“WHO ORDERED THAT?”
THE DANCE OF THE MUON

Tao Han
Pitt PACC
University of Pittsburgh

June 6, 2024
University of Bologna

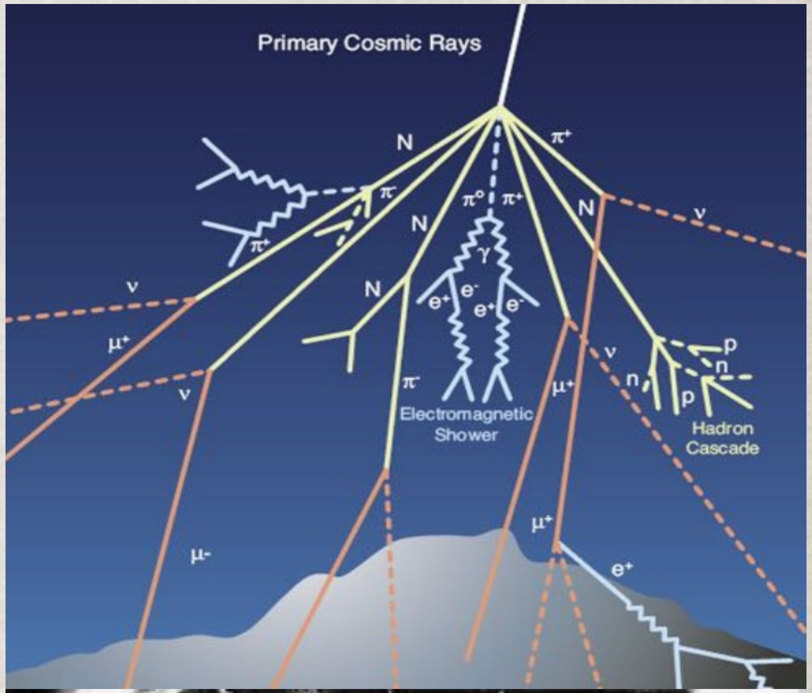

Founded 1787

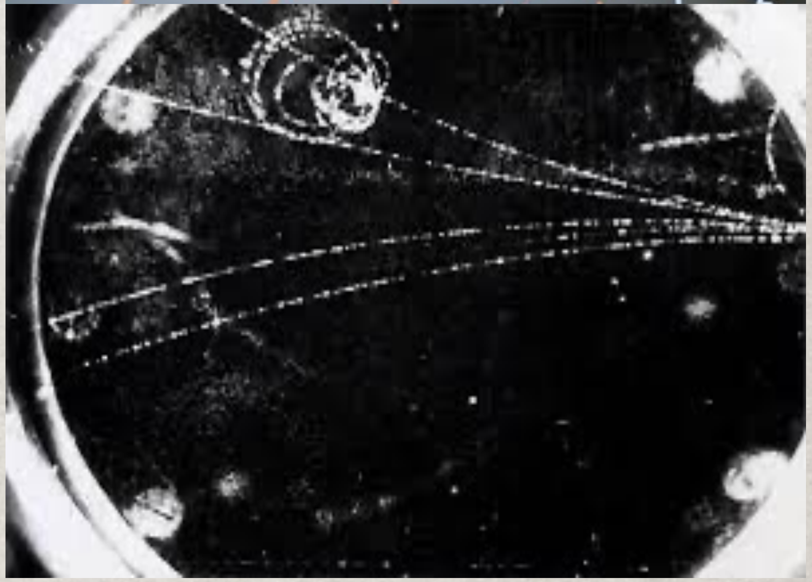

Founded 1088

WHO ORDERED THAT?!

- A surprising discovery

In 1936, Anderson & Neddermeyer used a cloud chamber and found a (±) charged particle in the cosmic ray: $m_{e-} < M < m_{p+}$





- Pair production from γ^*
- Highly ionizing: a slow-motion $M \sim 200\ m_{e-}$
- Decaying to electron with a lifetime $\tau \sim 2 \times 10^{-6}$ s
- Highly penetrating: no strong interactions, thus NOT Yukawa's "meson" to mediate p^+, n strong nuclear force.

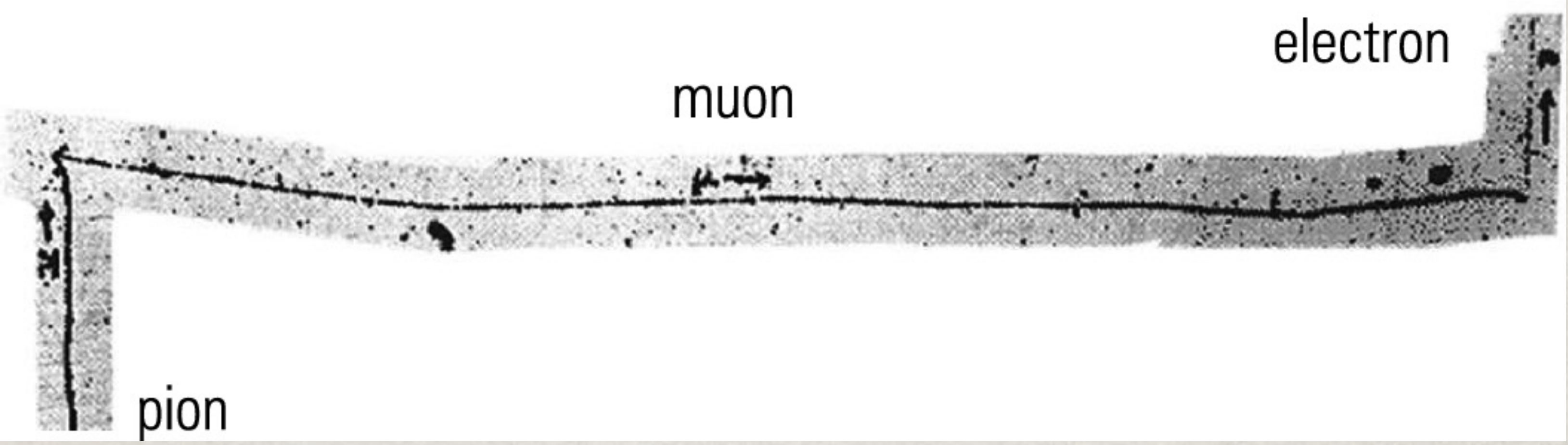
"Who ordered THAT ?!"

-- I. I. Rabi (1944 Nobel Laureate)

• The “usher” for particle physics:

-- there are two “mesons”!

In 1948, Lattes et al. used a photographic emulsion detector, observing two charged particles: $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$



The discovery of $\mu^\pm$ led to another discovery of $\pi^\pm$!
-- both particles named by Lattes.

The $\pi^{\pm,0}$ are the Yukawa mesons mediating the strong force!

(Yukawa, 1949)
(Powell, 1950)

• Parity violation in muon decay

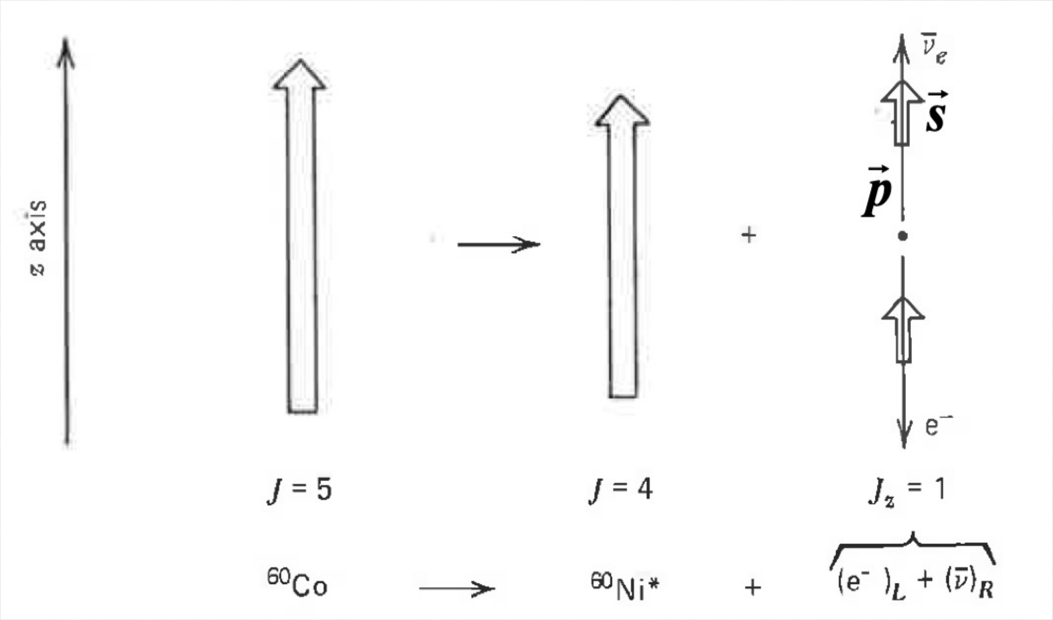
(Lee & Yang 1957)

Following Prof. C.S.Wu's experiment in **β**-decay:

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$

$$\frac{dN_e}{d\cos\theta} \propto a + b\,\vec{J}\cdot\vec{p}_e$$

Phys. Rev. 105, 1413 (1957)

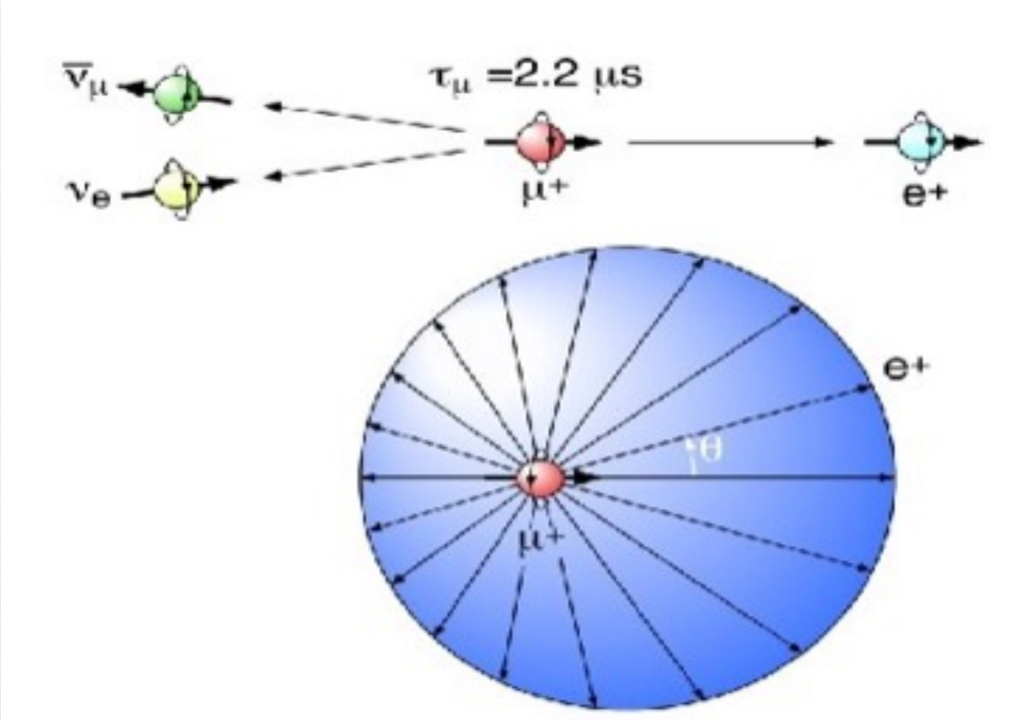


Neutrons and **μ**$^{\pm}$ decays involve the weak nuclear force:

Lederman et al. & Friedman et al. made it with polarized muons:

$$\frac{dN_e}{d\cos\theta} \propto 1 + \vec{p}_e\cdot\vec{n}_\mu \sim 1 - \frac{1}{3}\cos\theta_e$$

Phys. Rev. 105, 1415 (1957);
Phys. Rev. 106, 1290 (1957)



• Heavy Quark Onia:

“Lederman’s shoulder”:
1968-1969@BNL di-muon expt:
ushered the $J/\psi(c\bar{c})$ Discovery

“Oops-leon”
(Leon Lederman, 1976)
the $\Upsilon(b\bar{b}) \rightarrow \mu^{+}\mu^{-}$ Discovery

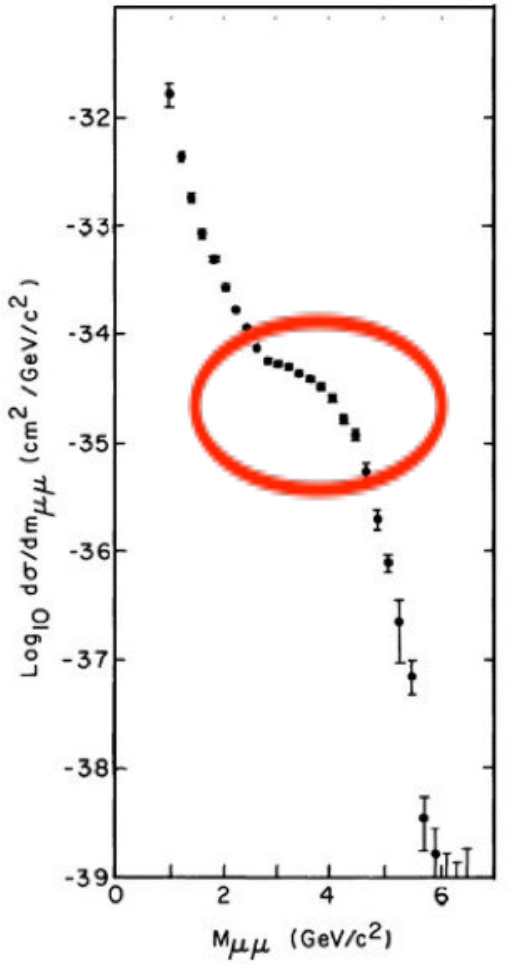
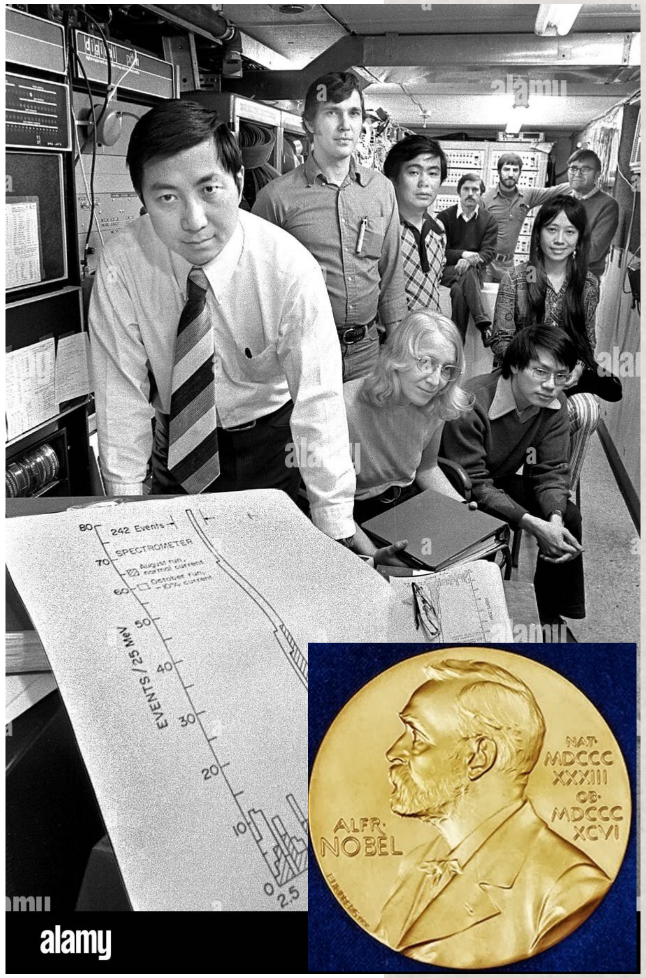
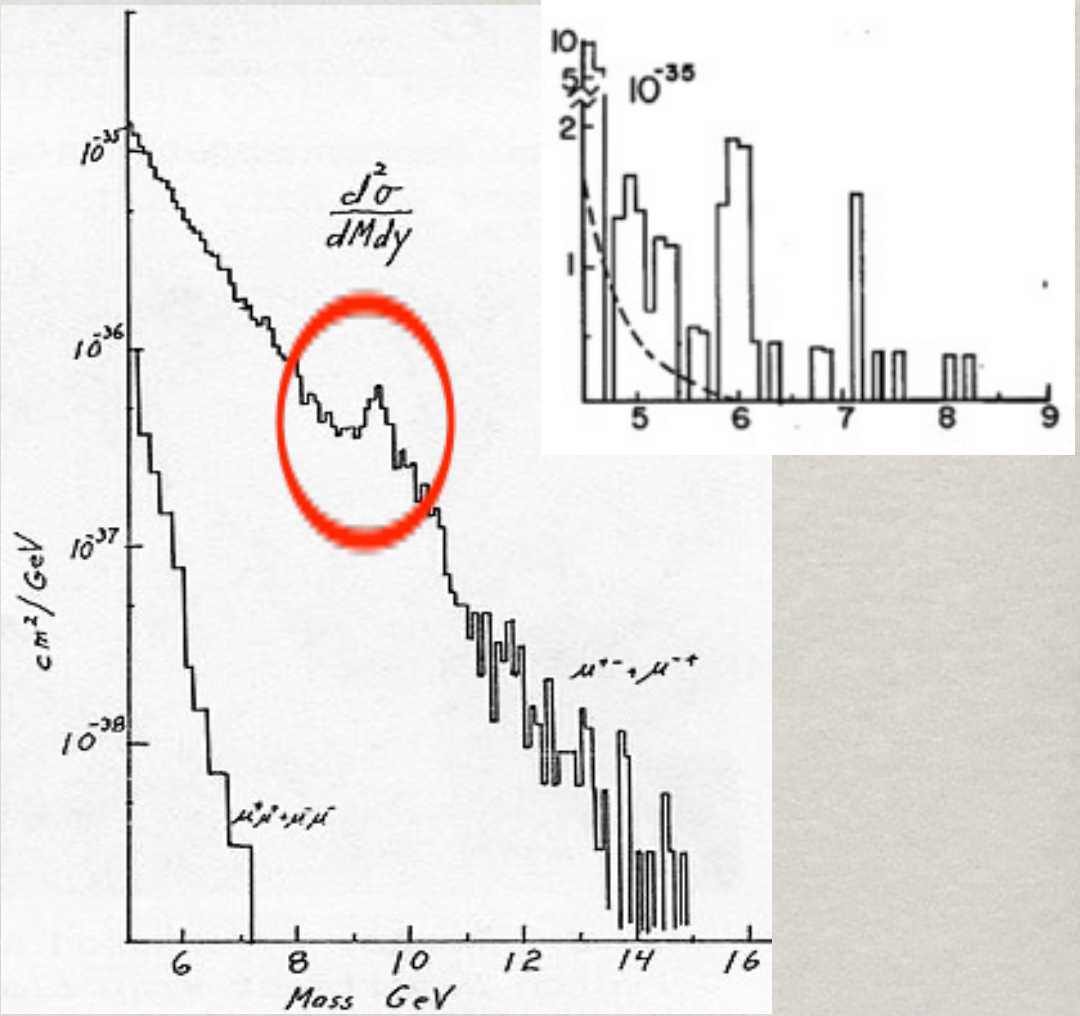


Fig. 1 - Dimuon yield from the 1968 BNL experiment. Source: J. H. Christenson, et al. (1970). Observation of massive muon pairs in hadron collisions. Physical Review Letters, 25(21), 1523.



