Muon Collider Physics
-- Recent Pheno Developments

Tao Han

"Muon Collider Exploration"

Dec. 10, 2020

- Brief Report on Pitt PACC Workshop
- Recent Developments in Phenomenology

https://indico.cern.ch/event/969815/

Search

Most Visited Yahoo AtlasSearches_susy... https://courseweb.p... Getting Started .Mac My Pitt Home Amazon .Mac Amazon eBay

PITT PACC Workshop: Muon collider physics

30 November 2020 to 2 December 2020
University of Pittsburgh
US/Eastern timezone

3 short days: 10:00am – 4:00pm, ~120 participants

- Machine R&D
- Detector simulations
- Physics motivations

Search...

- Overview
- Timetable
- Contribution List
- Registration
- Participant List

Support

bcarlson@cern.ch
kex10@pitt.edu

This virtual workshop will be focused on muon collider physics and comparison with the other next generation colliders for physics potential.

ZOOM VIDEO CONFERENCE:
https://pitt.zoom.us/j/99311942431

Meeting ID: 993 1194 2431

LOCAL ORGANIZERS: Ben Carlson, Tao Han, Brian Batell, Ayres Freitas, Keping Xie, Cedric Weiland

EXTERNAL ORGANIZERS: Xing Wang

ADMINISTRATOR: Joni George

Q&A. We plan to use the hand raise option in Zoom (you have to load the participants list to see whether a hand is raised). The session chairs will moderate the Q&A, and ask those with raised hands to unmute and proceed with the question. If it is not possible to speak, there will also be a chat box where a question can be typed and relayed to the speaker by the session chairs.

Picture. The zoom picture of all participants is available here and here

Accelerator R&D:

Day 1:

1. Nadia Pastrone: Muon collider: Are we ready?
2. Daniel Schulte: Current status of muon collider program

Formal collaboration at any moment

International Muon Collider Collaboration

Actual work started with meetings on design

- Accelerator design (-> daniel.schulte@cern.ch)
- Physics and detectors (-> nadia.pastrone@cern.ch)
- Physics potential (-> andrea.wulzer@cern.ch),
- Detector simulations (-> donatella.lucchesi@pd.infn.it),
- Muon cooling (-> chris.rogers@stfc.ac.uk, klaus.hanke@cern.ch)

Will have project meeting with accelerator and physics

- Every few months, half day long

Web page: http://muoncollider.web.cern.ch

- Find link to meetings in menu “Organisation”

Mailing lists: MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch, MUONCOLLIDER_FACILITY@cern.ch

Many thanks to all
MAP collaboration, M. Palmer
MICE collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
…

PITT PACC 30/11/2020 D. Schulte: Muon Collider Collaboration

Review Conclusion

We think we can answer the following questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged
  - But at this moment not mature enough for a proposal
- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - Should not miss this opportunity
- **What needs to be done?**
  - Muon production and cooling is key => A new test facility is required.
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source

Accelerator R&D:

Day 2:

1. Mark Palmer: MAP feasibility studies as basis for future capabilities
2. Diktys Stratakis: Overview of ionization cooling for a muon collider

Looking Forward...

- Muon Colliders offer an energy-efficient path to multi-TeV CoM energies
- Recent physics studies indicate that important collider physics is accessible
- The MAP R&D Program has successfully demonstrated critical technologies for the cooling channel ⇨ Now ready for:
  - Updated Cooling Channel Conceptual Design
  - Demonstrator of a high intensity cooling cell
- Other key developments to pursue for a TeV-class collider (pushing beyond the parameters and scope of MAP)
  - Ongoing physics studies
  - Detailed designs for TeV-class acceleration
  - Full end-to-end conceptual design
  - Mitigation approaches to minimize “ν Radiation” issues at the exit point on the surface

A new international design effort is timely and ready to evaluate an important option for the HEP community

Detector & Simulations:

Day 3:

1. Donatella Lucchesi:
   Muon collider: detector performances from full simulation
2. Michele Selvaggi: Simulations for muon colliders

Summary

First detector simulation performed with MAP design

- Muon Collider detectors have to be carefully designed with both physics goals and BIB in mind.
- General considerations: rad hard, high granularity, high time resolution.
- Using special and time information is crucial for on-detector filtering in order to reduce bandwidth and power requirements to a manageable level.
- Trigger-less readout is probably the way to go.
- Additional considerations should be given to special cases, for example very high energy muons, displaced tracking, slow particles.

Related topics: Simulation tools

1. Fabio Maltoni: MadGraph & VBF processes
2. Wolfgang Kilian: WHIZARD & Multiple boson production

Much work needed to handle the computation for $\mu^+\mu^-$ collisions @ ultra-high energies!

Theoretical motivations & physics potential:

Inspirational:

Nima Akarni-Hamed: Muon colliders rock!

Raman Sundrum: Muon collider against the backdrop of fundamental physics

General:

Andrea Wulzer: Why building a muon collider?

Keping Xie: Standard Model physics at HE muon colliders

Higgs & EWSB:

Zhen Liu: Physics at Higgs factories

Xing Wang: SM Higgs couplings at a HE muon collider

Shufang Su: 2HDM at a HE muon collider

… …

DM & Leptons:

Lian-Tao Wang: WIMP DM at HE muon colliders

Rodolfo Capdevilla: Guaranteed discovery at muon colliders

Patrick Huber: Neutrino physics at the neutrino factory

… …

It's just beginning …

Muon colliders:

Table 1: Main parameters of the proton driver muon facilities

Parameter	**Units**	**Higgs**		**Multi-TeV**	
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13'500	37'500	200'000	820'000
Circumference	km	0.3	2.5	4.5	6
No. of IP's		1	2	2	2
Repetition Rate	Hz	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1	0.5	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	μm-rad	200	25	25	25
Norm. Long. Emittance, ε_{LN}	μm-rad	1.5	70	70	70
Bunch Length, σ_{S}	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Each topic deserves an hour talk …
Will only talk about the HE option.

Multi-TeV muon colliders

- New physics threshold → higher energies
- EW interactions → high luminosities

Lumi-scaling scheme:
keep constant event rate for **σ**~ 1/s

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

1 ab^{-1} /yr

Benchmark points: (aggressive choices)

$$\sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30 \text{ and } 100\ \text{TeV}, \quad \mathcal{L} = 1,\ 4,\ 10,\ 20,\ 90,\ \text{and } 1000\ \text{ab}^{-1}$$

Exciting opportunities for new physics!

European Strategy, arXiv:1910.11775;
arXiv:1901.06150; arXiv:2007.15684.

The rest of the talk:

- SM physics at ultra-high energies
- Precision Higgs physics
- Discovery of new heavy states:

  Heavy Higgs bosons

  WIMP (SUSY) Dark matter

TH, Yang Ma, Keping Xie, arXiv:2007.14300
TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204
TH, Z. Liu, L.T. Wang, X. Wang, arXiv:2009.11287
TH, S.L. Li, S. Su, W. Su, Y.-C. Wu, to appear

- EW physics at ultra-high energies:

$$\frac{v}{E}: \ \frac{v\ (250\ \text{GeV})}{20\ TeV} \approx \frac{\Lambda_{QCD}\ (300\ \text{MeV})}{20\ GeV}$$

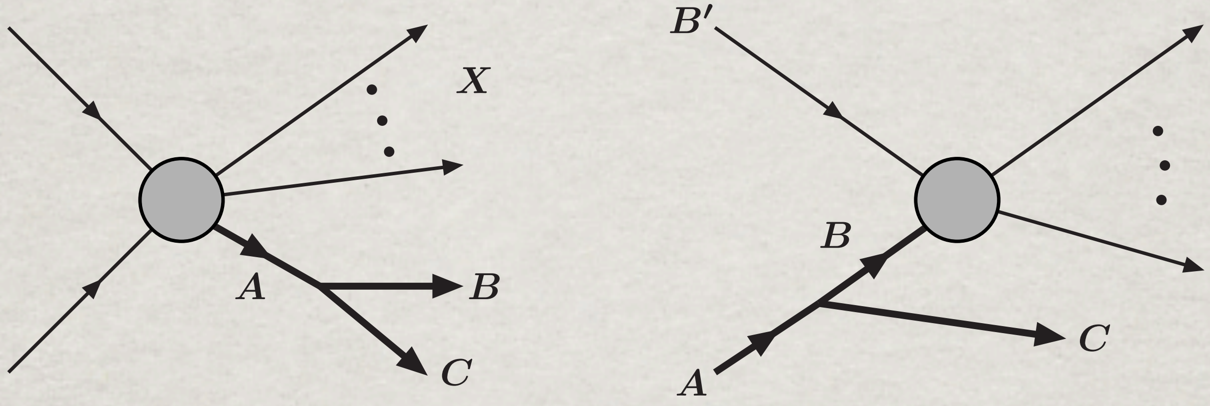
$$v/E,\ m_t/E,\ M_W/E \to 0!$$

- A massless theory:
  splitting phenomena dominate
- EW symmetry restored:
  $SU(2)_L$ x $U(1)_Y$ unbroken
- Goldstone boson Equivalence
  & its violation: $\epsilon(k)_L^\mu = \frac{E}{m_W}(\beta_W, \hat{k}) \approx \frac{k^\mu}{m_W}$ + $O(M_W/E)$

v/E power counting → Higher twist effects.

J. Chen, TH, B. Tweedie, arXiv:1611.00788;
G. Cuomo, A. Wulzer, arXiv:1703.08562; 1911.12366

EW splitting physics: the dominant phenomena at high energies



$$d\sigma_{X,BC} \simeq d\sigma_{X,A} \times d\mathcal{P}_{A\to B+C}$$

$$E_B \approx zE_A, \quad E_C \approx \bar{z}E_A, \quad k_T \approx z\bar{z}E_A\theta_{BC}$$

$$\frac{d\mathcal{P}_{A\to B+C}}{dz\, dk_T^2} \simeq \frac{1}{16\pi^2} \frac{z\bar{z}\,|\mathcal{M}^{(\mathrm{split})}|^2}{(k_T^2 + \bar{z}m_B^2 + zm_C^2 - z\bar{z}m_A^2)^2}$$

- On the dimensional ground: $|\mathcal{M}_{split}|^2 \sim k_T^2$ or m^2
- For the factorized formalism to be valid: infra-red safe & leading behavior: not guaranteed

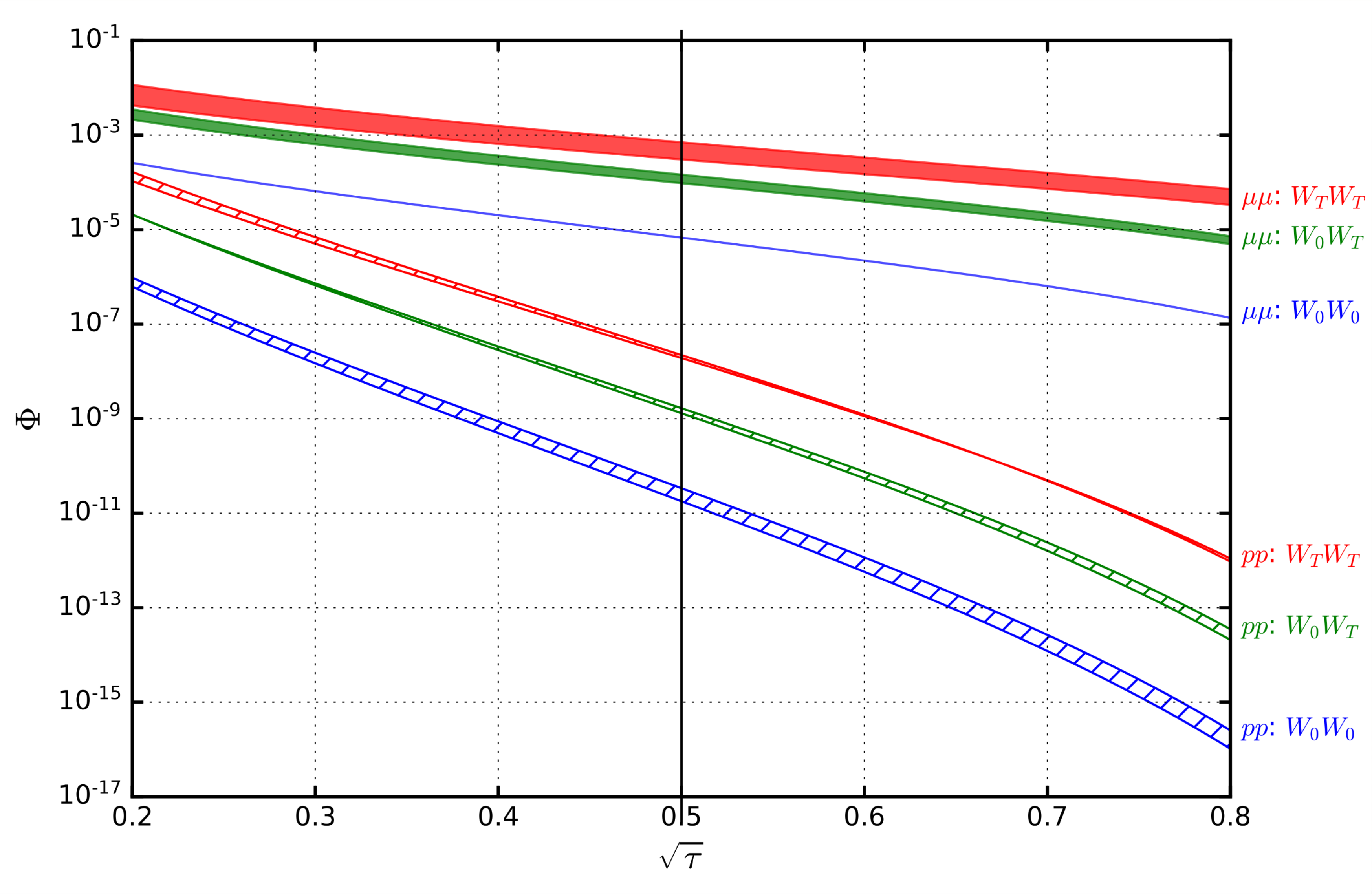
Ciafaloni et al., hep-ph/0004071; 0007096
C. Bauer, Ferland, B. Webber et al., arXiv:1703.08562; 1808.08831.
A. Manohar et al., 1803.06347.

