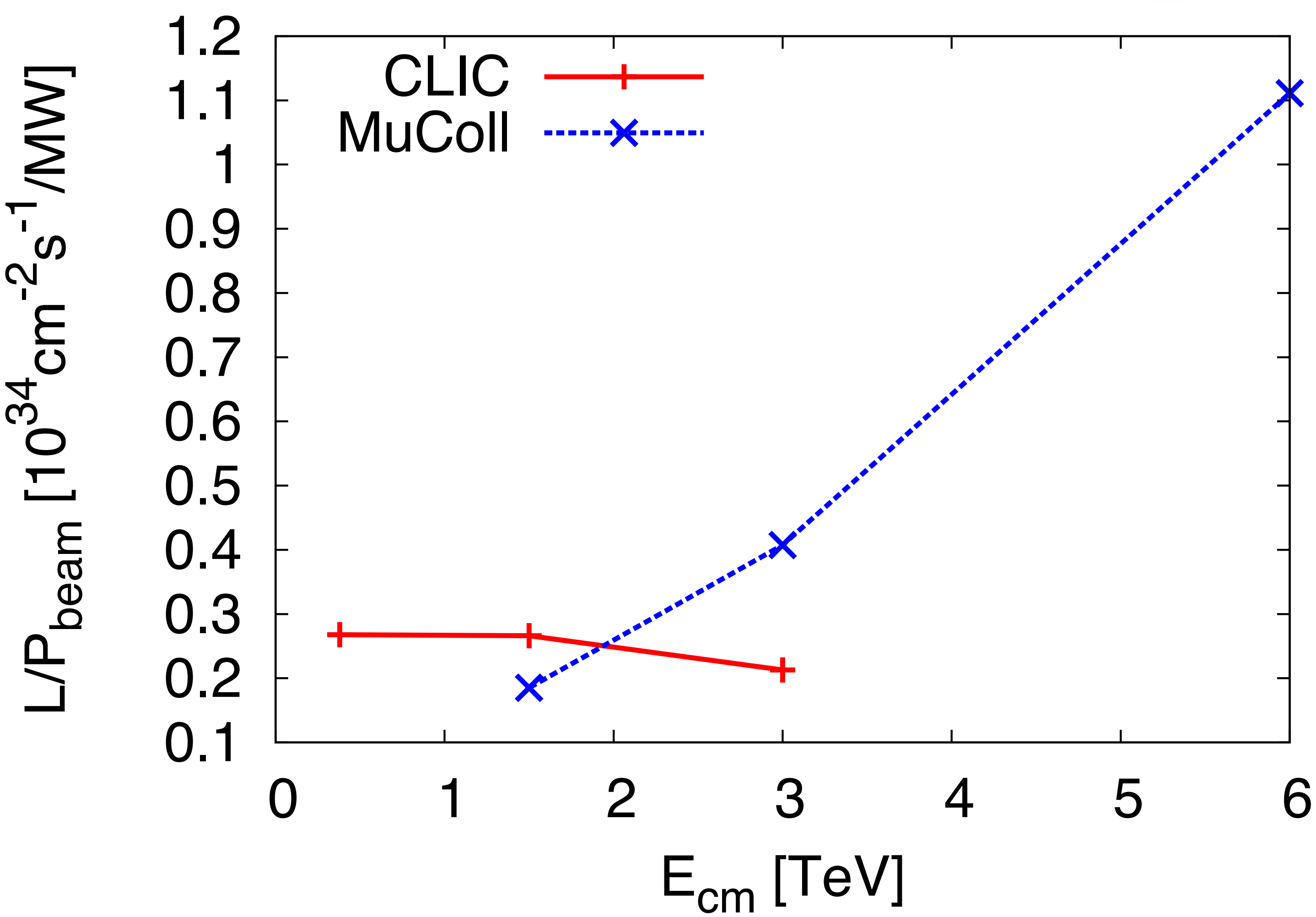
Muon Collider: physics case

LianTao Wang
Univ. of Chicago

GGI tea break, March 2, 2022

The obvious: higher energy, shorter distances

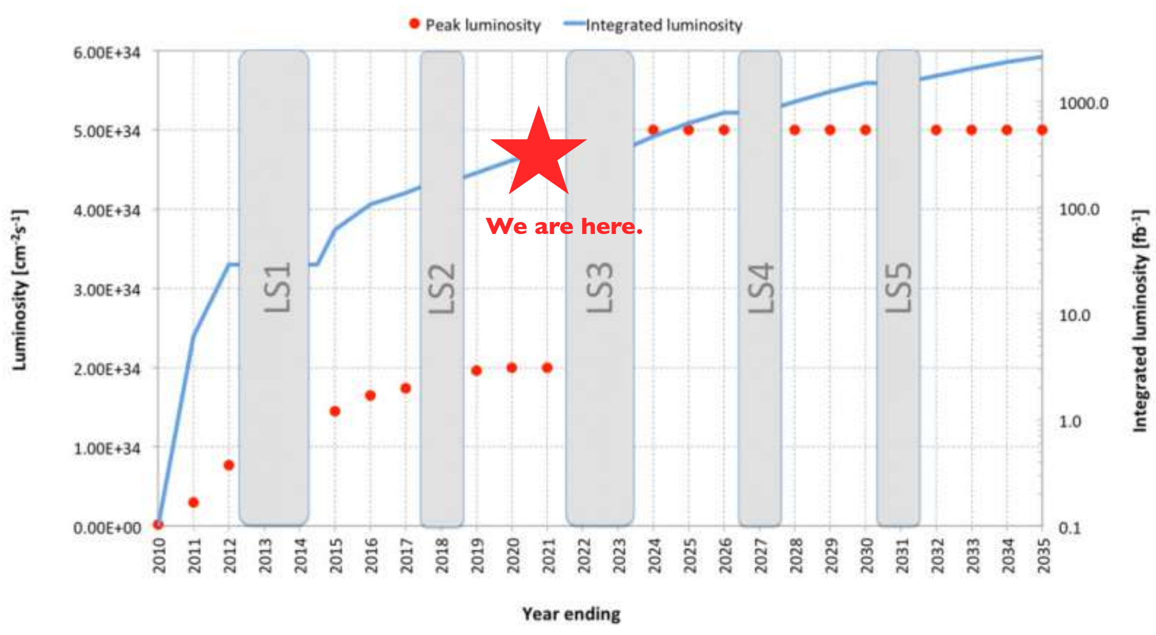


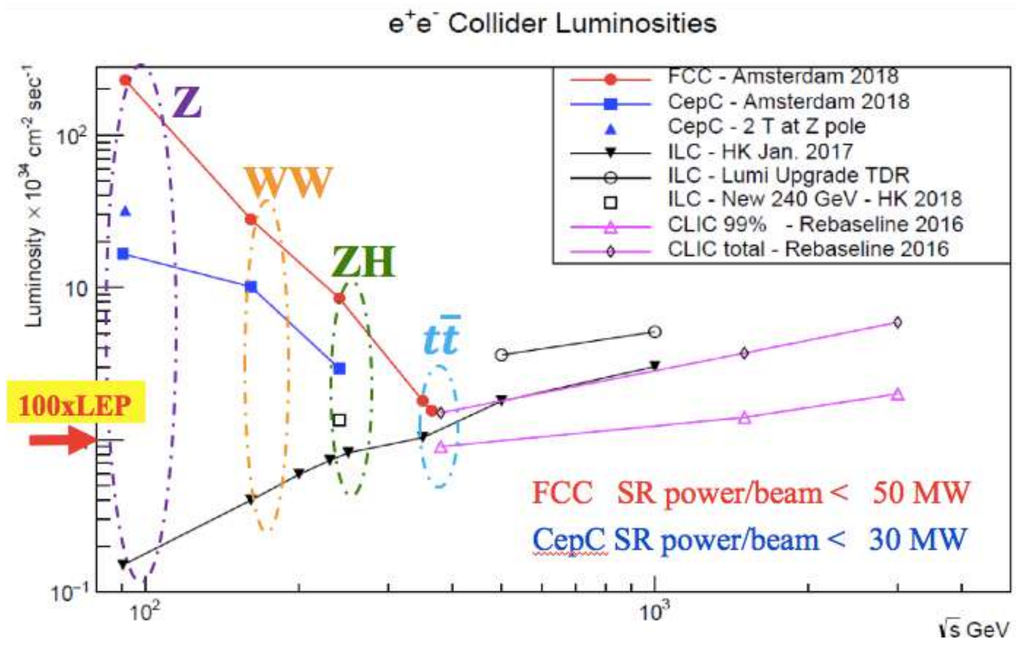
$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Good enough? Yes (for most of us).

Still, why muon collider at these energies?

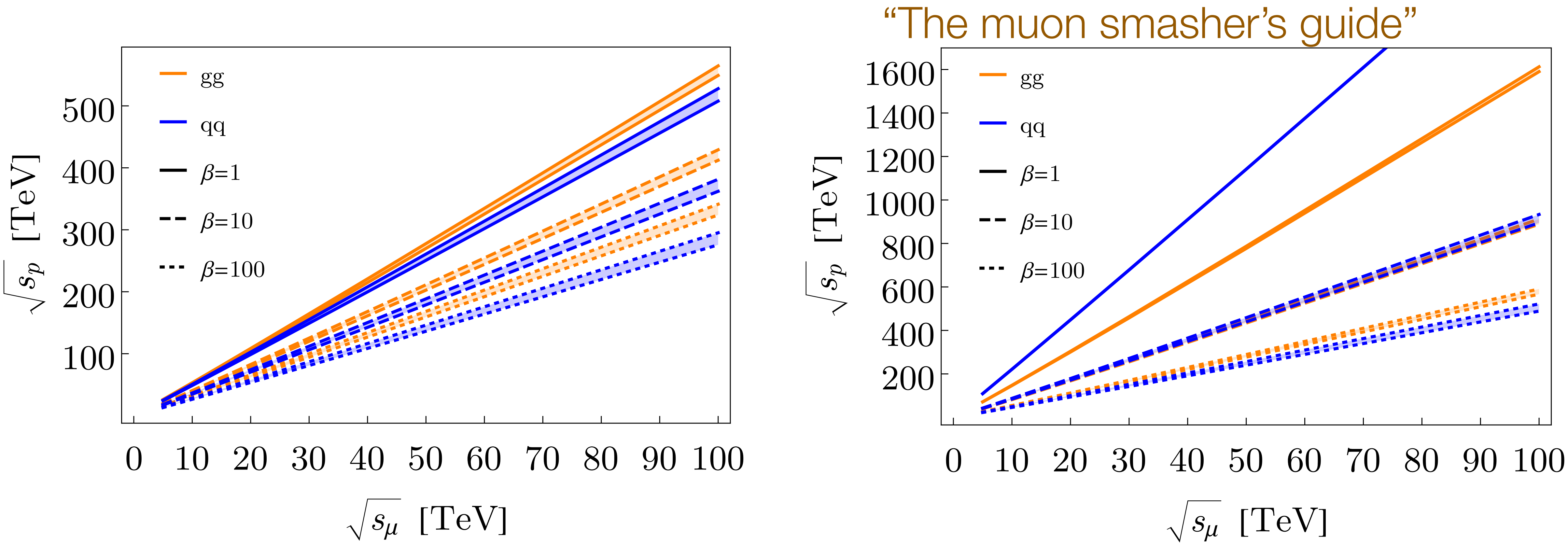
The coming decades





- Main “near term” targets: precision, rare processes.
- Muon collider, going beyond these options, such as the low energy Higgs factories.

Comparison with 100-ish TeV pp collider Such as FCC-hh or SPPC



- Naively, 100 TeV pp ≈ 10+ TeV muon collider.
- Lepton collider "cleaner". Good for precision, difficult channels.

Physics program at a muon collider

- Higgs properties.
- New physics at higher energies.

Higgs properties

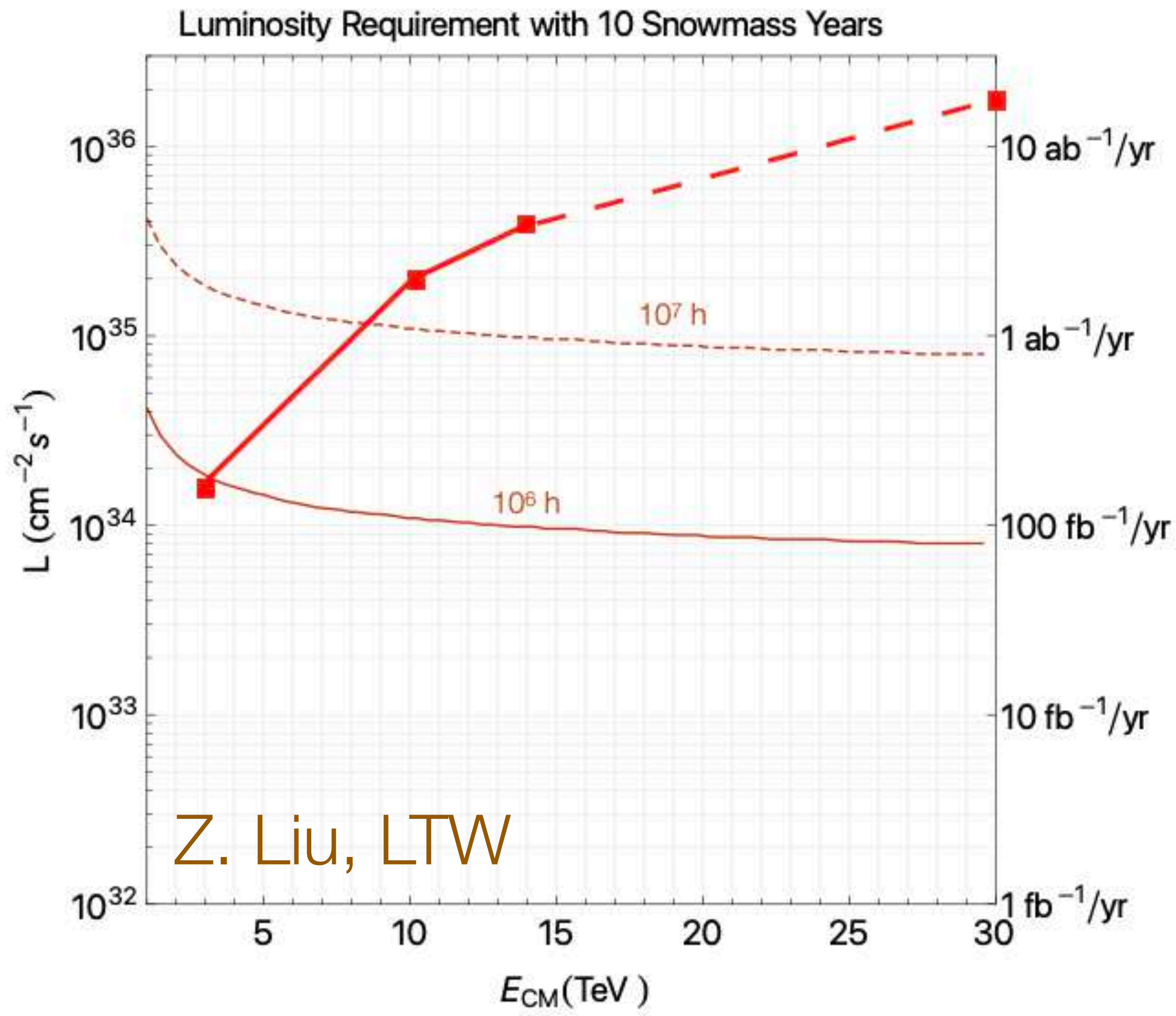
- Obvious: important to understand the Higgs properties.

  - Origin of the weak scale.
  - Nature of EW symmetry breaking.
  - Portal to dark sector.

Higgs properties

- Obvious: important to understand the Higgs properties.
  - Origin of the weak scale.
  - Nature of EW symmetry breaking.
  - Portal to dark sector.
- Not so obvious: what does muon collider bring to the table?

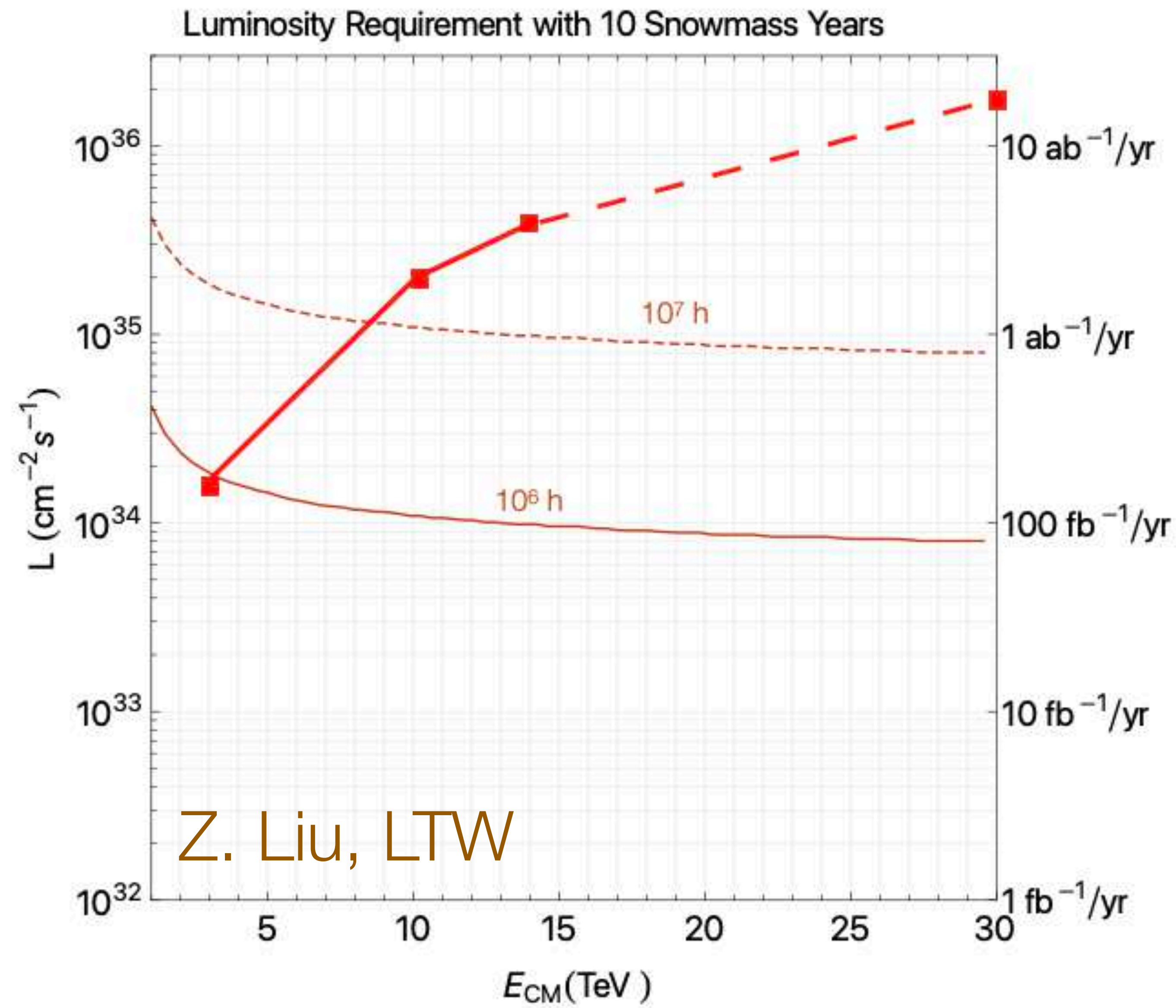
MC as Higgs factory



In comparison:

low(er) energy Higgs factories
~ 10^6 Higgses

MC as Higgs factory



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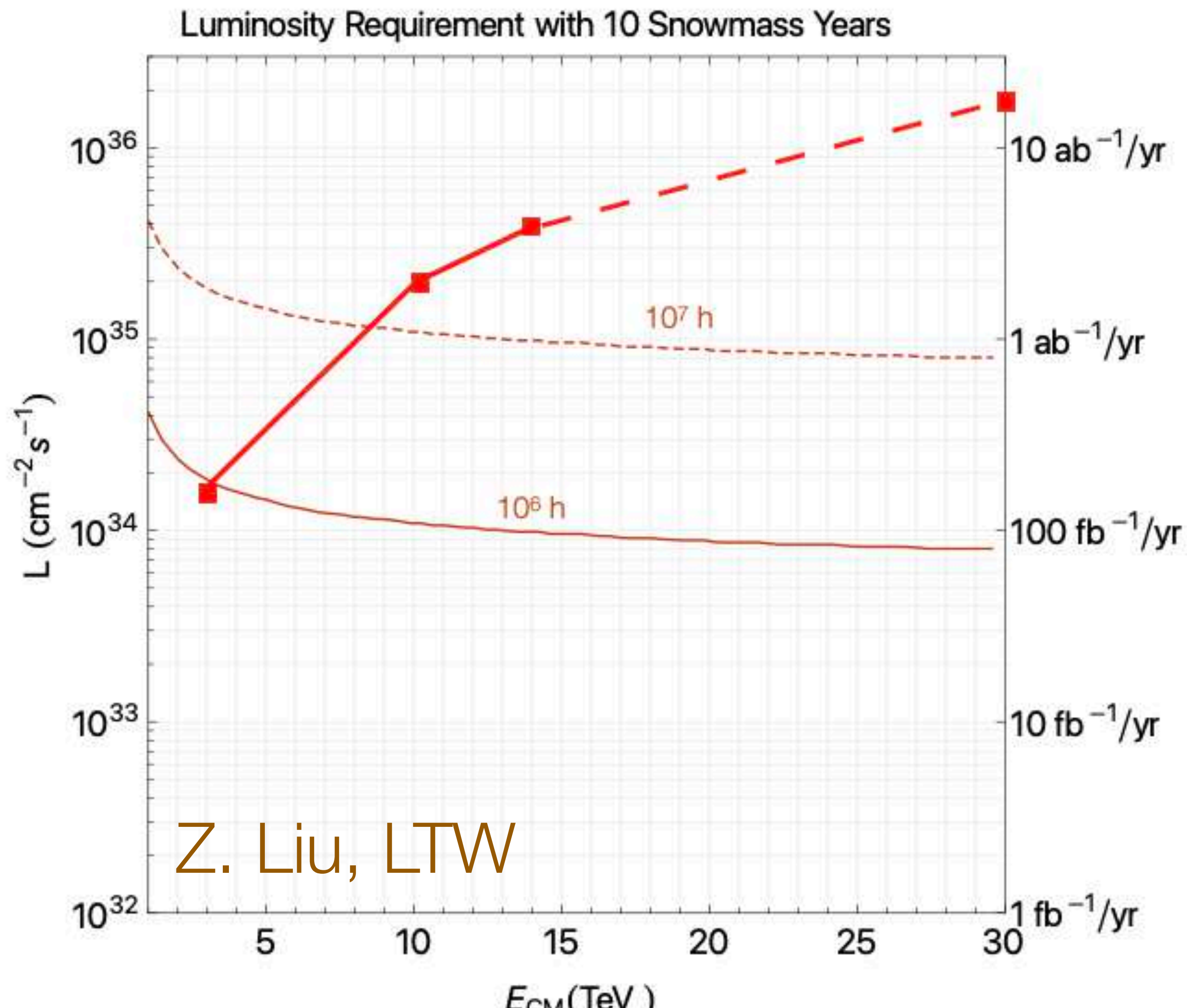
Assuming:

$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

E_{CM} :	125 GeV	1.5 TeV	3 TeV	6 TeV	10 TeV	30 TeV
# of Higgs/10^7s:	~10^{4-5}	~4×10^4	~2×10^5	10^6	10^7	10^8

MC as Higgs factory



In comparison:

low(er) energy Higgs factories
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better than low E higgs factories

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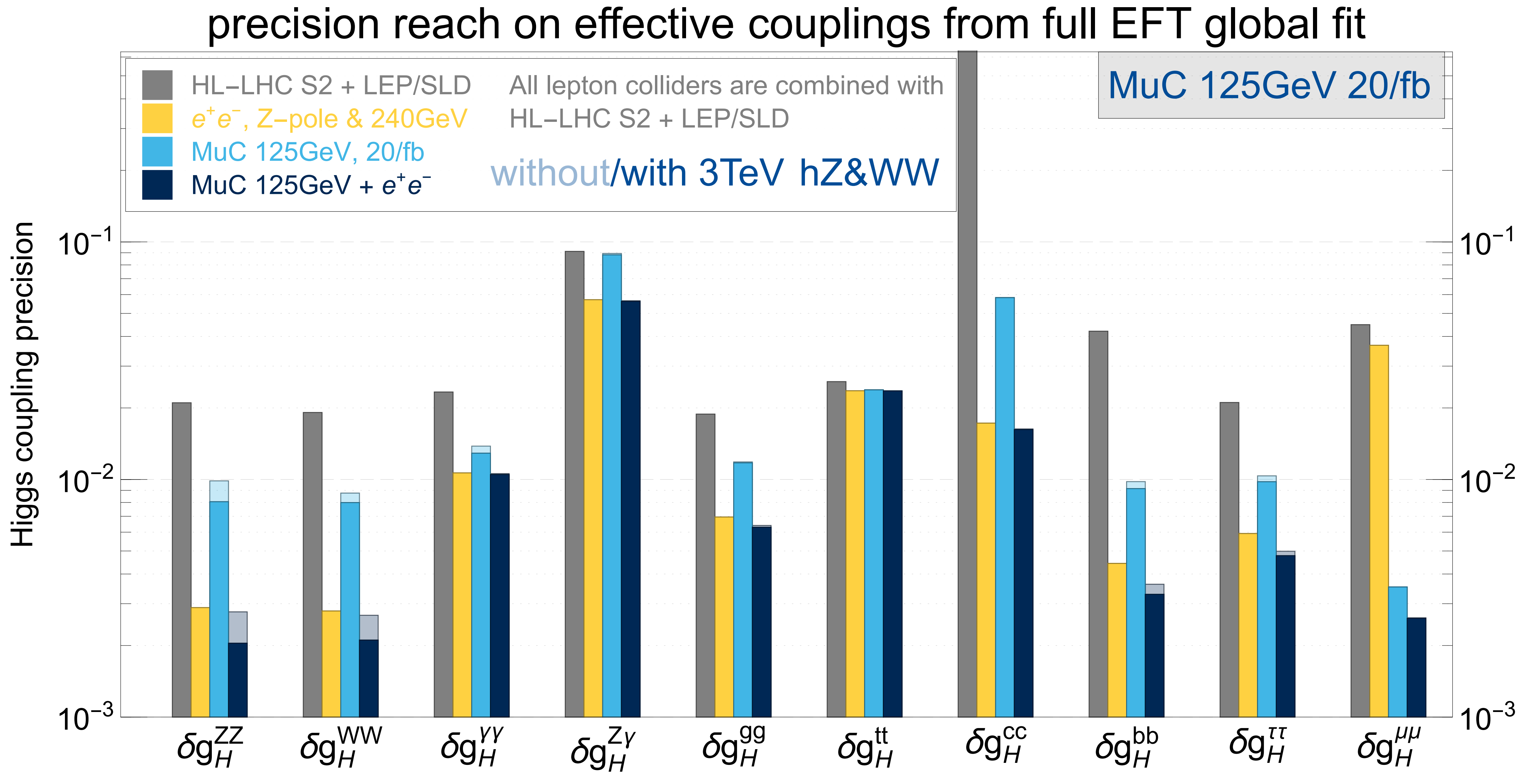
Higgs coupling

J. de Blas, J. Gu, Z. Liu, preliminary

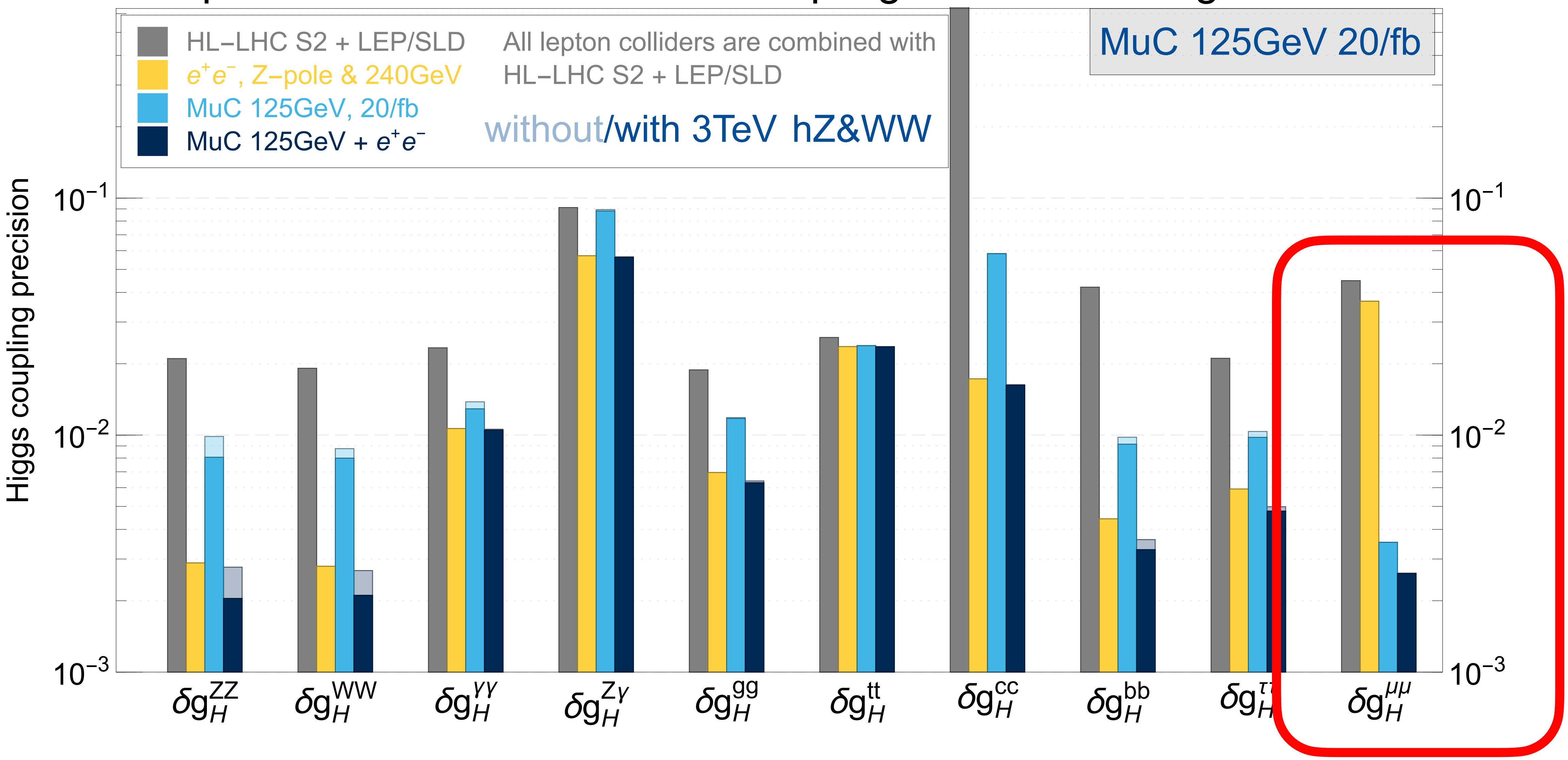


With only 125 GeV MC, less competitive.

Higgs coupling

J. de Blas, J. Gu, Z. Liu, preliminary

precision reach on effective couplings from full EFT global fit



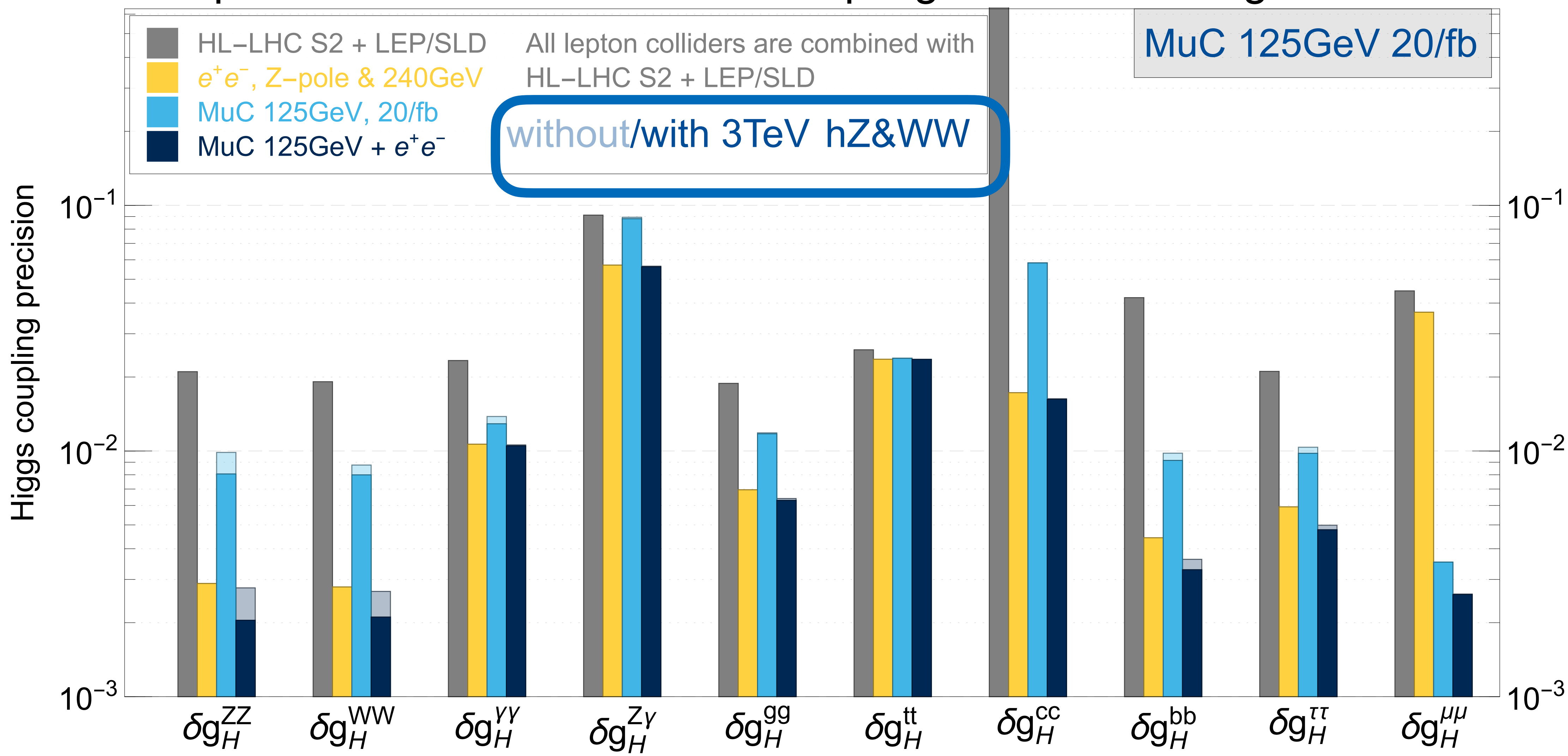
Except this!

