Higgs Production at mu+ mu+ Colliders

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Based on collaboration with

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arXiv:2408.01068

MuC Meeting by the Lake @ Northwestern University, 18 September 2024

Need next generation colliders

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- To dig deep into the nature of the Higgs boson

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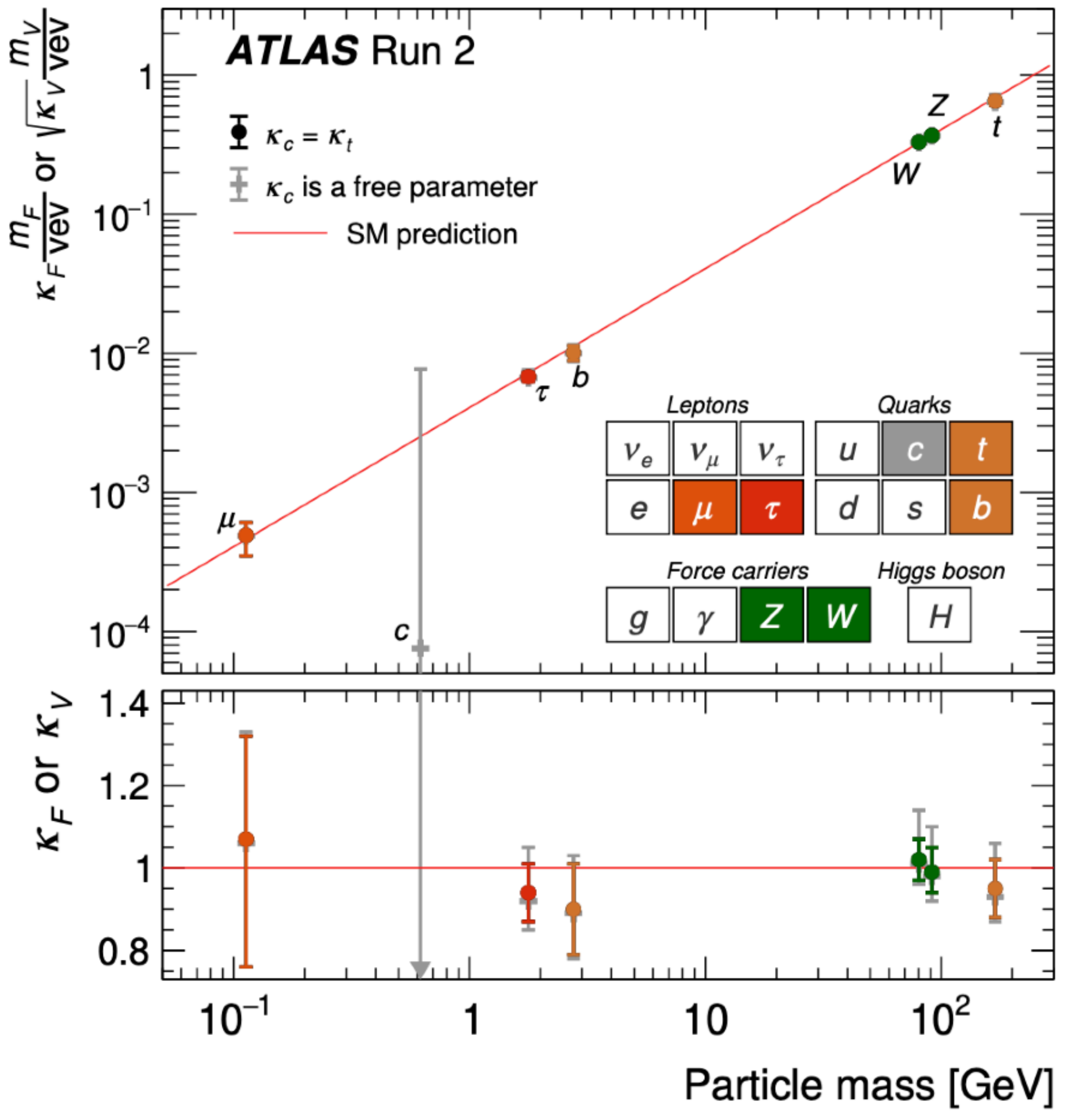

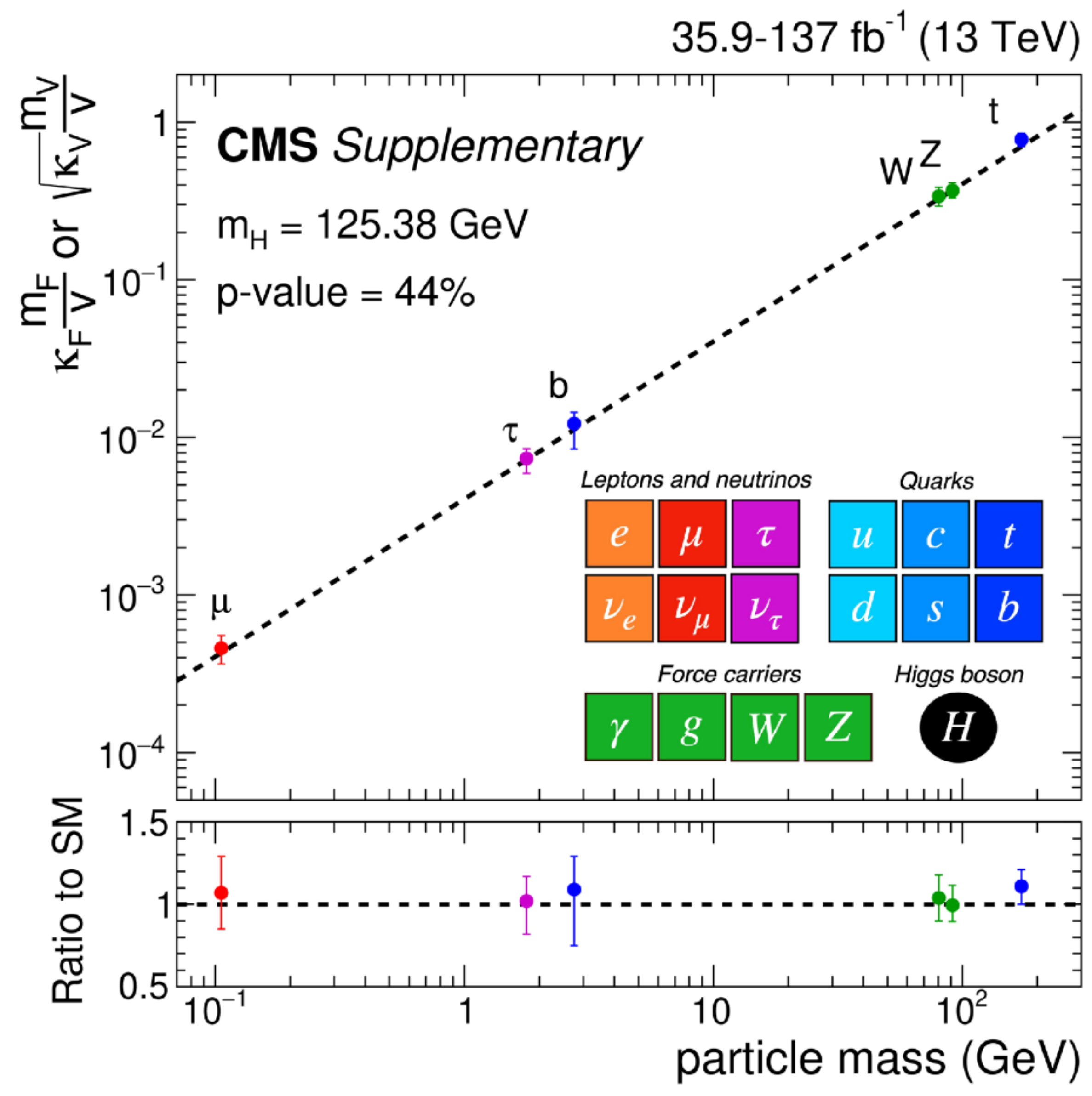

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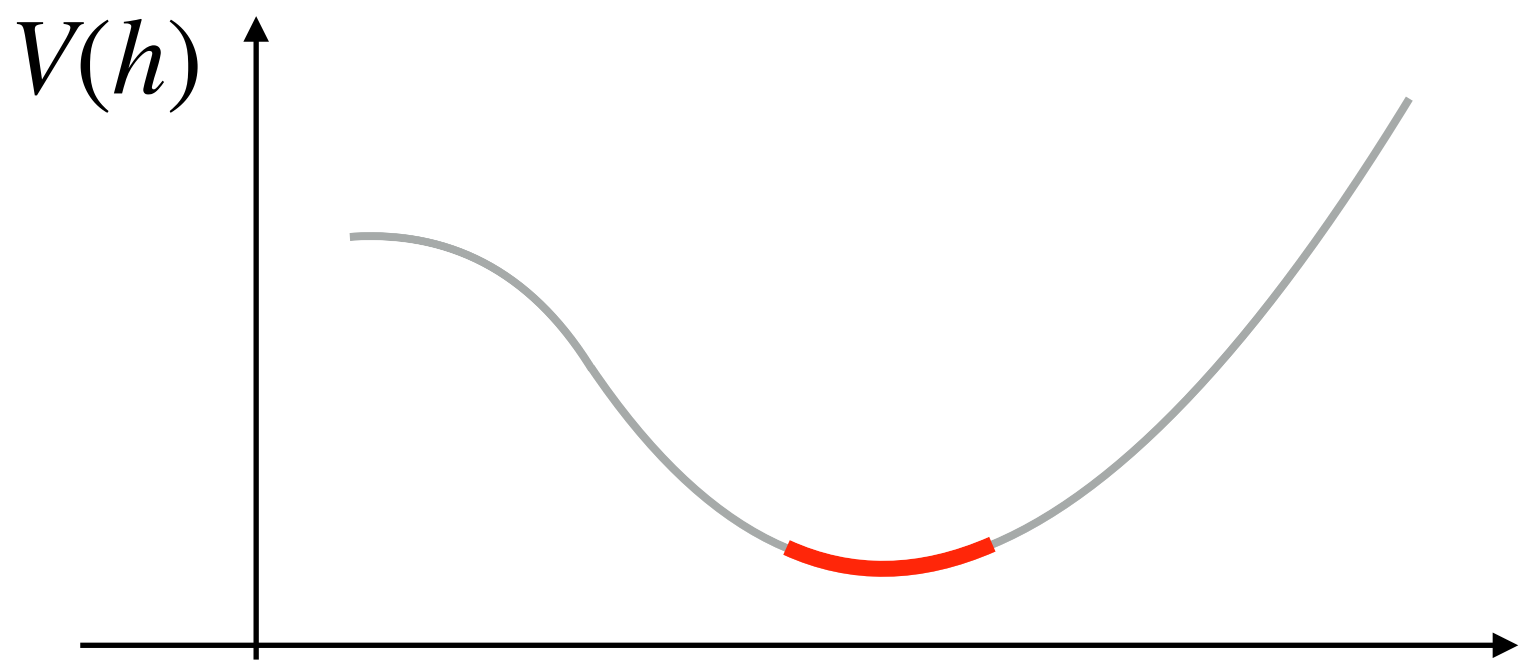

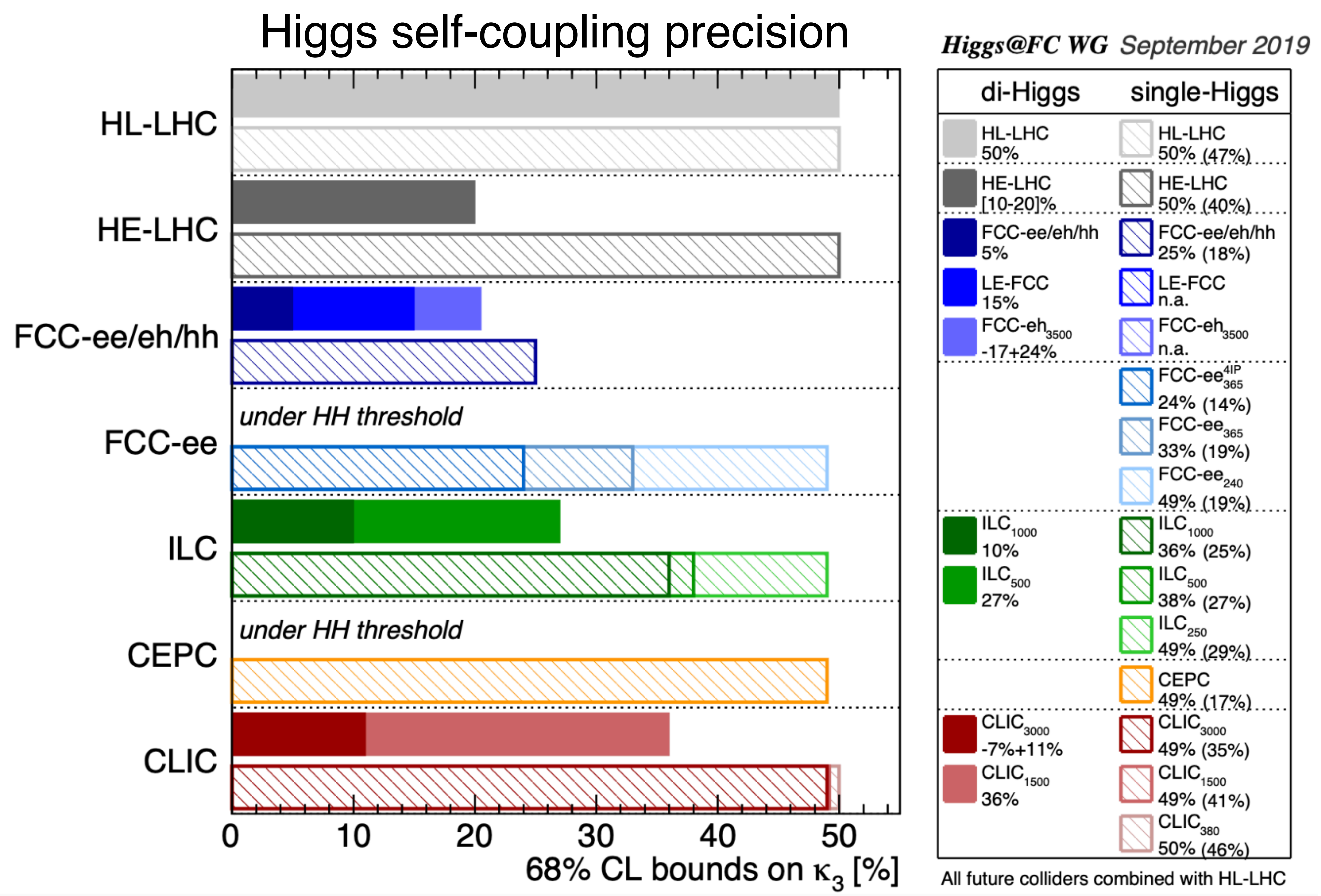

[J. de Blas et al., '20]

