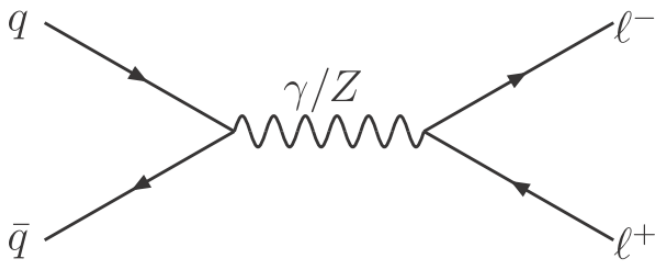
DARK MATTER SIGNALS IN DILEPTON PRODUCTION



Nirmal Raj

UNIVERSITY OF OREGON

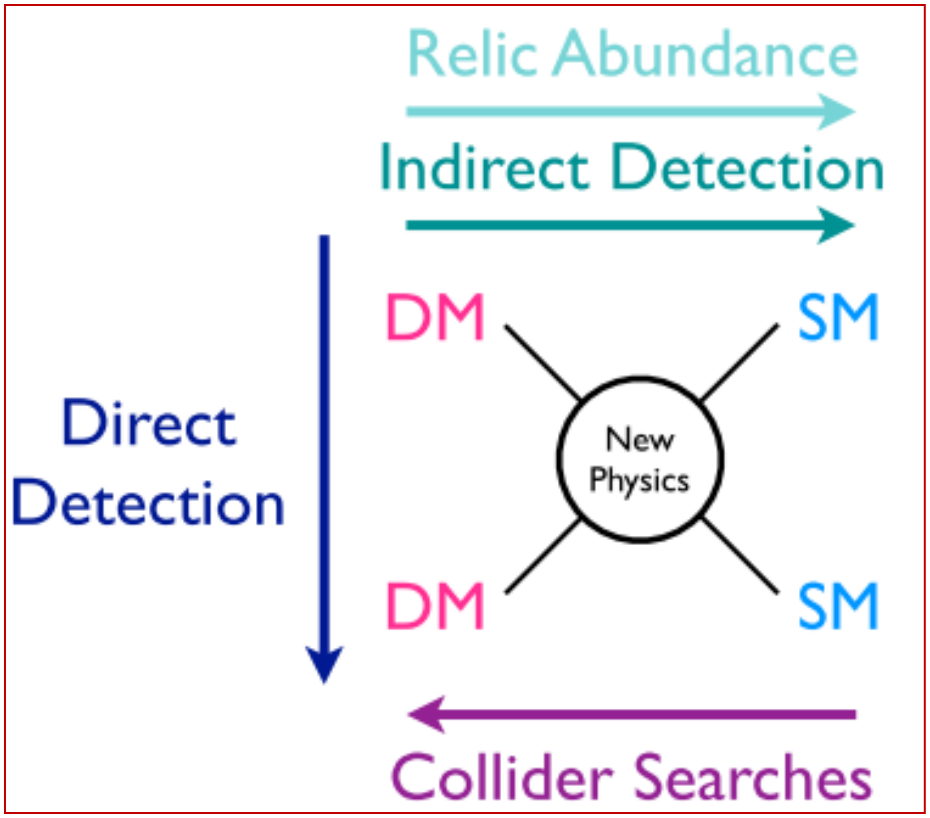
with
W. Altmannshofer
R. Harnik
P. J. Fox
G. D. Kribs

arXiv: 1411.6743 [hep-ph]

Argonne National Laboratory, 16 Dec 2014

WIMPs

Weakly Interacting Massive Particles:
Weak scale mass and weak coupling to SM => right relic abundance



Can be probed by all three approaches

WIMP studies

Effective operators

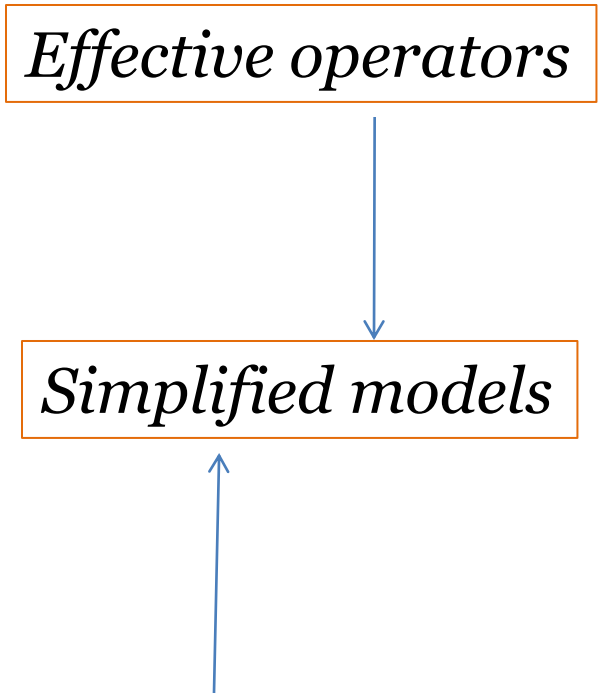
- 2-D parameter space
- Collider search complements direct detection
- UV-incomplete

Full models

e.g. SUSY

- All effects [NLO, etc.] calculable
- More complete
- Huge parameter space
- Theoretical assumption-sensitive

WIMP studies



- 2-D parameter space
- Collider search complements direct detection
- UV-incomplete

- Unites the best motivations of both
- Renormalizable
- Minimal field content:

$$\mathcal{L} \sim \lambda(\mathrm{SM})(\mathrm{mediator})(\mathrm{DM})$$

- All effects [NLO, etc.] calculable
- More complete
- Huge parameter space
- Theoretical assumption-sensitive

Simplified dark literature

QUARK PORTAL

- "Effective WIMPs" - Chang, Edezhath, Hutchinson, Luty [arXiv:1307.8120]
- "DM with *t*-channel mediator" - An, Wang, Zhang [arXiv:1308.0592]
- "Fermion Portal DM" - Bai, Berger [arXiv:1308.0612]
- "Simplified DM Models Interacting with Quarks" – DiFranzo, Nagao, Rajaraman, Tait [arXiv:1308.2679]
- "Monojet versus rest of the world" – Papucci, Vichi, Zurek [arXiv: 1402.2285]
- "Simplified DM Models and MET searches" Abdallah, et al [arXiv:1409.2893]

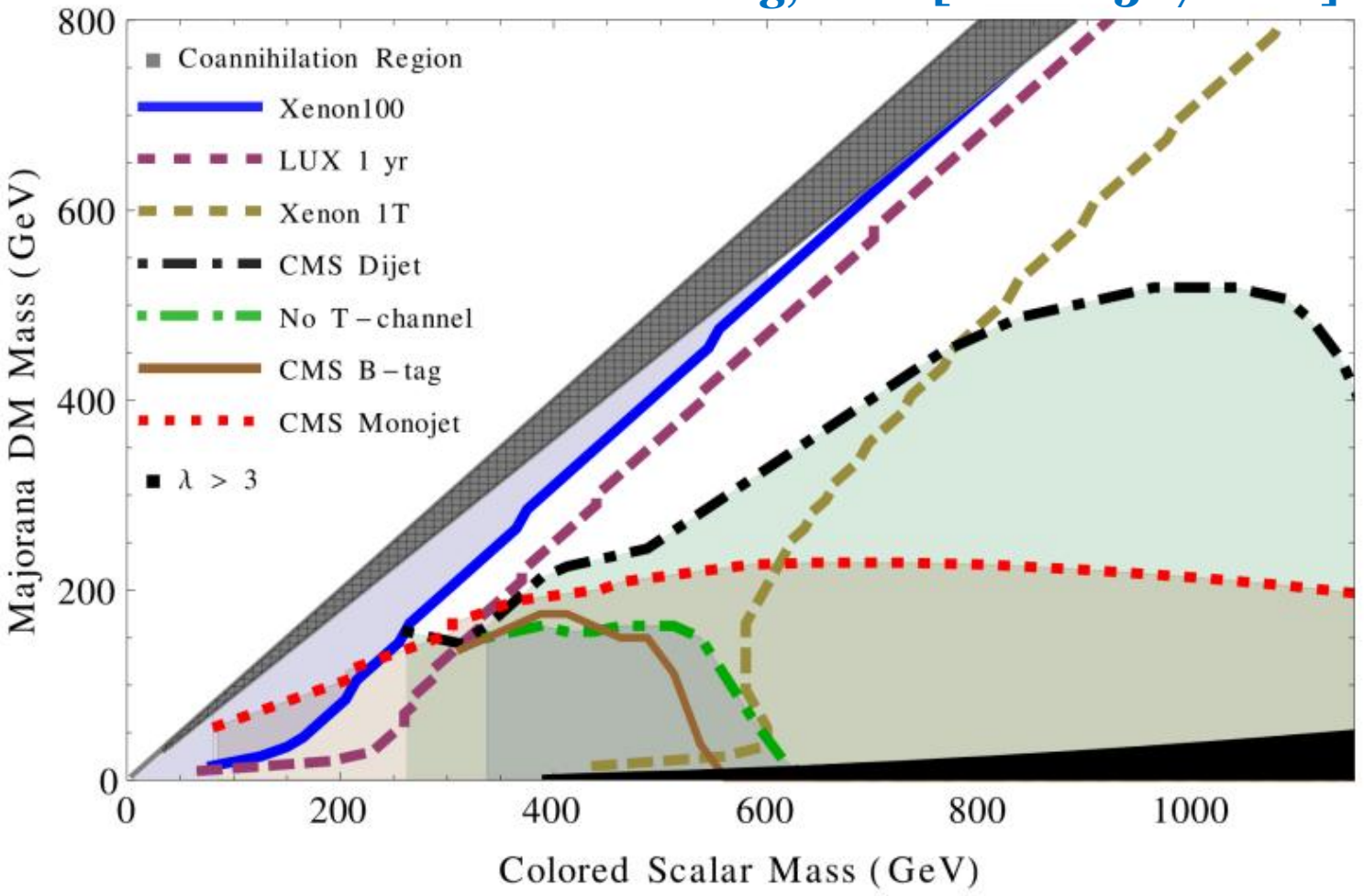
LEPTON PORTAL

- "Lepton Portal DM" –Bai, Berger [arXiv:1402.6696]
- "Leptophillic Effective WIMPs" -- Chang, et al. [arXiv: 1402.7358]

HIGGS PORTAL , *Z'* PORTAL, etc.

Constraints

Chang, et al. [arXiv:1307.8120]



Coupling extracted from matching relic abundance

Lessons

- Remarkable complementarity of probes

- Monojet searches generally less sensitive than jets + MET

-

Model		Relic Abundance	Direct Detection
χ	Q		
Majorana fermion	Complex scalar	$a \sim m_q^2$ $\lambda \sim 0.5 - 2$	Suppressed $\sigma_{\rm SI} \overset{m_Q \gg m_\chi}{\sim} \frac{m_p^4}{m_Q^4}\sigma_{\rm ann}$
Dirac fermion	Complex scalar	$\lambda \sim 0.2 - 1$	Unsuppressed $\sigma_{\rm SI} \overset{m_Q \gg m_\chi}{\sim} \frac{m_p^2}{m_\chi^2}\sigma_{\rm ann}$

"Effective WIMPs" - Chang, et al. [arXiv:1307.8120]

Lessons

- Remarkable complementarity of probes

- Monojet searches generally less sensitive than jets + MET

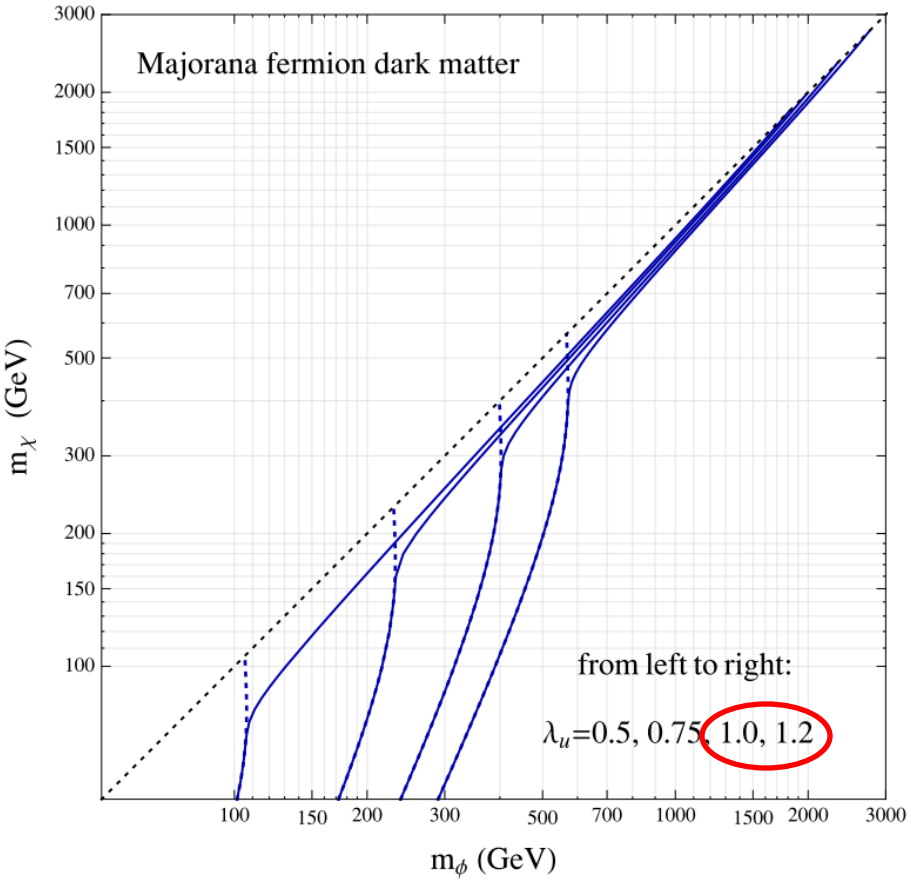
-

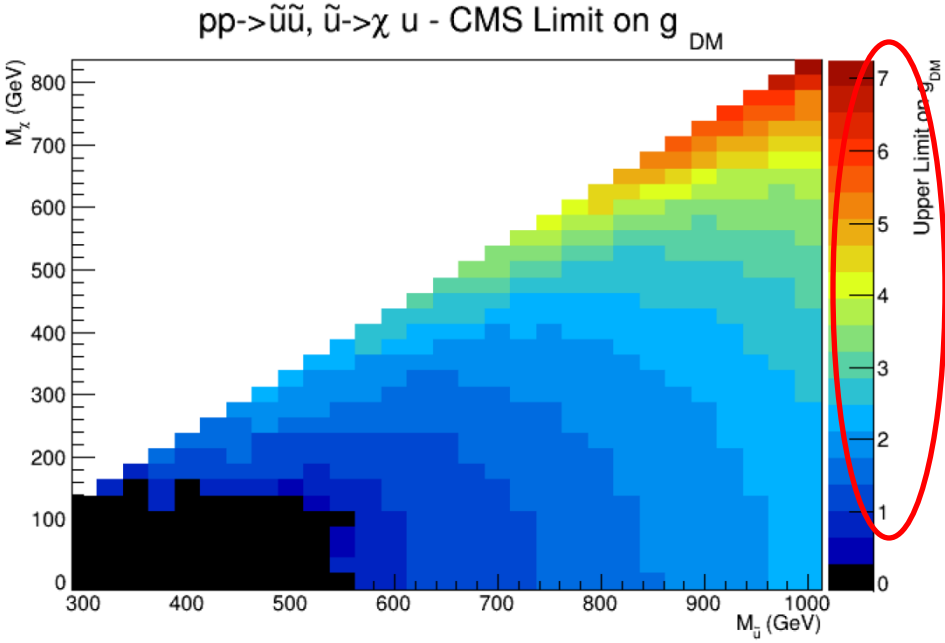
Model		Relic Abundance	Direct Detection
χ	Q		
Majorana fermion	Complex scalar	$a \sim m_q^2$ $\lambda \sim 0.5 - 2$	Suppressed $\sigma_{\rm SI} \overset{m_Q \gg m_\chi}{\sim} \frac{m_p^4}{m_Q^4} \sigma_{\rm ann}$
Dirac fermion	Complex scalar	$\lambda \sim 0.2 - 1$	Unsuppressed $\sigma_{\rm SI} \overset{m_Q \gg m_\chi}{\sim} \frac{m_p^2}{m_\chi^2} \sigma_{\rm ann}$

"Effective WIMPs" - Chang, et al. [arXiv:1307.8120]

- $\lambda \gtrsim 1$ possible from obtaining correct relic abundance

Lesson: large couplings





Bai, Berger [arXiv:1308.0612]

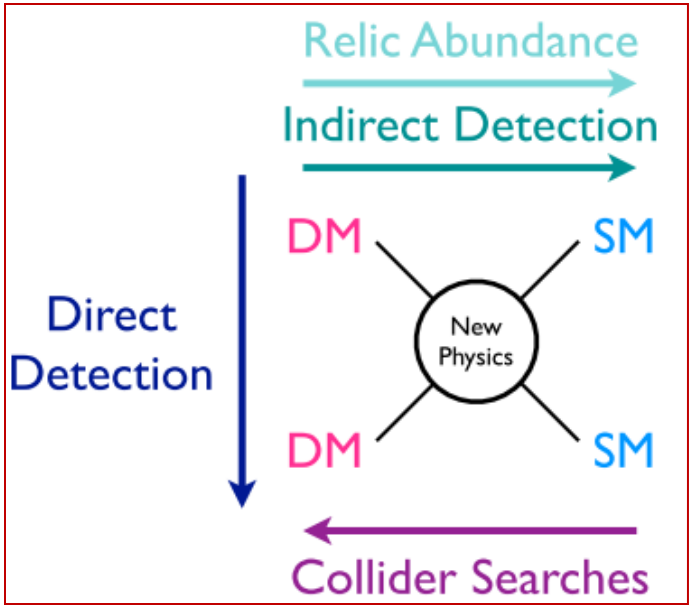
Tait, et al. [arXiv:1308.0612]

This talk: "matter portal dark matter"

$$\mathcal{L}_{\rm int}^{\rm quarks} \sim \lambda_q ({\rm DM})({\rm colored\ mediator})({\rm quark})$$

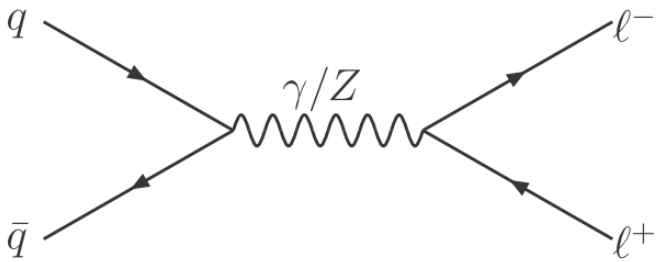
$$+$$

$$\mathcal{L}_{\rm int}^{\rm leptons} \sim \lambda_\ell ({\rm DM})({\rm lepton\ mediator})({\rm lepton})$$



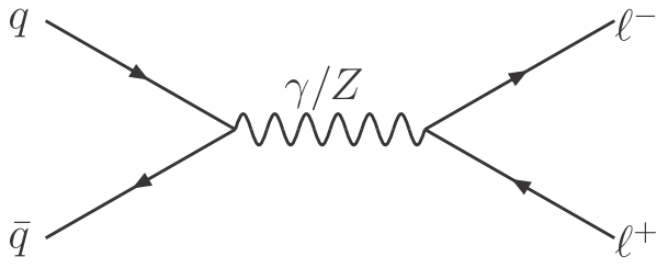
If the dark sector couples to
both quarks and leptons,
is there a ***new*** way to probe it?

Drell-Yan



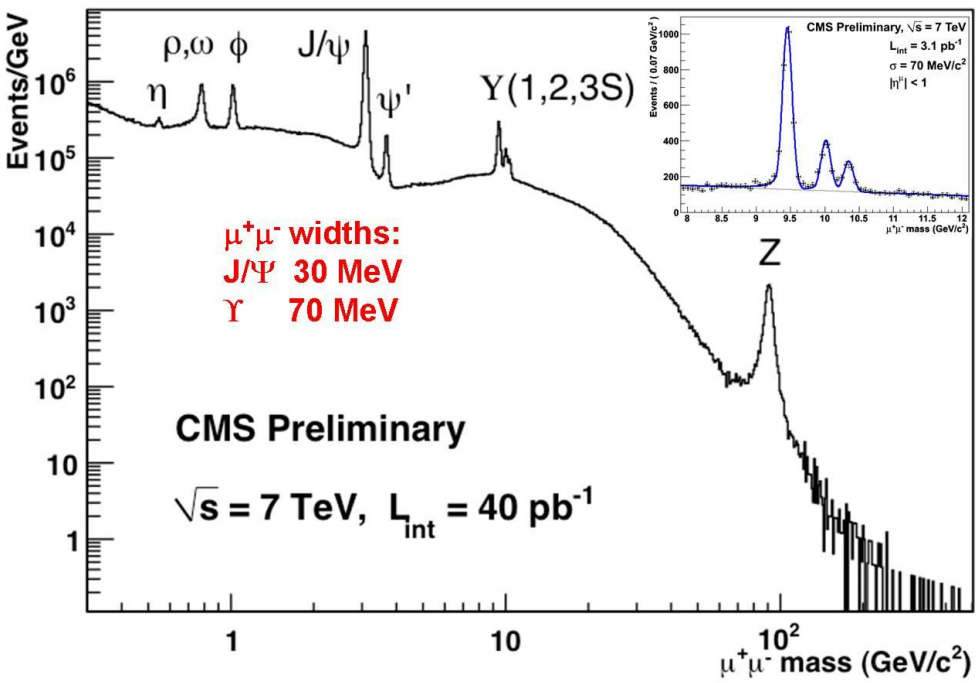
Source: Kyle Cranmer

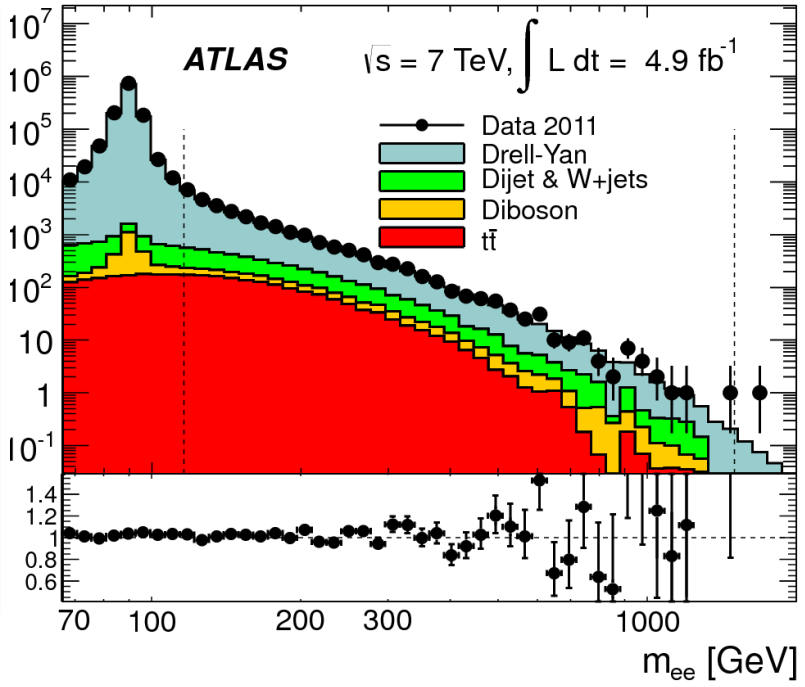
Good old Drell-Yan



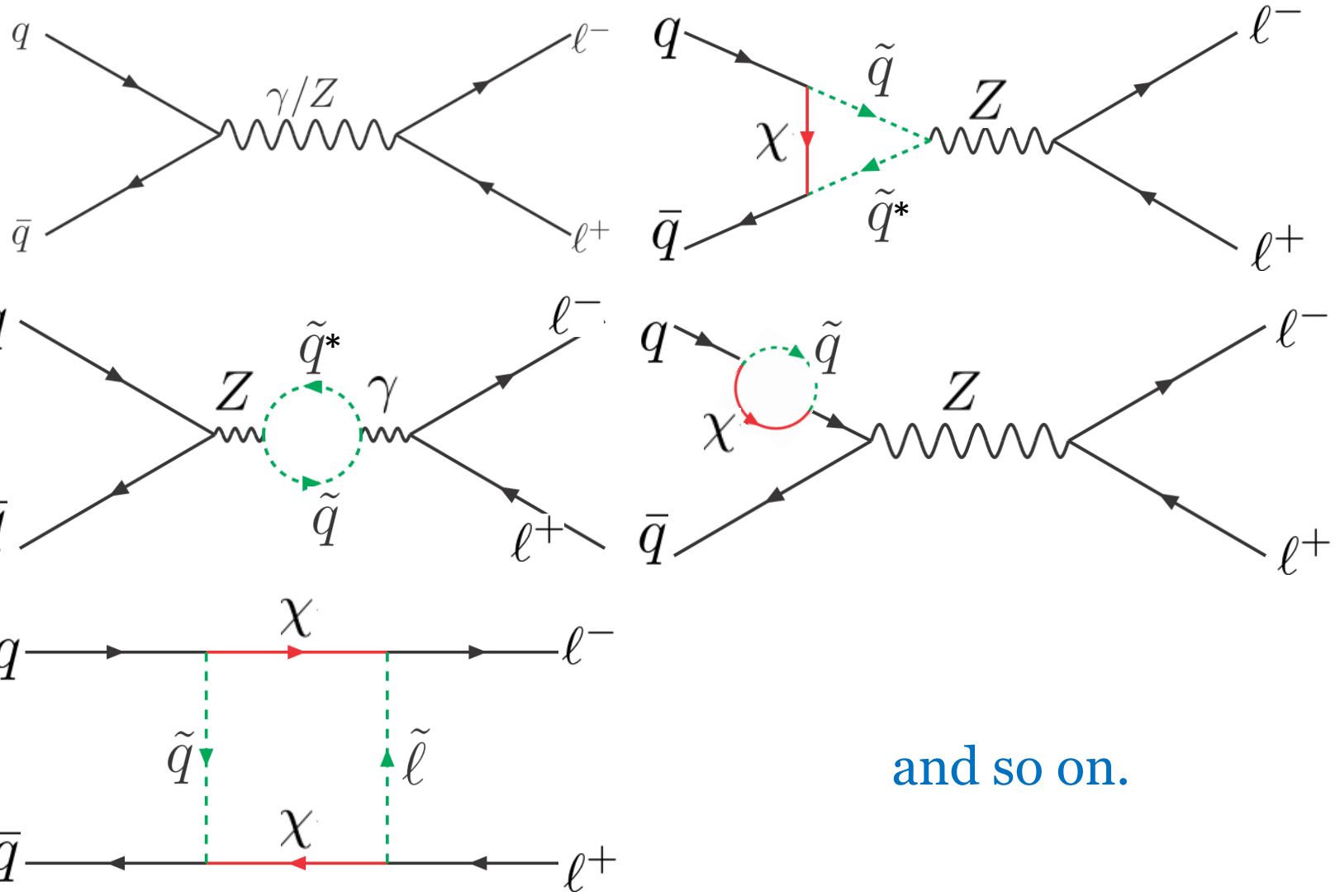
- Historical harbinger of new physics via ***INTERFERENCE EFFECTS***

- Clean backgrounds



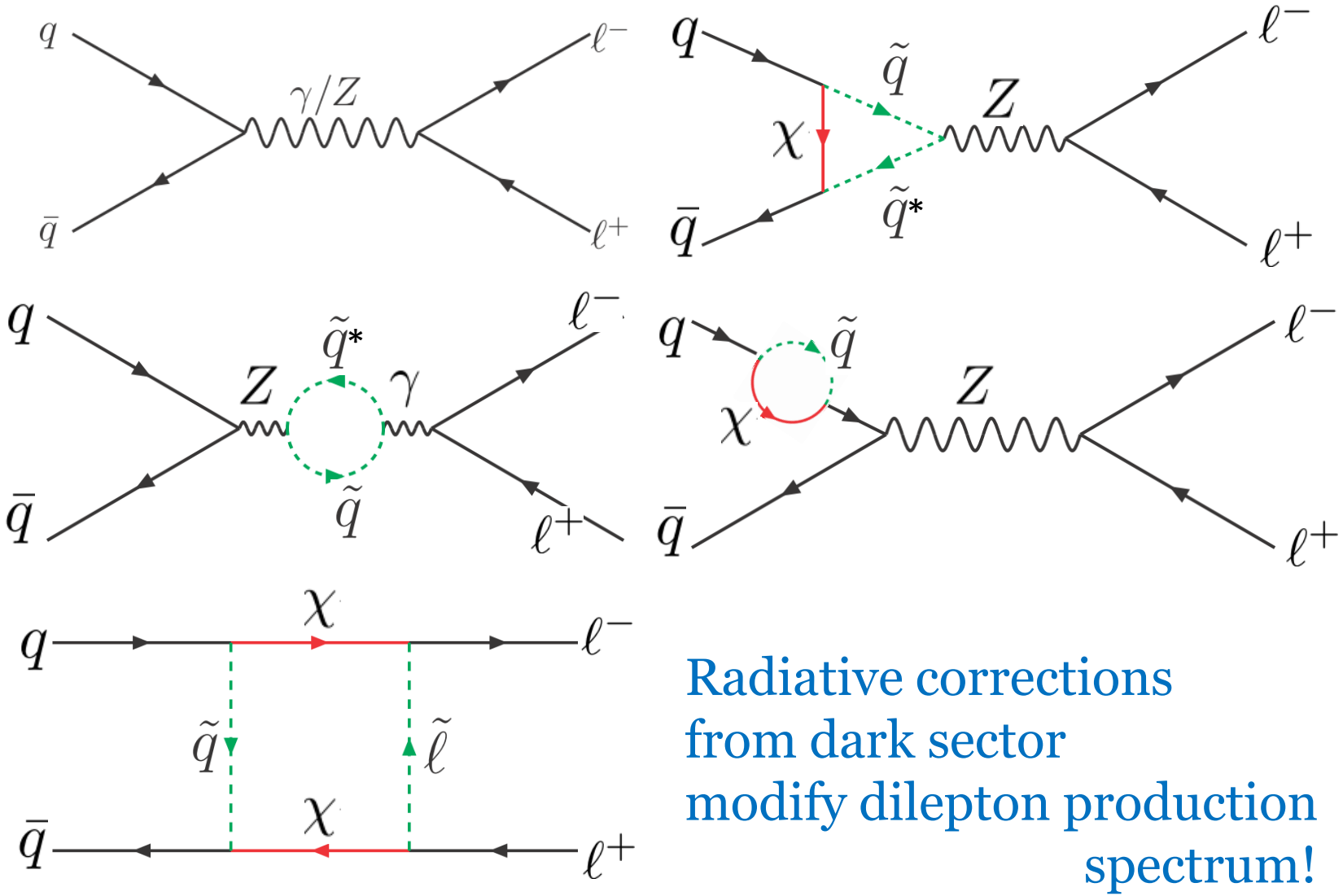


Dark Interference (fermionic DM)



and so on.

