Searching for Dark Matter Production at the LHC

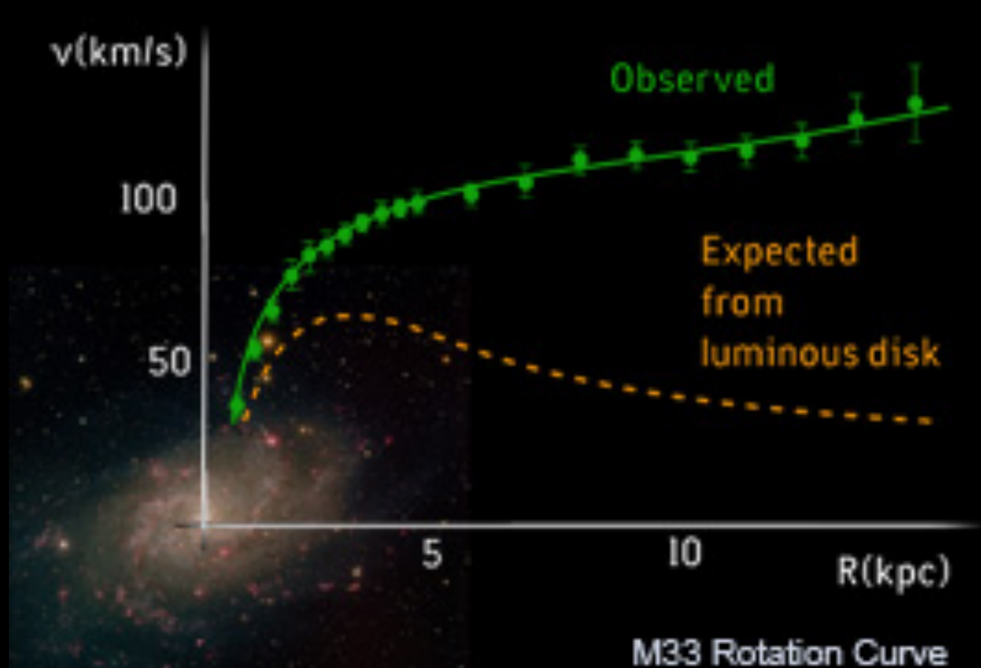
ATP Seminar

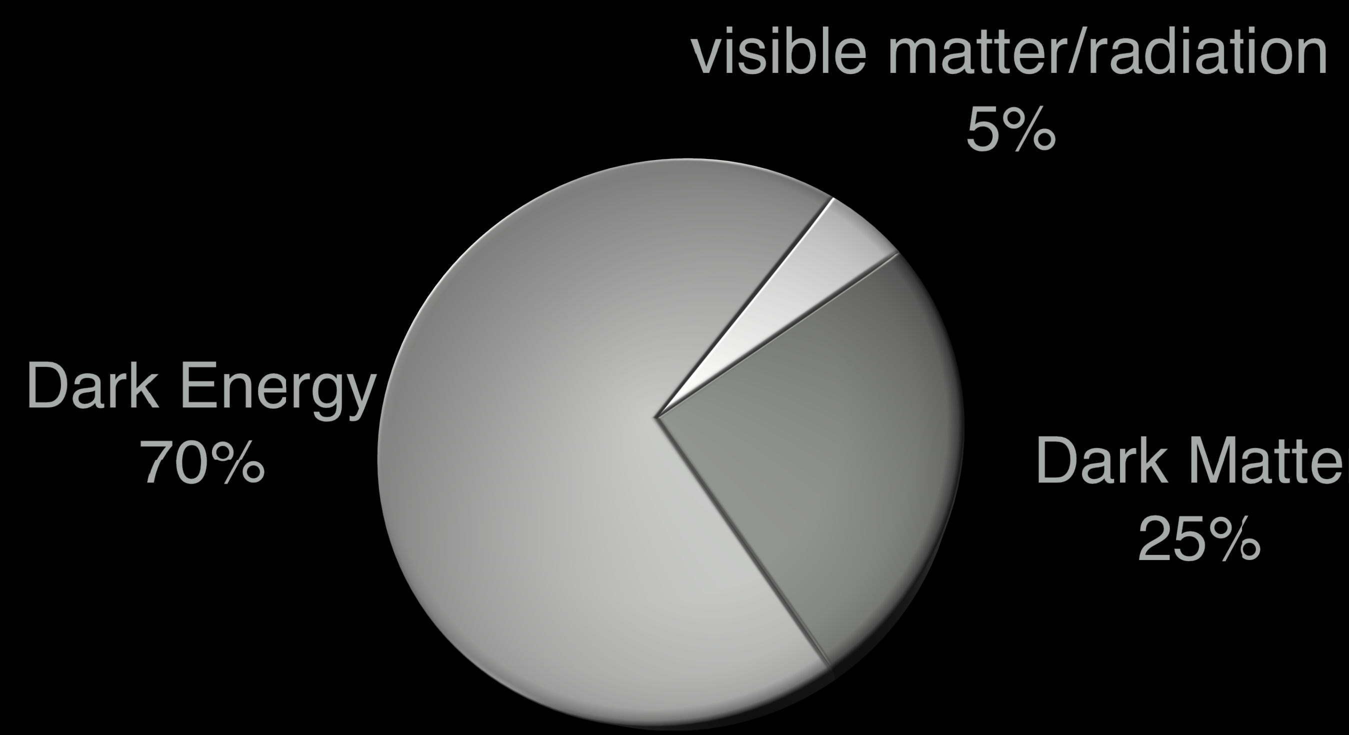
Ruth Pöttgen

26 April 2017

Why Dark Matter?

rotation velocity of stars in galaxies





Planck result

many **cosmological** observations

=> compelling **evidence** for

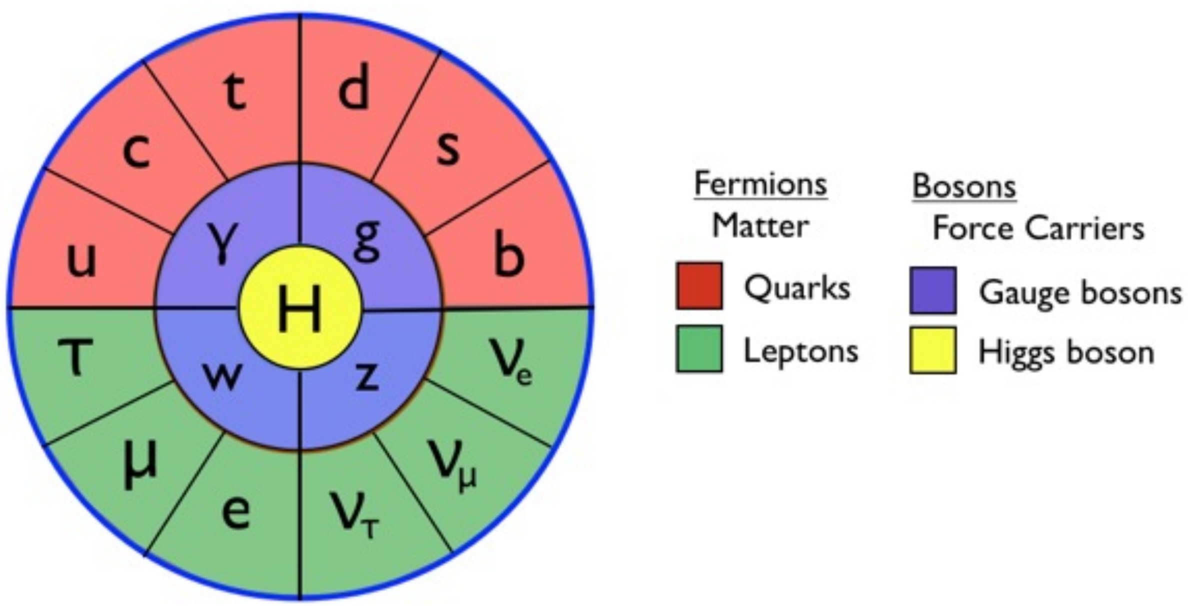
existence of “**dark matter**” (DM)

we can describe
merely ~5% of the universe!

Dark Matter Particles?

- particle physics:
  - what are the building blocks (=particles)?
  - current best knowledge: Standard Model (SM)

theoryandpractice.org



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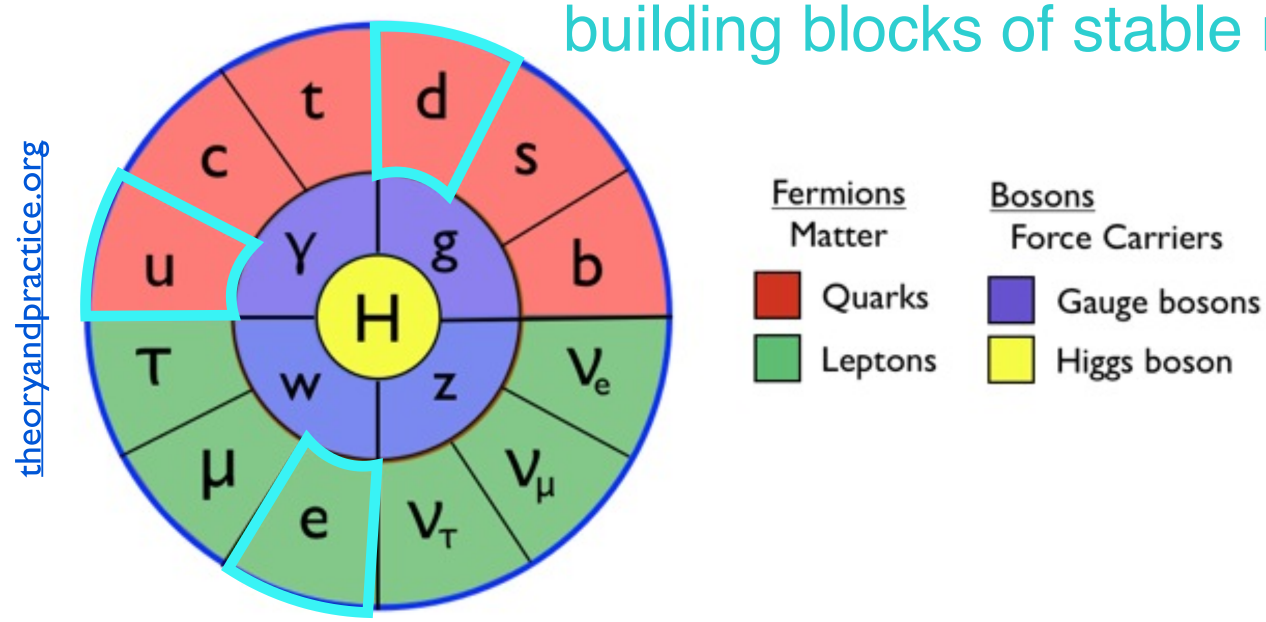
building blocks of stable matter



