Physics Opportunities at Muon Colliders

Tao Han, Univ. of Pittsburgh

The 4th Session of PLUB workshop

April 6, 2021

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, not covered here -- my apologies

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 (broad coverage on NP)
… …

Collider benchmark points:

- The Higgs factory:

$E_{cm} = m_H$

$L \sim 1\ \mathrm{fb}^{-1}/\mathrm{yr}$

$\Delta E_{cm} \sim 5$ MeV

Parameter	**Units**	**Higgs**
CoM Energy	TeV	0.126
Avg. Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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.

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

1 ab^{-1} /yr

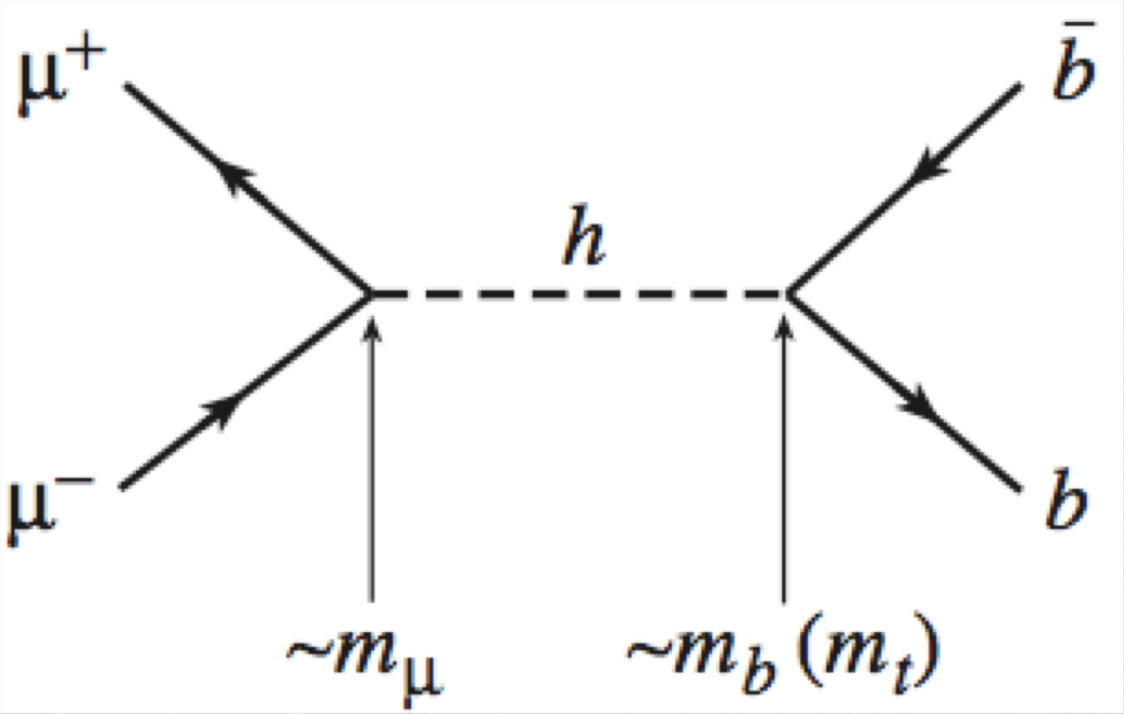
The aggressive choices:

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

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

1. A Higgs Factory

Resonant Production:



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

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

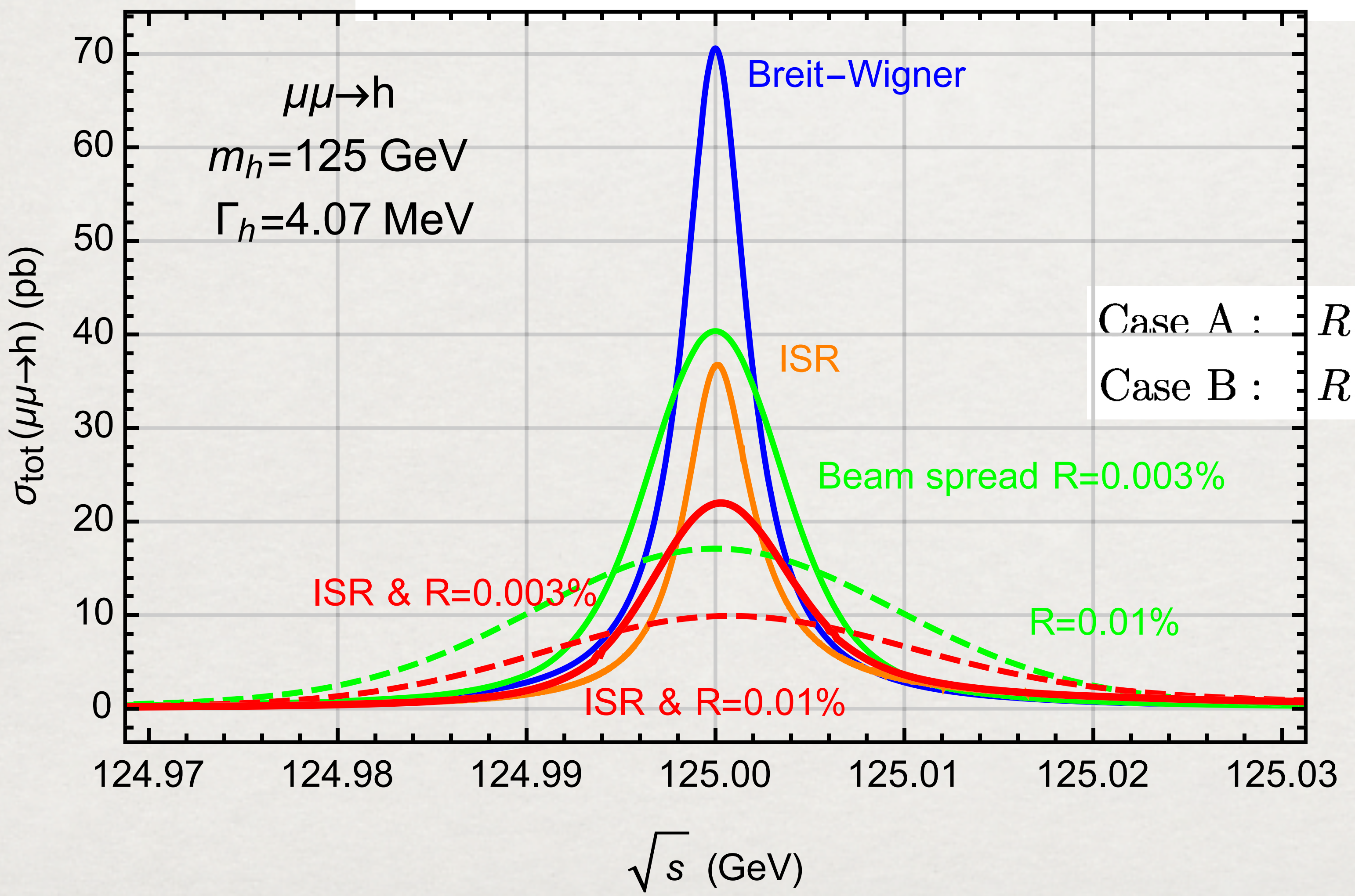
About O(40k) events produced per fb^{-1}

At m_h=125 GeV, Γ_h = 4.2 MeV

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

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

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



"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},

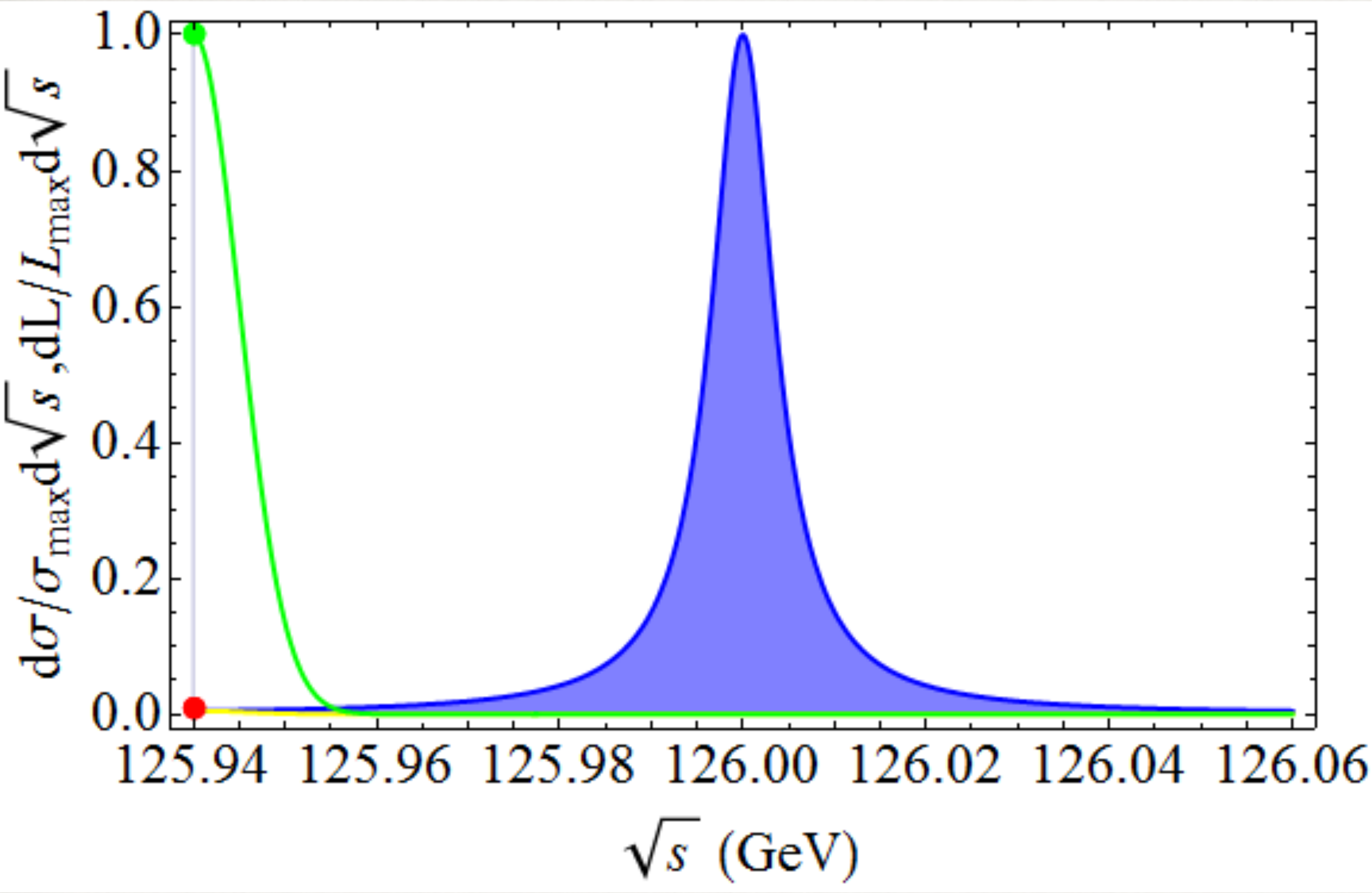
Case B : $R = 0.003\%$ ($\Delta = 2.7$ MeV), $L = 1$ fb^{-1}.

TH, Liu: 1210.7803;

Greco, TH, Liu: 1607.03210

Ideal, conceivable case:

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



An optimal fitting 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

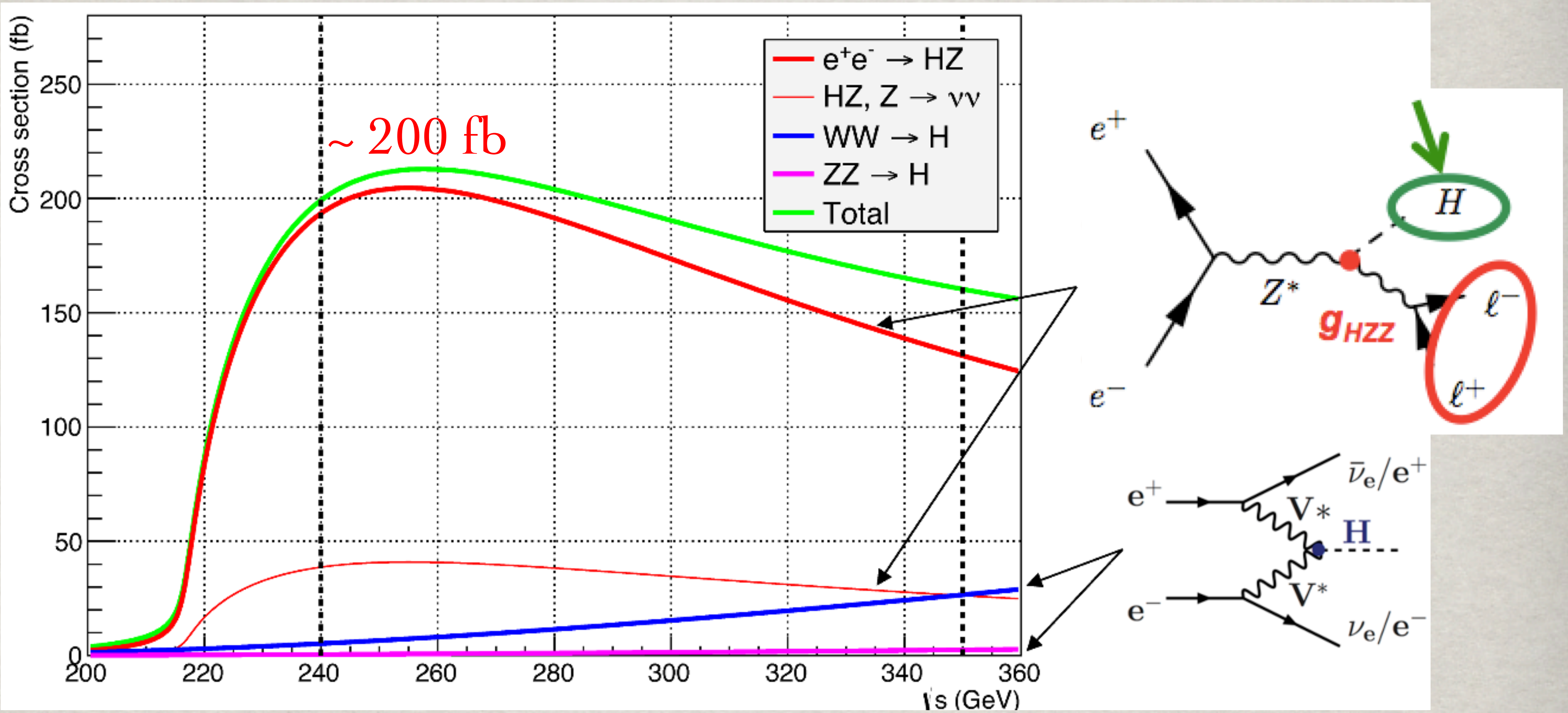
Table 3
Fitting accuracies for one standard deviation of Γ_h, B and m_h of the SM Higgs with the scanning scheme for two representative luminosities per step and two bench-mark beam energy spread parameters.

