Energy Frontier in Particle Physics:
LHC and Future Colliders

WIMP DM at High Energy Muon Colliders

Zhen Liu
University of Maryland
10/06/2020

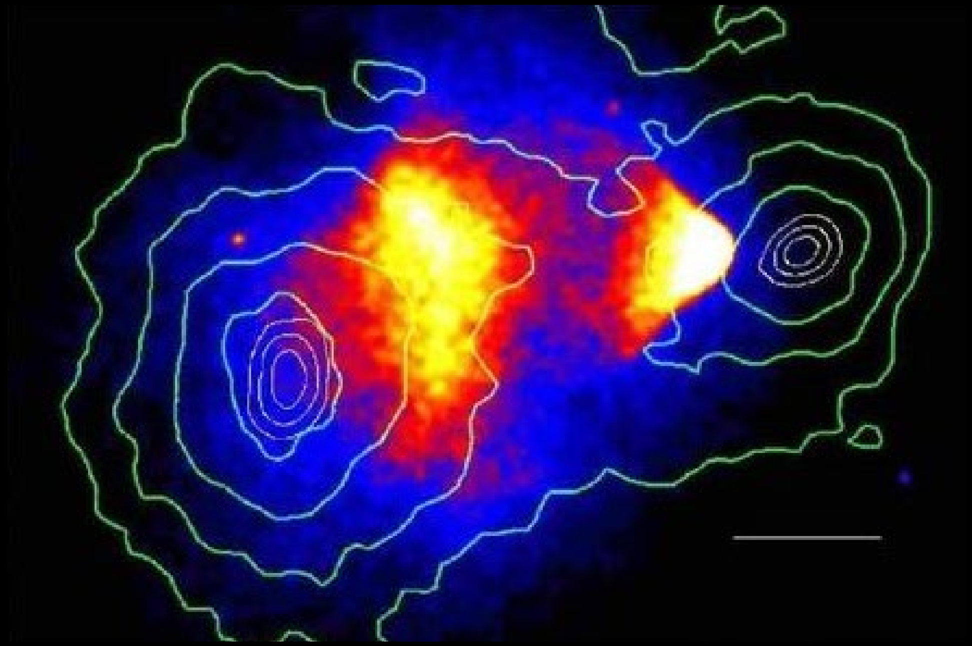
Mainly based on
T. Han, ZL, L.-T. Wang, X. Wang, 2009.11287

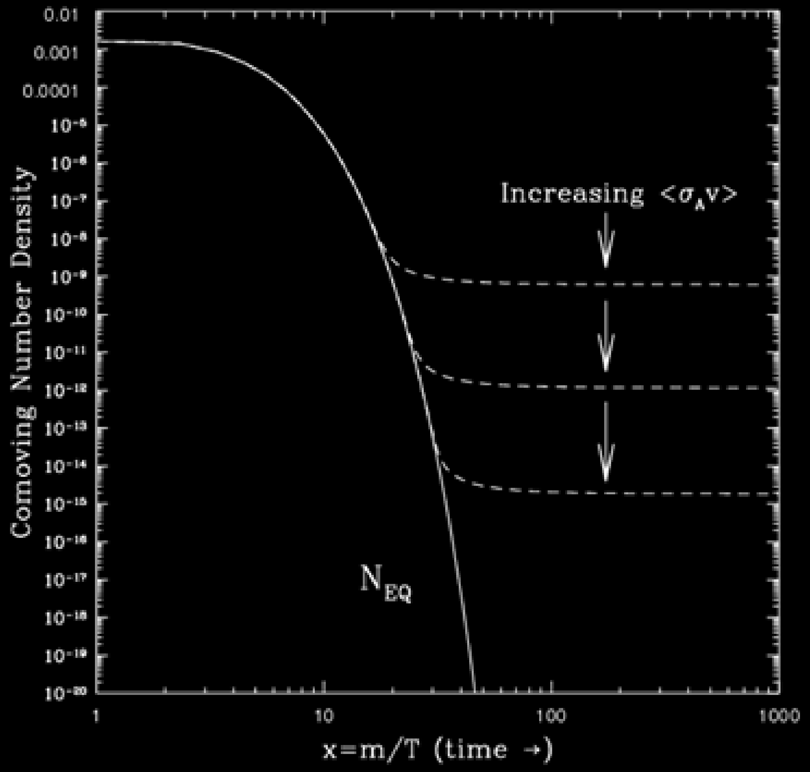
5-6 October, 2020, National Taiwan University, Taipei

NCTS

WIMP Dark Matter

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





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

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

Muon Collider

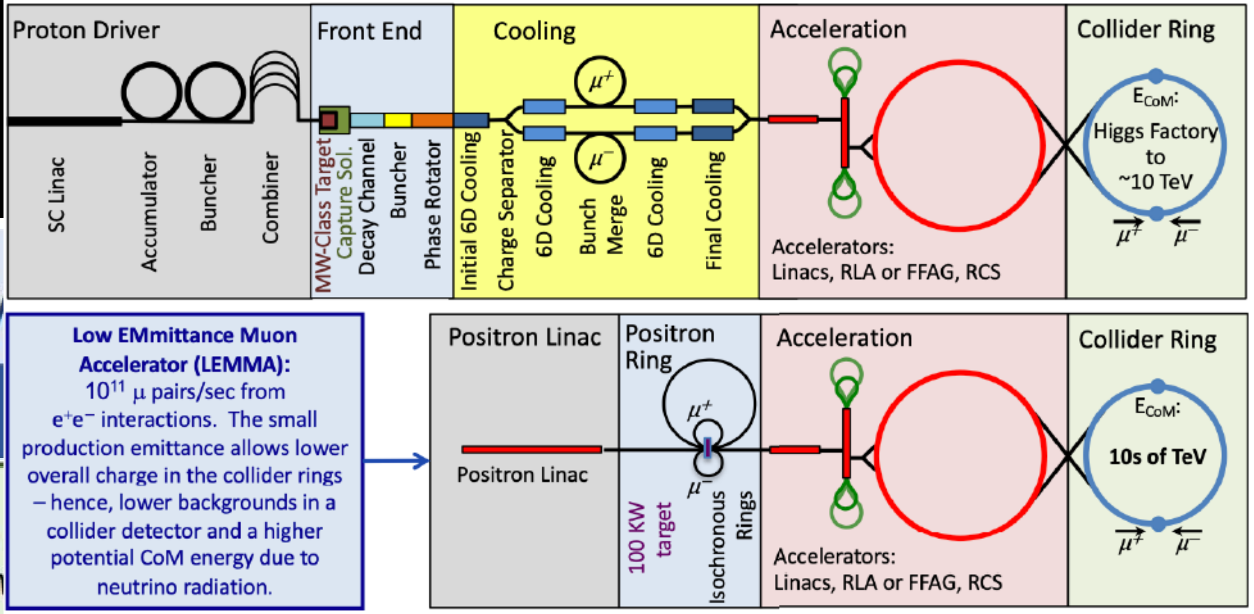
European Strategy Update

2020 Strategy

High-priority future initiatives

Accelerator R&D is crucial to prepare the future collider programme

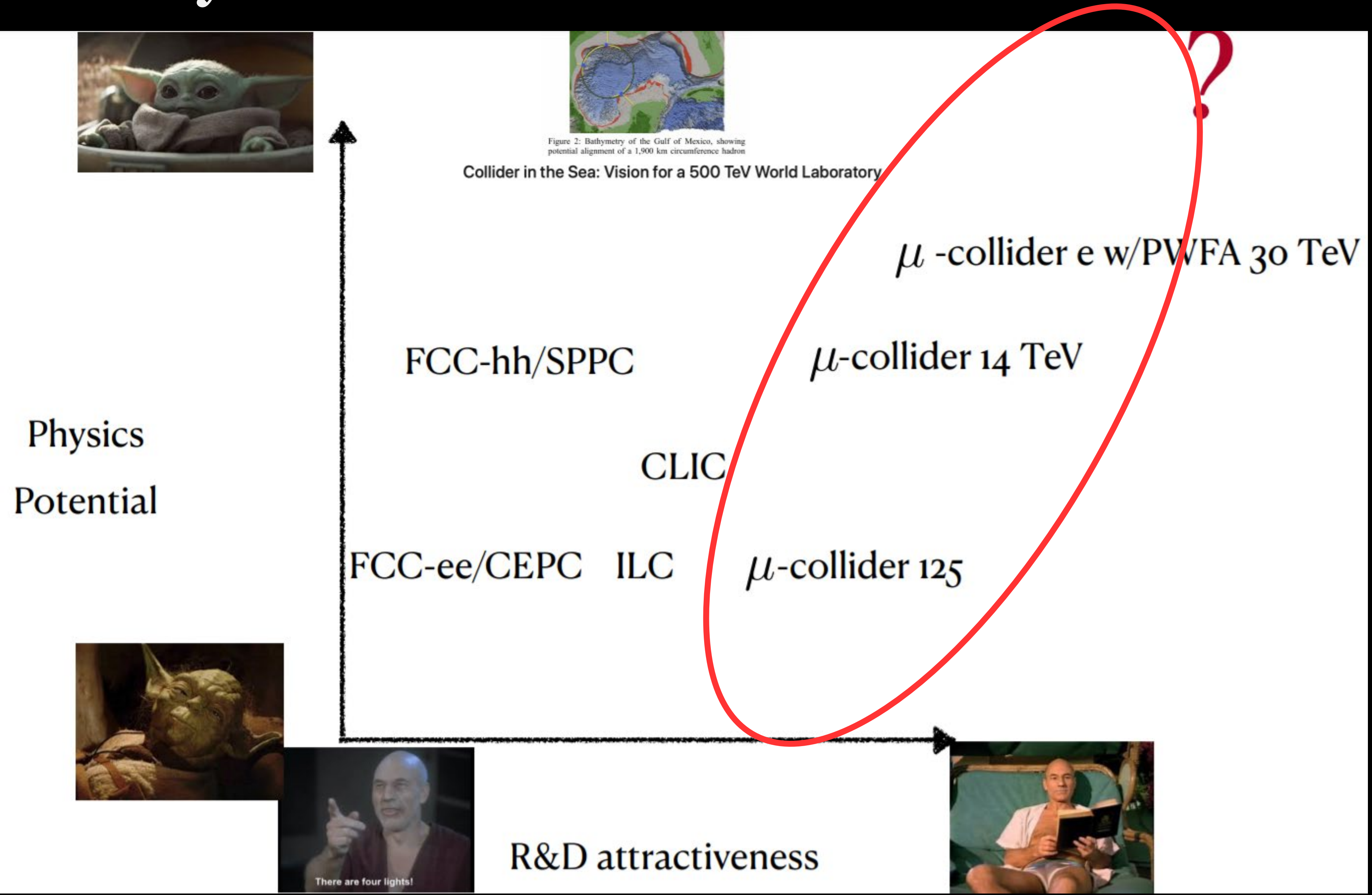
- The European particle physics community should develop an accelerator needed for future colliders, maintaining a beneficial link with other com fusion energy
- The roadmap should be established as soon as possible in close coordina
- A focused, mission-style approach should be launched for R&D on high-f temperature superconductor (HTS) option to reach 20 T. CERN's engagement in this process would have a catalysing effect on related work being performed in the National Laboratories and research institutions
- The roadmap should also consider: R&D for an effective breakthrough in plasma acceleration schemes, an international design study for a muon collider and R&D on high-intensity, multi-turn energy-recovery linac (ERL) machines



[Delahaye et al. arXiv:1901.06150]

b) Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

Physics-wise: do we want Muon Collider?



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

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

Fig. from P. Meade e tal @ Snowmass EF

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

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 (details next)

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)
- Consider up to 7-plet Unitarity breaking scale close to the thermal target (40 TeV)
- Summonfeld and bound-state effect

Basic Pheno Considerations

"non-trivial" to consider MuC

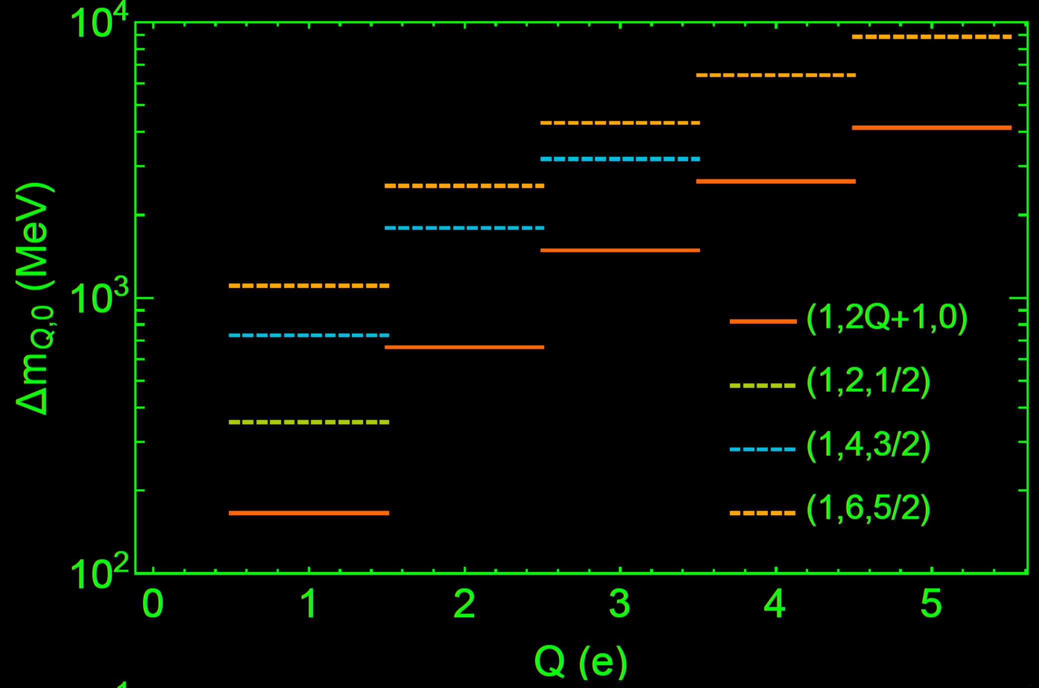
- Minimal signature
  - Mass splitting O(few hundred MeV)
  - Decay products soft
  - Transition between states fast (<mm for most of the cases)
- Missing ET (at LHC)➔Missing Mass (at MuC)

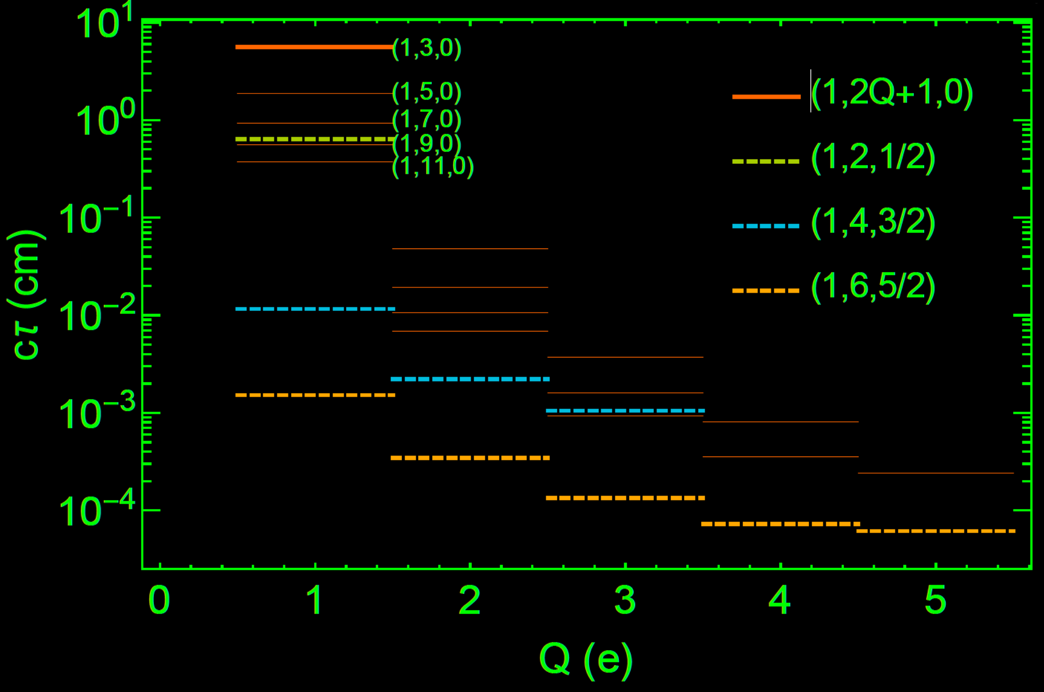
$$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$$

$$\Delta m_{Q,Q'} \equiv m_Q - m_{Q'} \simeq (Q - Q')\left(Q + Q' + \frac{2Y}{\cos\theta_W}\right)\delta m$$

$$\delta m = \frac{g^2}{4\pi} m_W \sin^2\frac{\theta_W}{2} \approx 160\text{–}170\ \text{MeV}$$

$$\kappa_W = \frac{2}{(T - Q + Y)(T + Q - Y + 1)}$$





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:

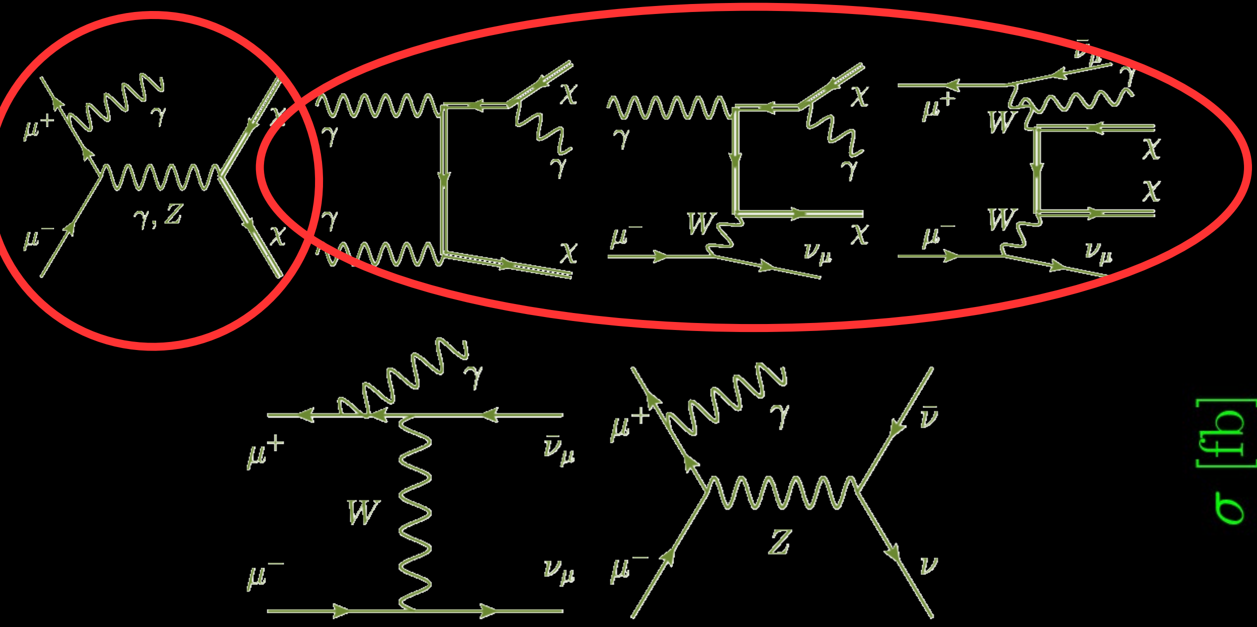
- Exclusive but challenging
- Most useful for Wino and Higgsinos
- Great potential

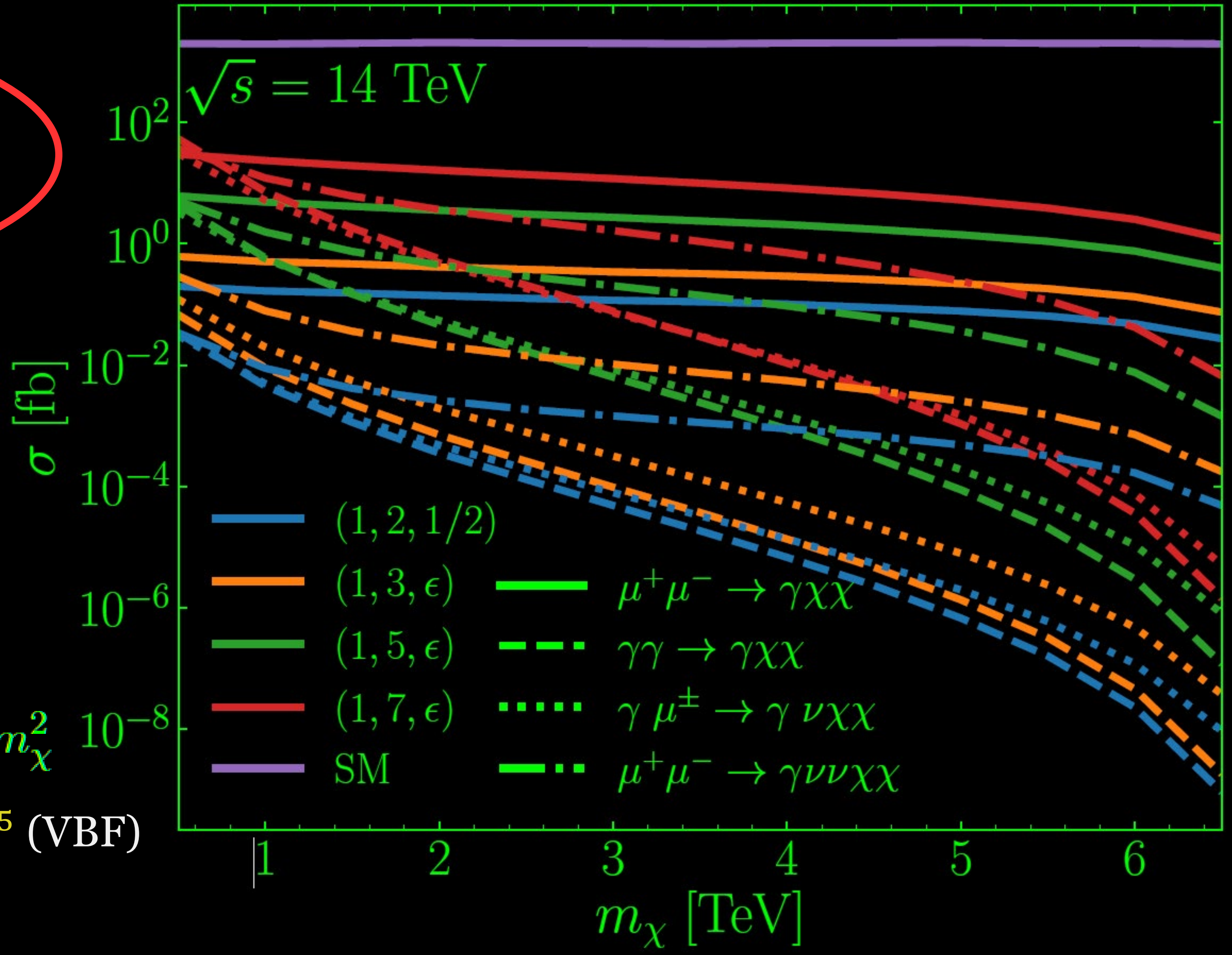
$$\sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30 \text{ and } 100 \text{ TeV}$$

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

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

Mono-Photon





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

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

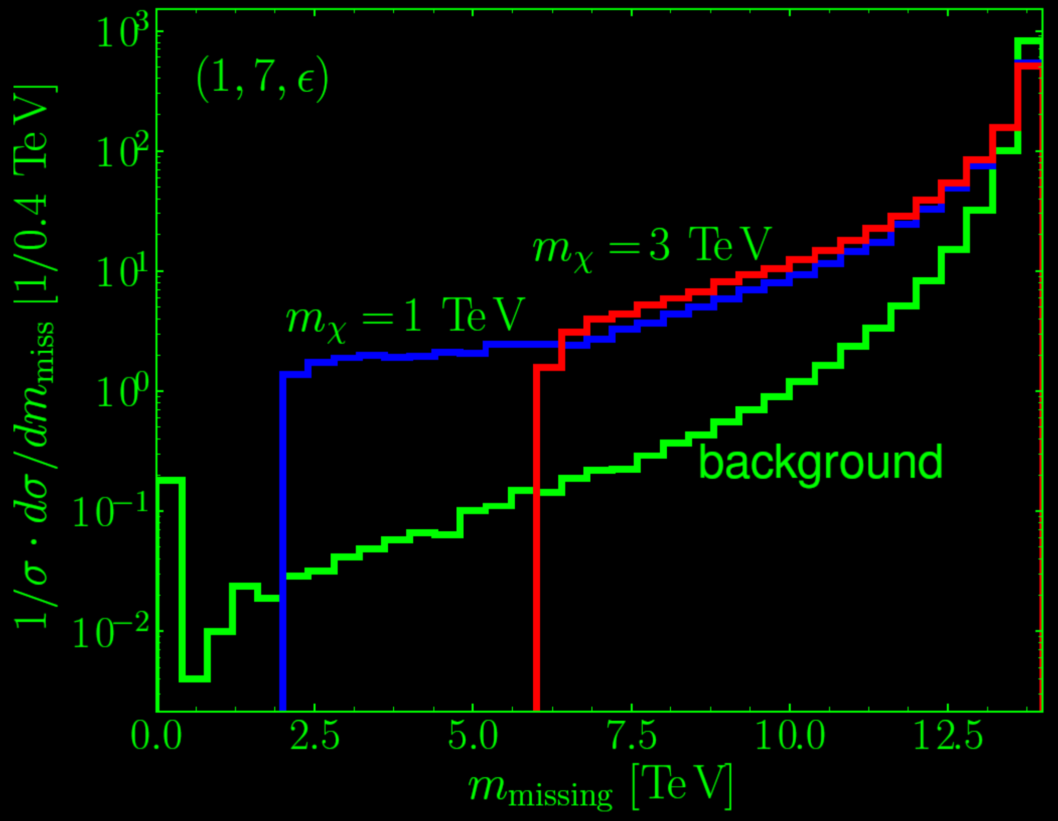
Rate grows with n-plets as roughly $n^{2\sim3}$ (DY) and $n^{4\sim5}$ (VBF)
Doublet and Triplet very hard to probe

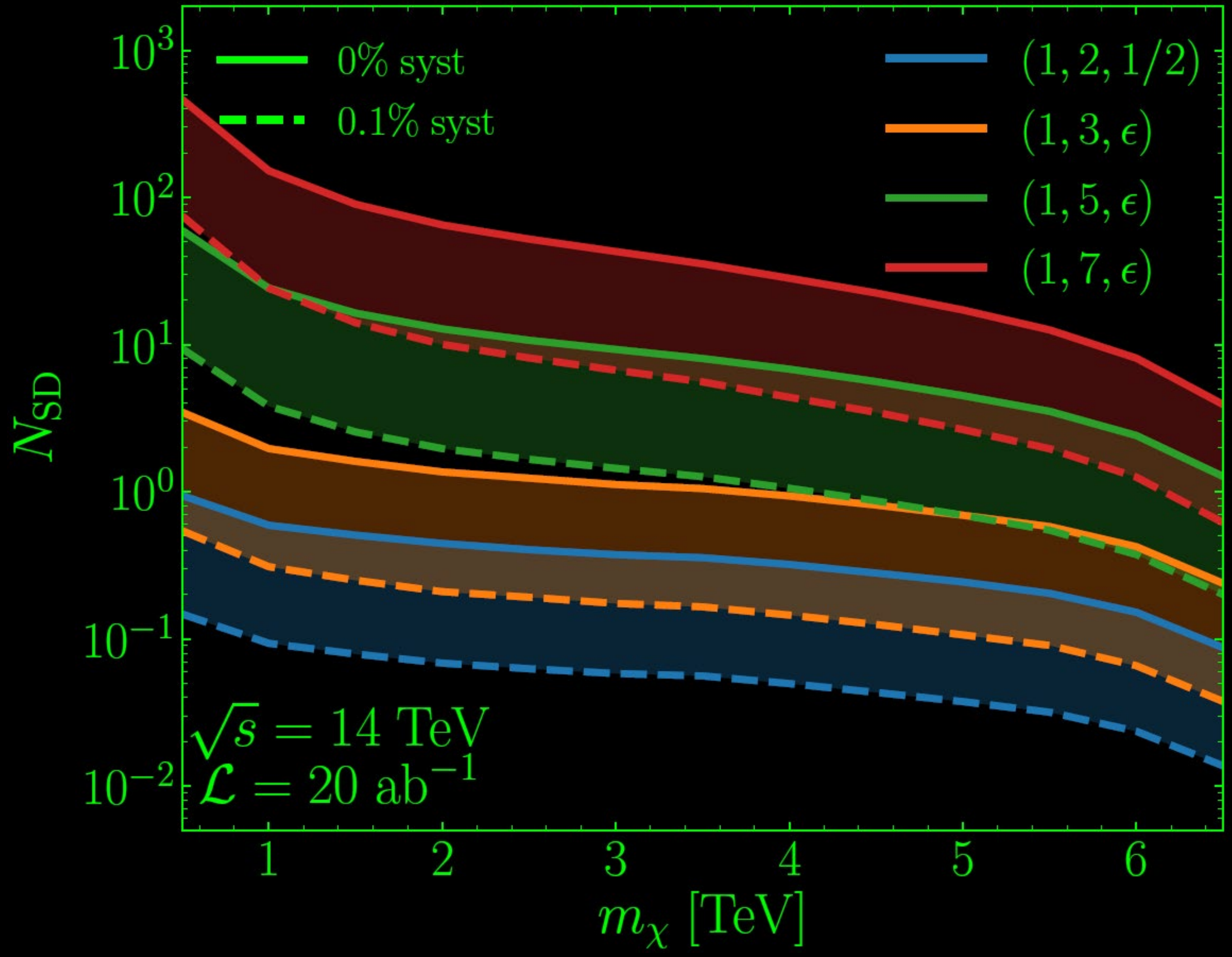
Signal-background ratio 10^-3
At lepton colliders systematics controlled to this level should be achievable but requires theory & experimental work

Mono-photon

Missing mass:

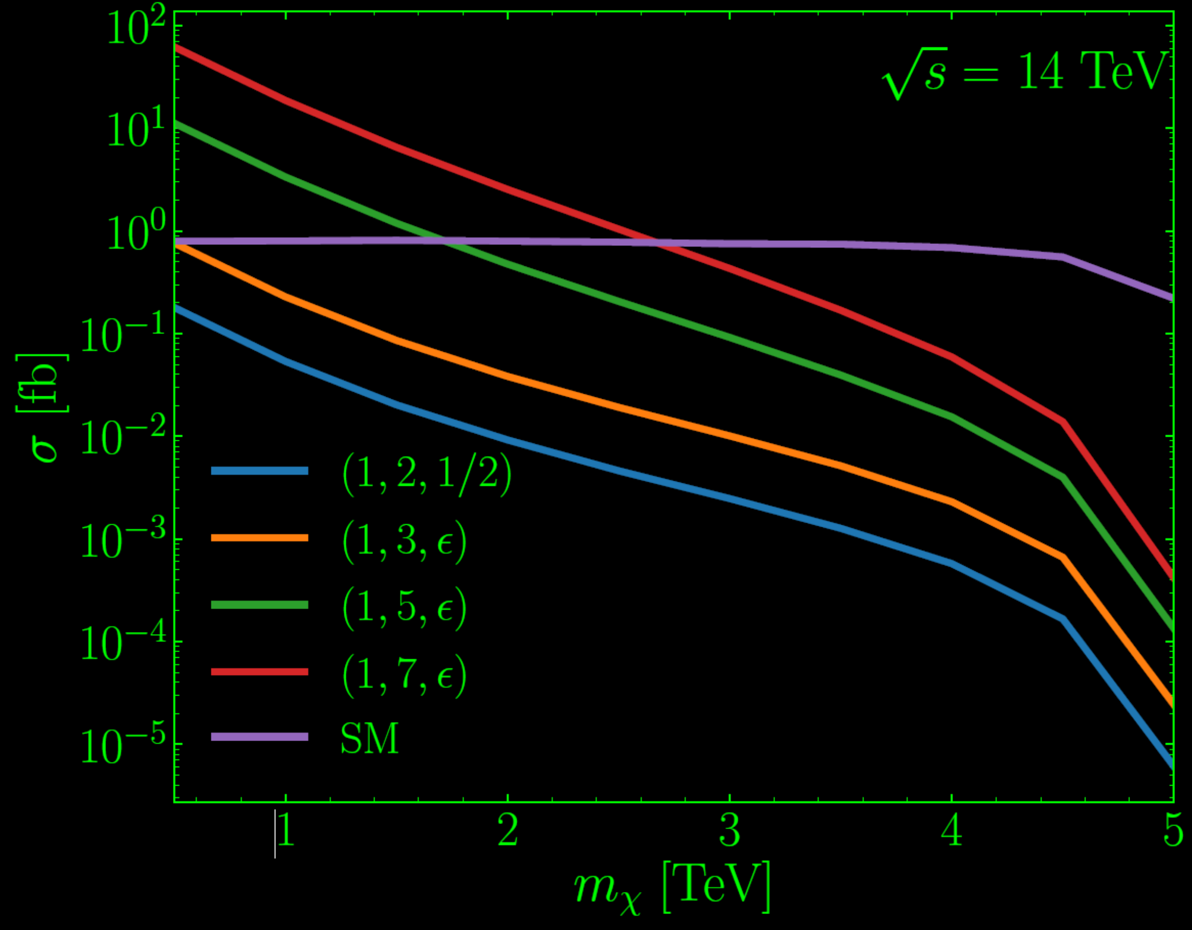
- Sharp kinematic features
- Signal-background separation
- Signal parameter determination



