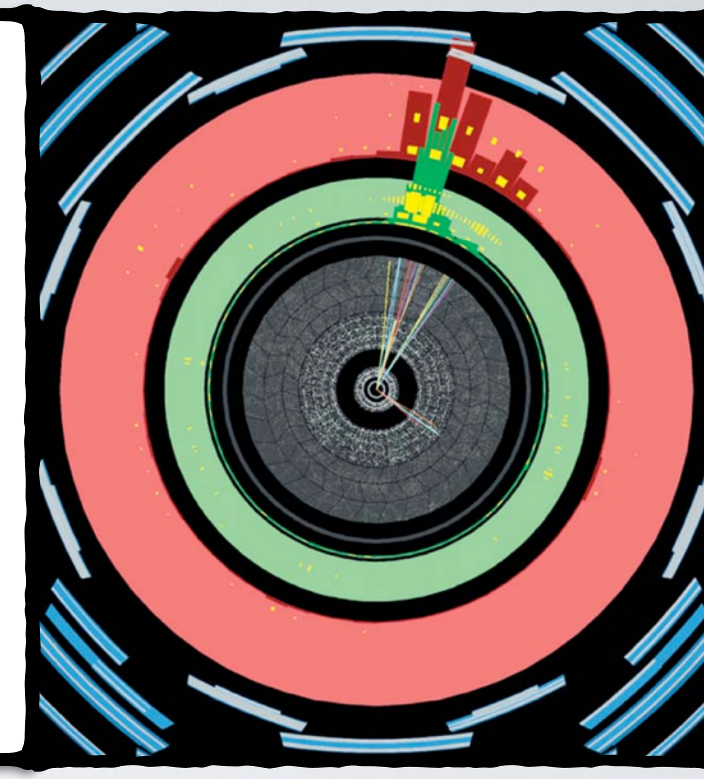
NEW OR ν MISSING ENERGY AT THE LHC?



Ian M. Shoemaker

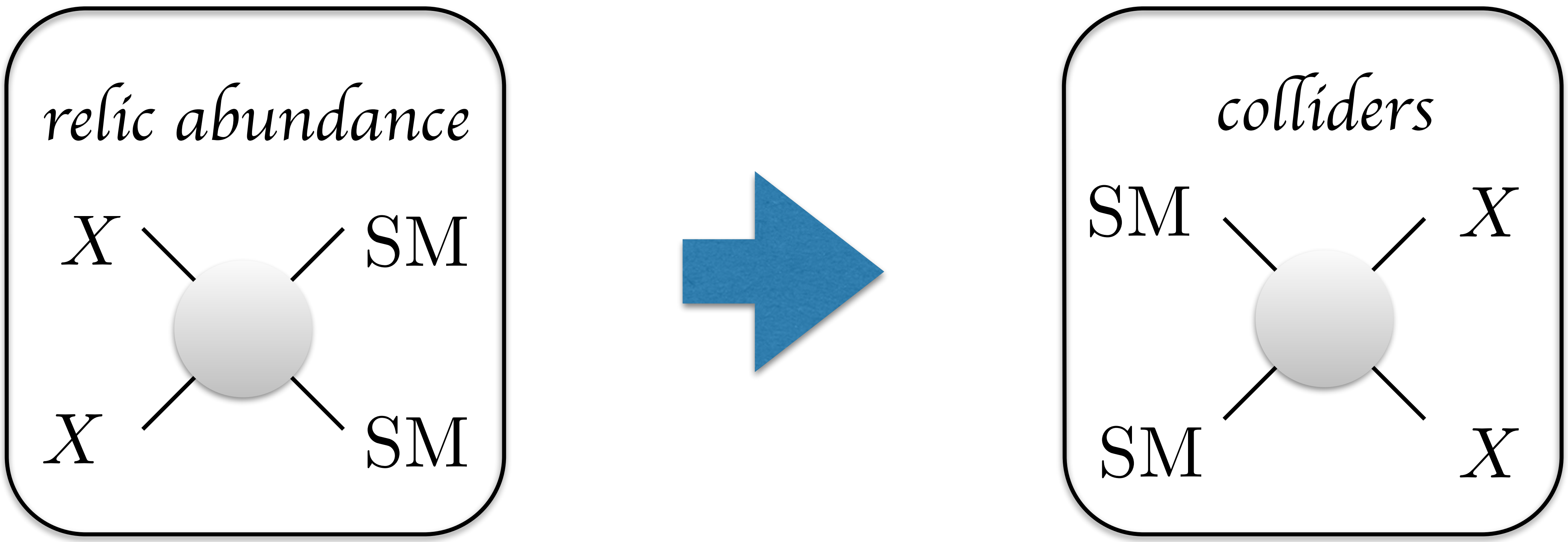
CP³ Origins
Cosmology & Particle Physics

The Pennsylvania State University
1855

Based on:

- Graesser, Friedland, **IMS**, Vecchi, Phys.Lett. B714 (2012) 267-275, arXiv: 1111.5331.
- Buarque Franzosi, Frandsen, IMS [1507.XXXX].

The Era of Data for Thermal Relics



For hadron colliders, monojet signal has dominated the field:

hep-ph/0403004, 0912.4511, 1002.4137, 1005.3797, 1107.2666 ,1109.4398, 1111.5331, 1112.5457,1202.2894 ,1203.1662 , 1204.0821 , 1204.3839, 1208.4605 , 1209.0231, 1211.6390, 1302.3619, 1307.2253, 1308.0592 , 1308.6799 , 1402.1275 , 1407.8257, 1409.2893, 1502.05721, 1503.05916, 1503.07874, …

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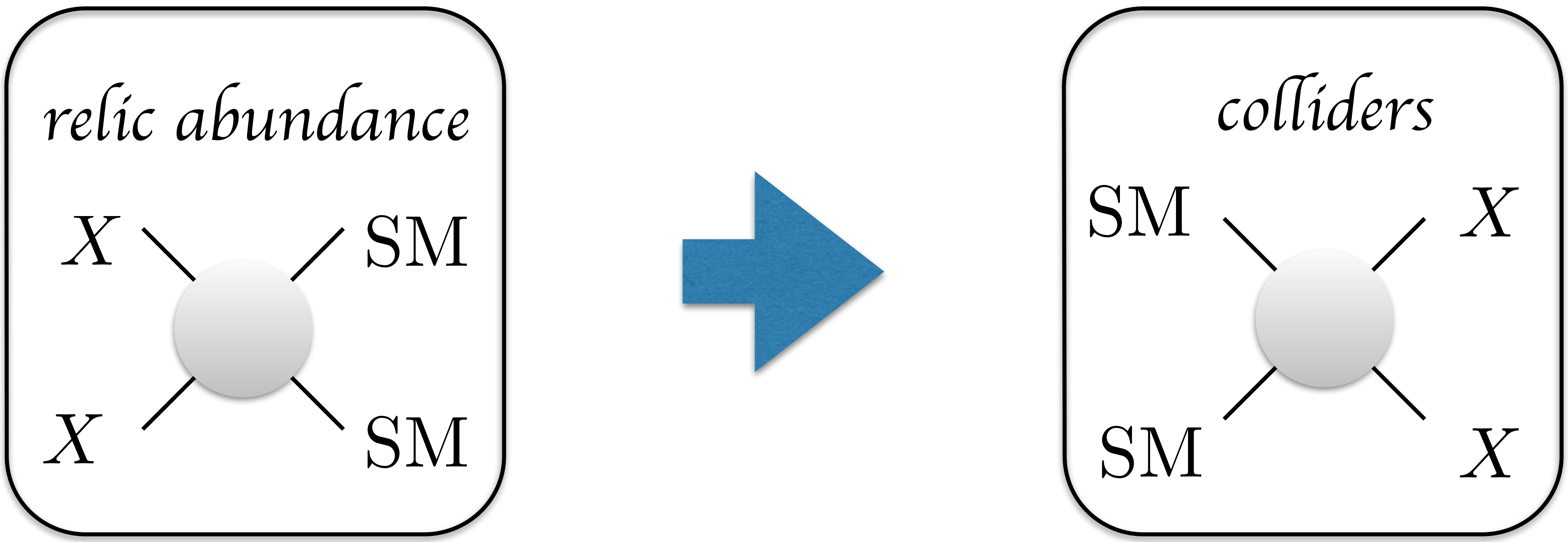

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- ***Now a standard search carried out by CMS & ATLAS.***

What to do with missing energy signals*?

* = assuming they appear in future data.

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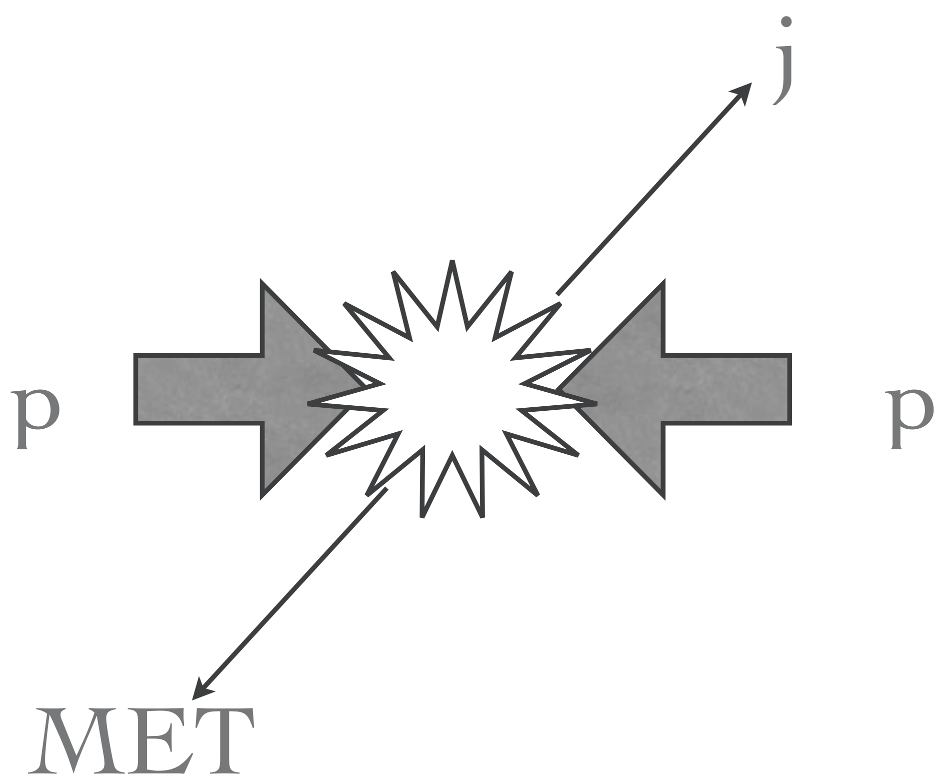
A point in LHC space



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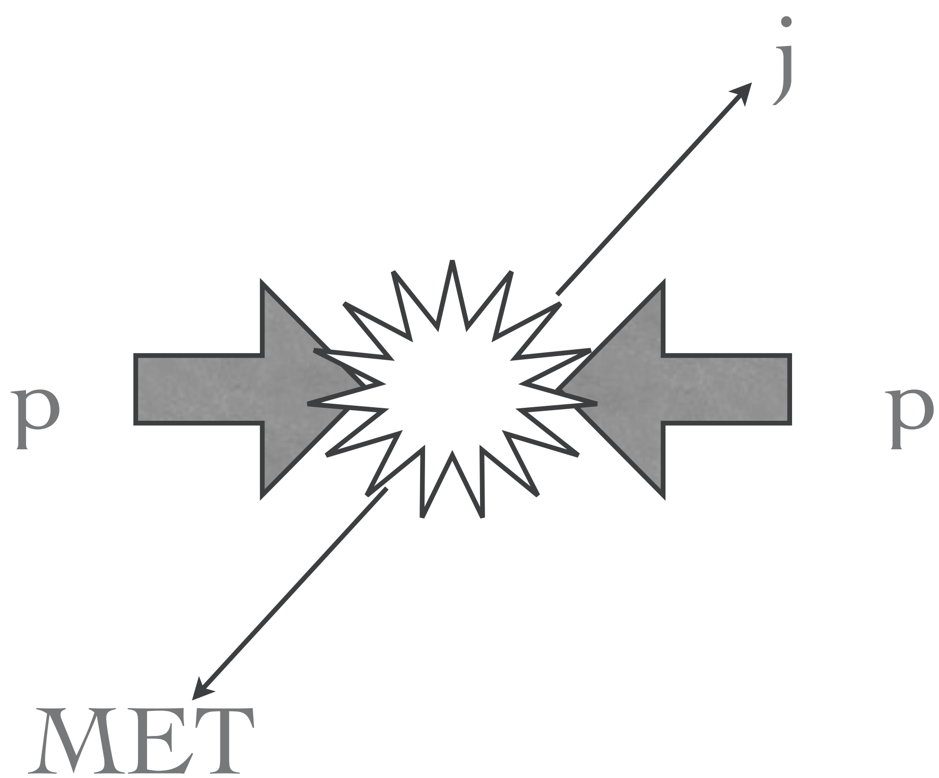
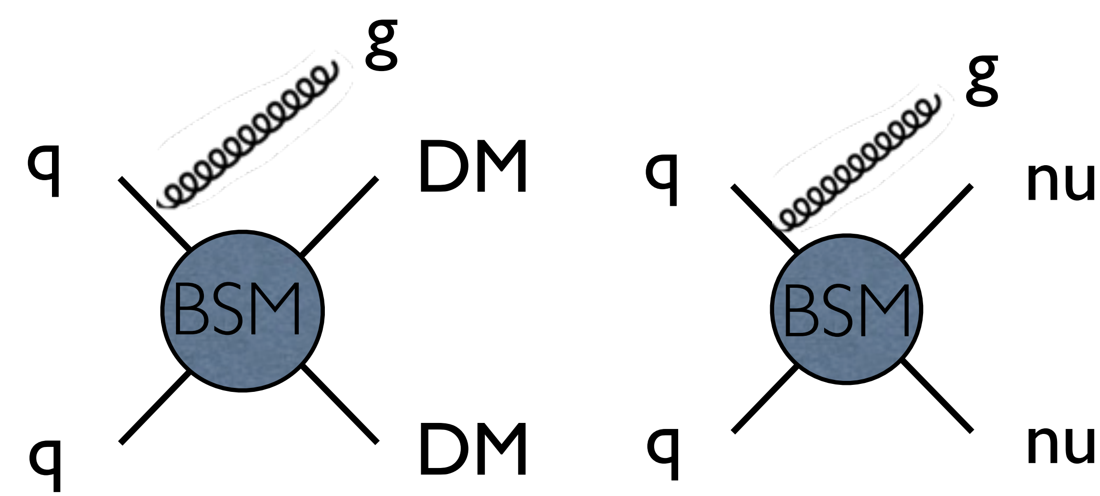


Many points in theory space



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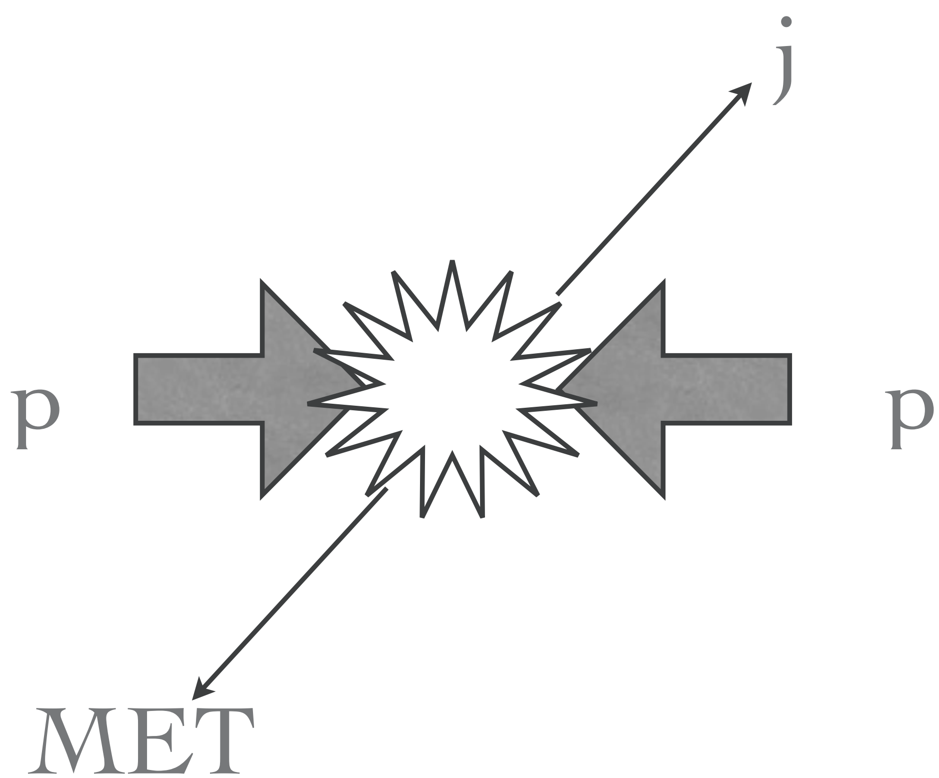

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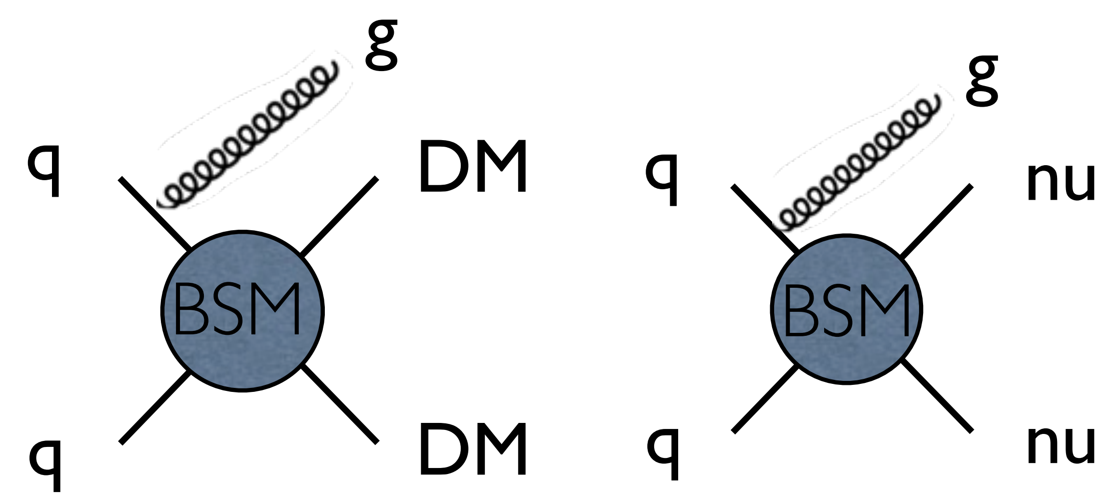

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Only confirmed source of missing energy are neutrinos.
Conservative to start with the neutrino hypothesis first.

