SUSY/Exotic Particle Production @ High-Energy Muon Colliders

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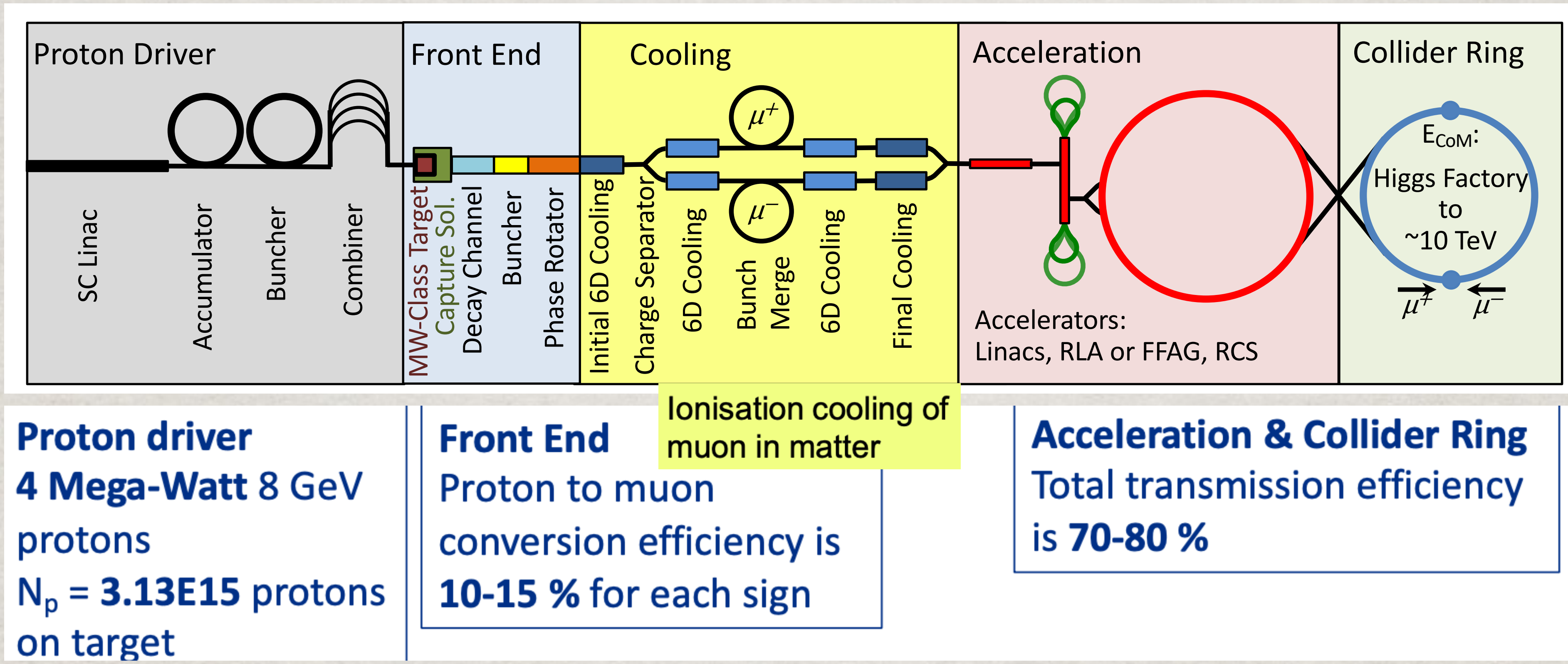
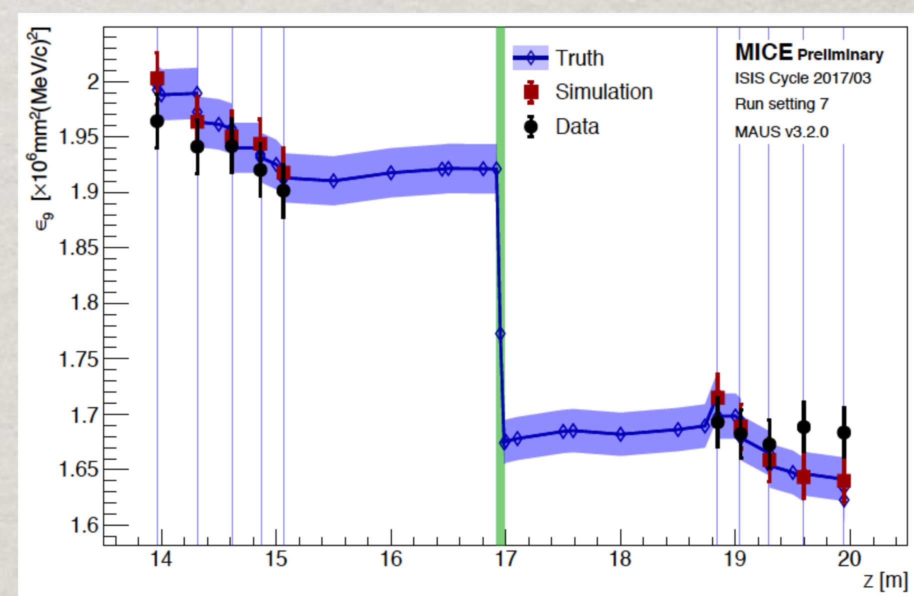
Renewed interests

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/

PARTICLE PHYSICS

Particle Physicists Dream of a Muon Collider

After years spent languishing in obscurity, proposals for a muon collider are regaining momentum among particle physicists

By Daniel Garisto on August 28, 2023

The international journal of science / 18 January 2024

nature

US and Europe should team up on muon collider

A feasibility study for a muon smasher in the United States could be an affordable way to maintain particle-physics unity.

U.S. P5 (Particle Physics Project Prioritization Panel)
The path to 10 TeV pCM (partonic c.m. energy):

...
Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

Collider benchmark points:

- The Higgs factory:

$E_{cm} = m_H$

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

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

Parameter	Units	Higgs
CoM Energy	TeV	0.126
Avg. Luminosity	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	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 conceivable choices:

Ecm = 3 TeV - 14 TeV

European Strategy: arXiv:1910.11775; arXiv:1901.06150; arXiv:2007.15684;
Muon Collider Forum Report: https://arxiv.org/abs/2209.01318

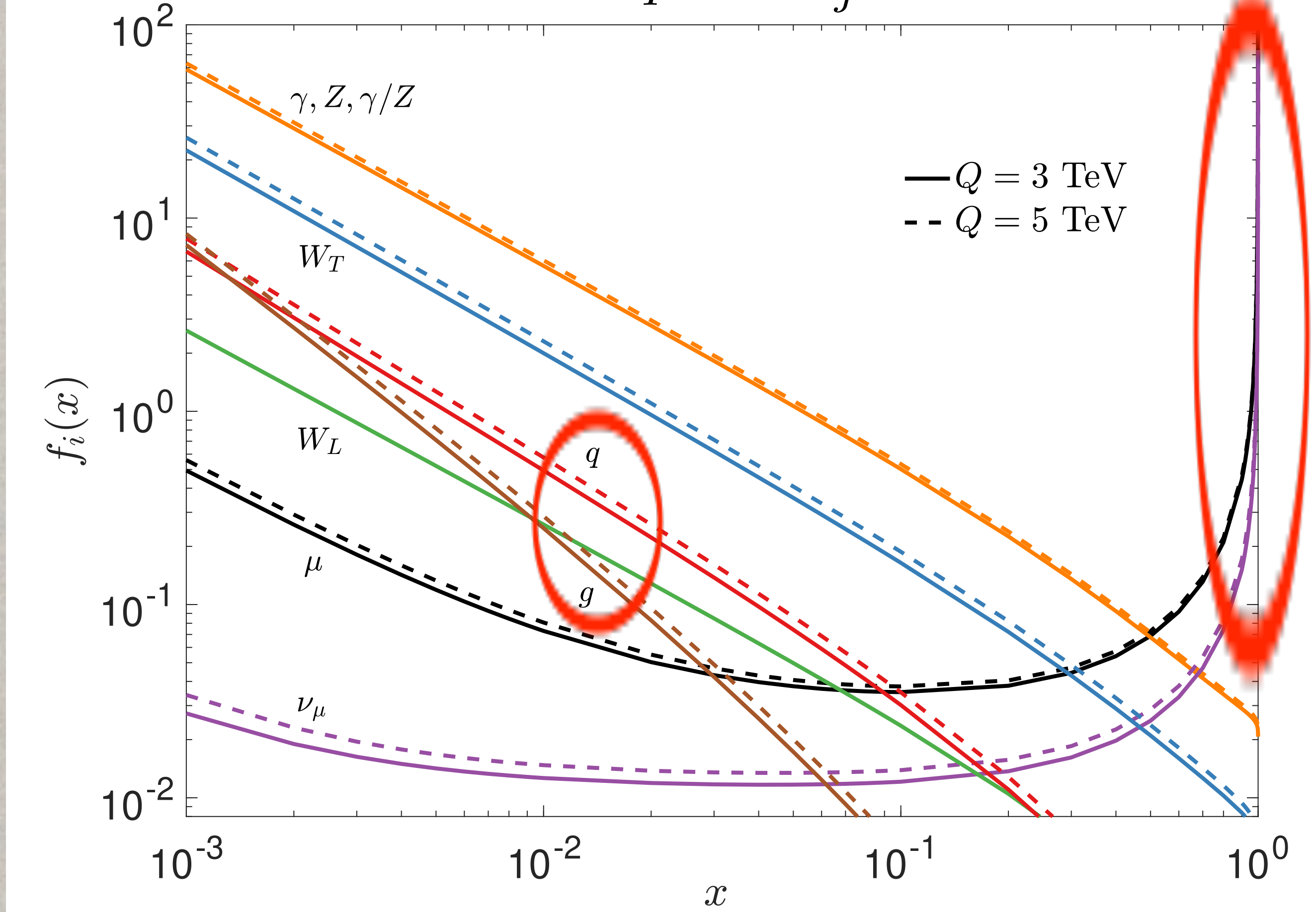
A $\mu^+\mu^-$ Collider at High Energies

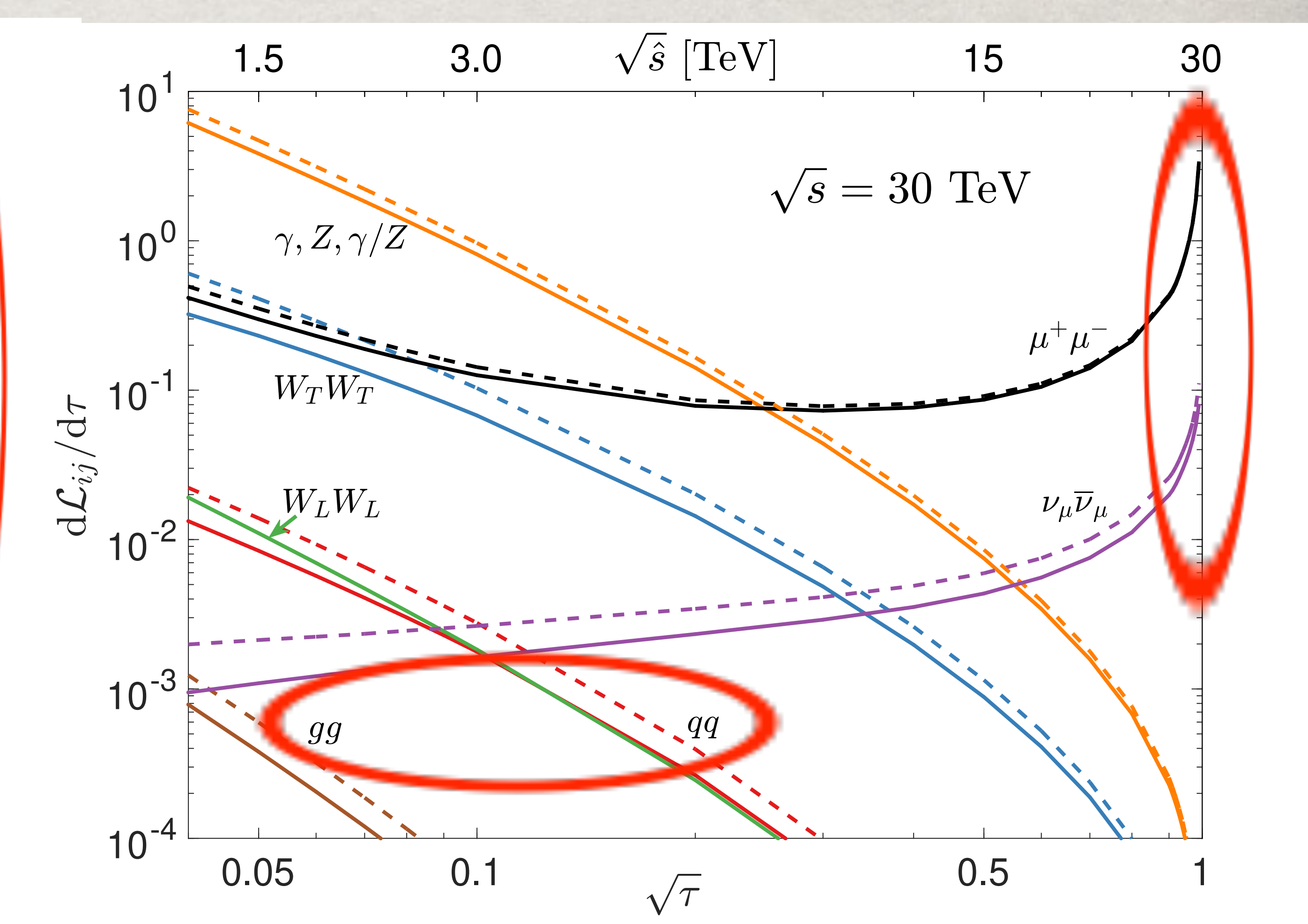
Collinear splitting phenomena dominate!

EW "partons" dynamically generated

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

TH, Yang Ma, Keping Xie, arXiv:2007.14300



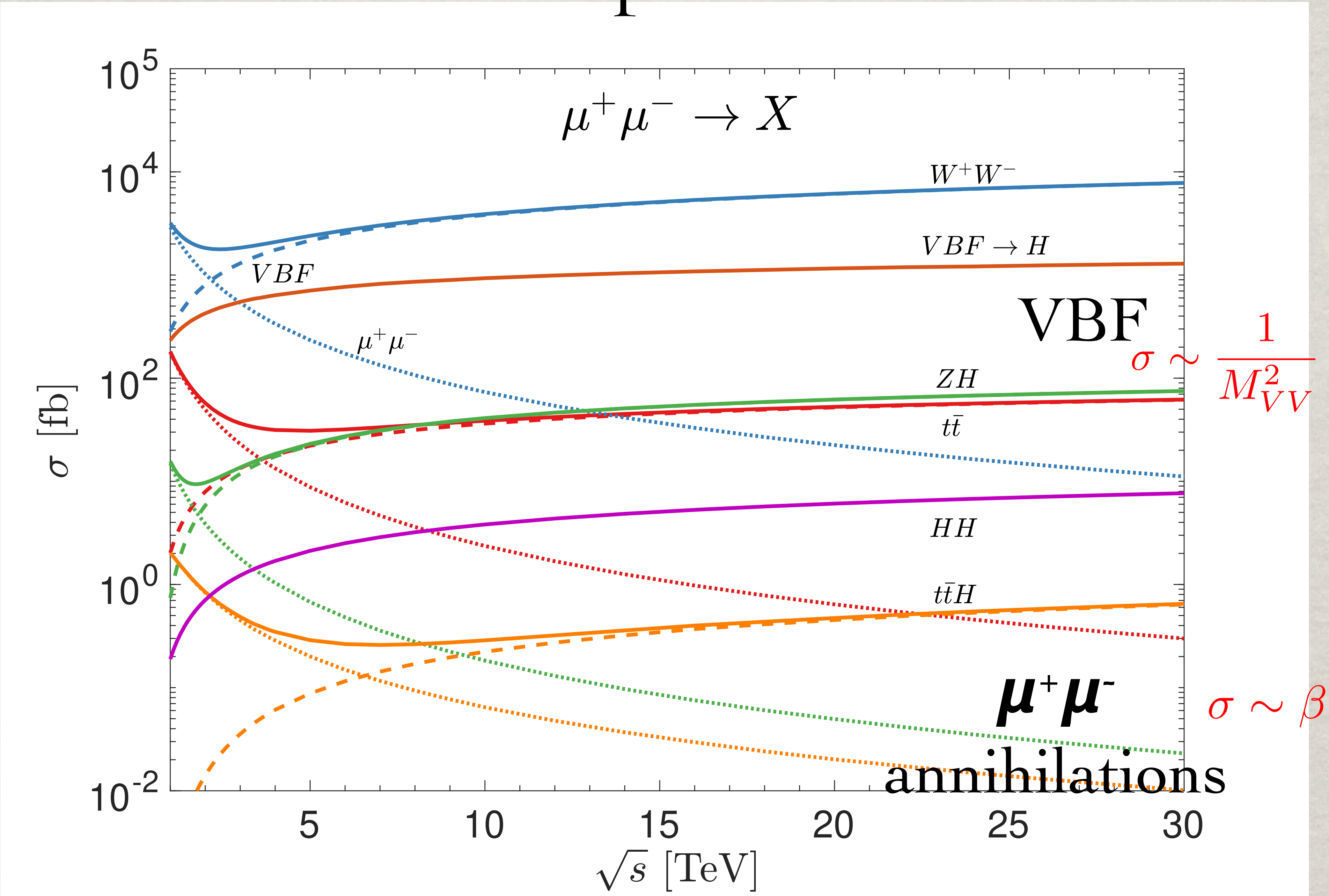


$\mu^\pm,\ \nu_\mu$: the valance. $\ell_R,\ \ell_L,\ \nu_L$ and $B, W^{\pm,3}$: LO sea.

Quarks: NLO; gluons: NNLO.