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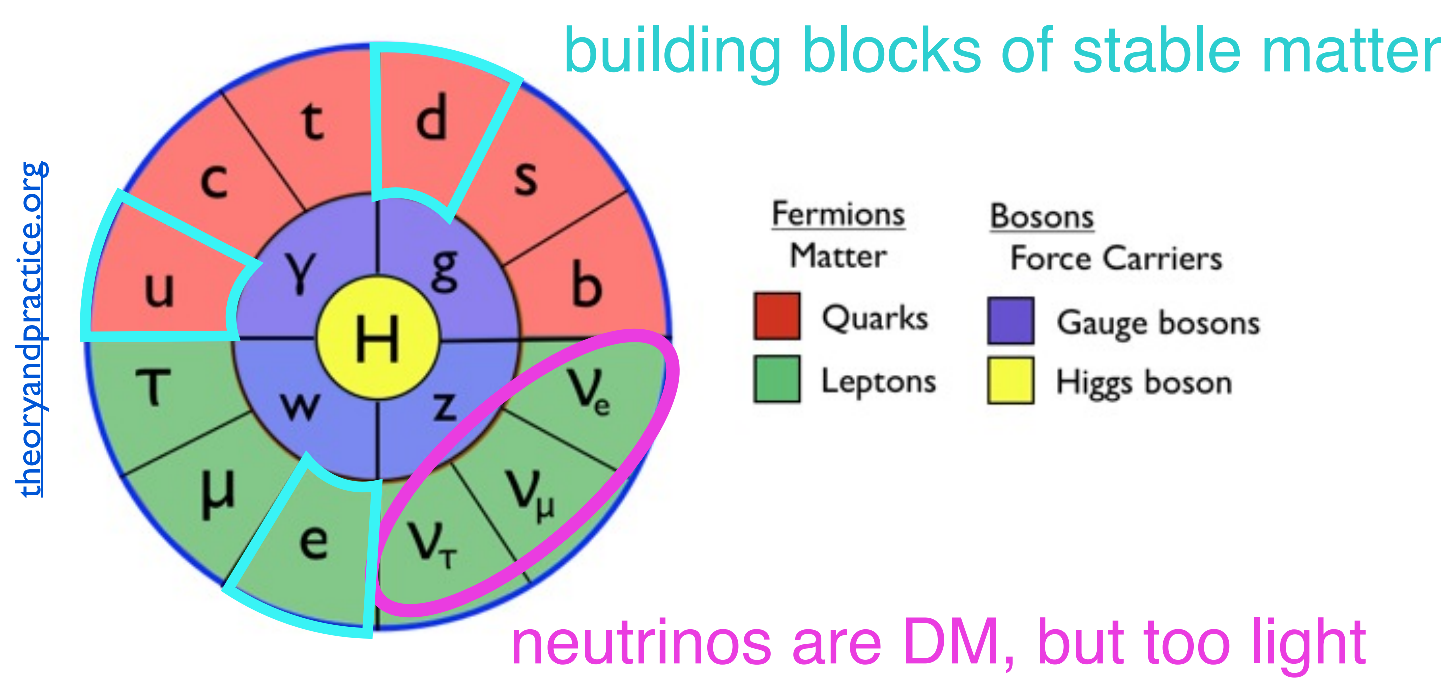

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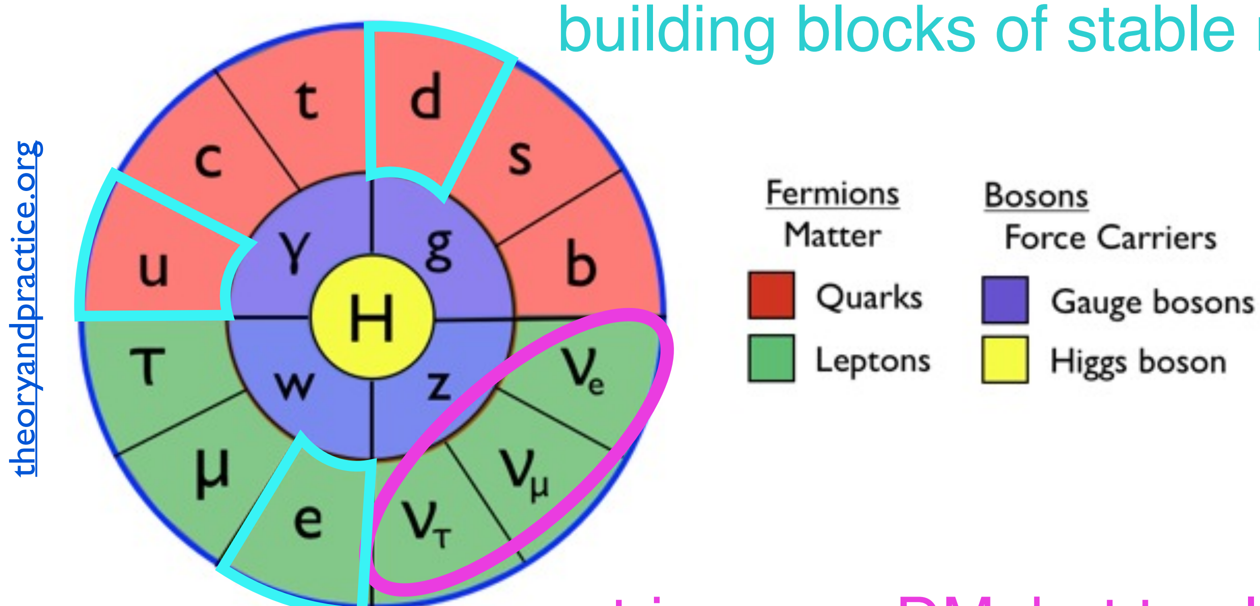

neutrinos are DM, but too light

no viable candidate within Standard Model

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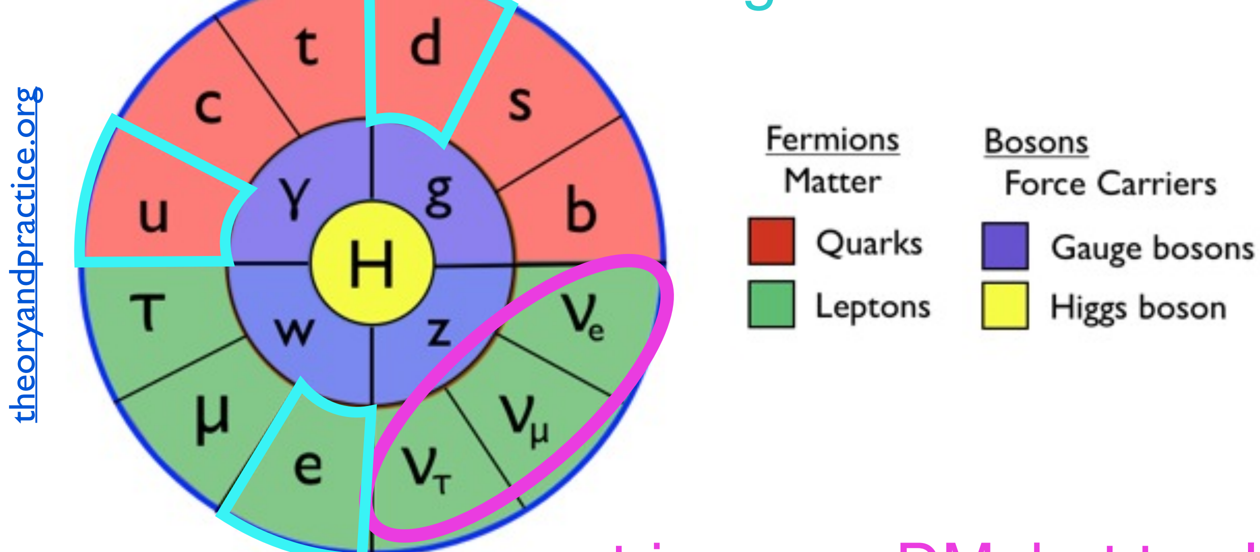


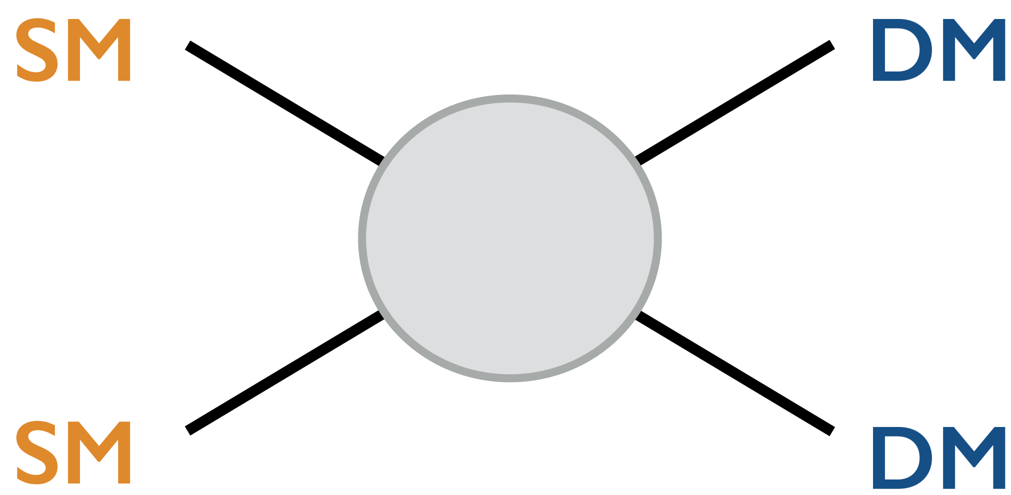
neutrinos are DM, but too light

no viable candidate within Standard Model

- need **new** particles!
- popular generic class: **weakly interacting massive particles** (WIMPs)
  - naturally explain present-day abundance

