Physics : benchmarks and planning

Muon Collider - Aggiornamento attivita' e piani futuri
Vidyo, 3 June 2020

μ^+ → ← μ^-

$\sqrt{S_{\mu\mu}} \sim$ 6, 10, 14, 30 TeV

3 sectors :

* direct pair production of new heavy states...

* $W^+W^- \to X\ \nu\nu$ (vs $\mu^+\mu^- \to X$)

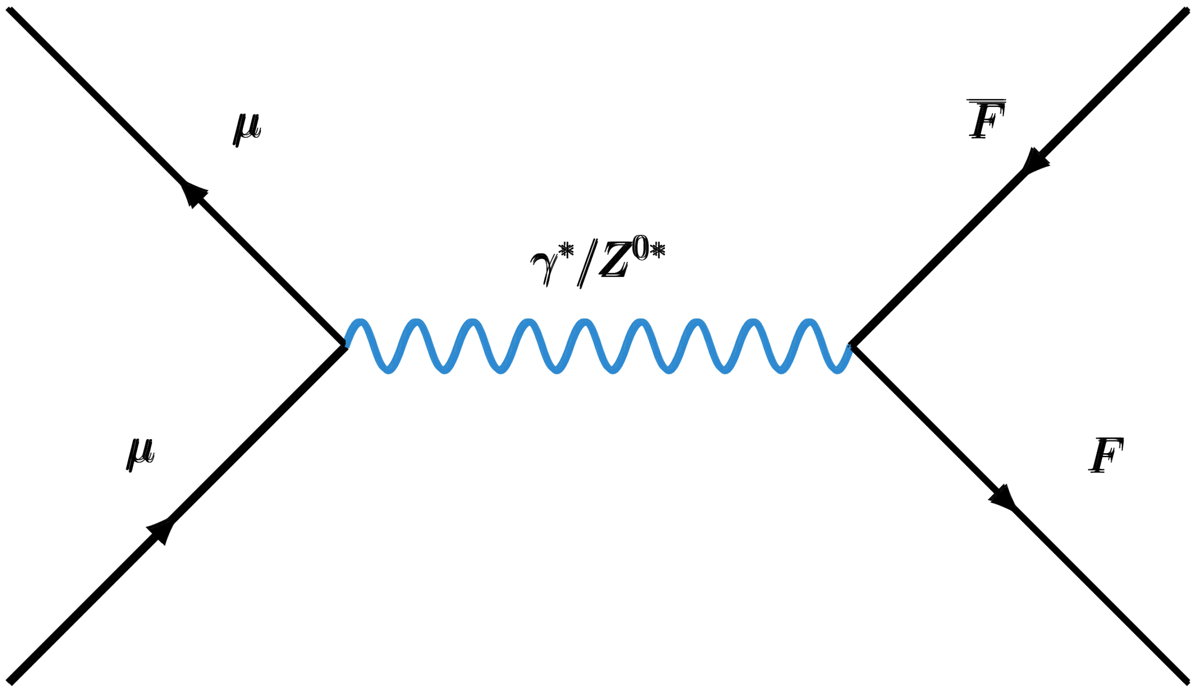
* indirect / off-shell / radiative effects of even heavier states (e.g. $\mu^+\mu^- \to Z'$ $(M_{Z'} > \sqrt{S})$)

INFN Roma Barbara Mele

✱ what can one do with muon collisions

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

FIRST AND FOREMOST



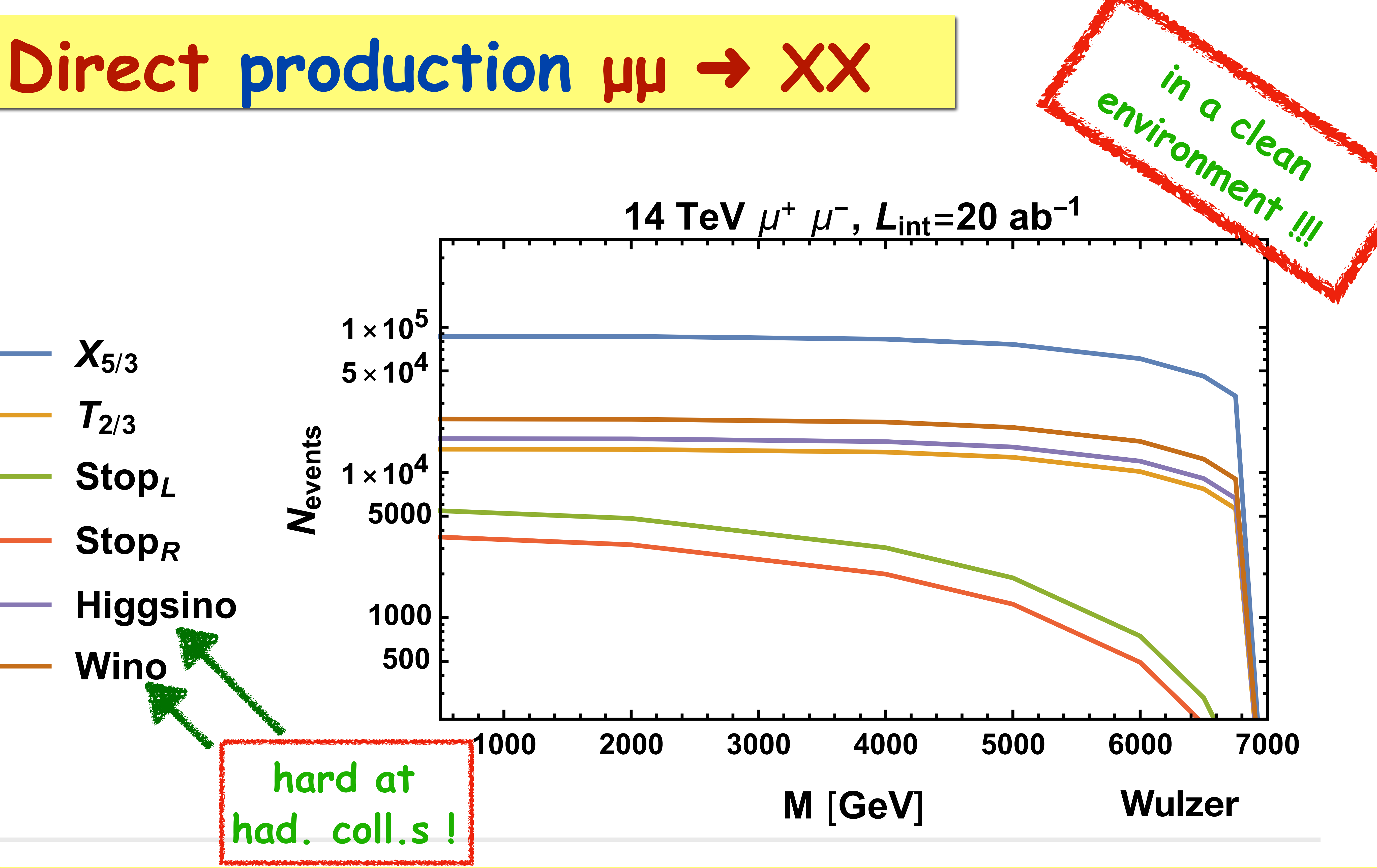
$$\mu^+\mu^- \to F\bar{F}$$

✱ plain pair production of new heavy states...