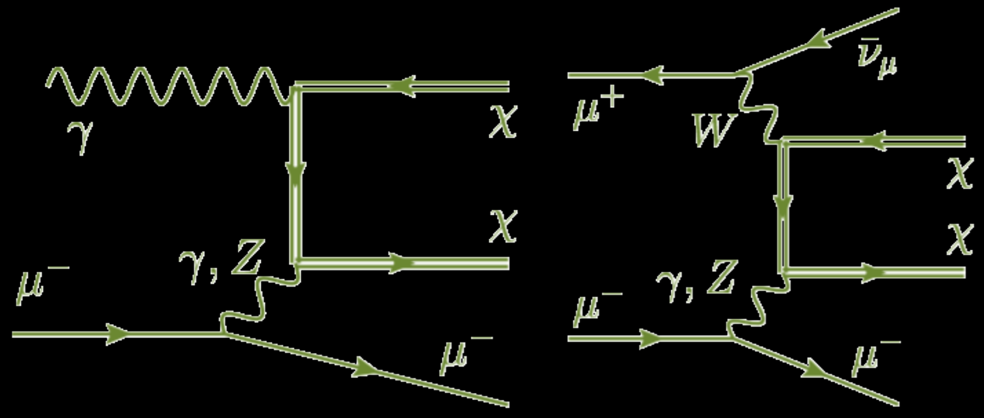


Unique Mono-Muon Channel

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



Signature: Energetic mono muon



Muon pairs → muon + missing mass

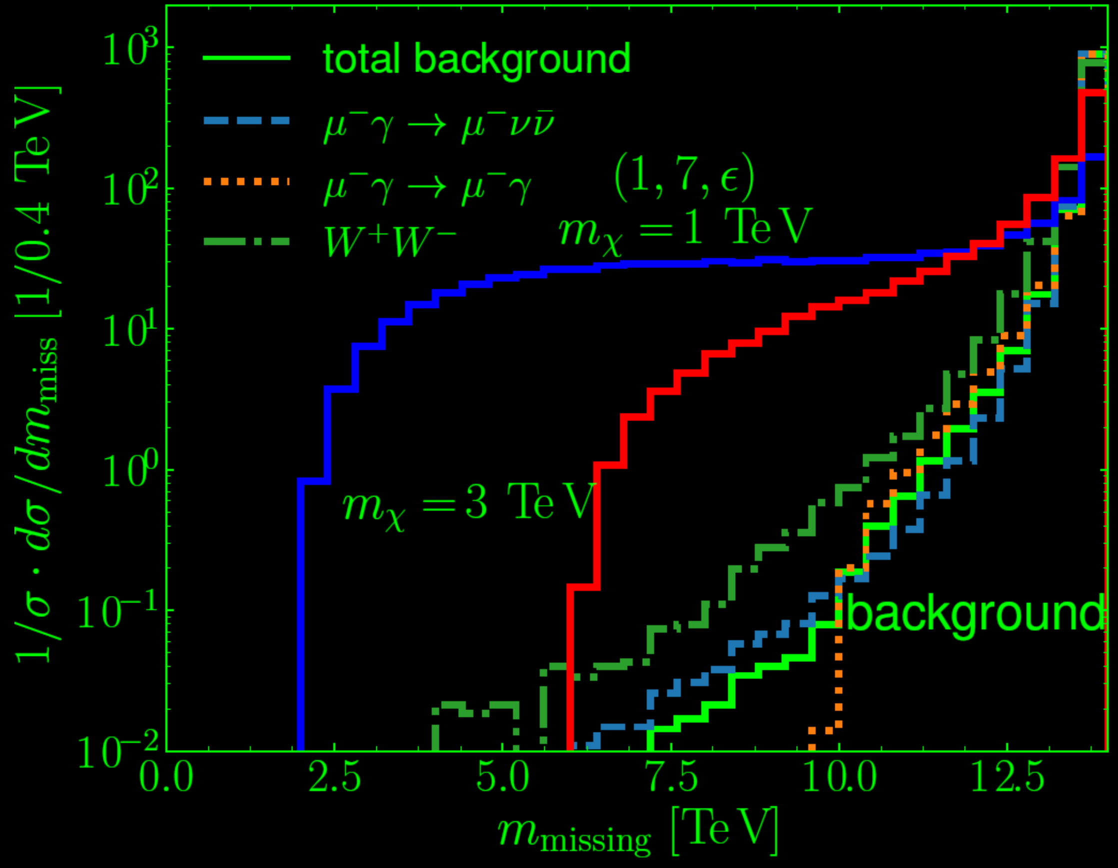
One charge is missed due to the soft (non-reconstructable) decays of the charged states

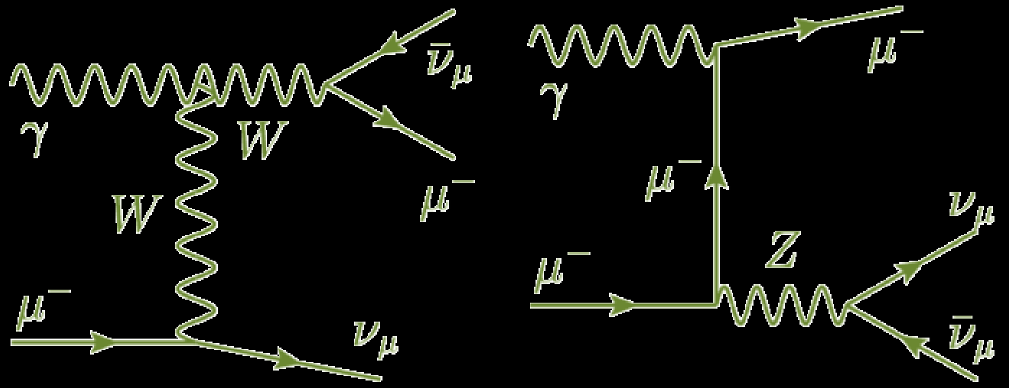
Unique and powerful channel for low-rate channels.

Unique Mono-Muon Channel

Complex background compositions:

from missing a SM particles via various mechanisms





Collinear emissions, missing final state muons, properly calculated using photon PDF

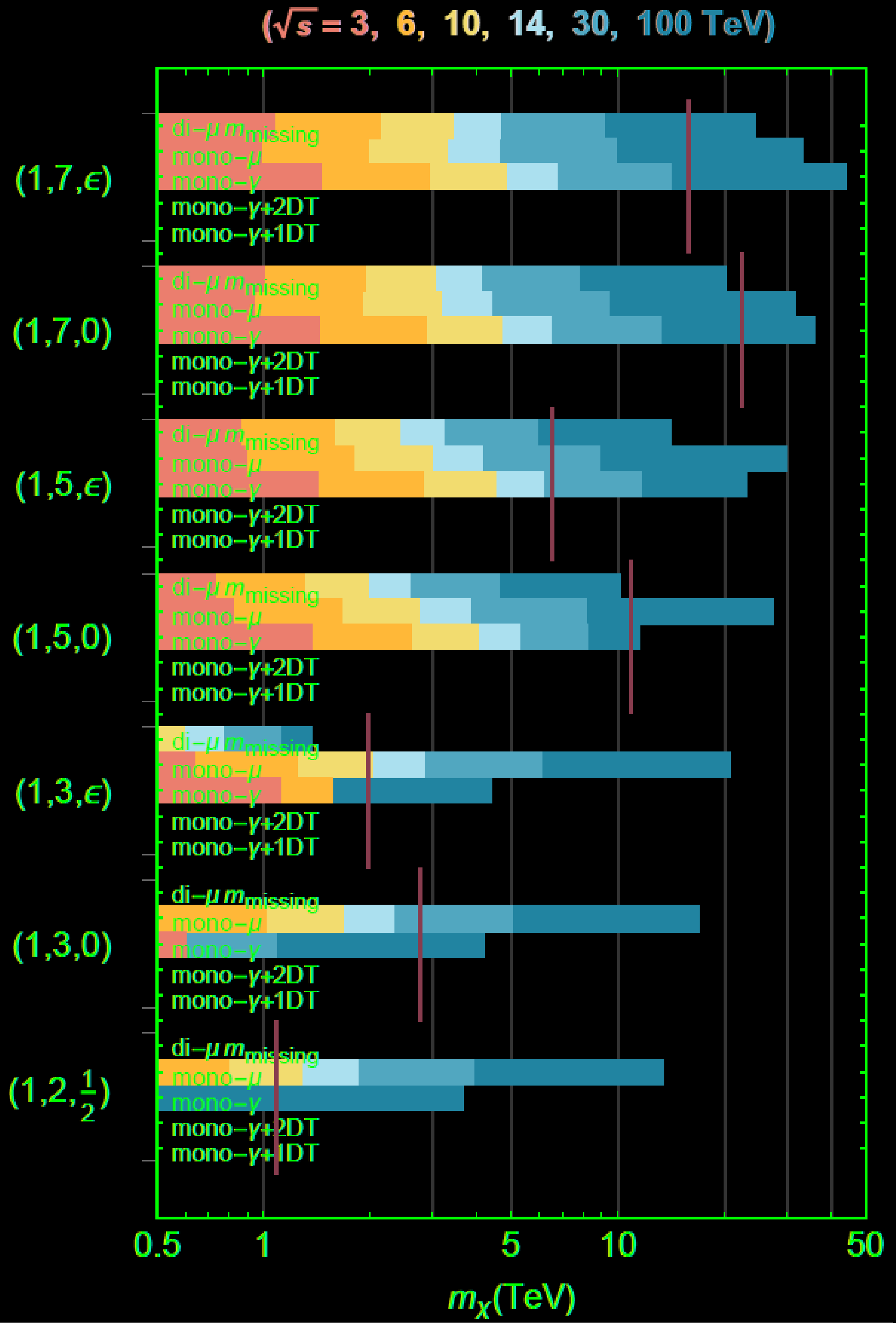
Also includes dominant 2->2 processes with one of them decays forward

$$10^\circ < \theta_{\mu^-} < 90^\circ, \quad 90^\circ < \theta_{\mu^+} < 170^\circ$$

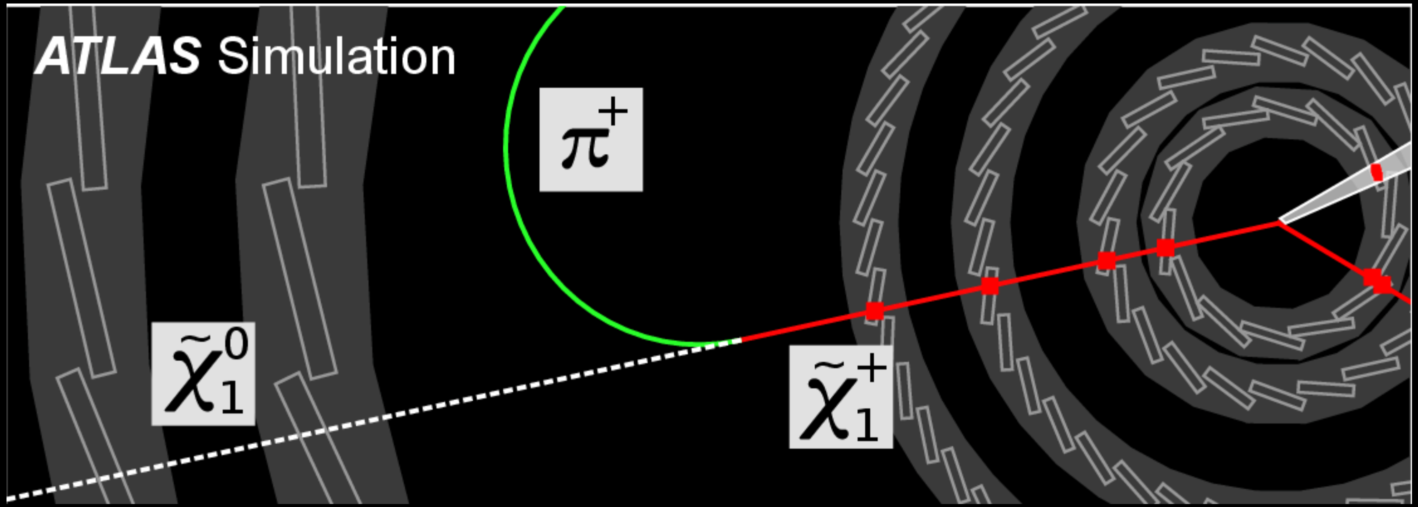
$$E_{\mu^\pm} > 0.71,\ 1.4,\ 2.3,\ 3.2,\ 6.9,\ 22.6\ \text{TeV}, \quad \text{for } \sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30,\ 100\ \text{TeV}$$

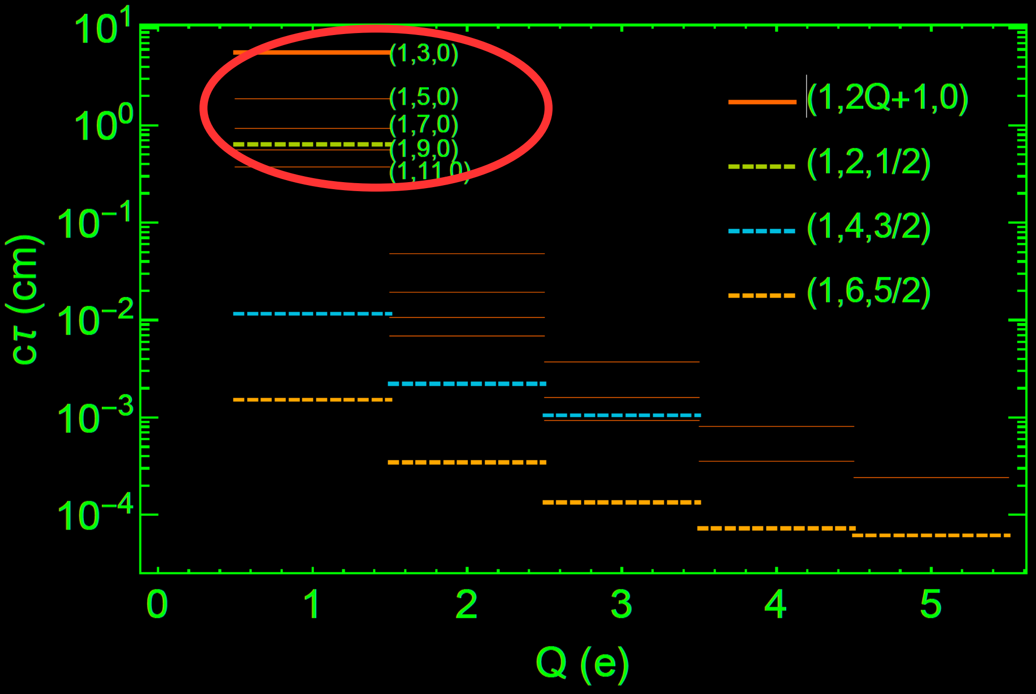
Summary (by channel)

