Physics & MonteCarlo's at muon colliders

A few considerations

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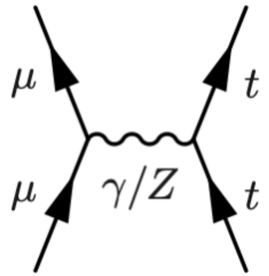
Muon collider physics 101

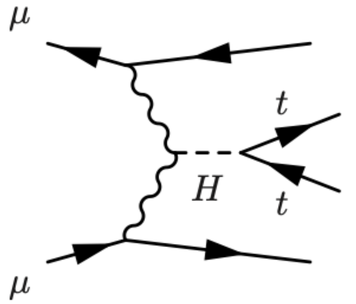
s-channel vs t-channel

$\sqrt{s} \lesssim$ 1-5 TeV



$$\sigma_s \sim \frac{1}{s} \quad \Leftrightarrow \quad \sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$

$\sqrt{s} \gtrsim$ 1-5 TeV



1) Is one mechanism dominating over the other?
2) Do they probe the same kind of physics?
3) Do they pose the same simulation challenges?

Muon collider physics 101

s-channel vs t-channel

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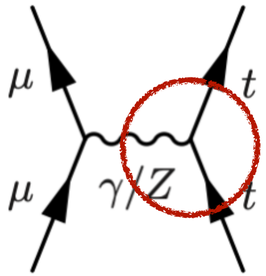

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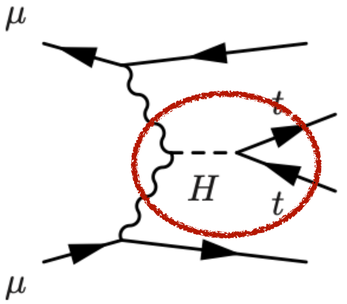
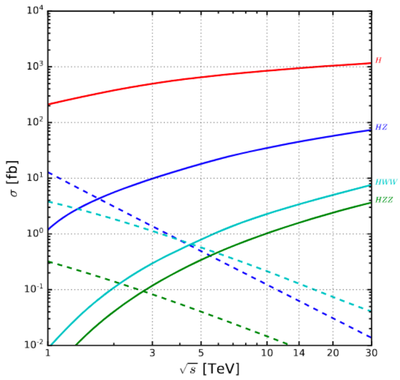
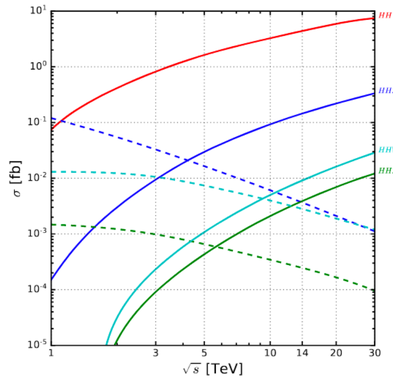
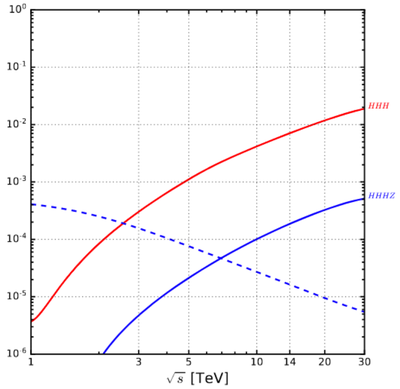
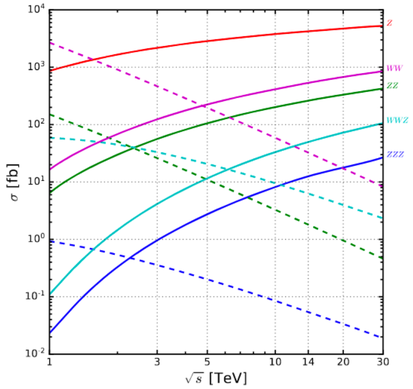
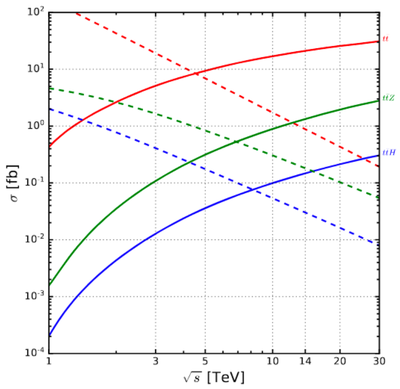