(1976)



• Two flavors of neutrinos:

Lederman-Schwartz-Steinberger made the ν_μ beam!

$$\pi^\pm \to \mu^\pm + \nu \;\Rightarrow\; \nu + N \to \mu^\pm + N'$$

(1988)

And there "ν" is NOT ν_e!

Phys. Rev. Lett. 9, 36 (1962)

(1). Muon flavor identified → flavor physics, before Cabibbo !

--- Two-neutrino mixing by S. Sakata: Prog. Theor. Phys. 28 (1962) 870.

(2). Neutrino beam and scattering opens a new avenue

• Neutrino Deeply Inelastic Scattering

In addition to $e^\pm + N \to^{(\gamma^*)} e^\pm + \text{hadrons}:$

$$F_2^e(x) = 2xF_1^e(x) = x\sum_q e_q^2[q(x) + \bar{q}(x)]$$

(DIS, 1990)

Discovery of "weak neutral current"

$$\nu_\mu + N \to^{(Z)} \nu_\mu + \text{hadrons}$$

Precisions: $F_2^\nu(x) = 2xF_1^\nu(x) = x\sum_{u,d}[d(x) + \bar{u}(x)], \quad F_3^\nu(x) = 2[d(x) - \bar{u}(x)]$

$$s(x) - \bar{s}(x),\; V_{cd},\; V_{cs},\; \sin\theta_W$$

• Who ordered That? A Tri-peat

(1995)

THE SEARCH FOR MUON-ELECTRON DIFFERENCES

AND MUON-PROTON DEEP INELASTIC SCATTERING*

Martin L. Perl

Stanford Linear Accelerator Center
Stanford University, Stanford, California

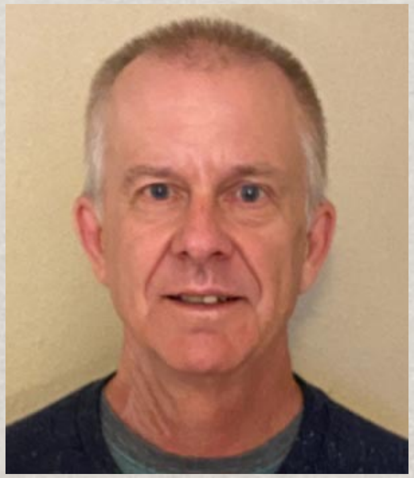
THE DISCOVERY OF THE TAU LEPTON*

(1975)

MARTIN L. PERL
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

Consequently, that led to yet another discovery: DONuT experiment @ FNAL (2000) detected the ν_τ

→ three generations of leptons completed!
→ 2022 Panofsky Prize!



Byron Lundberg

Kimio Niwa

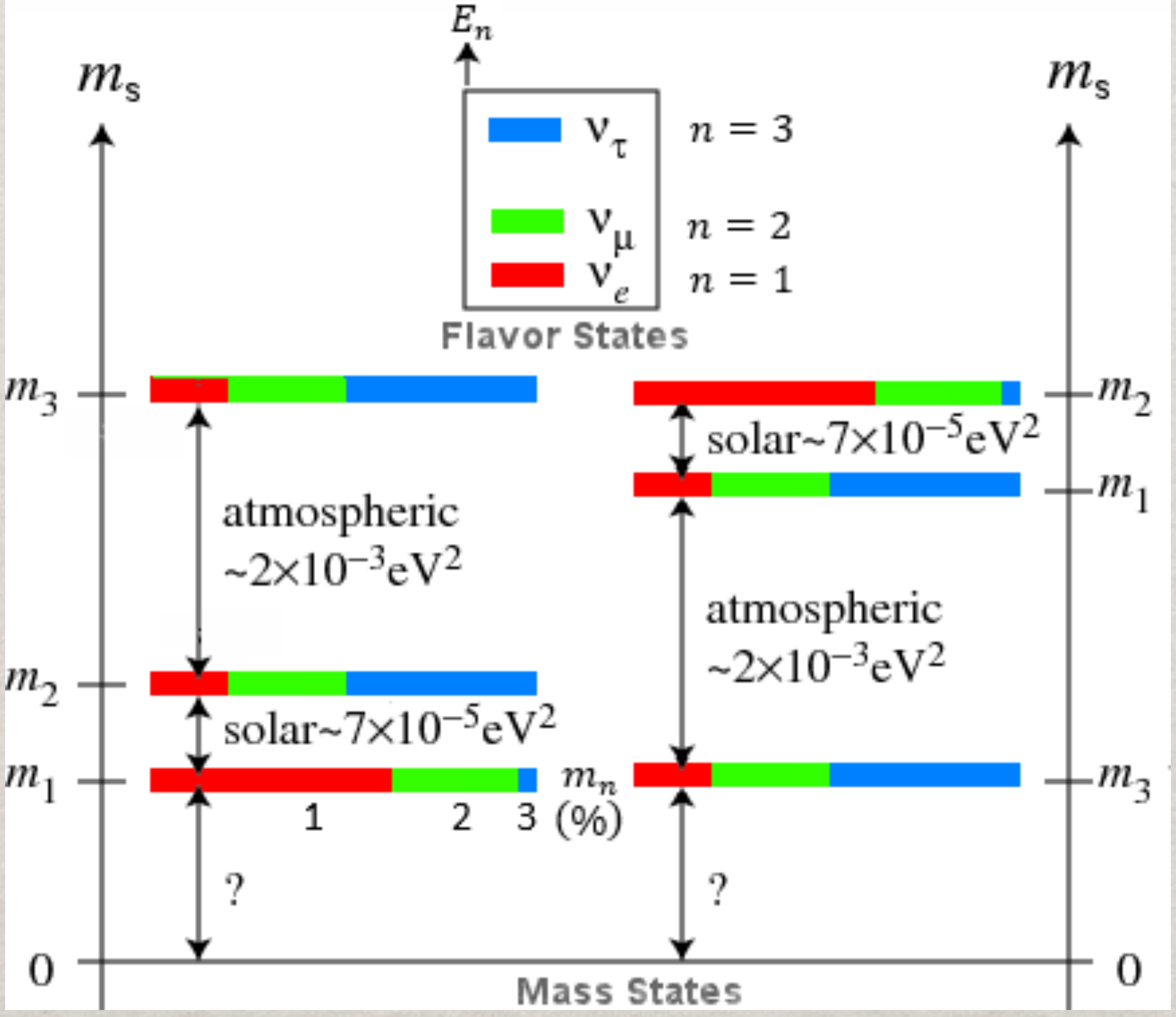
Regina Rameika

Vittorio Paolone

• Muons as sources of atmospheric $\nu_{\mu,e}$

$$\pi^{\pm},\ K^{\pm} \quad \to \quad \mu^{\pm} + \nu_{\mu}$$
$$\mu^{\pm} \quad \to \quad \nu_{\mu} + \nu_{e} + e^{\pm}$$

The Super-K / SNO experiments provided
very precise measurements of neutrino oscillations
among 3-flavors & 2 mass differences

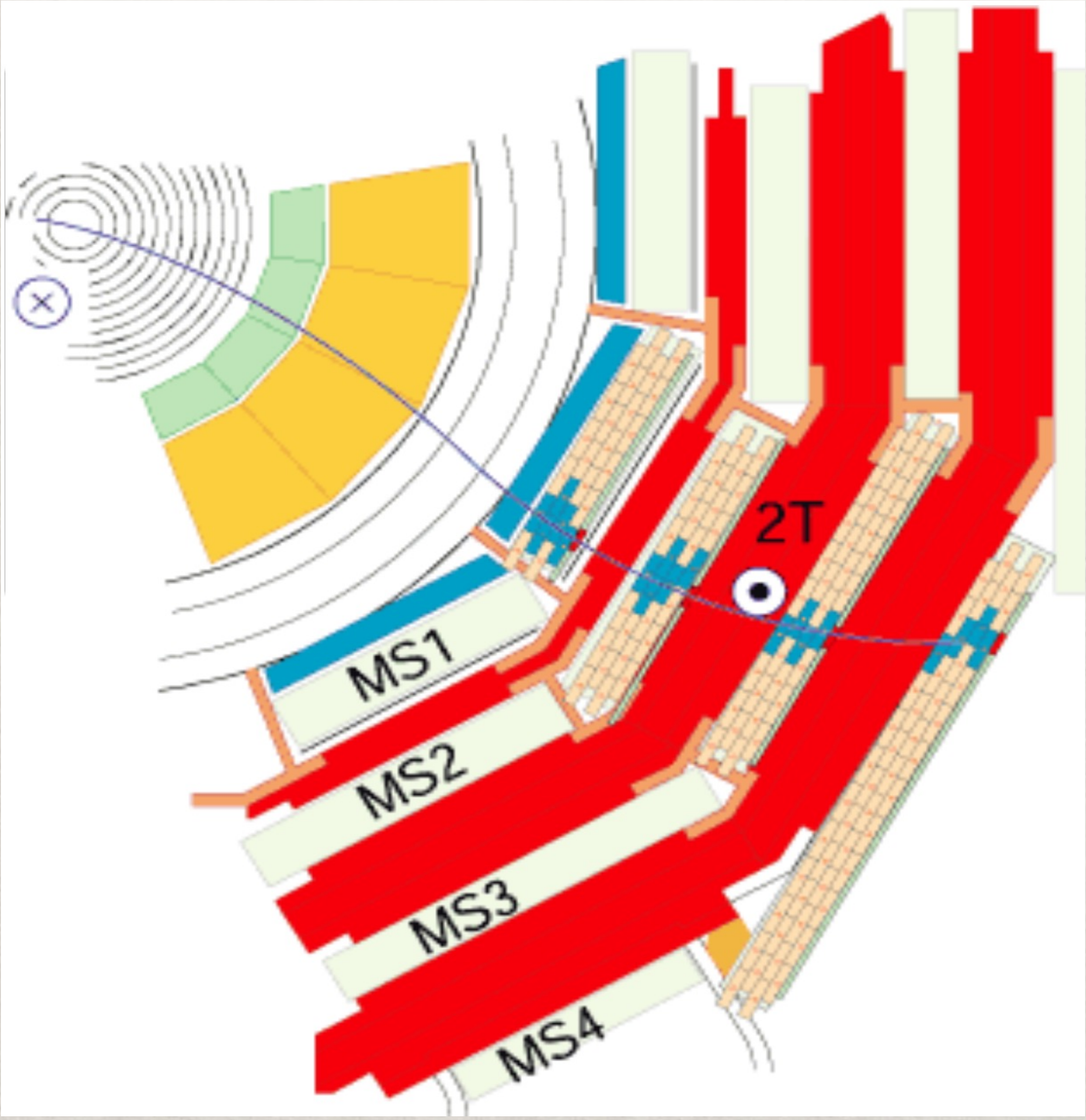


(2015: McDonald & Kajita)

• Muons for discovery @ Colliders

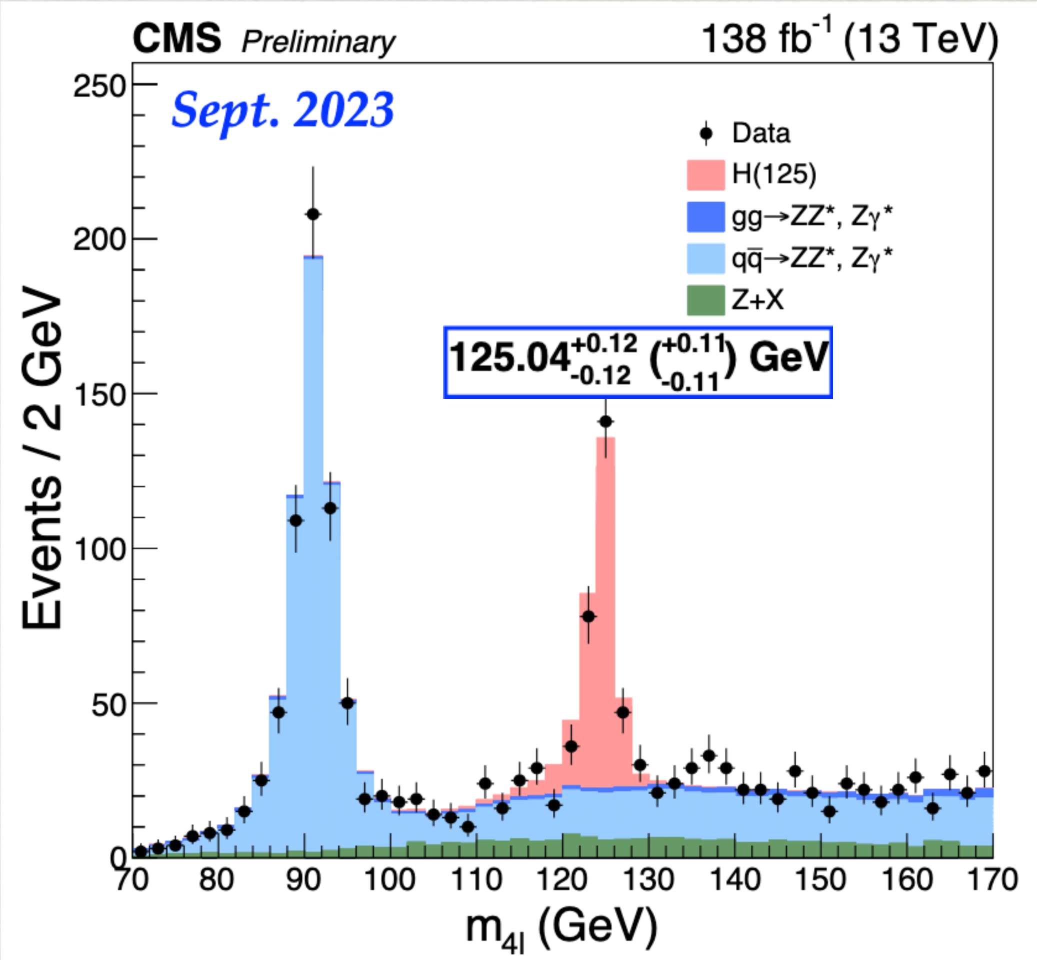
Muons are the most penetrating particle, thus most "visible" at the LHC: $W^{\pm}$, Z, top …

CMS: "Compact Muon Solenoid"



(2013)

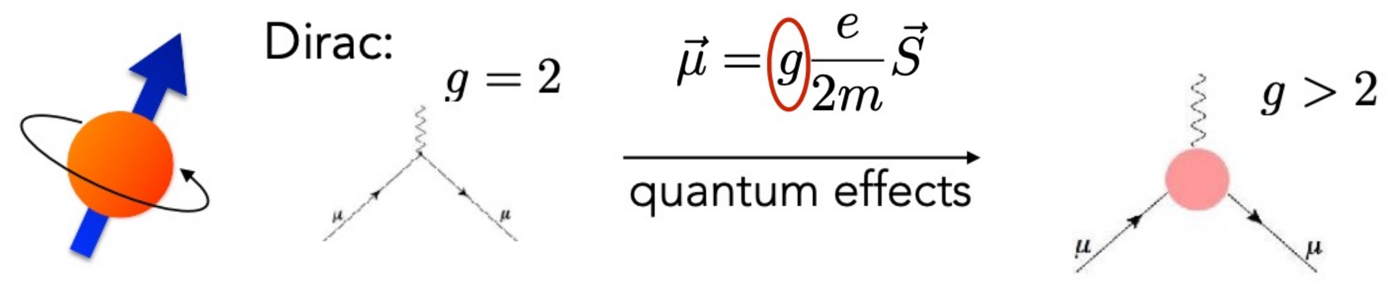
The Higgs boson discovery:



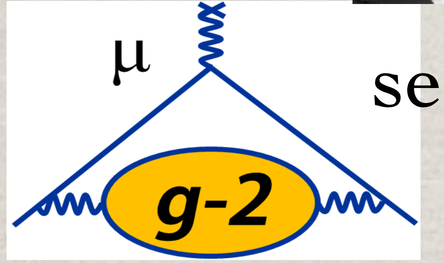
CONTINUING EXPLORATIONS

FNAL: “the muon campus”