- Mono-photon powerful for high n-plets
- Mono-muon uniquely powerful low multplets (Wino and Higgsinos)
- VBF dimuon large room to improve (we conservatively assumed |\eta mu|<2.5, losing lots of signals)

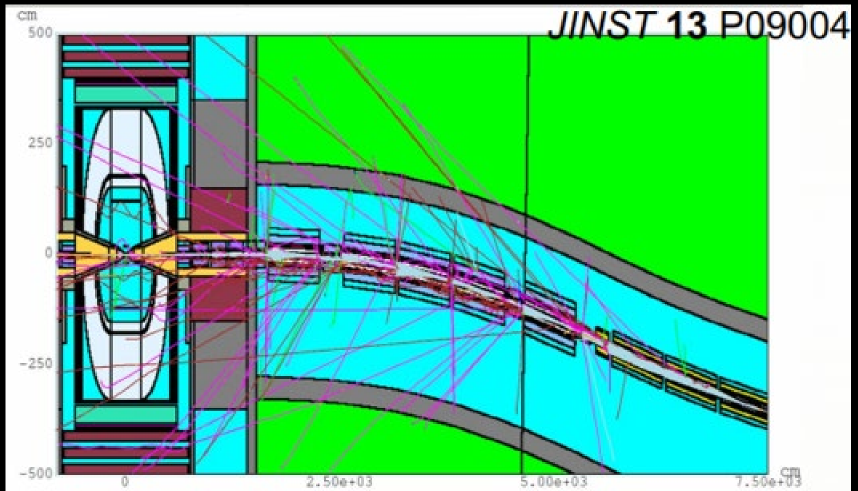


Disappearing Tracks: next to minimal signatures





- 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

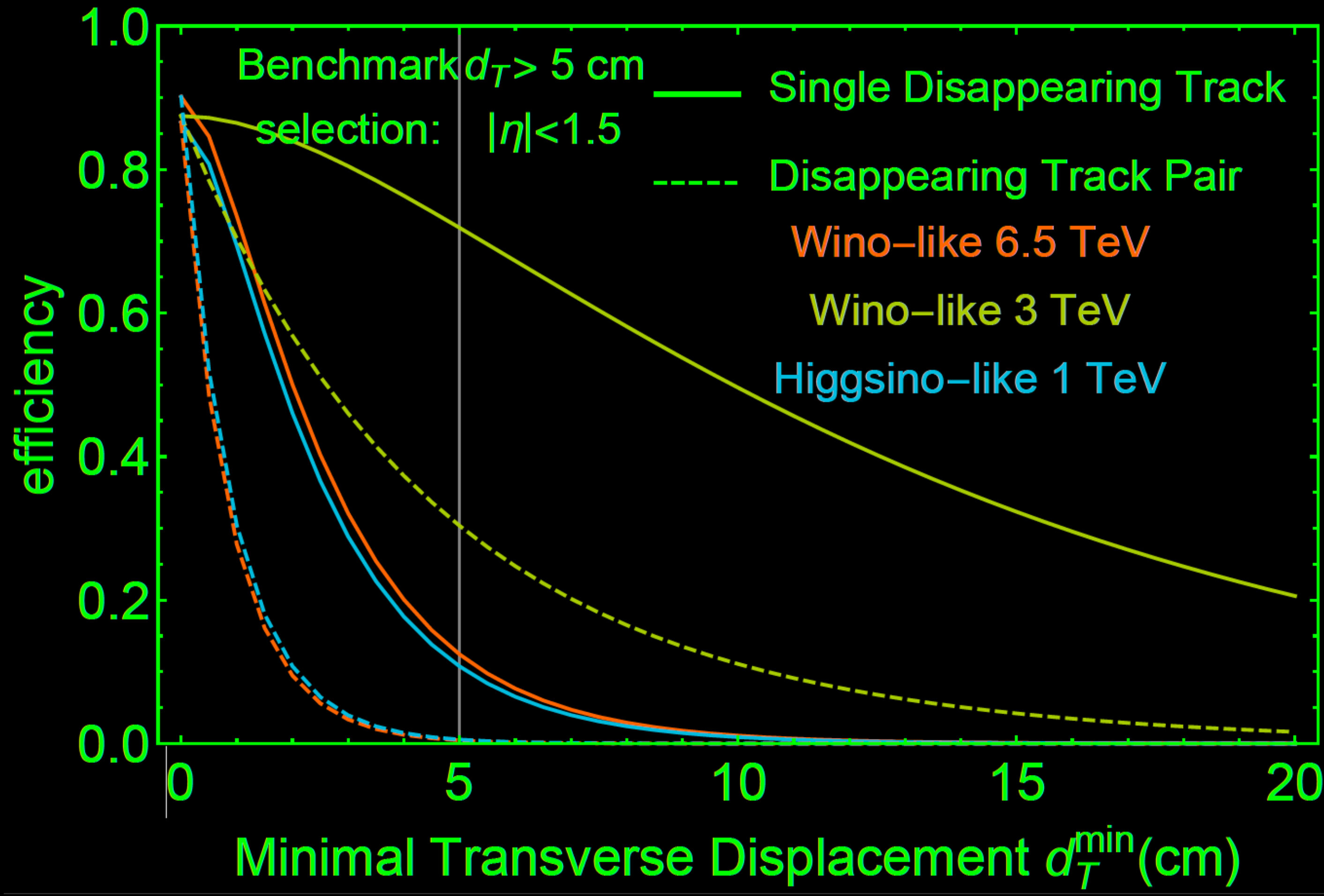


Minimal transverse displacement

- 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

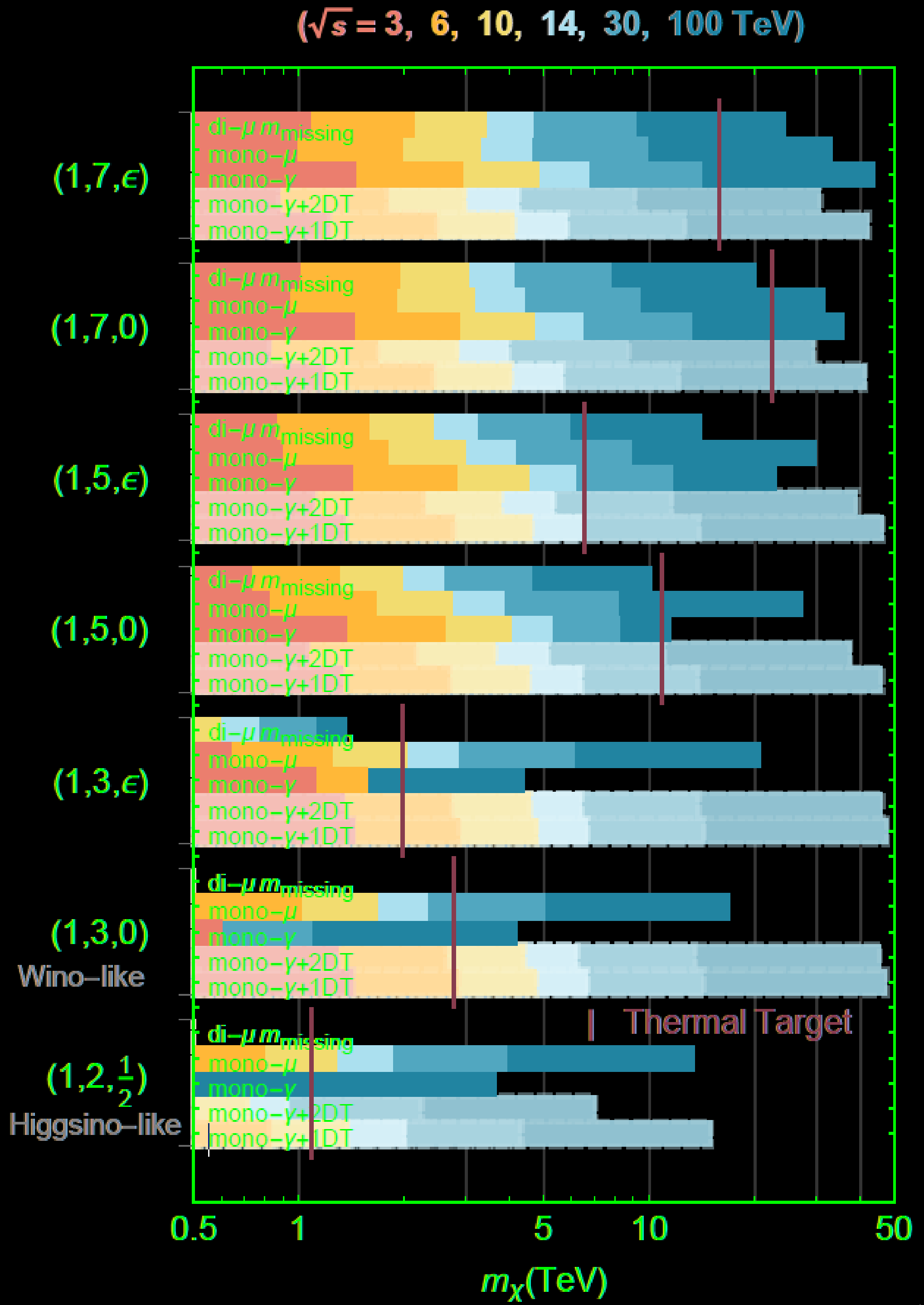
$$d_T^{\min} = 5 \text{ cm with } |\eta_\chi| < 1.5$$

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



Summary (by channel)

- Mono-photon powerful for high n-plets
- Mono-muon uniquely powerful low multplets (Wino and Higgsinos)
- VBF dimuon large room to improve (we conservatively assumed |\eta mu|<2.5, losing lots of signals)
- Disappearing track great potential (can push to the kinematic limit)!



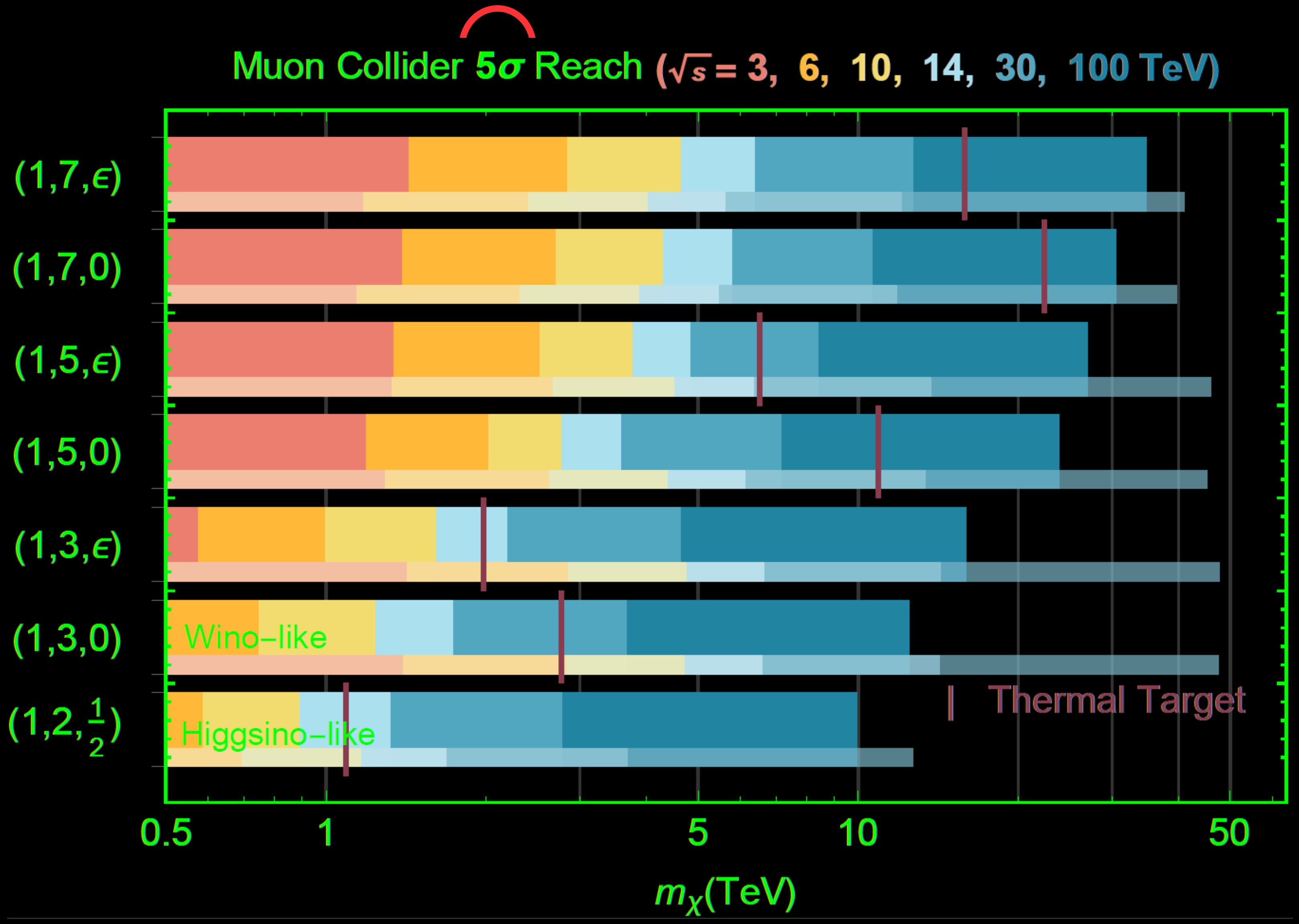
Summary (by energy)

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).