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

SM processes:



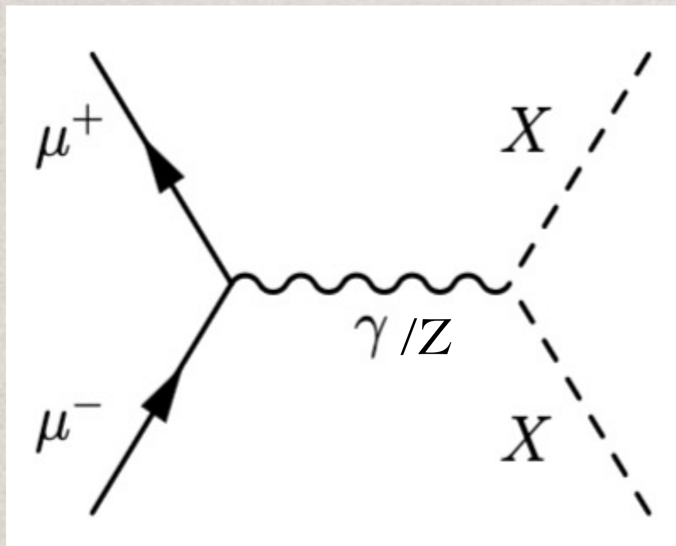
$$\sigma \sim \frac{1}{M_{VV}^2} \ln \frac{Q^2}{M_W^2}$$

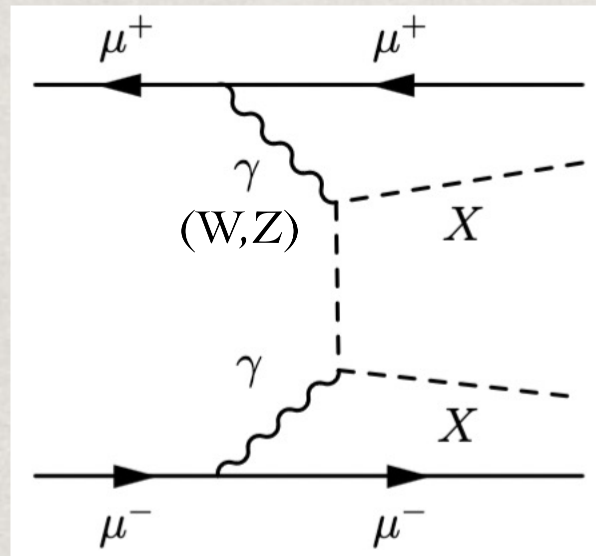
$$\sigma \sim \beta^{2\ell+1}/S$$

New Production Mechanisms at a $\mu^+\mu^-$ Collider

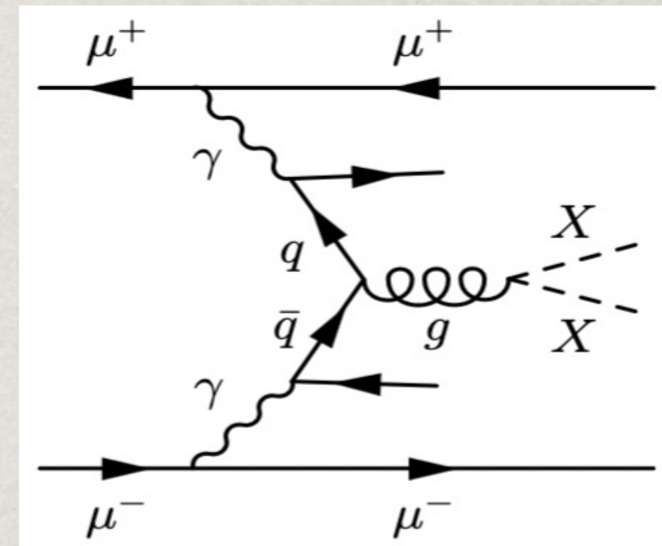
TH, Matt Low, Arthur Wu, Keping Xie, arXiv:24xx.xxxx

EW charged:

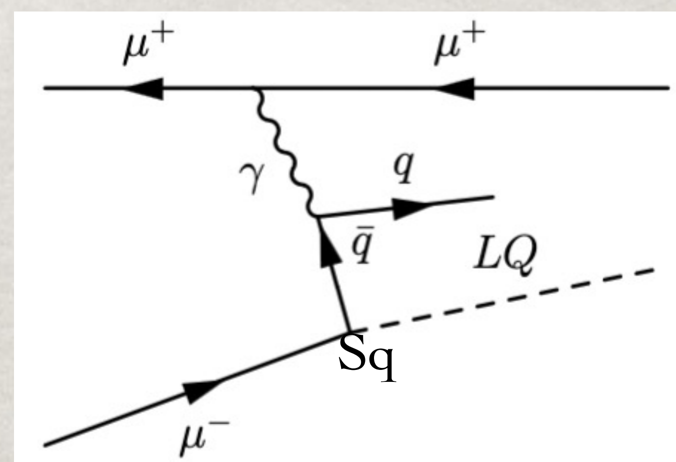




Color charged:



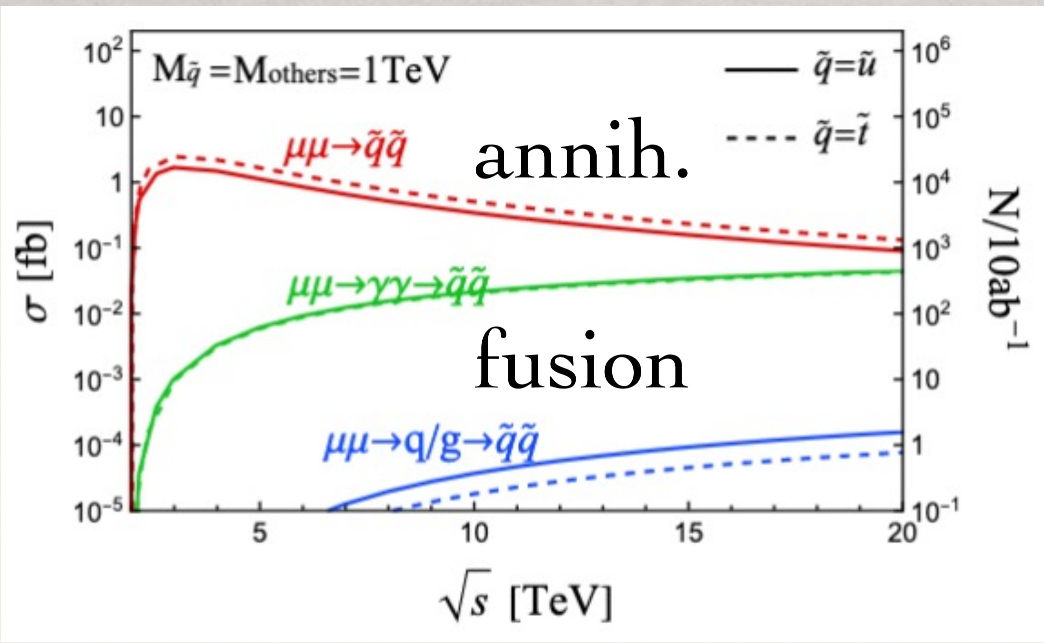
Rpv squark
or Lepto-quark:

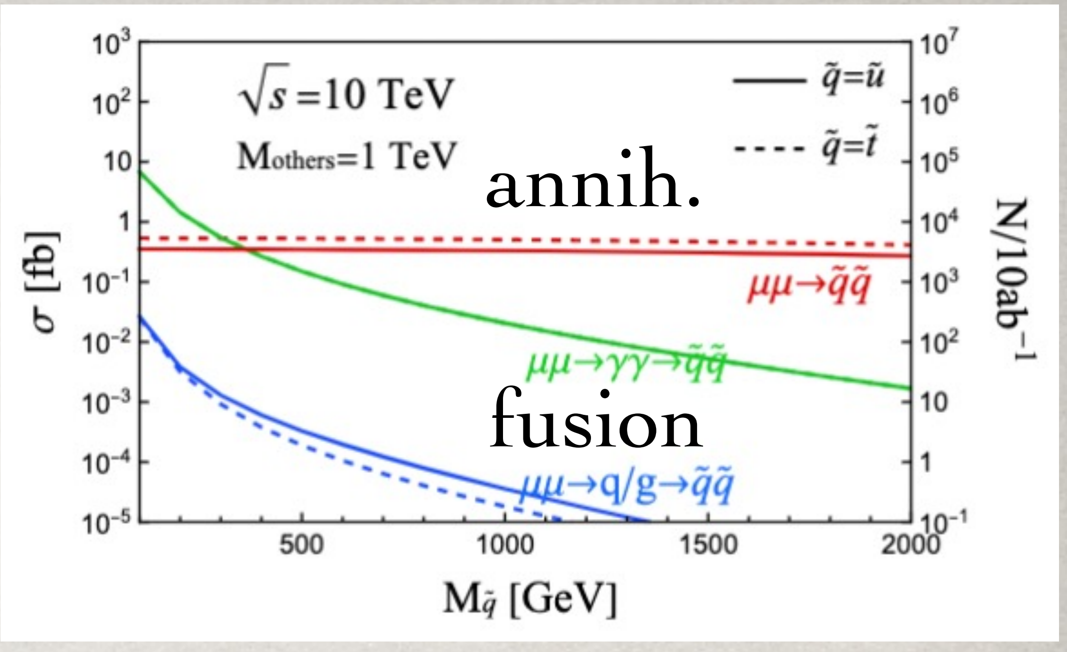


Some examples
for exotic states:

Spin \ Color	Triplet	Octet	Sextet
0	$\tilde{t}$/leptoquark (SLQ)	ScalarOctet(1,γ_5)	Diquark
1/2	T	$\tilde{g}$/leptogluon	
1	VectorTriplet/VLQ	VectorOctet (1,γ_5)	

SUSY: Squark production:

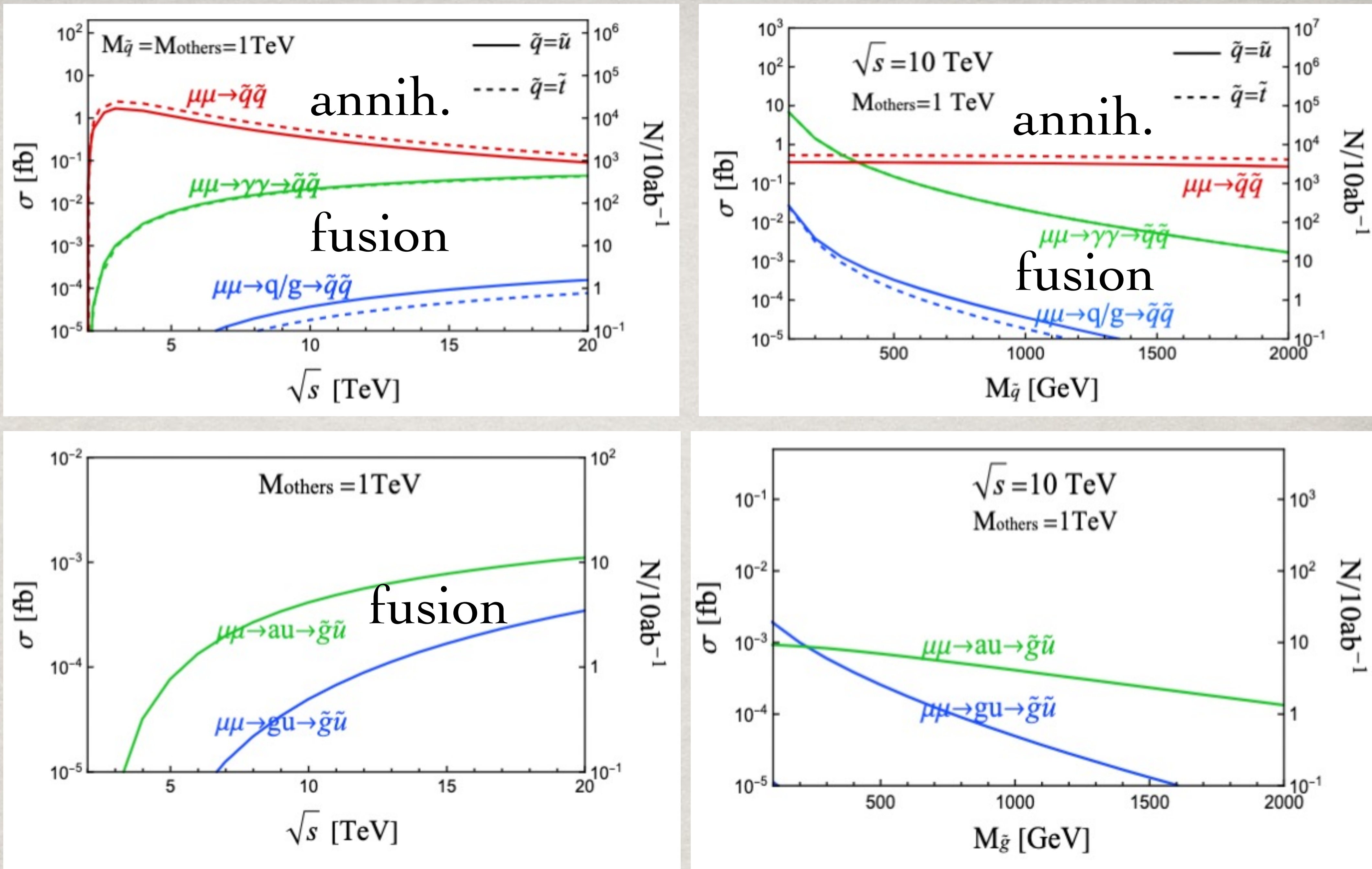




SUSY:

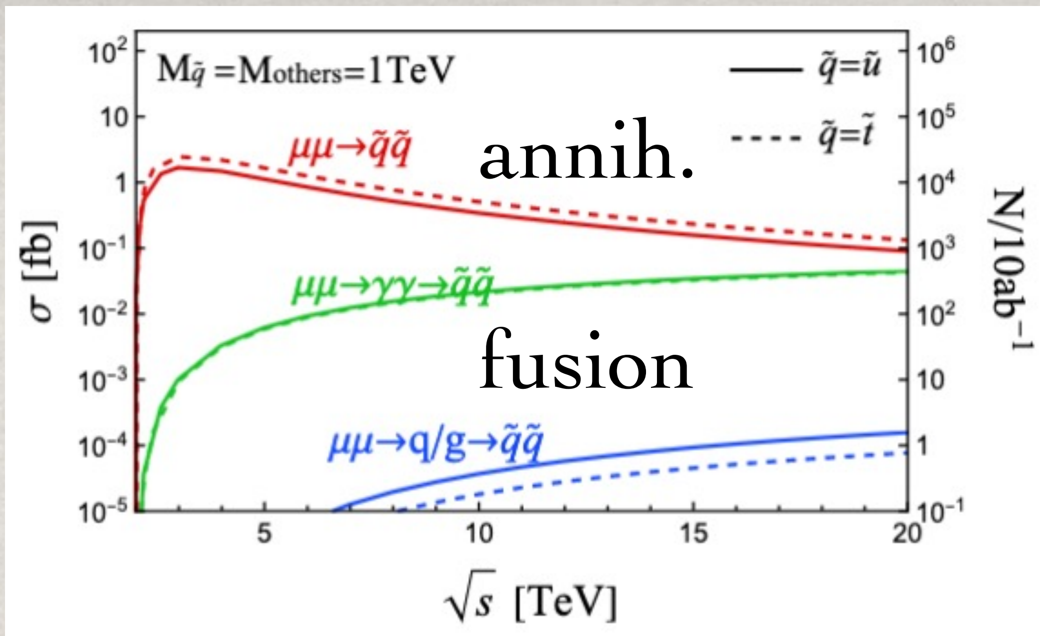
Squark production:

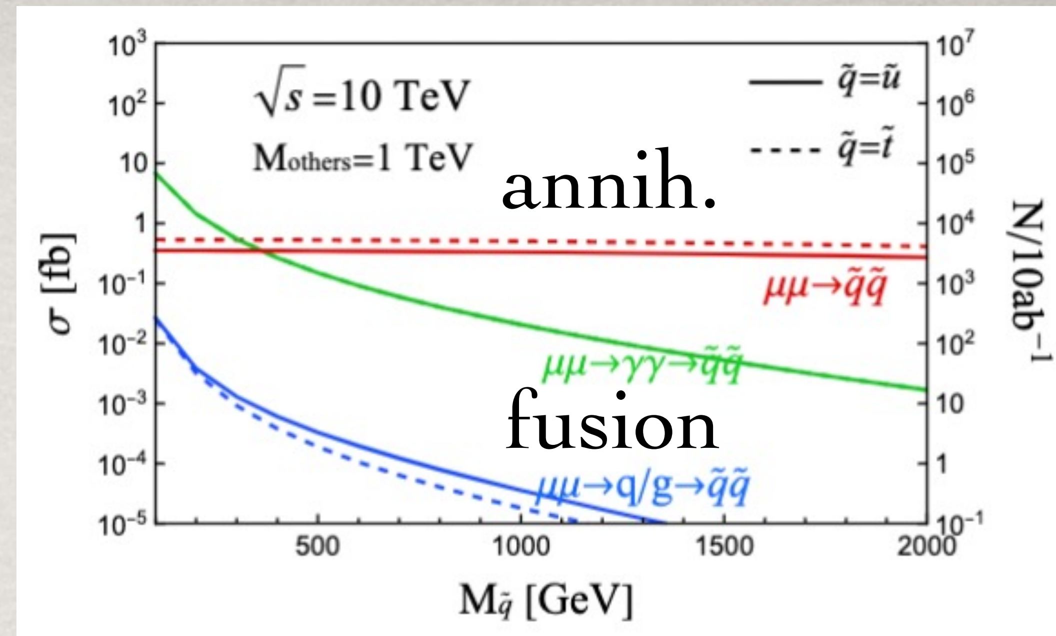
Sq-gluino production:



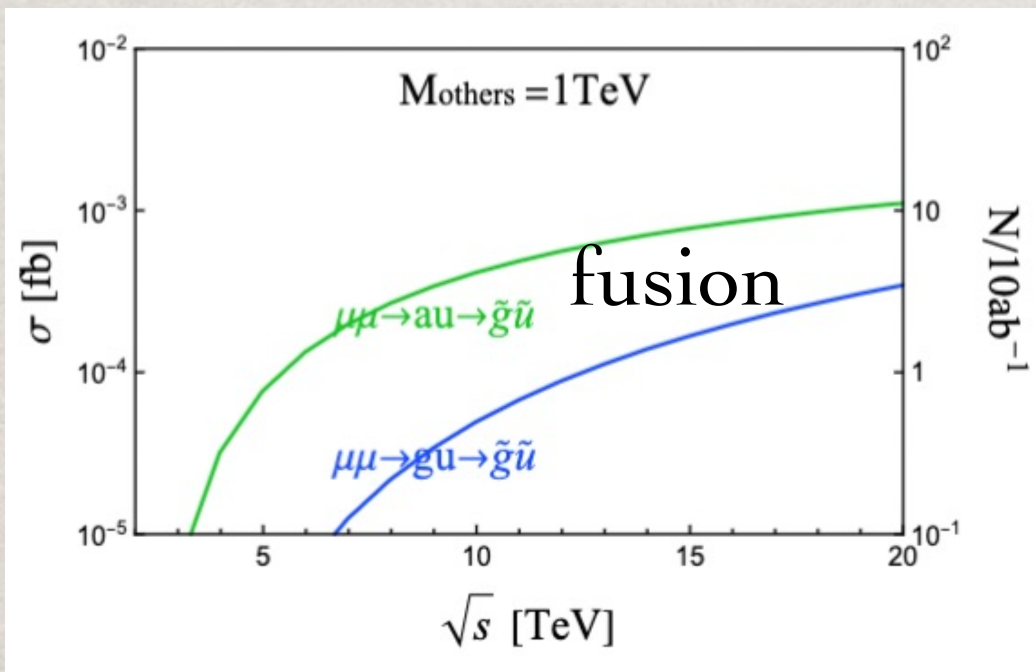
SUSY:

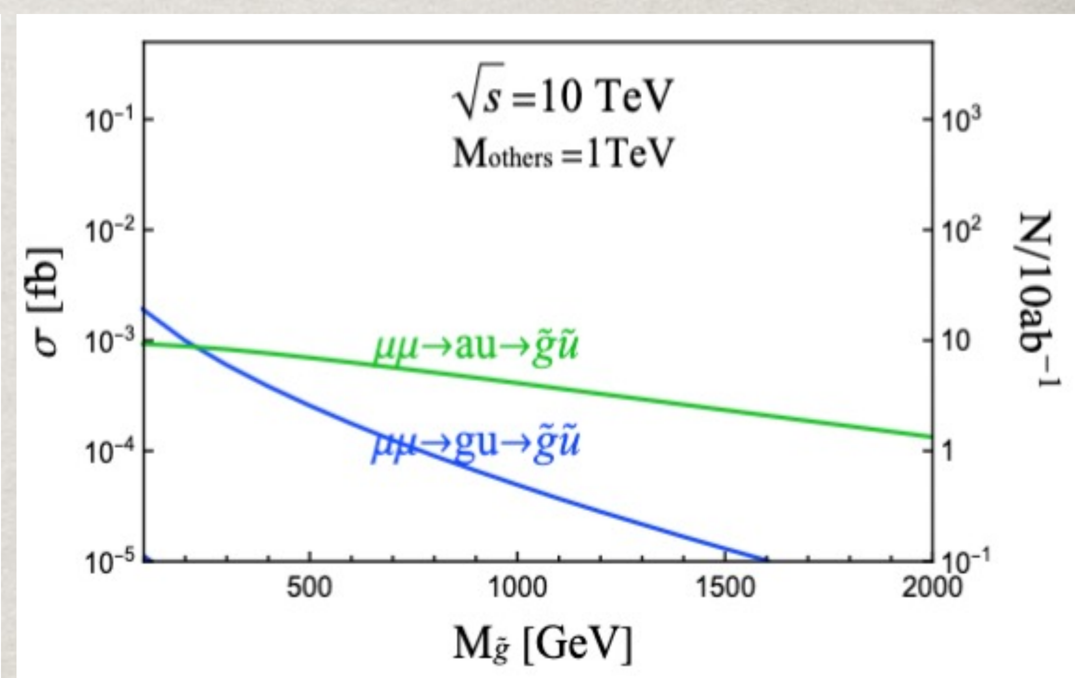
Squark production:



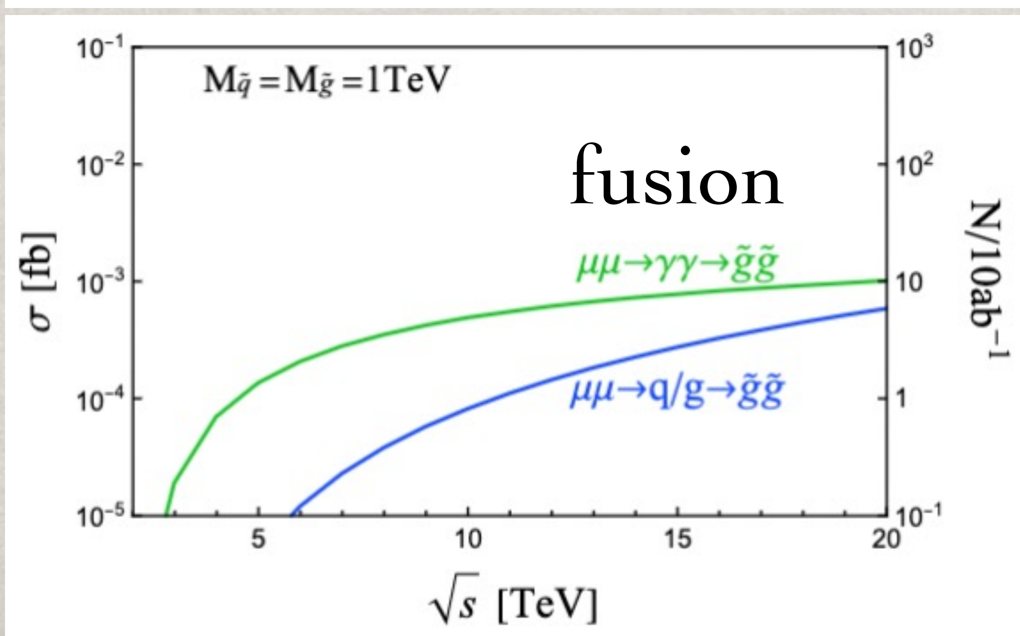


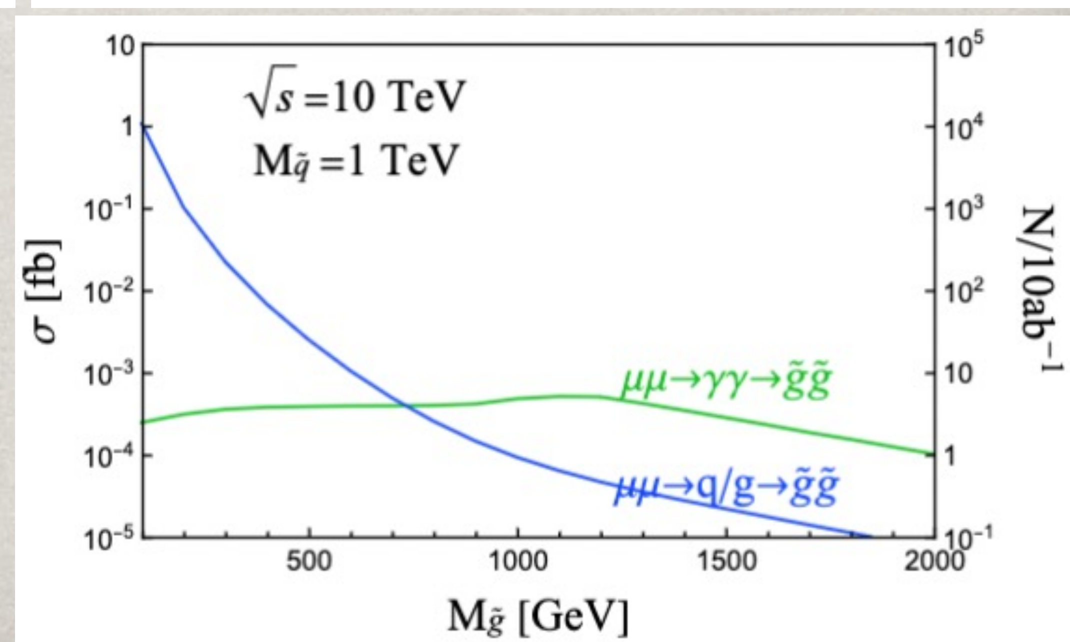
Sq-gluino production:





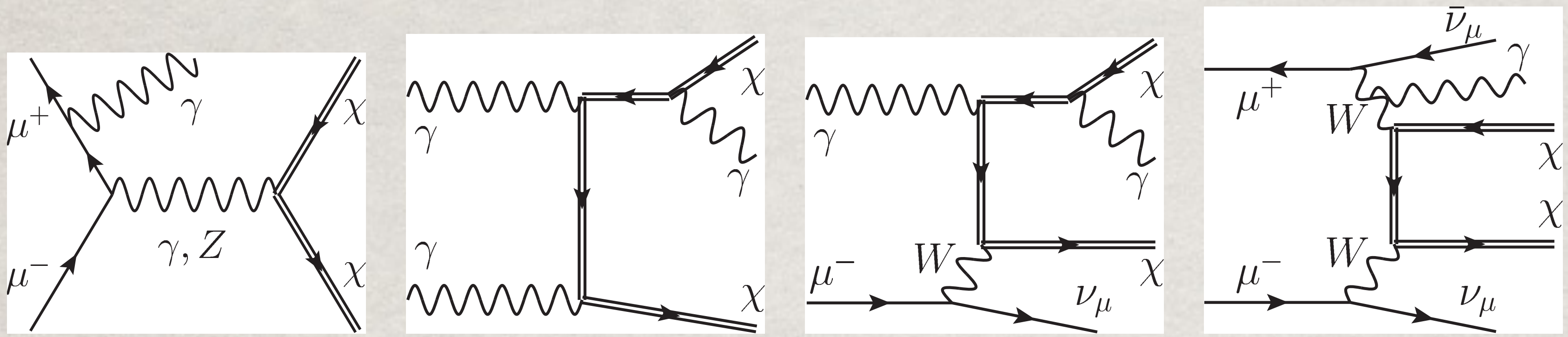
Gluino production:





EW Minimal Dark Matter:

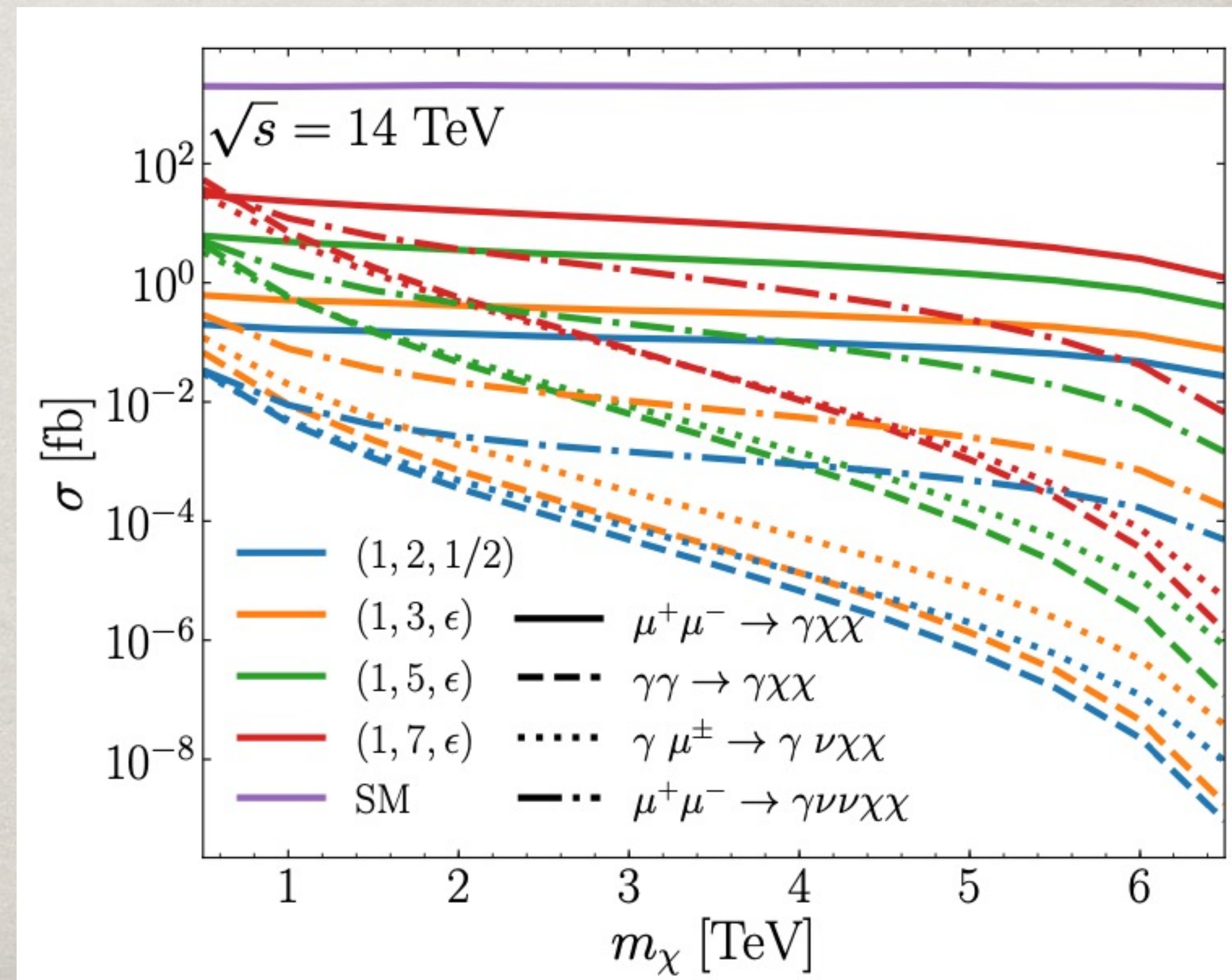
Generic EW (degenerate) multiplets



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

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

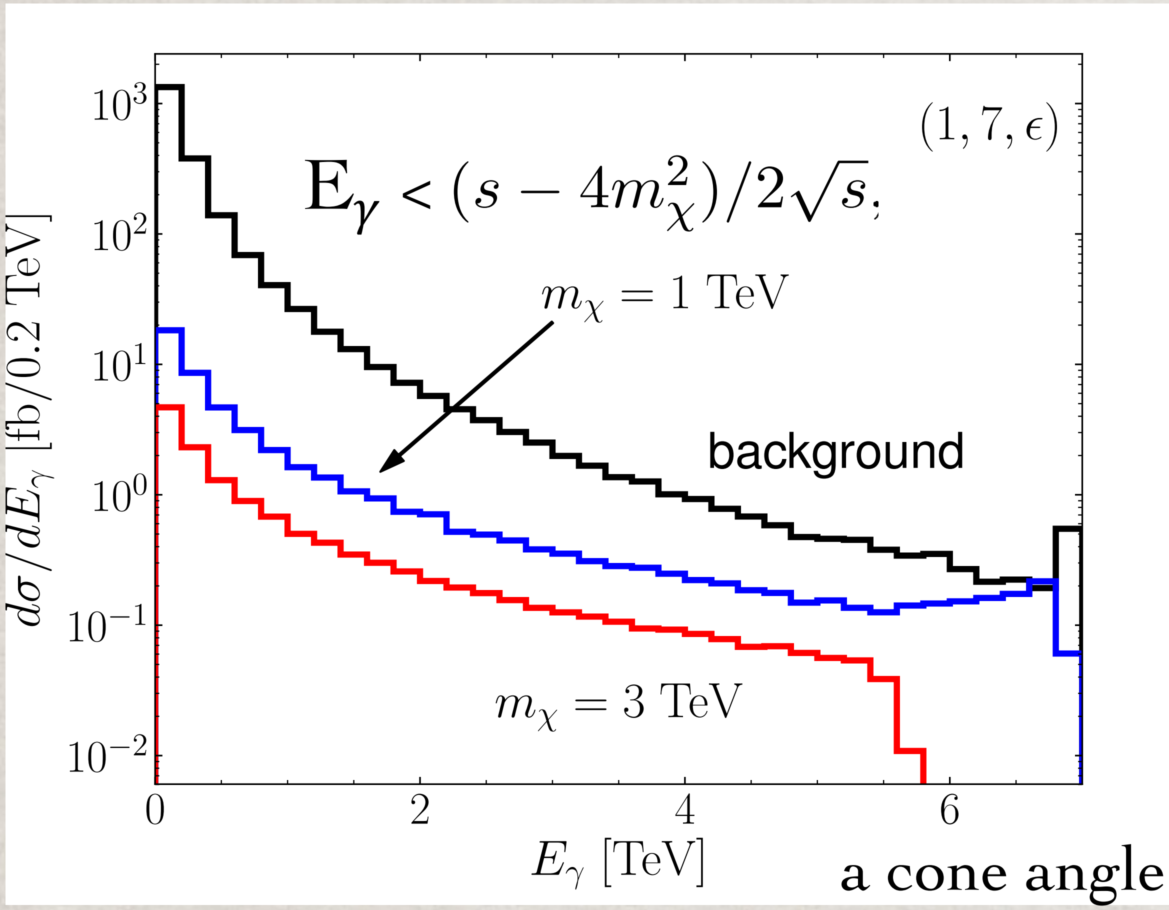
Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	11 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
(1,7,ϵ)	Dirac	16 TeV

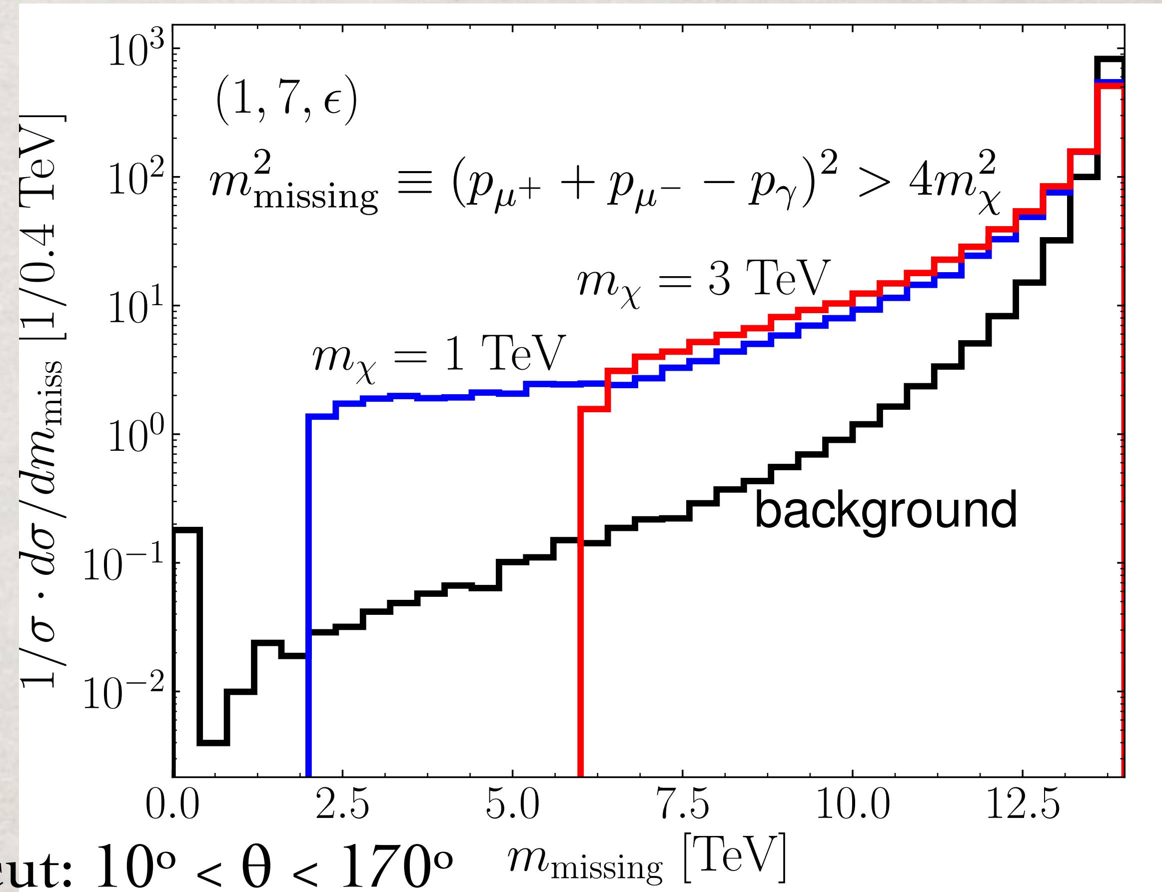


TH, Z. Liu, L.-T. Wang, X. Wang, arXiv:2009.11287.

