Probing Dark Matter Properties Using Dilepton Distributions at the LHC (Arxiv:1706.XXXX)

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Conclusions

- Besides jet+MET: Search for DM from interference effects e.g. Dilepton kinematical distributions (models with t-channel mediators).

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  - Dilepton invariant mass: DM mass (fermionic), DM spin (almost degenerate DM-mediators).
  - Dilepton angular distribution: SM chiralities (mediators' quantum numbers).

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Conclusions

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  - Dilepton invariant mass: DM mass (fermionic), DM spin (almost degenerate DM-mediators).
  - Dilepton angular distribution: SM chiralities (mediators' quantum numbers).

- Dilepton distributions provide competitive bounds with those from jets+MET and Direct Detection searches.

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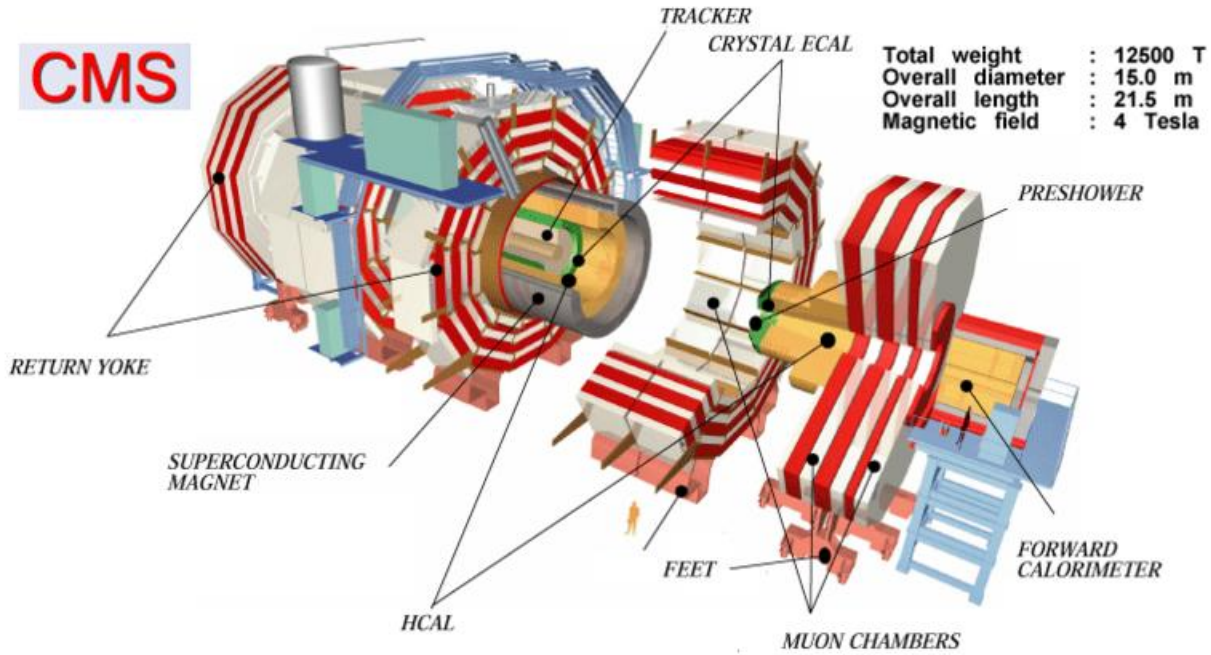
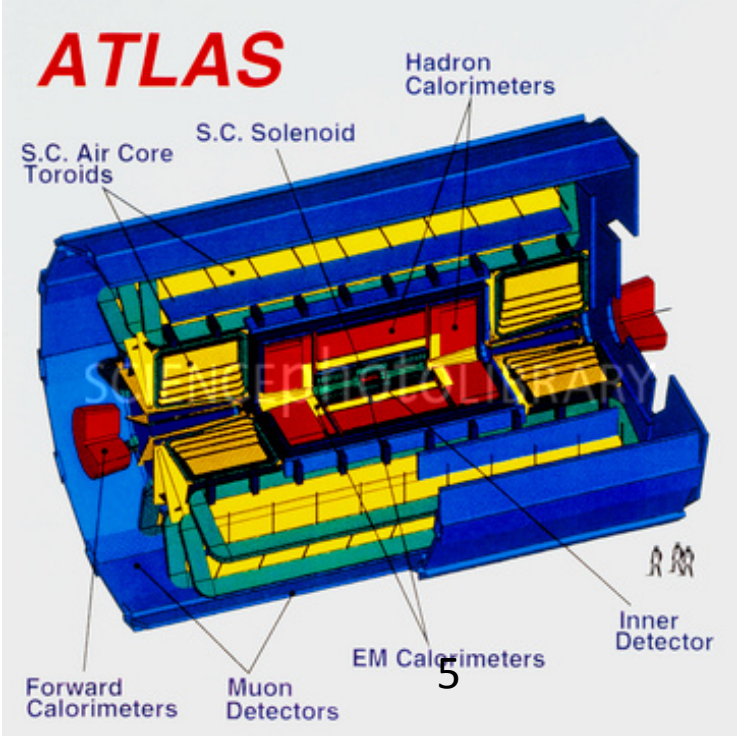
The LHC:





- Energy Frontier:

  (E_{CM} = 13 TeV)
- Sensitivity Frontier:

  ($\sigma \approx 10^{-4}$ pb)

What can the LHC tell us about Dark Matter?

1. Can we discover DM?

2. Can we learn something about DM properties?

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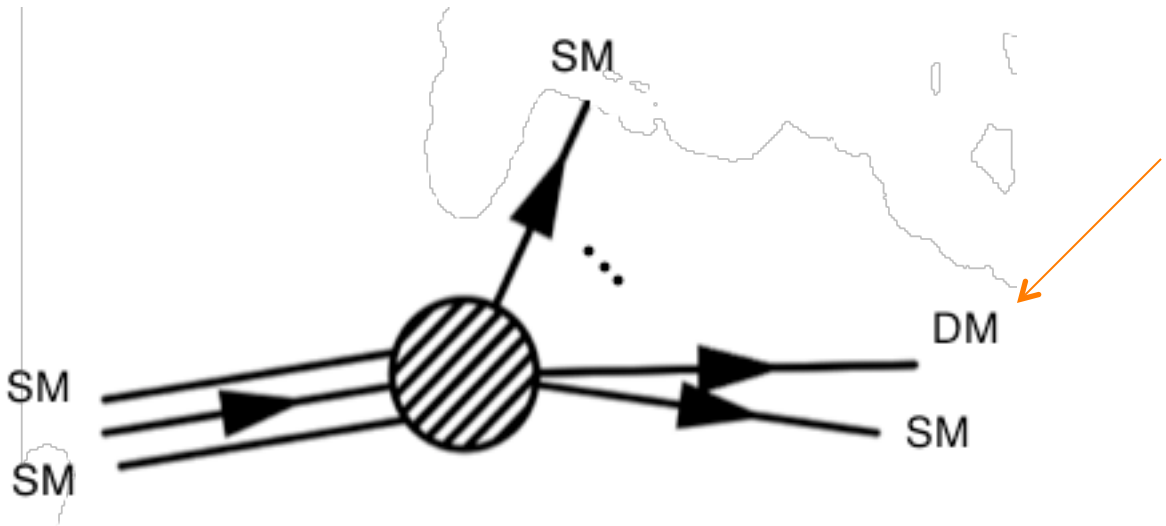
Jets + MET Searches



If DM is produced, we have Missing Transverse Energy (MET)

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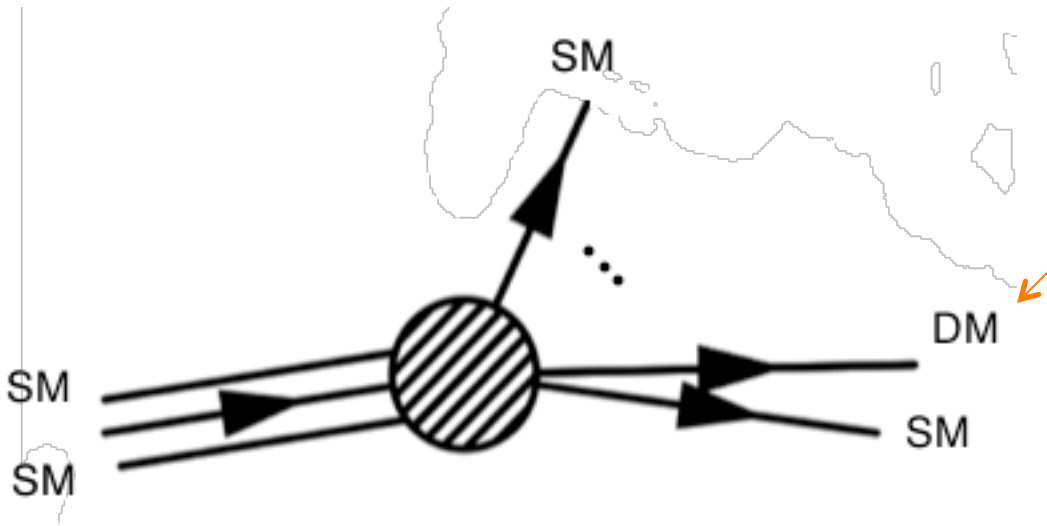
Jets + MET Searches



If DM is produced, we have Missing Transverse Energy (MET)

Search for physics beyond the standard model in events with two leptons of same sign, missing transverse momentum, and jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration

24 April 2017

Submitted to Eur. Phys. J. C

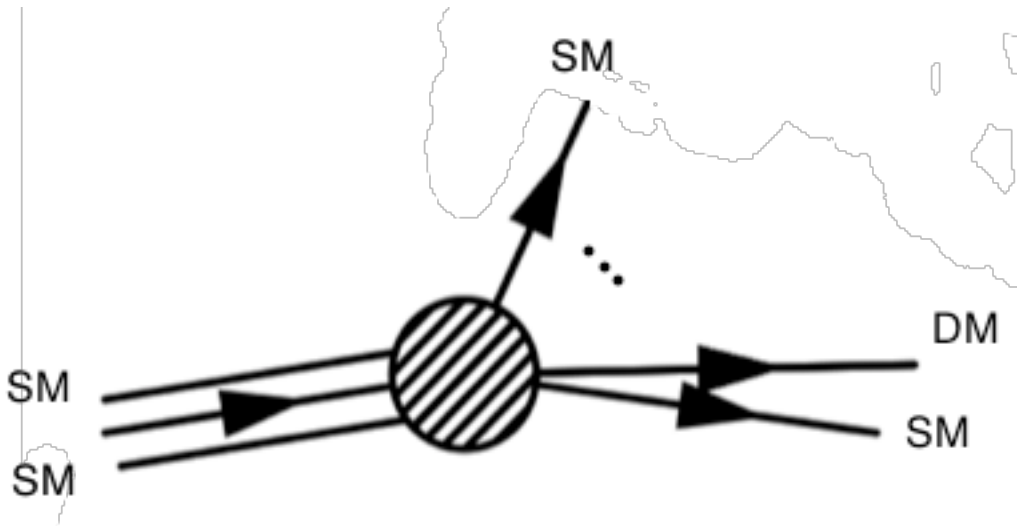
Search for supersymmetry in multijet events with missing transverse momentum in proton-proton collisions at 13 TeV

CMS Collaboration

25 April 2017

Submitted to Phys. Rev. D

Jets + MET Searches



But, what happens when DM is produced with low energy (low MET)?

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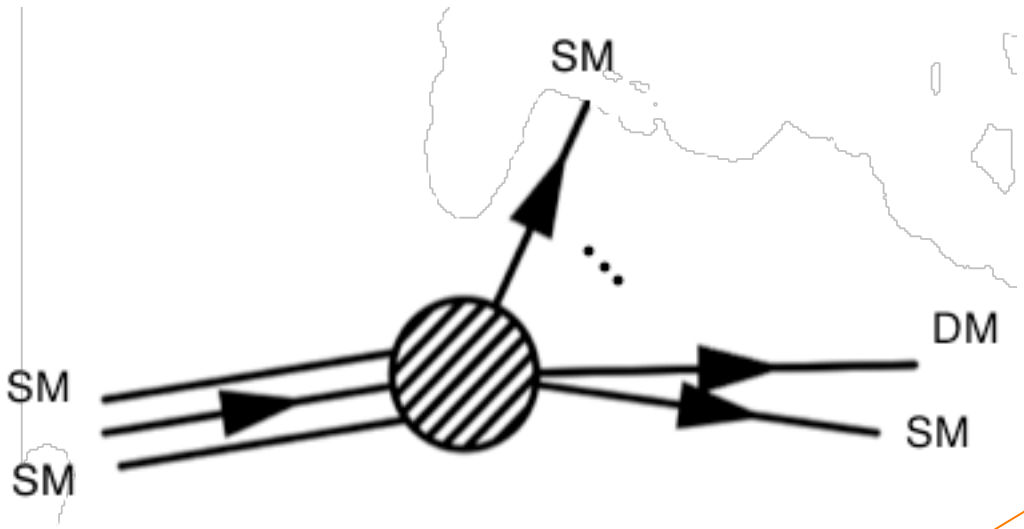
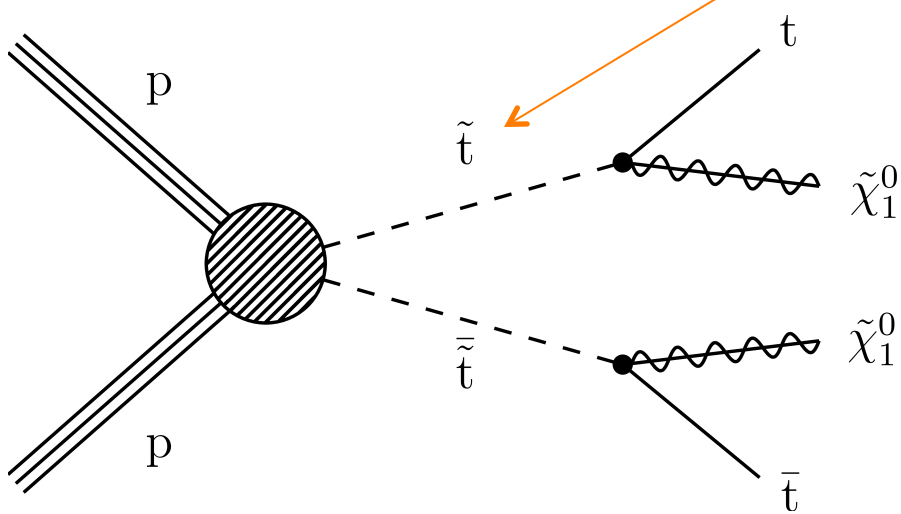
Jets + MET Searches



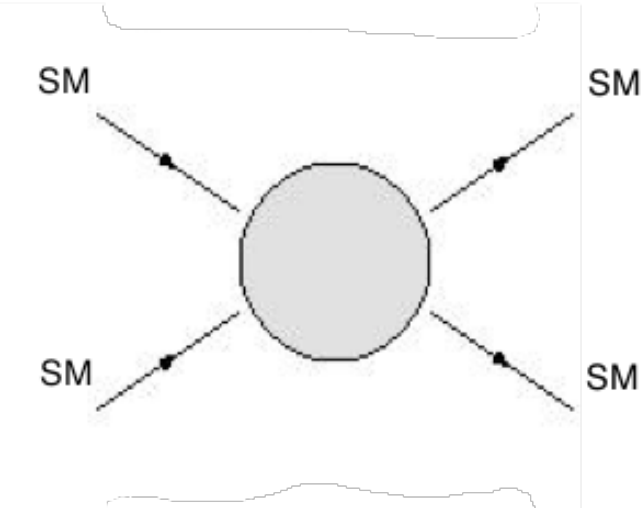


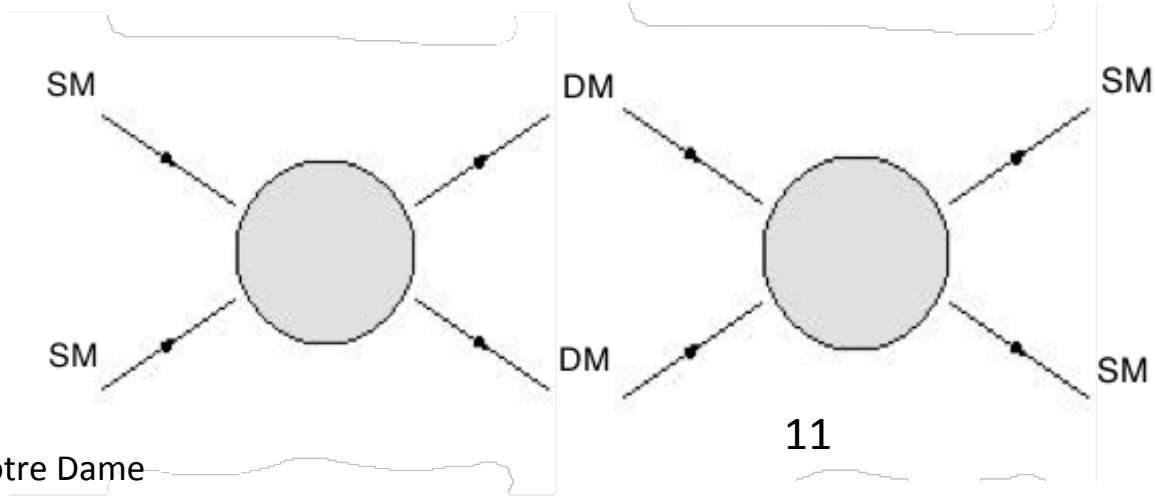
e.g.

Intermediate state nearly degenerate with DM

Can we perform other types of searches?

How about interference effects?





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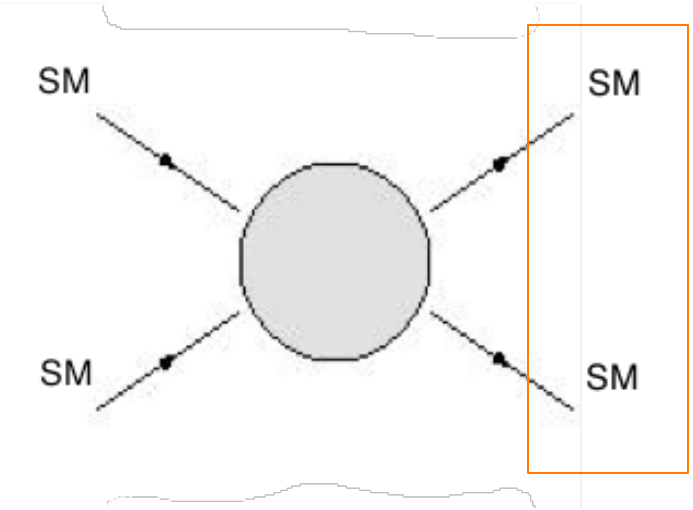
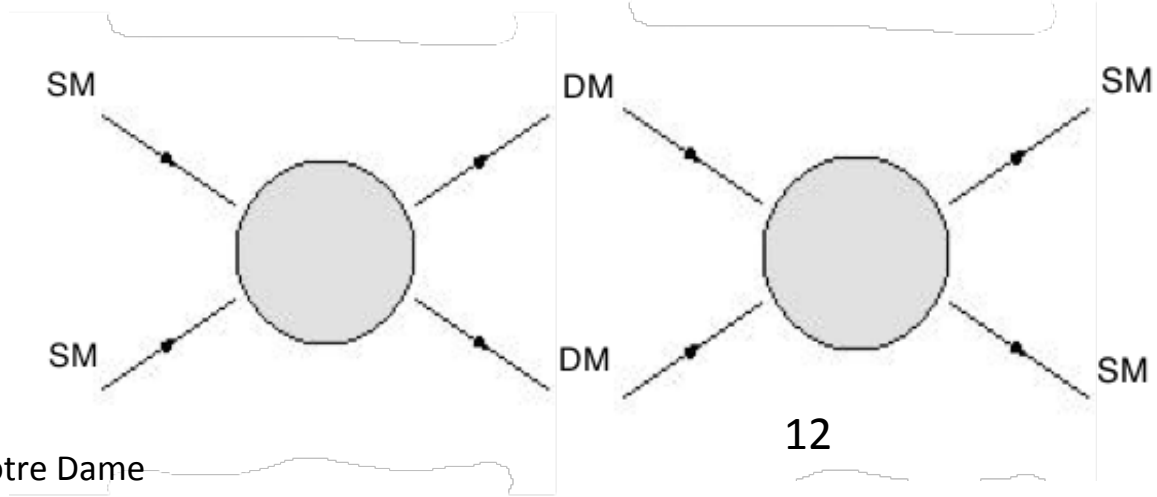


Very well understood final states!



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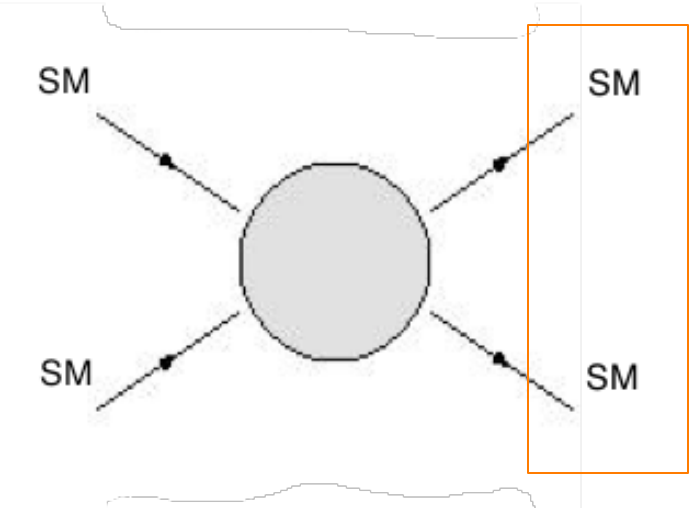
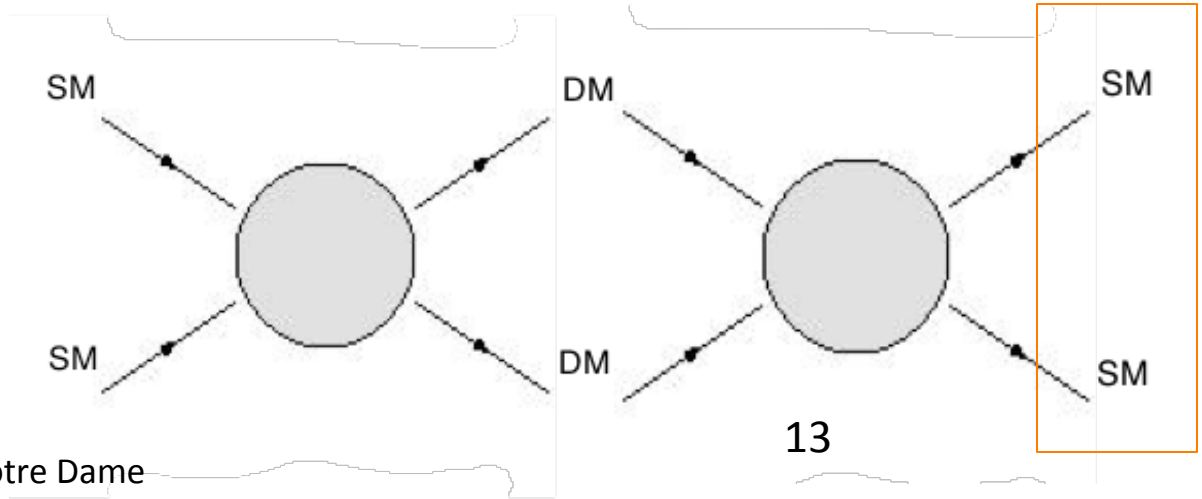
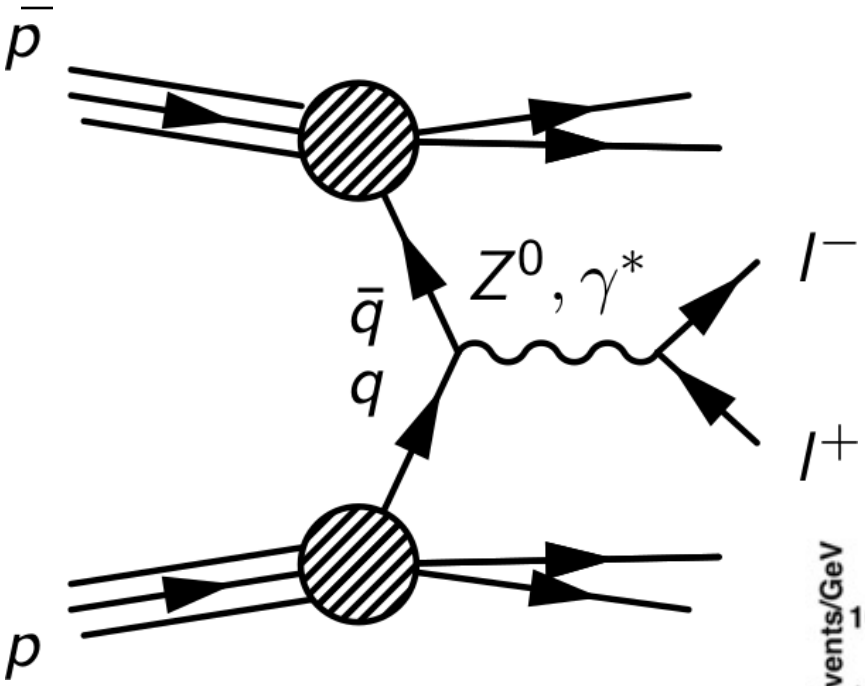


Same final states!

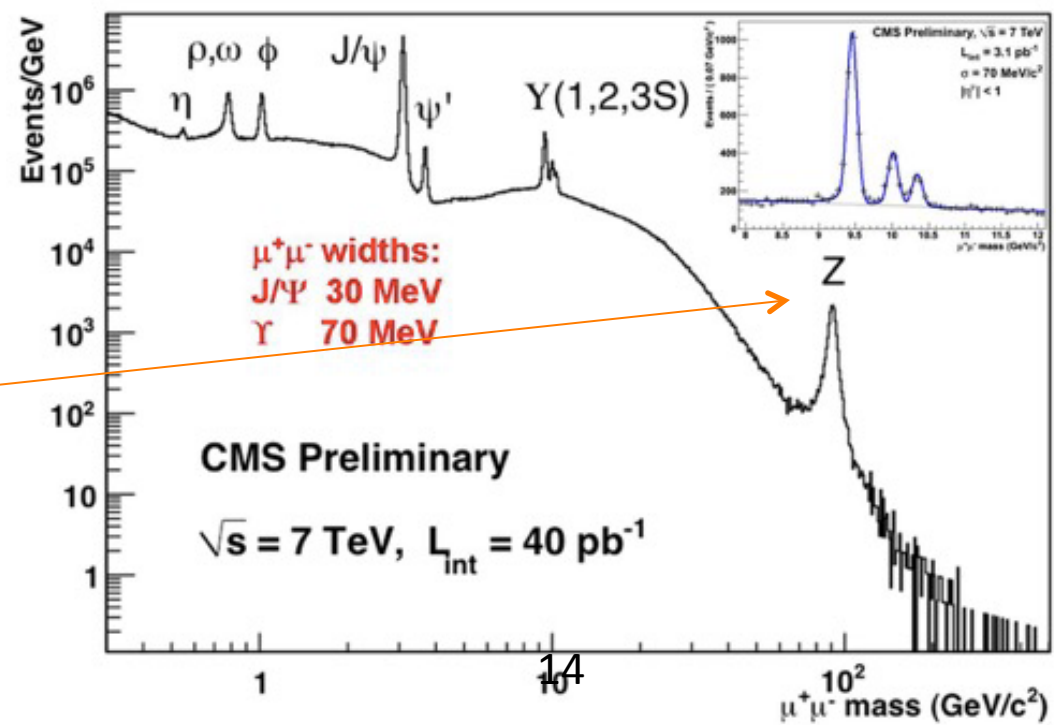


Dilepton Production



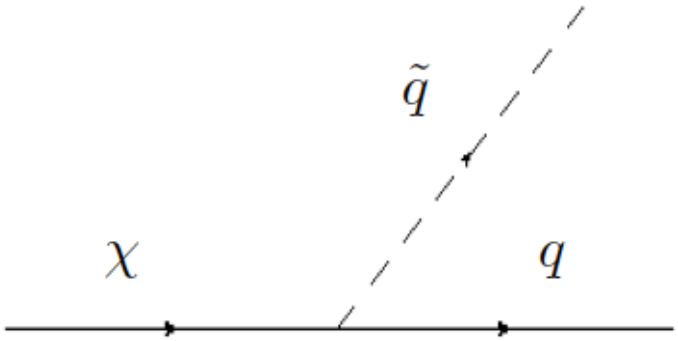
High rates, low uncertainties

(Historically important discovery mode!)