Dark Interference (fermionic DM)



Radiative corrections
from dark sector
modify dilepton production
spectrum!

The Model

$$\mathcal{L} = i\chi_A^\dagger \bar{\sigma}^\mu \partial_\mu \chi_A + i\chi_B^\dagger \bar{\sigma}^\mu \partial_\mu \chi_B + \mathcal{L}_{\text{DM mass}}$$
$$- \sum_{q=u,d} |D_\mu \tilde{q}|^2 - M_{\tilde{q}}^2 \tilde{q}\tilde{q}^* - (\sqrt{2}\ \lambda_{\tilde{q}} \tilde{q}^* \chi_B^\dagger q_R^\dagger + \text{h.c.})$$
$$- \sum_{\ell=e,\mu} |D_\mu \tilde{\ell}|^2 - M_{\tilde{\ell}}^2 \tilde{\ell}\tilde{\ell}^* - (\sqrt{2}\ \lambda_{\tilde{\ell}} \tilde{\ell}^* \chi_B^\dagger \ell_R^\dagger + \text{h.c.})$$

Field	Spin	$SU(3)_c \otimes SU(2)_W \otimes U(1)_Y$	Z_2
χ_A, χ_B	$\mathbf{1/2}$	$(\mathbf{1}, \mathbf{1}, \mathbf{0})$	$\mathbf{-1}$
$\tilde{u}$	$\mathbf{0}$	$(\mathbf{3}, \mathbf{1}, \frac{\mathbf{2}}{\mathbf{3}})$	$\mathbf{-1}$
$\tilde{d}$	$\mathbf{0}$	$(\mathbf{3}, \mathbf{1}, -\frac{\mathbf{1}}{\mathbf{3}})$	$\mathbf{-1}$
$\tilde{\ell} = \tilde{e}, \tilde{\mu}$	$\mathbf{0}$	$(\mathbf{1}, \mathbf{1}, \mathbf{-1})$	$\mathbf{-1}$

The Model

Sub-models for phenomenology

Model	Couplings	Mediator masses
U	$\lambda \equiv \lambda_{\tilde{\ell}} = \lambda_{\tilde{u}}$, $\lambda_{\tilde{d}} = 0$	$M_\phi \equiv M_{\tilde{\ell}} = M_{\tilde{u}}$
D	$\lambda \equiv \lambda_{\tilde{\ell}} = \lambda_{\tilde{d}}$, $\lambda_{\tilde{u}} = 0$	$M_\phi \equiv M_{\tilde{\ell}} = M_{\tilde{d}}$
UD	$\lambda \equiv \lambda_{\tilde{\ell}} = \lambda_{\tilde{u}} = \lambda_{\tilde{d}}$	$M_\phi \equiv M_{\tilde{\ell}} = M_{\tilde{u}} = M_{\tilde{d}}$

The Model

Assumptions

(a) Couplings only to

- right-handed SM fermions
- first generation quarks
- electron and muon

(b) No flavor violation from lepton mediators

(c) CP-violating phases vanish

Loop contributions: what dominates?

g : electroweak coupling

λ : matter-mediator-DM coupling

$$\lambda \gtrsim 1$$

feature of simplified DM models!

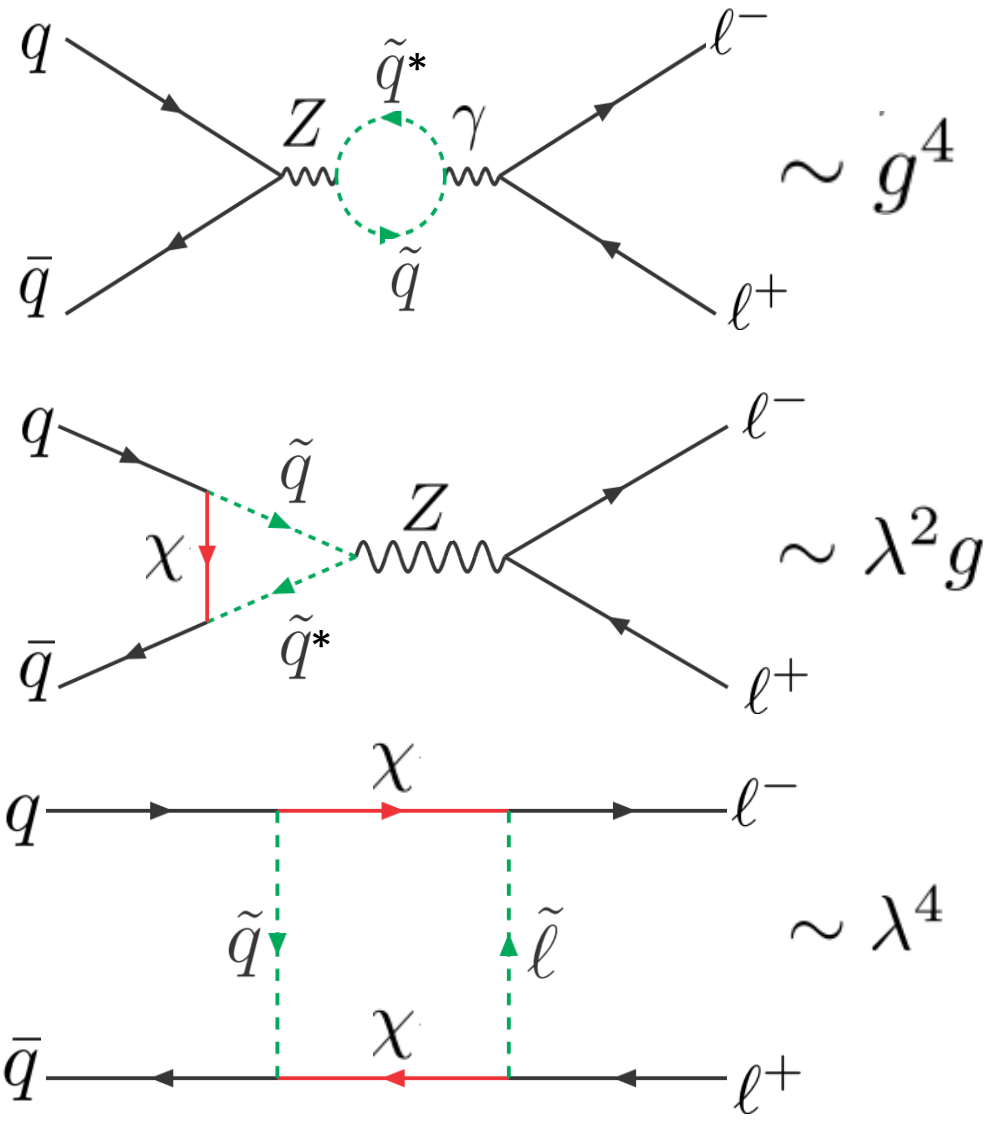
Loop contributions: boxes dominate!

g : electroweak coupling

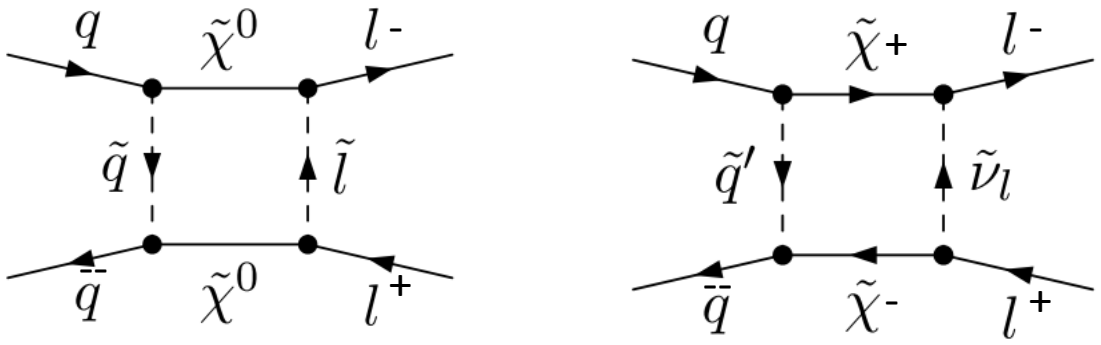
λ : matter-mediator-DM coupling

$\lambda \gtrsim 1$

feature of simplified DM models!

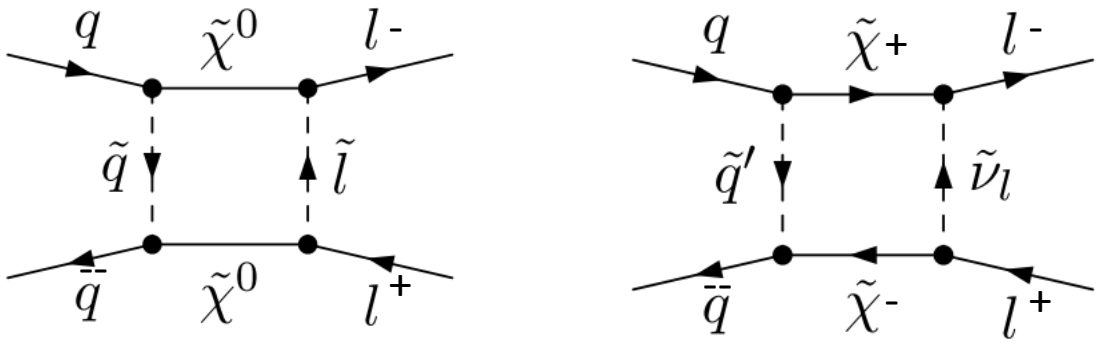


SUSY boxes: a contrast

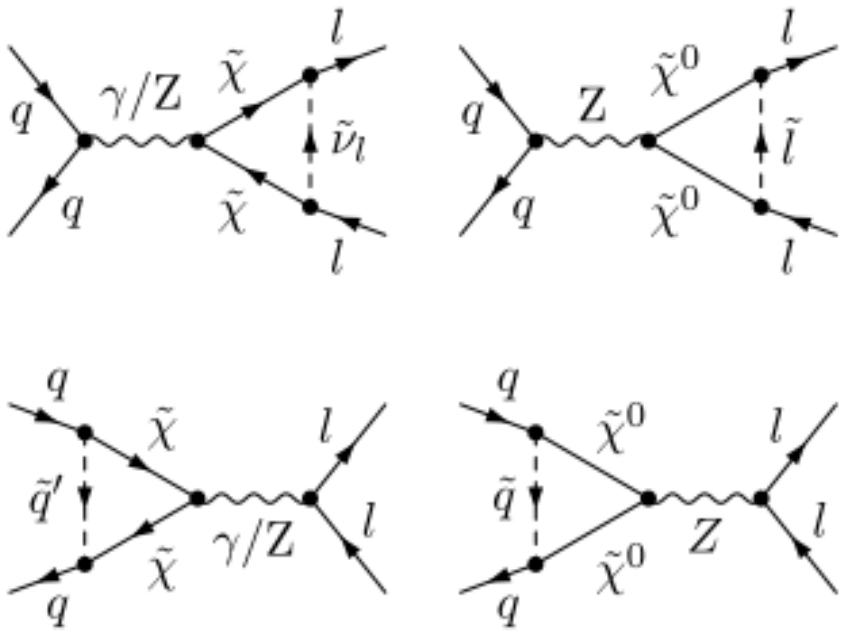


S. Dittmaier, M. Huber [arXiv: 0911.2329]

SUSY boxes: a contrast

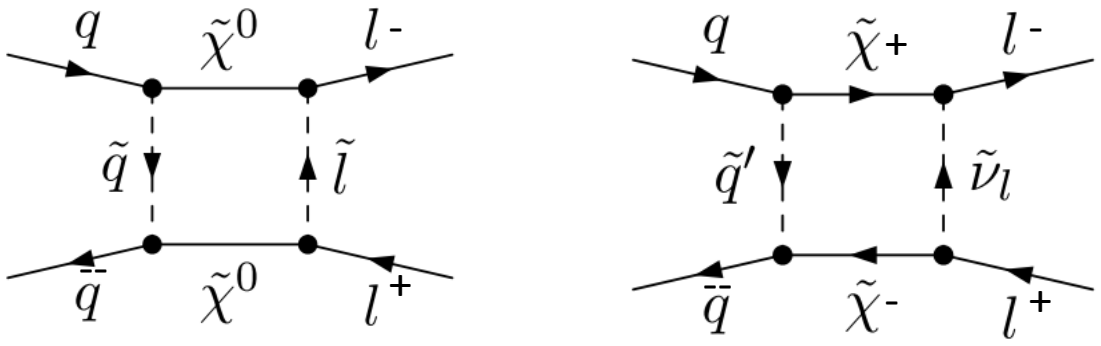


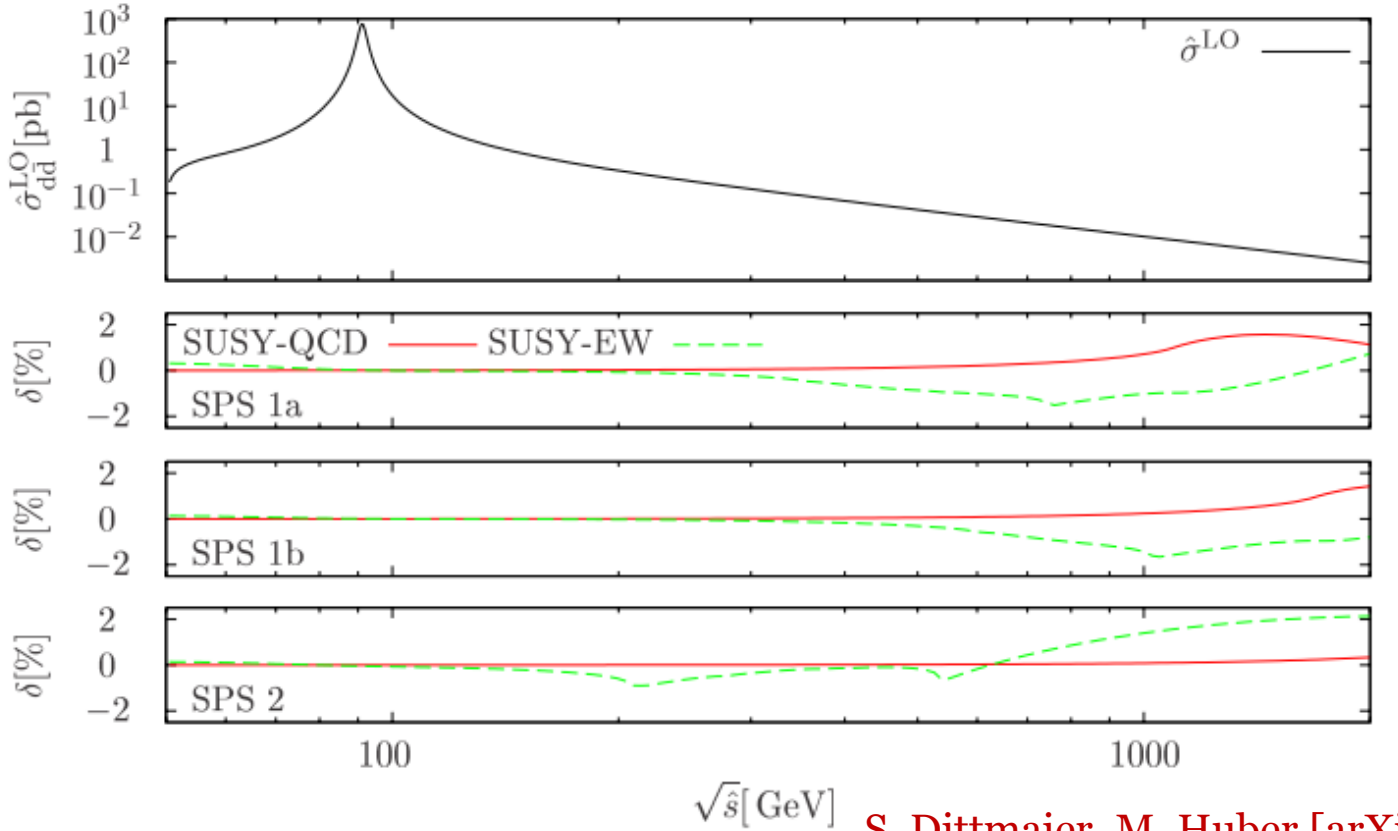
Not as important as diagrams like these:



S. Dittmaier, M. Huber [arXiv: 0911.2329]

SUSY boxes: a contrast





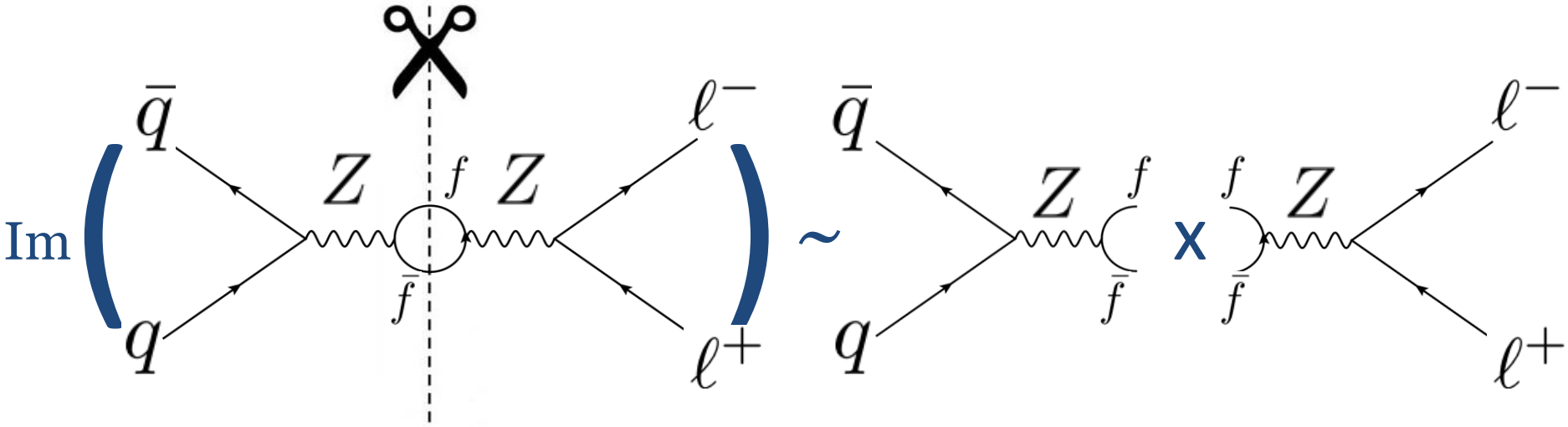
S. Dittmaier, M. Huber [arXiv: 0911.2329]

How do boxes impact dilepton production?

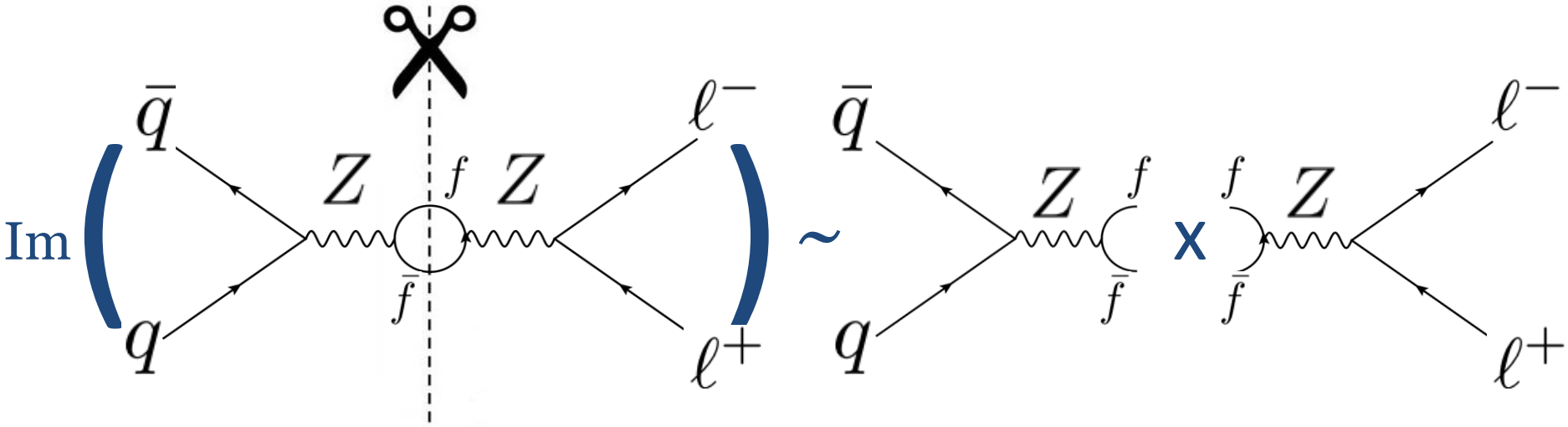
How do boxes impact dilepton production?

Optical Theorem

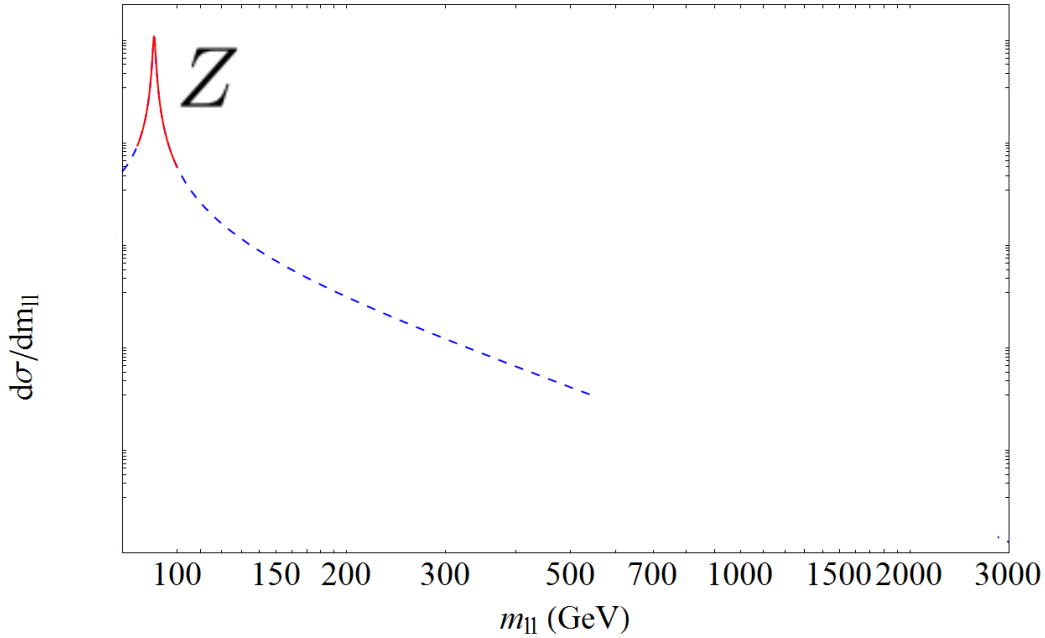
Optical Theorem: s-channel



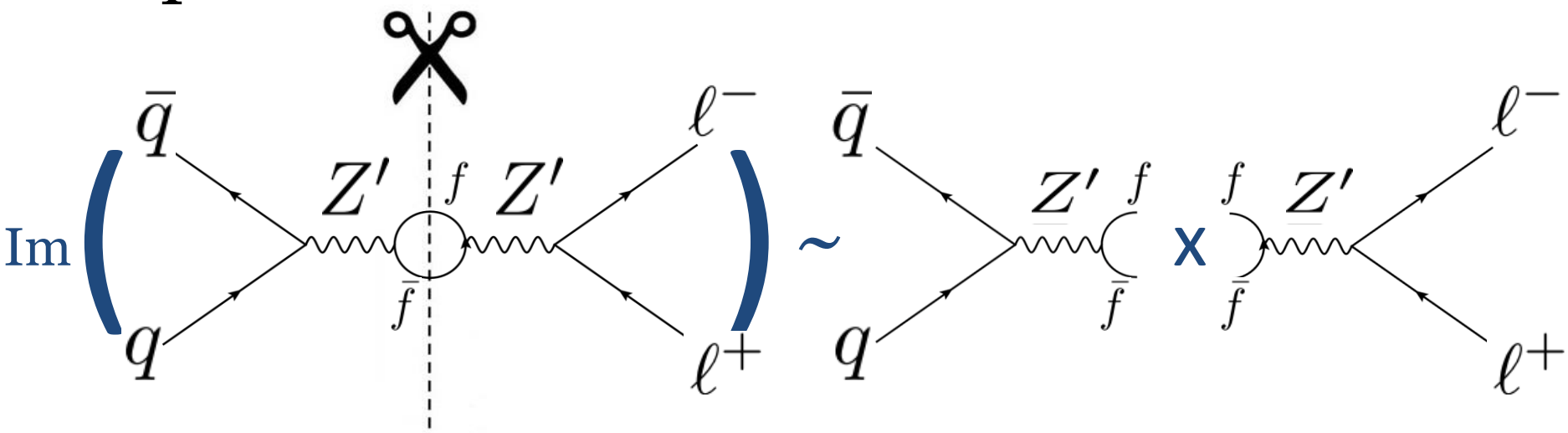
Optical Theorem: s-channel



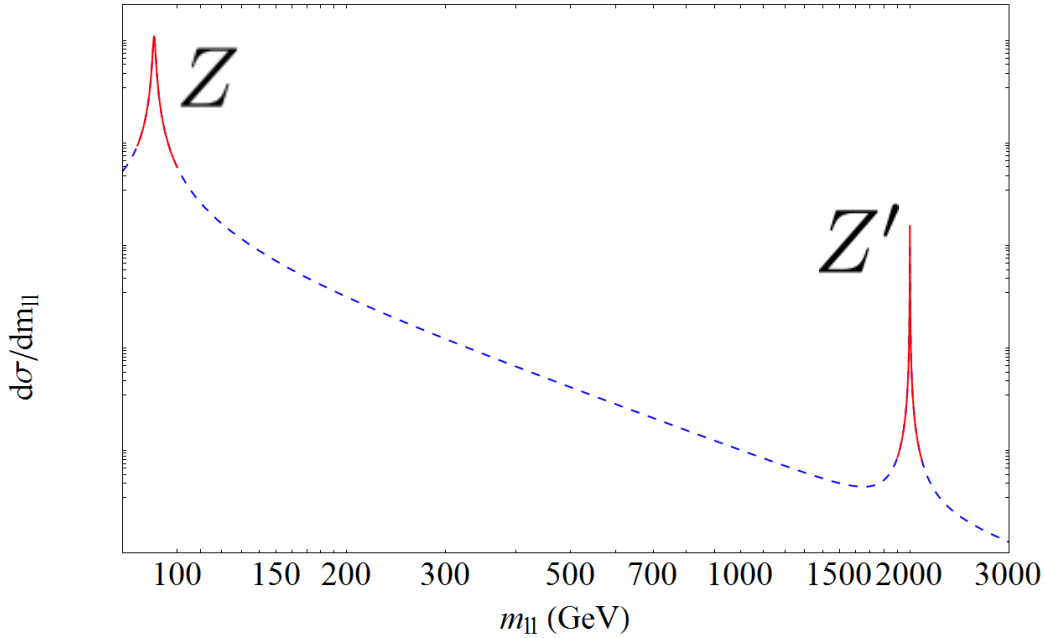
Resonance!