Key feature different from LHC: the "missing mass"

$$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum p_i^{\text{obs}})^2$$

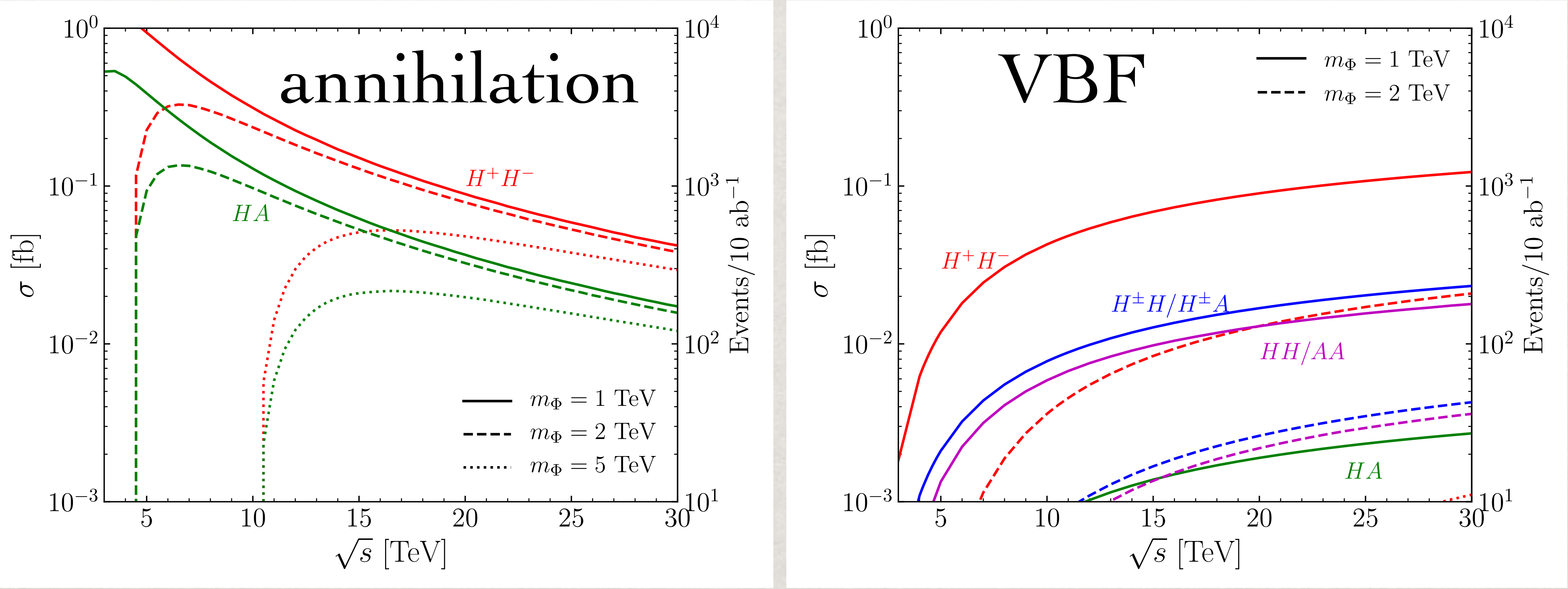




a cone angle cut: $10^\circ < \theta < 170^\circ$

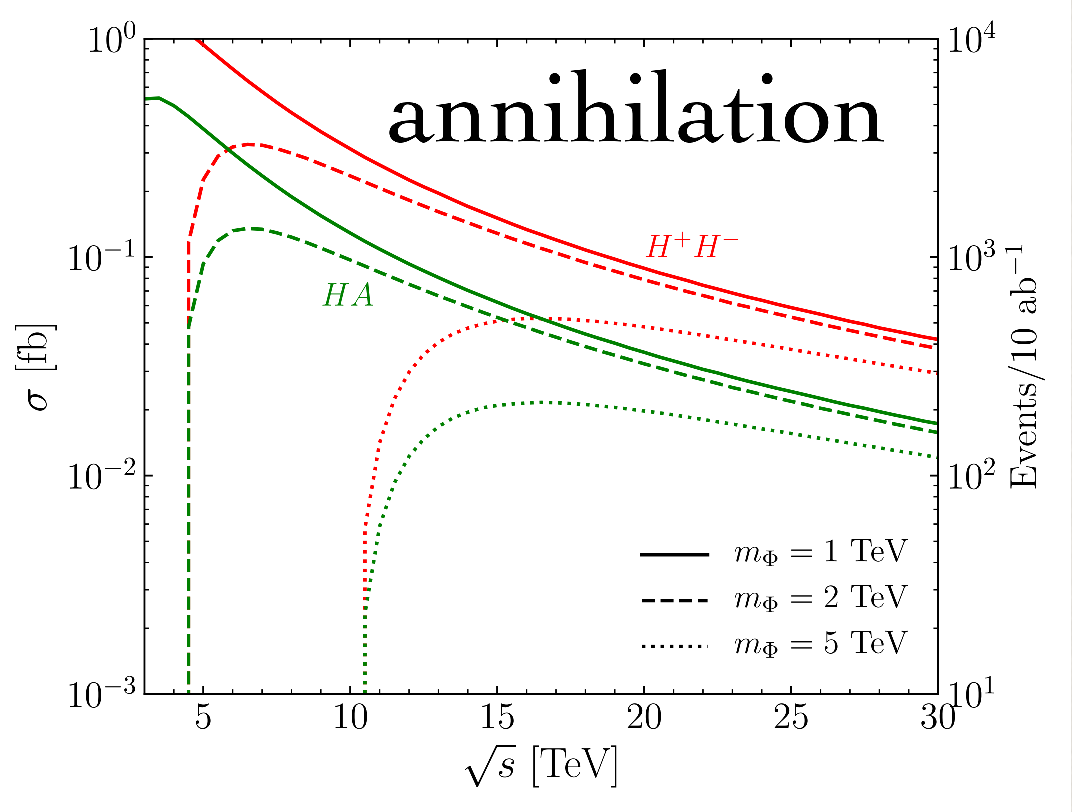
Model (color, n, Y)		Therm. target	5σ discovery coverage (TeV)			
			mono-γ	mono-μ	di-μ's	disp. tracks
(1,2,1/2)	Dirac	1.1 TeV	—	2.8	—	1.8 – 3.7
(1,3,0)	Majorana	2.8 TeV	—	3.7	—	13 – 14
(1,3,ϵ)	Dirac	2.0 TeV	0.9	4.6	—	13 – 14
(1,5,0)	Majorana	11 TeV	3.1	7.0	3.1	10 – 14
(1,5,ϵ)	Dirac	6.6 TeV	6.9	7.8	4.2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

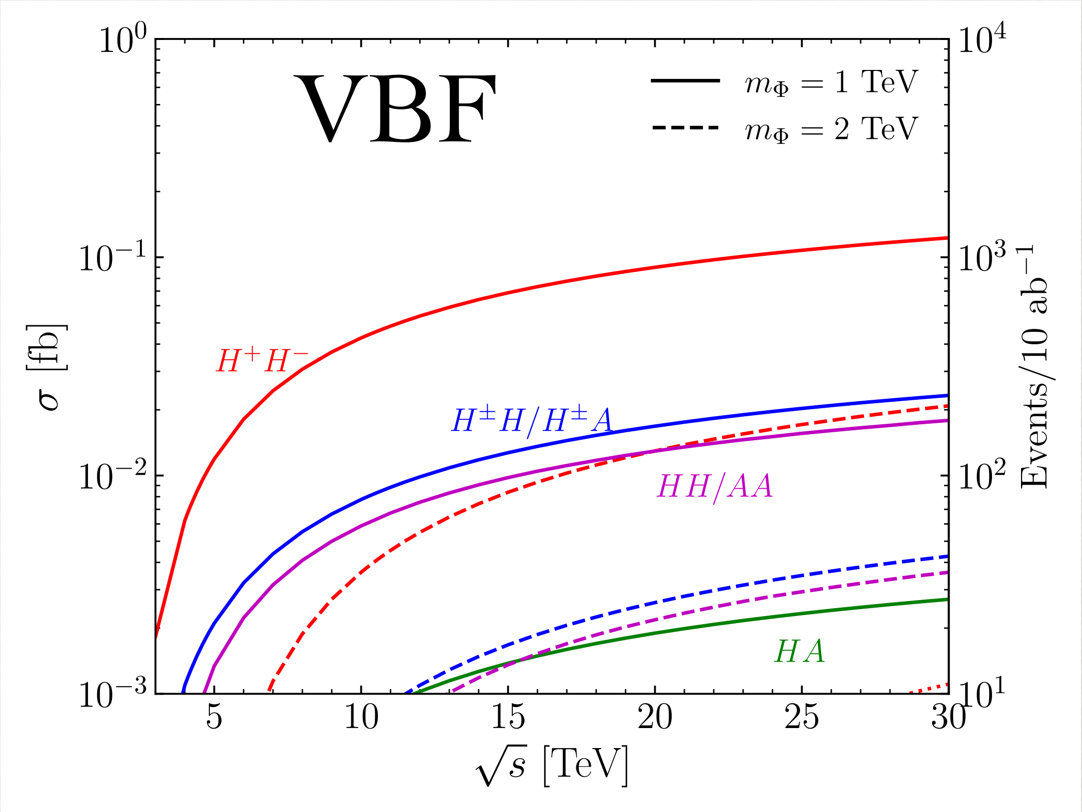
Heavy Higgs Boson Production



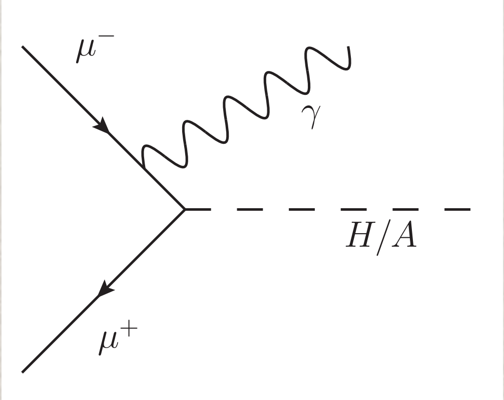
TH, S. Li, S. Su, W. Su, Y. Wu, arXiv:2102.08386.

Heavy Higgs Boson Production



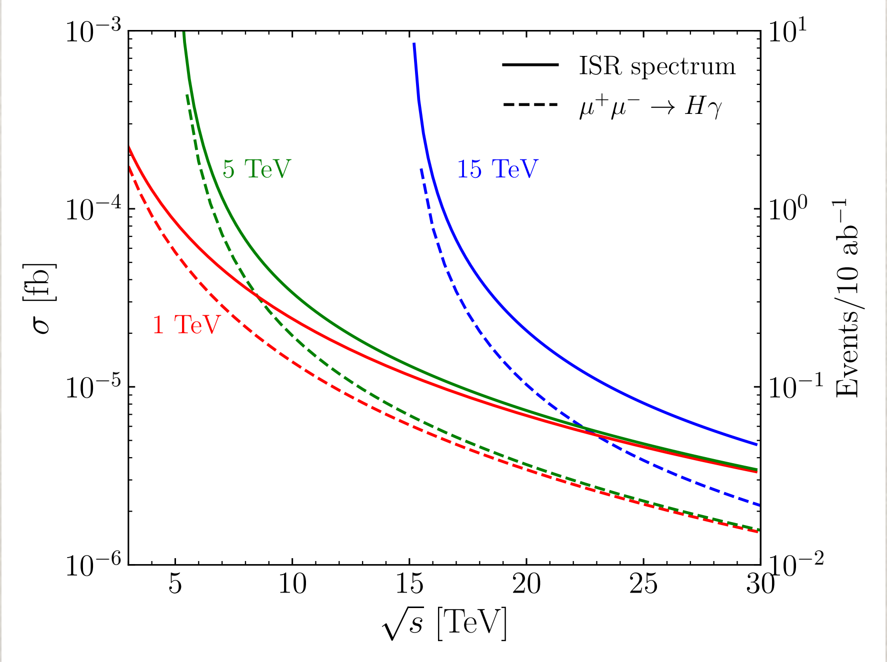


Radiative returns for single H production:



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

Reaching M ~ E_{cm} !



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

Summary

- **High energy muon-collider is a new endeavor:**

Challenging technology
Great physics potential at the energy frontier
Interdisciplinary/complementary to other fields

- **Multi-TeV colliders:**

- Bread & butter SM EW physics in the new territory
- Unprecedented accuracies for WWH, WWHH, H^3, H^4
- New particle (Q,L,H,…) mass coverage:

$$M_H \sim (0.5 - 1)E_{cm}$$

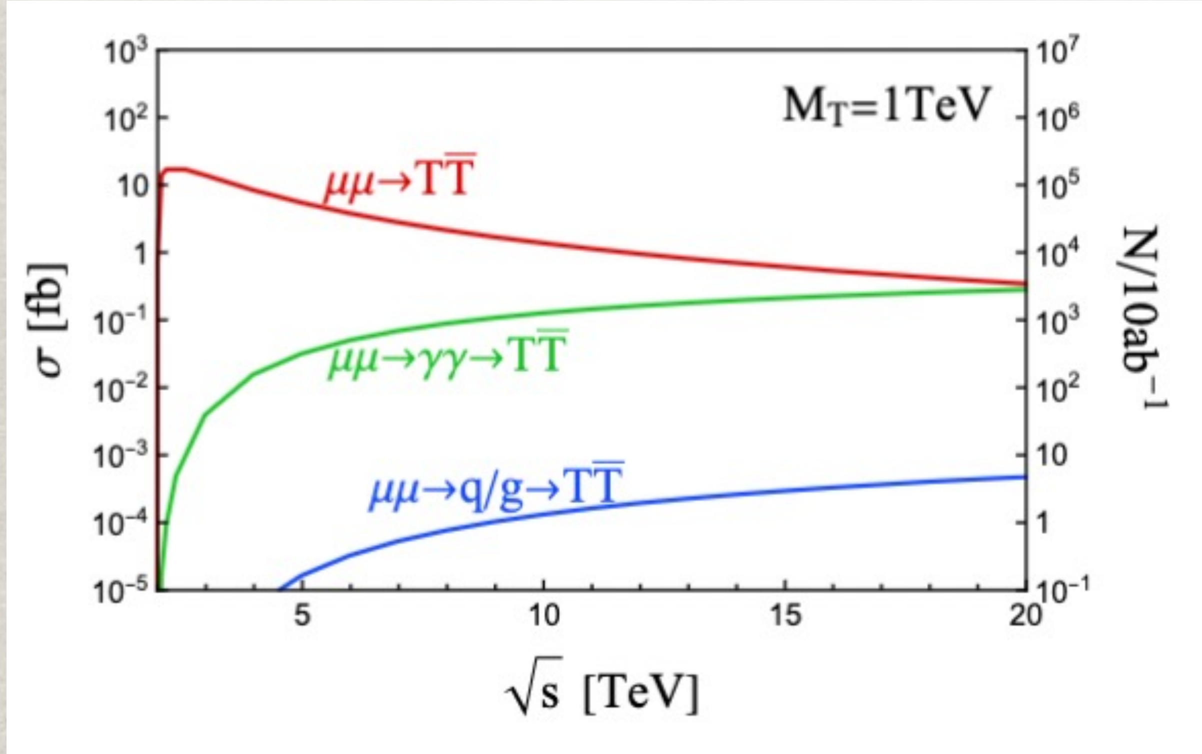
- Decisive coverage for minimal WIMP DM $M \sim 0.5\ E_{cm}$
- Complementary to Astro/Cosmo/GW & to FCC-hh:

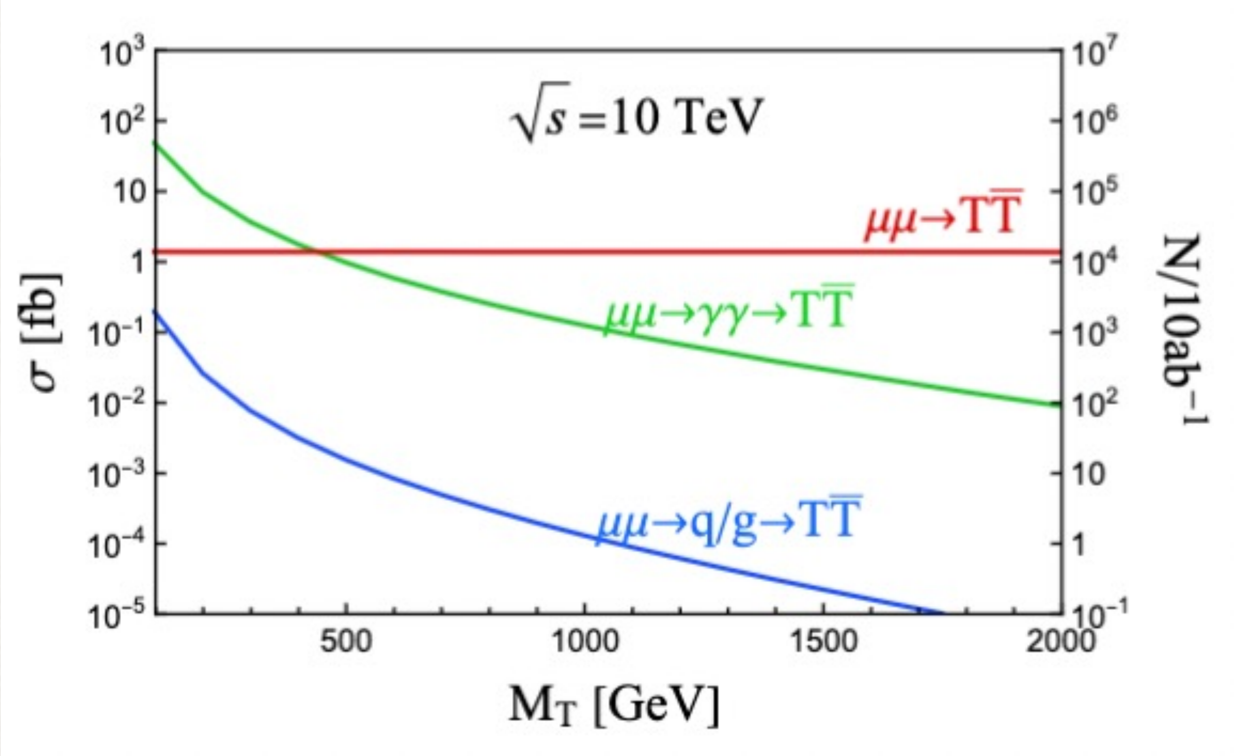
Exciting journey ahead!