VBF luminosities: μ-C versus pp

$$\Phi_{W^+_{\lambda_1} W^-_{\lambda_2}}(\tau,\mu_f) = \int_\tau^1 \frac{d\xi}{\xi}\ f_{W_{\lambda_1}/\mu}(\xi,\mu_f)\ f_{W_{\lambda_2}/\mu}\left(\frac{\tau}{\xi},\mu_f\right)$$

$$\Phi_{V_\lambda V'_{\lambda'}}(\tau,\mu_f) = \frac{1}{1+\delta_{V_\lambda V'_{\lambda'}}} \int_\tau^1 \frac{d\xi}{\xi} \int_{\tau/\xi}^1 \frac{dz_1}{z_1} \int_{\tau/\xi/z_1}^1 \frac{dz_2}{z_2} \sum_{q,q'} \tag{3.18}$$

$$\left[f_{V_\lambda/q}(z_2) f_{V'_{\lambda'}/q'}(z_1) f_{q/p}(\xi) f_{q'/p}\left(\frac{\tau}{\xi z_1 z_2}\right) + f_{V_\lambda/q}(z_2) f_{V'_{\lambda'}/q'}(z_1) f_{q/p}\left(\frac{\tau}{\xi z_1 z_2}\right) f_{q'/p}(\xi) \right].$$

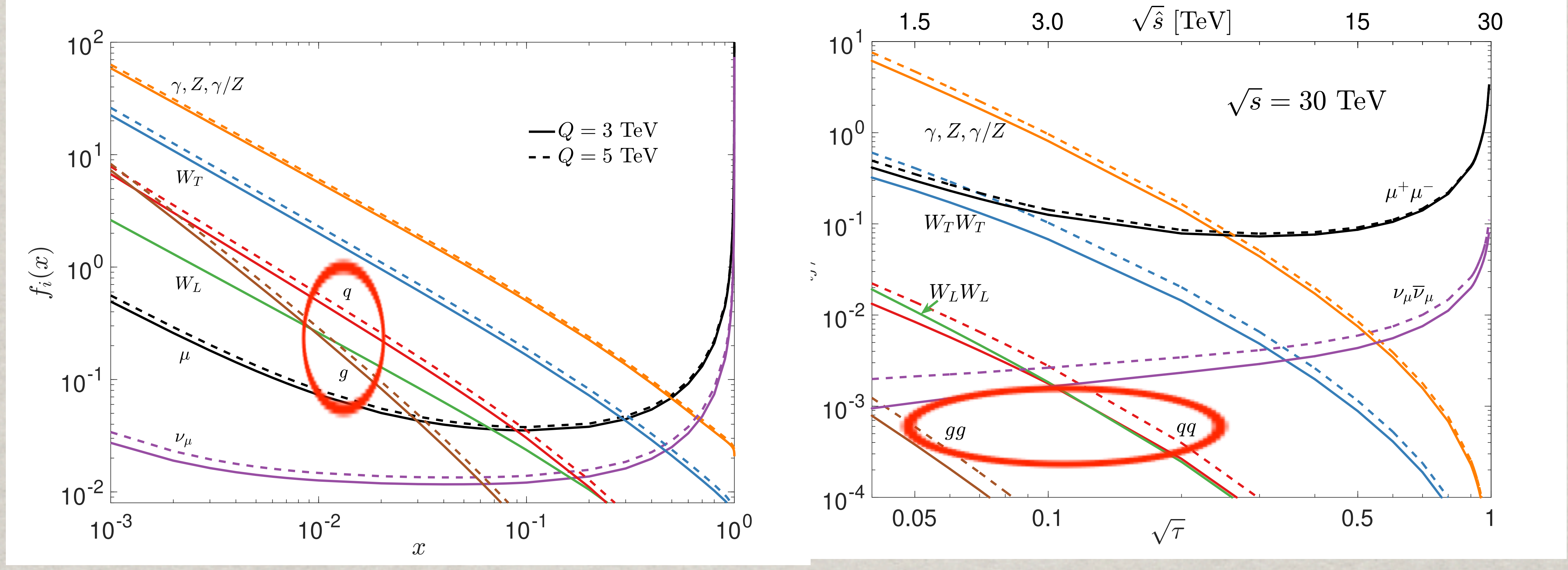


F. Maltoni, R. Ruiz et al., arXiv:2005.10289

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

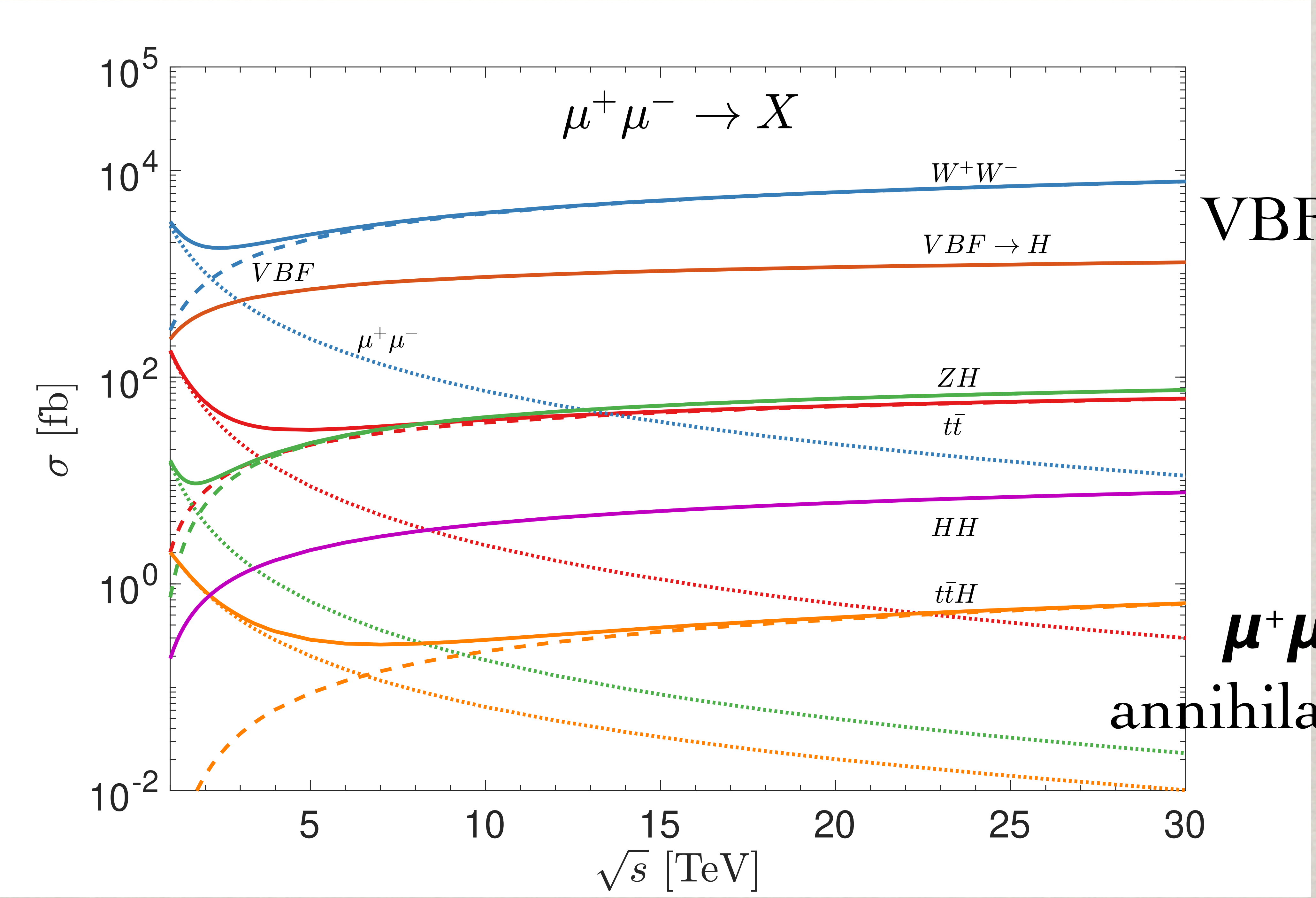
$$\frac{d\mathcal{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{d\xi}{\xi} \left[f_i(\xi, Q^2) f_j\left(\frac{\tau}{\xi}, Q^2\right) + (i \leftrightarrow j) \right]$$

- Coupled DGLAP Eqs under $SU(3)_c xSU(2)_L xU(1)_Y$
- Multiple scales: QED@ln(m_μ), Λ_{QCD} , EW@ln(M_W)



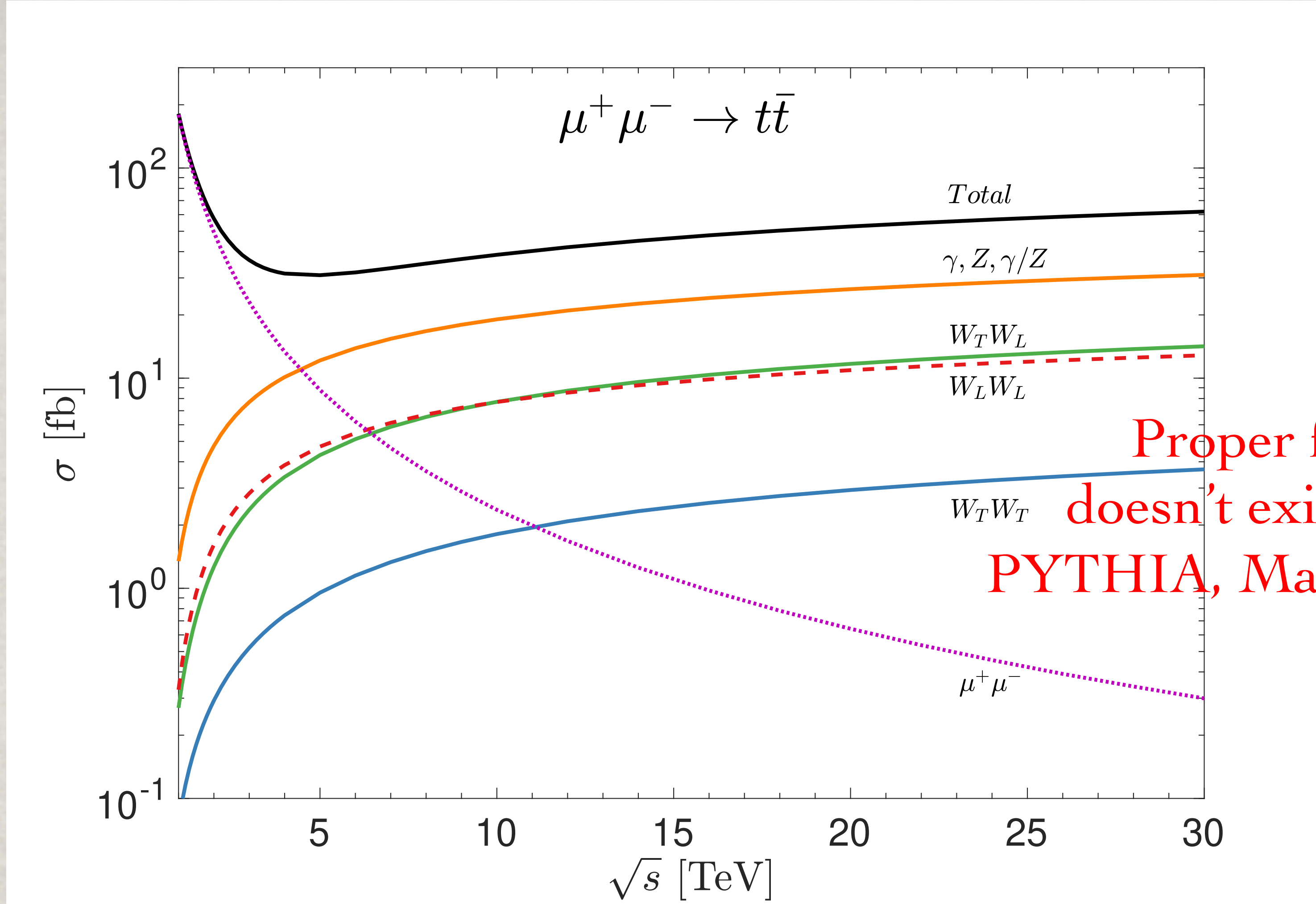
TH, Yang Ma, Keping Xie, arXiv:2007.14300

Semi-inclusive processes: Just like in hadronic collisions $\mu^+\mu^- \rightarrow$ exclusive particles + remnants