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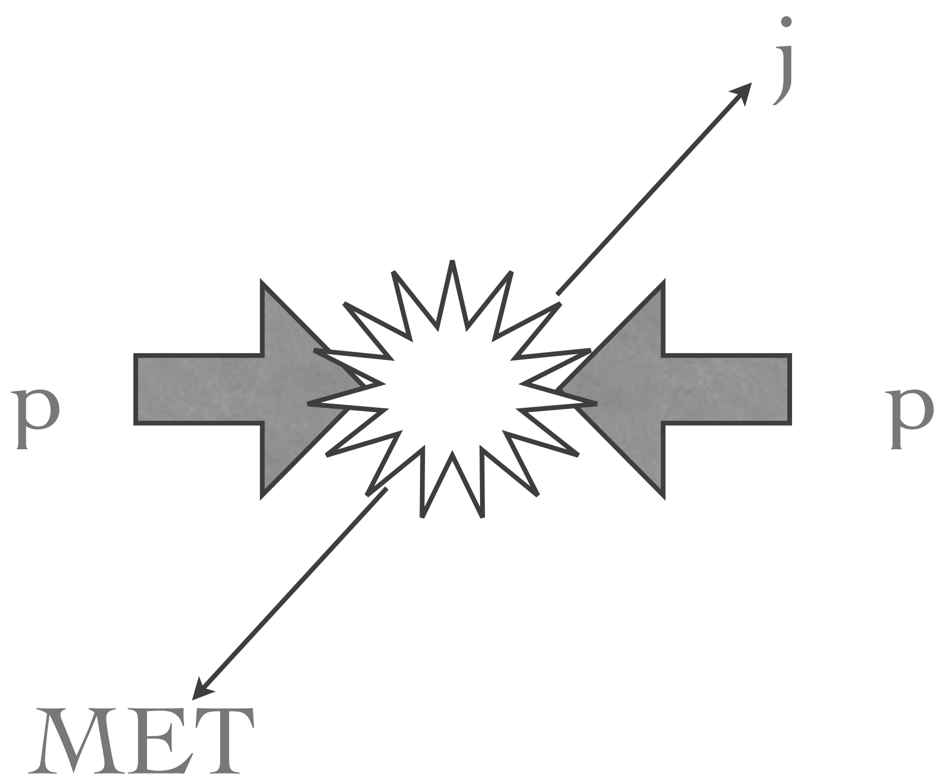

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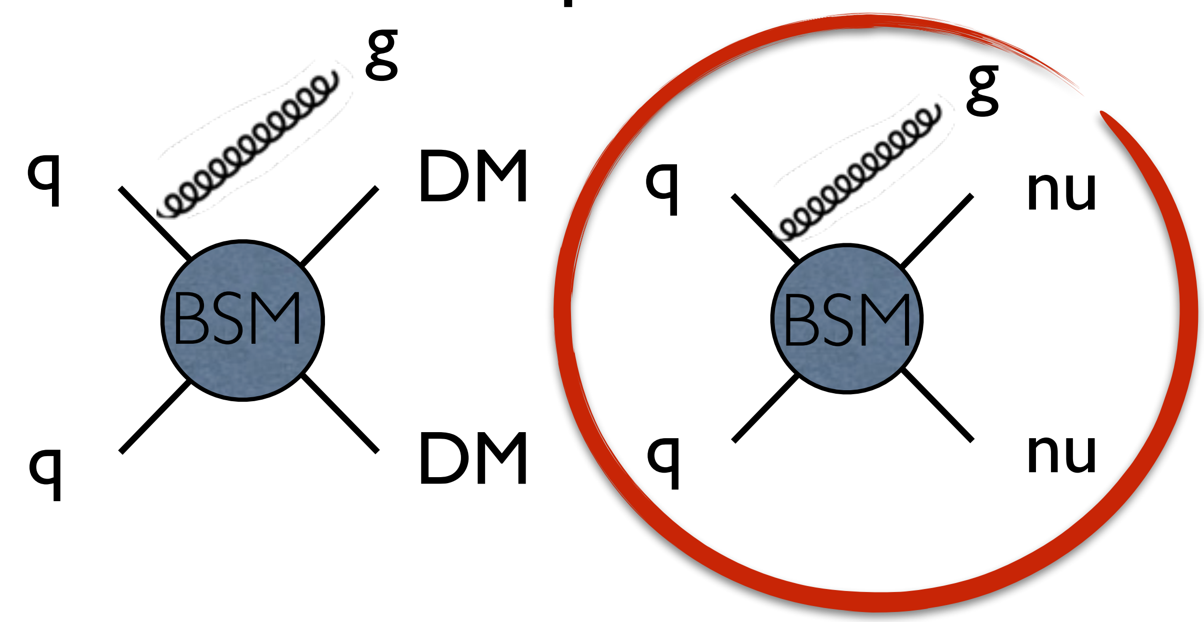

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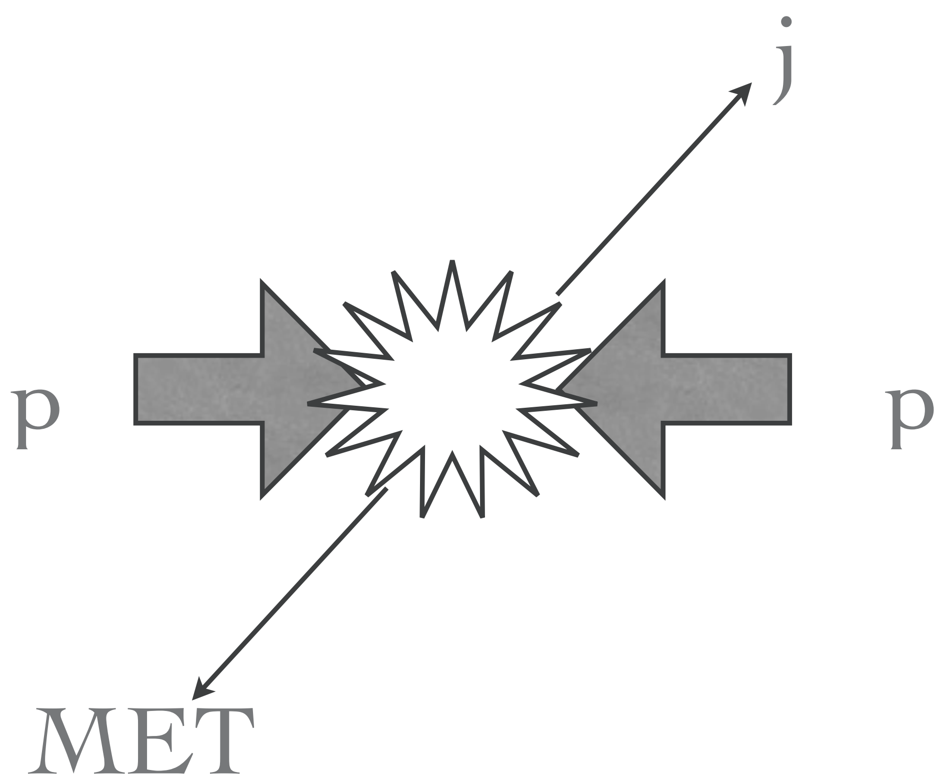

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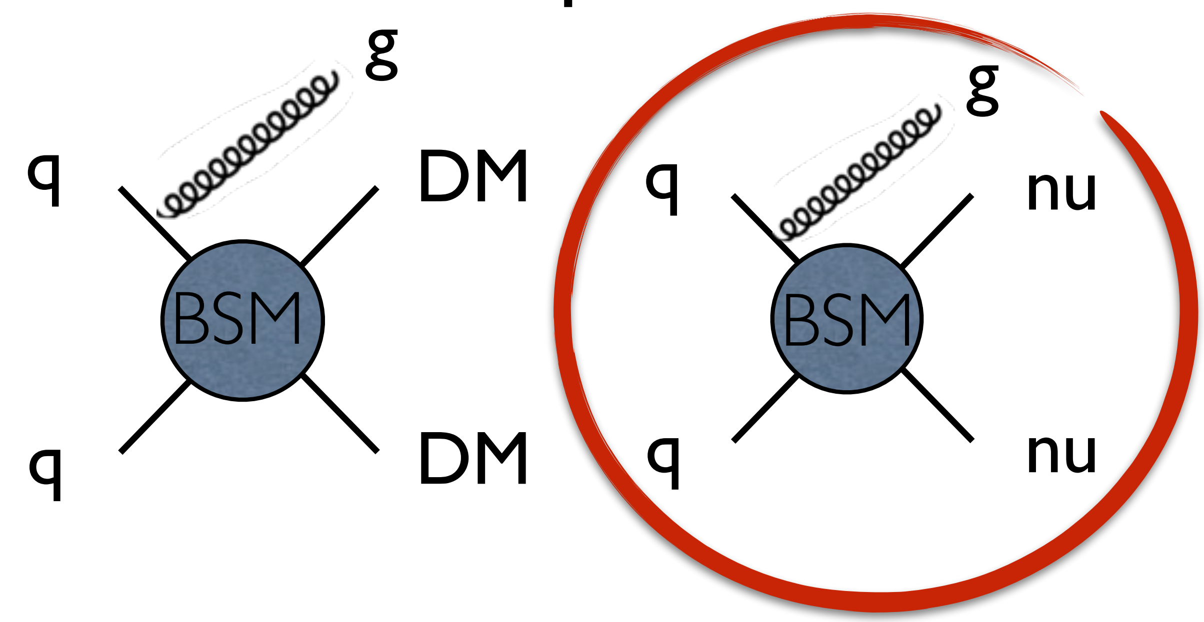

etc...

→ Only confirmed source of missing energy are neutrinos.
Conservative to start with the neutrino hypothesis first.

→ DM can be inferred at the LHC *if* *the neutrino hypothesis is rejected.*

How strong can neutrino-proton interactions be?

Simple parameterization of nu-proton interactions: EFT

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- First consider dimension-5 interactions, e.g. magnetic moment:

$$\mathscr{L} \supset \mu_\nu F^{\mu\nu} \overline{\nu} \sigma_{\mu\nu} \nu,$$

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→ Neutrino magnetic moments won’t produce much missing energy at the LHC.

Dim-6 Operators: Generalizing Fermi

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

Non-standard neutrino interactions (NSIs):

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F\,\epsilon^{fP}_{\alpha\beta}(\overline{\nu}_\alpha\gamma^\rho\nu_\beta)(\overline{f}\gamma_\rho P f)$$

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f =SM fermion
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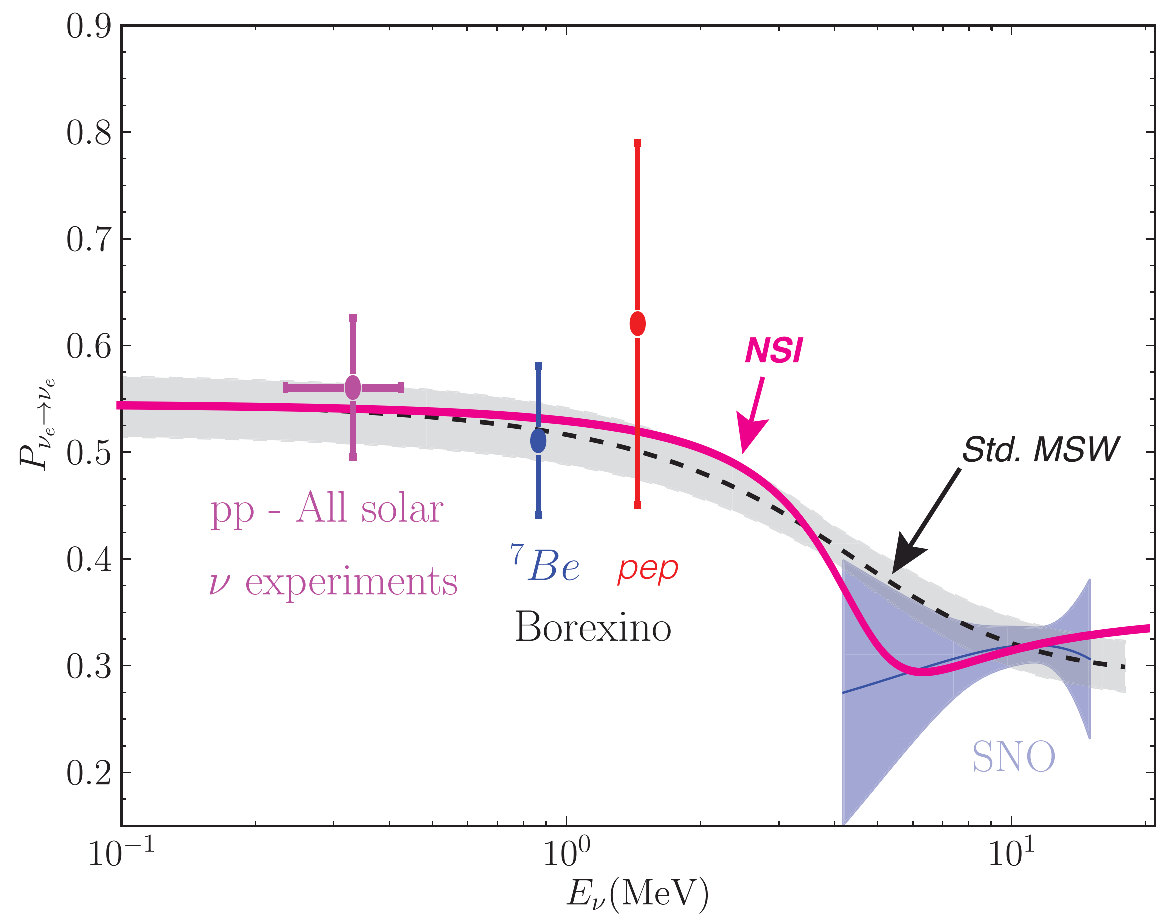
Laid the foundation for the MSW effect and pointed out that NSI can modify neutrino propagation.

Additional motivation from the Sun

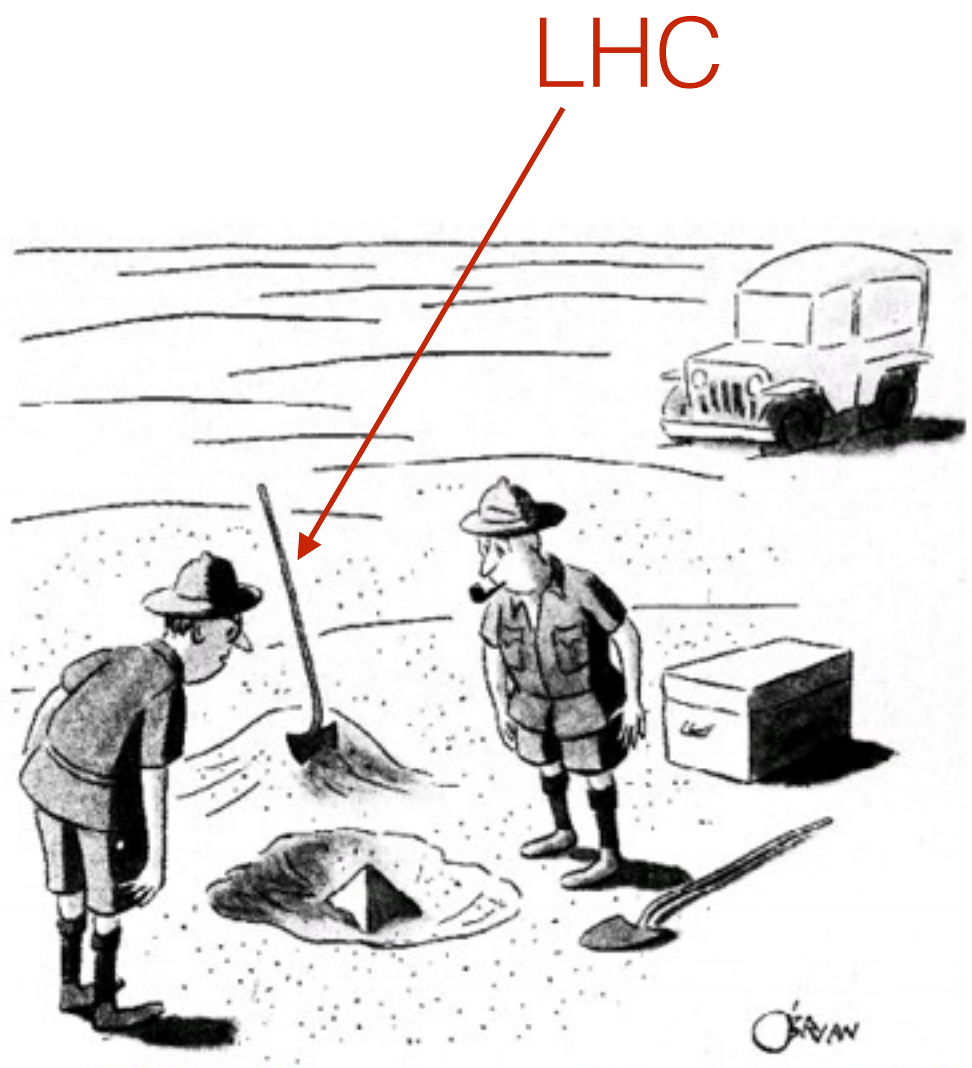
- Maximally minimal setup: just one NSI term nonzero, $\varepsilon_{e\tau}$
- Predicted MSW "upturn" so far unseen.
- NSI provides a better fit.
- Just below present CHARM limit (< 0.5).

$$\varepsilon_{e\tau} = 0.4$$



A. Friedland, IMS [1207.6642]

"This could be the discovery of the century. Depending, of course, on how far down it goes."



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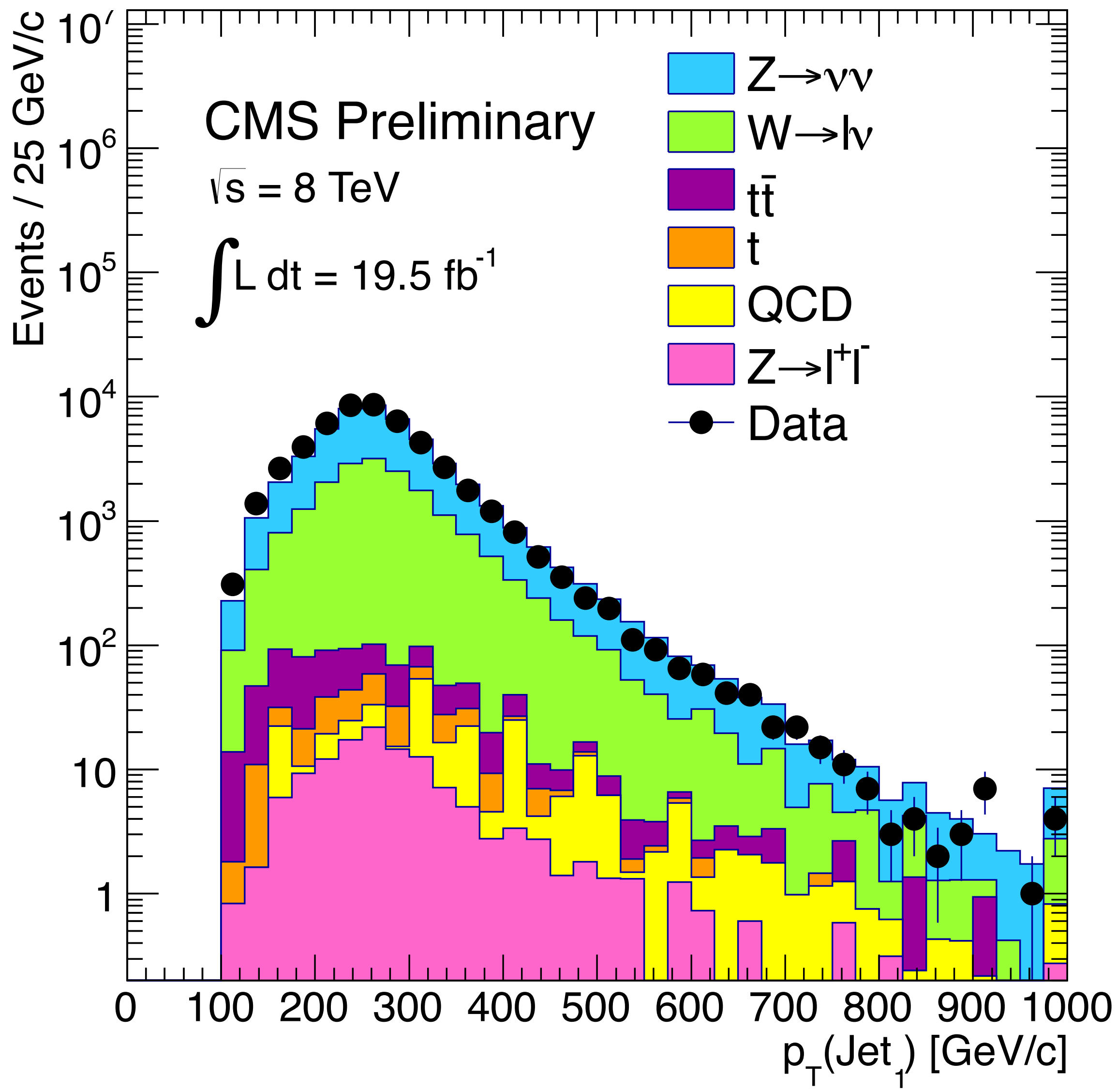
Monojet Backgrounds



