Brief Introduction to Muon Colliders

HPNP 2023 @ Osaka University
June 7, 2023

Tao Han
Pitt PACC, University of Pittsburgh

A Muon Collider

Why muons?

Although sharing the same EW interactions,
it isn't another electron:

$$m_\mu \approx 207\ m_e$$
$$\tau(\mu \to e\bar{\nu}_e\nu_\mu) \approx 2.2\ \mu s$$
$$c\tau \approx 660\ m.$$

Once accelerated:

$E_\mu \sim 1$ TeV → $\gamma \sim 10^4$ → $d = c\gamma\tau = 6{,}600$ km

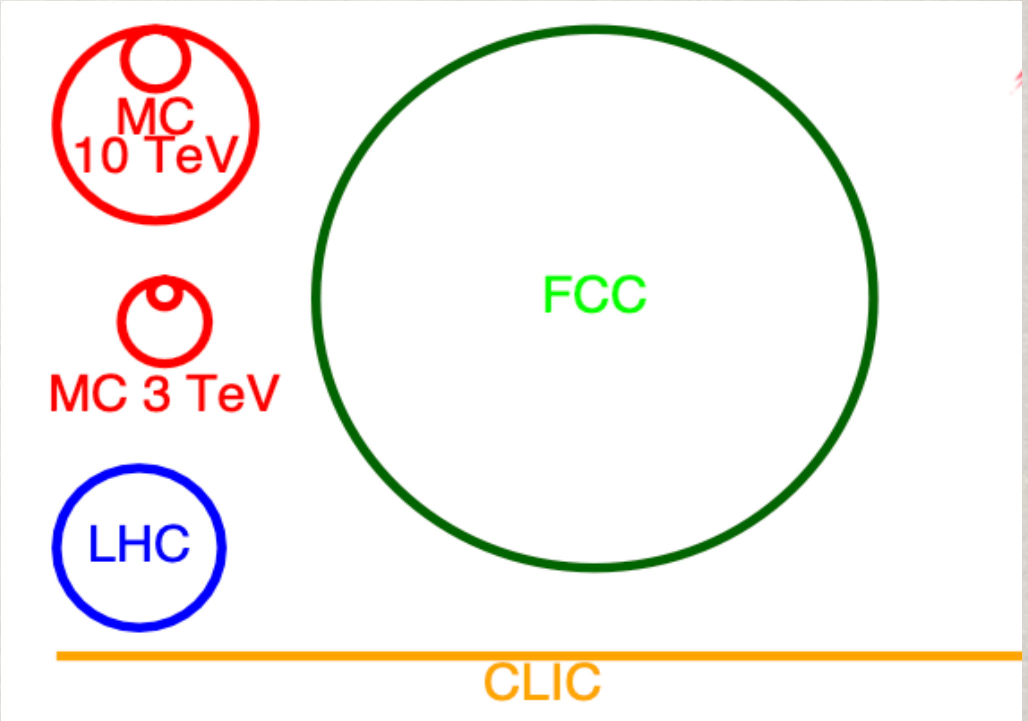
It is these features: heavy mass, short lifetime
that dictate the physics.

- # Advantages of a muon collider

- Much less synchrotron radiation energy loss than e's:

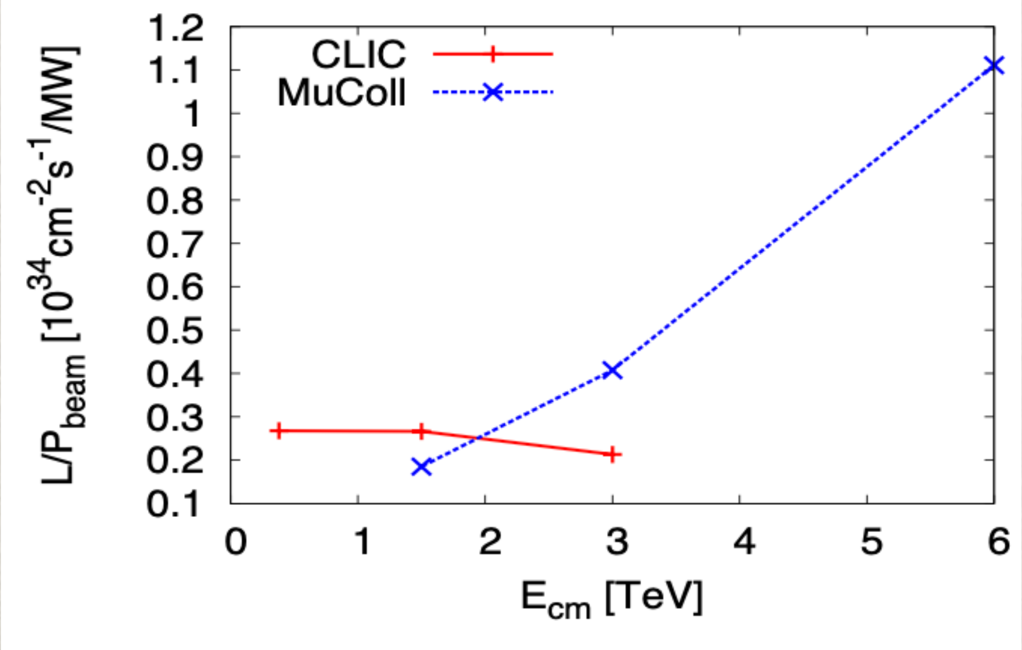
$$\Delta E \sim \frac{1}{R} \left(\frac{E}{m_\mu}\right)^4$$

which would allow a smaller and a circular machine, thus likely cost-effective:



- Luminosity scales with c.m. energy/power, ideally

$L \sim E^2_{CM}$



- Smaller beam-energy spread:

$\Delta E/E \sim 0.1\%$

potentially $\Delta E/E(m_H) \sim 0.01\% - 0.001\%$

• Advantages of a muon collider

- Unlike the proton as a composite particle, E_{CM} efficient in $\mu^+\mu^-$ annihilation, to reach higher new physics threshold $E_{CM} \sim 2\ M_{new}$

- Yet, high-energy collisions result in all sort of partons from Initial States Radiation

  $\sigma_{\mu\mu} \sim (1/M_W)^2 \ln^2(E_{CM}/M_W)$

"Buy one, get one free!"

- Lower (hadronic) background:

  σ_{pp}(total)~100 mb; $\sigma_{\mu\mu}$(total)~100 nb

• Disadvantages of a muon collider

- Production: Protons on target → pions → muons: Require sophisticated scheme for **μ** capture & transport

- Very short lifetime: in micro-second,

  Muons cooling in (x,p) 6-dimensions

  → Difficult to make quality beams and a high luminosity

- Beam Induced Backgrounds (BIB) from the decays in the ring at the interacting point

- Neutrino beam dump (environmental hazard)

  $\boldsymbol{\sigma_{\nu}} \sim G_F^2 E^2$ → Shielding?

Historically

- Concepts mentioned in the 60's
- Early collider design/physics studies in the 90's [*]
- 2011~2016: Muon Accelerator Program formed (MAP): to address key feasibility issues for μC with the proton driver technology
- MAP terminated in 2016, results published in

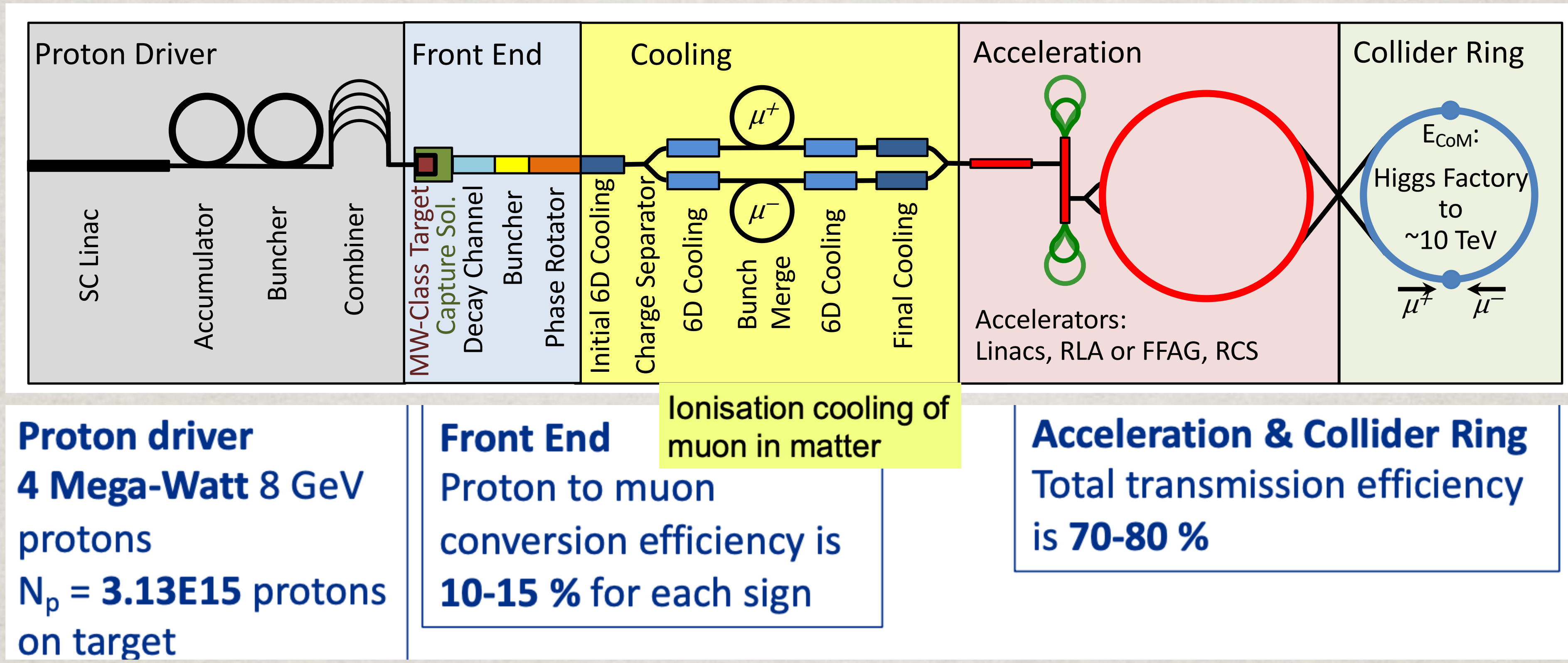
https://iopscience.iop.org/journal/1748-0221/page/extraproc46

[*] Some early work:

- *Proceedings of the 1st Workshop on the physics potential and Development of the $\mu\mu$ Coiliders,* Napa, California, 1992, Nucl. Inst. Methods. Phys. Res., Sect. A 350, 24 (1994).
- *S-channel Higgs boson production at a muon collider,* Barger et al., PRL75 (1995).
- *$\mu^+ \mu^-$ Collider: Feasibility study,* Muon collider collaboration (July, 1996).
- *Higgs boson physics in the s-channel muon collider,* Barger et al., Phys Rep. 186 (1997).
- *Status of muon collider research,* Muon collider collaboration (Aug., 1999).
- *Recent progress on neutrino factory and muon collider research,* Muon collider collaboration (July, 2003).

