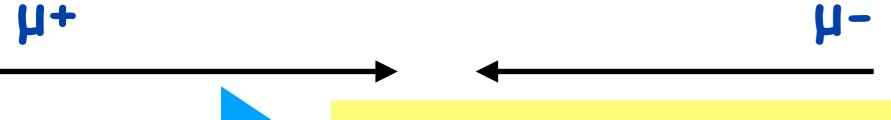
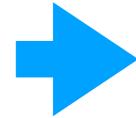
Physics: benchmarks and planning

RD_MUCOL -Incontro con i referee -16 Sett 2020





 $\int S_{\mu\mu} \sim 3$, 10, 14, 30 TeV

- 3 sectors: * direct pair production of new heavy states...
 - * W+W- \rightarrow X vv (vs $\mu^+\mu^- \rightarrow$ X)
 - * Precision measurements (including Higgs) probe indirect / off-shell / radiative effects of even heavier states (e.g. $\mu^{+}\mu^{-} \rightarrow Z'^{*} (M_{Z'} > \sqrt{S})$) N Barbara Mele

Tentative Target Parameters

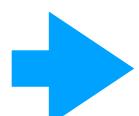
| Parameter | Unit | 3 TeV | 10 TeV | 14 TeV |
|----------------------|---|-------|--------|--------|
| L | 10 ³⁴ cm ⁻² s ⁻¹ | 1.8 | 20 | 40 |
| N | 10 ¹² | 2.2 | 1.8 | 1.8 |
| f_r | Hz | 5 | 5 | 5 |
| P _{beam} | MW | 5.3 | 14.4 | 20 |
| С | km | 4.5 | 10 | 14 |
| | Т | 7 | 10.5 | 10.5 |
| ε _L | MeV m | 7.5 | 7.5 | 7.5 |
| $\sigma_{\rm E}$ / E | % | 0.1 | 0.1 | 0.1 |
| σ_{z} | mm | 5 | 1.5 | 1.07 |
| β | mm | 5 | 1.5 | 1.07 |
| 3 | μm | 25 | 25 | 25 |
| $\sigma_{x,y}$ | μm | 3.0 | 0.9 | 0.63 |