With only 125 GeV MC, not too competitive.

Higgs coupling

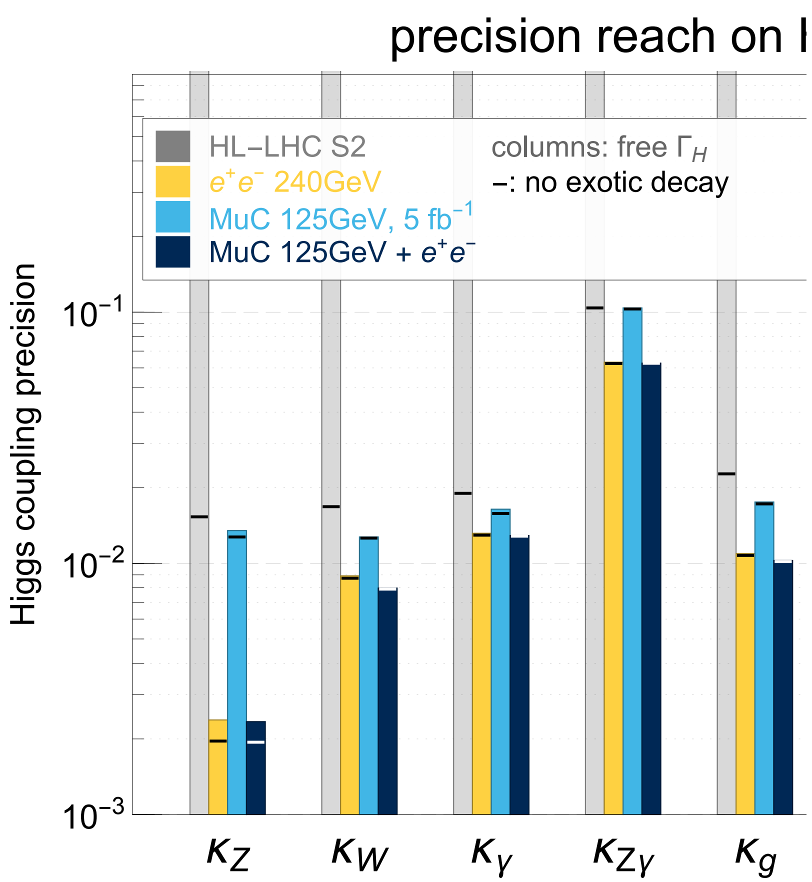
J. de Blas, J. Gu, Z. Liu, preliminary

precision reach on effective couplings from full EFT global fit



Higher energy helps.

Higher energy



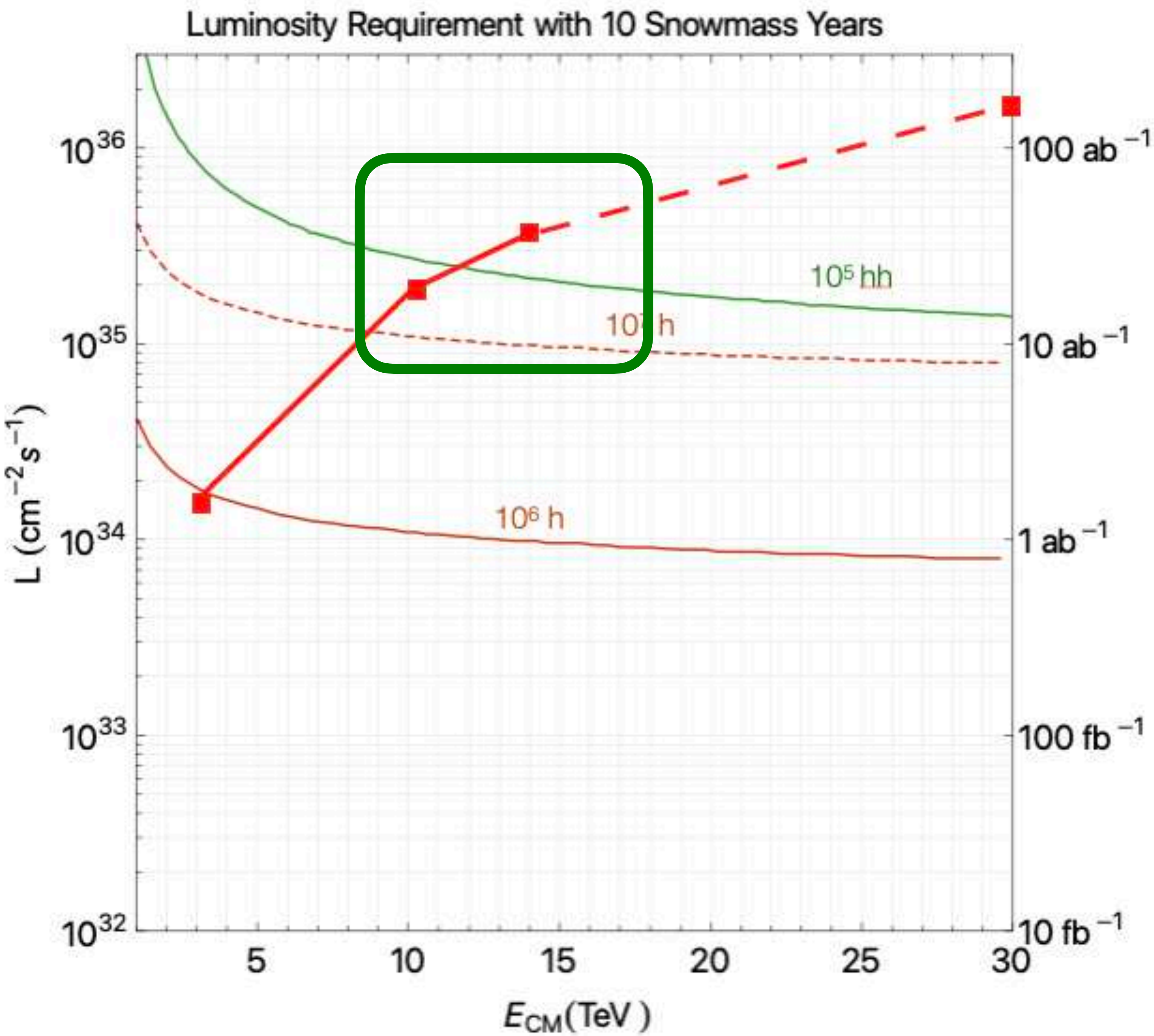
J. de Blas, J. Gu, Z. Liu, preliminary

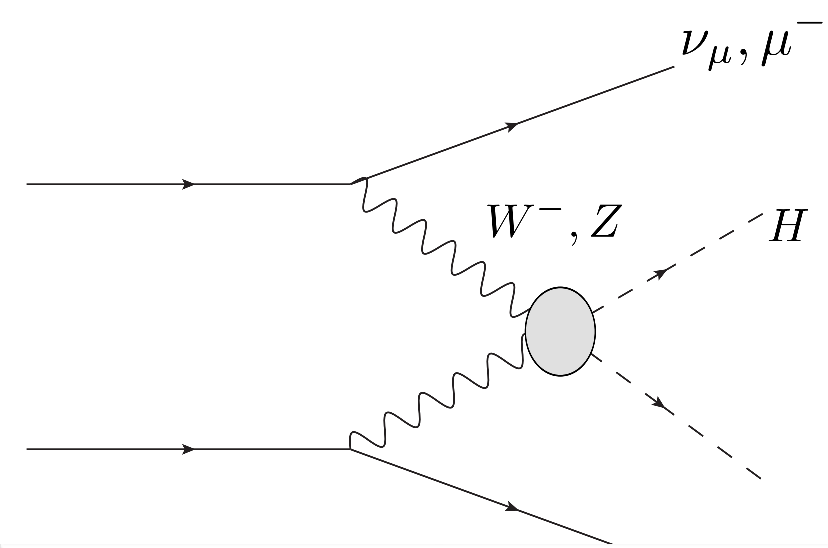
	Fit Result [%]	
	10 TeV Muon Collider	with HL-LHC
κ_W	0.06	0.06
κ_Z	0.23	0.22
κ_g	0.15	0.15
κ_γ	0.64	0.57
$\kappa_{Z\gamma}$	1.0	1.0
κ_c	0.89	0.89
κ_t	6.0	2.8
κ_b	0.16	0.16
κ_μ	2.0	1.8
κ_τ	0.31	0.30

Estimates in “muon smasher’s guide”

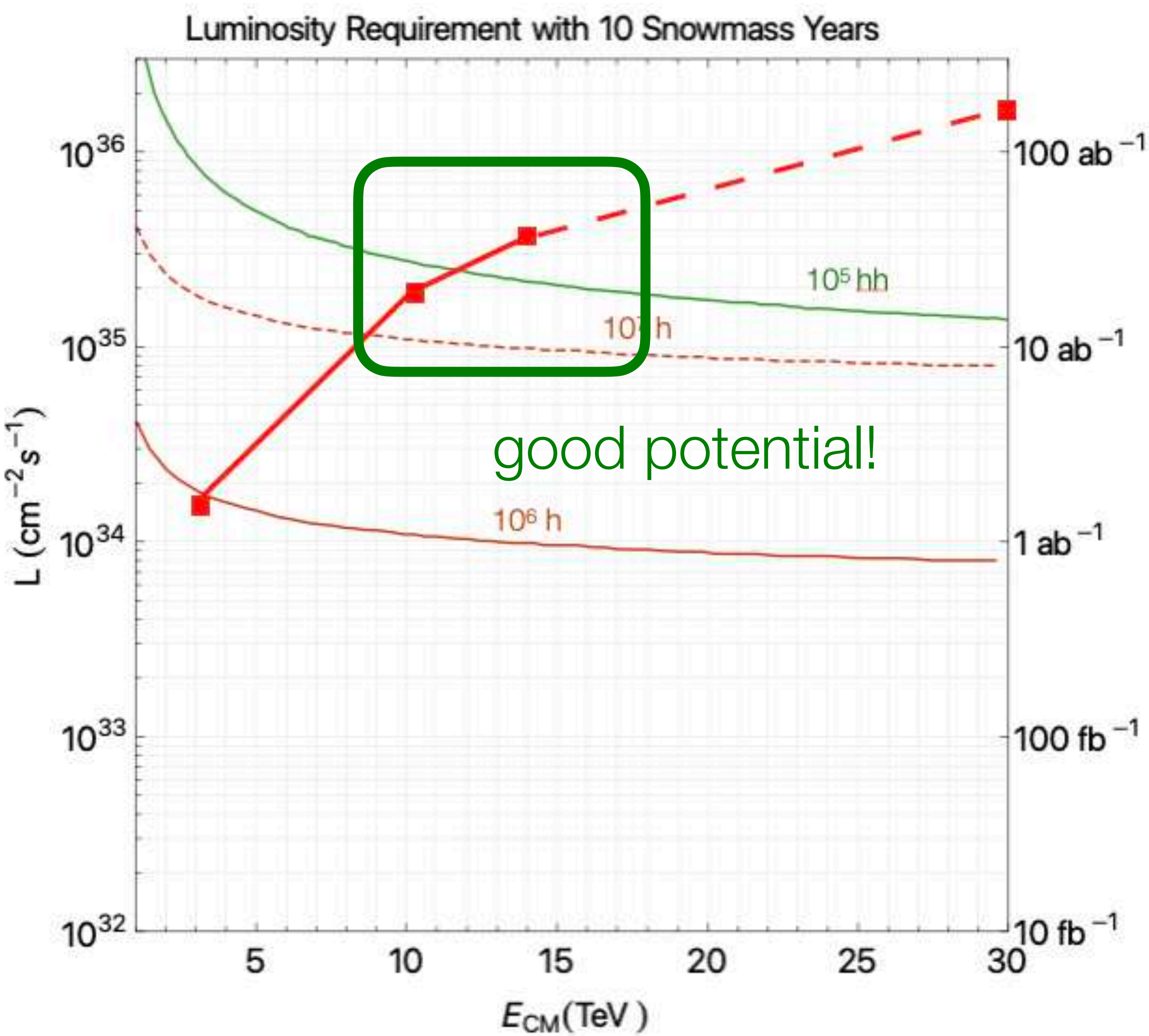
0.1% level or better measurement possible at higher energies

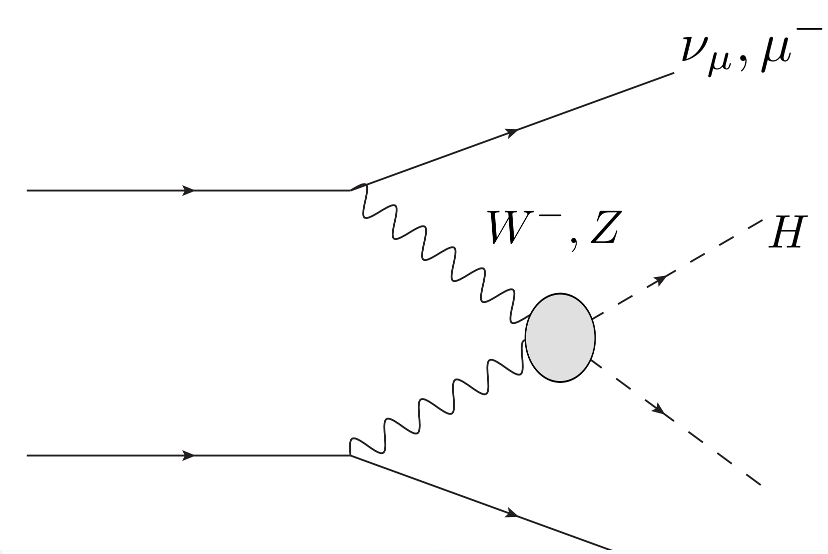
Double Higgs





Double Higgs

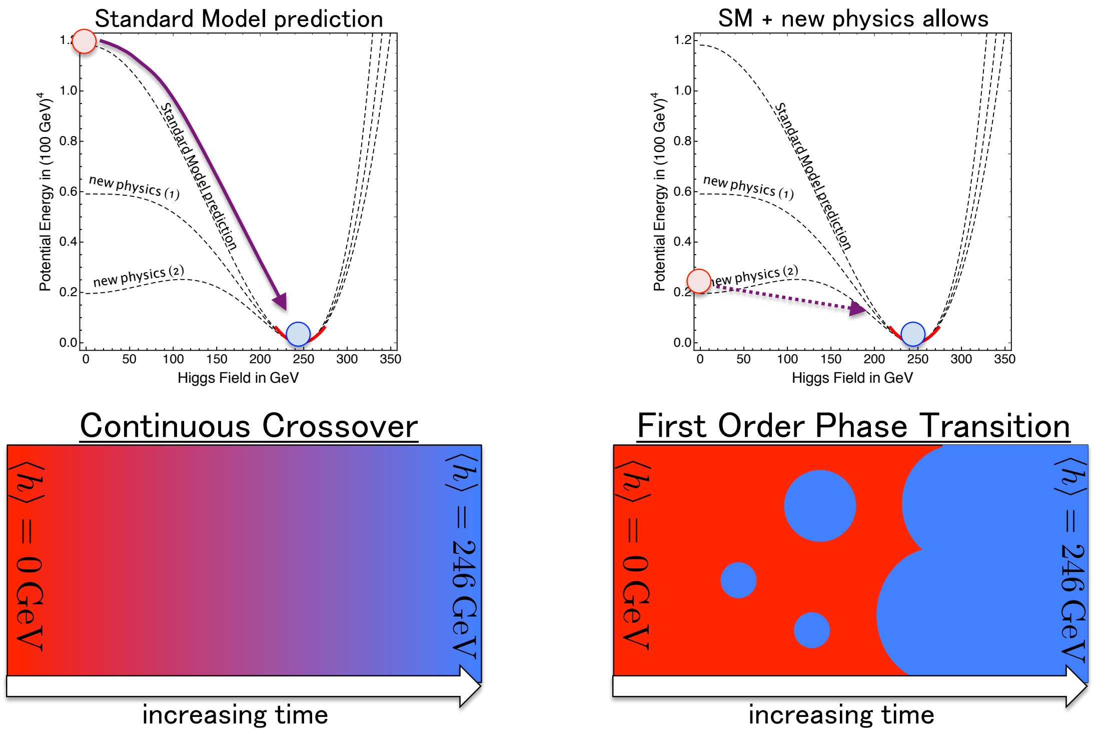


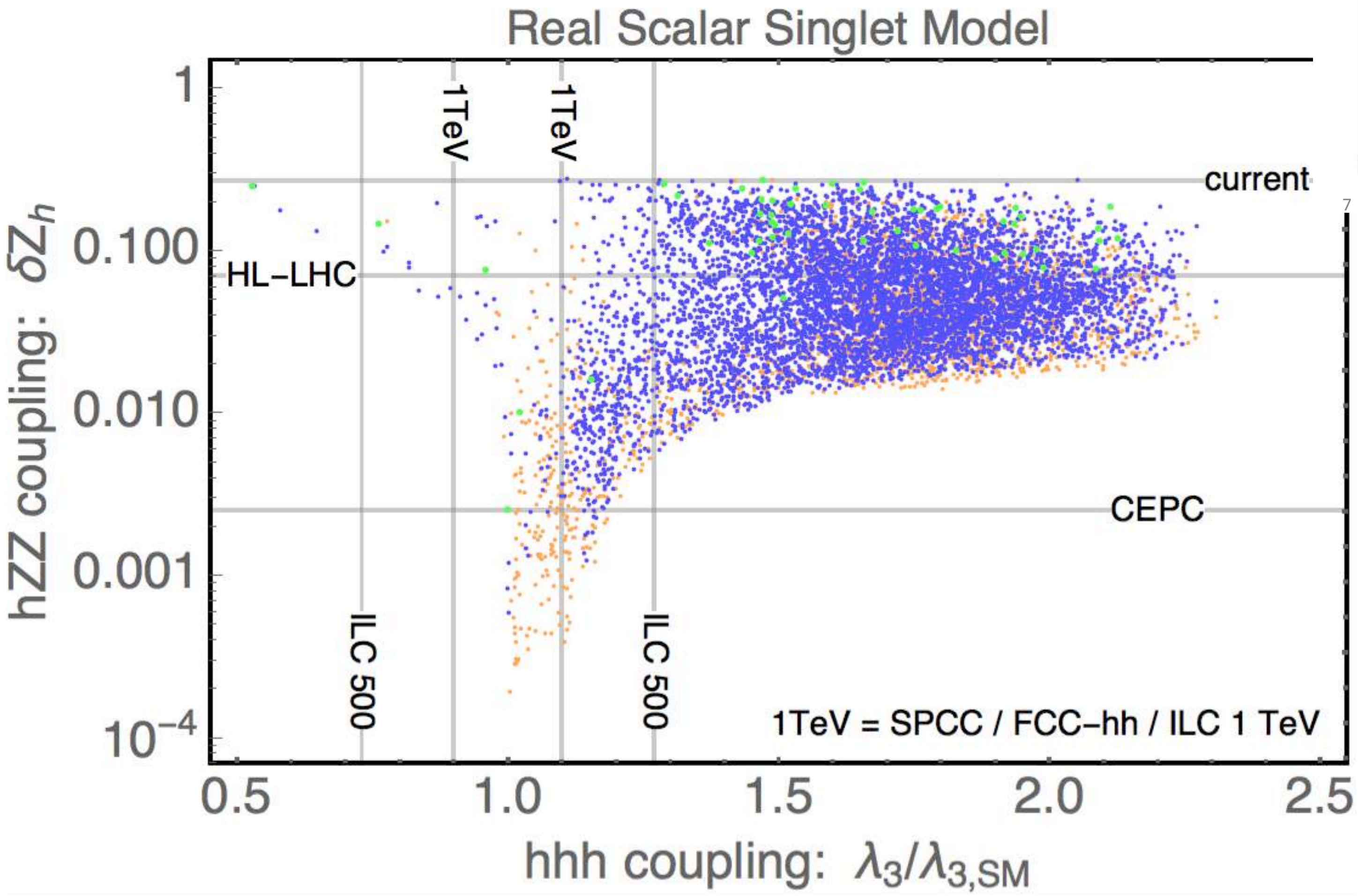


New physics effects also larger at higher energies.

Nature of EW phase transition

Which one is the right picture?

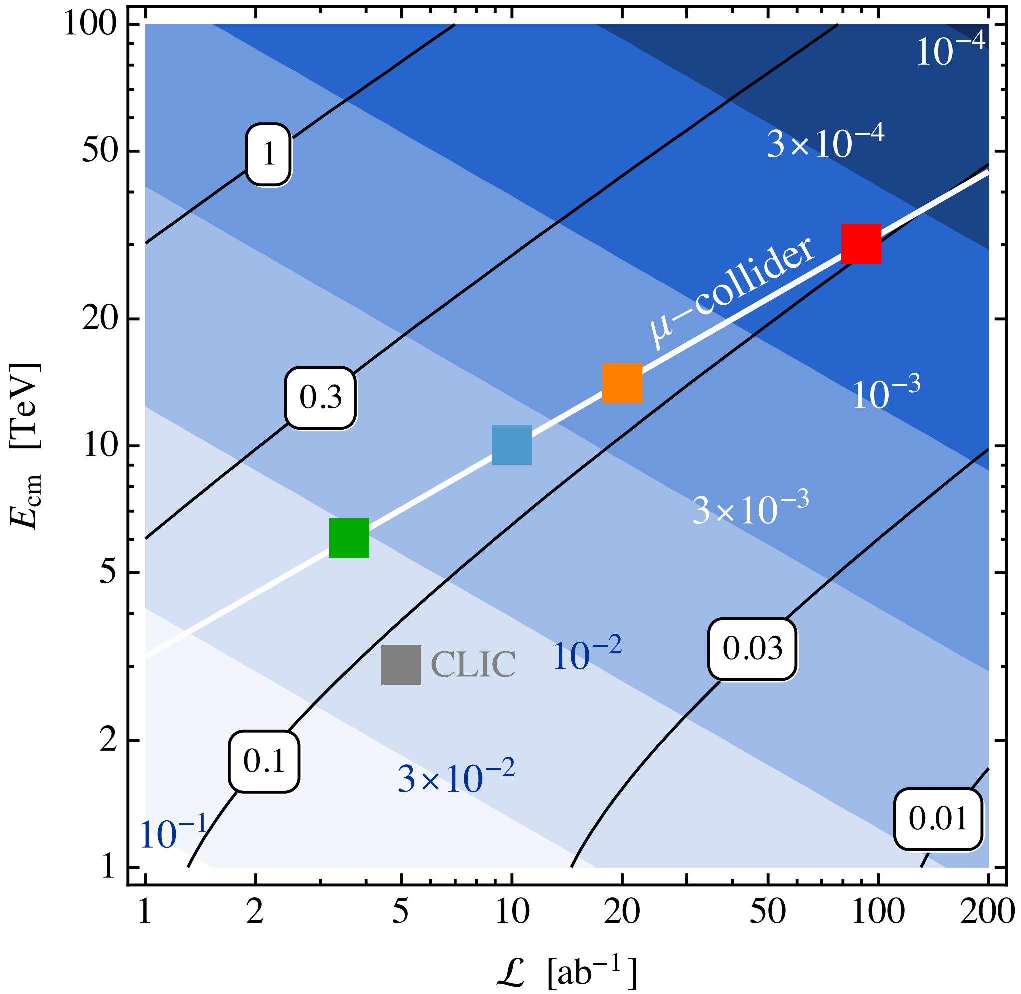




Precision Higgs measurements, self coupling and beyond, can reveal a lot.

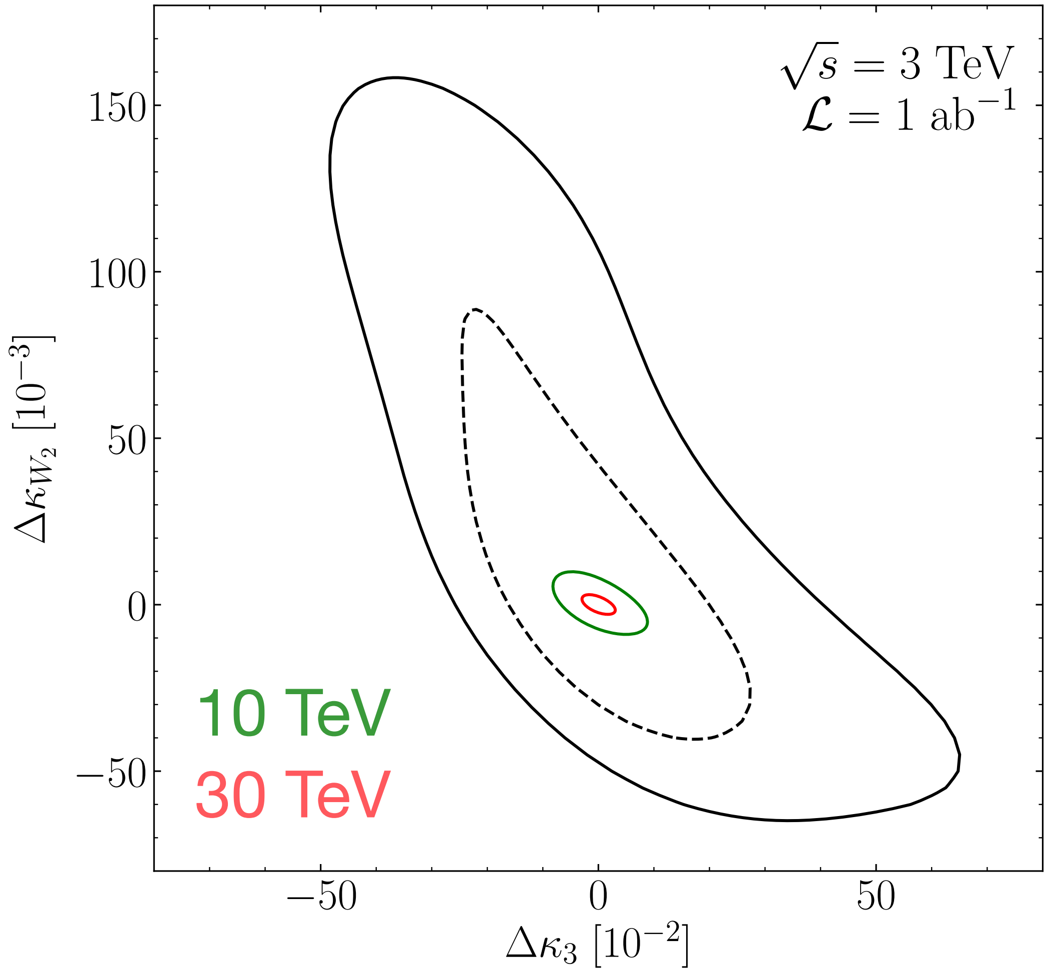
Self coupling modification

$$\xi \equiv C_H v^2$$



Buttazzo, Franceschini, Wulzer, 2012.11555

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu (H^\dagger H)\right)^2$$



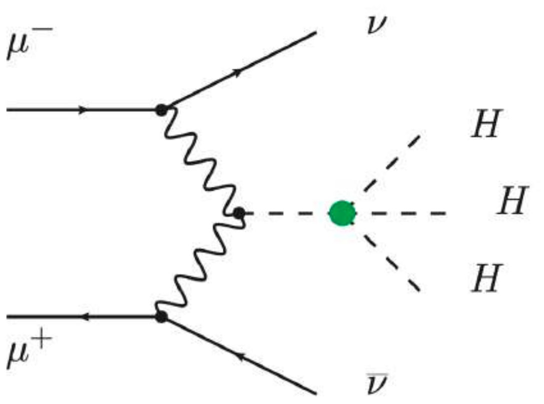
Han, Liu, Low, Wang, 2008.12204

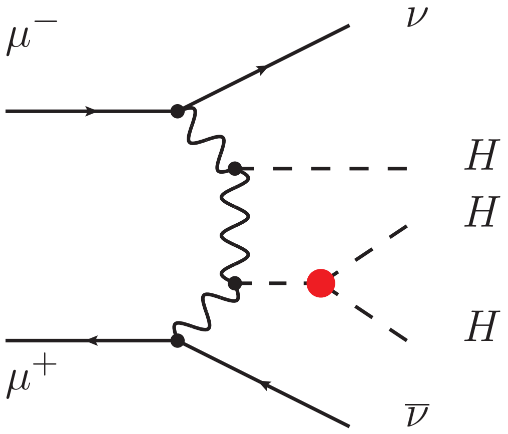
$$\mathscr{L} \supset -\frac{m_H^2}{2v}\left(\kappa_3 H^3 + \frac{1}{4v}\kappa_4 H^4\right)$$

Precision better than CLIC, FCC-hh for E_{CM} = 10 TeV

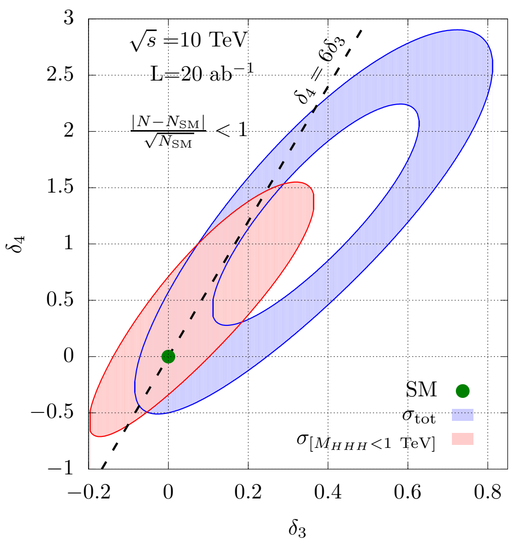
Higgs quartic coupling

3 Higgs final state

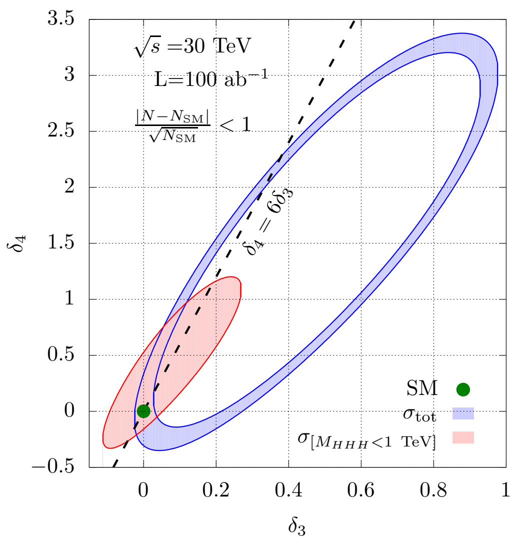




$$\frac{S}{\sqrt{B}} = \frac{|\mathcal{L}\cdot(\sigma - \sigma_{SM})|}{\sqrt{\mathcal{L}\cdot\sigma_{SM}}} \leq 1$$



10 TeV $\delta_4 \sim [-0.4, 0.7]$



30 TeV $\delta_4 \sim [-0.2, 0.5]$

Other colliders:

$$\text{ILC} \sim [-10, 10]$$
$$\text{CLIC} \sim [-5, 5]$$
$$\text{FCC} \sim [-2, 4]$$

A 10 TeV muon collider would do better than FCC

Slide of E. Vryonidou

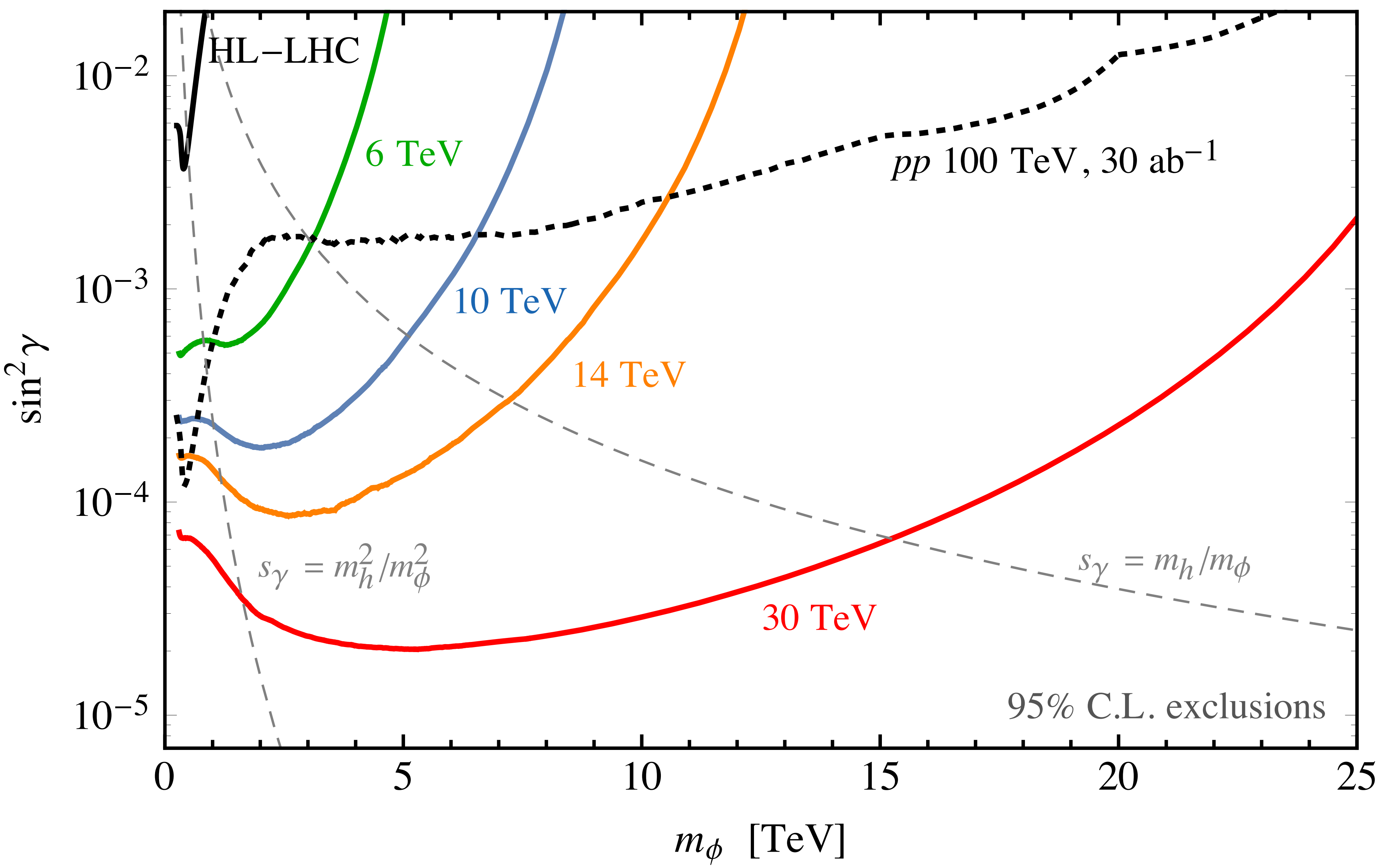
$$\lambda_3 = \lambda_{SM}(1+\delta_3) = \kappa_3\lambda_{SM}$$

$$\lambda_4 = \lambda_{SM}(1+\delta_4) = \kappa_4\lambda_{SM}$$

Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao, 2003.13628

Higgs's friends

D. Buttazzo, D. Redigolo, F. Sala, A. Tesi, 1807.04743



Singlet scalar mixing with the Higgs.

