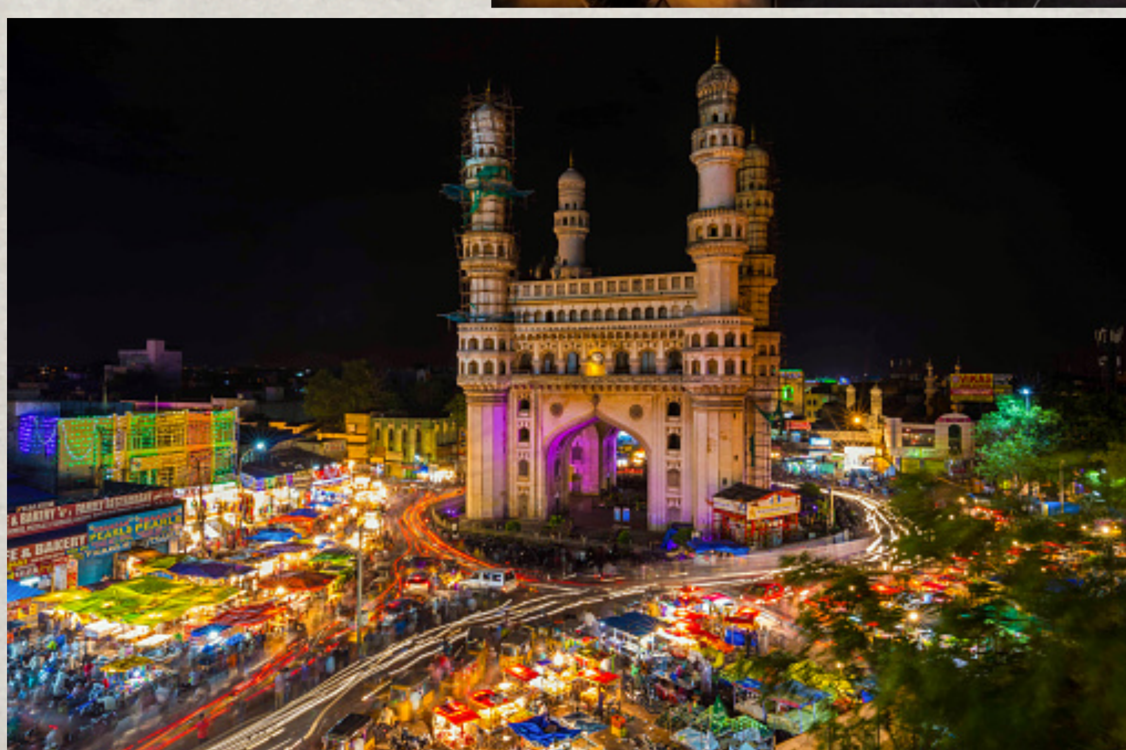
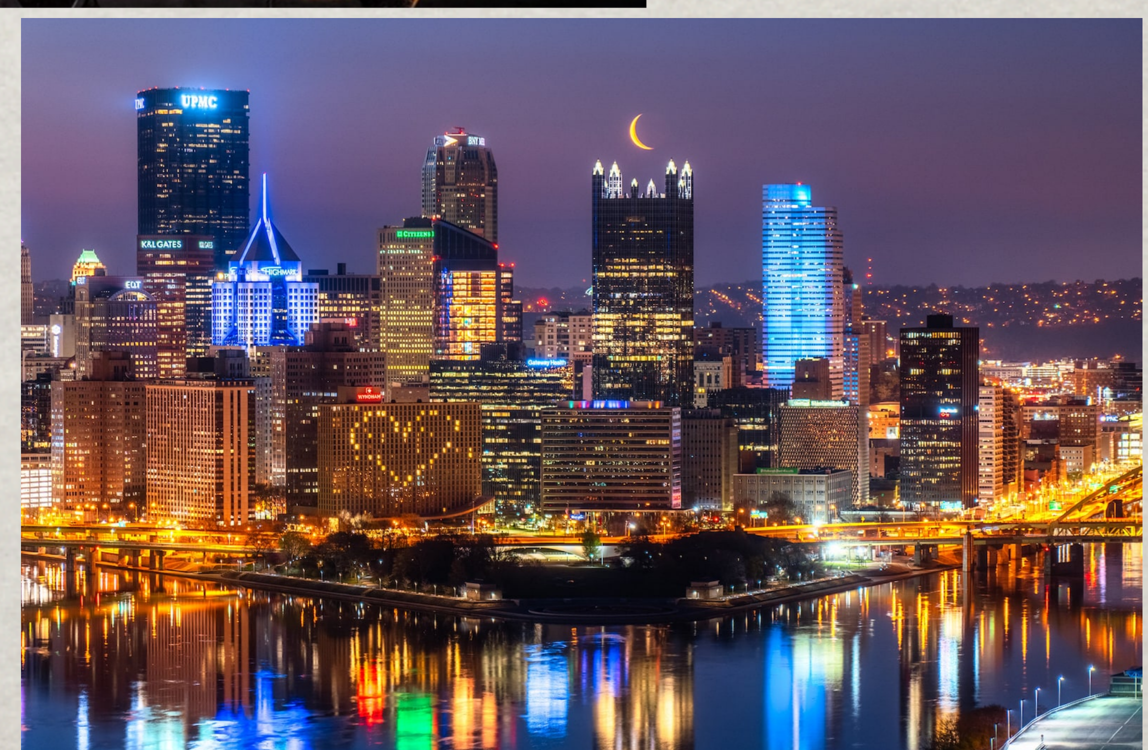
Physics Opportunities at Muon Colliders

Tao Han, University of Pittsburgh





Contents:

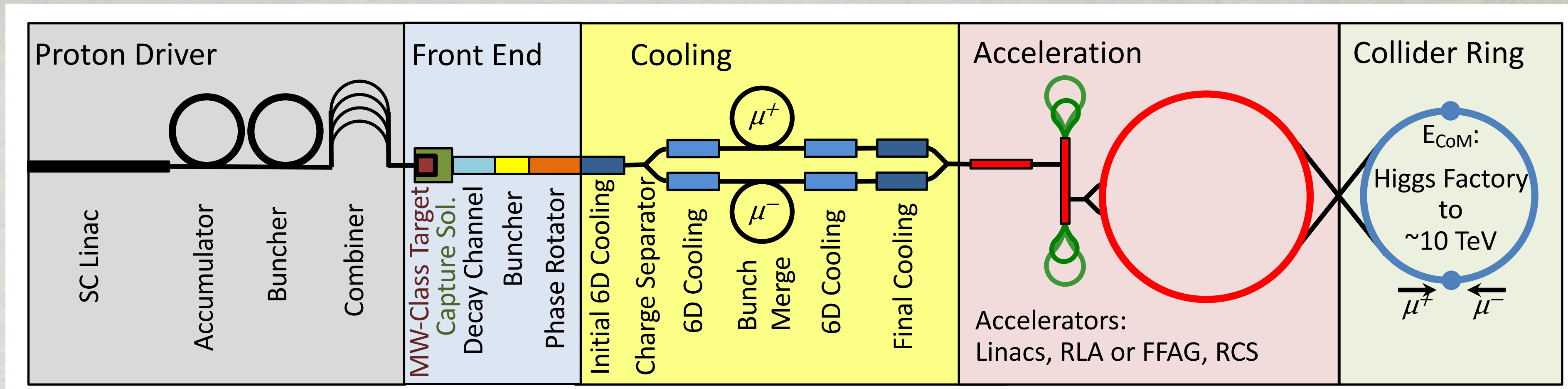
1. A Higgs factory
2. A Multi-TeV Muon Collider

- SM expectations:
  - QED & QCD
  - EW physics at ultra-high energies
  - Precision Higgs measurement
- Beyond the SM:
  - WIMP Dark Matter
  - Extended Higgs sector

Lots of recent works!
-- my apologies not to cover properly

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)
H. Ali, N. Arkani-Hamed, et al, arXiv:2103.14043 (Muon Smasher's Guide)
Richard Ruiz et al., arXiv:2111.02442 (MadGraph5)
… …

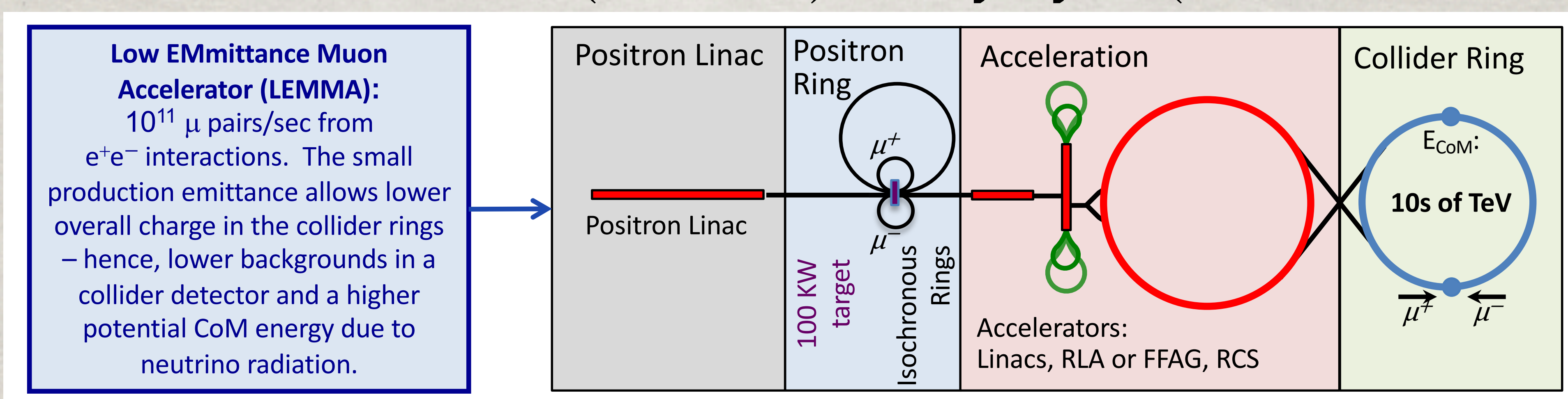
Proton Driver:



Muon Accelerator Program
map.fnal.gov

Transverse ionization cooling achieved by MICE in 2019.

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



Low EMittance Muon Accelerator
web.infn.it/LEMMA

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

Collider benchmark points:

- The Higgs factory:

$E_{cm} = m_H$
$L \sim 1\ fb^{-1}/yr$
$\Delta E_{cm} \sim 5$ MeV

Parameter	Units	Higgs
CoM Energy	TeV	0.126
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008
Beam Energy Spread	%	0.004
Higgs Production/10^7 sec		13'500
Circumference	km	0.3

- Multi-TeV colliders:

Lumi-scaling scheme: $\sigma L \sim$ const.

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

1 ab^{-1} /yr

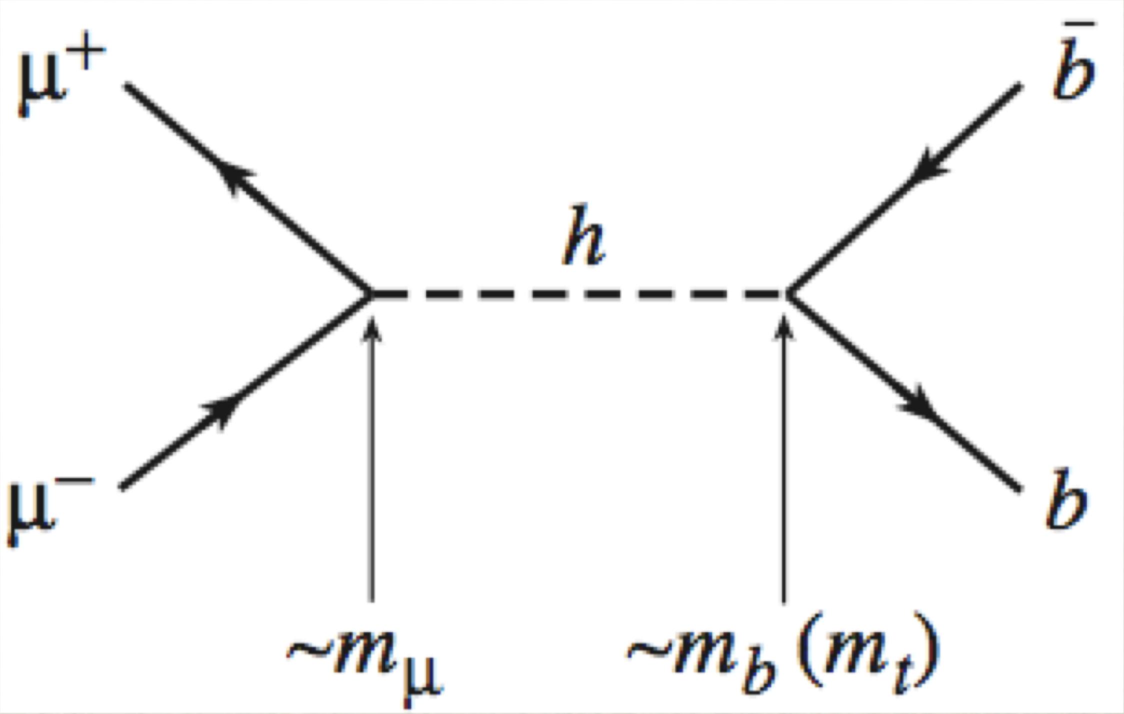
The aggressive choices:

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

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

1. A Higgs Factory

Resonant Production:



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

$$\begin{aligned}\sigma_{peak}(\mu^+\mu^- \to h) &= \frac{4\pi}{m_h^2} BR(h \to \mu^+\mu^-) \\ &\approx 41 \text{ pb at } m_h = 125 \text{ GeV}.\end{aligned}$$

