Dark matter at the muon colliders

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Backgrounds

- Dark matter is firmly established based on astrophysics observations and cosmology.
- Beyond the standard model
- Various candidates
  - Weakly interacting massive particles(WIMPs)
  - Axions
  - Sterile neutrinos
  - ...

Detecting DM

- Direct detection: DM+SM$\rightarrow$DM+SM,
- Indirect detection: DM+DM$\rightarrow$SM+SM
- Collider experiments: SM+SM$\rightarrow$DM+SM

The Minimal Dark Matter

Real scalar or Majorana fermion:

- Additional $SU(2)$ weak n-plet, which can be real scalar or Majorana fermion

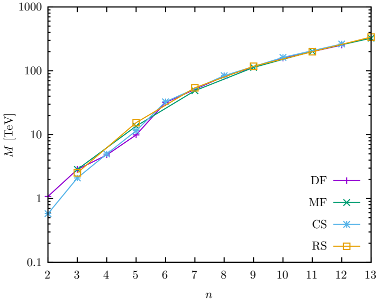
$$\mathcal{L}_S = \frac{1}{2}(D_\mu \chi)^2 - \frac{1}{2} M_\chi^2 \chi^2 \tag{1}$$

$$\mathcal{L}_F = \frac{1}{2}\chi(i\bar{\sigma}^\mu D_\mu - M_\chi)\chi \tag{2}$$

- Electroweak corrections introduce mass splitting
- The neutral one is also the lightest, hence DM candidates

Thermal Masses

Thermal masses including Sommerfeld enhancement and bound-state formation:



Bottaro et.al.2107.09688&2205.04486

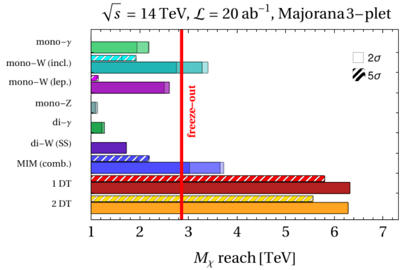
- MF and RS: odd n, $Y = 0$
- DF and CS: both even and odd n, non-zero Y
- Masses are determined by n.
- $n = 4, 5$ is at $\mathcal{O}(10)$ TeV,beyond the reach of LHC!

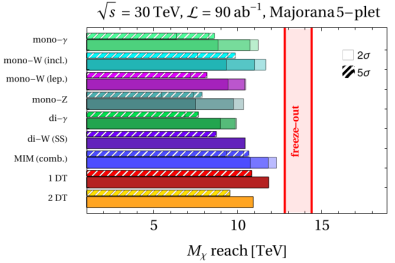
direct production at the muon collider

- mono-V: $\mu^+\mu^- \to \chi^i\chi^j + V, V = \gamma, Z, W$
- mono-μ: $\mu^+\mu^- \to \chi^i\chi^j + \mu^\pm\nu$, $\gamma\mu^\pm \to \chi^i\chi^j + \mu^\pm$
- VBF di-μ: $\mu^+\mu^- \to \chi^i\chi^j + \mu^+\mu^-$
- di-V: $\mu^+\mu^- \to \chi^i\chi^j + VV$
- Disappearing tracks due to decay of $\chi^i\chi^j$