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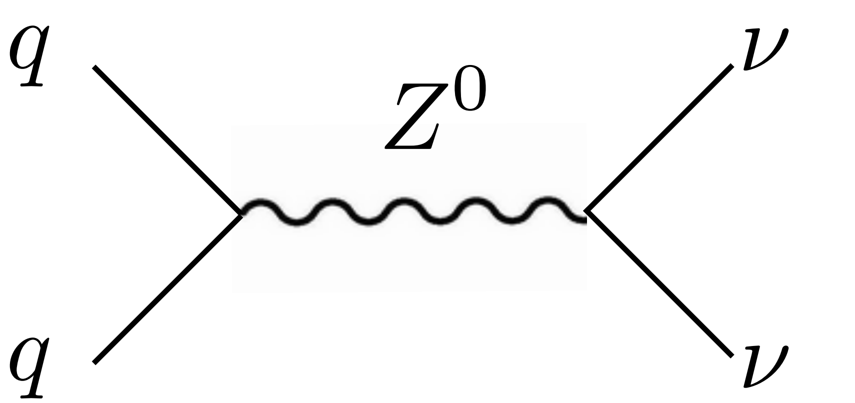

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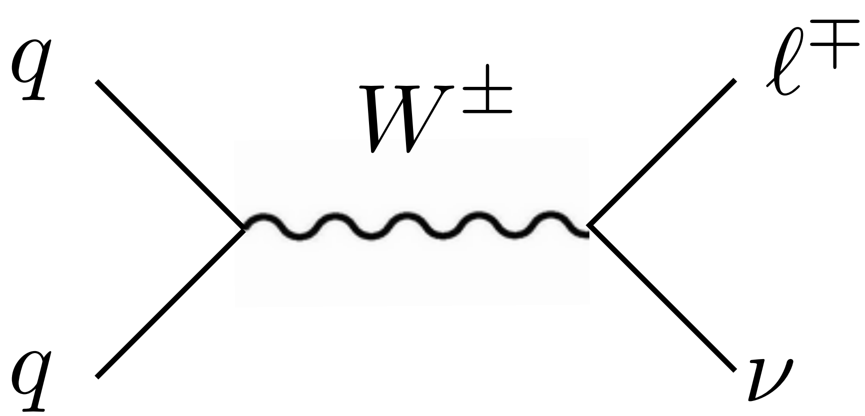

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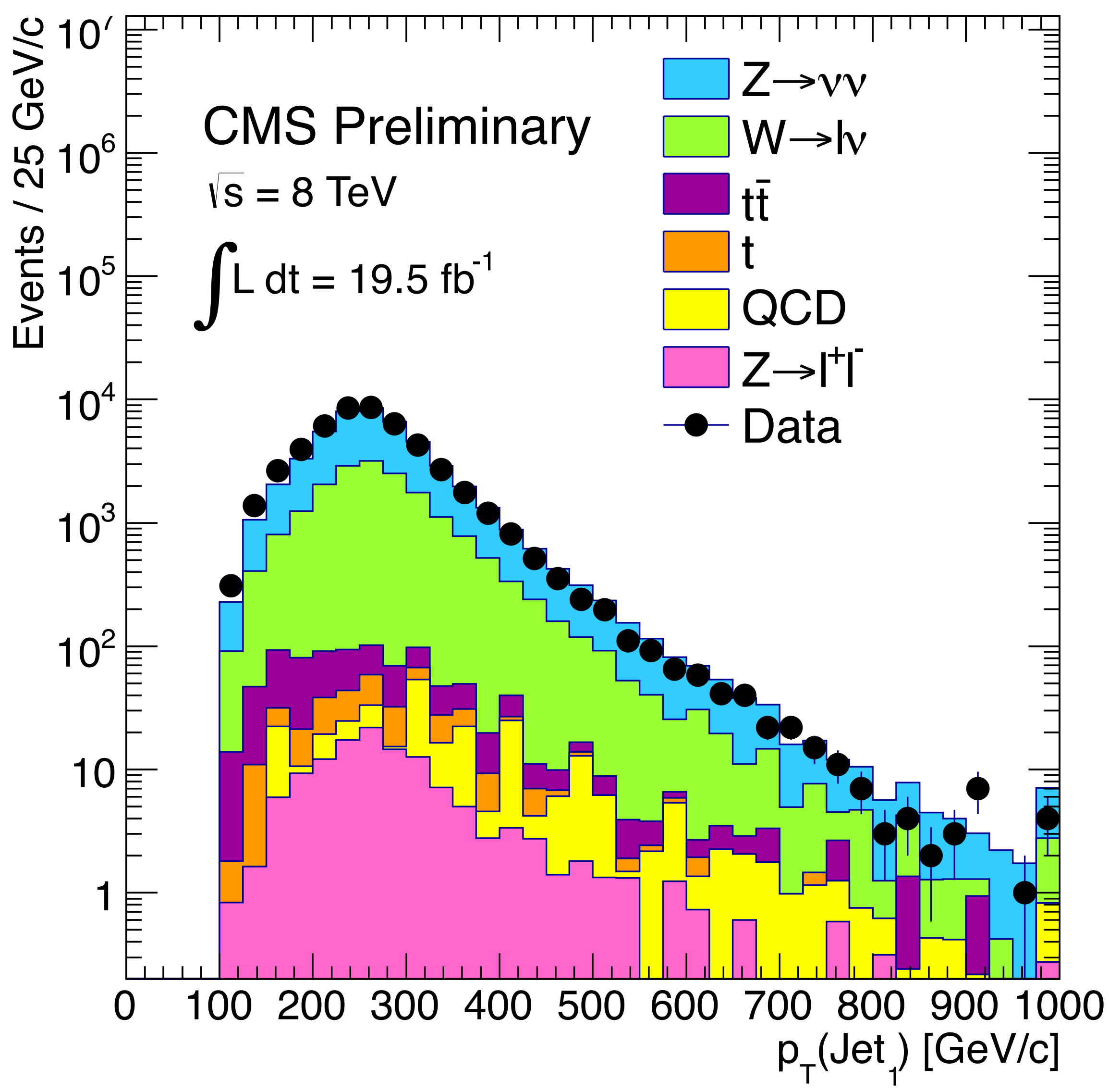

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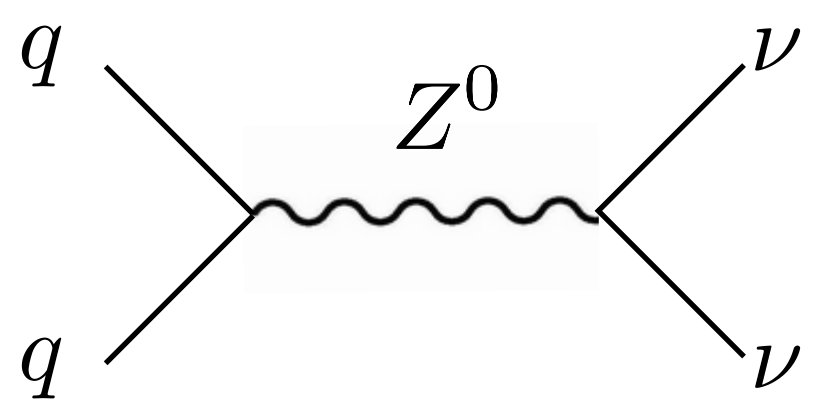

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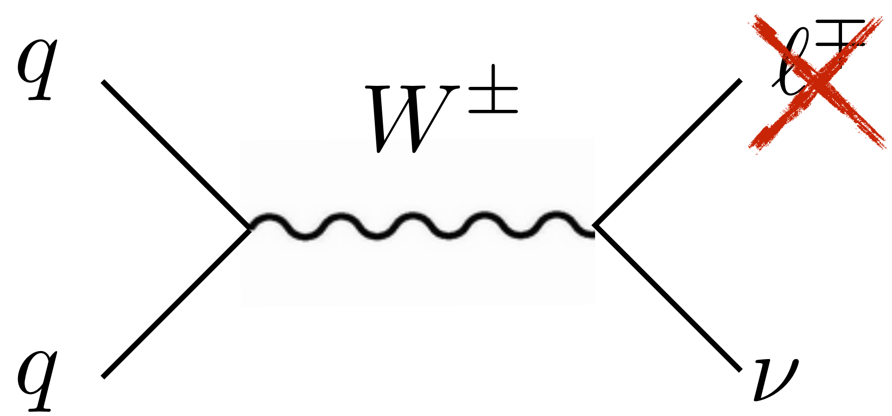

missed low-E or longitudinal lepton.

Contact NSI

$$\mathscr{L}_{NSI} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fP}\left(\overline{\nu}_\alpha\gamma_\rho\nu_\beta\right)\left(\overline{f}\gamma^\rho P f\right)$$

$$@ \sqrt{s} = 7 \text{ TeV}$$

- Notice that LHC limits on u-quarks are stronger than for d-quarks thanks to PDFs.

- Subtlety: *flavor off-diagonal* constraints stronger because conjugate reaction is distinct.

$$pp \longrightarrow j\overline{\nu}_\alpha\nu_\beta$$

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Sum two processes incoherently.

	CDF		ATLAS [31]		
	GSNP [32]	ADD [4, 5]	LowPt	HighPt	veryHighPt
$\varepsilon^{uP}_{\alpha\beta=\alpha}$	0.45	0.51	0.40	0.19	0.17
$\varepsilon^{dP}_{\alpha\beta=\alpha}$	1.12	1.43	0.54	0.28	0.26
$\varepsilon^{uP}_{\alpha\beta\neq\alpha}$	0.32	0.36	0.28	0.13	0.12
$\varepsilon^{dP}_{\alpha\beta\neq\alpha}$	0.79	1.00	0.38	0.20	0.18

Friedland, Graesser, IMS, Vecchi, [1111.5331]

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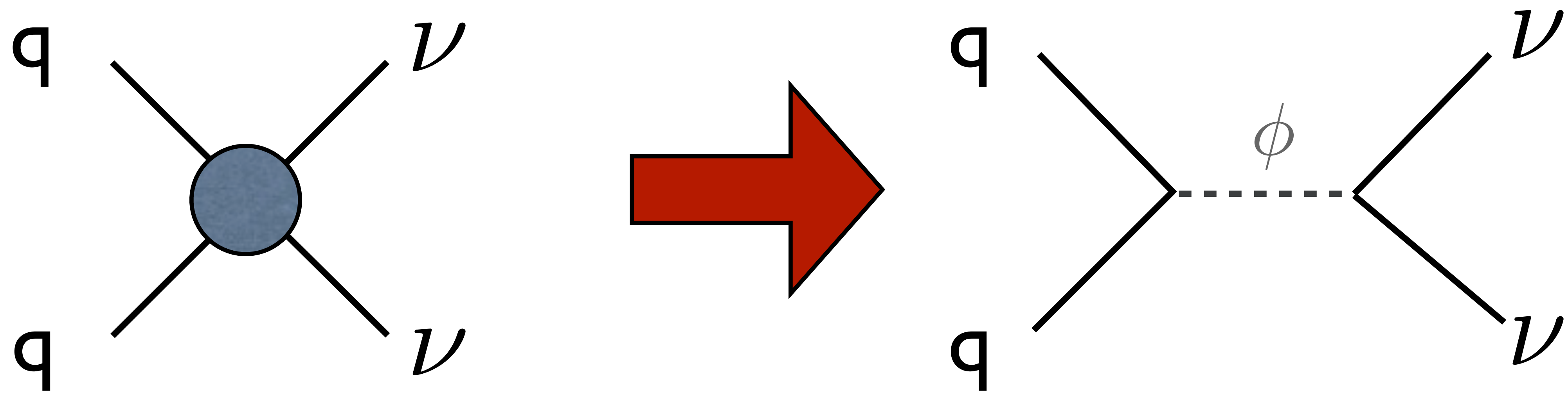
Already setting new limits stronger than low-energy constraints for some flavor-structures.

E.g. LHC bests the CHARM limit on $\varepsilon^{ee}_u, \varepsilon^{ee}_d$

On-shellness



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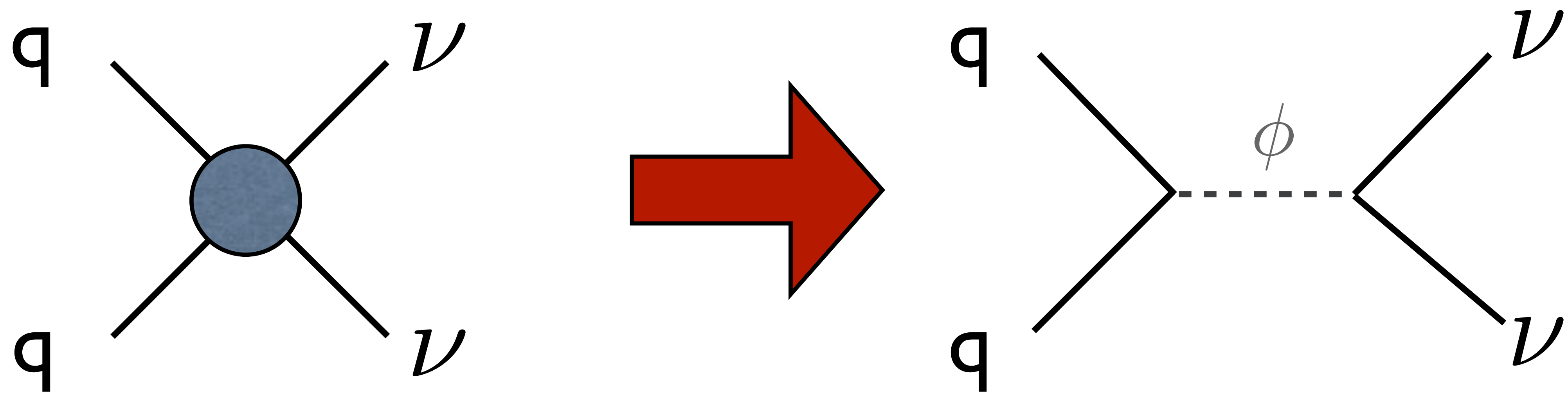

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What if it’s not?

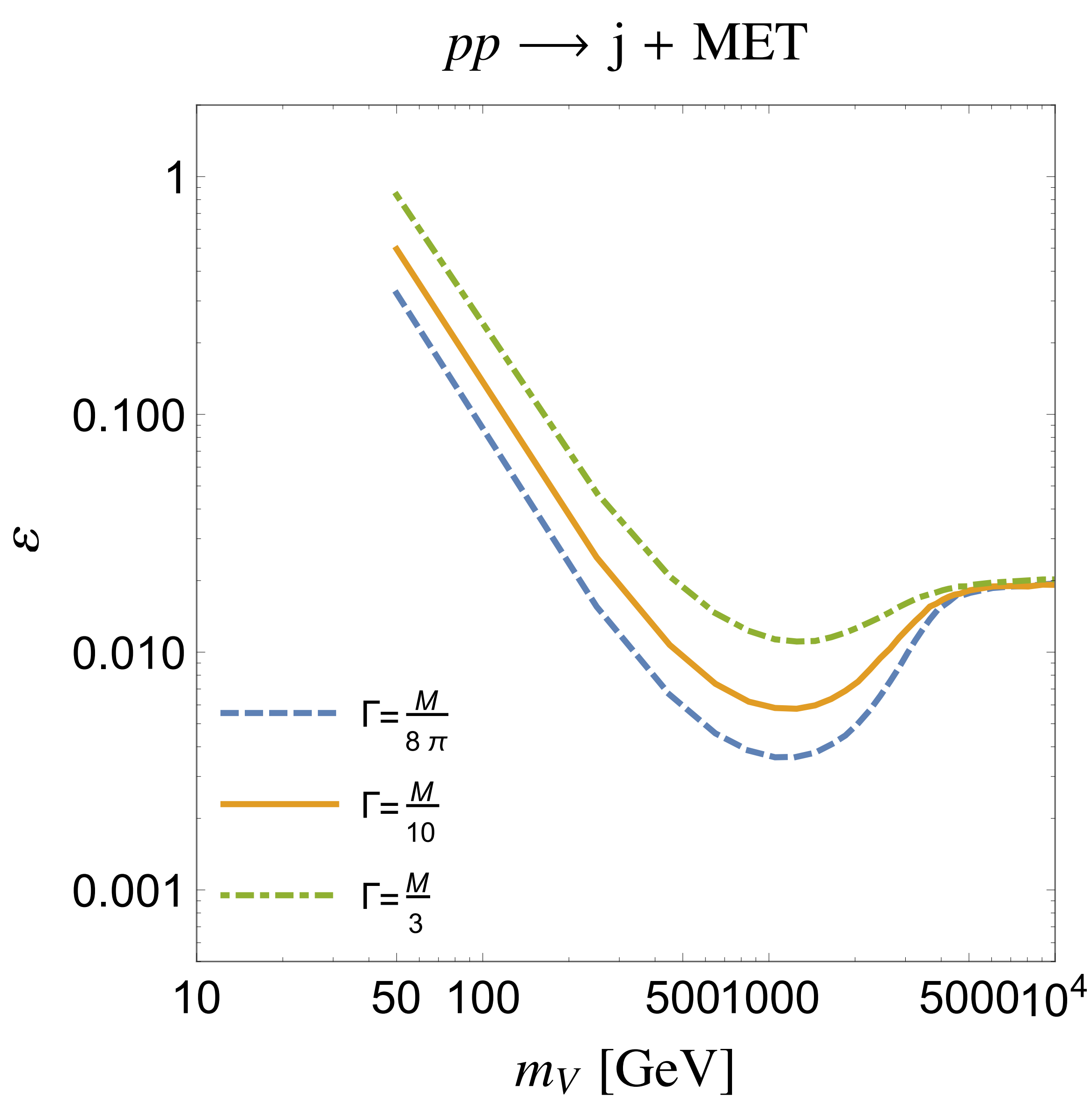
8 TeV CMS limits

EXO-12-048-pas

E_T^{miss} (GeV) $\rightarrow$	> 250	> 300	> 350	> 400	> 450
$Z(\nu\nu)$+jets	30600 ± 1493	12119 ± 640	5286 ± 323	2569 ± 188	1394 ± 127
W+jets	17625 ± 681	6042 ± 236	2457 ± 102	1044 ± 51	516 ± 31
$t\bar{t}$	470 ± 235	175 ± 87.5	72 ± 36	32 ± 16	13 ± 6.5
$Z(\ell\ell)$+jets	127 ± 63.5	43 ± 21.5	18 ± 9.0	8 ± 4.0	4 ± 2.0
Single t	156 ± 78.0	52 ± 26.0	20 ± 10.0	7 ± 3.5	2 ± 1.0
QCD Multijets	177 ± 88.5	76 ± 38.0	23 ± 11.5	3 ± 1.5	2 ± 1.0
Total SM	49154 ± 1663	18506 ± 690	7875 ± 341	3663 ± 196	1931 ± 131
Data	50419	19108	8056	3677	1772
Exp. upper limit	3580	1500	773	424	229
Obs. upper limit	4695	2035	882	434	157

Downward fluctuation in bkg, giving stronger than expected limits.

