The electroweak radiation picture of the future multi-TeV muon colliders

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Early Career Researchers & Muon Colliders (August 28, 2024)

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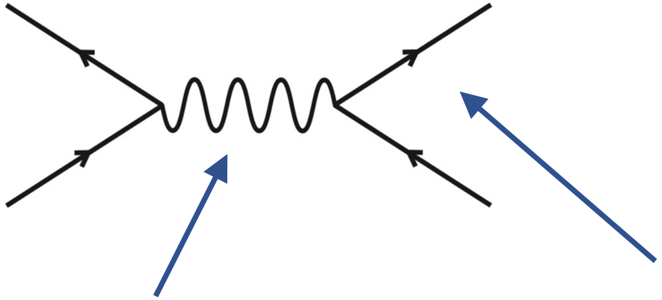
Myths about lepton colliders

Lepton colliders are s-channel machines



$$\sigma \sim \frac{1}{s} = \frac{1}{E^2}$$

Resonance peaks:

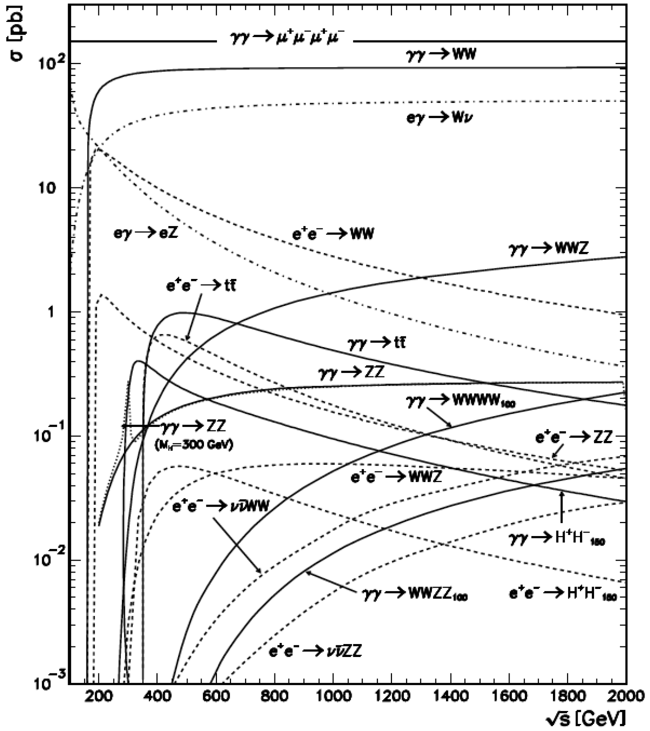
- B Factories: $\Upsilon(4S)$ peak (10.6 GeV) e.g. Babar, Belle II
- Z Factories, Z peak (91.188 GeV) e.g. LEP
- HE machines: BSM resonance peaks?

Pair production:

e.g. e+ e- Higgs Factory at 250 GeV

Look for a Z at 110 GeV, whatever on the other side, it is from Higgs decay!

Photon-Photon machine

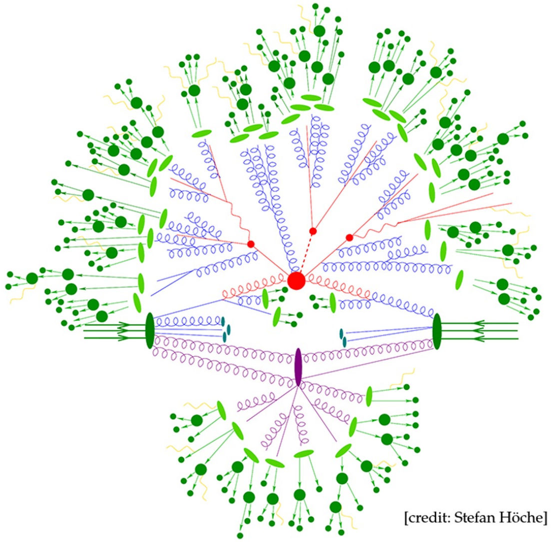


S. Brodsky, SLAC-PUB-11581

Lepton colliders are clean

Q: Is this still the case for multi-TeV lepton colliders?

