International Workshop on New Opportunities for Particle Physics 2024

Jul 19 – 21, 2024
Institute of High Energy Physics, Chinese Academy of Sciences

Muon Shot

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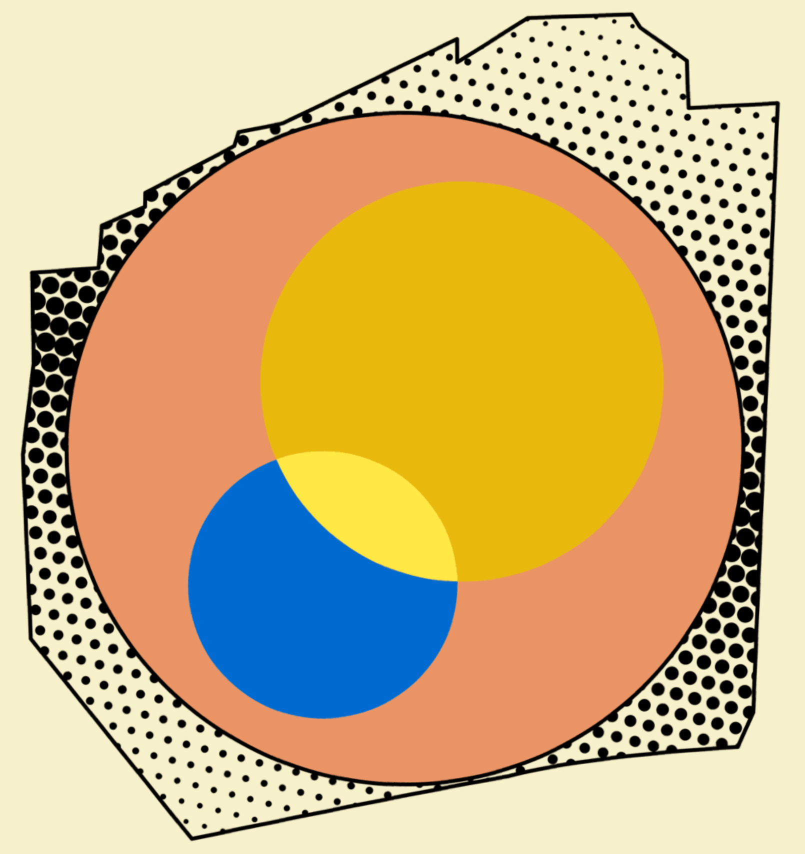
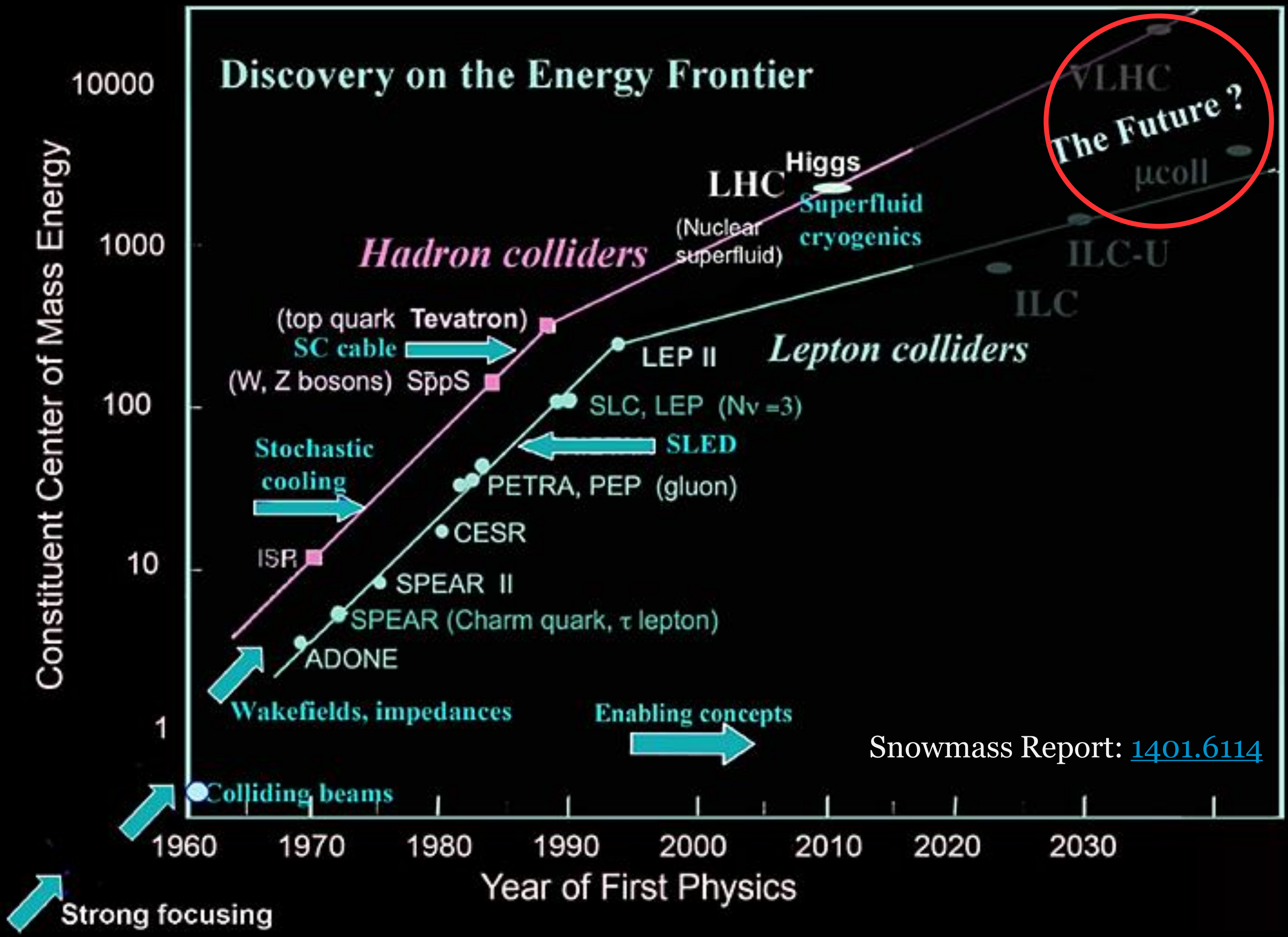
07/21/2024

GIF from US muon collider meeting:
https://indico.fnal.gov/event/64493/



High Energy Rules

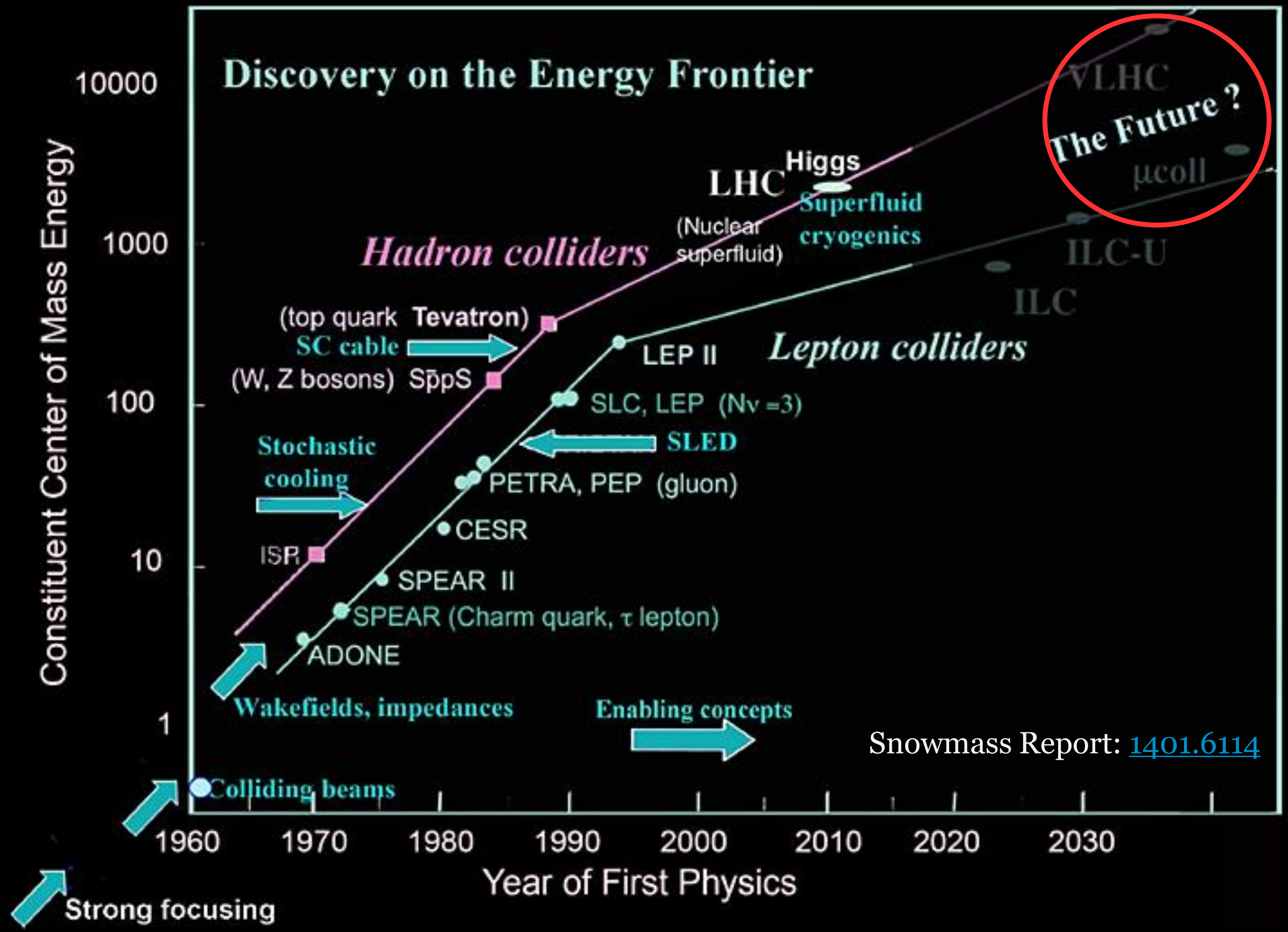


Snowmass Report: [1401.6114](https://arxiv.org/abs/1401.6114)

The forefront of tech & ambitions leads to discoveries.

The dream for high energy machines persists in our field

High Energy Rules



Snowmass Report: 1401.6114

The forefront of tech & ambitions leads to discoveries.

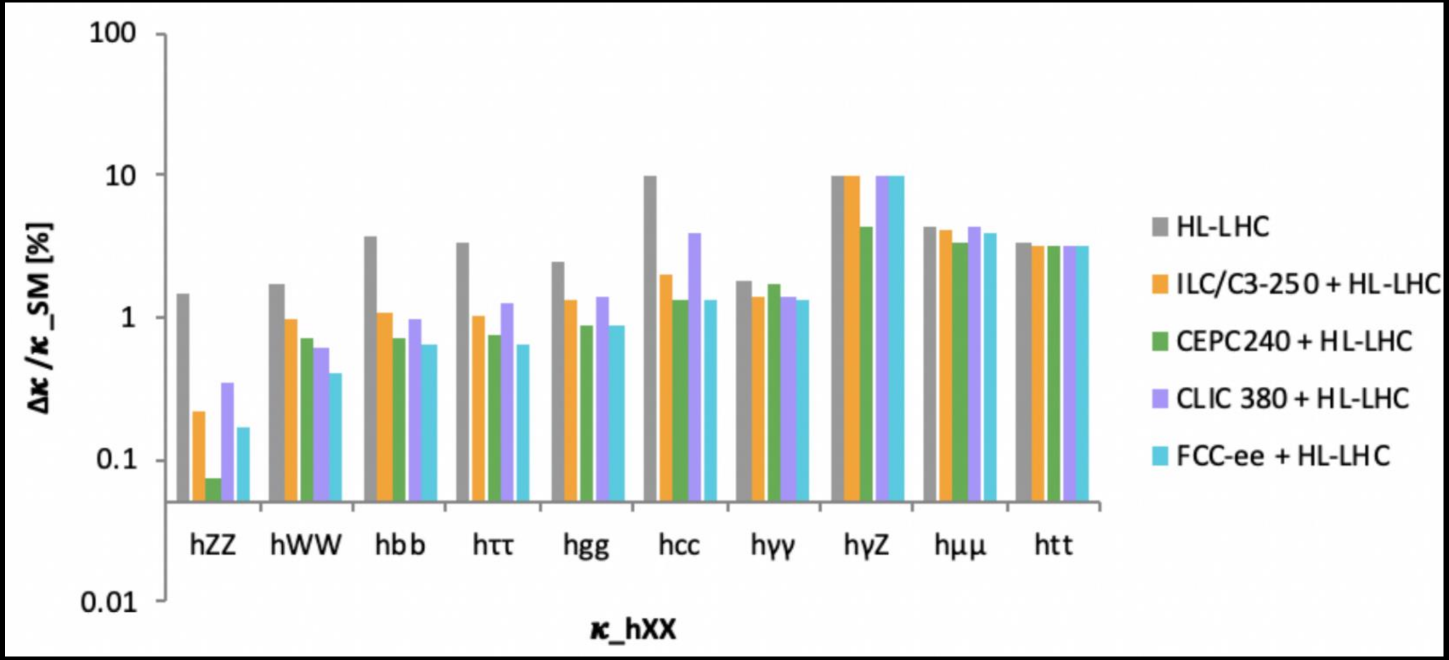
The dream for high energy machines persists in our field

People’s perspectives change over time, now:

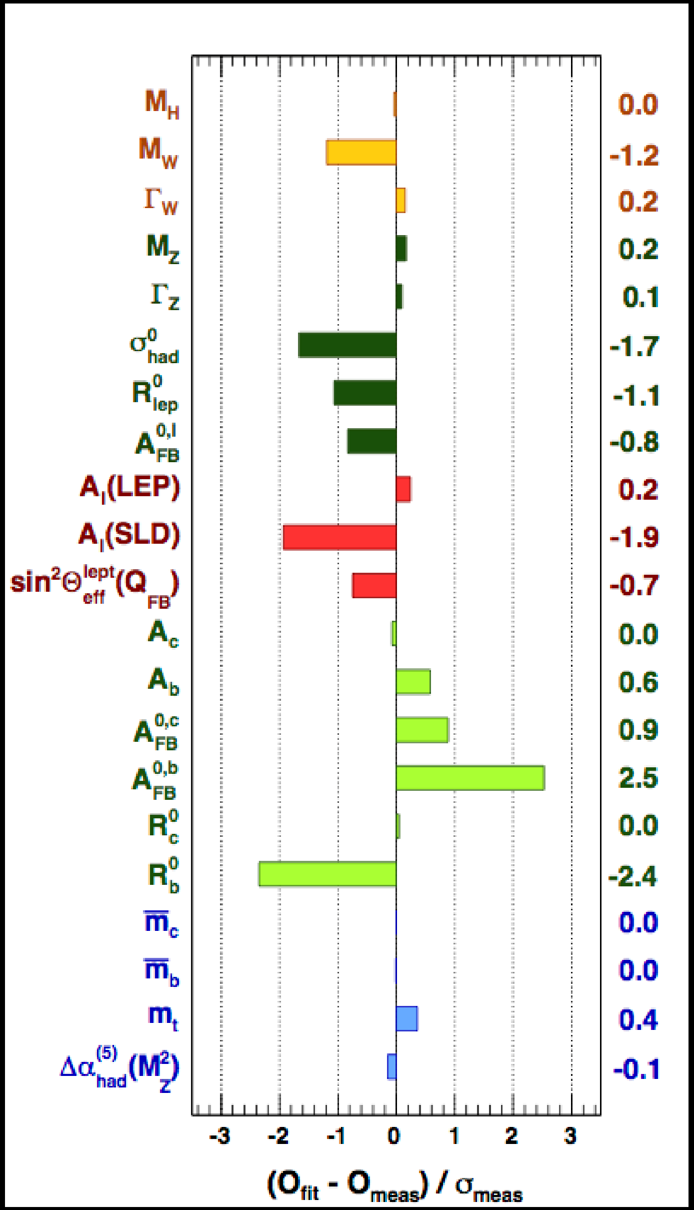
- there are excitement/call for future high energy muon collider from theory, accelerator and experimental community.
- Interesting aspects of physics to be examined.

The power of cleanness

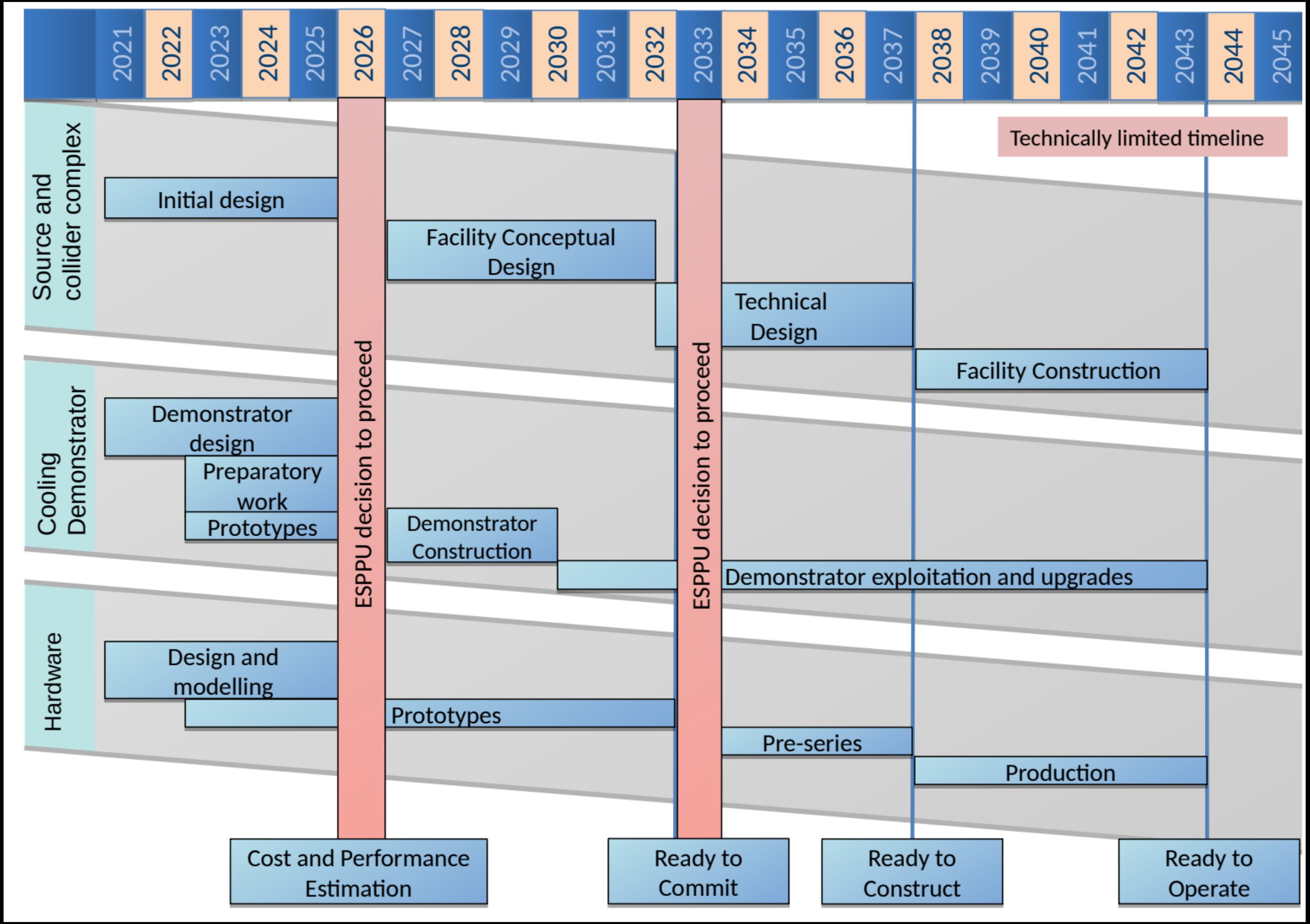
- LEP still is a headache/treasure of theorists
- 1-4M Higgs Higgs factory v.s. 0.5B Higgs HL-LHC



Dawson et al, [2209.07510](https://arxiv.org/abs/2209.07510)