About O(40k) events produced per fb^{-1}

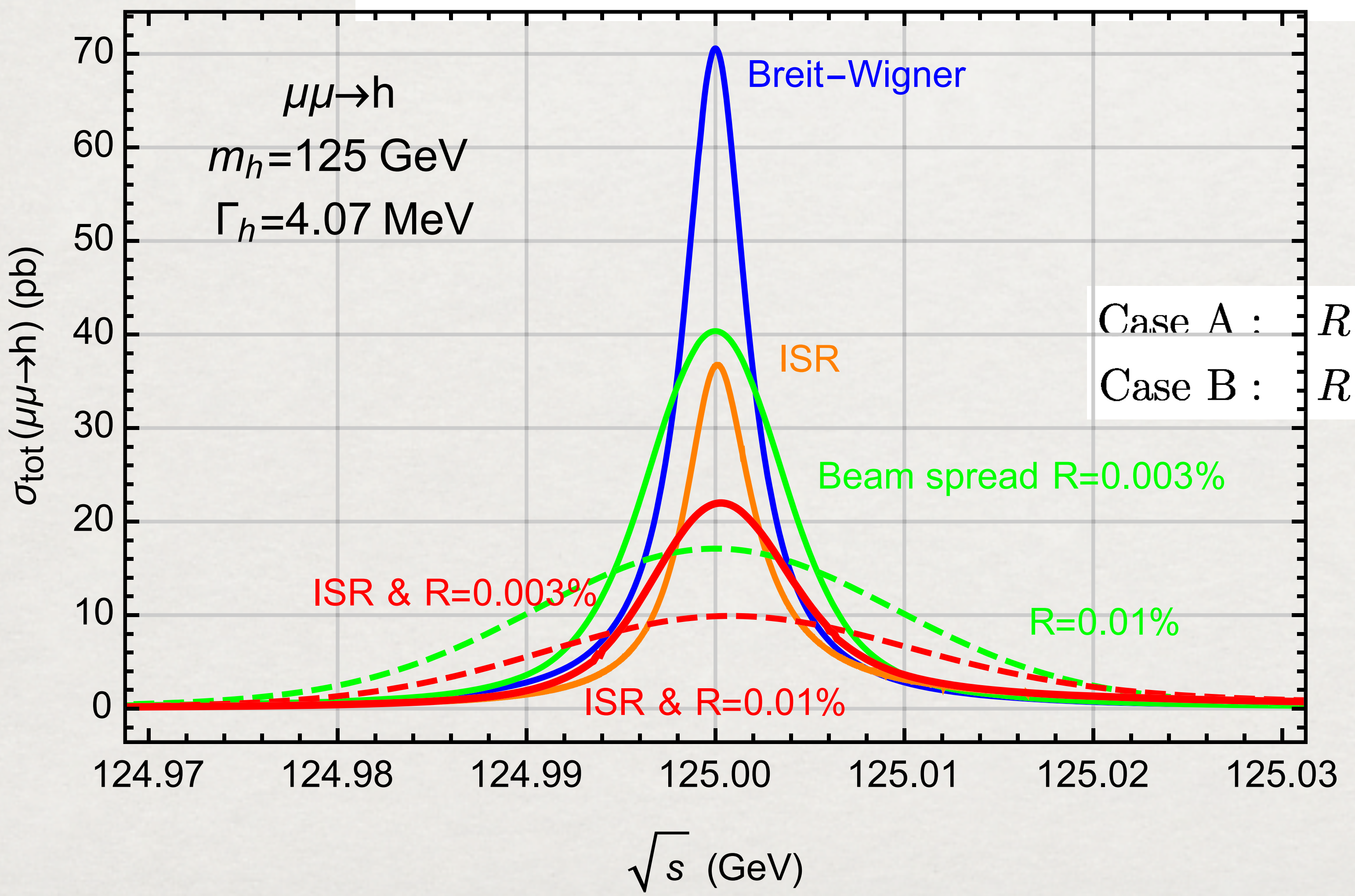
At m_h=125 GeV, Γ_h = 4.2 MeV

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

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

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

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



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

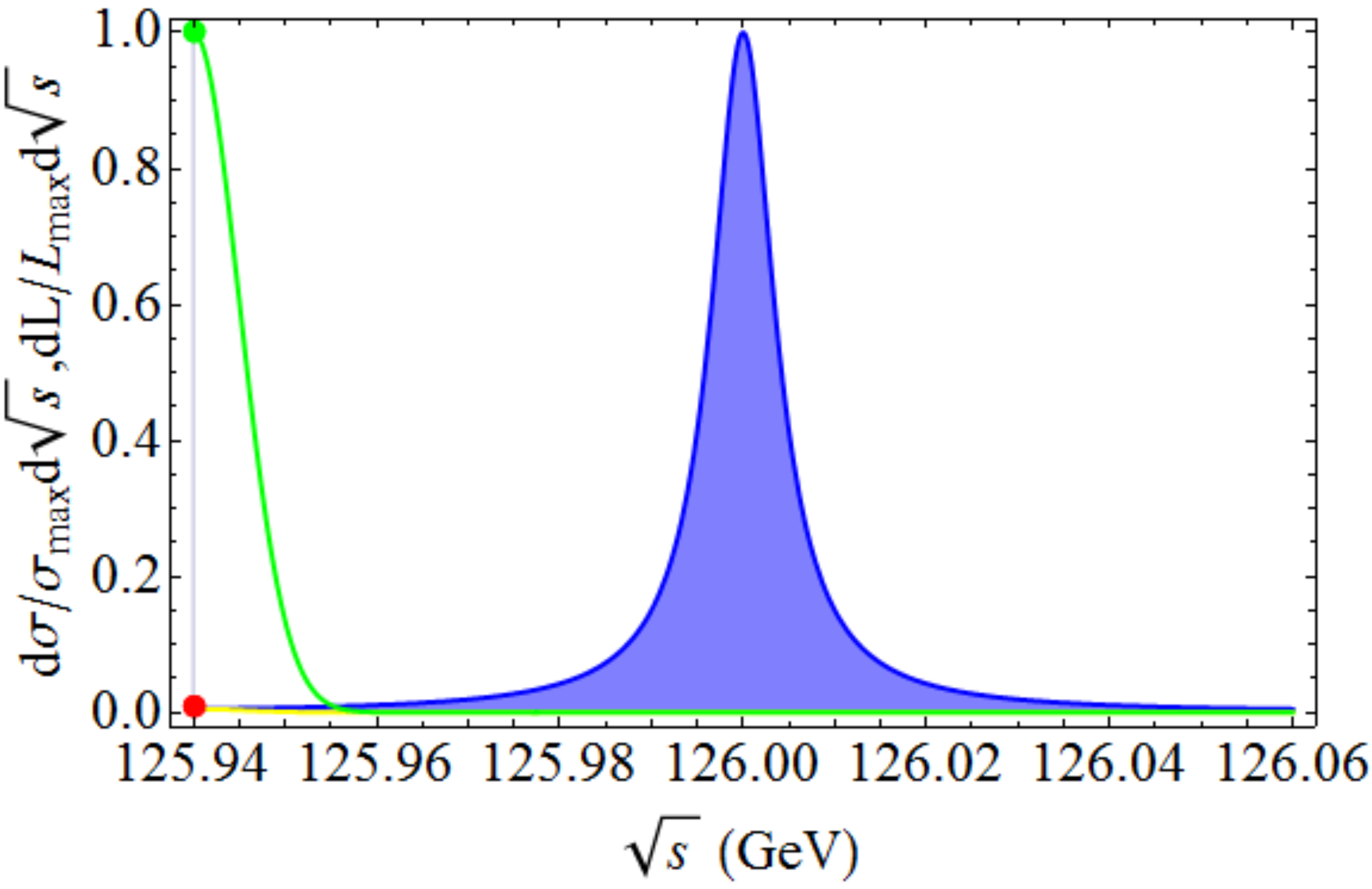
Case A : $R=0.01\%$ ($\Delta = 8.9$ MeV), $L = 0.5$ fb^{-1},
Case B : $R=0.003\%$ ($\Delta = 2.7$ MeV), $L = 1$ fb^{-1}.

Snowmass point: 2.5 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 would reveal Γ_h

Achievable accuracy at the Higgs factory:

TABLE I. Effective cross sections (in pb) at the resonance $\sqrt{s} = m_h$ for two choices of beam energy resolutions R and two leading decay channels, with the SM branching fractions $\mathrm{Br}_{b\bar{b}} = 56\%$ and $\mathrm{Br}_{WW^*} = 23\%$ [9]. a cone angle cut: $10^o < \theta < 170^o$

	$\mu^+\mu^- \to h$	$h \to b\bar{b}$		$h \to WW^*$	
R (%)	$\sigma_{\rm eff}$ (pb)	$\sigma_{\rm Sig}$	$\sigma_{\rm Bkg}$	$\sigma_{\rm Sig}$	$\sigma_{\rm Bkg}$
0.01	16	7.6		3.7	
0.003	38	18	15	5.5	0.051

Good S/B, S/√B → % accuracies

Table 3

Fitting accuracies for one standard deviation of Γ_h, B and m_h of the SM Higgs with the scanning scheme for two representative luminosities per step and two benchmark beam energy spread parameters.

$\Gamma_h = 4.07$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$R = 0.01\%$	0.05	0.79	3.0%	0.36
	0.2	0.39	1.1%	0.18
$R = 0.003\%$	0.05	0.30	2.5%	0.14
	0.2	0.14	0.8%	0.07

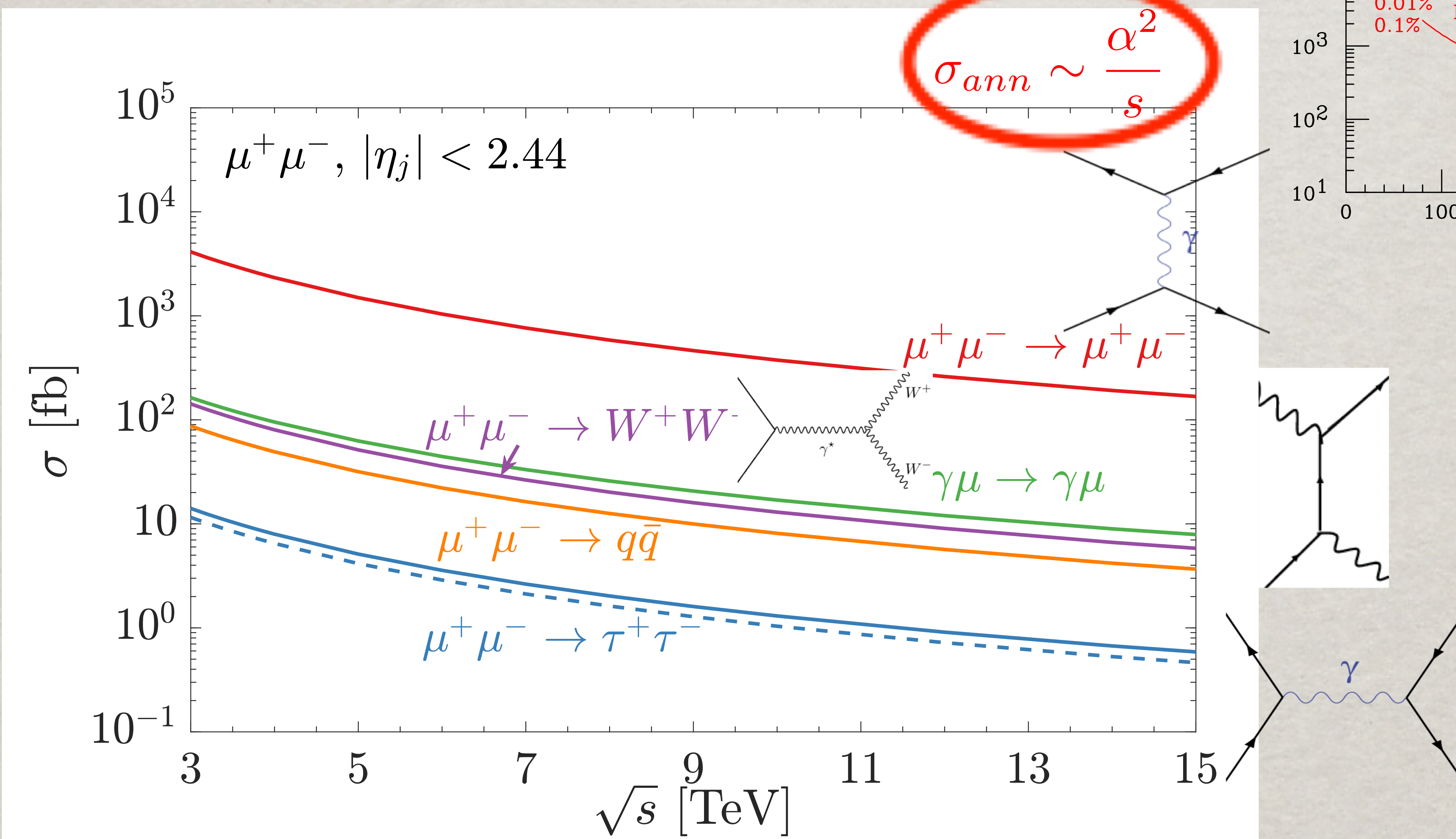
~ 3.5%

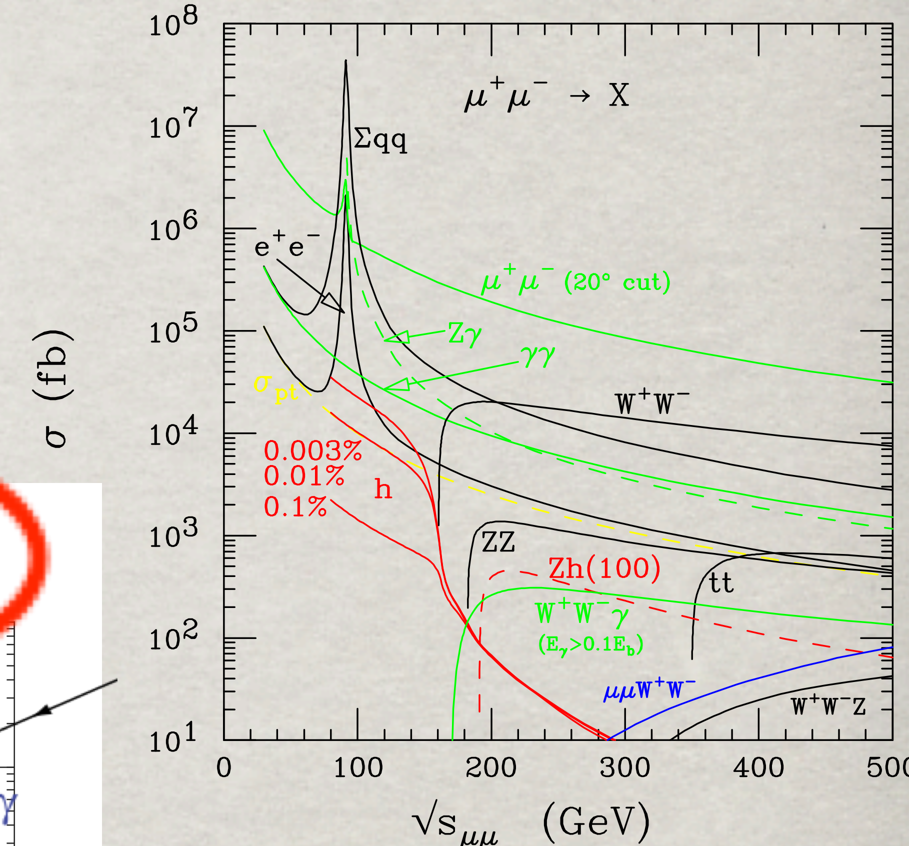
TH, Liu: 1210.7803;
Greco, TH, Liu: 1607.03210