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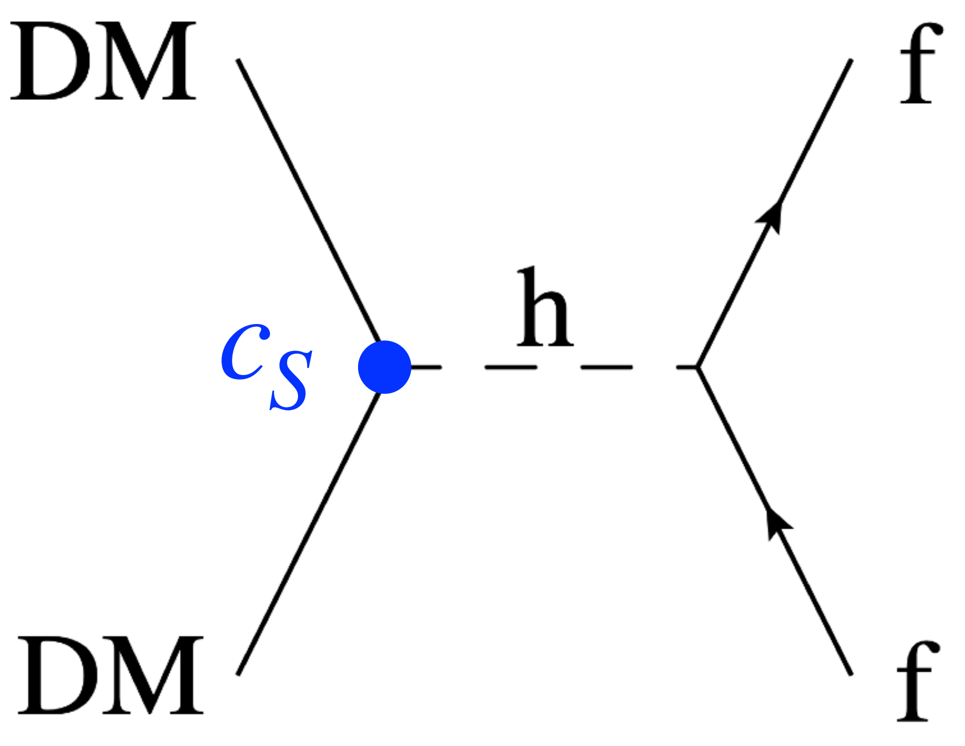

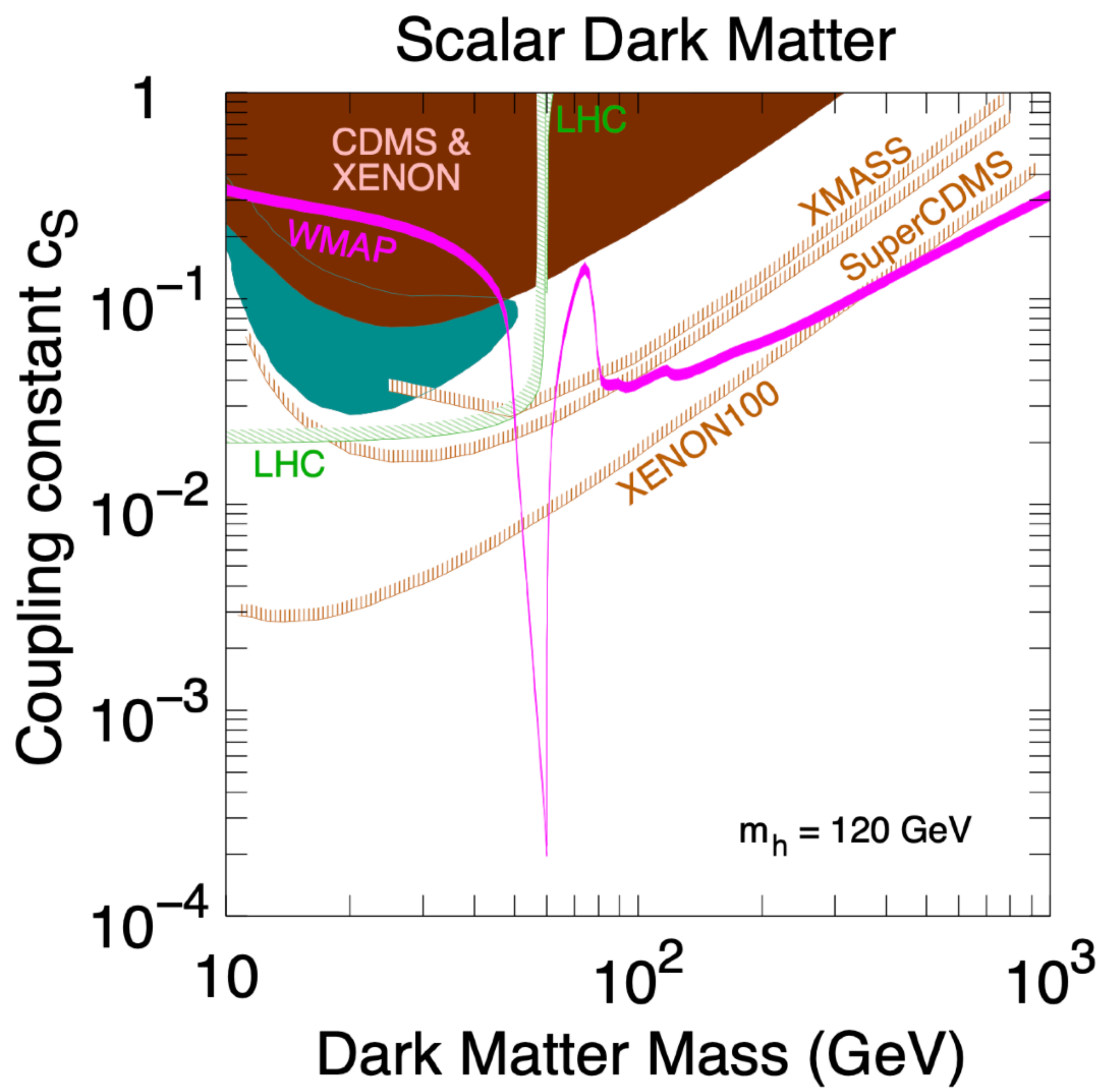

[Kanemura, Matsumoto, Nabeshima, Okada, '10]

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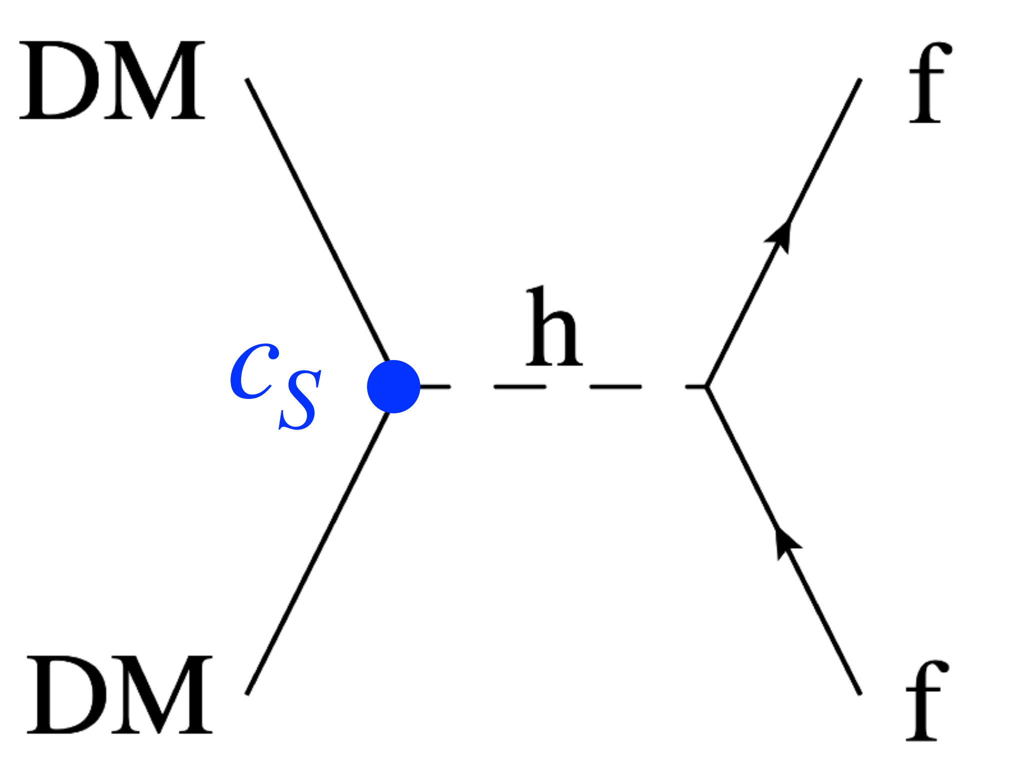

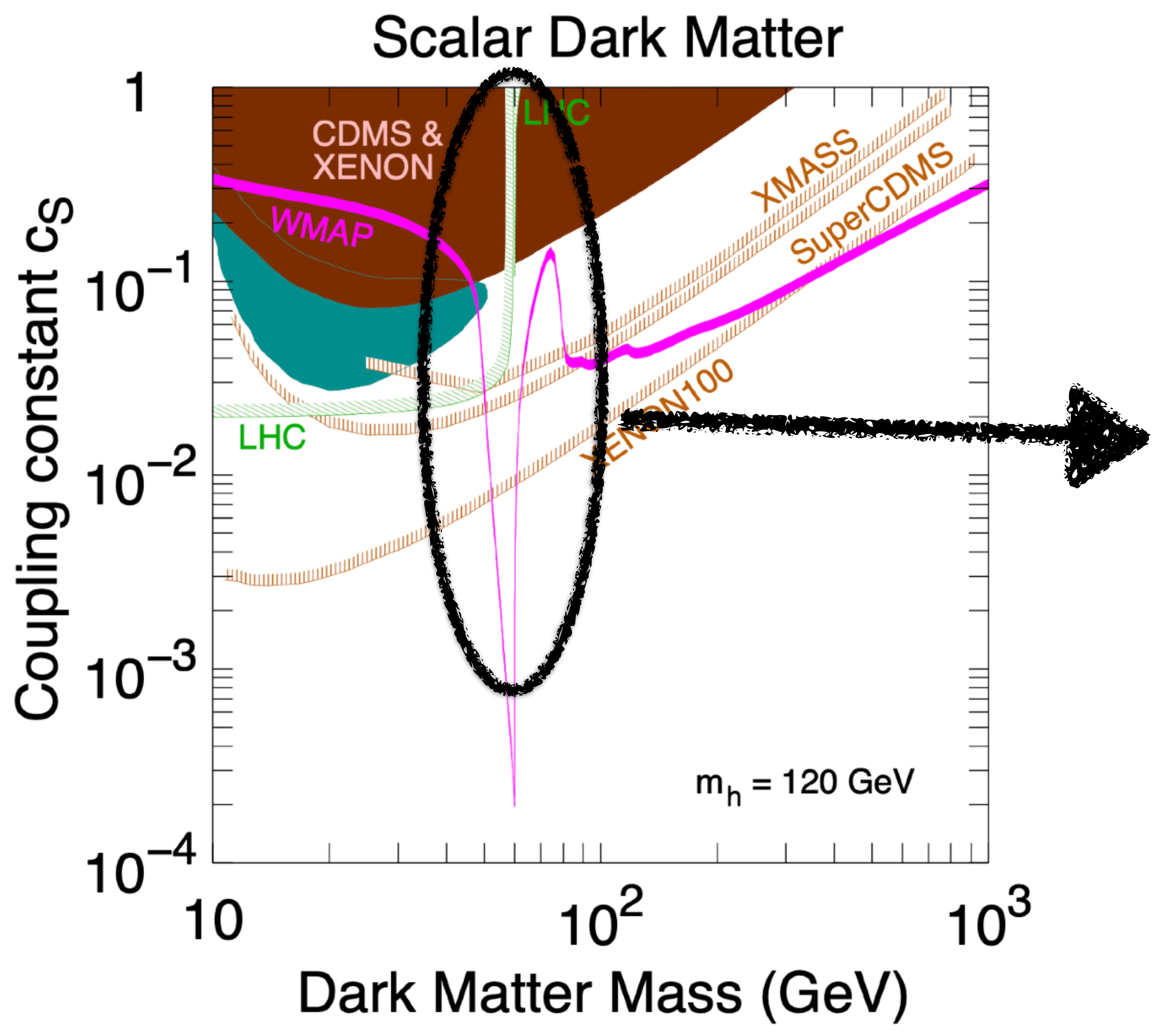

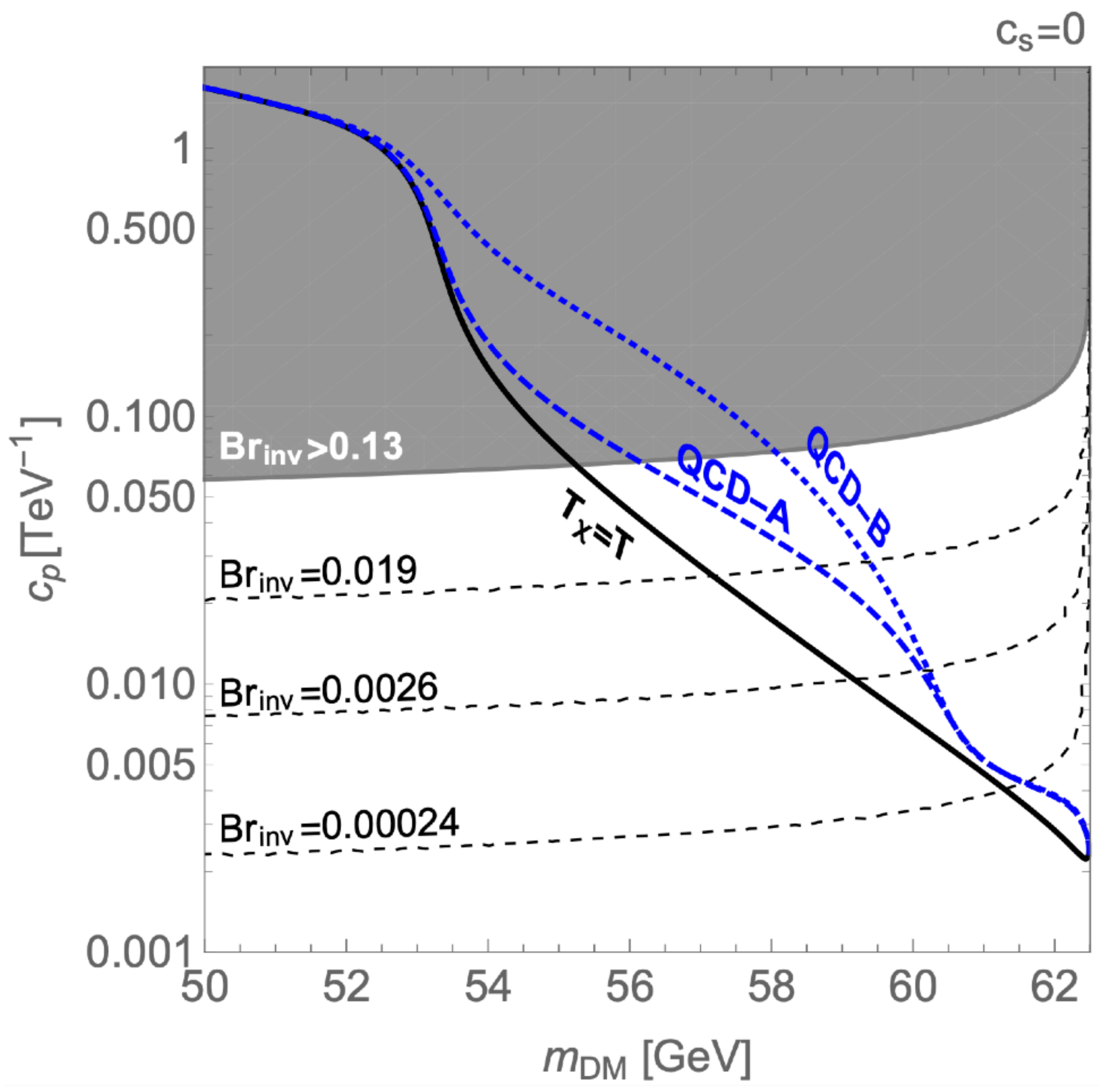

[Kanemura, Matsumoto, Nabeshima, Okada, '10]

[T. Abe '22]

Muon Colliders as a future machine

MuC is a good discovery and precision machine

- as compact as 10km in size to achieve 10TeV parton collisions
- as clean as e+e- colliders

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MuC is a Higgs factory

#(Higgs bosons): 5 x 10^5 at 3TeV (ab^-1) and 10^7 at 10TeV (10ab^-1)

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- as compact as 10km in size to achieve 10TeV parton collisions
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MuC is a Higgs factory

#(Higgs bosons): 5 x 10^5 at 3TeV (ab^-1) and 10^7 at 10TeV (10ab^-1)

However, many challenges to make it the real: μ cooling (luminosity), BIB, magnet, …