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

~ 3, 5, 7,15 TeV !!!

Direct production μμ → XX



$\sigma_{\mu\mu\to XX}$ ~ uniform up to threshold $m_F \sim \sqrt{S_{\mu\mu}}/2$!

→ 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 $m_e \sim \sqrt{S}/2$!

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

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

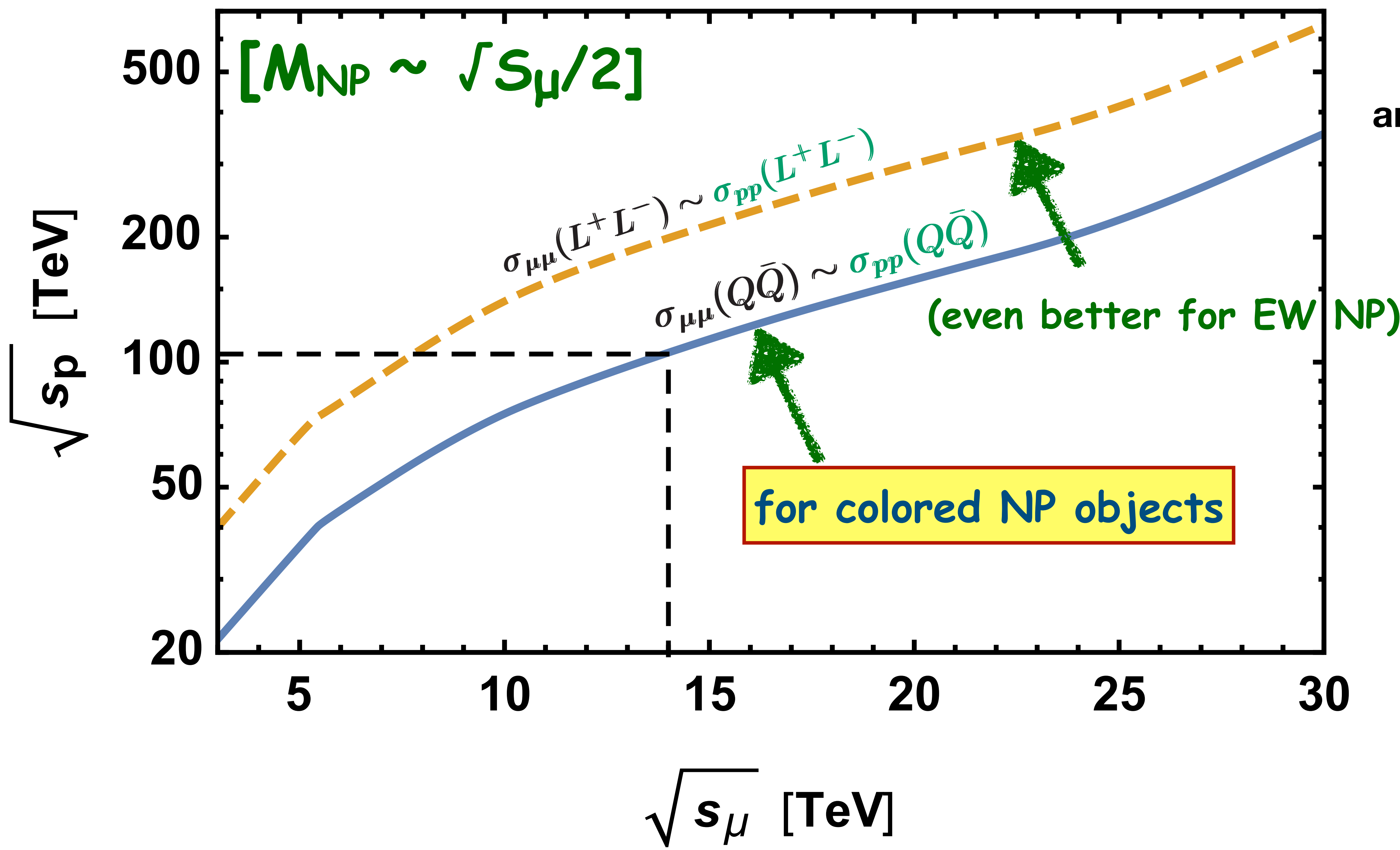
10^4 evs /(10 years)

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

$\sqrt{S_{\mu\mu}}$	$\int L_{10y}$
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



* μμ @ 14 TeV → pp @ 100 $(200)_{EW}$ TeV !

* μμ @ 30 TeV → pp @ 350 $(600)_{EW}$ TeV !!

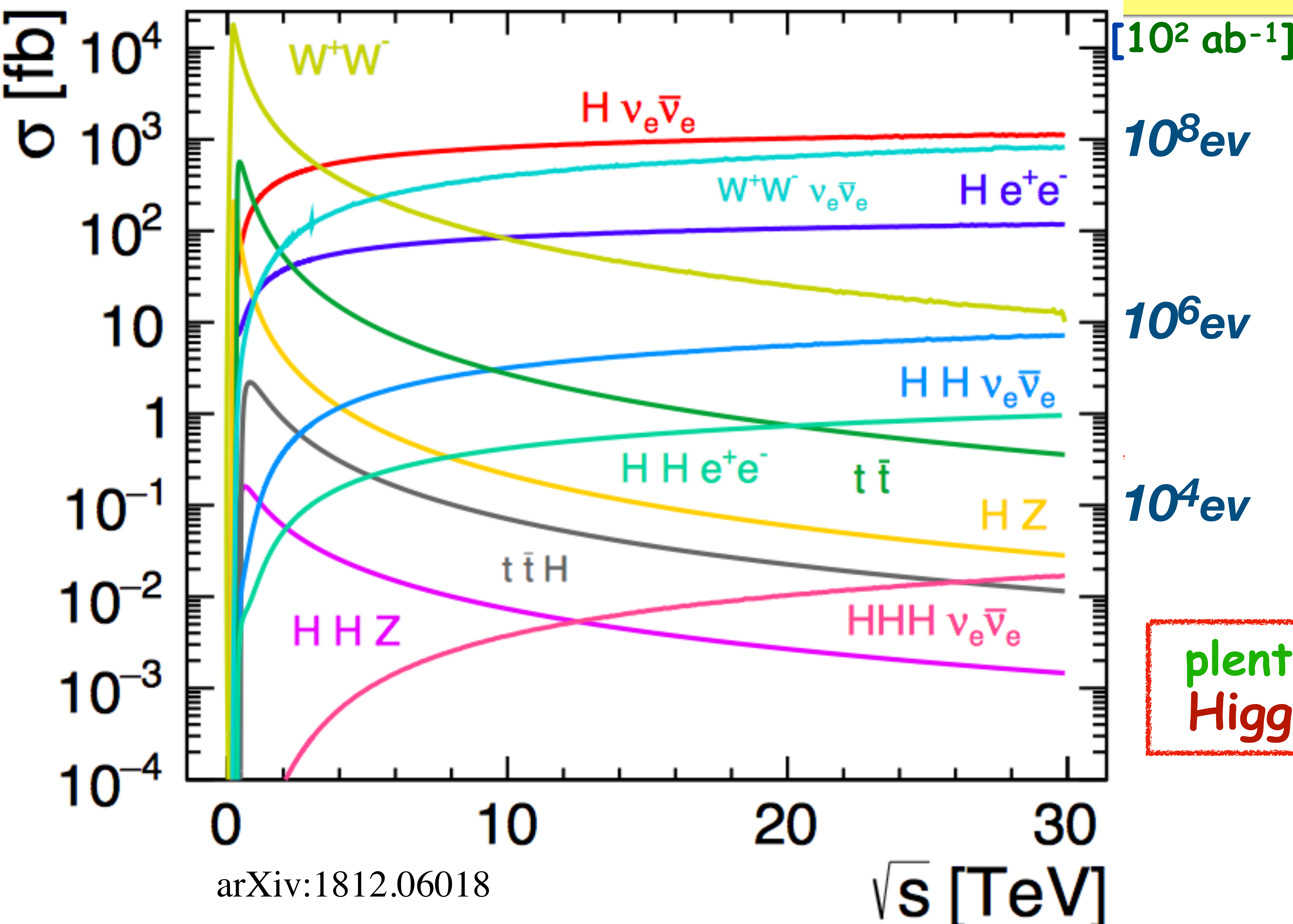
yet unexplored pheno !!!