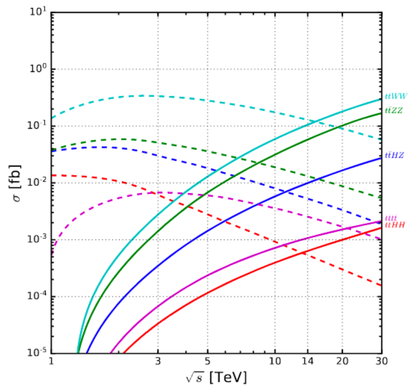






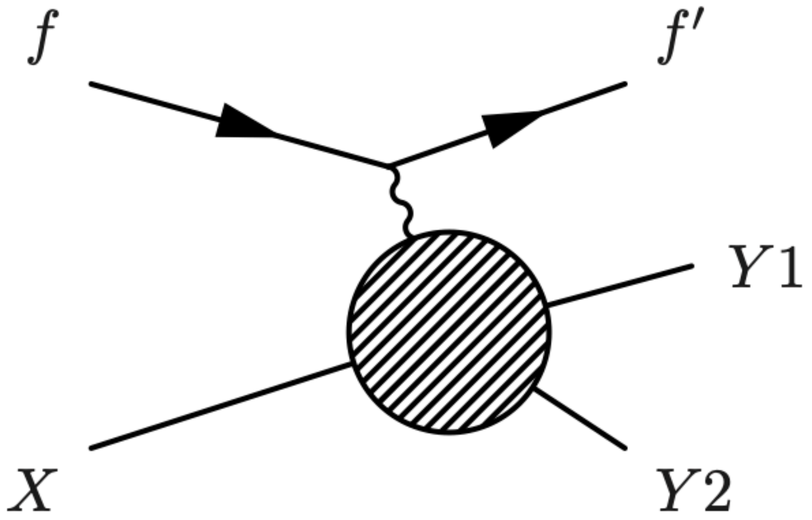






[Costantini et al. 2005.10289]

W,Z,γ as partons
EWA



[Kane Repko Rolnick, 1984] [Dawson 1985]

$$E \sim xE \sim (1-x)E, \qquad \frac{m}{E} \ll 1, \qquad \frac{p_\perp}{E} \ll 1$$

$$f_+ = \frac{(1-x)^2}{x} \frac{p_\perp^3}{(m^2(1-x)+p_\perp^2)^2}\,, \qquad \Rightarrow \log\left(\frac{\mu_F^2}{M_V^2}\right)$$

$$f_- = \frac{1}{x} \frac{p_\perp^3}{(m^2(1-x)+p_\perp^2)^2}\,,$$

$$f_0 = \frac{(1-x)^2}{x} \frac{2m^2 p_\perp}{(m^2(1-x)+p_\perp^2)^2}\,. \qquad \Rightarrow \text{const}\,.$$

$$\frac{d\sigma_{EWA}}{dx dp_\perp}(fX \to f'Y) = \frac{C^2}{2\pi^2} \sum_{i=+,-,0} f_i \times d\sigma(W_i X \to Y)$$