Zeroth Order Step: cut and count limit



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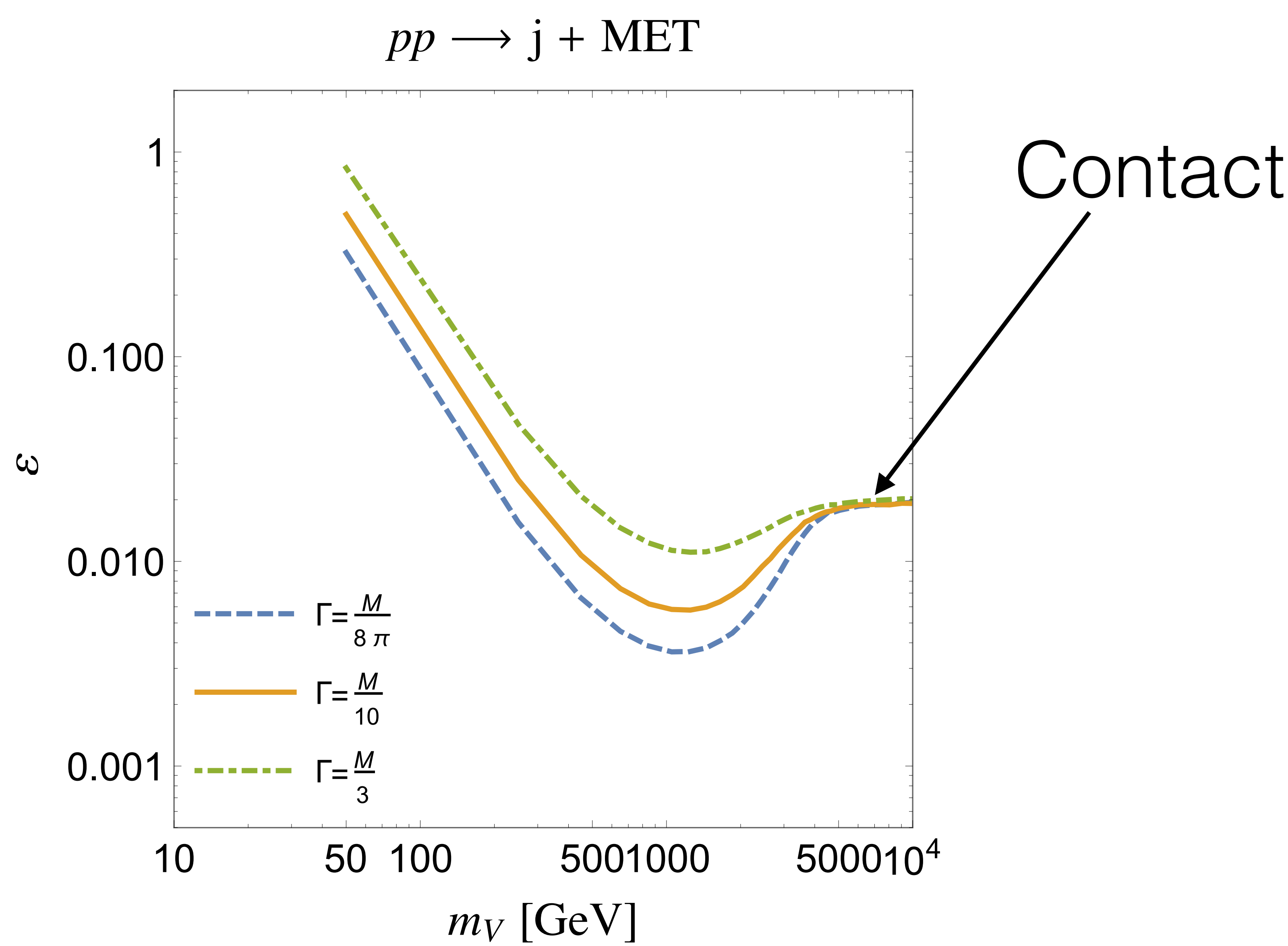

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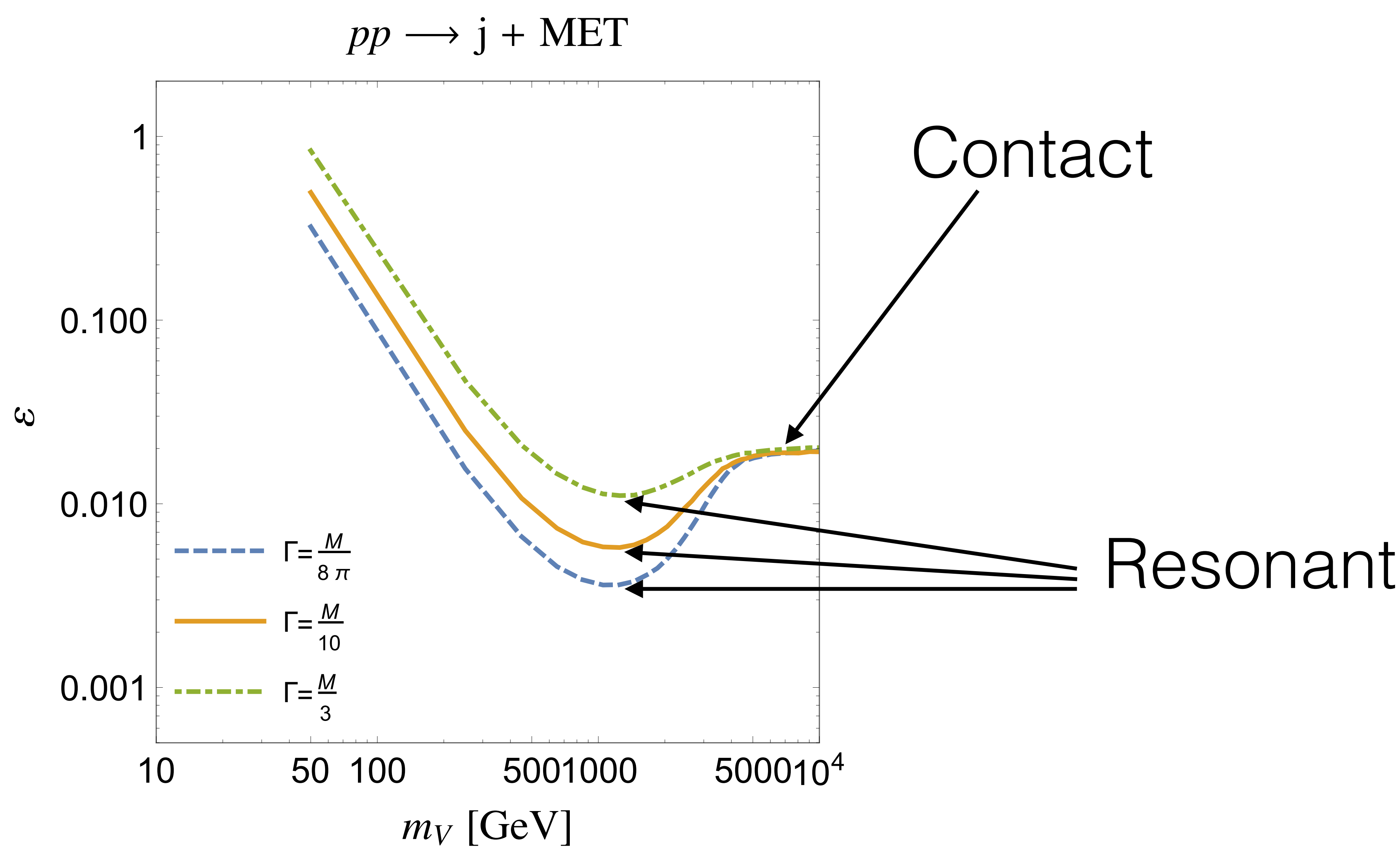

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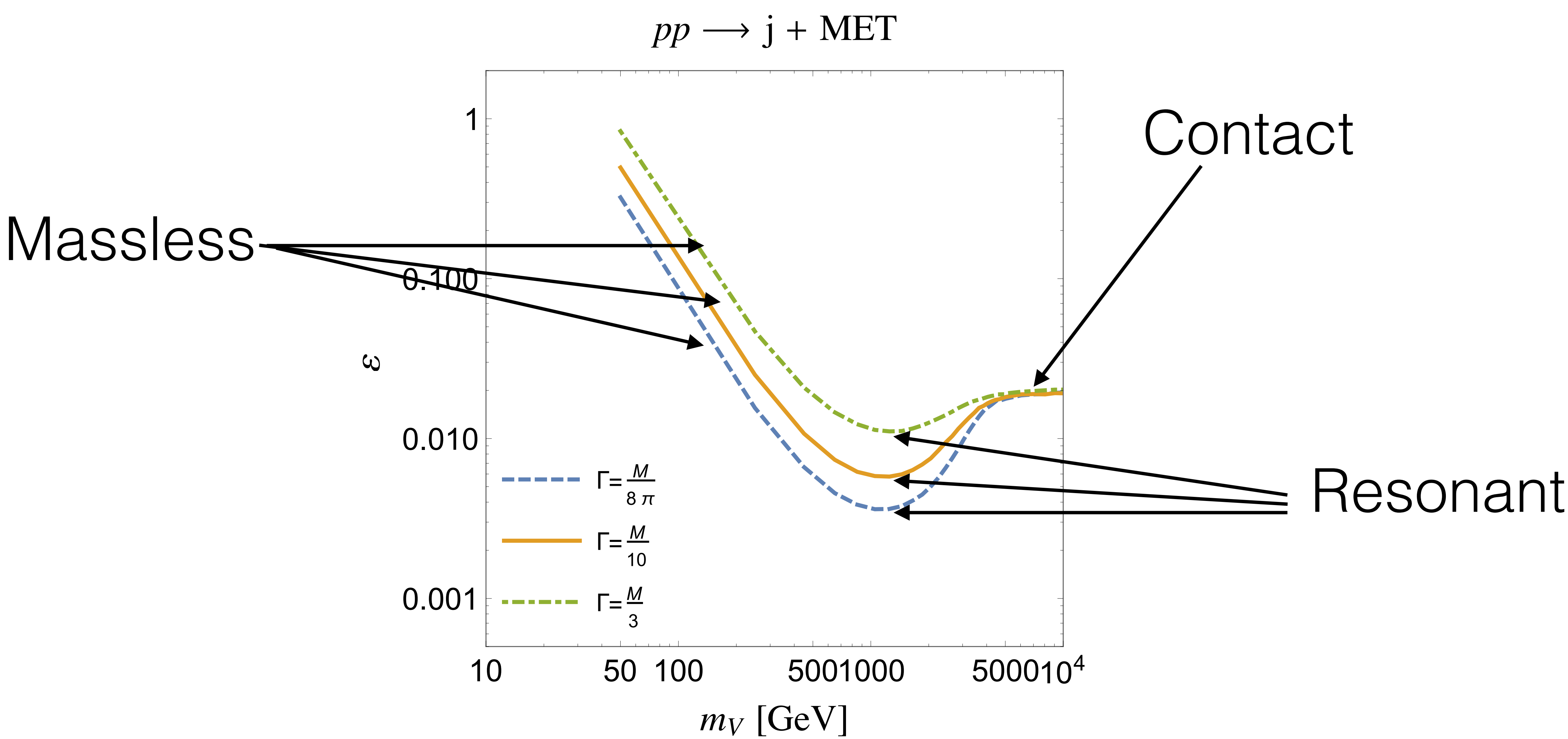

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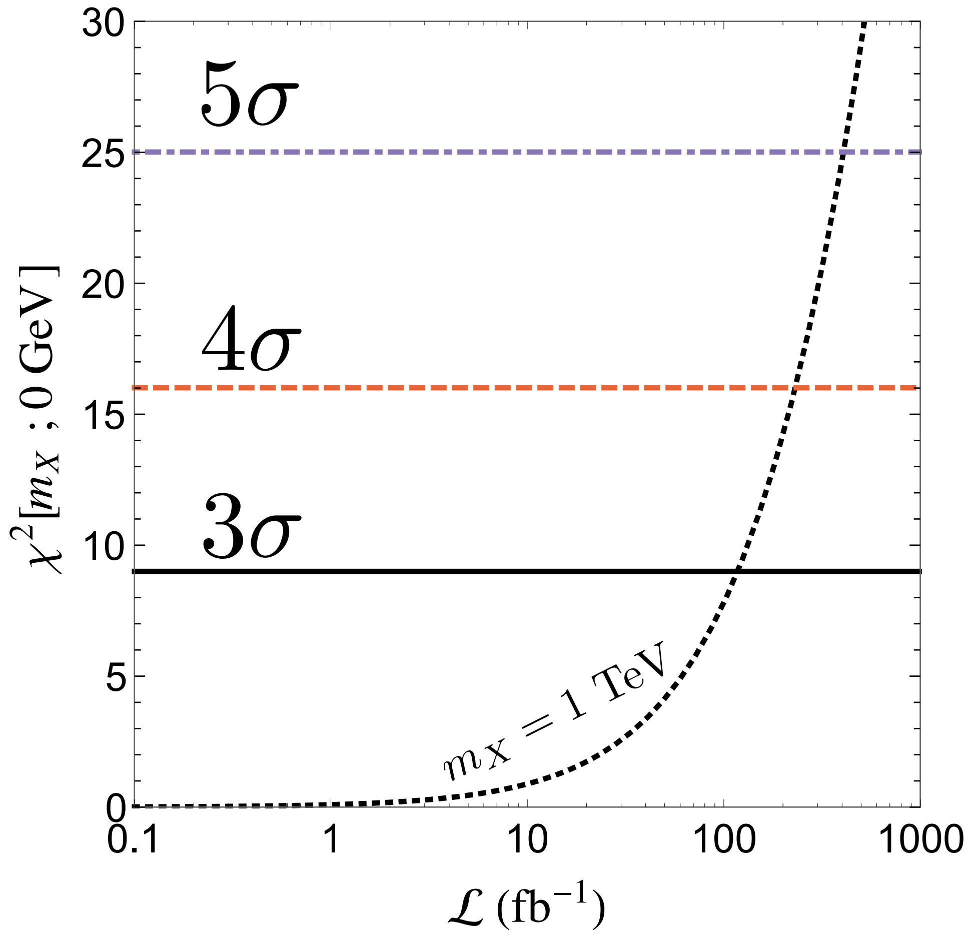
Monojet sensitivity to “invisible mass”

- Most obvious difference between neutrino and DM missing energy: final state mass!
  - Can appear in pT shape.

$$\chi^2[m_X; 0\ \mathrm{GeV}] = \sum_i \left[\frac{S_i(m_X) - S_i(0\,\mathrm{GeV})}{\sigma_i}\right]^2$$

$$\mathrm{stat.} \oplus 10\ \%\ \mathrm{sys.}$$

$$\sqrt{s} = 13\ \mathrm{TeV}$$



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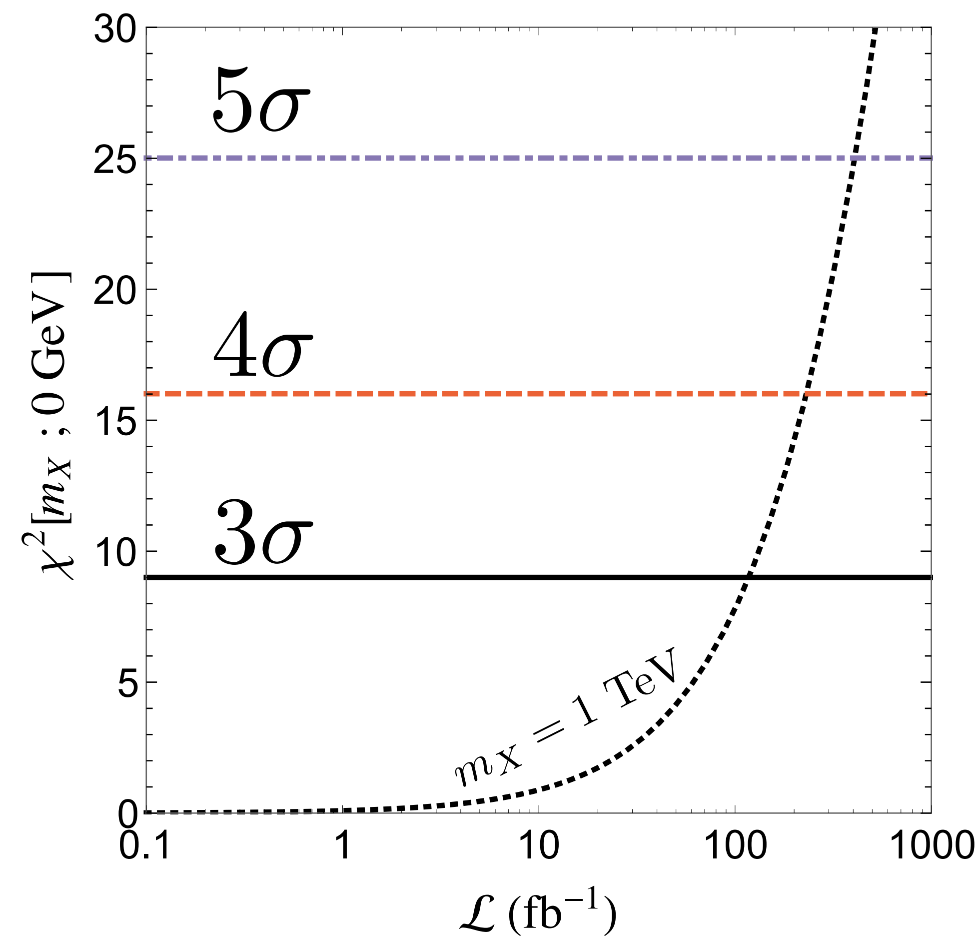
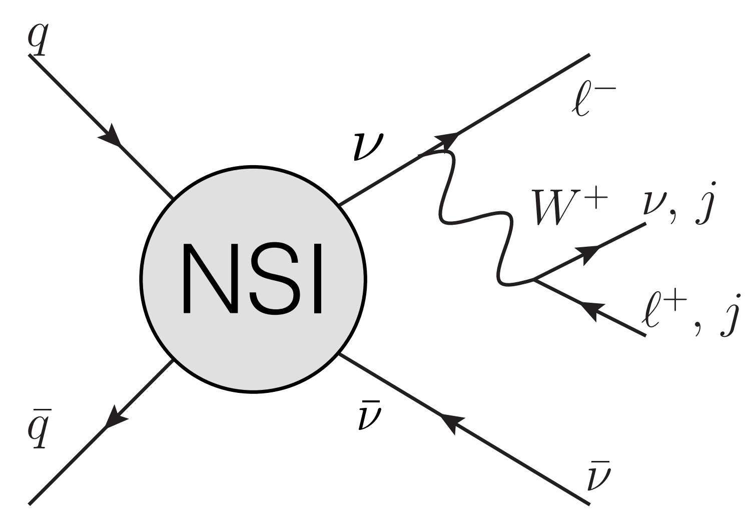
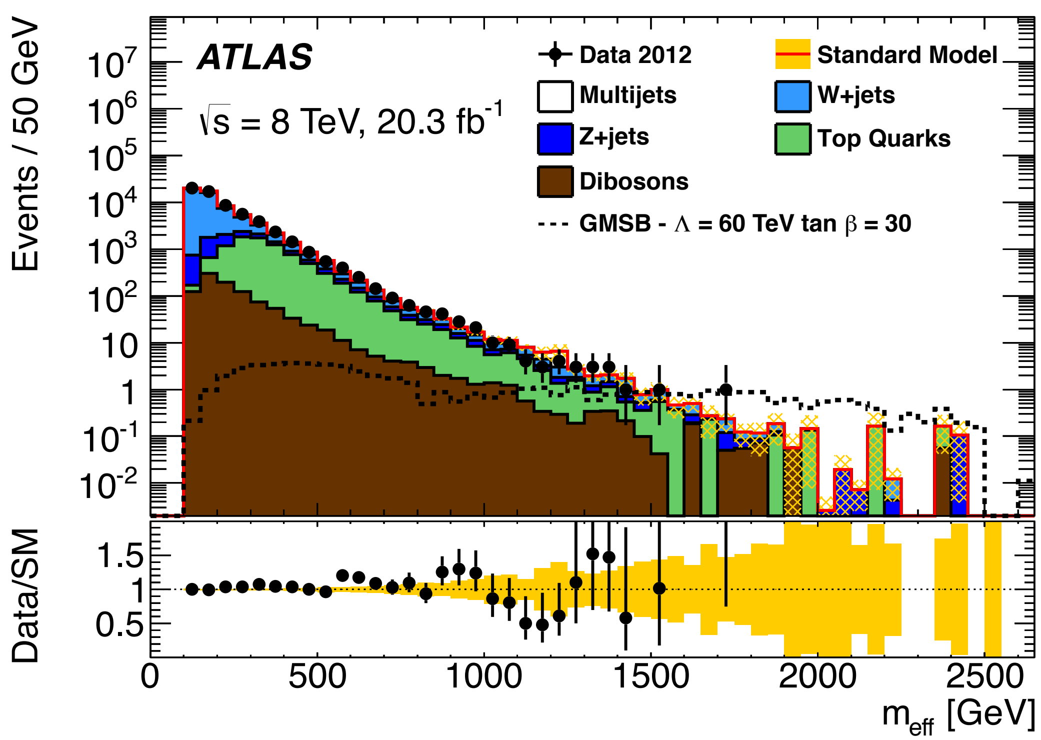


NSI and heavy DM are indeed distinguishable with pT shape.