2. A Multi-TeV Muon Collider

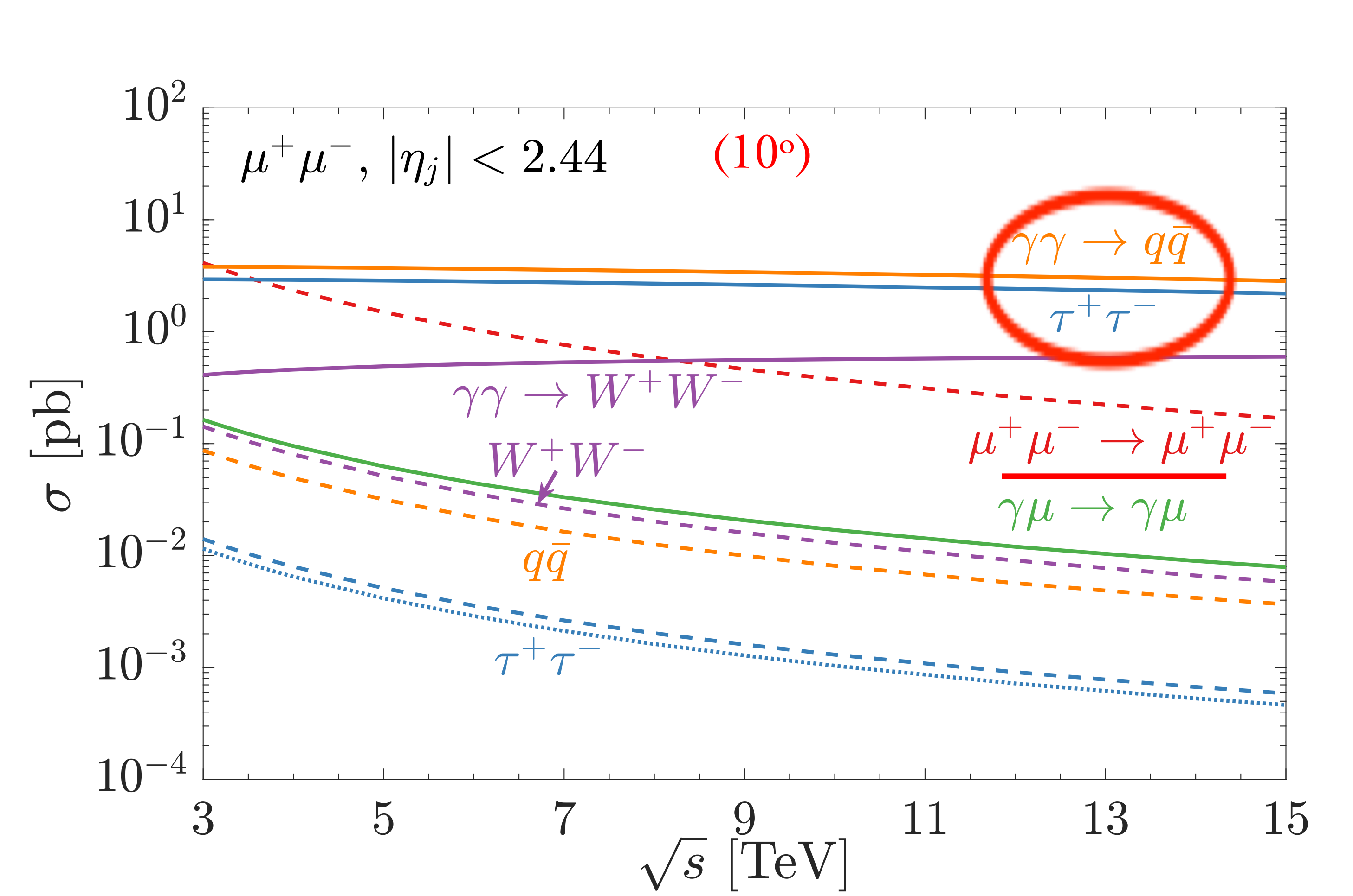
What will happen when you turn on a $\mu^+\mu^-$ Smasher?

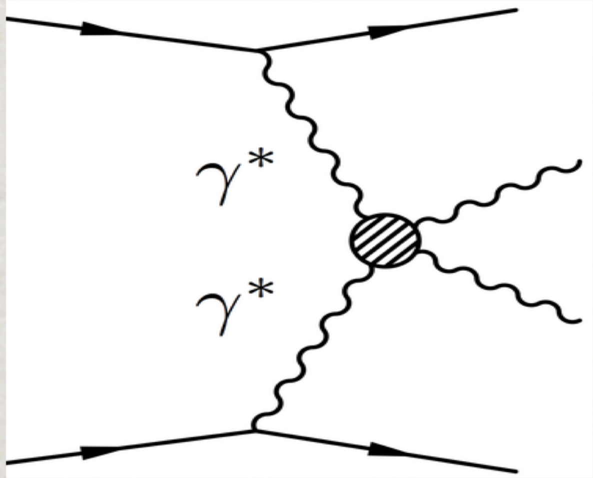
Leading-order $\mu^+\mu^-$ annihilation:



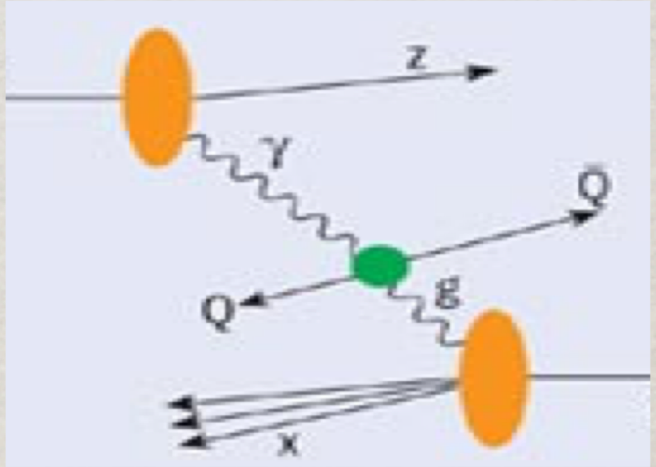


• Photon-induced QED cross sections have larger rates $\sigma_{fusion} \sim \frac{\alpha^2}{m_{jj}^2}\log^2(\frac{Q^2}{m^2})$





m_{jj}

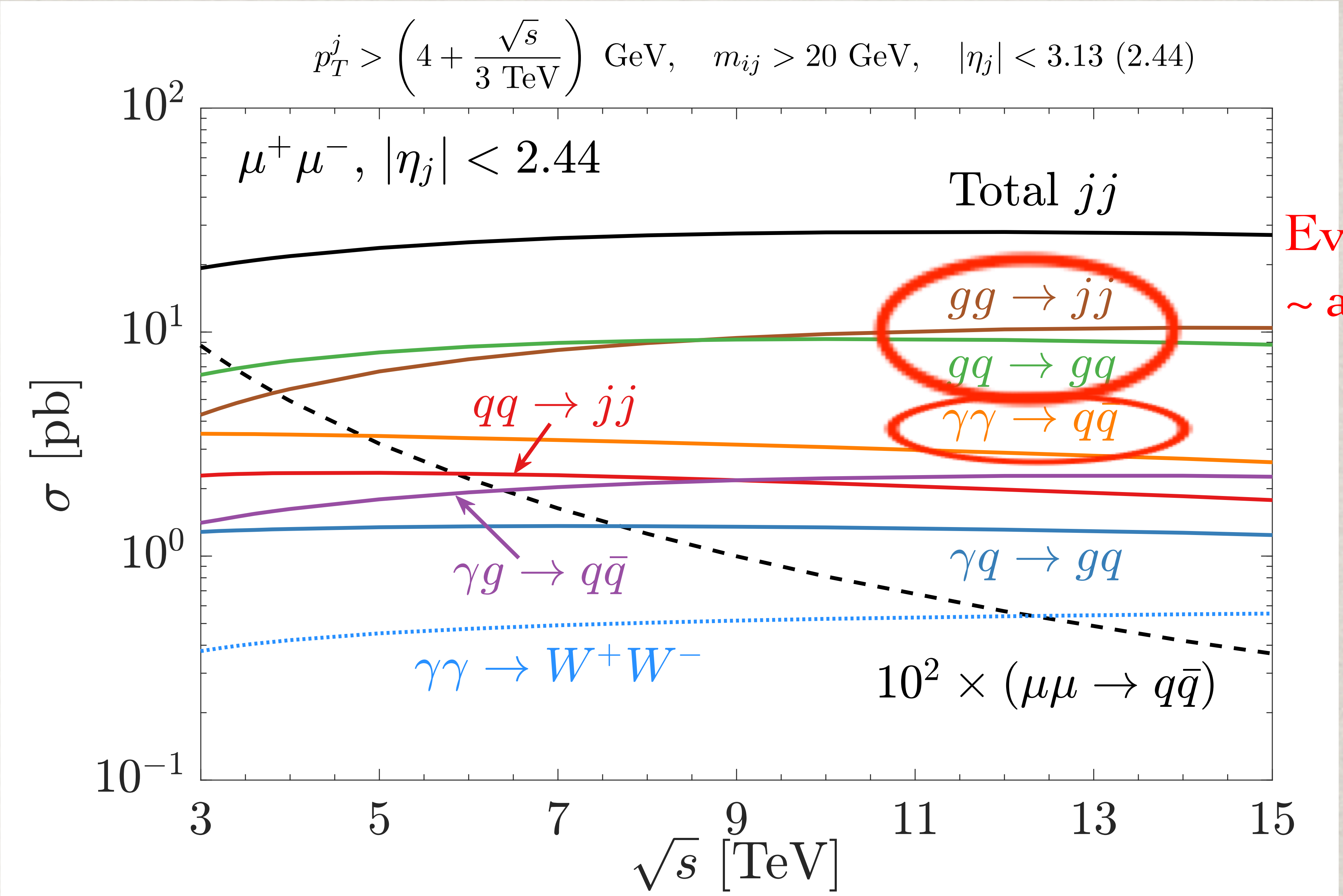


$$p_T^j > \left(4 + \frac{\sqrt{s}}{3\ \text{TeV}}\right)\ \text{GeV}, \quad m_{ij} > 20\ \text{GeV}, \quad |\eta_j| < 3.13\ (2.44)$$

Quarks/gluons come into the picture via SM DGLAP:

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

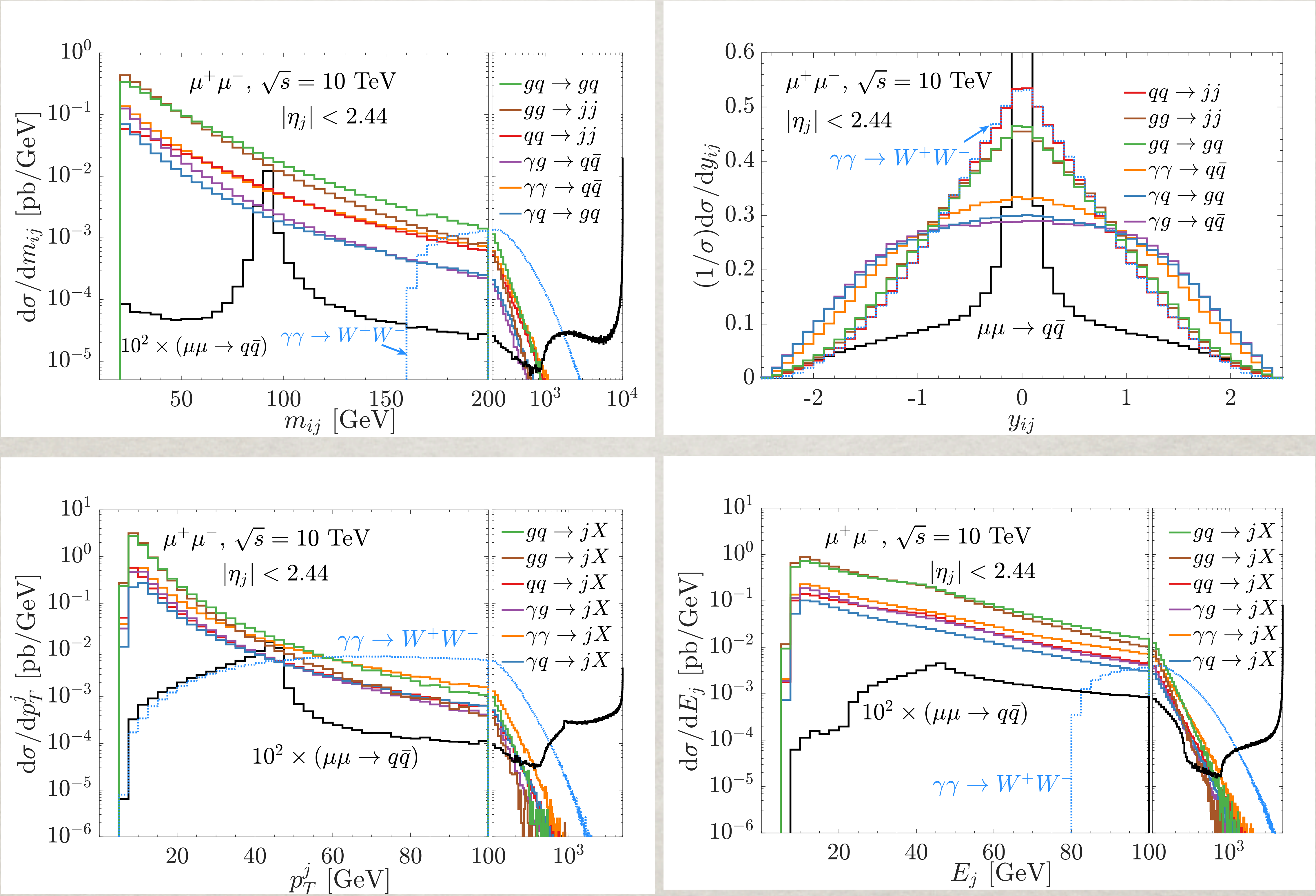
Di-jet production: $\gamma\gamma \to q\bar{q},\ \gamma g \to q\bar{q},\ \gamma q \to gq,$ $qq \to qq(gg),\ gq \to gq,$ and $gg \to gg(q\bar{q})$



→ Jet production dominates at low energies

TH, Yang Ma, Keping Xie, arXiv:2103.09844.

