Brookhaven National Laboratory
High Energy Theory Seminar

Physics Potential for High Energy Muon Colliders

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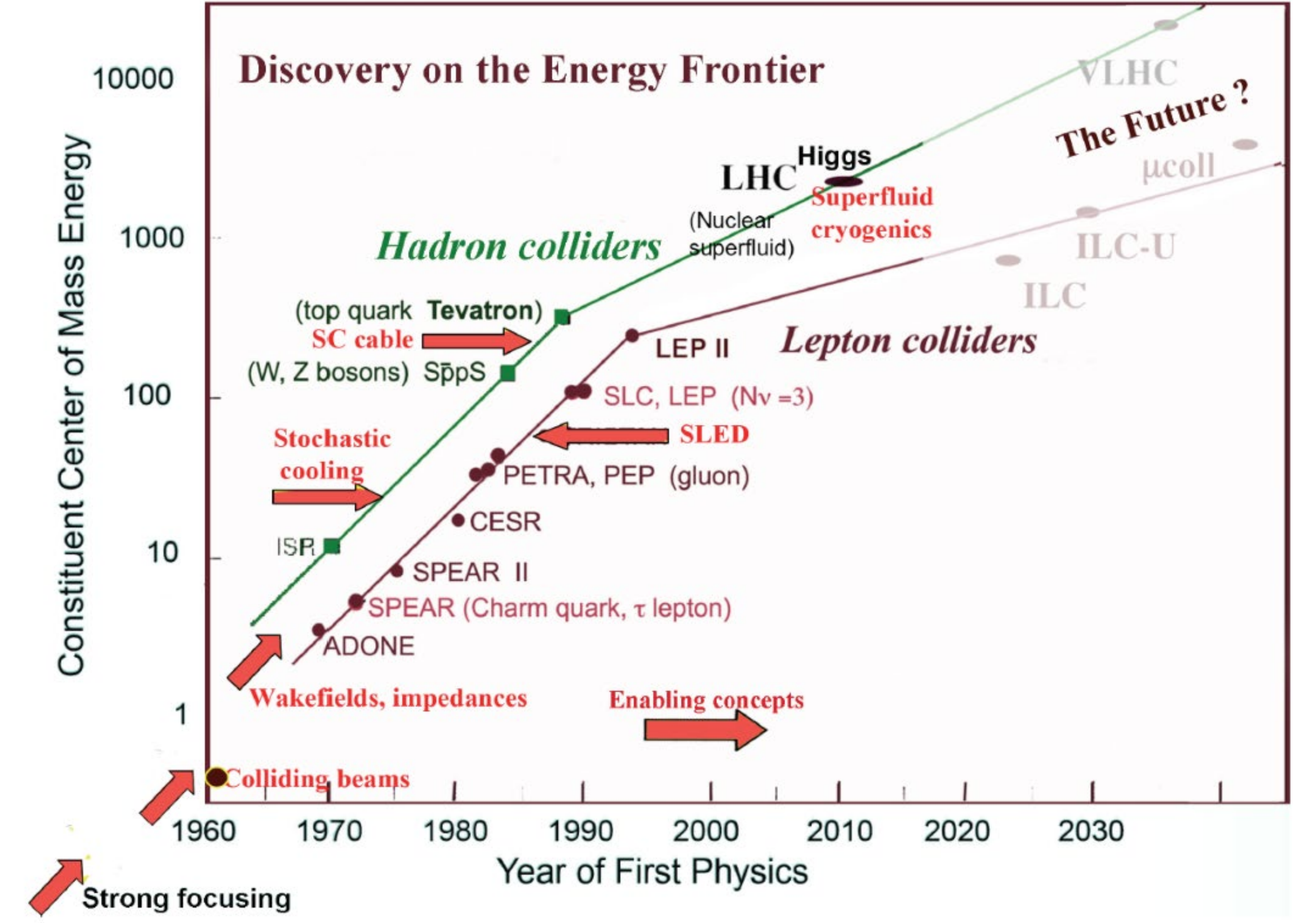
12/08/2022

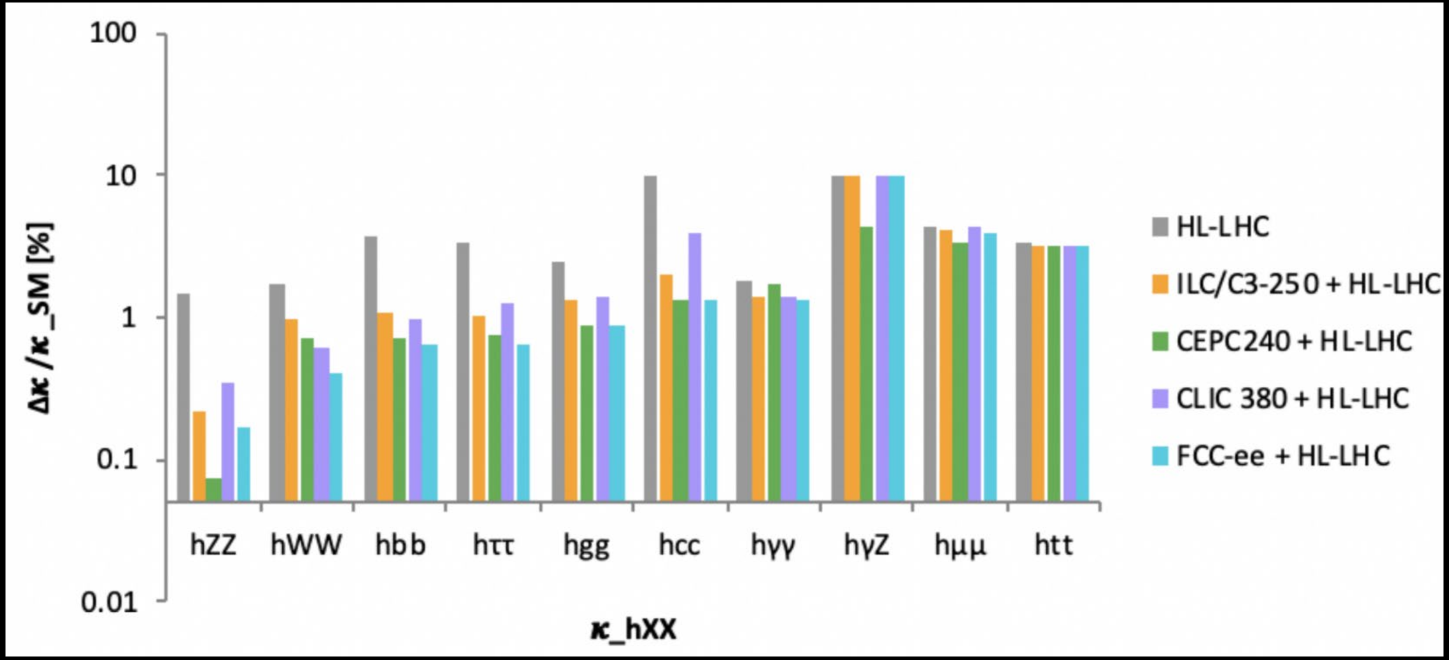
High Energy Rules



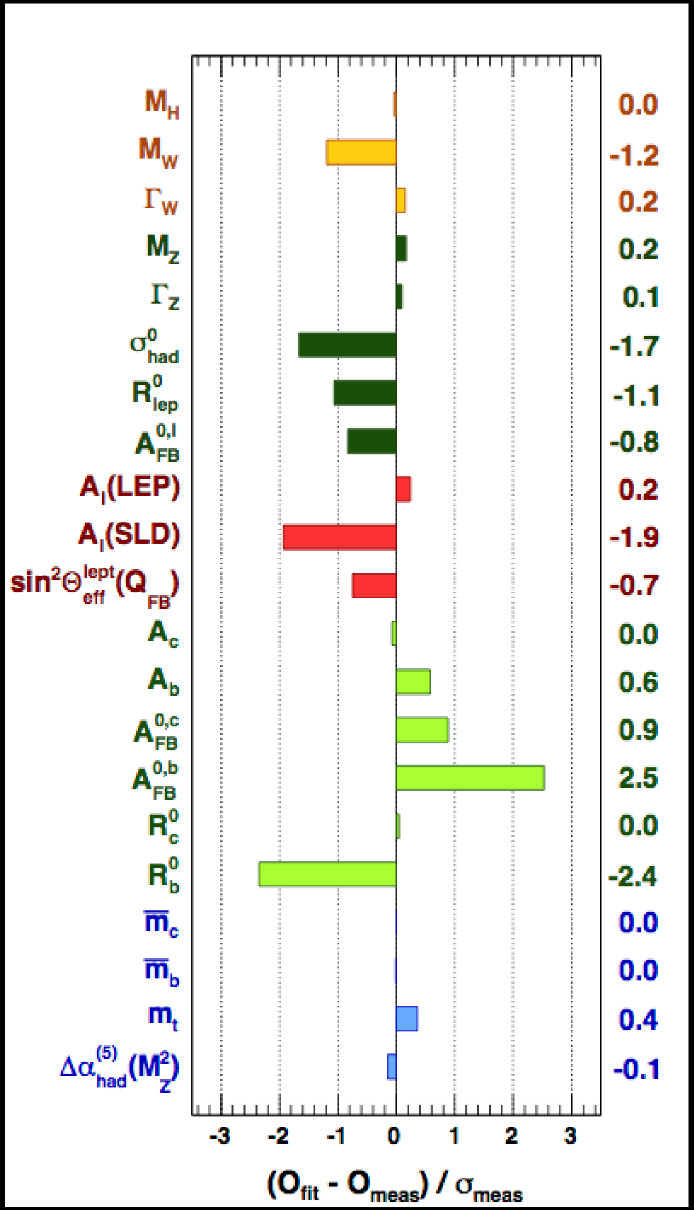
Snowmass Report:
1401.6114

The power of cleanness

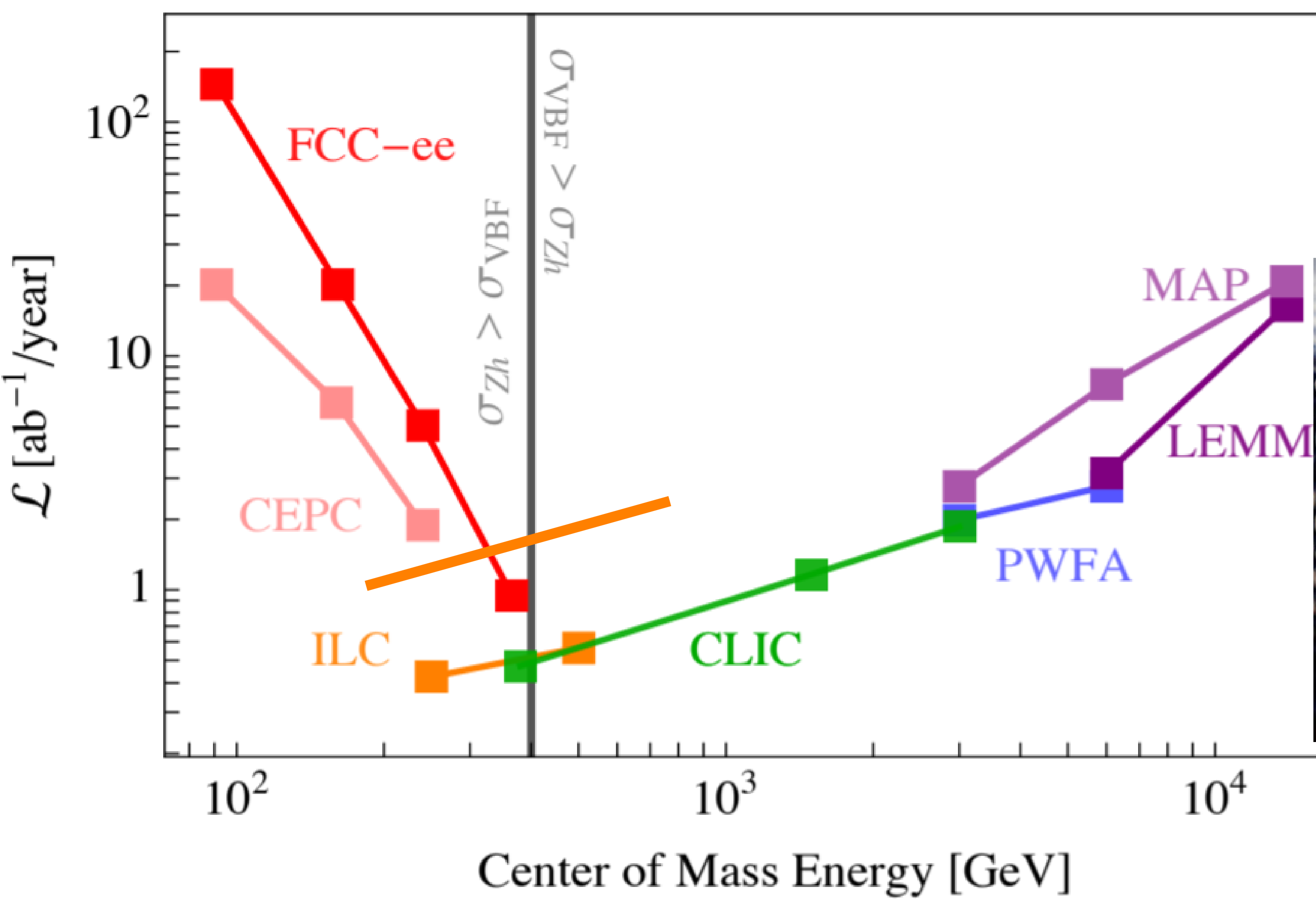
- LEP still is a headache/treasure of theorists
- 1M Higgs Higgs factory v.s. 0.5B Higgs HL-LHC



Dawson et al, 2209.07510

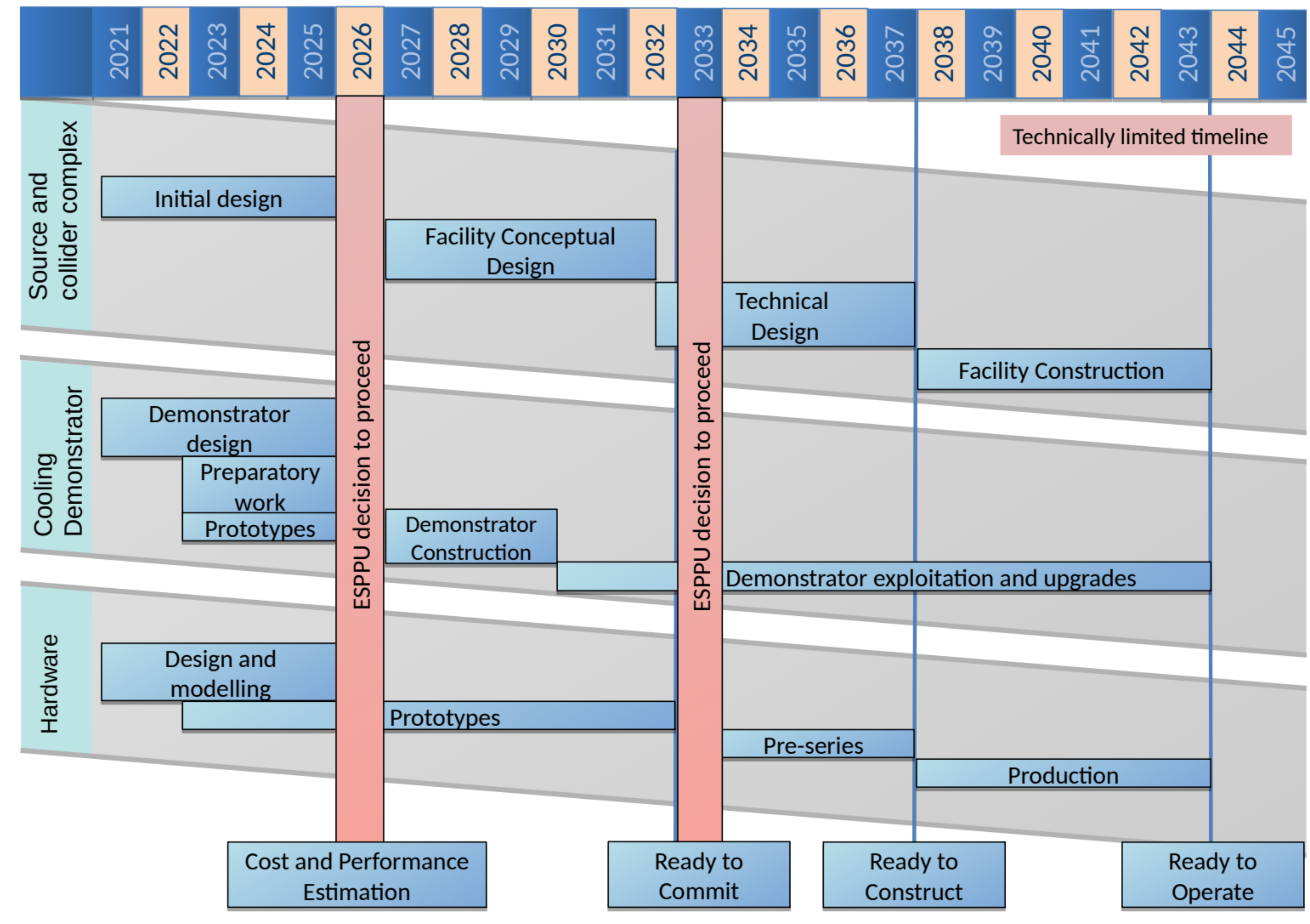


The power of cleanness ⊕ power of high energy!



NO Brainer

(A) Timeline



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Source and collider complex
- Initial design
- Facility Conceptual Design
- Technical Design
- Facility Construction

Cooling Demonstrator
- Demonstrator design
- Preparatory work
- Prototypes
- Demonstrator Construction
- Demonstrator exploitation and upgrades

Hardware
- Design and modelling
- Prototypes
- Pre-series
- Production

ESPPU decision to proceed

ESPPU decision to proceed

Cost and Performance Estimation

Ready to Commit

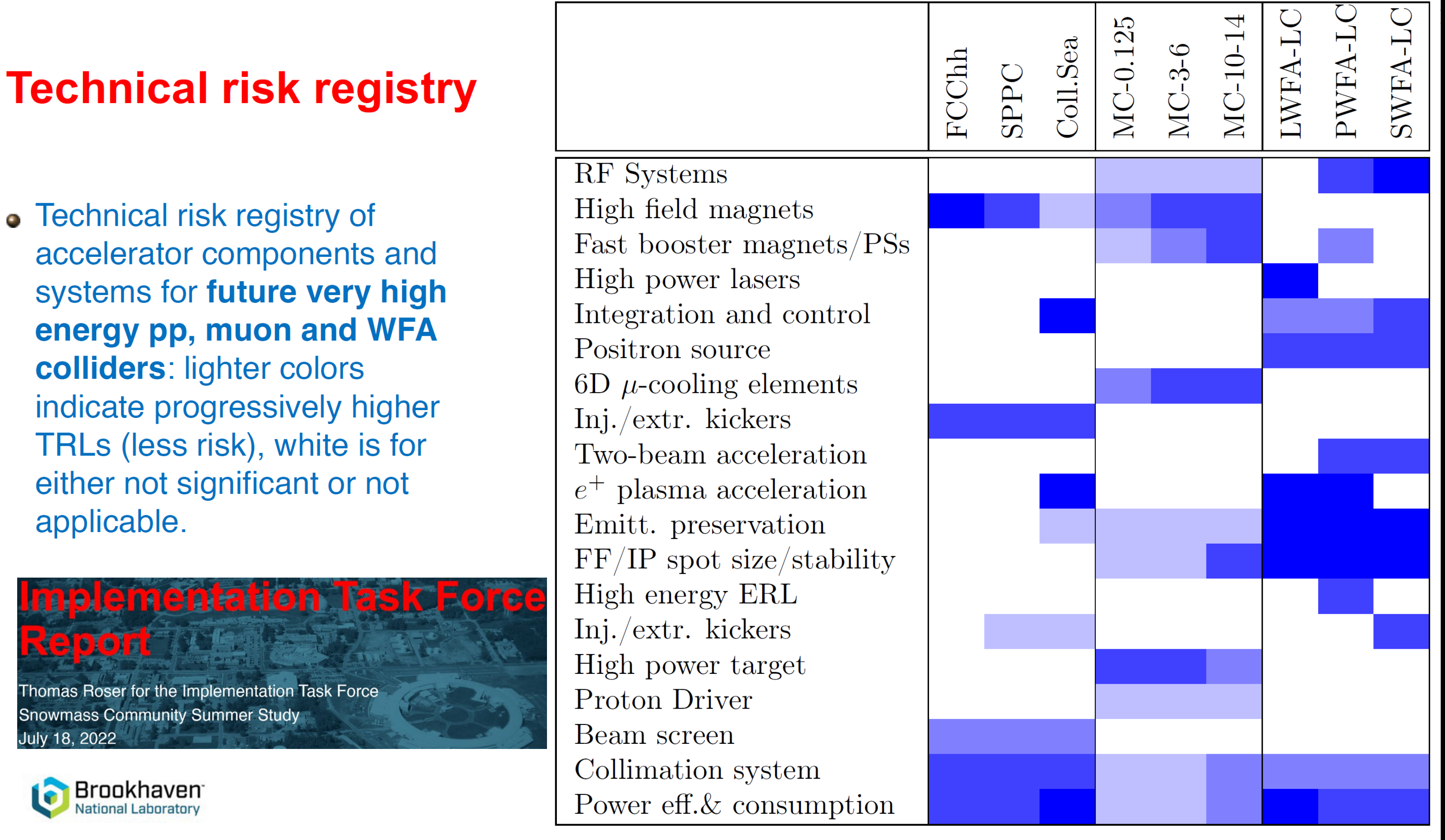
Ready to Construct

Ready to Operate

Muon forum report: [2209.01318](https://arxiv.org/abs/2209.01318)

Outline

- Thorny challenges
- Physics Cases



Technical risk registry

- Technical risk registry of accelerator components and systems for **future very high energy pp, muon and WFA colliders**: lighter colors indicate progressively higher TRLs (less risk), white is for either not significant or not applicable.