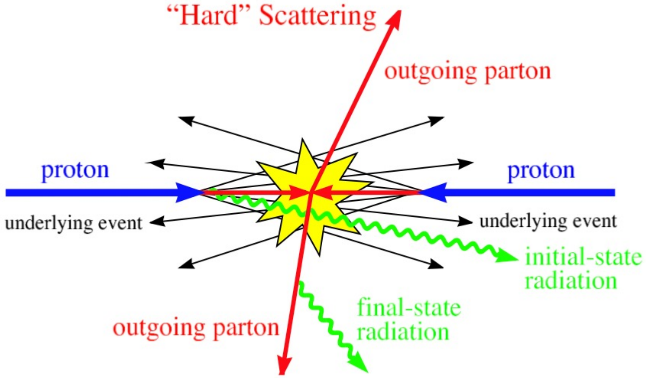
The picture of hadron colliders



What happens at Tevatron/LHC?

- Hard interaction: fixed-order calculation (in QCD $\equiv 1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2) + \ldots$)
- All-order radiative corrections: parton shower emissions
- Hadronisation from confinement property (quarks and gluons cannot live individually for long)
- Multiple parton interactions (MPI)
- Hadron decays

The QCD factorization formalism



- Hadrons are composite and contains "partons" inside them
- The parton distributon functions (PDF) describes the probability to find a parton with a particular momentum from the beam particle.

$$\sigma(AB \to X) = \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \hat{\sigma}(ab \to X)$$

The case for lepton colliders (QED only)

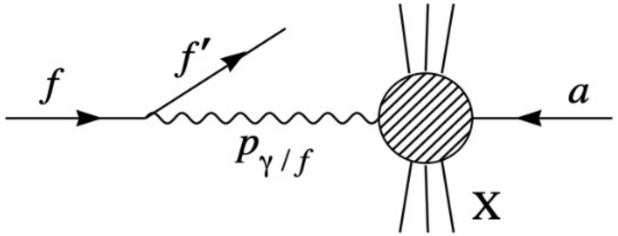
Q: how could an elementary particle contain a "parton" inside itself?

Equivalent photon approximation (EPA)

Treat radiation generated photon as the "parton"

$$\sigma(\ell^- + a \to \ell^- + X) = \int dx\, f_{\gamma/\ell}\hat{\sigma}(\gamma a \to X)$$

$$f_{\gamma/\ell,\mathrm{EPA}}(x_\gamma, Q^2) = \frac{\alpha}{2\pi}\frac{1+(1-x_\gamma)^2}{x_\gamma}\ln\frac{Q^2}{m_\ell^2}$$

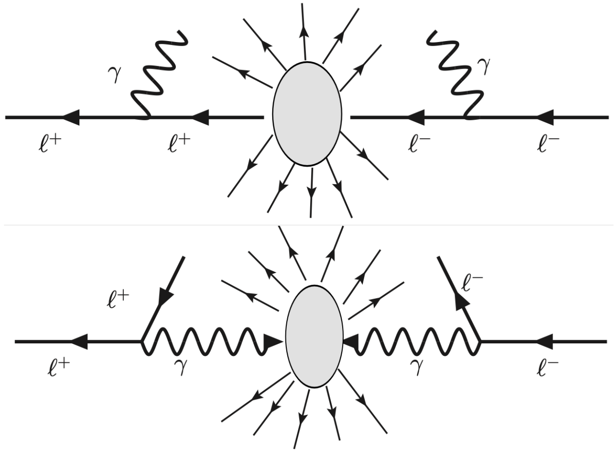


Applications on colliders

- Initial state radiation (ISR)
- Photon-photon collisions

$$\sigma(\ell^+\ell^- \to F + X) = \int_{\tau_0}^1 d\tau \sum_{ij}\frac{d\mathcal{L}_{ij}}{d\tau}\hat{\sigma}(ij \to F),\ \tau = \hat{s}/s$$

$$\frac{d\mathcal{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}}\int_\tau^1 \frac{d\xi}{\xi}\left[f_i(\xi, Q^2) f_j\left(\frac{\tau}{\xi}, Q^2\right) + (i \leftrightarrow j)\right]$$