Di-jet kinematical features



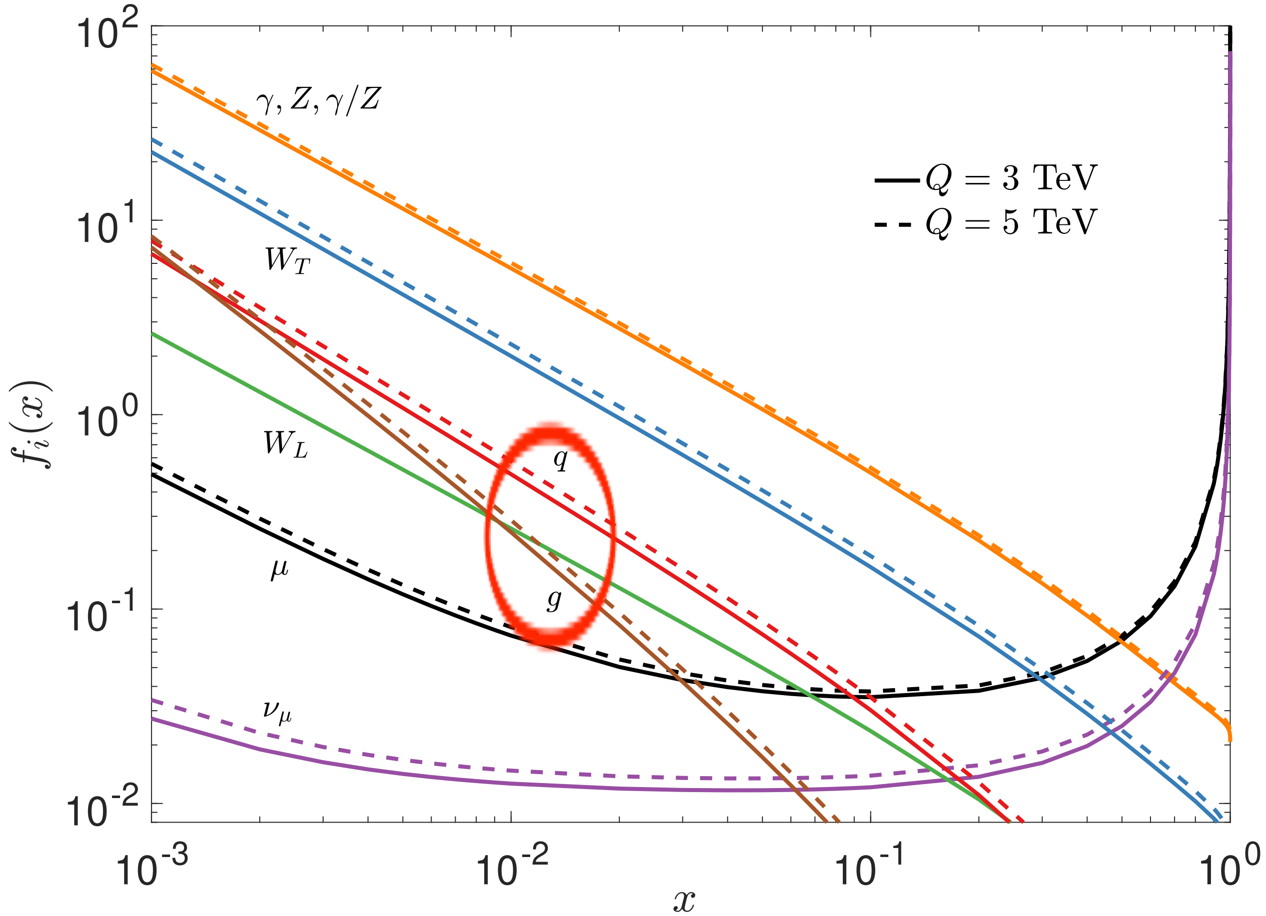
To effectively separate the QCD backgrounds:

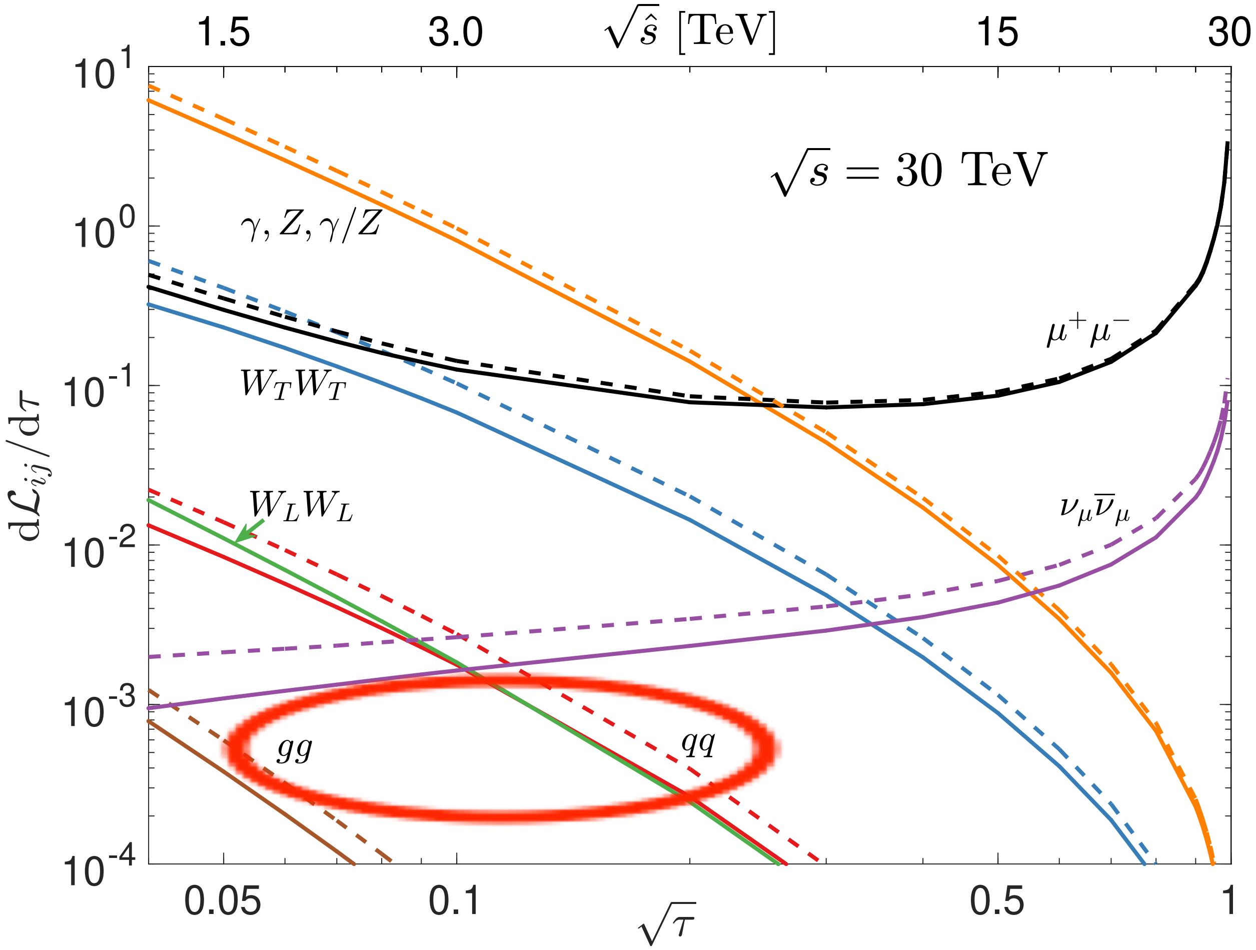
$p_T > 60$ GeV

• 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.

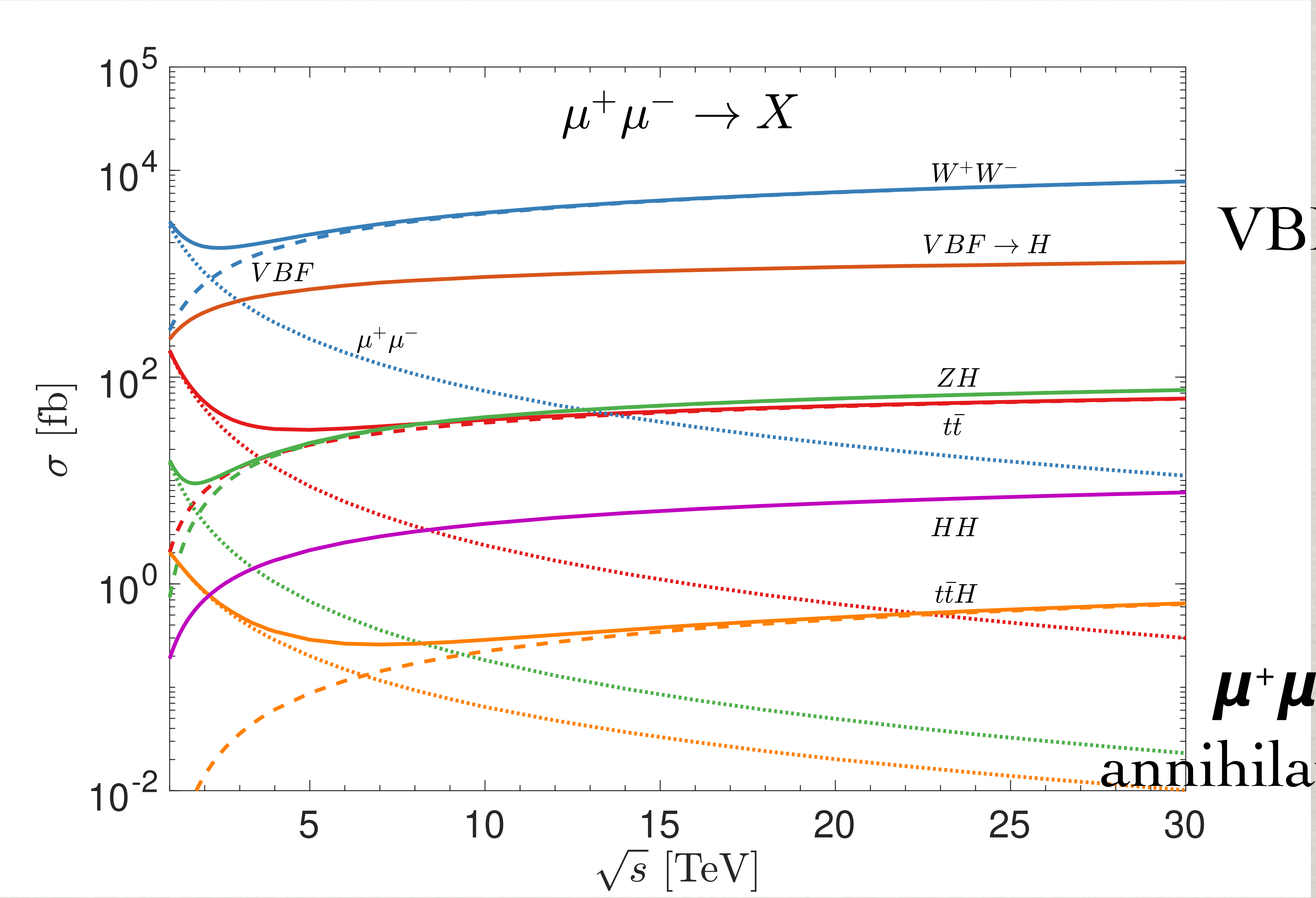
Quarks: NLO; gluons: NNLO.

TH, Yang Ma, Keping Xie, arXiv:2007.14300

• "Semi-inclusive" processes

Just like in hadronic collisions:

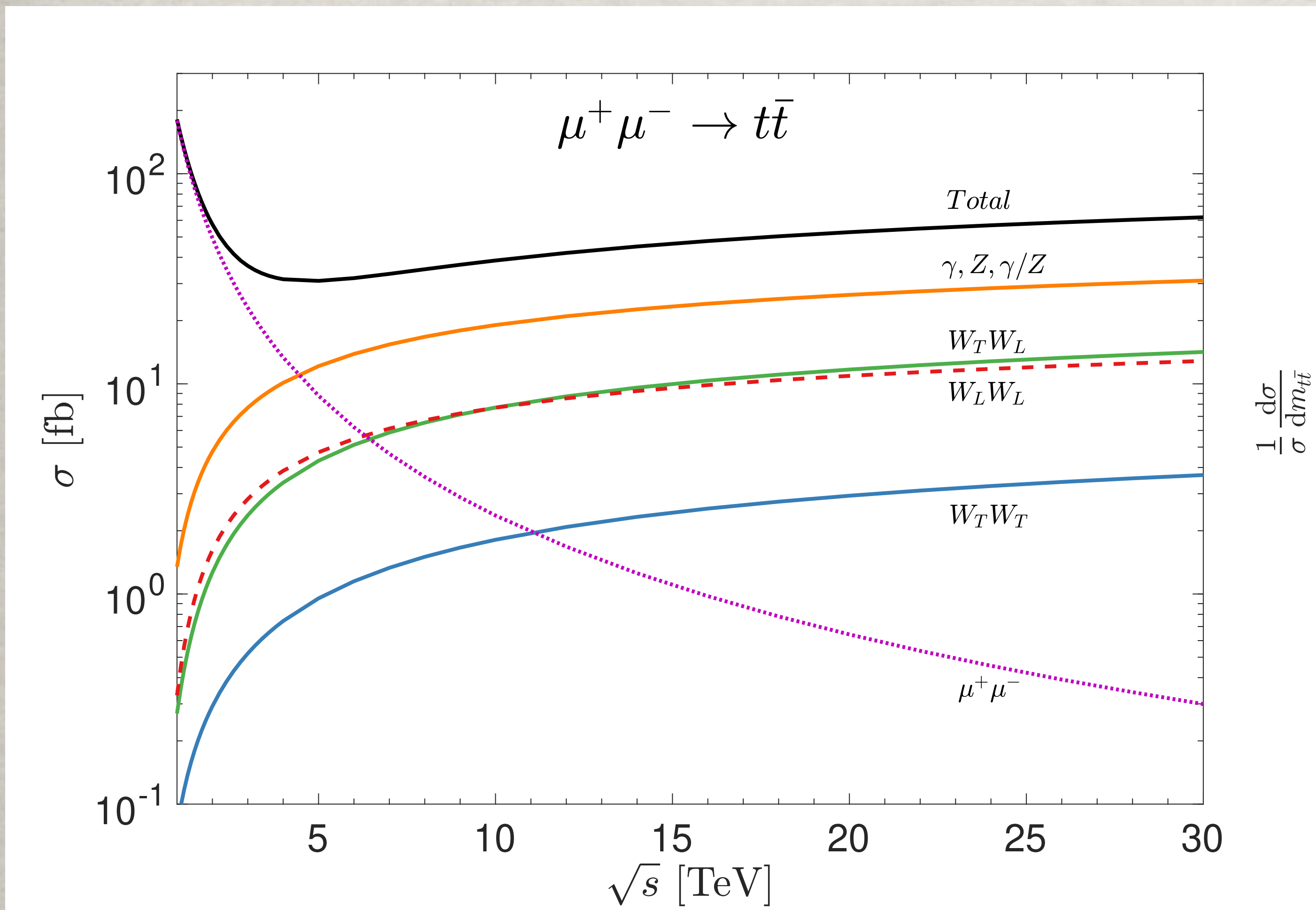
$\mu^+\mu^-$ → exclusive particles + remnants