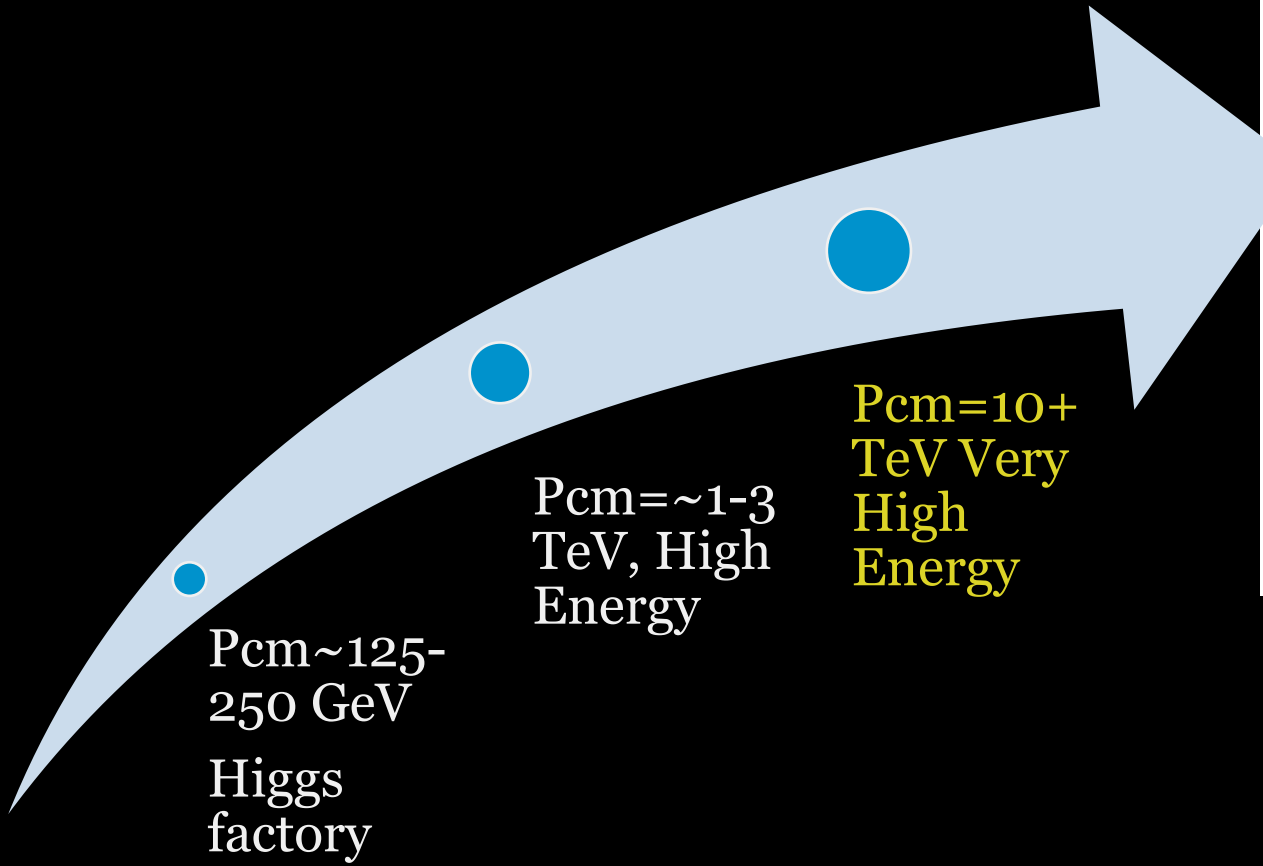


(Technical limited) Timeline



Muon forum report: 2209.01318

10+ TeV Muon Collider: basics

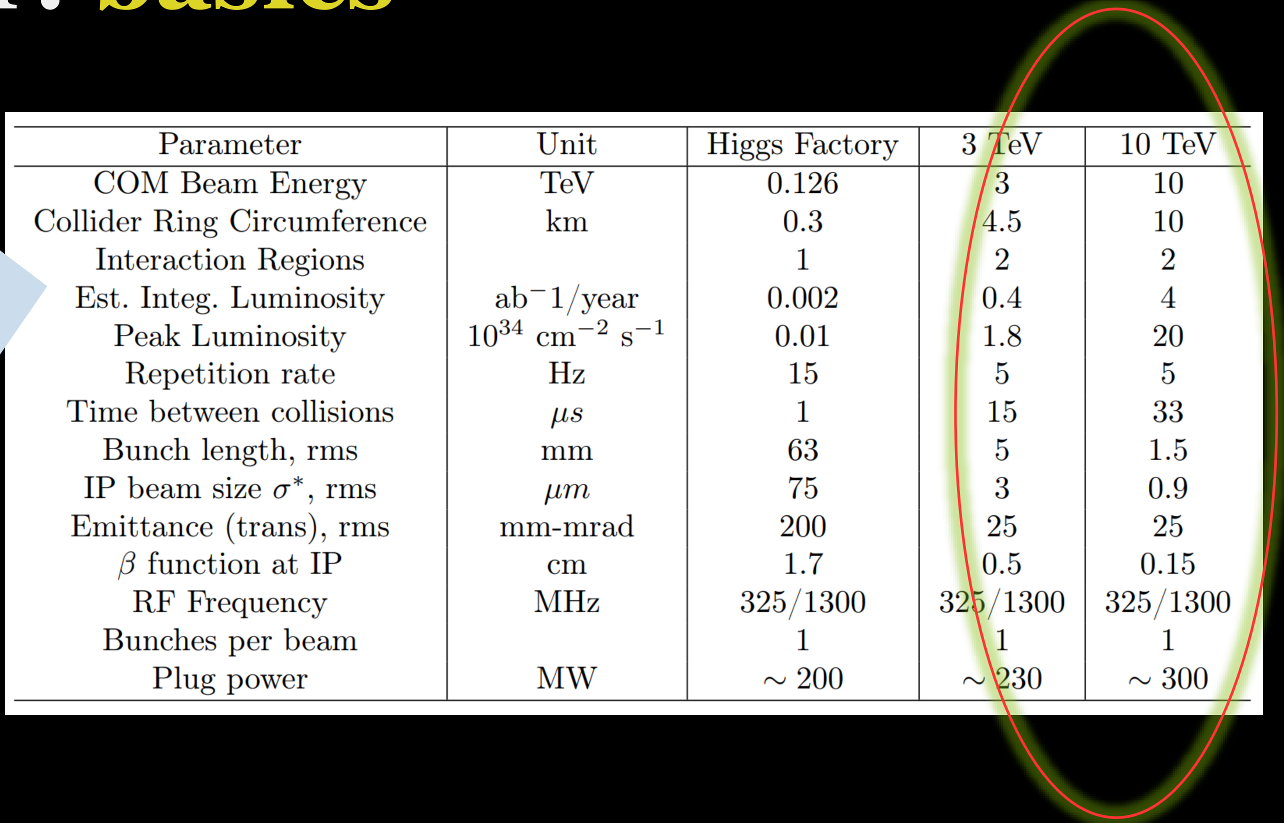


Pcm~125-250 GeV

Higgs factory

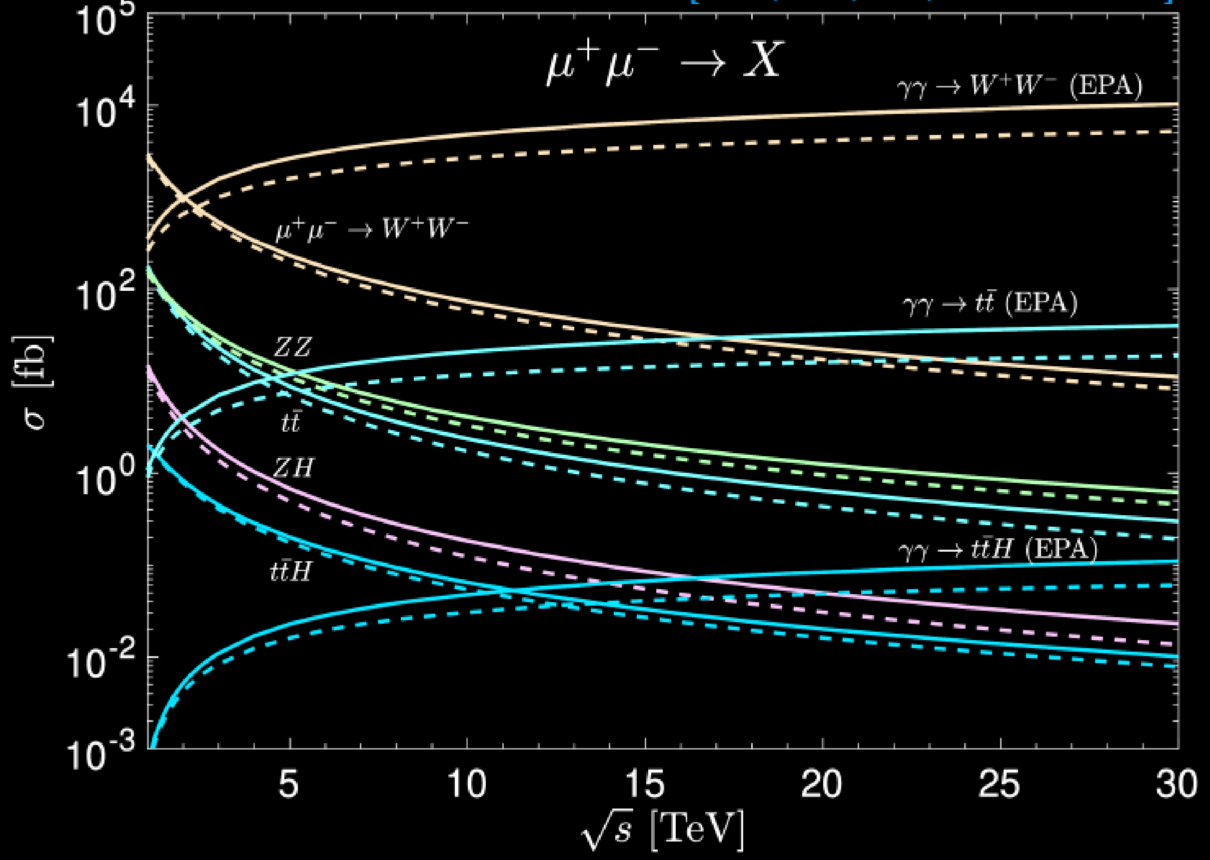
Pcm=~1-3 TeV, High Energy

Pcm=10+ TeV Very High Energy



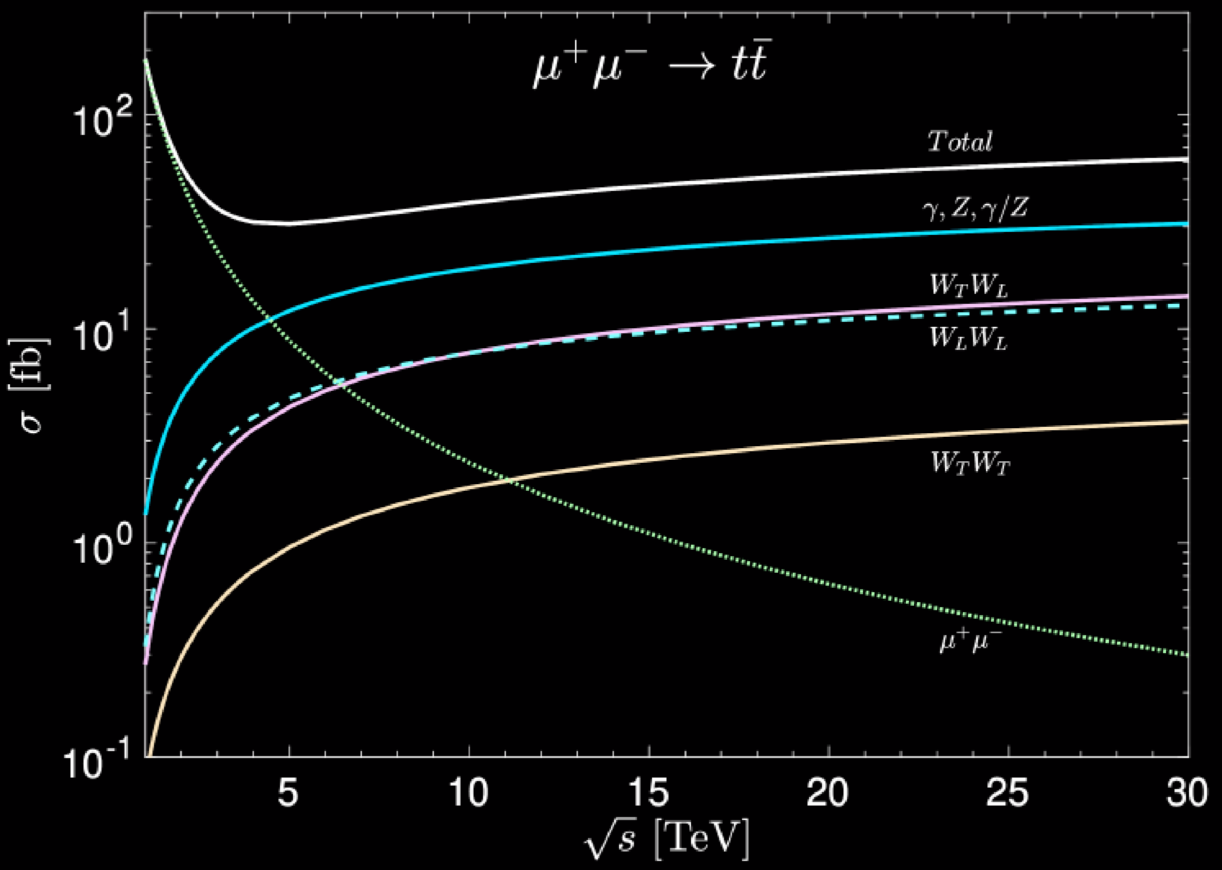
Parameter	Unit	Higgs Factory	3 TeV	10 TeV
COM Beam Energy	TeV	0.126	3	10
Collider Ring Circumference	km	0.3	4.5	10
Interaction Regions		1	2	2
Est. Integ. Luminosity	ab^{-}1/year	0.002	0.4	4
Peak Luminosity	10^{34} cm^{-2} s^{-1}	0.01	1.8	20
Repetition rate	Hz	15	5	5
Time between collisions	μs	1	15	33
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	$\sim$ 200	$\sim$ 230	$\sim$ 300

MuC is also a Vector Boson Machine



[Han, Ma, Xie, 2007.14300]

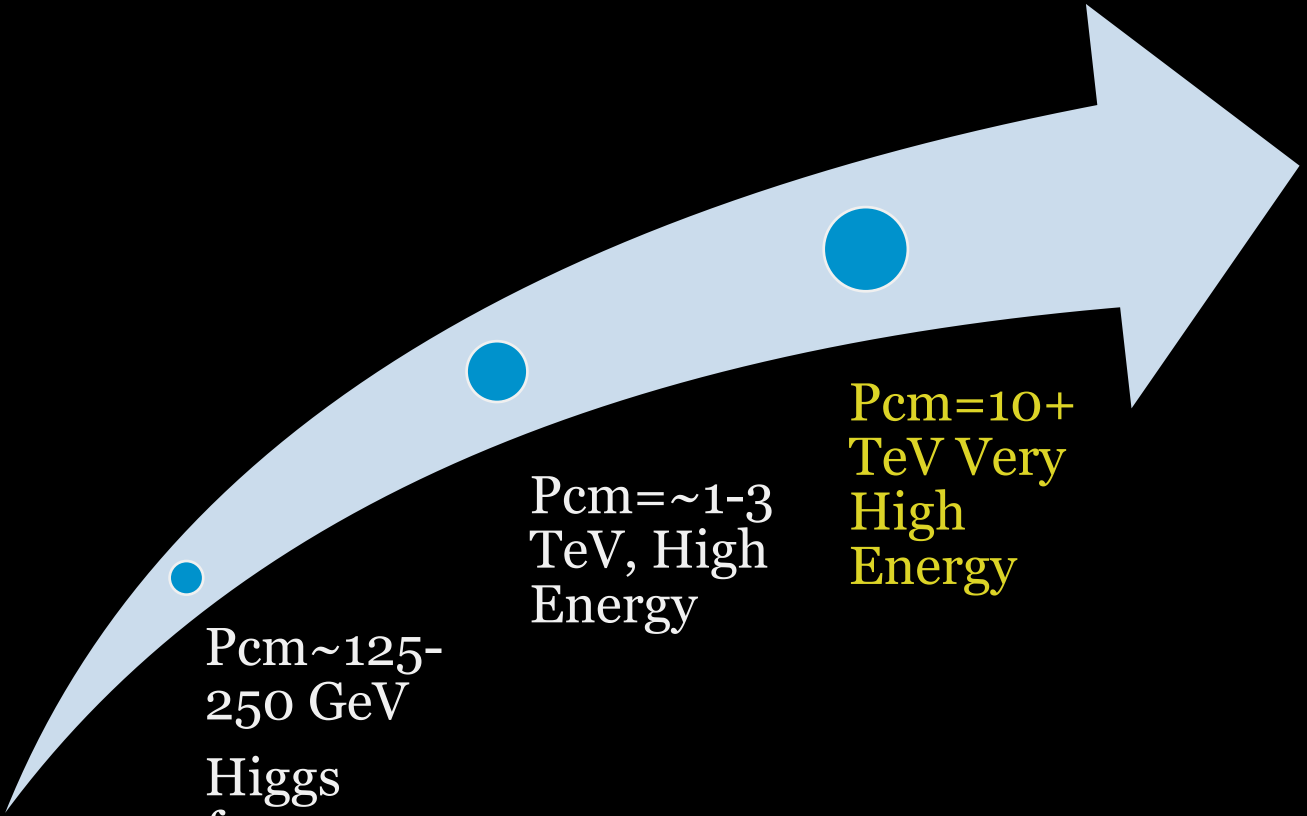
VBF dominates well above threshold due to logarithmic growth with E_{CM}



[Han, Ma, Xie, 2007.14300]

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

The Muon Shot



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Pcm=~1-3 TeV, High Energy

Pcm=10+ TeV Very High Energy

Physics Driver

Pheno Probes

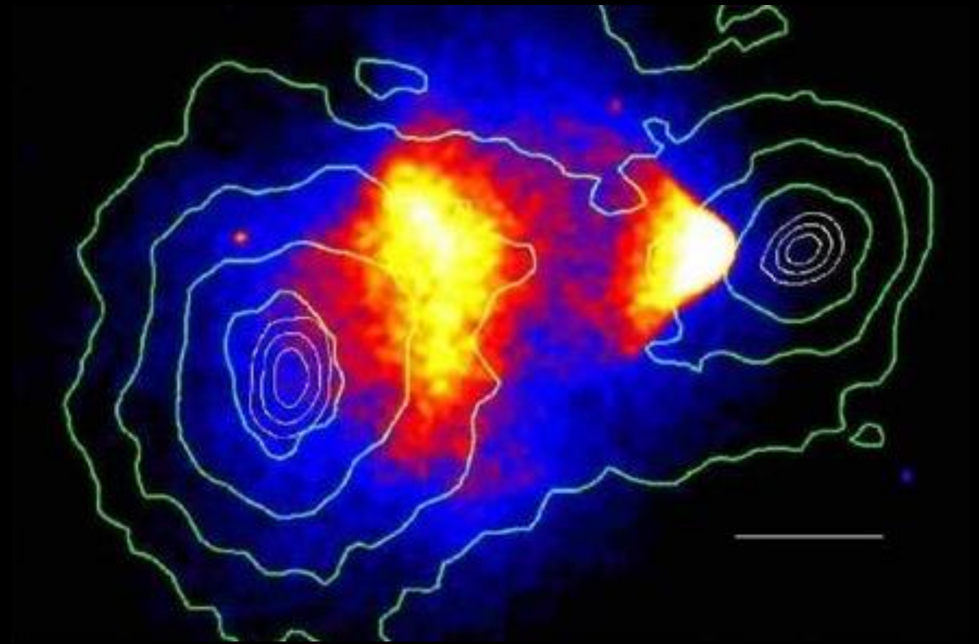
Higgs

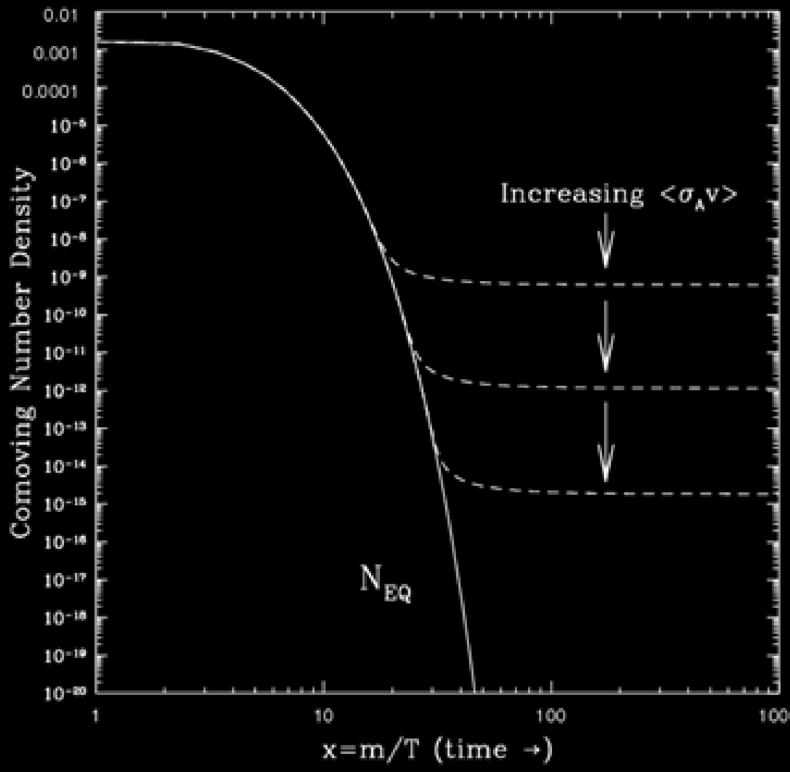
Dark Matter

New Physics

WIMP Dark Matter

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





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

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

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

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

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:

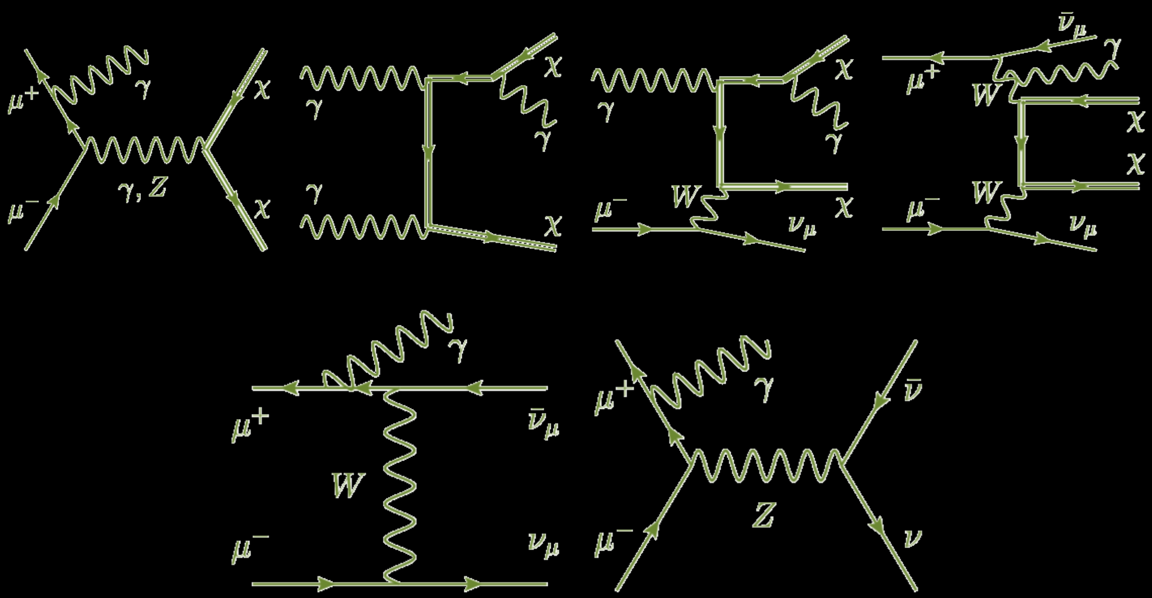
- Exclusive but challenging
- Most useful for Wino and Higgsinos
- Great potential

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

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

Mono-Photon

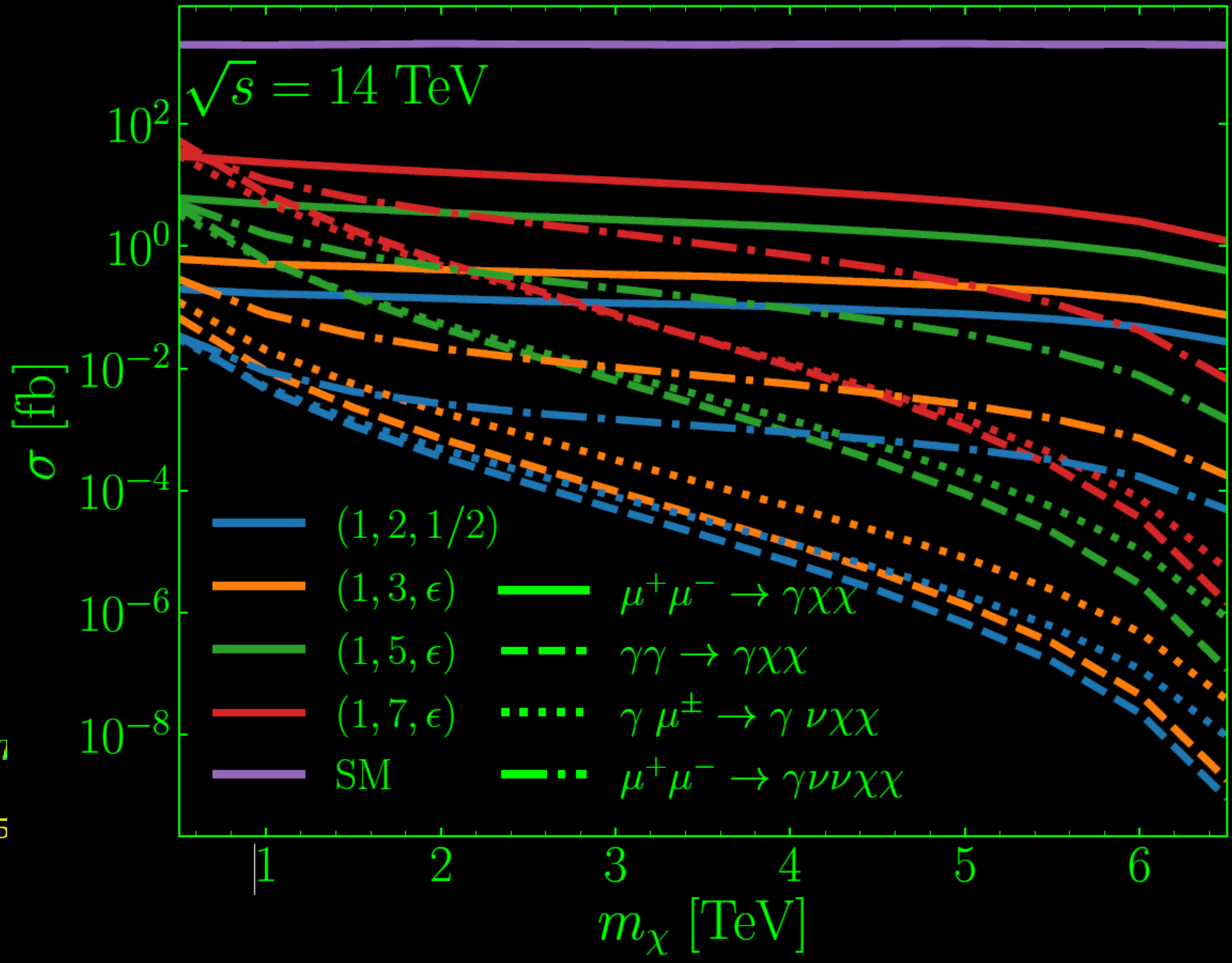
All combinations of components of the EW multiplet are included, so-long as they respect the underlying gauge symmetries



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

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

Rate grows with n-plets as roughly $n^{2\sim3}$ (DY) and $n^{4\sim5}$
Doubletand Triplet very hard to probe