Multi-lepton constraints on NSI

[1407.0603]





$$m_{\mathrm{eff}} = H_{\mathrm{T}}^{2\mathrm{j}} + E_{\mathrm{T}}^{\mathrm{miss}}$$

$$H_{\mathrm{T}}^{2\mathrm{j}} = \sum_{\mathrm{all}\ \ell} p_{\mathrm{T}}^{\ell} + \sum_{\mathrm{all}\ \tau} p_{\mathrm{T}}^{\tau} + \sum_{i=1,2} p_{\mathrm{T}}^{\mathrm{jet}_i}$$

- Again re-purpose existing searches.

(1) e/mu NSI: [1503.04677]

$$pp \to \overline{\nu} + W^{\pm}\ell^{\mp},\ W^{\pm} \to jj,\ \ell = e,\ \mu$$

(2) tau NSI: [1407.0603]

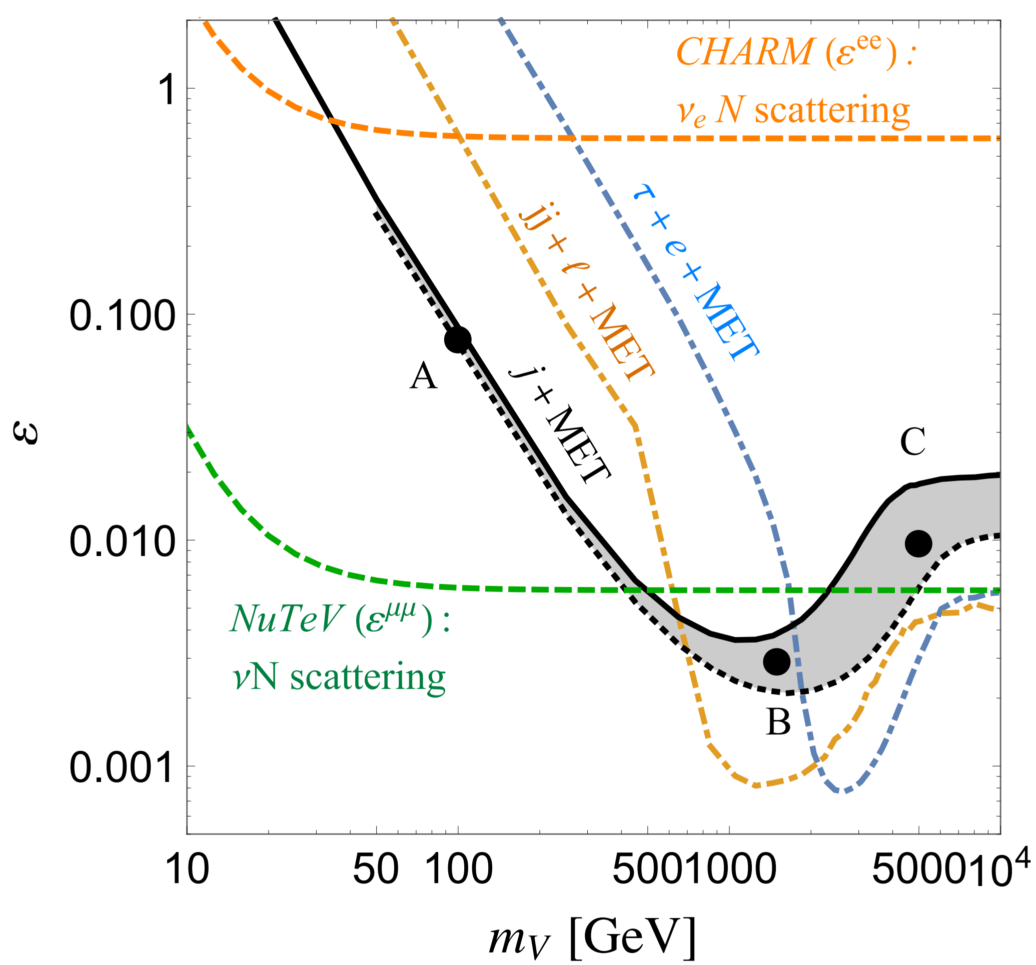
$$pp \to \overline{\nu} + W^{\pm}\tau^{\mp},\ W^{\pm} \to \ell\nu,\ \tau \to \textbf{hadrons},\ \ell = e,\ \mu$$

See also: Davidson, Sanz [1108.5320], Graesser, Friedland, IMS, Vecchi, [1111.5331].

Experimental Complementarity

- Even if low-m_V NSI escapes LHC constraints, there are a variety of low-energy probes.
  - ➡ ν-N scattering measurements from e.g. CHARM, NuTeV, etc.
  - ➡ General trend: heavy mediators are most strongly constrained by LHC data.

- How does this aid in neutrino-DM discrimination?
  - ➡ ***Answer depends on mediator mass.***



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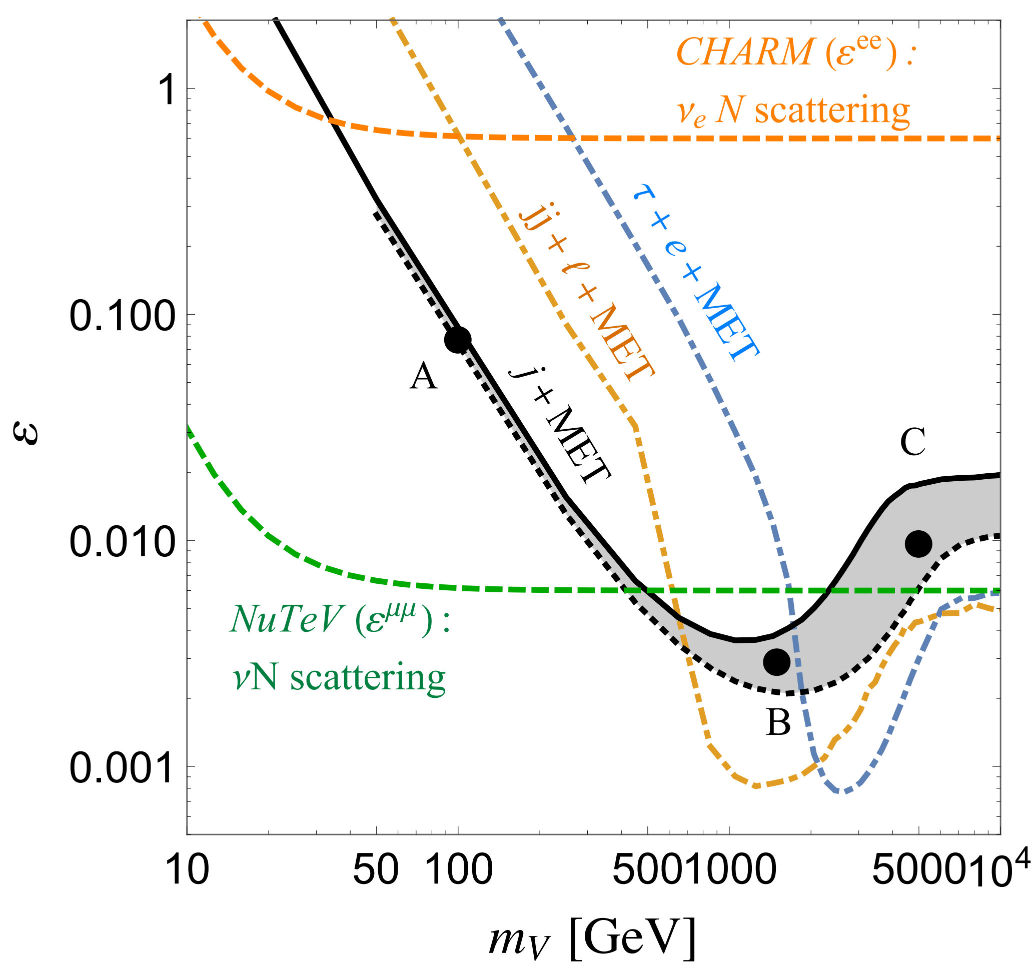

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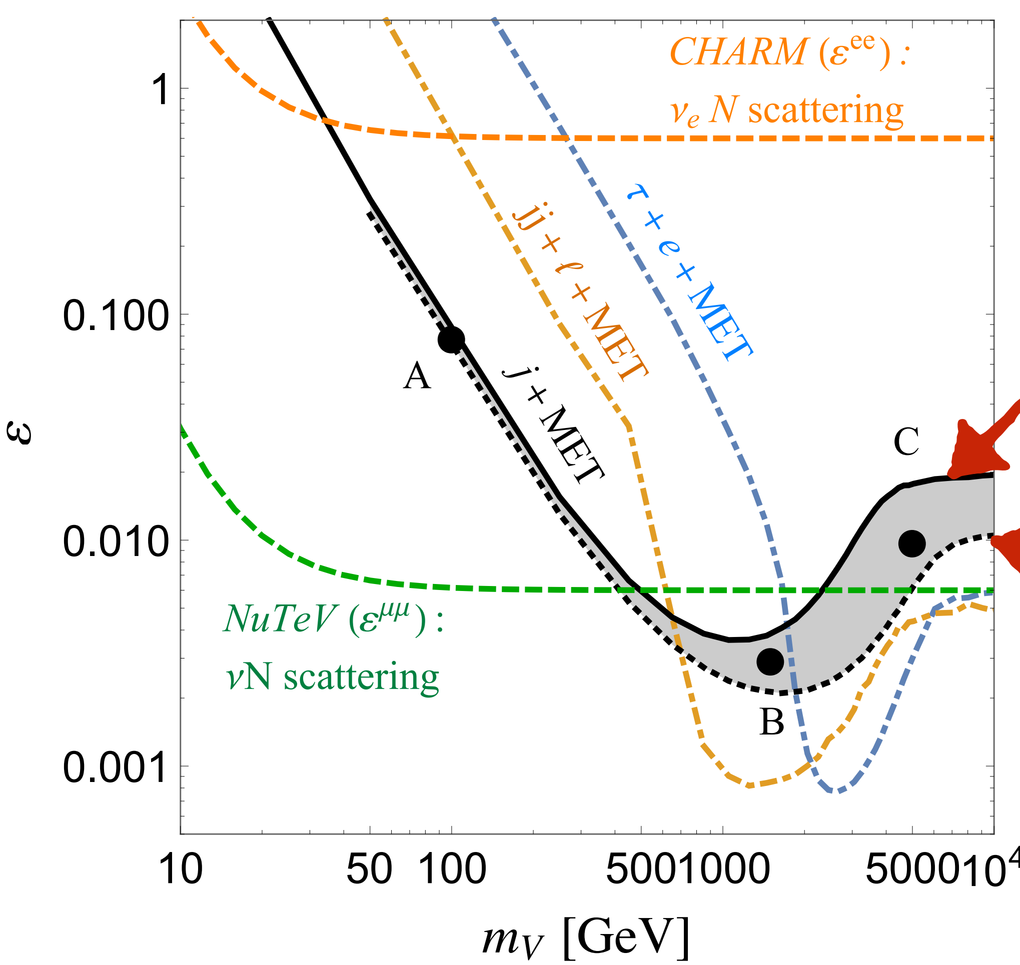

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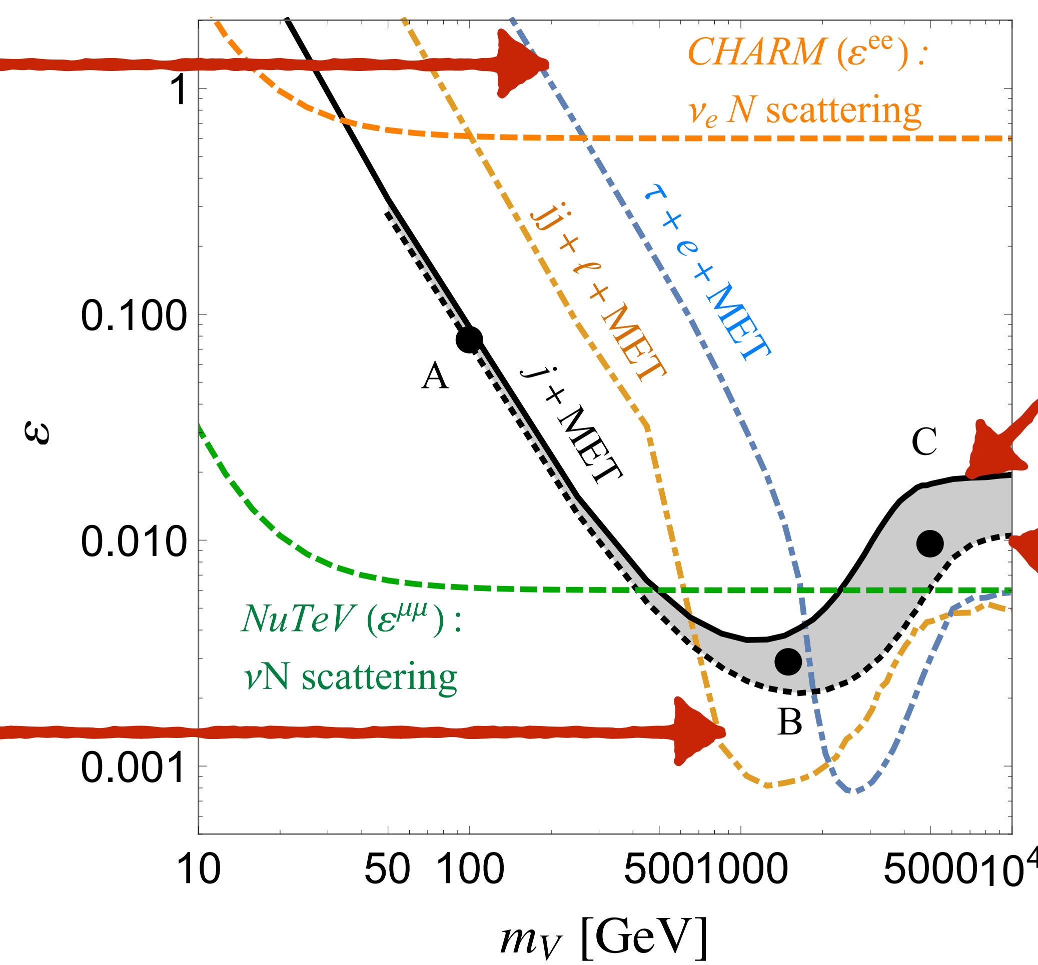
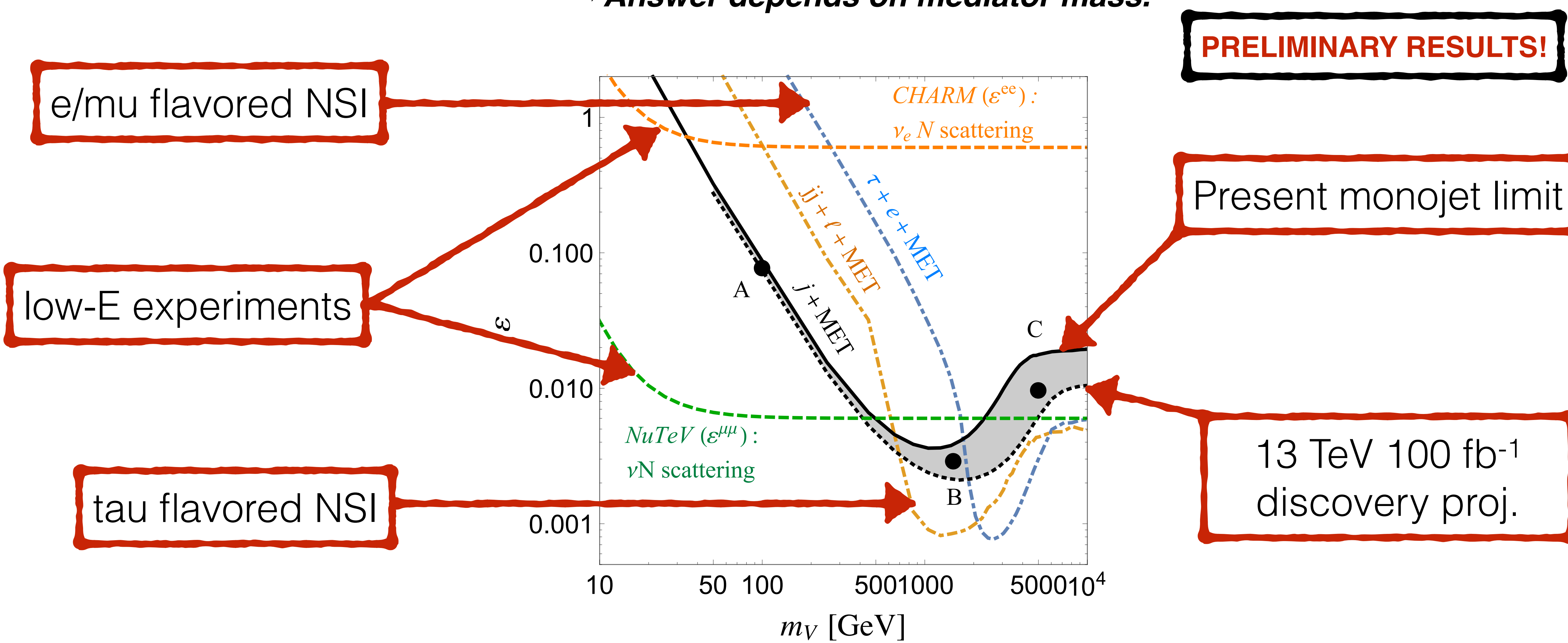


Experimental Complementarity

- Even if low-m_ν NSI escapes LHC constraints, there are a variety of low-energy probes.
  - ➡ ν-N scattering measurements from e.g. CHARM, NuTeV, etc.
  - ➡ General trend: heavy mediators are most strongly constrained by LHC data.