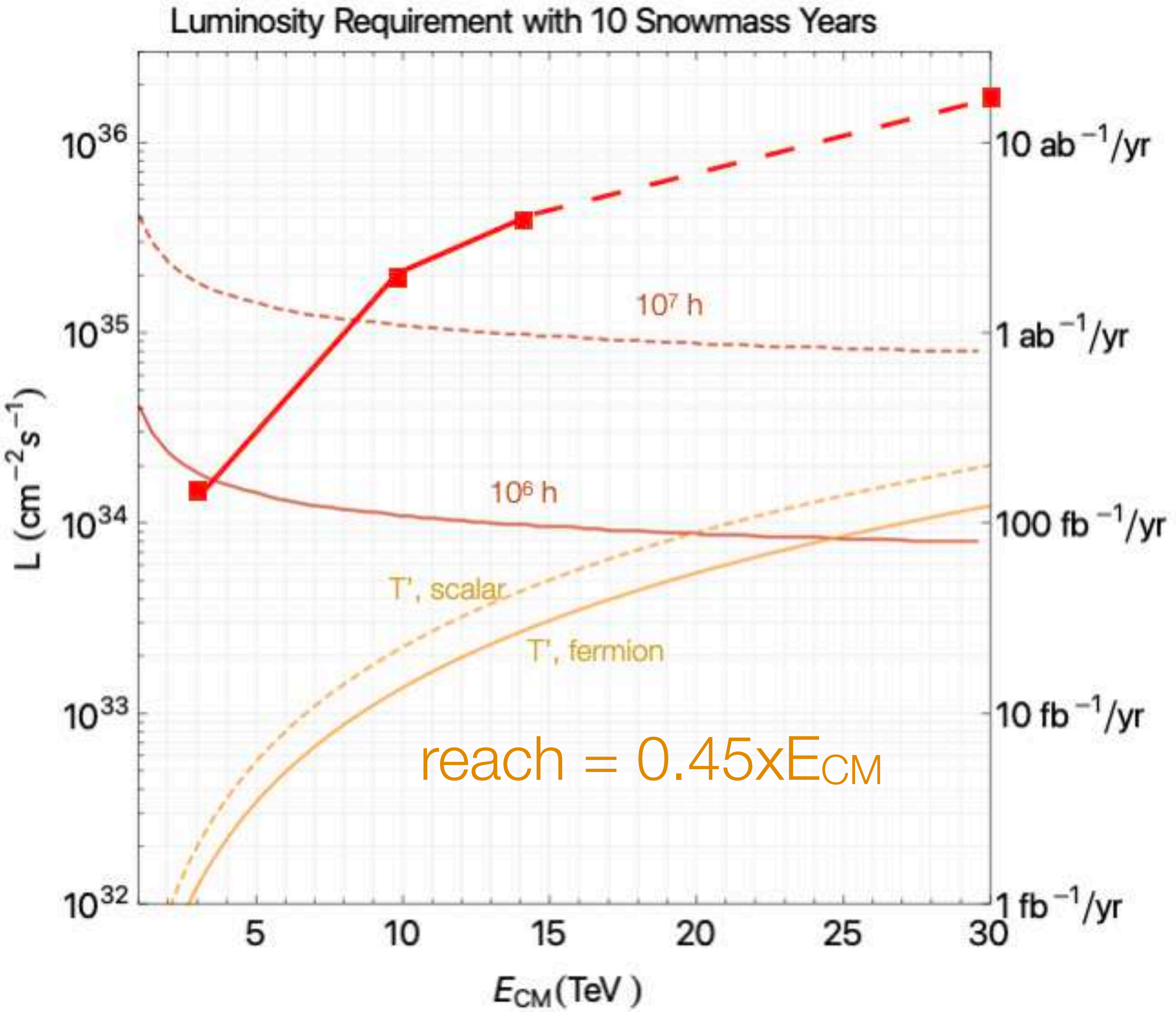
Origin of the weak scale

New physics at
TeVs-10 TeV ?

Λ_{EW}

The usual naturalness, not discovered at the LHC, just a little delayed?

Top partner



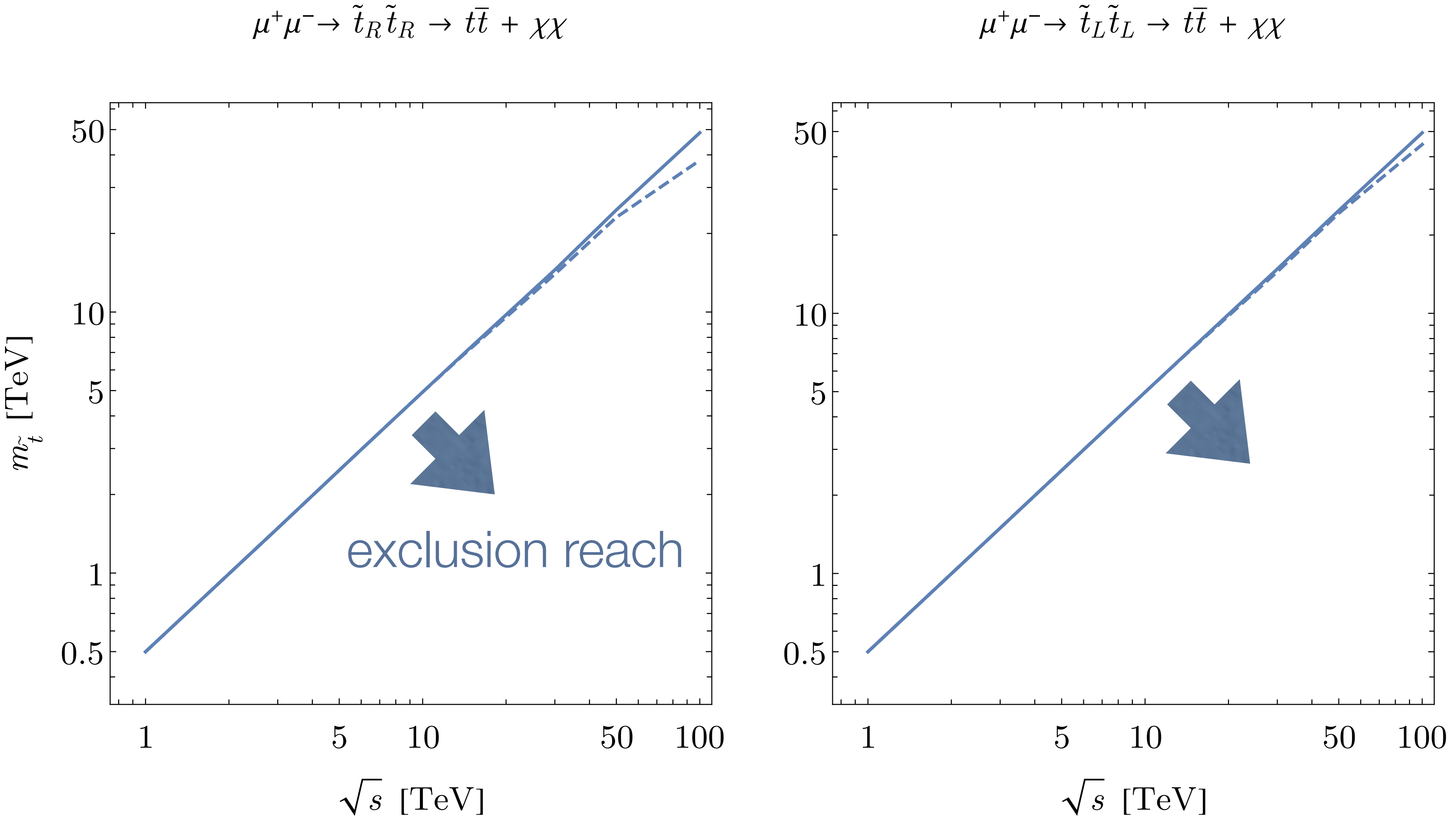
Pair production

$$\mu^+\mu^- \to T'\tilde{T}'$$

Spectacular signal, 10s event needed for discovery

SUSY top squark

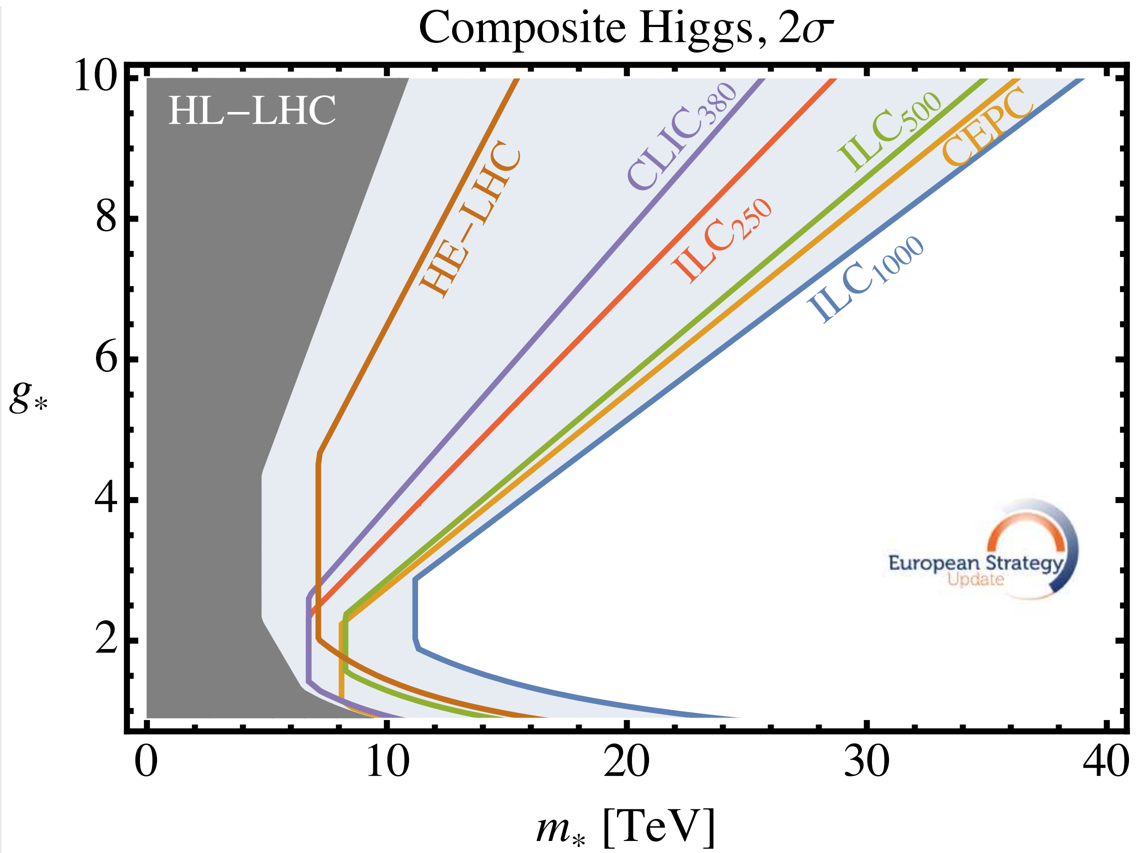
Estimates in “muon smasher’s guide”

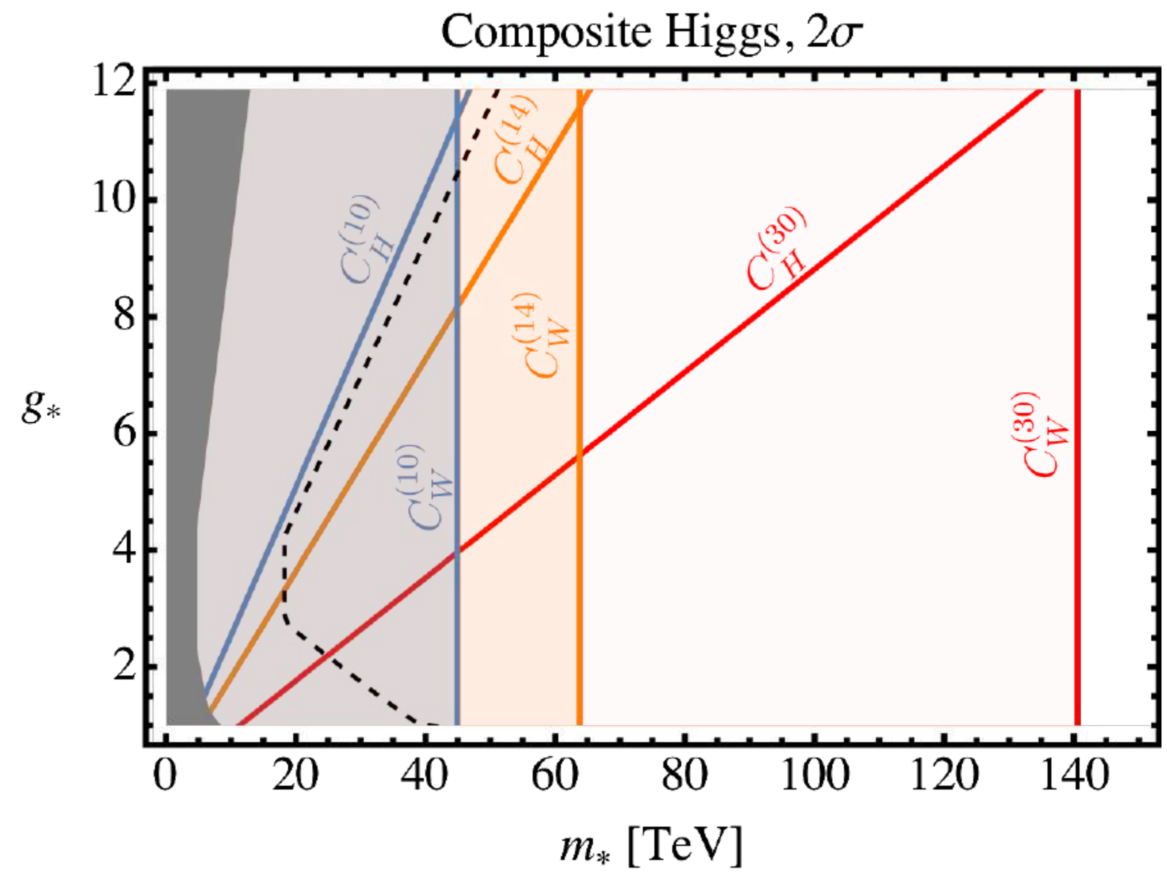


Reach quite close to $0.5\mathrm{xE_{CM}}$

Spectacular signal, 10s event needed for discovery

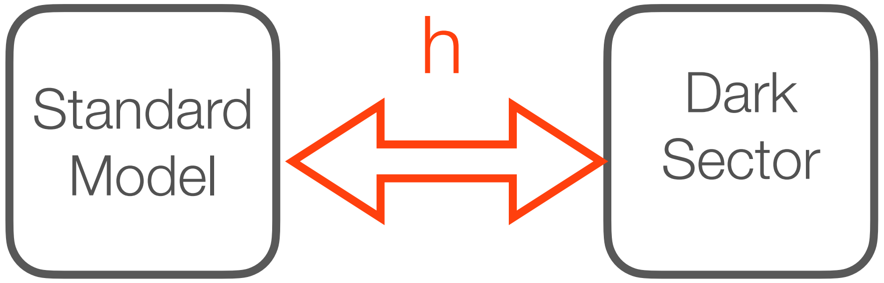
Composite





Through precision measurement at high energies.

Higgs portal



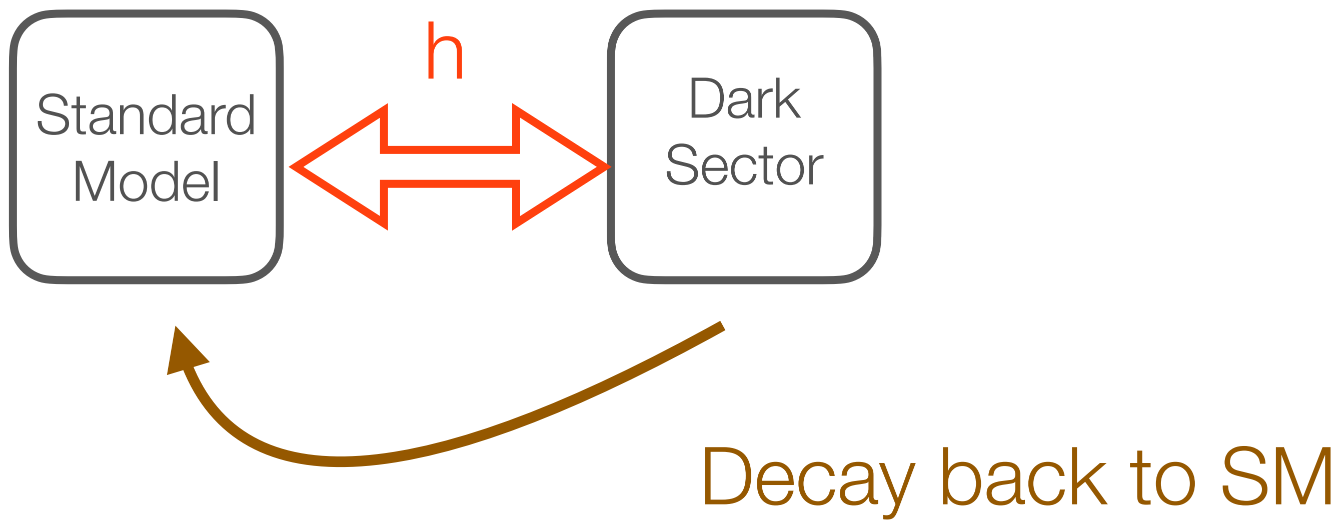
- Dark sector coupling to the SM

$$O_{\rm SM} \cdot O_{\rm dark}$$

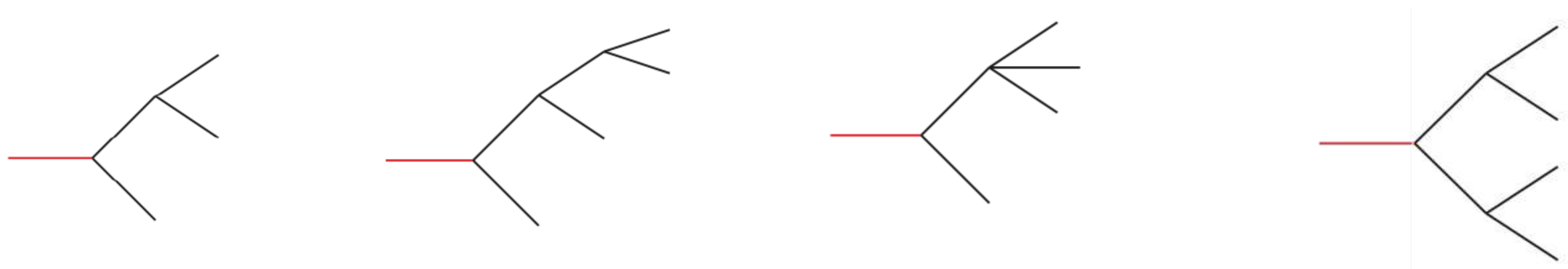
$O_{\rm SM}$: gauge inv. SM operator $O_{\rm dark}$: dark sector operator

- More relevant coupling ⇔ lowest dim operator
  - Unique choice: $O_{SM} = HH^{\dagger}$. Higgs portal.

Higgs rare decay

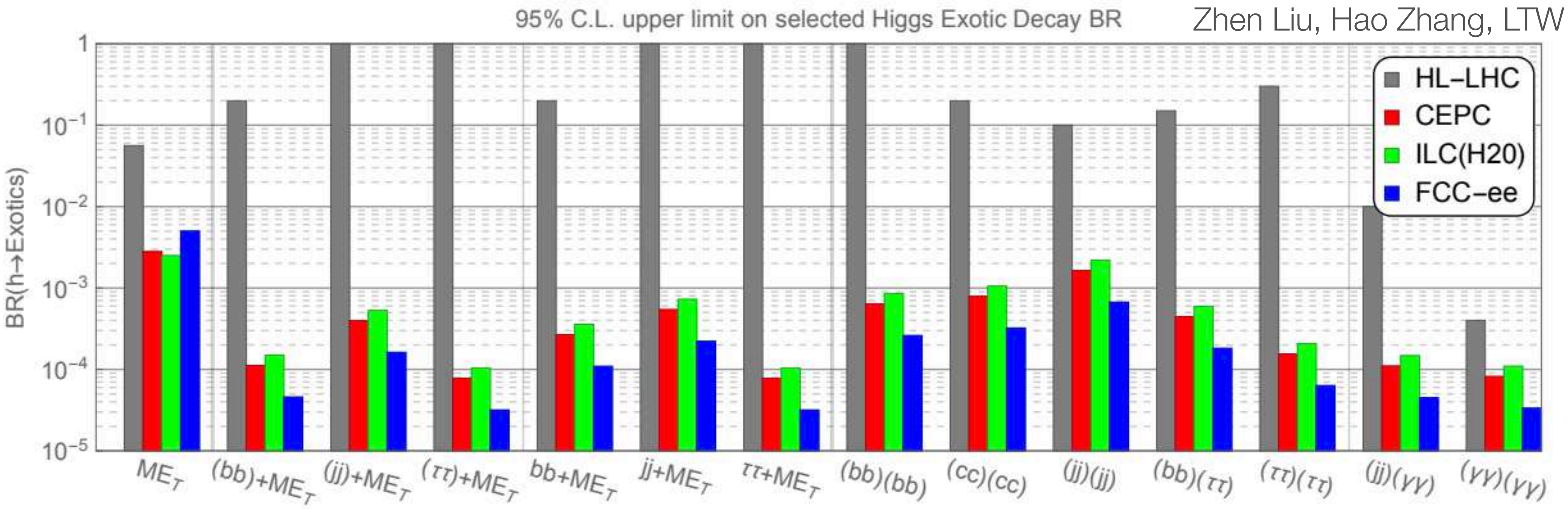


$h \to 2 \to 3$ $\quad$ $h \to 2 \to 3 \to 4$ $\quad$ $h \to 2 \to (1+3)$ $\quad$ $h \to 2 \to 4$



....

Higgs exotic decay



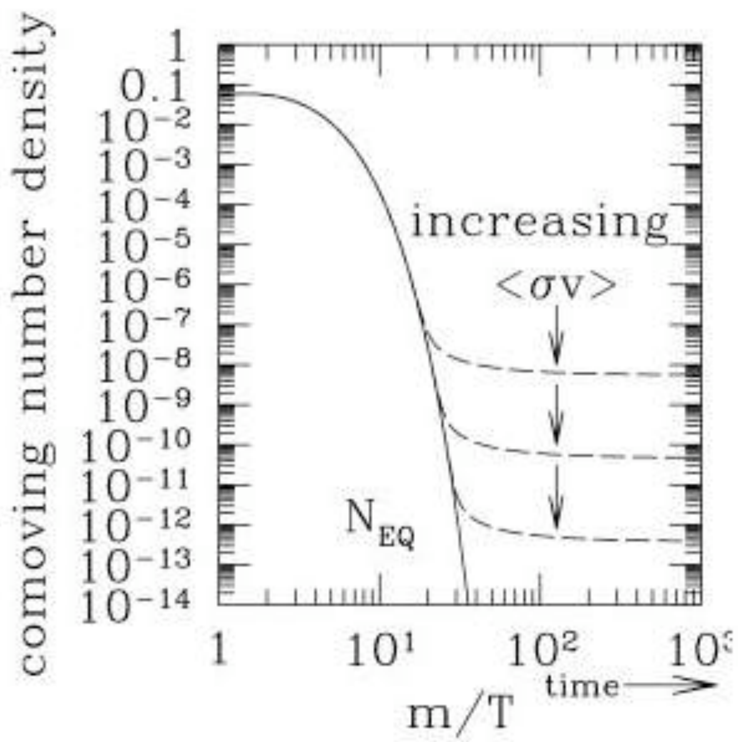
Complementary to hadron collider searches

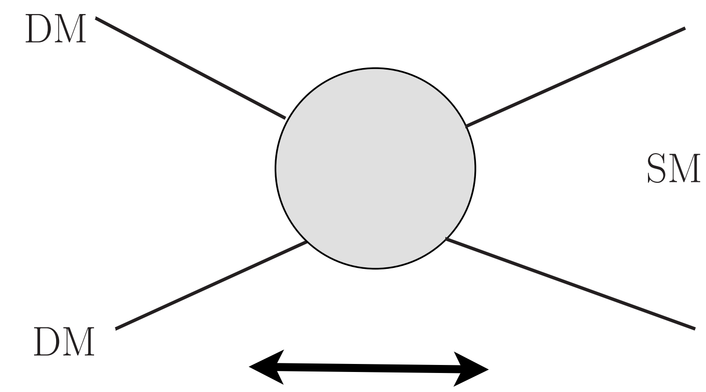
Studies done for low E Higgs factory with 10^6 Higgses. High energy muon colliders, with 10^7+ Higgses at 10+ TeV, will do even better.

(Other) new physics at high scale

* Dark matter (WIMP)
* Z'
* Flavor/CP
* Lepto-quark
* ...

WIMP:



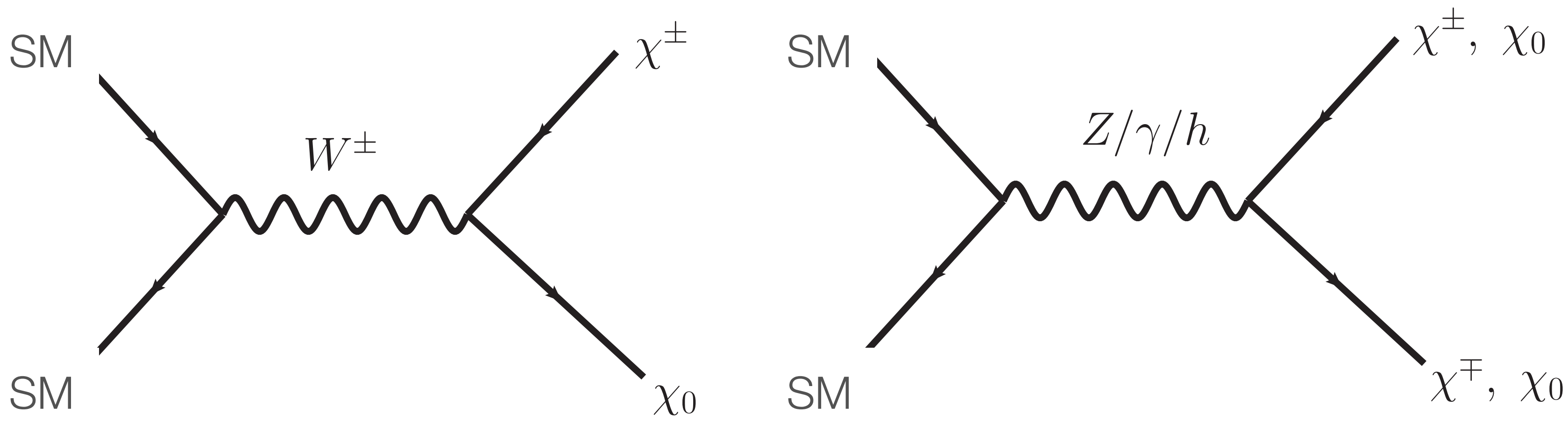


$$\langle \sigma v \rangle \sim \frac{g_{\mathrm{D}}^4}{m_{\mathrm{DM}}^2}$$

- Simple assumption: DM in thermal eq. with the SM in early universe

Simplest model: part of an EW multiplet

"Minimal dark matter", Cirelli, Fornengo and Strumia, hep-ph/0512090, 0903.3381



- Simplicity: there is no additional new mediator.
    - Mediated by W/Z/h. Very predictive.
- In SUSY, there are two such examples
    - Higgsino: doublet. Wino: triplet.

DM part of a EW multiplet

$$\text{DM} \in (1, n, \text{Y}) \text{ of } \text{SU(3)}_\text{C} \times \text{SU(2)}_\text{L} \times \text{U(1)}_\text{Y}$$

- Consider first the fermionic mulitplets.
  - Only couplings at the renormalizable level are the gauge interactions.
  - The only free parameter at this level is the mass, m_χ.
  - Very predictive.

DM part of a EW multiplet

$$\text{DM} \in (1, n, Y) \text{ of } SU(3)_C \times SU(2)_L \times U(1)_Y$$

- n odd. Fermionic.
  - n>7, Landau pole close to M_{DM} .
  - After EWSB, mass splitting (minimally) generated at 1-loop.
  - Choose Y=0. Lightest member electric neutral. Potential DM candidate.

DM part of a EW multiplet

$$\text{DM} \in (1, n, \mathrm{Y}) \text{ of } \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}}$$

- n even. Fermionic
  - Choose Y=(n-1)/2 ensures lightest member is neutral.
  - Direct detection rules out the minimal case due to tree level Z exchange.
    - Can be avoided to introduce a small splitting, $\delta m > 10^2$ keV, of the neutral states (for example, from a dim-5 operator). Not quite minimal (additional model dependence).
  - Famous example: Higgsino $(1,2)_{1/2}$

DM part of a EW multiplet

$$\text{DM} \in (1, n, Y) \text{ of } SU(3)_C \times SU(2)_L \times U(1)_Y$$

- Scalar (real and complex)
  - Minimal case: mass splitting, stability discussion parallel to that of the fermionic multiplets.
  - Addition couplings of the form $H^\dagger H X^\dagger X$. More parameters involved in a full analysis.
- More focus on the fermion case (so far).