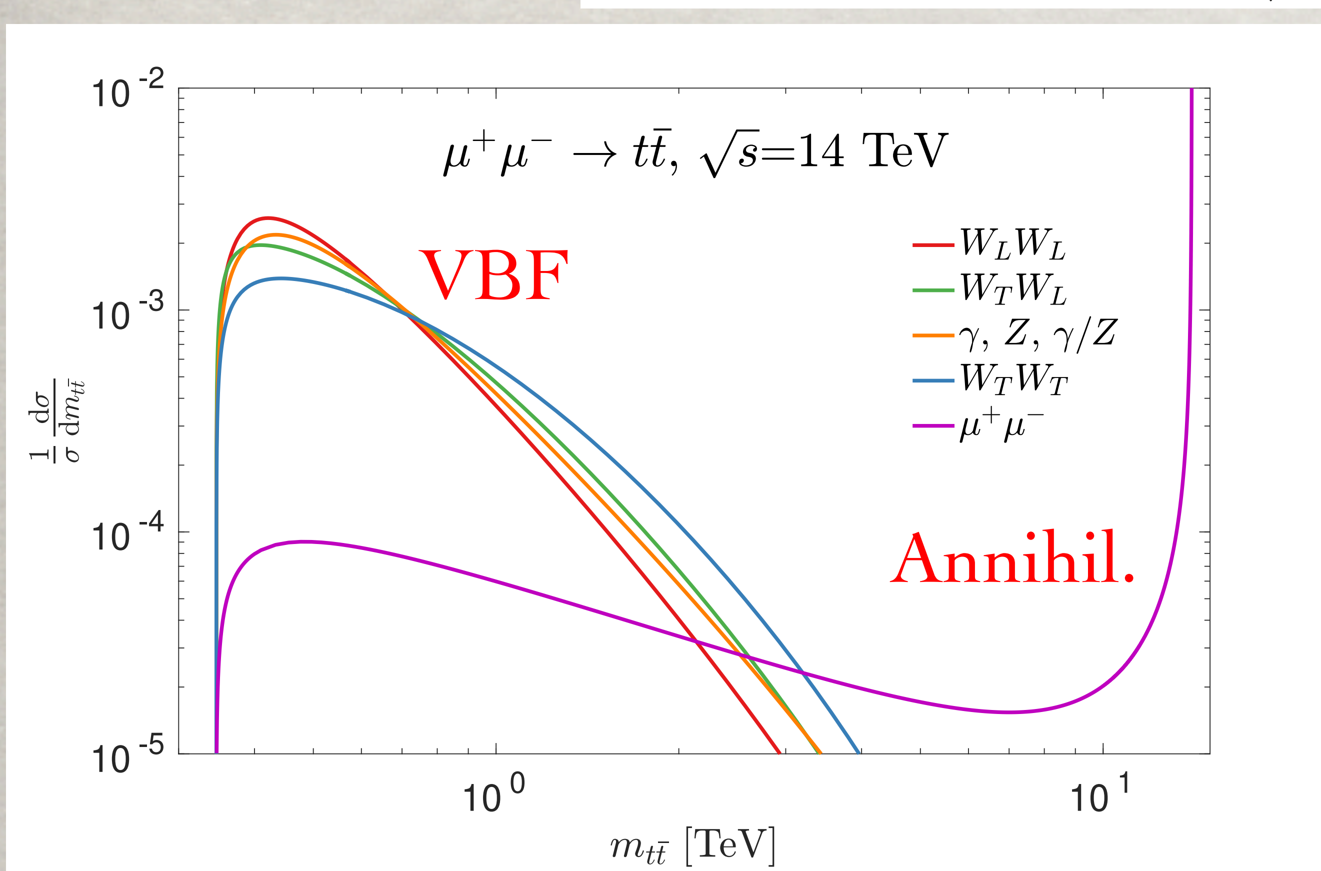


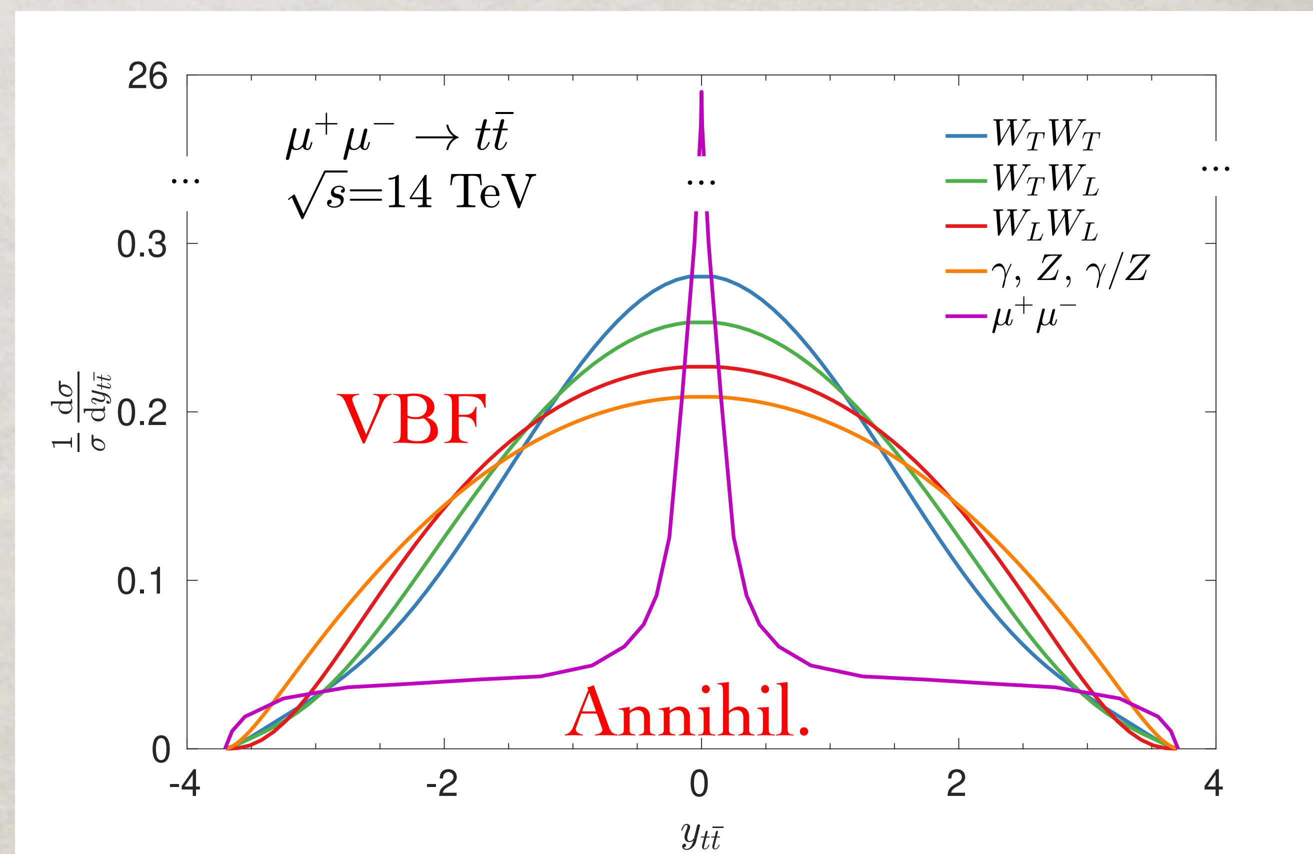
VBF

$\mu^+\mu^-$ annihilations



Proper formulation still
doesn't exist in the packages:
PYTHIA, MadGraph, WHIZARD





• Precision Higgs physics

$$\mu^+\mu^- \xrightarrow{\text{VBF}} H,\ ZH,\ HH \quad \text{and} \quad t\bar{t}H$$

10^4 fb^{-1}

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91
$WW \to ZH$	9.5	22	33	42	67
$WW \to t\bar{t}H$	0.012	0.046	0.090	0.14	0.28
$WW \to Z$	2200	3100	3600	4200	5200
$WW \to ZZ$	57	130	200	260	420

$$\mathcal{L} \supset \left(M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)\left(\kappa_V \frac{2H}{v} + \kappa_{V_2}\frac{H^2}{v^2}\right) - \frac{m_H^2}{2v}\left(\kappa_3 H^3 + \frac{1}{4v}\kappa_4 H^4\right)$$

$$\mathcal{O}_H = \frac{c_H}{2\Lambda^2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)\ , \qquad \mathcal{O}_6 = -\frac{c_6\lambda}{\Lambda^2}(\Phi^\dagger\Phi)^3$$

$$\Delta\kappa_V = -\frac{c_H}{2}\frac{v^2}{\Lambda^2}\ , \qquad \Delta\kappa_{V2} = -2c_H\frac{v^2}{\Lambda^2},$$

$$\Delta\kappa_3 \approx -\frac{3c_H}{2}\frac{v^2}{\Lambda^2} + c_6\frac{v^2}{\Lambda^2}\ , \qquad \Delta\kappa_4 \approx -\frac{25}{9}c_H\frac{v^2}{\Lambda^2} + 6c_6\frac{v^2}{\Lambda^2}$$

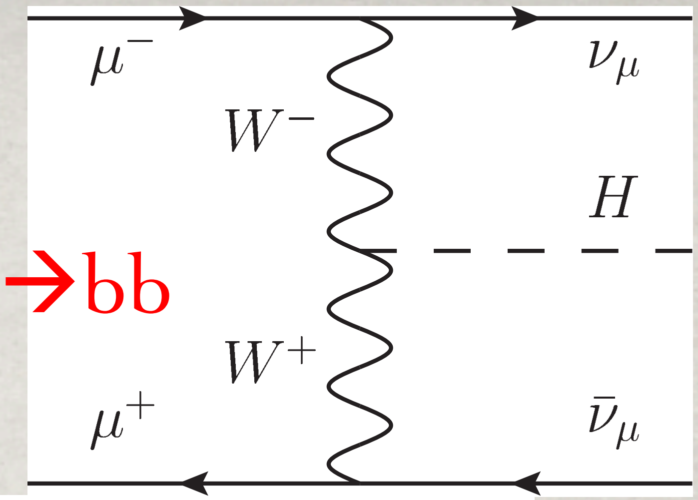
TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204

WWH / ZZH couplings:

$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu \; H \qquad (WW \text{ fusion}),$$

$$\mu^+\mu^- \to \mu^+\mu^- \; H \qquad (ZZ \text{ fusion}).$$

H→bb



$$10^\circ < \theta_{\mu^\pm} < 170^\circ. \qquad \Delta E/E = 10\%.$$

"adopt the inclusiveness"

$\theta_\mu \approx M_Z/E_\mu$

$\theta_\mu \sim 0.02 \approx 1.2^\circ$ at 10 TeV.

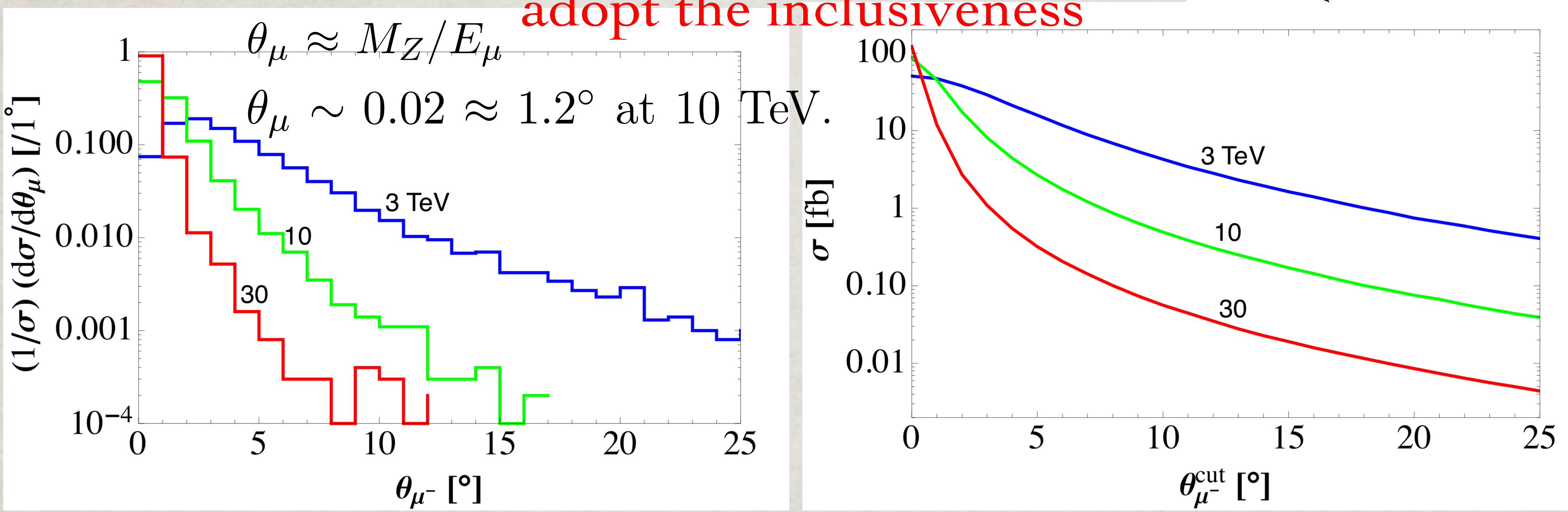
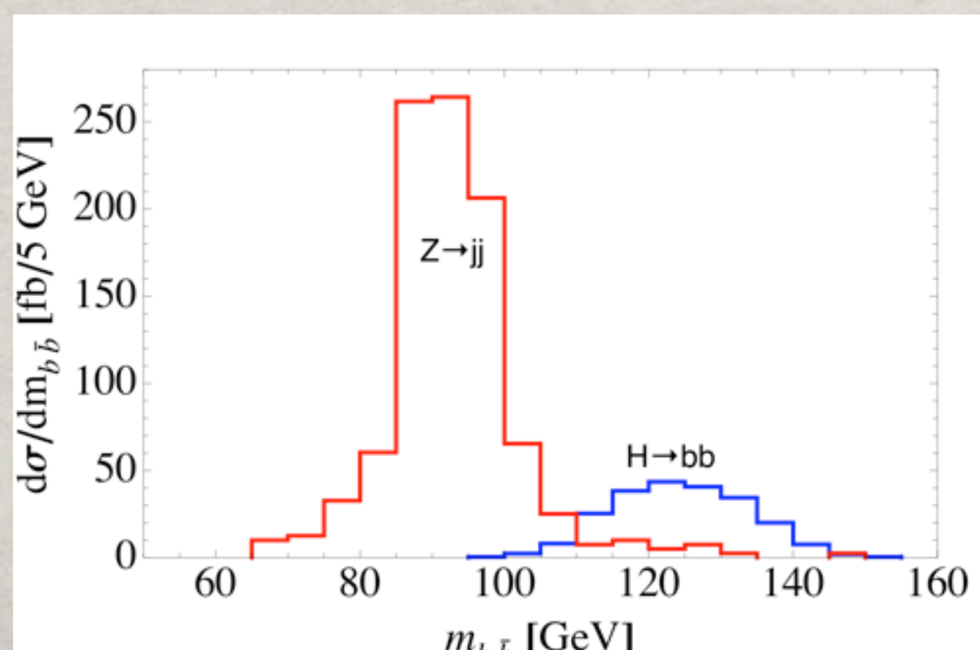
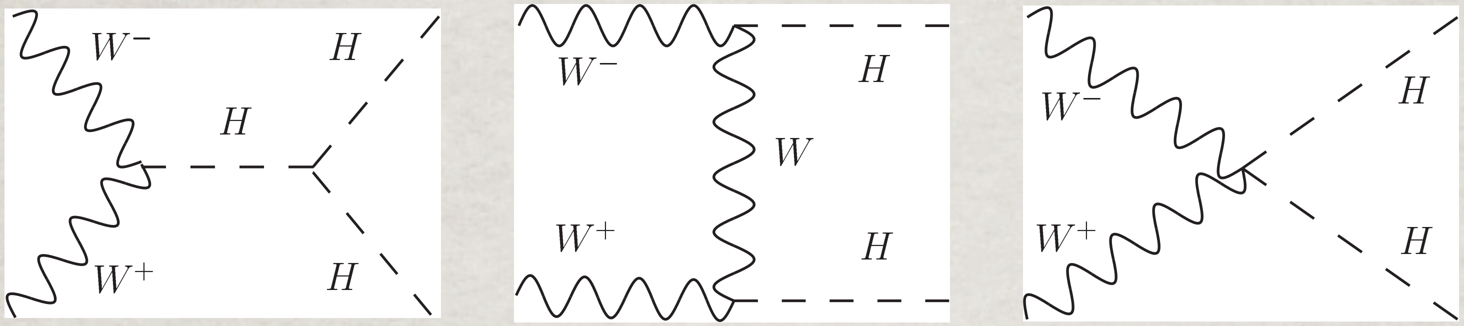


Figure 3: $\mu^+\mu^- \to \mu^+\mu^- H$ via ZZ fusion with $\sqrt{s} = 3, 10$ and 30 TeV for (a) angular distribution θ_{μ^-}, and (b) total cross section versus an angular cut $\theta^{\text{cut}}_{\mu^-}$.



