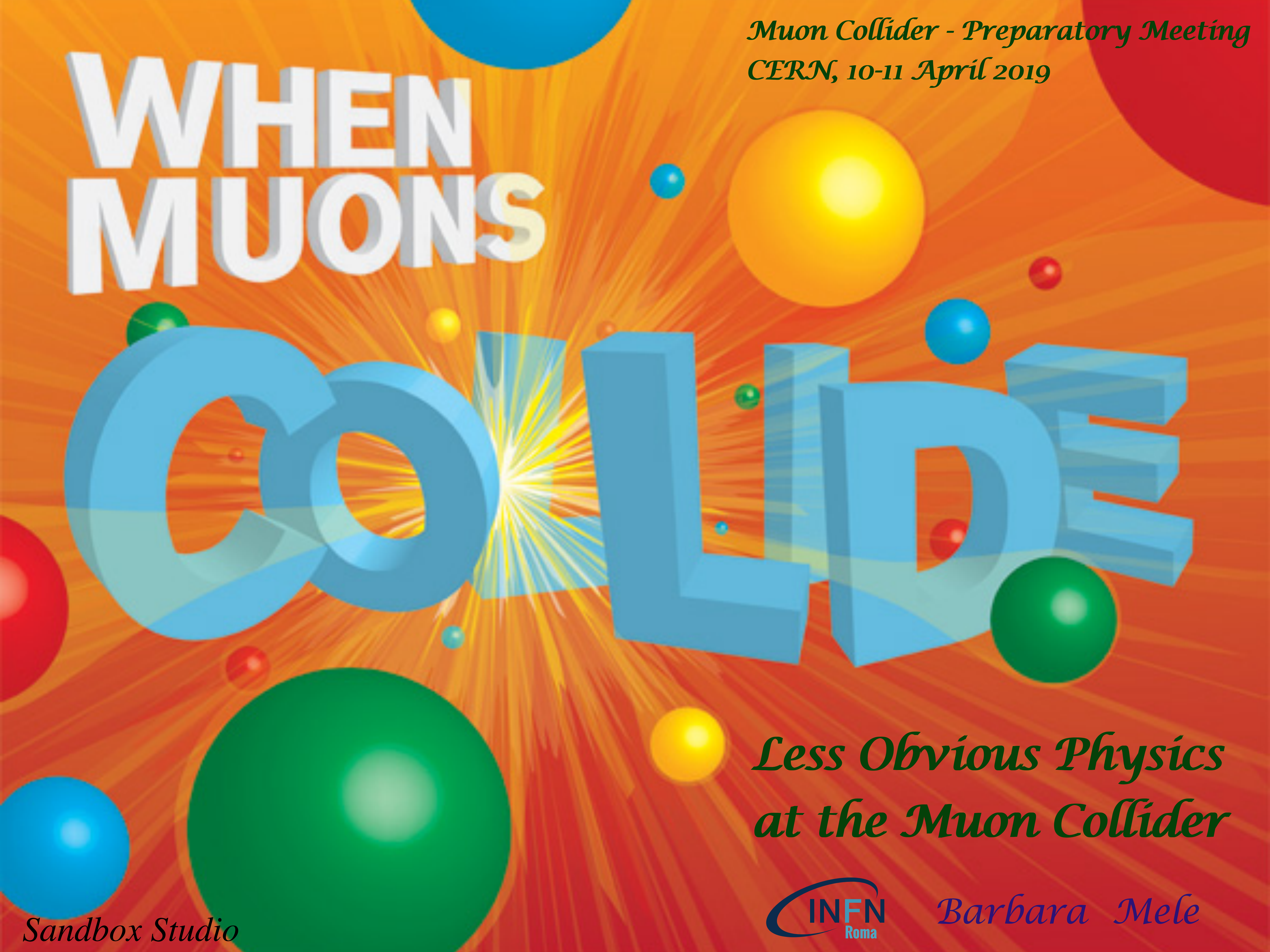

Sandbox Studio

Muon Collider - Preparatory Meeting
CERN, 10-11 April 2019

Less Obvious Physics at the Muon Collider

INFN Roma
Barbara Mele

our "reference frame"

μ+ → ← μ−

$\sqrt{S_{\mu\mu}} \sim 10, 14, 30$ TeV

✱ as envisaged in :

Input to the European Particle Physics Strategy Update

Muon Colliders

The Muon Collider Working Group
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Muon colliders have a great potential for high-energy physics. They can offer collisions of point-like particles at very high energies, since muons can be accelerated in a ring without limitation from synchrotron radiation. However, the need for high luminosity faces technical challenges which arise from the short muon lifetime at rest and the difficulty of producing large numbers of muons in bunches with small emittance. Addressing these challenges requires the development of innovative concepts and demanding technologies.

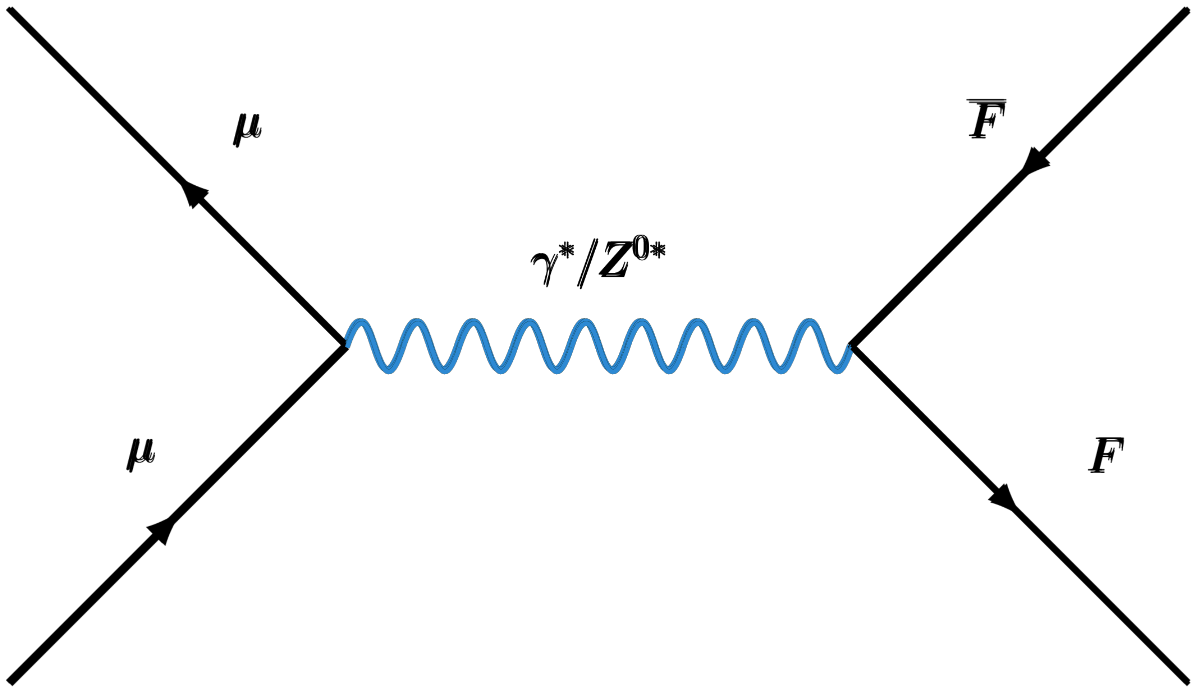
The document summarizes the work done, the progress achieved and new recent ideas on muon colliders. A set of further studies and actions is also identified to advance in the field. Finally, a set of recommendations is listed in order to make the muon technology mature enough to be favourably considered as a candidate for high-energy facilities in the future.

* what can one do with muon collisions

@ $\sqrt{S_{\mu\mu}}$ up to a few tens of TeV ???

* what can one do with muon collisions @ $\sqrt{S_{\mu\mu}}$ up to a few tens of TeV ???

FIRST AND FOREMOST



$$\mu^+\mu^- \to F\bar{F}$$

* plain pair production of new heavy states...

$m_F \lesssim \sqrt{S_{\mu\mu}}/2$

~ 5, 7,15 TeV !!!

→ Luminosity ruled by heavy pair x-section

rate for new p.le pair production :

$$\sigma_{EW} \sim \sigma(\mu^+\mu^- \to \gamma^* \to e^+e^-) \sim \frac{4\pi\alpha^2}{3\,S}$$

point x-section

$$\to 1\,fb\,(\frac{10\,TeV}{\sqrt{S}})^2$$

no m_e dependence up to $m_e \sim \sqrt{S}/2$!

$$L \sim 10^{35} cm^{-2} s^{-1} \sim 1\,ab^{-1}/y$$

$$\to 1000\;evs/y\;(\frac{10\,TeV}{\sqrt{S}})^2$$

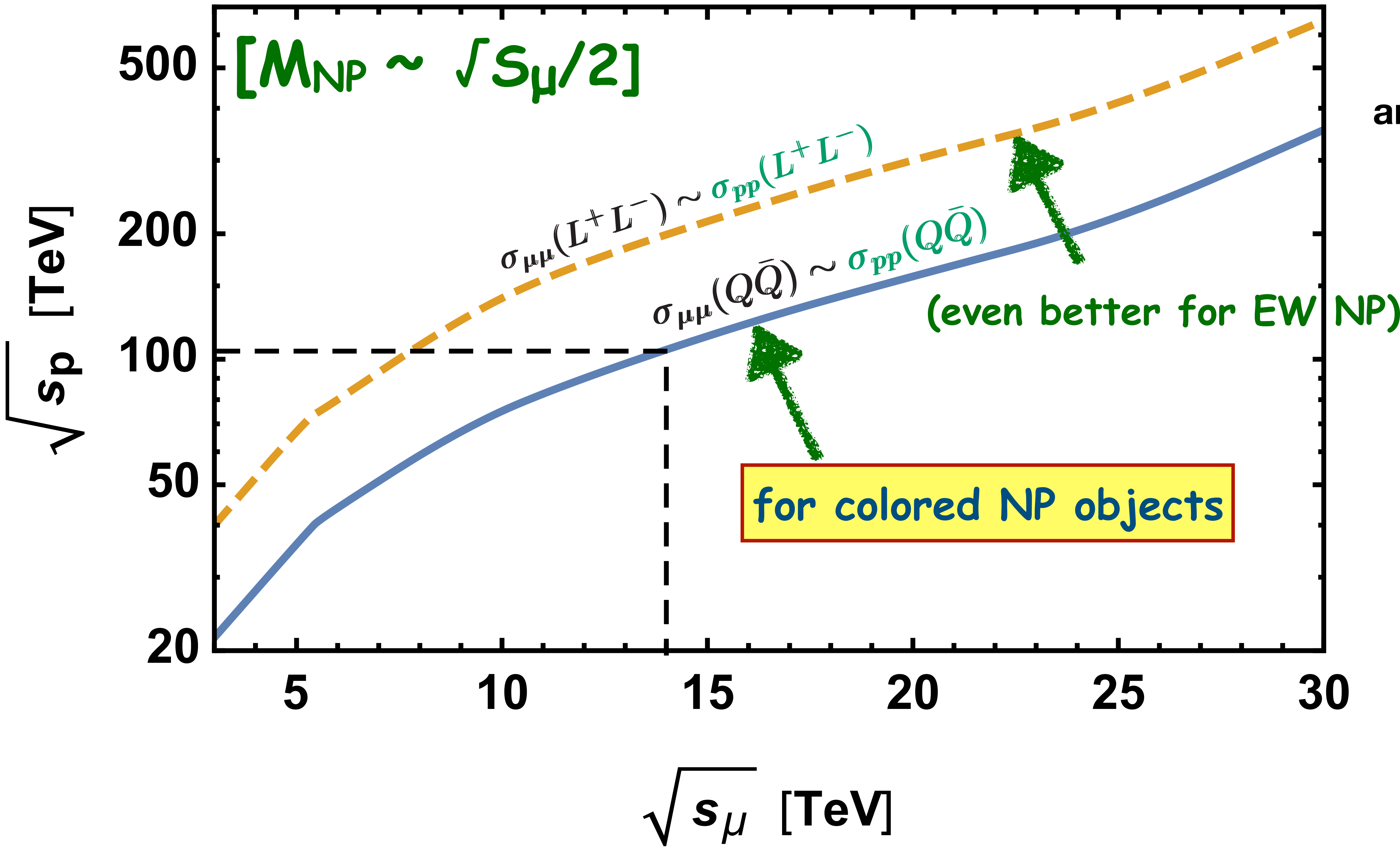
10^4 evs /(10 years)

$\delta_{stat} \sim 1\%$

$\sqrt{S_{\mu\mu}}$	$\int L_{10y}$
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}
30 TeV	100 ab^{-1}

$L \sim 10^{36} cm^{-2} s^{-1}$

"equivalent" reach in pp after rescaling for pdf's



arXiv:1901.06150

- μμ @ 14 TeV → pp @ 100 $(200)_{EW}$ TeV !
- μμ @ 30 TeV → pp @ 350 $(600)_{EW}$ TeV !!

yet unexplored pheno !!!