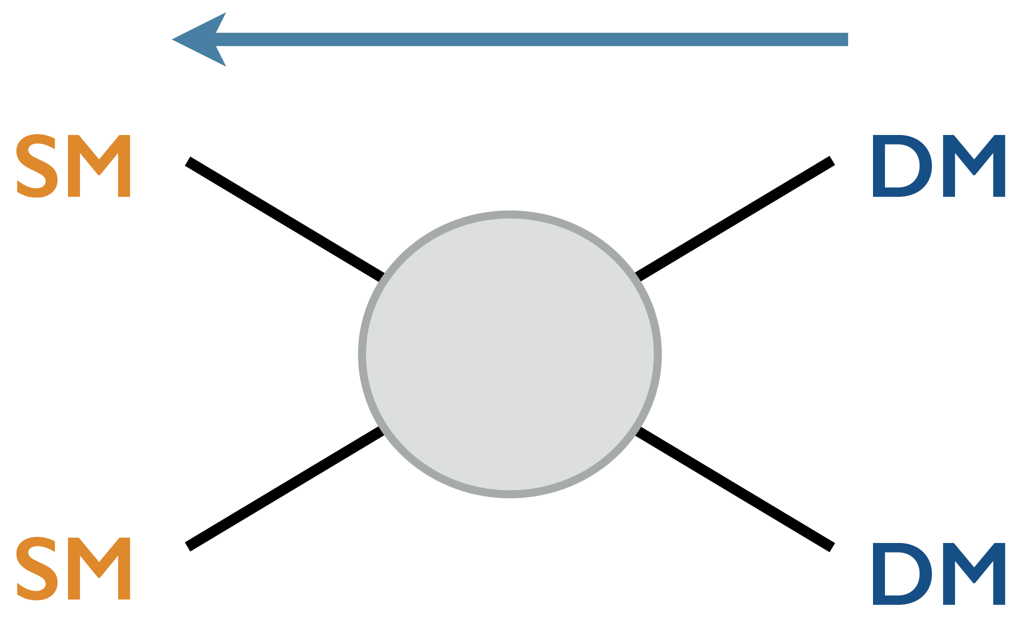
=> broad search programme

Ways to look for WIMPs



Ways to look for WIMPs

indirect
detect annihilation products



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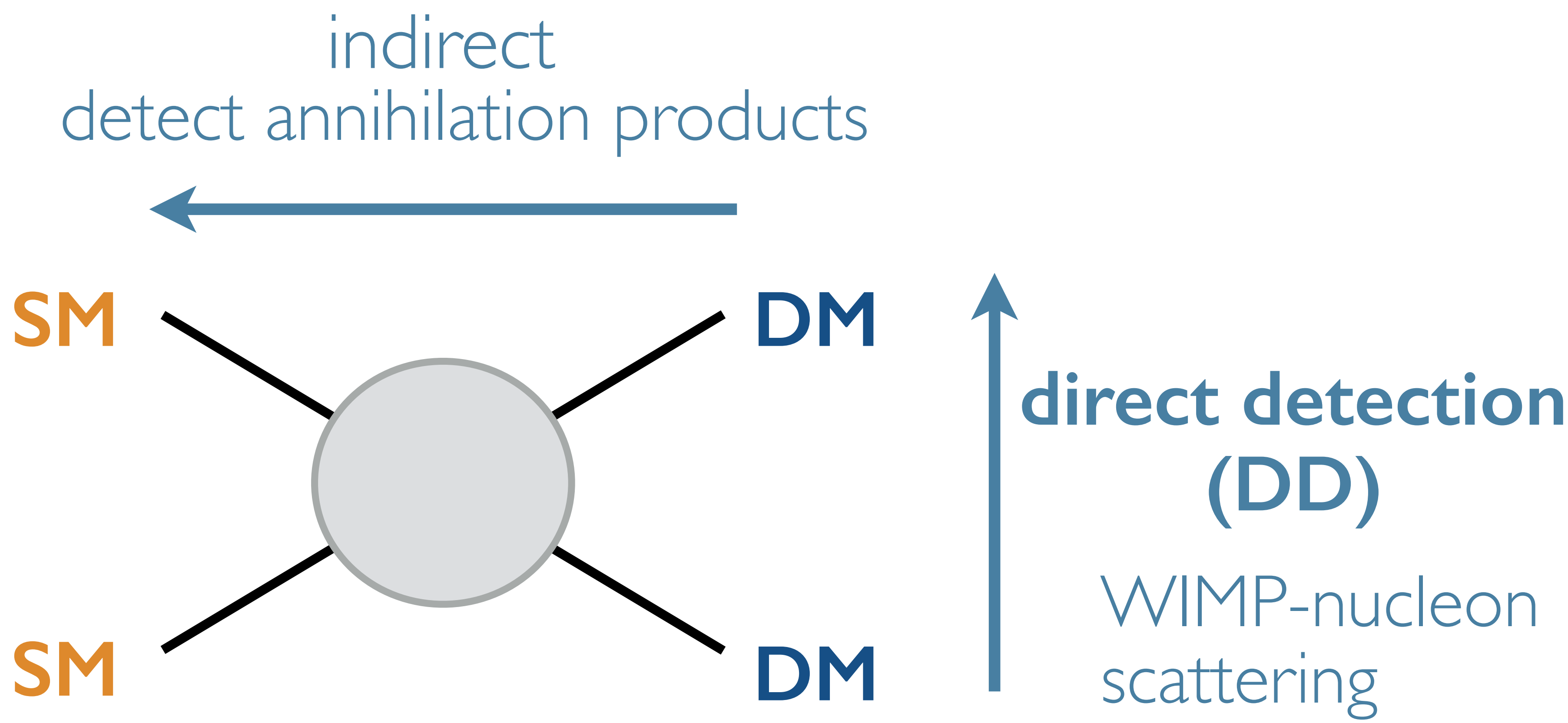

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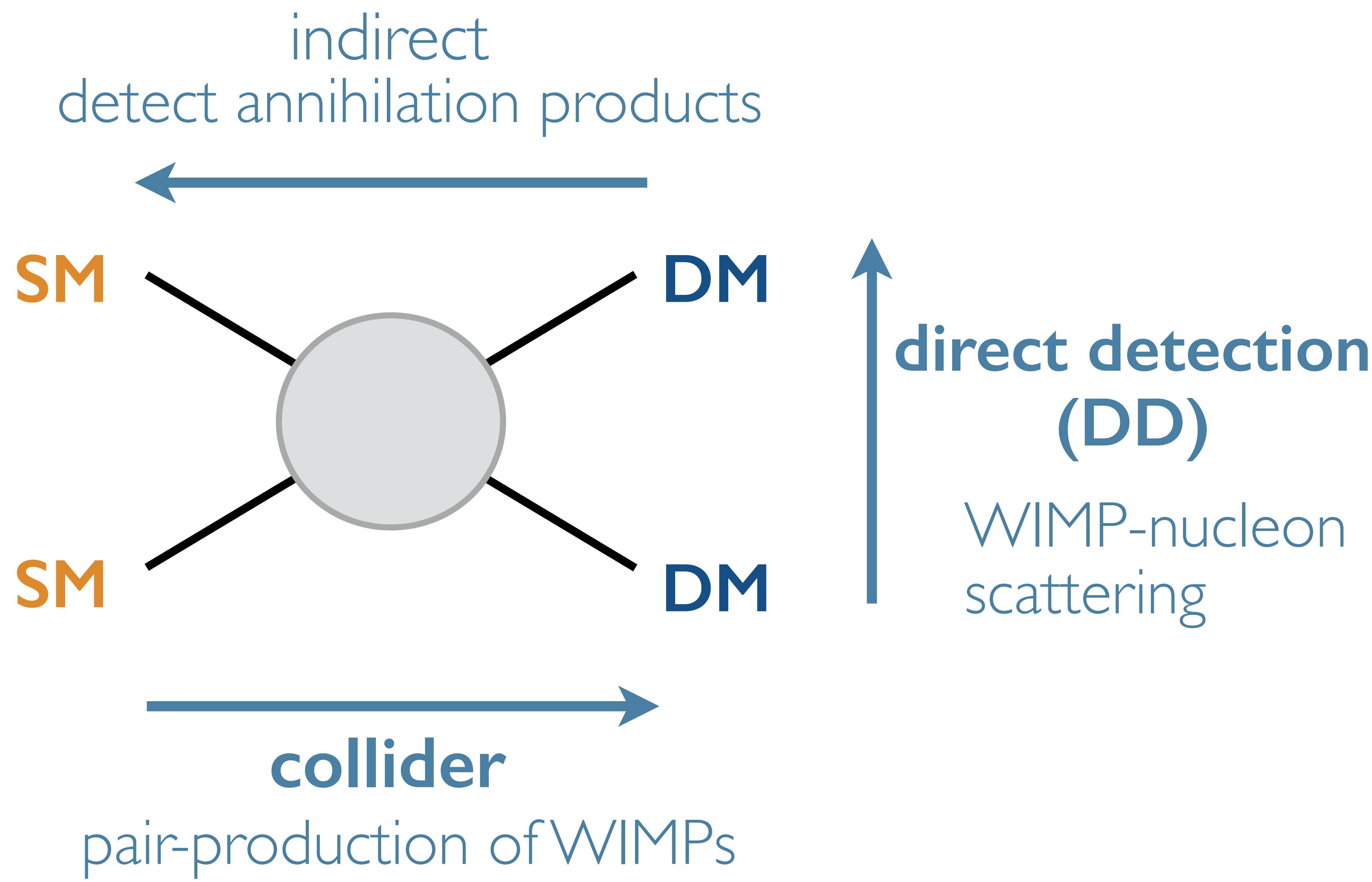
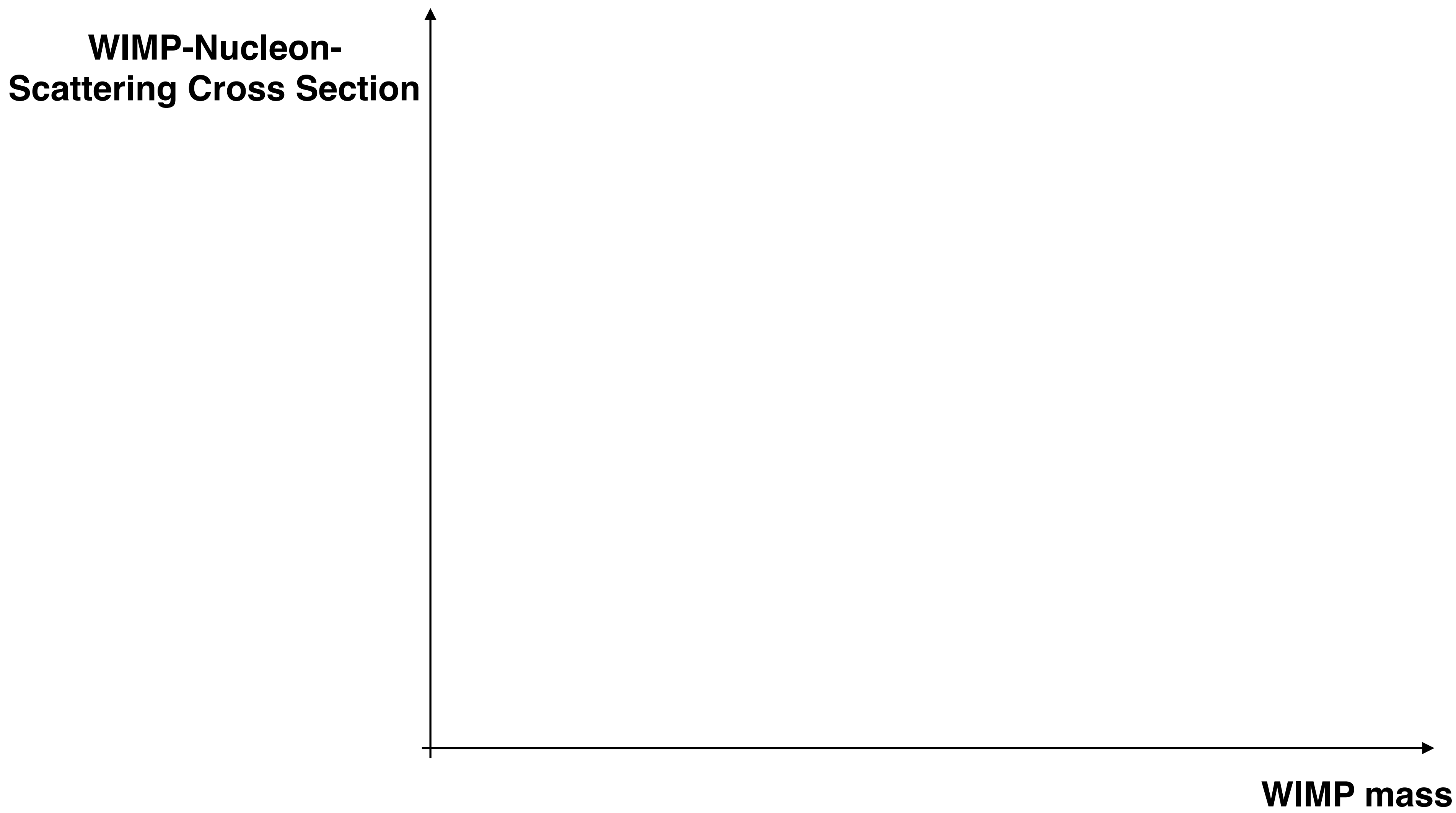