μTRISTAN

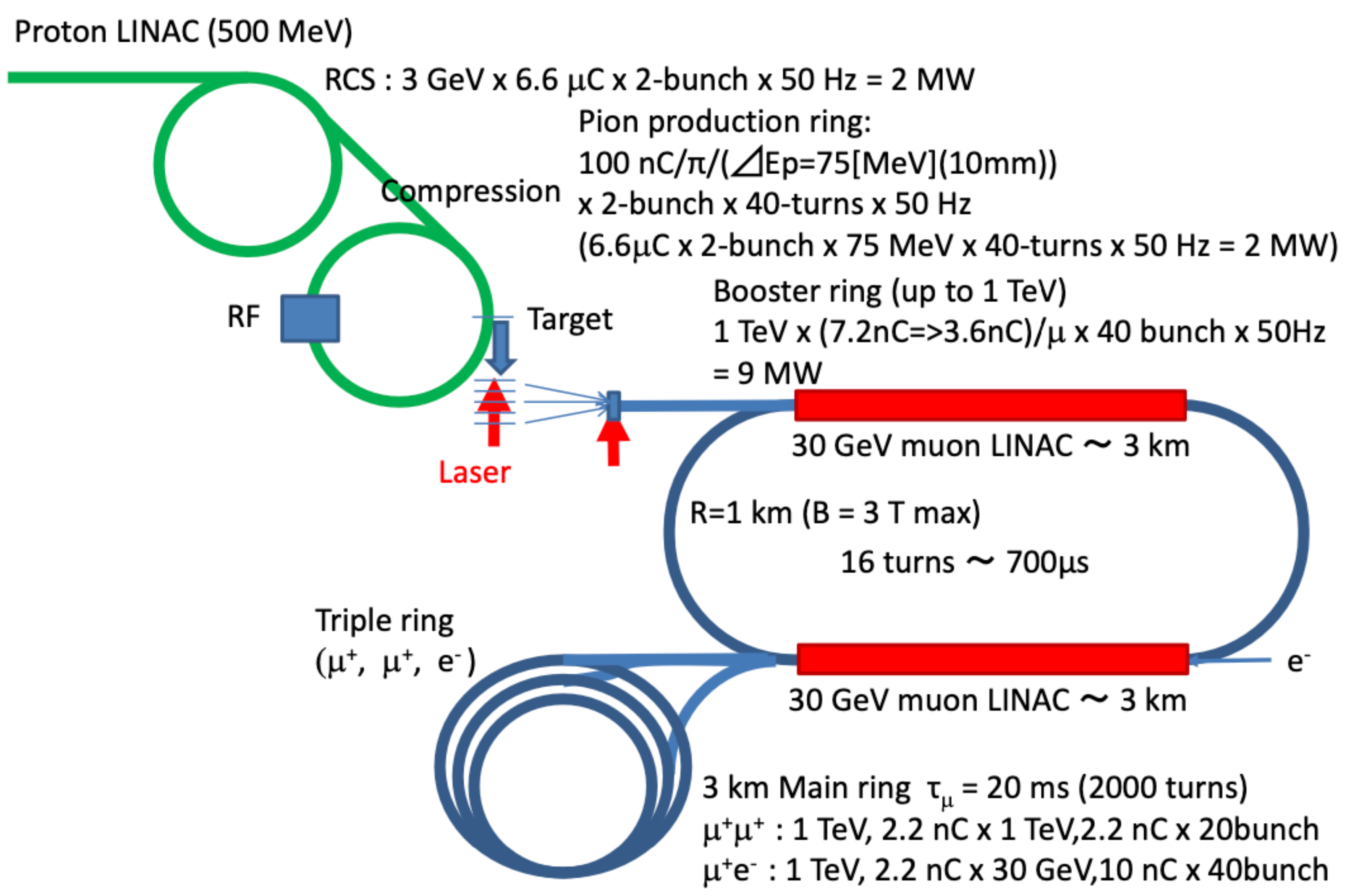
Hamada, Kitano, Matsudo, Takaura, Yoshida ('22)

Prototype Design:

- builds on an existing μ^+ cooling technology at J-PARC
- 3 km main ring
- two options
  - $\mu^+ e^-$: $\sqrt{s} = 346$ GeV (1TeV μ^+ / 30GeV e^-)
  - $\mu^+ \mu^+$: $\sqrt{s} = 2$ TeV (1TeV μ^+ each)

*polarized beams also possible (non-trivial though)

- luminosity $\sim 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (ab^-1 level for 10yrs running)



Physics Case: SUSY, Precision Tests, (E)WIMPs, LFVs, Neutrinos and more

next talk by Joe Sato

see also Hamada, Kitano, Matsudo, Takaura ('22); Fridell, Kitano, Takai ('23); Fukuda, Moroi, Niki, Wei ('23); Okabe, Shirai ('23); etc.

Muon Collider Comparison

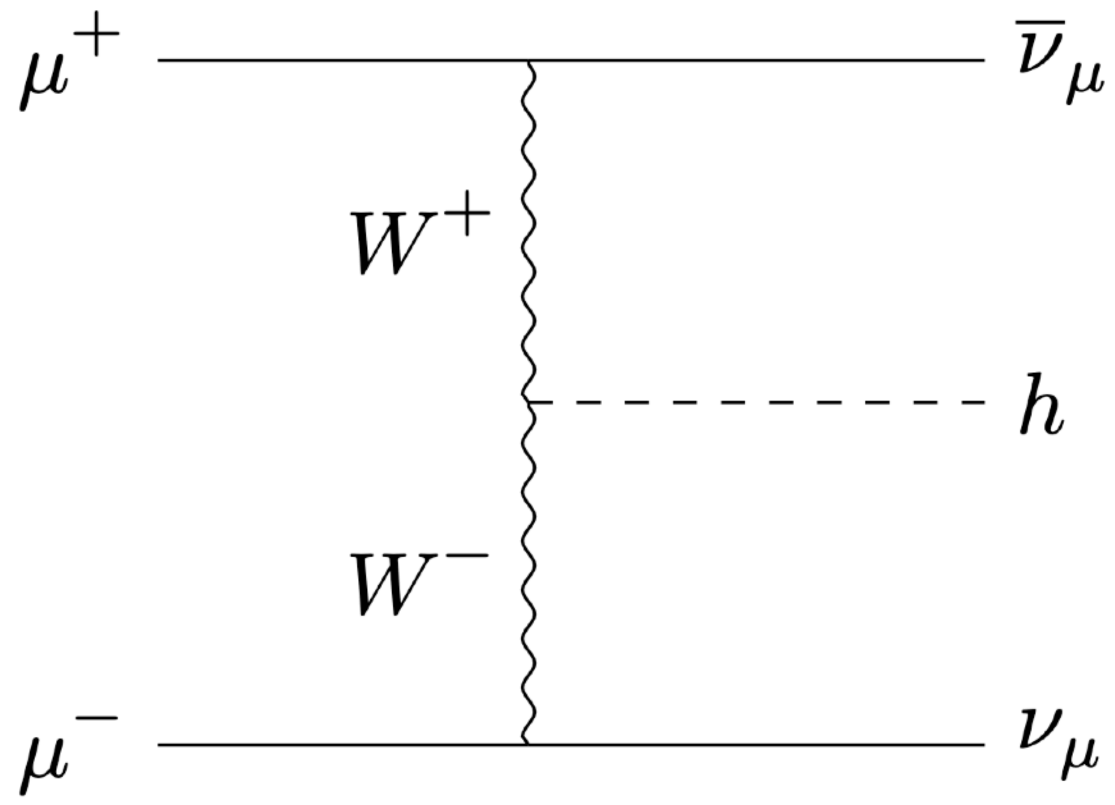
Today's focus

	$\mu^+\mu^-$	μ^+e^-	$\mu^+\mu^+$
Electrically Neutral	✓	✓	✗
Vector Boson Fusion (VBF) w/o s-Channel Background (e.g., W^+W^-, $q\bar{q}$)	✗	✓	✓
Special Advantage	Resonant s-Channel Production	Flavor Physics	μ^+ Cooling Technology Already Exsists!
Disadvantage	μ^- Cooling Technology Needed	Lower Energy	Suppression From Extra Vertex…?

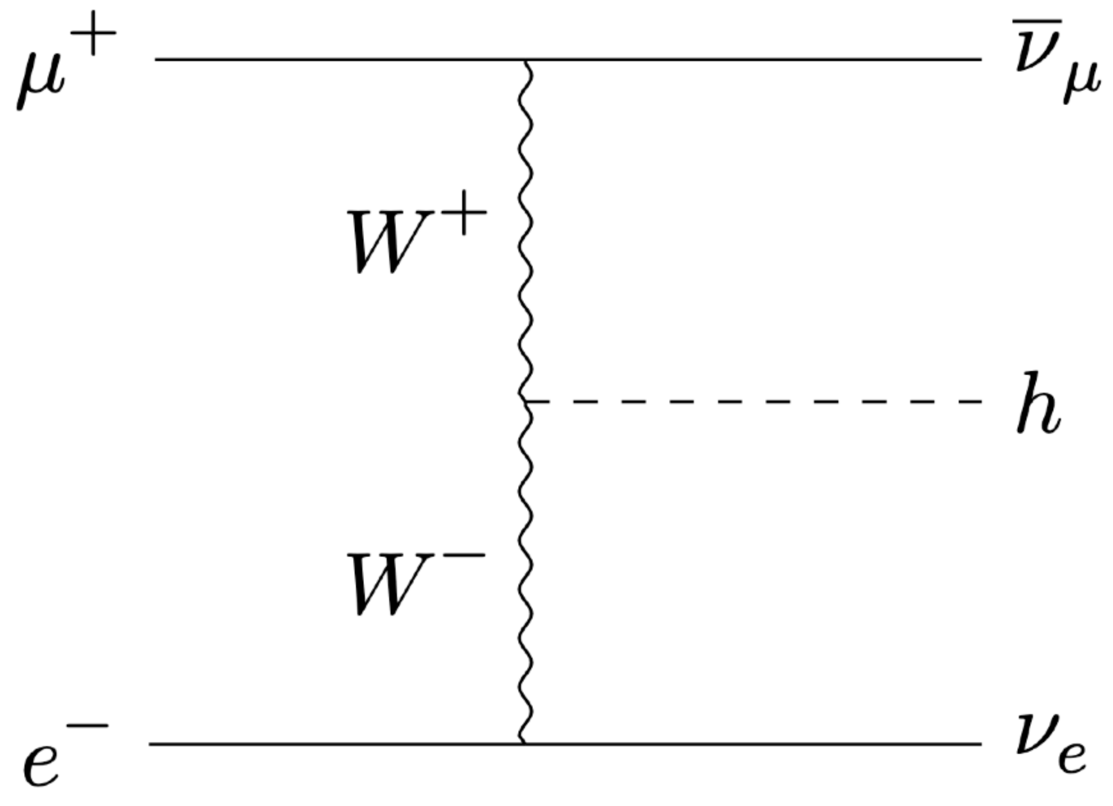
Table from a talk at LCWS2024
by Lukas Treuer

Higgs production at muon colliders

W-fusion processes are dominant at high energies at μ+μ- and μ+e- colliders



~ 400fb (1TeV x 1TeV)



~ 90fb (30GeV x 1TeV)

Higgs production at muon colliders

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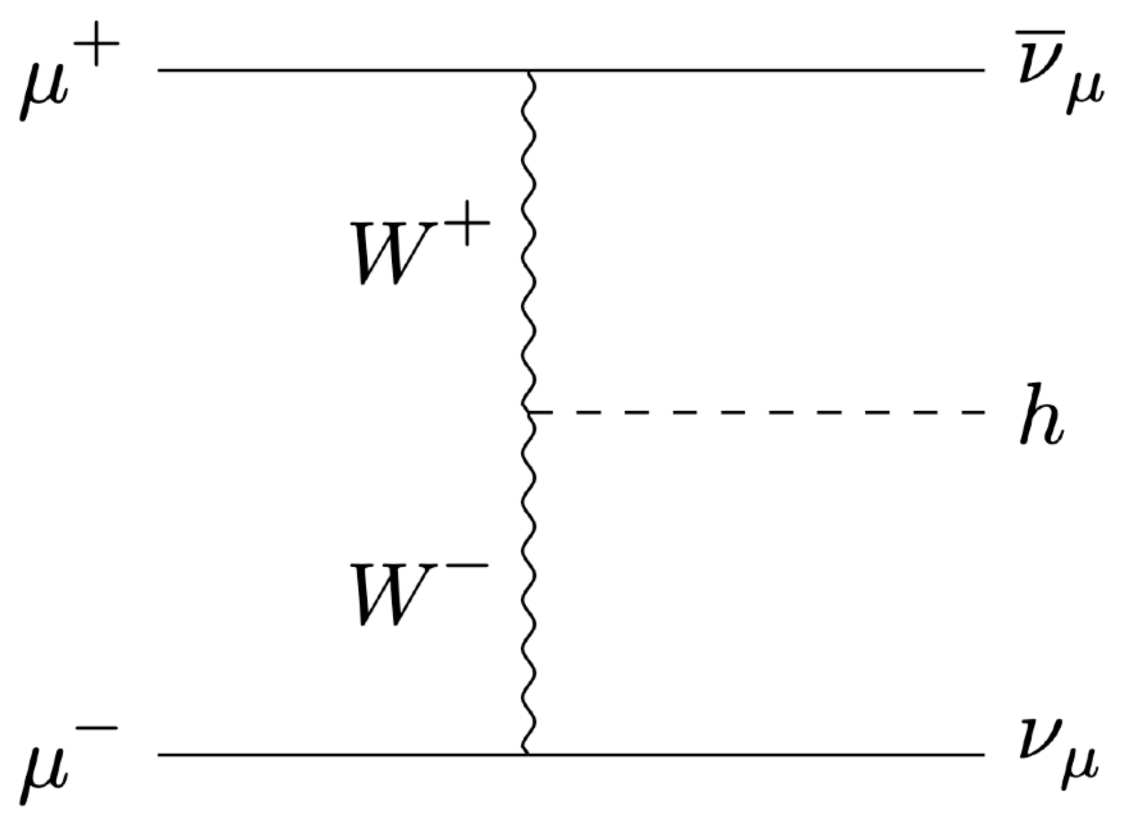
No leading W-fusion at μ+μ+ colliders



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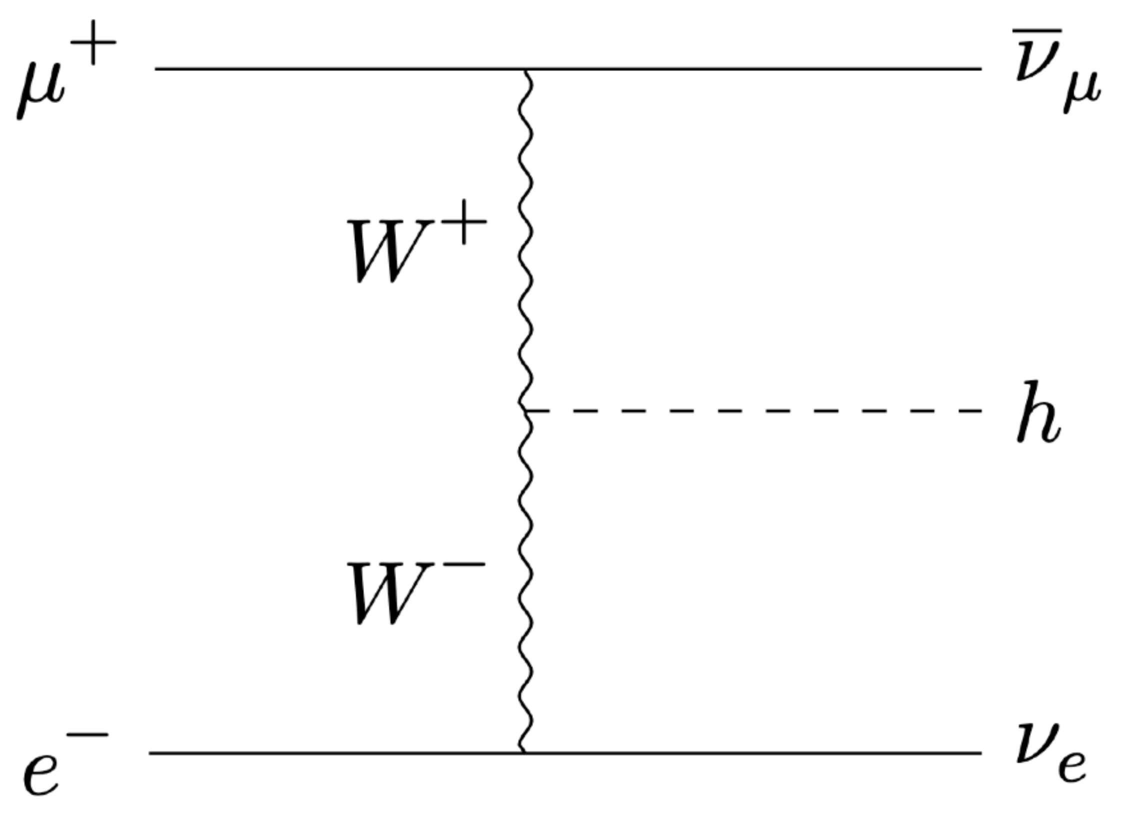