$\Gamma_h = 4.07$ 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

Comparison w/ an e^+e^- Higgs-Factory: 10^6 Higgs



ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1}

- Model-independent measurement: ILC Report: 1308.6176

  $\Gamma_H \sim 6\%$, $\Delta m_H \sim 30$ MeV

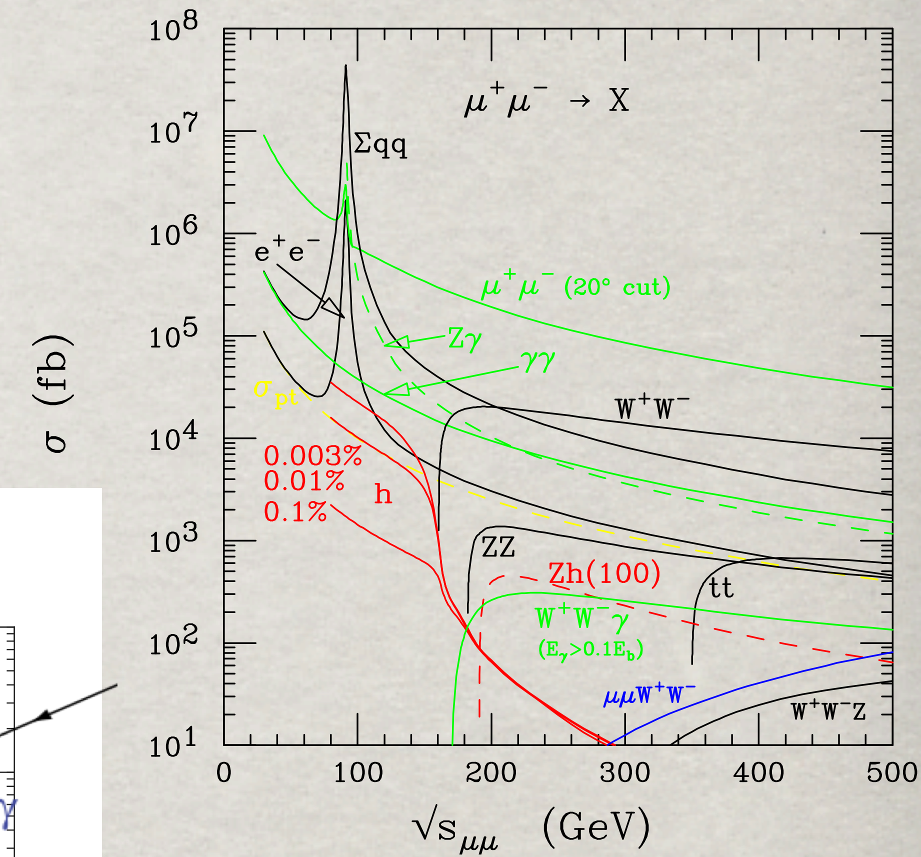
  (HL-LHC: assume SM, $\Gamma_H \sim$ 5-8%, $\Delta m_H \sim 50$ MeV)

- CEPC/FCC-ee: **10^6** Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

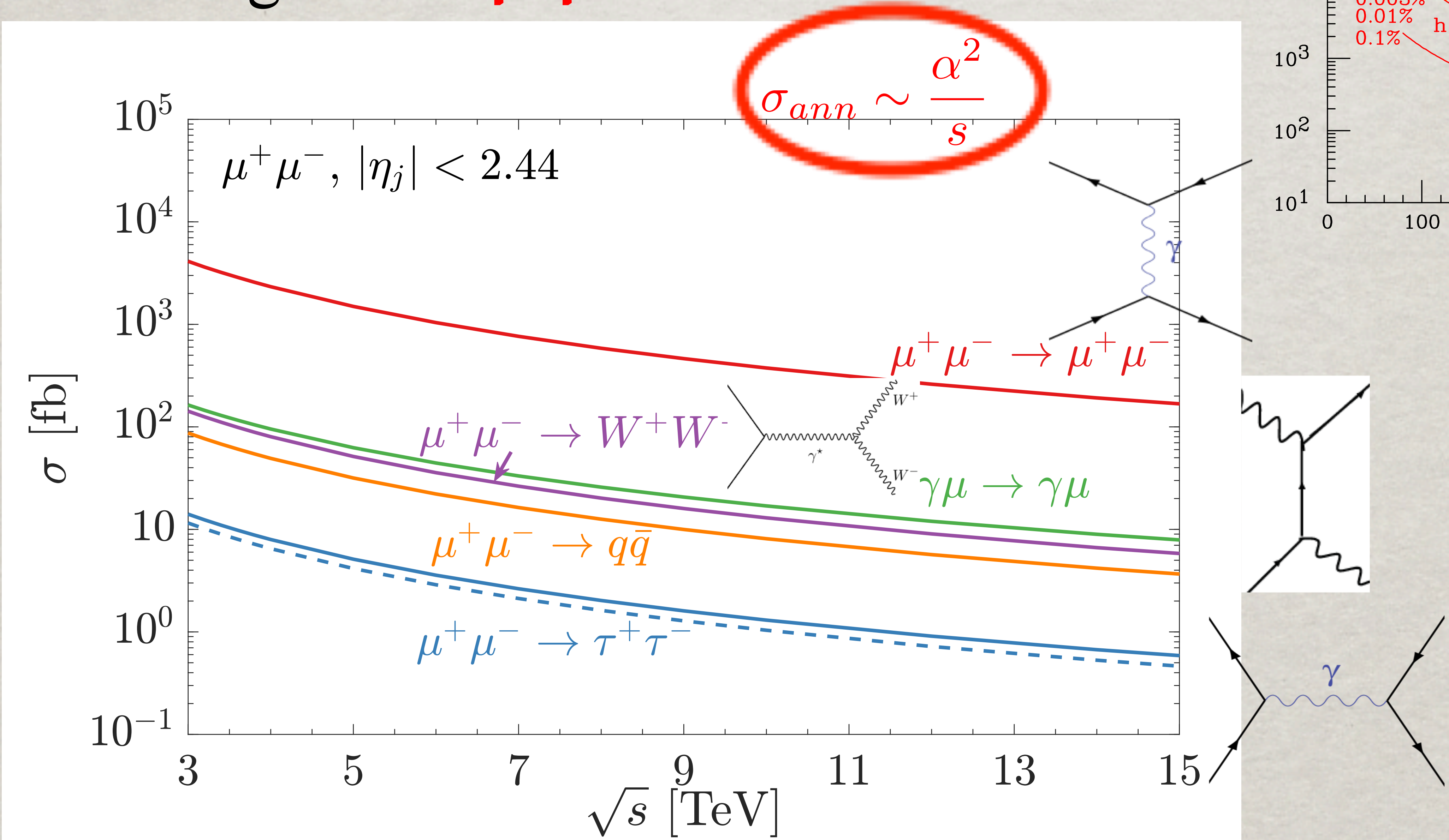
TLEP Report: 1308.6176; CEPC & FCC-ee CDRs

2. A Multi-TeV Muon Collider

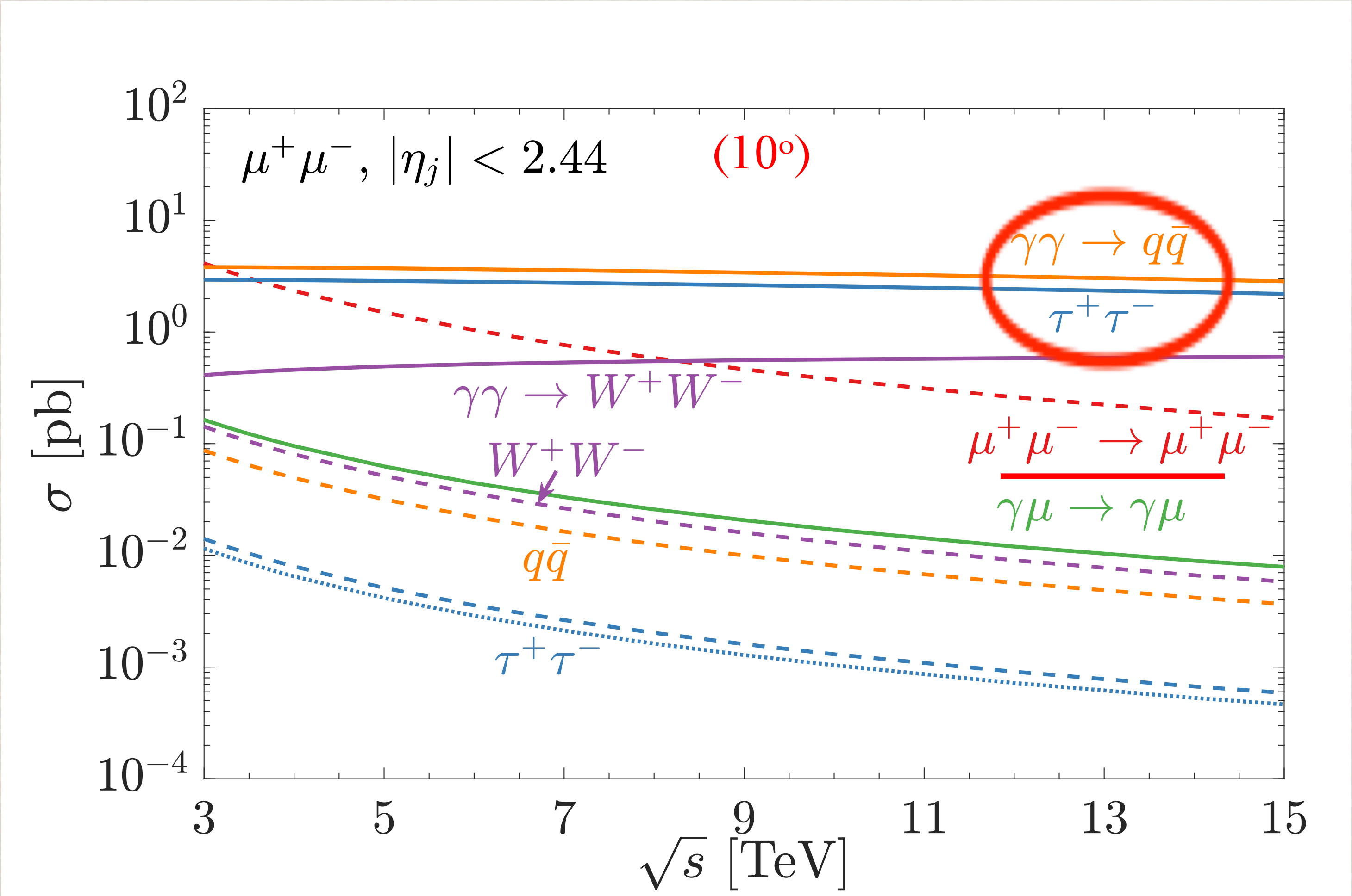
What will happen when you turn on a $\mu^+\mu^-$ Smasher?

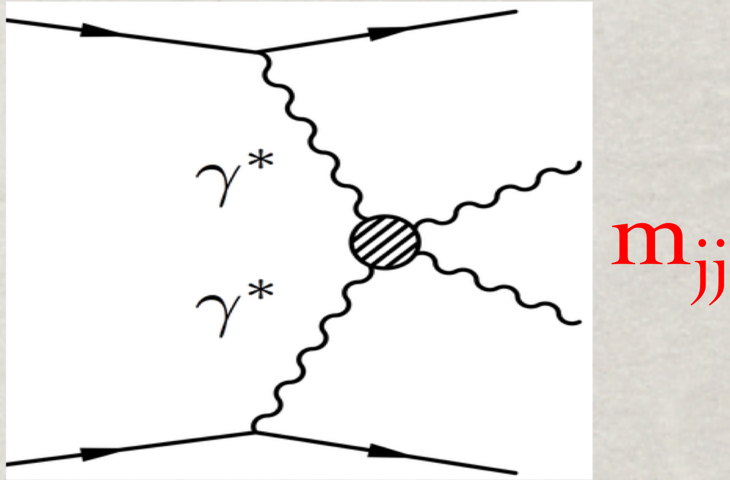


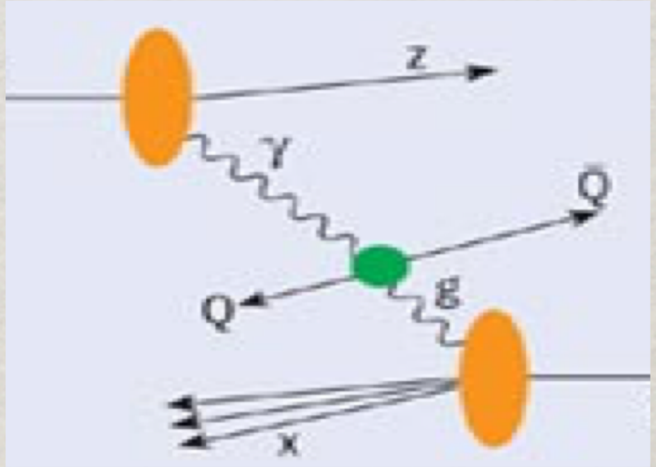
Leading-order $\mu^+\mu^-$ annihilation:



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





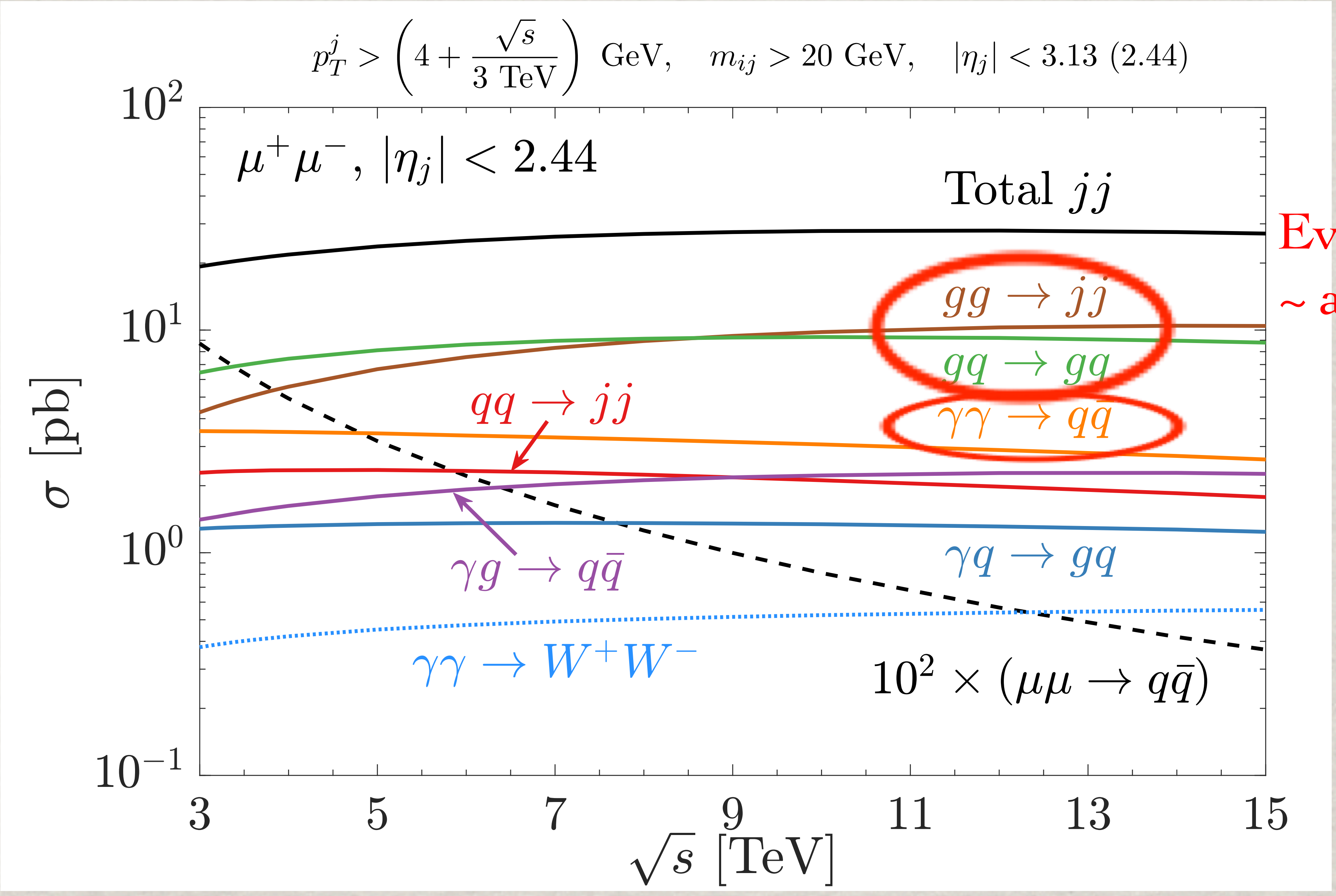


$$p_T^j > \left(4 + \frac{\sqrt{s}}{3\ \text{TeV}}\right)\ \text{GeV}, \quad m_{ij} > 20\ \text{GeV}, \quad |\eta_j| < 3.13\ (2.44)$$

