PHYSICS OPPORTUNITIES FOR MUON COLLIDERS

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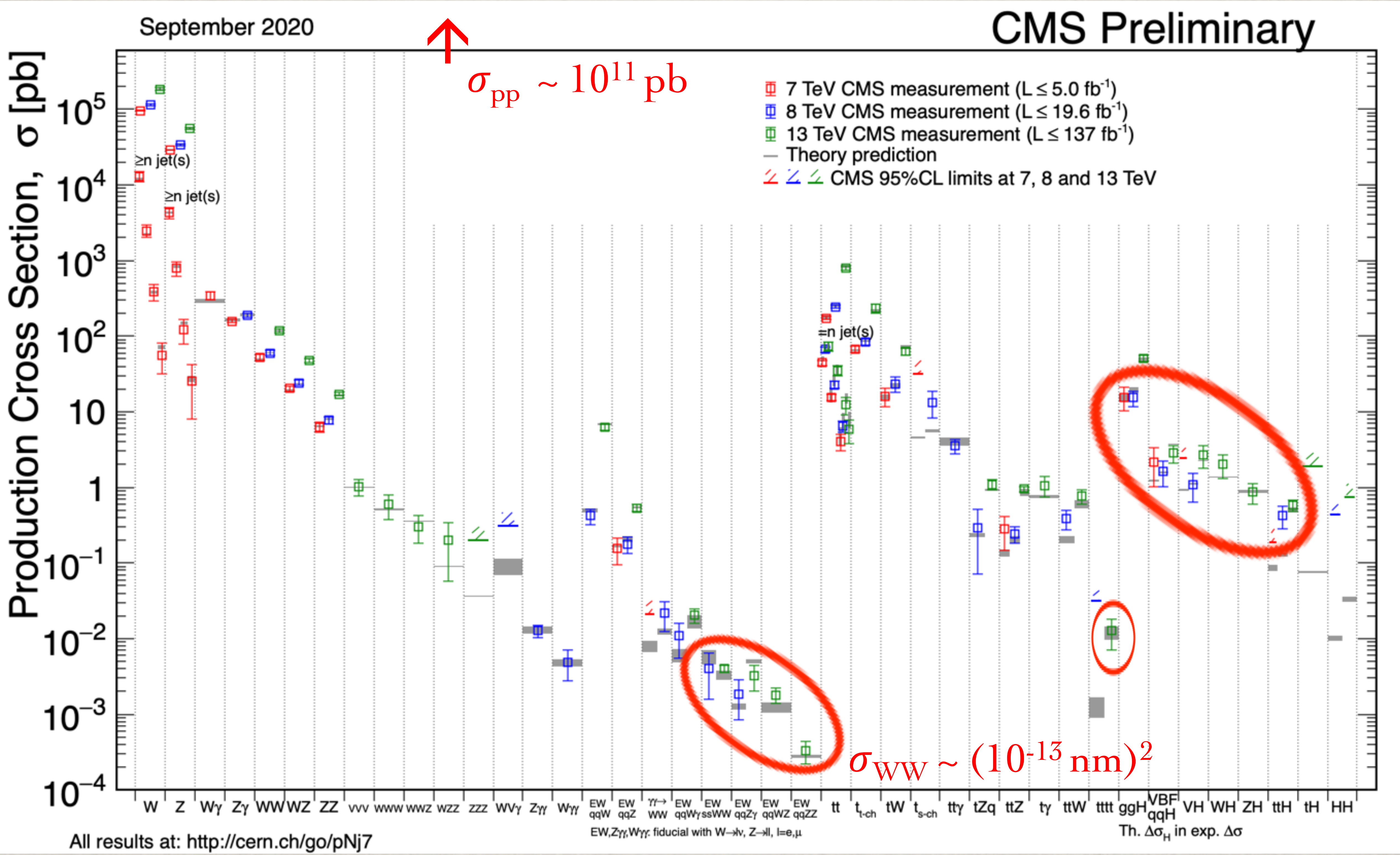
Pitt PACC, University of Pittsburgh
Colloquium at DESY, April 19, 2022

PITTPACC
PITTSBURGH PARTICLE PHYSICS ASTROPHYSICS COSMOLOGY CENTER

LHC ROCKS & SO DOES THE SM!



$\sigma_{pp} \sim 10^{11}$ pb

$\sigma_{WW} \sim (10^{-13}\ \mathrm{nm})^2$

LHC: The energy frontier & precision frontier!

With the Higgs discovery, completion of the SM:

A relativistic, QM, renormalizable, self-consistent theory, valid up to an exponentially high scale! … M_{Pl} **?**

"… most of the grand underlying principles have been firmly established. (An eminent physicist remarked that) the future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

Michelson–Morley experiments (1887):
"the moving-off point for the theoretical aspects
of the second scientific revolution"

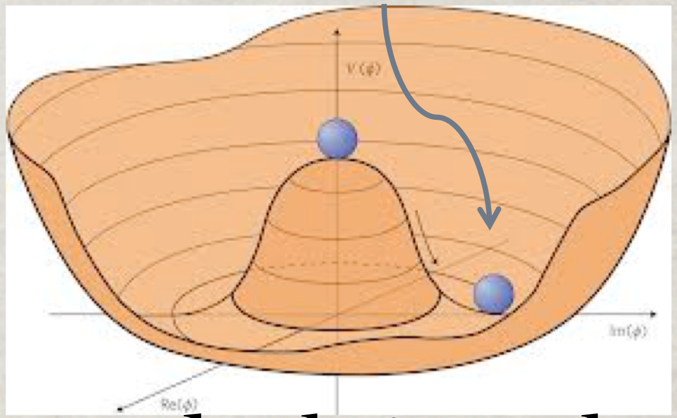
Will History repeat itself (soon)?

MOTIVATION FOR ENERGY FRONTIER

1. Electroweak Symmetry Breaking, EW Superconductivity & Phase Transition

$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

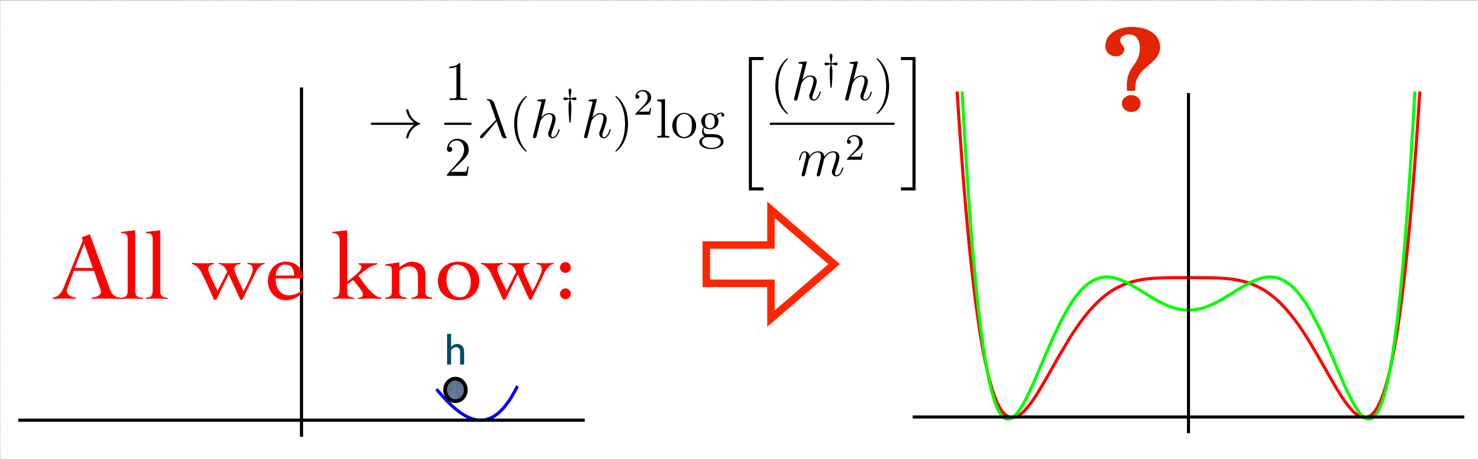
You are here



It's like Landau-Ginzburg theory,
but not!

- 😃 It is a relativistic QFT.
- 🙁 No EW analogue for BCS as the underlying theory to **understand** the dynamics, to **calculate** $\mu^2(\Lambda^2)$ & λ.

And the potential shape → early universe cosmology!



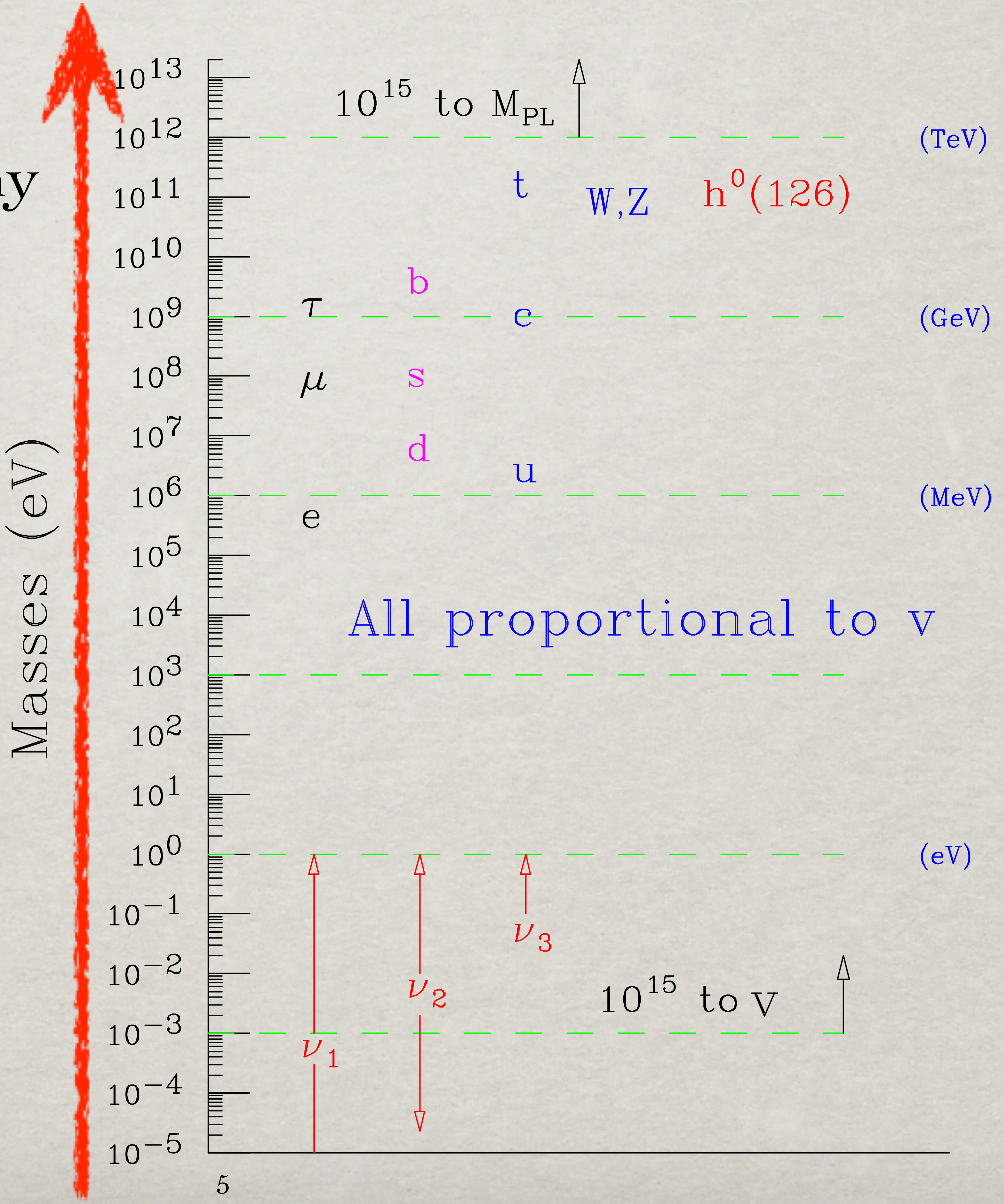
$$\rightarrow \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

All we know:

2. The “Flavor Puzzle”: fermion mass/mixing

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- Neutrino mass generation (seesaw)
- New CP-violation sources

Higgs is in a pivotal position.

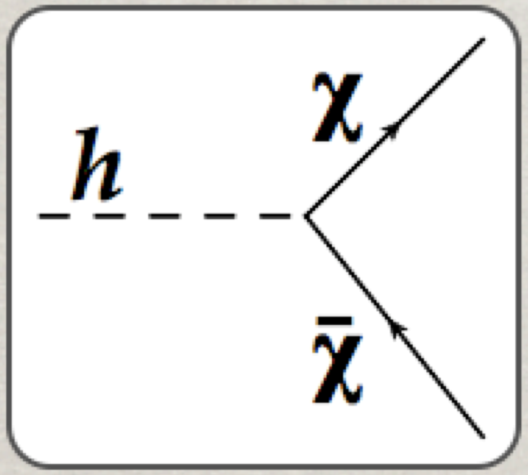


3. The Dark Sector: WIMP DM?

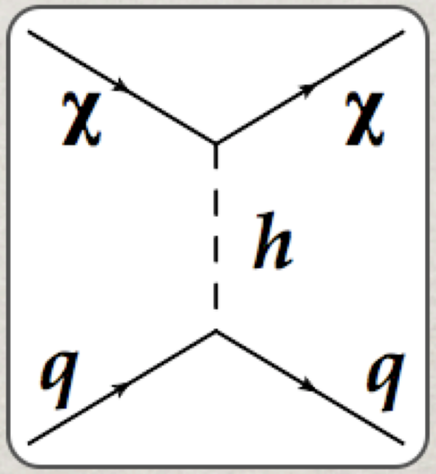
The nature of DM is among the most pressing issue.
Weakly Interacting DM strongly motivated.