The muon anomalous magnetic moment



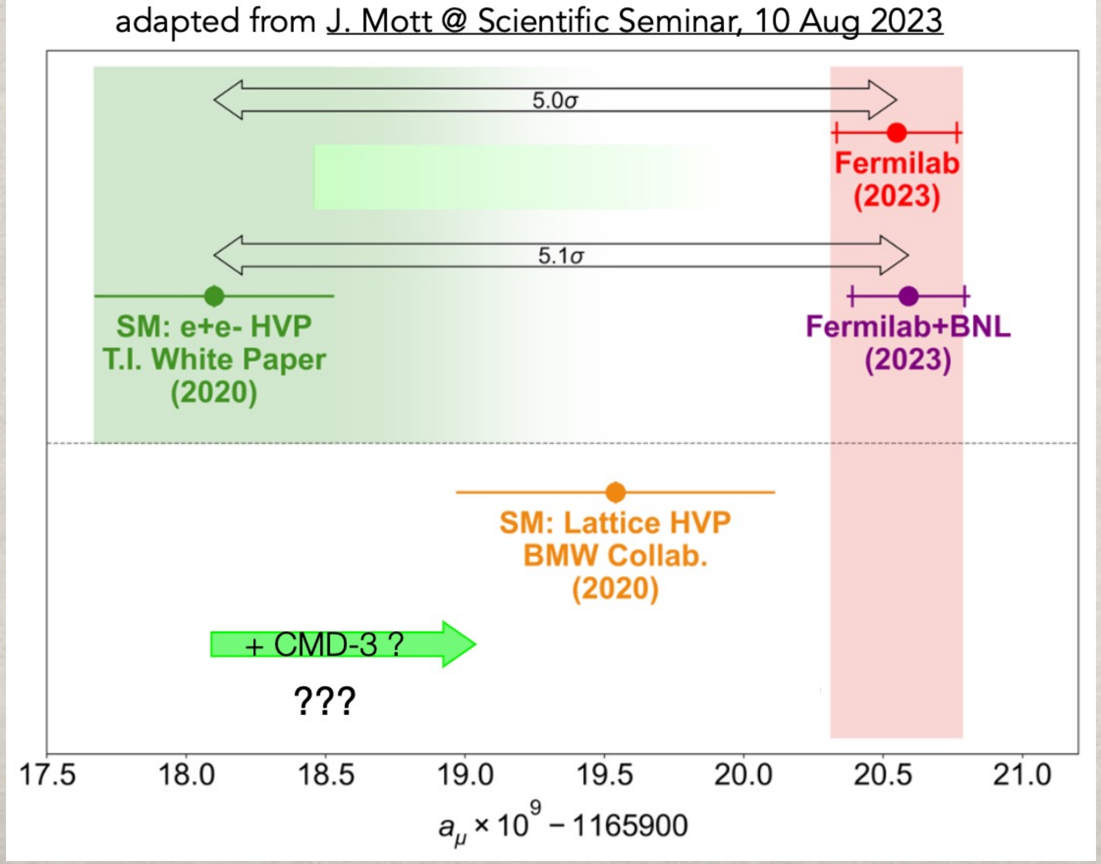
$$g_e = 2(1 + \frac{\alpha}{2\pi})$$
$$= 2(1 + 0.00116)$$



sensitive to new physics:

$(m_\mu/m_e)^2$~42,000

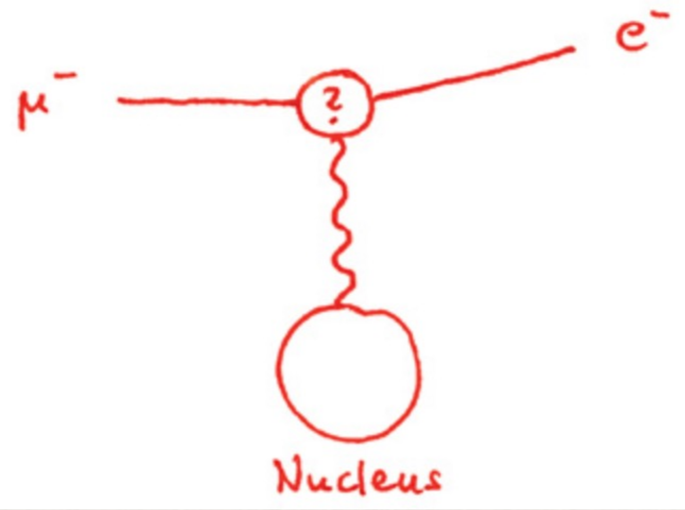
adapted from J. Mott @ Scientific Seminar, 10 Aug 2023



Fermilab Muon Department

Fermi National Accelerator Laboratory

The Mu2e Experiment at Fermilab



Current bound:

$B(\mu \rightarrow e\gamma) < 4\times10^{-13}$

$\sim (m_N/M_W)^4$

10^{17} μ’s data sample to come!

Also: COMET @ J-PARC;
AICap @ PSI

• Paul Sherrer Institute (PSI), Laboratory for Particle Physics

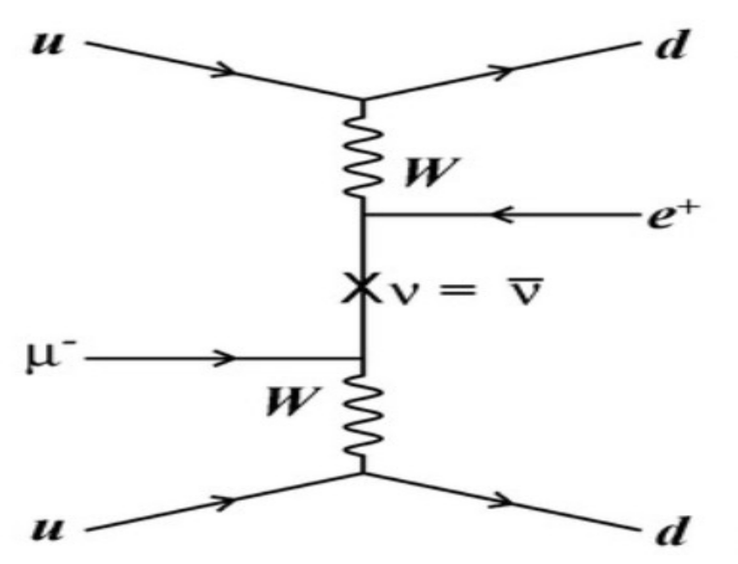
muon physics leader in Switzerland

- AICap: **μ**-e conversion
- FAST: muon lifetime
- Lambshift in muonic hydrogen
- MEG: **μ** → e**γ** @ 10^{-14} level
- **μ**3e: flavor violating decay
- **μ**-Mass: muonium transition
- MUSE: **μ**-proton scattering
- PIONEER: pion decays

Of particular interest, ***Δ***L=2 transition:
test neutrino Majorana nature

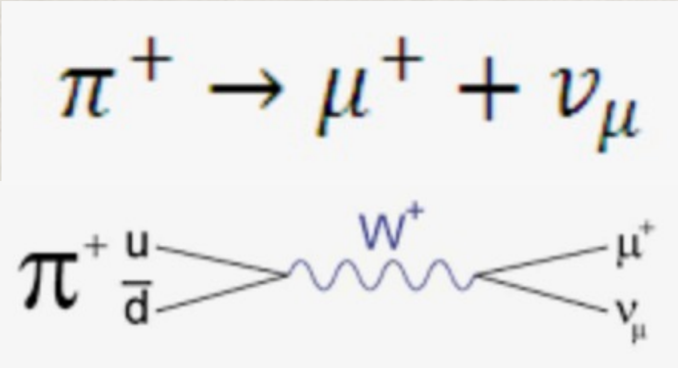
$$\mu^- + N(A, Z) \to e^+ + N'(A, Z-2)$$

(referred to as $\mu^- \to e^+$)



• Lepton Flavor non-universality

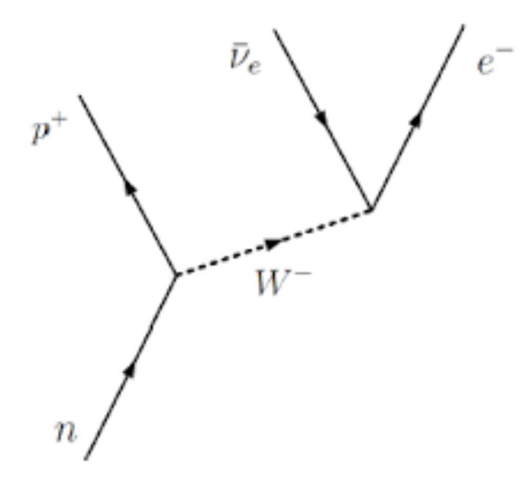
Meson's 2-body decays scale with m_l^2

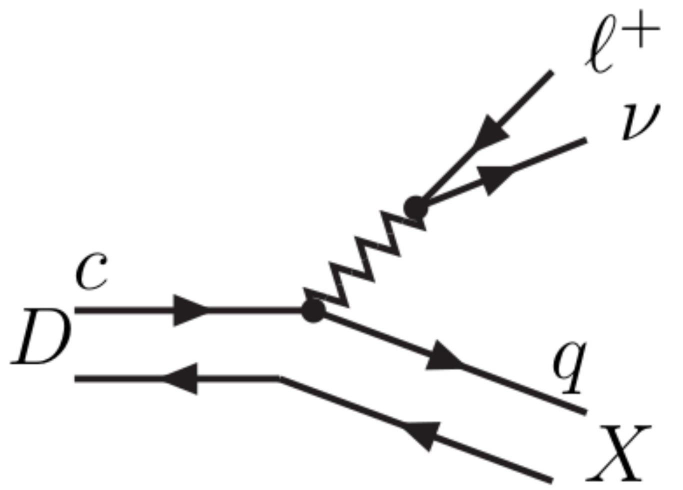


$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\Gamma = \frac{G^2 |V_{ud}|^2}{8\pi} f_\pi^2 \boxed{m_\mu^2} m_\pi \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2$$

Meson's 3-body decays, like the **β**–decay, are flavor-universal in the SM:





→ Universality in *K,D,B* meson decays has been a sensitive test to the SM, and possible new physics BSM.

For reference on flavor anomalies, e.g., e-Print: 1704.05435

• Nu-Storm @ FNAL / PIP-II

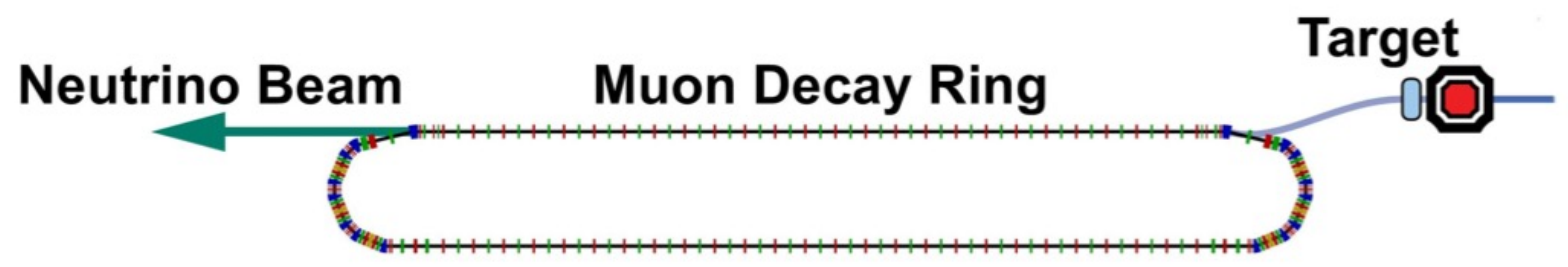
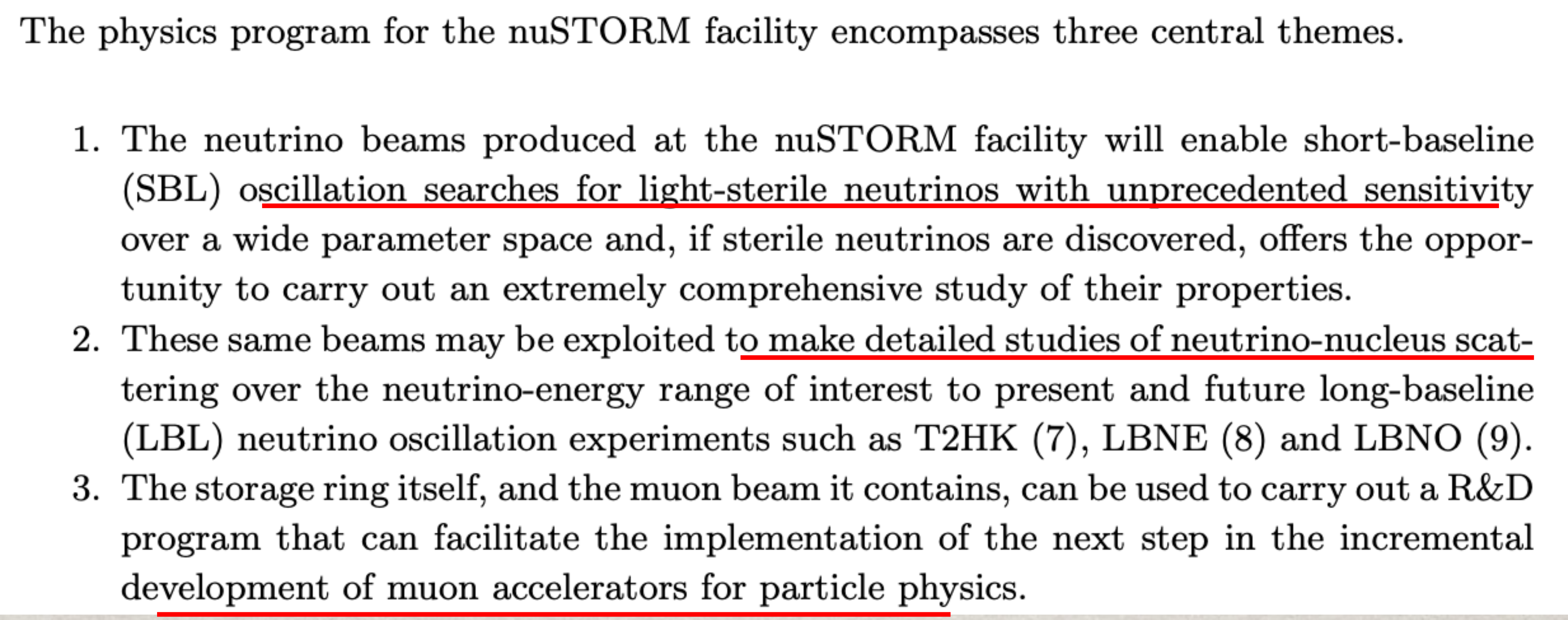


Figure 1

Schematic layout of the nuSTORM facility

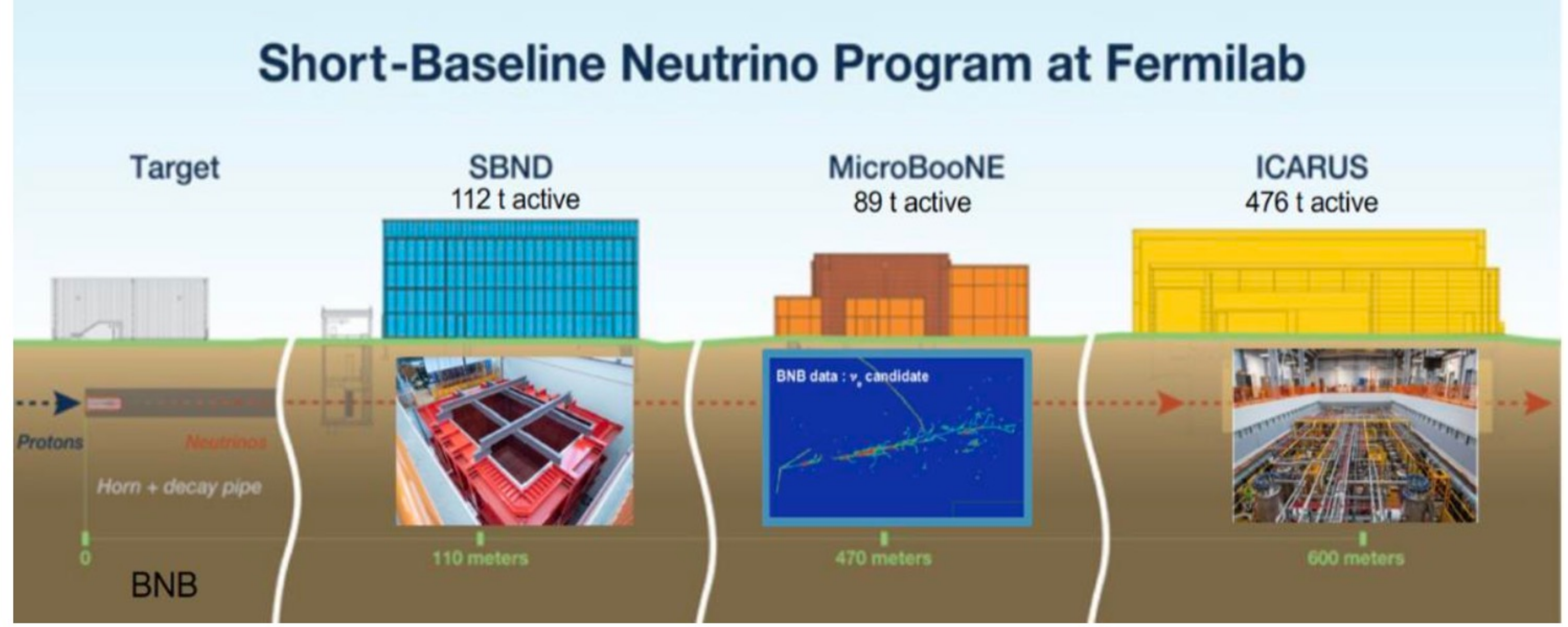
nuSTORM's physics program: Three themes



The physics program for the nuSTORM facility encompasses three central themes.