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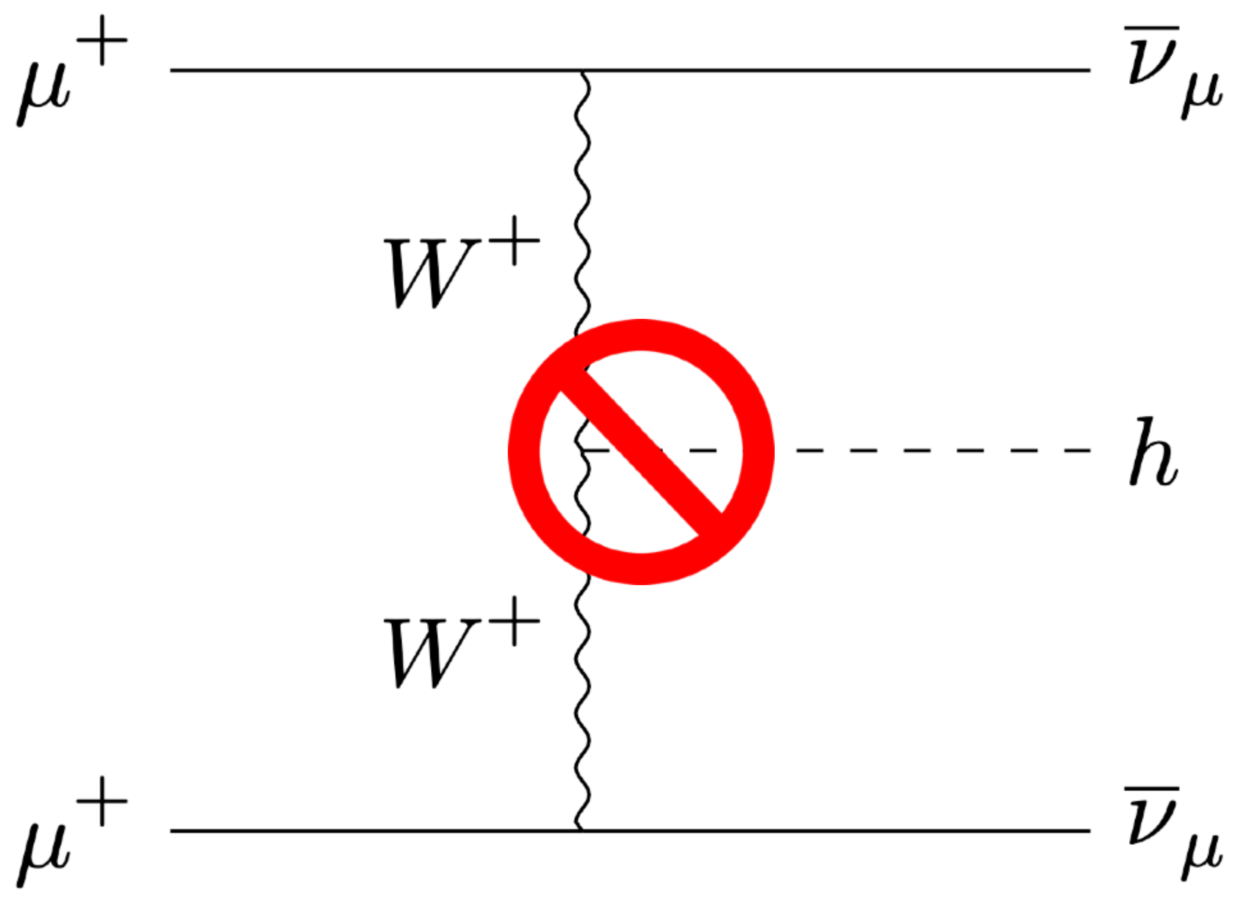
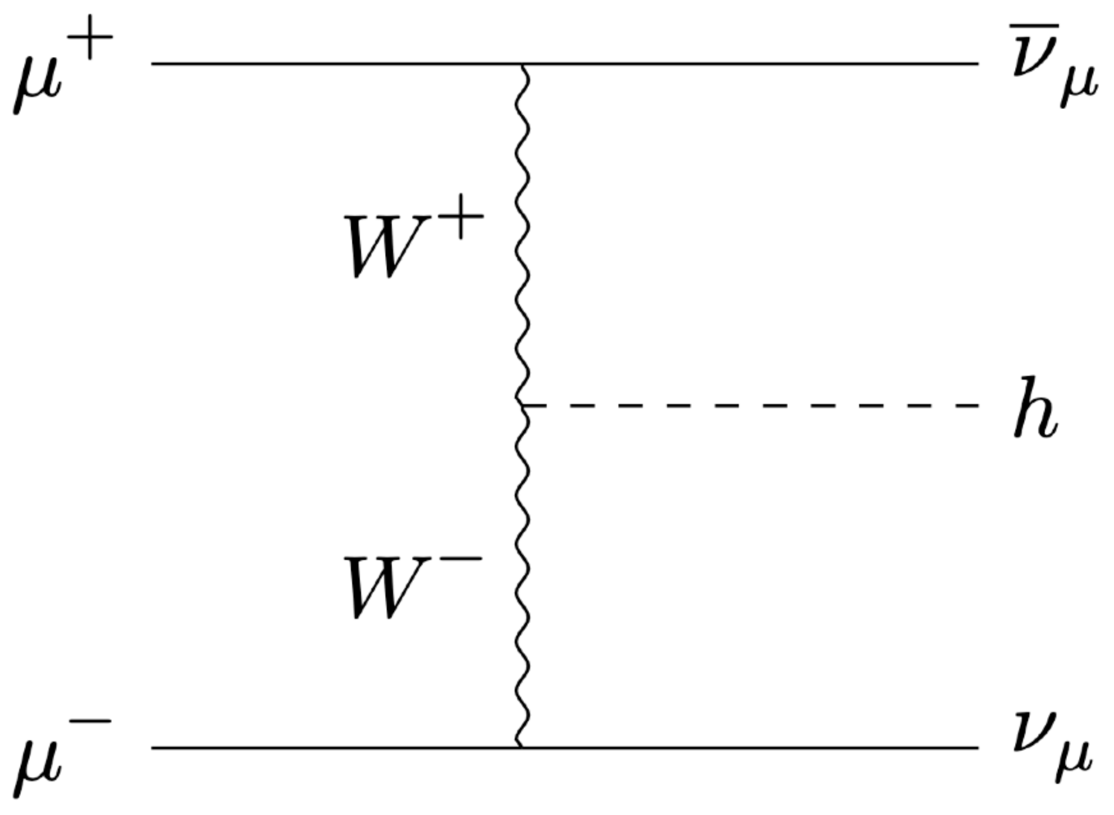


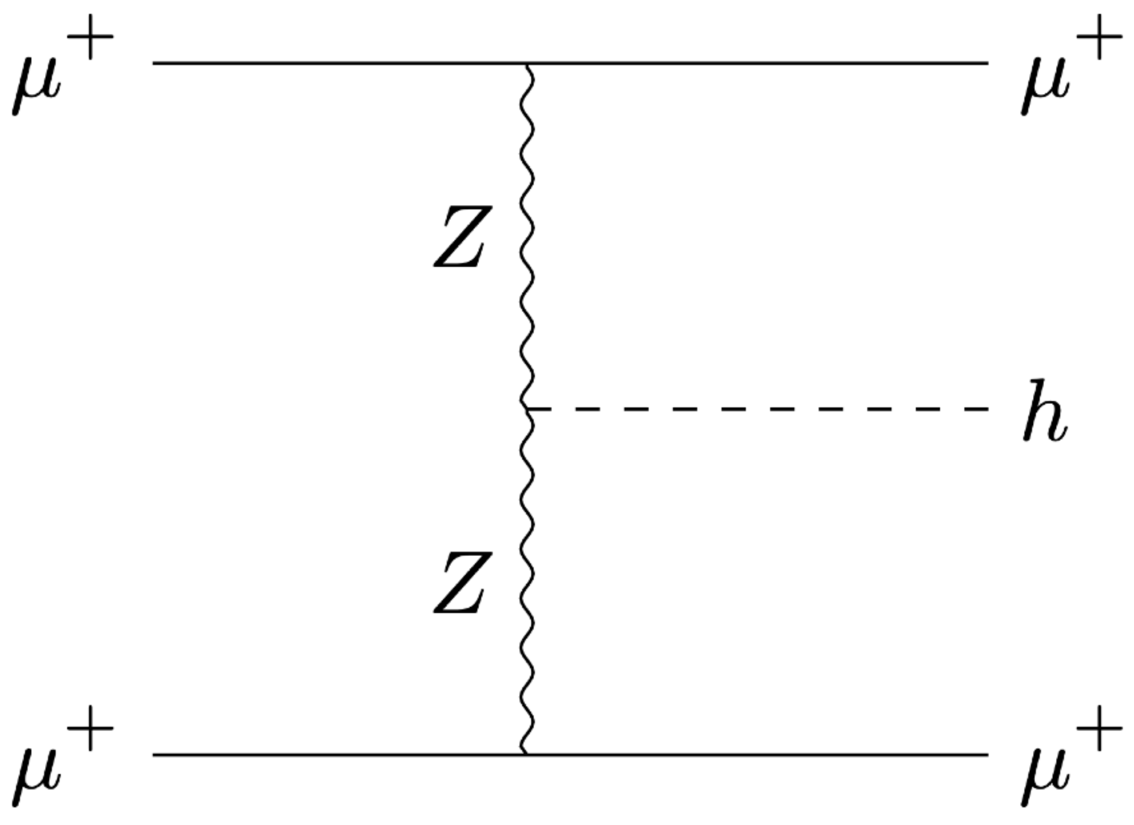
How to produce Higgs boson at mu+ mu+ colliders?

- Z-fusion process? → suppressed due to small Z coupling to muons



~ 400fb (1TeV x 1TeV)

vs



~ 40fb (1TeV x 1TeV)

$$\propto (1 - 4s_W^2 + 8s_W^4)^2$$

How to produce Higgs boson at mu+ mu+ colliders?

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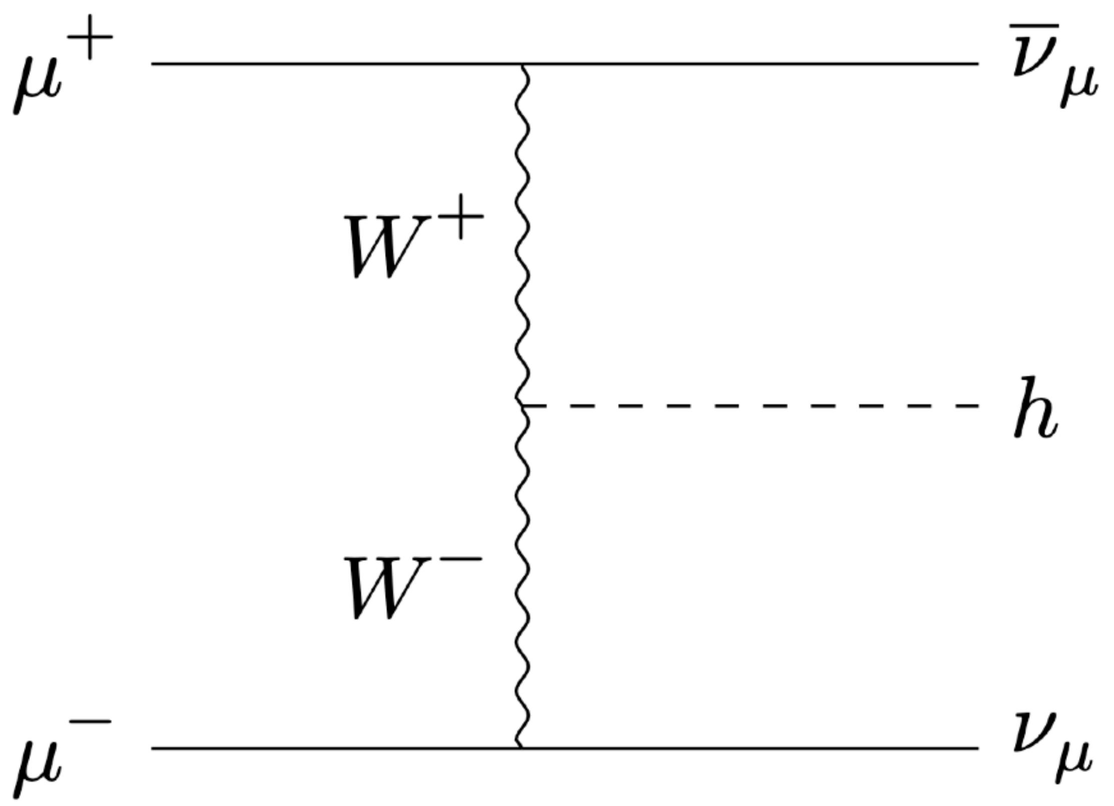
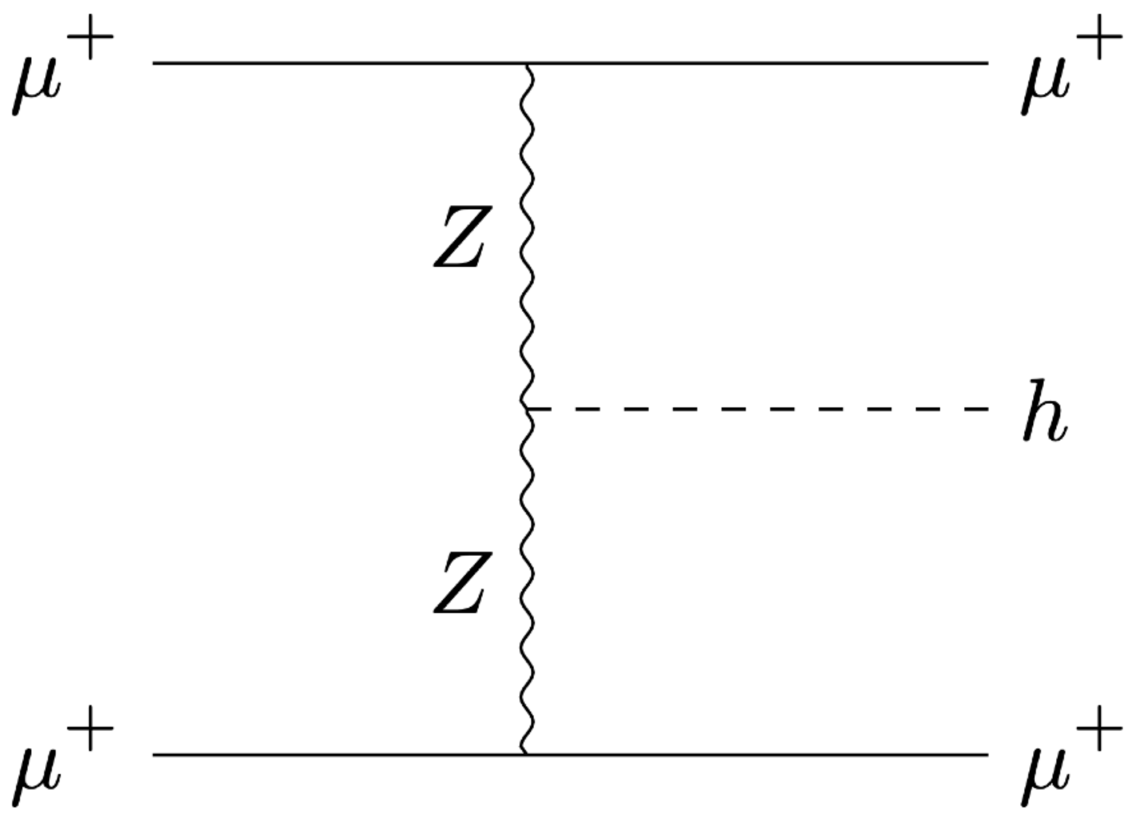
- **photon-mediated W-fusion process**