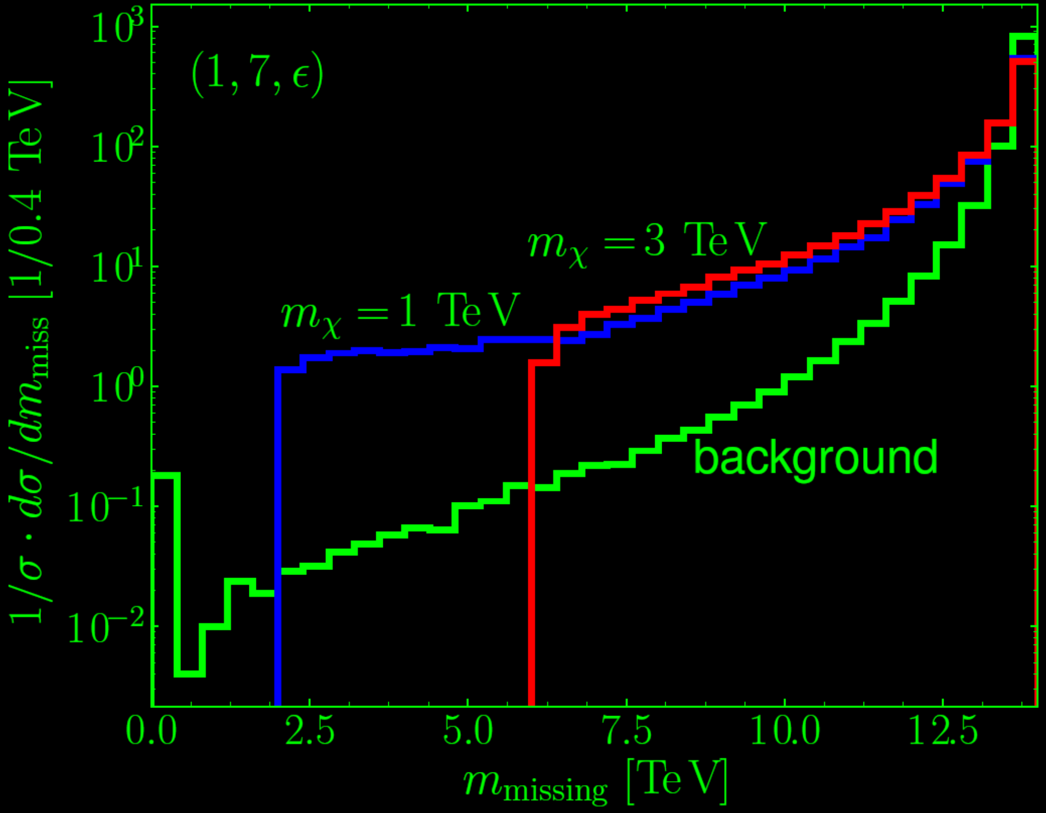


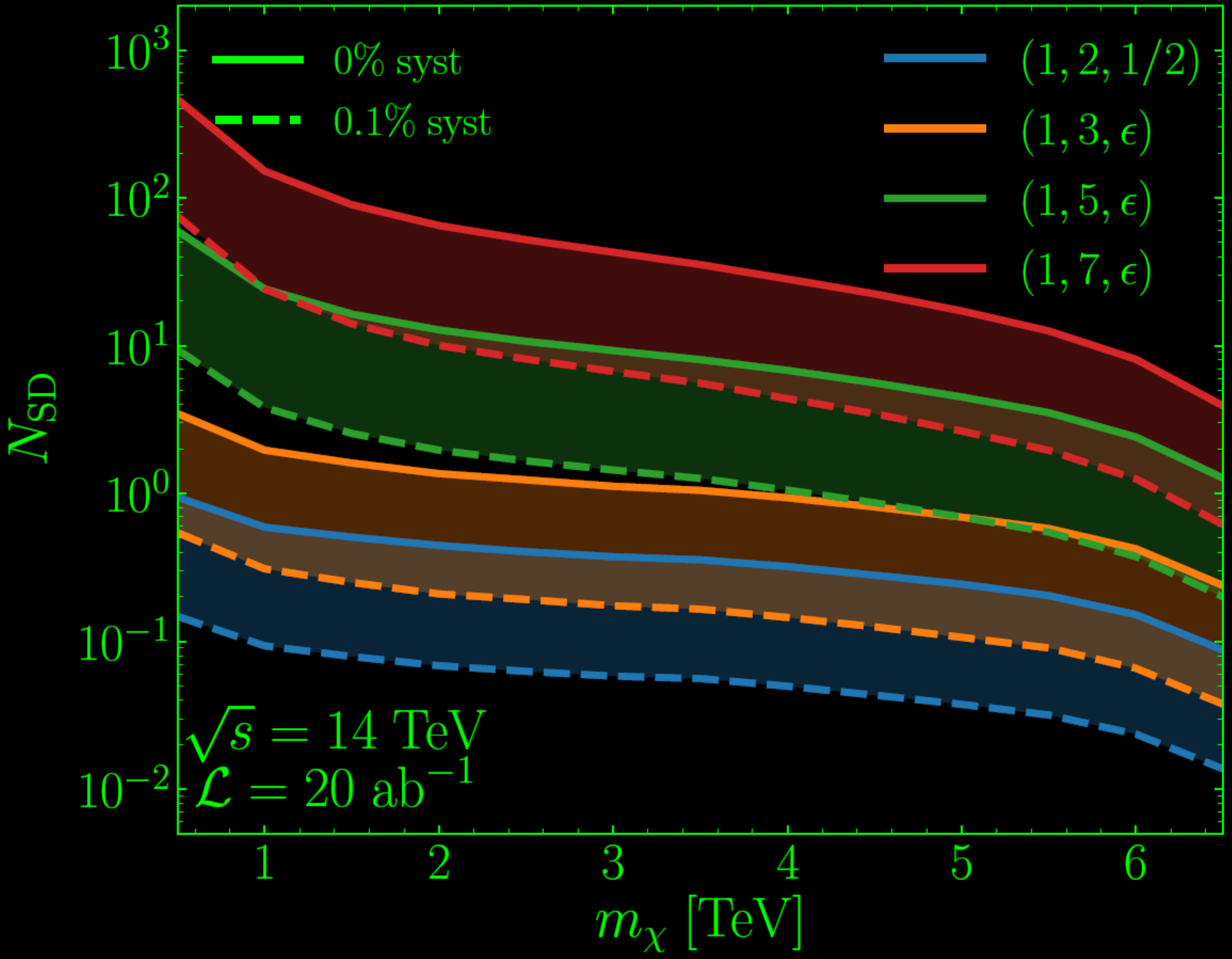
Mono-photon

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

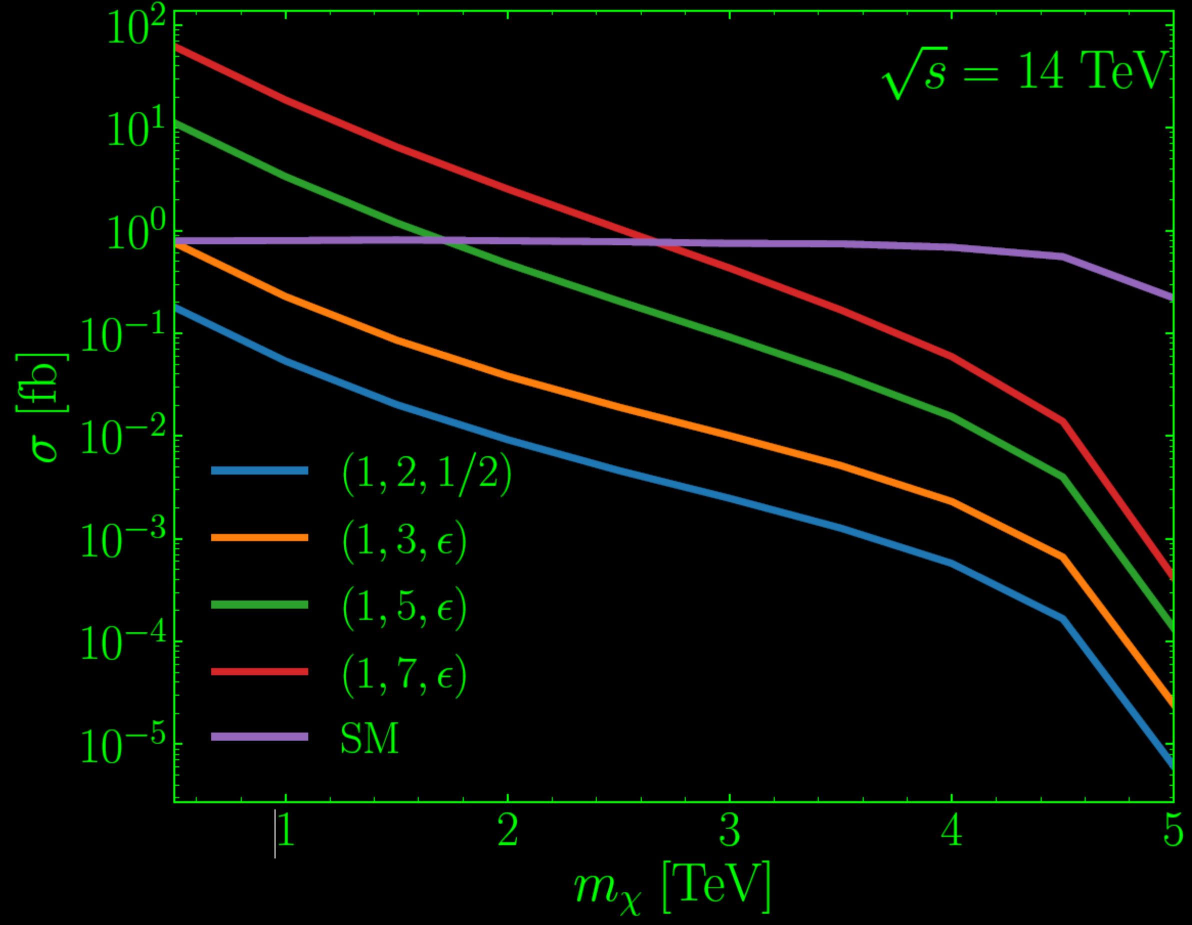




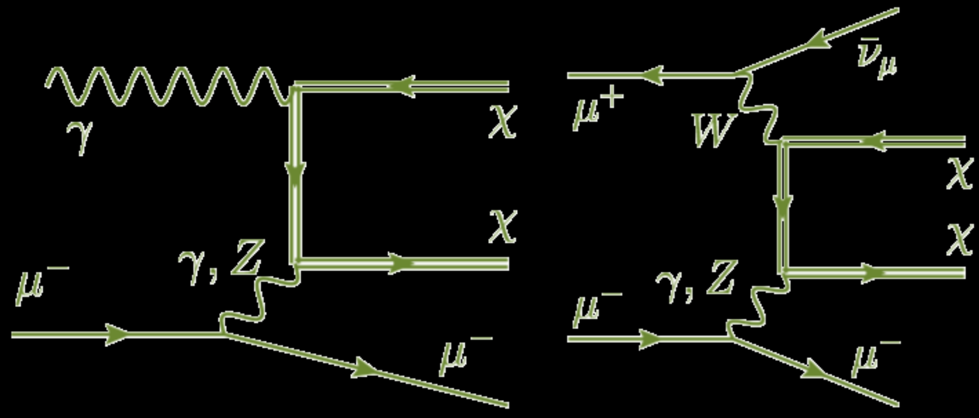
Unique Mono-Muon Channel

Apparent "Charge Violation" channel

(very different from the LHC)



Signature: Energetic mono muon

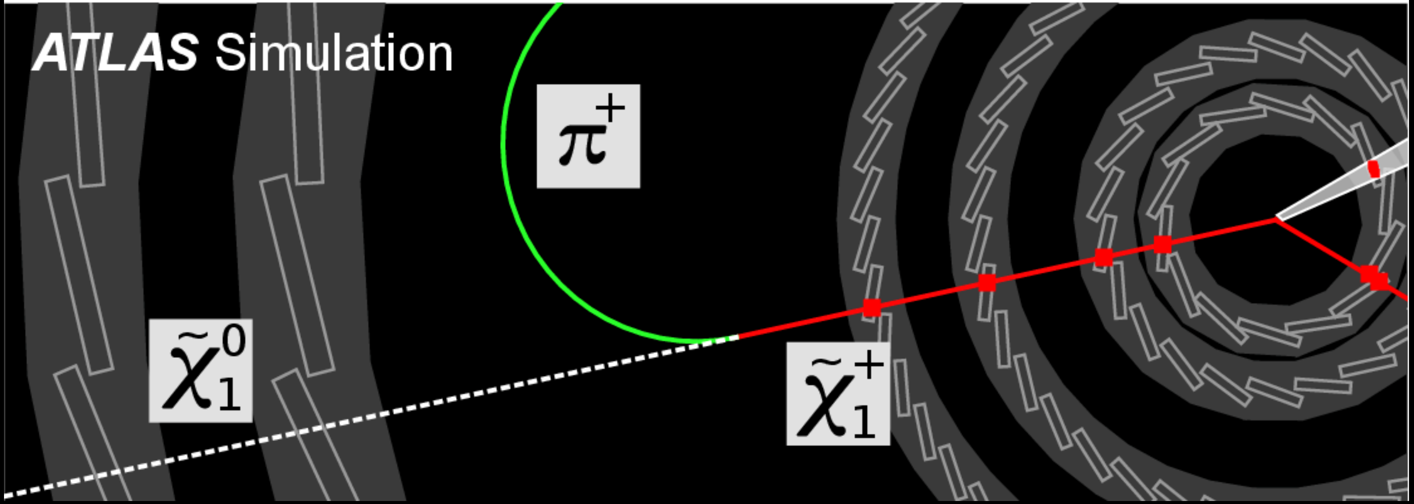


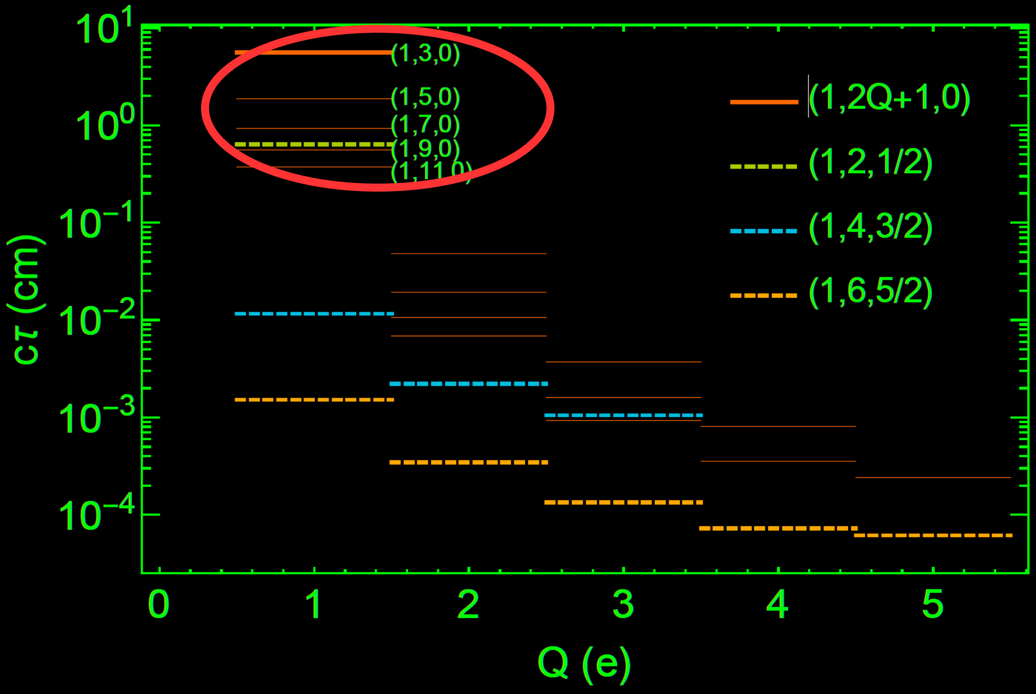
Muon pairs muon + missing mass

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

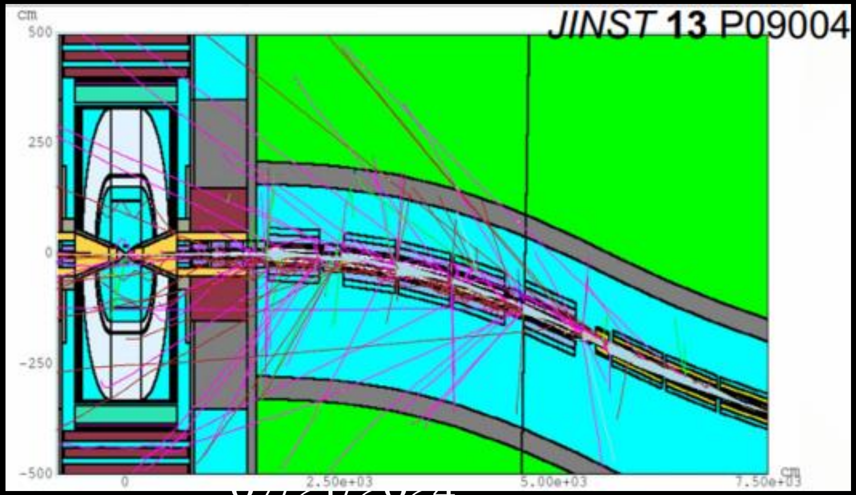
Unique and powerful channel for low-rate channels.

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



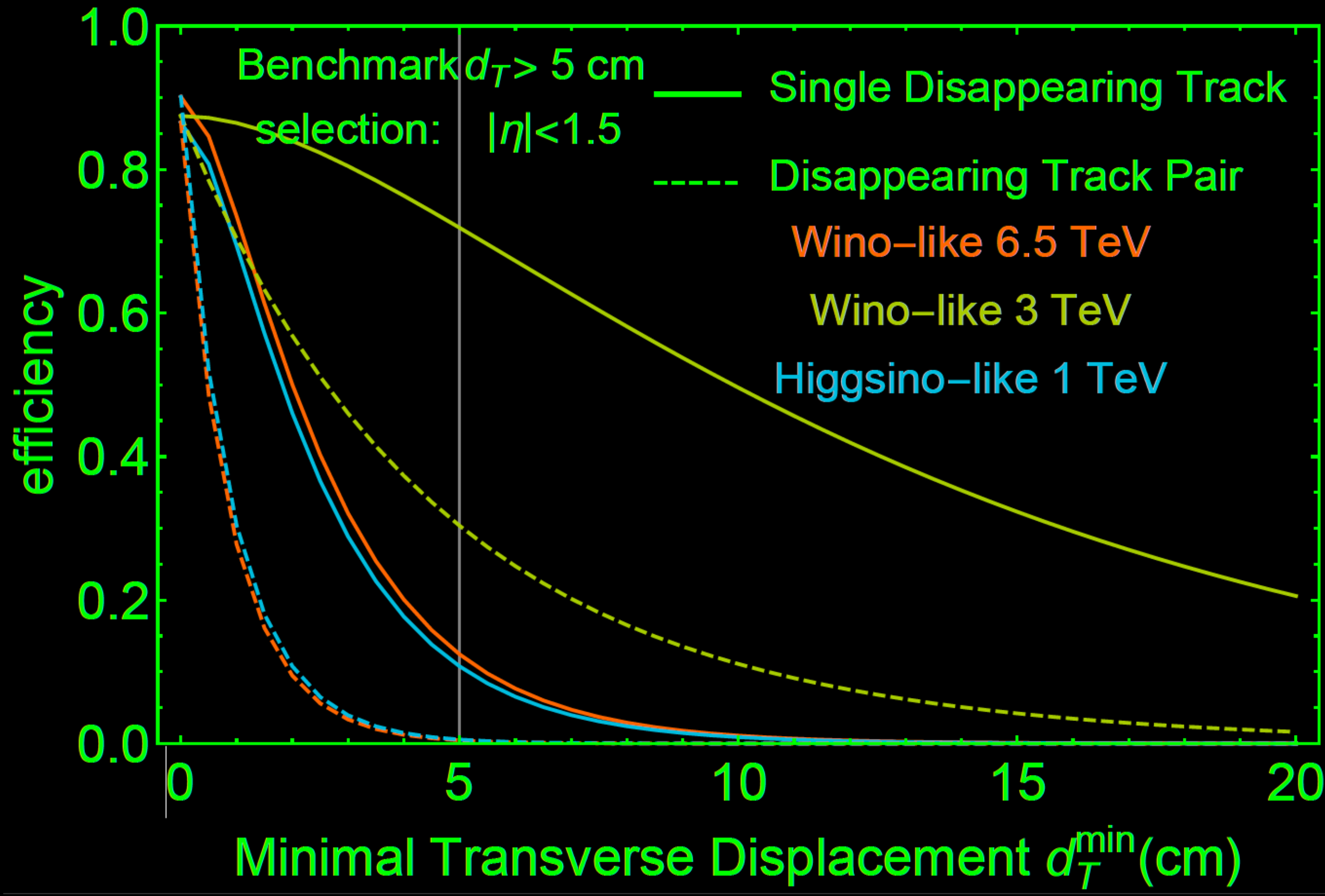
Also see a recent optimization work looking for soft pions, achieving sensivity to Higgsino at 3TeV MuC, Capdevilla, Meloni, Zurita, [2405.08858](https://arxiv.org/abs/2405.08858)

Minimal transverse displacement

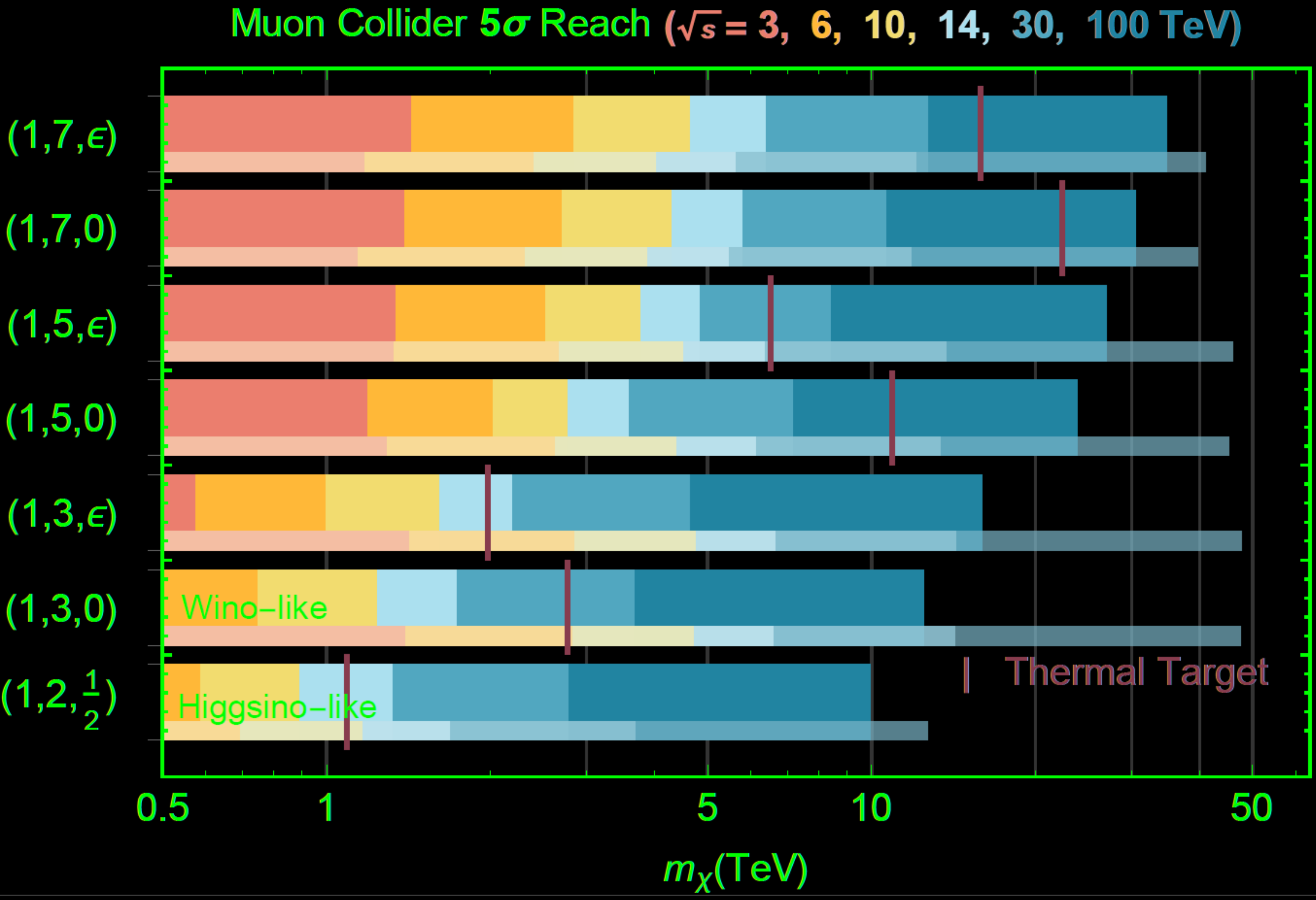
- Only use the central tracks, |eta|<1.5
- Current design have first layer of pixel detector at 3cm (new discussion about 2cm)
- We assume at least two-hits can be measured at 5cm
- Show both pair reconstruction or single reconstruction results
- Requiring 50 signal events for discovery