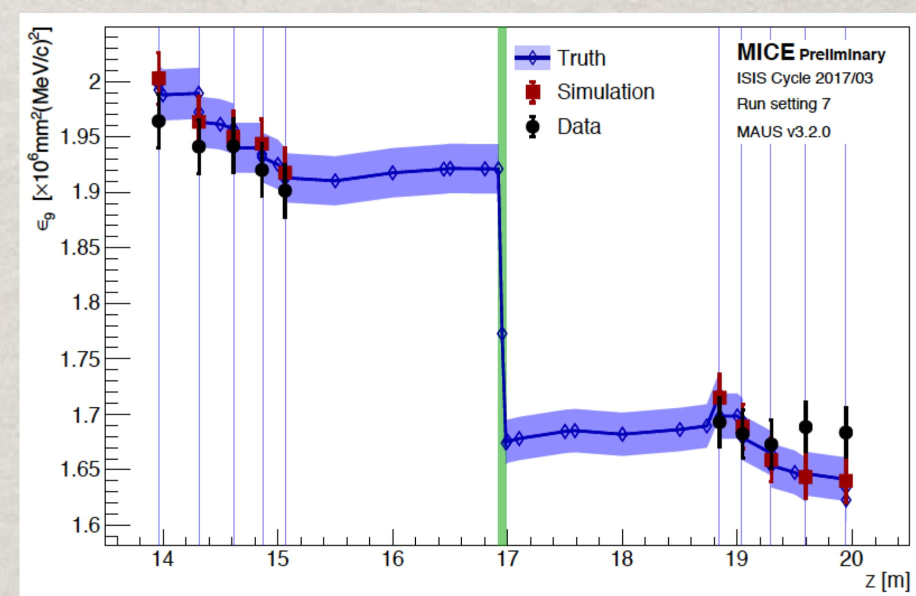
Renewed interests

Muon Accelerator Project (MAP)



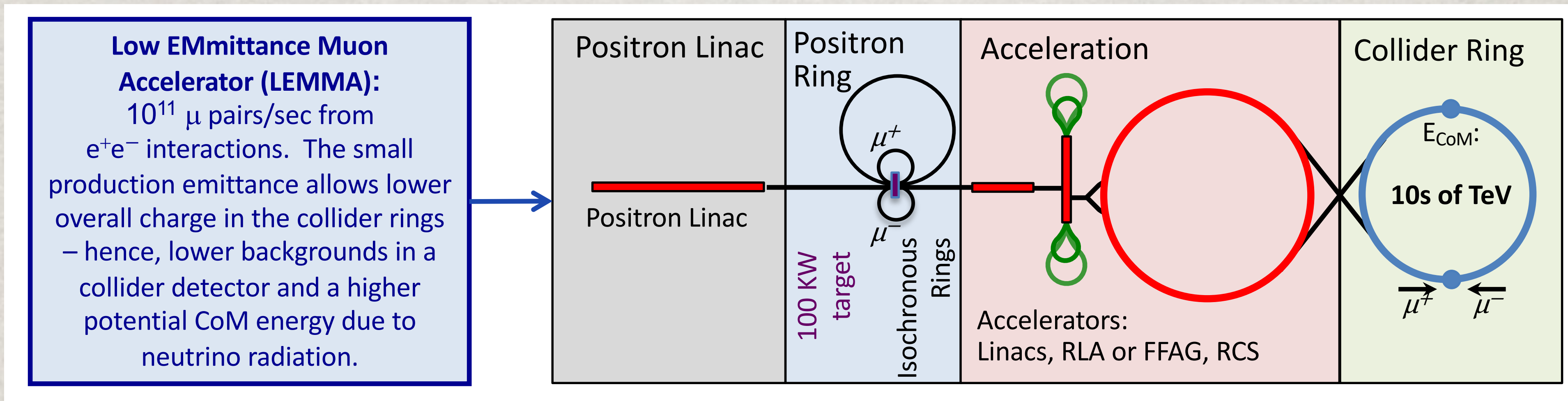
- Protons → pions → muons
- Transverse ionization cooling achieved by MICE
- Muon emittance exchange demonstrated at FNAL/RAL
- 6D cooling of 5-6 orders needed

Noticeable reduction of 9% emittance

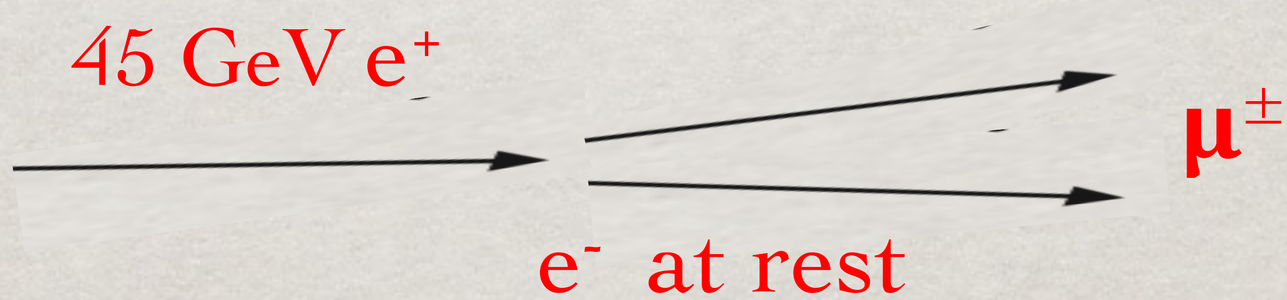


https://arxiv.org/abs/1907.08562, J.P. Delahauge et al., arXiv:1901.06150/

LEMMA: e^+e^- (at rest) → $\mu^+\mu^-$ (at threshold)



Low EMittance Muon Accelerator
web.infn.it/LEMMA



Cooling is not a problem;
but high luminosity is challenging:
large e^+ flux of $O(10^{17}/s)$!

J.P. Delahauge et al., arXiv:1901.06150

New ideas …

6664v2 [hep-ph] 21 Apr 2022

μTRISTAN

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[1] *KEK Theory Center, Tsukuba 305-0801, Japan*
[2] *KEK Accelerator department, Tsukuba 305-0801, Japan*
[3] *Graduate University for Advanced Studies (Sokendai), Tsukuba 305-0801, Japan*

Abstract

The ultra-cold muon technology developed for the muon $g-2$ experiment at J-PARC provides a low emittance μ^+ beam which can be accelerated and used for realistic collider experiments. We consider the possibility of new collider experi-

Friday, 9 June

00:00 → 01:30 **Lunch**

01:30 → 02:45 **Plenary: Plenary 13**

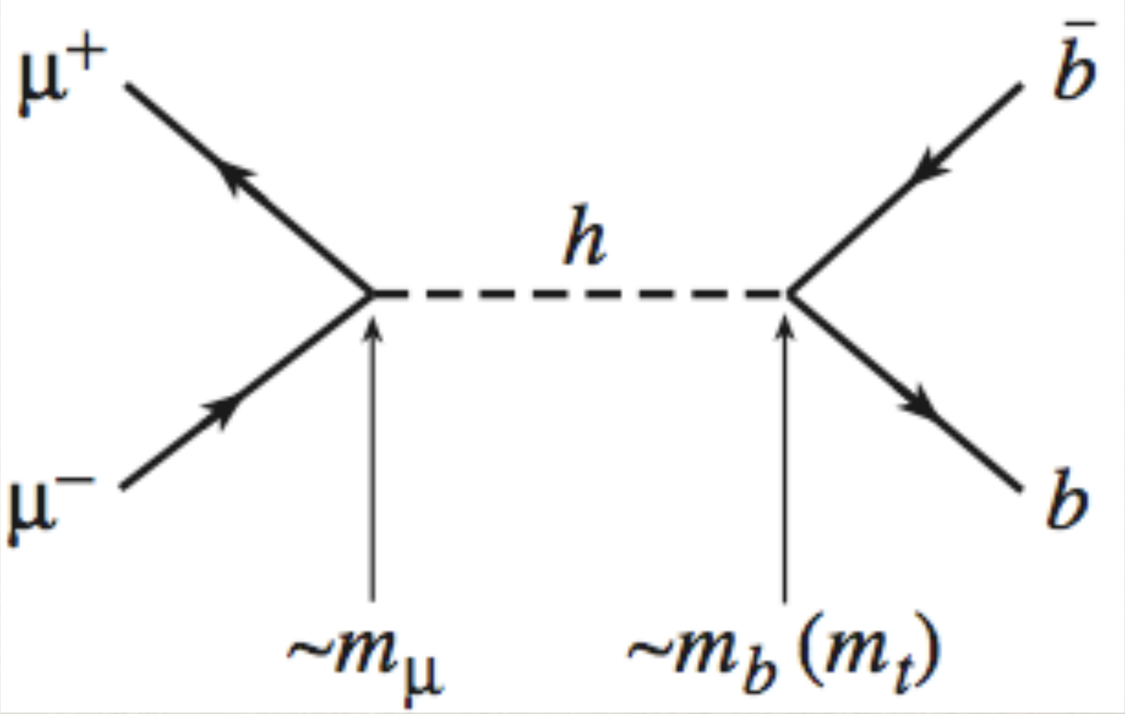
01:30 **muTRISTAN**
Speaker: Ryuichiro Kitano

02:00 **Probing new physics beyond the Standard Model at multi-TeV muon colliders**
Speaker: Dr Adil Jueid (Institute for Basic Science)

Physics potential

Higgs factory:

Resonant Production:



$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h \to \mu^+\mu^-)\mathrm{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$

$$\sigma_{peak}(\mu^+\mu^- \to h) \;=\; \frac{4\pi}{m_h^2} BR(h \to \mu^+\mu^-)$$
$$\approx\; 71 \text{ pb at } m_h = 125 \text{ GeV}.$$

About O(70k) events produced per fb^{-1}

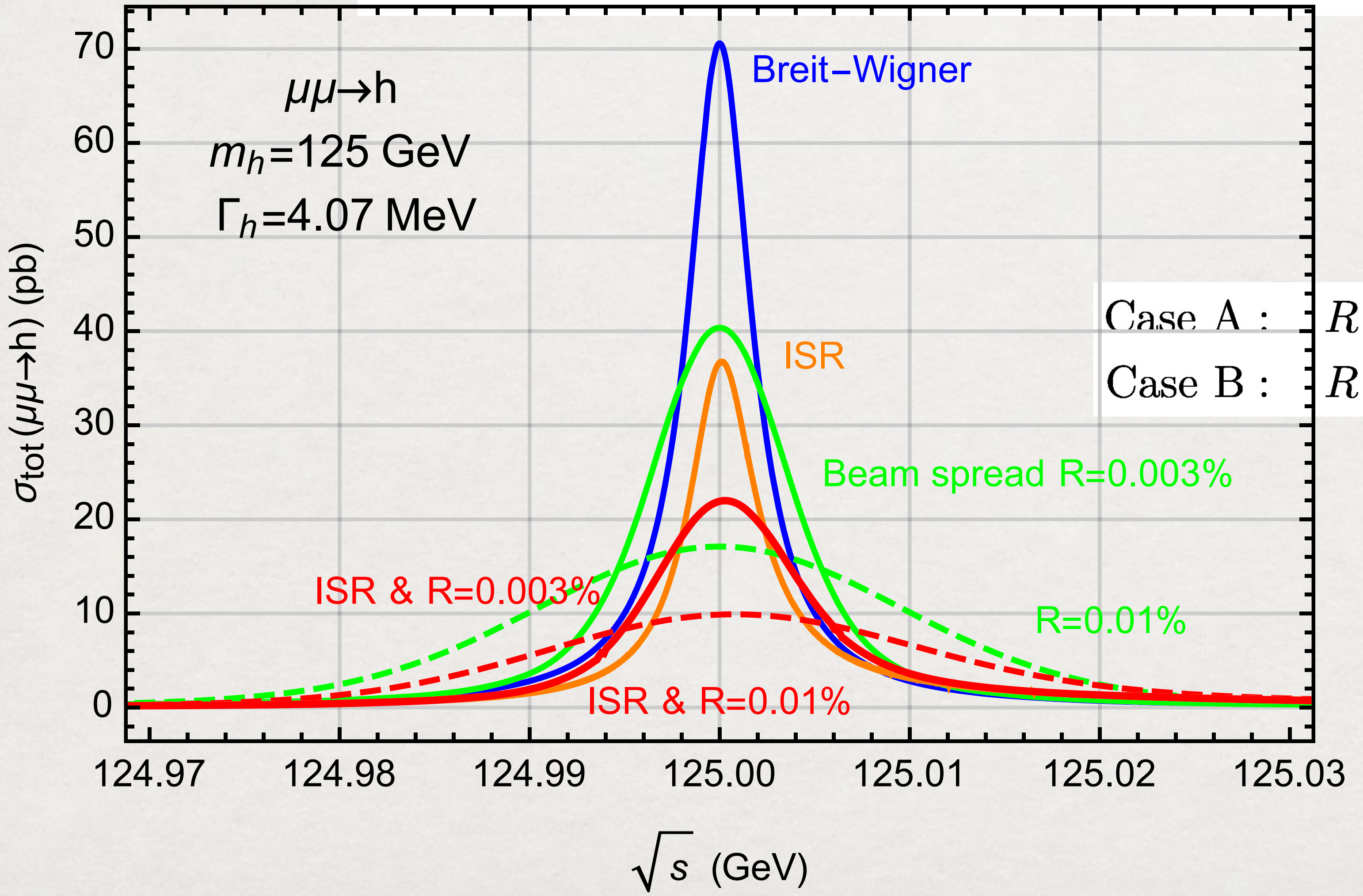
At m_h=125 GeV, Γ_h = 4.2 MeV

$$\frac{\exp[-(\sqrt{\hat{s}}-\sqrt{s})^2/(2\sigma^2_{\sqrt{s}})]}{\sqrt{2\pi}\sigma_{\sqrt{s}}}$$

$$\frac{4\pi\Gamma(h\to\mu\mu)\,\Gamma(h\to X)}{(\hat{s}-m_h^2)^2+m_h^2[\Gamma_h^{\rm tot}]^2}$$

$$\sigma_{\rm eff}(s)=\int d\sqrt{\hat{s}}\,\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}}\sigma(\mu^+\mu^-\to h\to X)$$

$$\propto\begin{cases}\Gamma_h^2 B/[(s-m_h^2)^2+\Gamma_h^2 m_h^2] & (\Delta\ll\Gamma_h),\\ B\exp[\frac{-(m_h-\sqrt{s})^2}{2\Delta^2}](\frac{\Gamma_h}{\Delta})/m_h^2 & (\Delta\gg\Gamma_h).\end{cases}$$