1. The neutrino beams produced at the nuSTORM facility will enable short-baseline (SBL) oscillation searches for light-sterile neutrinos with unprecedented sensitivity over a wide parameter space and, if sterile neutrinos are discovered, offers the opportunity to carry out an extremely comprehensive study of their properties.
2. These same beams may be exploited to make detailed studies of neutrino-nucleus scattering over the neutrino-energy range of interest to present and future long-baseline (LBL) neutrino oscillation experiments such as T2HK (7), LBNE (8) and LBNO (9).
3. The storage ring itself, and the muon beam it contains, can be used to carry out a R&D program that can facilitate the implementation of the next step in the incremental development of muon accelerators for particle physics.

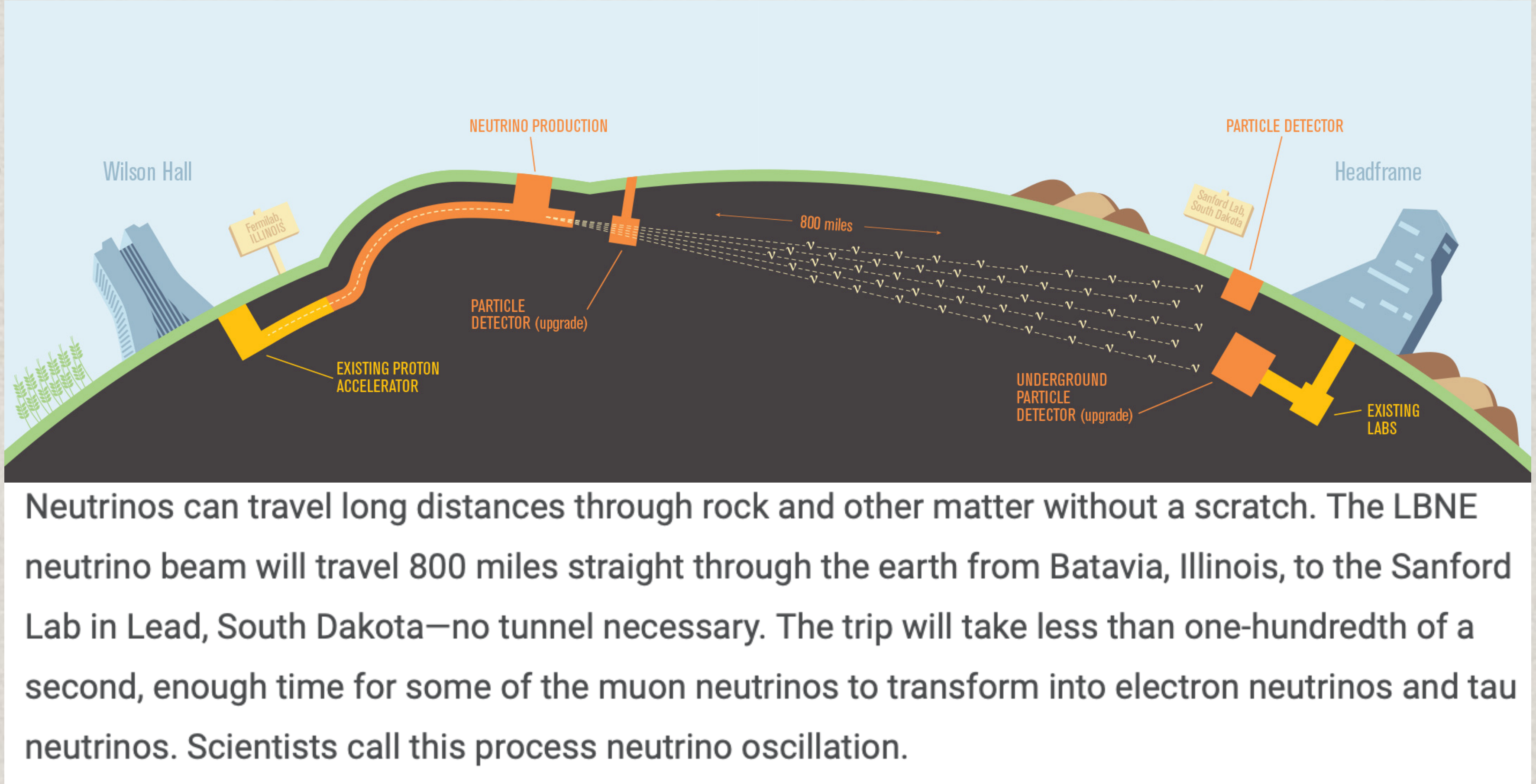
SBNE: Short-Baseline Neutrino Experiments



- Pioneer the Liquid Argon TPC technology
- Resolve LSND / MiniBooNE anomalies
- Search for (light) new physics

• LBNE: Long-Baseline Neutrino Experiments

DUNE: Deep Underground Neutrino Experiment, the "ultimate" neutrino experiment



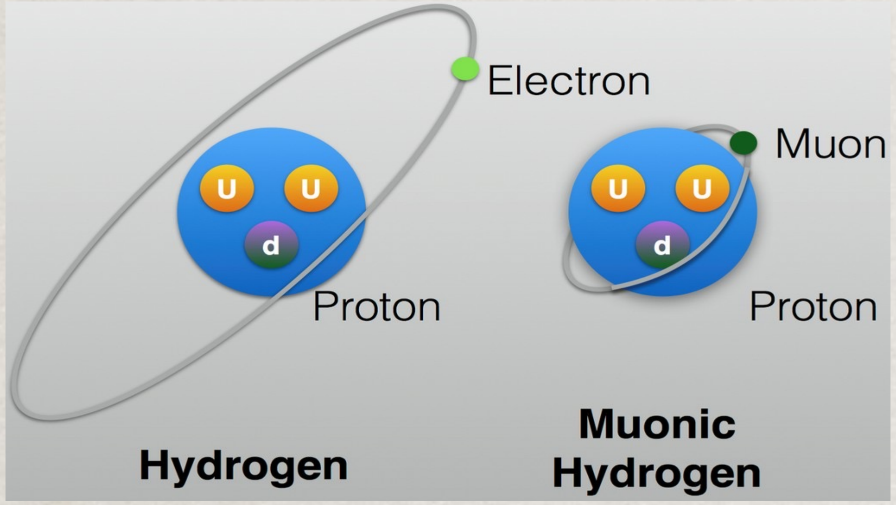
Neutrinos can travel long distances through rock and other matter without a scratch. The LBNE neutrino beam will travel 800 miles straight through the earth from Batavia, Illinois, to the Sanford Lab in Lead, South Dakota—no tunnel necessary. The trip will take less than one-hundredth of a second, enough time for some of the muon neutrinos to transform into electron neutrinos and tau neutrinos. Scientists call this process neutrino oscillation.

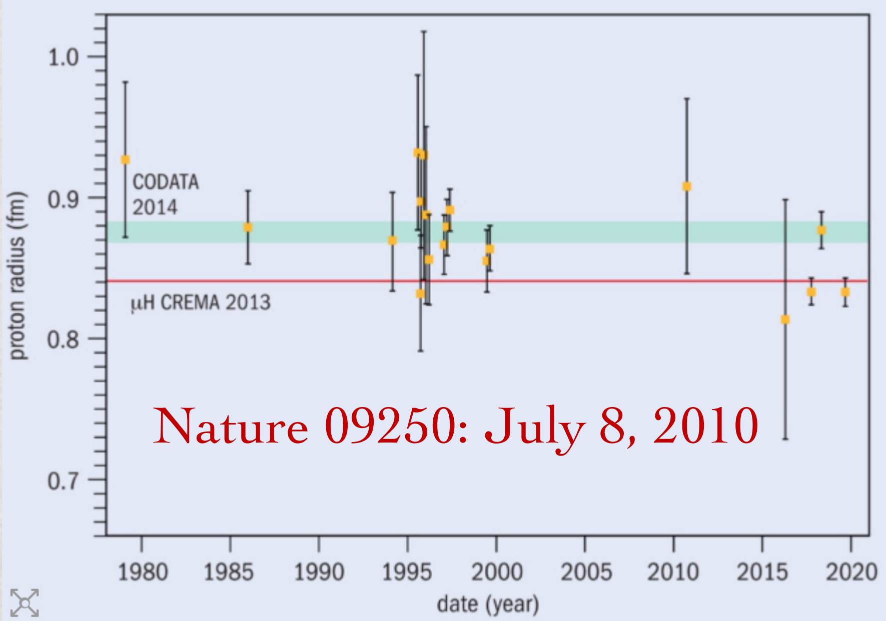
DUNE will pursue major science goals:

- Leptonic CP violation, precision measurements of θ_{13}, Δm^2_{13}
- Dark matter searches
- Proton decay
- Supernova, formation of neutron star/black holes

MUONS BEYOND HEP

- Muonic atom for precision physics





Nature 09250: July 8, 2010

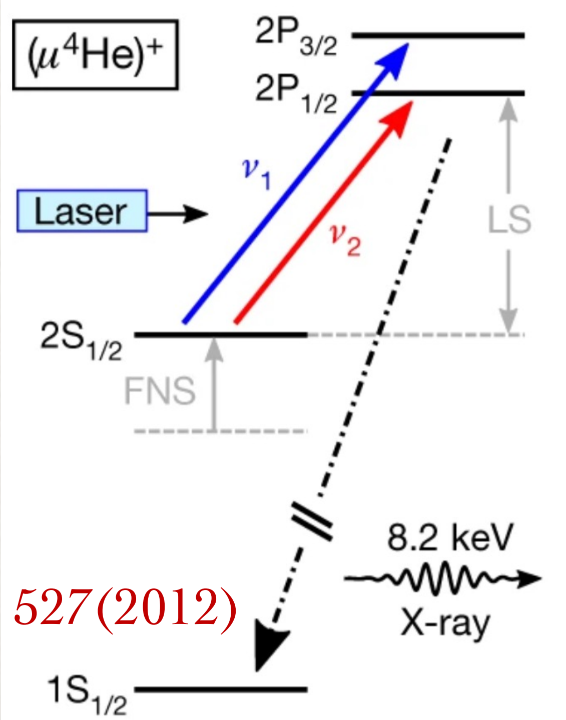
- $r_B = (\alpha\ m)^{-1}$: $r_B(\mu^-) = r_B(e^-)/207 = 2.2\text{x}10^{-5}$ nm
- Wavefunction overlap: $(m_\mu/m_e)^3 \sim 10^7$ stronger
- Lamb shift: 10^5 larger

Very sensitive to probe
the **proton size**/properties: PSI, CREMA

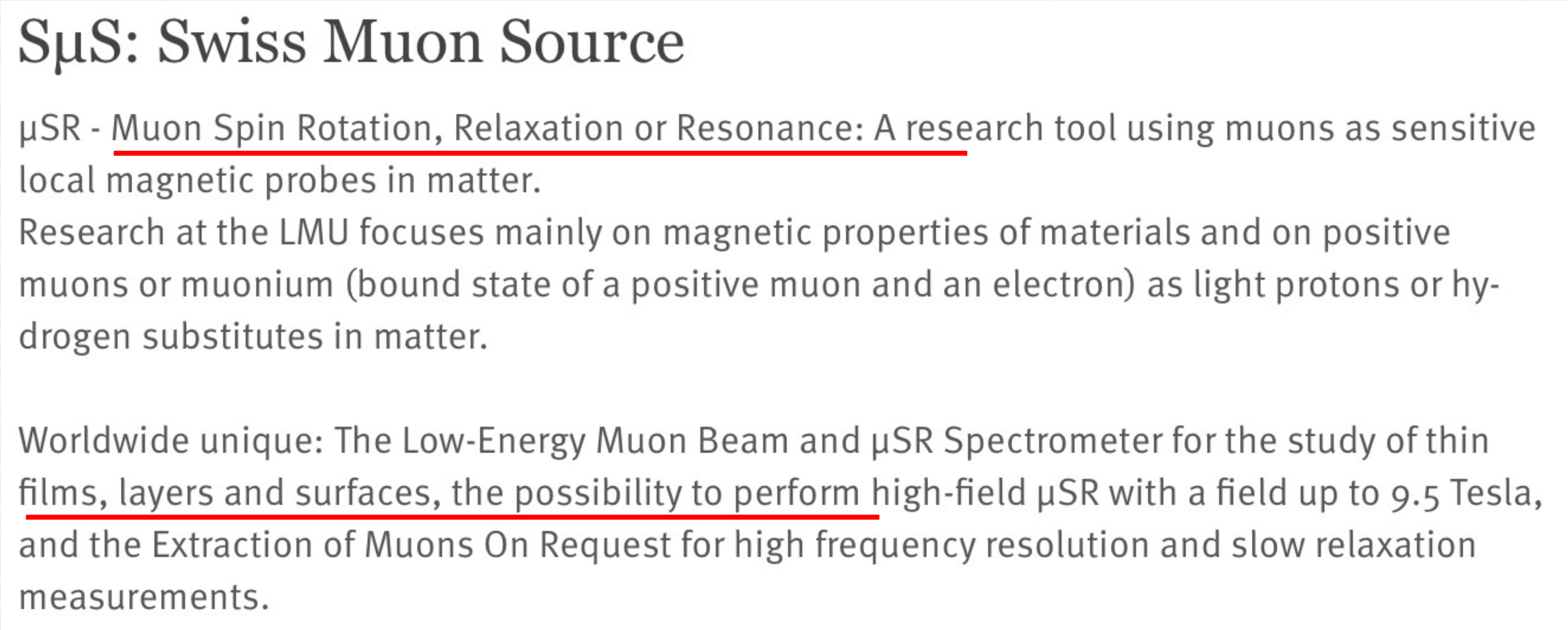
Best precision for the helium nucleus size:

$$r_\alpha = 1.67824(13)_{\text{exp}}\ (82)_{\text{theo}}\ \text{fm}.$$

PSI: Nature 589, 527(2012)



• Muons for material science: PSI



SμS: Swiss Muon Source

μSR - Muon Spin Rotation, Relaxation or Resonance: A research tool using muons as sensitive local magnetic probes in matter.
Research at the LMU focuses mainly on magnetic properties of materials and on positive muons or muonium (bound state of a positive muon and an electron) as light protons or hydrogen substitutes in matter.

Worldwide unique: The Low-Energy Muon Beam and μSR Spectrometer for the study of thin films, layers and surfaces, the possibility to perform high-field μSR with a field up to 9.5 Tesla, and the Extraction of Muons On Request for high frequency resolution and slow relaxation measurements.

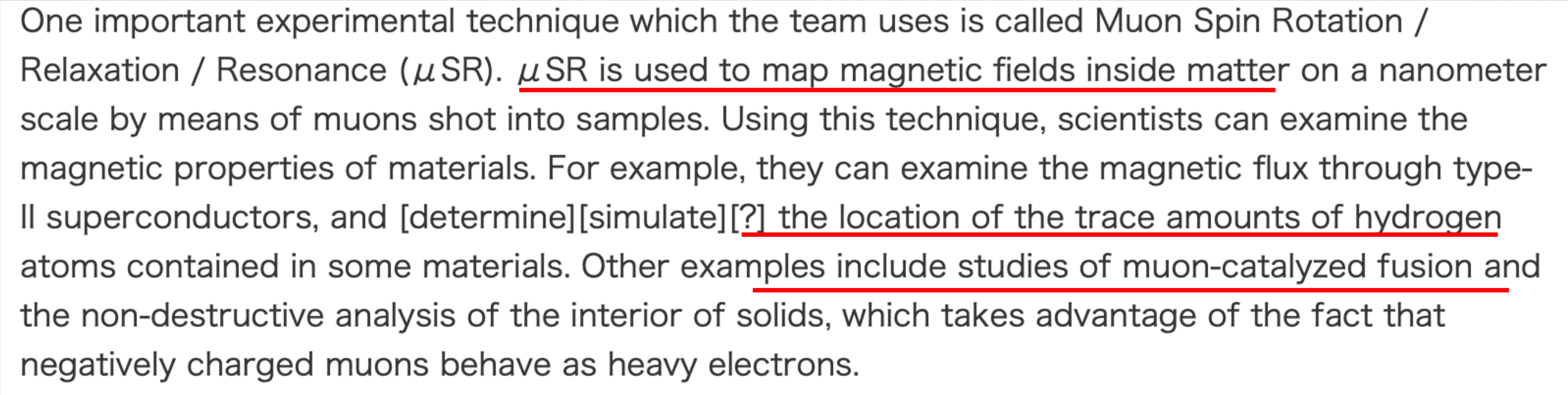
• Muons for material science: KEK

KEK, Japan:

MSL

Muon Science Laboratory

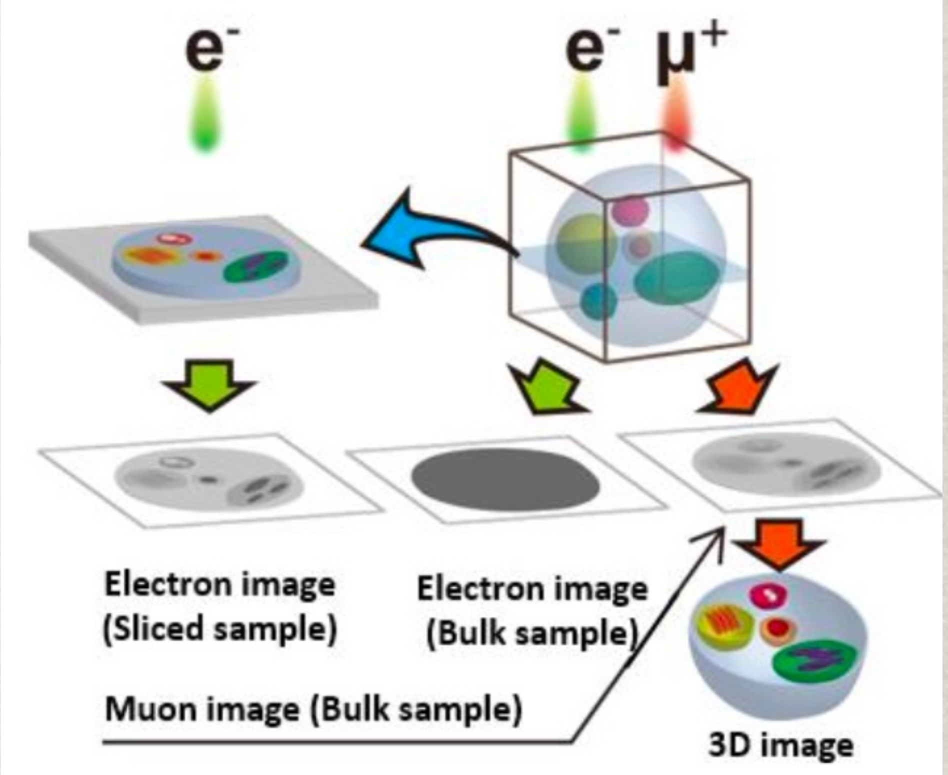
Institute of Materials Structure Science
High Energy Accelerator Research Organization,KEK



One important experimental technique which the team uses is called Muon Spin Rotation / Relaxation / Resonance (μSR). μSR is used to map magnetic fields inside matter on a nanometer scale by means of muons shot into samples. Using this technique, scientists can examine the magnetic properties of materials. For example, they can examine the magnetic flux through type-II superconductors, and [determine][simulate][?] the location of the trace amounts of hydrogen atoms contained in some materials. Other examples include studies of muon-catalyzed fusion and the non-destructive analysis of the interior of solids, which takes advantage of the fact that negatively charged muons behave as heavy electrons.