Polarizations

	e_L^-	e_R^-	$\langle e^-\rangle$	e_L^+	e_R^+	$\langle e^+\rangle$
γ_-	$\frac{1}{x}$	$\frac{(1-x)^2}{x}$	$\frac{1+(1-x)^2}{2x}$	$\frac{(1-x)^2}{x}$	$\frac{1}{x}$	$\frac{1+(1-x)^2}{2x}$
γ_+	$\frac{(1-x)^2}{x}$	$\frac{1}{x}$	$\frac{1+(1-x)^2}{2x}$	$\frac{1}{x}$	$\frac{(1-x)^2}{x}$	$\frac{1+(1-x)^2}{2x}$
$\sum\gamma_\lambda$	$\frac{1+(1-x)^2}{x}$	$\frac{1+(1-x)^2}{x}$	$\frac{1+(1-x)^2}{x}$	$\frac{1+(1-x)^2}{x}$	$\frac{1+(1-x)^2}{x}$	$\frac{1+(1-x)^2}{x}$

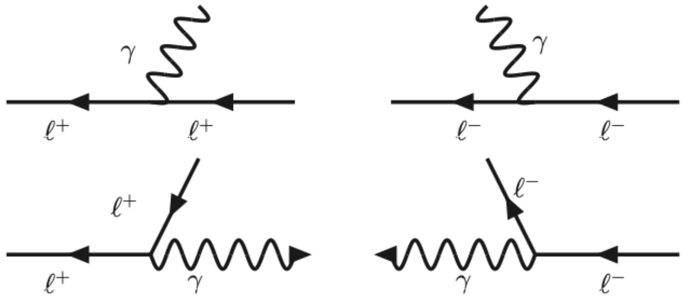
For unpolarized beam, it is okay to average over parton's polarization

The full EW partonic picture

People have been doing:

- $\ell^+\ell^-$ annihilation

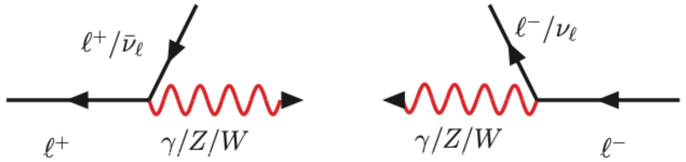
- EPA and ISR



- "Effective W Approx." (EWA)

[G. Kane, W. Repko, and W. Rolnick, PLB 148 (1984) 367]

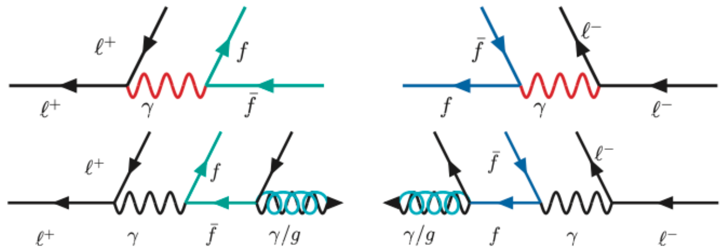
[S. Dawson, NPB 249 (1985) 42]



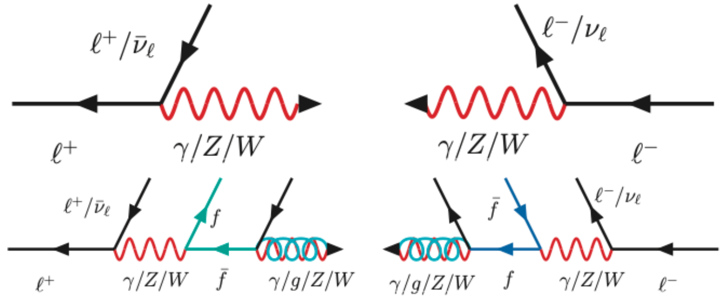
We will add [T. Han, Y. Ma, K.Xie 2007.14300, 2103.09844]

[F. Garosi, D. Marzocca, S. Trifinopoulos 2303.16964]