Implementation Task Force Report

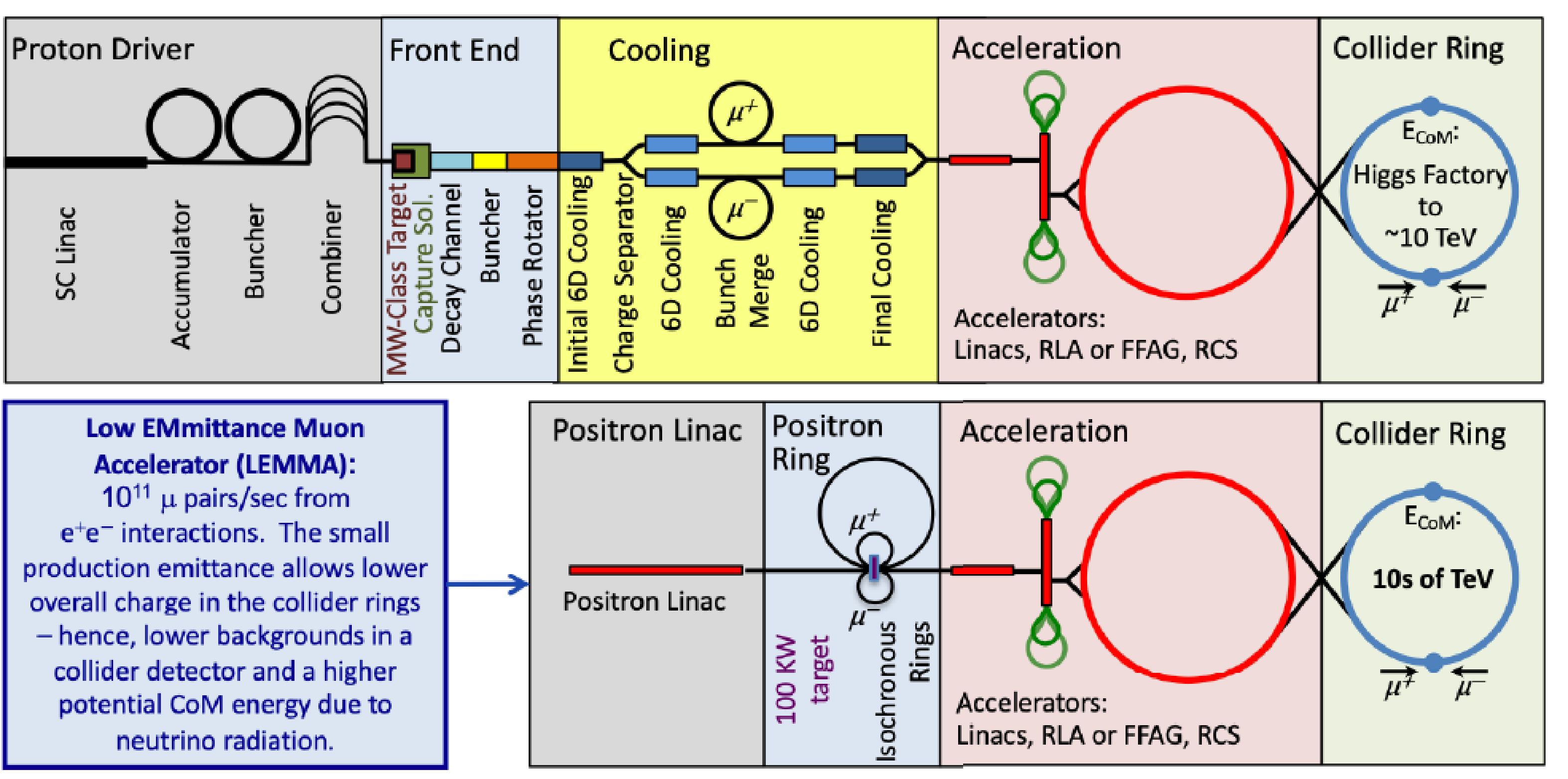
Thomas Roser for the Implementation Task Force
Snowmass Community Summer Study
July 18, 2022

Brookhaven National Laboratory

	FCChh	SPPC	Coll.Sea	MC-0.125	MC-3-6	MC-10-14	LWFA-LC	PWFA-LC	SWFA-LC
RF Systems				░	░	░		▓	█
High field magnets	█	▓	░	▒	▓	▓			
Fast booster magnets/PSs				░	▒	▓		▒	
High power lasers							█		
Integration and control			█				▒	▒	▓
Positron source							▓	▓	▓
6D μ-cooling elements				▒	▓	▓			
Inj./extr. kickers	▓	▓	▓						
Two-beam acceleration								▓	▓
e^+ plasma acceleration			█				█	█	
Emitt. preservation			░	░	░	░	█	█	█
FF/IP spot size/stability				░	░	▓	█	█	█
High energy ERL								▓	
Inj./extr. kickers		░	░						▓
High power target				▓	▓	▒			
Proton Driver				░	░	░			
Beam screen	▒	▒	▒						
Collimation system	▓	▓	▓	░	░	▒	▒	▒	▒
Power eff.& consumption	▓	▓	█	░	░	▒	█	▓	▓

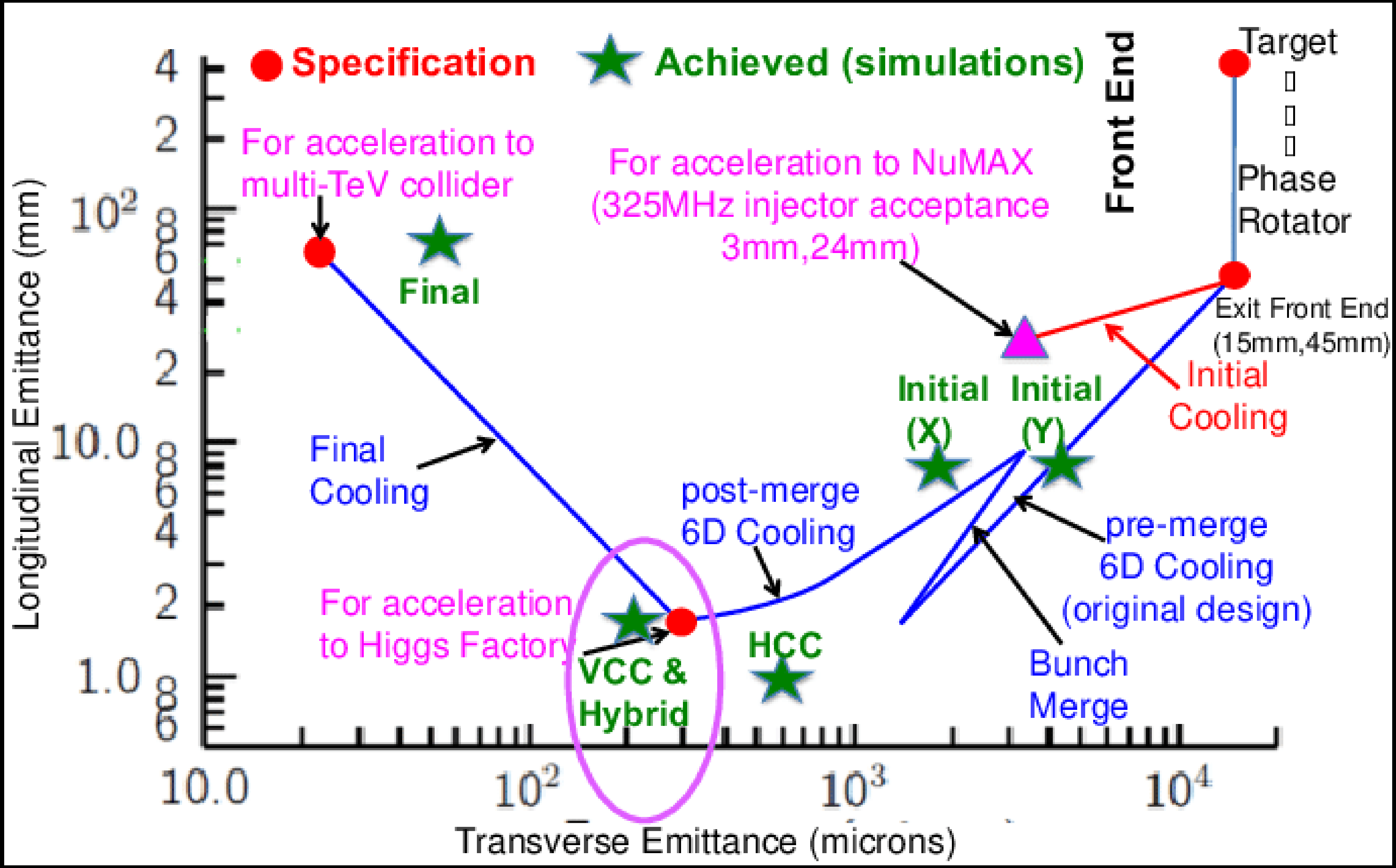
Outline

- Thorny challenges
  - Cooling
  - BIB
- Physics Cases

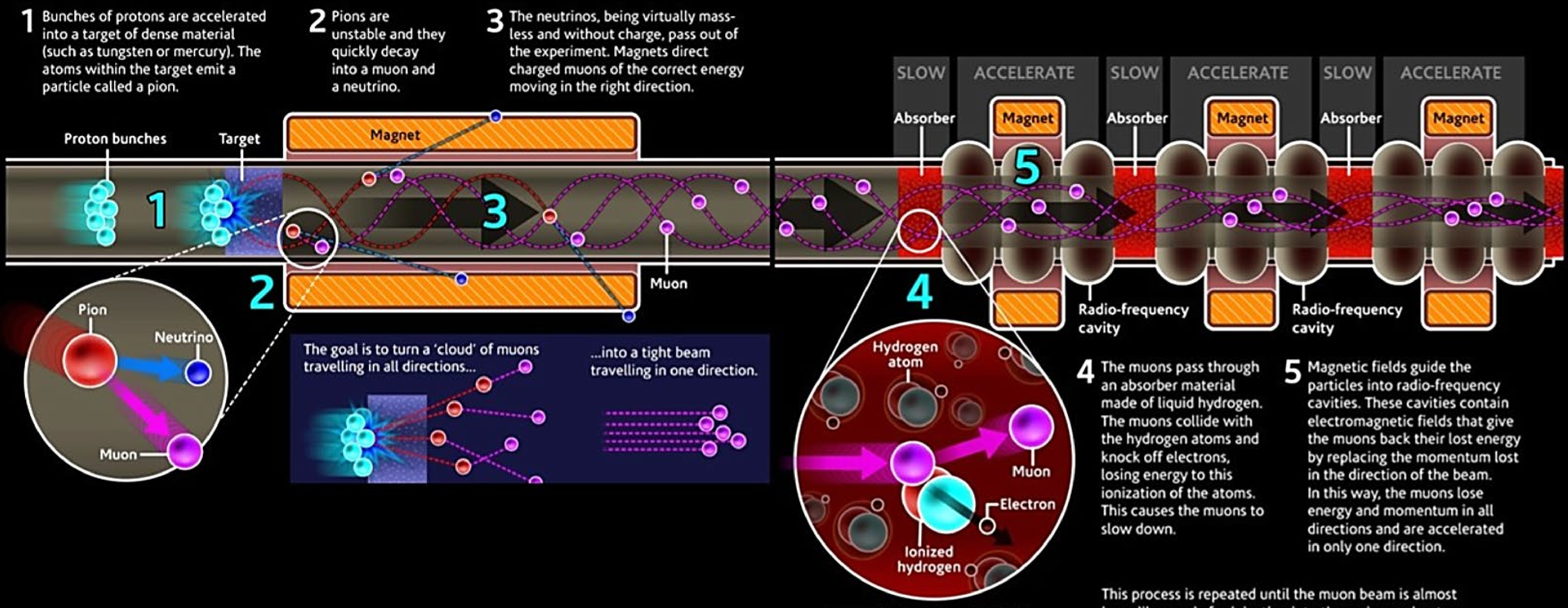


Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

Challenges: Muon Decays!



Muon Ionization Cooling (MICE)



1 Bunches of protons are accelerated into a target of dense material (such as tungsten or mercury). The atoms within the target emit a particle called a pion.

2 Pions are unstable and they quickly decay into a muon and a neutrino.

3 The neutrinos, being virtually massless and without charge, pass out of the experiment. Magnets direct charged muons of the correct energy moving in the right direction.

The goal is to turn a 'cloud' of muons travelling in all directions...

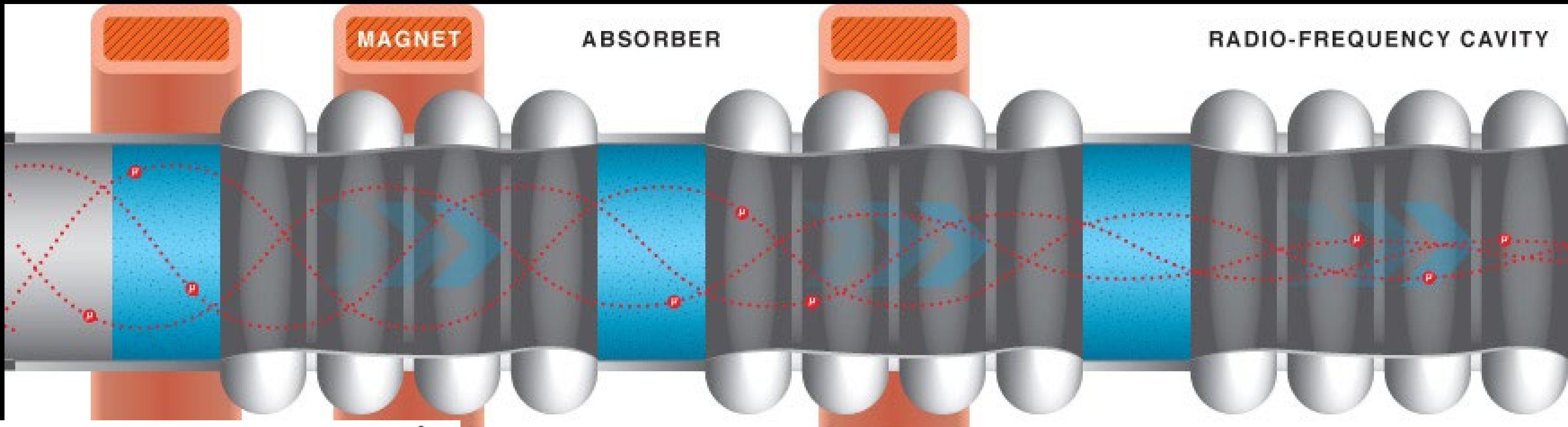
...into a tight beam travelling in one direction.

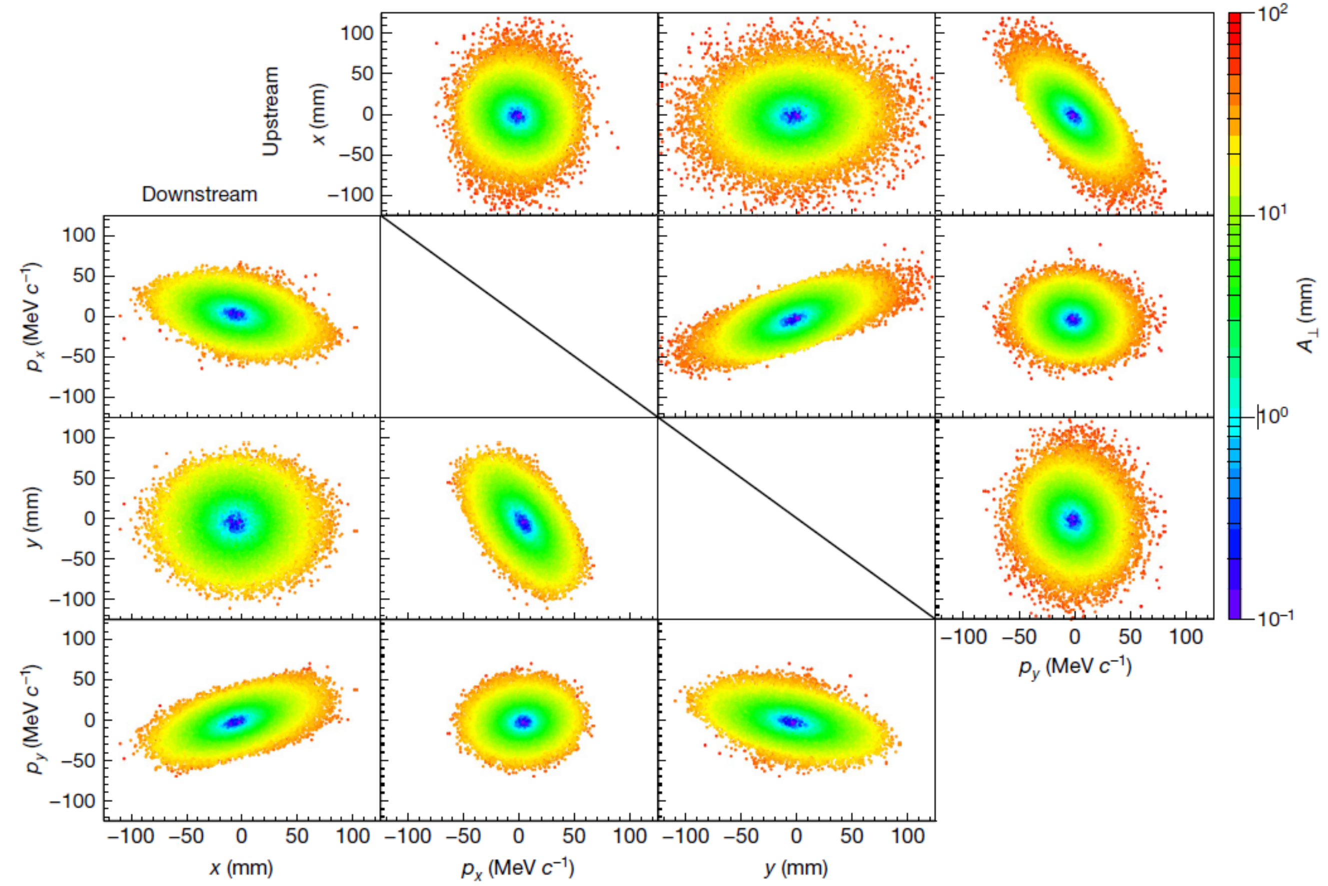
4 The muons pass through an absorber material made of liquid hydrogen. The muons collide with the hydrogen atoms and knock off electrons, losing energy to this ionization of the atoms. This causes the muons to slow down.

5 Magnetic fields guide the particles into radio-frequency cavities. These cavities contain electromagnetic fields that give the muons back their lost energy by replacing the momentum lost in the direction of the beam. In this way, the muons lose energy and momentum in all directions and are accelerated in only one direction.

This process is repeated until the muon beam is almost laser-like, ready for injection into the main accelerator.

Infographic: STFC, Ben Gilliland






nature

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Article | Open Access | Published: 05 February 2020

Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

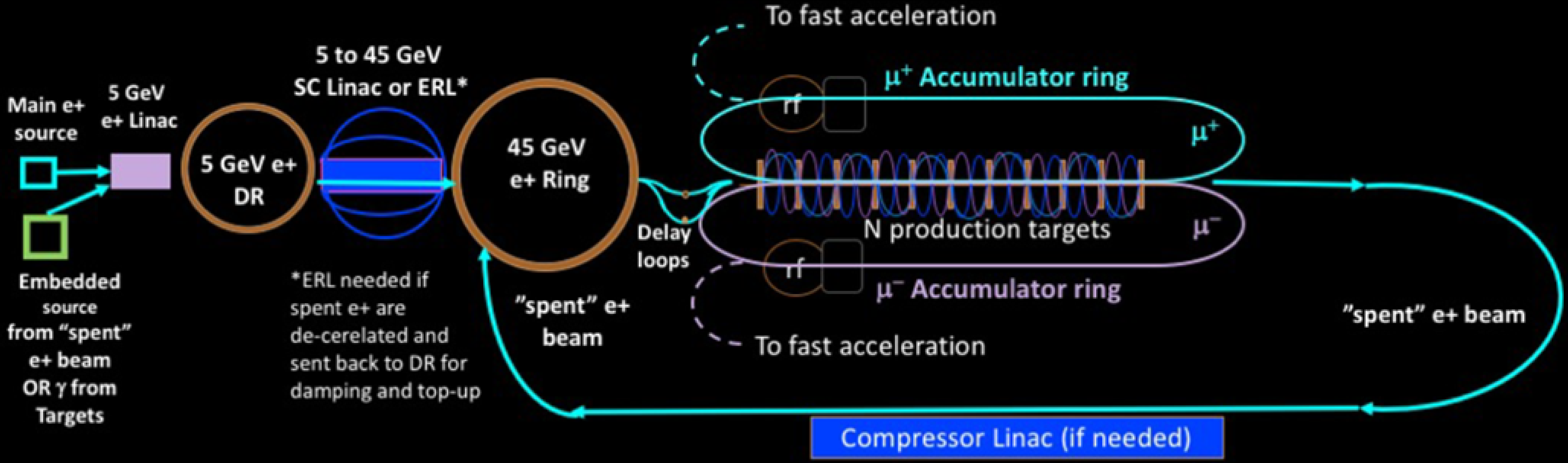
Nature **578**, 53–59(2020) | Cite this article

13k Accesses | **7** Citations | **276** Altmetric | Metrics

LEMMA new scheme in brief

arXiv:1905.05747v2 [physics.acc-ph]

- e^+ for first fill produced by Main e^+ source (MPS) and accelerated to 5 GeV for damping in a 5 GeV Damping Ring (DR)
- Acceleration to 45 GeV in a SC Linac or ERL and storage of 1000 e^+ bunches in a Positron Ring (PR)
- Extraction of e^+ bunches to one or more muon production lines, while produced muons are accumulated in two AR and a muon bunch is “built” by several passages through the targets, to be then delivered to the fast acceleration chain
- Re-injection and damping in the PR @45 GeV of the spent e^+ beam to save on the number of needed e^+, the MPS and a possible γ-embedded source will provide the refilling of lost e^+. Other option: send e^+ back to DR (through decelerating ERL) for damping and top-up