Outline

- complementarity of searches
- LHC and ATLAS
- X+E_T^{miss} signatures
- Results and Interpretations
- future prospects

Complementarity



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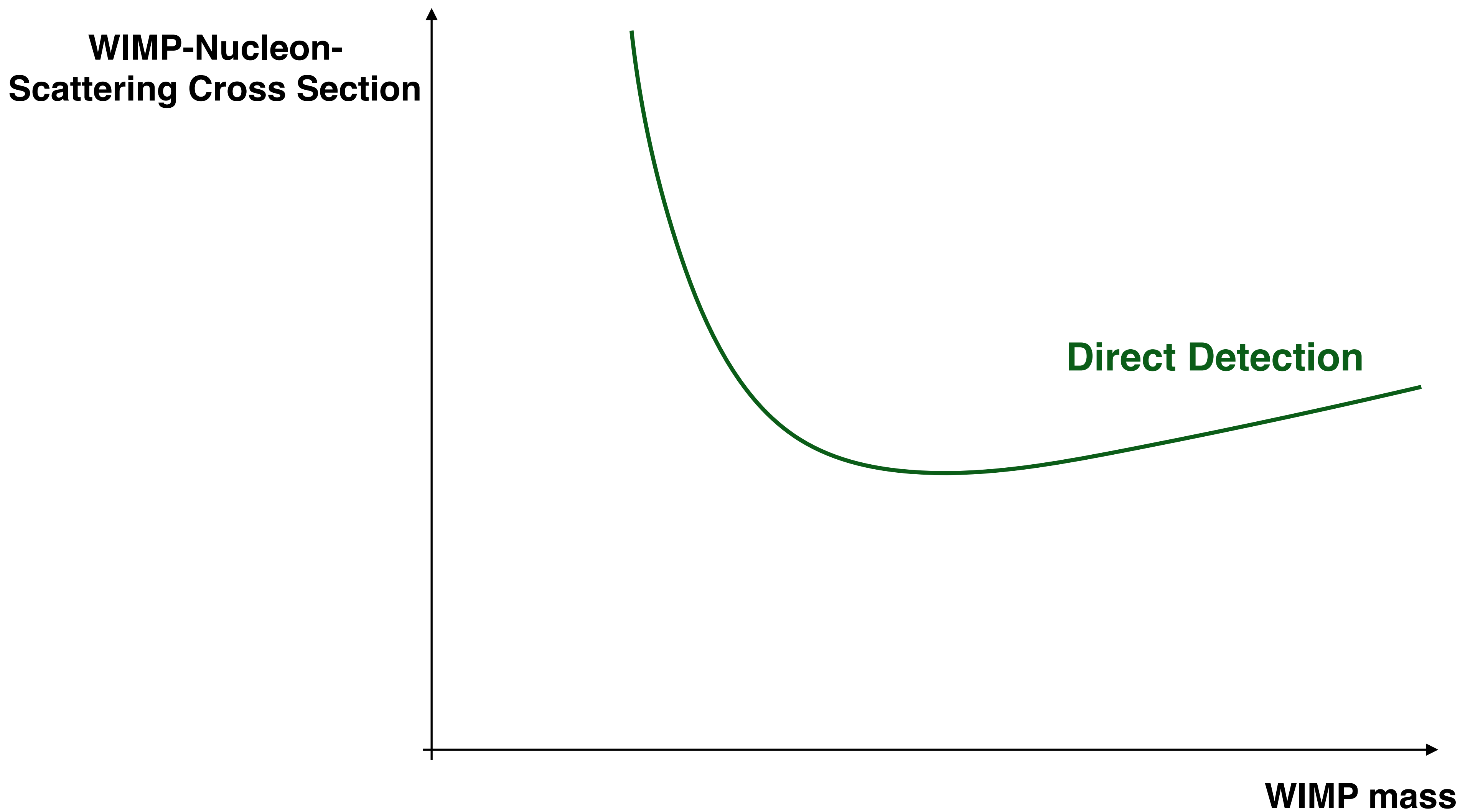

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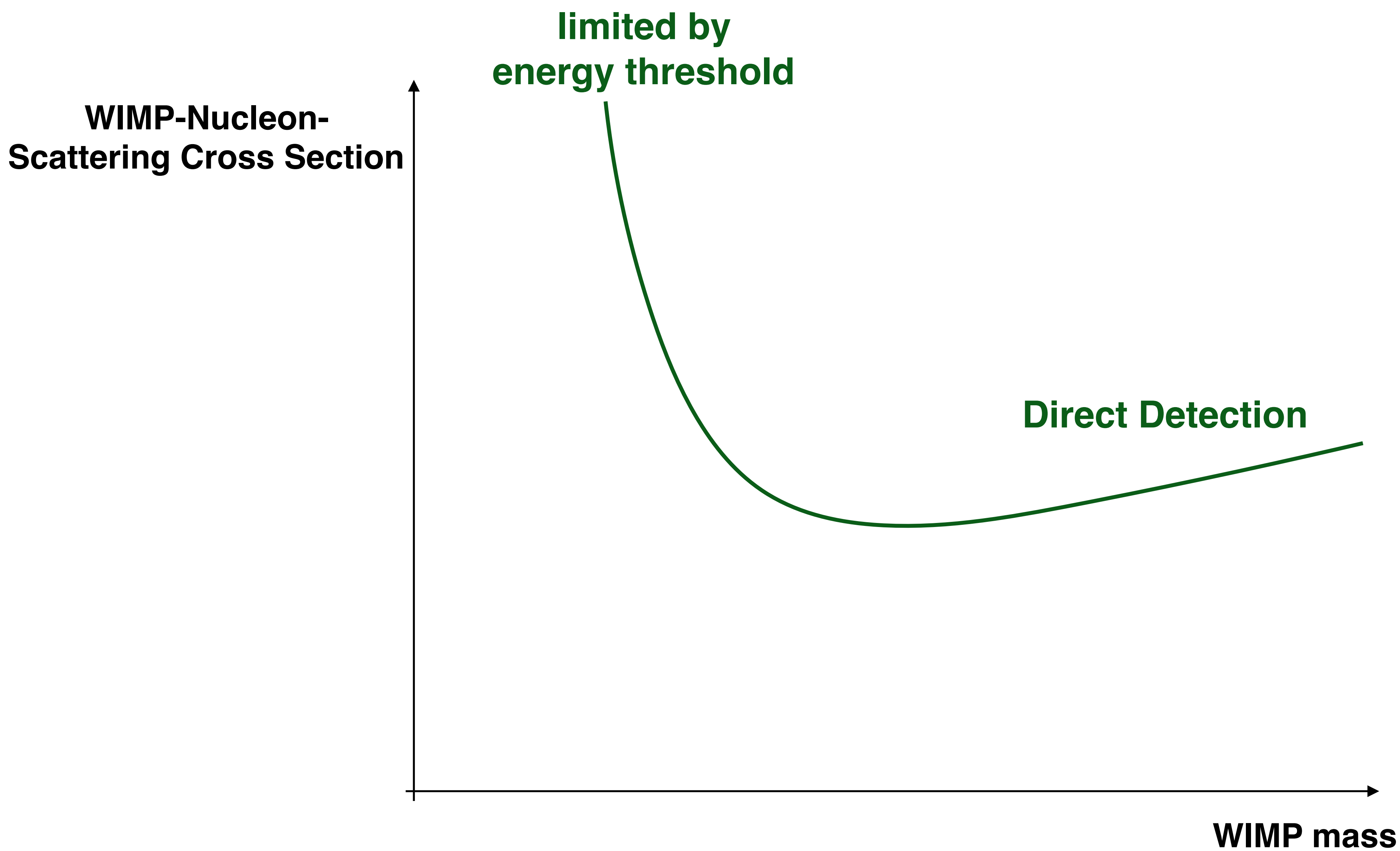

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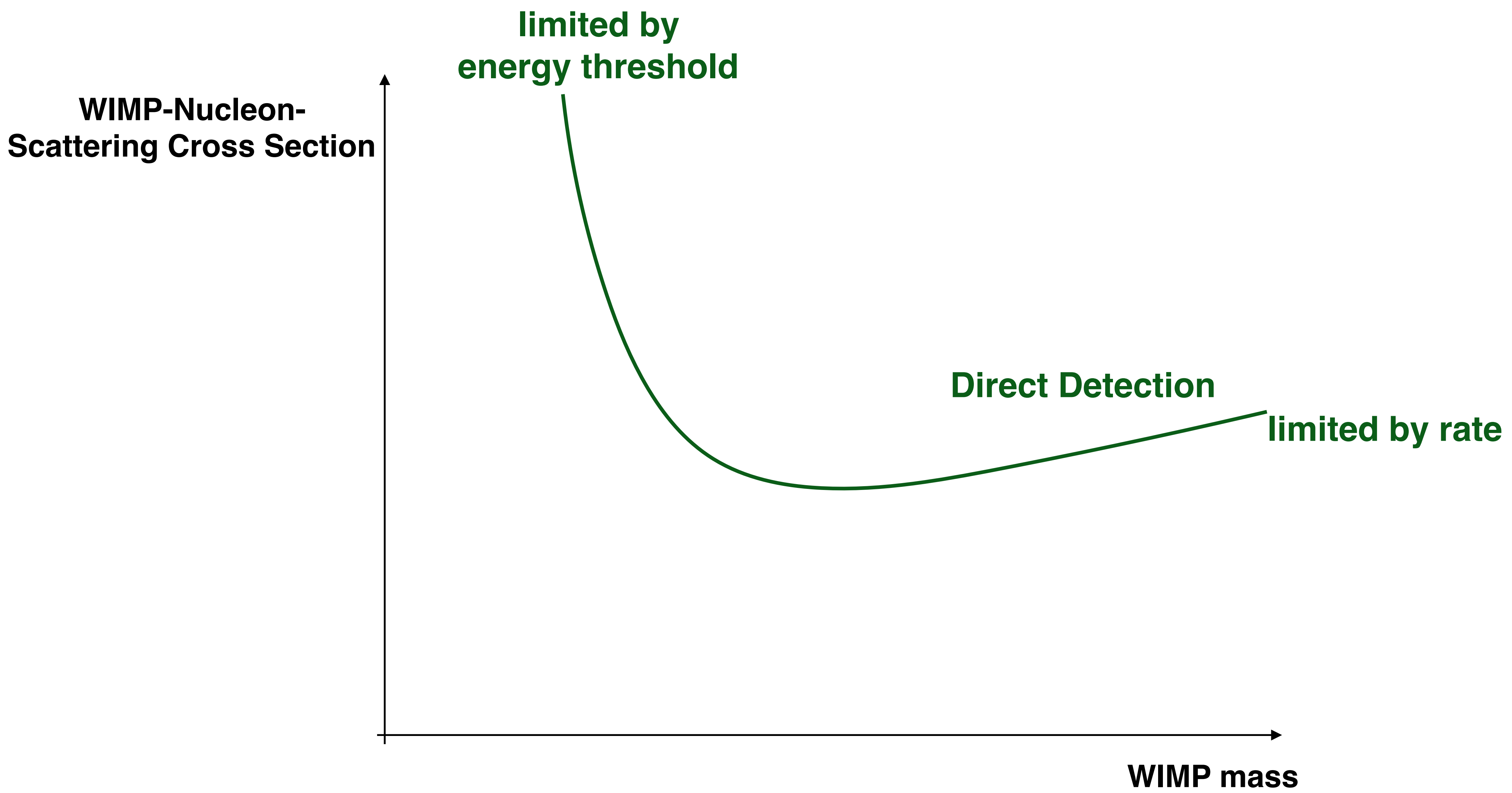

