Physics @ Future Circular ~~e^+e^-~~ & $\mu^+\mu^-$ Colliders

Tao Han

University of Pittsburgh

Workshop on Future Accelerators
Corfu, April 26, 2023

Table of Contents

- Snowmass 2021 summary from
  Energy Frontier (EF)/Accelerator Frontier (AF)
- ~~Future Circular Collider (FCC-ee)~~
  ~~& Circular Electron-Position Collider (CEPC)~~
- Muon colliders:
  a Higgs factory & a Multi-TeV collider
- Summary

Complementary talks:

T. You; J. List; L. Gouskos; J. Wang; H. Baer;
K. Kaadze; R. Torre; S. Pokorski; Alain Blondel …

- **Snowmass 2021: A decadal study**

Community Planning Exercise

US APS DPF-led effort

Snowmass 2021

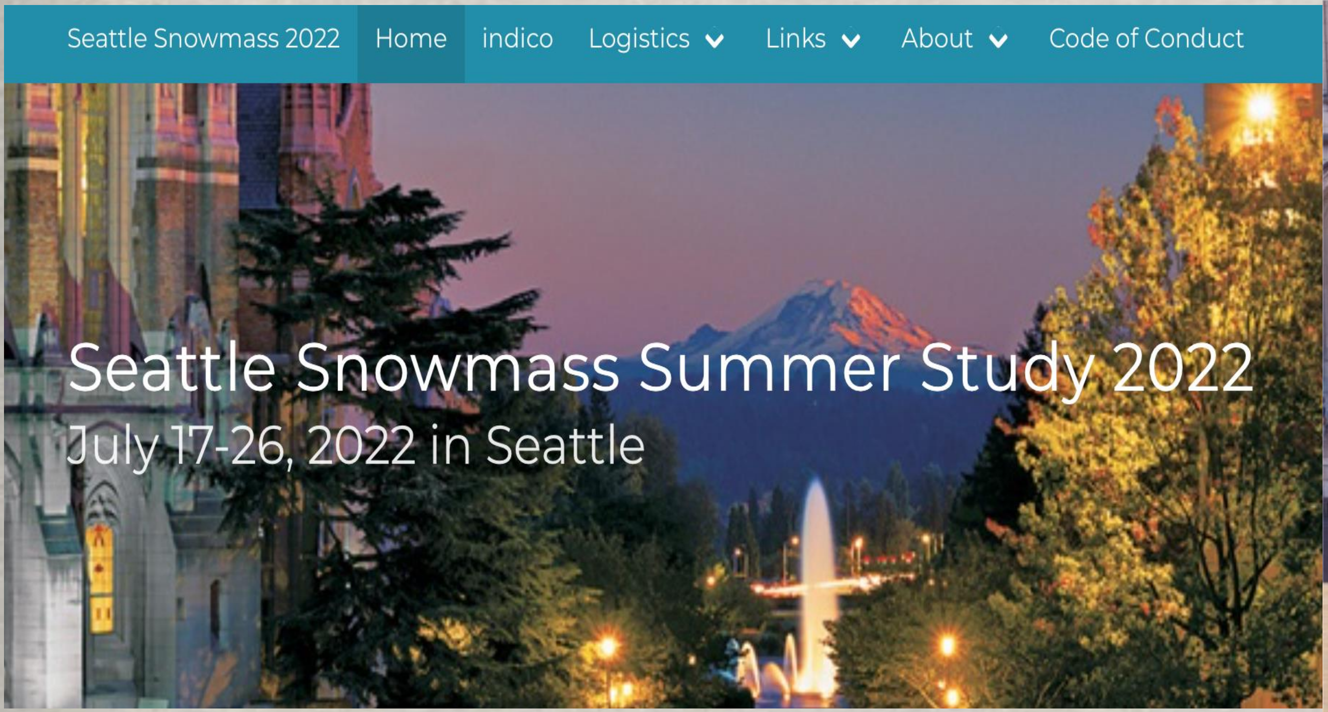
To define the most important questions for the field of particle physics

To identify promising opportunities to address them, for the decades to come

Community Summer Study: Snowmass 2021

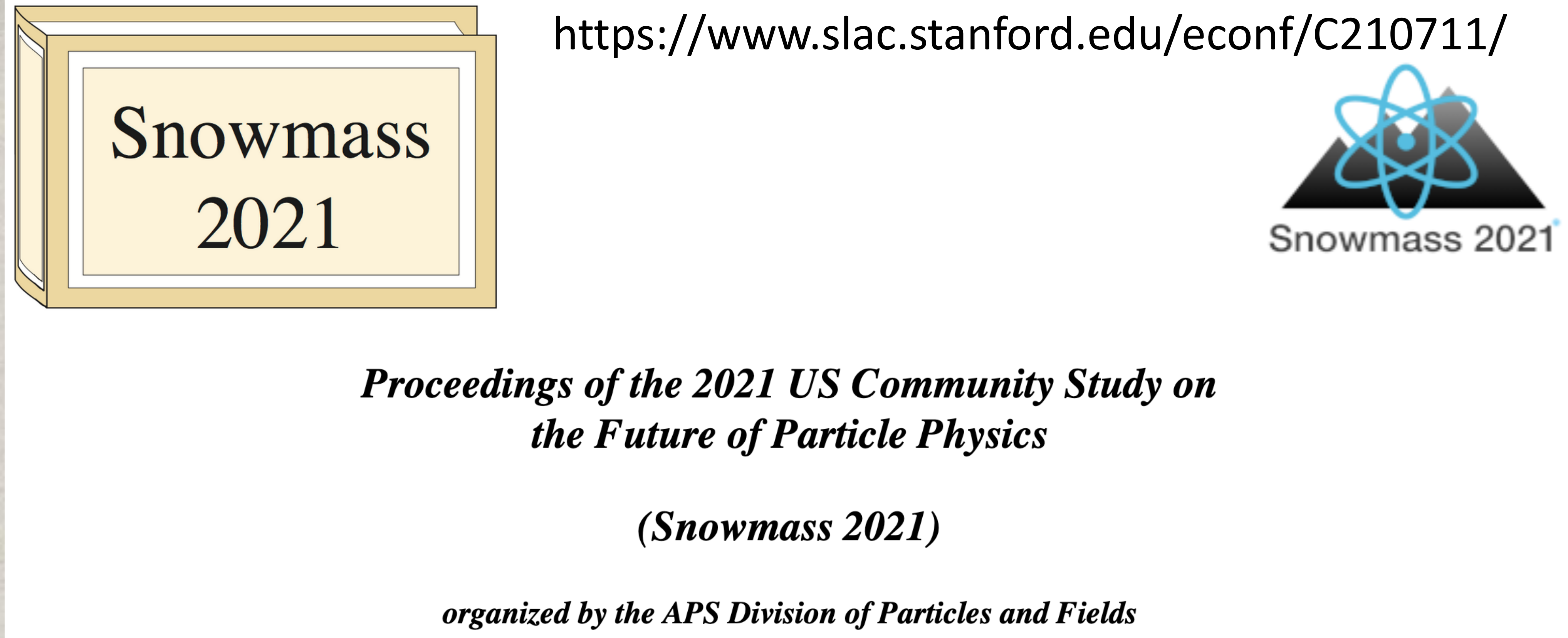
July 17 – 26, 2022 @ UW – Seattle

http://seattlesnowmass2021.net



Seattle Snowmass Summer Study 2022

July 17-26, 2022 in Seattle

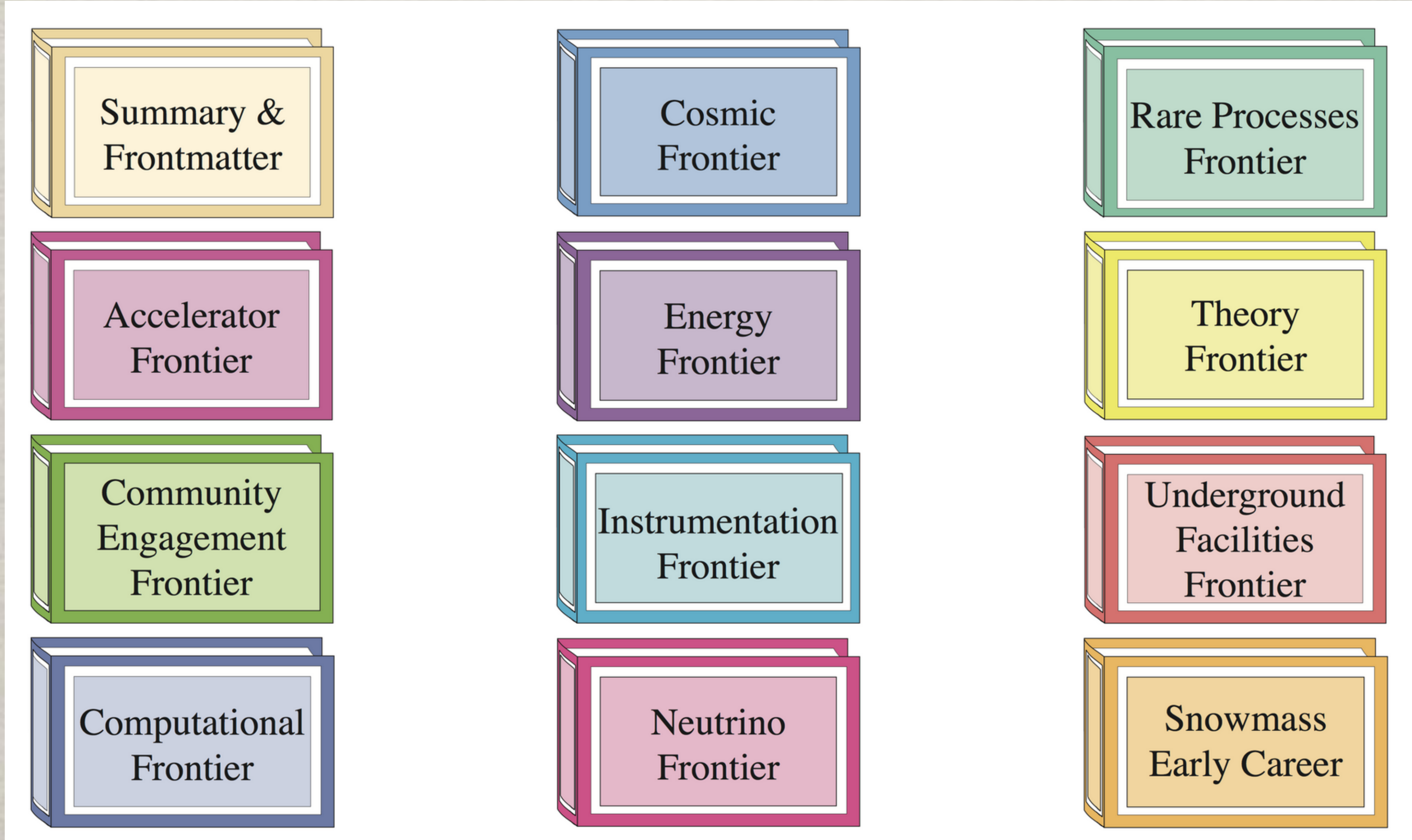


https://www.slac.stanford.edu/econf/C210711/

Proceedings of the 2021 US Community Study on the Future of Particle Physics

(Snowmass 2021)

organized by the APS Division of Particles and Fields



Collider needs

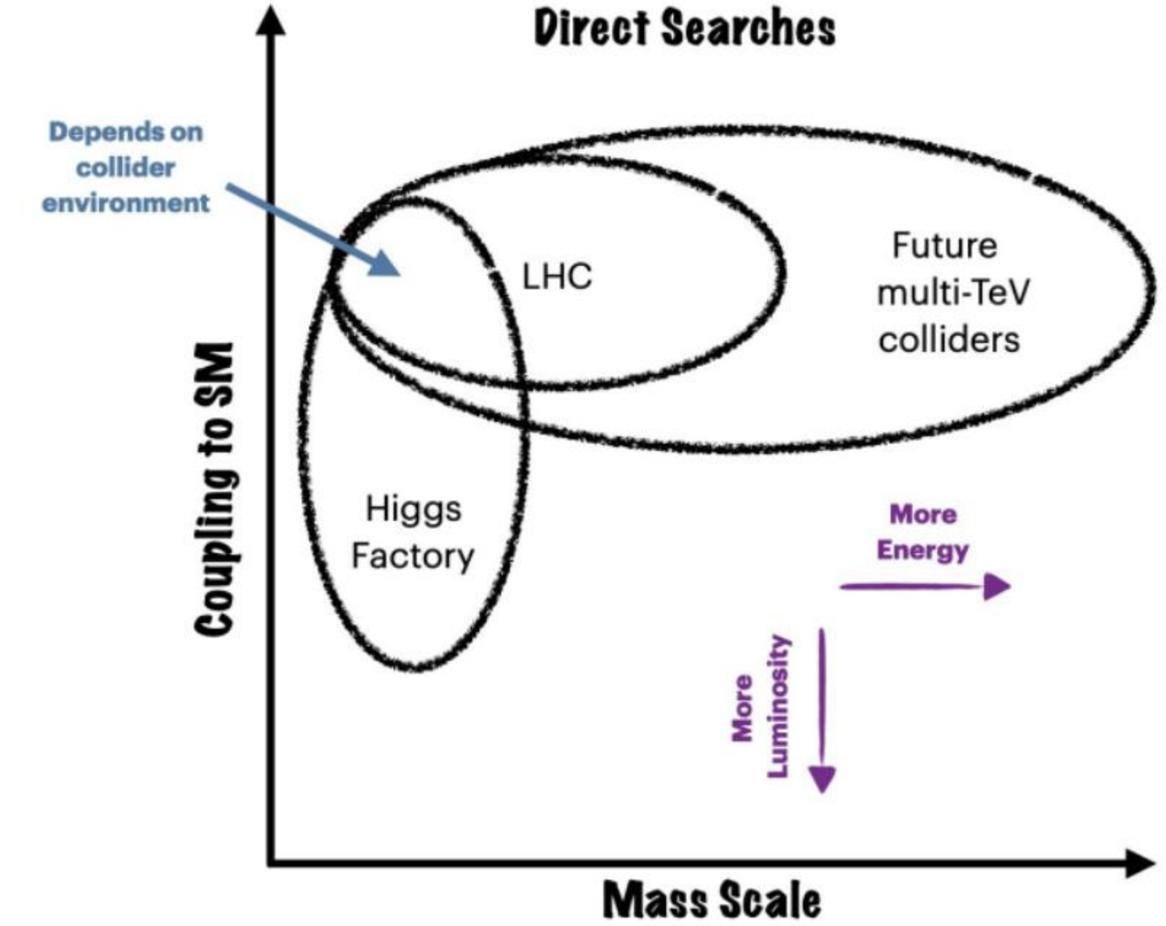


Figure 1-2. *The direct coverage of various colliders in the schematic space of coupling to the SM versus mass scale of BSM physics. "Higgs factory" and "multi-TeV colliders" correspond to a generic option among the ones listed in Table 1-1 and Table 1-2 respectively.*

The Energy Frontier Vision

- **Complete the HL-LHC program,**
- **Start now a targeted program for detector R&D for Higgs Factories**
- **Support construction of a Higgs factory**
- **Ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a *muon collider* or a *hadron collider*.**

A Higgs factory is a must !

ANY elementary particle needs a factory to scrutinize:

- Pion/Kaon (μ,ν) factories: CERN, TRIUMF, FNAL, JLab …
- tau/charm factories: CESR, BEPC …
- B-factories: Belle, BaBar, LHCb …
- $Z/W^{\pm}$ factories: SLC, LEP-I, LEP-II, Tevatron, LHC …
- Top-quark factories: Tevatron, LHC.

The Higgs boson is NO exception !

LHC Run 3 / HL-LHC will lead the way: 50M/ab !

We need O(10^5 - 10^6) "clean" Higgs bosons:

- well-constrained kinematics in e^+e^- collisions
- model-independent, absolute measurements
- sub-percentage accuracy
- challenging decay processes $H \to \tau^{\pm}\mu^{\mp}, c\bar{c}, \ldots$

Snowmass 2021, EF report

arXiv:2211.11084

EF benchmark parameters for future colliders

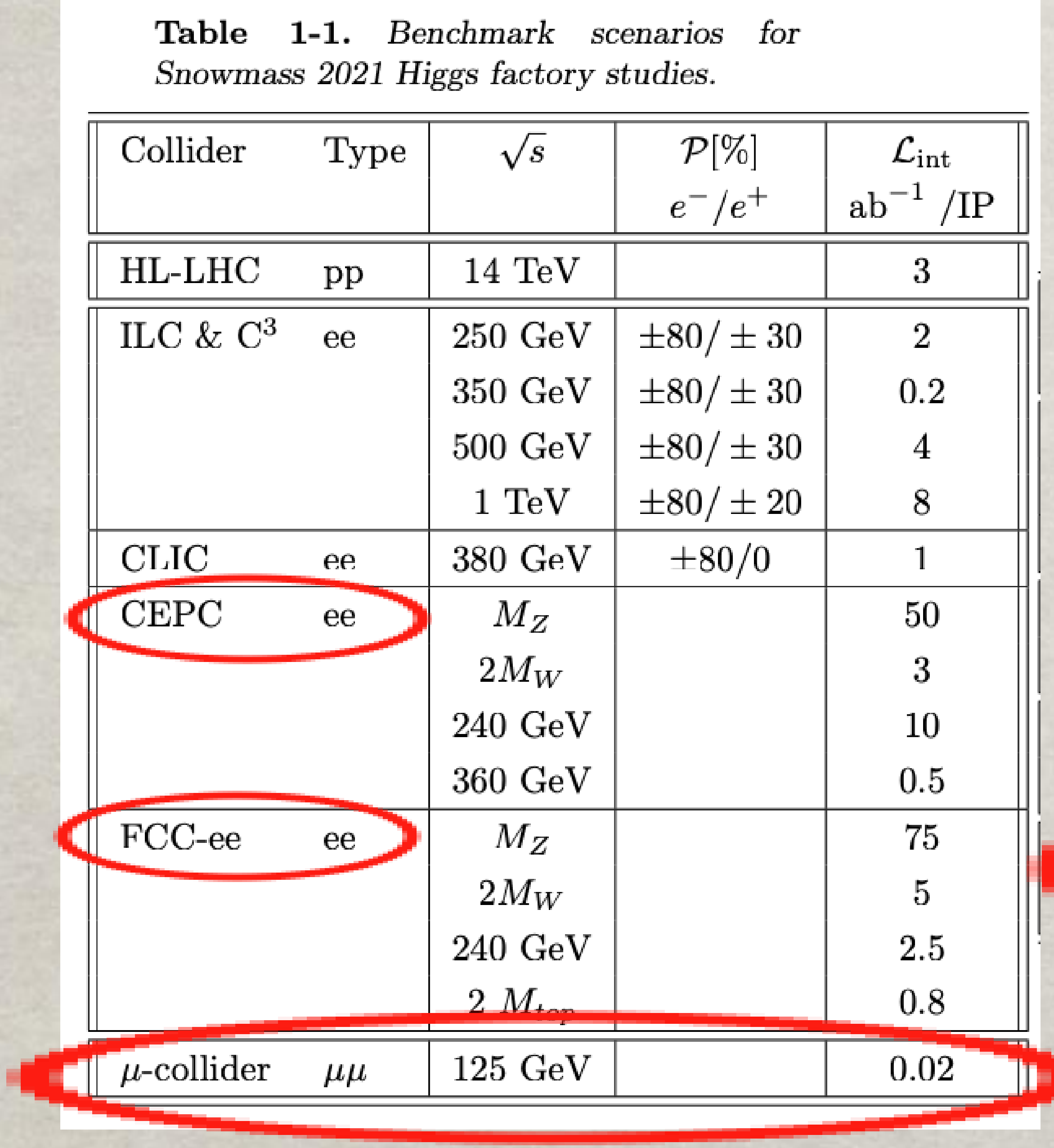


Table 1-1. *Benchmark scenarios for Snowmass 2021 Higgs factory studies.*

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$+80/0$	1
CEPC	ee	M_Z		50
		$2M_W$		3
		240 GeV		10
		360 GeV		0.5
FCC-ee	ee	M_Z		75
		$2M_W$		5
		240 GeV		2.5
		$2\ M_{top}$		0.8
μ-collider	$\mu\mu$	125 GeV		0.02

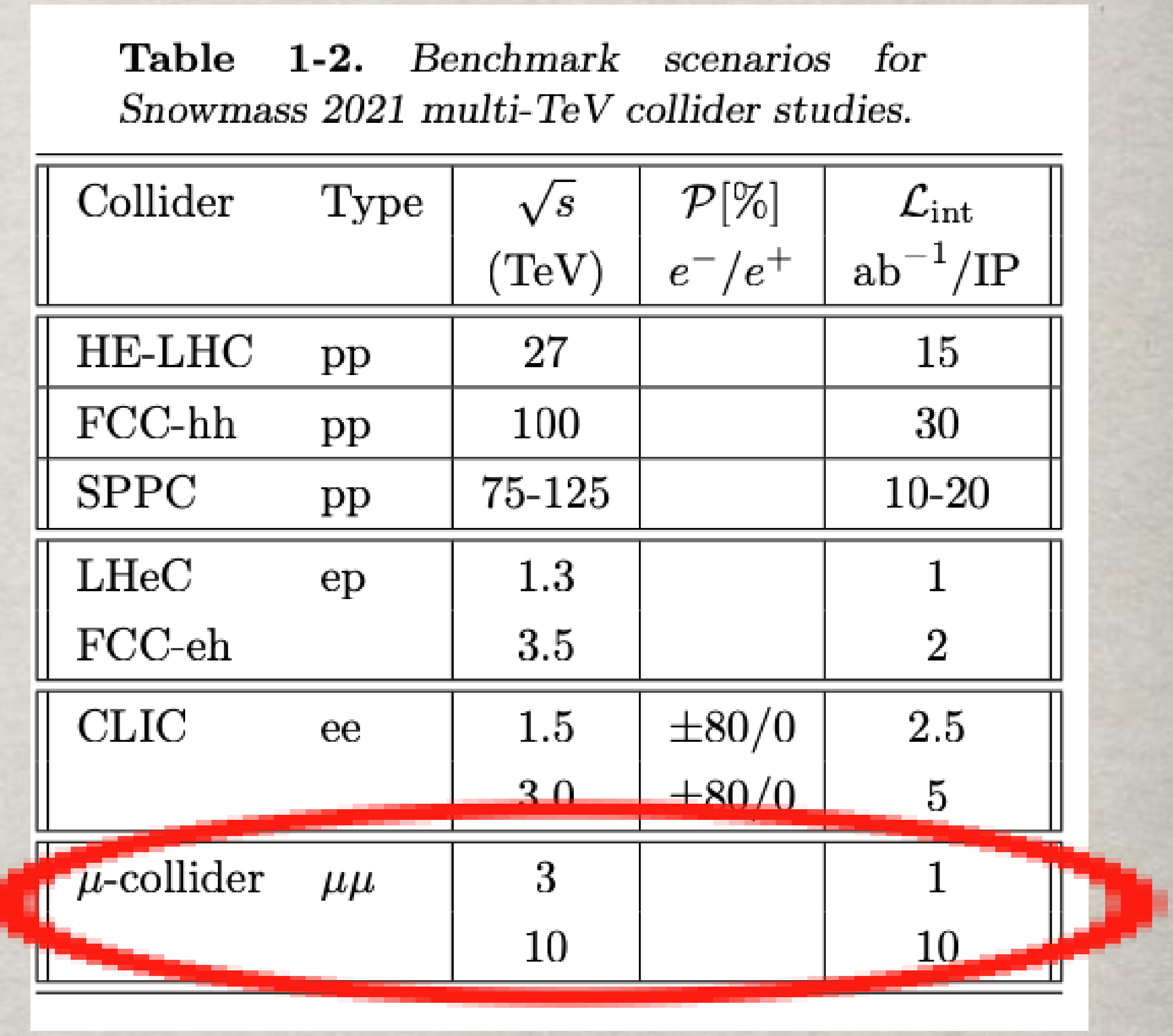


Table 1-2. *Benchmark scenarios for Snowmass 2021 multi-TeV collider studies.*

Collider	Type	$\sqrt{s}$ (TeV)	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}/IP
HE-LHC	pp	27		15
FCC-hh	pp	100		30
SPPC	pp	75-125		10-20
LHeC	ep	1.3		1
FCC-eh		3.5		2
CLIC	ee	1.5	$\pm80/0$	2.5
		3.0	$\pm80/0$	5
μ-collider	$\mu\mu$	3		1
		10		10

This talk: muon colliders

• A Muon Collider

Why muons?