W,Z,γ as partons

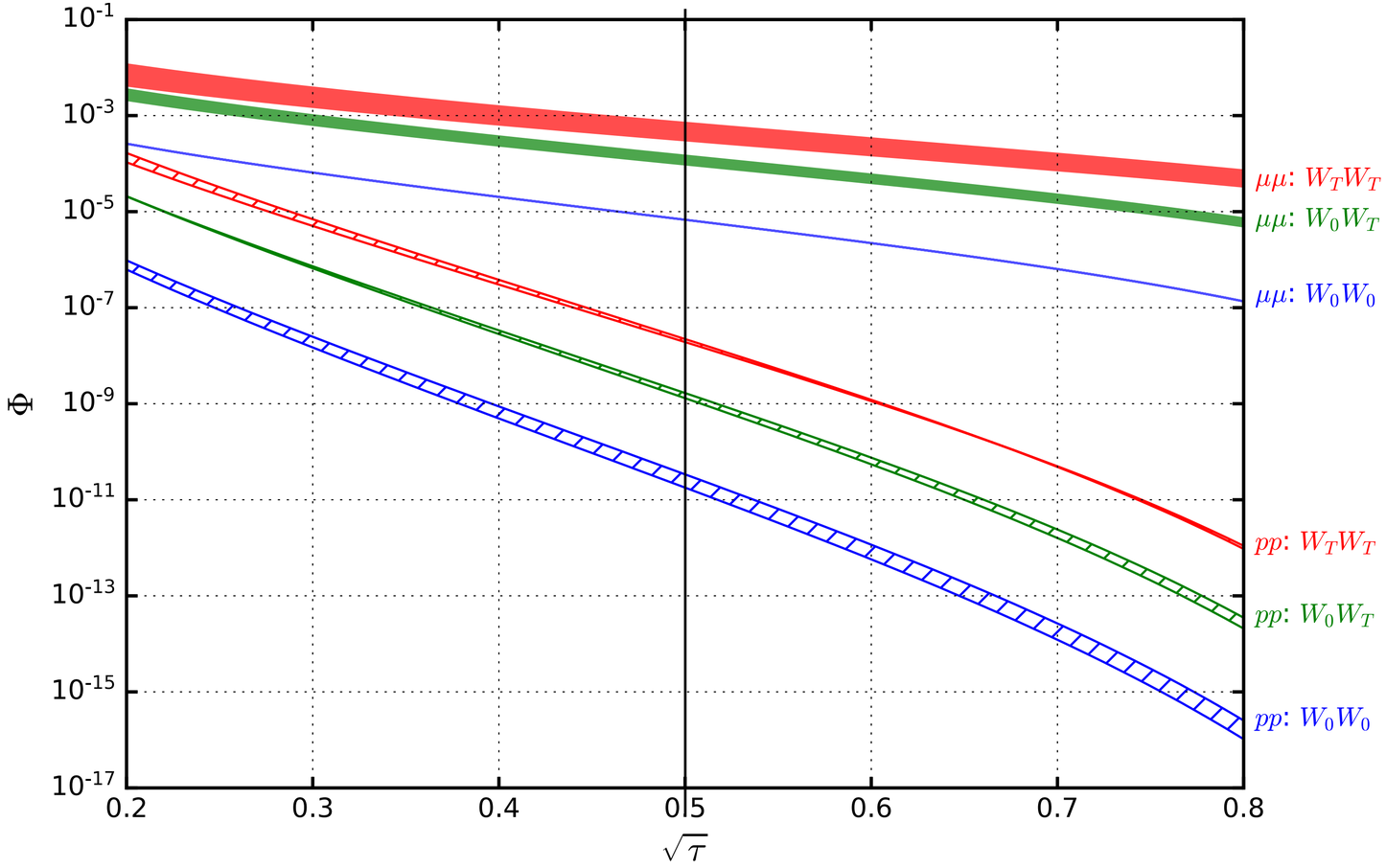
pp vs $\mu\mu$

$$\Phi_{W^+_{\lambda_1}W^-_{\lambda_2}}(\tau,\mu_f)=\int_\tau^1\frac{d\xi}{\xi}\,f_{W_{\lambda_1}/\mu}\left(\xi,\mu_f\right)f_{W_{\lambda_2}/\mu}\left(\frac{\tau}{\xi},\mu_f\right)$$

This plot can be used in any case, but it is particularly simple when considering a muon-collider in the same ring of a proton collider, $\sqrt{s}_{\mu\mu}=\sqrt{s}_{pp}$.

For 2->1, let's take for example $\sqrt{\tau}=\frac{M}{\sqrt{s}}=\frac{1}{2}$

the luiminosity ratio $\mu\mu/pp$ is larger than 10^4 !

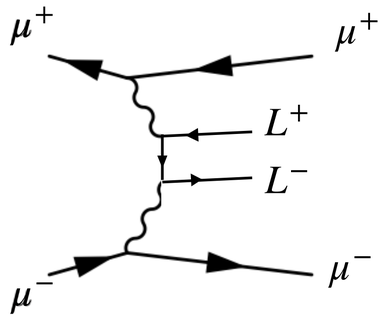


W,Z,γ as partons
$\gamma\gamma$ initial state

Neutral final states can be obtained from quasi-real IS photons. There are now two cases:

1) The final state leptons are detected (min p_T, max η) then q^2 of the photon is sizable ⇒ $\mu^+\mu^- \to X\mu^+\mu^-$ calculation.