Based on extrapolation of MAP parameters

Note: The study will have to verify that these parameters can be met

Develop emittance budgets

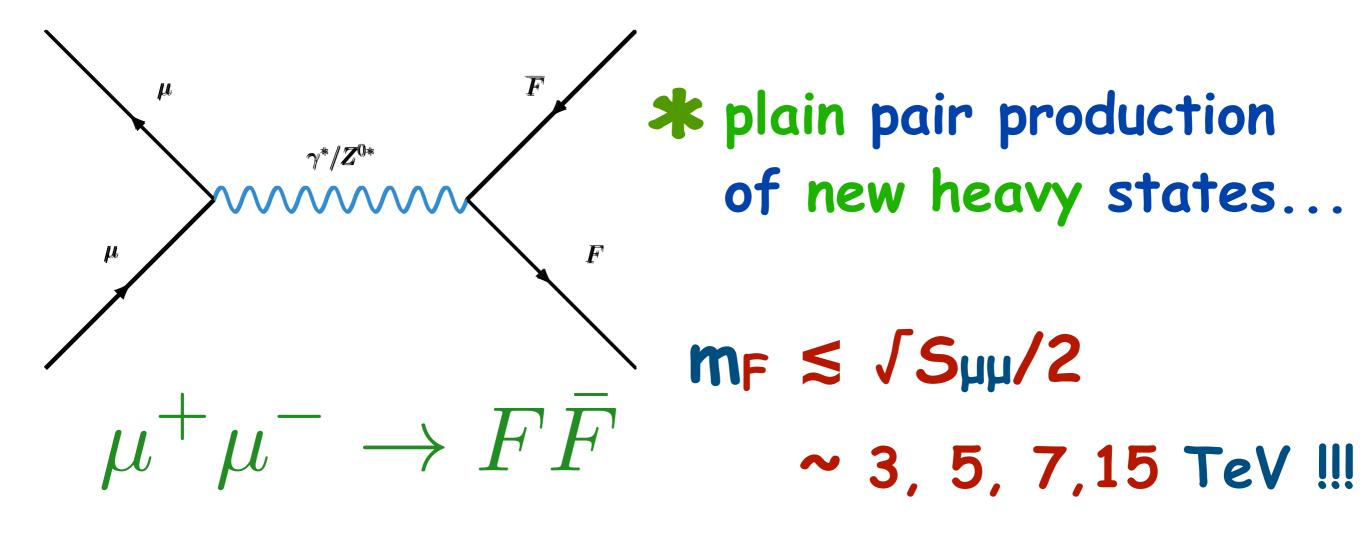
Schulte, July 2020



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

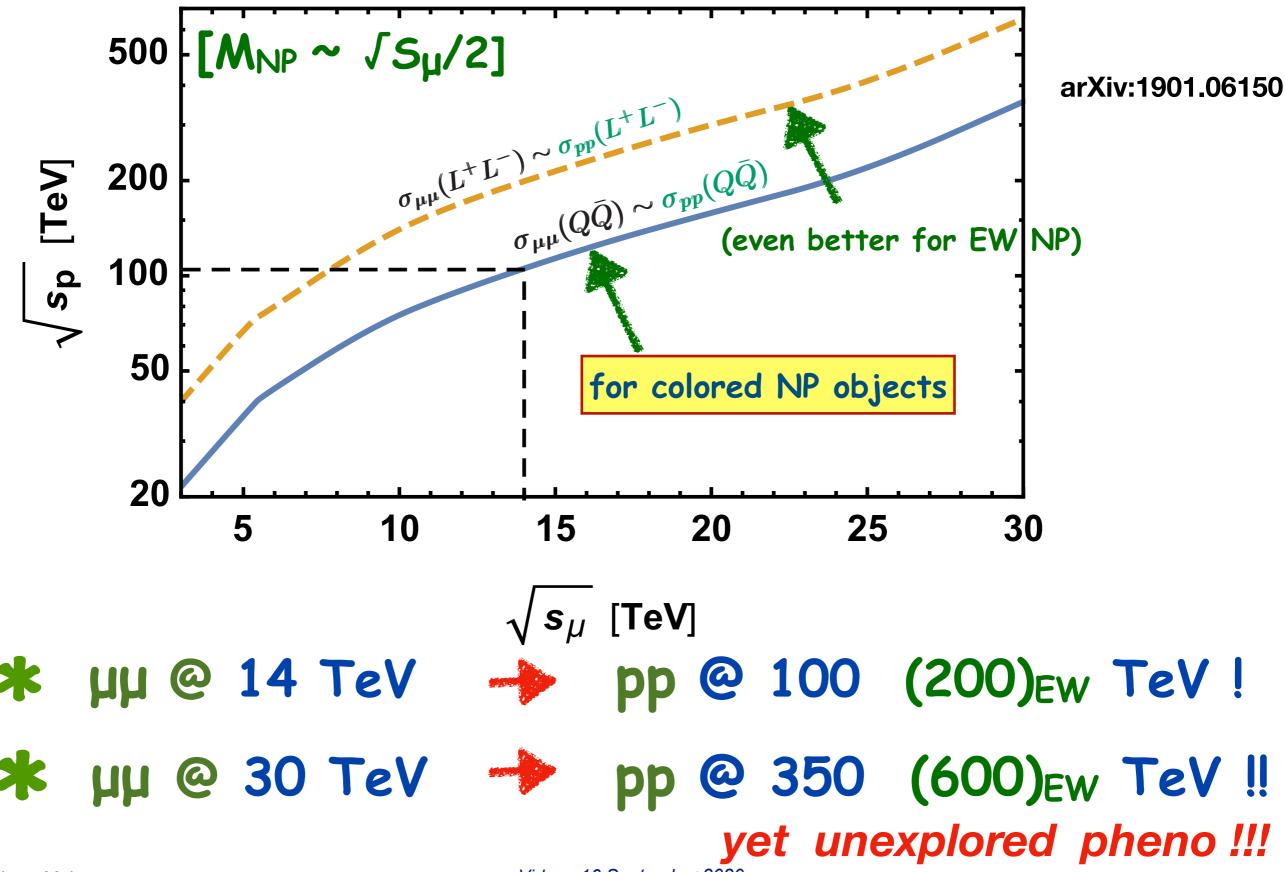
* what can one do with muon collisions @ $\int S\mu\mu$ up to tens of TeV ???

FIRST AND FOREMOST



Barbara Mele Vidyo, 16 September 2020

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



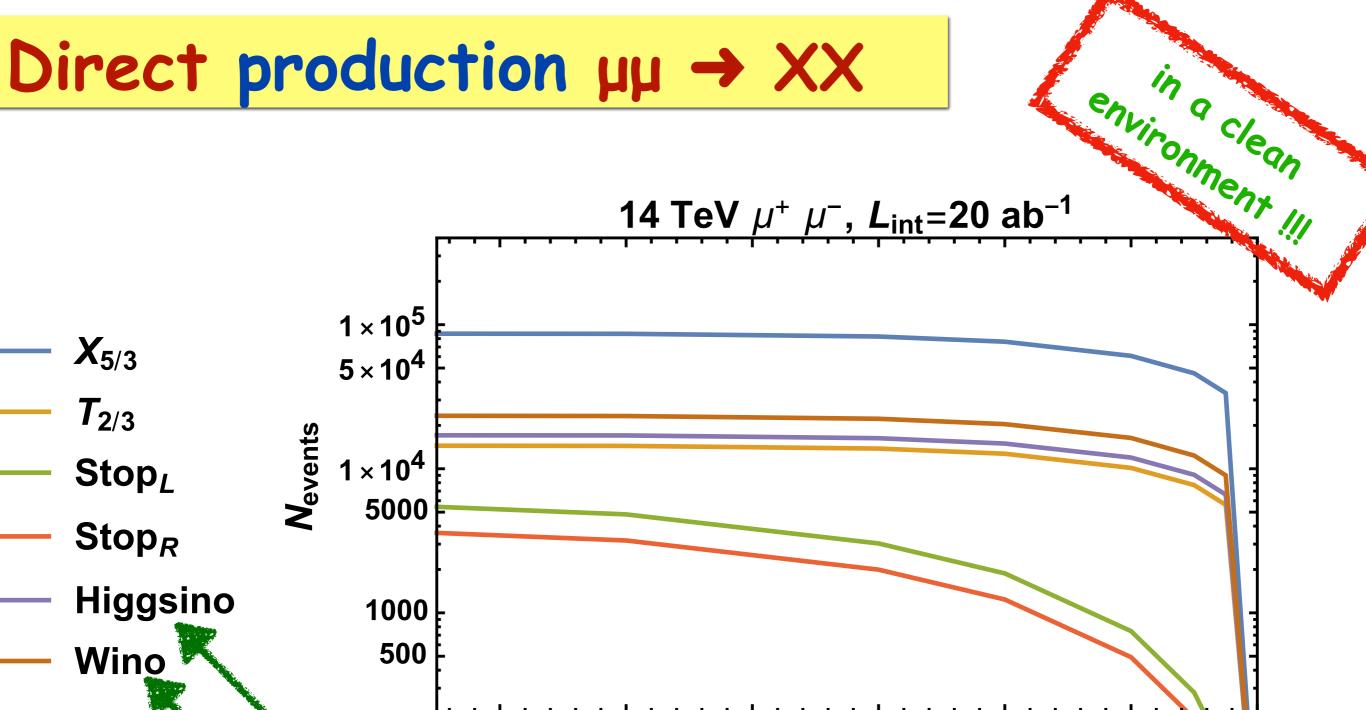
WARNING!!