$H^\dagger H$ Higgs portal: $k_s H^\dagger H\ S^* S, \quad \frac{k_\chi}{\Lambda} H^\dagger H\ \bar{\chi}\chi.$

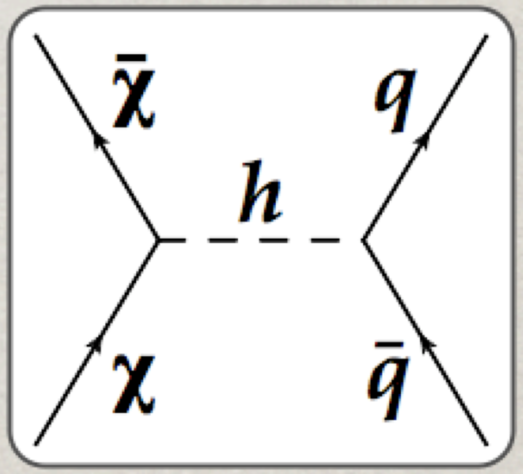
Dark matter at colliders

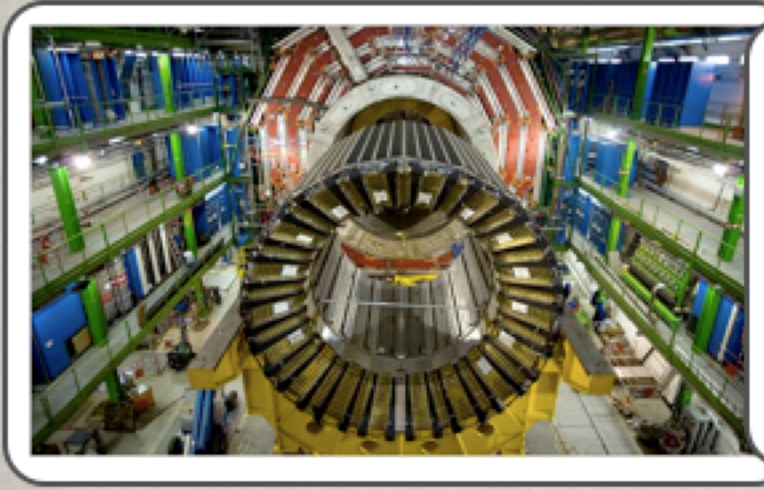


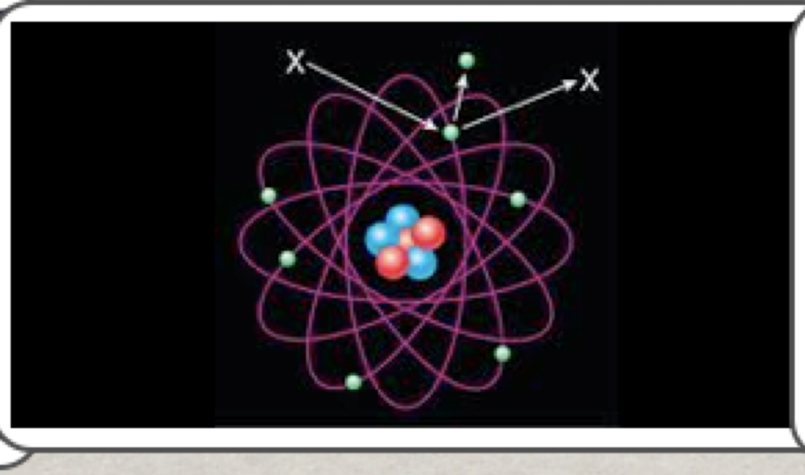
Direct detection

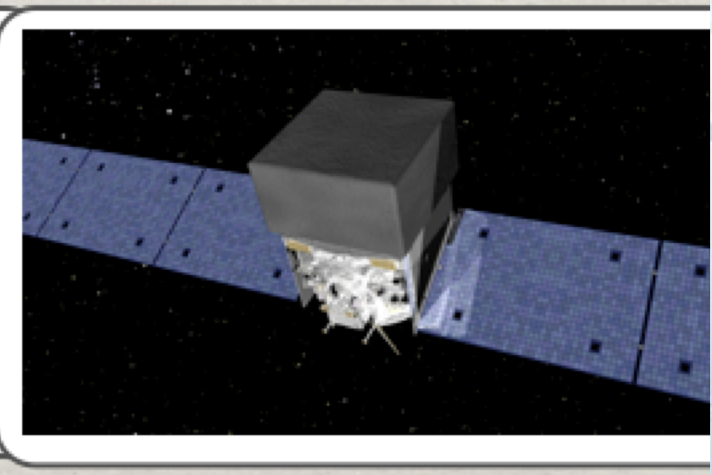


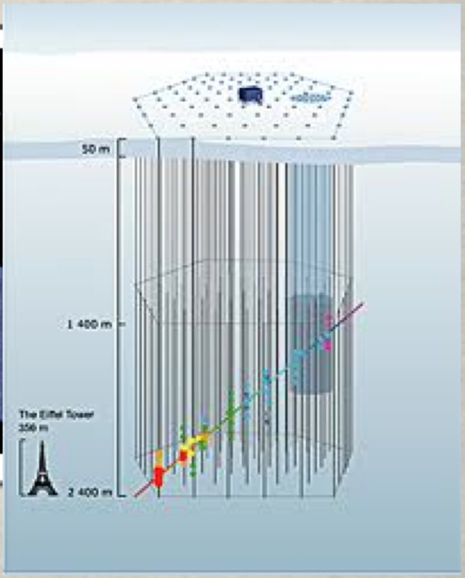
Indirect detection







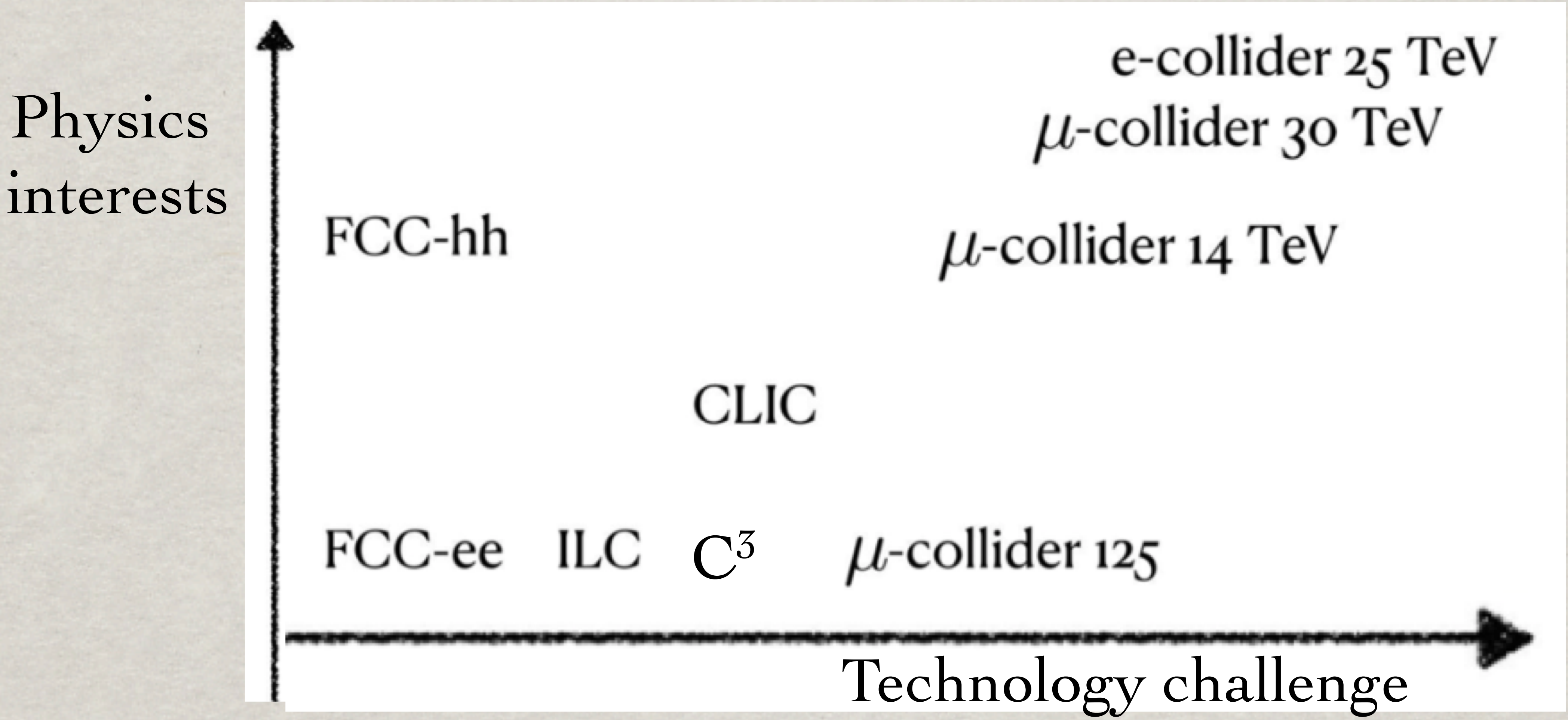




Snowmass on Future Colliders:

Energy Frontier / Accelerator Frontier

https://snowmass21.org



Physics interests

e-collider 25 TeV

μ-collider 30 TeV

FCC-hh

μ-collider 14 TeV

CLIC

FCC-ee ILC C^3 μ-collider 125

Technology challenge

Renewed interests:

- Muon colliders
- C^3: Cool Copper Collider (Linear e^+e^-)

A MUON COLLIDER

Why muons?

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

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

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

Some early work in the 90's :

- *S-channel Higgs boson production at a muon collider,* Barger et al., PRL75 (1995).
- ***$\mu^+ \mu^-$*** *Collider: Feasibility study,* Muon collider collaboration (July, 1996).
- *Higgs boson physics in the s-channel muon collider,* Barger et al., Phys Rep. 186 (1997).
- *Status of muon collider research,* Muon collider collaboration (Aug., 1999).
- *Recent progress on neutrino factory and muon collider research,*
  Muon collider collaboration (July, 2003).

😀 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:

  - Unlike the proton as a composite particle, E_{CM} efficient in $\boldsymbol{\mu^+\mu^-}$ annihilation

  - Much smaller beam-energy spread:

$$\Delta E/E \sim 0.01\% - 0.001\%$$

☹️ Disadvantages of a muon collider

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

"Never play with an unstable thing!"

- Very short lifetime: in micro-second,

Muons cooling in (x,p) 6-dimensions

→ Difficult to make quality beams and a high luminosity

[Note👍: $E_\mu \sim 1$ TeV → $\gamma \sim 10^4$ → $\gamma\tau = 0.02$ s → d=6,000 km]

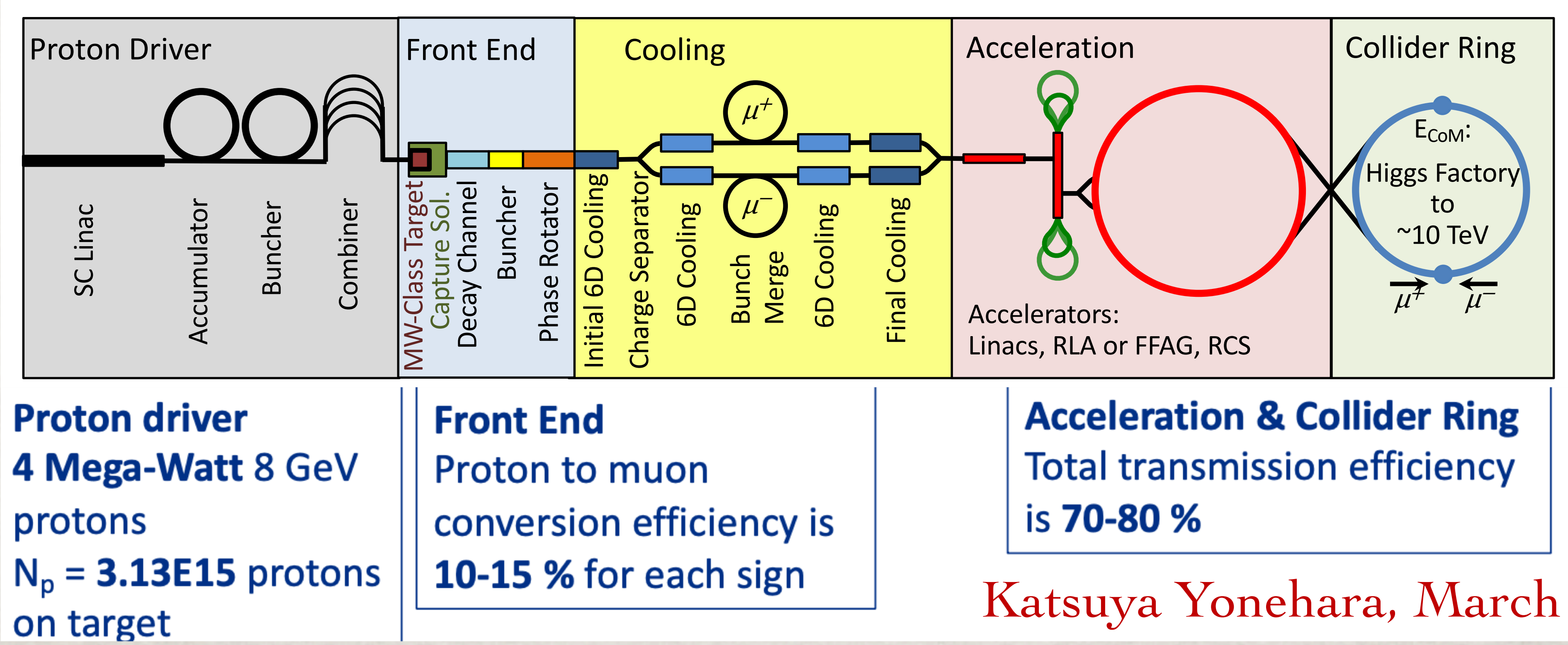
- Beam Induced Backgrounds (BIB) from the decays in the ring at the interacting point,

[Note👍: $\boldsymbol{\sigma}_{pp}$(total)~100 mb; $\boldsymbol{\sigma}_{\mu\mu}$(total)~100 nb]

- Neutrino beam dump (environmental hazard)

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

Proton Driver Option: Muon Accelerator Project (MAP)



Proton driver
4 Mega-Watt 8 GeV protons
N_p = **3.13E15** protons on target

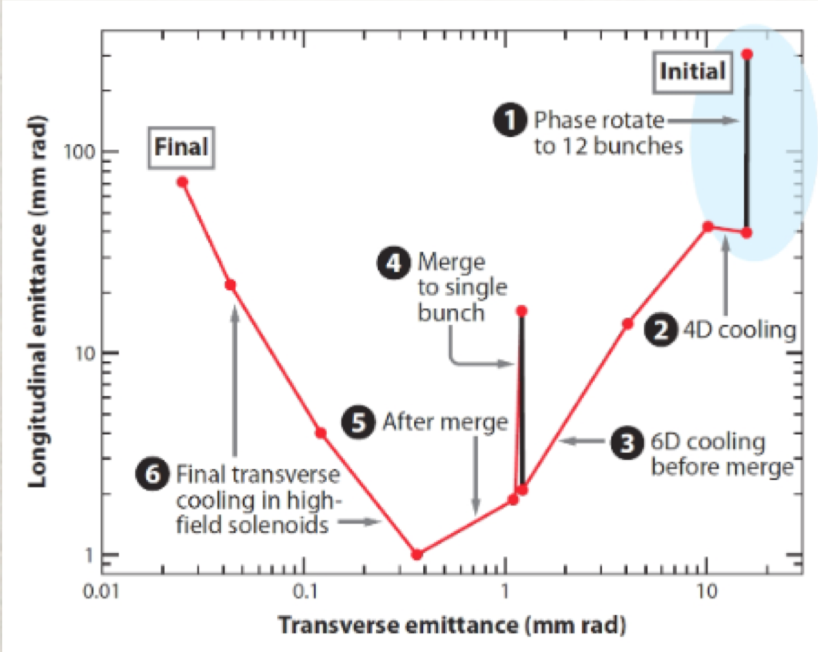
Front End
Proton to muon conversion efficiency is **10-15 %** for each sign