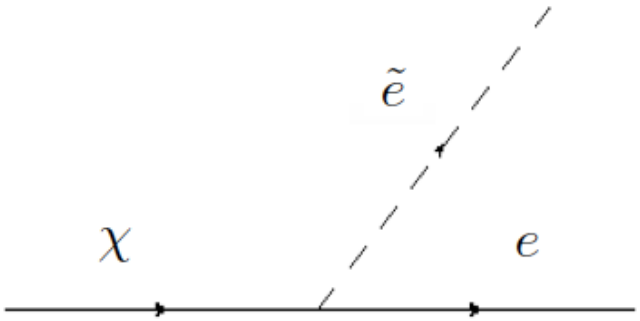


How can DM produce dilepton signals?

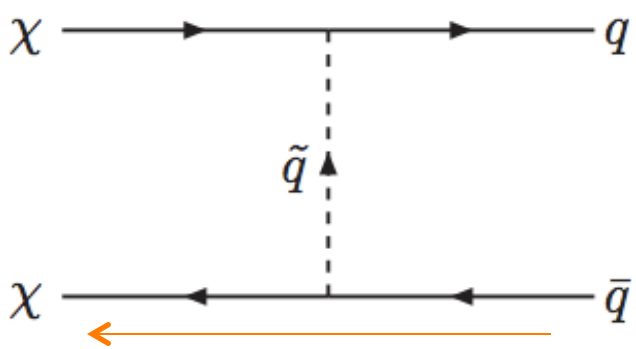
- DM with t-channel mediators:



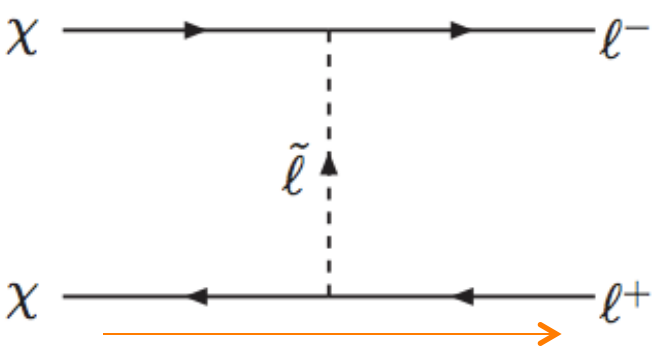
Quark portal – colored mediator



Lepton portal – uncolored mediator



DM production in pp collider



Dilepton production

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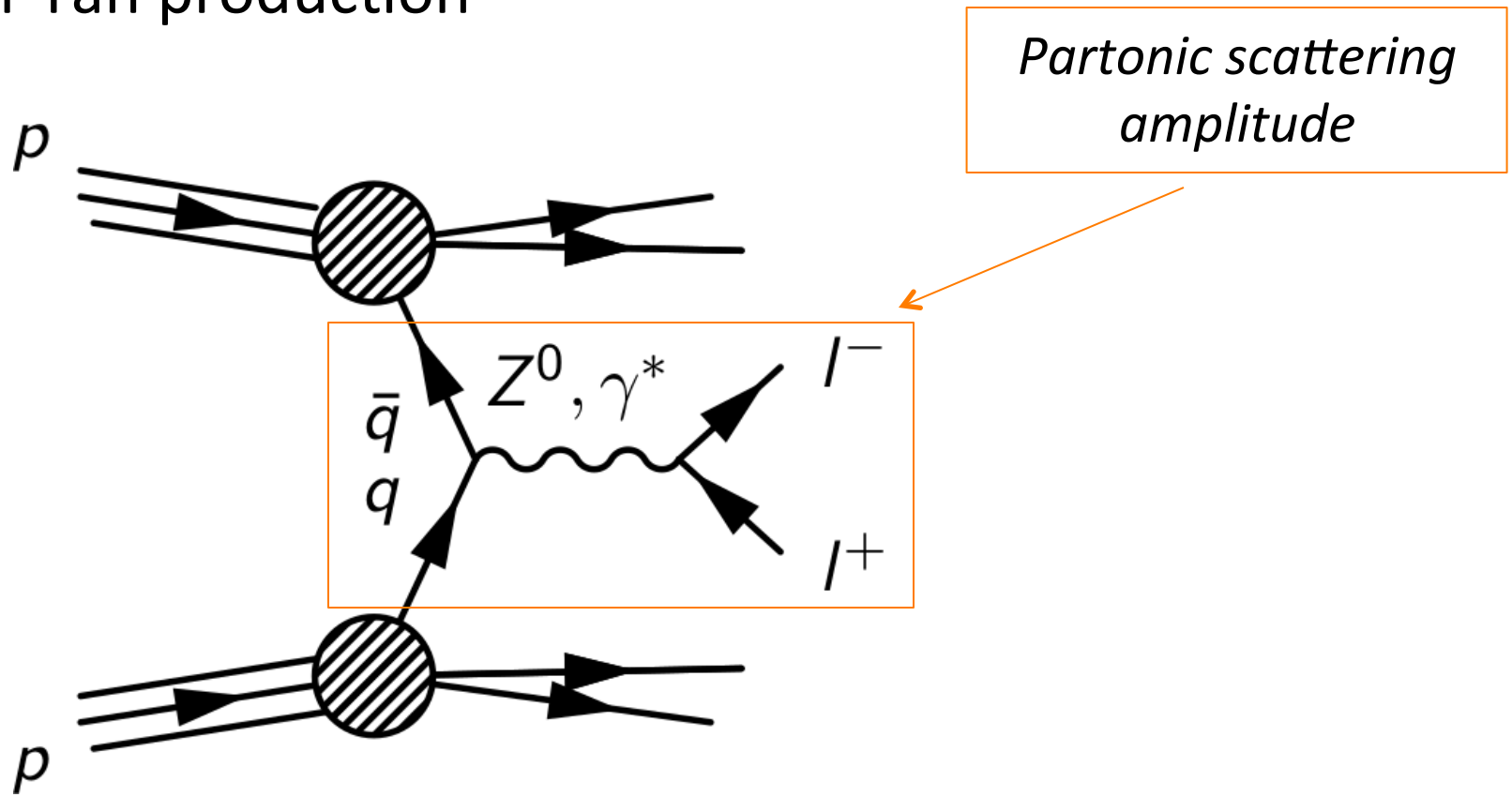
Dilepton Distributions at the LHC
(what do we measure?)

- Drell-Yan production



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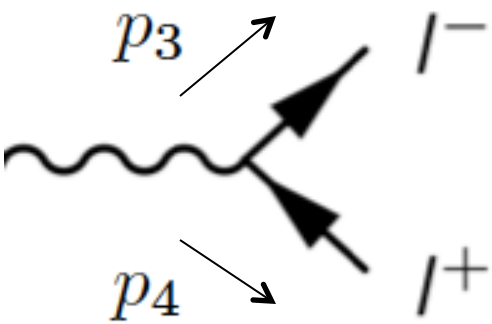
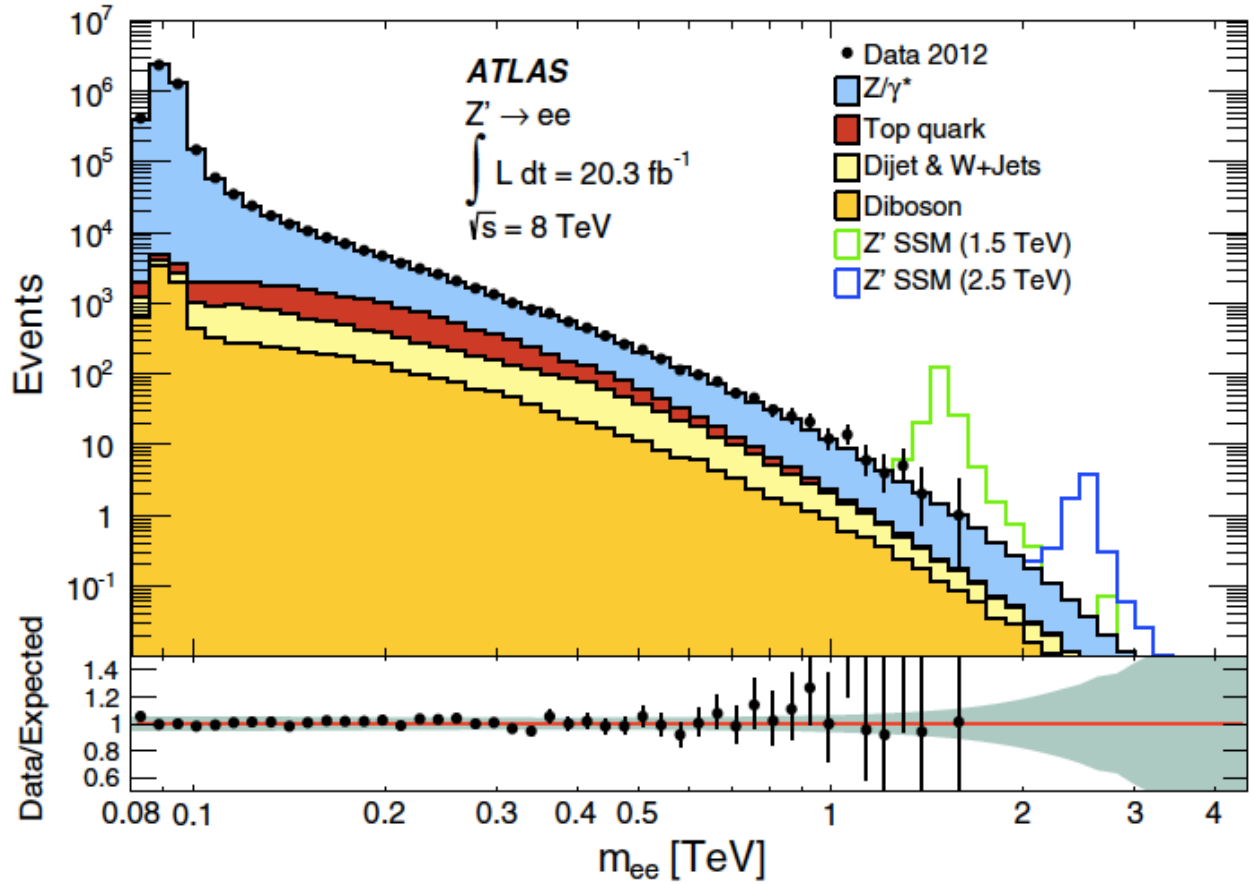
1) Dilepton Invariant Mass



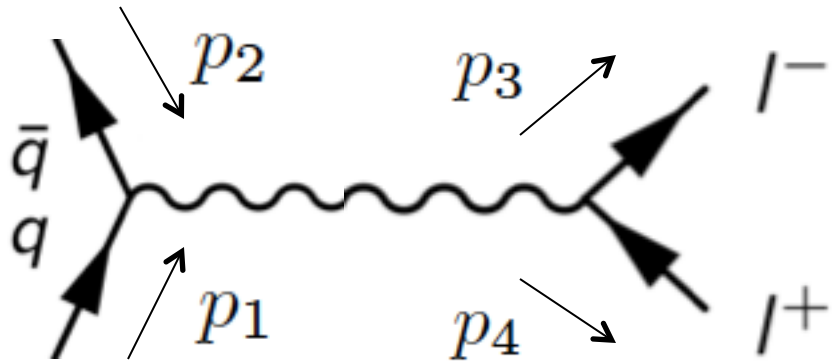
$$\hat{s} = (p_3 + p_4)^2$$

$$m_{ll} = \sqrt{\hat{s}}$$

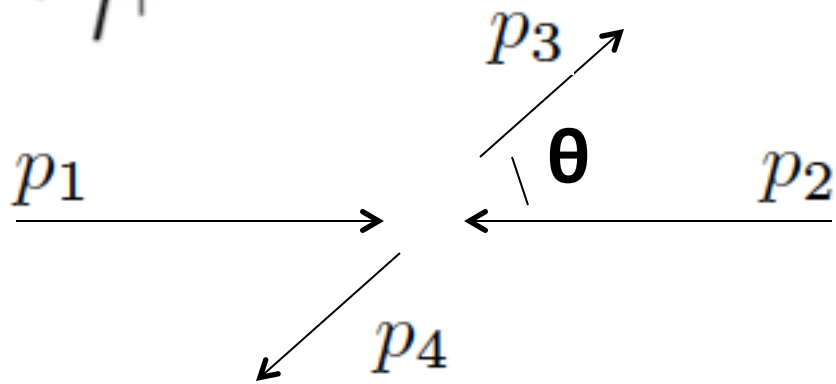
Dilepton invariant mass = C.M. energy



2) Dilepton Angular Distribution



Outgoing lepton



Incoming quark

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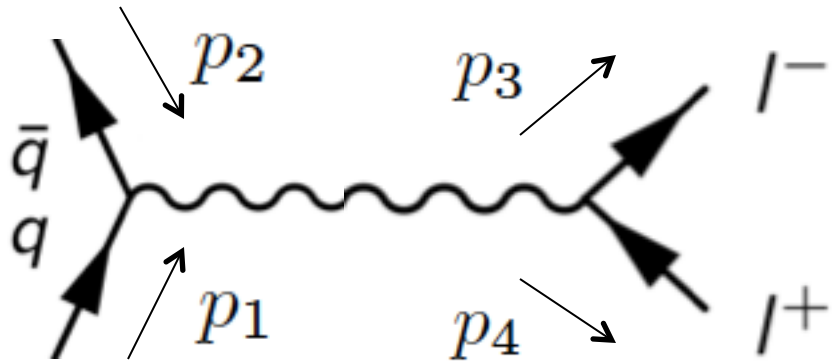
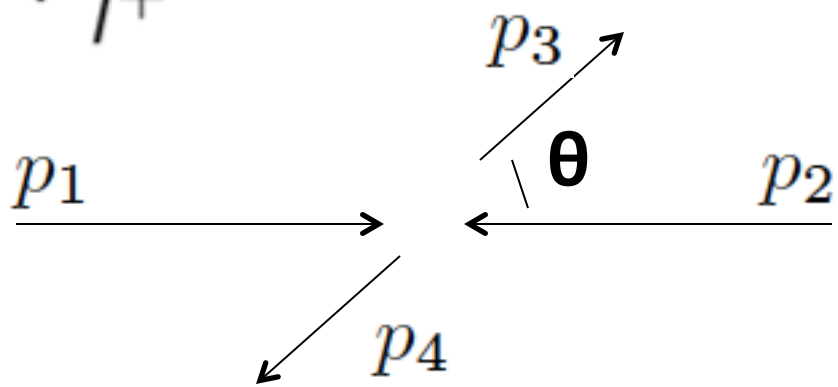
Dilepton Angular Distribution

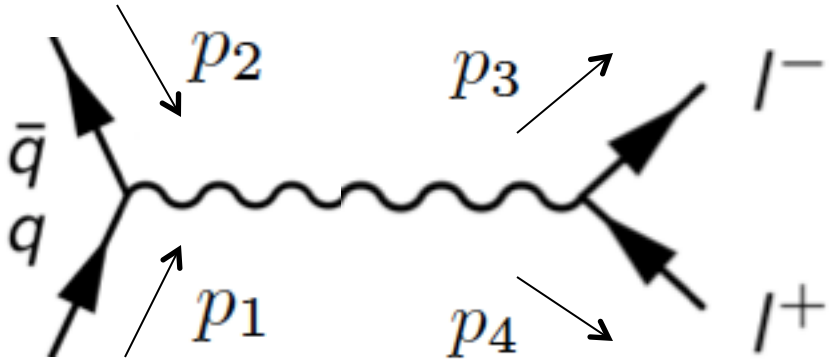


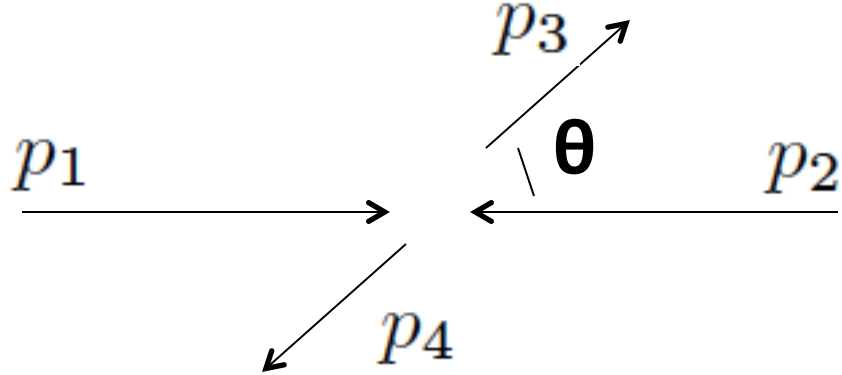


But, in pp collisions

we do not know the direction of the incoming quark!

Dilepton Angular Distribution





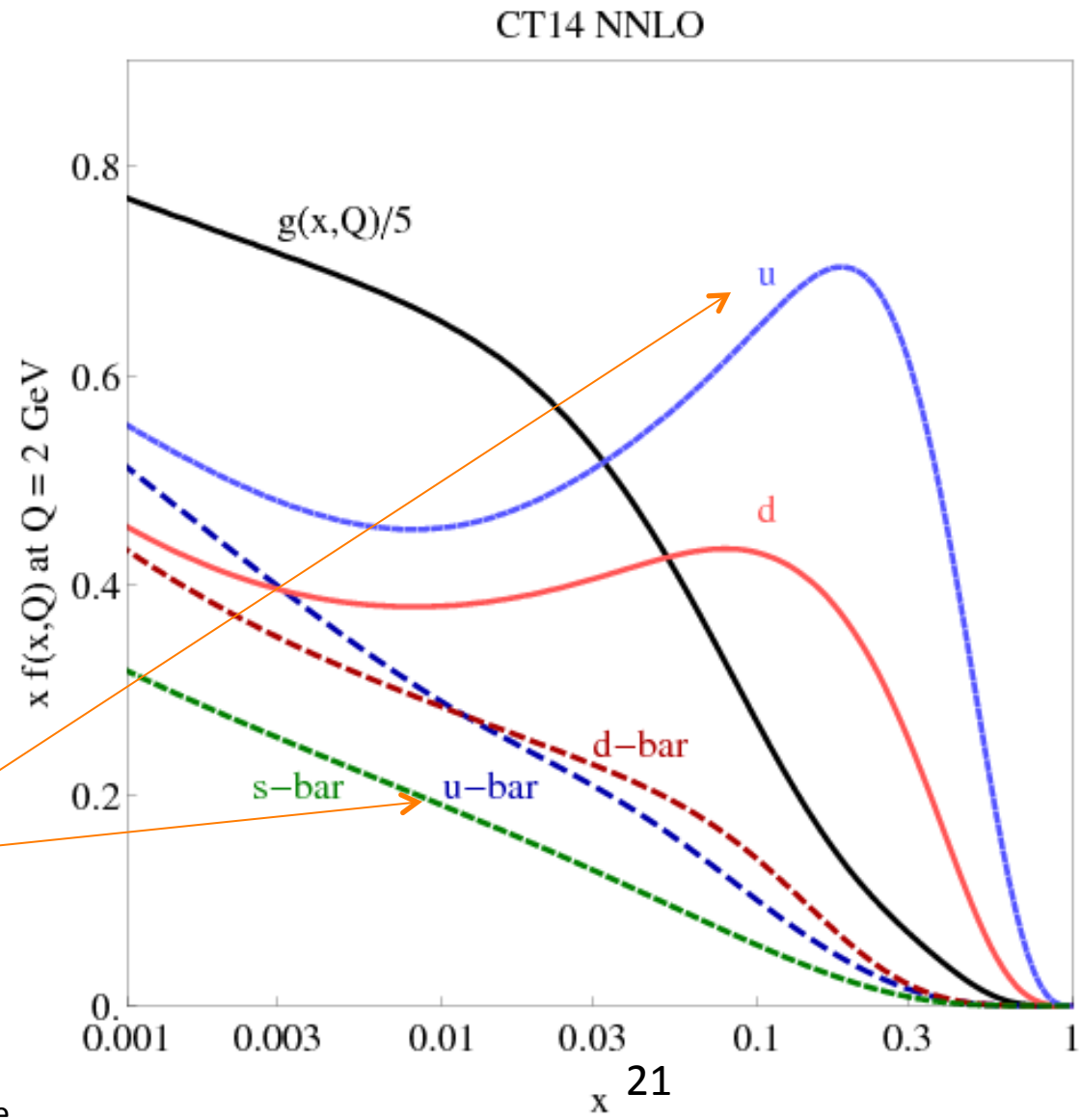
proton level

parton distribution functions (PDF)

parton level

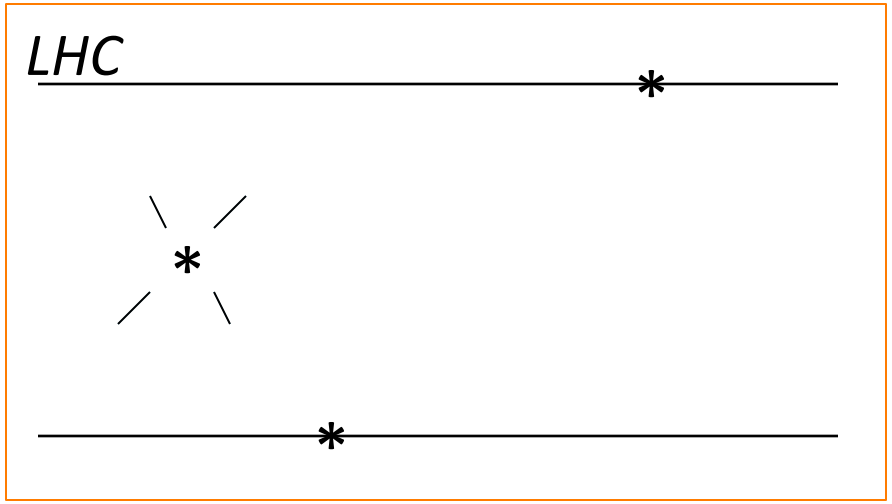
$$\frac{d\sigma}{dC\theta} = \int dx_1 dx_2 \left[f_q(x_1) f_{\bar{q}}(x_2) + f_q(x_2) f_{\bar{q}}(x_1) \right] \frac{d\hat{\sigma}}{dC\theta}$$

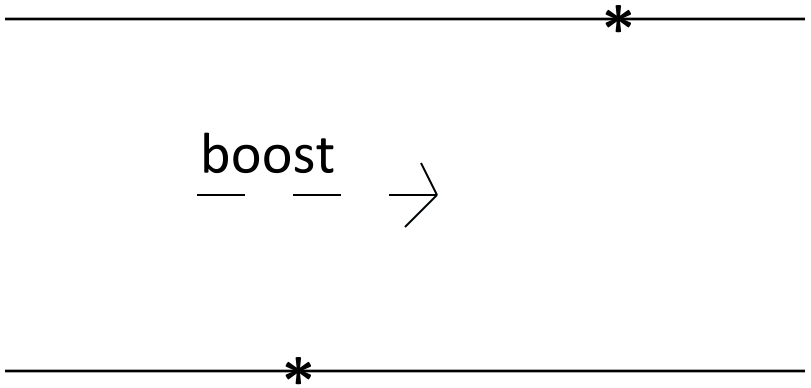
Parton Distribution Functions

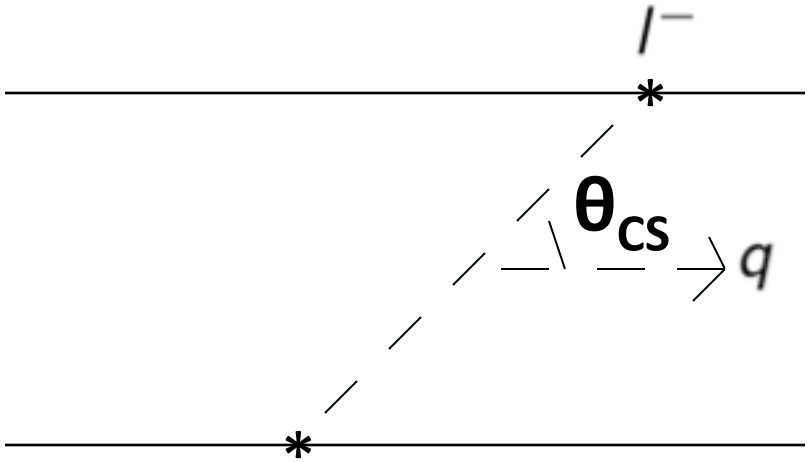


IMPORTANT! the PDF are higher for q than for q-bar

Collin-Soper Frame







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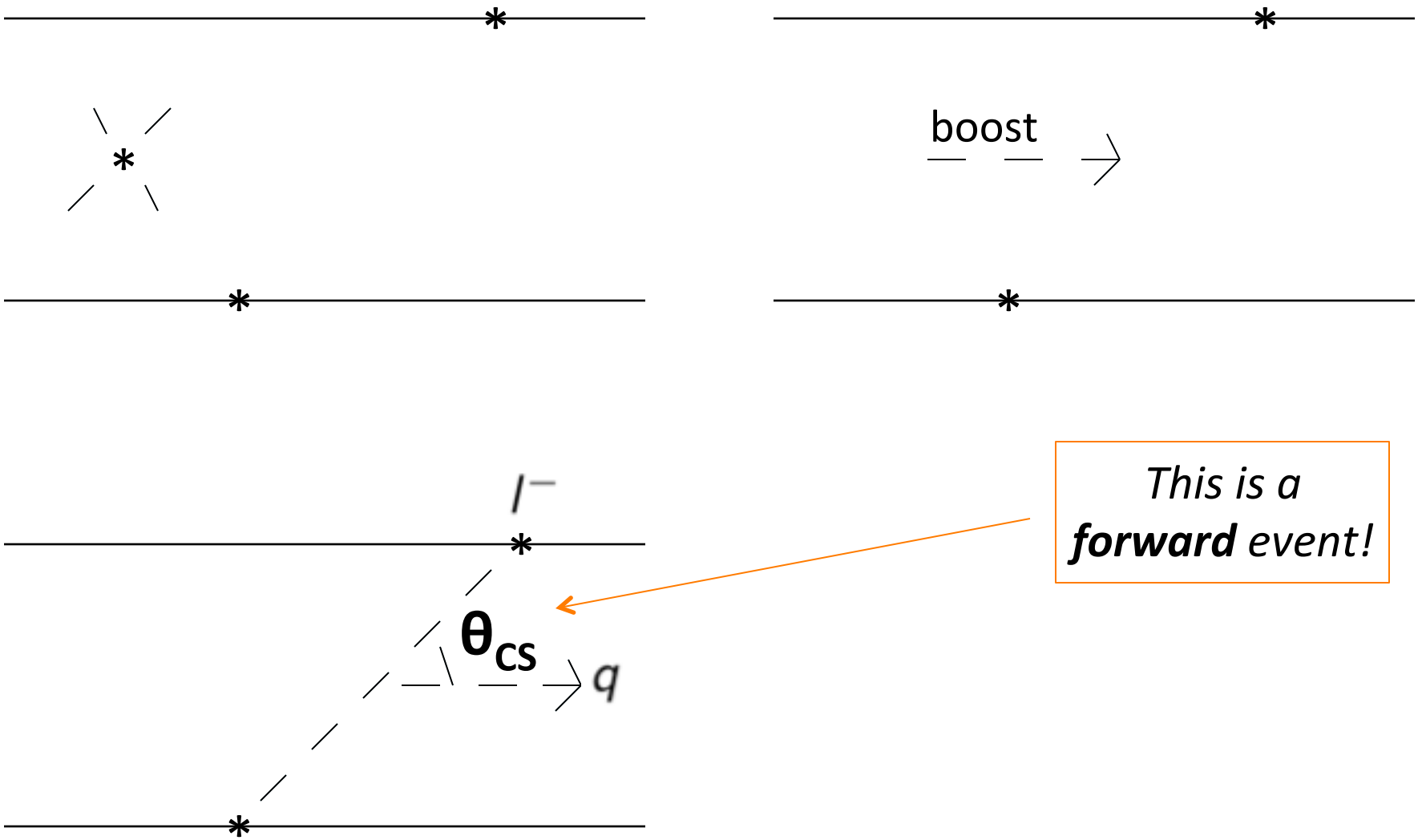