Backup slides …

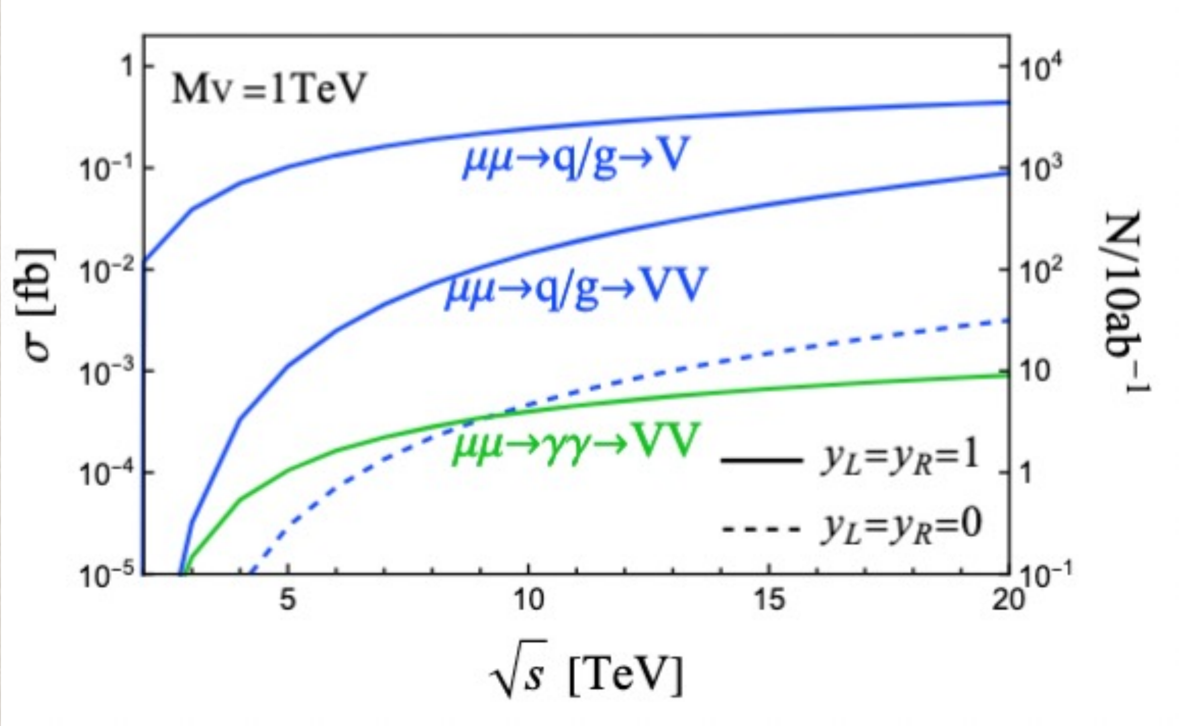
Non SUSY heavy pair production:

Color-triplet vector-like-fermion production:

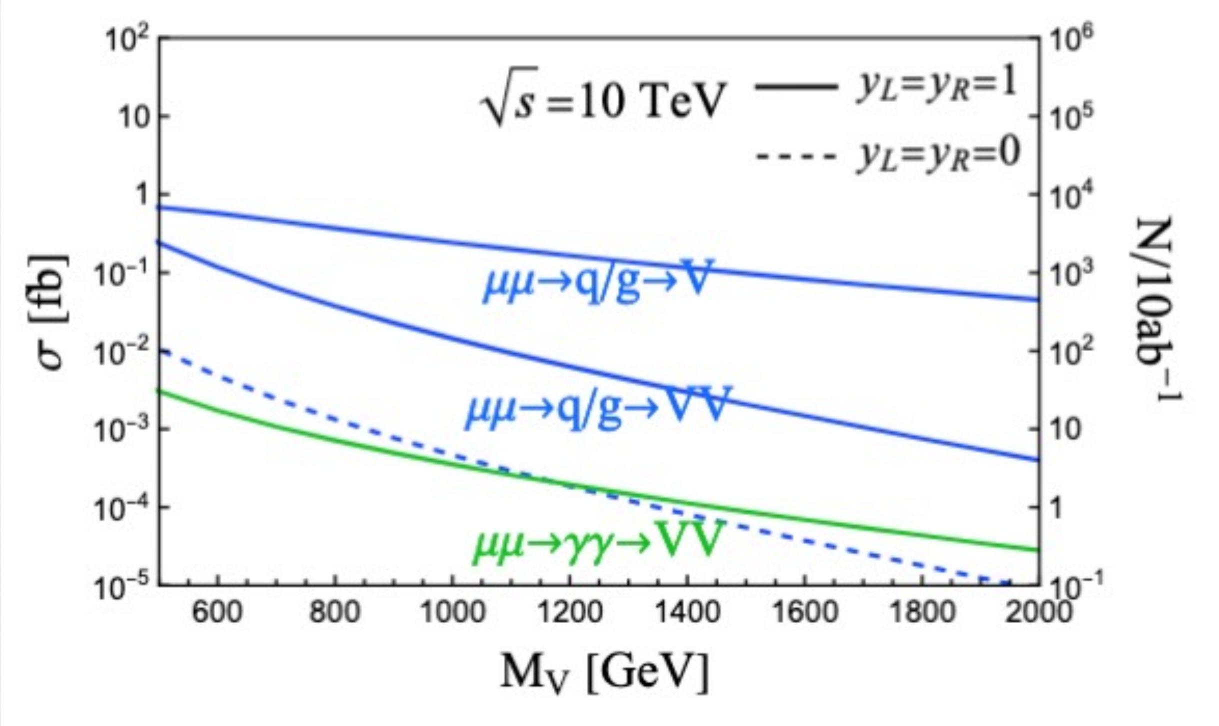




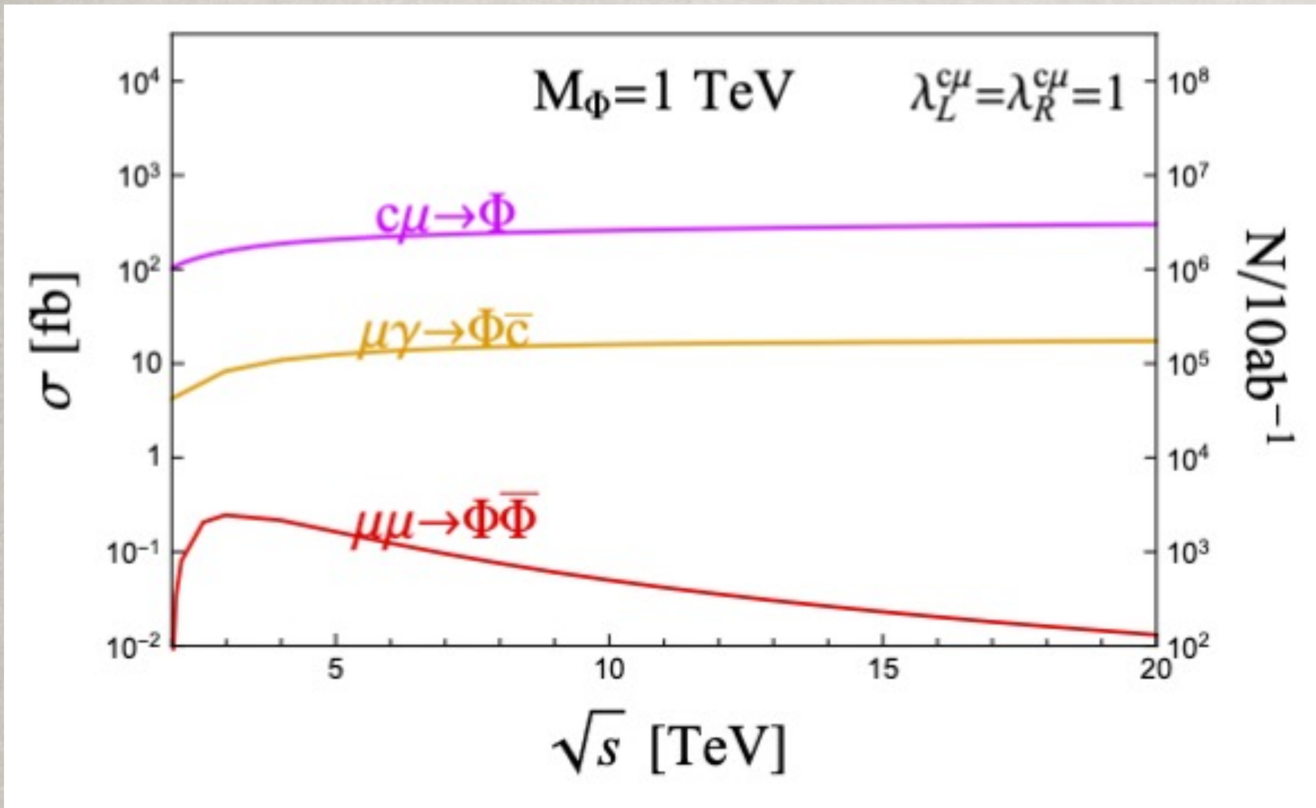
TH, Matt Low, Arthur Wu, Keping Xie, arXiv:24xx.xxxx



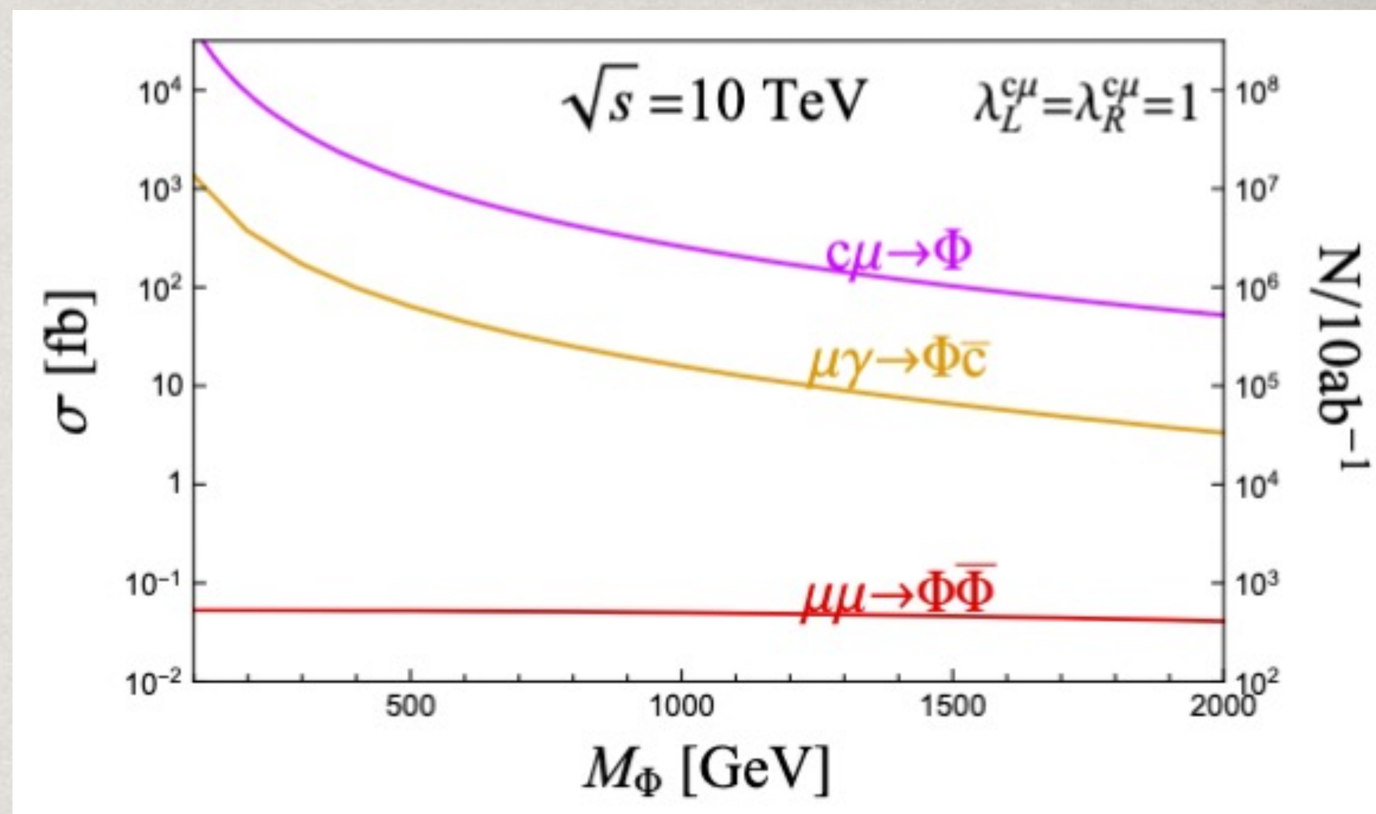
Mv =1TeV
μμ→q/g→V
μμ→q/g→VV
μμ→γγ→VV
$y_L=y_R=1$
$y_L=y_R=0$
σ [fb]
N/10ab^{-1}
$\sqrt{s}$ [TeV]



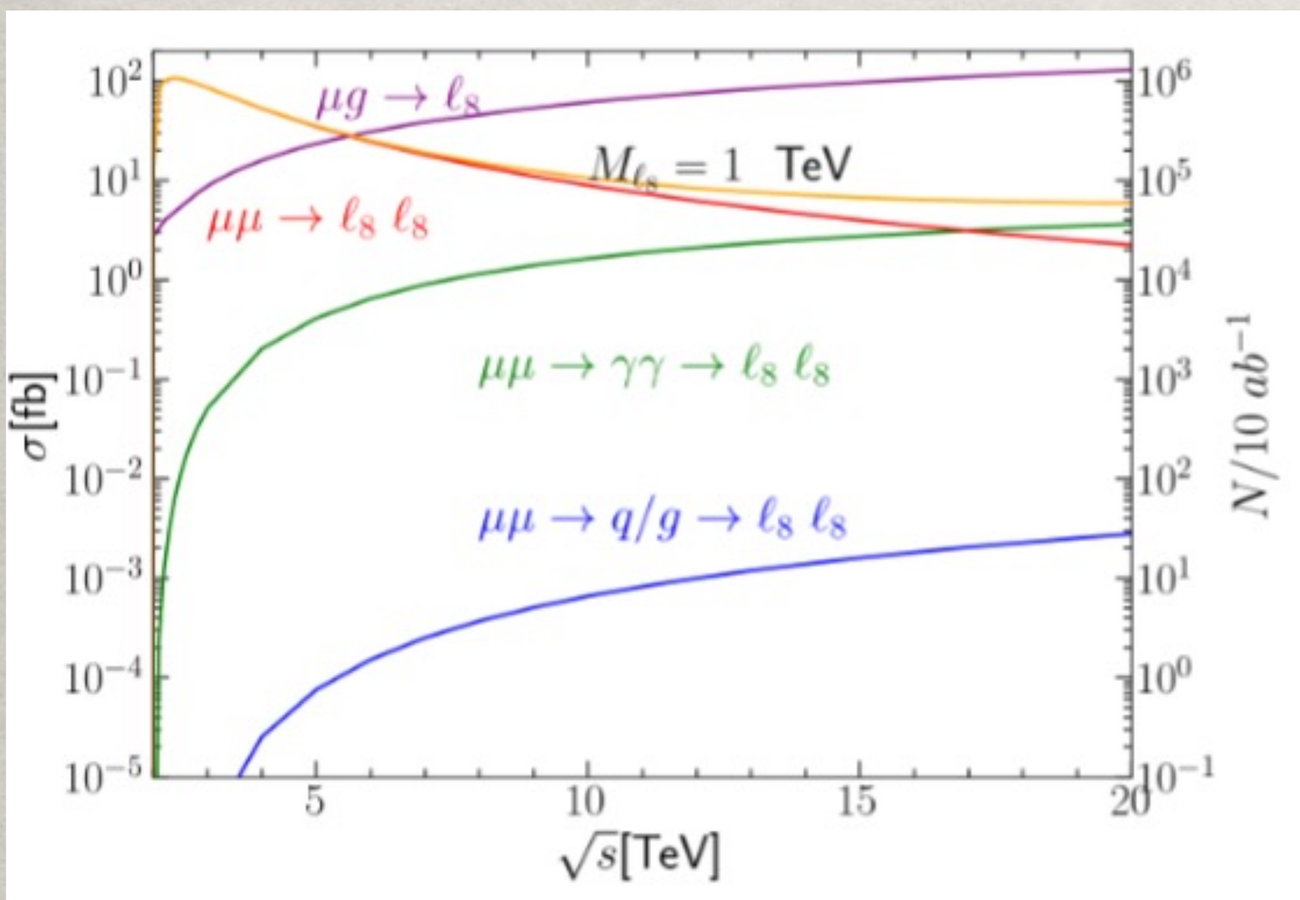
$\sqrt{s}$ =10 TeV
$y_L=y_R=1$
$y_L=y_R=0$
μμ→q/g→V
μμ→q/g→VV
μμ→γγ→VV
σ [fb]
N/10ab^{-1}
M_V [GeV]



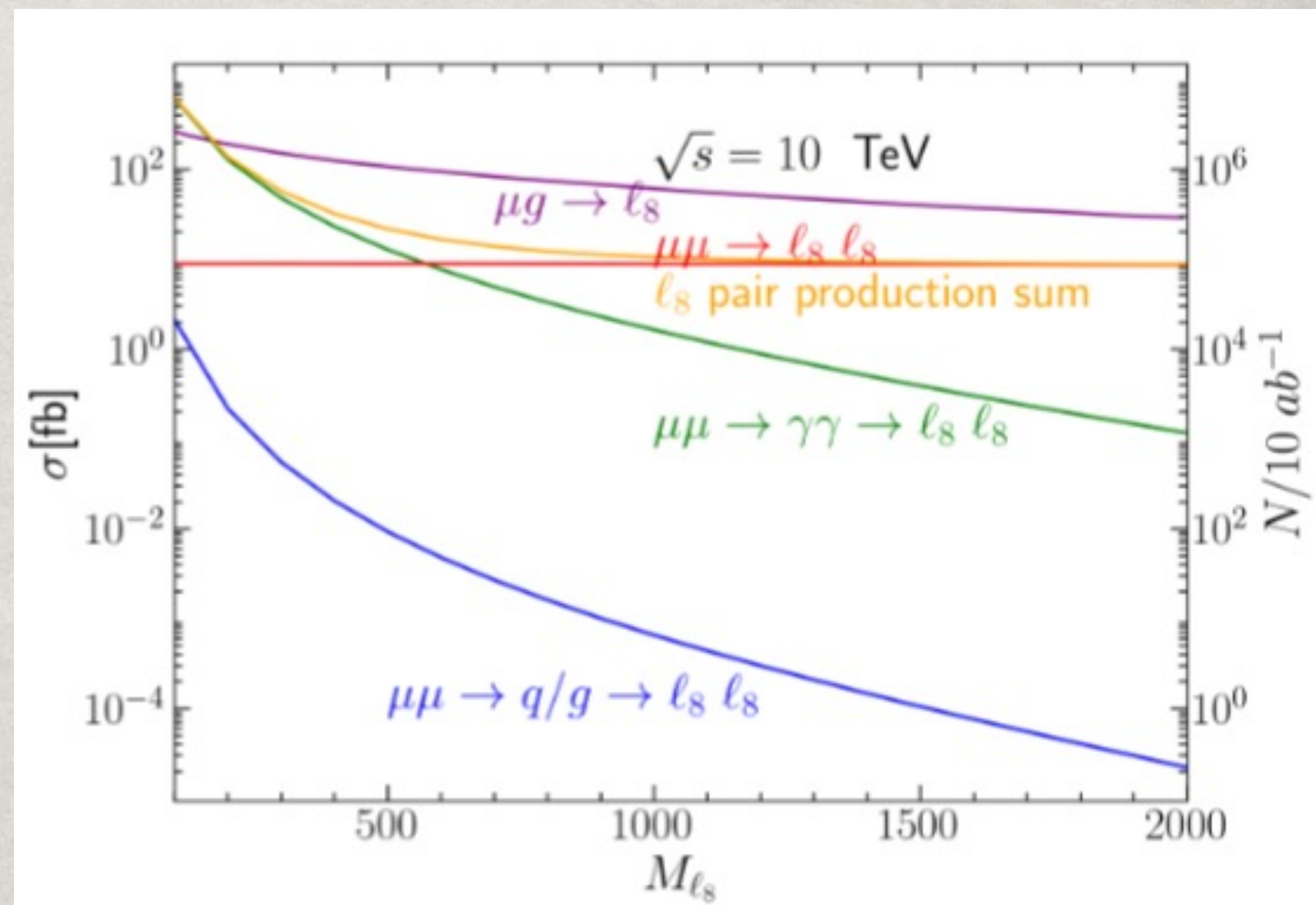
MΦ=1 TeV
λ_L^cμ=λ_R^cμ=1
cμ→Φ
μγ→Φc̄
μμ→ΦΦ̄
σ [fb]
N/10ab⁻¹
√s [TeV]



