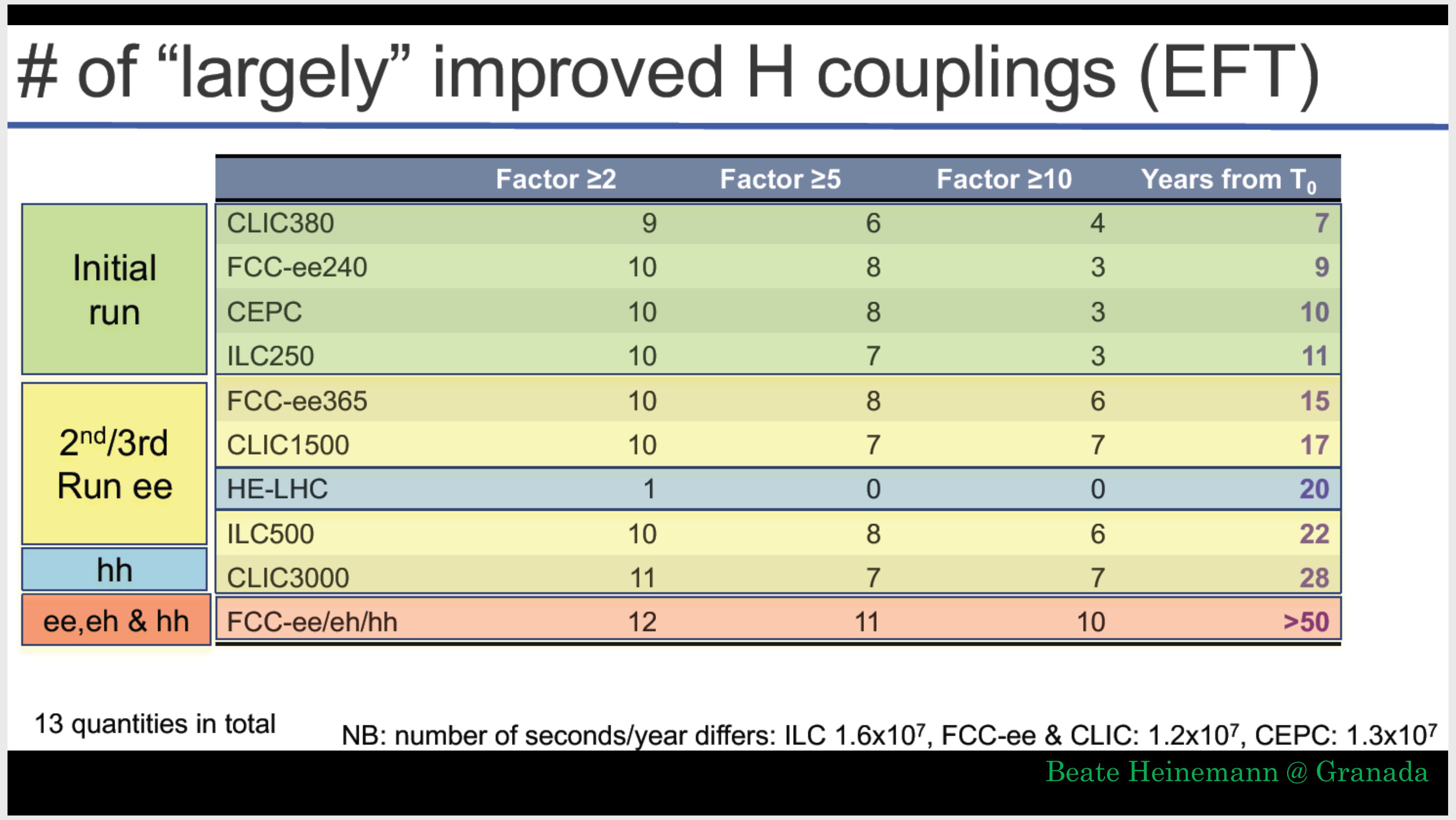
improvements wrt HL-LHC

	LHeC	HE-LHC	ILC$_{250}$	ILC$_{500}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCCee$_{240}$	FCCee$_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
g^{eff}_{Htt}	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
g^{eff}_{Hcc}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{eff}_{H\mu\mu}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta \kappa_{\gamma}[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10^2	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	≥ 10^2	≥ 10	≥ 10^2	≥ 10^3	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured in HL-LHC

Beate Heinemann @ Granada

arXiv:1905.03764 (ECFA/PPG working group: “*Higgs Boson Studies at Future Particle Colliders*”)



of “largely” improved H couplings (EFT)

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2^{nd}/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

13 quantities in total

NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3×10^7

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