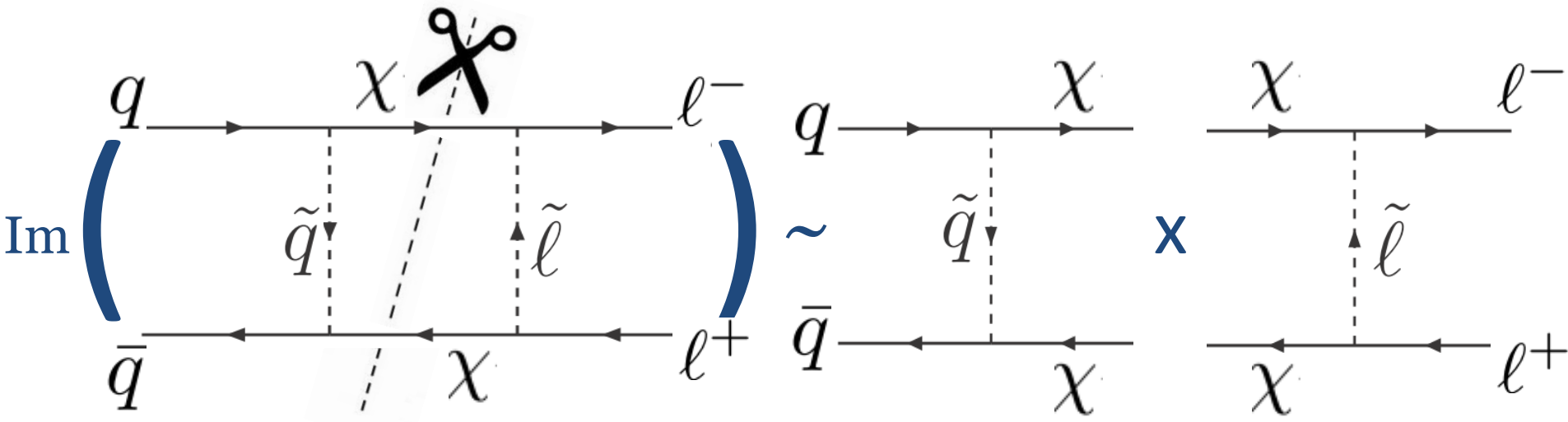
Optical Theorem: s-channel



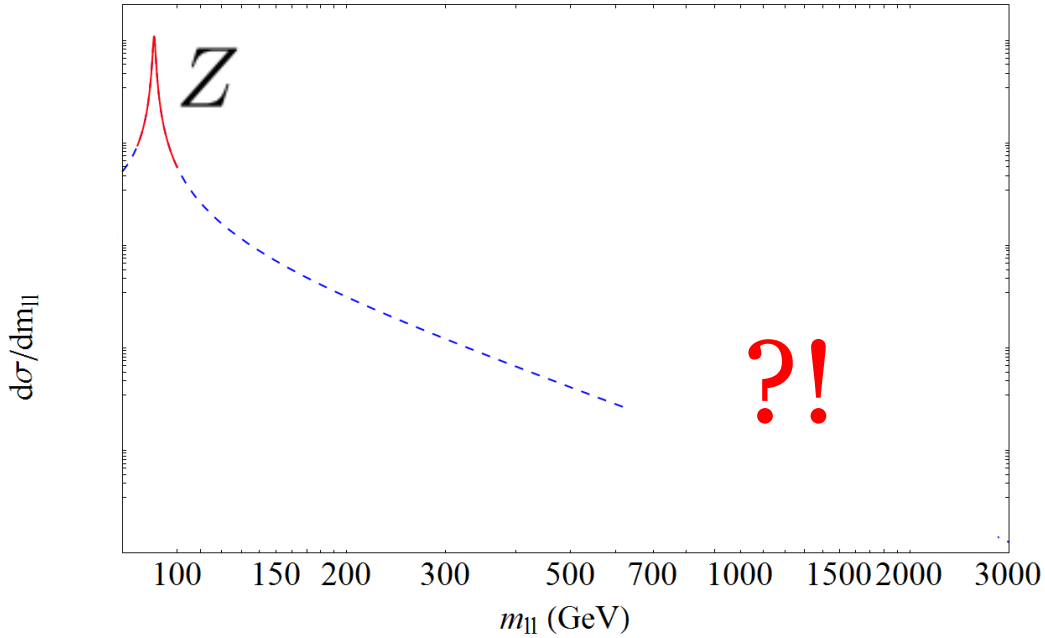
Resonance!



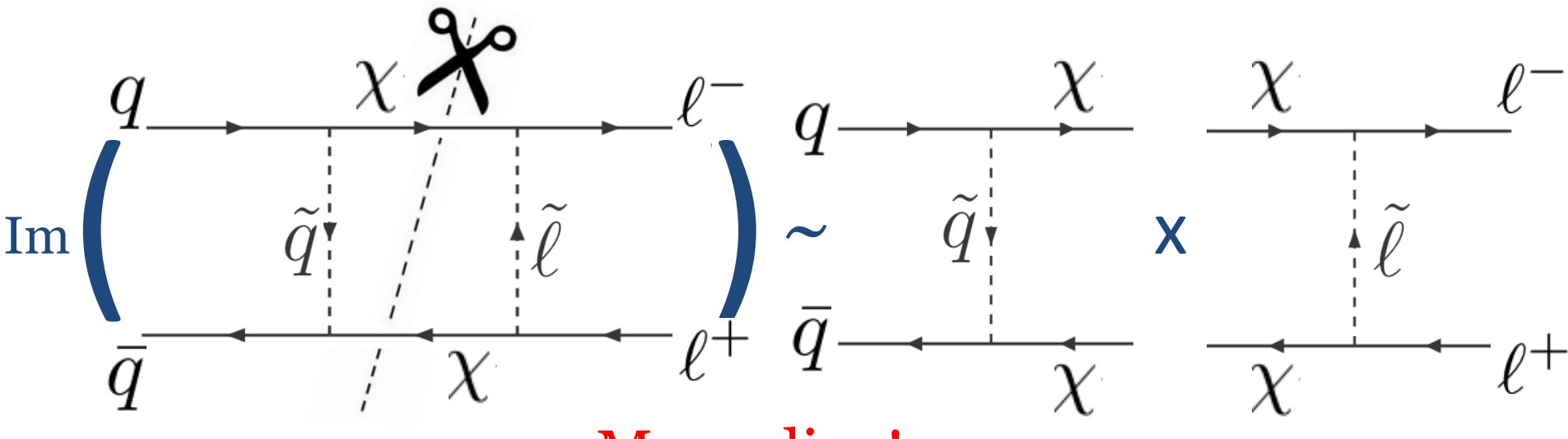
Optical Theorem: box correction



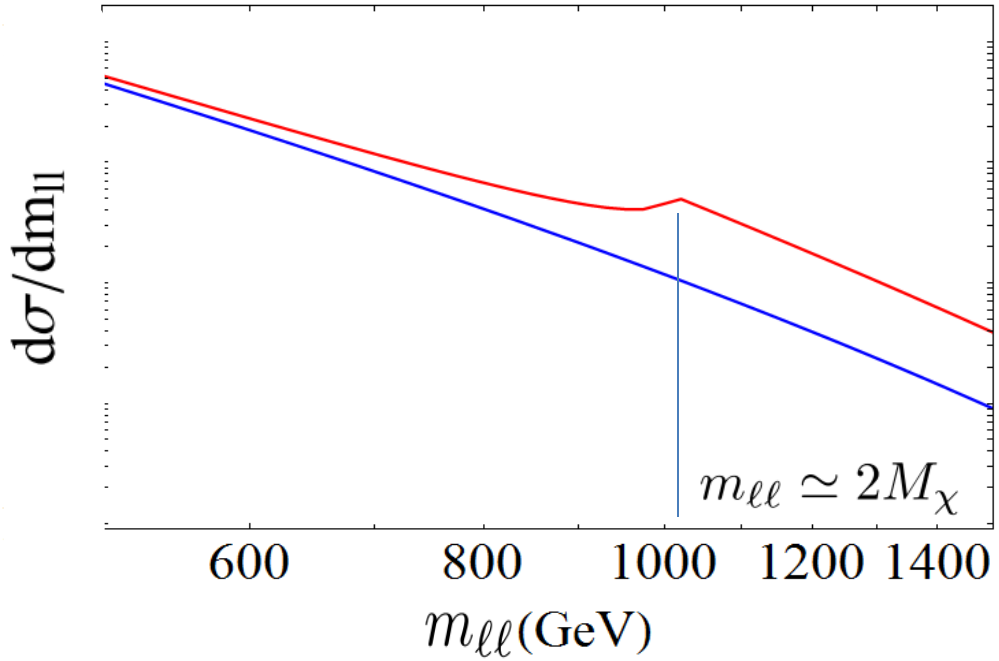
Resonance?



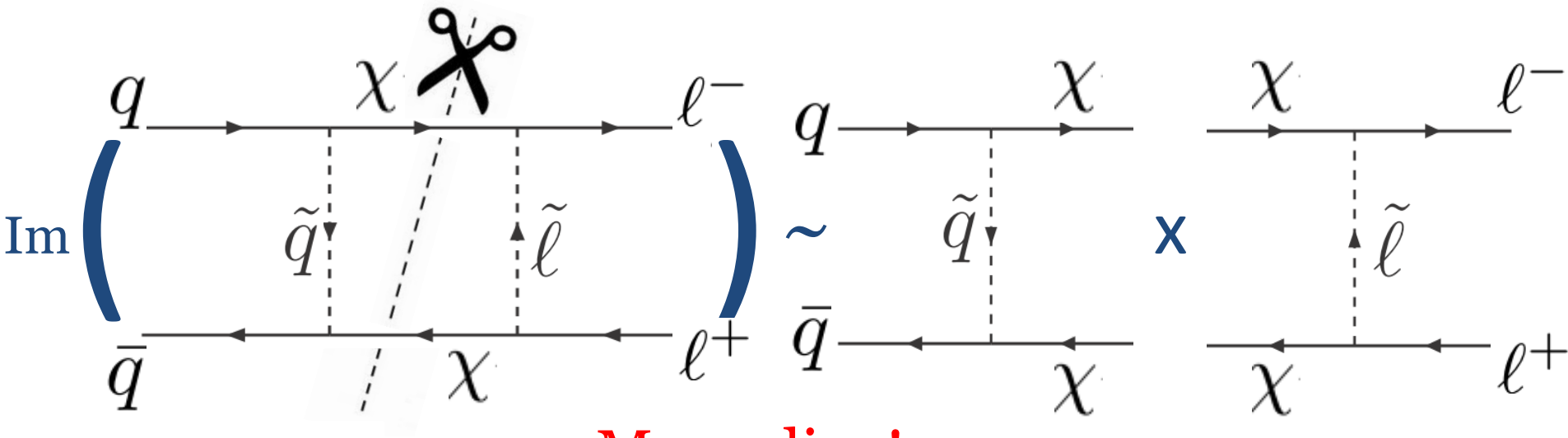
Optical Theorem



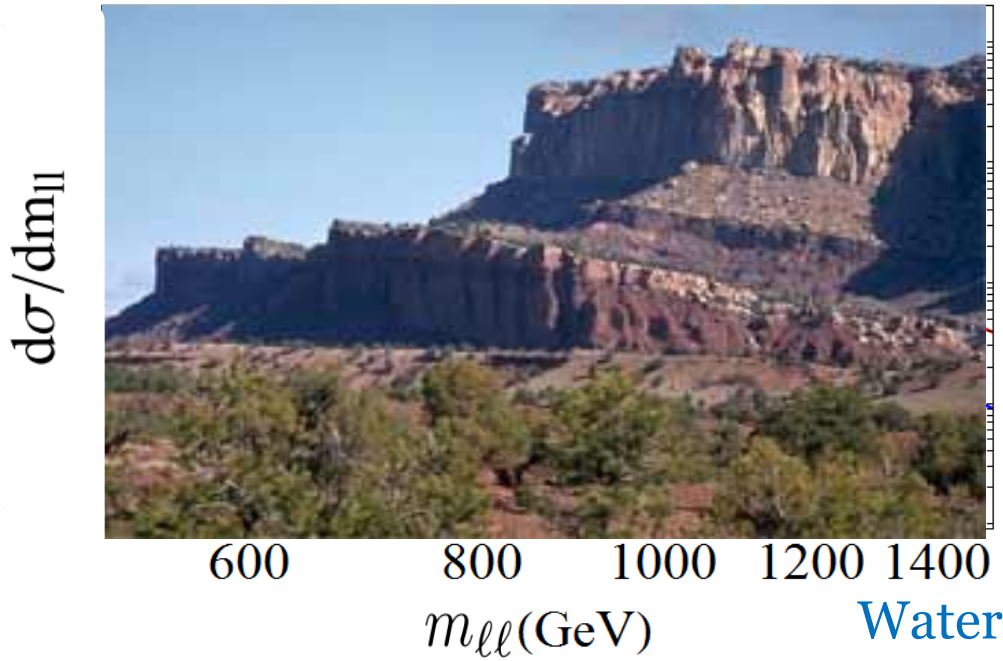
Monocline!



Optical Theorem



Monocline!



Waterpocket Fold, Utah

Signal breakdown

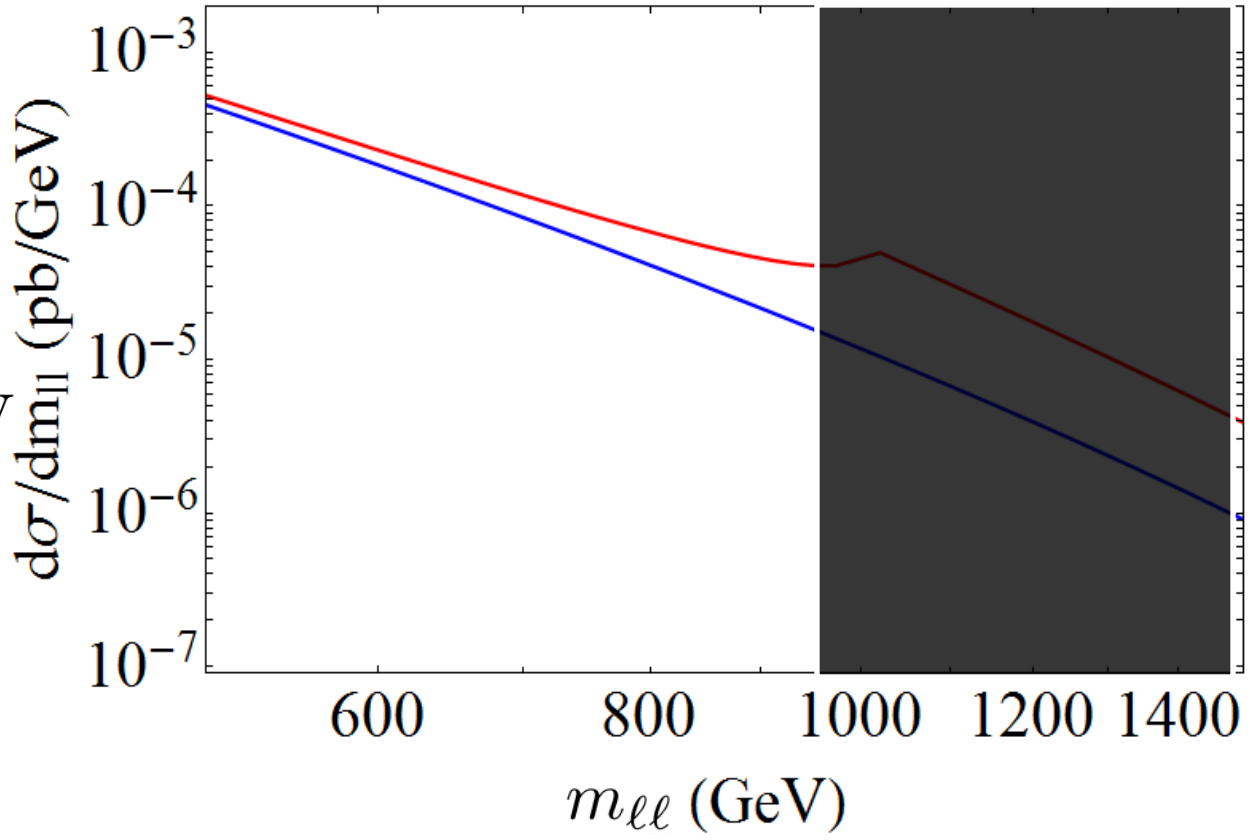
Model U, Dirac DM

Blue $\lambda = 0$ (SM)

Red $\lambda = 1.8$,

$M_\chi = M_\phi = 500$ GeV

Contact operator



“ $\sigma_{\rm tot} = \sigma_{\rm DY} - \eta_{ij}\frac{F_{\rm I}}{\Lambda^2} + \frac{F_{\rm C}}{\Lambda^4}$ ”

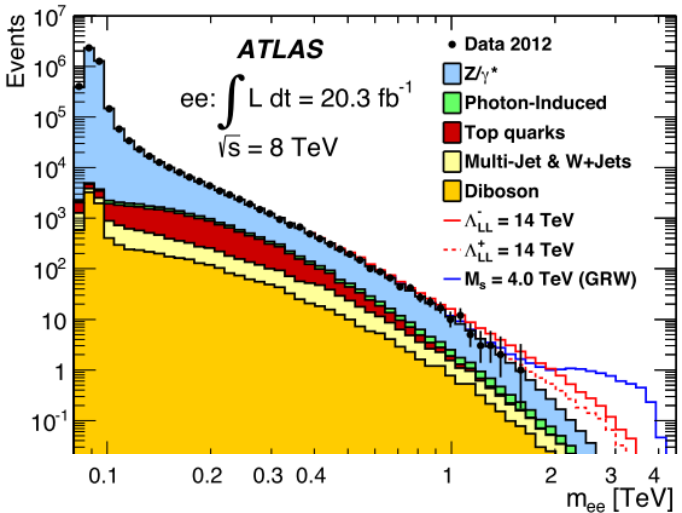
Signal breakdown

Model U, Dirac DM

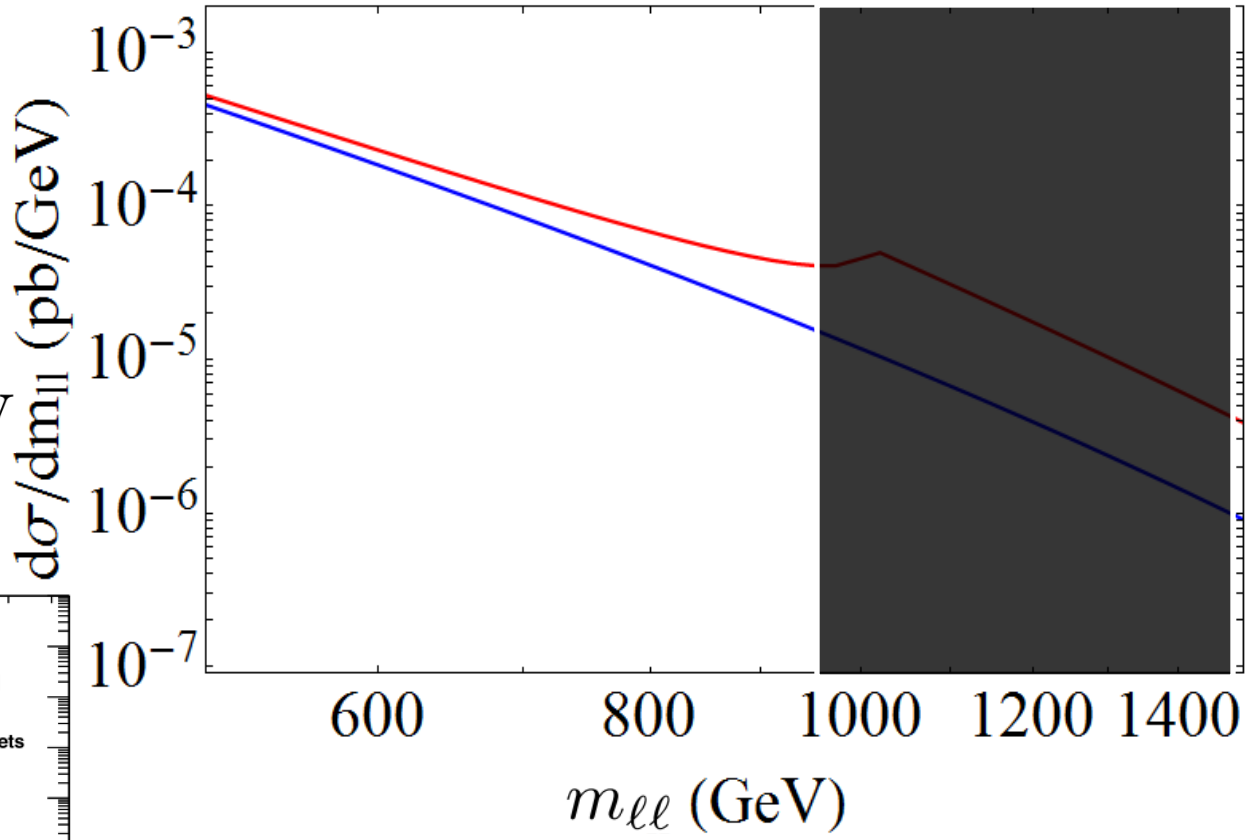
Blue $\lambda = 0$ (SM)

Red $\lambda = 1.8$,

$M_\chi = M_\phi = 500$ GeV



Contact operator



arXiV: 1407.2410

“ $\sigma_{\rm tot} = \sigma_{\rm DY} - \eta_{ij}\frac{F_{\rm I}}{\Lambda^2} + \frac{F_{\rm C}}{\Lambda^4}$ ”

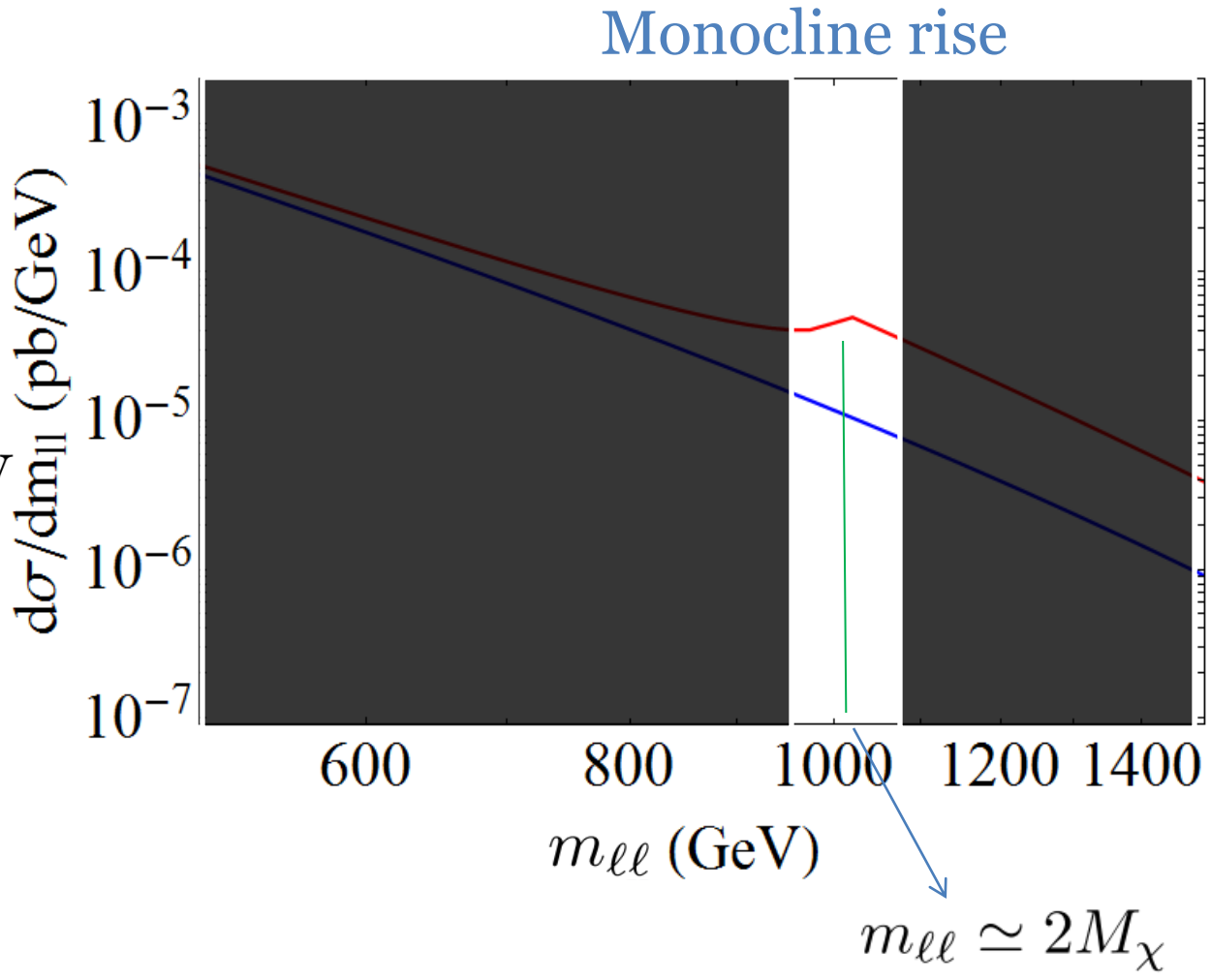
Signal breakdown

Model U, Dirac DM

Blue $\lambda = 0$ (SM)