√s =10 TeV
λ_L^cμ=λ_R^cμ=1
cμ→Φ
μγ→Φc̄
μμ→ΦΦ̄
σ [fb]
N/10ab⁻¹
MΦ [GeV]



μg → ℓ8
M_ℓ8 = 1 TeV
μμ → ℓ8 ℓ8
μμ → γγ → ℓ8 ℓ8
μμ → q/g → ℓ8 ℓ8
σ[fb]
N/10 ab⁻¹
√s[TeV]



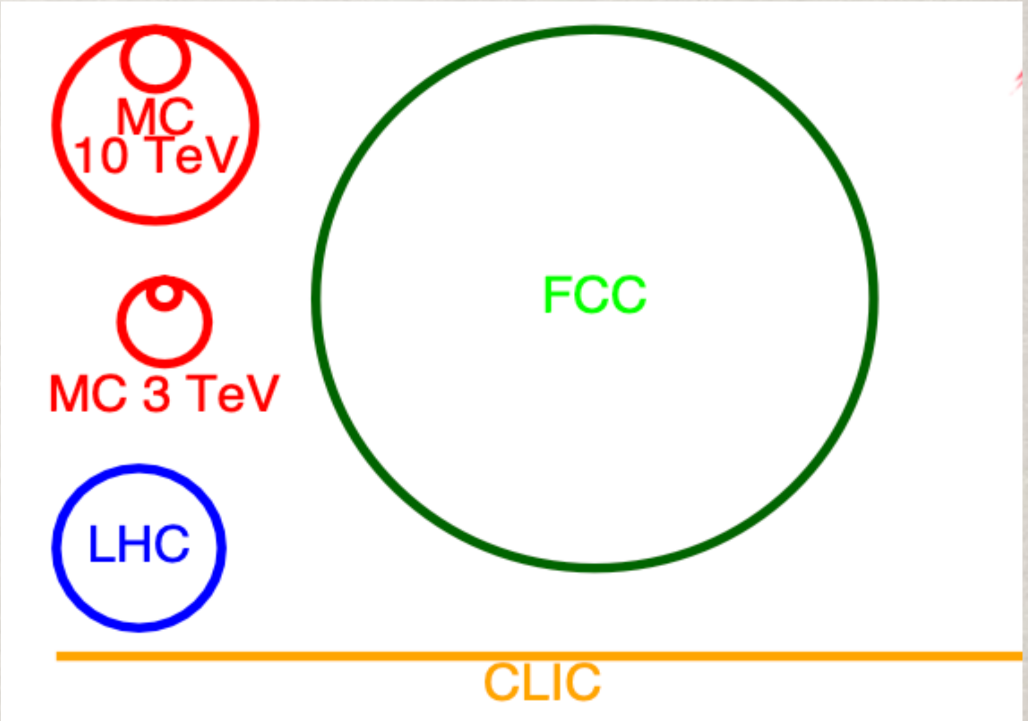
√s = 10 TeV
μg → ℓ8
μμ → ℓ8 ℓ8
ℓ8 pair production sum
μμ → γγ → ℓ8 ℓ8
μμ → q/g → ℓ8 ℓ8
σ[fb]
N/10 ab⁻¹
M_ℓ8

• Advantages of a muon collider

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

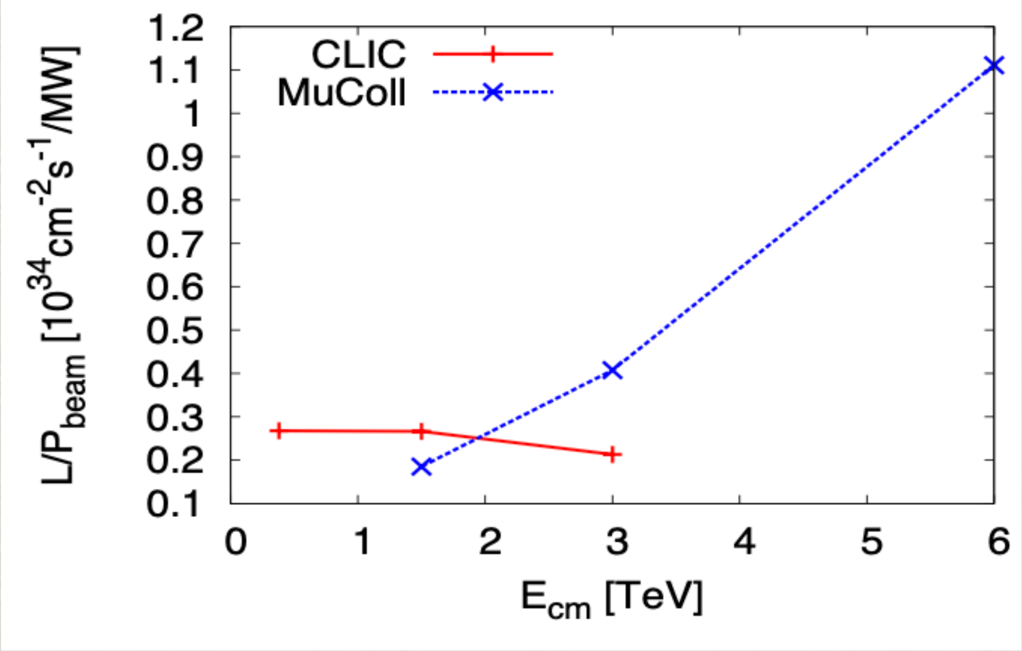
$$\Delta E \sim \frac{1}{R}\,(\frac{E}{m_\mu})^4$$

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:

ΔE/E ~ 0.1%

potentially **Δ**E/E(m_H) ~ 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

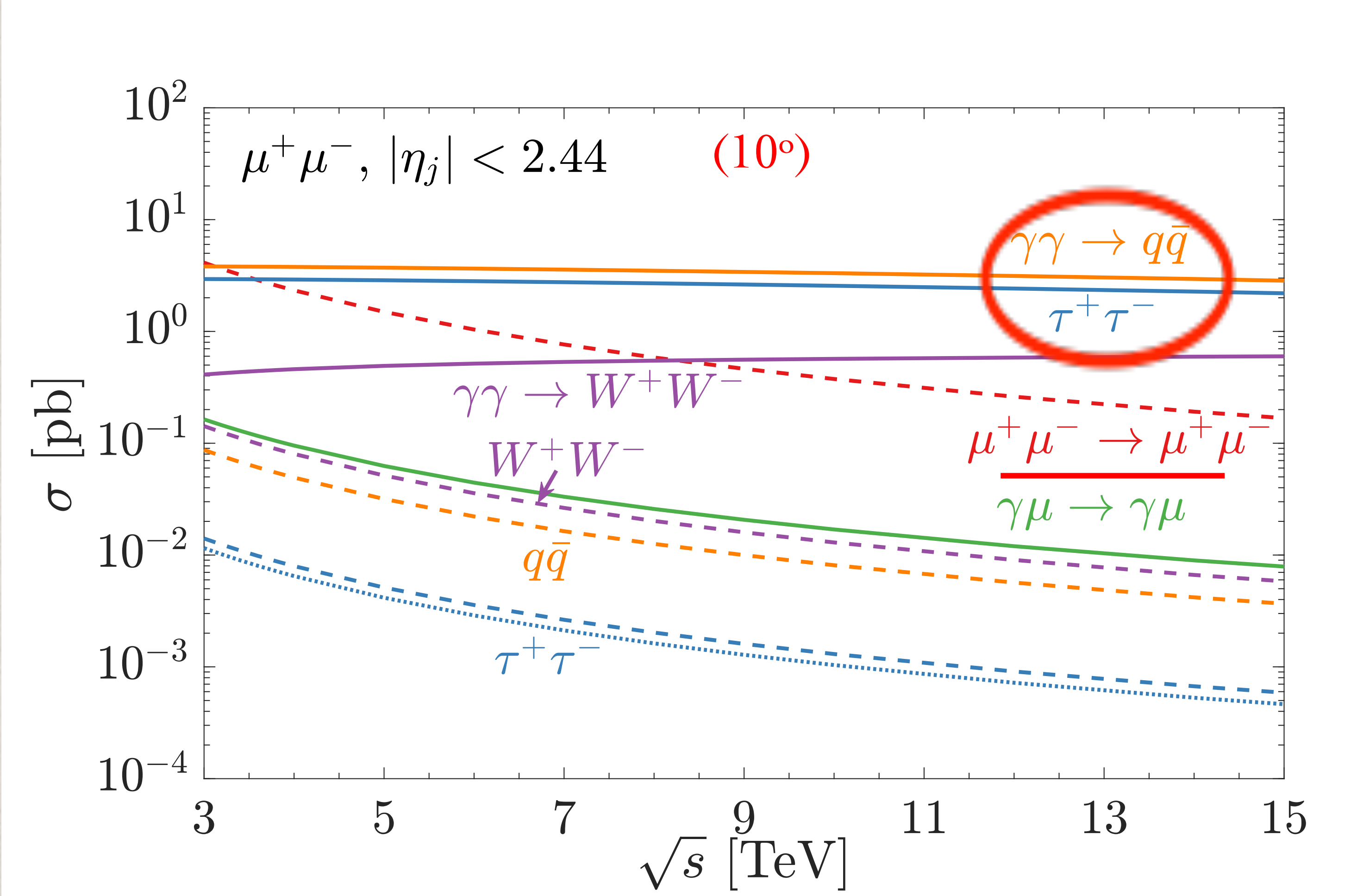
- Beam Induced Backgrounds (BIB) from the decays in the ring at the interacting point

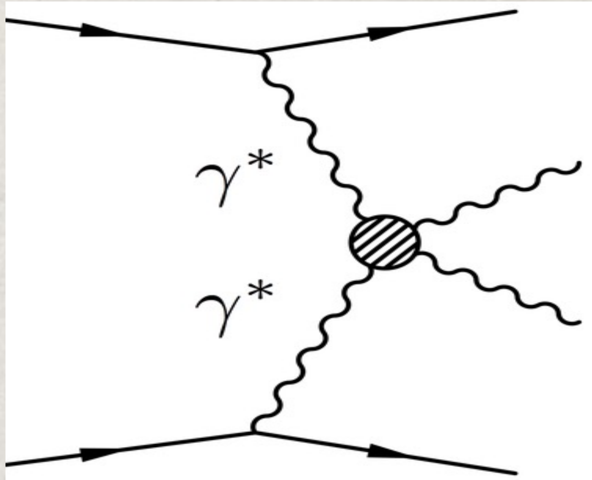
- Neutrino beam dump (environmental hazard)

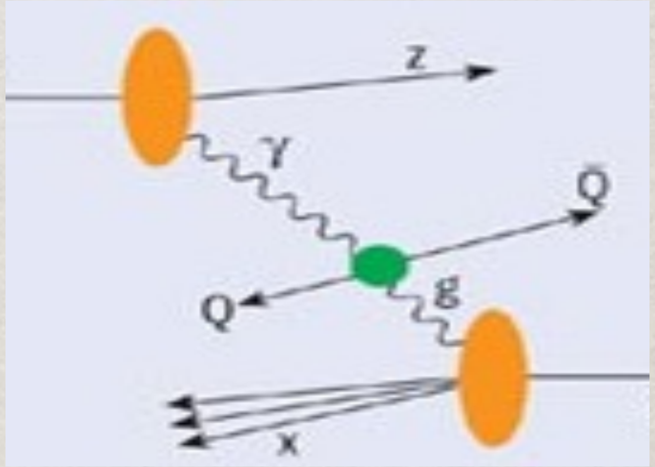
$\boldsymbol{\sigma_\nu} \sim G_F^2\, E^2$ → Shielding?

• Photon-induced QED cross sections

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





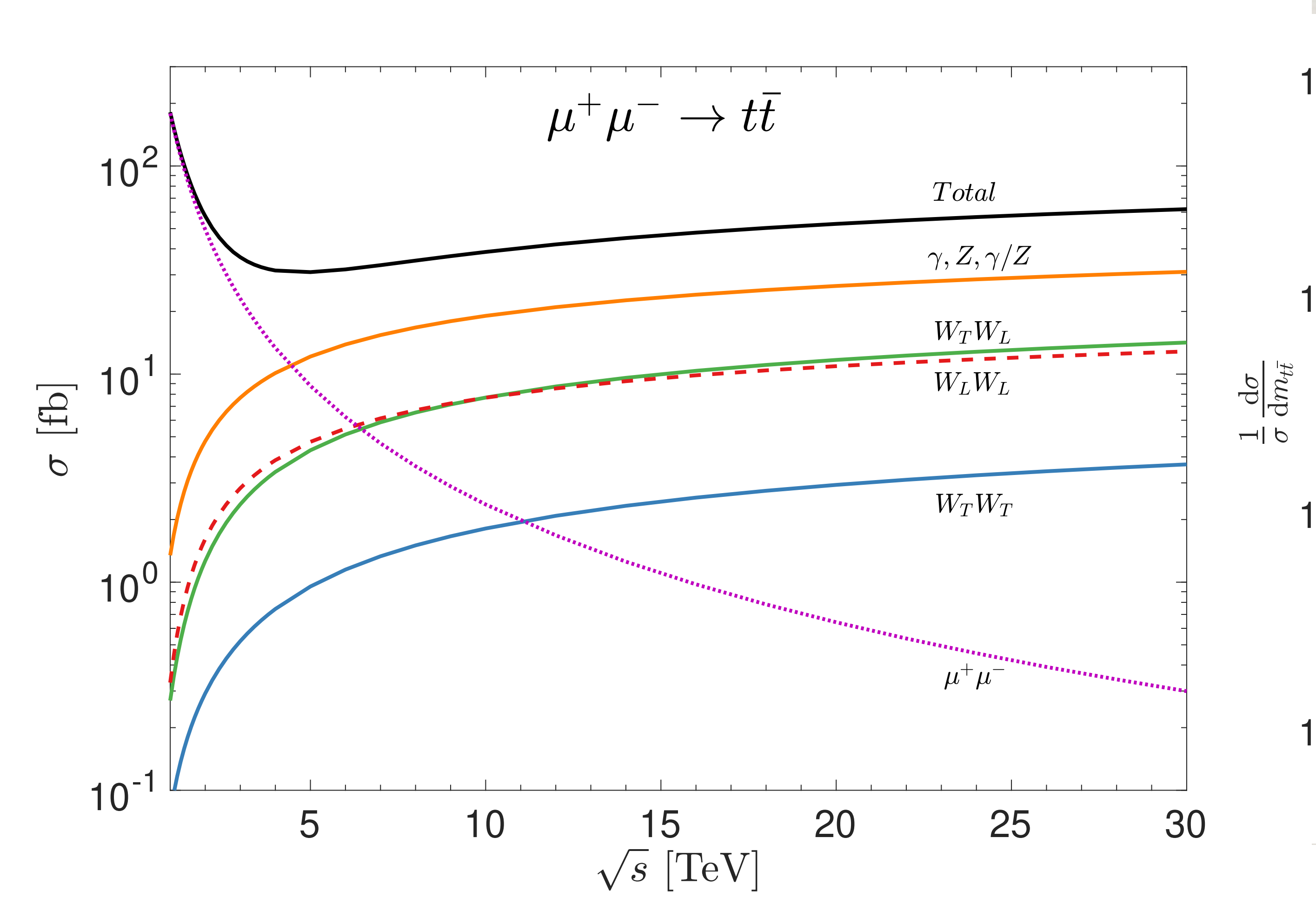


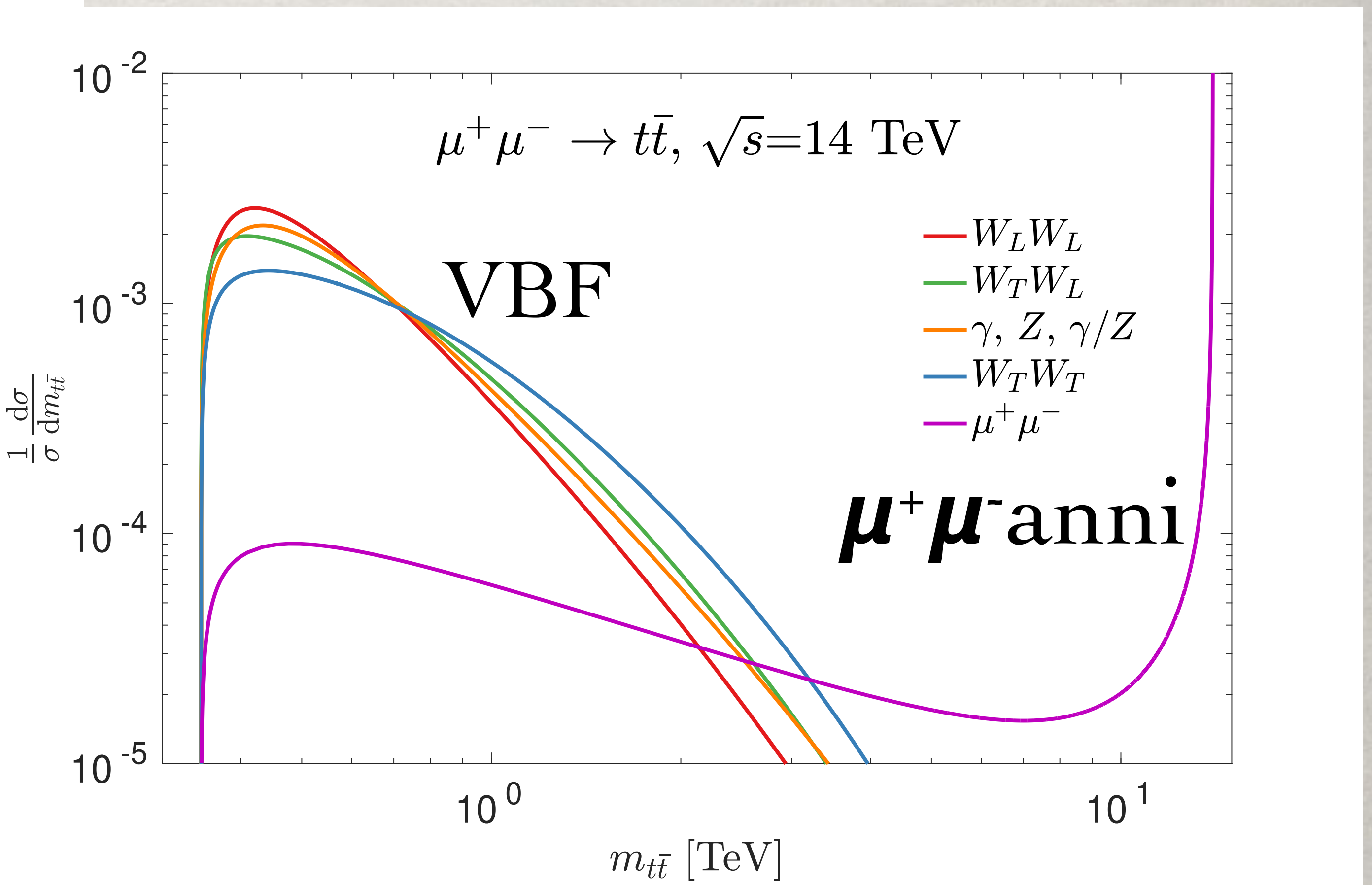
$p_T^j > \left(4 + \frac{\sqrt{s}}{3\ \text{TeV}}\right)$ GeV, $\quad m_{ij} > 20$ GeV, $\quad |\eta_j| < 3.13\ (2.44)$