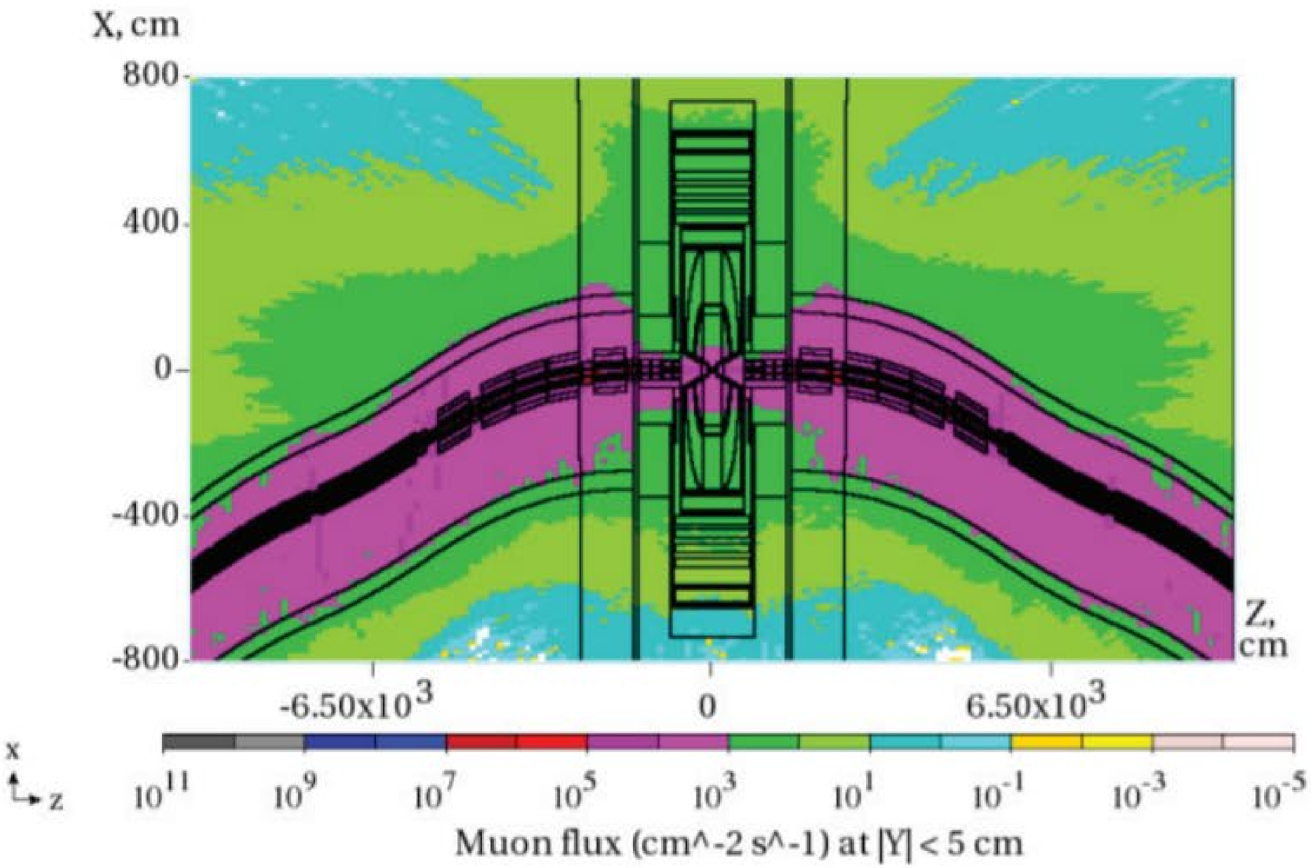


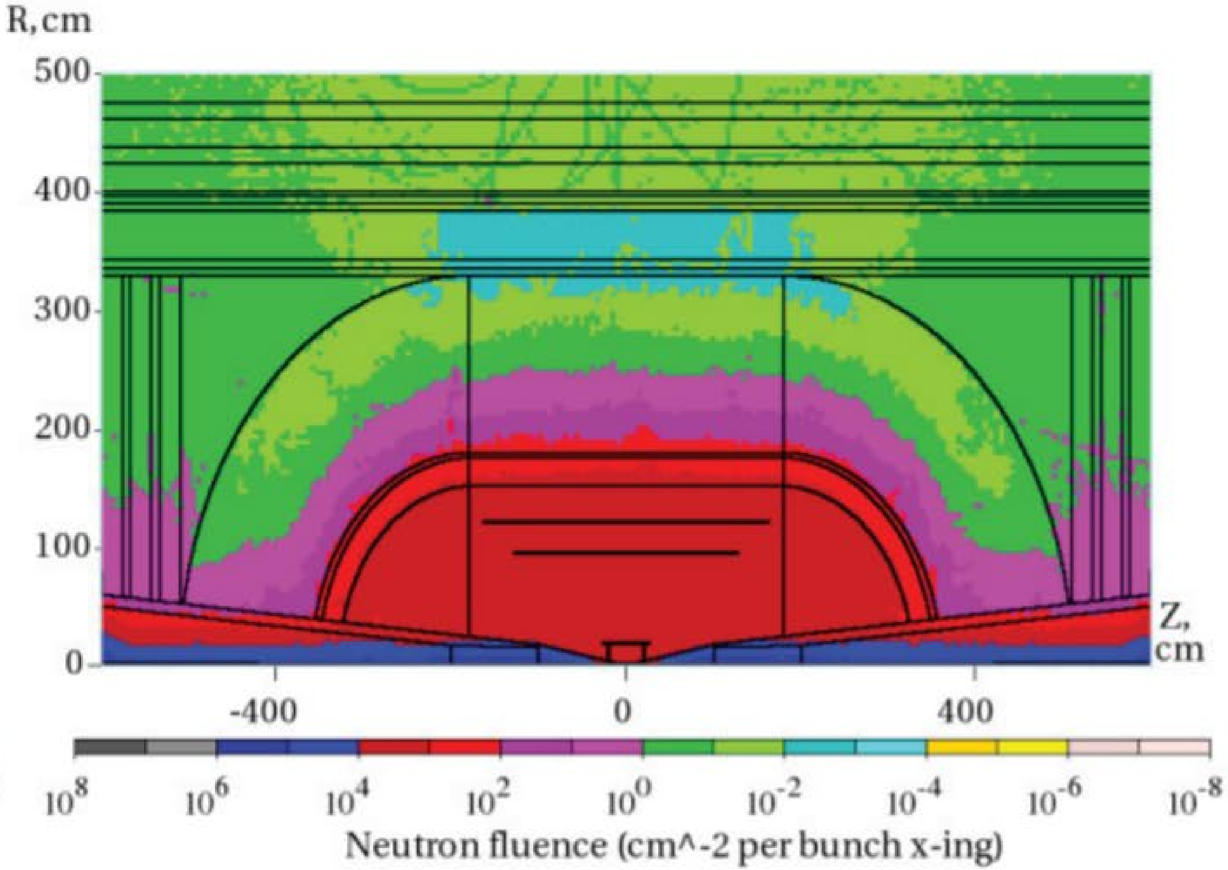
The beam-induced background simulation

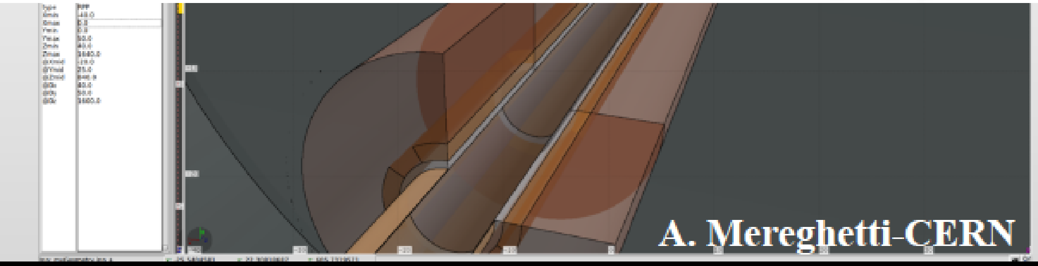
machine lattice

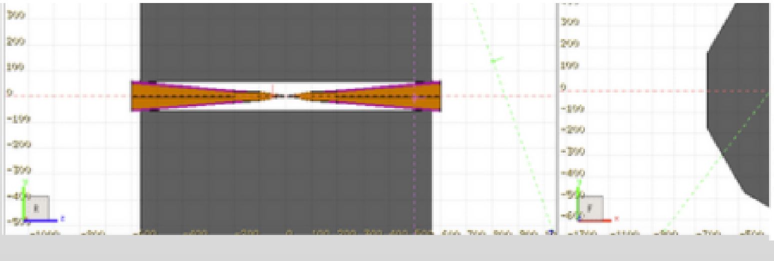
See F. Collamati talk at ICHEP2020

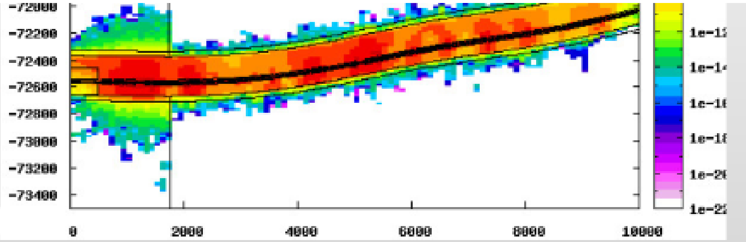
Input data
Output data



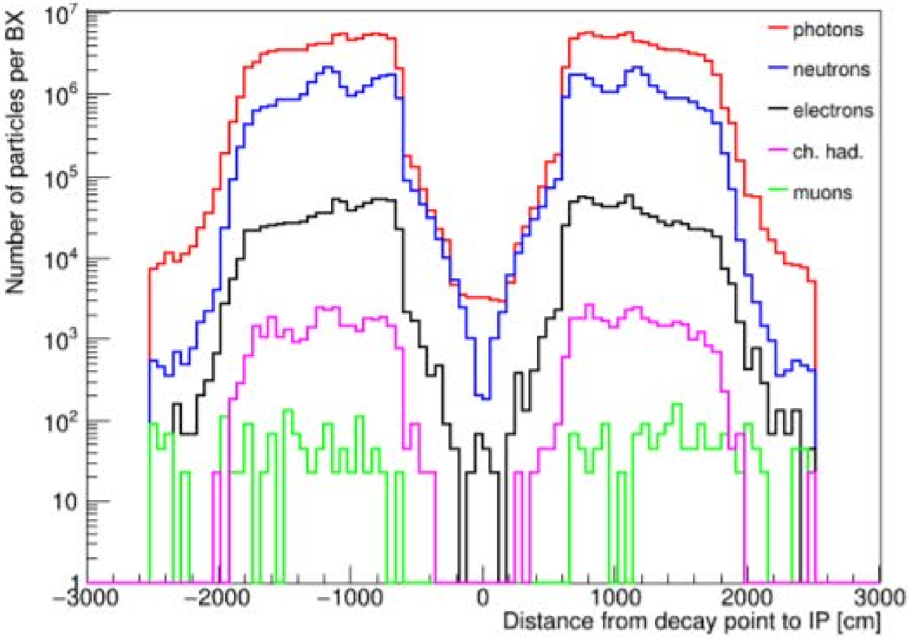



A. Mereghetti-CERN

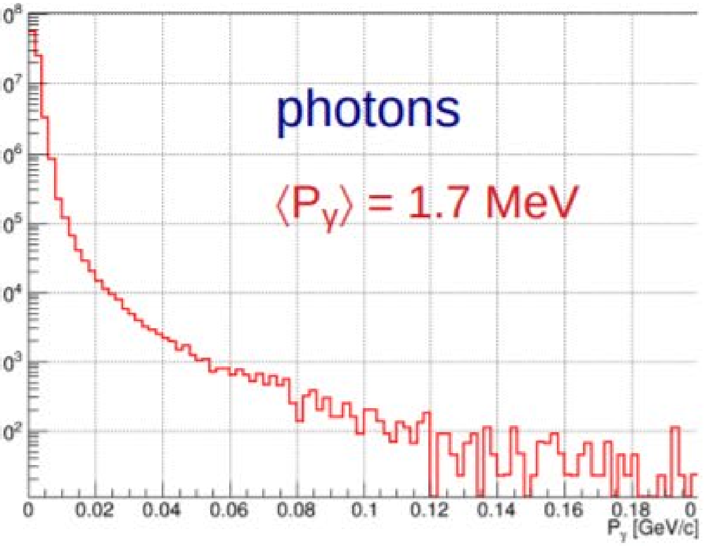


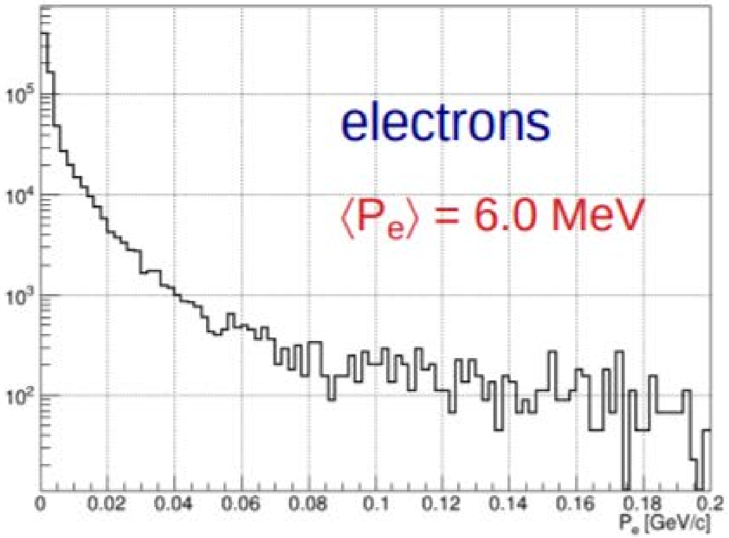


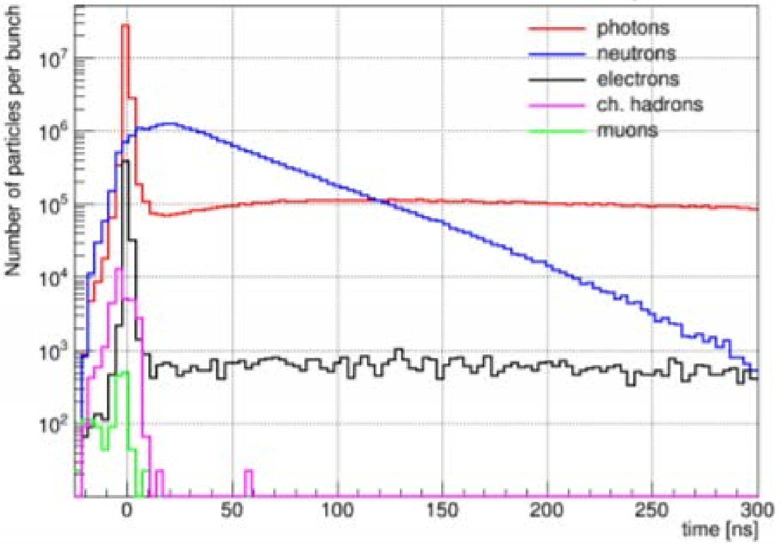
Beam-induced background Studies at $\sqrt{s} = 1.5$ TeV



Contributions form μ decays $|z| > 25$ m become negligible for all background species but Bethe-Heitler muons



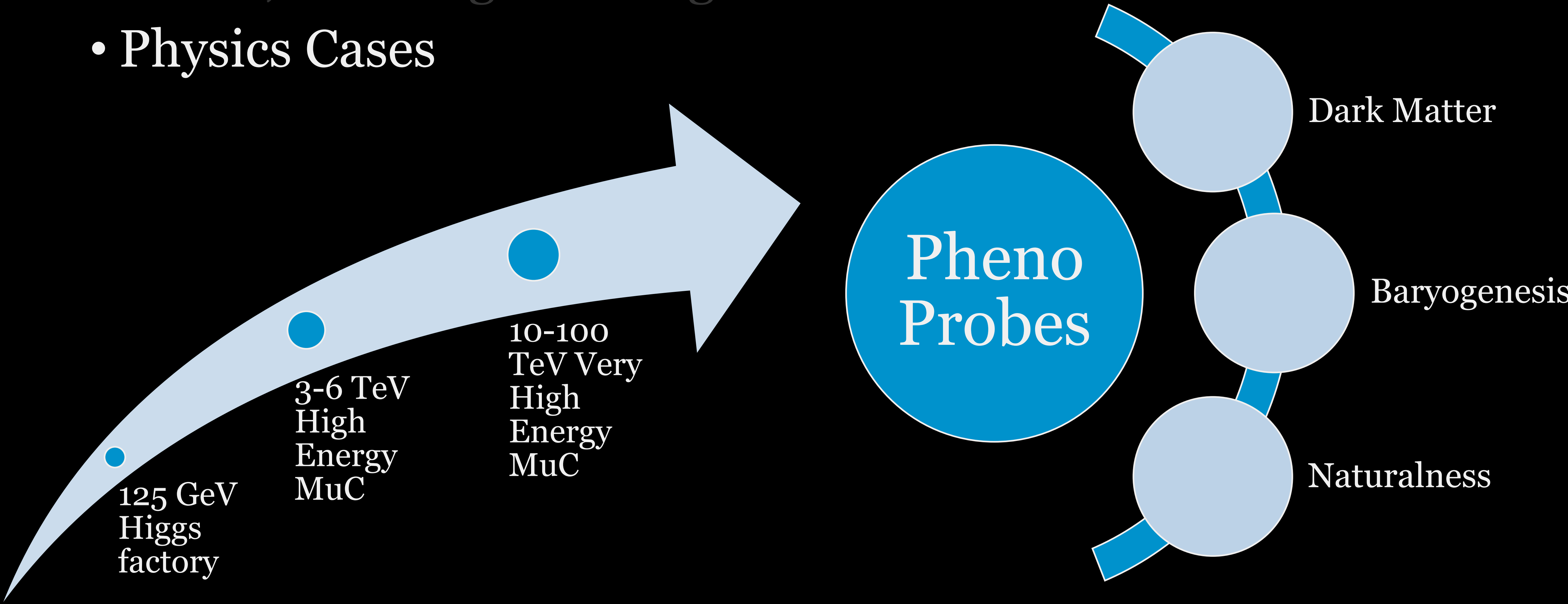




Secondary and tertiary particles have low momentum and different arrival time in the IP.

Outline

- Basics, Challenges & Progress
- Physics Cases



125 GeV Higgs factory

3-6 TeV High Energy MuC

10-100 TeV Very High Energy MuC

Pheno Probes

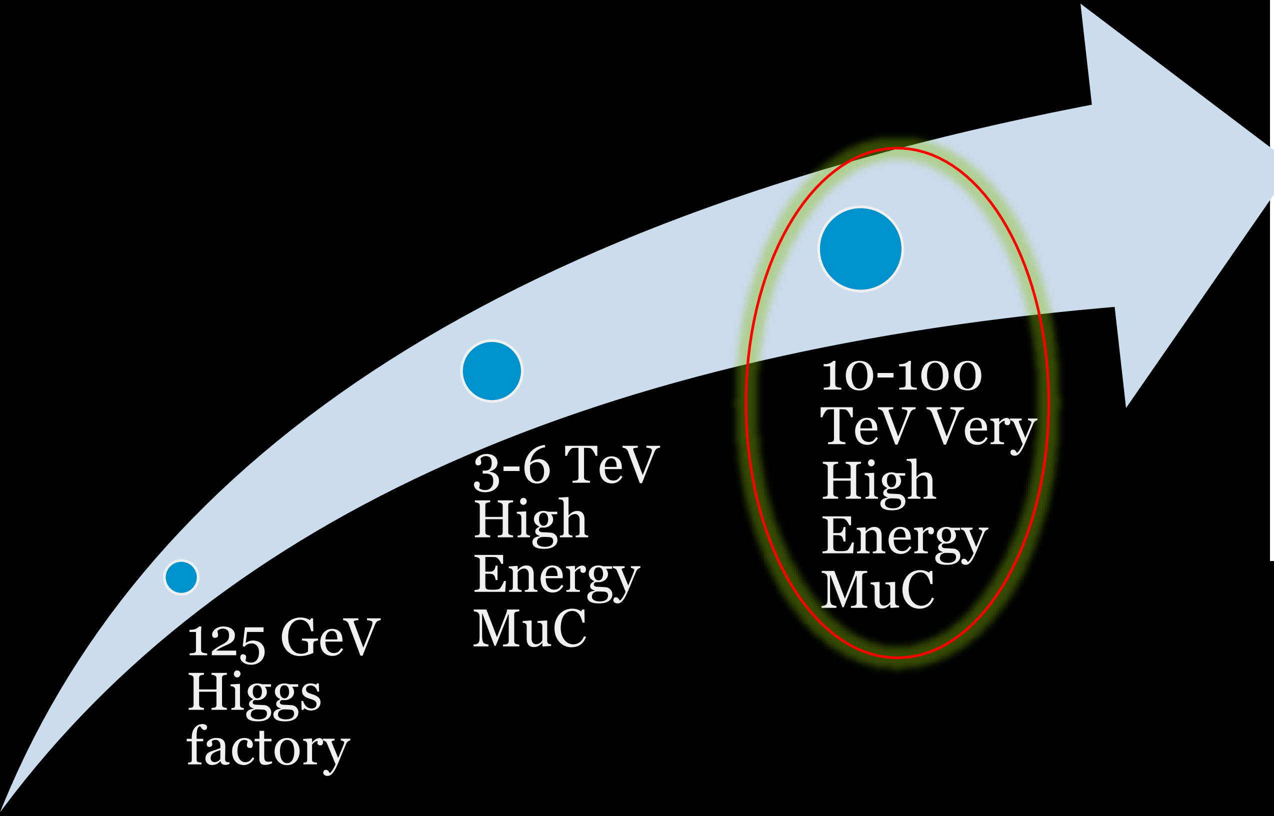
Physics Driver

Dark Matter

Baryogenesis

Naturalness

10+ TeV Muon Collider: basics



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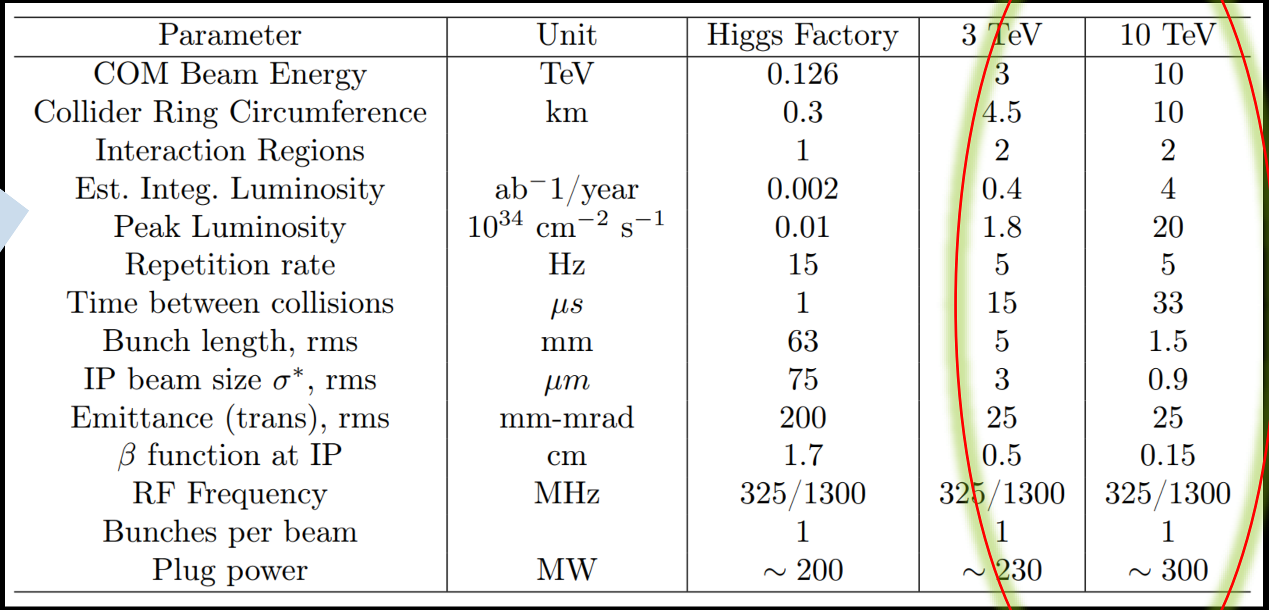
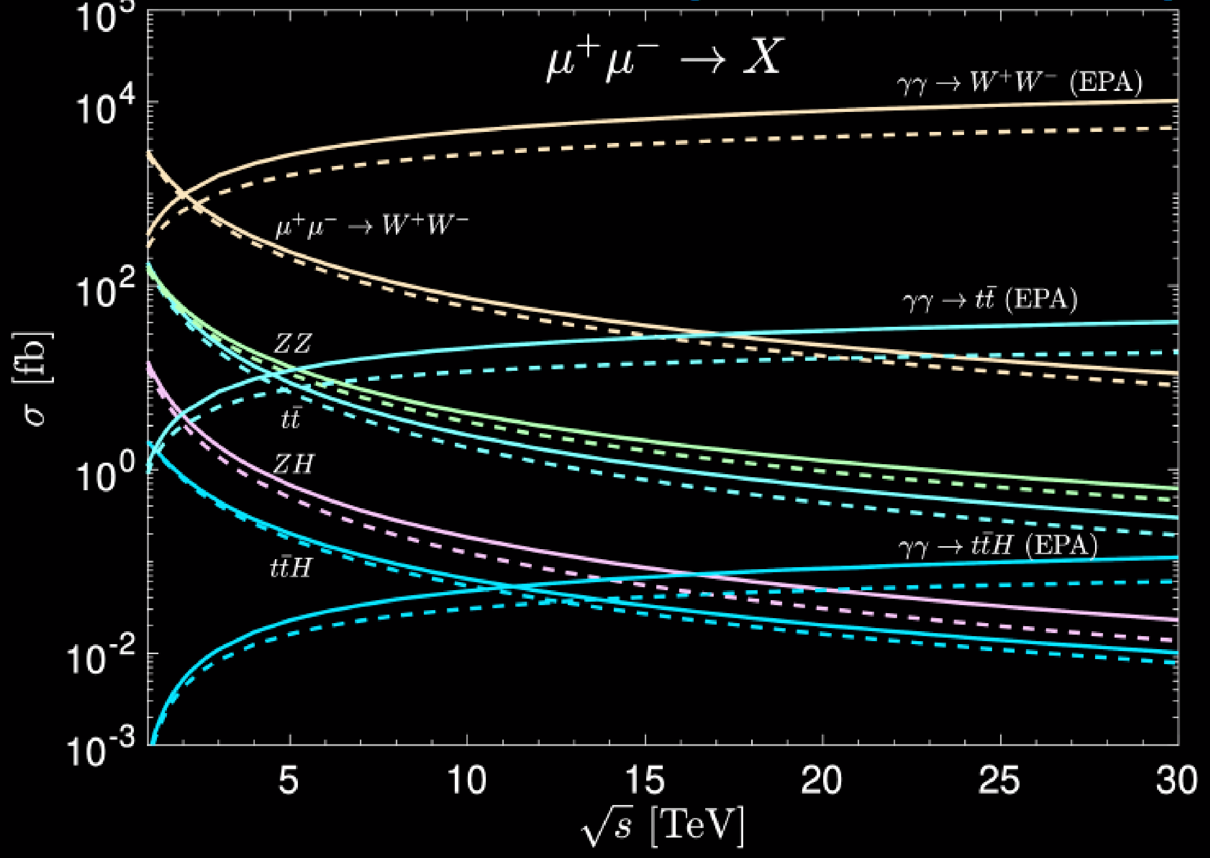


