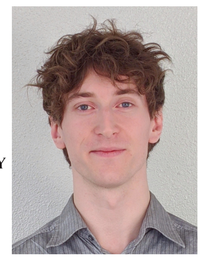
Lukas Treuer（ルーカス・トロイヤ） – lukas.treuer@yukawa.kyoto-u.jp.ac
2nd year PhD student at Yukawa Inst., Kyoto U and KEK, SOKENDAI
In collaboration with Y. Hamada (DESY, Keio U.), R. Kitano (YITP, Kyoto U.), R. Matsudo (YITP),
S. Okawa (YITP), R. Takai (YITP, Kyoto U., SOKENDAI, KEK), H. Takaura (YITP) – hep-ph/2408.01068 | PRD 110 (2024) 11,11



HIGGS BOSON PRODUCTION AT $\mu^+\mu^+$ COLLIDERS

1. PRODUCING THE HIGGS BOSON AT MUON COLLIDERS

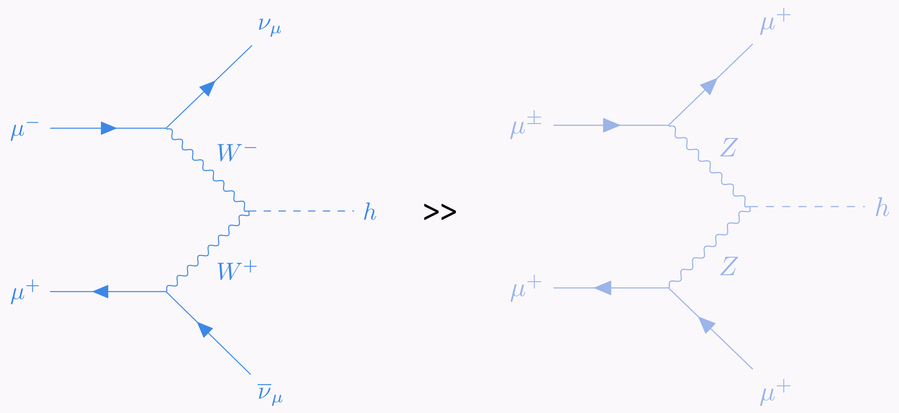
New: $\mu^+\mu^+$

- Higgs production: precision measurements of Higgs couplings, understanding electroweak symmetry breaking, determine Higgs potential, dark matter (?), etc.

Usual approach:

- Vector boson fusion (VBF) generally enhanced as $\sim \log\left(s/M_V^2\right)$
- Z boson fusion suppressed by lepton couplings

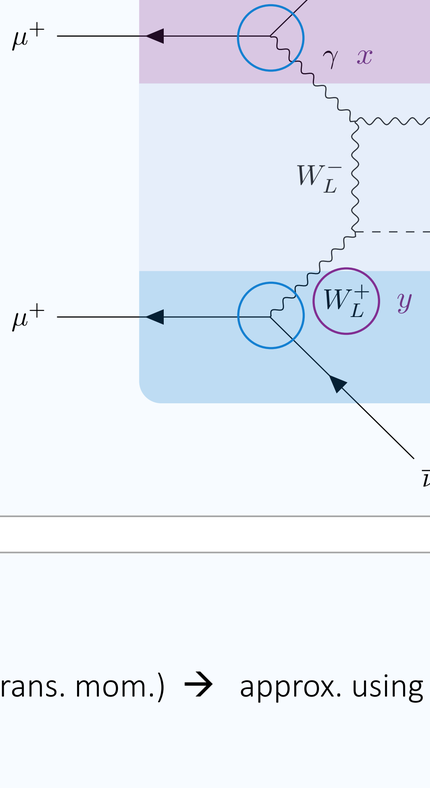
$\mu^+\mu^-$



vs.

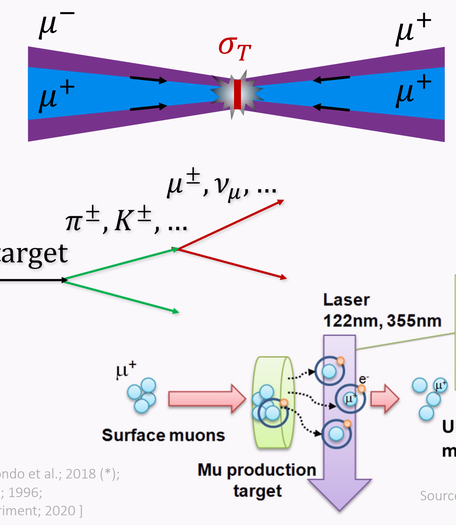
Need extra coupling due to same charge!

→ Suppressed by factor $\alpha_{\mathrm{EM}} \sim \mathcal{O}(1/100)$



So why $\mu^+\mu^+$? → COOLING!