*This is a **forward** event!*

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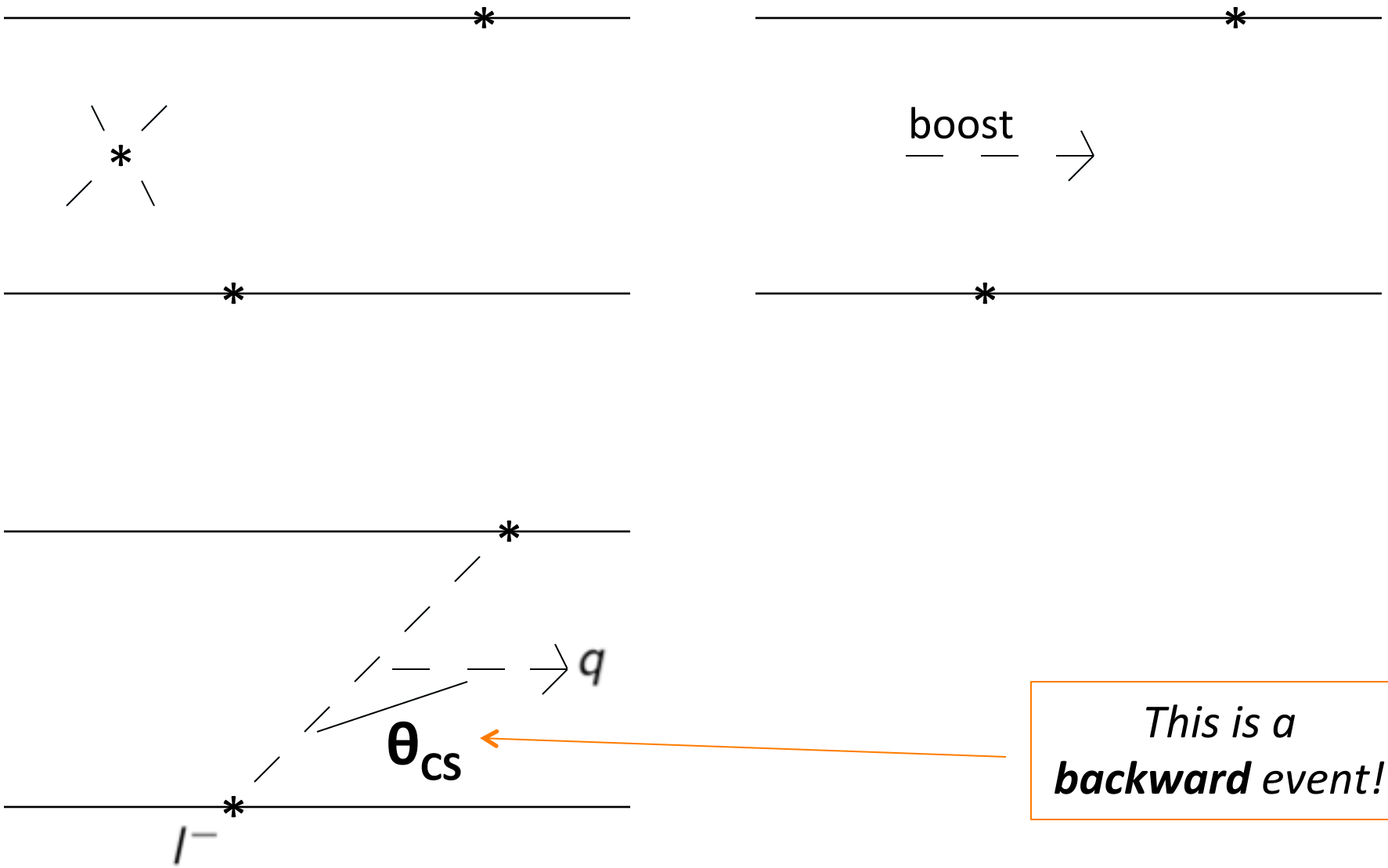
Collin-Soper Frame



This is a ***backward*** *event!*

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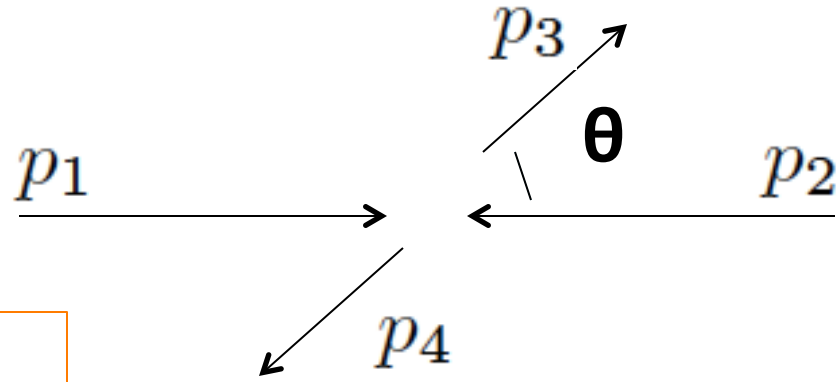
How can we calculate θ_{CS}?

$$\frac{d\sigma}{dC\theta} = \int dx_1 dx_2 \left[f_q(x_1) f_{\bar{q}}(x_2) + f_q(x_2) f_{\bar{q}}(x_1) \right] \frac{d\hat{\sigma}}{dC\theta}$$



Split integration:

$(X_1 > X_2)$ and $(X_1 < X_2)$

Here quark carries X_1

Here quark carries X_2

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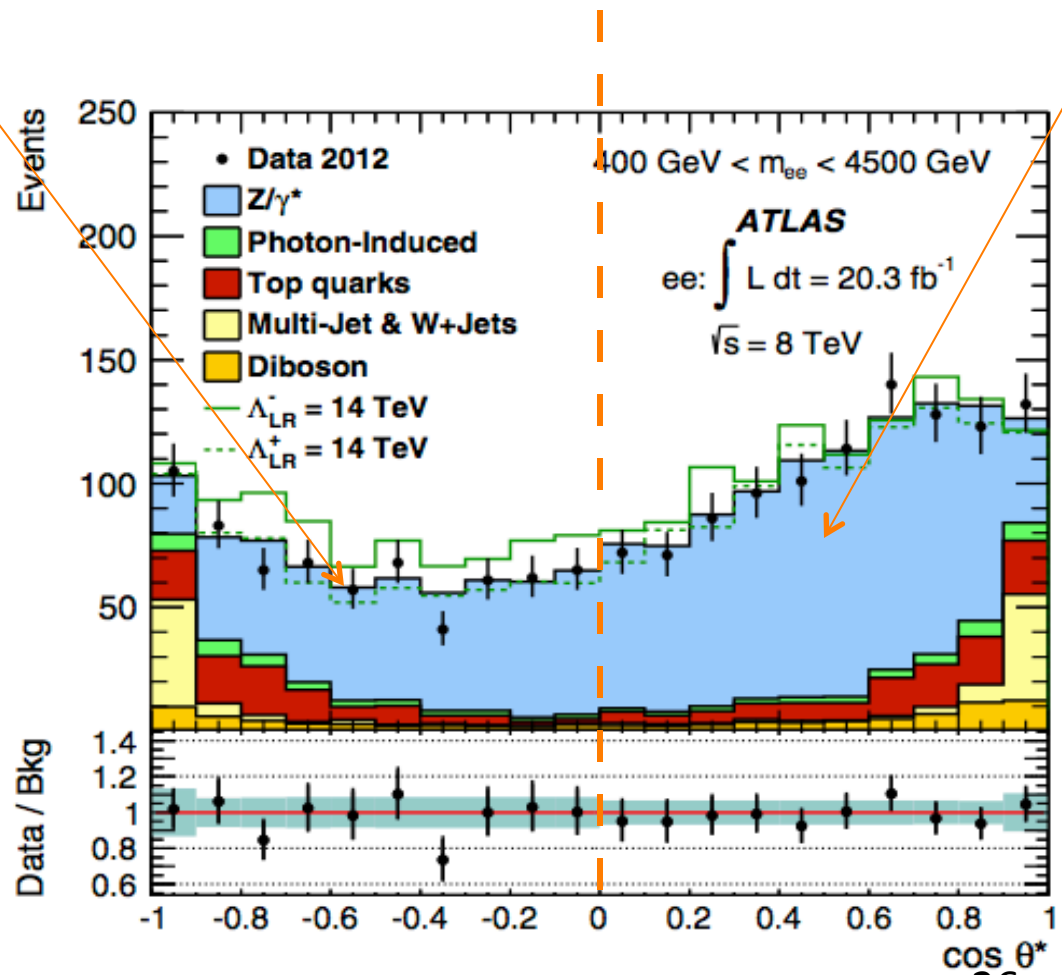
Lepton Angular Distribution

Backward events

Forward events



Models to Study:

Model	DM Spin	Lepton Chirality	Interactions
pD_{RR}	$1/2$	right-handed	$\tilde{u}\,(\bar{u}P_L\chi) + \tilde{e}\,(\bar{e}P_L\chi)$
pD_{RL}	$1/2$	left-handed	$\tilde{u}\,(\bar{u}P_L\chi) + \tilde{e}\,(\bar{e}P_R\chi)$
pCS_{RR}	0	right-handed	$\chi\,(\bar{u}P_L\tilde{u}) + \chi\,(\bar{e}P_L\tilde{e})$
pCS_{RL}	0	left-handed	$\chi\,(\bar{u}P_L\tilde{u}) + \chi\,(\bar{e}P_L\tilde{e})$

- Two DM particles χ and χ^c
- If same masses $\longrightarrow$ Dirac, if mixing $\longrightarrow$ Majorana

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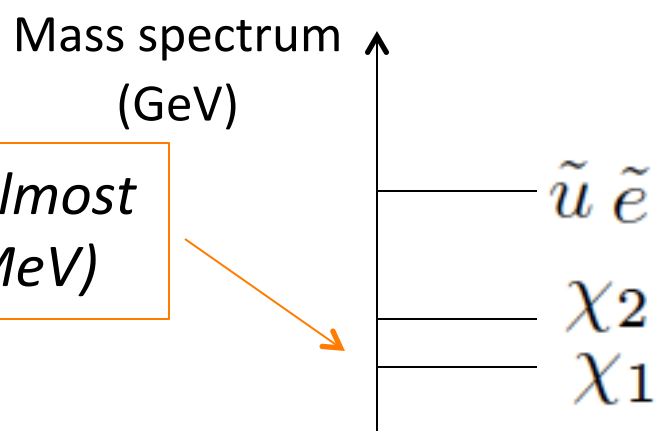
DM eigenstates almost degenerate (1 MeV)



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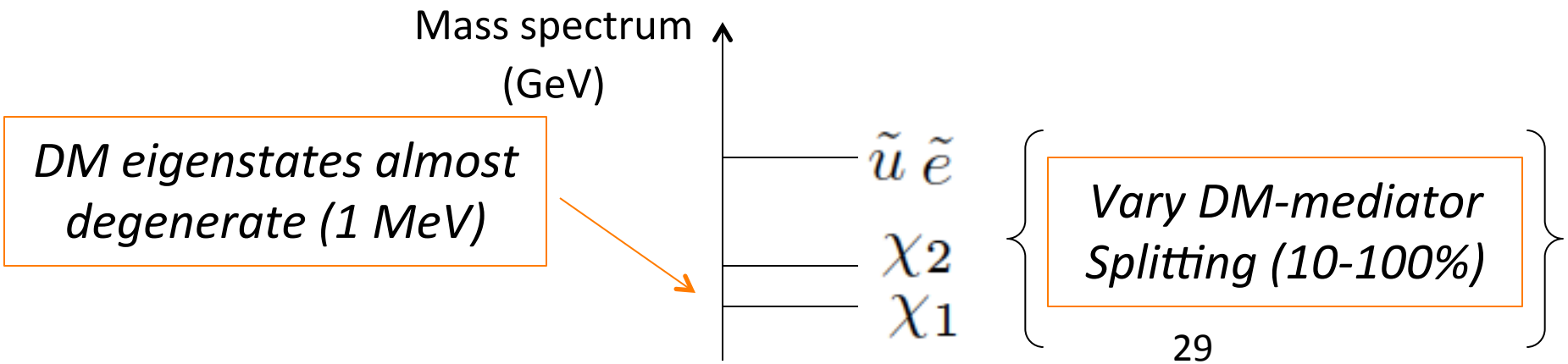

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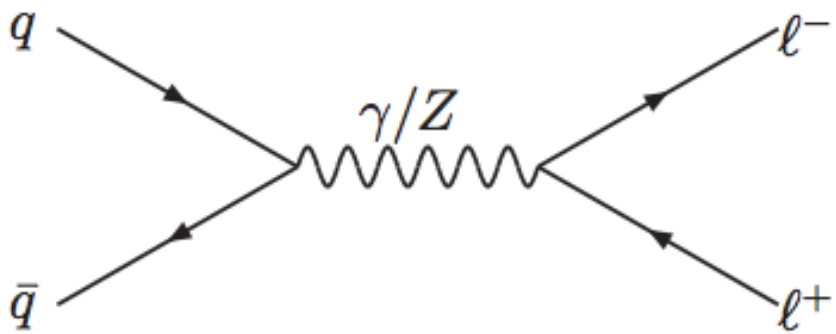
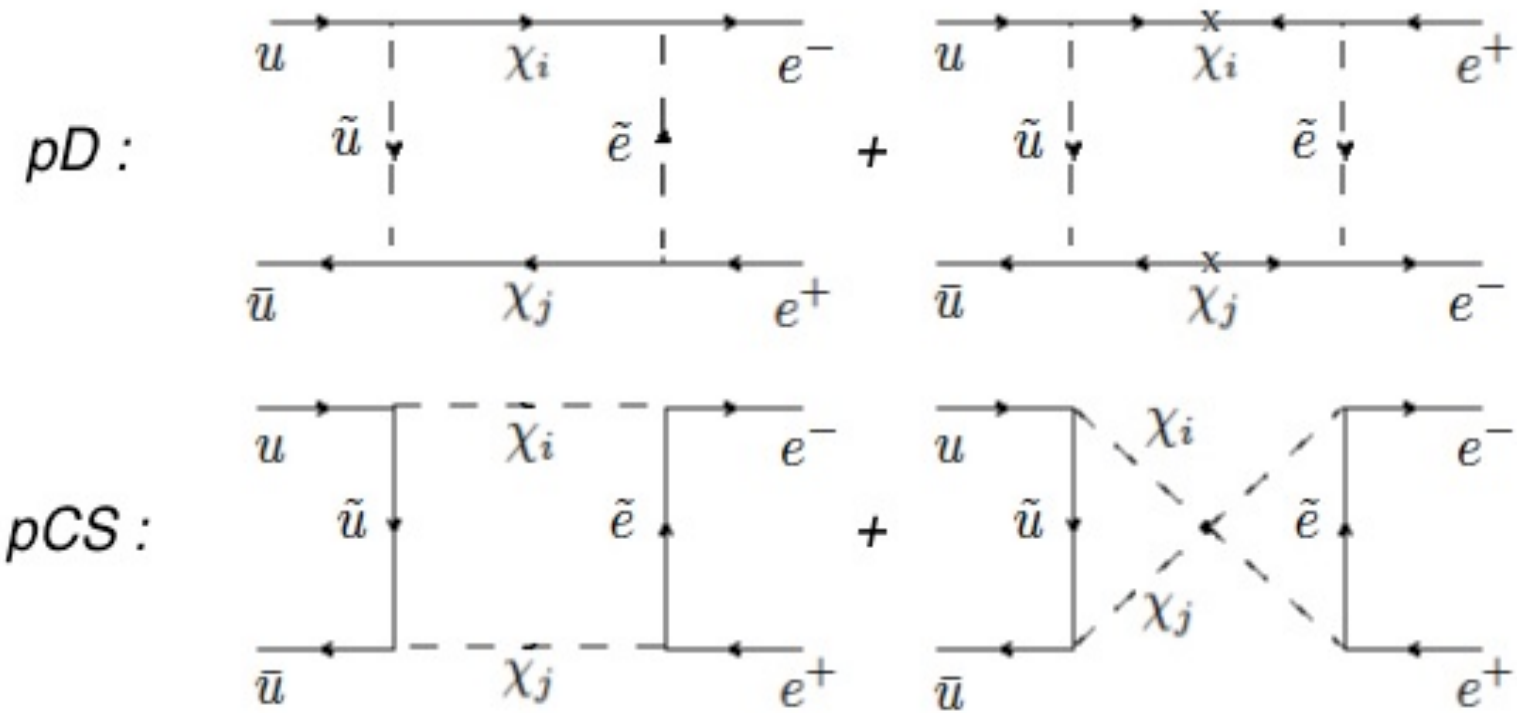
Discussion:

- For a given DM spin, what happens if we change the lepton's chirality?

- For a given lepton's chirality, what happens if we change DM spin?

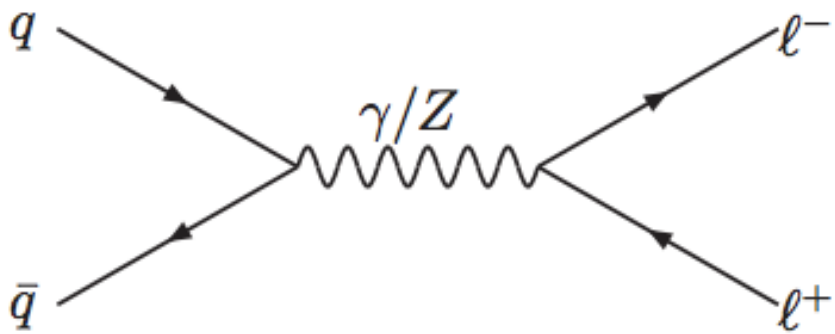
Contributions to dilepton production



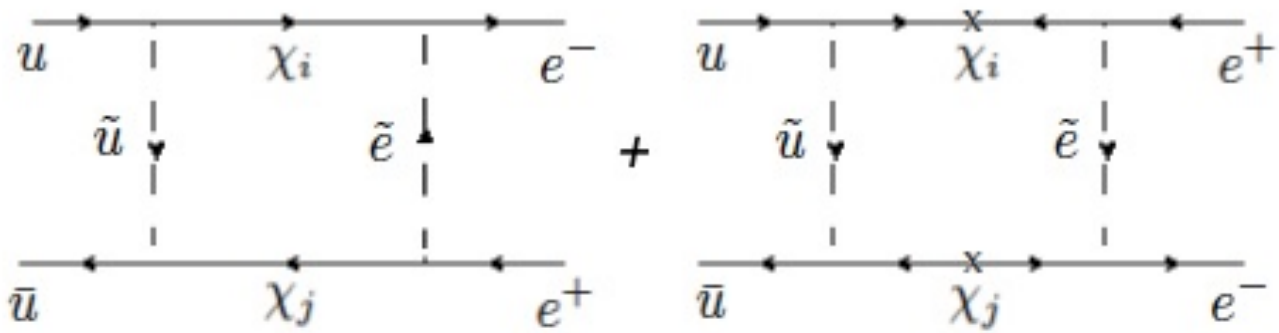


Contributions to dilepton production

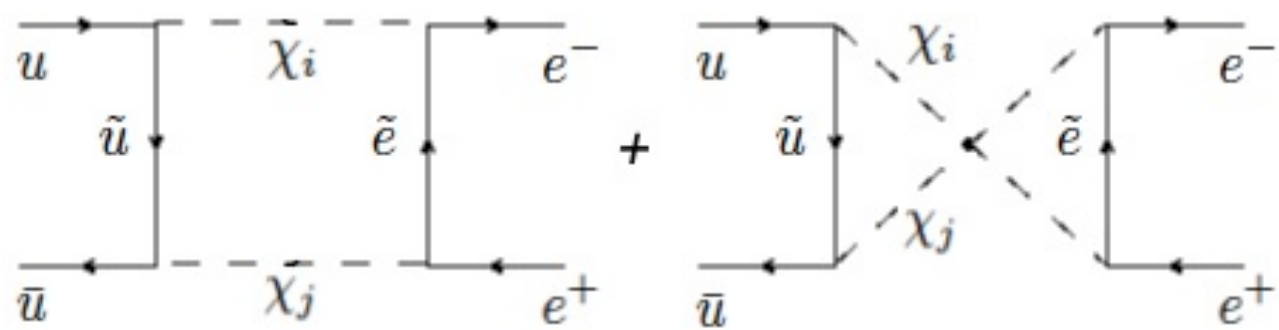
Drell-Yan, SM dominating background



pD :

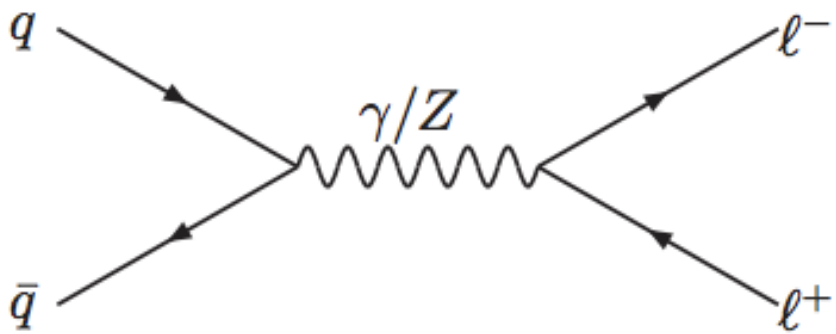


pCS :



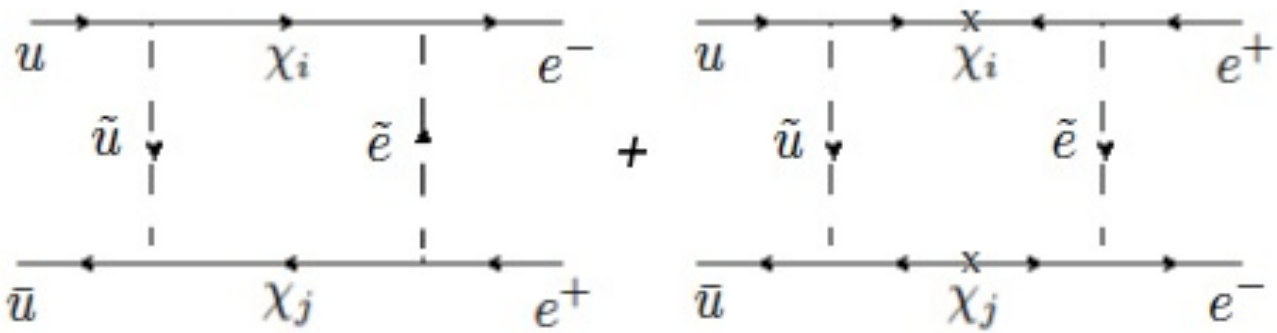
Contributions to dilepton production

Drell-Yan, SM dominating background

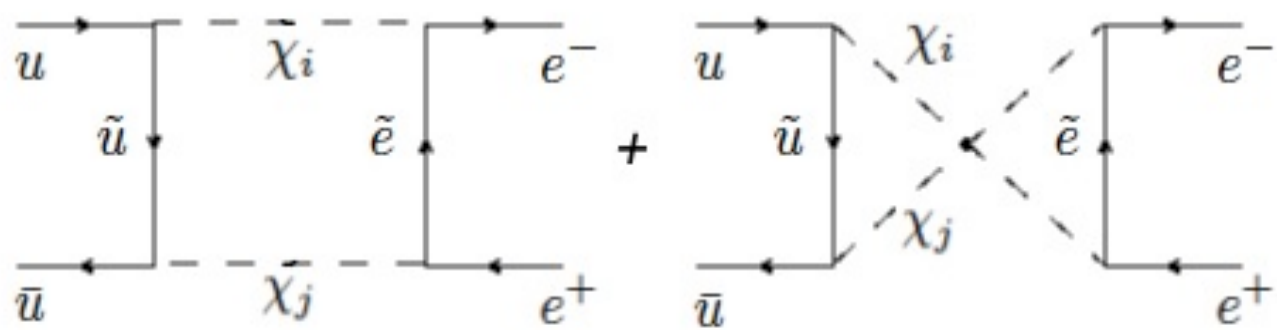


New physics contributions

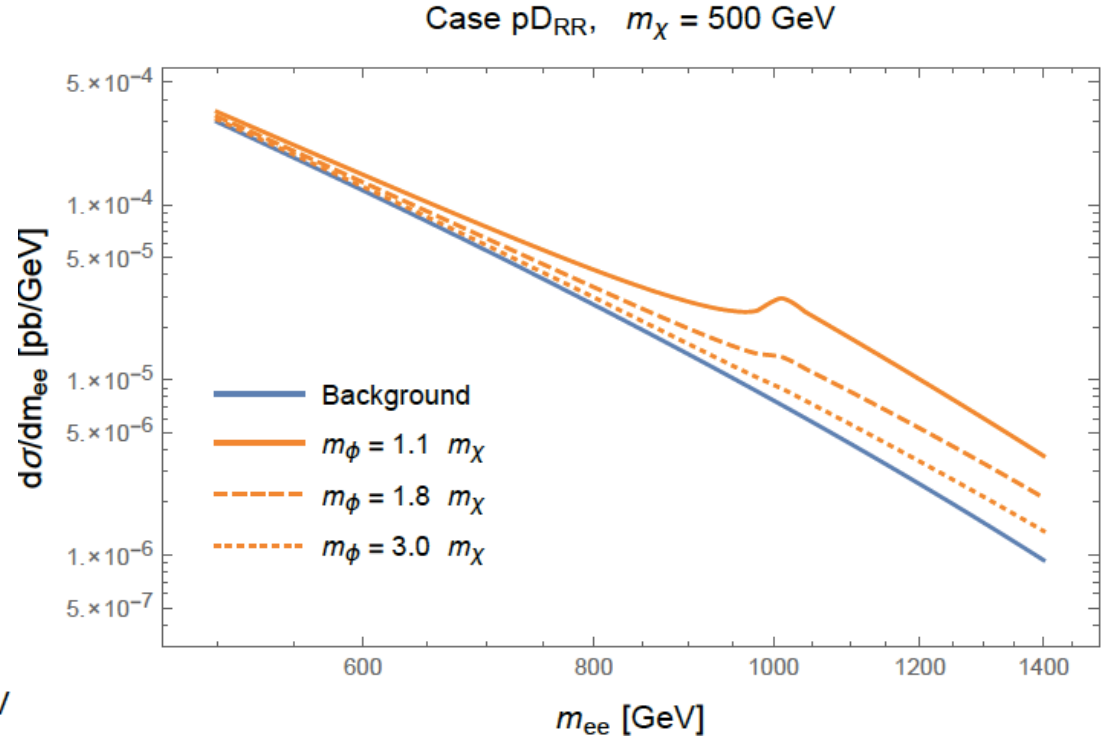
pD :

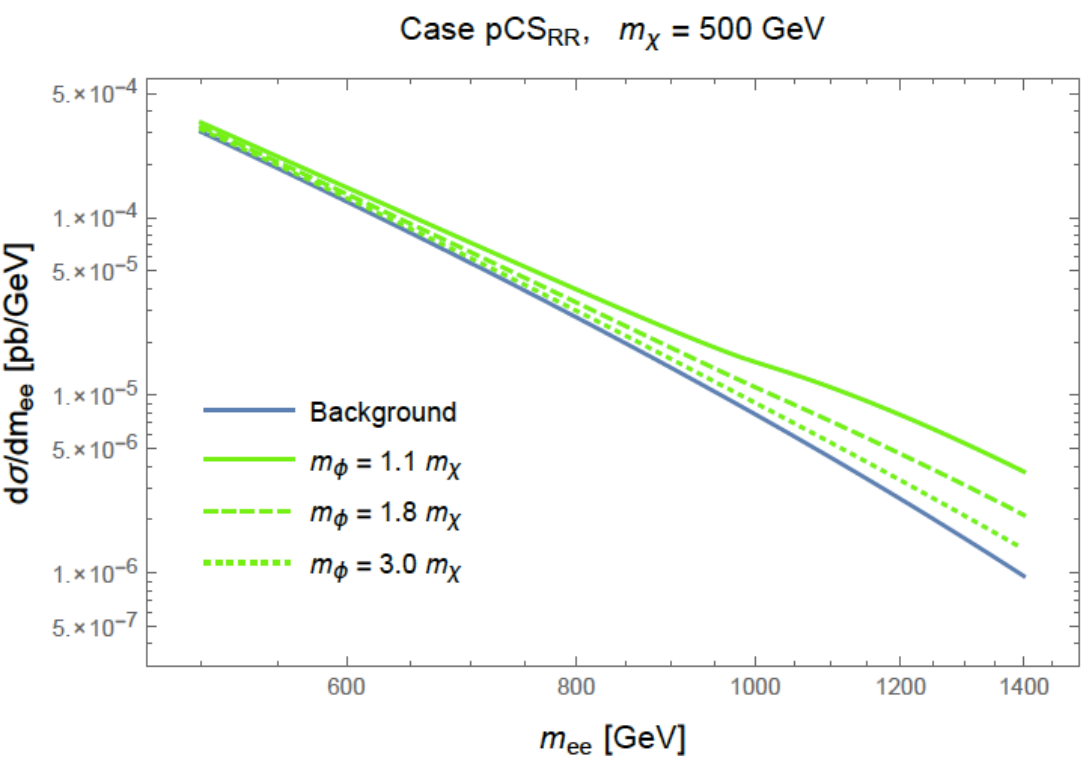


pCS :