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 $gg \to gg(q\bar{q})$

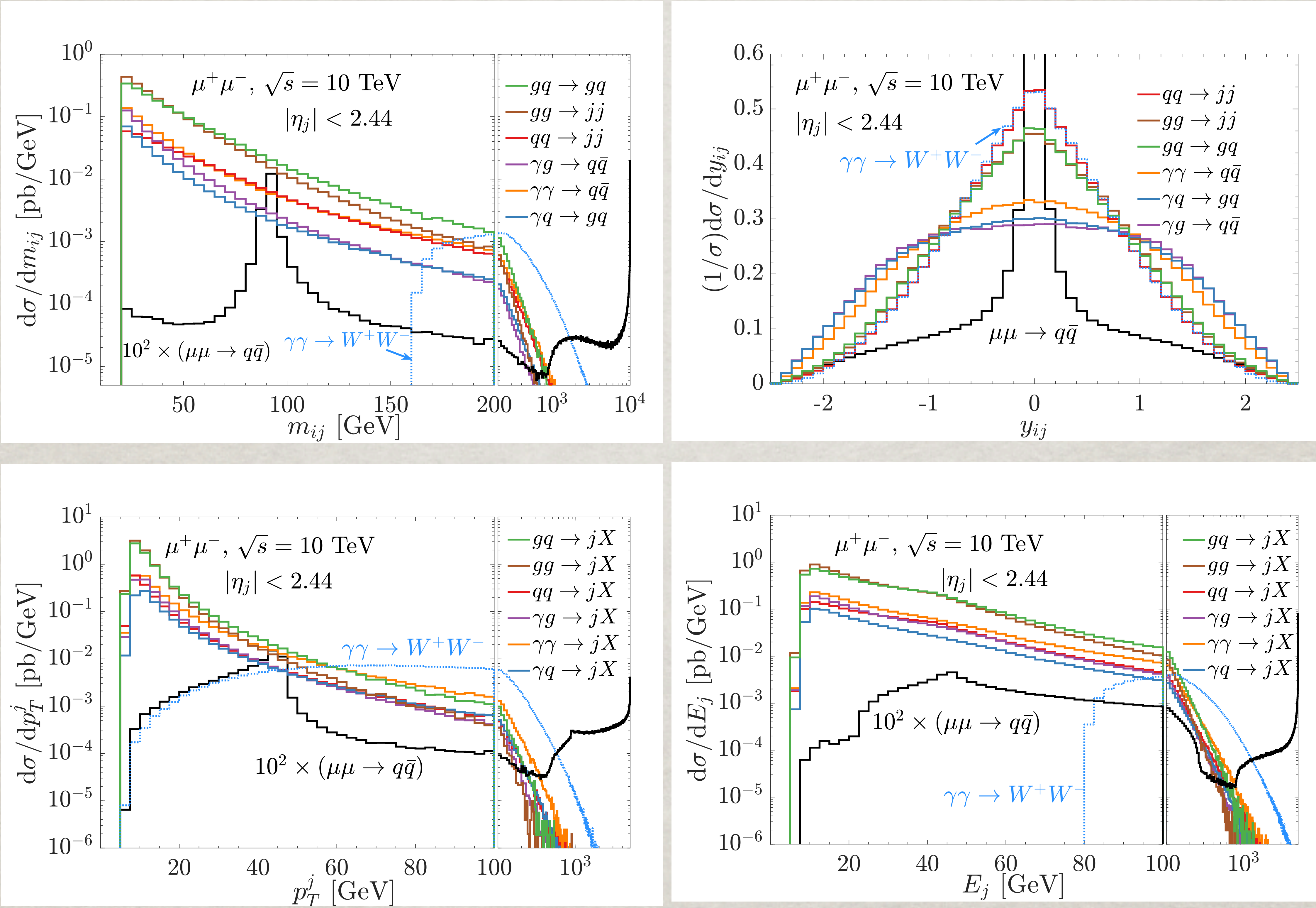


Event rate ~ a few Hz

→ Jet production dominates at low energies

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

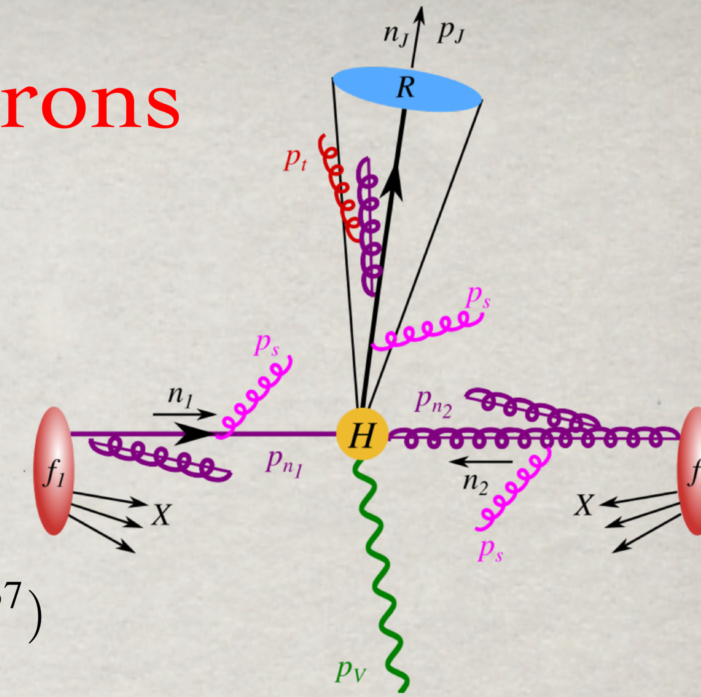
Di-jet kinematical features



To effectively separate the QCD backgrounds:

$p_T > 60$ GeV

Total cross sections: **γγ** and **μ⁺μ⁻ → hadrons**

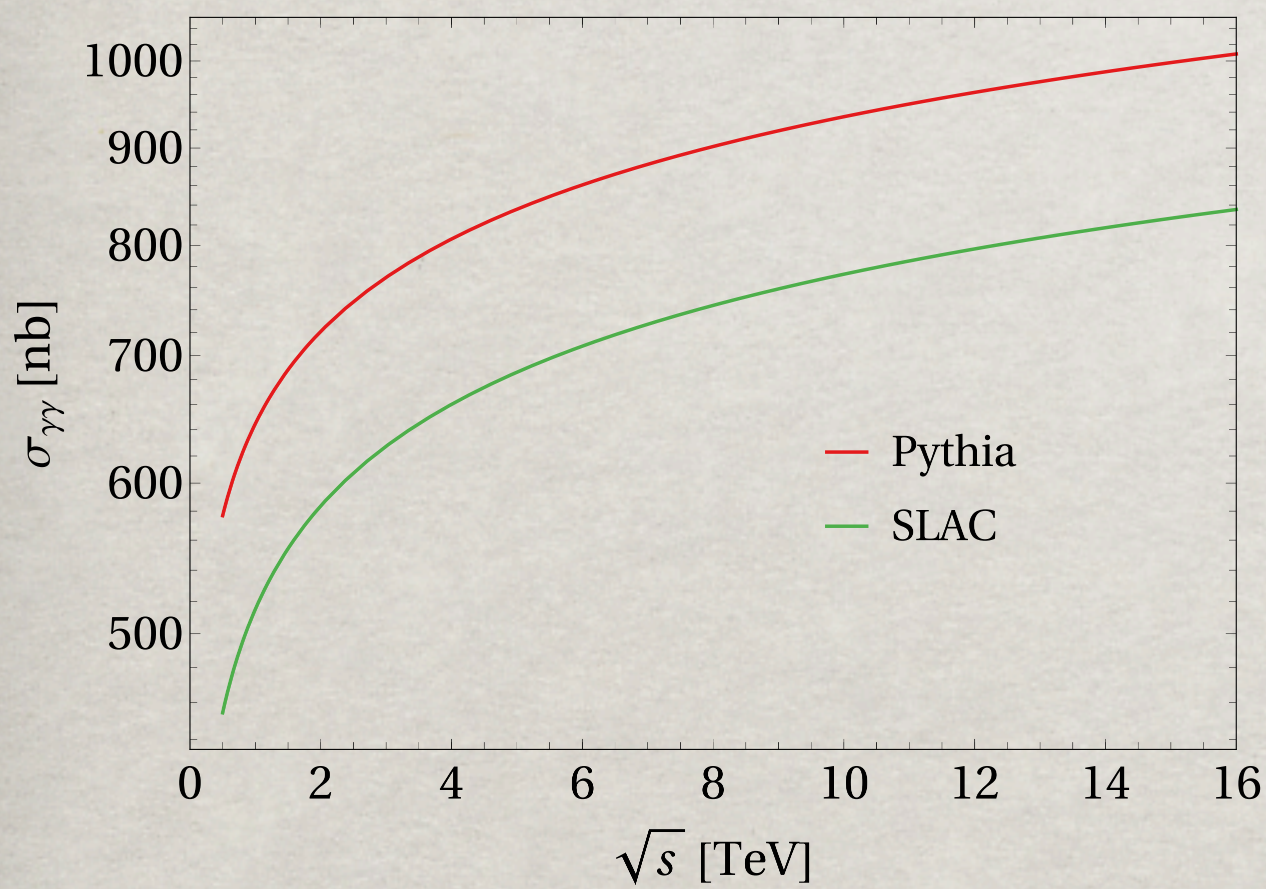


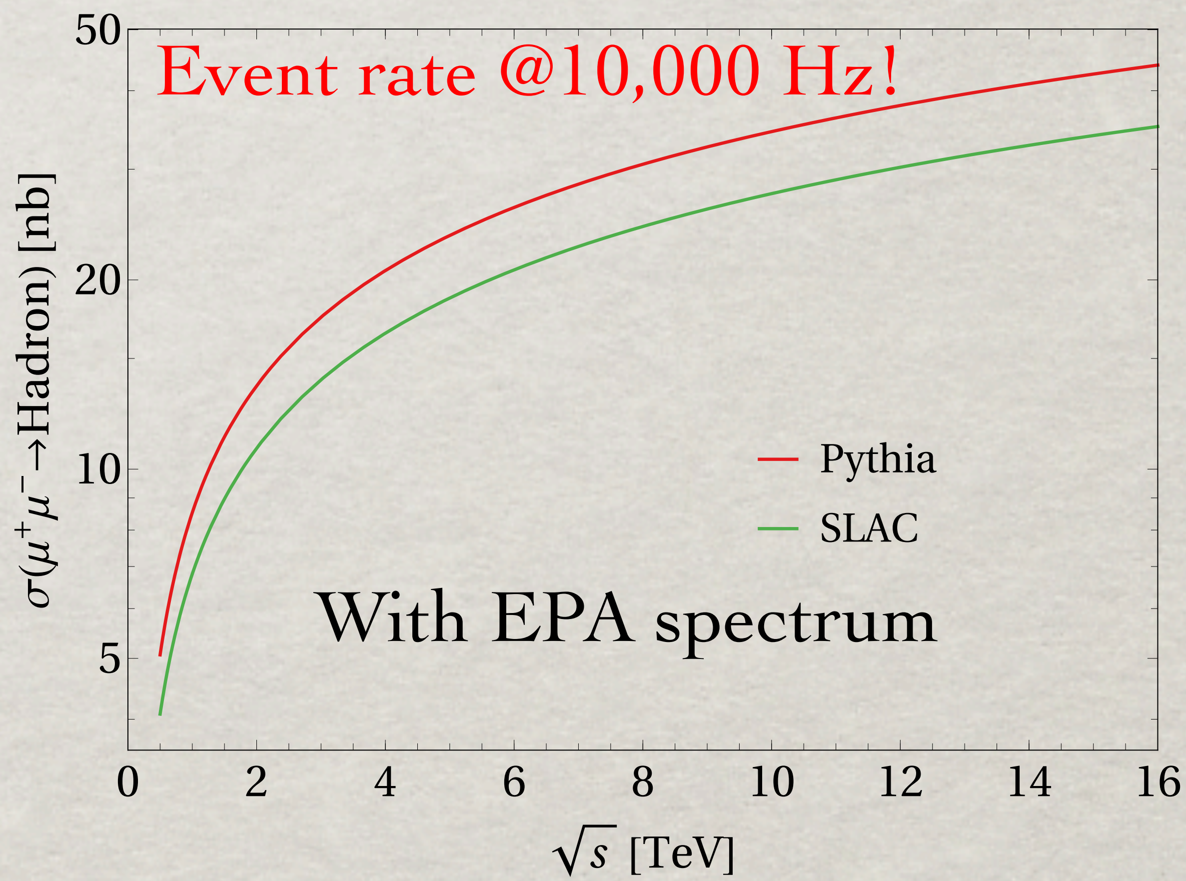
PYTHIA parameterization:

$$\sigma_{\gamma\gamma}(E^2_{cm}) = 211\ \mathrm{nb}(E^2_{cm}\mathrm{GeV}^{-2})^{0.0808} + 215\ \mathrm{nb}(E^2_{cm}\mathrm{GeV}^{-2})^{-0.4525}$$

SLAC parameterization:

$$\sigma_{\gamma\gamma}(E^2_{cm}) = 200\ \mathrm{nb}(1 + 0.0063[\ln(E^2_{cm}\mathrm{GeV}^{-2})]^{2.1} + 1.96(E^2_{cm}\mathrm{GeV}^{-2})^{-0.37})$$





Events populated at $p_T^{hadrons}$ < a few GeV

T. Barklow, D. Dannheim, M.O. Sahin & D. Schulte, LCD-Note-2011-020.

- **EW physics at ultra-high energies:**

$$\frac{v}{E}: \ \frac{v\ (250\ \mathrm{GeV})}{10\ \mathrm{TeV}} \approx \frac{\Lambda_{QCD}\ (300\ \mathrm{MeV})}{10\ \mathrm{GeV}}$$

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

- A massless theory:
  → splitting phenomena dominate!
- EW symmetry restored:
  → $SU(2)_L \times U(1)_Y$ unbroken gauge theory
- v/E as power corrections
  → Higher twist effects.

J. Chen, TH, B. Tweedie, arXiv:1611.00788;
G. Cuomo, A. Wulzer, arXiv:1703.08562; 1911.12366.
Ciafaloni et al., hep-ph/0004071; 0007096; A. Manohar et al., 1803.06347.
C. Bauer, Ferland, B. Webber et al., arXiv:1703.08562; 1808.08831.

EW splitting functions:

Start from the unbroken phase – all massless.

$$\mathcal{L}_{SU(2)\times U(1)} = \mathcal{L}_{gauge} + \mathcal{L}_{\phi} + \mathcal{L}_{f} + \mathcal{L}_{Yuk}$$

Chiral fermions: f_s, gauge bosons: $B, W^0, W^{\pm}$; $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(h - i\phi^0) \end{pmatrix}$

e.g.: fermion splitting:

	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{1+\bar{z}^2}{z}\right)$		$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{z}{2}\right)$
	$\to V_T\ f_s^{(\prime)}$	$[BW]_T^0\ f_s$	$H^{0(*)}\ f_{\text{-}s}$ or $\phi^{\pm}\ f'_{\text{-}s}$
$f_{s=L,R}$	$g_V^2 (Q_{f_s}^V)^2$	$g_1 g_2 Y_{f_s} T_{f_s}^3$	$y^2_{f_R^{(\prime)}}$

Ciafaloni et al., Hep-ph/0505047.