Red $\lambda = 1.8$,

$M_\chi = M_\phi = 500$ GeV



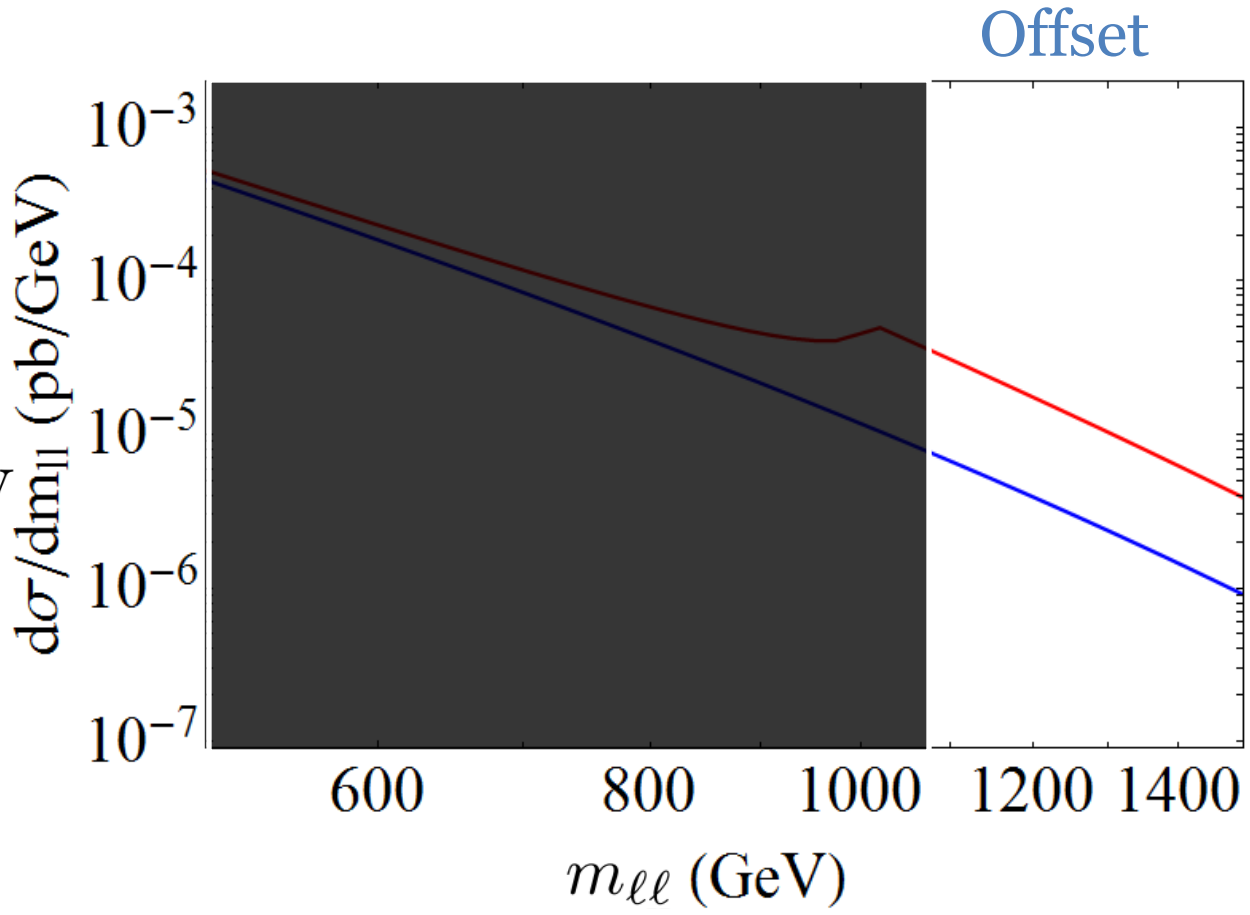
Signal breakdown

Model U, Dirac DM

Blue $\lambda = 0$ (SM)

Red $\lambda = 1.8$,

$M_\chi = M_\phi = 500$ GeV

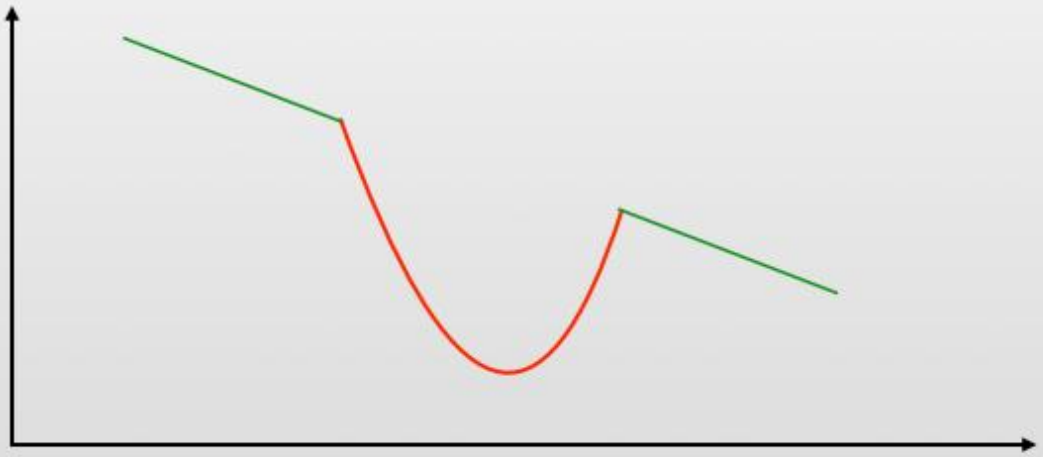


Yang Bai's query: GOAL Workshop

Bai, Keung [arXiv: 1407.6355]

How about other shapes at colliders:

edges, shoulders, end-points, dips, fake-resonance ……

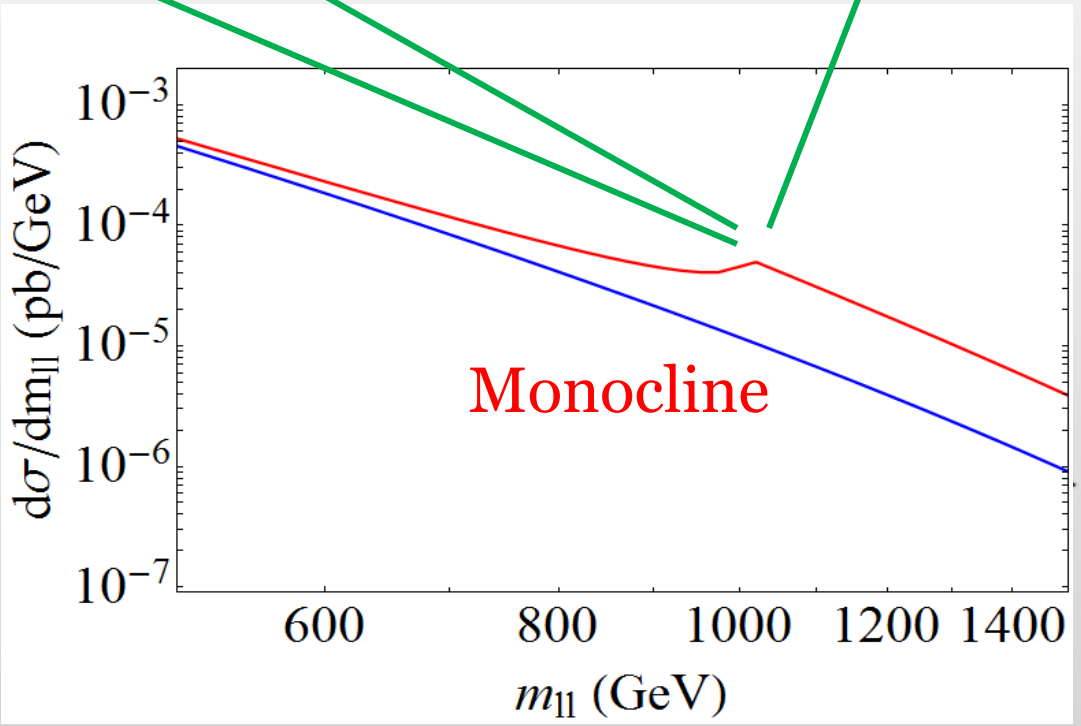


Yang Bai's query: GOAL Workshop

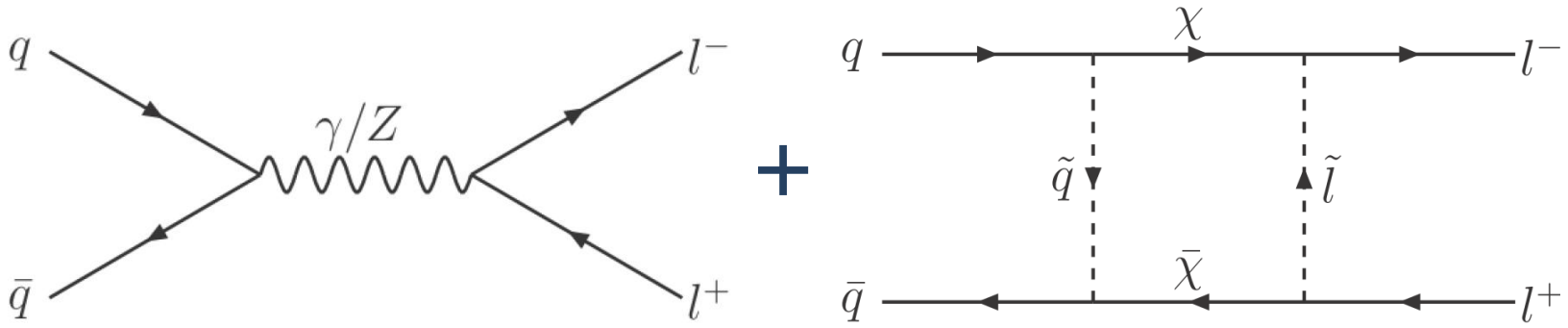
Bai, Keung [arXiv: 1407.6355]

How about other shapes at colliders:

edges, shoulders, end-points, dips, fake-resonance ……



Splitting the amplitude



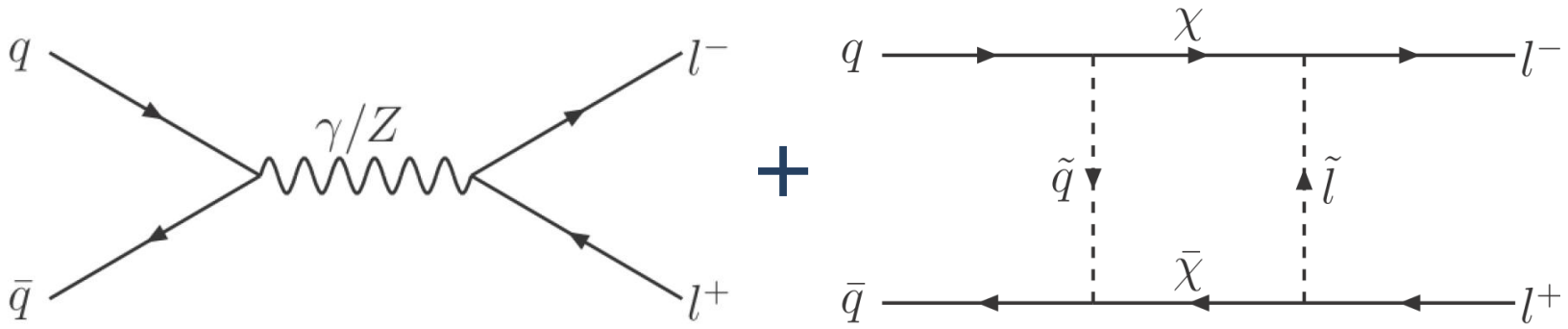
$$|A_{\text{tree}} + A_{\text{box}}|^2$$

$$d\sigma_{\text{tree}} + d\sigma_{\text{int}} + d\sigma_{\text{box}}$$

$$|A_{\text{tree}} + A_{\text{box}}^{\text{real}} + iA_{\text{box}}^{\text{imag}}|^2$$

from Optical Theorem

Splitting the amplitude



$$|A_{\text{tree}} + A_{\text{box}}|^2$$

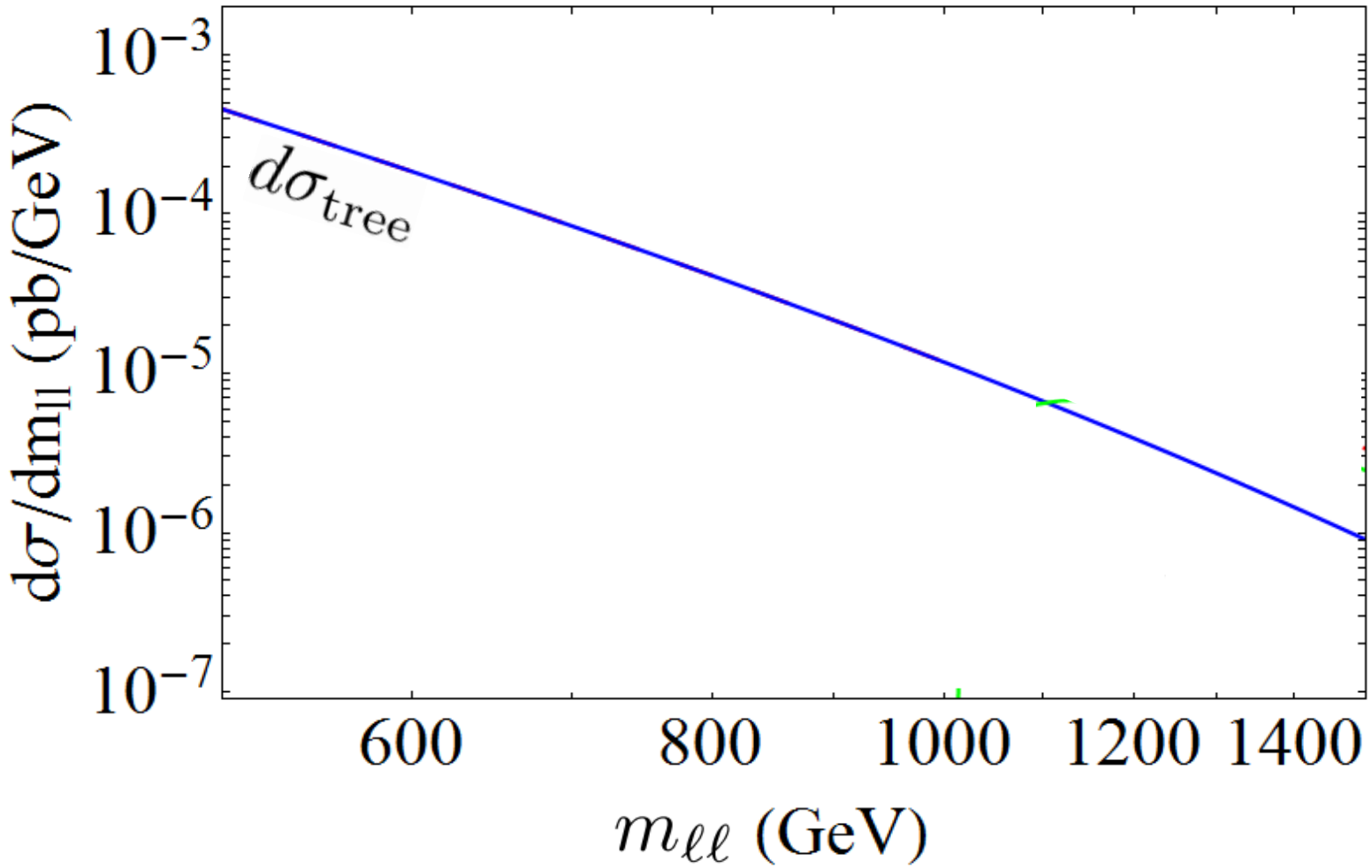
$$d\sigma_{\text{tree}} + d\sigma_{\text{int}} + d\sigma_{\text{box}}$$

$$|A_{\text{tree}} + A_{\text{box}}^{\text{real}} + iA_{\text{box}}^{\text{imag}}|^2$$

$$d\sigma_{\text{tree}} + d\sigma_{\text{int}} + d\sigma_{\text{box}}^{\text{real}} + d\sigma_{\text{box}}^{\text{imag}}$$

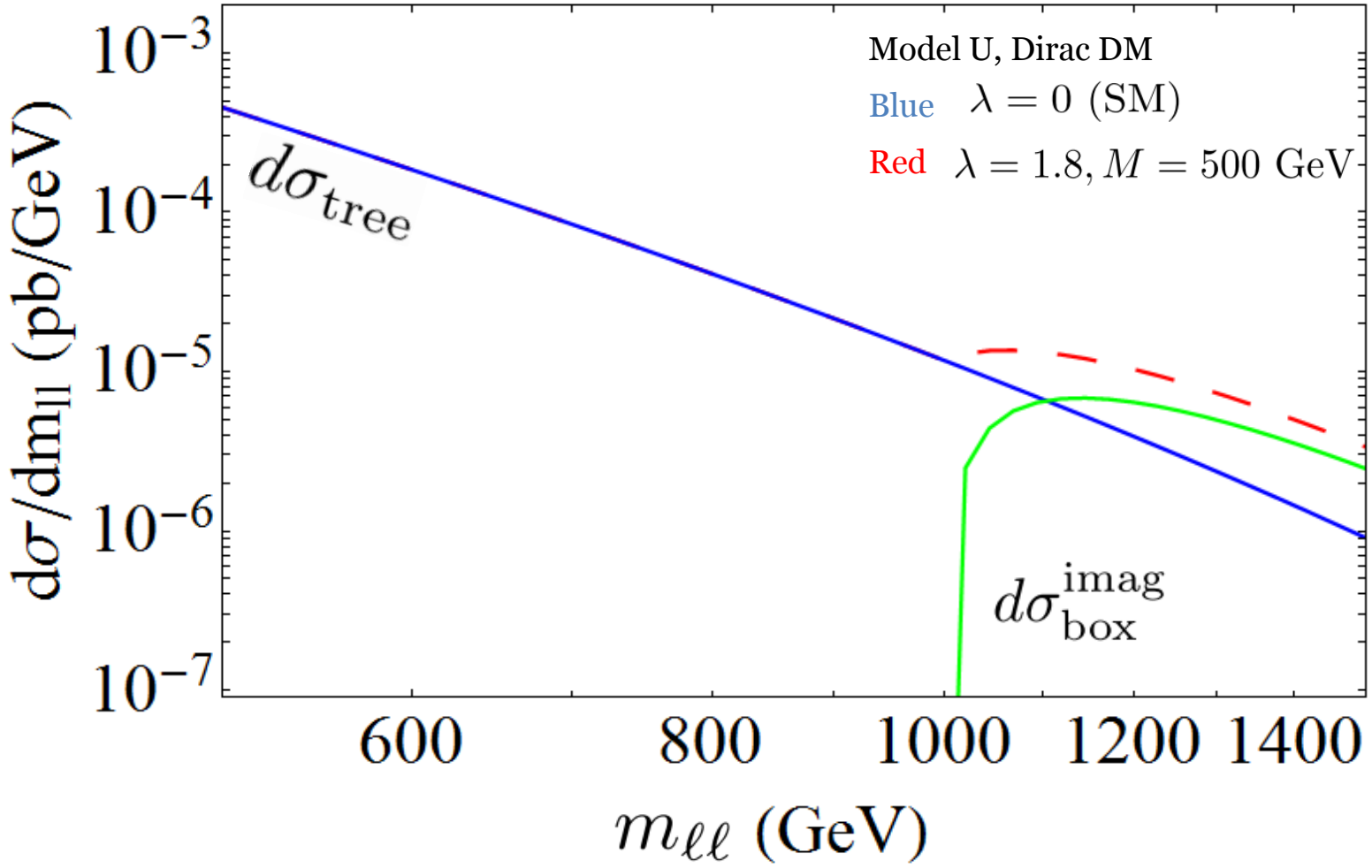
from Optical Theorem

Breakdown of rates



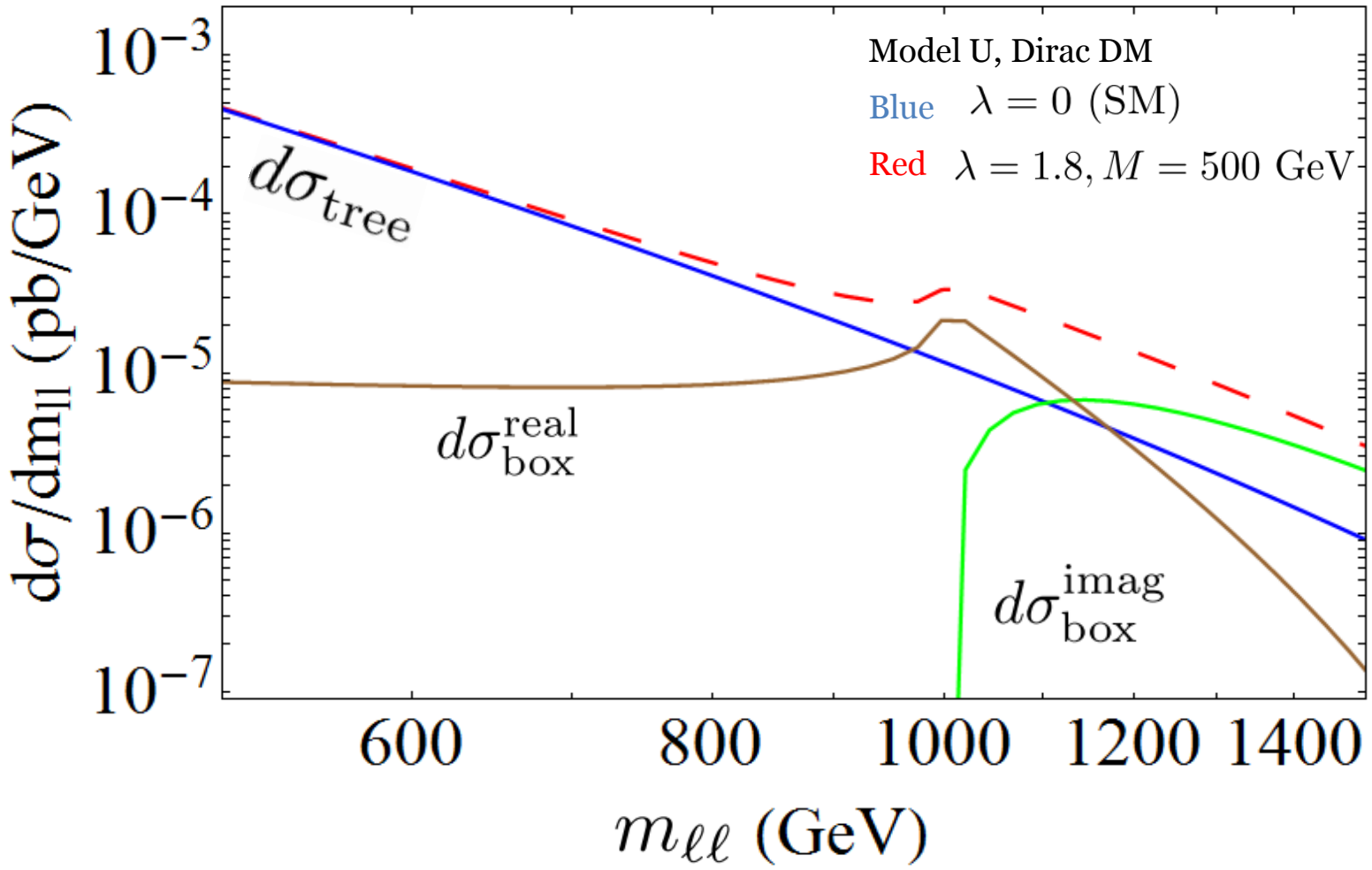
$d\sigma_{\rm tree}$

Breakdown of rates



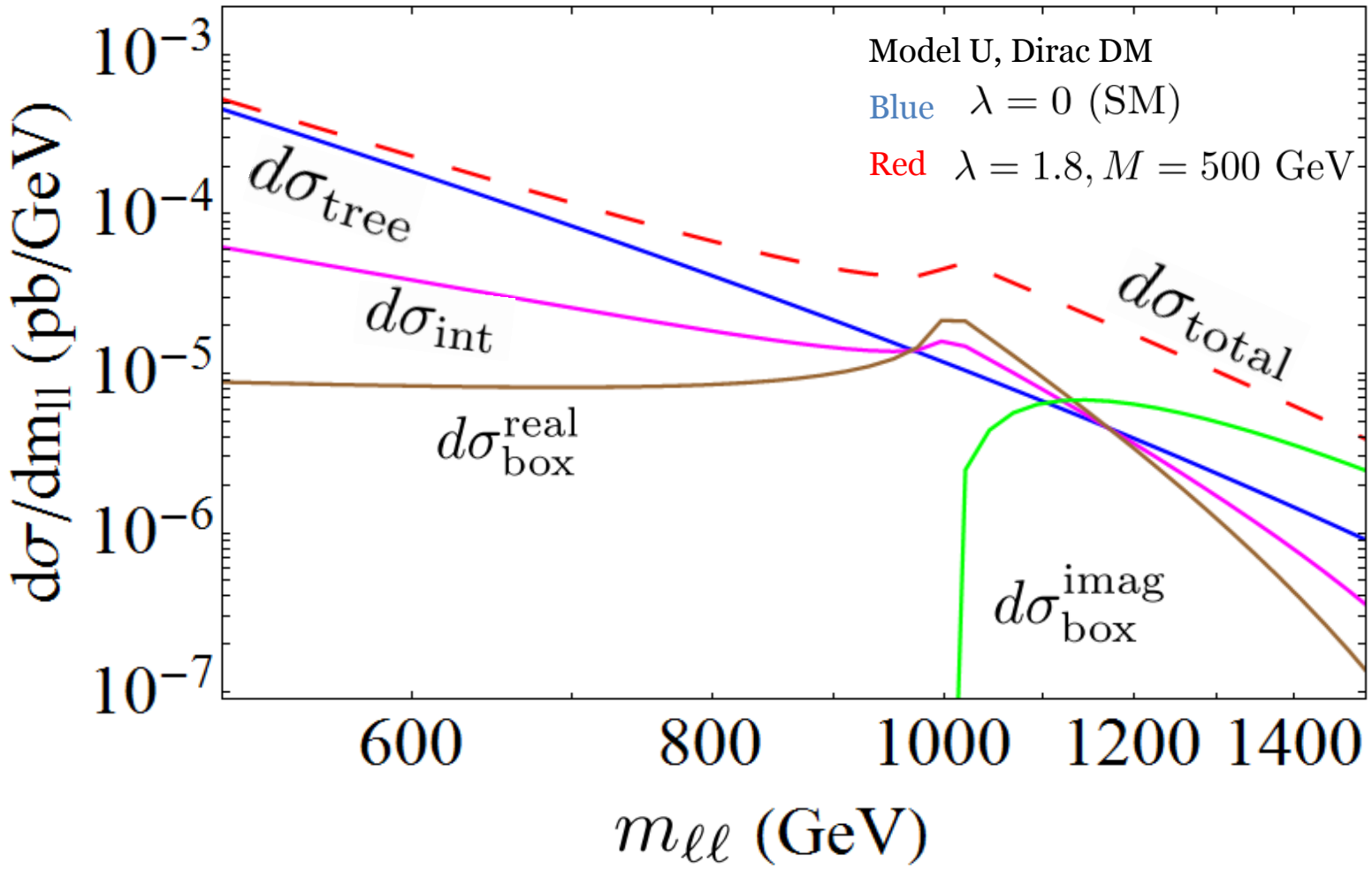
$$d\sigma_{\rm tree} + d\sigma^{\rm imag}_{\rm box}$$

Breakdown of rates



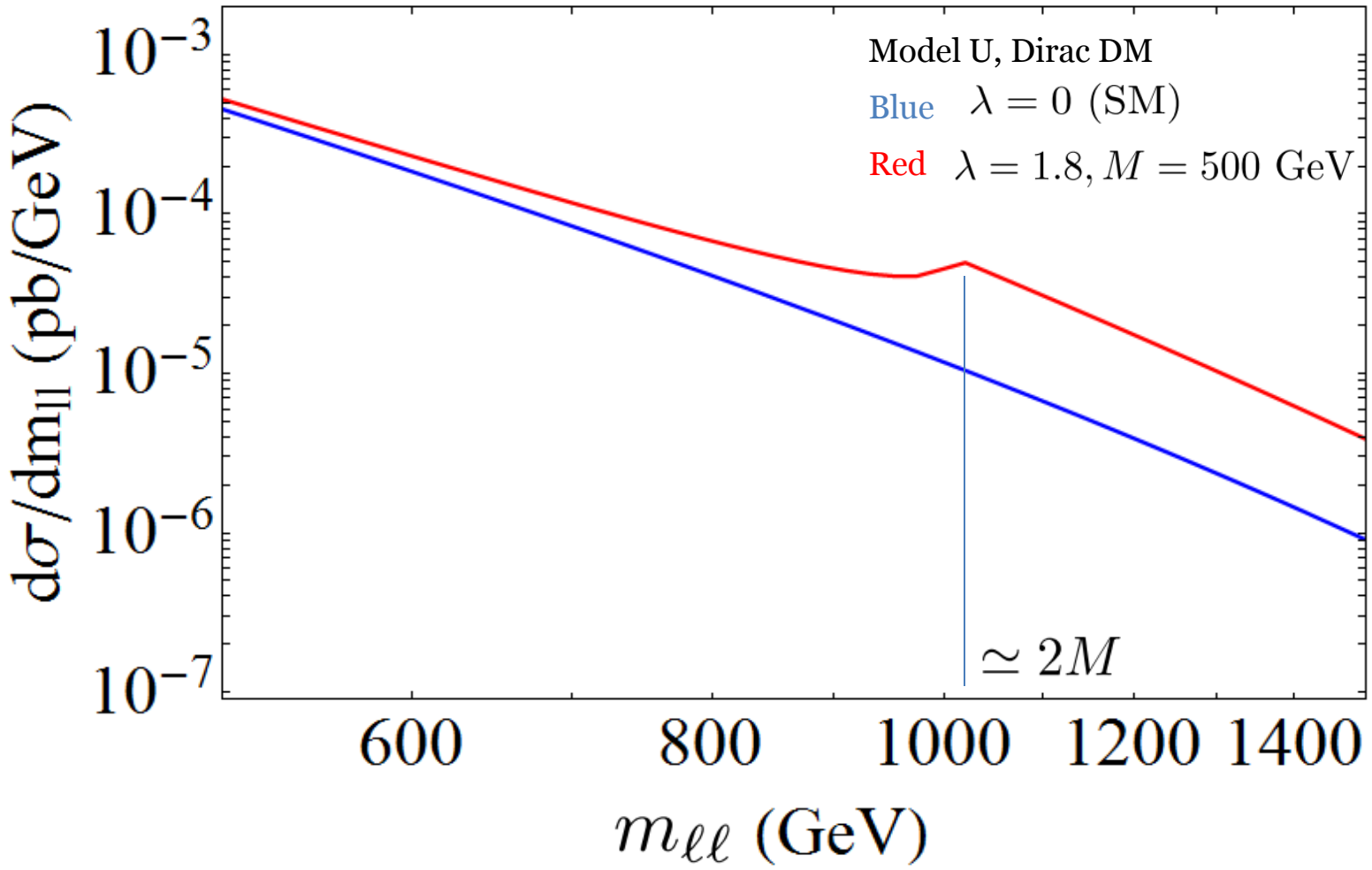
$$d\sigma_{\rm tree} + d\sigma^{\rm real}_{\rm box} + d\sigma^{\rm imag}_{\rm box}$$

