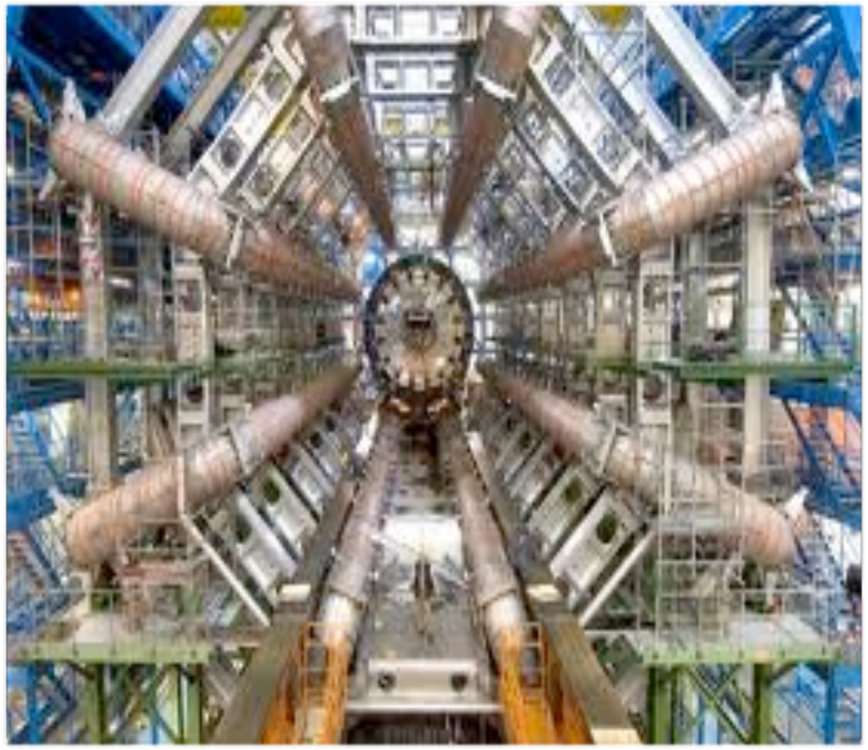
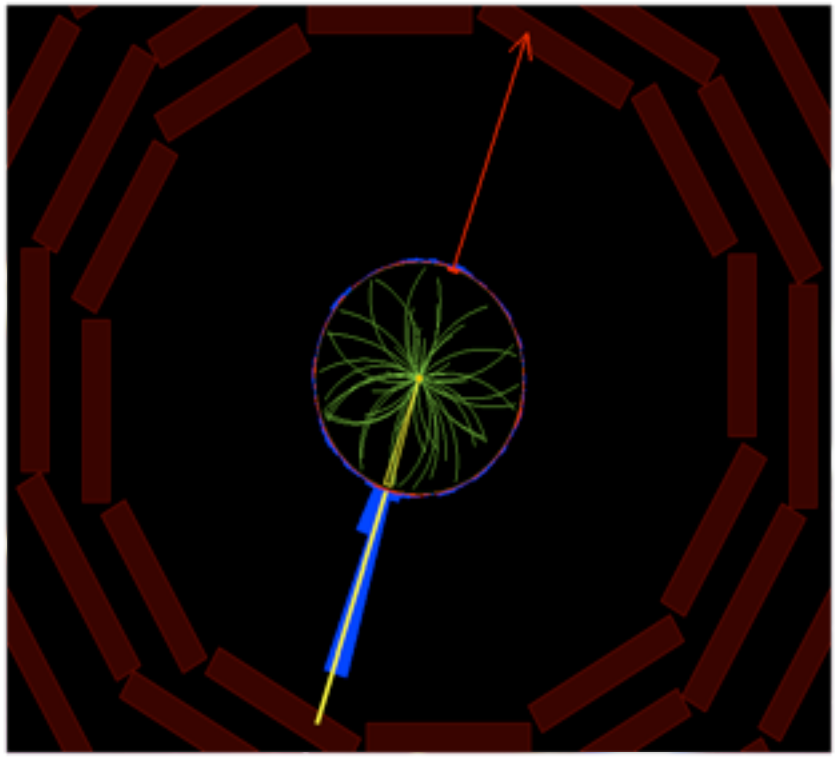
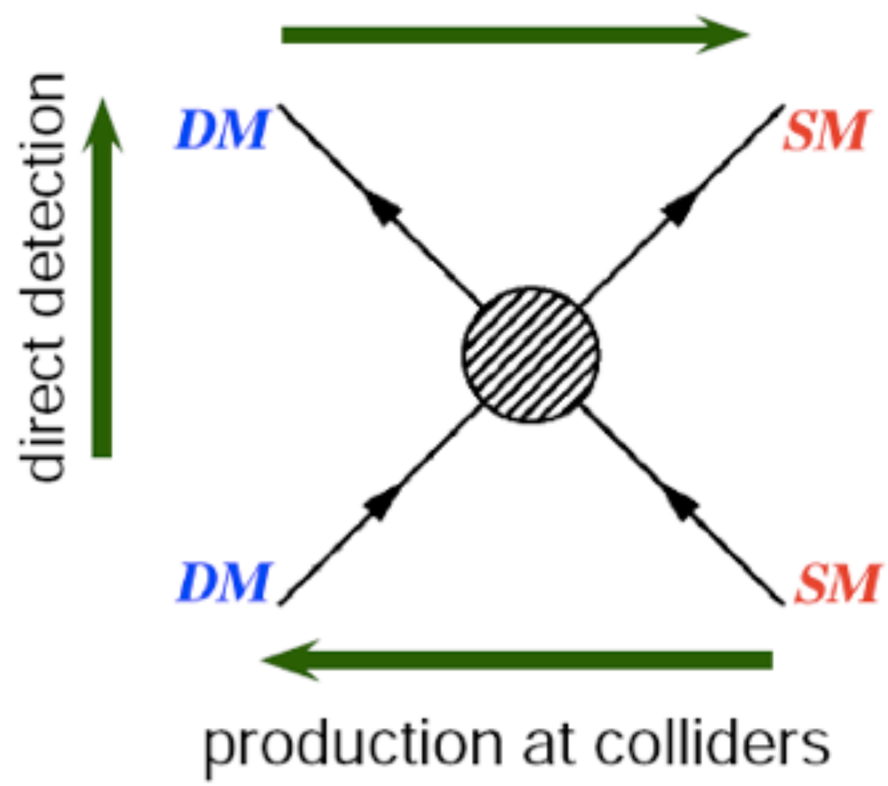



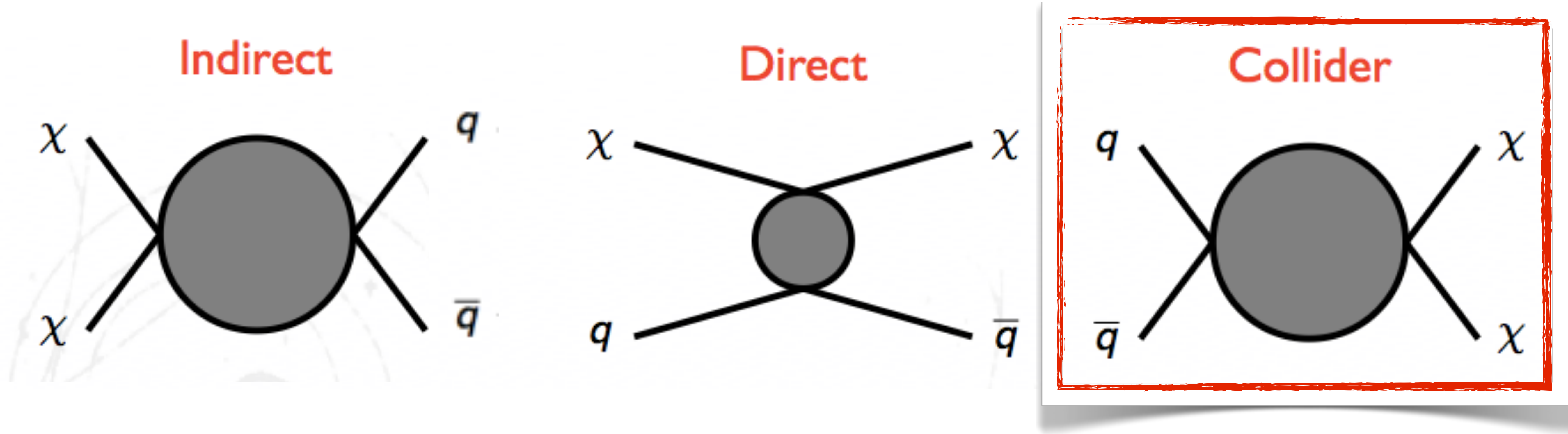

Dark matter: collider searches

Sarah Alam Malik
Imperial College London

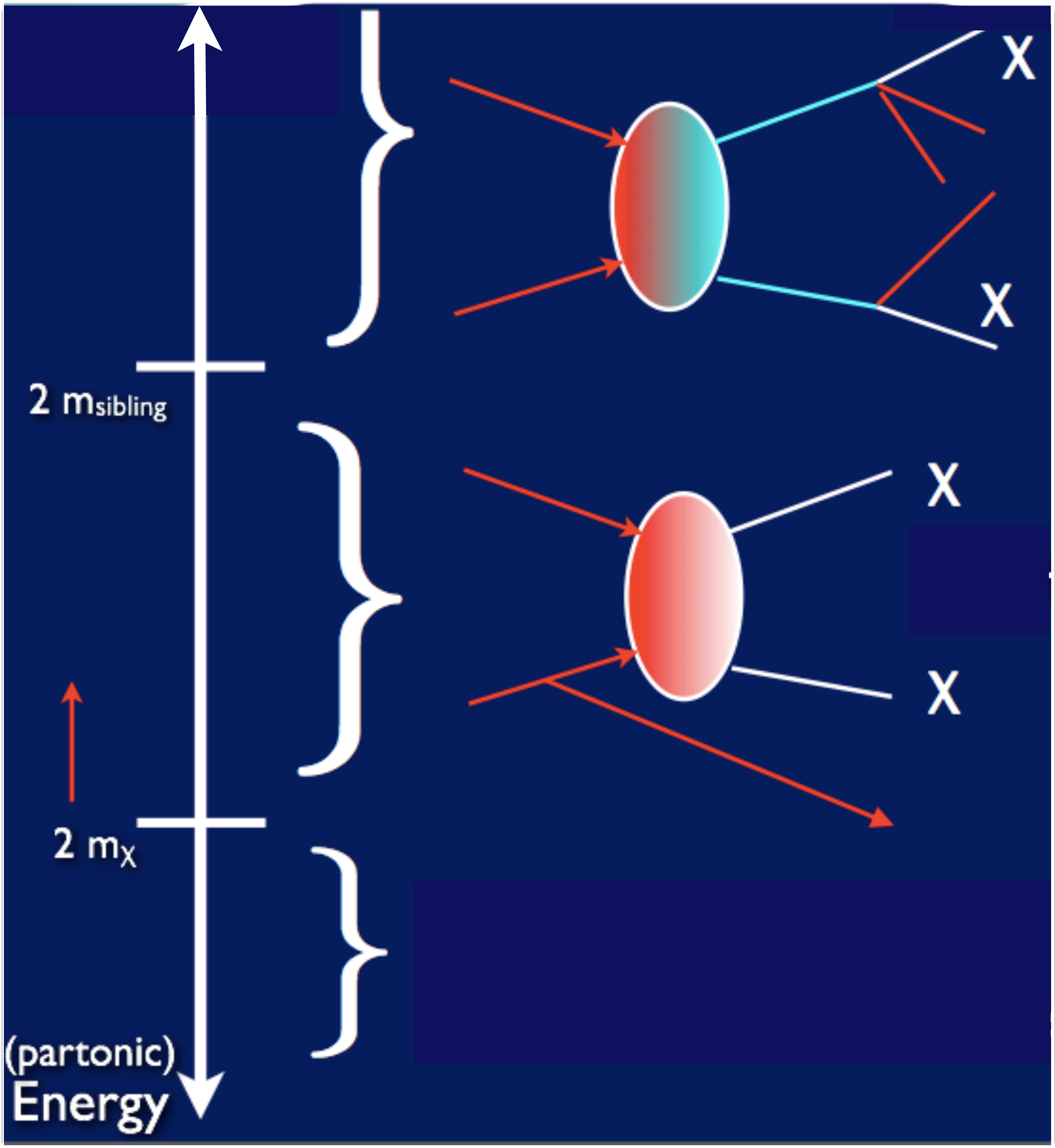
Searching for dark matter at colliders



- 3 independent approaches to searching for Weakly Interacting Massive Particles (WIMPs)
- At colliders, aim to produce dark matter particles



Searching for dark matter at colliders



LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

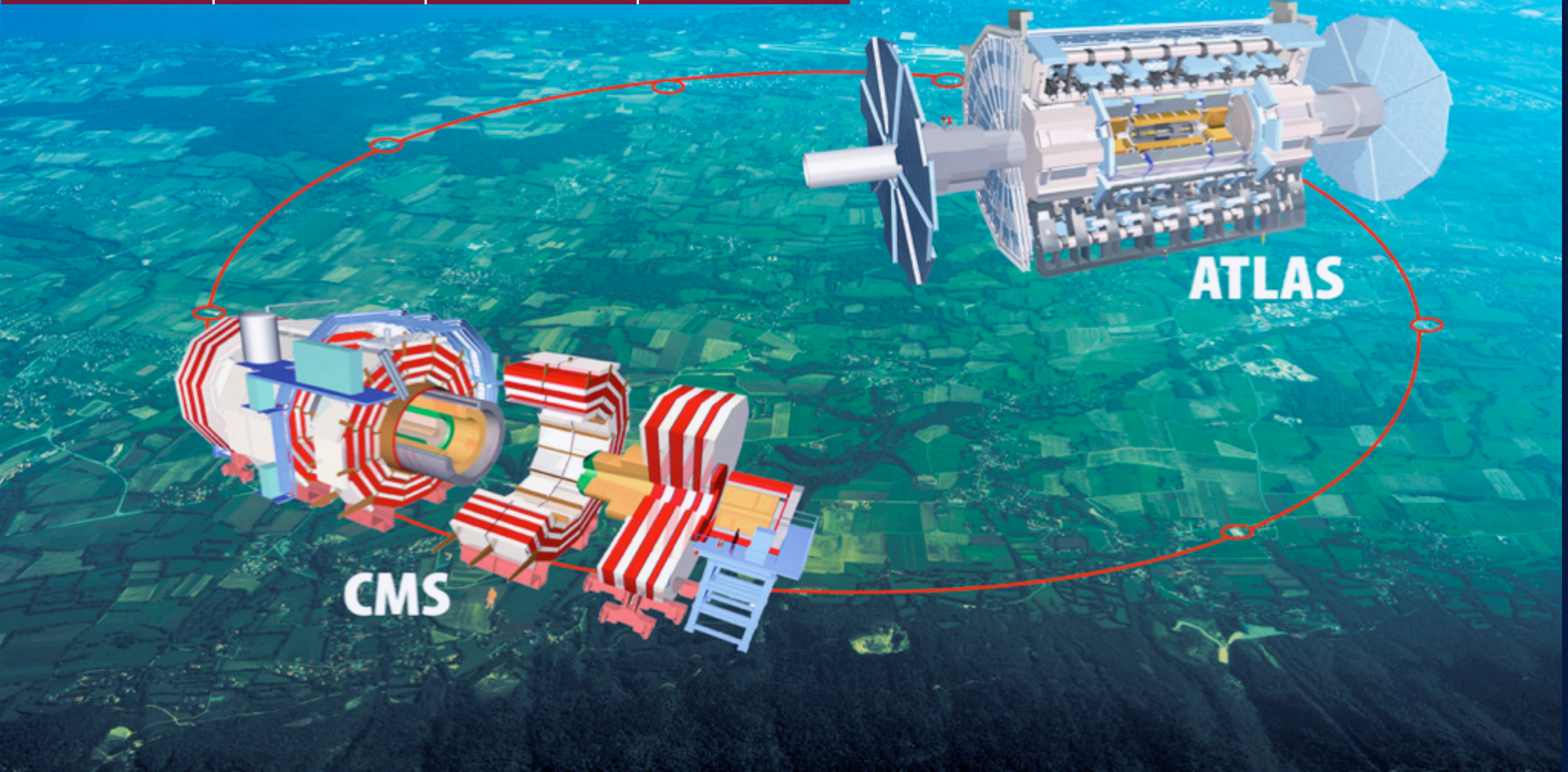
LHC cannot produce WIMPs

Slide taken from Tim Tait talk at Moriond

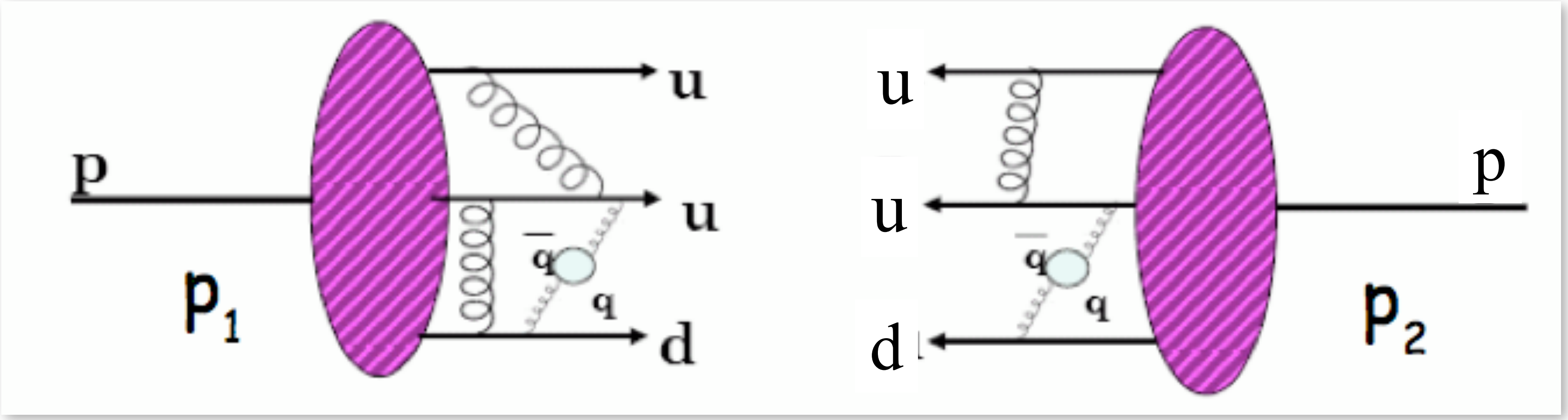
The Large Hadron Collider

	2011	2012	2015
Energy	7 TeV	8 TeV	13 TeV
Integrated luminosity	5 fb^{-1}	20 fb^{-1}	30 fb^{-1} ?

- proton-proton collider
- two general, multi-purpose detectors
- ATLAS and CMS

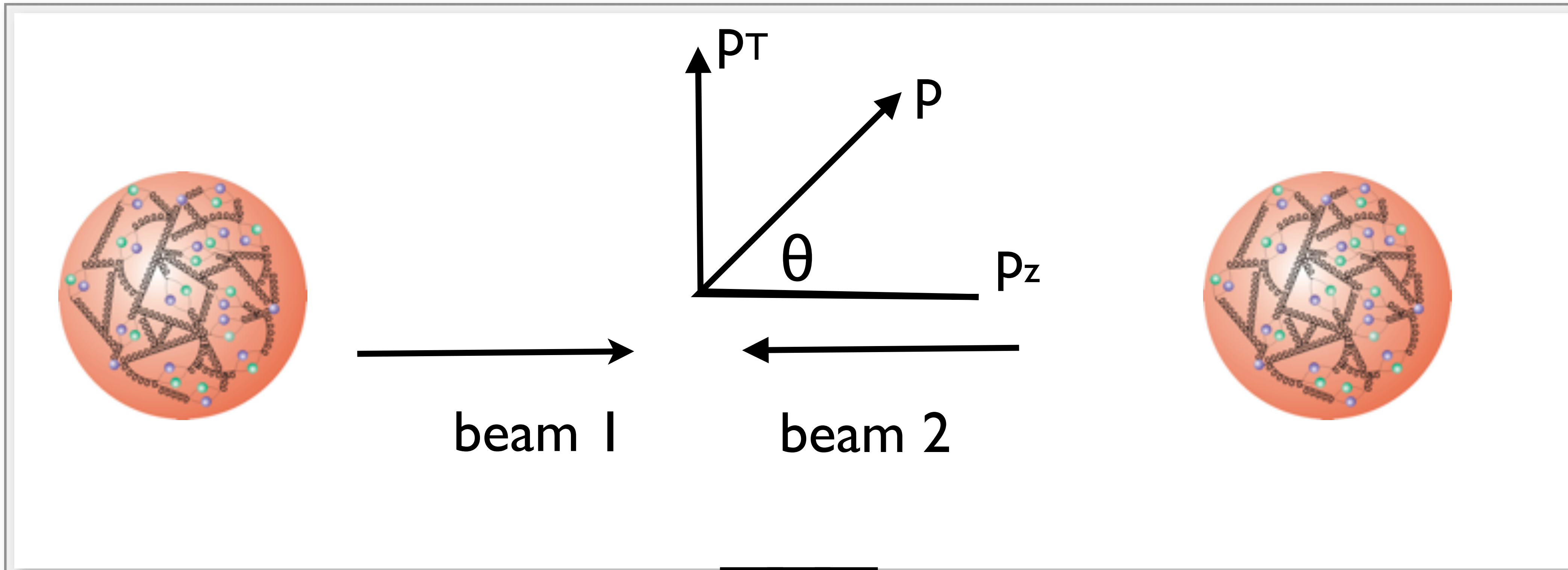


Collider basics



- Constituents of protons (quarks/antiquarks, gluons) means that a proton beam offers wide range of collision energies
- Fraction of energy of proton carried by a parton (x)
- Distribution of partons in the proton ascertained from Deep Inelastic Scattering experiments.
- Because p-p collisions are not collisions between pointlike particles, this complicates kinematics

Transverse quantities



- Hadronic center of mass frame is not the same as parton center of mass frame
- parton center of mass frame, longitudinal momentum unknown, partons carrying unknown fraction x of proton momentum
- Use kinematic quantities that are invariant under longitudinal boosts, such as transverse momentum
- Transverse momentum conserved, can assume it to be zero before collision

Energy and Luminosity

At high energy, collision occurs between partons within the proton which are carrying only a fraction (x_1, x_2) of the proton momentum

$$M^2 = (x_1 p_1 + x_2 p_2)^2$$

center of mass energy squared available to produce new particle of mass M

$$s = (p_1 + p_2)^2$$

$$\sqrt{s} = 8\,\text{TeV}$$

So, with 8 TeV collider,
To produce a DM particle of mass 100 GeV need $x_1, x_2 = 0.0125$ (for 13 TeV, $x = 0.008$)
For DM = 3 TeV, need $x_1, x_2 = 0.38$ (for 13 TeV, $x=0.23$)

So, to produce heavier DM particle, need higher energy!