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

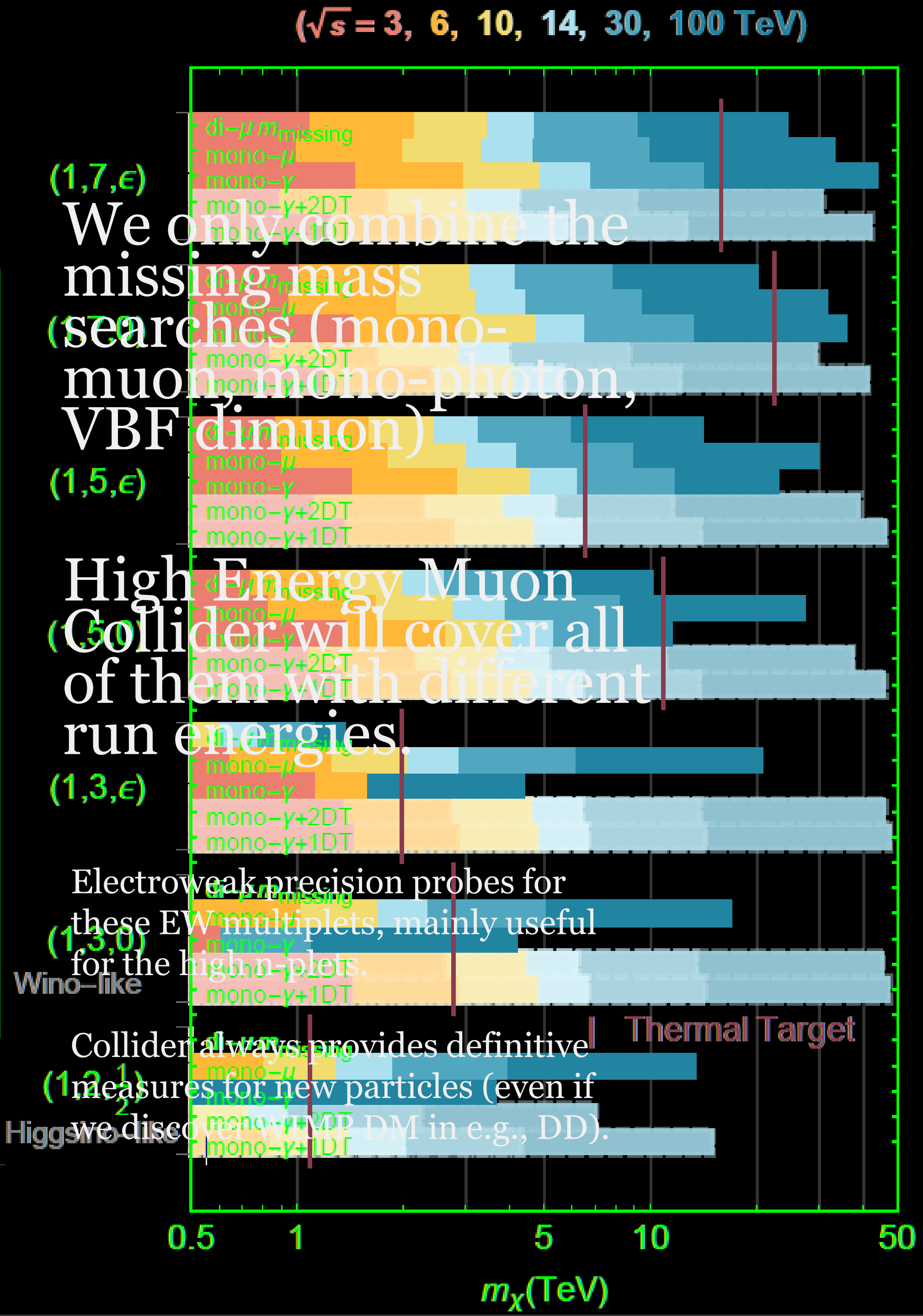
$$\epsilon_\chi(\cos\theta, \gamma, d_T^{\rm min}) = \exp\left(\frac{-d_T^{\rm min}}{\beta_T \gamma c\tau}\right)$$



WIMP discovery Machine



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



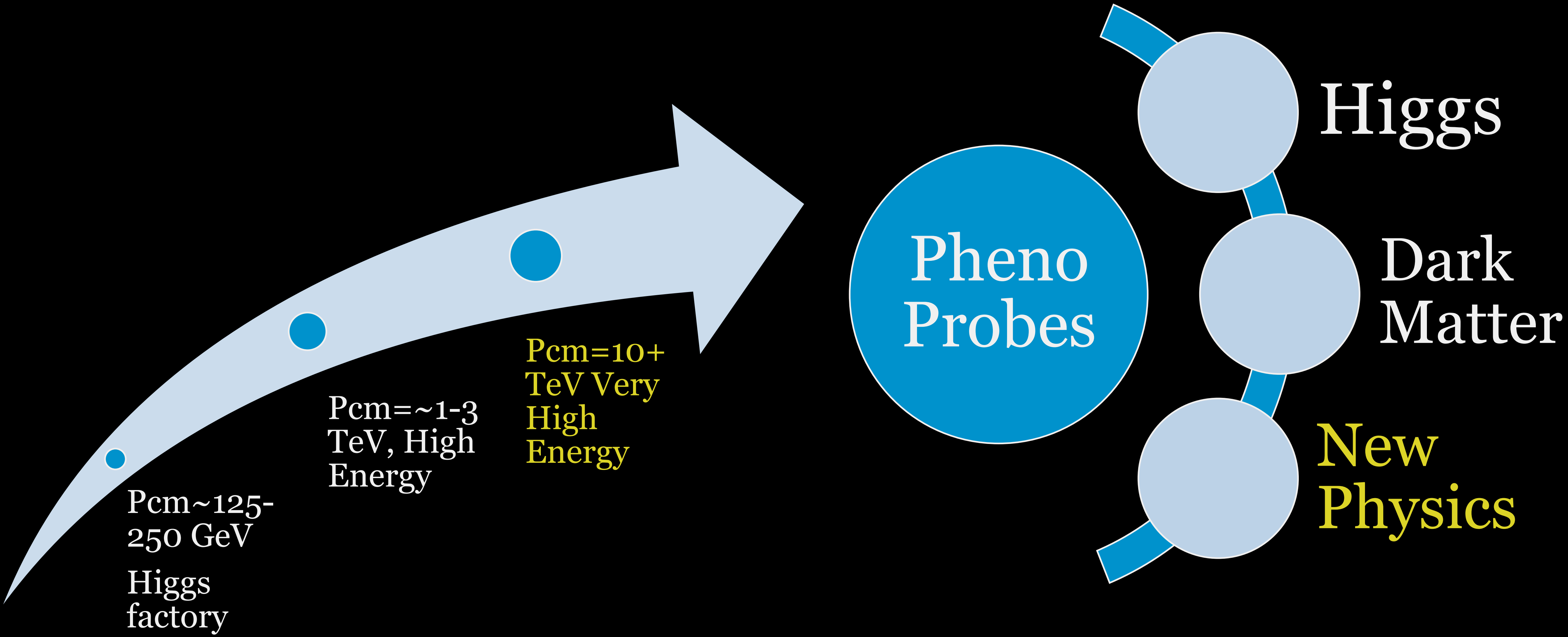
We only combine the missing mass searches (mono-muon, mono-photon, VBF dimuon)

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).

The Muon Shot



Pcm~125-250 GeV

Higgs factory

Pcm=~1-3 TeV, High Energy

Pcm=10+ TeV Very High Energy

Pheno Probes

Physics Driver

Higgs

Dark Matter

New Physics

Neutrino is a puzzling sector

- In SM, neutrino is massless. While the experiments have confirmed its tiny mass <0.1 eV.
- Seesaw mechanism
- We choose to work in a simple scenario. Suppose there is a heavy neutral lepton. We can parametrize its mass m_N and mixing angle with SM neutrino $U_\ell = sin\theta_\ell$.

$$\mathcal{L} = \mathcal{L}_W + \mathcal{L}_Z + \mathcal{L}_H$$

$$\mathcal{L}_W = \frac{gU_l}{\sqrt{2}}\left(W_\mu \bar{l}_L \gamma^\mu N + h.c.\right)$$

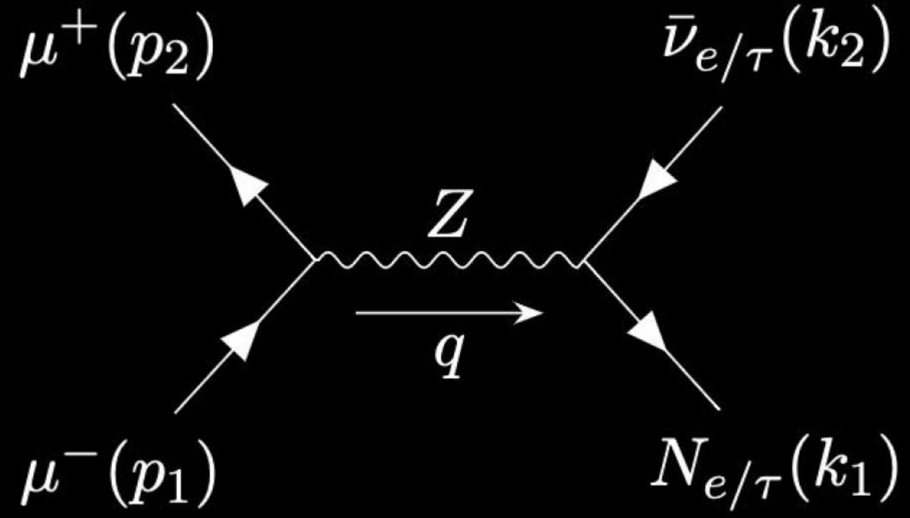
$$\mathcal{L}_Z = -\frac{gU_l}{2\cos\theta_w} Z_\mu \left(\bar{\nu}_L \gamma^\mu N + \bar{N}\gamma^\mu \bar{\nu}_L\right)$$

$$\mathcal{L}_H = -\frac{U_l m_N}{v} h\left(\bar{\nu}_L N + \bar{N}\nu_L\right)$$

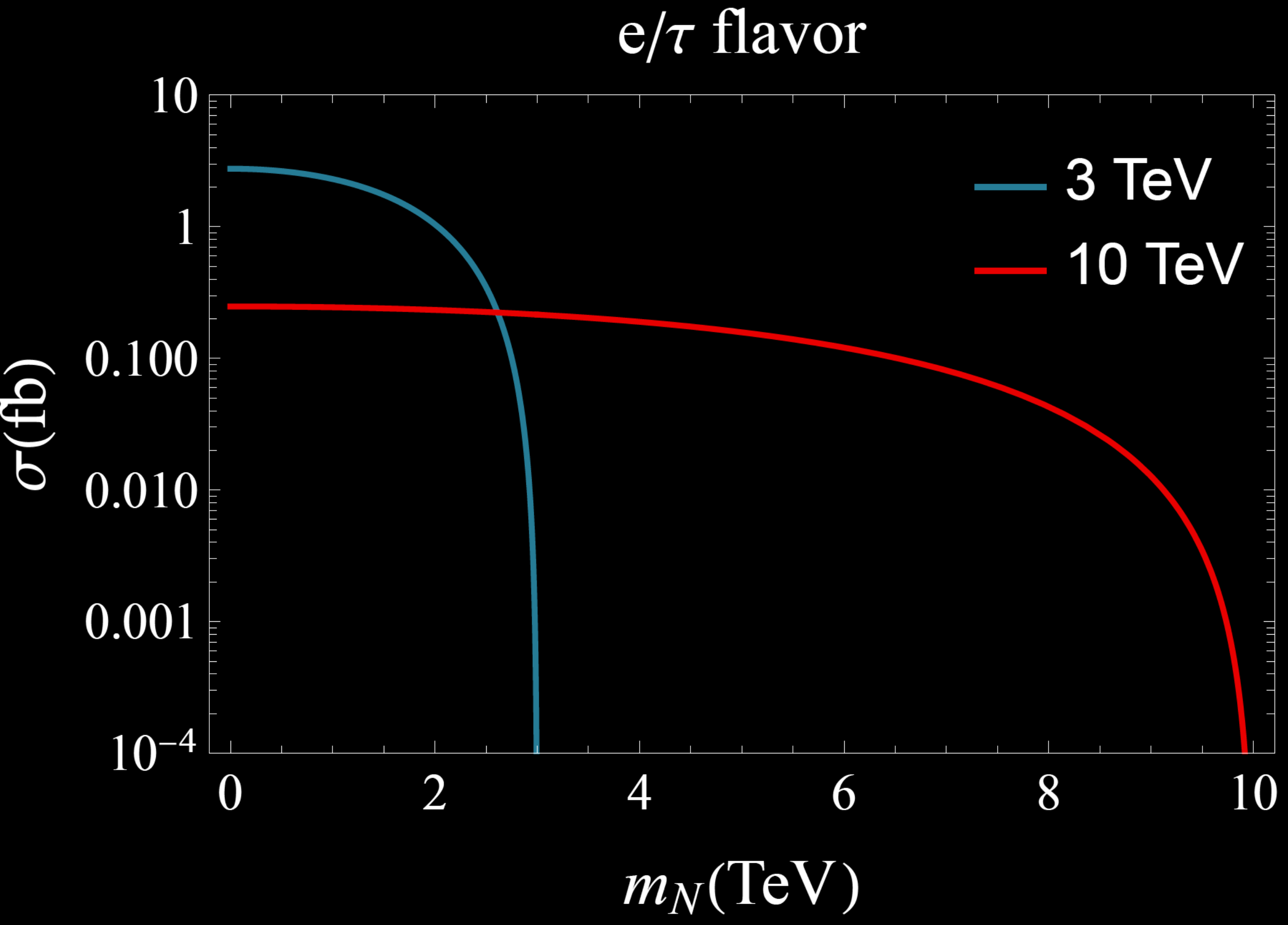
The physics is rich

- Direct Particle Probes:
  - Production
    - Meson decay, heavy lepton decay
    - (On-shell/Off-shell) Gauge/Higgs boson decay
  - Decay
    - Short-lived
    - Long-lived
- Cosmo and astrophysical probe: BBN, CMB, etc
- Indirect constraints: branching ratio of SM particles decays, oscillations, etc.

S-channel production ($e/\ \mu\ /\tau$ flavored)



- 1/s suppressed;
- Flat rate until near the threshold s/2
- $O(fb)$ cross section;

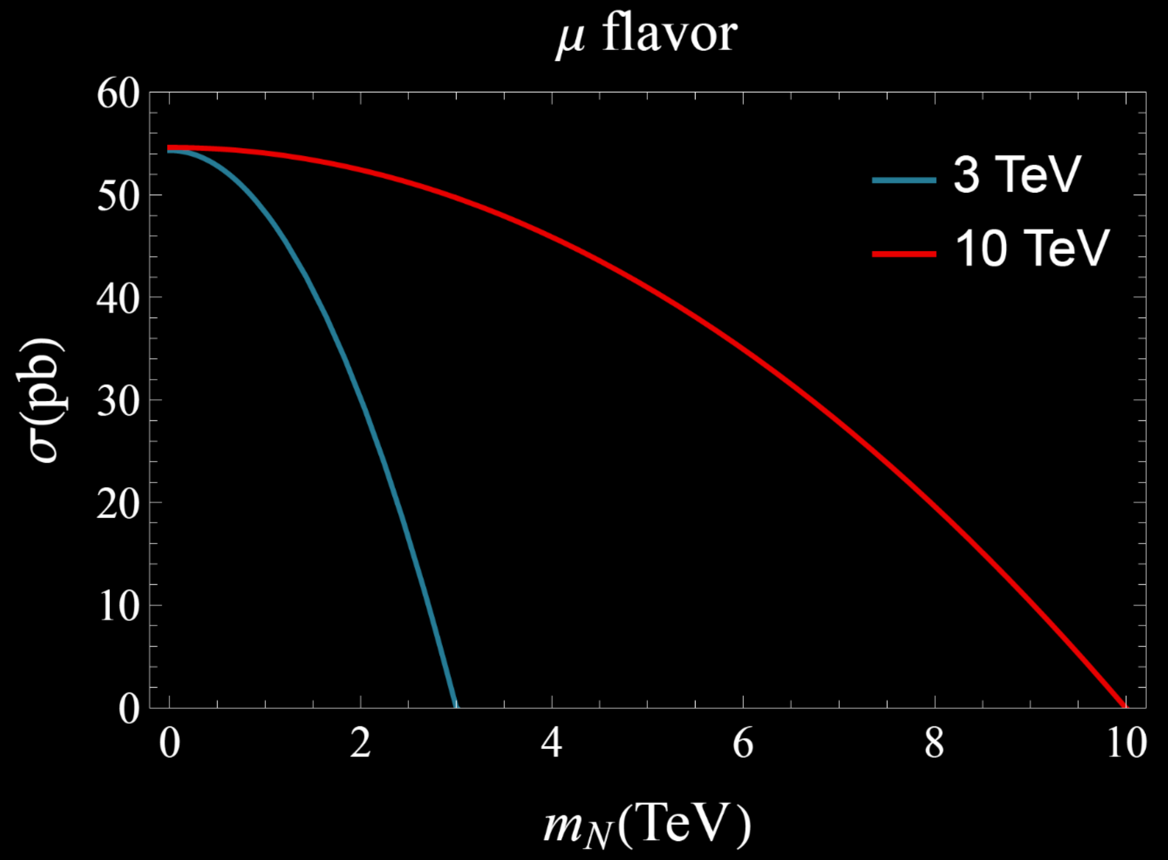


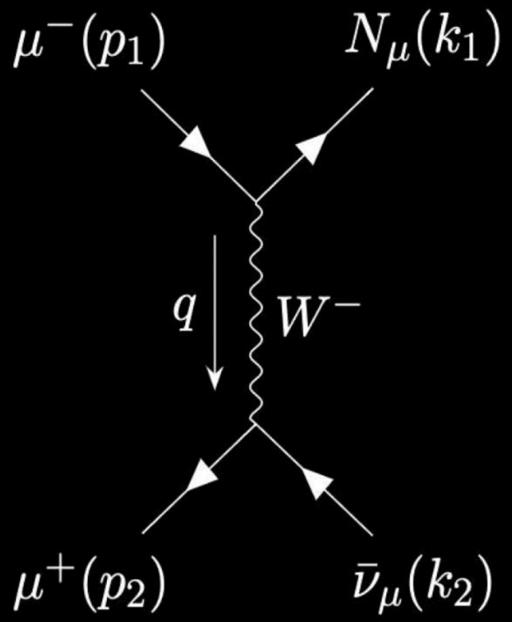
Peiran Li, Kun-Feng Lyu, ZL, 2301.07117

Muon Flavor

Production dominated by t-channel

$$\mu^+ + \mu^- \to N_\mu + \bar{\nu}_\mu$$





Type	Signal process	$\sigma/\lvert U_\mu\rvert^2$ (w. conj. channel) $m_N = 1$ TeV
t-channel	$\mu^+\mu^- \longrightarrow N_\mu\bar{\nu}_\mu$	20.28 pb
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- N_\mu\bar{\nu}_\mu$	~ 1 pb
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu N_\mu\bar{\nu}_\mu$	~ 0.1 pb

Decay selection $m_N > O(100)$ GeV

- $\boxed{N_\mu \to W^+ + \mu^-}$
- $N_\mu \to Z + \nu_\mu$
- $N_\mu \to H + \nu_\mu$

$$\boxed{N_\mu \to W^+ + \mu^-, \qquad W \to jj}$$

$$\mu^+ + \mu^- \to N_\mu + \bar{\nu}_\mu \to \boxed{jj + \mu^- + \bar{\nu}_\mu}$$

The dijets almost come from onshell W/Z boson.

We focus on the final states of W and μ and reconstruct its invariant mass distribution.

Including the charge conjugation process

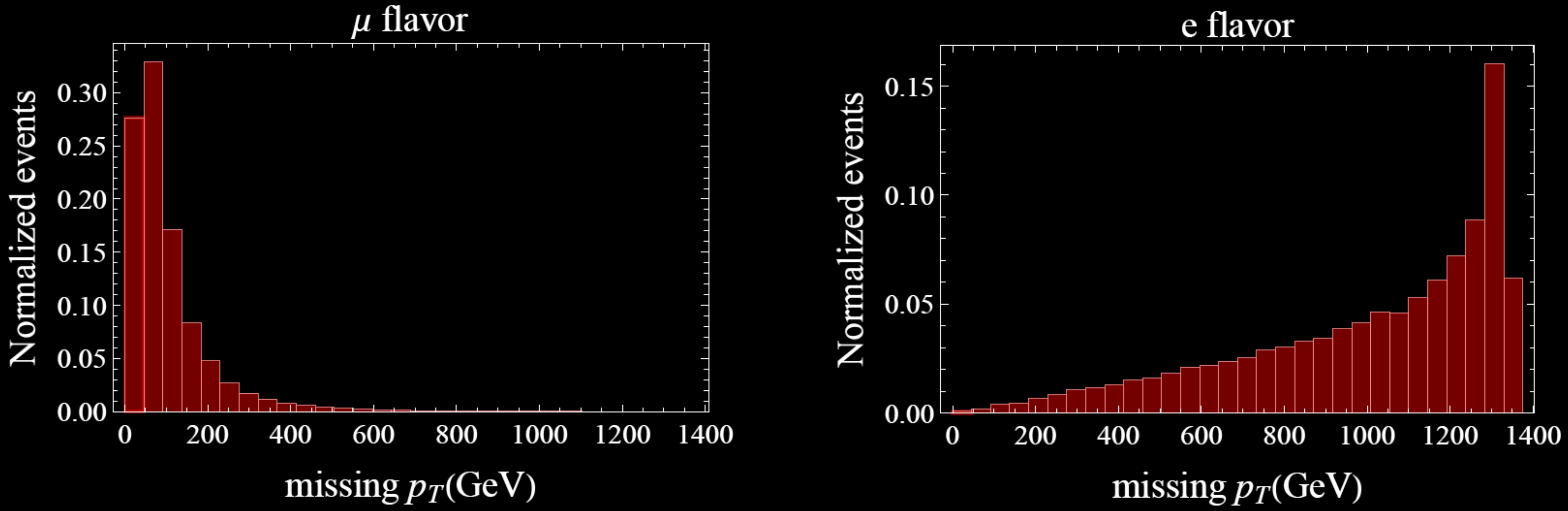
10TeV Background

Type	Background process	σ (w. conj. channel)	Pre-selection cut (PSC)
t-channel	$\mu^+\mu^- \longrightarrow W^+\mu^-\bar{\nu}_\mu$	0.214 pb	PSC
t-channel	$\mu^+\mu^- \longrightarrow Z\mu^+\mu^-$	0.464 pb	PSC & missing μ^+
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^-W^+\mu^-\bar{\nu}_\mu$	0.401 pb	PSC & missing $\mu^+\mu^-$
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu W^+\mu^-\bar{\nu}_\mu$	0.0686 pb	PSC

- Using EVA in MadGraph, especially photon PDF
  (EVA: Effective Vector-Boson Approximation)

- Including Z boson: Dijets can come from either W or Z boson.

