Physics at future muon colliders

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@ GGI, Firenze
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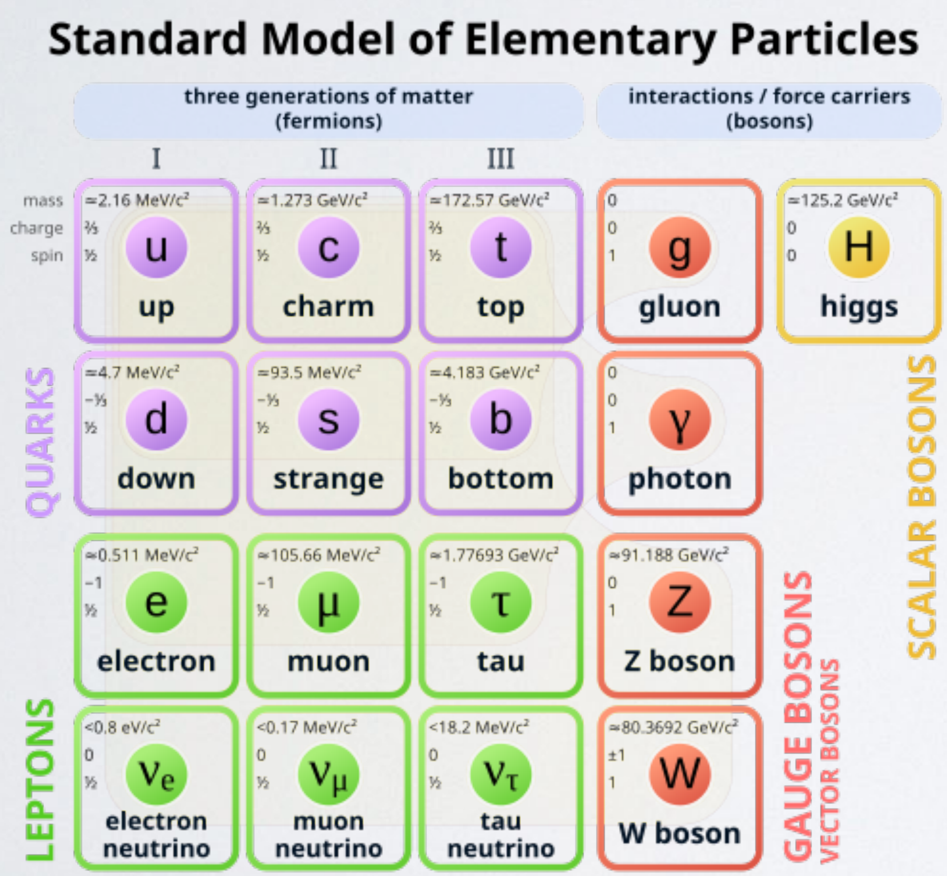
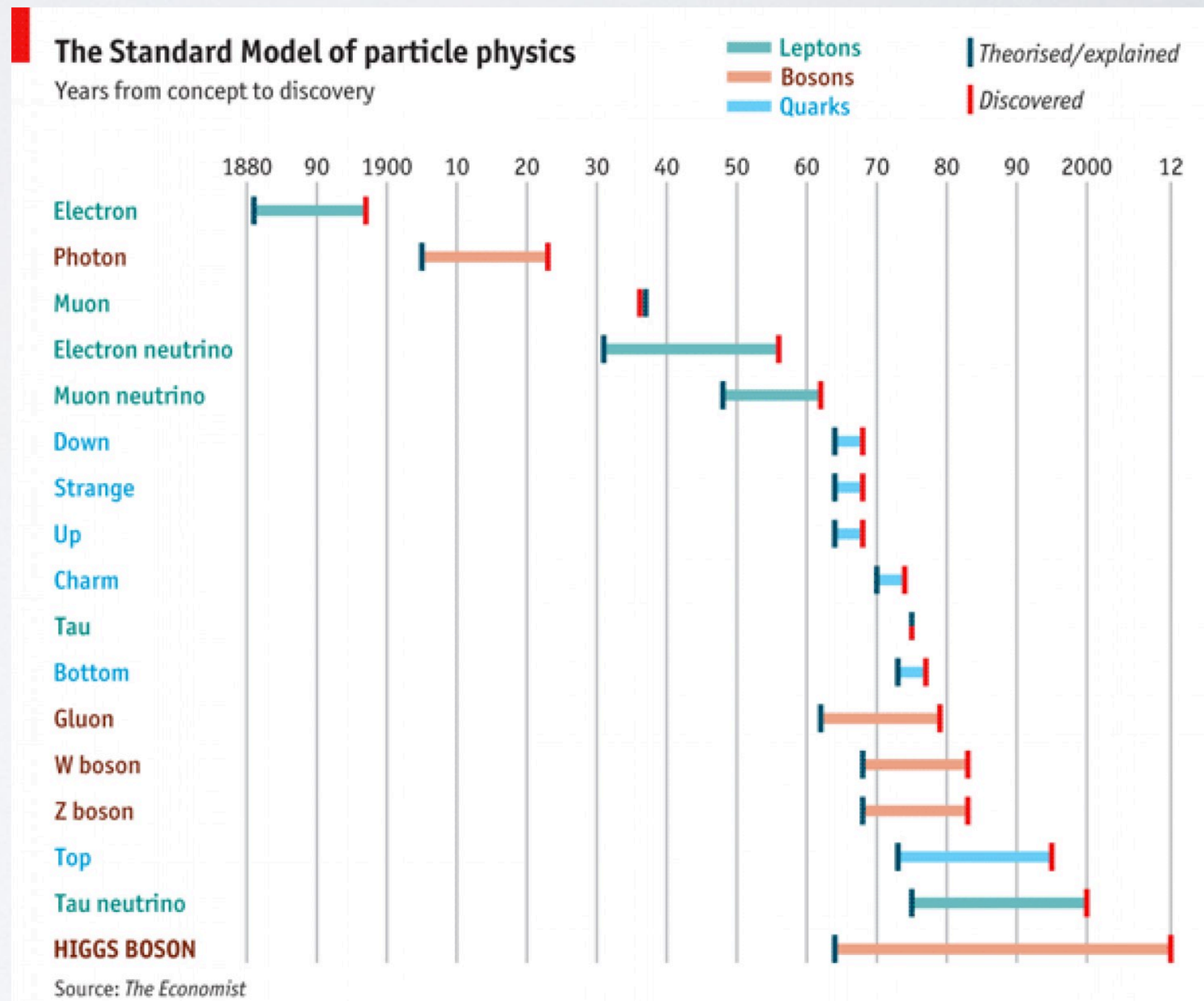
Standard Model

- The Standard Model has been quite successful in describing the physics at small scales.





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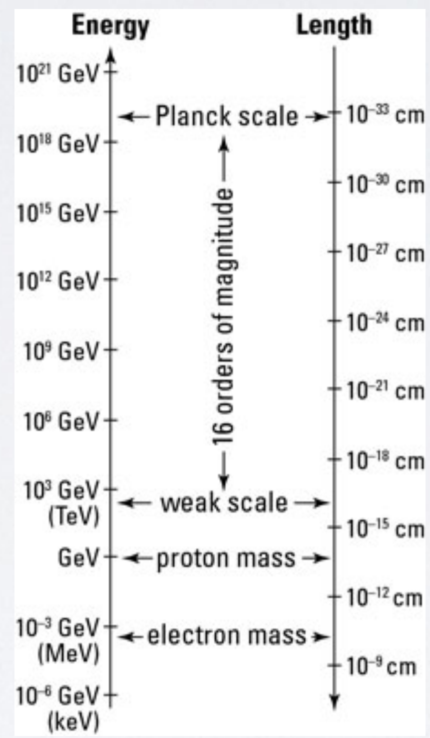
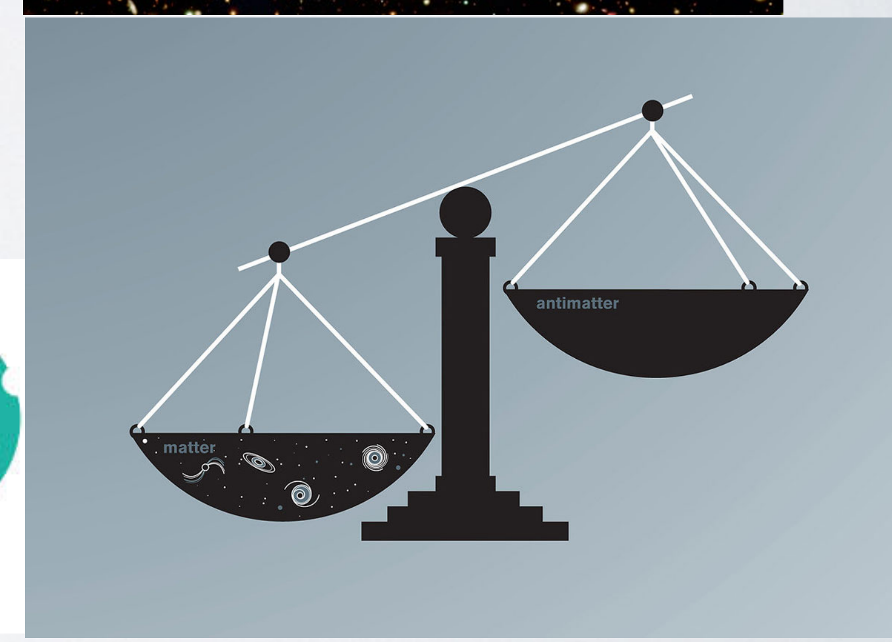
Standard Model

- The Standard Model has been quite successful in describing the physics at small scales.
- Intriguing puzzles:
  - Hierarchy problem
  - Dark matter
  - Neutrino oscillation
  - Baryon asymmetry
  - …





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Standard Model

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- Intriguing puzzles:
  - Hierarchy problem
  -
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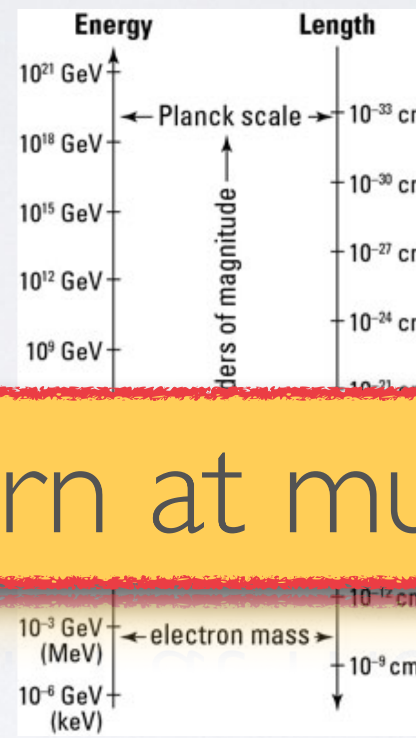
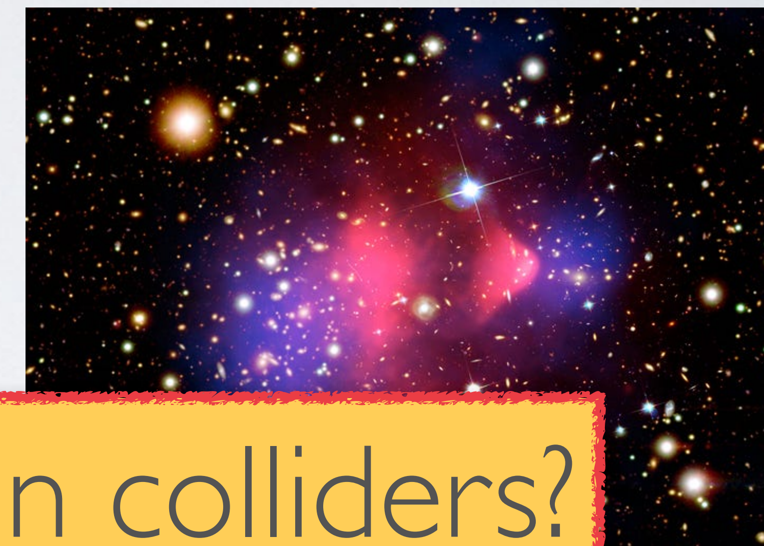
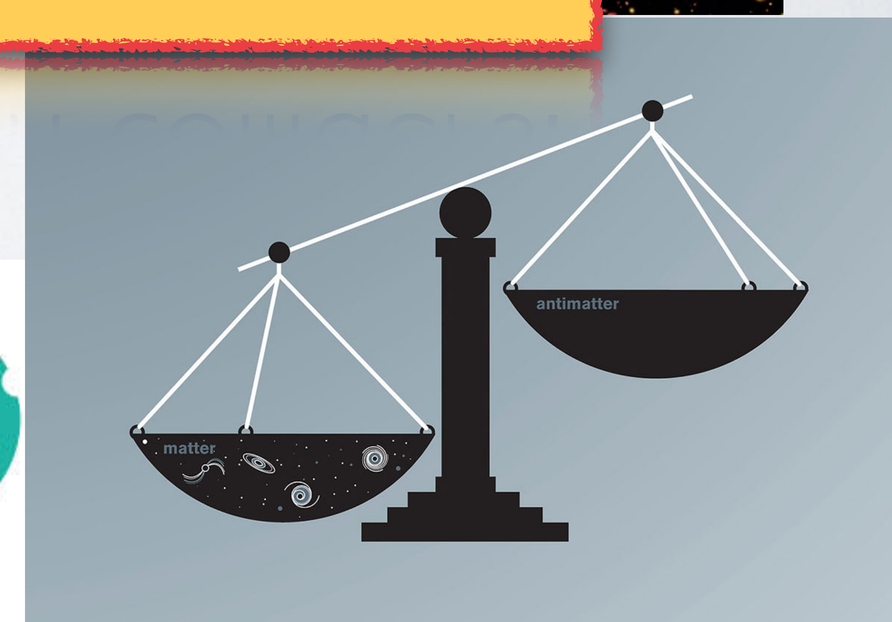
  - Baryon asymmetry
  - ...

What can we learn at muon colliders?







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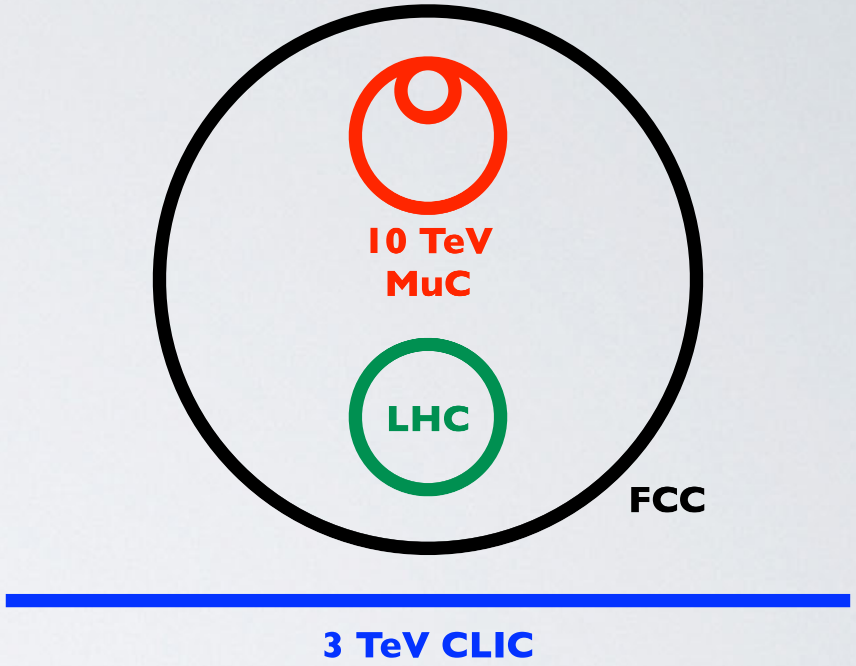
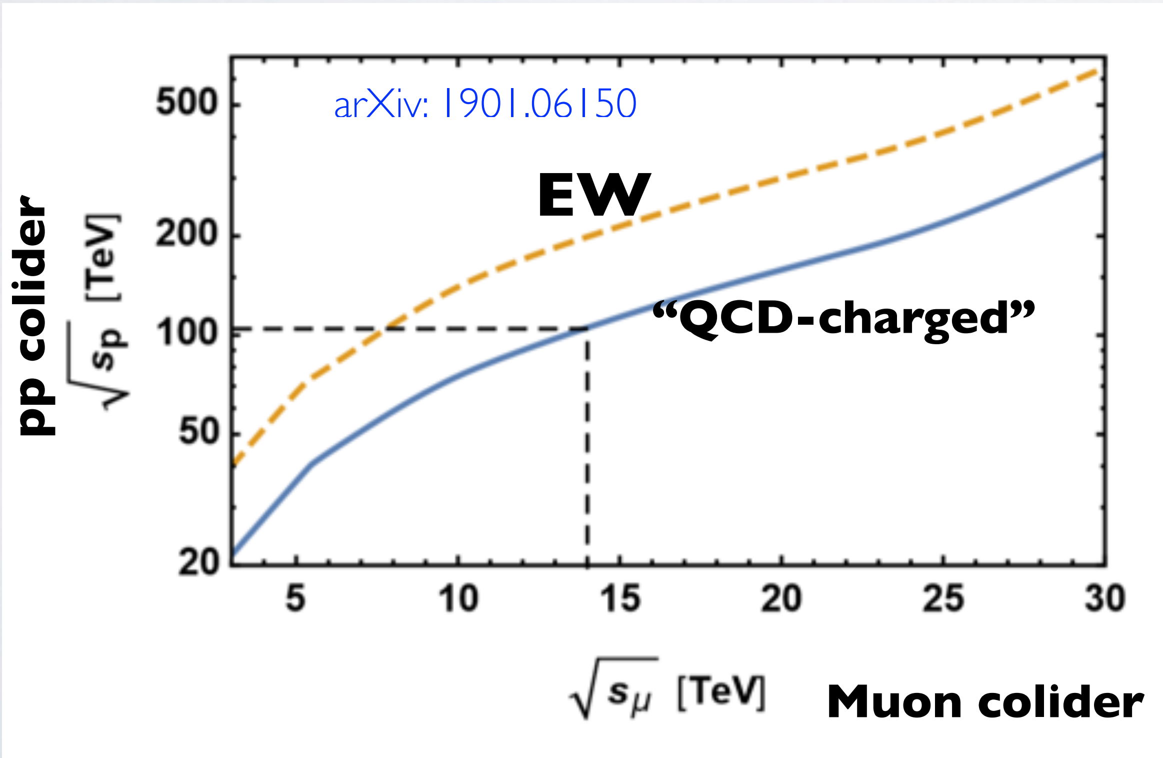
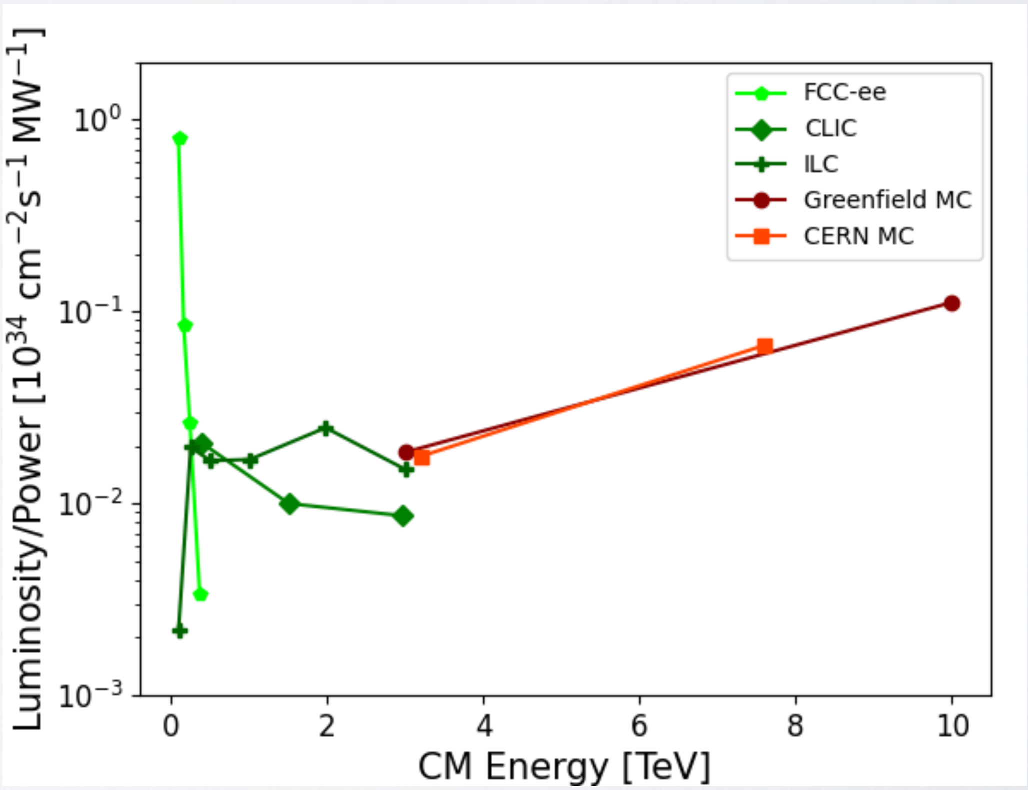
Muon Collider

- Muon colliders offer:
  - Compact machine
  - Less synchrotron radiation / beamstrahlung
  - Point-like particle, no energy "waste"







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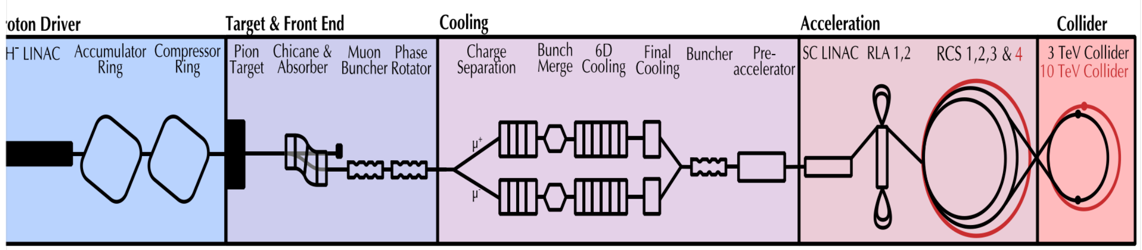
Muon Collider

- Building a muon colliders is also challenging:

Accelerator challenges
See Neuffer's talk

IMCC Scenario (2025)



➢Demos needed
- **Ionization cooling**
  - Can components be built?
  - Rf within B-fields and with beam
  - Cool by large factor? >2?
- **Target**
  - Can be built?
  - Target production/heating ?
  - π/μ capture?
- **Acceleration**
  - Rf/magnets can be built?
  - Operate in desired mode?

➢Demos needed
- **Final Cooling**
  - B=40?T, low-frequency rf ?
  - Operate with beam ?
  - Wedge alternative ?
- **Front End**
  - Optimize, demonstrate ???
- **Magnets**
  - Build, test, operate
  - High field,
    - RCS ramp ?