Energy and Luminosity

Energy is not enough, we need luminosity too

Number of events produced for a given process per sec

$$N = \sigma \times L$$

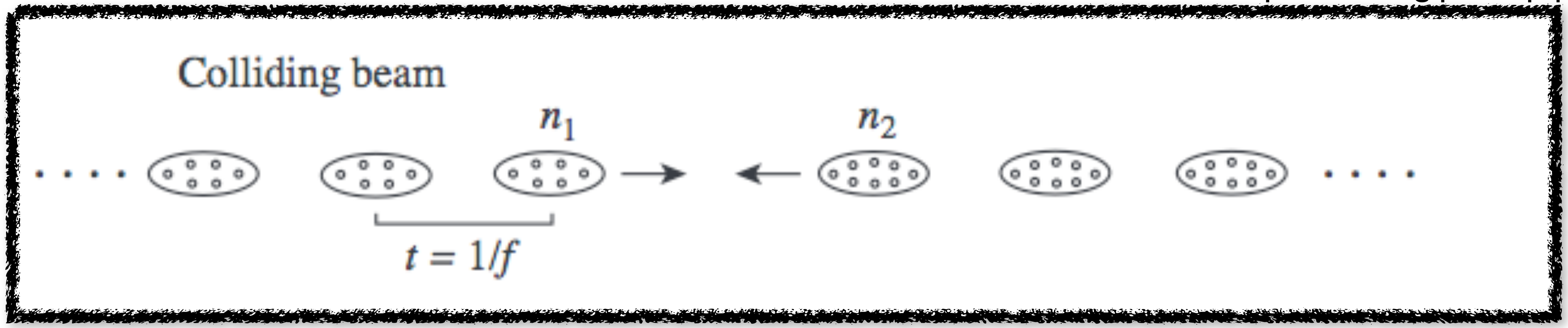
luminosity : provided by machine

cross section of process of interest

For a process with small cross section, need high luminosity L

Energy and Luminosity

http://arxiv.org/pdf/hep-ph/0508097v1.pdf



Luminosity roughly scales as

$$L \propto f \frac{n_1 n_2}{a}$$

\# of particles per bunch

beam crossing frequency

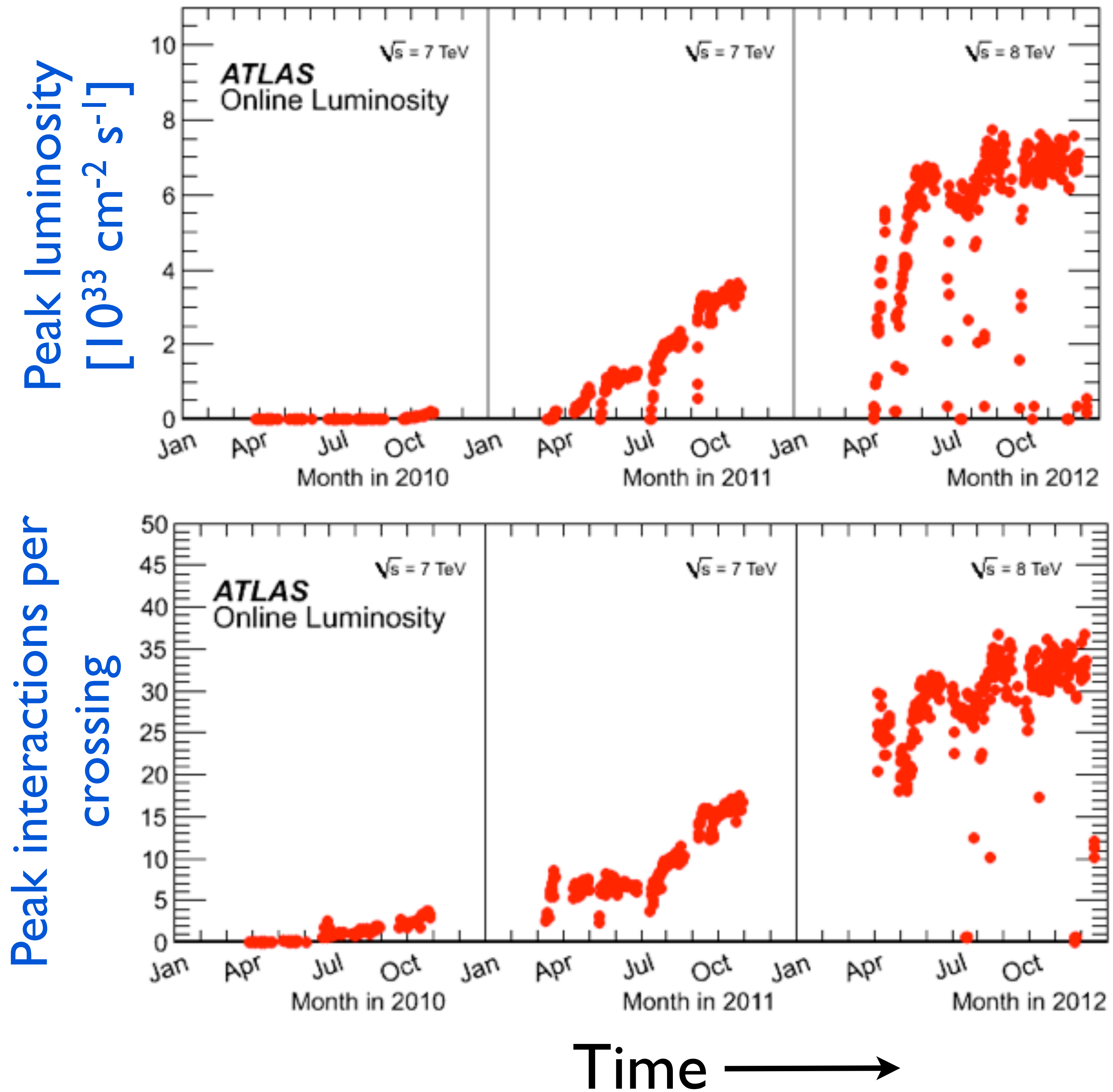
transverse profile of bunches

Under nominal design conditions for 14 TeV LHC,

- Each proton beam has 2808 bunches
- Each bunch containing 10^{11} protons
- Design luminosity 10^{34} cm^{-2}s^{-1}

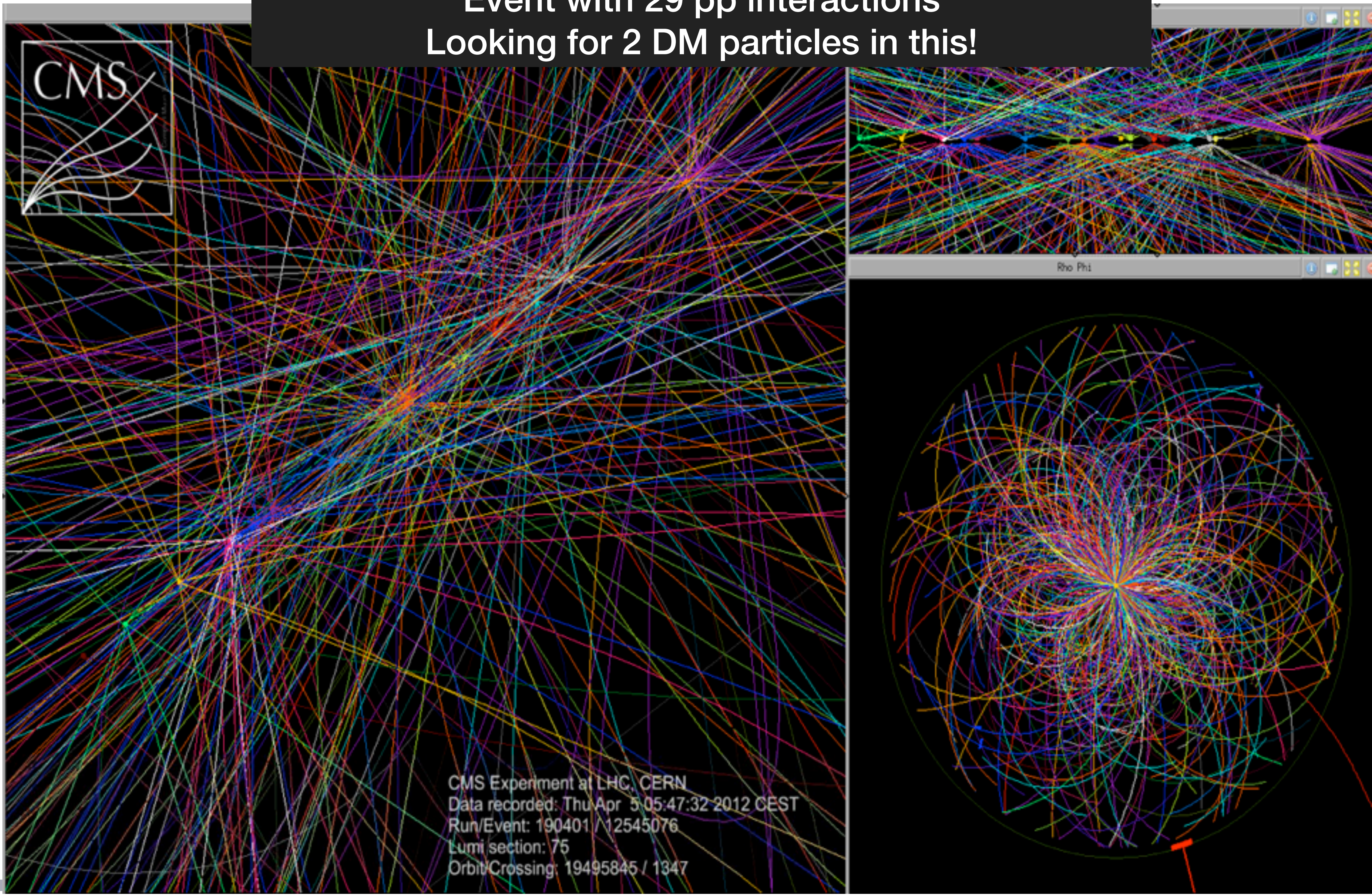
Energy and Luminosity

Instantaneous luminosity gradually increases over time.
As a result, more pp interactions per bunch crossing

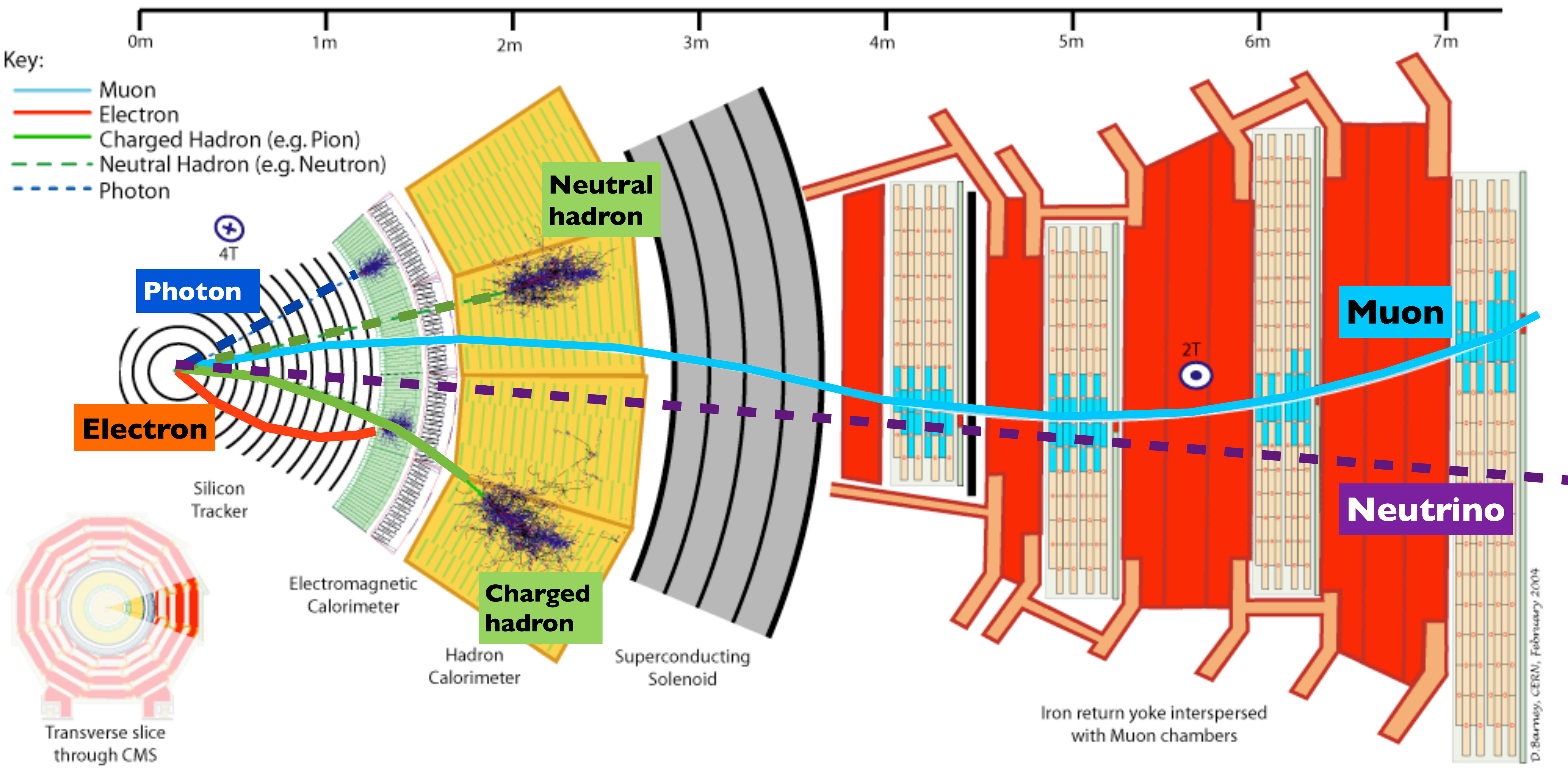


Collisions

Event with 29 pp interactions
Looking for 2 DM particles in this!



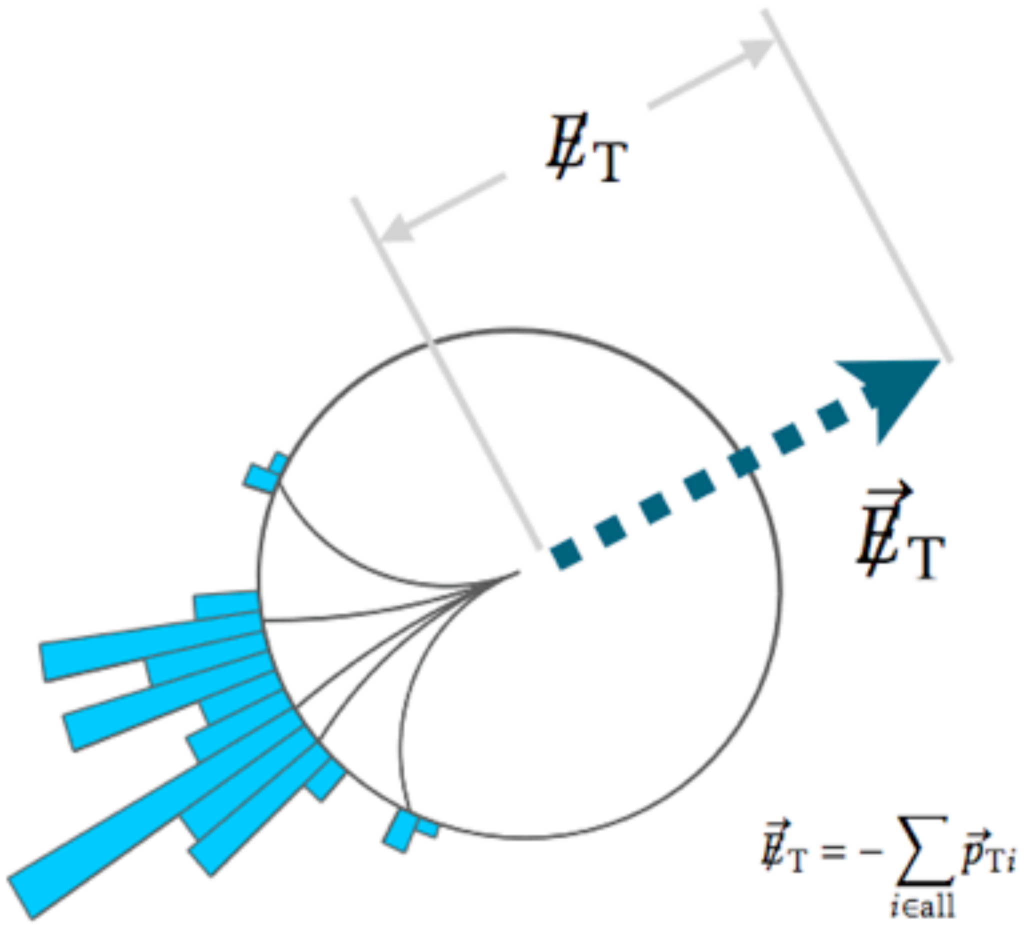
Passage of particles through the CMS detector



Neutrinos traverse the detector without any interaction
DM particles, being neutral and weakly interacting will look much like neutrinos in our detectors

At the heart of all DM searches at colliders : Missing transverse energy (MET)

➡ DM neutral and weakly interacting
➡ only infer its presence in detector from imbalance in transverse momentum of all visible particles

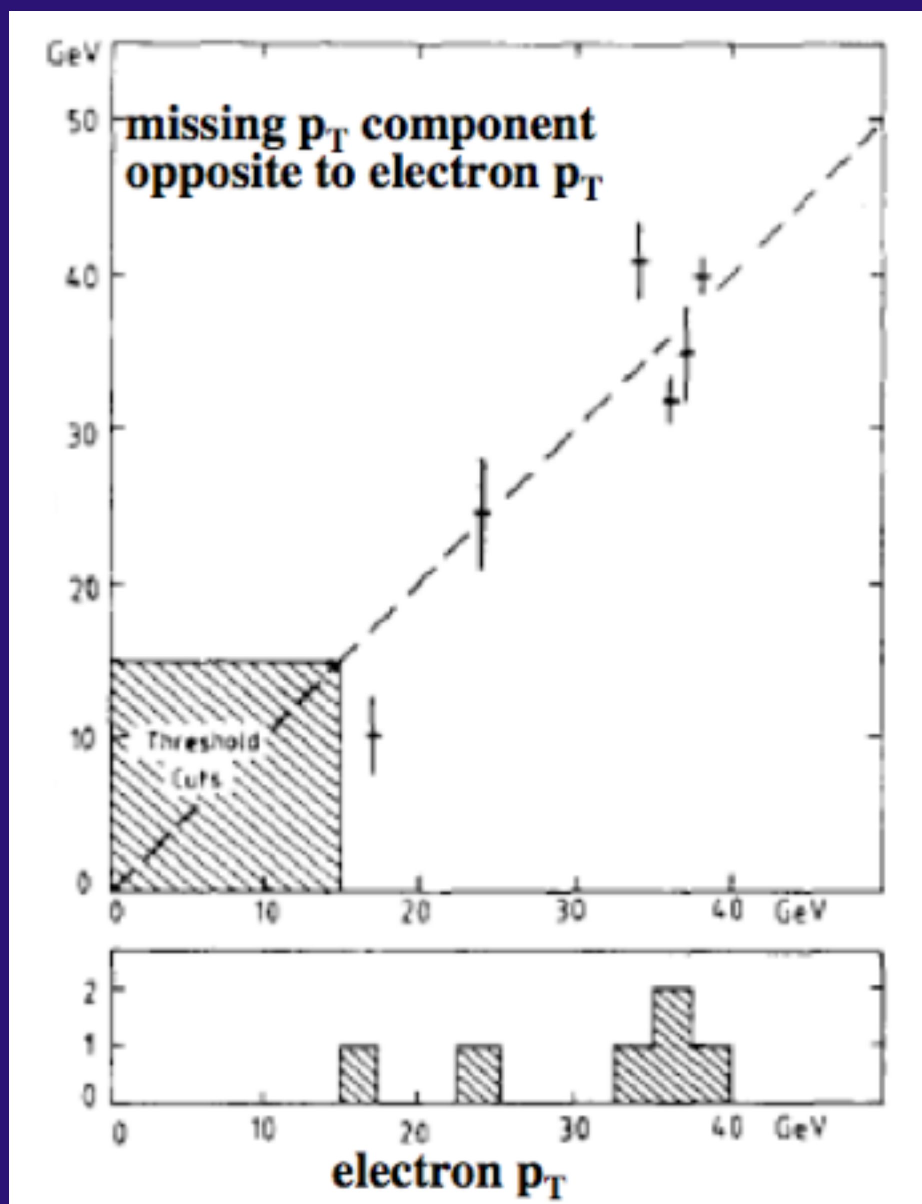


➡MET = negative of the vector sum of the transverse momenta of all particles reconstructed in the event

Missing Transverse Energy

At the

Missing transverse energy (MET) has been a major tool in our discovery of new phenomena at hadron colldiers



MET used by UA1 experiment in 1983 to discover W boson
- Discovery made using just 6 events and mass determined to 3% due to ability of UA1 to infer presence of neutrinos with resolution of a few GeV.

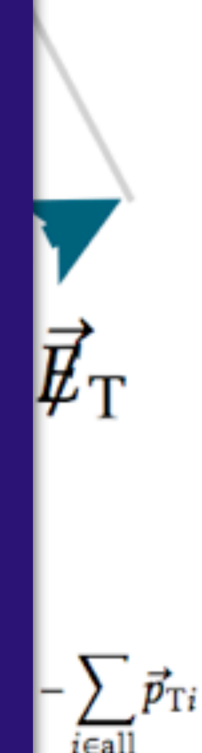
$$m_W = 81 \pm 5\,\mathrm{GeV/c^2}$$

➡ DN

➡ on

imba

visib



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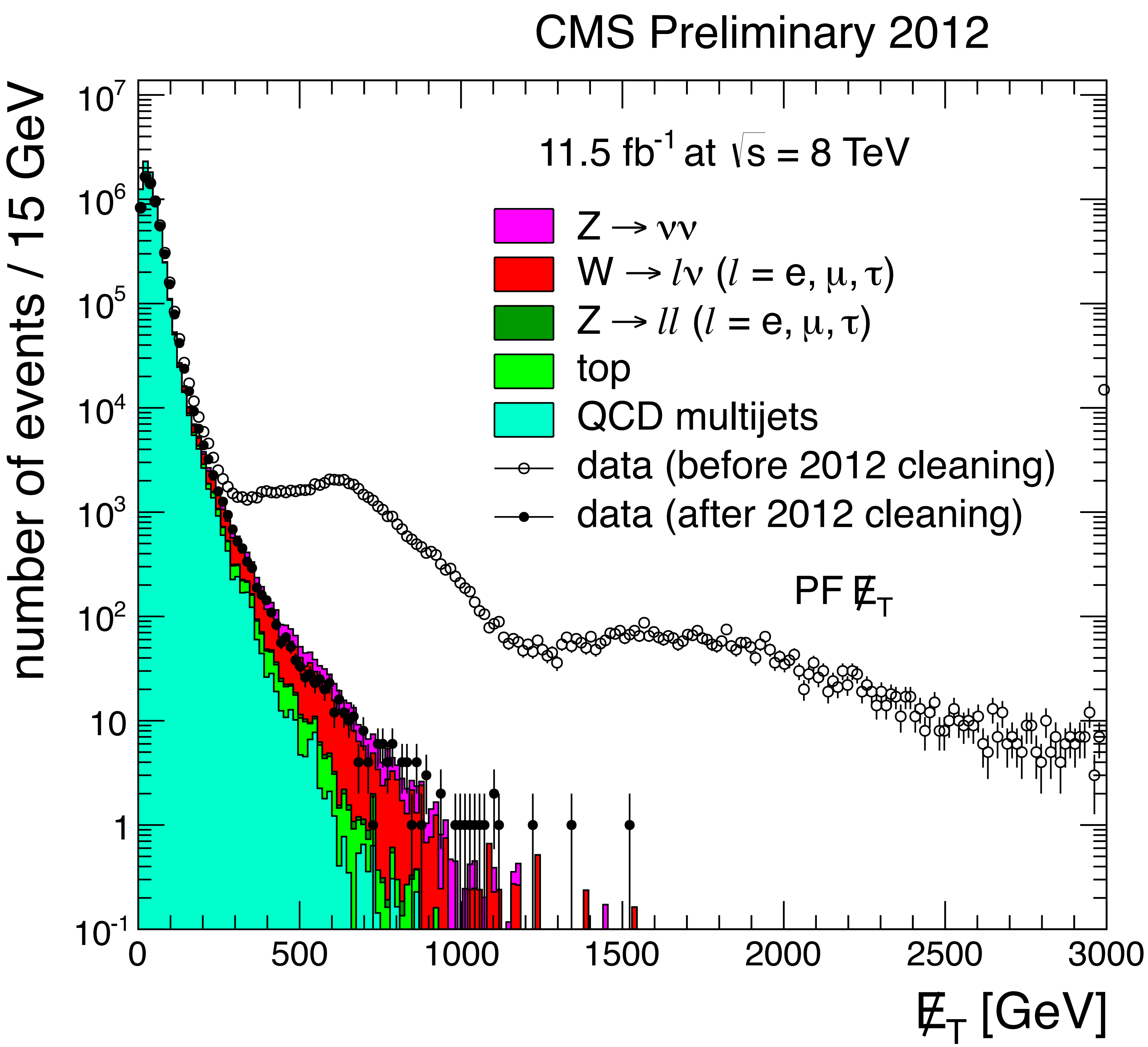
Missing Transverse Energy



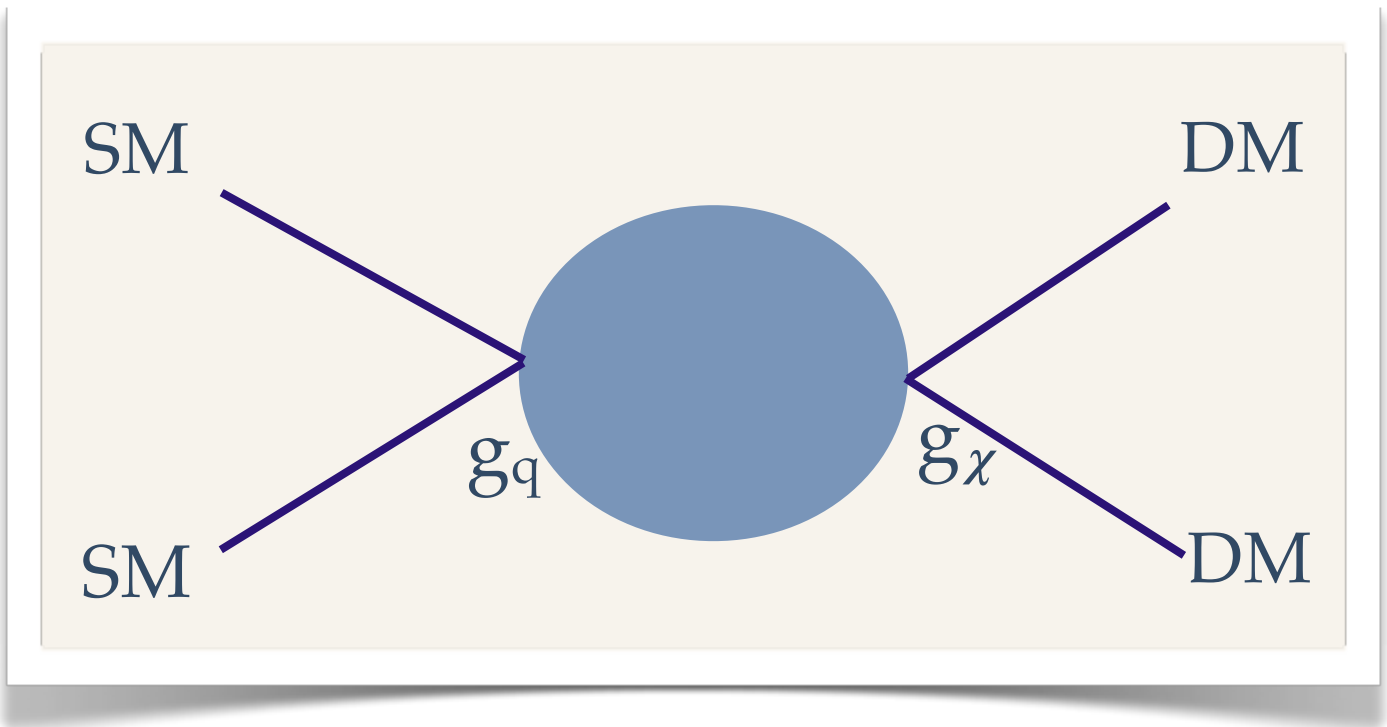
- challenging quantity to measure
- sensitive to mis-measurements, detector effects, backgrounds
- but well controlled