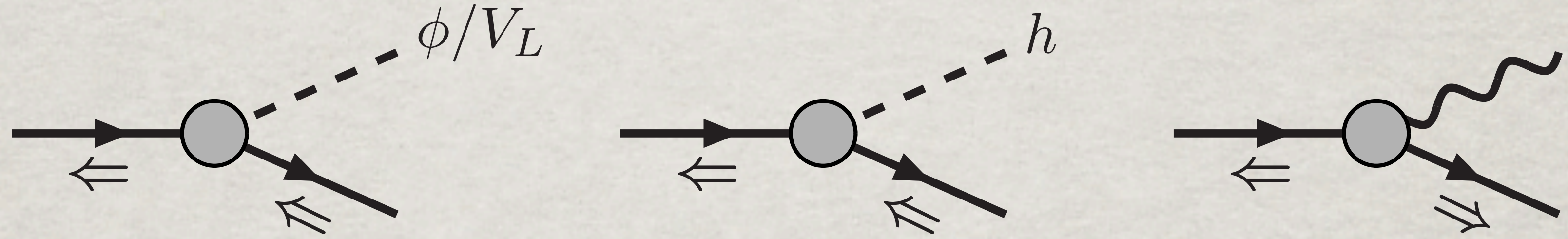
Infrared & collinear singularities (P_{gq})

Collinear singularity, Chirality-flip, Yukawa

Splitting in a broken gauge theory:

New fermion splitting: $\frac{v^2}{k_T^2}\,\frac{dk_T^2}{k_T^2} \sim (1 - \frac{v^2}{Q^2})$

V_L is of IR, h no IR



$$\frac{\frac{1}{16\pi^2}\,\frac{v^2}{\tilde{k}_T^4}\left(\frac{1}{z}\right)}{\to\ V_L\ f_s^{(\prime)}\ (V\neq\gamma)} \qquad \frac{\frac{1}{16\pi^2}\,\frac{v^2}{\tilde{k}_T^4}}{h\ f_s} \qquad \frac{\frac{1}{16\pi^2}\,\frac{v^2}{\tilde{k}_T^4}}{V_T\ f_{\text{-}s}^{(\prime)}}$$

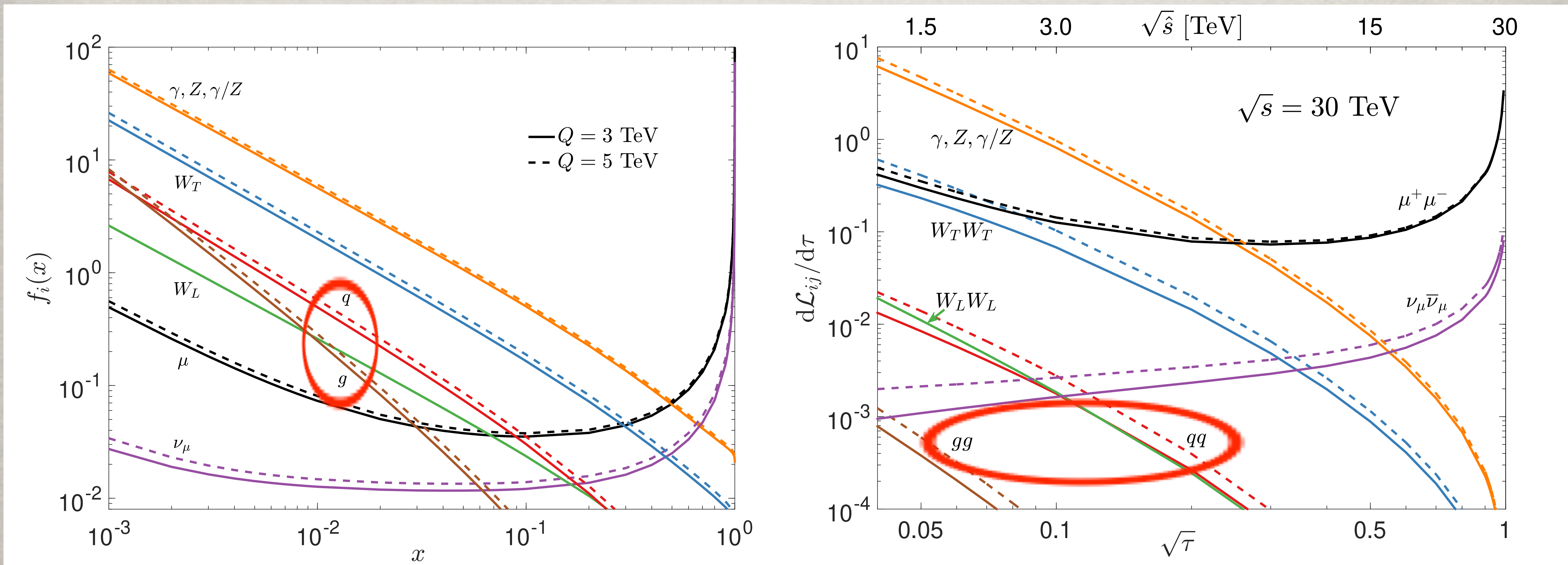
Chirality conserving:
Non-zero for massless f

Chirality flipping:
$\sim m_f$

The DPFs for W_L thus don't run at leading log:
"Bjorken scaling" restored (higher-twist effects)!

• 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.

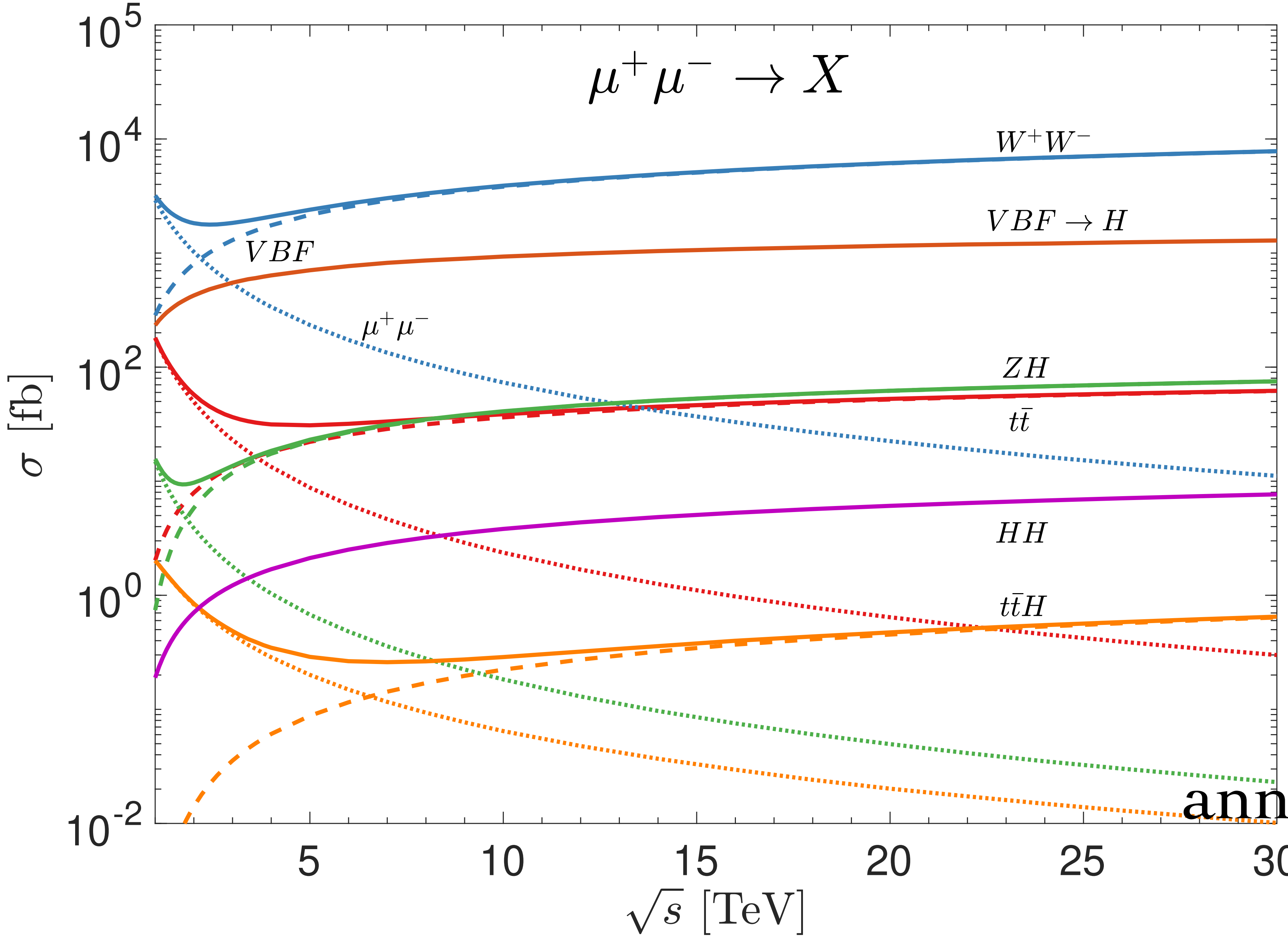
Quarks: NLO; gluons: NNLO.

TH, Yang Ma, Keping Xie, arXiv:2007.14300

• "Semi-inclusive" processes

Just like in hadronic collisions:

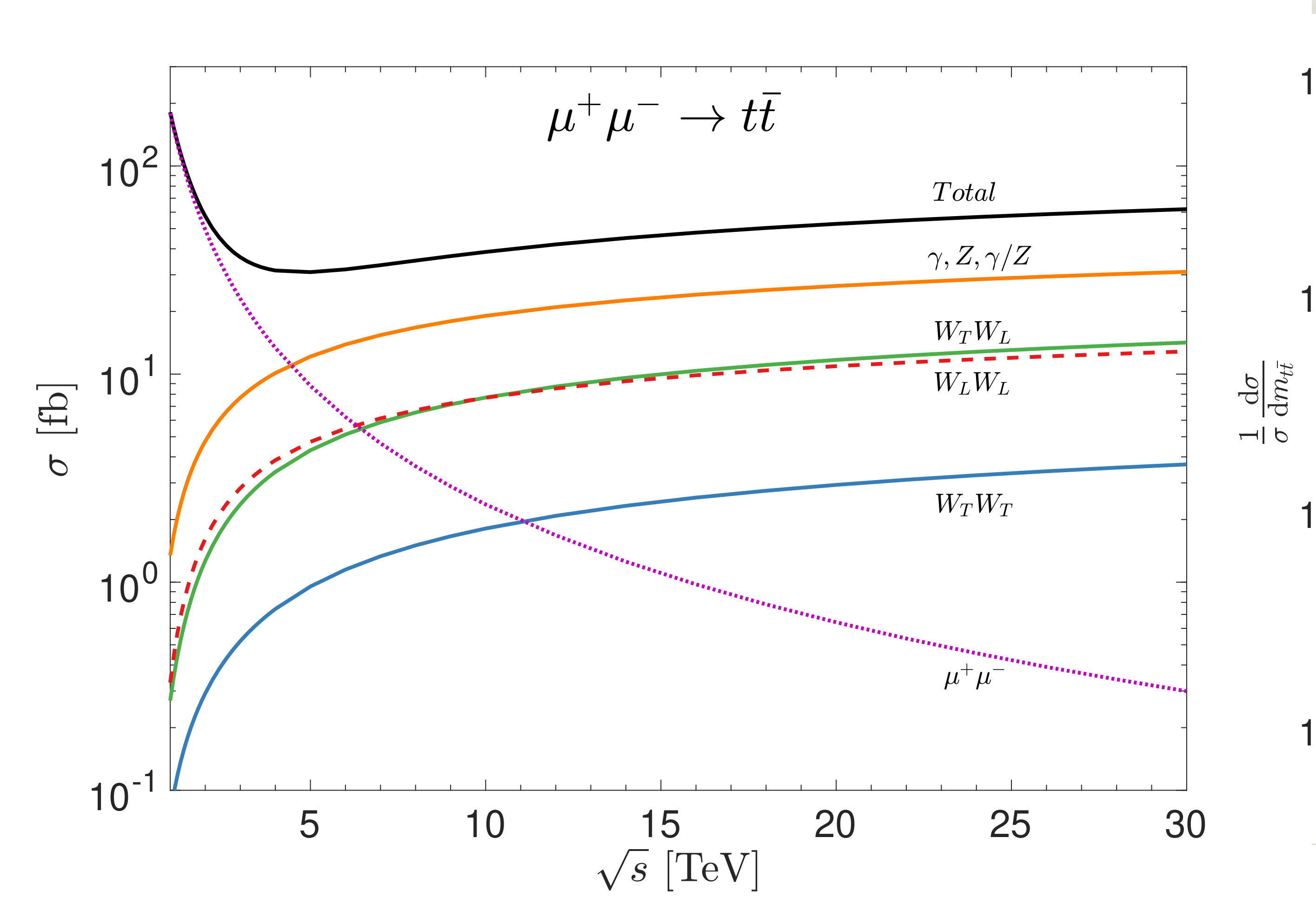
$\mu^+\mu^-$ → exclusive particles + remnants