Thermal targets

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	48.8 TeV
(1,7,ϵ)	Dirac	16 TeV

Correct relic abundance
⇒ Thermal targets

Reach up to thermal target
≈
complete coverage for WIMP candidate

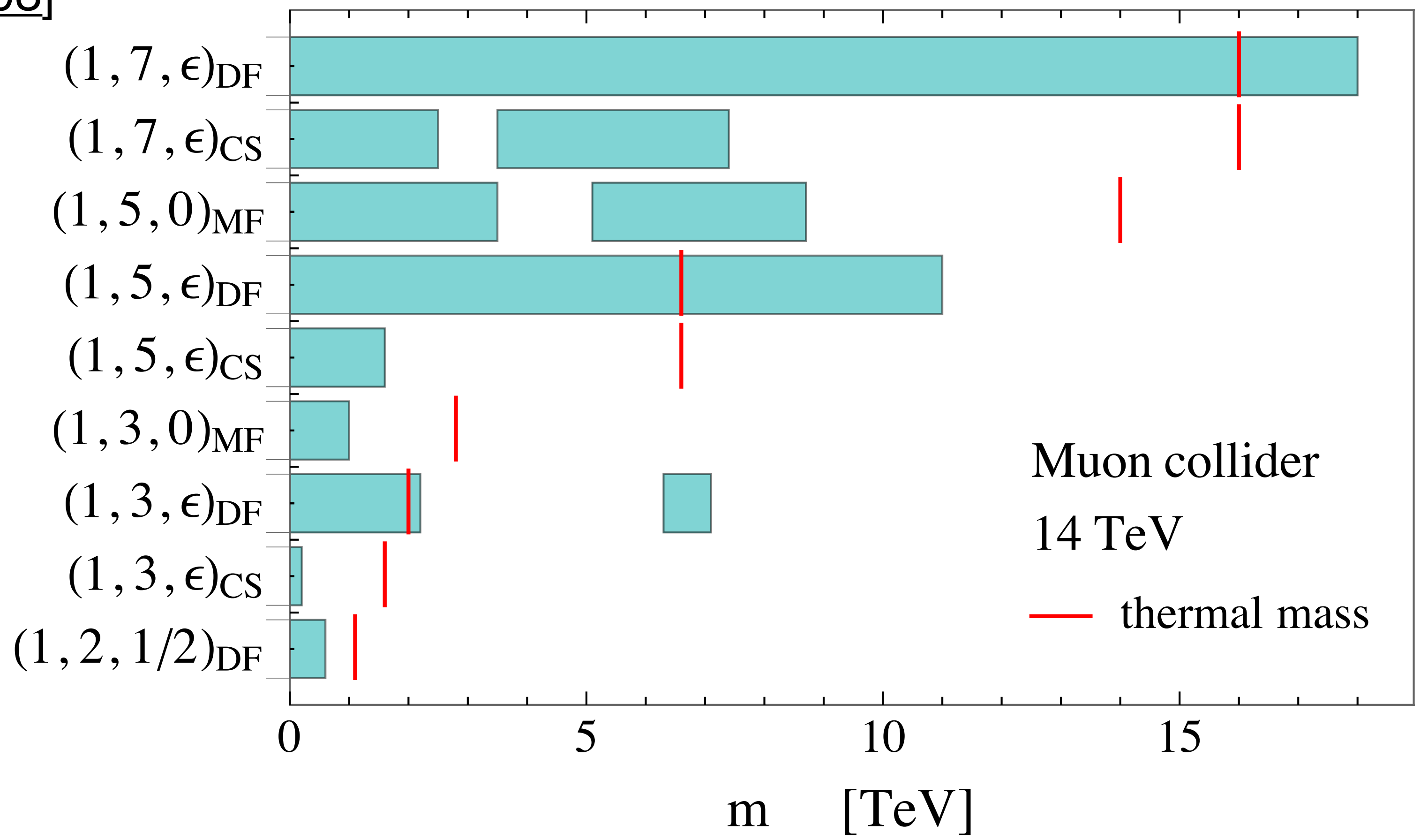
Mitridate, Redi, Smirnov, Strumia, 1702.01141

S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, D. Redigolo, L. Vittorio, 2107.09688

“indirect”, from precision measurement

indirectly [1810.10993]

Di Luzio, Grober, Panico, 1810.10993

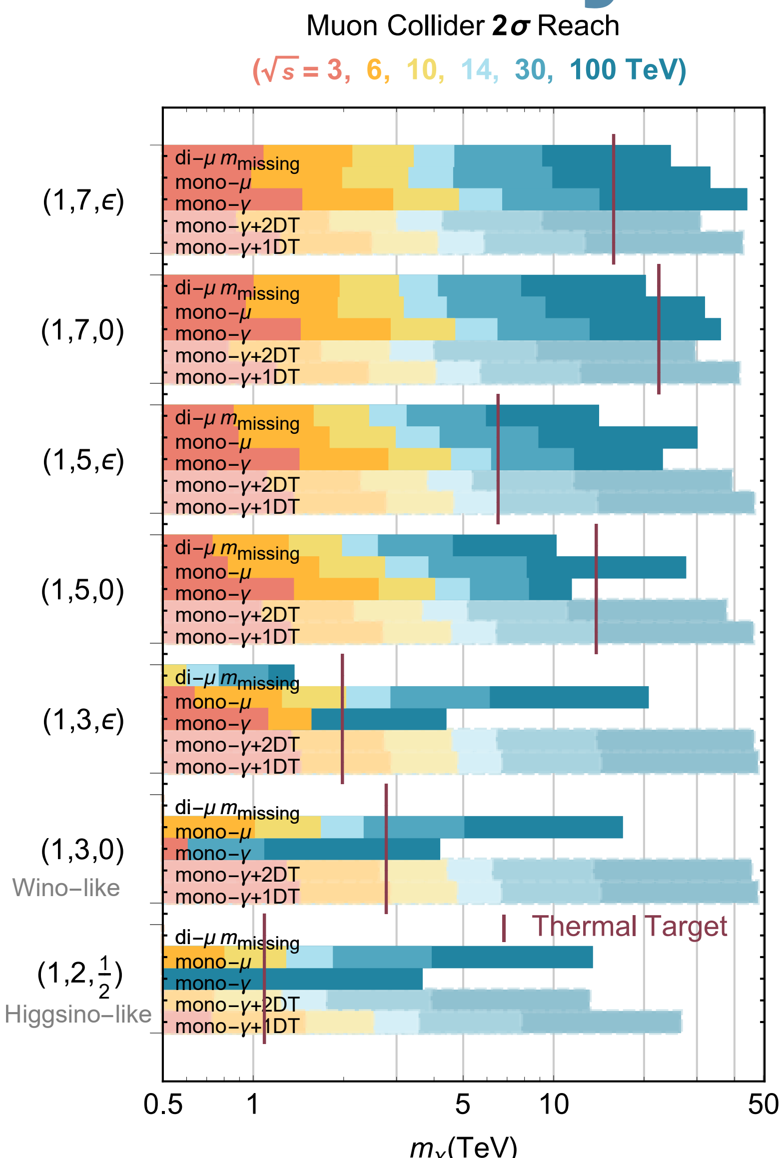


At loop level, modifying the $q\bar{q}($ or $\ell^+\ell^-) \to f\bar{f}$ amplitude

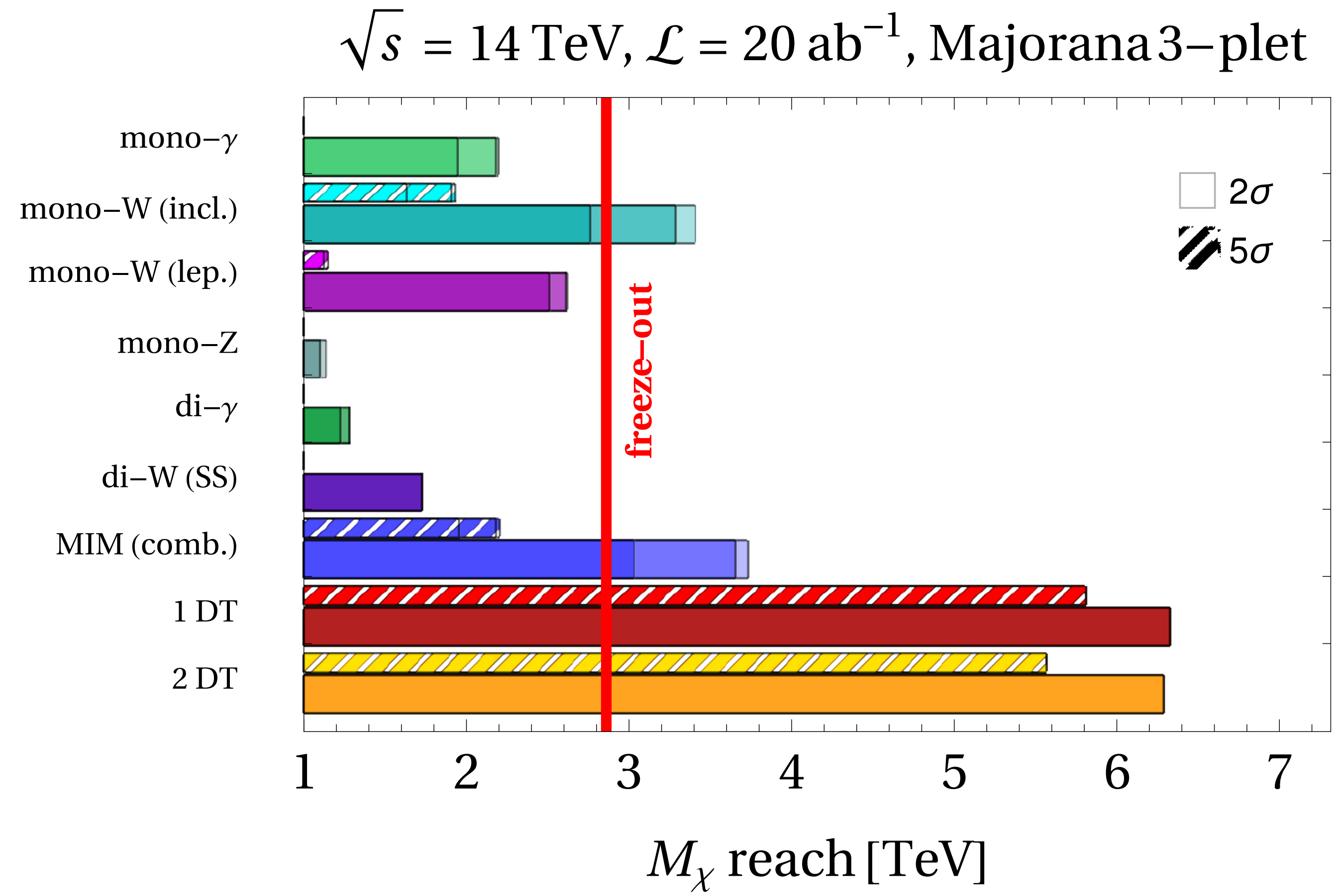
Two classes of “direct” DM signals at colliders

- Production of dark matter particle.
  - Inclusive search for X+MET
    - similar to mono-jet at hadron colliders.
- Small EW induced mass splitting, charged member long-lived.
  - Disappearing track

Reach by channel



T. Han, Z. Liu, X. Wang, LTW 2009.11287

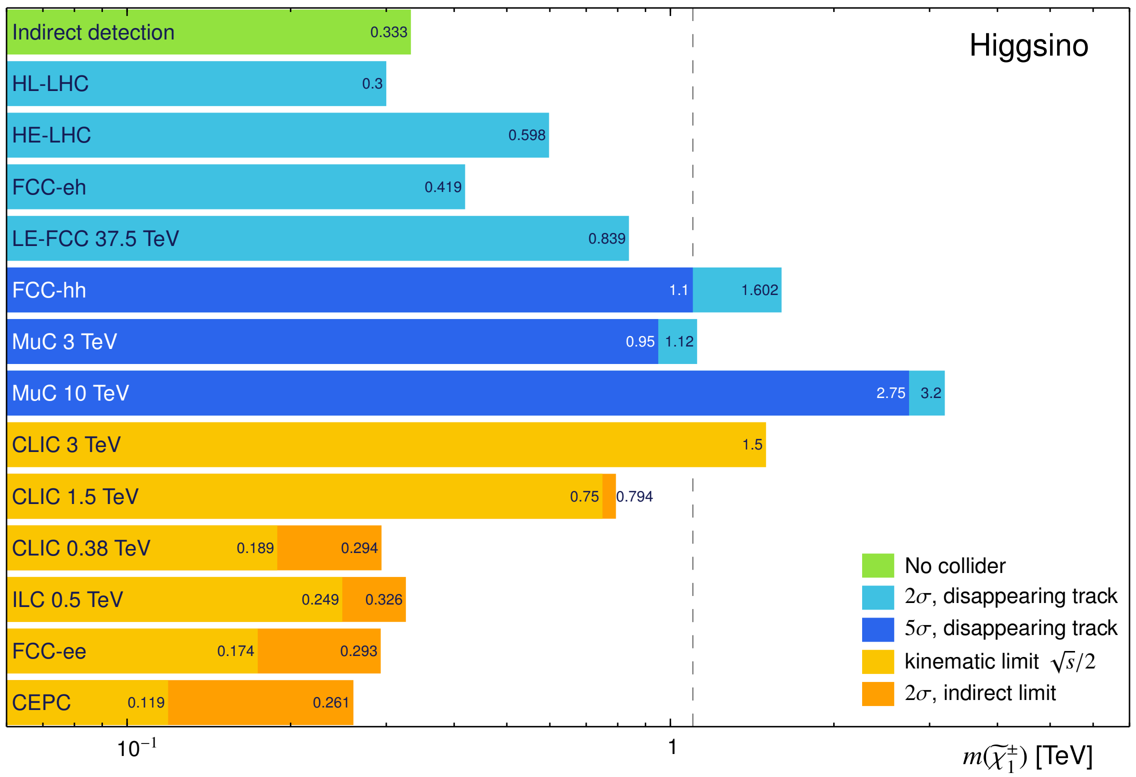


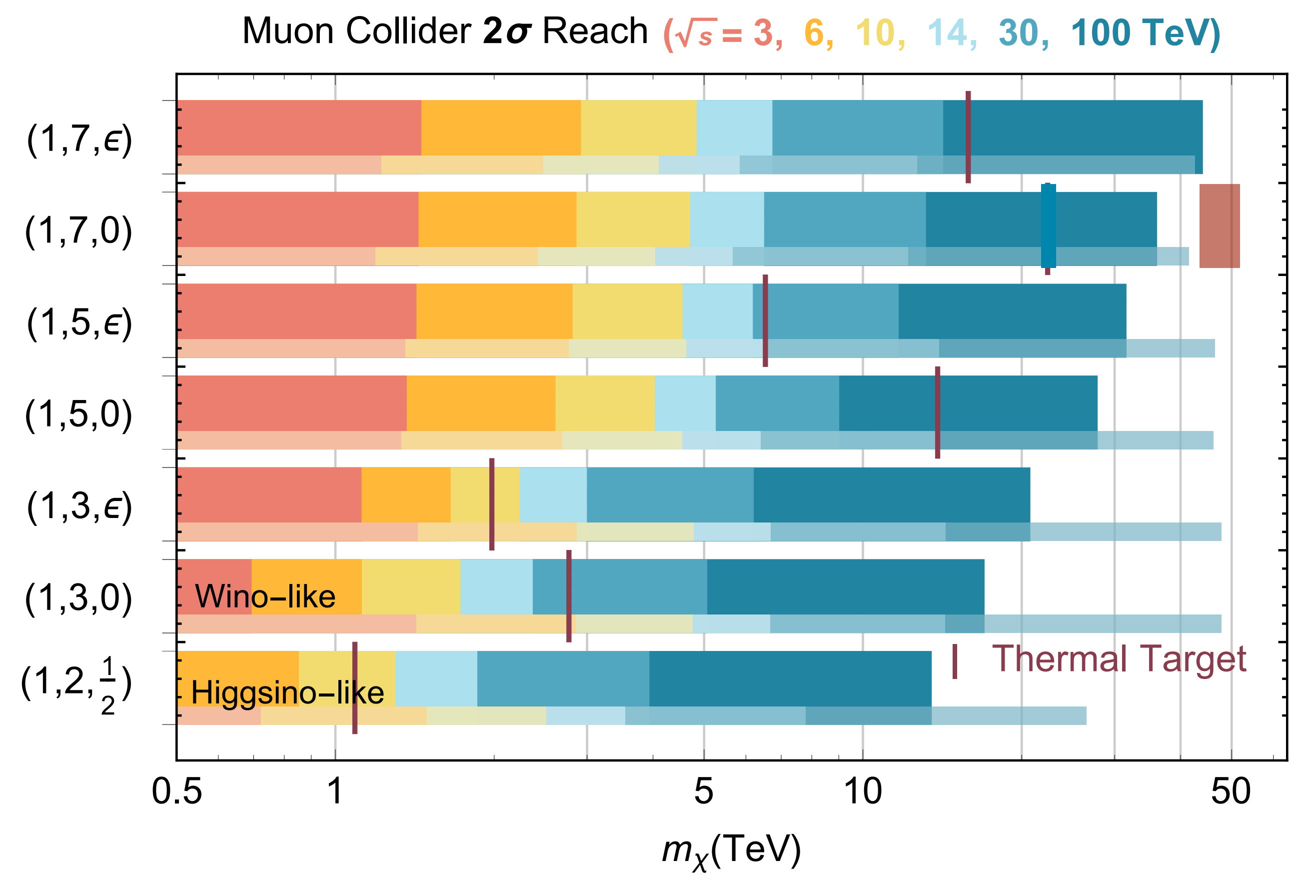
S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, D. Redigolo, L. Vittorio, 2107.09688

mono-X, more generic model independent. Interesting channels: muon-mu, mono-W.

Disappearing track. Some model dependence. Important to have the right BIB estimates.

Reach





R. Capdevilla F. Meloni, J. Zurita, 2102.11292 T. Han, Z. Liu, X. Wang, LTW 2009.11287

With inclusive signal: E_{CM} ≈ 14 TeV enough to cover n≤3 multiplets.
Higher energy needed to cover higher multiplets.

If we have disappearing track: potential to reach almost $m_\chi \approx 1/2\ E_{CM}$

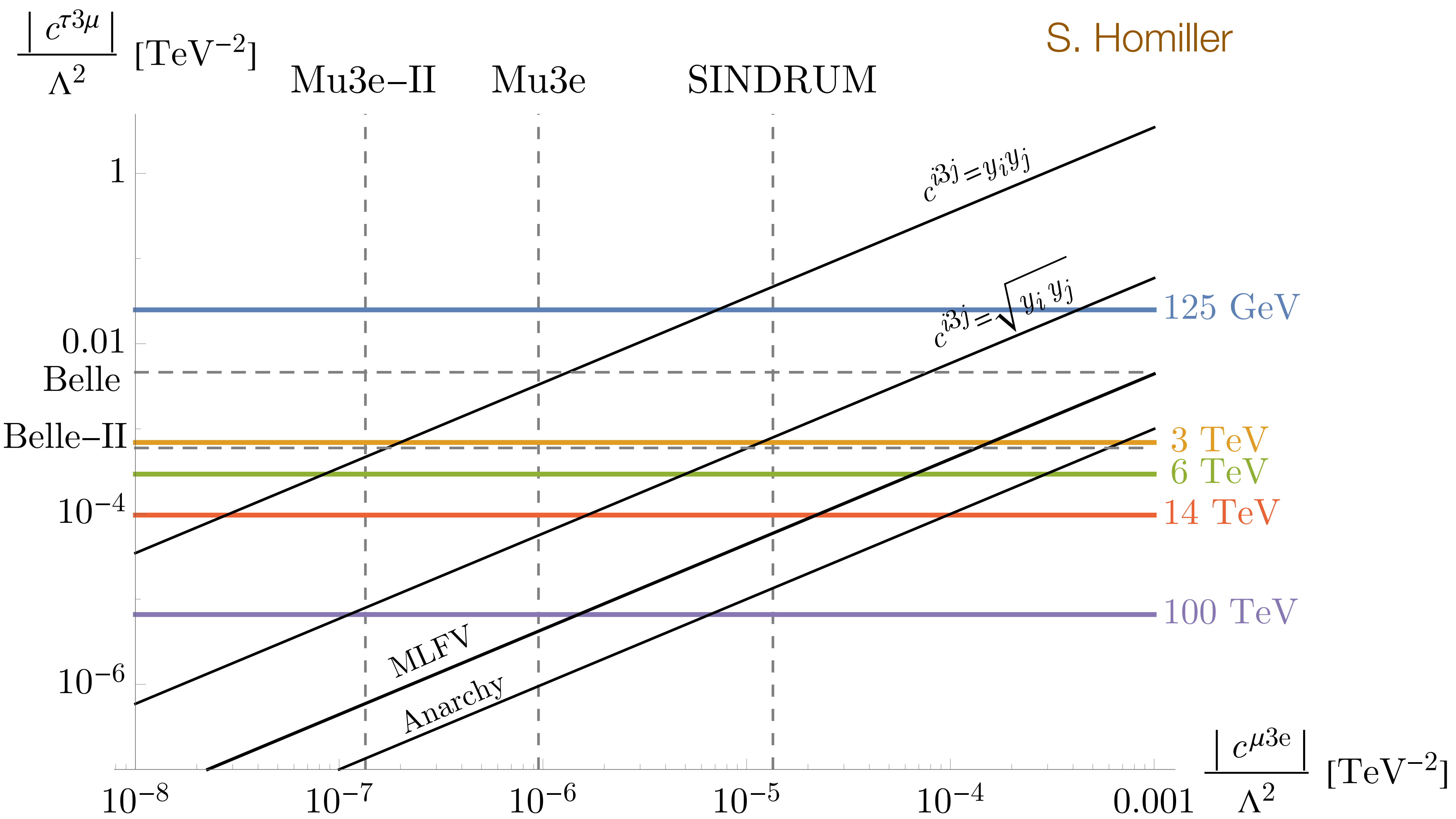
(Other) new physics at high scale

- Dark matter (WIMP)
- Z'
- Flavor/CP
- Lepto-quark
- ...

Flavor (CP), complementarity

- The absence of (confirmed) BSM flavor (CP) signal point to a higher scale for flavor violation
  - $\Lambda_{\text{flavor}} > 10\text{(s) TeV}$
- Muon collider can (both directly and indirectly) probe this scale.

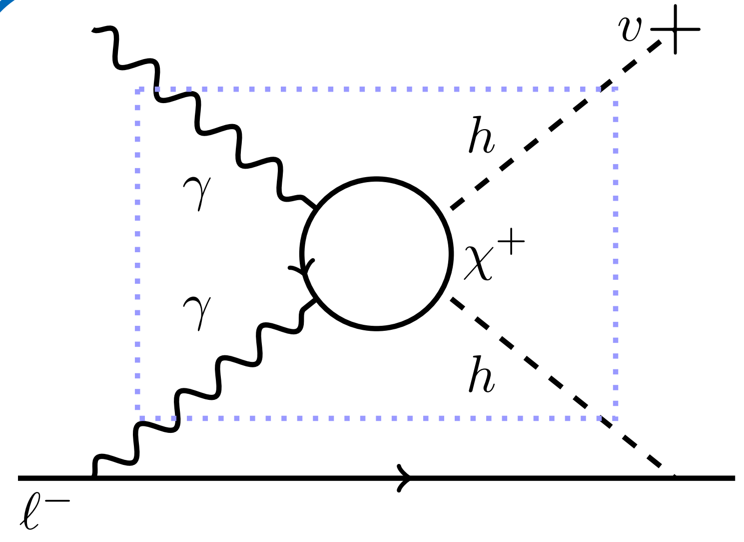
Probing lepton flavor violation

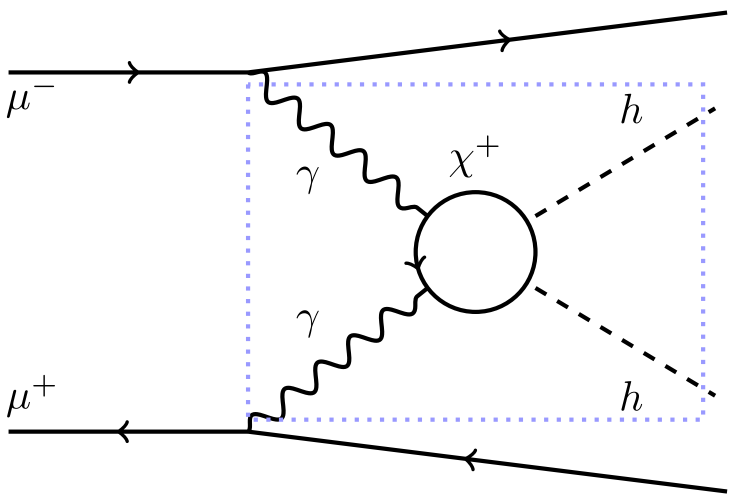


See also (b anomaly motivated)

P. Asadi, R. Capdeville, C. Cesarotti, S. Homiller, 2014.05720

EDM



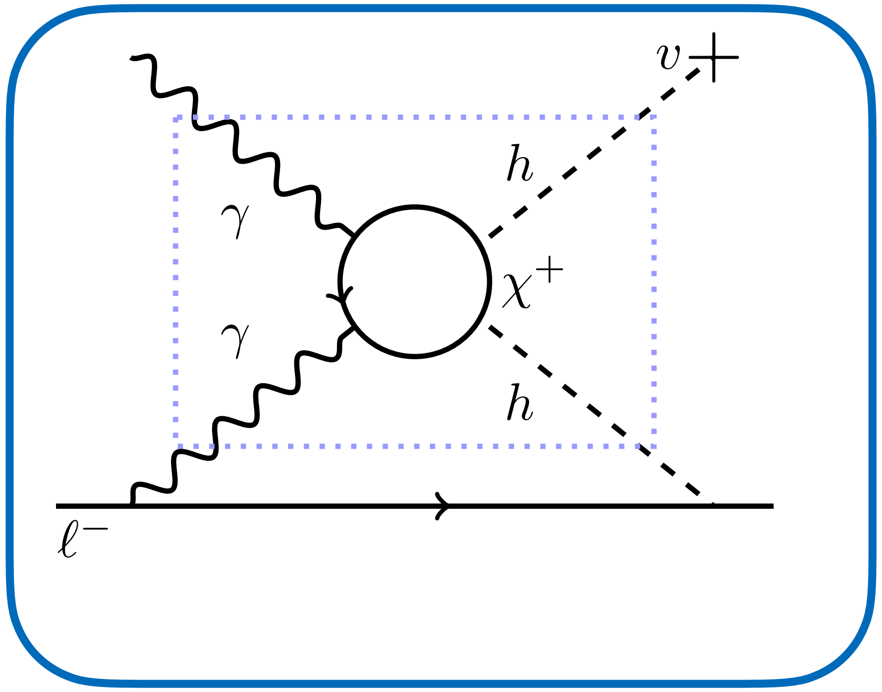


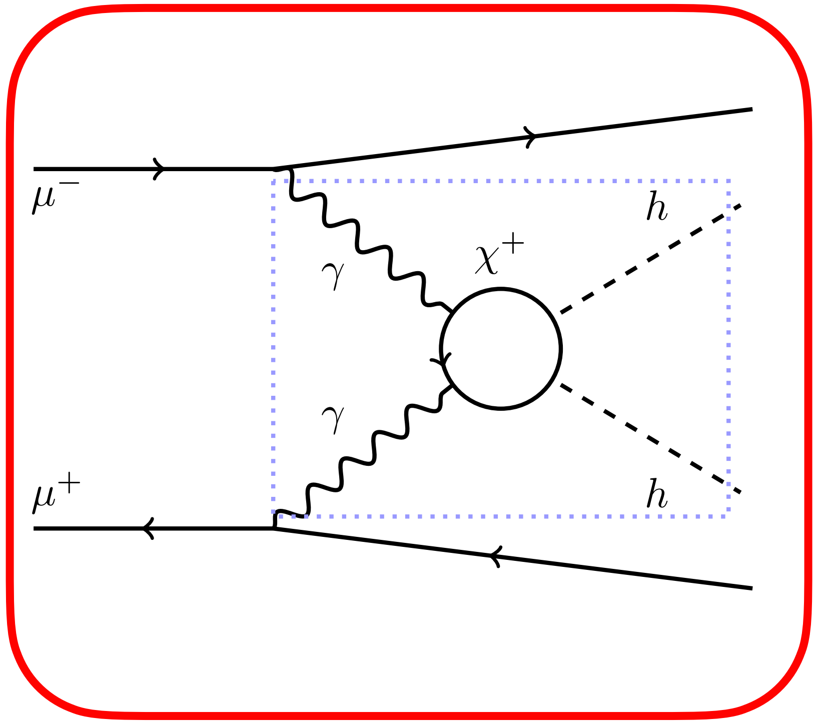
$$d_e \sim \sin(\delta_{\rm CP}) \frac{e\, m_e}{M^2} \left(\frac{\alpha}{4\pi}\right)^k \simeq 10^{-32}\, e\, {\rm cm}\, \sin(\delta_{\rm CP}) \times \begin{cases} (1\ {\rm PeV}/M)^2 & \text{for } k=1 \\ (20\ {\rm TeV}/M)^2 & \text{for } k=2 \end{cases}$$

2-loop Barr-Zee

Potential sensitivity of next generation exp.

EDM





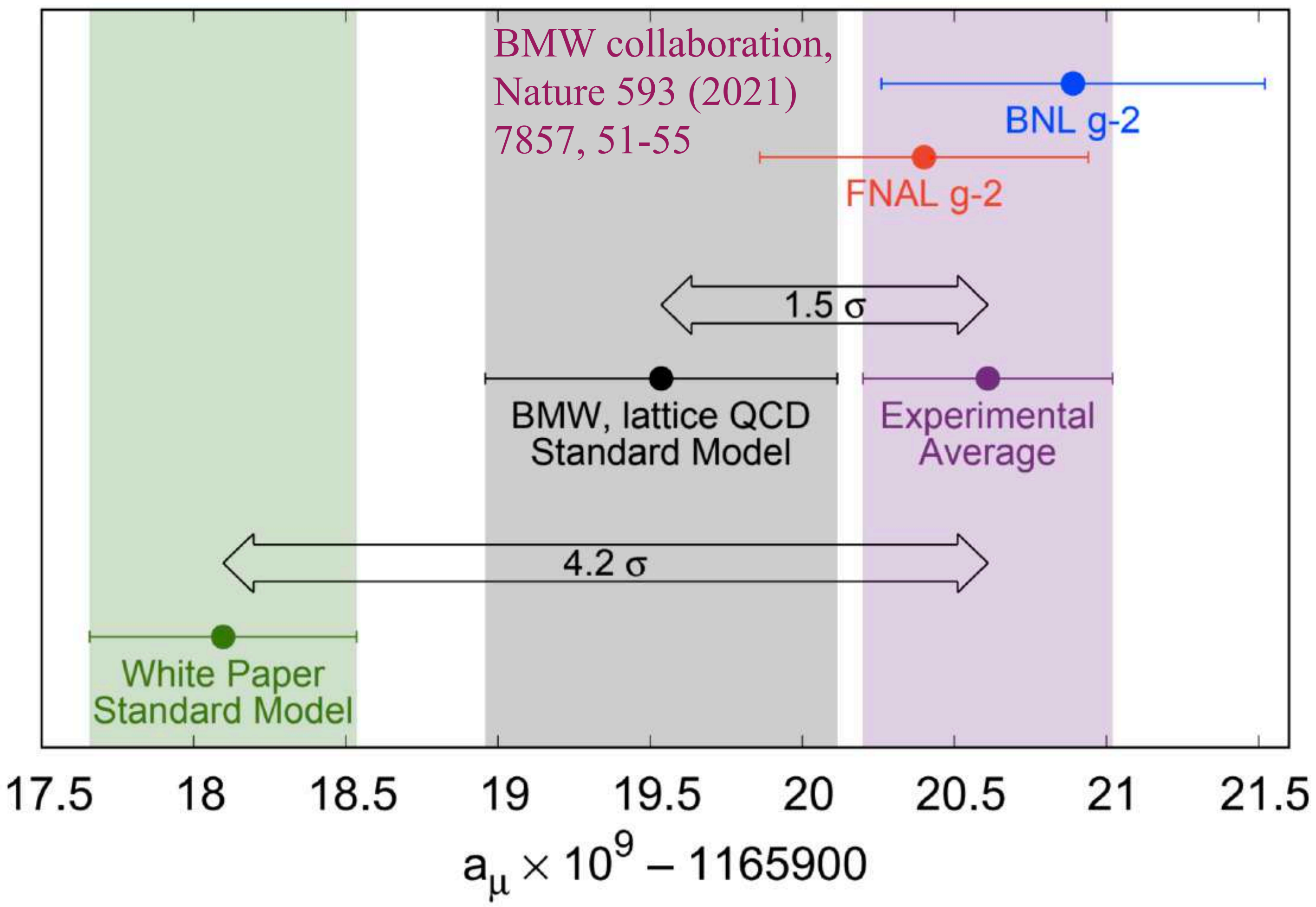
$$d_e \sim \sin(\delta_{\mathrm{CP}}) \frac{e\, m_e}{M^2} \left(\frac{\alpha}{4\pi}\right)^k \simeq 10^{-32}\, e\,\mathrm{cm}\, \sin(\delta_{\mathrm{CP}}) \times \begin{cases} (1\ \mathrm{PeV}/M)^2 & \text{for } k=1 \\ (20\ \mathrm{TeV}/M)^2 & \text{for } k=2 \end{cases}$$

2-loop Barr-Zee

Potential sensitivity of next generation exp.

Same process probed by 10(s) TeV muon collider!

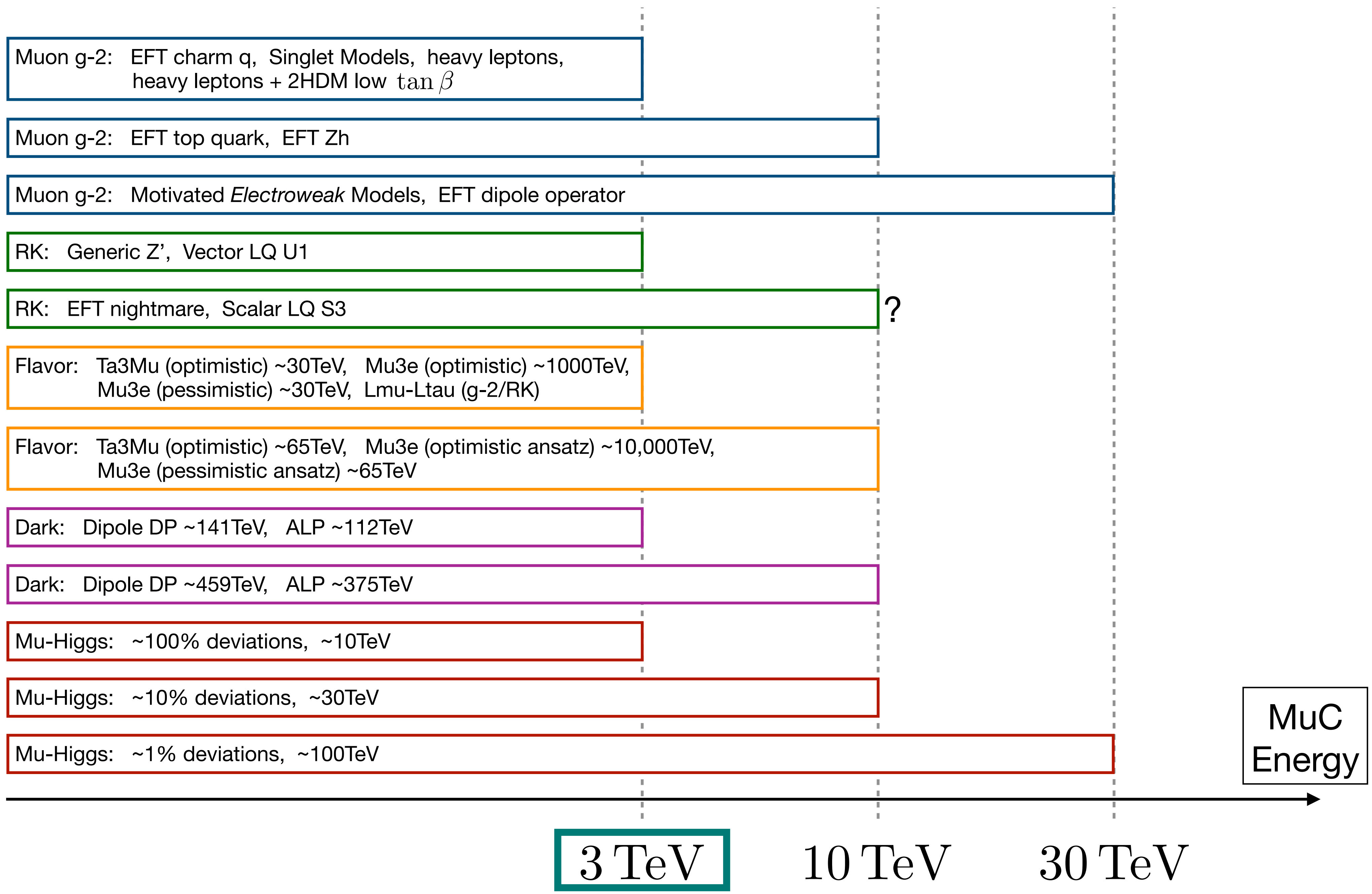
What if new physics just like muon



Will be a new era, with a new definitive target.
Much of the current would have to be re-done.

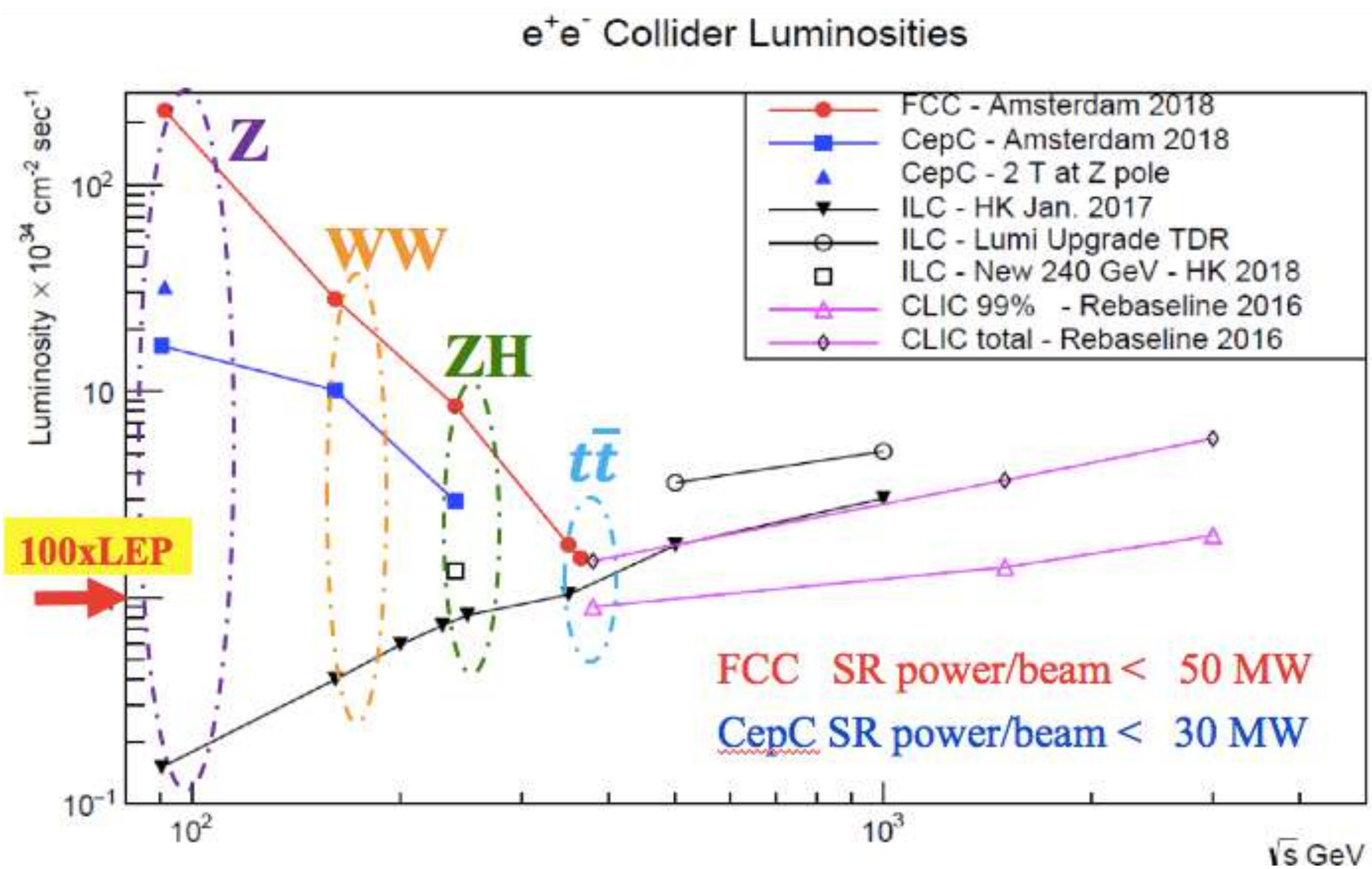
Muon collider can do it, of course.