DM searches at colliders

Phenomenology

Assumptions:

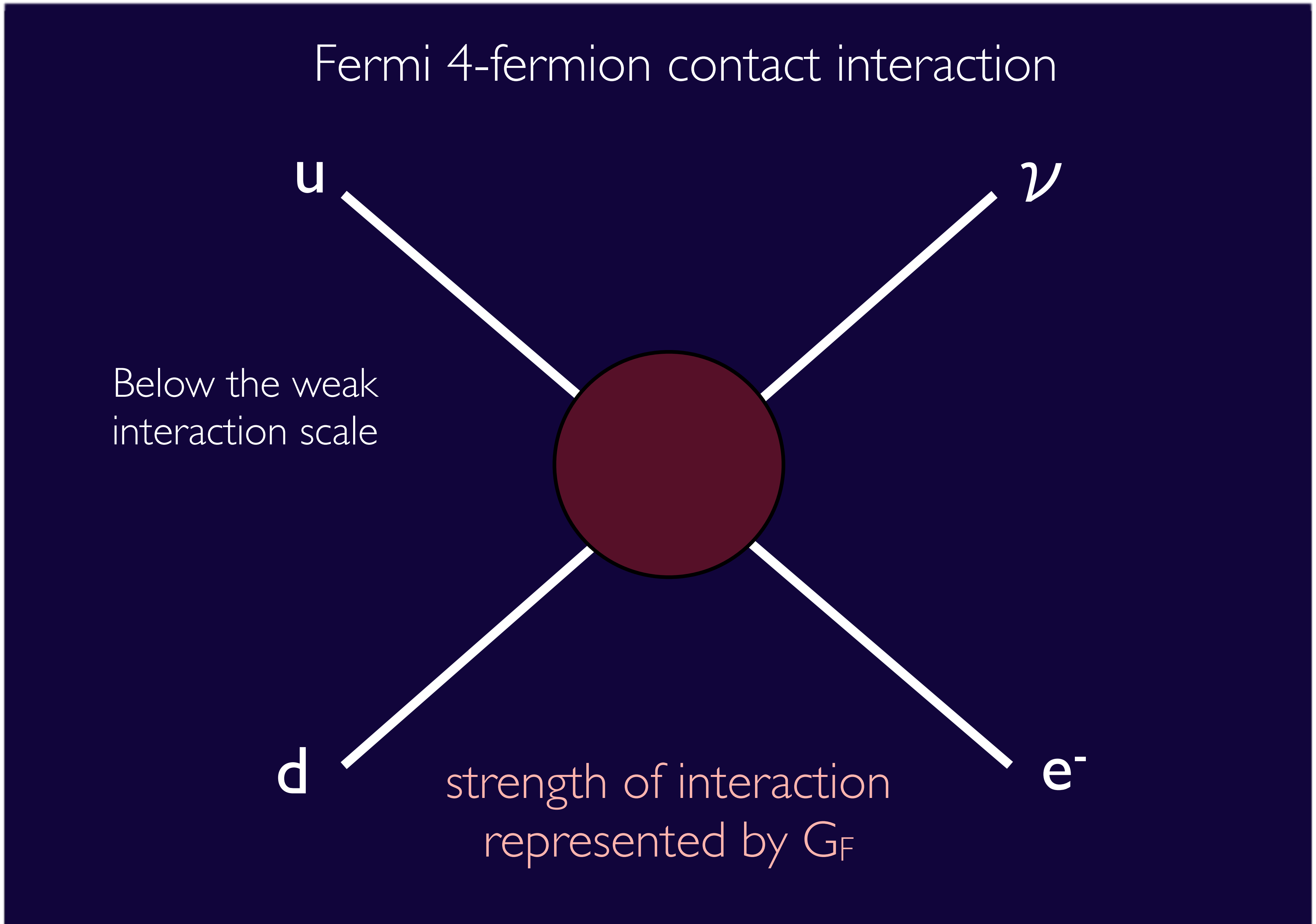
- DM particle is only new state accessible to the collider
- Effective field theory so interaction between DM and SM particles is contact interaction



Phenomenology

Assumptio

- DM part
- Effective ... t interaction
- Mediato



$$M_{fi} = G_F\, g_{\mu\nu} [\overline{\psi}\gamma^{\mu}\psi][\overline{\psi}\gamma^{\nu}\psi]$$

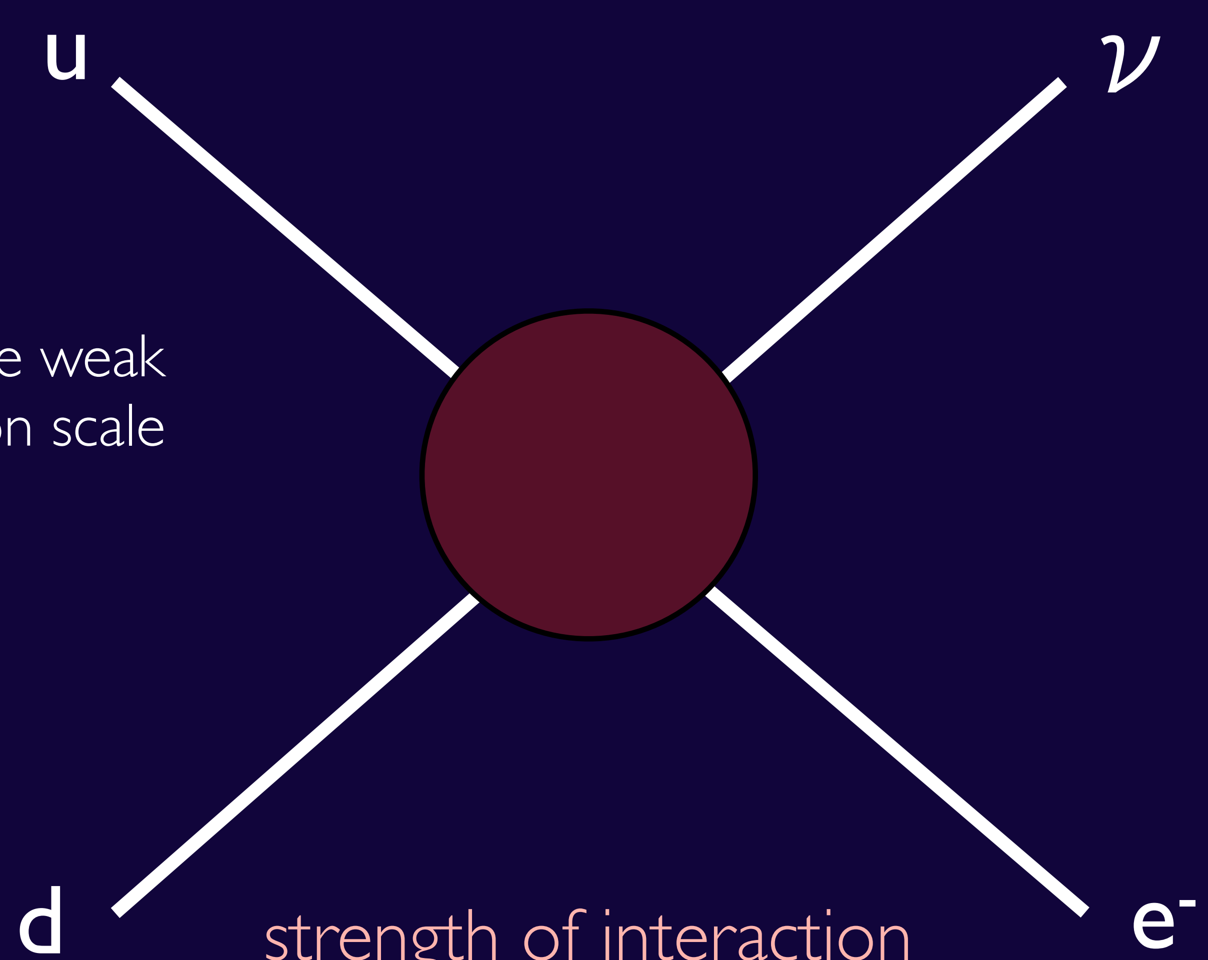
Phenomenology

Assumptio

- DM part
- Effective
- Mediato

t interaction

Fermi 4-fermion contact interaction



Below the weak interaction scale

strength of interaction represented by G_F

After discovery of parity violation n 1957........

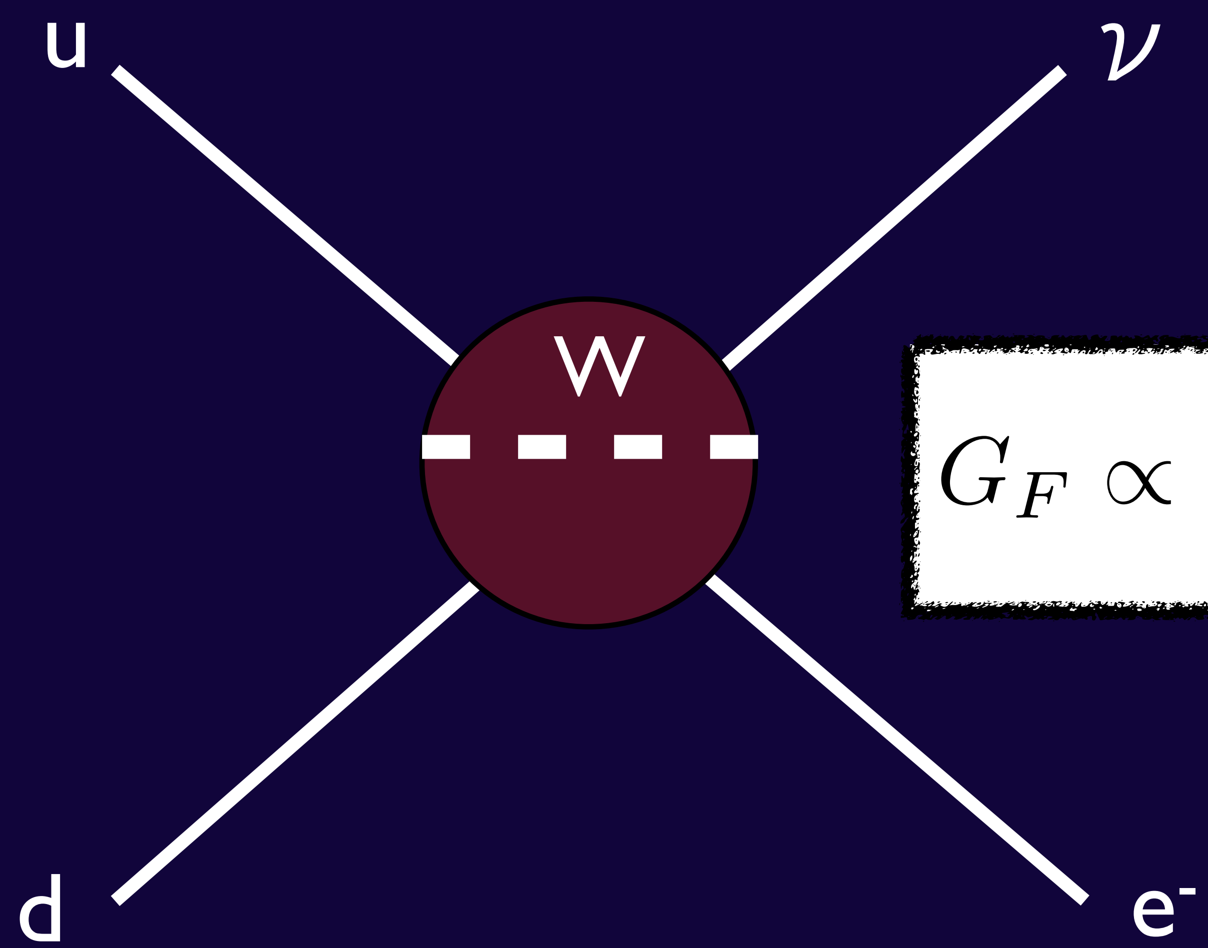
$$M_{fi} = \frac{G_F}{\sqrt{2}} g_{\mu\nu} [\overline{\psi}\gamma^{\mu}(1-\gamma^5)\psi][\overline{\psi}\gamma^{\nu}(1-\gamma^5)\psi]$$

Phenomenology

Assumptio

- DM part
- Effective … t interaction
- Mediato

After discovery of W boson.........



$$G_F \propto \frac{{g_w}^2}{{M_w}^2}$$

$$M_{fi} = \left[\frac{g_W}{\sqrt{2}}\overline{\psi}\frac{1}{2}\gamma^{\mu}(1-\gamma^5)\psi\right]\boxed{\frac{g_{\mu\nu}-q_{\mu}q_{\nu}/m_W^2}{q^2-m_W^2}}\left[\frac{g_W}{\sqrt{2}}\overline{\psi}\frac{1}{2}\gamma^{\nu}(1-\gamma^5)\psi\right]$$

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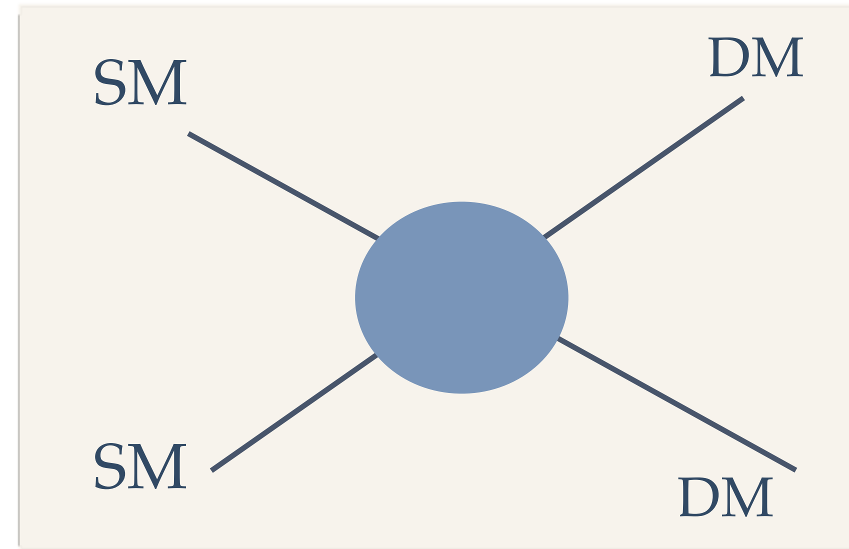


$$\mathcal{L} = \underbrace{\mathcal{L}_{SM}}_{\text{SM Lagrangian}} + \underbrace{i\bar{X}\gamma^{\mu}\partial_{\mu}X - M_X\bar{X}X}_{\text{kinetic terms for DM}} + \underbrace{\sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} \, [\bar{X}\Gamma_i^X X]\, [\bar{q}\Gamma_q^j q]}_{\text{set of 4-Fermion interactions between DM and SM quarks}},$$

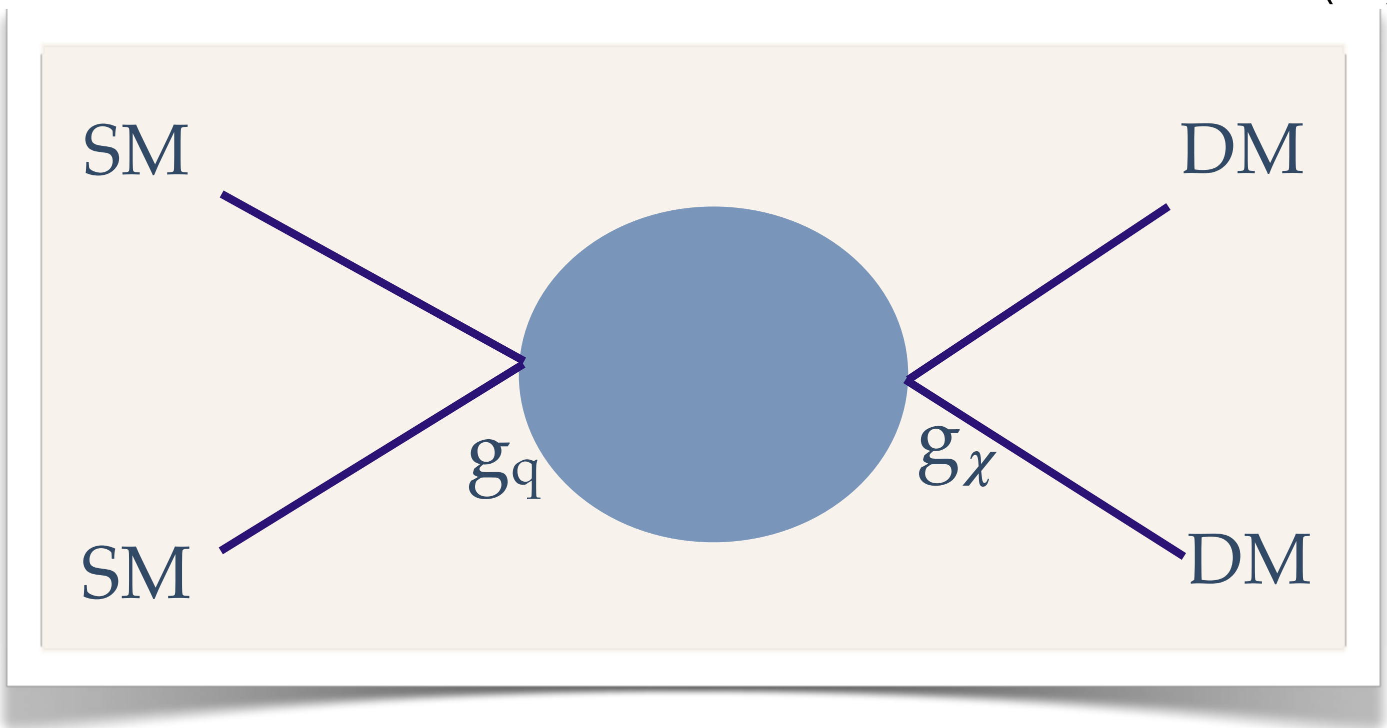
Operators $\mathbf{\Gamma}$ describe scalar, pseudoscalar, vector, axial vector, tensor interactions

Phenomenology

Assume DM is a Dirac fermion and interaction is characterized by contact interaction,

Bai, Fox and Harnik, JHEP 1012:048 (2010)

Set mass of mediator (M) to very high value



(a) For vector mediator, effective operator

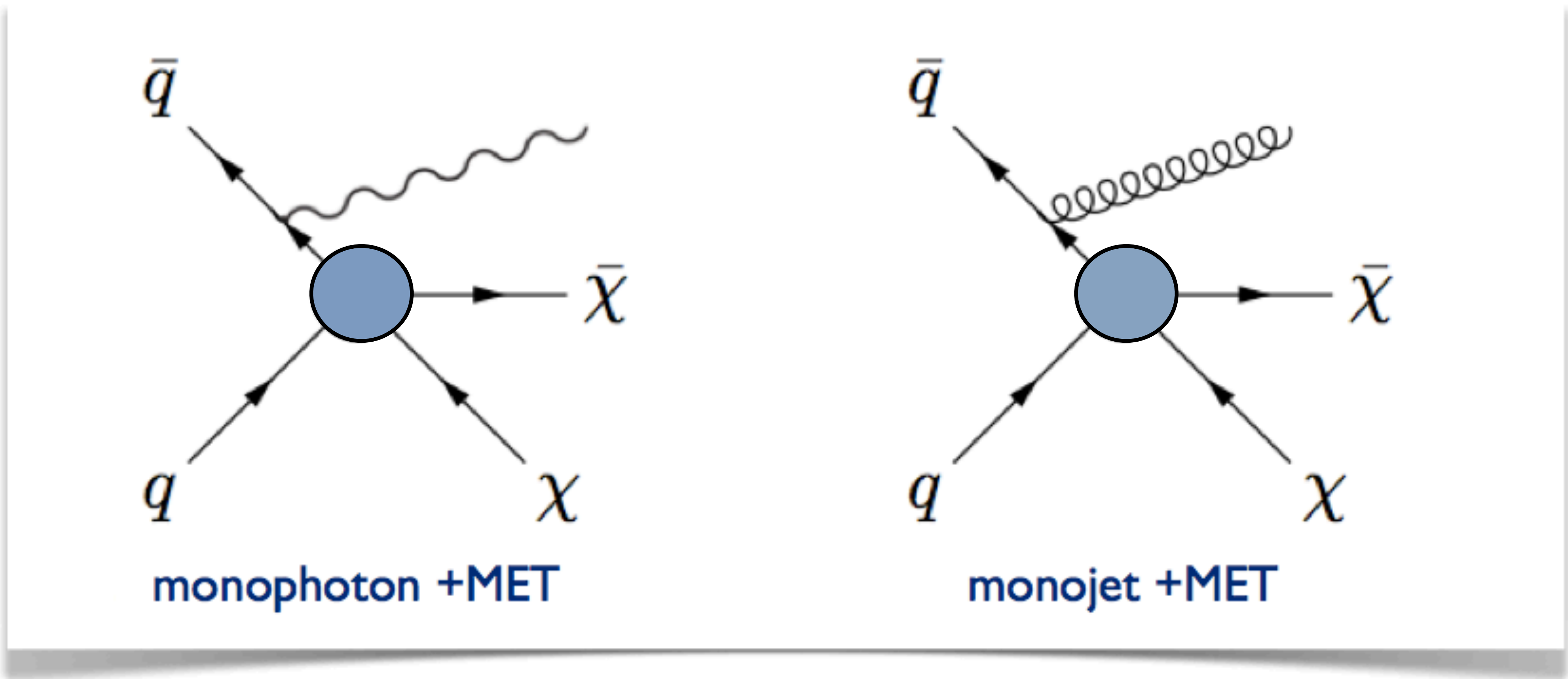
$$\boxed{\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}}$$

$$\Lambda = M/\sqrt{g_\chi g_q}$$

spin-independent

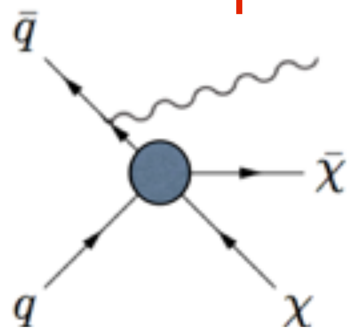
Signatures for dark matter searches

Dark matter pair production at LHC
- DM particles produce missing energy
- radiation of a photon/jet from initial state