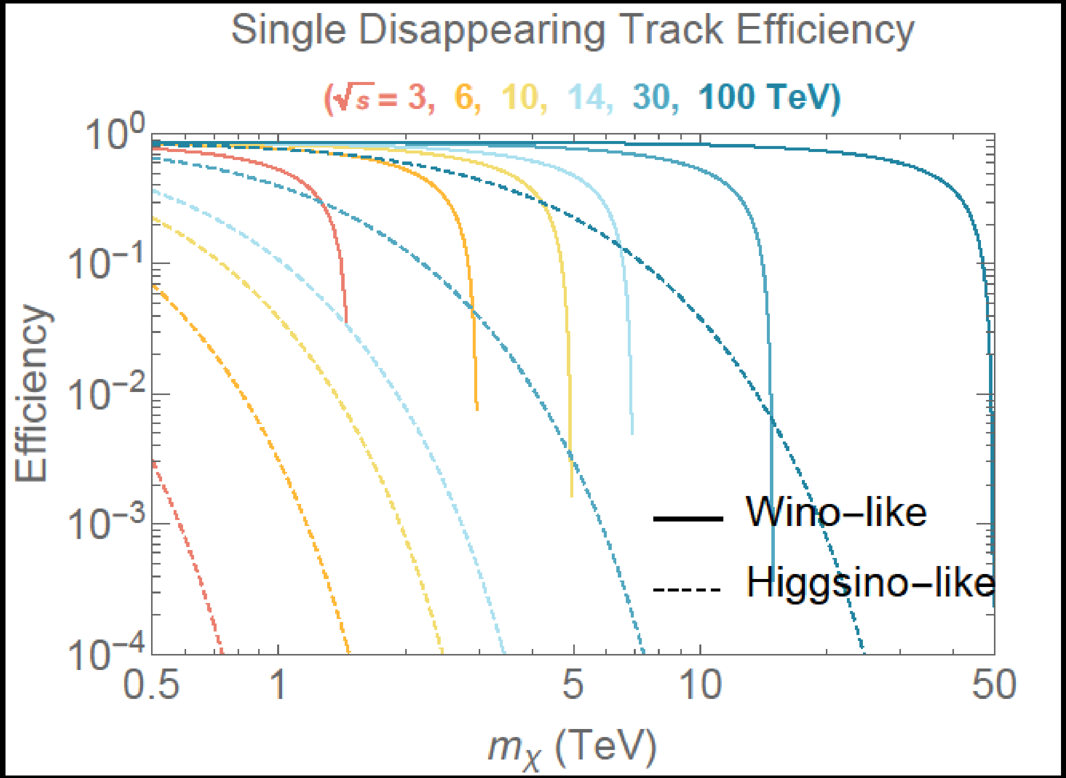


Summary & Outlook

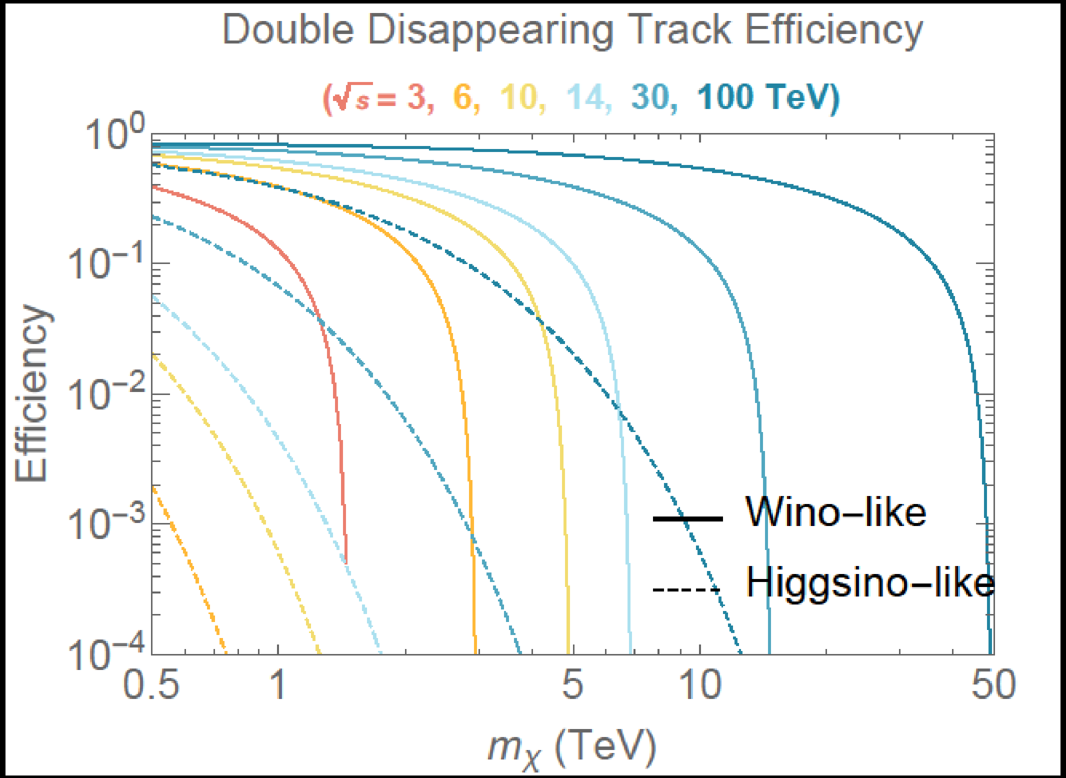
- Muon Collider (MuC) an exciting future
- Ask the physics driver cases
- WIMP Dark Matter fully testable at MuC
    - Demonstrated using EW multiplets
    - Missing mass signature
    - Disappearing track signature
    - Interplay between channels
- Further studies on optimization needed
- One can consider general new EW states or co-annihilation, the reaches should be better than our minimal "nightmare scenario"
- More new physics driver cases to consider

Thank you!

Back up

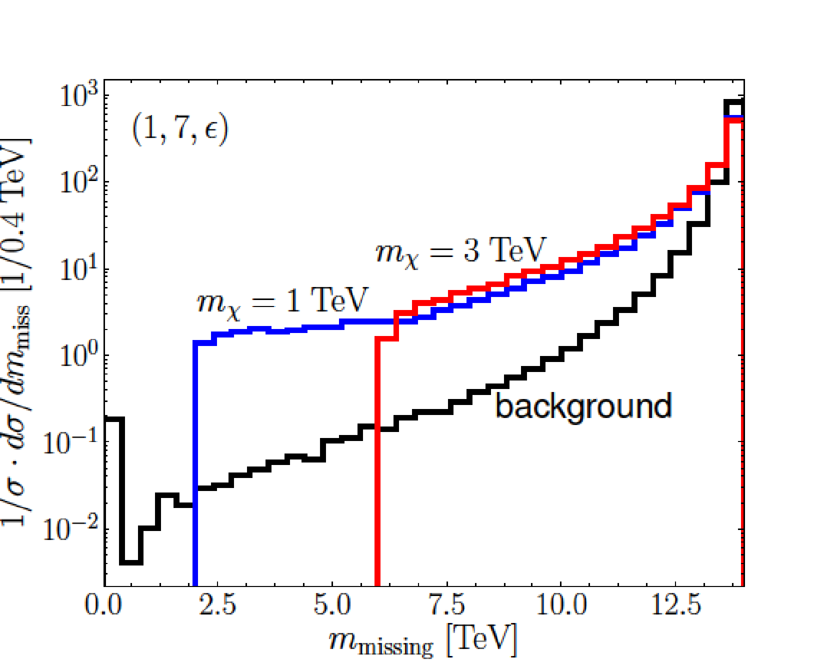


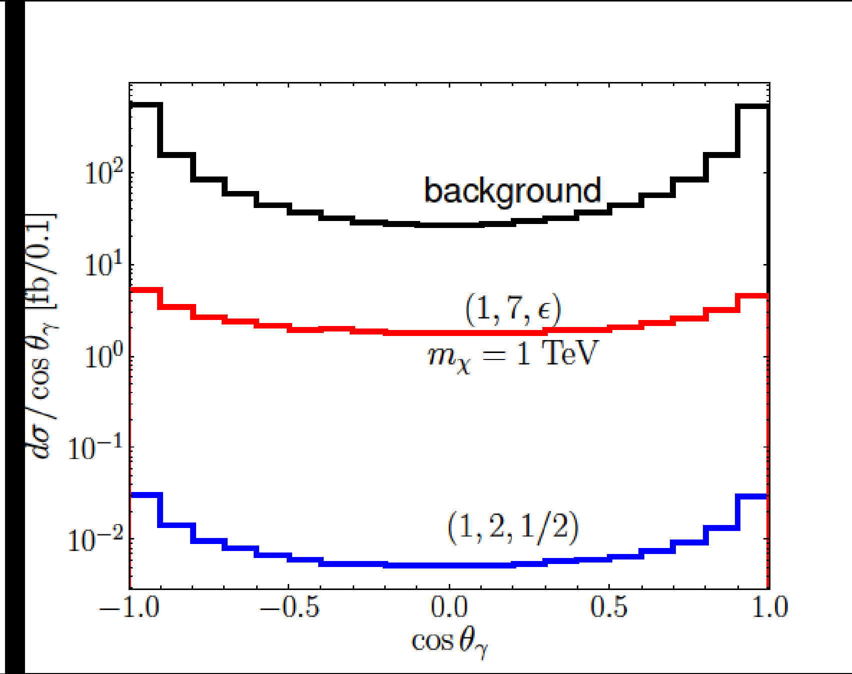
Single Disappearing Track Efficiency
($\sqrt{s}$ = 3, 6, 10, 14, 30, 100 TeV)
Efficiency
m_χ (TeV)
Wino–like
Higgsino–like

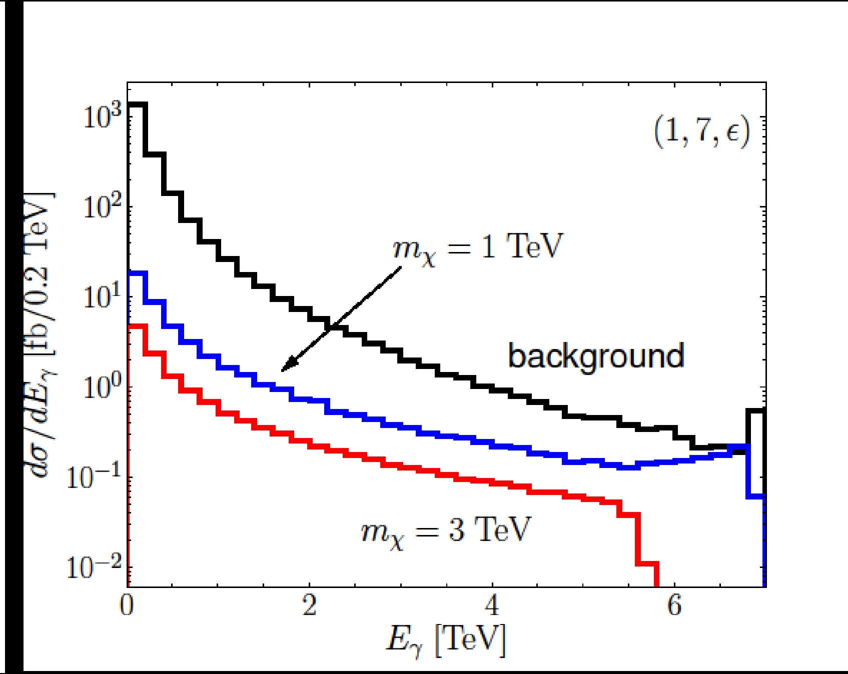


Double Disappearing Track Efficiency
($\sqrt{s}$ = 3, 6, 10, 14, 30, 100 TeV)
Efficiency
m_χ (TeV)
Wino–like
Higgsino–like