$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$(\Delta\kappa_W)_{\text{in}}$	0.26%	0.12%	0.073%	0.050%	0.023%
$(\Delta\kappa_Z)_{\text{in}}$	2.4%	1.1%	0.65%	0.46%	0.20%
$(\Delta\kappa_Z)_{1\mu}$	1.7%	1.5%	1.5%	1.5%	1.5%

HHH / WWHH couplings:



(a) (b) (c)

HH→bb, bb

$$\sigma = \sigma_{\rm SM}\left[1 + r_1 \Delta\kappa_{W_2} + r_2 \Delta\kappa_3 + r_3 \Delta\kappa_{W_2}\Delta\kappa_3 + r_4 \left(\Delta\kappa_{W_2}\right)^2 + r_5 \left(\Delta\kappa_3\right)^2\right]$$

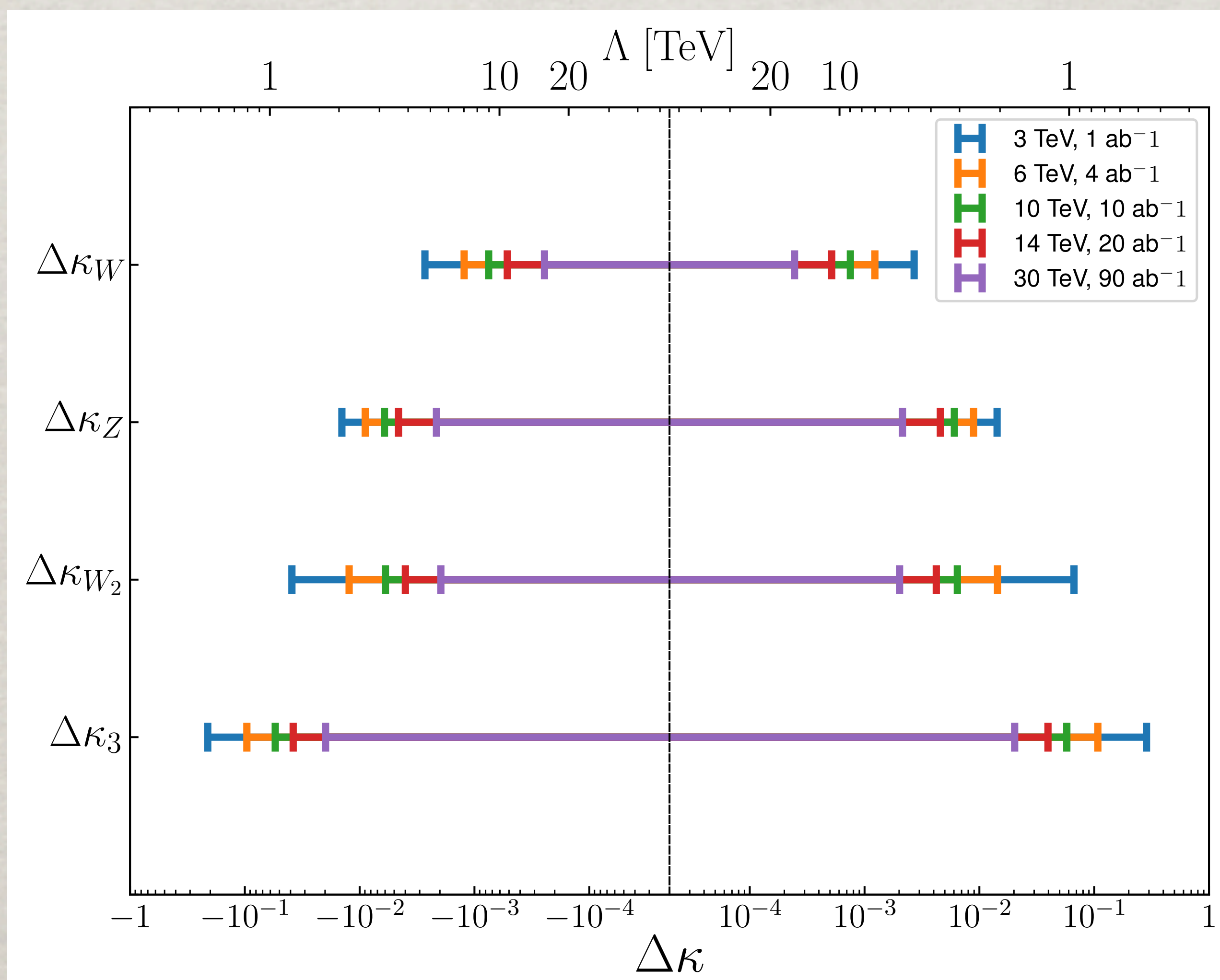
m_{HH} [GeV]	$\sigma_{\rm SM}$ [ab]	r_1	r_2	r_3	r_4	r_5
[0, 350)	15	−2.7	−1.7	7.6	6.7	2.6
[350, 450)	24	−3.4	−1.2	5.2	7.8	0.95
[450, 550)	24	−4.0	−0.91	4.6	12	0.52
[550, 650)	21	−4.6	−0.70	4.7	17	0.36
[650, 750)	17	−5.3	−0.60	5.1	26	0.28
[750, 950)	24	−6.9	−0.52	6.3	46	0.23
[950, 1350)	23	−11	−0.47	8.7	120	0.19
[1350, 5000)	15	−18	−0.30	7.2	240	0.075

TABLE V: Cross sections of the inclusive $\mu^+\mu^- \to HH + X \to b\bar{b}\, b\bar{b} + X$ in different m_{HH} ranges as the coefficients corresponding to the five terms in Eq. (25) with $\sqrt{s} = 10$ TeV.

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$(\Delta\kappa_{W_2})_{\rm in}$	5.3%	1.3%	0.62%	0.41%	0.20%
$(\Delta\kappa_3)_{\rm in}$	25%	10%	5.6%	3.9%	2.0%

$\sqrt{s}$ (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]	CLIC
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)	
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.[illegible]6%	0.21%	0.13% [17]	CEPC
$\Lambda/\sqrt{c_i}$ (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]	CLIC
$\Lambda/\sqrt{c_i}$ (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]	FCC-hh
$\Lambda/\sqrt{c_i}$ (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 [illegible]plings at a variety of muon collider collider energies and luminosities.



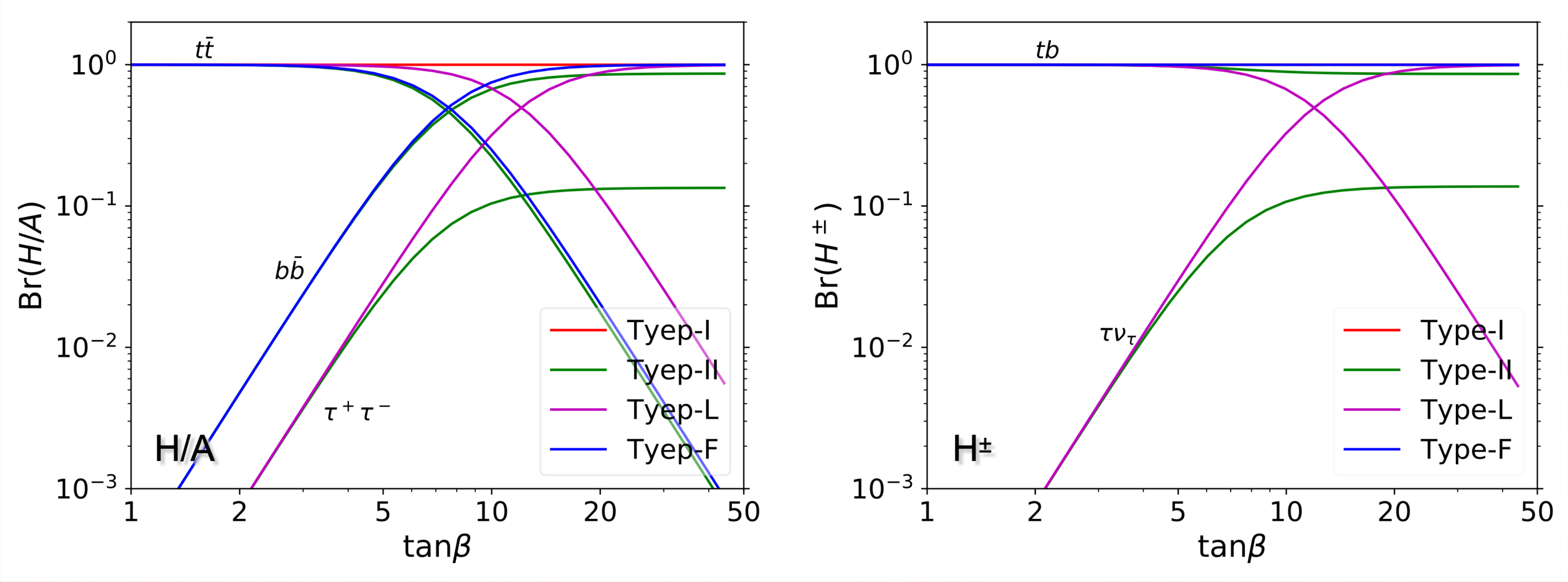
• Heavy Higgs bosons in 2HDM

after EWSB, 5 physical Higgses

CP-even Higgses: h, H , CP-odd Higgs: A, Charged Higgses: H±

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

Types	Φ_1	Φ_2	κ_A^u	κ_A^d	κ_A^e
Type-I		$u,\ d,\ \ell$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	$d,\ \ell$	u	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-L	ℓ	$u,\ d,$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-F	d	$u,\ \ell$	$\cot\beta$	$\tan\beta$	$-\cot\beta$