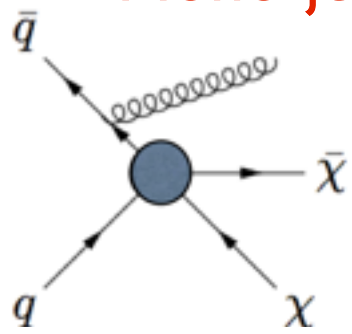


Signatures for dark matter searches: Mono-X

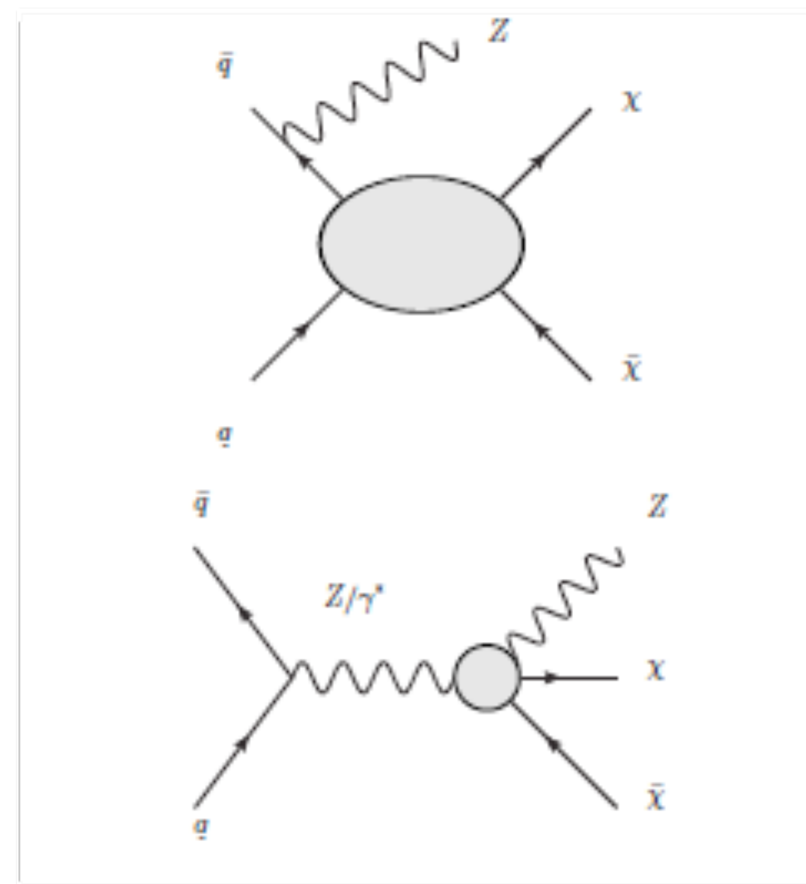
Mono-photon



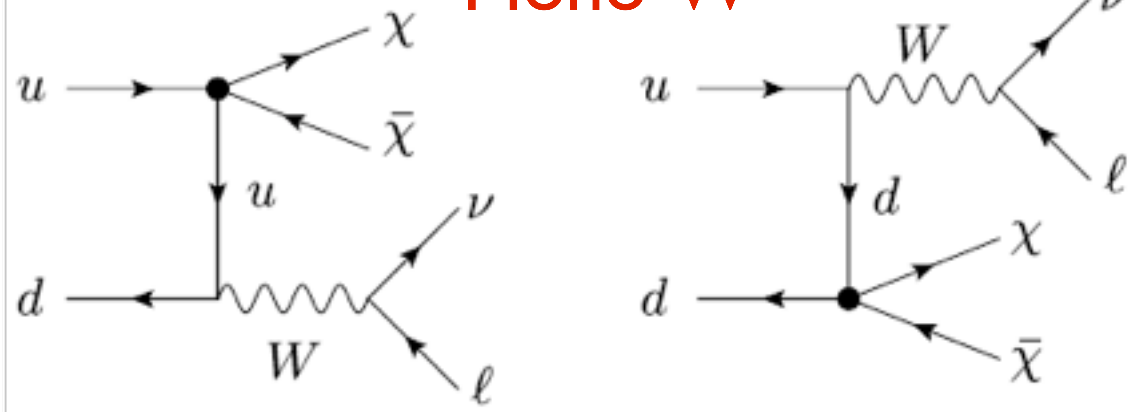
Mono-jet



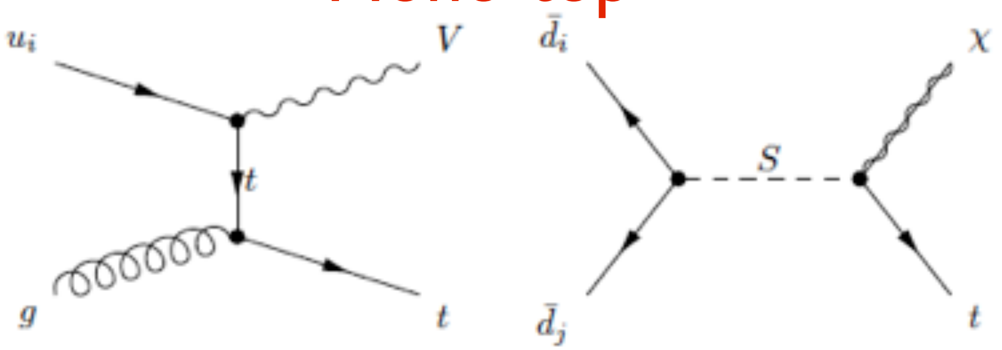
Mono-Z



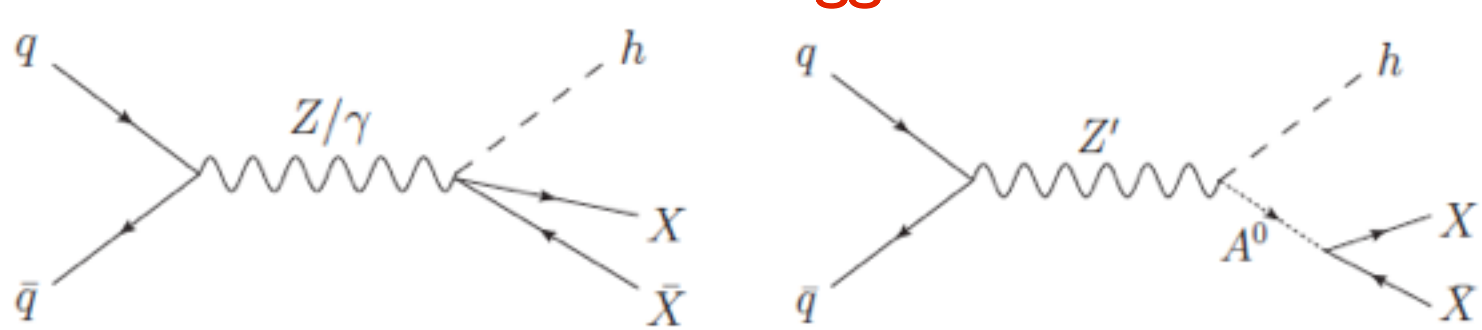
Mono-W



Mono-top

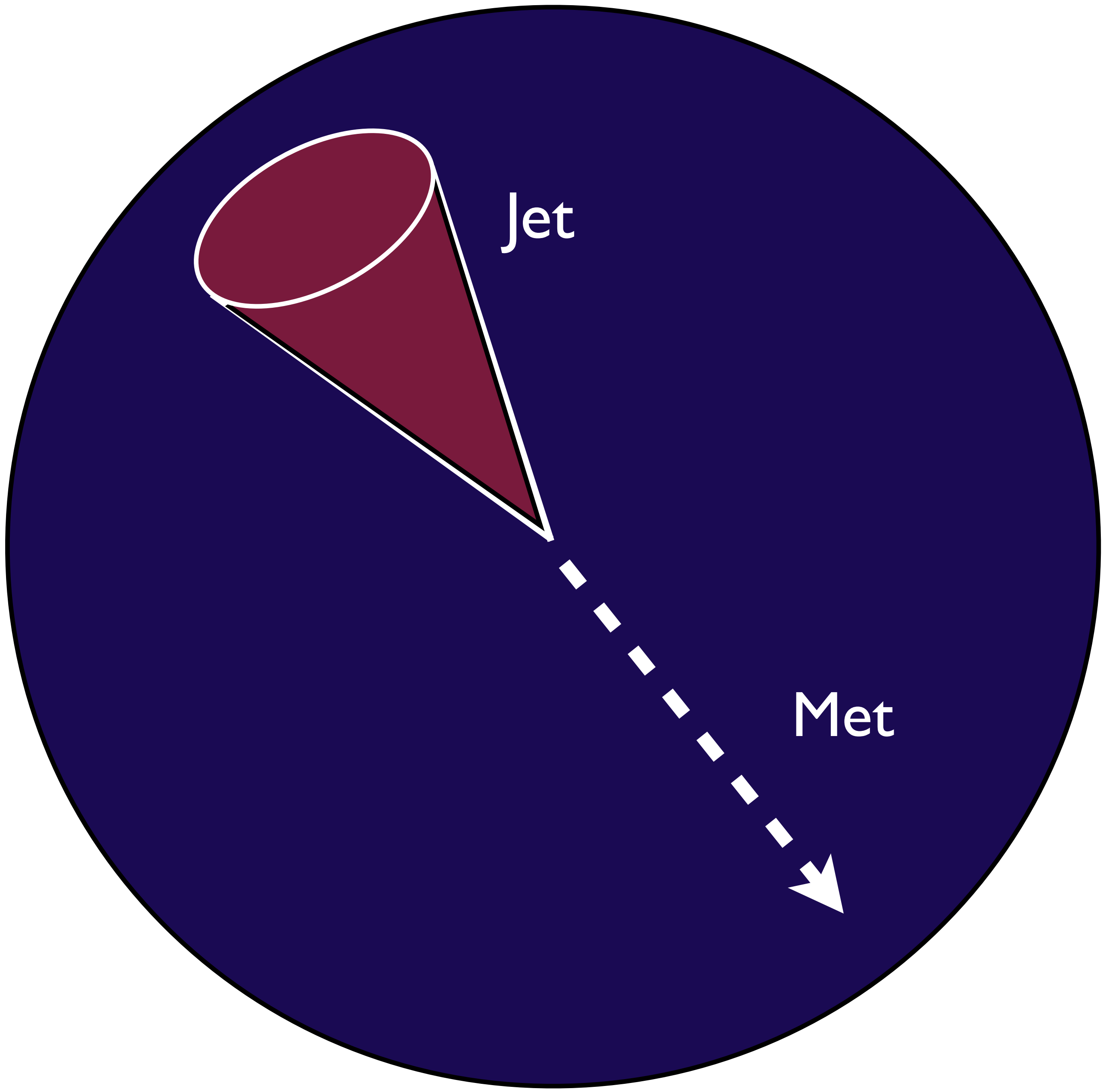


Mono-Higgs



Monojet Signature

Simple and striking signature



- Simplest collider signature

- visible energy from jet, recoiling against particle(s) that do not interact with detector

Measurement Strategy

- ‘cut and count’ : apply event selection and count number of events in signal region
- look for excess of events above those expected from SM backgrounds
- understanding of backgrounds is crucial

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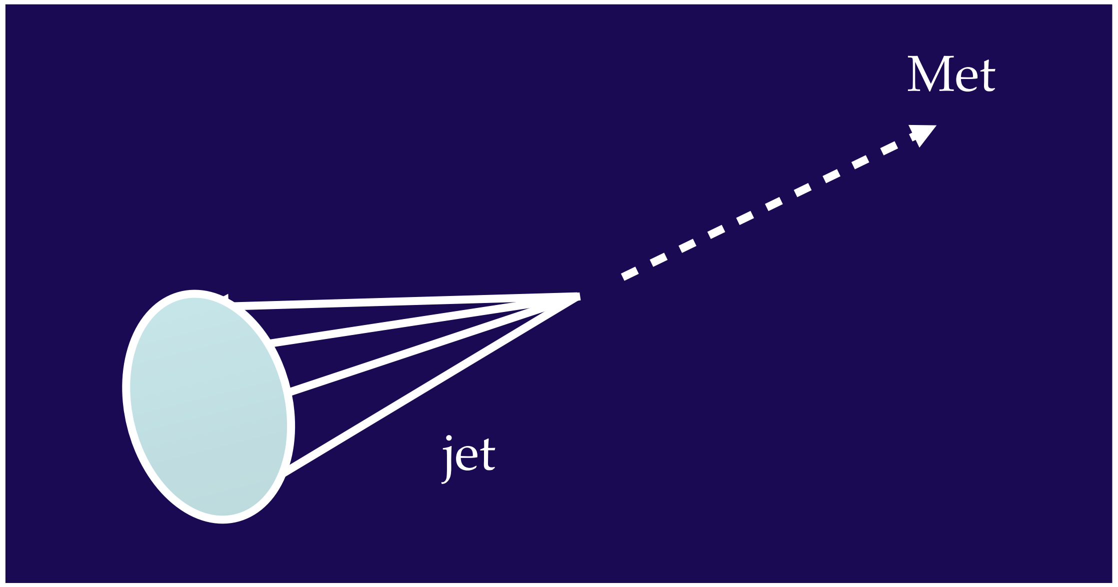

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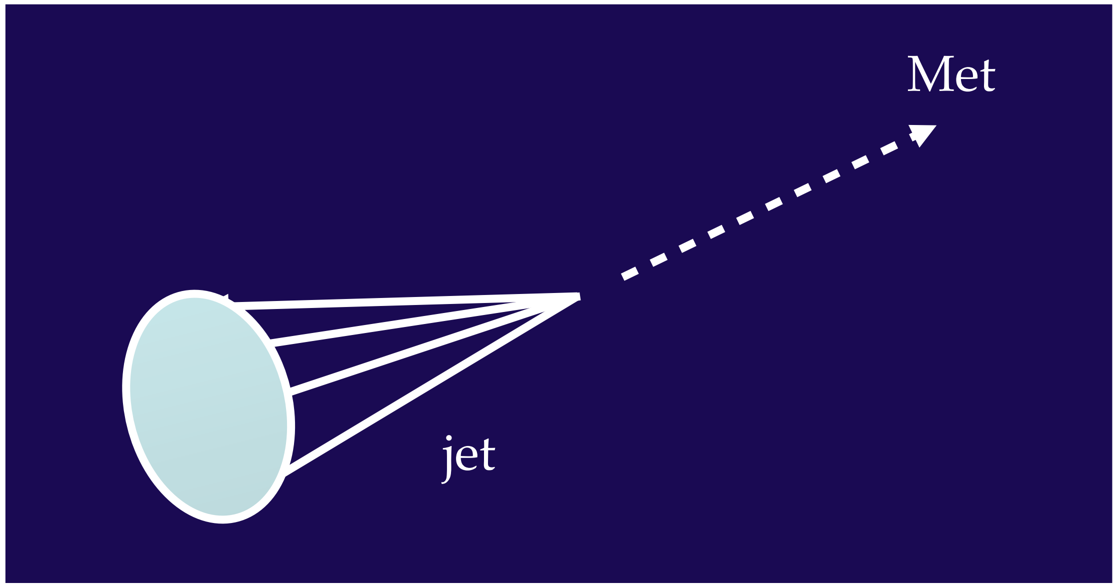
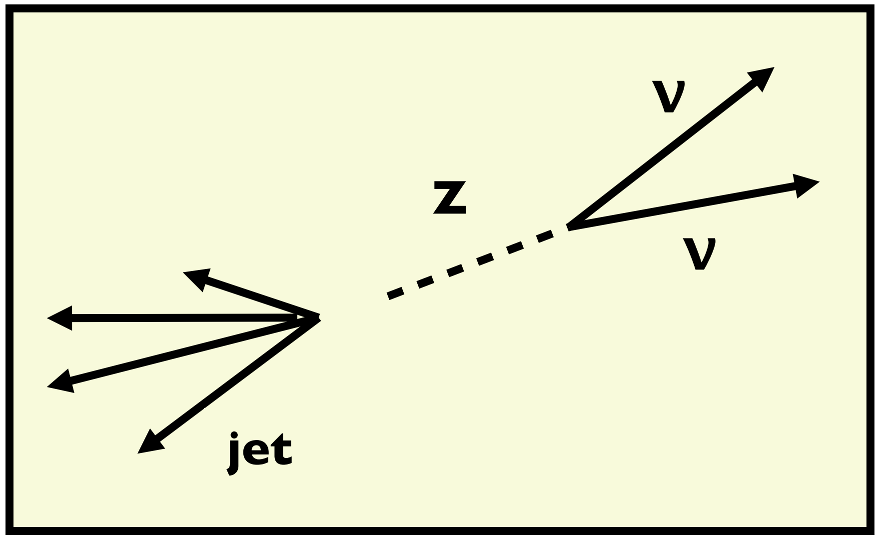


Backgrounds

$Z \rightarrow \nu\nu$ +jet, irreducible background, looks just like signal



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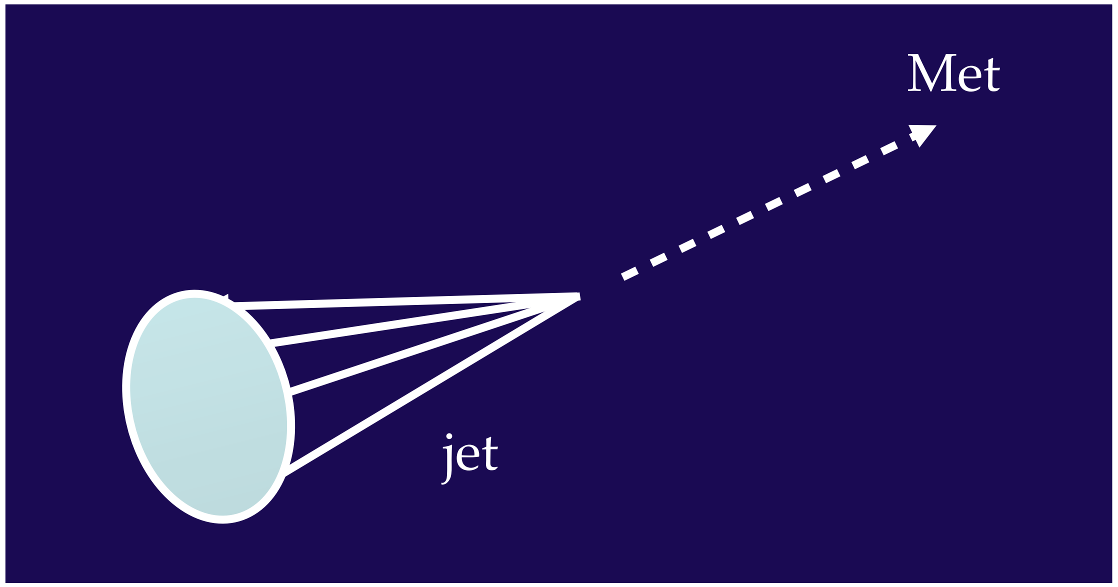

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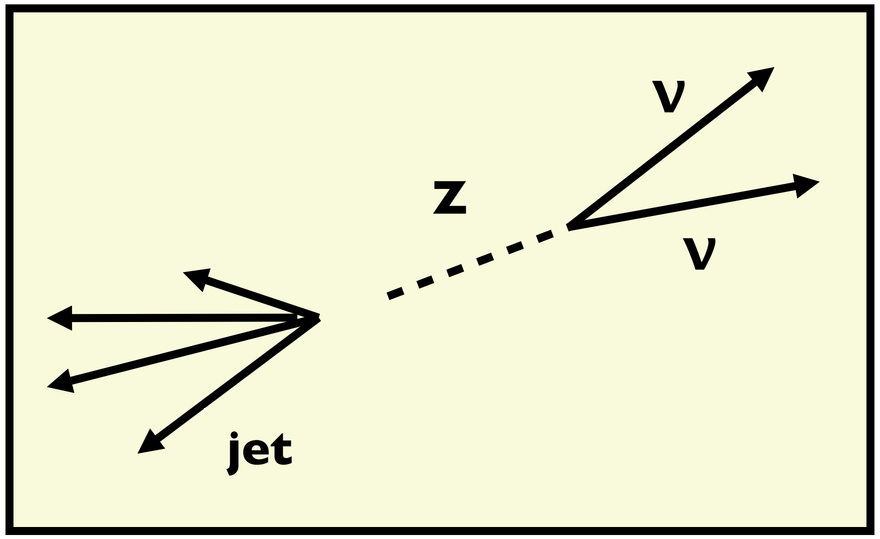
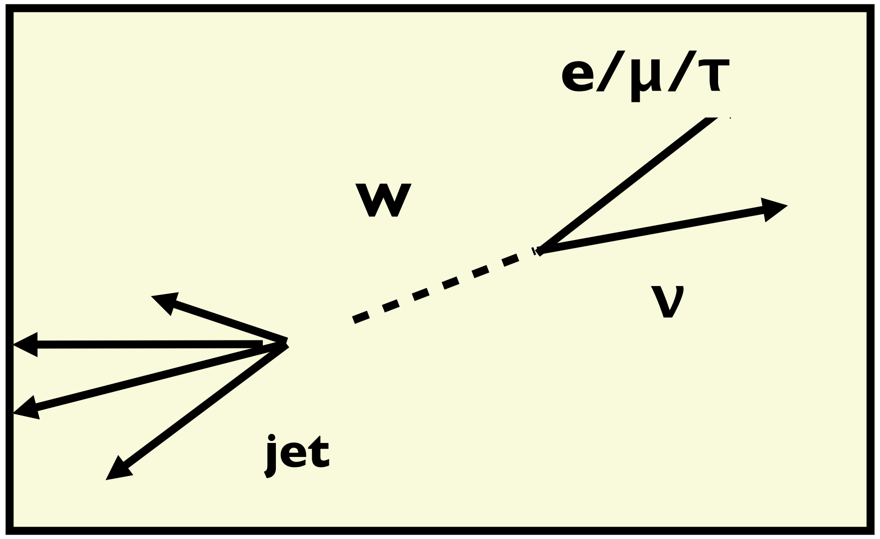


W+jets, e/u is not detected, tau decays hadronically



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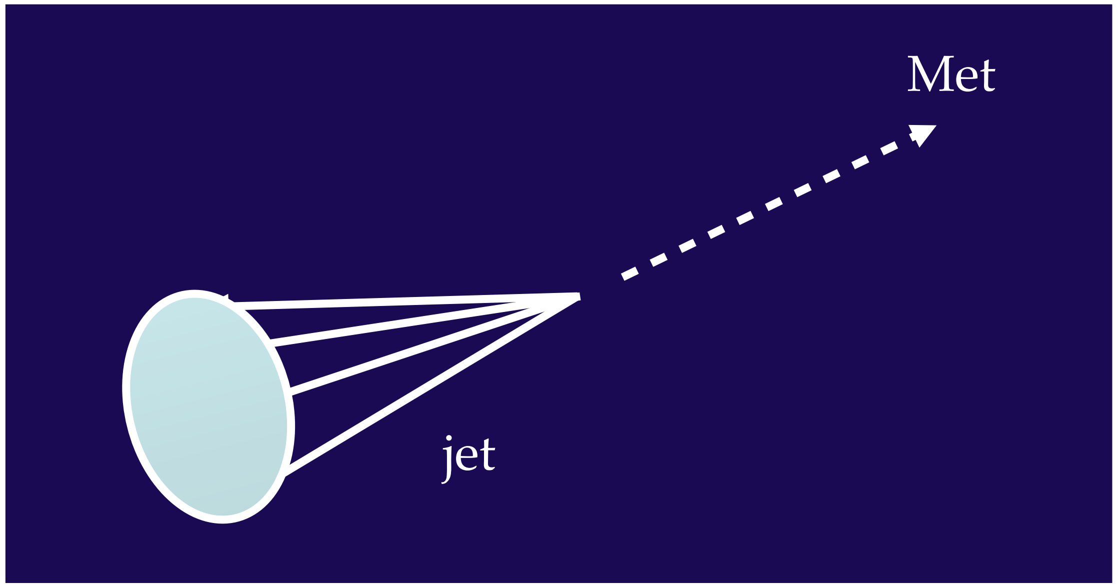

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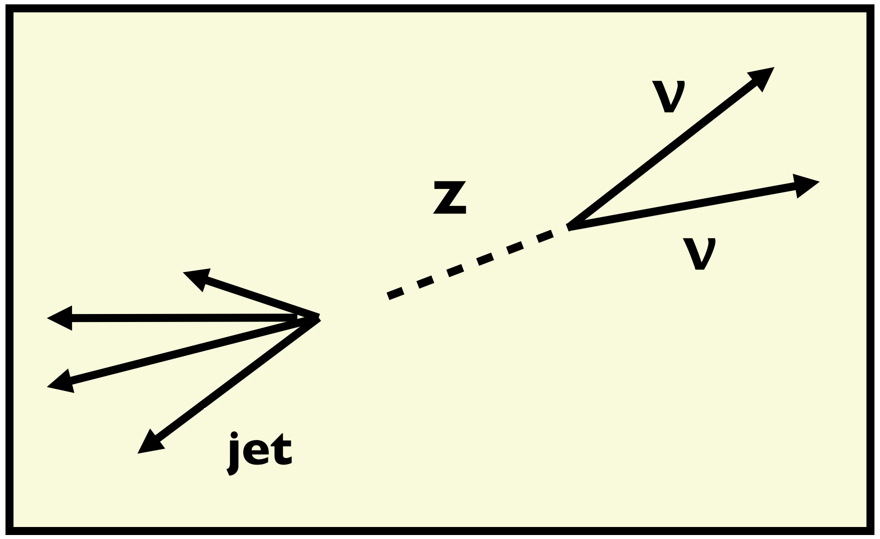

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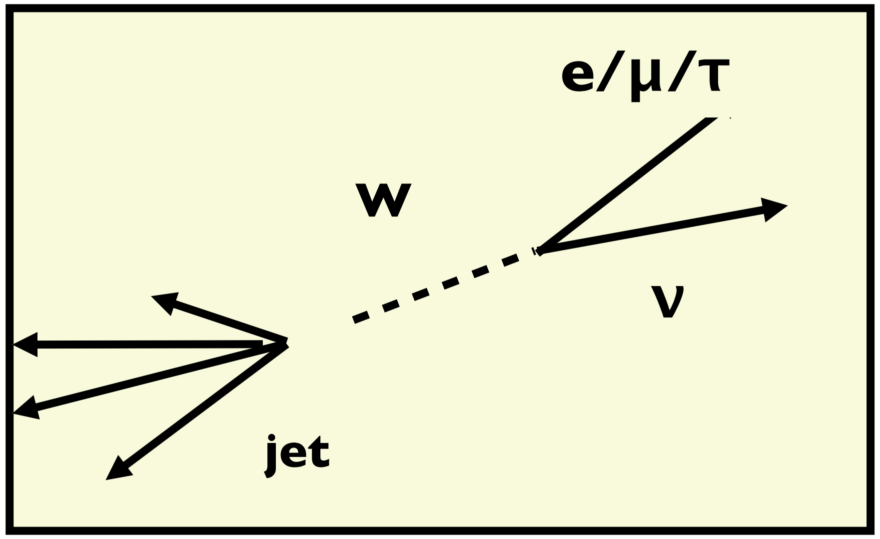
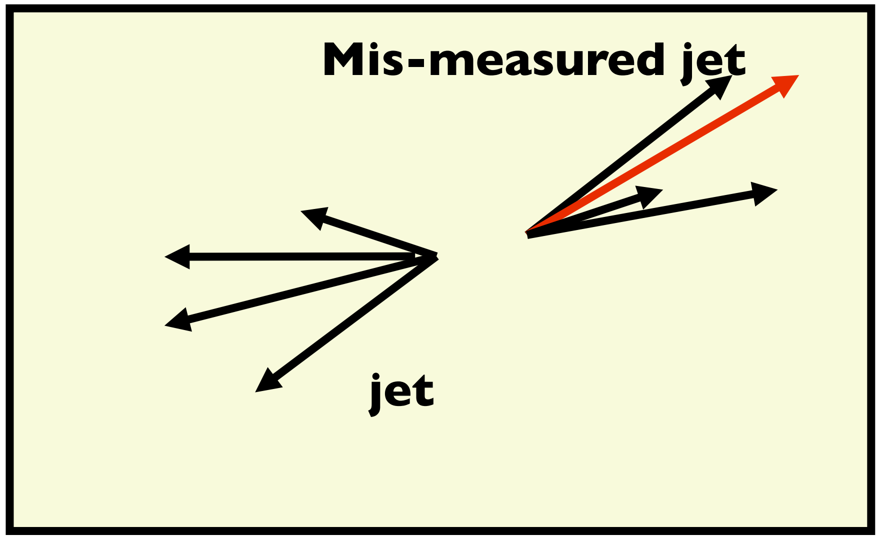


QCD, jet is mismeasured, producing Met.