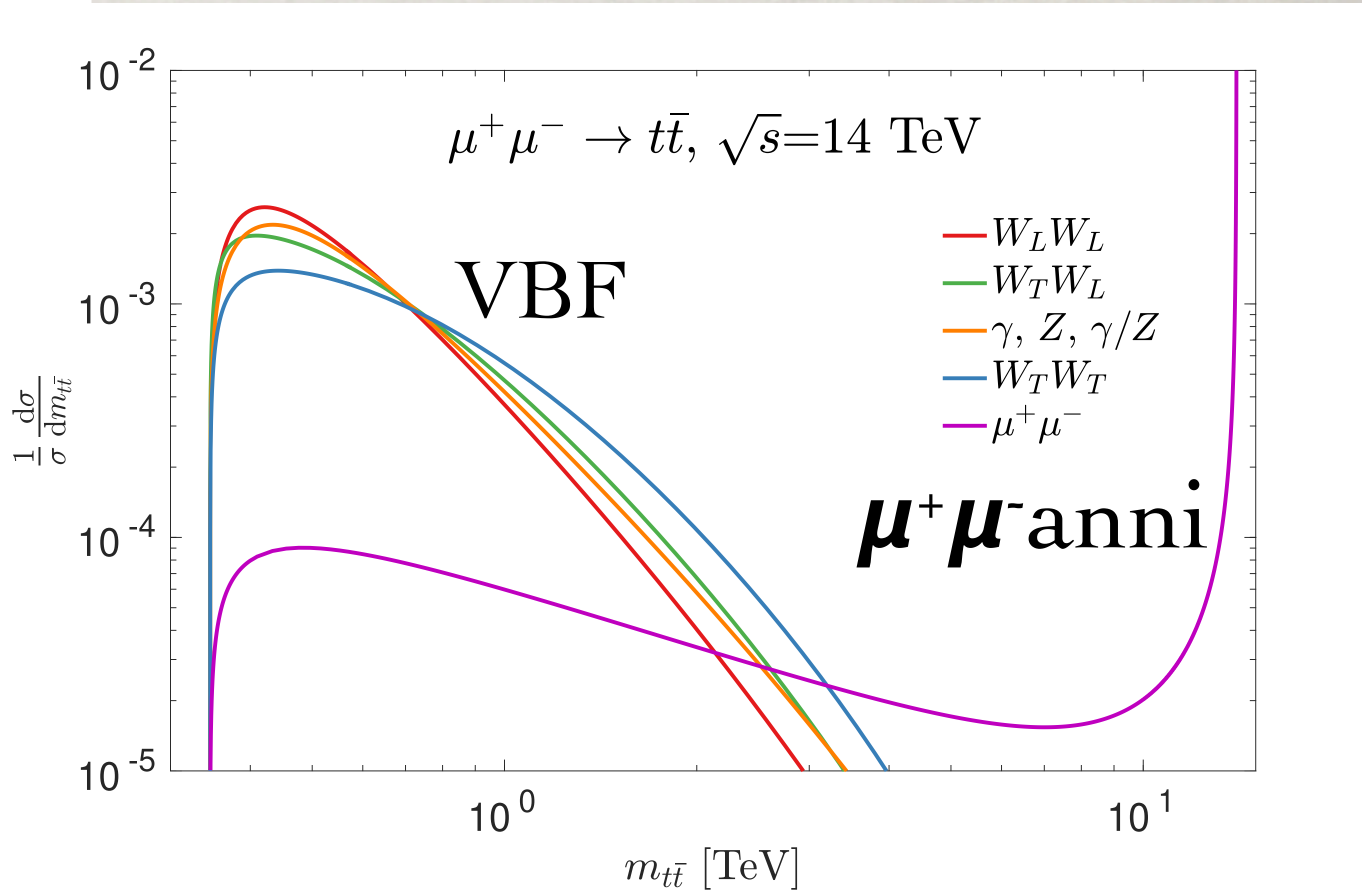


VBF

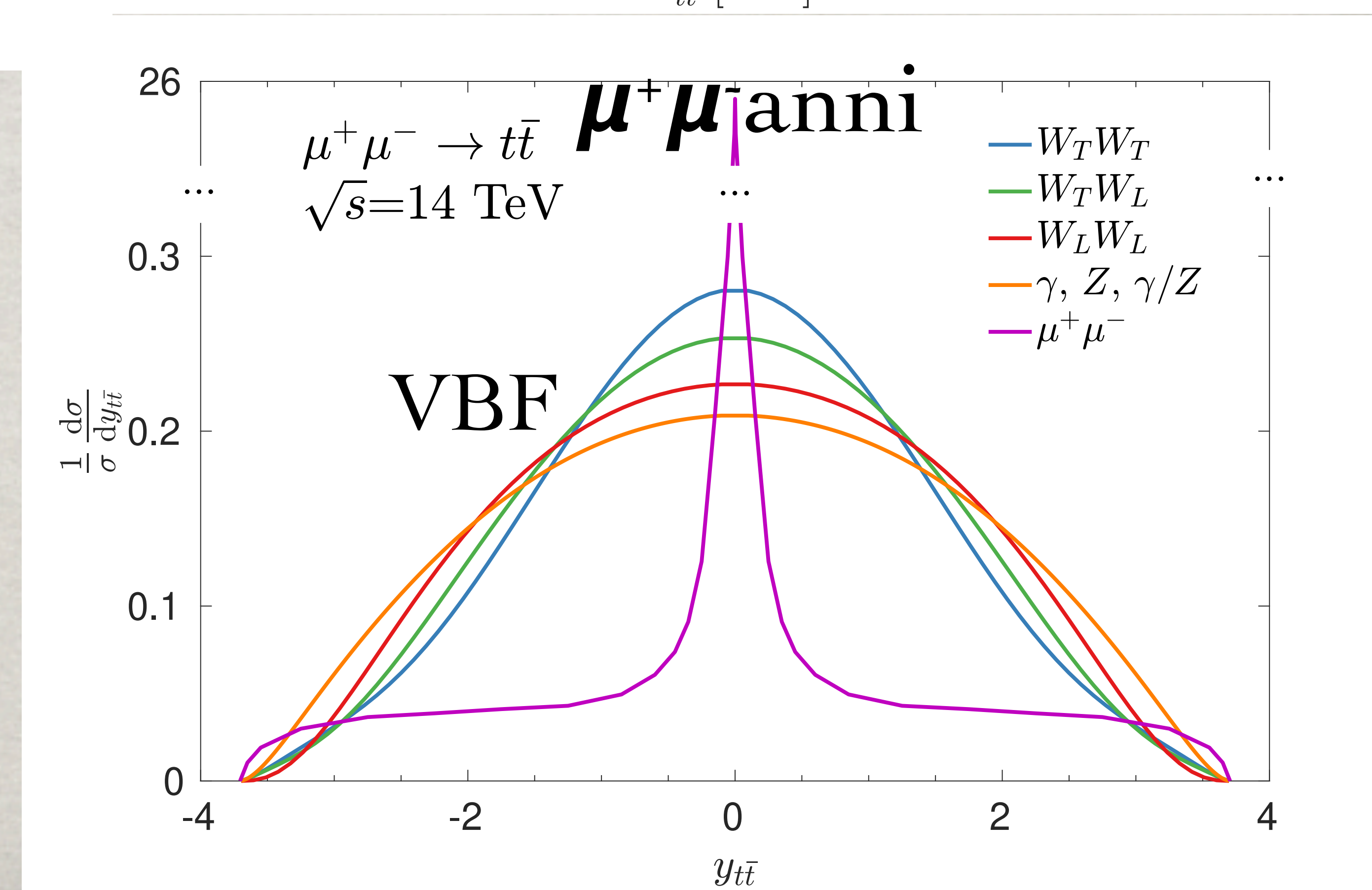
$\mu^+\mu^-$ annihilations

Underlying sub-processes:





Partonic contributions



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

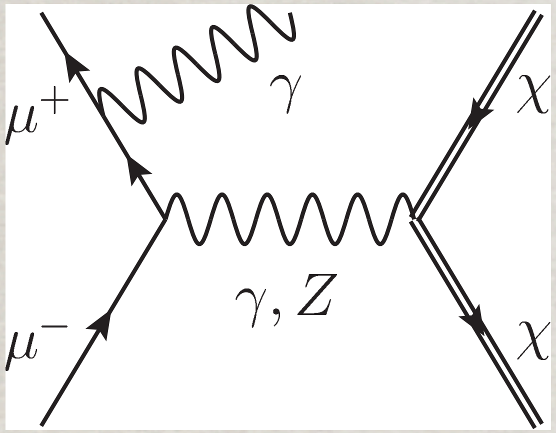
"Buy one, get one free"

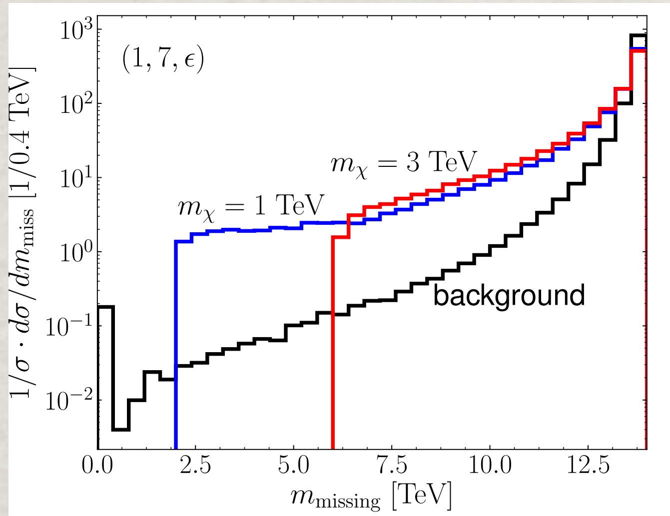
Annihilation +VBF

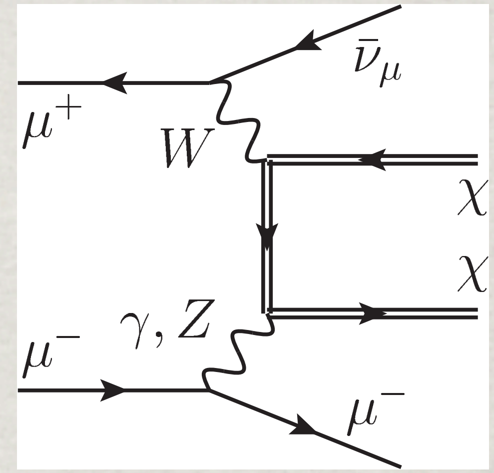
Unique kinematic features:

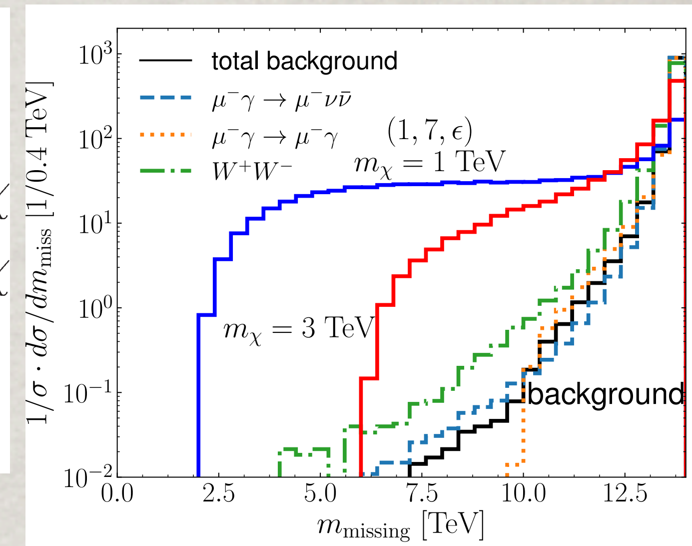
- "Recoil mass" → "missing mass": $m^2_{\rm missing} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\rm obs})^2$

$m^2_{\rm missing} \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > 4m_\chi^2$ $\quad$ $m^2_{\rm missing} = (p^{\rm in}_{\mu^+} + p^{\rm in}_{\mu^-} - p^{\rm out}_{\mu^\pm})^2 > 4m^2_\chi.$