Acceleration & Collider Ring
Total transmission efficiency is **70-80 %**

Katsuya Yonehara, March 2022

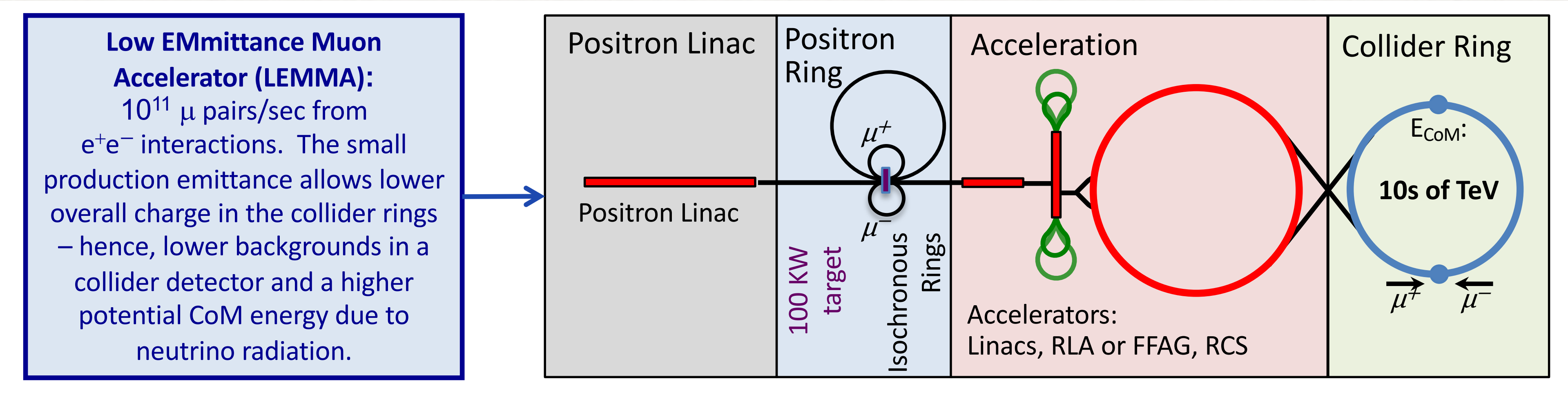
During 2011-2016, MAP collaboration formed:
to address key feasibility issues for **μ**C

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



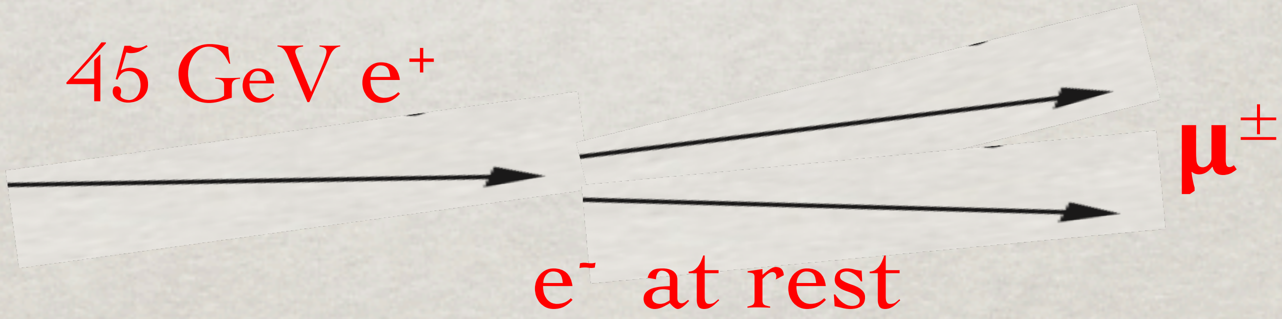
https://arxiv.org/abs/1907.08562, J.P. Delahauge et al., arXiv:1901.06150/

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



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

Low EMittance Muon Accelerator
web.infn.it/LEMMA



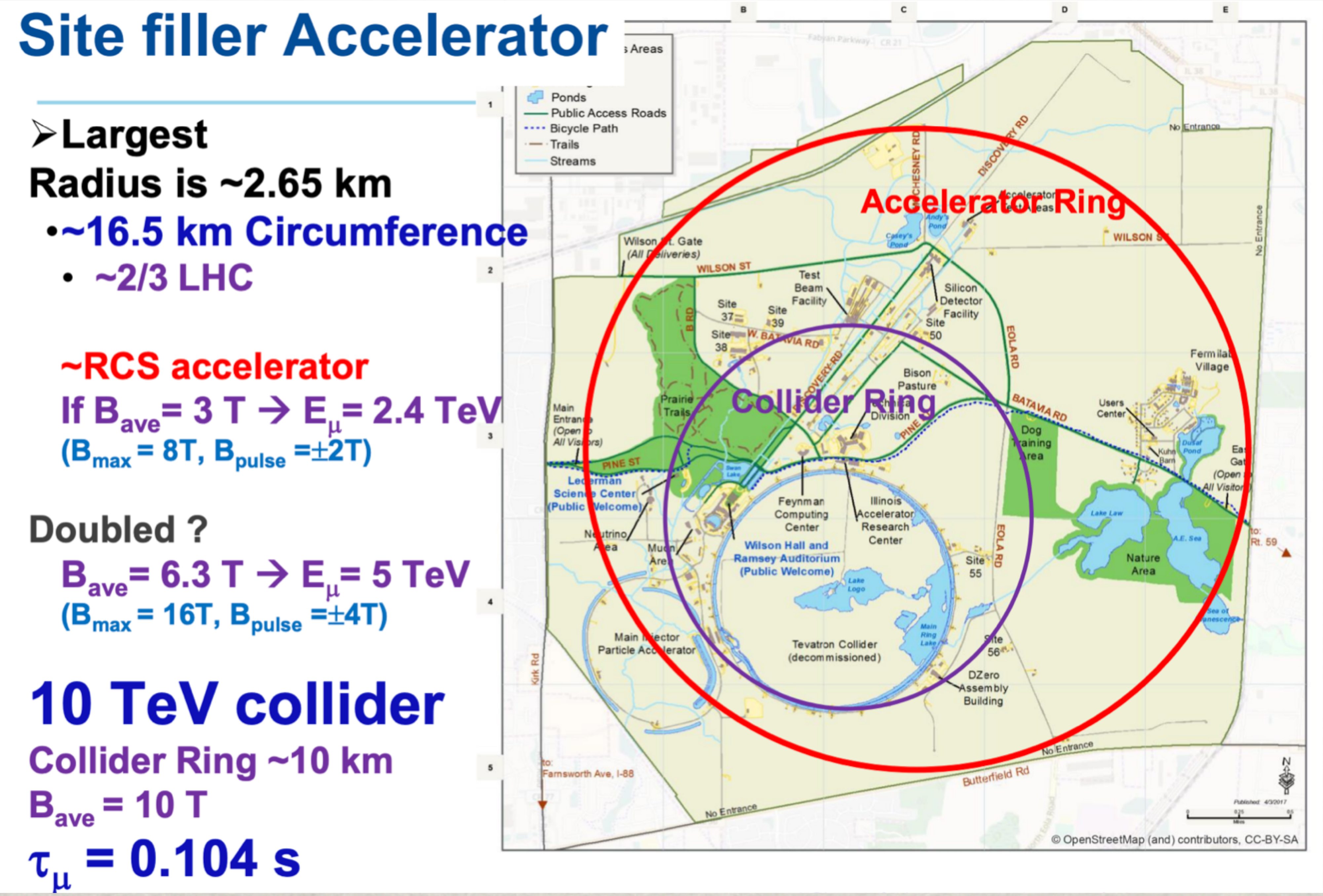
Cooling is not a problem;
but high luminosity is challenging!

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

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

Collider benchmark points:

- The Higgs factory:

$E_{cm} = m_H$

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

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

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

Current Snowmass 2021 point: 4 fb^{-1} / yr

- Multi-TeV colliders:

Lumi-scaling scheme: **σ** $L \sim$ 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

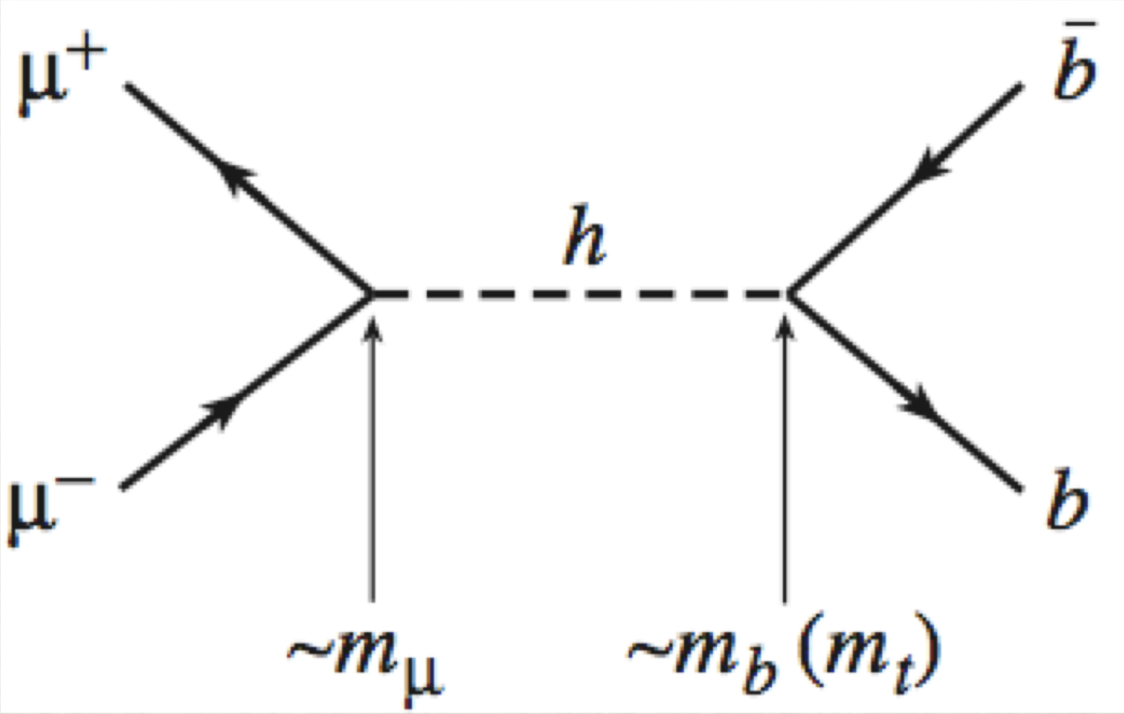
The aggressive choices:

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

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

A HIGGS FACTORY

Resonant Production:



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

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

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

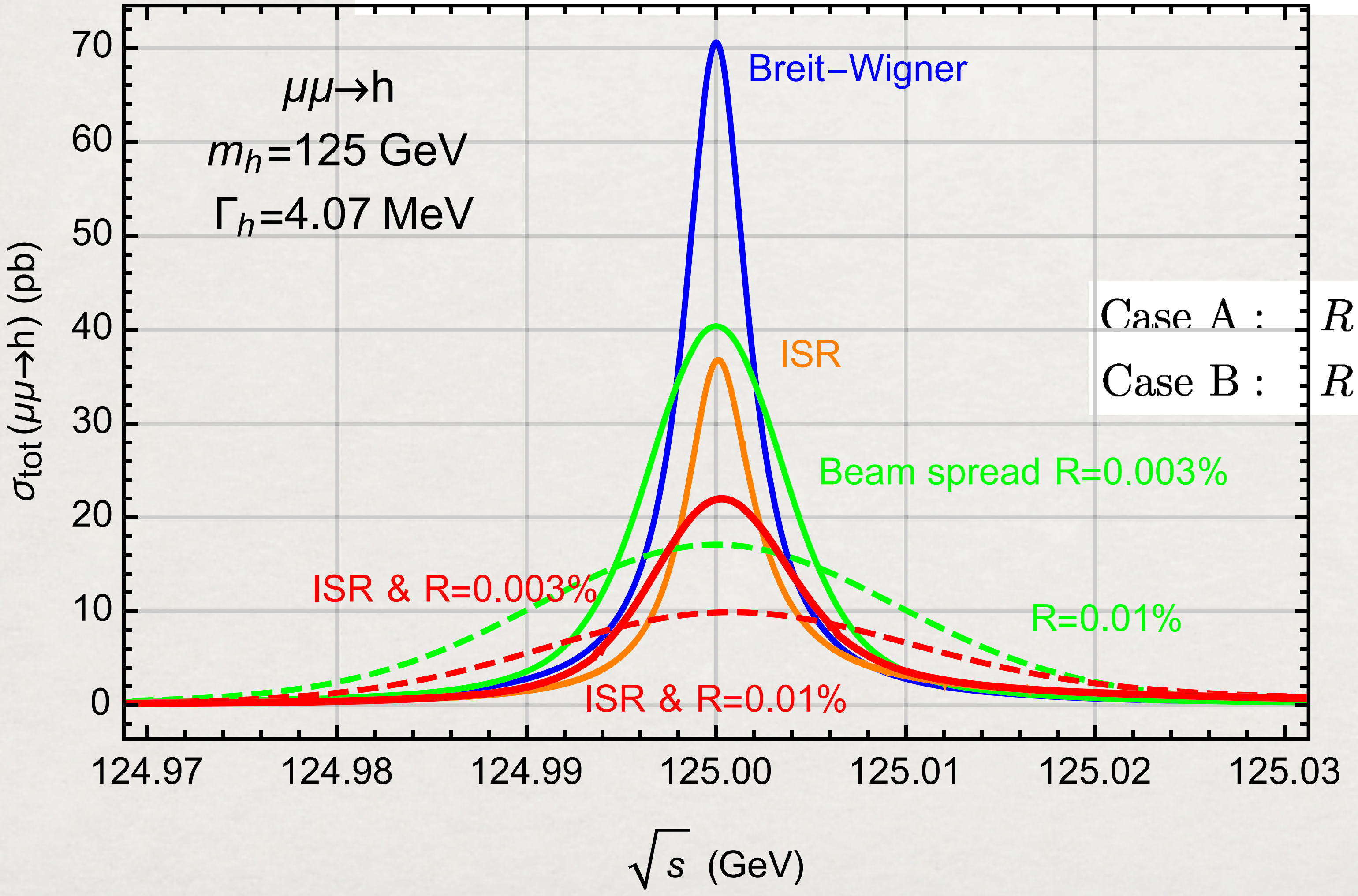
At m_h=125 GeV, Γ_h = 4.2 MeV

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

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

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

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



“Muon Collider Quartet”:

Barger-Berger-Gunion-Han

PRL & Phys. Report (1995)

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

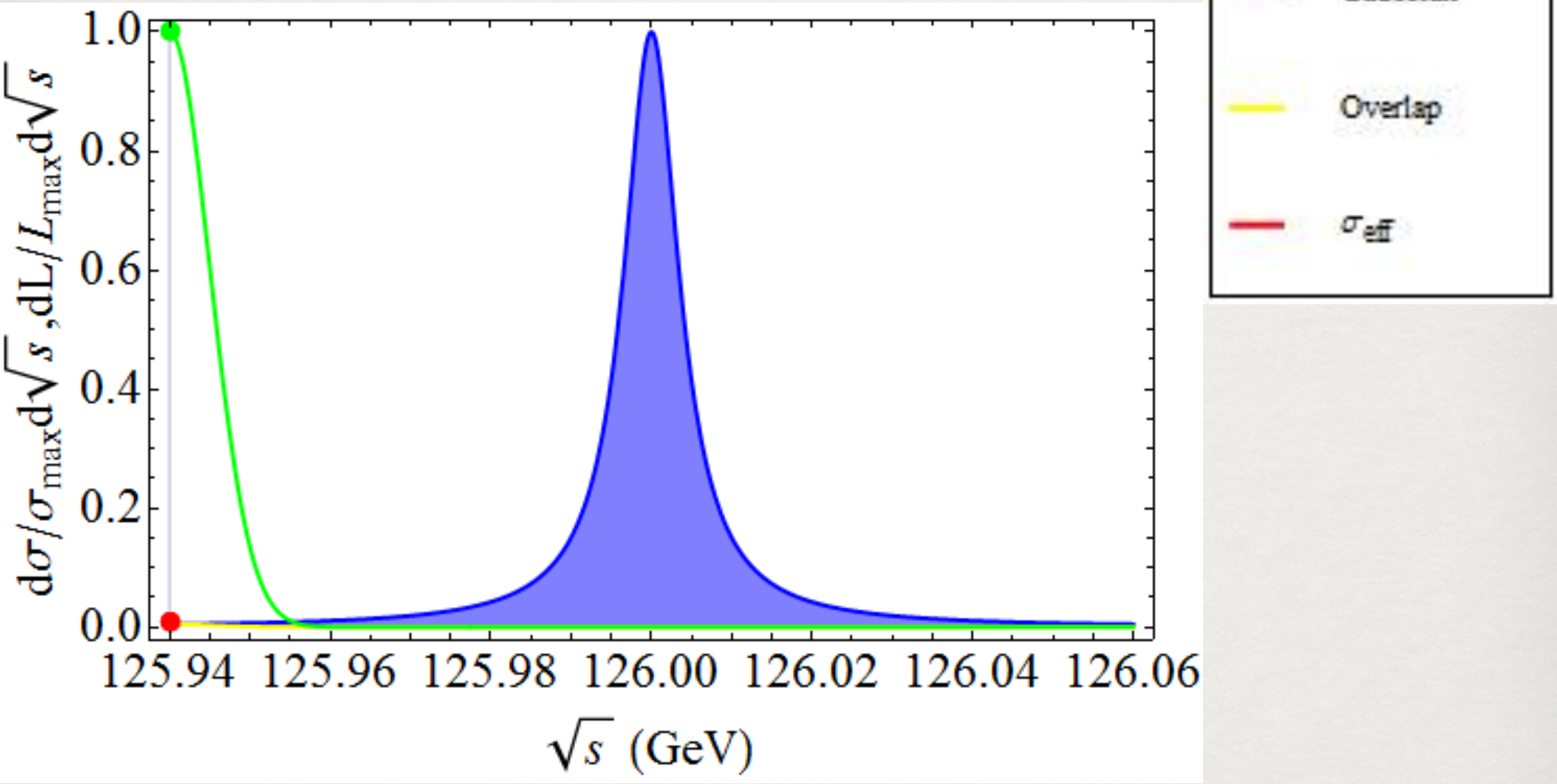
Case B : $R=0.003\%$ ($\Delta=2.7$ MeV), $L=1$ fb^{-1}.

TH, Liu: 1210.7803;

Greco, TH, Liu: 1607.03210

Ideal, conceivable case:

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



An optimal fitting would reveal Γ_h

Achievable accuracy at the Higgs factory:

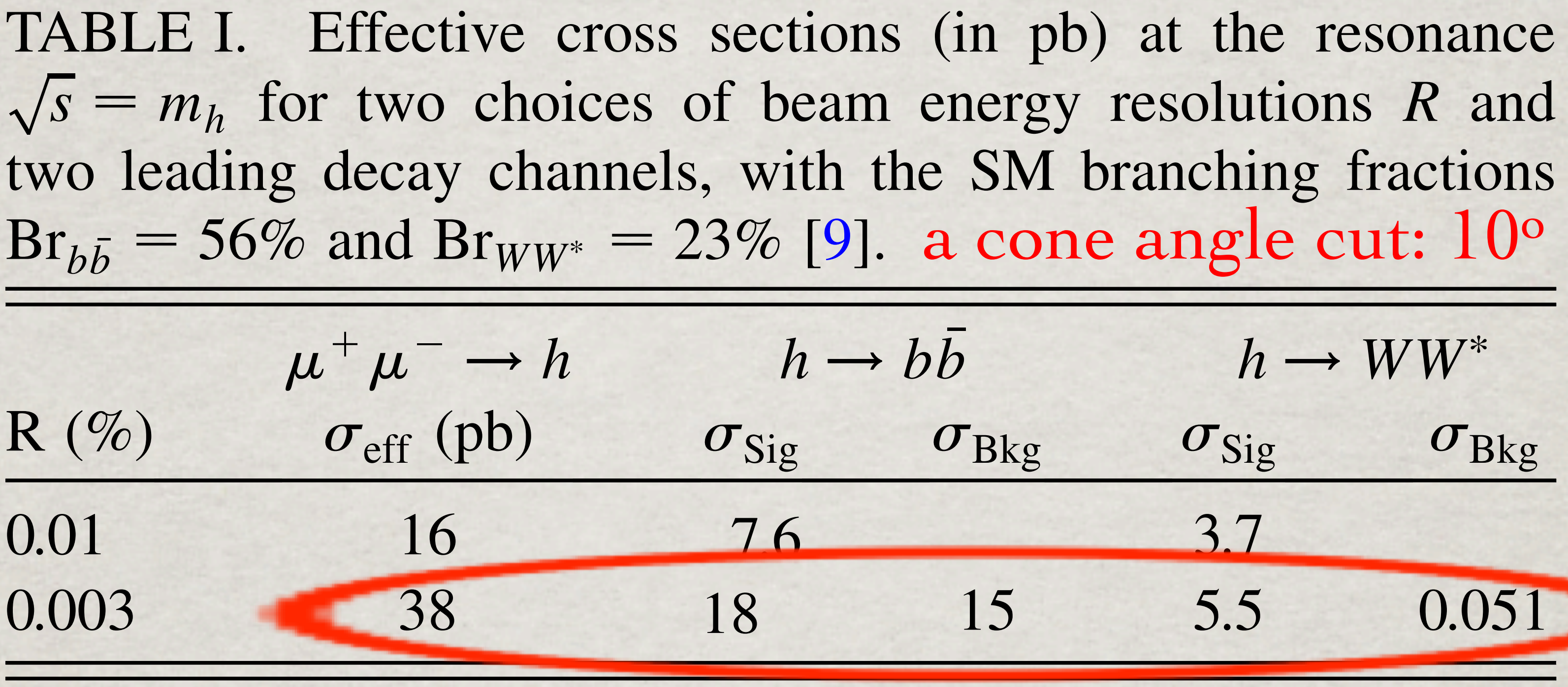


TABLE I. Effective cross sections (in pb) at the resonance $\sqrt{s} = m_h$ for two choices of beam energy resolutions R and two leading decay channels, with the SM branching fractions $\mathrm{Br}_{b\bar{b}} = 56\%$ and $\mathrm{Br}_{WW^*} = 23\%$ [9].