Transmission Muon Microscope TMM @ KEK

Advantages of TMM versus an electron microscope



• Muon Tomography: Cosmic muons

Atmospheric muon flux ~ 200/m^2/s

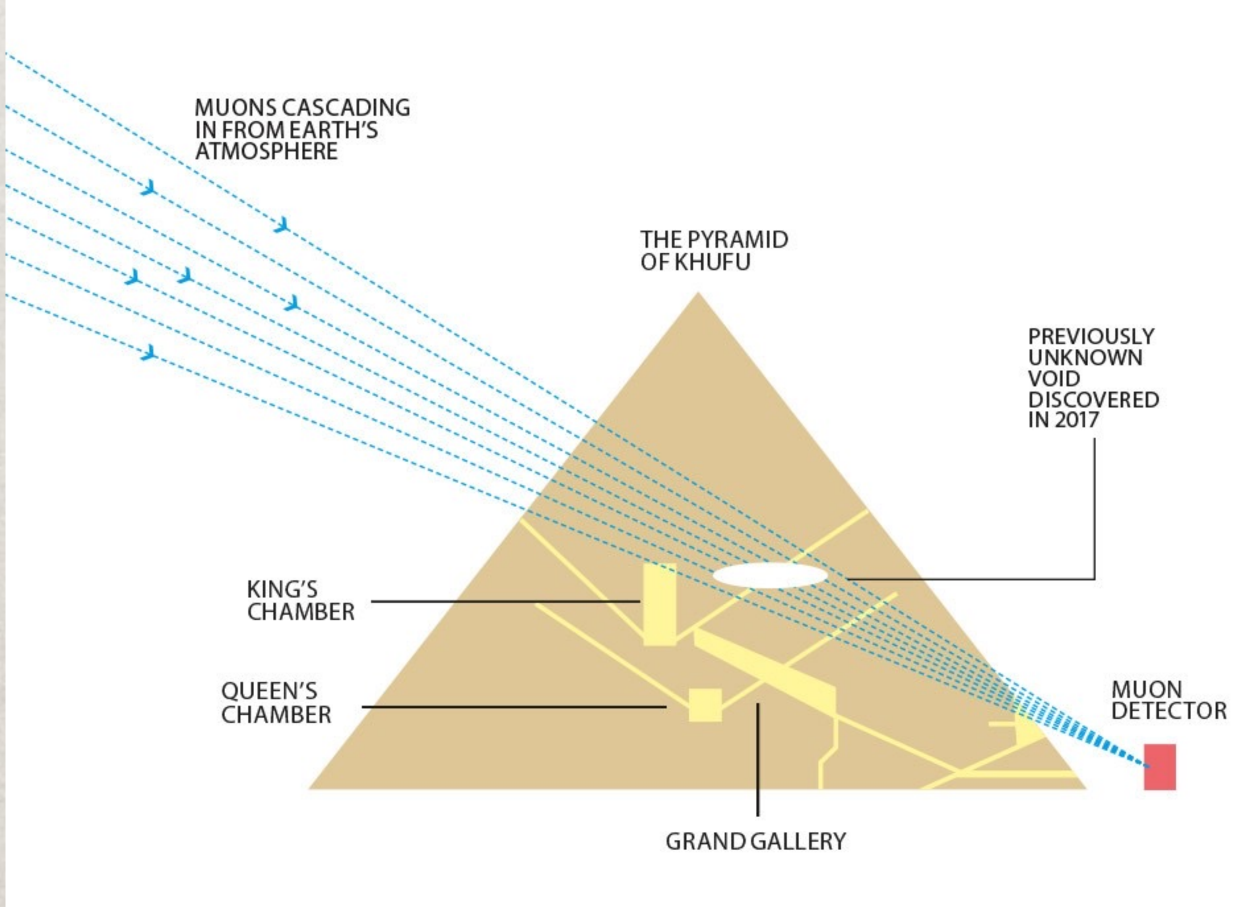
Muons are penetrating!

nature

(November 2, 2017, and update Jan. 2023)

Cosmic-ray particles reveal secret chamber in Egypt's Great Pyramid

A previously unknown chamber has been found in the largest of the pyramids in Giza, Egypt. Credit: Tomasz Tomaszewski/VISUM creativ/eyevine



A MUON COLLIDER

Who Ordered That Collider?

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

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

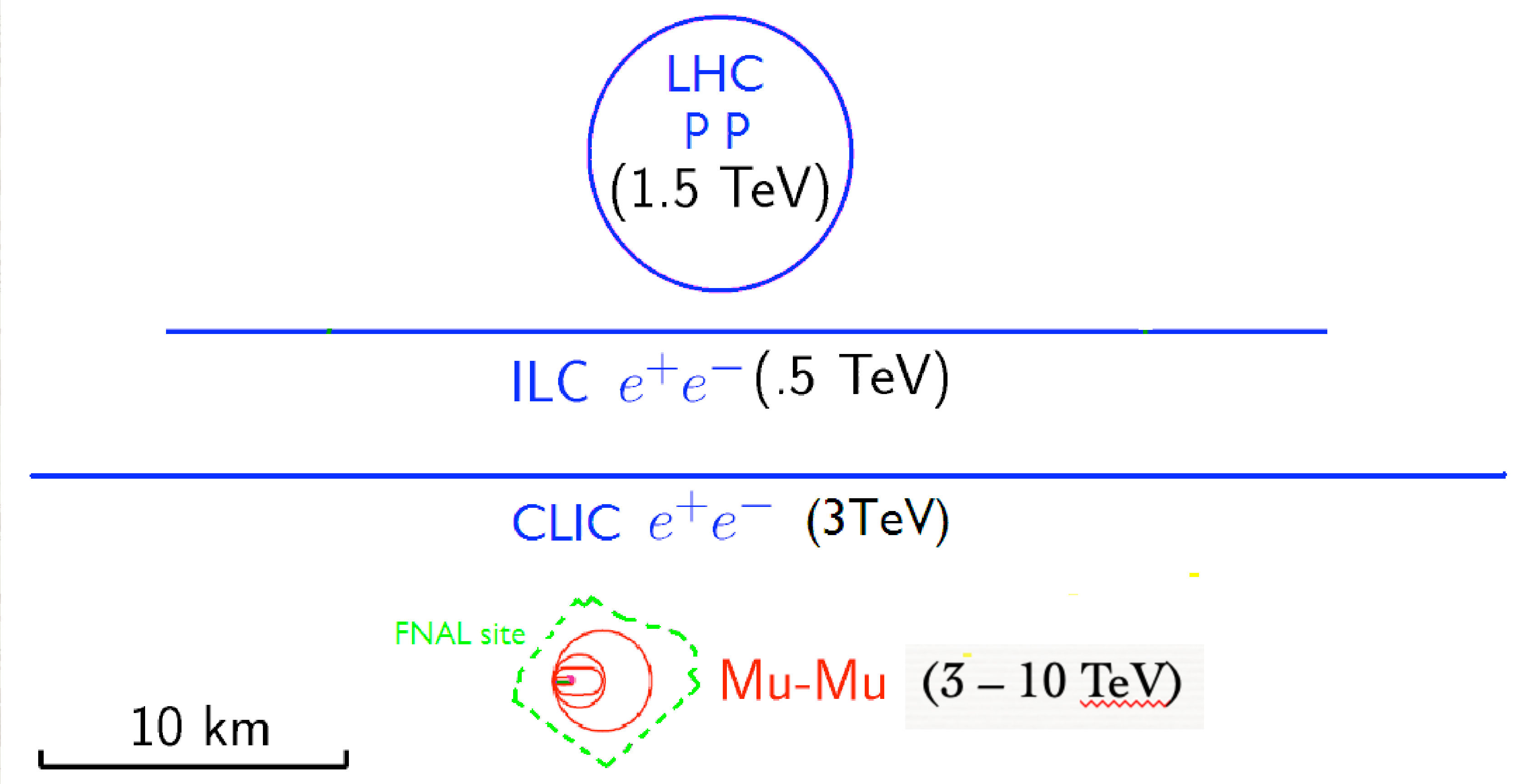
It is these features: heavy mass, short lifetime
that dictate the physics.

Advantages of a muon collider

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

$$\Delta E \sim \gamma^4 = (\frac{E}{m_\mu})^4$$

which would allow a smaller and a circular machine:



- Unlike the proton as a composite particle, E_{CM} efficient in $\mu^+\mu^-$ 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: σ_{pp}(total)~100 mb; $\sigma_{\mu\mu}$(total)~100 nb]

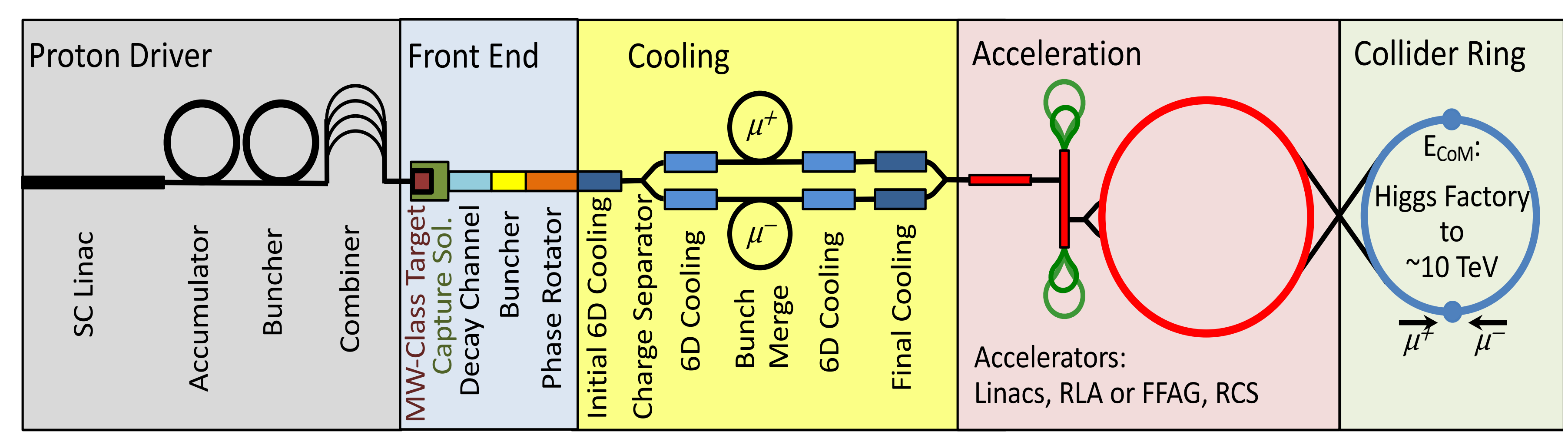
- Neutrino beam dump (environmental hazard)

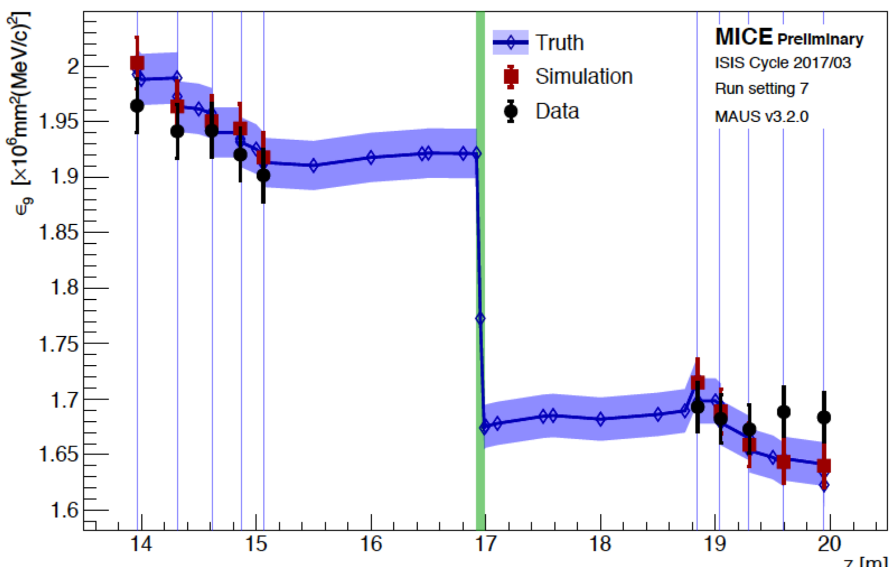
$\sigma_\nu \sim G_F^2 E^2$ → Shielding?

The recent excitement: the "Muon Shot"

Muon Accelerator Project (MAP)

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

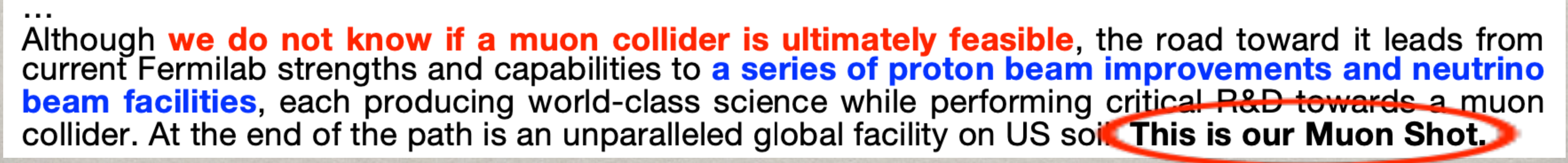
nature

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:

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

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.