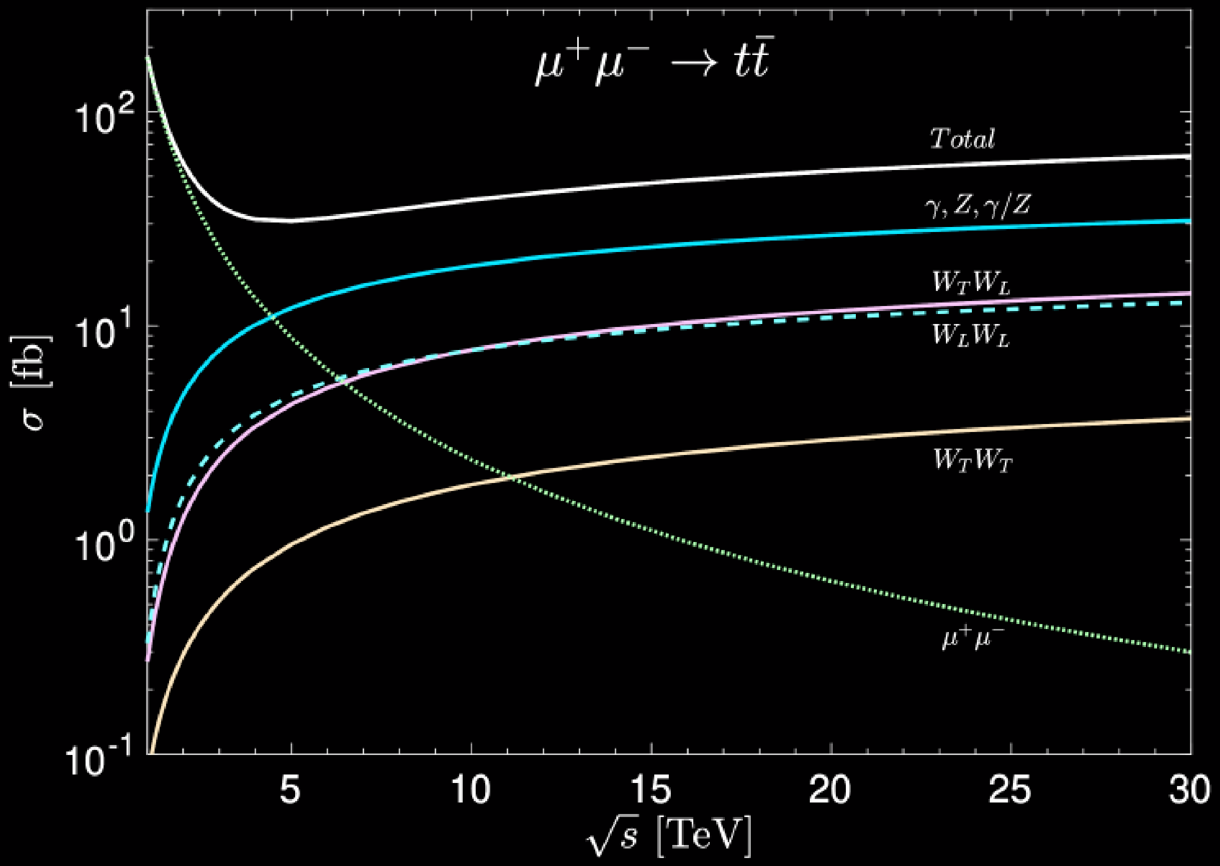
Parameter	Unit	Higgs Factory	3 TeV	10 TeV
COM Beam Energy	TeV	0.126	3	10
Collider Ring Circumference	km	0.3	4.5	10
Interaction Regions		1	2	2
Est. Integ. Luminosity	$\mathrm{ab}^{-1}/\mathrm{year}$	0.002	0.4	4
Peak Luminosity	$10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	0.01	1.8	20
Repetition rate	Hz	15	5	5
Time between collisions	μs	1	15	33
Bunch length, rms	mm	63	5	1.5
IP beam size σ^*, rms	μm	75	3	0.9
Emittance (trans), rms	mm-mrad	200	25	25
β function at IP	cm	1.7	0.5	0.15
RF Frequency	MHz	325/1300	325/1300	325/1300
Bunches per beam		1	1	1
Plug power	MW	~ 200	~ 230	~ 300

Dream Machine: no rivals

MuC is also a Vector Boson Machine


[Han, Ma, Xie, 2007.14300]

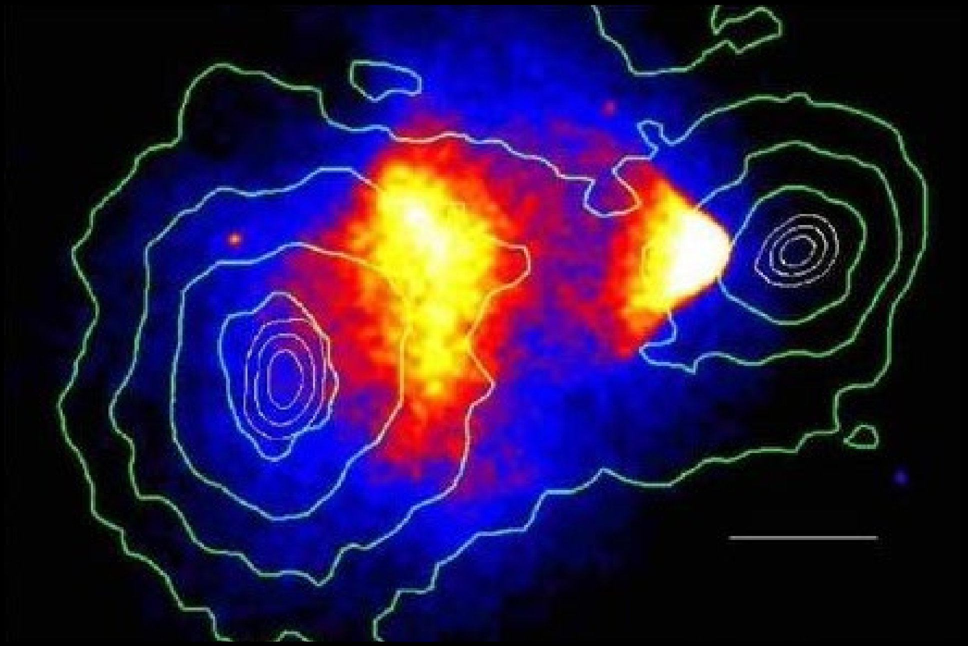
VBF dominates well above threshold due to logarithmic growth with E_{CM}

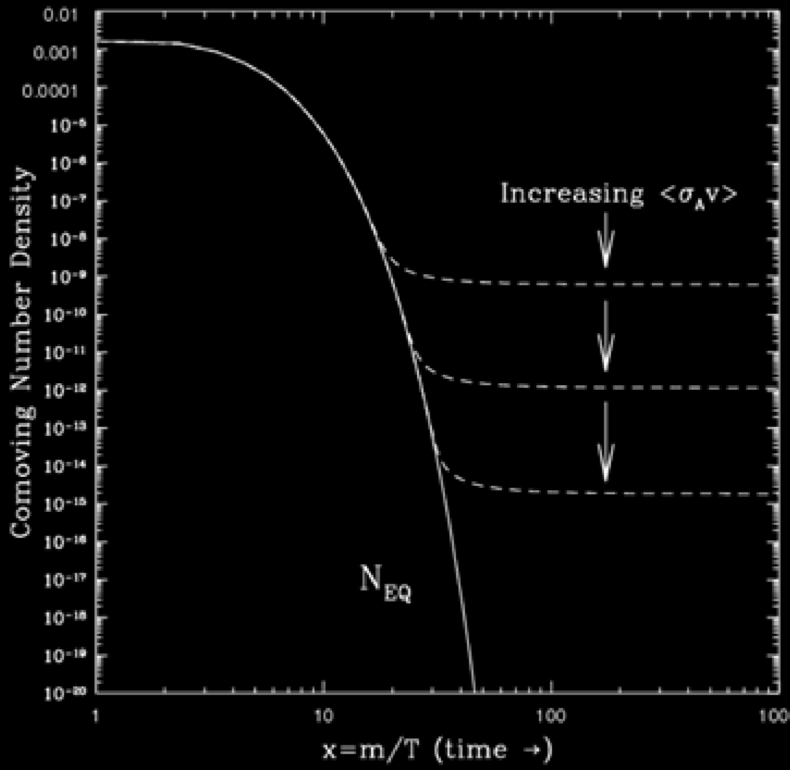

[Han, Ma, Xie, 2007.14300]

Longitudinal polarizations play a key role, making an extraordinary laboratory for EWSB

WIMP Dark Matter

Compelling, simple, predictive explanation for thermal, cold dark matter





$$\Omega h^2 \simeq 0.1 \times \left(\frac{2 \times 10^{-26}\text{cm}^3/\text{sec}}{< \sigma_{\text{eff}} v >_{\text{freeze-out}}}\right)$$

$$< \sigma_{\text{eff}} v >_{\chi\bar{\chi}\to VV} \simeq \frac{\pi \alpha_\chi^2}{m_\chi^2}$$

There is a scale…

Han, ZL, Wang, Wang, 2009.11287, 2203.07351

Our Approach: work on the "nightmare" scenario

Consider the following "Minimal Dark Matter"*:

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

"Nightmare":

- High thermal targets
  - 23 TeV for 7-plet Majarona
- Minimal signatures
  - Only missing energy

Additional considerations:

- Doublet → "Higgsino"
- Triplet → "Wino"
- Use "epsilon" notation to indicate Dirac case
- Even-plet requires non-zero Y (and additional splitting to suppress direct detection)
- Perturbative Unitarity
- Summonfeld and bound-state effect

$$< \sigma_{\chi\bar{\chi}\to VV} v > \simeq \frac{g_2^4\, n^4 + 16 Y^4 g_1^4 + 8 g_2^2 g_1^2 Y^2 n^2}{64\pi\, M_\chi^2 g_\chi}$$

Basic Pheno Considerations

“non-trivial” to consider muon collider reaches

- Minimal signature
  - Mass splitting O(few hundred MeV)
  - Decay products soft
  - Transition between states fast (<mm for most of the cases)
- Missing ET (at LHC)➔Missing Mass (at MuC)
- The interplay between different channels:
  - DY-type dominance but large background
  - VBF-type log-growth but limited available energy
- Photon initial state process important
  - Needs to use photon PDF or Weizsacker-Williams approximation
  - Hacked Madgraph to implement
  - Additional divergences often-appear
- Beam induced background (BIB)
  - Affects detector coverage
  - Affects photon, muon threshold
  - Affects disappearing track considerations

Missing Mass signature:

- Simple and inclusive (hence also most conservative)
- Mono-photon
- VBF-dimuon
- Mono-muon

Disappearing track signature:

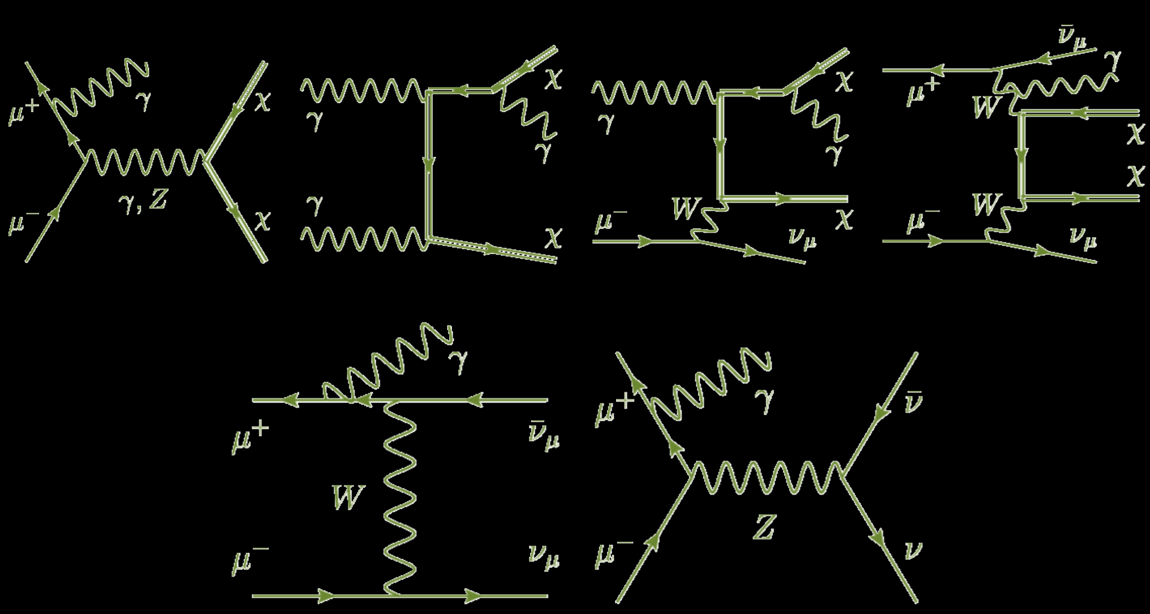
- Exclusive but challenging
- Most useful for Wino and Higgsinos
- Great potential

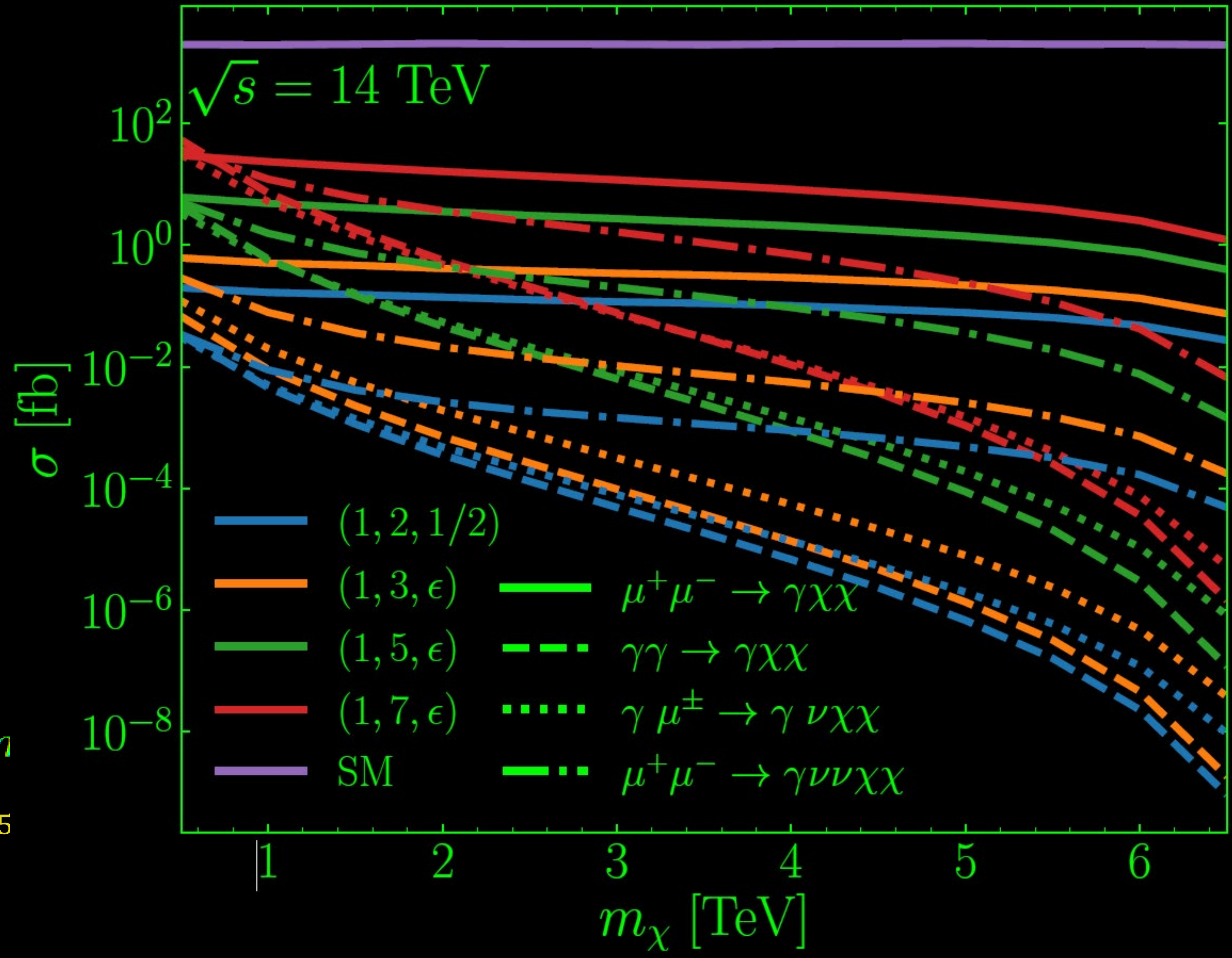
$$\sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30 \text{ and } 100 \text{ TeV}$$

$$\mathcal{L} = 1,\ 4,\ 10,\ 20,\ 90,\ \text{and } 1000 \text{ ab}^{-1}$$

Mono-Photon

All combinations of components of the EW multiplet are included, so-long as they respect the underlying gauge symmetries





$$10^\circ < \theta_\gamma < 170^\circ$$

$$E_\gamma > 50\ \mathrm{GeV}, \quad m^2_{\mathrm{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > 4n$$

Rate grows with n-plets as roughly $n^{2\sim3}$ (DY) and $n^{4\sim5}$

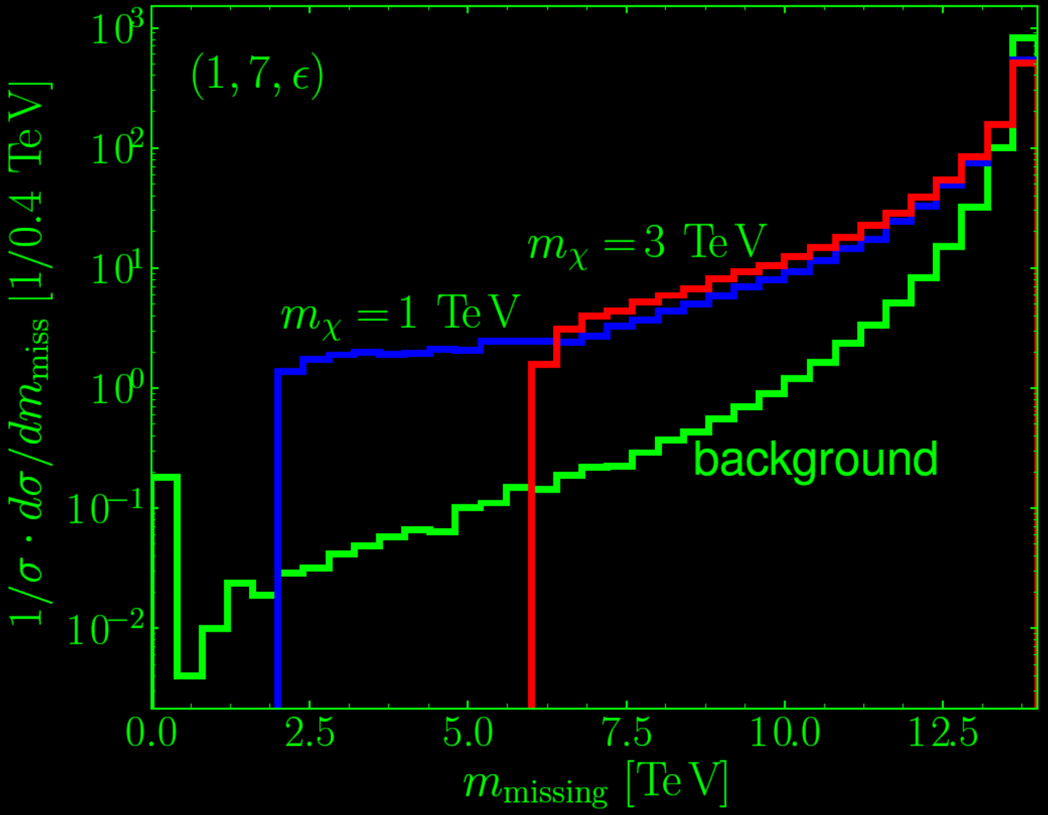
Doublet and Triplet very hard to probe

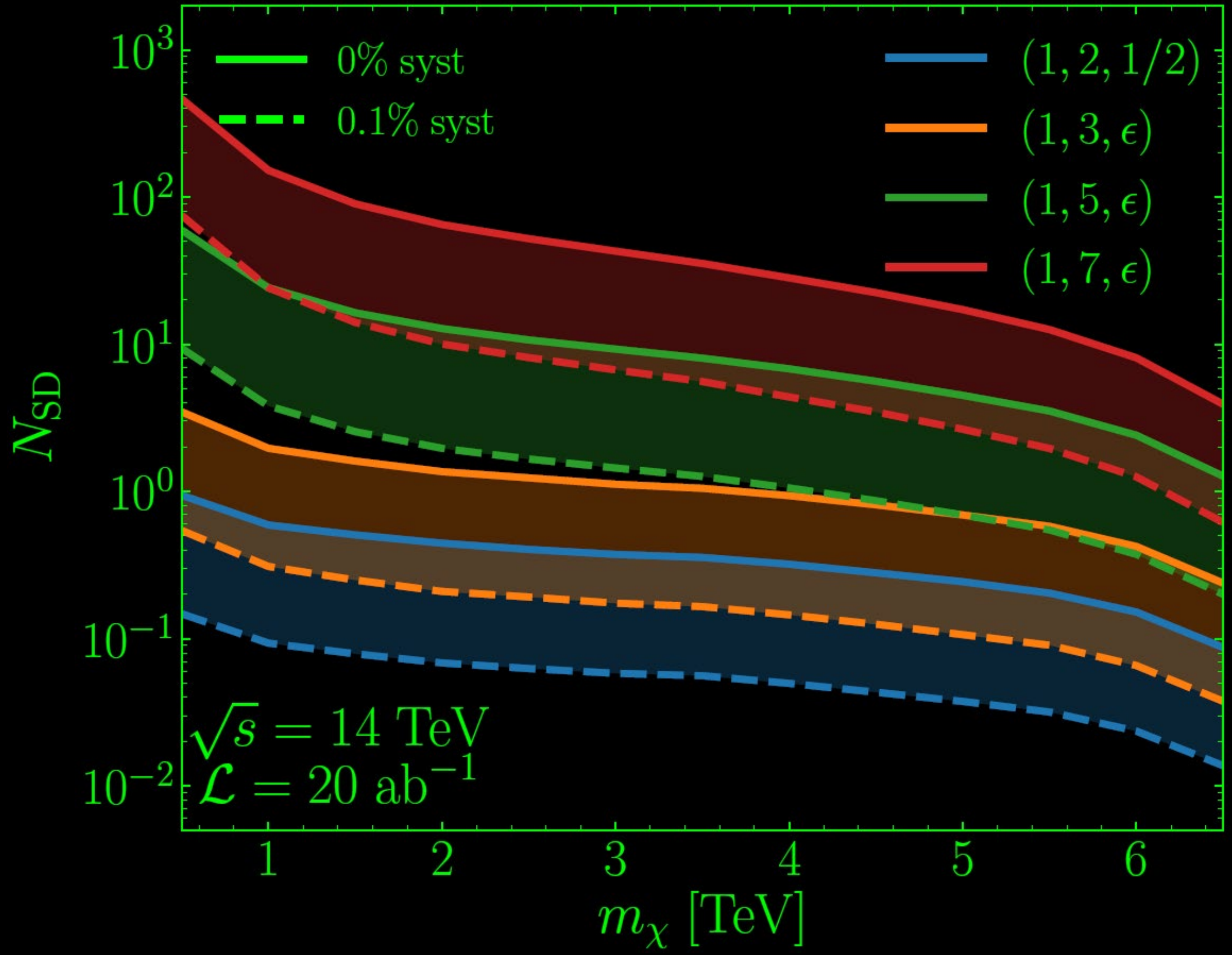
Mono-photon

Signal-background ratio 10^-3
At lepton colliders systematics controlled to this level should be achievable but requires theory & experimental work