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Detector challenges
See Lee's talk

Central Challenges

1. Build a detector robust against residual BIB
2. At 10 TeV, annihilation processes will always give multi-TeV objects!

Challenging environment for particle physics.
Let's try to build an experiment…

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But very often, challenging is also synonymous to exciting!

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Content

- Introduction
- (Novel) SM physics at MuC
- BSM physics at MuC
  - BSM at energy frontier
  - BSM at precision frontier
- Conclusion

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SM Physics at MuC

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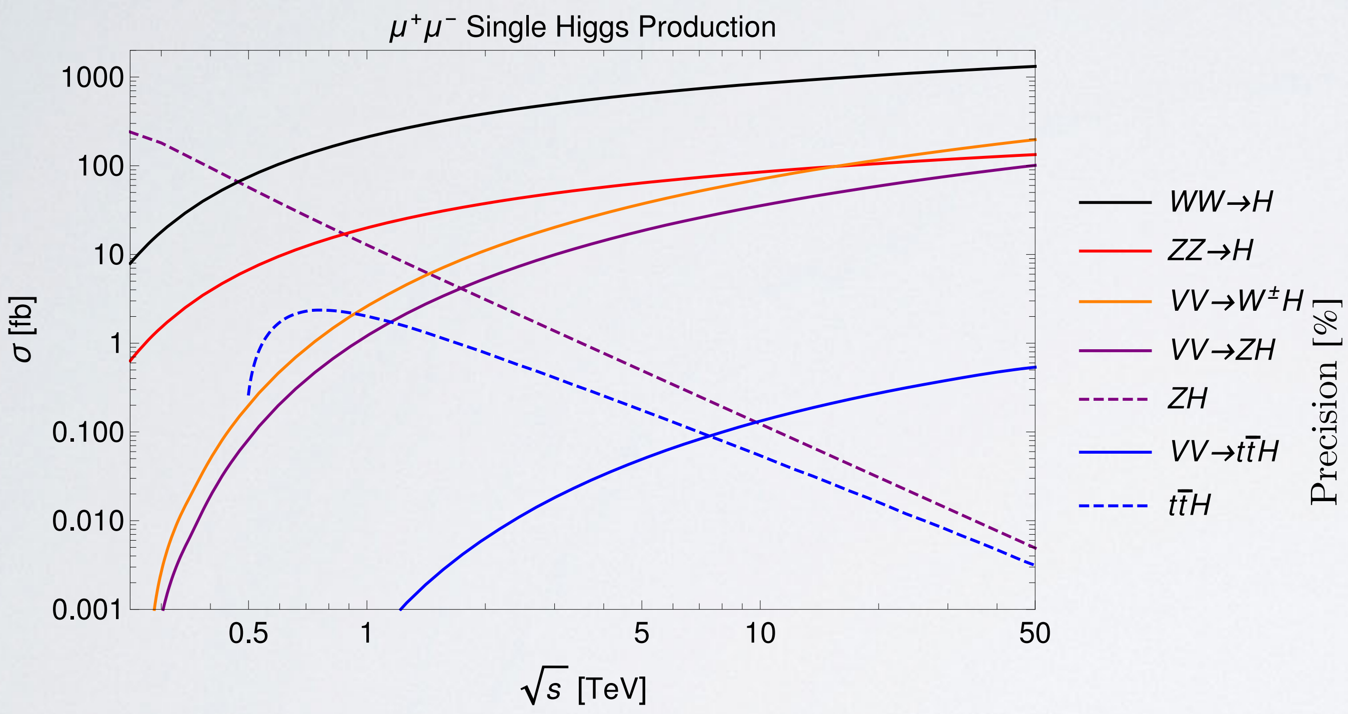
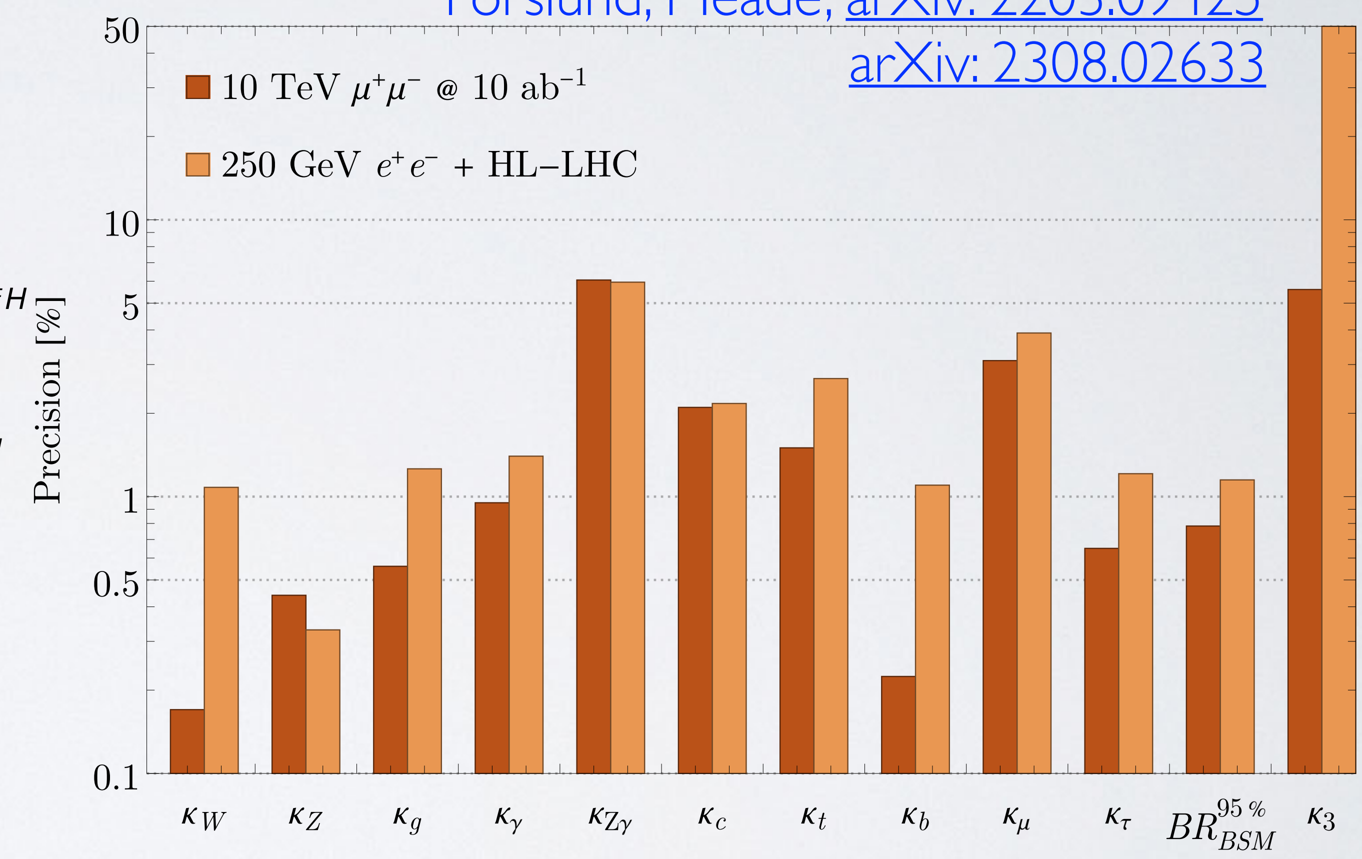
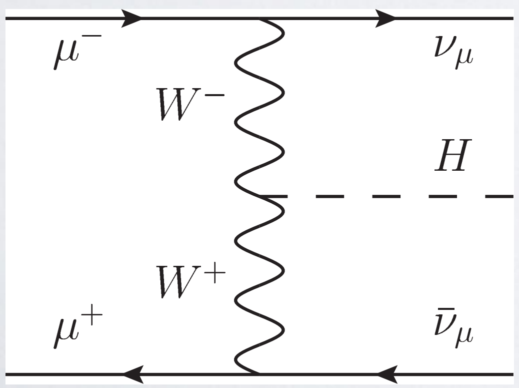
Higgs Precision

- Precision measurement of Higgs couplings.



Forslund, Meade, arXiv: 2203.09425
arXiv: 2308.02633





$$\mathcal{O}(10^6 - 10^8)\ \text{Higgs} \Rightarrow \mathcal{O}(10^{-3} - 10^{-4})\ \text{precision}$$

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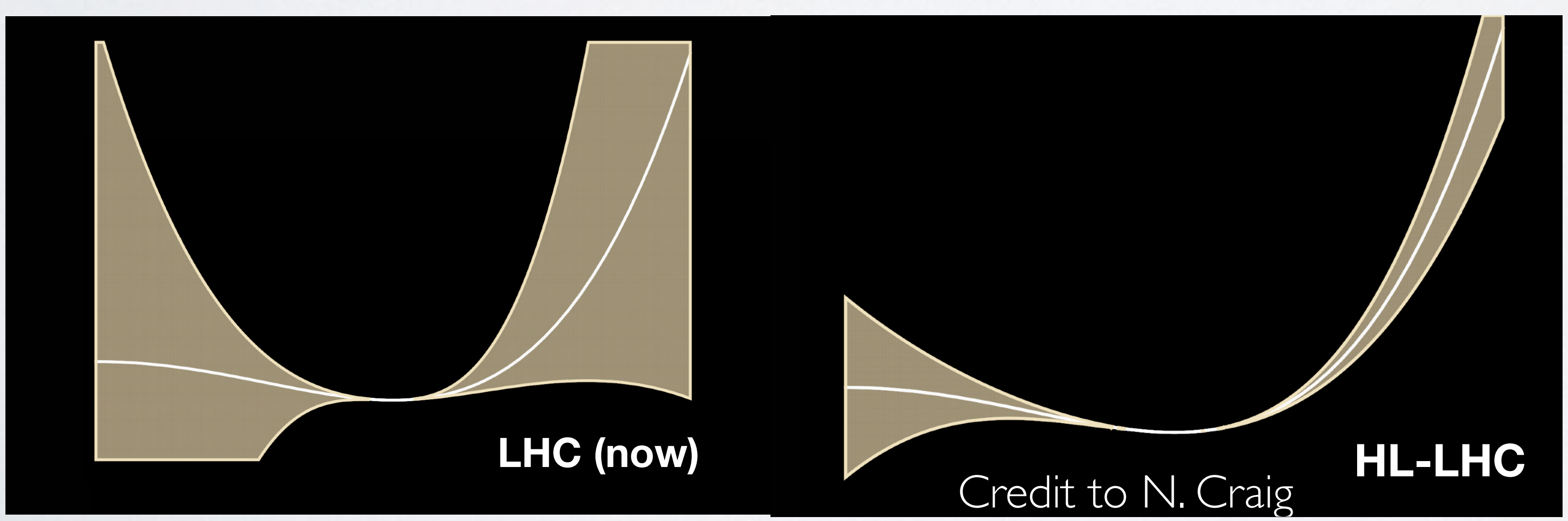
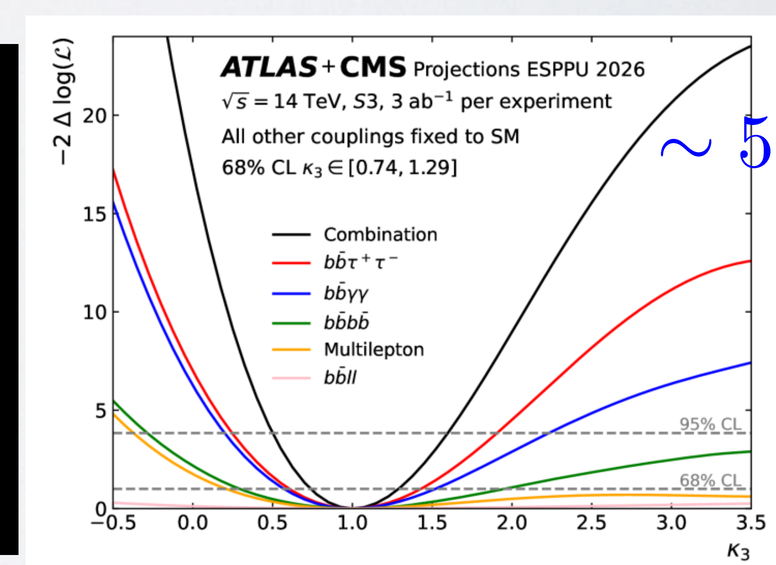
Higgs Pairs

- The Higgs self-coupling is the least measured SM parameter.
- It may shed light on the origin of EWSB.
- Hard to measure at LHC due to destructive interference.
- FCC-ee/CEPC can only measure via loop effects.





$\sim 50\%$

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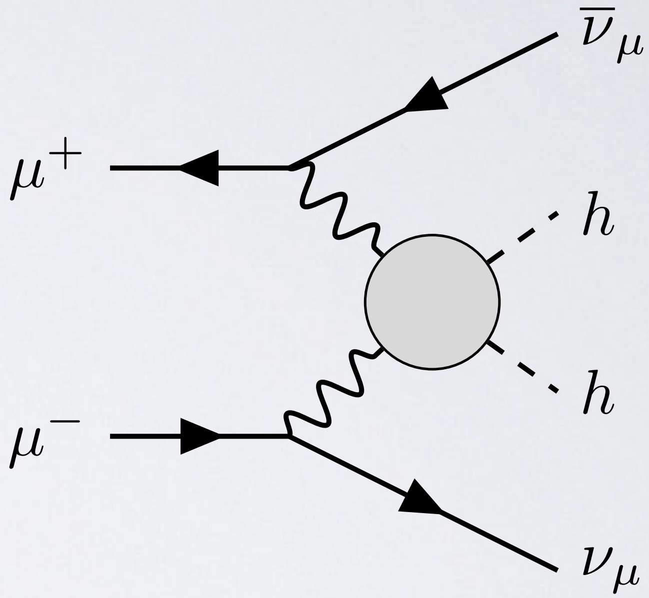
Higgs Pairs

- Plenty of Higgs pairs will be produced at MuC.

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91



$\mathcal{O}(10^3 - 10^5)$ di-Higgs

$\Rightarrow \mathcal{O}(10^{-2} - 10^{-3})$ precision

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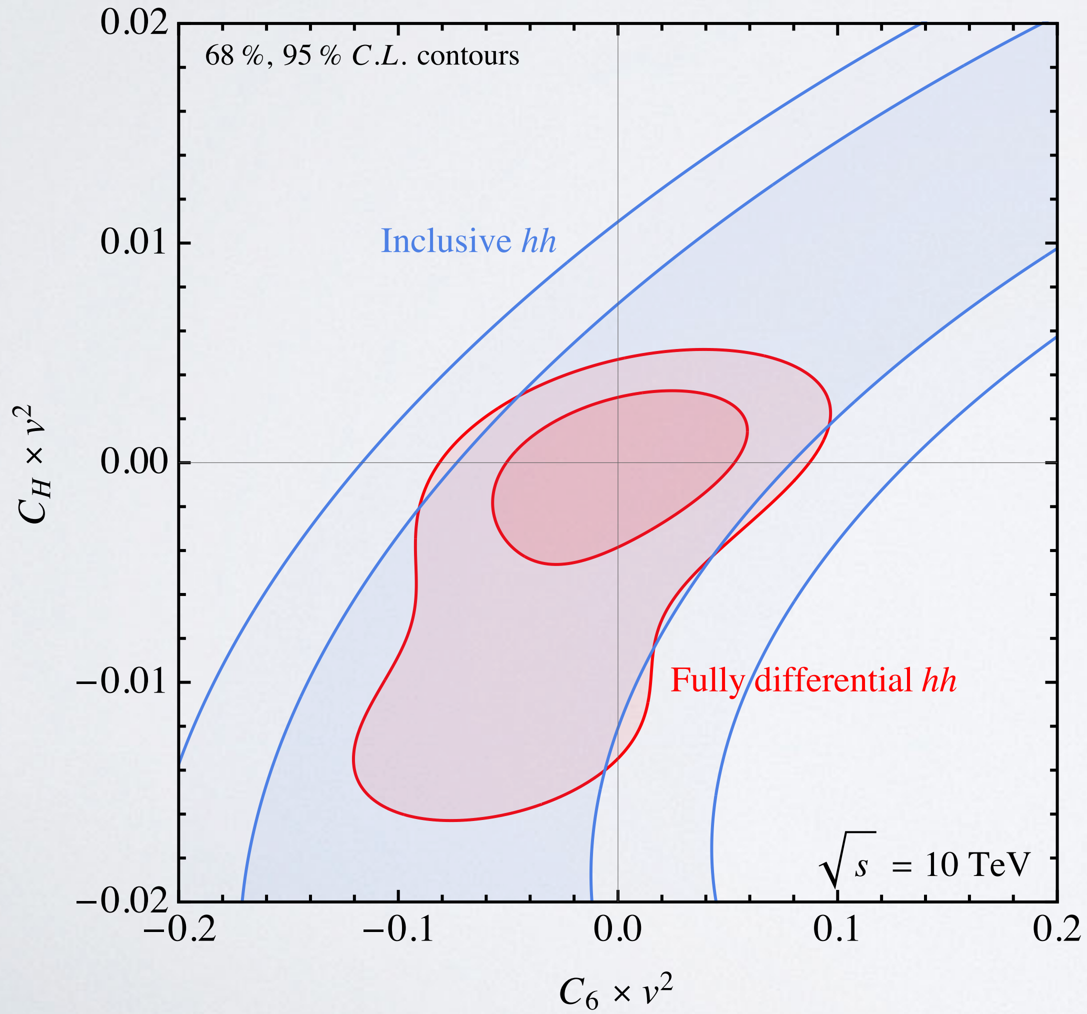
Higgs Pairs

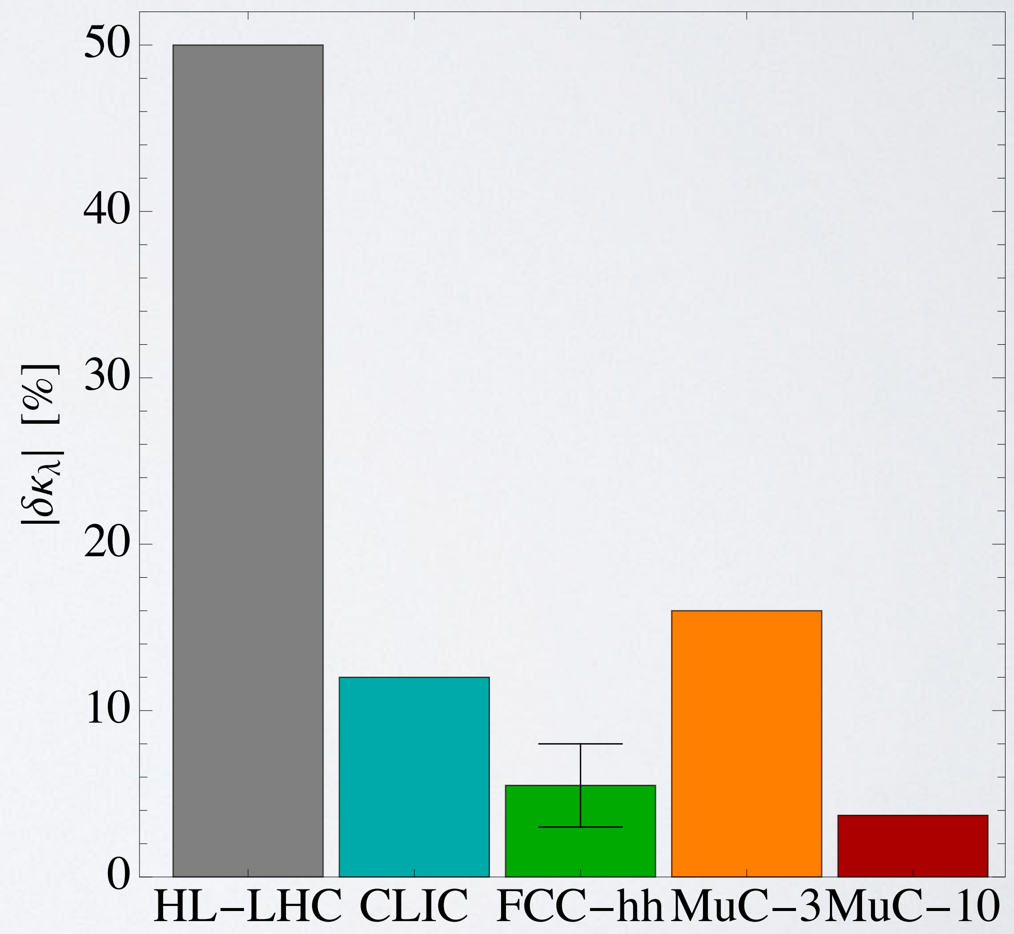
- Muon colliders offer us the opportunity to precisely measure the Higgs self-coupling

T. Han, D. Liu, I. Low, XW arXiv: 2008.12204

Buttazzo, Franceschini, Wulzer arXiv: 2012.11555

$\delta\kappa_3 \simeq 5\%$ @ 10 TeV





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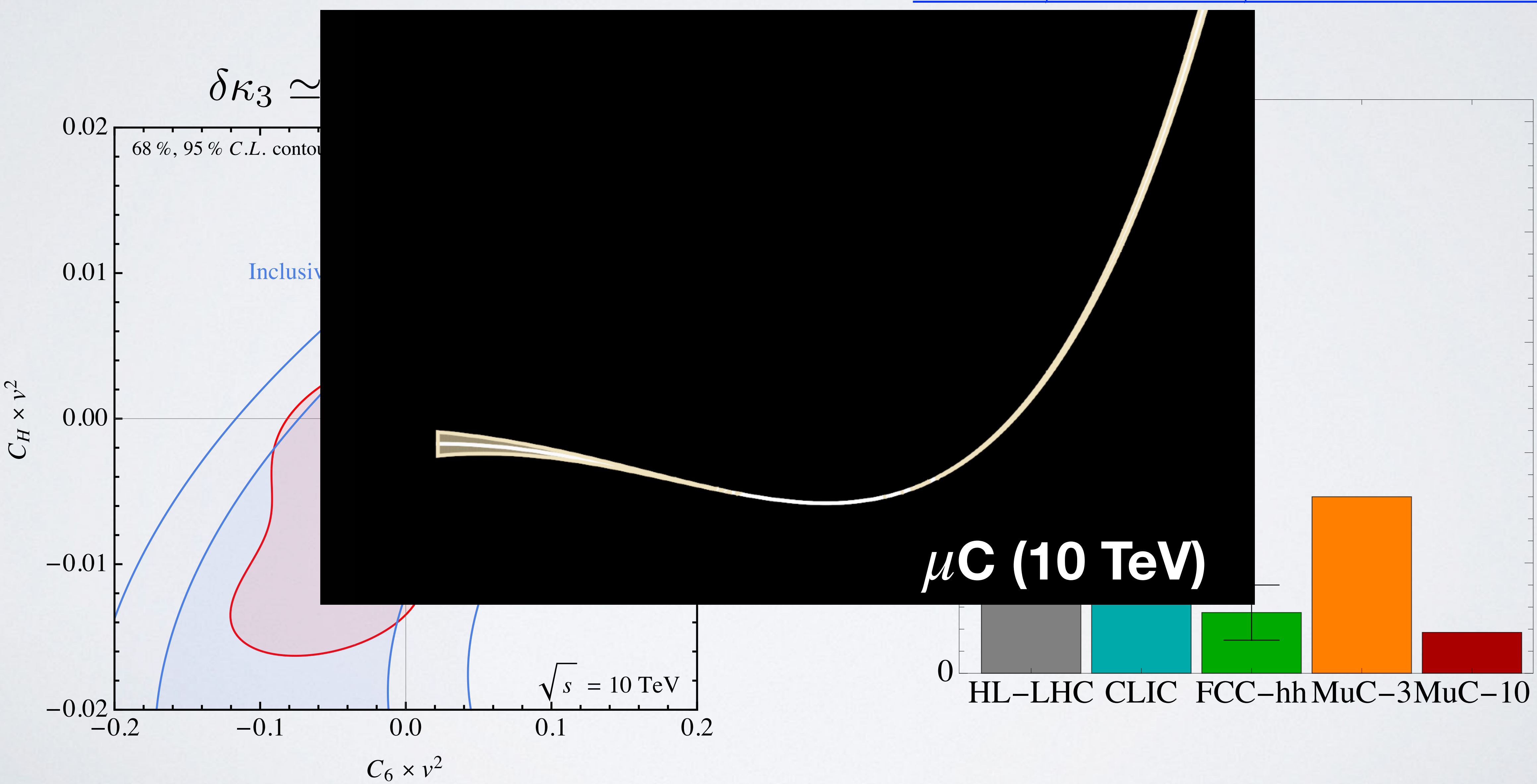