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

* this moves equivalent $\int S_{\mu\mu}$ (at fixed $\int S_{pp}$) at even lower values in general...

* Beam-induced Background !!!

(requires work and assumptions...)



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

3000

4000

M [GeV]

5000

6000

Wulzer

7000

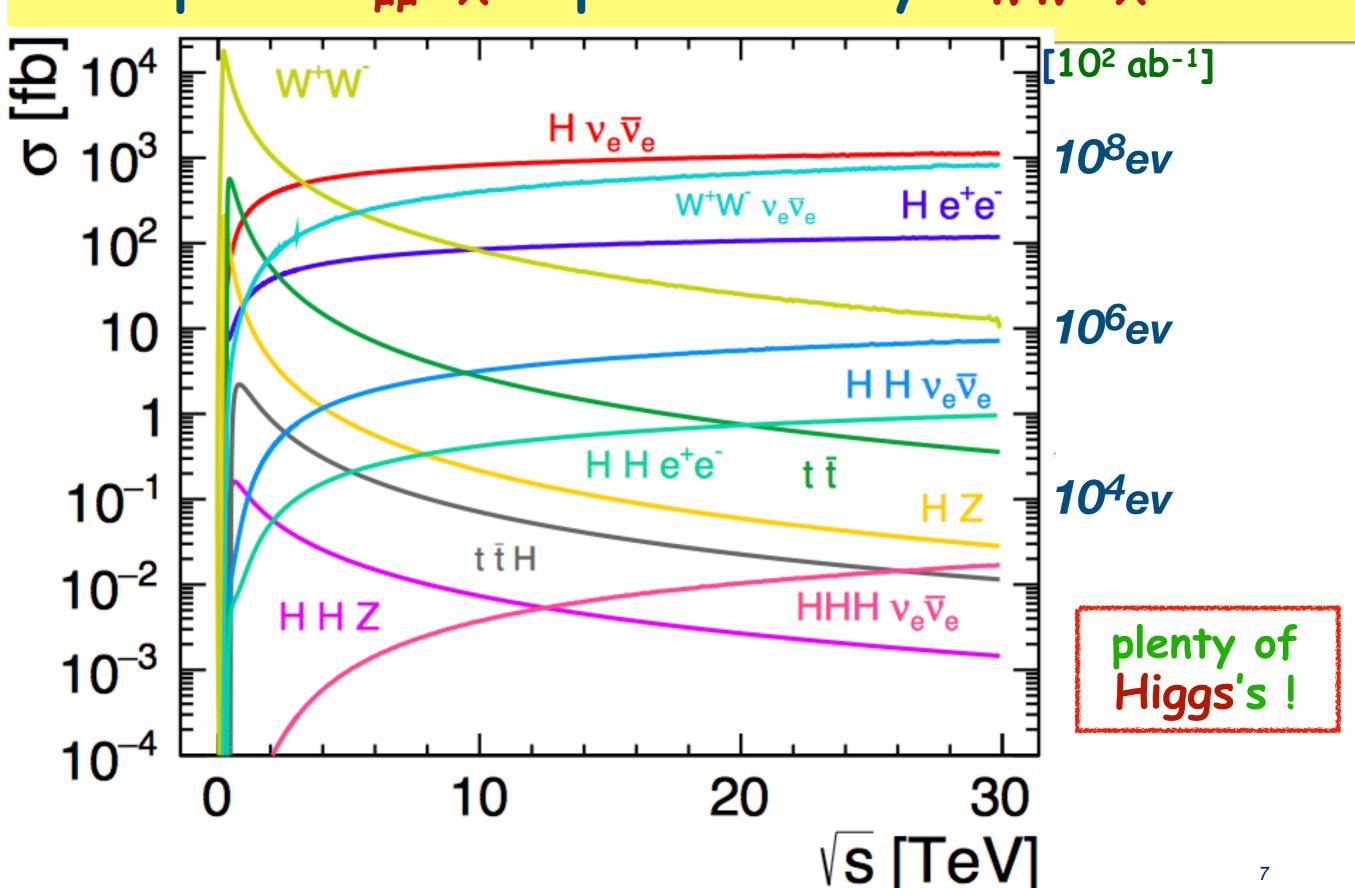
2000

1000

hard at

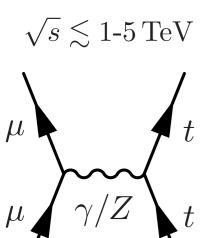
had. coll.s!