WARNING !!

- actually physical BACKGROUND to $\mu^+\mu^-$ (e^+e^-) collisions hugely better than in hadron collisions

- this moves equivalent $\sqrt{S_{\mu\mu}}$ (at fixed $\sqrt{S_{pp}}$) at even lower values in general…

at $\sqrt{S_{\mu\mu}}$ > a few TeV's
point $\sigma_{\mu\mu\to X}$ superseded by $\sigma_{WW\to X}$!



arXiv:1812.06018

plenty of Higgs's !

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

[Maltoni et al]

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

brand new study on VBF vs s-channel

Vector boson fusion at multi-TeV muon colliders

Costantini, De Lillo, Maltoni, Mantani, Mattelaer, Ruiz, Zhao
arXiv:2005.10289v1 [hep-ph] 20 May 2020

Contents

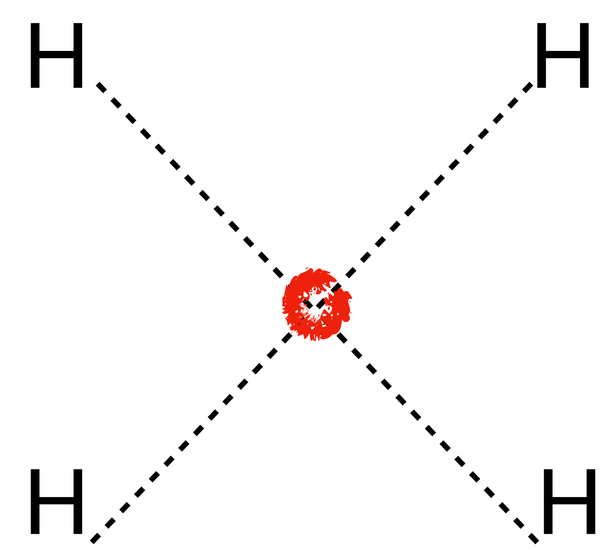
Higgs self-interaction couplings

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

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

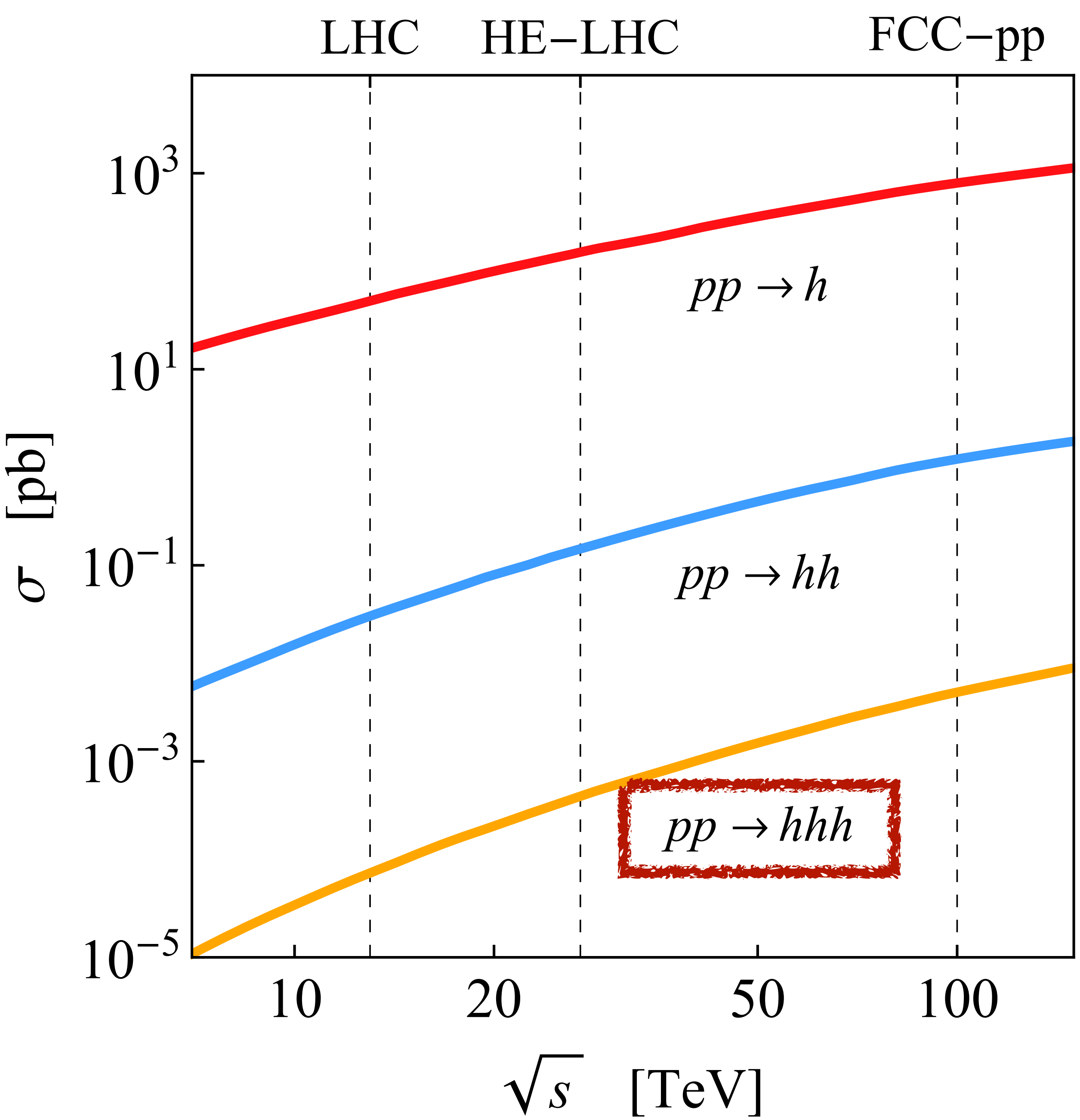
$$\lambda_3^{SM} = \lambda_4^{SM} = 1$$

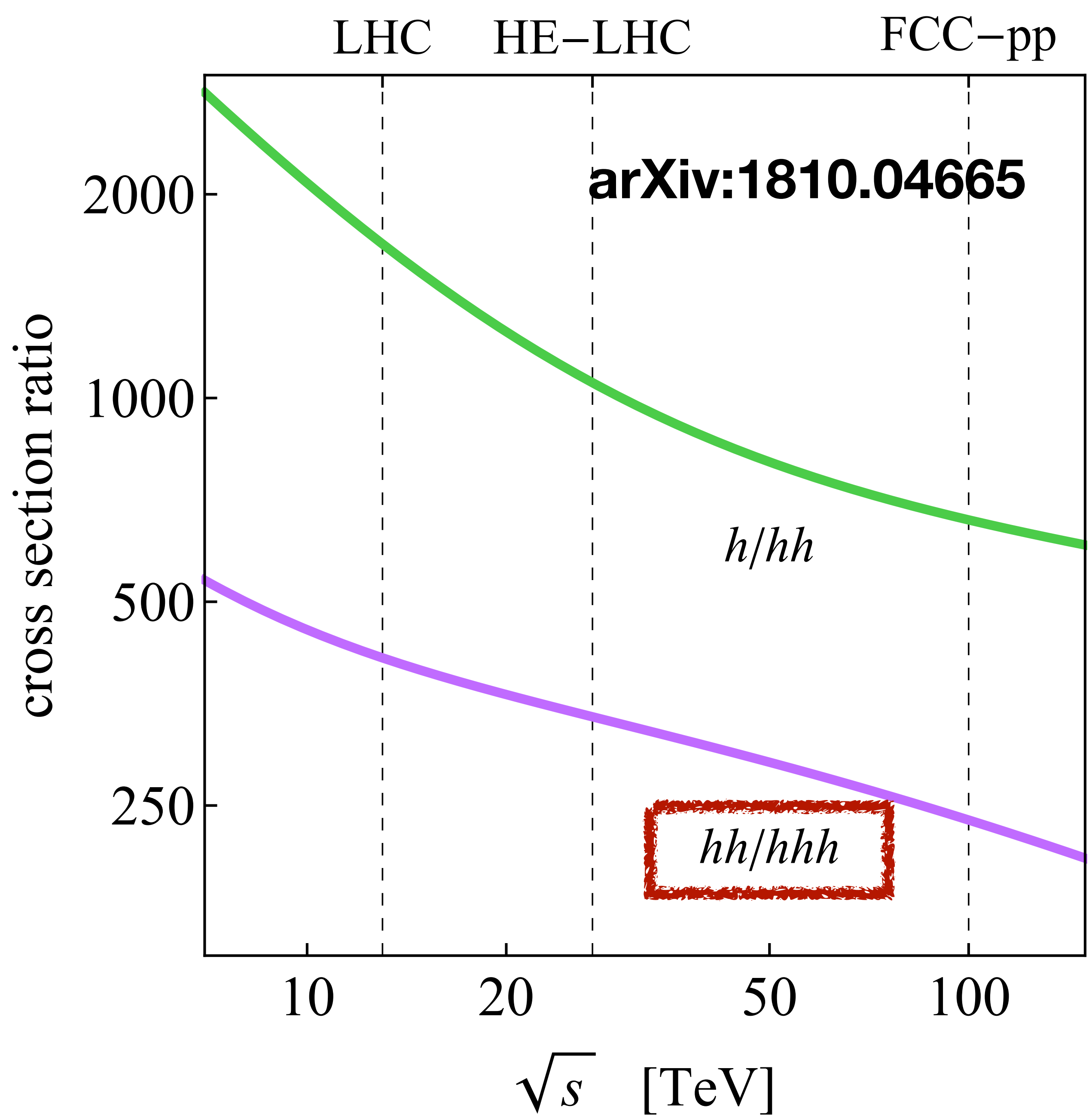
what about quartic H self-coupling ?



FCC-pp : λ_4

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

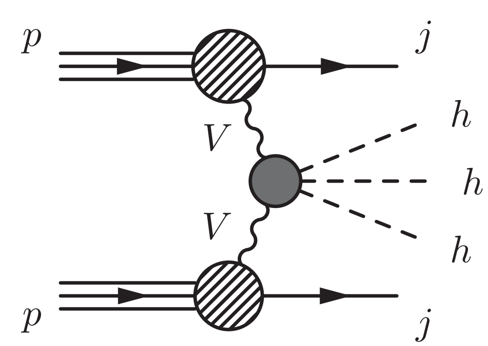




hhh → ($b\bar{b}$)($b\bar{b}$)(γγ) [optimistic scenario !!!] :

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

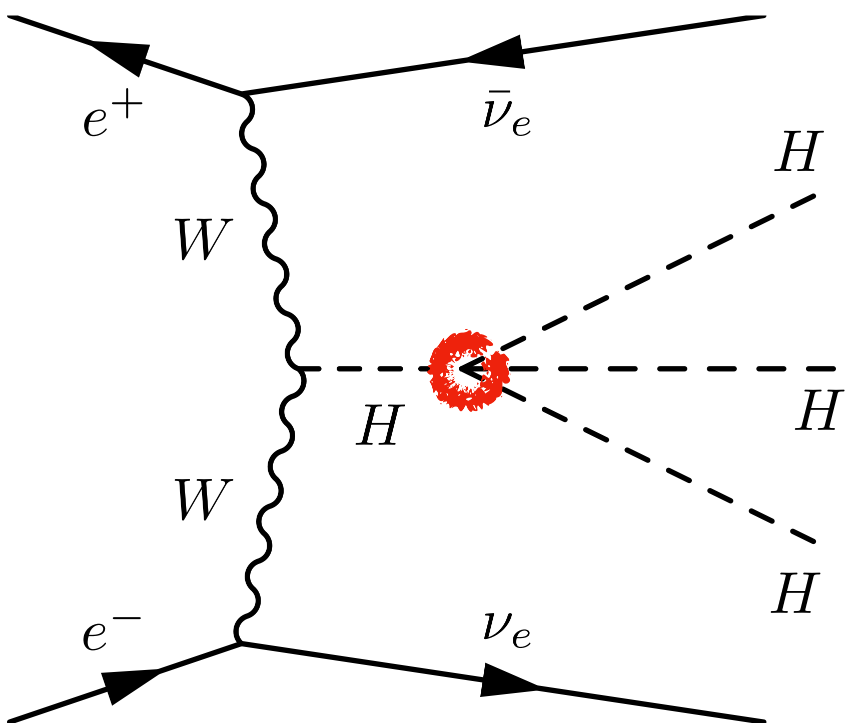
(95%C.L.)