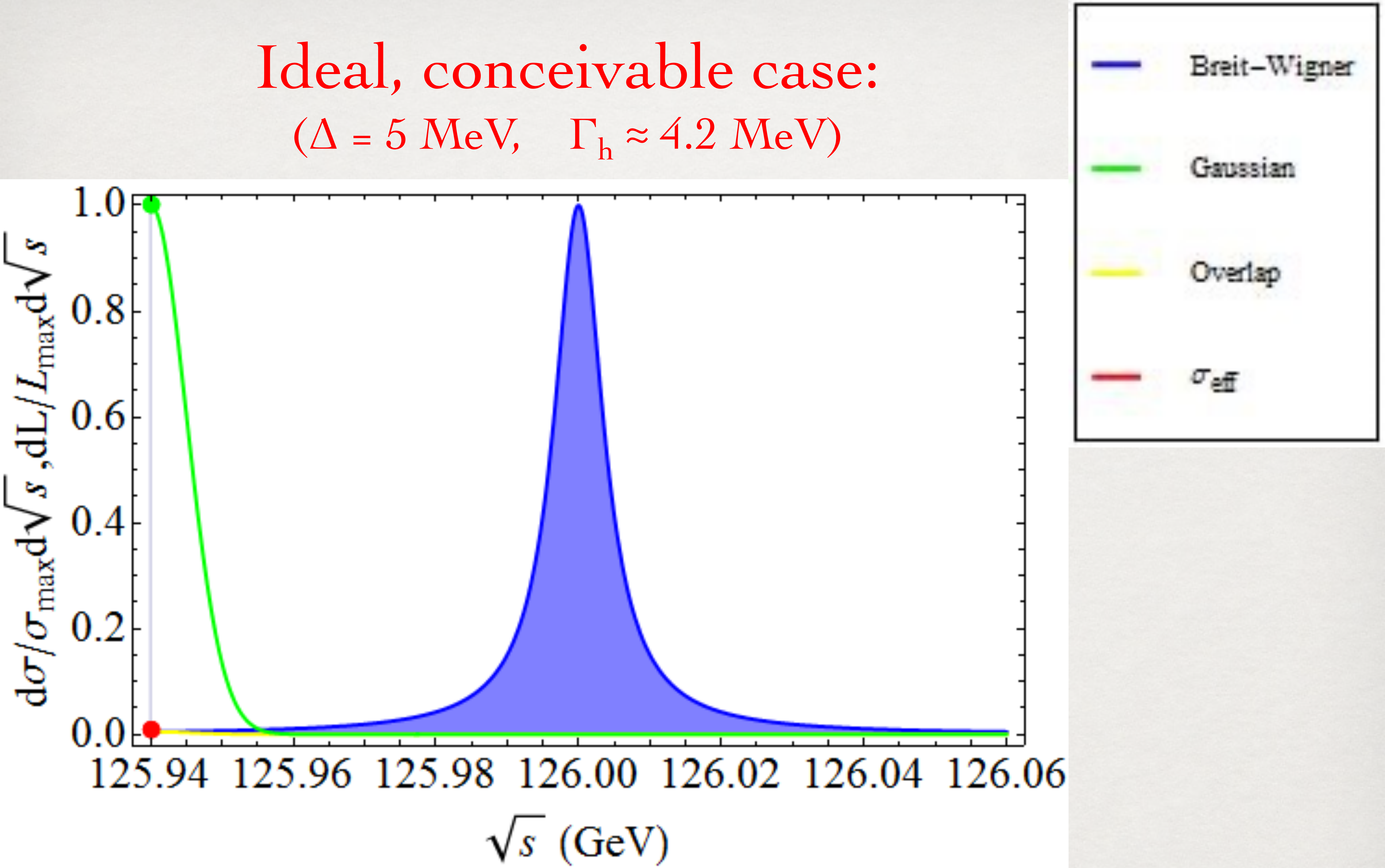
"Muon Collider Quartet":
Barger-Berger-Gunion-Han
PRL & Phys. Report (1995)

Case A : $R=0.01\%$ ($\Delta=8.9$ MeV), $L=0.5$ fb^{-1},
Case B : $R=0.003\%$ ($\Delta=2.7$ MeV), $L=1$ fb^{-1}.

TH, Liu: 1210.7803;
Greco, TH, Liu: 1607.03210

Ideal, conceivable case:

(Δ = 5 MeV, $\Gamma_h \approx 4.2$ MeV)



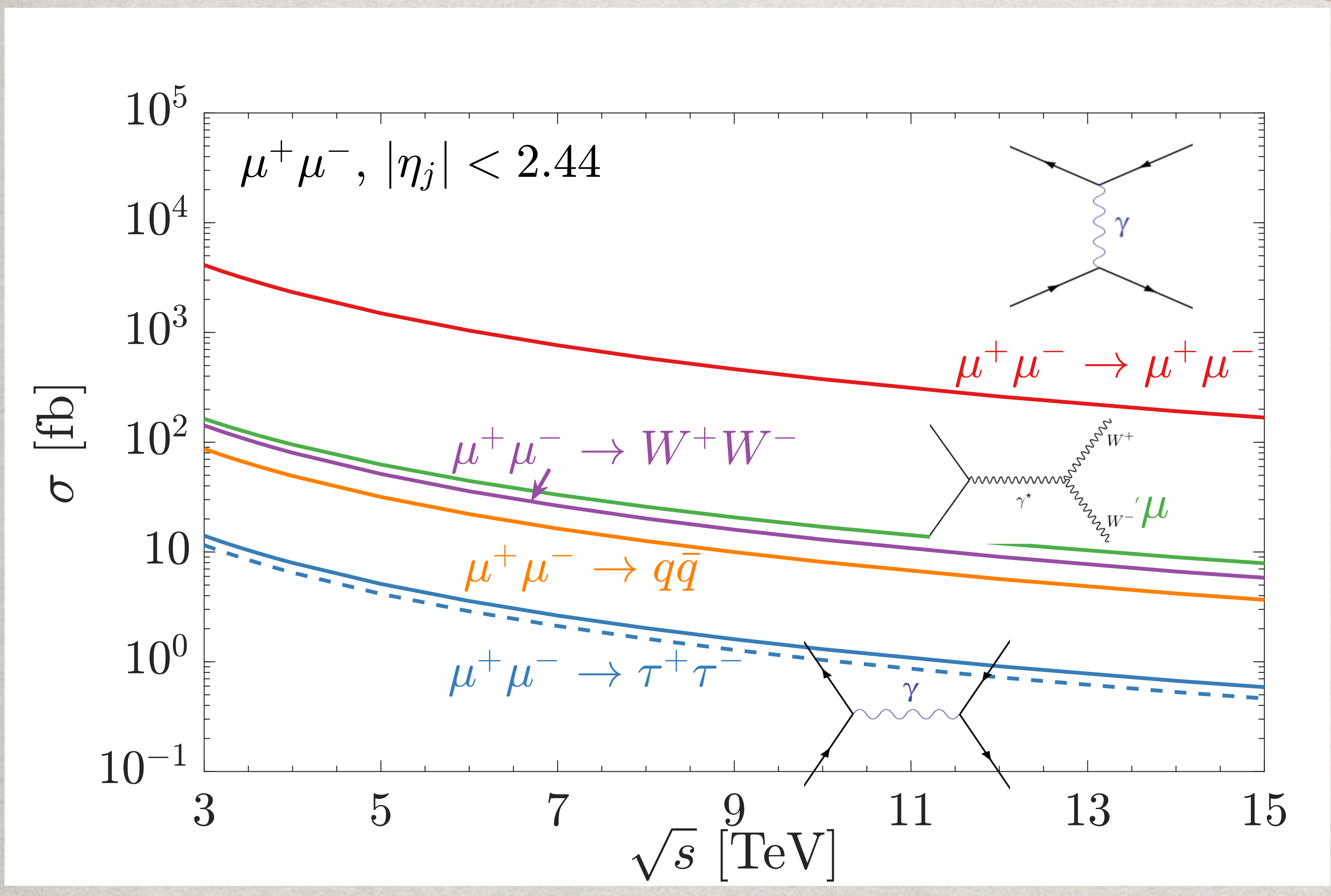
An optimal fitting could reach $\delta\Gamma_h \sim 0.15$ MeV, or 3.5%

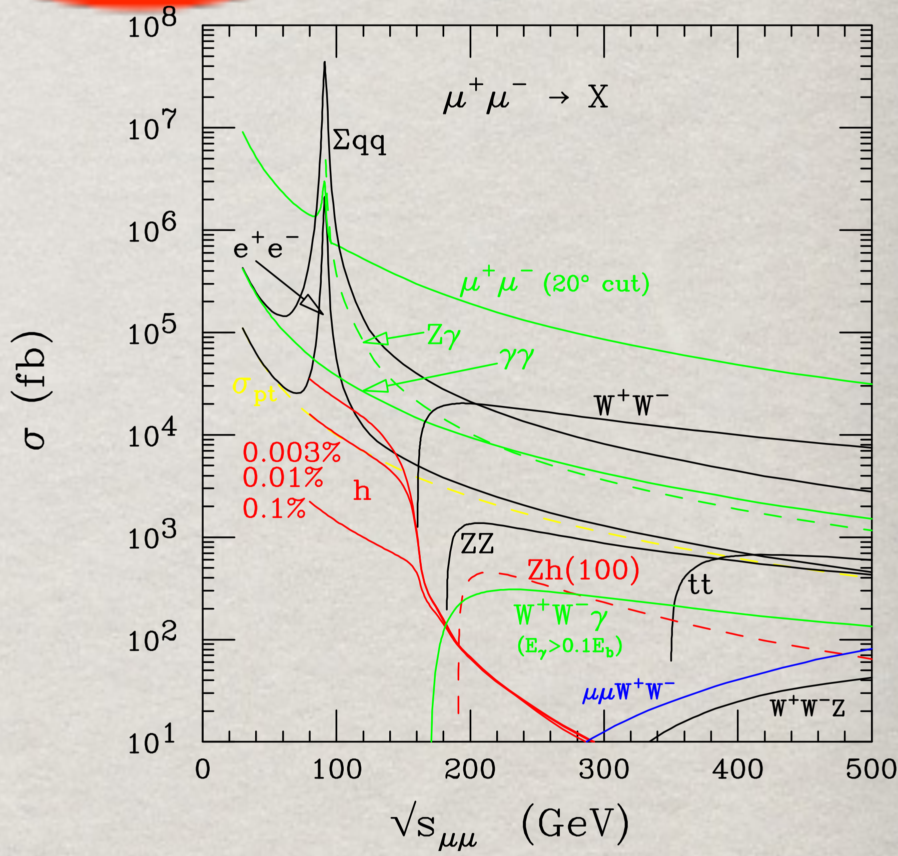
TH, Liu: 1210.7803; Greco, TH, Liu: 1607.03210