Breakdown of rates

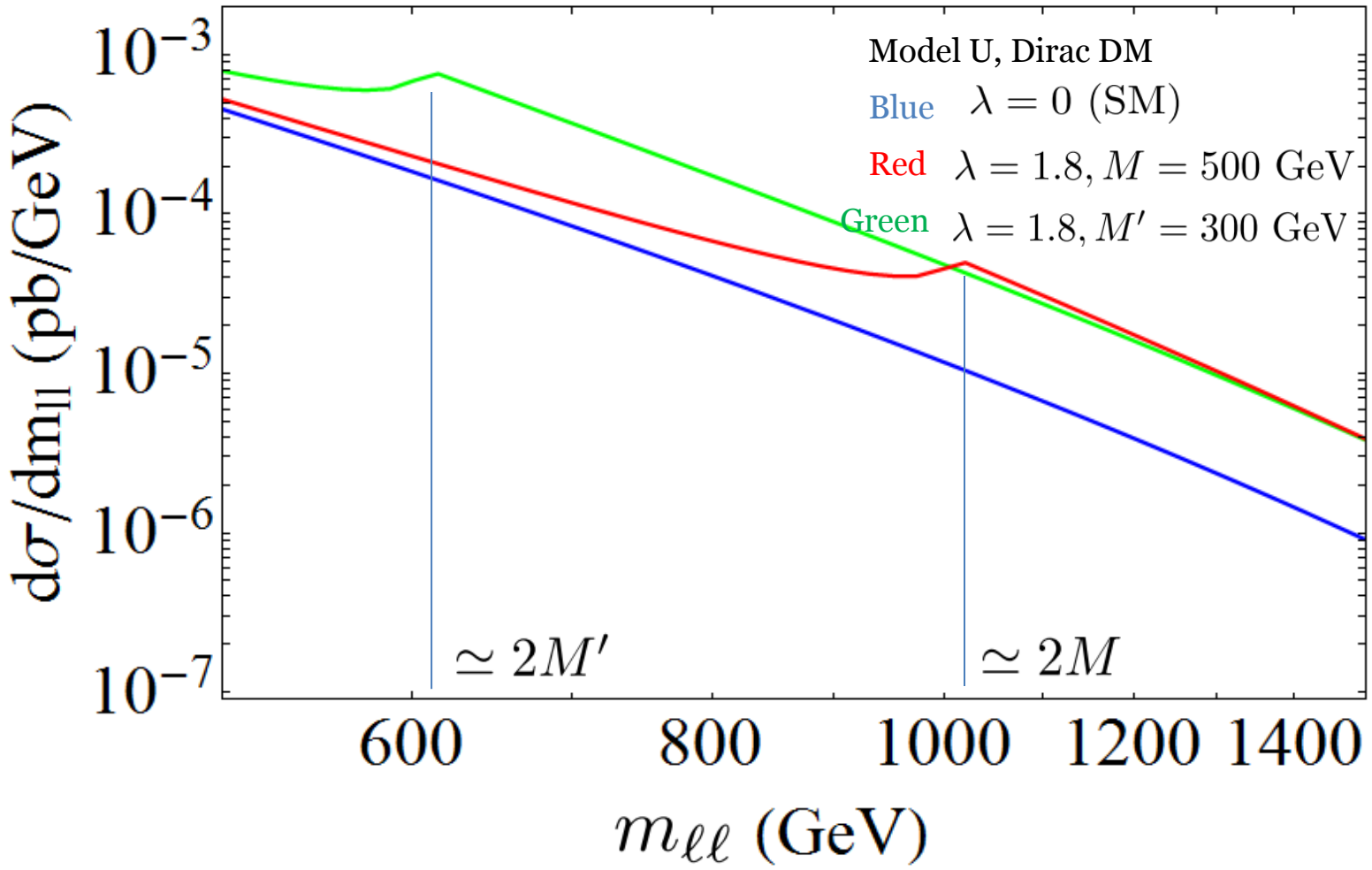


$$d\sigma_{\rm tree} + d\sigma_{\rm int} + d\sigma_{\rm box}^{\rm real} + d\sigma_{\rm box}^{\rm imag}$$

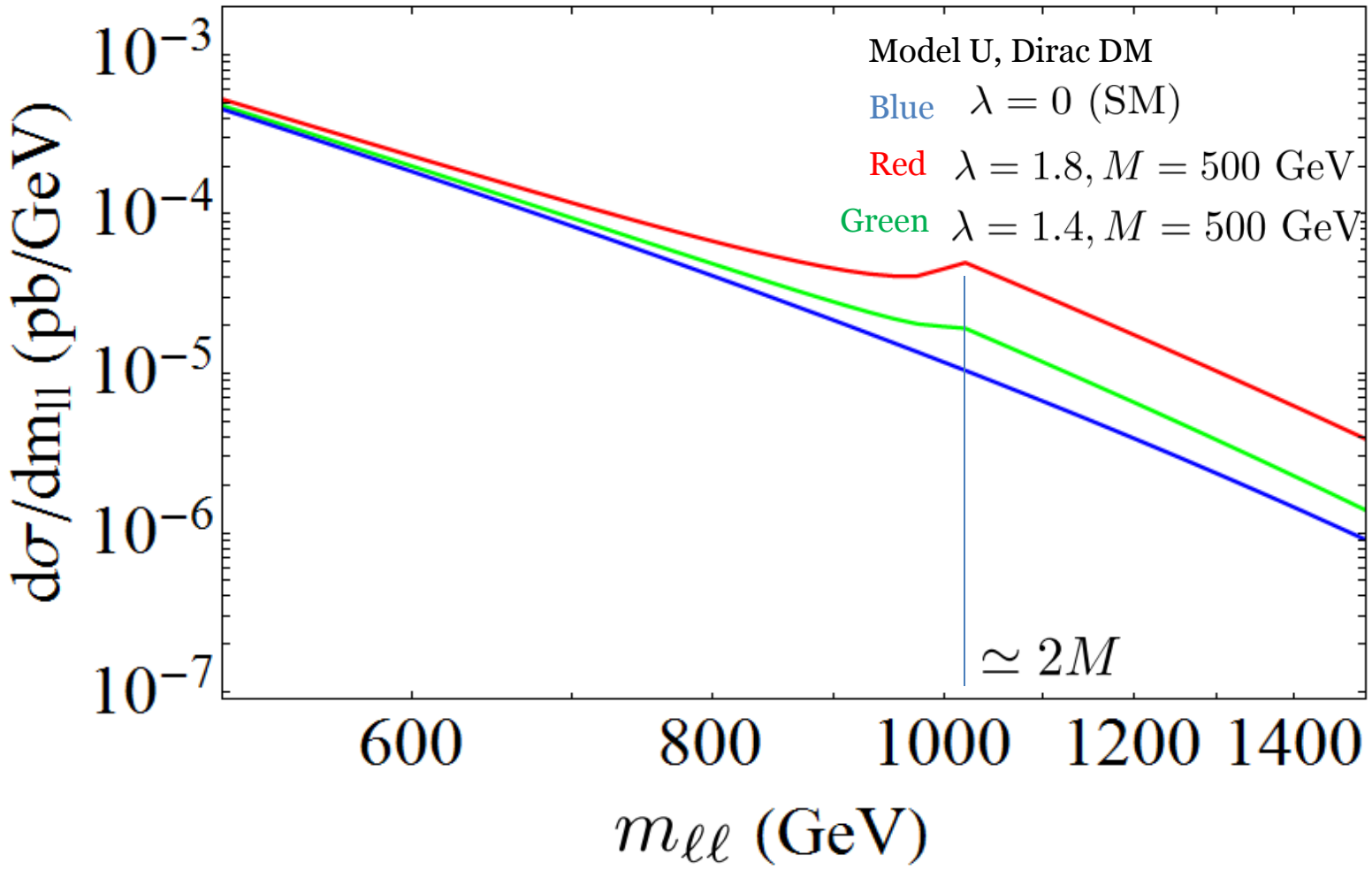
The signal (again)



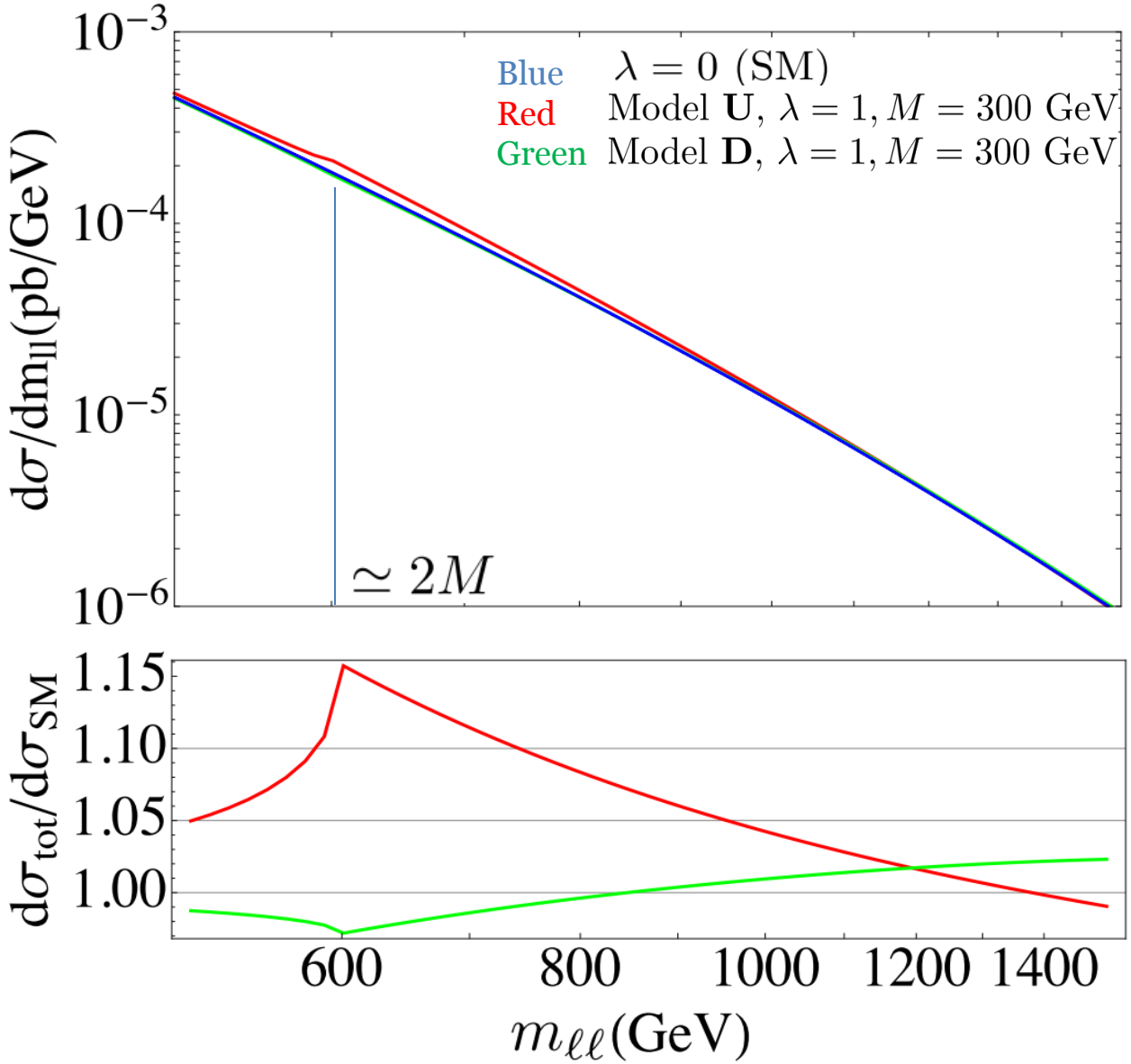
Mass information



λ large: $d\sigma_{\rm box}$ dominance

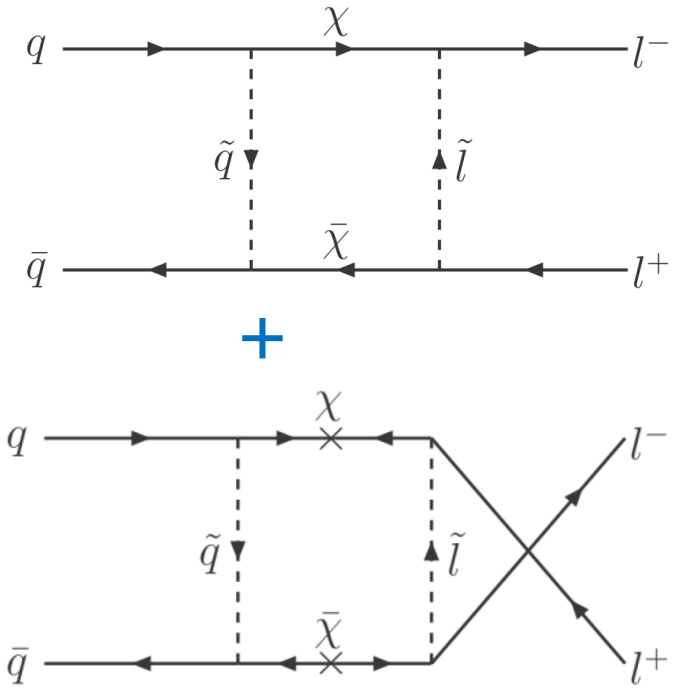


λ small: $d\sigma_{\rm int}$ dominance



Dirac v Majorana

Majorana:

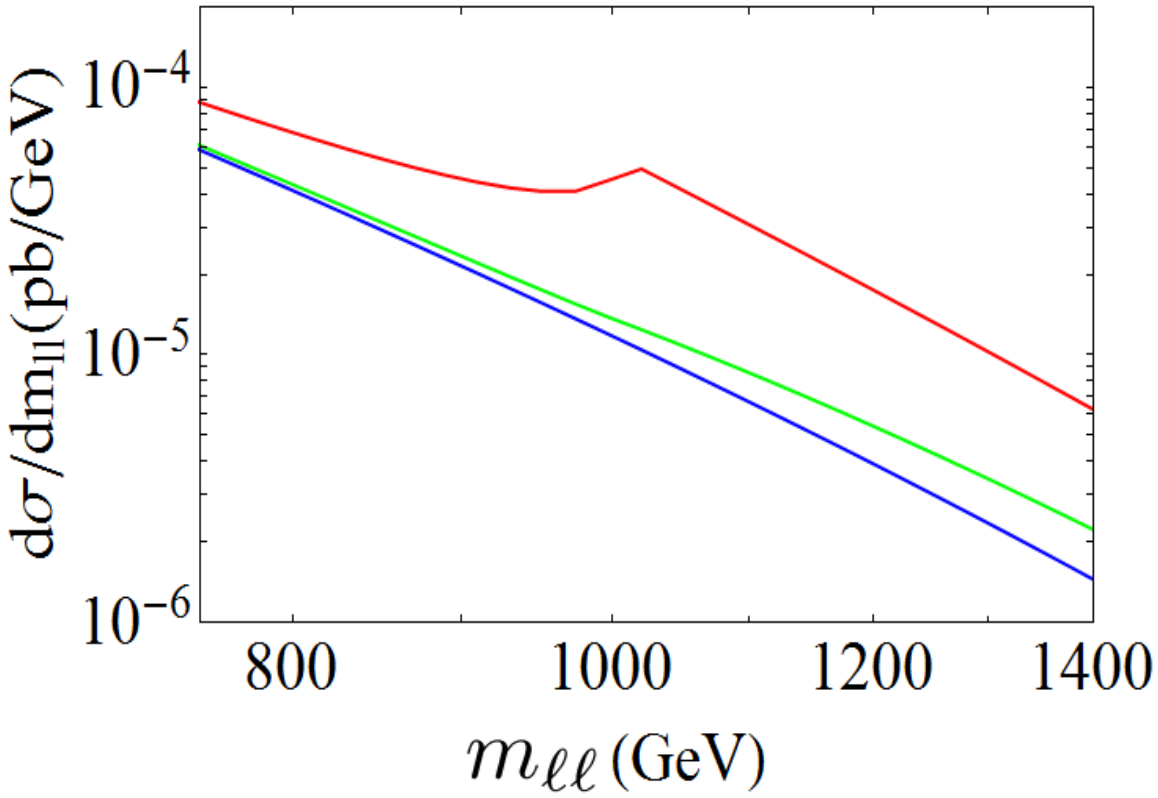


Model **U**

Blue $\lambda = 0$ (SM)

Red $\lambda = 1.8, M = 500$ GeV , DIRAC

Green $\lambda = 1.8, M = 500$ GeV , MAJORANA

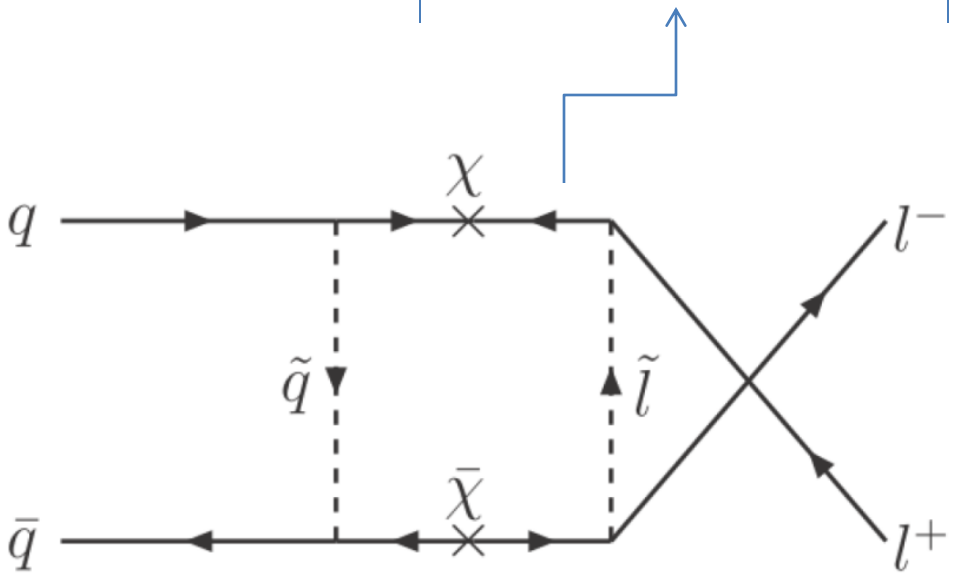


Mass of χ

	Dirac	Majorana	Mixed
Spin-indep. direct detection	✗ Unsuppressed	✓ Suppressed	✓ Majorana-like
	..	..	..

Mass of χ

	Dirac	Majorana	Mixed
Spin-indep. direct detection	X Unsuppressed	✓ Suppressed	✓ Majorana-like
Monocline feature	✓ Distinct	X Suppressed	✓ Dirac-like



Mixed dark matter

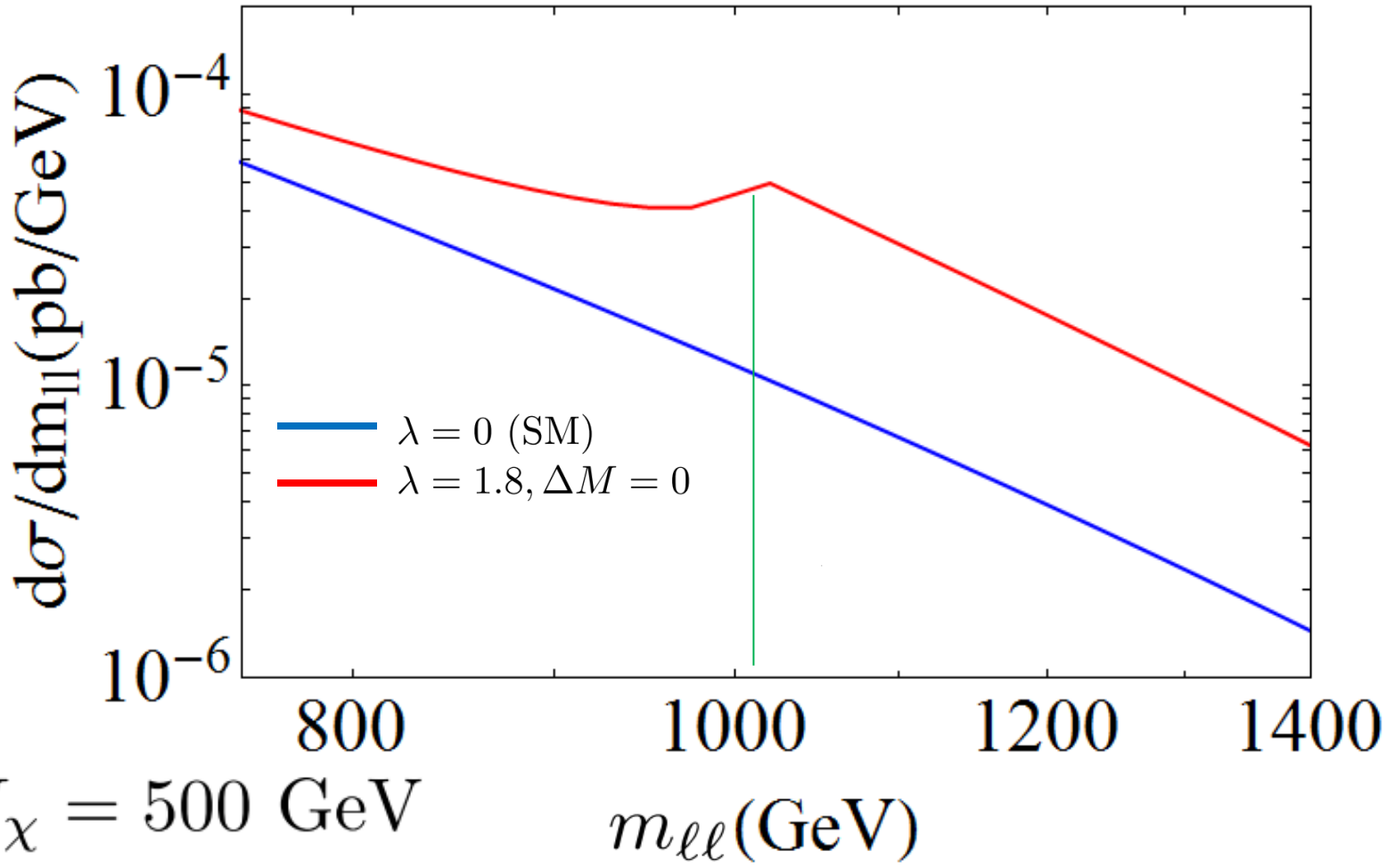
$$\mathcal{L}_{\text{DM mass}} = \begin{pmatrix} \chi_A & \chi_B \end{pmatrix} \begin{pmatrix} \Delta M & M_d \\ M_d & \Delta M' \end{pmatrix} \begin{pmatrix} \chi_A \\ \chi_B \end{pmatrix} + \text{h.c.}$$

$$\begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \chi_A \\ \chi_B \end{pmatrix}$$