Kinematics


μ flavor
Normalized events
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
200
400
600
800
1000
1200
1400
missing p_T(GeV)
e flavor
Normalized events
0.00
0.05
0.10
0.15
0
200
400
600
800
1000
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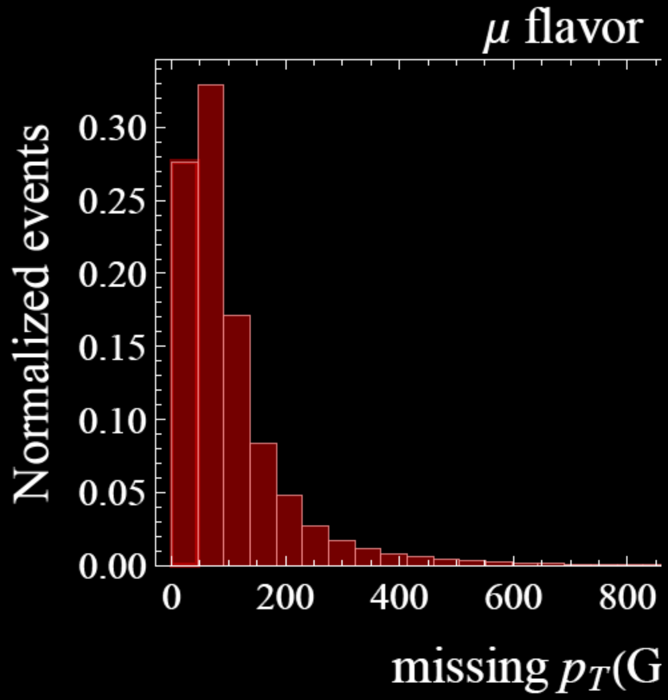
Kinematics


μ flavor
Normalized events
0.00
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0.10
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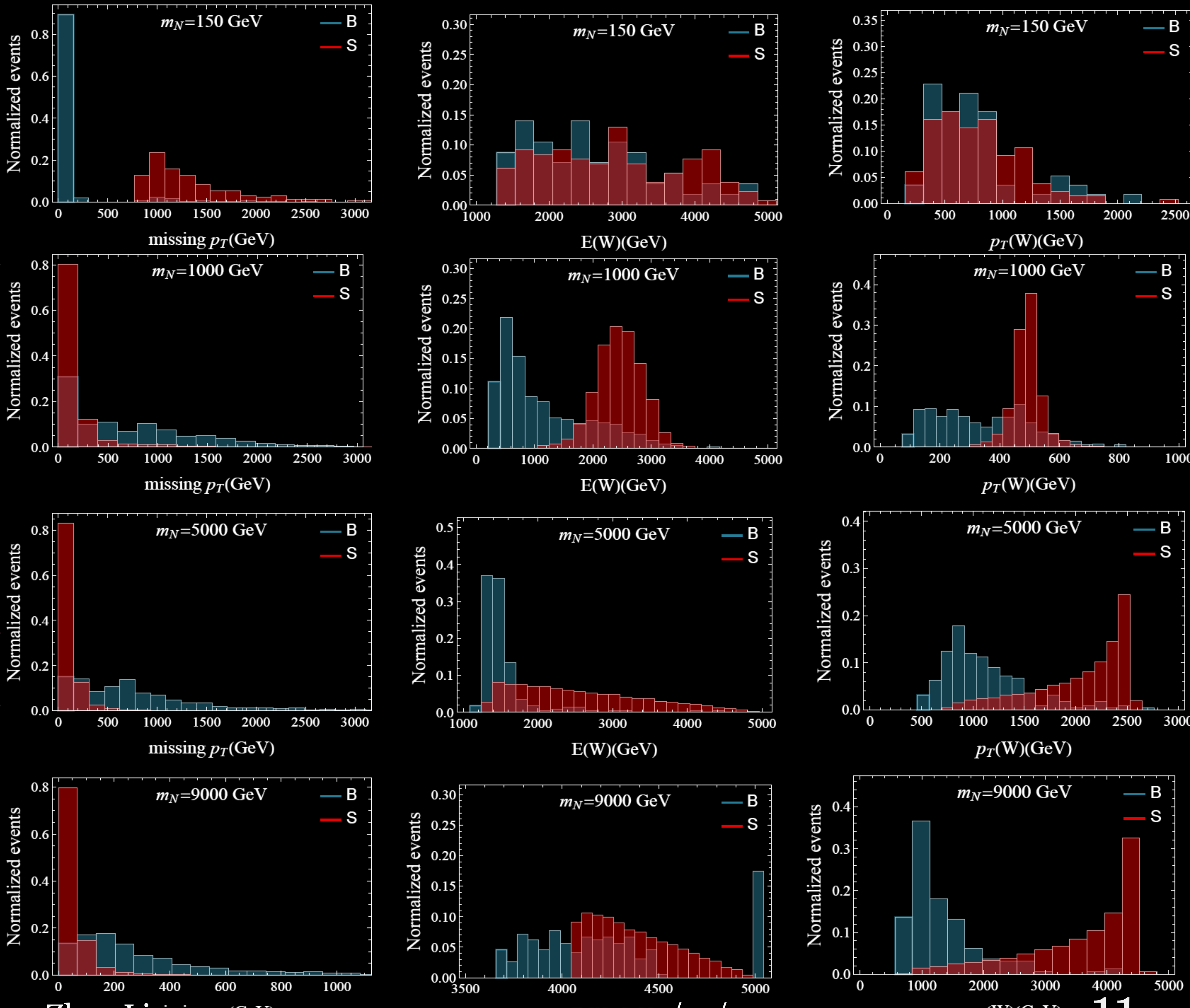
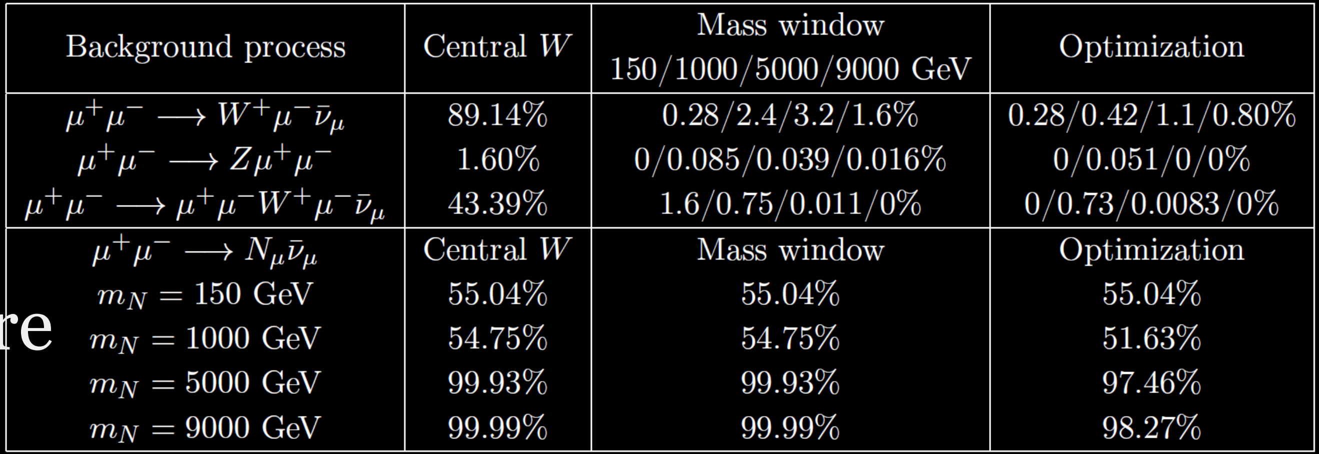

m_N=150 GeV
m_N=1000 GeV
m_N=5000 GeV
m_N=9000 GeV
B
S
Normalized events
missing p_T(GeV)
E(W)(GeV)
p_T(W)(GeV)

Cutflow Analysis

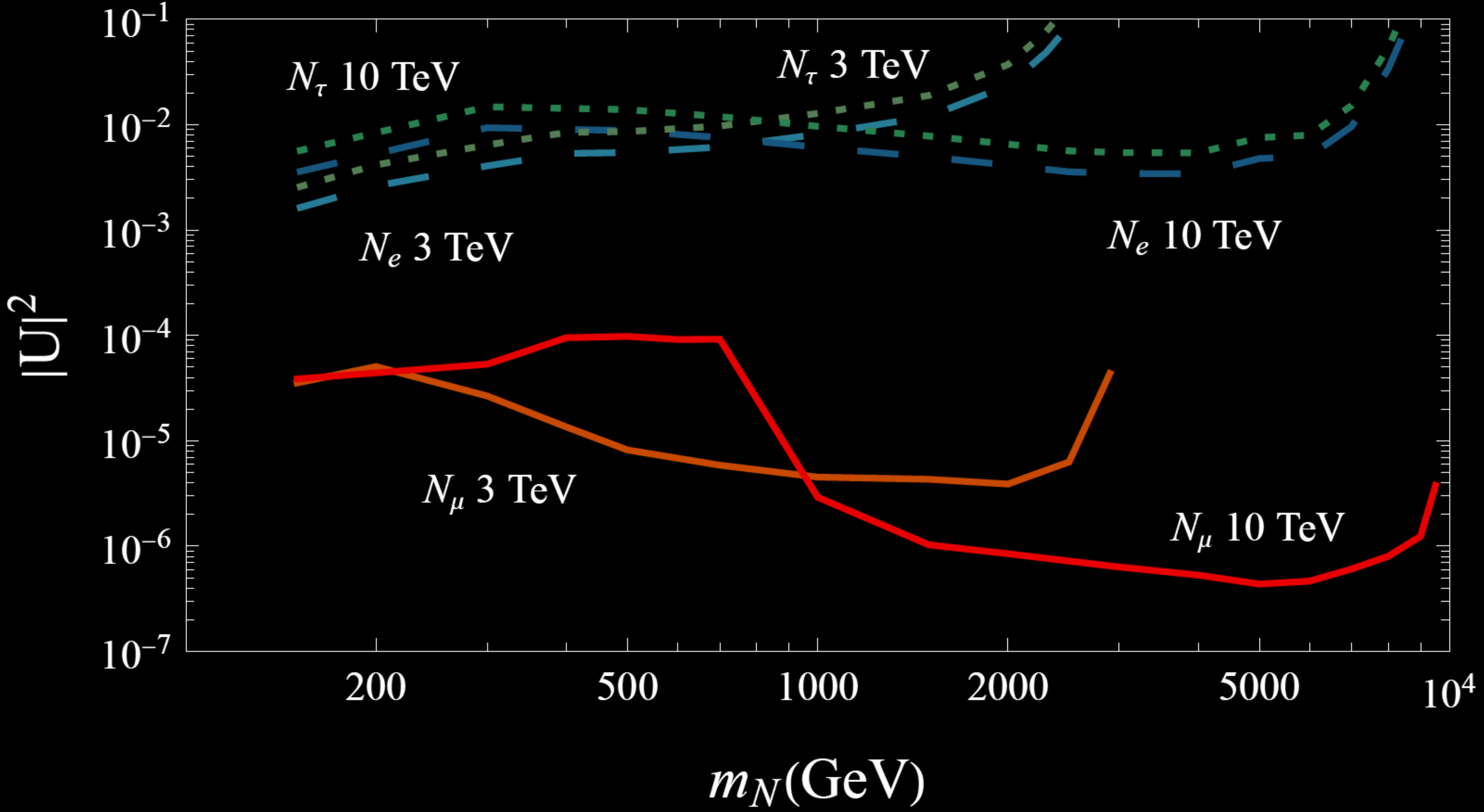
$$\mu^+ + \mu^- \;\rightarrow\; N_\mu + \bar{\nu}_\mu \;\rightarrow\; jj + \mu^- + \bar{\nu}_\mu$$

- Pre-selection: require single visible charged lepton
  - $|\eta(\mu)| < 2.5$ and $p_T(\mu) > 20$ GeV
- Central hadronic W selection: require visible on-shell W boson
  - $|\eta(W)| < 2.5$ and $p_T(W) > 20$ GeV
- Mass window: reconstructed mass $m_{W\mu}$ within $m_N \pm 5\% m_N$
- Optimization cuts:
  - Customized cut on missing p_T, $E(W)$, $p_T(W)$ for each m_N benchmark



Background process	Central W	Mass window 150/1000/5000/9000 GeV	Optimization
$\mu^+\mu^- \longrightarrow W^+\mu^-\bar{\nu}_\mu$	89.14%	0.28/2.4/3.2/1.6%	0.28/0.42/1.1/0.80%
$\mu^+\mu^- \longrightarrow Z\mu^+\mu^-$	1.60%	0/0.085/0.039/0.016%	0/0.051/0/0%
$\mu^+\mu^- \longrightarrow \mu^+\mu^-W^+\mu^-\bar{\nu}_\mu$	43.39%	1.6/0.75/0.011/0%	0/0.73/0.0083/0%
$\mu^+\mu^- \longrightarrow N_\mu\bar{\nu}_\mu$	Central W	Mass window	Optimization
$m_N = 150$ GeV	55.04%	55.04%	55.04%
$m_N = 1000$ GeV	54.75%	54.75%	51.63%
$m_N = 5000$ GeV	99.93%	99.93%	97.46%
$m_N = 9000$ GeV	99.99%	99.99%	98.27%

Projected sensitivity



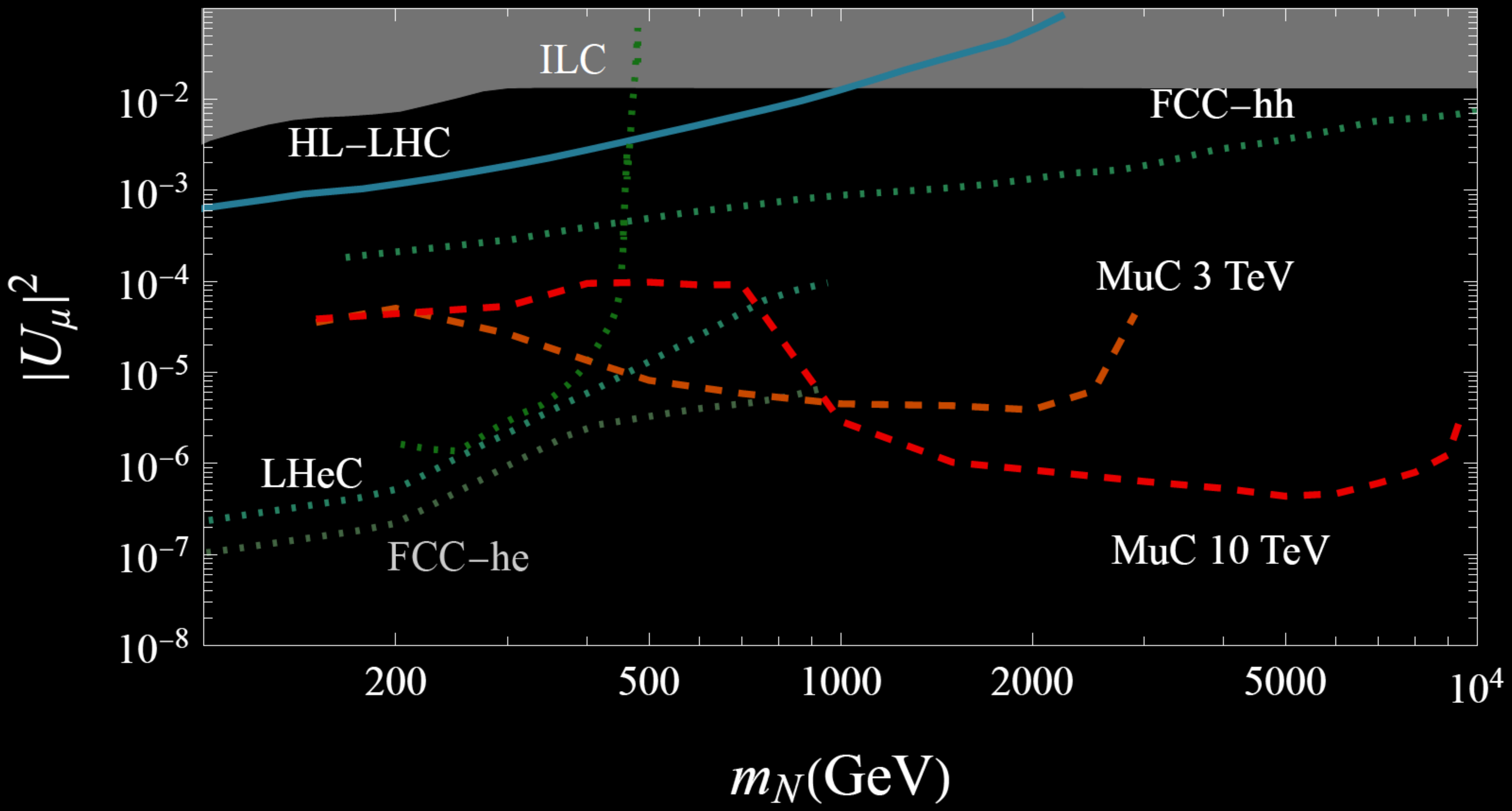
Sensitivity to e and τ flavor is moderate

Muon Collider features the strong direct probe of the μ flavored HNL

10 TeV muon collider can probe the $|U_\mu|^2$ to a few 10^{-7} for TeV scale HNLs.

The VBF background increases for high energy muon colliders and renders the 3 TeV muon collider competitive in sub TeV scale.

Projections w. others



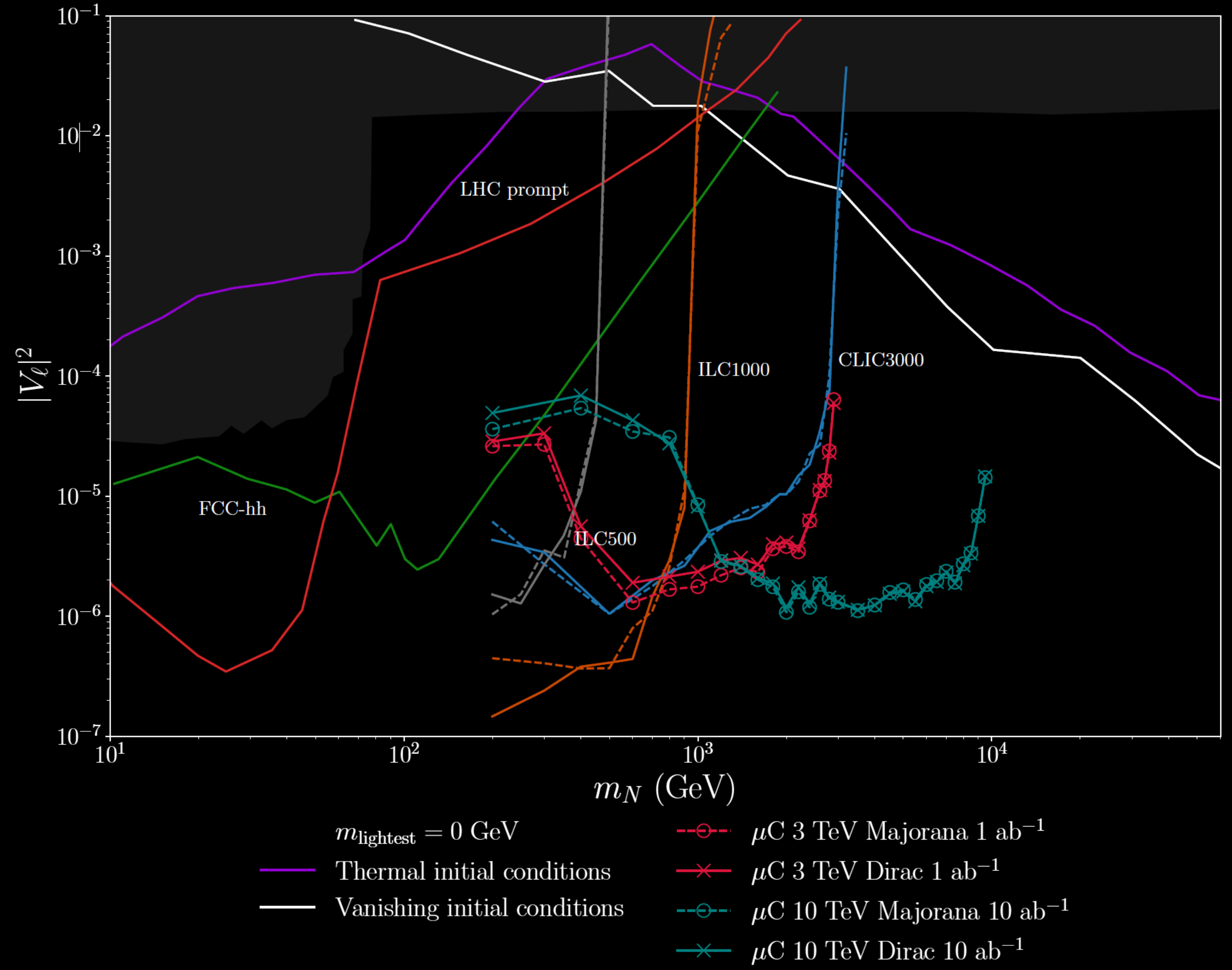
Focusing on the muon-flavored case:

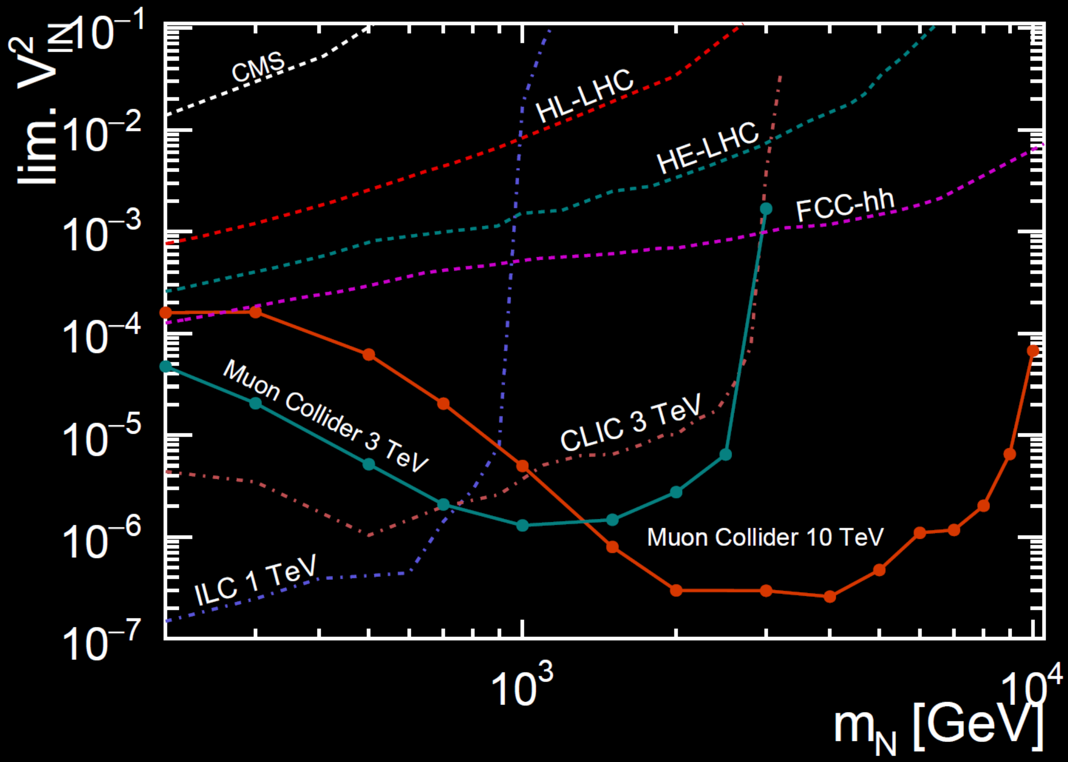
LHC and EWPD probe $O(10^{-3})$

Muon Collider has unique roles in probing the parameter space (thanks to the t-channel enhancement).

In the inverse seesaw setup, $|U_\ell|^2 = \left(\frac{\lambda v}{m_N}\right)^2$, and hence a unitarity limit exist on the upper right corner, overlapping very little with the region of our interests.