A Multi-TeV Muon Collider

Naïve expectation: leading-order **μ⁺μ⁻** annihilation:

$$\sigma_{ann} \sim \frac{\alpha^2}{s}$$

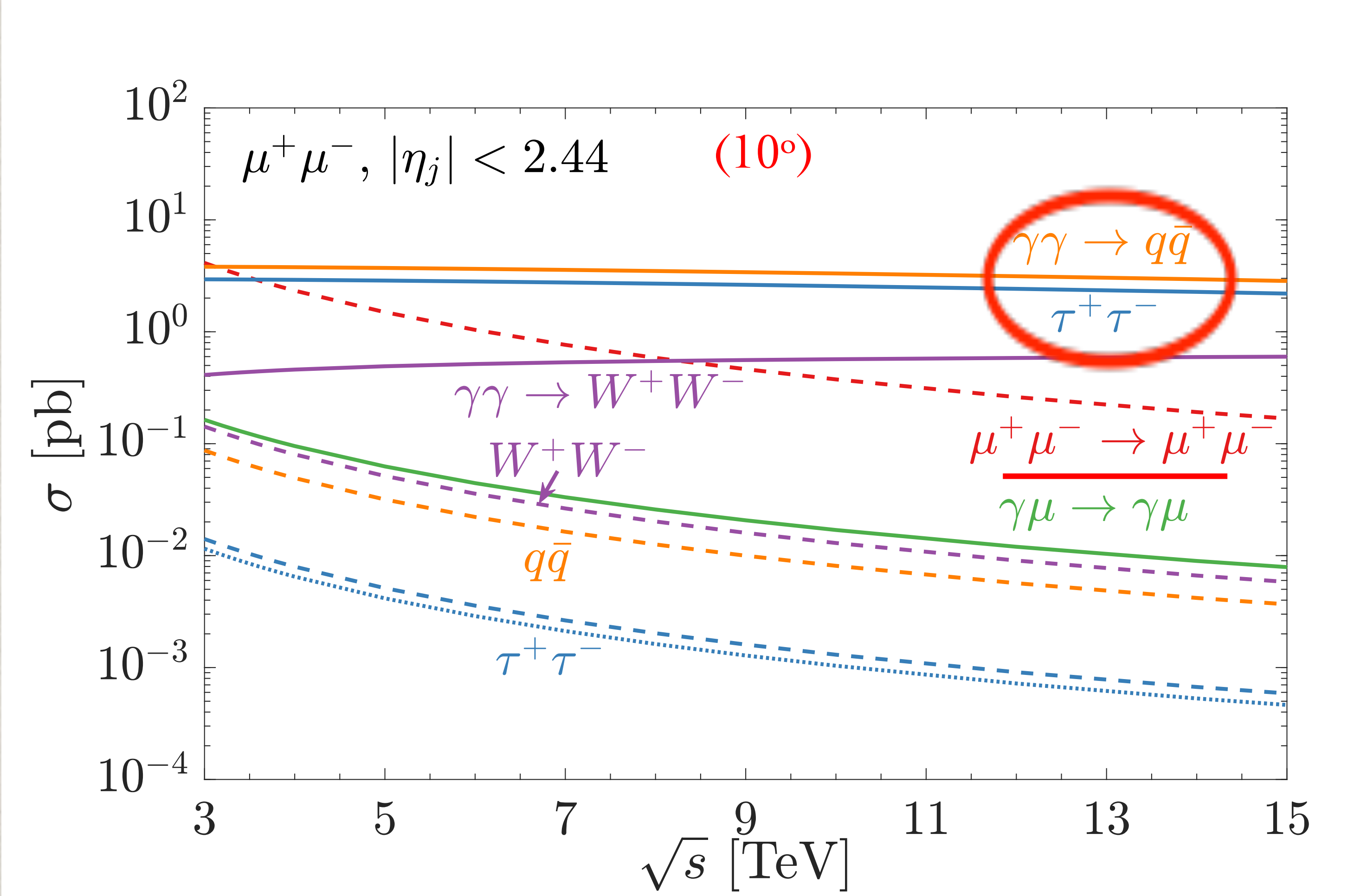


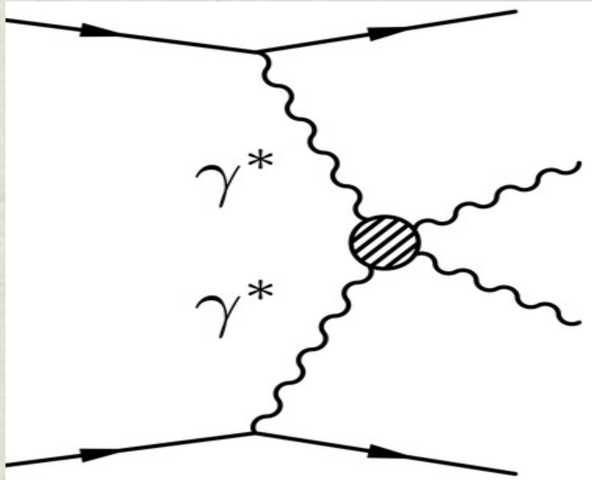


Those aren't what you would first see when you turned on the machine!

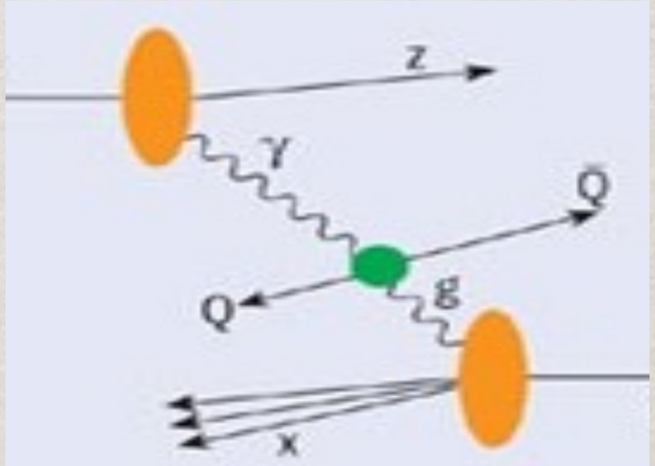
• Photon-induced QED cross sections

large rates $\sigma_{fusion} \sim \frac{\alpha^2}{m_{jj}^2}\log^2(\frac{Q^2}{m^2})$





m_{jj}



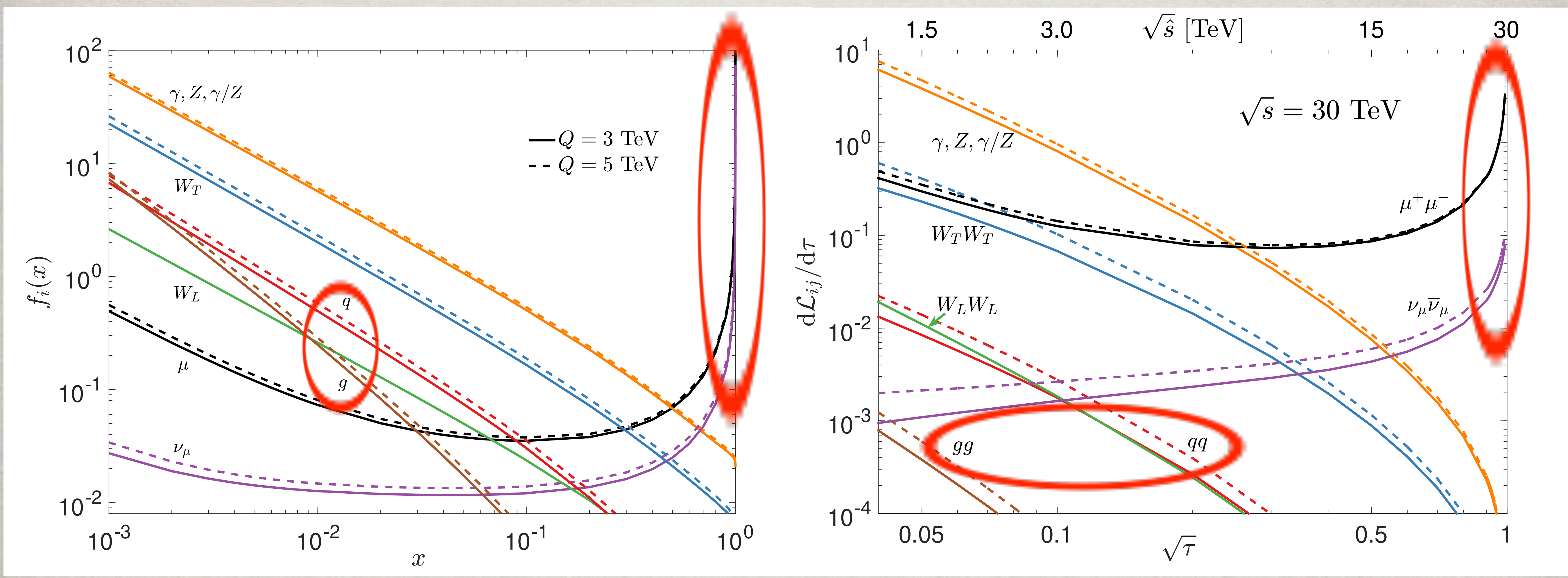
$$p_T^j > \left(4 + \frac{\sqrt{s}}{3\ \text{TeV}}\right)\ \text{GeV}, \quad m_{ij} > 20\ \text{GeV}, \quad |\eta_j| < 3.13\ (2.44)$$

Quarks/gluons come into the picture via SM DGLAP:

$$\frac{d}{d\log Q^2}\begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix} = \begin{pmatrix} P_{\ell\ell} & 0 & 0 & 2N_\ell P_{\ell\gamma} & 0 \\ 0 & P_{uu} & 0 & 2N_u P_{u\gamma} & 2N_u P_{ug} \\ 0 & 0 & P_{dd} & 2N_d P_{d\gamma} & 2N_d P_{dg} \\ P_{\gamma\ell} & P_{\gamma u} & P_{\gamma d} & P_{\gamma\gamma} & 0 \\ 0 & P_{gu} & P_{gd} & 0 & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix}$$

• EW PDFs at a muon collider:

"partons" dynamically generated $\frac{\mathrm{d} f_i}{\mathrm{d}\ln Q^2} = \sum_I \frac{\alpha_I}{2\pi} \sum_j P^I_{i,j} \otimes f_j$



$\mu^\pm$: the valance. $\ell_R,\ \ell_L,\ \nu_L$ and $B, W^{\pm,3}$: LO sea.

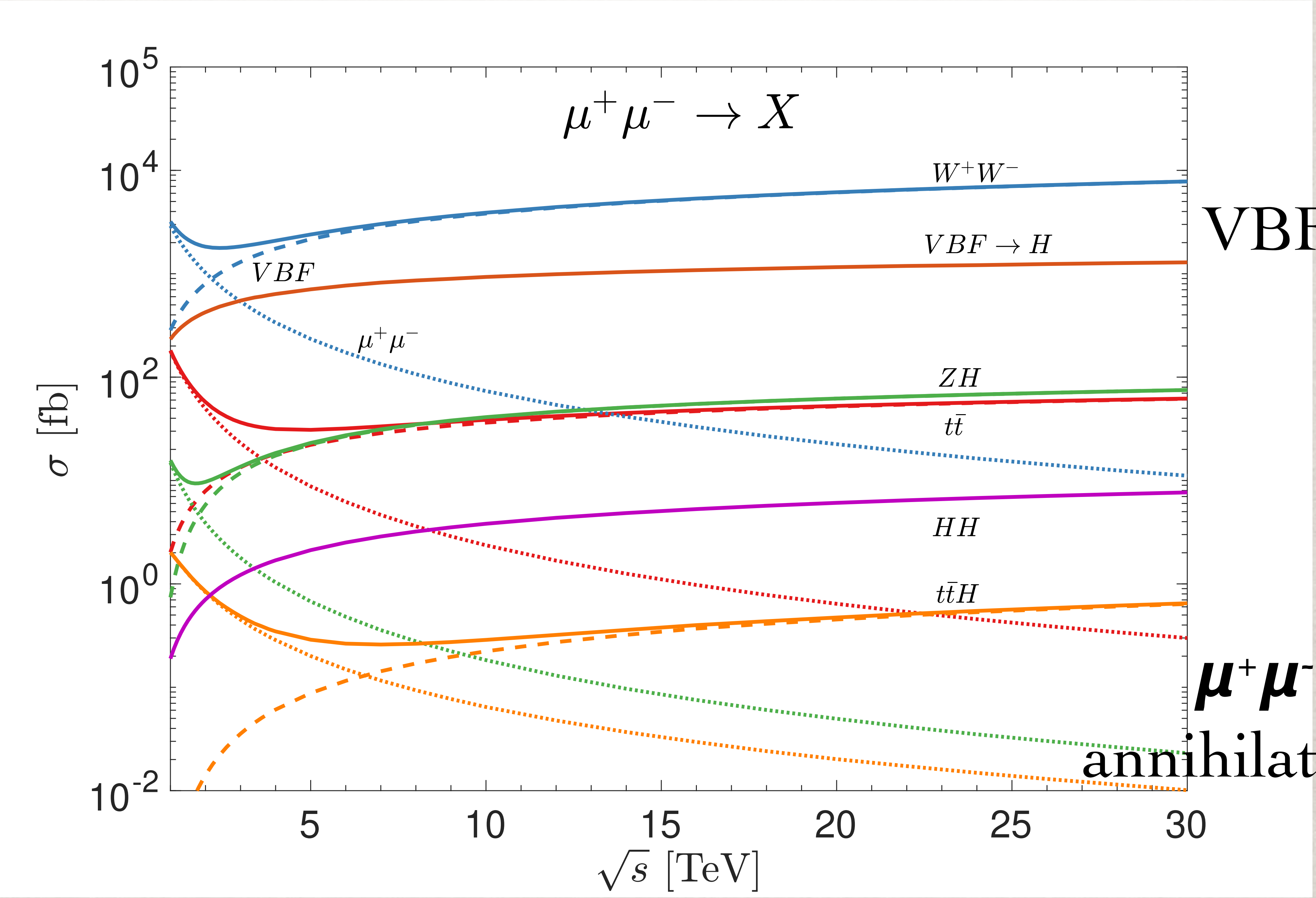
Quarks: NLO; gluons: NNLO.

