Dark matter at the LHC

GRAPPA
GRavitation AstroParticle Physics Amsterdam
UNIVERSITY OF AMSTERDAM

Christopher McCabe

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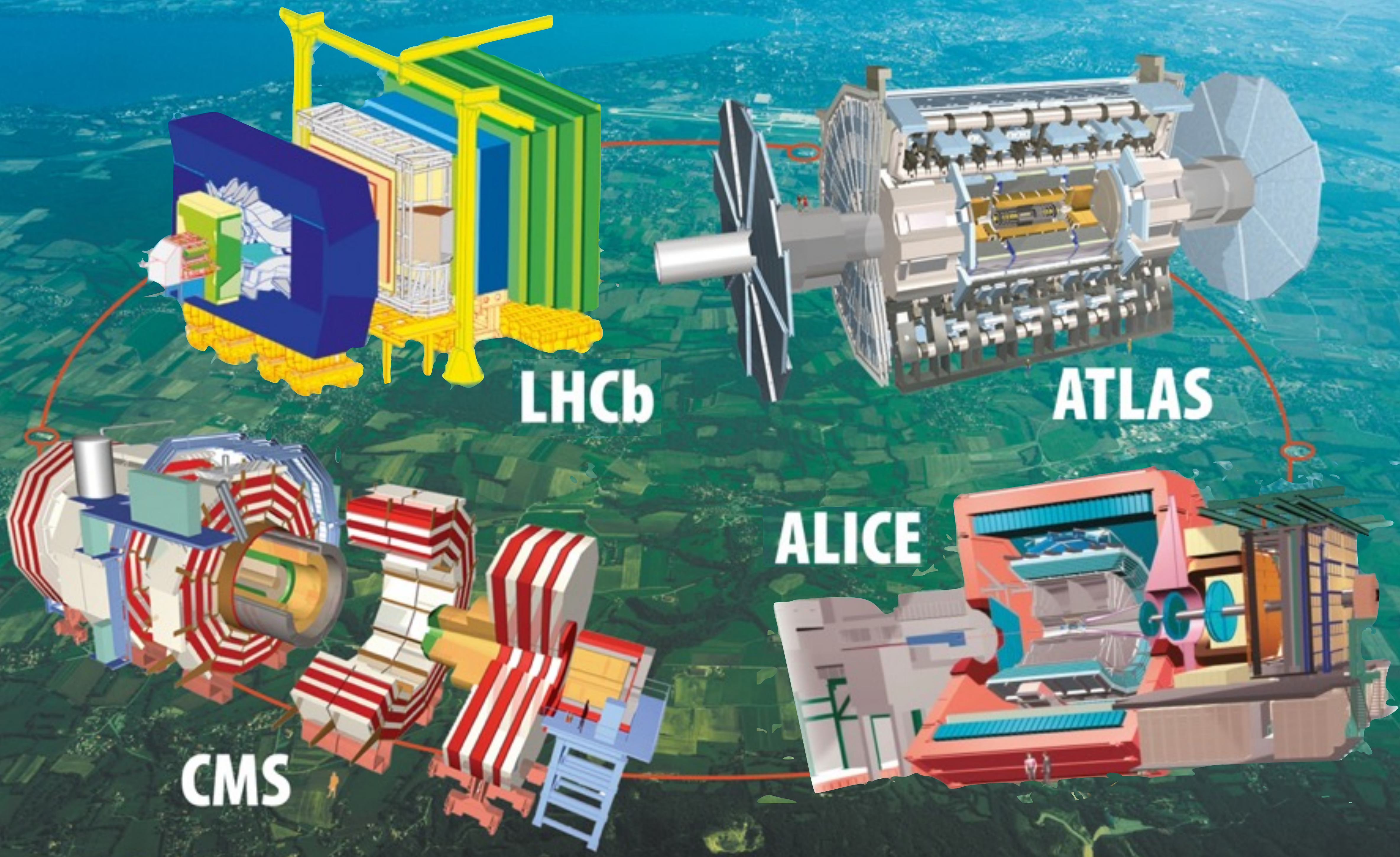
Outline

- Prelude: The Large Hadron Collider (LHC)
- Searching for dark matter at colliders from
  - *pair production (monojet)*
  - cascade decays (SUSY)

Prelude:
The Large Hadron Collider (LHC)

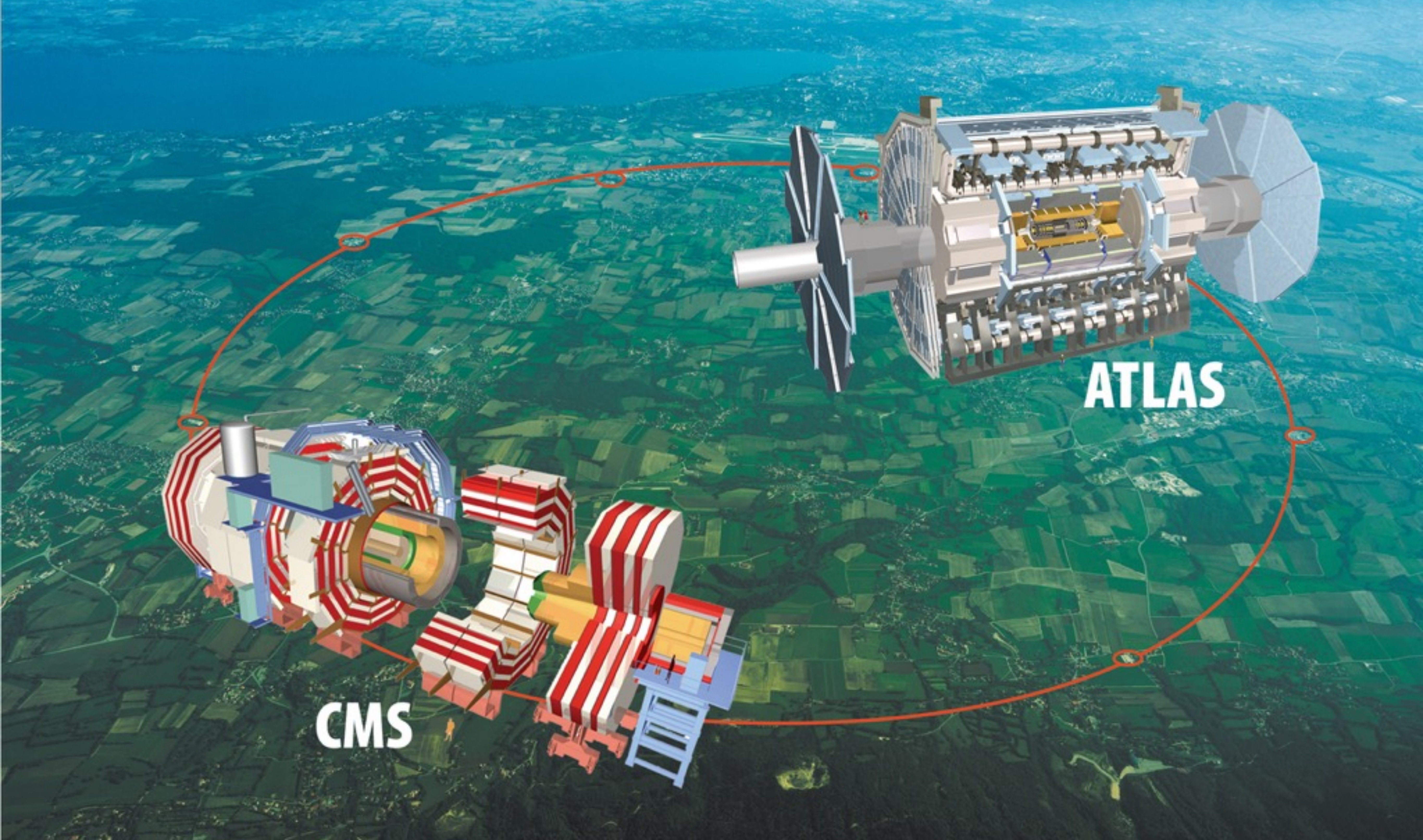
The Large Hadron Collider

- **Proton collider (mostly - short periods of lead/gold collisions)**
- **There are four large experiments at different collision points**

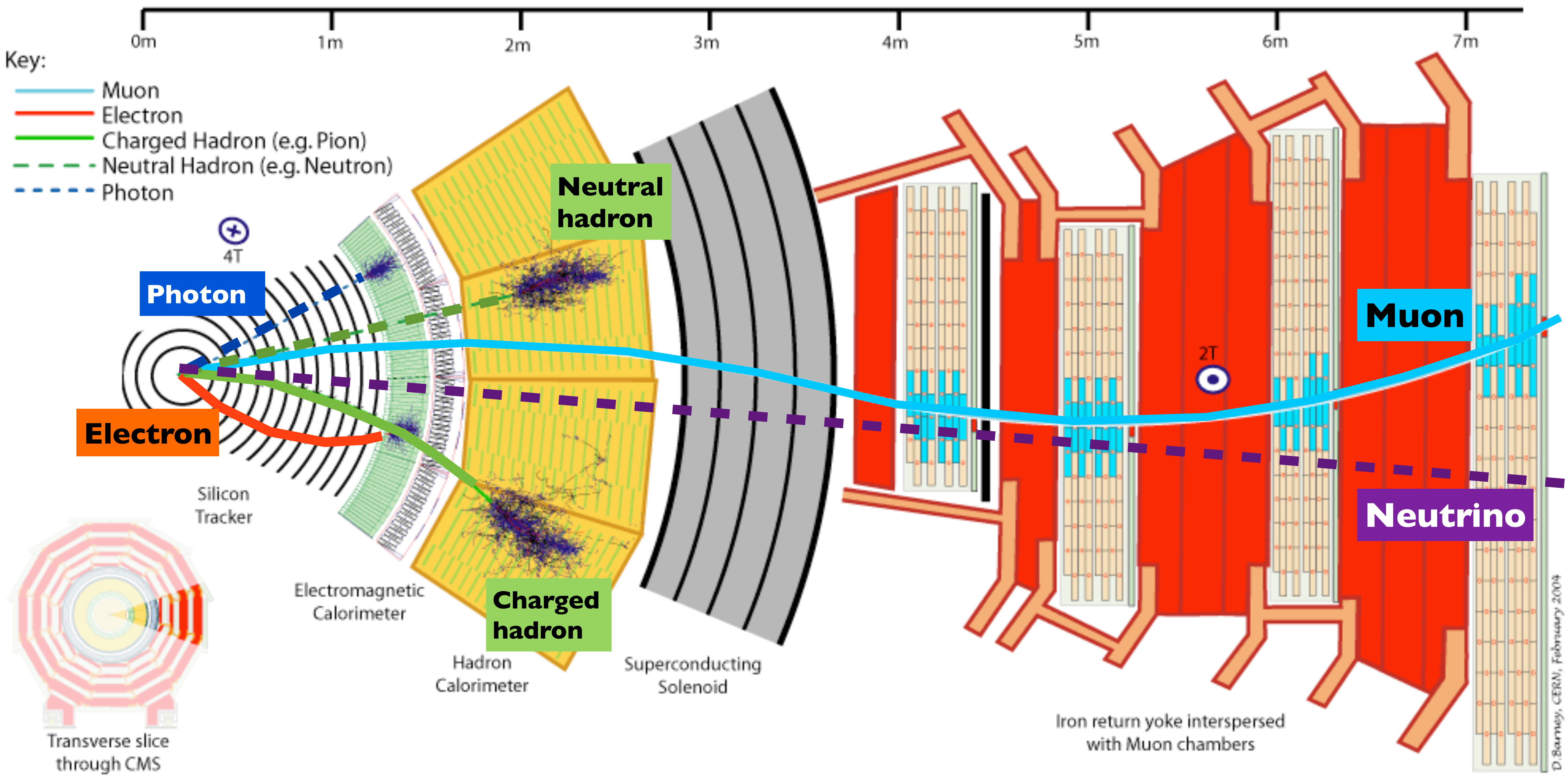


The Large Hadron Collider

- **Focus on the two ‘general purpose’ detectors**



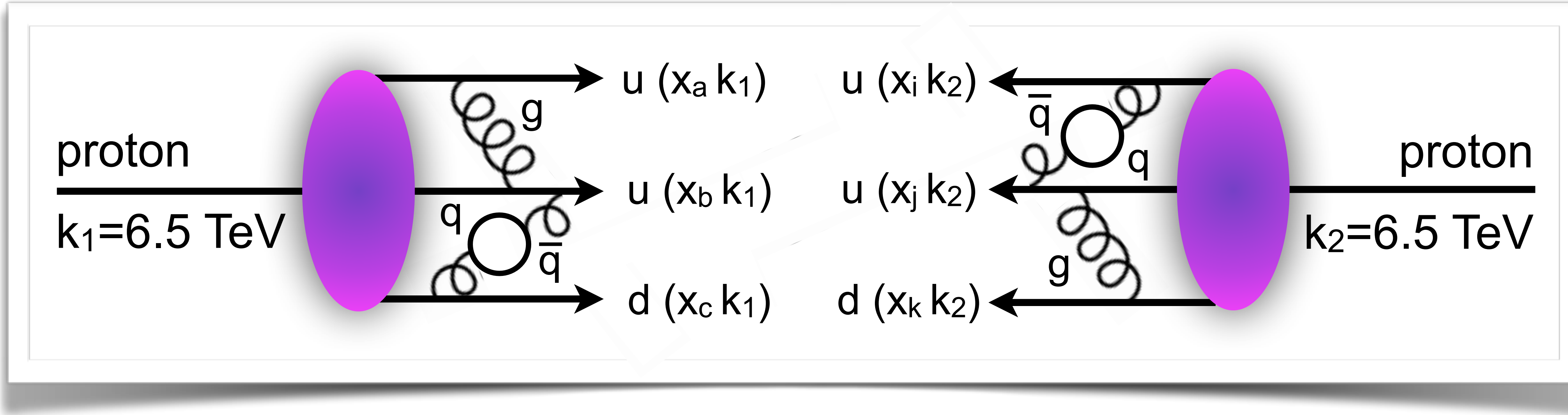
A slice through CMS



Neutrinos traverse the detector without any interaction

Collider basics

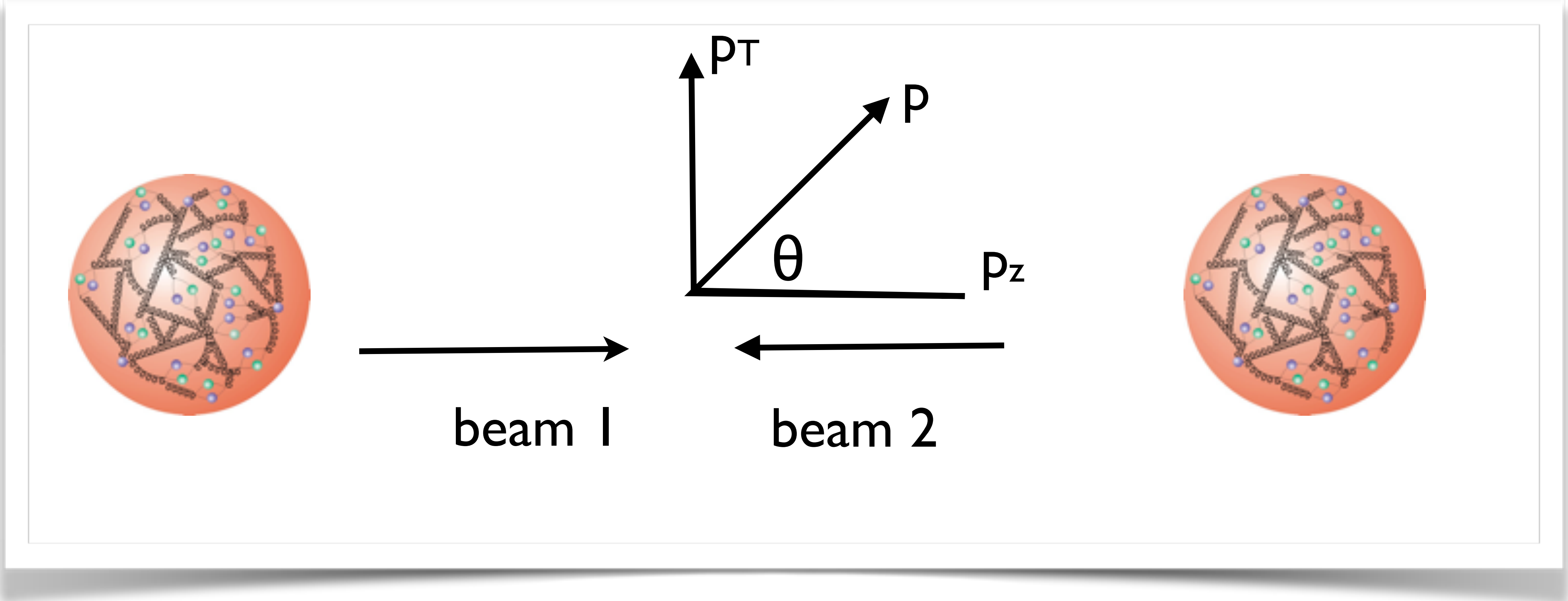
- LHC collides protons each with an energy 6.5 TeV



- Protons are not point-like particles
- Quarks/anti-quarks/gluons generally called ***partons***
- Partons carry a fraction ***x*** of the protons energy
- Parton distribution functions (pdf) tell us the probability of finding a parton with energy fraction x

➡ proton beam offers a wide range of collision energies

Transverse quantities



- Proton centre of mass (COM) frame ***not*** the same as the parton COM frame
- Parton's initial momentum along beam direction (z) unknown

➡ Can't use full momentum conservation

- But…transverse momentum (p_T) is known: initially zero

➡ Use transverse quantities: $p_{\mathrm{T}} = p \sin\theta$

Luminosity

- We need high luminosity as well as high energy

$$N_{\text{events}} = \sigma \times \int L\, dt$$

number of events produced

cross-section of process of interest

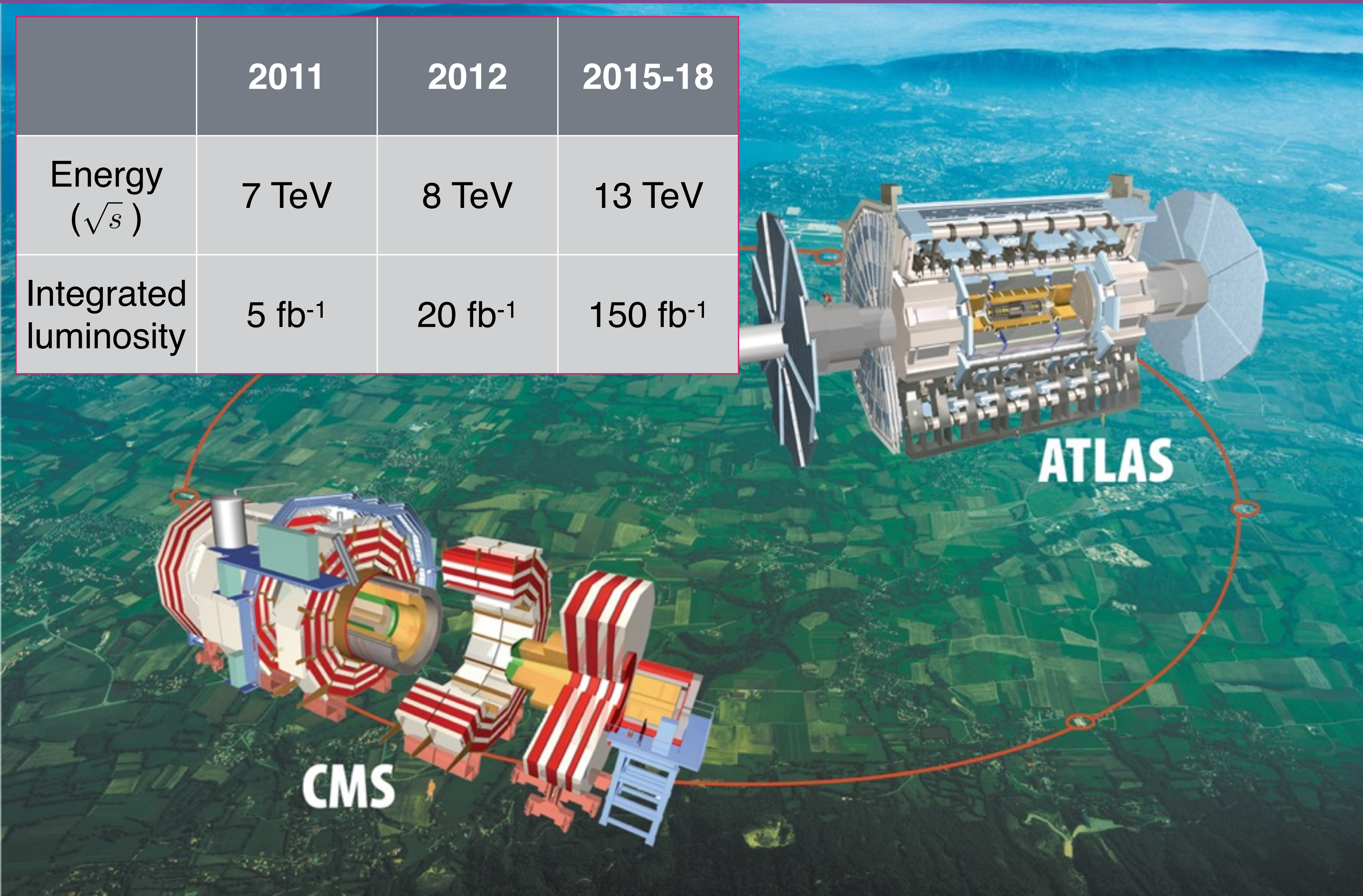
integrated luminosity from the collider

- Cross-section has units barn, pico-barn (pb), femto-barn (fb), …
- Integrated luminosity has units inverse barn, pb^{-1}, fb^{-1}, …

- To observe rare processes (small cross-section) need a larger integrated luminosity

The Large Hadron Collider

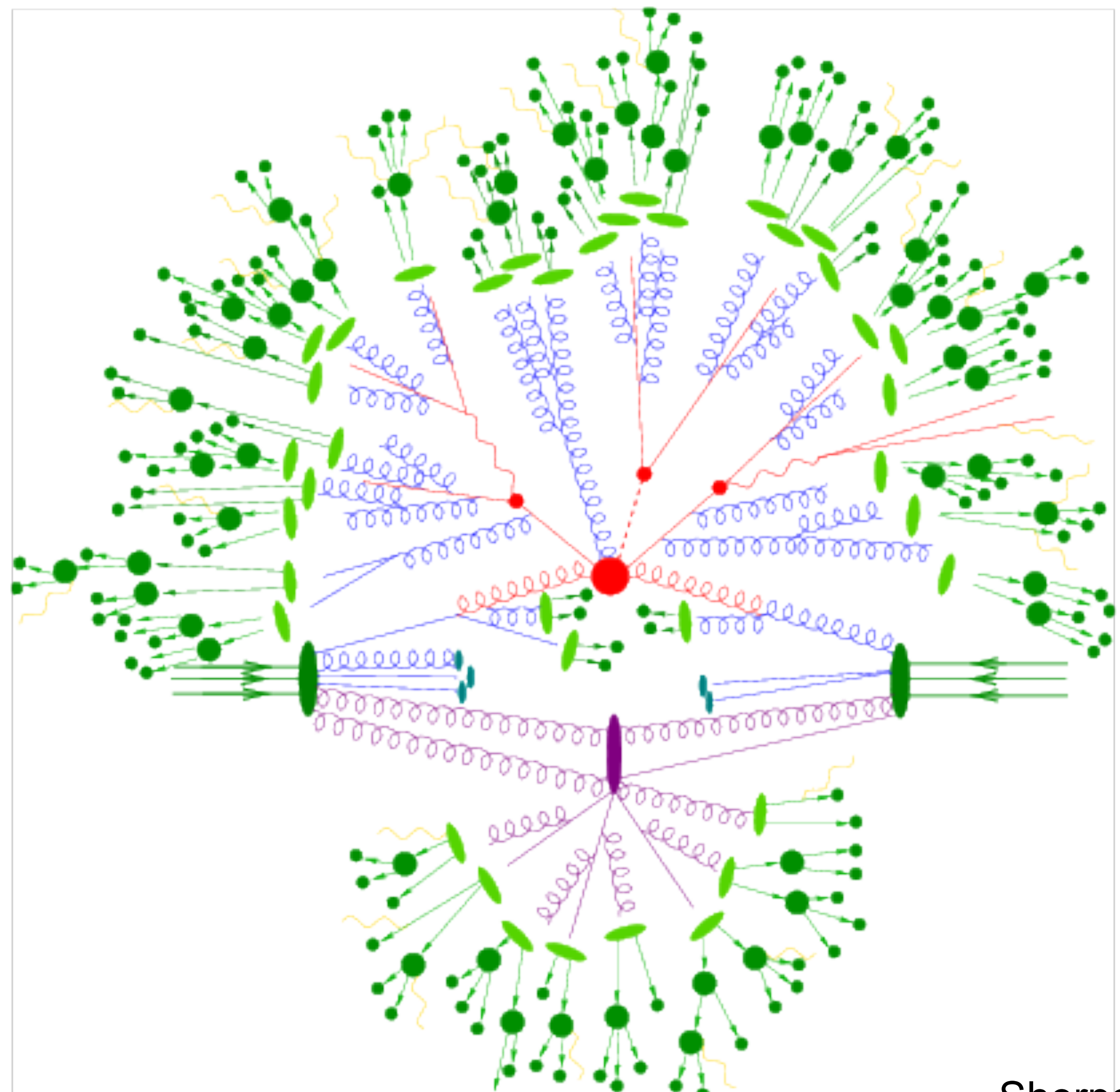
	2011	2012	2015-18
Energy ($\sqrt{s}$)	7 TeV	8 TeV	13 TeV
Integrated luminosity	5 fb^{-1}	20 fb^{-1}	150 fb^{-1}



Proton collisions are messy

One event has multiple stages:

- Signal
  (production and decays)
- QCD-Bremsstrahlung
- Multiple interactions
- Hadronisation

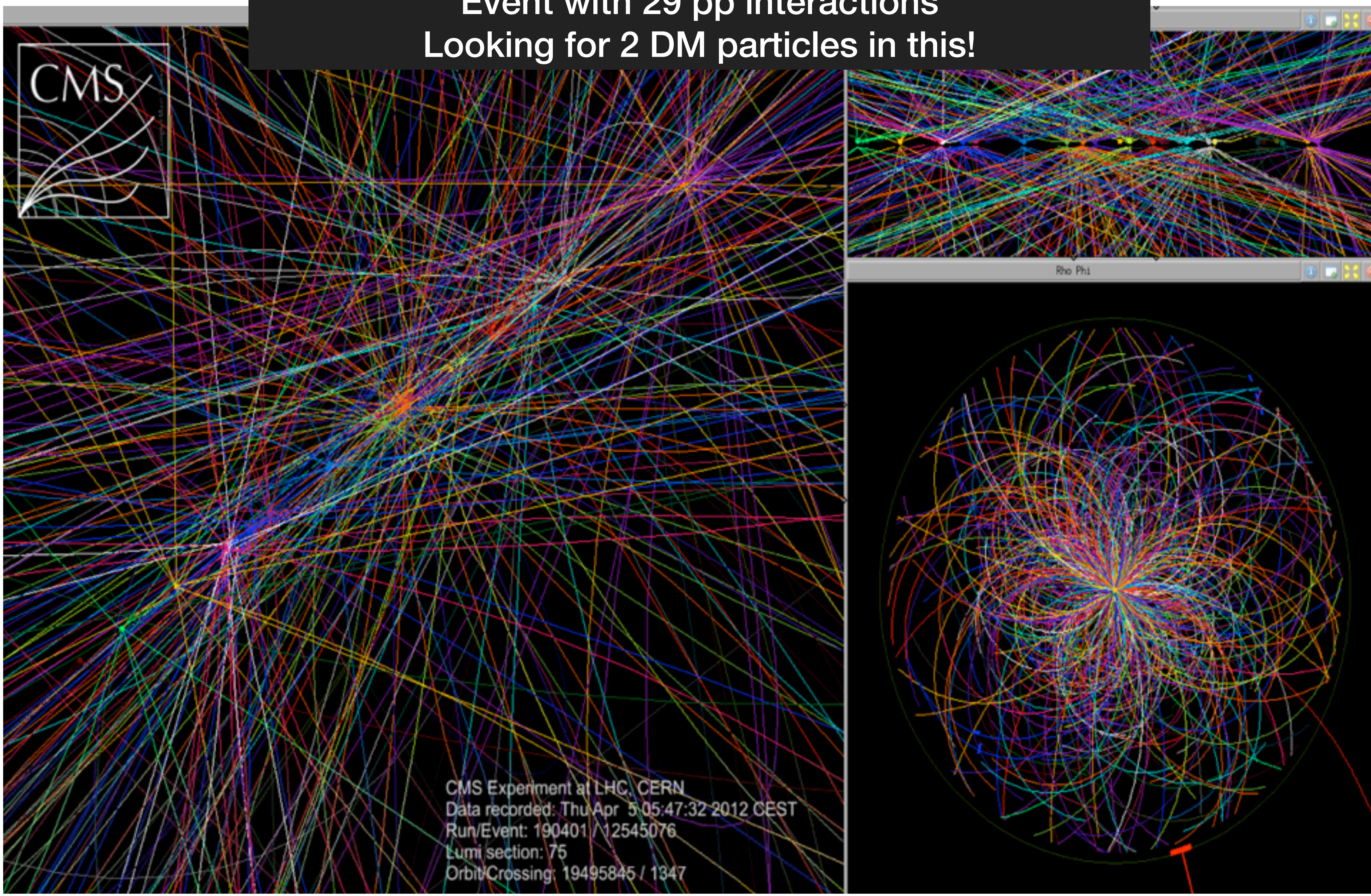


Sherpa

Monte Carlo event generators can simulate this!