TH, S.L. Li, S. Su, W. Su, Y.-C. Wu, to appear

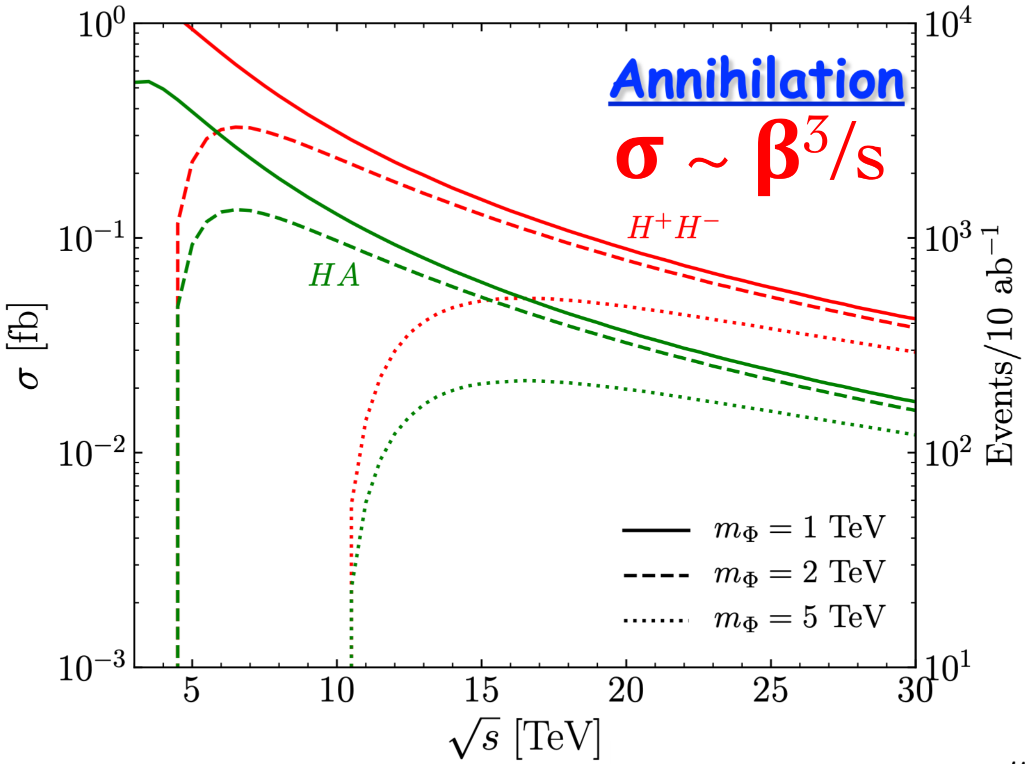
Pair production

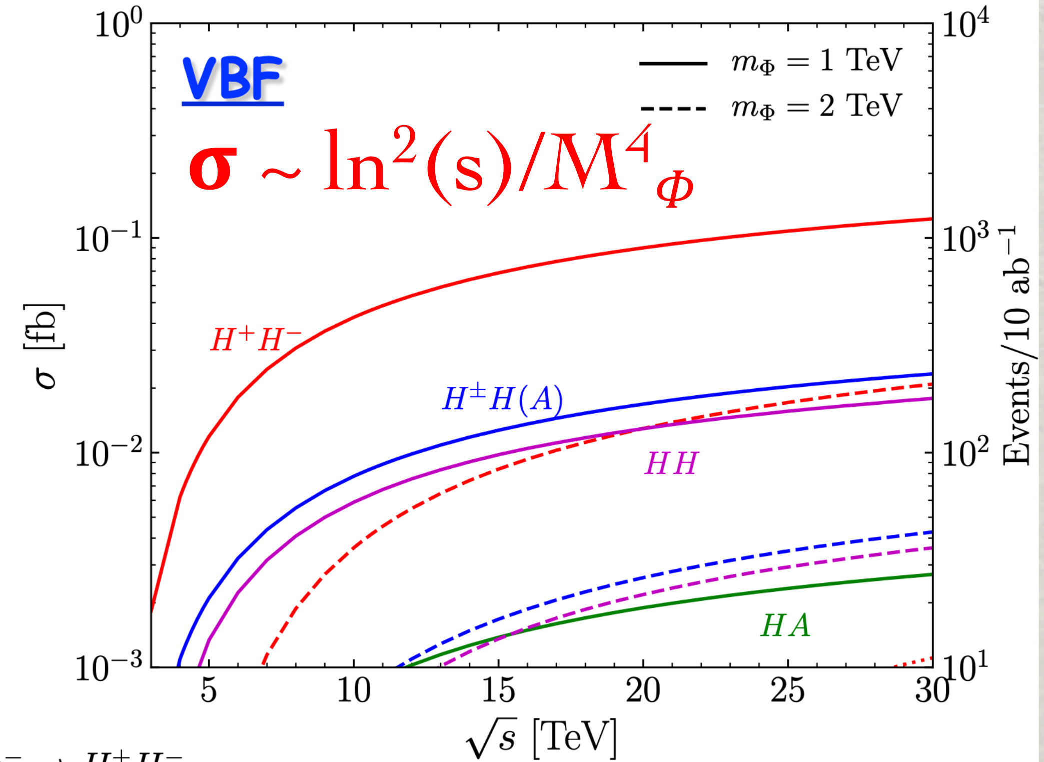
Annihilation

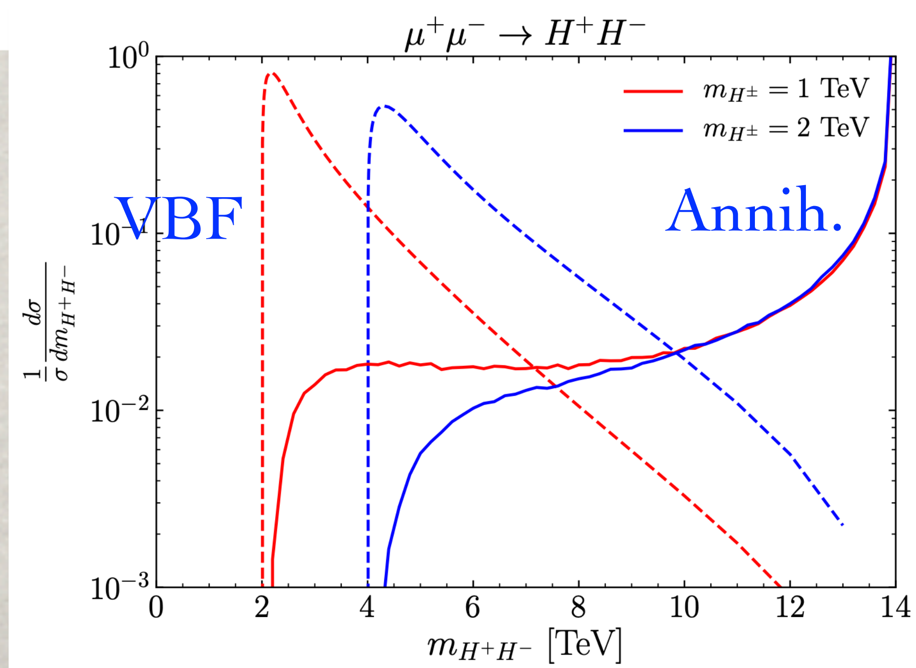
$$\mu^+\mu^- \to \gamma^*, Z^* \to H^+H^-$$
$$\mu^+\mu^- \to Z^* \to HA$$

VBF

$$\mu^+\mu^- \to V_1V_2 \to$$
$$H^+H^-,\ HA,\ H^\pm H(A), HH/AA$$







Discriminating 2HDM models:

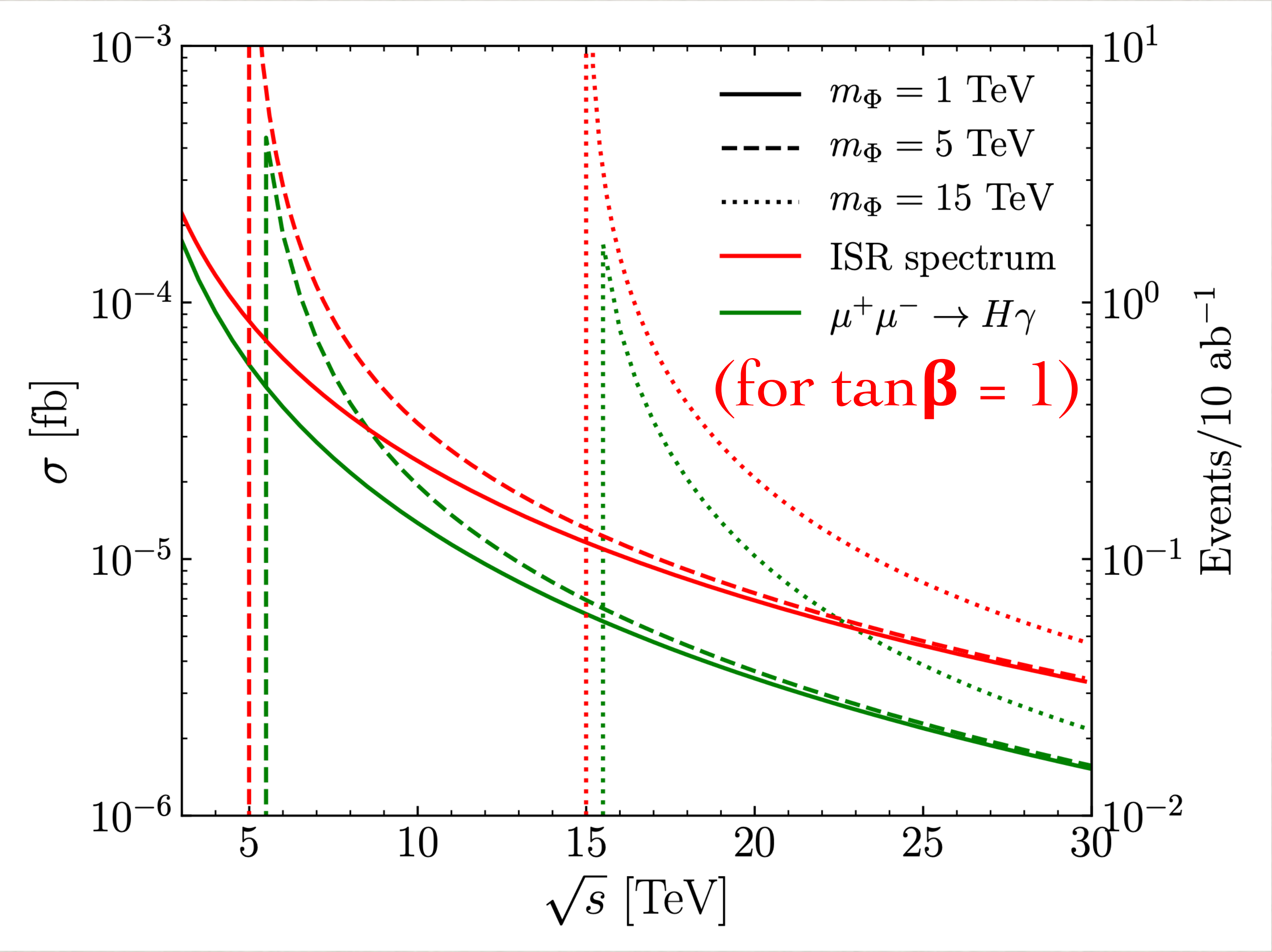
<table>
<tr><th></th><th>production</th><th>Type-I</th><th>Type-II</th><th>Type-F</th><th>Type-L</th></tr>
<tr><td rowspan="3">small $\tan\beta < 5$</td><td>H^+H^-</td><td colspan="4">$t\bar{b}, \bar{t}b$</td></tr>
<tr><td>$HA/HH/AA$</td><td colspan="4">$t\bar{t}, t\bar{t}$</td></tr>
<tr><td>$H^\pm H/A$</td><td colspan="4">$tb, t\bar{t}$</td></tr>
<tr><td rowspan="3">intermediate $\tan\beta$</td><td>H^+H^-</td><td colspan="3">$t\bar{b}, \bar{t}b$</td><td>$tb, \tau\nu_\tau$</td></tr>
<tr><td>$HA/HH/AA$</td><td>$t\bar{t}, t\bar{t}$</td><td colspan="2">$t\bar{t}, b\bar{b}$</td><td>$t\bar{t}, \tau^+\tau^-$</td></tr>
<tr><td>$H^\pm H/A$</td><td>$tb, t\bar{t}$</td><td colspan="2">$tb, t\bar{t};\ tb, b\bar{b}$</td><td>$tb, t\bar{t};\ tb, \tau^+\tau^-;$
$\tau\nu_\tau, t\bar{t};\ \tau\nu_\tau, \tau^+\tau^-$</td></tr>
<tr><td rowspan="3">large $\tan\beta > 10$</td><td>H^+H^-</td><td>$t\bar{b}, \bar{t}b$</td><td>$tb, tb(\tau\nu_\tau)$</td><td>$t\bar{b}, \bar{t}b$</td><td>$\tau^+\nu_\tau, \tau^-\nu_\tau$</td></tr>
<tr><td>$HA/HH/AA$</td><td>$t\bar{t}, t\bar{t}$</td><td>$b\bar{b}, b\bar{b}(\tau^+\tau^-)$</td><td>$b\bar{b}, b\bar{b}$</td><td>$\tau^+\tau^-, \tau^+\tau^-$</td></tr>
<tr><td>$H^\pm H/A$</td><td>$tb, t\bar{t}$</td><td>$tb(\tau\nu_\tau), b\bar{b}(\tau^+\tau^-)$</td><td>$tb, b\bar{b}$</td><td>$\tau^\pm\nu_\tau, \tau^+\tau^-$</td></tr>
</table>

Table 6. leading signal channels of Higgs pair production for various 2HDMs in different regions of small, intermediate and large $\tan\beta$. Channels in the parenthesis are the sub-leading channels.

Radiative returns: Pushing the heavy mass reach

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

$$\sigma = 2\int dx_1 f_{\ell/\ell}(x_1)\hat{\sigma}(\tau = x_1) = \frac{\alpha Y_\mu^2}{4s}\frac{s + m_H^4/s}{s - m_H^2}\log\frac{s}{m_\mu^2}$$



• WIMP (SUSY) DM

Consider the "minimal EW dark matter":
The lightest neutral component in an EW multi-plet

- Interactions well defined → pure gauge
- Mass upper limit predicted → thermal relic abundance

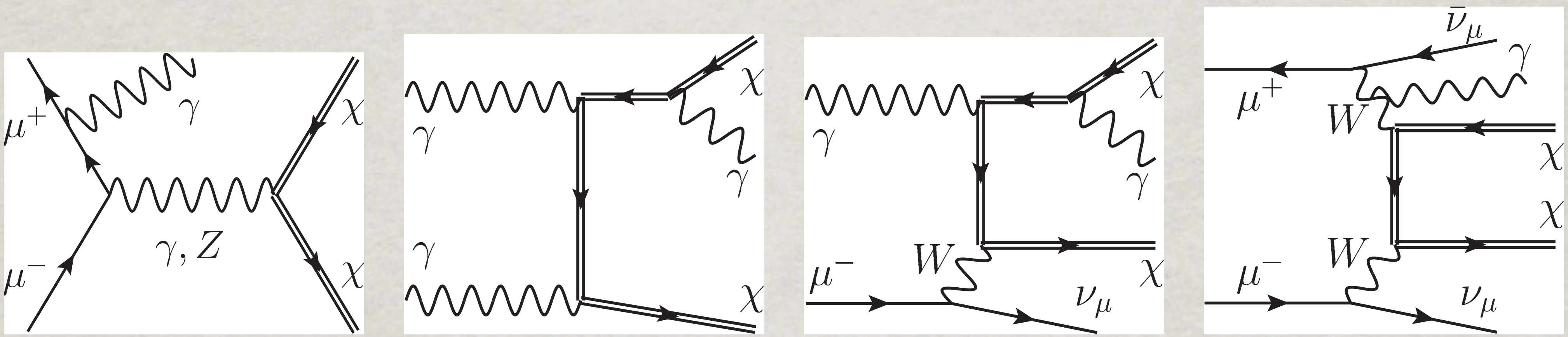
$SU(3)_c x SU(2)_L x U(1)_Y$

Model (color, n, Y)		Therm. target	5σ discovery coverage (TeV)			
			mono-γ	mono-μ	di-μ's	disp. tracks
(1,2,1/2)	Dirac	1.1 TeV	—	2.8	—	1.8 – 3.7
(1,3,0)	Majorana	2.8 TeV	—	3.7	—	13 – 14
(1,3,ϵ)	Dirac	2.0 TeV	0.9	4.6	—	13 – 14
(1,5,0)	Majorana	11 TeV	3.1	7.0	3.1	10 – 14
(1,5,ϵ)	Dirac	6.6 TeV	6.9	7.8	4.2	11 – 14
(1,7,0)	Majorana	23 TeV	11	8.6	6.1	8.1 – 12
(1,7,ϵ)	Dirac	16 TeV	13	9.2	7.4	8.6 – 13