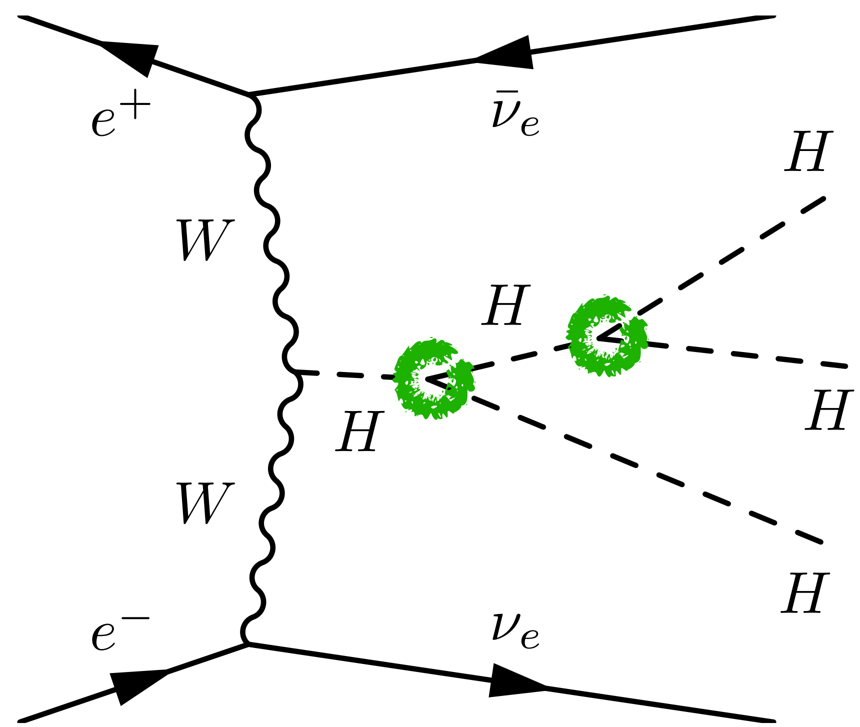


arXiv:1606.09408

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

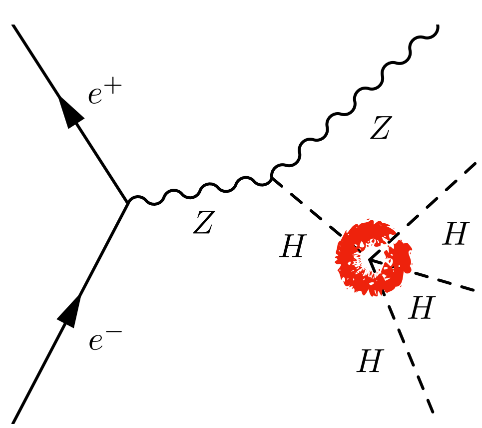
$$V_{\rm h} = \frac{m_h^2}{2}h^2 + (1+\kappa_3)\lambda_{hhh}^{\rm SM} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{\rm SM} h^4$$

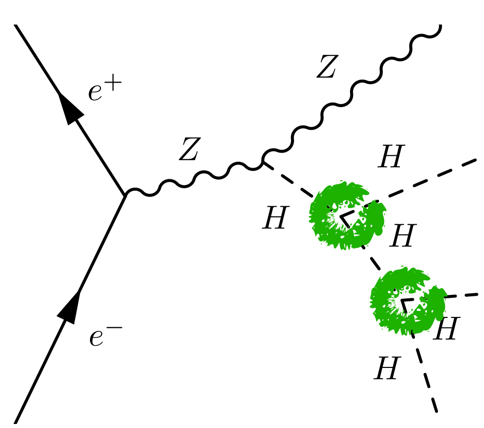




$(\kappa_i \to \delta_i)$

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





HHHZ negligible !

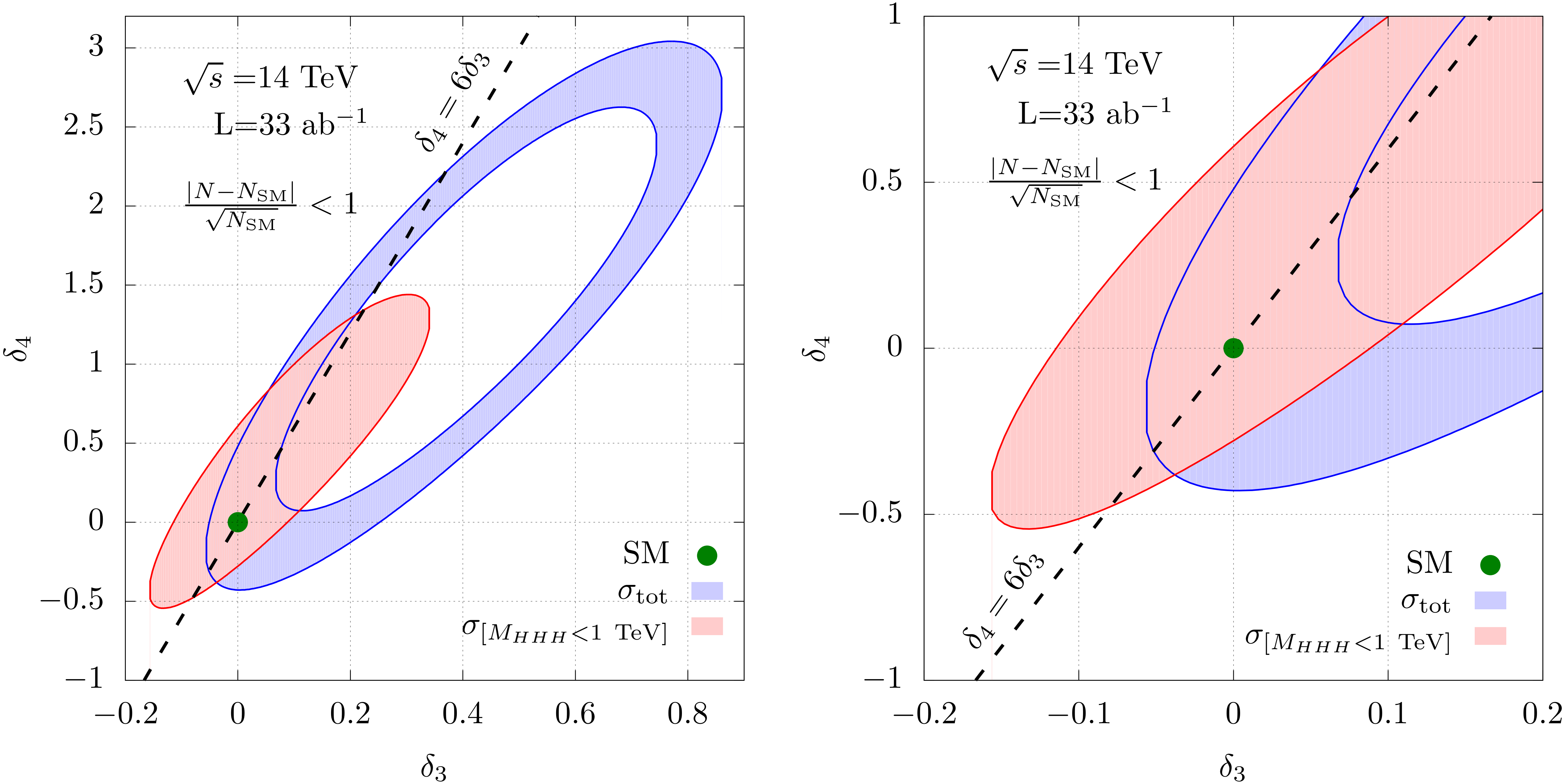
$\sigma_{HHHZ} \sim 1/2\ \sigma_{HHH}$ @ 3TeV

$\sim 1/50\ \sigma_{HHH}$ @ 30TeV

$(N-N_{SM})/\sqrt{N_{SM}}$ versus (δ_3,δ_4)

VBF→HHH

Chiesa, Maltoni, Mantani, BM, Piccinini, Zhao, 2003.13628



[δ_3=0] -0.4< δ_4 <0.4 (68%CL) !!!