$$\Delta M' = 0 \Rightarrow |\bar{M}_2| - |\bar{M}_1| = \Delta M$$

Interpolator between Dirac and Majorana

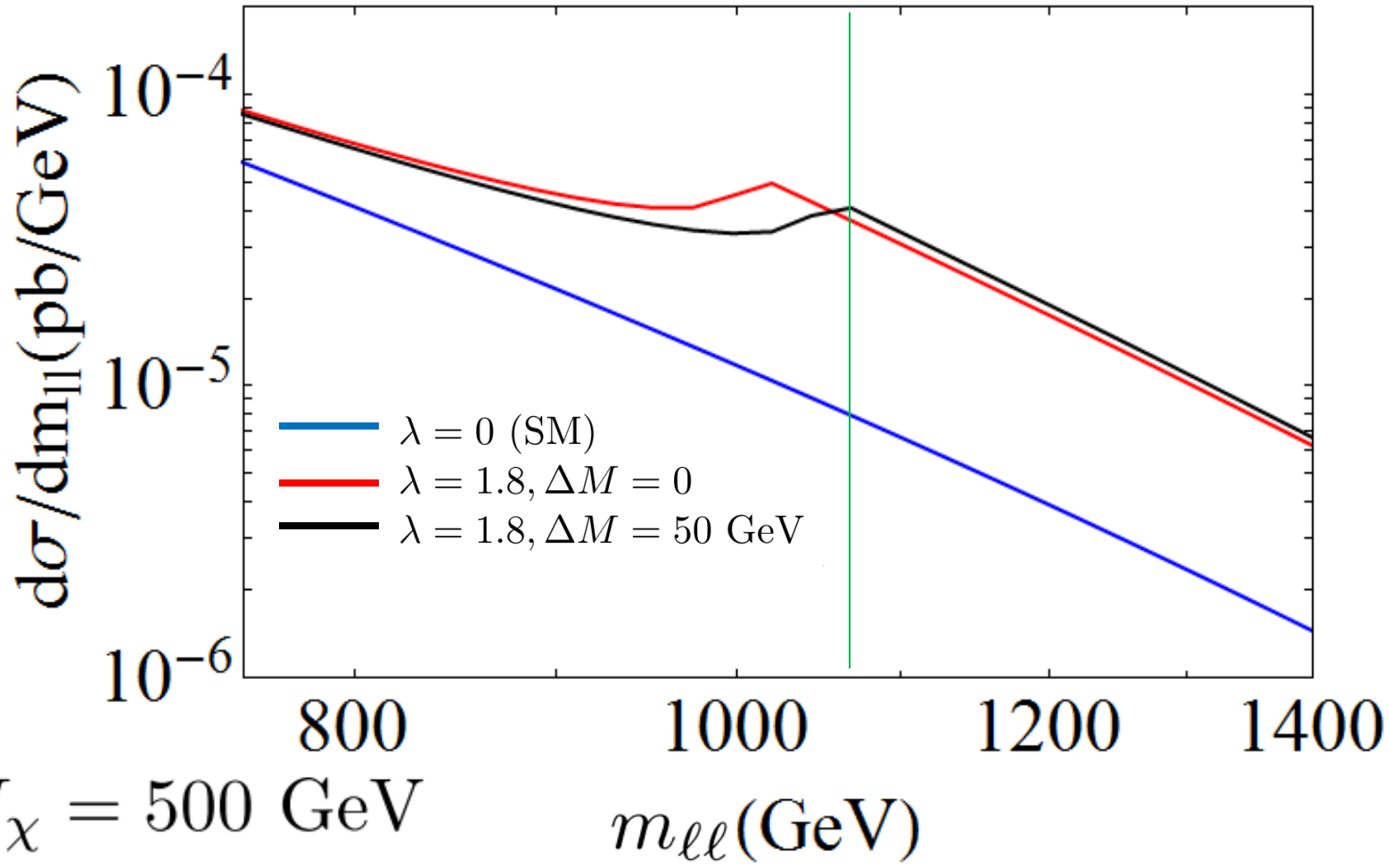
Mixed dark matter: monocline



$M_\chi = 500$ GeV

$\Delta M = 0$: Dirac

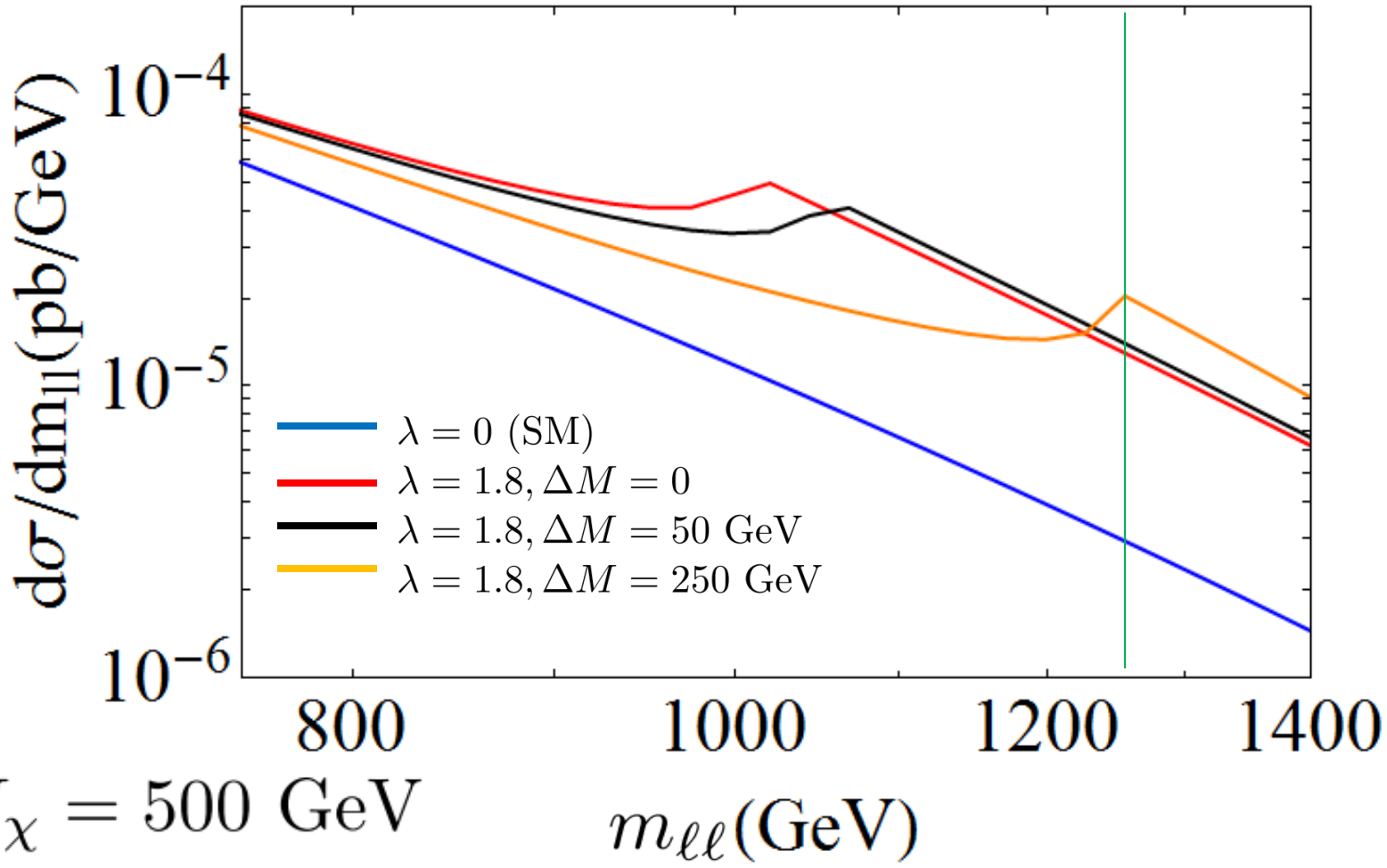
Mixed dark matter: monocline



$M_\chi = 500$ GeV

$\Delta M = 50$ GeV

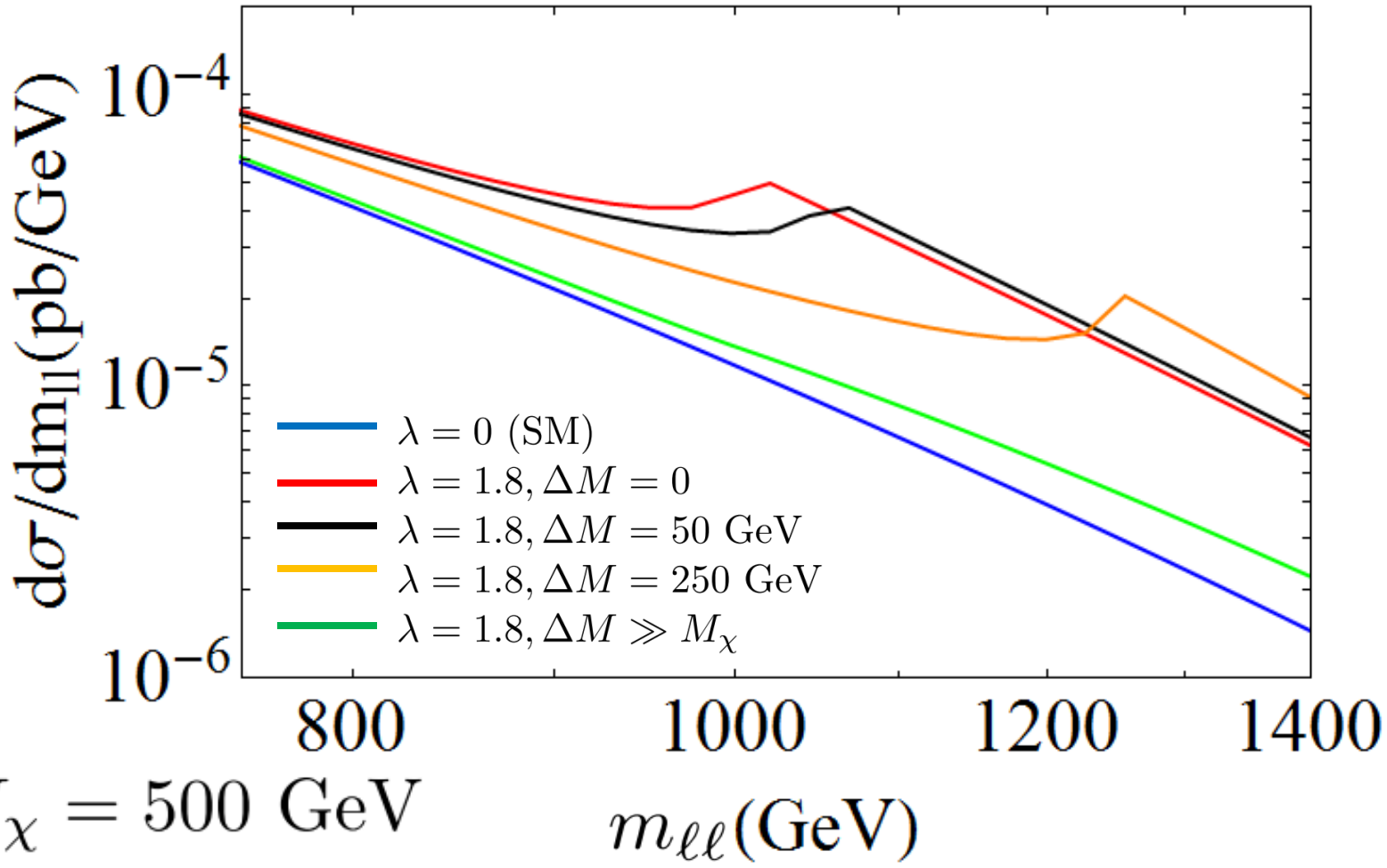
Mixed dark matter: monocline



$M_\chi = 500$ GeV

$\Delta M = 250$ GeV

Mixed dark matter: monocline



$M_\chi = 500$ GeV

ΔM large : Majorana

Constraints menu

Relic abundance ..... *Planck*

Direct detection

Spin-dependent scattering ..... *XENON100, 225 days*

Spin-independent scattering ... *LUX, 85.3 days*

Jets + MET searches ..... *CMS @ 8 TeV*

Dilepton spectrum ..... *ATLAS, CMS @ 8 TeV*

Constraints: Operation

Relic abundance, direct detection

Algebraically computed

New calculation:
co-annihilation between
singlets! cf. K. Hsieh, 0708.3970

Jets + MET searches

(a) *MadGraph5* for colored mediator production cross-section,

(b) Coupling bounded using CMS exclusion cross-sections.

Dilepton spectrum

(a) *LoopTools* and *FeynCalc* for cross-sections,

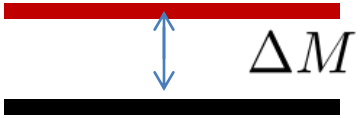
(b) Background events from experiment,

(c) Signal events from scaling background up by $d\sigma_{\rm tot}/d\sigma_{\rm SM}$