- How does this aid in neutrino-DM discrimination?
  - ➡ ***Answer depends on mediator mass.***



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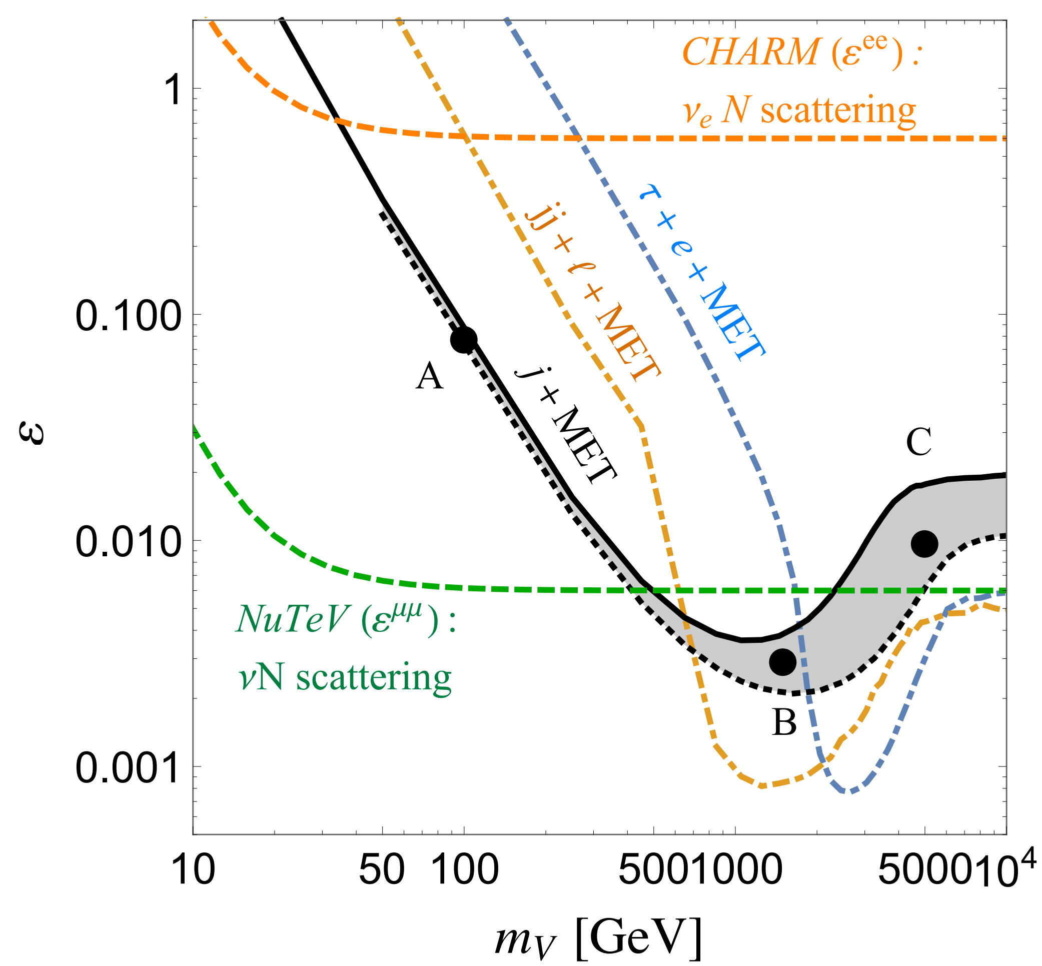

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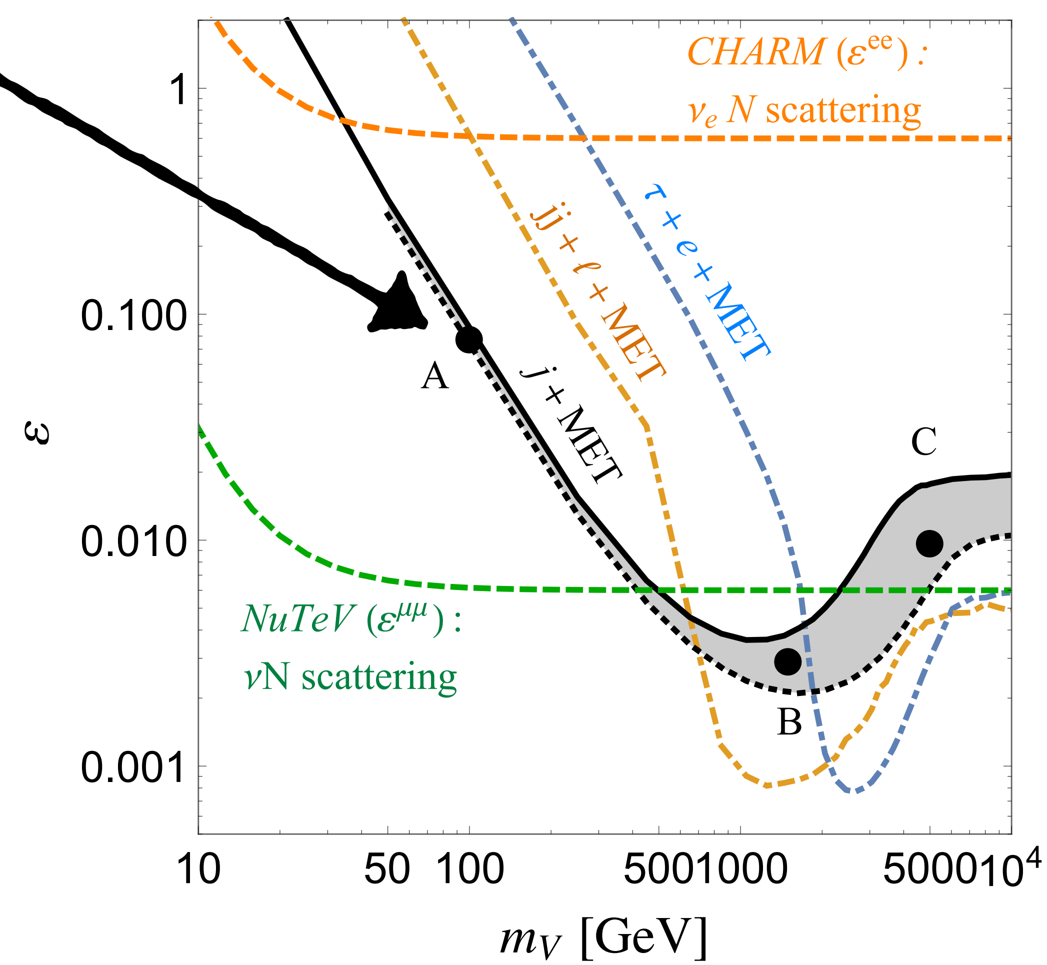

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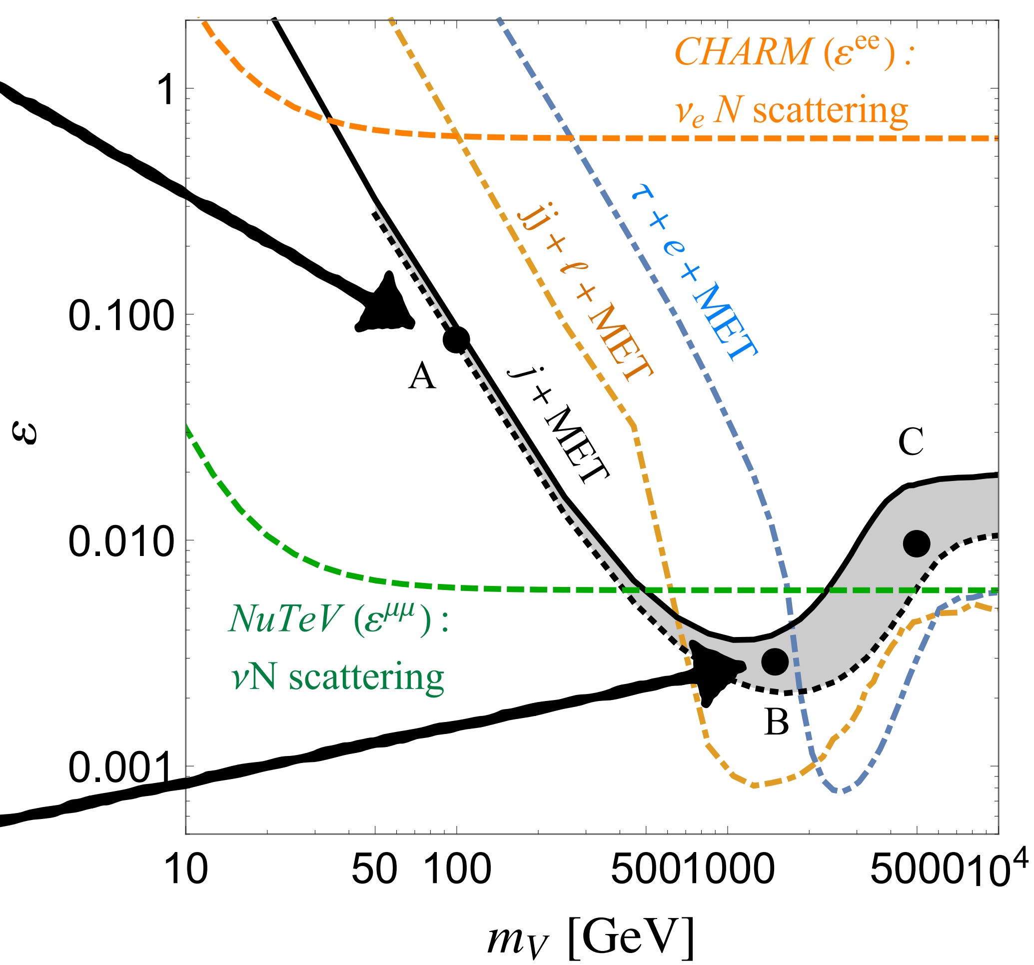

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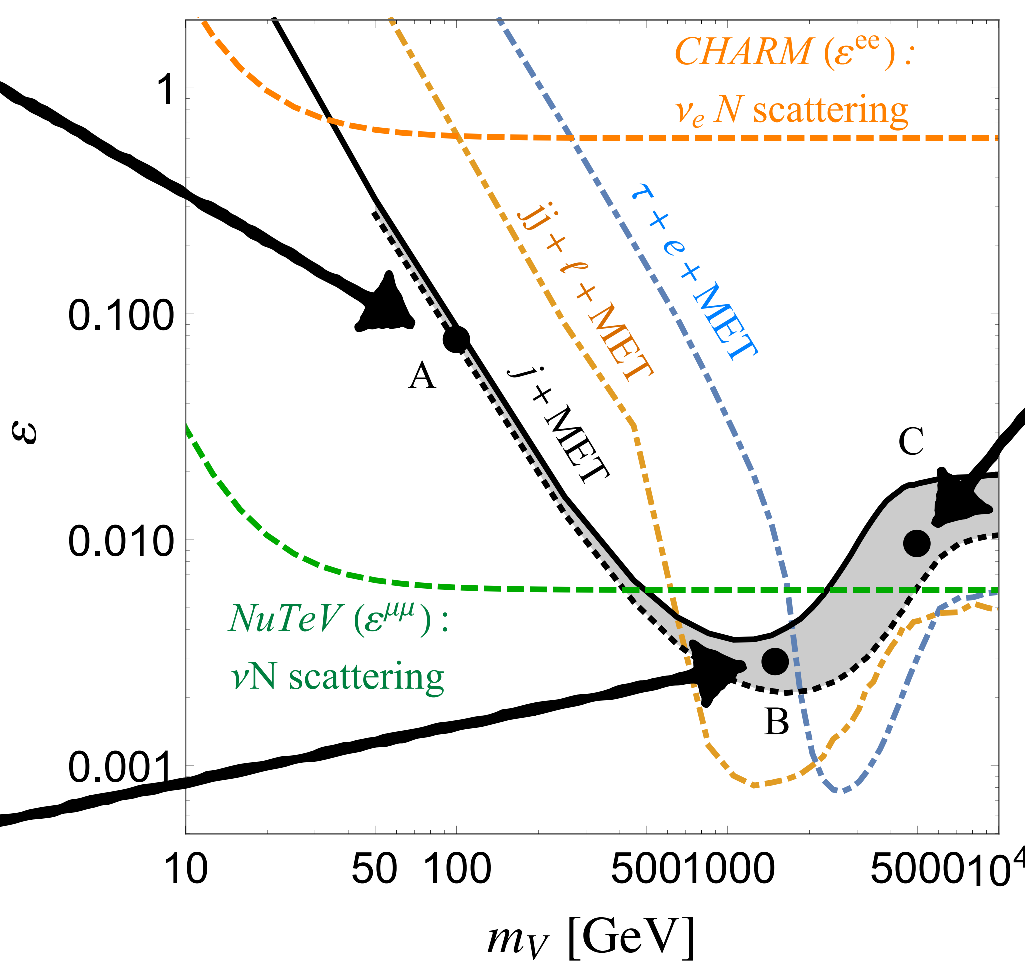

Benchmark B (e/mu NSI):
- Monojet "BSM discovery" potential.
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Benchmark C (e/mu/tau NSI):
- LHC data is sufficient to exclude NSI as an explanation.

Coming soon

- More probes are on the way:
  - **Long-baseline probes**: NOvA, DUNE (see A. Friedland, IMS [1207.6642])
  - **Solar**: ton-scale DM experiments (see Billard, Strigari, Figueroa-Feliciano [1409.0050])
  - **Neutrino-nucleus scattering**: COHERENT.
  - **Atmospheric data**: IceCube DeepCore (see Mocioiu, Wright [1410.6193]).

Conclusions

- ***Heavy DM*** can be discriminated from NSI with monojet data alone with pT shape information.

- ***Light DM*** is more difficult, but can be discriminated from ***heavy mediator-NSI*** using multi-lepton channels.

    - ***Light mediator-NSI*** is difficult to constrain at the LHC: best at faking (light) DM.

    - *Low-energy probes will aid further in breaking the nu-DM degeneracy.*

Zeroth Order: cut and count limit

Madgraph for parton-level signal.

Pythia for hadronization/showering.

Bounds obtained via simple counting experiment.

For example, ATLAS HighPT search obtained:

$$N_{obs} = 965$$

$$N_{\rm bkg} = 1010 \pm 37 \pm 65$$

$$N_{\rm BSM} < 192$$
$$@\ 95\%{\rm CL}$$

Phenomenological Approach

- For simplicity, we focus on a “simplified models”

$$\mathscr{L}_{\rm NSI} \;=\; g_\nu \,(\overline{\nu} P_L \gamma_\mu \nu)\, V^\mu + \big(\bar{q}\gamma_\mu (g_q^V + g_q^A \gamma^5) q\big)\, V^\mu,$$

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- Core goal is how to discriminate this NSI Lagrangian from its DM cousin:

$$\begin{aligned} \mathscr{L}_{\rm DM} &= g_X \left(\overline{X} P_L \gamma_\mu X\right) V^\mu + \left(\overline{q}\gamma_\mu (g_q^V + g_q^A \gamma^5) q\right) V^\mu \\ &+ m_X \overline{X} X \end{aligned}$$

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$$\mathcal{L}_{\rm NSI}^{\rm dim-8} = -\frac{4\epsilon_{\alpha\beta}^{qP}}{v^4}(\overline{HL_\alpha}\gamma^\mu HL_\beta)(\overline{q}\gamma_\mu Pq)$$

$$\to -\,2\sqrt{2}\,G_F\,\epsilon_{\alpha\beta}^{qP}\,(\overline{\nu}_\alpha\gamma^\mu\nu_\beta)\,(\overline{q}\gamma_\mu Pq)\left(1+\frac{h}{v}\right)^2$$

Berezhiani, Rossi [hep-ph/0111137]

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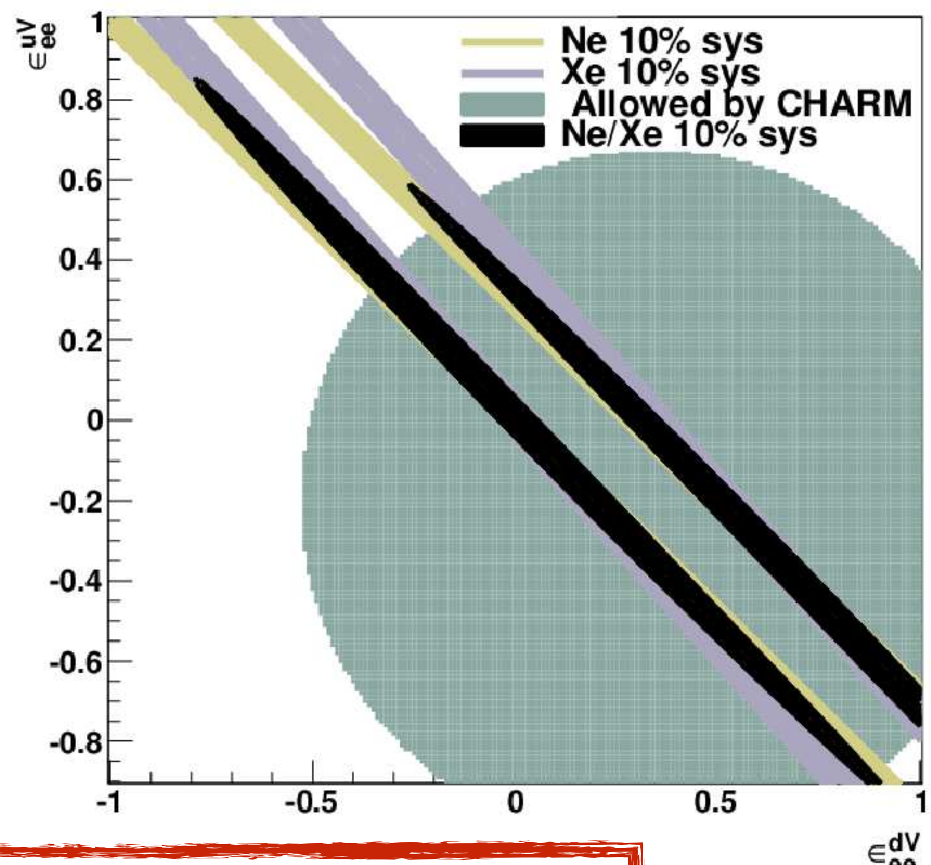
Proof of principle model with these features:
See Pospelov's "baryonic neutrino" [1103.3261] with a Z' coupling to neutrinos and baryons.

FUTURE CONSTRAINTS

COHERENT improvements

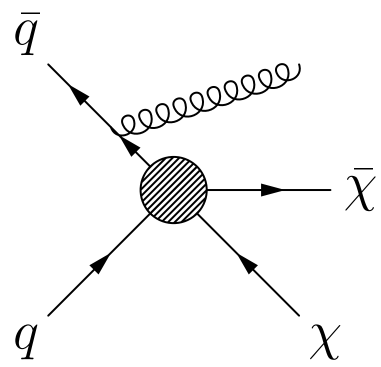
- Coherent elastic neutral current scattering has yet to be detected.
- A neutrino of any flavor scatters off a nucleus at low momentum transfer Q such that the nucleon wavefunction amplitudes are in phase and add coherently.

K. Scholberg (2005)

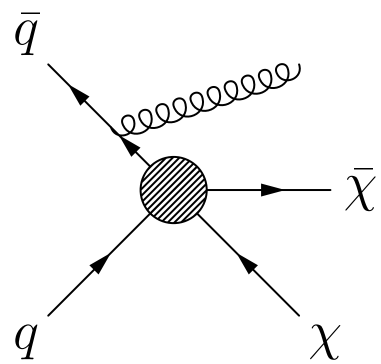


$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times$$
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$
$$+ \sum_{\alpha\neq\beta} [Z(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + N(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})]^2\},$$

COHERENT collaboration looking at CsI, Ge and LXe targets to get reasonable exposures in 5 years.