Slide of R. Capdevilla



Conclusions

- Muon collider is a powerful machine at the energy frontier, with a rich physics program.
- Great Higgs measurements for E_{CM} > 3 TeV.
- Exciting reaches for a broach spectrum of new physics in the range multiple - 10(s) TeV.
  - Tests of WIMP DM, naturalness, flavor violations, …



e^+ e^- colliders will play an essential role!

Offer rich program, covering 90 eV - TeV(s).

Muon Collider

Daniel Schulte for the Muon Collider Collaboration

Why Muon Collider?

Most of the muon collider R&D has been done by MAP in the US

- Experimental programme at MICE in the UK
- alternative LEMMA concept considered mainly at INFN
- Still the basis for our designs

Interest in Europe started with last Strategy Update

- **Change of goals**: Started looking for very high energy high-luminosity lepton collider
  - The champion is CLIC at 3 TeV, which has been optimised over decades for this
    - 18 GCHF, 590 MW power consumption
  - The muon collider promises to be able to go to 10 TeV or higher
- **Technology and design advances** since MAP
  - e.g. superconducting magnet technology (HTS)
  - e.g. rectilinear cooling channel
  - Progress on specific technologies for the muon collider
  - Expect competitive cost and power consumption

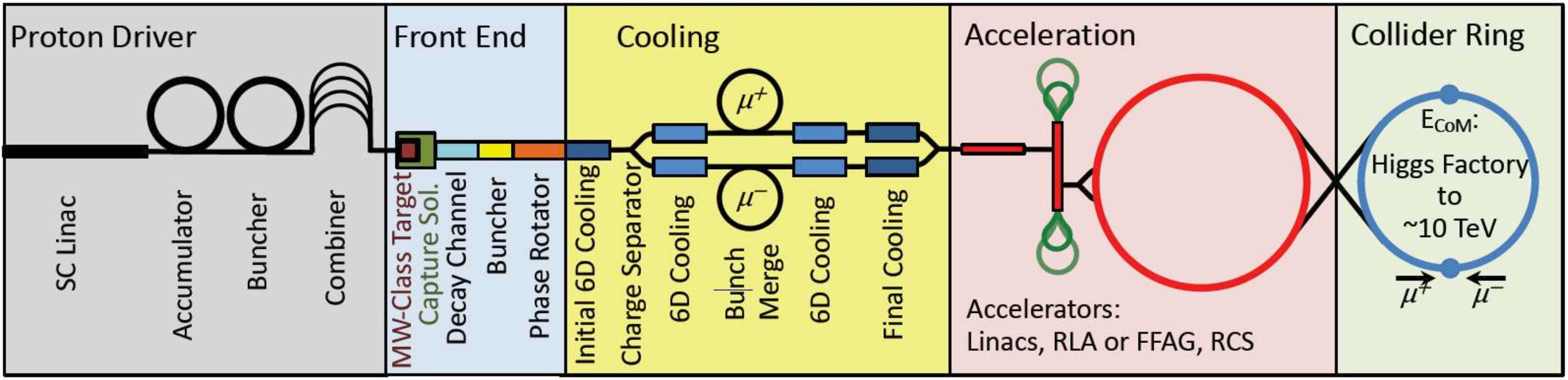
CERN allocated budget to muon collider and initiated collaboration

Muon collider is part of European Accelerator R&D Roadmap

- evaluated in detail, with **lots of help from US experts**

Proton-driven Muon Collider Concept

Some exploration long time ago in Europe
MAP study in US developed the concept, MICE experiment in UK (but US did not go for high-energy collider)
Alternative developed at INFN (but needs consolidation)
With last Strategy for Particle Physics interest in Europe started
Also interest in US and elsewhere again



Produce short, intense proton bunch

Protons in target produce pions which decay into muons muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$

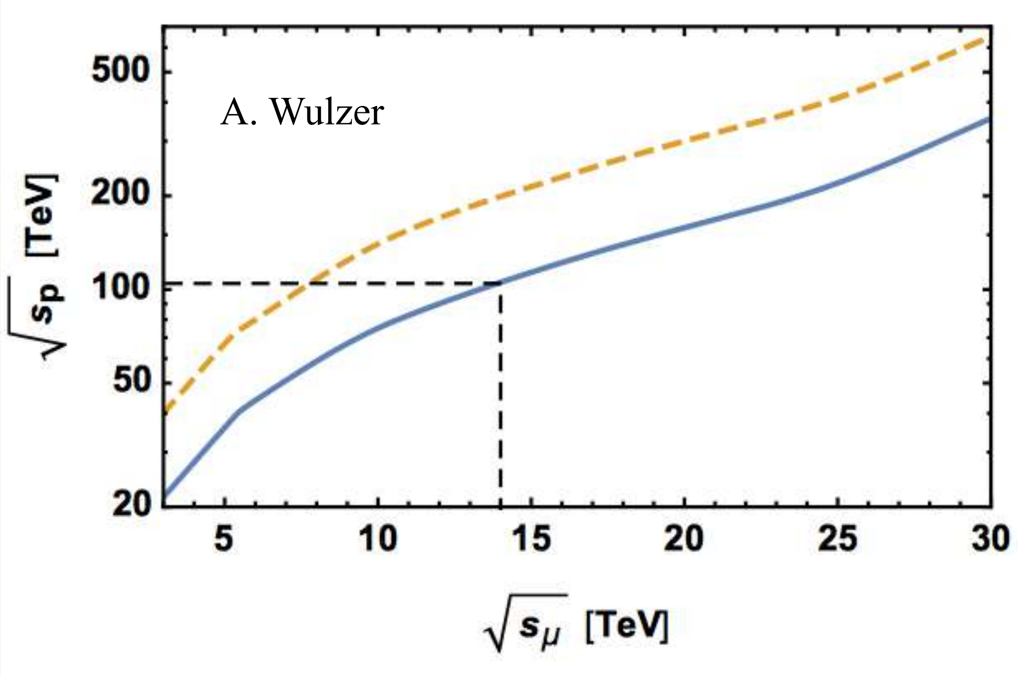
Lepton Physics at High Energy

International MUON Collider Collaboration

High energy lepton colliders are precision and discovery machines

$$V = \frac{1}{2} m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao
Muon Collider - Preparatory Meeting



Precision potential

Measure k_4 to some 10%
With 14 TeV, 20 ab^{-1}

Discovery reach

14 TeV lepton collisions are comparable to 100 TeV proton collisions for production of heavy particle pairs

Luminosity goal

(Factor O(3) less than CLIC at 3 TeV)
$4 \times 10^{35}\ cm^{-2}s^{-1}$ at 14 TeV

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

Muon Collider Promises

CLIC is at the limit of what one can do (decades of R&D)

- No obvious way to improve luminosity

Luminosity per beam power increases with energy in muon collider

- **power efficient**

Site is **compact**

- 10 TeV comparable to 3 TeV CLIC

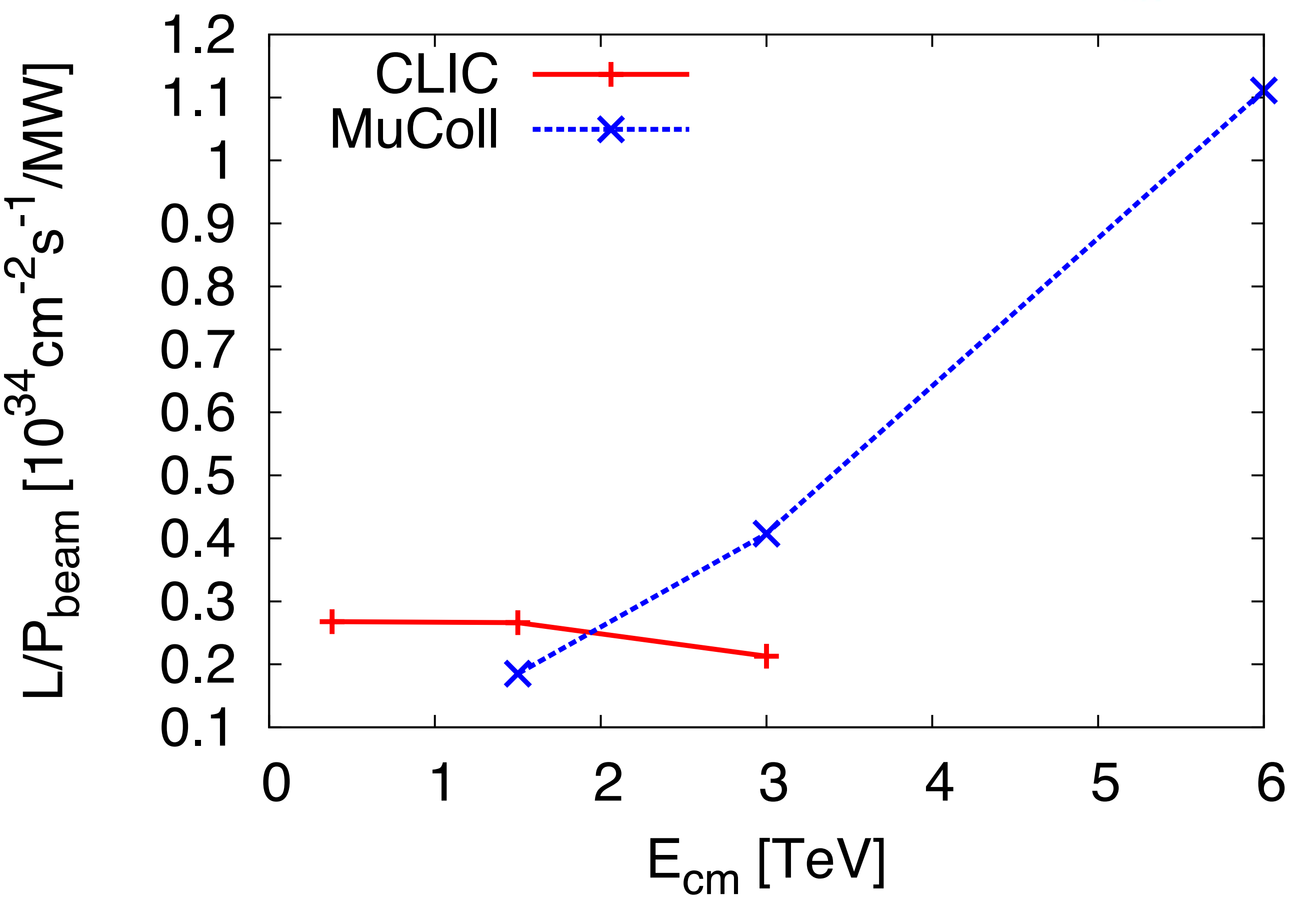
Staging is natural

- Each ring accelerates by a factor of a few

Promises **cost effectiveness**

- but need detailed study

Other **synergies** (neutrino/higgs)



Muon collider promises unique opportunity for a **high-energy, high-luminosity lepton collider**

Luminosity Goals

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	$1\ ab^{-1}$
10 TeV	$10\ ab^{-1}$
14 TeV	$20\ ab^{-1}$

Note: currently consider 3 TeV and either 10 or 14 TeV

- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

Now study if these parameters lead to realistic design with acceptable cost and power

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

International Muon Collider Collaboration

Memorandum on Cooperation
for the Muon Collider (MC) Study

THE INSTITUTES, LABORATORIES, UNIVERSITIES AND FUNDING AGENCIES AND OTHER SIGNATORIES OF THIS MEMORANDUM ON COOPERATION AND CERN AS THE HOST ORGANIZATION **("the Participants")**

CERN is the initial host organization for the MC Study.
Goal is to

- [..] establish whether the investment into a full Conceptual Design Report ("CDR") and demonstrator for a muon collider is scientifically justified. [..]
- [..] focus on the high-energy frontier and consider options with a centre-of-mass energy of 3 TeV and of 10 TeV or more.
    - **10+ TeV option** is the reason to study muon colliders,
    - **3 TeV option** might be initial energy step with technologies available in 10-20 years
- Potential synergies [..] shall be explored [..].
    - Neutrino facilities and potentially higgs factories

muon.collider.secretariat@cern.ch

Partners
(in some cases formal procedure is not yet completed)

- INFN
- Commissariat à l'Energie Atomique (CEA)
- Iowa State University
- University of Huddersfield
- University of Warwick
- Institute of High Energy Physics
- University of Rostock
- University of Oxford (JAI)
- Tampere University
- Uppsala University
- TU Darmstadt
- Peking University
- Sun Yat-Sen University

- European Spallation Source (ESS)
- Rutherford Appleton Laboratory (RAL)
- University de Genève

Muon Collider Luminosity Scaling

Fundamental limitation

Assumes no emittance growth after source and no technical limitation

Applies to MAP and LEMMA scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring
= small ring
= many collisions

Large energy acceptance
= short bunch
= small betafunction

Dense beam

High beam power

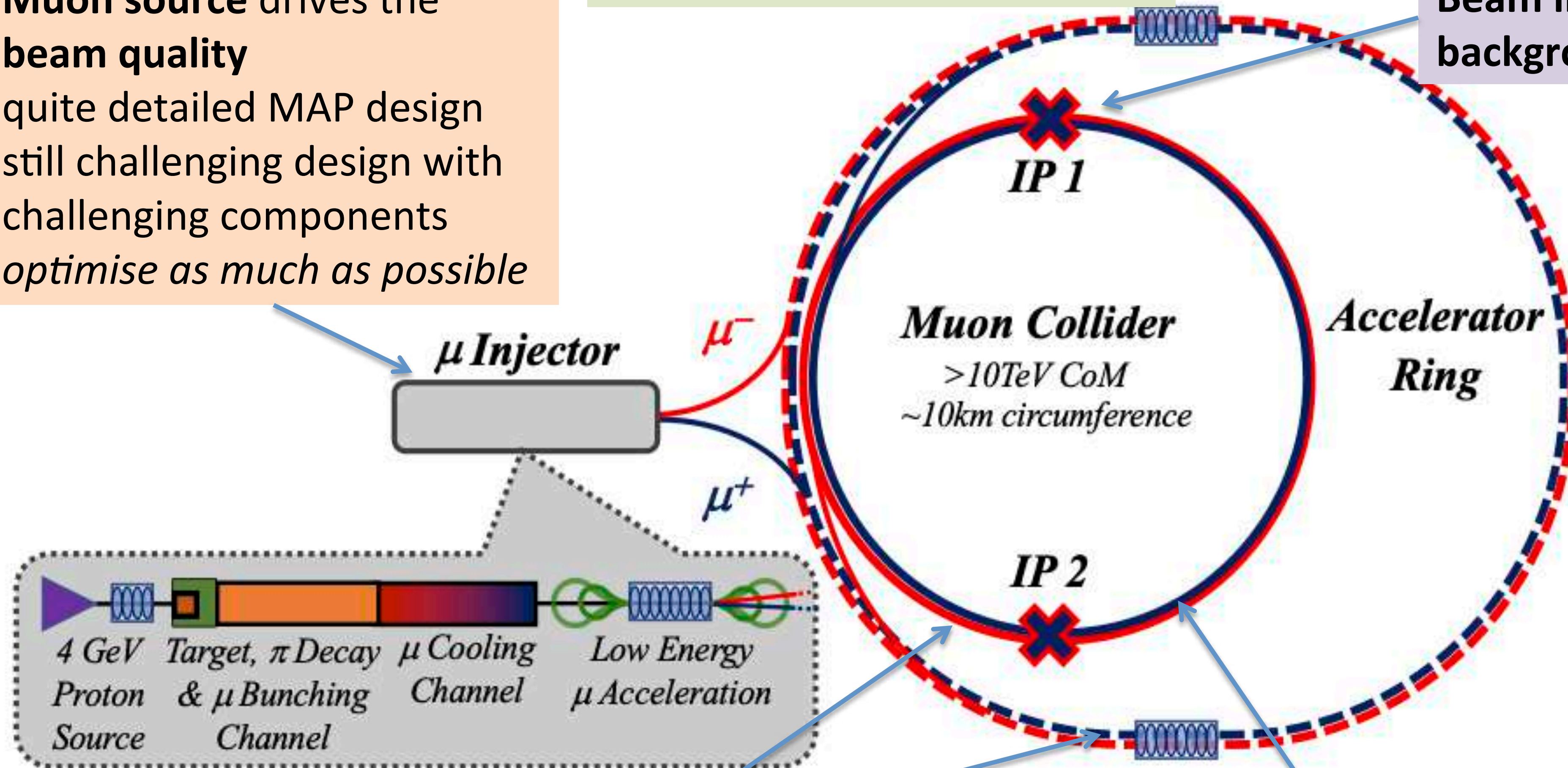
Note: emittances are normalised

Key Challenges

Muon source drives the **beam quality**
quite detailed MAP design
still challenging design with challenging components
optimise as much as possible

Physics potential assessment

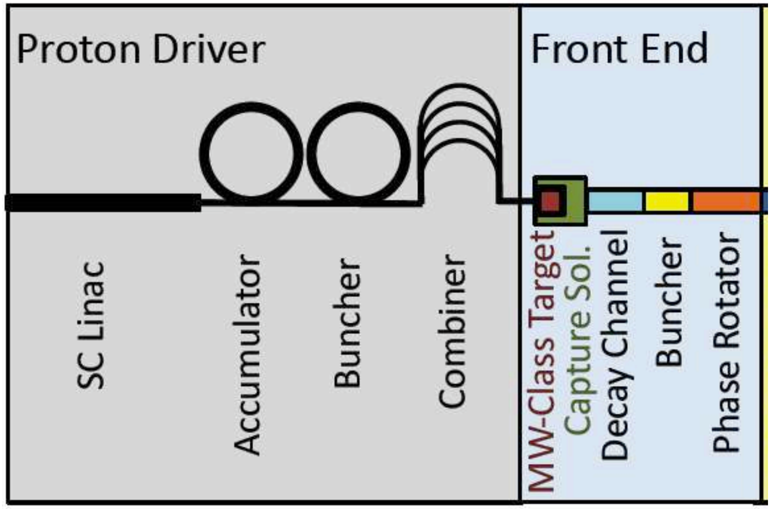
Beam induced background



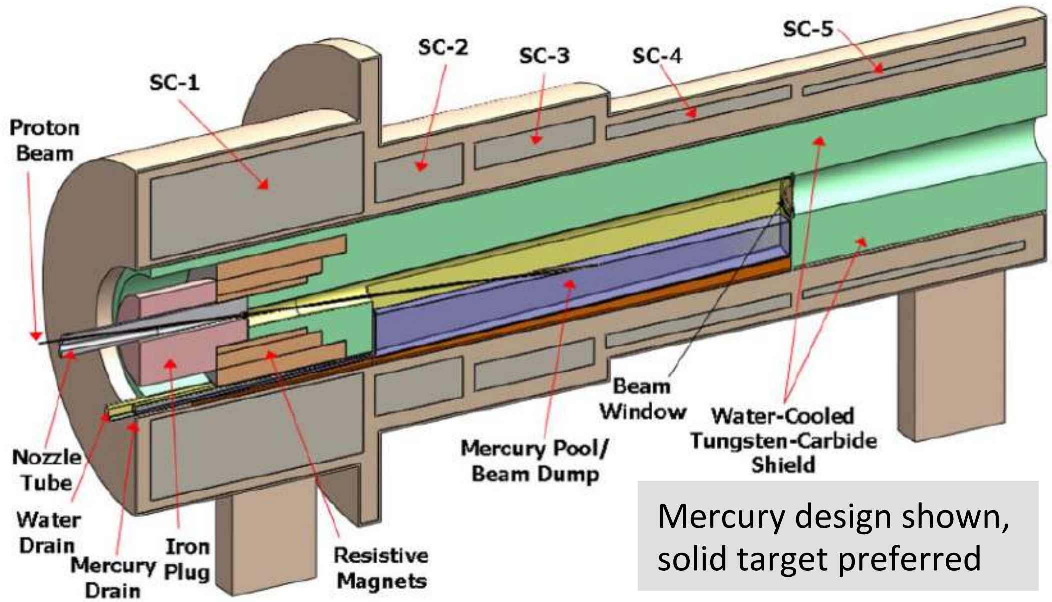
Dense neutrino flux
mitigated by mover system and site selection

High energy complex
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**

Proton Complex and Target Area



Proton beam power is no issue, some look required at **H- source** and **accumulator and combiner complex**



Mercury design shown, solid target preferred

2 MW proton beam
requires radiation protection

High field to efficiently collect pions/ muons: 20 T, then tapering
Using copper solenoid in superconducting solenoid

Large aperture O(1.2m) to allow shielding

Target Design

Two approaches:

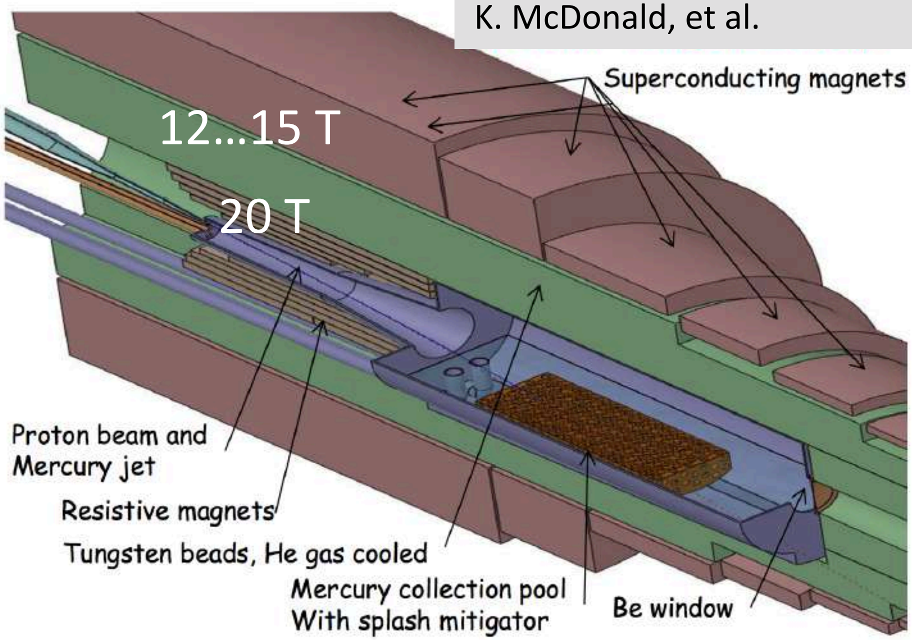
- Superconducting O(15 T) outer solenoid boosted by resistive inner solenoid
- O(20 T) HTS solenoid

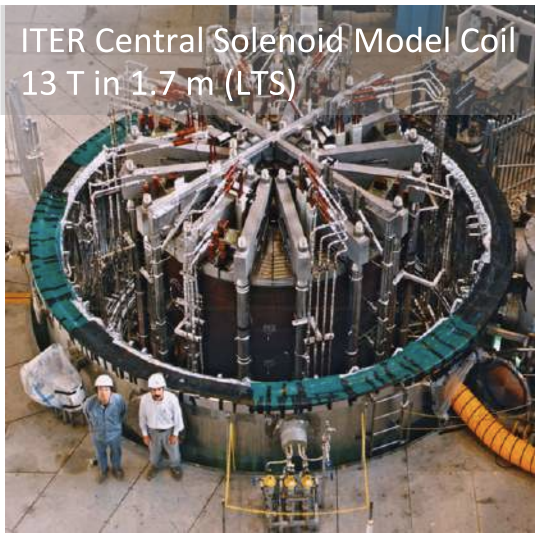
Need to shield superconducting solenoid
⇒ larger aperture

Past simulations showed

- 5 kW to outer (O(2 m) aperture)
- 100 kW to inner

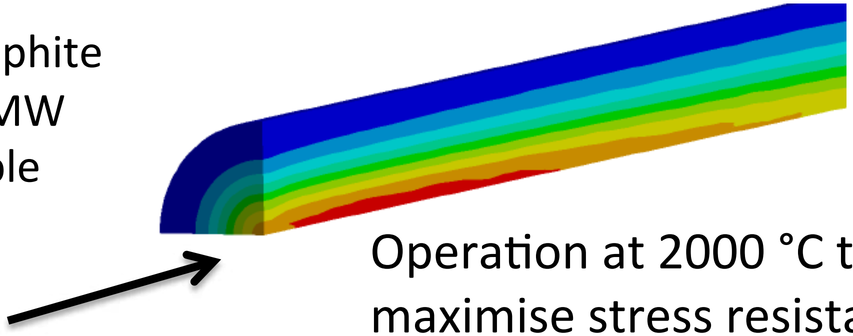
MAP target design
K. McDonald, et al.





ITER Central Solenoid Model Coil
13 T in 1.7 m (LTS)

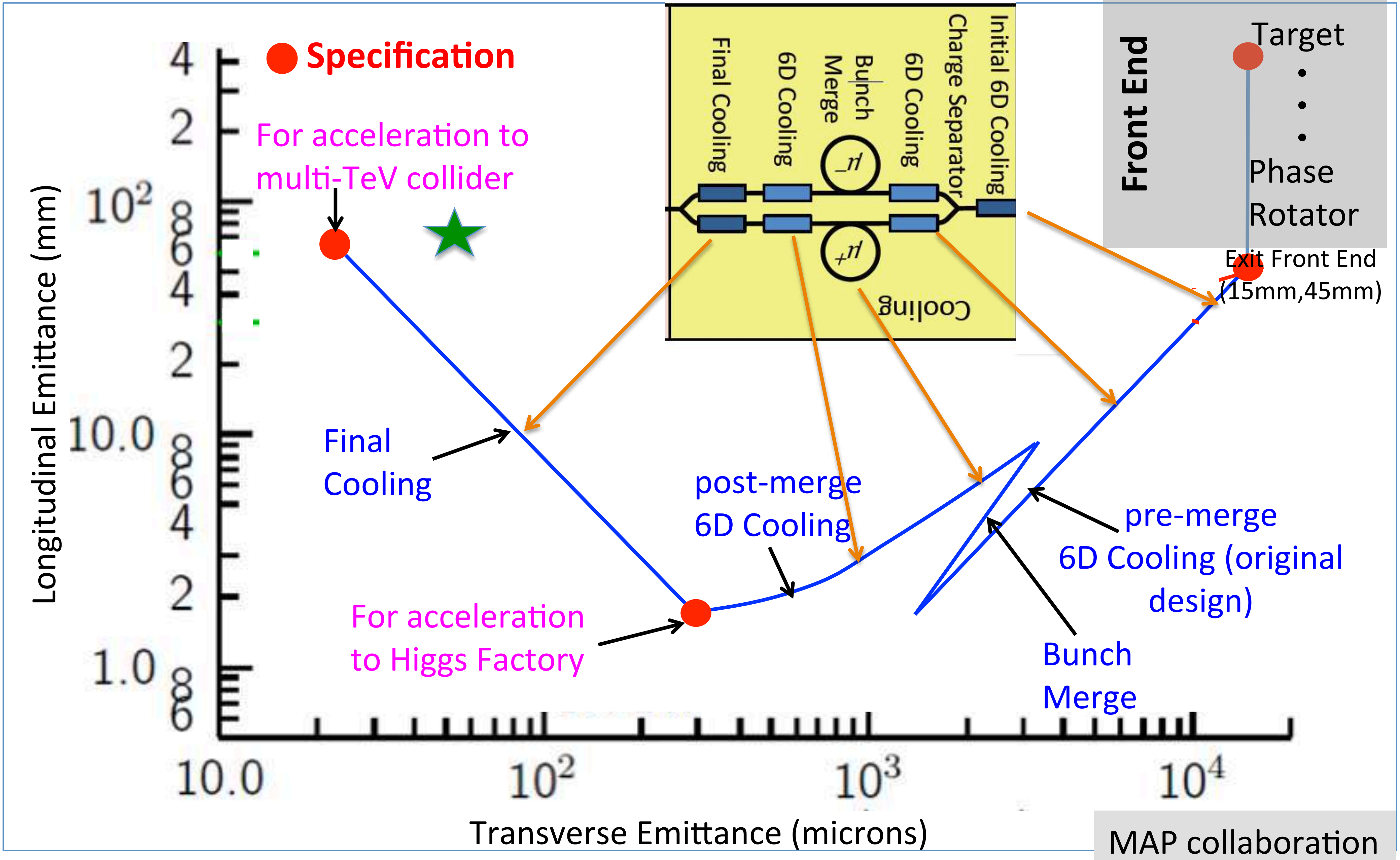
Shock in target:
Simulations of graphite target indicate 2 MW could be acceptable



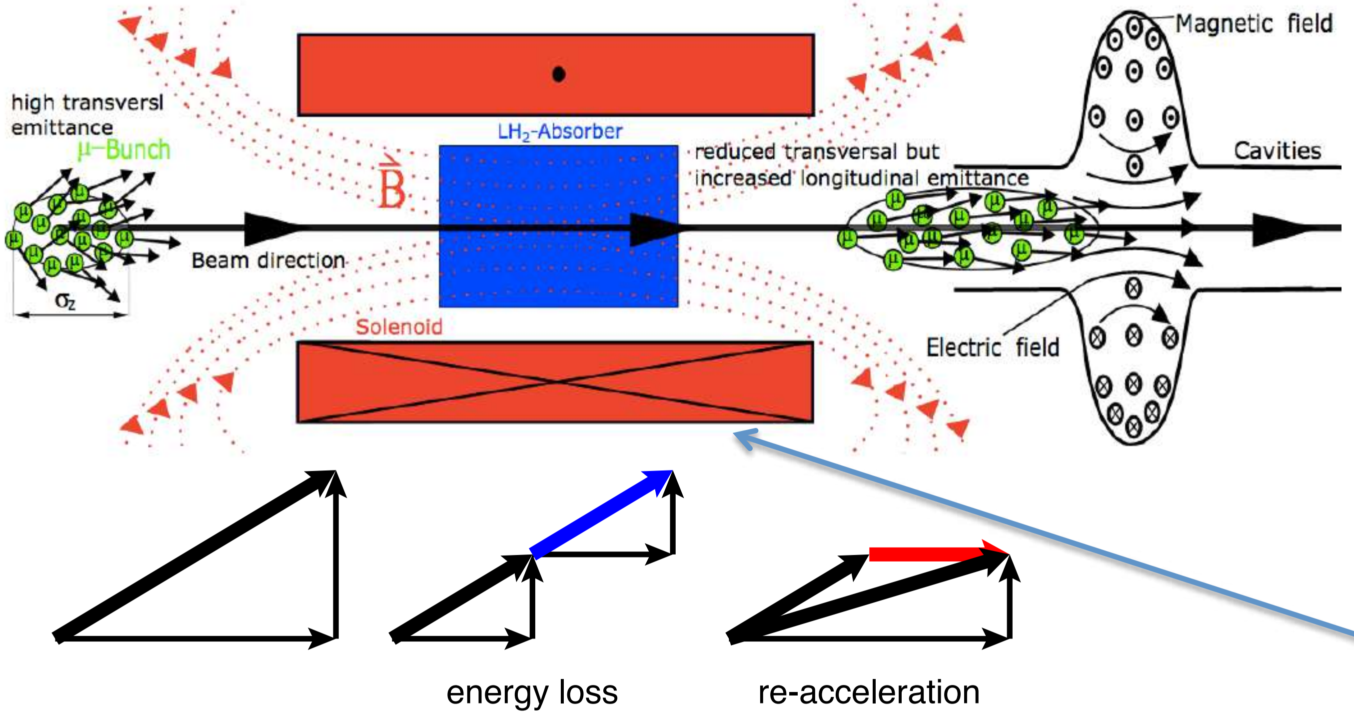
Proton beam

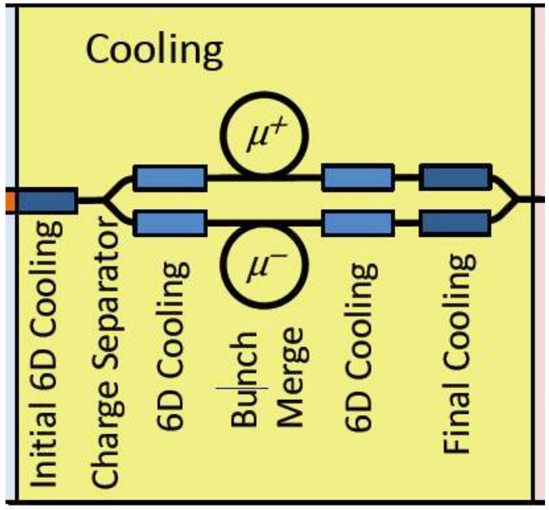
Operation at 2000 °C to maximise stress resistance

Cooling: The Emittance Path



Final Cooling Challenge





High field solenoids minimise beta-function and impact of multiple scattering

Energy loss = cooling

Multiple scattering = heating

$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

Equilibrium Emittance, Material and Energy

$$\epsilon_{equ}(E_\mu) \propto \frac{1}{L_R \left.\frac{dE}{ds}\right|_{E_\mu}} \frac{1}{B_z}\gamma$$