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \mathcal{L}\cdot\sigma\,, \qquad \mathcal{L} \sim \frac{1}{\sigma_T} \sim \frac{1}{\epsilon}$$



[See, e.g.: Re-Acceleration of Ultra Cold Muon in J-PARC Muon Facility; Kondo et al.; 2018 (*);
Polarized Beams in a Muon Collider; Cline, Norum, Rossmanith; 1996;
Demonstration of colling by the Muon Ionization Cooling Experiment; 2020]

2. ANALYTICAL APPROXIMATION – ENHANCEMENT

- Photon and W boson collinear
- Fusion of longitudinal W-boson polarizations dominates

$$\sigma_{\mu^+\mu^+\to\mu^+\overline{\nu}_\mu W^+h}(s) = 2\int_{xys>s_{\min}} \mathrm{d}x\,\mathrm{d}y\,\sigma_{\gamma W_{\mathrm{L}}^+\to\overline{\nu}_\mu W^+h}(xy\,s)\,f_{W_{\mathrm{L}}^+/\mu^+}(y)\,f_{\gamma/\mu^+}(x)$$

$$\sim \frac{(1+P_{\mu^+})\,\alpha^4}{4\pi m_W^2\sin^4\theta_{\mathrm{W}}}\left[\log\frac{s}{m_\mu^2}\left(\log\frac{s}{(m_h+m_W)^2}\right)^2 - \frac{2}{3}\left(\log\frac{s}{(m_h+m_W)^2}\right)^3\right]$$

High-energy enhancement with three logarithms!
Only one log for leading process at $\mu^+\mu^-$!

– Numerical Simulation Problem –
Collinear "divergence" at high energies in num. phase space integral from massless photon and light muon

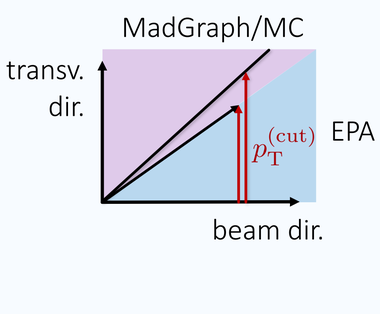
[See, e.g.: Improving the Weizsacker-Williams approximation in electron-proton collisions; Frixione, Mangano, Nason, Ridolfi; 1993;
The Effective Vector Boson Approximation in High-Energy Muon Collisions; Ruiz, Costantini, Maltoni, Mattelaer; 2022;
Electroweak Splitting Function and High Energy Showering; Chen, Han, Tweedie; 2018;
Theory of e+e- Collisions at Very High Energy; Peskin; 1988
Higgs boson production in eγ collisions; Hagiwara, Watanabe, Zerwas; 1992]

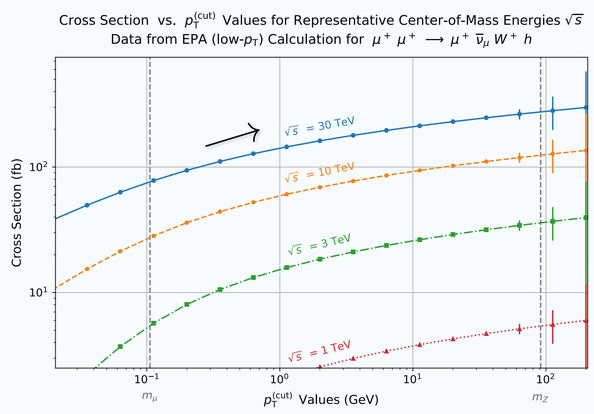
3. SPLITTING THE CROSS SECTION

Split phase-space integral into collinear (small trans. mom.) and non-collinear regime (large trans. mom.) → approx. using PDF, and MC w/ massless muon, respectively

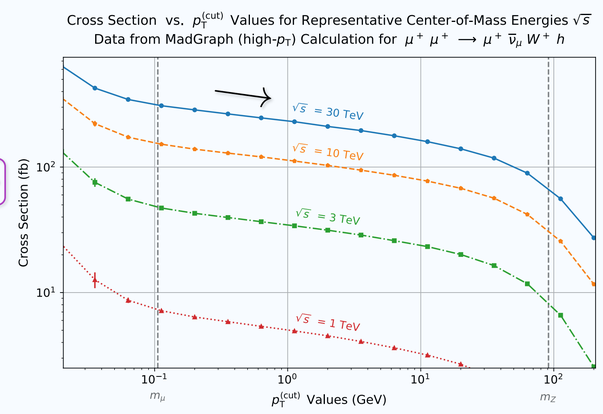
$$\sigma \simeq \sigma_{\mathrm{EPA}}\Big|_{p_{\mathrm{T}}<p_{\mathrm{T}}^{(\mathrm{cut})}} + \sigma_{\mathrm{MG}}\Big|_{p_{\mathrm{T}}\geq p_{\mathrm{T}}^{(\mathrm{cut})}}$$