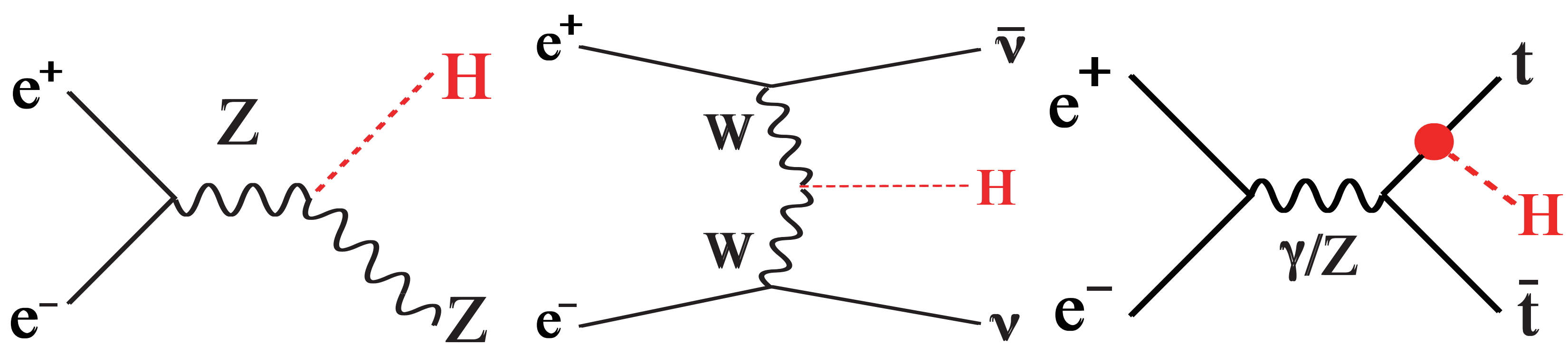
WHAT ELSE ?

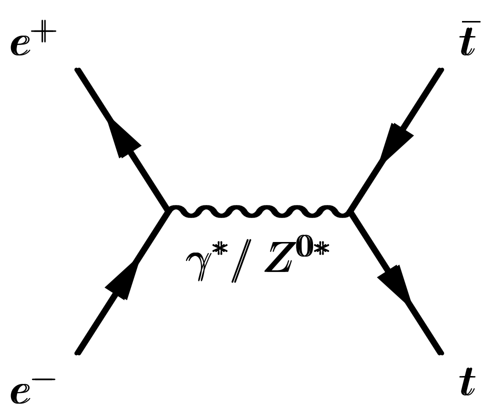
WHAT ELSE ?

✱ μ+μ- scattering very similar to e+e- one

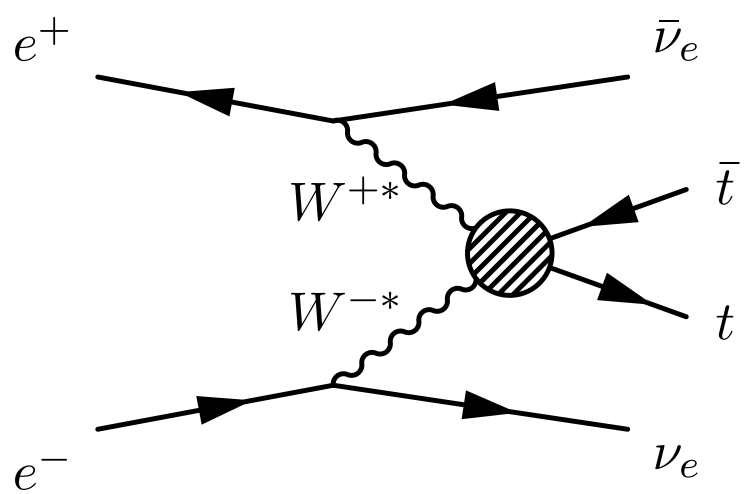
[apart from QED-radiation and (tiny !) Yukawa effects]

→ try and extrapolate CLIC studies @3TeV to higher √S





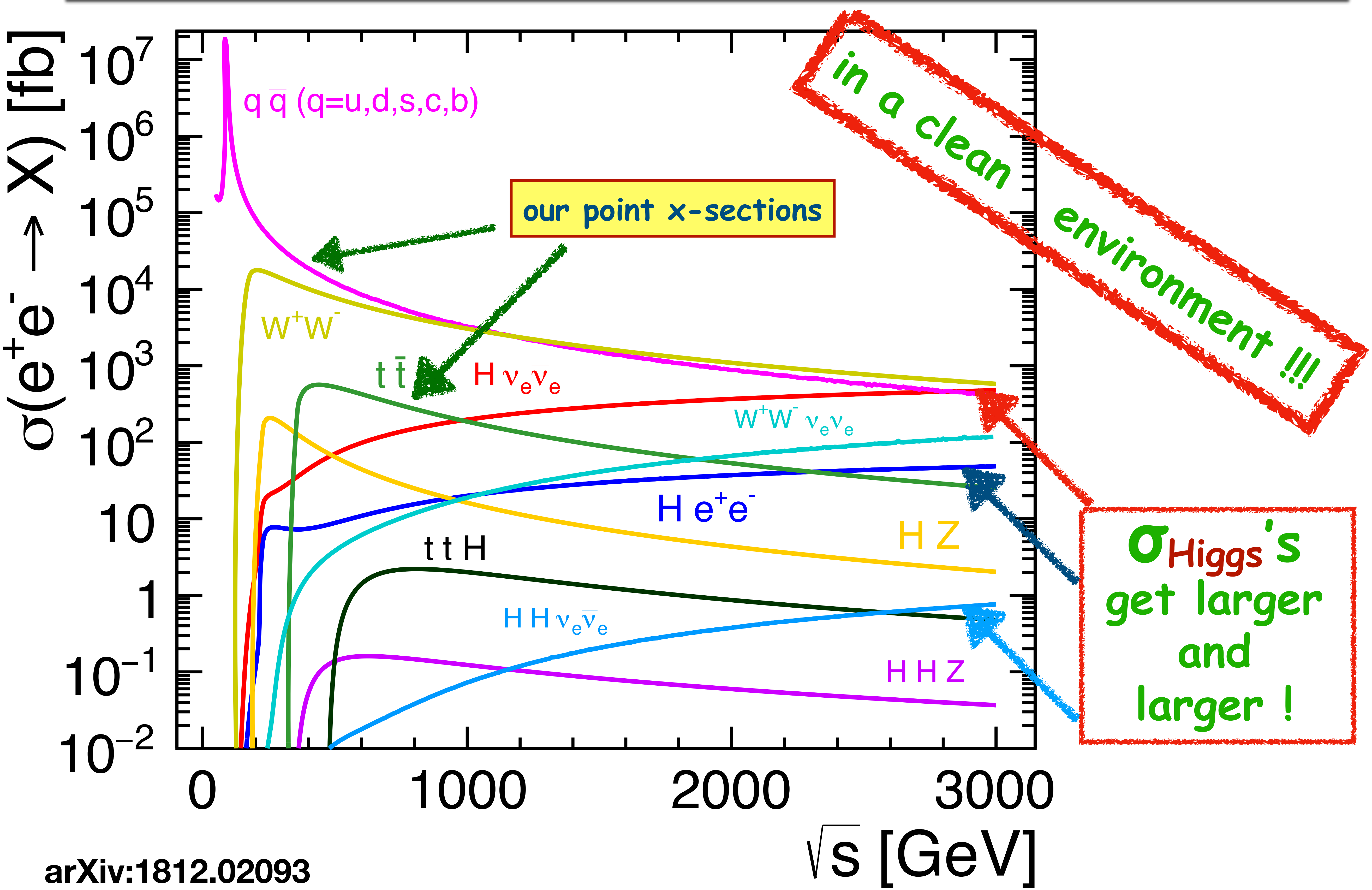
$e^+e^- \to t\bar{t}$



$e^+e^- \to t\,\bar{t}\,\nu_e\bar{\nu}_e$

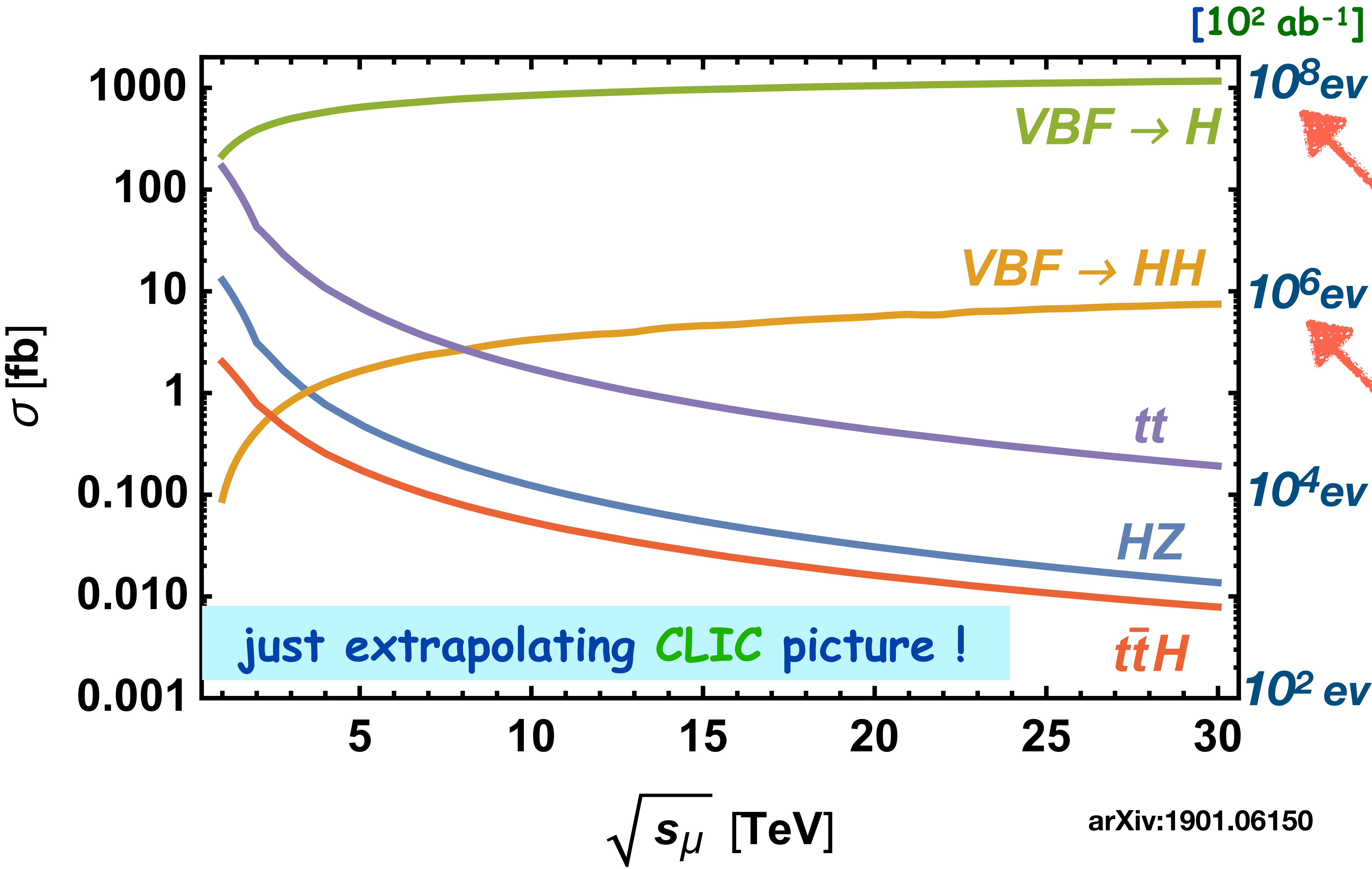
$$(e^+, e^-, \nu_e, \bar{\nu}_e) \to (\mu^+, \mu^-, \nu_\mu, \bar{\nu}_\mu)$$

point x-sections dominant at CLIC !