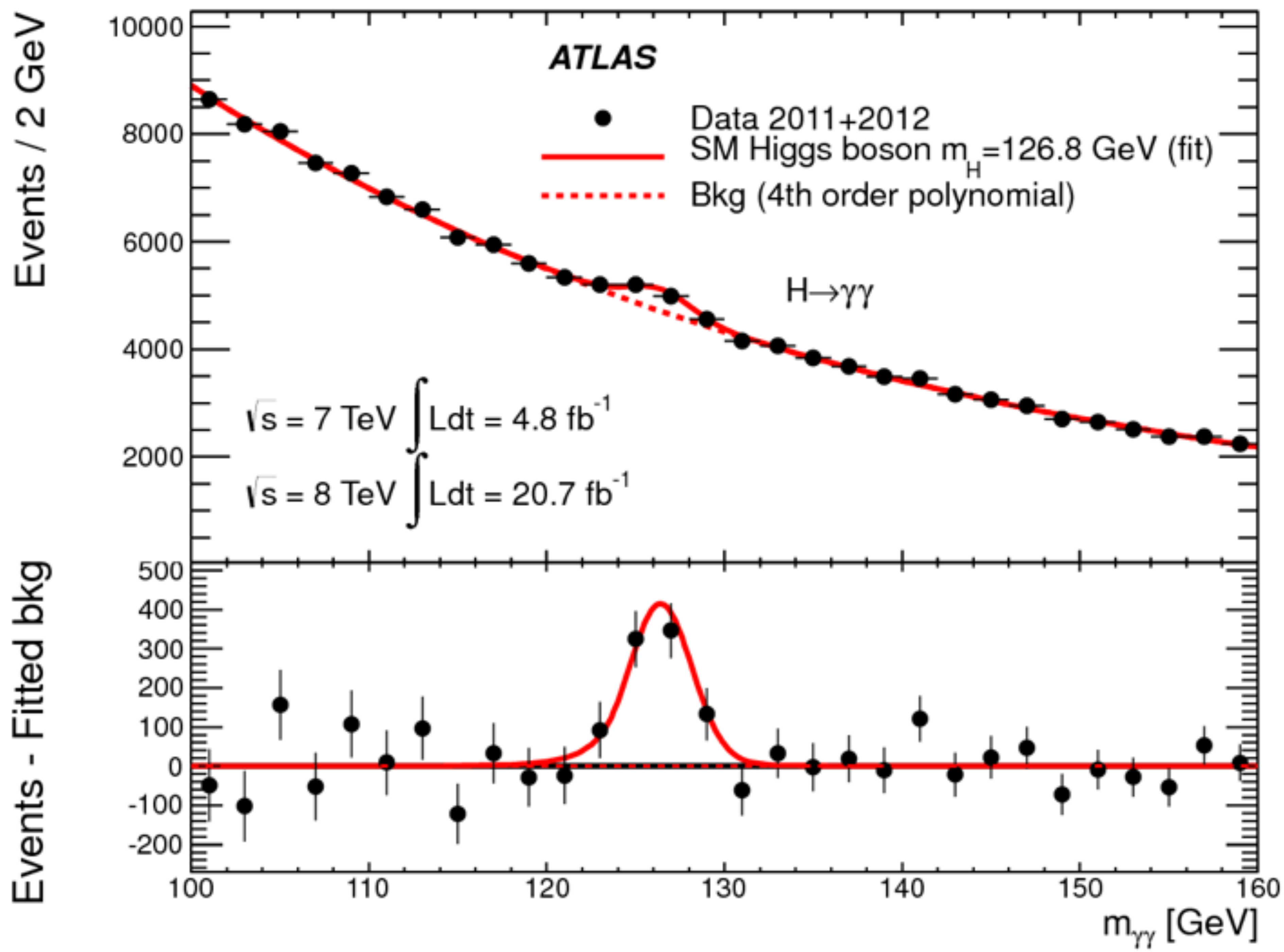
Many interactions!

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



Messy…but still useful

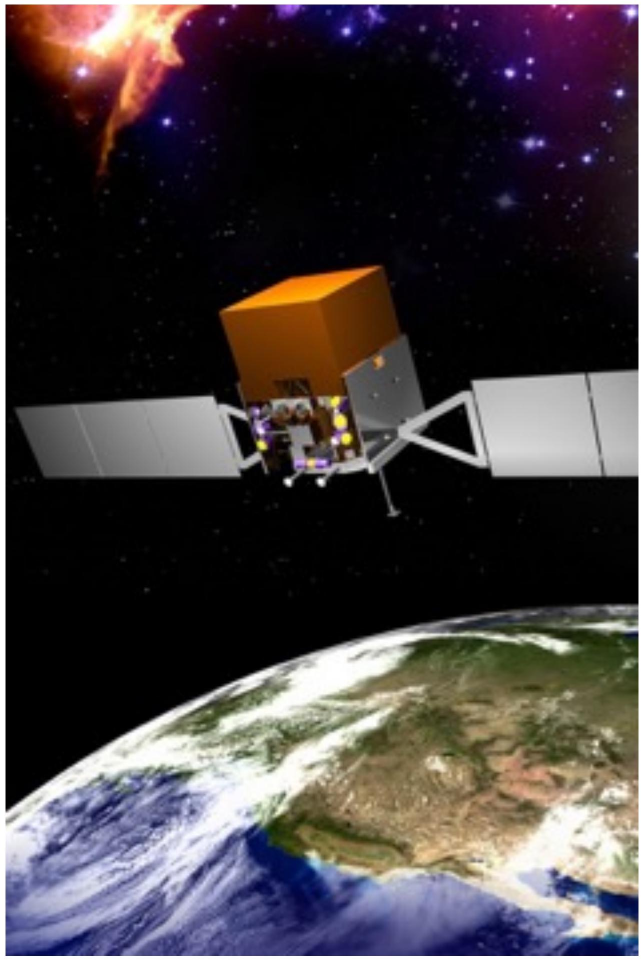
2012: Higgs discovery!



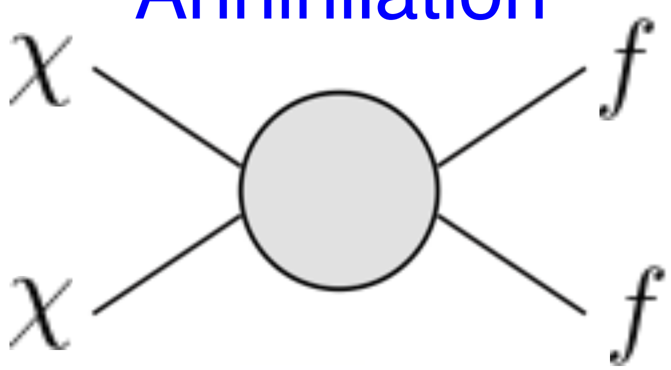
Searching for dark matter

Three popular strategies

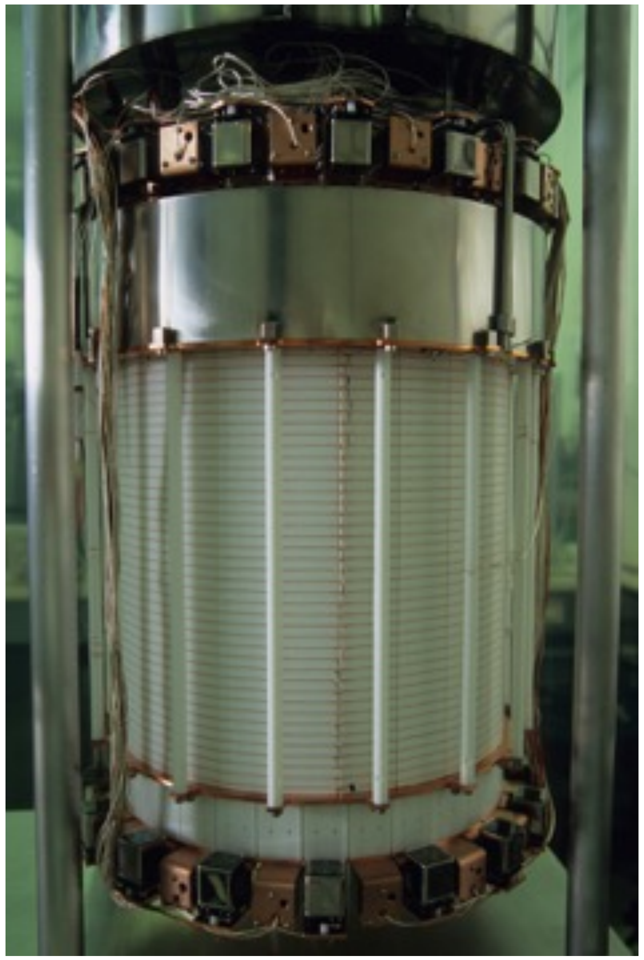
Indirect detection



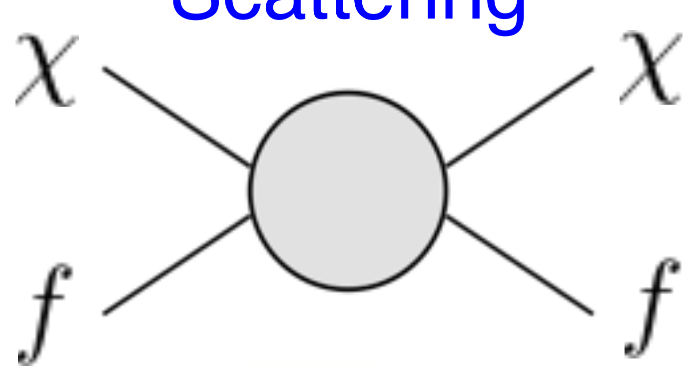
Annihilation



Direct detection

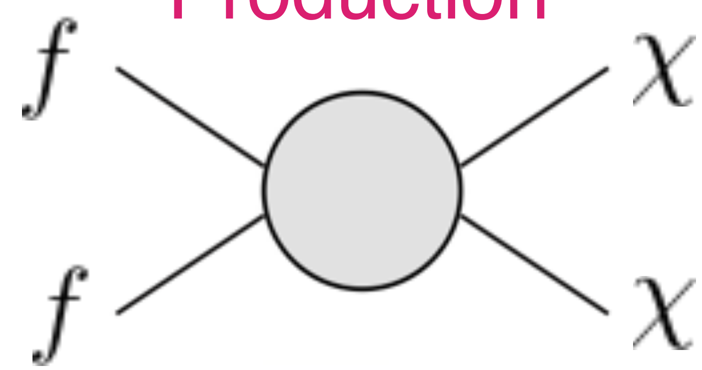


Scattering



Collider

Production

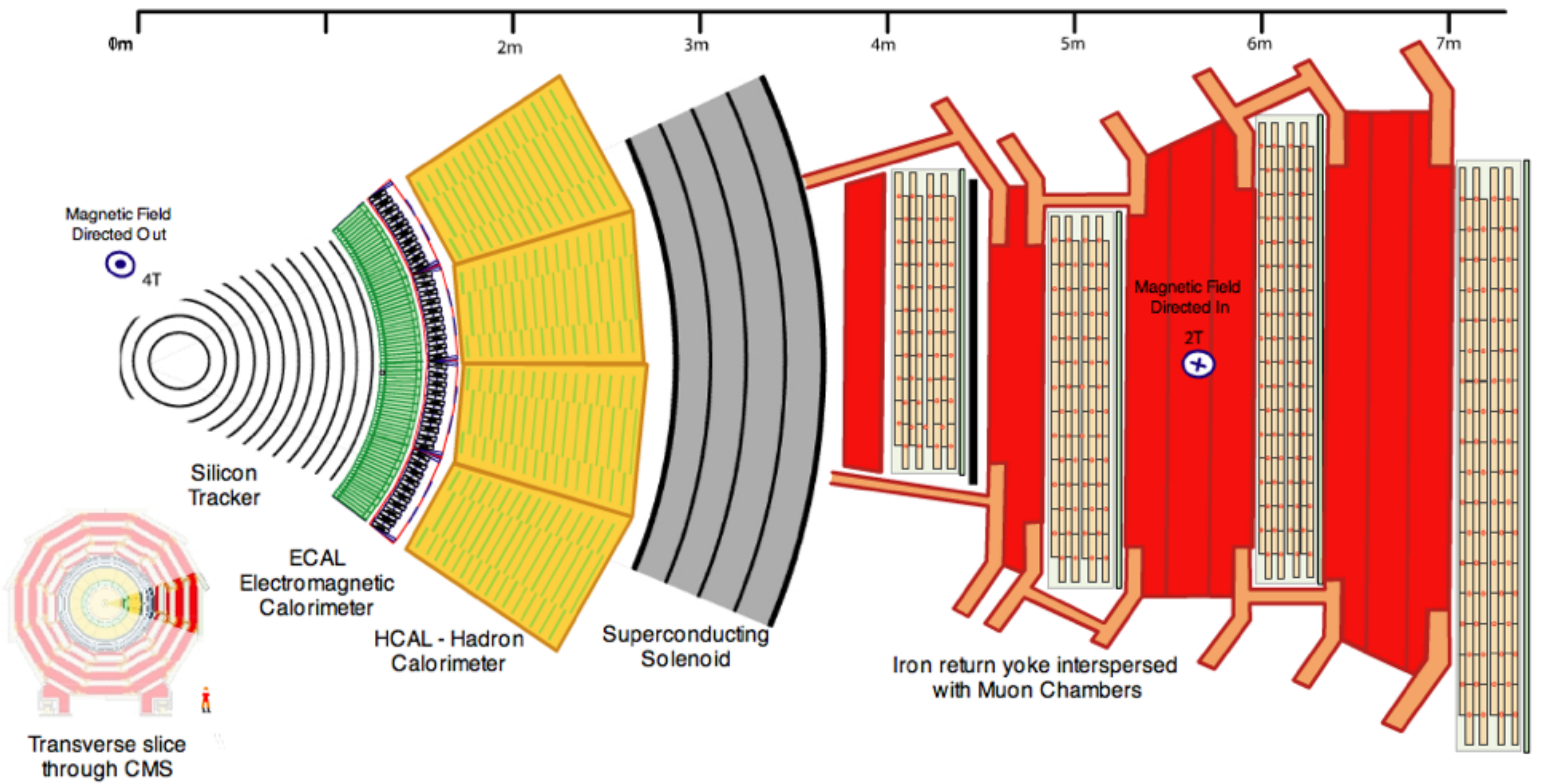


Warning

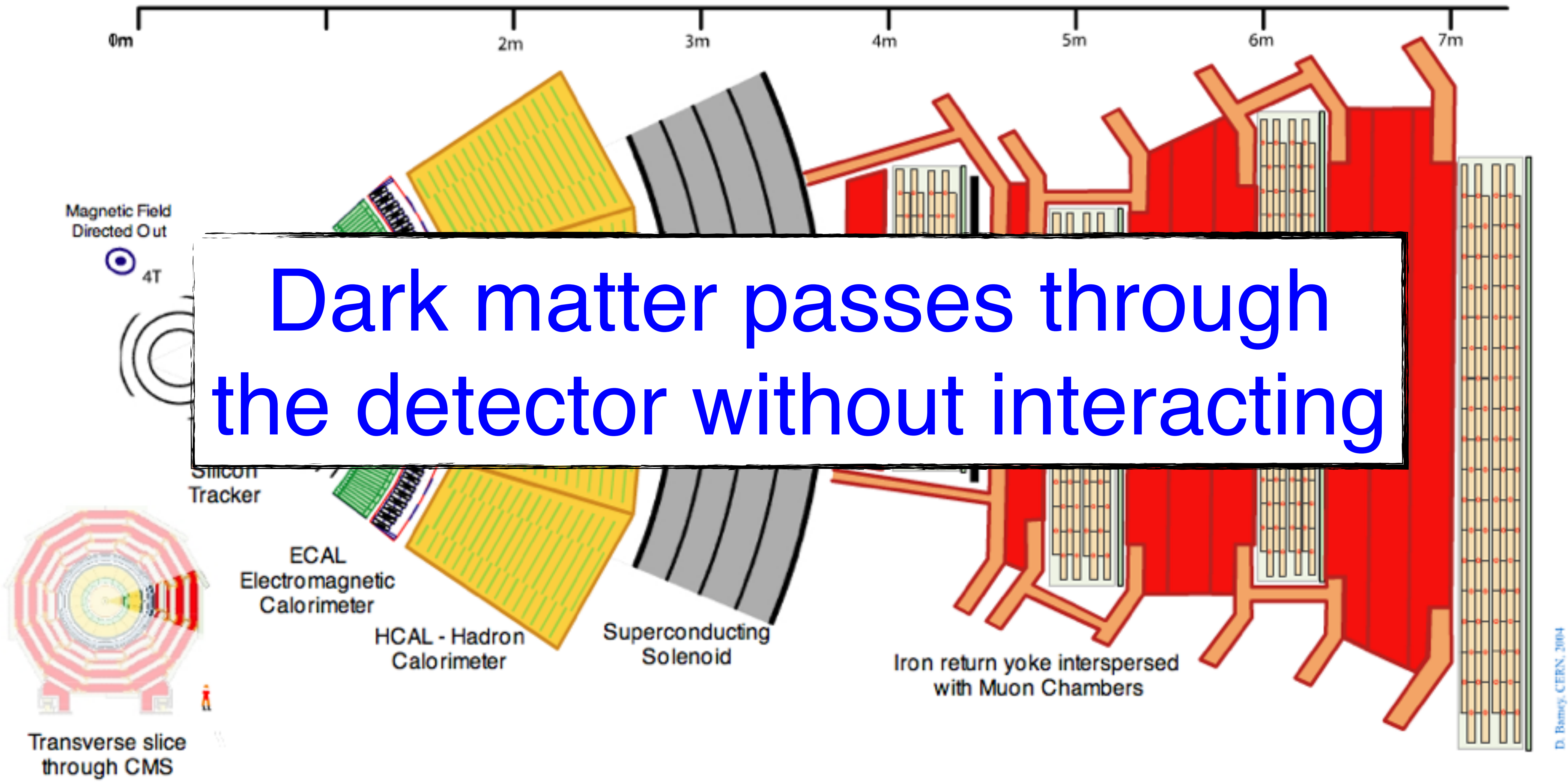
- Things to remember:
  - Colliders cannot prove stability beyond the apparatus
  - The dark matter mass reconstruction will be poor
  - Colliders cannot distinguish single and multiple invisible particles
  - May give little information on the nature of interaction, spin of the dark matter, its quantum numbers…

Interpreting any signal will be challenging

A dark matter event



A dark matter event

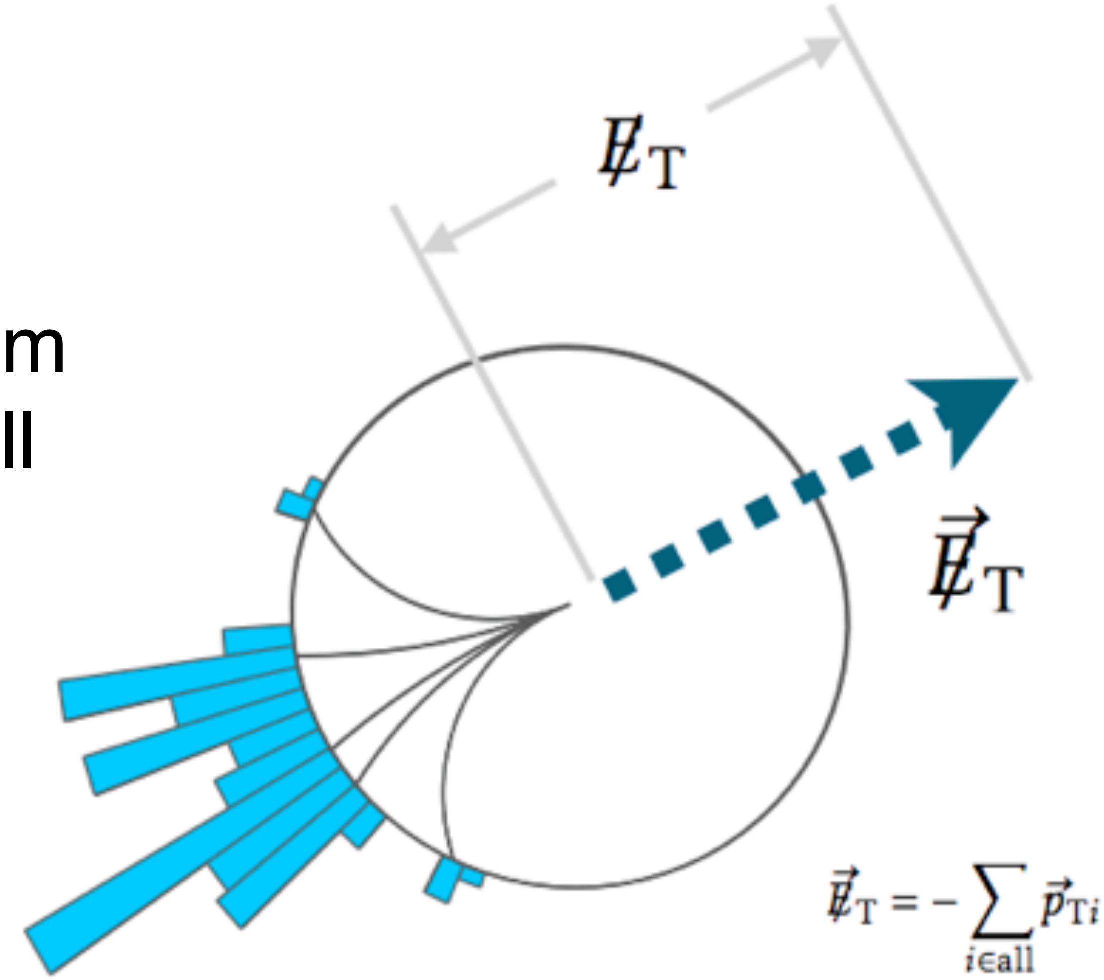


Dark matter passes through the detector without interacting

Missing transverse energy (MET or $\not{E}_T$)