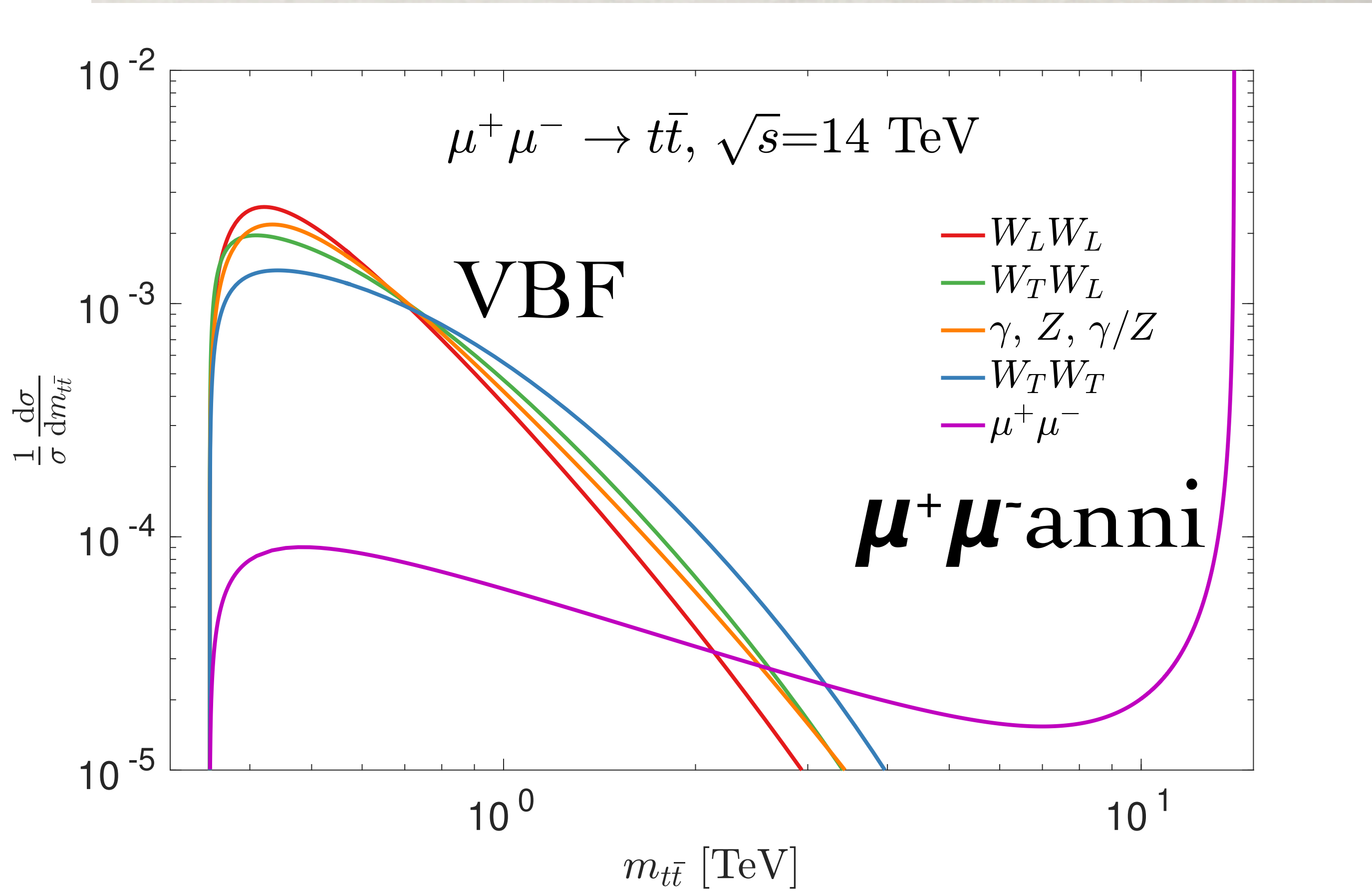


VBF

$\mu^+\mu^-$ annihilations

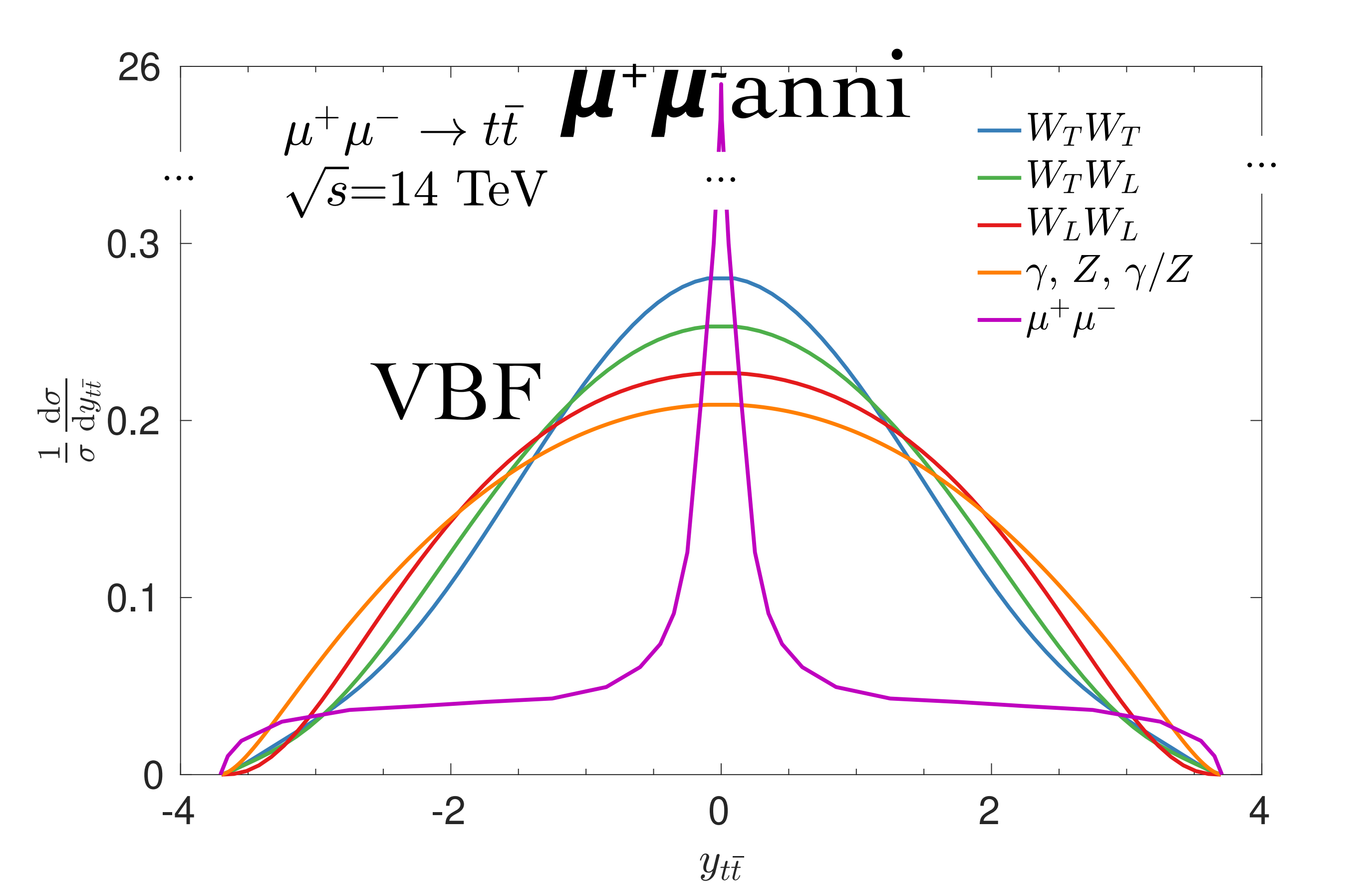
Underlying sub-processes:





Partonic contributions

$\mu^+\mu^-$ Collider:
"Buy one, get one free"
Annihilation +VBF

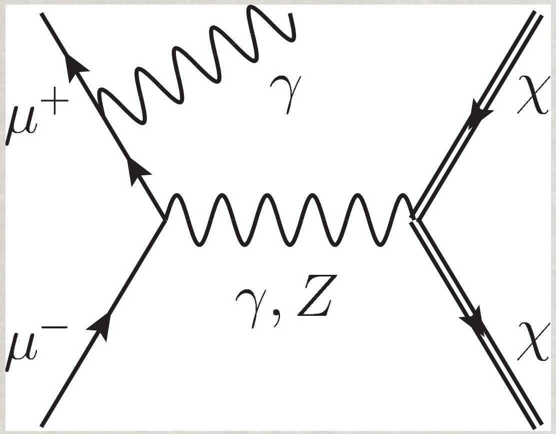


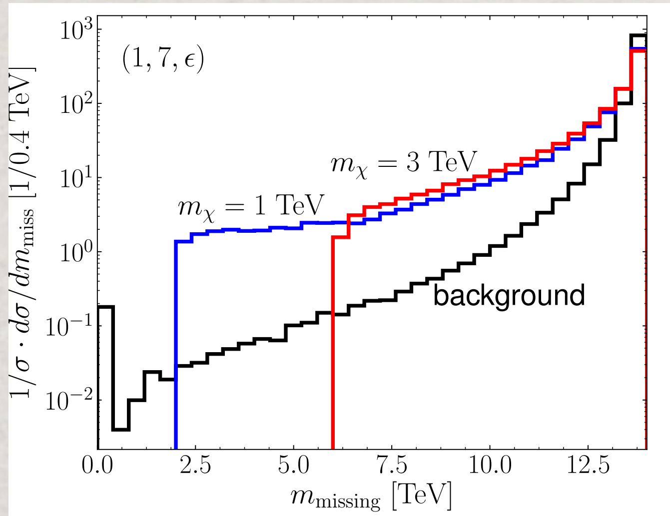
Unique kinematic features:

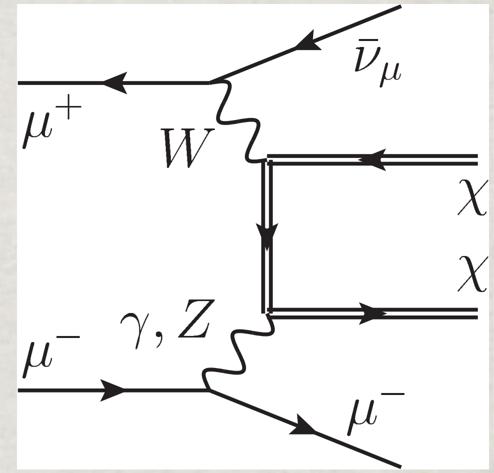
- "Recoil mass" → "missing mass": $m^2_{\rm missing} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\rm obs})^2$

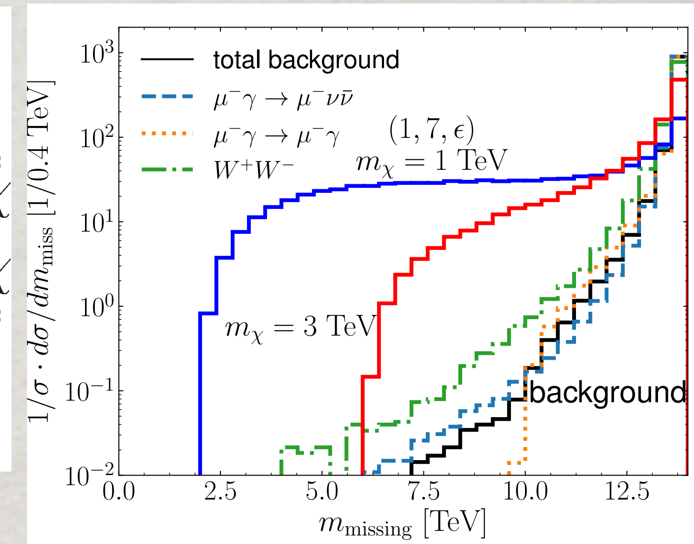
$m^2_{\rm missing} \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > 4m_\chi^2$

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



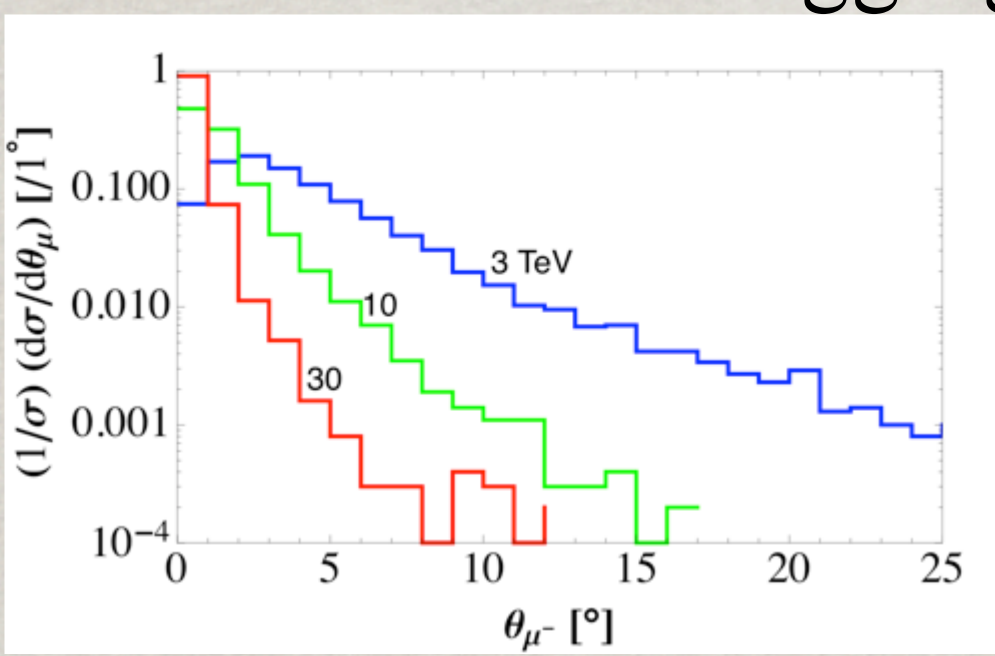


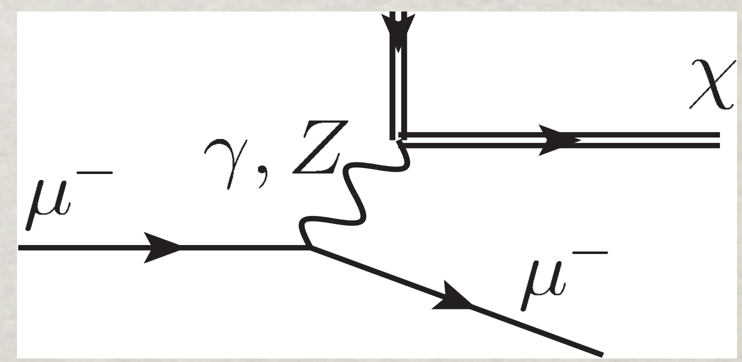




Unavailable in hadronic collisions!

- 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 ?

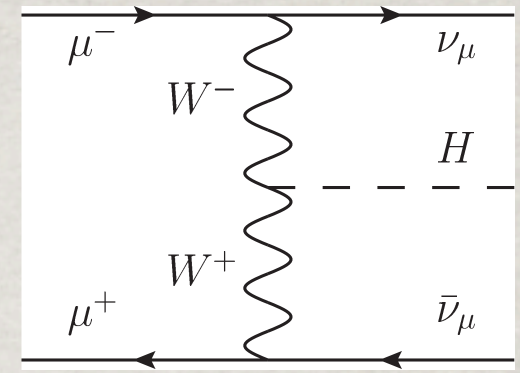
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

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

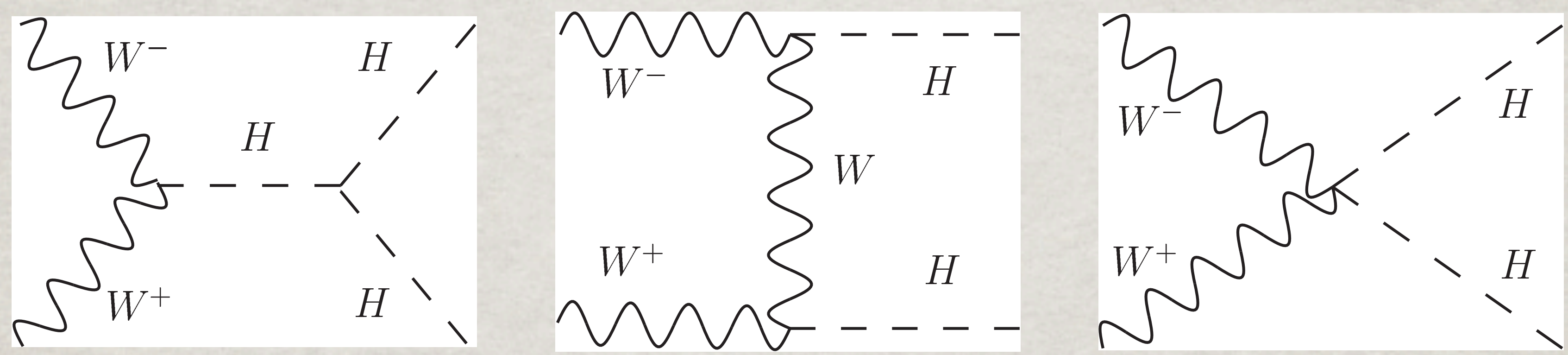
- # Precision Higgs Physics

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

WWH / ZZH couplings



HHH / WWHH couplings:



(a) (b) (c)

$\sqrt{s}$ (TeV)	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

10M H

500k HH

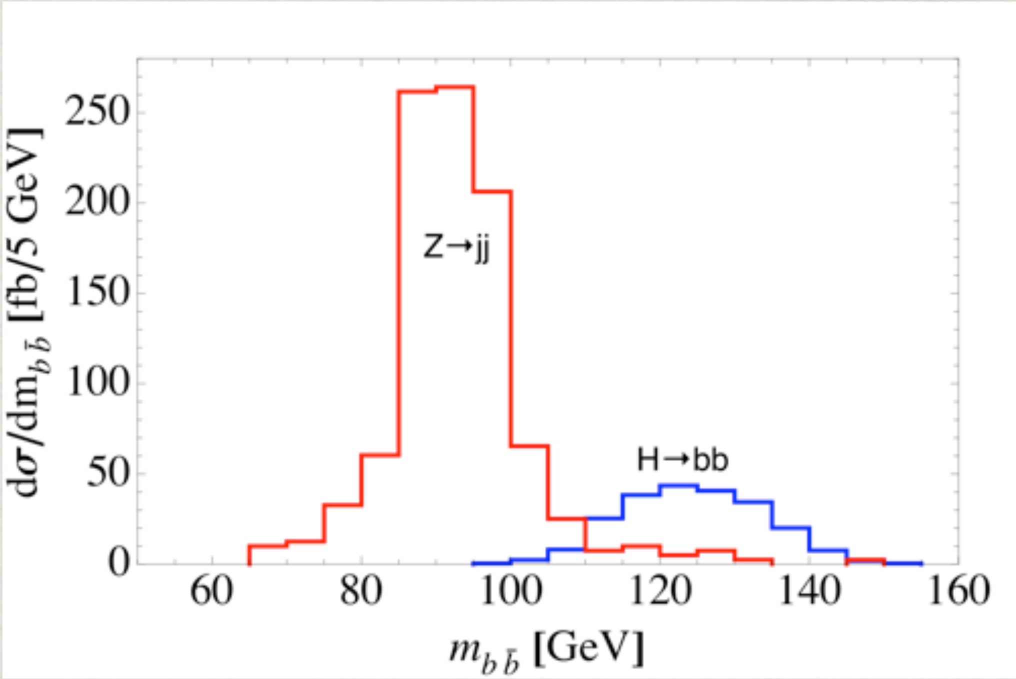
TH, D. Liu, I. Low,
X. Wang, arXiv:2008.12204