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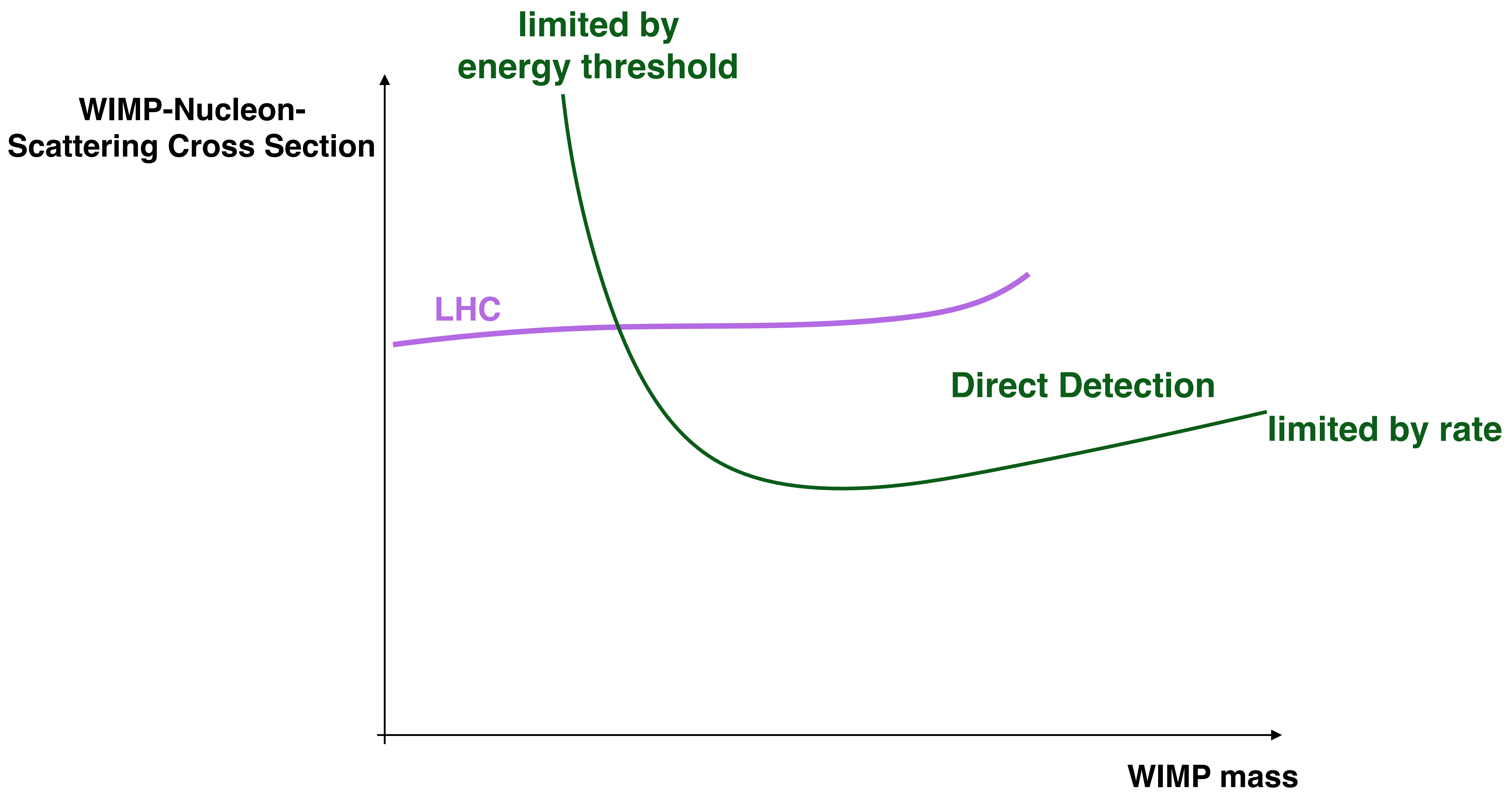

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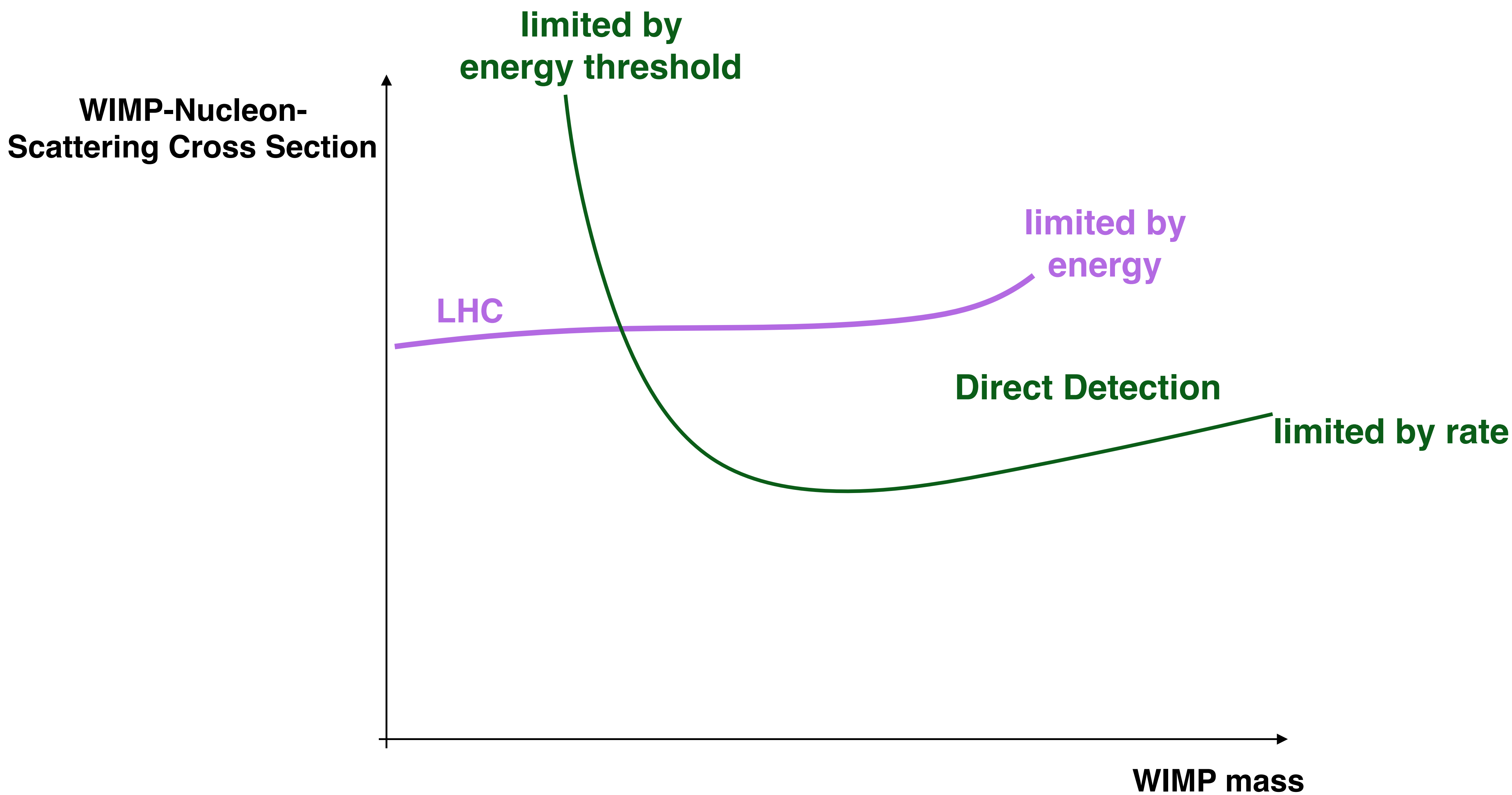