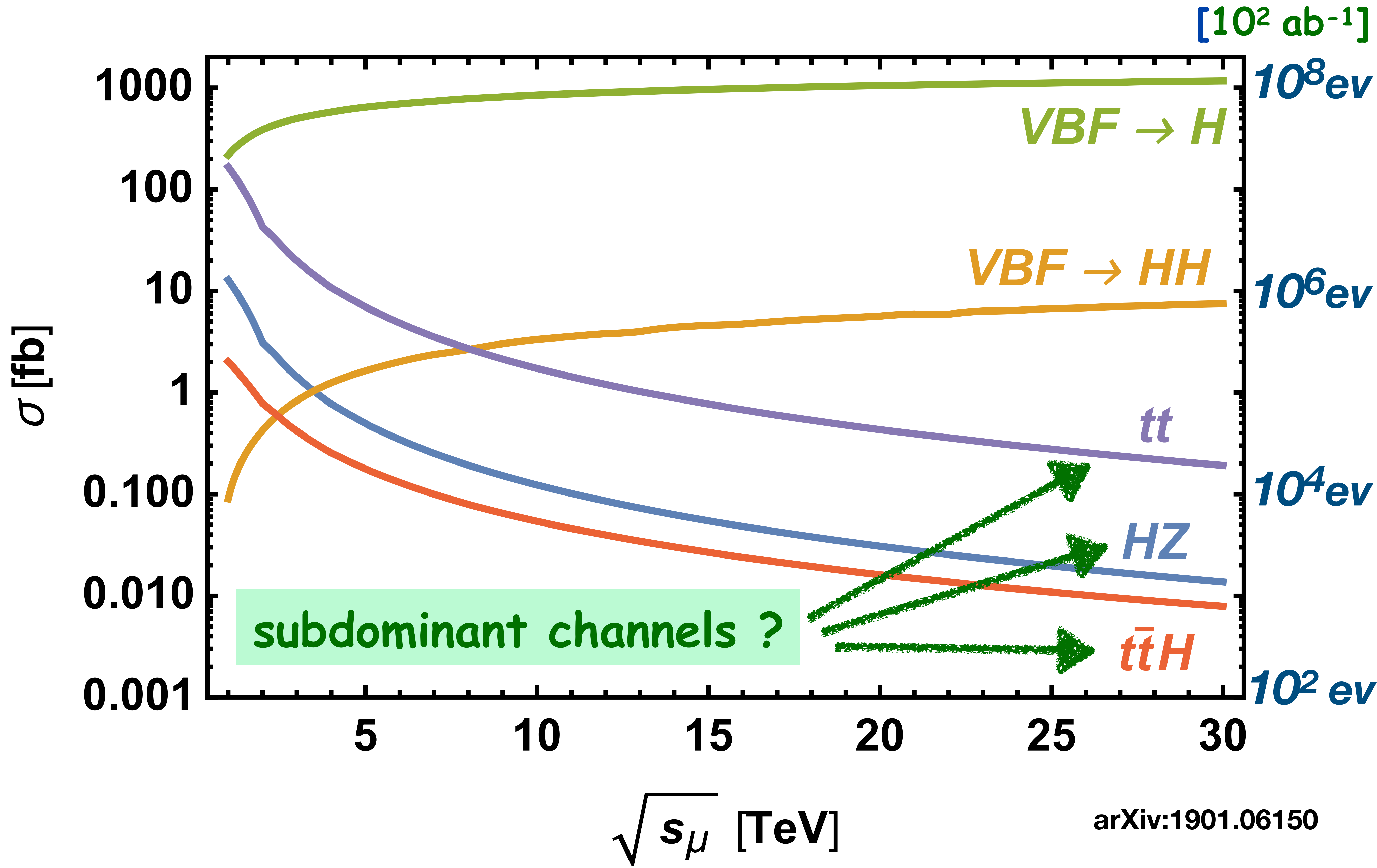
arXiv:1812.02093

at $\sqrt{s_{\mu\mu}}$~10-30TeV [L~10$^{1-2}$ ab^{-1}] plenty of Higgs's !