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

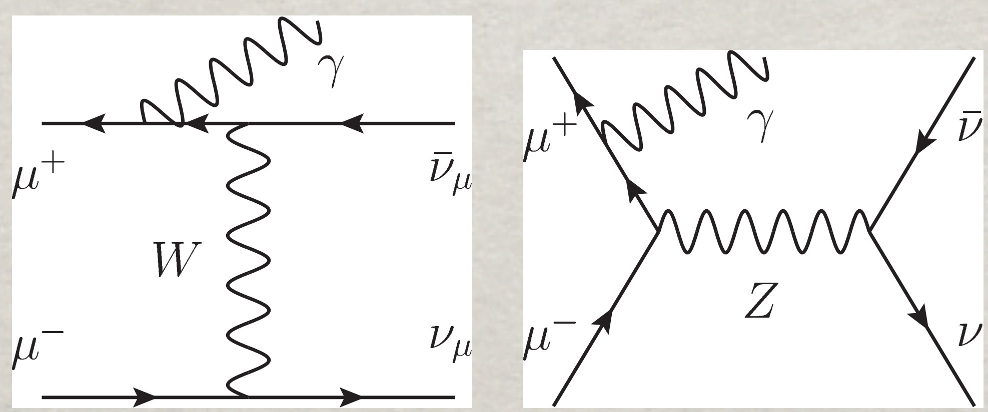
Mono-photon signal: A single photon against missing particles

$$\mu^+\mu^- \to \gamma\chi\chi \quad \text{via annihilation } \mu^+\mu^- \to \chi\chi,$$
$$\gamma\gamma \to \gamma\chi\chi \quad \text{via } \gamma\gamma \to \chi\chi,$$
$$\gamma\mu^\pm \to \gamma\nu\chi\chi \quad \text{via } \gamma W \to \chi\chi,$$
$$\mu^+\mu^- \to \gamma\nu\nu\chi\chi \quad \text{via } WW \to \chi\chi \text{ and } \mu^+\mu^- \to \chi\chi Z.$$



(a) (b) (c) (d)

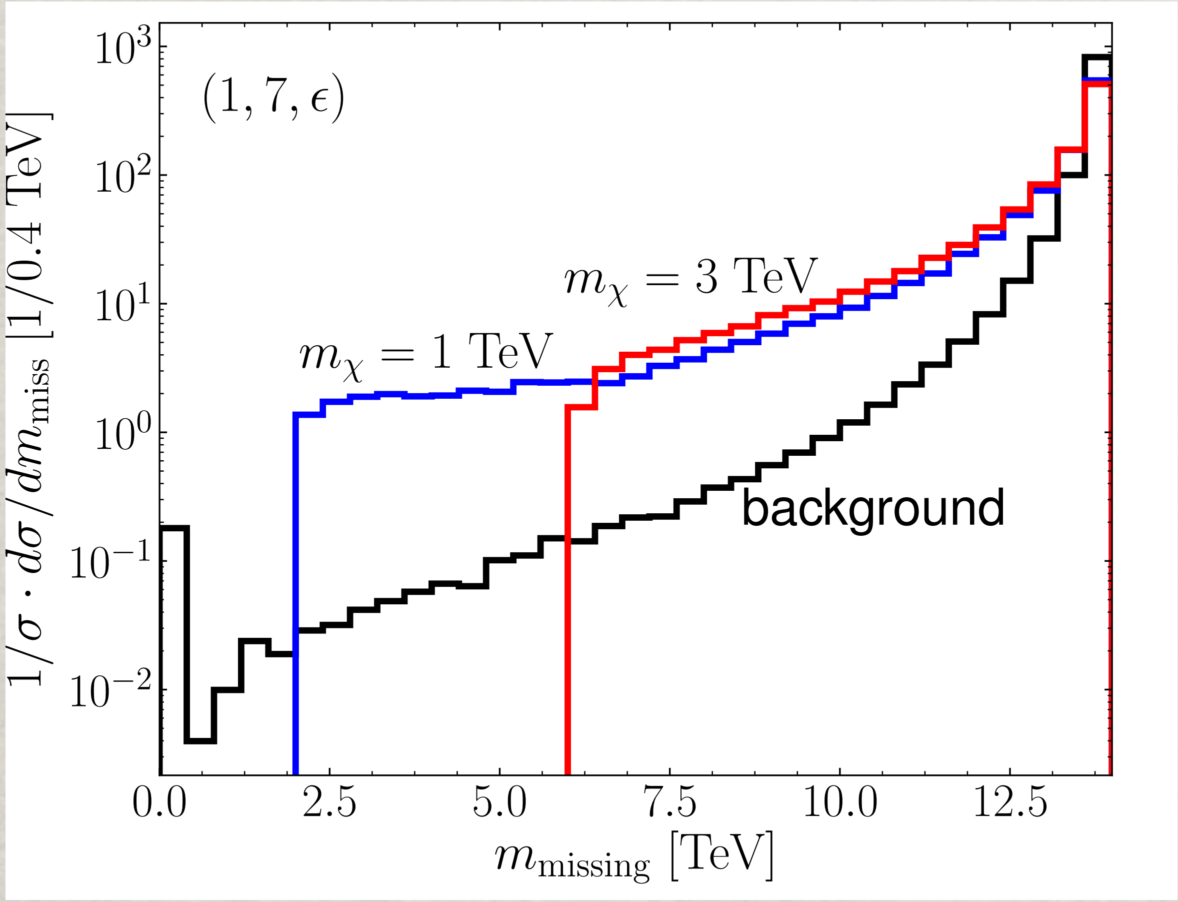
Key feature: "missing mass" $m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$

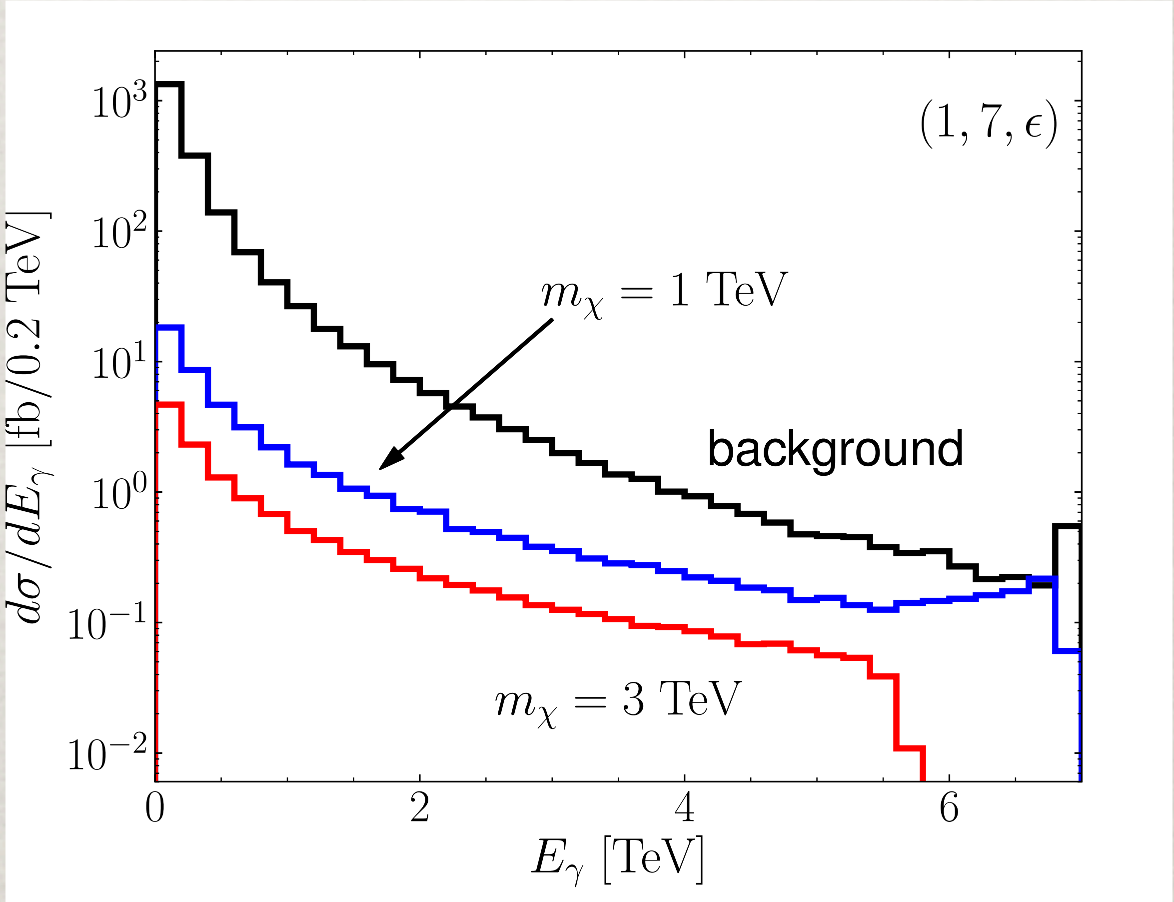


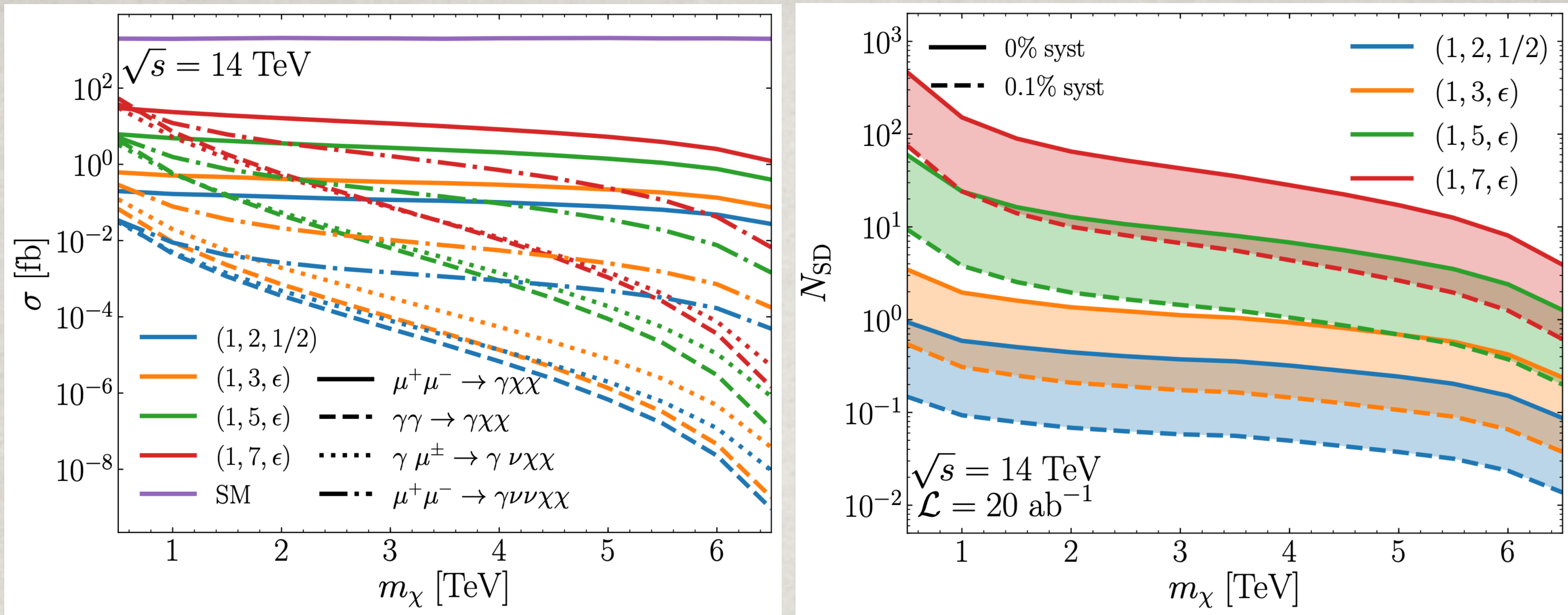
(a) (b)

$$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > 4m^2_\chi$$

$$\mathrm{E}_\gamma < (s - 4m^2_\chi)/2\sqrt{s},$$

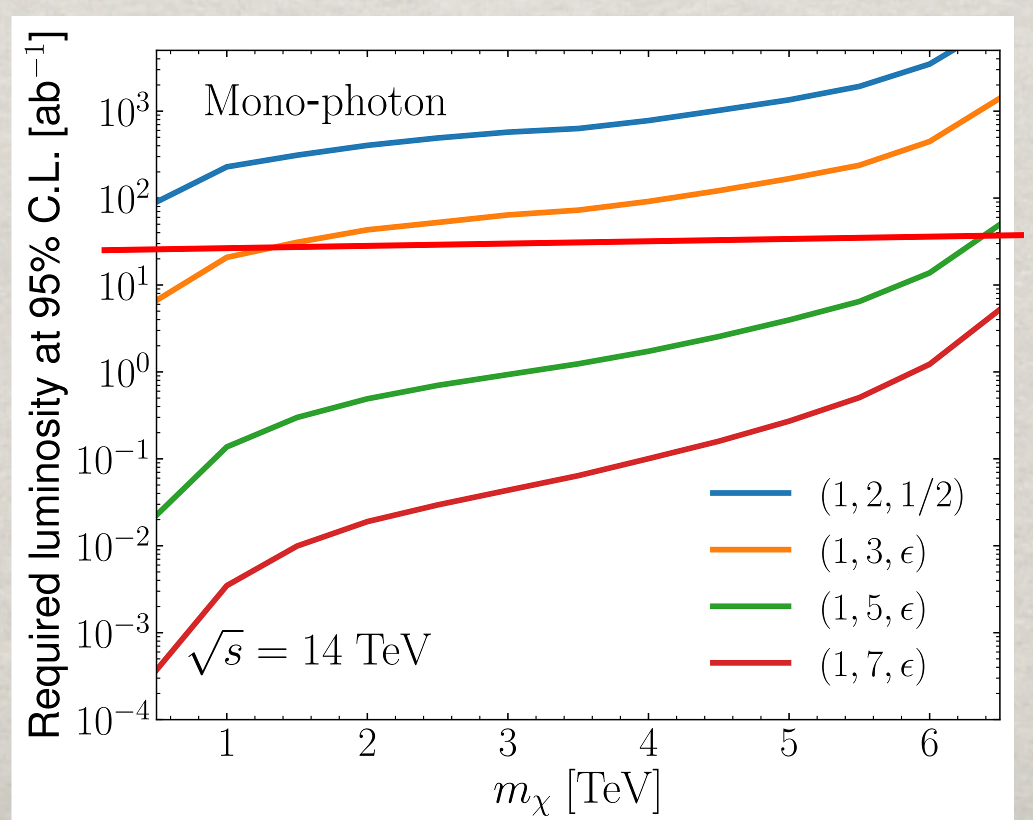






(a) (b)

