# **Physics Overview:** 1-Year Progress

# Tao Han Pitt PACC, University of Pittsburgh IMCC & MuCol Annual Meeting 2025 May 12, 2025, DESY, Hamburg



### **Great µC Community**





#### Fermilab, August 7-9, 2024

#### Inaugural US Muon Collider Meeting

indico.fnal.gov/e/usmc2024

**Documents & Contributions to ESPPU:** 

Interim Report for IMCC: <u>https://arxiv.org/pdf/2407.12450</u> MuCol Milestone Report #5: <u>https://arxiv.org/abs/2411.02966</u> The muon collider: <u>https://arxiv.org/abs/2504.21417</u> USMCC White paper: <u>https://arxiv.org/abs/2503.23695</u>

### Last Year's Publications (ti muon & collider)

NSPIRE	literature ${}^{\vee}$	find ti collider and t	i muon and date after 202
		Citeable ⑦	Published ⑦
Papers		137	69
Citations		882	758
h-index ⑦		11	11
Citations/paper (avg)		6.4	11
Papers — Citeable — Publishe	ed		
80 <b>81</b> 60 <b>47</b>			
40 - <b>40</b> 20 - <b>7</b>	14 13	2 2	
0 1-9	10-49 50	0-99 100-249 2	250-499 500+ Citations

#### Physics / Phenomenology:

BSM @ Energy Frontier (~8) SM / top / Higgs (~6) Dark Sector/Neutrinos (~2) Neutrino Osc. / **v**Storm (~2)

EIC / µIC (~3) Cosmo/GW (~2) ML / QI (~4) ... ...

→ Will show some selected results (apologies for the incompleteness!)

## 1. Reflection of Main Futures: μ<sup>+</sup>μ<sup>-</sup> Annihilation +VBF at Once Typical SM processes:



μ<sup>+</sup>μ<sup>-</sup> annihilation opens new energy threshold.
 EW partonic processes provides a variety of channels.
 J.M. Chen, TH & B. Tweedie, arXiv:1611.00788; TH, Ma, Xie, arXiv:2203.11129.

# **Kinematically Separable:**



**Recoil mass:**  $m_{\text{rec}}^2 \quad \mathscr{H}(p_{\mu^+} + p_{\mu^-} - p_i^{\text{obs}})^2$ 





### **EW Physics @ Very High Energies**

 $\frac{v}{E}: \frac{v \ (250 \ \text{GeV})}{10 \ \text{TeV}} \approx \frac{\Lambda_{QCD} \ (300 \ \text{MeV})}{10 \ \text{GeV}} \quad v/E, \ m_t/E, \ M_W/E \to 0!$ Splitting: the dominant phenomena



 $\begin{array}{ccc} \vdots & x \\ & & \\$ 

- Power corrections suppressed:  $M_W^2/Q^2 \ll 1$
- Log corrections (RGE) large:  $\alpha_2 \ln^2(Q^2/M_W^2) \sim \mathcal{O}(1)$

#### EW "partons" dynamically generated

$$\mu \xrightarrow{\mu}_{\gamma} q \xrightarrow{\bar{q}}_{q} q \xrightarrow{q}_{g} \frac{\mathrm{d}f_{i}}{\mathrm{d}\ln Q^{2}} = \sum_{I} \frac{\alpha_{I}}{2\pi} \sum_{j} P_{i,j}^{I} \otimes f_{j}$$

**EW shower/jets:**  $W^* \rightarrow q\bar{q}g \dots, \ell^{\pm}\nu\gamma \dots$  $t^* \rightarrow b\bar{b}W^*, tZ^*, th^* \dots$  $\nu^* \rightarrow \ell^{\pm}W^* \dots \rightarrow EW jets$ 

# 2. Most Wanted: Precision Higgs physics

H<sup>3</sup> self-coupling  $\rightarrow$  EW phase transition & early universe cosmology!



TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204, Interim Report for IMCC, arXiv:2407.12450v2



#### Recent updates:

### detector simulation plus BIB

P. Andreetto et al., arXiv:2405.19314



M. Forslund, P. Meade, arXiv:2308.02633



# **3. Most direct probe:** $\mu$ **Yukawa coupling:** $\mathbf{Y}_{\mu} = \mathbf{\kappa}_{\mu} \mathbf{Y}_{\mu}^{SM}$ plus $\sum_{n=1}^{\infty} \alpha_n \frac{m_{\mu}}{v^n} \bar{\mu} \mu H^n$

New physics modification of SM leads to notable deviation. Multiple gauge boson/Higgs production can be highly enhanced, and eventually saturate perturbative unitarity.



TH, Wolfgang Kilian, Nils Kreher, Yang Ma, Juergen Reuter, Tobias Striegl and Keping Xie: arXiv:2108.05362; E. Celada et al., arXiv:2312.13082

### 4. Heavy Higgs Boson Production

TH, S. Li, S. Su, W. Su, Y. Wu, arXiv:2102.08386.



#### Reach the kinematic limit $M \sim E_{cm}/2$ .

"Inert Higgs Doublet" (no SM fermion couplings)  $H^{\pm}, A^0 \rightarrow H^0_D \ \ell \bar{\ell}'$ 

> J. Braathen, M. Gabelmann, T. Robens, P. Stylianon, arXiv:2411.13729.