~ 400fb (1TeV x 1TeV)

vs

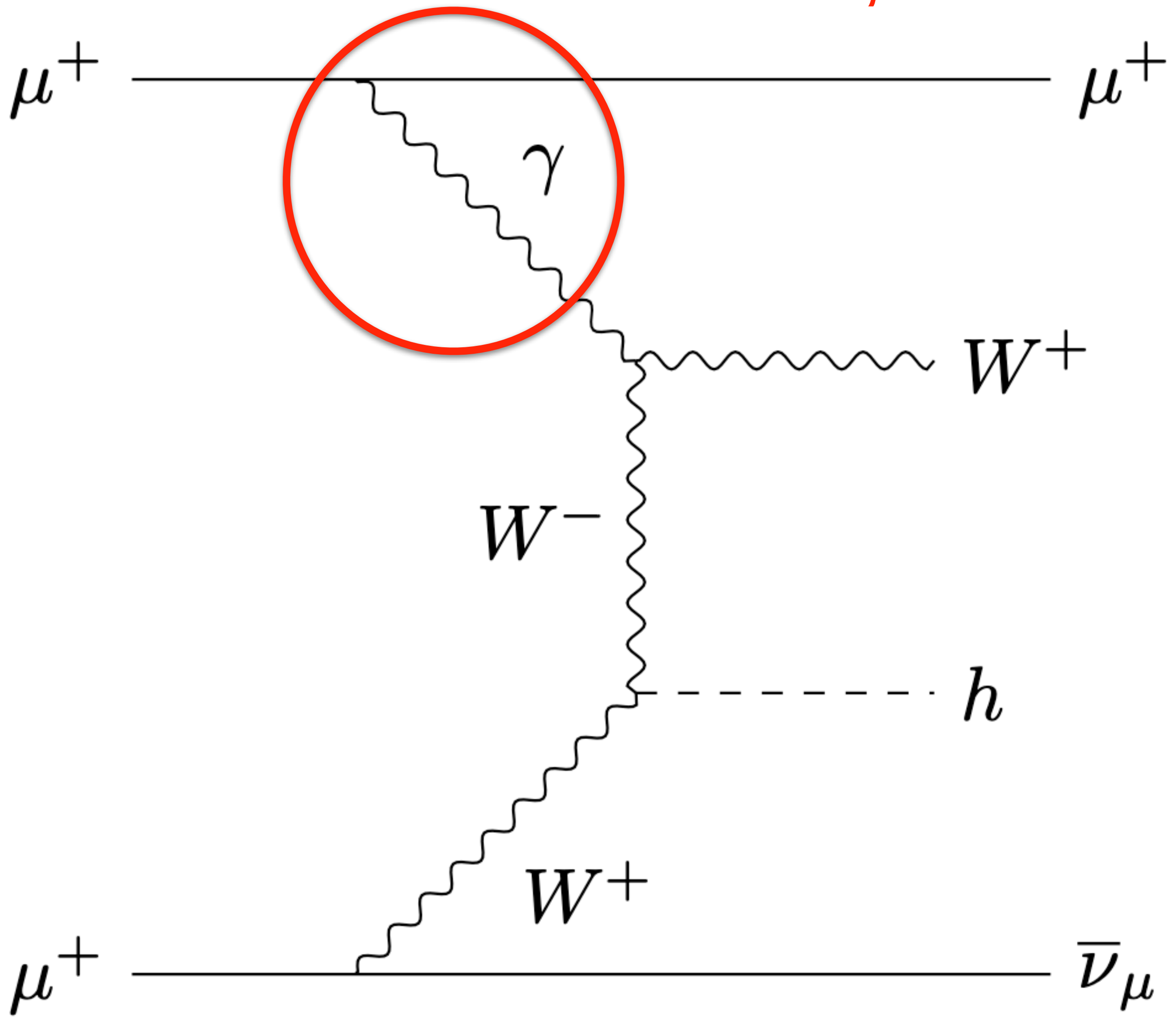


~ 40fb (1TeV x 1TeV)

vs

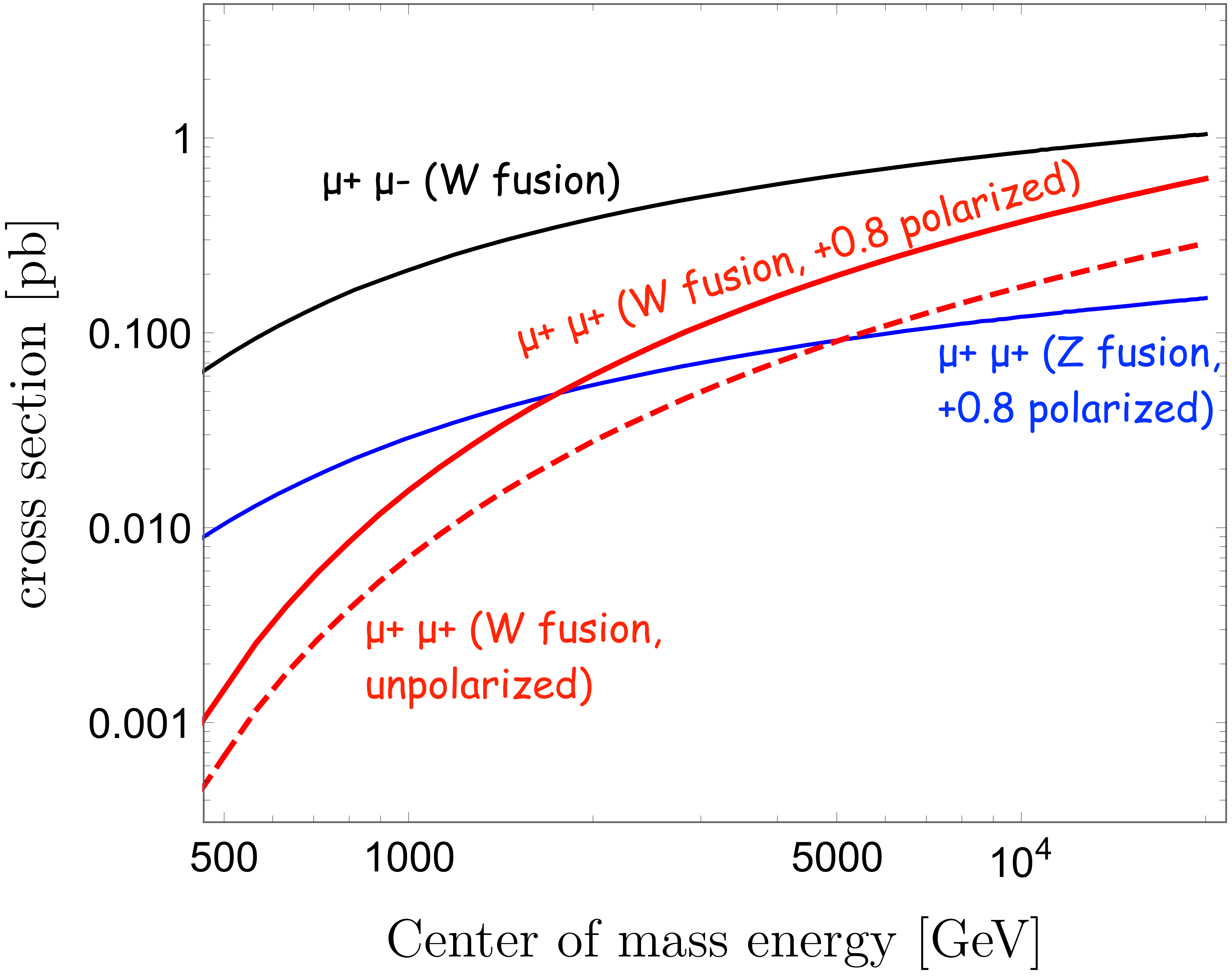
not significantly suppressed

$\sim \alpha \log(s/m_\mu^2)$



~ ??fb (1TeV x 1TeV)

Comparison of Higgs production



- Photon-mediated W-fusion can
  - surpass Z-fusion at ~TeV
  - be as large as half of $\mu^+\mu^-$ W-fusion at ~10TeV
- Polarization is important

Why photon-mediated W-fusion is so large?

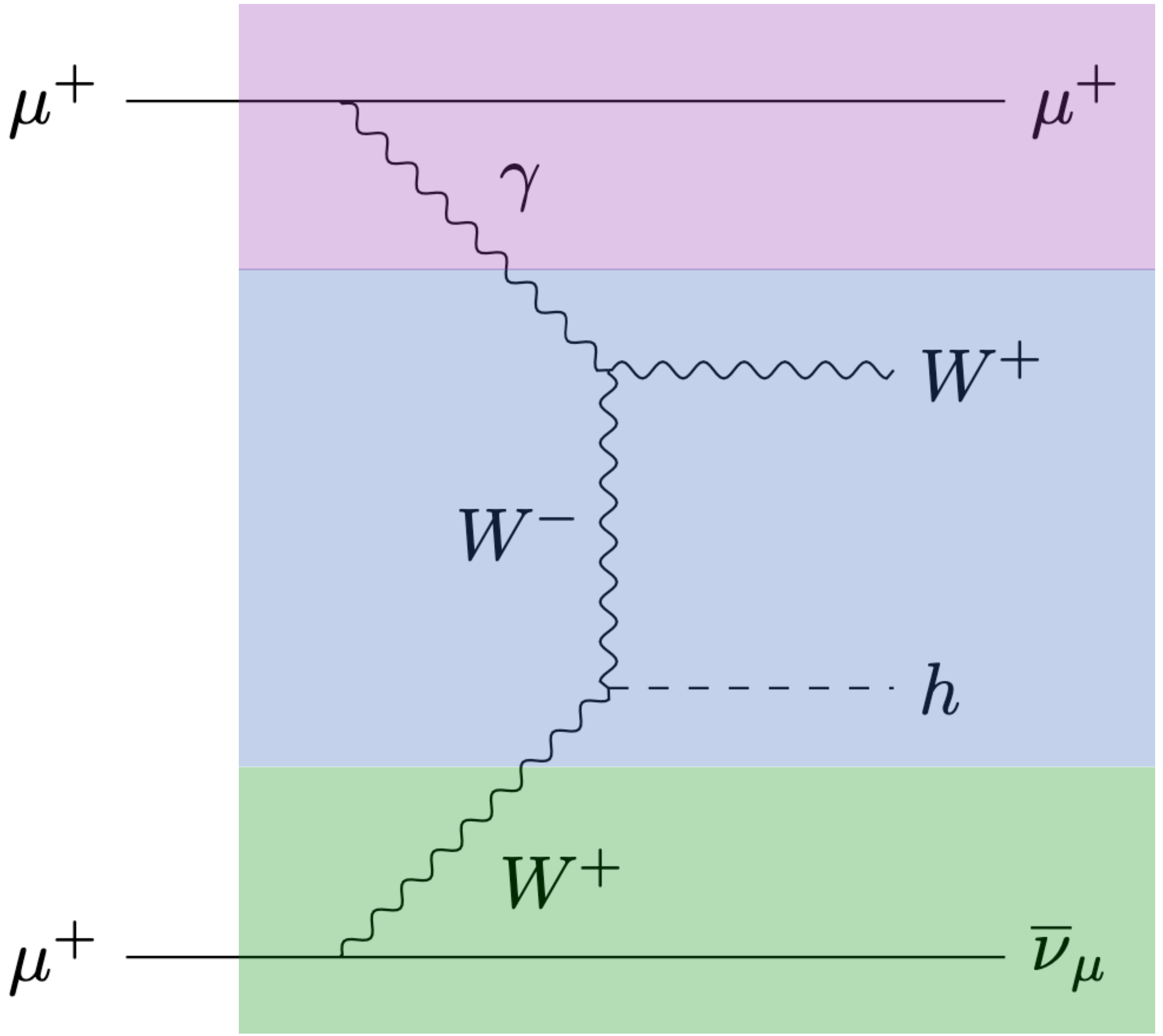
Cross sections have soft/collinear logarithms at high energies

- Leading log analysis:

photon-W xsec | W PDF | photon PDF

$$\sigma(s) \sim \int \mathrm{d}x\,\mathrm{d}y\ \sigma_{\gamma W_L^+ \to W^+ h}(xys)\ f_{W_L^+/\mu^+}(y)\ f_{\gamma/\mu^+}(x)$$

$\sim 1/y$ | $\sim \log(s/m_\mu^2)/x$



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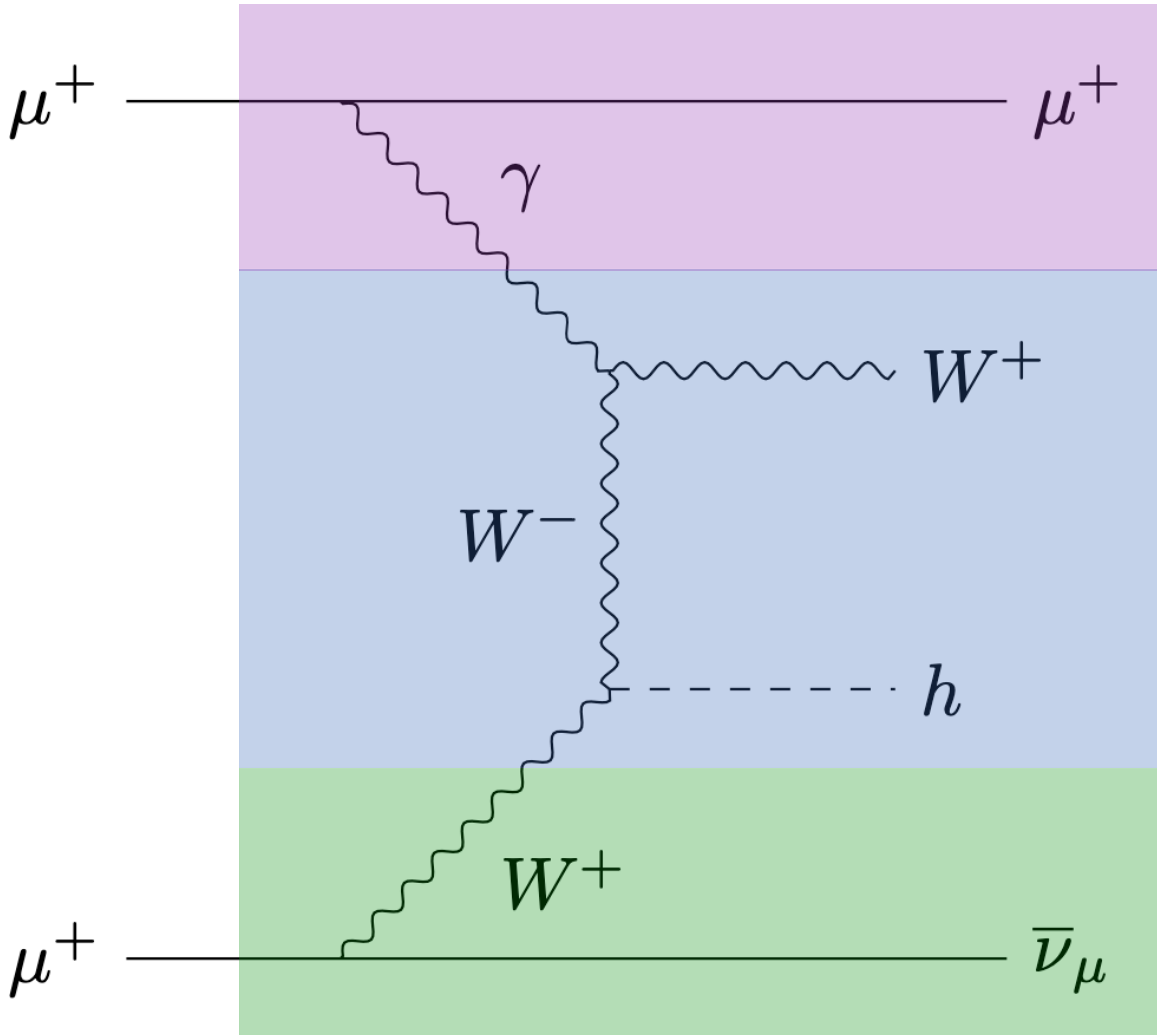
~1/y   ~log(s/m_μ^2)/x

$$\sim \frac{(1+P_\mu^+)\alpha^4}{4\pi m_W^2 \sin^4\theta_W} \log\frac{s}{m_\mu^2}\left(\log\frac{s}{(m_h+m_W)^2}\right)^2$$