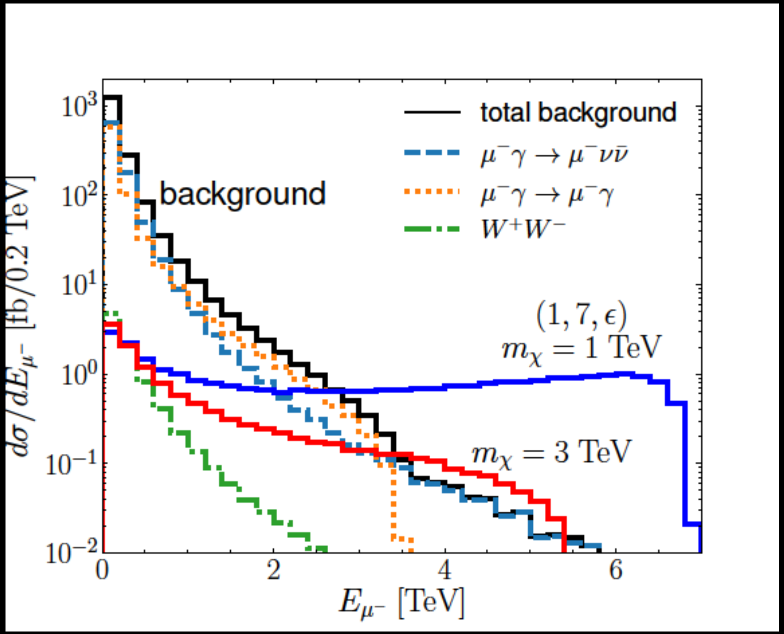
Mono-Photon Kinematics

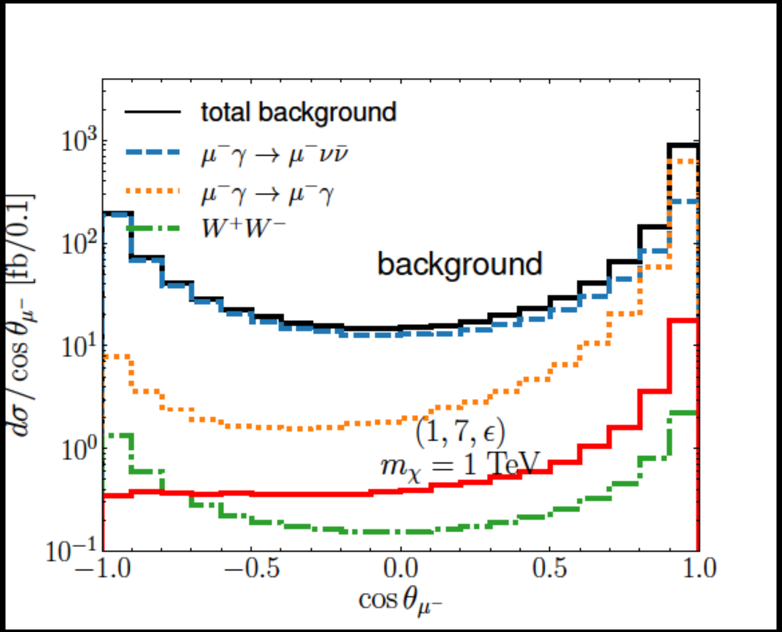


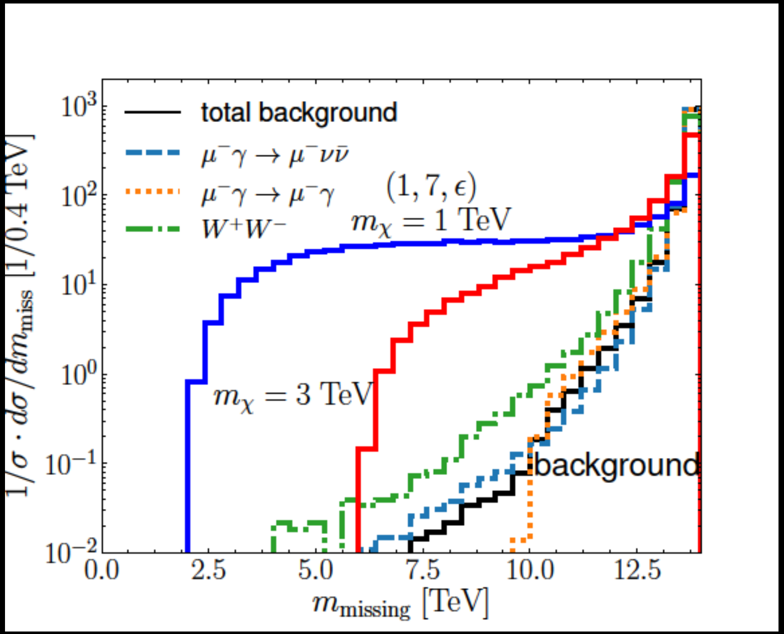


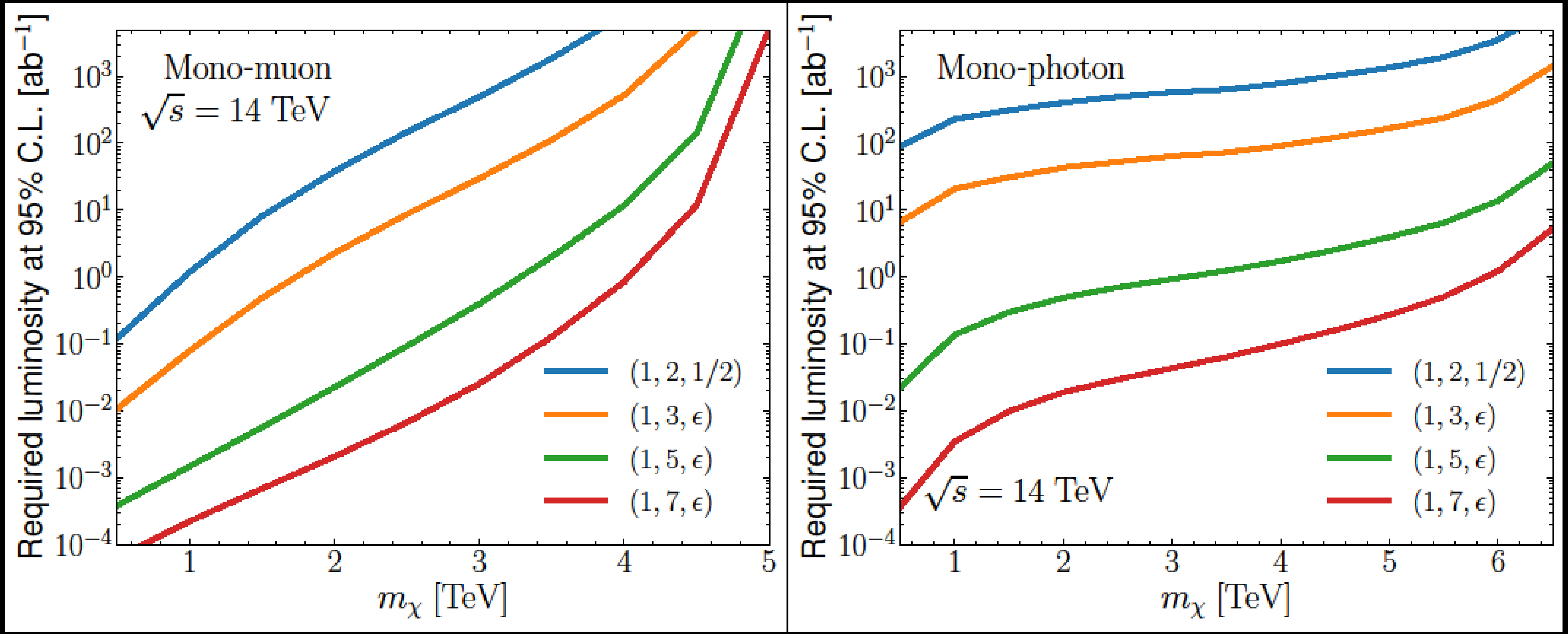


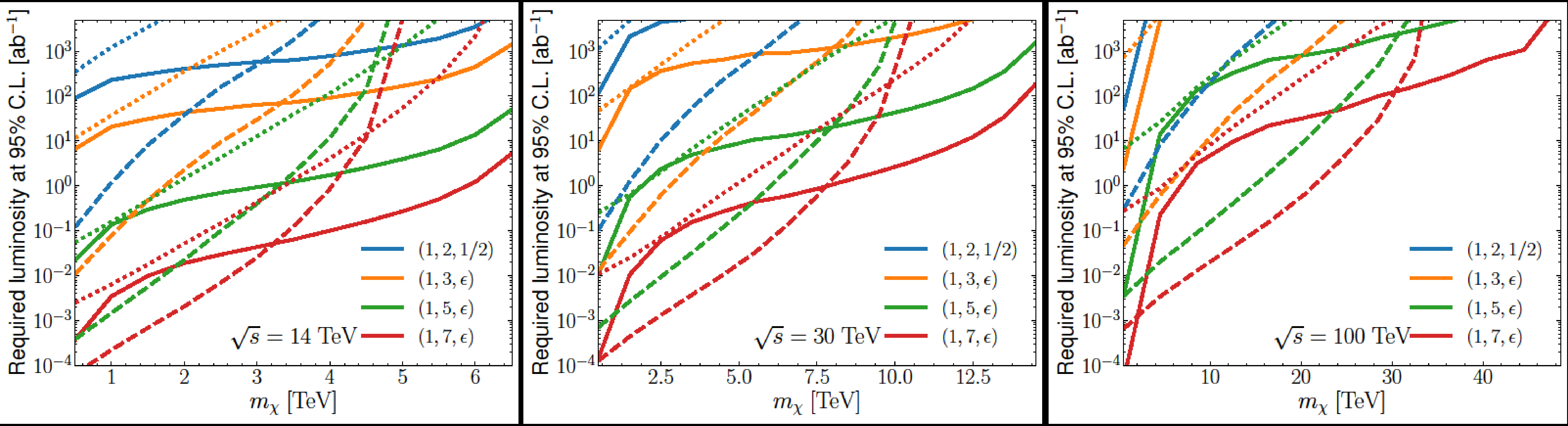
Mono-muon Kinematics



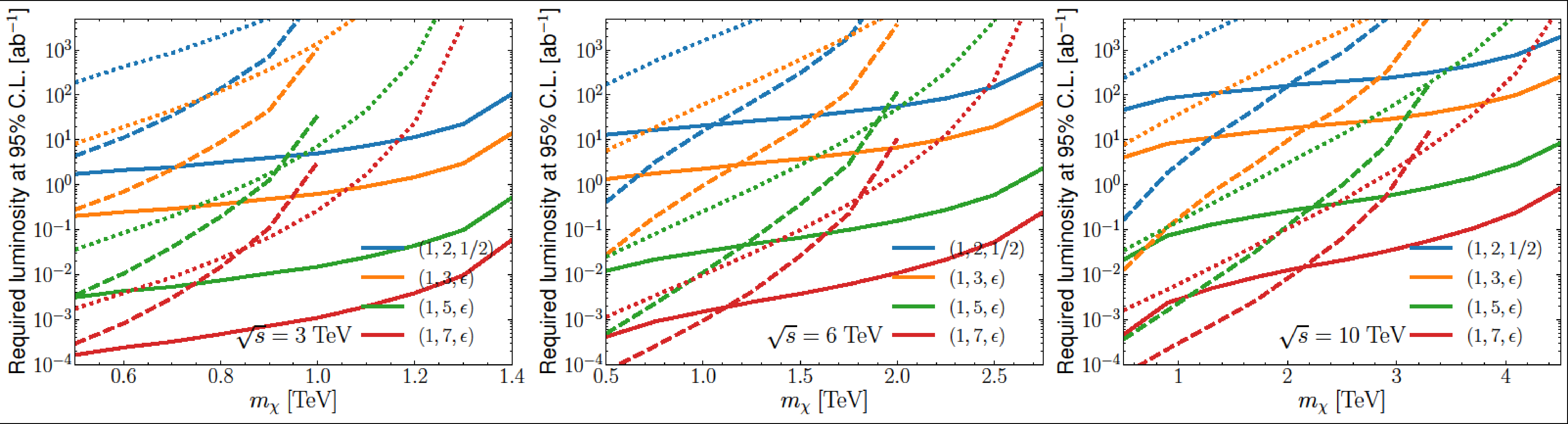


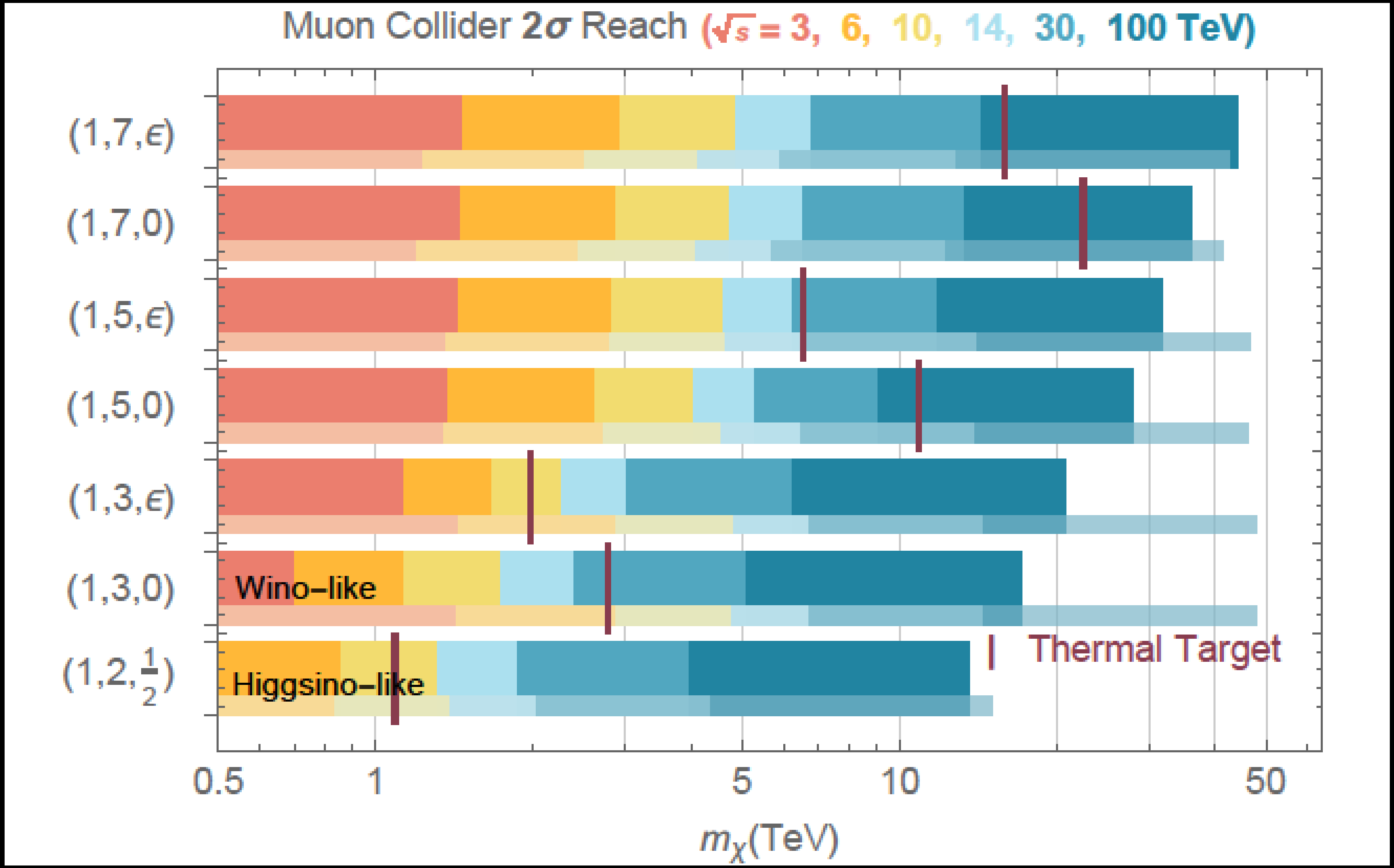



Mono-muon
$\sqrt{s} = 14$ TeV
Mono-photon
$\sqrt{s} = 14$ TeV
Required luminosity at 95% C.L. [ab^{-1}]
m_χ [TeV]
$(1, 2, 1/2)$
$(1, 3, \epsilon)$
$(1, 5, \epsilon)$
$(1, 7, \epsilon)$



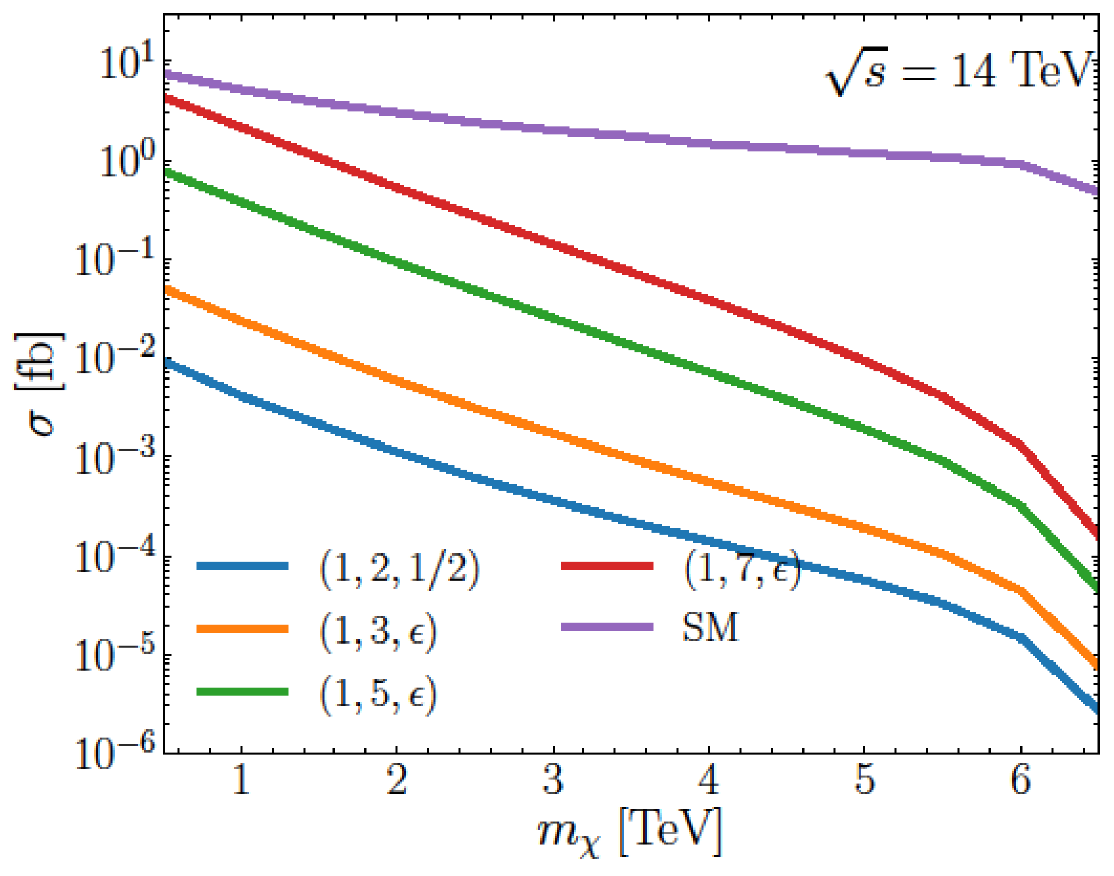
Required luminosity at 95% C.L. [ab^{-1}]
m_χ [TeV]
$\sqrt{s}$ = 14 TeV
$\sqrt{s}$ = 30 TeV
$\sqrt{s}$ = 100 TeV
(1, 2, 1/2)
(1, 3, ϵ)
(1, 5, ϵ)
(1, 7, ϵ)

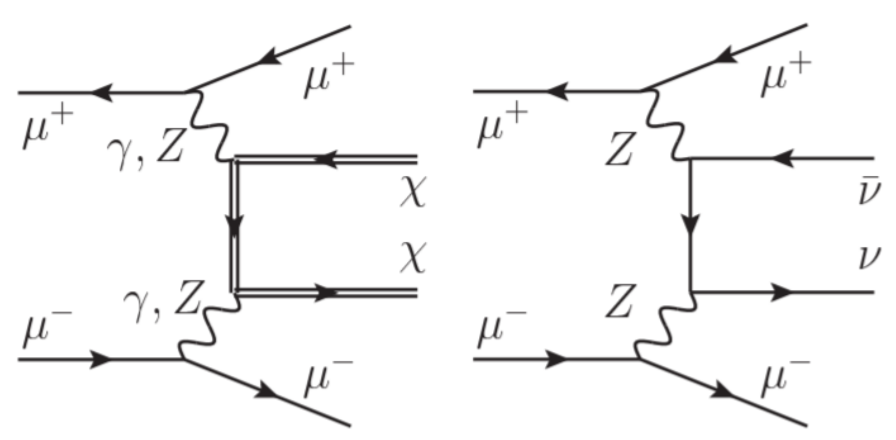

Required luminosity at 95% C.L. [ab^{-1}]
m_χ [TeV]
$\sqrt{s} = 3$ TeV
$\sqrt{s} = 6$ TeV
$\sqrt{s} = 10$ TeV
$(1, 2, 1/2)$
$(1, 3, \epsilon)$
$(1, 5, \epsilon)$
$(1, 7, \epsilon)$



Muon Collider 2σ Reach ($\sqrt{s}$ = 3, 6, 10, 14, 30, 100 TeV)
(1,7,ϵ)
(1,7,0)
(1,5,ϵ)
(1,5,0)
(1,3,ϵ)
(1,3,0)
(1,2,1/2)
Wino–like
Higgsino–like
Thermal Target
0.5
1
5
10
50
m_χ(TeV)