Quarks/gluons come into the picture via SM DGLAP:

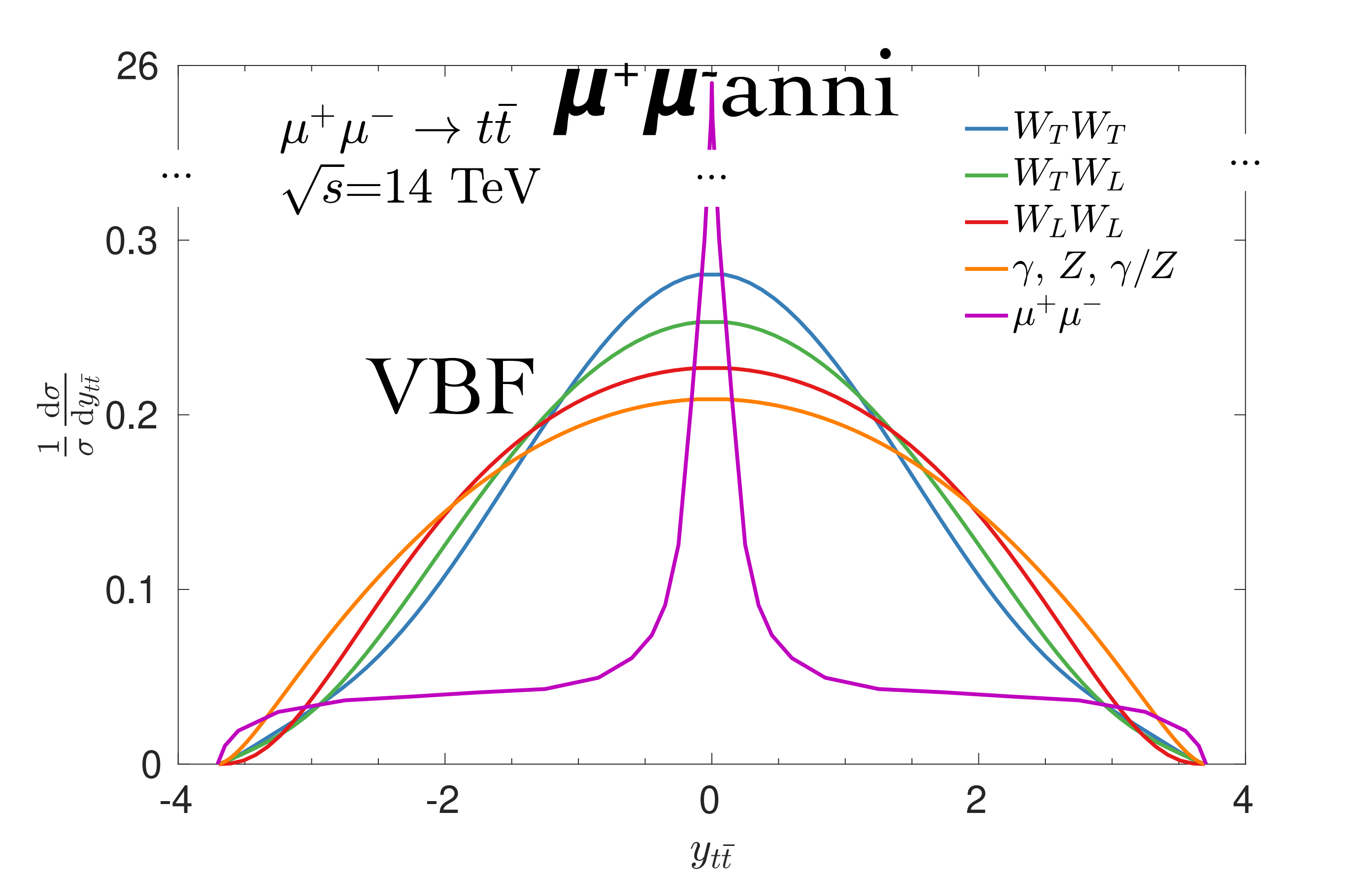
$$\frac{d}{d\log Q^2}\begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix} = \begin{pmatrix} P_{\ell\ell} & 0 & 0 & 2N_\ell P_{\ell\gamma} & 0 \\ 0 & P_{uu} & 0 & 2N_u P_{u\gamma} & 2N_u P_{ug} \\ 0 & 0 & P_{dd} & 2N_d P_{d\gamma} & 2N_d P_{dg} \\ P_{\gamma\ell} & P_{\gamma u} & P_{\gamma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

• Underlying sub-processes:





Partonic contributions

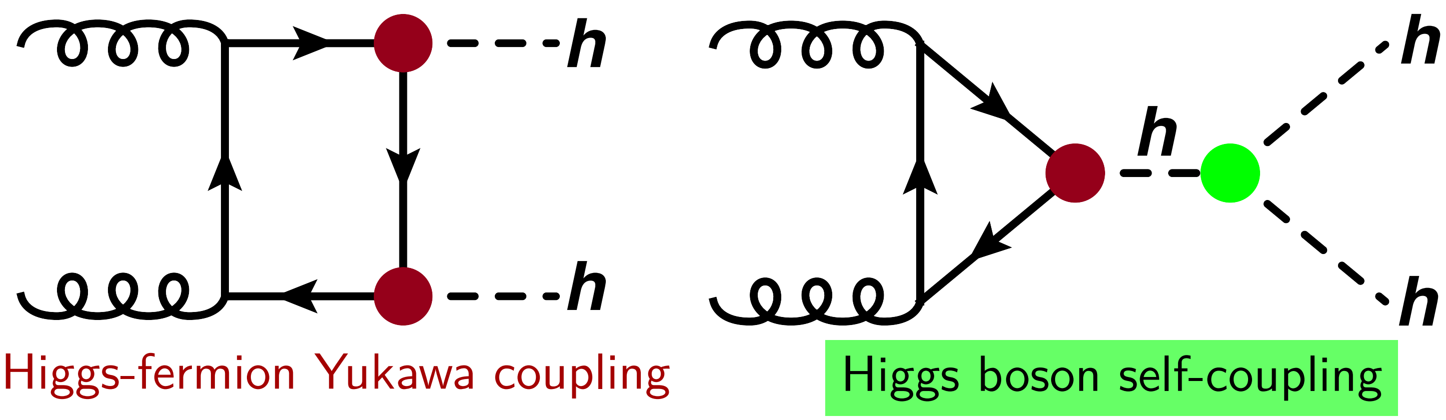


$\mu^+\mu^-$ Collider --
"Buy one, get one free":
Annihilation +VBF

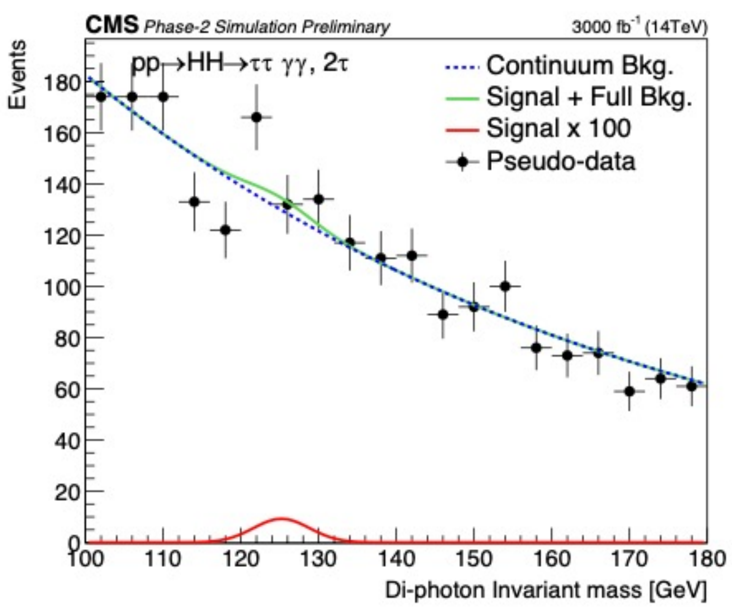
Higgs pair production & triple coupling:

SM Higgs boson pair production at the LHC

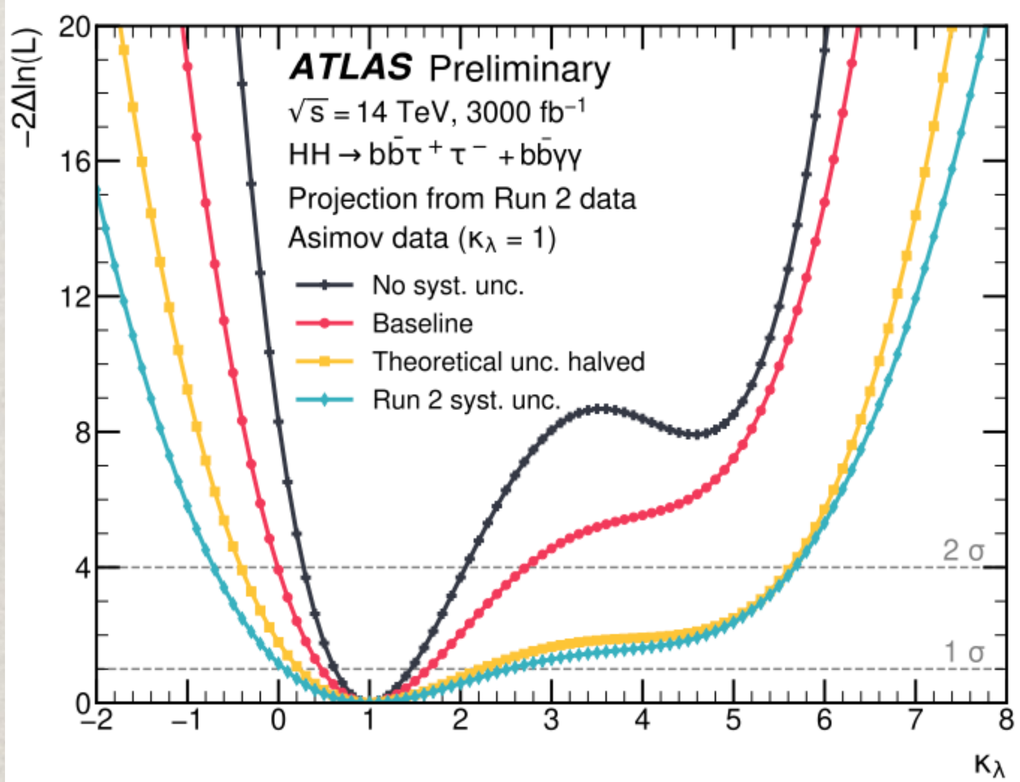
SM Higgs boson pair production (gluon-gluon fusion - ggF):