Selecting monojet events

Basic Selection and Event Cleaning

- Primary vertex
- cuts based on jet constituents (charged and neutral hadron and electromagnetic energies), removes cosmics, instrumental backgrounds

Select topology

- Large missing energy, Met > 200 GeV
- One energetic jet, p_T > 110 GeV, $|\eta|$ < 2.4
- Allow one additional jet (if it has p_T > 30 GeV)
- Veto event if it has more than 2 jets

Reject background

- QCD

- $\Delta\varphi(j1,j2) > 2.5$

-remove events with back to back jets

- EWK

lepton rejection

-reject events with isolated electrons, muons

-veto events with isolated tracks

Selecting monojet events

Basic Selection and Event Cleaning

- Primary vertex
- cuts based on jet constituents (charged and neutral hadron and electromagnetic energies), removes cosmics, instrumental backgrounds

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- Large missing energy, Met > 350 GeV
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- Allow one additional jet (if it has p_T > 30 GeV)
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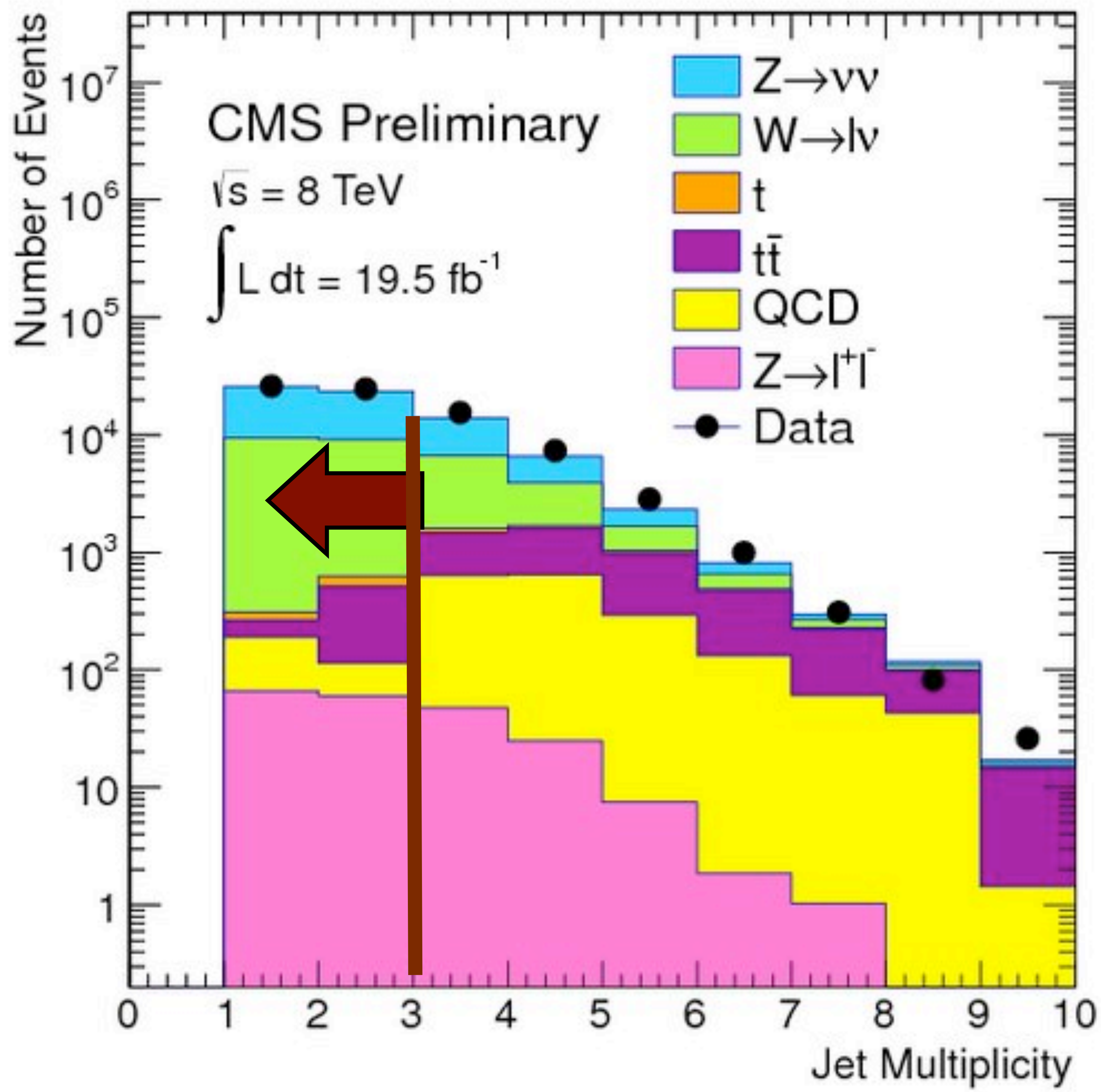

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Selecting monojet events

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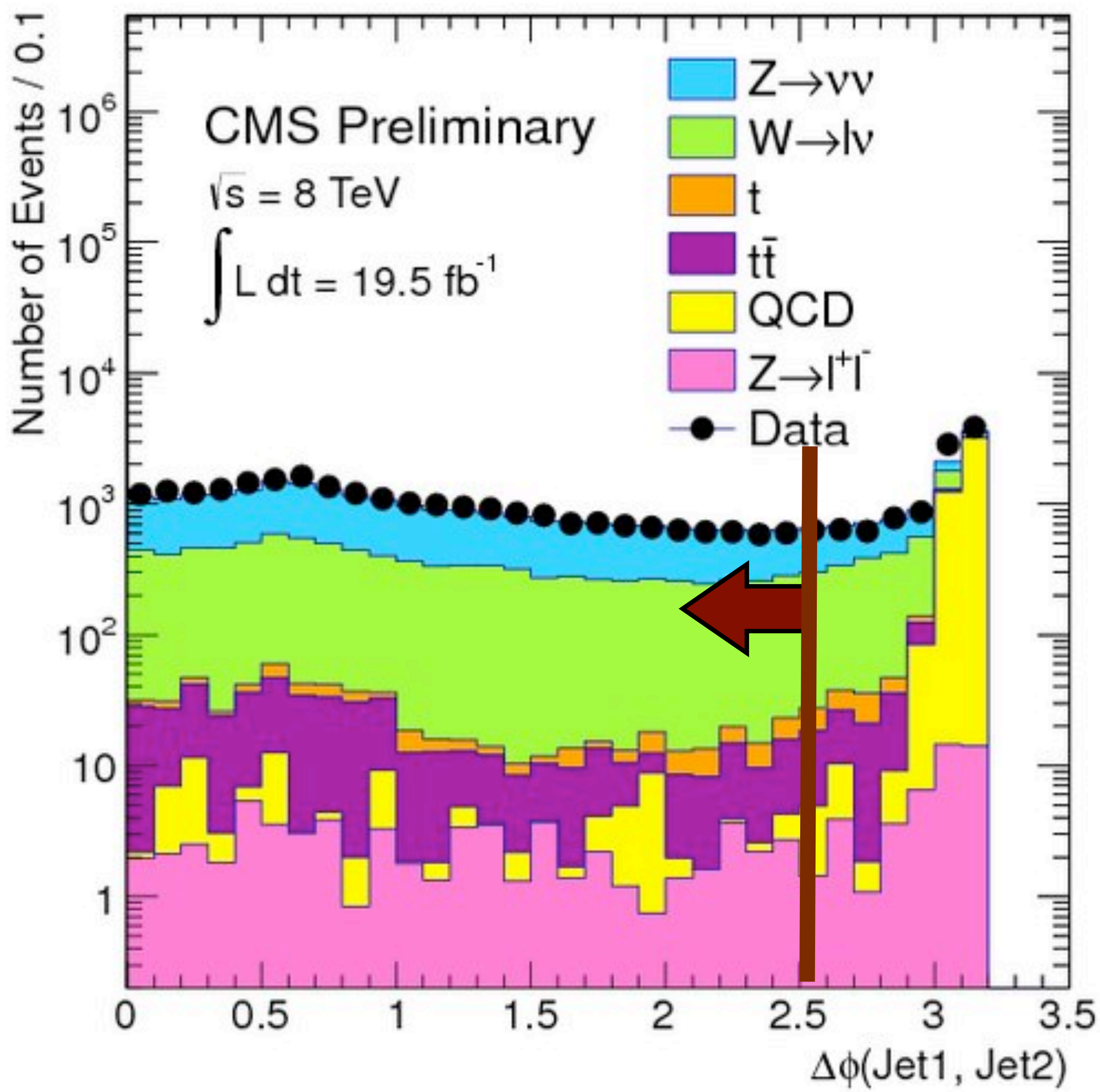
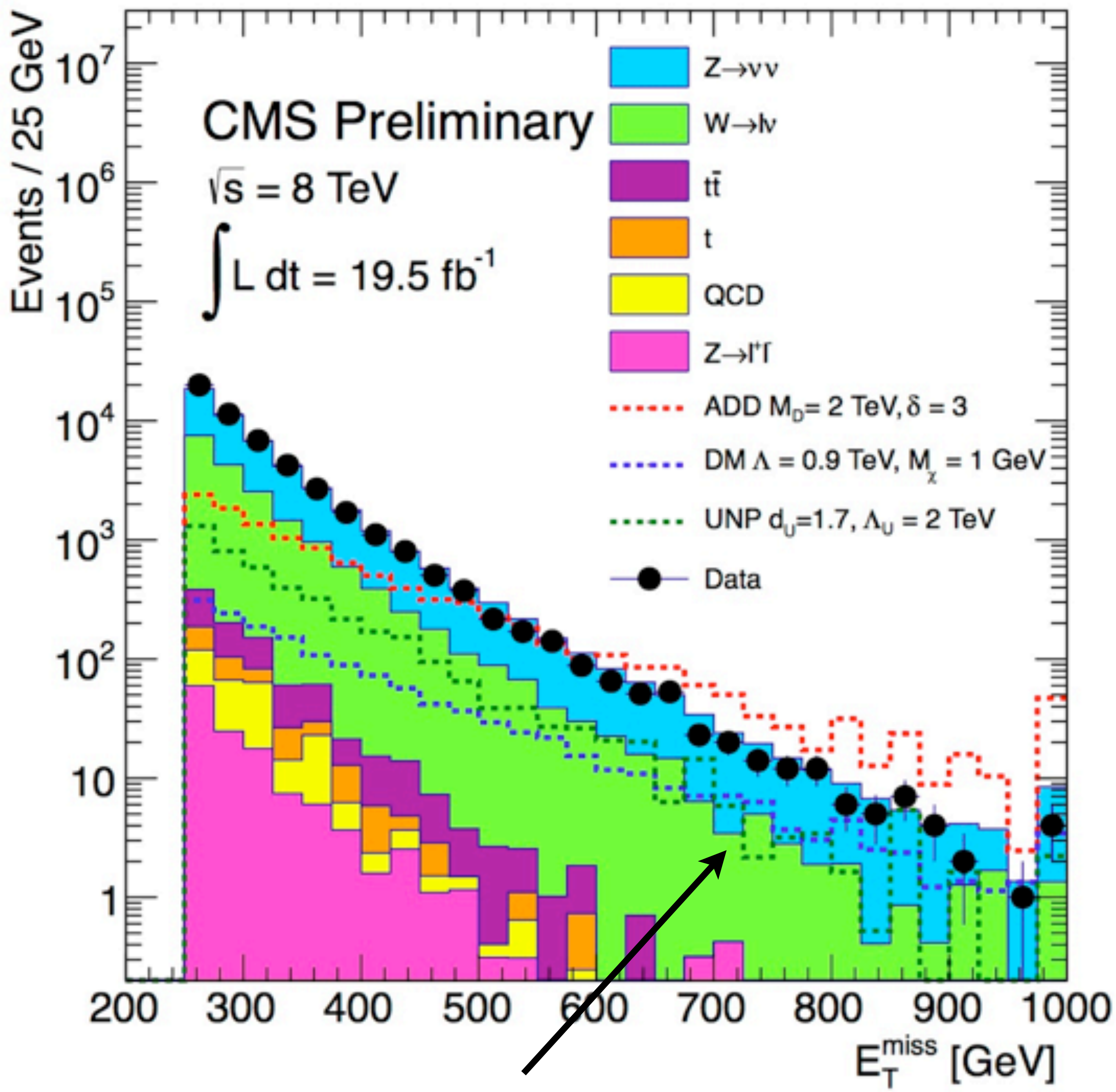
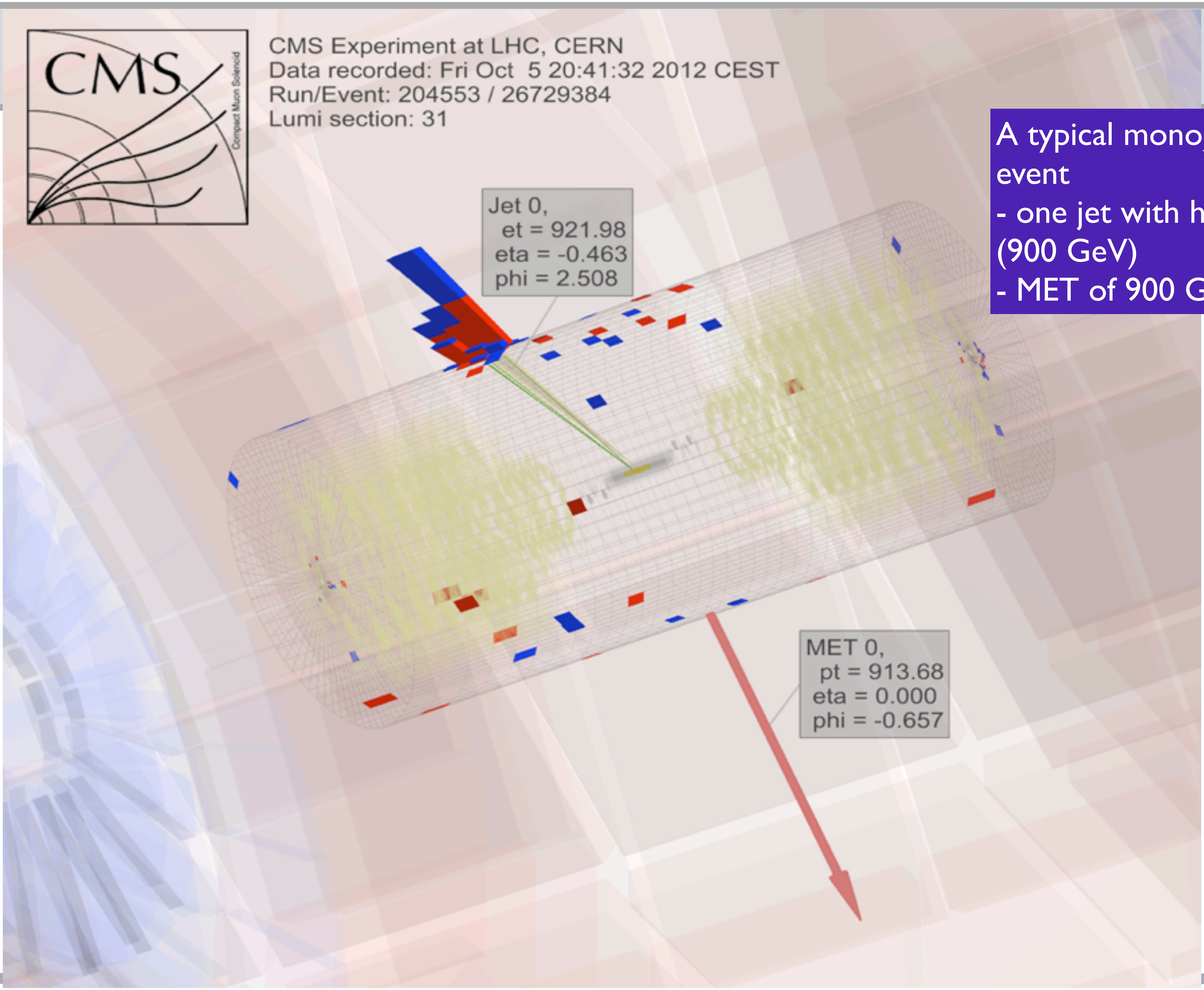


-veto events with isolated tracks

Selecting monojet events



this is what a potential signal would look like



A typical monojet event
- one jet with high p_T (900 GeV)
- MET of 900 GeV

Results

Z(νν)+jets	2569 ± 188
W+jets	1044 ± 51
tt	32 ± 16
Z(ll)+jets	8 ± 4
Single top	7 ± 3.5
QCD multijets	3 ± 1.5
Total Background	3663 ± 196
Observed in data	3677

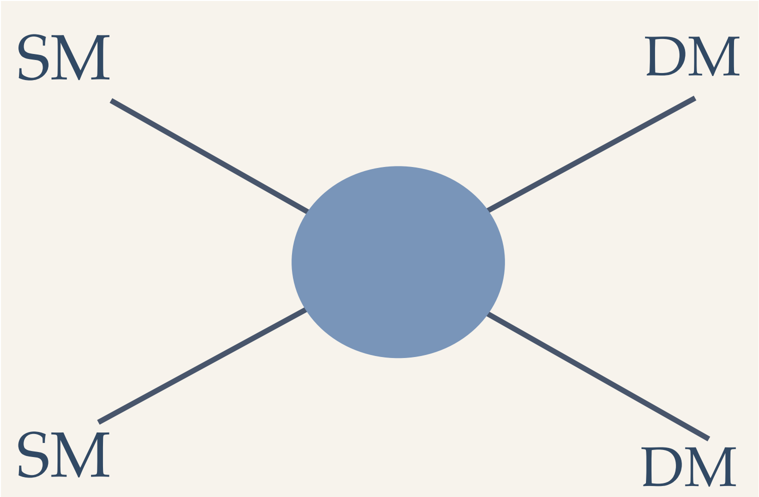
No excess of events over expected SM backgrounds

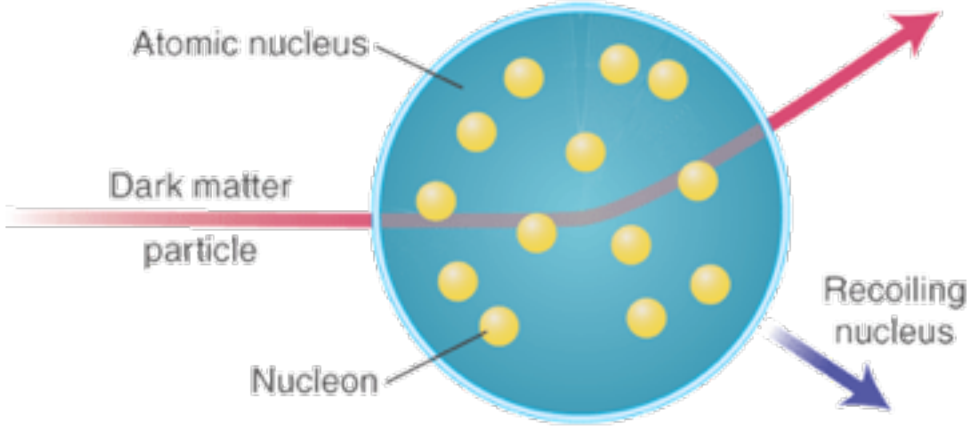
Setting limits on DM-nucleon cross section

Translate collider limits to the same plane as direct detection experiments

Setting limits on DM-nucleon cross section

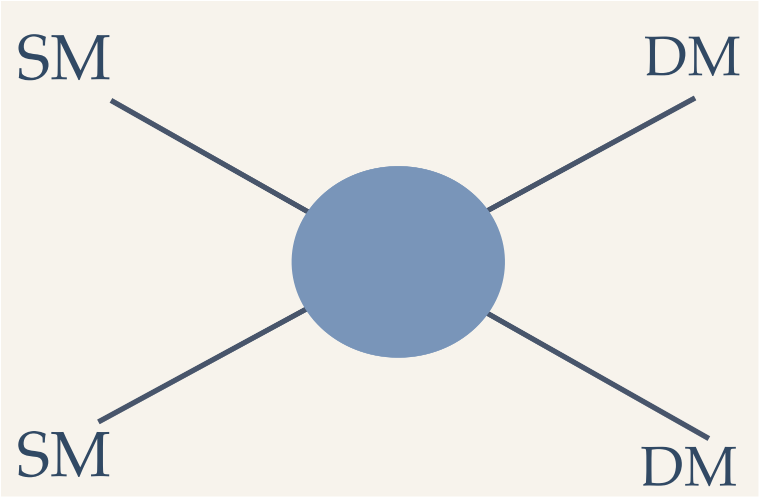
Translate collider limits to the same plane as direct detection experiments

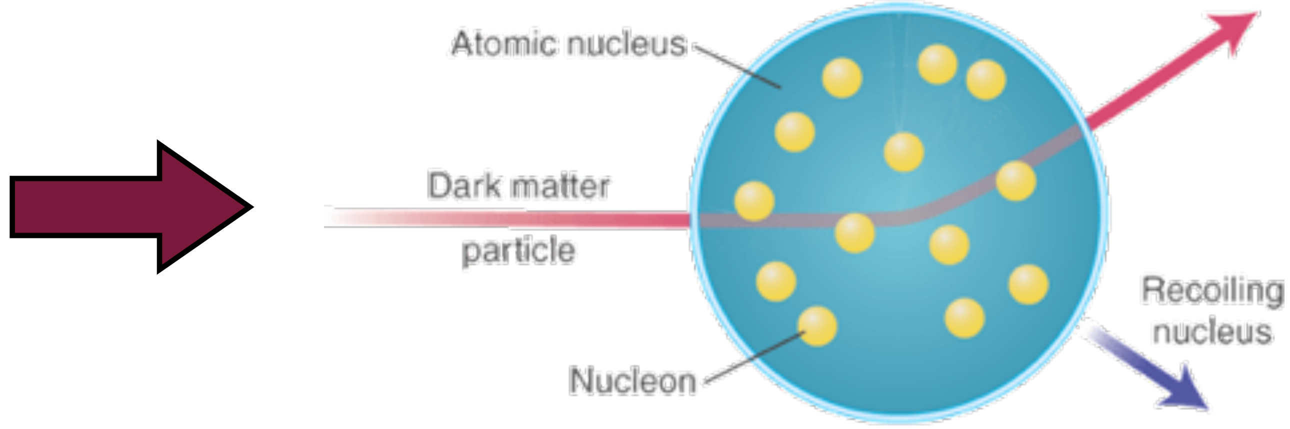




Setting limits on DM-nucleon cross section

Translate collider limits to the same plane as direct detection experiments





For vector operator

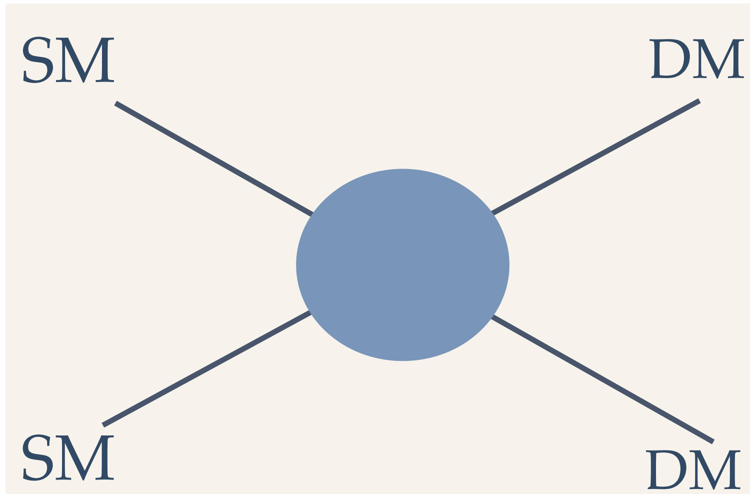
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