Although sharing the same EW interactions

it isn't another electron!

$m_\mu \approx 207\ m_e$

$\tau(\mu \to e\nu_e\nu_\mu) \approx 2.2\ \mu s$

$c\tau \approx 660\ m$

Once accelerated:

E_μ ~ 1 TeV → γ ~ 10^4 → d = $c\gamma\tau$ = 6,600 km

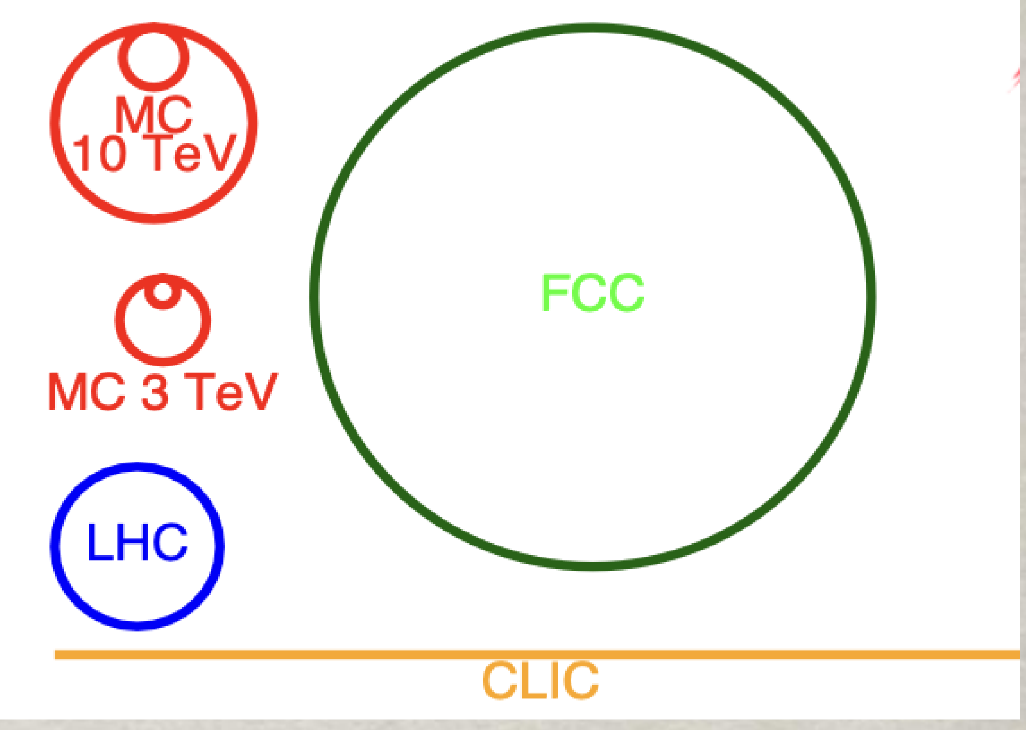
[illegible]

Advantages of a muon collider

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

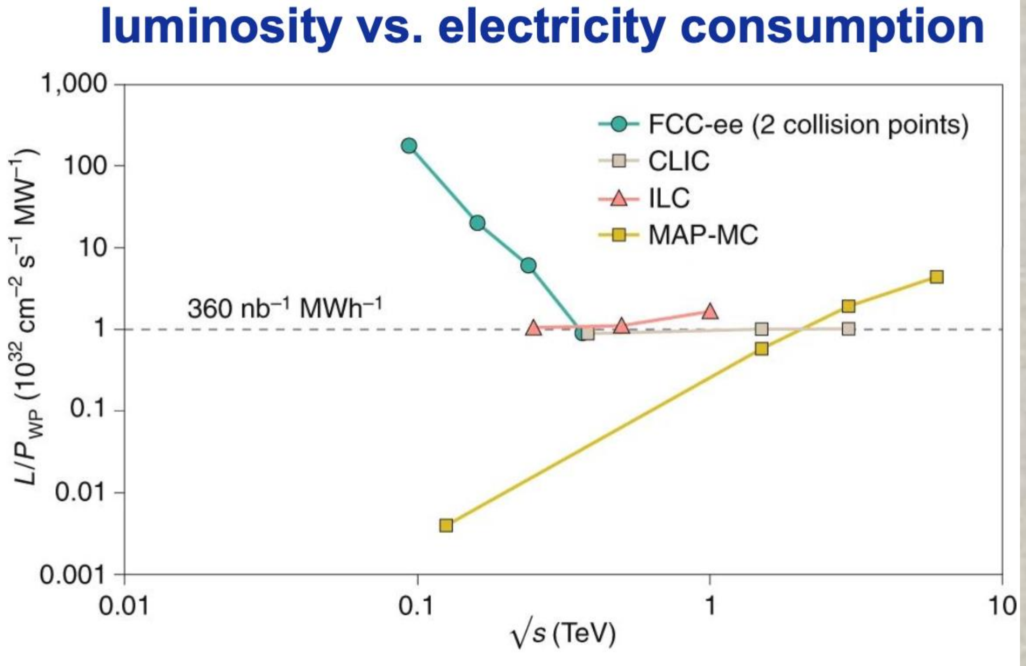
$$\Delta E \sim \frac{1}{R}\,(\frac{E}{m_\mu})^4$$

which would allow a smaller and a circular machine, thus likely cost-effective:



- Luminosity scales with c.m. energy/power, ideally

$L \sim E^2_{CM}$


luminosity vs. electricity consumption

- Smaller beam-energy spread:

$\Delta E/E \sim 0.1\%$

potentially $\Delta E/E(m_H) \sim 0.01\% - 0.001\%$

• 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?

Historically

- Concepts mentioned in the 60’s
- Early collider design/physics studies in the 90’s [*]
- 2011~2016: Muon Accelerator Program formed (MAP): to address key feasibility issues for $\boldsymbol{\mu}$C with the proton driver technology
- MAP terminated in 2016, results published in

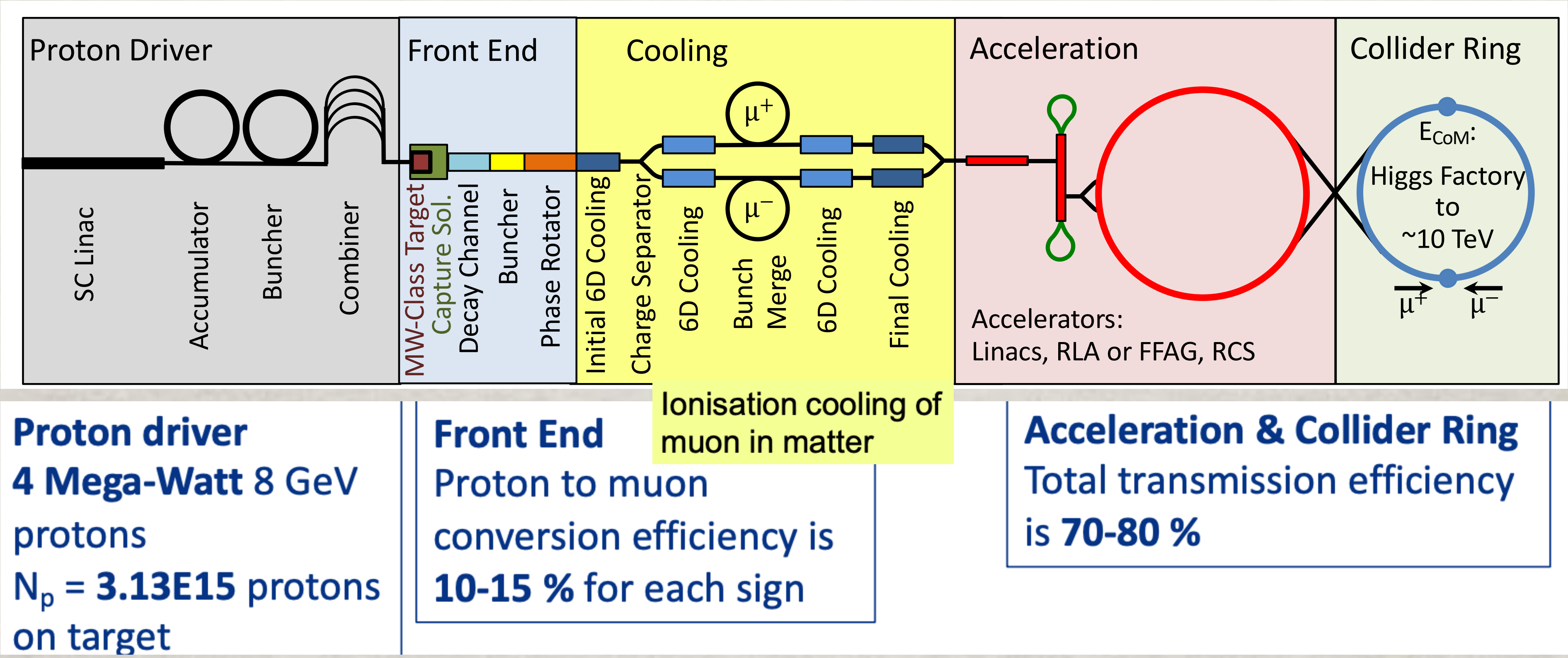
https://iopscience.iop.org/journal/1748-0221/page/extraproc46

[*] Some early work:

- *Proceedings of the 1st Workshop on the physics potential and Development of the* $\boldsymbol{\mu\mu}$ *Coiliders,* Napa, California, 1992, Nucl. Inst. Methods. Phys. Res., Sect. A 350, 24 (1994).
- *S-channel Higgs boson production at a muon collider,* Barger et al., PRL75 (1995).
- $\boldsymbol{\mu^+ \mu^-}$ *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,*

Renewed interests

Muon Accelerator Project (MAP)



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

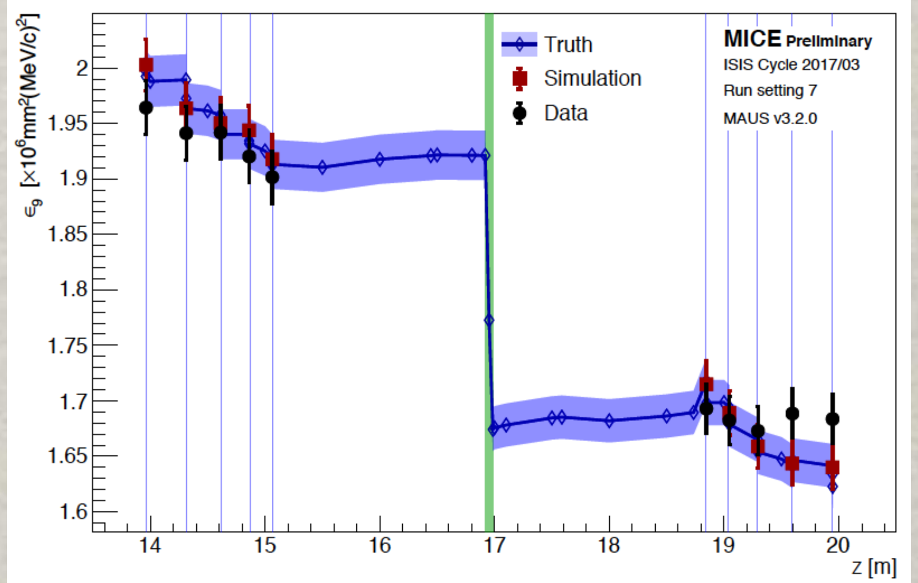
Front End
Proton to muon conversion efficiency is **10-15 %** for each sign

Ionisation cooling of muon in matter

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

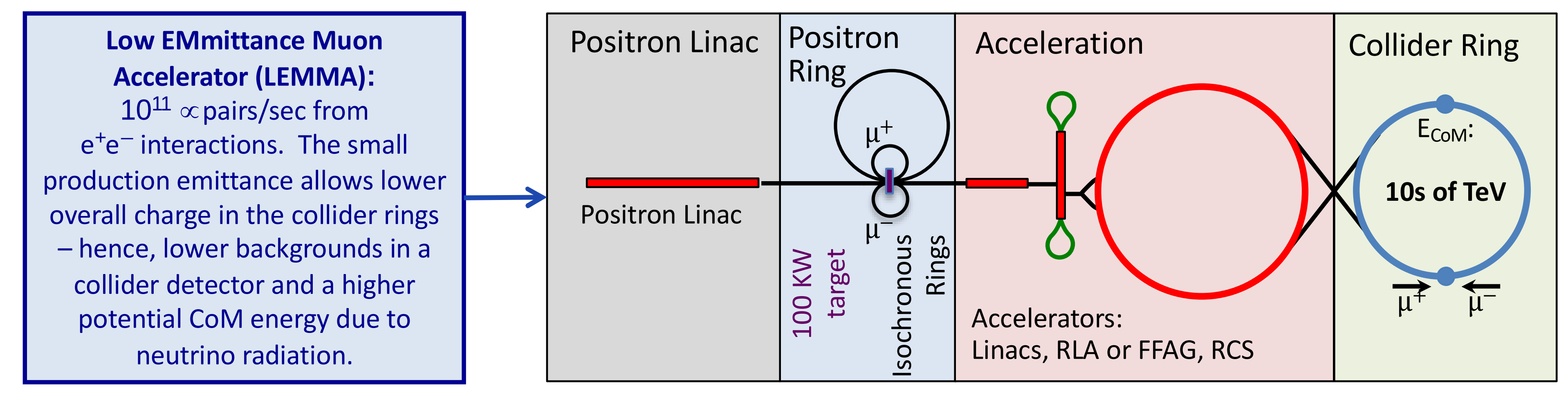
- Protons → pions → muons
- Transverse ionization cooling achieved by MICE
- Muon emittance exchange demonstrated at FNAL/RAL
- 6D cooling of 5-6 orders needed

Noticeable reduction of 9% emittance



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

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



Low EMmittance Muon Accelerator (LEMMA):
10^{11} ∝ 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

45 GeV e^+

$\mu^\pm$

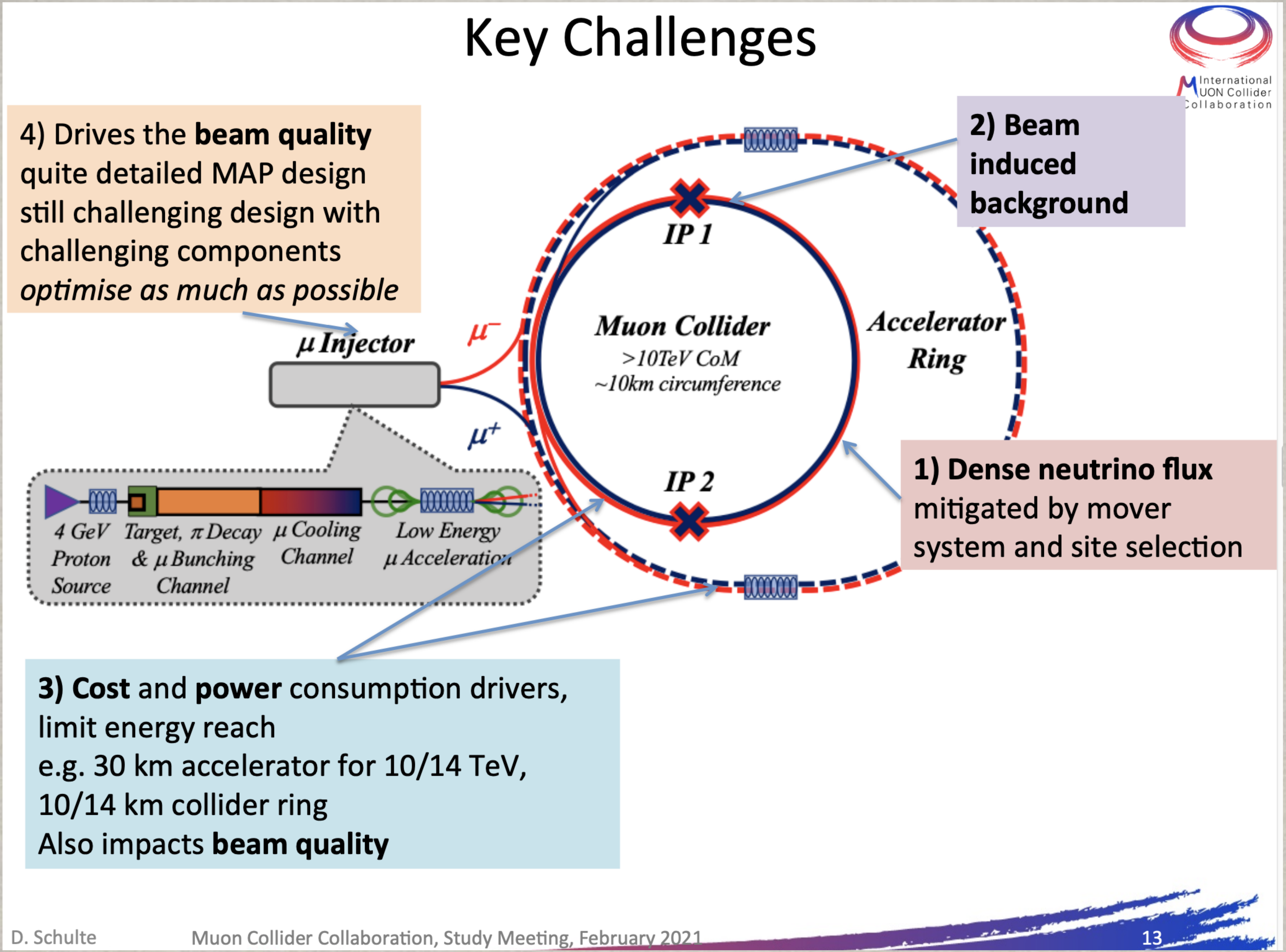
e^- at rest

Cooling is not a problem;
but high luminosity is challenging:
large e^+ flux of $O(10^{17}/s)$!