Missing mass:

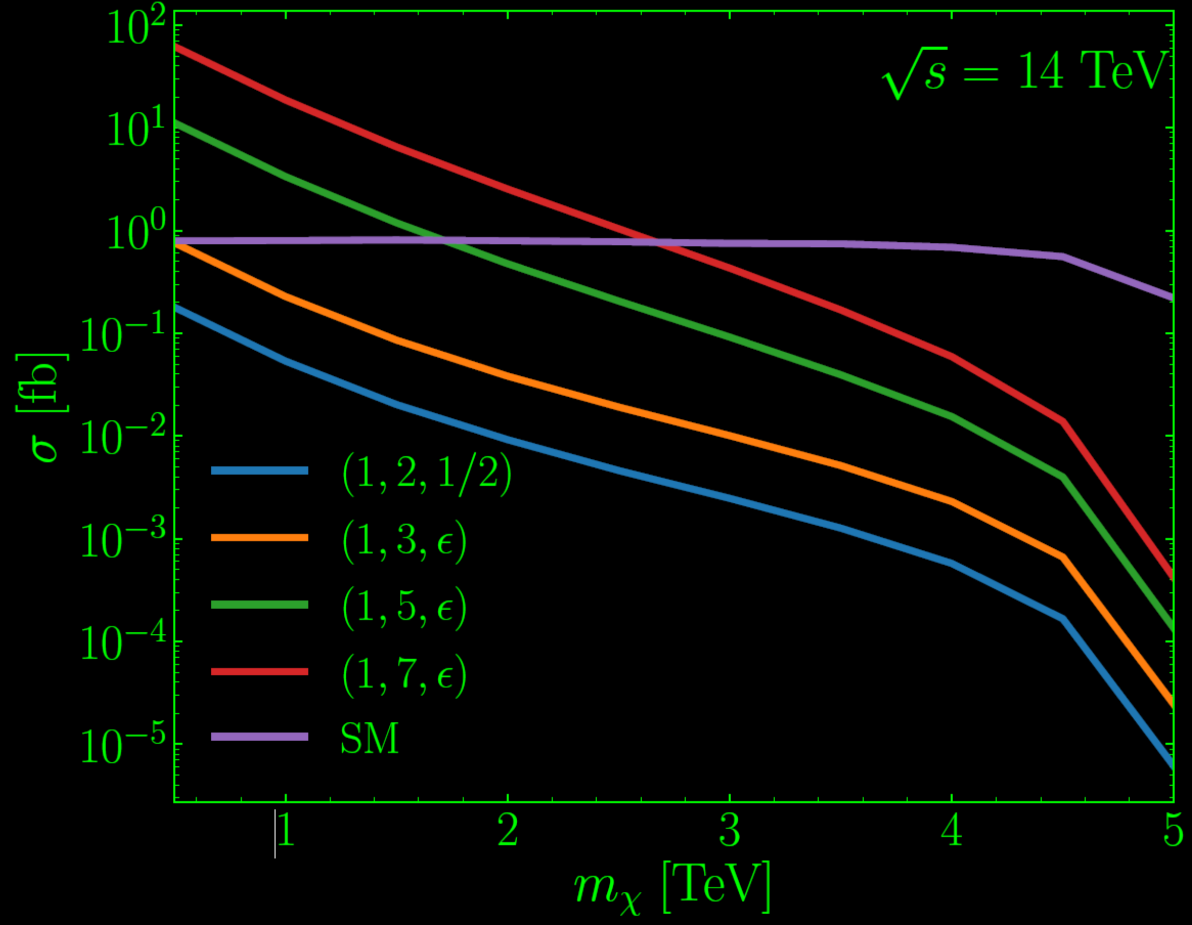
- Sharp kinematic features
- Signal-background separation
- Signal parameter determination



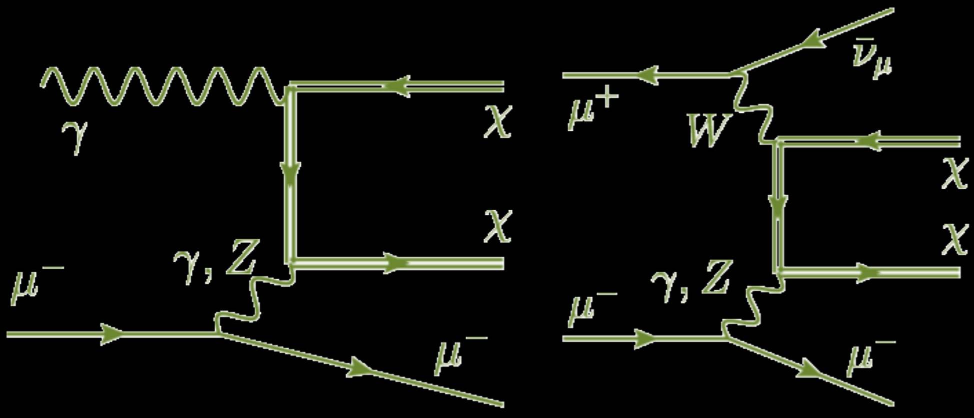


Unique Mono-Muon Channel

Apparent “Charge Violation” channel
(very different from the LHC)



Signature: Energetic mono muon

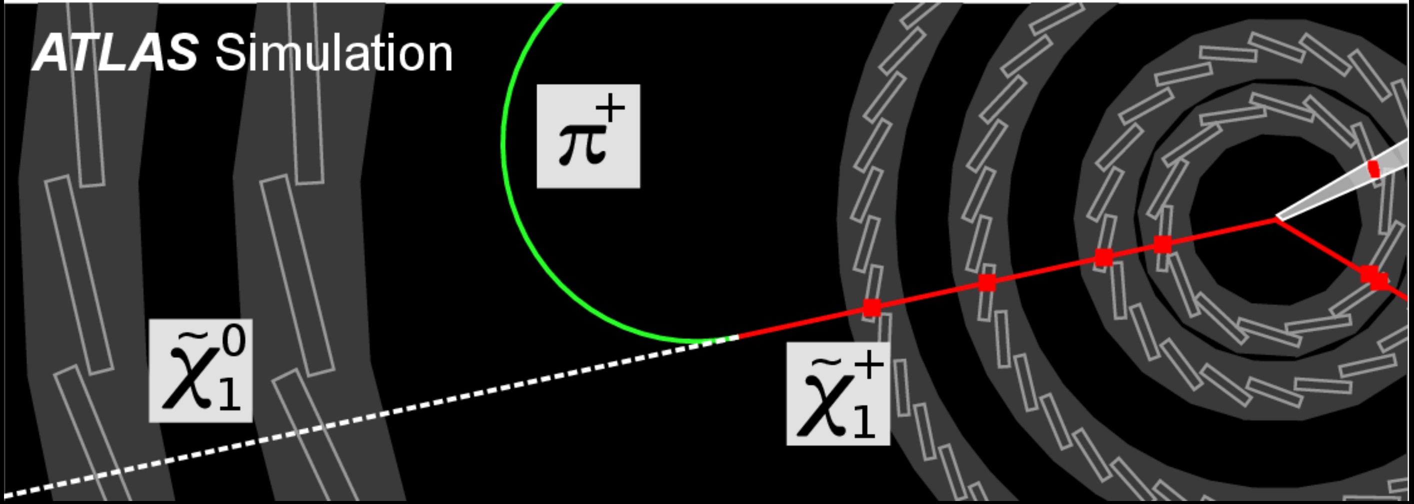


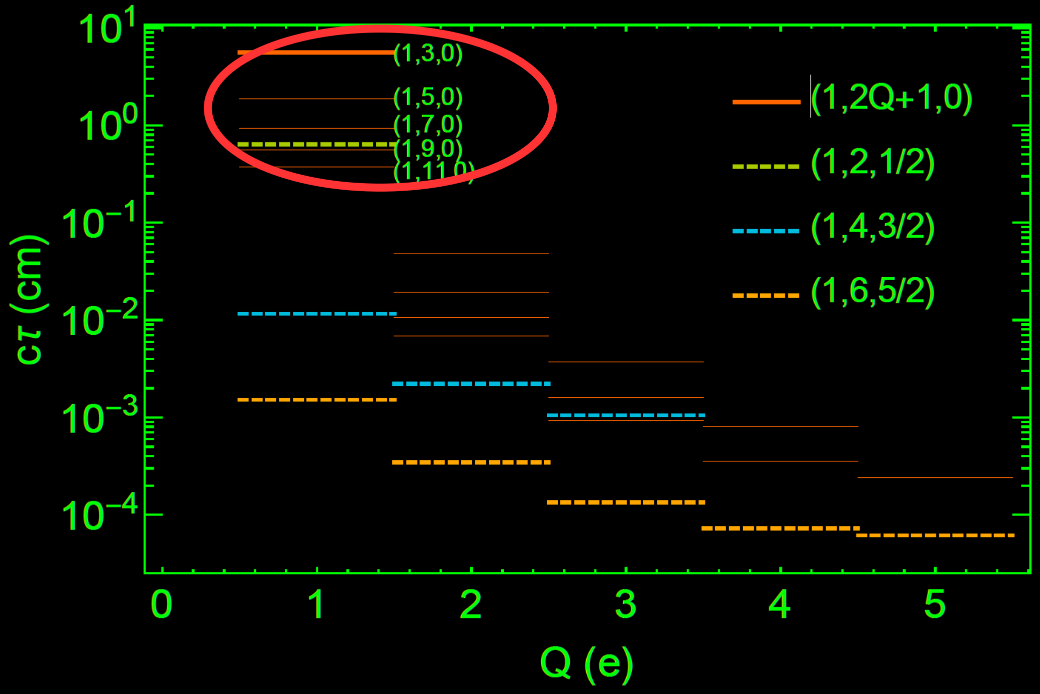
Muon pairs → muon + missing mass

One charge is missed due to the soft (non-reconstructable) decays of the charged states

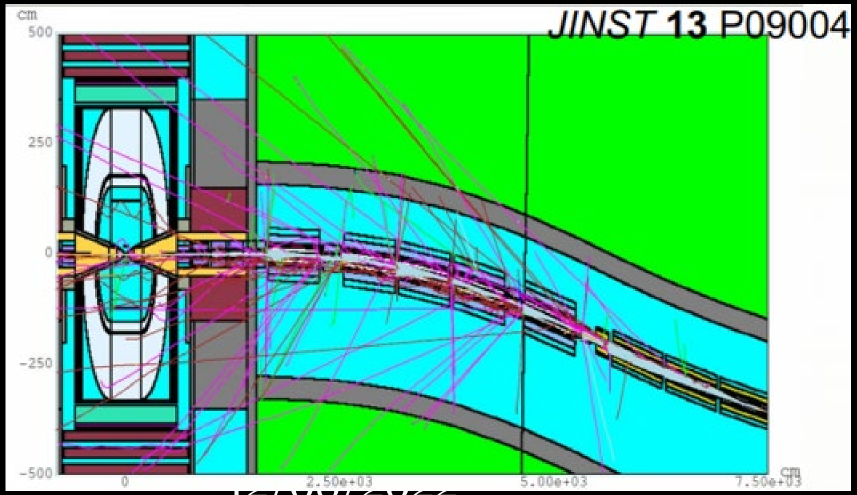
Unique and powerful channel for low-rate channels.

Disappearing Tracks: next to minimal signatures





- Only useful for searches using charge 1 states
- Still, all higher charged states will cascade back to charge 1 states promptly
- Use all the production rates of charged states
- Mono-photon+disappearing tracks
- Beam Induced Background

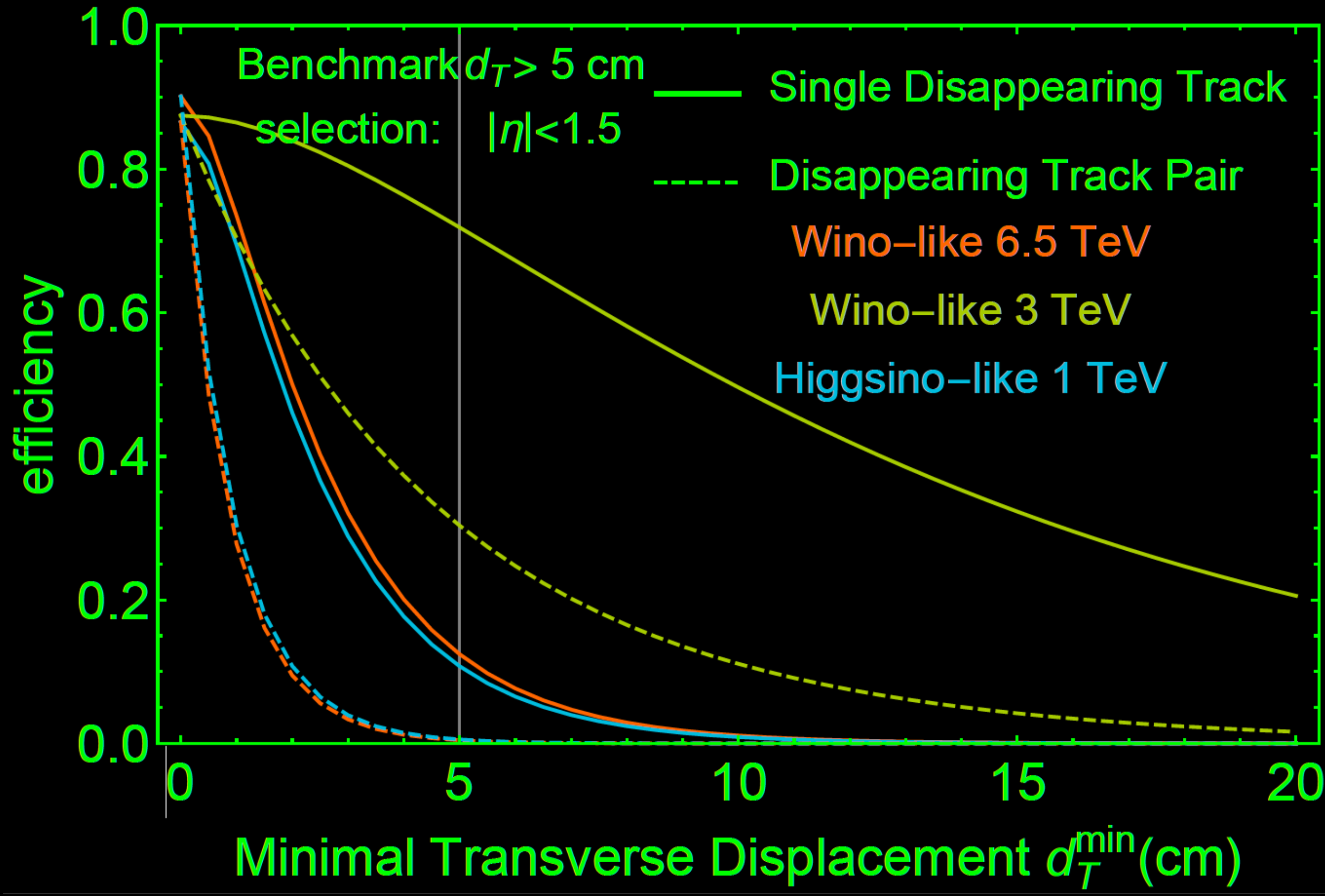


Minimal transverse displacement

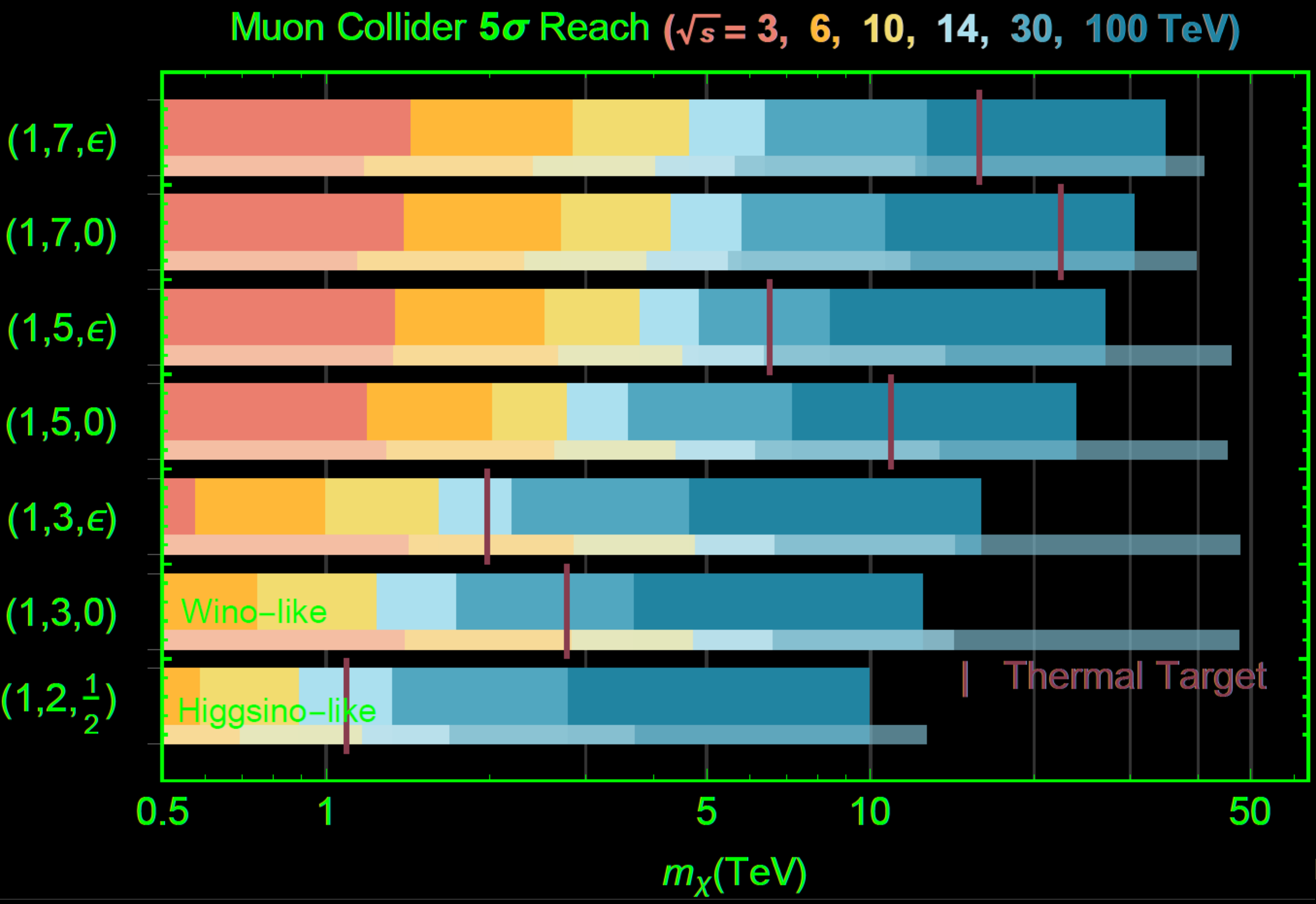
- Only use the central tracks, |eta|<1.5
- Current design have first layer of pixel detector at 3cm (new discussion about 2cm)
- We assume at least two-hits can be measured at 5cm
- Show both pair reconstruction or single reconstruction results
- Requiring 50 signal events for discovery

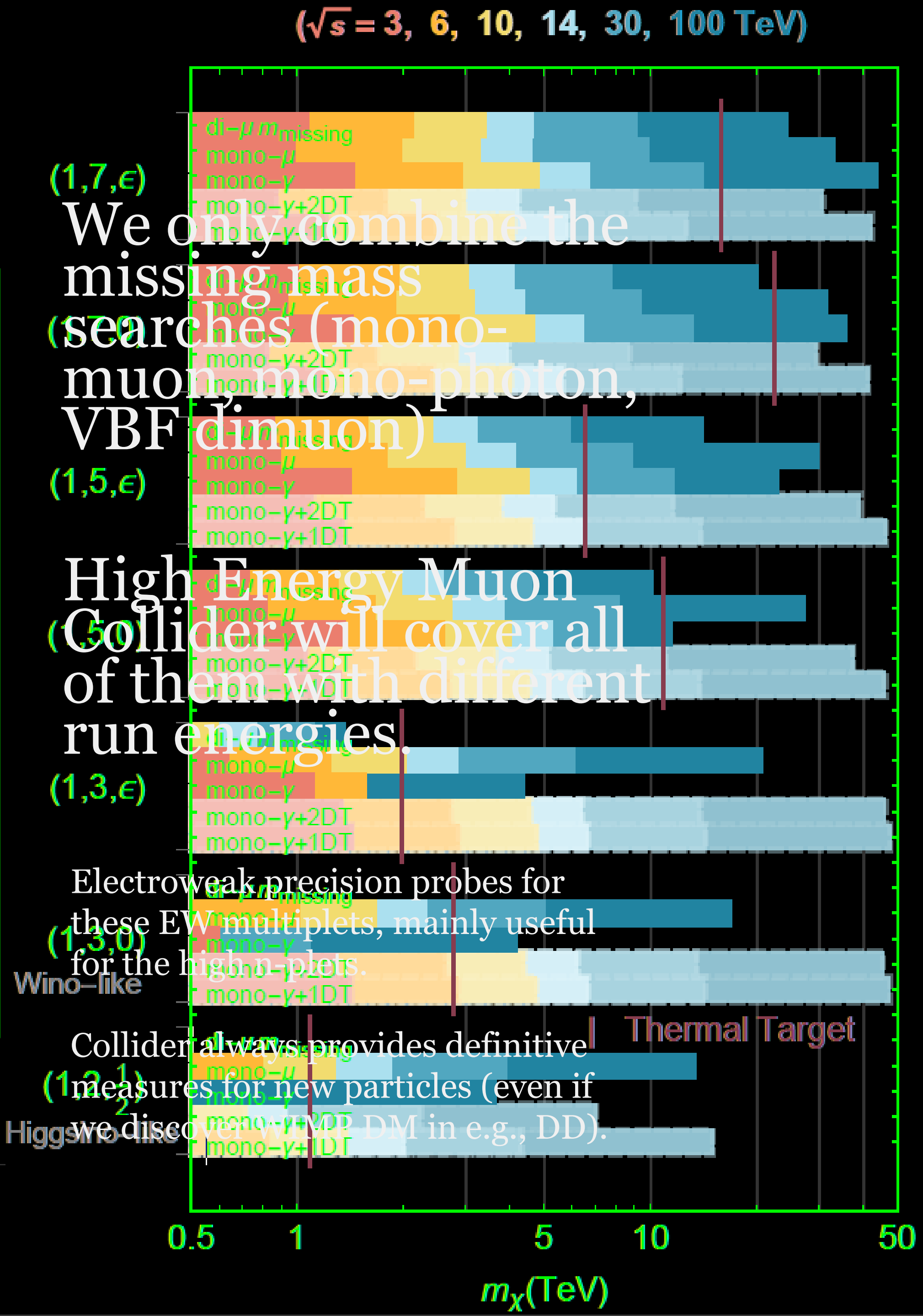
$$d_T^{\min} = 5 \text{ cm with } |\eta_\chi| < 1.5$$

$$\epsilon_\chi(\cos\theta, \gamma, d_T^{\min}) = \exp\left(\frac{-d_T^{\min}}{\beta_T \gamma c \tau}\right)$$