2) The final state leptons are "lost" ⇒ equivalent photon approximation via Weizsacker-Williams PDF:



$$f_\gamma^{(\ell)}(y) = \frac{\alpha_{\rm em}}{2\pi}\left[2m_\ell^2 y\left(\frac{1}{q^2_{max}} - \frac{1}{q^2_{min}}\right) + \frac{1+(1-y)^2}{y}\log\frac{q^2_{min}}{q^2_{max}}\right]$$

These effects are large for charged final states. A factor 5 for WW, and a factor 2 for tt [Han, Ma, Xie, to appear]. Note that the two approaches can be used together if q^2_{max} is matched.

EPA (W.W.) implementation available in MadGraph and Whizard.

Available products

MonteCarlos for muon colliders

- Event generation at LO based on matrix elements available (e.g. MadGraph and Whizard) for s-channel

  - $\mu^+\mu^- \to X$

  and t-channel (MadGraph and Whizard)

  - $\mu^+\mu^- \to X + \nu_\mu\bar{\nu}_\mu$ W·W fusion
  - $\mu^+\mu^- \to X + \nu_\mu\mu$ W·Z/γ* fusion
  - $\mu^+\mu^- \to X + \mu\bar{\mu}$ Z/γ*·Z/γ* fusion

Recent Examples:

- 2006.16277 * Capdevilla et al. (MadGraph)
- 2005.10289 * Costantini et al. (MadGraph)
- 2003.13628 * Chiesa et al (MadGraph and Whizard)
- 2002.12218 * Kumar et al. (MadGraph)
- 2001.04431 * Bartosik et al. (Pythia8)
- 1810.10993 * Di Luzio et al. (by hand)
- 1807.04743 * Buttazzo et al. (MadGraph)
- more…

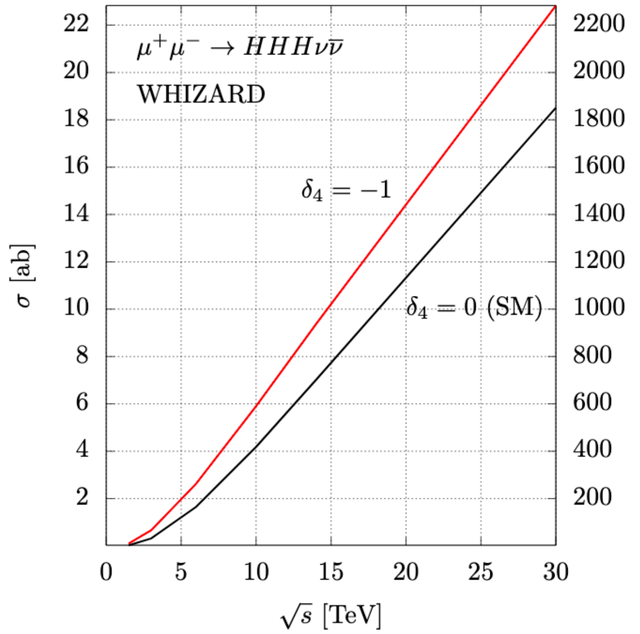
- EWA/EZA(/EPA) LL implementations being validated in MadGraph to be compared with available resummed results [Han, Ma, Xie, to appear].