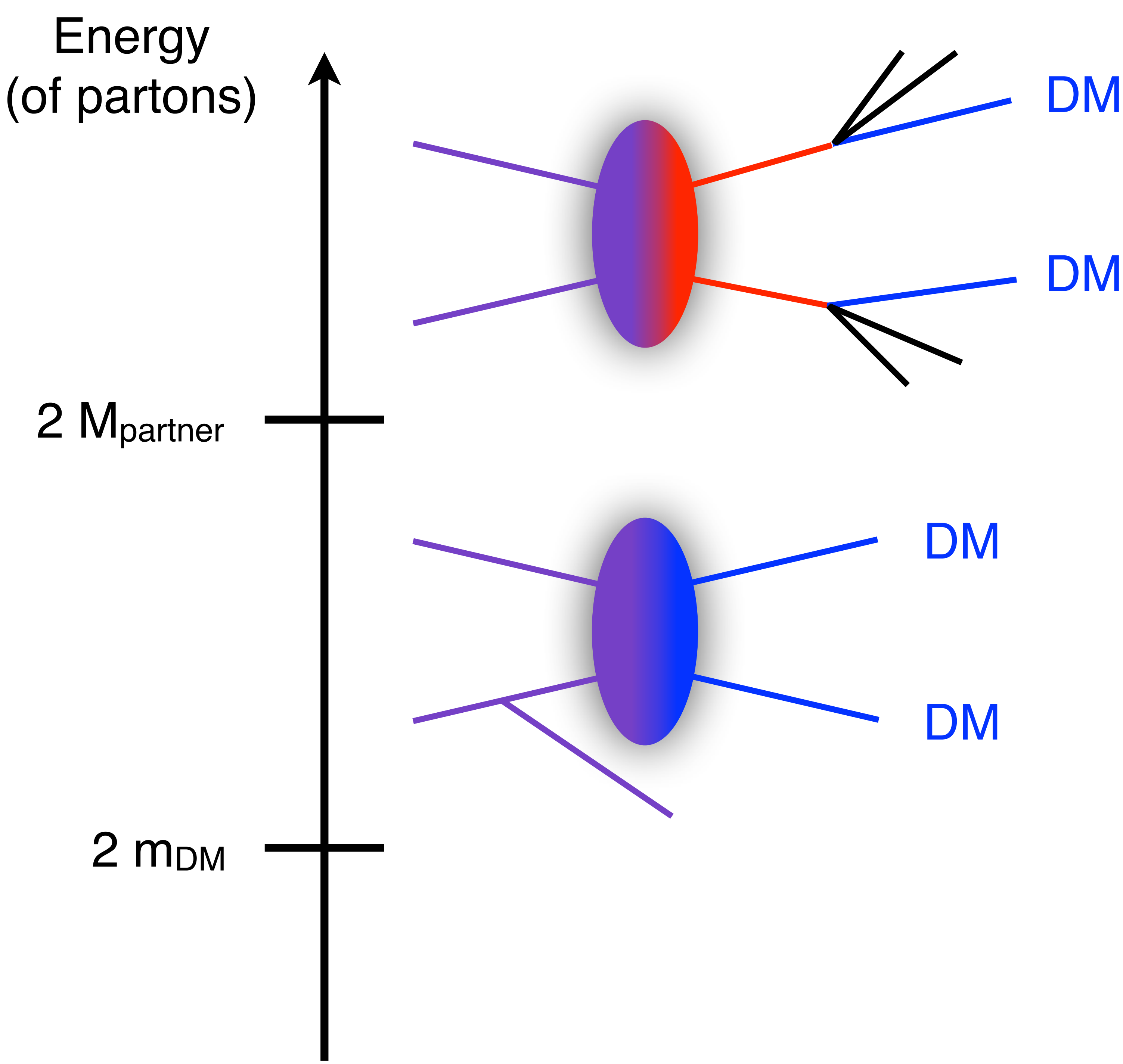
- At the heart of all collider searches for dark matter

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



- MET search used to discover *W*-boson with UA1
  ➡ has been a major tool for hadron colliders ever since

LHC search categorisation

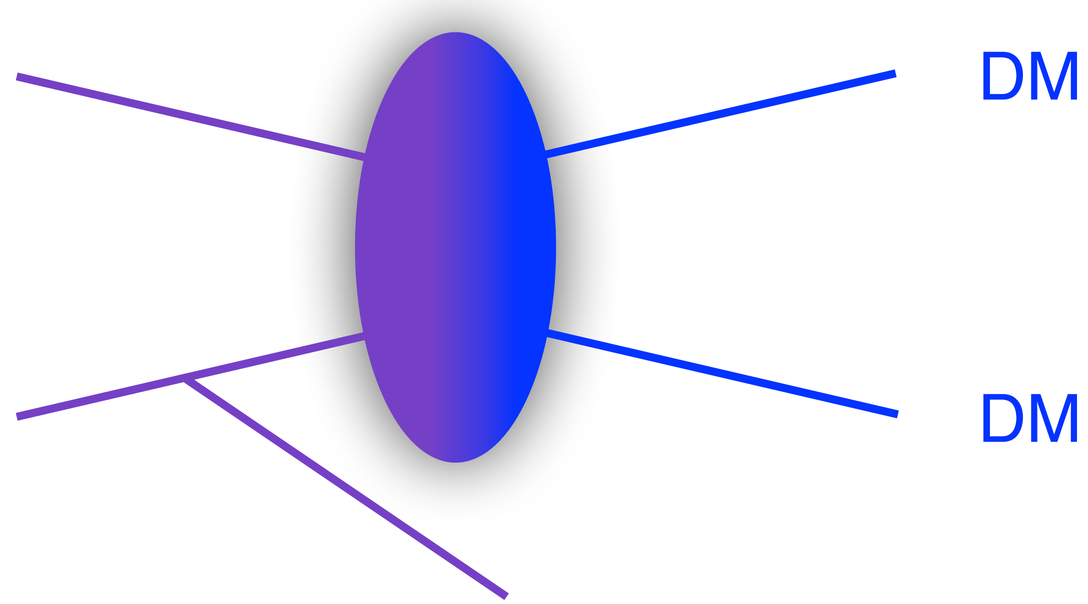


Dark matter produced in cascade decays from heavier new states
eg SUSY cascade searches

LHC directly produces dark matter pairs
eg Mono-X searches

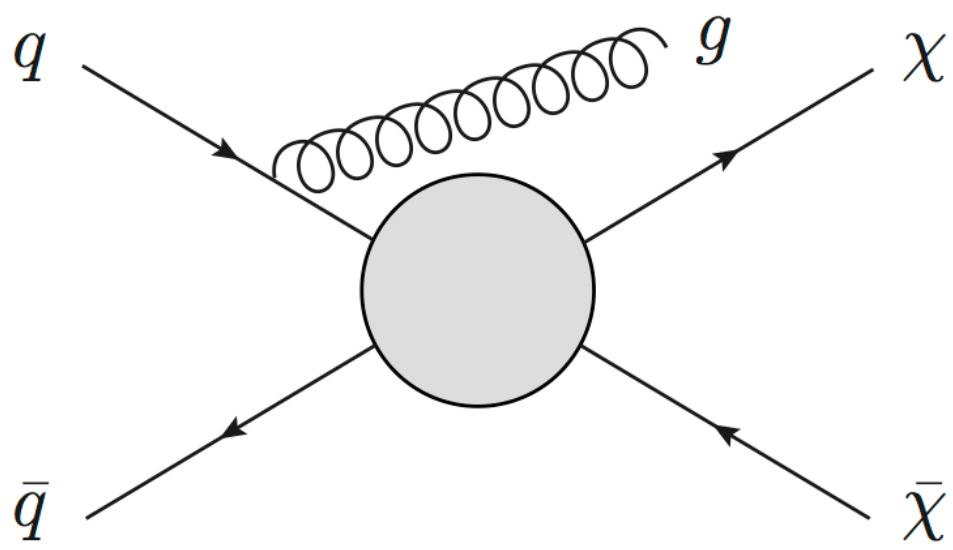
LHC cannot produce dark matter

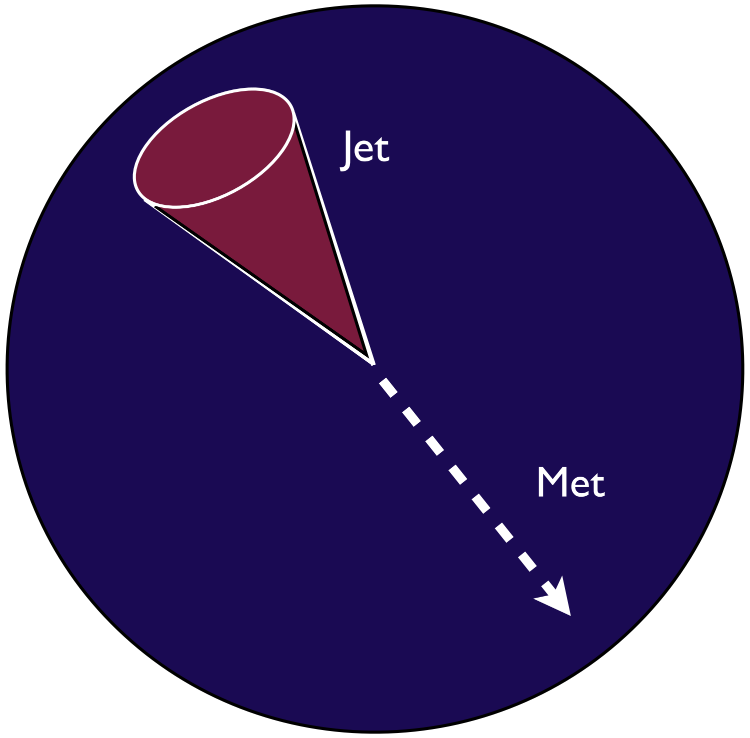
Searches for dark matter pair production



Monojet signature

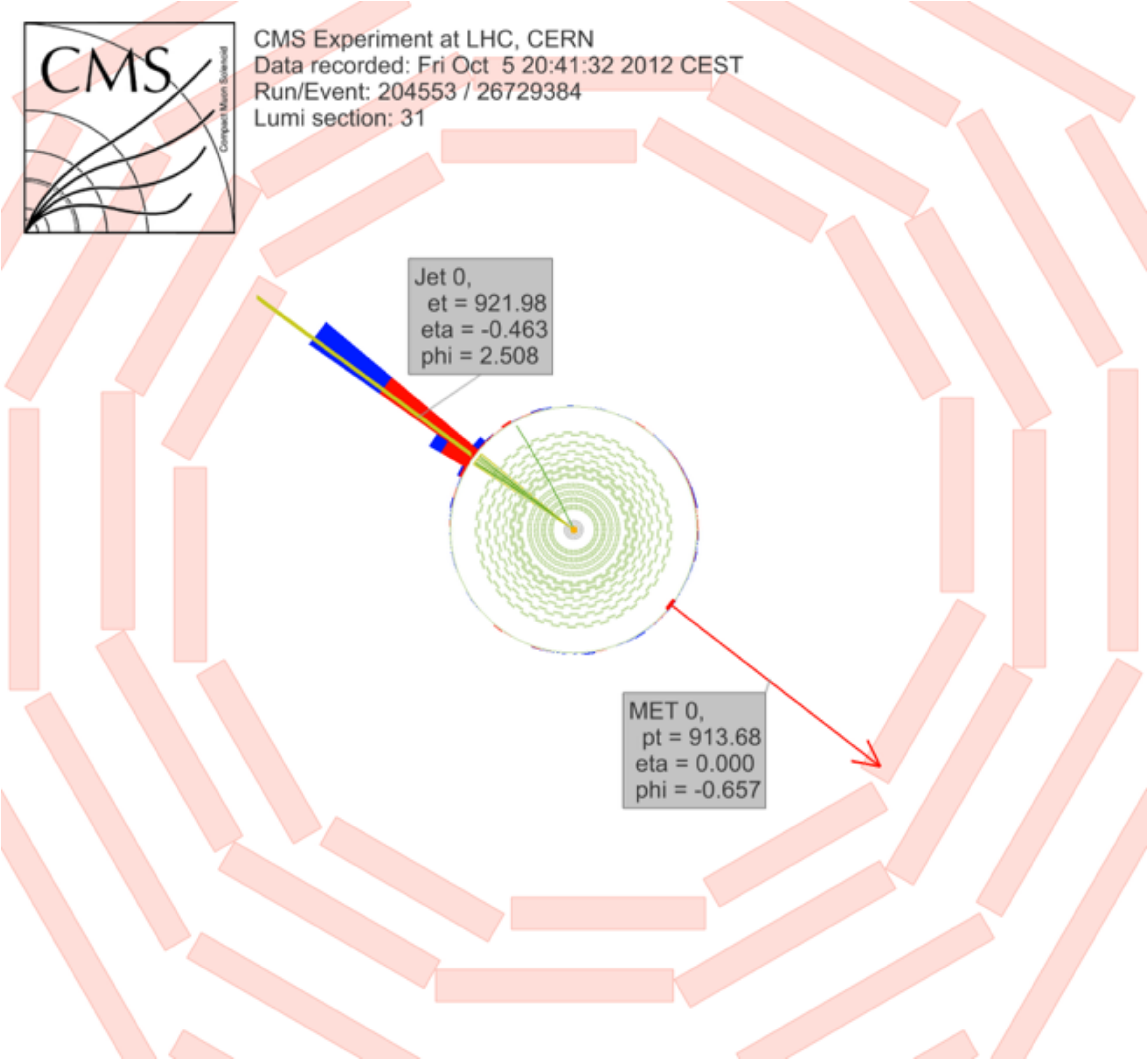
- ‘Classic’ pair production search
  - ➡ Simple and striking signature: hard jet and MET





- Dark matter recoils against a QCD jet from initial state radiation (ISR)

Monojet: a real event



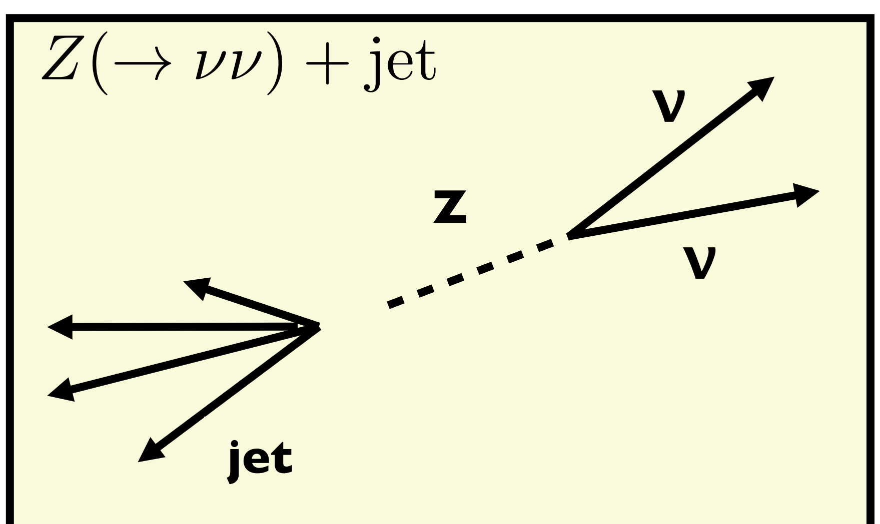
CMS search search (ATLAS similar)

CMS: 1408.3583
ATLAS: 1502.01518

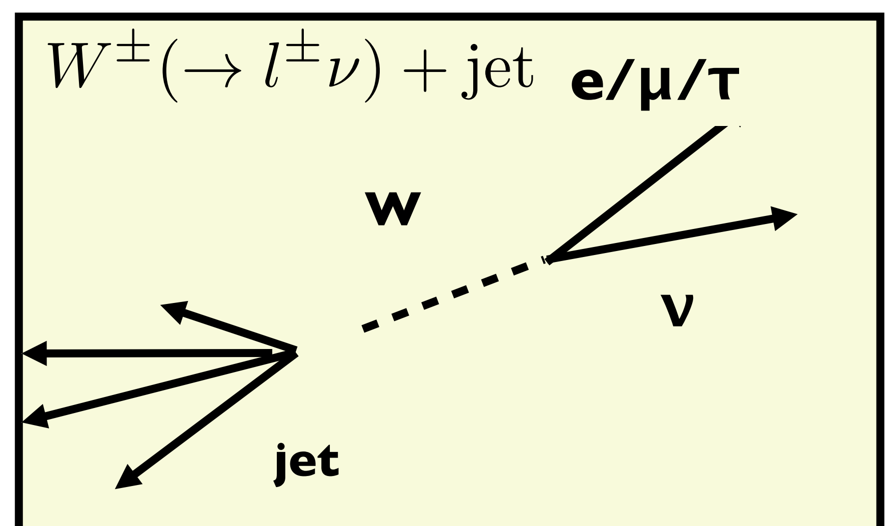
- Event selection:
  - Large missing transverse energy: $\not{E}_{\mathrm{T}} > 500\ \mathrm{GeV}$
  - One energetic jet: $p_{\mathrm{T}} > 100\ \mathrm{GeV}$
  - One additional jet if $p_{\mathrm{T}} > 30\ \mathrm{GeV}$ and $\Delta\phi(j_1, j_2) < 2.5$

- Main backgrounds:

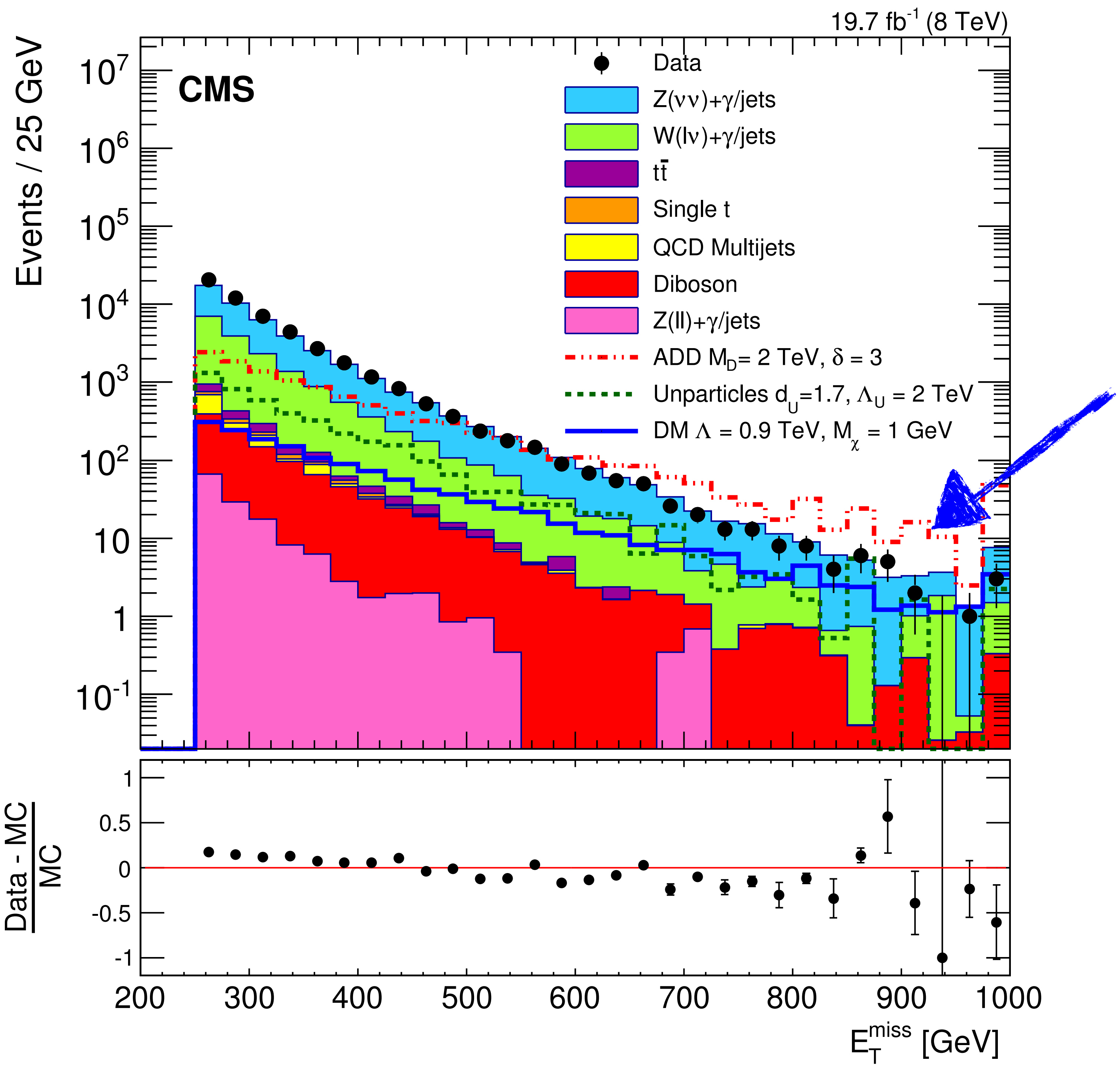
Irreducible background;
looks like signal



e/μ not detected
τ decays hadronically



Monojet results



- Signal is a slight increase in the tail of the distribution
- Difficult to observe
- So far, no excess

Interpretation

Problem: In which framework should we interpret the search?

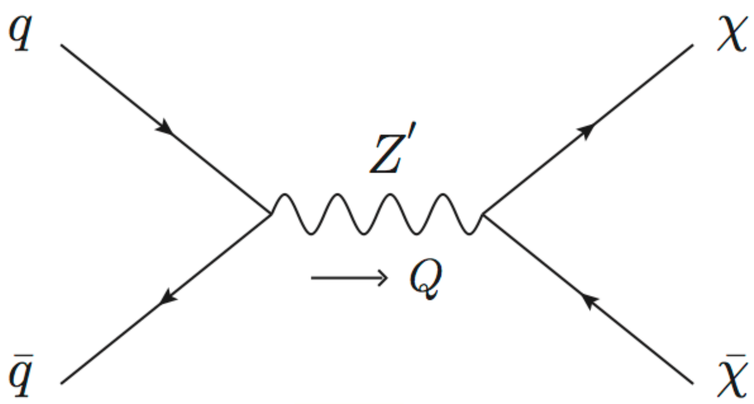
➡ There is no canonical dark matter model (outside SUSY…)

Different approaches taken:

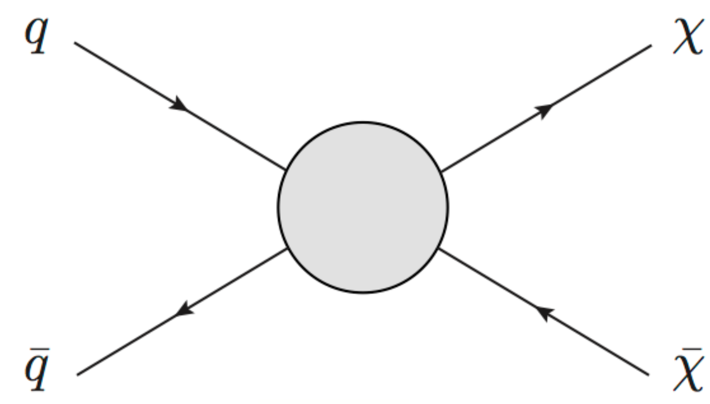
1. Effective field theory/contact interaction
2. Simplified models

1. Effective field theory (EFT)

- Treat the interaction as a contact (point-like) interaction



'Integrate out the mediator'



$$\begin{aligned}\mathcal{L} \sim\ & g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi \\ & + g_q Z'_\mu \bar{q}\gamma^\mu q \\ & + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu + \cdots\end{aligned}$$

$$\mathcal{L} \sim \frac{1}{\Lambda^2}\bar{q}\gamma_\mu q\, \bar{\chi}\gamma^\mu \chi$$

- Parameter of interest is the contact interaction scale Λ

- Related to parameters in the full theory: $\Lambda = \dfrac{m_{Z'}}{\sqrt{g_q g_\chi}}$

This is not a new idea

- Fermi could describe β-decay without knowing the microscopic details:

$$\mathcal{L} = \frac{G_{\rm F}}{\sqrt{2}} \left[\bar{\psi}\gamma^{\mu}(1-\gamma^5)\psi\right] \left[\bar{\psi}\gamma_{\mu}(1-\gamma^5)\psi\right] \text{ where } G_{\rm F} \propto \frac{g^2_{\rm weak}}{M_W^2}$$

- It is a very useful idea
- we don't need to know all details of the full theory

- Can (in principle) constrain many different theories:

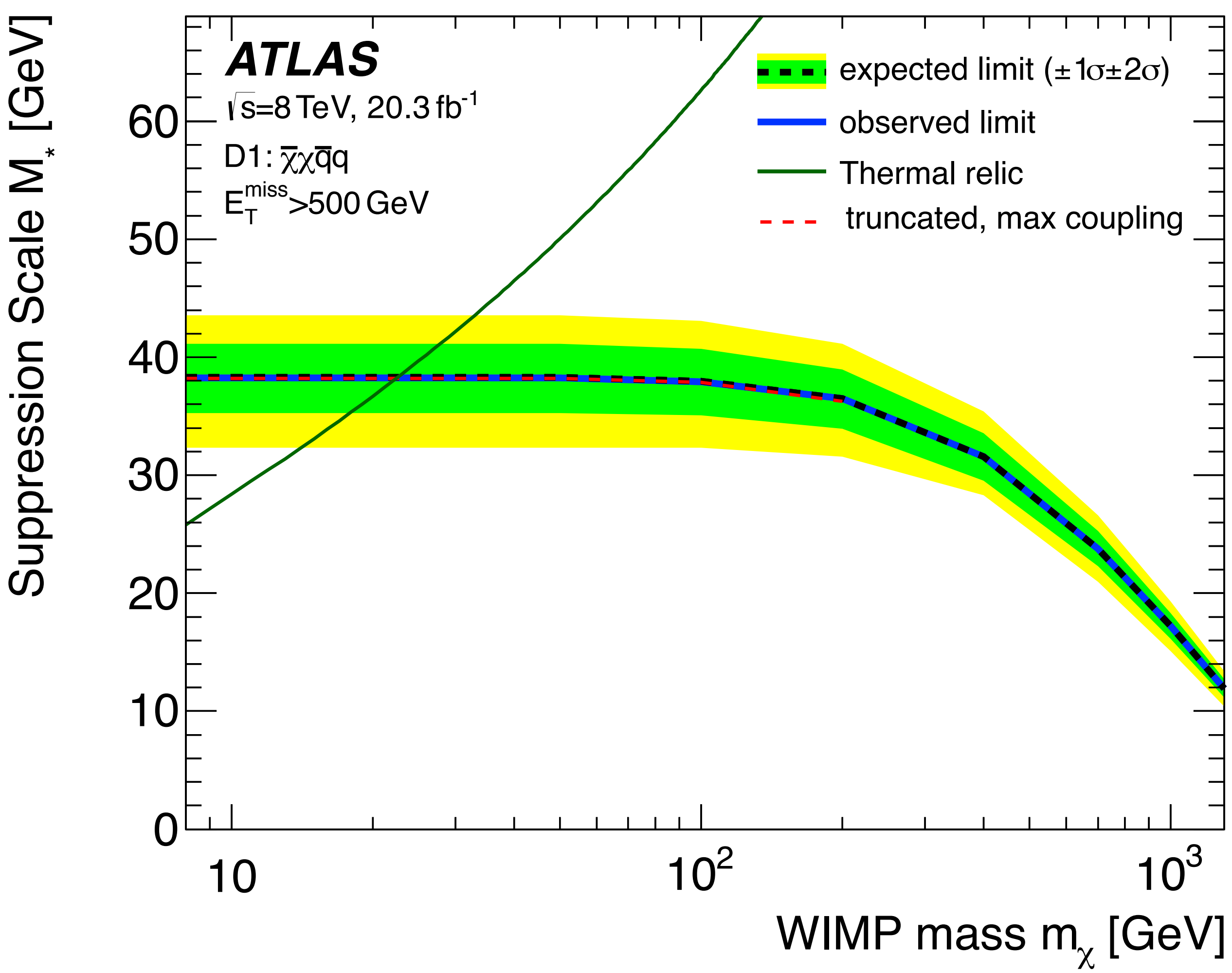
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