Results: Invariant Mass

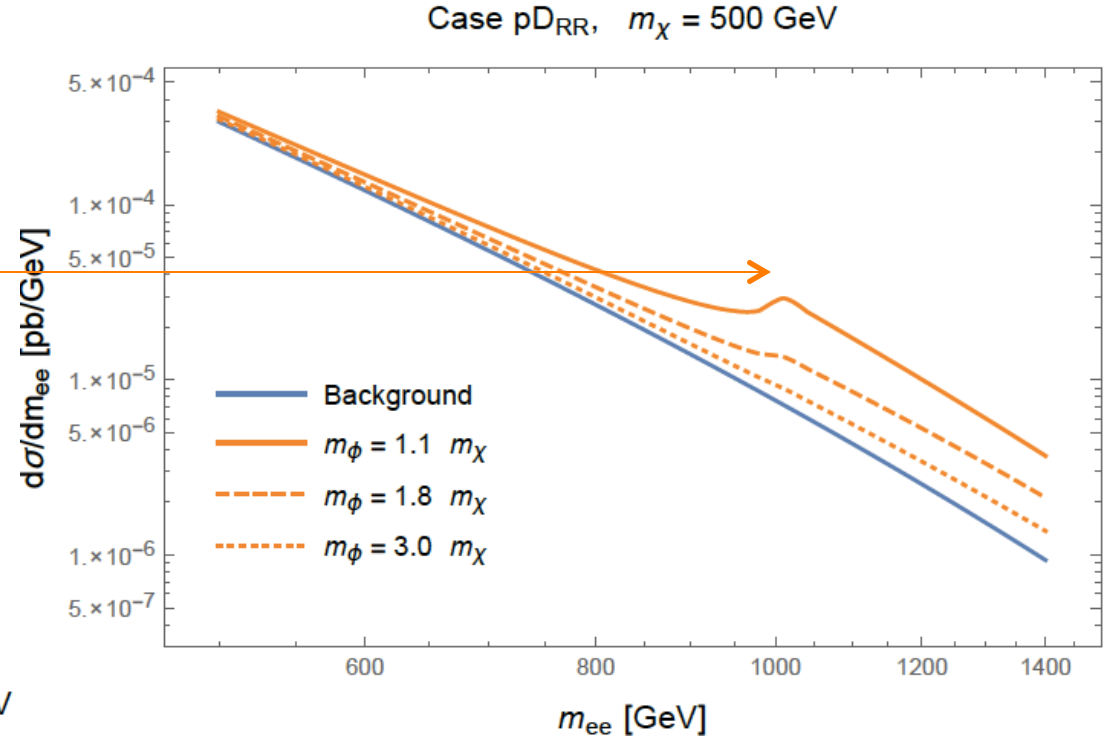


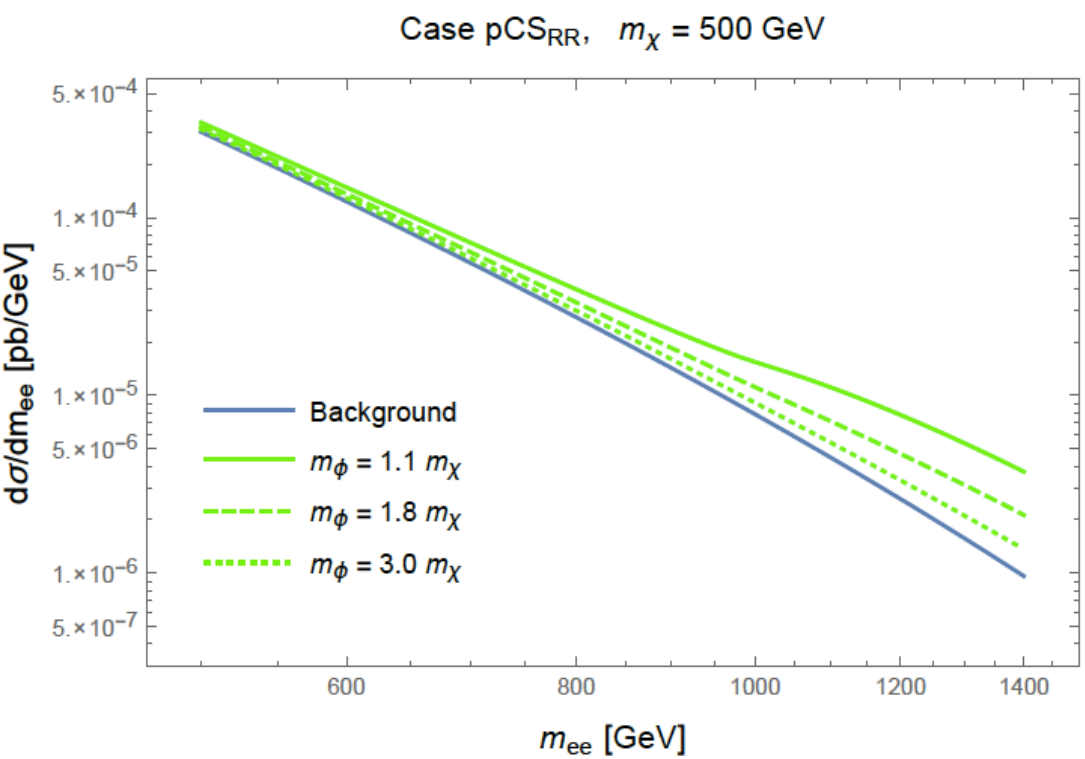


Results: Invariant Mass

Fermionic DM;
Monocline feature

N. Raj et al Phys. Rev. D 91, 115006 (2015)





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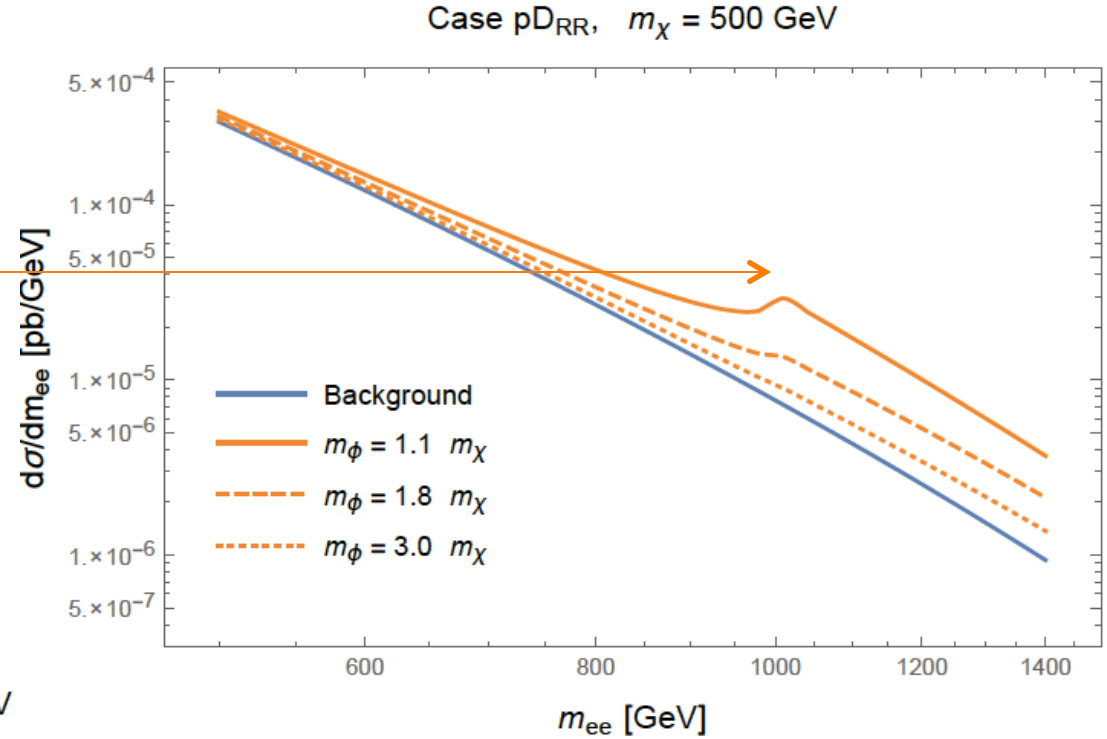
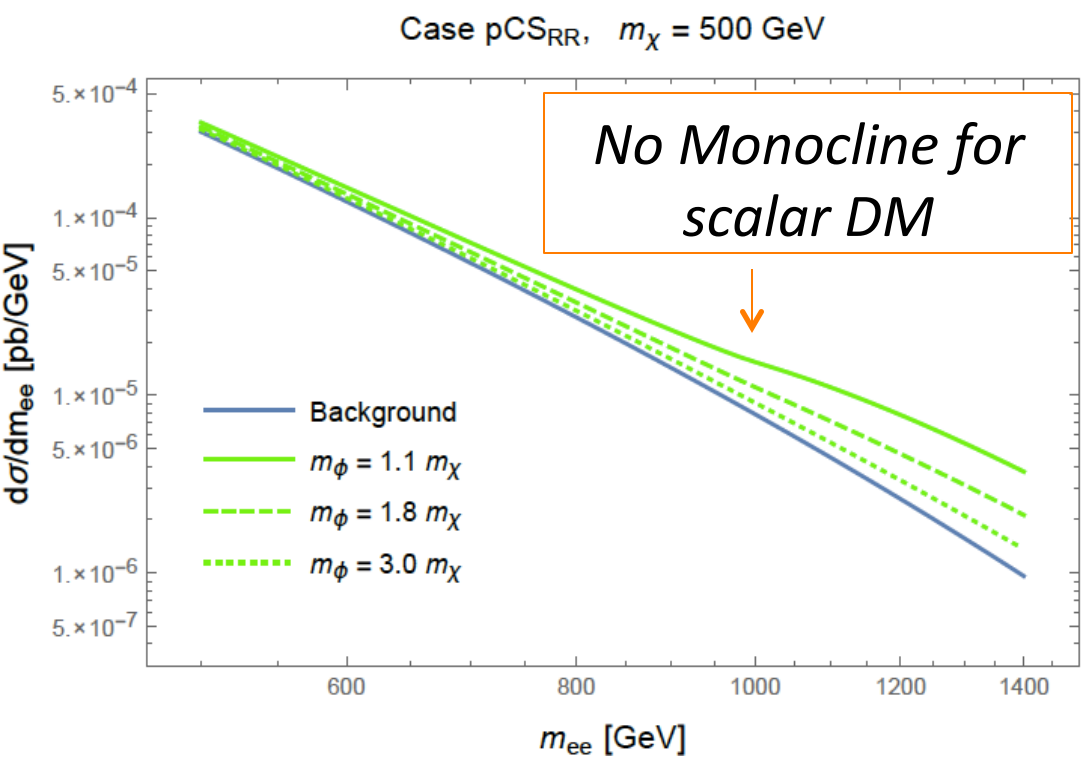


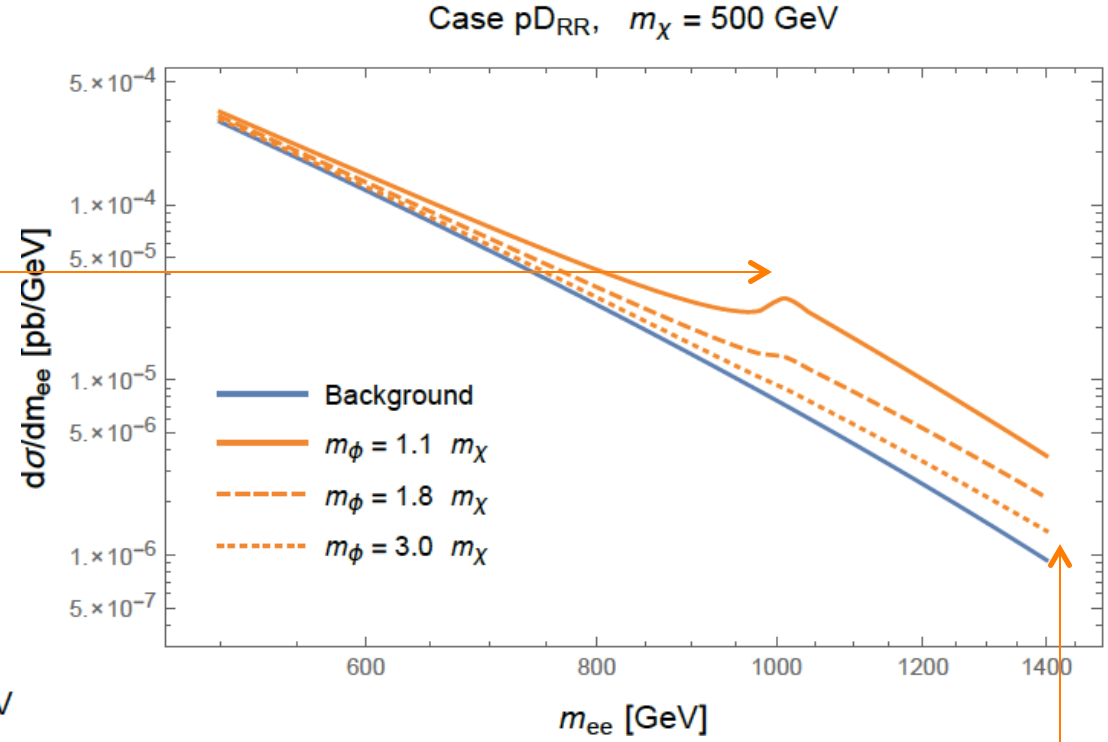


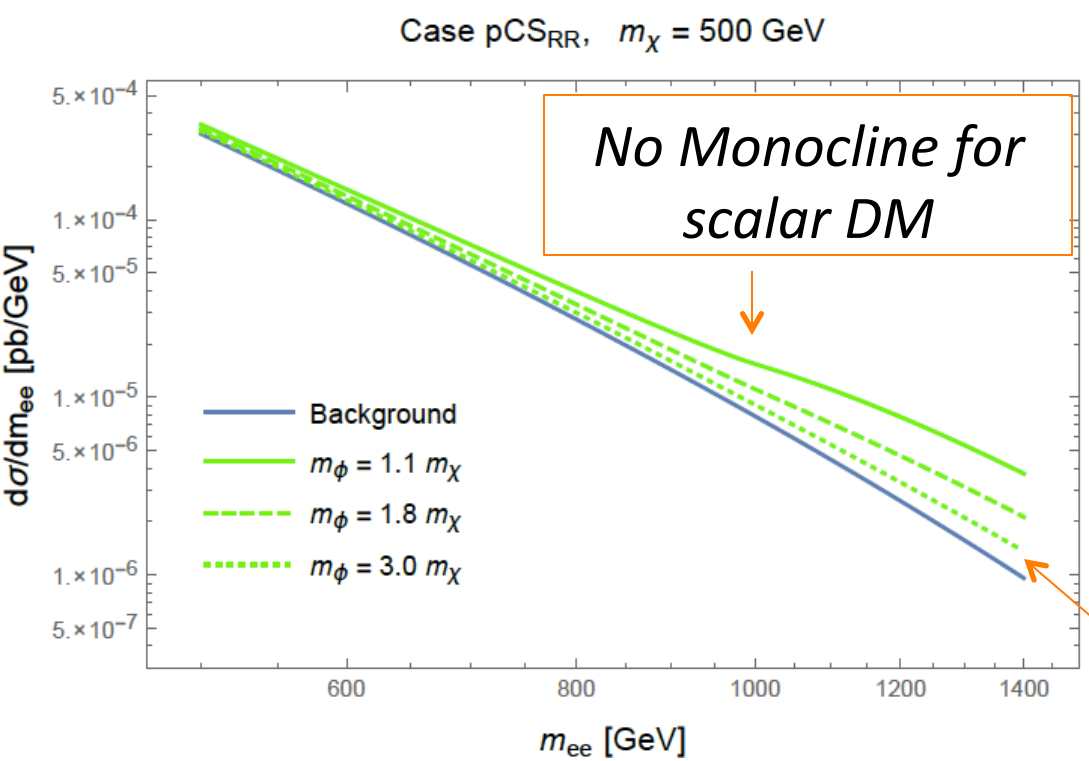
No Monocline for scalar DM

Results: Invariant Mass

Fermionic DM; Monocline feature

N. Raj et al Phys. Rev. D 91, 115006 (2015)



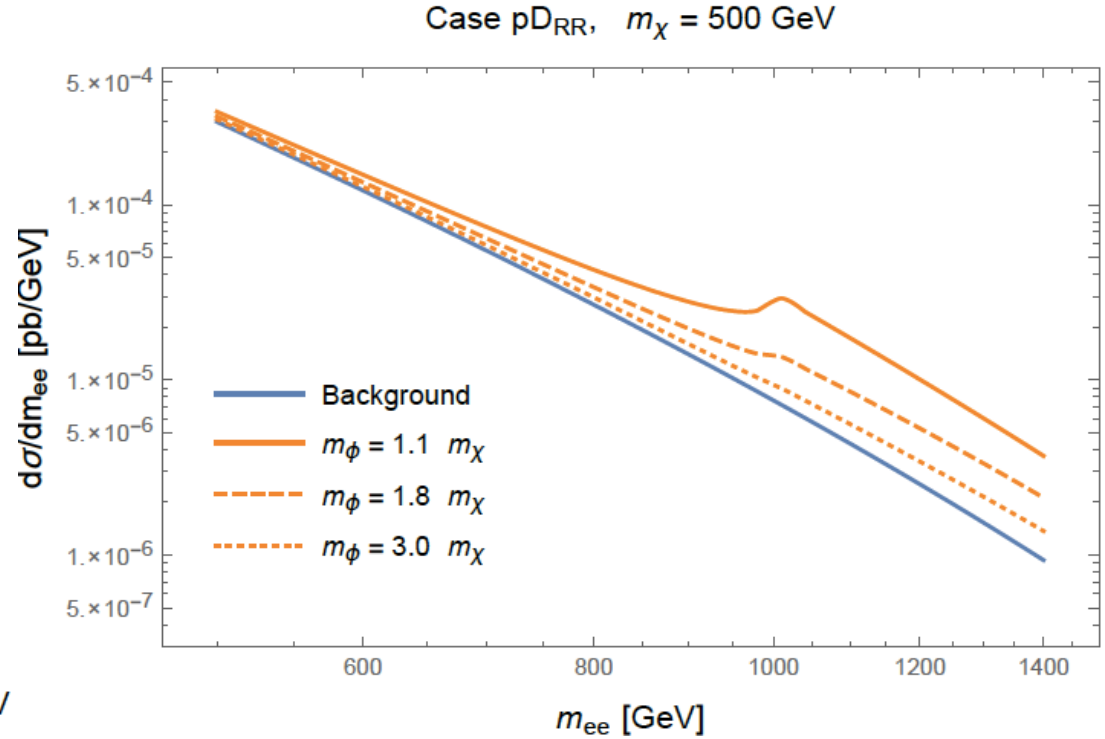


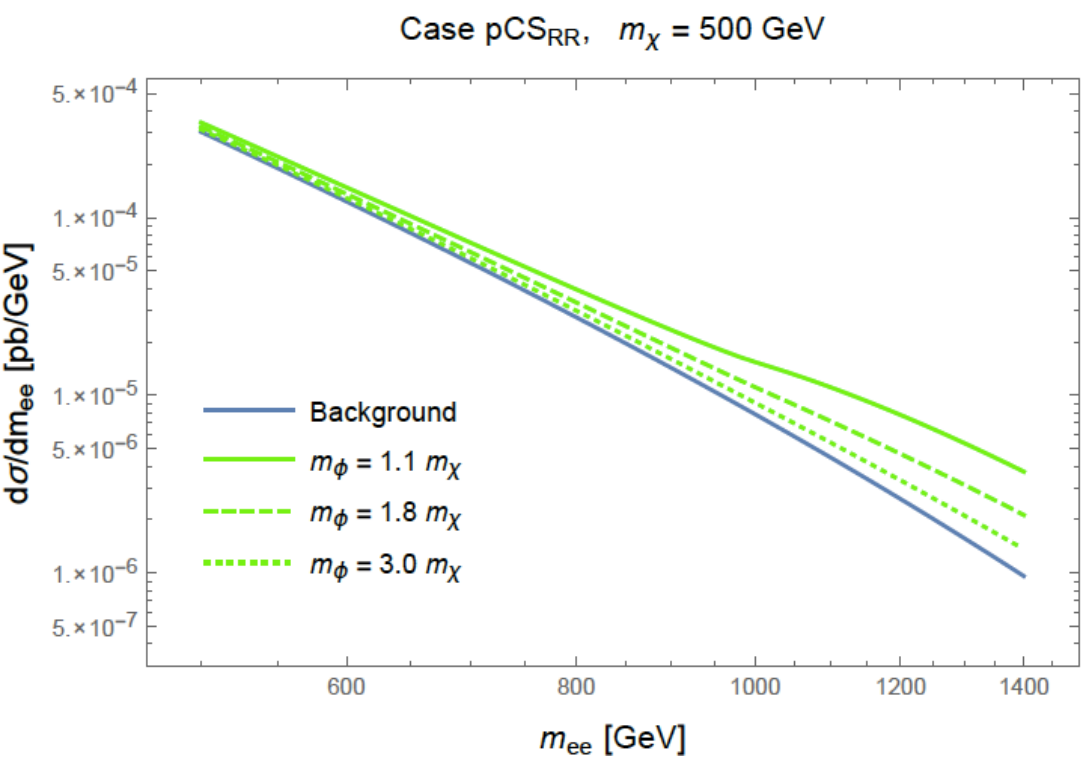
No Monocline for scalar DM

Monocline appears for very compress spectrum!

For large splitting the distributions look the same

Results: Invariant Mass



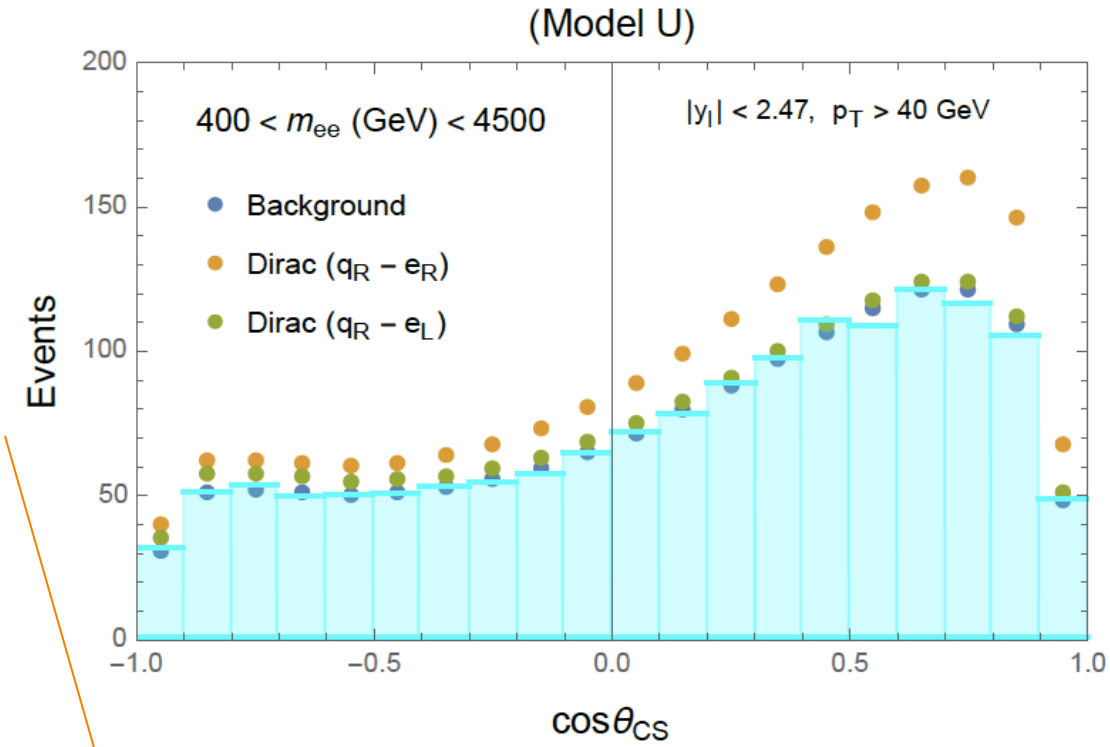


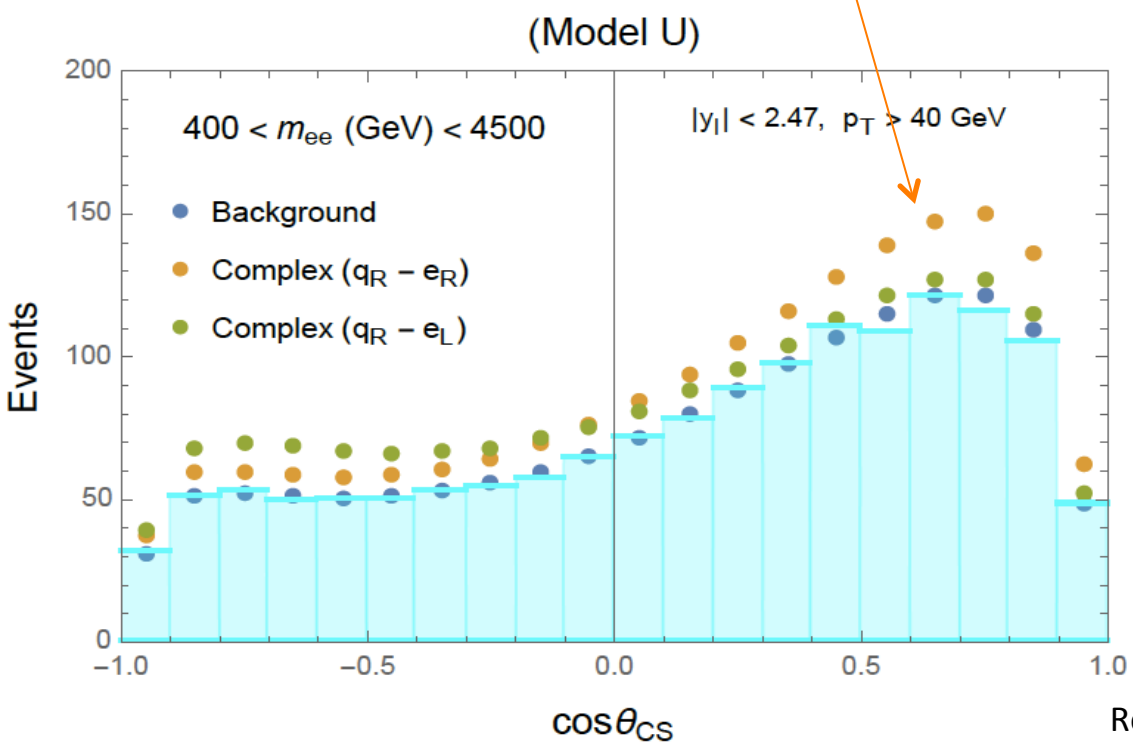
The invariant mass identifies:

- *The MASS (fermion case)*
- *the SPIN (very compressed spectrum)*

Results: Angular Distribution

*The chirality choice RR produces **more forward** events*

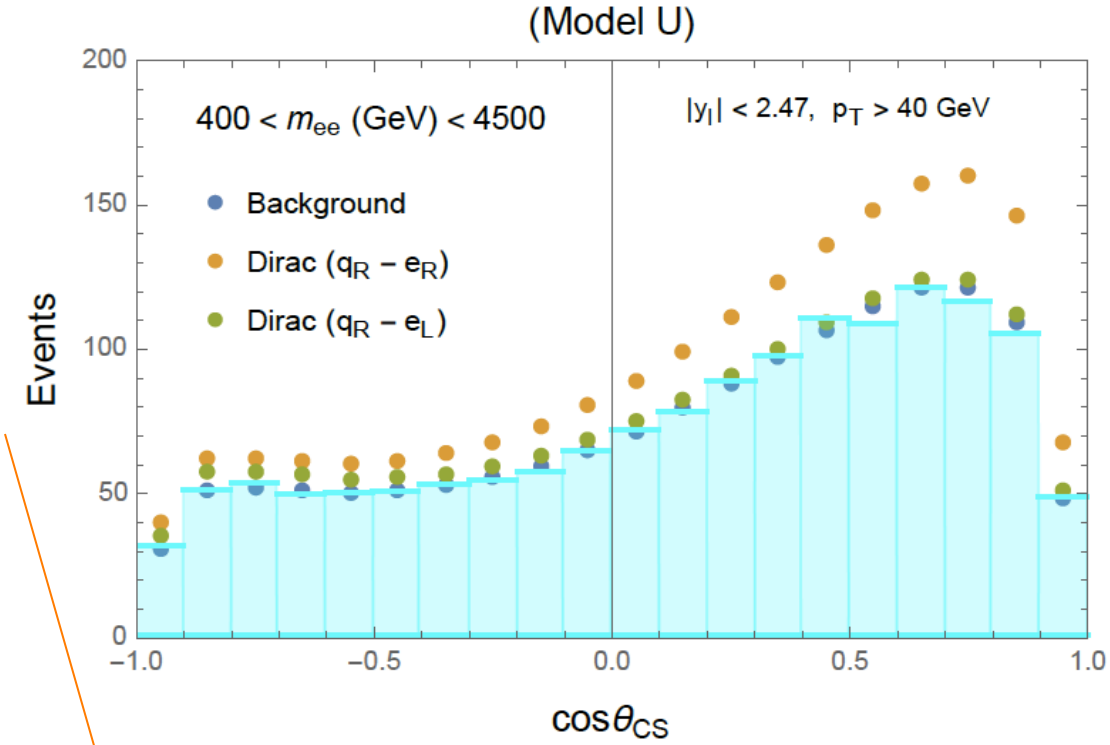


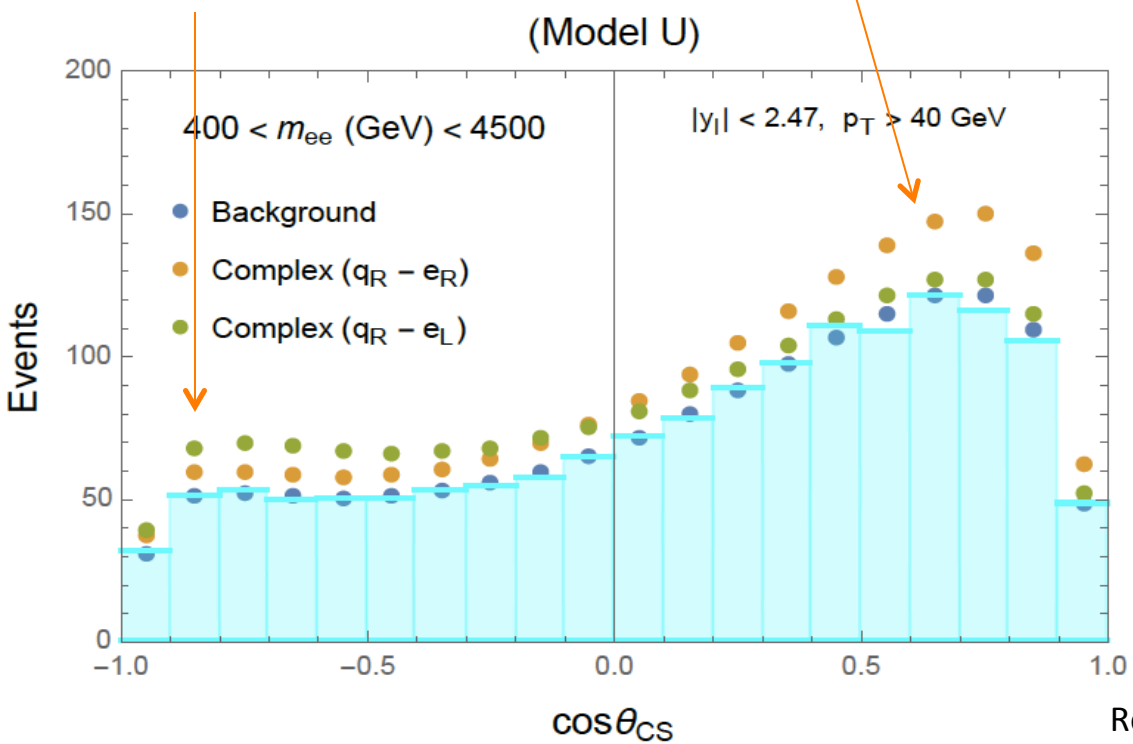


Results: Angular Distribution

*The chirality choice RR produces **more forward** events*

*Choosing RL produces **more backward** events*





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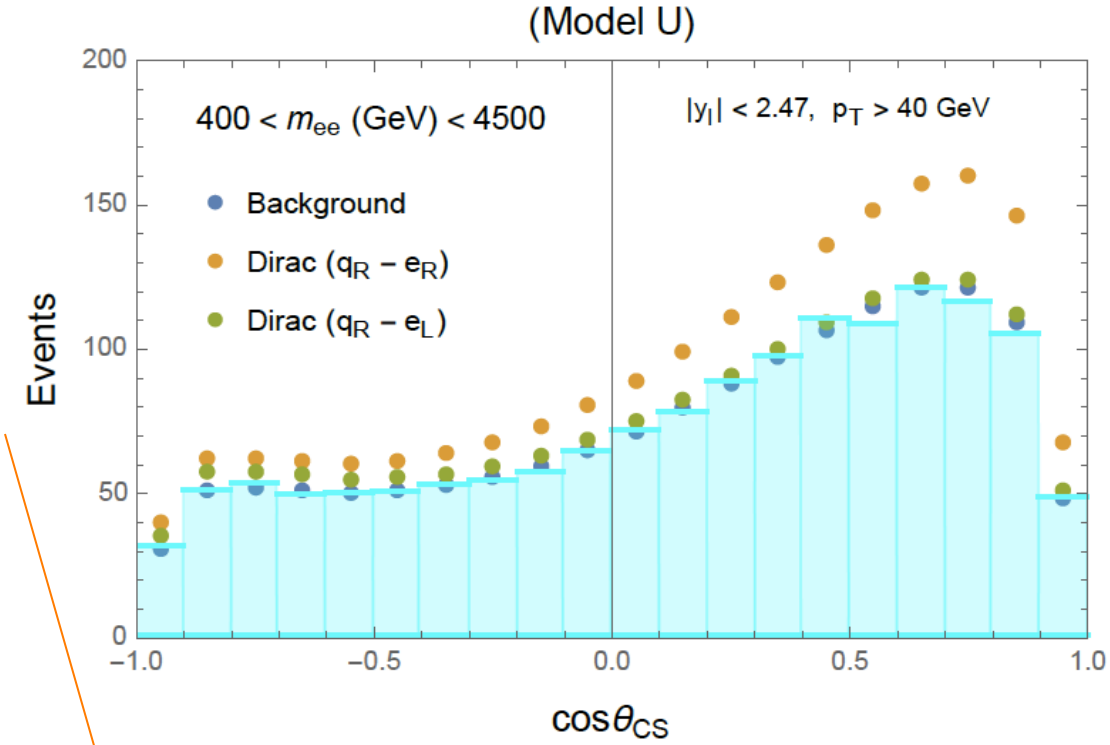
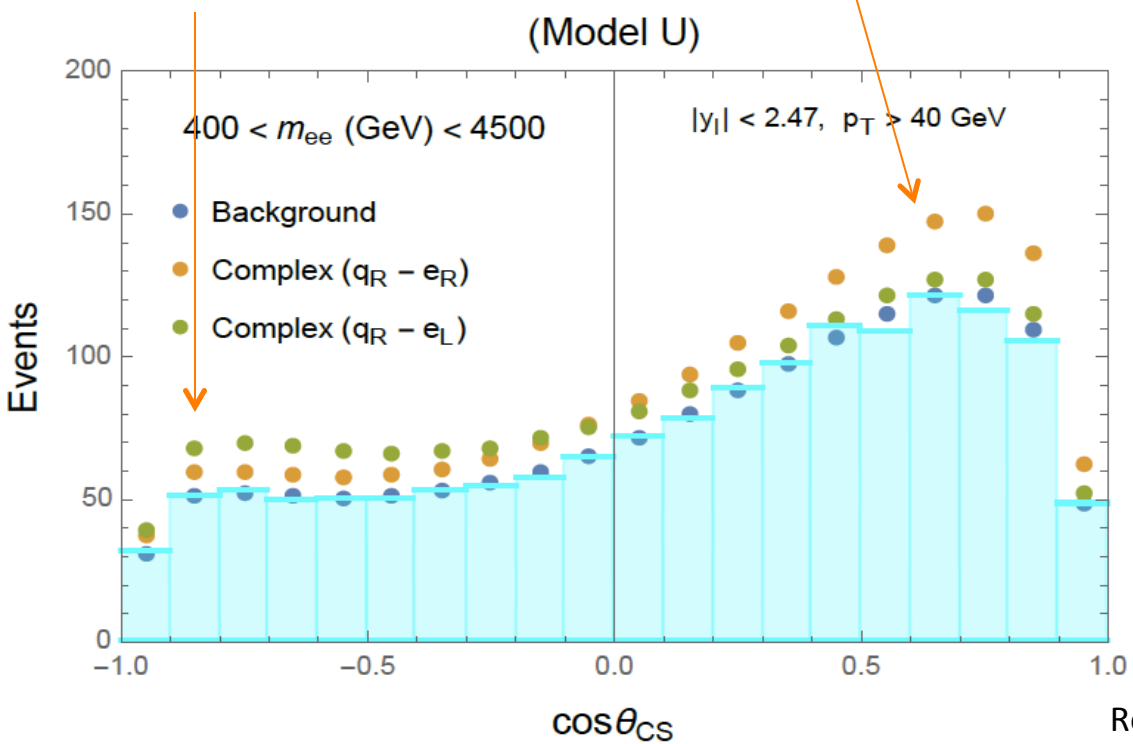


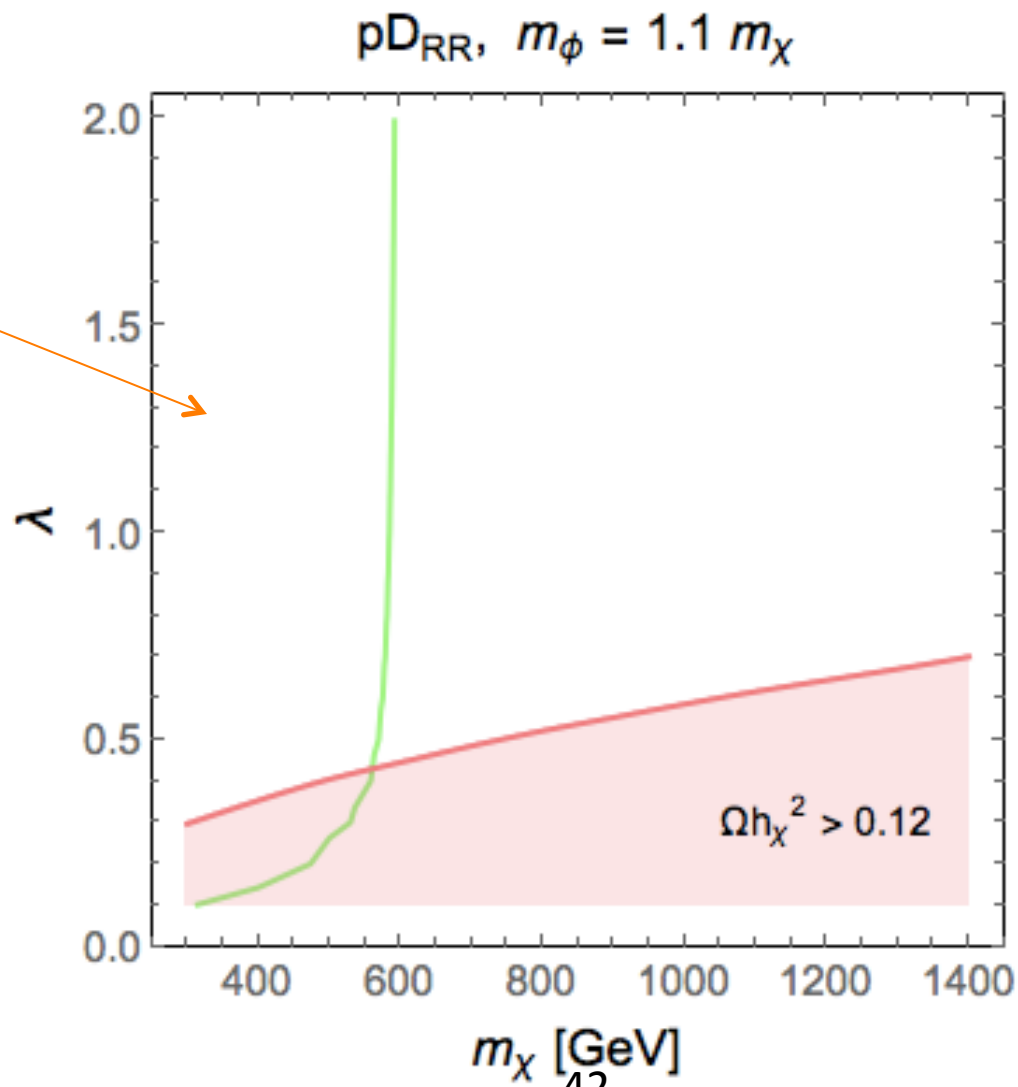


The angular distribution distinguishes relative chirality of SM particles!

Other Bounds:

- Direct Detection of DM

Region Excluded by Direct Detection

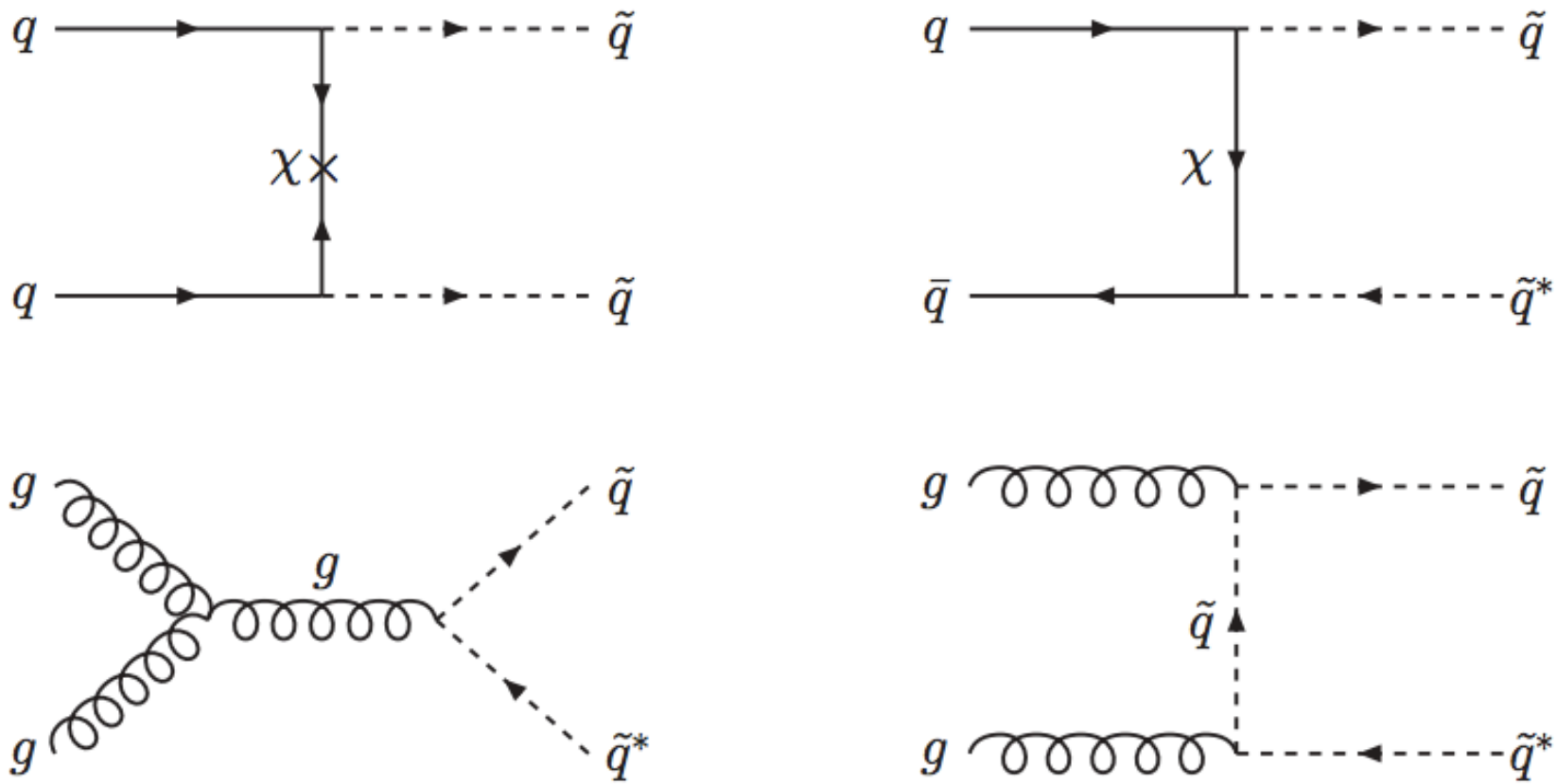


Bounds disappear for 100% splitting!

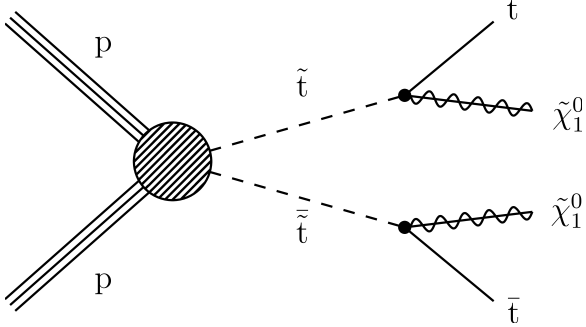
Rodolfo M. Capdevilla, University of Notre Dame

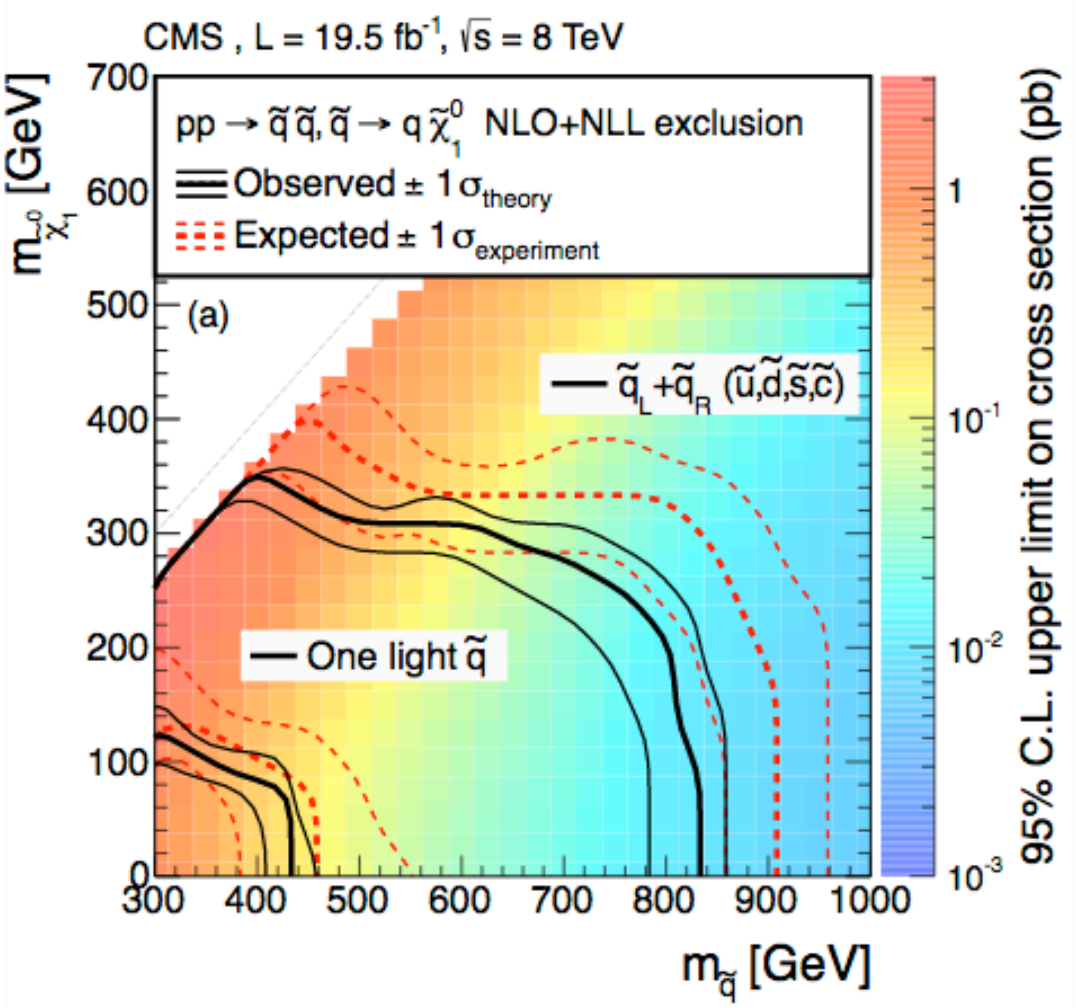
Other Bounds:

- Searches for jets+MET at the LHC



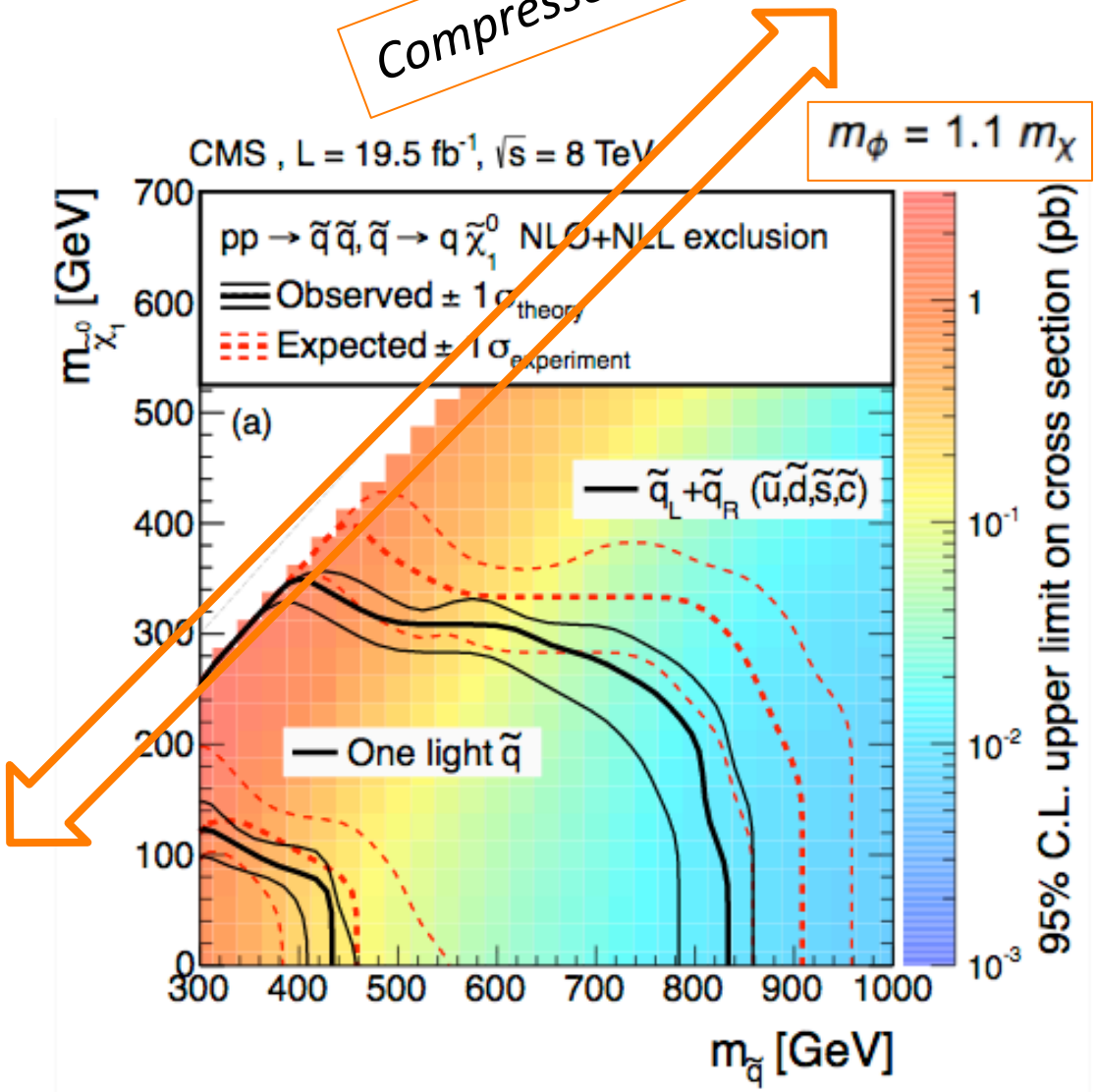
- Jets + MET

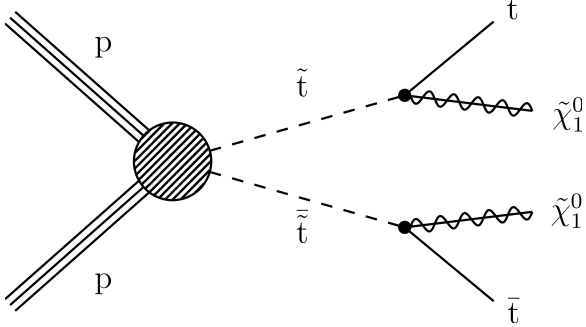

p
p
$\tilde{t}$
$\bar{\tilde{t}}$
t
$\bar{t}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$


CMS , L = 19.5 fb^{-1}, $\sqrt{s}$ = 8 TeV
$pp \to \tilde{q}\tilde{q}, \tilde{q} \to q\tilde{\chi}_1^0$ NLO+NLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
(a)
$\tilde{q}_L + \tilde{q}_R$ ($\tilde{u},\tilde{d},\tilde{s},\tilde{c}$)
One light $\tilde{q}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{q}}$ [GeV]
95% C.L. upper limit on cross section (pb)
0
100
200
300
400
500
600
700
300
400
500
600
700
800
900
1000
1
10^{-1}
10^{-2}
10^{-3}

- Jets + MET

Compressed spectrum





- Jets + MET

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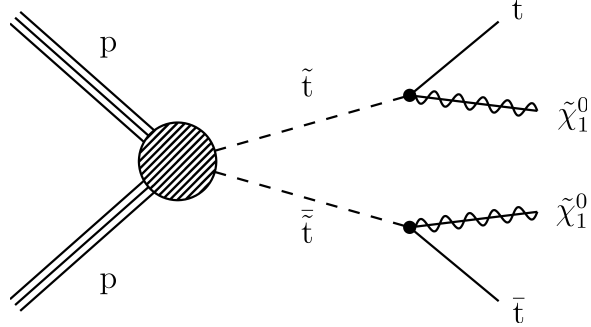
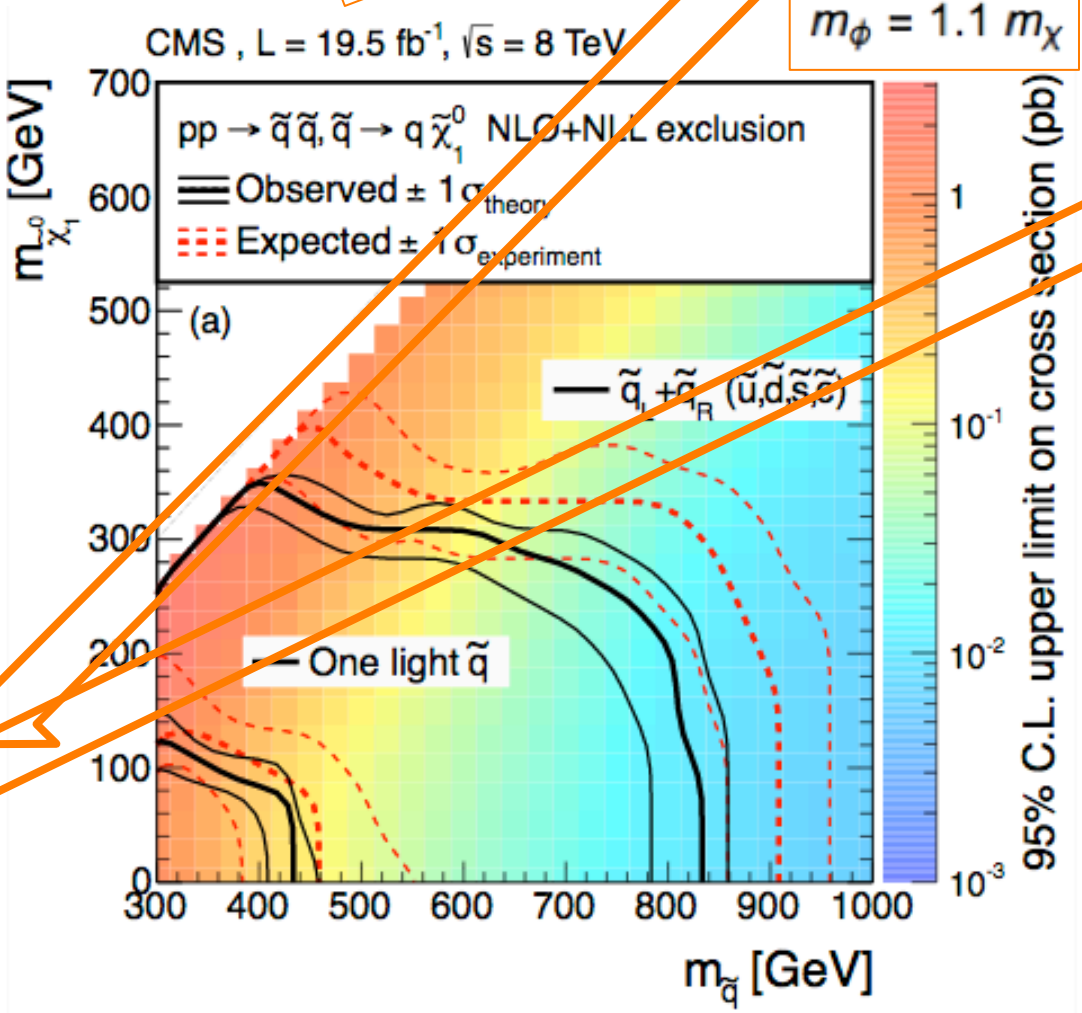