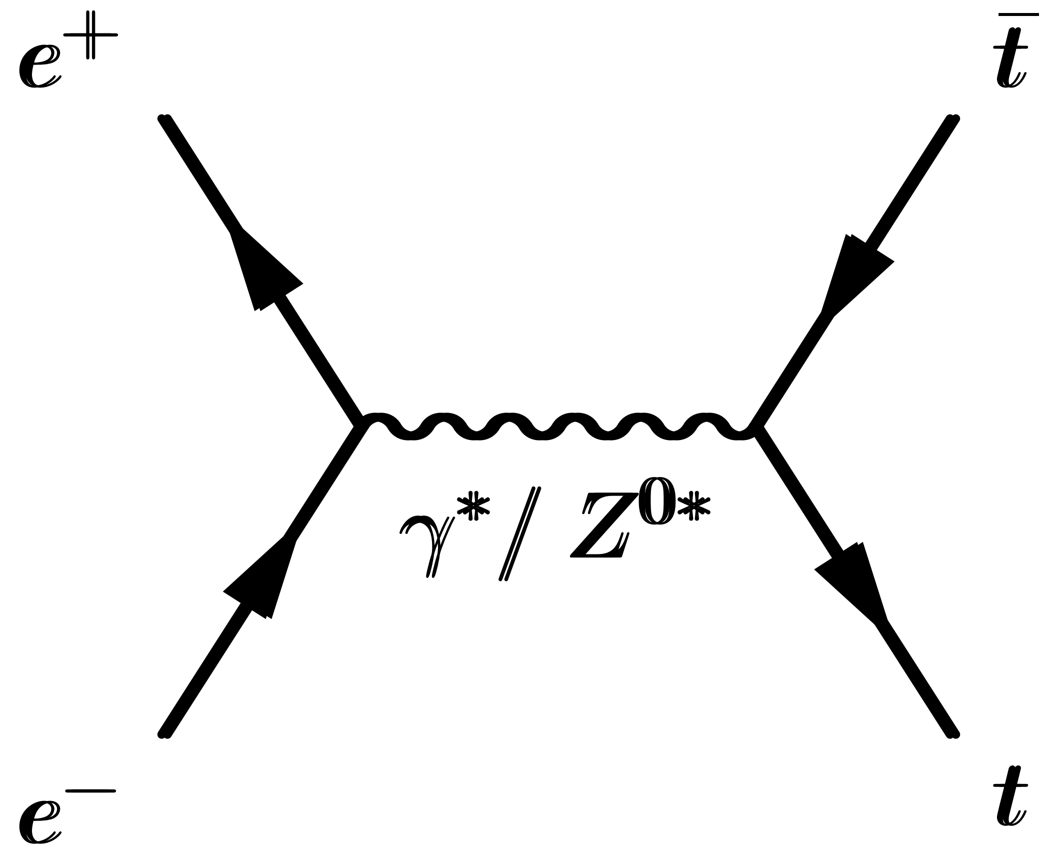
arXiv:1901.06150

at $\sqrt{s_{\mu\mu}}$~10-30TeV plenty of Higgs's with L ~ 10^{1-2} ab^{-1}

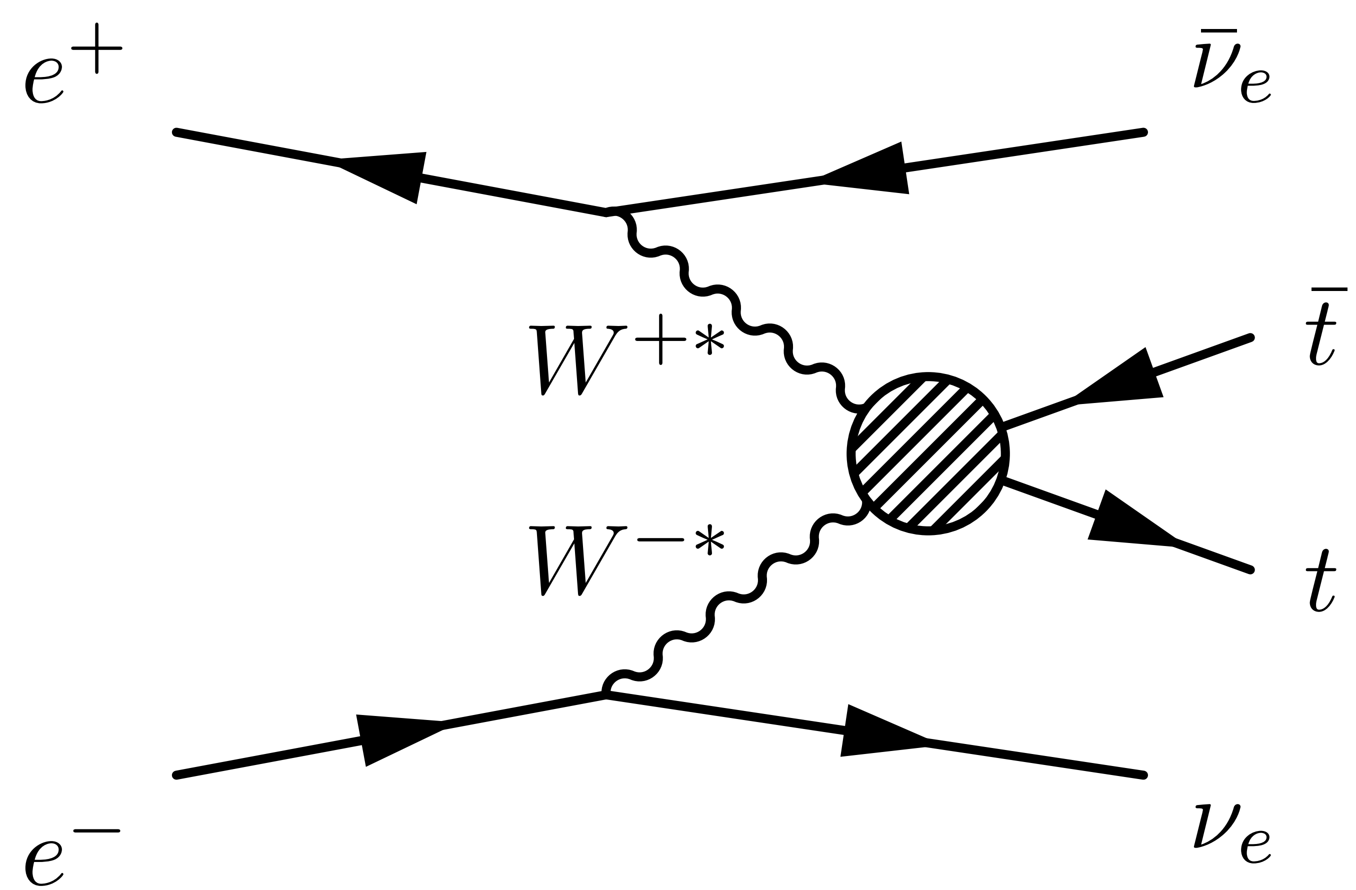


arXiv:1901.06150

$\mu^+\mu^- \to X$ versus $W^+W^- \to X\,\nu\nu$

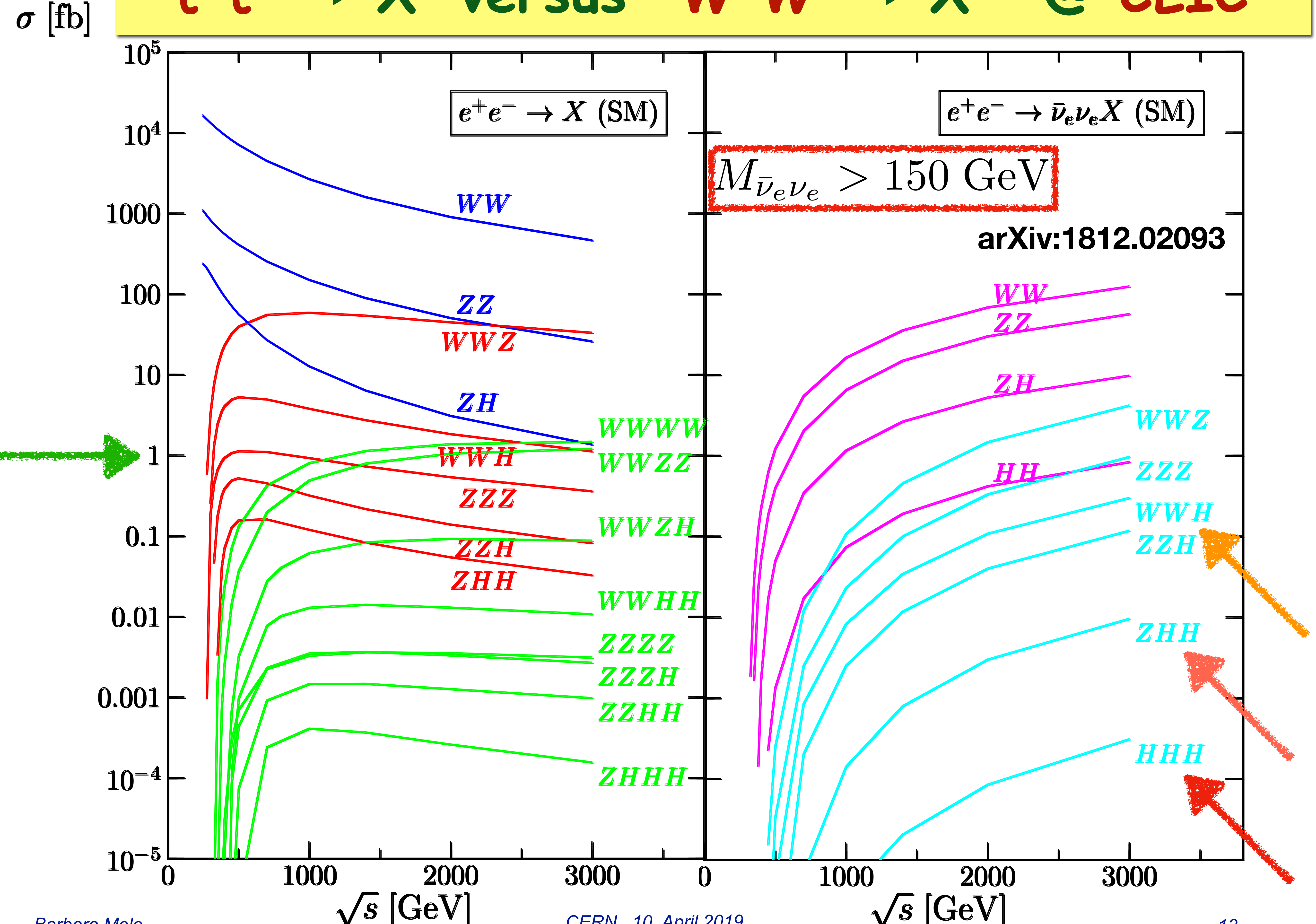


$e^+e^- \to t\bar{t}$

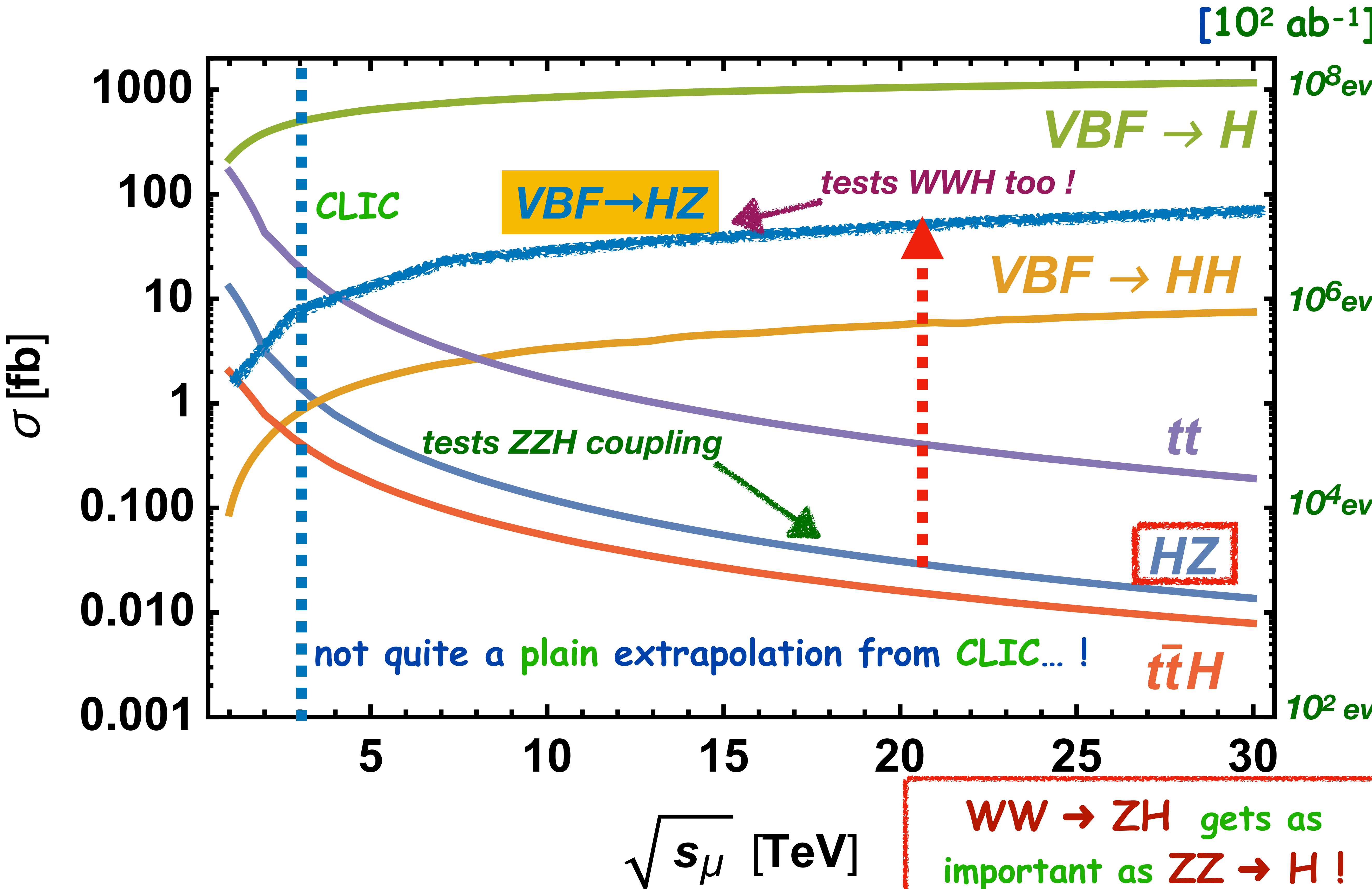


$e^+e^- \to t\,\bar{t}\,\nu_e\bar{\nu}_e$

$\ell^+\ell^- \to X$ versus $W^+W^- \to X$ @ CLIC

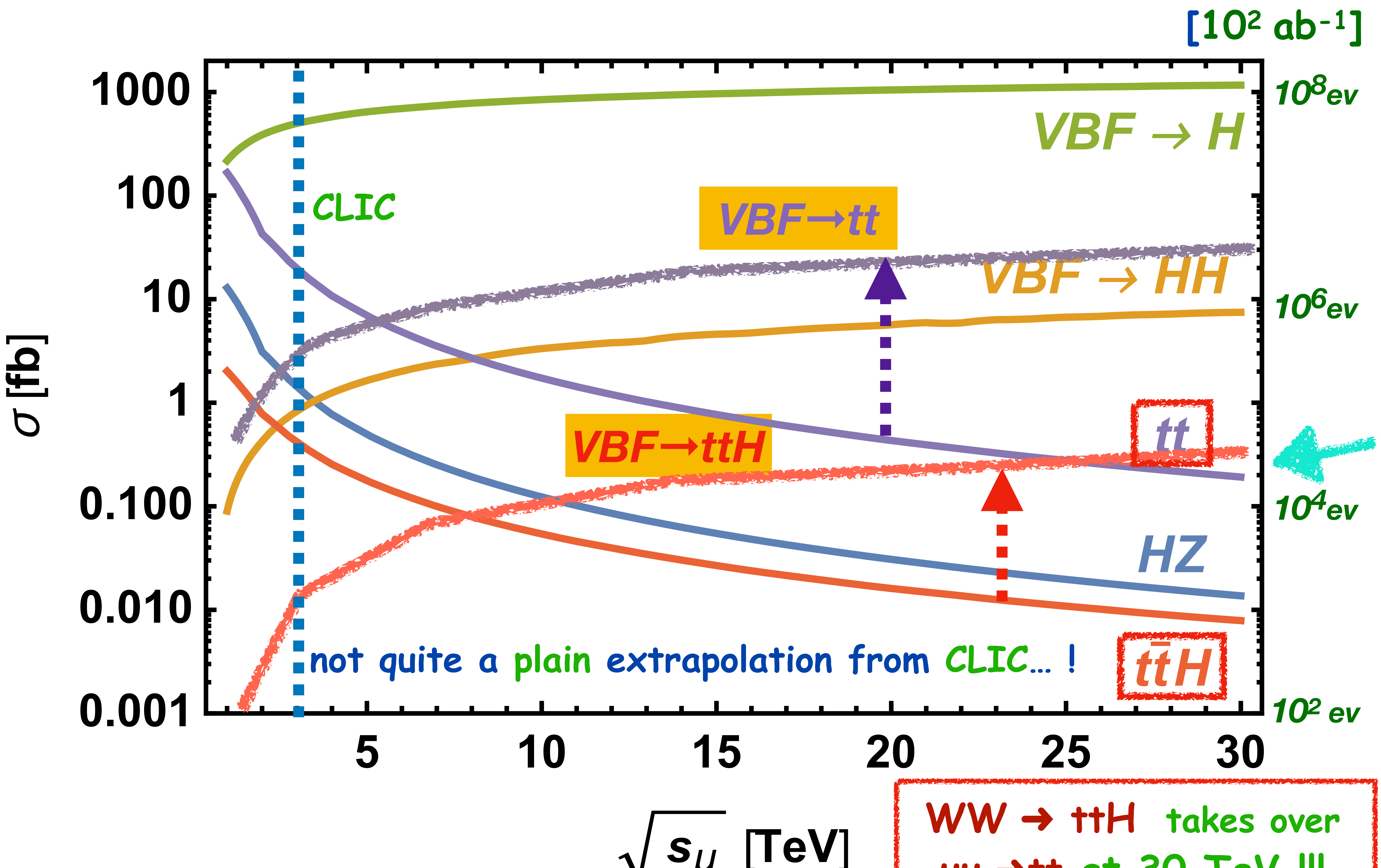


$\ell^+\ell^- \rightarrow ZH$ vs $WW \rightarrow ZH$



WW → ZH gets as important as ZZ → H !

$\ell^+\ell^- \rightarrow$ tt (H) vs WW$\rightarrow$ tt (H)



WW → ttH takes over μμ →tt at 30 TeV !!!

VBF events (green) + $\sigma_{WW \to X} / \sigma_{\mu\mu \to X}$ (red)

# events	3 TeV/5/ab	(VBF)/(s-ch)3TeV	14 TeV/20/ab	(VBF)/(s-ch)14TeV	30 TeV/100/ab	(VBF)/(s-ch)30TeV
H	2,5E+06		1,9E+07		1,2E+08	
HZ	4,9E+04	7	9,0E+05	700	7,4E+06	5300
HZZ	6,0E+02	1,5	3,2E+04	180	3,7E+05	1500
HWW	1,5E+03	0,3	6,8E+04	30	7,6E+05	190
HH	4,1E+03		8,8E+04		7,4E+05	
HHZ	4,7E+01	0,3	2,8E+03	40	3,3E+04	300
HHZZ	4,6E-01	0,1	7,8E+01	16	1,2E+03	130
HHWW	1,2E+00	0,02	1,8E+02	1	2,9E+03	1
HHH	1,5E+00		1,4E+02		1,9E+03	
HHHZ	2,4E-02	0,3	3,8E+00	12	5,1E+01	100

[MadGraph]

tt	2,6E+04	0,3	4,2E+05	24	3,1E+06	160
ttH	6,5E+01	0,03	3,0E+03	5	3,1E+04	40
ttZ	5,5E+02	0,07	2,6E+04	7	2,8E+05	50
ttHH	1,7E-01	0,006	1,3E+01	1	1,6E+02	10
ttHZ	1,8E+00	0,01	2,0E+02	2	2,7E+03	14
ttZZ	7,0E+00	0,03	1,2E+03	4	1,7E+04	30
ttWW	1,4E+01	0,008	2,2E+03	0,8	3,0E+04	5
tttt	3,4E-01	0,01	2,2E+01	0,4	2,1E+02	2