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

Key Challenges

International
MUON Collider
Collaboration



4) Drives the **beam quality**
quite detailed MAP design
still challenging design with challenging components
optimise as much as possible

2) Beam induced background

1) Dense neutrino flux
mitigated by mover system and site selection

3) Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**

Collider benchmark points:

- The Higgs factory:

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

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

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

- 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:

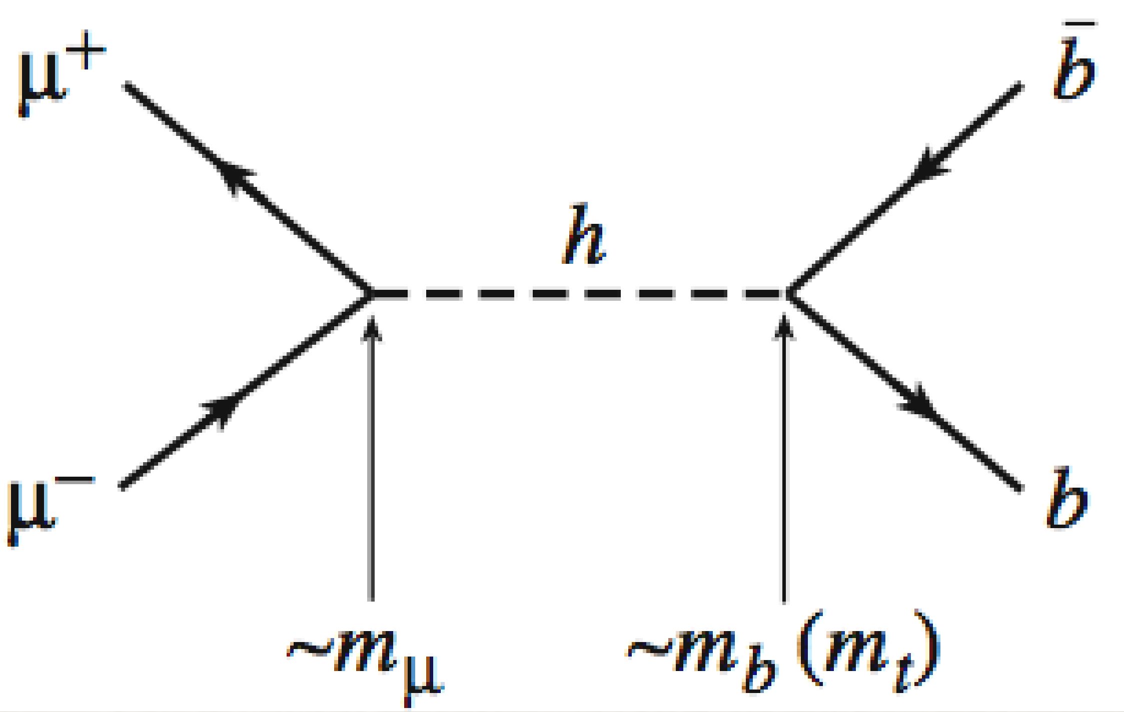
$\sqrt{s}$ = 3, 6, 10, 14, 30 and 100 TeV, L = 1, 4, 10, 20, 90, and 1000 ab^{-1}

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

Physics potential

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

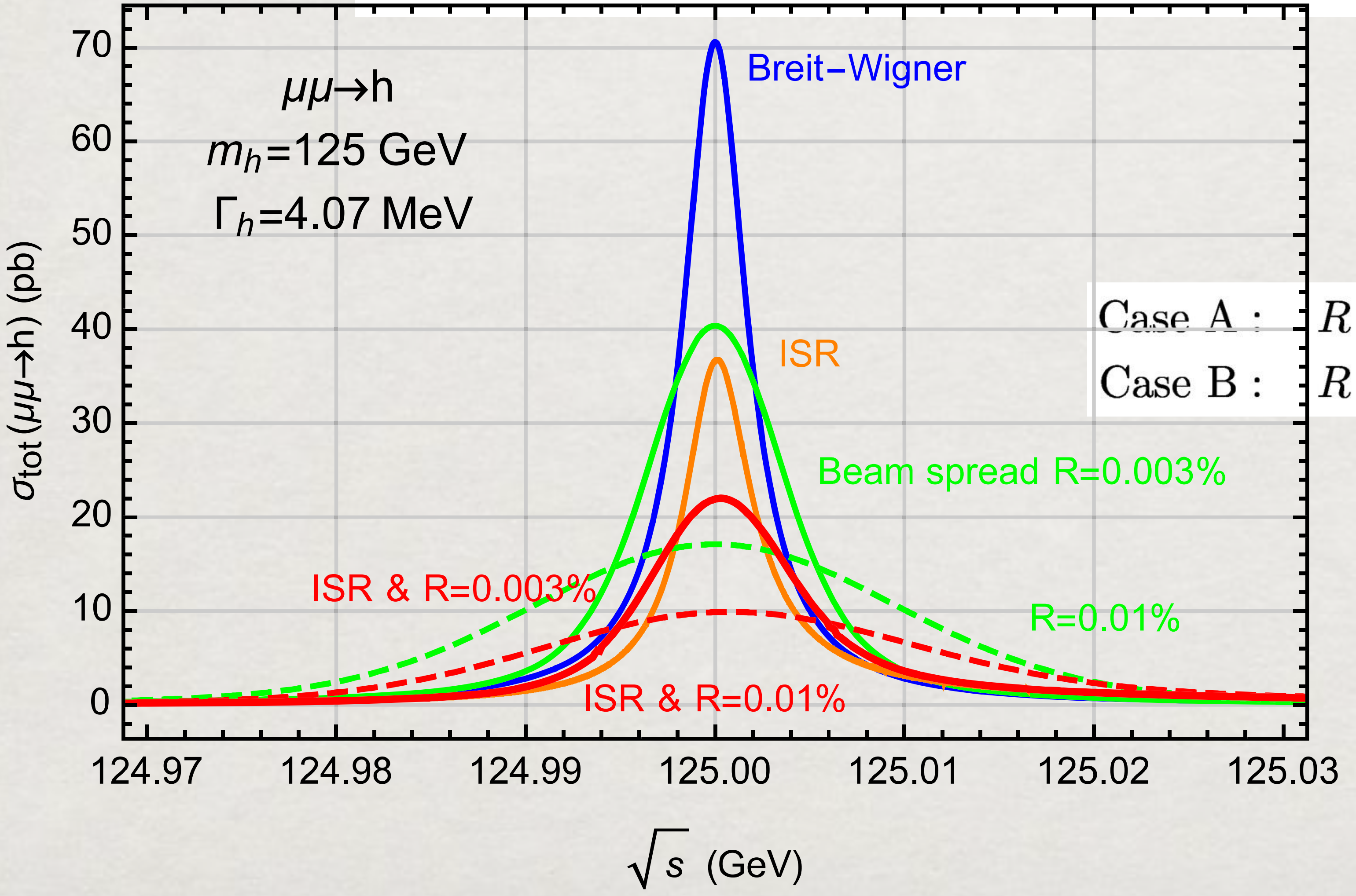
SM Higgs is (very) narrow:

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

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

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

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



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

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

“Muon Collider Quartet”:

Barger-Berger-Gunion-Han

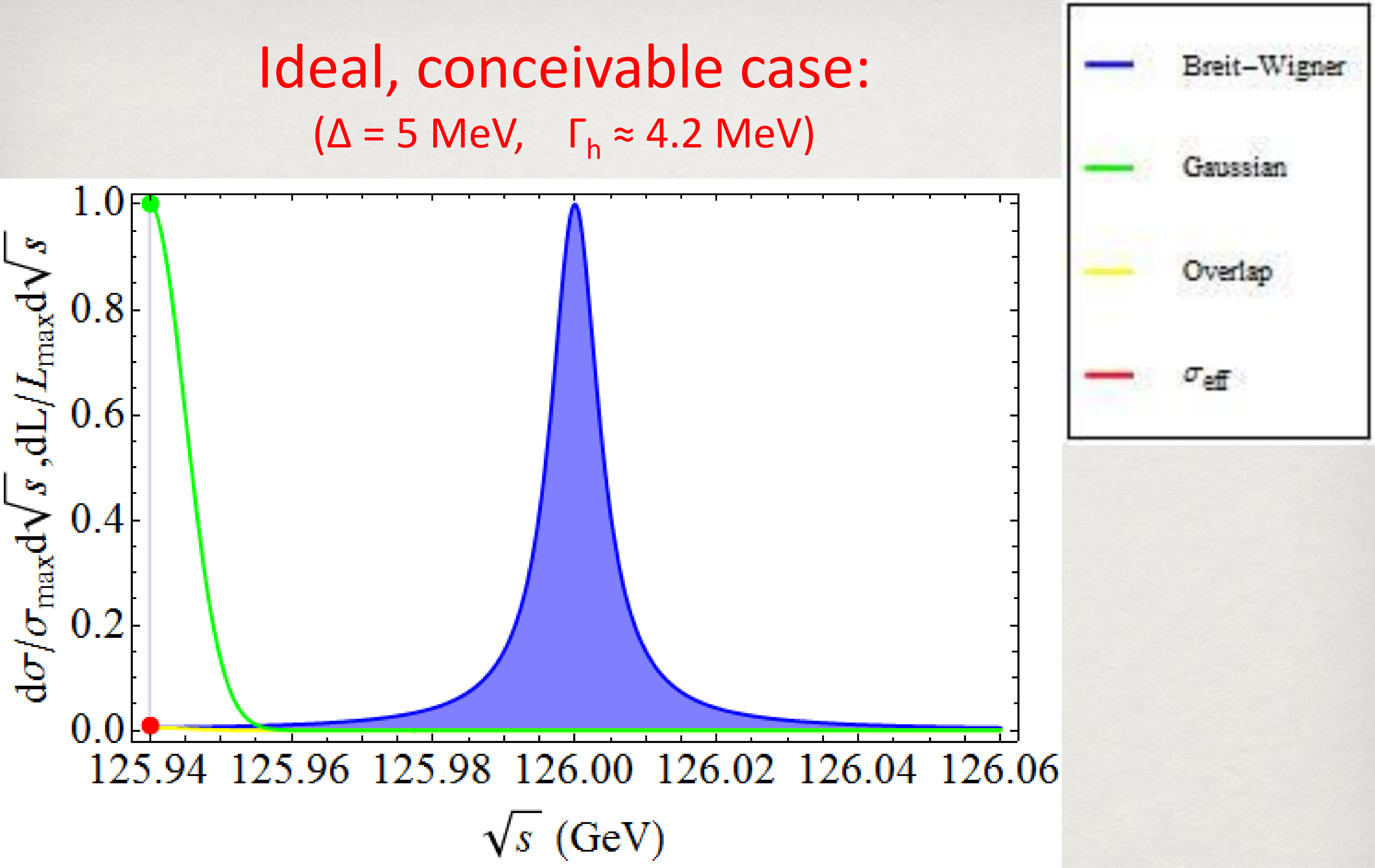
PRL & Phys. Report (1995)

TH, Liu: 1210.7803;

Greco, TH, Liu: 1607.03210

Ideal, conceivable case:

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



An optimal fitting could reach $\delta\Gamma_h \sim 0.15$ MeV, or 3.5%

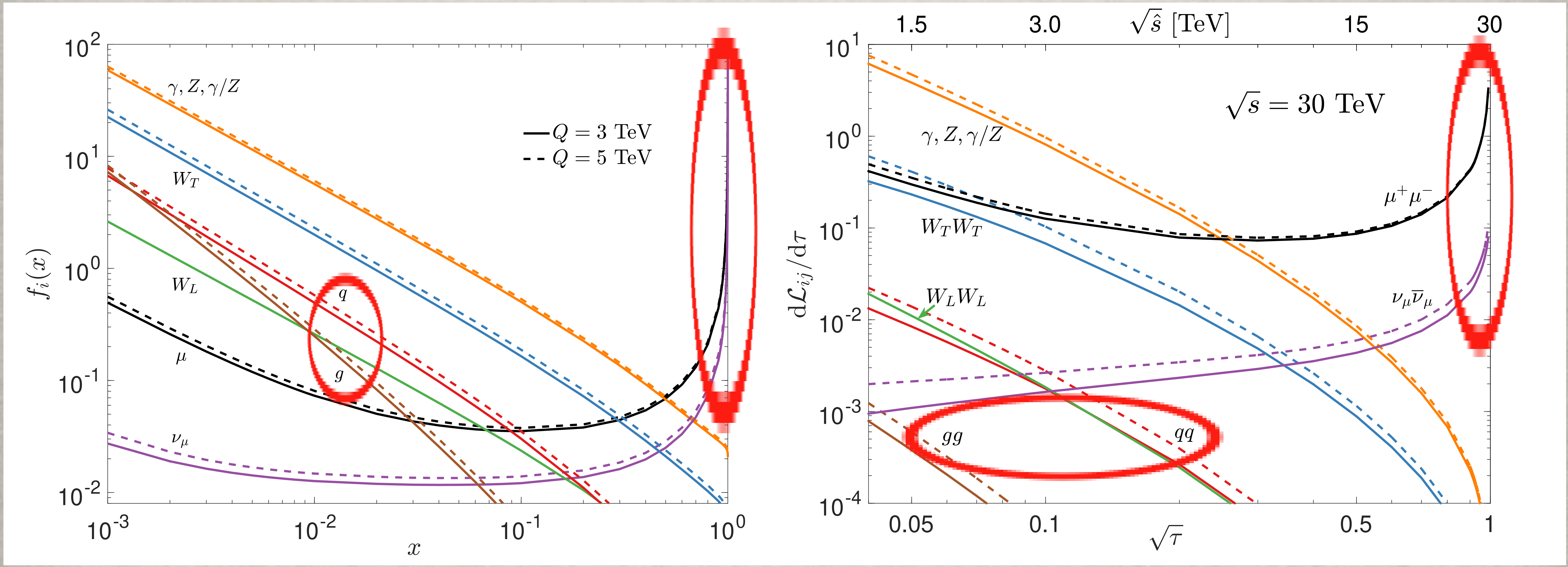
TH, Liu: 1210.7803; Greco, TH, Liu: 1607.03210

HE muon colliders: EW PDFs

“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

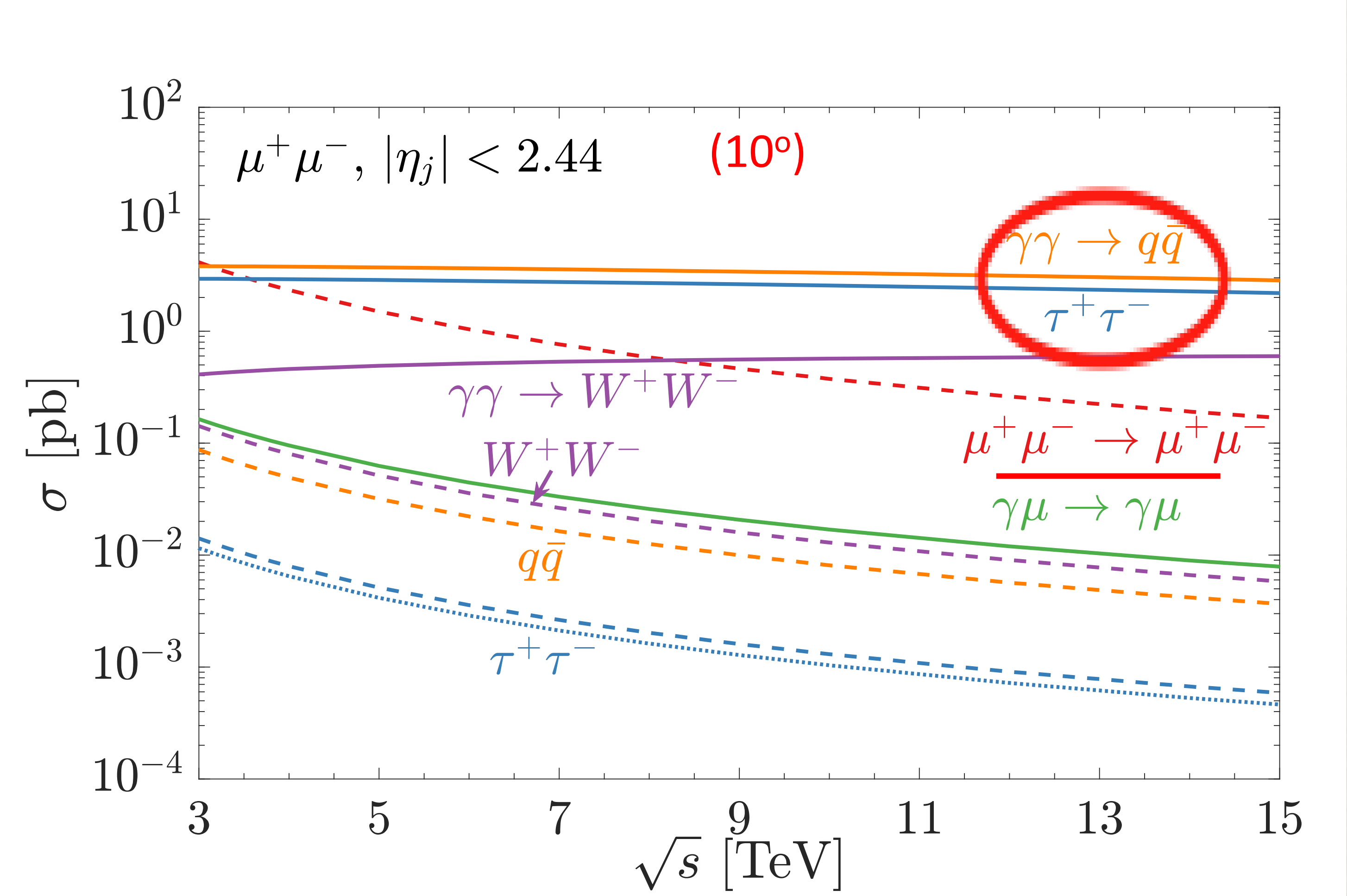


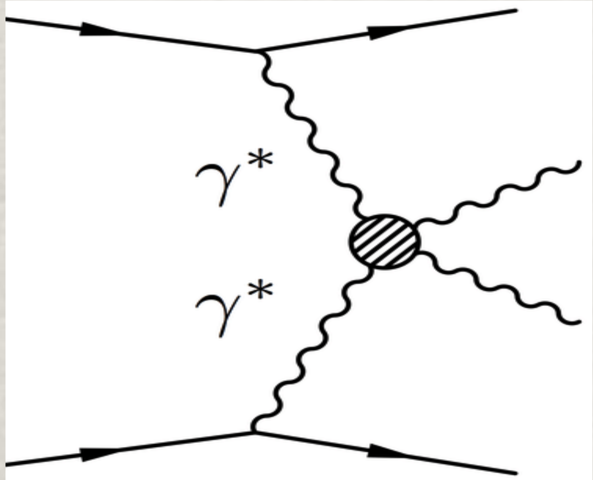
$\mu^{\pm}$: the valance. $\ell_R,\ \ell_L,\ \nu_L$ and $B, W^{\pm,3}$: LO sea.

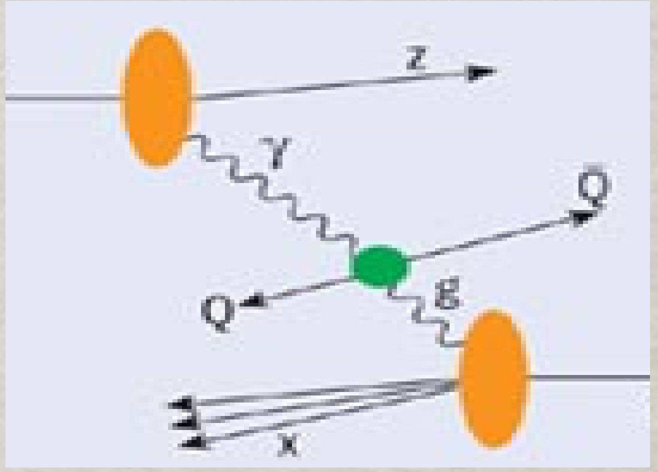
- High-energy neutrino collider!
- Hadron collider! Quarks: NLO; gluons: NNLO.

- # Photon-induced QED cross sections

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







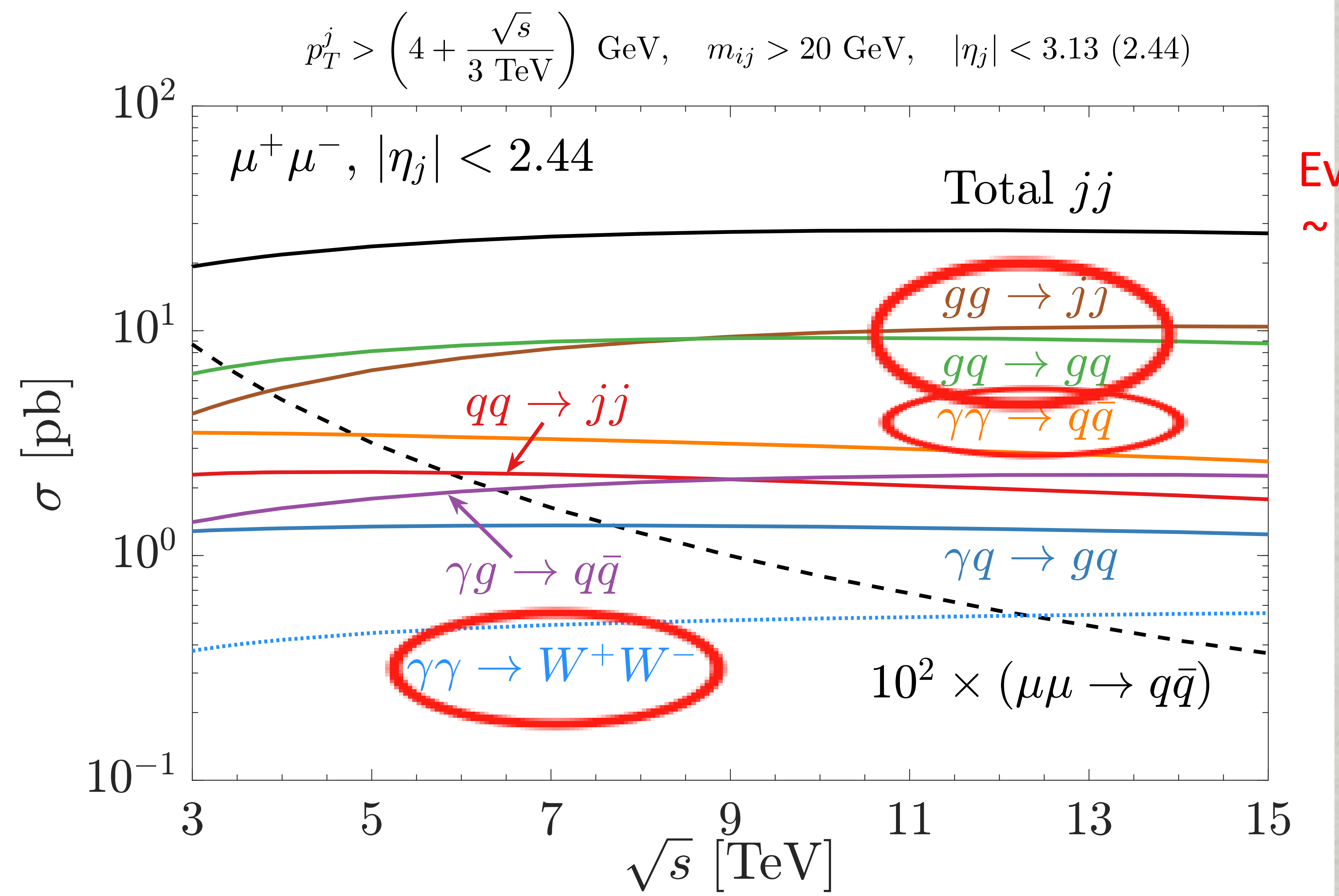
$$p_T^j > \left(4 + \frac{\sqrt{s}}{3\ \text{TeV}}\right)\ \text{GeV}, \quad m_{ij} > 20\ \text{GeV}, \quad |\eta_j| < 3.13\ (2.44)$$