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

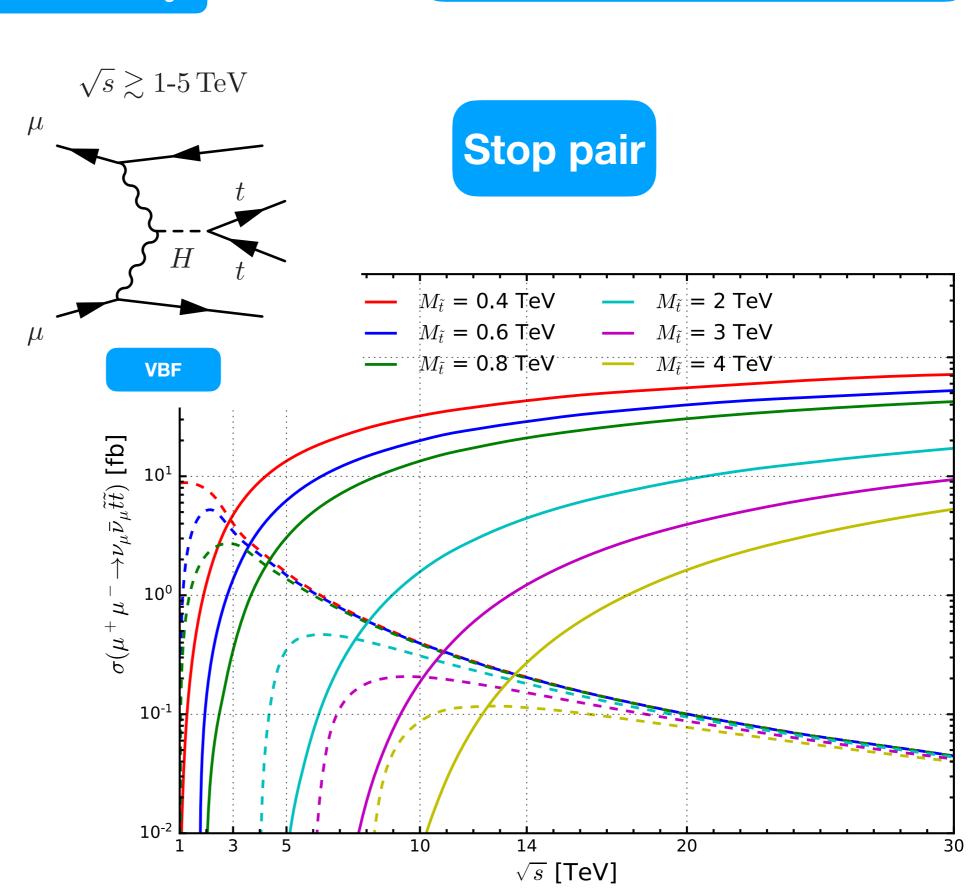


Effectively a EW boson collider!

Different mode of production at different energies



s-channel



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

- 1 Introduction
- 2 Computational setup
- 3 Comparing proton colliders and muon colliders
 - $3.1 \quad 2 \rightarrow 1 \text{ annihilations}$
 - $3.2 \quad 2 \rightarrow 2 \text{ annihilations}$
 - 3.3 Weak boson fusion
- 4 Standard Model processes at muon colliders
 - 4.1 Technical nuances at high energies
 - $4.2 \quad W^+W^- \text{ fusion}$
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5 Precision electroweak measurements

- 5.1 SMEFT formalism
- 5.2 Higgs self-couplings at muon colliders
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6 Searches for new physics

- 6.1 Scalar singlet extension of the Standard Model
- 6.2 Two Higgs Doublet Model
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- 6.6 Heavy Dirac and Majorana neutrinos
- 6.7 Vector-like quarks
- 6.8 Overview of vector boson fusion sensitivity
- 7 New physics processes at muon colliders: annihilation vs fusion
- 8 Conclusions

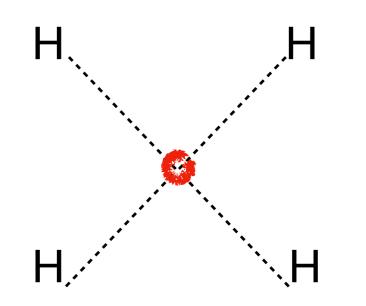
Higgs self-interaction couplings

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

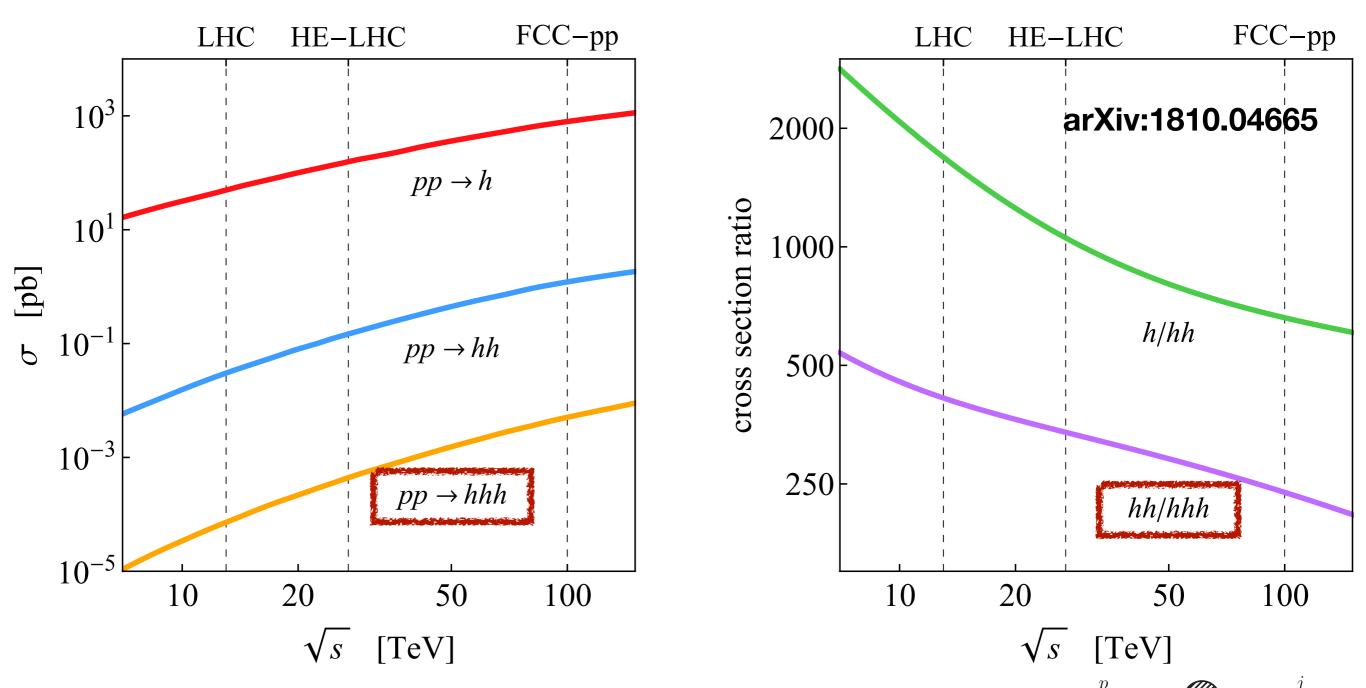
$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