$(N-N_{SM})/\sqrt{N_{SM}}$ versus δ_4

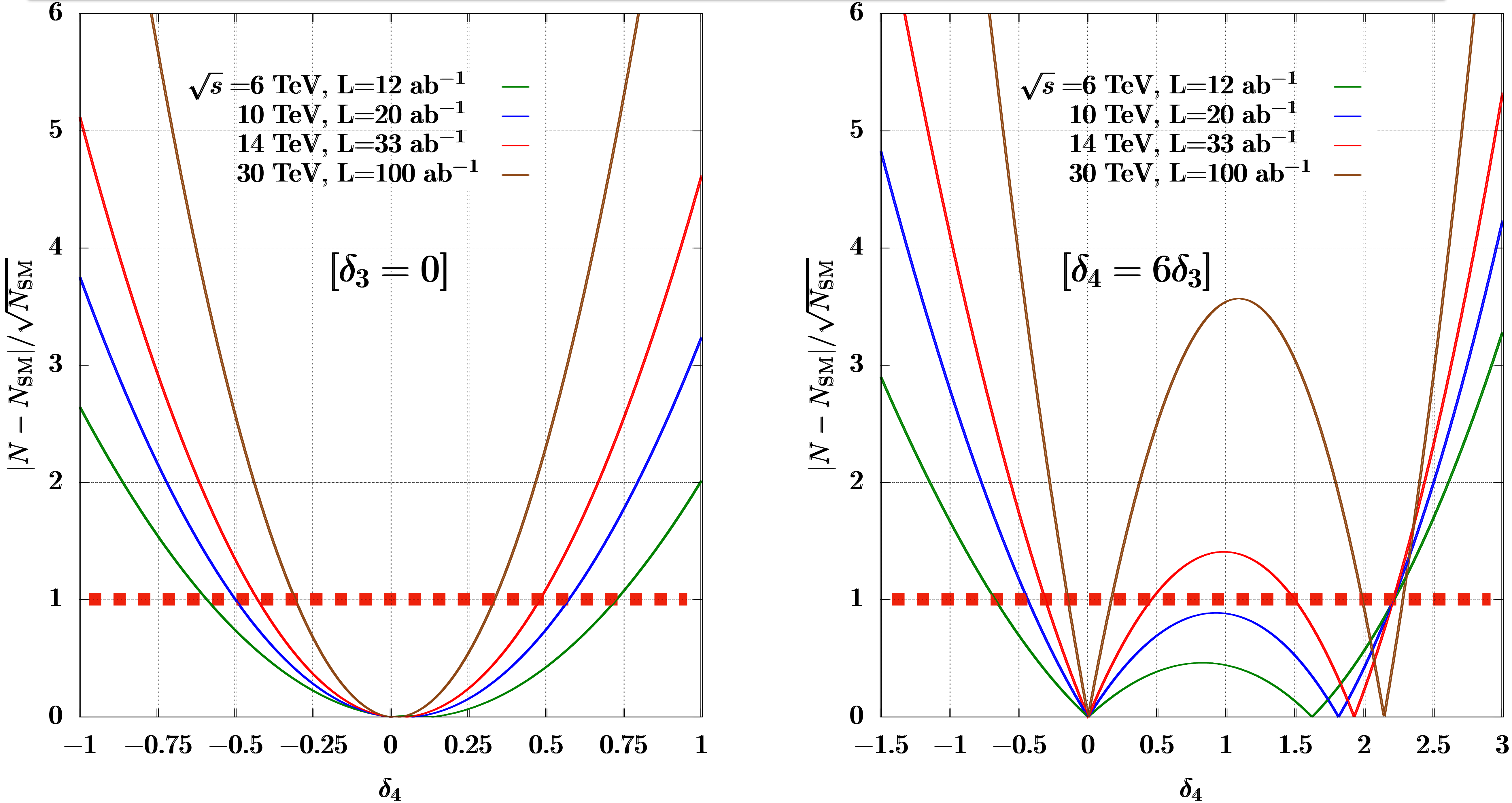
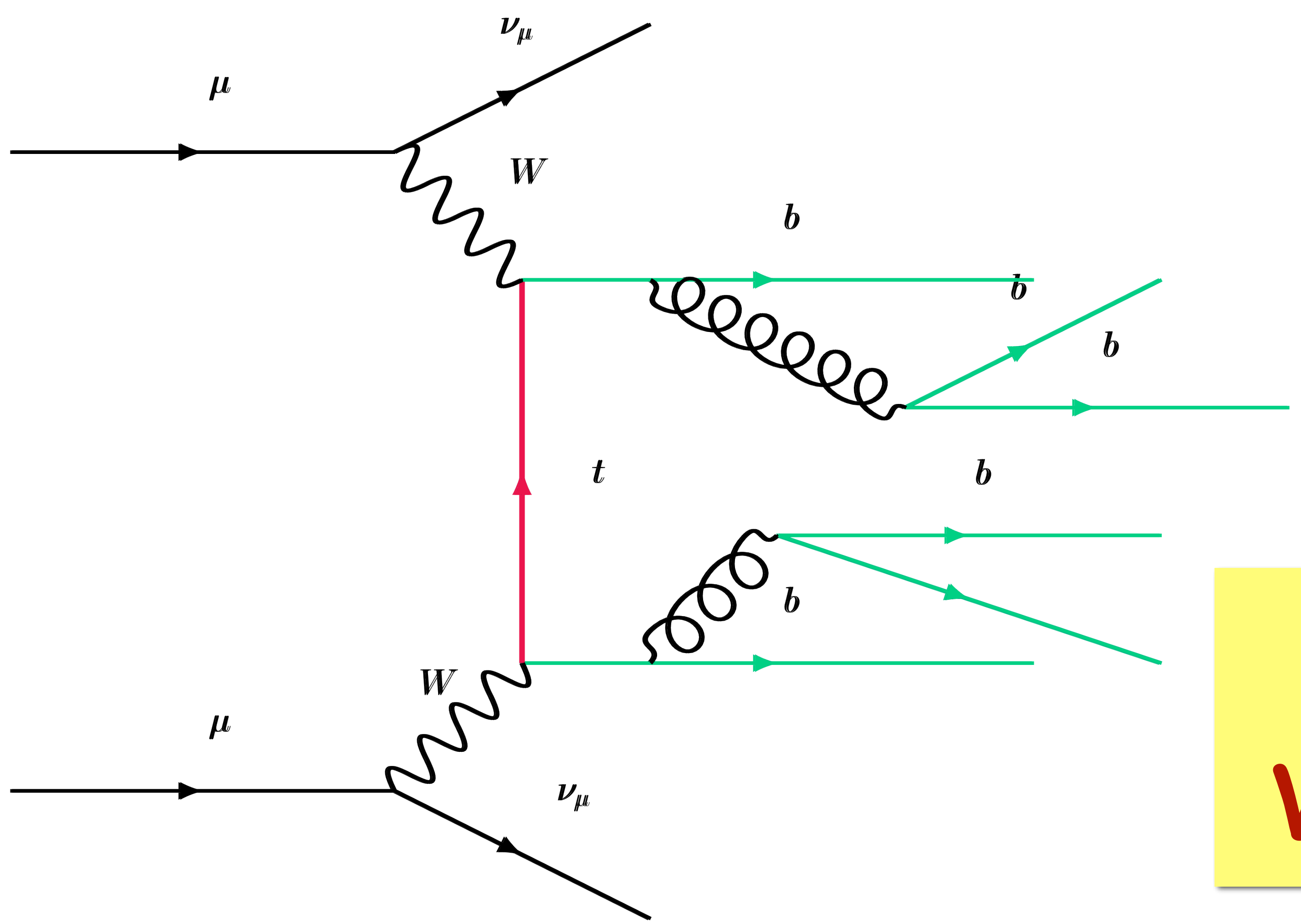