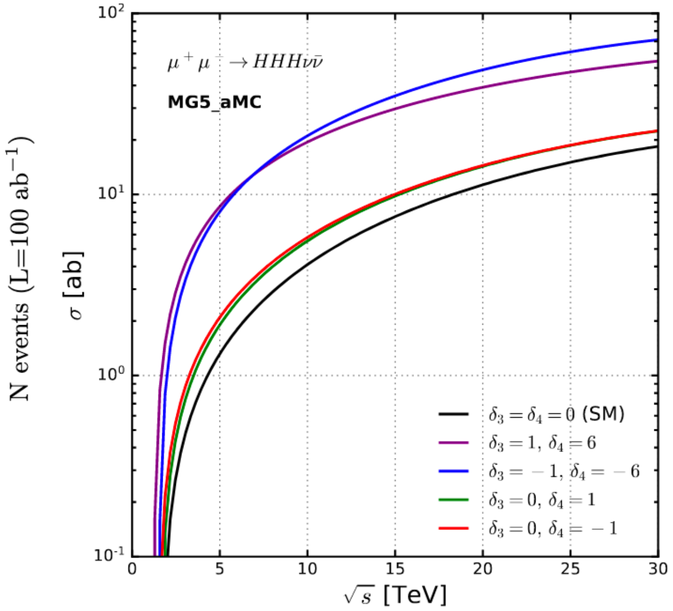
- BSM scenarios including EFT available in FeynRules/MadGraph

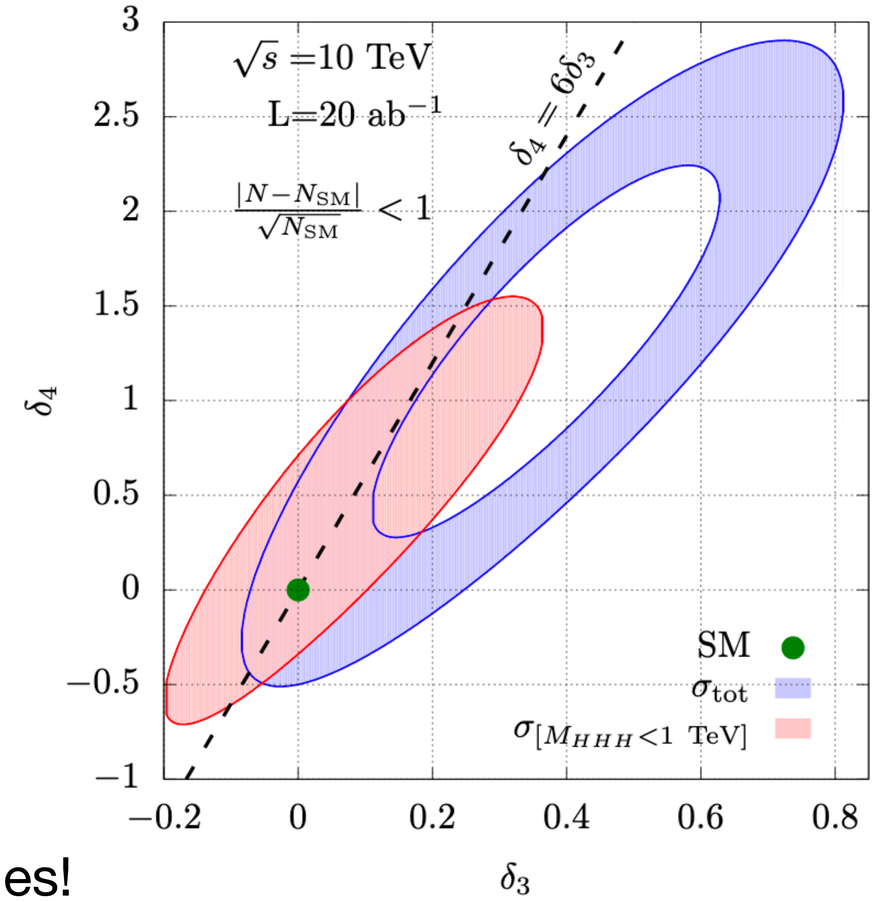
Available products

Example: Sensivity to the Higgs quartic self-interactions

[Chiesa et al. 2003.13628]







Process not so easy to calculate even at LO. Cross-check between Whizard and MadGraph.

First exploration provides motivations for more detailed studies!