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

what about quartic H self-coupling?



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



hhh → (b̄b)(b̄b)(γγ) [optimistic scenario !!!]

 $\lambda 4 \in [\sim -4, \sim +16]$

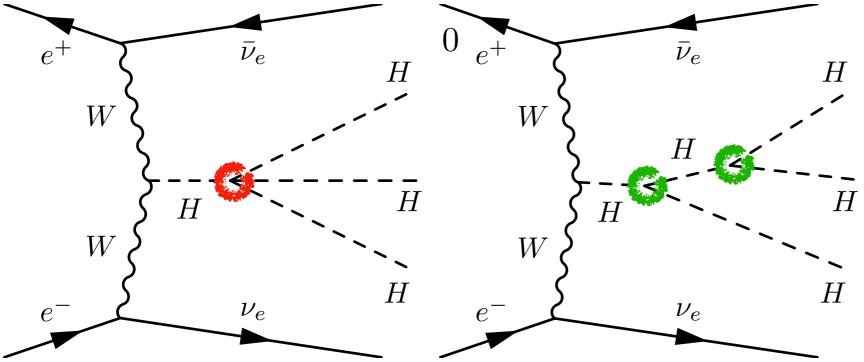
at 100 TeV, 30 ab-1

(95%C.L.)

arXiv:1606.09408

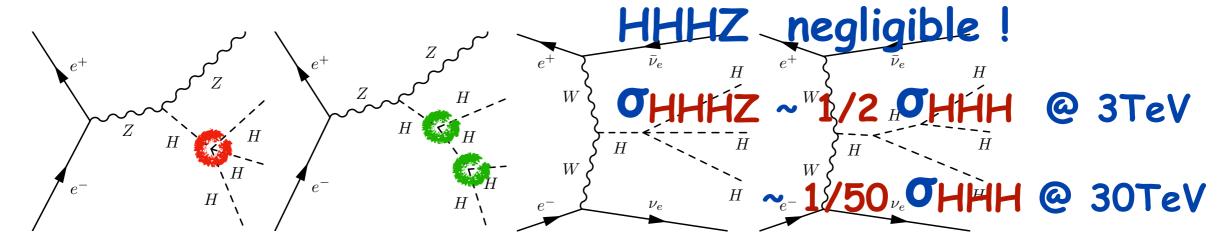
$\mu^+\mu^- \to HHH\nu\overline{\nu}, \ (\nu=\nu_e,\nu_\mu,\nu_\tau)$

$$V_{h} = \frac{m_{h}^{2}}{2}h^{2} + (1 + \kappa_{3})\lambda_{hhh}^{SM}v^{0}h^{3} + \frac{1}{4}(1 + \kappa_{4})\lambda_{hhhh}^{SM}h^{4}$$



$$(\kappa_i \rightarrow \delta_i)$$

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



Barbara Mele

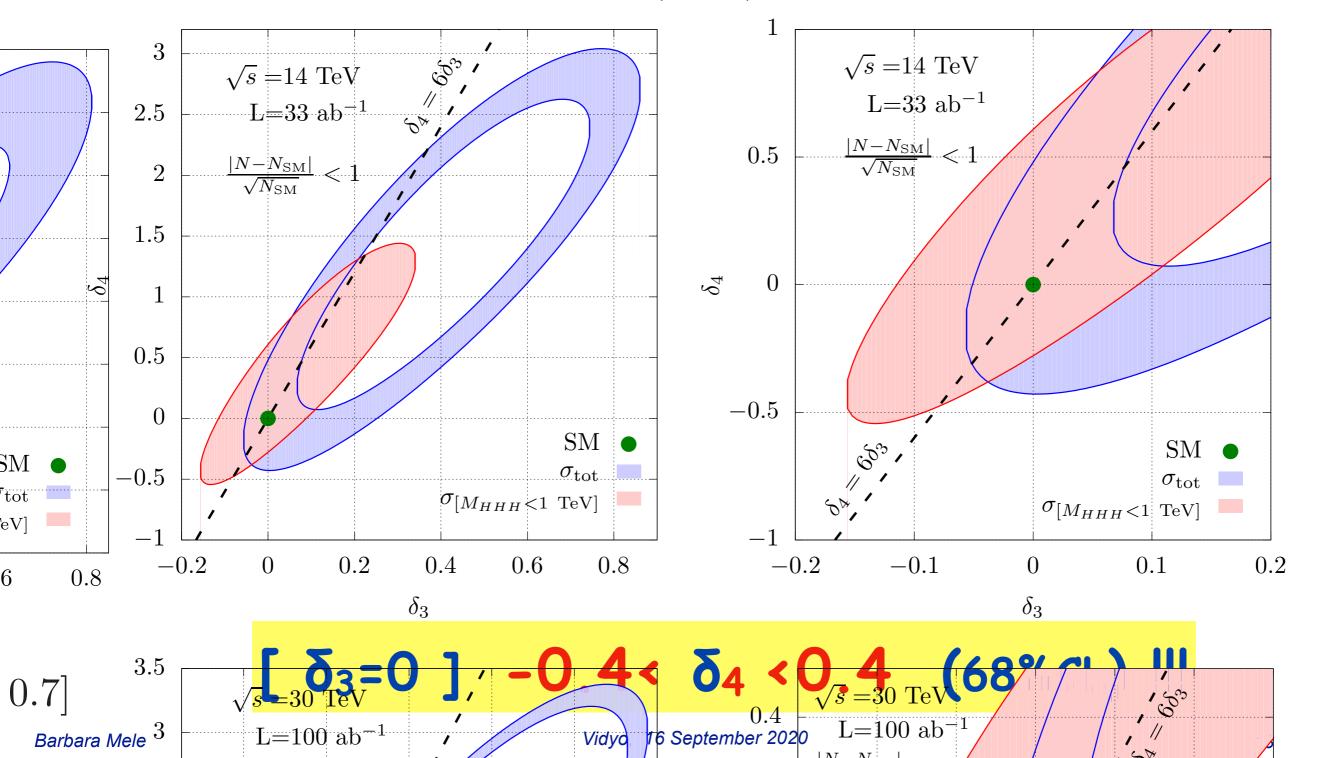
$(N-N_{SM})/\sqrt{N_{SM}}$ versus (δ_3, δ_4)