1 ab^{-1} /yr

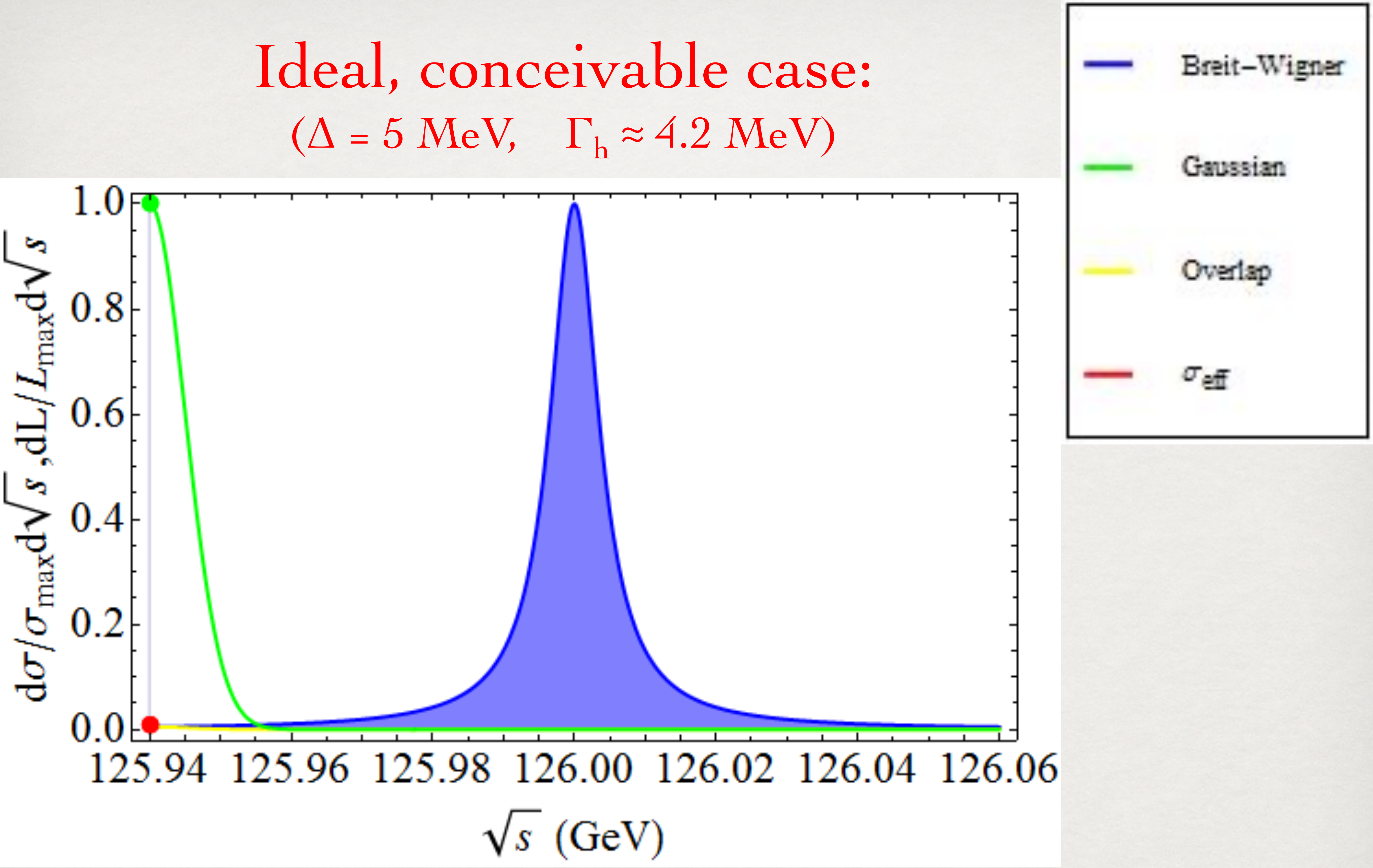
$$L \gtrsim \frac{5\text{ years}}{\text{time}}\left(\frac{\sqrt{s_\mu}}{10\text{ TeV}}\right)^2 2\cdot\boxed{10^{35}\text{cm}^{-2}\text{s}^{-1}}$$

The conceivable choices:
Ecm = 3 TeV - 14 TeV

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

Ideal, conceivable case:

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



An optimal fitting would reveal Γ_h → O(3.5%)

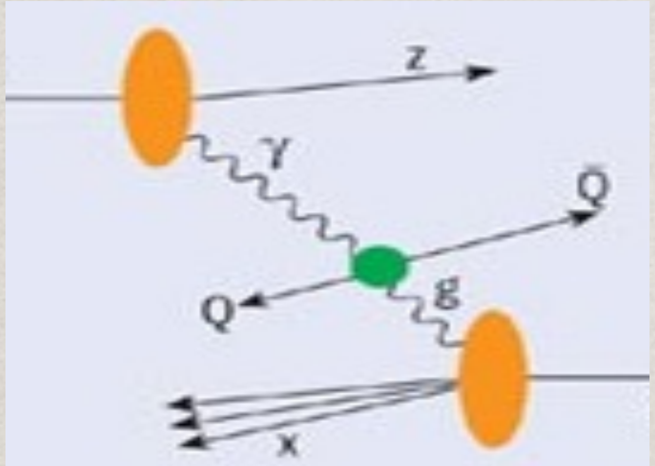
A MULTI-TEV MUON COLLIDER

Exciting energy-frontier!

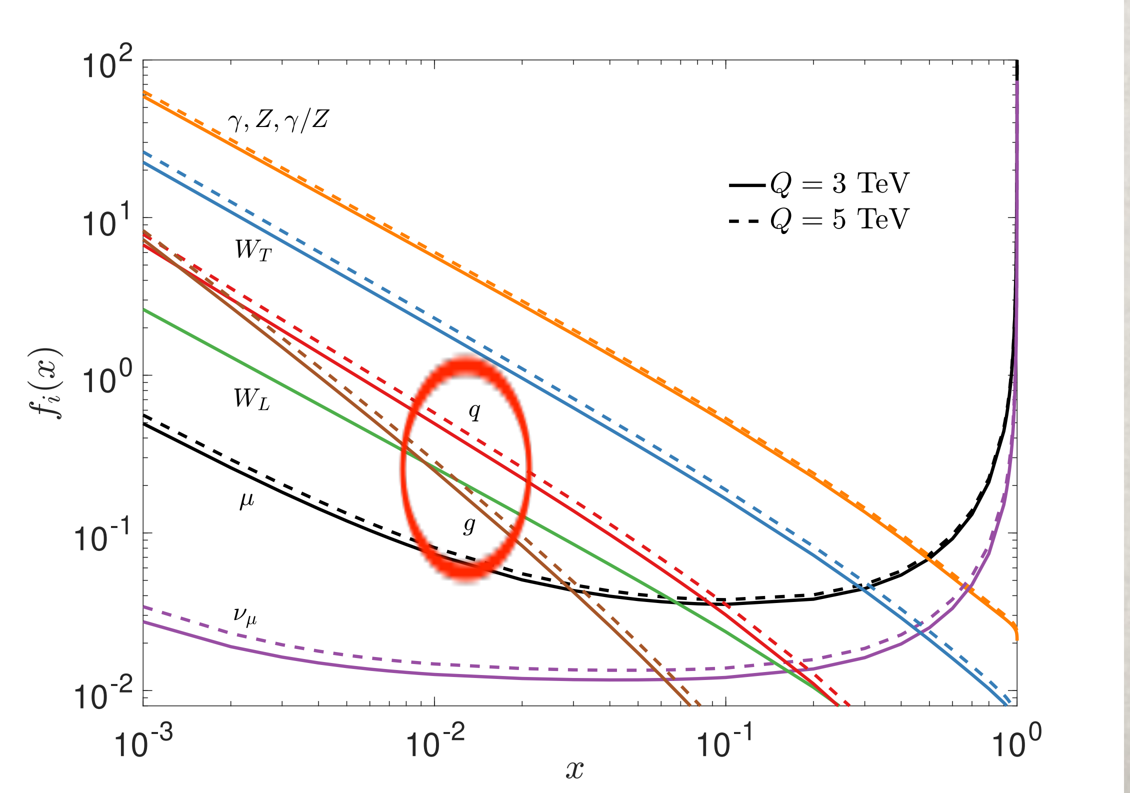
Photon-induced QED cross sections

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

Quarks/gluons come into the picture via SM DGLAP:



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



$\mu^\pm$: the valance.

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

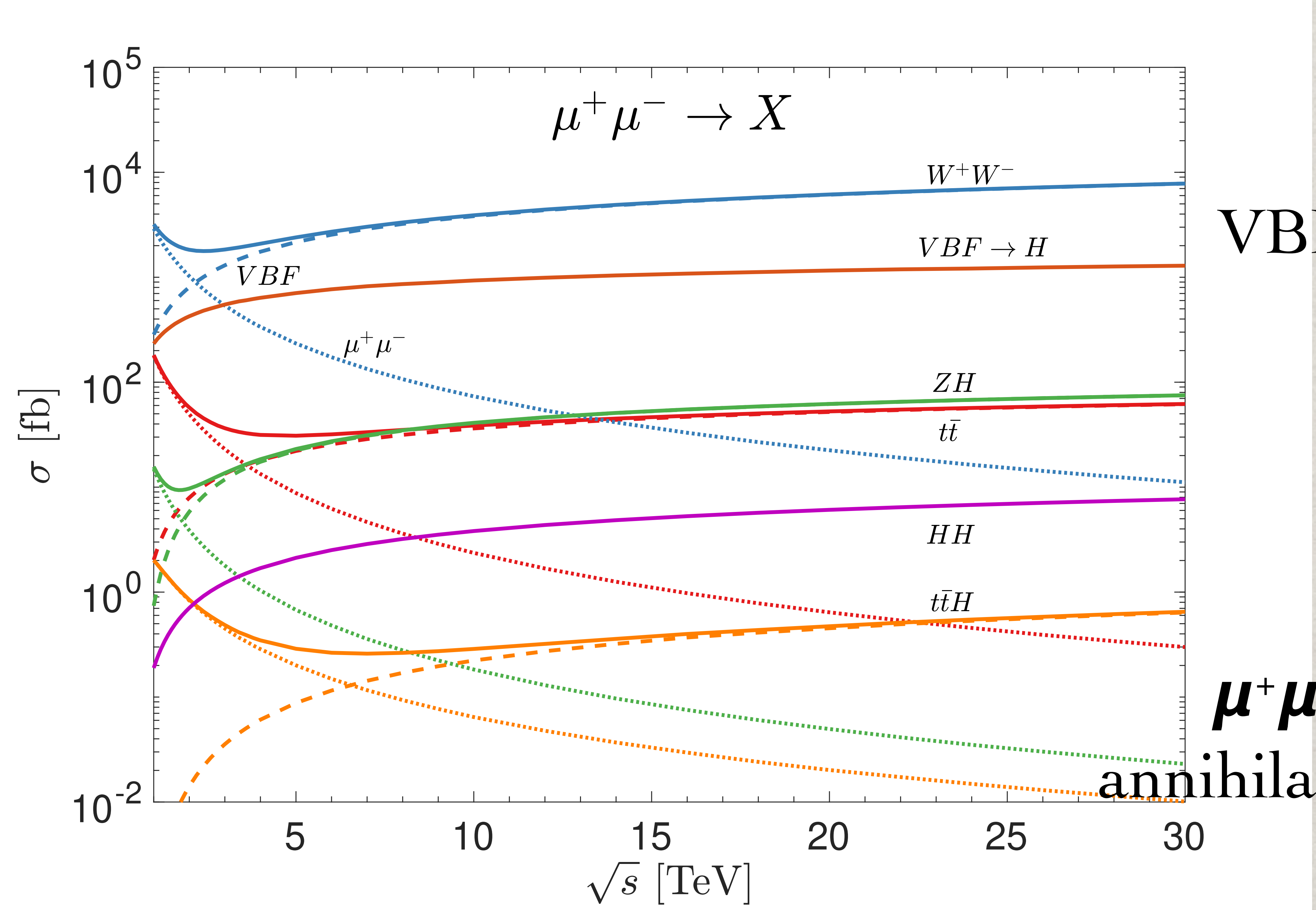
Quarks: NLO; gluons: NNLO.

TH, Yang Ma, Keping Xie,
arXiv:2007.14300

- **“Semi-inclusive” processes**

Just like in hadronic collisions:

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

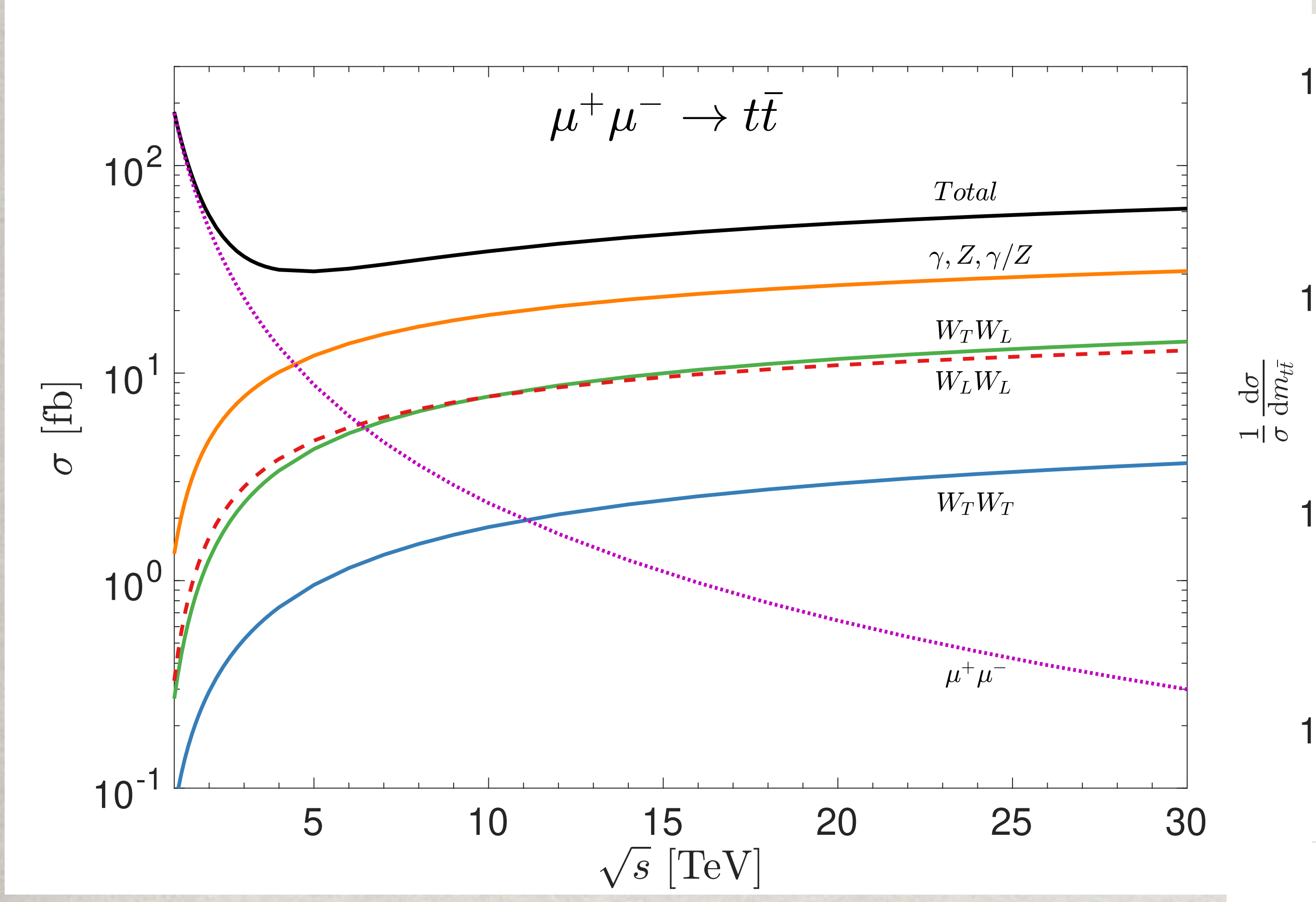


VBF

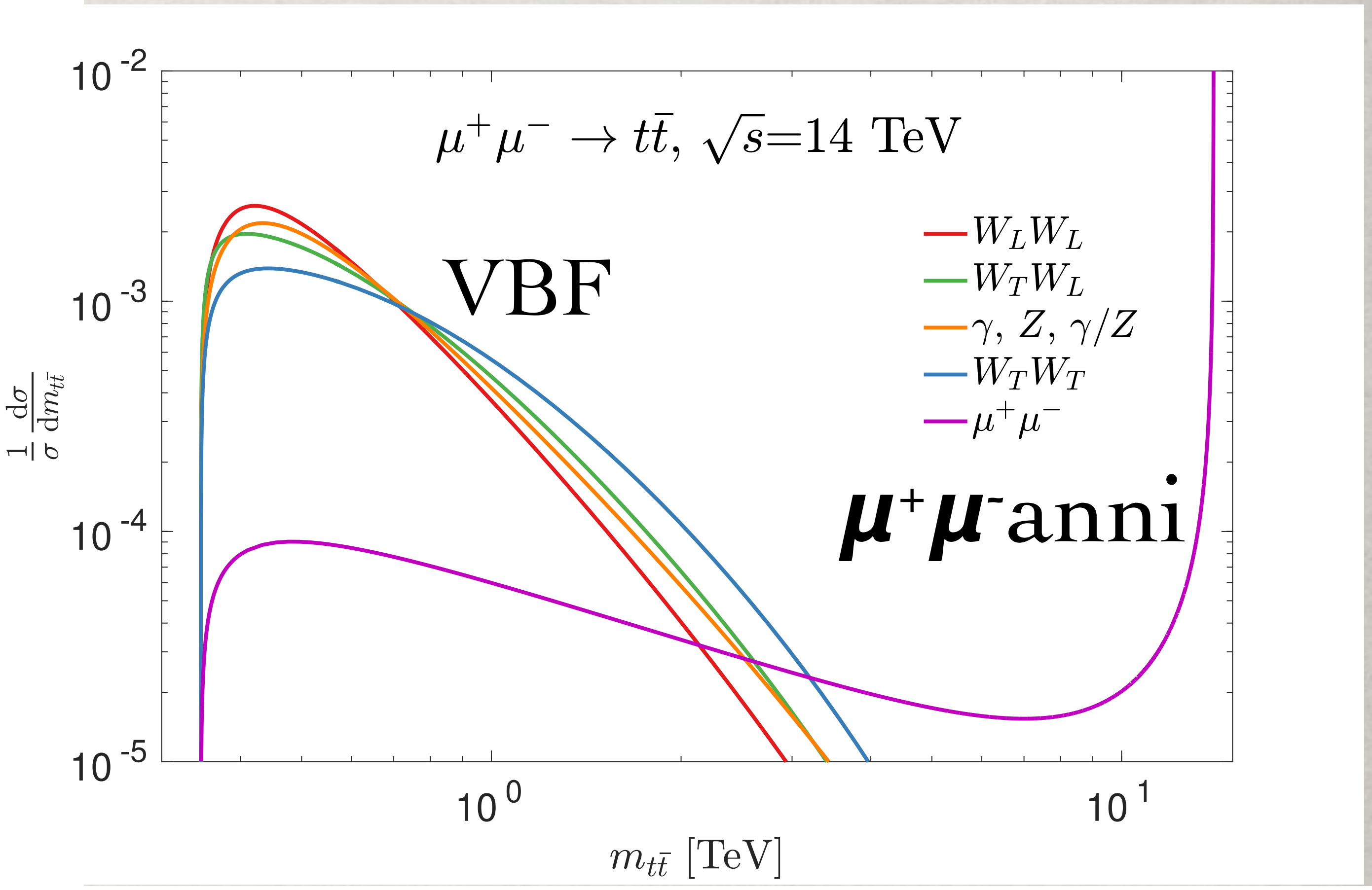
$\mu^+\mu^-$ annihilations

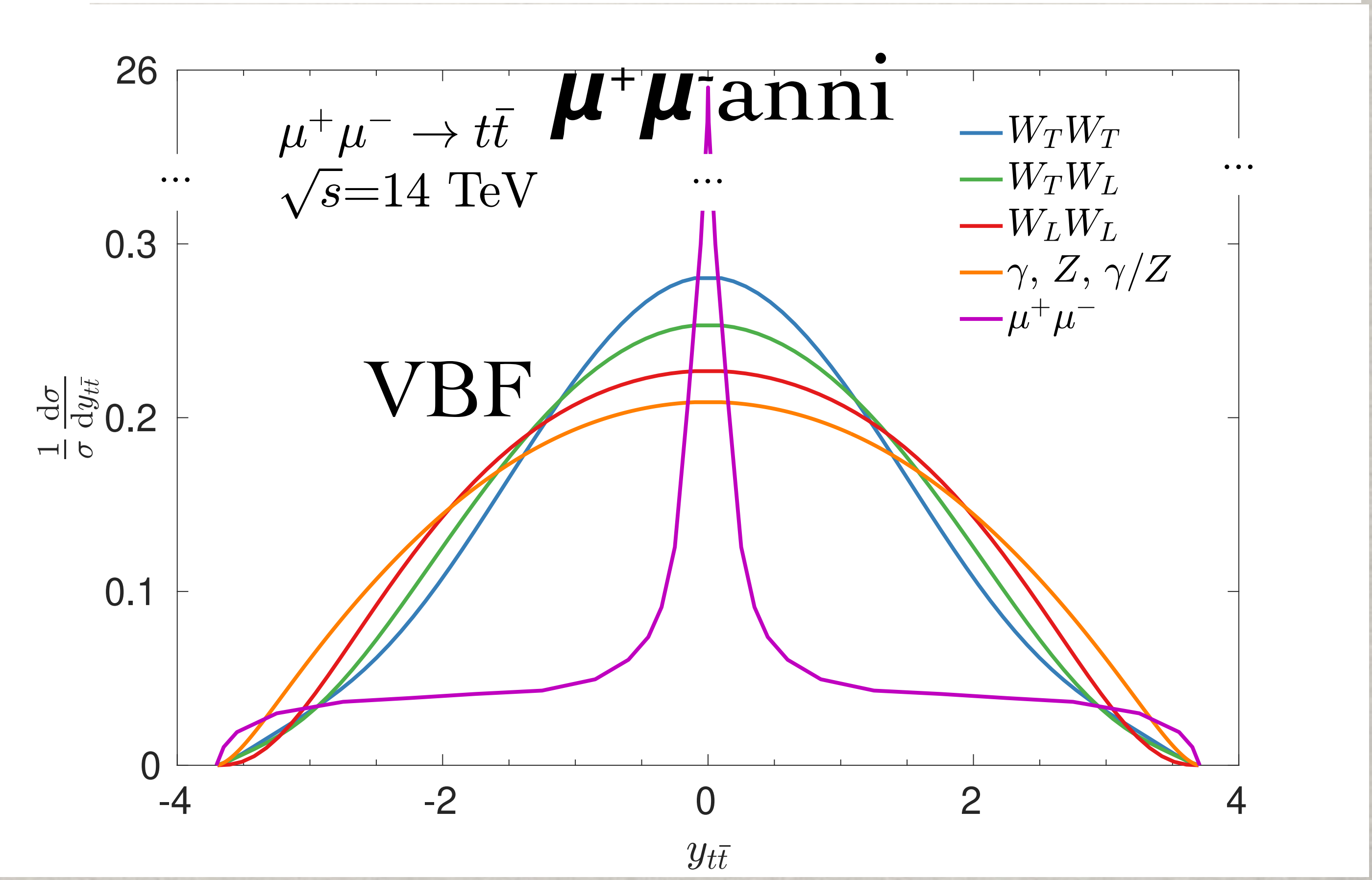
Costantini, F. Maltoni, et al., arXiv:2005.10289; Y. Ma et al., arXiv:2007.14300

• Underlying sub-processes:



Partonic contributions



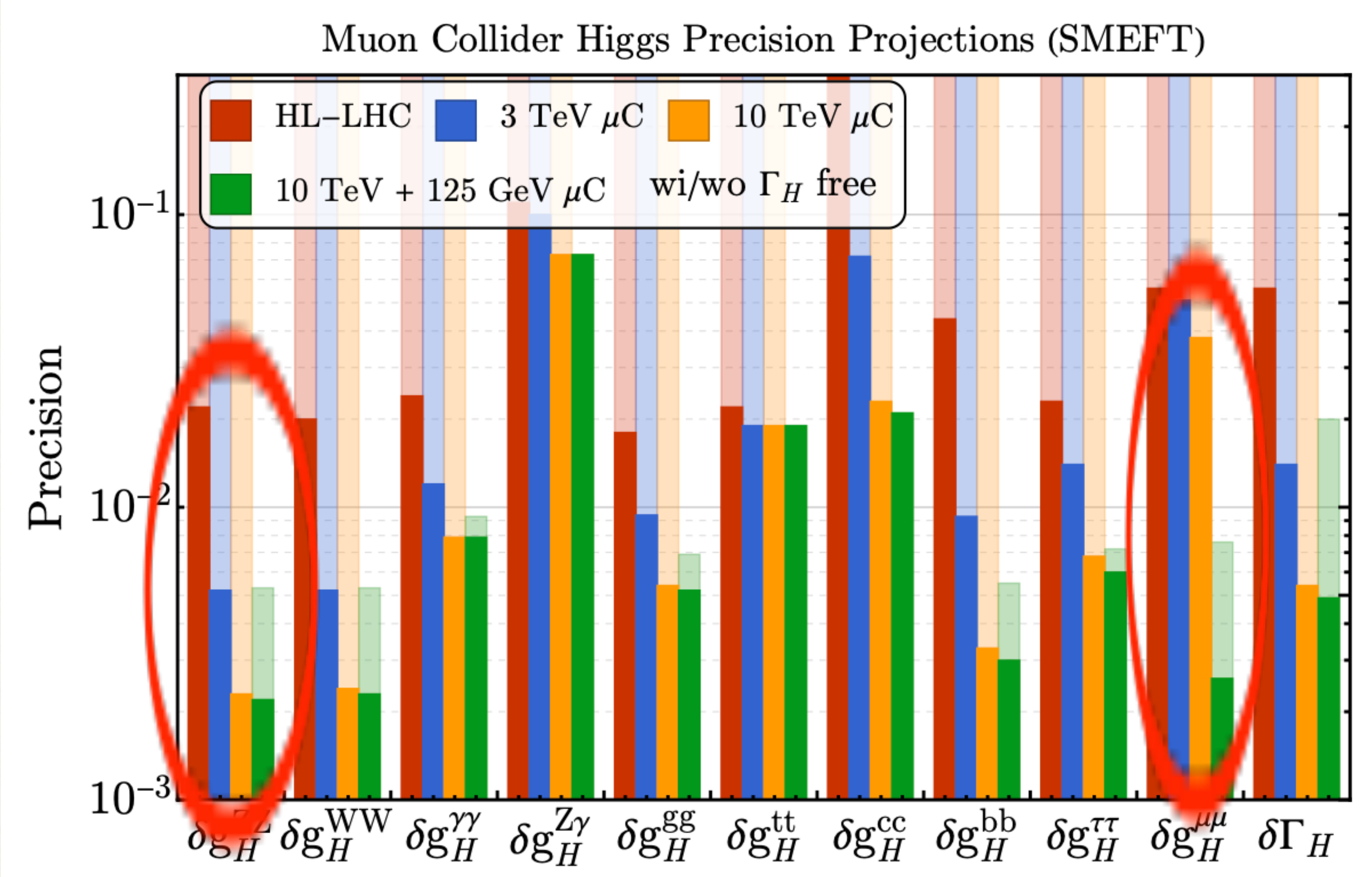


$\mu^+\mu^-$ Collider --
“Buy one, get one free”:
Annihilation +VBF

Precision Higgs physics

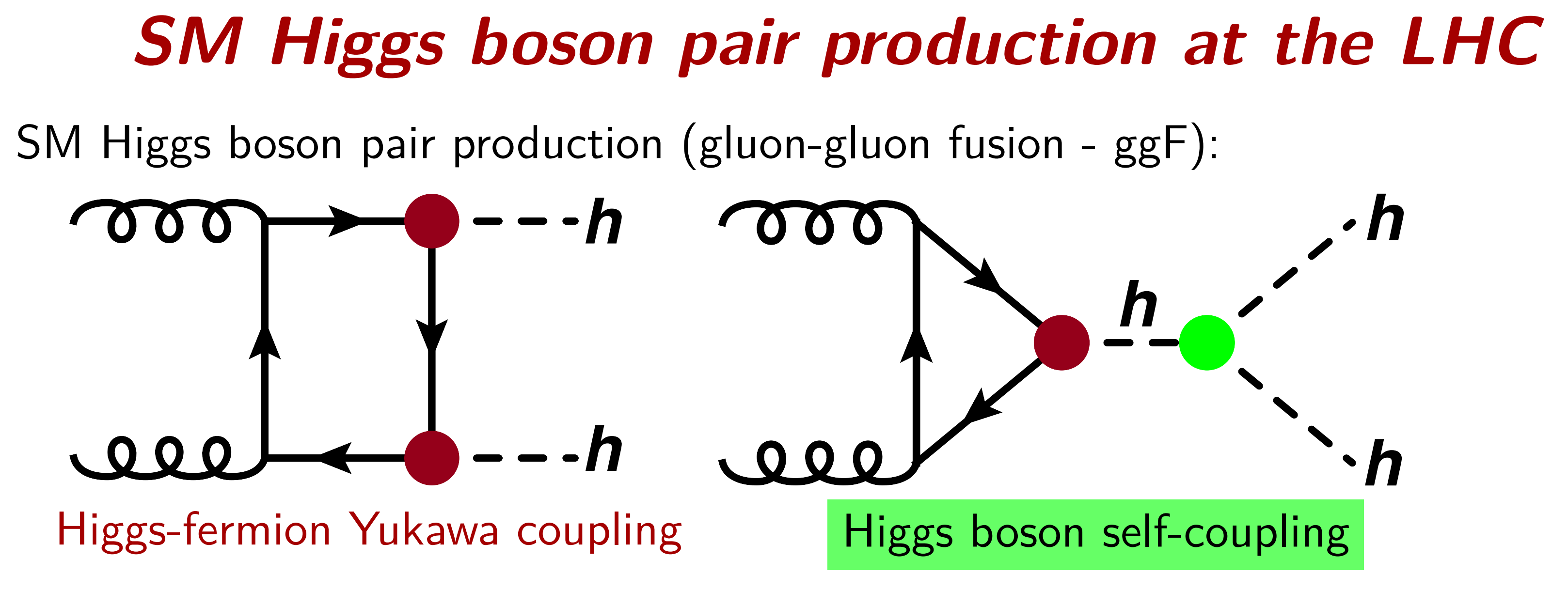
10M H, 500K HH @ 10 TeV

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



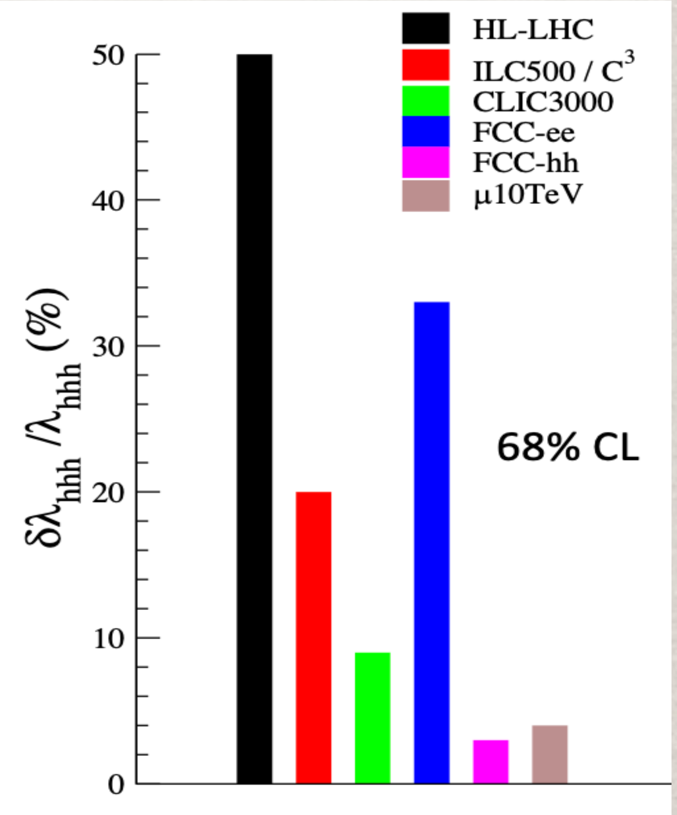
$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2) \approx$ sub % → M > 2 TeV

Higgs pair production & triple coupling:

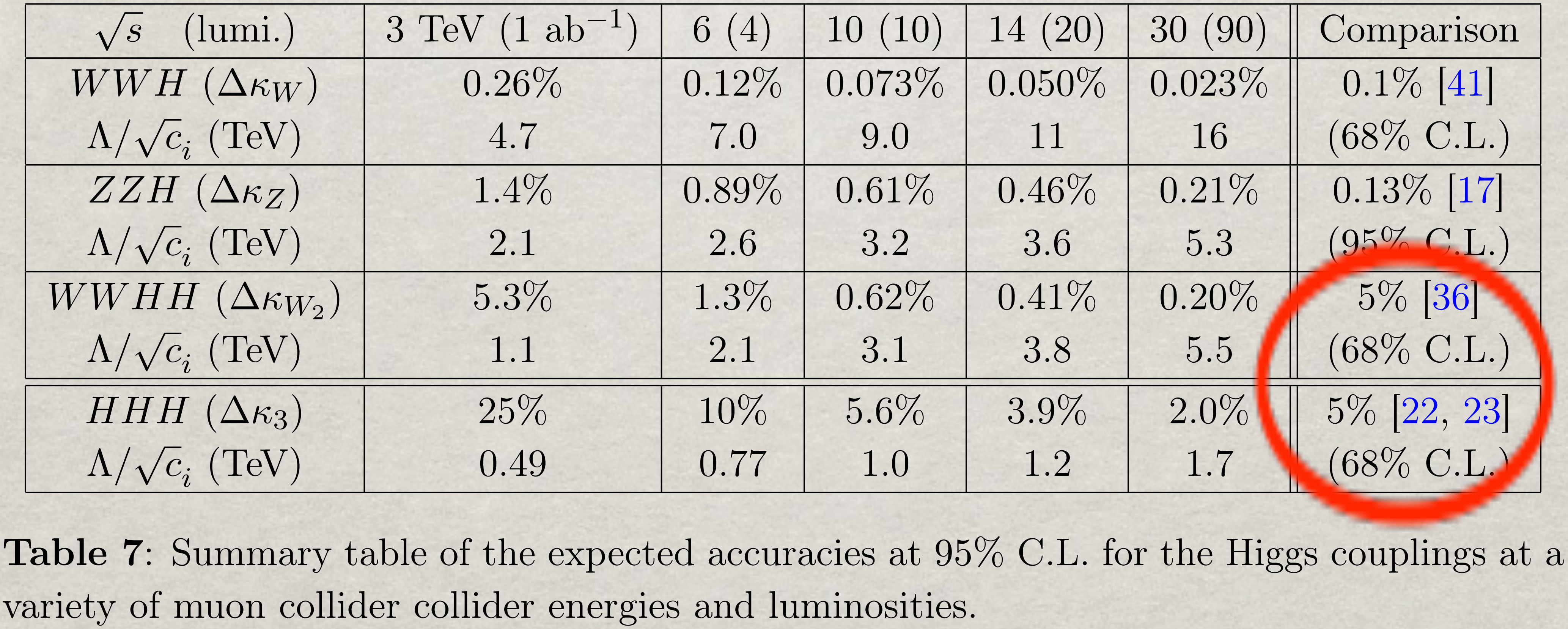


SM Higgs boson pair production at the LHC

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



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



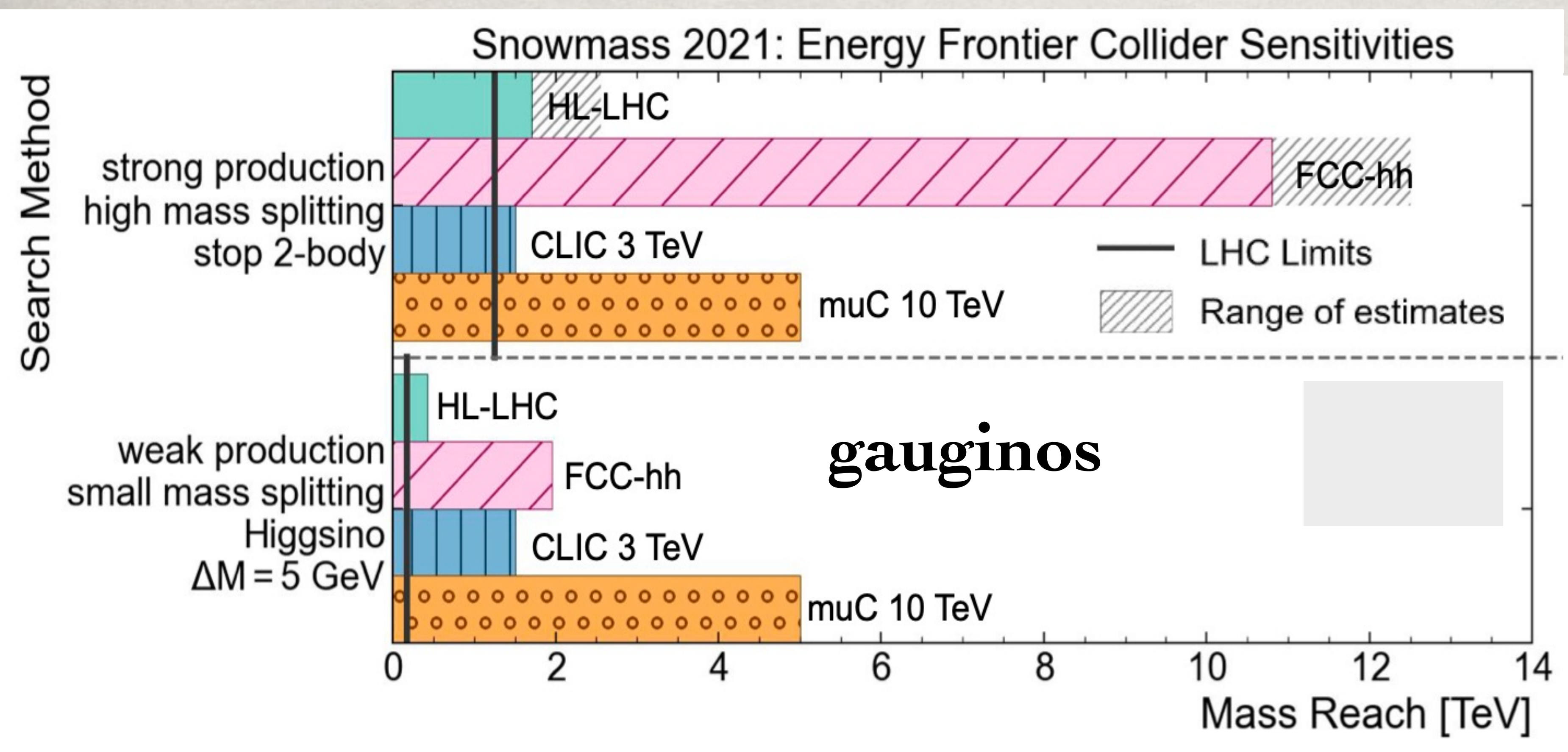
$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	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.