For Snowmass, CMS updated γγbb, added γγWW, γγττ, ttHH

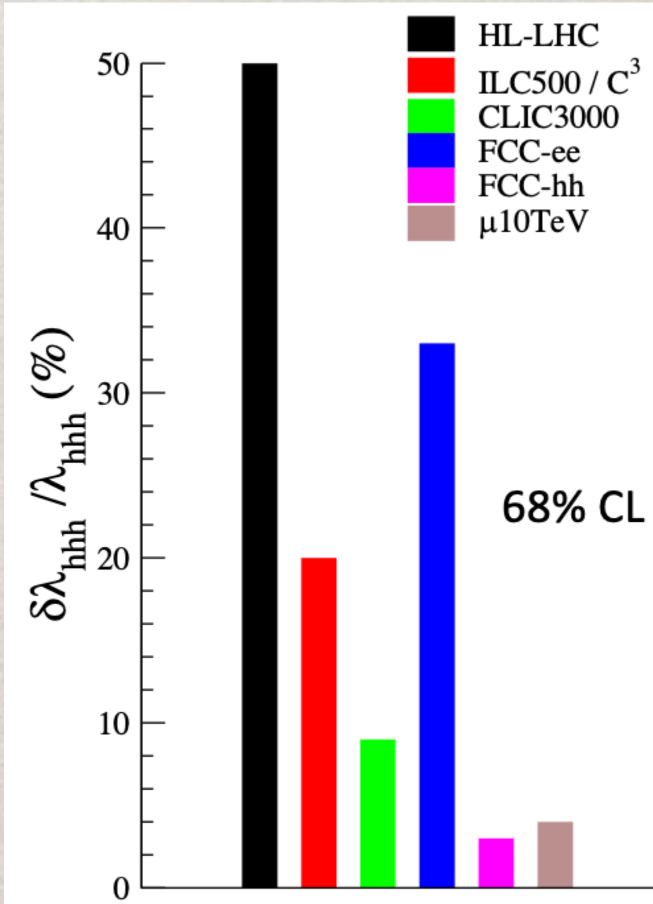


CMS-PAS-FTR-21-003



3.2σ with systematic uncertainty

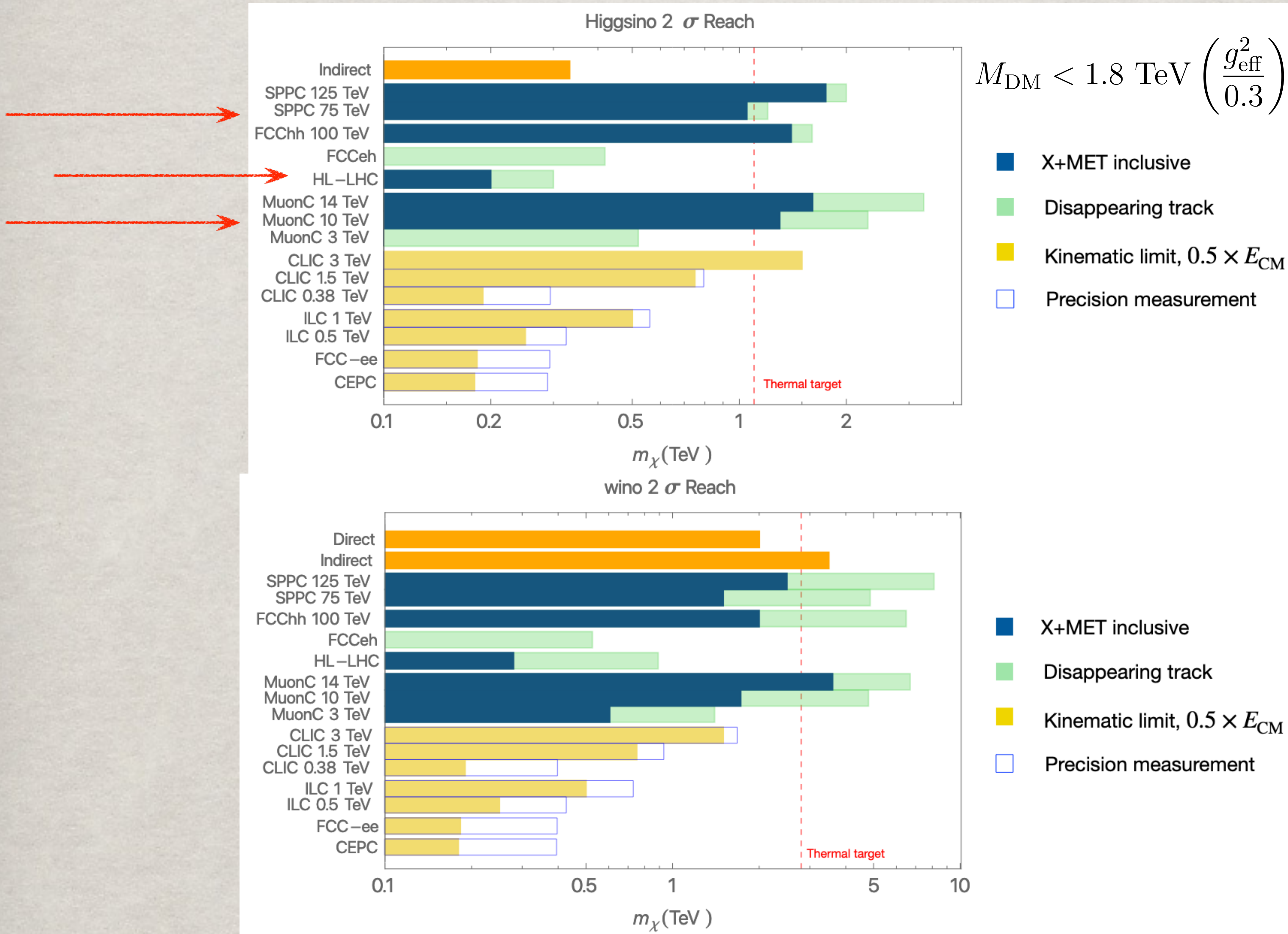
ATLAS-2022-005



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

WIMP Dark Matter

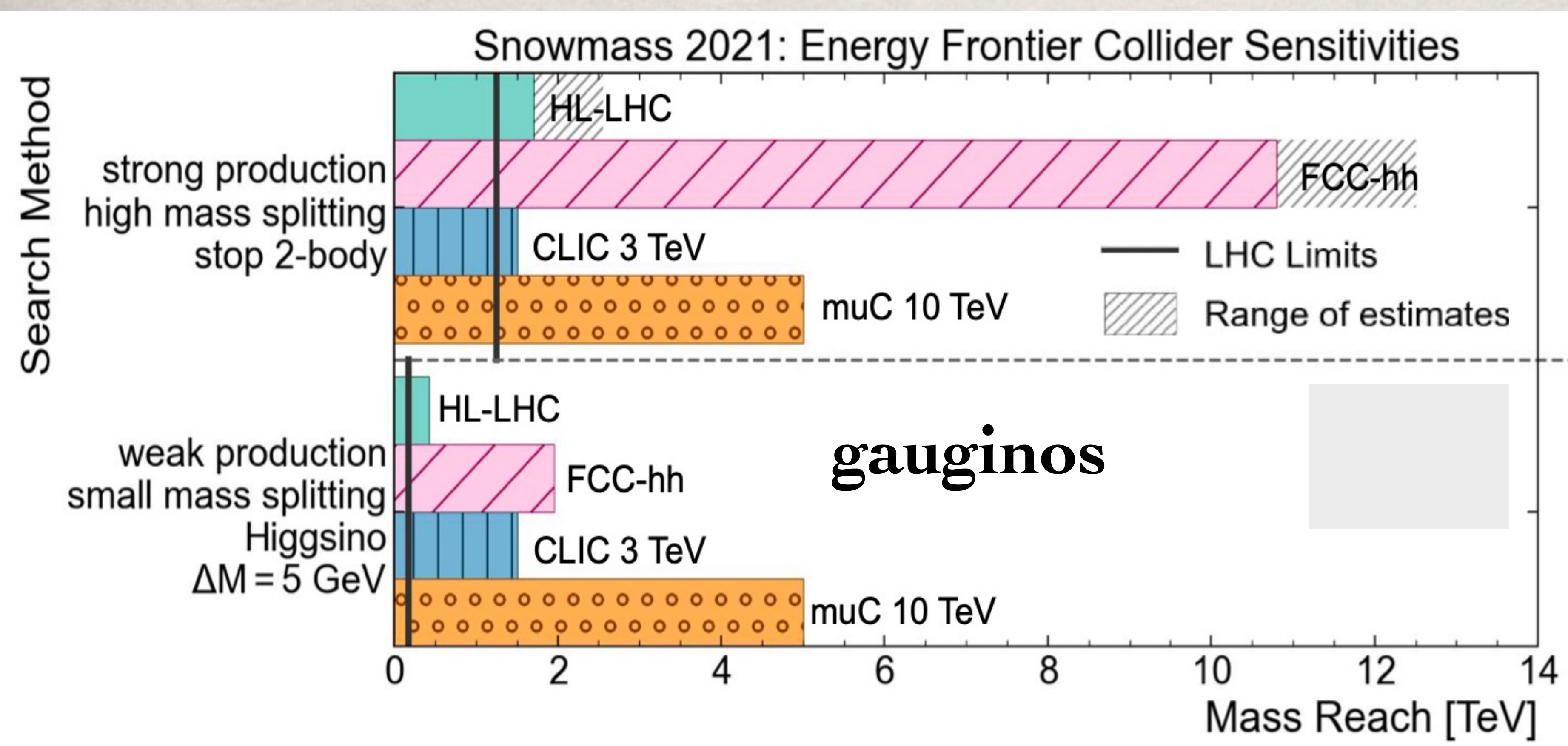
Covering the thermal target

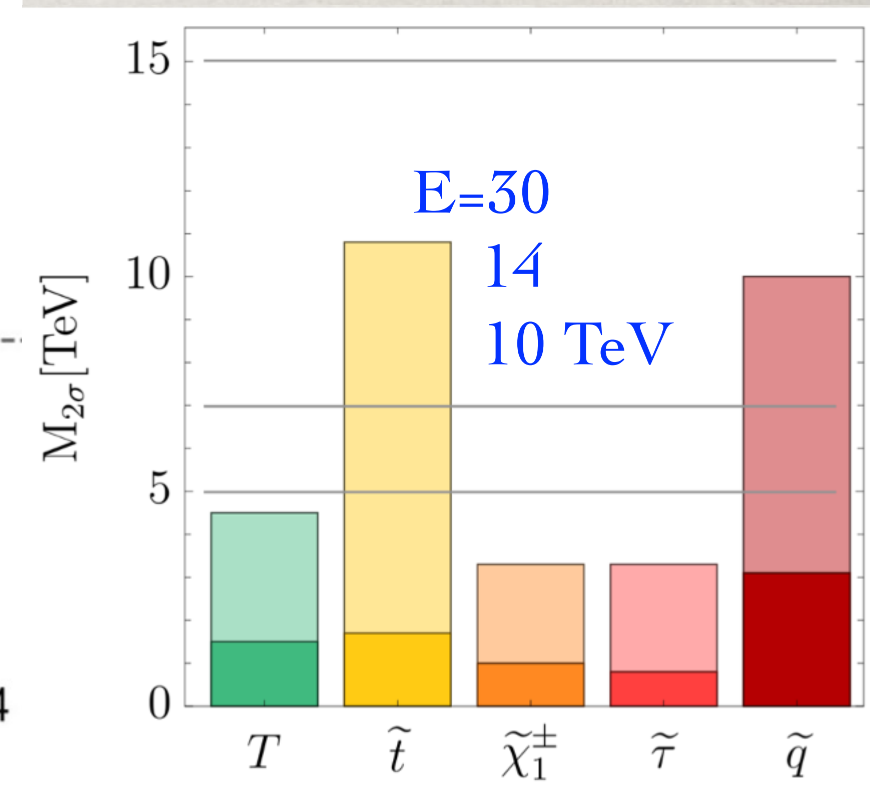


TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287; arXiv:2203.07351

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!

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

Snowmass 2021, EF report

arXiv:2211.11084

The US EF community proposes to develop plans to site an e^+e^- collider in the US. A Muon Collider remains a highly appealing option for the US, and is complementary to a Higgs factory. For example, some options which are considered as attractive opportunities for building a domestic EF collider program are:

- **A US-sited linear e^+e^- (ILC/CCC) Collider**
- **Hosting a 10 TeV range Muon Collider**
- **Exploring other e^+e^- collider options to fully utilize the Fermilab site**

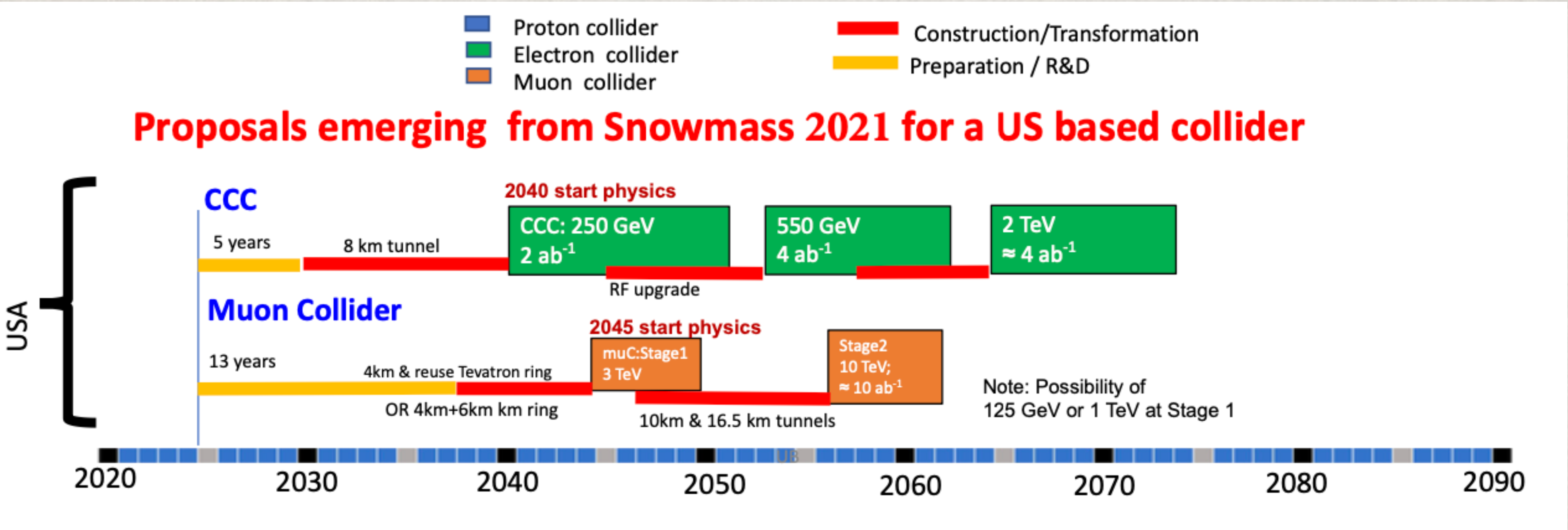


Figure 6-41. *Approximate timelines for proposals for ILC/CCC and Muon Collier emerging from Snowmass 2021 for a US based collider option.*

International Muon Collider Collaboration

https://muoncollider.web.cern.ch

Fermilab on site:

Site filler Accelerator

- **Largest**

Radius is ~2.65 km

- **~16.5 km Circumference**
  - **~2/3 LHC**

~RCS accelerator

If B_{ave}= 3 T → E_{μ}= 2.4 TeV

(B_{max} = 8T, B_{pulse} =±2T)

Doubled ?

B_{ave}= 6.3 T → E_{μ}= 5 TeV

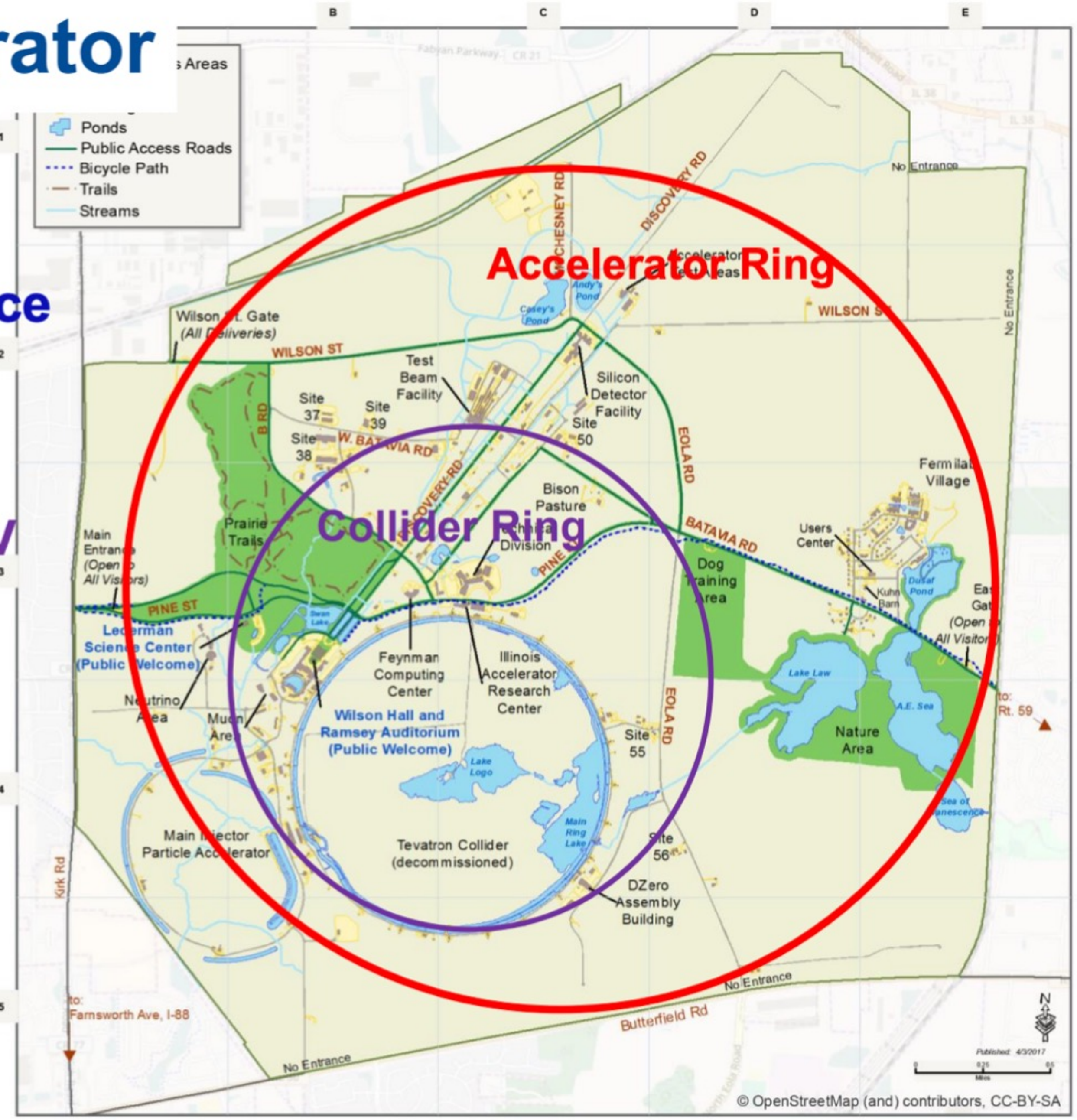
(B_{max} = 16T, B_{pulse} =±4T)

10 TeV collider

Collider Ring ~10 km

B_{ave} = 10 T

τ_{μ} = 0.104 s

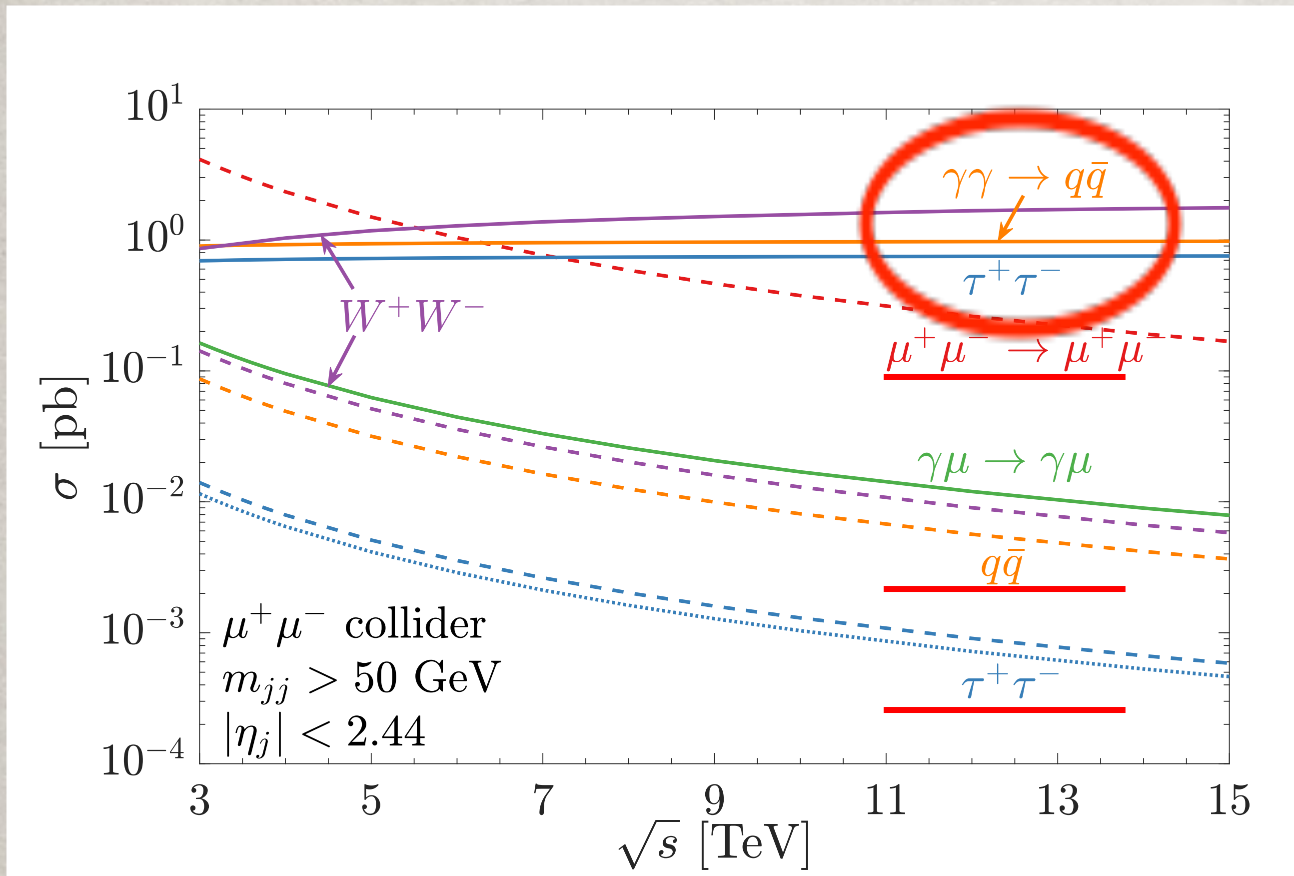


Daniel Schulte; Mark Palmer; Katsuya Yonehara talk, March 2022

• Jets at low energies

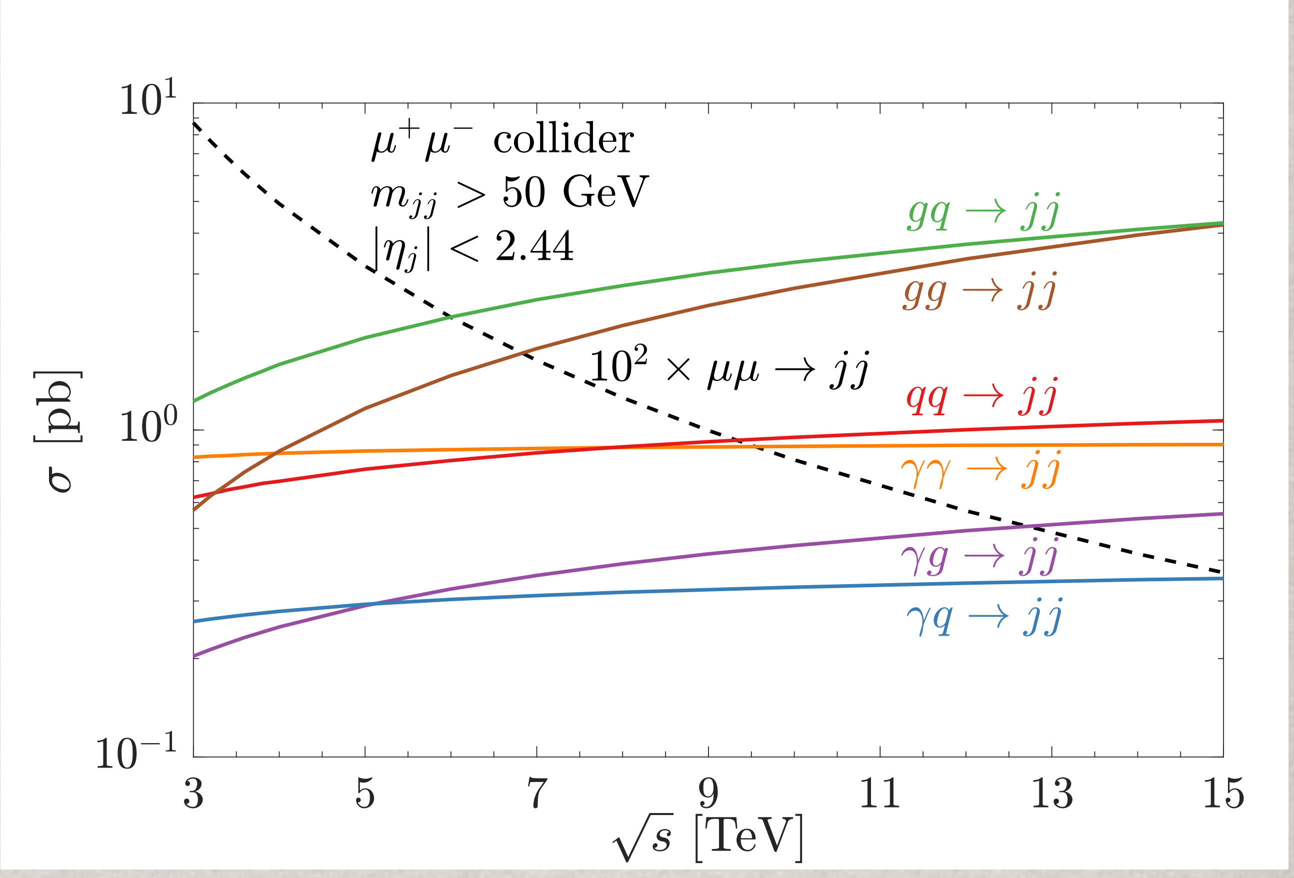
For **μ⁺μ⁻** annihilation: $\sigma_{ann} \sim \frac{\alpha^2}{s}$

For partonic fusion: $\sigma_{fusion} \sim \frac{\alpha^2}{m_{jj}^2} \log^2(\frac{Q^2}{m^2})$



Di-jet production: QCD dominates

$\gamma\gamma \to q\bar{q},\ \gamma g \to q\bar{q},\ \gamma q \to gq,$
$qq \to qq(gg),\ gq \to gq,$ and $gg \to gg(q\bar{q})$



TH, Yang Ma, Keping Xie, to appear soon.