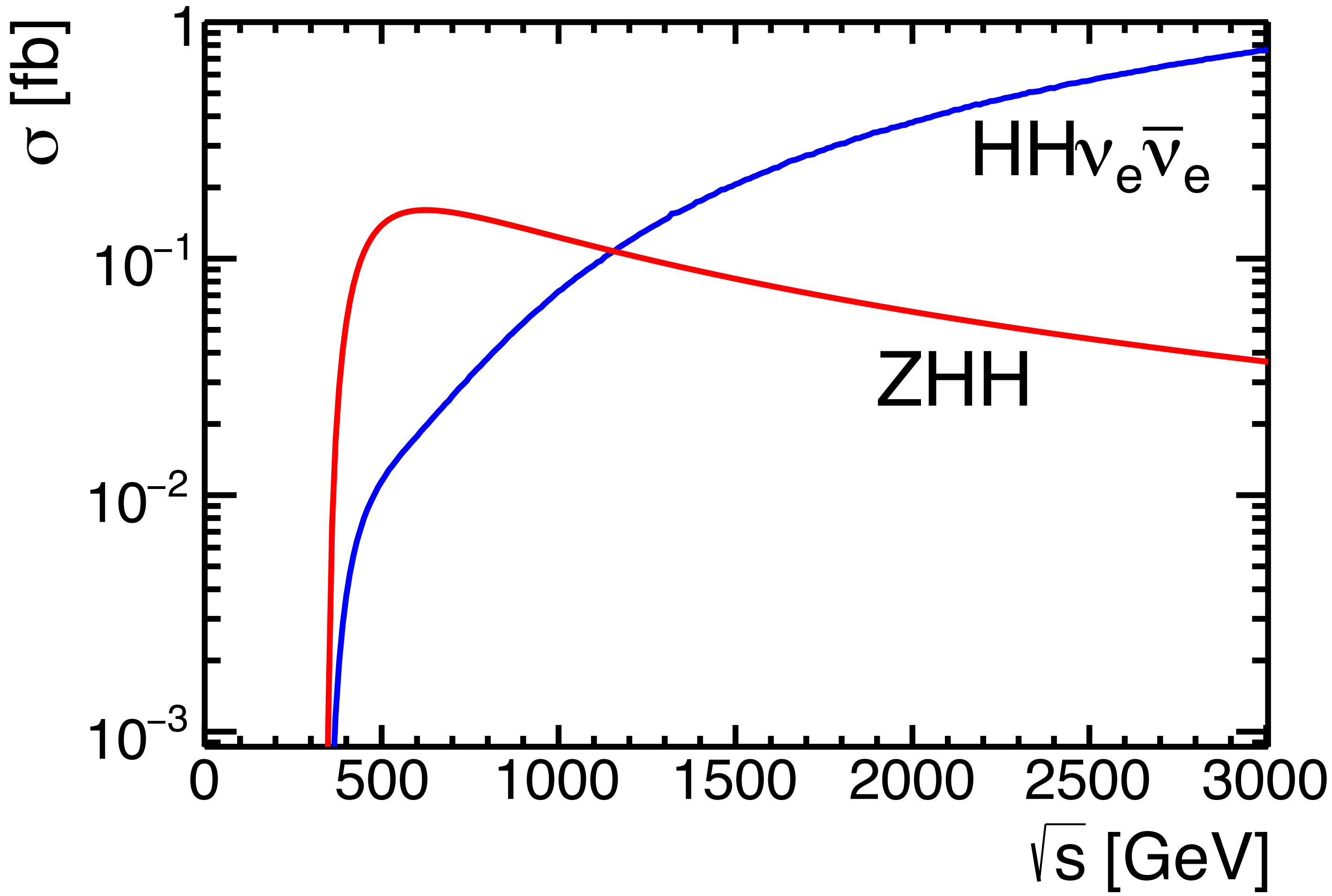
Higgs self-interaction couplings

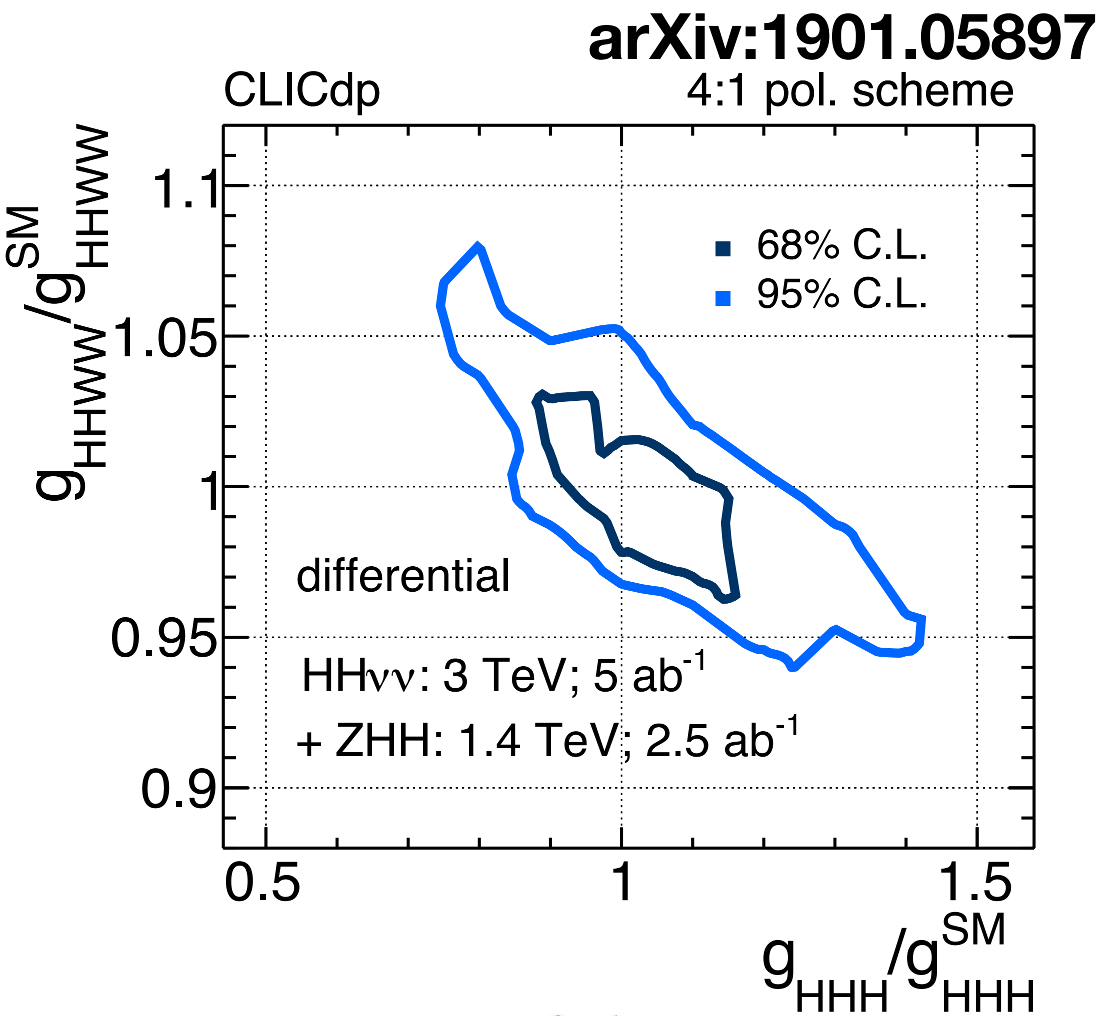
* the "tough topic" even at "most-future" colliders
* most interesting to measure from theory side....

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \boxed{\lambda_3} \frac{m_h^2}{2v} h^3 - \boxed{\lambda_4} \frac{m_h^2}{8v^2} h^4$$

$$\lambda_3^{SM} = \lambda_4^{SM} = 1$$

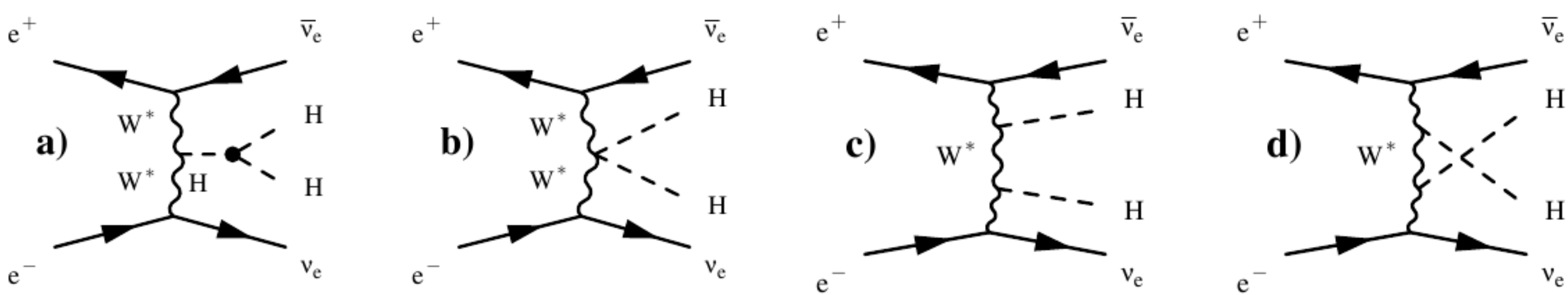
trilinear Higgs coupling at CLIC





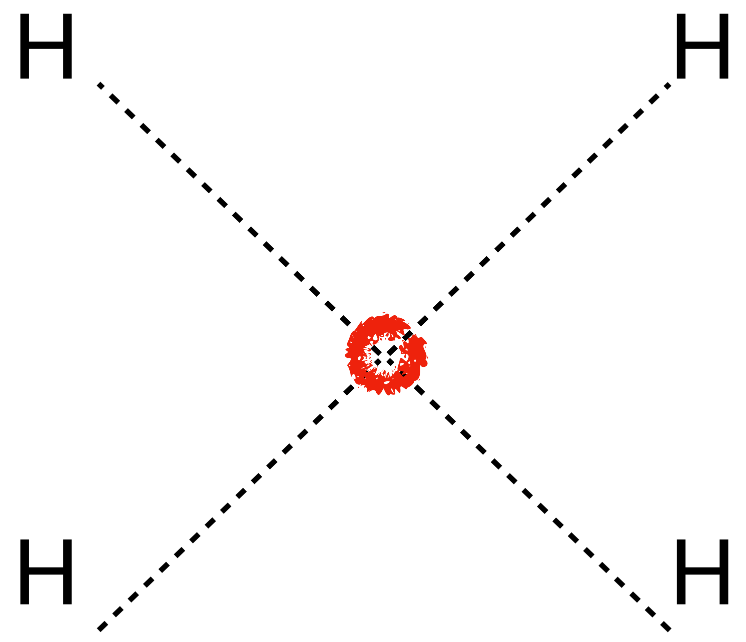
$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

$$\Delta\lambda_3 \sim 10\%$$



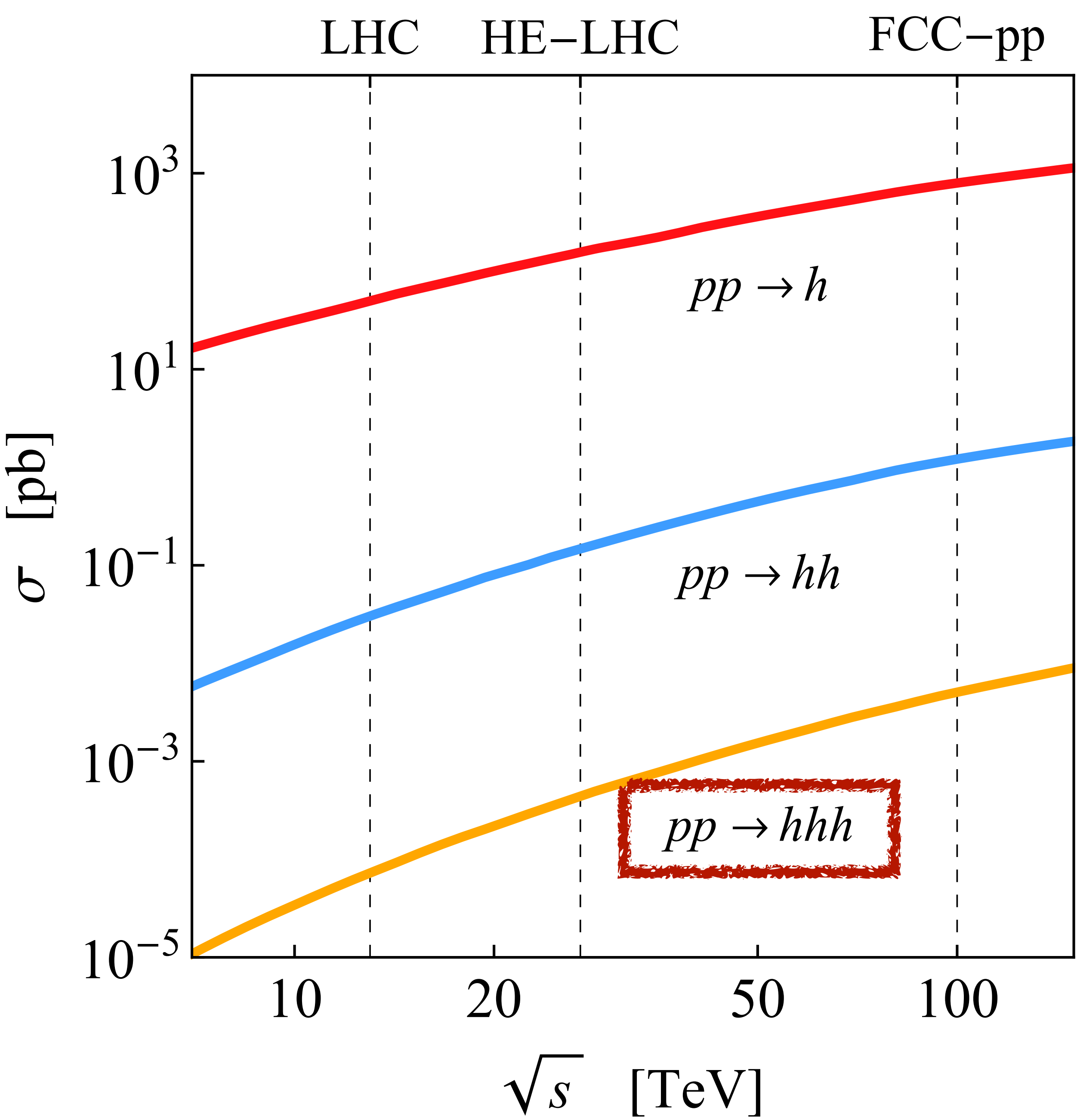
what about 4-linear Higgs coupling ?