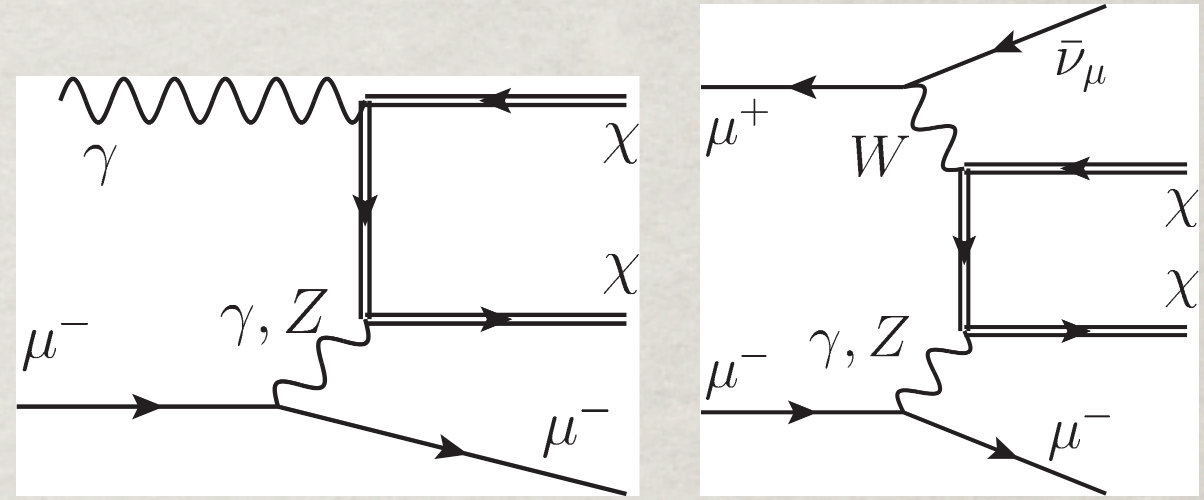
Figure 3: (a) Total cross section and (b) the significance defined in Equation 3.9 for a pair of EW multiplets plus a mono-photon at a muon collider with $\sqrt{s} = 14$ TeV. In (b) the solid and dashed lines correspond to the systematic uncertainties of 0% and 0.1%, respectively.



Mono-muon signal:
A single muon against missing particles

$$\gamma\,\mu^\pm \to \mu^\pm \chi\chi \quad \text{via} \quad \gamma Z \to \chi\chi,$$
$$\mu^+\mu^- \to \mu^\pm \nu\chi\chi \quad \text{via} \quad \gamma W, ZW \to \chi\chi,$$

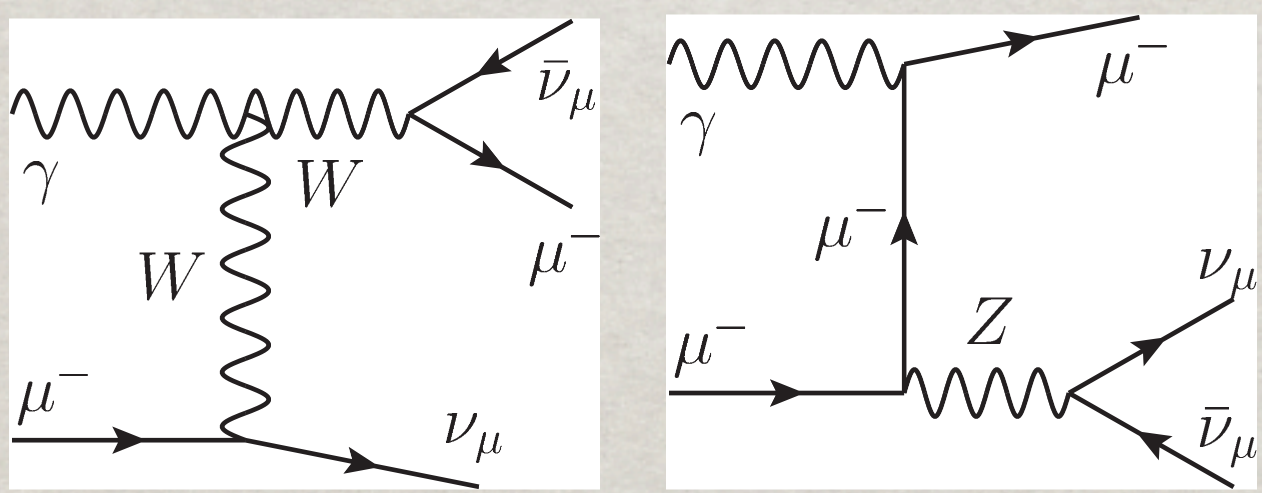
$$10^\circ < \theta_{\mu^-} < 90^\circ, \quad 90^\circ < \theta_{\mu^+} < 170^\circ$$



(a) (b)

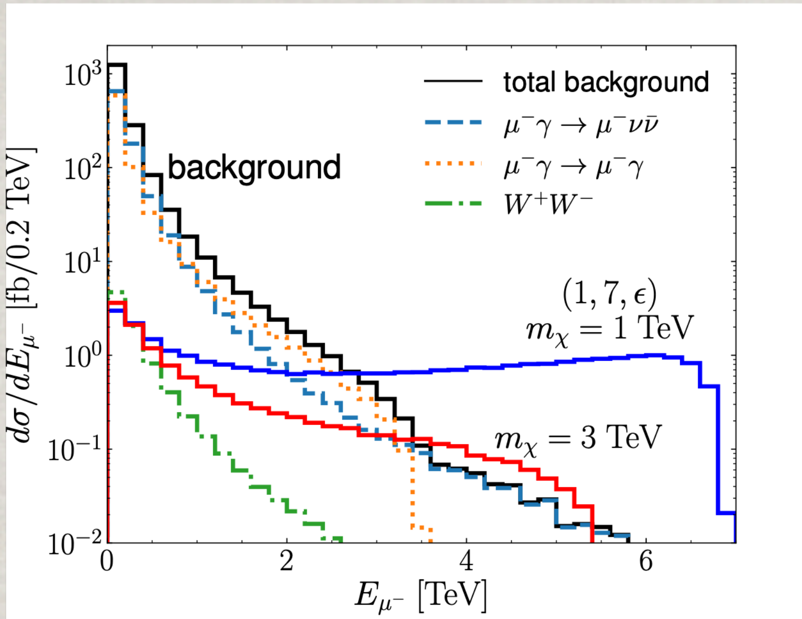
Again, large missing mass: $m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$

SM backgrounds: $\gamma\,\mu^\pm \to \mu^\pm \nu\bar{\nu},$

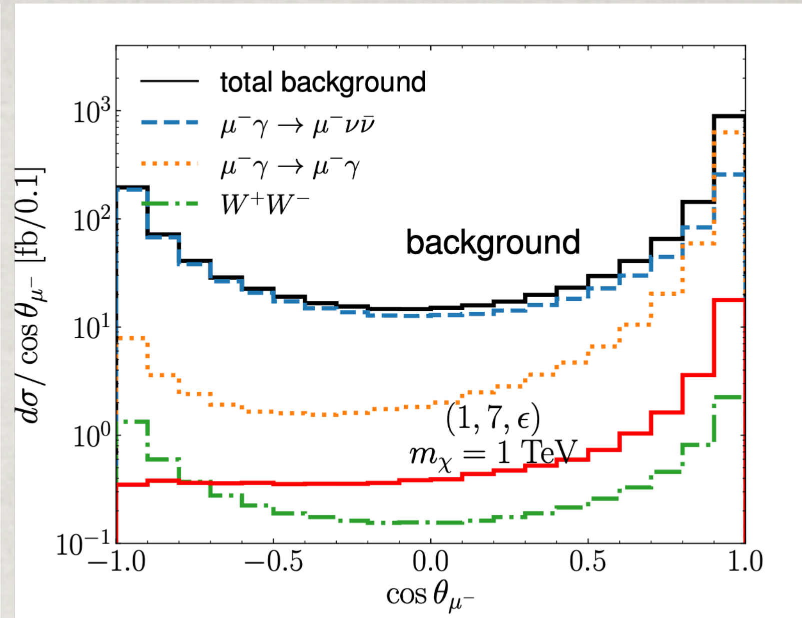


(a) (b)

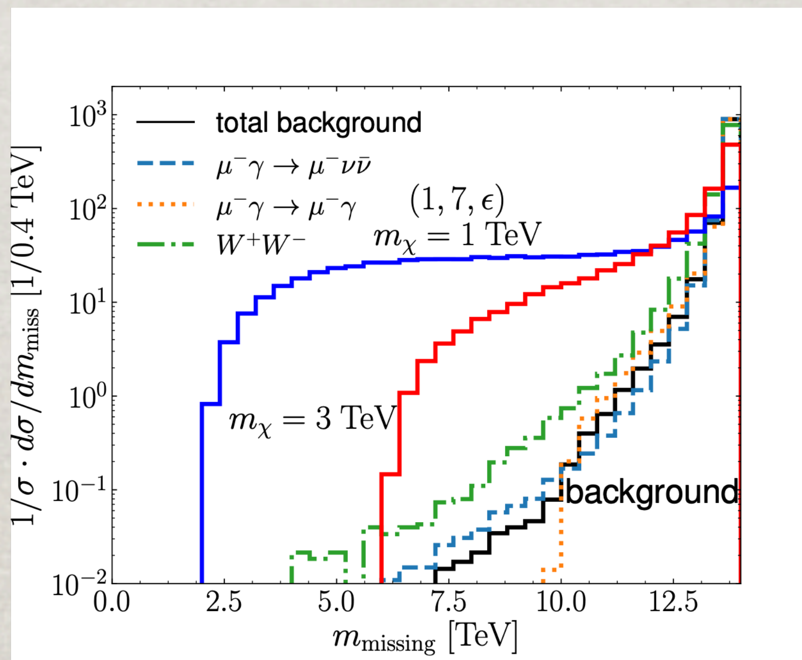
As well as $\gamma\,\mu^\pm \to \gamma\,\mu^\pm$ with a γ gone missing



(a)



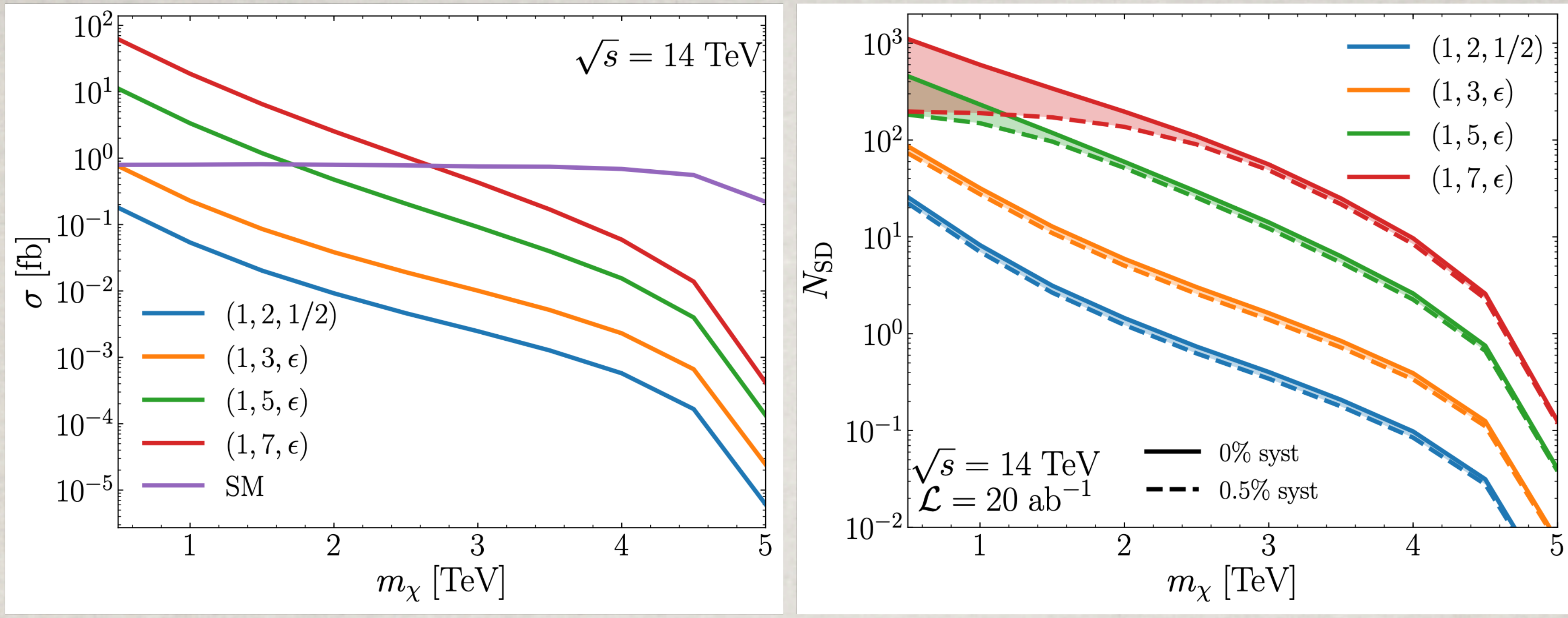
(b)



$$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > 4m^2_\chi$$

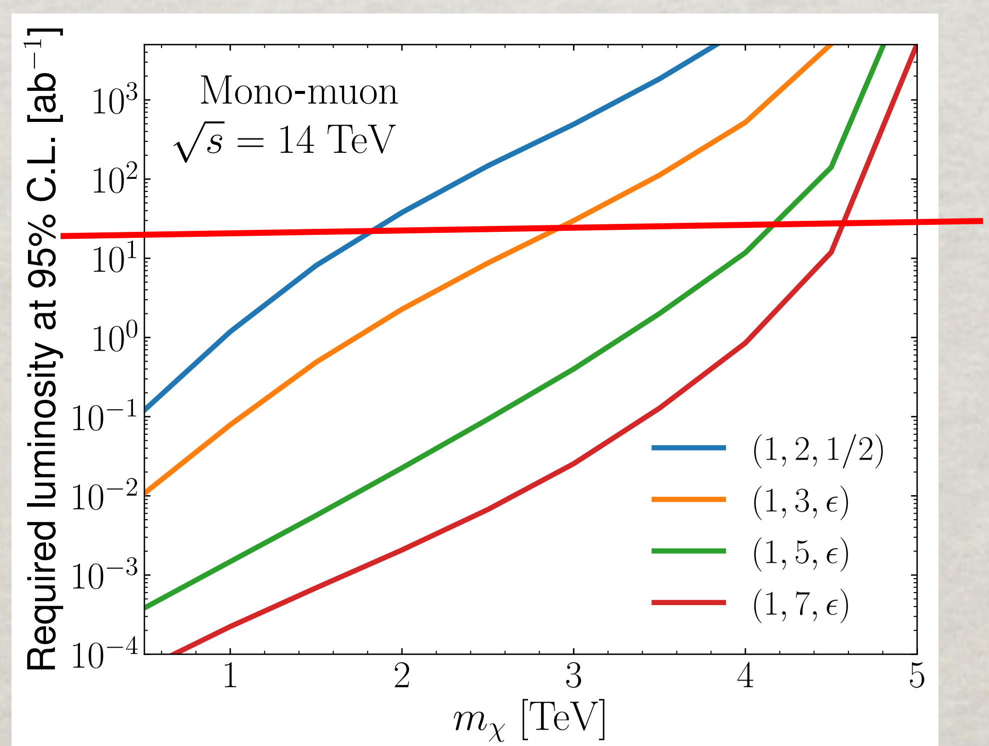
(c)