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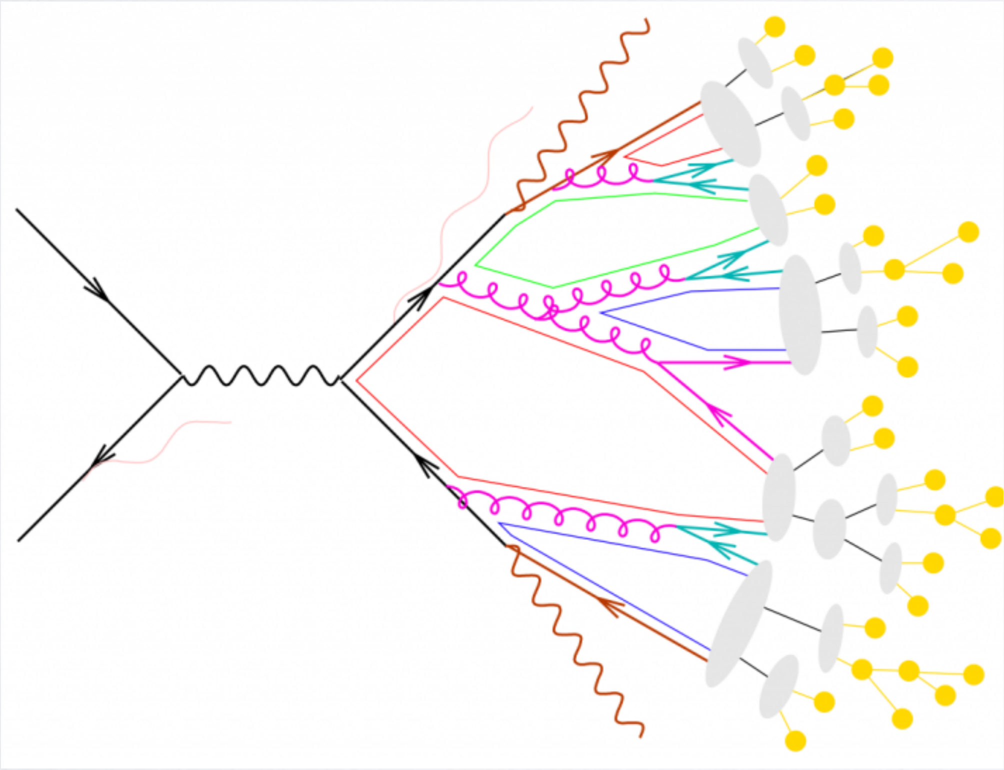
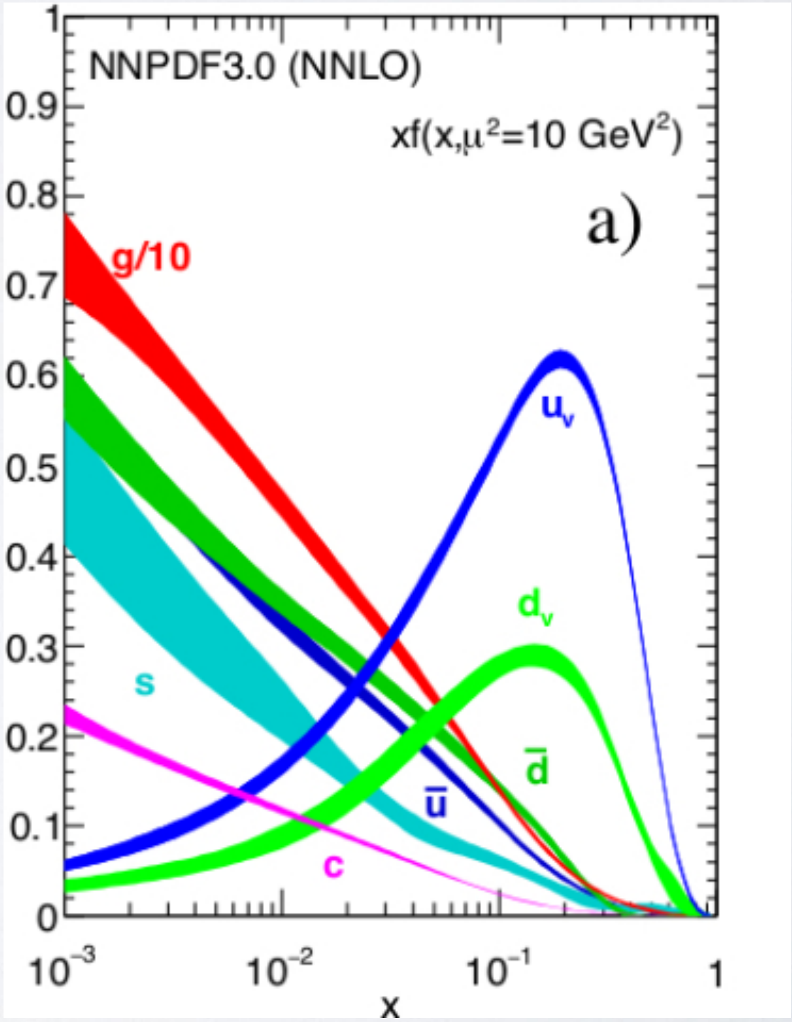
Electroweak Radiation

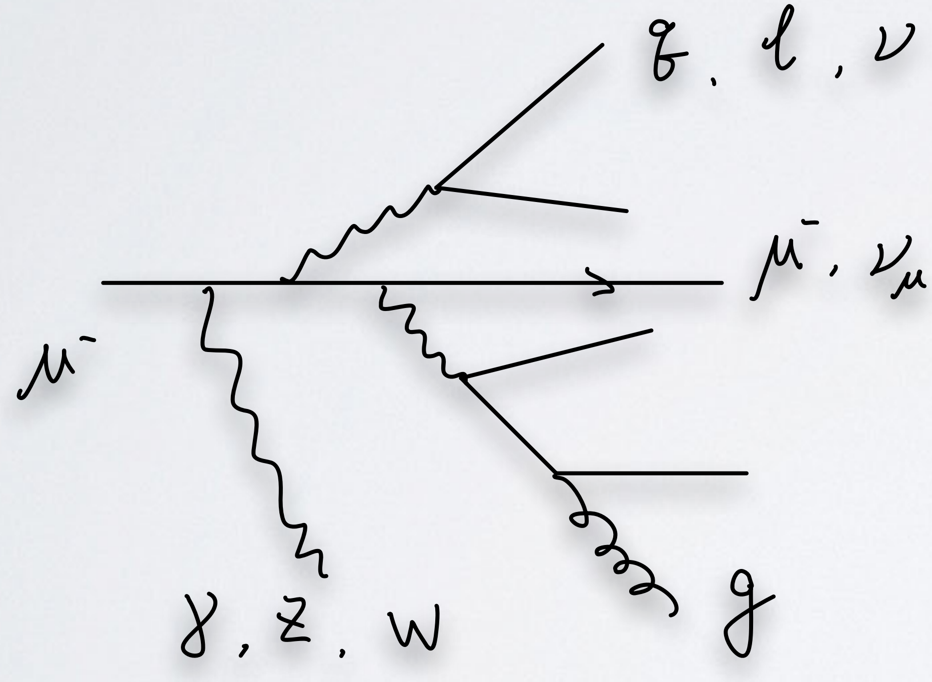
- At high energies $E \gg m_W$, the EW group $SU(2) \times U(1)$ is approximately unbroken — EW restoration.
- EW radiation will behave like QCD!





Electroweak Radiation

- High energy muons can have rich parton contents due to EW radiations.



EW radiation enhanced by $\log^2 \frac{Q^2}{m_W^2}$

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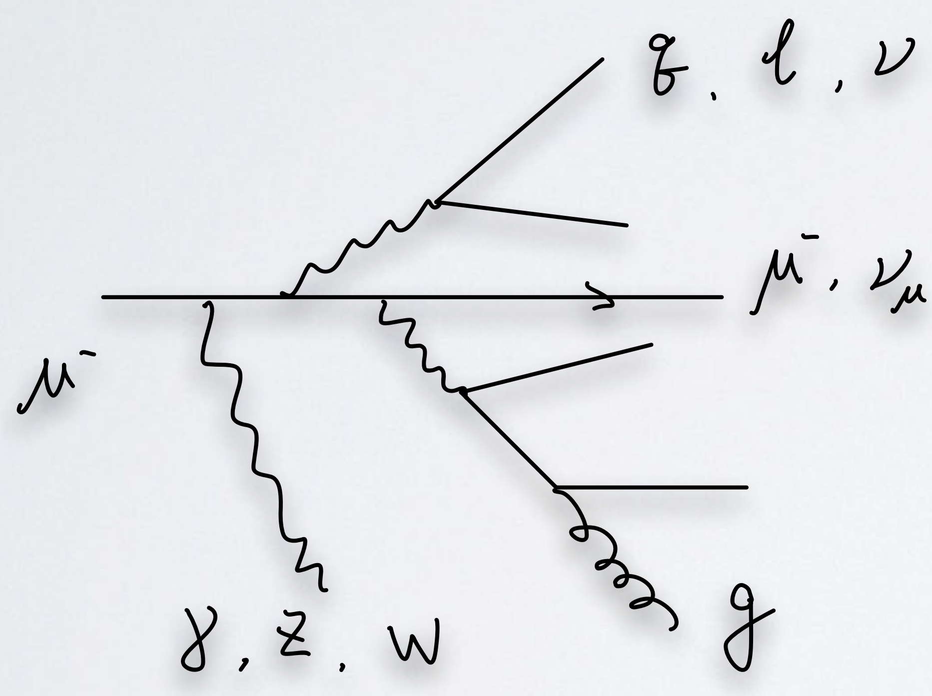
Electroweak Radiation

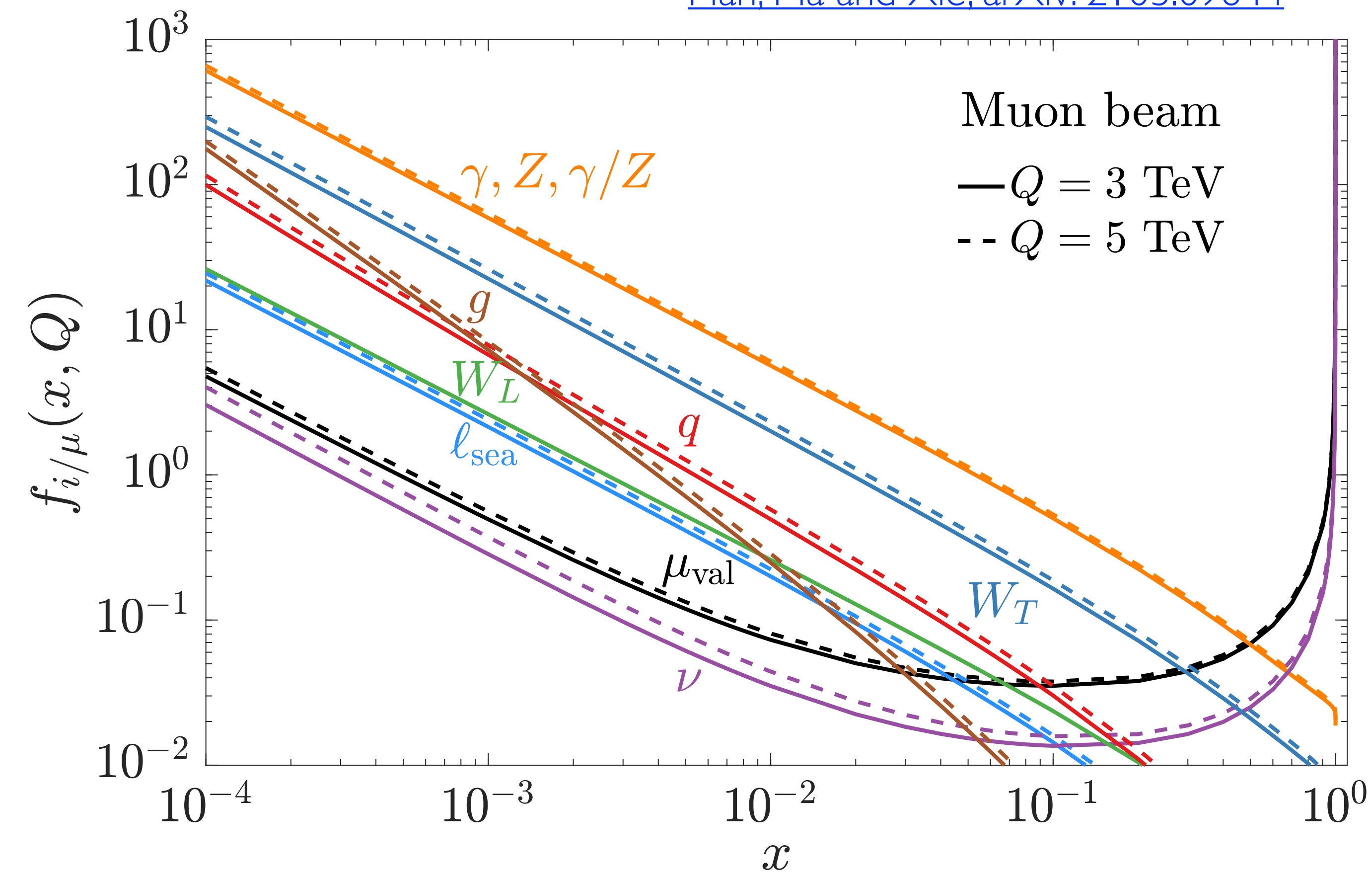
See also Pagani's lecture

- High energy muons can have rich "parton" contents due to EW radiations.



EW radiation enhanced by $\log^2 \frac{Q^2}{m_W^2}$

Han, Ma and Xie, arXiv: 2103.09844



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Electroweak Radiation

- Parton description of W/Z bosons?

$$\sigma_{pp\to VV\to X'}(s) = \int_{\tau_{\min}}^{1} d\tau \frac{dL}{d\tau}\bigg|_{pp/VV} \sigma_{VV\to X'}(\tau s)\,.$$

$$\frac{dL}{d\tau}\bigg|_{qq/V'V'} = \int_{\tau}^{1} f_{q/V'}(x) f_{q/V'}(\tau/x)\frac{dx}{x}$$

$$f_{q/V'}(x) \xrightarrow[E\gg M_V]{} \frac{C_V^2+C_A^2}{8\pi^2 x}(x^2+2(1-x))\log(4E^2/M_V^2)\,.$$

$$f_{q/V'}(x) \xrightarrow[E\gg M_V]{} \frac{C_V^2+C_A^2}{4\pi^2}\frac{1-x}{x}\,.$$

THE EFFECTIVE $W^{\pm}$, Z^0 APPROXIMATION FOR HIGH ENERGY COLLISIONS

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Received 7 May 1984

THE EFFECTIVE W APPROXIMATION*

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Received 30 April 1984

THE TeV PHYSICS OF STRONGLY INTERACTING W's AND Z's*

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Mary K GAILLARD
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Received 24 June 1985

- Unlike QCD, the EW group $SU(2)\times U(1)$ is broken after all.

  EW symmetry restored at $E \gg v$

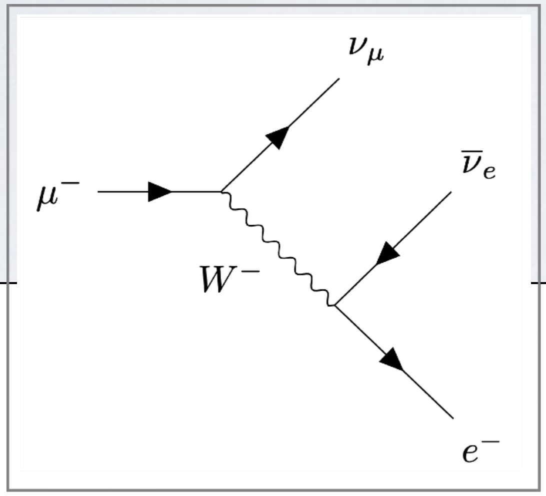
  Physical IR cutoff $\Lambda_{\rm IR} \sim m_W$

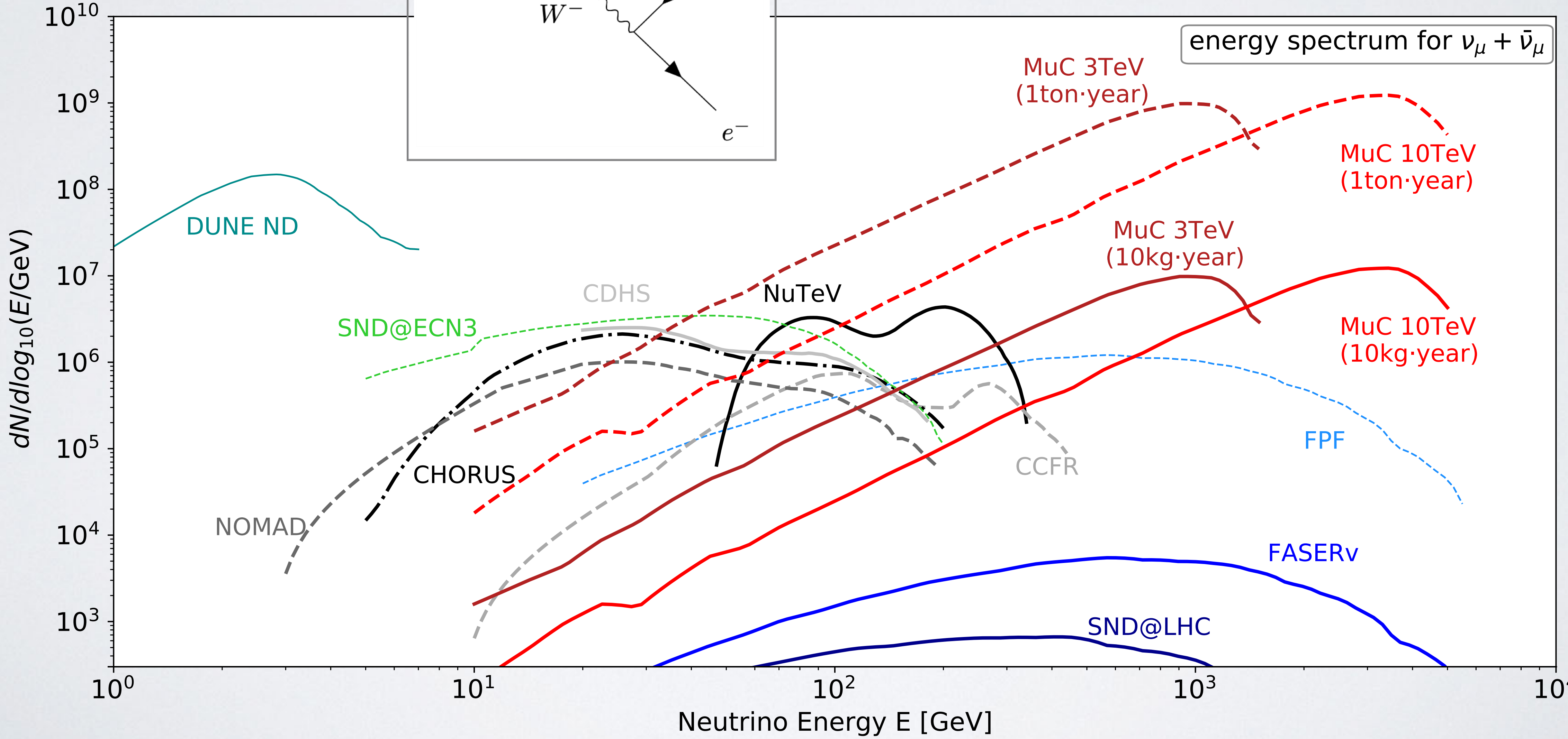
  EW "color" is observable (ν_μ, μ^-)

- Active field, many questions still to be addressed!

Neutrino Beam

- Muon colliders offer high energy / high quality neutrino beams.