TH, Yang Ma, Keping Xie, arXiv:2007.14300

• "Semi-inclusive" processes

Just like in hadronic collisions:

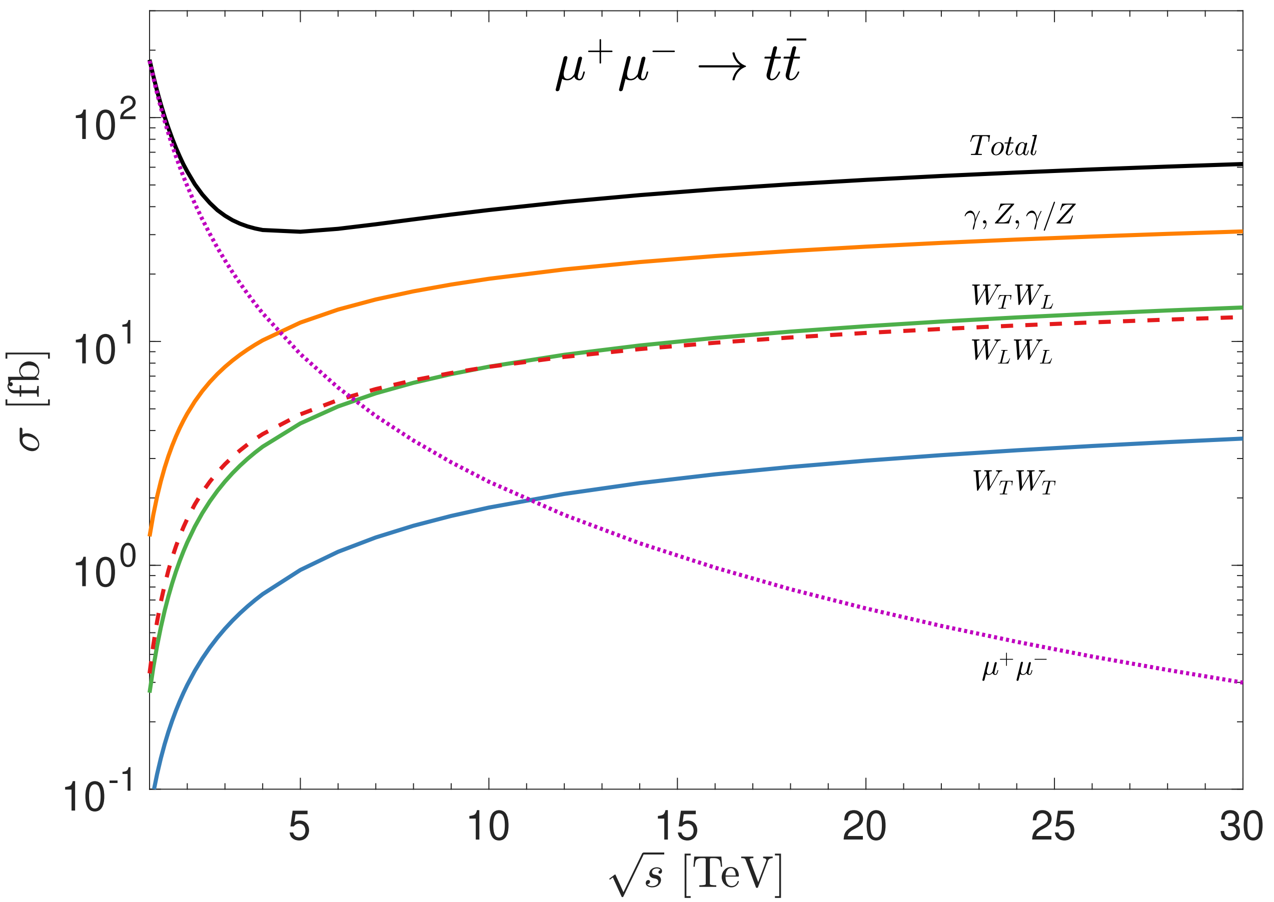
$\mu^+\mu^-$ → exclusive particles + remnants

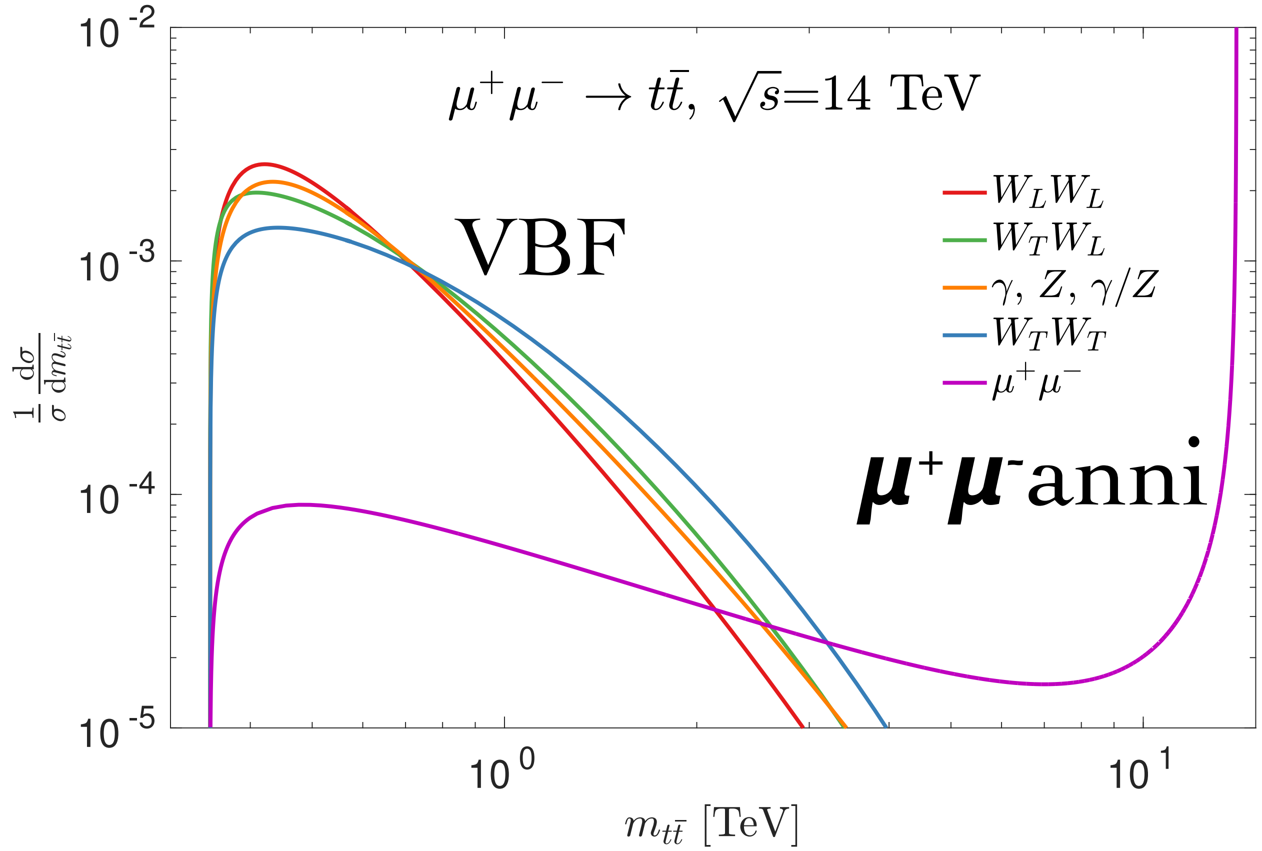


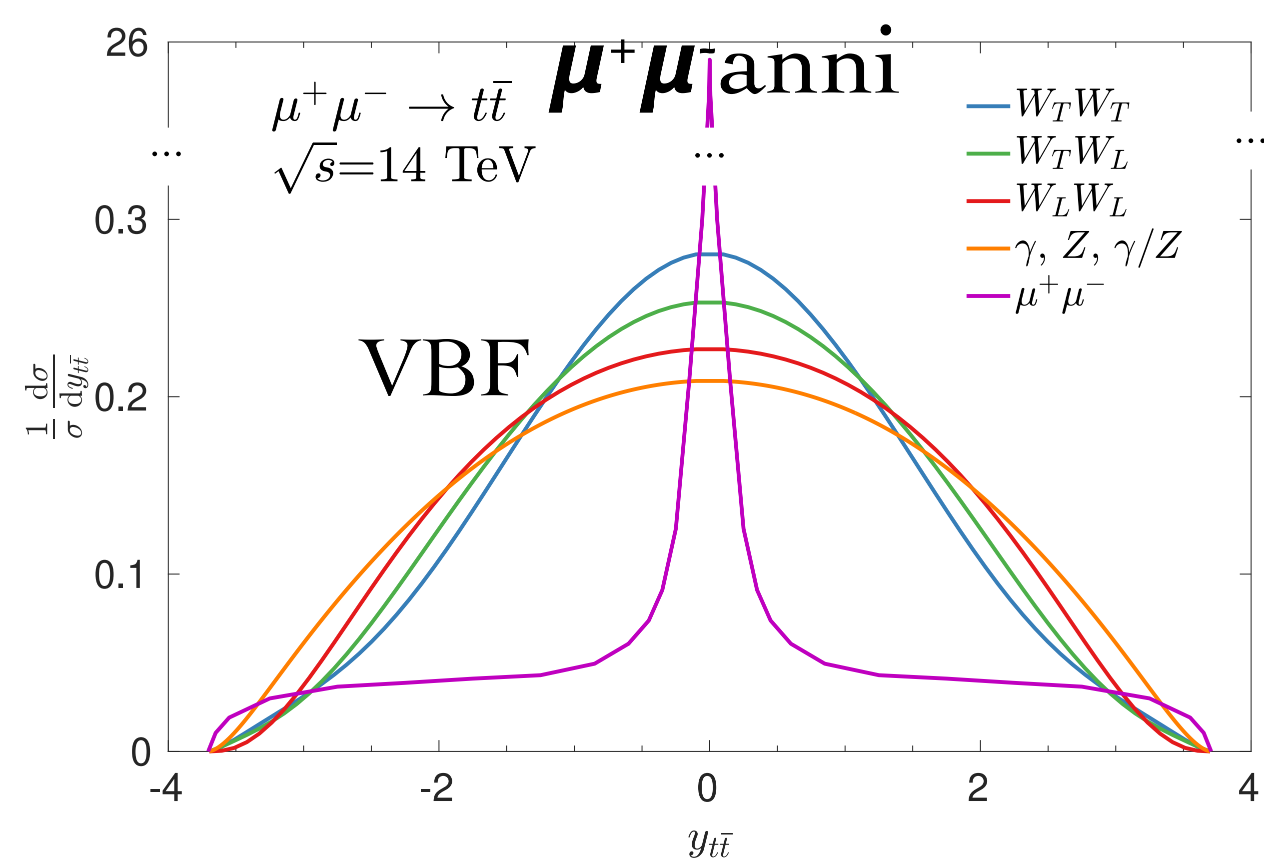
VBF

$\mu^+\mu^-$ annihilations

• separable sub-processes:







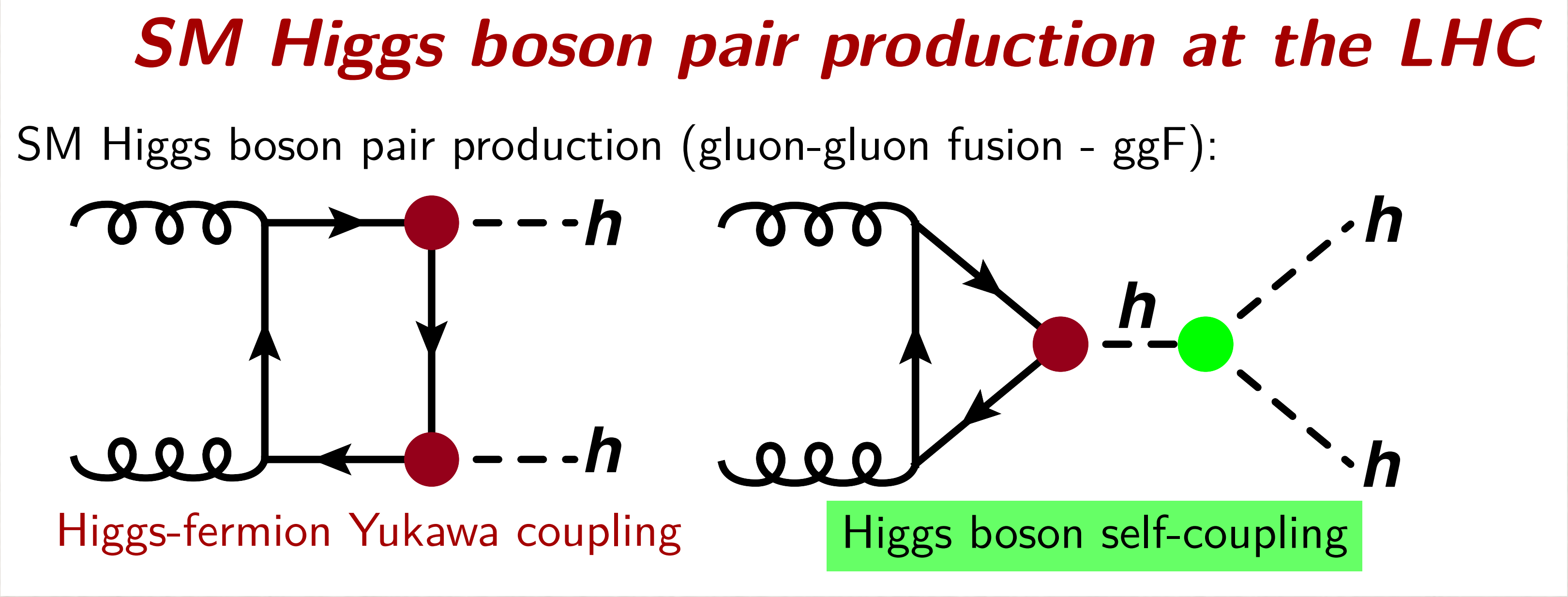
Partonic contributions

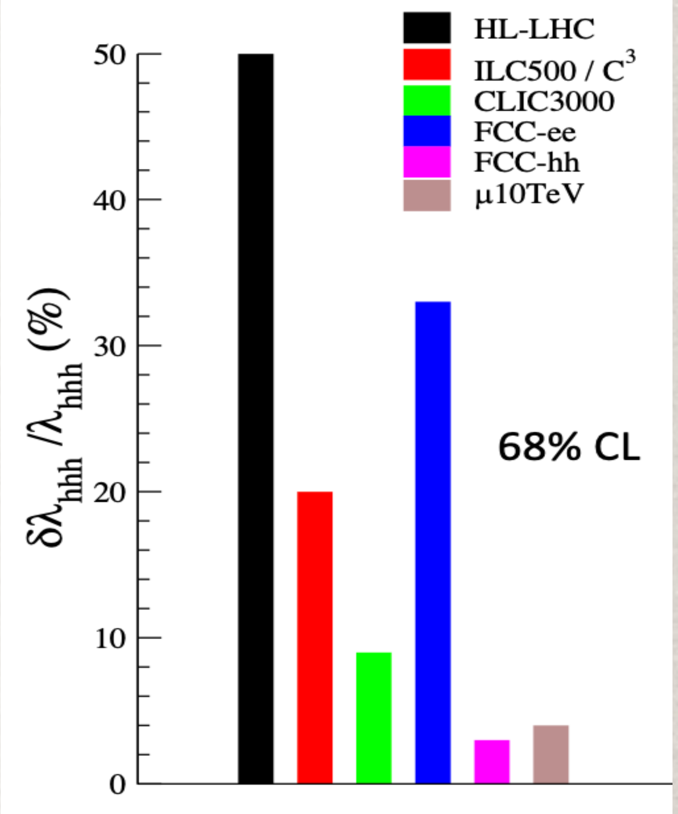
$\mu^+\mu^-$ Collider:

"Buy one, get one free"

Annihilation +VBF

Higgs pair production & triple coupling:





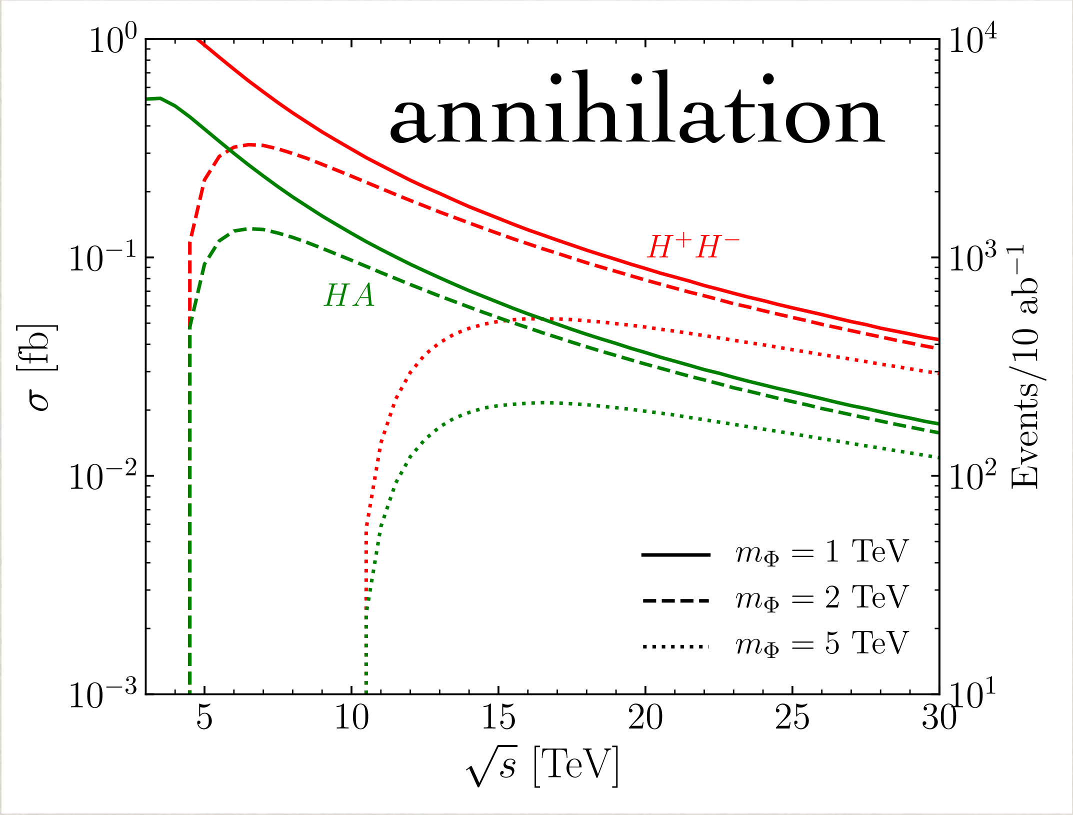
→dictate EW phase transition & impact on early universe cosmology!

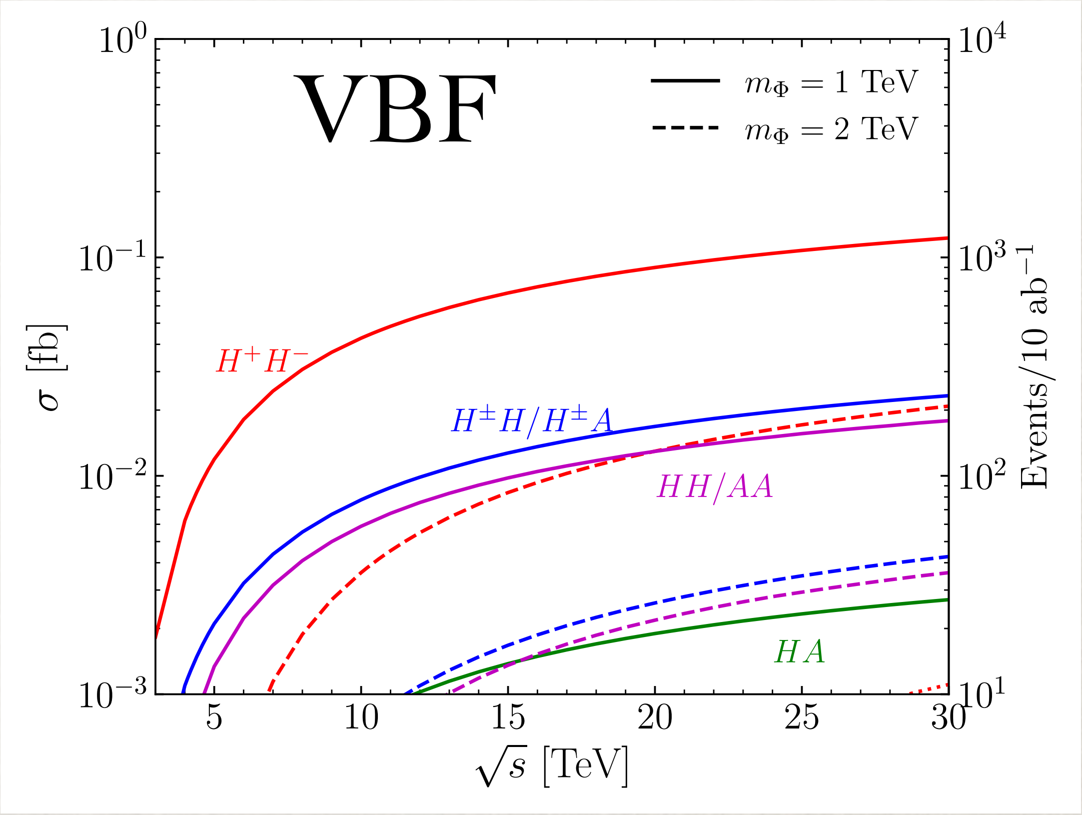
$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

Table 7: Summary table of the expected accuracies at 95% C.L. for the Higgs couplings at a variety of muon collider collider energies and luminosities.

TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204

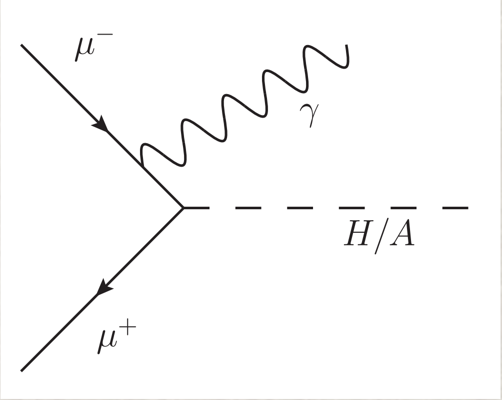
• Heavy Higgs Bosons Production

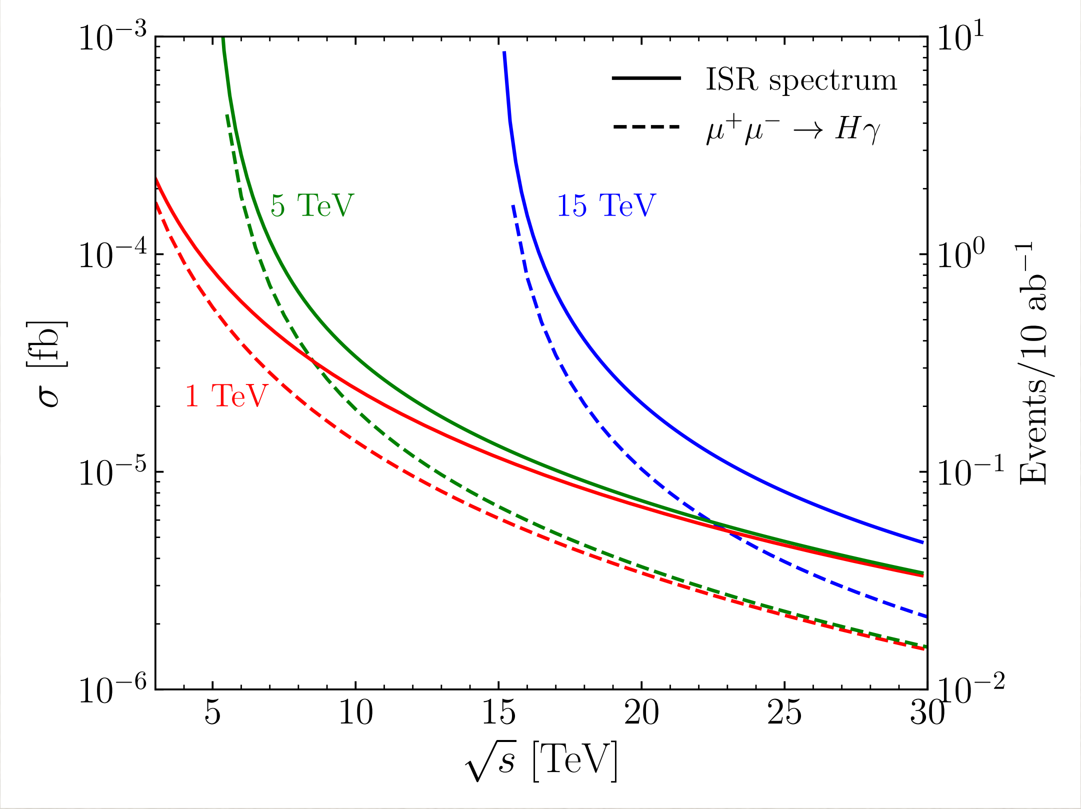




Radiative returns:

$$\hat{\sigma}(\mu^+\mu^- \to H) = \frac{\pi Y_\mu^2}{4}\delta(\hat{s} - m_H^2) = \frac{\pi Y_\mu^2}{4s}\delta(\tau - \frac{m_H^2}{s})$$



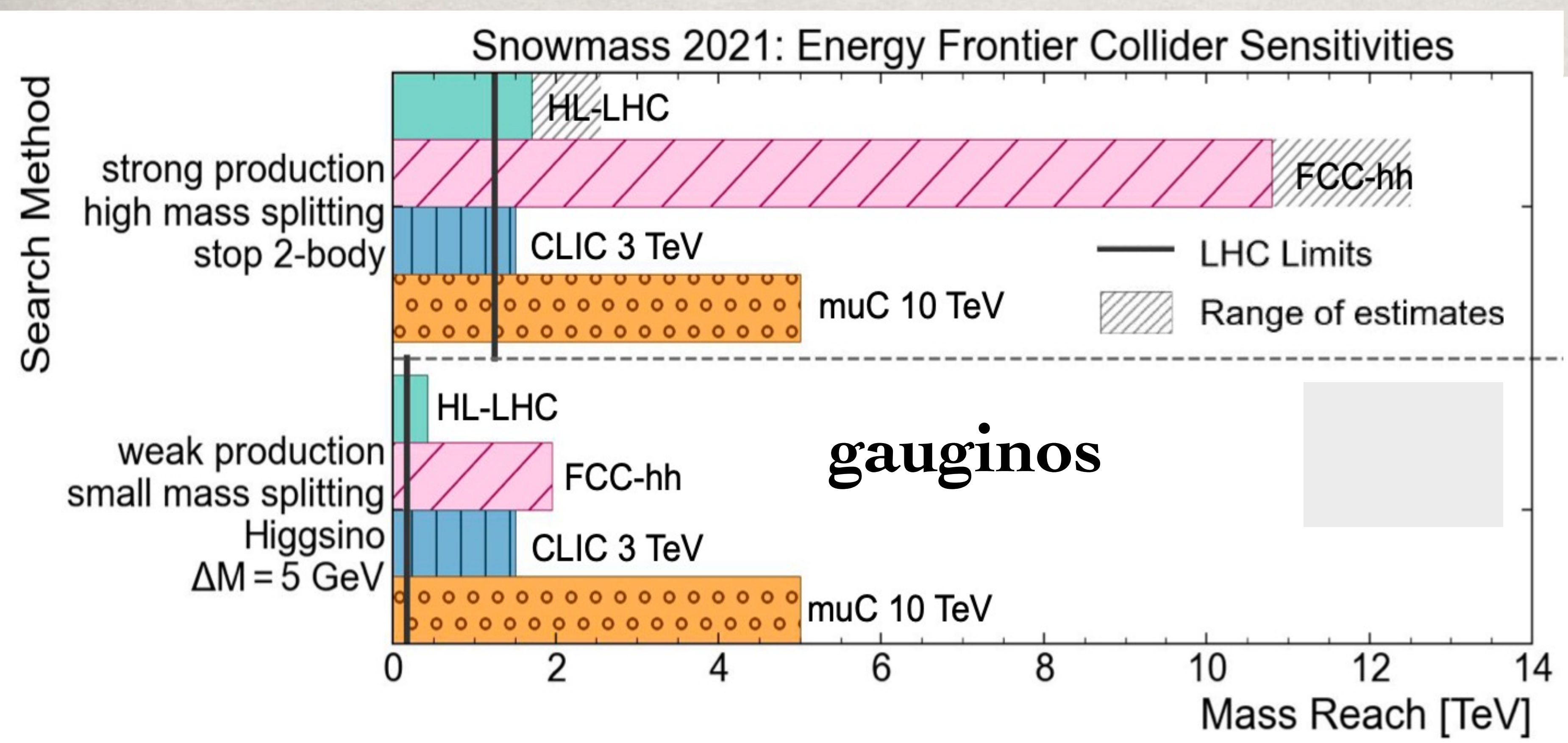


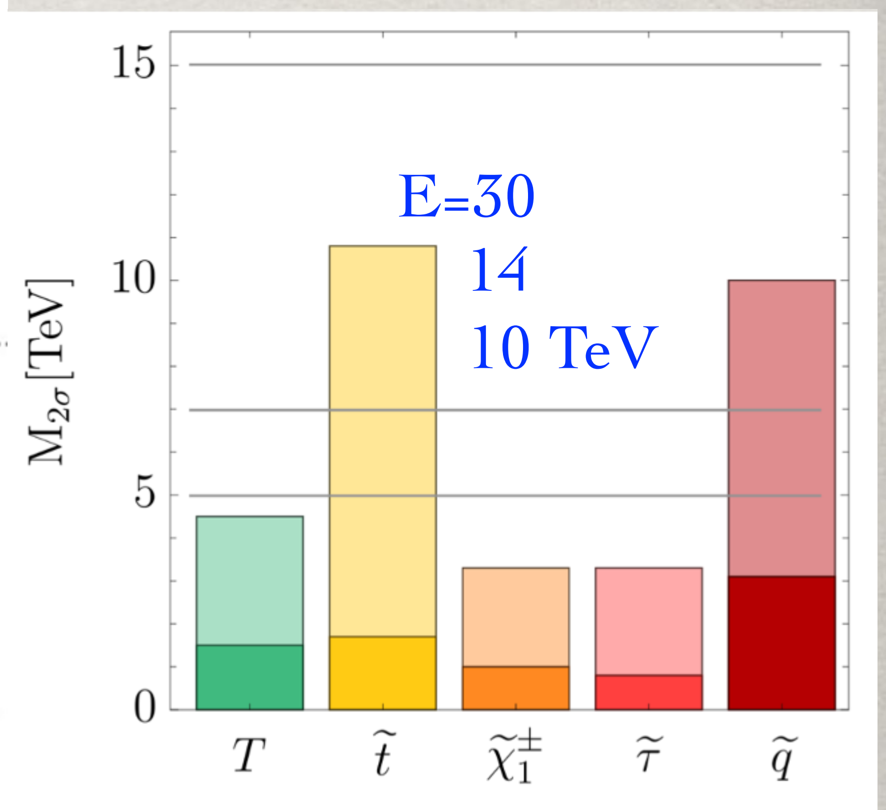
Reach M ~ E_{cm}!

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

Pushing the "Naturalness" limit

The searches for top quark partners
(most wanted in "naturalness");
& gluinos, gauginos …