Figure 8: (a) The energy distributions of the μ^- at $\sqrt{s} = 14$ TeV, for the backgrounds and two representative benchmarks for 7-plet $(1, 7, \epsilon)$ with $m_\chi = 1$ TeV (blue) and 3 TeV (red), respectively; (b) the angular distributions of the μ^- at $\sqrt{s} = 14$ TeV, for the backgrounds and 7-plet $(1, 7, \epsilon)$ (red) with $m_\chi = 1$ TeV; (c) normalized missing-mass distributions for the signals and backgrounds.



(a) (b)

Figure 9: (a) Total cross section and (b) the significance defined in Equation 3.9 for a pair of EW multiplets plus a mono-muon at a muon collider with $\sqrt{s} = 14$ TeV. In (b), the solid and dashed lines correspond to the systematic uncertainties of 0% and 0.5%, respectively.



Missing-track signal for LLP: A single photon plus missing tracks

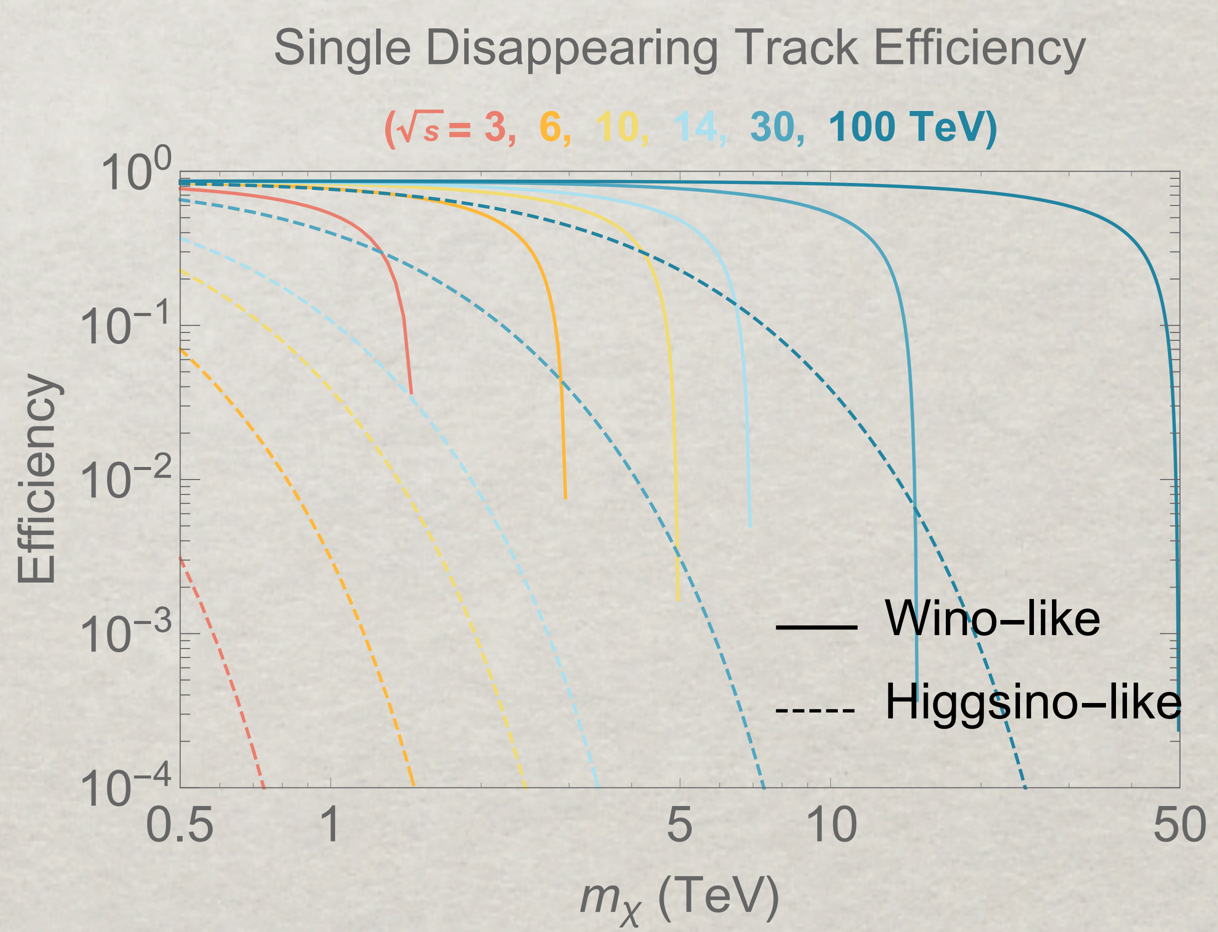
$$\delta m = \frac{g^2}{4\pi} m_W \sin^2 \frac{\theta_W}{2} \approx 160\text{–}170 \text{ MeV}.$$

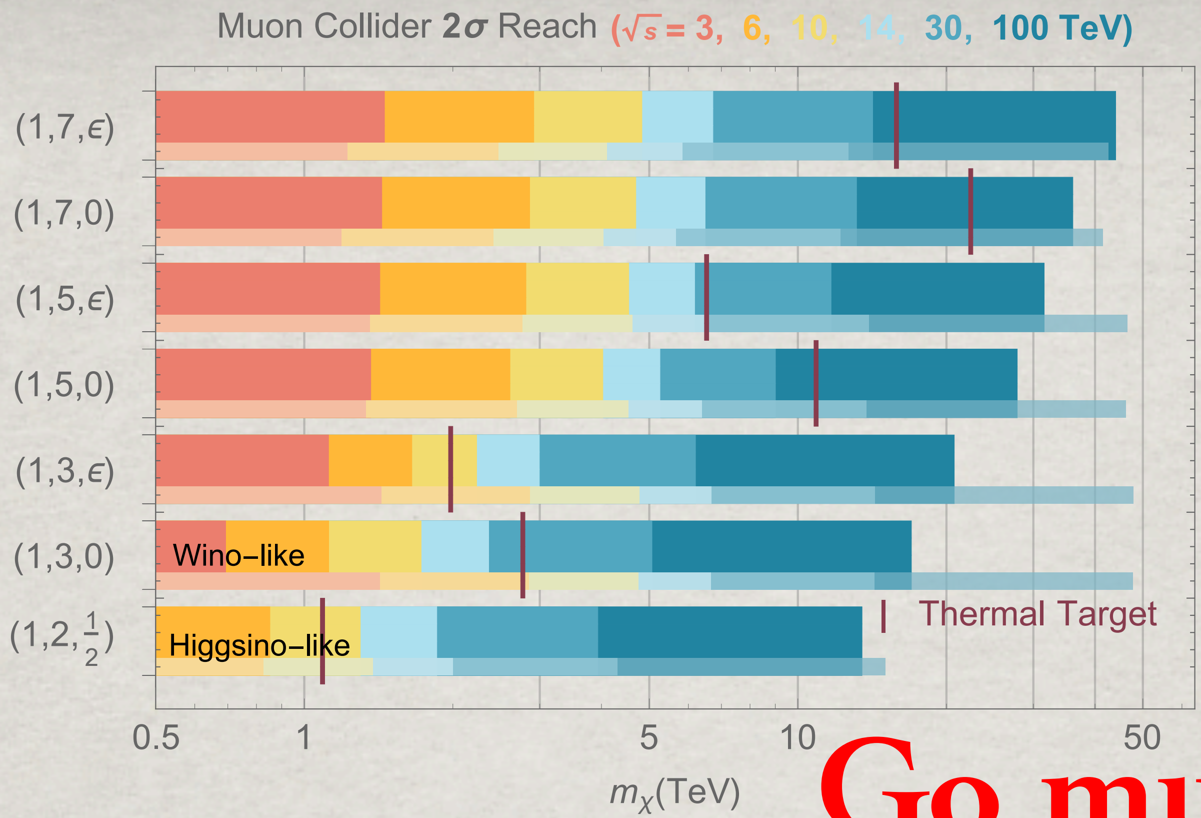
$$c\tau(\chi^Q \to \chi^{Q-1}\pi^+) \simeq c\tau(\pi^\pm)\frac{\kappa_W m_\pi m_\mu^2}{16\Delta m_{Q,Q-1}^3}\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2\left(1 - \frac{m_\pi^2}{\Delta m_{Q,Q-1}^2}\right)^{-1/2}$$

$$= 5.7\kappa_W \left(1 - \frac{m_\pi^2/(134\text{ MeV})^2}{\Delta m_{Q,Q-1}^2/(165\text{ MeV})^2}\right)^{-1/2}\left(\frac{165\text{ MeV}}{\Delta m_{Q,Q-1}}\right)^3 \text{ cm}$$

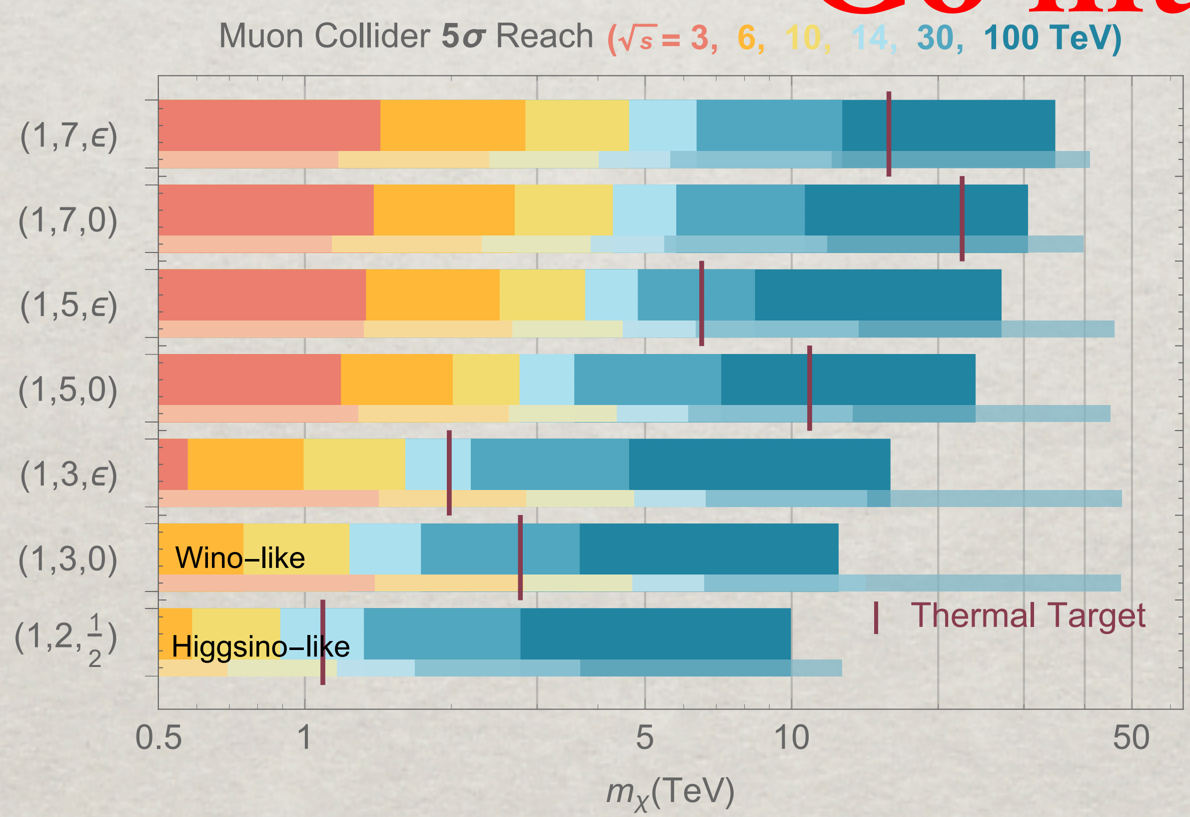
$$\epsilon_\chi(\cos\theta, \gamma, d_T^{\min}) = \exp\left(\frac{-d_T^{\min}}{\beta_T \gamma c\tau}\right)$$

with a reconstruction cut $d_T^{\min} = 5$ cm





Go muon collider!



possible to cover the thermal targets of doublet and triplet with a 10 TeV muon collider. Higher energies, 14 TeV–75 TeV, would ensure a 5σ reach above the thermal targets for the higher EW multiplets. We also estimate the reach of a search for disappearing tracks, demonstrating the potential significant enhancement of the sensitivity.