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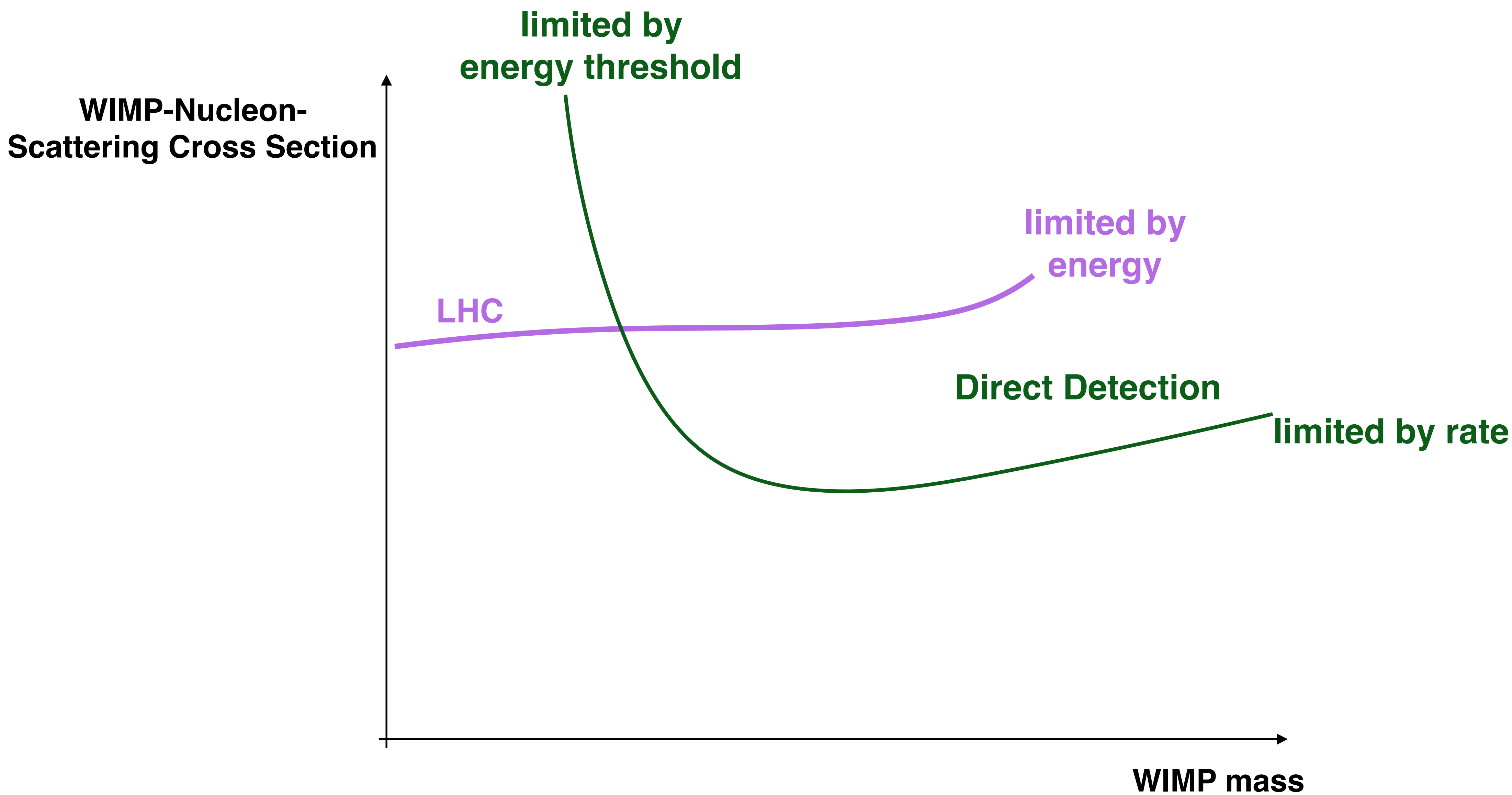
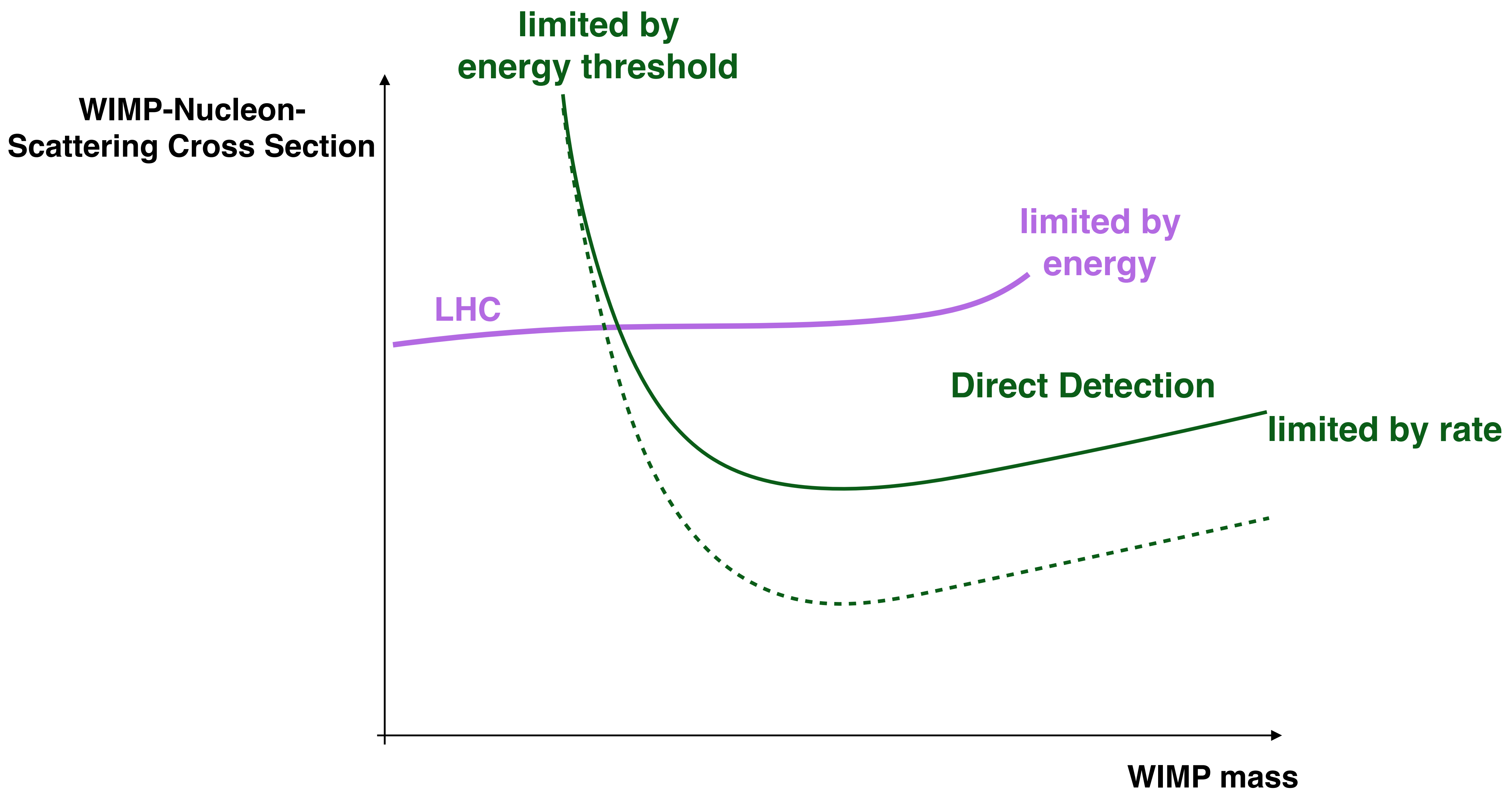


low mass: collider more sensitive

high mass: direct detection more sensitive

Complementarity



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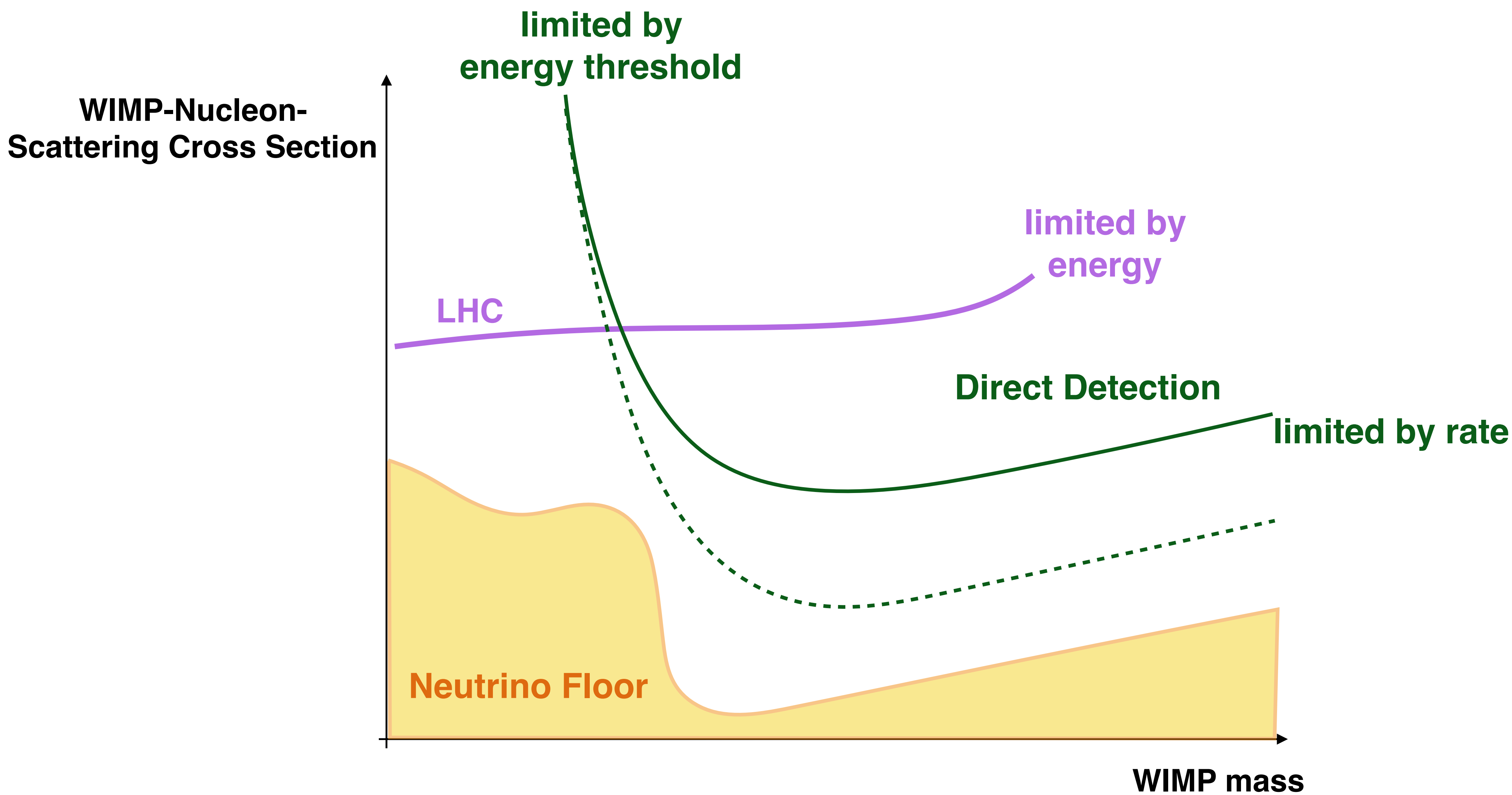