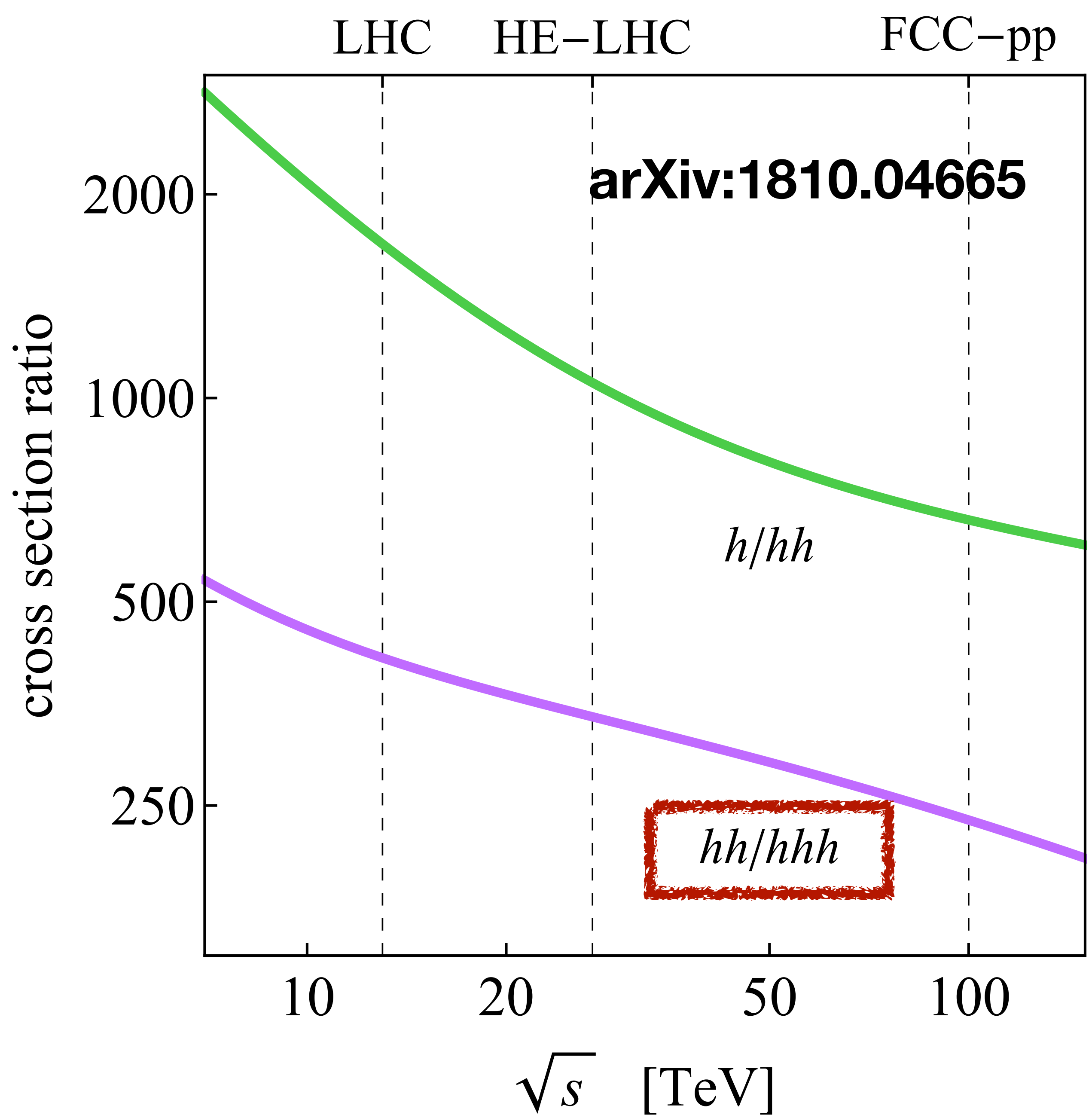
$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$



FCC-pp : λ_4

$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

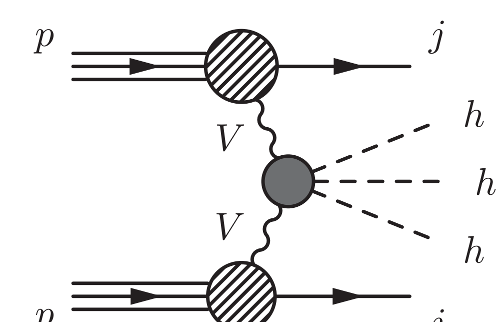




hhh → $(b\bar{b})(b\bar{b})(\gamma\gamma)$ [optimistic scenario !!!] :

$\lambda_4 \in [\sim -4, \sim +16]$ at 100 TeV, 30 ab^{-1}

(95%C.L.)



arXiv:1606.09408

anomalous Higgs self-coupling parametrization

$$\lambda_{hhh}^{\rm SM} = \lambda_{hhhh}^{\rm SM} = \frac{m_h^2}{2v^2}$$

$$V_{\rm h} = \frac{m_h^2}{2} h^2 + (1+\kappa_3)\lambda_{hhh}^{\rm SM} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{\rm SM} h^4$$

typical of well-behaved EFTs ➜ ➜ $\kappa_3 = \bar{c}_6$ $\kappa_4 = 6\,\bar{c}_6 + \bar{c}_8$

$$V^{\rm NP}(\Phi) \equiv \sum_{n=3}^{\infty} \frac{c_{2n}}{\Lambda^{2n-4}} \left(\Phi^\dagger\Phi - \frac{1}{2}v^2\right)^n$$

$$\bar{c}_6 \equiv \frac{c_6 v^2}{\lambda^{SM}\Lambda^2} = \kappa_3$$

$$\bar{c}_8 \equiv \frac{4 c_8 v^4}{\lambda^{SM}\Lambda^4} = \kappa_4 - 6\kappa_3$$

two interesting benchmarks :

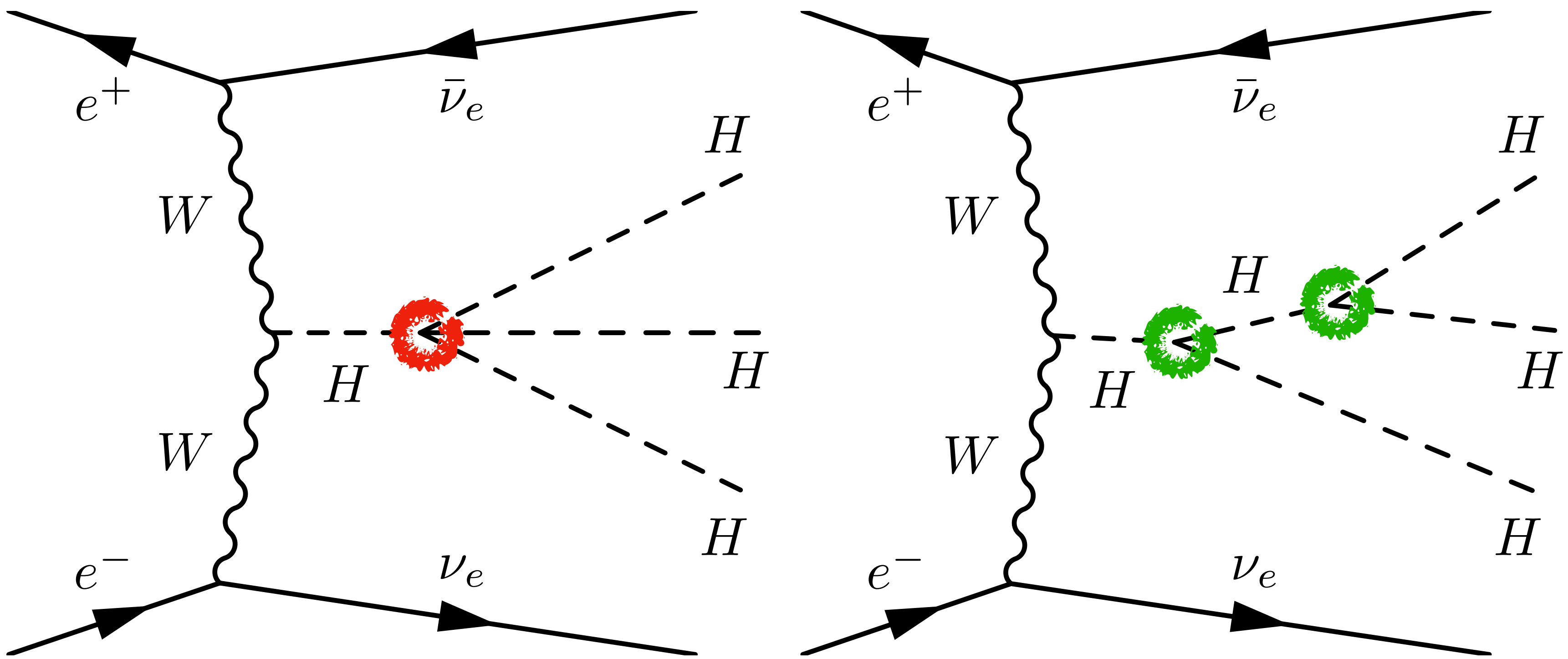
- $g_{3H} = g_{3H}^{SM}\,,\ g_{4H} = \Big(1+\kappa_4\Big) g_{4H}^{SM}$ **("free" κ_4)**
- $g_{3H} = \Big(1+\kappa_3\Big) g_{3H}^{SM}\,,\ g_{4H} = \Big(1+6\kappa_3\Big) g_{4H}$

well-behaved EFTs

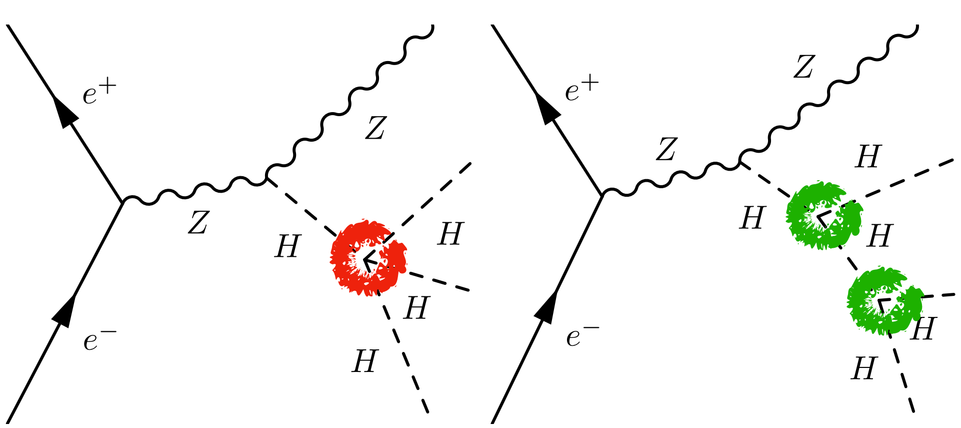
otherwise : ***be agnostic about how UV dynamics modifies Higgs self-interact.s ➜ no assumption about the actual size of (κ_3,κ_4)***

$\mu^+\mu^- \to HHH\nu\bar{\nu}$, $(\nu = \nu_e, \nu_\mu, \nu_\tau)$

$$V_{\mathrm{h}} = \frac{m_h^2}{2} h^2 + (1+\kappa_3)\lambda_{hhh}^{\mathrm{SM}} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{\mathrm{SM}} h^4$$



$$\Delta = \frac{N - N_{SM}}{\sqrt{N_{SM}}} = \left(c_1\kappa_3 + c_2\kappa_4 + c_3\kappa_3\kappa_4 + c_4\kappa_3^2 + c_5\kappa_4^2 + c_6\kappa_3^3 + c_7\kappa_3^2\kappa_4 + c_8\kappa_3^4\right)$$

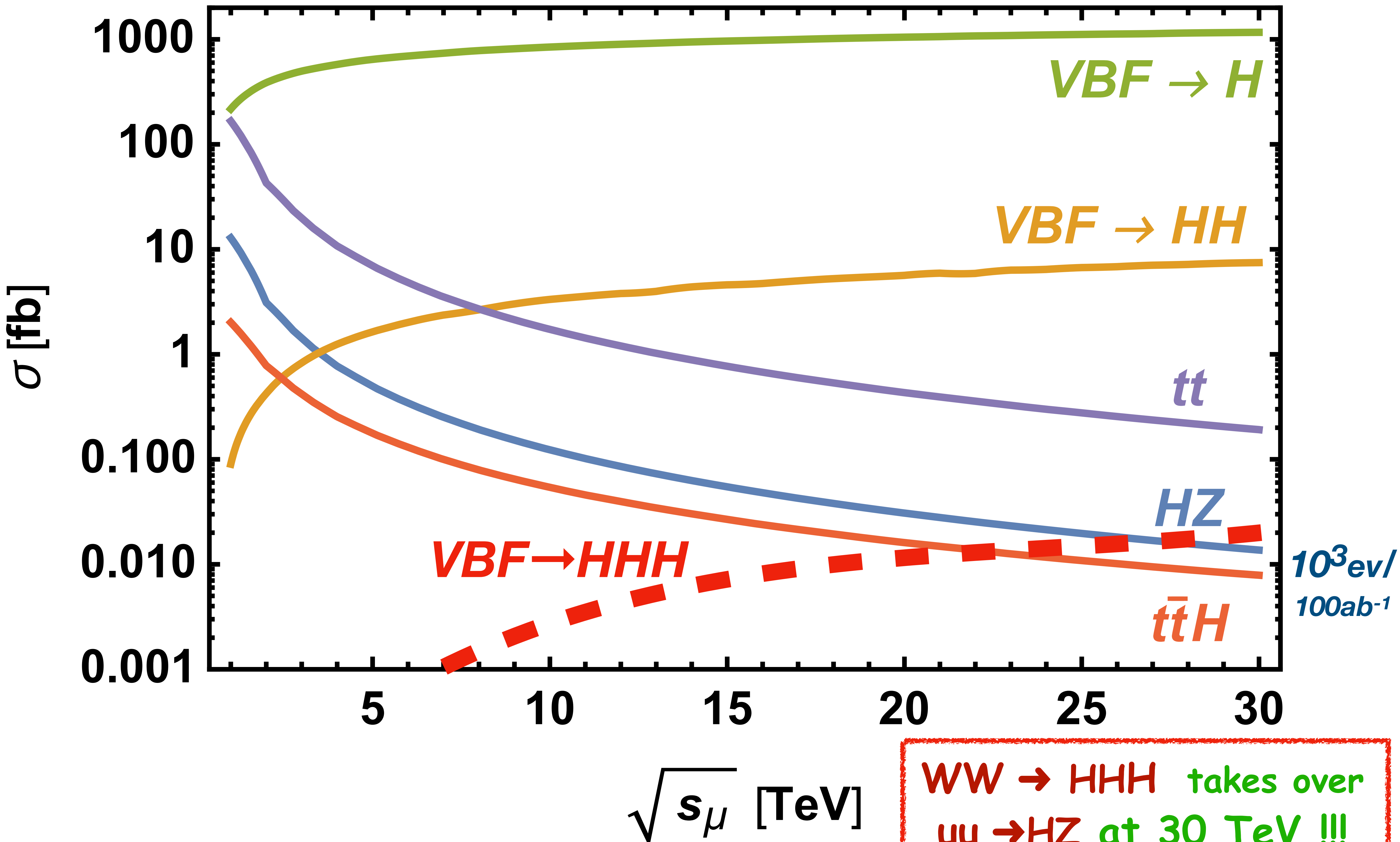


HHHZ negligible !