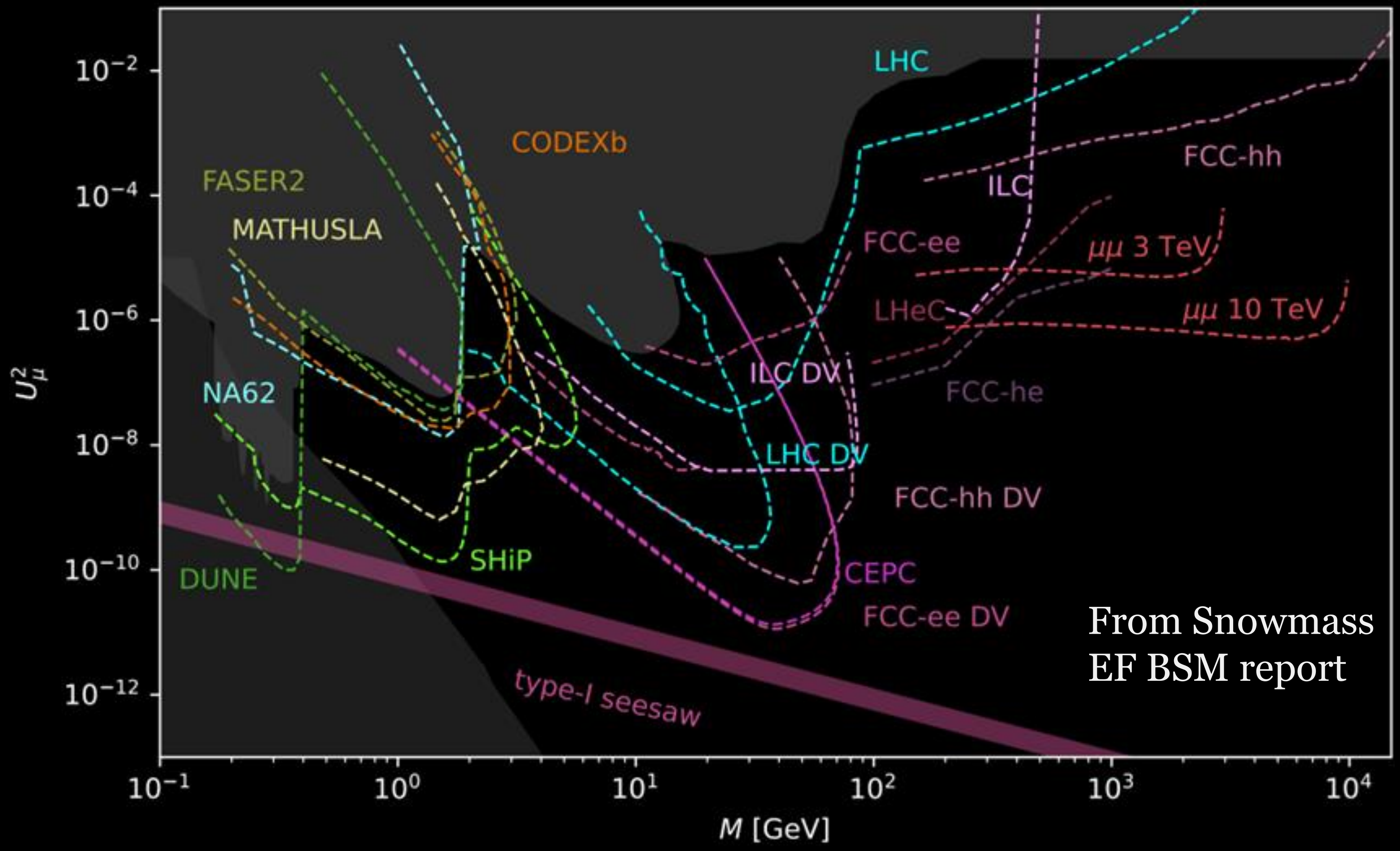
BDT-based projections





T.H. Kwok, L. Li, T. Liu and A. Rock, arXiv:2301.05177
K. Mekała, J. Reuter and A.F. Zarnecki, arXiv:2301.02602

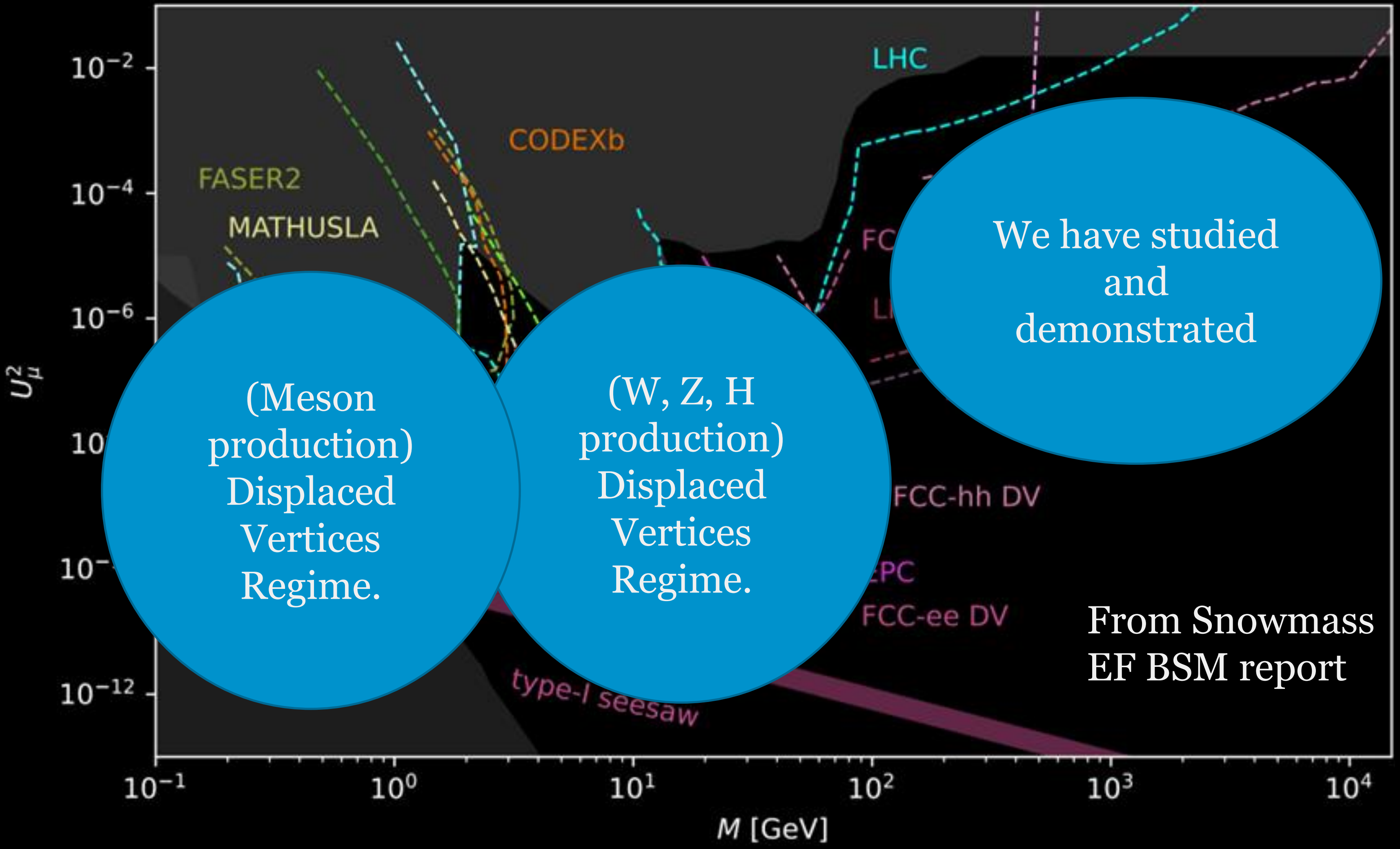
New studies for other regions



From Snowmass
EF BSM report

The bottom left “type-I seesaw” represents the most pessimistic seesaw benchmarks. In general multi-generation seesaw, the motivated parameter regions spans over the space above that line, very much like the inverse seesaw spectra.

New studies for other regions



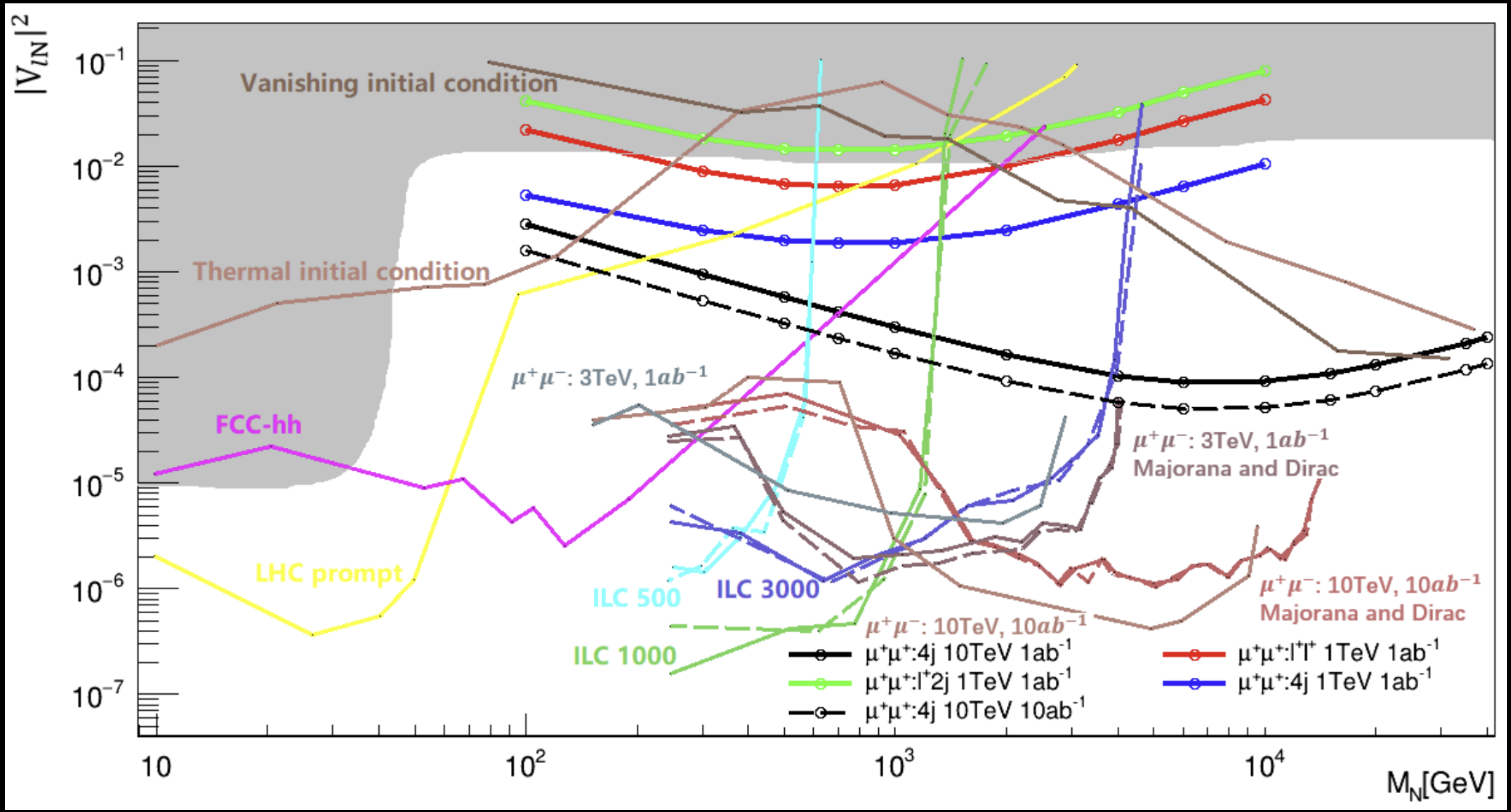
(Meson production) Displaced Vertices Regime.

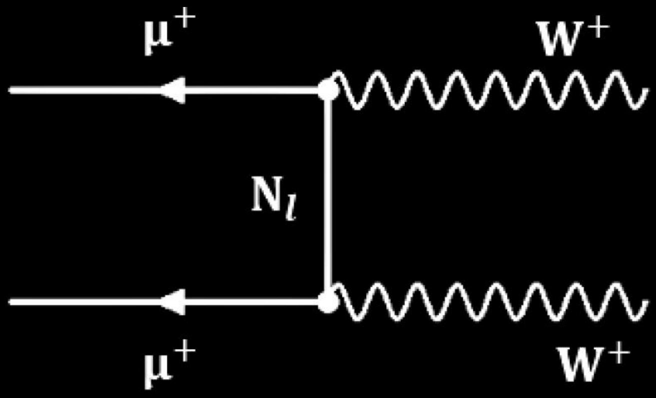
(W, Z, H production) Displaced Vertices Regime.

We have studied and demonstrated

From Snowmass EF BSM report

Same-sign muon collider



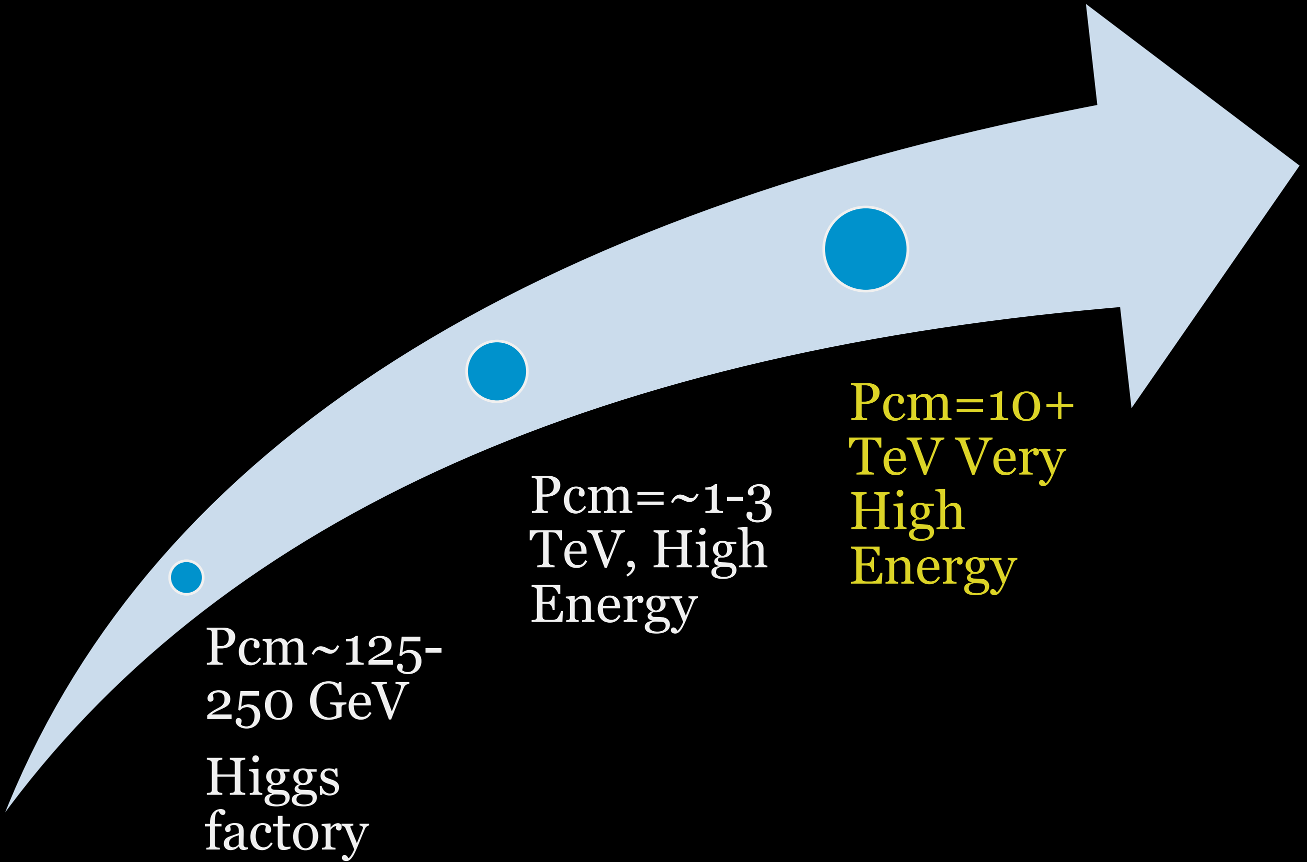


$\mu^+\mu^+$ collider, KEK muon program motivated, see, Kitano et al, 2304.14020, 2210.11083, 2201.06664

Jiang, Yang, Qian, Ban, Li, You, Li, 2304.04483

Generically, such a process is suppressed by neutrino mass (the target line is below this plot).
On the other hand, there can be threshold enhancement to be exploited to a certain extent.

The Muon Shot



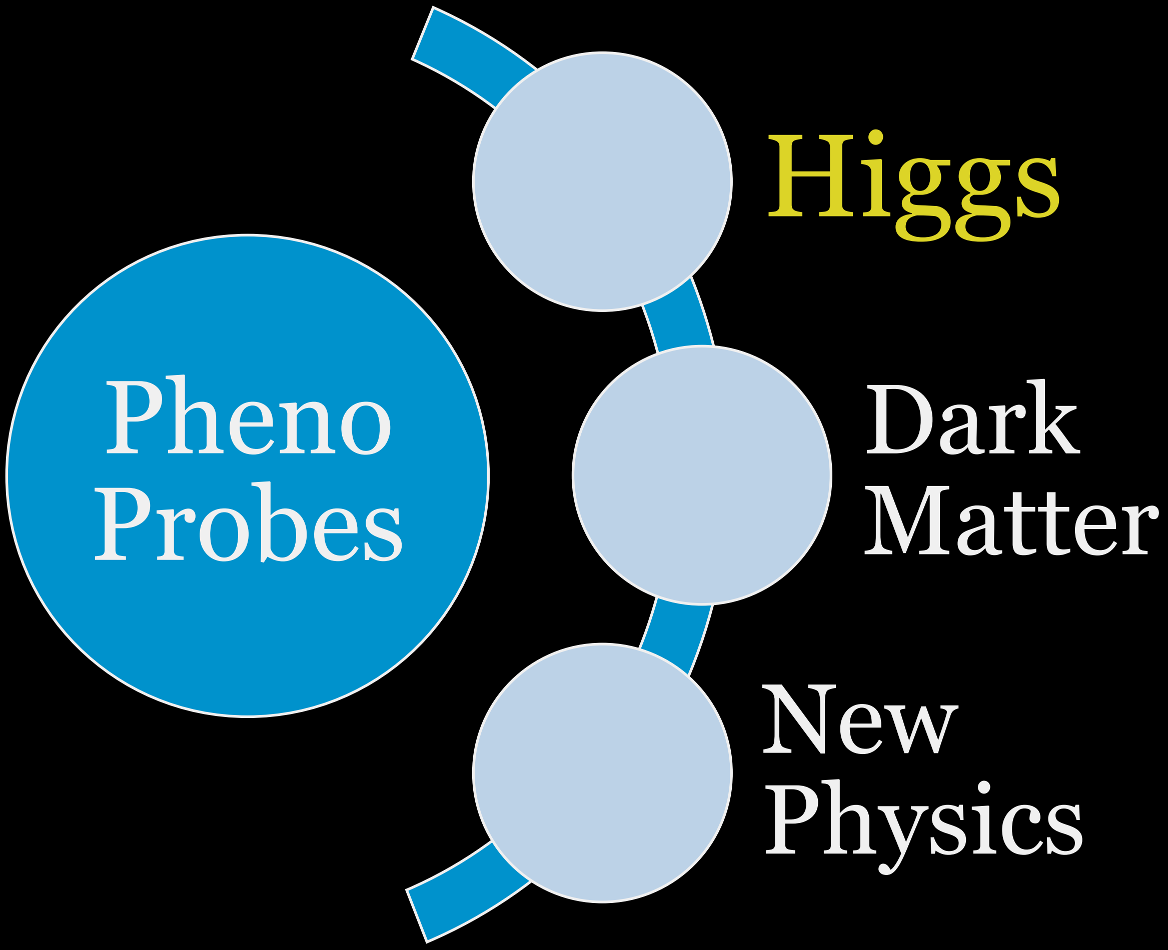
Pcm~125-250 GeV

Higgs factory

Pcm=~1-3 TeV, High Energy

Pcm=10+ TeV Very High Energy

Physics Driver



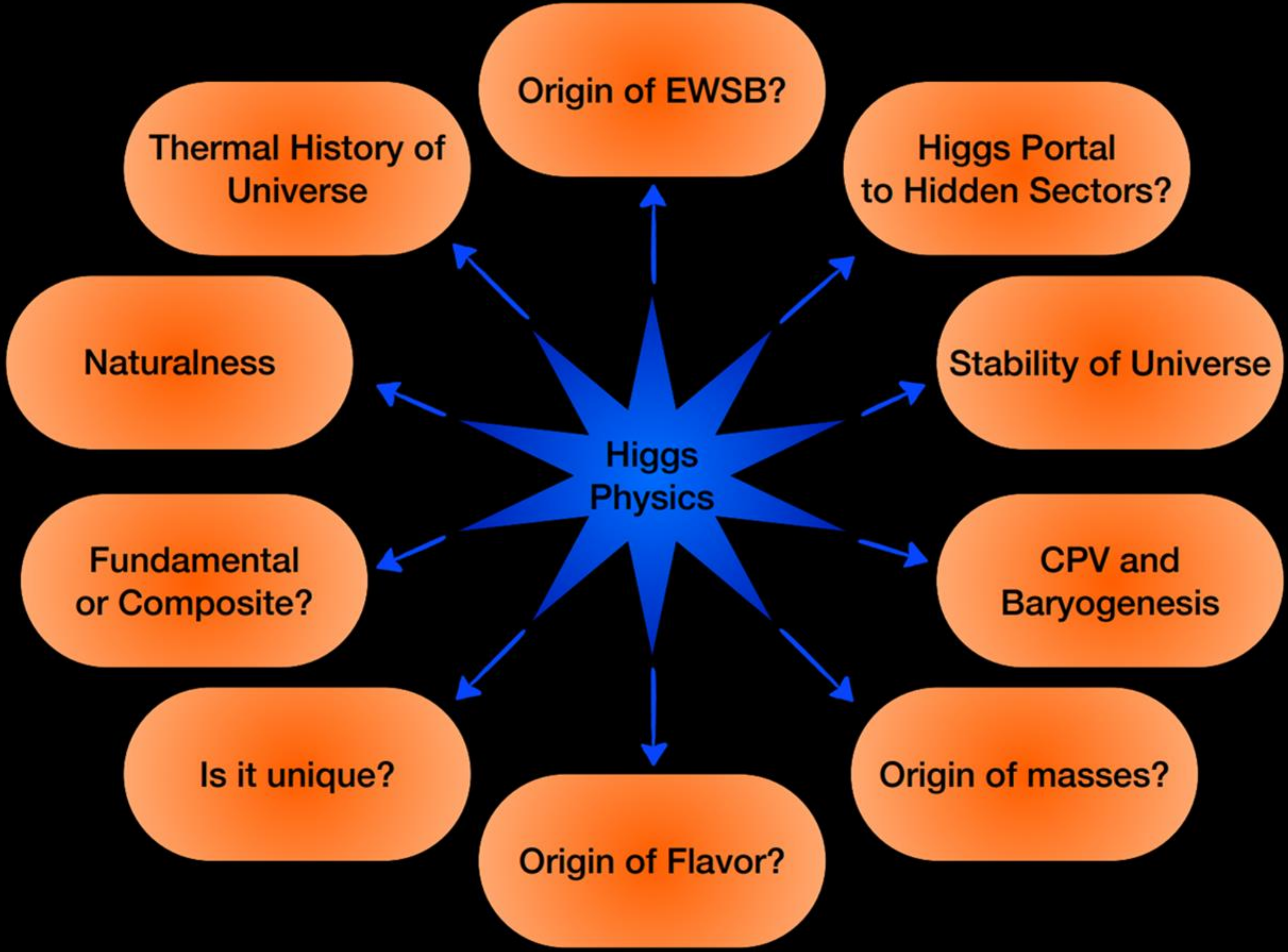
Pheno Probes

Higgs

Dark Matter

New Physics

10 years after discovery, do we know the Higgs?



Higgs Physics

Origin of EWSB?

Higgs Portal
to Hidden Sectors?

Stability of Universe

CPV and
Baryogenesis

Origin of masses?

Origin of Flavor?

Is it unique?

Fundamental
or Composite?

Naturalness

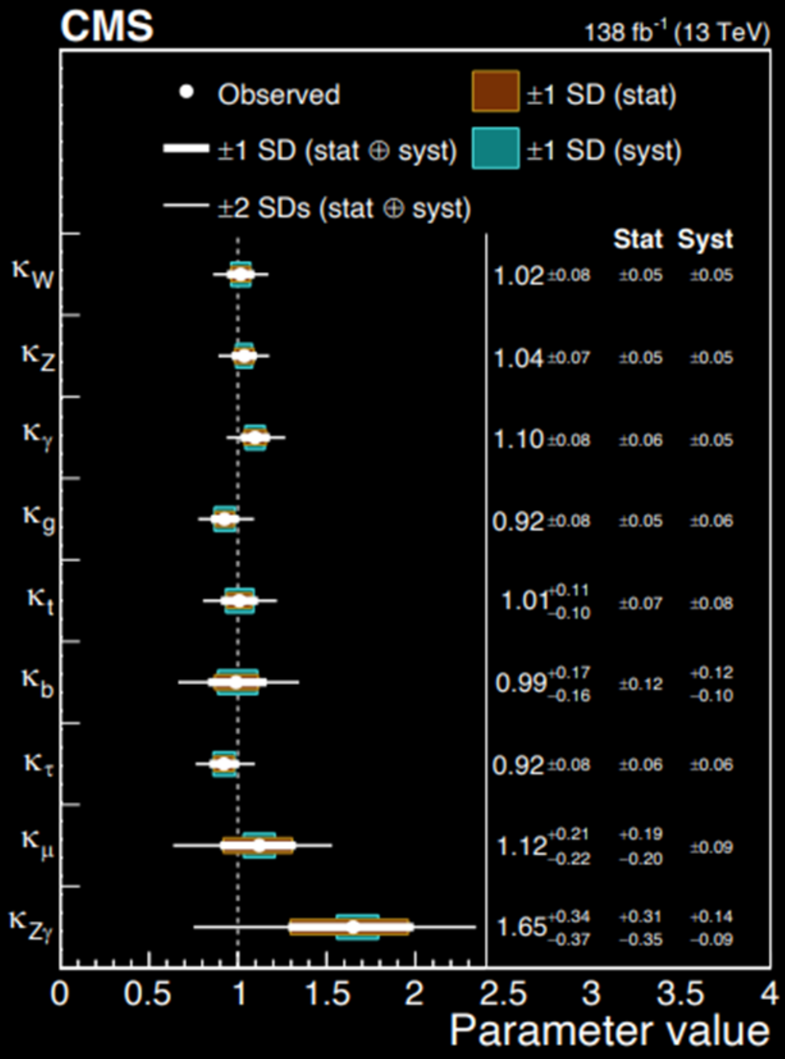
Thermal History of
Universe

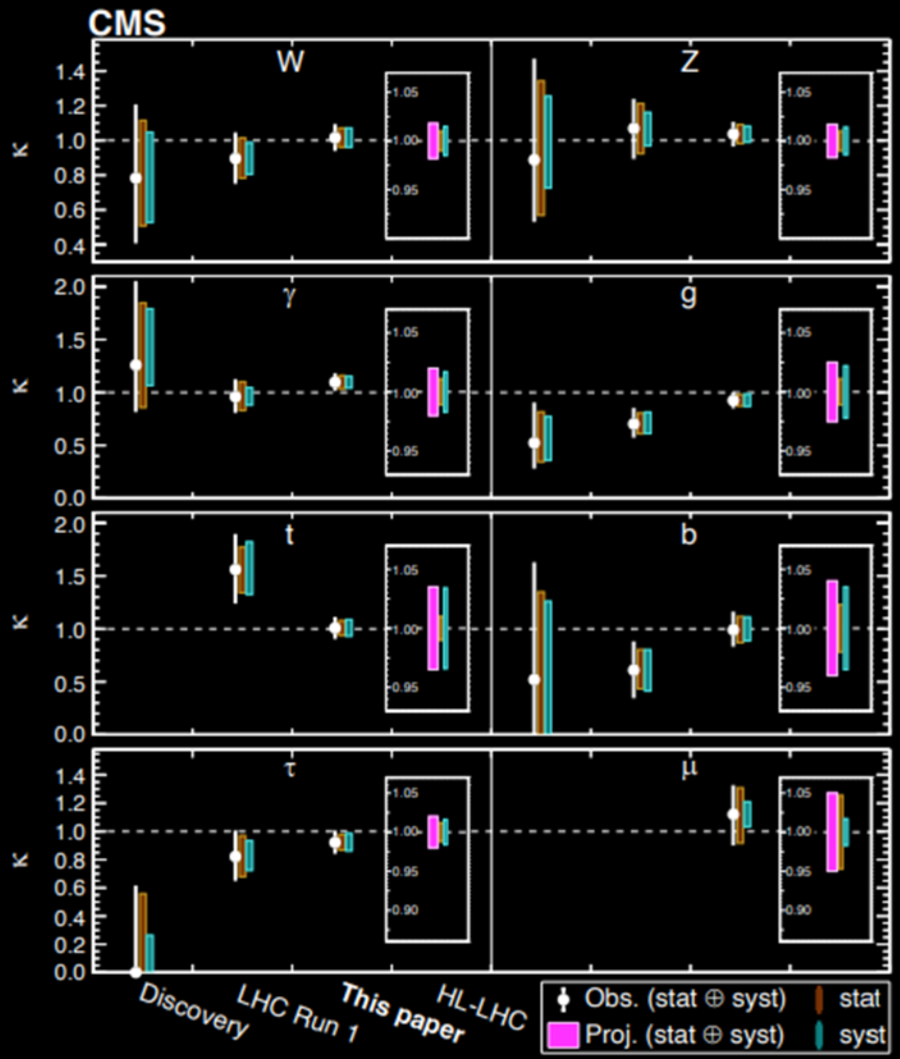
Higgs is still the central player of many puzzles in nature.