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, like hadron colliders

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



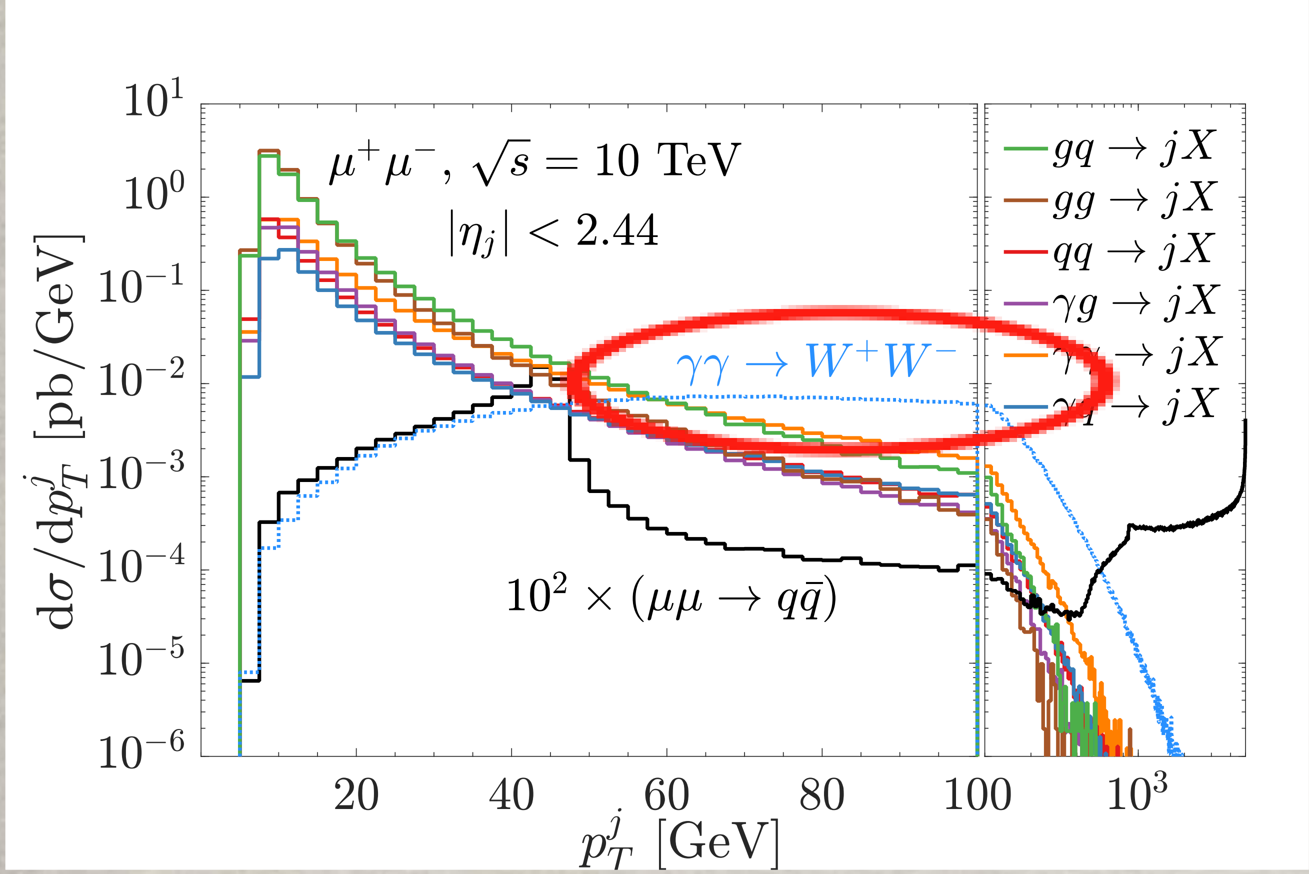
Event rate
~ a few Hz

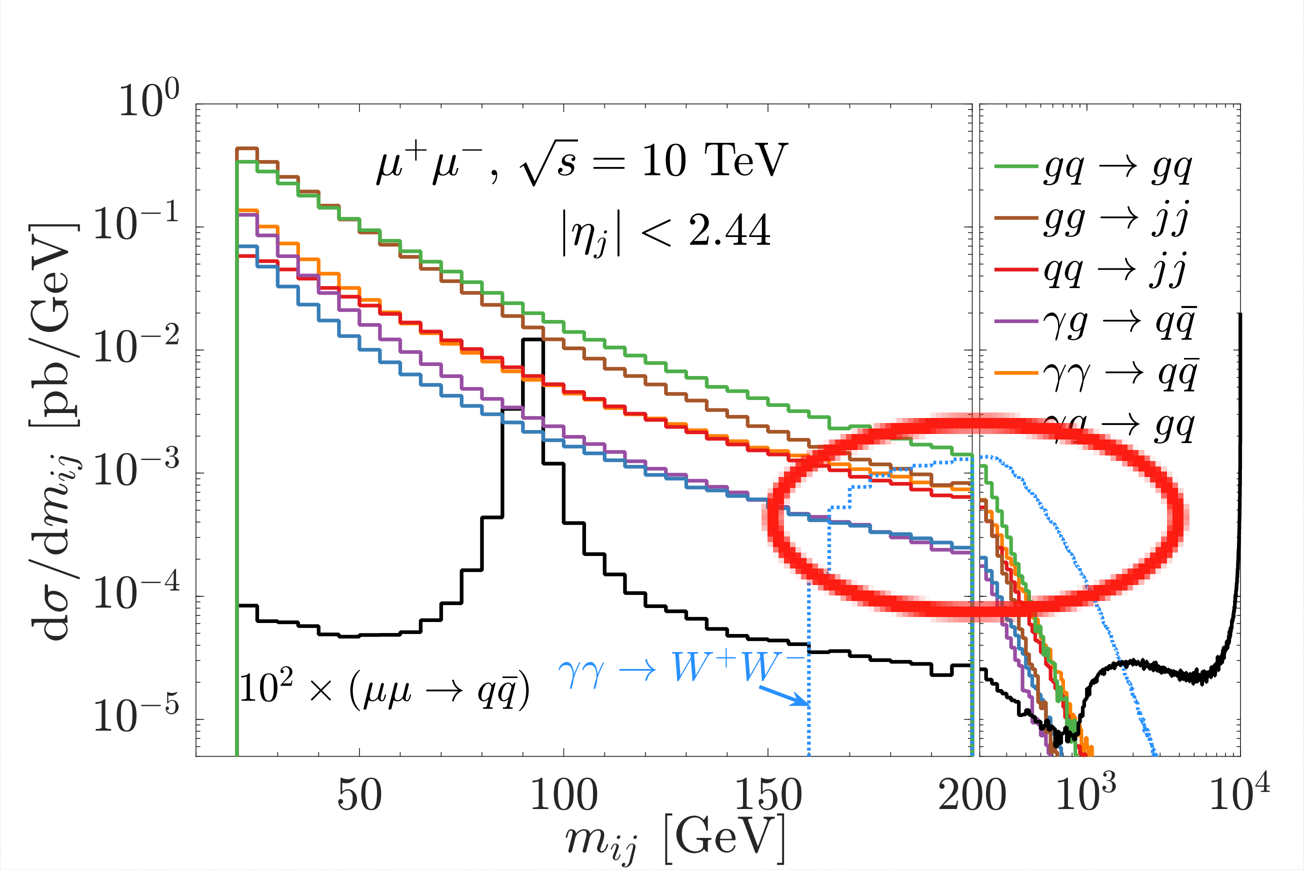
- Jet production dominates at low energies
- EW processes take over at high scales!

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

Di-jet kinematical features:

High p_T physics strikes back!





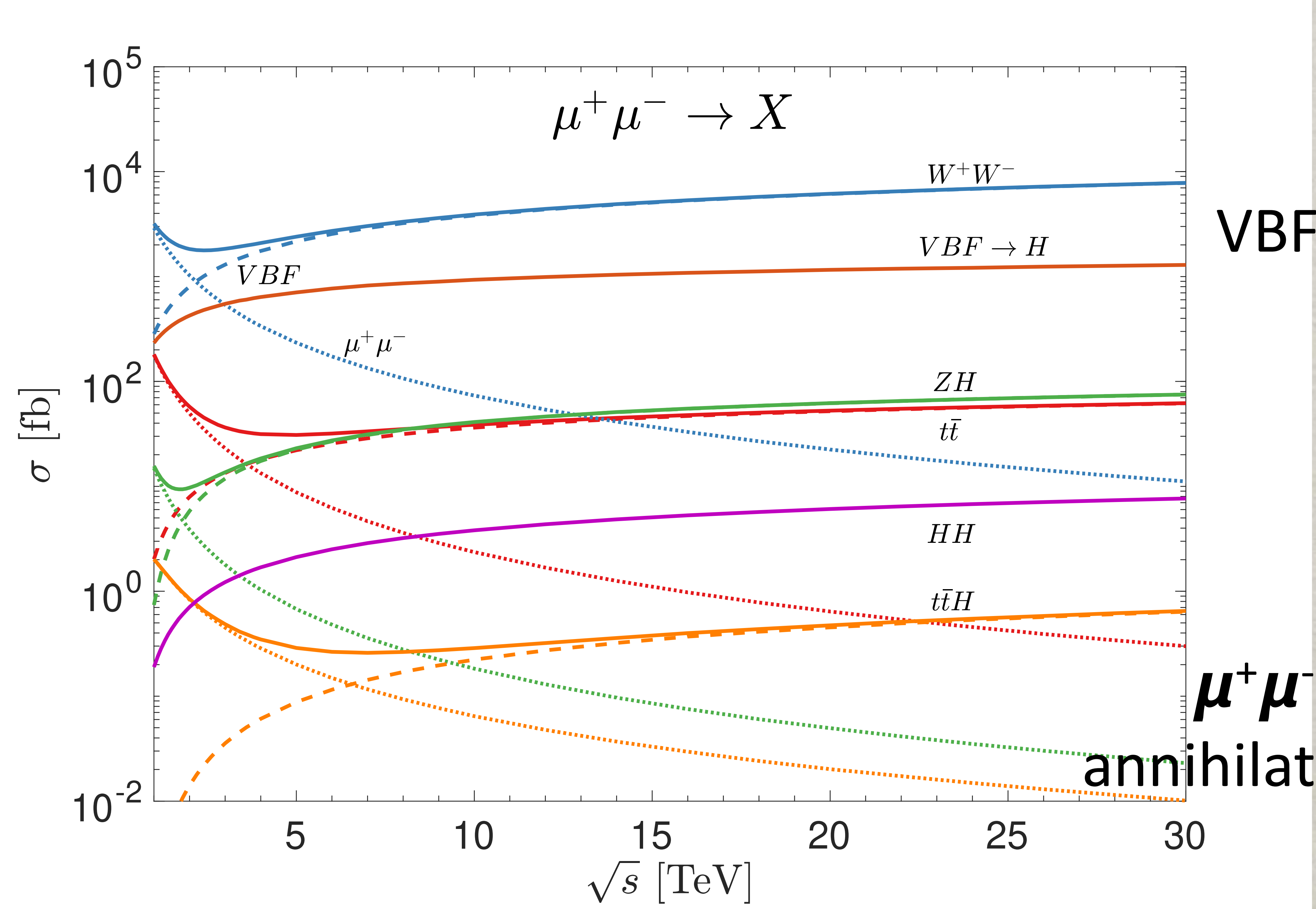
To effectively separate the QCD backgrounds:

$p_T > 60$ GeV

• "Semi-inclusive" processes

Just like in hadronic collisions:

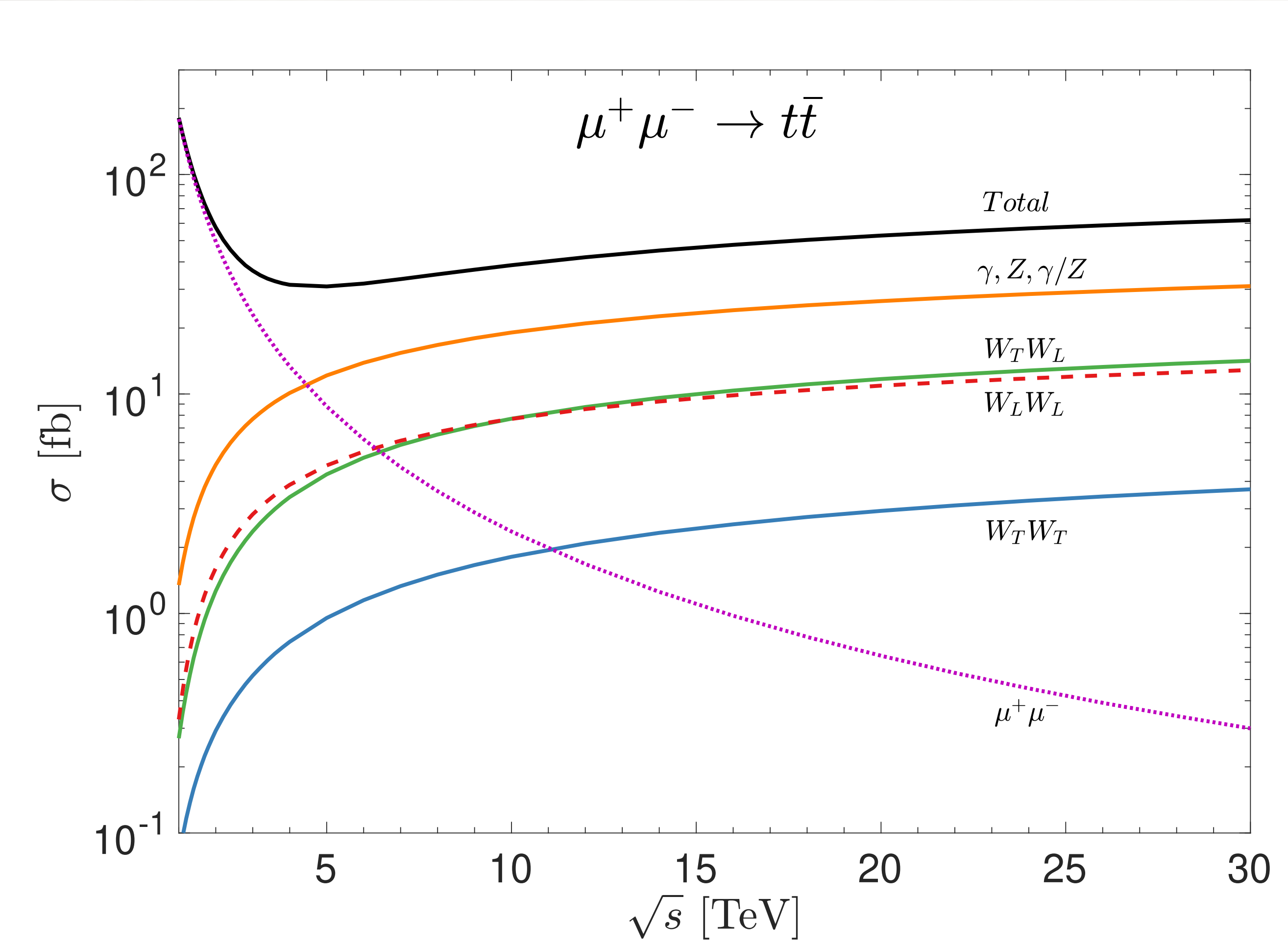
$\mu^+\mu^-$ → exclusive particles + remnants

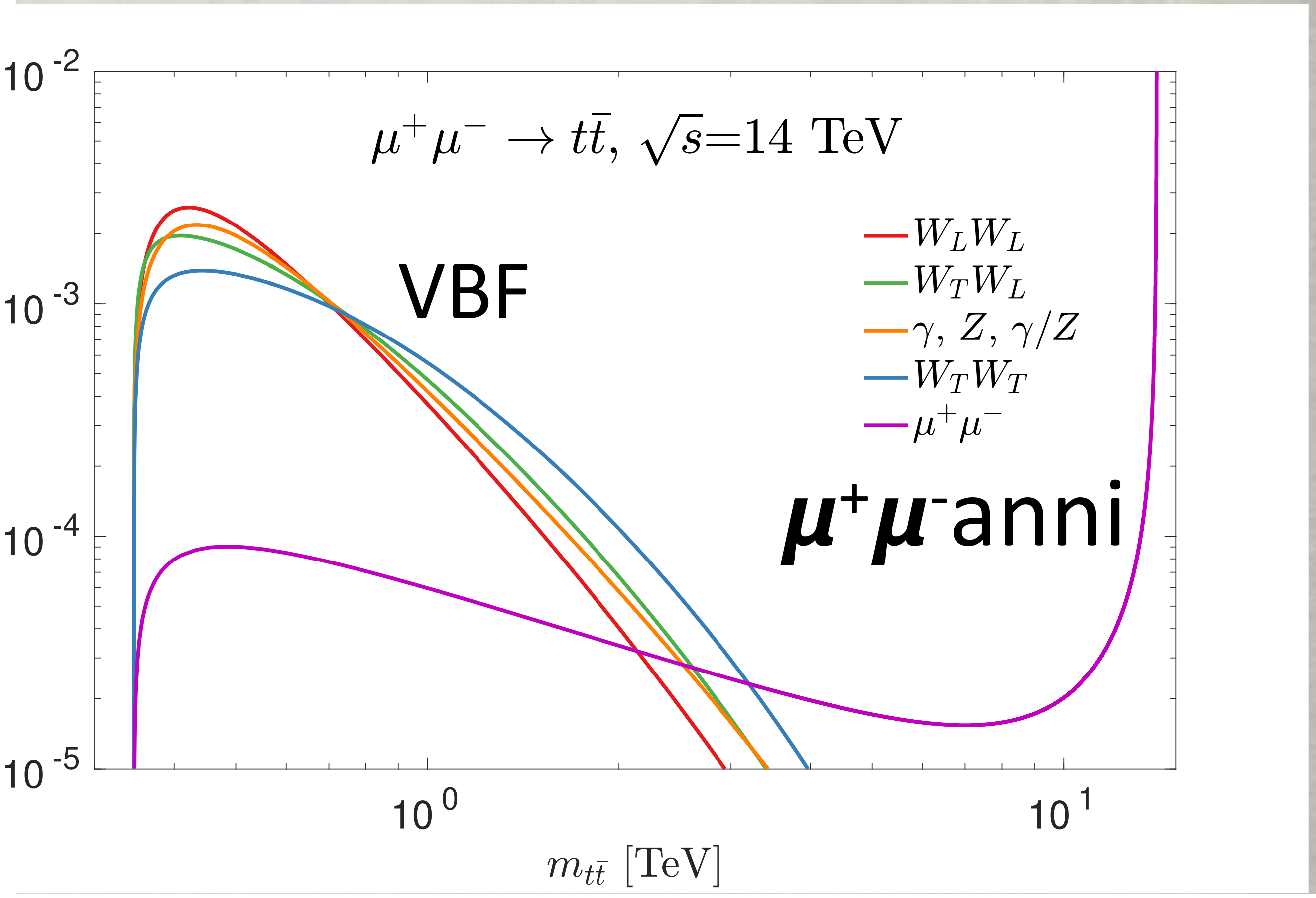


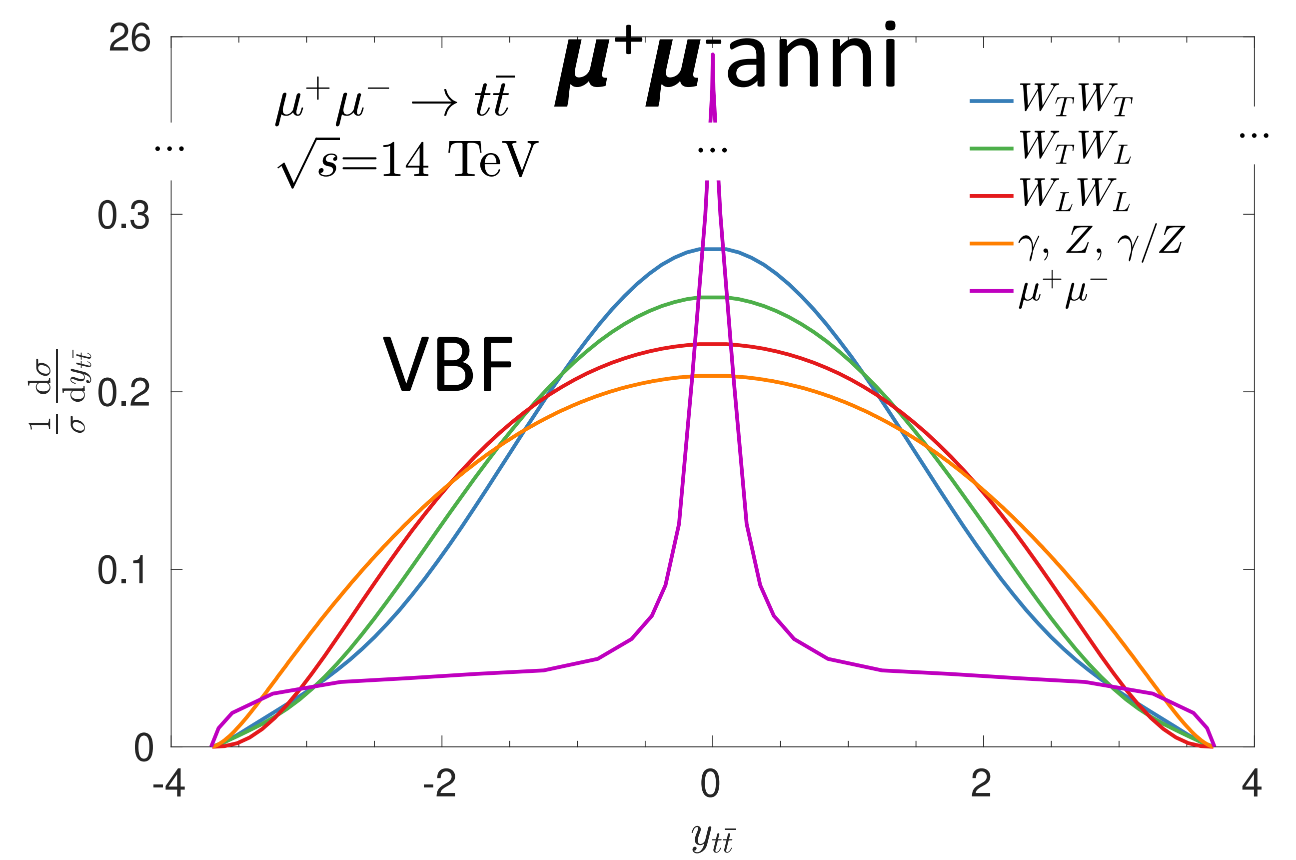
VBF

$\mu^+\mu^-$ annihilations

• separable sub-processes:







Partonic contributions

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

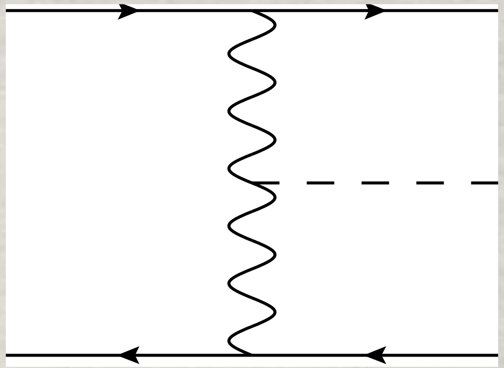
“Buy one, get one free”

Annihilation +VBF

• Precision Higgs Physics

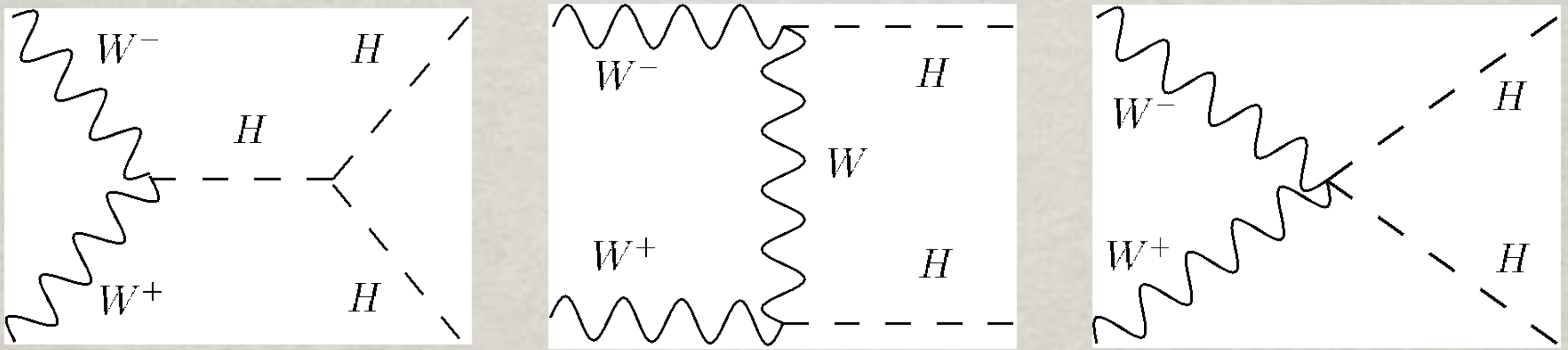
$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu \; H \qquad (WW \text{ fusion}),$$

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



WWH / ZZH couplings

HHH / WWHH couplings:



(a) (b) (c)

$\sqrt{s}$ (TeV) 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

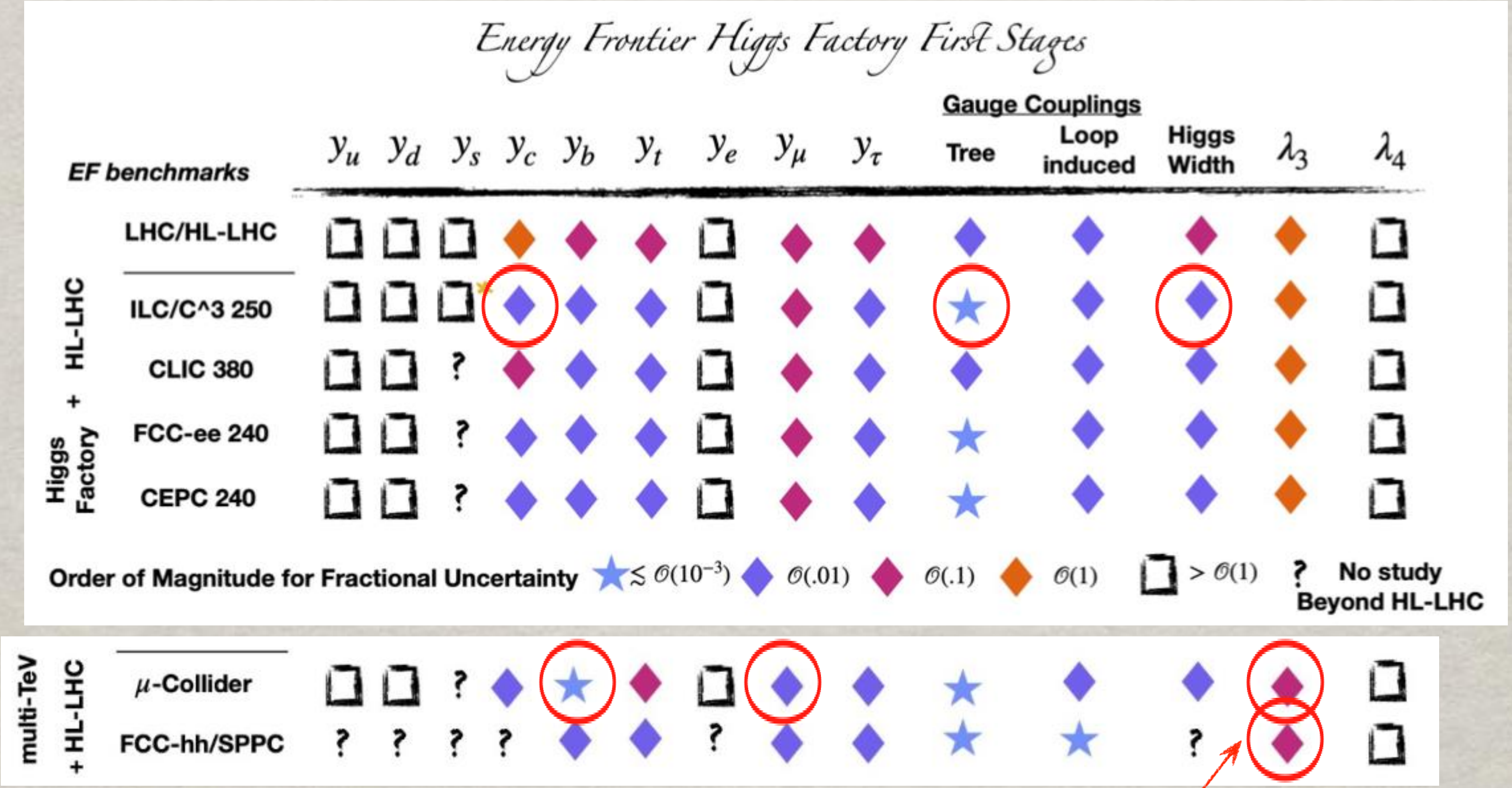
500k HH

$\Delta\lambda_{hhh} \sim 2\%$,
$\Delta k_{WWhh} \sim 0.2\%$

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

Sensitivity reach for Higgs couplings for Higgs factories and multi-TeV colliders

Energy Frontier report: arXiv:2211.11084



Energy Frontier Higgs Factory First Stages

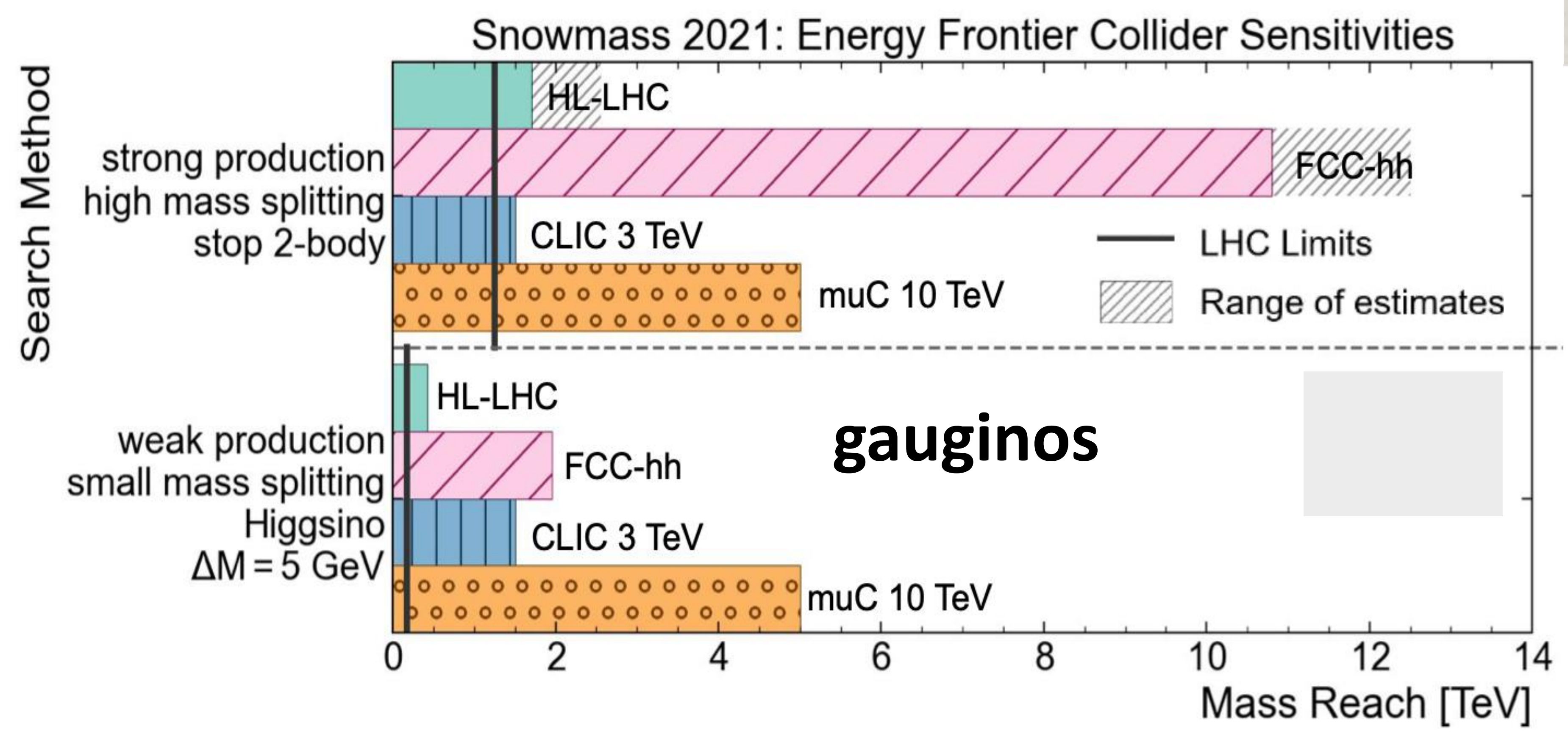
											Gauge Couplings				
	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Tree	Loop induced	Higgs Width	λ_3	λ_4
	LHC/HL-LHC	☐	☐	☐	🔶	◆	◆	☐	◆	◆	🔷	🔷	◆	🔶	☐
Higgs Factory + HL-LHC	ILC/C^3 250	☐	☐	☐	🔷	🔷	🔷	☐	◆	🔷	★	🔷	🔷	🔶	☐
	CLIC 380	☐	☐	?	◆	🔷	🔷	☐	◆	🔷	🔷	🔷	🔷	🔶	☐
	FCC-ee 240	☐	☐	?	🔷	🔷	🔷	☐	◆	🔷	★	🔷	🔷	🔶	☐
	CEPC 240	☐	☐	?	🔷	🔷	🔷	☐	◆	🔷	★	🔷	🔷	🔶	☐
multi-TeV + HL-LHC	μ-Collider	☐	☐	?	🔷	★	◆	☐	🔷	🔷	★	🔷	🔷	◆	☐
	FCC-hh/SPPC	?	?	?	?	🔷	🔷	?	🔷	🔷	★	★	?	◆	☐

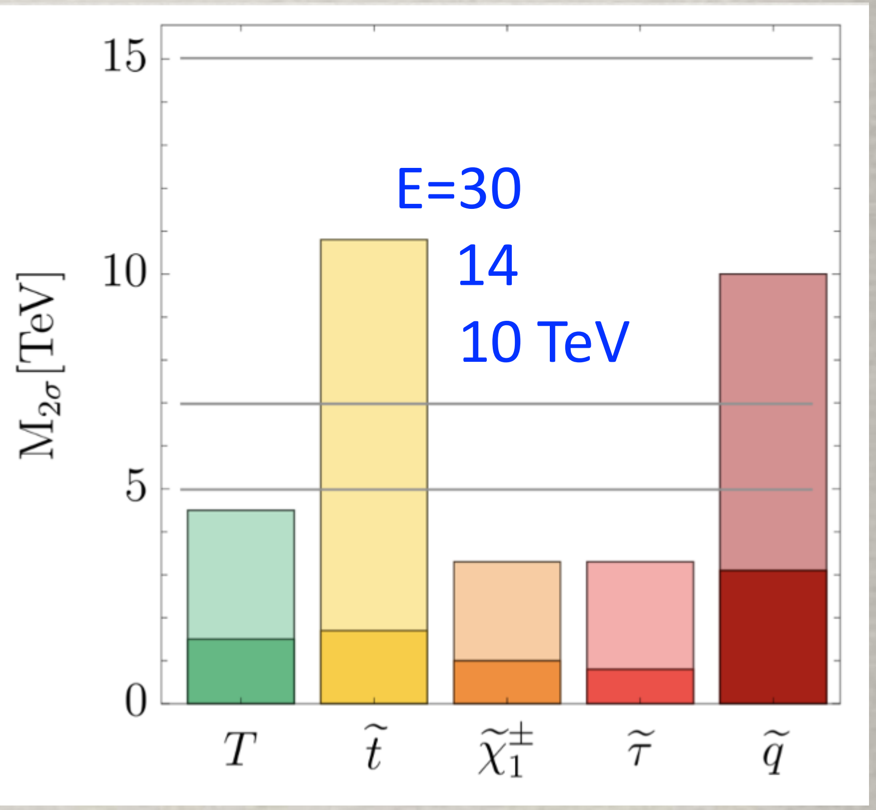
Order of Magnitude for Fractional Uncertainty ★ $\lesssim \mathcal{O}(10^{-3})$ 🔷 $\mathcal{O}(.01)$ ◆ $\mathcal{O}(.1)$ 🔶 $\mathcal{O}(1)$ ☐ $> \mathcal{O}(1)$ **? No study Beyond HL-LHC**

Most wanted in order to understand EWSB!

Pushing the "Naturalness" limit

The searches for top quark partners
(most wanted in "naturalness");
& gluinos, gauginos …





→ Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \, (1\ \text{TeV}/\Lambda)^2$

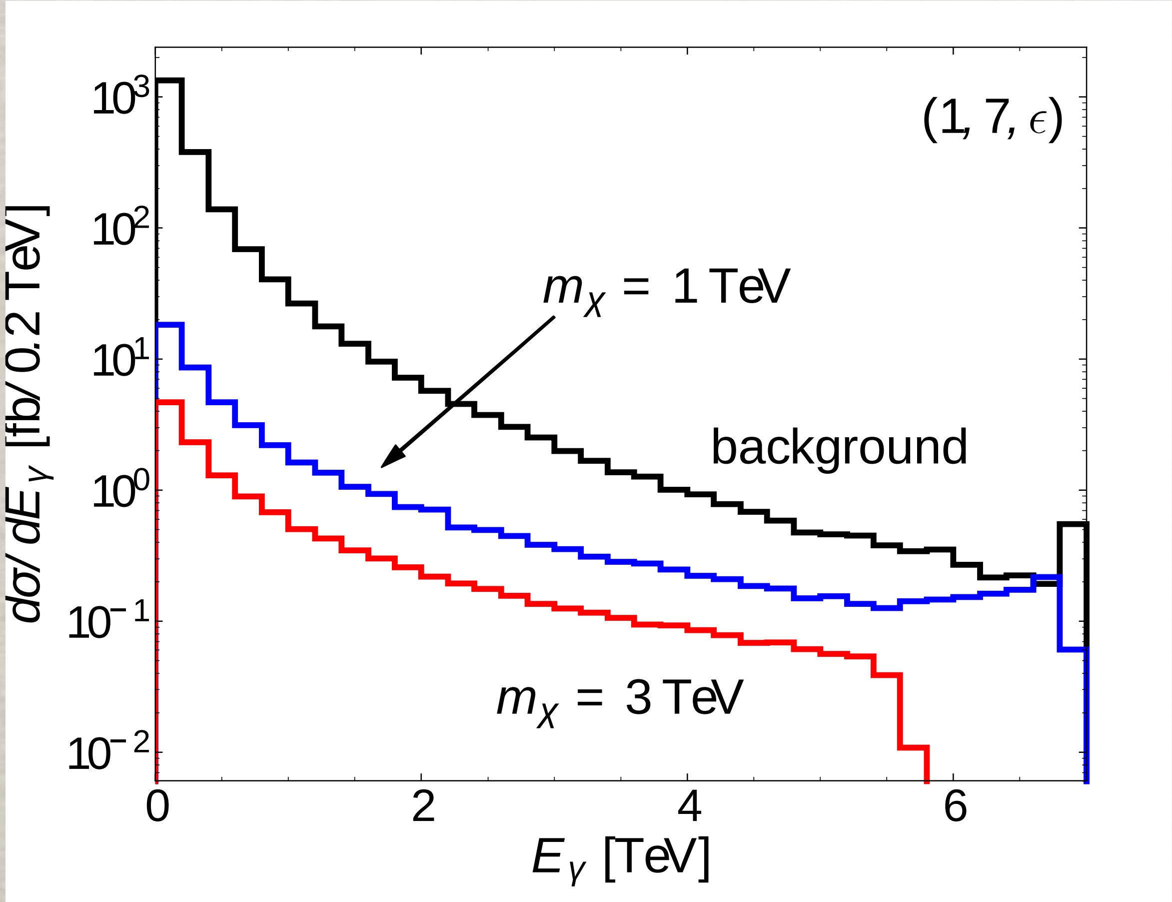
Thus, $m_{stop} > 8$ TeV → 10^{-4} fine-tune!

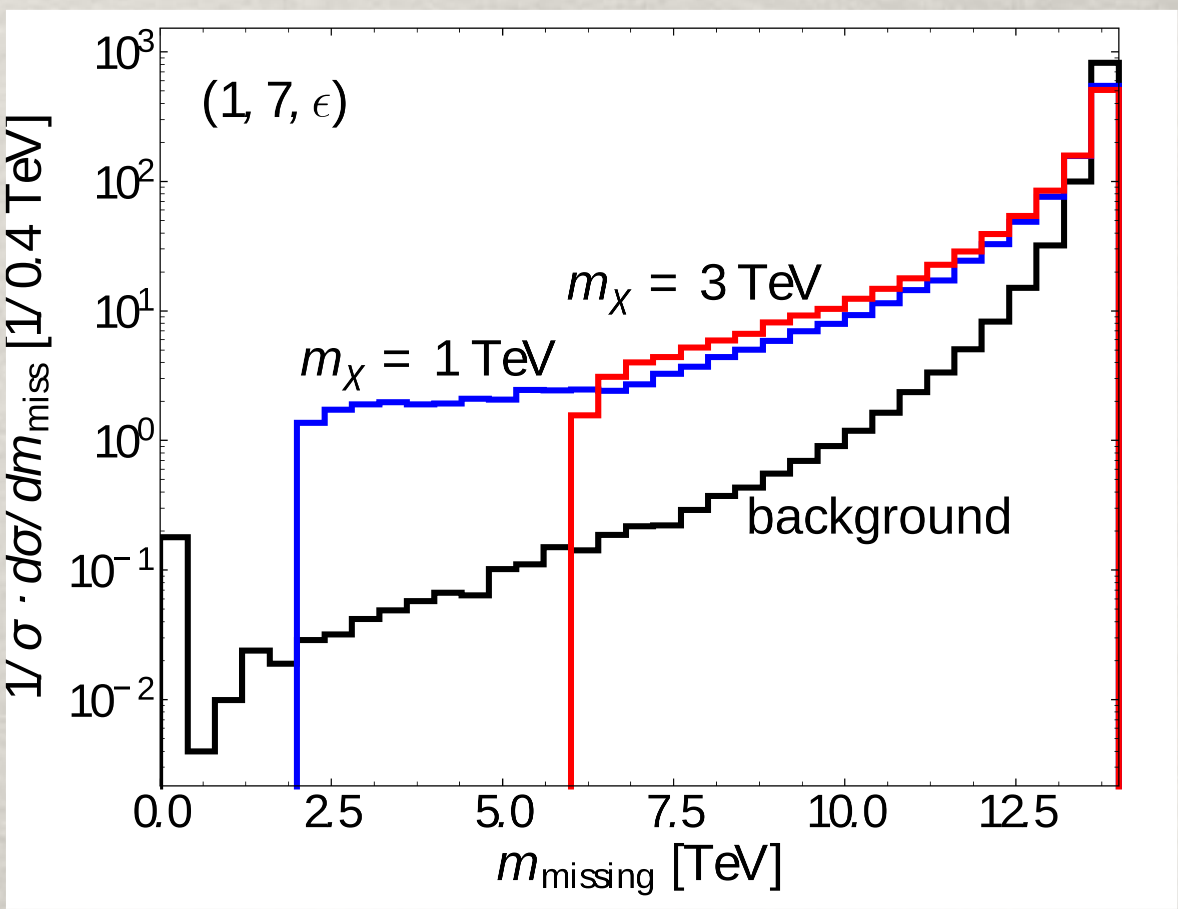
Muon Collider Forum Report: https://arxiv.org/abs/2209.01318