$\frac{\mathbf{VBF} \rightarrow \mathbf{HHH}}{S} = \frac{|\mathcal{L} \cdot (\sigma - \sigma_{SM})|}{\sqrt{\mathcal{L} \cdot \sigma_{SM}}} \le 1$

Chiesa, Maltoni, Mantani, BM, Piccinini, Zhao, 2003.13628 to appear in JHEP

$$\lambda_3 = \lambda_{SM}(1 + \delta_3) = \kappa_3 \lambda_{SM}$$

$$\lambda_4 = \lambda_{SM}(1 + \delta_4) = \kappa_4 \lambda_{SM}$$



$(N-N_{SM})/\sqrt{N_{SM}}$ versus δ_4

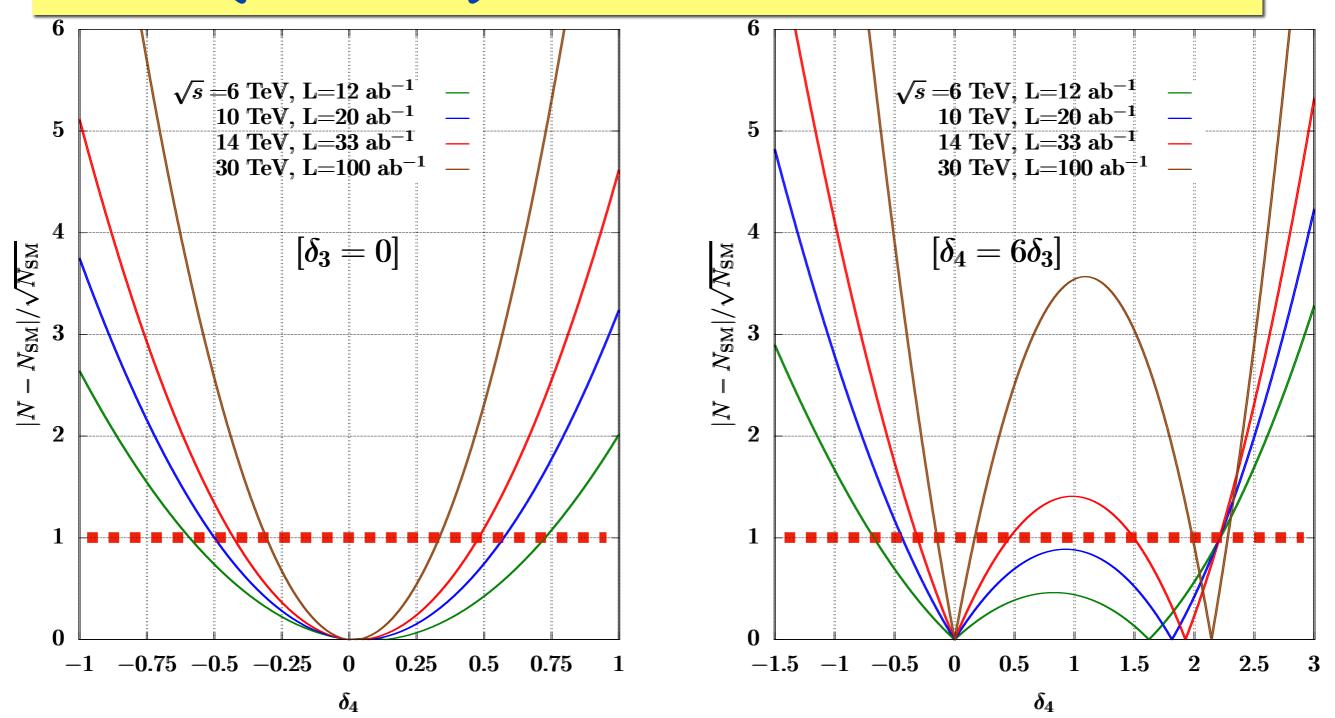
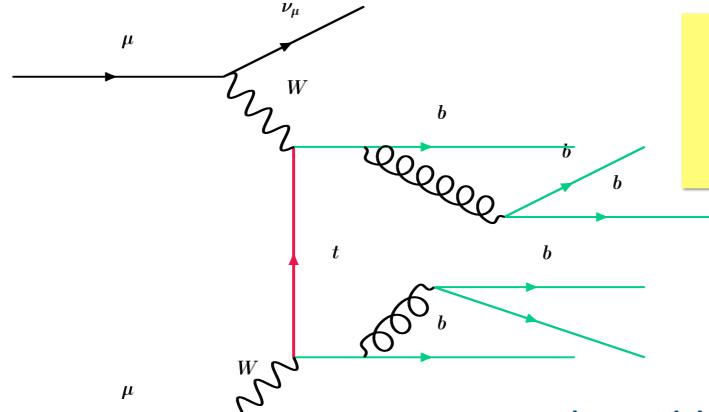