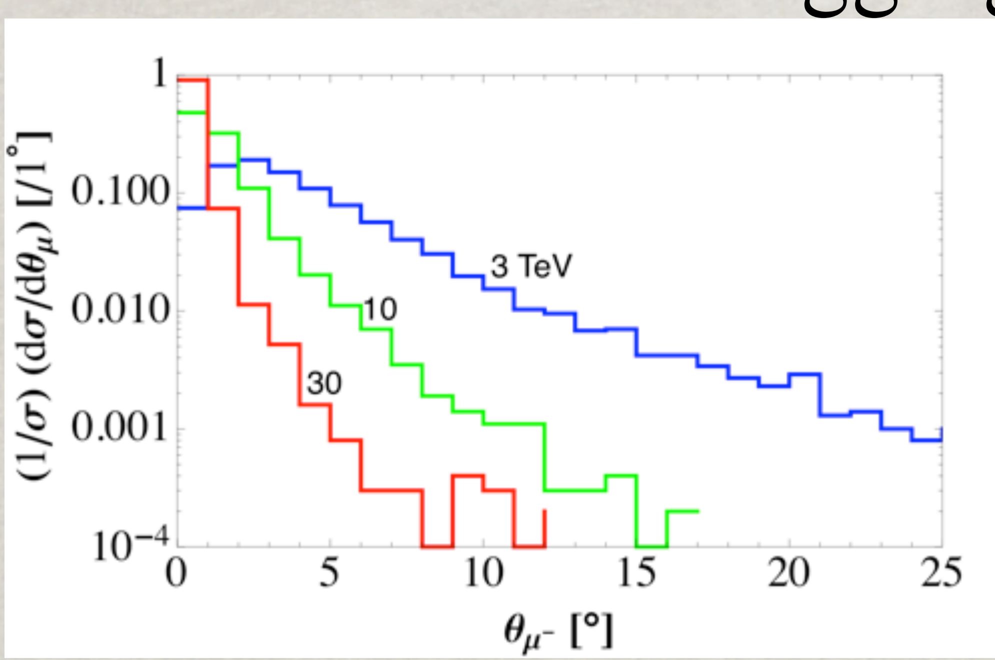


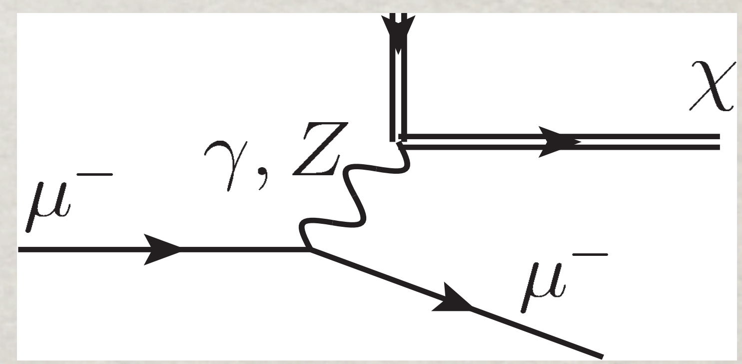




Unavailable in hadronic collisions!

- Forward tagging:





$\theta_\mu \approx M_Z/E_\mu \quad \theta_\mu \sim 0.02 \approx 1.2^\circ$ at 10 TeV.

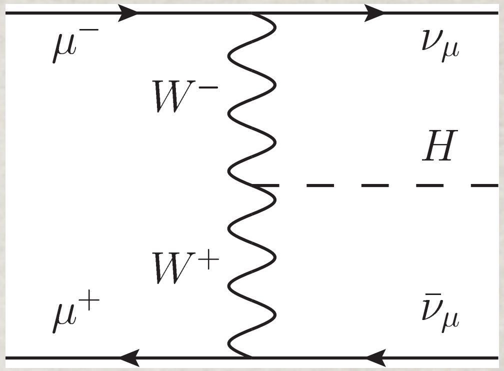
Tagging is costly: forward detector ?

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

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

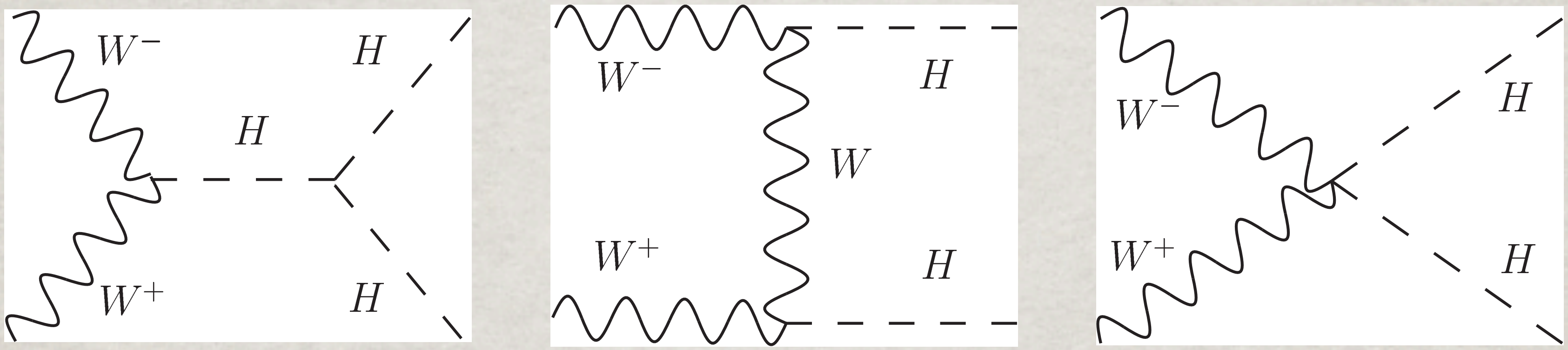
• Precision Higgs Physics

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



WWH / ZZH couplings

HHH / WWHH couplings:



(a) (b) (c)

$\sqrt{s}$ (TeV) benchmark lumi (ab^{-1})	3 1	6 4	10 10	14 20	30 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

10M H

500k HH

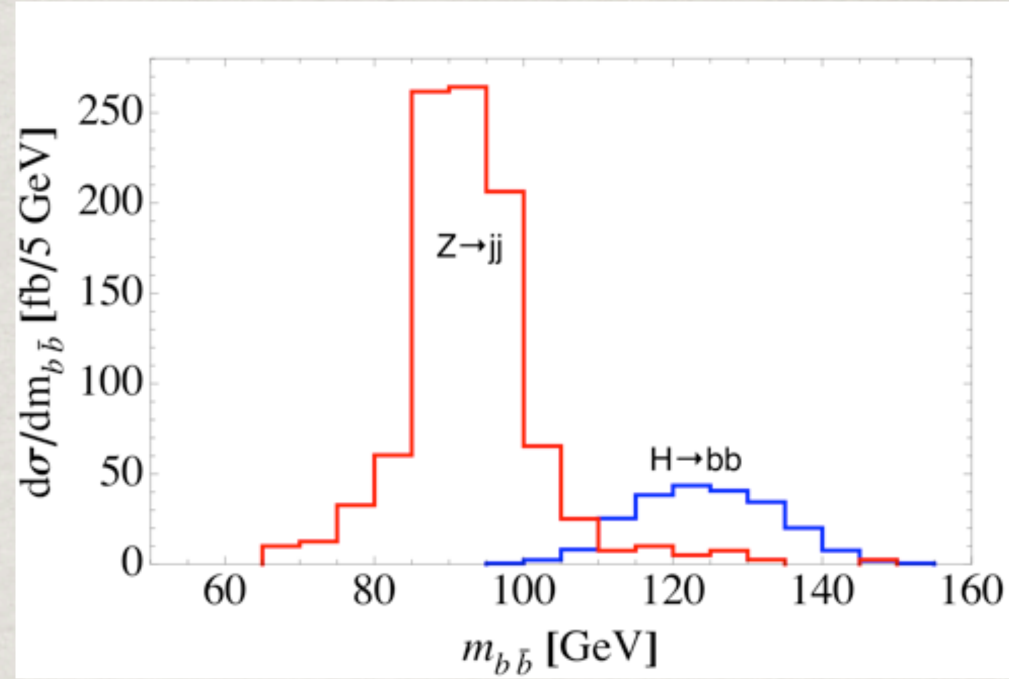
TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204

Achievable accuracies

Leading channel H → bb:

$$\Delta E/E = 10\%.$$

$$10^\circ < \theta_{\mu^\pm} < 170^\circ.$$



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

$\sqrt{s}$ (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

• WIMP Dark Matter (a conservative SUSY scenario)

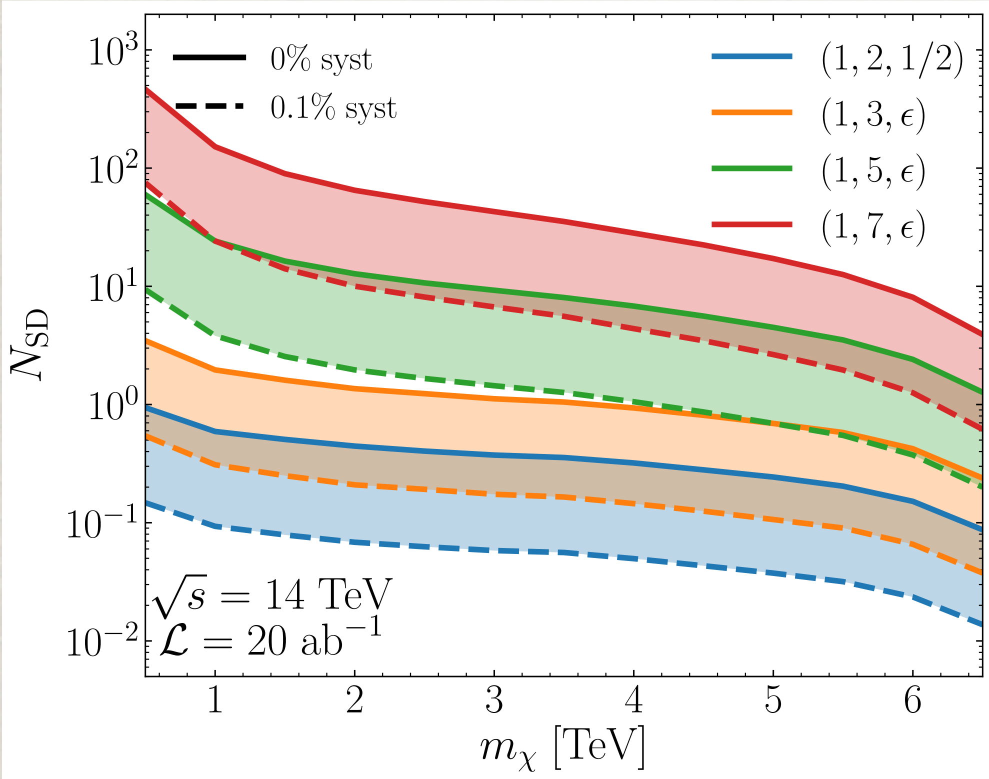
Consider the “minimal EW dark matter”: an EW multi-plet

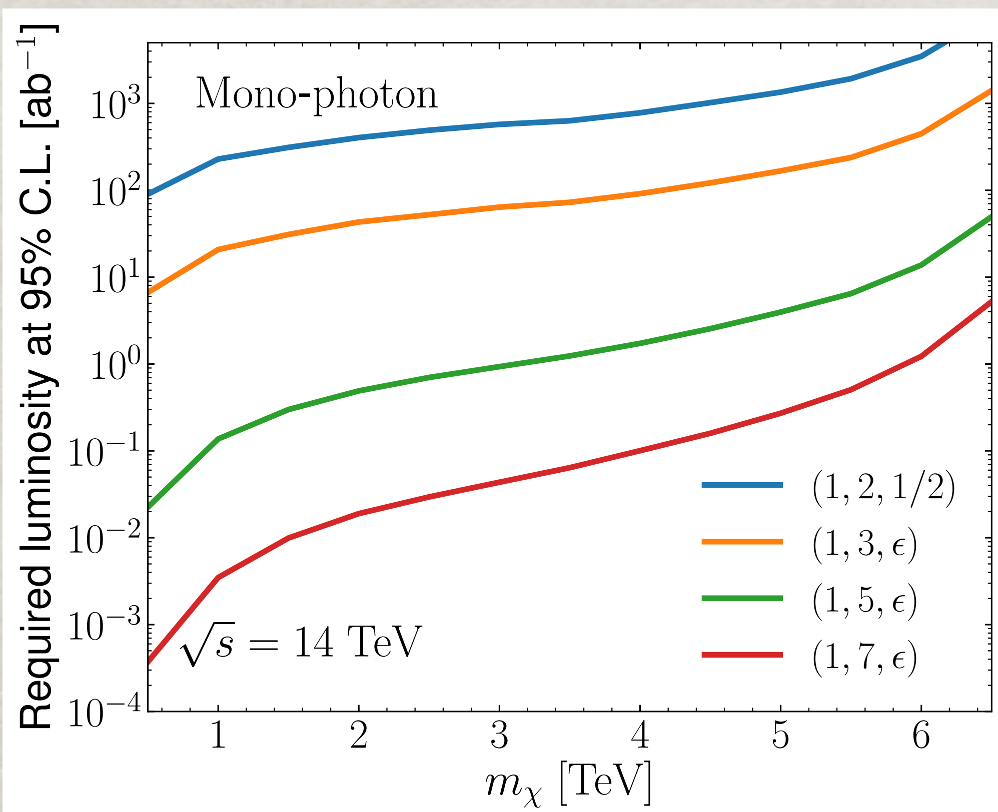
- The lightest neutral component as DM
- Interactions well defined → pure gauge
- Mass upper limit predicted → thermal relic abundance