Key feature different from LHC: the “missing mass”

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

$$E_\gamma < (s - 4m_\chi^2)/2\sqrt{s} \qquad m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > 4m_\chi^2$$

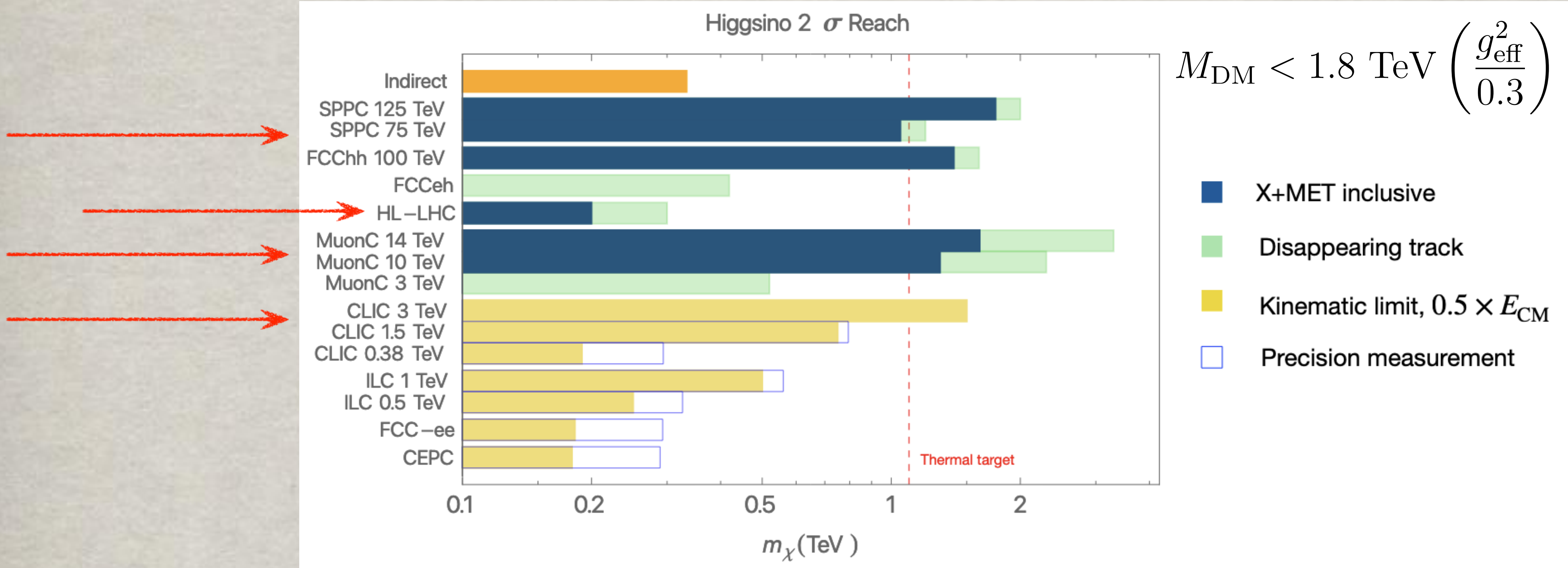




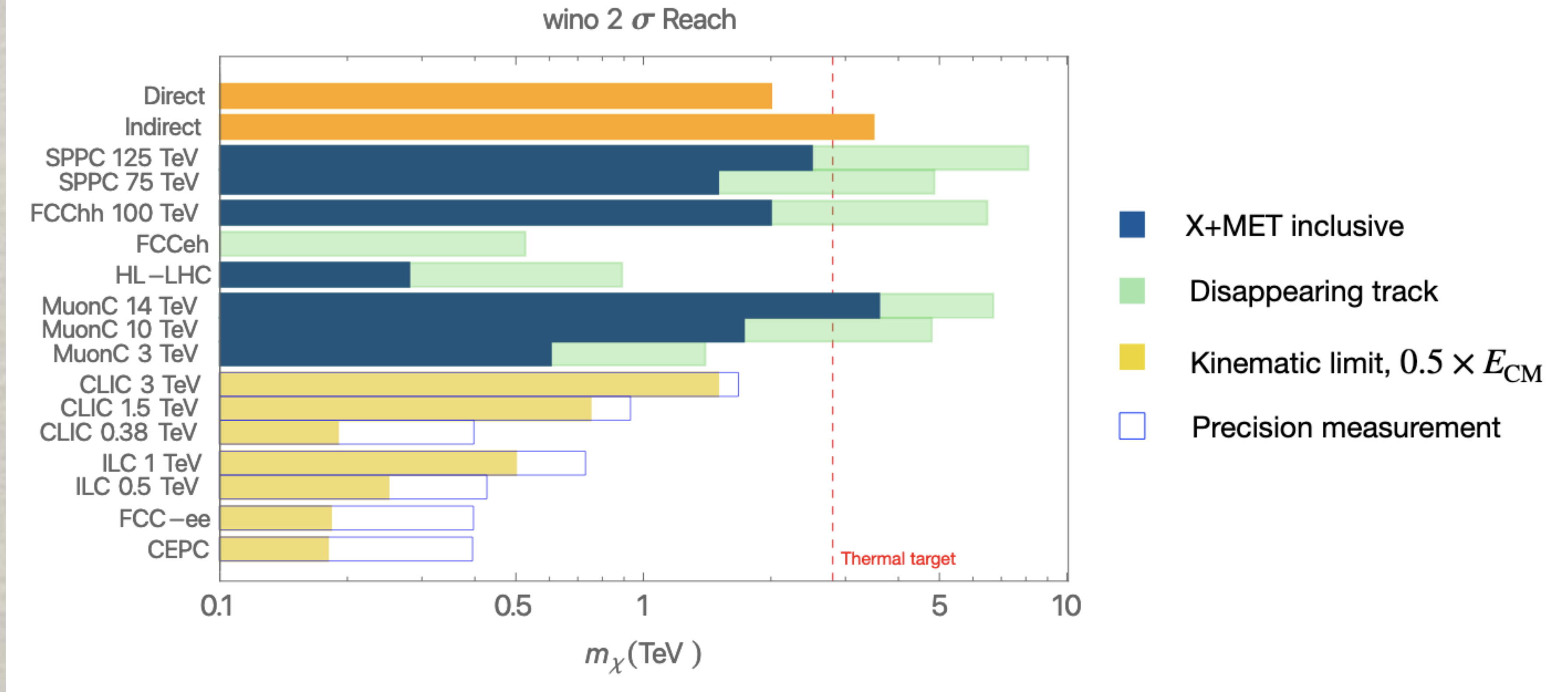
a cone angle cut: 10° < θ < 170°

WIMP Dark Matter @ Colliders

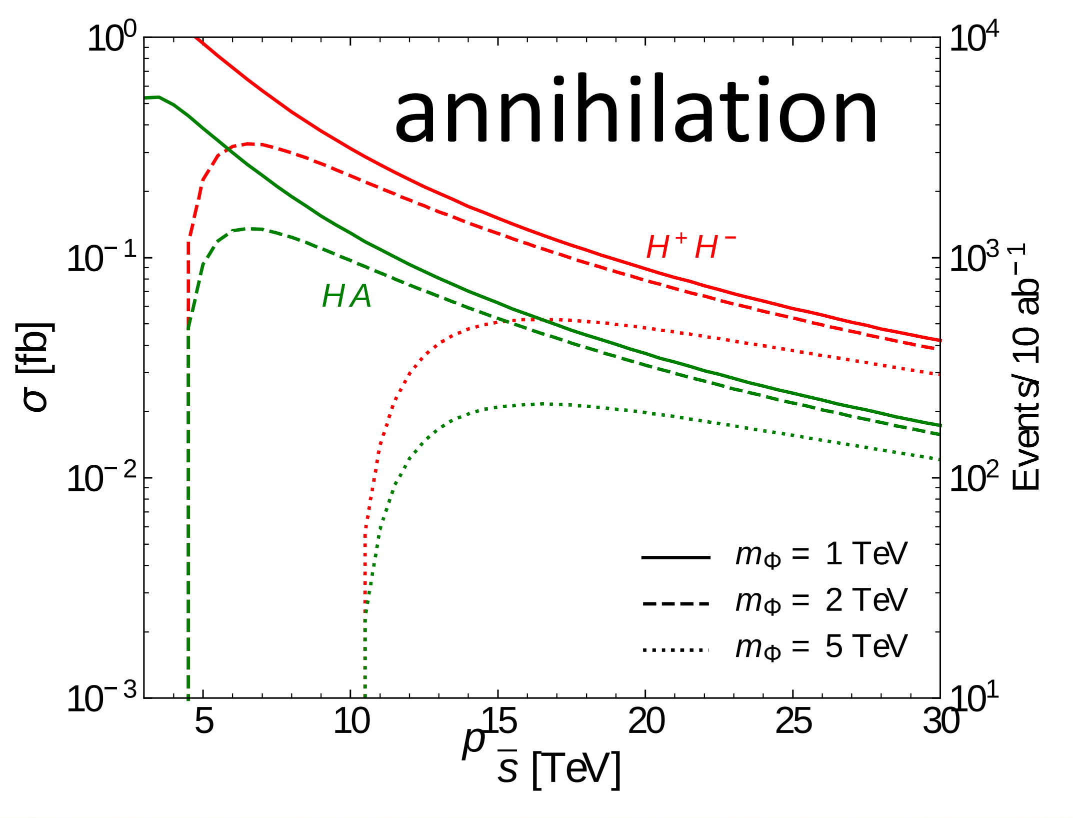
Covering the thermal target

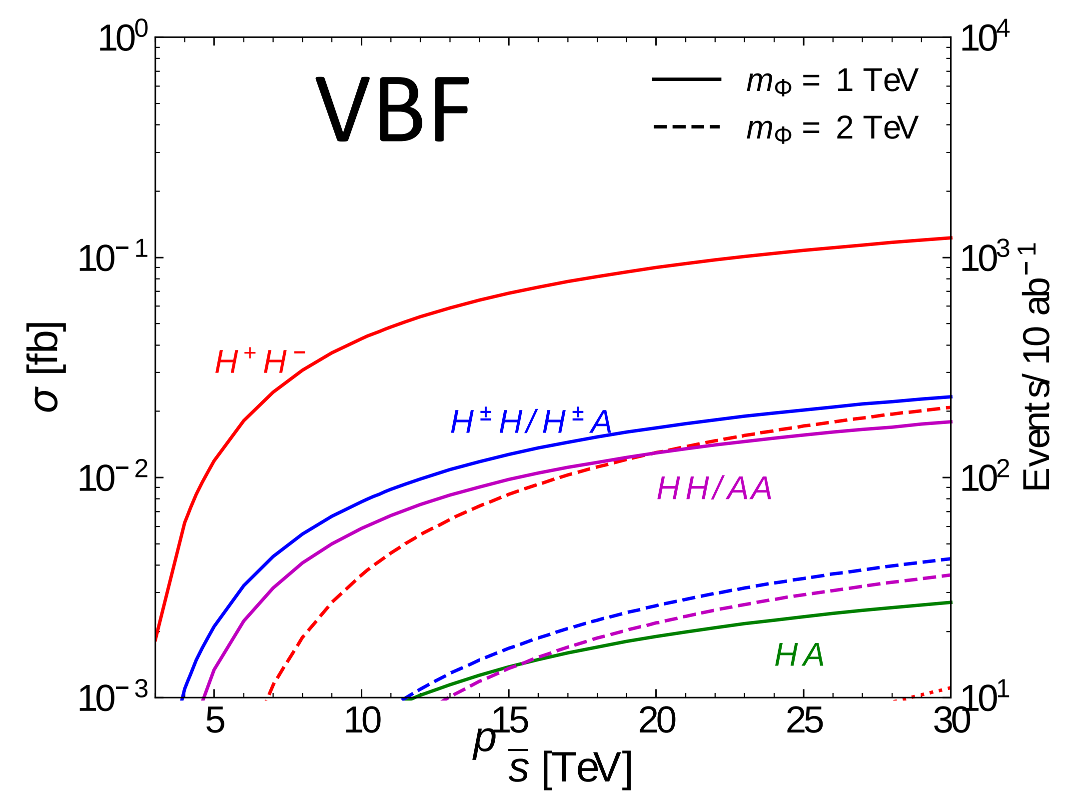


$$M_{\rm DM} < 1.8\ {\rm TeV}\left(\frac{g_{\rm eff}^2}{0.3}\right)$$



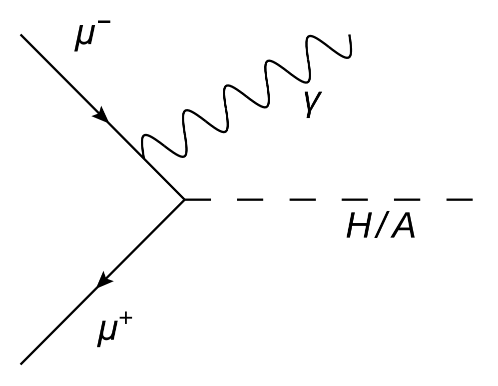
- # Cross/close the threshold: Heavy Higgs Bosons



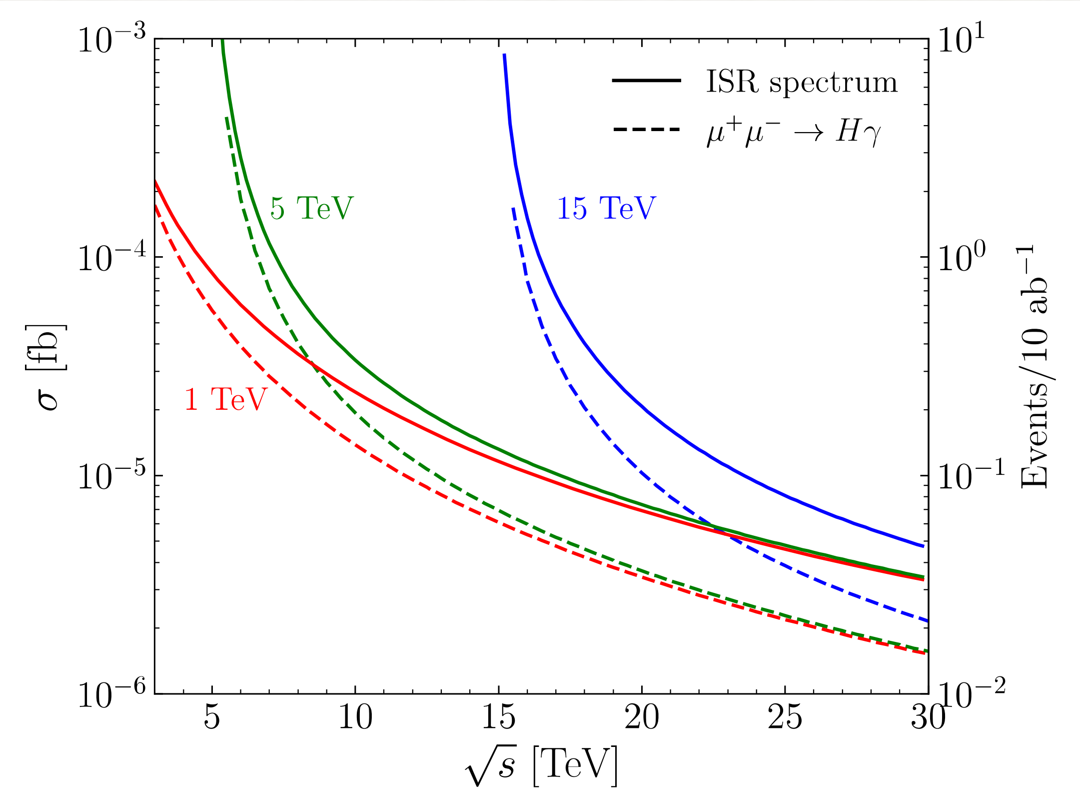


Radiative returns:

$$\hat{\sigma}(\mu^+\mu^- \; ! \;\; H) = \frac{\uparrow Y_\mu^2}{4}\delta(\hat{s}-m_H^2) = \frac{\uparrow Y_\mu^2}{4s}\delta(\boxtimes - \frac{m_H^2}{s})$$



Reach M ~ E_{cm}!



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

Global activities

European Strategy activities:

Under CERN Council,

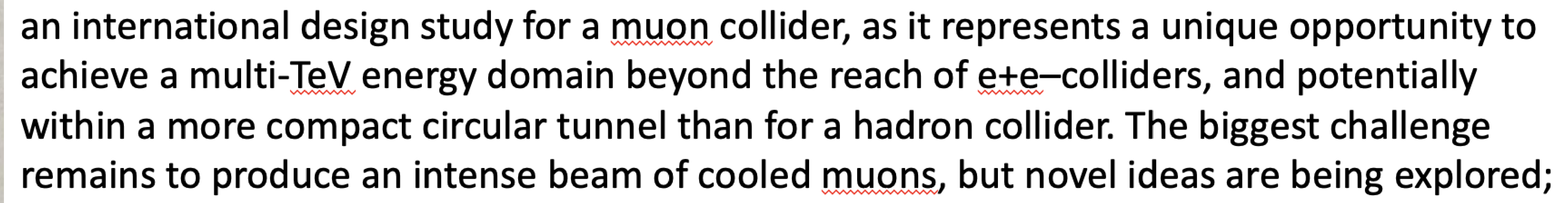
the Laboratory Directors Group developed

European Strategy for Particle Physics

Accelerator R&D Roadmap

Input to European Strategy of Particle Physics:

High-priority future initiatives:

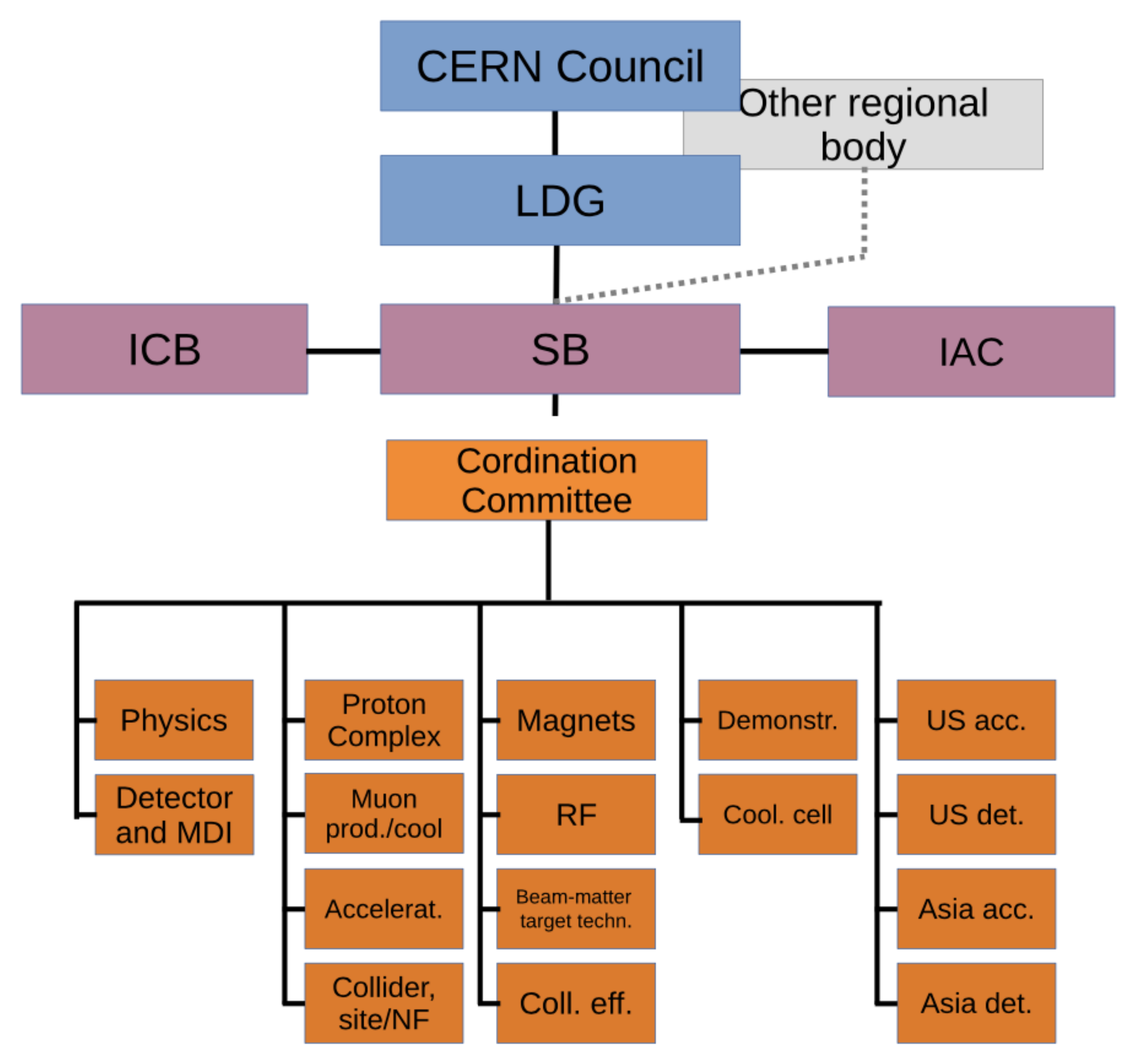


an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e+e–colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;

arXiv:1901.06150,
CERN-2022-001: arXiv:2201.07895;
http://muoncollider.web.cern.ch

International Muon Collider Collaboration (IMCC, 2022)

European Commission grant: HORIZON INFRA-DEV



CERN Council
Other regional body
LDG
ICB
SB
IAC
Cordination Committee
Physics
Detector and MDI
Proton Complex
Muon prod./cool
Accelerat.
Collider, site/NF
Magnets
RF
Beam-matter target techn.
Coll. eff.
Demonstr.
Cool. cell
US acc.
US det.
Asia acc.
Asia det.