# 5. "Colorful" Particle Production Most wanted: Top-quark partners







annih.

fusion



10<sup>5</sup>

104

10<sup>3</sup>

10<sup>2</sup>

10









10

### Lepto-quark & lepto-gluon

 $\mu^{+} \mu^{-} \xrightarrow{} S_{1}^{1/3} S_{1}^{1/3*}, \ S_{1}^{1/3} \to u \mu$ 

 $\mathcal{L} = 1 \text{ ab}^{-1}$ 

HL-LHC

 $g\mu^{-} \rightarrow \ell$ 

 $\gamma\gamma \rightarrow \ell_q^+ \ell_q^-$ 

2

 $M_{\ell_q} = 2 \text{ TeV}$ 

 $\widetilde{\gamma}\mu^- \rightarrow \ell_g^- g$ 

 $\mathcal{L} = 10 \text{ ab}^{-1}$ 

4

-  $\Lambda = 10 \text{ TeV}$ 

15

 $\Lambda = 100 \, \text{TeV}$ 

15 events

 $\mu^+\mu^- \rightarrow \ell_q^+ \ell_q^-$ 

5 events

 $M_{S_{I}^{l/3}}$  [TeV]

 $\sqrt{s} = 10 \text{ TeV}$ 

LHC

10-2

1

10<sup>3</sup>

10<sup>2</sup>

10

10<sup>-1</sup>

10<sup>-2</sup>

10-3

5



N. Ghosh et al., 2309.07583; TH, M. Low, T. A. Wu, K. Xie: arXiv:2502.20443

#### Lq cross section:



#### Lg production



#### The reach:

5

10<sup>7</sup>

10<sup>6</sup>

10<sup>5</sup>

10<sup>4</sup>

10<sup>3</sup>

10<sup>2</sup>

10

20

50

10

5

00 fb<sup>-</sup>

LHC

2

**300 fb<sup>-1</sup>** 

LHC

4



 $\mathcal{L} \geq 1 a b^{-1}$ 

6

 $M_{\ell_g}$  [TeV]

15 events

8

10

5 events

 $\sqrt{s}$  [TeV]

10

11

### **General Physics Reach**



### **Radiative return to extend the reach**

 $10^{1}$ 

 $10^{-1} {\rm Events}/10 {\rm ~ab^{-1}}$ 

 $-10^{-2}$ 

---- ISR spectrum $---- \mu^+ \mu^- \to H\gamma$ 

25

15 TeV

20

10

15

 $\sqrt{s}$  [TeV]

$$\hat{\sigma}(\mu^{+}\mu^{-}! H) = \frac{\hat{\tau}Y_{\mu}^{2}}{4}\delta(\hat{s} - m_{H}^{2}) = \frac{\hat{\tau}Y_{\mu}^{2}}{4s}\delta(\mathbb{Z} + \frac{m_{H}^{2}}{s})$$

$$\int_{\mu^{+}}^{\mu^{-}} \int_{H/\overline{A}}^{\pi} - \frac{\operatorname{Reach} M \sim E_{cm}!}{H/\overline{A}}$$

## 6. Discrimination Power on Z' Couplings A common BSM extension









(c)  $M_{Z'} = 15 \,\text{TeV}$ 

K. Korshynska, M. Loschner, M. Marinichnko, K. Mekala, J. Reuter, arXiv:2402.18460.

### 7. Connection to Cosmology / GW

Spontaneous symmetry breaking  $\rightarrow$  cosmo phase transition Strong 1<sup>st</sup> order phase transition  $\rightarrow$  Rich physics + GWs Complementary signals: Colliders  $\leftarrow \rightarrow$  GWs

#### A leptophilic Z' example:



A. Dasgupta, B. Dev, TH, R. Padhan, S. Wang, K. Xie, arXiv:2308.12804

### 8. Forward Muon Detection

Forward muon detection:  $2.44 < \eta < 6$ 

- Single out HZZ coupling
- Invisible H decay
- Reconstruct missing mass





. . .



FIG. 7. 95% C.L. limit on  $BR_{inv}^{BSM}$  at a 10 TeV muon collider with 10 ab<sup>-1</sup>, as a function of the uncertainty on the muon direction measurement. An angular acceptance  $\eta_{\mu}^{max} = 6$  of the forward muon detector is assumed.

P. Li, Z. Liu, K. Lyu, arXiv:2401.08756; M. Ruhdorfer, E. Salvioni, A. Wulzer, arXiv:1910.04170; arXiv:2411.00096.

# **9. Continuing / Future Efforts:**

- EW @ high energies; EW corrections Y. Ma, D. Pagani, M. Zaro., arXiv:2409.09129 .....
- Connection to neutrino physics

P. Jurj, nuStorm, ICHEP2024 (2025) 825; MuCol-ν ; J. Adhikary, K. Kelly, F. Kling, S. Trojanowski, arXiv:2412.10315.

- Connection to flavor physics / CPv
- Connection to cosmology / astro-particle
- Phenomenology of  $\mu$ IC;  $\mu^+\mu^+$  collider ...

D. Acosta, et al., arXiv:2203.06258; H. Davoudiasl, H. Liu, R. Marcarelli, Y. Soreq, S. Trifinopoulos, arXiv:2412.13289;R. Kitano et al.

# **Exciting exploration in the coming years!**

# **Back ups**

#### • **EW Minimal Dark Matter:** Generic EW (degenerate) multiplets

$egin{array}{c} \mathrm{Model} \ (\mathrm{color},n,Y) \end{array}$		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
$(1,3,\epsilon)$	Dirac	2.0 TeV
(1,5,0)	Majorana	11 TeV
$(1,5,\epsilon)$	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
$(1,7,\epsilon)$	Dirac	16 TeV

M. Cirelli, N. Fornengo, A. Strumia, hep-ph/0512090; 0903.3381.



TH, Z. Liu, L.-T. Wang, X. Wang, arXiv:2009.11287.

### Heavy Neutral Lepton @ muC





# [Color-octet fermion gluino (g) not show ]