Main limitation: $M_\chi < \frac{\sqrt{s}}{2}$

direct production at muon colliders





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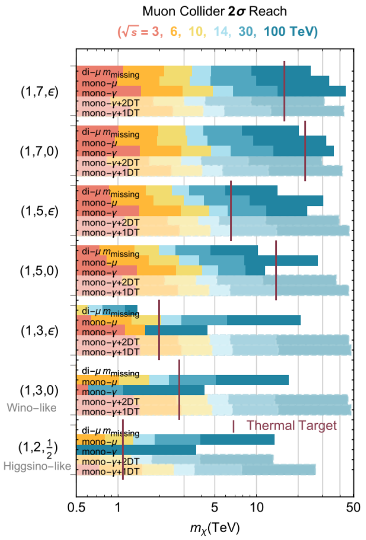
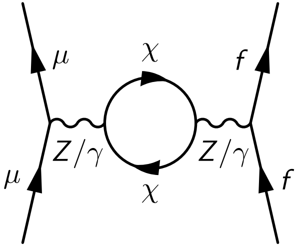
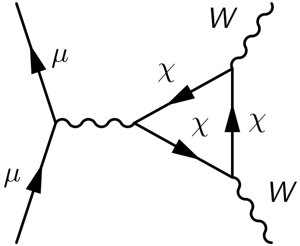


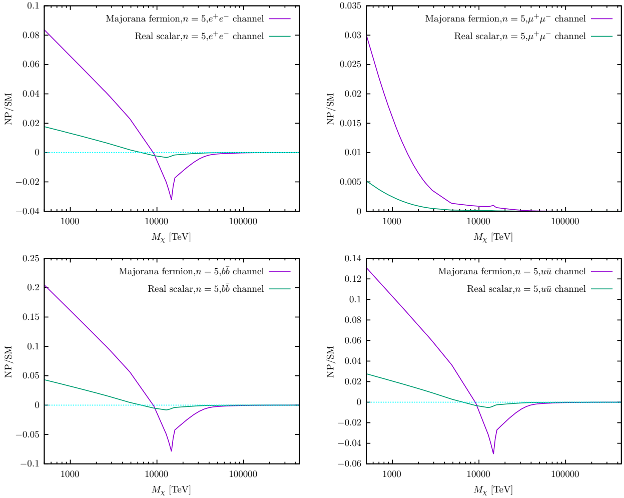
Han,Liu,Wang,Wang,2009.11287

- Direct production is limited by $M < \frac{\sqrt{s}}{2}$.
- Indirect probes through loop corrections: no such limit!



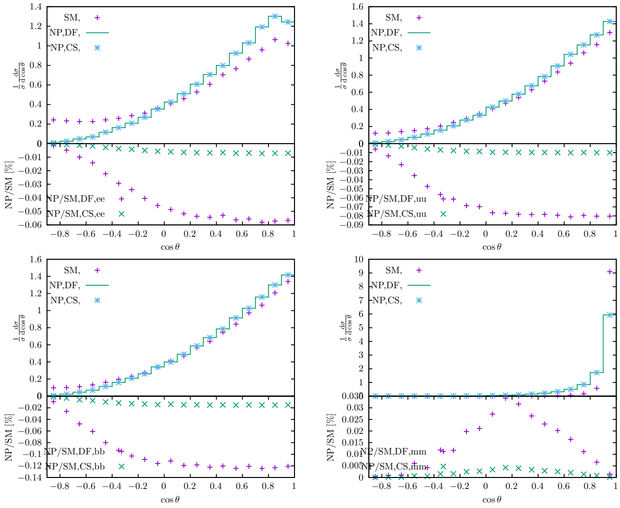


30 TeV muon collider:



- Effects of fermions are much larger than scalars
- Large effects for low mass
- small effects for large mass(EFT regime)
- local peak for the threshold $M_\chi = \frac{\sqrt{s}}{2}$

Differential distribution



e^+e^-, $u\bar{u}$, $b\bar{b}$

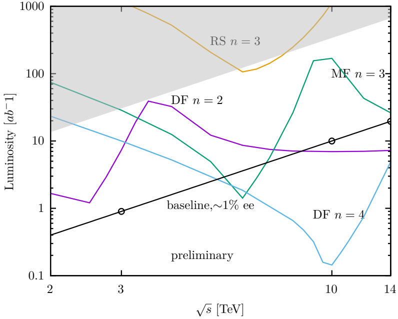
- peaks in forward region
- θ coverage of detectors
- Inclusive