Strong solenoid field helps

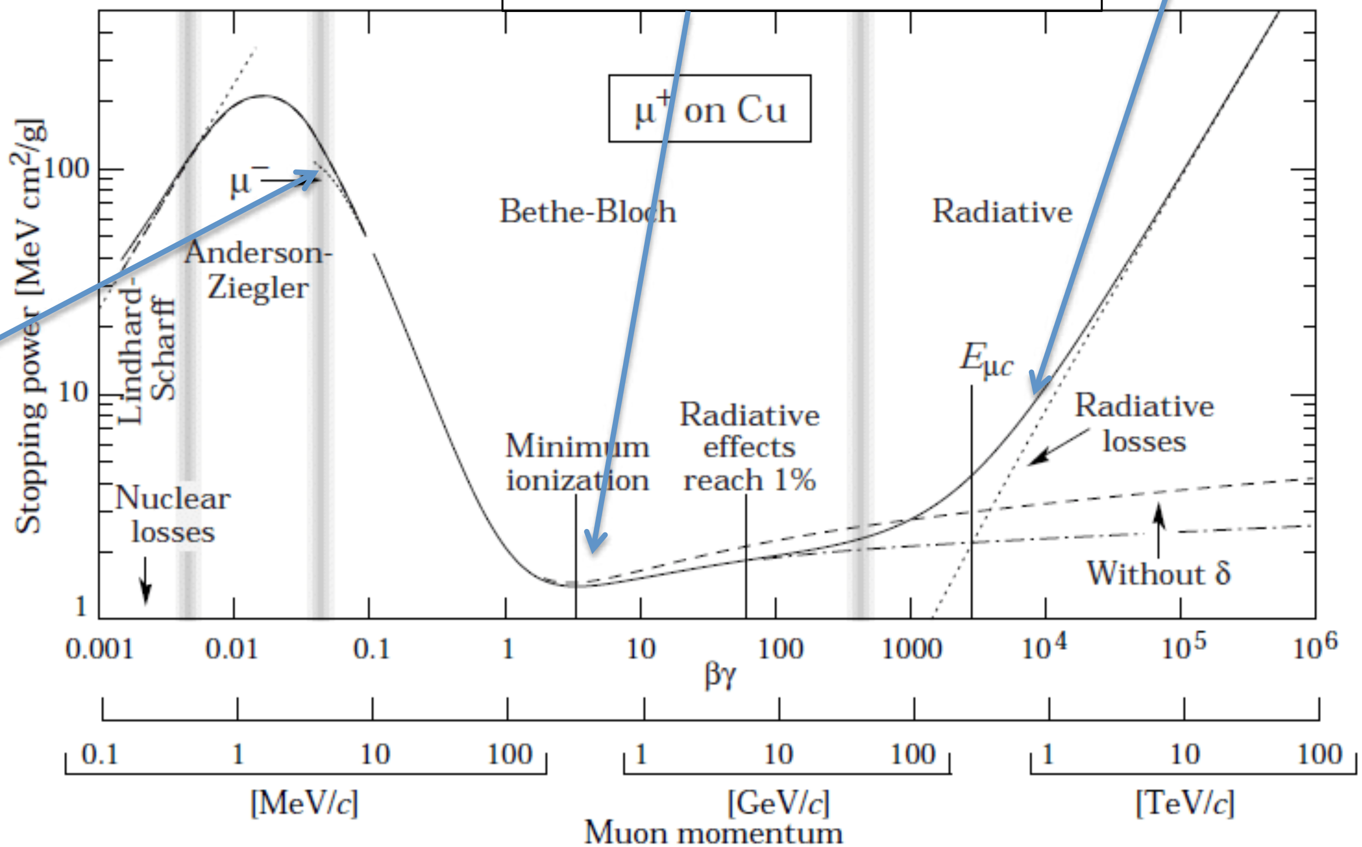
Hard stochastic losses

Most of cooling is done here

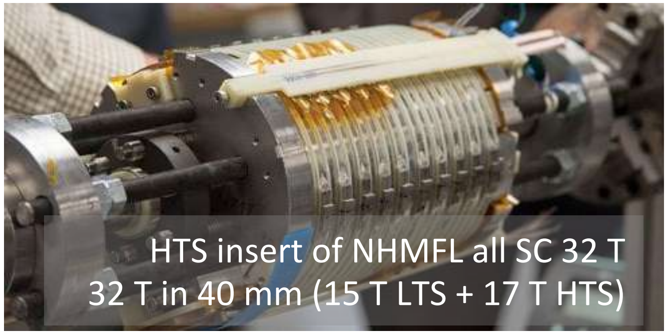
Material property best is hydrogen

Lithium hydride is good solid material

best at low energies but rapidly increasing energy spread
⇒ use for final cooling



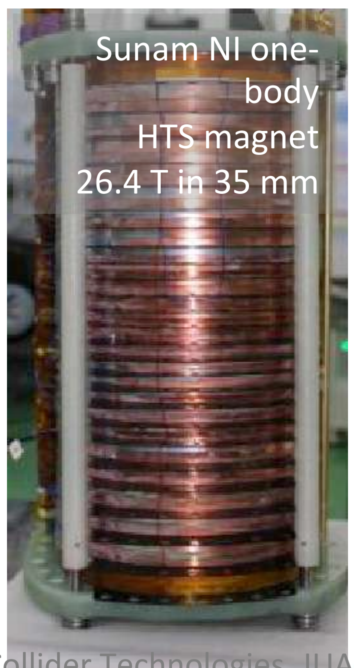
Solenoid Fields



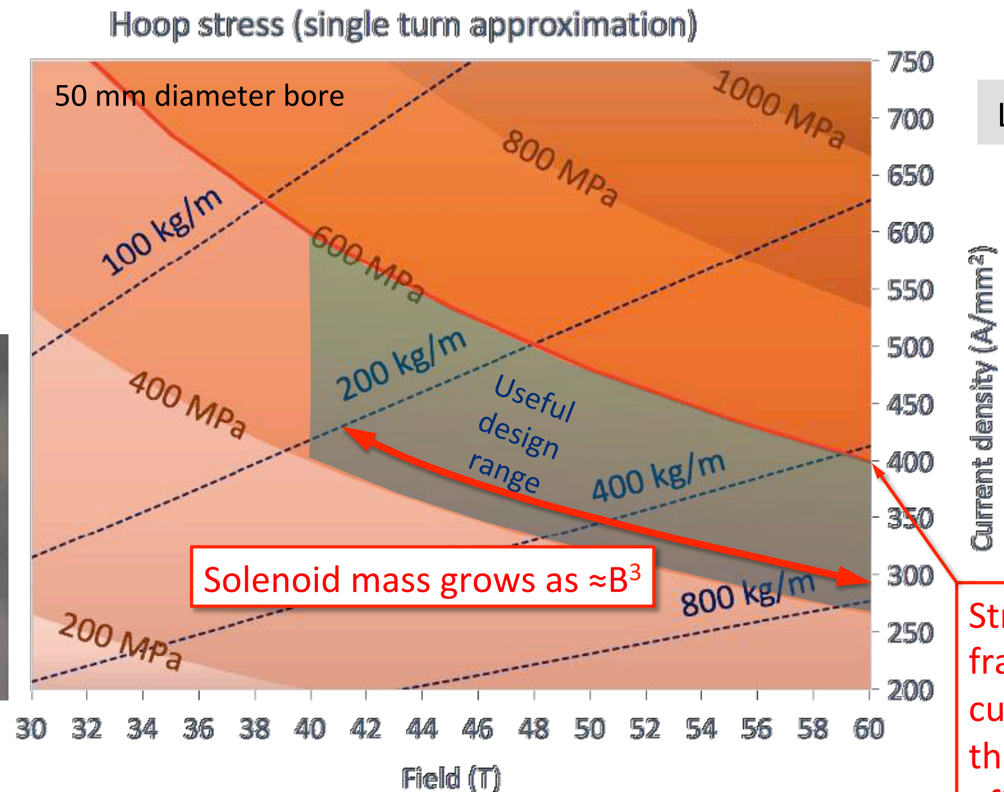
HTS insert of NHMFL all SC 32 T
32 T in 40 mm (15 T LTS + 17 T HTS)

NHMFL HTS Little Big Coil
45.5 T in 14 mm (14.5 T HTS + 31 T resistive)

LNCMI/CEA Nougat HTS insert
32.5 T in 50 mm (12. 5 T HTS + 20 T resistive)



Sunam NI one-body HTS magnet
26.4 T in 35 mm



Luca Bottura

Stress limits the fraction of HTS current density that can be effectively used

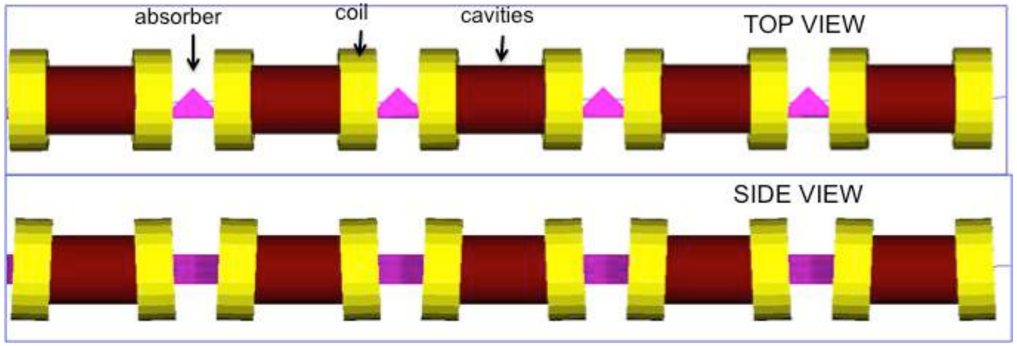
Solenoids with >30 T and aperture of 50 mm exist for high magnetic field science

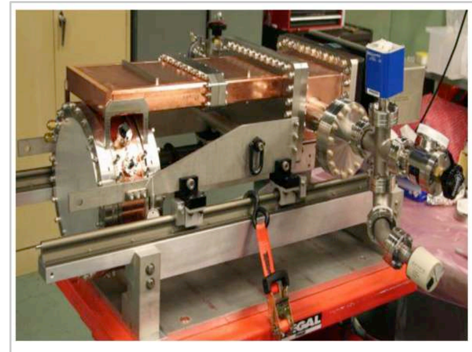
The limit is the stress in the HTS

Even 60 T might be possible

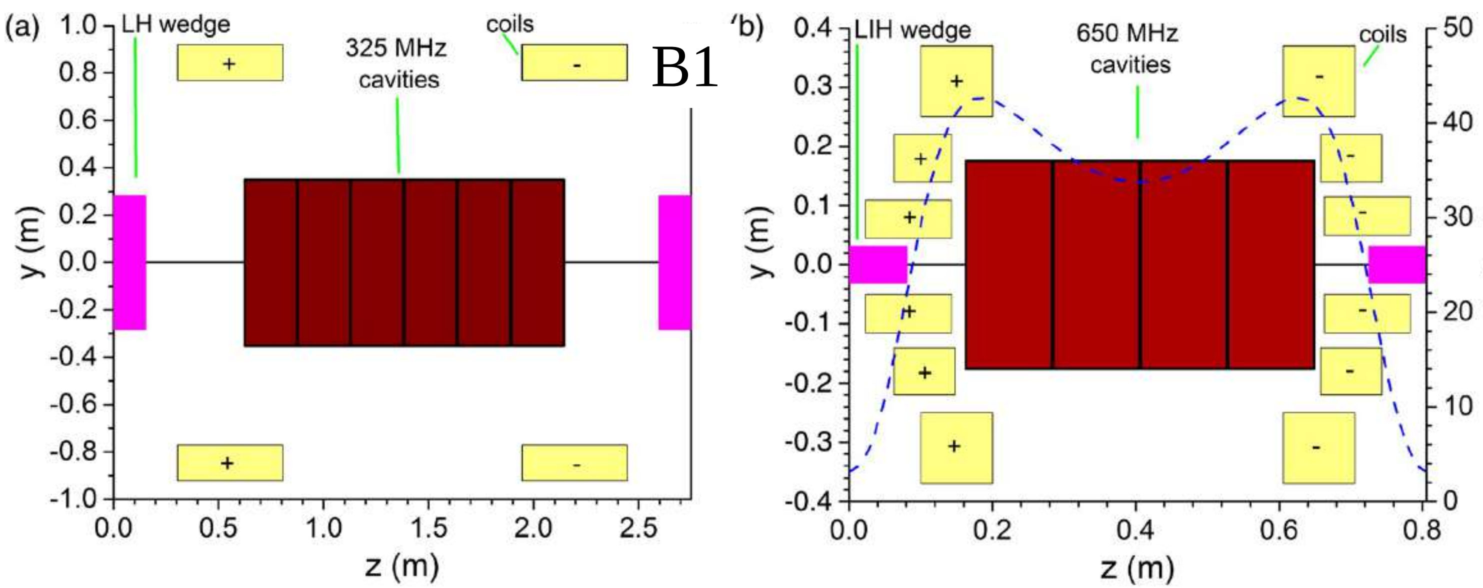
- but important R&D required to see how far we can push

6D Cooling Cell Design





MuCool: >50 MV/m in 5 T
Two solutions
- H2-filled copper cavities
- Cavities with Be end caps



High-gradient cavities in high magnetic field

Tight integration of solenoids, RF, absorbers, instrumentation, cooling, vacuum, alignment, …

Will aim for further optimisation
This is the **unique** and **novel** system of the muon collider
Will need a **test facility**

RF Cavity Challenge

Gradient of normal-conducting RF cavities is typically limited by breakdown

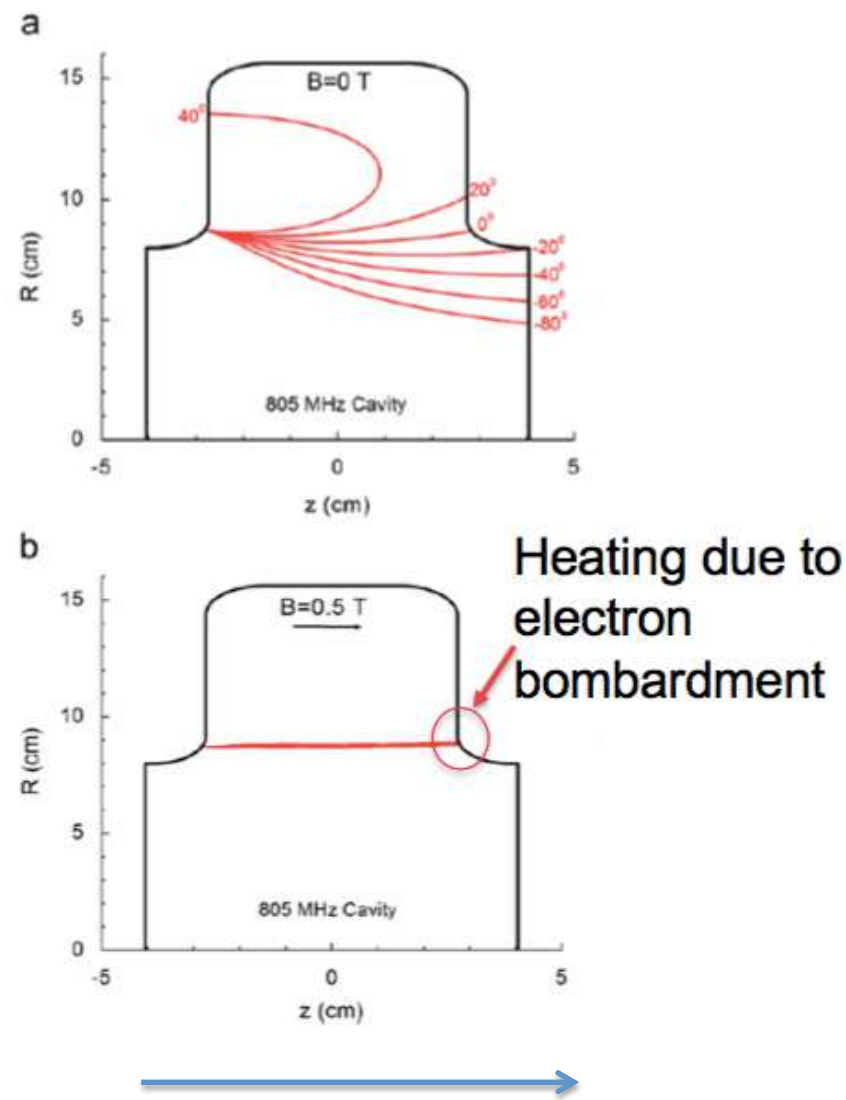
Model:

- electrons start at one emitter site
- electrons are accelerated by cavity field and hit other side

In solenoid field:

- electrons spiral around magnetic field line
- they all hit one spot on the other site
- this can heat spot above plastic deformation stress
- and lead to breakdown

- in any case electrons bounce back and forth between sites



RF Cavities: Solutions

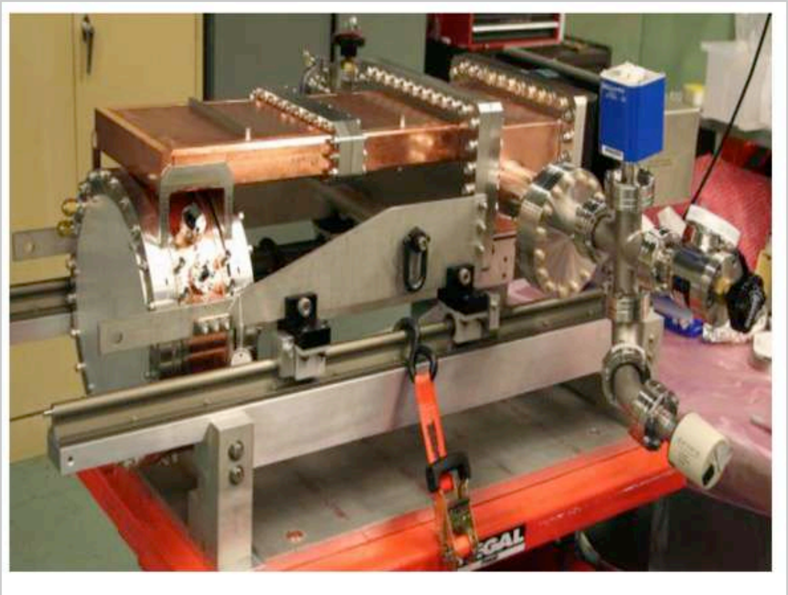
Solution 1: Reduce losses in the wall

- Shorter pulses
- Replace copper with beryllium
  - lower density, smaller Z

Experimental result (MUCOOL):

- Beryllium cavity in 3 T: 50 MV/m with 30 μs RF pulse

To be studied: gradient in higher field

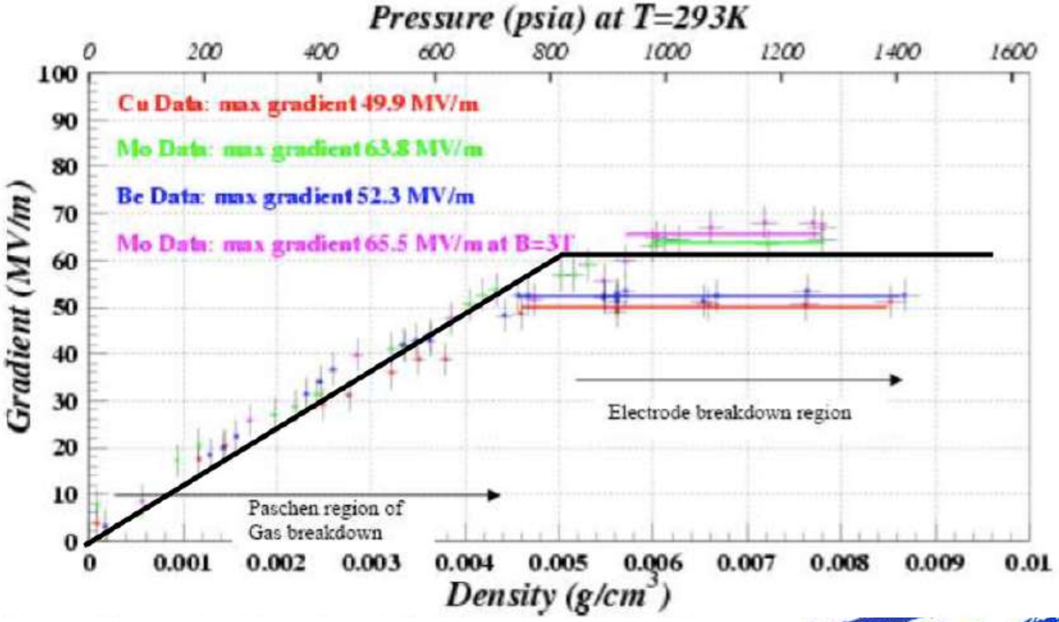


Solution 2: Use high-pressure hydrogen gas

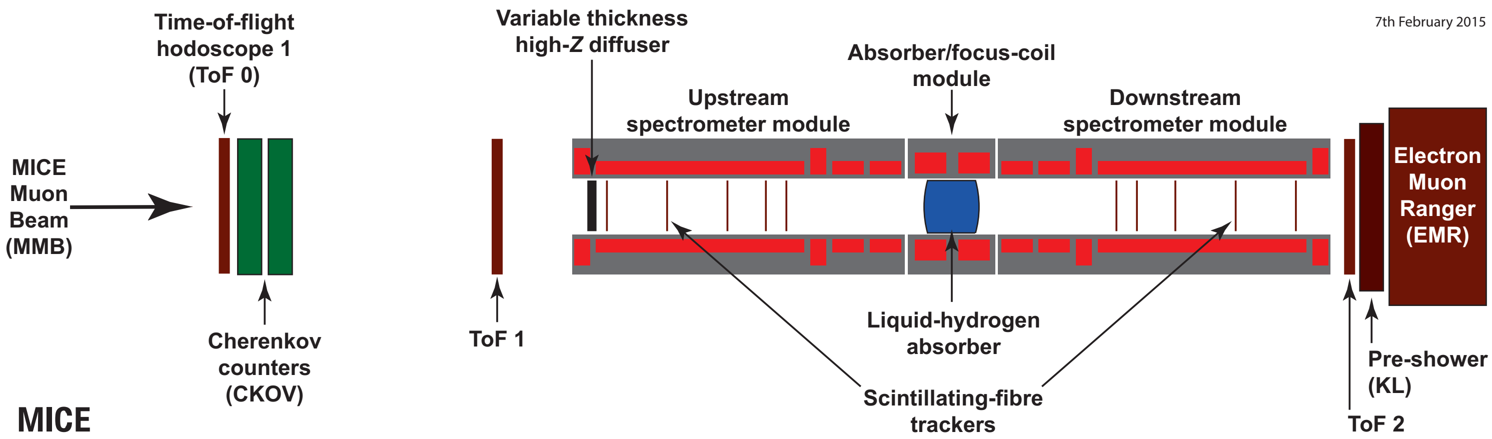
- until mean free path allows less than 15 eV energy gain (ionisation energy)

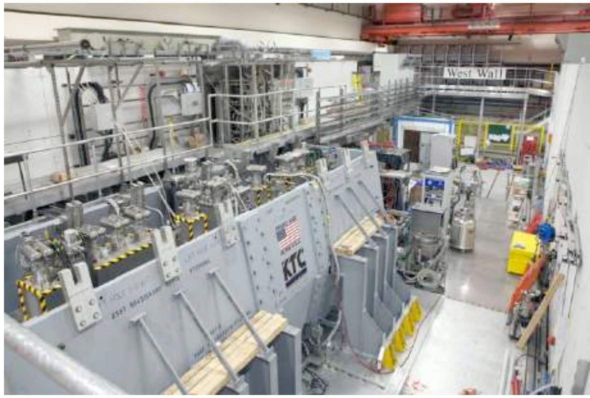
Experimental results (MUCOOL):

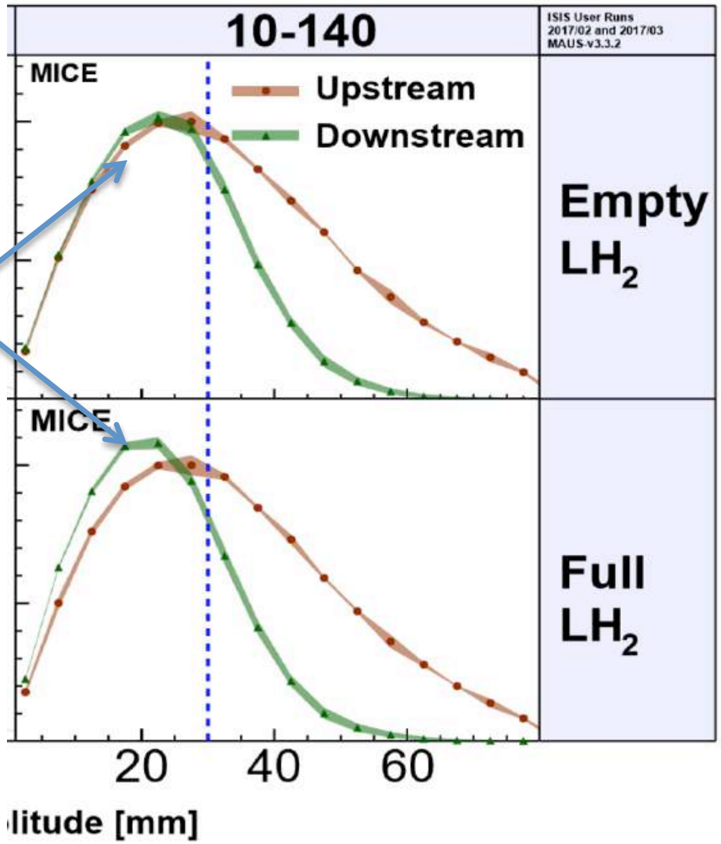
- Molybdenum cavity in 3 T: 65 MV/m
- for low density, limited by gas density (gradient is proportional to density)
- Final value depends on surface property



MICE (in the UK)







More particles at smaller amplitude after absorber is put in place

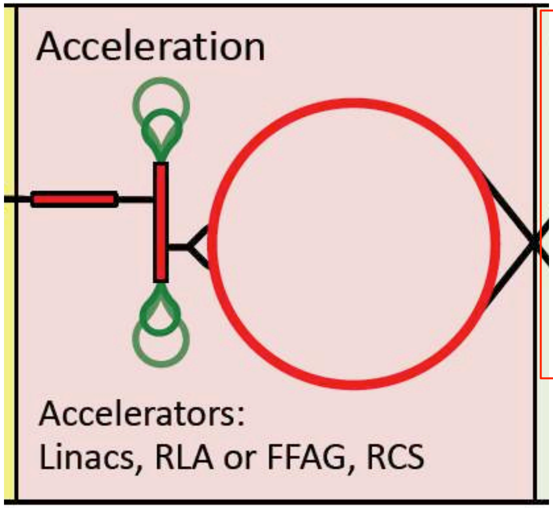
Principle of ionisation cooling has been demonstrated

Nature volume 578, pages 53-59 (2020)

More complete experiment with higher statistics, more than one stage required

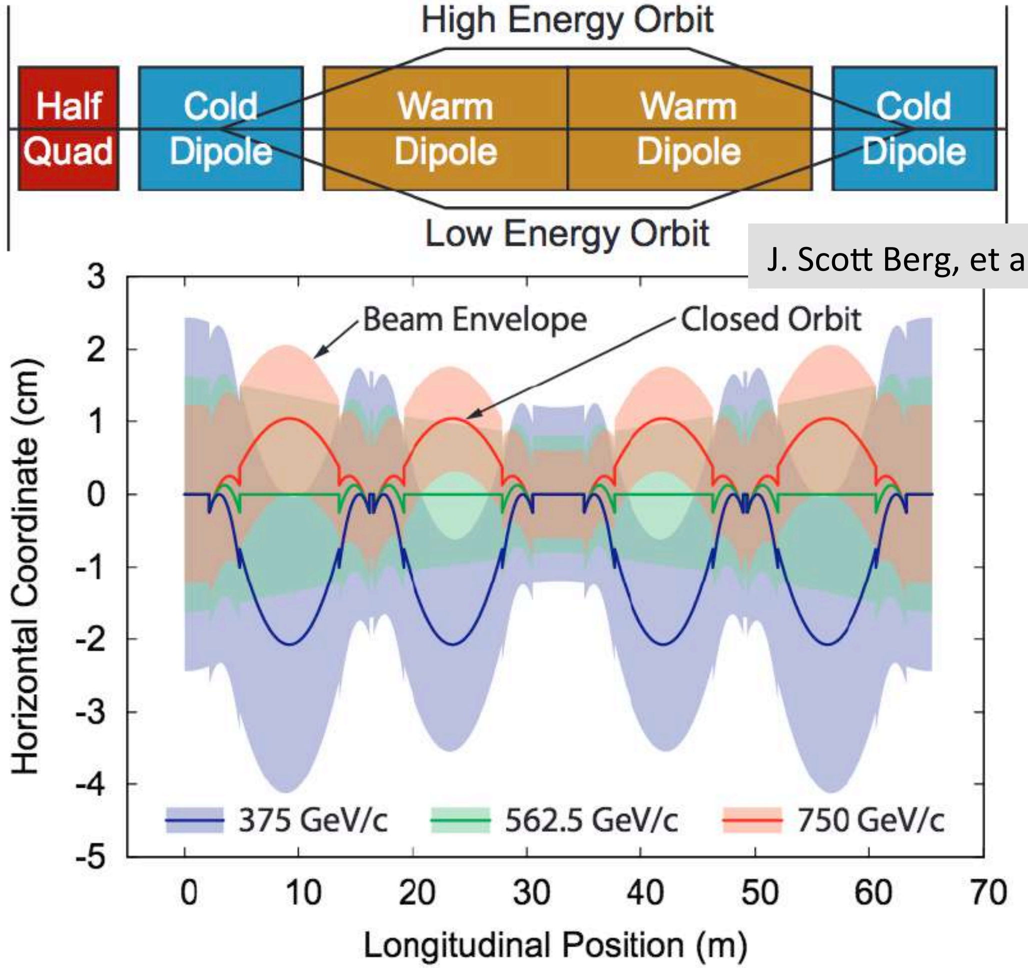
Integration of magnets, RF, absorbers, vacuum is engineering challenge

Acceleration

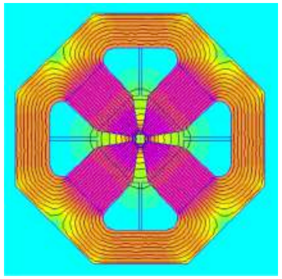


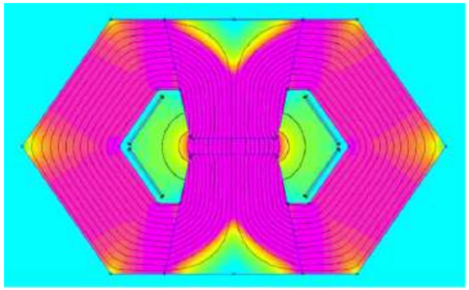
Linac
Recirculating linacs
Sequence of rings
- baseline: pulsed synchrotron (RCS)
- alternative: FFA

Hybrid RCS combines static superconducting magnets and fast-ramping normal-conducting magnets

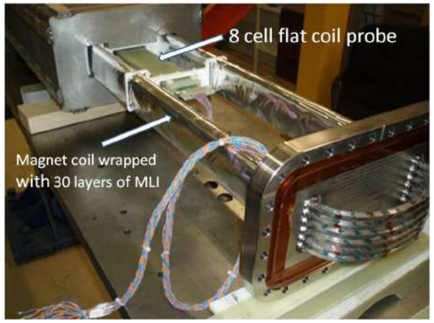


J. Scott Berg, et al.





Test of **fast-ramping normal-conducting magnet** design

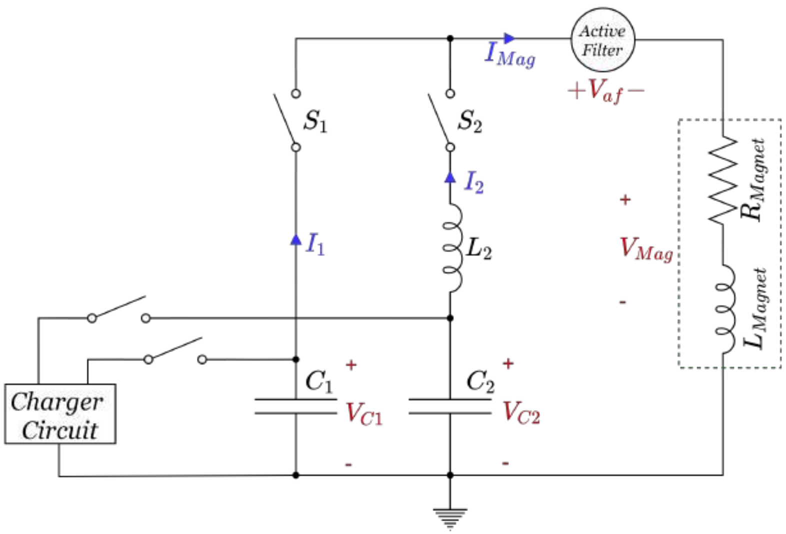


Power Converter Challenge

Total stored energy in ramped magnets: O(300 MJ), OK

Peak power during ramp (all rings combined) O(200 GW), OK

Average power to magnets 3.3 GW
- novel regime
- requires outstanding energy recovery (98%)
- close interaction between beam physicists and power experts required to limit system cost



Laser Mega Joule (France)
400 MJ, 480 x 5.76 GW peak power
1 pulse every 25min

Synergy with power grid applications

POPS (CERN)
20MJ, 6 x 10 MW peak power
1 pulse every 1.2s;

Collider Ring Arc Challenge

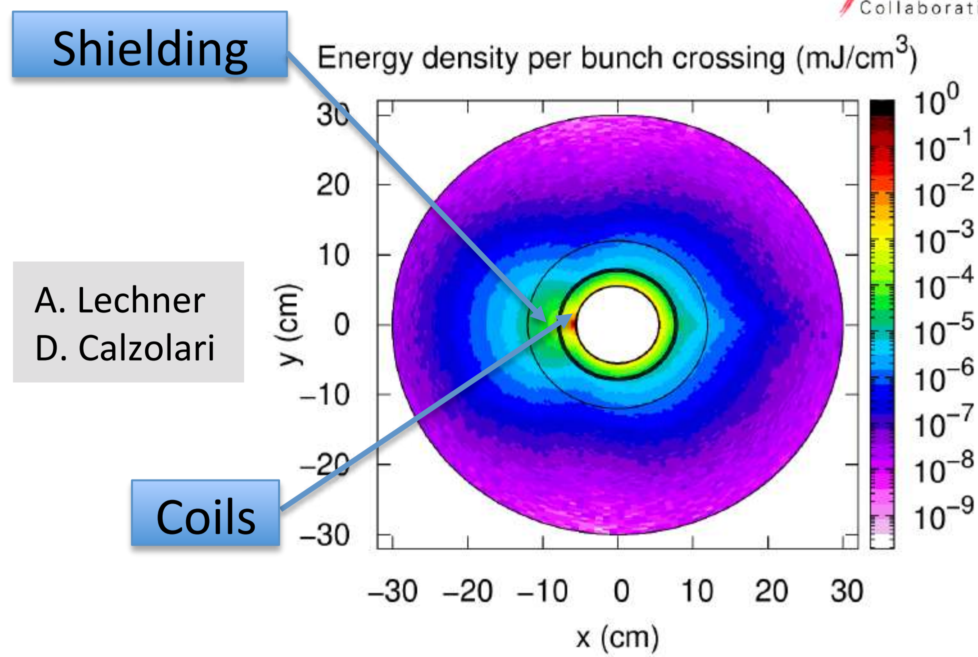
Beam loss protection O(500 W/m)