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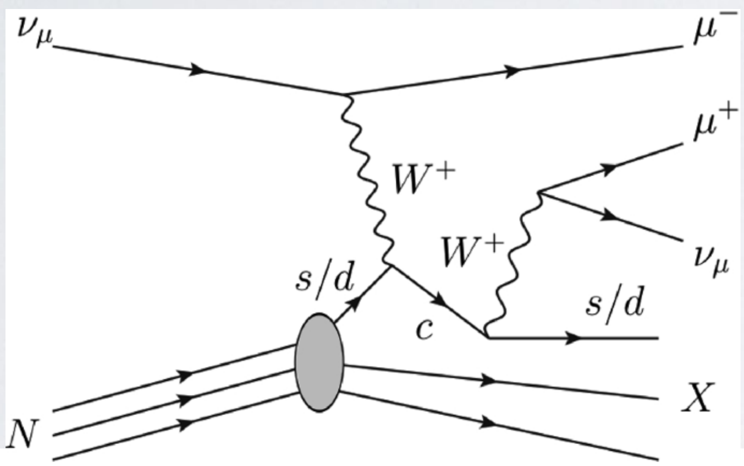
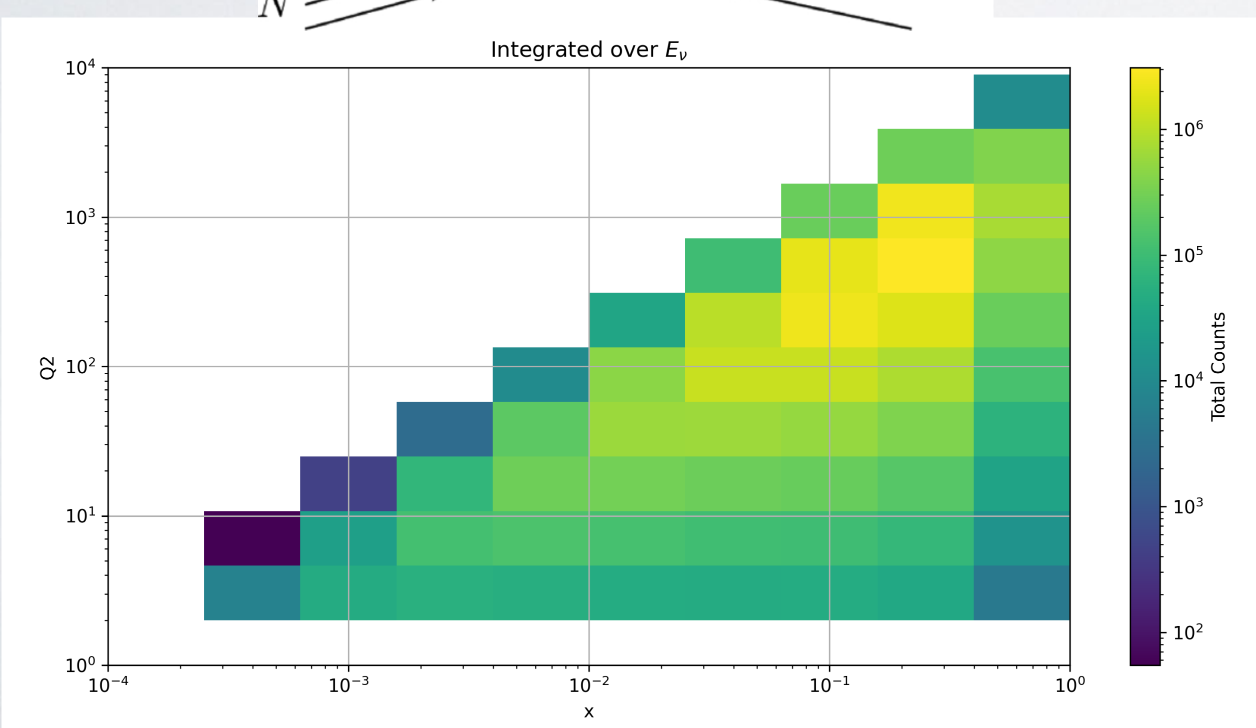
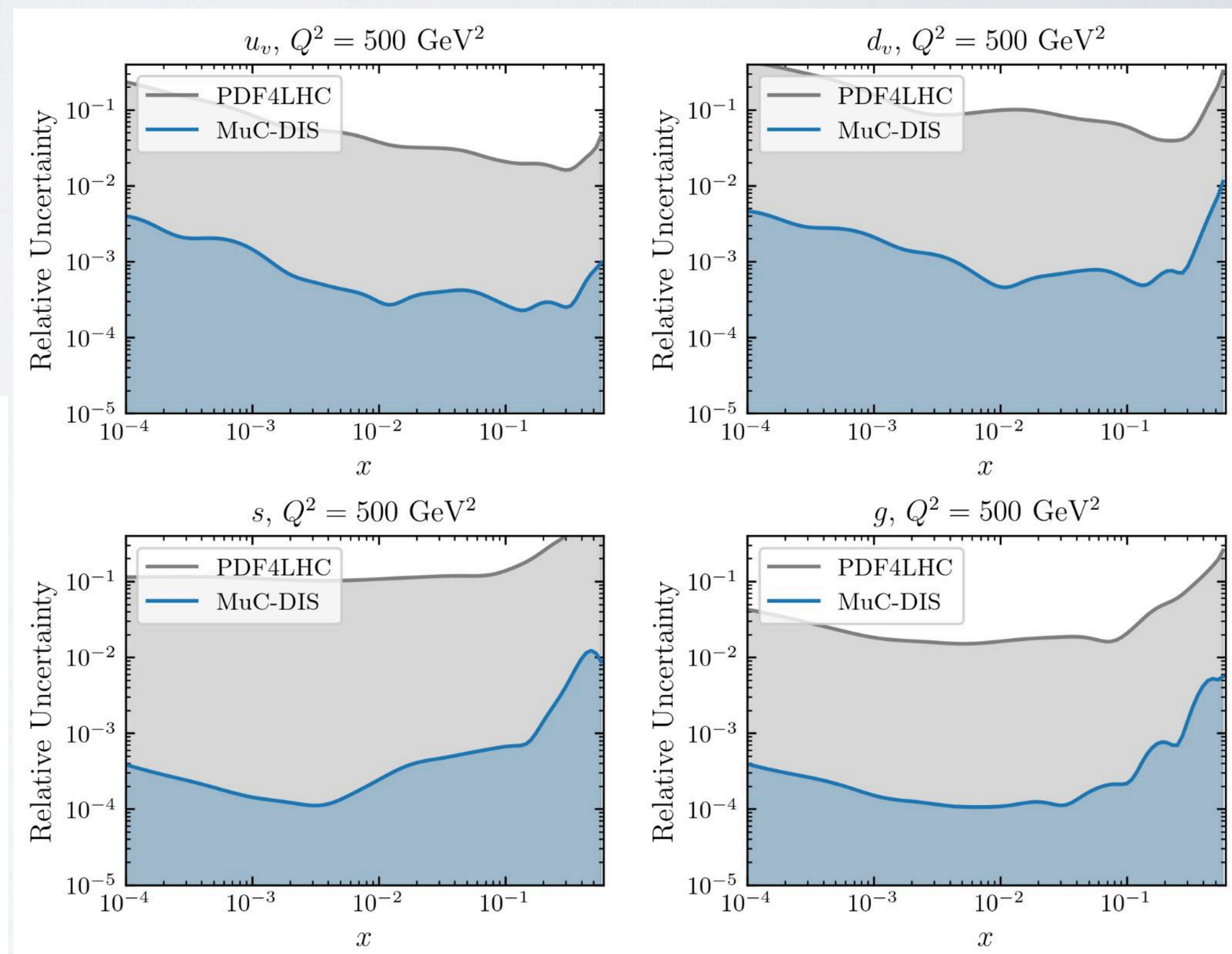
Neutrino DIS

See Morales-Alvarado's talk

- Muon colliders offer high energy / high quality neutrino beams.







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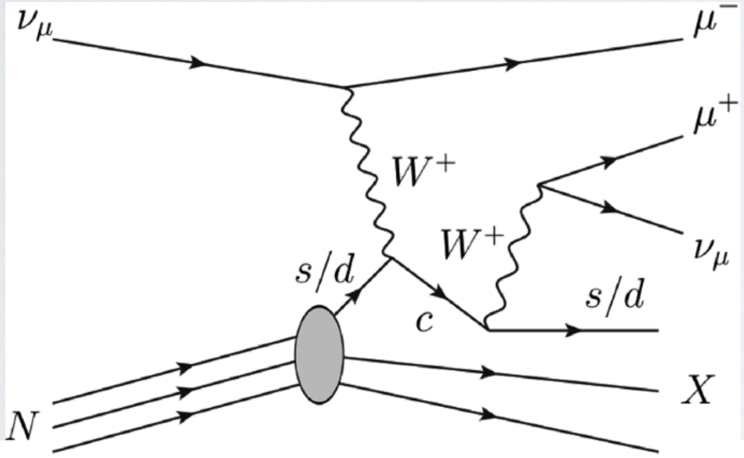

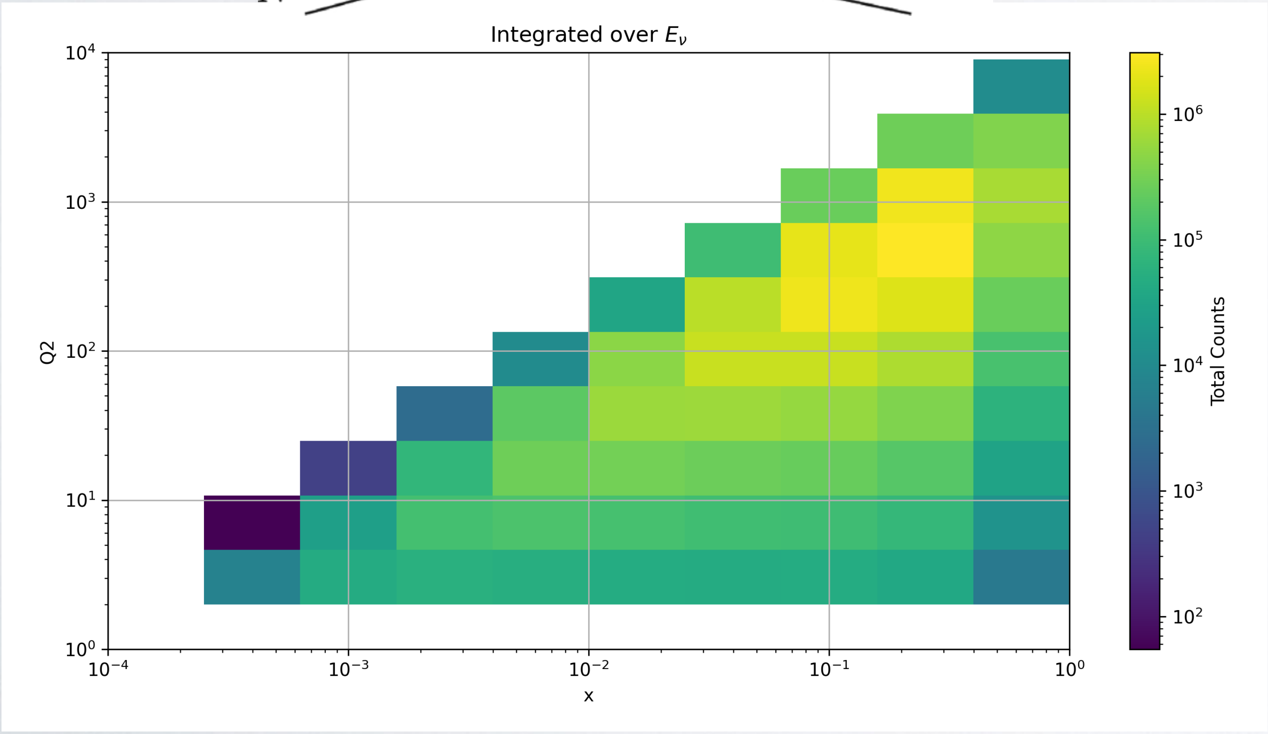

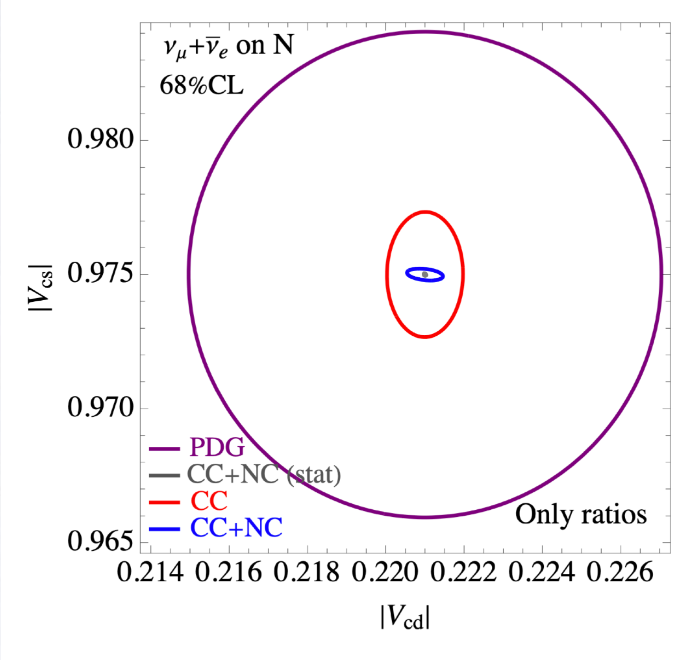

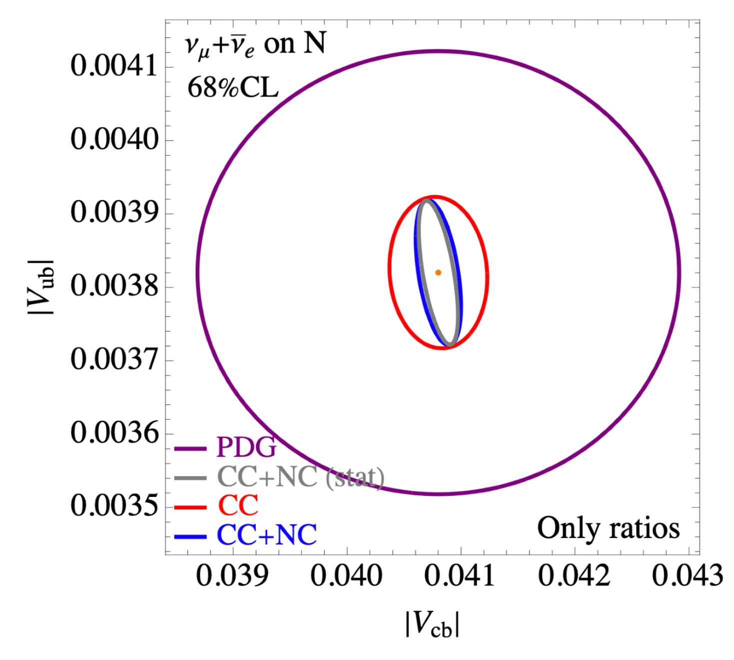

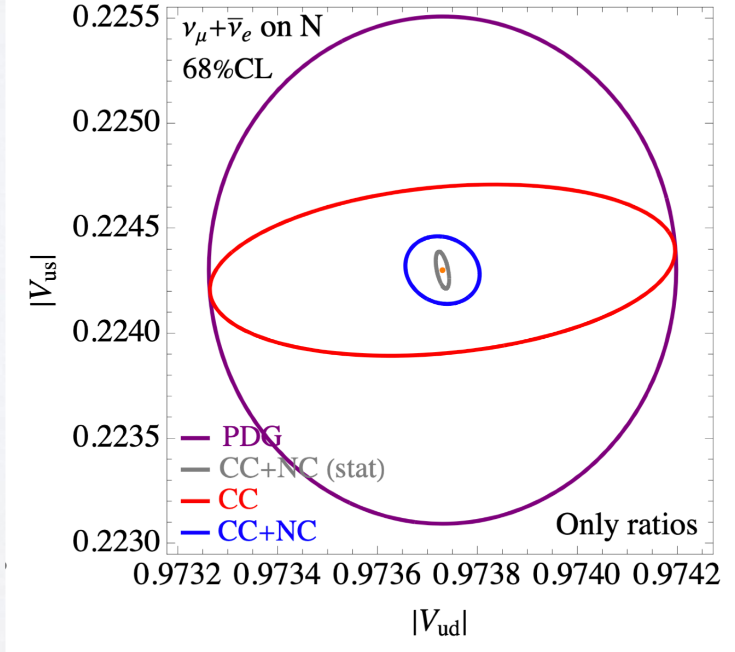

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BSM Searches at MuC

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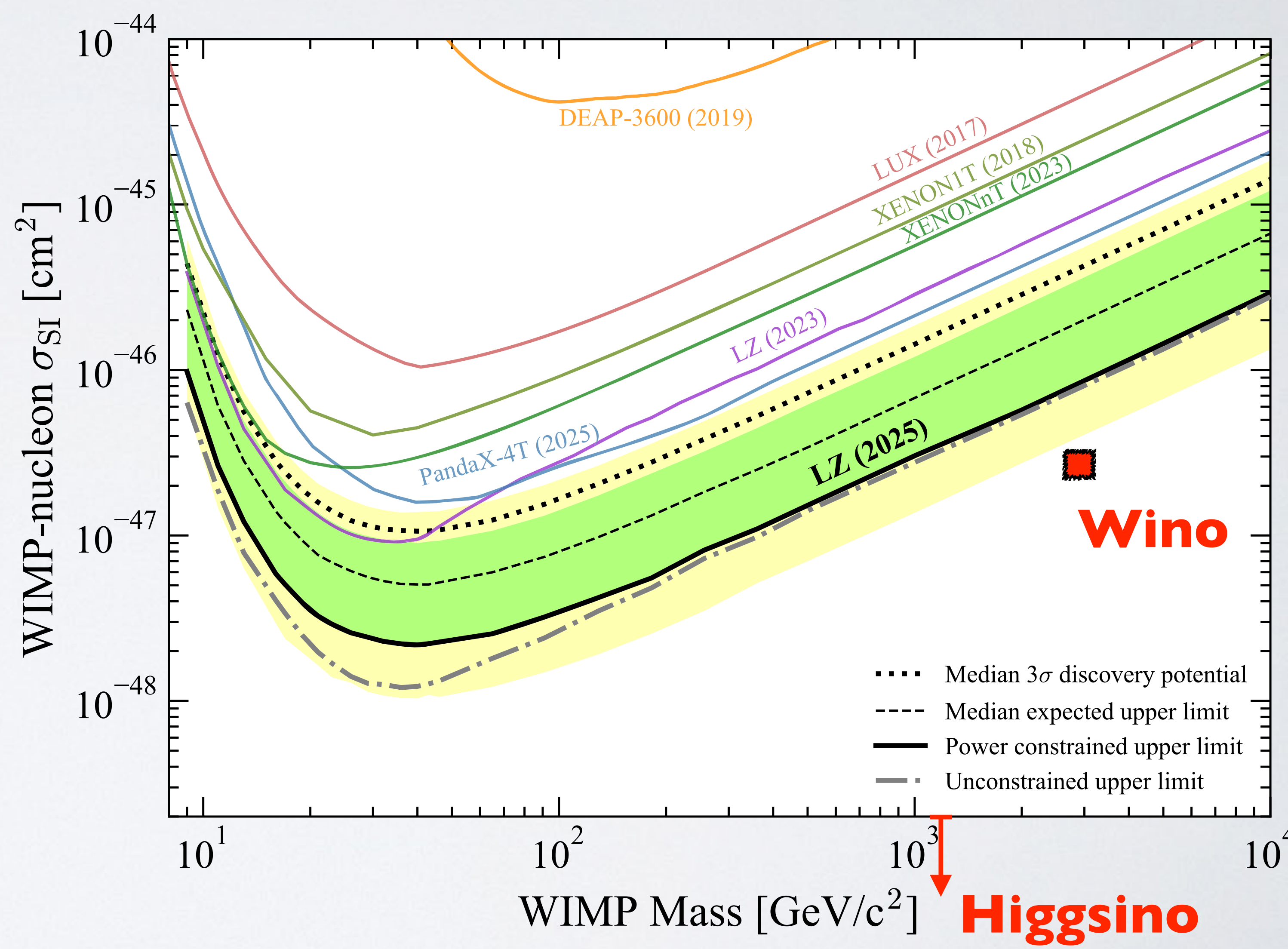
Minimal Dark Matter

- Simple but well-motivated model.

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



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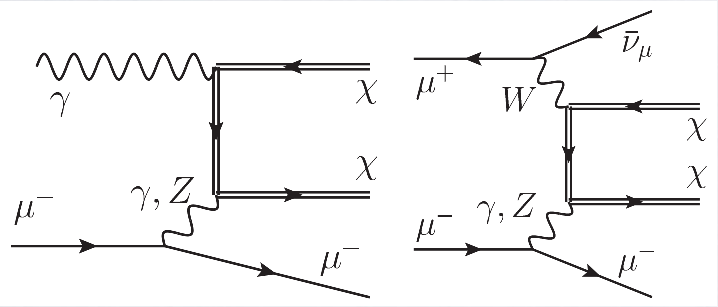
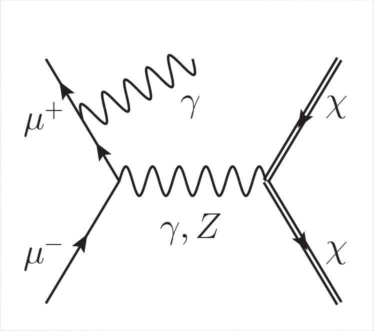
Minimal Dark Matter

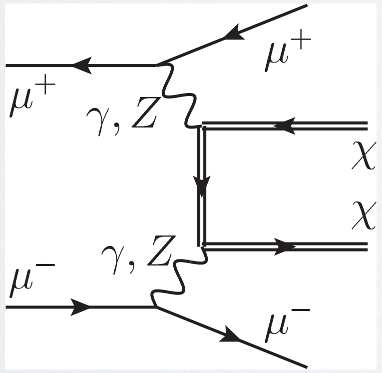
- Conventional missing mass searches
  - mono-muon



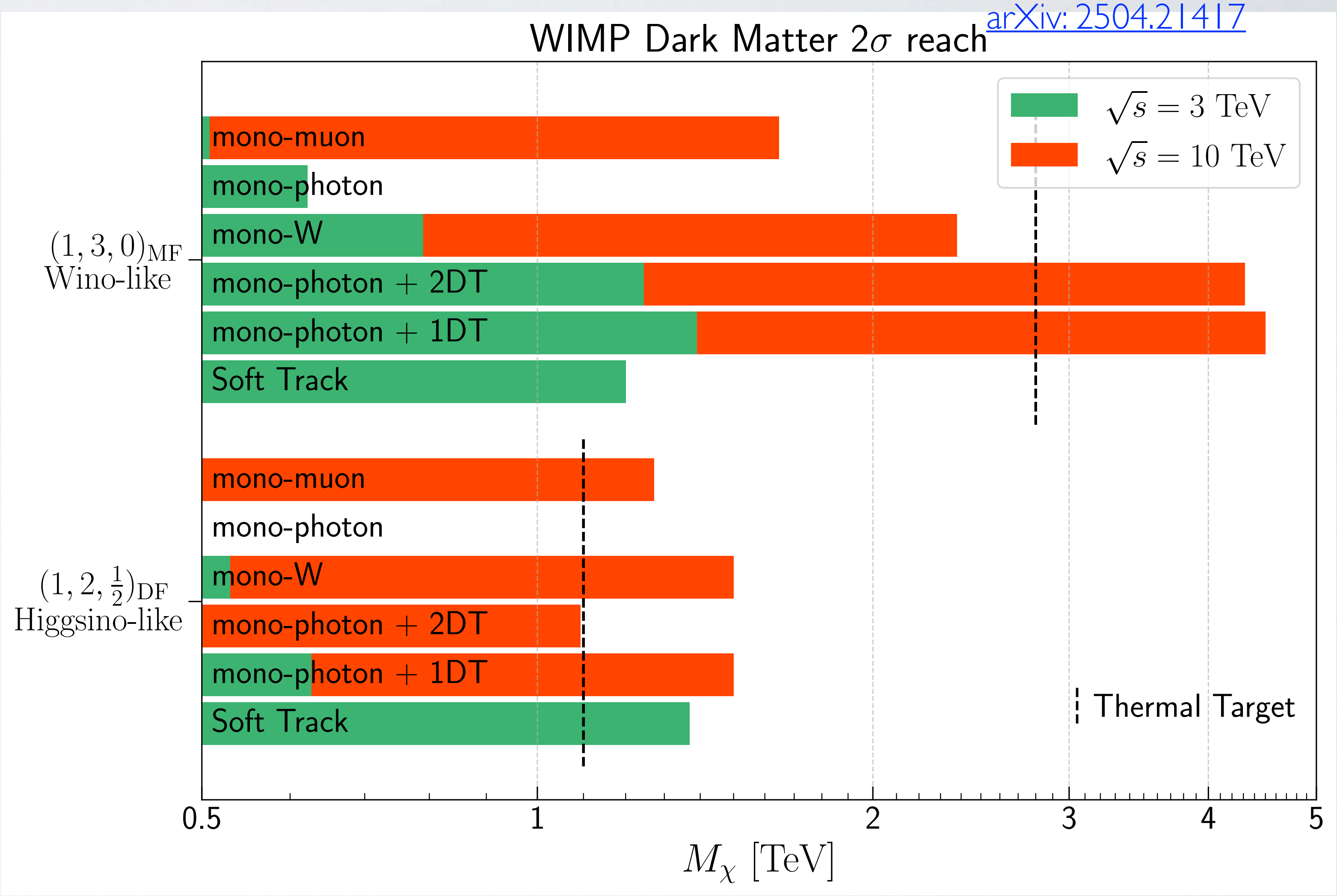
  - mono-photon/W



  - di-muon



[ESPPU Muon Collider Report](#)
[arXiv: 2504.21417](#)