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
(1,7,ϵ)	Dirac	16 TeV

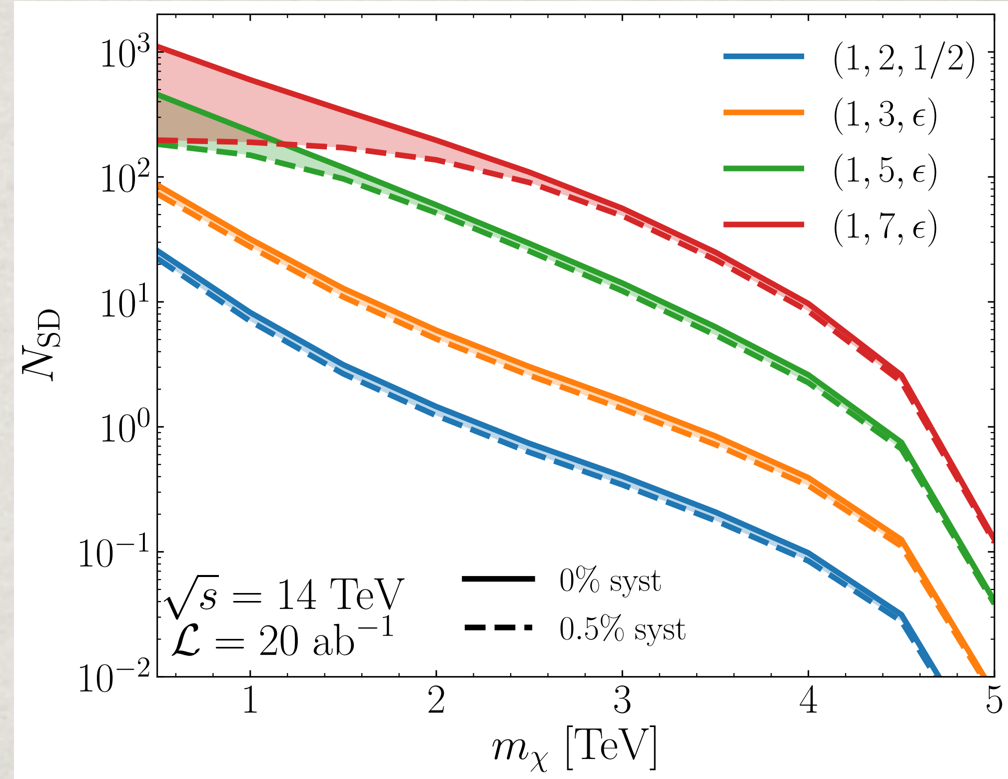
Cirelli, Fornengo and Strumia: hep-ph/0512090, 0903.3381;
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

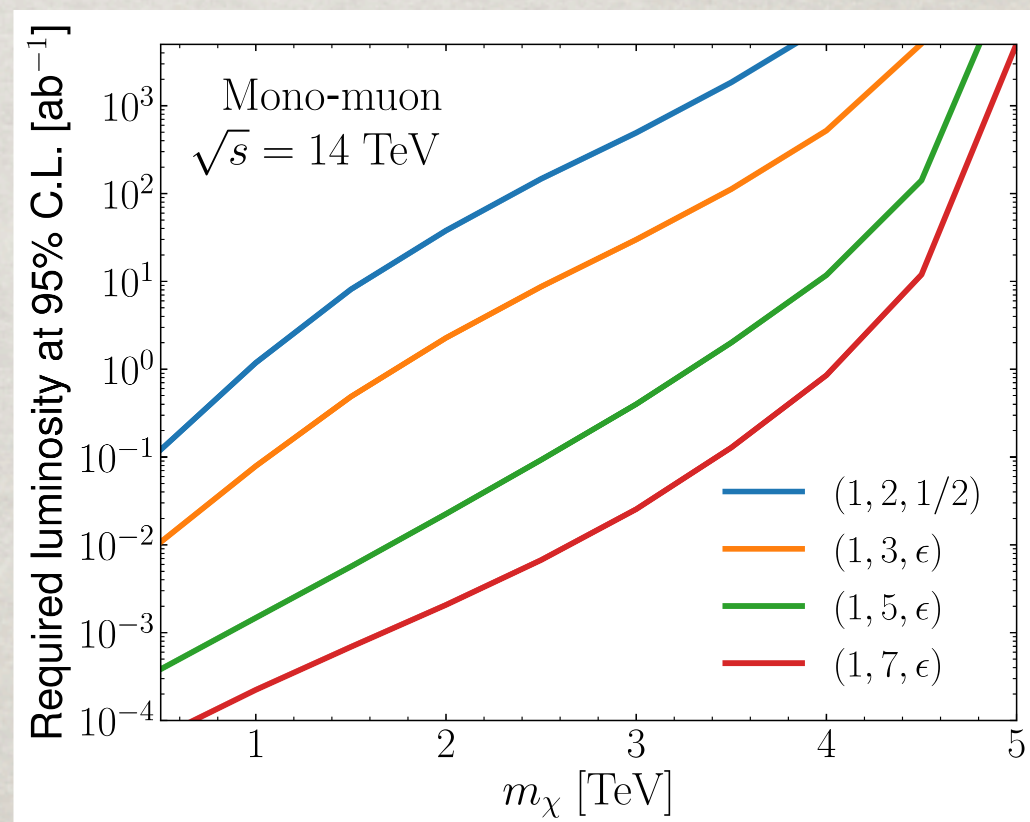
Mono-photon channel:





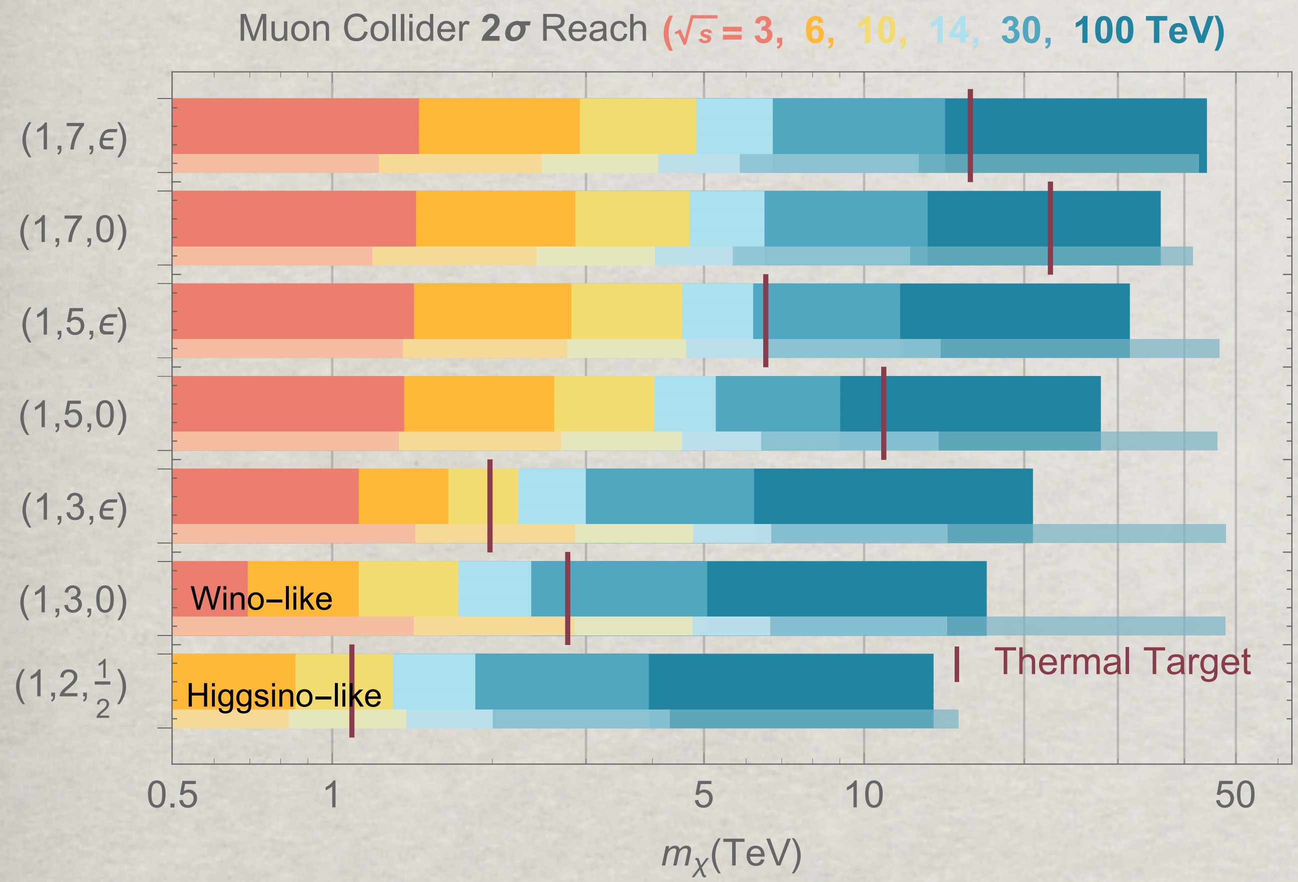
Mono-muon channel:

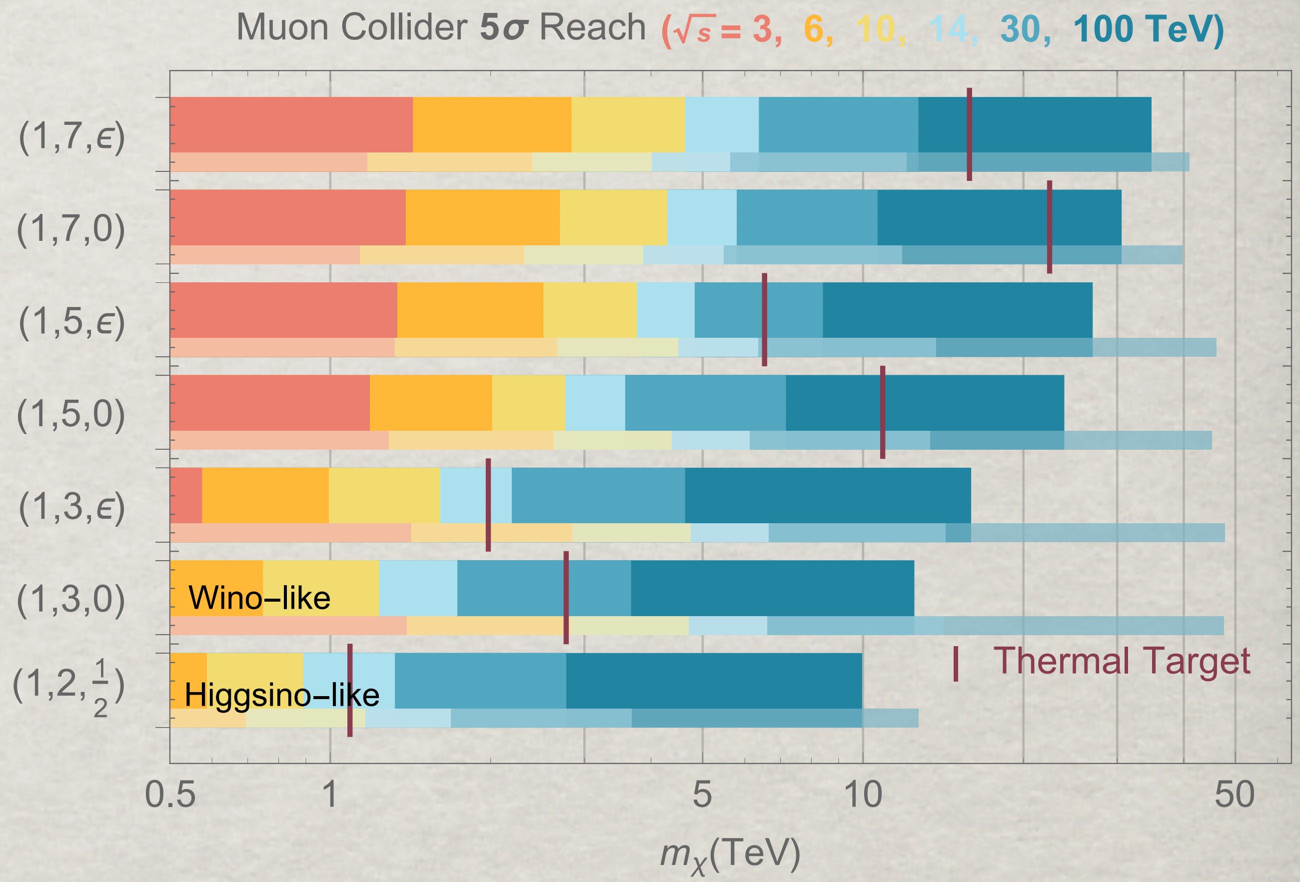




TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

The mass reach for minimal WIMP DM:





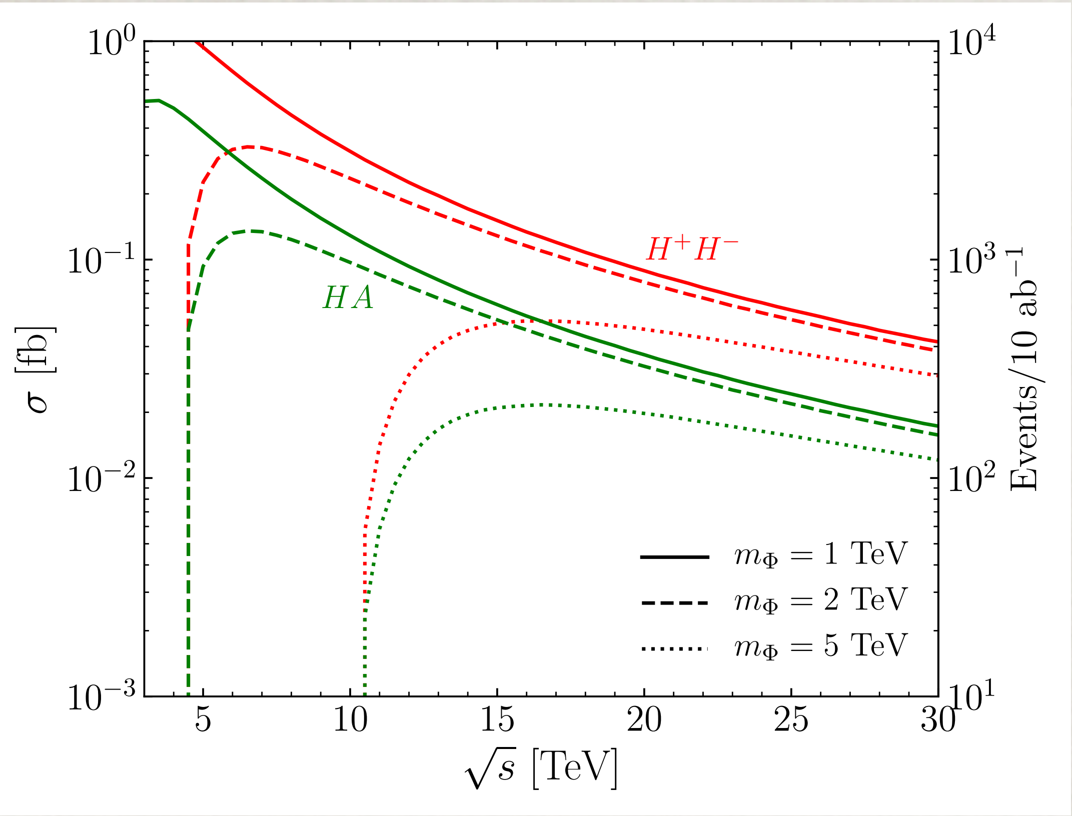
E_{CM} ≈ 14 TeV enough to cover n≤3 multiplets.