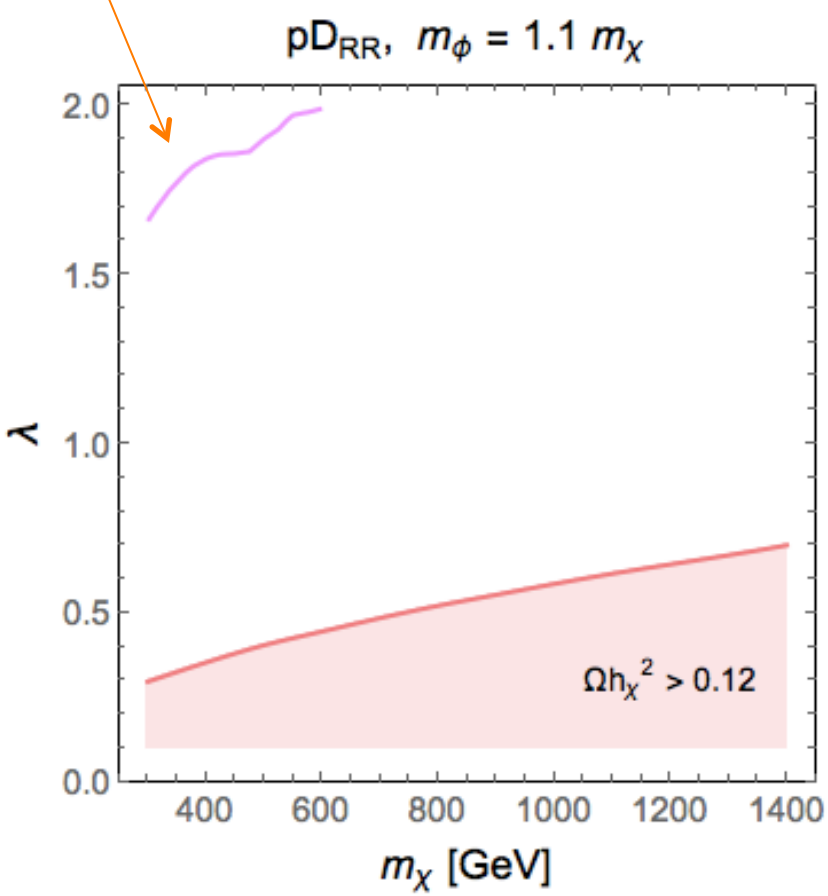
$m_\phi = 1.1\ m_\chi$

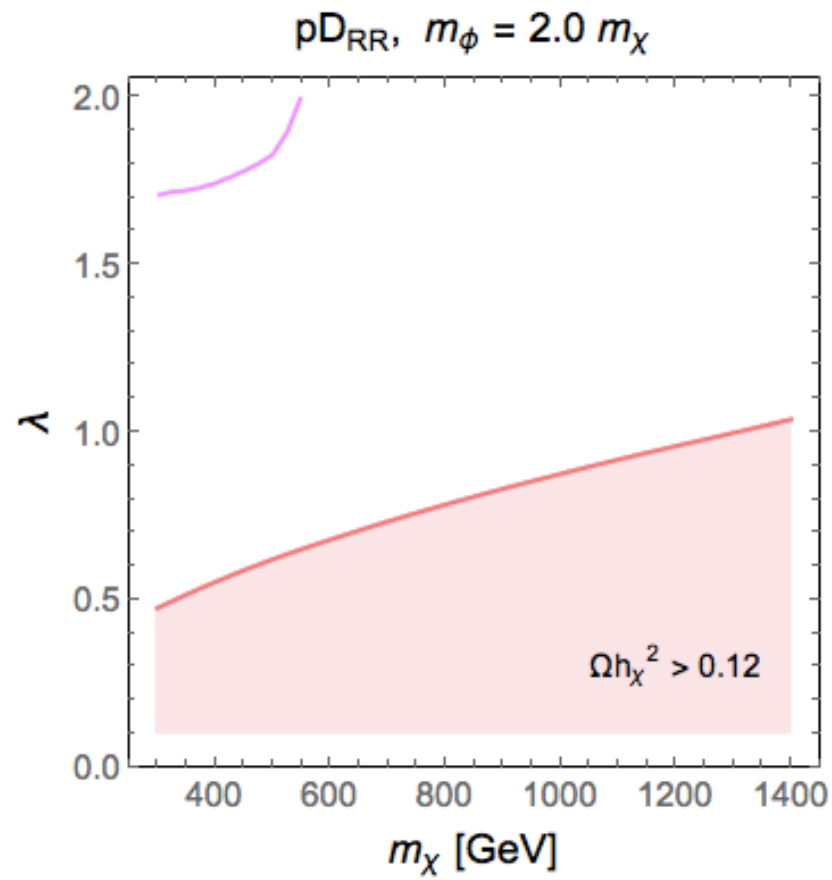
$m_\phi = 2.0\ m_\chi$



- Jets + MET

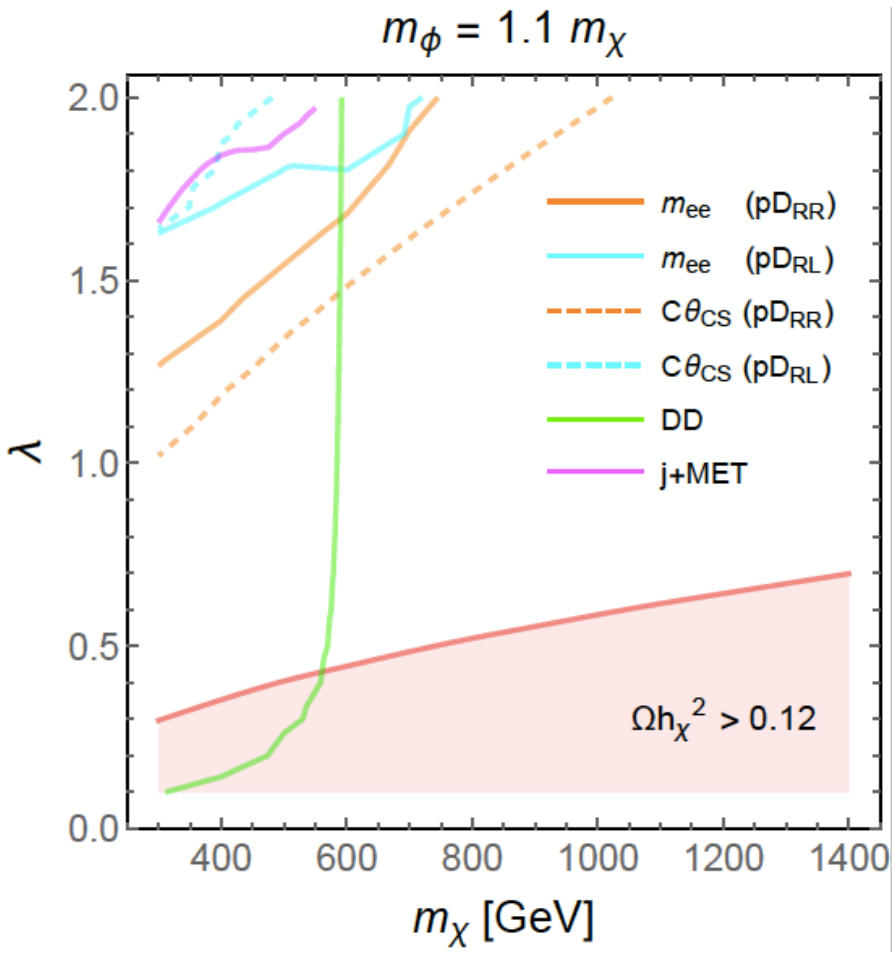
Excluded





Bounds:

- Bounds for Fermionic DM cases



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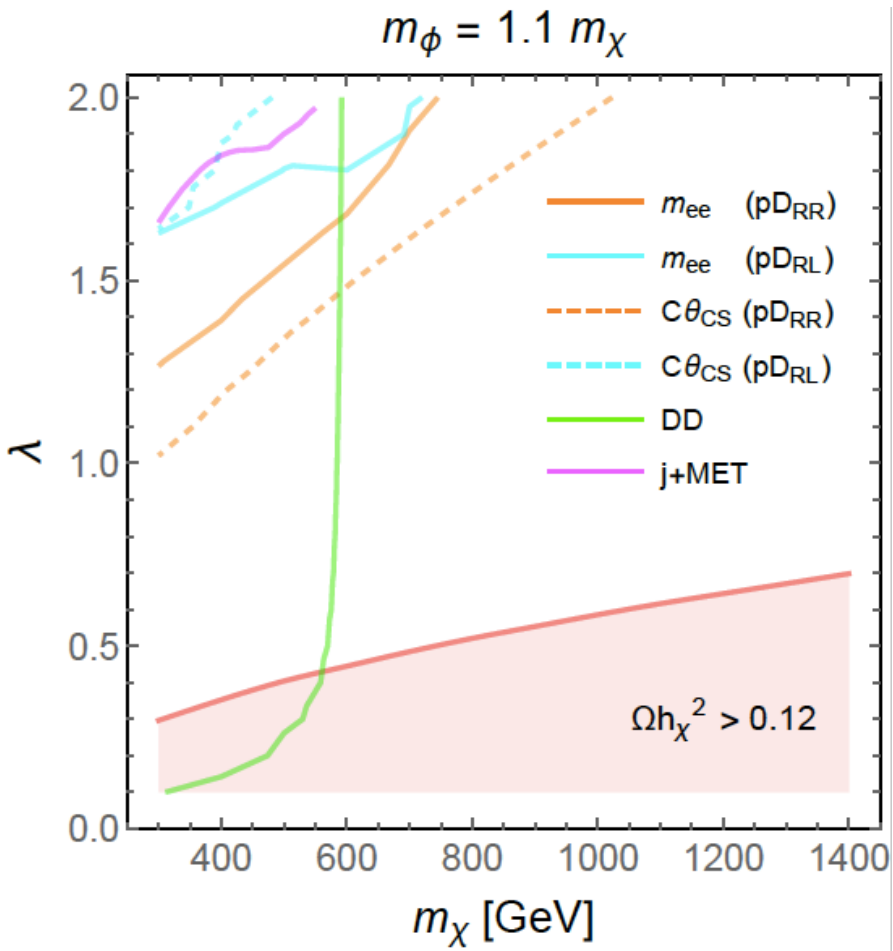

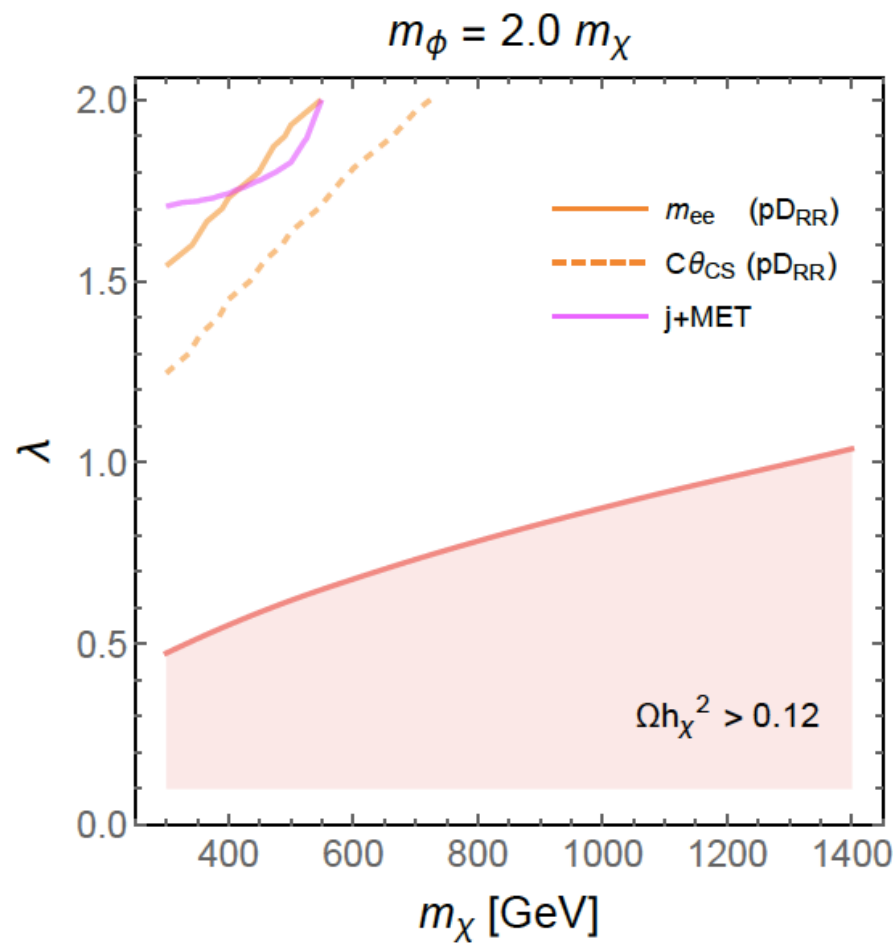

Conclusions

- Dilepton distributions can give bounds for DM simplified models with t-channel mediators. These bounds are competitive with those from jets+MET and direct detection searches.

- The dileptonic invariant mass distribution can provide information about the mass and spin of DM in the limit of almost degenerate DM-mediator masses.

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Yes, we can!!!

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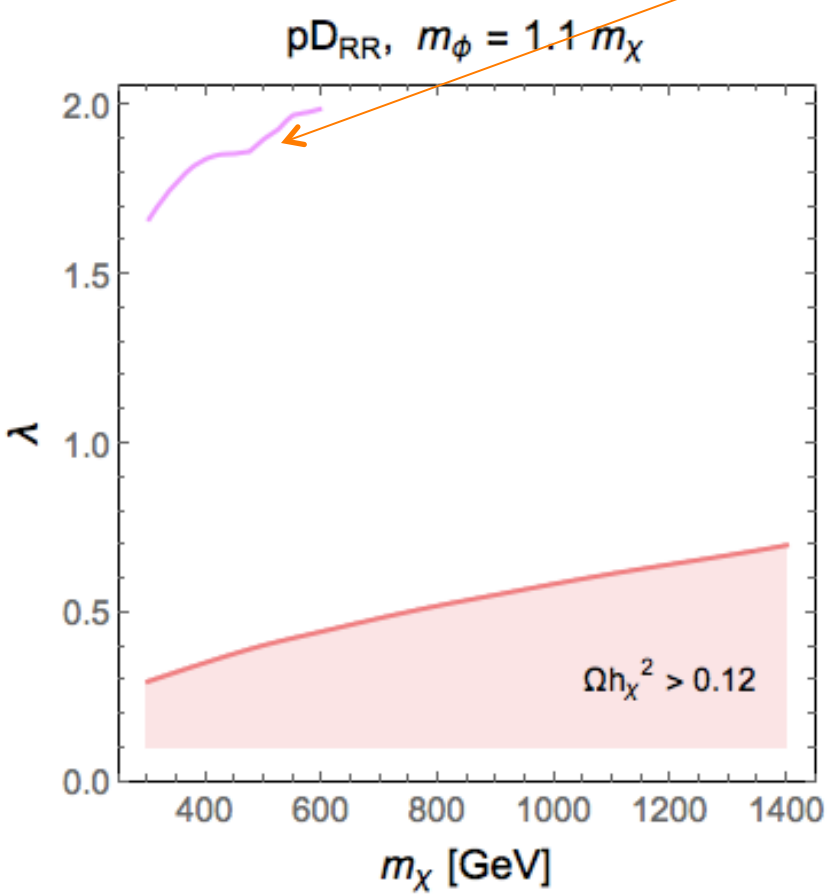
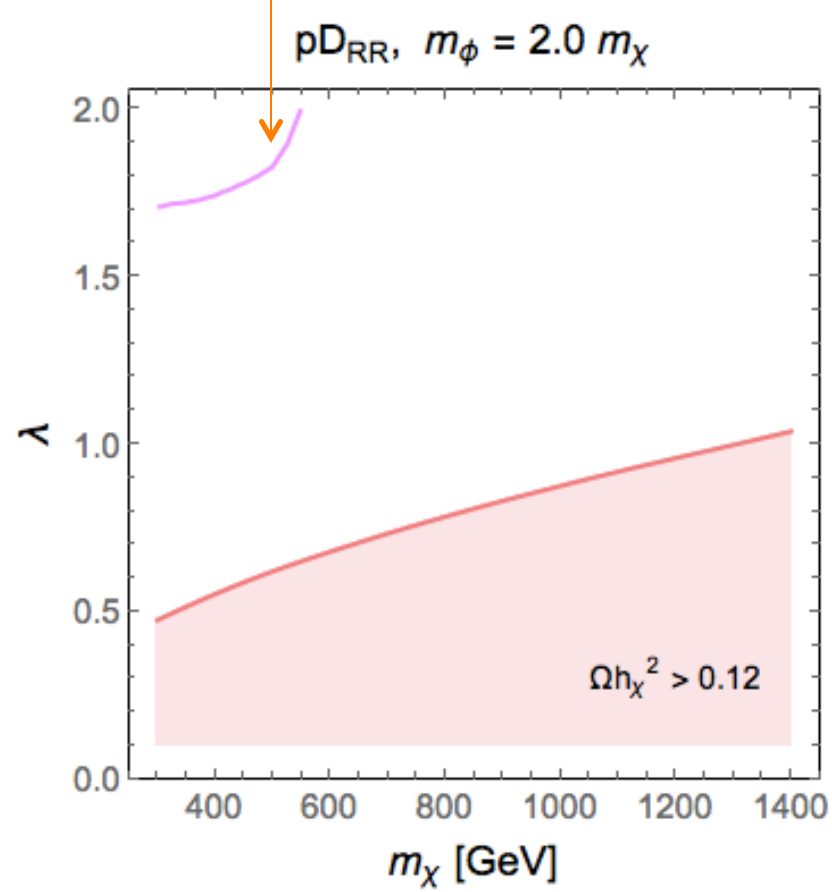
THANK YOU!

- Jets + MET

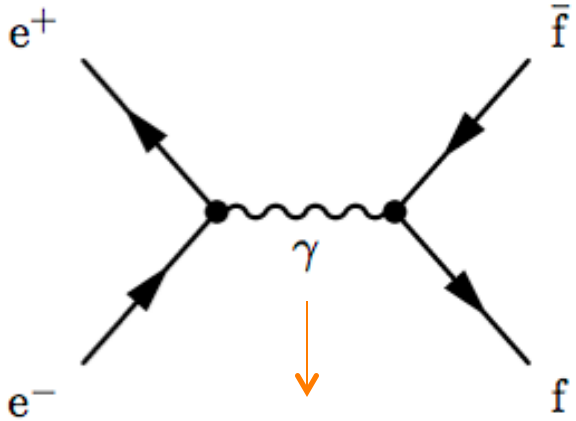
Similar bounds;

As mediator is heavier, the cross section drops but bounds also decrease

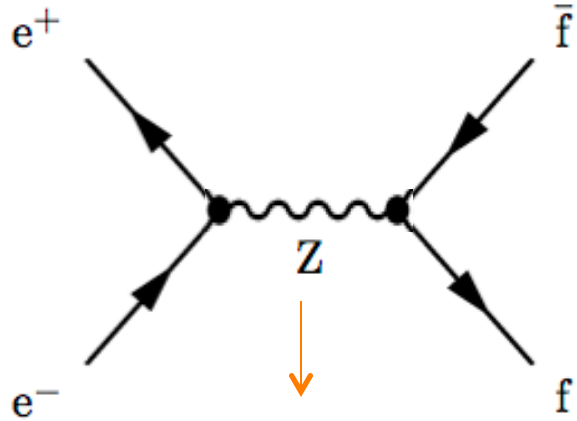




1) Threshold Effects

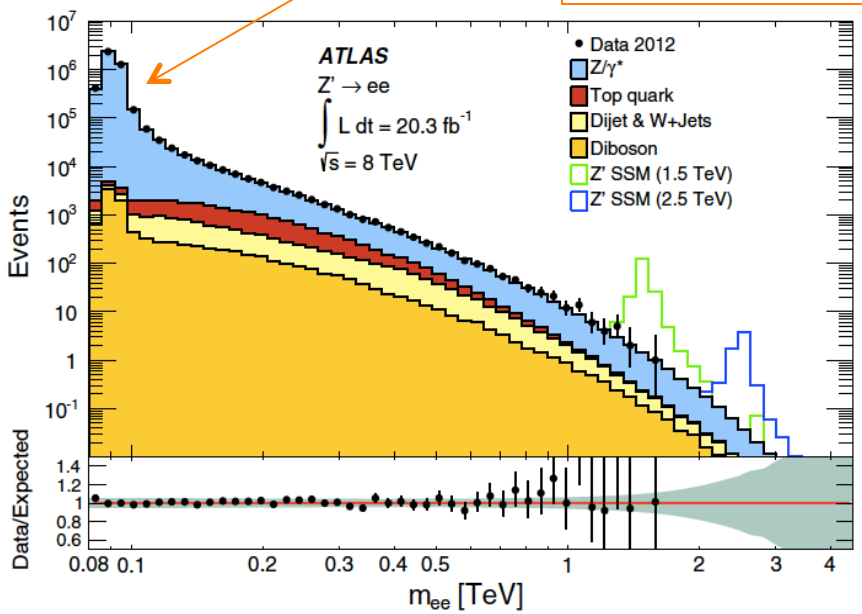


$$\frac{1}{\hat{s}}$$

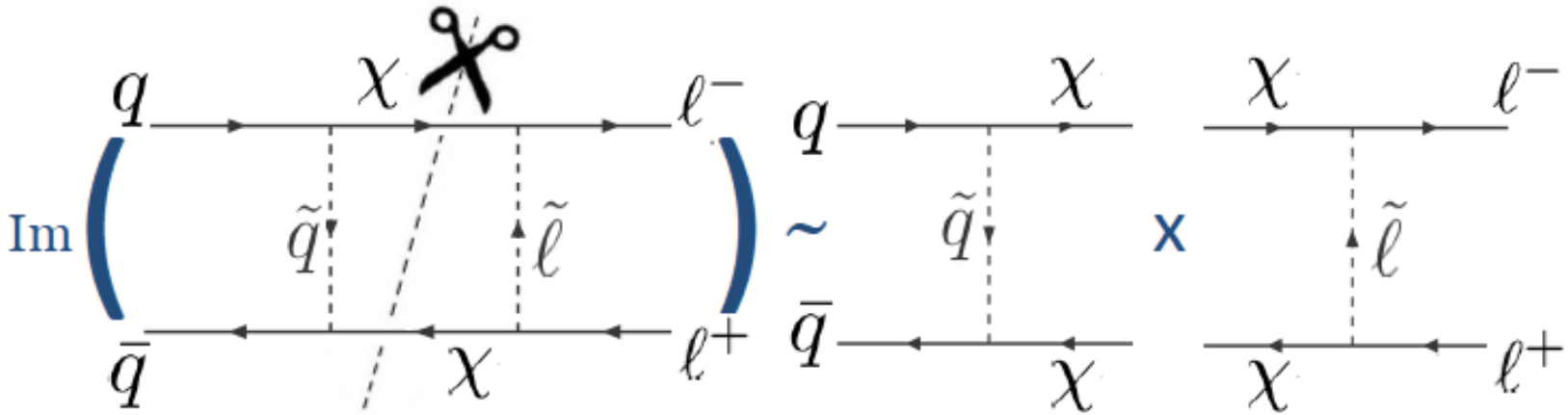


$$\frac{1}{(\hat{s} - m_Z^2) + i m_Z \Gamma_Z}$$

Resonant production of the Z boson



Optical theorem



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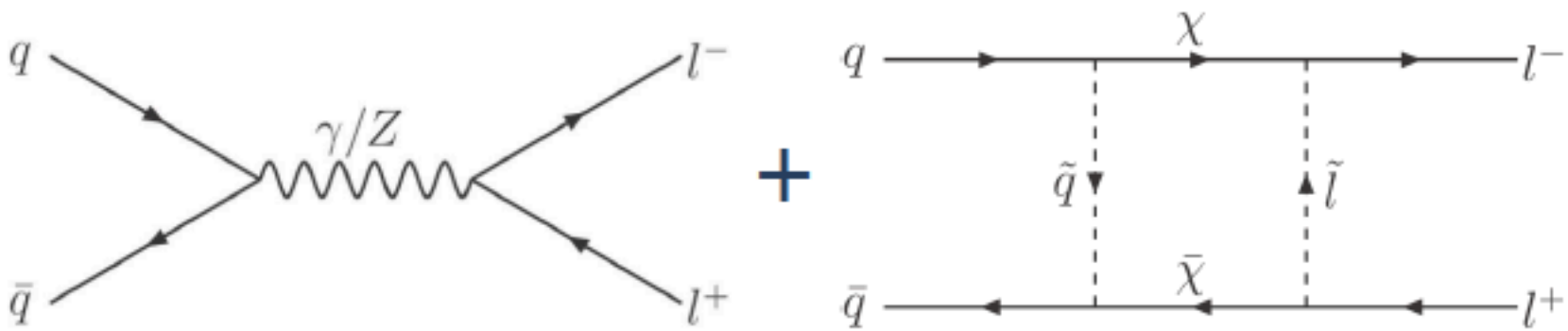


$$|A_{\text{tree}} + A_{\text{box}}|^2$$

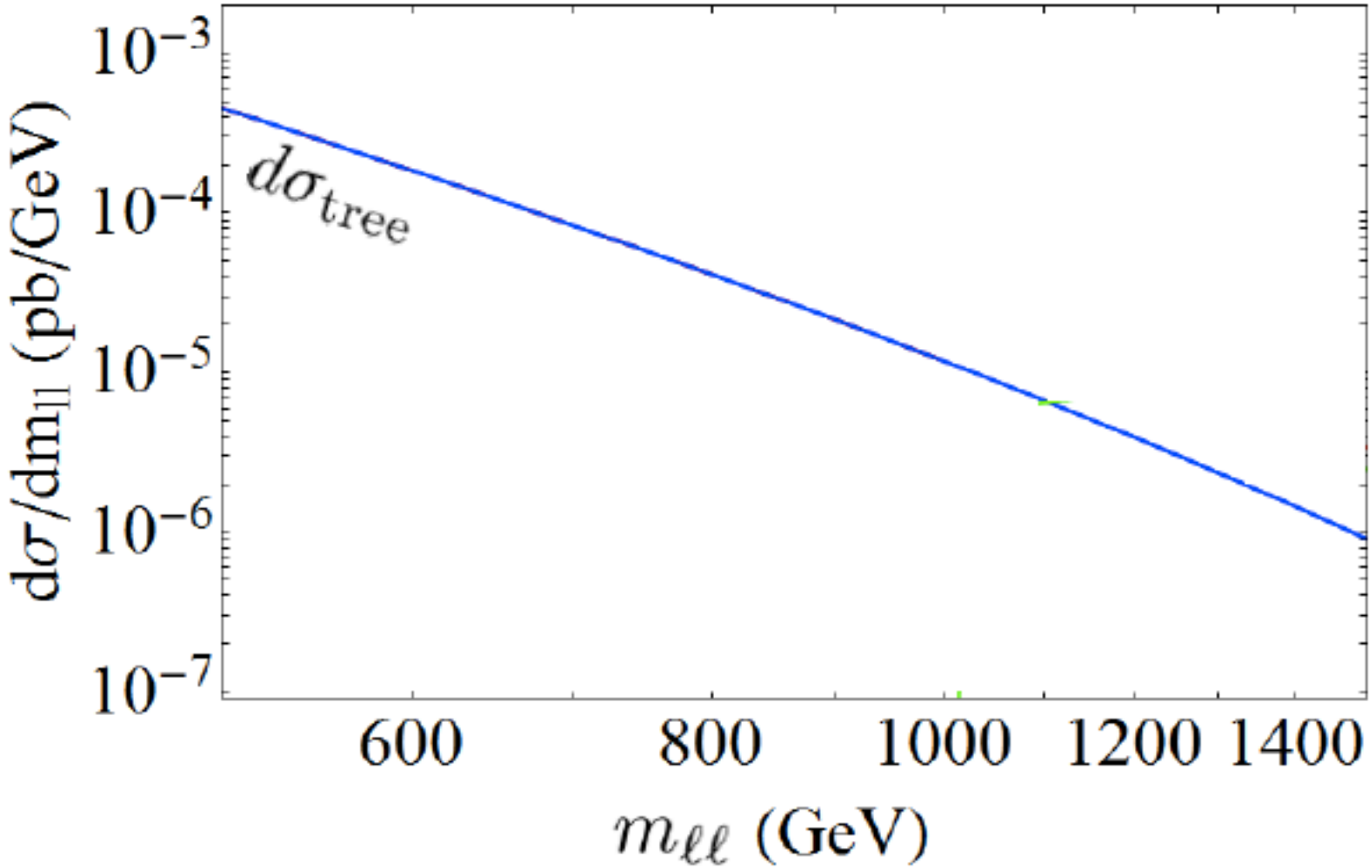
$$d\sigma_{\text{tree}} + d\sigma_{\text{int}} + d\sigma_{\text{box}}$$