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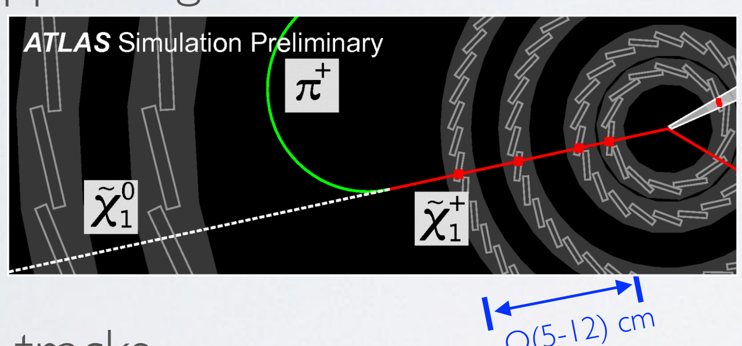
Minimal Dark Matter

- Search for Exotic signatures from **compressed spectra**

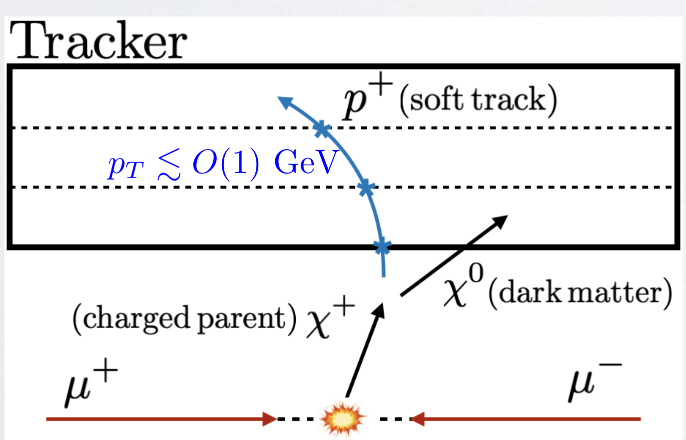
$$m_{\chi^\pm} - m_{\chi^0} \simeq \begin{cases} 355 \text{ MeV} & \text{Higgsino} \\ 164 \text{ MeV} & \text{Wino} \end{cases}$$

$$\tau \sim \mathcal{O}(0.01 - 0.1) \text{ ns}$$

- Disappearing track



- Soft tracks



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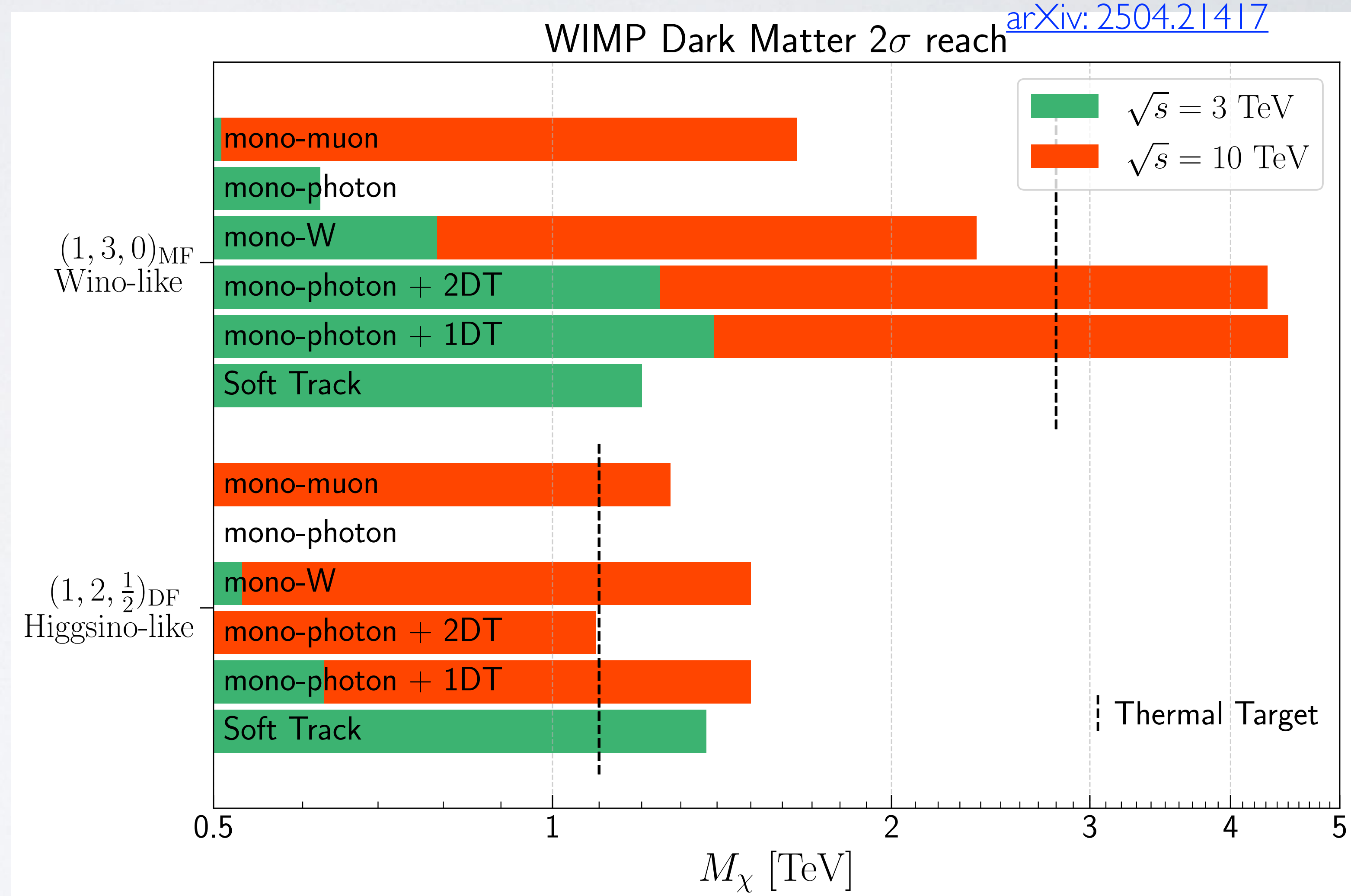

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Extension of SM (+singlet)

- Simplest extension of the Higgs sector

$$h = h_0 \cos\gamma + S \sin\gamma,$$

$$\phi = S \cos\gamma - h_0 \sin\gamma,$$

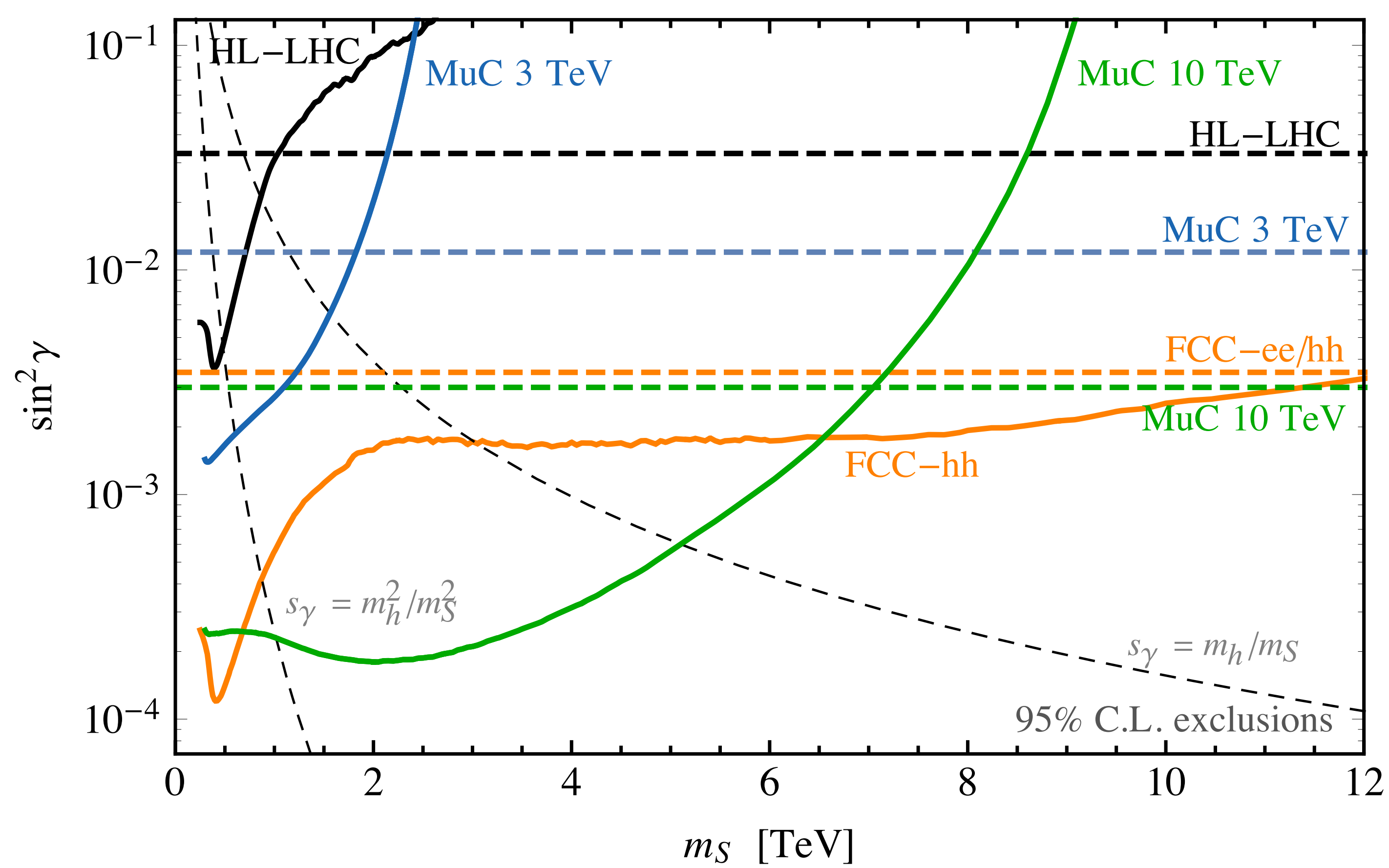
- Indirect probe

$$\mu_h = \mu_h^{\rm SM} \cos^2\gamma\,.$$

- Direct search

$$VV \to \phi$$

Buttazzo, Redigolo, Sala, Tesi, arXiv: 1807.04743



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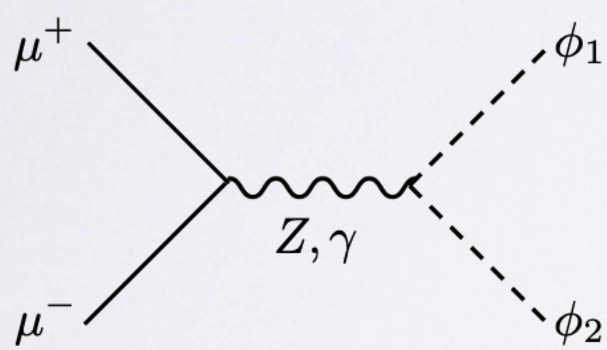
Extension of SM (2HDM)

- Heavy Higgs can be produced in pair

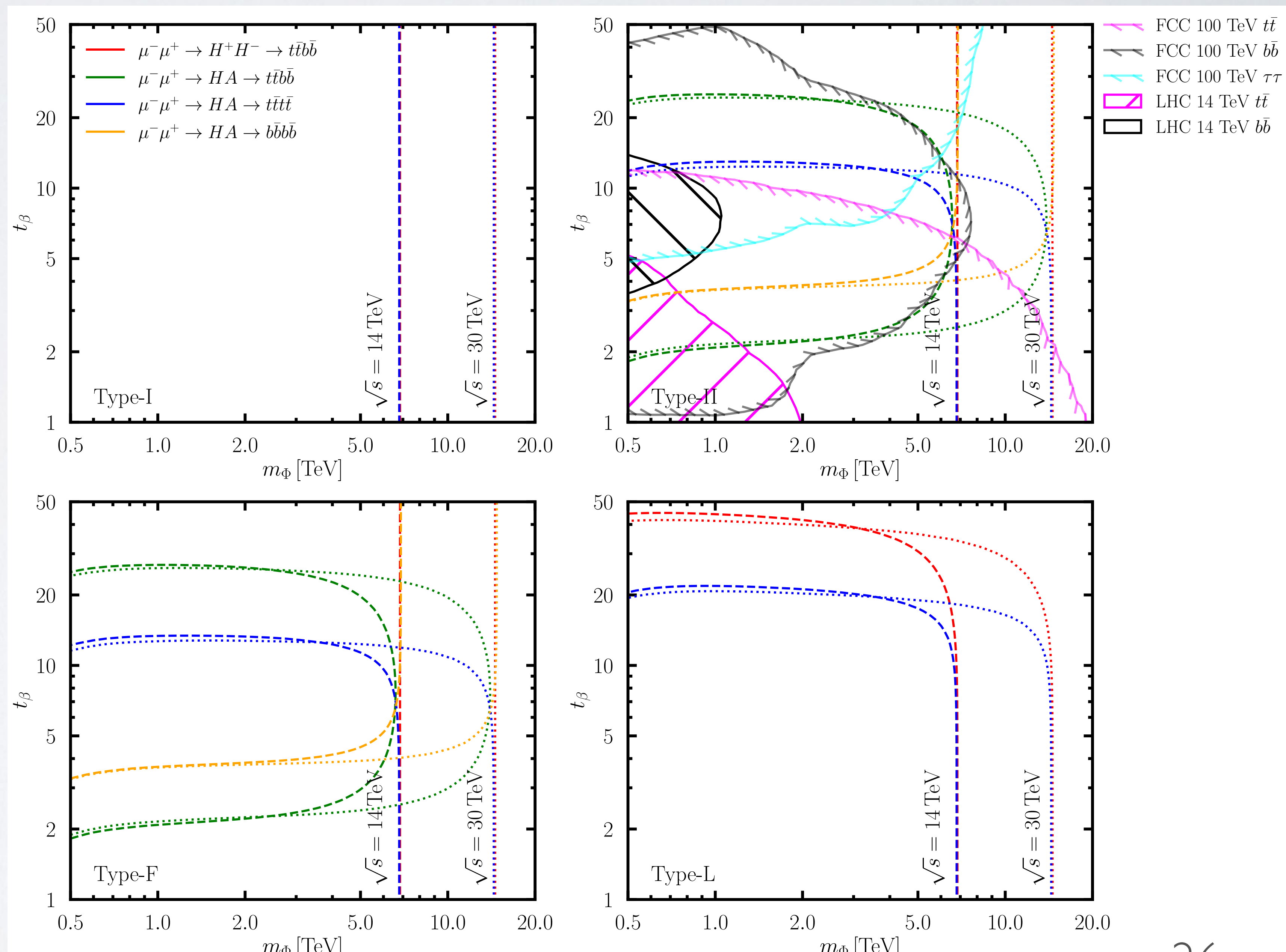
$$\mu^+\mu^- \to \gamma^*, Z^* \to H^+H^-,$$
$$\mu^+\mu^- \to Z^* \to HA.$$



$$m_\Phi \sim \frac{\sqrt{s}}{2}$$

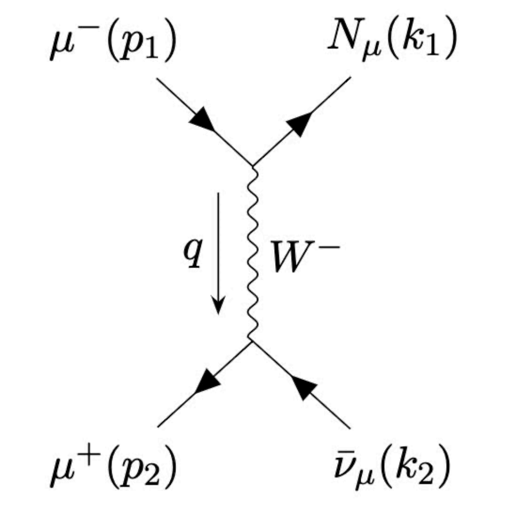
Buttazzo, Redigolo, Sala, Tesi, arXiv: 1807.04743

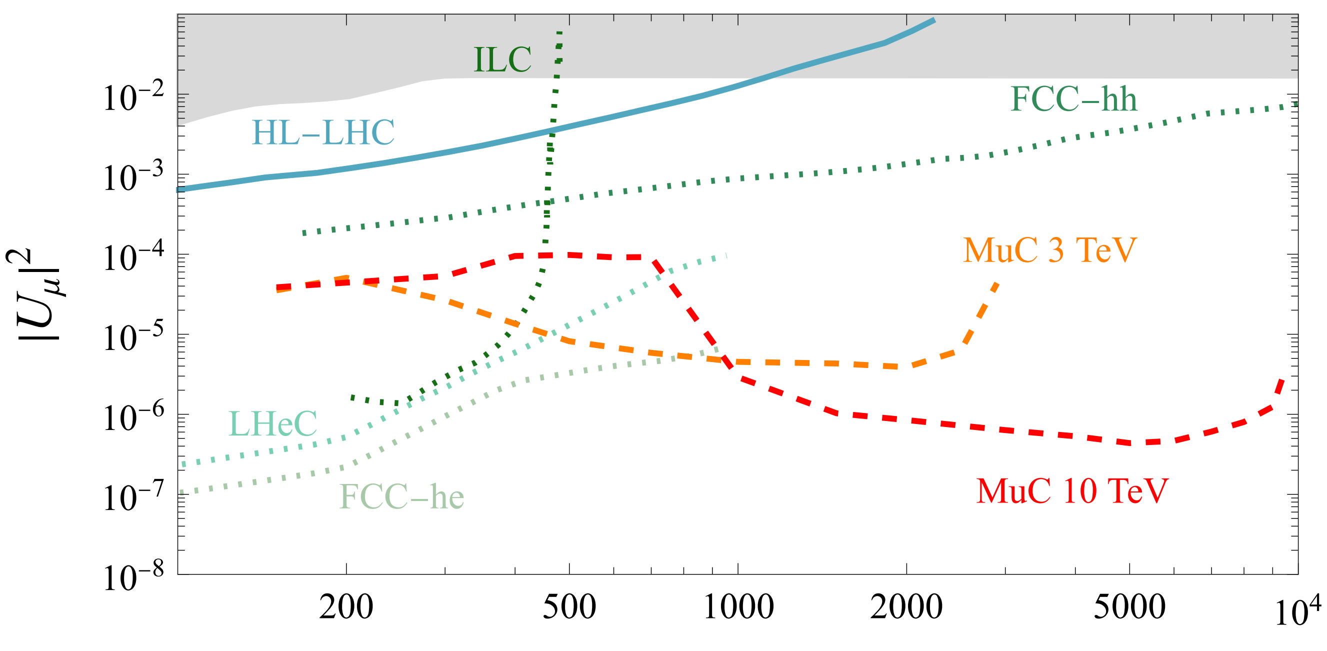
Han, Li, Su, Su, Wu arXiv: 2102.08386



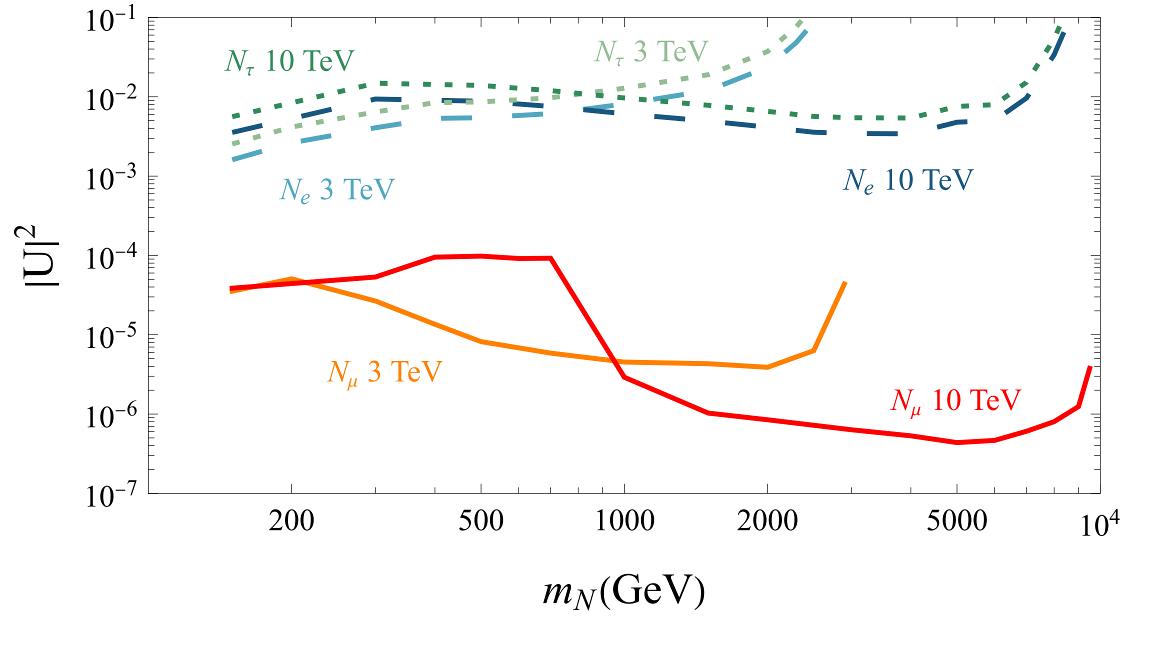
Heavy Neutral Lepton

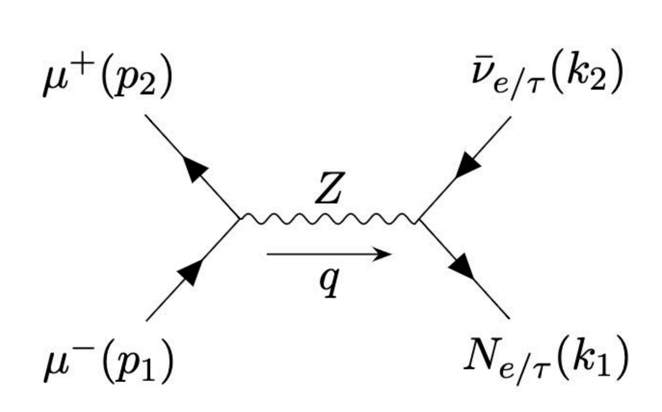
- HNL is ubiquitous in BSM models that address neutrino masses.