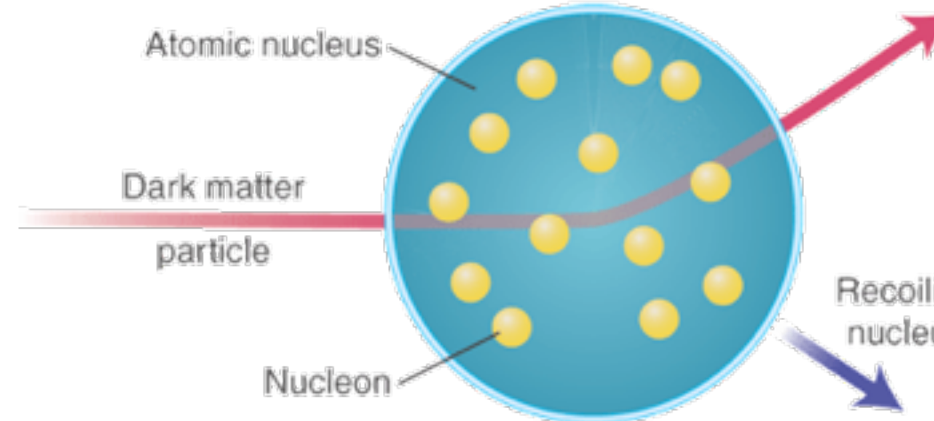
$$\mathcal{O}^N = f_q^N \frac{\left(\bar{N}\gamma^\mu N\right)\left(\bar{\chi}\gamma_\mu\chi\right)}{\Lambda^2}$$

coefficient relates nucleon and
quark operator

Setting limits on DM-nucleon cross section

Translate collider limits to the same plane as direct detection experiments





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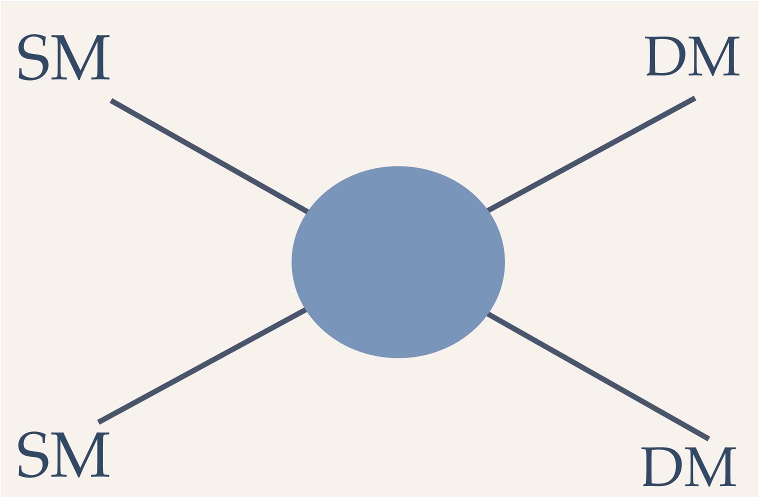
coefficient relates nucleon and quark operator

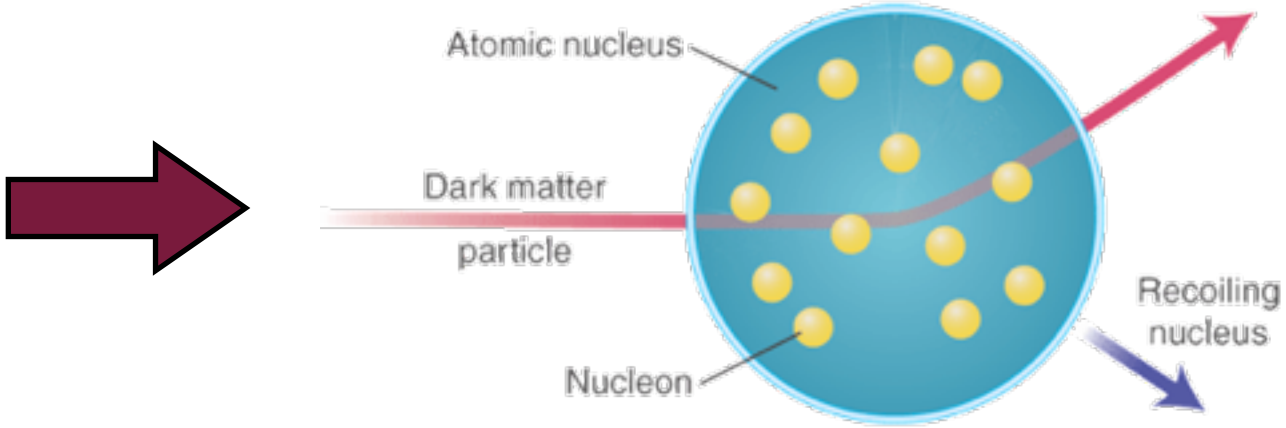
$$\sigma_{SI} = \frac{\mu^2}{\pi\Lambda^4} f_q^{N2}$$

- Upper limits on monojet cross sections converted to lower limits on Λ
- Lower limits on Λ then translated to spin-independent DM-nucleon cross-section

Setting limits on DM-nucleon cross section

Translate collider limits to the same plane as direct detection experiments





For axial-vector operator

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

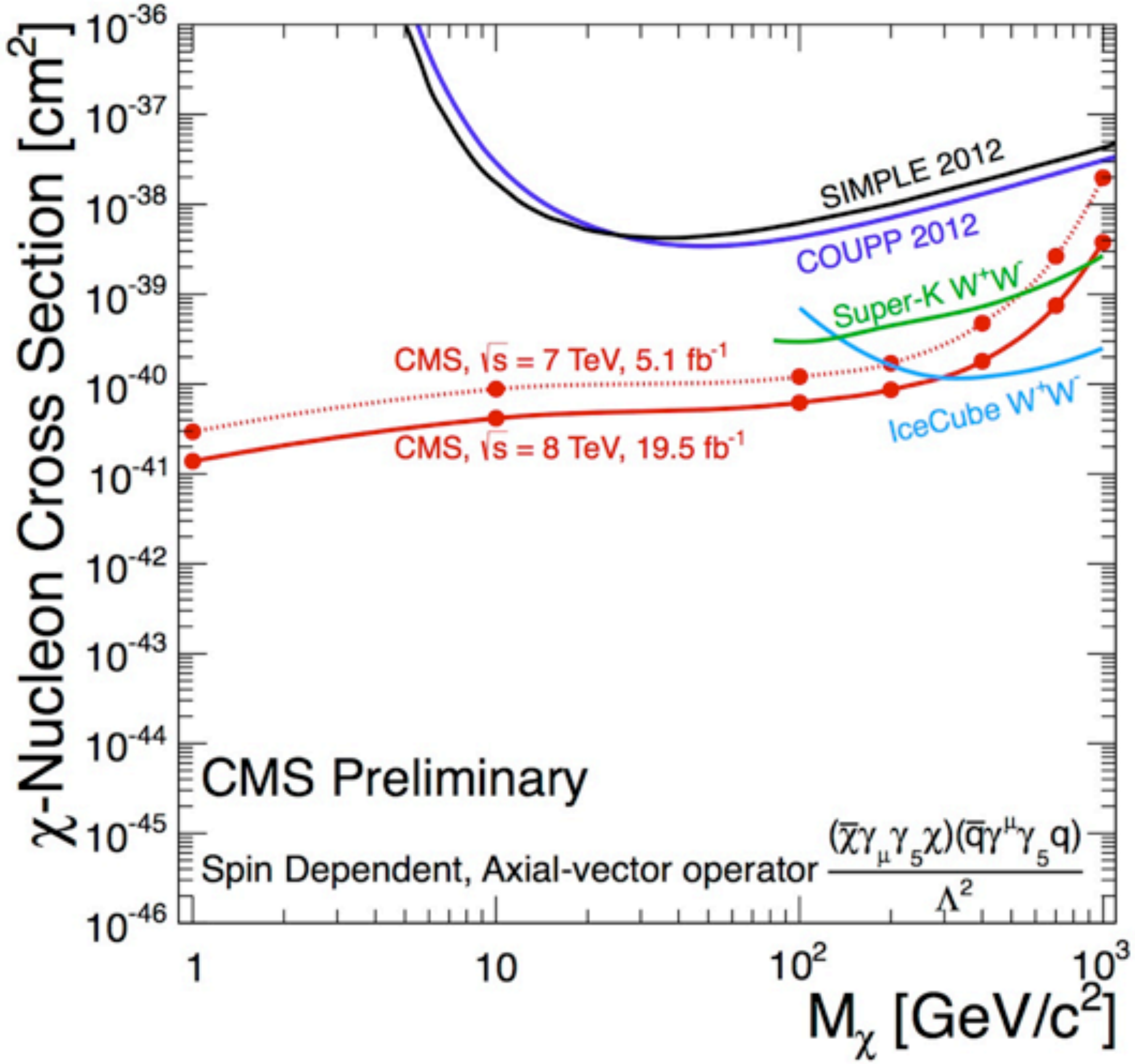
$$\mathcal{O}^{Nq} = \Delta_q^N \frac{(N\gamma^\mu\gamma_5 N)\,(\bar{\chi}\gamma_\mu\gamma_5\chi)}{\Lambda^2}$$

sum of quark helicities

$$\sigma^{Nq} = \frac{3\,\mu^2}{\pi\,\Lambda^4}\,(\Delta_q^N)^2\,.$$

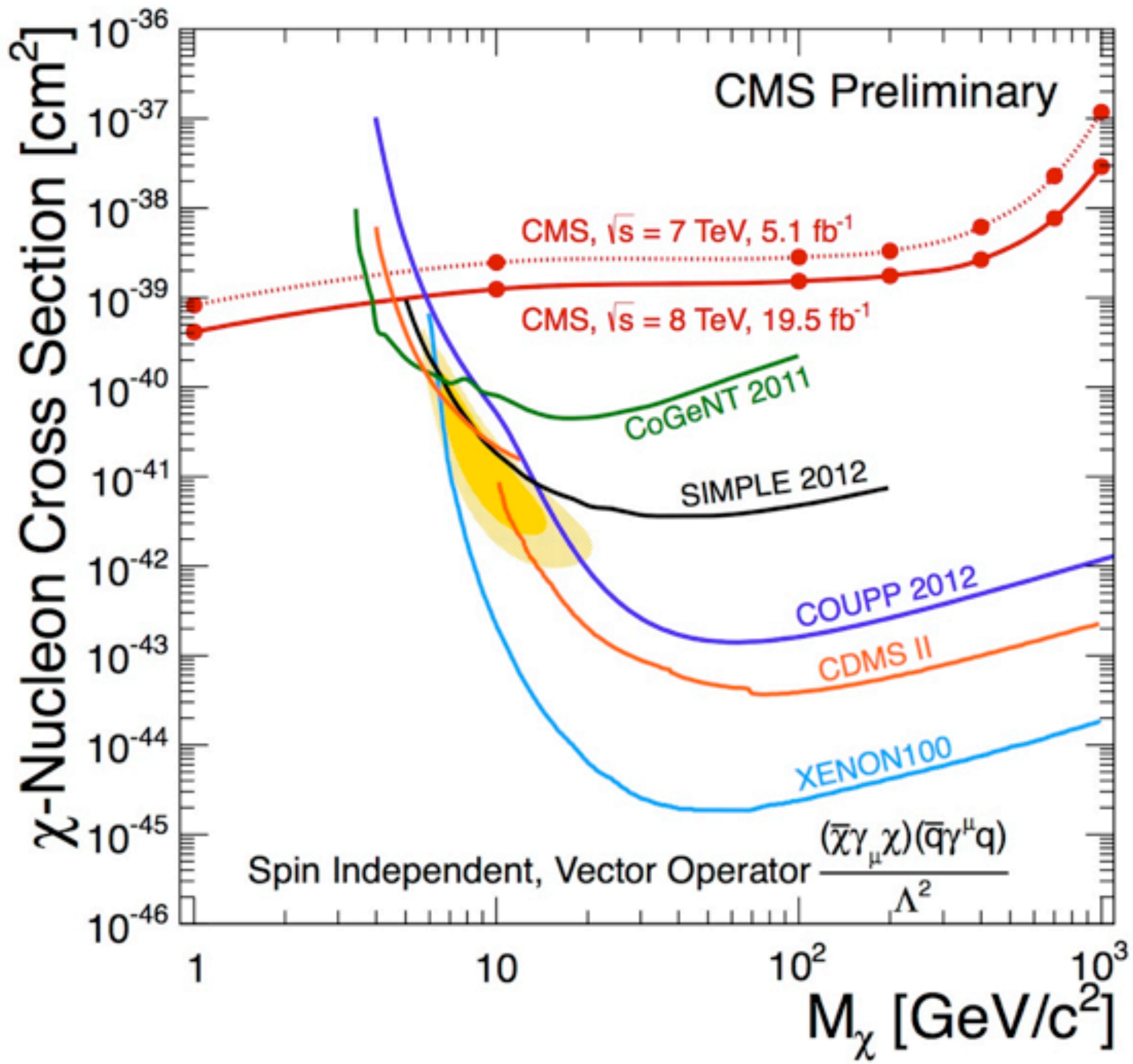
- Upper limits on monojet cross sections converted to lower limits on Λ
- Lower limits on Λ then translated to spin-dependent DM-nucleon cross-section

For axial-vector mediator, in context of EFT...

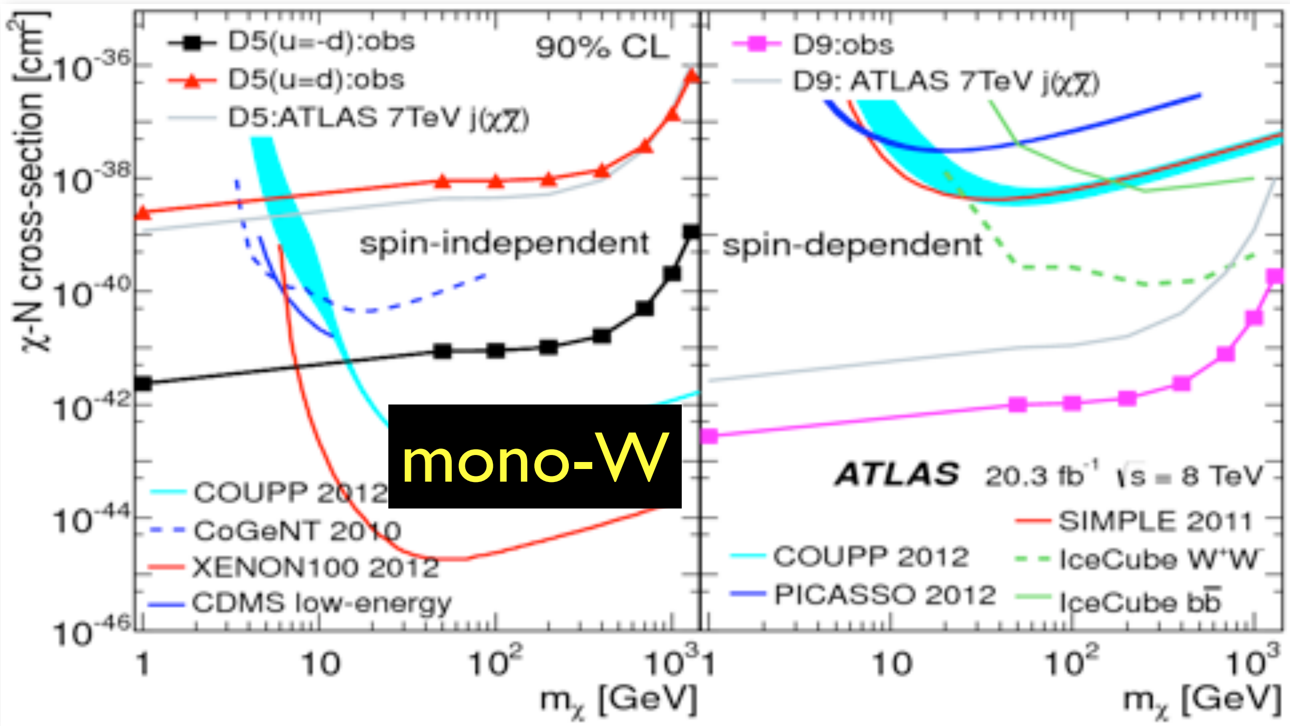


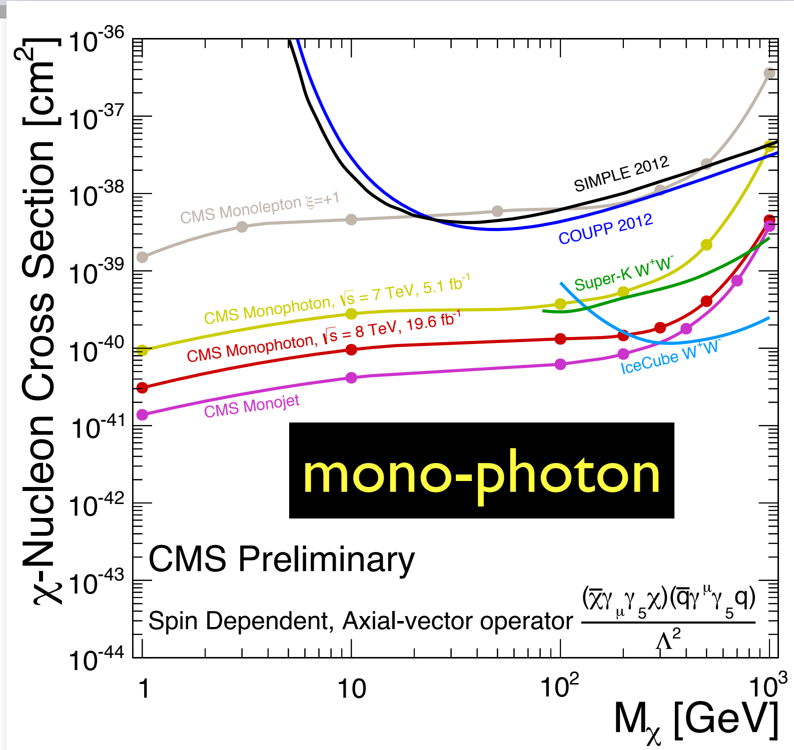
Dark matter spin dependent limits

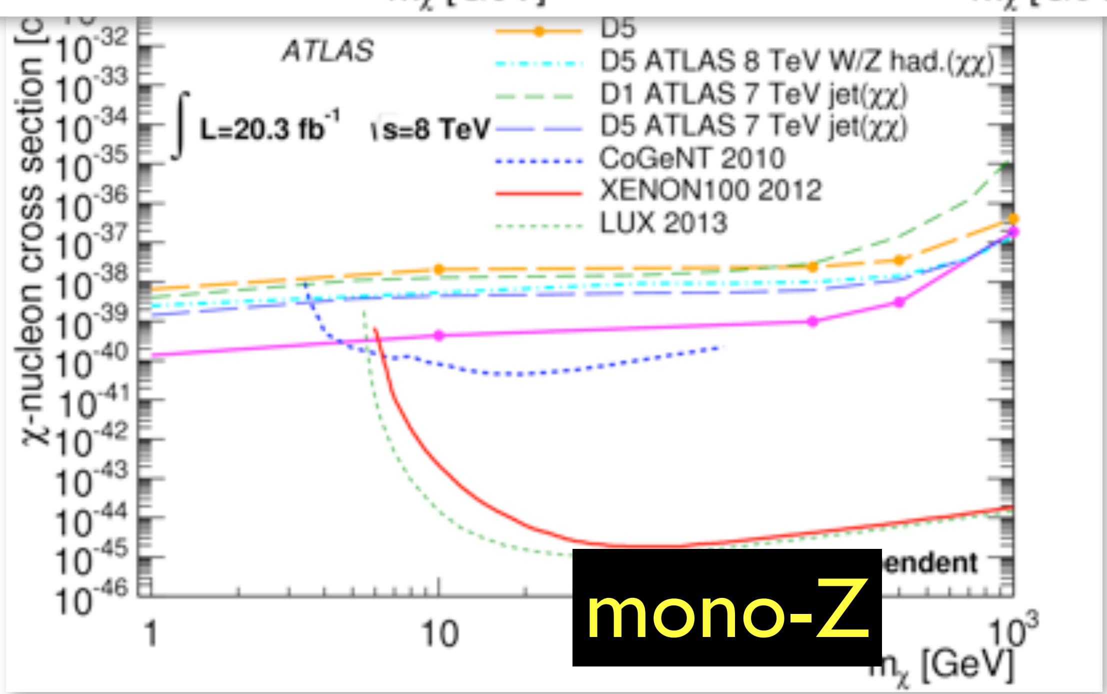
For vector mediator, in context of EFT...

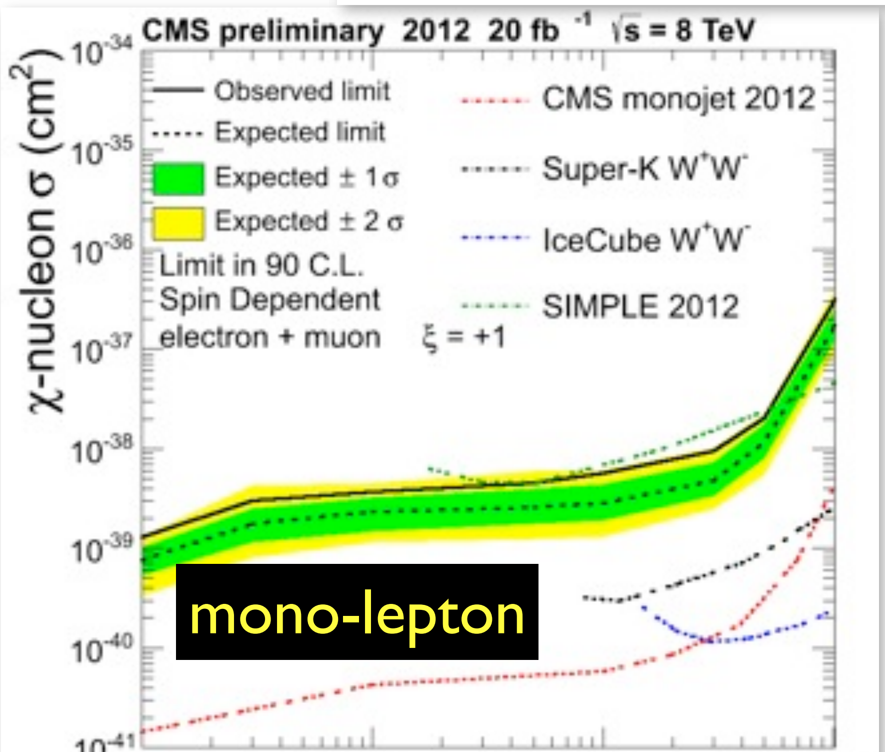


Searches for dark matter with mono-X









Many different signatures employed to search for dark matter at LHC, will become especially important if signal is observed by collider/DD/ID experiments

Interpretation of searches

Limitations of EFT

arXiv:1308.6799

O. Buchmueller,[a] Matthew J. Dolan,[b] and Christopher McCabe[b]

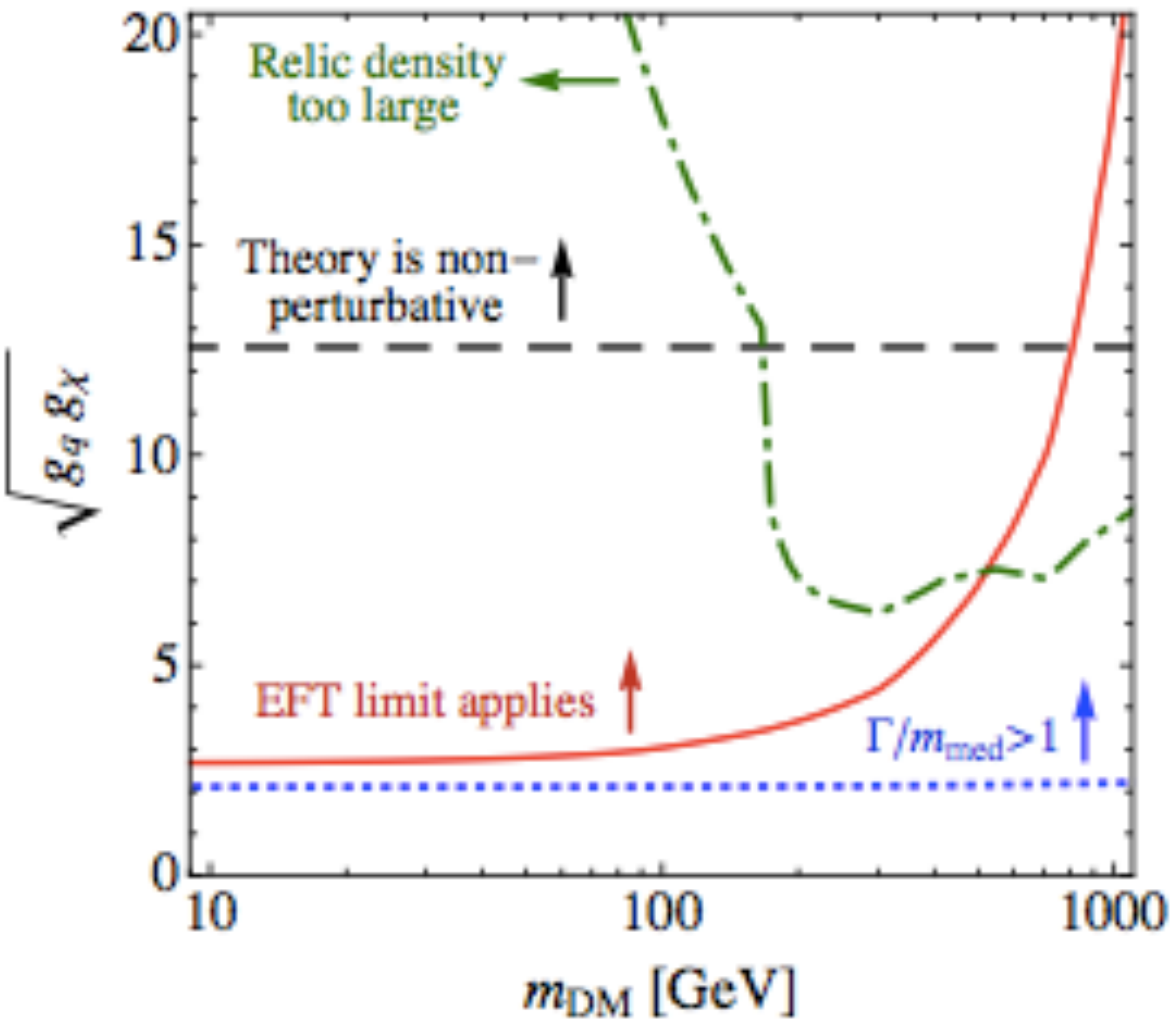
- Effective field theory is valid when mediator mass > a few TeV
- The couplings required are large