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

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

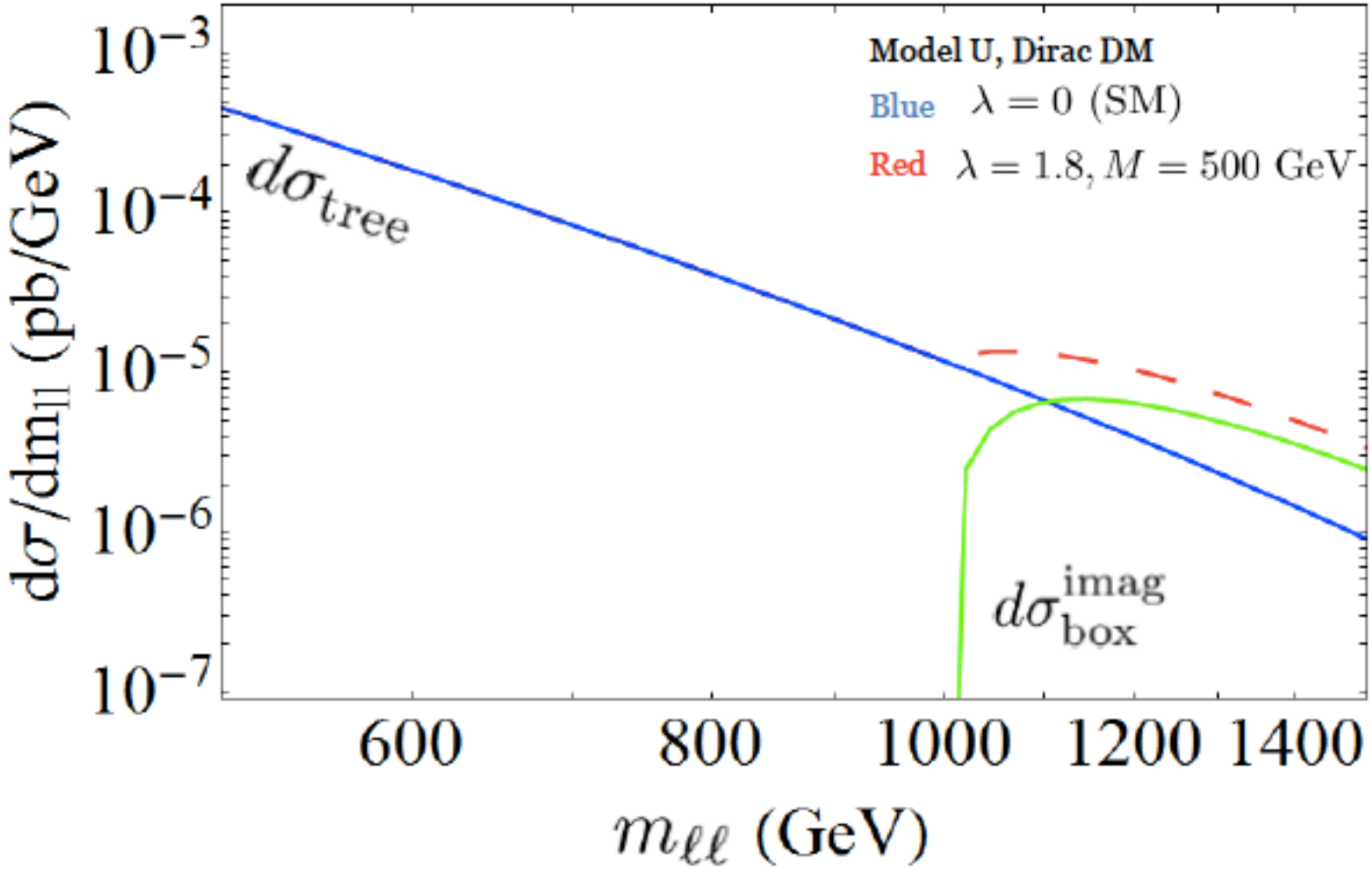
from Optical Theorem

Breakdown of rates



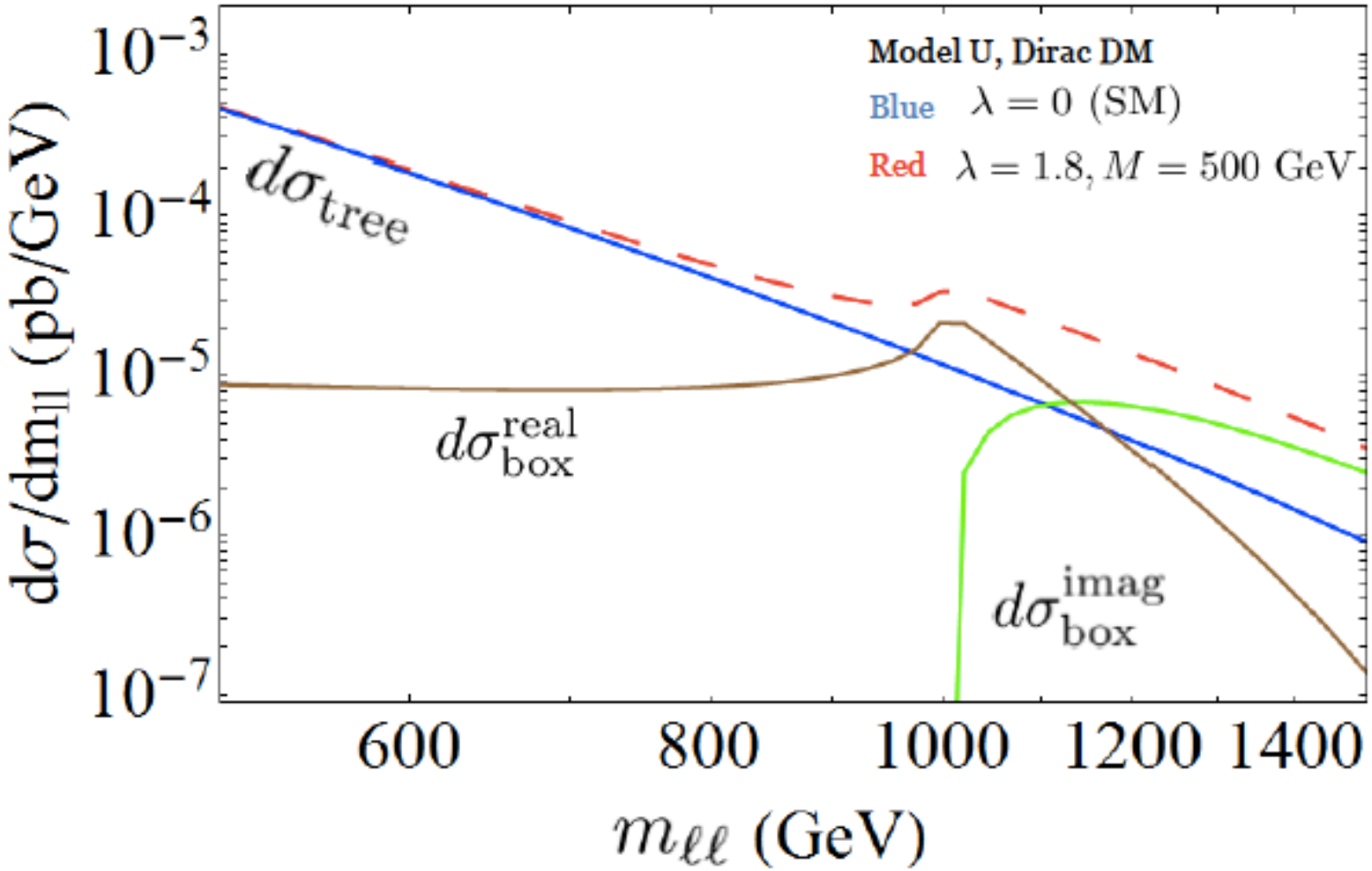
$d\sigma_{\rm tree}$

Breakdown of rates



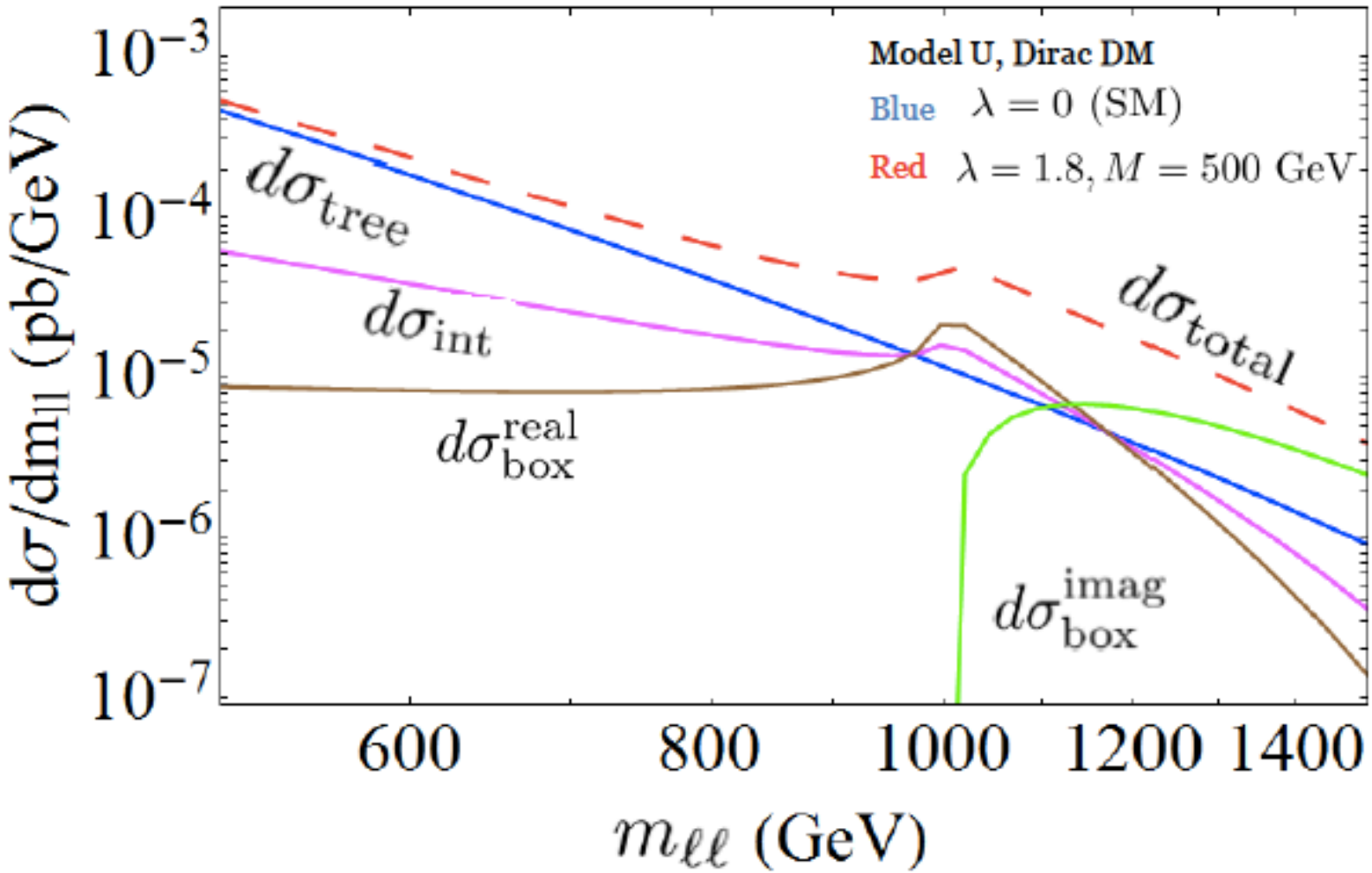
$d\sigma_{\rm tree} + d\sigma^{\rm imag}_{\rm box}$

Breakdown of rates



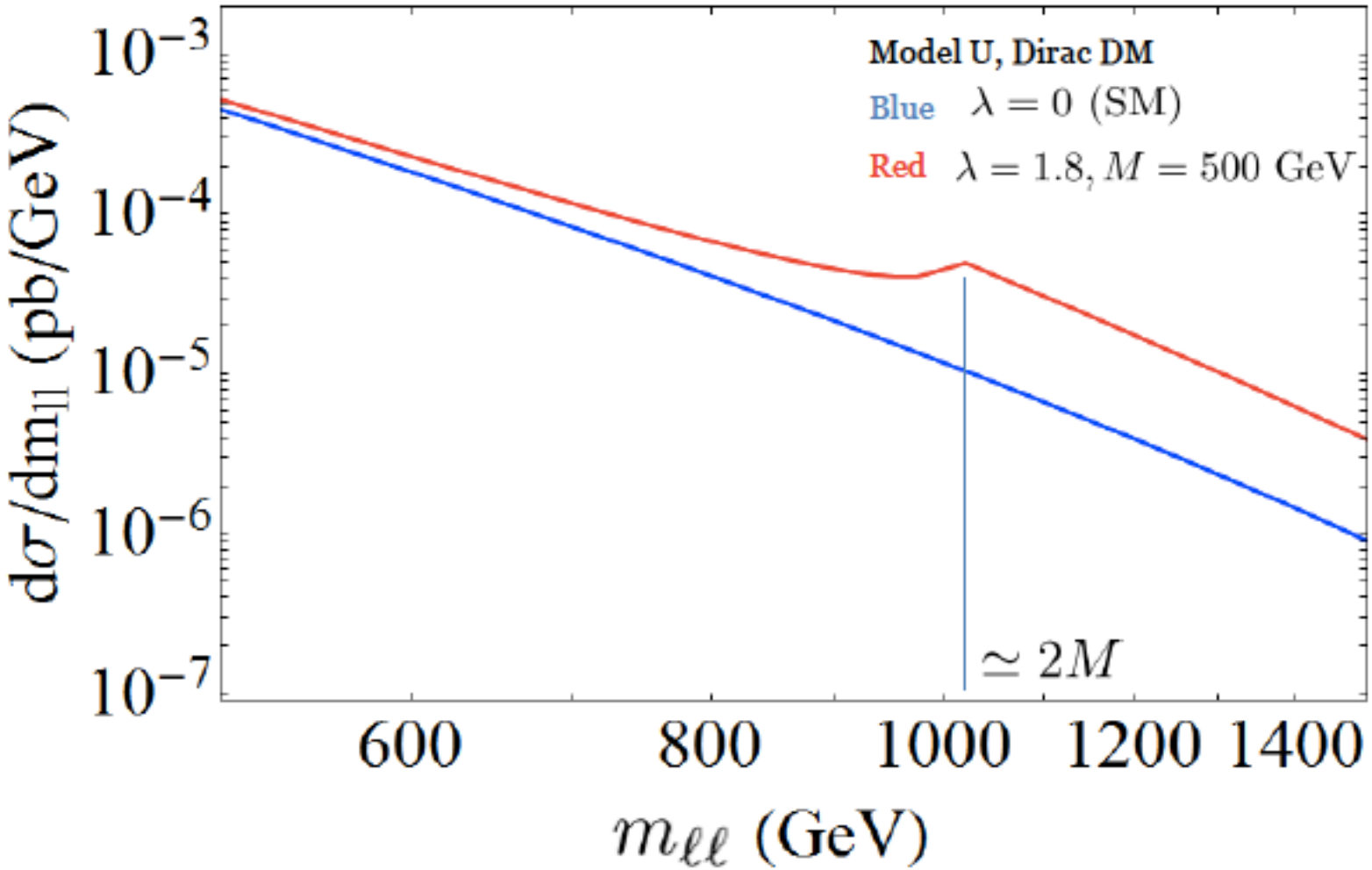
$$d\sigma_{\rm tree} + d\sigma^{\rm real}_{\rm box} + d\sigma^{\rm imag}_{\rm box}$$

Breakdown of rates

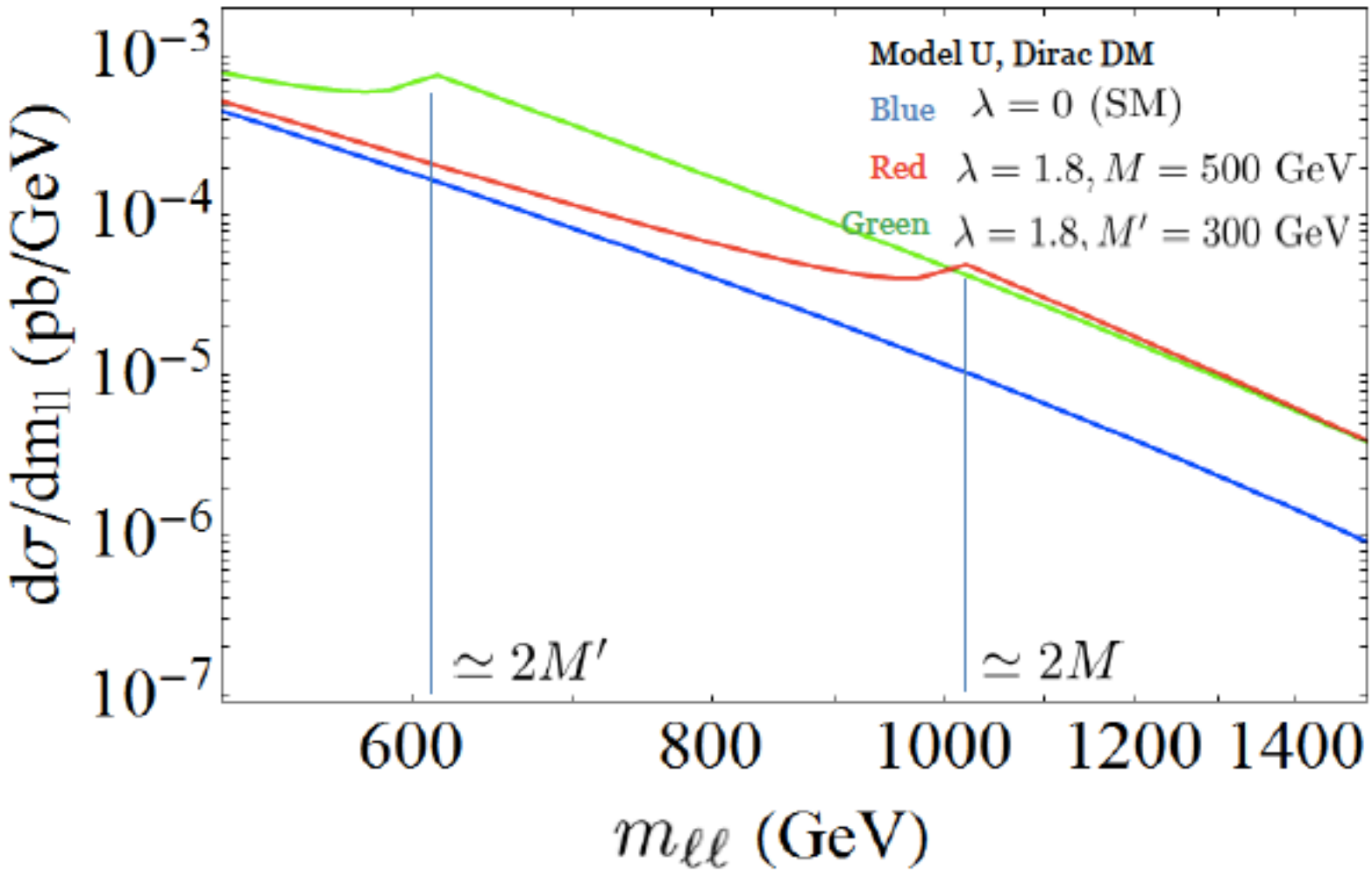


$$d\sigma_{\rm tree} + d\sigma_{\rm int} + d\sigma_{\rm box}^{\rm real} + d\sigma_{\rm box}^{\rm imag}$$

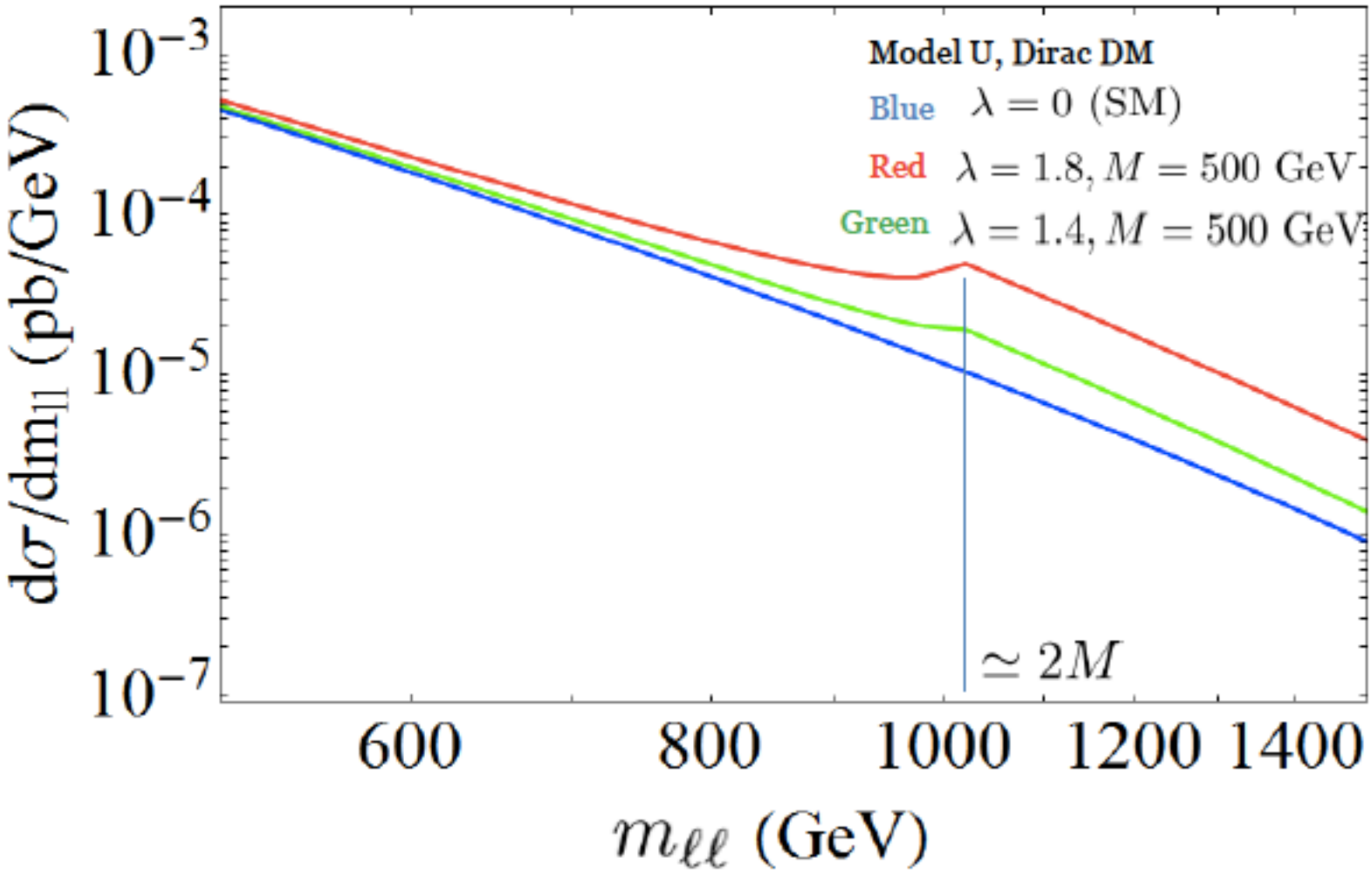
The signal (again)



Mass information

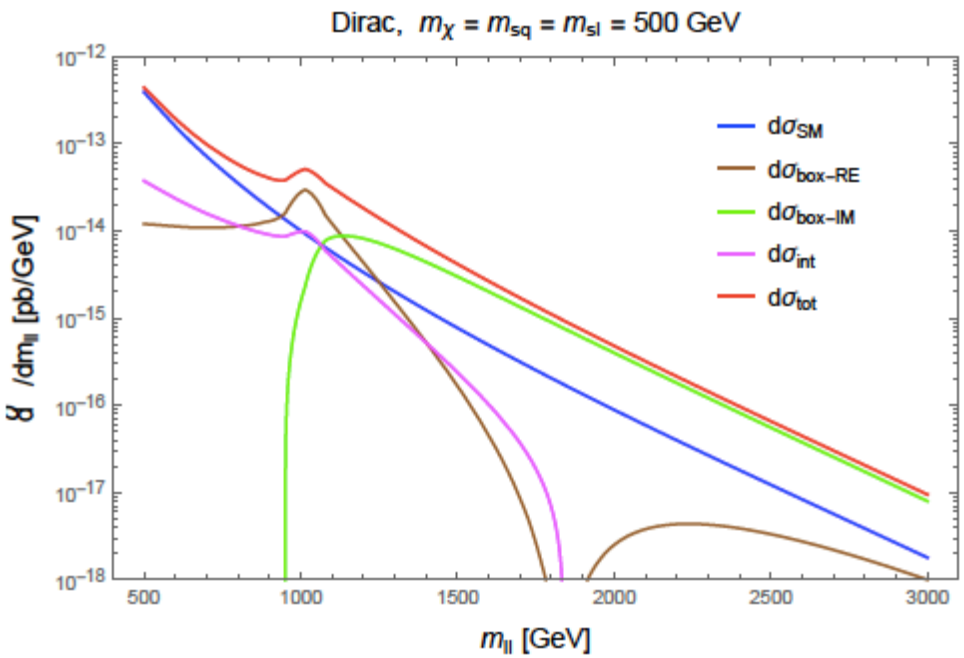


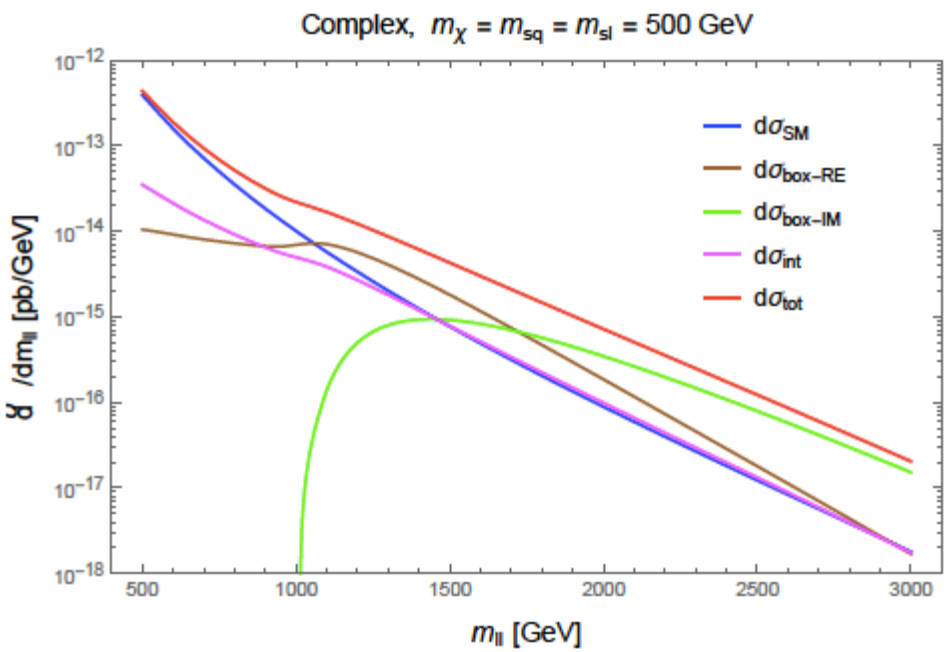
λ large: $d\sigma_{\rm box}$ dominance



2) Numeric of Box Diagrams

Scalar vs. Fermion Boxes

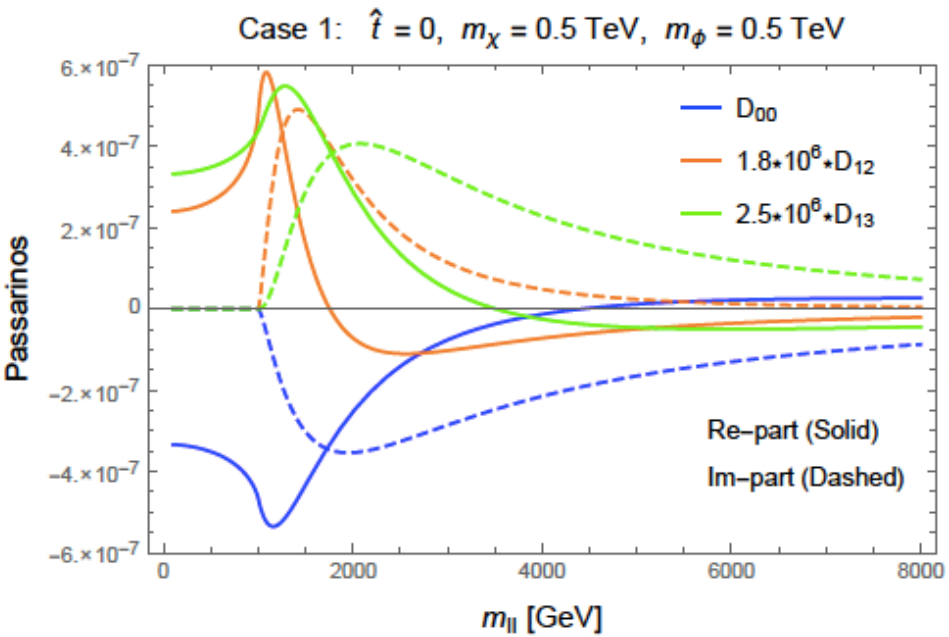


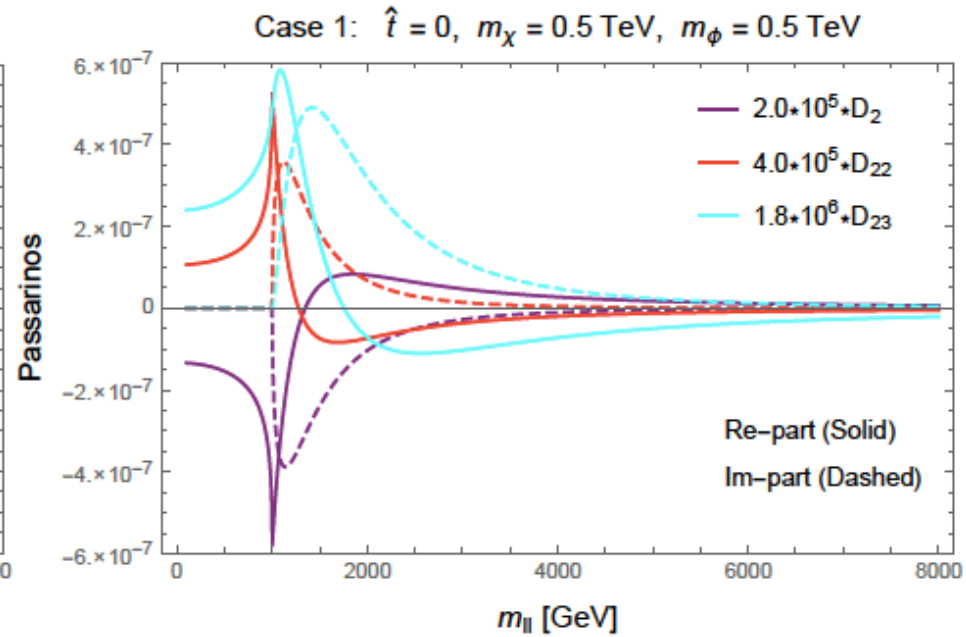


Scalar vs. Fermion Boxes

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)^{\mathrm{Re}}_{\mathrm{Fermion}\,\chi} = \frac{\lambda^8}{64\pi^4}\left(\hat{s}+\hat{t}\right)^2 \mathrm{Re}\left[2D_{00}+\hat{s}\left(D_2+D_{12}+D_{22}+D_{23}\right)\right]^2 \equiv d\sigma_{pD},$$