- Above μ_{QCD}: QED$\otimes$QCD
  q/g emerge



- Above $\mu_{\mathrm{EW}} = M_Z$: EW$\otimes$QCD
  EW partons / corrections to the above

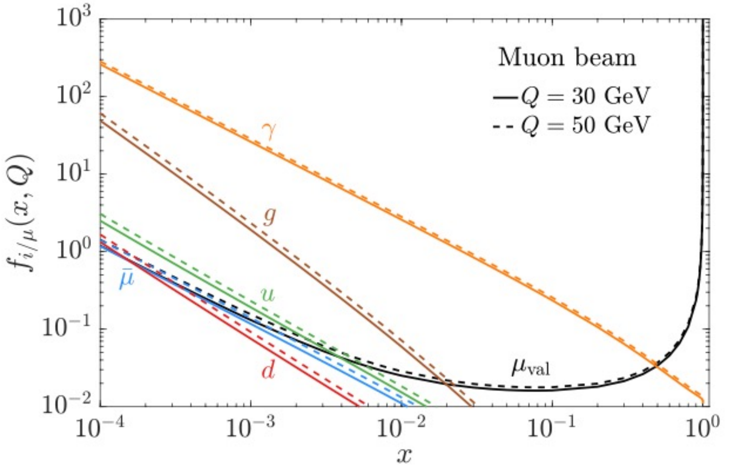


In the end, everything is parton, i.e. need the full SM PDFs.

The Eletroweak PDFs

Below the EW scale

- **Muon PDFs**: $f_{\mu_{\rm val}}$, f_γ, $f_{\ell_{\rm sea}}$, f_q, f_g
- Scale uncertainty: 20% for $f_{g/\mu}$



Above the EW scale

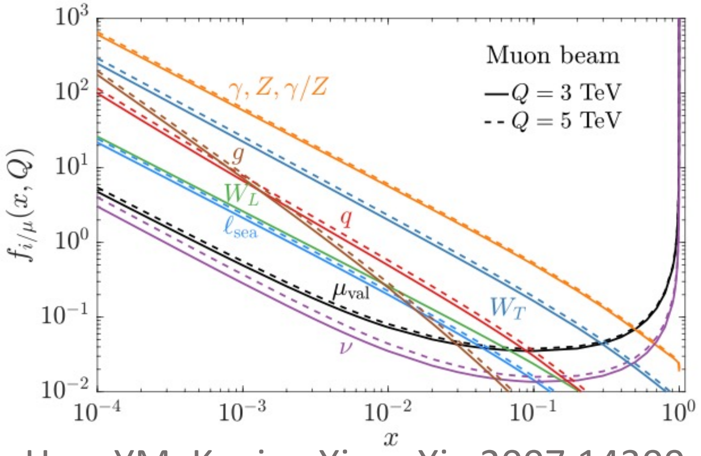
- **All SM particles are partons**

[T. Han, Y. Ma, K.Xie 2007.14300, 2103.09844]

- The sea leptonic and quark PDFs show up

$\nu = \sum_i (\nu_i + \bar{\nu}_i)$,
$\ell{\rm sea} = \bar{\mu} + \sum_{i \neq \mu} (\ell_i + \bar{\ell}_i)$,
$q = \sum_{i=d}^{t} (q_i + \bar{q}_i)$