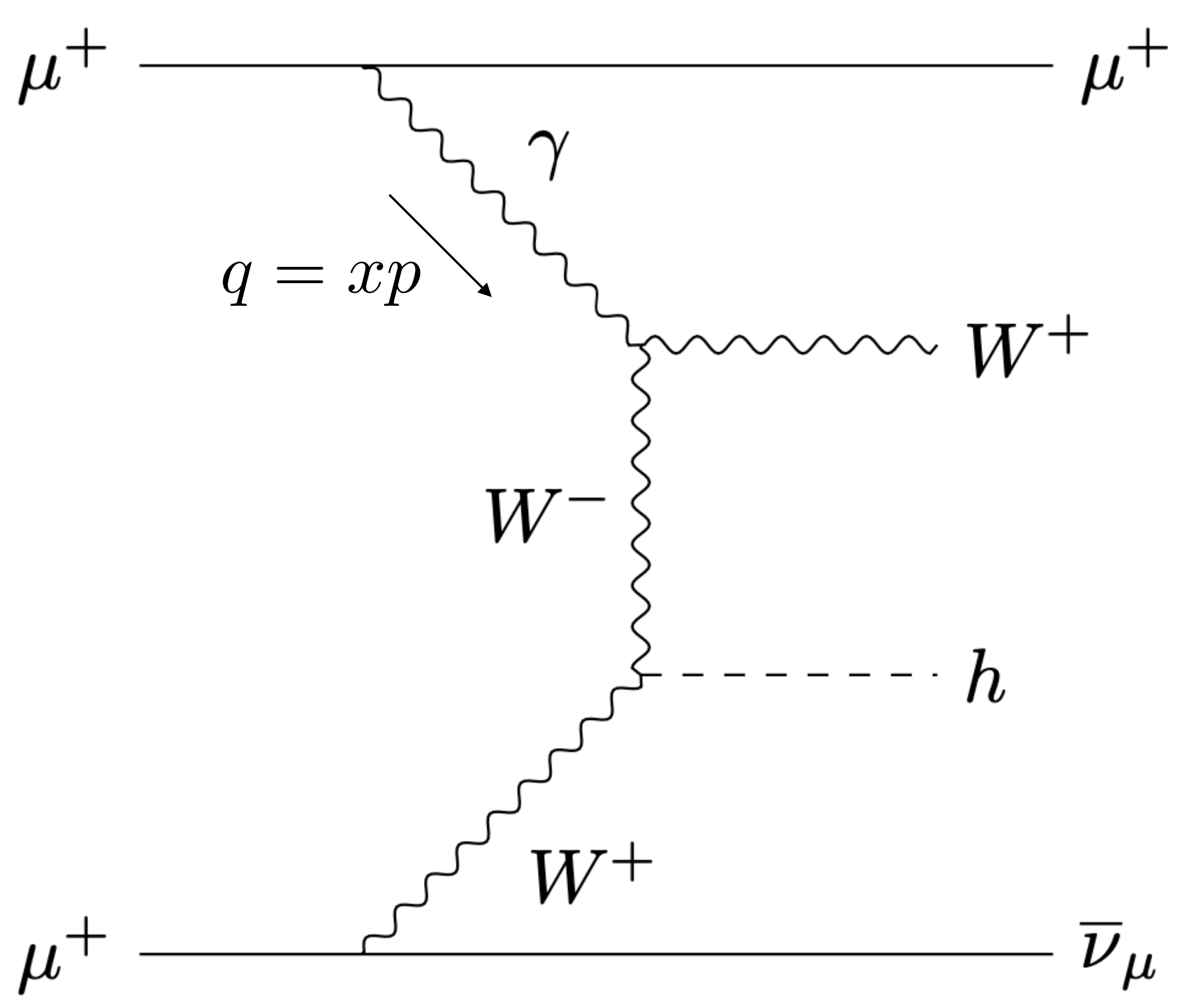
Triple Logarithms!

c.f. μ+μ- W-fusion $\sigma(s) \sim \frac{\alpha^3}{16 m_W^2 \sin^6\theta_W}\log\frac{s}{m_h^2}$ → only a single log



A difficulty in numerical calculation

Collinear photon emission causes a problem in MadGraph calculation



$$\mathrm{d}\sigma = \frac{1}{8k \cdot p} \frac{\alpha}{4\pi} \frac{W^{\mu\nu} T_{\mu\nu}}{q^4} \mathrm{d}q^2 \mathrm{d}x$$

$$\simeq \mathrm{d}x \, \frac{\mathrm{d}q^2}{q^4} \frac{\alpha}{2\pi} \left[2m_\mu^2 + q^2 \frac{1 + (1-x)^2}{x^2} \right] \sigma_{\gamma\mu^+ \to W^+ \bar{\nu}_\mu h}(xs) \big|_{q^2 \to 0}$$

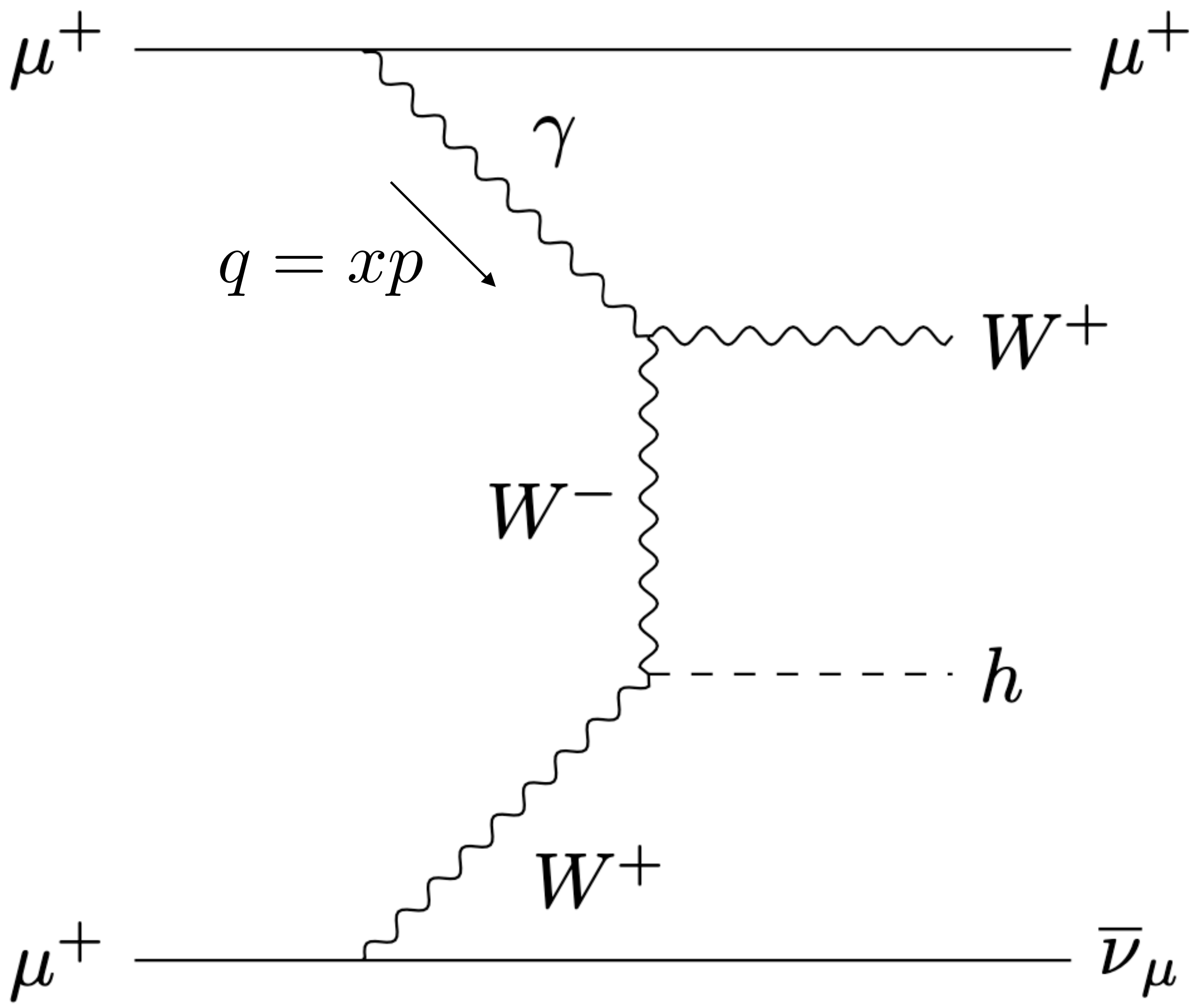
xsec of sub-process

divergent in a forward region (q^2 -> 0)

→ instability in numerical phase-space integral

Equivalent Photon Approximation (EPA)

Analytically perform the q^2-integral over forward phase-space



$$\mathrm{d}\sigma \simeq \mathrm{d}x \, \frac{\mathrm{d}q^2}{q^4} \frac{\alpha}{2\pi} \left[2m_\mu^2 + q^2 \frac{1+(1-x)^2}{x^2} \right] \sigma_{\gamma\mu^+ \to W^+ \bar{\nu}_\mu h}(xs) \Big|_{q^2 \to 0}$$

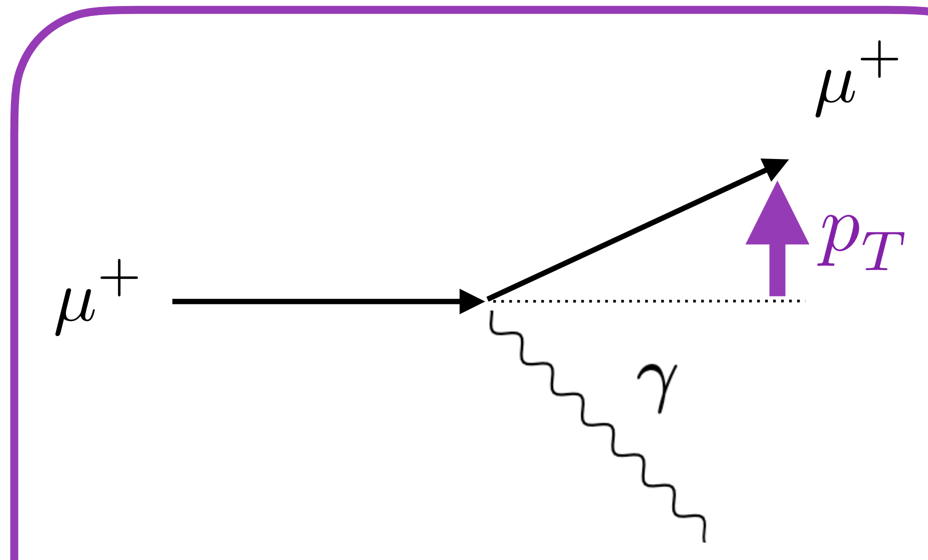
$$\sigma_{\mathrm{EPA}} \simeq \int \mathrm{d}x \, \sigma_{\gamma\mu^+}(xs) \overbrace{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{\mathrm{d}q^2}{q^4} \frac{\alpha}{2\pi} \left[2m_\mu^2 + q^2 \frac{1+(1-x)^2}{x^2} \right]}^{f_{\gamma/\mu}(x, p_T^{(\mathrm{cut})})}$$

$$p_T^2 = -q^2(1-x) - m_\mu^2 x^2$$

pT-cut calculation scheme

phase-space of muon emitting photon

$$\sigma = \int d^3p_\ell \frac{d\sigma}{d^3p_\ell} = \int dp_T \frac{d\sigma}{dp_T}$$



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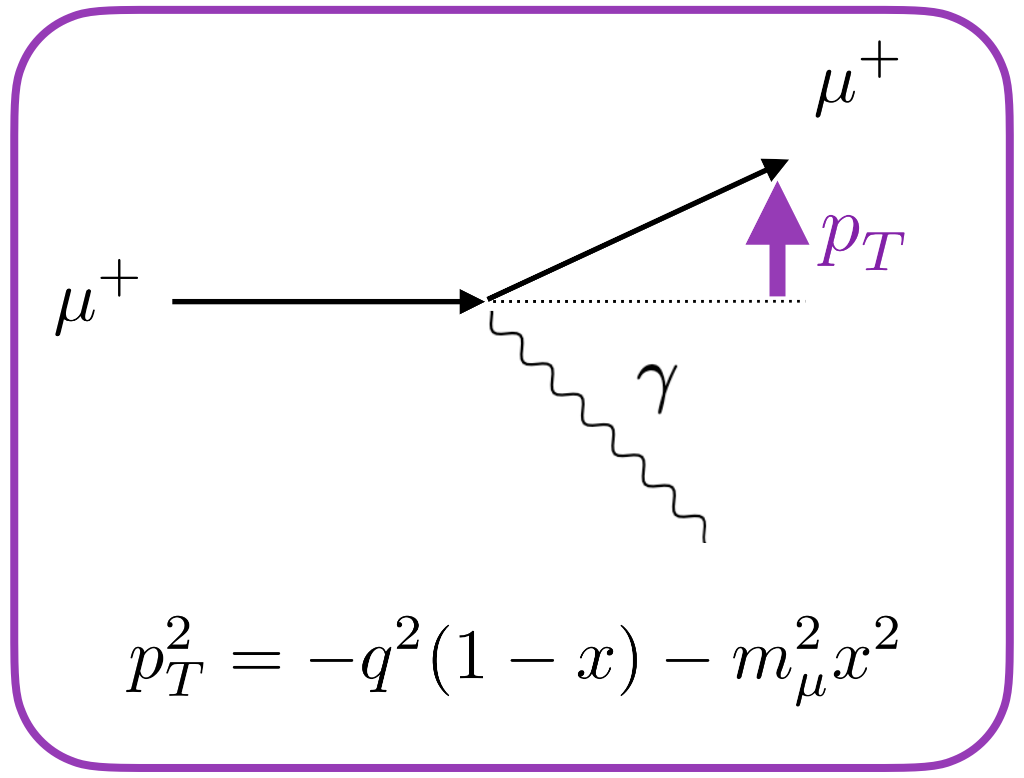
$$= \int_{p_T < p_T^{(\mathrm{cut})}} \mathrm{d}p_T \frac{\mathrm{d}\sigma}{\mathrm{d}p_T} + \int_{p_T > p_T^{(\mathrm{cut})}} \mathrm{d}p_T \frac{\mathrm{d}\sigma}{\mathrm{d}p_T}$$