We realize that we need deeper and more precise understanding of Higgs.

Any future collider needs to have is Higgs potential understood.

Current Status





The Higgs looks like the SM Higgs boson at 10% level now.

We are to measure it to 5% level.

Measurements to be interpreted

Observables at the colliders are the cross sections, a convolution of PDF, hard scattering, parton shower, detector response …

$$\kappa_i = \frac{g_i}{g_i^{SM}}, \kappa_\Gamma = \frac{\Gamma_{tot}}{\Gamma_{tot}^{SM}}$$

For the hard scattering*:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

All exclusive channels can be parametrized this way, simple extension possible for more channels/observables.

*zero-width approximation, Higgs width 10^{-5} of its mass, in general valid. Violations (% level correction) see Campbell, Carena, Harnik, ZL, PRL 18'

Measurements to be interpreted

Observables at the colliders are the cross sections, a convolution of PDF, hard scattering, parton shower, detector response …

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For the hard scattering:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

If $\kappa_\Gamma = \kappa_i^2 \kappa_j^2$, the observed rates do not change.

We **cannot** measure Higgs couplings strength, without some inputs to break this flat direction!

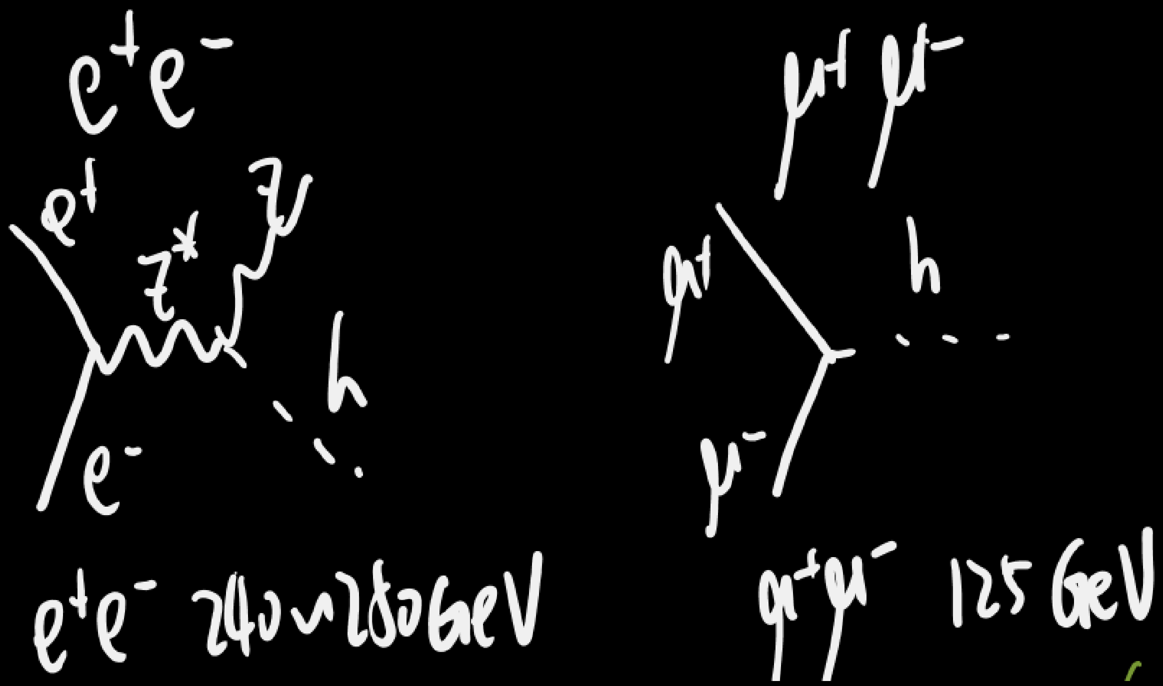
- All Kappas are positively correlated with the total width (from the point of cross sections);
- The naïve scaling of $\kappa_{tot} \propto \kappa_{i,f}^2$, does not reflect this flat direction, one needs additional particle width to enter;
- In principle, a given specific BSM model might have more constraints to all stronger constraints, but generally, this direction is unconstrained that leads to a bad projection of sensitivity (without the correlation matrix).

Is the Higgs fundamental?

Measurements to be interpreted

Future Higgs factories, e.g., can solve this issue by inclusive Higgs measurement or lineshape scan.

- Inclusive rate: $\sigma(i \to H) = \sum_j \sigma(i \to H \to j) \propto \sum_j \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} = \Gamma_i$
- Lineshape scan: break the parameterization $\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}^2}$



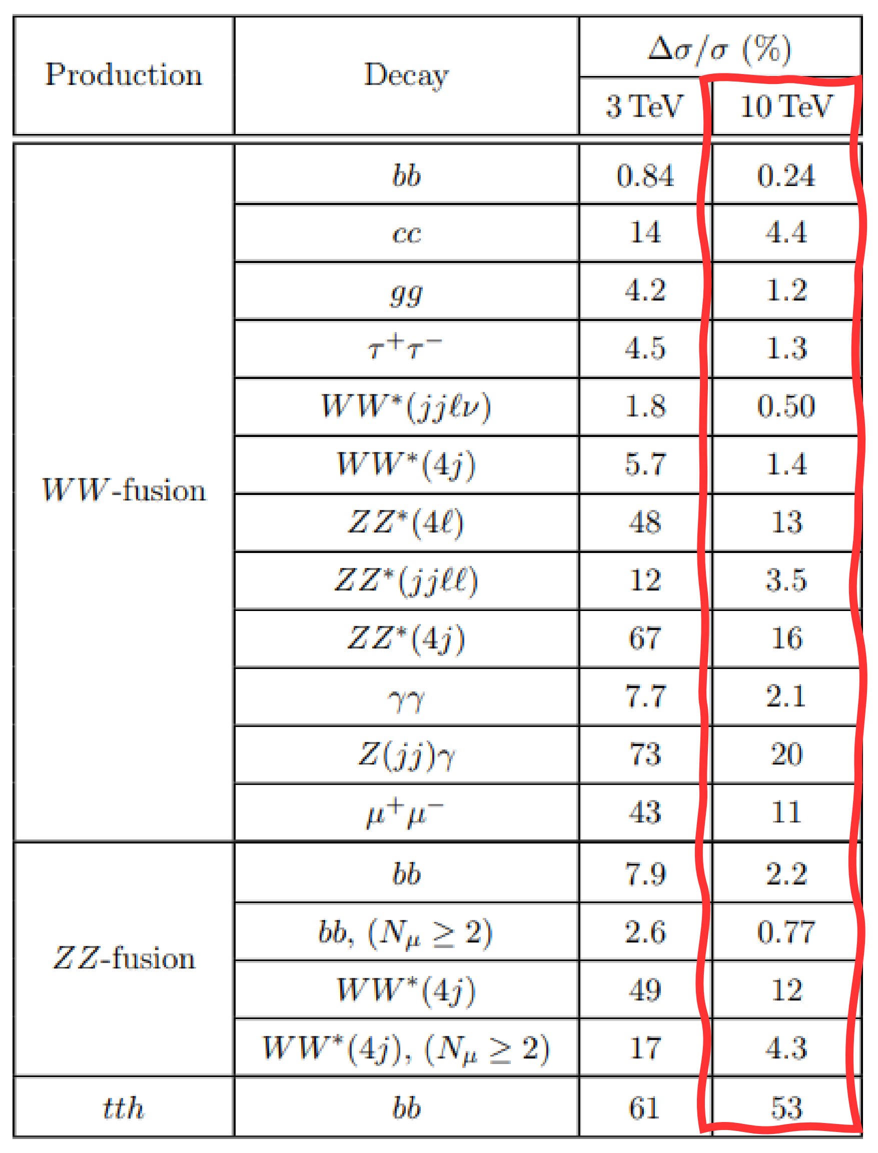
e^+e^-

$\mu^+\mu^-$

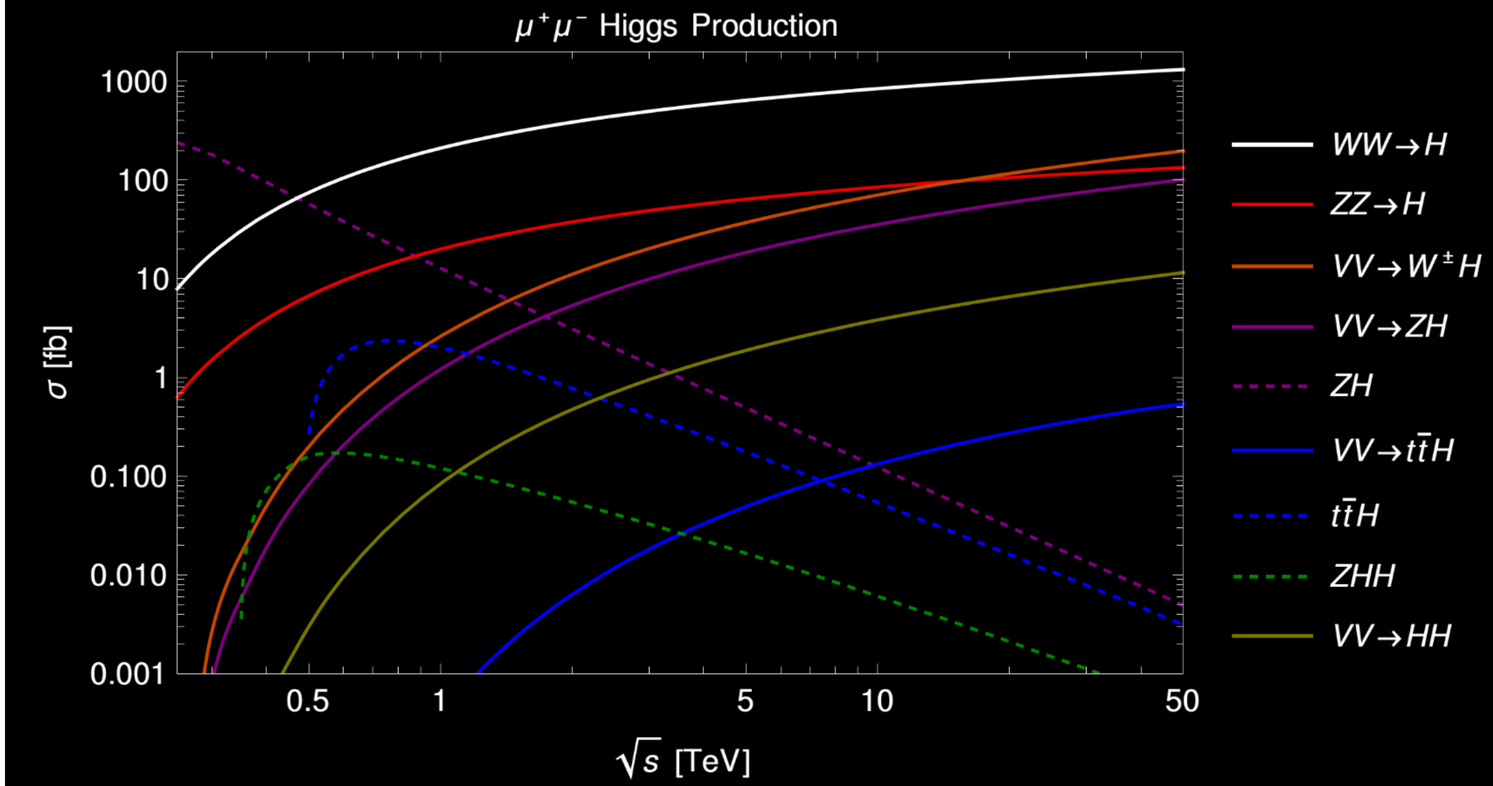
e^+e^- 240~250 GeV

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

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

Inclusive Higgs rate from ZZ fusion

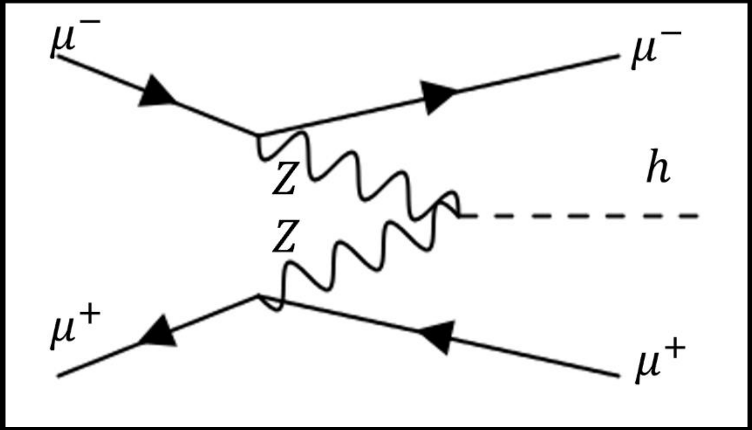
Forward muon coverage: $2.5 < \eta(\mu) < 4, 6, 8$

Peiran Li, Kun-Feng Lyu, ZL, 2401.08756

$$p_h = (\sqrt{s}, 0,0,0) - p_{\mu^+} - p_{\mu^-}$$

$$m_h^2 = \left[(\sqrt{s}, 0,0,0) - p_{\mu^+} - p_{\mu^-}\right]^2$$

Recoil mass of dimuon

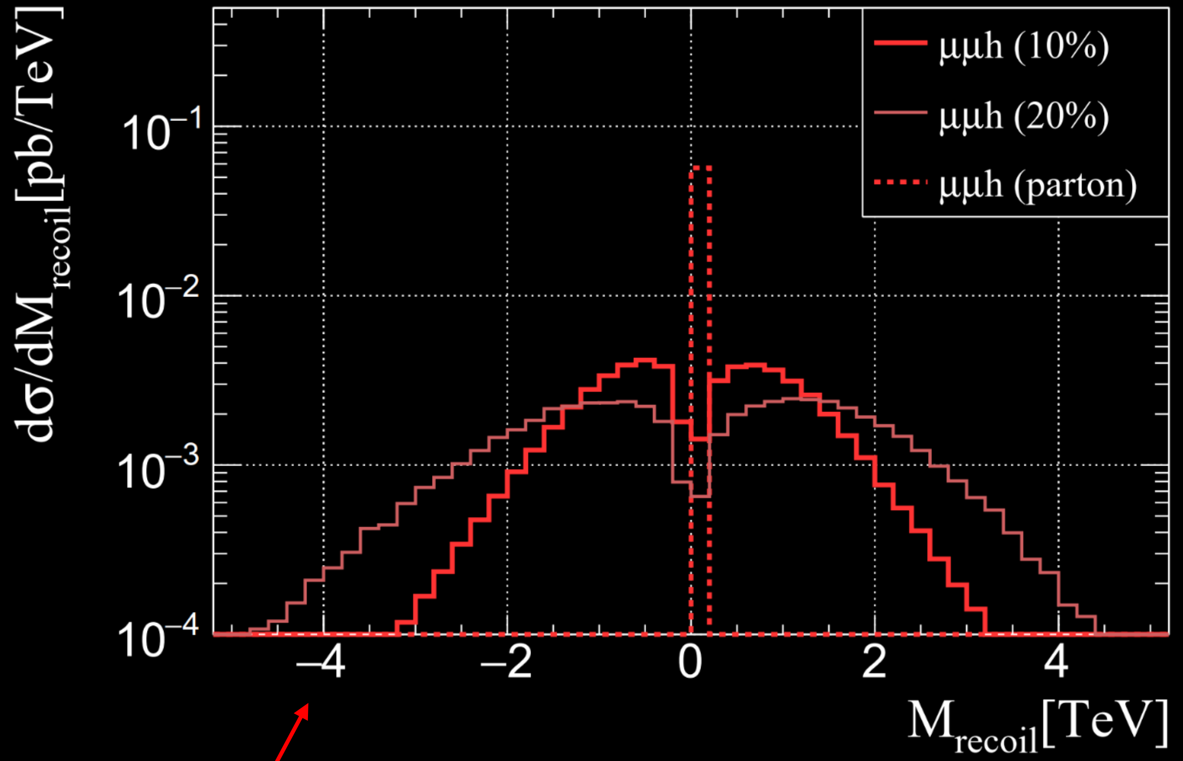


This subleading Higgs production channel, once tagged, does not rely on the detection of Higgs decay channel.

Inclusive rate: $\sigma(i \to H) = \sum_j \sigma(i \to H \to j) \propto \sum_j \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} = \Gamma_i$

Inclusive Higgs rate from ZZ fusion

Due to the uncertainty of high energy measurement, the smearing effect dominate the recoil mass distribution.

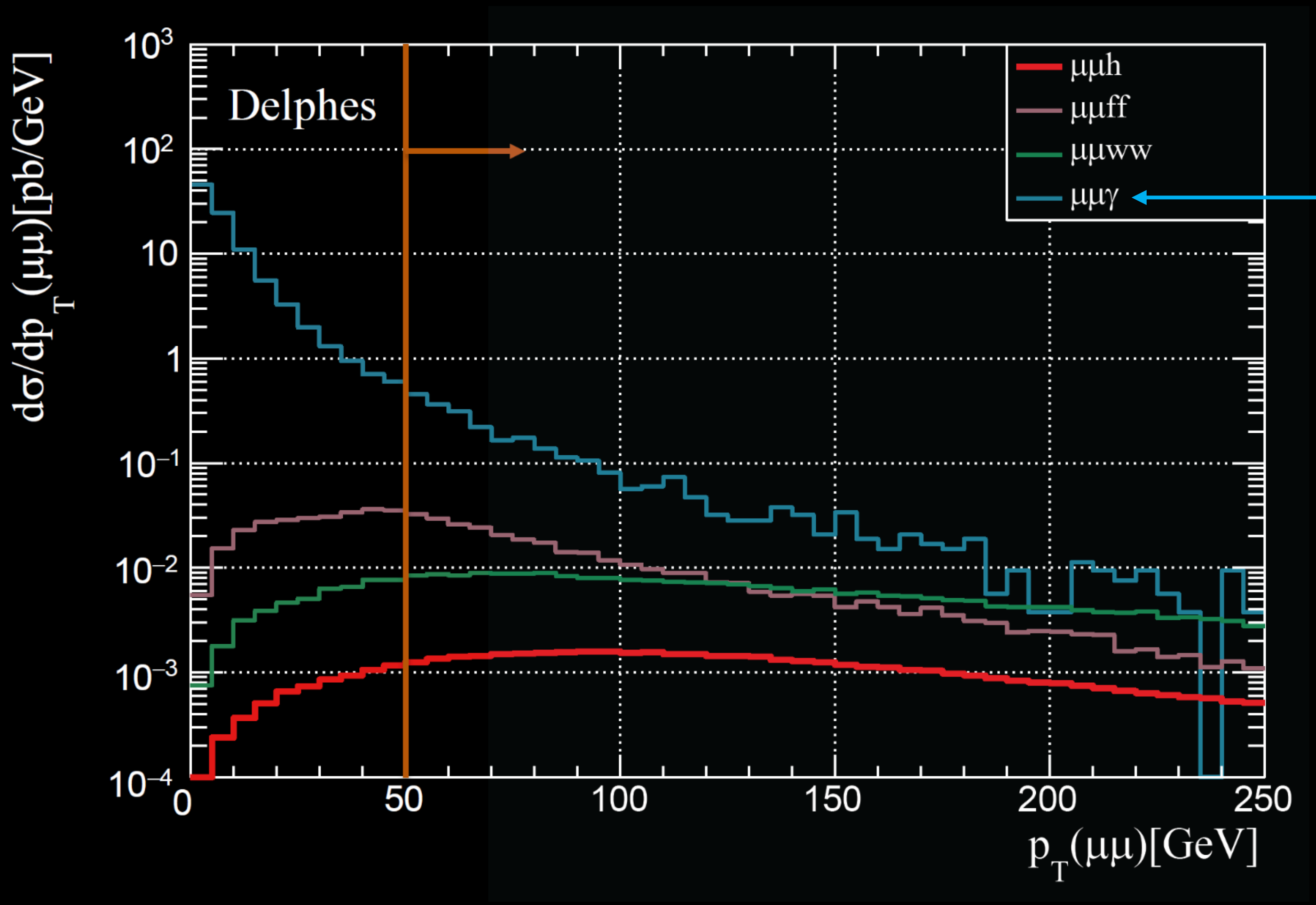


$[(\sqrt{s},0,0,0) - p_{\mu^+} - p_{\mu^-}]^2 < 0$

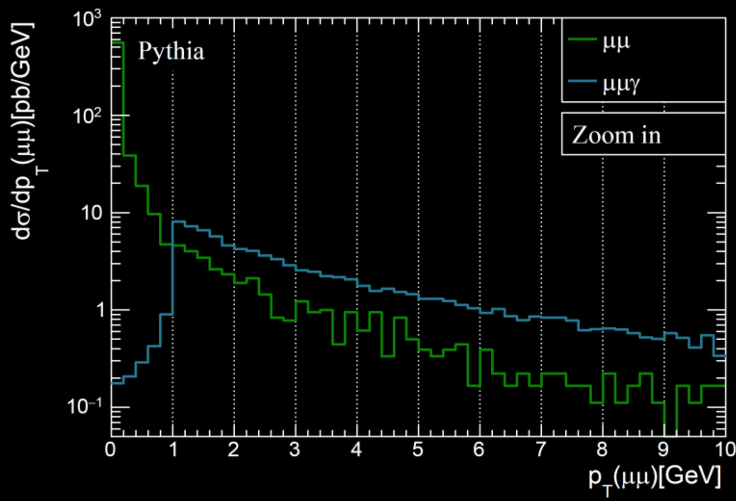
Fast detector simulation using Delphes.