Higher energy needed to cover higher multiplets.

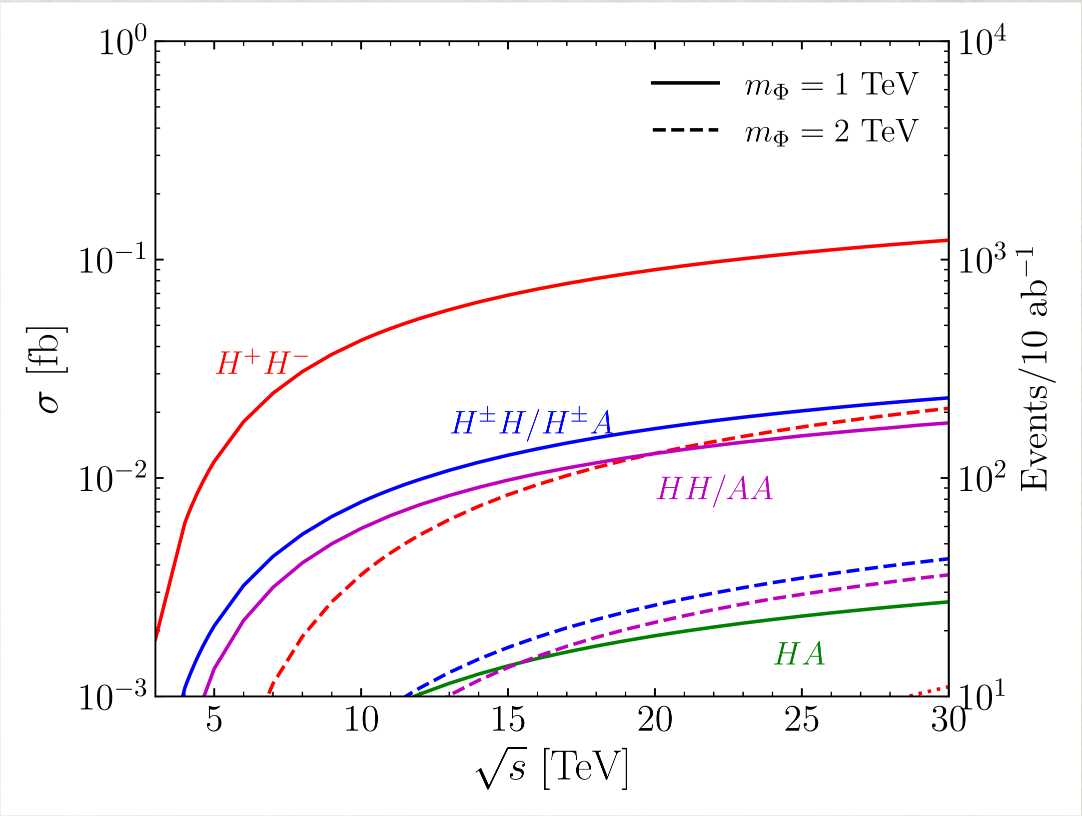
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

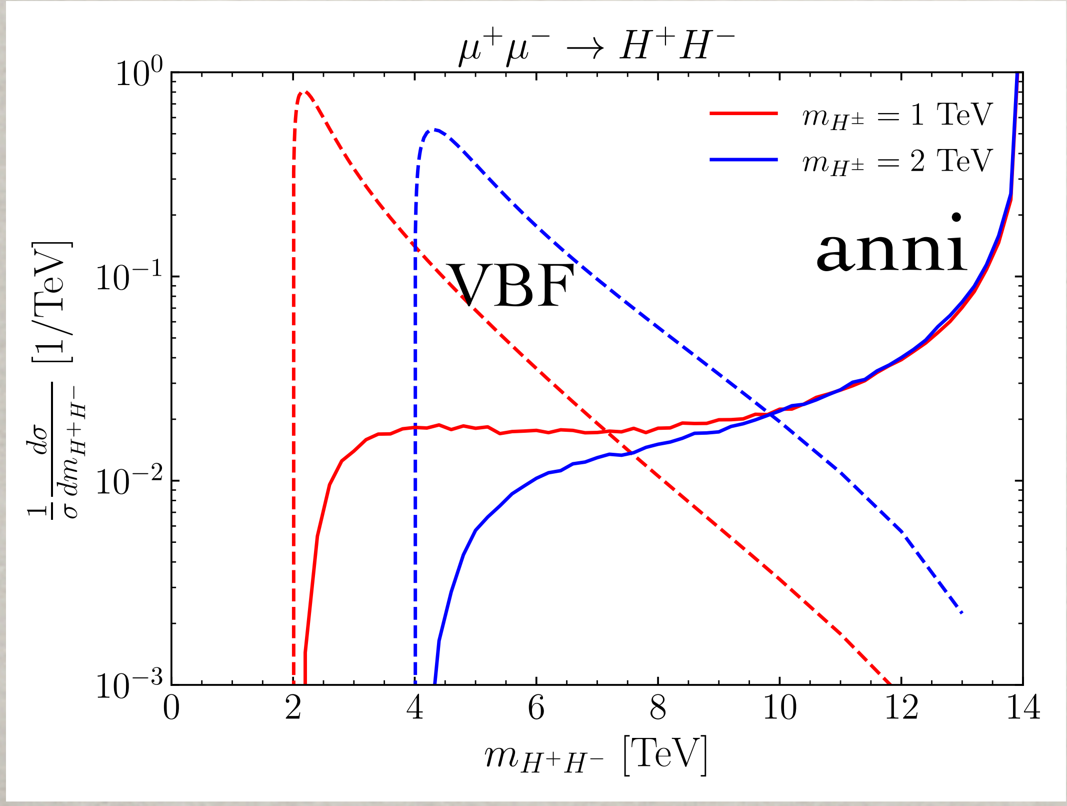
• Heavy Higgs Bosons Production

annihilation



VBF

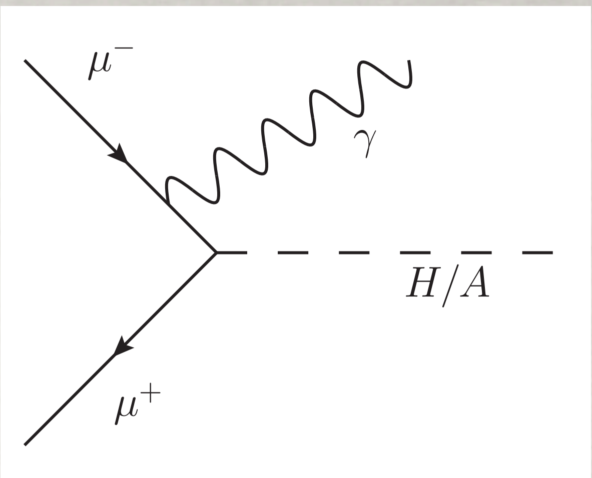


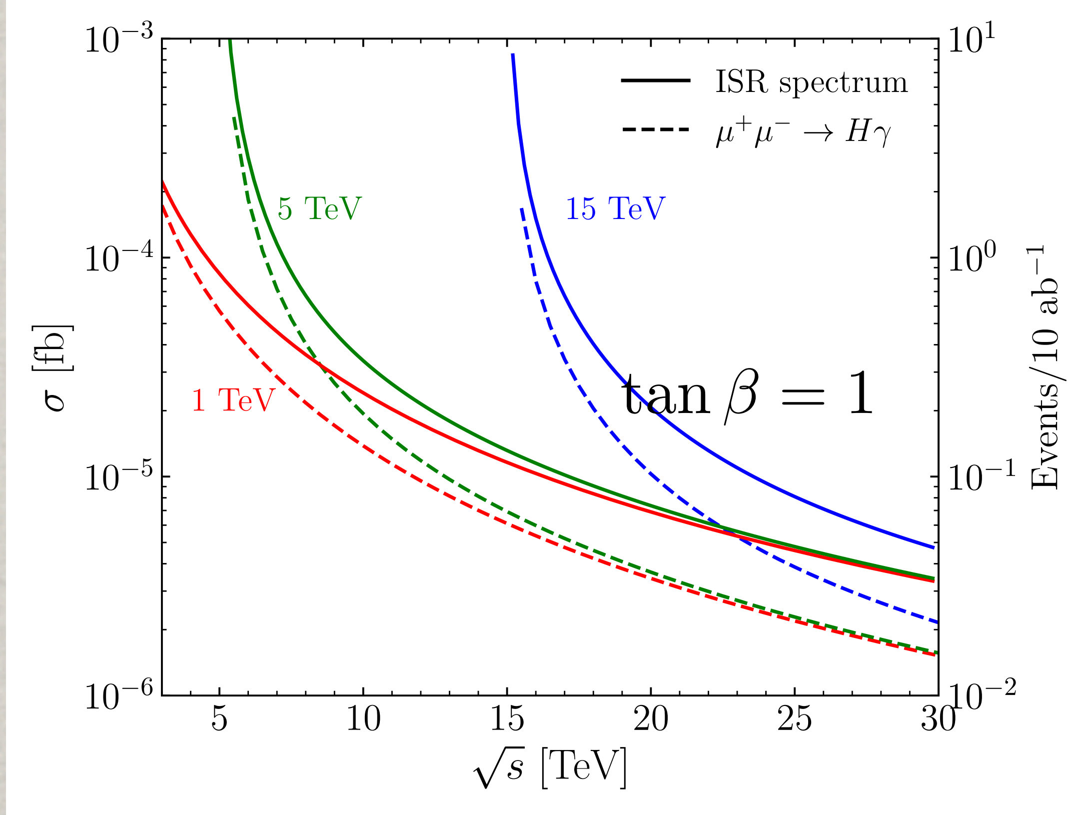


<table>
<tr><th></th><th>production</th><th>Type-I</th><th>Type-II</th><th>Type-F</th><th>Type-L</th></tr>
<tr><td rowspan="3">small $\tan\beta < 5$</td><td>H^+H^-</td><td colspan="4">$t\bar{b}, \bar{t}b$</td></tr>
<tr><td>$HA/HH/AA$</td><td colspan="4">$t\bar{t}, t\bar{t}$</td></tr>
<tr><td>$H^\pm H/A$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

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

Radiative returns:

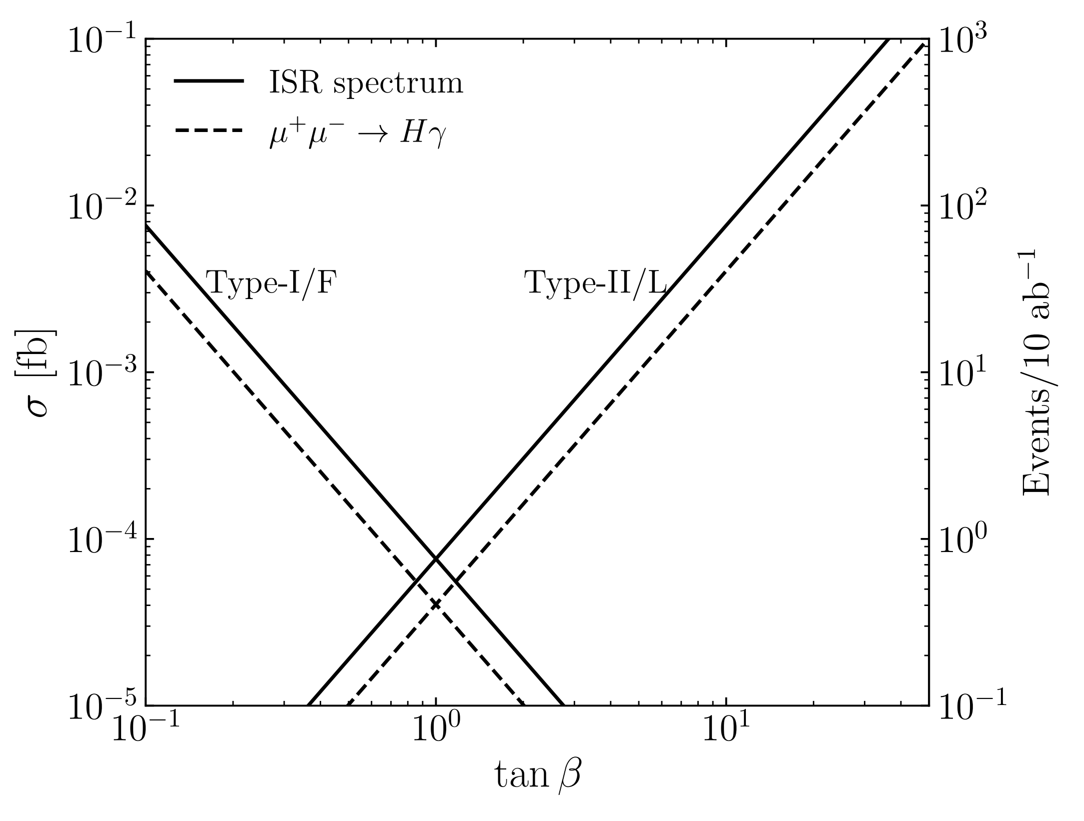




$$\hat\sigma(\mu^+\mu^- \to H) = \frac{\pi Y_\mu^2}{4}\delta(\hat s - m_H^2) = \frac{\pi Y_\mu^2}{4s}\delta(\tau - \frac{m_H^2}{s})$$

$$f_{\ell/\ell}(x) = \frac{\alpha}{2\pi}\frac{1+x^2}{1-x}\log\frac{s}{m_\mu^2}$$

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



Depending on the coupling,

$M_H \sim E_{cm}$

TH, S. Li, S. Su, W. Su, Y. Wu, arXiv:2102.08386;
TH, Z.Liu et al., arXiv:1408.5912.

Summary

- **s-channel Higgs factory:**
  - Direct measurements on Y_μ & Γ_H
  - Other BRs comparable to e^+e^- Higgs factories

- **Multi-TeV colliders:**
  - Unprecedented accuracies for WWH, WWHH, H^3, H^4
  - Bread & butter SM EW physics in the new territory

  - New particle (Q,H…) mass coverage $M_H \sim (0.5 - 1)E_{cm}$
  - Decisive coverage for minimal WIMP DM $M \sim 0.5\ E_{cm}$
  - Complementary to Astro/Cosmo/GW & to FCC-hh:

Exciting journey ahead!