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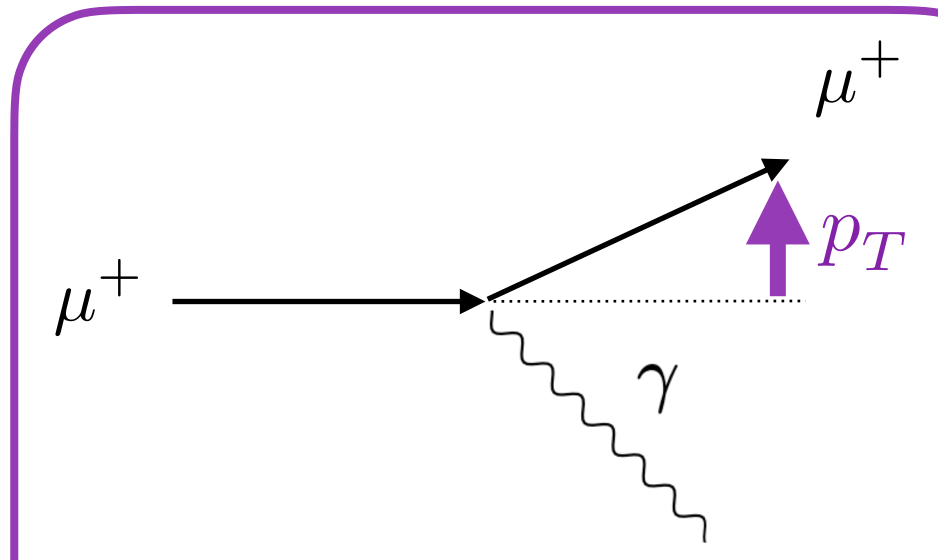
origin of instability in MG calculation
-> evaluated with **EPA**

evaluated with MadGraph



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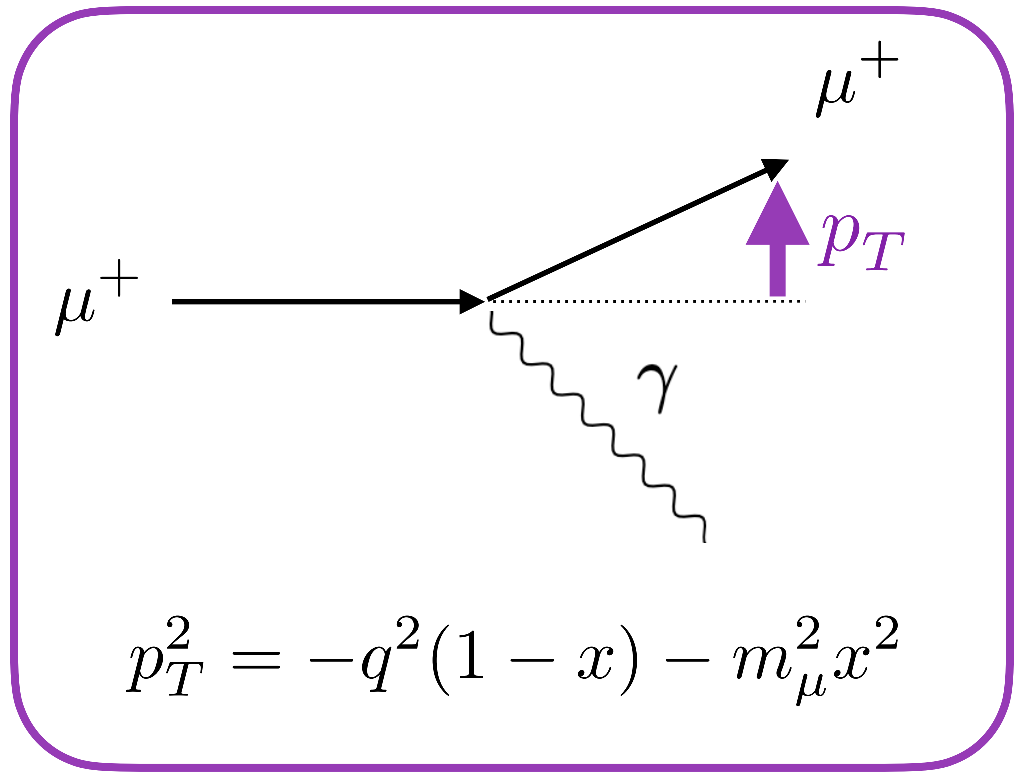
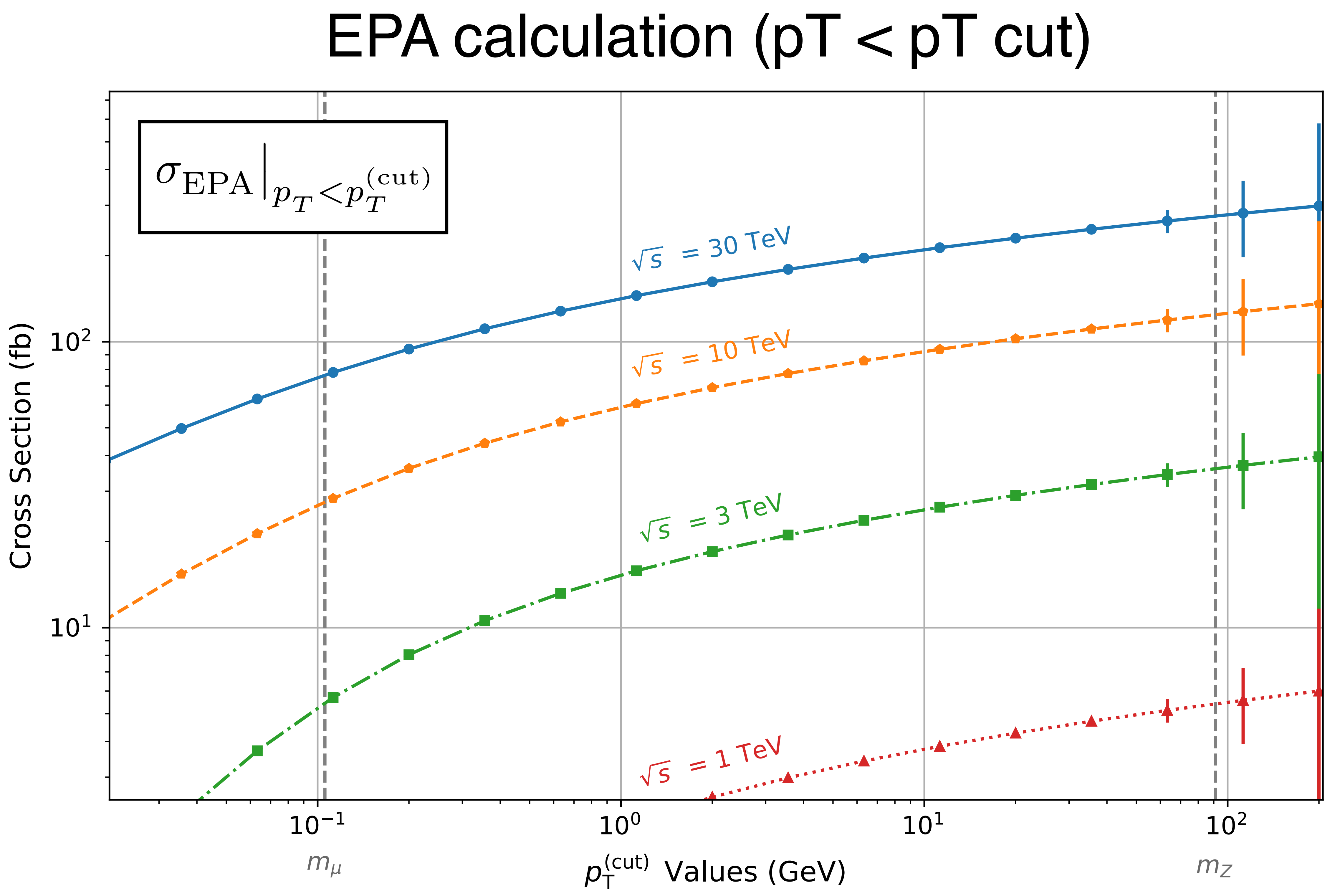
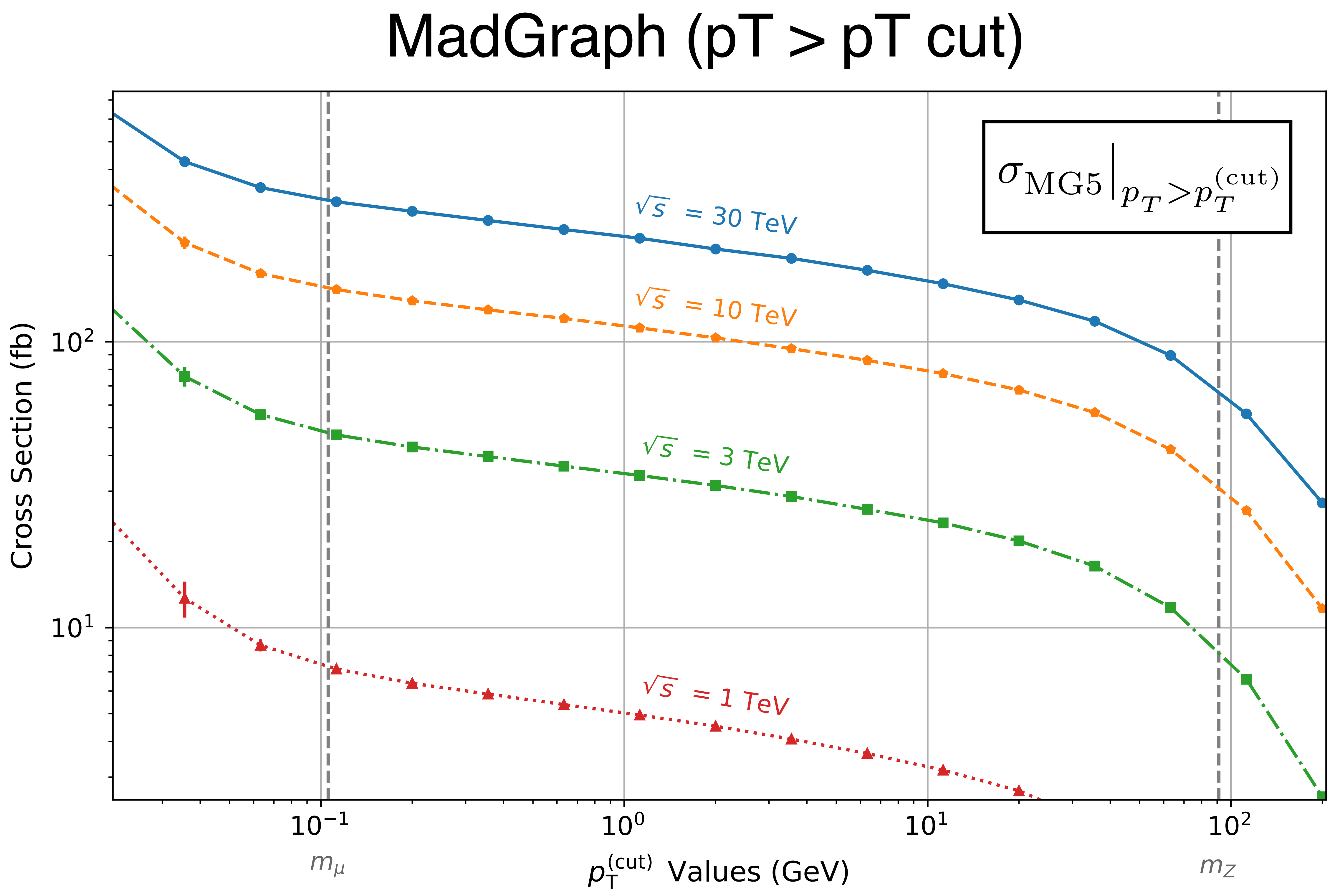
$$\simeq \sigma_{\mathrm{EPA}} \Big|_{p_T < p_T^{(\mathrm{cut})}} + \sigma_{\mathrm{MG5}} \Big|_{p_T > p_T^{(\mathrm{cut})}}$$



Sum of these two should be independent of pT-cut value if correctly calculated

Calculation in the pT-cut scheme





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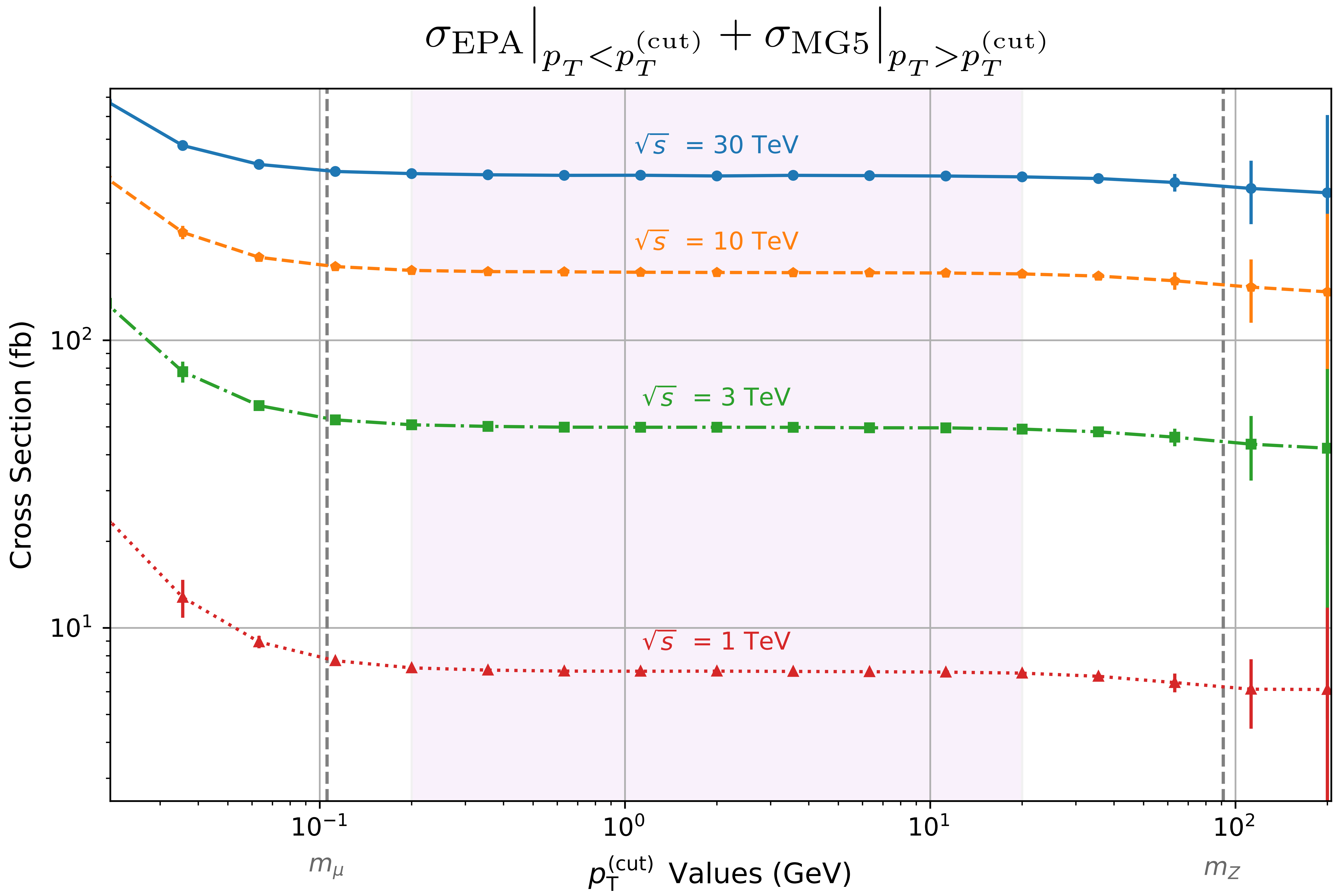
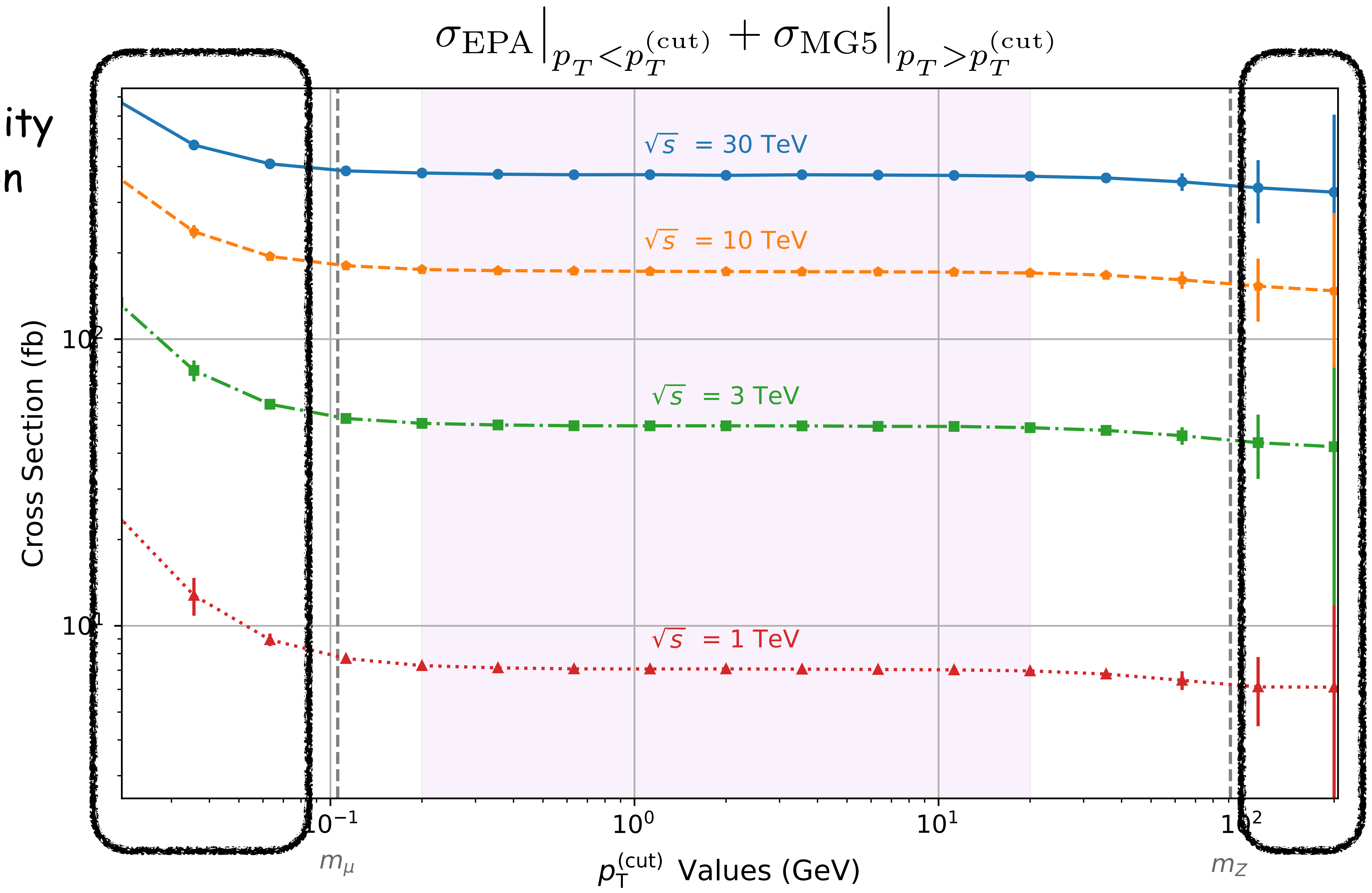