- requires larger aperture for shielding
- will be optimised

30 mm W shielding for 10 years:

- suppresses neutrons very well: DPA $O(10^{-4})$
- 30-40 MGy (3, 10 TeV), very local can be reduced by slightly increased shielding

⇒ taken care of



A. Lechner
D. Calzolari

Arc dipoles

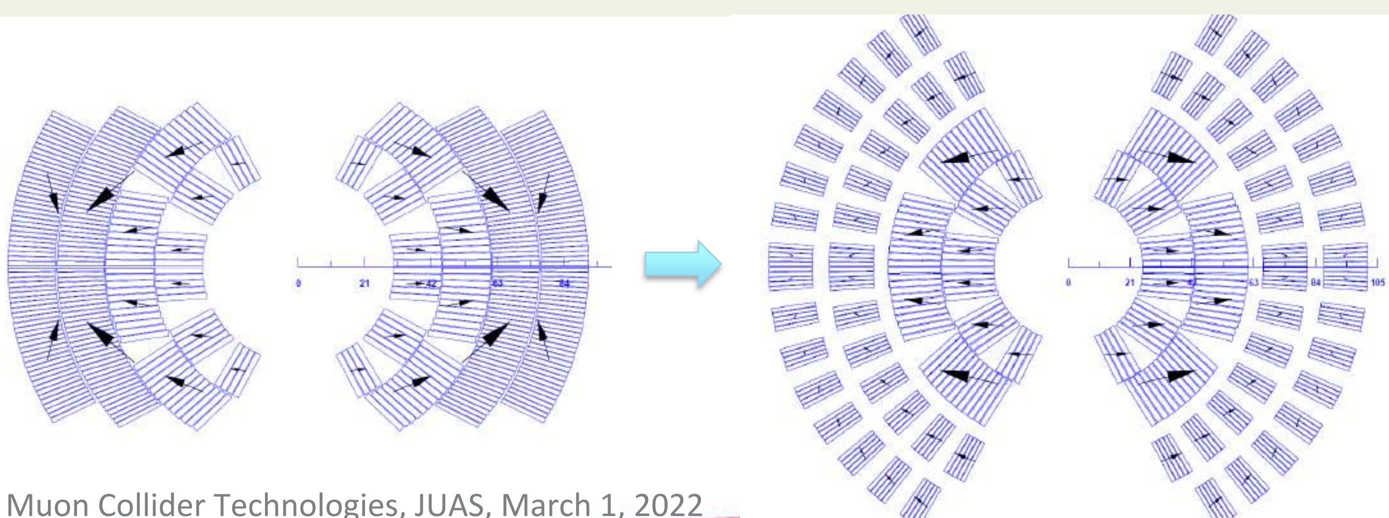
aperture O(150 mm), stress limited

3 TeV: 3 km of 11 T

- Nb_3Sn dipoles (HL-LHC level)

10 TeV: 7 km of 16 T

- stress managed Nb_3Sn dipoles
- or HTS

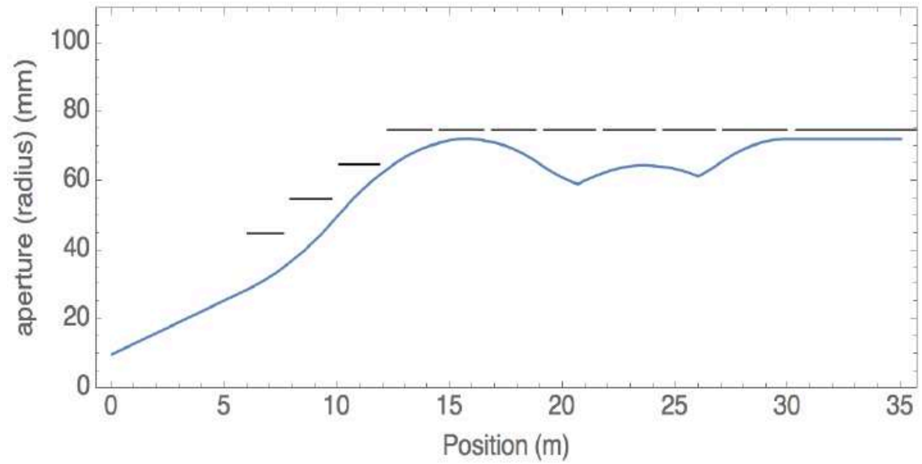


Final Focus Magnet Challenge

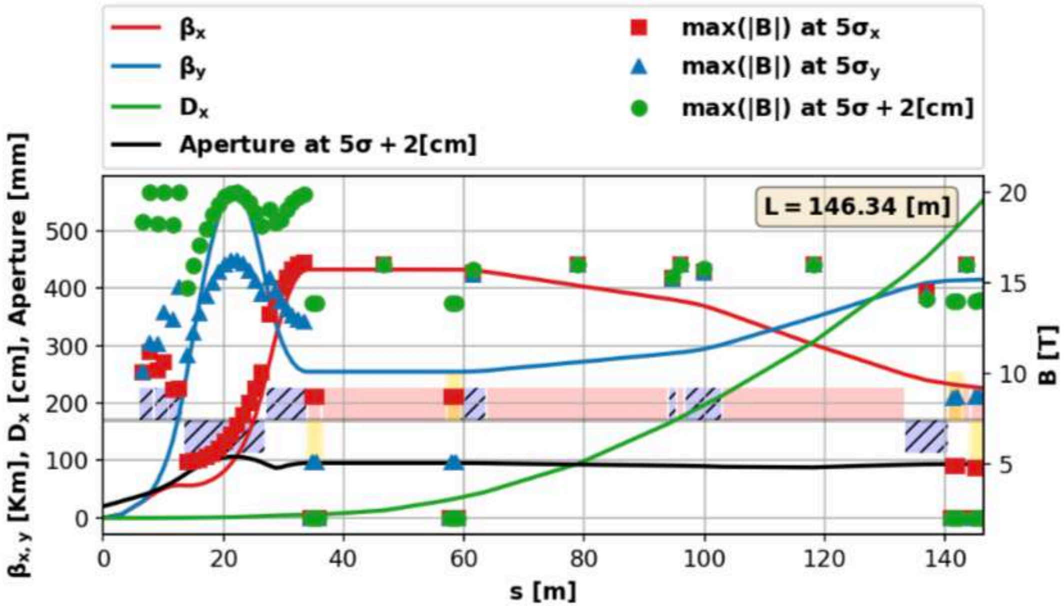
At 3 TeV:
Up to 12 T in aperture 150 mm
Similar to HL-LHC final focus magnets
Close to state of the art with Nb_3Sn

At 10+ TeV:
Aperture of 200+ mm
20 T field in aperture
⇒ Stress is significantly higher
⇒ Will need HTS

3 TeV FFS Design (MAP)

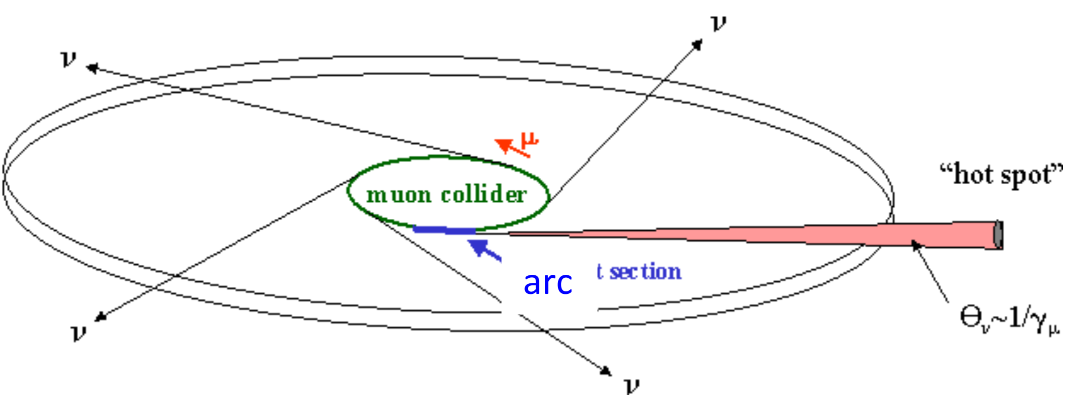


Parameter	Q1	Q1	Q3	Q4
Aperture (mm)	90	110	130	150
Gradients (T/m)	267	218	-154	-133.5
Peak field (T)	12	12	10+	10+
Dipole field (T)	0	0	2.00	2.00



HTS magnet development is essential for 10 TeV

Neutrino Flux

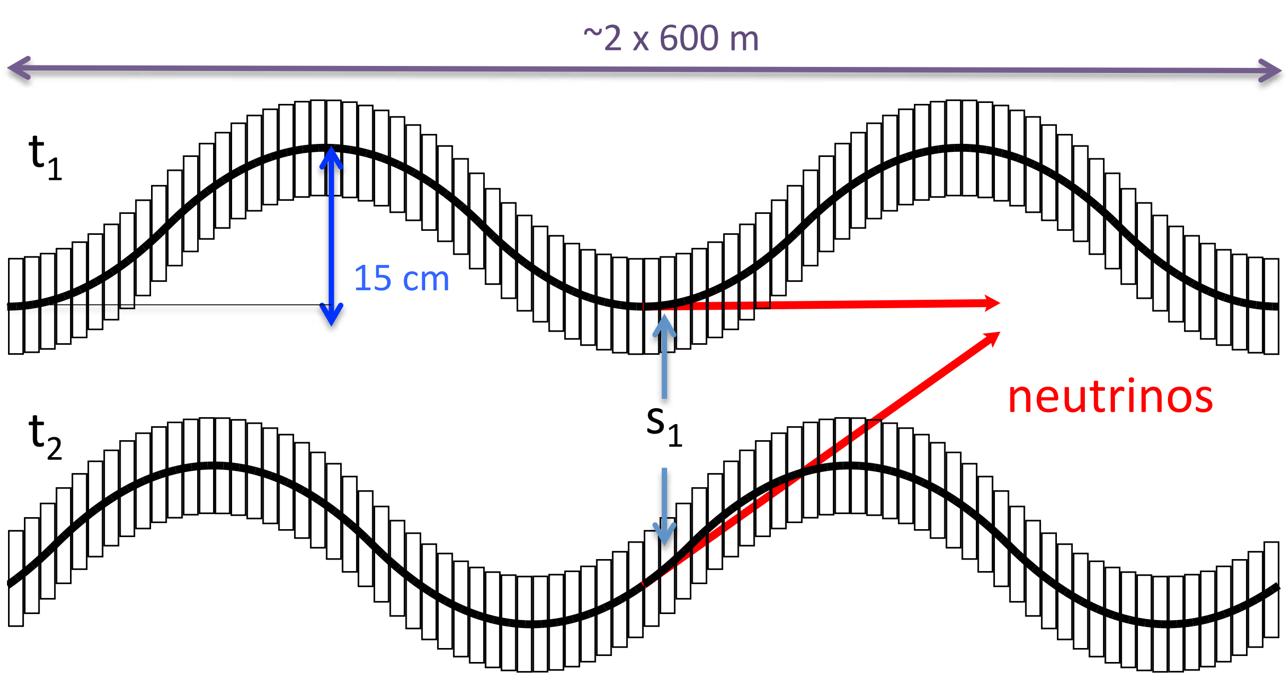


Concentrate neutrino cone from arcs can approach legal limits for 14 TeV

Goal is to reduce to level similar to LHC

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV: idea of Mokhov, Ginneken to move beam in aperture
Our approach: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradian

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

Neutrino Flux Mitigation

Team of RP experts, civil engineers, beam physicist and FLUKA experts

Goal to be **similar to LHC**: i.e**. negligible**, “fully optimised” (10 x better than MAP goal, 100 x better than legal requirements)

- With indirect effects (air, ground water, …)

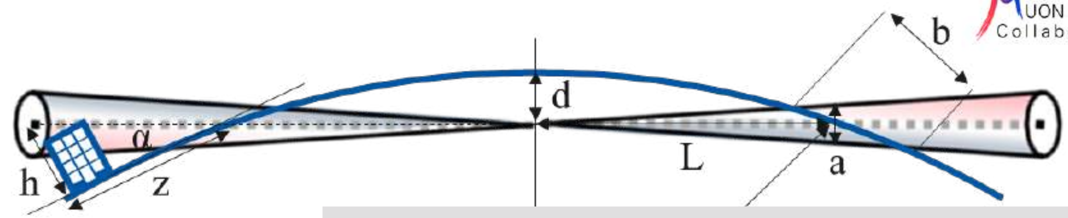
Addressed by:

Site choice in direction of experiments

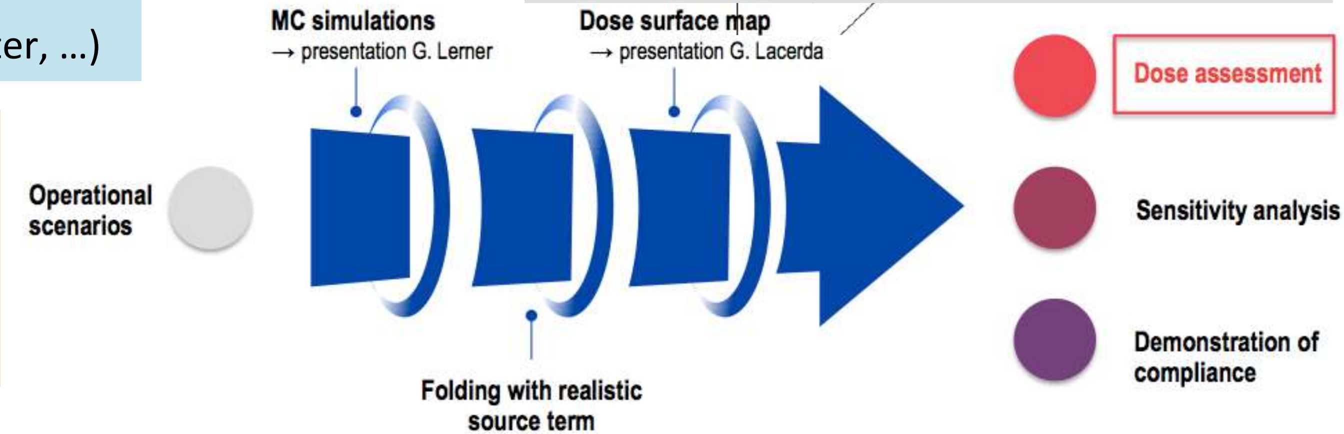
- tools in preparation

Mechanical mover system in arcs

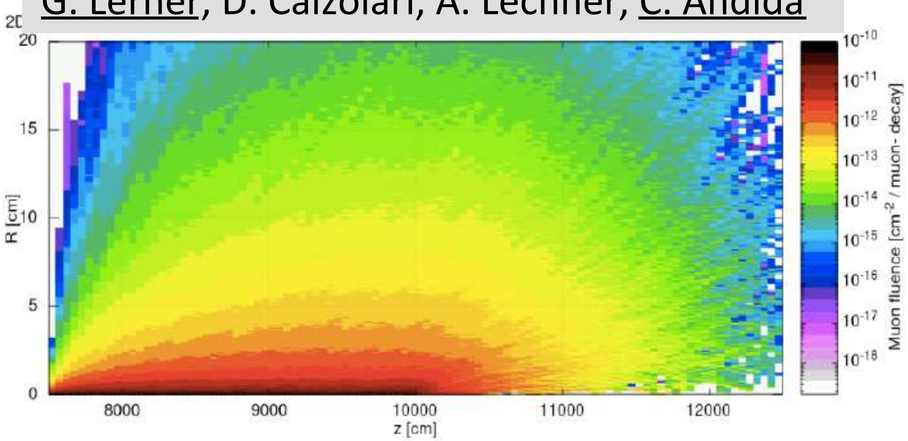
- allows 14 TeV in 200 m deep tunnel



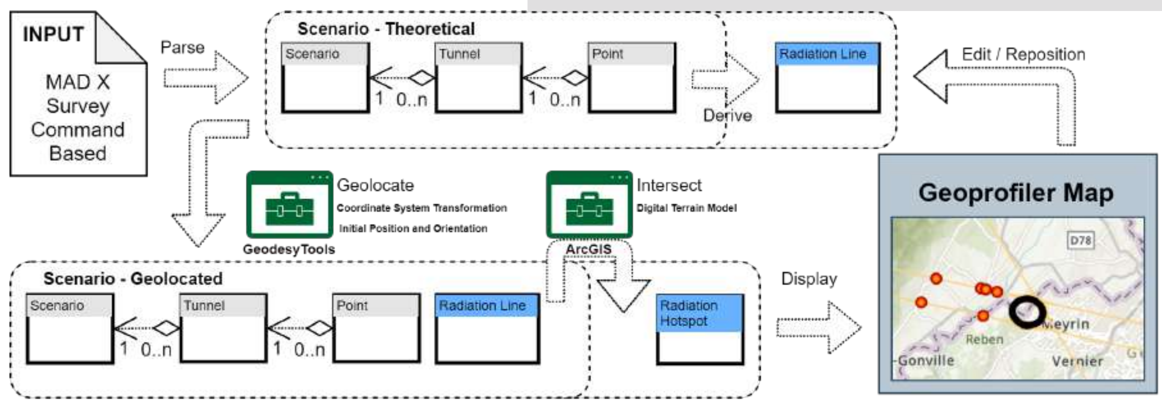
C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke



G. Lerner, D. Calzolari, A. Lechner, C. Ahdida



G. Lacerda, Y. Robert, N. Guilhaudin

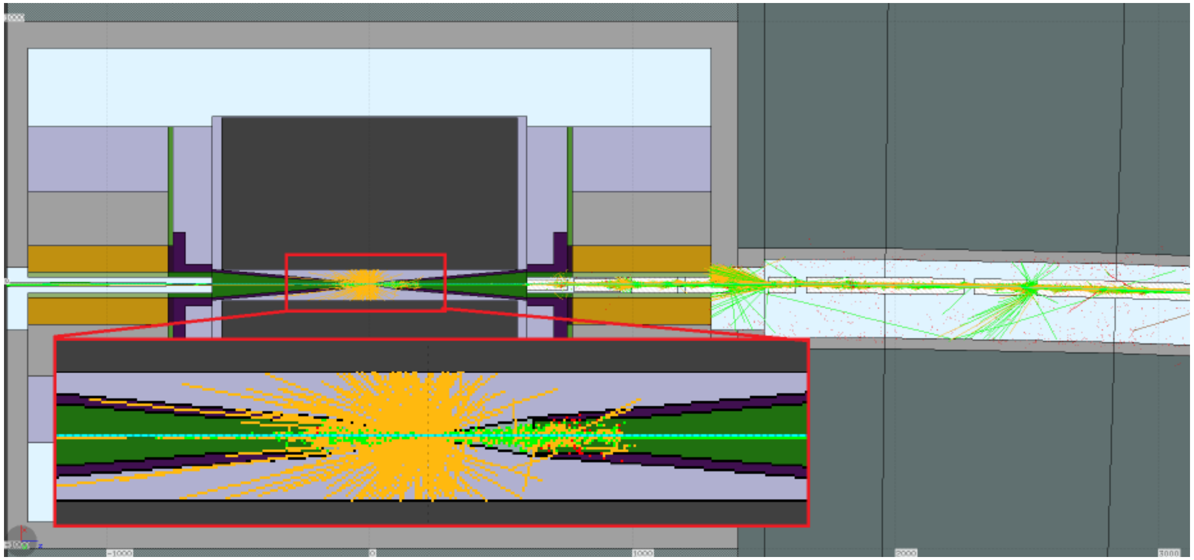


Mover system and impact on beam will be addressed in the coming years before end if 2025

Machine Detector Interface

Main background sources
- Muon decay products (40,000 muons/m/crossing at 14 TeV)
- Beam-beam background
- Note: background reduces while beam burns off

Mitigation methods
- masks
- detector granularity
- detector timing
- solenoid field
- event reconstruction strategies
- …



- Driven by INFN, Padua, (Donatella Lucchesi et al.), contributions from CERN and FNAL
  - interest exists: JAI-Oxford, Sussex, CEA, LIP Lisbon, DESY
- First studies at lower energies (125 GeV and 1.5 TeV are encouraging (D. Lucchesi et al.)
- 10 TeV studies started
- beam-beam started

Opportunities to help exist

Demonstrator Considerations

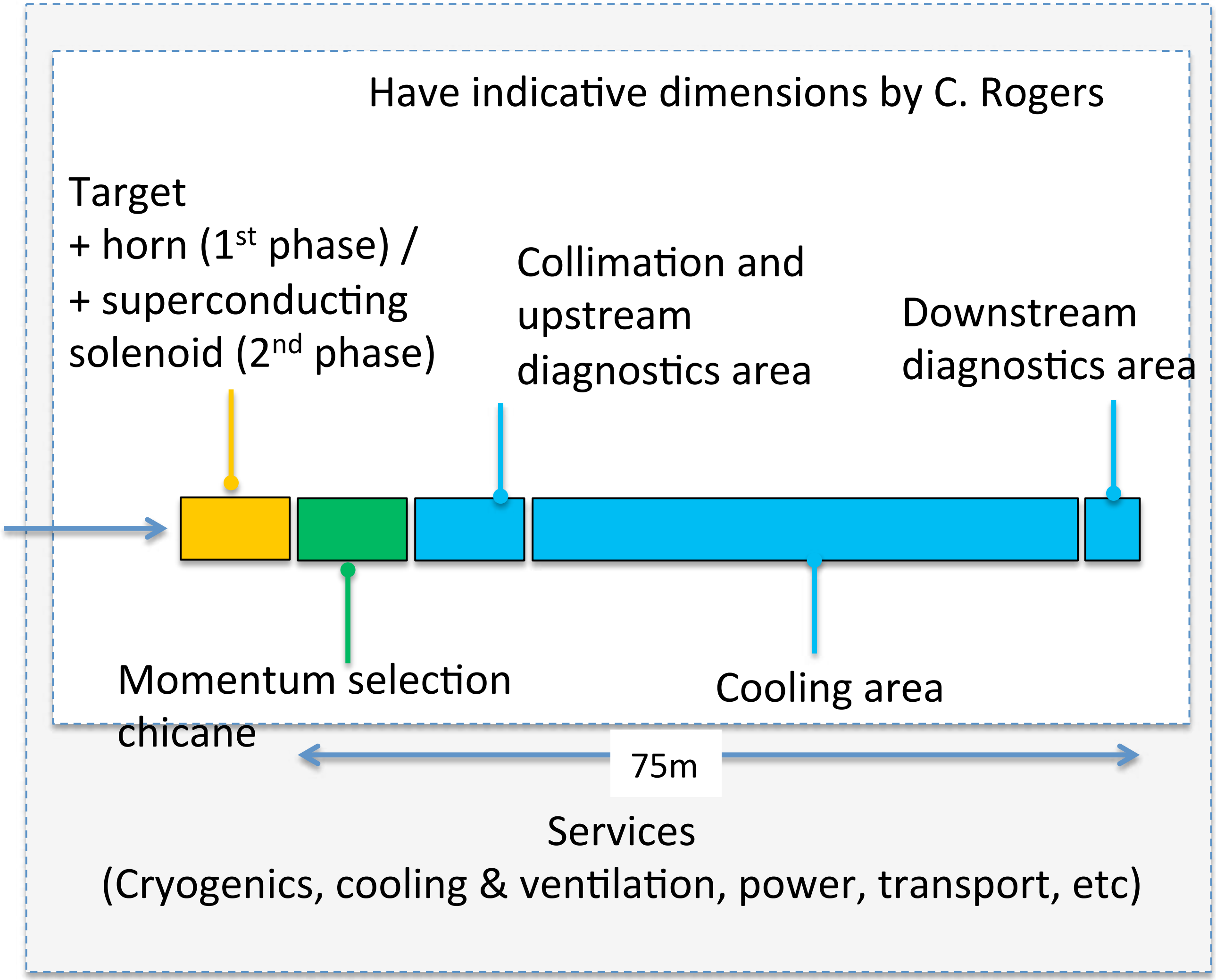
Muon cooling is the key novel and unique component of muon collider
⇒ need a test in a demonstrator
Other technology challenges exist but can be addressed with prototypes (e.g. collider dipoles), also in other locations

Modular approach to demonstrator: start with minimum complex and upgrade as demonstration progresses

Identified components of test facility with approximate dimensions

Will also explore alternative options, if resources permit

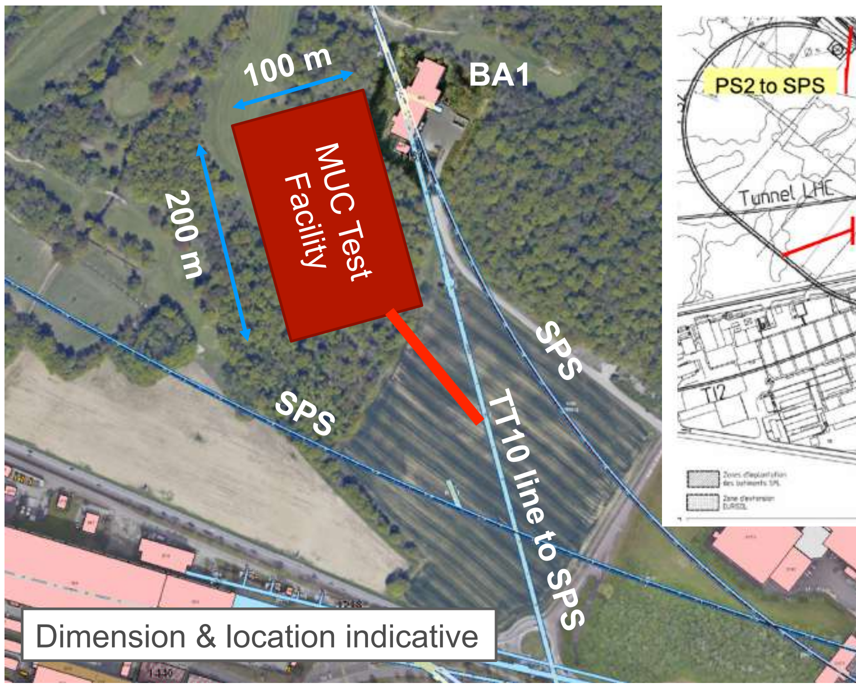
- e.g. PIC, parametric ionization cooling

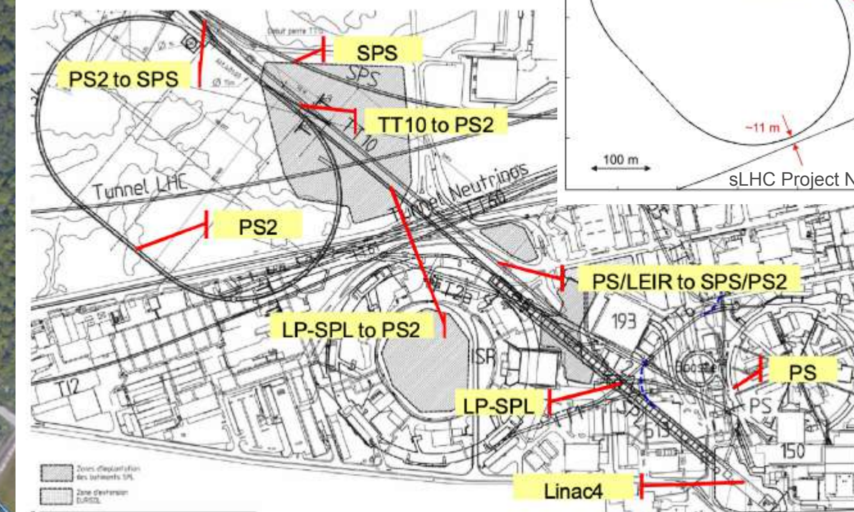


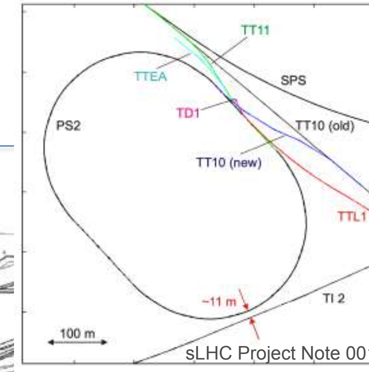
CERN Site Example

Will consider site proposed by partners and at CERN, but need at least one

Possibility around TT10

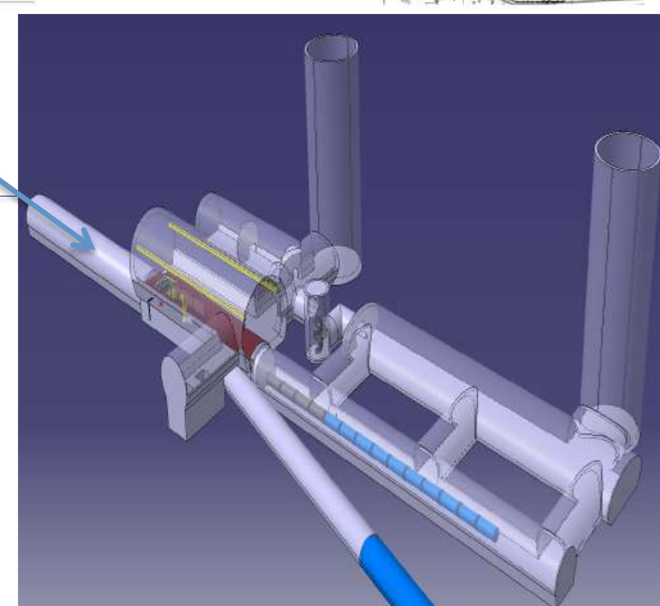






First option considered:
Could use CERN land close to TT10 and inject beam from PS

- 10^{13} 26 GeV protons in 7ns, produces a few 10^{12} muons per pulse
- Would be in molasse (no radiation to ground water), could accommodate 4 MW
- Could later upgrade with SPL and accumulator ring to have full power option



European Accelerator R&D Roadmap

International MUON Collider Collaboration

CERN Council charged Laboratory Directors Group (LDG) to develop Roadmap

- reviewed by SPC
- agreed by Council December 2021

CERN Council charged LDG to develop implementation plan by March 2022

Roadmap identifies muon collider challenges and two R&D scenarios to address them

- An **aspirational scenario**
- A **minimal scenario**

Scenario	FTEy	kCHF
Aspirational	445.9	11,875
Minimal	193	2,445

http://arxiv.org/abs/2201.07895

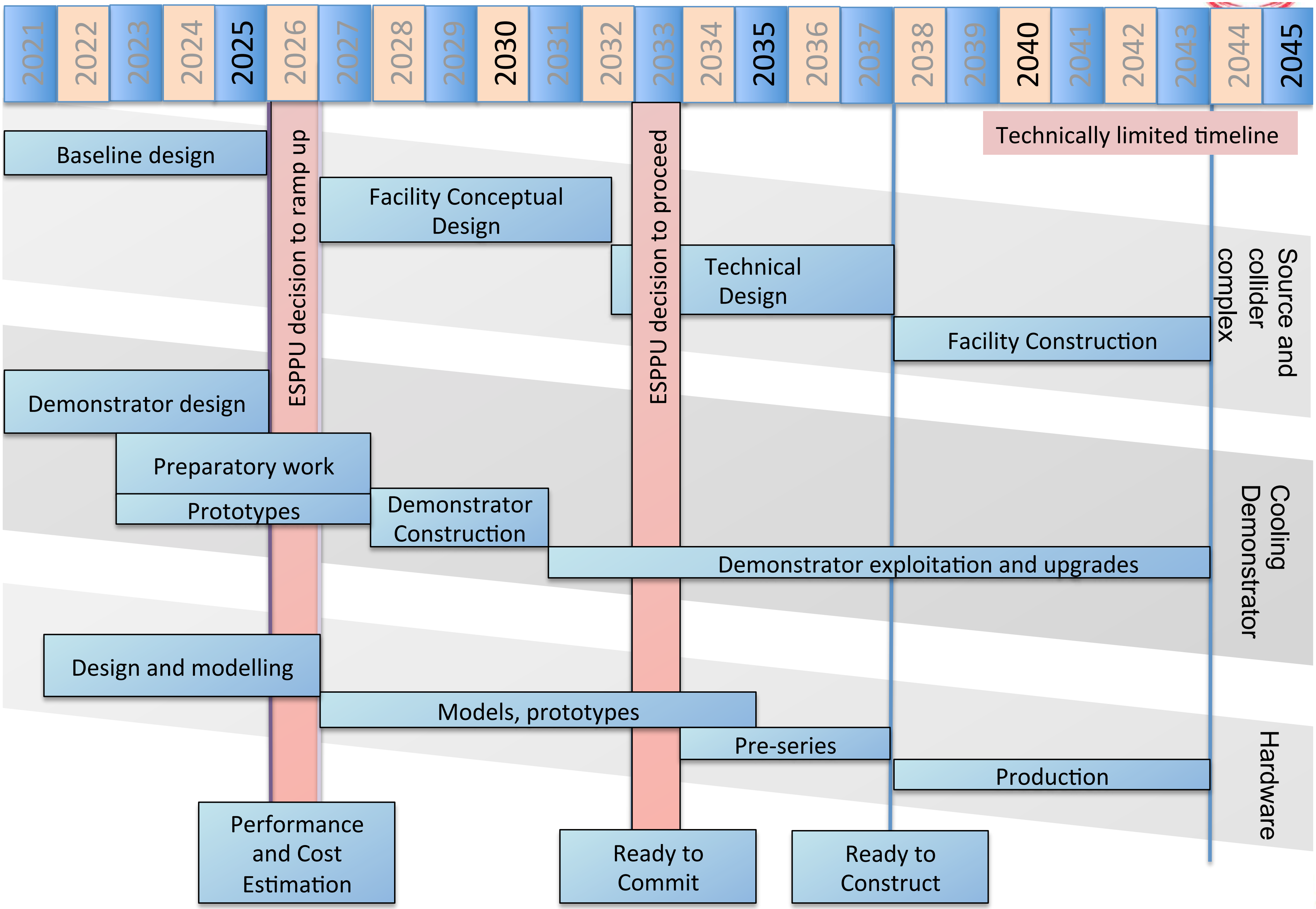
Aspirational scenario = 10 years of MAP (up to 45 FTE)

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment and similar costs. Colours are included for comparison with the resource profile Fig. 5.7.