[Li, Lyu, Liu, arXiv: 2301.07117](https://arxiv.org/abs/2301.07117)





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(BSM) Precision From Energy

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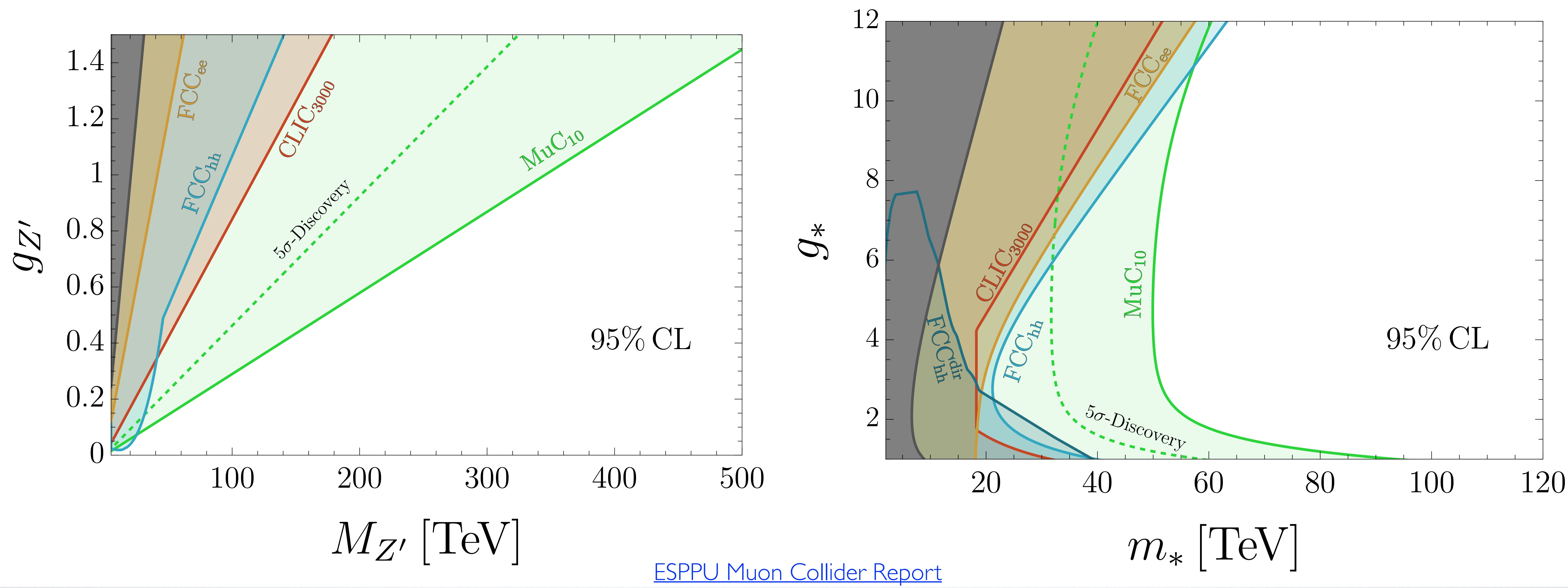
Precision at Higher Energies

- 10 TeV MuC can probe new physics well beyond 10 TeV!



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Precision at Higher Energies

- SMEFT is a useful framework to study indirect effects of BSM physics

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \cdots$$

- At dimension-6, BSM amplitudes can have scaling

$$\mathcal{A} = \mathcal{A}_{\rm SM} + \left(\frac{v^2}{\Lambda^2}\mathcal{A}_0^{(6)} + \frac{vE}{\Lambda^2}\mathcal{A}_1^{(6)} + \frac{E^2}{\Lambda^2}\mathcal{A}_2^{(6)}\right) + \cdots$$

- For high energy muon colliders, $\frac{E^2}{\Lambda^2} \gg \frac{v^2}{\Lambda^2}$

$$\sigma_{\rm BSM} \sim \frac{E^2}{\Lambda^2}\Re\left[\mathcal{A}_{\rm SM}\left(\mathcal{A}_2^{(6)}\right)^*\right]$$

- BSM reach at muon colliders

$$\frac{1}{\sqrt{N}} \sim \frac{E^2}{\Lambda^2} \qquad \Lambda \sim 100\ {\rm TeV}\left(\frac{E}{10\ {\rm TeV}}\right)\left(\frac{\sigma}{1\ {\rm fb}}\right)^{\frac{1}{4}}\left(\frac{\mathcal{L}}{10\ {\rm fb}^{-1}}\right)^{\frac{1}{4}}$$

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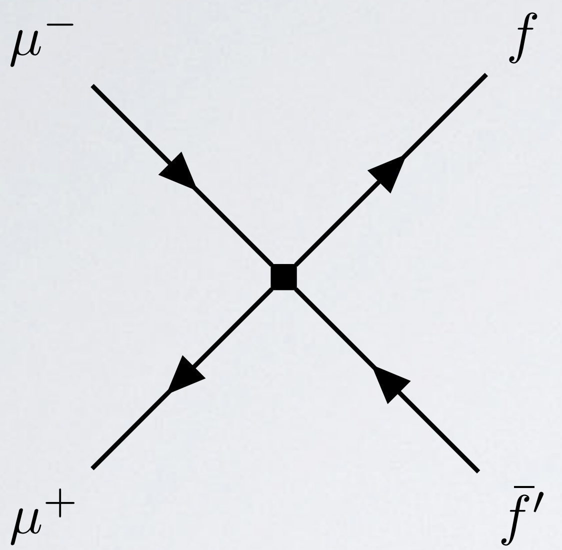
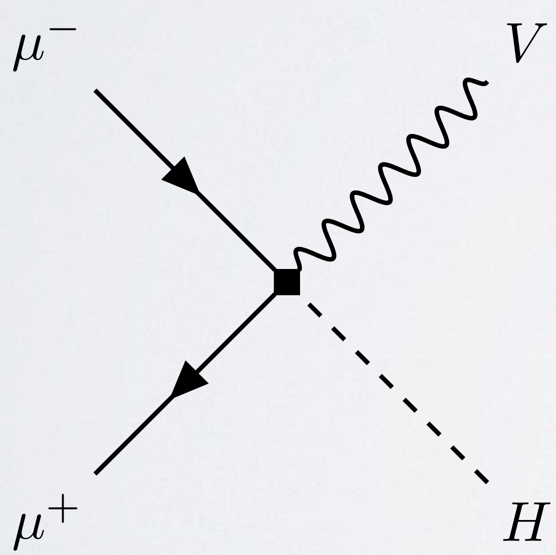
2-to-2 Processes



$$
\begin{aligned}
\mathcal{O}_{\ell\ell} &= (\overline{\ell_L}\gamma^\mu \ell_L)(\overline{\ell_L}\gamma_\mu \ell_L), \\
\mathcal{O}^{(1)}_{\ell q} &= (\overline{\ell_L}\gamma^\mu \ell_L)(\overline{q_L}\gamma_\mu q_L), \\
\mathcal{O}^{(3)}_{\ell q} &= (\overline{\ell_L}\gamma^\mu \sigma^I \ell_L)(\overline{q_L}\gamma_\mu \sigma^I q_L), \\
&\vdots
\end{aligned}
\qquad \sim \frac{E^2}{\Lambda^2}
$$



$$
\begin{aligned}
\mathcal{O}_{H\ell} &= i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{\ell}_L\gamma^\mu \ell_L), \\
\mathcal{O}_{He} &= i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{e}_R\gamma^\mu e_R). \\
&\vdots
\end{aligned}
\qquad \sim \frac{E^2}{\Lambda^2}
$$

$E \sim 10\ \mathrm{TeV} \qquad 1\% \Rightarrow \Lambda \sim 100\ \mathrm{TeV}$

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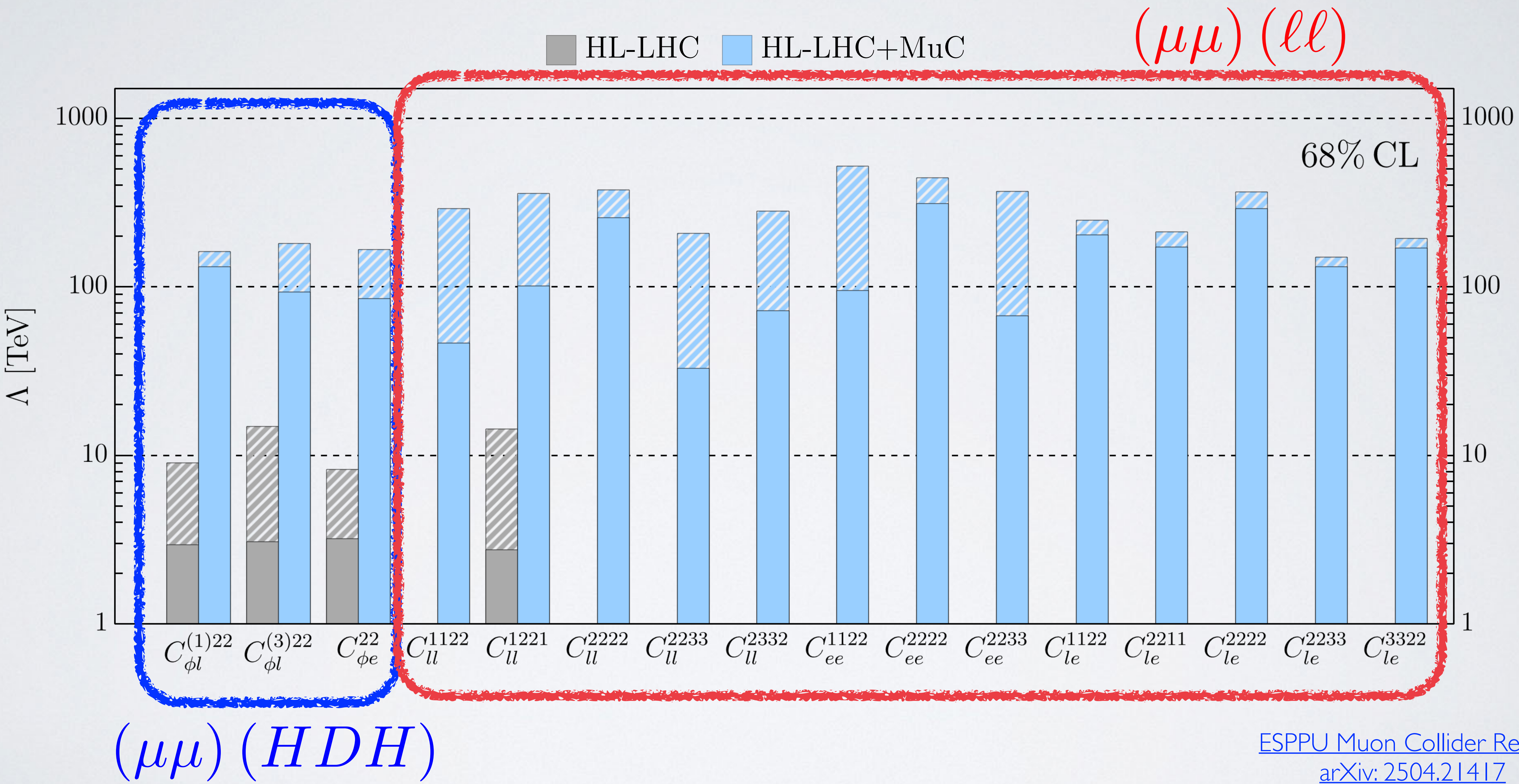
2-to-2 Processes

Also see Glioti's talk for details



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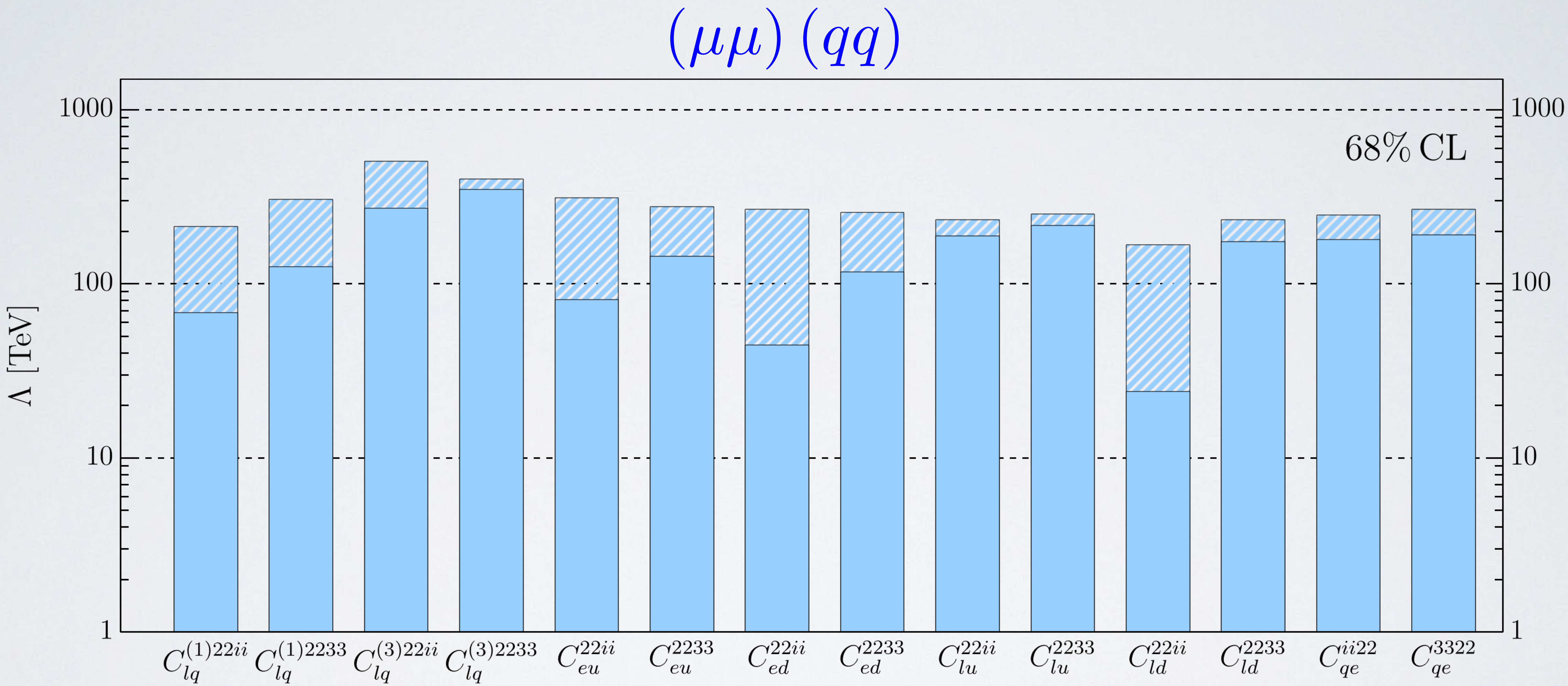
2-to-2 Processes

Also see Glioti's talk for details



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2-to-2 Processes

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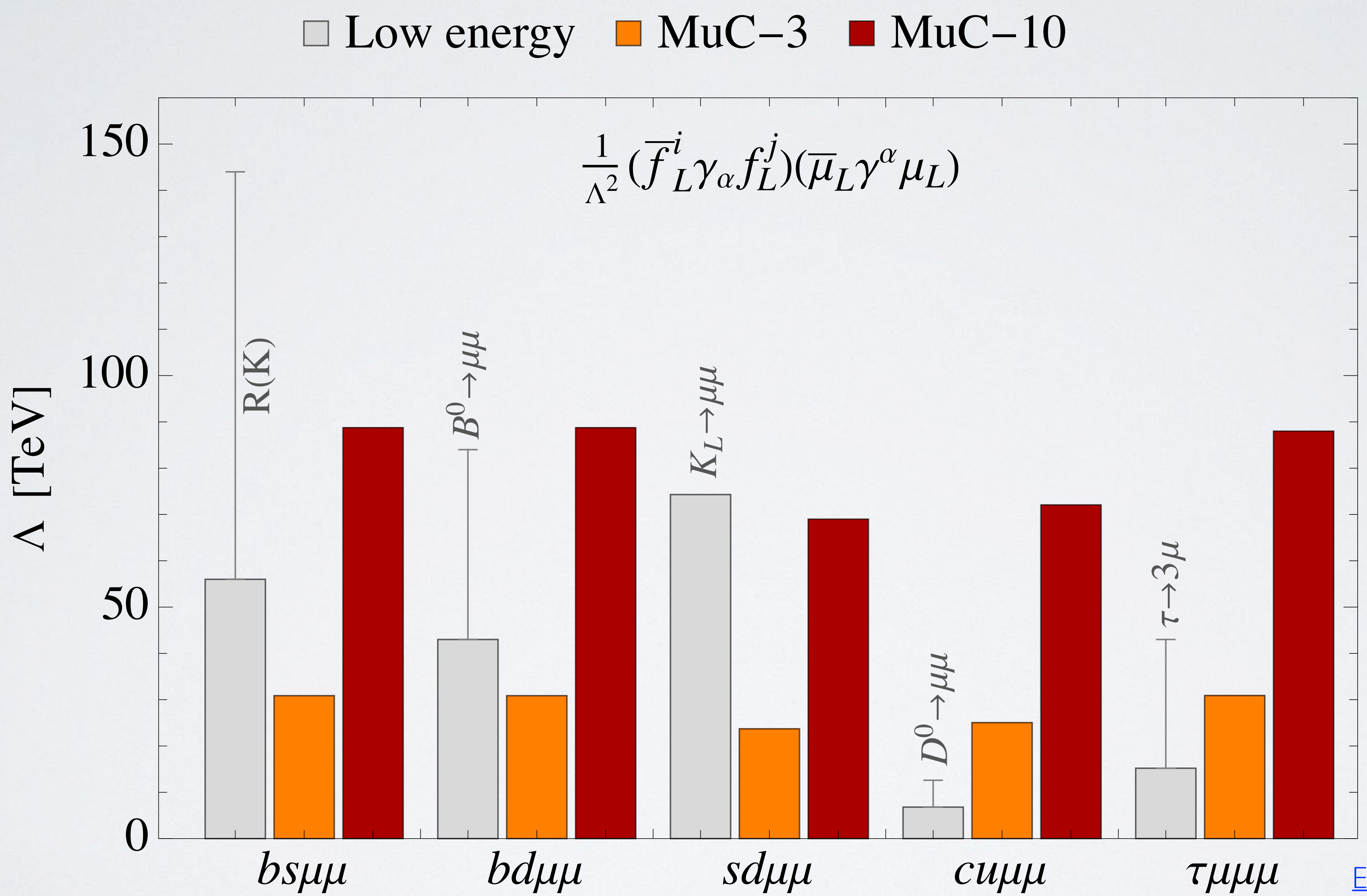

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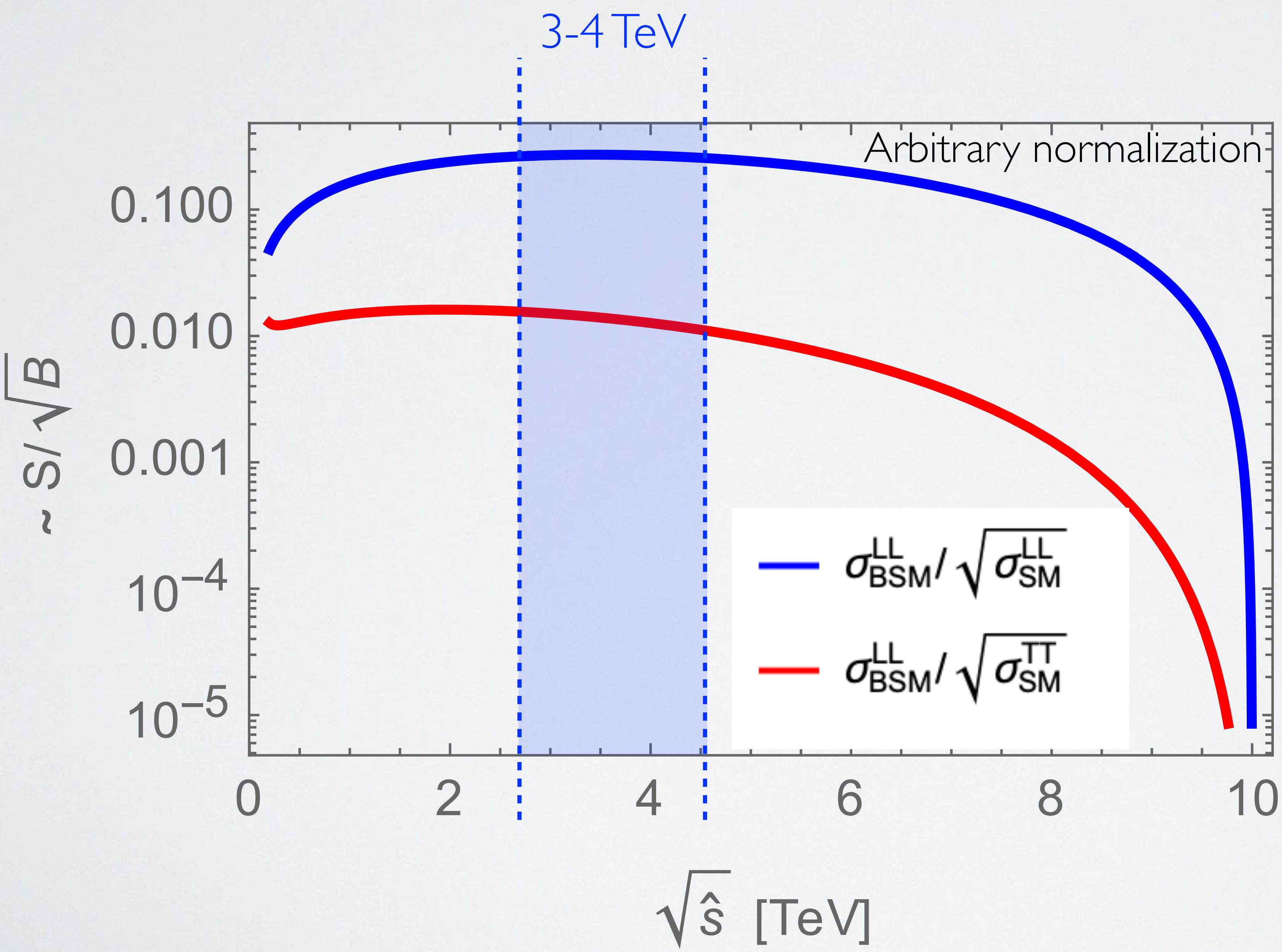
BSM with VBF