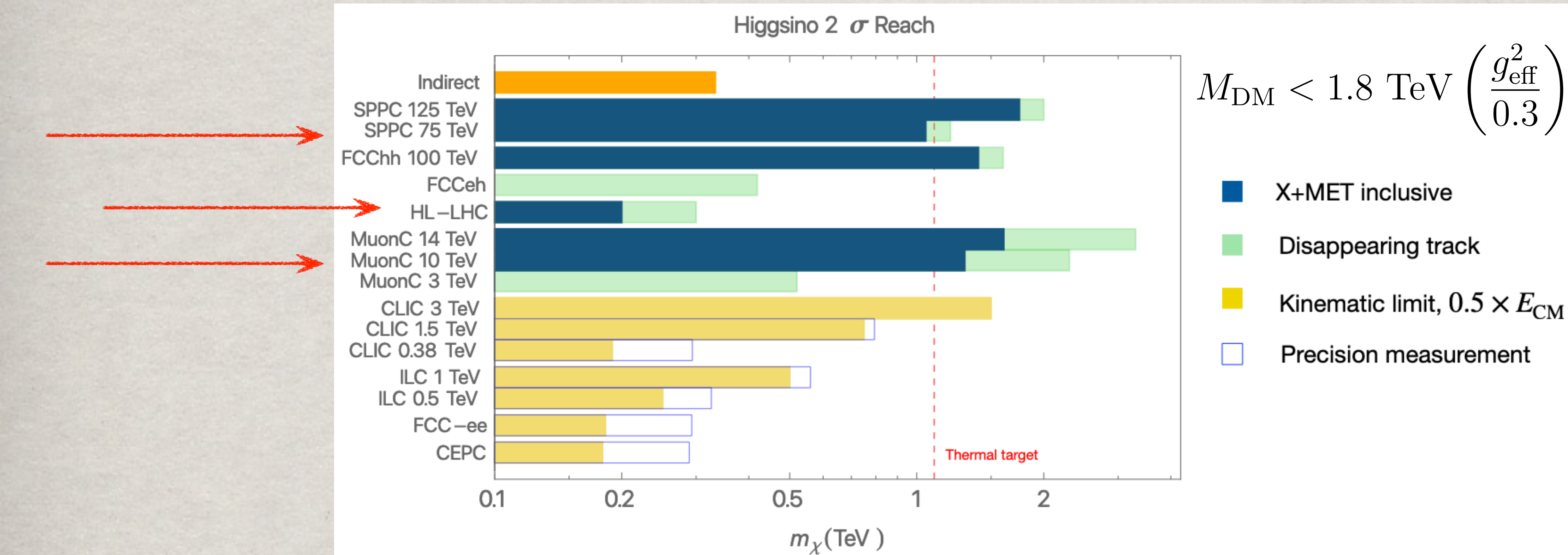


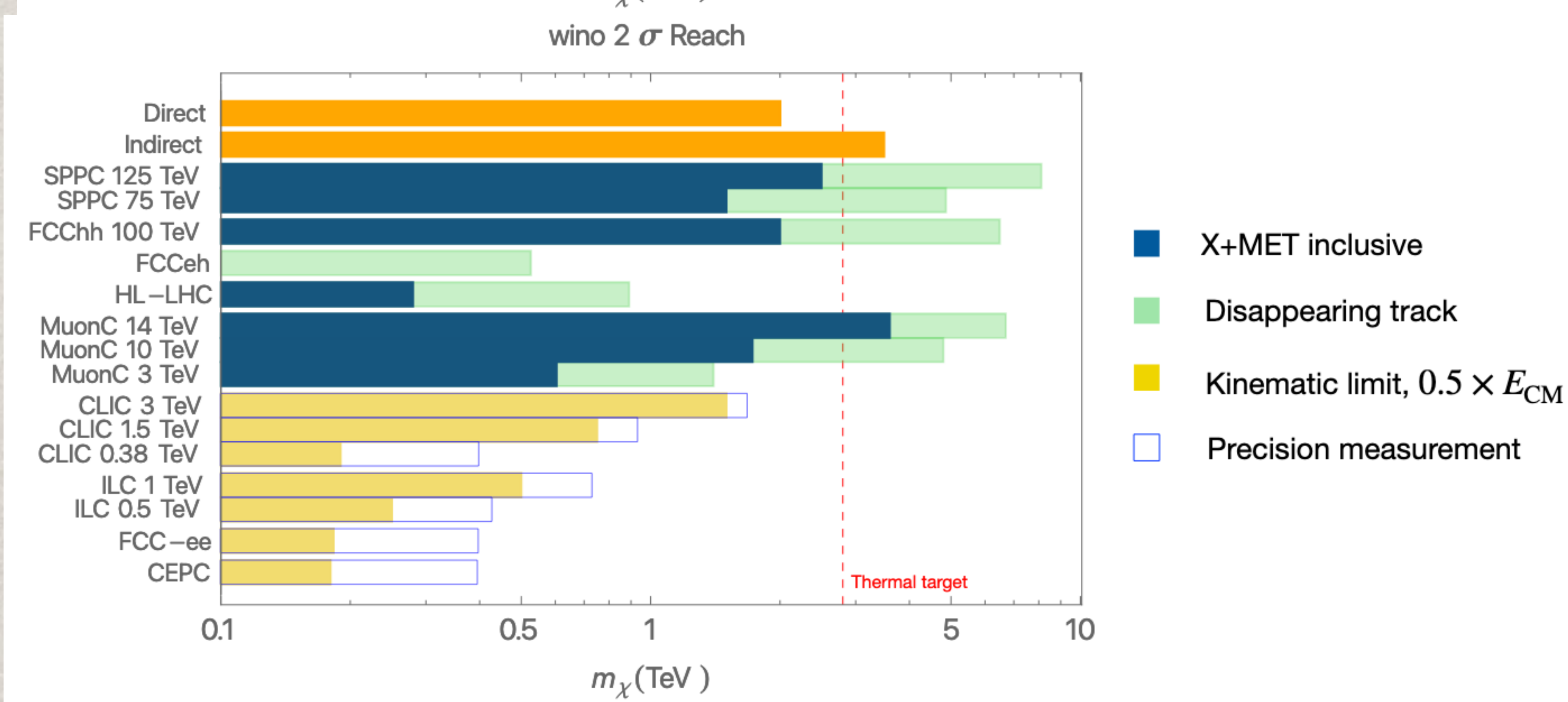
→ Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \, (1 \text{ TeV}/\Lambda)^2$

Thus, $m_{stop} > 8$ TeV → 10^{-4} fine-tune!

WIMP Dark Matter

Covering the thermal target



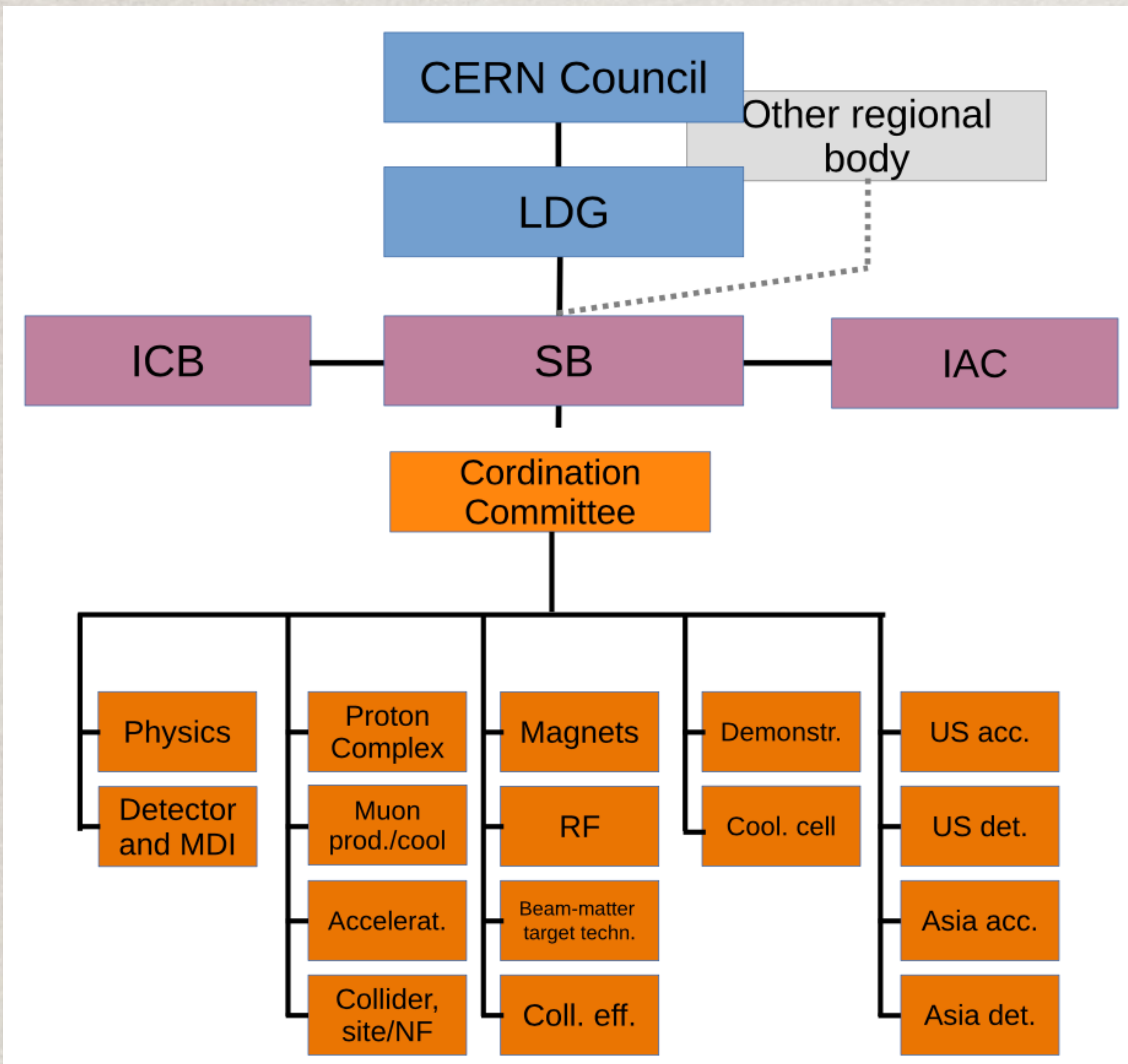


TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287; arXiv:2203.07351

International Muon Collider Collaboration (IMCC, 2022)

International MUON Collider Collaboration

European Commission grant: HORIZON INFRA-DEV



Cordination Committee

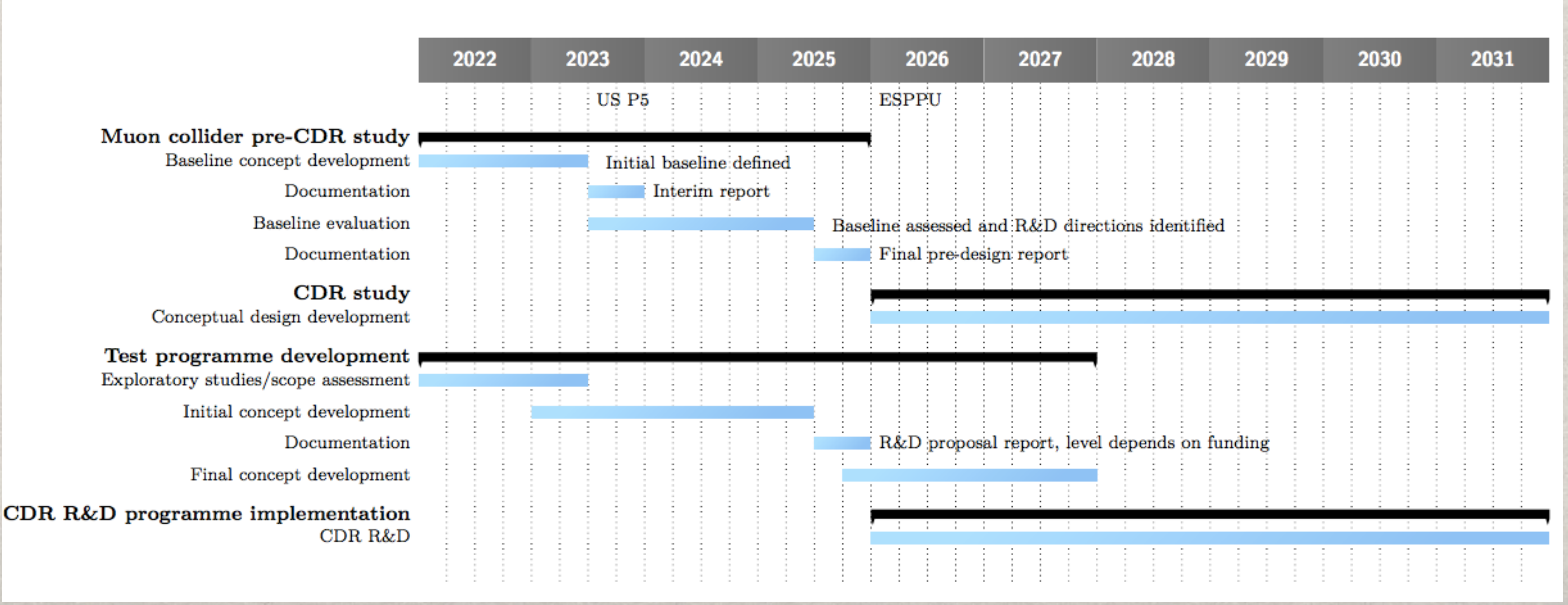
Alexej Grudiev
Andrea Wulzer
Antoine Chance
Anton Lechner
Chris Rogers
Christian Carli
Claude Marchand
Daniel Schulte (Study Leader)
Donatella Lucchesi
Elias Metral
Jingyu Tang
Luca Bottura
Lucio Rossi
Mark Palmer
Nadia Pastrone (Collaboration Board Chair)
Natalia Milas
Roberto Losito
Sergo Jindariani
Steinar Stapnes (Steering Board Chair)

Physics	Andrea Wulzer
Detector and MDI	Donatella Lucchesi

US (detector)	Sergo Jindariani
US (accelerator)	Mark Palmer
Asia (China)	Jingyu Tang

Initial Target Parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40	2 (6)
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	MW	5.3	14.4	20	28
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	
β	mm	5	1.5	1.07	
ε	µm	25	25	25	
$\sigma_{x,y}$	µm	3.0	0.9	0.63	



Mark Palmer @ 1st IMCC Conference
CERN, Oct. 11, 2022

Conclusion

International MUON Collider Collaboration

The MC option was well-received as a potential Energy Frontier option during Snowmass

- Implementing a US Accelerator R&D Program for Future Colliders would provide a mechanism to:
  - Let US accelerator experts engage with ongoing MC development activities
  - Formally participate in the IMCC
  - Explore potential options for US siting
- Developing critical elements of the design between now and the next Snowmass (and European Strategy Update) is crucial!

Brookhaven National Laboratory

13

Exciting journey ahead!

Lots of recent works!

D. Buttazzo, D. Redogolo, F. Sala, arXiv:1807.04743 (VBF to Higgs)

A. Costantini, F. Maltoni, et al., arXiv:2005.10289 (VBF to NP)

M. Chiesa, F. Maltoni, L. Mantani, B. Mele, F. Piccinini, and X. Zhao, arXiv:2005.10289 (SM Higgs)

R. Capdevilla, D. Curtin, Y. Kahn, G. Krnjaic, arXiv:2006.16277; arXiv:2101.10334 (g-2, flavor)

P. Bandyopadhyay, A. Costantini et al., arXiv:2010.02597 (Higgs)

D. Buttazzo, P. Paradisi, arXiv:2012.02769 (g-2)

W. Yin, M. Yamaguchi, arXiv:2012.03928 (g-2)

R. Capdevilla, F. Meloni, R. Simoniello, and J. Zurita, arXiv:2012.11292 (MD)

D. Buttazzo, F. Franceschini, A. Wulzer, arXiv:2012.11555 (general)

G.-Y. Huang, F. Queiroz, W. Rodejohann, arXiv:2101.04956; arXiv:2103.01617 (flavor)

W. Liu, K.-P. Xie, arXiv:2101.10469 (EWPT)

Richard Ruiz et al., arXiv:2111.02442 (MadGraph5) … … …

… …

Numerous Snowmass White papers & summary reports

Muon Smasher's Guide: H. Ali, N. Arkani-Hamed, et al, arXiv:2103.14043

Muon Collider Physics Summary: https://arxiv.org/abs/2203.07256

Muon Collider Forum Report: https://arxiv.org/abs/2209.01318