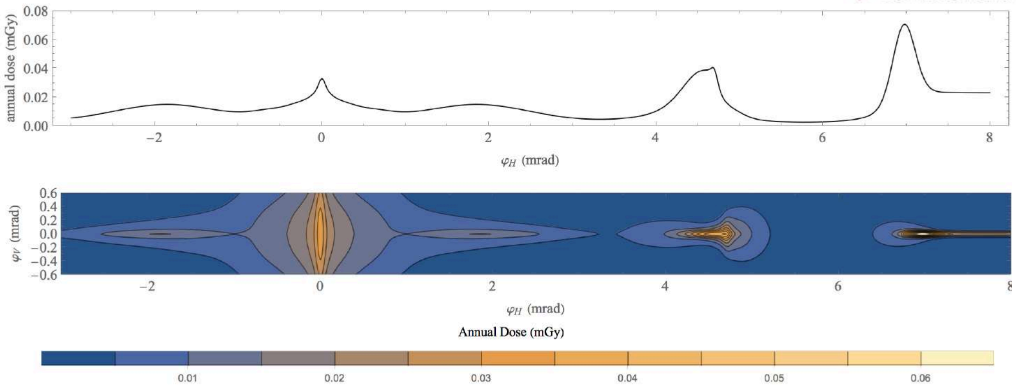
Aspirational Timeline

in case muon collider is next project after HL-LHC



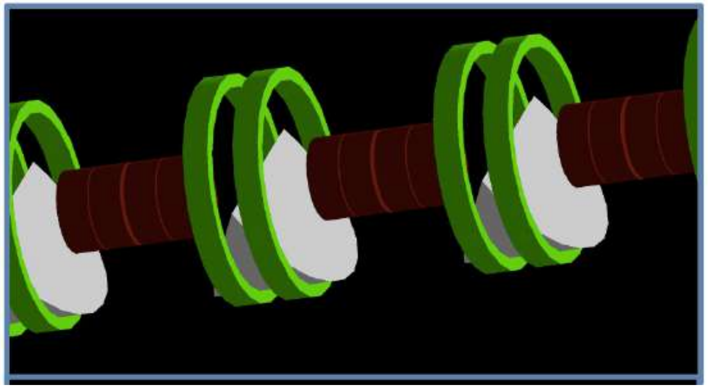
Ongoing Activities

- Identification of challenges and workplan
  - many contributors



- Radiation protection (CERN, FNAL)
- MDI (INFN, Padua, CERN, FNAL)
- Collider ring (CERN)

- Muon cooling system (RAL, CERN)



- Target (CERN)
- RF team is very active (CEA, CERN, Rostock)
- Power converter for fast-ramping magnets
- Demonstrator site and scope identification (all)

- A number of key “small” contributions
  - e.g. RF calculation (Rostock), solenoid stress estimate (KIT), lattice design (JAI students), RF test stand estimates (CEA), …

People started the journey

Interest (in part some work done)

- Pulsed synchrotrons (CEA-IRFU)
- (Recirculating) linacs (IJCLab, BNL, CERN software)
- Proton complex (ESS, Uppsala)
- Alternatives (e.g. FFA, final muon cooling) (UK)

Preparing an EU Design Study

- Target and target area (ESS, Uppsala, RAL, Warwick, ENEA)

- High-field collider ring magnets (KEK-CERN, Tokyo)
- Fast-ramping magnet systems (LNCMI/EMFL/Dresden, Darmstadt, KIT, PSI, EPFL, CERN)
- High-field solenoids (CEA-IRFU, KIT, looking for more)

- Superconducting high-energy RF (Rostock, INFN-Milano)
- Normal-conducting muon cooling RF (CEA-IRFU, RAL, Cockroft Institute, Lancaster, Strathclyde, Daresbury, INFN-Catania))

- Integration challenges of muon cooling cell (INFN, …)

- Test facility (CERN, all)

- Ongoing activities still need more resources

People getting ready to start the journey

Thanks for the Roadmap

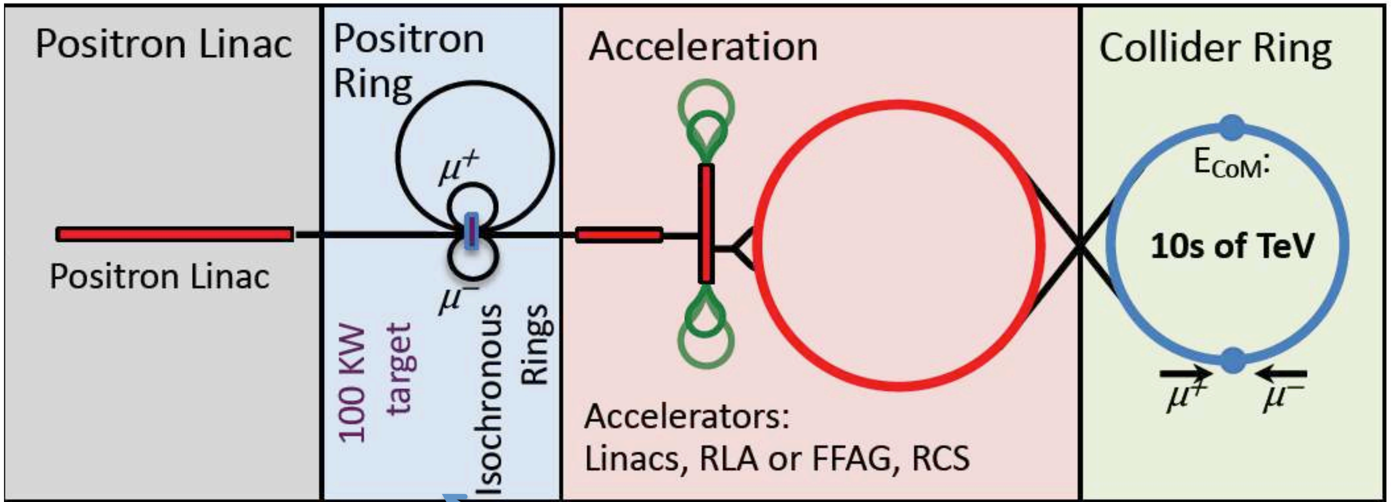
Muon Beam Panel: Daniel Schulte (CERN, chair), Mark Palmer (BNL, co-chair), Tabea Arndt (KIT), Antoine Chance (CEA/IRFU) Jean-Pierre Delahaye (retired), Angeles Faus-Golfe (IN2P3/IJClab), Simone Gilardoni (CERN), Philippe Lebrun (European Scientific Institute), Ken Long (Imperial College London), Elias Metral (CERN), Nadia Pastrone (INFN-Torino), Lionel Quettier (CEA/IRFU), Magnet Panel link, Tor Raubenheimer (SLAC), Chris Rogers (STFC-RAL), Mike Seidel (EPFL and PSI), Diktys Stratakis (FNAL), Akira Yamamoto (KEK and CERN) **Contributors:** Alexej Grudiev (CERN), Roberto Losito (CERN), Donatella Lucchesi (INFN)

Community conveners: *Radio-Frequency (RF):* Alexej Grudiev (CERN), Jean-Pierre Delahaye (CERN retiree), Derun Li (LBNL), Akira Yamamoto (KEK). *Magnets:* Lionel Quettier (CEA), Toru Ogitsu (KEK), Soren Prestemon (LBNL), Sasha Zlobin (FNAL), Emanuela Barzi (FNAL). *High-Energy Complex (HEC):* Antoine Chance (CEA), J. Scott Berg (BNL), Alex Bogacz (JLAB), Christian Carli (CERN), Angeles Faus-Golfe (IJCLab), Eliana Gianfelice-Wendt (FNAL), Shinji Machida (RAL). *Muon Production and Cooling (MPC):* Chris Rogers (RAL), Marco Calviani (CERN), Chris Densham (RAL), Diktys Stratakis (FNAL), Akira Sato (Osaka University), Katsuya Yonehara (FNAL). *Proton Complex (PC):* Simone Gilardoni (CERN), Hannes Bartosik (CERN), Frank Gerigk (CERN), Natalia Milas (ESS). *Beam Dynamics (BD):* Elias Metral (CERN), Tor Raubenheimer (SLAC and Stanford University), Rob Ryne (LBNL). *Radiation Protection (RP):* Claudia Ahdida (CERN). *Parameters, Power and Cost (PPC):* Daniel Schulte (CERN), Mark Palmer (BNL), Jean-Pierre Delahaye (CERN retiree), Philippe Lebrun (CERN retiree and ESI), Mike Seidel (PSI), Vladimir Shiltsev (FNAL), Jingyu Tang (IHEP), Akira Yamamoto (KEK). *Machine Detector Interface (MDI):* Donatella Lucchesi (University of Padova), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergo R Jindariani (FNAL). *Synergy:* Kenneth Long (Imperial College), Roger Ruber (Uppsala University), Koichiro Shimomura (KEK). *Test Facility (TF):* Roberto Losito (CERN), Alan Bross (FNAL), Tord Ekelof (ESS,Uppsala University).

And the participants to the community meetings and the study

Alternatives: The LEMMA Scheme

LEMMA scheme (INFN)
P. Raimondi et al.

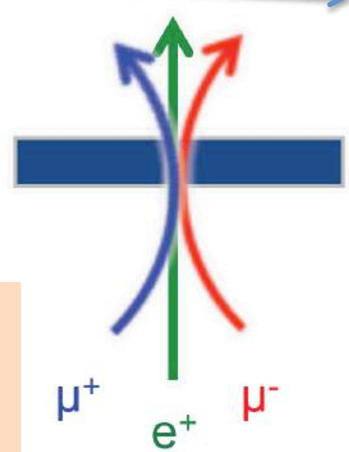


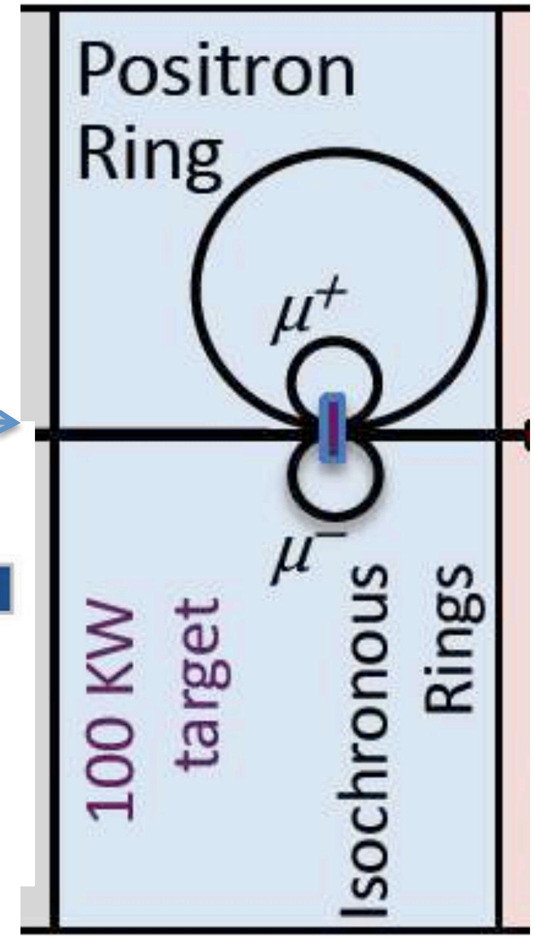
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

- Uses Bethe-Heitler production with electrons

45 GeV positrons to produce muon pairs
Accumulate muons from several passages

$$e^+e^- \rightarrow \mu^+\mu^-$$





Excellent idea, but nature is cruel

Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme

$\Rightarrow$ **Need same game changing invention**

Conclusion

- Muon colliders are a unique opportunity for a high-energy, high-luminosity lepton collider
  - high luminosity to beam power ratio
  - cost efficiency to be assessed

- Two different options considered
  - 3 TeV collider that can start construction in less than 20 years
  - 10 TeV collider that uses advanced technologies

- Not as mature as ILC or CLIC
  - have to address **important R&D** items
  - but **no showstopper** identified

- Aim to develop concept to a **maturity level** that allows to make **informed choices by the next ESPPU** and other strategy processes
  - Baseline design
  - R&D and demonstration programme

- An important opportunity that we should not miss
- http://muoncollider.web.cern.ch

Many thanks to the Muon Beam Panel, the collaboration, the MAP study, the MICE collaboration, and many others

Reserve

Muon Collider Luminosity Scaling

Fundamental limitation

Assumes no emittance growth after source and no technical limitation

Applies to MAP and LEMMA scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon\epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring
= small ring
= many collisions

Large energy acceptance
= short bunch
= small betafunction

Dense beam

High beam power

Note: emittances are normalised

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International MUON Collider Collaboration

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$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

Same for MAP and LEMMA

O(1%) of proton scheme
= 100 MW of positrons lost

$$e^+e^- \to \mu^+\mu^-$$

$$e^+e^- \to e^+e^-\gamma$$

Bremsstrahlung $O(10^5)$ times more likely than pair production
O(150mb), $E_\gamma \geq 0.01\ E_p$
O(60mb), $E_\gamma \geq 0.1\ E_p$

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O(60mb), $E_\gamma \geq 0.1\ E_p$

Each passage in target increases emittance (multiple scattering)
⇒ Need to produce enough muons per passage for high N/ε

Example to reach luminosity is
- 3 mm BE target, 0.86 mm betafunction (optimum)
- 3 x 10^{15} positrons per bunch (22 MJ)
  - 60 kJ lost in target, temperature jump of MK
- at least 100 bunches per pulse (2 GJ)
  - (only 1% is lost)

Note: Additional beam combination schemes can reduce positron bunch charge but increase energy in pulse

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O(150mb), $E_\gamma \geq 0.01\ E_p$
O(60mb), $E_\gamma \geq 0.1\ E_p$

Unfortunately, seems too hard from fundamental physics
Need a new game-changing invention

Muon Collider Luminosity Scaling

Fundamental limitation

Assumes no emittance growth after source and no technical limitation

Applies to MAP and LEMMA scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

Assume 3 mm thick Be target, 0.86 mm beta

⇒ 0.6 nm emittance growth per muon beam passage through target (optimum case)

⇒ Need bunches with 3 x 10^{15} positrons (=22 MJ) to obtain required

⇒ Positron beam energy 2 GJ/burst, 5 burst per second

⇒ Energy deposition in target 60 kJ per pulse (minimum ionisation) 4.5 MK temperature rise per bunch (linear approximation)

⇒ Extremely challenging, not sure even a fluid target can do this

LEMMA scheme needs O(0.7 mJ) positrons lost per produced muon pair

⇒ 100 MW loss yield 1.4 x 10^{11} s^{-1} muon pairs

- (proton case: 1 x 10^{13} s^{-1})

⇒ Need 70 times denser beam for same luminosity

⇒ Lose 1.4 10^{16} positrons per second

Note: Stacking

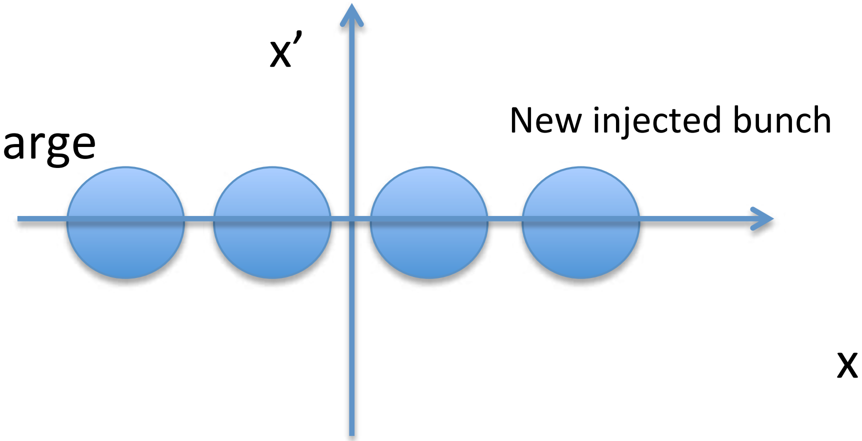
$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

stacking in longitudinal plane does not increase luminosity

bunch length and beta-function increase with the charge

Stacking in transverse plane can help because

$$\epsilon = \sqrt{\epsilon_x \epsilon_y}$$



stacking m² bunches leads to

$$N = m^2 N_1 \qquad \epsilon = m \epsilon_1$$

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N}{\epsilon \epsilon_L} f_r N \gamma$$

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta m \frac{N_0}{\epsilon_0 \epsilon_{L,0}} f_{r,0} N_0 \gamma$$

and the luminosity scales as

$$\frac{N}{\epsilon} = m \frac{N_1}{\epsilon_1}$$

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \sqrt{f_{r,0} \tau \gamma} \frac{N_0}{\epsilon_0 \epsilon_{L,0}} f_{r,0} N_0 \gamma$$

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Applies to MAP and LEMMA scheme

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High energy

High field in collider ring
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Large energy acceptance
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Dense beam

High beam power

Note: emittances are normalised

Some Comments

F. Zimmermann 2018 J. Phys.: Conf. Ser.1067 022017 claims

$$L \approx f_{\rm rev} \dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \frac{1}{3^6} \gamma \tau^2 \frac{1}{4\pi\beta^*}$$

$$= \frac{1}{3^6} \left\{ \left(\frac{eF_{\rm dip}}{2\pi m_\mu} \right)^3 \frac{\tau_0^2}{4\pi c^2} \right\} \left[B^3 C^2 \right] \left[\dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \right] \frac{1}{\beta^*}$$

$$\mathcal{L} \propto \frac{(f_r N)^2}{\epsilon}$$

The paper assumes that muons can be stacked but ignores the associated emittance growth
This is wrong, with these assumption LEMMA would be viable

the LEMMA scheme

scheme	p-γ	G.-F. μ	e^+	G.-F. e^+
base	LHC/FCC-hh		FCC-ee	FCC
rate $\dot{N}_\mu$ [GHz]	1	400	0.003	100
μ/pulse [10^4]	0.01	4	0.2	6,000
p. spacing [ns]	100	100	15	15
energy [GeV]	2.5	0.1	22	22
rms en. spread	3%	10%	10%	10%
n. emit. [μm]	7	2000	0.04	0.04
$\dot{N}_\mu/\varepsilon_N$ [10^{15} m^{-1}s^{-1}]	0.1	0.2	0.1	3,000

New proposal by C. Curatolo and L. Serafini needs to be looked at
Uses Bethe-Heitler production with electrons

at 14 TeV:
9 GW beam power

even 30 times more beam particles

Physics at Muon Collider

Muon Collider can be the game changer

[The Muon Smasher's Guide]

Muon collider physics potential

D. Buttazzo

A high-energy muon collider is simply a dream machine: allows to probe unprecedented energy scales, exploring many different directions at once!

Direct searches
Pair production, Resonances, VBF, Dark Matter, ...

High-rate measurements
Single Higgs, self coupling, rare and exotic Higgs decays, top quarks, ...

High-energy probes
Di-boson, di-fermion, tri-boson, EFT, compositeness, ...

Muon physics
Lepton Flavor Universality, b → sμμ, muon g-2, ...

- Theory input needed: define energy, luminosity and detector performance goals — physics potential of a multi-TeV muon collider
- Great interest in the theory community:

1807.04743 2005.10289 2008.12204 2012.11555 2102.11292 2104.05720
1901.06150 2006.16277 2009.11287 2101.10334 2103.01617 etc ...
2003.13628 2007.14300 2012.02769 2102.08386 2103.14043

R. Sundrum

CONCLUSIONS

There are BROAD EXCITING PHYSICS THEMES to pursue at future colliders:

Dark Matter, Baryogenesis, SUSY, Compositeness, flavor origins, parallel gauge sectors, long-lived particles, precision Higgs structure

Need a collider at highest energies, clean enough & with sensitive enough detectors, to pursue both high mass &/or weakly coupled BSM at high precision & to excite & challenge next generation of experimentalists.

If new physics (dimly) seen in DM, flavor, EDM, precision, gravitational wave, cosmological expts., we need collider with reach/precision to complement, corroborate, clarify

A Muon Collider is great!

P. Maede

κ-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/	$\mu^+\mu^-$
fit			S2	S2′	250	500	1000	380	1500	3000		240	365	eh/hh	10000
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.31

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P. Maede

Di-Higgs too!

Double Higgs production

- Reach on Higgs trilinear coupling: hh → 4b

B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204

E [TeV]	$\mathcal{L}$ [ab^{-1}]	N_{rec}	$\delta\sigma \sim N_{rec}^{-1/2}$	$\delta\kappa_3$
3	5	170	~ 7.5%	~ 10%
10	10	620	~ 4%	~ 5%
14	20	1340	~ 2.7%	~ 3.5%
30	90	6'300	~ 1.2%	~ 1.5%

Challenges and Status

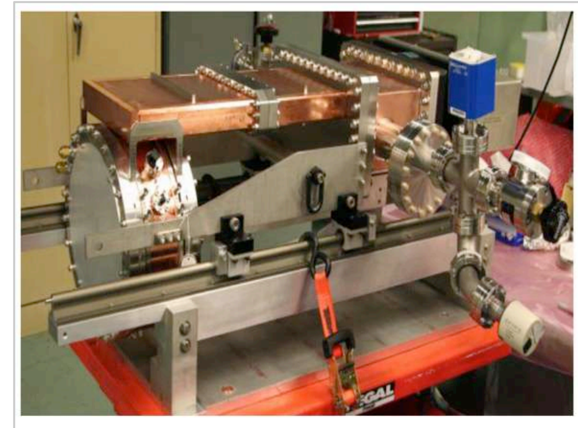
FNAL
12 T/s HTS
0.6 T max

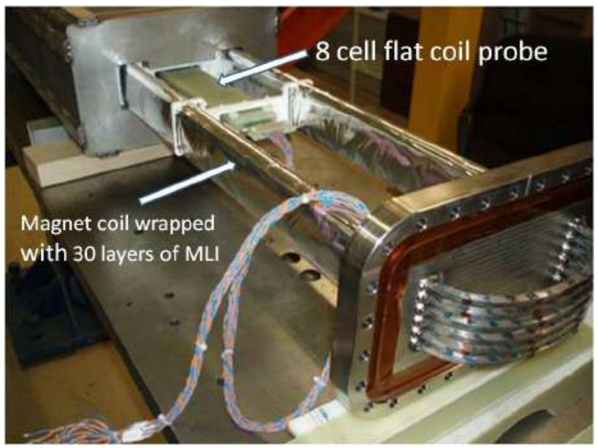
now 290 T/s

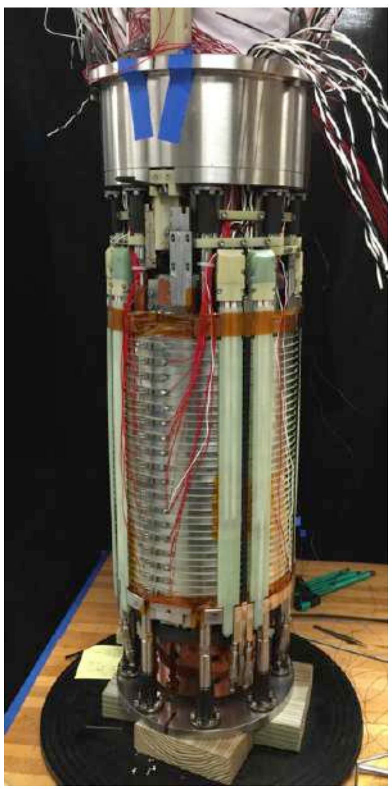
Test of **fast-ramping normal-conducting magnet** design

MuCool: >50 MV/m in 5 T field

Two solutions
- Copper cavities filled with hydrogen
- Be end caps







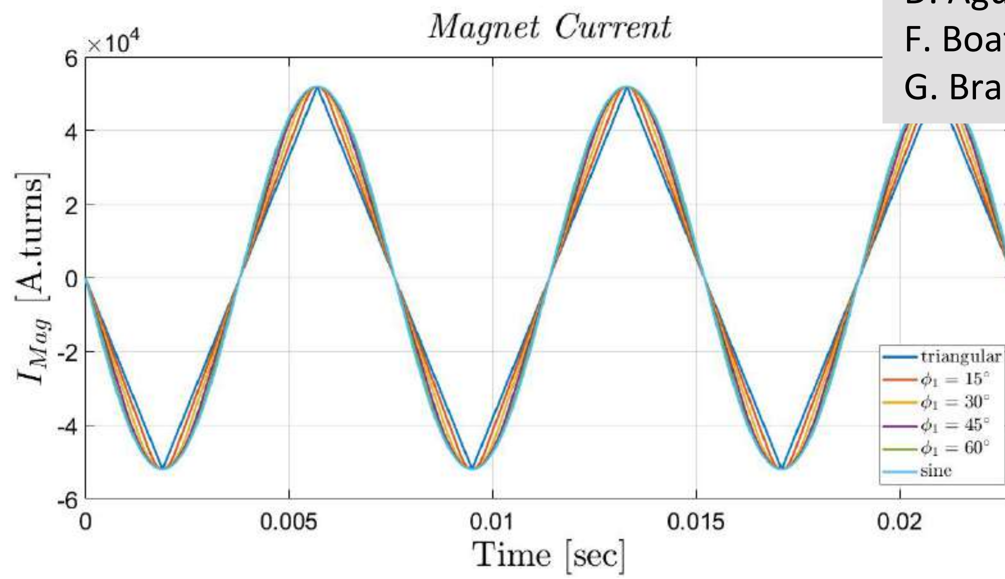
NHFML
32 T solenoid
with HTS

Planned efforts
to push even
further

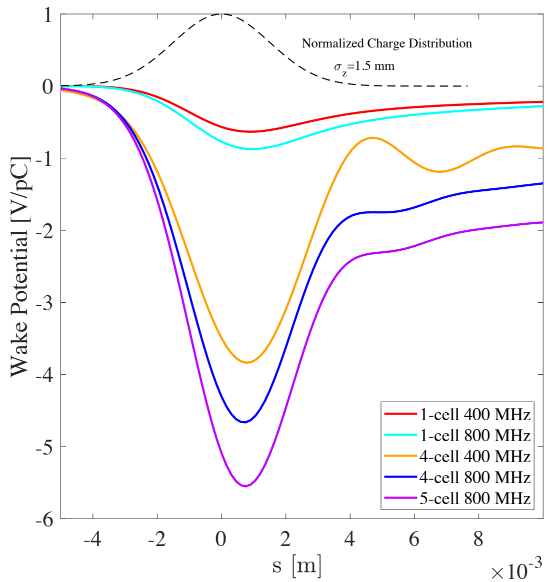
MICE (UK) Muon cooling principle

Selected Recent Progress

Ramping **magnet challenge**
At 14 TeV, energy in field is O(200 MJ)
ramped 5 x 2 times per second
Need to recover energy pulse to pulse
Started to develop **powering scheme** with energy recovery

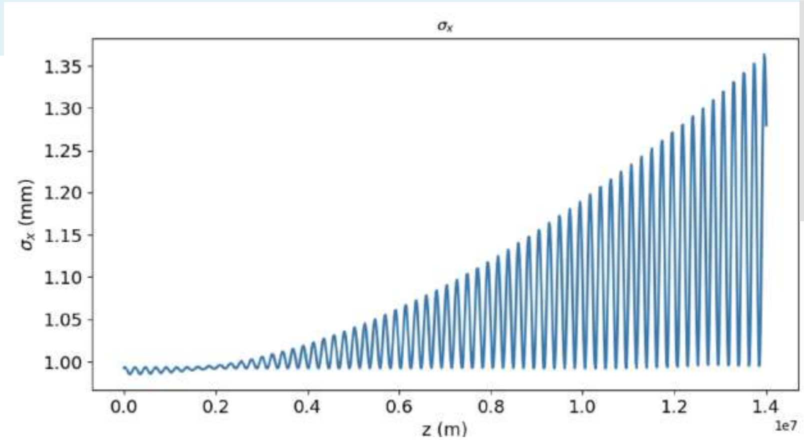


D. Aguglia
F. Boattini
G. Brauchli



University of Rostock
S. Zadeh
U. van Rienen

RF challenge (also for FFA):
High efficiency for power consumption
High-charge (10 x HL-LHC), short, single-bunch beam
Maintain small longitudinal emittance
Studies on cavity wakefields and longitudinal dynamics started

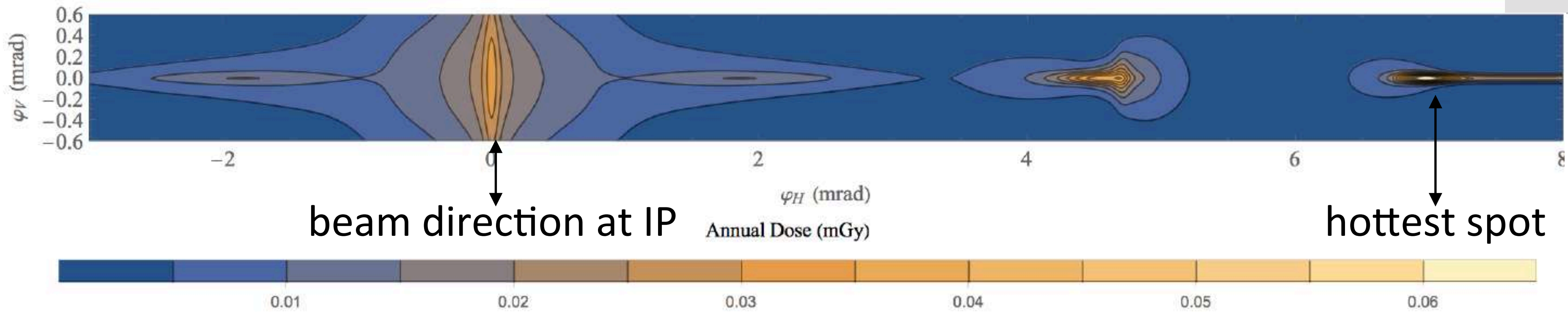


M. Magliorati
E. Metral,
T. Raubenheimer
D.S.

Collective effects might be a bottleneck
Revisiting for higher energies
Need to develop tools for collective effects in matter

Selected Recent Progress, cont.

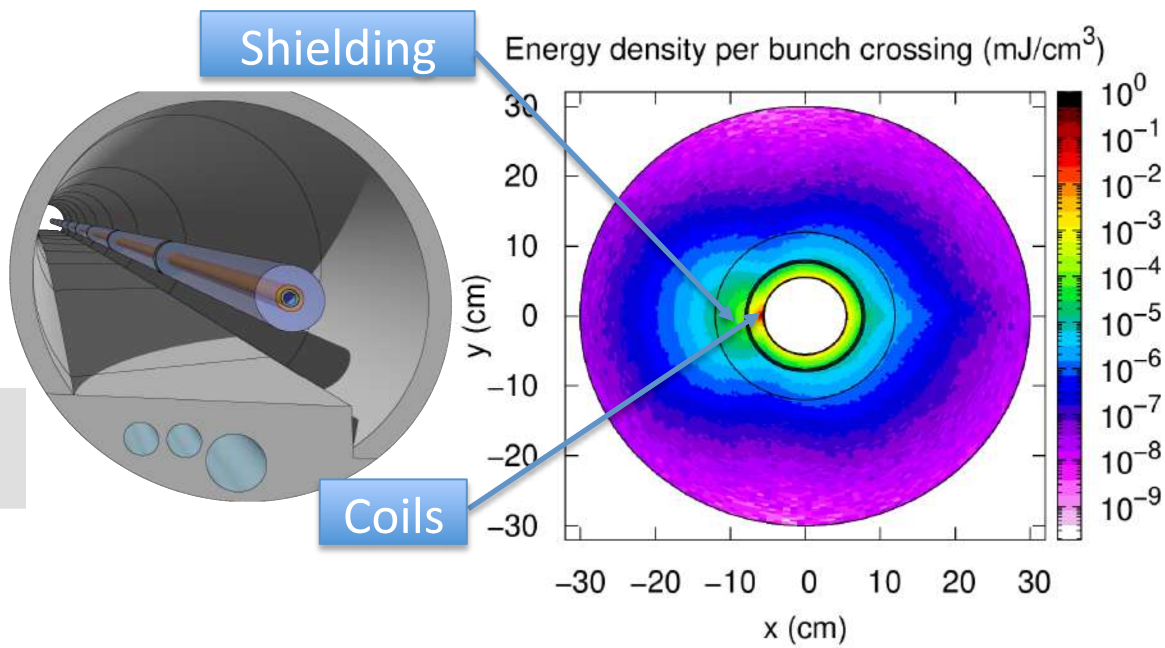
C. Carli



Collider Ring Lattice Design:
Based on MAP design, lattice design for high energy is starting
Started production of **radiation maps** and identified hot spots around IP and in arcs
Need to include radiation considerations in lattice design

Loss challenge in collider ring:
Loss per unit length is constant
fewer, but higher energy particles
Simulations of shielding started

A. Lechner
D. Calzolari



High-energy Acceleration

Rapid cycling synchrotrons (RCS)
- Combine static and ramping magnets

- **Fast-ramping magnets** to follow beam energy
    - normal conducting or novel HTS
    - O(kT/s) required

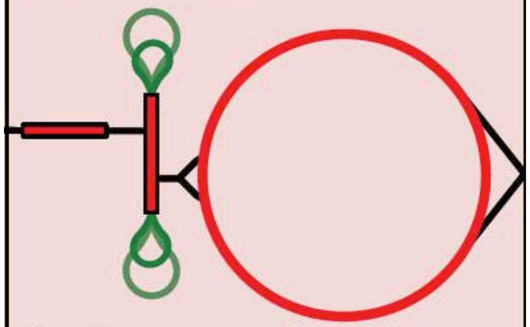
- **Efficient magnets and power converters** with energy recovery
    - Highest efficiency

RF system
- **Important single-bunch beam loading**
- 2 x 10 ^{12} particles in O(mm)-long bunch at 5 TeV

FFA
- Fixed (high-field) magnets but large energy acceptance
- Challenging **lattice design** for large bandwidth and limited cost
- **Complex high-field magnets**
- Challenging beam dynamics

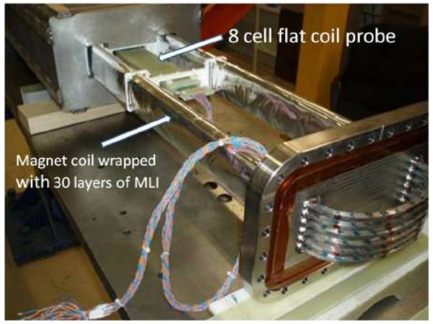
FNAL 290 T/s HTS magnet

Acceleration



Accelerators:
Linacs, RLA or FFAG, RCS

Test of **fast-ramping normal-conducting magnet** design



EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)