More details in previous talk

- VBF in general has weaker sensitivity compared to annihilation processes.



$$S \sim \hat{\sigma}_{\rm BSM} \int_{\hat{s}/S}^{1} f_L(x,\hat{s}) f_L(\frac{\hat{s}}{xS},\hat{s}) \frac{dx}{x}$$

$$B \sim \hat{\sigma}_{\rm SM} \int_{\hat{s}/S}^{1} f_{T/L}(x,\hat{s}) f_{T/L}(\frac{\hat{s}}{xS},\hat{s}) \frac{dx}{x}$$

$$f_T \sim \frac{1+(1-x)^2}{x} \log \frac{Q^2}{m_V^2}$$

$$f_L \sim \frac{1-x}{x}$$

$$\hat{\sigma}_{\rm SM} \sim 1$$

$$\hat{\sigma}_{\rm BSM} \sim \frac{\hat{s}}{\Lambda^2}$$

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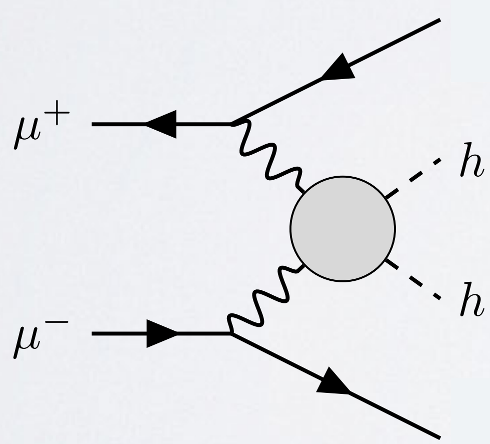
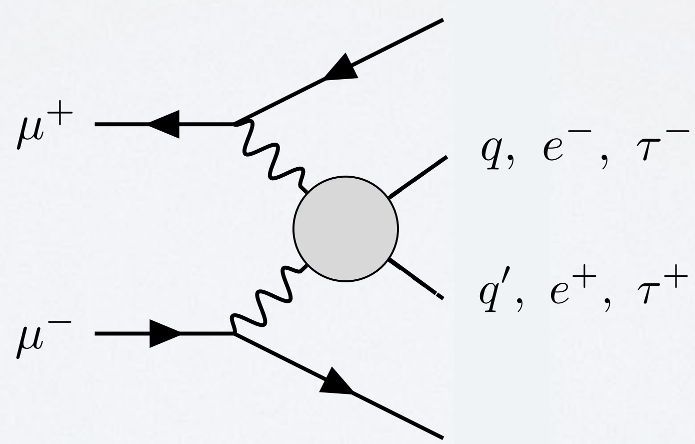
BSM with VBF

More details in previous talk

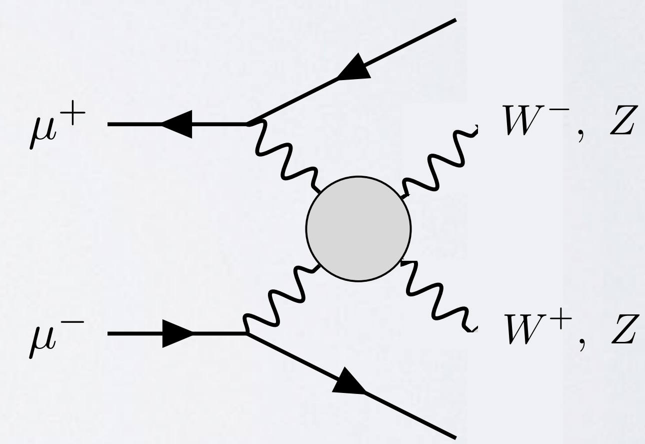
- VBF in general has weaker sensitivity compared to annihilation processes.
- Useful for operators that are not directly accessible via annihilations or complementarity to resolve flat directions.
- Generically,



$$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)\,,$$
$$\mathcal{O}_{HD} = (D^\mu H^\dagger H)(H^\dagger D_\mu H)\,,$$
$$\vdots$$



$$\mathcal{O}_{Hq} = i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{q}_L\gamma^\mu q_L)\,,$$
$$\mathcal{O}_{H\ell} = i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{\ell}_L\gamma^\mu \ell_L)\,,$$
$$\vdots$$



$$\mathcal{O}_{3W} = \varepsilon_{abc} W_\mu^{a\,\rho} W_\rho^{b\,\nu} W_\nu^{c\,\mu}\,.$$
$$\vdots$$

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BSM with VBF

[ESPPU Muon Collider Report](arXiv: 2504.21417)
arXiv: 2504.21417

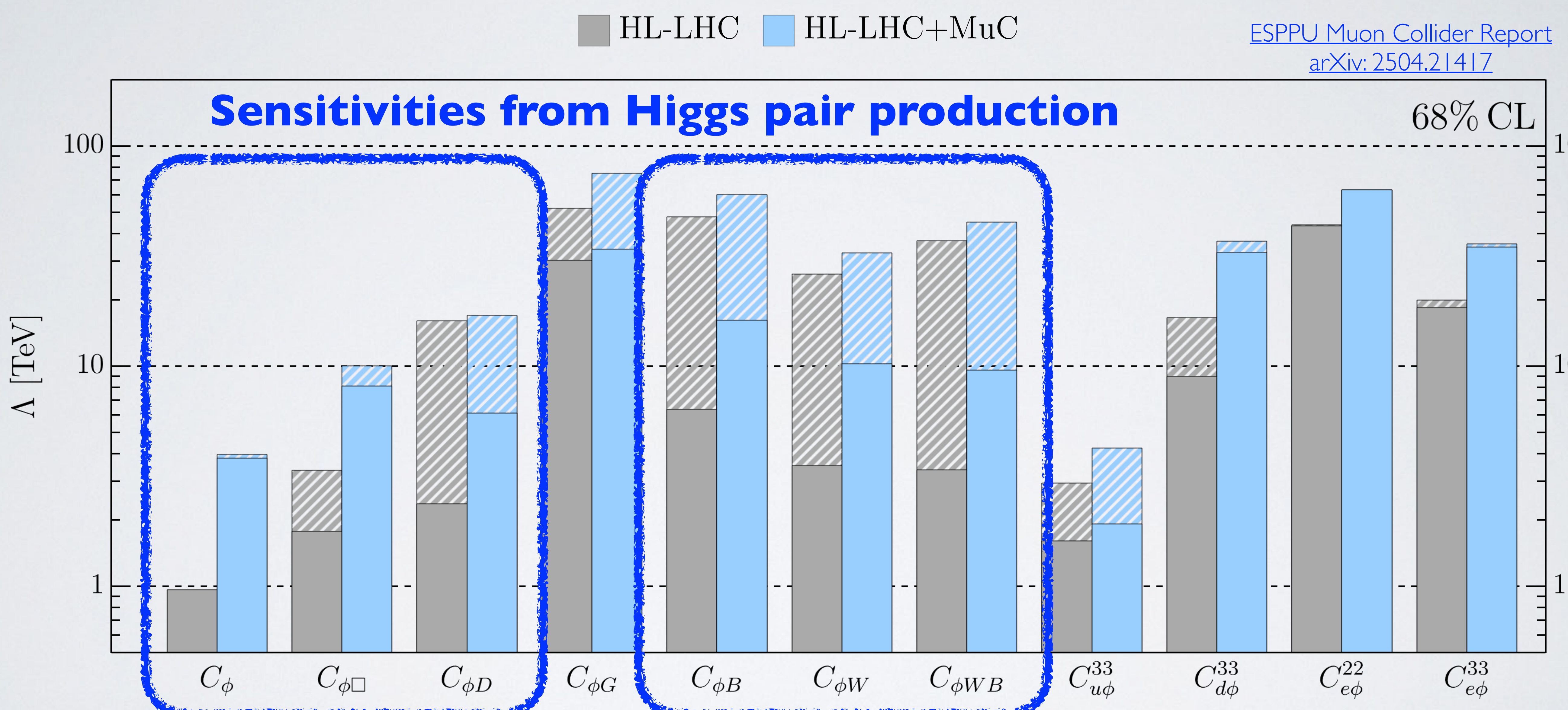

Figure 16.3.3: 68% CL reach on EFT from a global fit at the 10 TeV muon collider.

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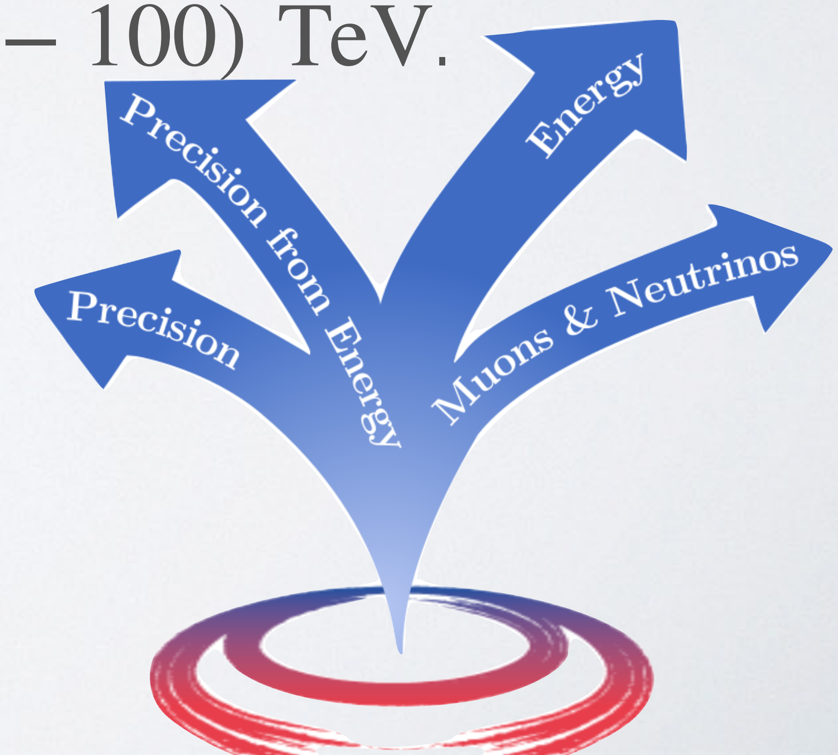
Conclusion

- Muon collider not only probes exciting new physics, it is also an technologically exciting project to work on.
- We not only measure SM more precisely, we will see new (SM) phenomena.
- Directly probe BSM states up to $\sqrt{s}/2$ (pair) or $\sqrt{s}$ (single).
- Indirectly probe BSM effects up to $\mathcal{O}(10-100)$ TeV.



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Thanks!

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Backups

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Higgs Cross Sections

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91
$WW \to ZH$	9.5	22	33	42	67
$WW \to t\bar{t}H$	0.012	0.046	0.090	0.14	0.28
$WW \to Z$	2200	3100	3600	4200	5200
$WW \to ZZ$	57	130	200	260	420

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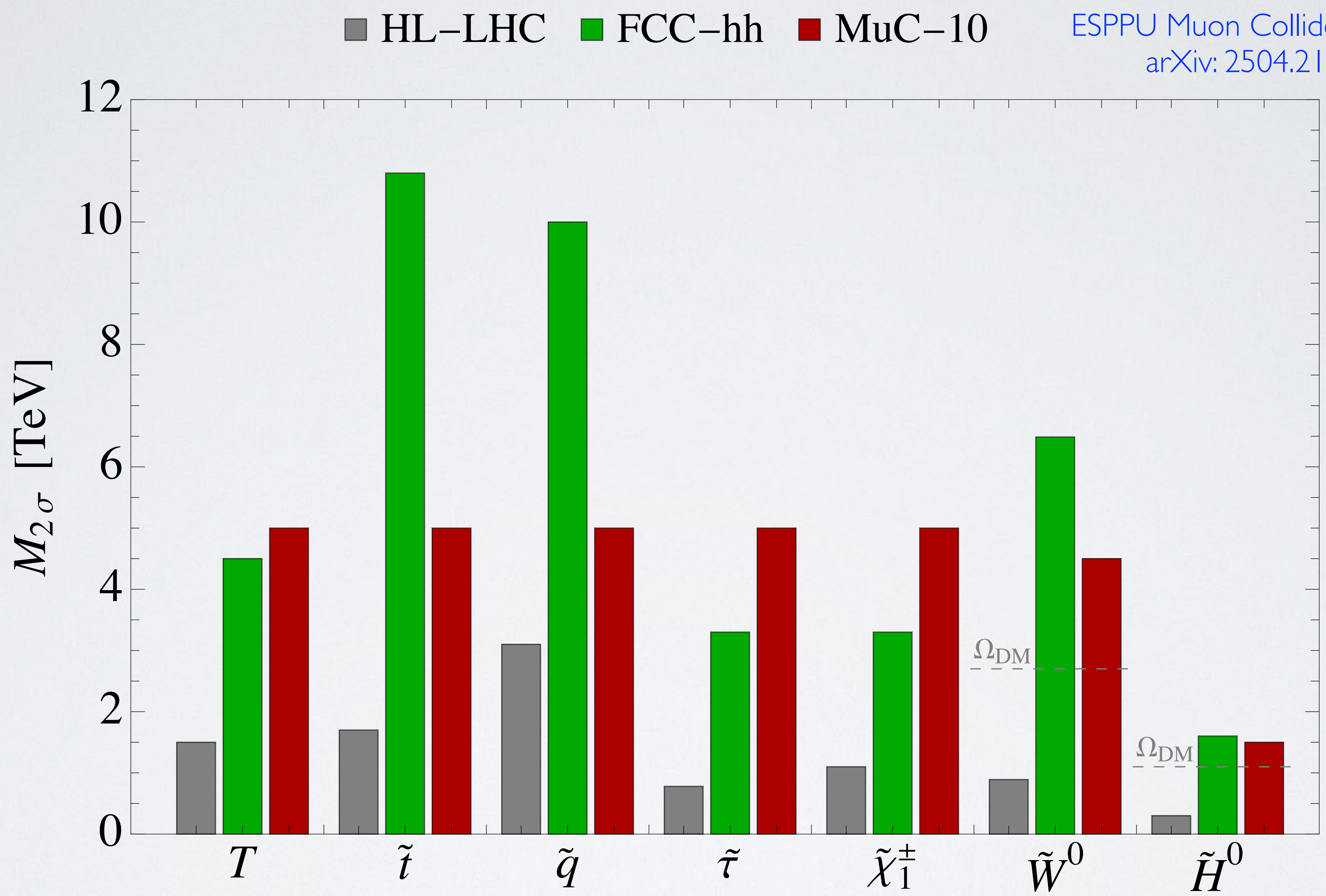

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Generic BSM reach

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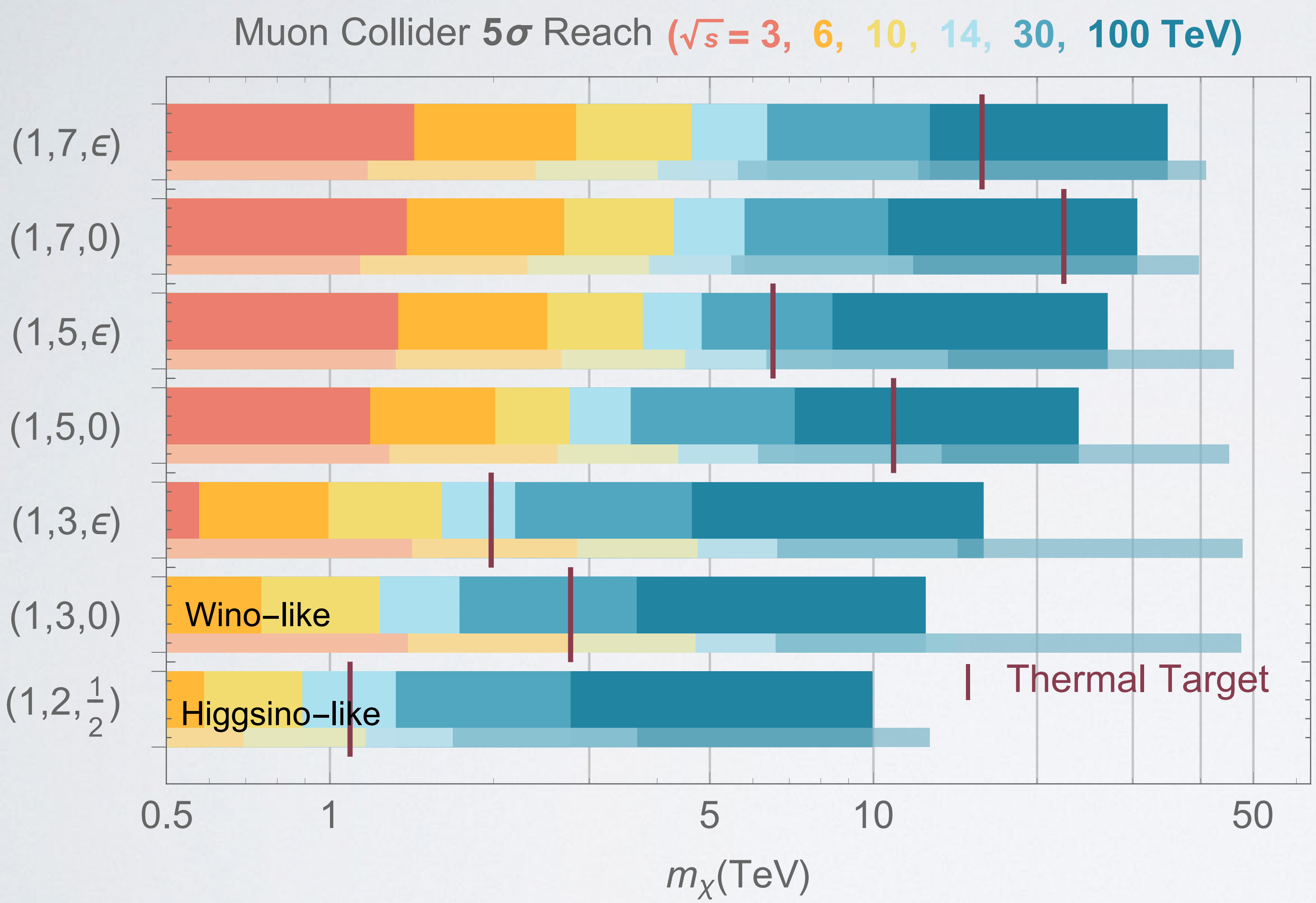
WIMP



Combined missing mass search
&
Disappearing track

- Muon collider has great potential in DM search
- Decisive statements on Minimal DM.
  - Missing mass
  - Disappearing tracks
- Further optimizations
- Can be extended beyond minimal DM.

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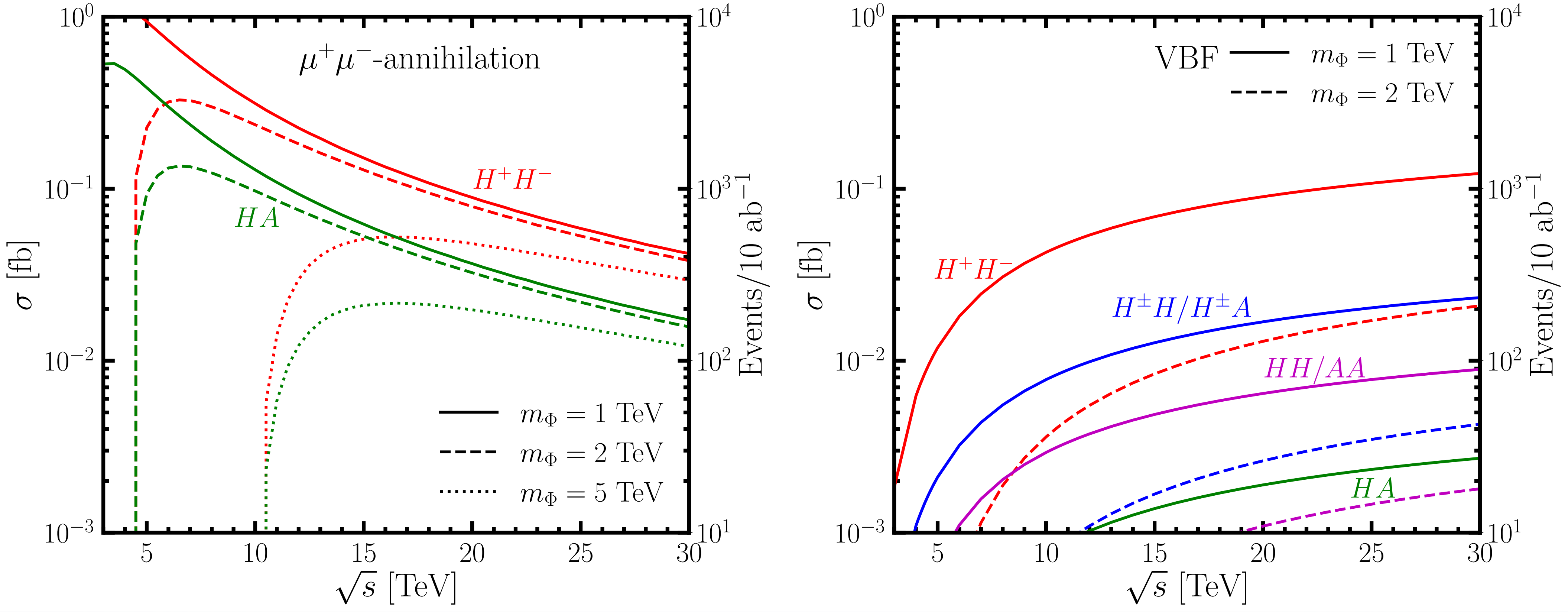
2HDM



Type-I: $\xi_{Huu} = \xi_{Auu} = \cot\beta$, $\xi_{Hdd} = -\xi_{Add} = \cot\beta$, $\xi_{H\ell\ell} = -\xi_{A\ell\ell} = \cot\beta$;

Type-II: $\xi_{Huu} = \xi_{Auu} = \cot\beta$, $-\xi_{Hdd} = \xi_{Add} = \tan\beta$, $-\xi_{H\ell\ell} = \xi_{A\ell\ell} = \tan\beta$;

Type-L: $\xi_{Huu} = \xi_{Auu} = \cot\beta$, $\xi_{Hdd} = -\xi_{Add} = \cot\beta$, $-\xi_{H\ell\ell} = \xi_{A\ell\ell} = \tan\beta$;

Type-F: $\xi_{Huu} = \xi_{Auu} = \cot\beta$, $-\xi_{Hdd} = \xi_{Add} = \tan\beta$, $\xi_{H\ell\ell} = -\xi_{A\ell\ell} = \cot\beta$.