Calculation in the pT-cut scheme

numerical instability
in MG calculation

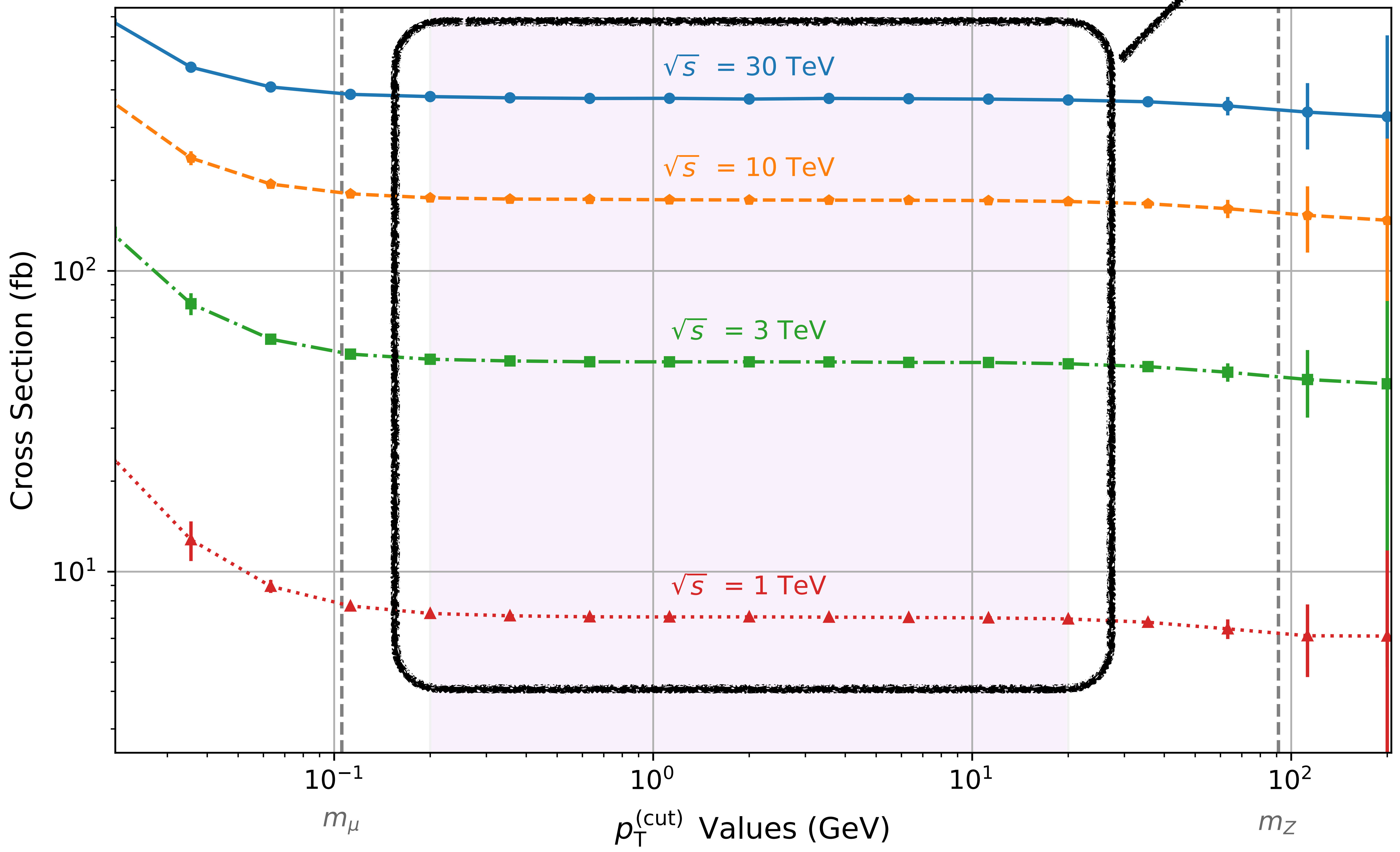


Z contribution
non-negligible

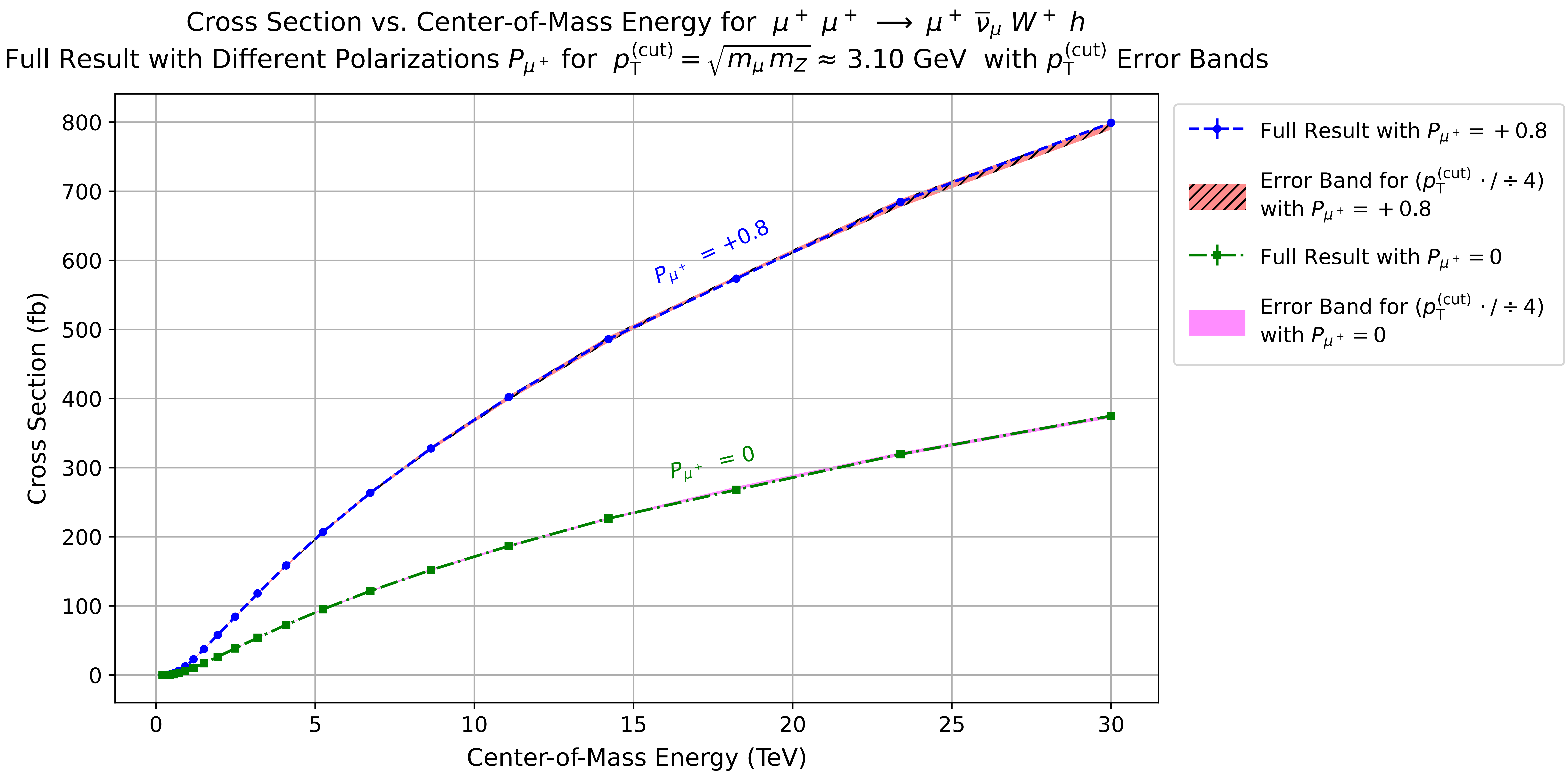
Calculation in the pT-cut scheme

$$\sigma_{\rm EPA}\Big|_{p_T<p_T^{\rm (cut)}} + \sigma_{\rm MG5}\Big|_{p_T>p_T^{\rm (cut)}}$$

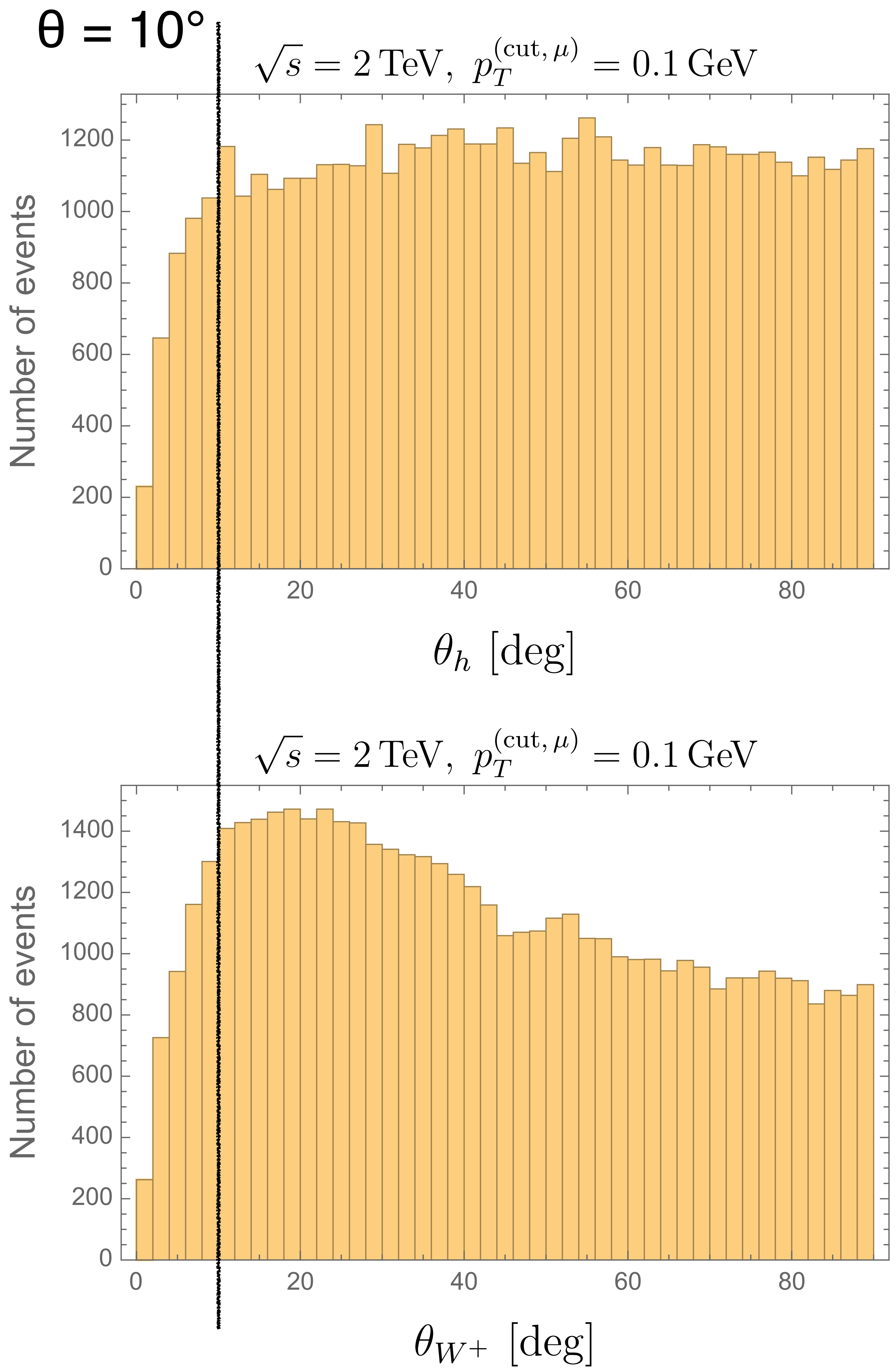
reliably calculate xsec
in this pT-cut range



Results for Higgs production



Angular distributions for Higgs and W bosons



Parton level analysis

- #(events generated) = 50,000
- hadron calorimeter coverage: θ > 10°

→ ~83% of events detectable!

background discrimination? ongoing, stay tuned!

Summary

- Muon Colliders are a good Higgs factory.

- At high energy mu+ mu+ colliders,
  - $\mu^+\mu^+ \to \mu^+\bar{\nu}_\mu W^+ h$ is the leading process
  - calculation not straightforward (pT-cut scheme)

- Corrections from collinear photon would important at mu+ mu- colliders

Thanks for your attention

Back up

Cross section comparison