There is even neutrino due to the EW sector

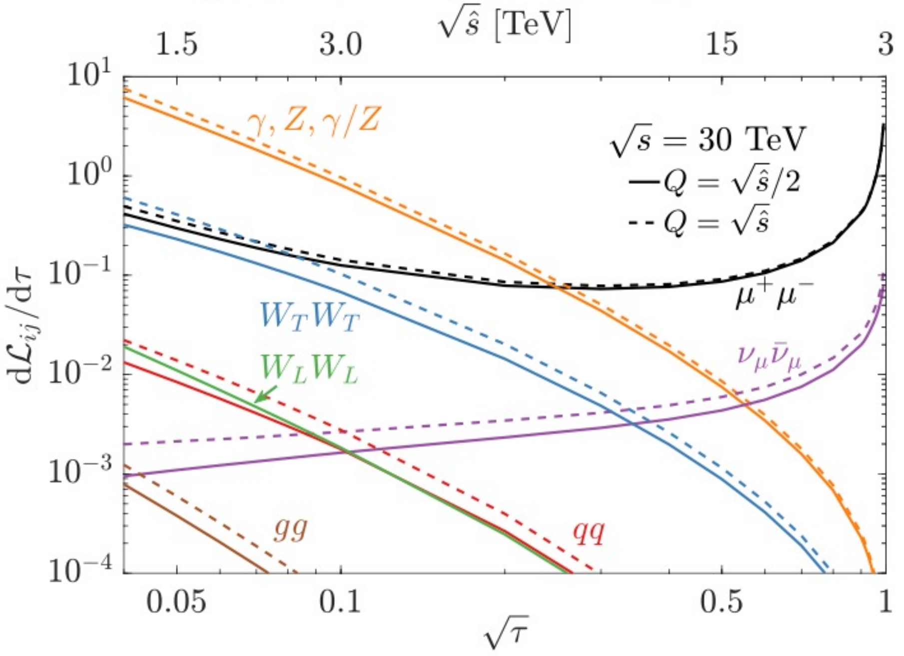


Tao Han, YM, Keping Xie,arXiv:2007.14300

MuC: An EW version of LHC

Partonic luminosity of a 30 TeV MuC

$$\frac{d\mathcal{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_\tau^1 \frac{d\xi}{\xi} \left[f_i(\xi, Q^2) f_j\left(\frac{\tau}{\xi}, Q^2\right) + (i \leftrightarrow j) \right]$$

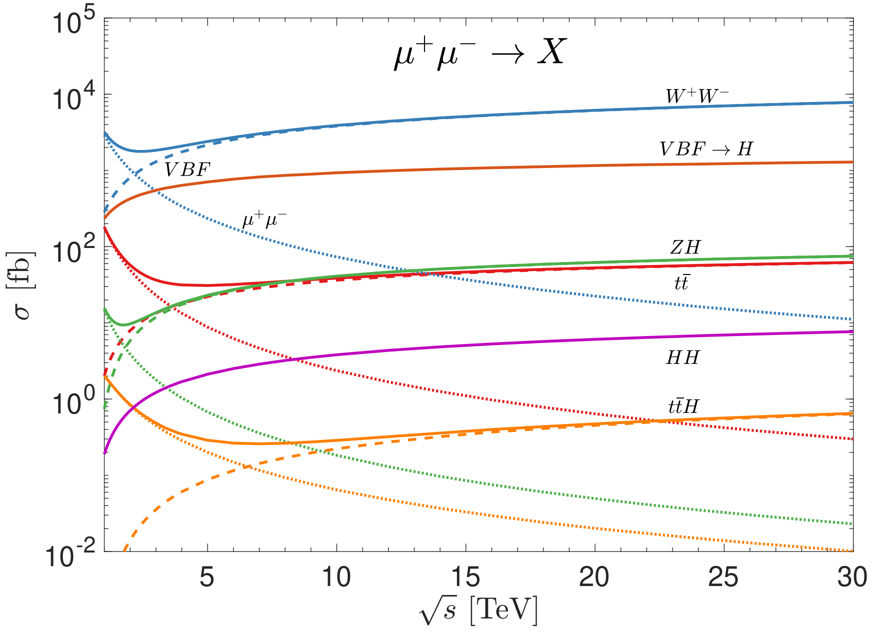


The polarization is counted

Semi-inclusive processes

Just like in hadronic collisions:

$\mu^+\mu^-$ → exclusive particles + remnants



VBF

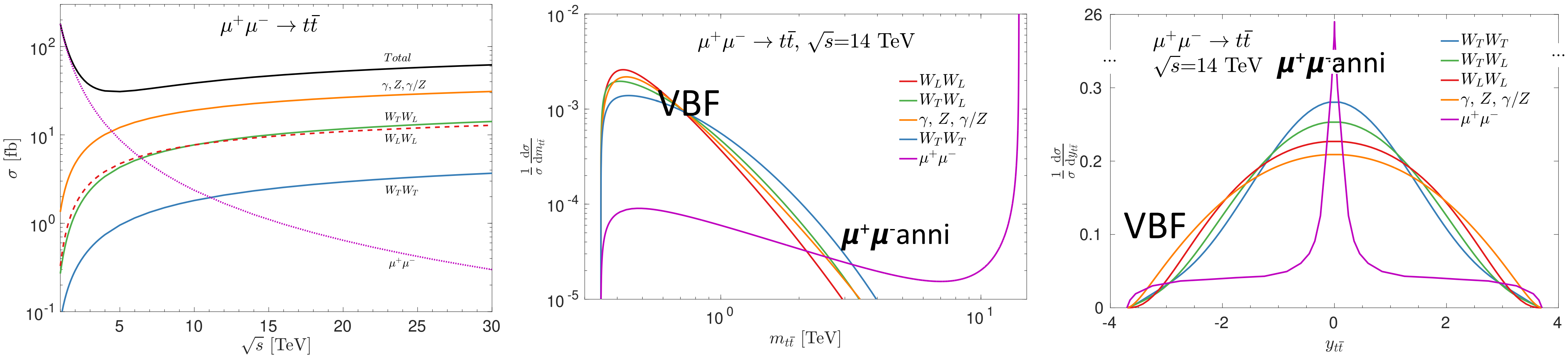
$\mu^+\mu^-$ annihilations

pp → t t = g g → t t + q q → t t

$\mu^+\mu^-$ → t t = annihilation + VBFs

Underlying sub-processes

Partonic contributions



Tao Han, YM, Keping Xie, arXiv:2007.14300

$\mu^+\mu^-$ Collider -- "Buy one, get one free":
Annihilation + VBF

Thank you

International MUON Collider Collaboration

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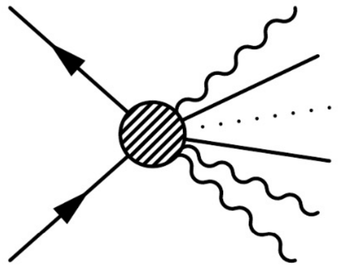
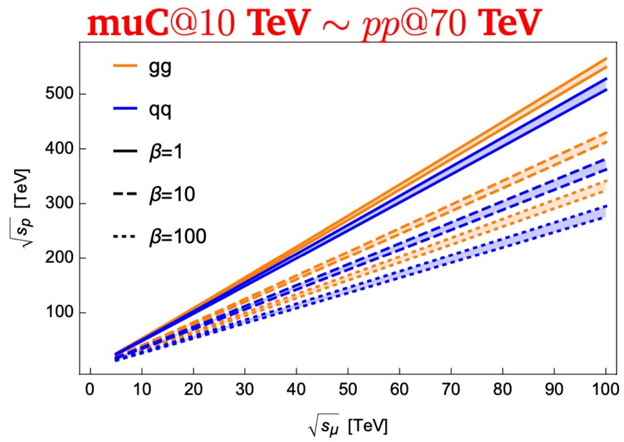
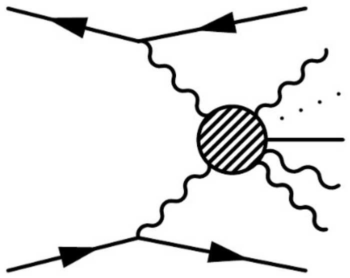
The general physics picture of muC

Annihilation





VBF



Take luminosity 10 ab^{-1}

10M H, 500K HH @ 10 TeV

- ► $\ell^+\ell^-$ annihilation **probes TeV scale directly**
- ► VBF **scans physics in the full spectrum of energy**
  From the threshold to up to 2 orders of magnitude above EW scale.
- ► It produces a lot of H, top quarks, W/Z, ... as **a "factory" for SM precision test**
- ► **An "EW jet factory"**
  In addition to QCD jets, there are W/Z jet, H jet, t jet, neutrino jet,$\cdots$
  Even neutrino collision is not impossible!

Challenges:

Be careful about the radiation!

EW NLO shall be necessary, just like the NLO QCD at LHC.

More Examples