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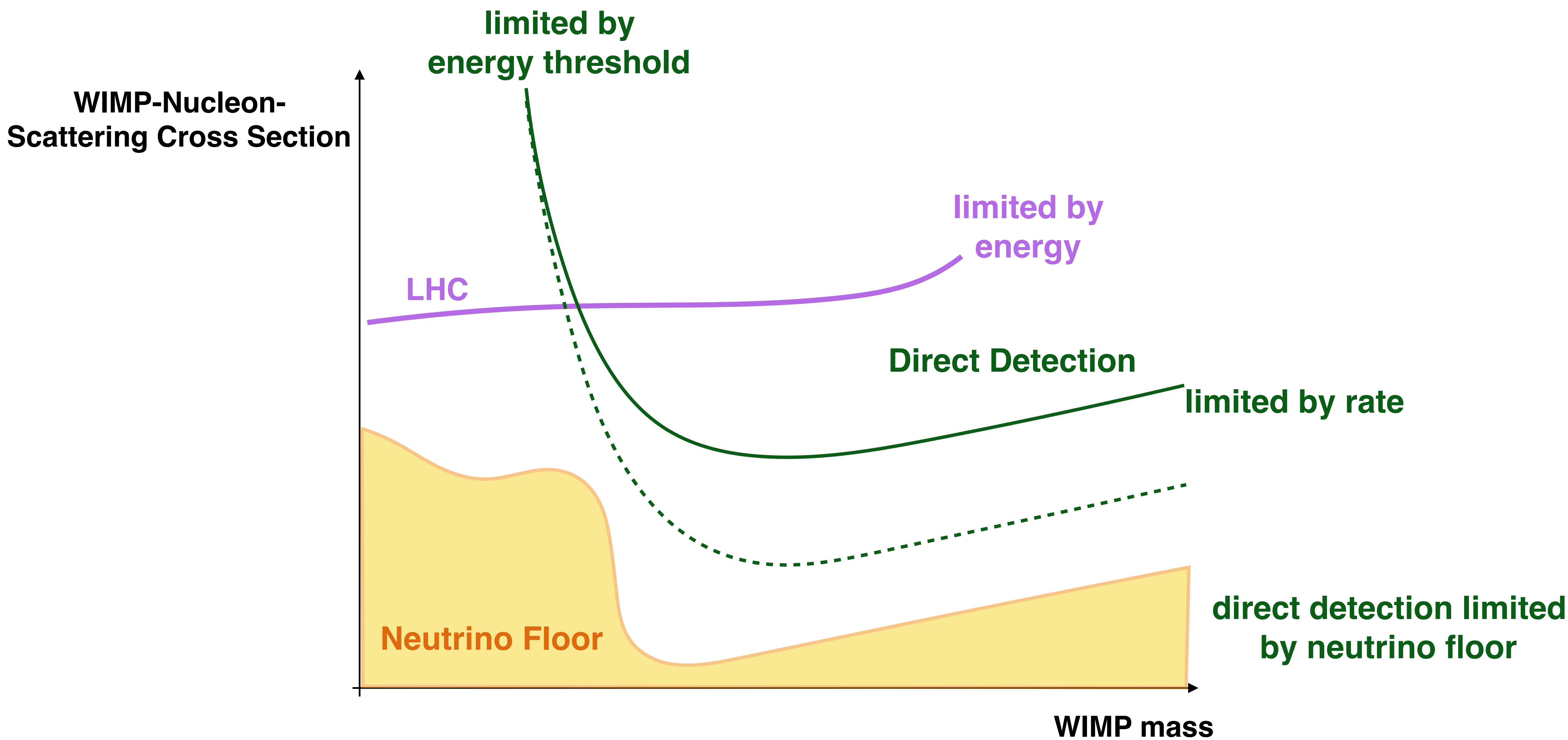

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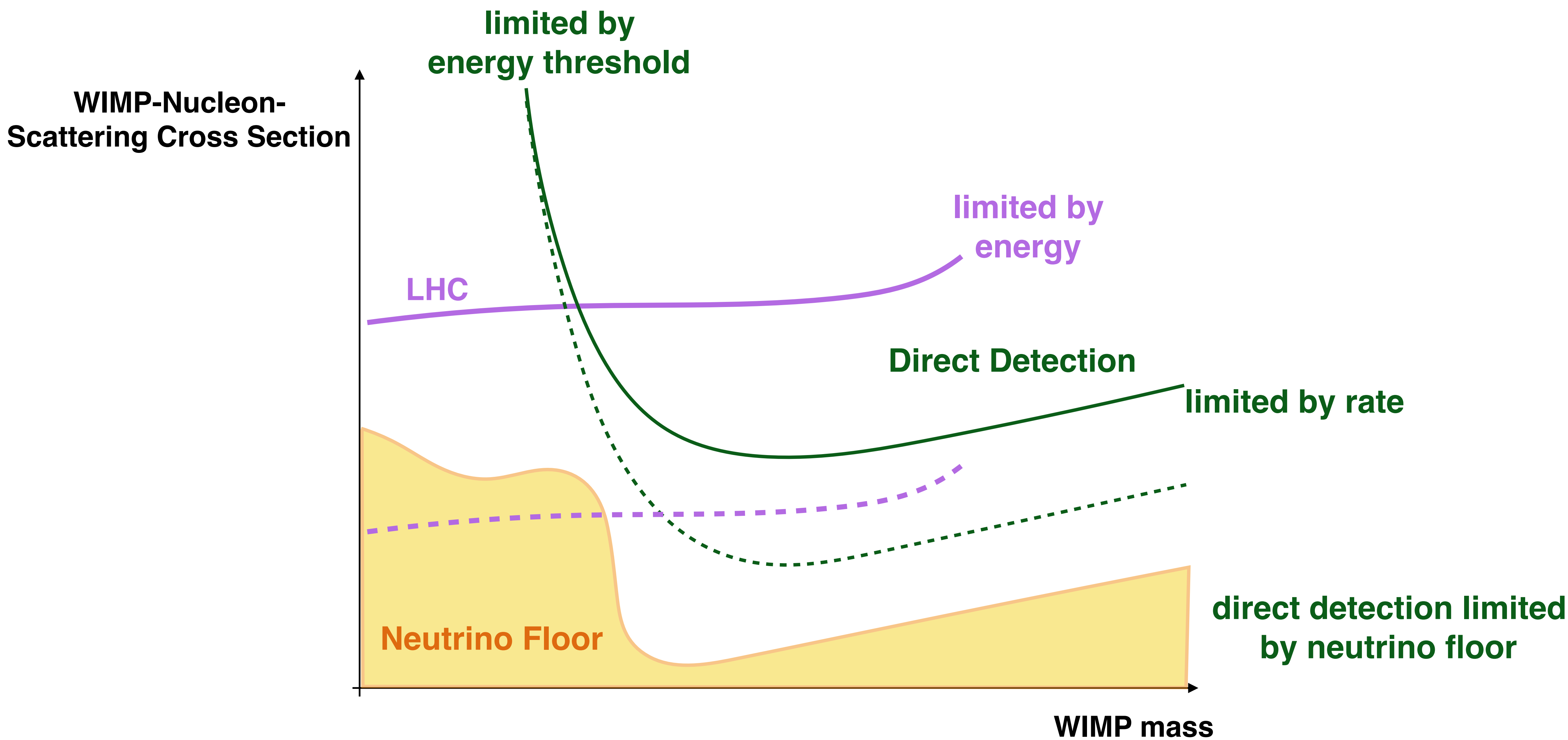

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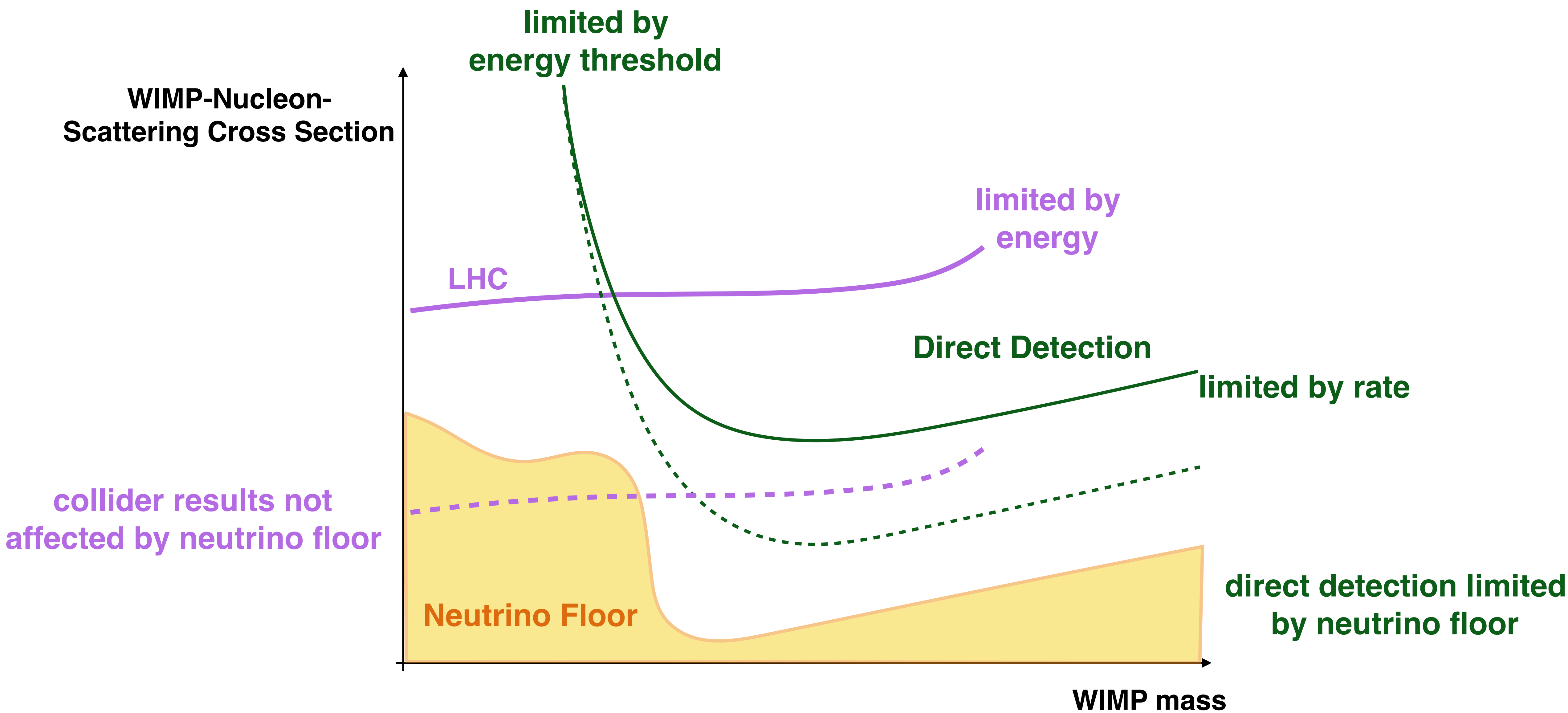