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

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

Good S/B>1, S/√B → % accuracies

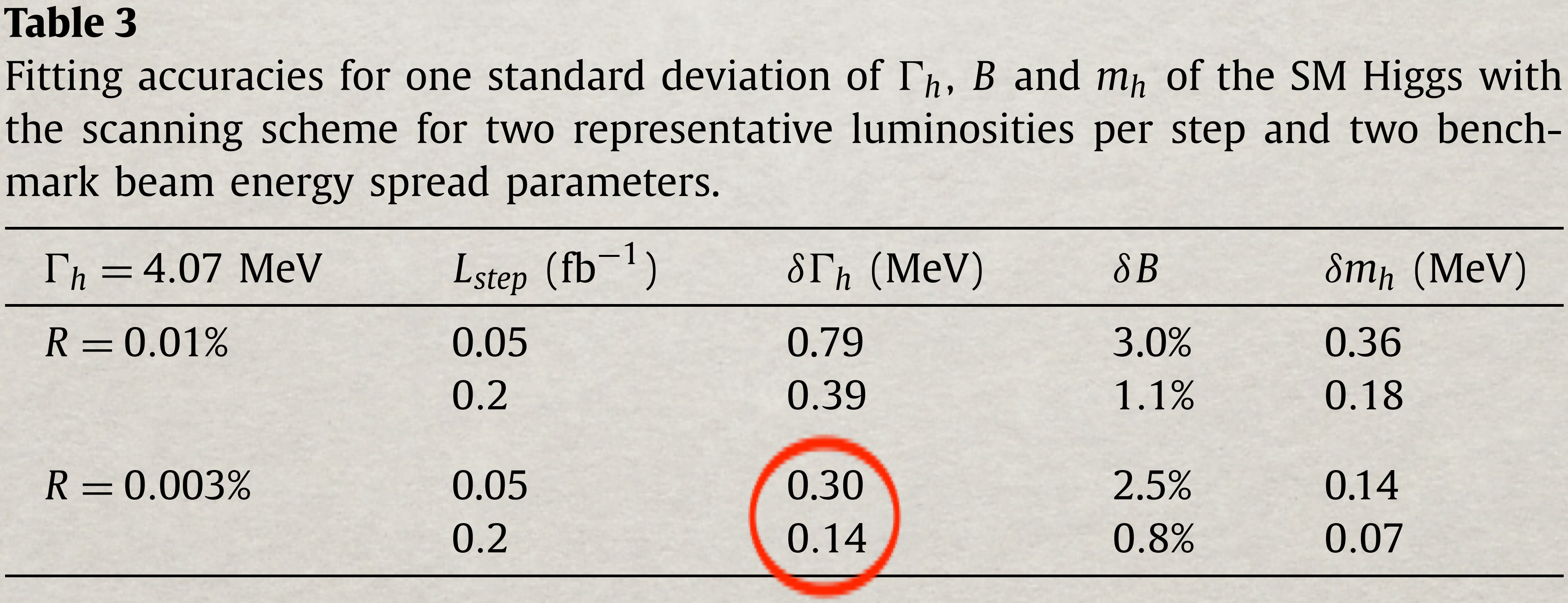


Table 3

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

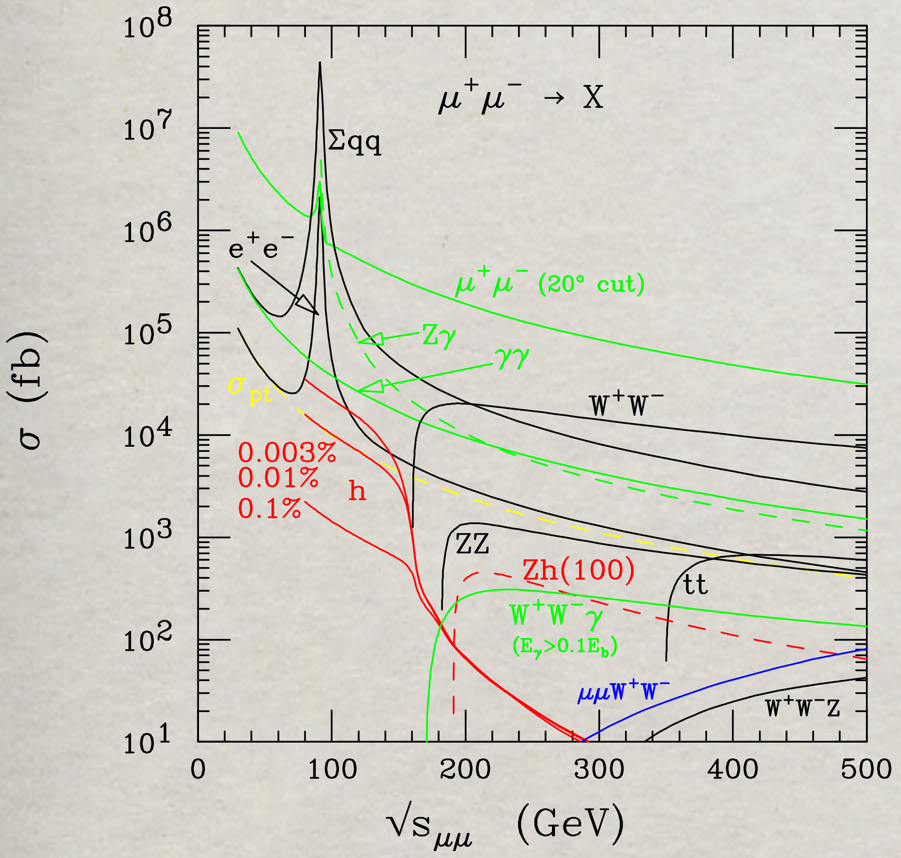
A MULTI-TEV MUON COLLIDER

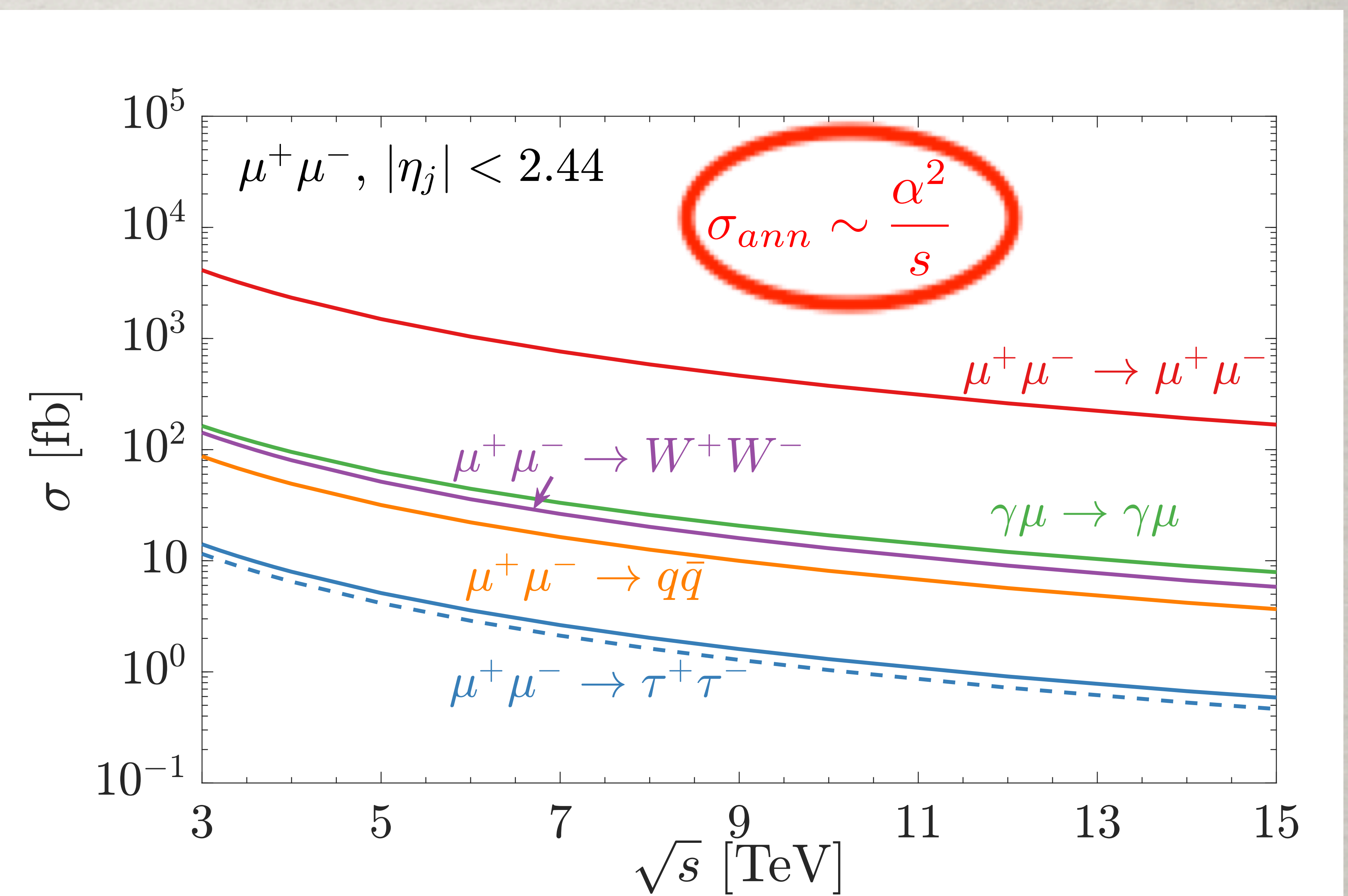
Exciting new energy-frontier!

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

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

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

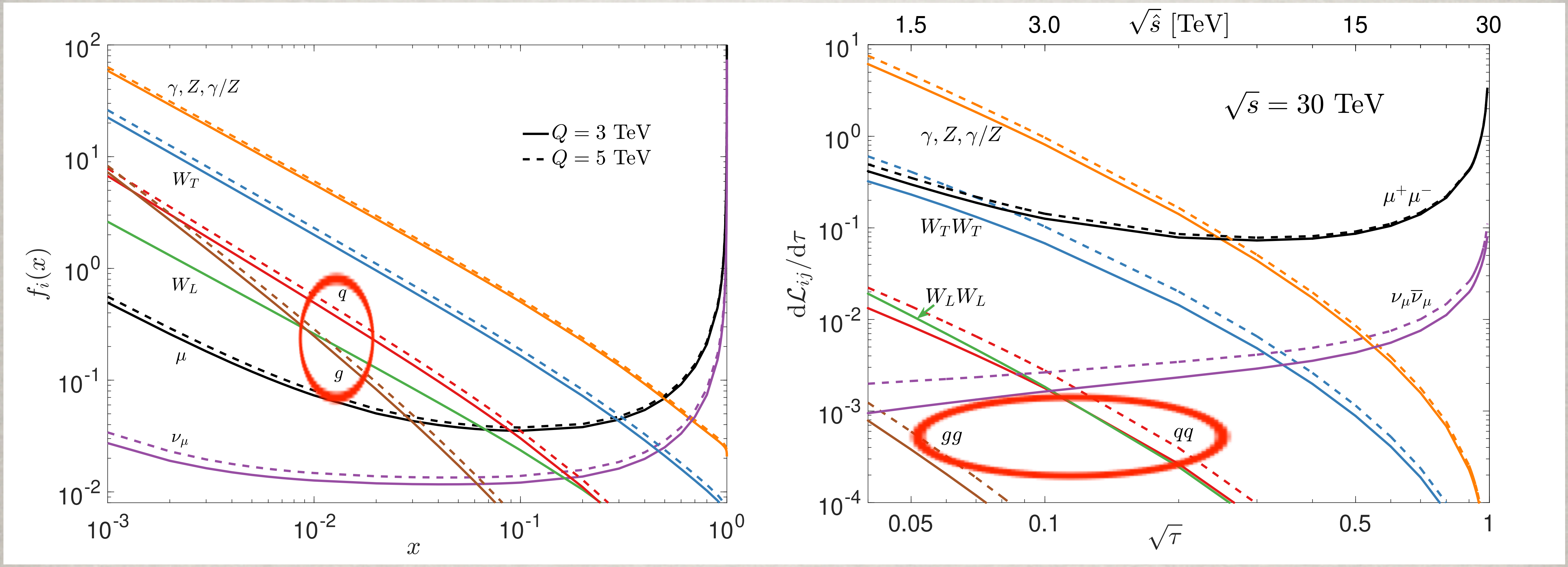




• EW PDFs at a muon collider:

Collinear splitting phenomena dominate,
“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.

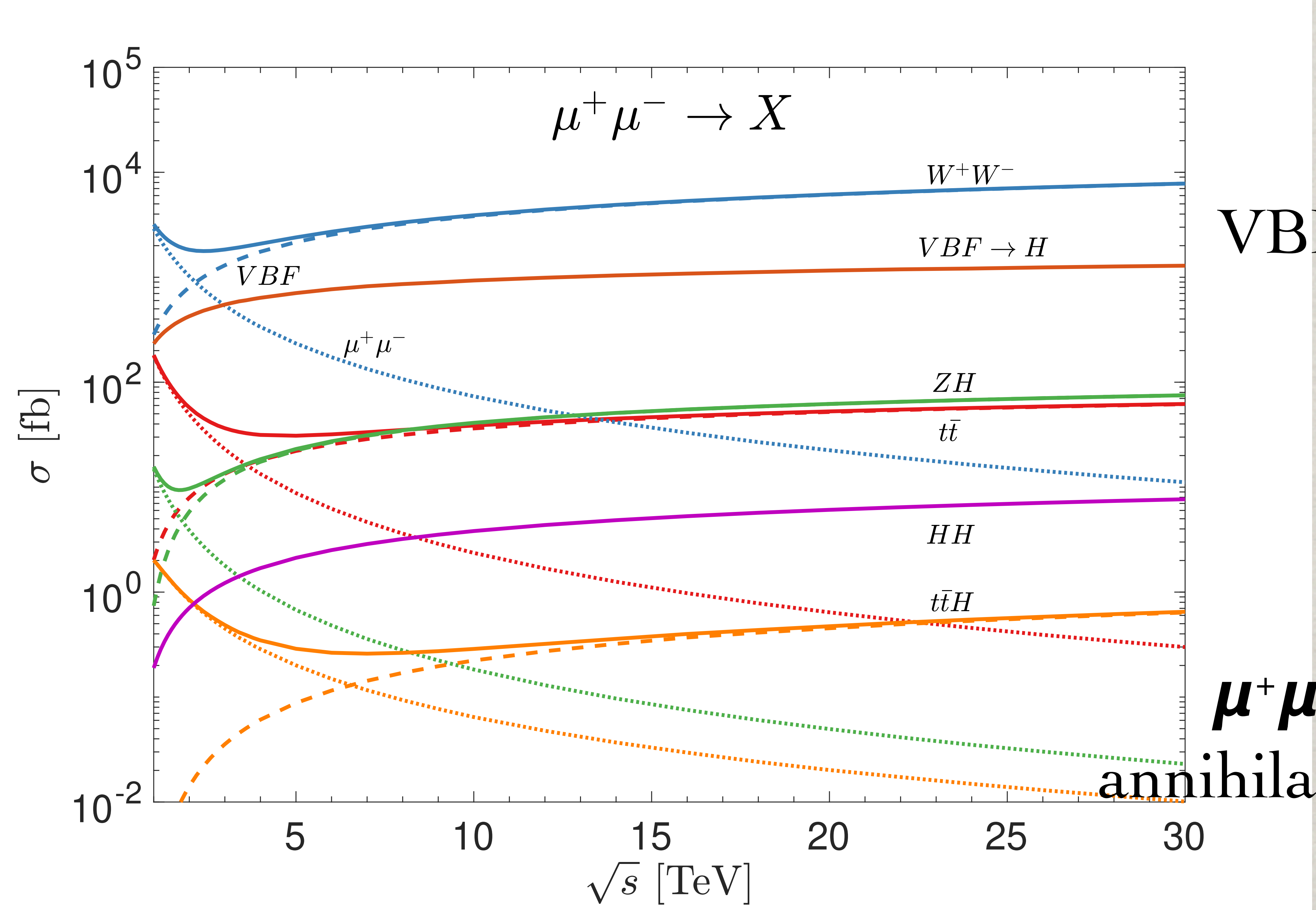
Quarks: NLO; gluons: NNLO.

TH, Yang Ma, Keping Xie, arXiv:2007.14300

• "Semi-inclusive" processes

Just like in hadronic collisions:

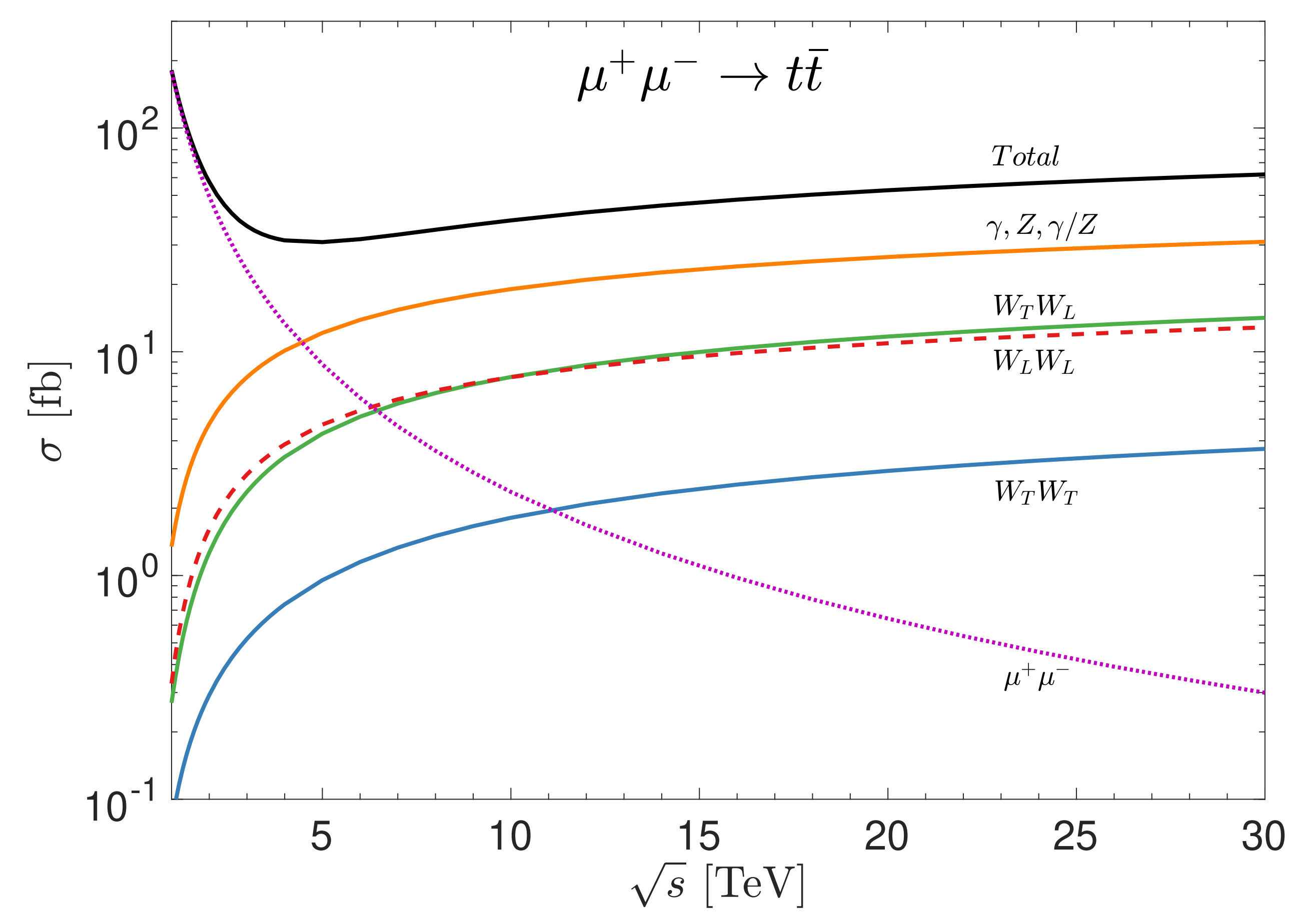
$\mu^+\mu^-$ → exclusive particles + remnants