Figure 13: Sensitivity to the quartic Higgs self-coupling in terms of standard deviations $|N - N_{SM}|/\sqrt{N_{SM}}$ with respect to the SM configuration, where the event numbers N refer to $\sigma(\mu^+\mu^- \to HHH\nu\bar{\nu})$, for $M_{\bar{\nu}\nu} \gtrsim 150$GeV, for $\delta_3 = 0$ (left), and $\delta_4 = 6\delta_3$ (right). Results are obtained considering deviations from the inclusive cross sections only.

backgrounds to VBF → HHH

- 8-body final states (at least !)
  → very 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...



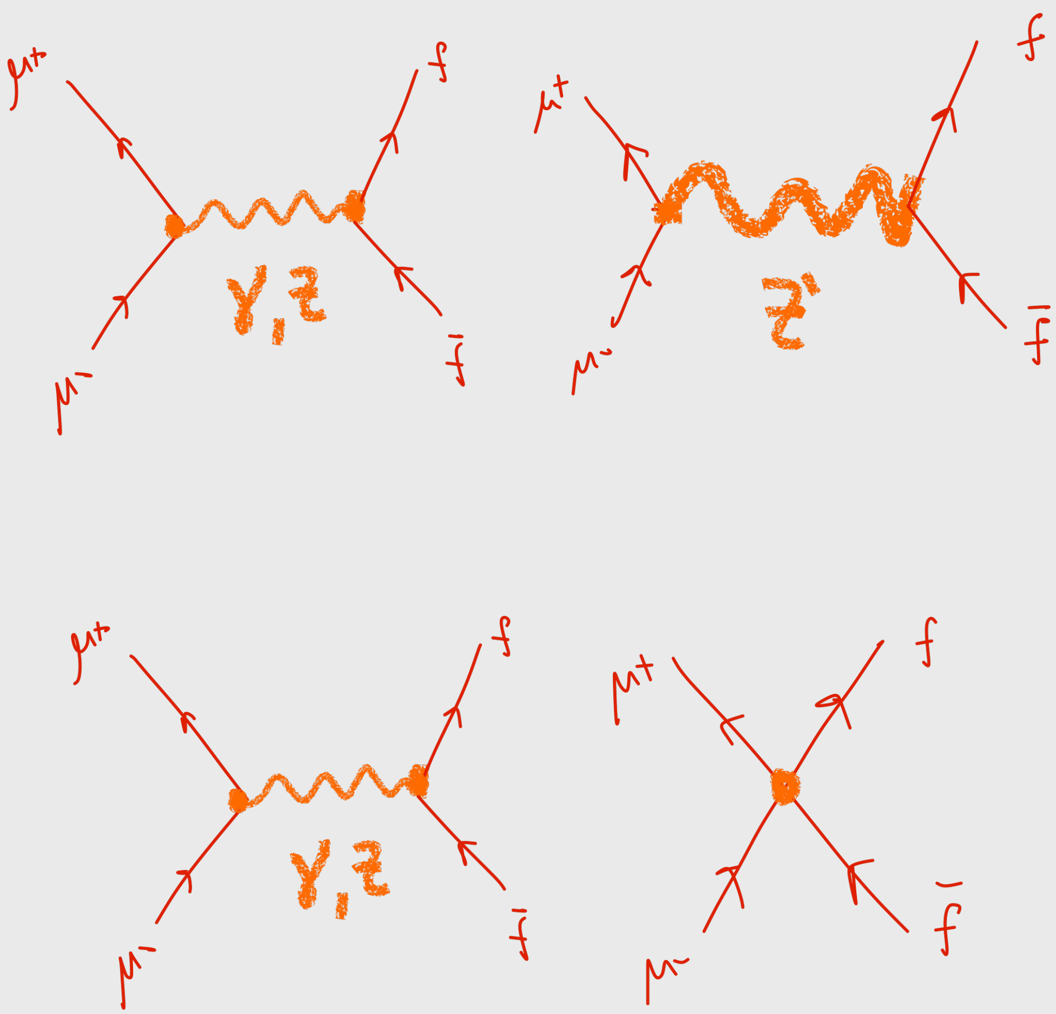
MC development for WW approx. needed !