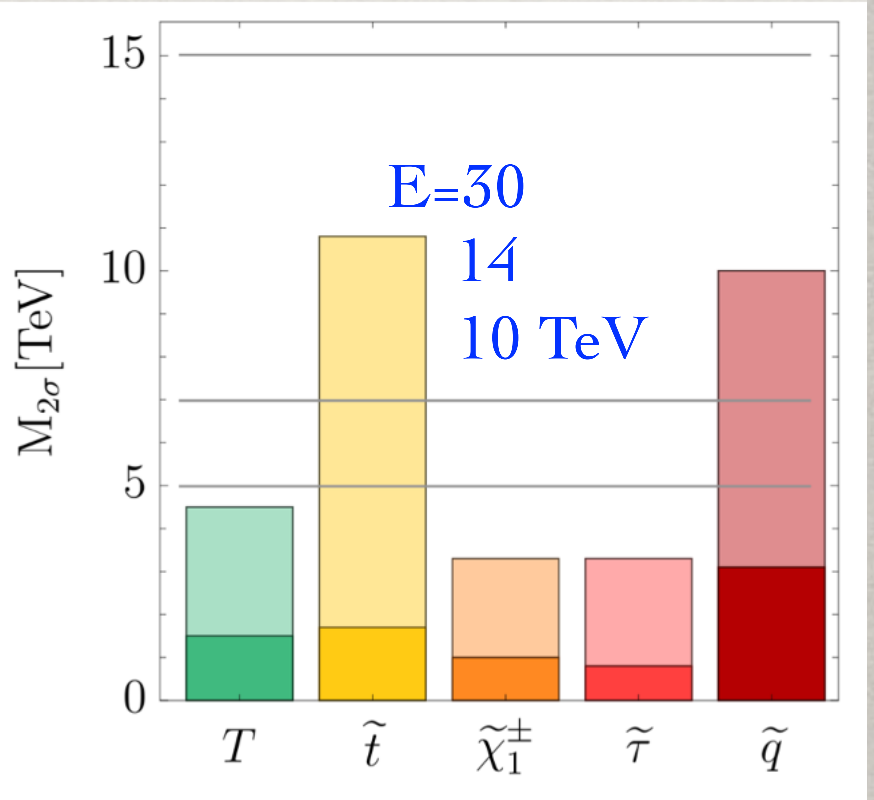
D. Buttazzo, D. Redogolo, F. Sala, arXiv:1807.04743;
TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204

Pushing the “Naturalness” limit

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



gauginos



E=30
14
10 TeV

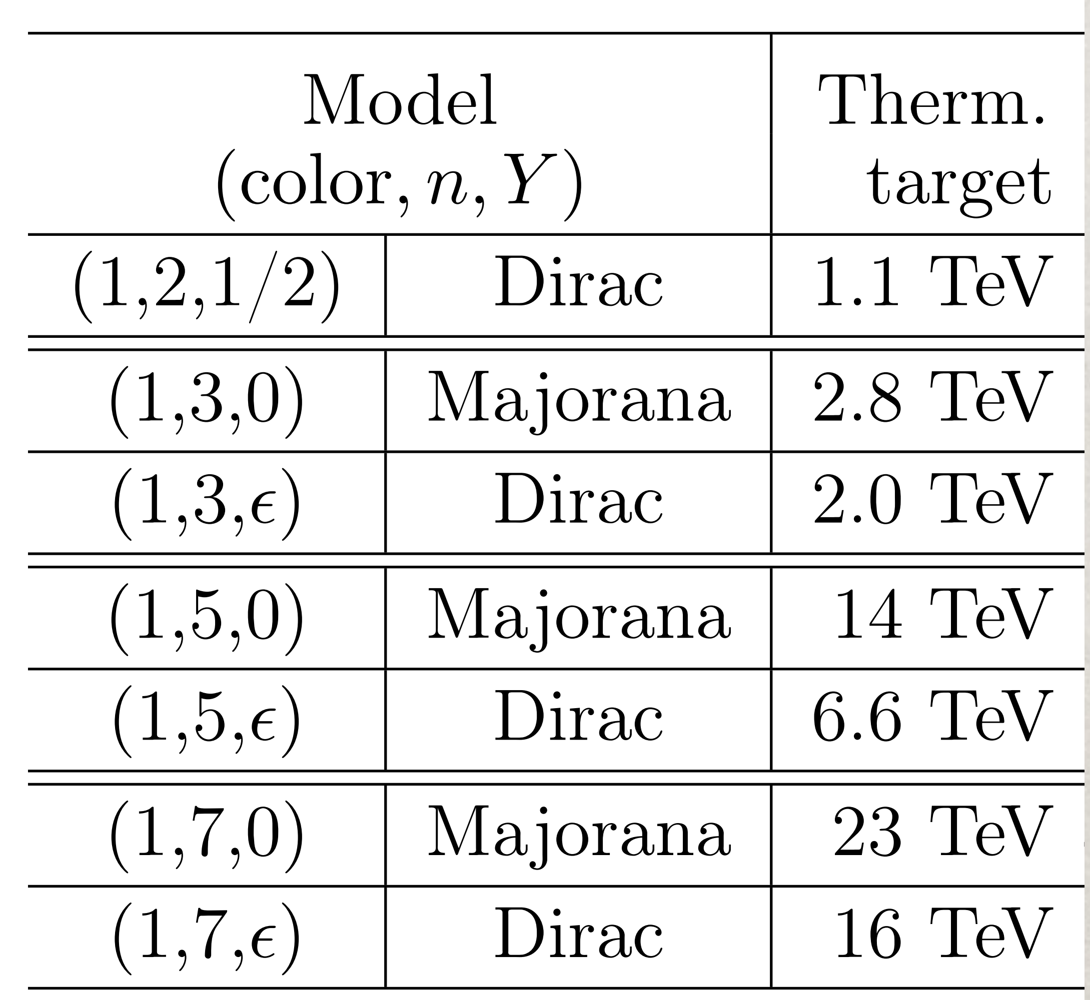
→ Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \, (1\ \mathrm{TeV}/\Lambda)^2$

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

• 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

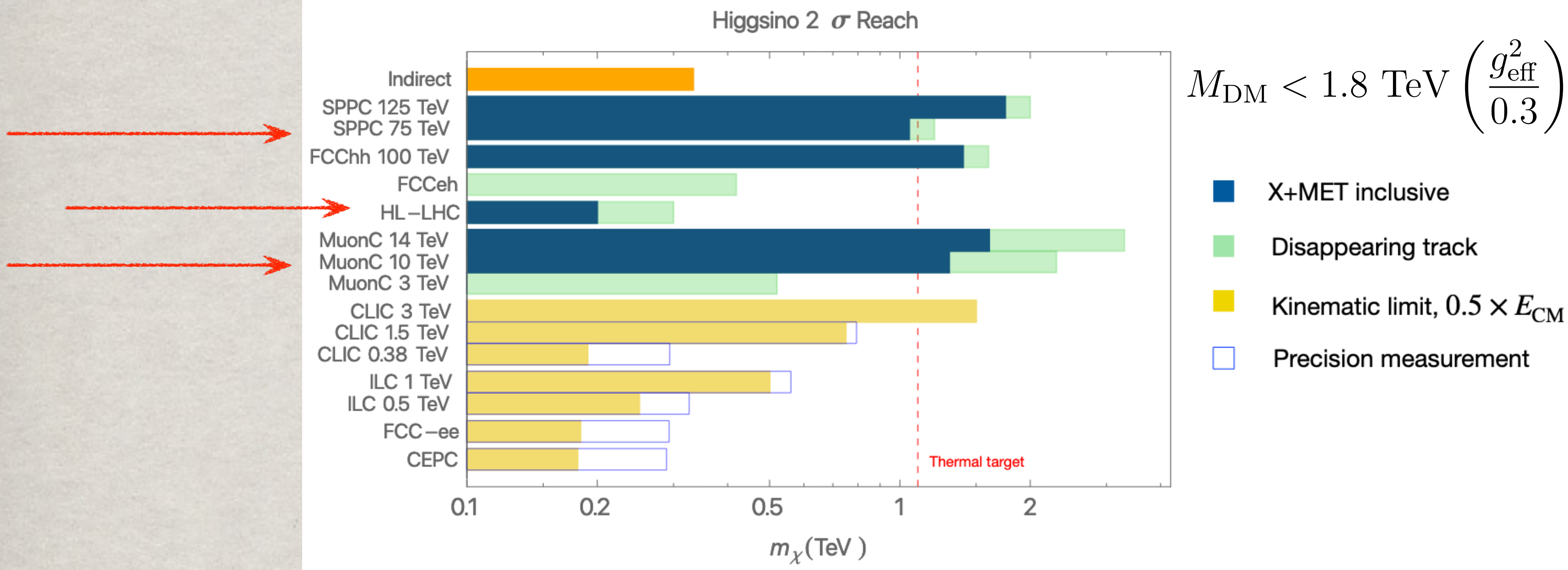


Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
(1,7,ϵ)	Dirac	16 TeV

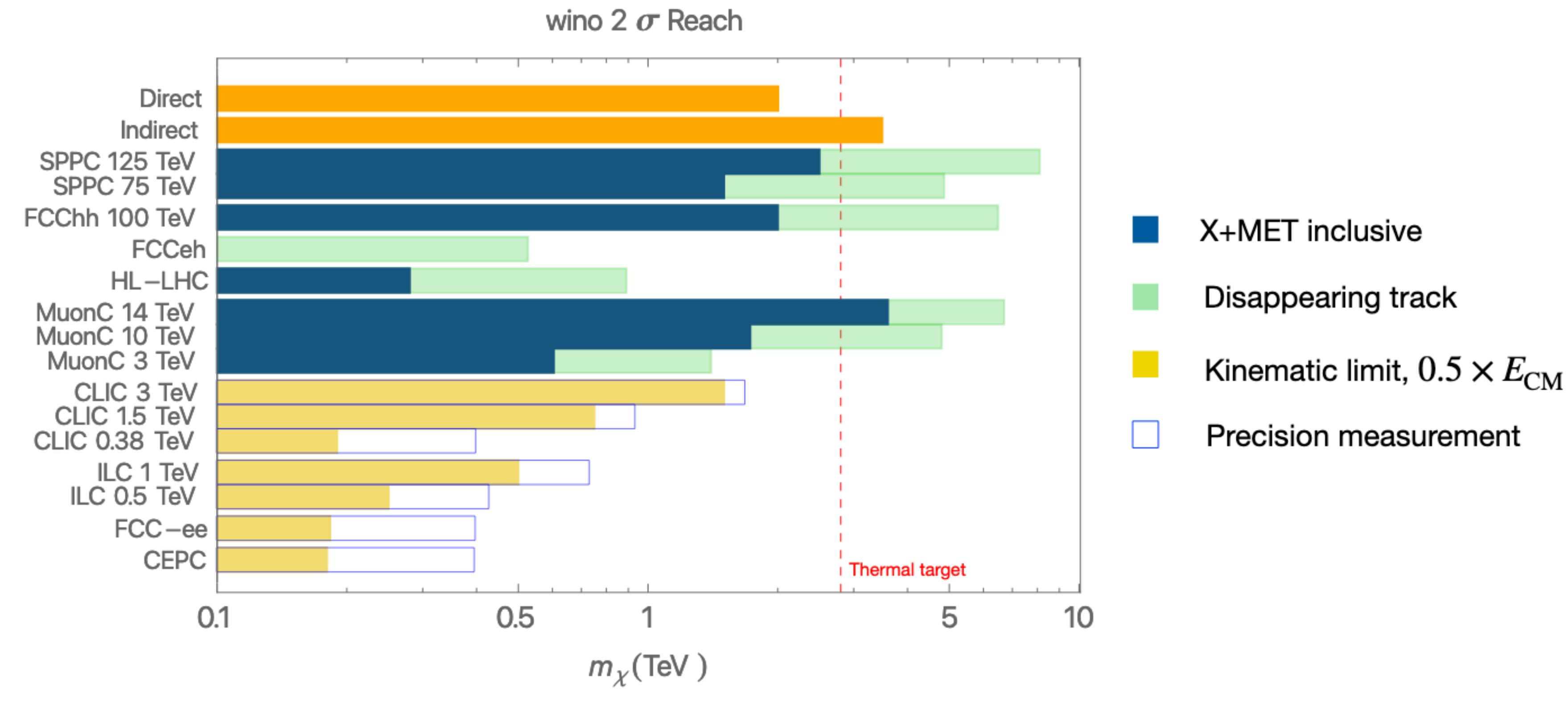
Cirelli, Fornengo and Strumia: hep-ph/0512090, 0903.3381;
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

WIMP Dark Matter

Covering the thermal target



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



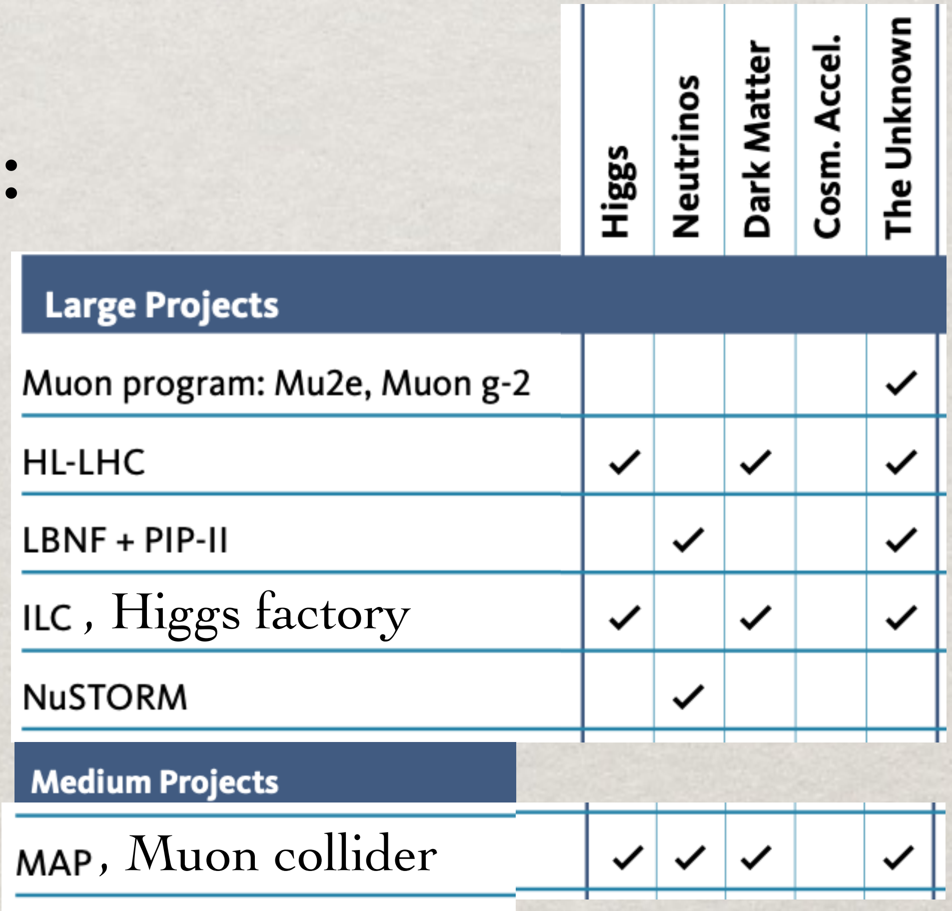
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287; arXiv:2203.07351

Summary: “Who ordered That?”

The muon is such a pleasant surprise Nature offers us!

- **Leads to many discoveries**
- **Provides deeper understanding of Nature**
- **Continues to play a key role in going forward**

Far reaching scope:
all involves with
muon physics →



	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown
Large Projects					
Muon program: Mu2e, Muon g-2					✓
HL-LHC	✓		✓		✓
LBNF + PIP-II		✓			✓
ILC , Higgs factory	✓		✓		✓
NuSTORM		✓			
Medium Projects					
MAP , Muon collider	✓	✓	✓		✓

Muon physics has taken many spot-lights in contemporary HEP!

Look forward to more surprises with muons!

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)

… …