Figure 13: Sensitivity to the quartic Higgs self-coupling in terms of standard deviations $|N - N_{\rm SM}|/\sqrt{N_{\rm SM}}$ with respect to the SM configuration, where the event numbers N refer to $\sigma(\mu^+\mu^- \to HHH\nu\bar{\nu})$, for $M_{\bar{\nu}\nu} \gtrsim 150 {\rm GeV}$, for $\delta_3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

Barbara Mele Vidyo, 16 September 2020 14

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 5/B >> 1 at multi-TeV muon colliders...



MC development for WW approx. needed!

ongoing activity Pavia (M.Chiesa and F.Piccinini)

Bologna (F. Maltoni, L. Mantani, X. Zhao) Roma1 (BM)

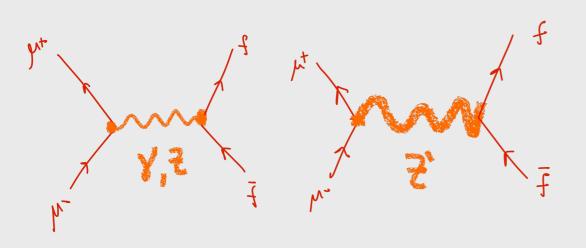
off-shell effects

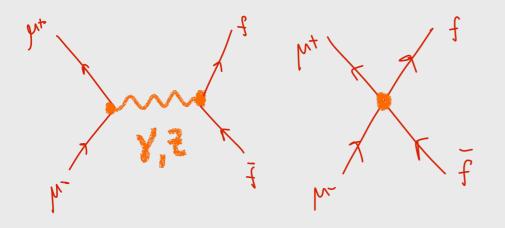
A heavy Z'