VBF diphoton

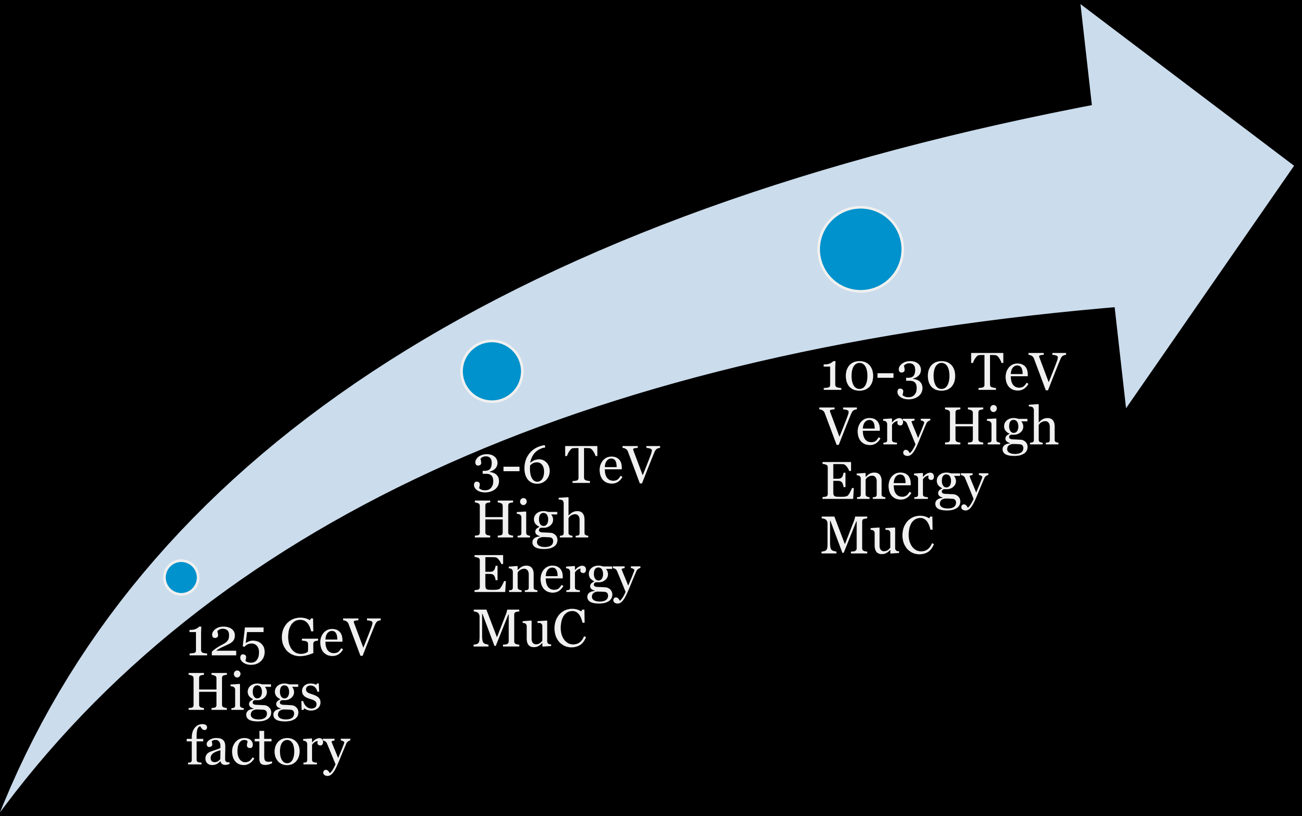




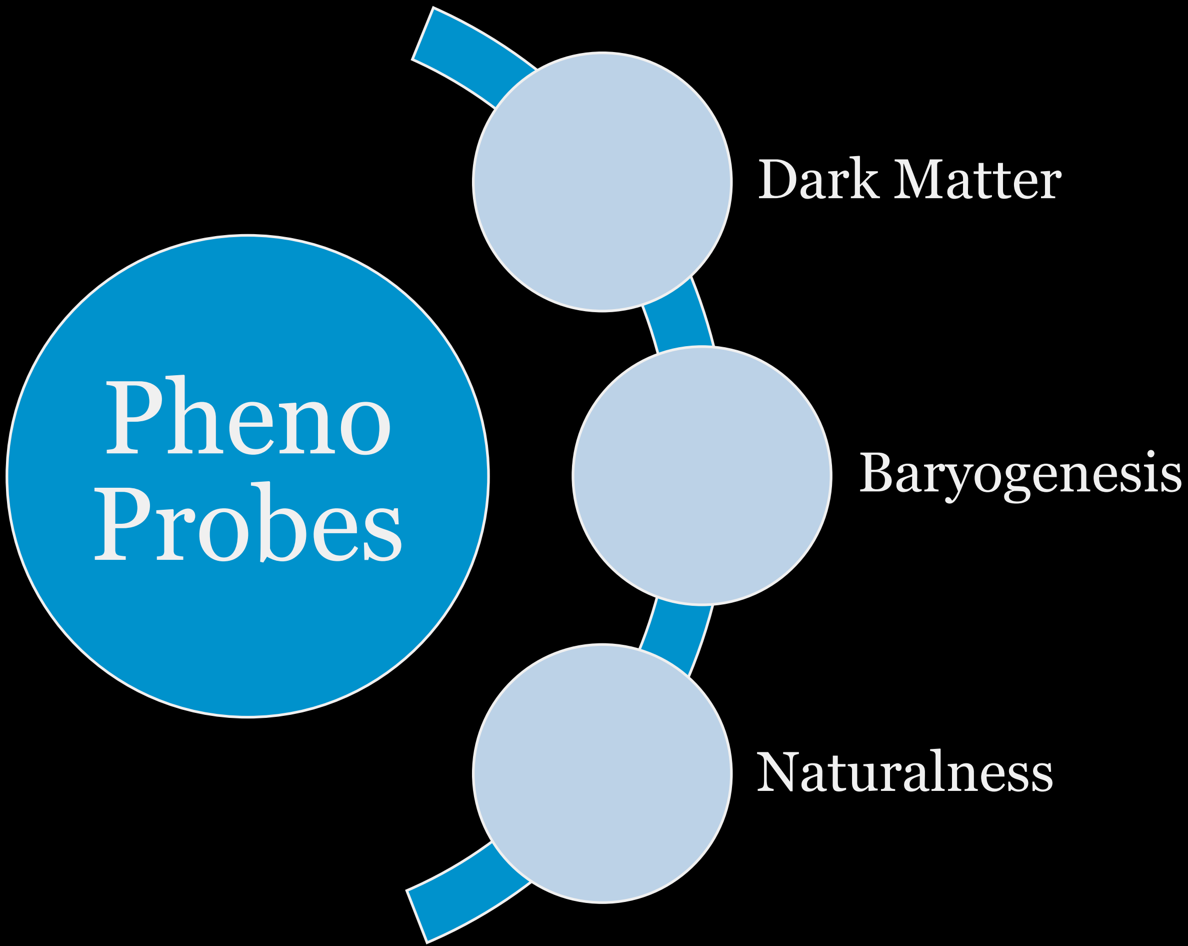
Signal cross sections decreases as 1/mchi^4, but grows logarithmically with beam energy for a fixed mchi.

$$m_{\mu^+\mu^-} > 300\ \text{GeV}, \quad m_{\text{missing}} = (p^{\text{in}}_{\mu^+} + p^{\text{in}}_{\mu^-} - p^{\text{out}}_{\mu^+} - p^{\text{out}}_{\mu^-})^2 > 4m_\chi^2$$

The Dream Machine

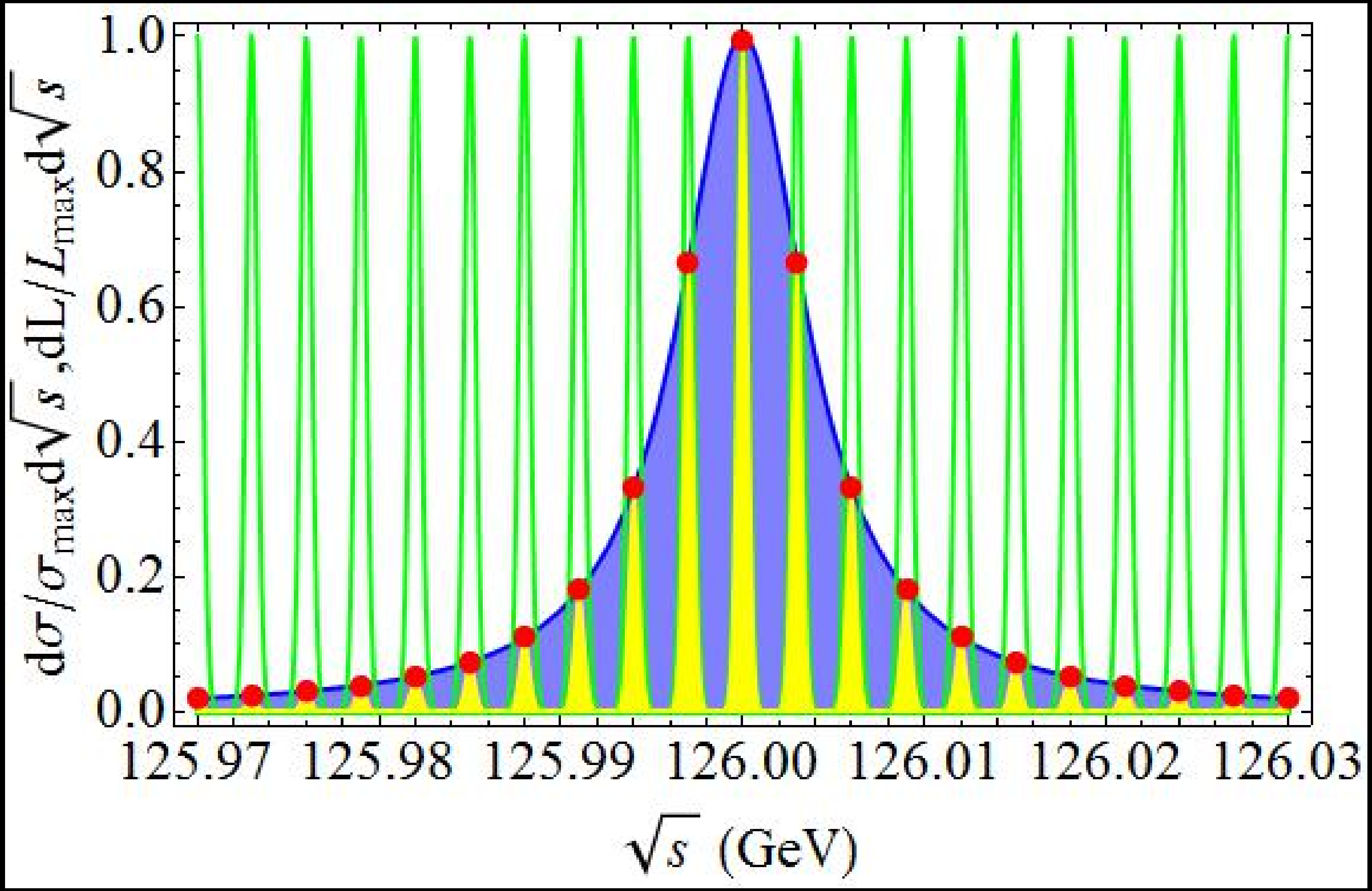


Physics Driver



We shall be open to new theory paradigm shift, and experimental new physics discoveries (cannot rely on that happening, though)

Extreme (good) Case:



Energy Spread much narrower than the physical width:

Δ = 0.3 MeV

Γ_h = 4.2 MeV

Breit-Wigner

Gaussian Profile (beam)

Overlap (observable rate)

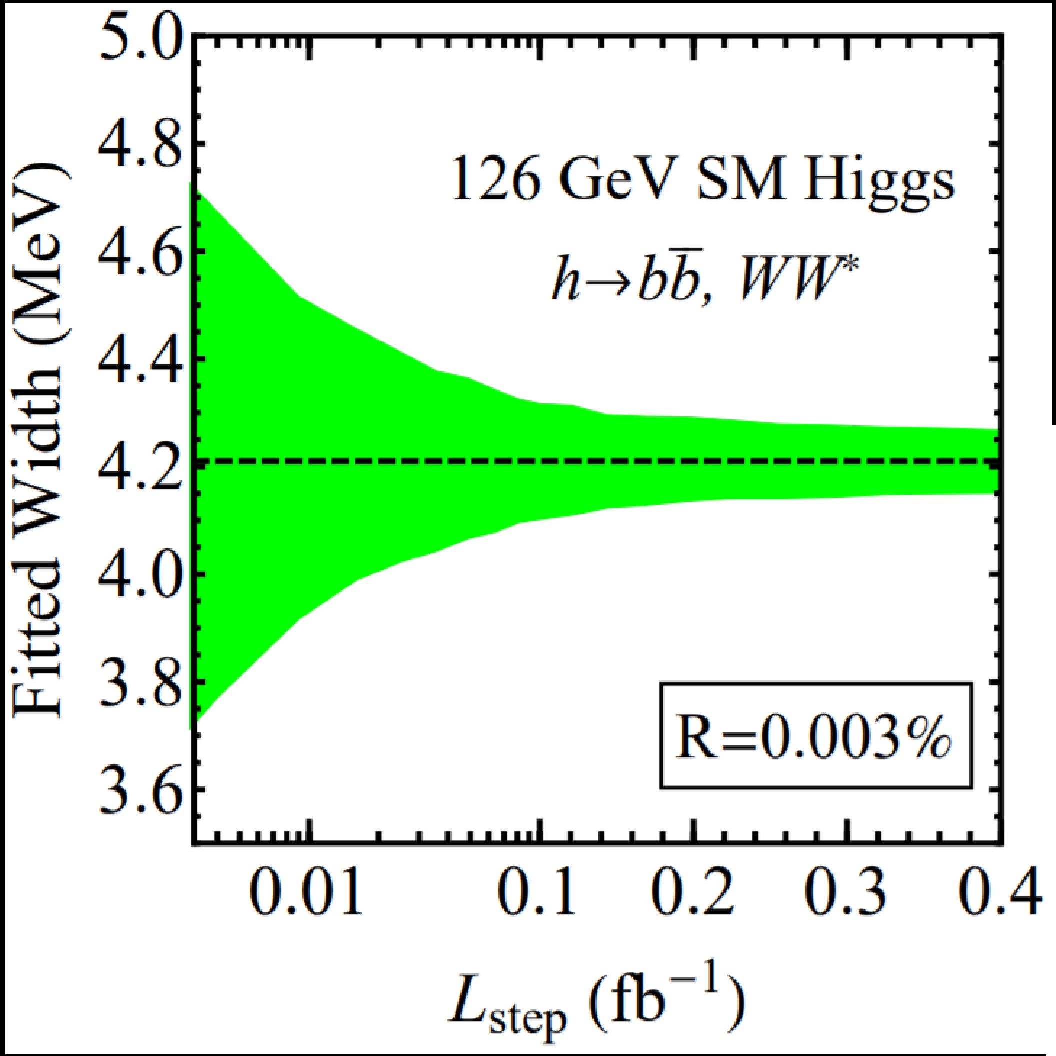
Effective cross section (observable scan)