[Similar procedure "matrix element matching" in: The Effective Vector Boson approximation in High-Energy Muon Collisions; Ruiz, Costantini, Maltoni, Mattelaer; 2022]

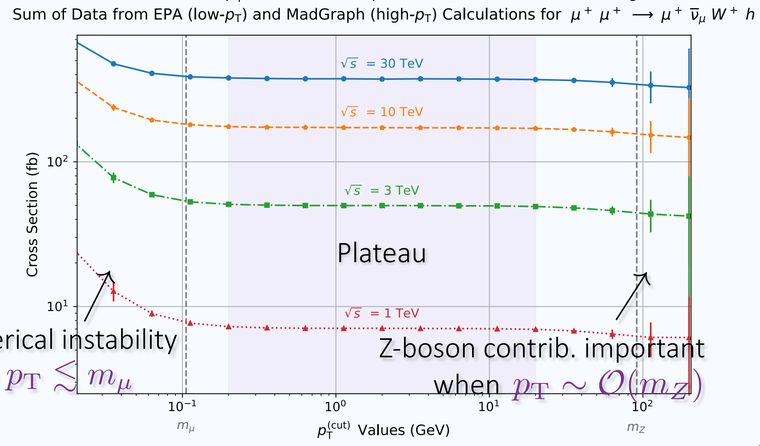




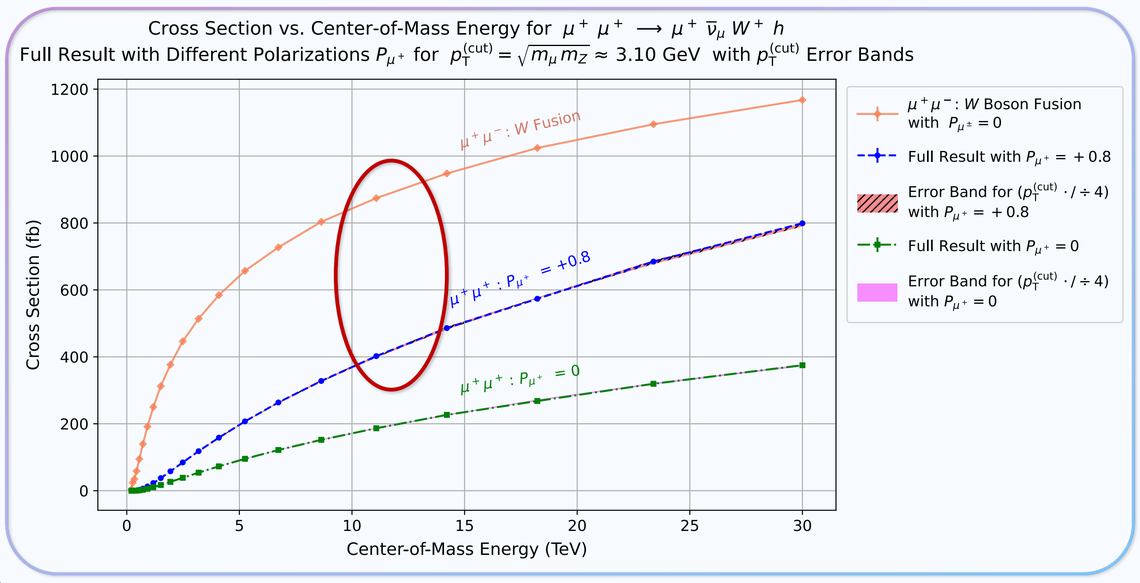
+



=



4. THE ENHANCEMENT IN ACTION



- Only factor of ~2 at $\mathcal{O}(10)$ TeV! → $\sim(\log s)^3$ enhancement!
- Small errors associated with choice of $p_{\mathrm{T}}^{(\mathrm{cut})}$ (<1%)
- Can physically motivate $p_{\mathrm{T}}^{(\mathrm{cut})}$ val.
- Verified validity of fixed-order calculation → still perturbative
- Large enough decay angles to be detectable!

Summary

- Recent advancements in μ^+ cooling motivate $\mu^+\mu^+$ colliders → high luminosities
- $p_{\mathrm{T}}^{(\mathrm{cut})}$-separated scheme works well to deal w/ num. coll. div.
- At $\mathcal{O}(10)$ TeV, only factor ~2 w.r.t. LO at $\mu^+\mu^-$ despite suppression! → $\sim(\log s)^3$ enhancement
- Relevant at NLO for any high-energy (lepton) collider inclunding $\mu^+\mu^-$ and e^+e^-!

$\mu^+\mu^+$ Collider Is a Great Higgs Factory!