WIMP discovery Machine





We only combine the missing mass searches (mono-muon, mono-photon, VBF dimuon)

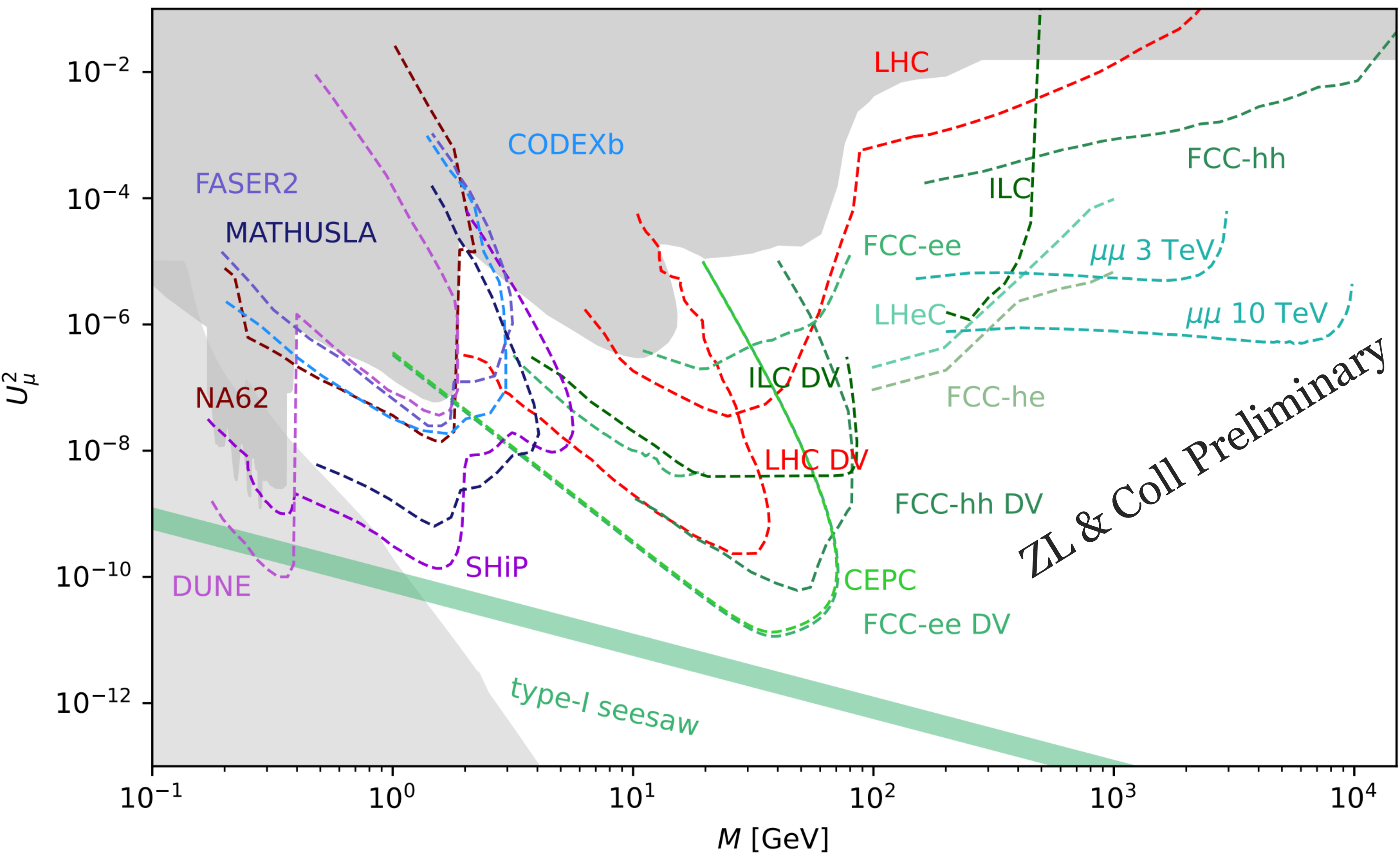
High Energy Muon Collider will cover all of them with different run energies.

Electroweak precision probes for these EW multiplets, mainly useful for the high n-plets.

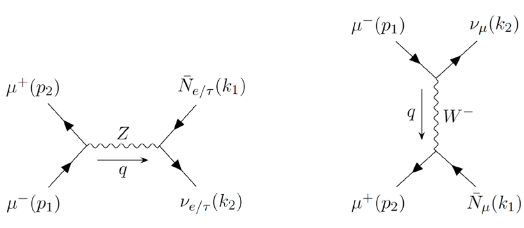
Collider always provides definitive measures for new particles (even if we discover WIMP DM in e.g., DD).

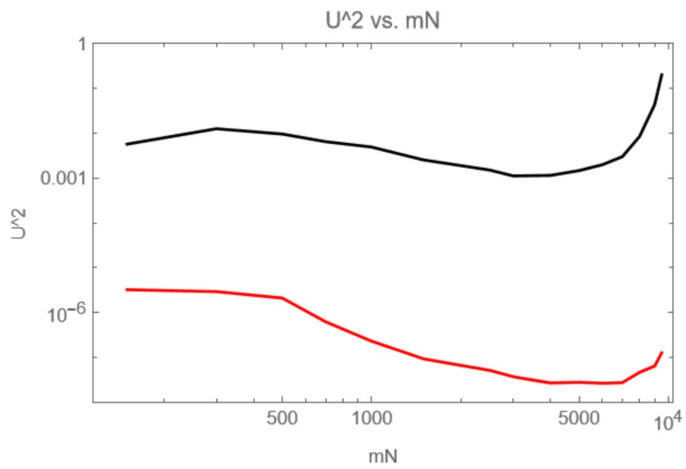
High Energy Muon Collider will cover all of them with different run energies.

Another EW BSM example: Heavy Neutral Leptons



P.R. Li, ZL, **K.F. Lyu**, in progress





Basics: s-channel Higgs

pp

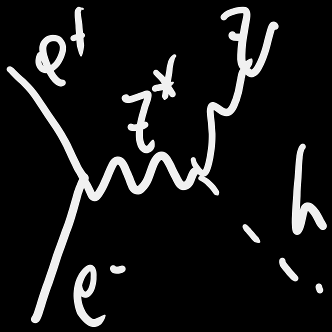
LHC 14 TeV

50 pb

3 ab^{-1}

150 million Higgs

e^+e^-



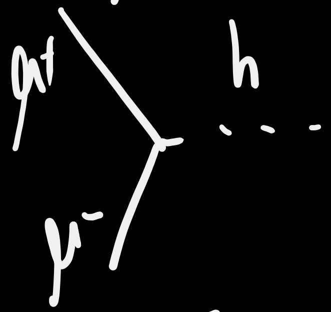
e^+e^- 240~250 GeV

200 fb

5 ab^{-1}

1 million Higgs

$\mu^+\mu^-$



$\mu^+\mu^-$ 125 GeV

22 pb × 65%

5~20 fb^{-1}

0.07 ~0.28 million Higgs

$\mu^+\mu^-$

$\mu^+\mu^-$ 10 TeV

~ 1 pb

10 ab^{-1}

~10 million Higgs

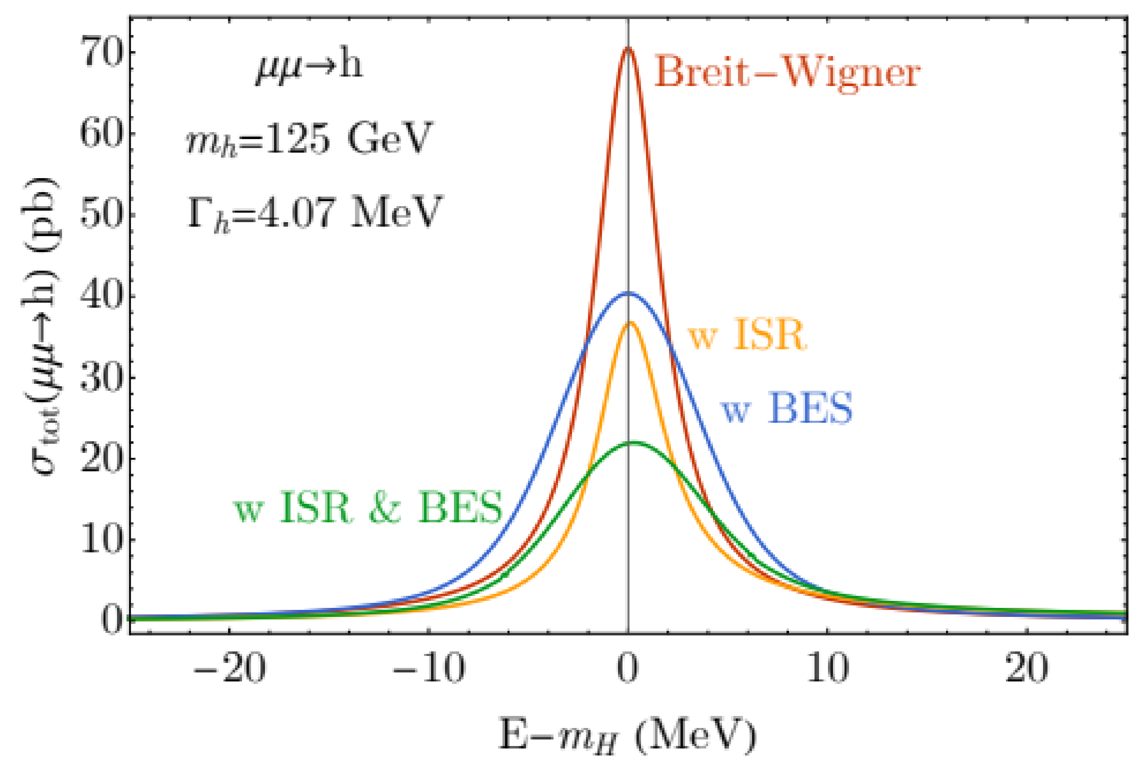
Lots of open questions

How would the width, mass, signal strength fit scale in various scenarios?

- Change of Luminosity (expecting some non-linearities from the beam energy spread);
- Lineshape scanning steps
- Lineshape scanning range
- Inclusion of more channels

The convolution of various effects are highly non-trivial. So new studies will help understand better:

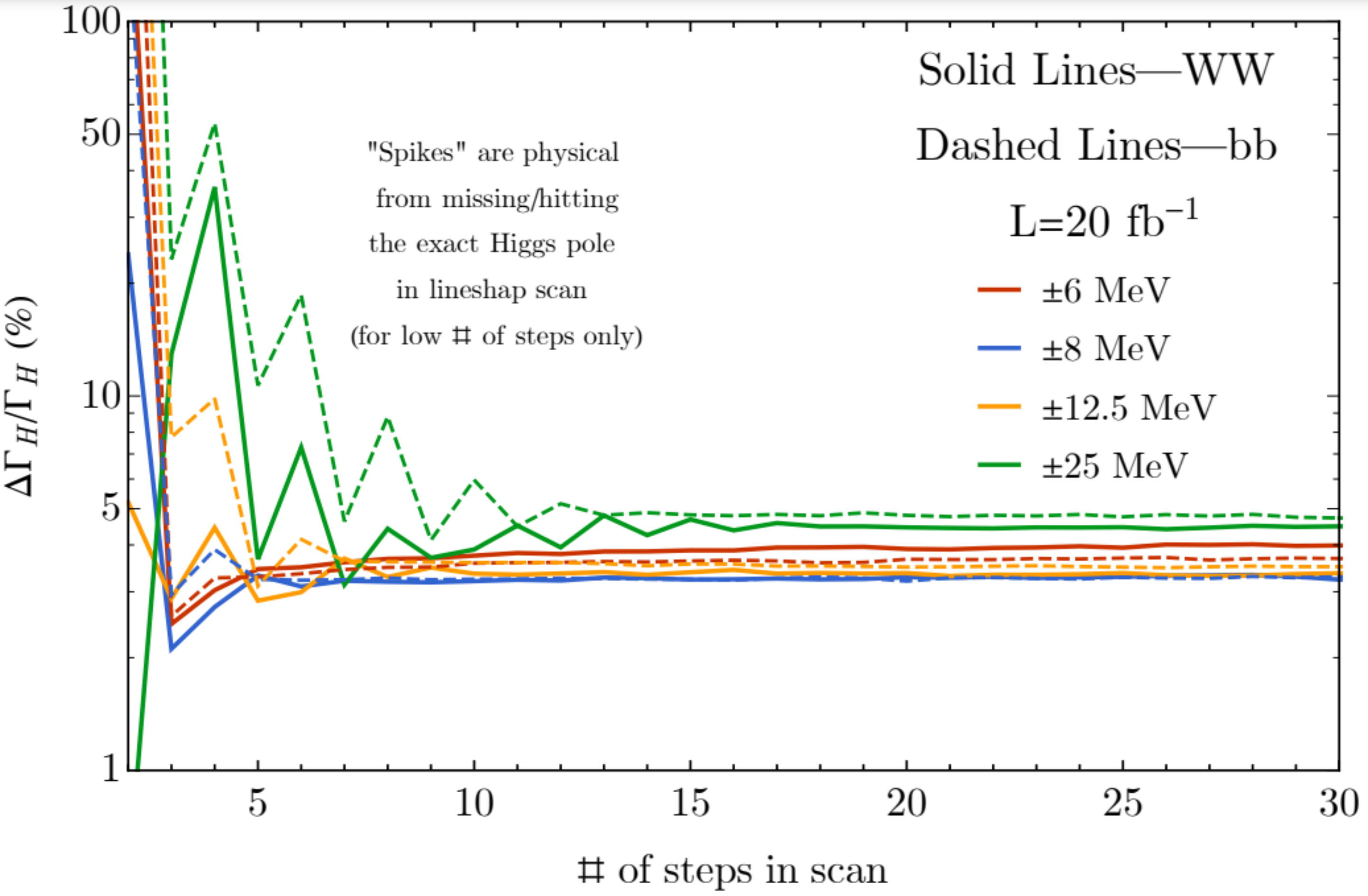
- 125 MuC Higgs physics
- Robustness of the width fit
- Allowing future studies on systematics

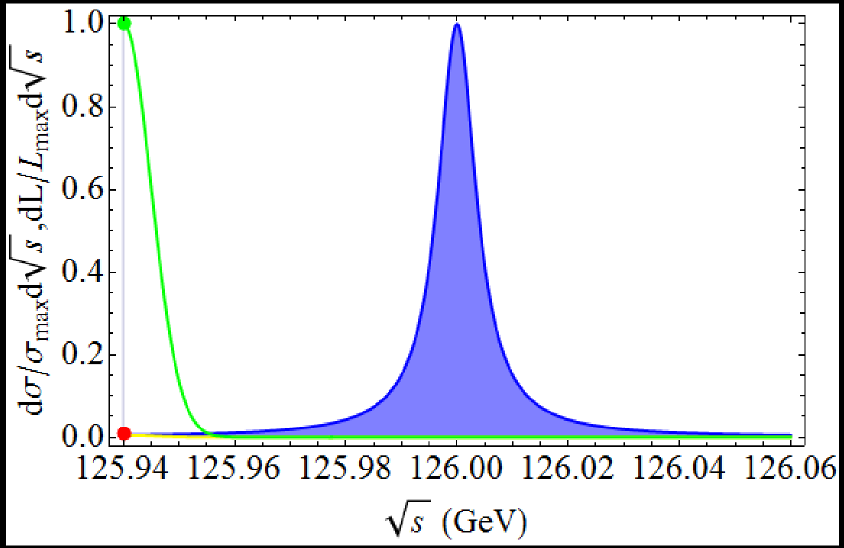


We made attempt to address these in our recent study,
J. de Blas, Jiayin Gu, ZL, 2203.04324

We initially worked on Higgs width alone T. Han, ZL, 1210.7803

Scanning Range & Steps



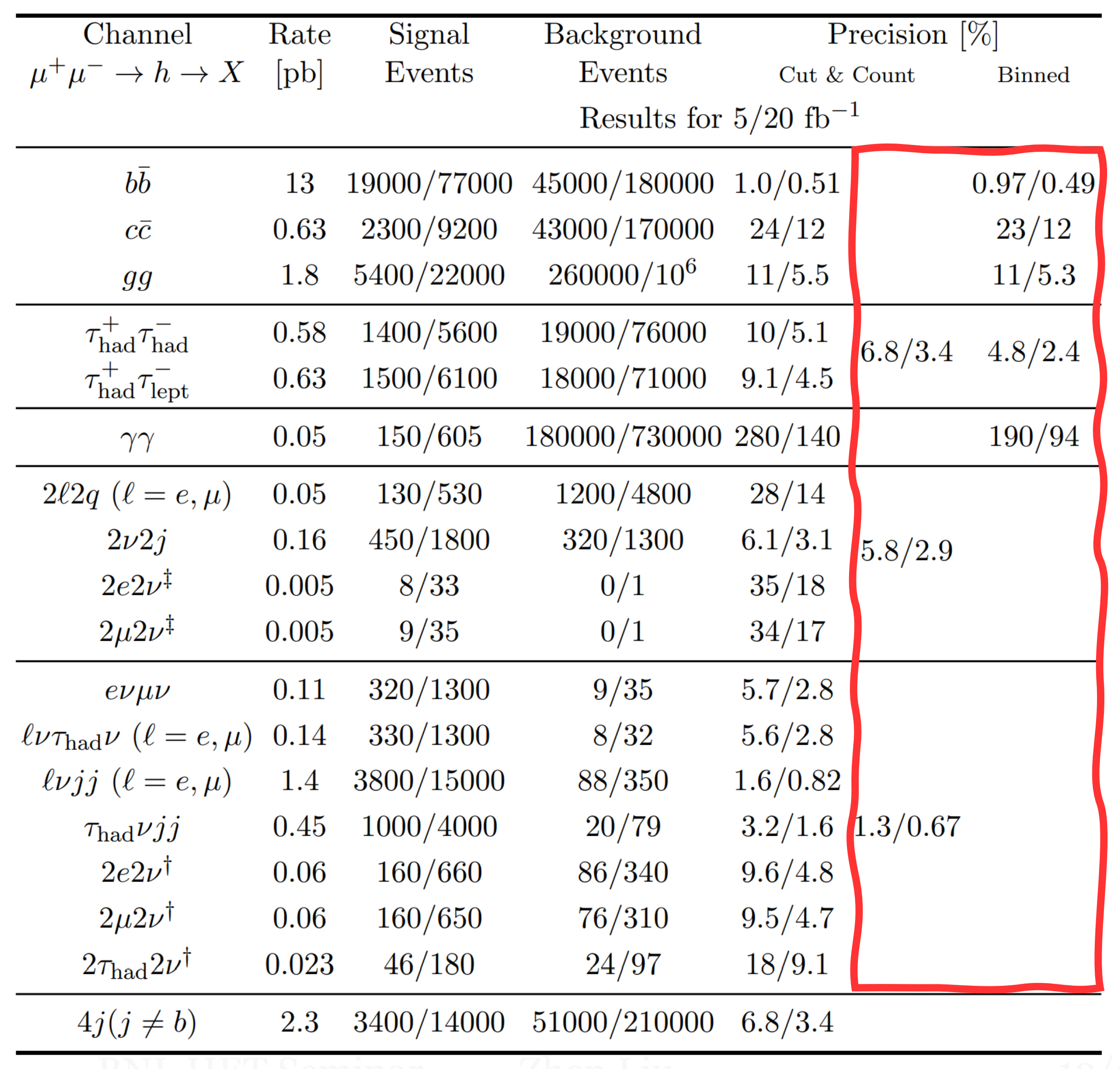


New insights:

- Optimal scanning range around +-10 MeV
- Need at least 6 points to stabilize, 10 points scan should be sufficient

Individual Channel Precision

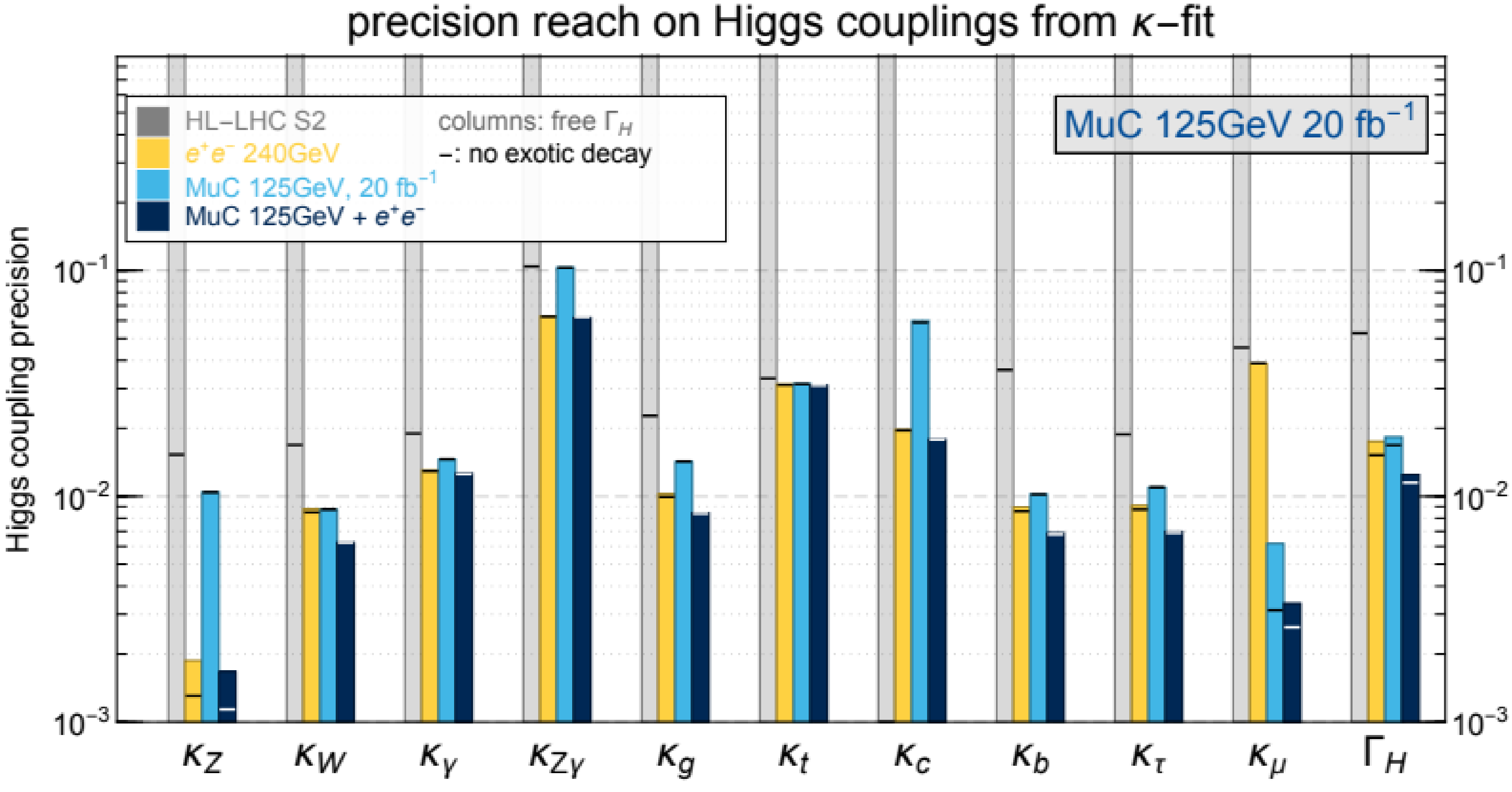
Let's check precision with ~1/4 on-shell statistics (with different bkg)



Channel $\mu^+\mu^- \to h \to X$	Rate [pb]	Signal Events	Background Events	Precision [%] Cut & Count		Binned
			Results for 5/20 fb^{-1}			
$b\bar{b}$	13	19000/77000	45000/180000	1.0/0.51		0.97/0.49
$c\bar{c}$	0.63	2300/9200	43000/170000	24/12		23/12
gg	1.8	5400/22000	260000/10^6	11/5.5		11/5.3
$\tau^+_{\text{had}}\tau^-_{\text{had}}$	0.58	1400/5600	19000/76000	10/5.1	6.8/3.4	4.8/2.4
$\tau^+_{\text{had}}\tau^-_{\text{lept}}$	0.63	1500/6100	18000/71000	9.1/4.5		
$\gamma\gamma$	0.05	150/605	180000/730000	280/140		190/94
$2\ell 2q$ $(\ell = e, \mu)$	0.05	130/530	1200/4800	28/14	5.8/2.9	
$2\nu 2j$	0.16	450/1800	320/1300	6.1/3.1		
$2e2\nu^{\ddagger}$	0.005	8/33	0/1	35/18		
$2\mu 2\nu^{\ddagger}$	0.005	9/35	0/1	34/17		
$e\nu\mu\nu$	0.11	320/1300	9/35	5.7/2.8	1.3/0.67	
$\ell\nu\tau_{\text{had}}\nu$ $(\ell = e, \mu)$	0.14	330/1300	8/32	5.6/2.8		
$\ell\nu jj$ $(\ell = e, \mu)$	1.4	3800/15000	88/350	1.6/0.82		
$\tau_{\text{had}}\nu jj$	0.45	1000/4000	20/79	3.2/1.6		
$2e2\nu^{\dagger}$	0.06	160/660	86/340	9.6/4.8		
$2\mu 2\nu^{\dagger}$	0.06	160/650	76/310	9.5/4.7		
$2\tau_{\text{had}}2\nu^{\dagger}$	0.023	46/180	24/97	18/9.1		
$4j (j \neq b)$	2.3	3400/14000	51000/210000	6.8/3.4		

Now the Model-Independent MuC Width matters!