Comparing this with known couplings:

strong interaction ~1.2

weak interaction ~0.6

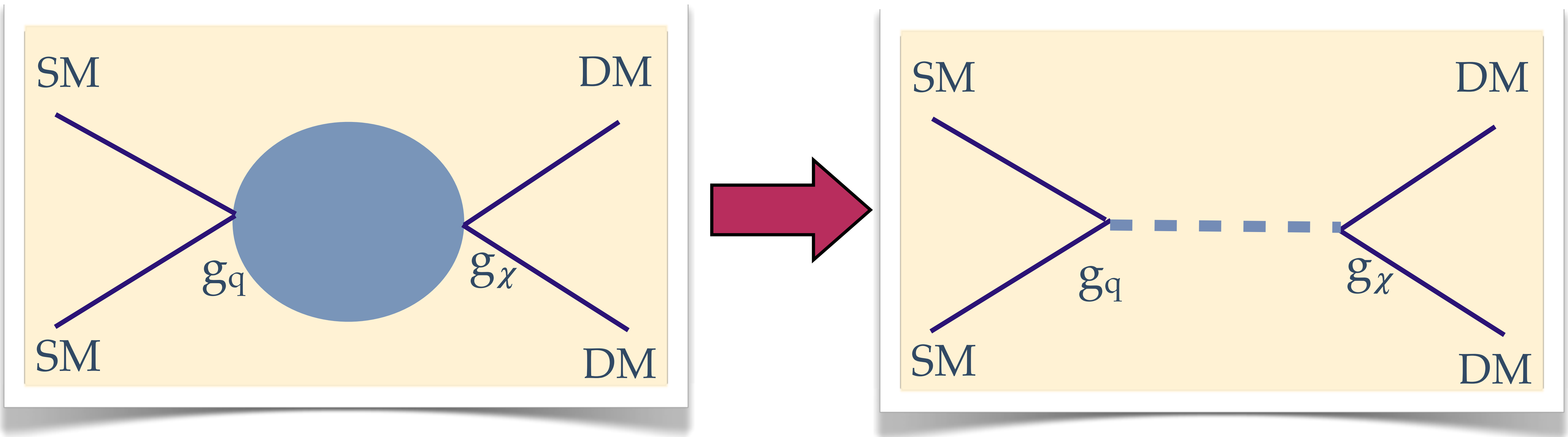
- Theory is non-perturbative if $\sqrt{g_q g_{DM}} > 4\pi$
- Width larger than mass, so unlikely mediator will be identified as a particle



Phenomenology

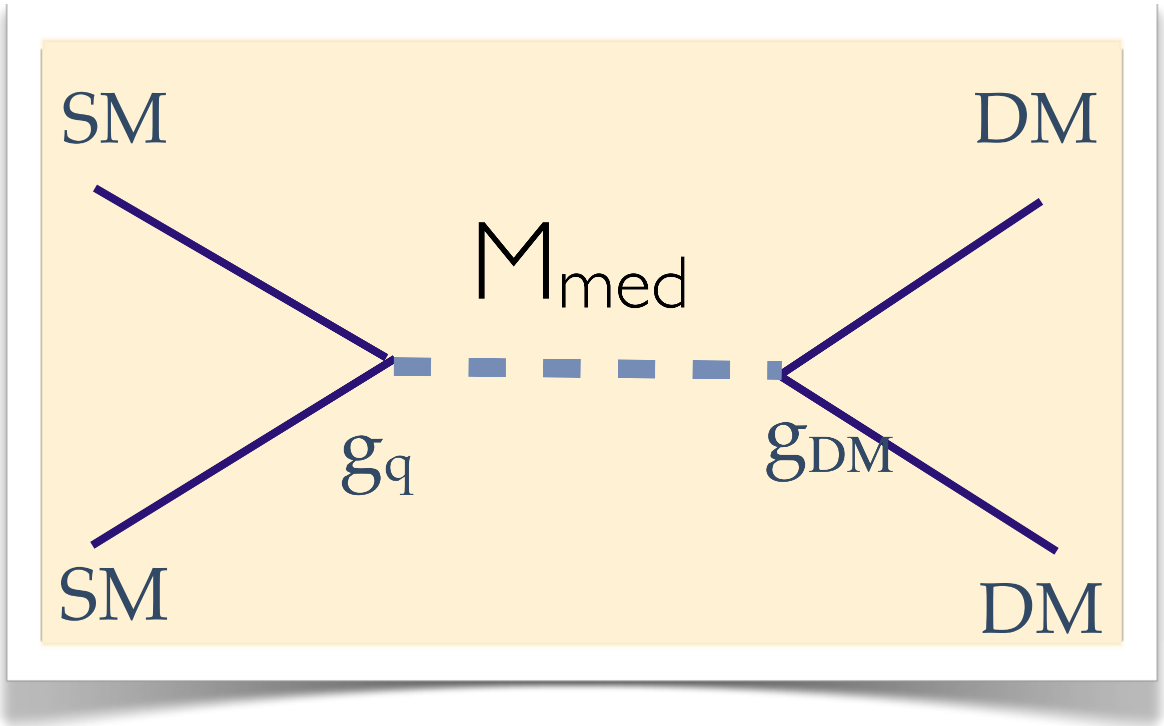
Light mediator

- Assume DM interaction is mediated by light particle
- Effective theory breaks down and explicitly have to include mediator mass.



Minimal Simplified model of dark matter

arXiv:1407.8257



s-channel

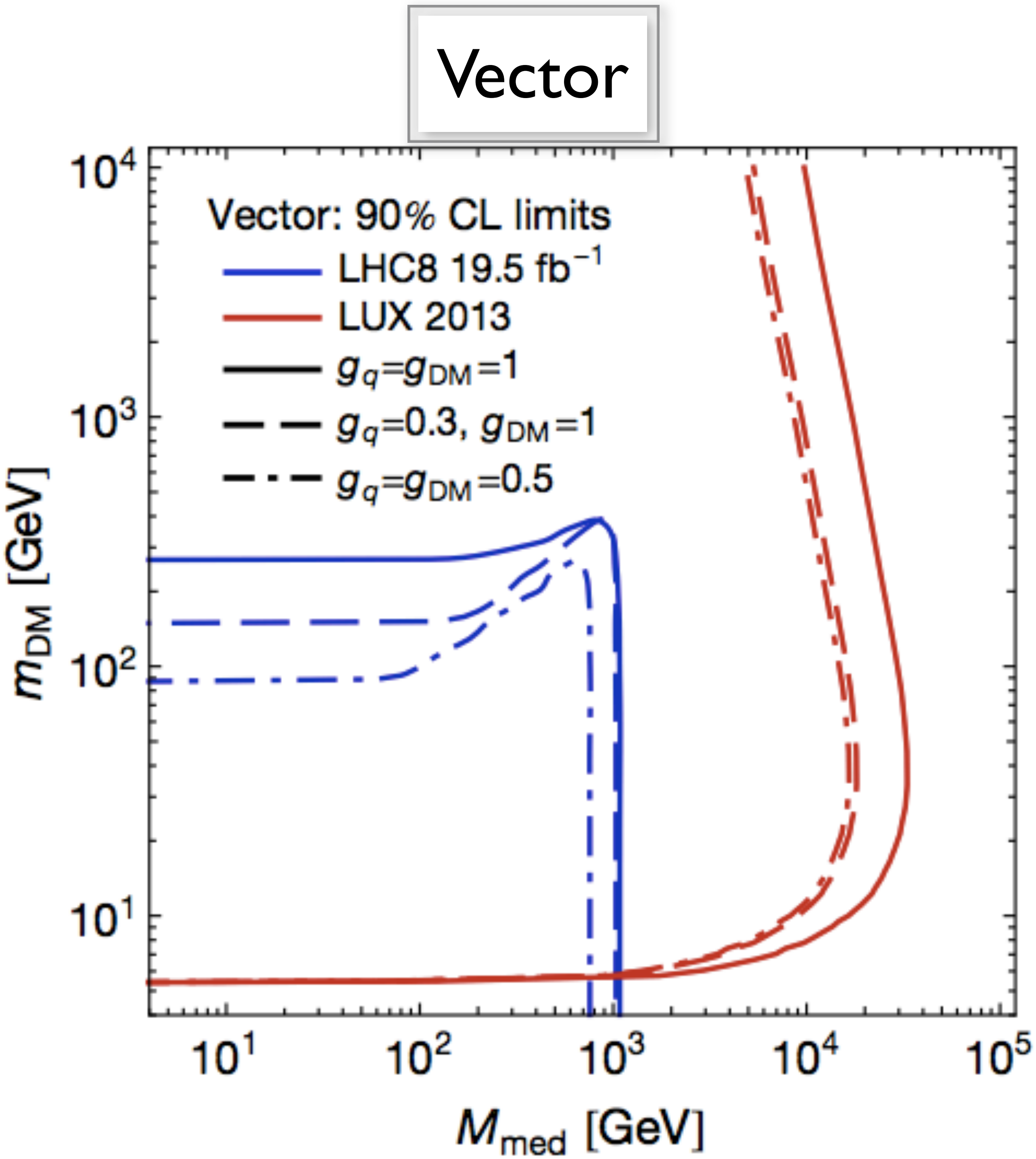
Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

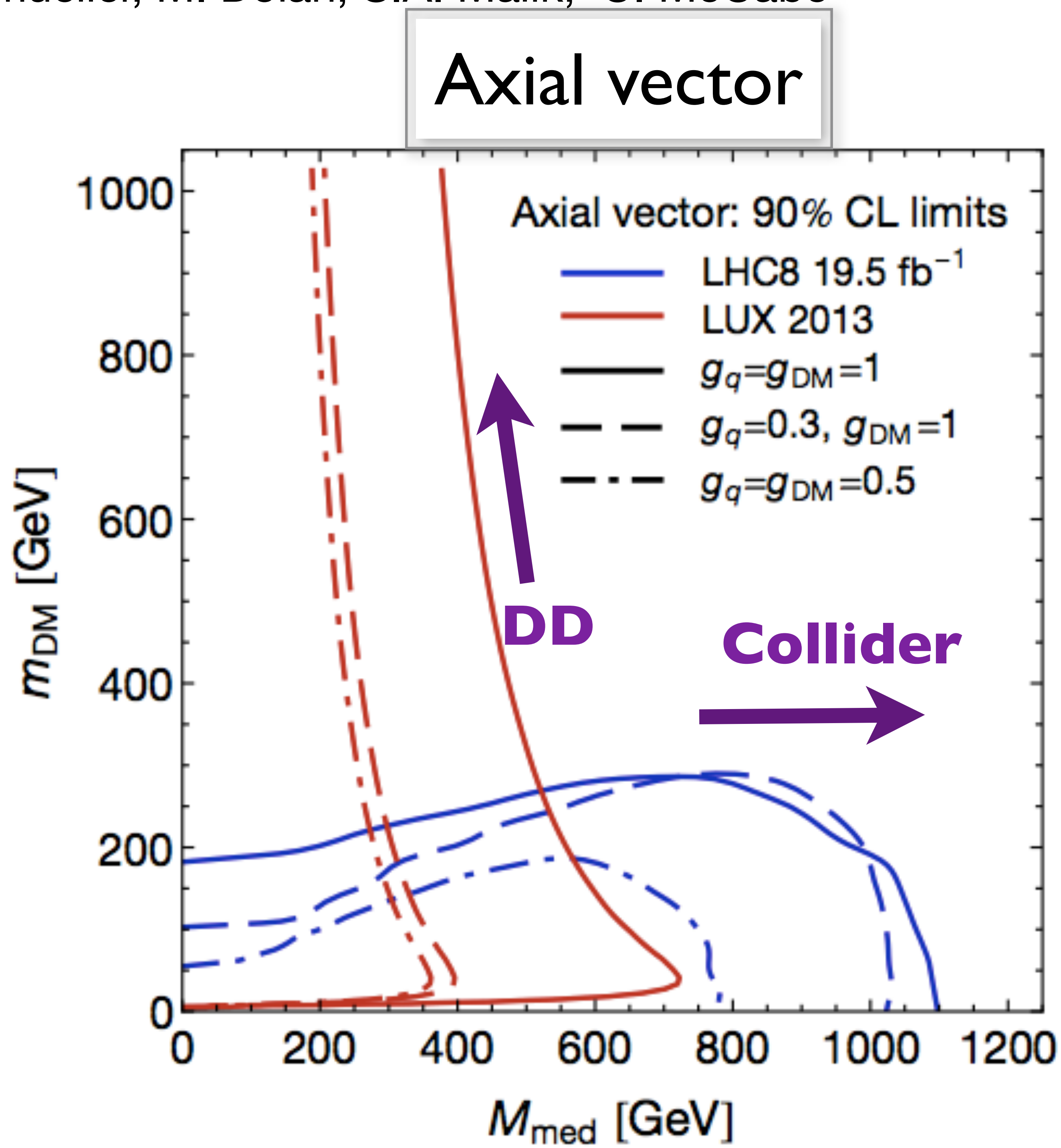
DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

Simplified models :Vector/axial-vector

arXiv:1407.8257 O. Buchmueller, M. Dolan, S.A. Malik, C. McCabe

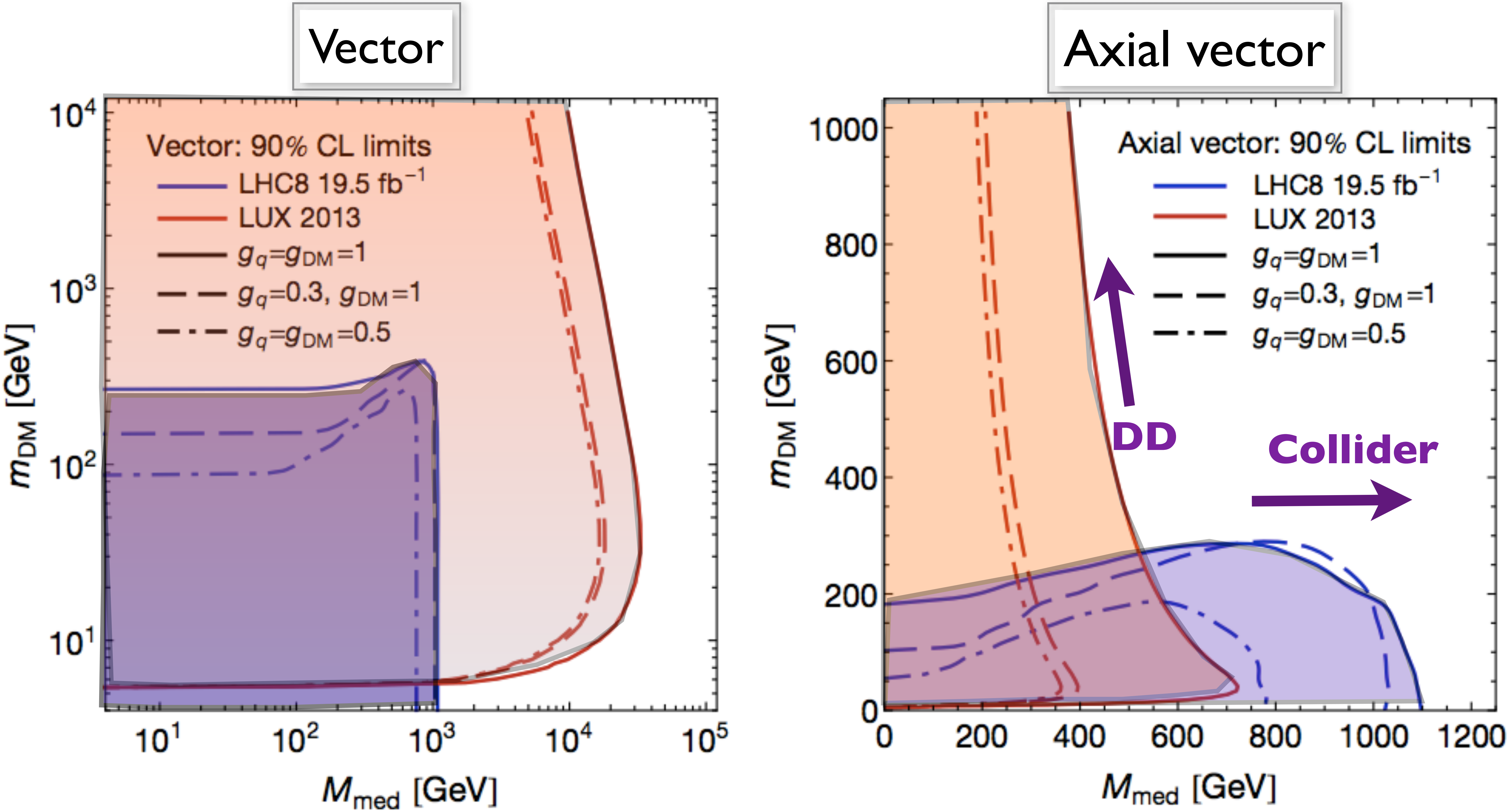




Elucidates more accurately the complementarity between collider and direct detection experiments

Simplified models :Vector/axial-vector

arXiv:1407.8257 O. Buchmueller, M. Dolan, S.A. Malik, C. McCabe

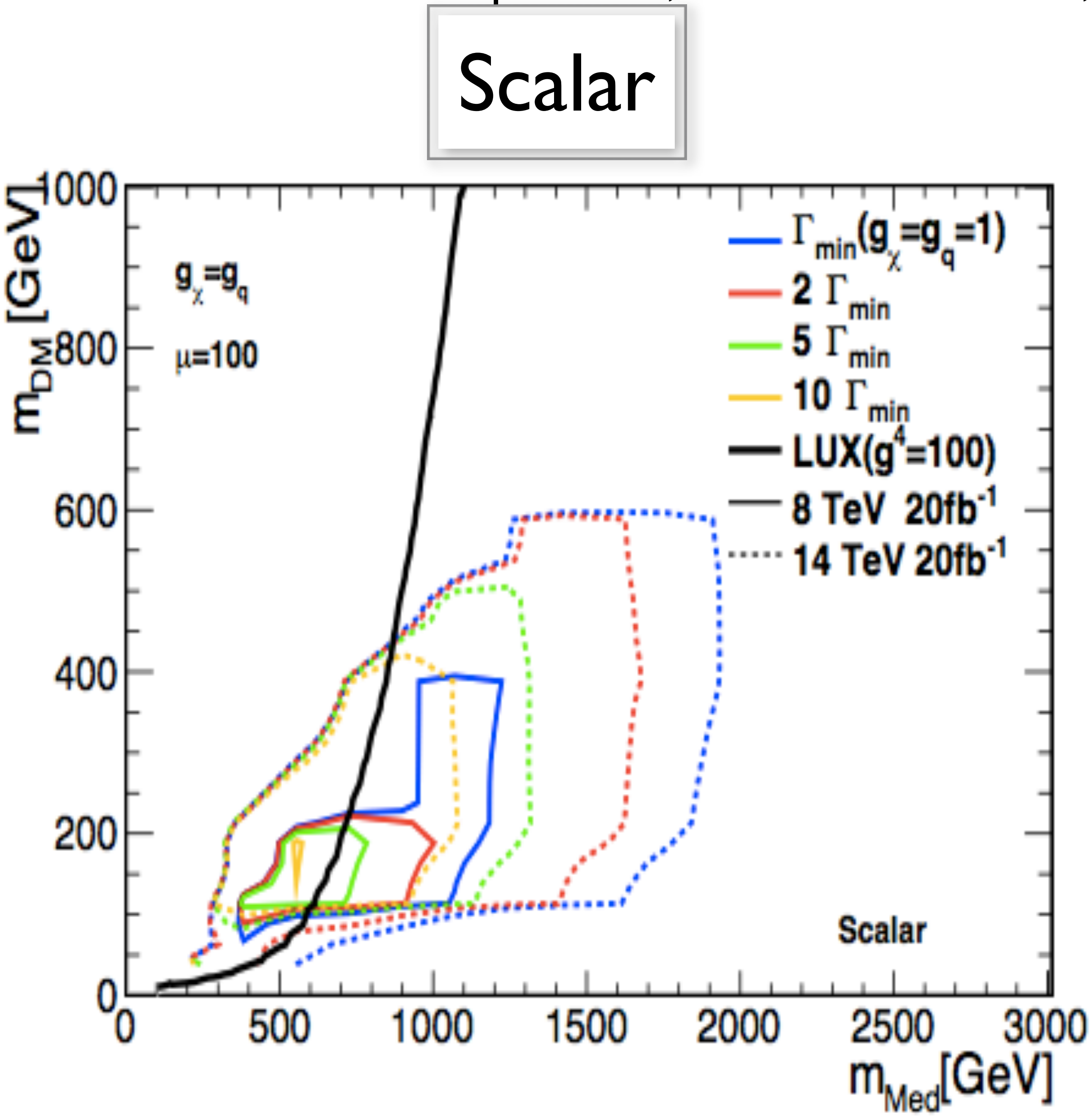


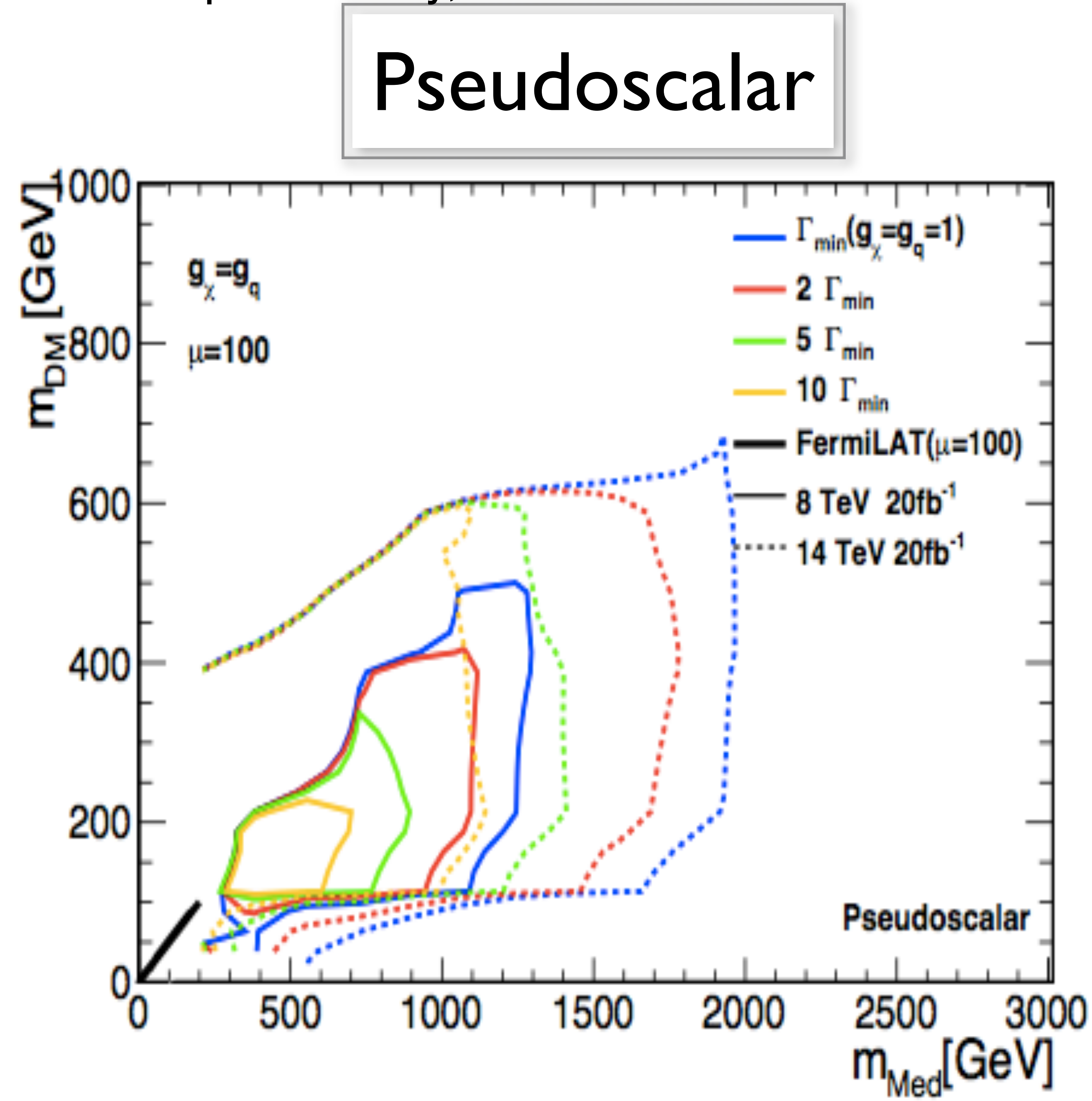
Elucidates more accurately the complementarity between collider and direct detection experiments