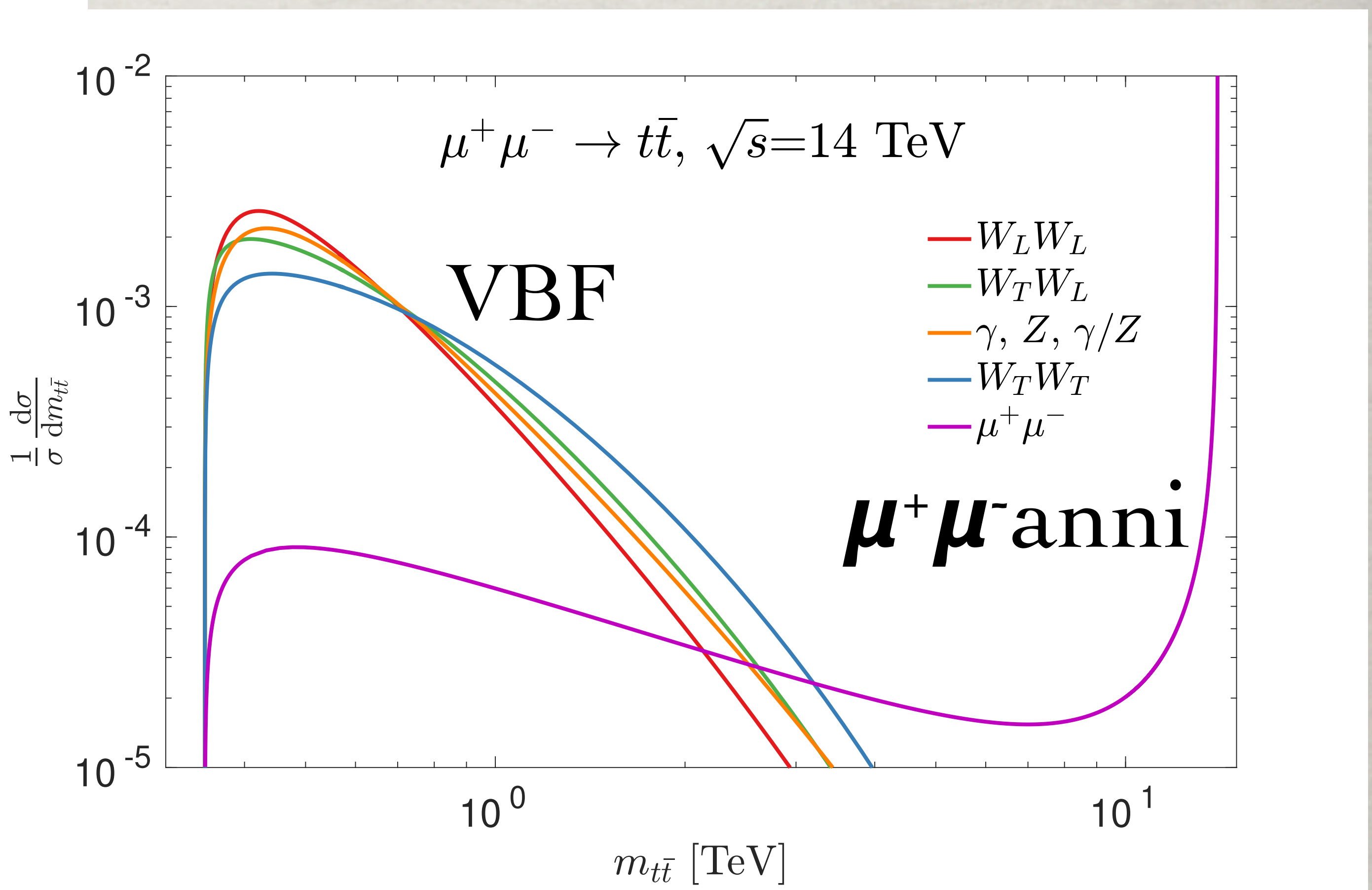


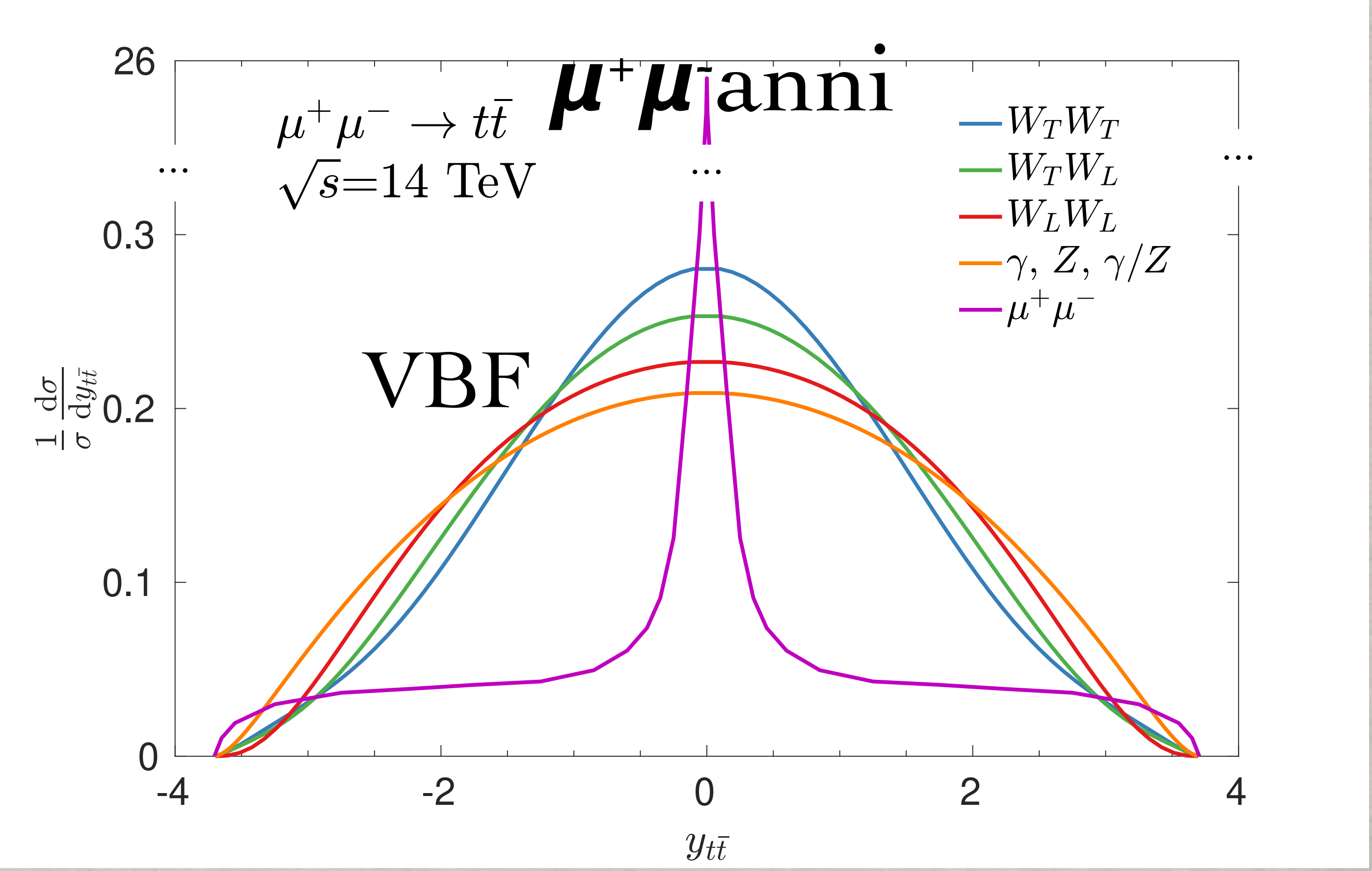
VBF

$\mu^+\mu^-$ annihilations

- Underlying sub-processes:







Decomposed partonic contributions

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

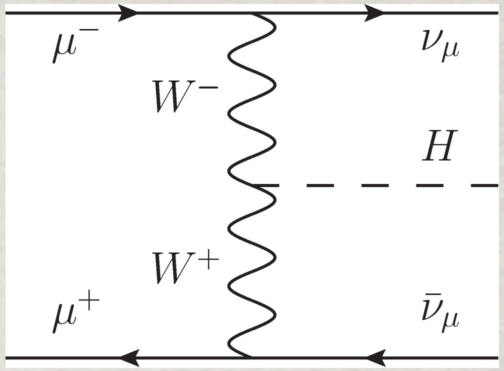
“Buy one, get one free”

Annihilation +VBF

• Precision Higgs Physics

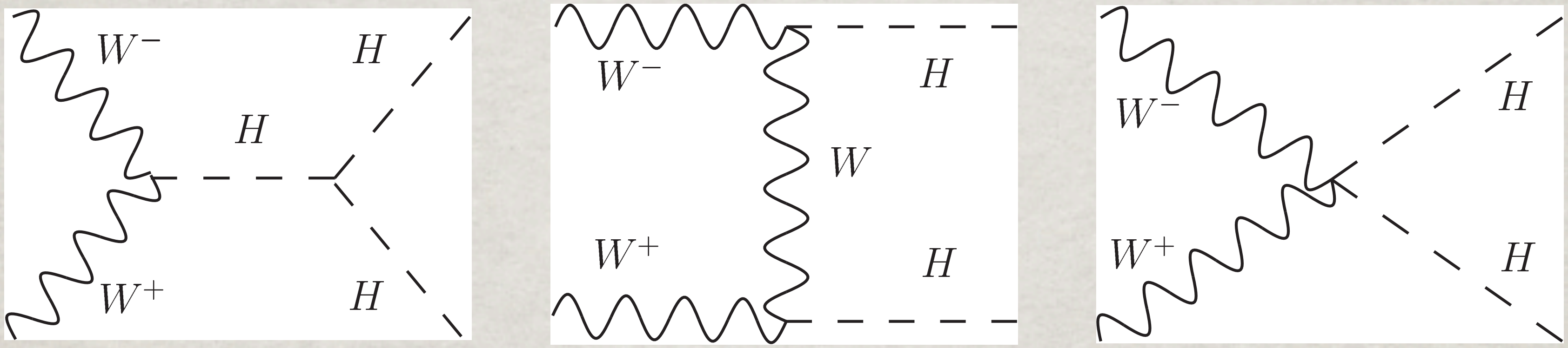
$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu \, H \qquad (WW \text{ fusion}),$$

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



WWH / ZZH couplings

HHH / WWHH couplings:



(a) (b) (c)

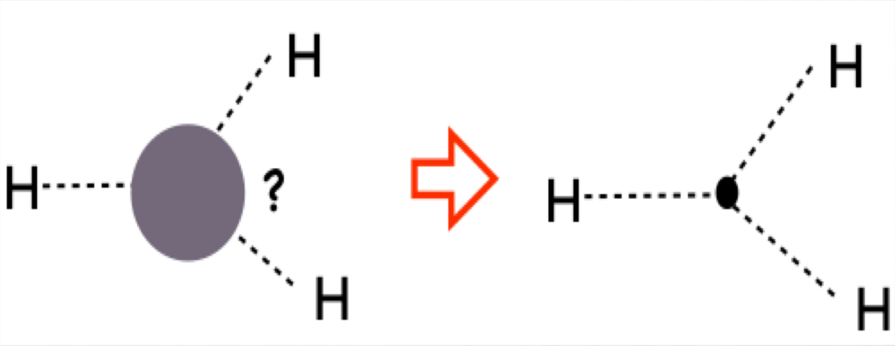
$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91
$WW \to ZH$	9.5	22	33	42	67
$WW \to t\bar{t}H$	0.012	0.046	0.090	0.14	0.28
$WW \to Z$	2200	3100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

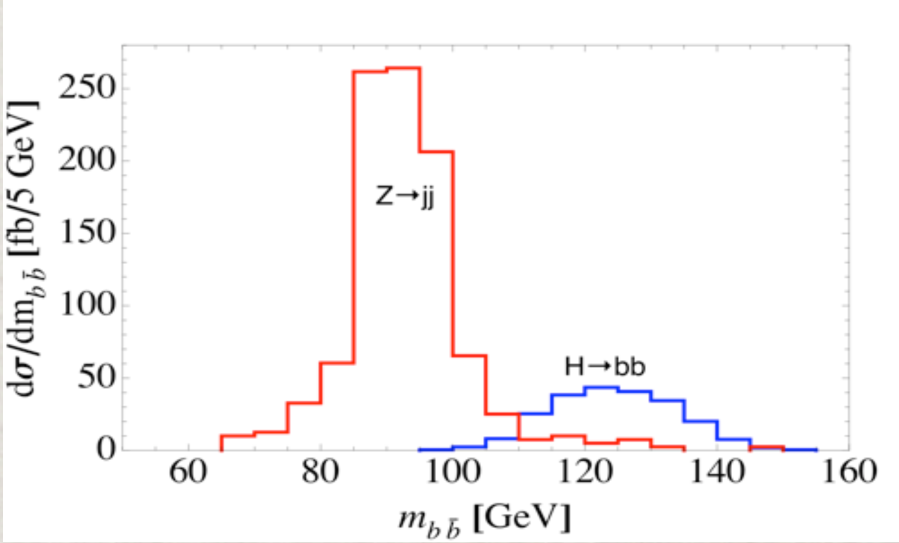
Achievable accuracies



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.)