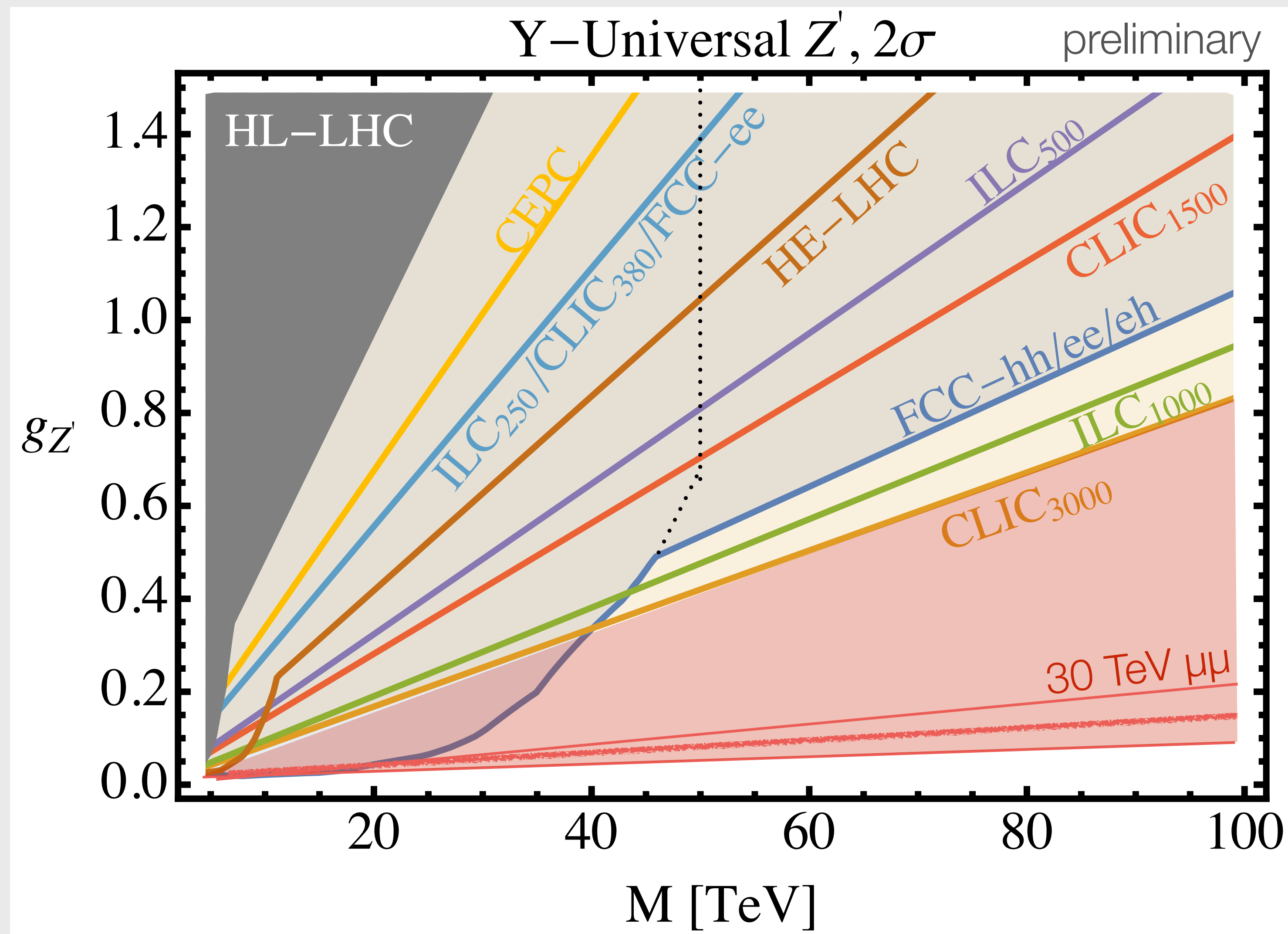
off-shell effects

A heavy Z'

Franceschini

DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

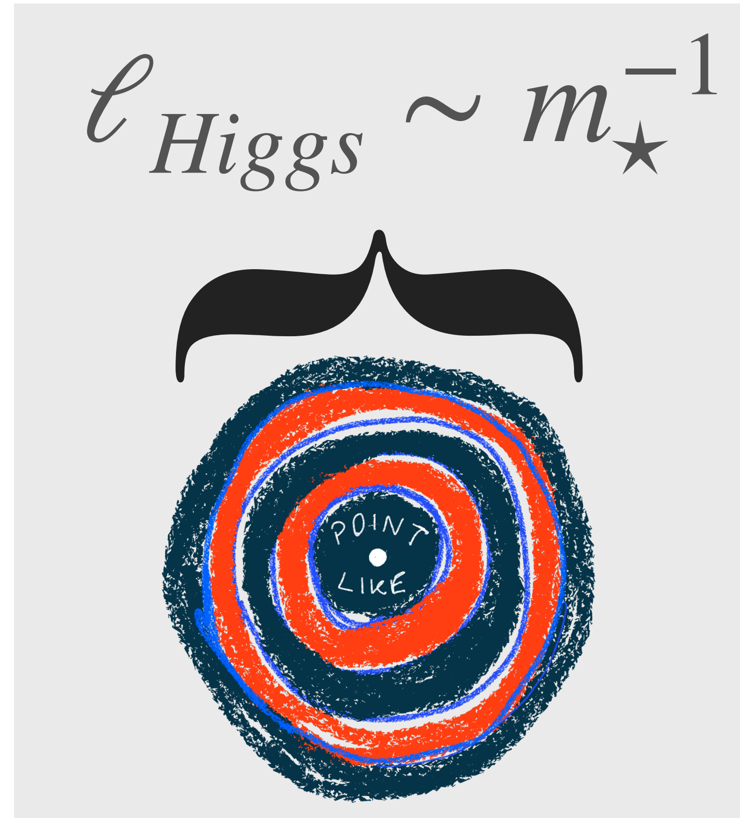




o Franceschini Muon Collider Workshop https://indico.cern.ch/event/845054/contributions/3573348/

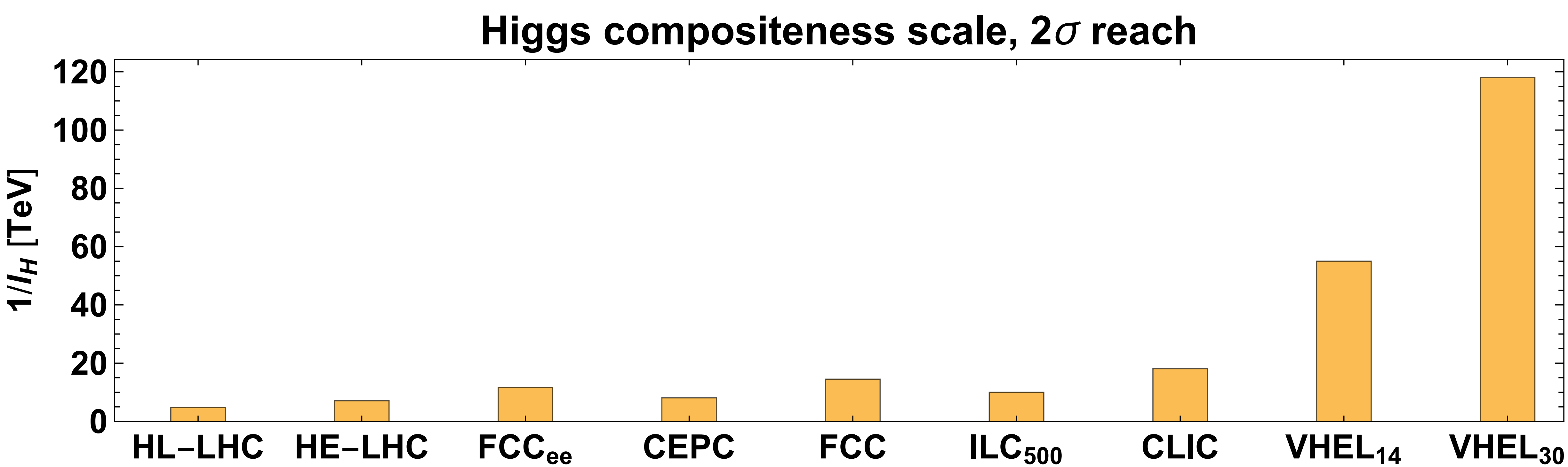
the “size” of the Higgs boson

Buttazzo, Franceschini, Wulzer



(EFT approach)

Compositeness Reach:



a few final comments

* such a high energy at pointlike level opens up
  hugely new perspectives !
* capability of direct production of new heavy states paramount!
* μ colliders @10'sTeV can be considered WW colliders !
* qualitatively new Higgs physics (test quartic self-coupl.)
* physics bckgds expected mild also for hadronic final states
  BUT simulations are quite hard (many particles in phase-space)
  → implement Equivalent Vector-Boson Approx. in MC's !
* many many possible new directions for exploring BSM
  in off-shell/indirect effects via precision measurements
  [also VBF-production role to be extensively considered…]