Cordination Committee

Alexej Grudiev
Andrea Wulzer
Antoine Chance
Anton Lechner
Chris Rogers
Christian Carli
Claude Marchand
Daniel Schulte (Study Leader)
Donatella Lucchesi
Elias Metral
Jingyu Tang
Luca Bottura
Lucio Rossi
Mark Palmer
Nadia Pastrone (Collaboration Board Chair)
Natalia Milas
Roberto Losito
Sergo Jindariani
Steinar Stapnes (Steering Board Chair)

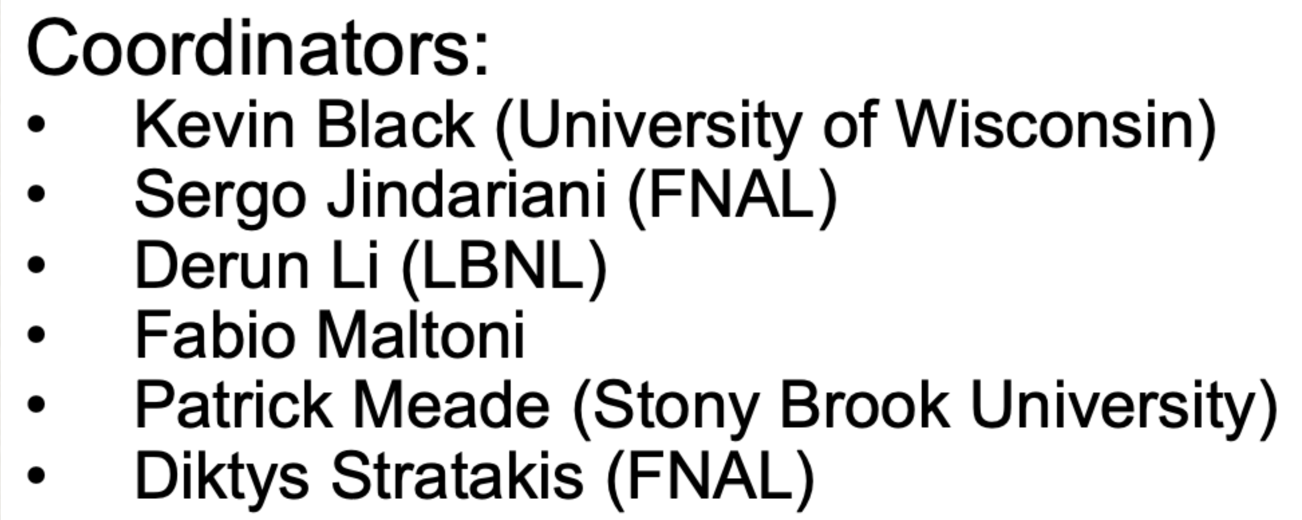
Physics	Andrea Wulzer
Detector and MDI	Donatella Lucchesi

US (detector)	Sergo Jindariani
US (accelerator)	Mark Palmer
Asia (China)	Jingyu Tang

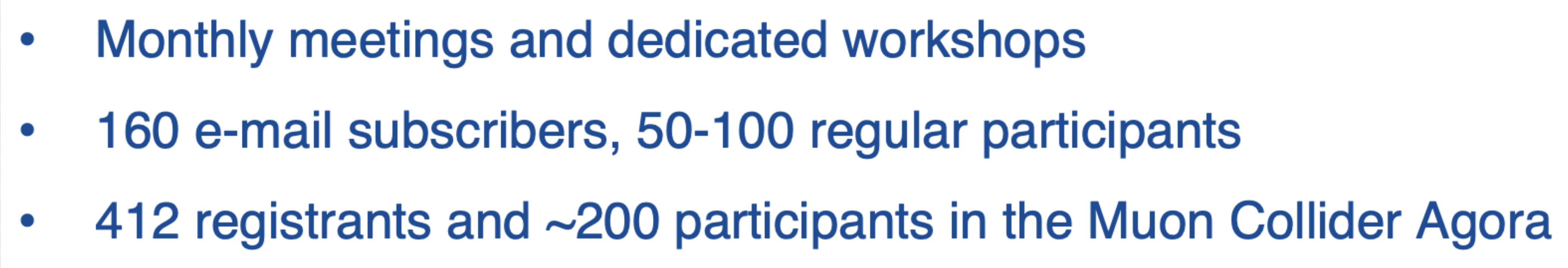
Snowmass 2021:

In 2020, AF+EF+TF created **Muon Collider Forum**

https://snowmass21.org/energy/muon_forum



Coordinators:
- Kevin Black (University of Wisconsin)
- Sergo Jindariani (FNAL)
- Derun Li (LBNL)
- Fabio Maltoni
- Patrick Meade (Stony Brook University)
- Diktys Stratakis (FNAL)



- Monthly meetings and dedicated workshops
- 160 e-mail subscribers, 50-100 regular participants
- 412 registrants and ~200 participants in the Muon Collider Agora

https://indico.fnal.gov/event/53010/

New mailing list: MuCUS@listserv.fnal.gov

You can subscribe to the mailing a message to listserv@fnal.gov
Leave the subject line blank, and “SUBSCRIBE MUCUS FIRSTNAME LASTNAME”.

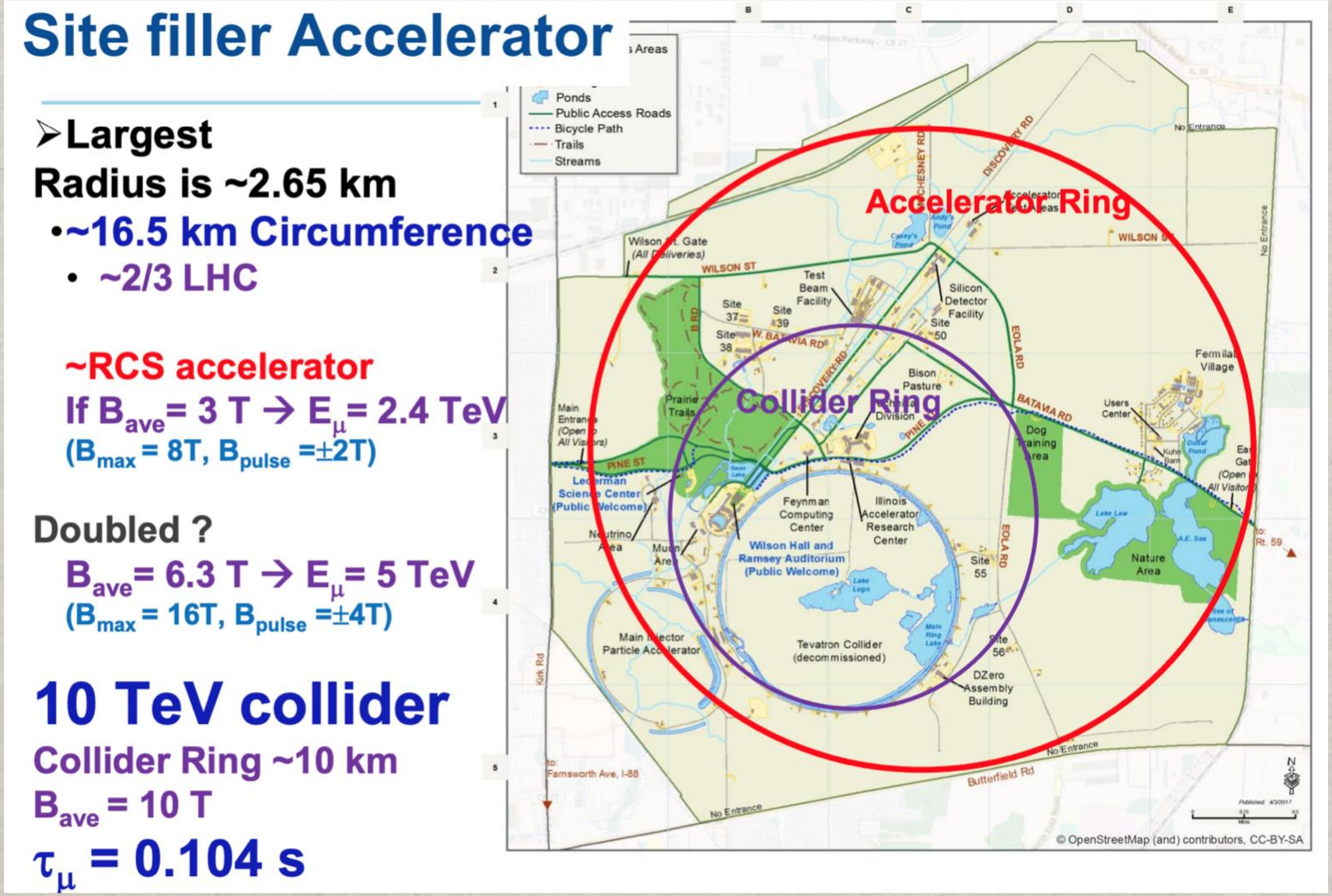
Muon Collider Forum Report delivered

https://arxiv.org/abs/2209.01318

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 → $E_\mu = 2.4$ TeV

($B_{max} = 8$T, $B_{pulse} = \pm 2$T)

Doubled ?

$B_{ave} = 6.3$ T → $E_\mu = 5$ TeV

($B_{max} = 16$T, $B_{pulse} = \pm 4$T)

10 TeV collider

Collider Ring ~10 km

$B_{ave} = 10$ T

$\tau_\mu = 0.104$ s

Summary

- **HEP is in an exciting time:**

  The SM is complete, and is potentially valid to a very high energy scale. Yet, there are strong indications for the existence of new physics not far above the EW scale.

- **The Higgs factory ~250 GeV is the clear target:**

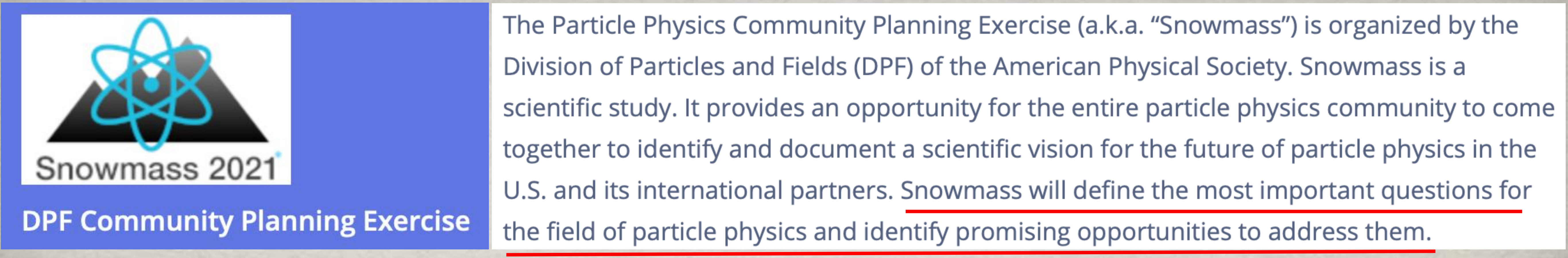
  → New physics under the Higgs lamp-post.

- **Multi-TeV lepton colliders will lead the way:**

  μ - Col. = Cool !

  → Promise great opportunities for discoveries for BSM physics.

Exciting journey ahead !

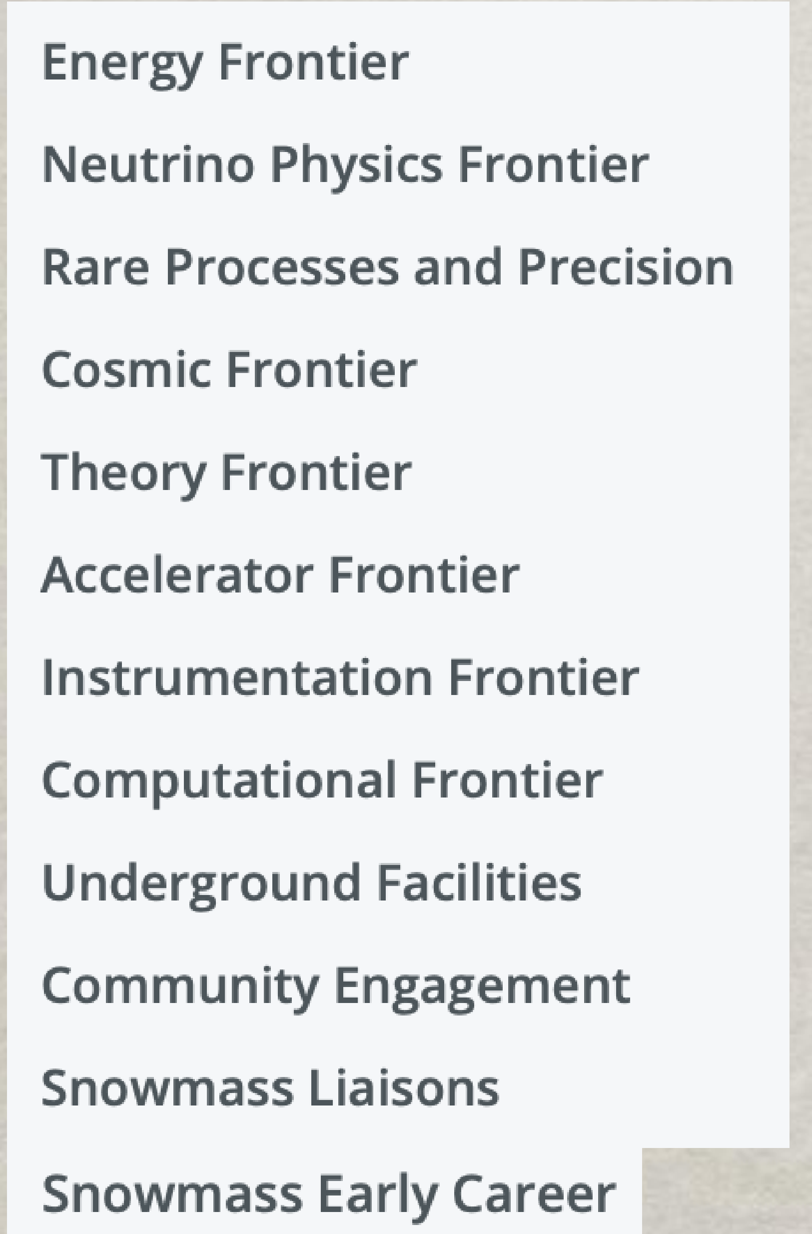


Snowmass 2021

DPF Community Planning Exercise

The Particle Physics Community Planning Exercise (a.k.a. “Snowmass”) is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. Snowmass will define the most important questions for the field of particle physics and identify promising opportunities to address them.

Snowmass frontiers:



Energy Frontier

Neutrino Physics Frontier

Rare Processes and Precision

Cosmic Frontier

Theory Frontier

Accelerator Frontier

Instrumentation Frontier

Computational Frontier

Underground Facilities

Community Engagement

Snowmass Liaisons

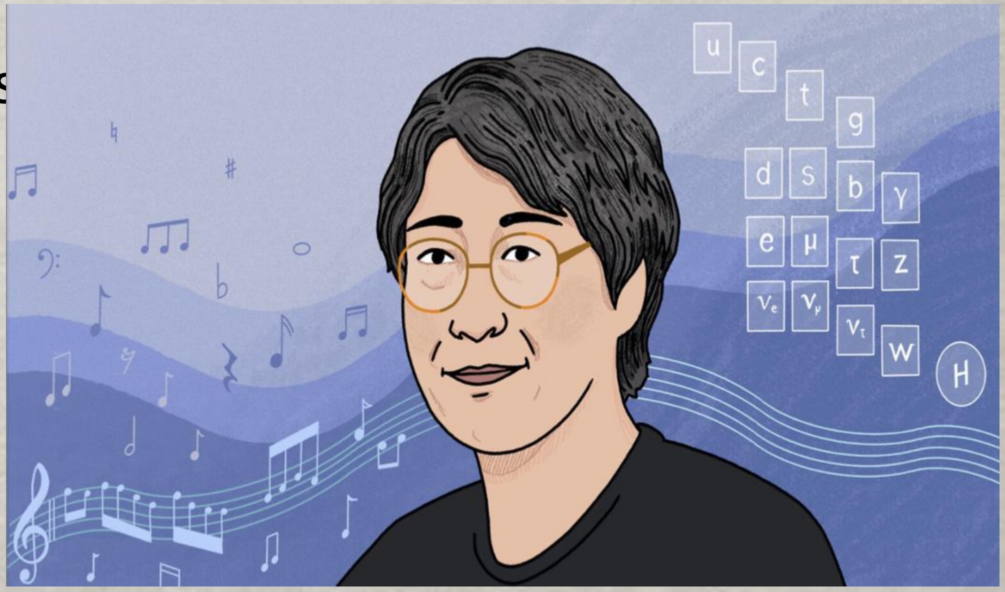
and Snowmass Early Career

https://snowmass21.org

With this year-long study, the Snowmass output will provide inputs for the prioritization of the research directions of the field in the decade to come: the “P5” process

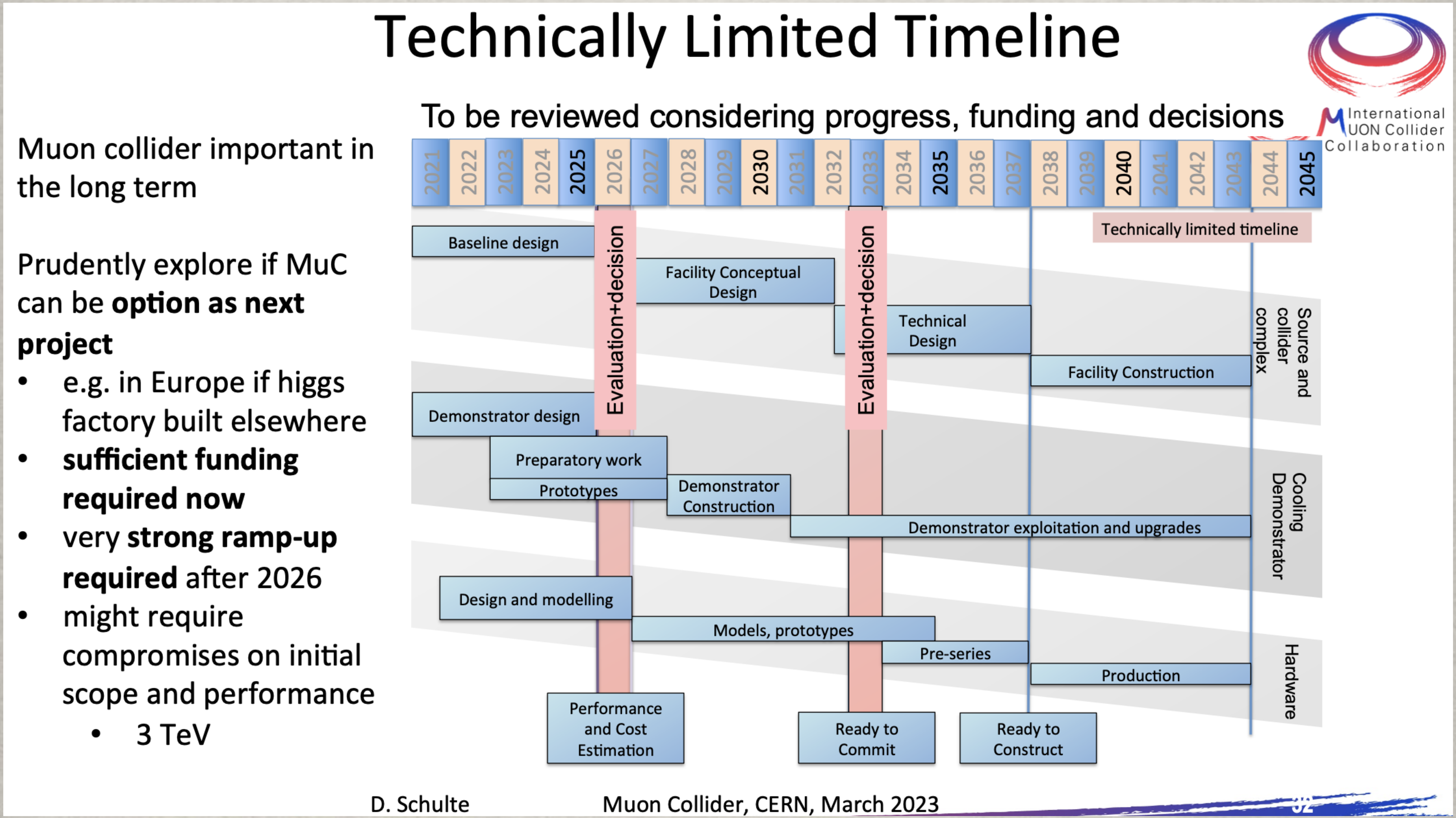
(Particle Physics

The P5 chair: Prof. Hitoshi Murayama



Several Useful References:

1. Overview of accelerators – V.Shiltsev, Physics Today **73**, 4, 32 (2020).
2. RMP colliders – V.Shiltsev, F.Zimmermann, Rev.Mod.Phys. **93**, 015006 (2021).
3. Ultimate limits of colliders – V.Shiltsev, Proc. IPAC'21, WEPAB017 (2021).
4. Snowmass Accelerator Frontier report – arxiv:2209.14136
5. ITF Report – T.Roser, V.Shiltsev, et al, arXiv:2208.06030
6. *αβγ* cost model – V.Shiltsev, JINST **9** T07002 (2014).
7. Crystal collider – V.Shiltsev, Physics Uspekhi, **55** (10), 1033 (2012).
8. *CPT*-theorem – V.Shiltsev, Mod. Phys. Lett. *A*, **26**, 11, 761 (2011)



Technically Limited Timeline

Muon collider important in the long term

Prudently explore if MuC can be **option as next project**

- e.g. in Europe if higgs factory built elsewhere
- **sufficient funding required now**
- very **strong ramp-up required** after 2026
- might require compromises on initial scope and performance
    - 3 TeV

To be reviewed considering progress, funding and decisions

D. Schulte Muon Collider, CERN, March 2023 32

Snowmass 2021, AF report
Implementation Task Force recommendations:

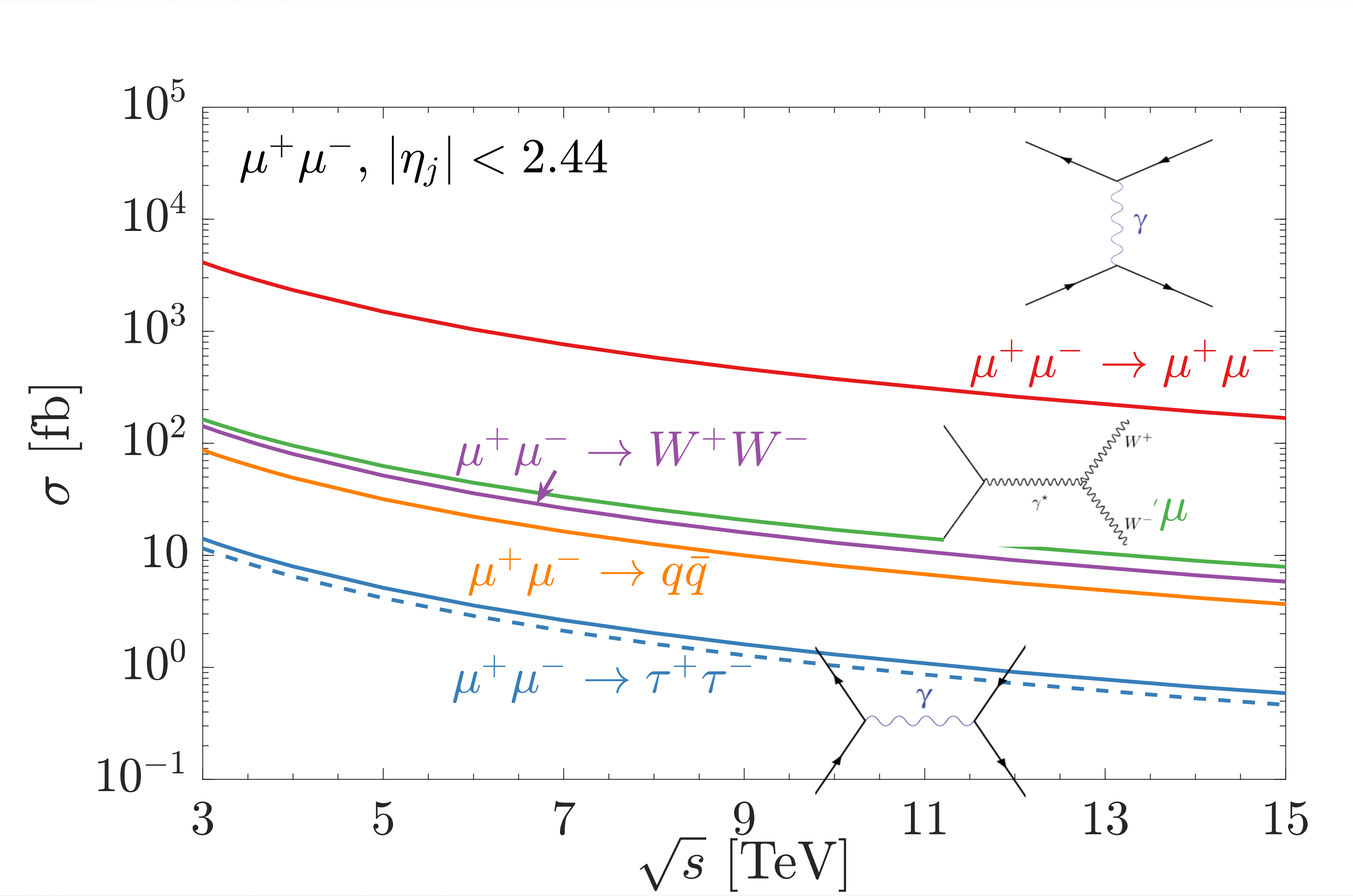
arXiv:2209.14136

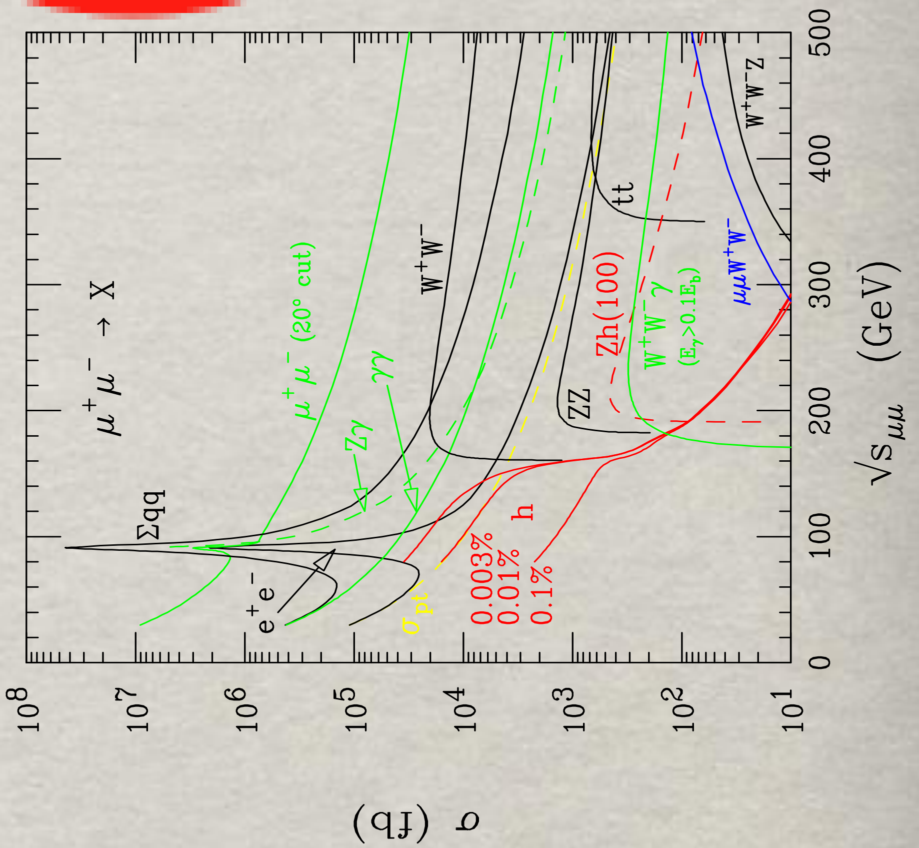
Proposal Name	c.m. energy [TeV]	Luminosity/IP [10^{34} cm^{-2} s^{-1}]	Yrs. pre-project R&D	Yrs. to 1st physics	Constr. cost [2021 B$]	Electr. power [MW]
FCC-ee[1,2]	0.24	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3]-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC[3]-0.38	0.38	2.3	0-2	13-18	7-12	110
CCC[3]	0.25	1.3	3-5	13-18	7-12	150
HELEN[3]	0.25	1.4	5-10	13-18	7-12	110
FNAL e^+e^- circ.	0.24	1.2	3-5	13-18	7-12	200
CERC[3]	0.24	78	5-10	19-24	12-30	90
ReLiC[1,3]	0.24	165 (330)	5-10	>25	7-18	315
ERLC[3]	0.24	90	5-10	>25	12-18	250
XCC $\gamma\gamma$	0.125	0.1	5-10	19-24	4-7	90
$\mu\mu$-Higgs	0.13	0.01	>10	19-24	4-7	200
ILC-3	3	6.1	5-10	19-24	18-30	~400
CLIC-3	3	5.9	3-5	19-24	18-30	~550
CCC-3	3	6.0	3-5	19-24	12-18	~700
ReLiC-3	3	47(94)	5-10	>25	30-50	~780
$\mu\mu$Collider[1]-3	3	2.3(4.6)	>10	19-24	7-12	~230
LWFA-LC-3	3	10	>10	>25	12-80	~340
PWFA-LC-3	3	10	>10	19-24	12-30	~230
SWFA-LC-3	3	10	5-10	>25	12-30	~170
FNAL$\mu\mu$[1]	6-10	20(40)	>10	19-24	12-18	~300
LWFA-LC-15	15	50	>10	>25	18-80	~1030
PWFA-LC-15	15	50	>10	>25	18-50	~620
SWFA-LC-15	15	50	>10	>25	18-50	~450
FNAL pp circ.	24	3.5(7)	>10	>25	18-30	~400
FCC-hh[1]	100	30(60)	>10	>25	30-50	~560
SPPS[1]	125	13(26)	>10	>25	30-50	~400
LHeC	1.2	1	0-2 ?	13-18	<4	~140
FCC-eh	3.5	1	0-2 ?	>25	<4	~140
CEPC-SPPC-ep	5.5	0.37	3-5	>25	<4	~300

A Multi-TeV Muon Collider

Naïve expectation: leading-order $\mu^+\mu^-$ annihilation:

$$\sigma_{ann} \sim \frac{\alpha^2}{s}$$

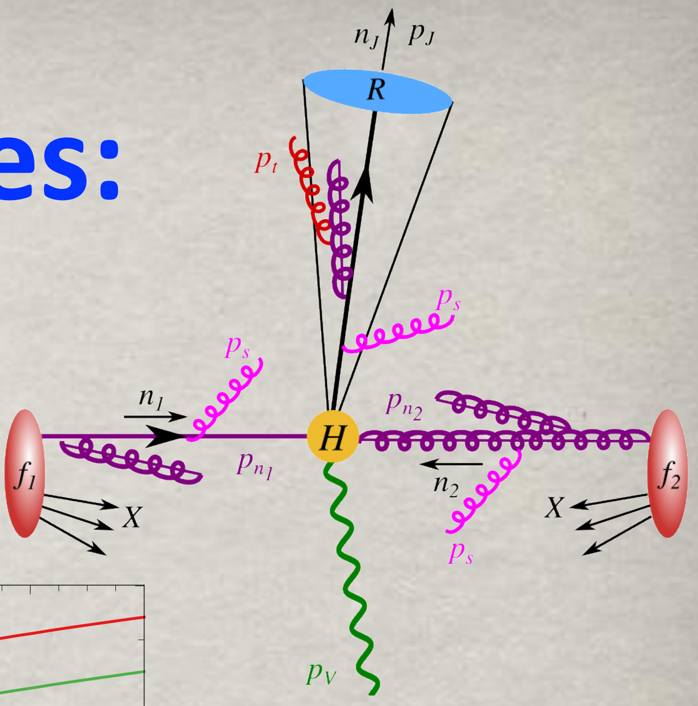




Those aren't what you would first see when you turned on the machine!

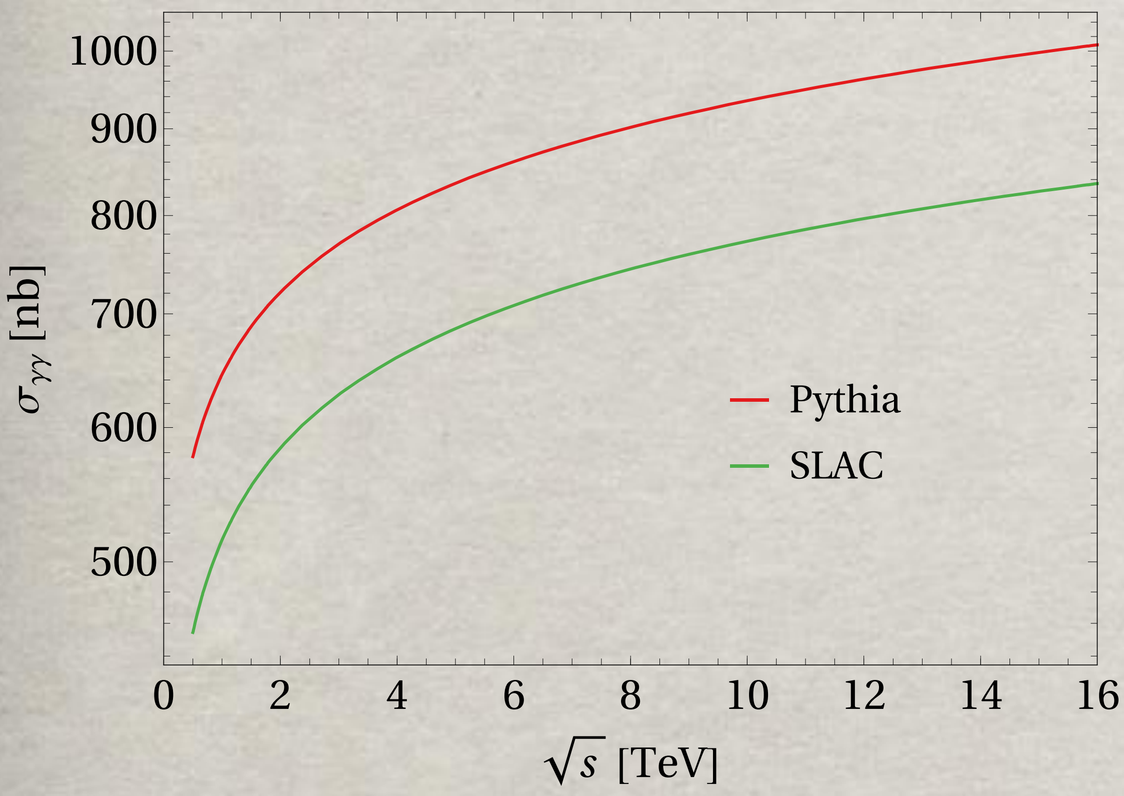
Total cross section @ high energies:

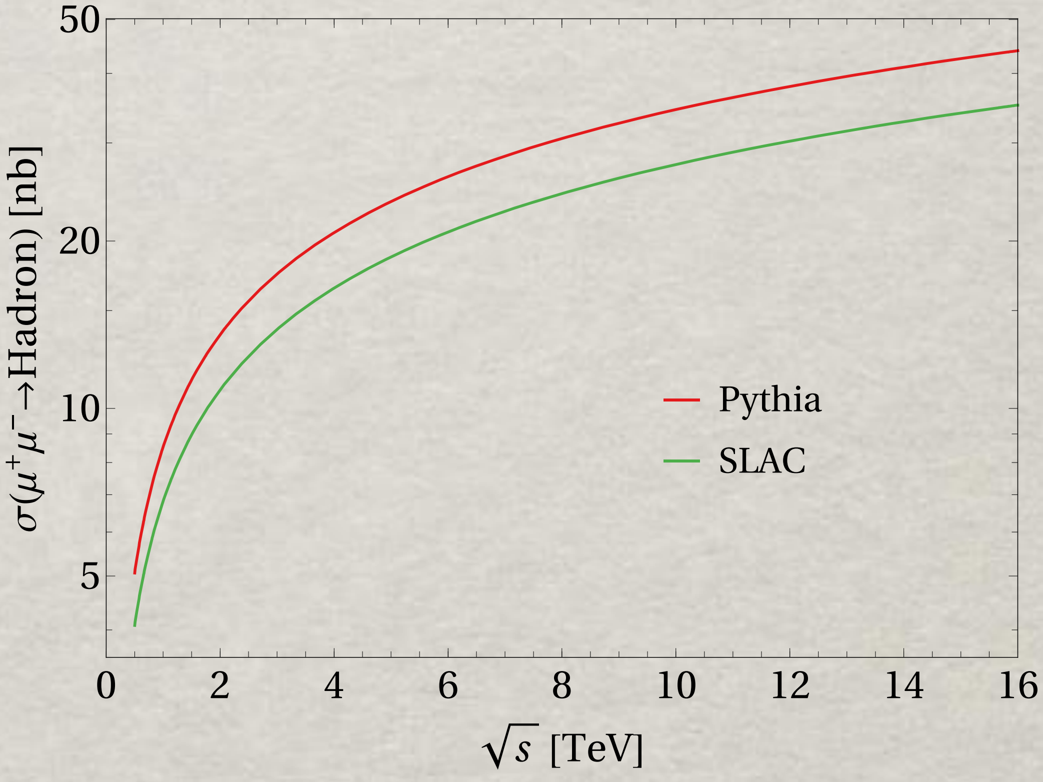
$\gamma\gamma$ and $\mu^+\mu^-$ → hadrons



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

Event rate @10,000 Hz!





Note: σ_{pp}(total) ~ 100 mb; $\sigma_{\mu\,\mu}$(total)~ 50 nb

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

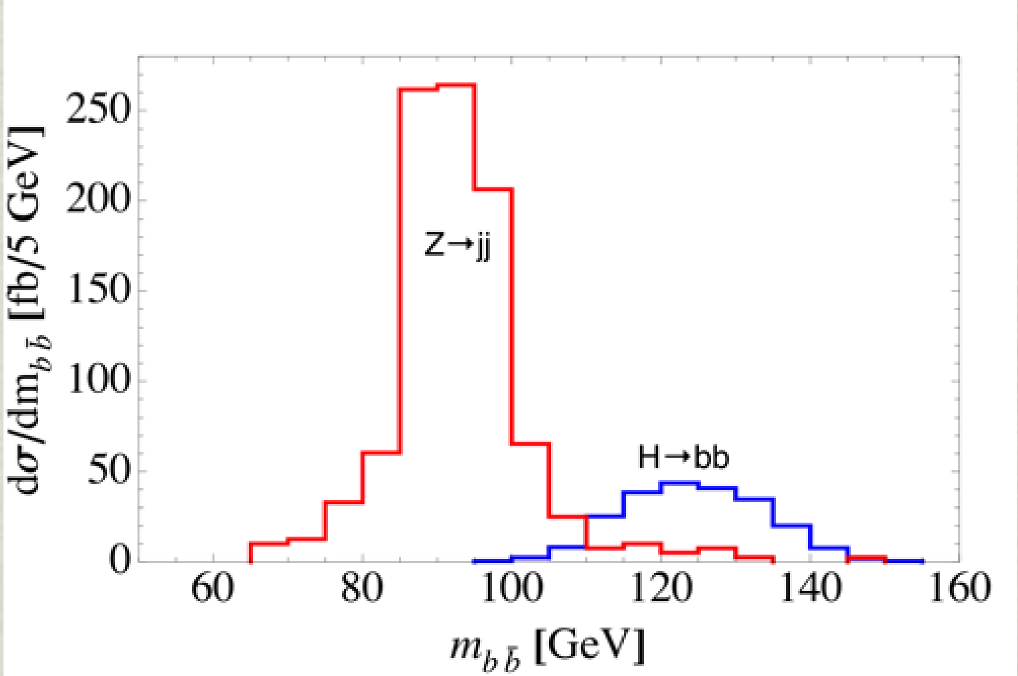
TH, Yang Ma, Keping Xie, arXiv:2103.09844.
T. Barklow, D. Dannheim, M.O. Sahin & D. Schulte, LCD-Note-2011-020.

Achievable accuracies

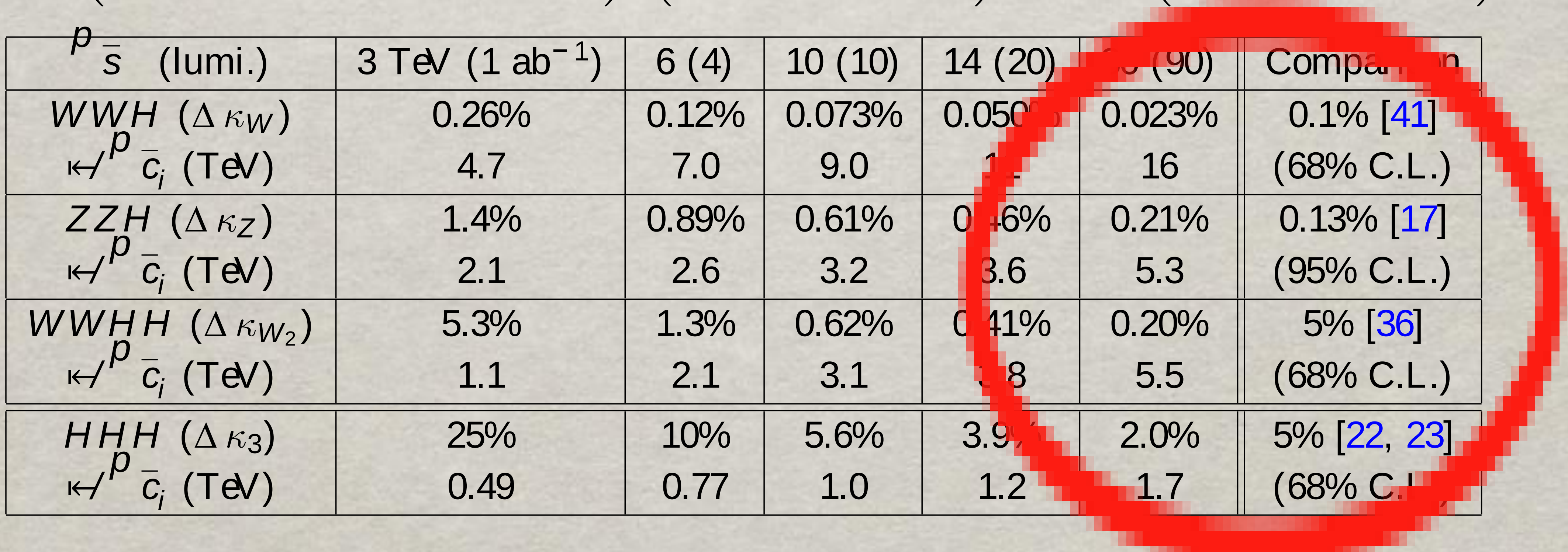
Leading channel H → bb:

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

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



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



$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$) $\Lambda/\sqrt{c_i}$ (TeV)	0.26% 4.7	0.12% 7.0	0.073% 9.0	0.050% 1[illegible]	0.023% 16	0.1% [41] (68% C.L.)
ZZH ($\Delta\kappa_Z$) $\Lambda/\sqrt{c_i}$ (TeV)	1.4% 2.1	0.89% 2.6	0.61% 3.2	0.46% 3.6	0.21% 5.3	0.13% [17] (95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$) $\Lambda/\sqrt{c_i}$ (TeV)	5.3% 1.1	1.3% 2.1	0.62% 3.1	0.41% 3.8	0.20% 5.5	5% [36] (68% C.L.)
HHH ($\Delta\kappa_3$) $\Lambda/\sqrt{c_i}$ (TeV)	25% 0.49	10% 0.77	5.6% 1.0	3.9% 1.2	2.0% 1.7	5% [22, 23] (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