Recall: Z scan @LEP

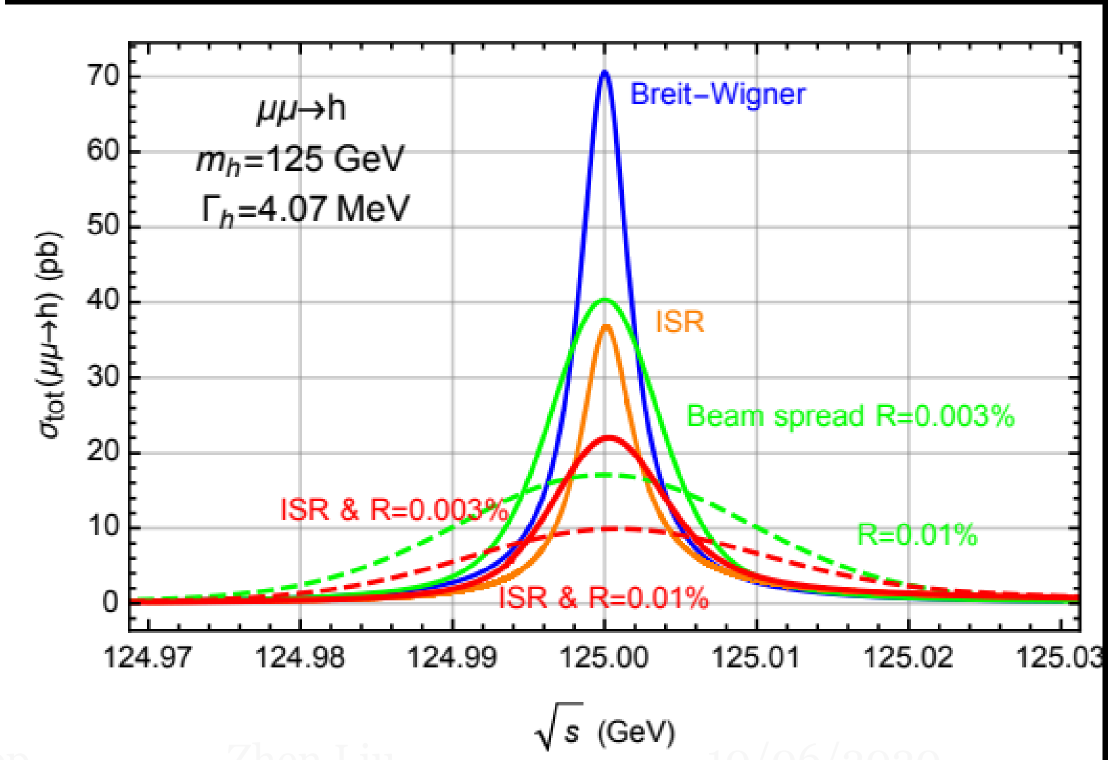
Γ = 2.5 GeV

Fitting the SM Higgs

Han, ZL, 1210.7803; also see Conway, Wenzel 1304.5270



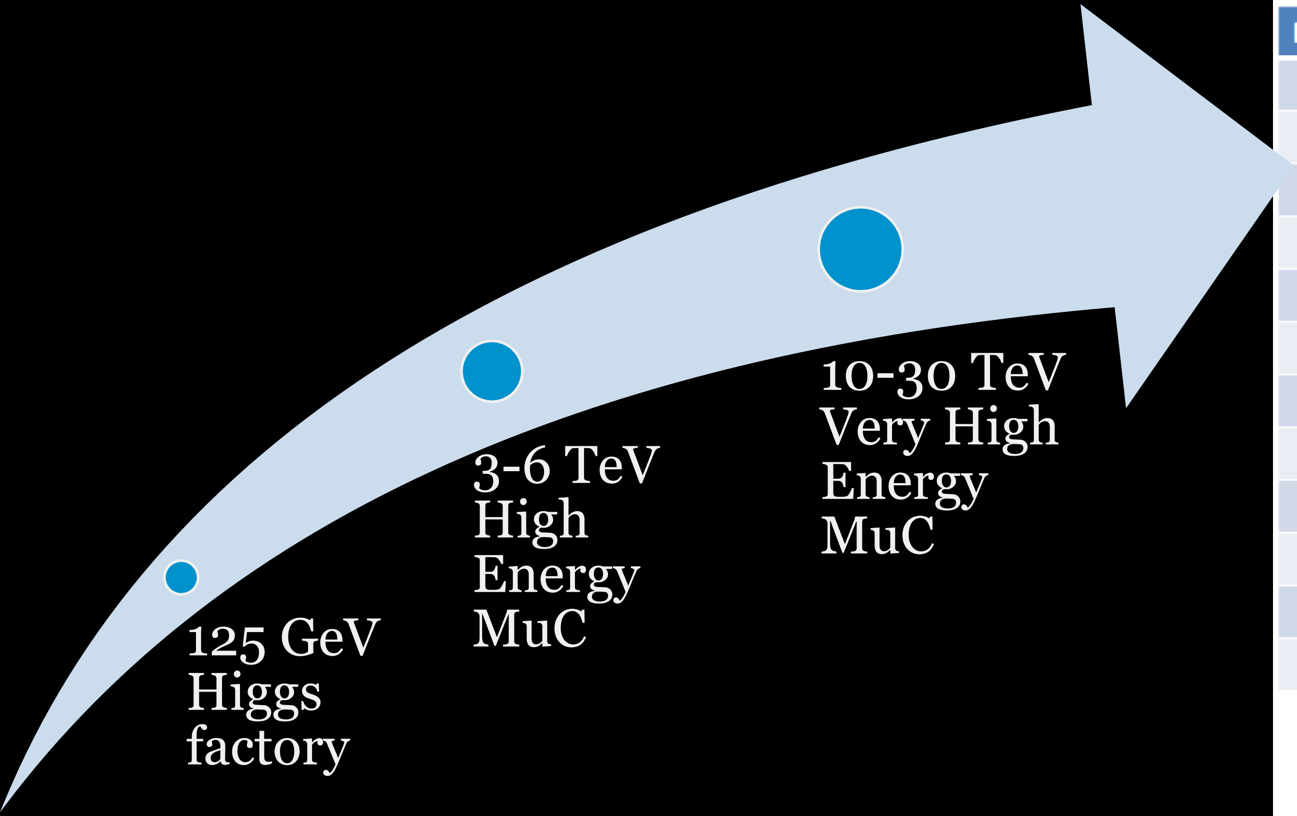
$\Gamma_h = 4.21$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$R = 0.01\%$	0.005	0.73	6.5%	0.25
	0.025	**0.35**	**3.0%**	**0.12**
	0.2	0.17	1.1%	0.06
$R = 0.003\%$	0.01	0.30	4.4%	0.12
	0.05	**0.15**	**2.0%**	**0.06**
	0.2	0.08	1.0%	0.03



Greco, Han, ZL, 1607.03210

Resolving interferences, ZL, et al, arXiv:1308.2143

10+ TeV Muon Collider: game changer & dream machine



Tentative Target Parameters

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

Based on MAP source and concept

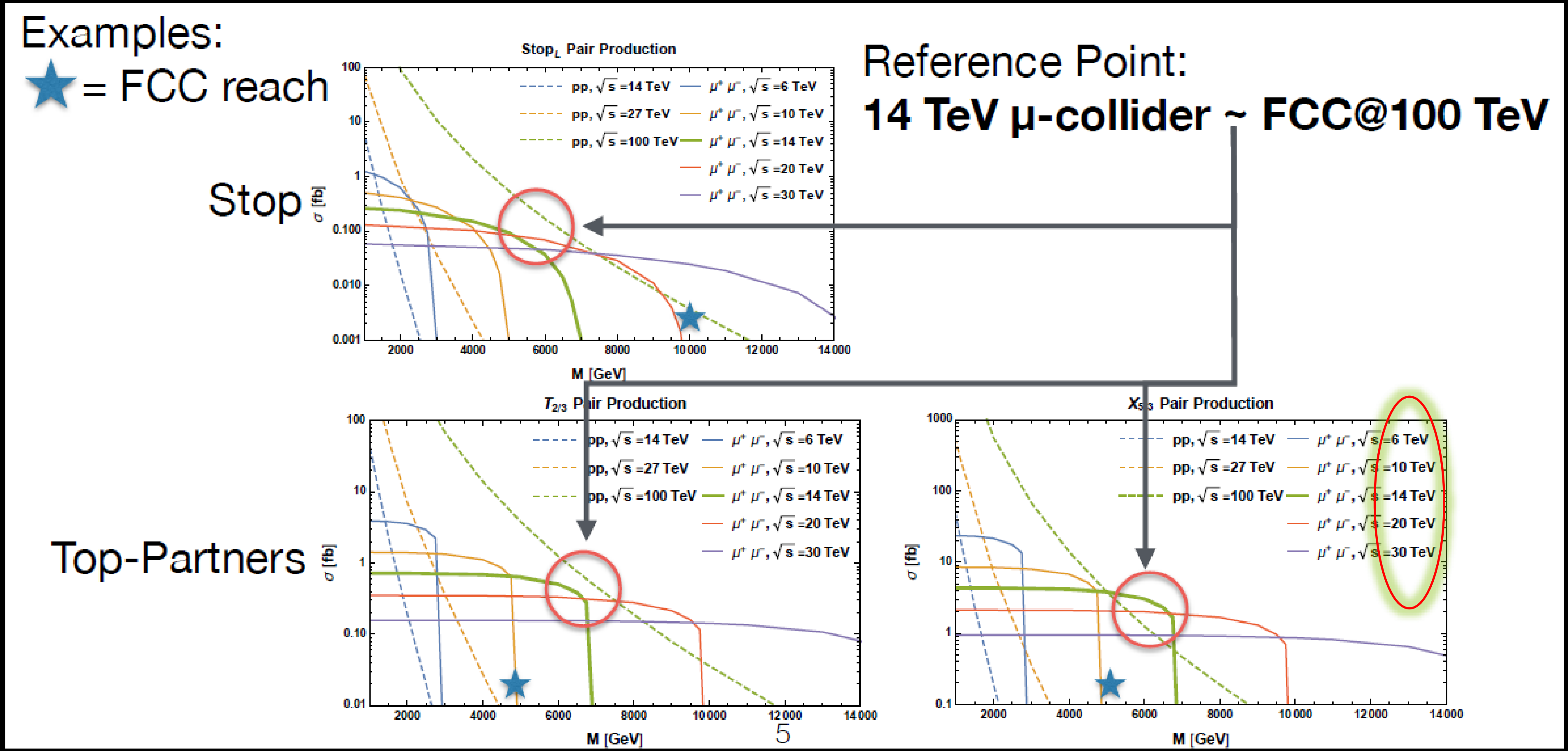
The same source for all energies

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

D. Schulte Interna CERN, July 3, 2020

Dream Machine: no rivals

High Energies—the dream machine



Outperform 100 TeV collider in almost every aspect

(except for dijet resonances; particles only color charged, no EW charges)

For electroweak states, already winning if MuC have 3+ TeV energy

Suggested Studies (and things to pay attention to):

- Higgs trilinear extrapolation
  - (need solid prediction, with background, with some basic EFT treatment, e.g., simplified version of ZL et al, 1711.03978, Maltoni et al, 2003.13628)
- DM-motivated considerations and WIMP coverage
  - Mono-photon (consider beam spread and machine induced background)
  - Disappearing tracks (in the small lifetime region, in particular)
  - (in addition) soft particles plus missing momentum
  - (Refs, e.g., 1812.02093, 1805.00015, 1404.0682)
- Higgs precision projections (high energy measurement only)
  - Higgs factory projections reasonably understood (unless there is a new machine benchmark with orders of magnitude improvement in luminosity)
  - See the previous talk, more can be done to reach the robustness of the projections like in other colliders. Basically, one need to provide a list of projected sensitivities on different Higgs production and decay channels.
- Some generic Extensions of the SM
  - Zprime projections (through precision dilepton/dijet measurements, following ESU 1910.11775)
  - Heavy Higgs searches (somewhat known for 3 TeV, ZL et al 1408.5912)
- Naturalness-motivated consideration, top partner pair production pheno
  - (VBF matters) e.g., 2005.10289, Need to go beyond, 1901.06150

In all the above, pay attention to muon beam induced background & dare to work with the most optimistic machine parameters.

I compiled this list assuming the audience are more experimental oriented; for theorists, making more killer-cases (e.g., unique VBF for aQGC) and setting nice benchmarks for the following cases.

A side note

MAP is a extremely valuable contribution to the field, a US advantage, an FNAL advantage.

Increasing interests from international efforts, new LEMMA scheme

95’→00’→10’→20’→??

MuC meeting, many institutions (globally) expressed interests, more than 250 participants

The muon quartet: Gunion, Barger, Berger , Han hep-ph/9504330

Establishment of the MICE & **MAP** program

Discontinued funding for MAP

Higgs Discovery & much improved understanding of the physics of Higgs muon factory
Han & ZL, Eichten et al

Overall physics evaluation: physics/9901022

You will always hear two leading “criticism” (excuse of not thinking) on muon colliders:

- Where is the beam? (cooling and luminosity)
  - Solution: participate, understand, appreciate the muon cooling researches (as well as LEMMA), and be optimistic
- Background from muons decaying in flight
  - Solution: try to estimate and convince yourself it won’t be a problem.

Path Forward

Highest priority is to form the collaboration

- All partners taking ownership
  - define the work programme
  - find resources
  - start to work

Web page: http://muoncollider.web.cern.ch

- Will upload information

Mailing lists: MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch, MUONCOLLIDER_FACILITY@cern.ch

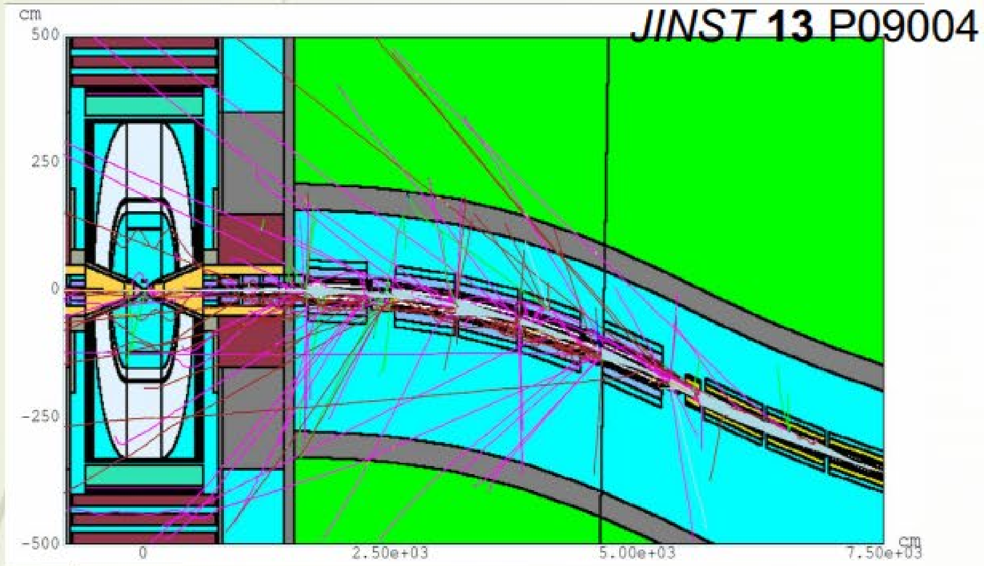
More details will come in the next three talks

Note: If you urgently need specific topics for your funding agency we will discuss this directly, we do have some good initial list

Many thanks to all that contributed
MAP collaboration
MICE collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
...

Main Challenge

A muon collider experiment has to cope with the large beam-induced background (BIB).

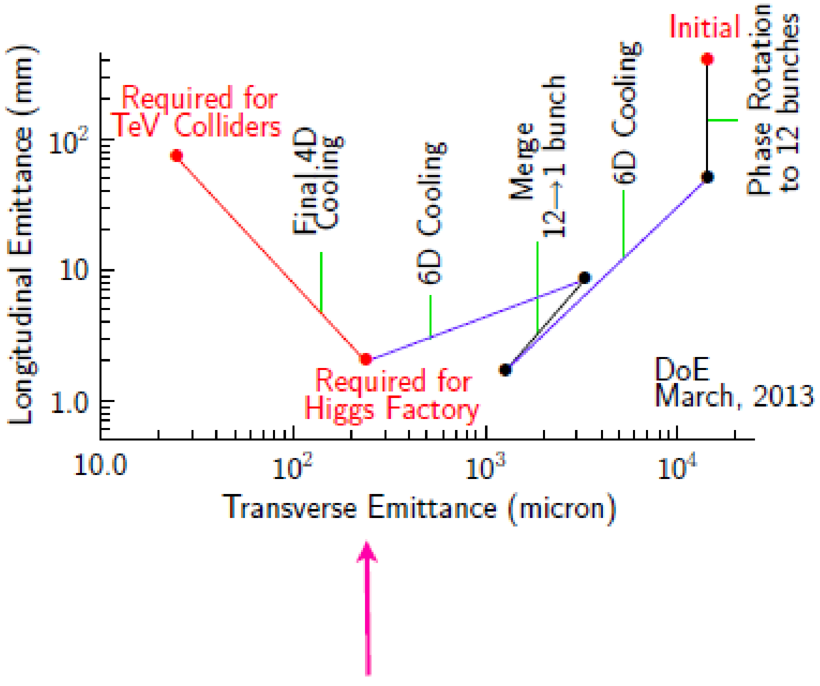


- MAP developed a realistic simulation of beam-induced backgrounds in the detector by implementing a model of the tunnel and accelerator ±200 m from the interaction point.
- Secondary and tertiary particles from muon decays are simulated with MARS15 then transported to the detector.
- Two tungsten nozzles play a crucial role in background mitigation inside the detector.

By using the MAP framework (thanks to A. Mazzacane, V. Di Benedetto) including the already simulated background, we demonstrated that challenging physics measurements are possible.

Muon Collider

- But muons decay:
  - The muon beams must be accelerated and cooled in phase space (factor $\approx 10^6$) rapidly -> ionization cooling
  - requires a complex cooling scheme
  - The decay products ($\mu^- \to \nu_\mu \bar{\nu}_e e^-$) have high energies.
    - Detector background issues
    - Neutrino beam issue for Ecm ≥ 4 TeV. Beam steering resolves this for Ecm ≤ 10 TeV.
- The issues need dedicated R&D
  - MICE
  - MAP
  - nuStorm - Definitive 6D cooling demo.



Higgs Factory