The DM monojet industry



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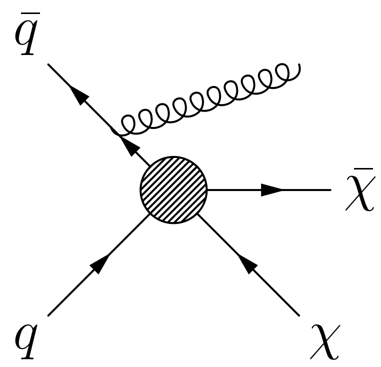
- Take an interaction: $\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$



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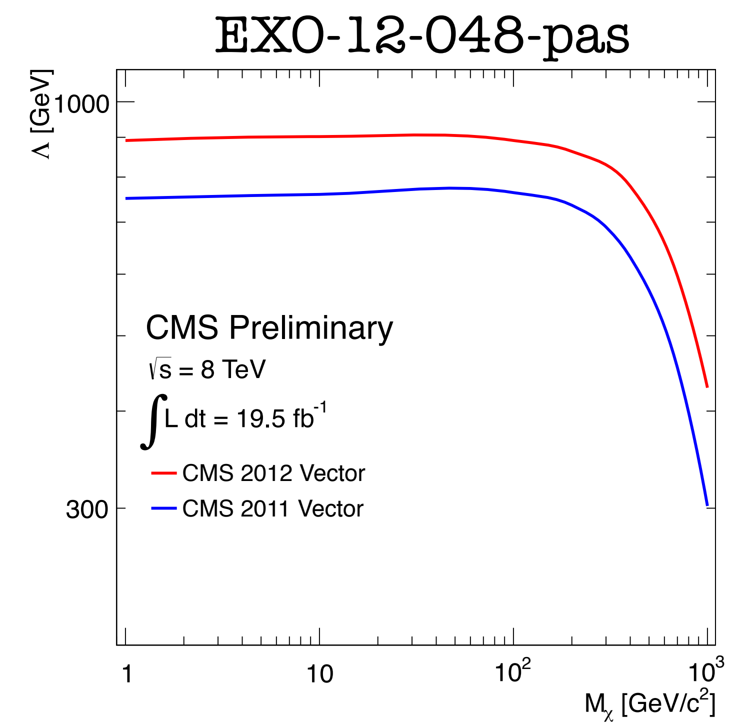

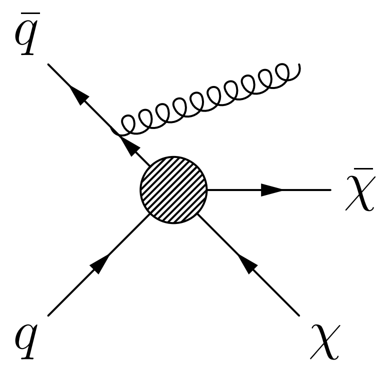

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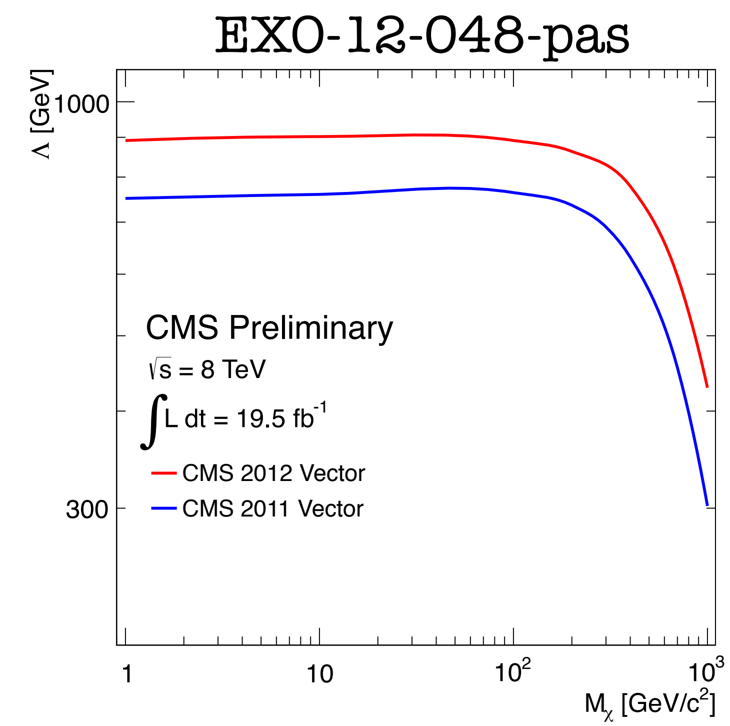

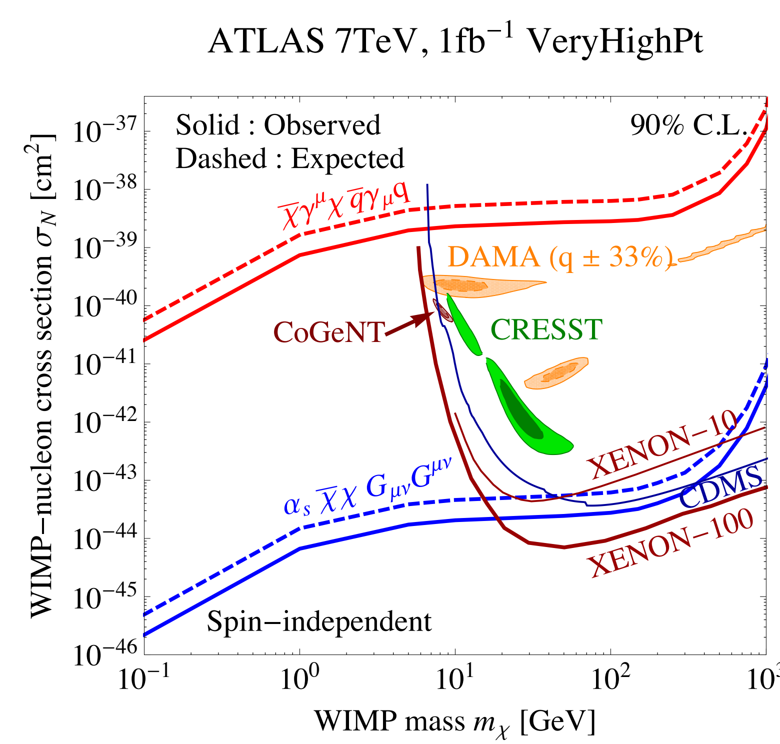

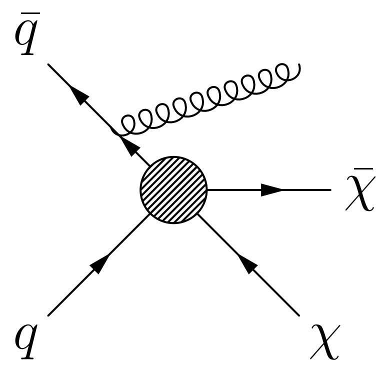

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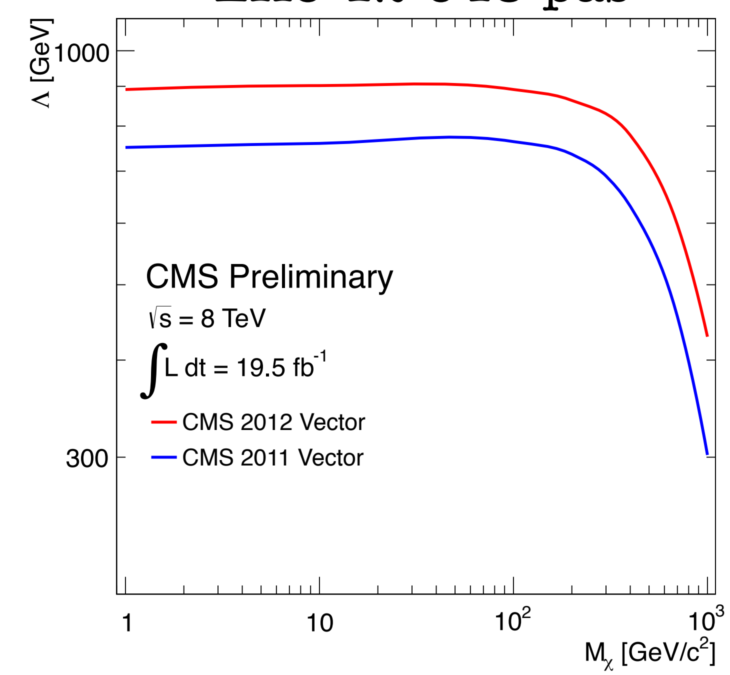
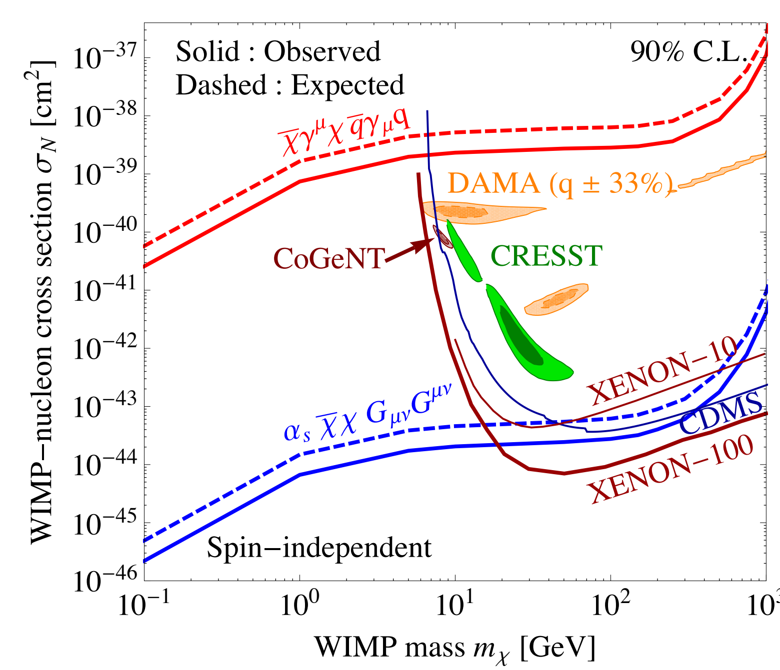
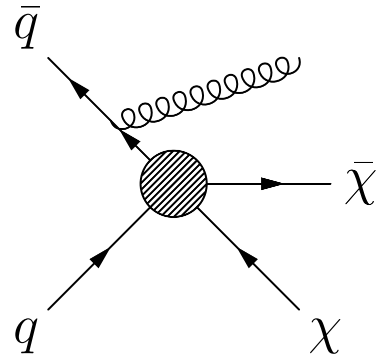
hep-ph/0403004, 0912.4511, 1002.4137, 1005.3797, 1107.2666 ,1109.4398, 1111.5331, 1112.5457,1202.2894 , 1203.1662 , 1204.0821 , 1204.3839, 1208.4605 , 1209.0231, 1211.6390, 1302.3619, 1307.2253, 1308.0592 , 1308.6799 , 1402.1275 , 1407.8257, 1409.2893, 1502.05721, 1503.05916, 1503.07874, …

EXO-12-048-pas



ATLAS 7TeV, 1fb⁻¹ VeryHighPt





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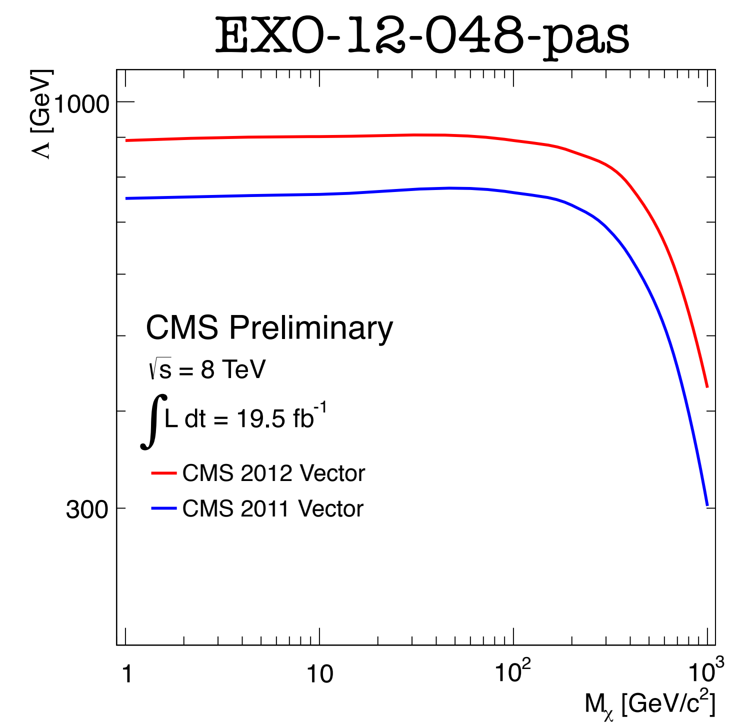
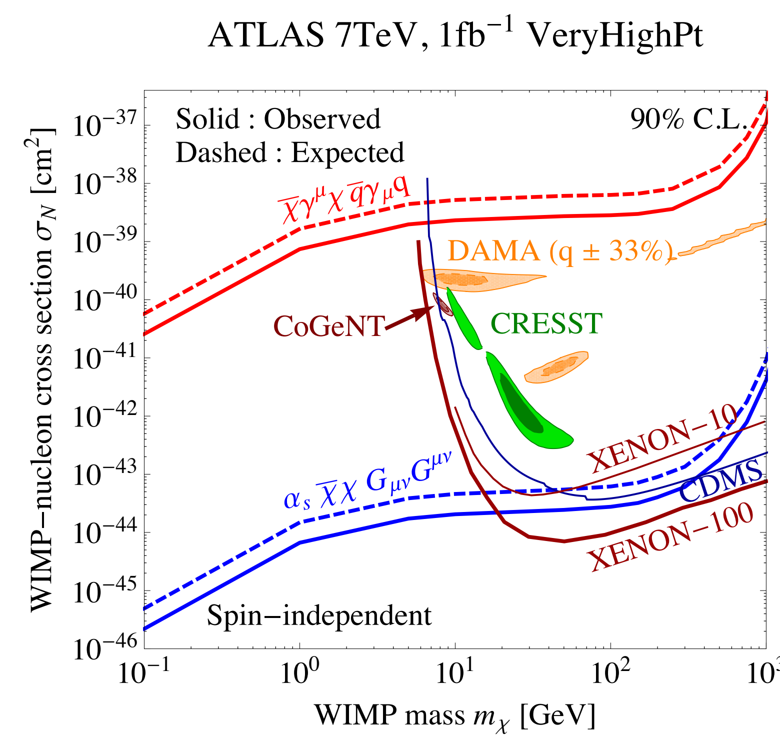
- ***Now a standard search carried out by CMS & ATLAS.***





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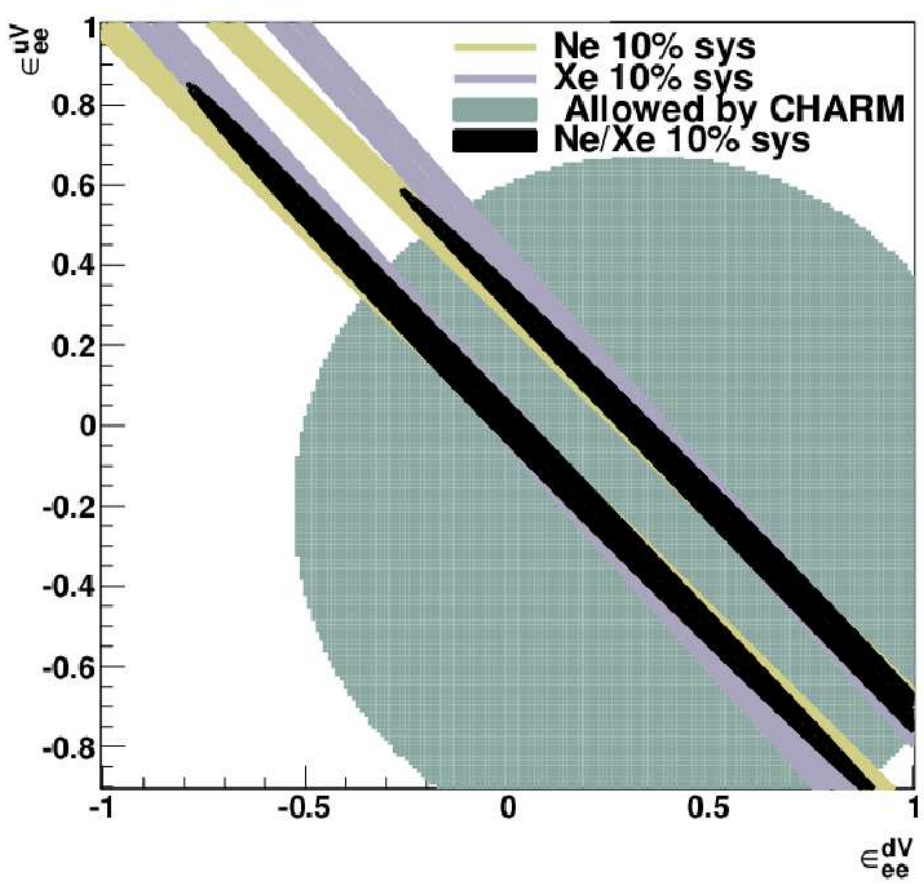
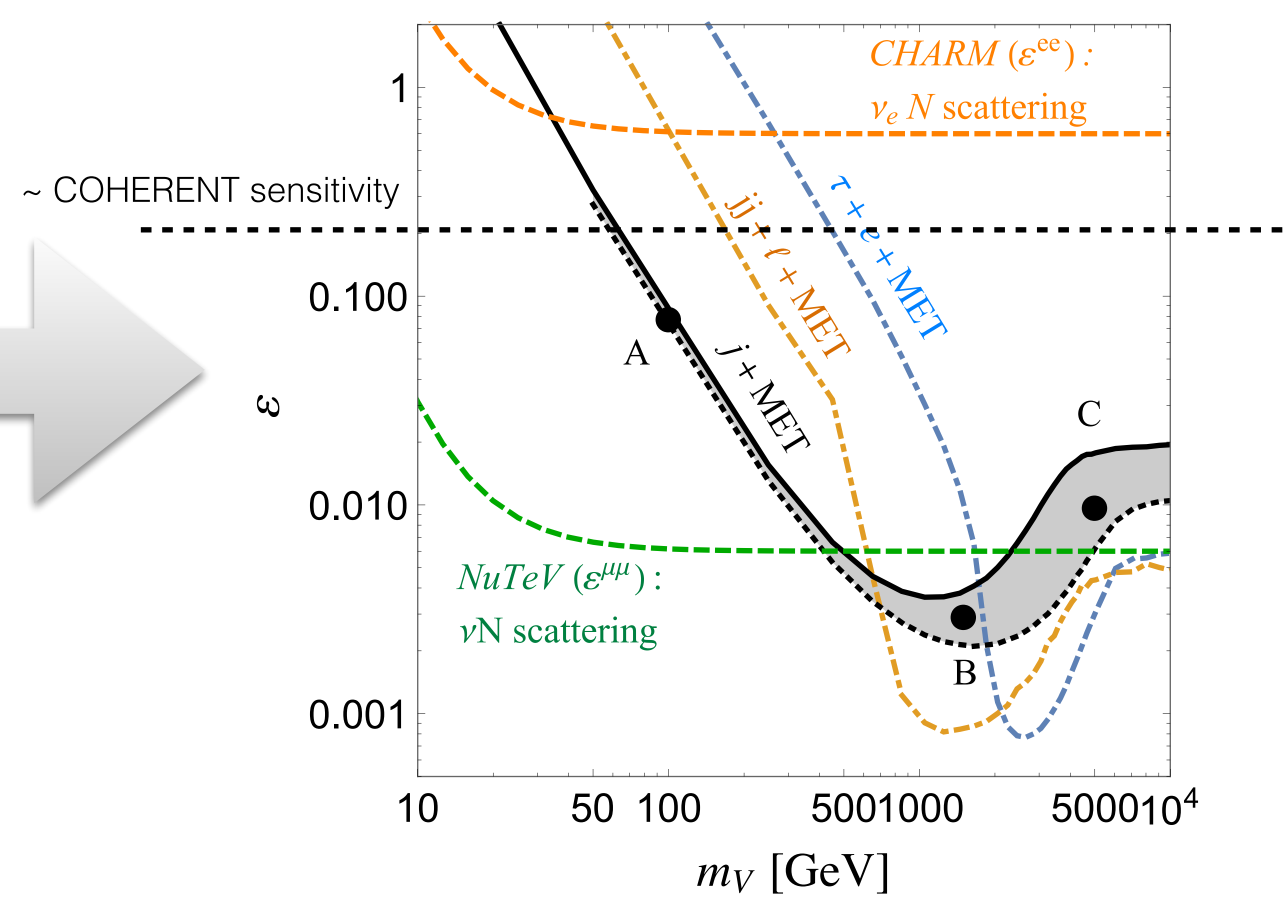
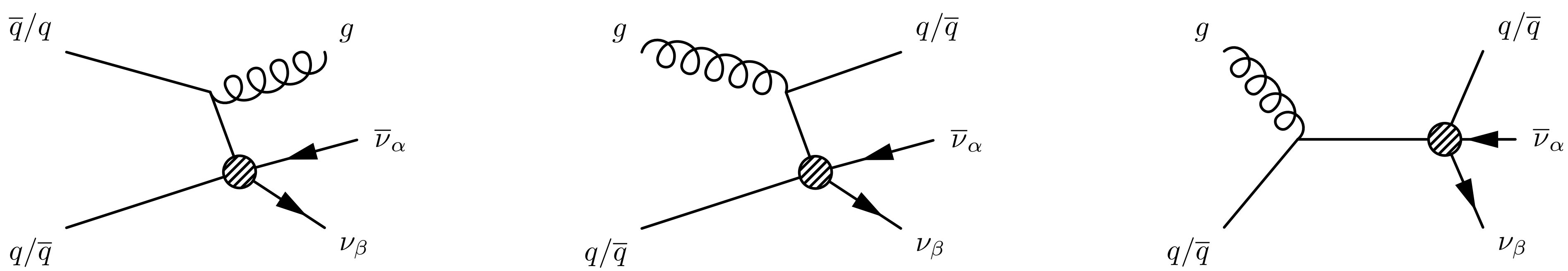