σ_{HHHZ} ~ 1/2 σ_{HHH} @ 3TeV

~ 1/50 σ_{HHH} @ 30TeV

VBF → HHH : SM x-sections

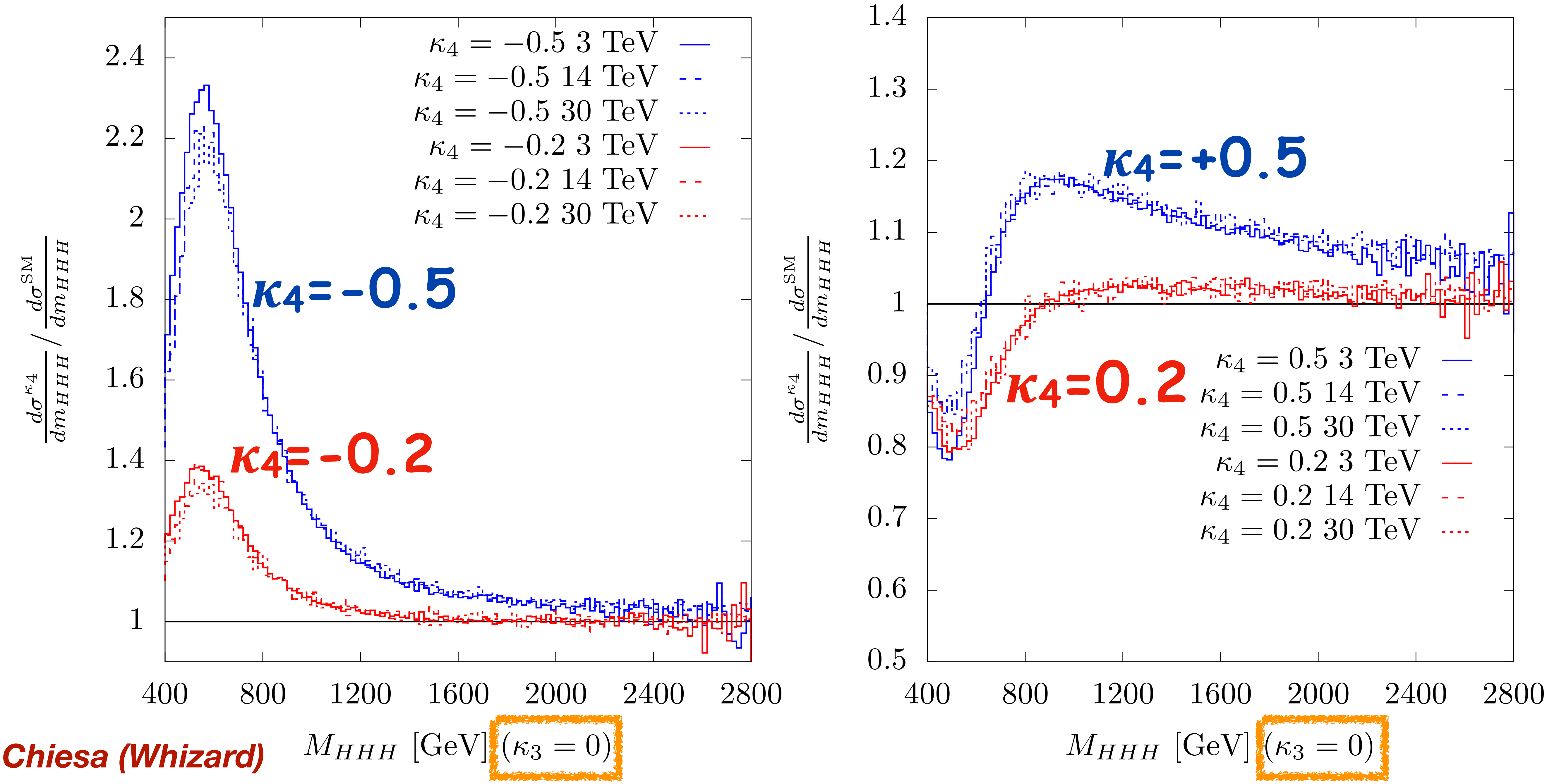


WW → HHH takes over $\mu\mu$ →HZ at 30 TeV !!!

m_{HHH} distribution versus $g_{4H} = \left(1 + \kappa_4\right) g_{4H}^{SM}$

VBF → HHH

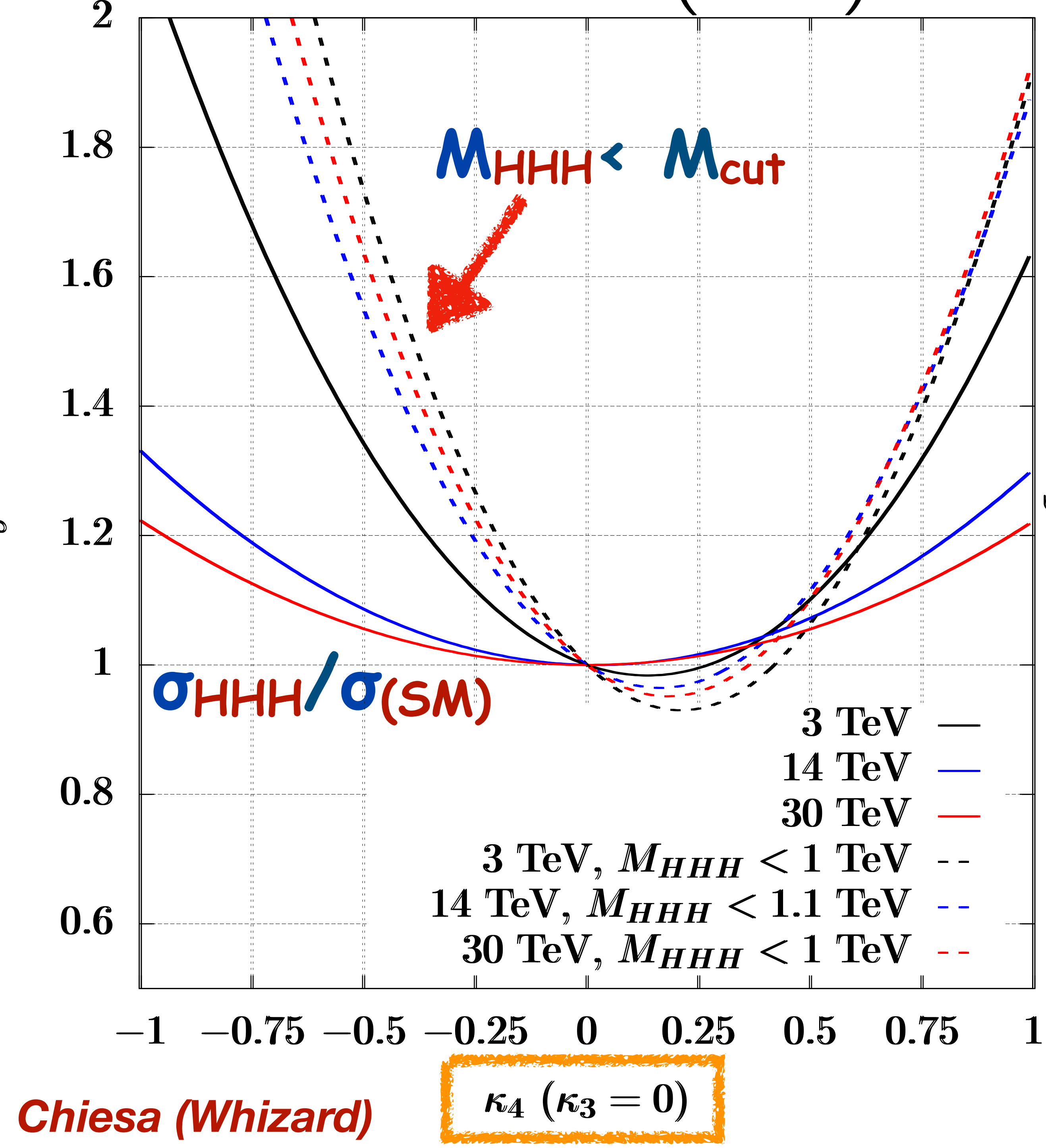
- m_{HHH} shape variation (normalized to SM shapes) insensitive to $\sqrt{S_{\mu\mu}}$!



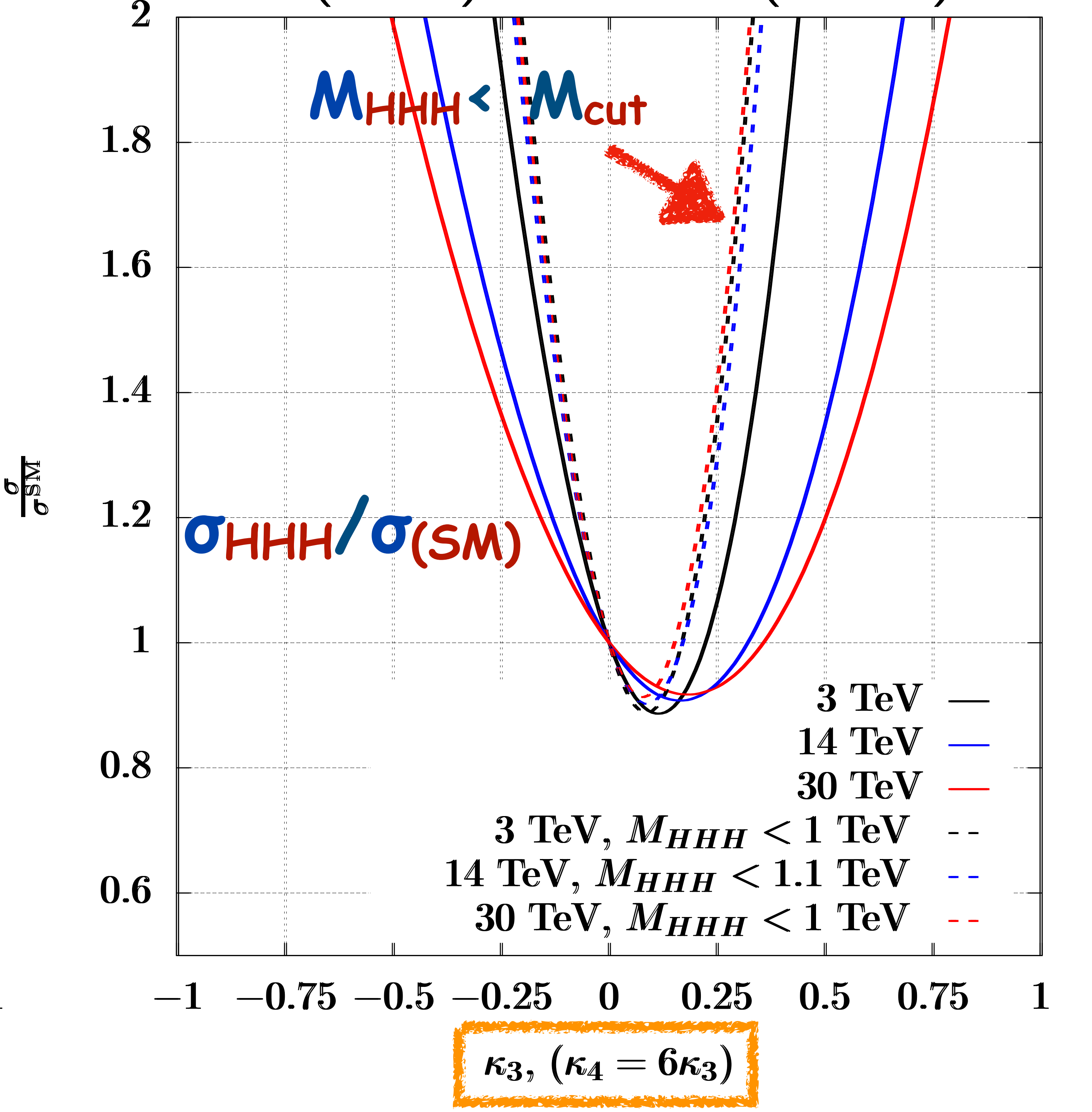
Chiesa (Whizard)

σ_{HHH} (VBF)/σ(SM) versus (κ_3, κ_4)