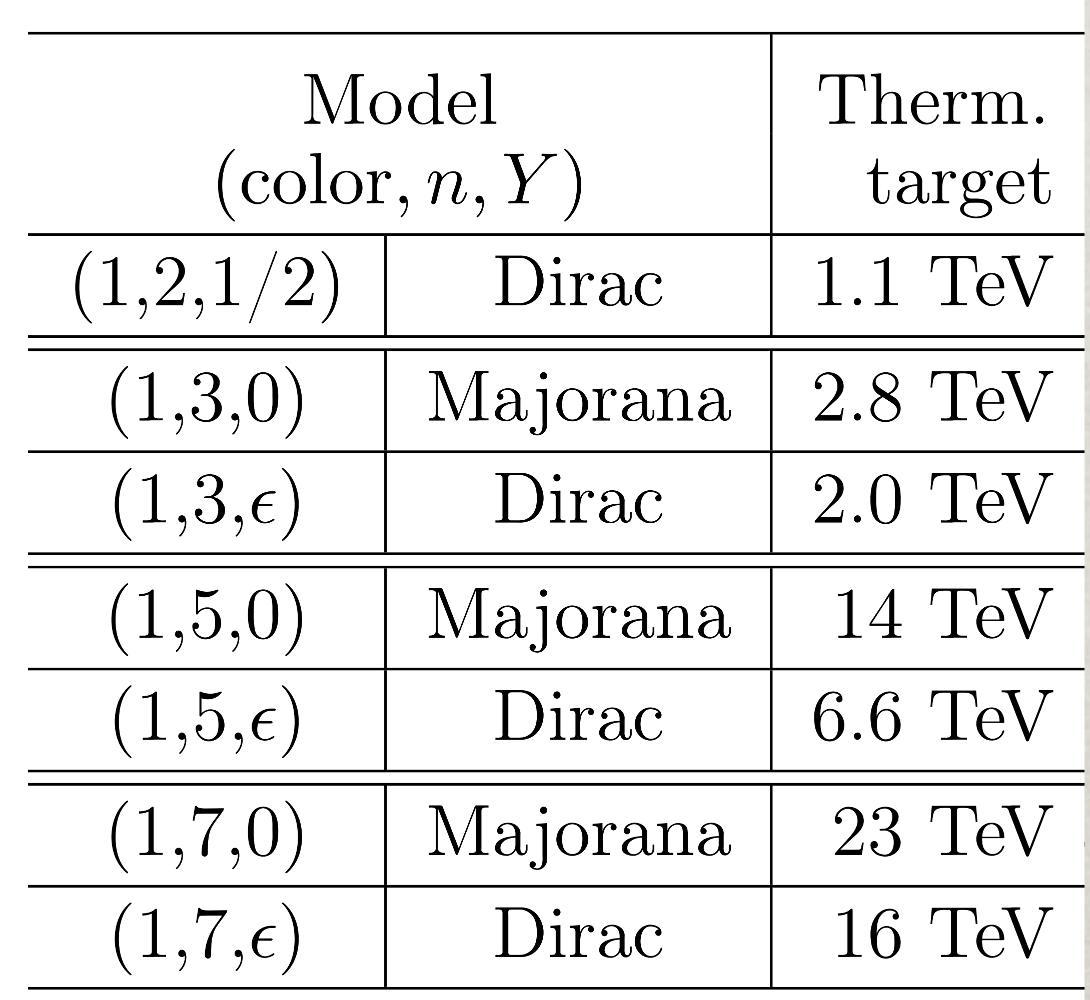
Table 7: Summary table of the expected accuracies at 95% C.L. for the Higgs couplings at a variety of muon collider collider energies and luminosities.

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

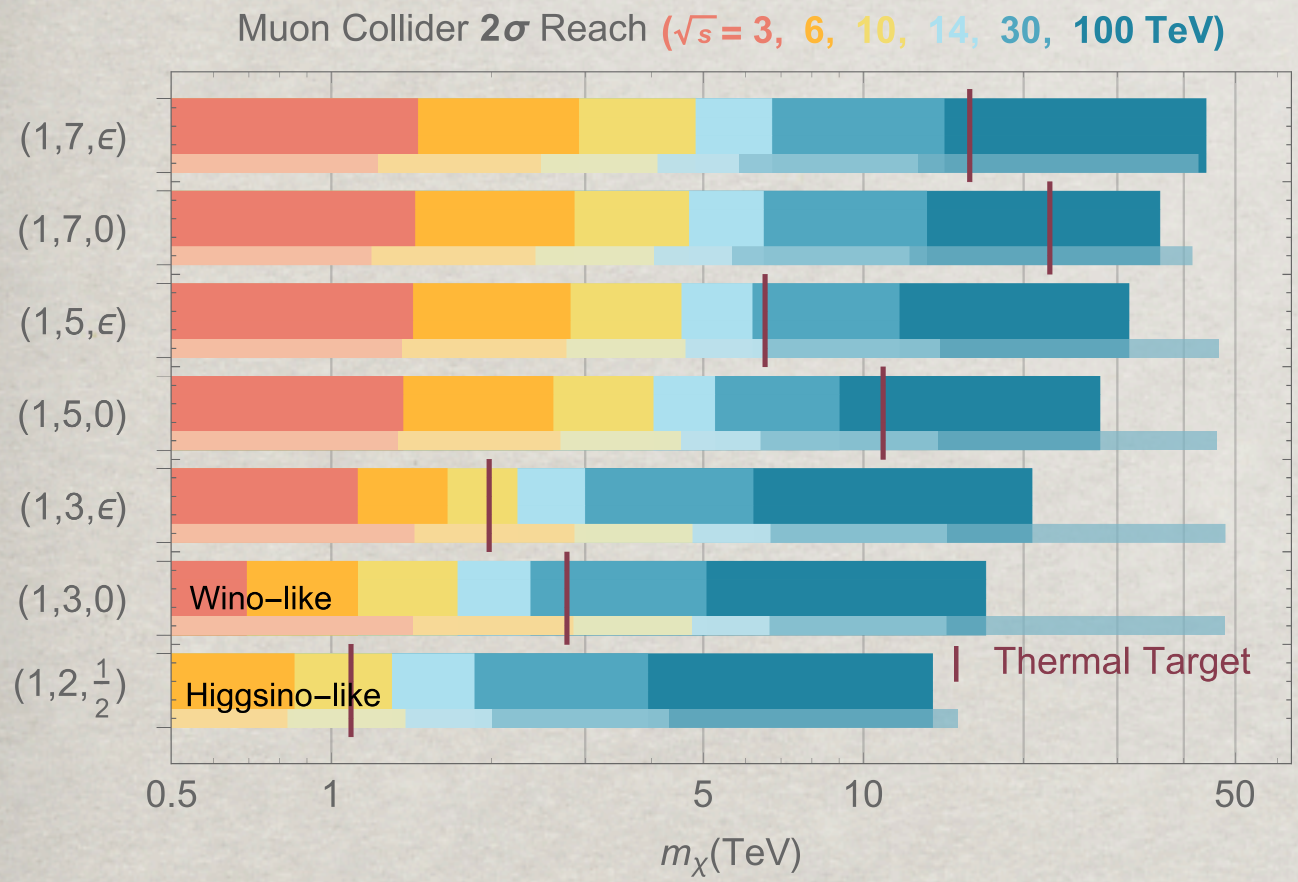
- The lightest neutral component as DM
- Interactions well defined → pure gauge
- Mass upper limit predicted → thermal relic abundance

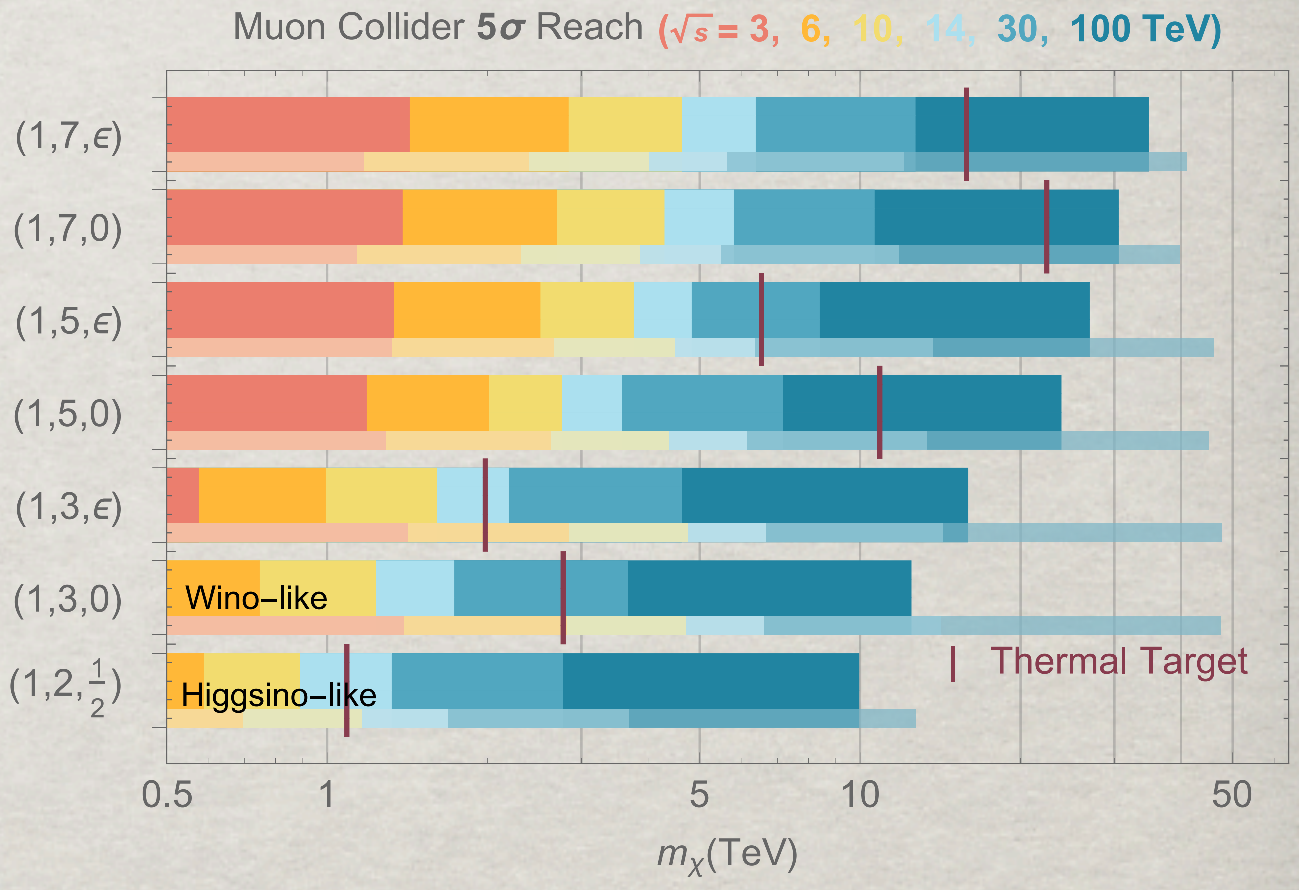


Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
(1,7,ϵ)	Dirac	16 TeV

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

The mass reach for minimal WIMP DM:





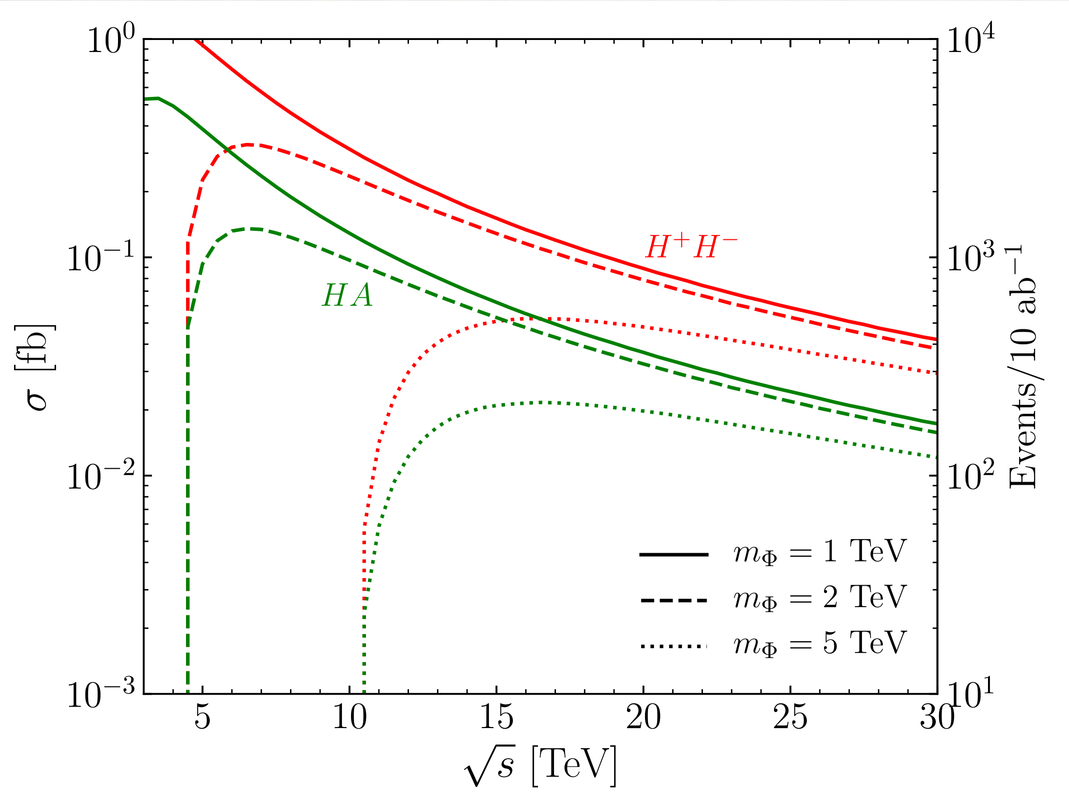
E_{CM} ≈ 14 TeV enough to cover n≤3 multiplets.

Higher energy needed to cover higher multiplets.