- This MuC width is a parametrically new measurement; the correlations with other parameters are distinctive.
- Complementary to other lepton collider Higgs factories
- Sub-percent muon Yukawa
- Good lumi scaling with couplings
- Excellent improvement when combined with e+e- Higgs factories

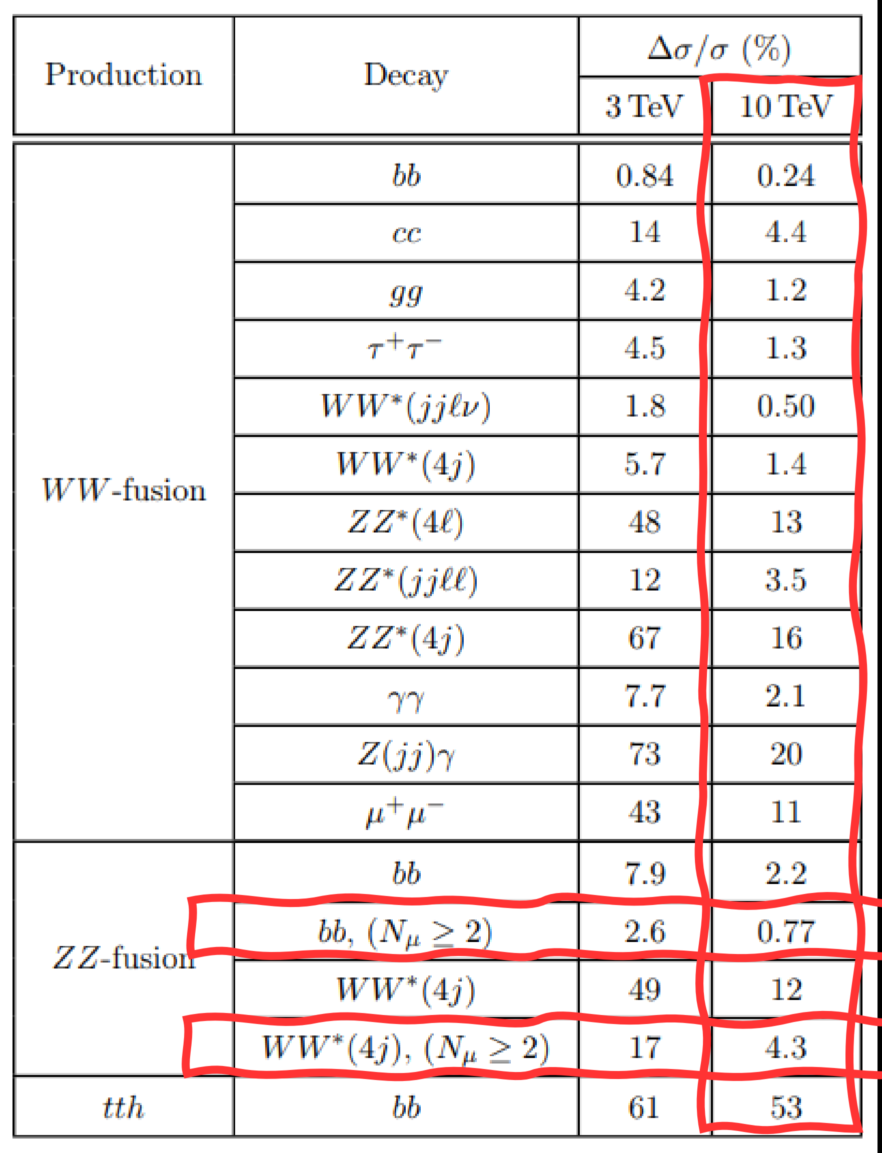


Higgs at High-Energy MuC

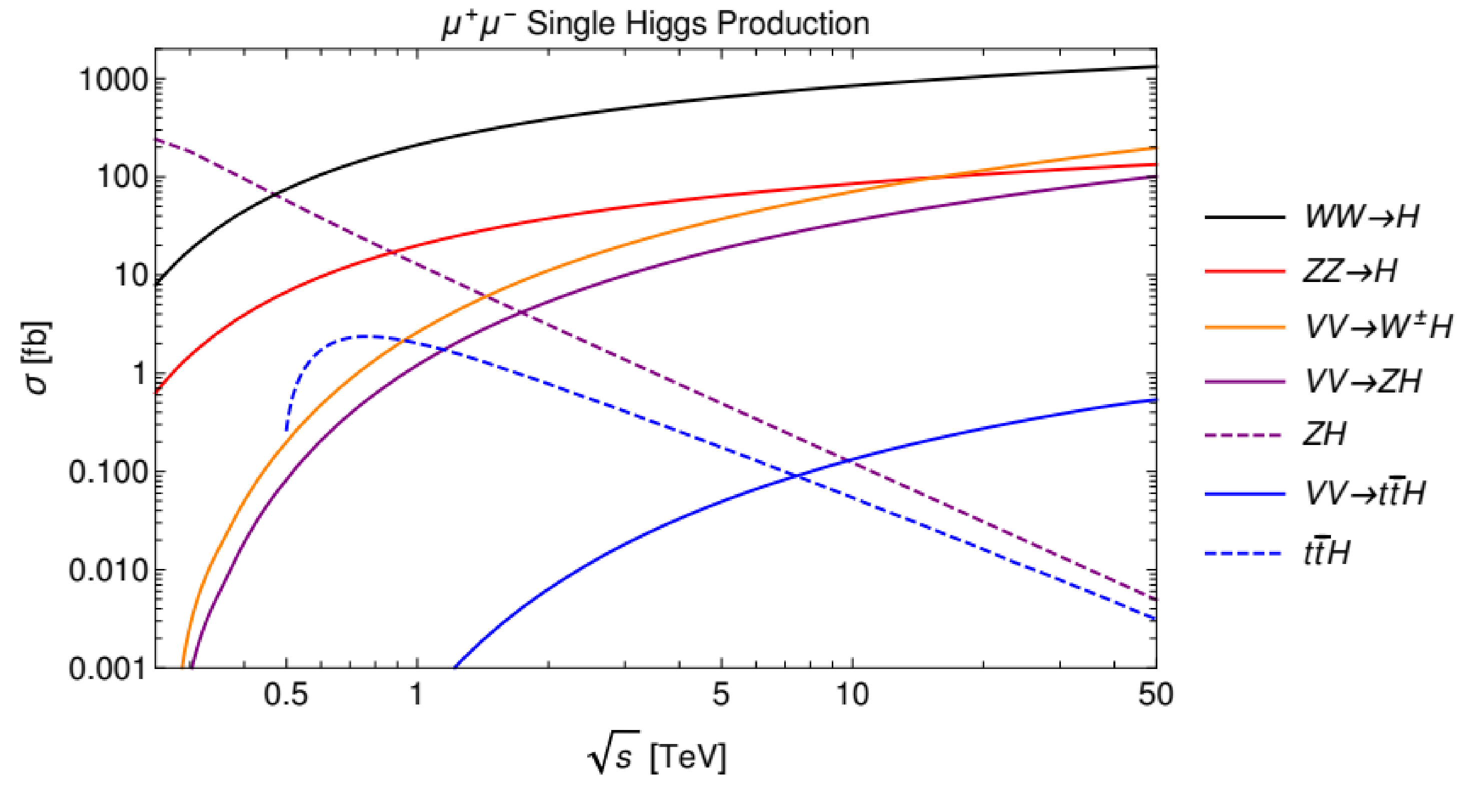
High Energy Muon Collider provides a vibrant and growing Higgs physics program:

- Baseline Precision couplings
- Higgs Self-coupling
- Top Yukawa through interference
- + many more

Baseline Higgs Measurements



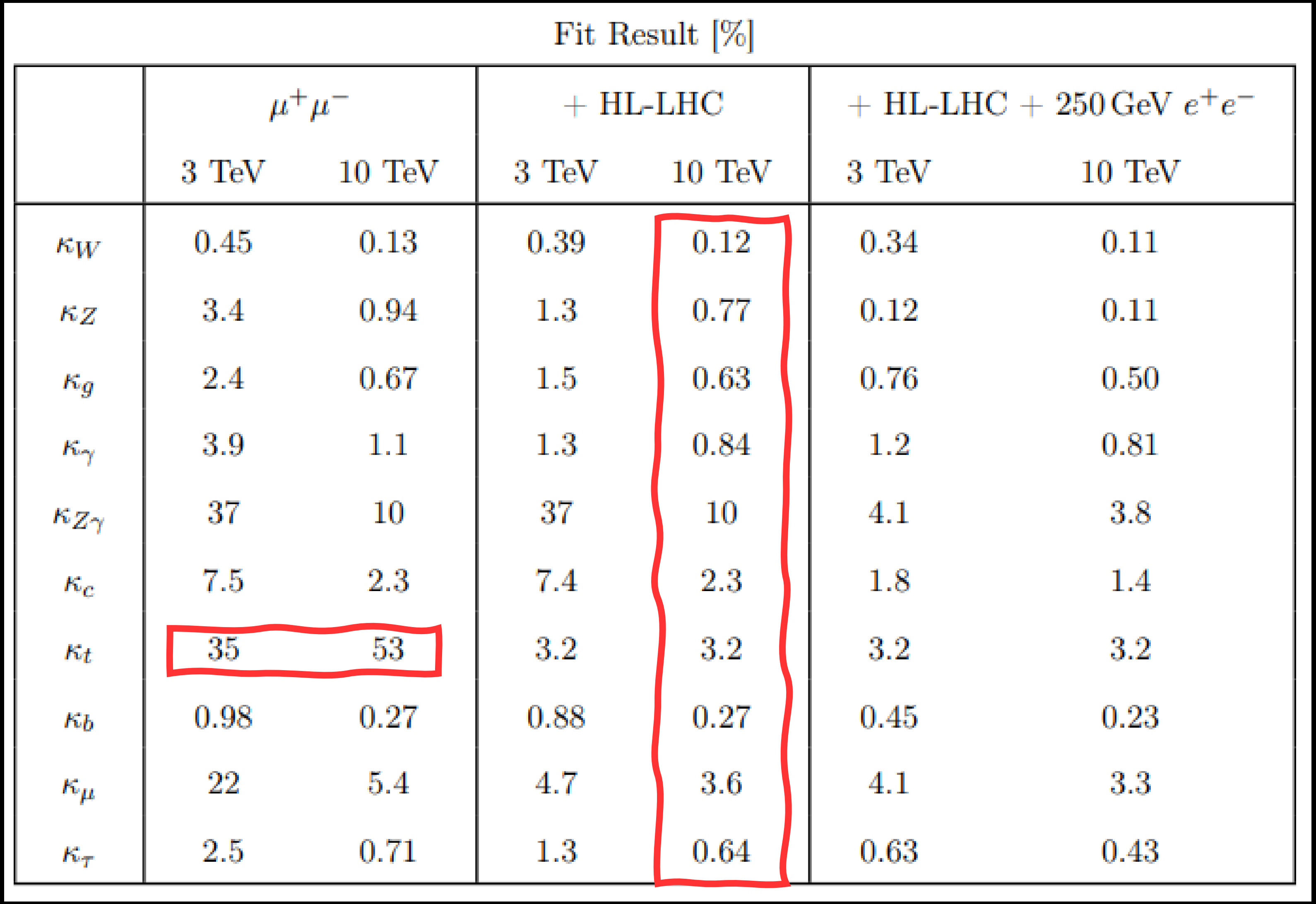
Production	Decay	$\Delta\sigma/\sigma$ (%)	
		3 TeV	10 TeV
WW-fusion	bb	0.84	0.24
	cc	14	4.4
	gg	4.2	1.2
	$\tau^+\tau^-$	4.5	1.3
	$WW^*(jj\ell\nu)$	1.8	0.50
	$WW^*(4j)$	5.7	1.4
	$ZZ^*(4\ell)$	48	13
	$ZZ^*(jj\ell\ell)$	12	3.5
	$ZZ^*(4j)$	67	16
	$\gamma\gamma$	7.7	2.1
	$Z(jj)\gamma$	73	20
	$\mu^+\mu^-$	43	11
ZZ-fusion	bb	7.9	2.2
	bb, $(N_\mu \geq 2)$	2.6	0.77
	$WW^*(4j)$	49	12
	$WW^*(4j)$, $(N_\mu \geq 2)$	17	4.3
tth	bb	61	53



M. Forslund, P. Meade, 2203.09425

See also discussion in
Muon Smasher's Guide, 2103.14043
T. Han, Y. Ma, K.-P. Xie, 2007.14300;
Costanini, De Lillo, Maltoni, Mantani, Mattelaer, 2005.10289

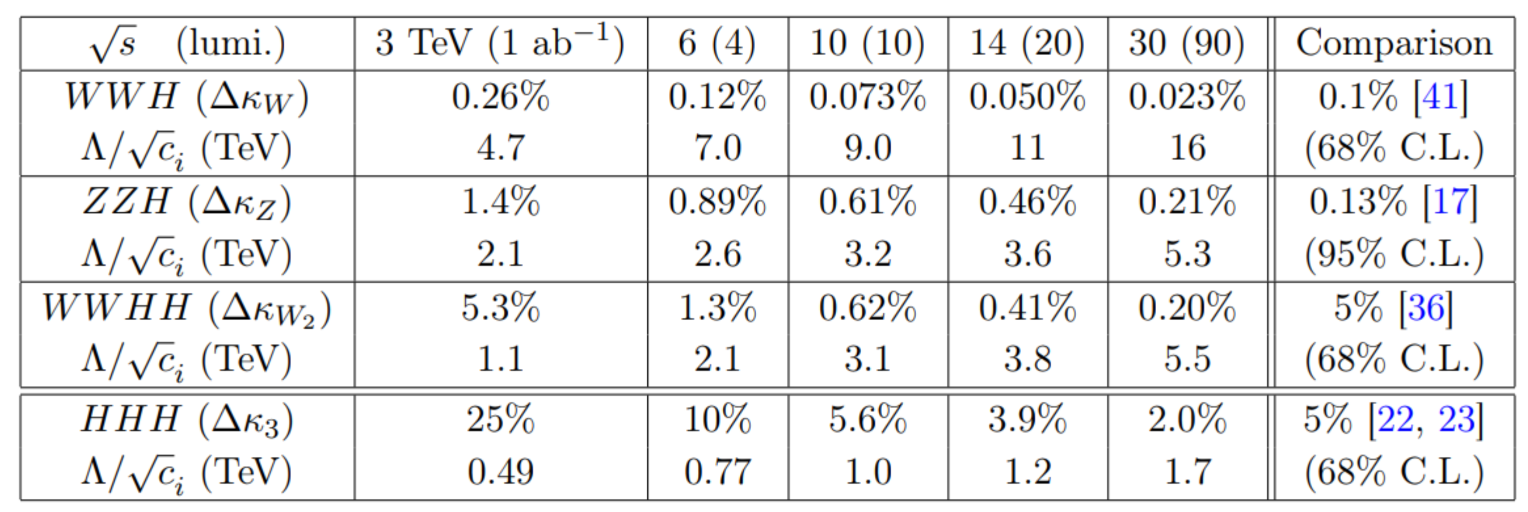
Higgs Precision



Fit Result [%]

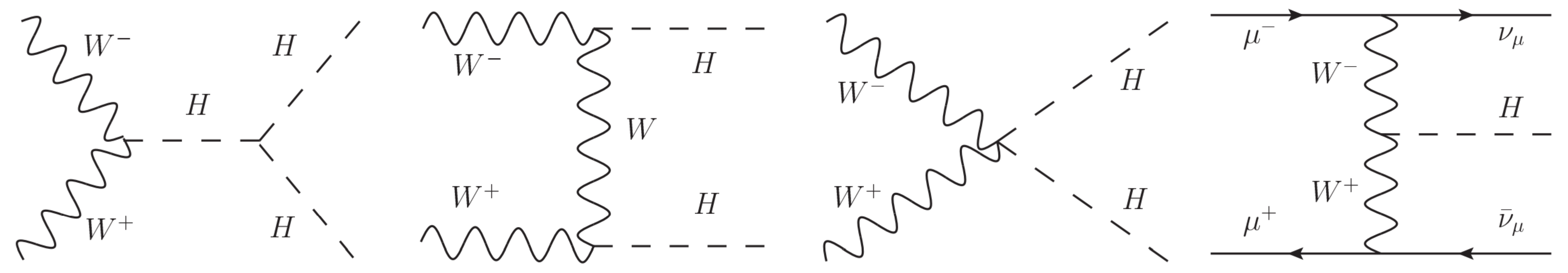
	$\mu^+\mu^-$		+ HL-LHC		+ HL-LHC + 250 GeV e^+e^-	
	3 TeV	10 TeV	3 TeV	10 TeV	3 TeV	10 TeV
κ_W	0.45	0.13	0.39	0.12	0.34	0.11
κ_Z	3.4	0.94	1.3	0.77	0.12	0.11
κ_g	2.4	0.67	1.5	0.63	0.76	0.50
κ_γ	3.9	1.1	1.3	0.84	1.2	0.81
$\kappa_{Z\gamma}$	37	10	37	10	4.1	3.8
κ_c	7.5	2.3	7.4	2.3	1.8	1.4
κ_t	35	53	3.2	3.2	3.2	3.2
κ_b	0.98	0.27	0.88	0.27	0.45	0.23
κ_μ	22	5.4	4.7	3.6	4.1	3.3
κ_τ	2.5	0.71	1.3	0.64	0.63	0.43

Multi-Higgs & Higgs Self-couplings



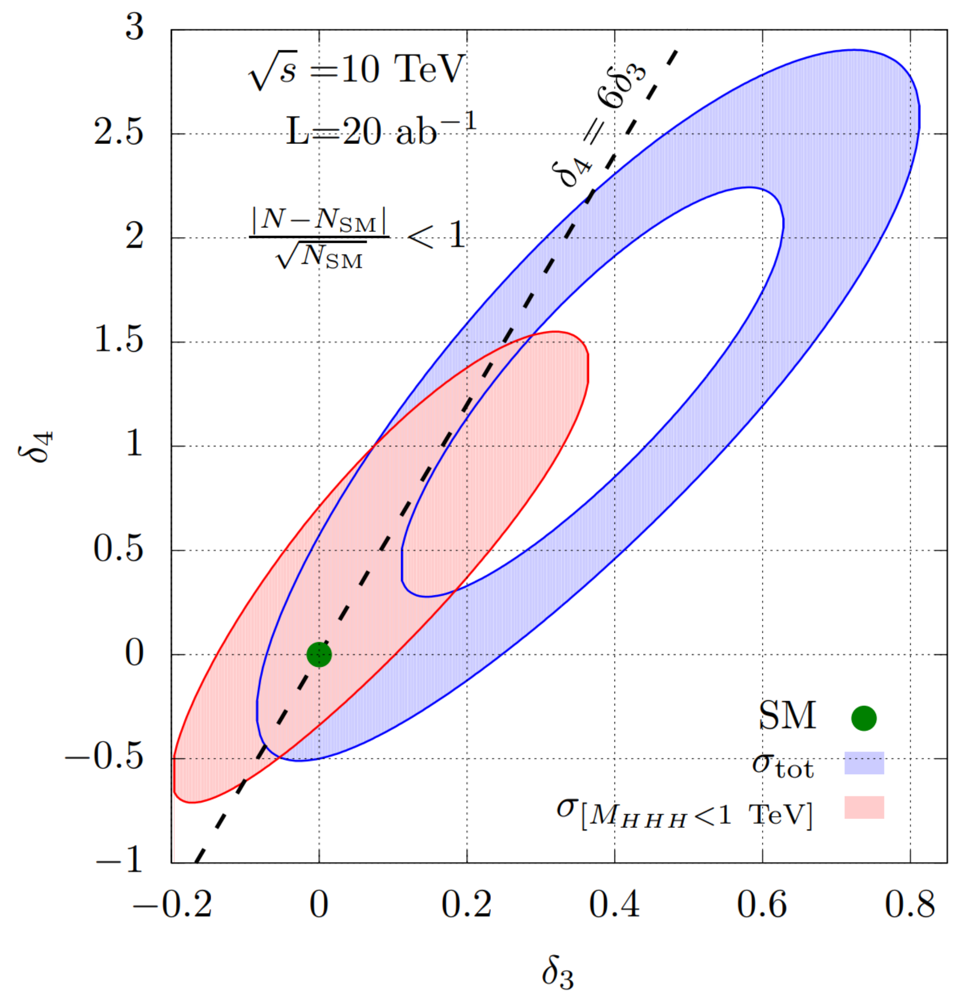
$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2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

Allow %-level trilinear Higgs measurements, and a consistent measurement between gauge boson-Higgs coupling measurements.