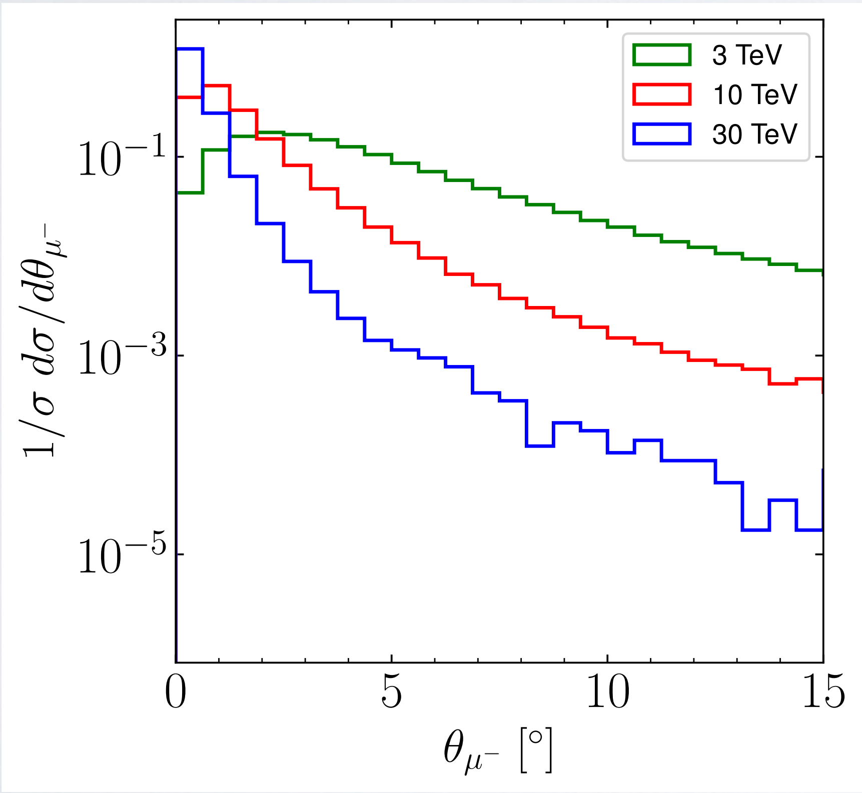
WW vs. ZZ Fusion

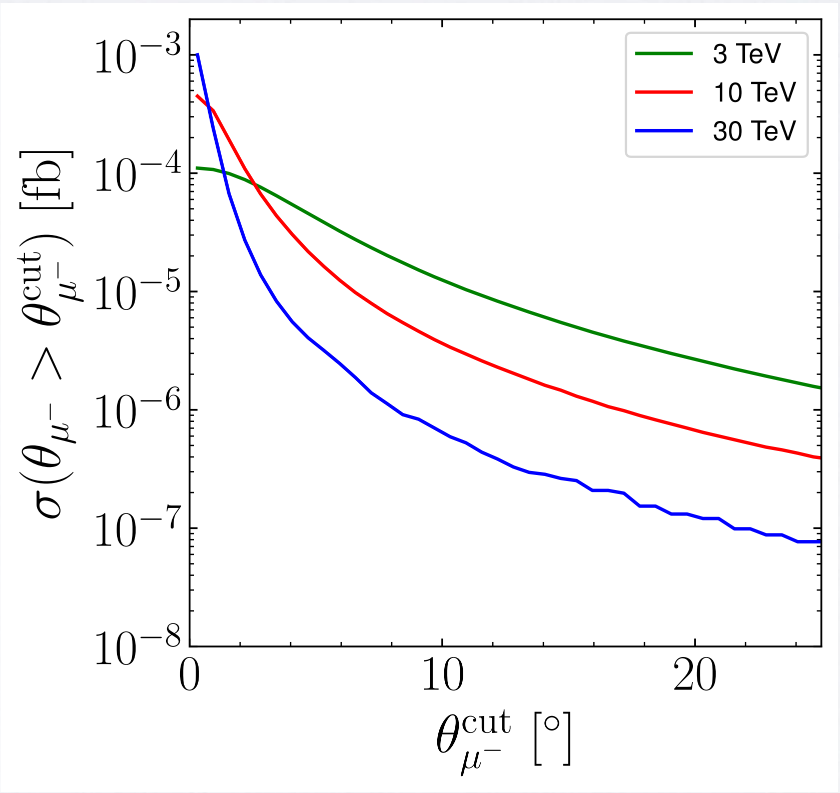
- Can we distinguishing WW vs. ZZ fusion ?

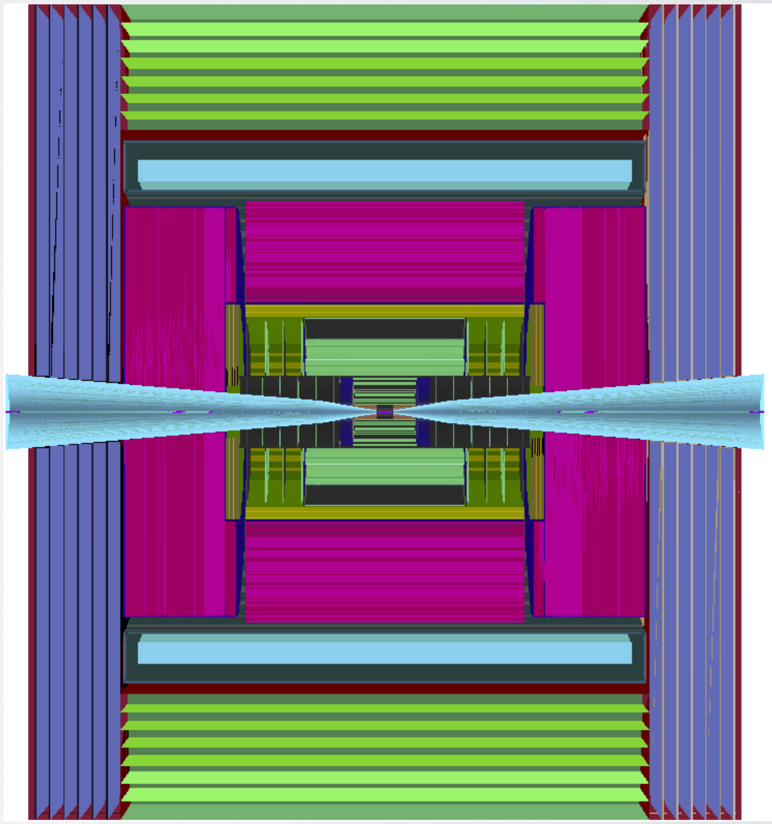
$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu \; HH \quad (WW \text{ fusion}),$$

$$\mu^+\mu^- \to \mu^+\mu^- \; HH \quad (ZZ \text{ fusion}).$$

- But the outgoing muons are quite forward!







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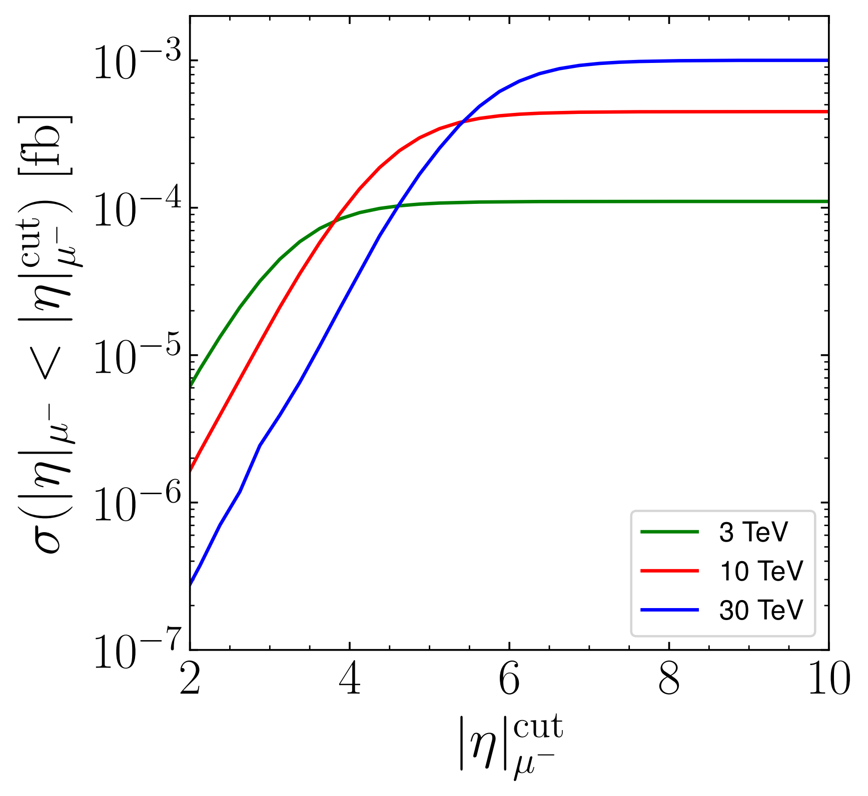
WW vs. ZZ Fusion

- Distinguishing WW vs. ZZ fusion

$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu \; HH \quad (WW \text{ fusion}),$$

$$\mu^+\mu^- \to \mu^+\mu^- \;\; HH \quad (ZZ \text{ fusion}).$$

- Forward muon tagging $|\eta| < 6$ (even poor resolution is still ok)



$$p_T \sim \mathcal{O}(m_Z)$$

$$\eta \sim \cosh^{-1}\left(\frac{\sqrt{s}}{2m_Z}\right)$$

$$\sim 3.5,\;\; 4.7,\;\; 5.8$$

for $3, 10, 30$ TeV

For more applications/discussions: Li, Liu, Lyu, arXiv: 2401.08756

Ruhdorfer, Salvioni, Wulzer, arXiv: 2411.00096,

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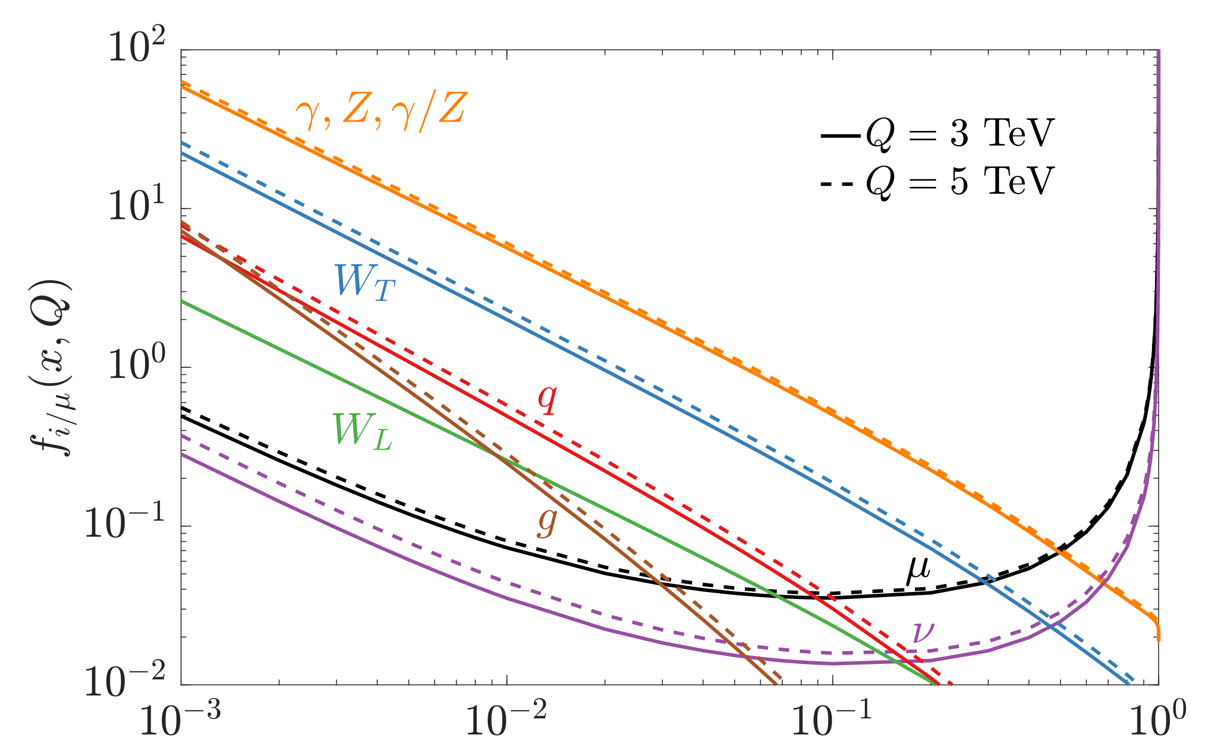
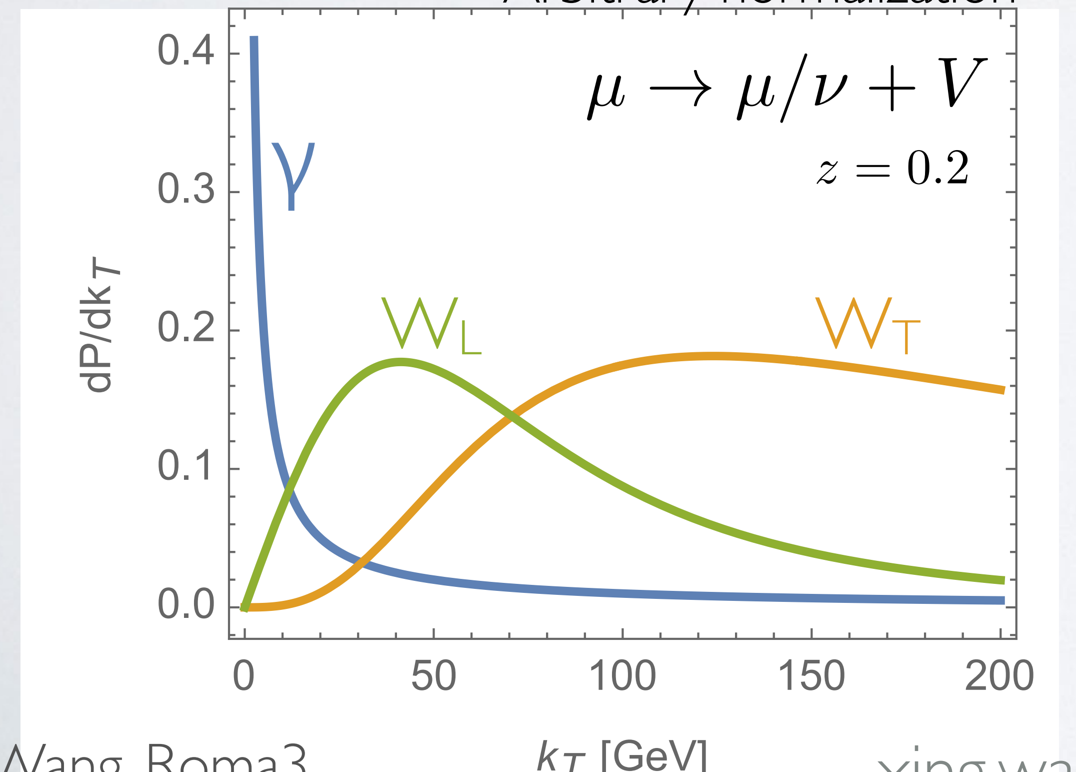
$VV \to ff$

- Large SM rate from
  $$\gamma\gamma \to ff$$
- Forward muon tagging ?
  $$E = 3\ \text{TeV}, \quad \eta = 6 \quad \Rightarrow \quad p_T \sim 15\ \text{GeV}$$
- Cannot distinguish W vs. γ



Han, Ma and Xie, arXiv: 2007.14300

Arbitrary normalization



- Different kT dependence

$$\frac{dP}{dk_T} \sim \begin{cases} \dfrac{dk_T^2}{k_T^2} & \text{for } \gamma \\ \dfrac{k_T^2 dk_T^2}{(k_T^2 - (1-z)m_V^2)^2} & \text{for } V_T \\ \dfrac{m_V^2 dk_T^2}{(k_T^2 - (1-z)m_V^2)^2} & \text{for } V_L \end{cases}$$

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$VV \to ff$

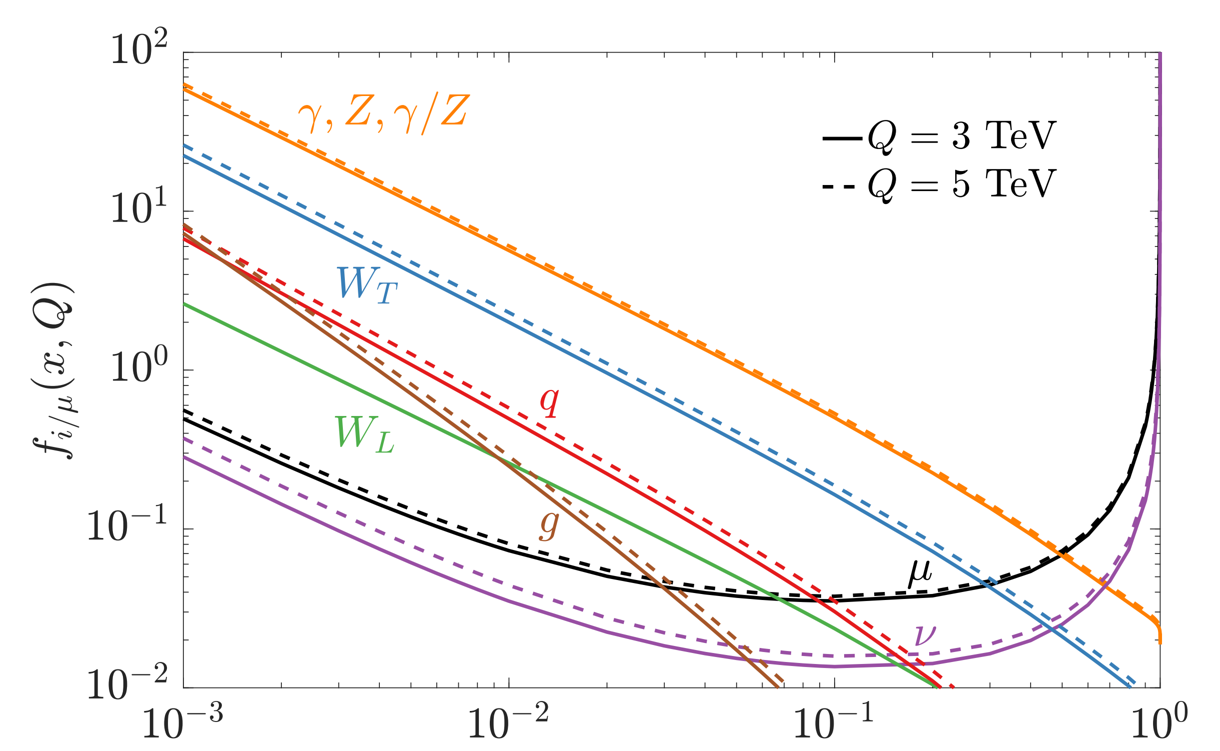
- Large SM rate from

$$\gamma\gamma \to ff$$

- Forward muon tagging ?

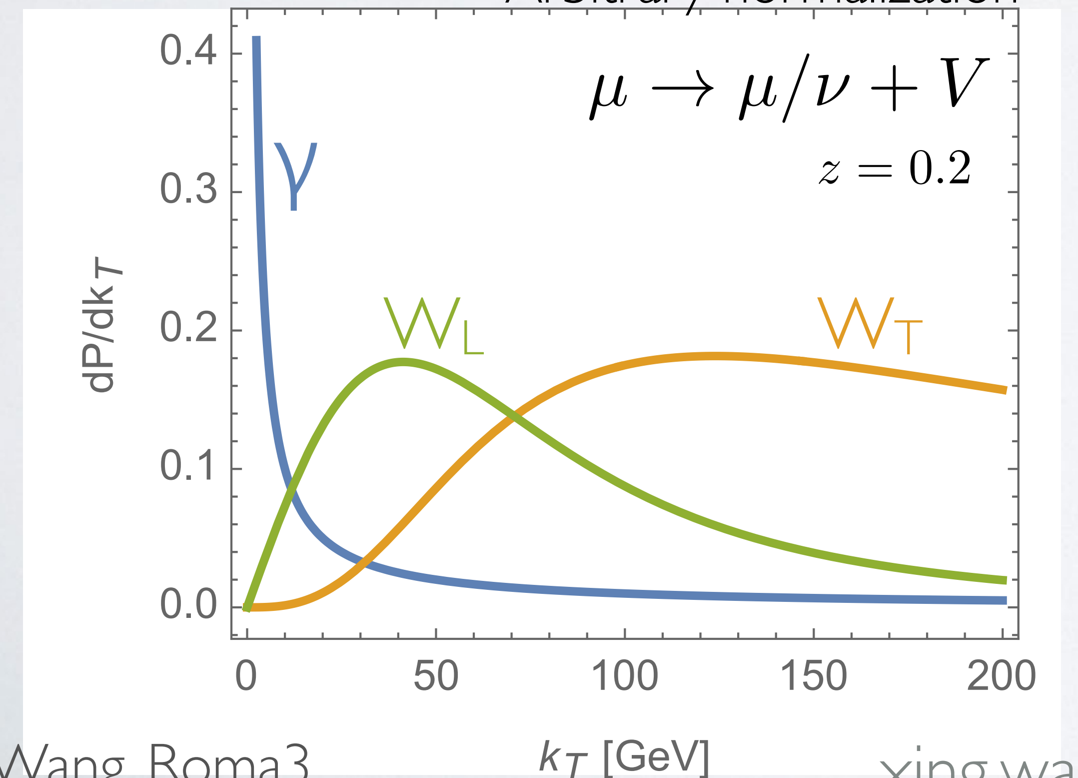
$$E = 3\ \mathrm{TeV}, \quad \eta = 6 \quad \Rightarrow \quad p_T \sim 15\ \mathrm{GeV}$$

- Cannot distinguish W vs. γ



[Han, Ma and Xie, arXiv: 2007.14300](#)

Arbitrary normalization



- Different pT spectra $p_{T,ff}$

$VV \to ff$

- For bb final state,

$$\mathcal{O}_{Hq} = i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{q}_L \gamma^\mu q_L)\,, \qquad \mathcal{O}'_{Hq} = i\left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)(\bar{q}_L \sigma^a \gamma^\mu q_L)\,,$$