Signal vs. Background $(\sqrt{s} = 10\ \mathrm{TeV})$

Require $p_T(\mu\mu) > 50$ GeV

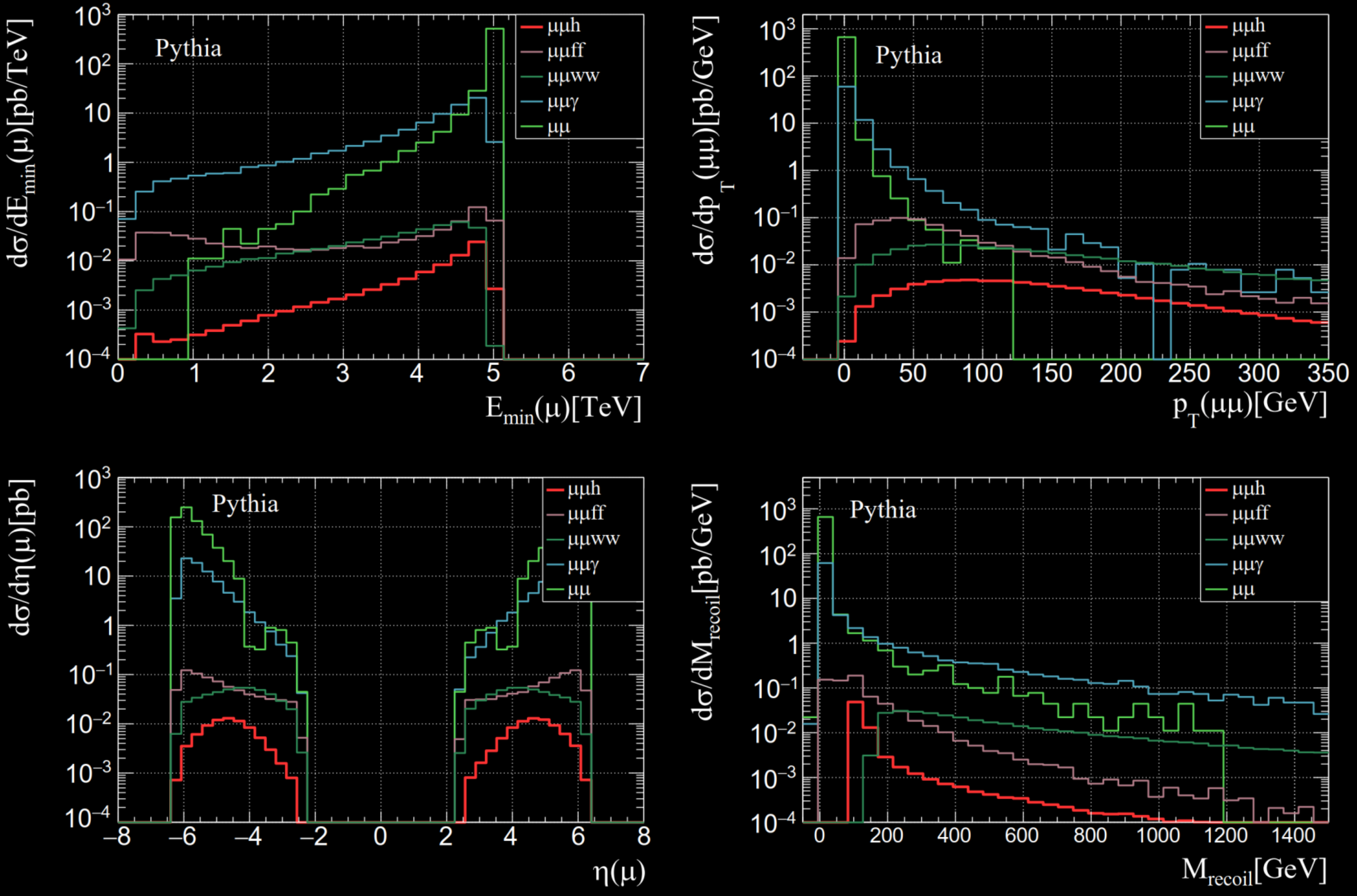


Merging $\mu\mu \to \mu\mu$ and $\mu\mu \to \mu\mu\gamma$



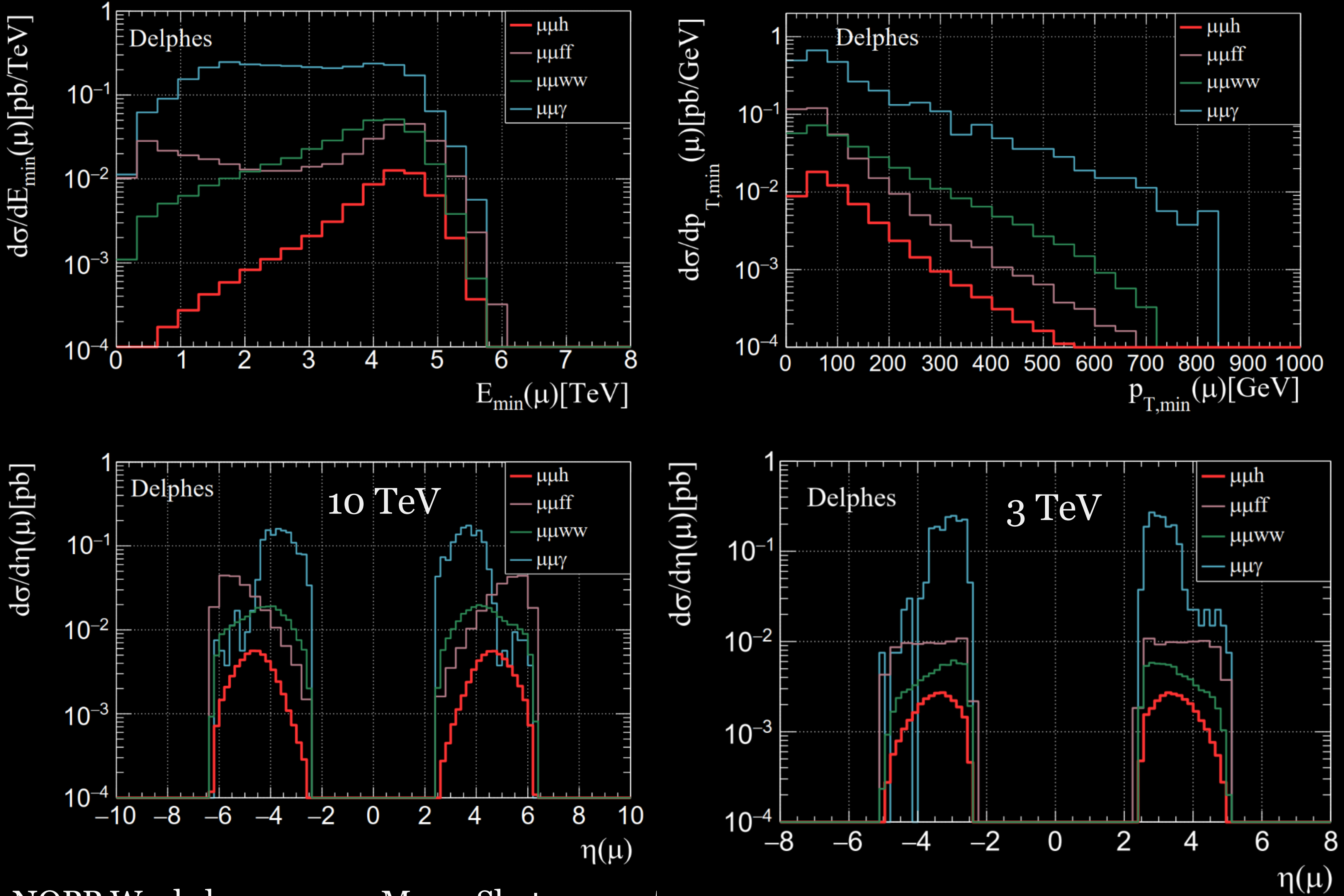
Also see a similar treatment in Higgs invisible study, Ruhdorfer, Salvioni, Wulzer, 2303.14202

Other relevant distributions



For the signal muons, the typical eta is around 5. Dominant background is more forward.

Other relevant distributions (reconstruction)



For the signal muons, the typical eta is around 5. Dominant background is more forward.

Sensitivity

Process	Pre-selection	$p_T(\mu\mu) > 50$ GeV	$E(\mu) > 3000$ GeV & $p_{T,\min}(\mu) < 300$ GeV
$\mu^+\mu^- \to \mu^+\mu^- h$	73.3%	65.7%	56.4% (0.0489 pb)
$\mu^+\mu^- \to \mu^+\mu^- \gamma$	13.1%	0.38%	0.12% (0.906 pb)
$\mu^+\mu^- \to \mu^+\mu^- f\bar{f}$	8.13%	4.69%	2.58% (0.199 pb)
$\mu^+\mu^- \to \mu^+\mu^- W^+W^-$	40.0%	34.9%	22.0% (0.207 pb)

10 TeV

Benchmark	$\lvert\eta(\mu)\rvert < 4$	$\lvert\eta(\mu)\rvert < 6$	$\lvert\eta(\mu)\rvert < 8$
$\Delta\sigma/\sigma$	15%	0.75%	0.74%

Now High Energy Muon Collider is a full-fledged Higgs factory

$\eta(\mu) < 6$

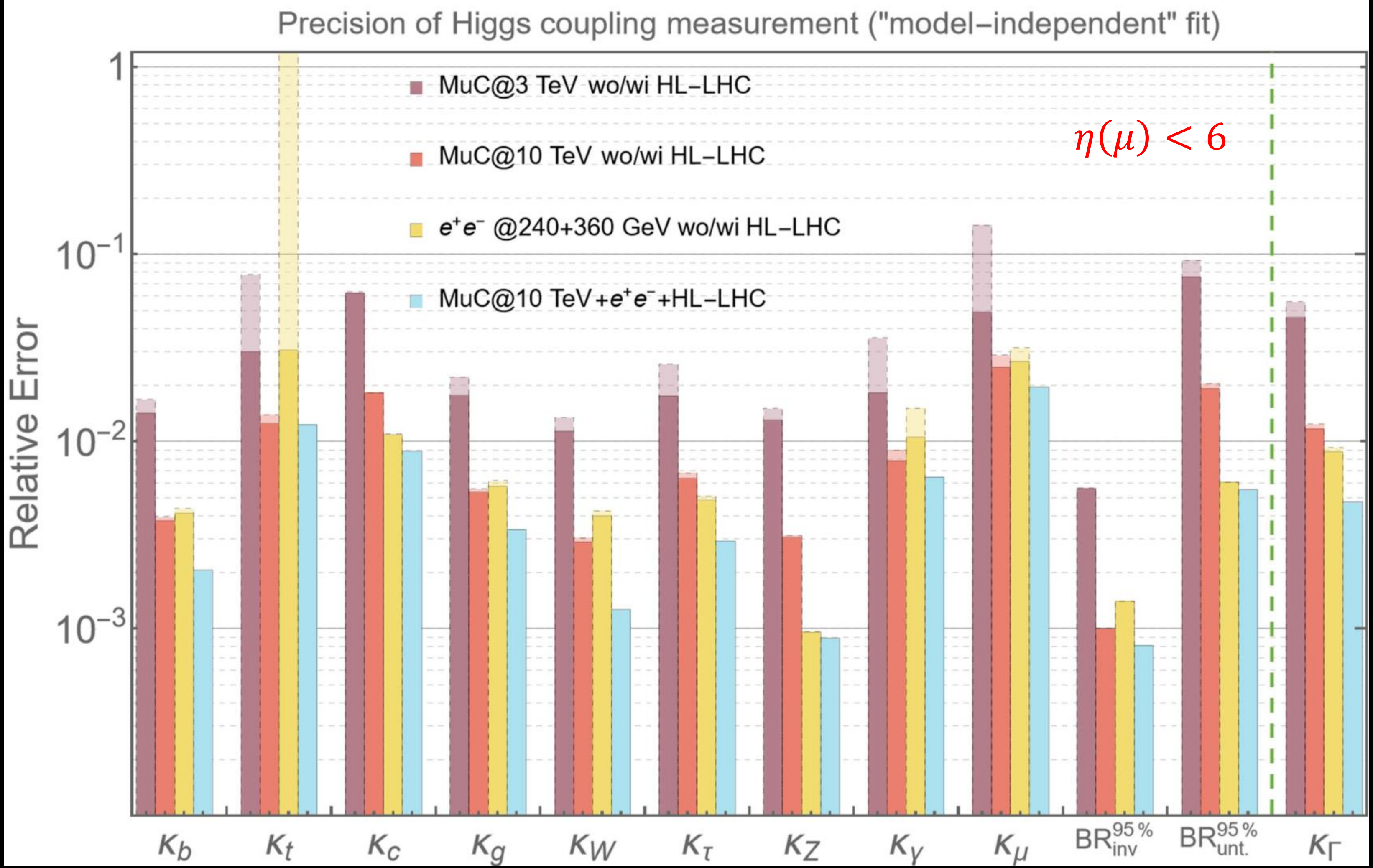
$\mu^{\text{decay}}_{\text{production}}$	μ^{tt}_{VV}	μ^{bb}_{WW}	μ^{cc}_{WW}	μ^{gg}_{WW}	$\mu^{\tau\tau}_{WW}$	μ^{WW}_{WW}	μ^{ZZ}_{WW}	$\mu^{\gamma\gamma}_{WW}$	$\mu^{\mu\mu}_{WW}$
$\Delta\sigma/\sigma(\%)$	2.8	0.22	3.6	0.79	1.1	0.40	3.2	1.7	5.7
$\mu^{\text{decay}}_{\text{production}}$	μ^{bb}_{ZZ}	μ^{cc}_{ZZ}	μ^{gg}_{ZZ}	$\mu^{\tau\tau}_{ZZ}$	μ^{WW}_{ZZ}	μ^{ZZ}_{ZZ}	$\mu^{\gamma\gamma}_{ZZ}$	μ^{inv}_{ZZ}	μ^{H}_{ZZ}
$\Delta\sigma/\sigma(\%)$	0.77	17	3.3	4.8	1.8	11	4.8	0.05	0.75

Requires forward muon

Other inputs used in this study.

- (Exclusive Higgs) M. Forslund and P. Meade. [2203.09425]
- (Invisible Higgs) M. Ruhdorfer, E. Salvioni, A. Wulzer. [2303.14202]
- (Top Yukawa) Z. Liu, K.F. Lyu, I. Mahbub, L.T. Wang. [2308.06323]
- (off-shell Higgs; not used but relevant) M. Forslund and P. Meade [2308.02633]

Now High Energy Muon Collider is a full-fledged Higgs factory



New inclusive Higgs rate result enables a full-fledges Higgs precision.

- With forwarded detection $2.5<\eta(\mu)<6$, the cross-section precision is ~0.75%
- Combining with other studies, we can constraint on Γ_H~2% and Higgs couplings in 0.5% level.

Other inputs used in this study.

- (Exclusive Higgs) M. Forslund and P. Meade. [2203.09425]
- (Invisible Higgs) M. Ruhdorfer, E. Salvioni, A. Wulzer. [2303.14202]
- (Top Yukawa) Z. Liu, K.F. Lyu, I. Mahbub, L.T. Wang. [2308.06323]
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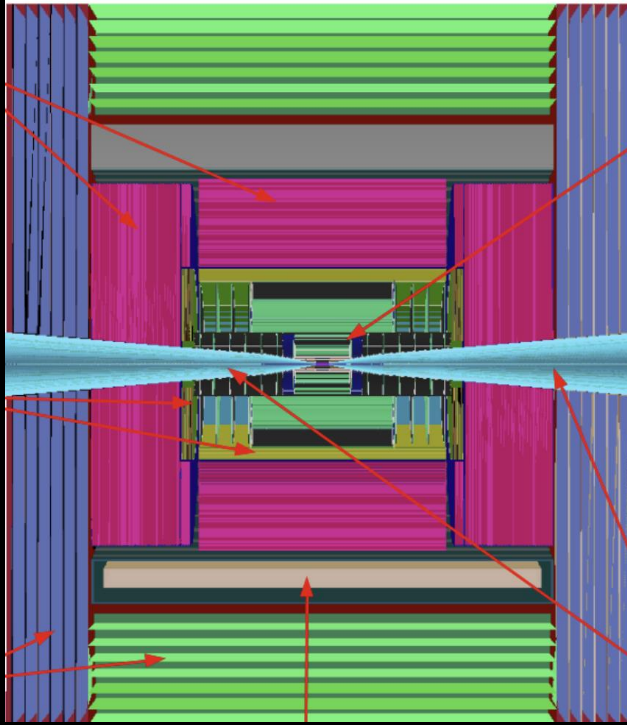
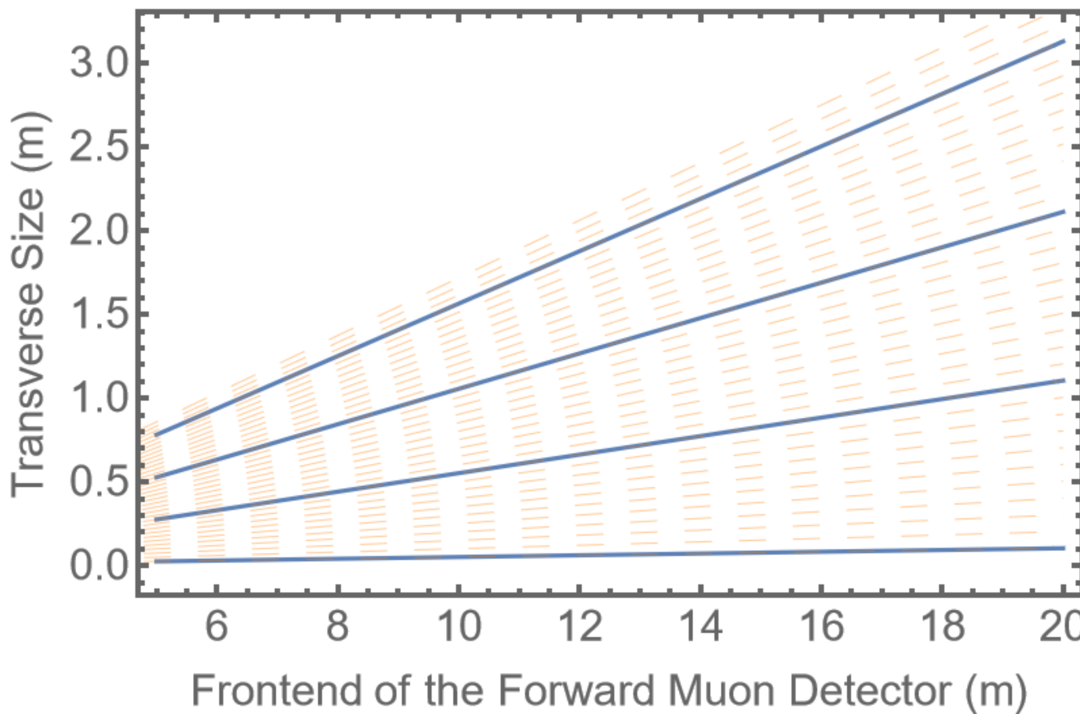
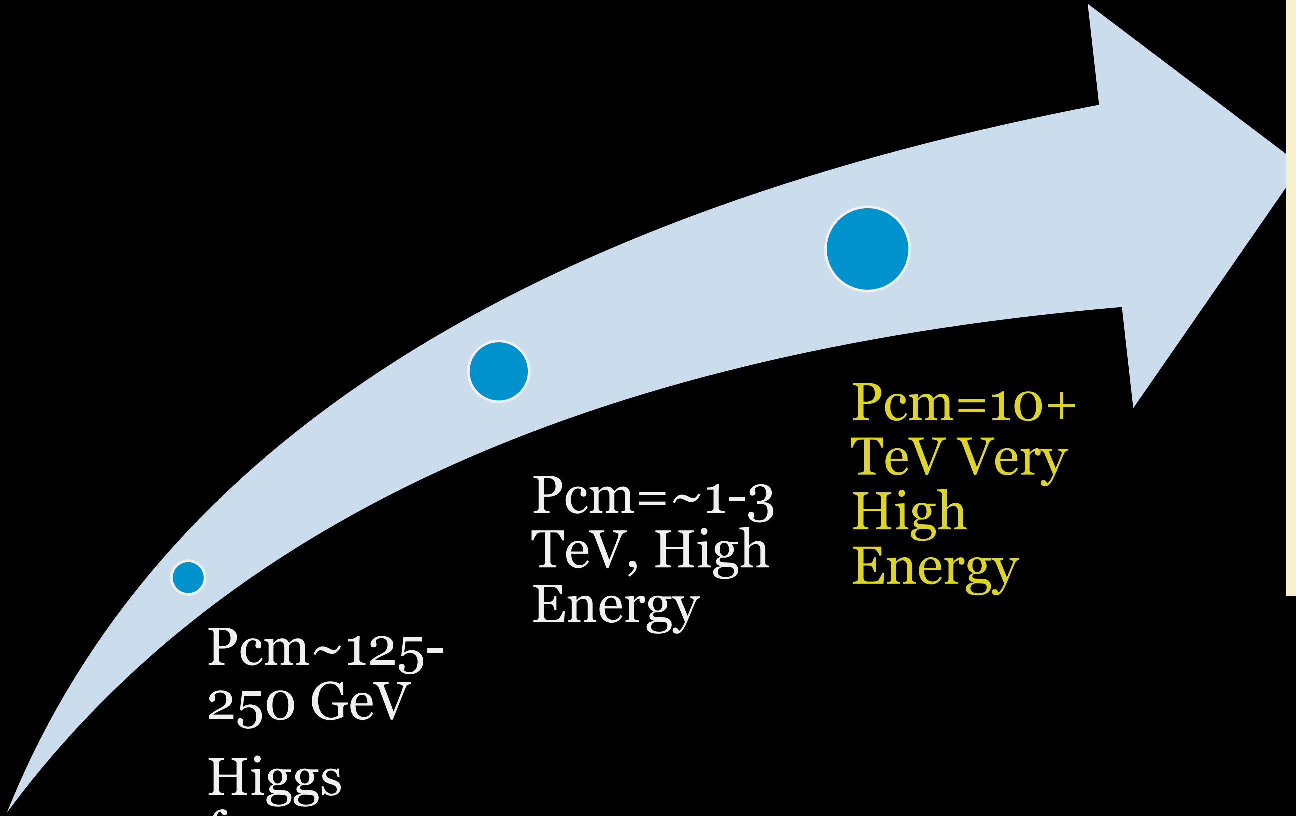
Forward Muon Detector Required!

- Is it feasible?
- We only require to tag Energetic Muons.
- Muons pass through the nozzle regions
- Energy resolution is not important (basically need to separate TeV scale energetic muons from soft muons)
- Angular resolution is not important (~50mrad should be good enough;)
- This is a very strong case for a forward muon detector
- Happy to discuss more and collaborate





The Muon Shot

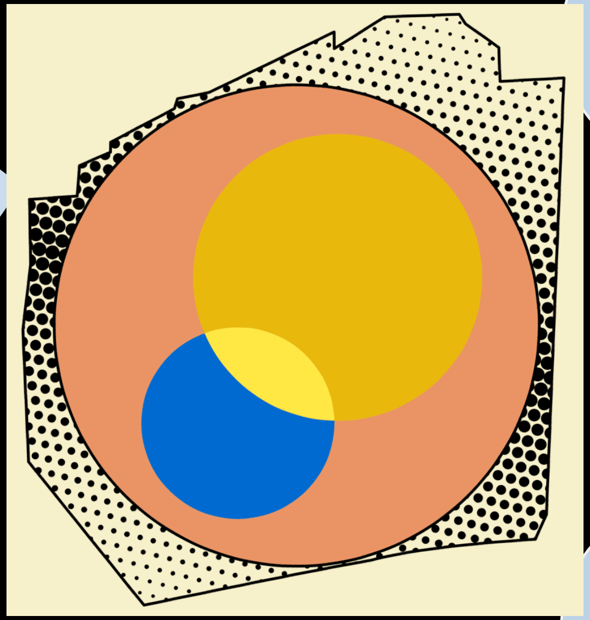


Pcm~125-250 GeV

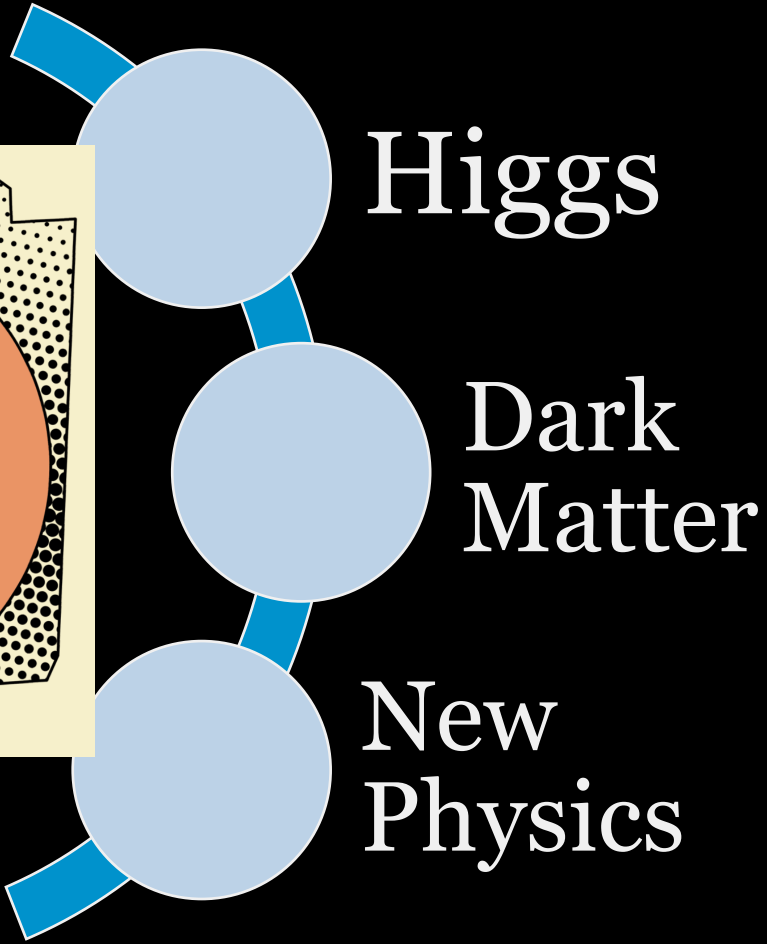
Higgs factory

Pcm=~1-3 TeV, High Energy

Pcm=10+ TeV Very High Energy



Physics Driver



Higgs

Dark Matter

New Physics