T. Han, D. Liu, I. Low, X. Wang, 2008.12204

Multi-Higgs & Higgs Self-couplings

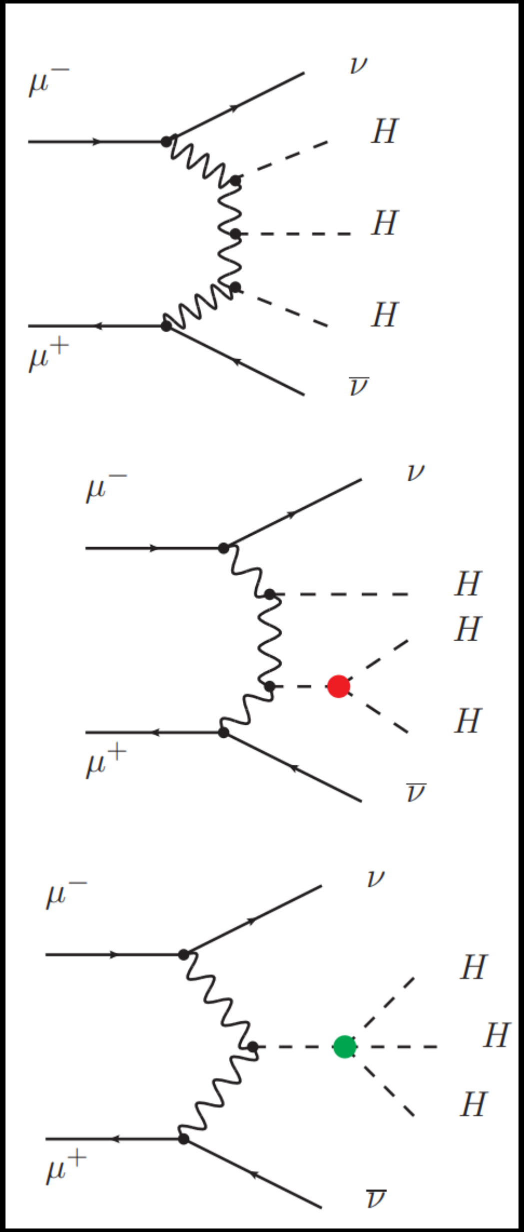


O(1) quartic determination possible.

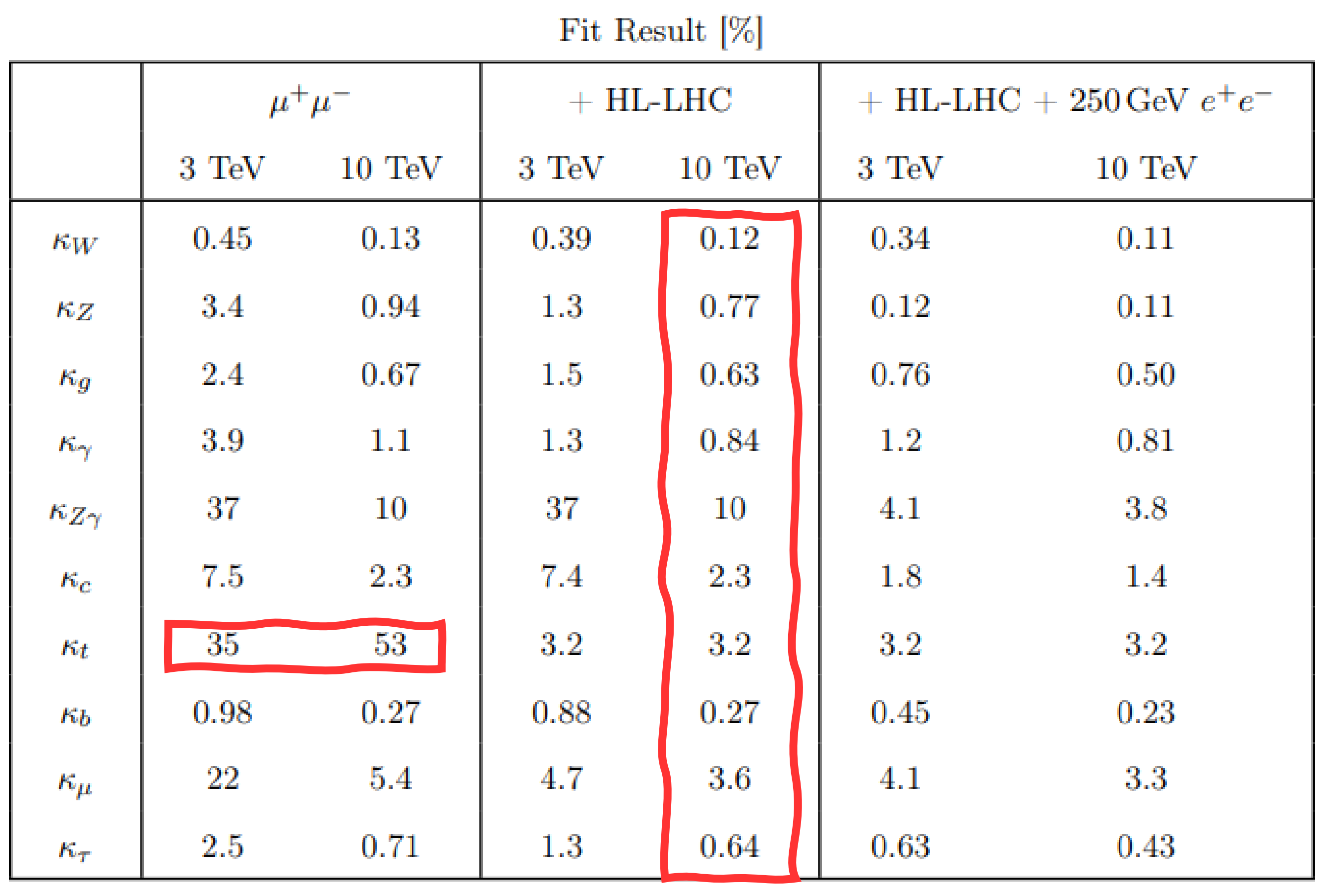
Chiesa, Maltoni, Mantani, Mele, Piccinini, 2003.13628

Correlated measurements of trilinear and quartic couplings reveals deep information about EFT and EWPT.

e.g, Huang, Joglekar, Wagner, 1512.00068 , Falkowski, Gonzalez-Alonso, Grejio, Marzocca, M. Son, 1609.06312, Chang, Luty, 1902.05556,+Abu-Ajamieh, M. Chen, 2009.11293; DiHiggs review 1910.00012



Top Yukawa (in an interesting way)



Fit Result [%]

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	3 TeV	10 TeV	3 TeV	10 TeV	3 TeV	10 TeV
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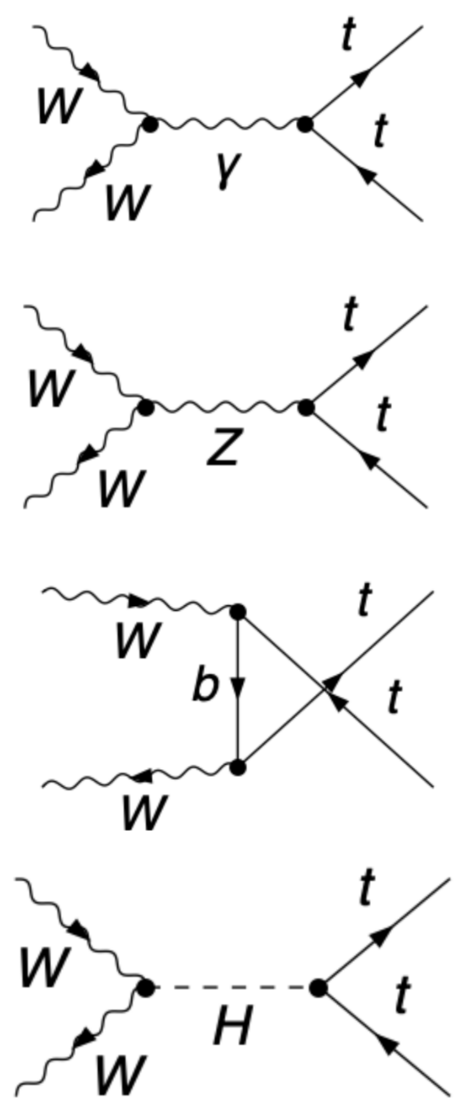
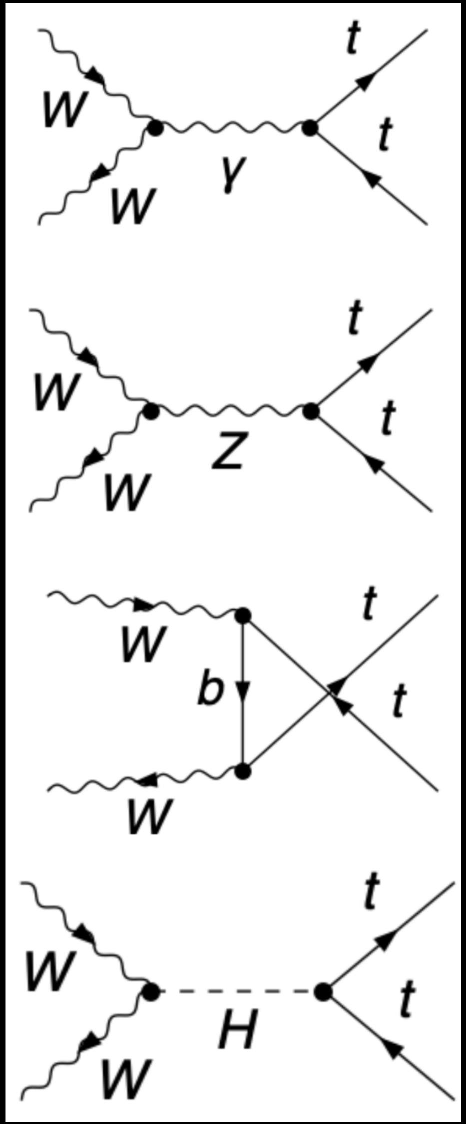
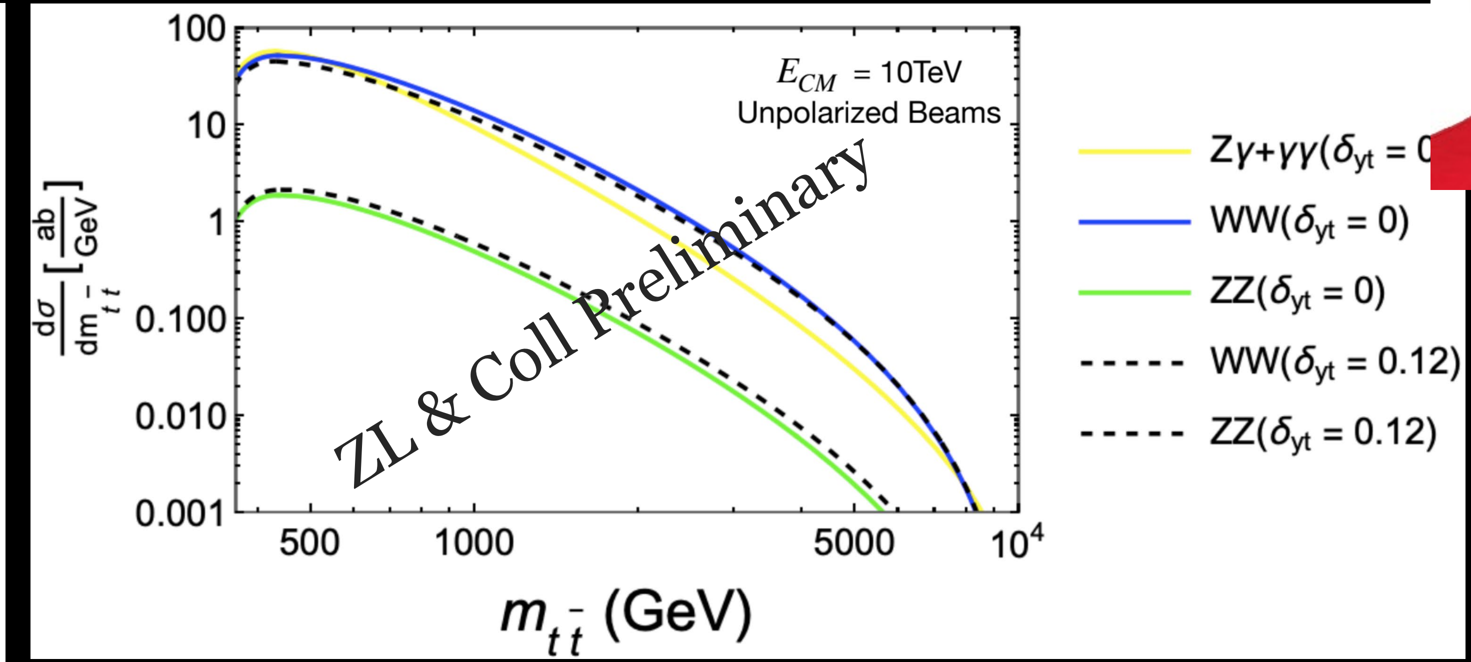
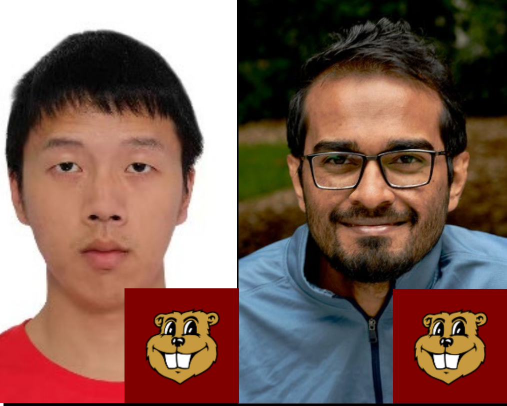
κ_Z	3.4	0.94	1.3	0.77	0.12	0.11
κ_g	2.4	0.67	1.5	0.63	0.76	0.50
κ_γ	3.9	1.1	1.3	0.84	1.2	0.81
$\kappa_{Z\gamma}$	37	10	37	10	4.1	3.8
κ_c	7.5	2.3	7.4	2.3	1.8	1.4
κ_t	35	53	3.2	3.2	3.2	3.2
κ_b	0.98	0.27	0.88	0.27	0.45	0.23
κ_μ	22	5.4	4.7	3.6	4.1	3.3
κ_τ	2.5	0.71	1.3	0.64	0.63	0.43



Measuring Top Yukawa

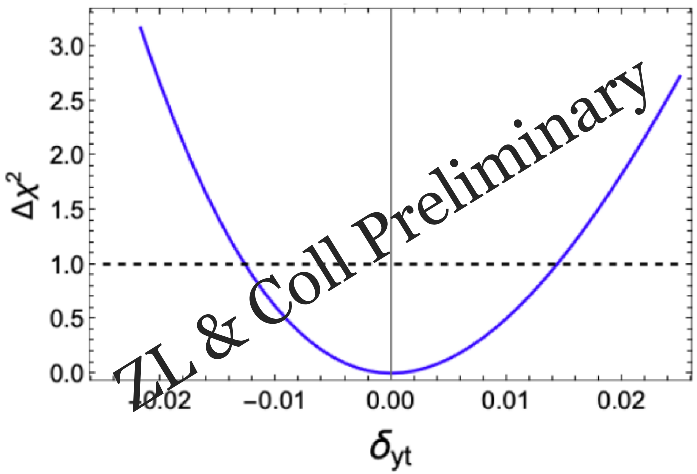




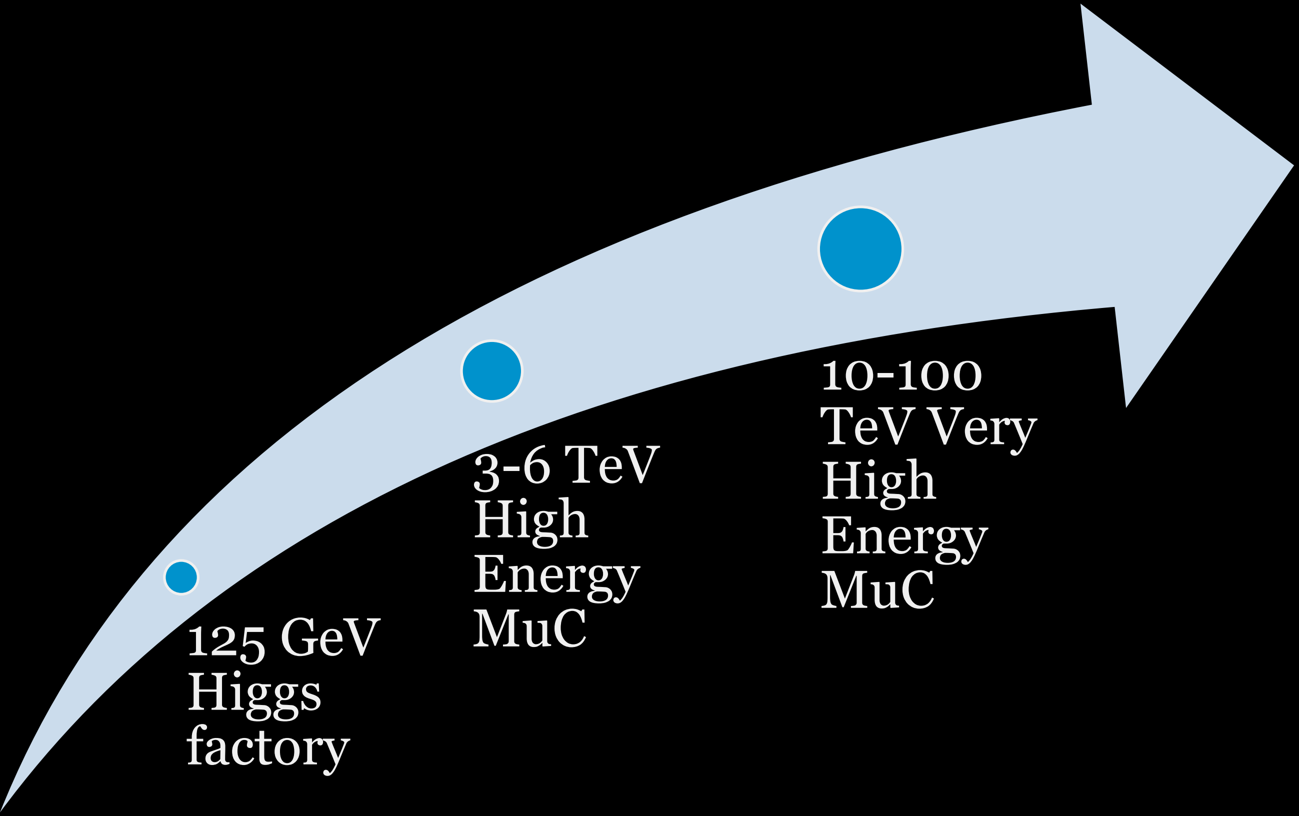


K.F. Lyu, ZL, **I. Mahbub**, in progress

$$\boxed{\mathcal{M}(t\bar{t} \to W_L^+ W_L^-) = \frac{m_t}{v^2}\delta_{BSM}\sqrt{s}} \quad \sqrt{s} >> m_t, M_Z, M_W$$



The Dream Machine

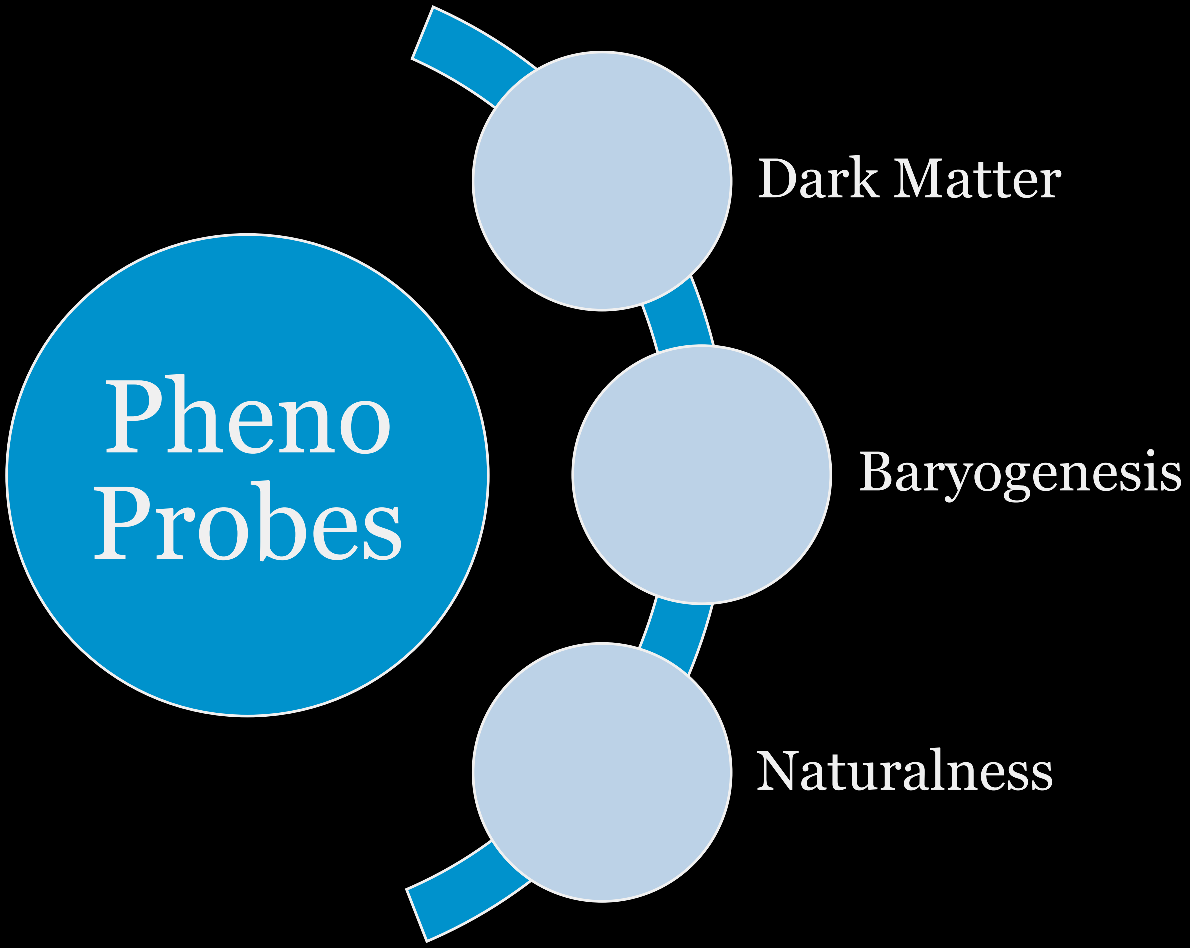


125 GeV Higgs factory

3-6 TeV High Energy MuC

10-100 TeV Very High Energy MuC

Physics Driver



Pheno Probes

- Dark Matter
- Baryogenesis
- Naturalness

International muon collider collaboration: https://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=MUONCOLLIDERDETECTOR-PHYSICS

Muon Collider Forum: SNOWMASS-MUON-COLLIDER-FORUM@FNAL.GOV at https://snowmass21.org/energy/start#communications.

Thank you!