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

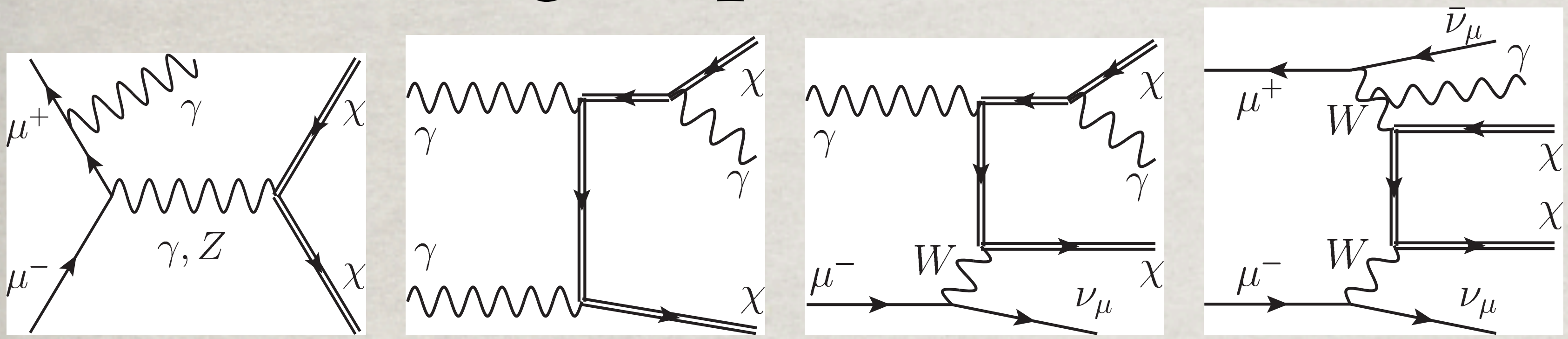
- The lightest neutral component as DM
- Interactions well defined → pure gauge
- Mass upper limit predicted → thermal relic abundance

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

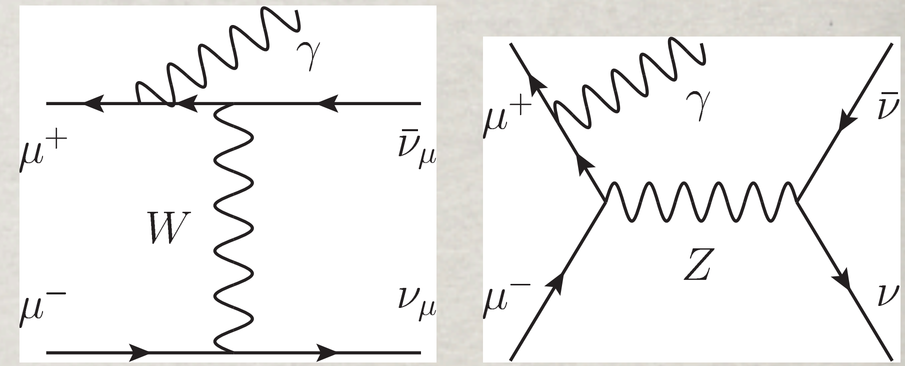
1. Mono-photon signal: A single photon against missing particles

Signal production:



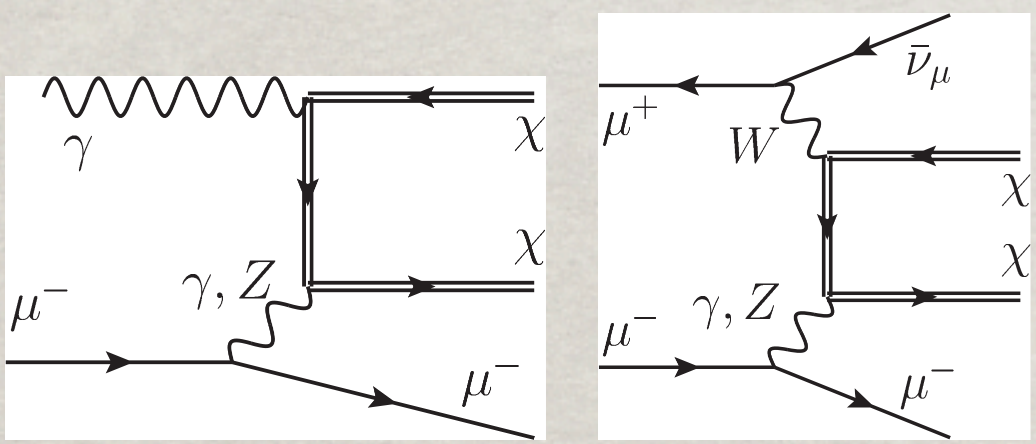
(a) (b) (c) (d)

Backgrounds:

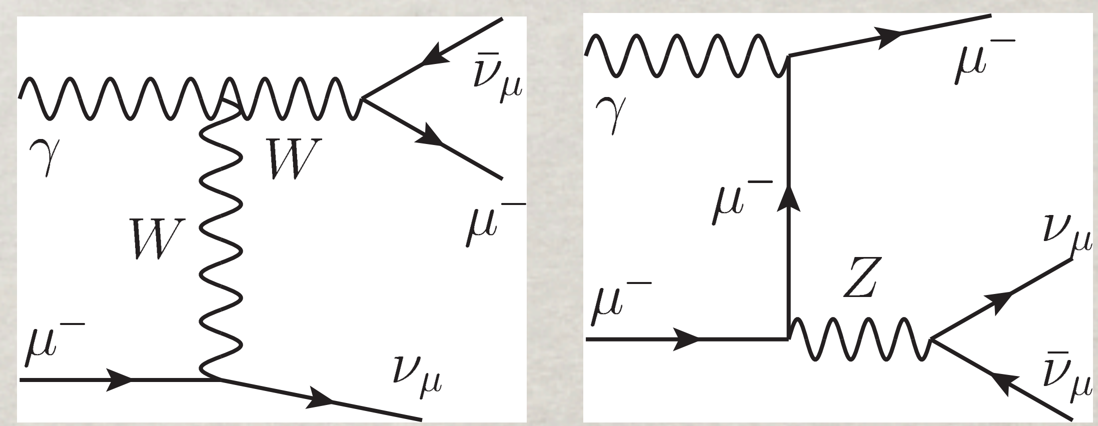


(a) (b)

2. Mono-muon signal: A single muon against missing particles



(a) (b)

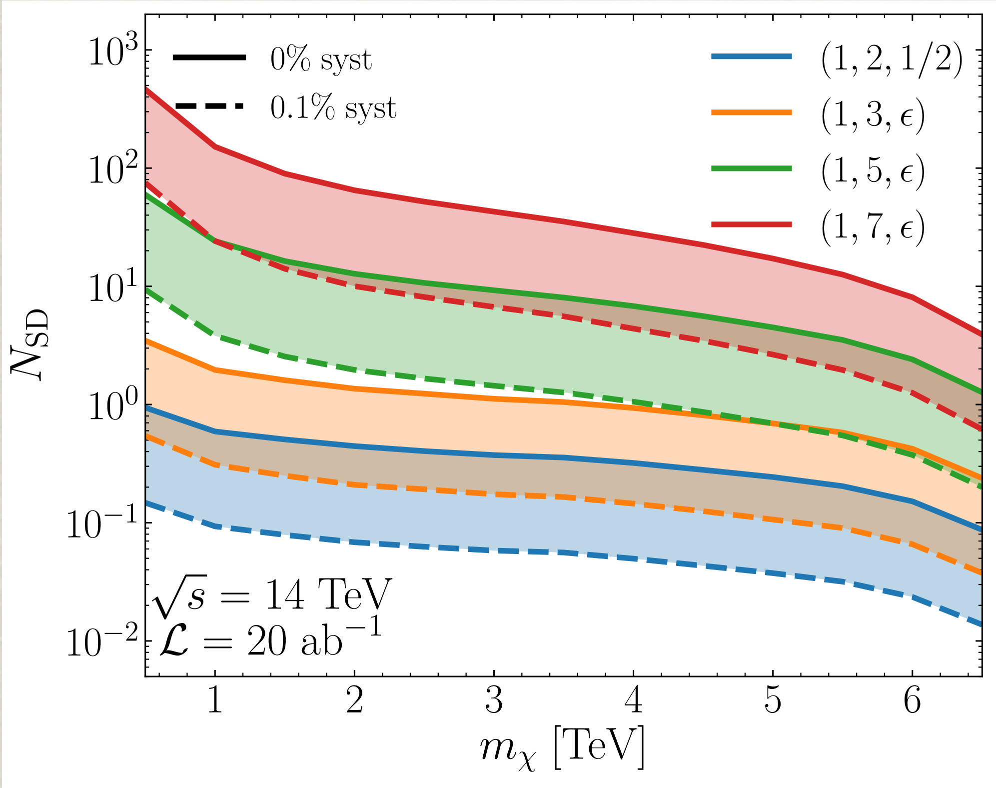


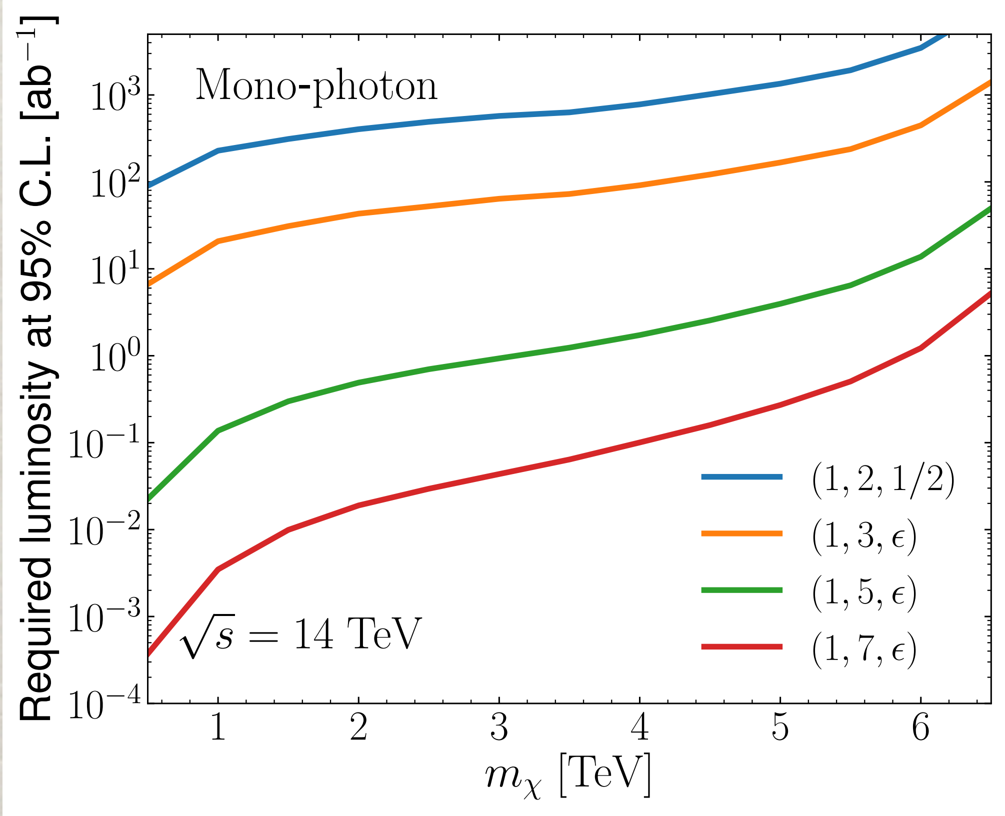
(a) (b)

$\chi^{\pm} \rightarrow \chi_0 +$ soft particles

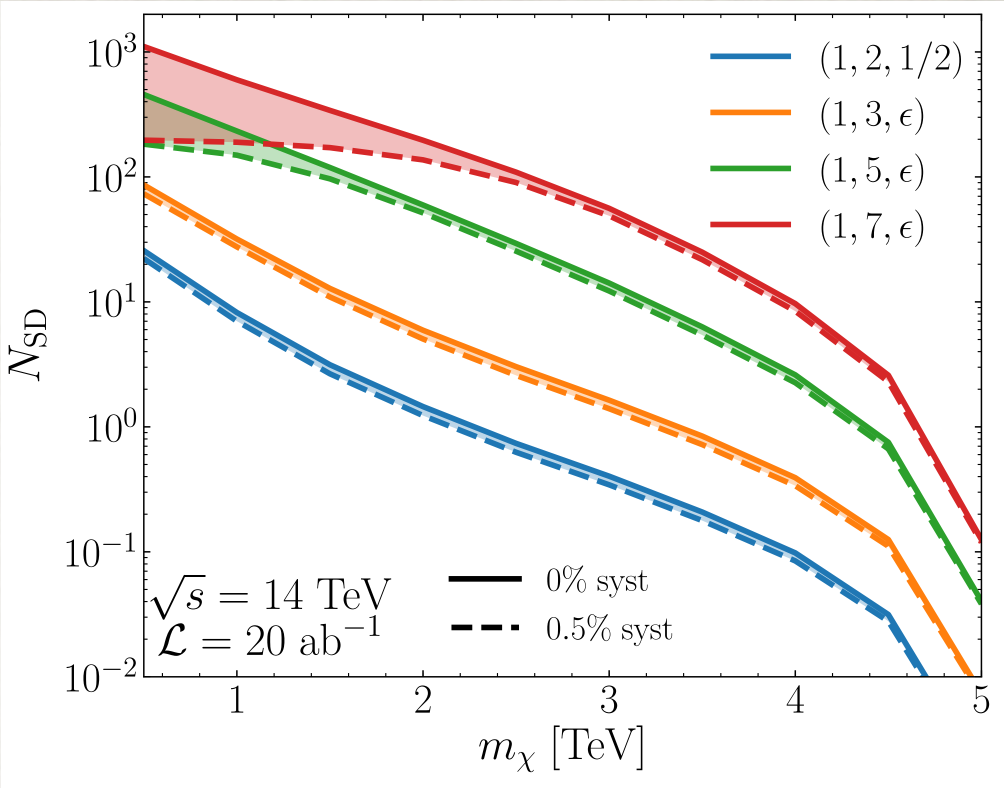
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