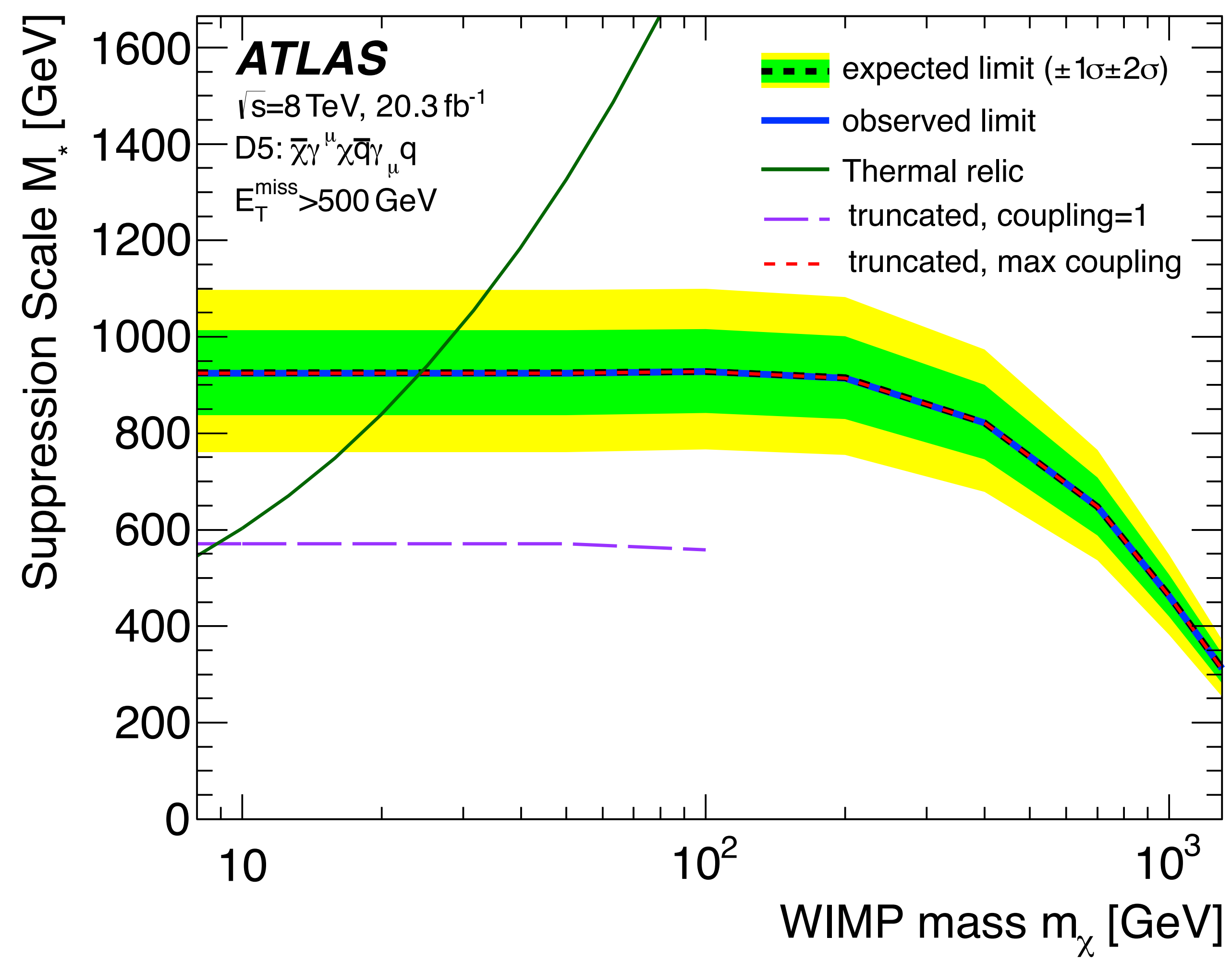
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Goodman et al
arXiv:1008.1783

Advantage of EFT approach

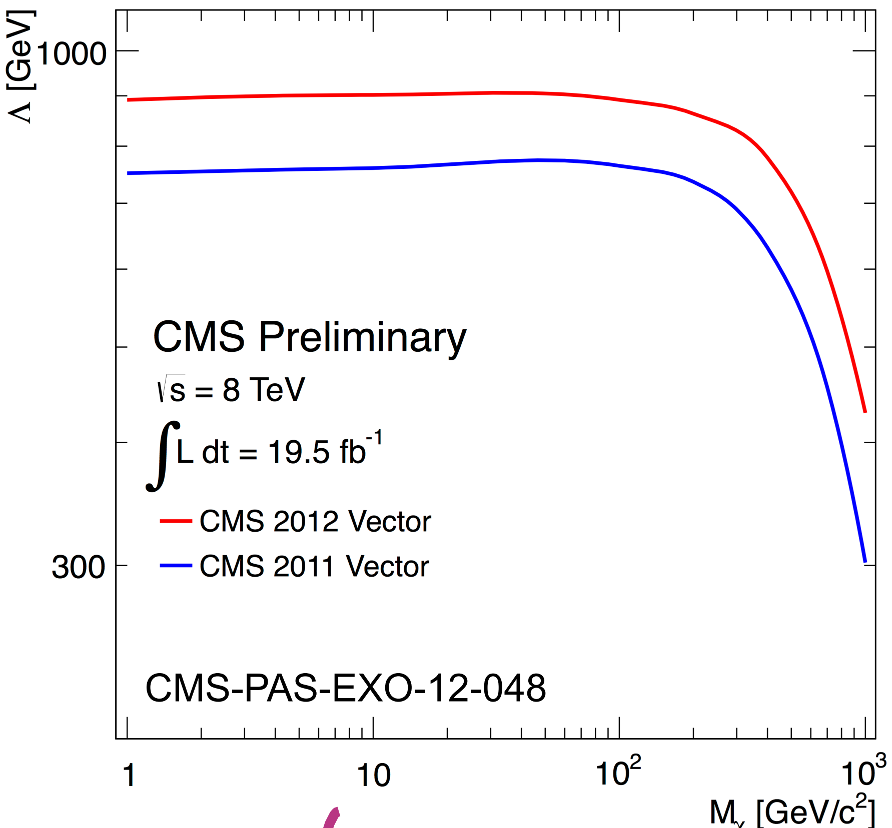
- Straightforward to constrain Λ (or $M_\star$) for various operators



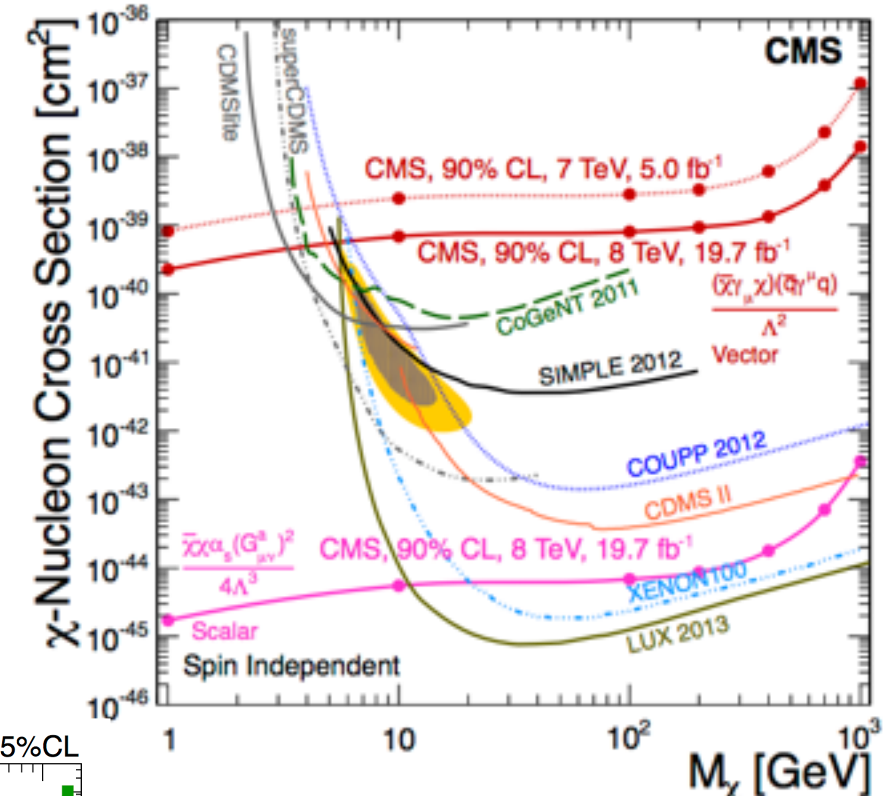


Advantage of EFT approach

- Comparison with other dark matter searches is straightforward



with direct detection limits



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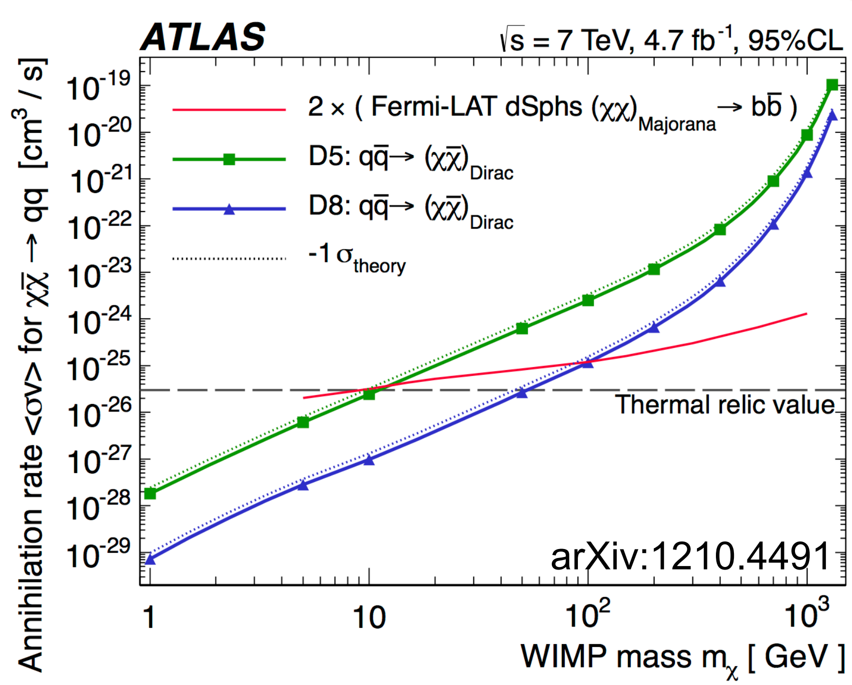
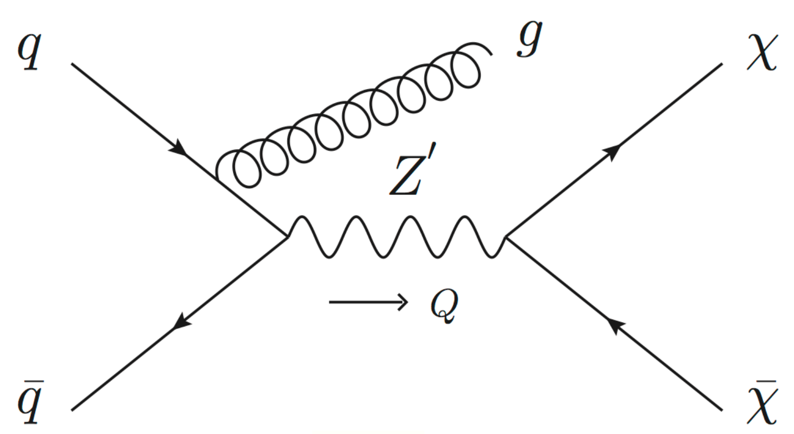


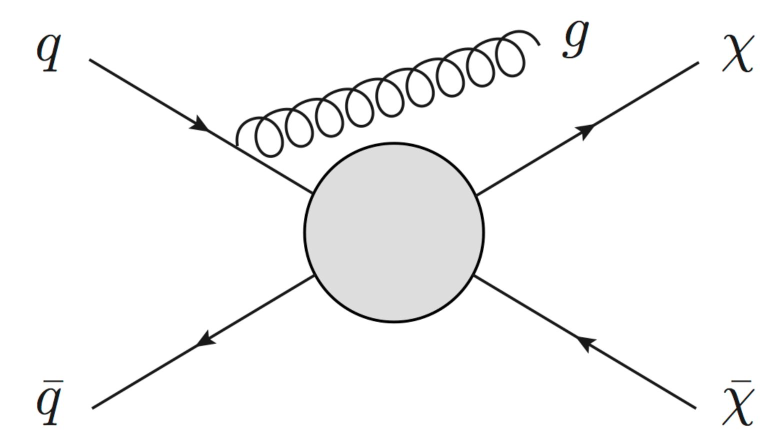
Disadvantage of EFT approach

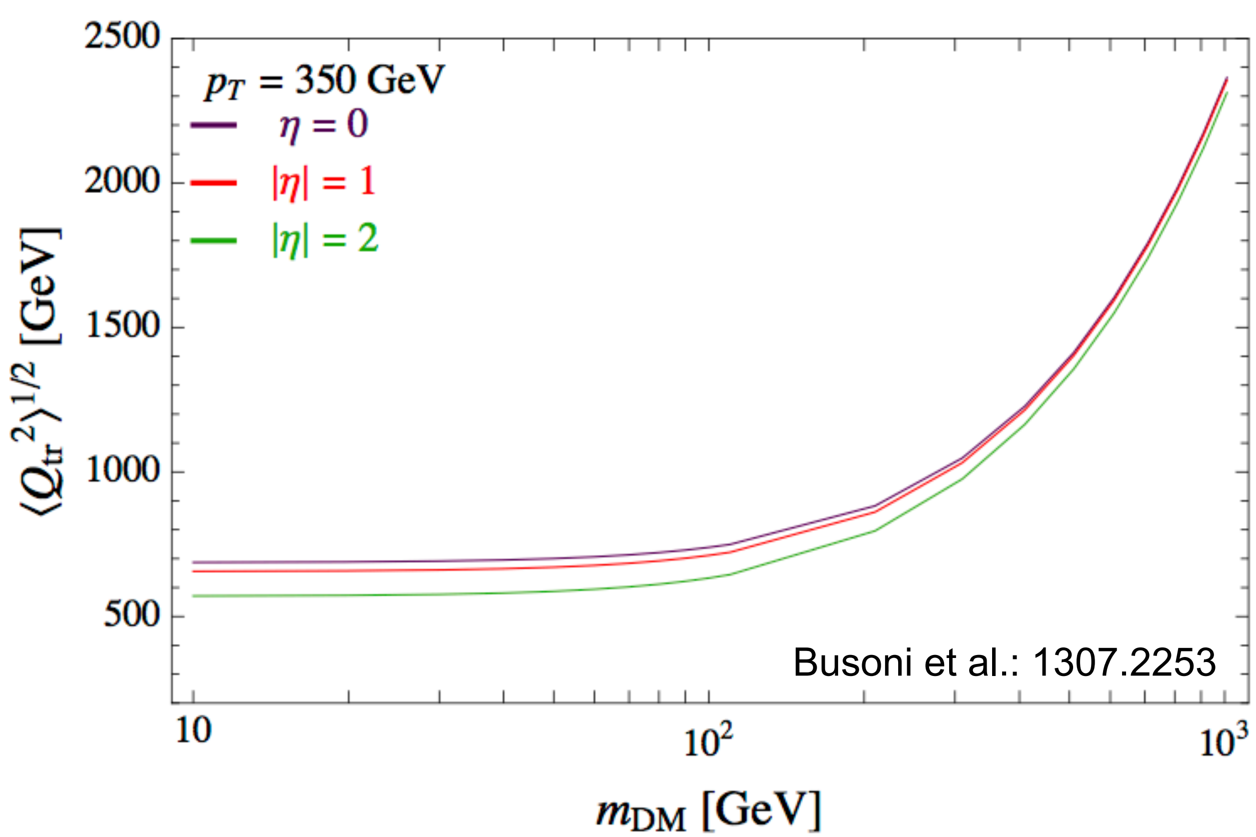
- Is it valid…?



Good approximation if

$$M_{Z'} \gg Q$$

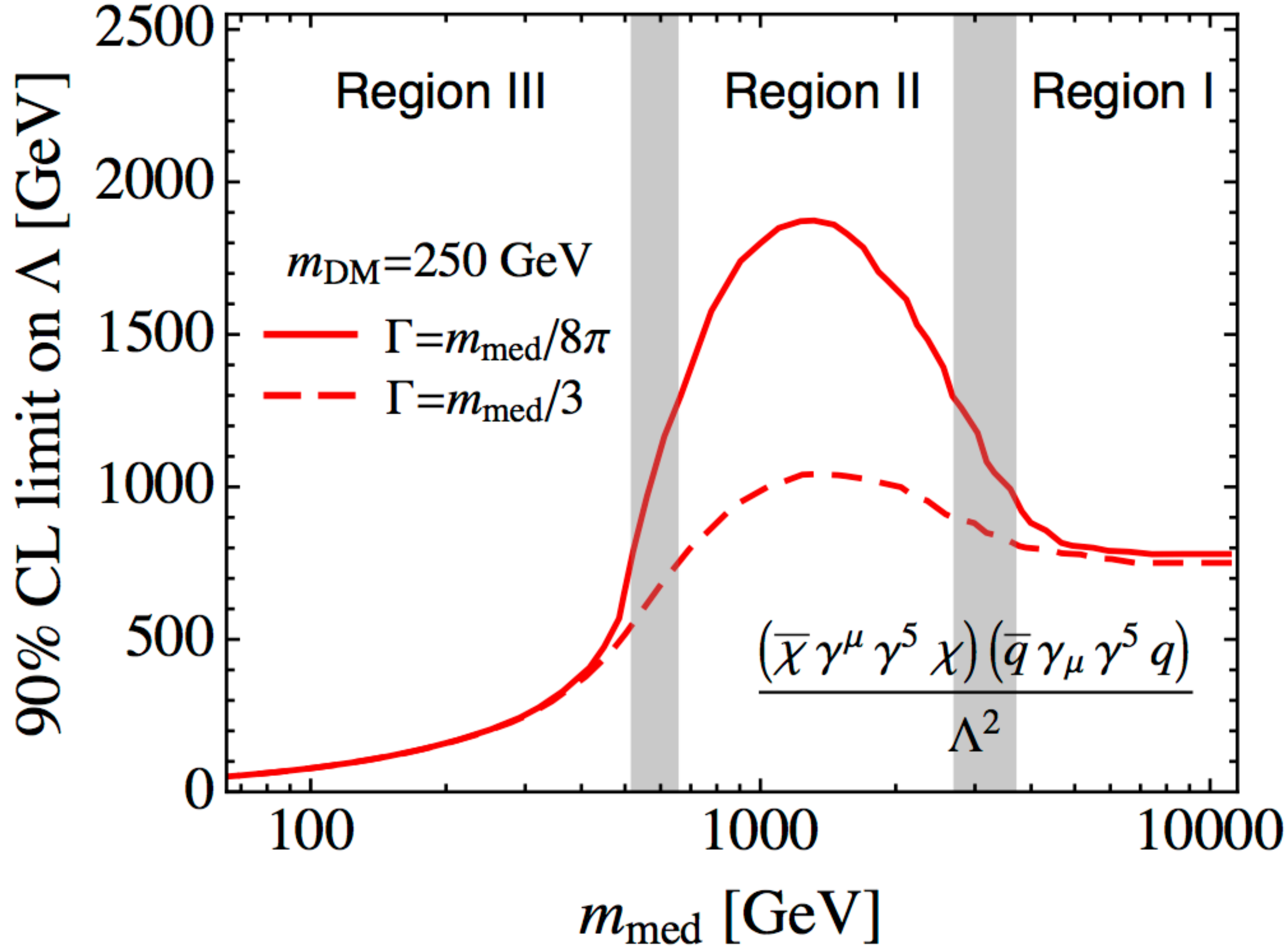




$$\boxed{M_{Z'} \gtrsim \mathrm{TeV}}$$

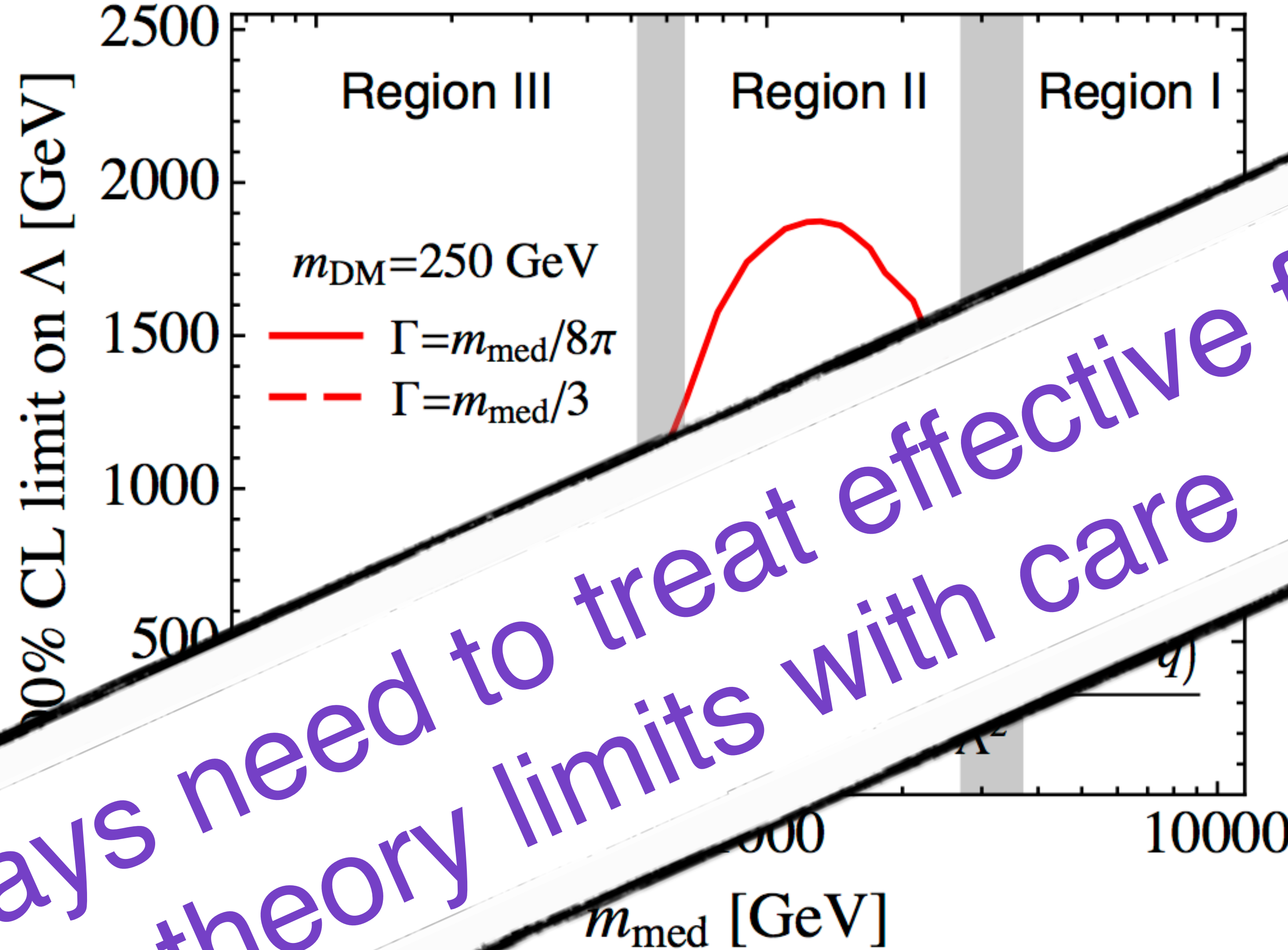
EFT validity: what goes wrong?

Buchmueller, Dolan, CM arXiv:1308.6799



- Region I: EFT limit is valid
- Region II: EFT limit is too weak (no s-channel enhancement)
- Region III: EFT limit is too strong (no off-shell suppression)

EFT validity: what goes wrong?