Available products

Example: BSM exploration

[Costantini et al. 2005.10289]

(a) Singlet production

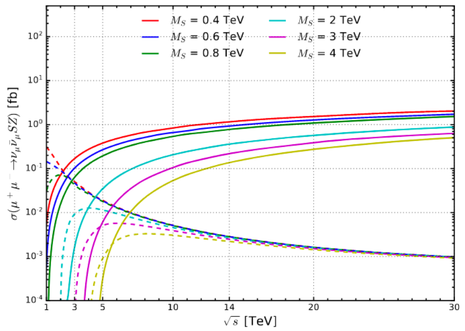
(b) HZ in 2HDM

(c) $\tilde{t}\tilde{t}^*$

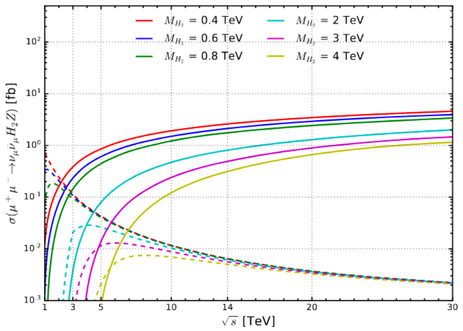
(d) $t'\bar{t}'$

(e) $\tilde{\chi}^0\tilde{\chi}^0$

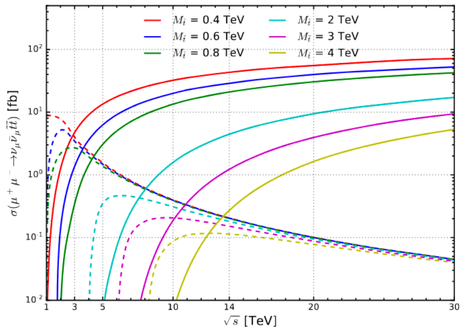
(f) $\chi^+\chi^-$



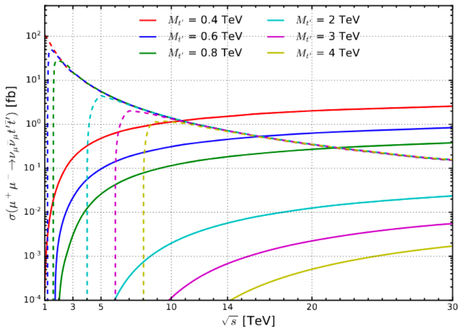
(a)



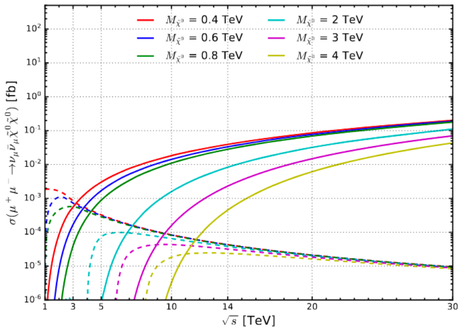
(b)



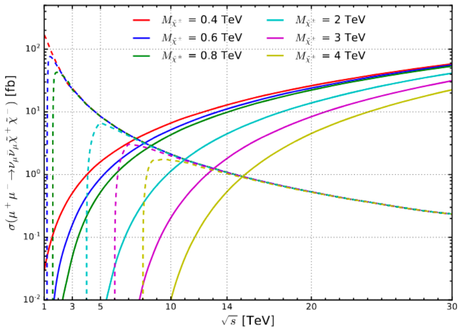
(c)



(d)



(e)



(f)

Sample of BSM processes explored s-channel vs t-channel. Just scratched the surface. Proof of principle: no technical problems encountered.

Opens the way for more studies from the BSM community and prepare representative BSM scenarios to be identified and used as “official” benchmarks.

Next steps
short-term goals

- Make a DELPHES card available for a prototype detector with limited rapidity access
  [input from detector development group]

- Prepare BSM benchmark models/scenarios exploiting s- and t-channel possibilities
  [input from TH community]

- Add the possibility of modeling BES and ISR muon effects in MadGraph (Whizard ⇒OK)
  [input from accelerator group (BES)]

Tools ready ⇒ more physics studies from the pheno/exp community!

Explorations

advancing our understanding and tools

- For t-channel processes make the EWA/EZA approach available in MadGraph (Whizard ⇒OK)
- Study the impact of NLO EW and QCD effects in the SM and selected BSM
- Are ISR EW resummation effects important? Is the FSR EW showering important?
- Implement smart proposal to improve the M^2 calculation in VBF (Cuomo et al. 1911.12366)

THANKS

For infecting me with the meme of the muon collider dream a special thanks to Barbara Mele and Andrea Wulzer.

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