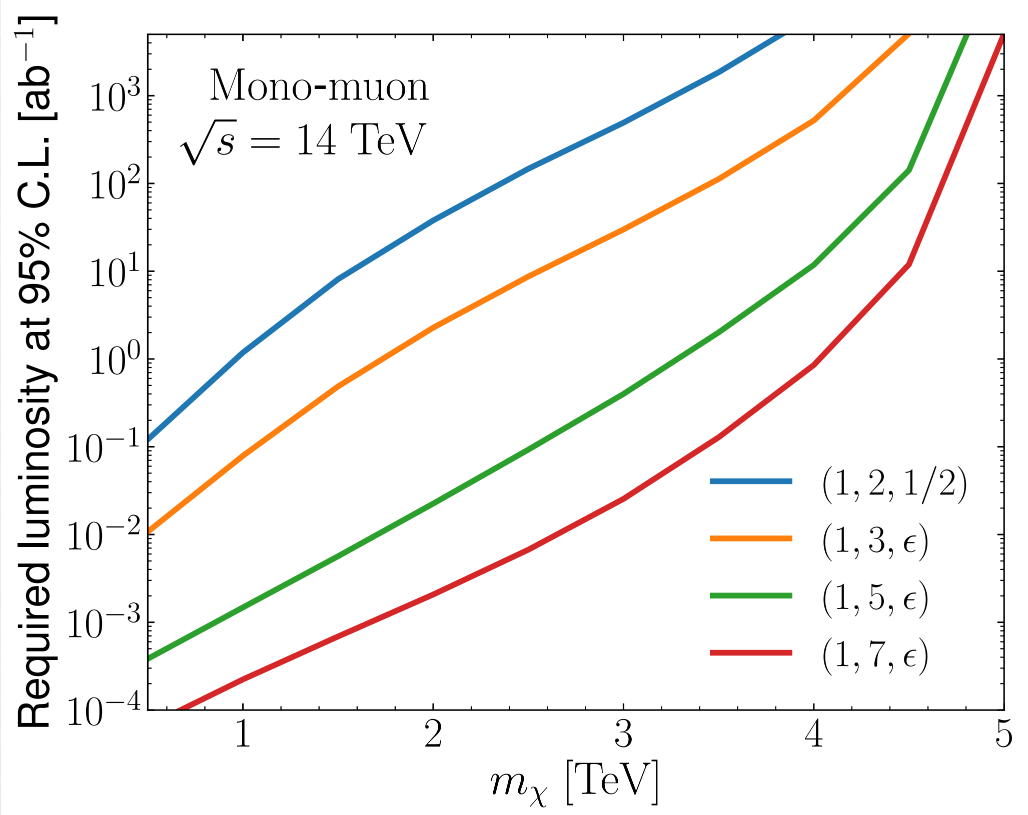
Mono-photon channel:





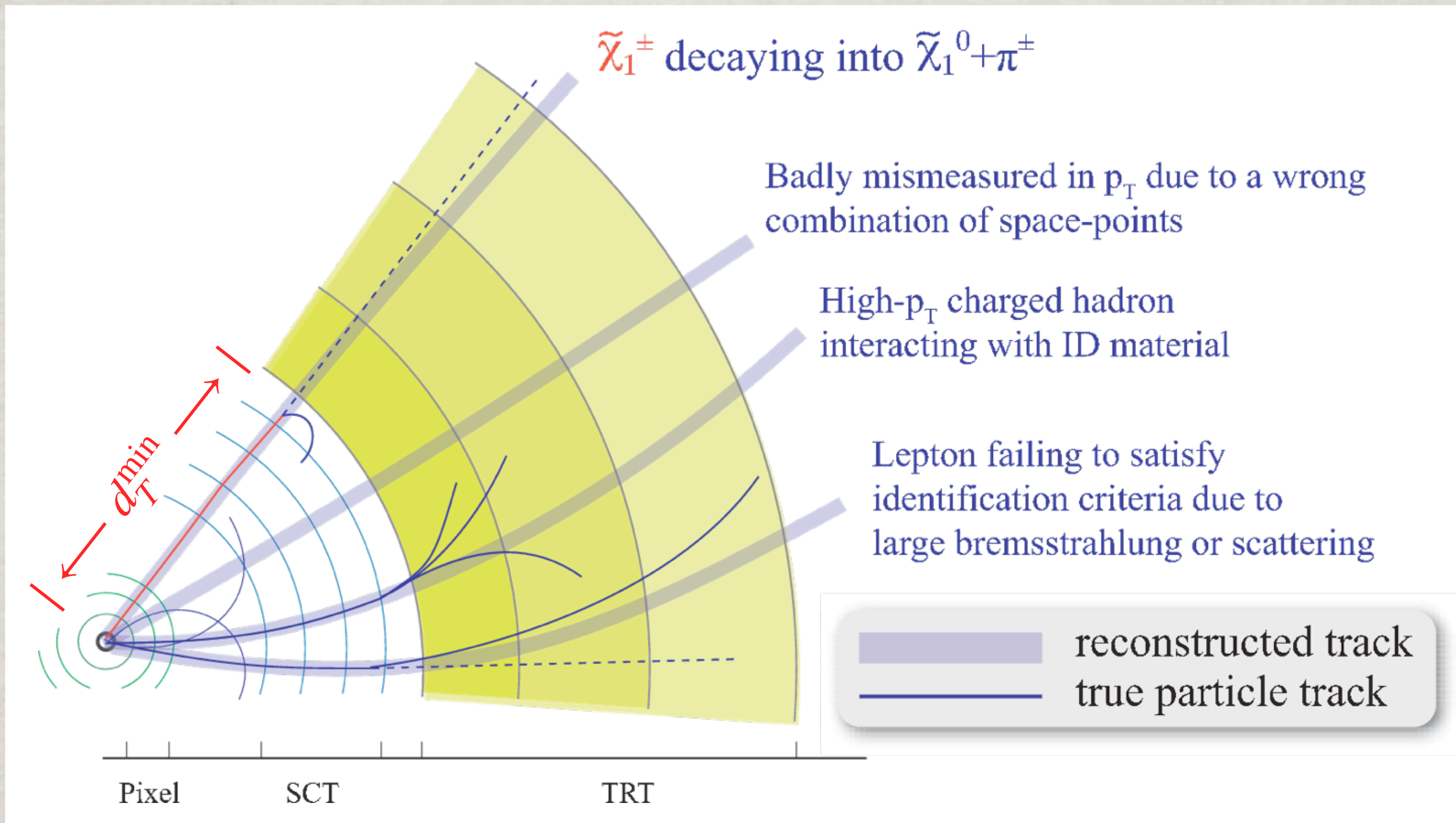
Mono-muon channel:





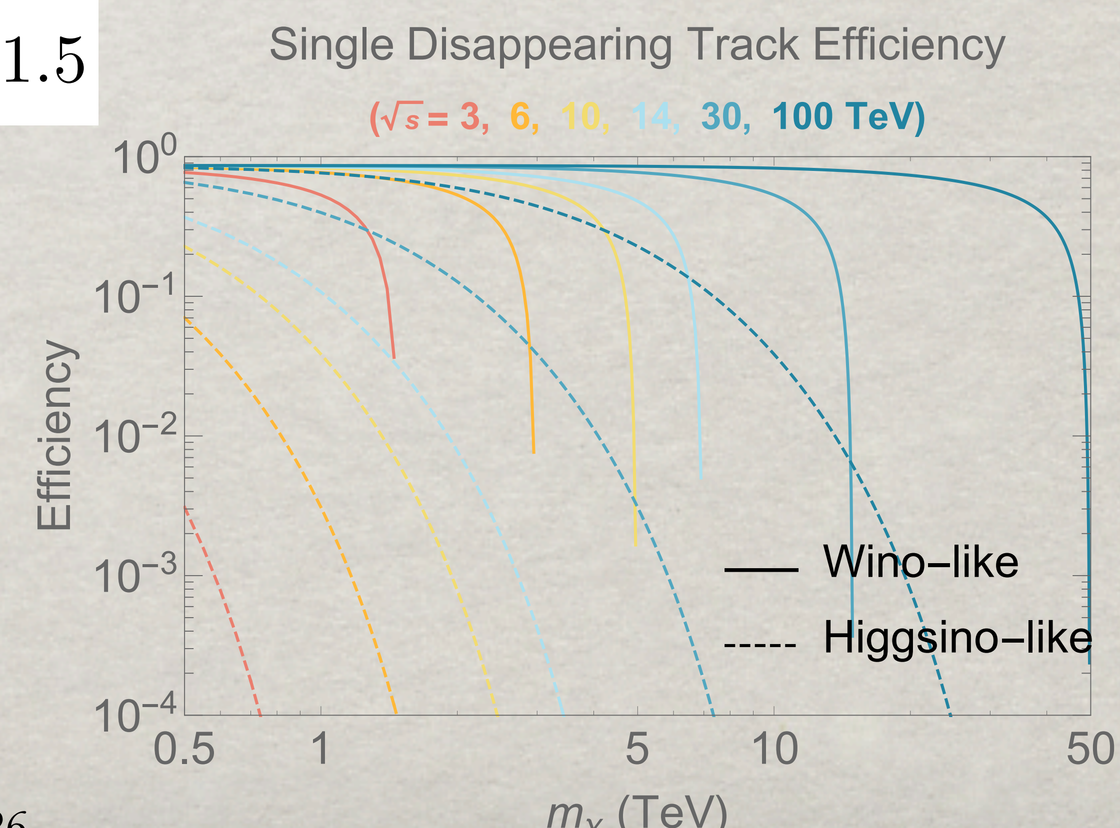
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

Missing-track signal:
A single photon plus missing tracks

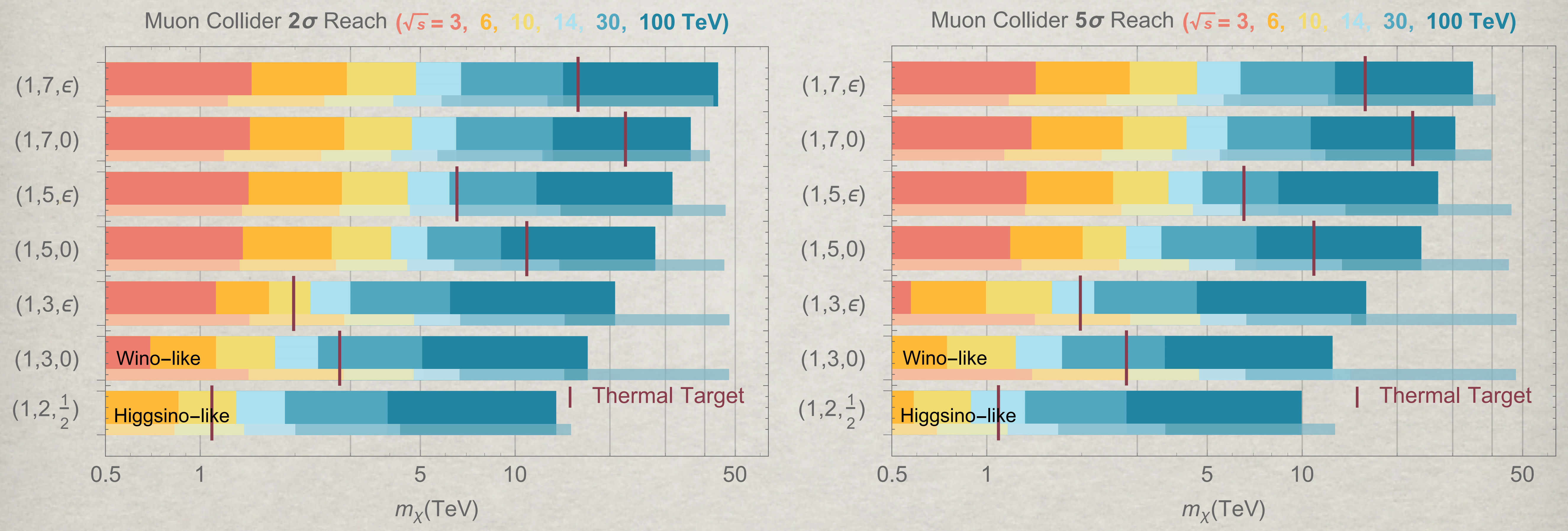


$$d_T^{\rm min} = 5 \text{ cm with } |\eta_\chi| < 1.5$$

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



The mass reach for minimal WIMP DM:



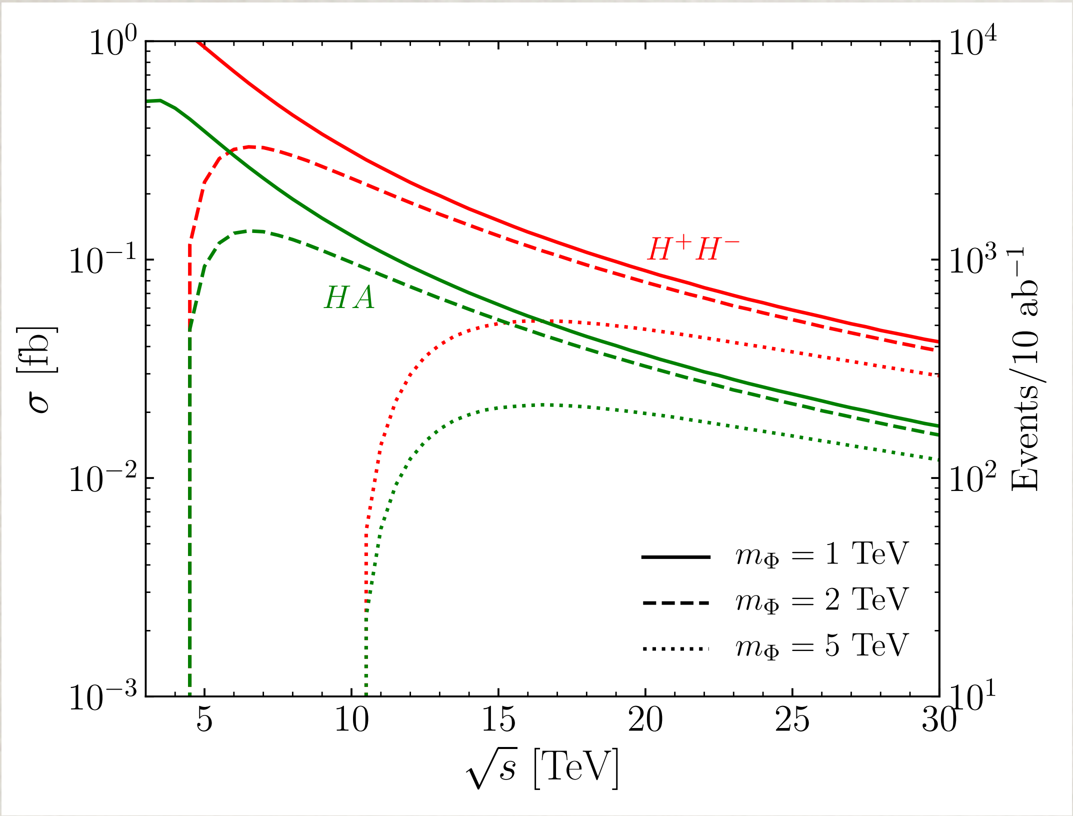
E_{CM} ≈ 14 TeV enough to cover n≤3 multiplets.

Higher energy needed to cover higher multiplets.