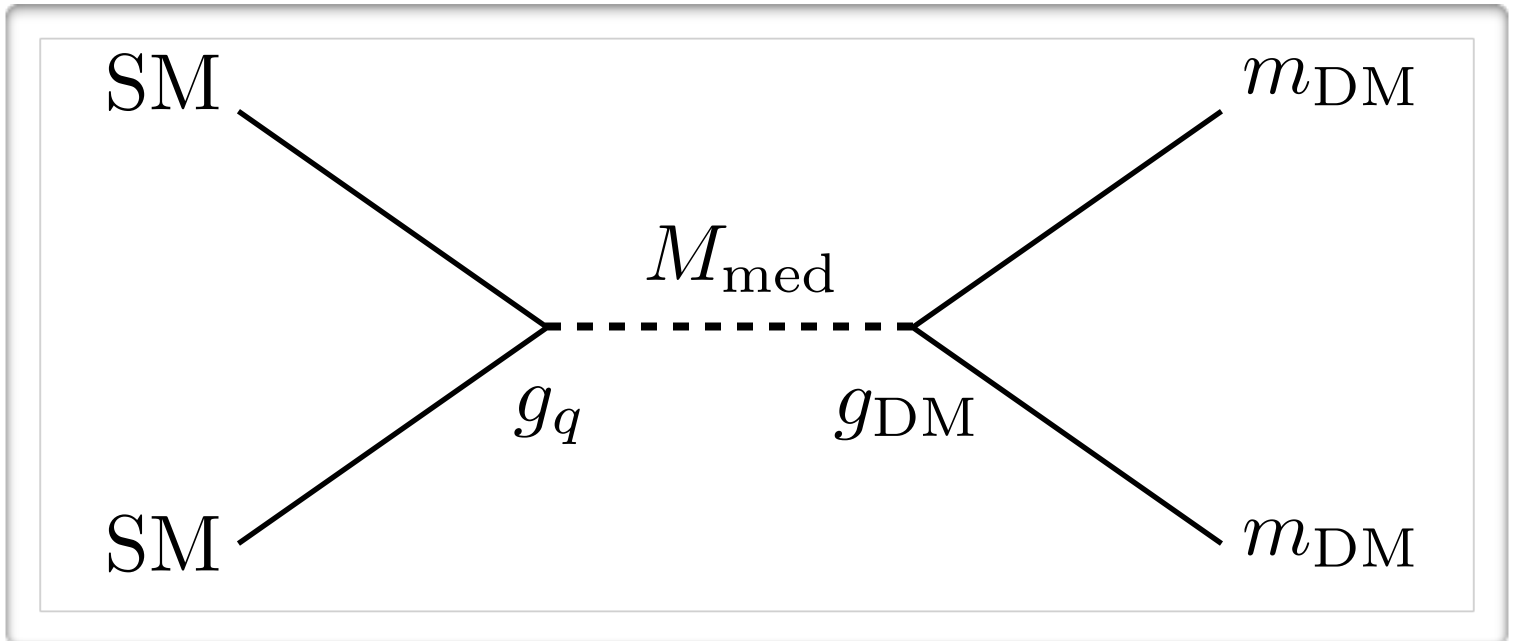
Always need to treat effective field theory limits with care

- R… …it is valid
- Re… …I: EFT limit is too weak (no s-channel enhancement)
- Region III: EFT limit is too strong (no off-shell suppression)

2. Simplified models

Buchmueller, Dolan, Malik, CM arXiv:1407.8257

- Characterise collider dark matter production with a small number of variables



Minimum 4 parameters	
m_{DM}	M_{med}
g_q	g_χ

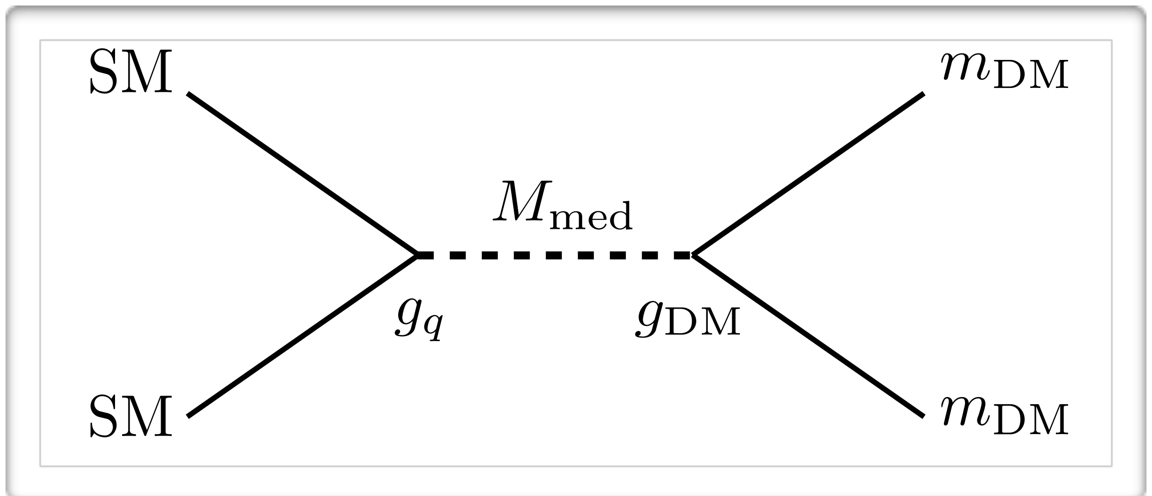
Mediators	
Vector	Axial-Vector
Scalar	Pseudo-scalar

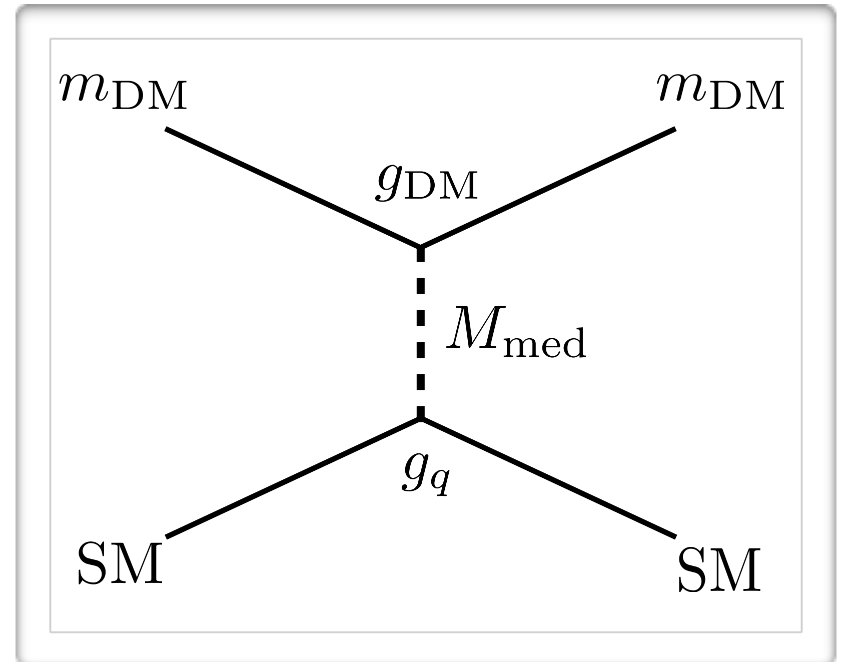
Dark matter	
Dirac	Complex scalar
Majorana	Real scalar

2. Simplified models

Buchmueller, Dolan, Malik, CM
arXiv:1407.8257

- Same parameters also characterise direct searches





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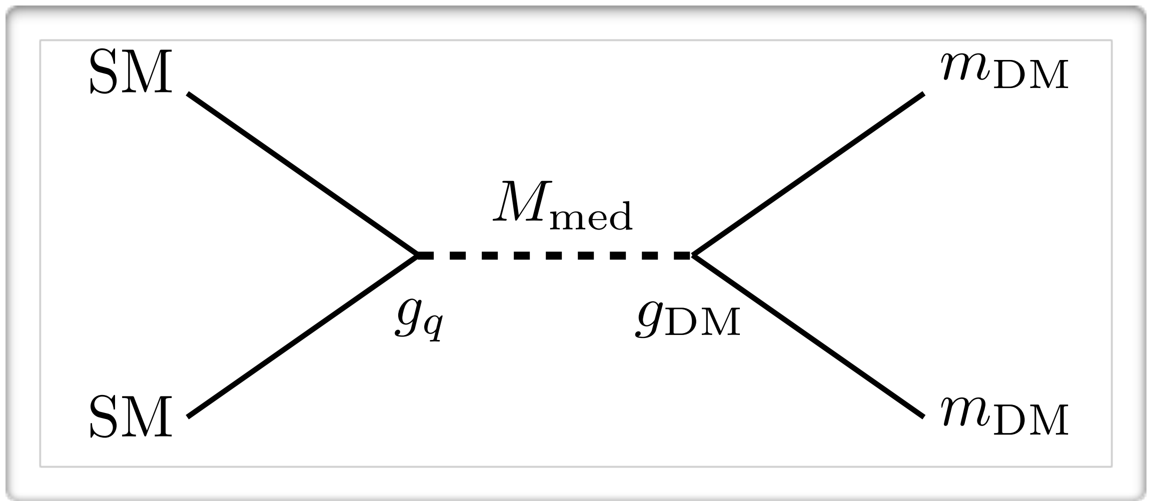

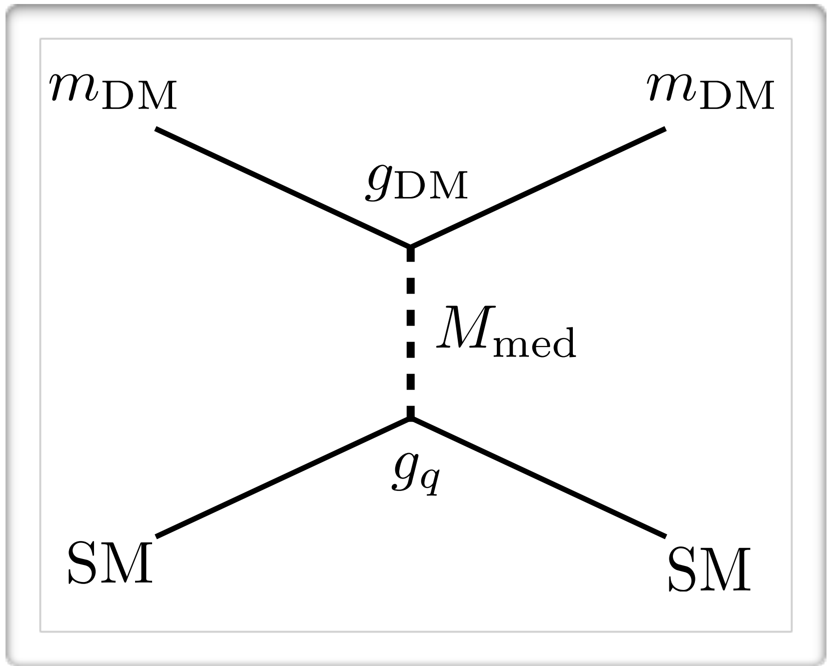

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Dark matter	
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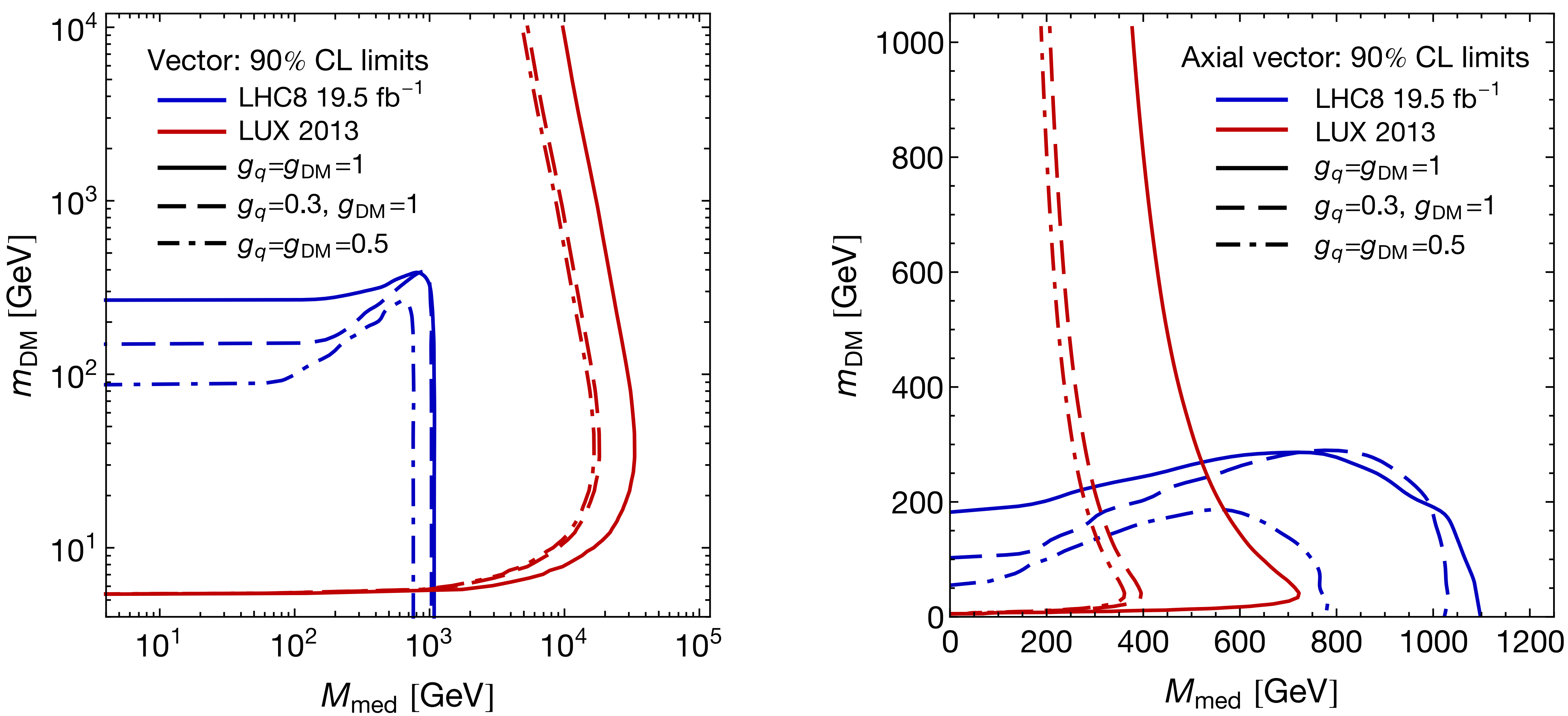
Slicing through parameter space

- We need to fix two parameters to show results:

m_{DM}	g_χ
M_{med}	g_q

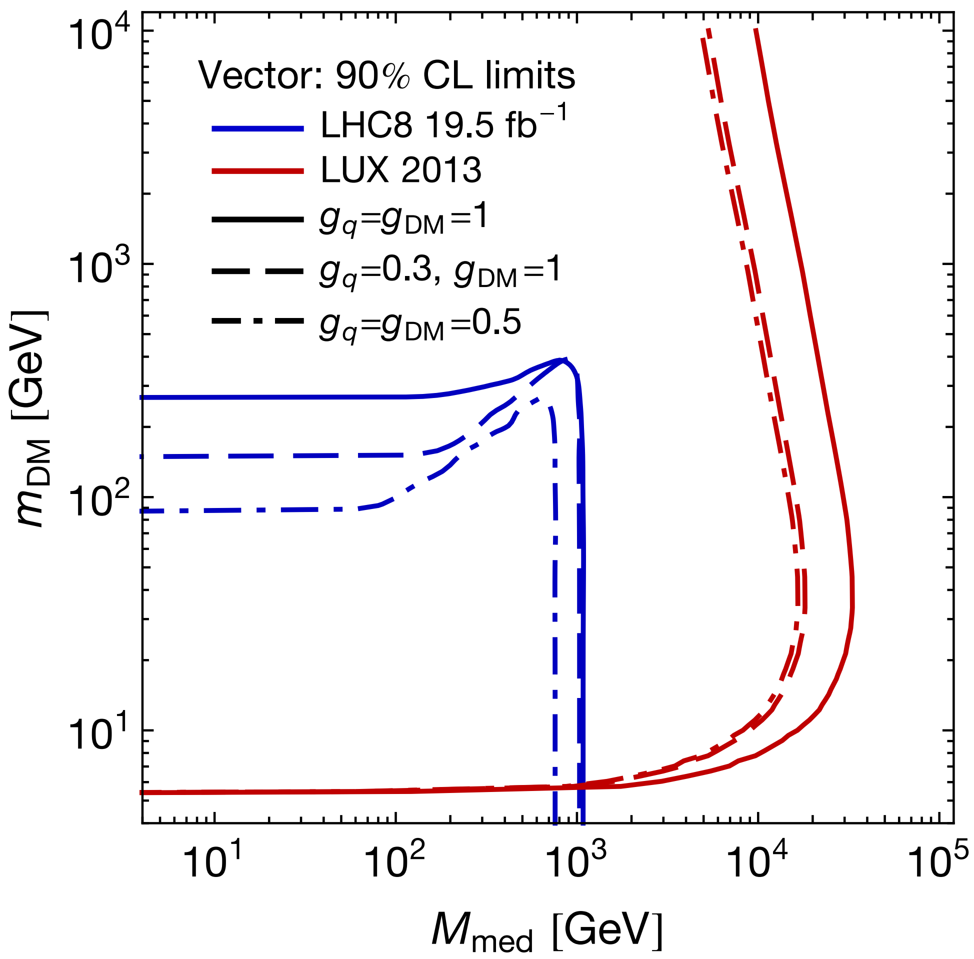


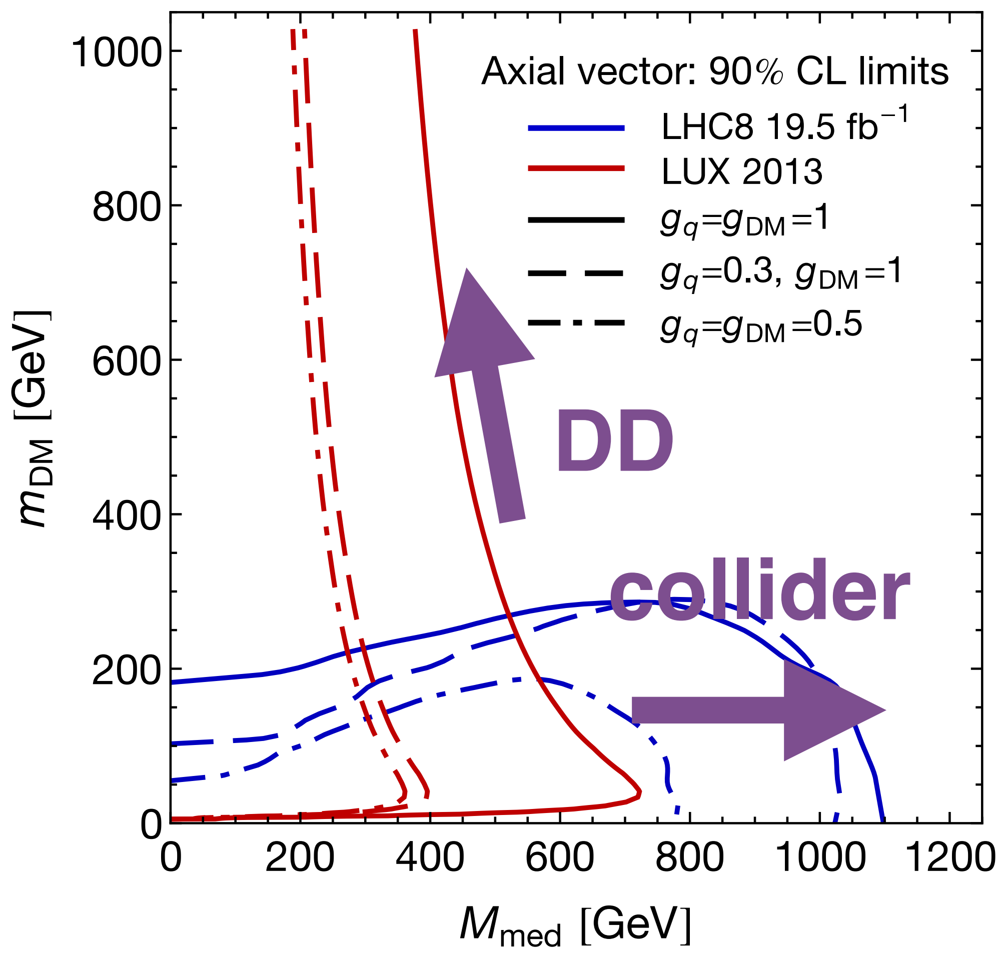
- Limits valid for all dark matter and mediator masses
- Includes resonant enhancement/off-shell suppression effects

Slicing through parameter space

- We need to fix two parameters to show results:

m_{DM}	g_χ
M_{med}	g_q



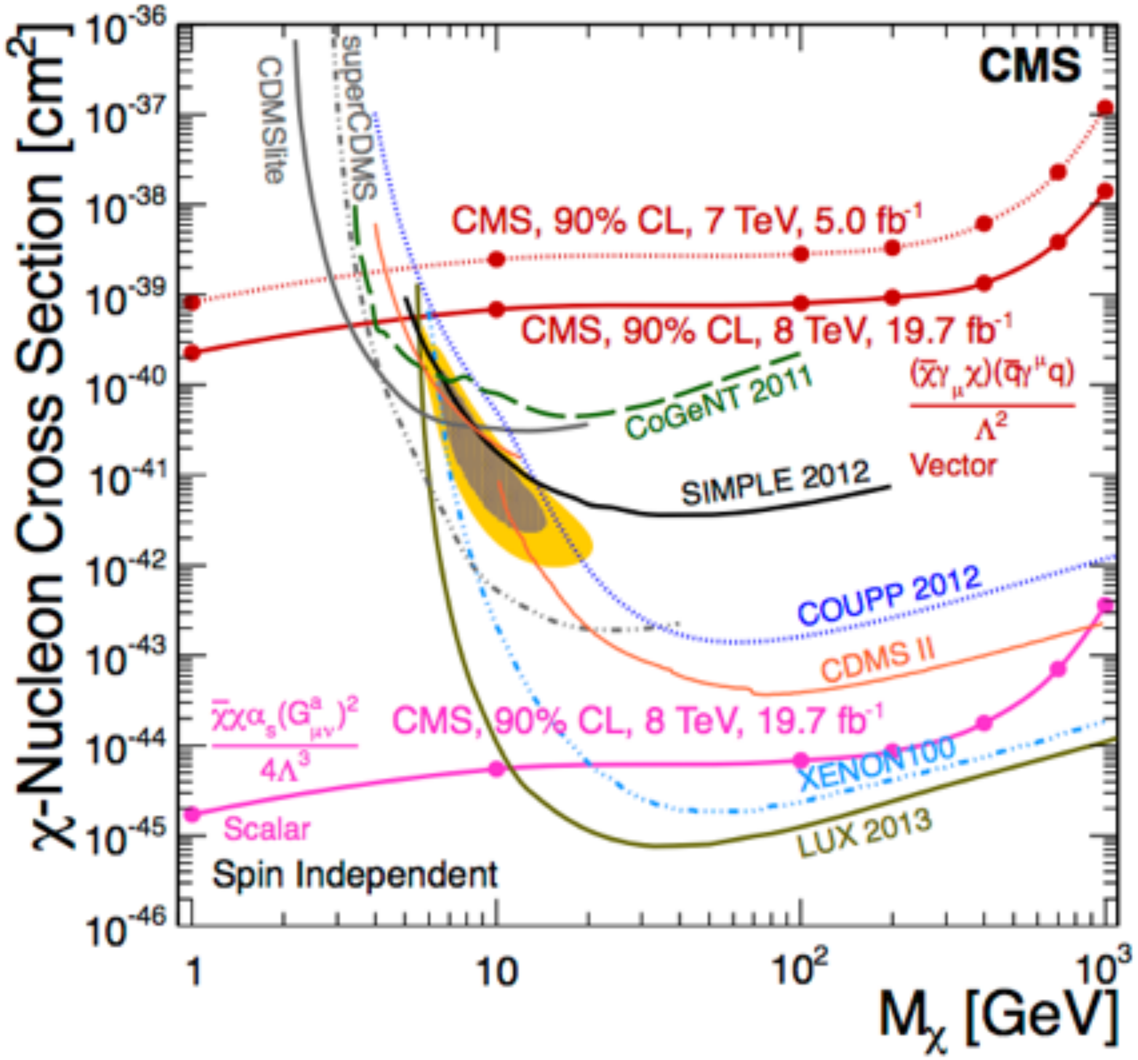


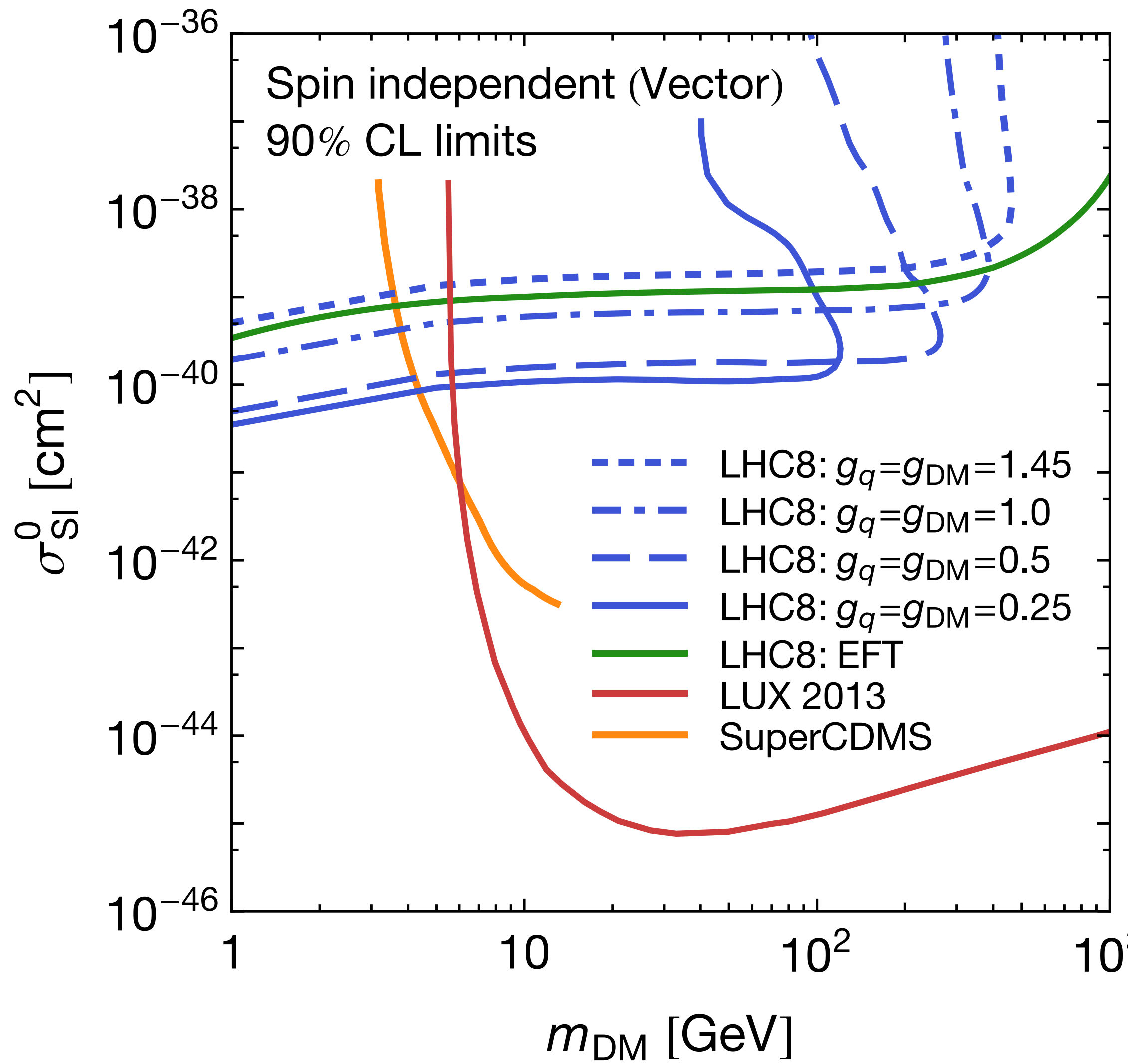
- Better elucidation of the complementarity between collider and direct searches