Benchmark point

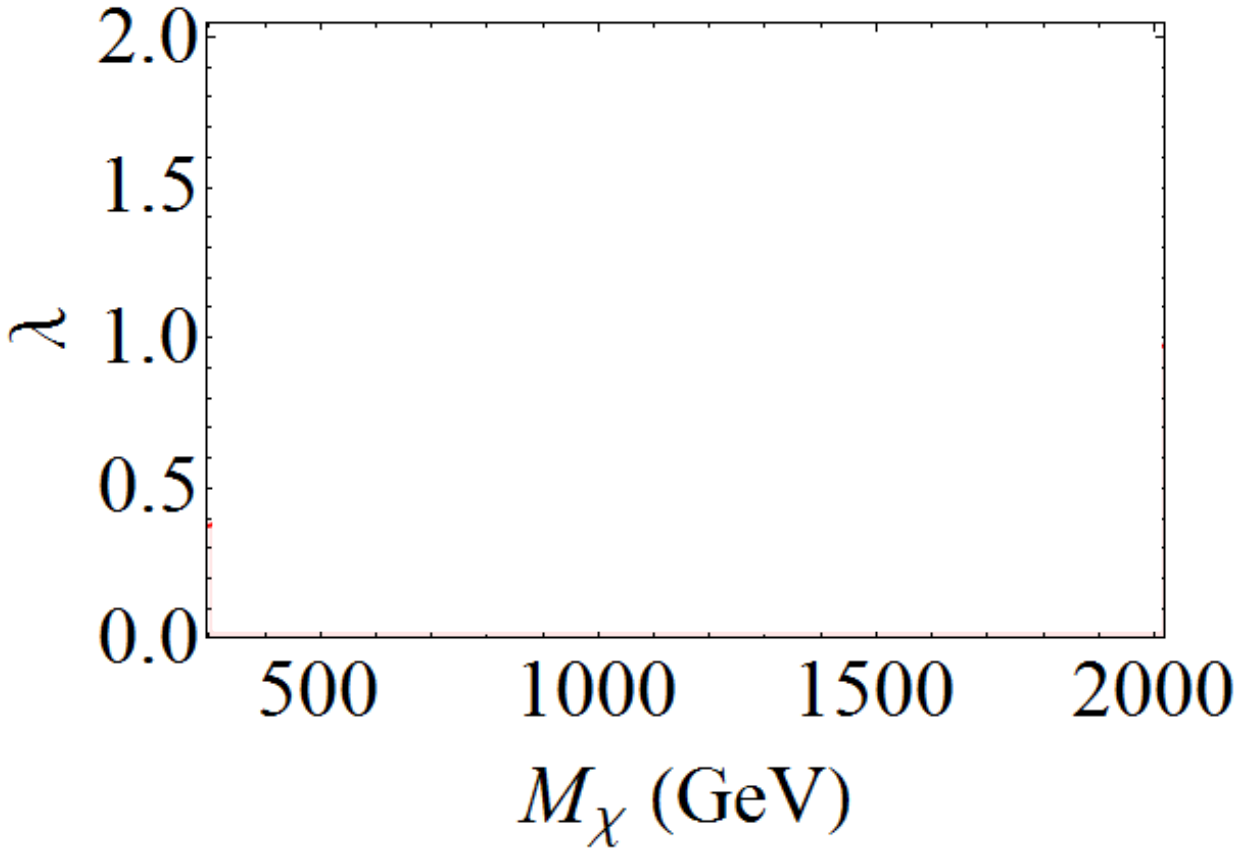
Model **U**

$M_\phi = 1.5\ M_\chi$

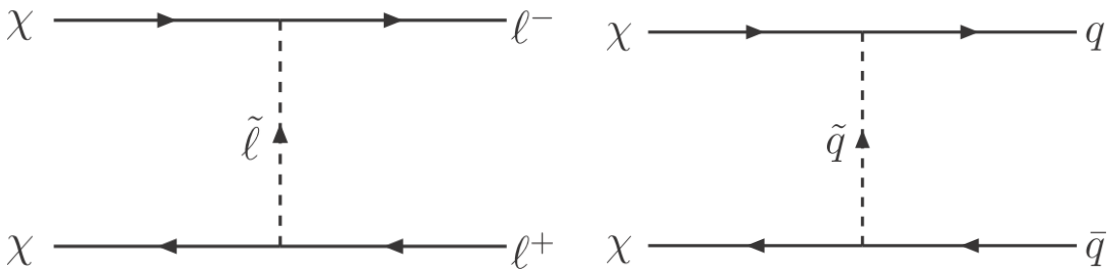


$\Delta M = 0.1\ M_\chi$

M_χ



Relic abundance

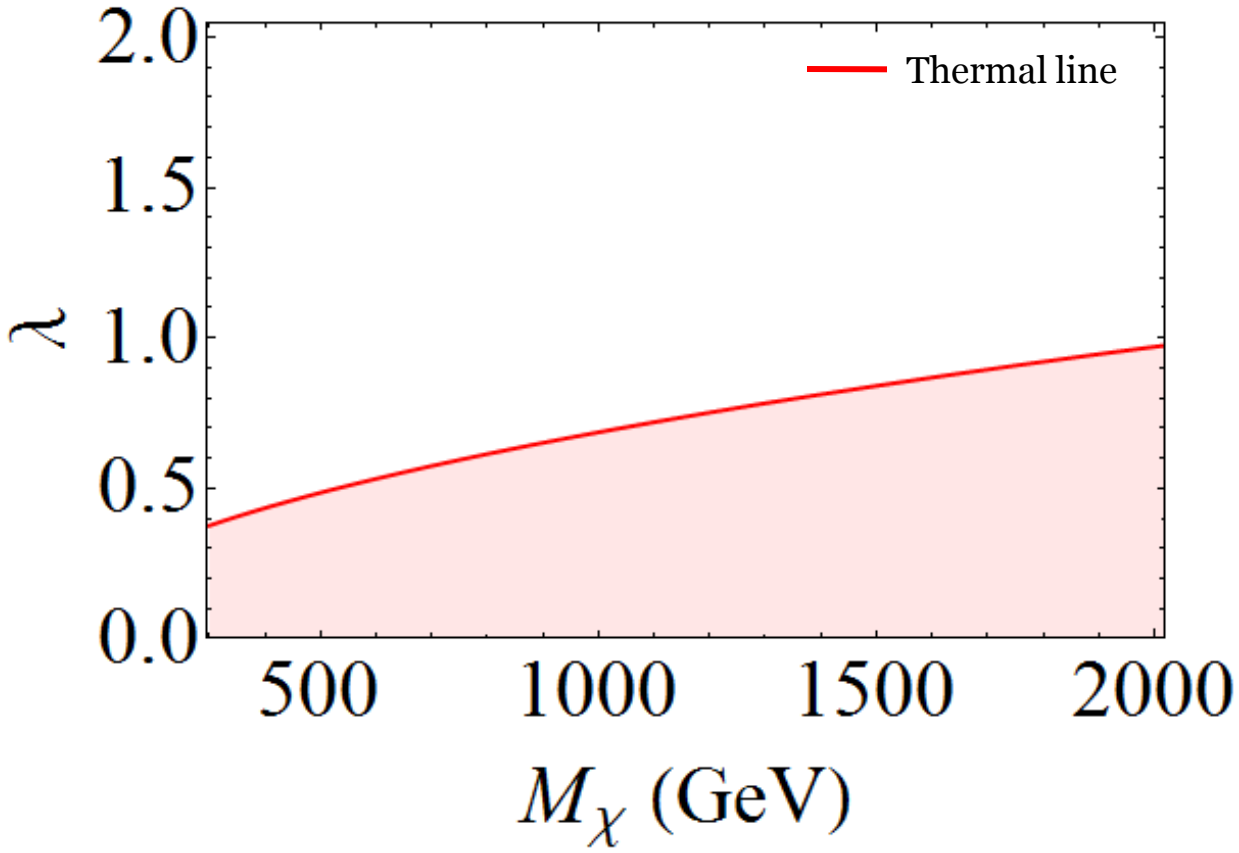


Model **U**

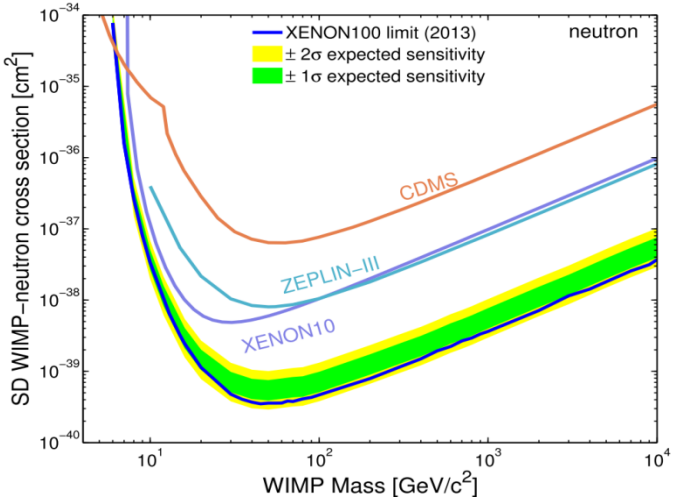
$M_\phi = 1.5\ M_\chi$

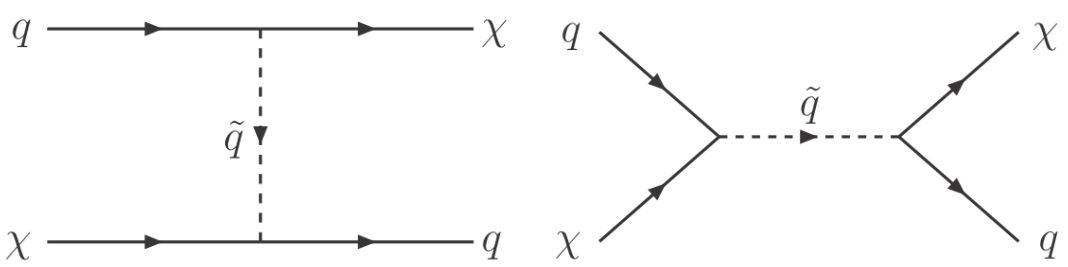
$\Delta M = 0.1\ M_\chi$

M_χ



Direct detection – spin-dependent



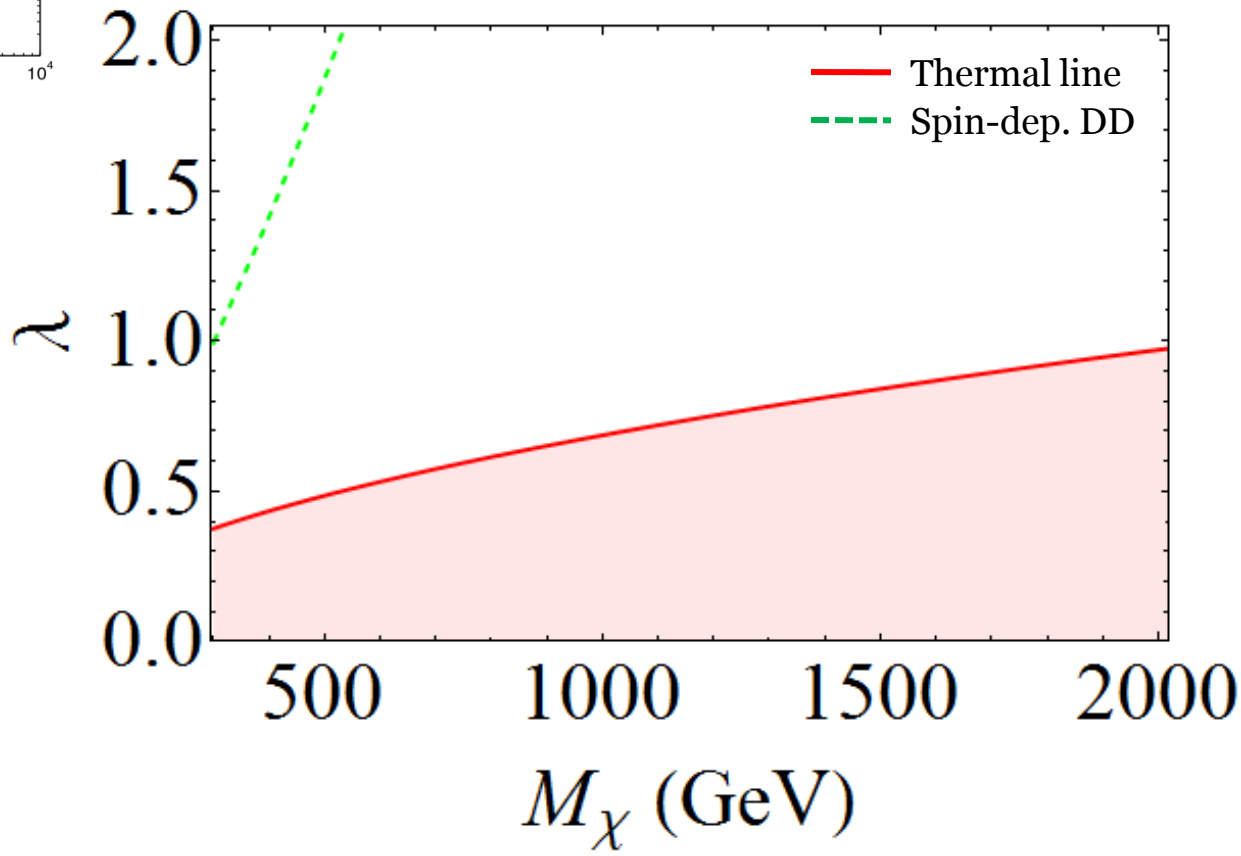


Model **U**

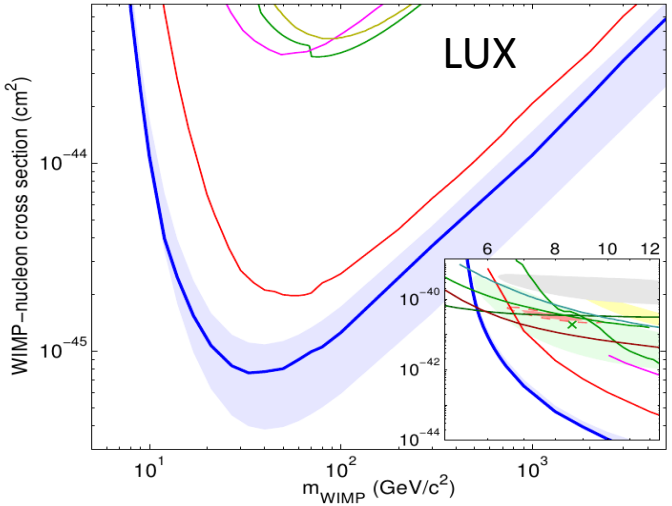
$M_\phi = 1.5\ M_\chi$

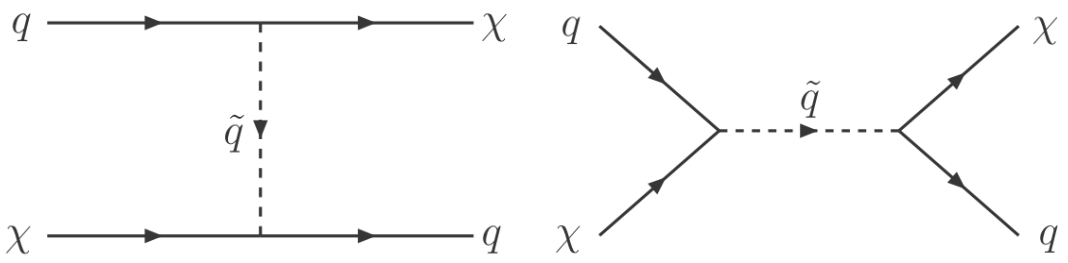
$\Delta M = 0.1\ M_\chi$

M_χ



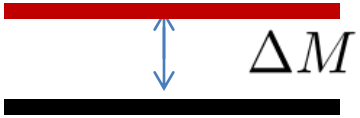
Direct detection – spin-independent





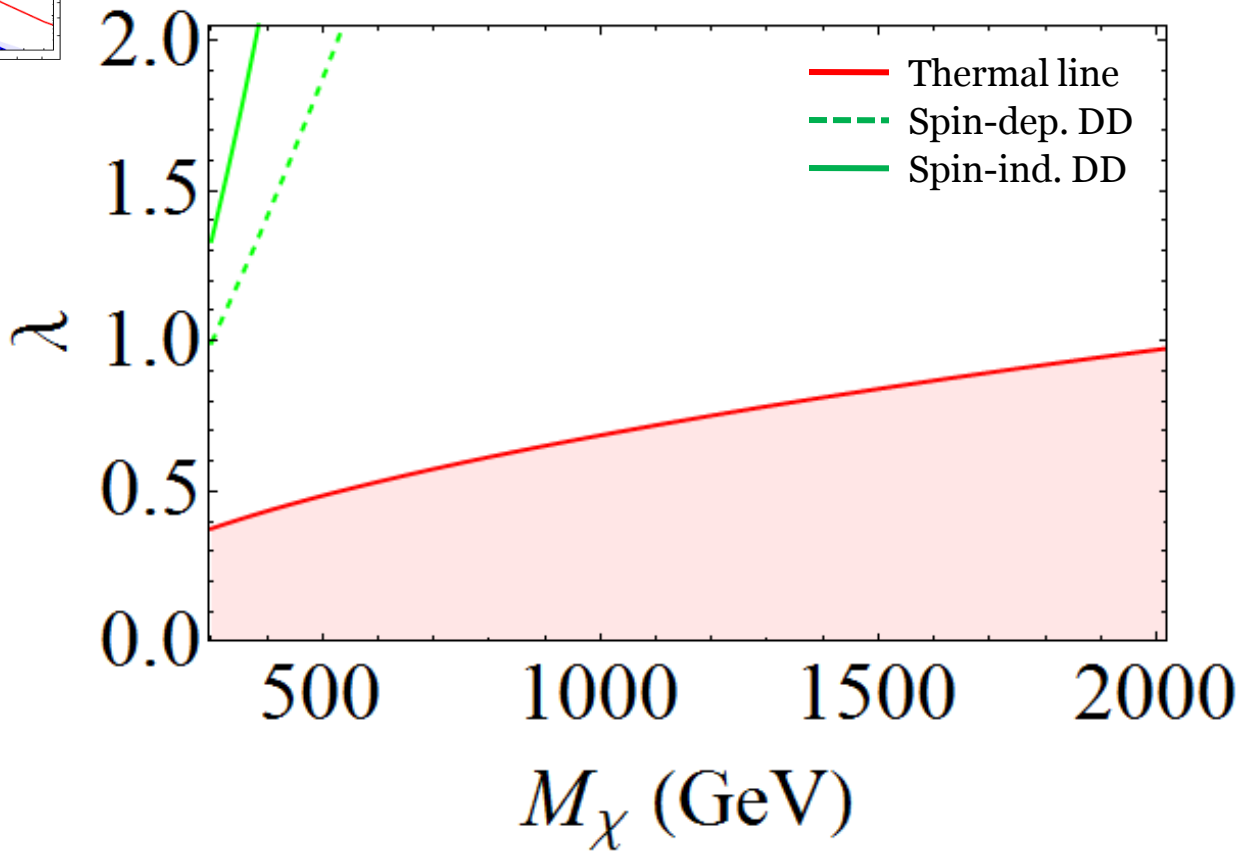
Model **U**

$M_\phi = 1.5\ M_\chi$

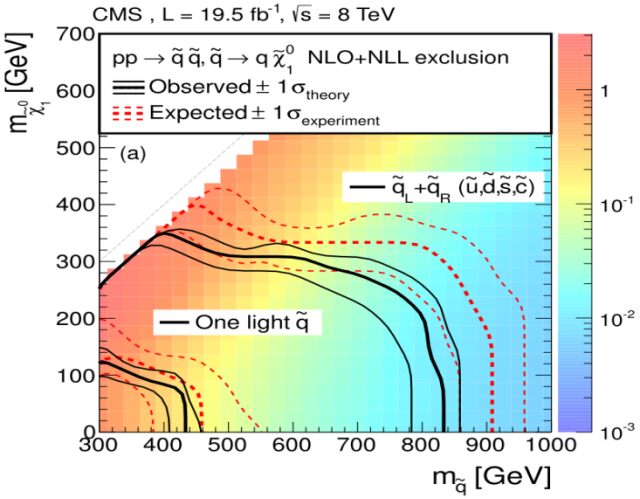


$\Delta M = 0.1\ M_\chi$

M_χ



Jets + $\not{E}_T$

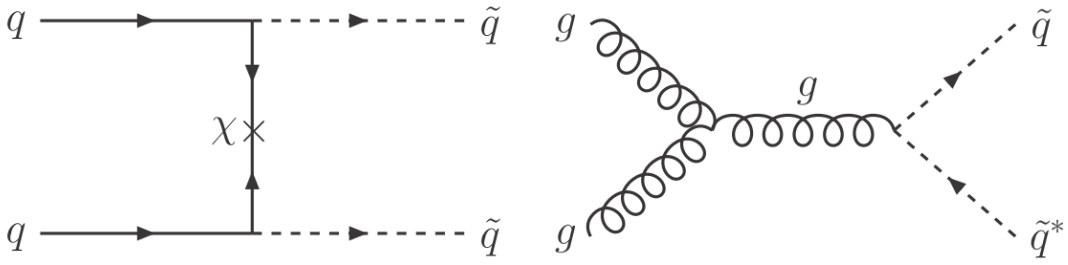


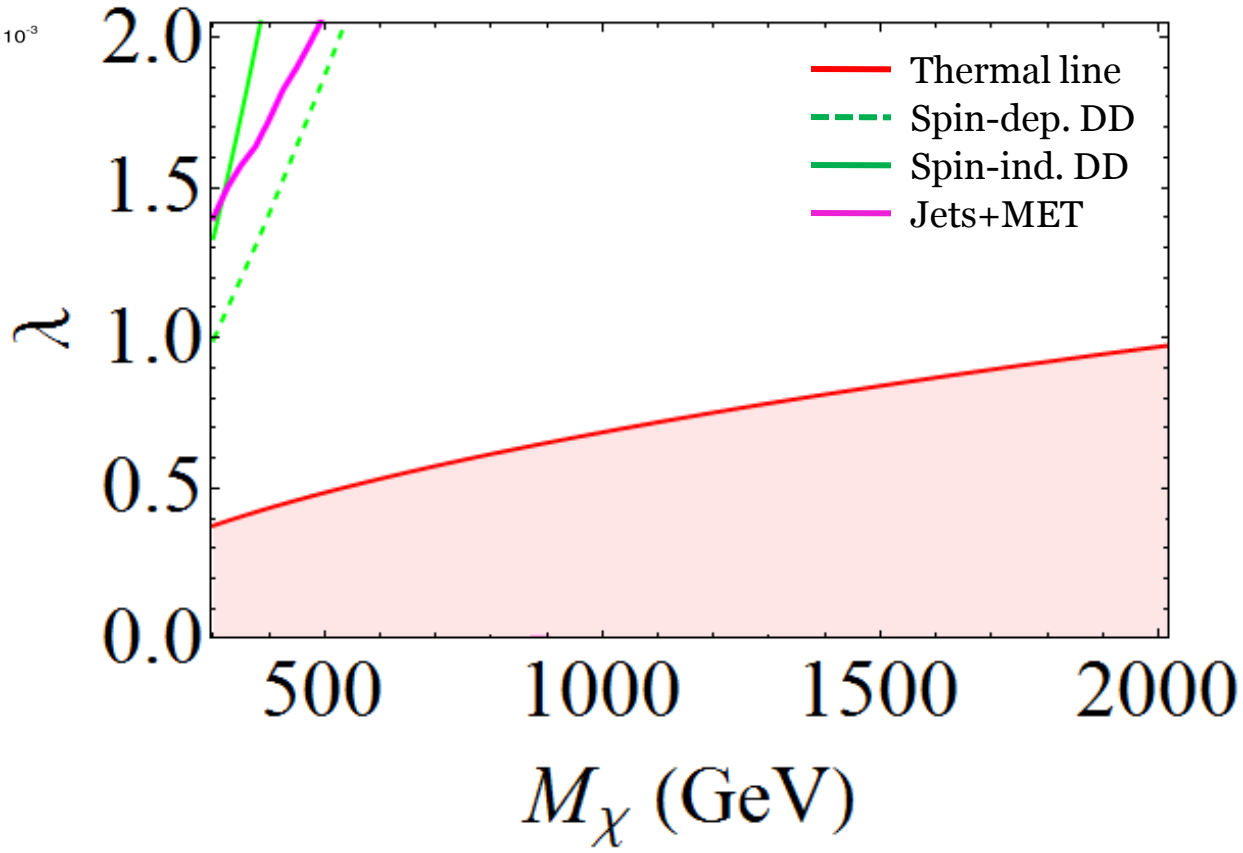
Model **U**

$M_\phi = 1.5\ M_\chi$

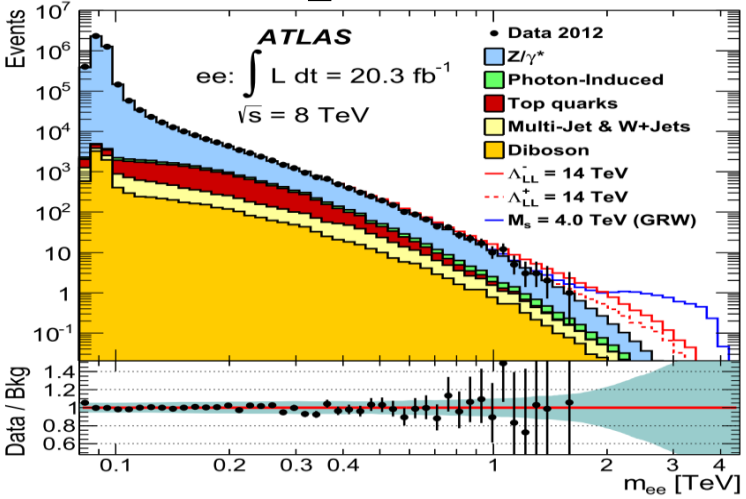
$\Delta M = 0.1\ M_\chi$

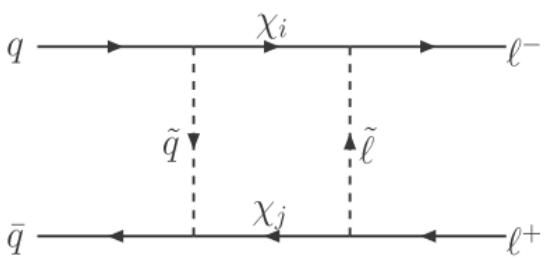
M_χ

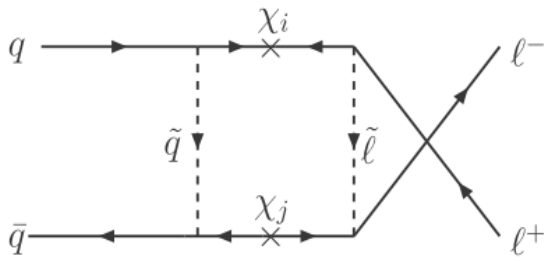




Dileptons – $\Delta\chi^2 = \chi^2_{\rm NP} - \chi^2_{\rm SM}$





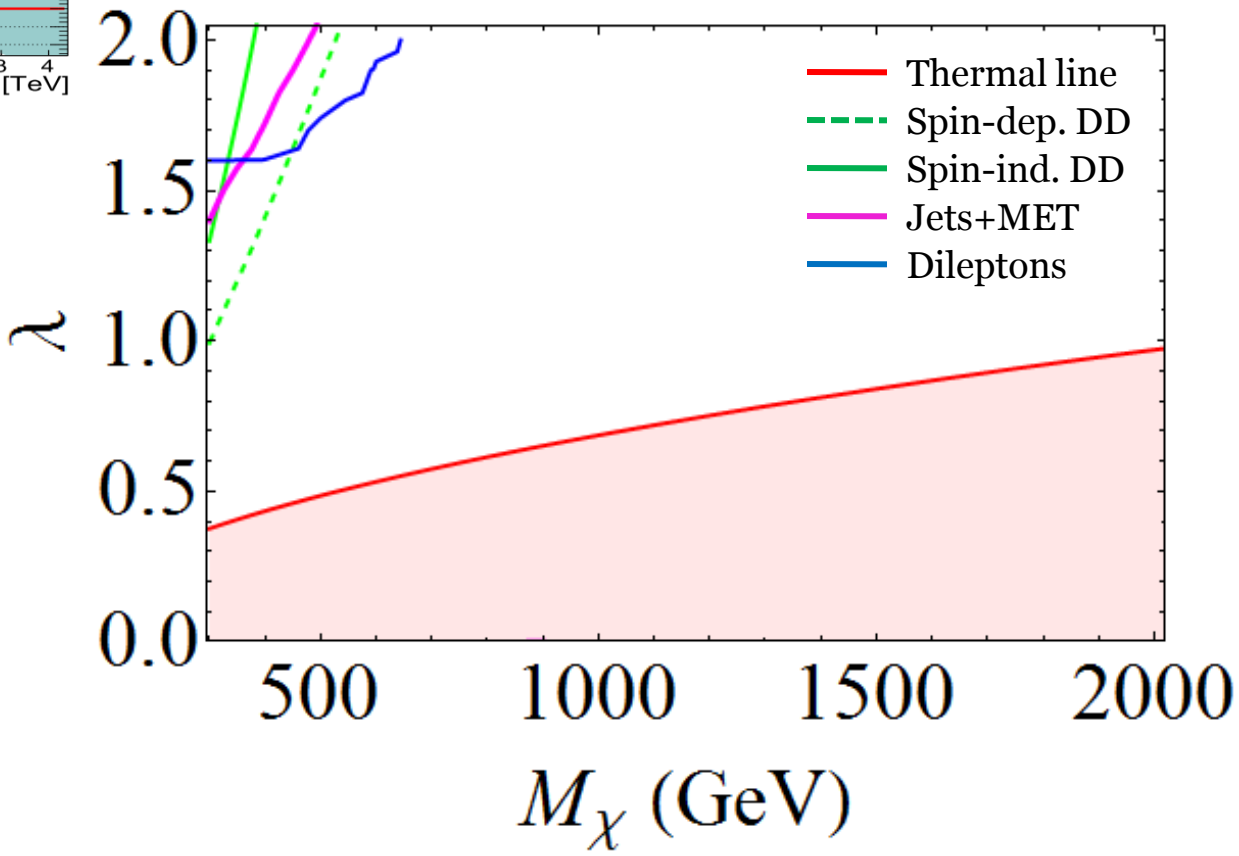


Model **U**

$M_\phi = 1.5\ M_\chi$

$\Delta M = 0.1\ M_\chi$

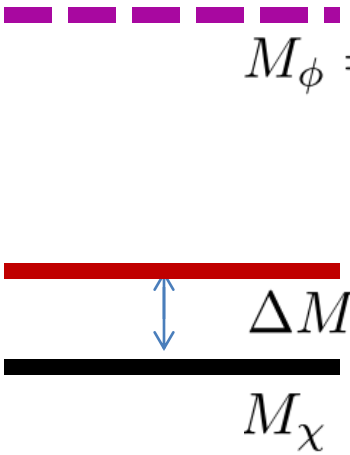
M_χ

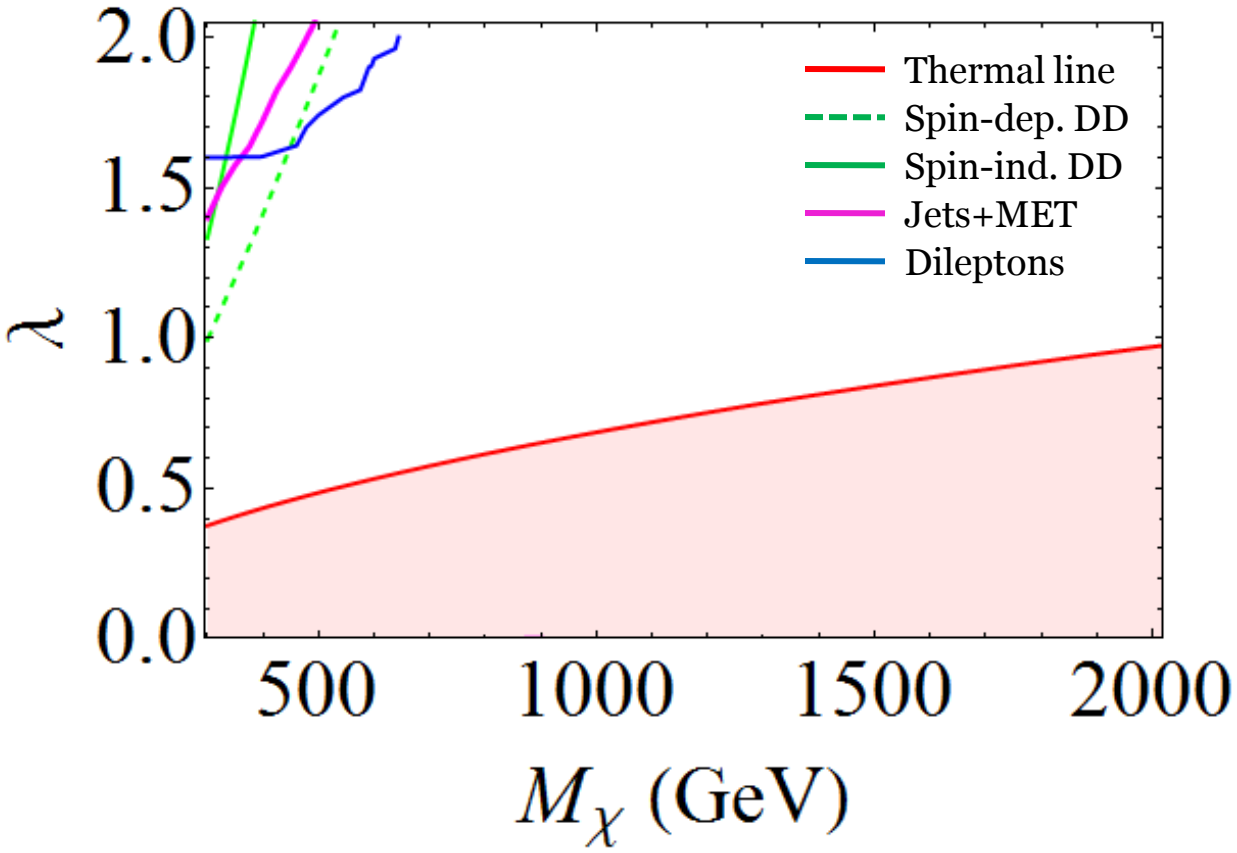


Comparison: Freezeout regime

Dirac-like at freezeout

Model **U**

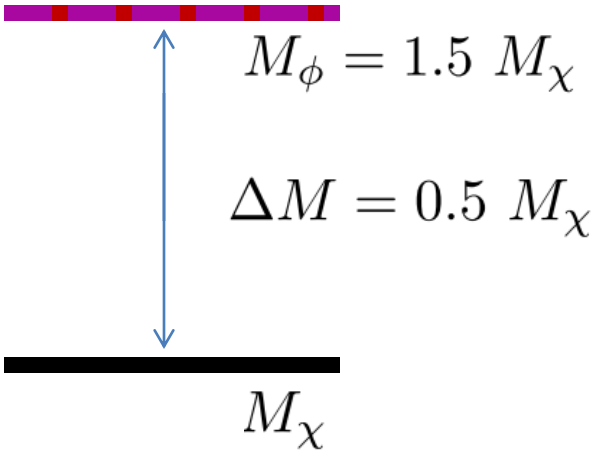


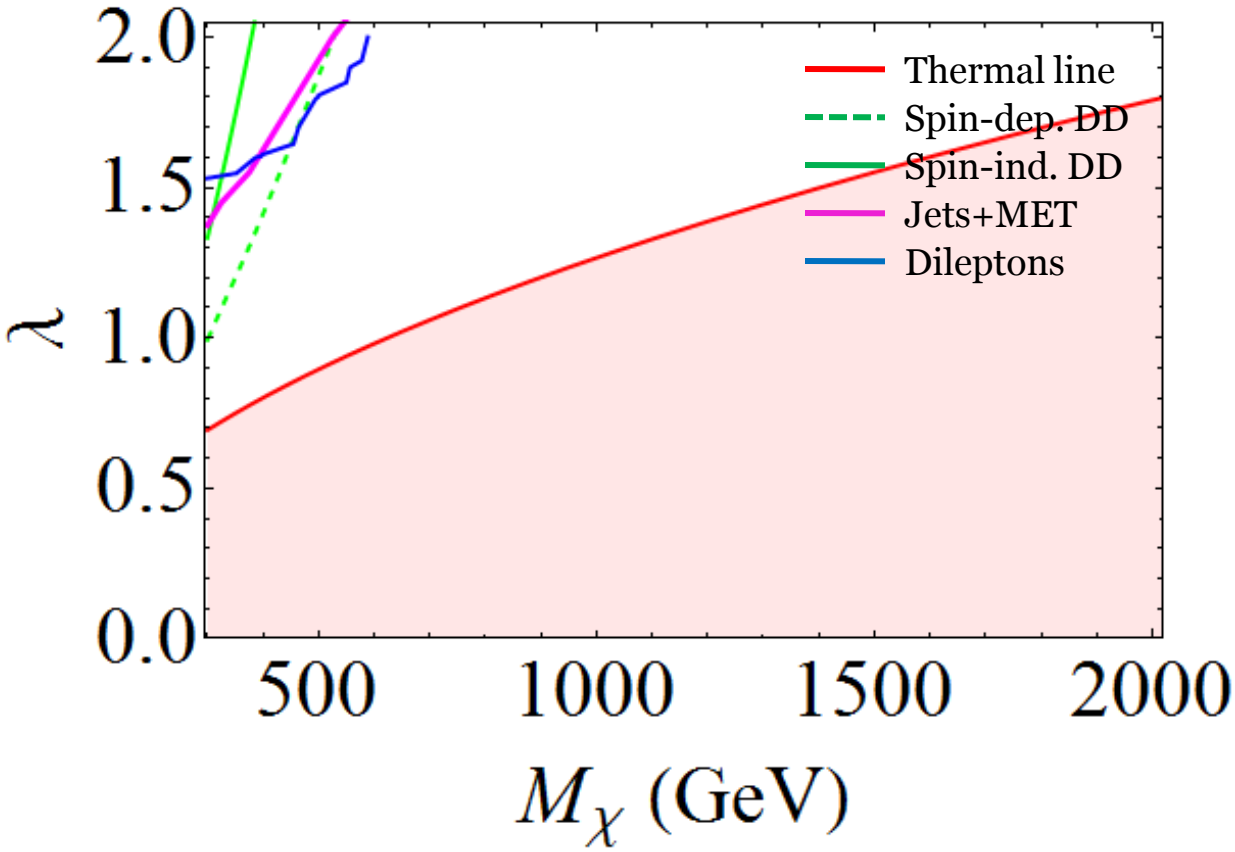


Comparison: Freezeout regime

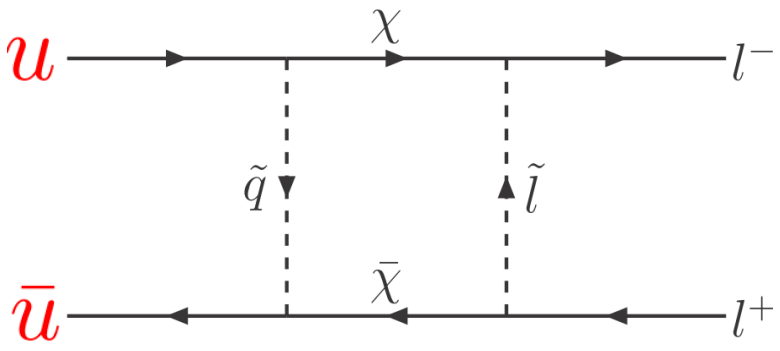
Majorana-like at freezeout

Model **U**



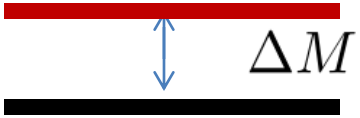


Comparison: initial state quarks



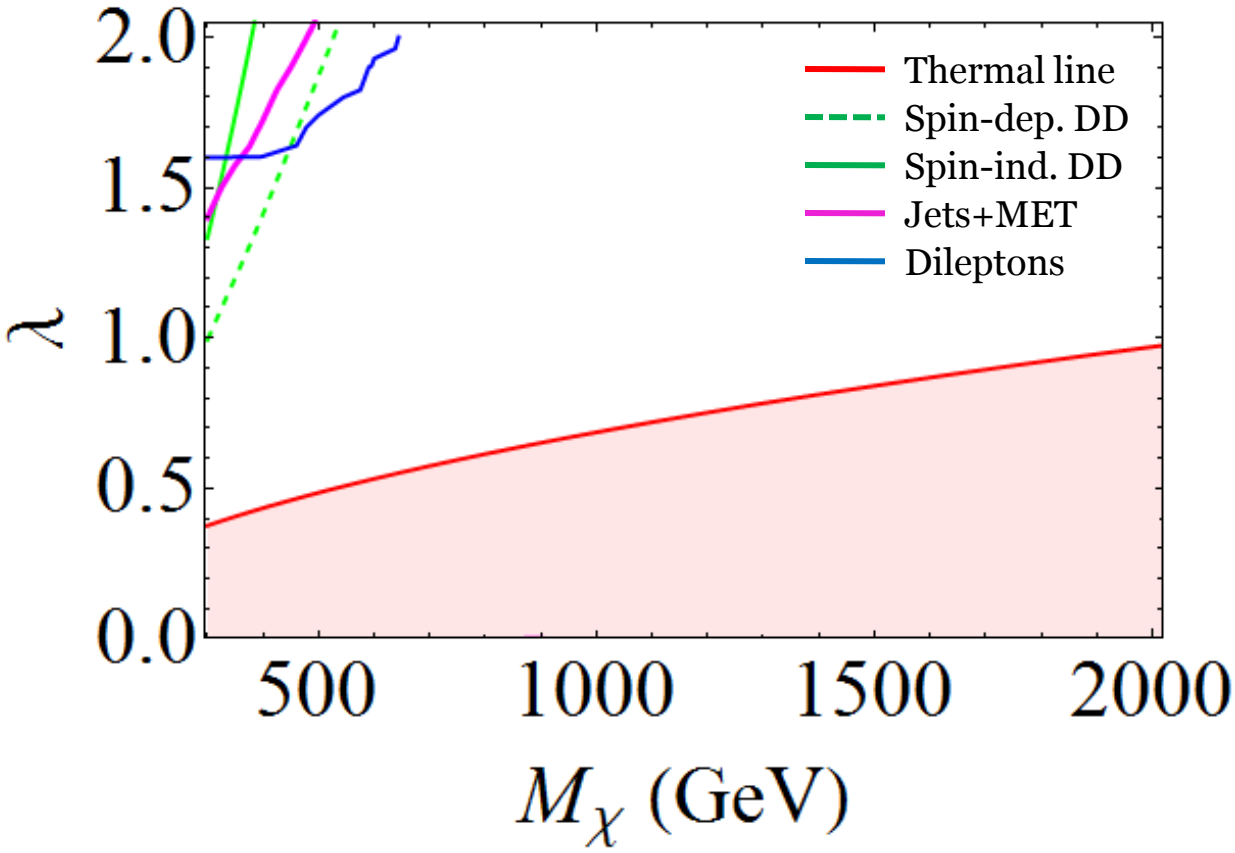
Model **U**

$M_\phi = 1.5\ M_\chi$

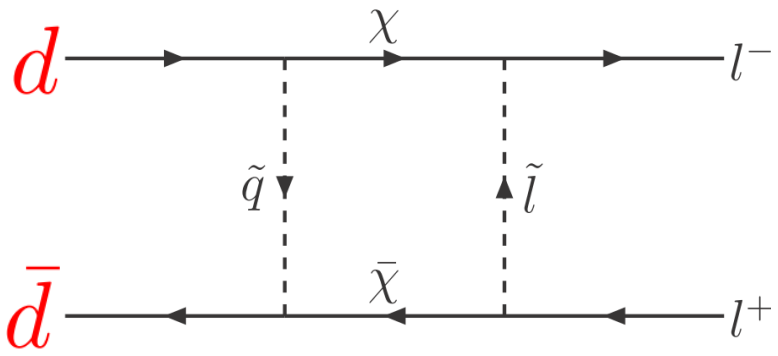


$\Delta M = 0.1\ M_\chi$

M_χ

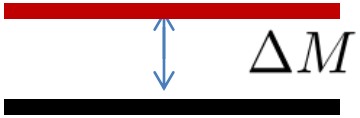


Comparison: initial state quarks



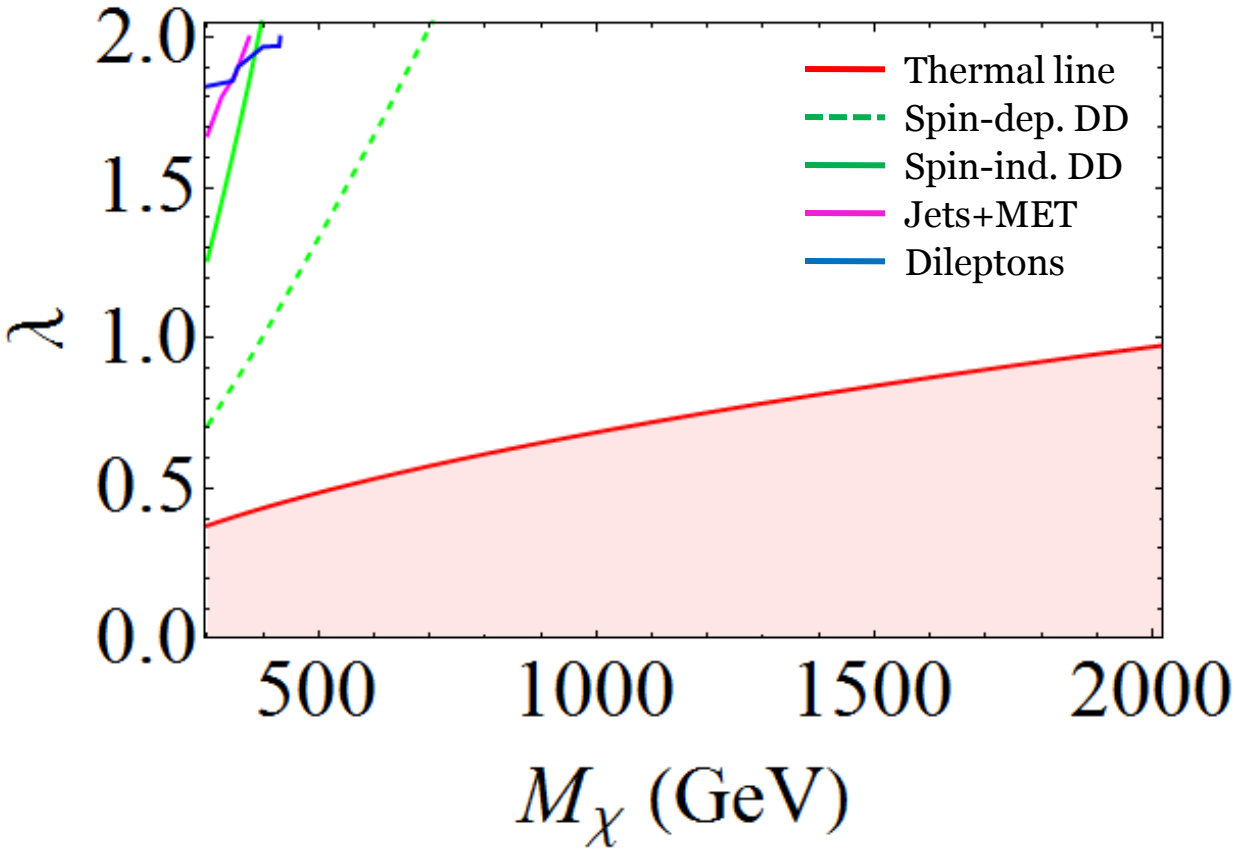
Model **D**

$M_\phi = 1.5\ M_\chi$

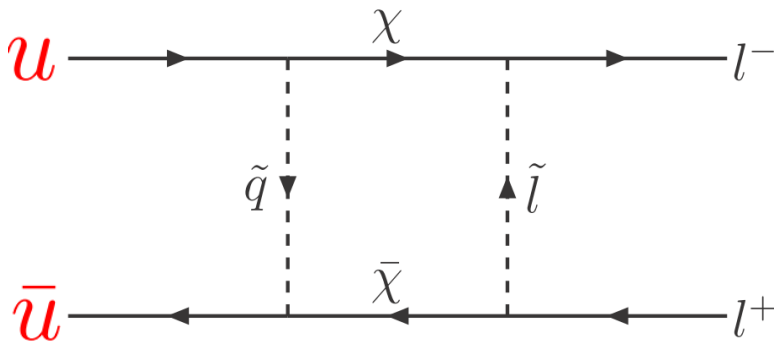


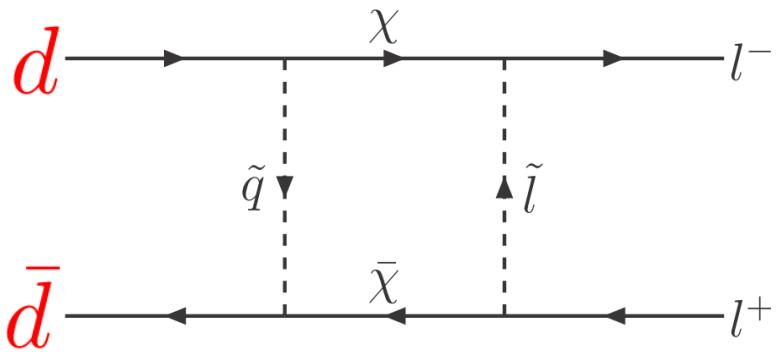
$\Delta M = 0.1\ M_\chi$

M_χ



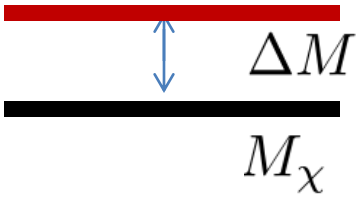
Comparison: initial state quarks





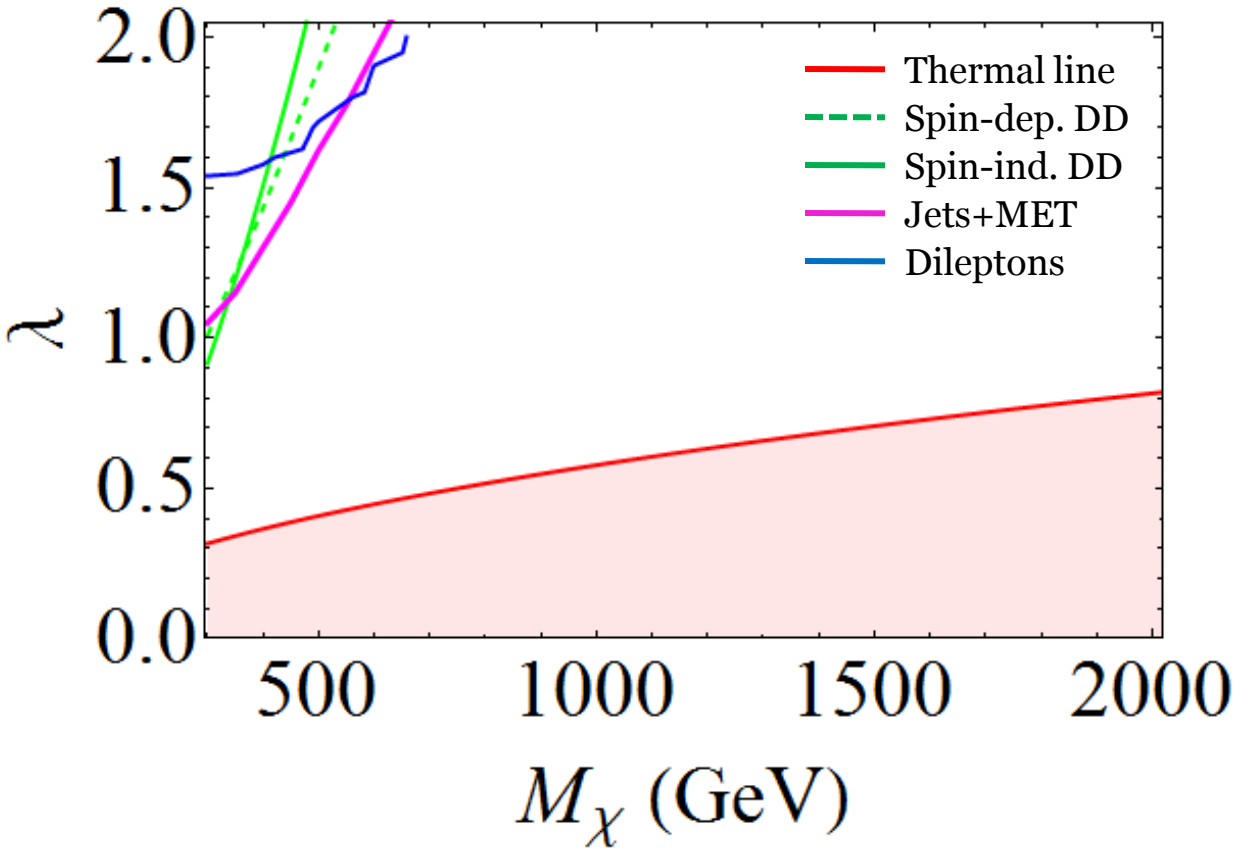
Model **UD**