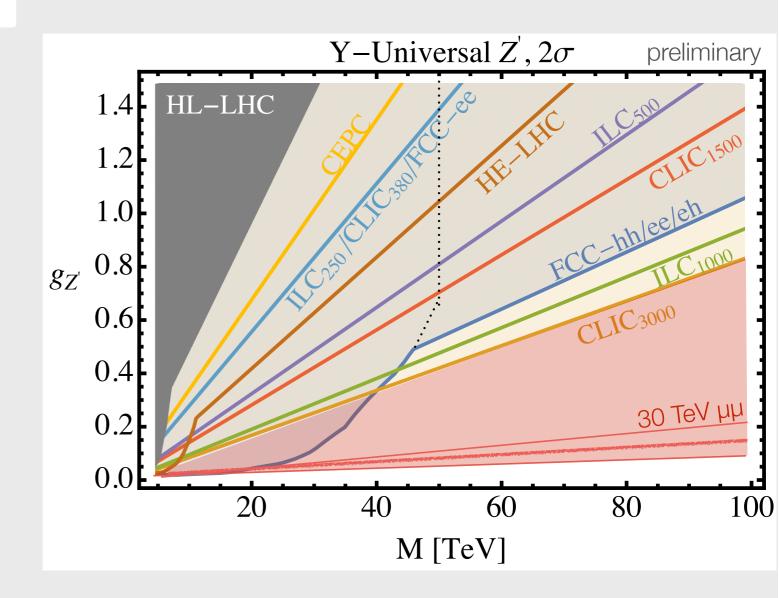
Franceschini

DRELL-YAN

RATES AND ANGULAR DISTRIBUTIONS

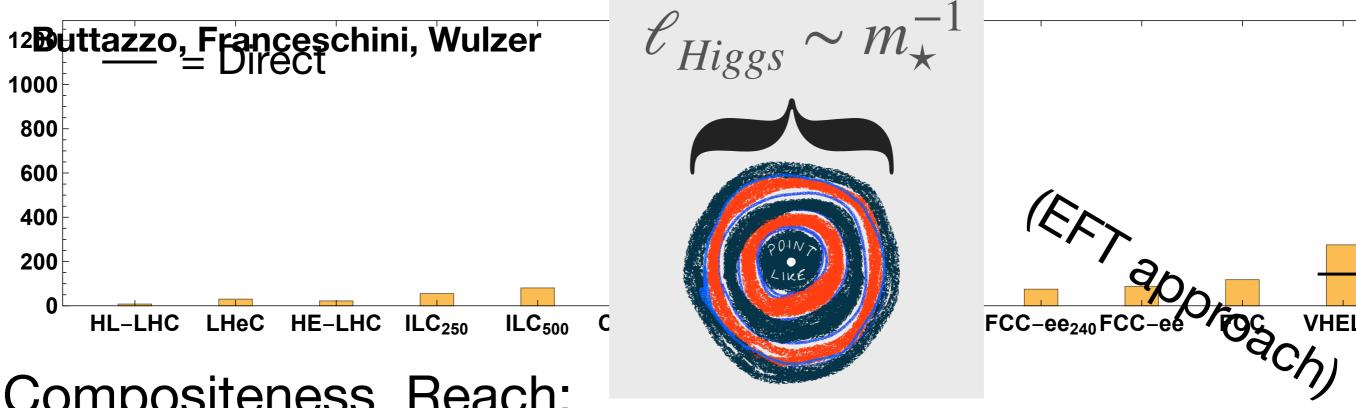




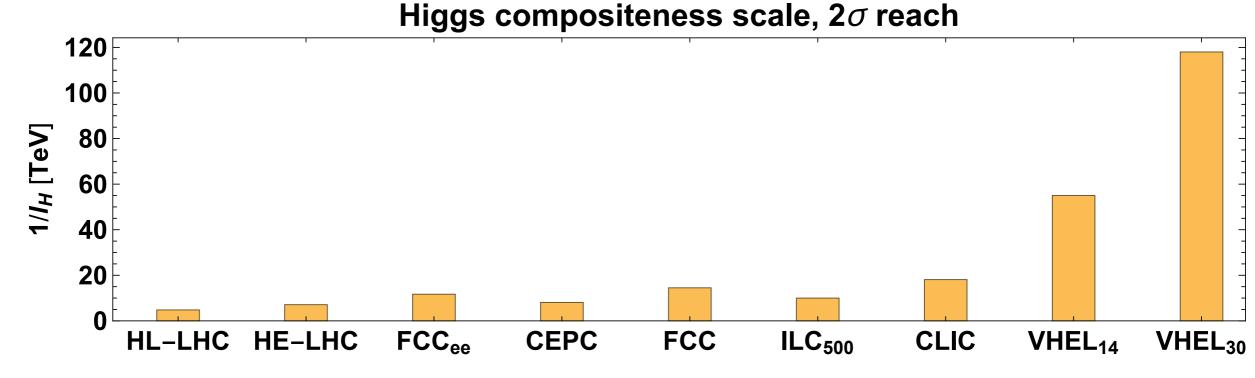


o Franceschini Muon Collider Workshop https://indico.cern.ch/event/845054/contributions/3573348/

Tuning Reach; (very) tentative [Buttazzo, Franceschihi, AW. in prog.] liggs boson



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...]

topics submitted as LoI to Snowmass2021 on Physics at Muon Colliders (a lot of Italian contributions...)

Letter of Interest: Muon Collider Physics Potential

- D. Buttazzo, R. Capedevilla, M. Chiesa, A. Costantini, D. Curtin, R. Franceschin, T. Han, B. Heinemann, C. Helsens, Y. Kahn, G. Krnjaic, I. Low, Z. Liu,
- F. Maltoni, B. Mele, F. Meloni, M. Moretti, G. Ortona, F. Piccinini, M. Pierini,
- R. Rattazzi, M. Selvaggi, M. Vos, L.T. Wang, A. Wulzer *, M. Zanetti, J. Zurita

Muon Collider: Study of Higgs couplings and self-couplings precision

- C. Aimè^a, F. Balli^b, N. Bartosik^c, L. Buonincontri^d, M. Casarsa^e, M. Chiesa^f, F. Collamati^g,
- C. Curatolo^d, D.Lucchesi^d, B. Mele^g, F. Maltoni^h, B. Mansoulié^b, A. Nisati^g,
- N. Pastrone^c, F. Piccininiⁱ, C. Riccardi^a, P. Sala^l, P. Salviniⁱ, L. Sestini^m, I. Vai^a, D. Zuliani^d

Muon Collider: Study of methods for the luminosity measurement

- C. Aimè^a, N. Bartosik^b, L. Buonincontri^c, M. Casarsa^d, M. Chiesa^e, C.M. Carloni Calame^a,
- F. Collamati^f, C. Curatolo^c, U. Dosselli^g, A. Ferrari^h, S. Giovannellaⁱ, C. Giraldin^c,
- F. Happacherⁱ, G. Krintiras^l, D.Lucchesi^c, A. Mereghetti^m, S. Miscettiⁱ, G. Montagna^a,
- O. Nicrosiniⁿ, N. Pastrone^b, F. Piccininiⁿ, C. Riccardi^a, P. Sala^o, P. Salviniⁿ, I. Sarraⁱ, L. Sestini^g,

I. Vai^a, D. Zuliani^c

Letter of Interest: EW effects in very high-energy phenomena

C. Arina, G. Cuomo, T. Han, Y.Ma, F. Maltoni, A. Manohar, S. Prestel, R. Ruiz, L. Vecchi, R. Verheyen, B. Webber, W. Waalewijn, A. Wulzer, K. Xie to be submitted to the Theory Frontier (TF07) and Energy Frontier (EF04)

- e purpose of this LoI is to undertake a critical assessment of recent pro
 - Letter of Interest: Tau-neutrino Production at a multi-TeV Lepton Collider
 - GaetanoMarco Dallavalle, Fabio Maltoni, Silvia Pascoli, Antonio Sidoti to be submitted to
 - the Accelerator Frontier (AF04), Energy Frontier (EF03), and Neutrino Frontier (NF06)
- ssary for a precise description of EW interactions at high energies

d

Experiments being planned at LHC have the potential to fill in the energy gap between 350 GeV and a few TeV, and test different neutrino flavours [7–9]. Their detectors will intercept the flux of neutrinos from b and c decays, and those from pion and kaon decays. However the sample of observed tau-neutrino interactions in the LHC Run 3 (2022-2024) is expected to be marginal for precision measurements. Extension of those experiments in the High Luminosity LHC era beyond 2028 is unlikely, because the LHC environmental background will become prohibitive, ten times worse than at the LHC.

On the other hand, neutrinos will be abundant in a multi-TeV muon collider. They will arise in muon decays and will be produced promptly in many processes, in particular those involving Barbara I production of W and Z, subsequently decaying leptonically.