Comparison with direct detection

Malik, CM etal
arXiv:1409.4075

- EFT limit overestimates at high mass/underestimates at low mass

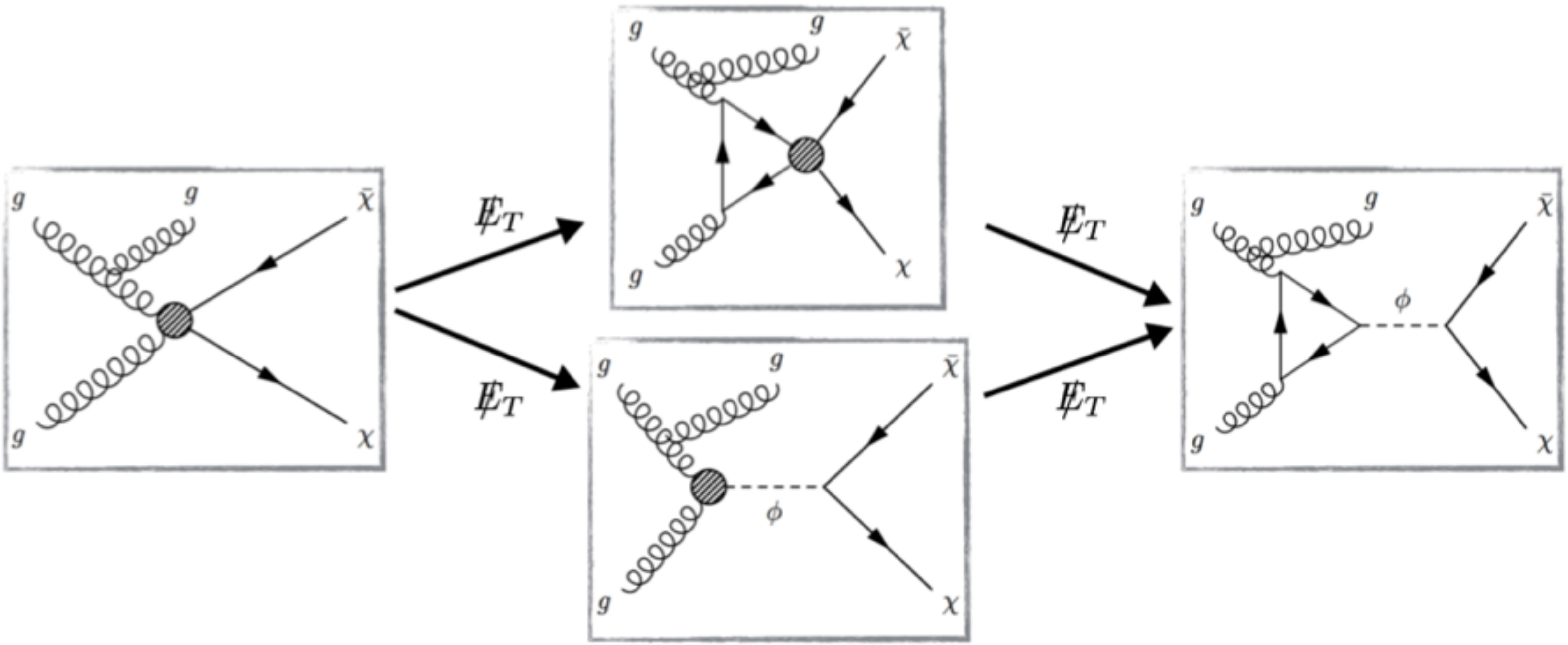




Scalar/Pseudoscalar

Buckley, Feld, Goncalves arXiv:1410.6497

- Extendable to other mediators

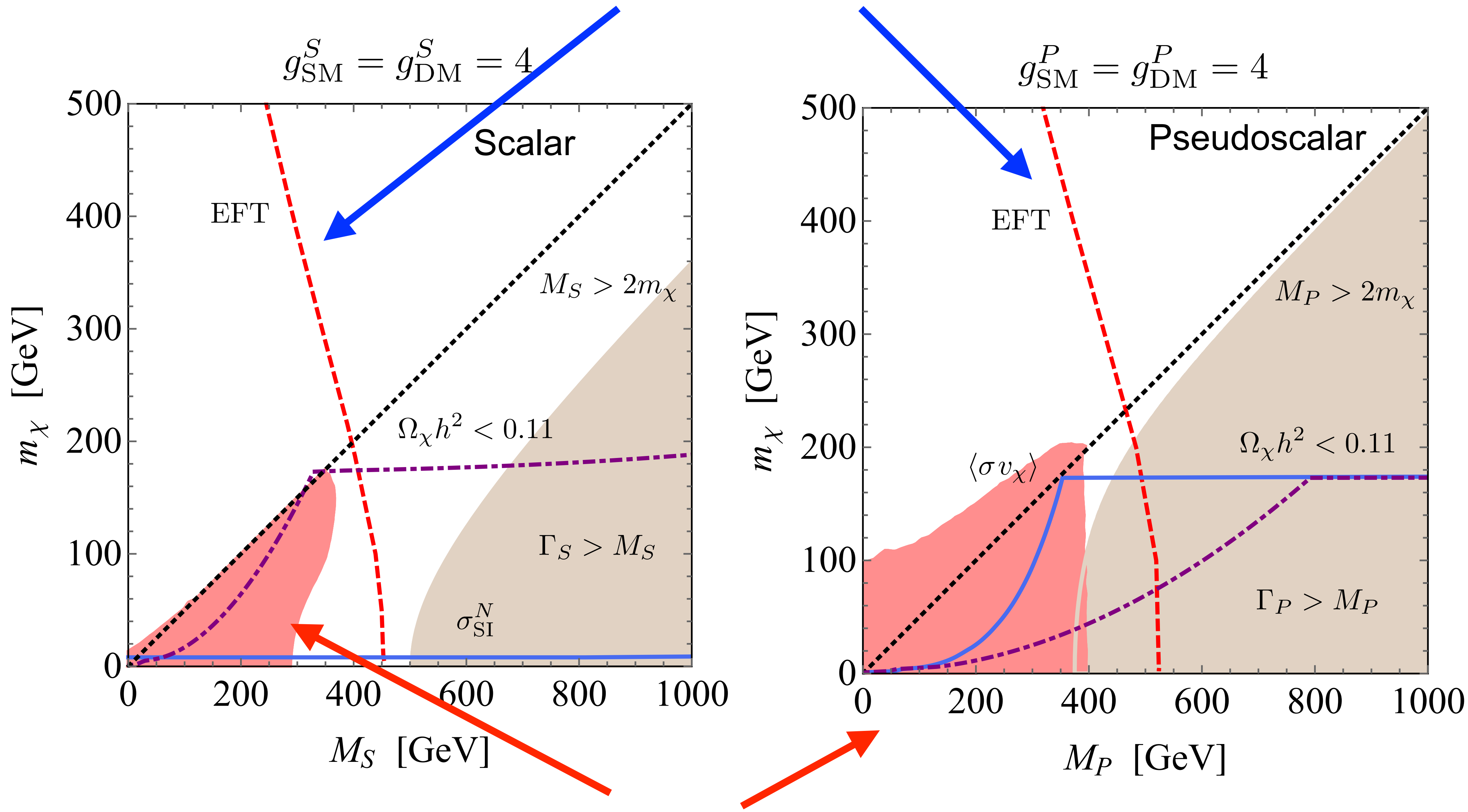


- Additional complexity resolving both the top-loop and mediator

Scalar/Pseudoscalar

Haisch, Re
arXiv:1503.00691

Exclusion limit if you naively used the EFT limit



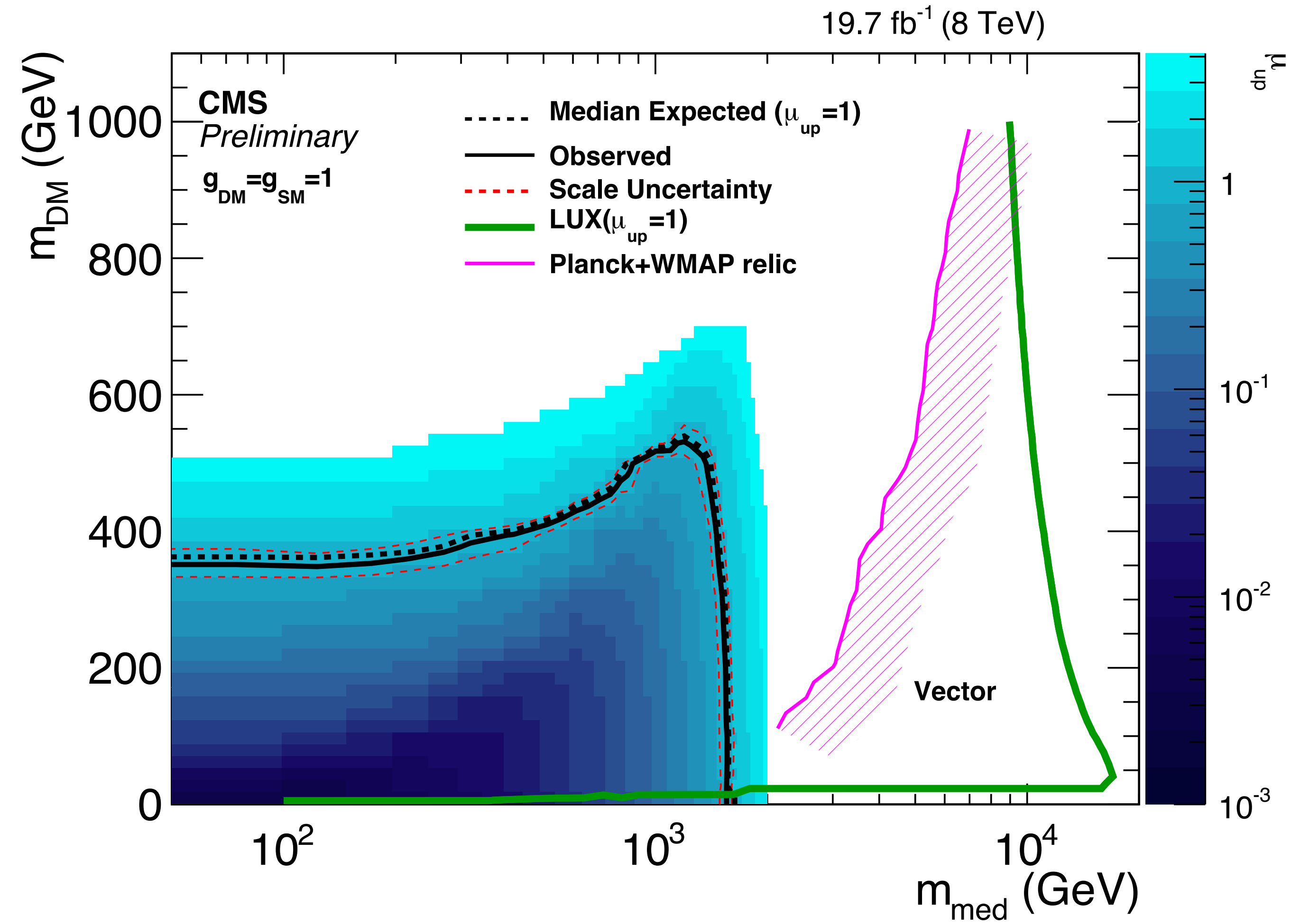
LHC excluded region

Future recommendations

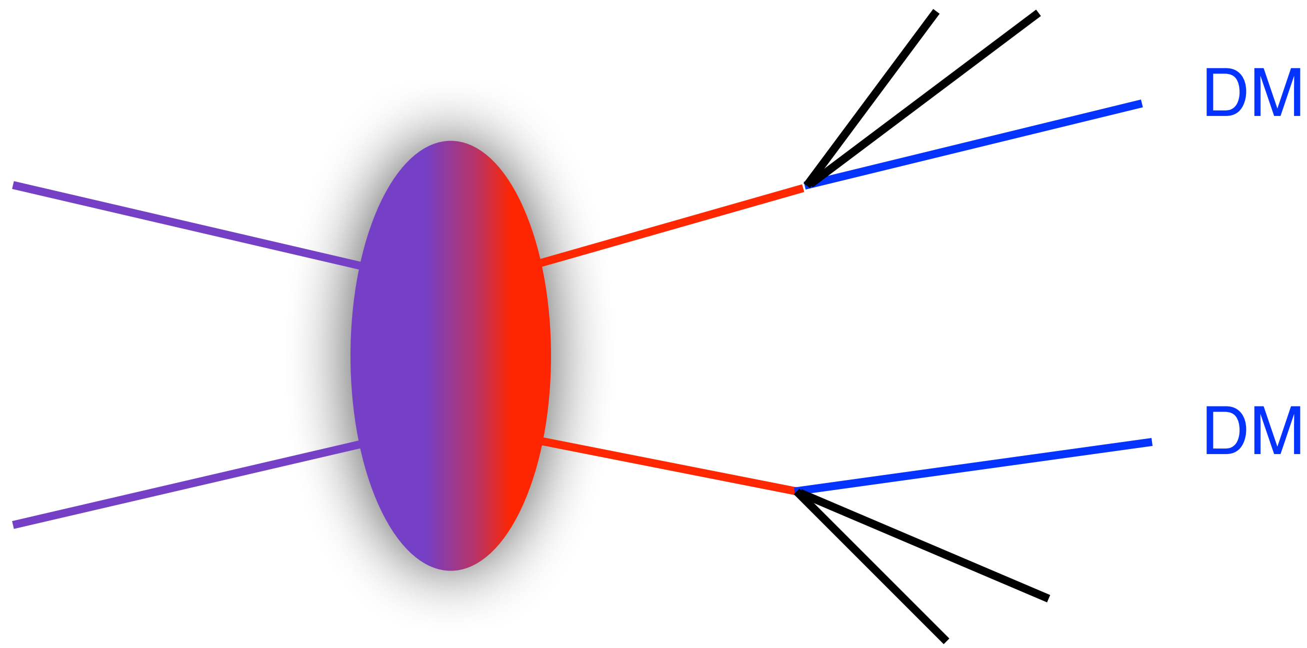
- ATLAS and CMS formed a working group to reach a consensus on which approach to take going forward
  arXiv:1507.00966

Use simplified models when possible - will also still see some EFT results for certain benchmark models

CMS have shown first results in the simplified model framework
CMS-EXO-12-055-pas



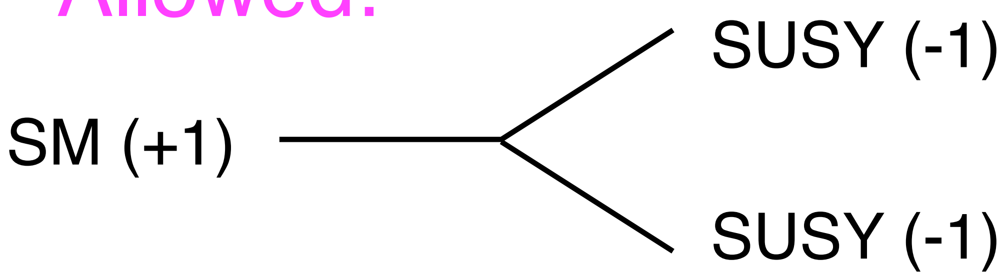
Dark matter produced in cascade decays



SUSY: searching for decay chains

- SUSY has R-parity: {SM: R-parity +1, SUSY: R-parity -1}

Allowed:



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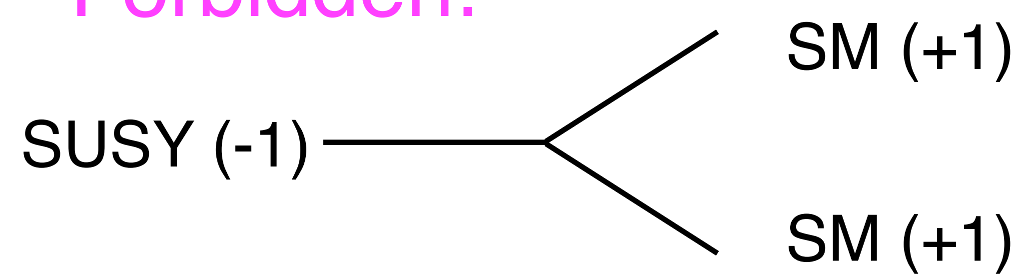
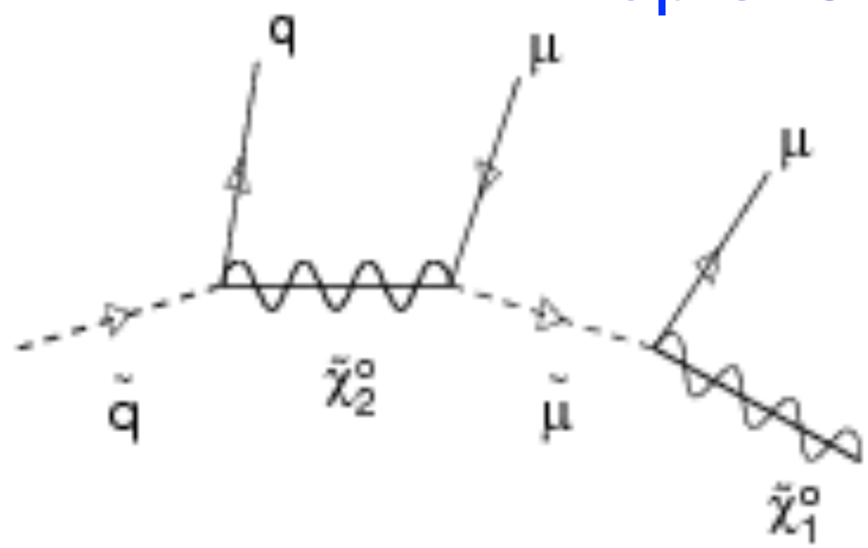


- If a heavier SUSY particle is produced, can have long decay chains terminating in the lightest supersymmetric particle