$M_\phi = 1.5\ M_\chi$



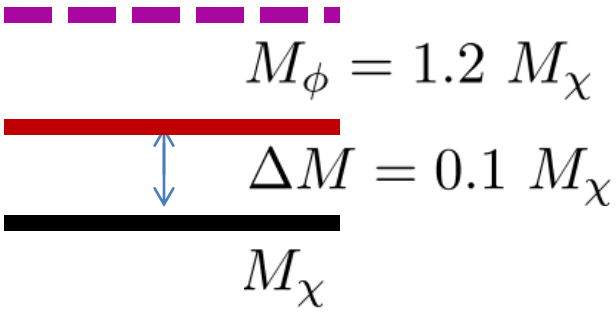
$\Delta M = 0.1\ M_\chi$

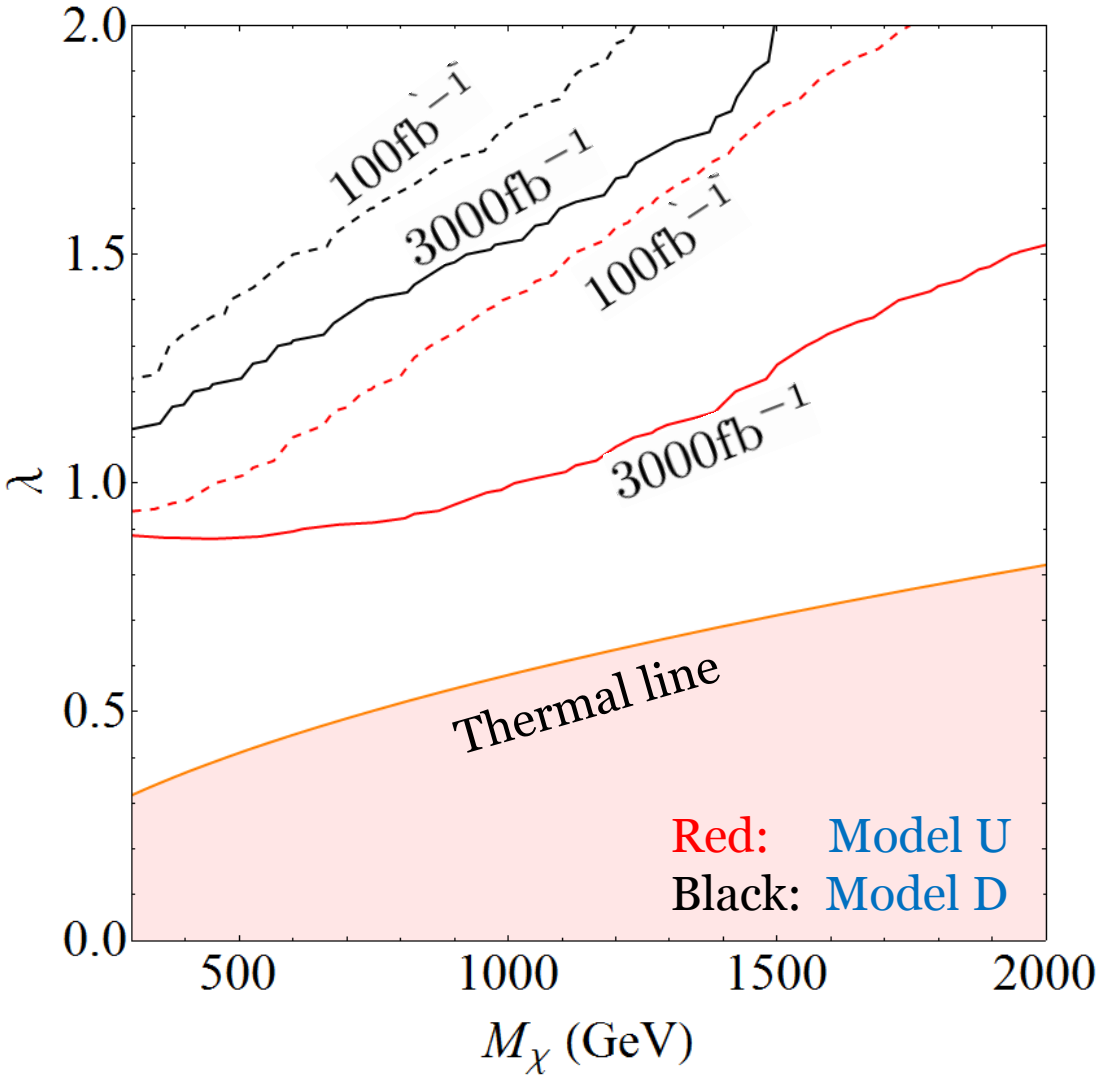
M_χ



14 TeV LHC: 95% C.L. sensitivity

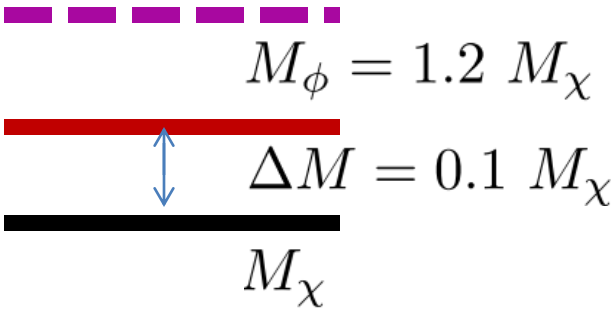
$$\Delta\chi^2 = \chi^2_{\rm NP} - \chi^2_{\rm SM}$$

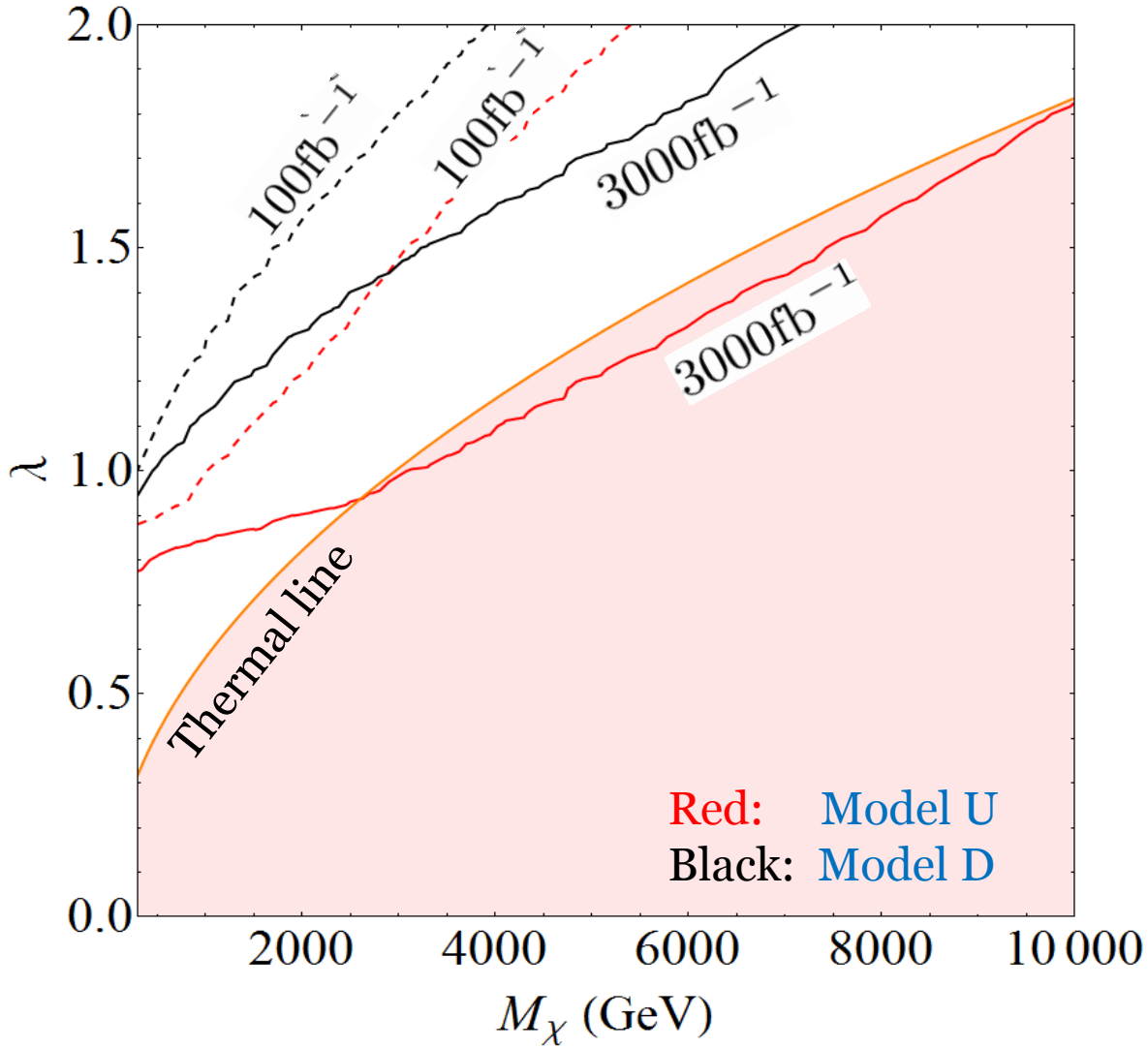




100 TeV p-p collider: 95% C.L. sensitivity

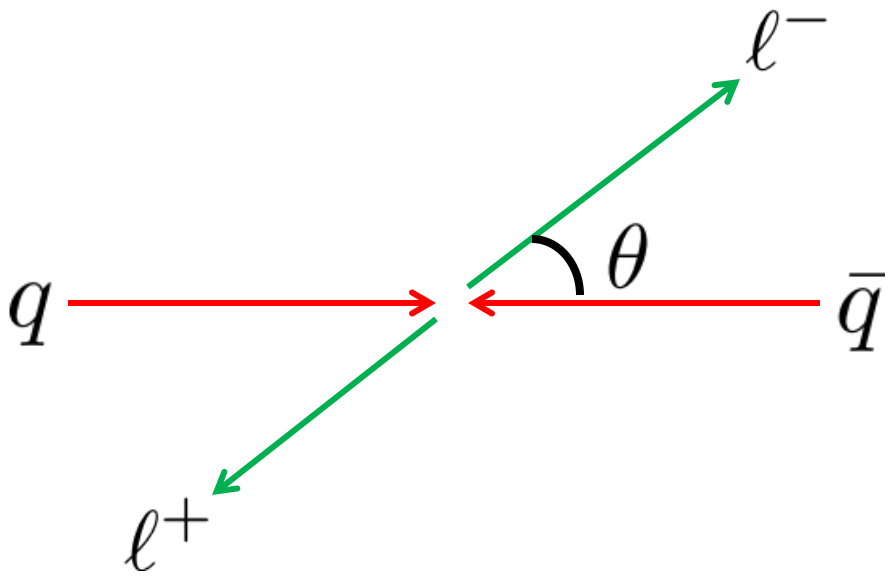
$$\Delta\chi^2 = \chi^2_{\rm NP} - \chi^2_{\rm SM}$$





Angular distributions

$$\frac{d^2\sigma}{dm_{\ell\ell}dc_\theta} = \sum_{n=0}^{\infty} a_n c_\theta^n$$



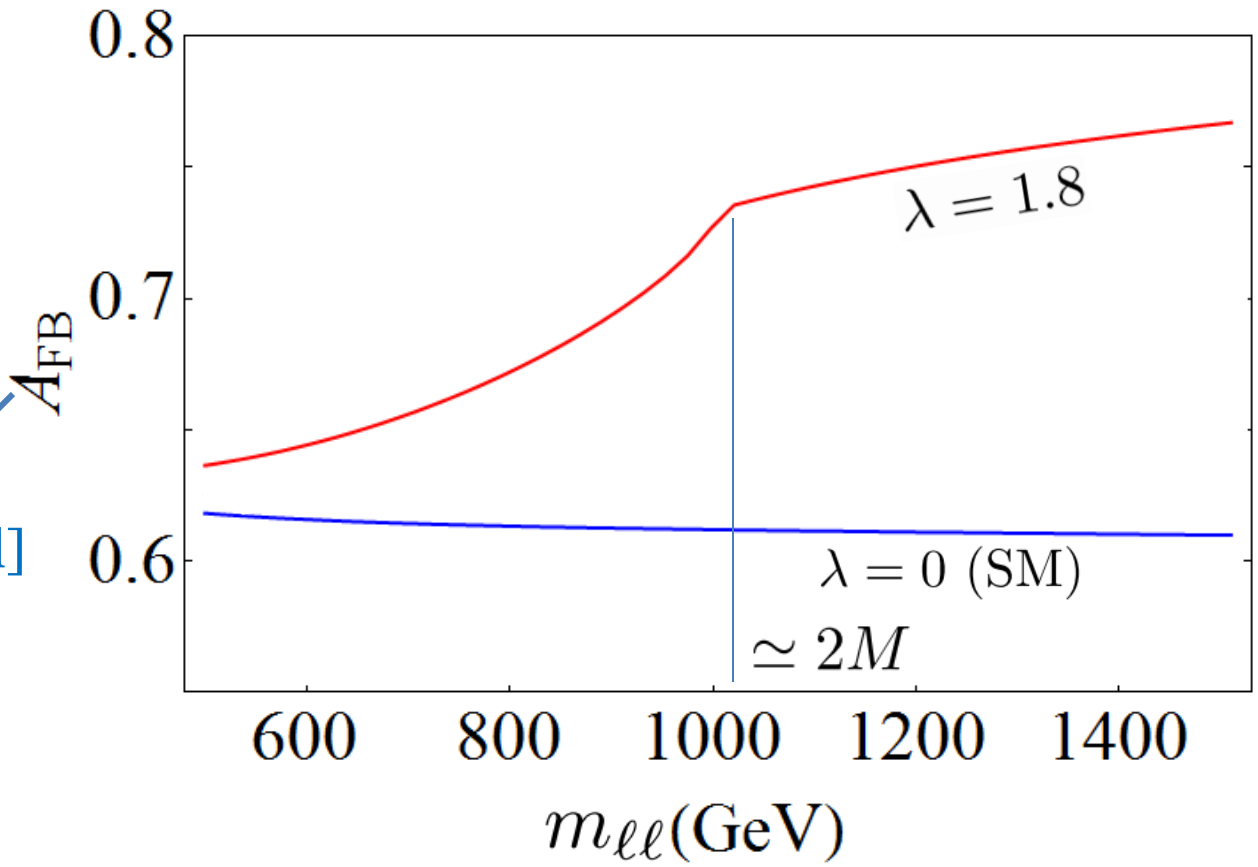
To probe, measure spatial asymmetries in events

Forward versus backward

$$A_{\rm FB} \equiv \frac{\int_0^1 dc_\theta (d^2\sigma/dm_{\ell\ell}dc_\theta) - \int_{-1}^0 dc_\theta (d^2\sigma/dm_{\ell\ell}dc_\theta)}{\int_{-1}^1 dc_\theta (d^2\sigma/dm_{\ell\ell}dc_\theta)}$$

$$= \frac{N_F - N_B}{N_{\rm tot}}$$

[Partonic level]

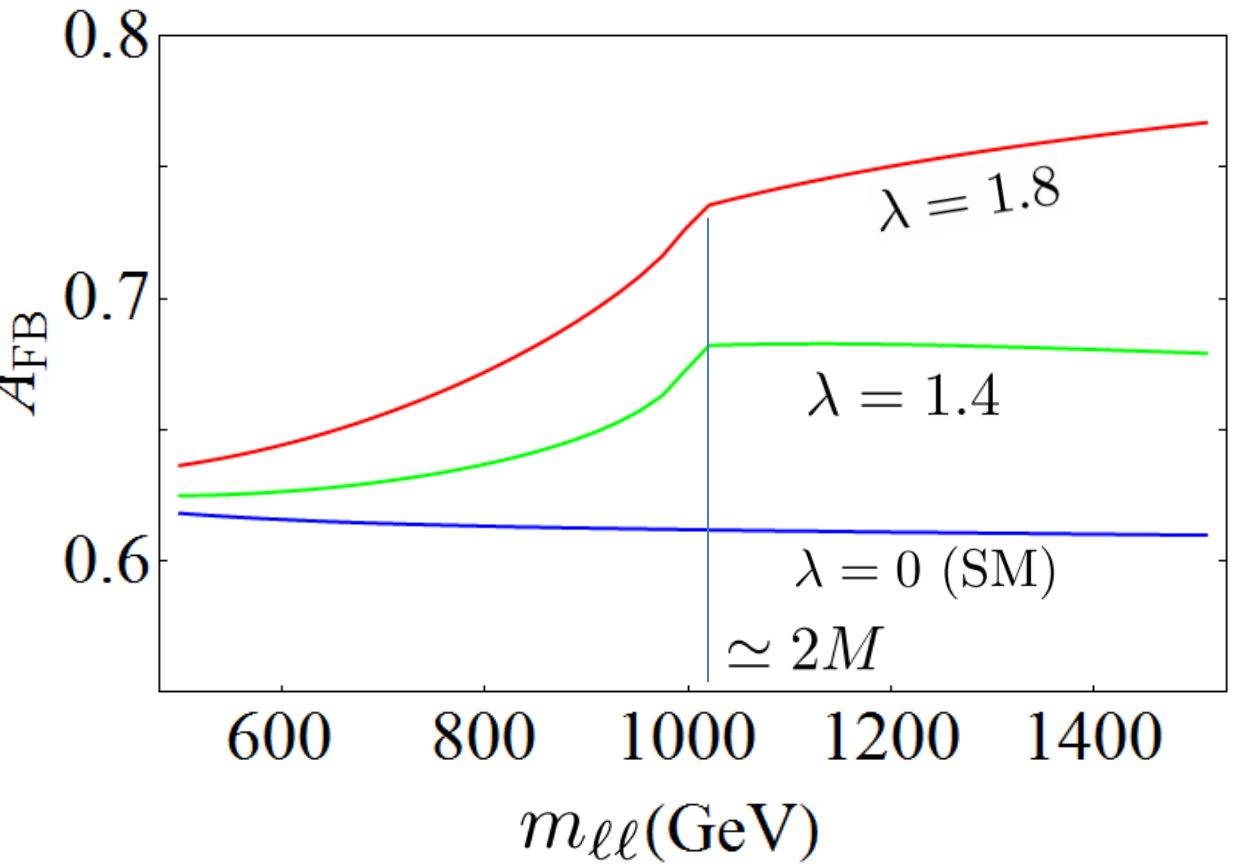


Forward versus backward

$$A_{\rm FB} \equiv \frac{\int_0^1 dc_\theta (d^2\sigma/dm_{\ell\ell}dc_\theta) - \int_{-1}^0 dc_\theta (d^2\sigma/dm_{\ell\ell}dc_\theta)}{\int_{-1}^1 dc_\theta (d^2\sigma/dm_{\ell\ell}dc_\theta)}$$

$$= \frac{N_F - N_B}{N_{\rm tot}}$$

[Partonic level]

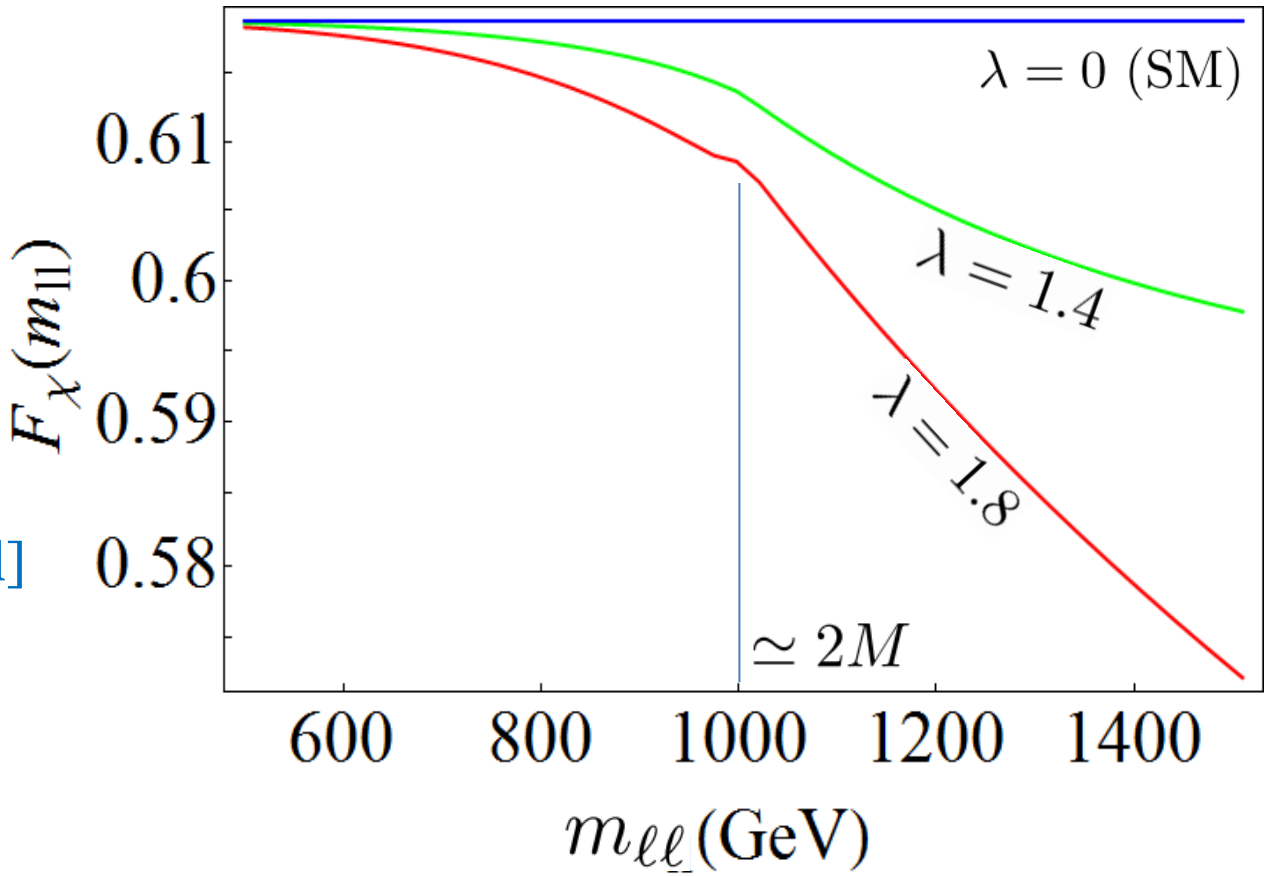


Central versus outer

$$F_\chi(m_{\ell\ell}) \equiv \frac{\int_{-a}^{a}(d\sigma/dc_\theta)dc_\theta}{\int_{-1}^{1}(d\sigma/dc_\theta)dc_\theta}$$

$$= \frac{N_{\rm central}}{N_{\rm total}}$$

[Partonic level]



Conclusions

Dilepton production: new probe to test interactions between dark and visible sectors.

Radiative corrections from dark sector modify dilepton spectrum.

Box diagrams dominate for large DM-SM coupling strengths
=> **monocline** features.

Information on dark matter mass directly obtained from monocline peak!

Affects both distributions: invariant mass and angular.

Sensitivity better in future collider runs.

Future directions

Experiment

* Encourage ATLAS and CMS to explore
sensitivity of features in dilepton spectra.

* If discovered, knowledge of mass scale *very* helpful for direct detection!

Theory

* Non-minimality

  - Couplings to more/all flavors
  - More chiralities
  - CP-violating phases
  - Scalar DM + fermion mediator, other combinations

* UV completion at Landau pole

Thank you!