- $g_{3H} = g_{3H}^{SM}$, $g_{4H} = \left(1 + \kappa_4\right) g_{4H}^{SM}$



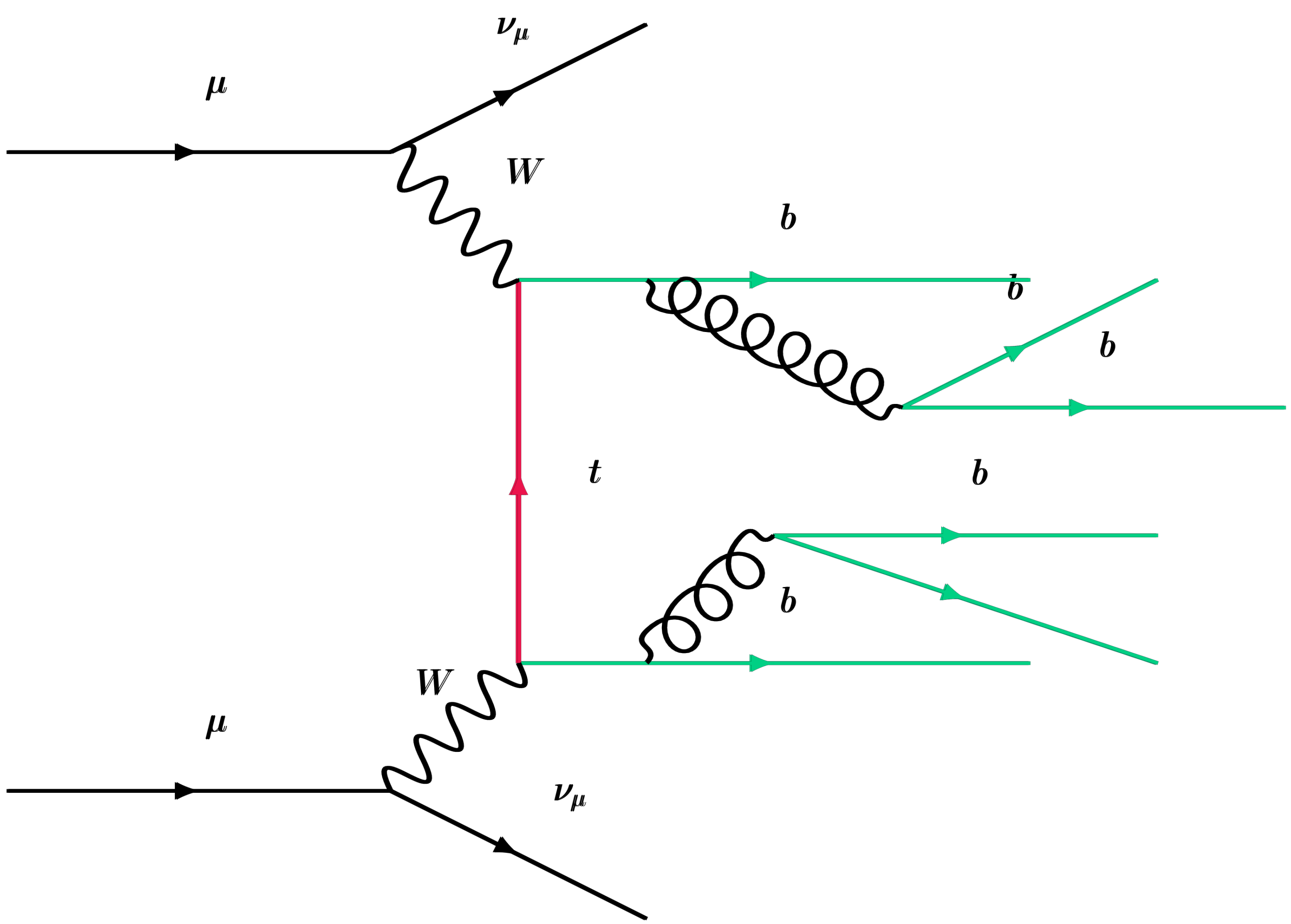
- $g_{3H} = \left(1 + \kappa_3\right) g_{3H}^{SM}$, $g_{4H} = \left(1 + 6\kappa_3\right) g_{4H}$



Chiesa (Whizard)

backgrounds to VBF → HHH

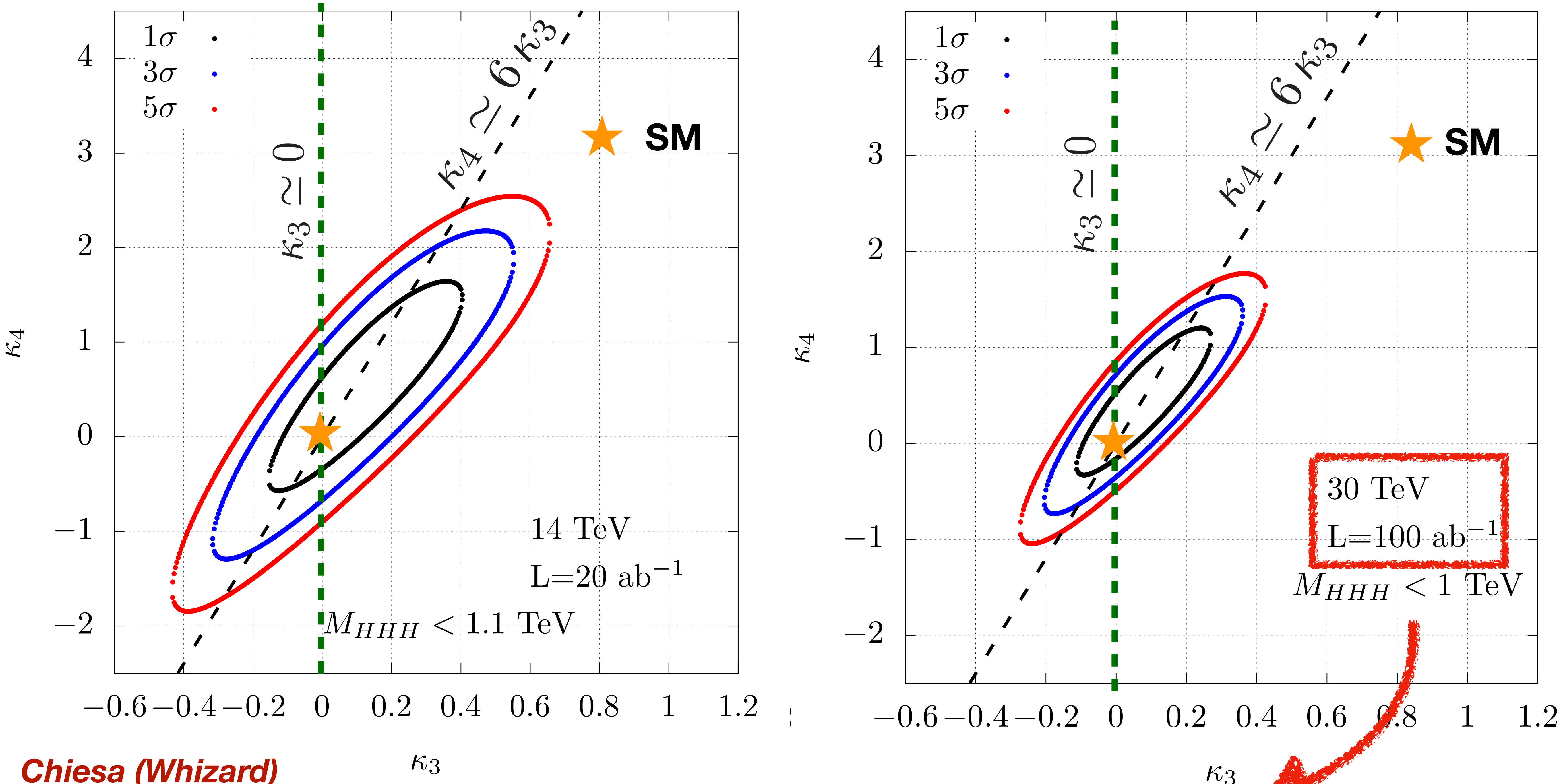
* 8-body final states (at least !)
  → hard to evaluate via MC's
* all H decay modes are relevant ! [BR(HHH → 6 b) ~ 20 %]
* 6b-jet bckgr moderate at FCC-pp [arXiv:1801.10157]
* might be S/B >> 1 at multi-TeV muon colliders...



$(N-N_{SM})/\sqrt{N_{SM}}$ versus (κ_3, κ_4)

VBF→HHH

see also talk by M.Chiesa

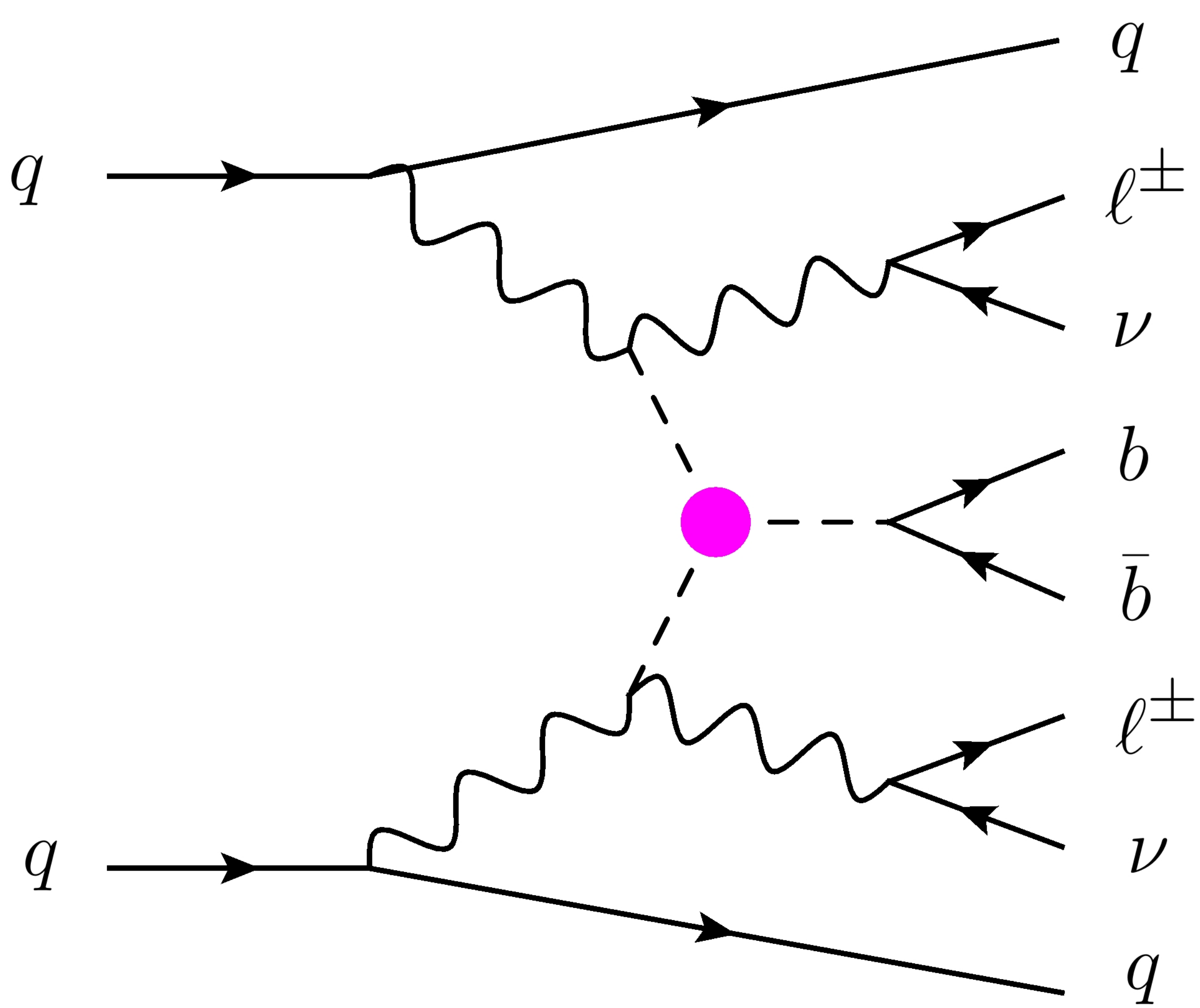


Chiesa (Whizard)

[κ_3=0] -0.2< κ_4 <0.5 (68%CL) !!!

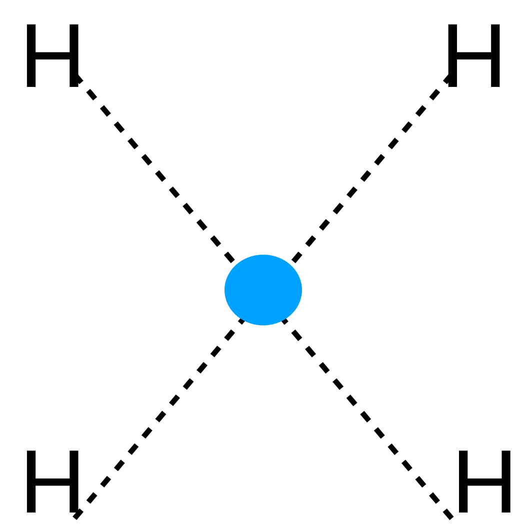
VBF → HVV, HHVV

anomalous Higgs couplings induce energy-growing effects in amplitudes involving longitudin. polarized vector bosons



energy-growing sensitivity to λ_3

• same in VBF→HHVV for $\lambda_3, \ \lambda_4$



arXiv:1812.09299

a few final comments

- such a high energy at pointlike level opens up hugely new perspectives !
- μ colliders @10'sTeV can be considered WW colliders !
- qualitatively new Higgs physics
- physics bckgds expected mild also for hadronic final states but simulations are quite hard (many particles in phase-space)
- explore goodness of Equivalent Vector-Boson Approx.
- many many possible new directions for exploring BSM [VBF-production role to be extensively considered…]
- comparison with FCC (pp,ee) to be kept in mind …

- see also talks by M.Chiesa, X. Zhao....

* thanks to M.Chiesa, F.Maltoni, F.Piccinini, A.Wulzer for discussions !!!