jet

leptons

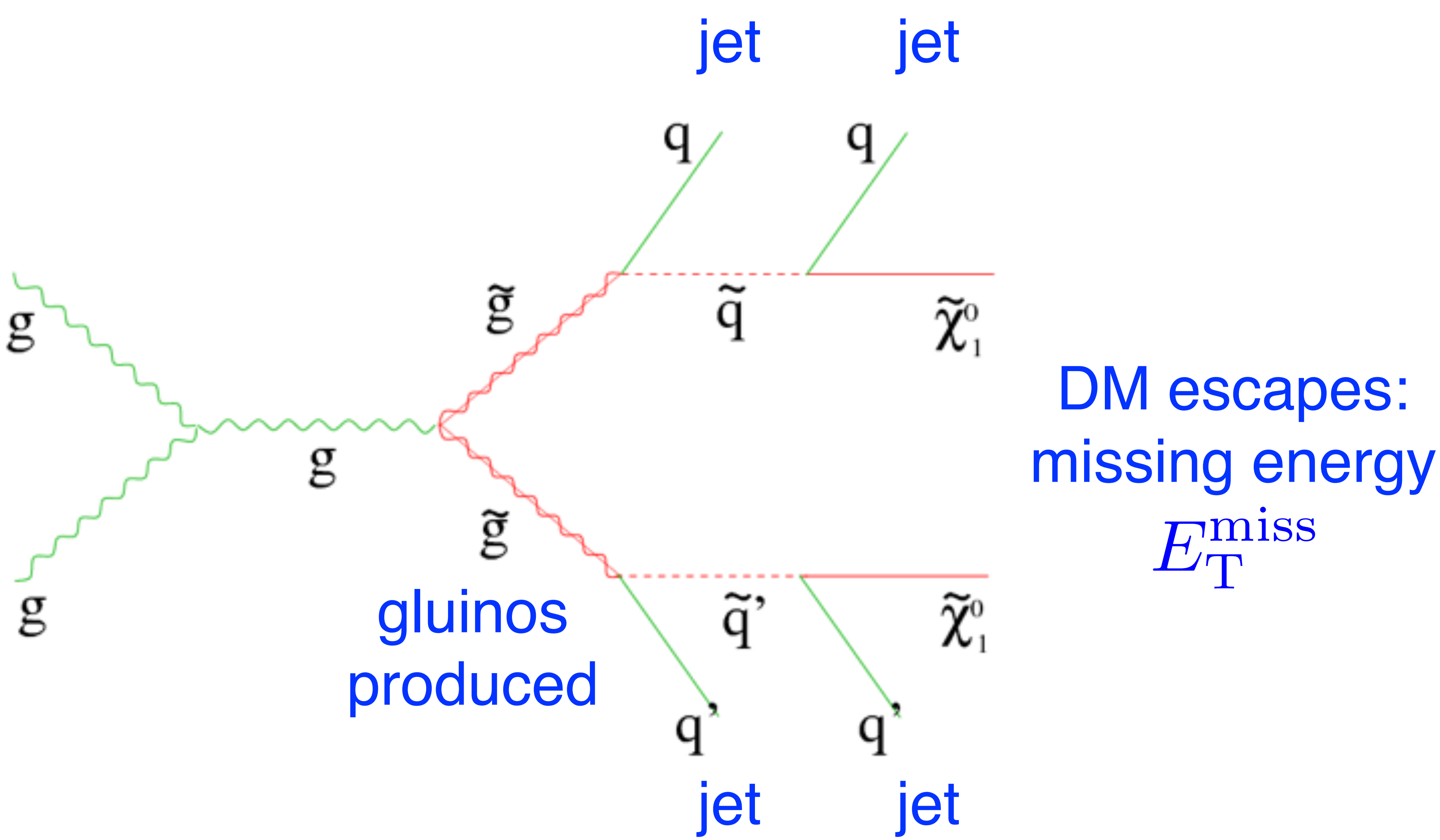


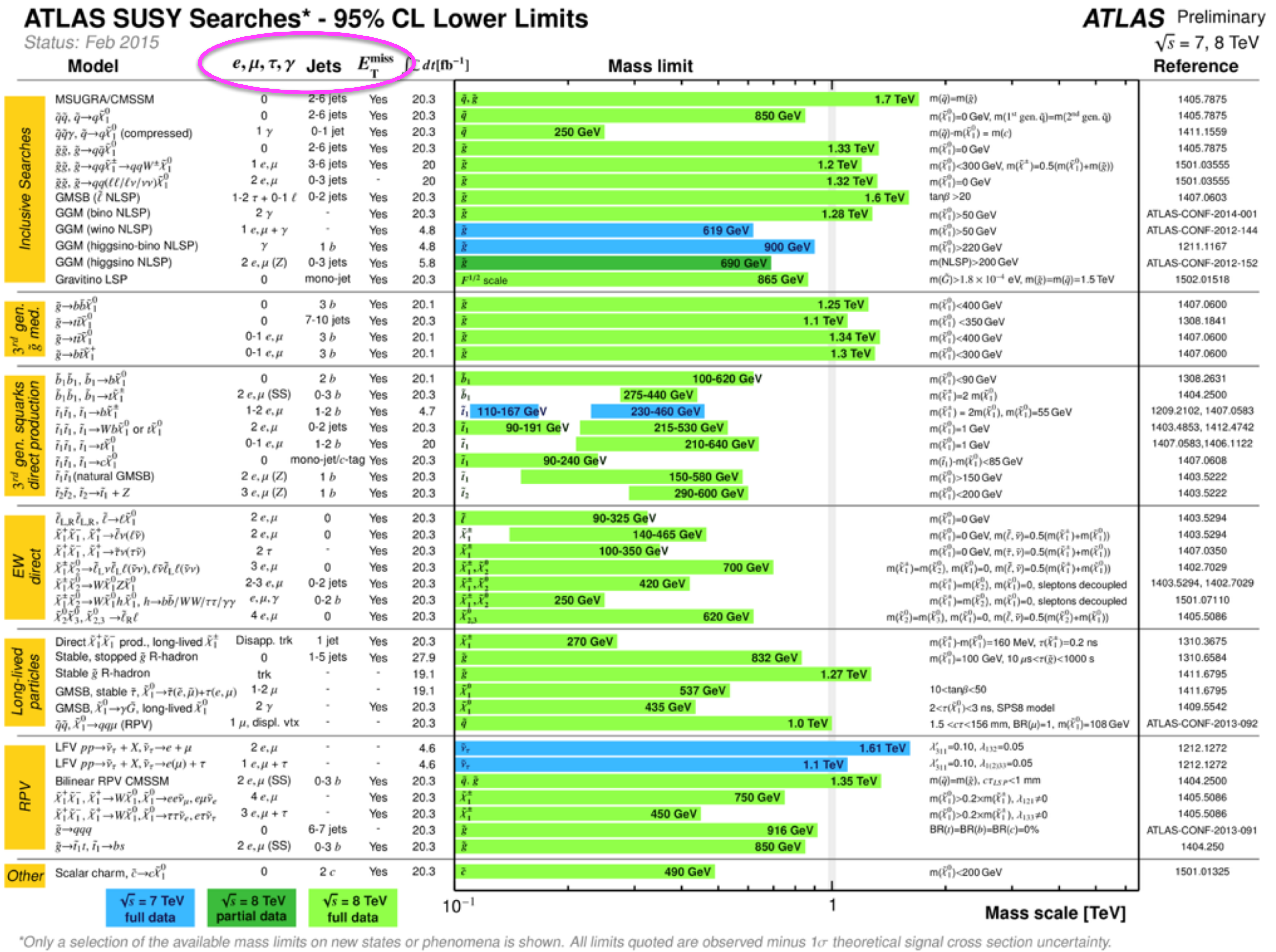
squark produced

DM escapes: MET

SUSY: searches

- Basic idea: always searching for jets + leptons + missing energy




ATLAS SUSY Searches* - 95% CL Lower Limits
Status: Feb 2015
ATLAS Preliminary
$\sqrt{s}$ = 7, 8 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
$\int \mathcal{L}\, dt[\text{fb}^{-1}]$
Mass limit
Reference
Inclusive Searches
MSUGRA/CMSSM 0 2-6 jets Yes 20.3 $\tilde{q},\tilde{g}$ 1.7 TeV $m(\tilde{q})=m(\tilde{g})$ 1405.7875
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ 0 2-6 jets Yes 20.3 $\tilde{q}$ 850 GeV $m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$) 1405.7875
$\tilde{q}\tilde{q}\gamma, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed) 1 γ 0-1 jet Yes 20.3 $\tilde{q}$ 250 GeV $m(\tilde{q})-m(\tilde{\chi}_1^0) = m(c)$ 1411.1559
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ 0 2-6 jets Yes 20.3 $\tilde{g}$ 1.33 TeV $m(\tilde{\chi}_1^0)$=0 GeV 1405.7875
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$ 1 e,μ 3-6 jets Yes 20 $\tilde{g}$ 1.2 TeV $m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ 1501.03555
$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ 2 e,μ 0-3 jets - 20 $\tilde{g}$ 1.32 TeV $m(\tilde{\chi}_1^0)$=0 GeV 1501.03555
GMSB ($\tilde{\ell}$ NLSP) 1-2 τ + 0-1 ℓ 0-2 jets Yes 20.3 $\tilde{g}$ 1.6 TeV $\tan\beta$ >20 1407.0603
GGM (bino NLSP) 2 γ - Yes 20.3 $\tilde{g}$ 1.28 TeV $m(\tilde{\chi}_1^0)$>50 GeV ATLAS-CONF-2014-001
GGM (wino NLSP) 1 $e,\mu + \gamma$ - Yes 4.8 $\tilde{g}$ 619 GeV $m(\tilde{\chi}_1^0)$>50 GeV ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP) γ 1 b Yes 4.8 $\tilde{g}$ 900 GeV $m(\tilde{\chi}_1^0)$>220 GeV 1211.1167
GGM (higgsino NLSP) 2 e,μ (Z) 0-3 jets Yes 5.8 $\tilde{g}$ 690 GeV m(NLSP)>200 GeV ATLAS-CONF-2012-152
Gravitino LSP 0 mono-jet Yes 20.3 $F^{1/2}$ scale 865 GeV $m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV 1502.01518
3rd gen. $\tilde{g}$ med.
$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ 0 3 b Yes 20.1 $\tilde{g}$ 1.25 TeV $m(\tilde{\chi}_1^0)$<400 GeV 1407.0600
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ 0 7-10 jets Yes 20.3 $\tilde{g}$ 1.1 TeV $m(\tilde{\chi}_1^0)$ <350 GeV 1308.1841
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ 0-1 e,μ 3 b Yes 20.1 $\tilde{g}$ 1.34 TeV $m(\tilde{\chi}_1^0)$<400 GeV 1407.0600
$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ 0-1 e,μ 3 b Yes 20.1 $\tilde{g}$ 1.3 TeV $m(\tilde{\chi}_1^0)$<300 GeV 1407.0600
3rd gen. squarks direct production
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$ 0 2 b Yes 20.1 $\tilde{b}_1$ 100-620 GeV $m(\tilde{\chi}_1^0)$<90 GeV 1308.2631
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$ 2 e,μ (SS) 0-3 b Yes 20.3 $\tilde{b}_1$ 275-440 GeV $m(\tilde{\chi}_1^\pm)=2\, m(\tilde{\chi}_1^0)$ 1404.2500
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$ 1-2 e,μ 1-2 b Yes 4.7 $\tilde{t}_1$ 110-167 GeV 230-460 GeV $m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV 1209.2102, 1407.0583
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ 2 e,μ 0-2 jets Yes 20.3 $\tilde{t}_1$ 90-191 GeV 215-530 GeV $m(\tilde{\chi}_1^0)$=1 GeV 1403.4853, 1412.4742
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$ 0-1 e,μ 1-2 b Yes 20 $\tilde{t}_1$ 210-640 GeV $m(\tilde{\chi}_1^0)$=1 GeV 1407.0583,1406.1122
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ 0 mono-jet/c-tag Yes 20.3 $\tilde{t}_1$ 90-240 GeV $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV 1407.0608
$\tilde{t}_1\tilde{t}_1$(natural GMSB) 2 e,μ (Z) 1 b Yes 20.3 $\tilde{t}_1$ 150-580 GeV $m(\tilde{\chi}_1^0)$>150 GeV 1403.5222
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$ 3 e,μ (Z) 1 b Yes 20.3 $\tilde{t}_2$ 290-600 GeV $m(\tilde{\chi}_1^0)$<200 GeV 1403.5222
EW direct
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ 2 e,μ 0 Yes 20.3 $\tilde{\ell}$ 90-325 GeV $m(\tilde{\chi}_1^0)$=0 GeV 1403.5294
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ 2 e,μ 0 Yes 20.3 $\tilde{\chi}_1^\pm$ 140-465 GeV $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ 1403.5294
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ 2 τ - Yes 20.3 $\tilde{\chi}_1^\pm$ 100-350 GeV $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ 1407.0350
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ 3 e,μ 0 Yes 20.3 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 700 GeV $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ 1402.7029
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$ 2-3 e,μ 0-2 jets Yes 20.3 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 420 GeV $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled 1403.5294, 1402.7029
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$ e,μ,γ 0-2 b Yes 20.3 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 250 GeV $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled 1501.07110
$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$ 4 e,μ 0 Yes 20.3 $\tilde{\chi}_{2,3}^0$ 620 GeV $m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ 1405.5086
Long-lived particles
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ Disapp. trk 1 jet Yes 20.3 $\tilde{\chi}_1^\pm$ 270 GeV $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns 1310.3675
Stable, stopped $\tilde{g}$ R-hadron 0 1-5 jets Yes 27.9 $\tilde{g}$ 832 GeV $m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s 1310.6584
Stable $\tilde{g}$ R-hadron trk - - 19.1 $\tilde{g}$ 1.27 TeV 1411.6795
GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$ 1-2 μ - - 19.1 $\tilde{\chi}_1^0$ 537 GeV 10<$\tan\beta$<50 1411.6795
GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ 2 γ - Yes 20.3 $\tilde{\chi}_1^0$ 435 GeV 2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model 1409.5542
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV) 1 μ, displ. vtx - - 20.3 $\tilde{q}$ 1.0 TeV 1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV ATLAS-CONF-2013-092
RPV
LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$ 2 e,μ - - 4.6 $\tilde{\nu}_\tau$ 1.61 TeV λ'_{311}=0.10, λ_{132}=0.05 1212.1272
LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$ 1 $e,\mu+\tau$ - - 4.6 $\tilde{\nu}_\tau$ 1.1 TeV λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05 1212.1272
Bilinear RPV CMSSM 2 e,μ (SS) 0-3 b Yes 20.3 $\tilde{q},\tilde{g}$ 1.35 TeV $m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm 1404.2500
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ 4 e,μ - Yes 20.3 $\tilde{\chi}_1^\pm$ 750 GeV $m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^\pm)$, $\lambda_{121}\neq0$ 1405.5086
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ 3 $e,\mu+\tau$ - Yes 20.3 $\tilde{\chi}_1^\pm$ 450 GeV $m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$ 1405.5086
$\tilde{g}\to qqq$ 0 6-7 jets - 20.3 $\tilde{g}$ 916 GeV BR(t)=BR(b)=BR(c)=0% ATLAS-CONF-2013-091
$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$ 2 e,μ (SS) 0-3 b Yes 20.3 $\tilde{g}$ 850 GeV 1404.250
Other
Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$ 0 2 c Yes 20.3 $\tilde{c}$ 490 GeV $m(\tilde{\chi}_1^0)$<200 GeV 1501.01325
$\sqrt{s}$ = 7 TeV full data
$\sqrt{s}$ = 8 TeV partial data
$\sqrt{s}$ = 8 TeV full data
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Summary

- Exciting times for dark matter searches at the LHC
- There is lots of activity from the collaborations

- Generic signature is missing transverse energy

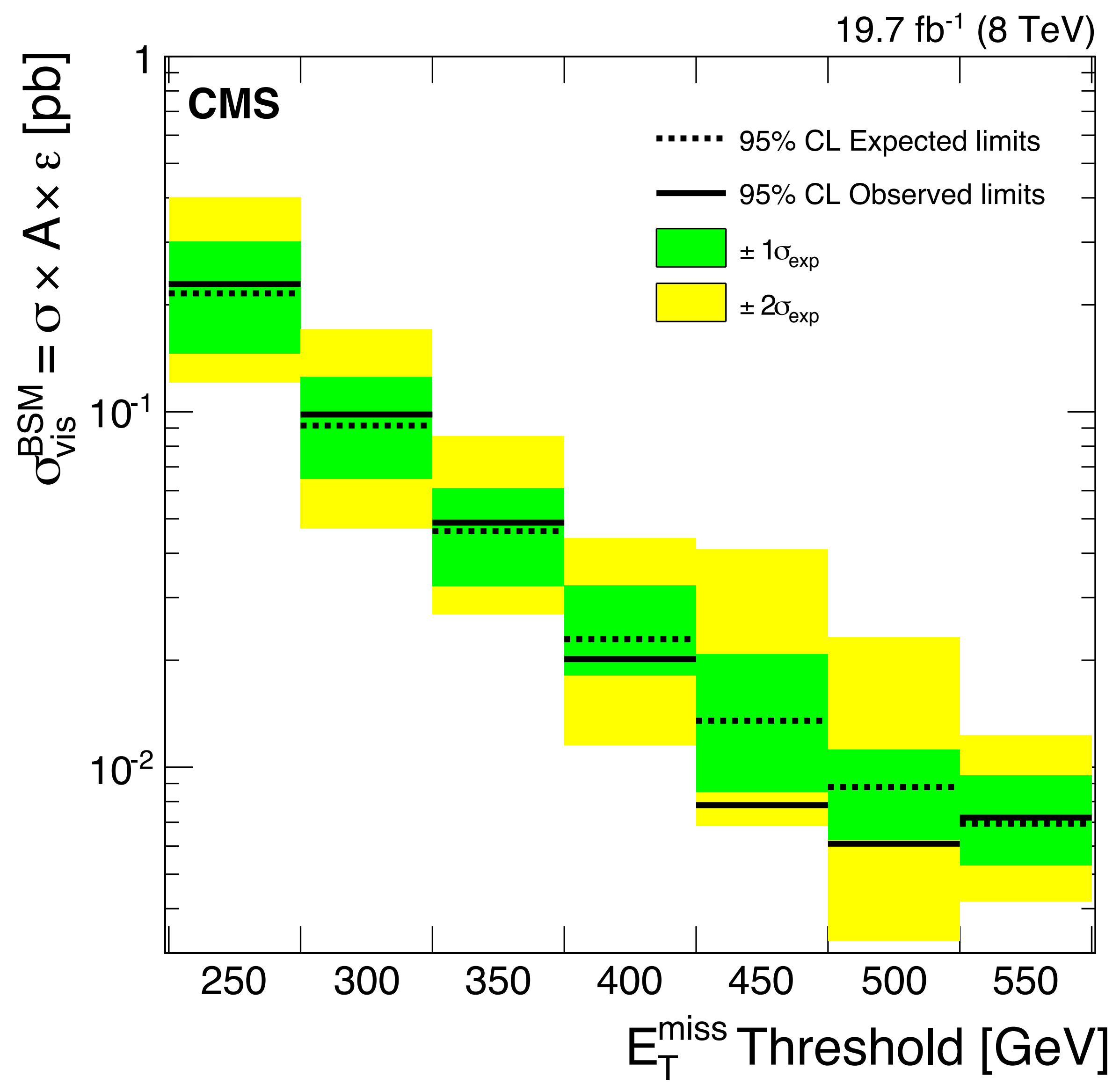
- Interpreting searches outside SUSY framework is challenging
- ATLAS/CMS will use more simplified models going forward

Thank you

Backup

True model independent limit

- What the experiments constrain:
  cross-section x acceptance x efficiency



Useful if I want to constrain my theory but not particularly informative

Region I: EFT valid

EFT limit applies to a small class of theories

- Large mediator mass:

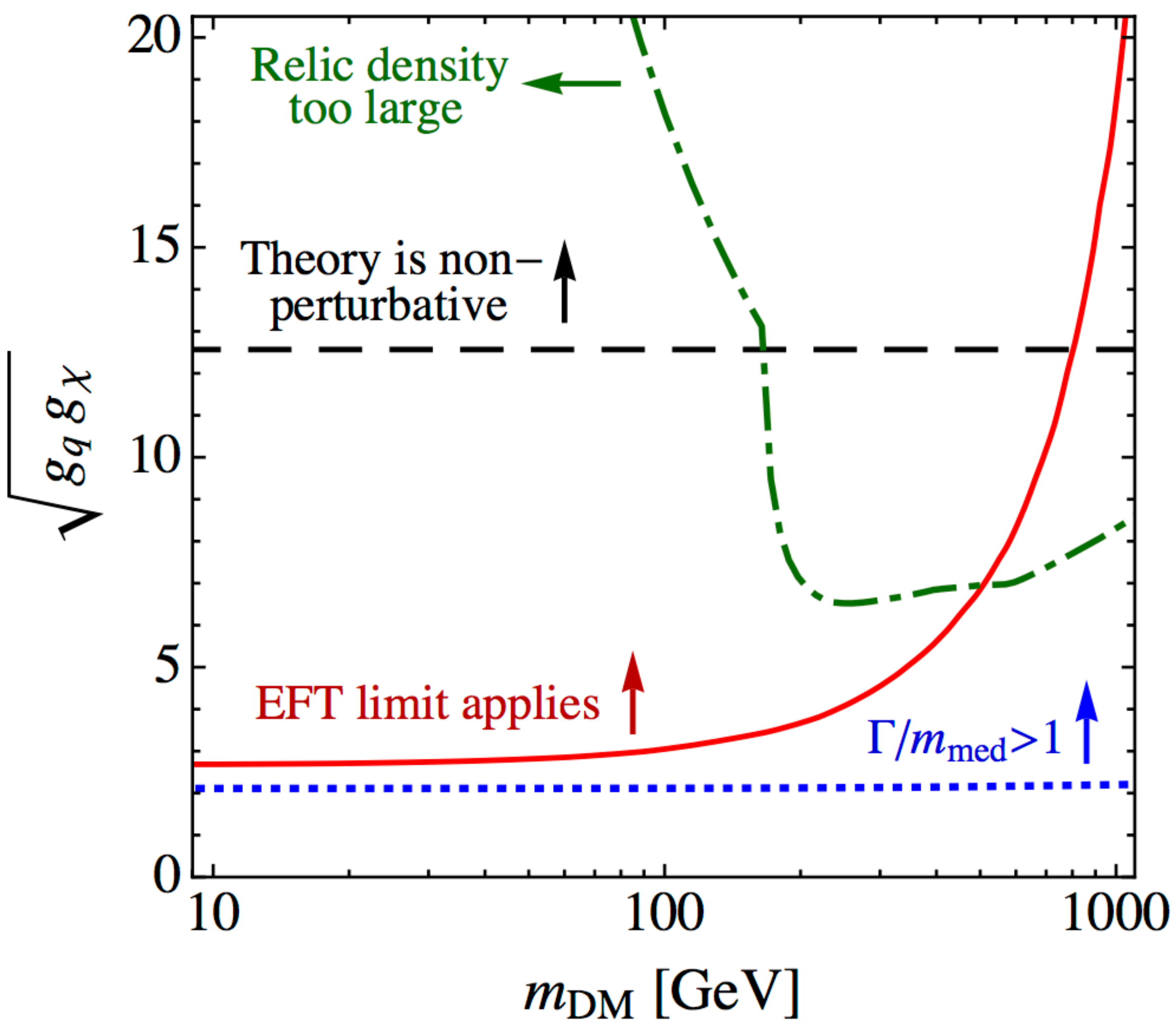
$$m_{\rm med} \gtrsim 3\ \text{TeV}$$

- Large couplings:

$$\sqrt{g_q g_\chi} = \frac{m_{\rm med}}{\Lambda}$$

- Large mediator width:

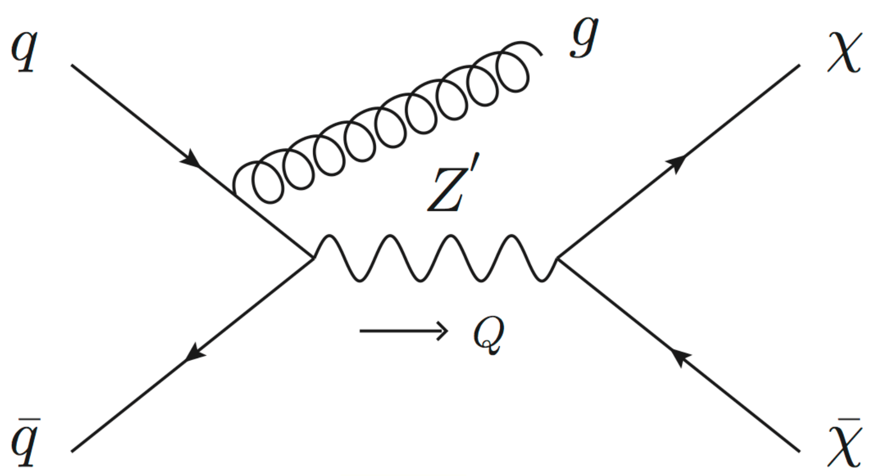
$$\Gamma > m_{\rm med}$$



Region II: EFT too weak

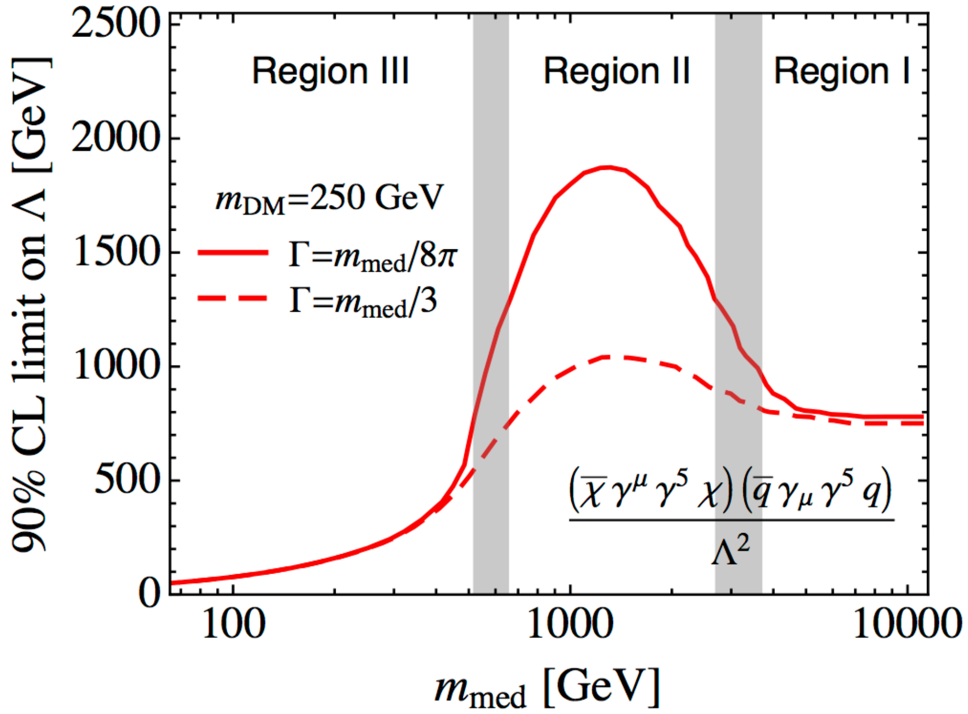
EFT does not account for s-channel resonant enhancement

- Enhanced when
$$m_{\text{med}}^2 \sim 4m_{\text{DM}}^2 + \not{E}_{\text{T}}^2$$



- The width plays a crucial role

- Peak height scales as $\Gamma^{-1/4}$



Region III: EFT too strong

EFT does not account for off-shell production

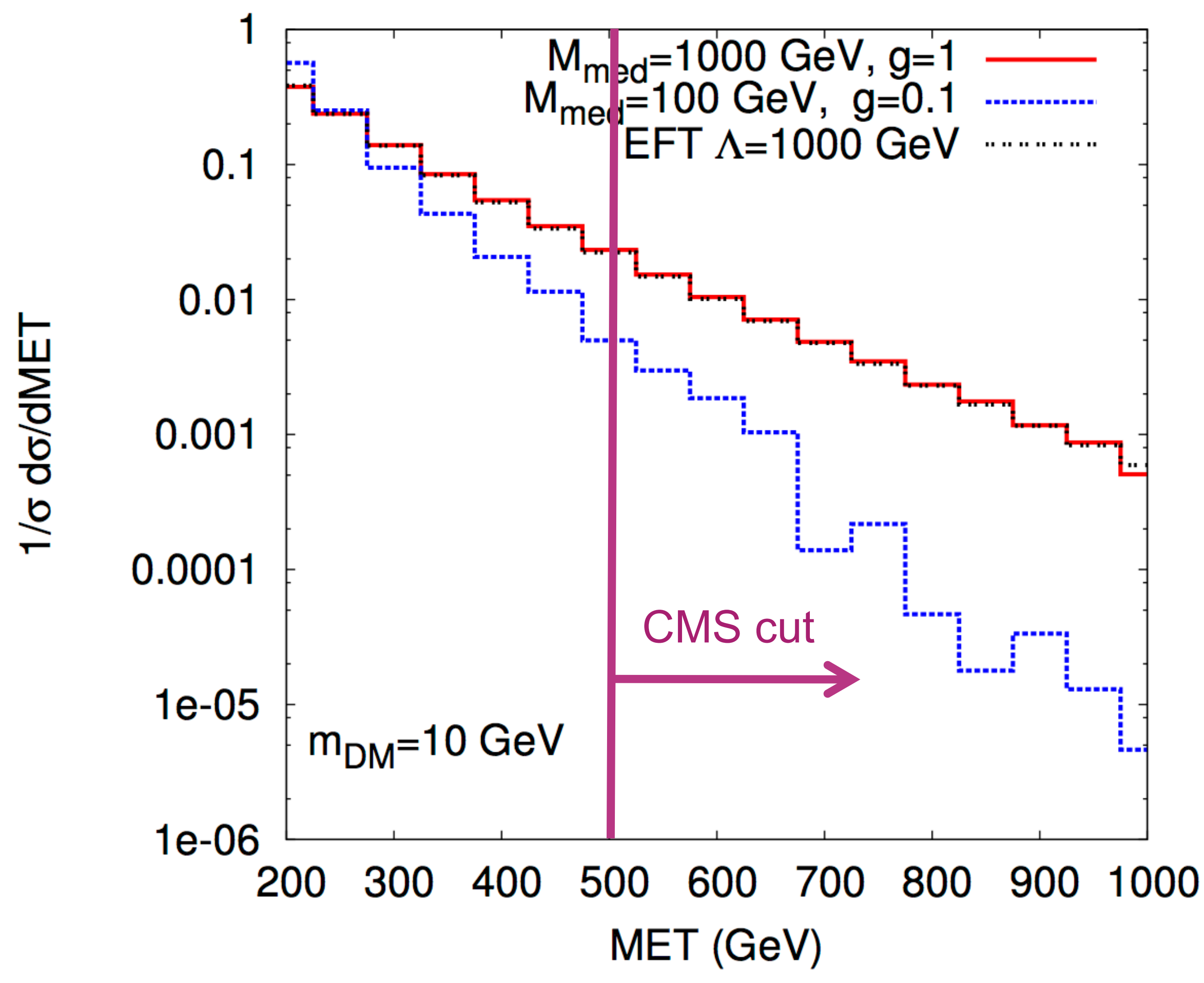
- Light mediator masses

  $$m_{\rm med} < 500\ \mathrm{GeV}$$

- Events with a light mediator are much softer

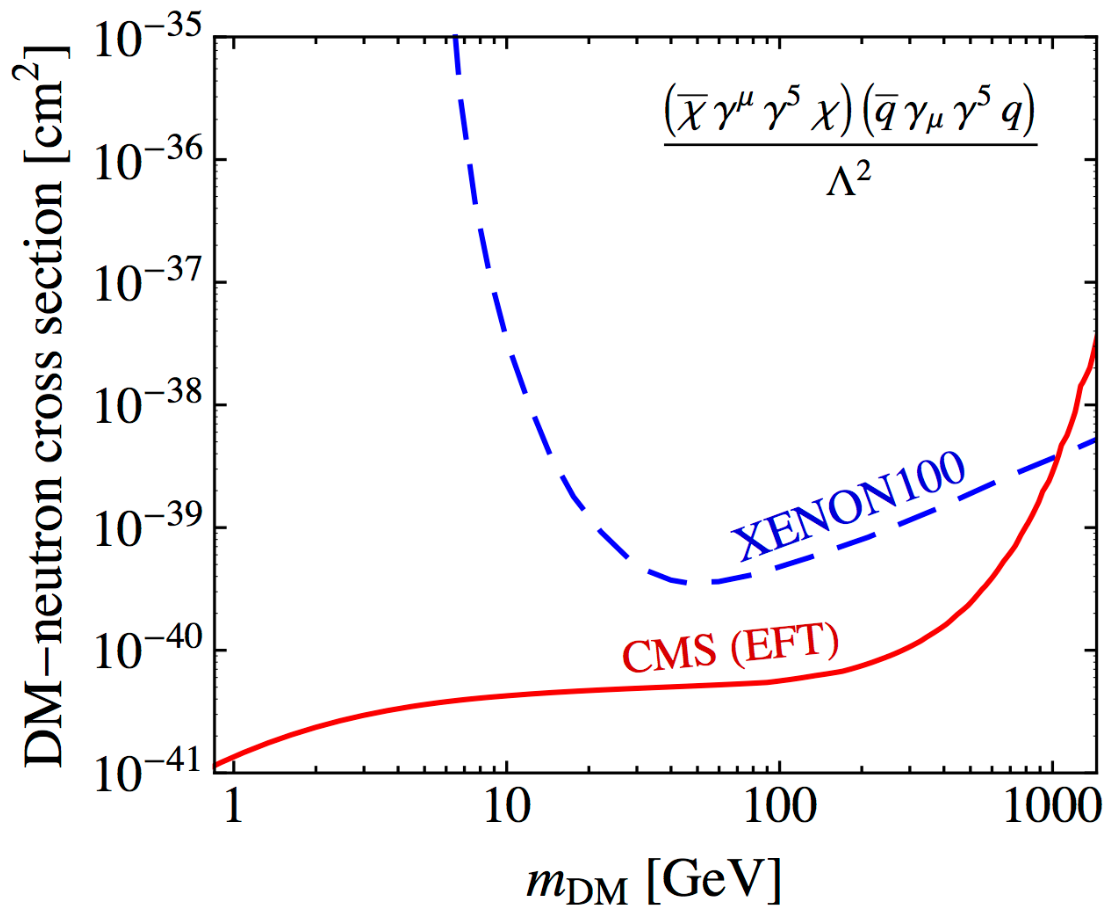
- EFT limit on g weaker

  ➡ limit on $\Lambda \sim \dfrac{m_{\rm med}}{g}$ is strong



Other problems

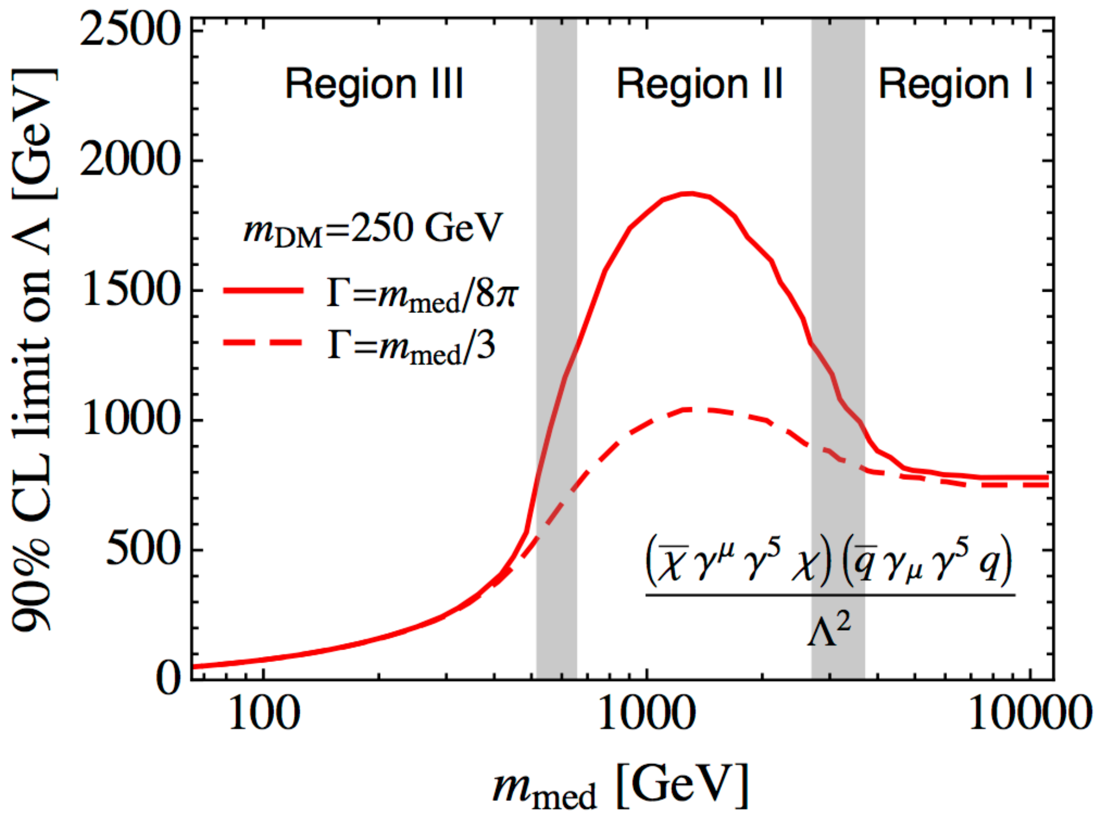
- Comparison with direct detection:

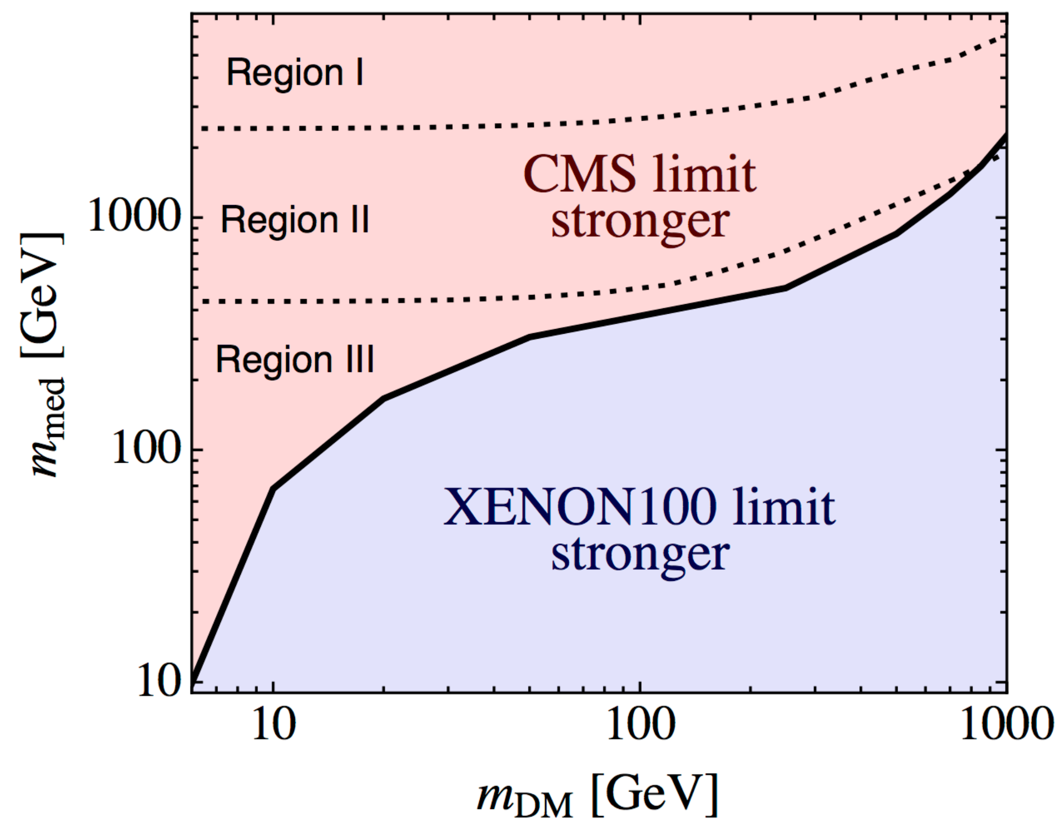


- Naive application of EFT limit gives the impression that the LHC limit is stronger for $m_{\rm DM} \lesssim 1\ \mathrm{TeV}$

Other problems

- Comparison with direct detection:
  - Important to remember dependence on $m_{\rm med}$
- Scattering cross section $\sigma_n \propto \Lambda^{-4}$

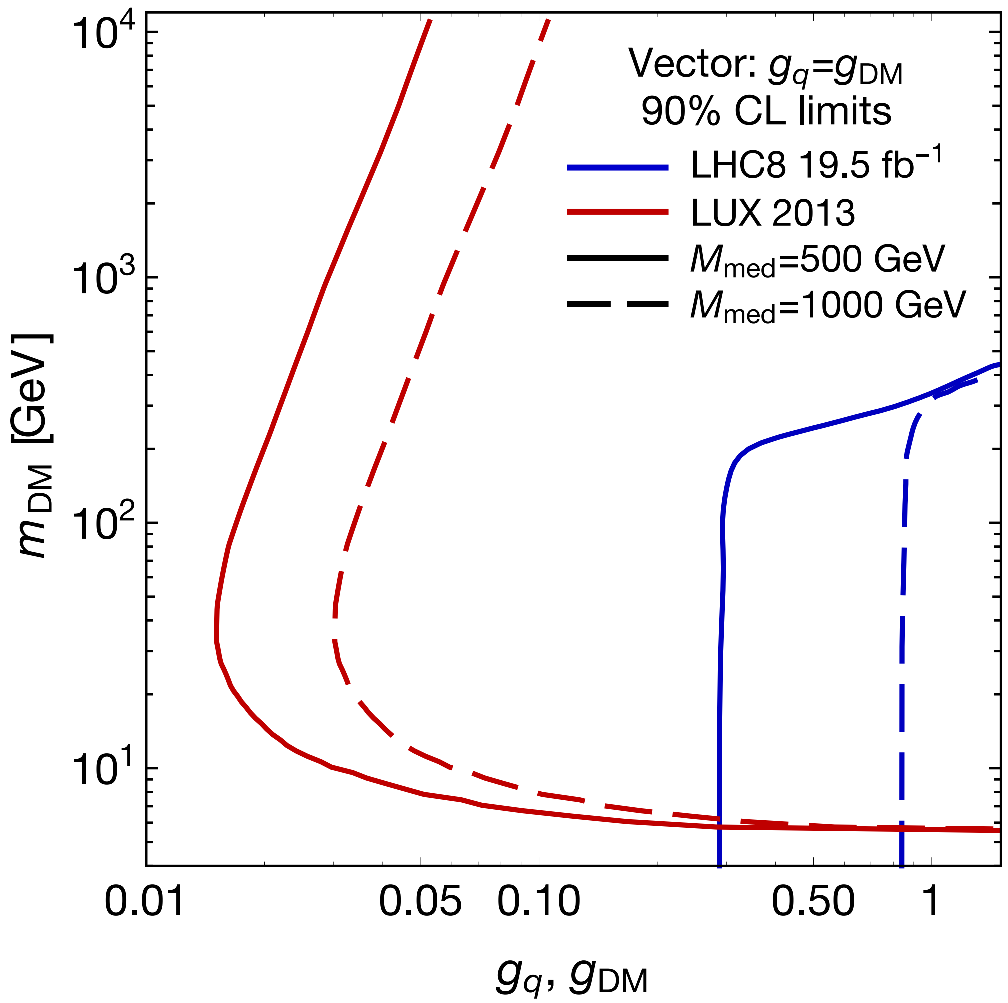


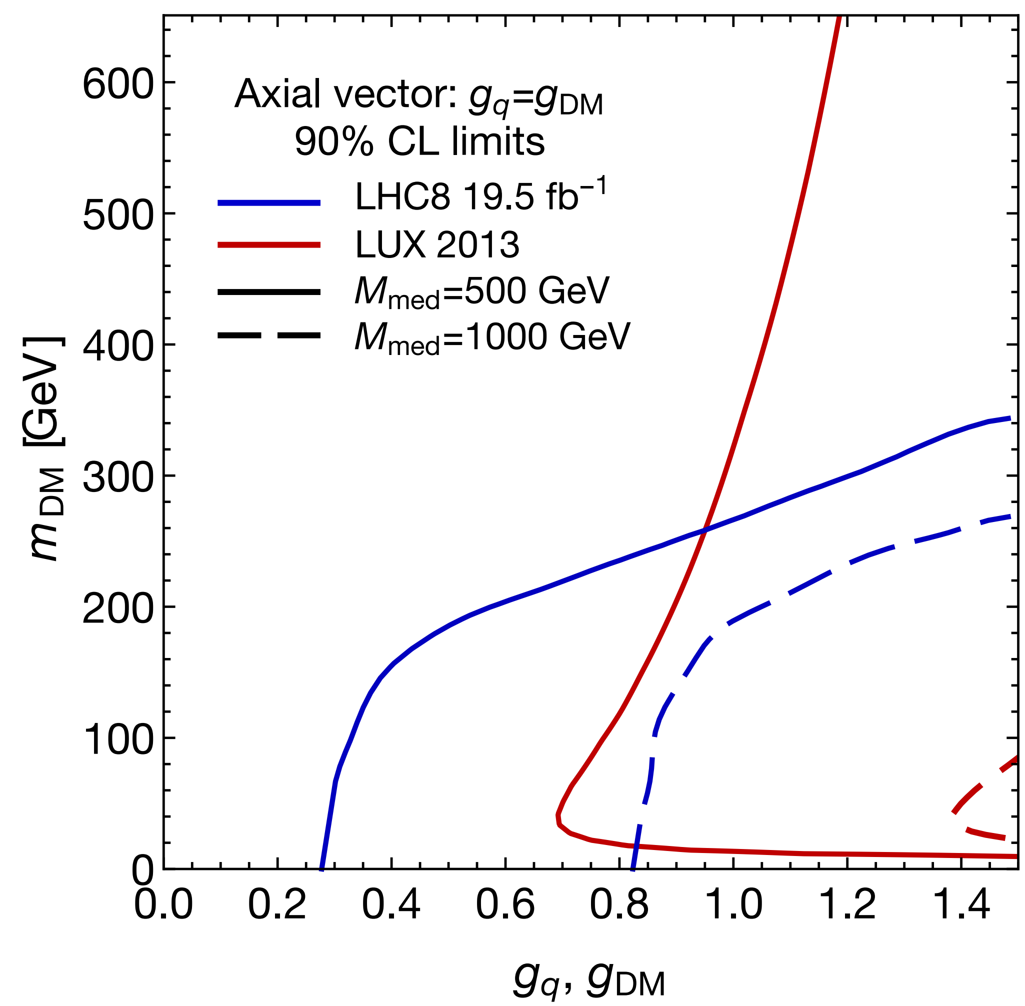


- As $m_{\rm med}$ decreases, direct detection limit is stronger

- We need to fix two parameters to show results:

$m_{\rm DM}$	g_χ
$M_{\rm med}$	g_q



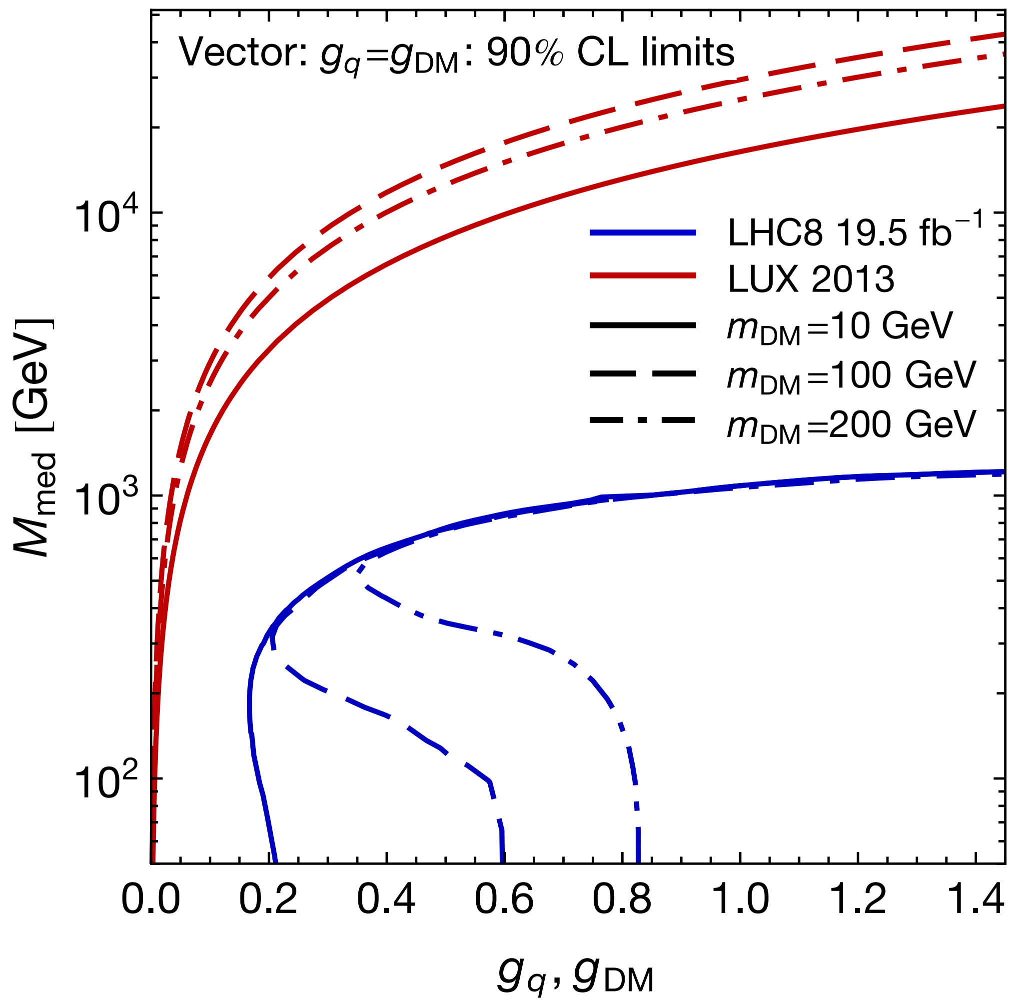


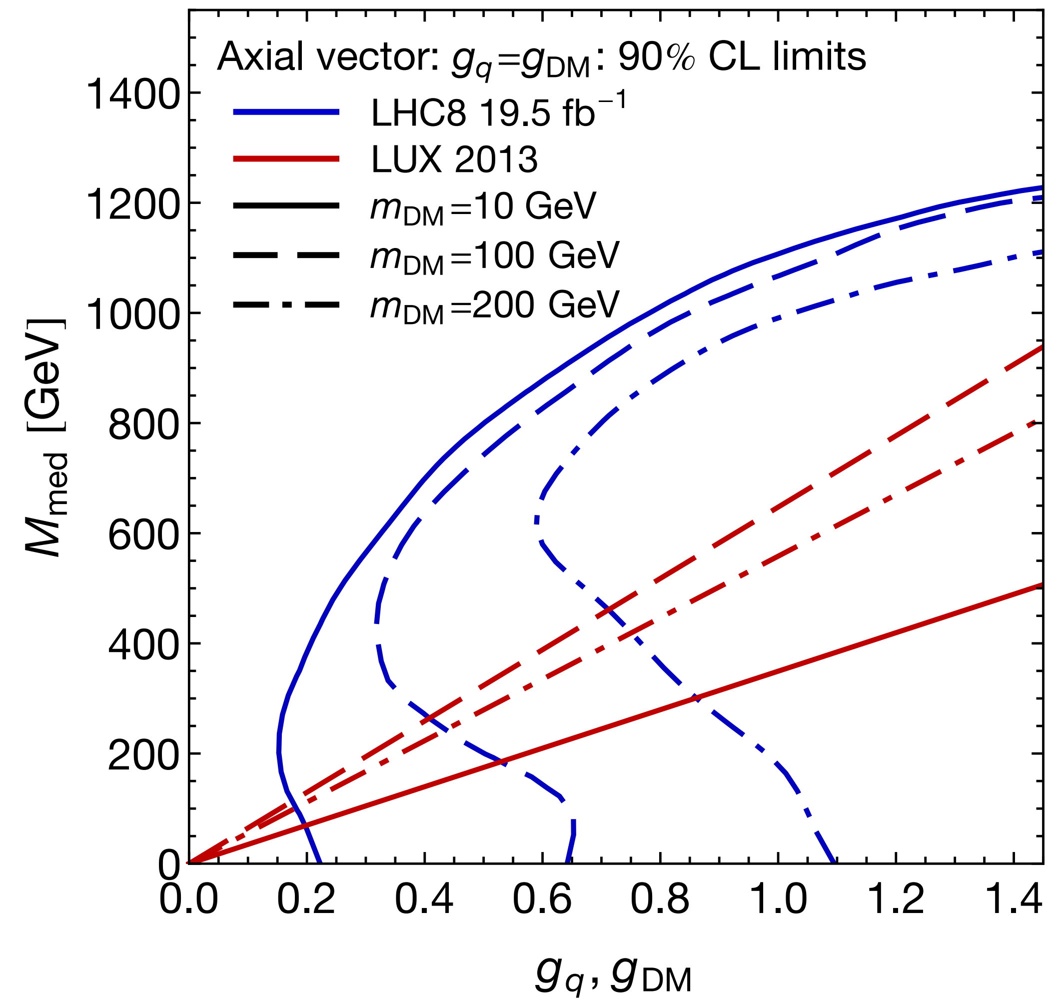
- Better elucidation of the complementarity between collider and direct searches

Slicing through parameter space

- We need to fix two parameters to show results:

m_{DM}	g_χ
M_{med}	g_q





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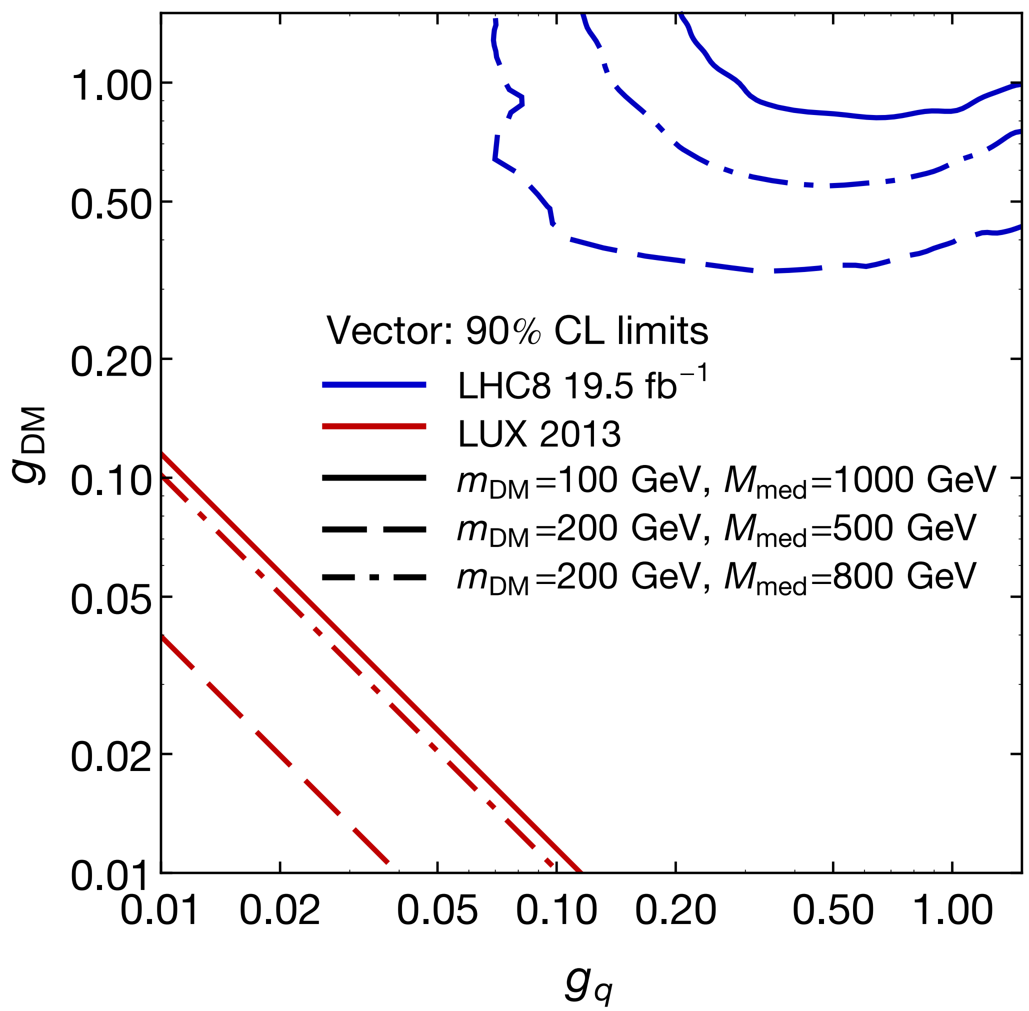

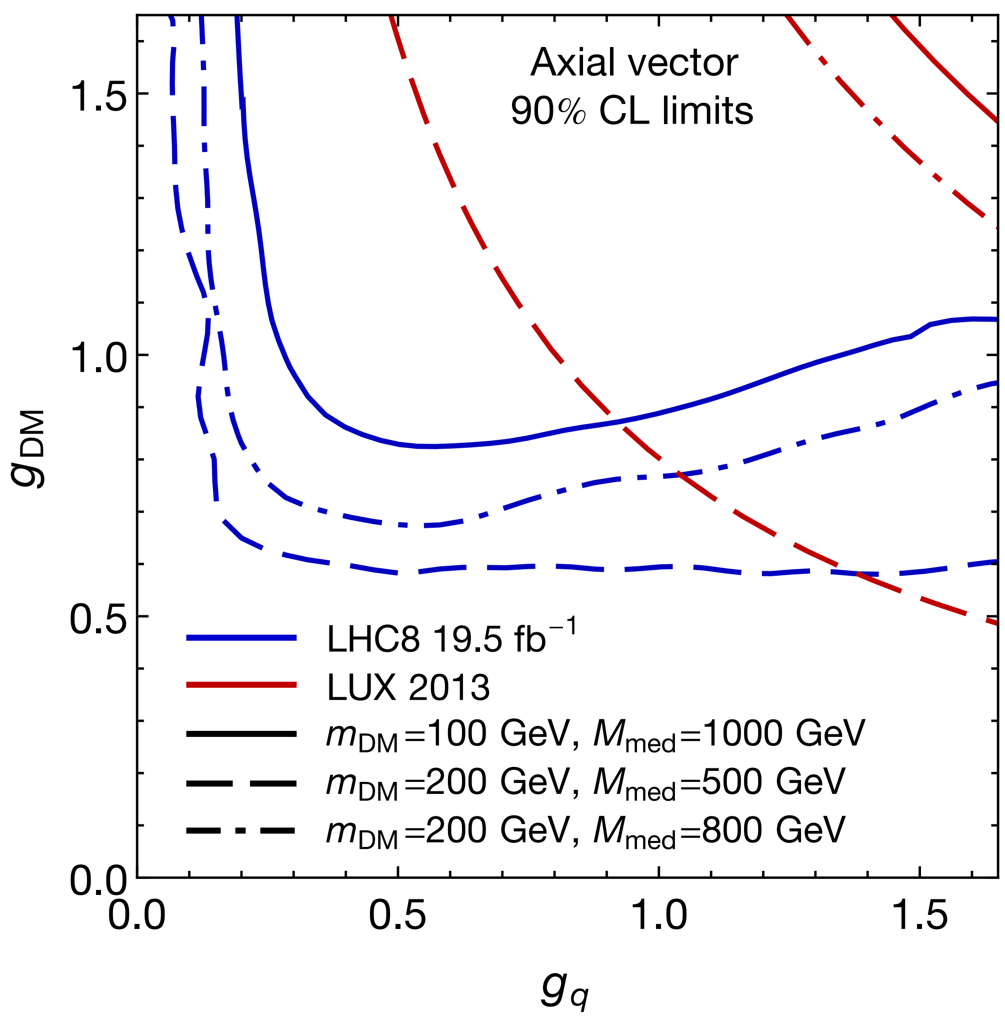

- Better elucidation of the complementarity between collider and direct searches