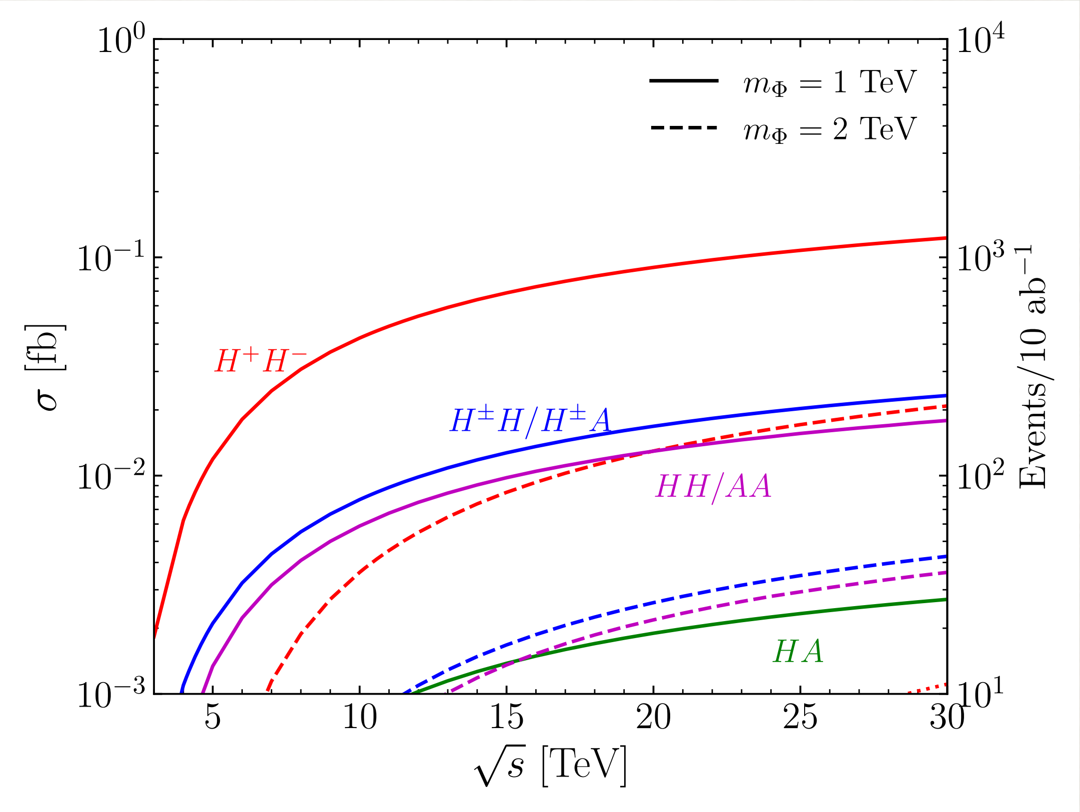
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

• Heavy Higgs Bosons Production

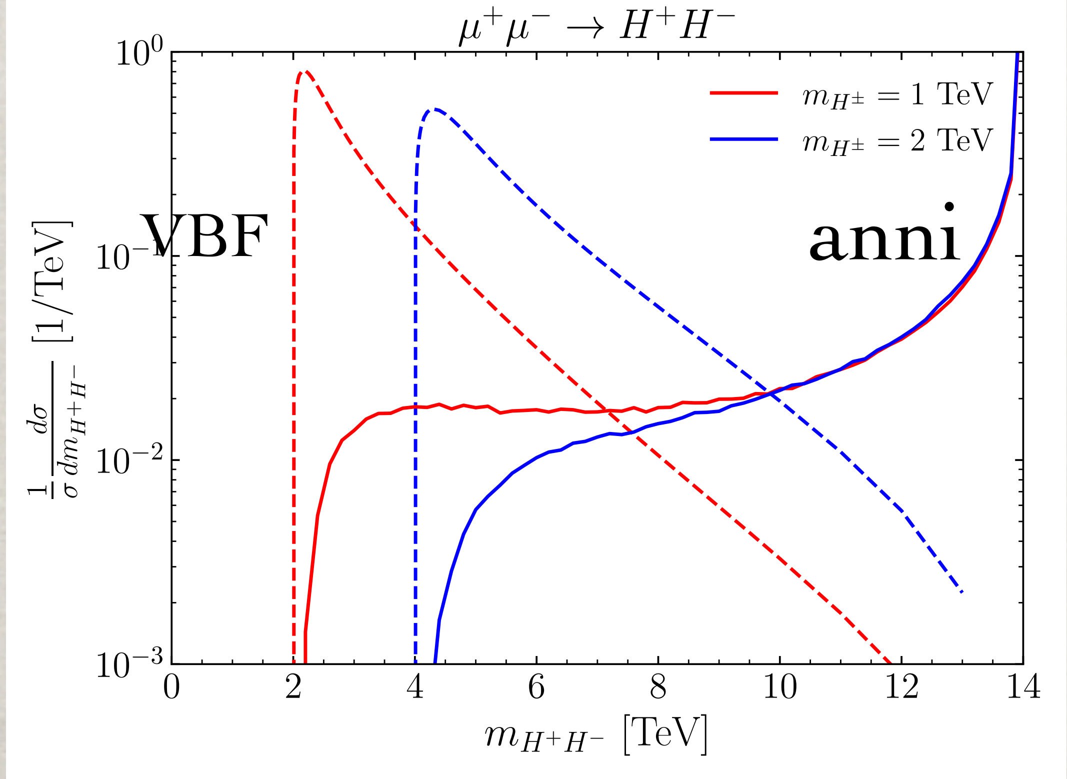
annihilation



VBF



VBF

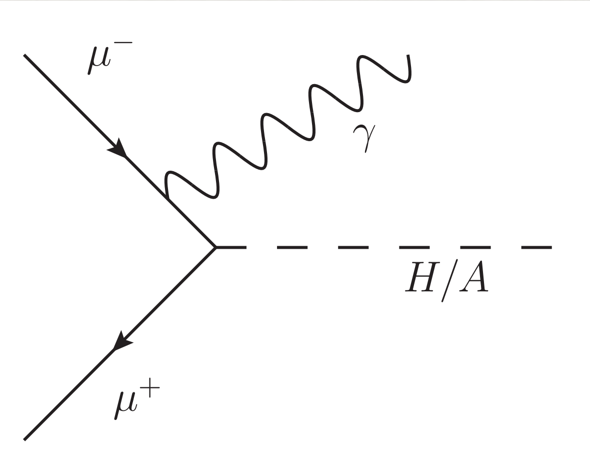


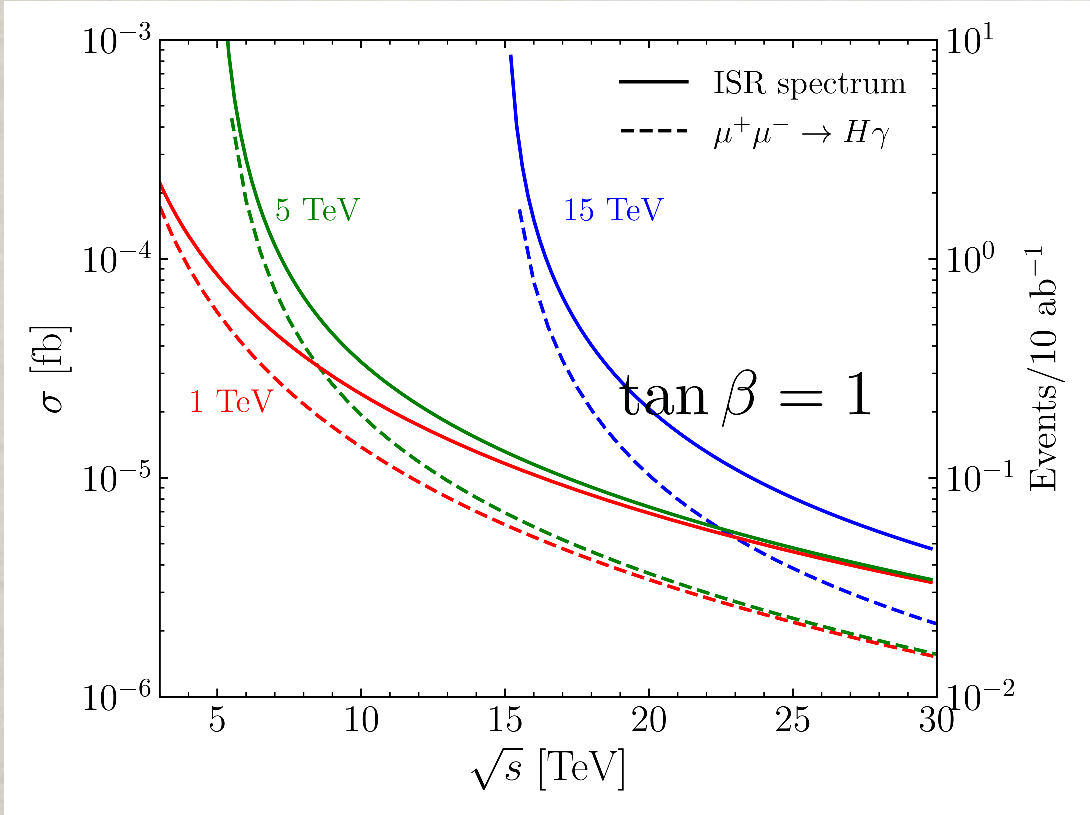
VBF

anni

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

Radiative returns:





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

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

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

Depending on the coupling,
one may reach the kinematic limit:

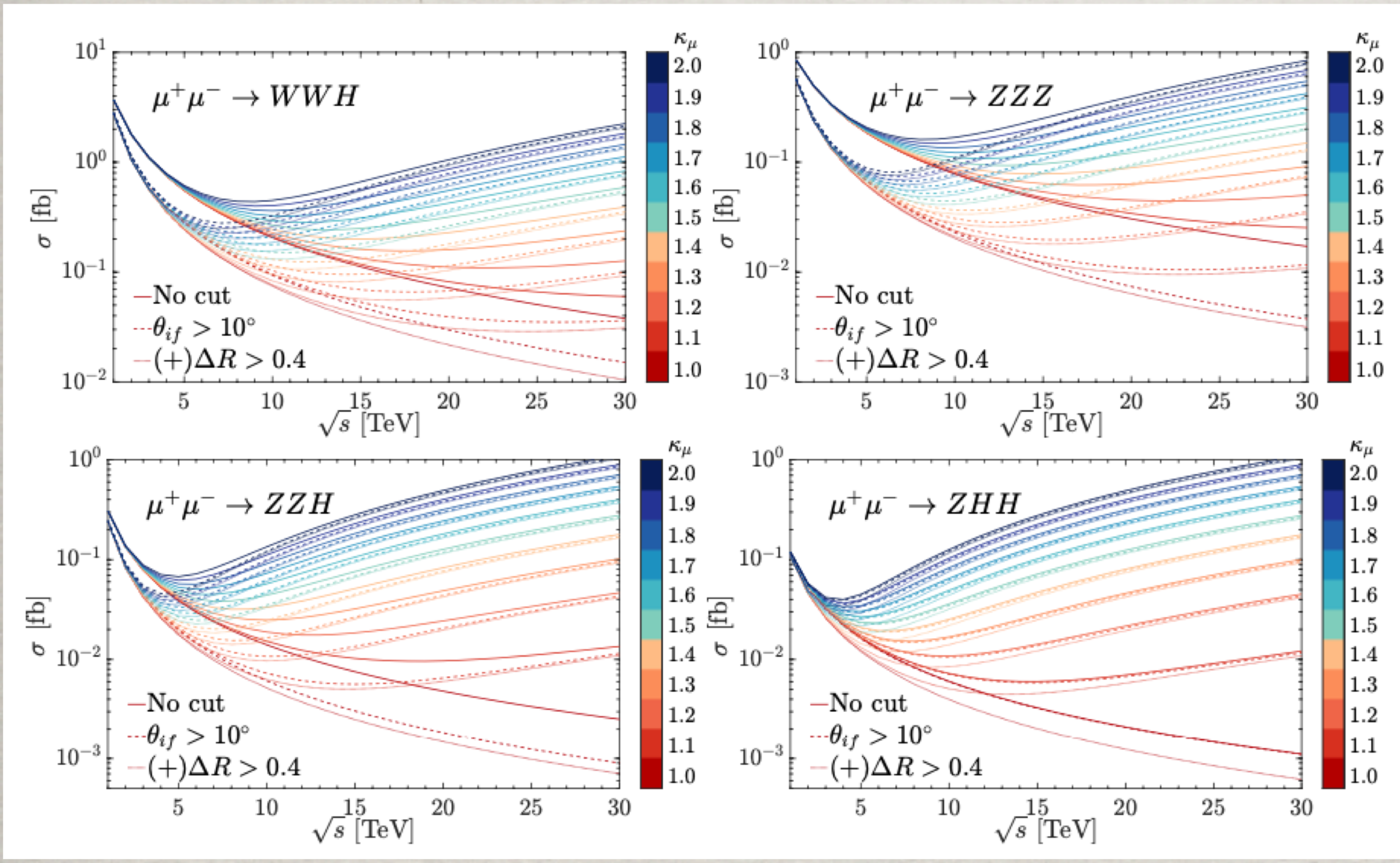
$M_H \sim E_{cm}$

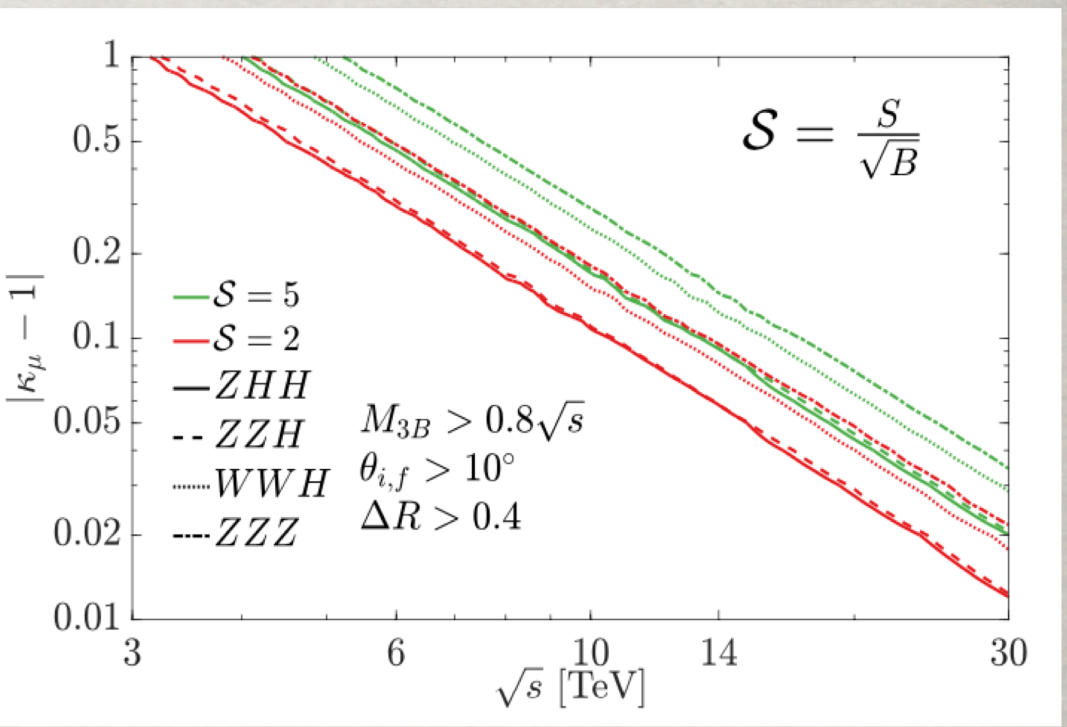
TH, S. Li, S. Su, W. Su, Y. Wu, arXiv:2102.08386;
TH, Z. Liu et al., arXiv:1408.5912.

- # Model-independent sensitivity:

$$Y_\mu = \kappa_\mu Y_\mu^{SM}$$

New physics modification of SM leads to notable deviation, eventually violate unitarity.





TH, Wolfgang Kilian, Nils Kreher, Yang Ma, Juergen Reuter, Tobias Striegl and Keping Xie: arXiv:2108.05362.

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)
… …

Summary

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

  Challenging technology; interdisciplinary to other fields; great physics potential!

- **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!