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)^{\mathrm{Re}}_{\mathrm{Scalar}\,\chi} = \frac{\lambda^8}{64\pi^4}\left(\hat{s}+\hat{t}\right)^2 \mathrm{Re}\left[-2D_{00}+\hat{t}\,D_{13}\right]^2 \equiv d\sigma_{pCS},$$





Scalar vs. Fermion Boxes

Assuming $\hat{t} = 0$, one can expand the functions $d\sigma_{pD}$ and $d\sigma_{pCS}$ (using Package-X)

$$d\sigma_{pD}\left(\hat{t}=0\right) = \frac{1}{64\pi^4} m_{ll}^4 \lambda^8 \mathrm{Re}\left[A_D + B_D + C_D\right]^2,$$

$$d\sigma_{pCS}\left(\hat{t}=0\right) = \frac{1}{64\pi^4} m_{ll}^4 \lambda^8 \mathrm{Re}\left[A_{CS} + B_{CS} + C_{CS}\right]^2,$$

where, for the Dirac case:

$$A_D = -\frac{2}{m_{ll}^2} - \frac{m_\phi^2\left(m_{ll}^2 + 2m_\phi^2 - 2m_\chi^2\right)\log\left(m_\phi^2/m_\chi^2\right)}{m_{ll}^2\left[m_{ll}^2 m_\phi^2 + \left(m_\phi^2 - m_\chi^2\right)^2\right]},$$

$$B_D = -\frac{\sqrt{m_{ll}^2\left(m_{ll}^2 - 4m_\chi^2\right)}\left[m_{ll}^2 m_\phi^2 + 2\left(m_\phi^2 - m_\chi^2\right)^2\right]}{\left[m_{ll}^2 m_\phi^2 + \left(m_\phi^2 - m_\chi^2\right)^2\right]}\log\left[Arg\left(m_{ll}^2\right)\right],$$

$$C_D = -\frac{2\left(m_\phi^2 - m_\chi^2\right)}{m_{ll}^2}\mathrm{ScalarC0}\left[0, 0, m_{ll}^2, m_\chi^2, m_\phi^2, m_\chi^2\right],$$

$$Arg\left(m_{ll}^2\right) = \frac{-m_{ll}^2 + 2m_\chi^2 + \sqrt{m_{ll}^2\left(m_{ll}^2 - 4m_\chi^2\right)}}{2m_\chi^2},$$

For degenerate DM-mediator masses, this contribution vanishes!

Scalar vs. Fermion Boxes

$$\text{ScalarC0} \to \frac{1}{2m_{ll}^2} \log\left[Arg\left(m_{ll}^2\right)\right]^2 .$$

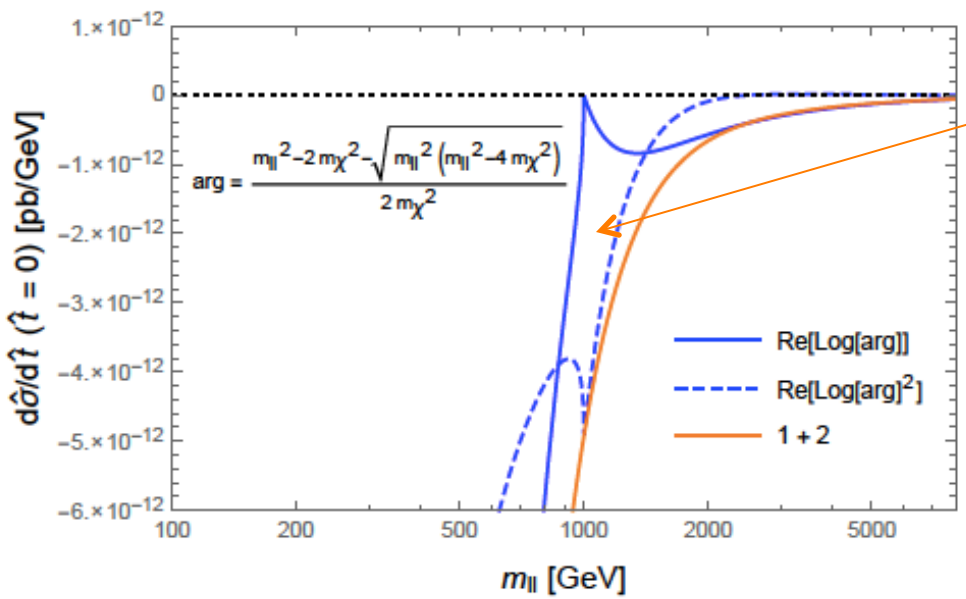
and for the scalar case:

$$A_{CS} = -\frac{2}{m_{ll}^2} - \frac{2m_\phi^2 \log\left(m_\phi^2/m_\chi^2\right)}{m_{ll}^2\left(m_\phi^2 - m_\chi^2\right)},$$

$$B_{CS} = -\frac{2\sqrt{m_{ll}^2\left(m_{ll}^2 - 4m_\chi^2\right)}}{m_{ll}^4} \log\left[Arg\left(m_{ll}^2\right)\right],$$

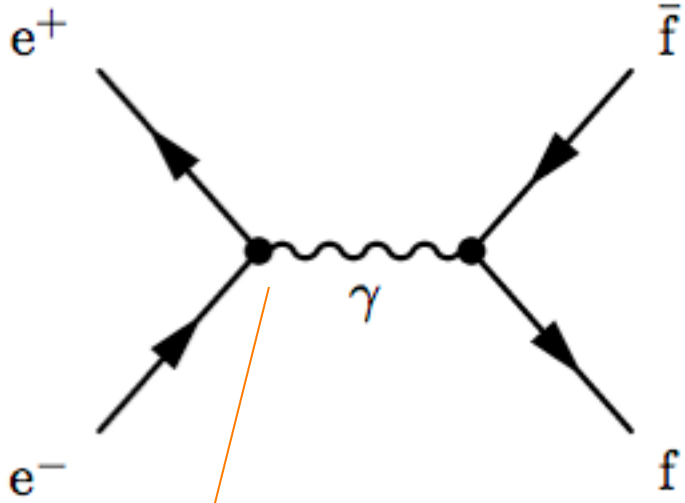
$$C_{CS} = -\frac{m_{ll}^2 + 2\left(m_\phi^2 - m_\chi^2\right)}{m_{ll}^2} \text{ScalarC0}\left[0, 0, m_{ll}^2, m_\chi^2, m_\phi^2, m_\chi^2\right].$$

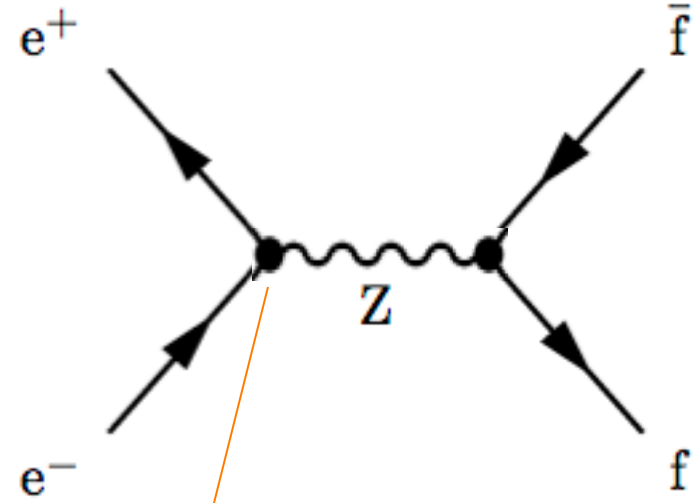
Scalar case presents log vs. log-squared cancellations at the threshold



The line 1 + 2 is the sum of the purple solid and dashed lines.

3) Forward-Backward Asymmetry



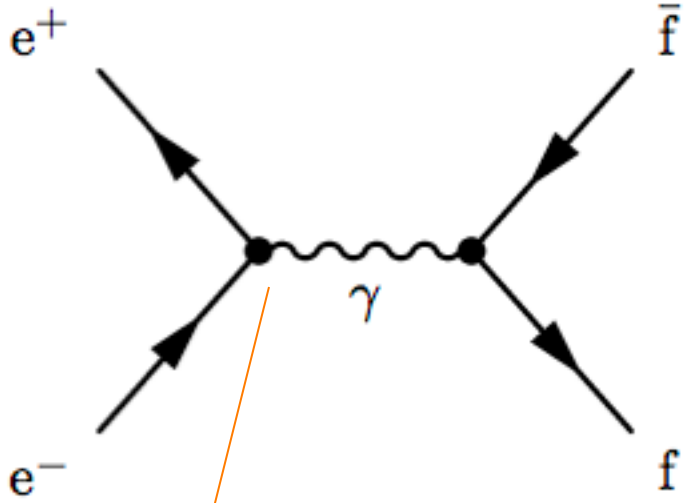


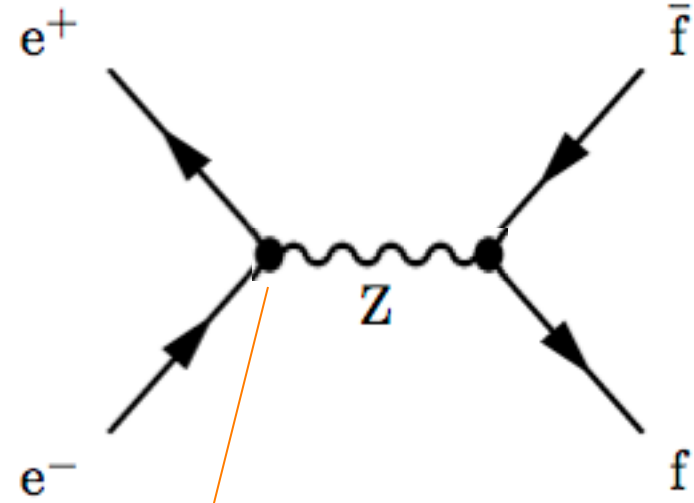
$$\boxed{\gamma_\mu}$$

$$\boxed{(c_V + c_A\gamma_5)\,\gamma_\mu}$$

$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta)$$

$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + a\cos\theta$$





$$\boxed{\gamma_\mu}$$

$$\boxed{(c_V + c_A\gamma_5)\,\gamma_\mu}$$

$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta)$$

$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + a\cos\theta$$

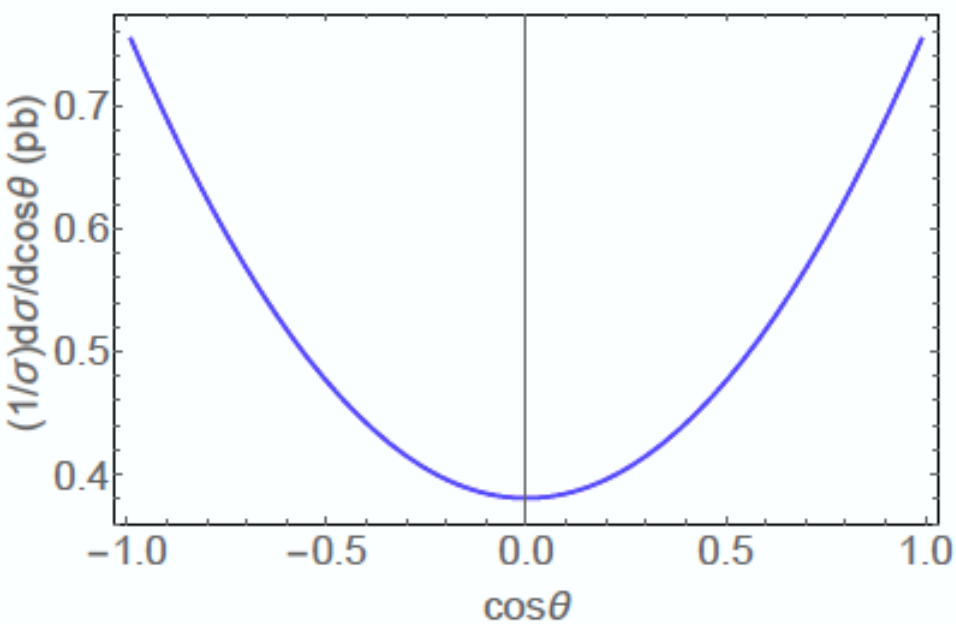
Out[87]= $(1 + C\theta^2)\, e^4\, Qq^2$

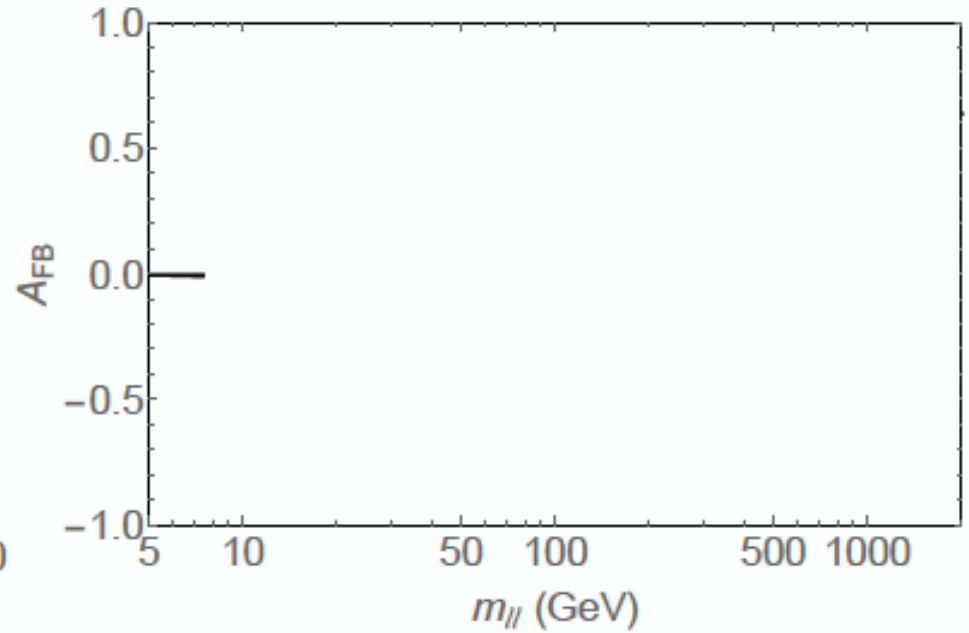
Out[86]= $$\frac{\left(8\,al\,aq\,bl\,bq\,C\theta + al^2\left(aq^2+bq^2\right)\left(1+C\theta^2\right) + bl^2\left(aq^2+bq^2\right)\left(1+C\theta^2\right)\right) g^4\, shat^2}{16\, cW^4\left(mZ^4 + shat^2 + mZ^2\left(-2\, shat + \Gamma z^2\right)\right)}$$

Forward-backward asymmetry

e+ e- —> l+ l-

m_{ll} ~ 10 GeV



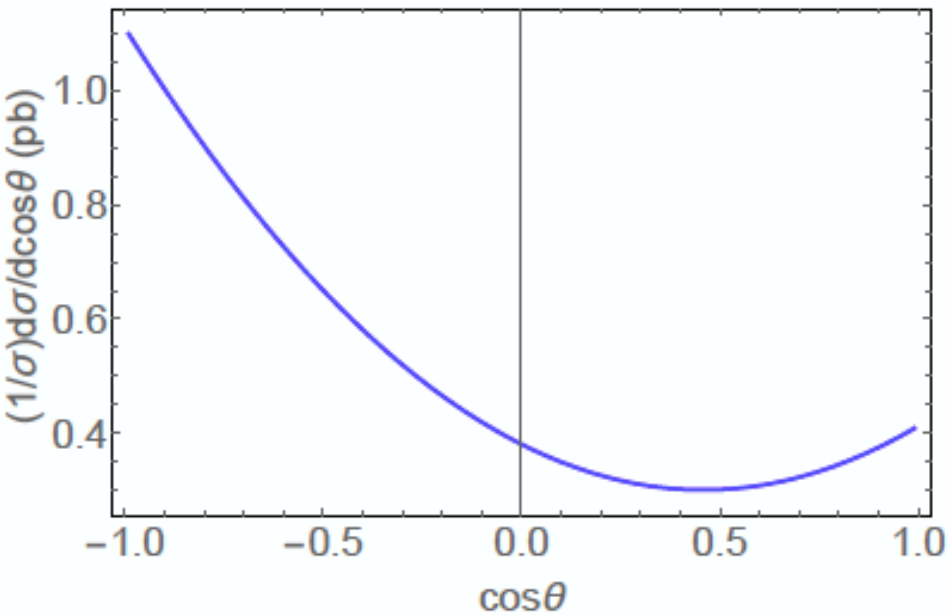


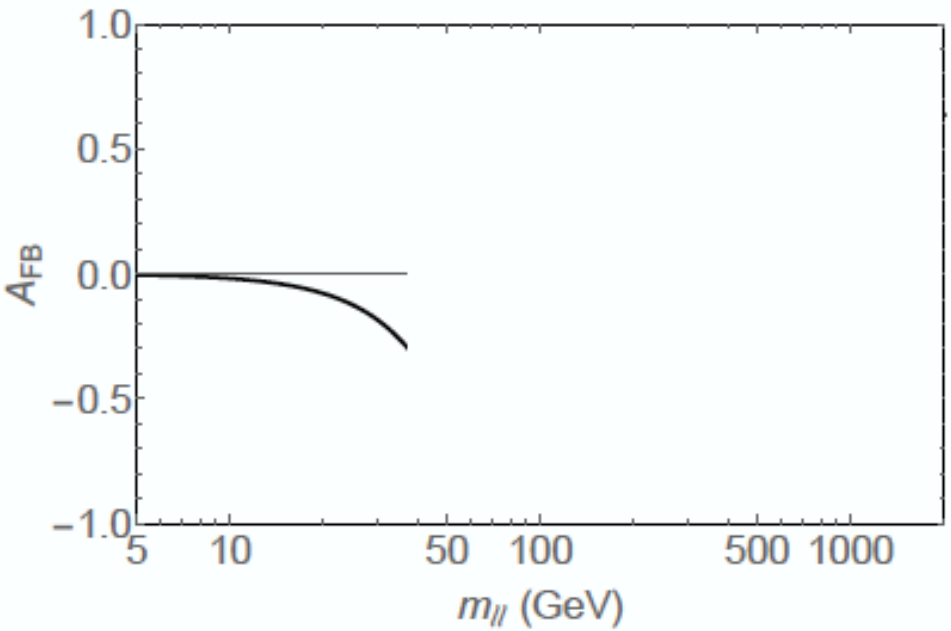
A_{FB} = area of right half minus left half
(normalized with total area)

Forward-backward asymmetry

e+ e- —> l+ l-

$m_{//}$ = 40 GeV



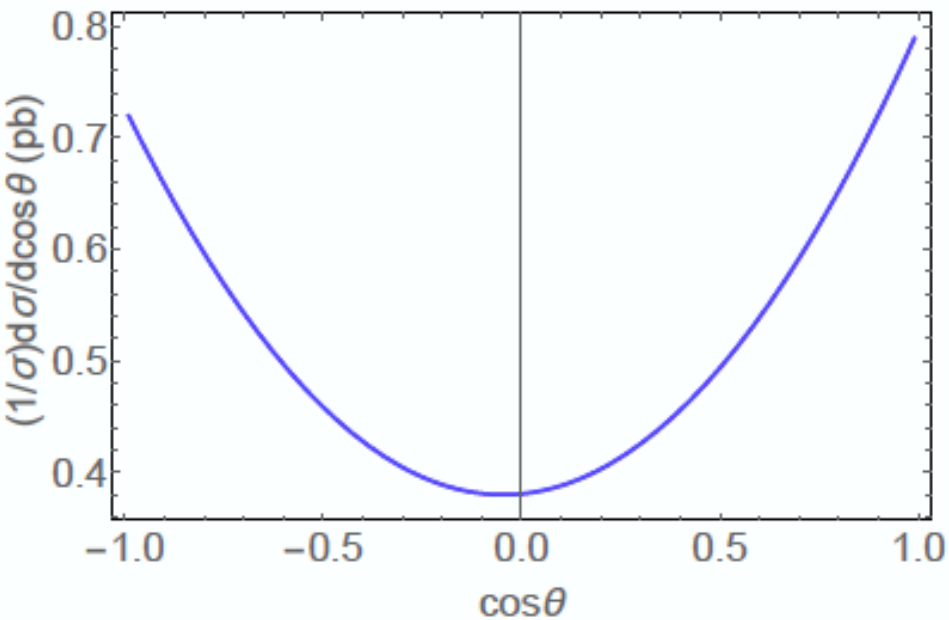


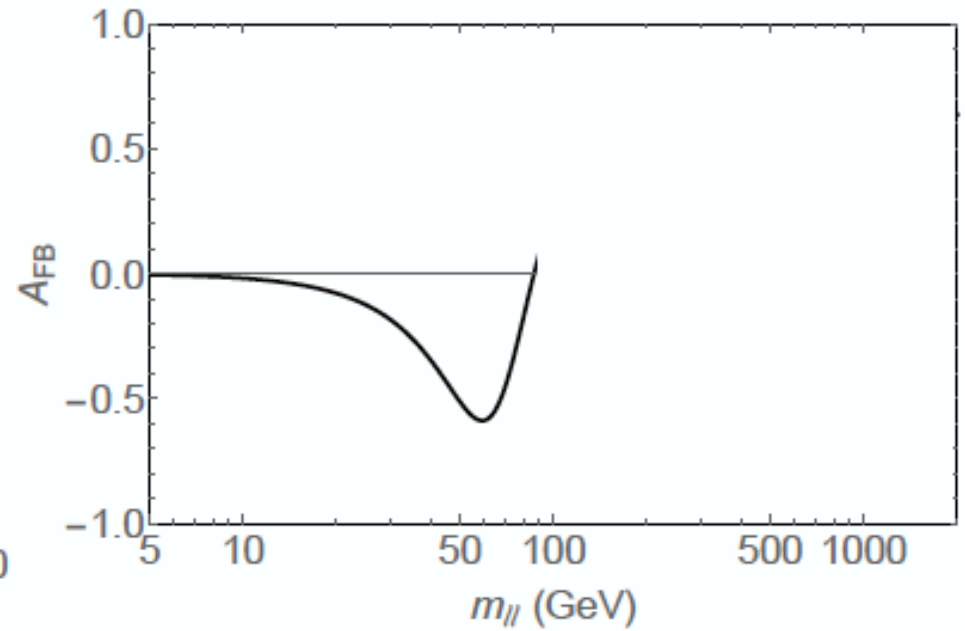
A_{FB} = area of right half minus left half
(normalized with total area)

Forward-backward asymmetry

e+ e- —> l+ l-

m_{ll} = 88 GeV



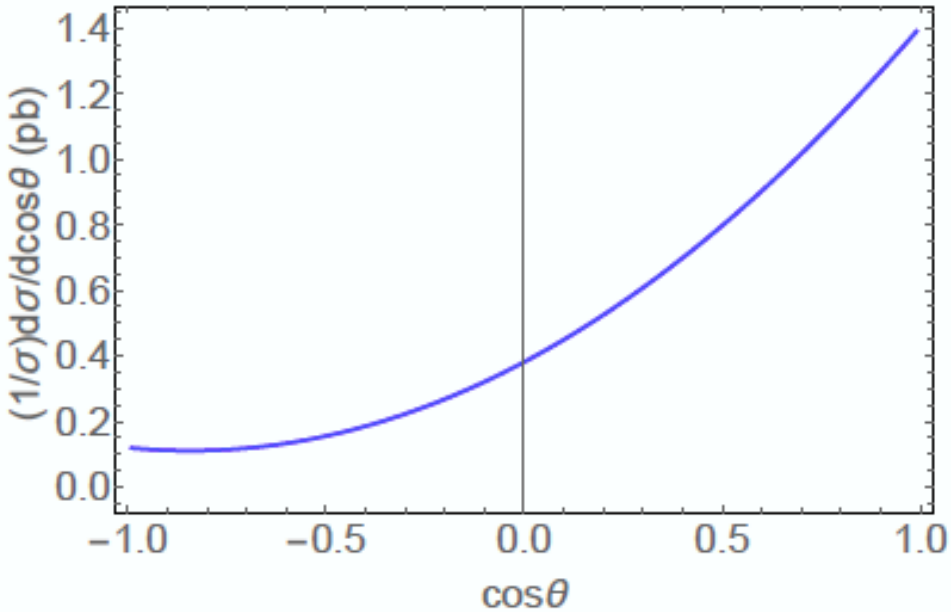


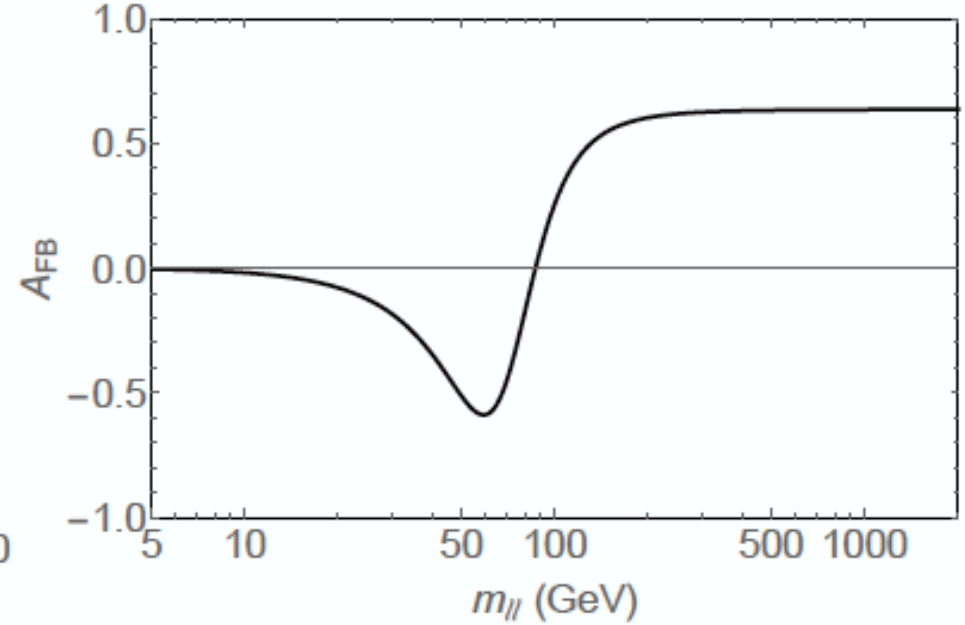
A_{FB} = area of right half minus left half
(normalized with total area)

Forward-backward asymmetry

e+ e- —> l+ l-

$m_{ll} >> M_Z$





A_{FB} = area of right half minus left half
(normalized with total area)