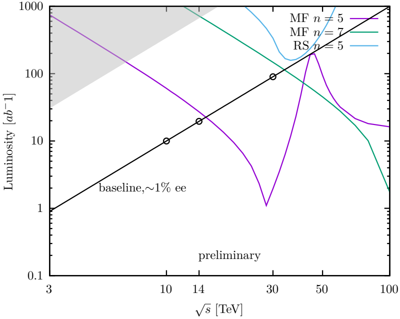
$\mu^+\mu^-$:

- SM peak in forward region
- NP effects peak in center region
- Need differential

Analysis

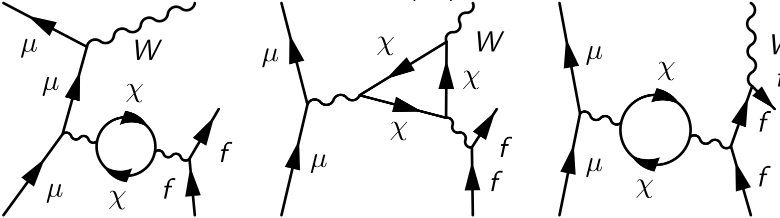
- Inclusive level: e^+e^-, $\tau^+\tau^-$, jj, $t\bar{t}$, HZ, W^+W^-
- Differential level: $\mu^+\mu^-$





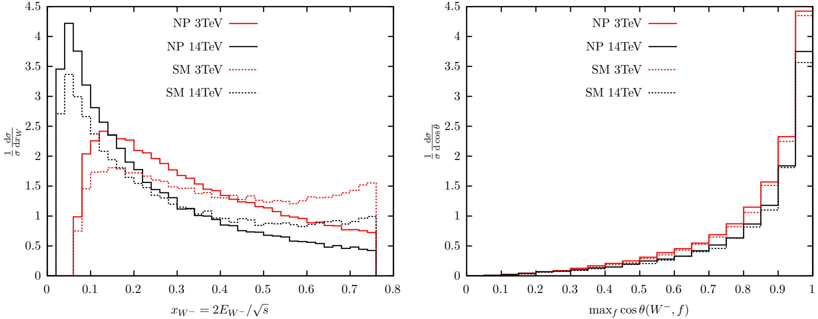
charged currents

Extra W radiation: $\mu^+\mu^- \to Wf\bar{f}'$



Differential distributions

$\mu^+\mu^- \to W^- u\bar{d}$



Dominated by soft and collinear W bosons.

Soft and collinear radiation

Double logarithm $\ln^2 \frac{s}{m_W^2}$ and single logarithm are large: NC at fixed order→NC+CC with resummation

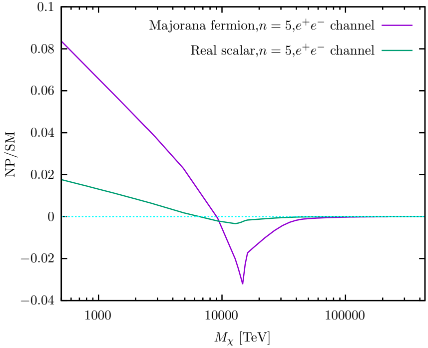
	3 TeV			10 TeV			30 TeV		
	DL	$e^{\mathrm{DL}}-1$	$\mathrm{SL}(\frac{\pi}{2})$	DL	$e^{\mathrm{DL}}-1$	$\mathrm{SL}(\frac{\pi}{2})$	DL	$e^{\mathrm{DL}}-1$	$\mathrm{SL}(\frac{\pi}{2})$
$\ell_L \to \ell'_L$	-0.46	-0.37	0.25	-0.82	-0.56	0.33	-1.23	-0.71	0.41
$\ell_L \to q_L$	-0.44	-0.36	0.25	-0.78	-0.54	0.34	-1.18	-0.69	0.42
$\ell_L \to e_R$	-0.32	-0.27	0.13	-0.56	-0.43	0.17	-0.85	-0.57	0.21
$\ell_L \to u_R$	-0.27	-0.24	0.11	-0.48	-0.38	0.15	-0.72	-0.51	0.18
$\ell_L \to d_R$	-0.24	-0.21	0.10	-0.43	-0.35	0.13	-0.64	-0.47	0.16
$\ell_R \to \ell'_L$	-0.32	-0.27	0.13	-0.56	-0.43	0.17	-0.85	-0.57	0.21
$\ell_R \to q_L$	-0.30	-0.26	0.12	-0.53	-0.41	0.16	-0.79	-0.55	0.21
$\ell_R \to \ell'_R$	-0.17	-0.16	0.07	-0.30	-0.26	0.09	-0.46	-0.37	0.12
$\ell_R \to u_R$	-0.12	-0.12	0.05	-0.22	-0.20	0.07	-0.33	-0.28	0.08
$\ell_R \to d_R$	-0.09	-0.09	0.04	-0.17	-0.16	0.05	-0.25	-0.22	0.06