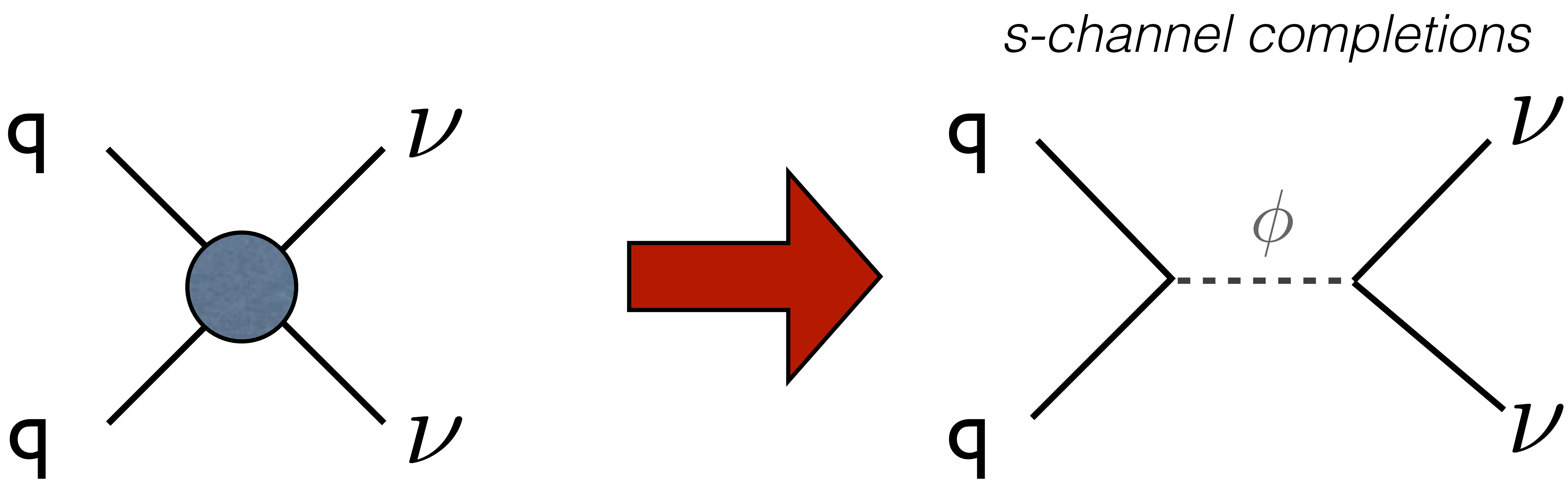
Multipurpose Monojets: not just for DM anymore

$$pp/p\overline{p} \to j+\mathrm{MET}$$



First consider the case where the interaction is contact.

On-shellness



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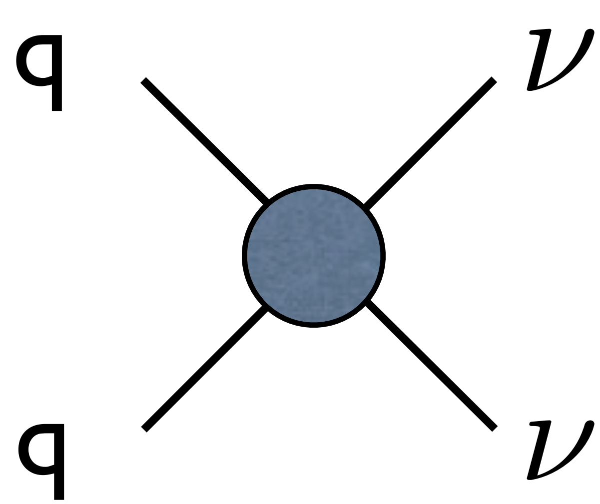
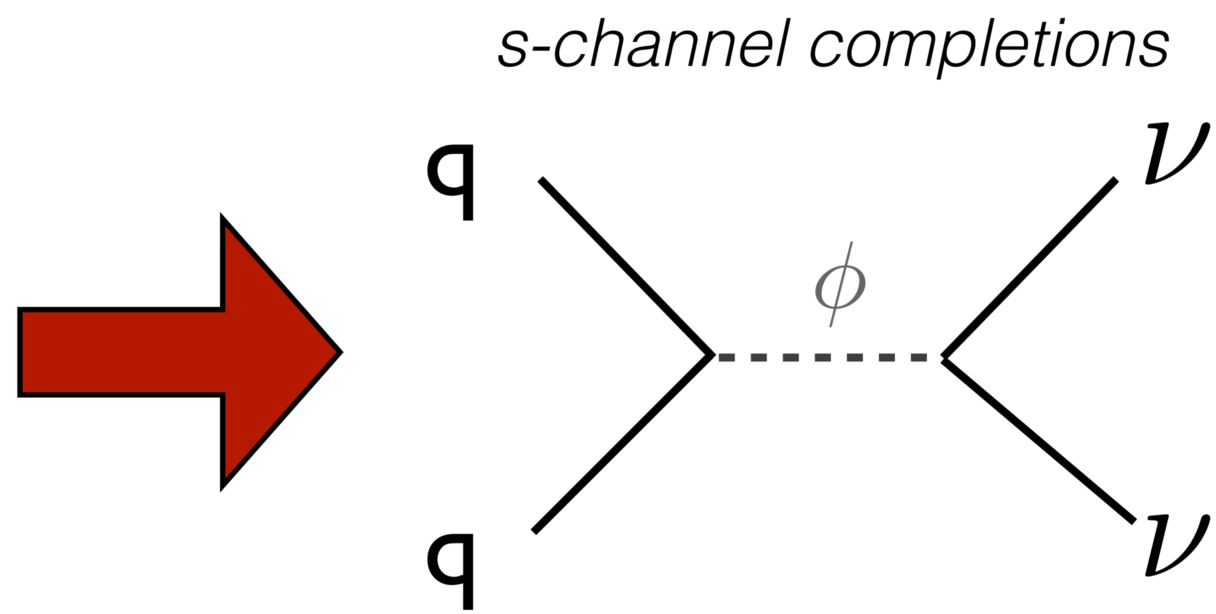
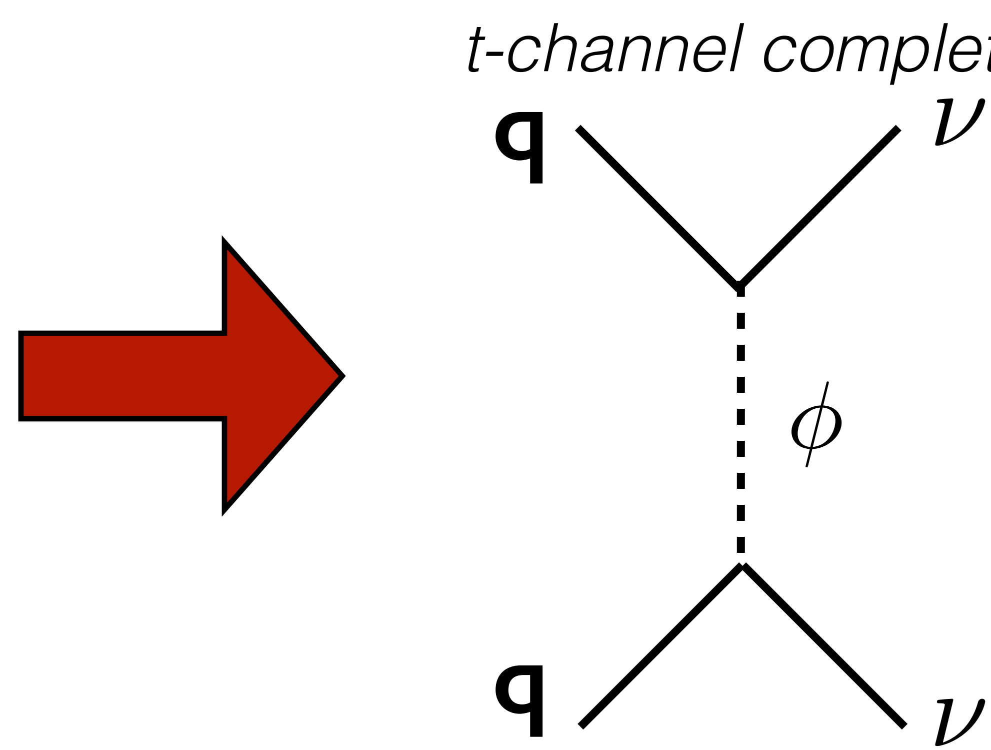
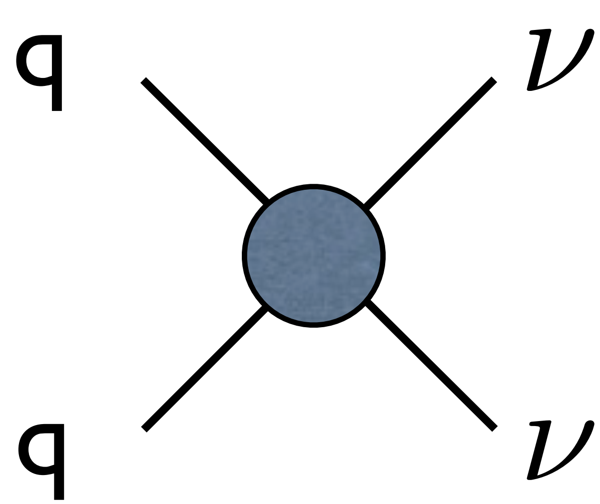


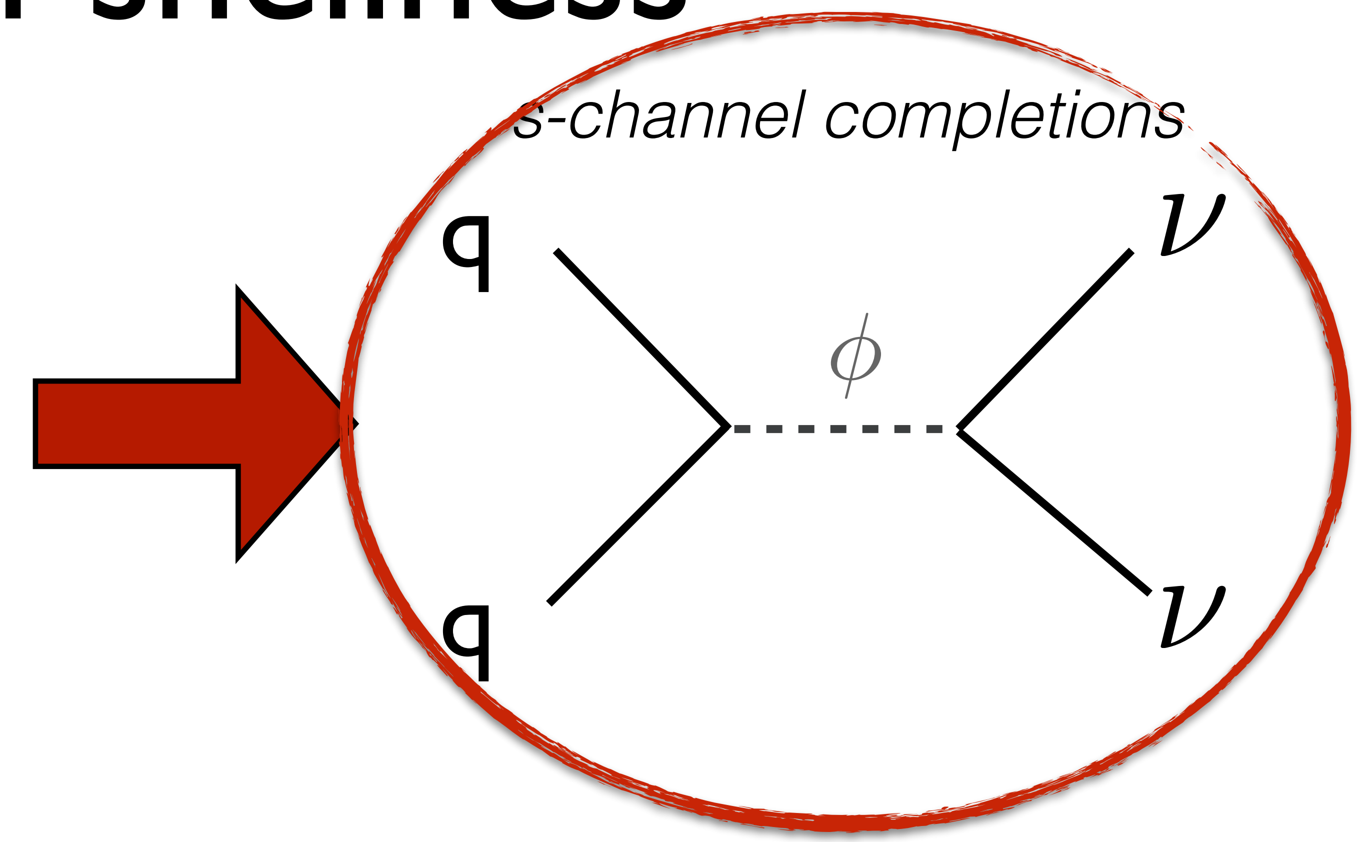




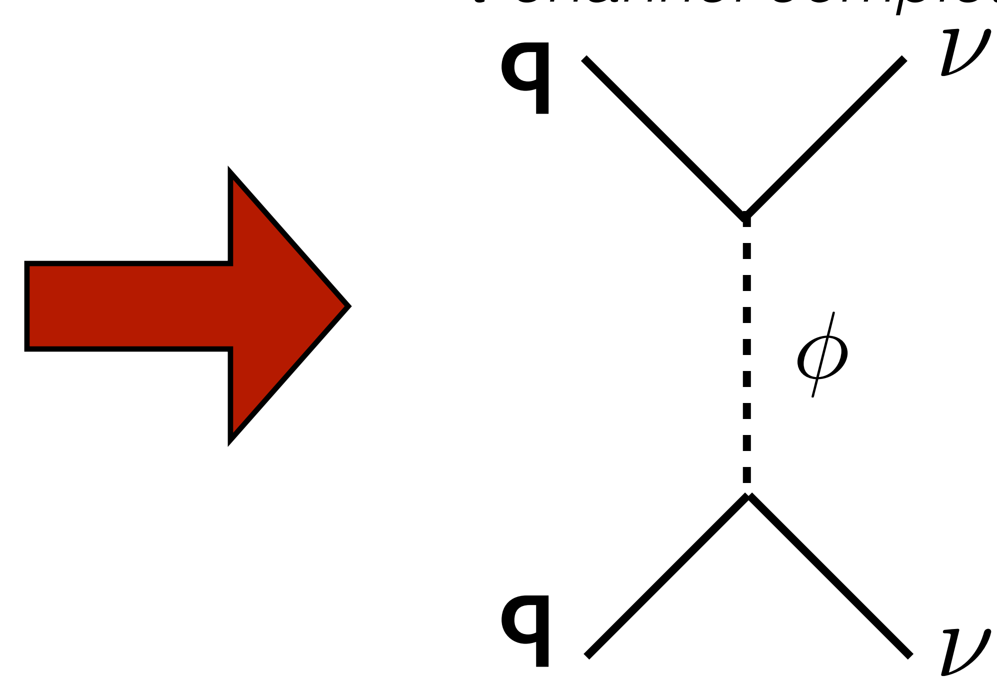
See Wise, Zhang
1404.4663

On-shellness





t-channel completions



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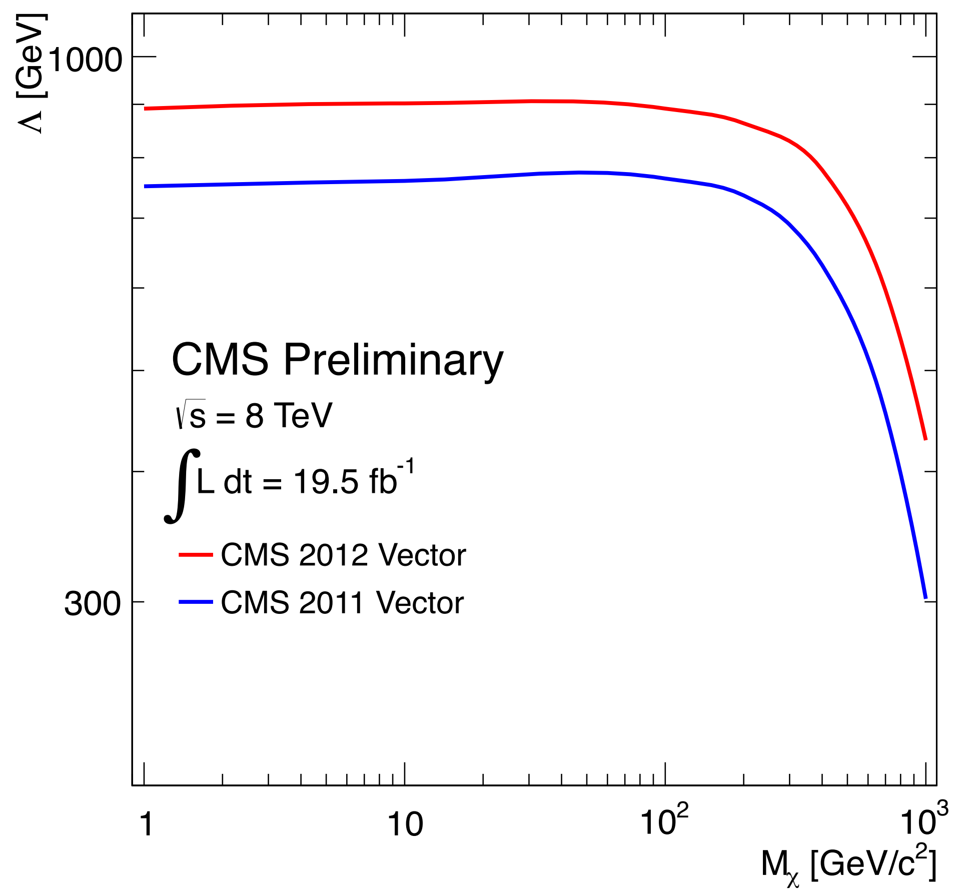

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