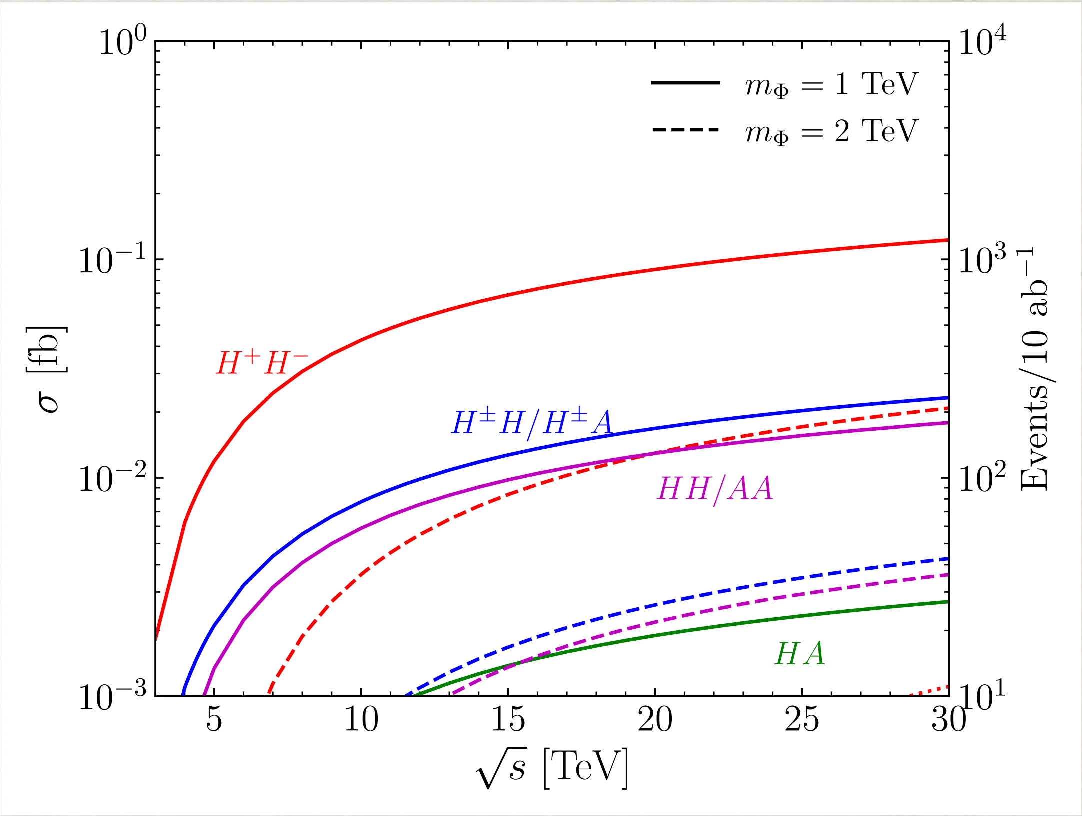
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

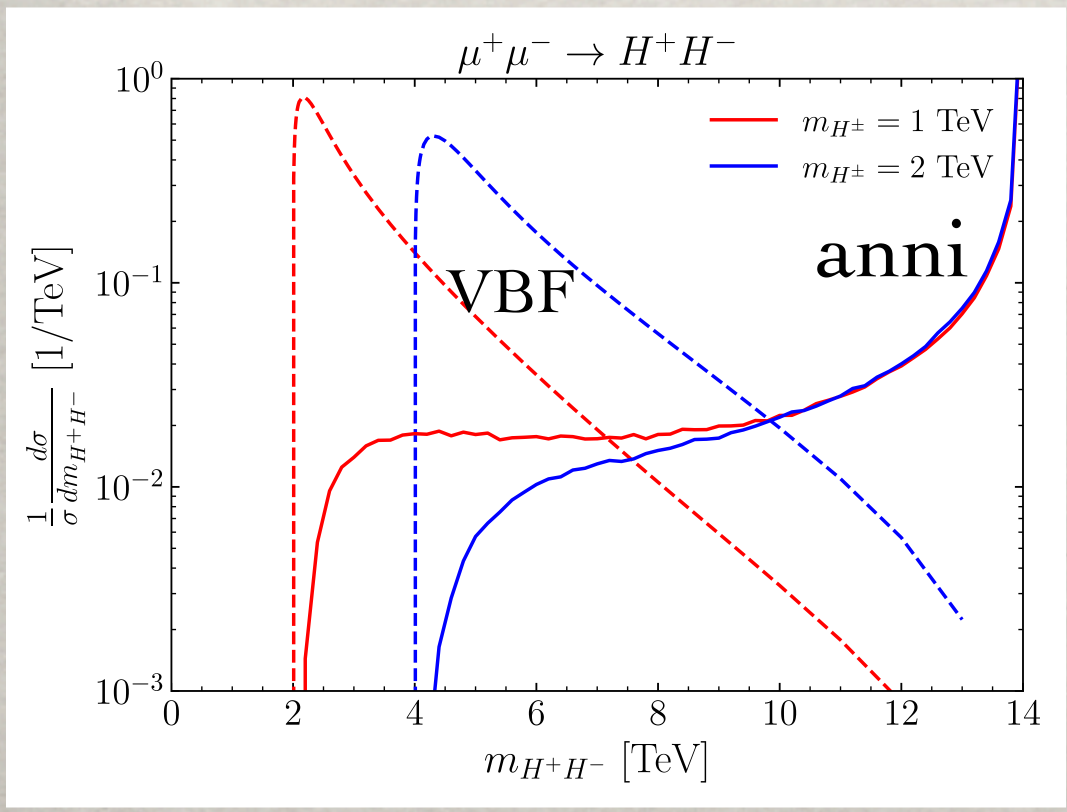
• Heavy Higgs Bosons Production

annihilation



VBF

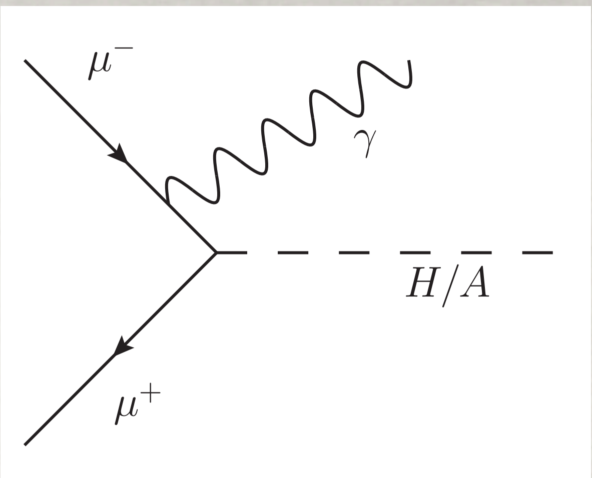


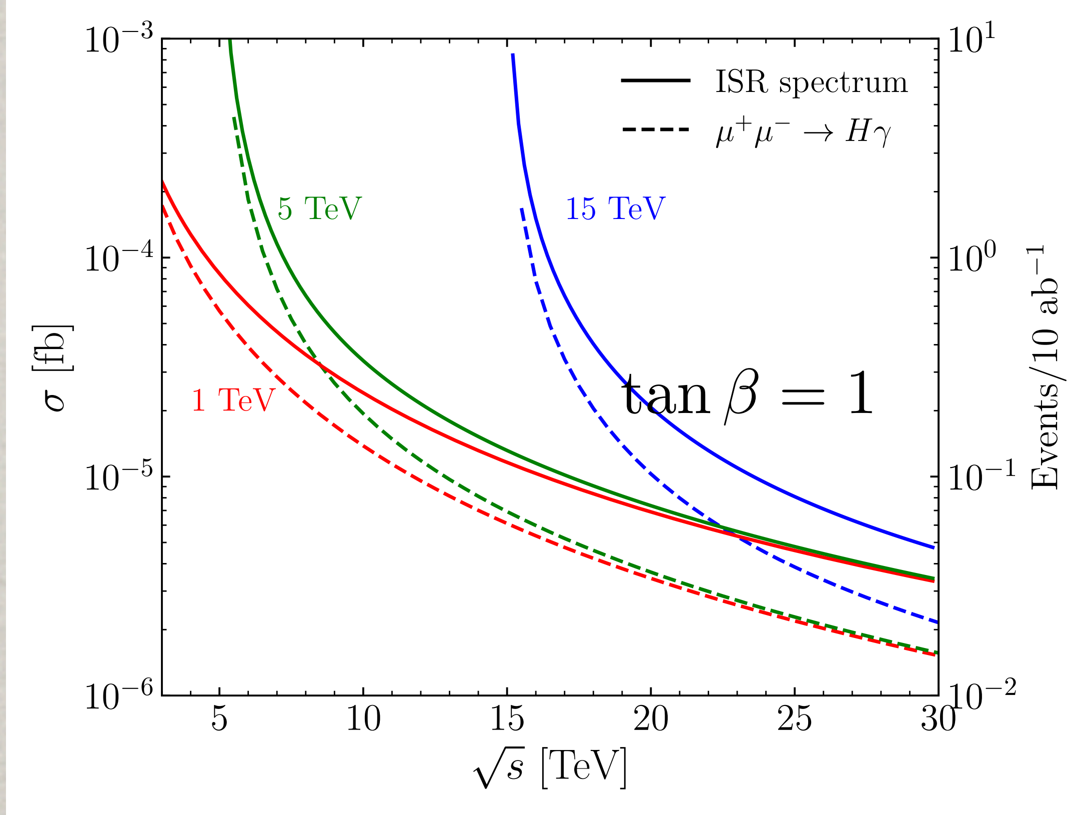


	production	Type-I	Type-II	Type-F	Type-L
small $\tan\beta < 5$	H^+H^-	$t\bar{b}, \bar{t}b$			
	$HA/HH/AA$	$t\bar{t}, t\bar{t}$			
	$H^\pm H/A$	$tb, t\bar{t}$			
intermediate $\tan\beta$	H^+H^-	$t\bar{b}, \bar{t}b$			$tb, \tau\nu_\tau$
	$HA/HH/AA$	$t\bar{t}, t\bar{t}$	$t\bar{t}, b\bar{b}$		$t\bar{t}, \tau^+\tau^-$
	$H^\pm H/A$	$tb, t\bar{t}$	$tb, t\bar{t}$; $tb, b\bar{b}$		$tb, t\bar{t}$; $tb, \tau^+\tau^-$; $\tau\nu_\tau, t\bar{t}$; $\tau\nu_\tau, \tau^+\tau^-$
large $\tan\beta > 10$	H^+H^-	$t\bar{b}, \bar{t}b$	$tb, tb(\tau\nu_\tau)$	$t\bar{b}, \bar{t}b$	$\tau^+\nu_\tau, \tau^-\nu_\tau$
	$HA/HH/AA$	$t\bar{t}, t\bar{t}$	$b\bar{b}, b\bar{b}(\tau^+\tau^-)$	$b\bar{b}, b\bar{b}$	$\tau^+\tau^-, \tau^+\tau^-$
	$H^\pm H/A$	$tb, t\bar{t}$	$tb(\tau\nu_\tau), b\bar{b}(\tau^+\tau^-)$	$tb, b\bar{b}$	$\tau^\pm\nu_\tau, \tau^+\tau^-$

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

Radiative returns:

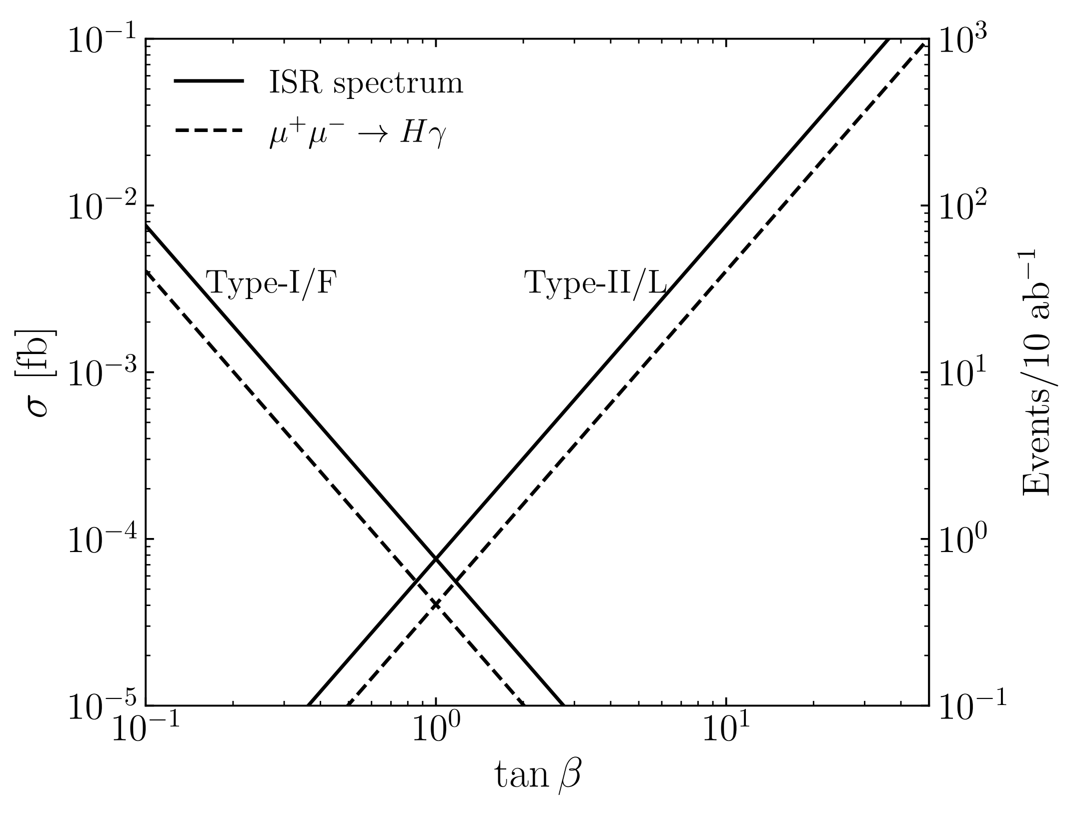




$$\hat{\sigma}(\mu^+\mu^- \to H) = \frac{\pi Y_\mu^2}{4}\delta(\hat{s} - m_H^2) = \frac{\pi Y_\mu^2}{4s}\delta(\tau - \frac{m_H^2}{s})$$

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

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



Depending on the coupling,

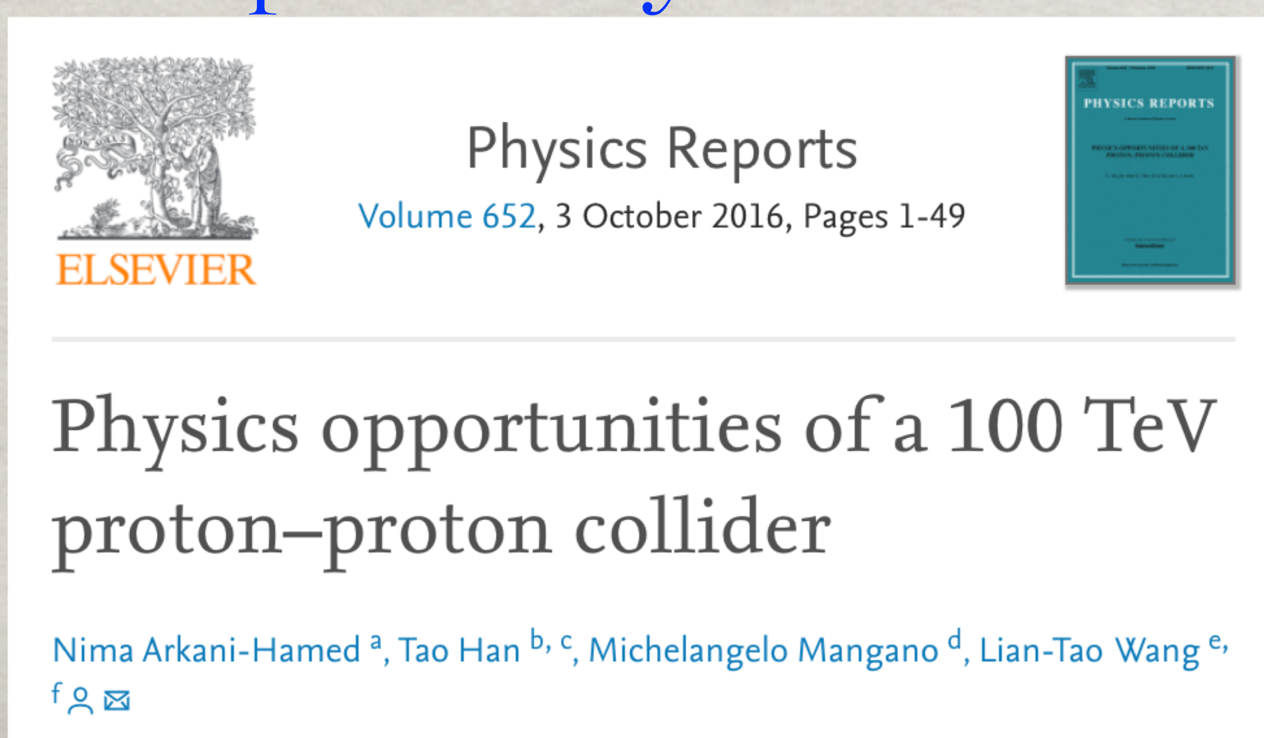
$M_H \sim E_{cm}$

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:



ELSEVIER

Physics Reports

Volume 652, 3 October 2016, Pages 1-49

Physics opportunities of a 100 TeV proton–proton collider

Nima Arkani-Hamed [a], Tao Han [b, c], Michelangelo Mangano [d], Lian-Tao Wang [e, f]

Exciting journey ahead!