Simplified models : Scalar/pseudoscalar

arXiv:1411.0535

Philip Harris, Valentin V. Khoze, Michael Spannowsky, Ciaran Williams



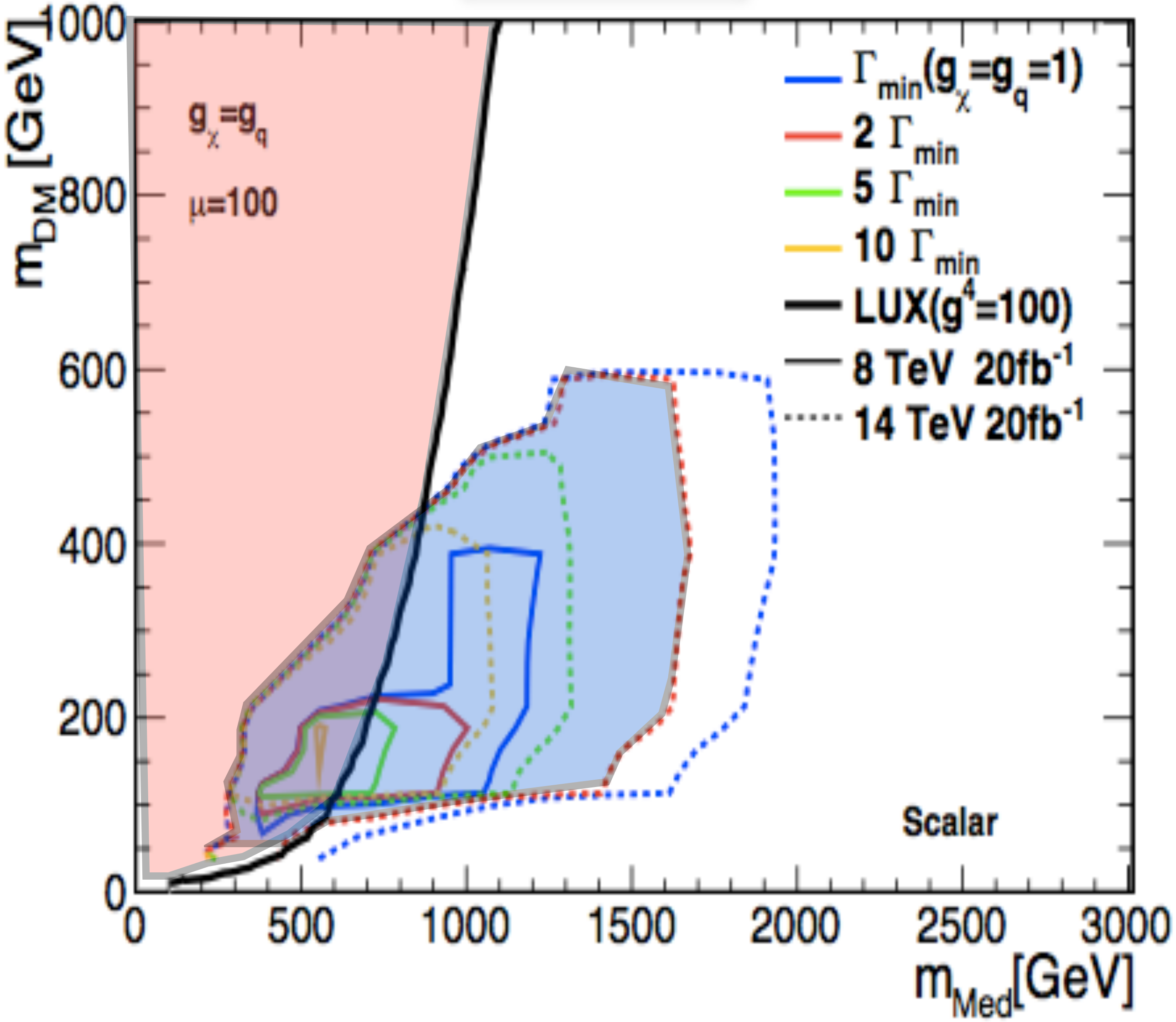


Simplified models : Scalar/pseudoscalar

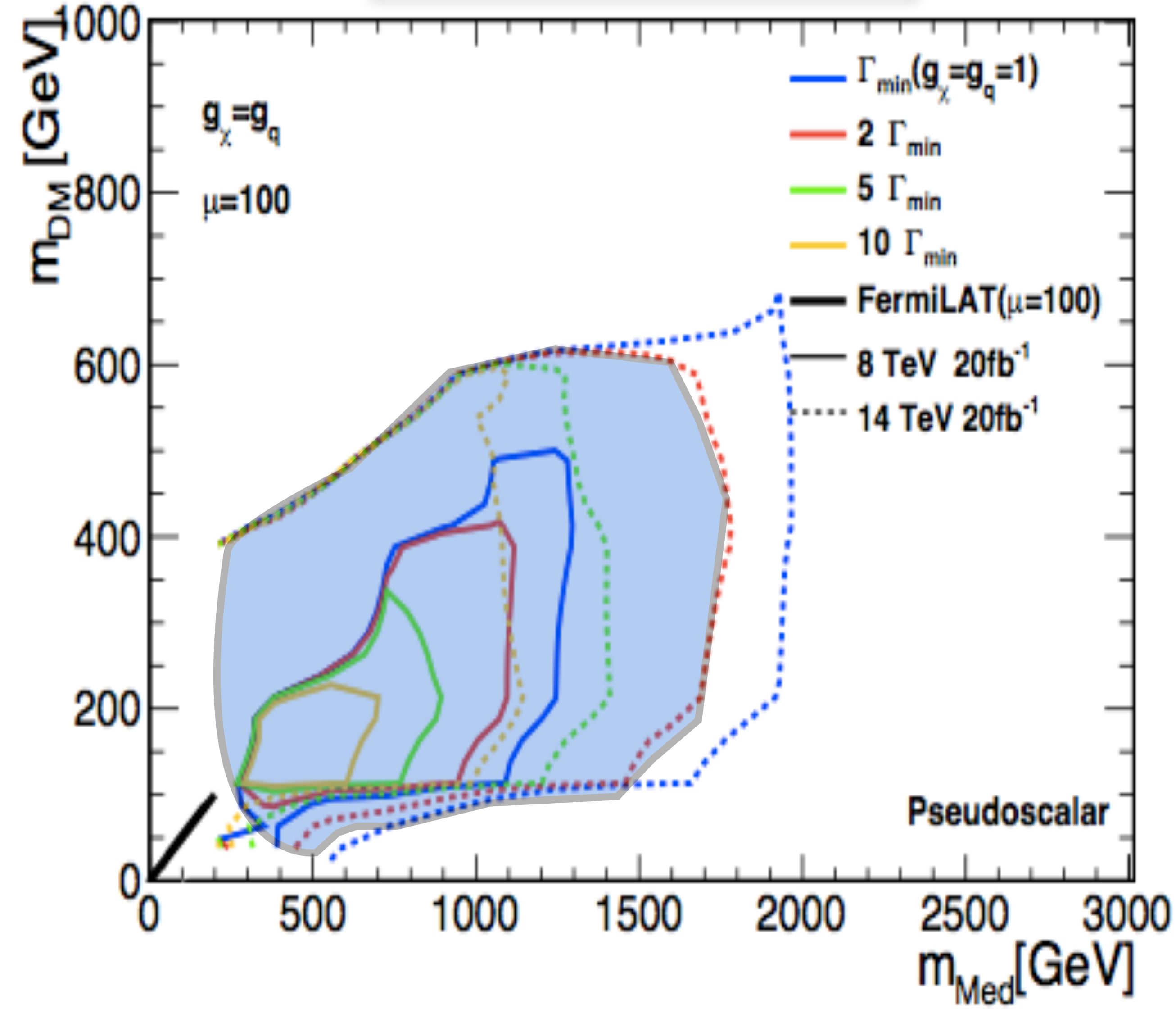
arXiv:1411.0535

Philip Harris, Valentin V. Khoze, Michael Spannowsky, Ciaran Williams

Scalar



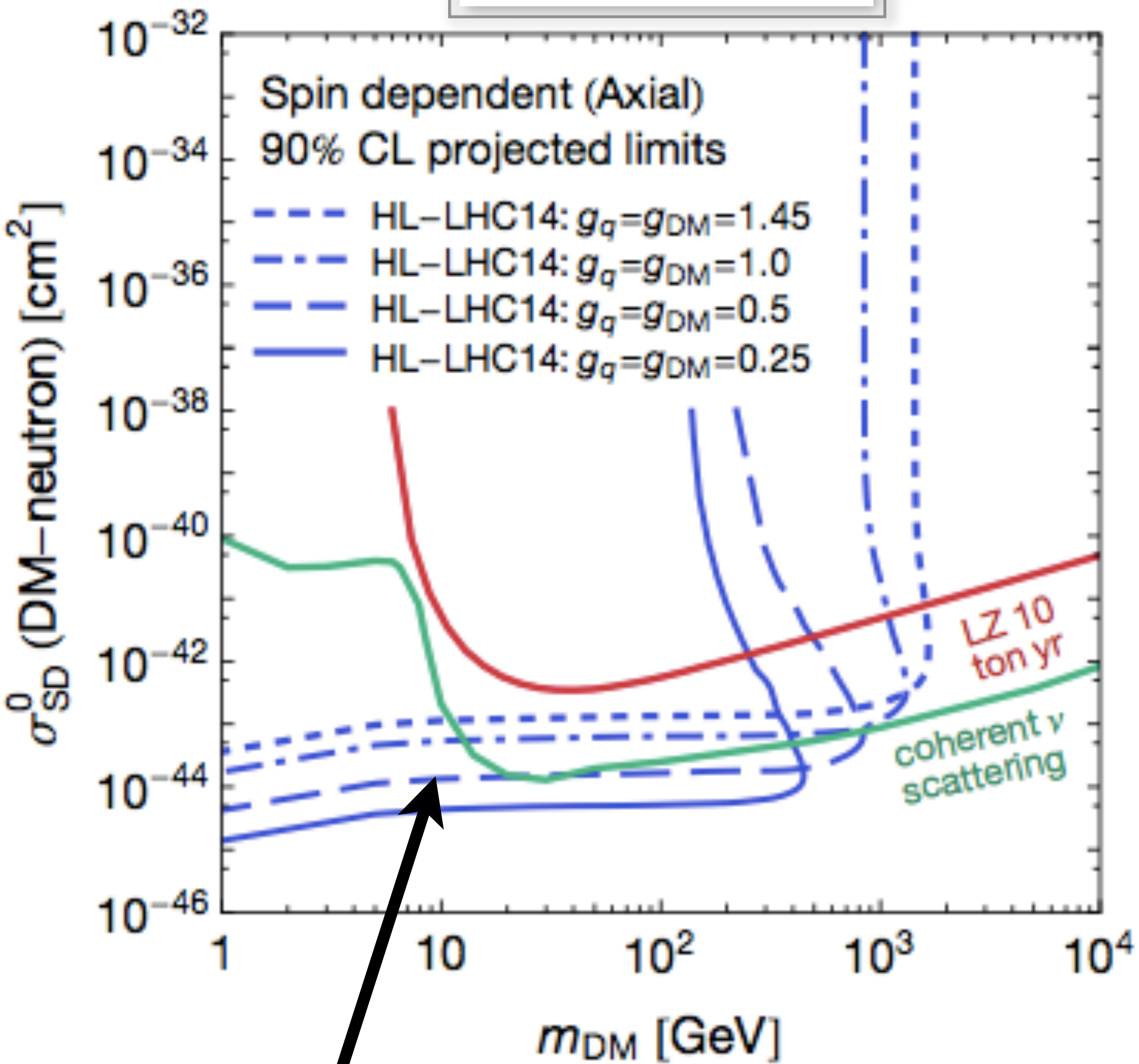
Pseudoscalar



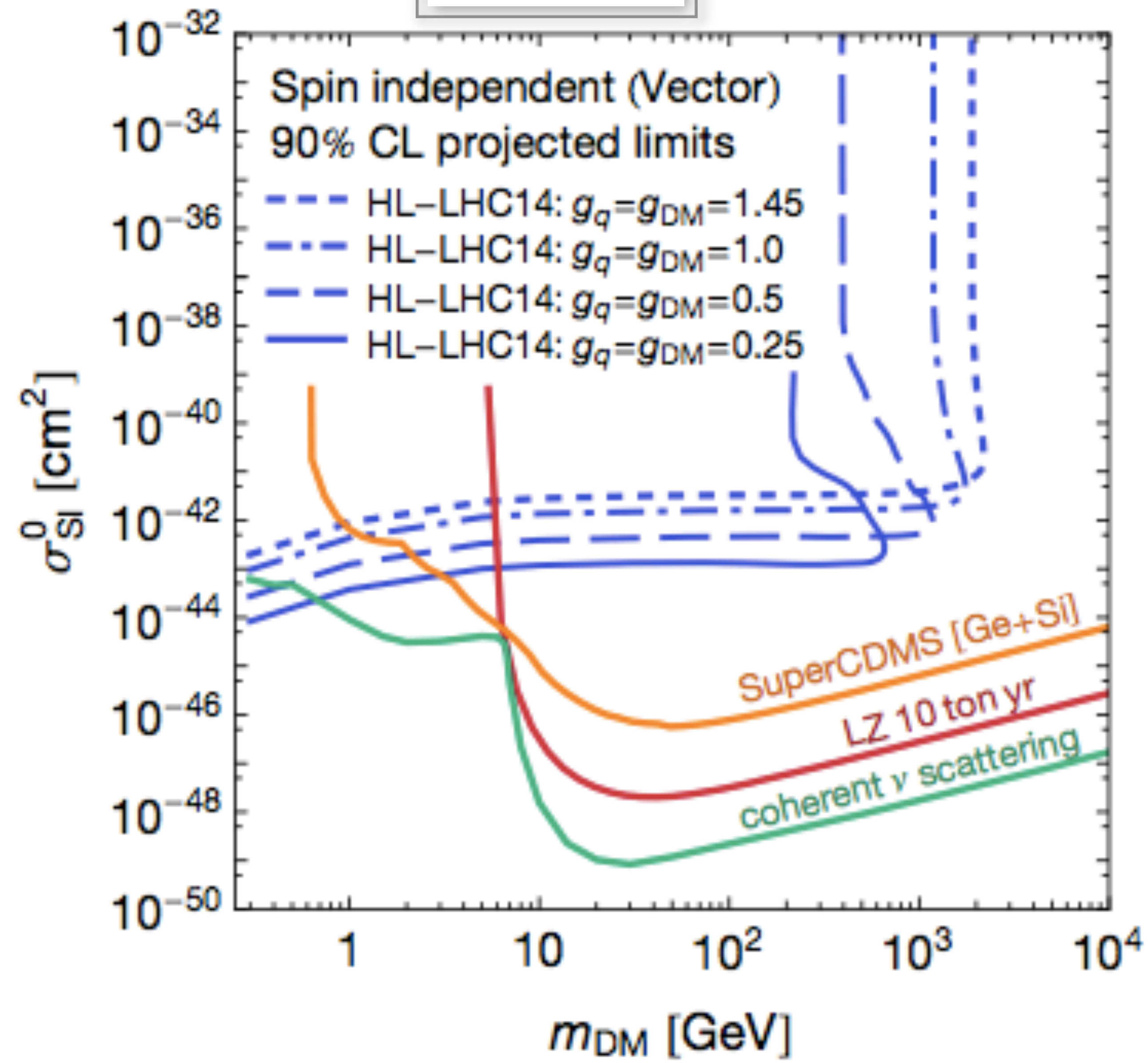
Future projections

arXiv:1409.4075

Axial vector



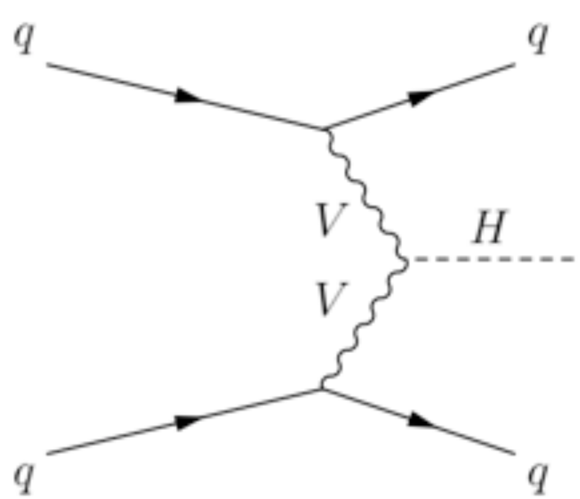
Vector

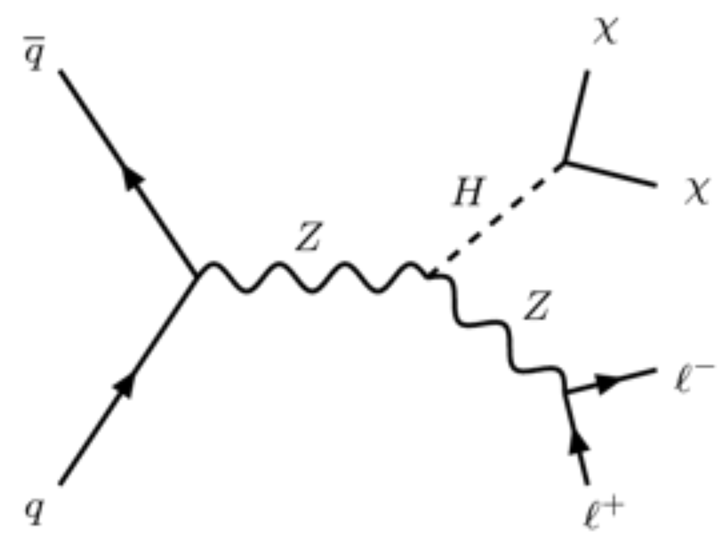


Colliders able to probe all the way up to neutrino barrier with HL-LHC

Invisible Higgs - Higgs as a portal into the dark sector

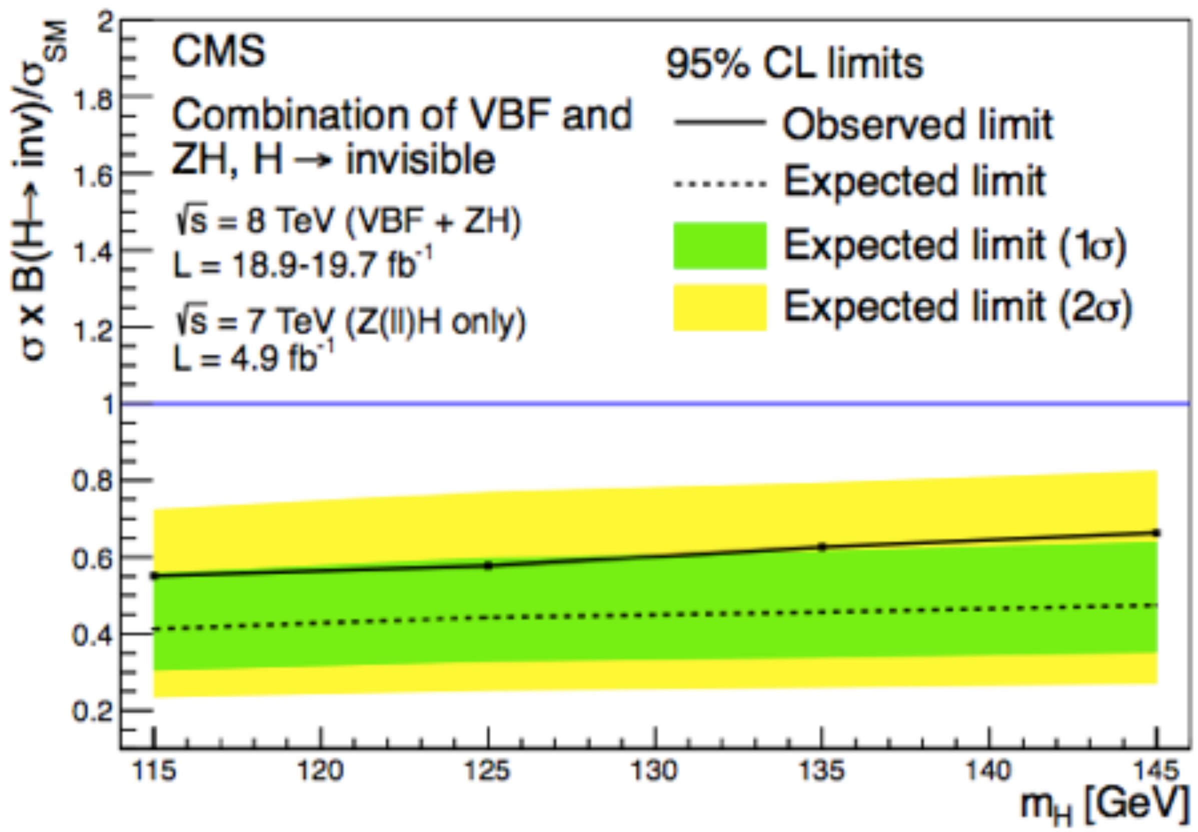
- Higgs at 125 GeV, may have other decay channels not predicted by the SM
- measure the Higgs invisible width by looking for decays of the Higgs to invisible particles, which could be DM

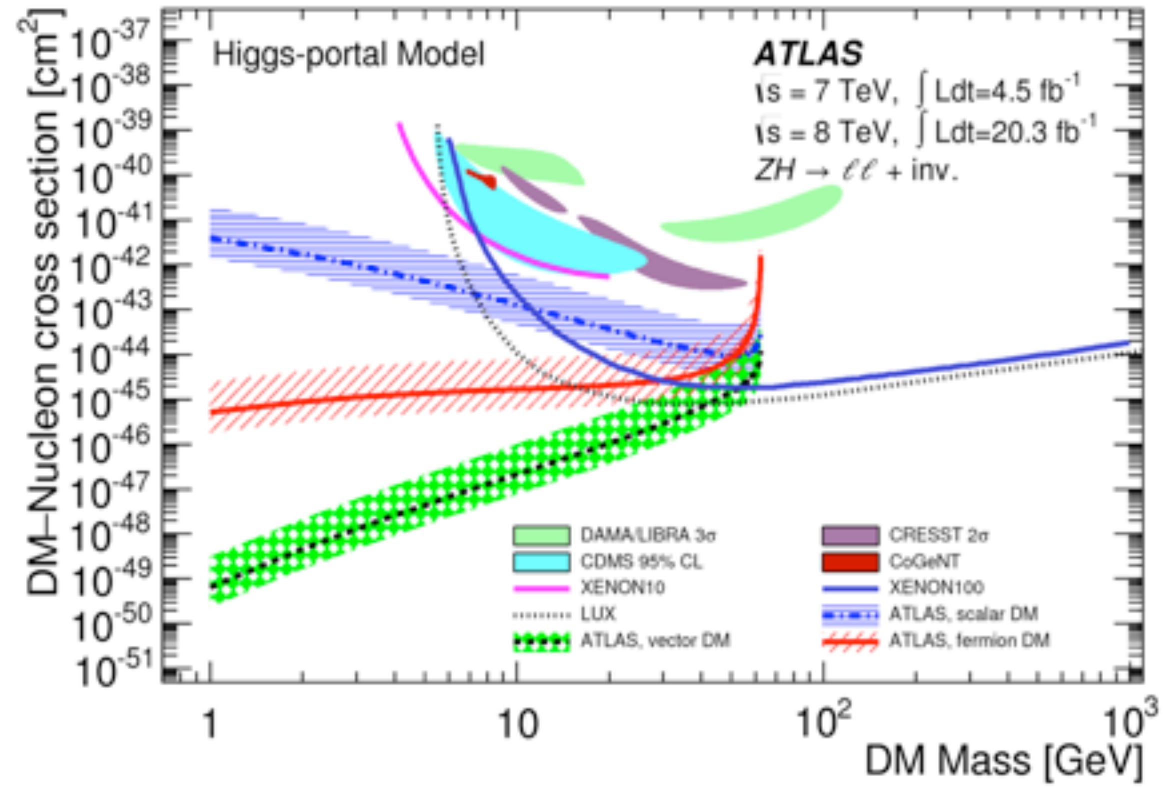




Invisible Higgs searches

Phys. Rev. Lett. 112, 201802





Current limit on Branching fraction of H->invisible < 0.58 @ 95%CL

(assuming SM production cross section and kinematics)

Studies on future projections with 14 TeV, High Luminosity LHC 3000 fb^{-1} show that we may be able to constrain BF(H_{125}→invisible) at few-% level

Summary

- Many signatures being employed at LHC to search for dark matter
- Results show a lot of complementarity with direct detection experiments, in particular for
    - * low mass DM
    - * spin dependent interactions of DM
- Also searches for Higgs decay to invisible particles
- Variety of topologies being used will become especially important if signal is seen by direct detection and/or colliders
- Future projections for 13 TeV and High Luminosity LHC show similar complementarity going forward