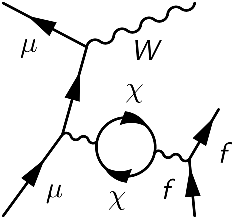
Table 1: Double and single logarithmic corrections to the exclusive processes $\ell^+\ell^- \to \bar{f}f$. The single-logarithmic corrections are evaluated at $\theta_* = \pi/2$.

Chen et.al.2202.10509

Hard radiation

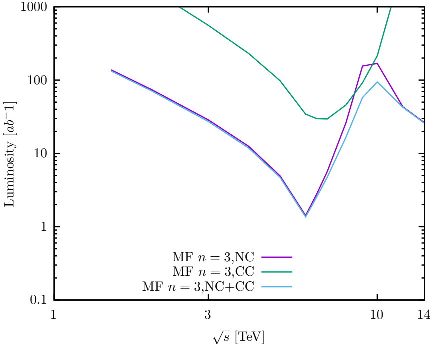
- NP effects is about 0 when $\sqrt{s} \sim 3.2 M_\chi$ for NC
- Initial state hard radiation can reduce $m(f\bar{f})$ from $\sqrt{s}$ to $\sim 2M_\chi$(threshold region)





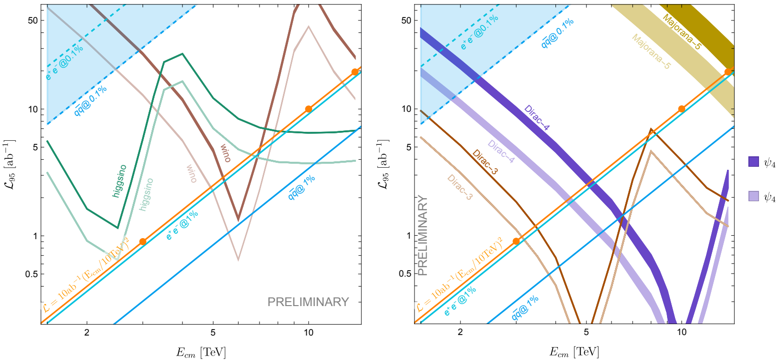
Combination of NC and CC

With hard W radiation:



- Neutral current provides most of the constraints
- Hard W radiation helps to resolve the region $\sqrt{s} \sim 3.2 M_\chi$
- Need further improvements on theoretical prediction
- Need to combine with direct productions

Combined NC+CC



Conclusion

- mono-X,di-X and DT for low mass region $M_\chi < \frac{\sqrt{s}}{2}$
- Indirect probes are good at thresholds $M_\chi \sim \frac{\sqrt{s}}{2}$
- and can probe high mass $M_\chi > \frac{\sqrt{s}}{2}$
- Soft/collinear radiations shift NC to NC+CC
- Hard radiations affect the dynamics and sensitivities
- Statistic uncertainties in $\mathcal{O}(0.1 \sim 1\%)$ level: need further improvements on theoretical predictions(NLO+NLL or higher?)

Backup slides