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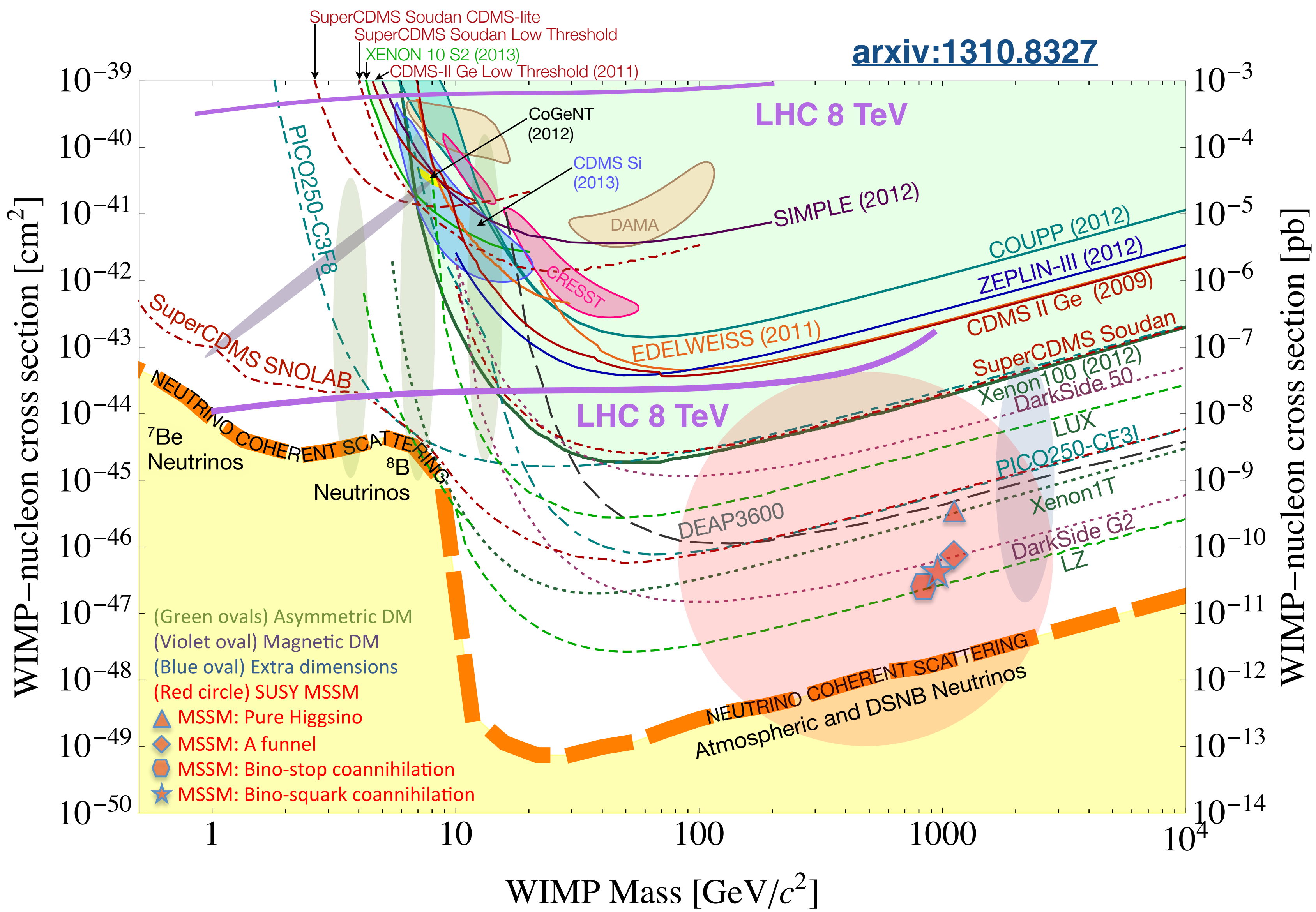
Experimental Landscape



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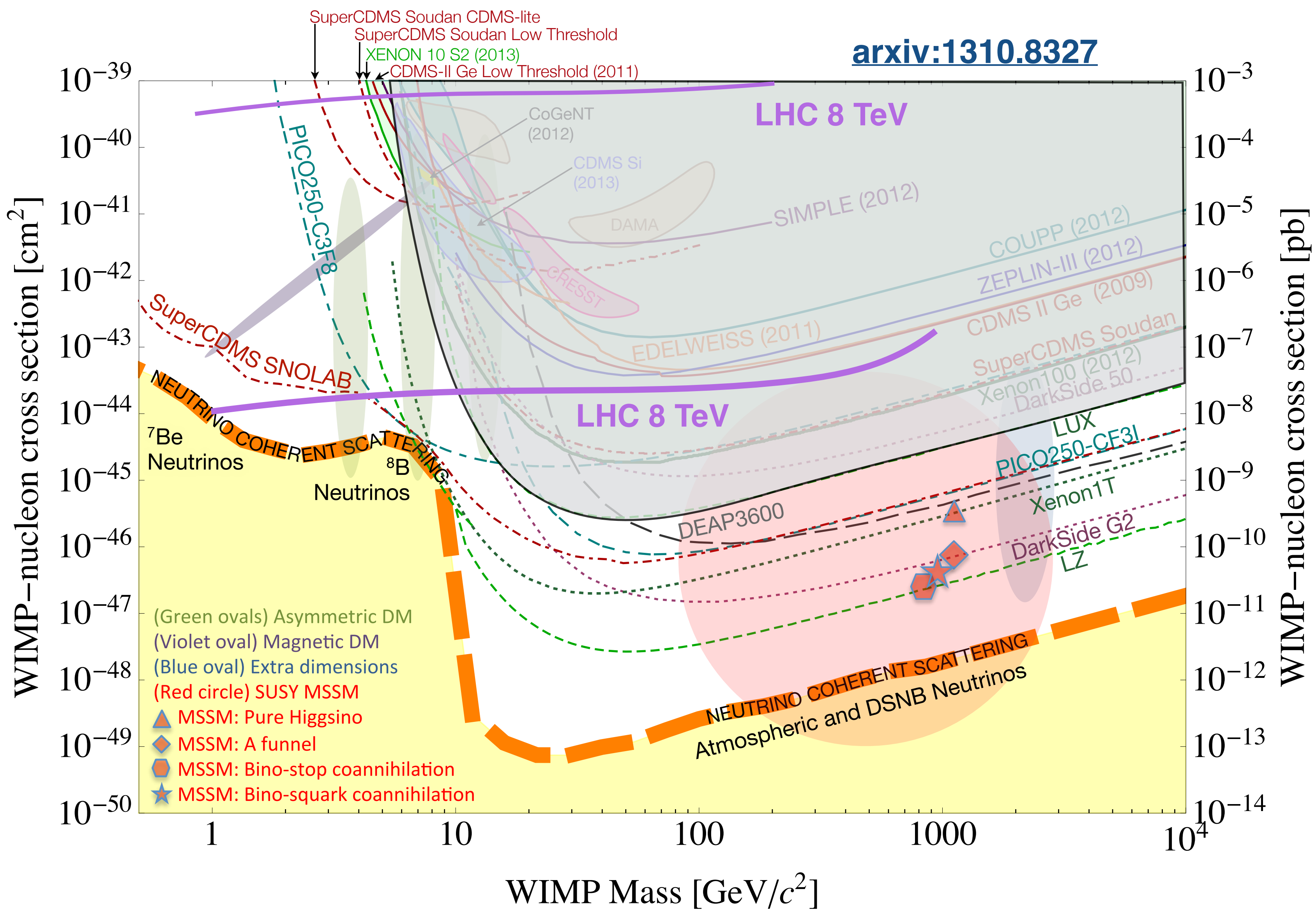
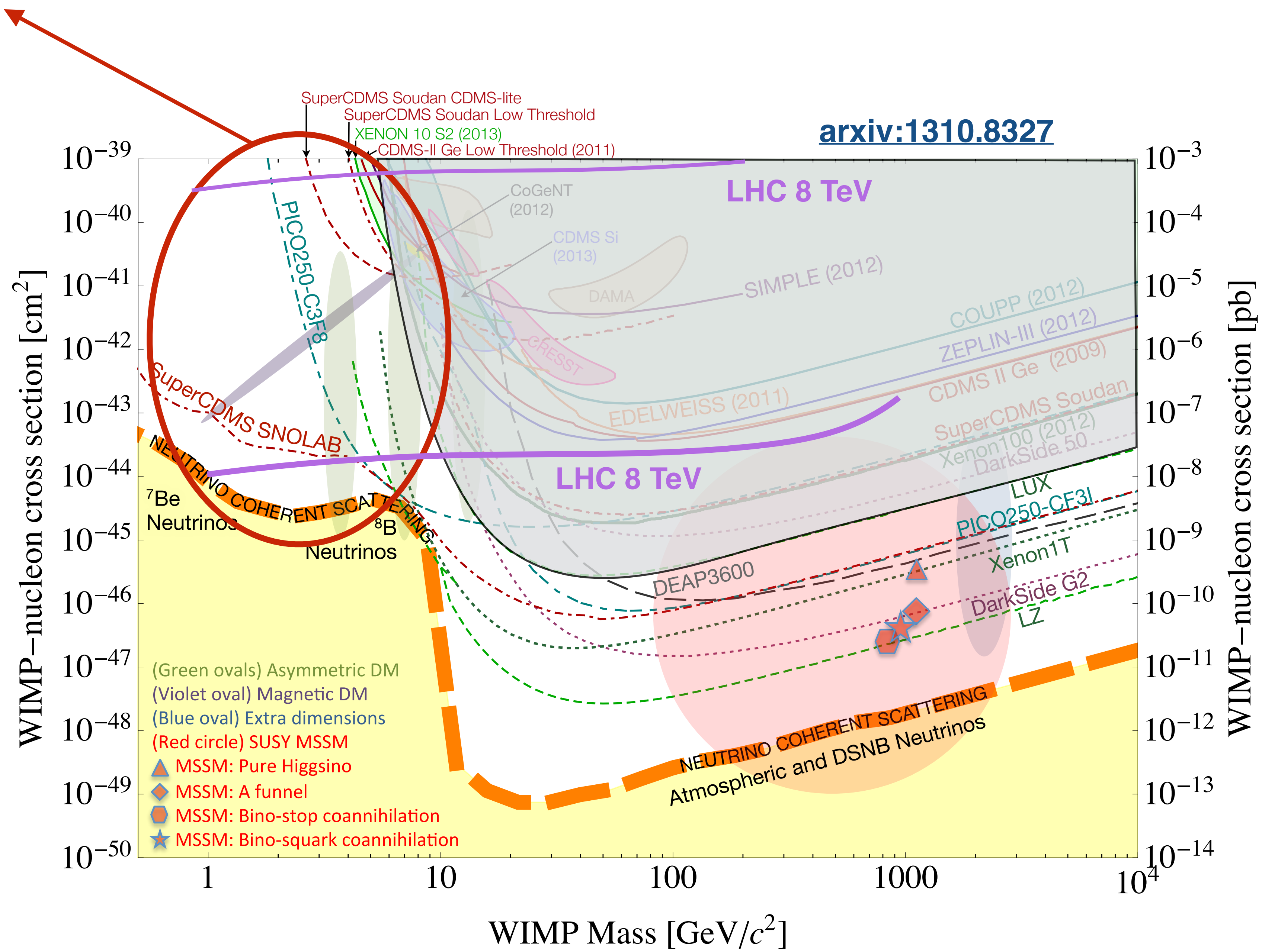


Experimental Landscape

collider experiments more sensitive at **low** masses



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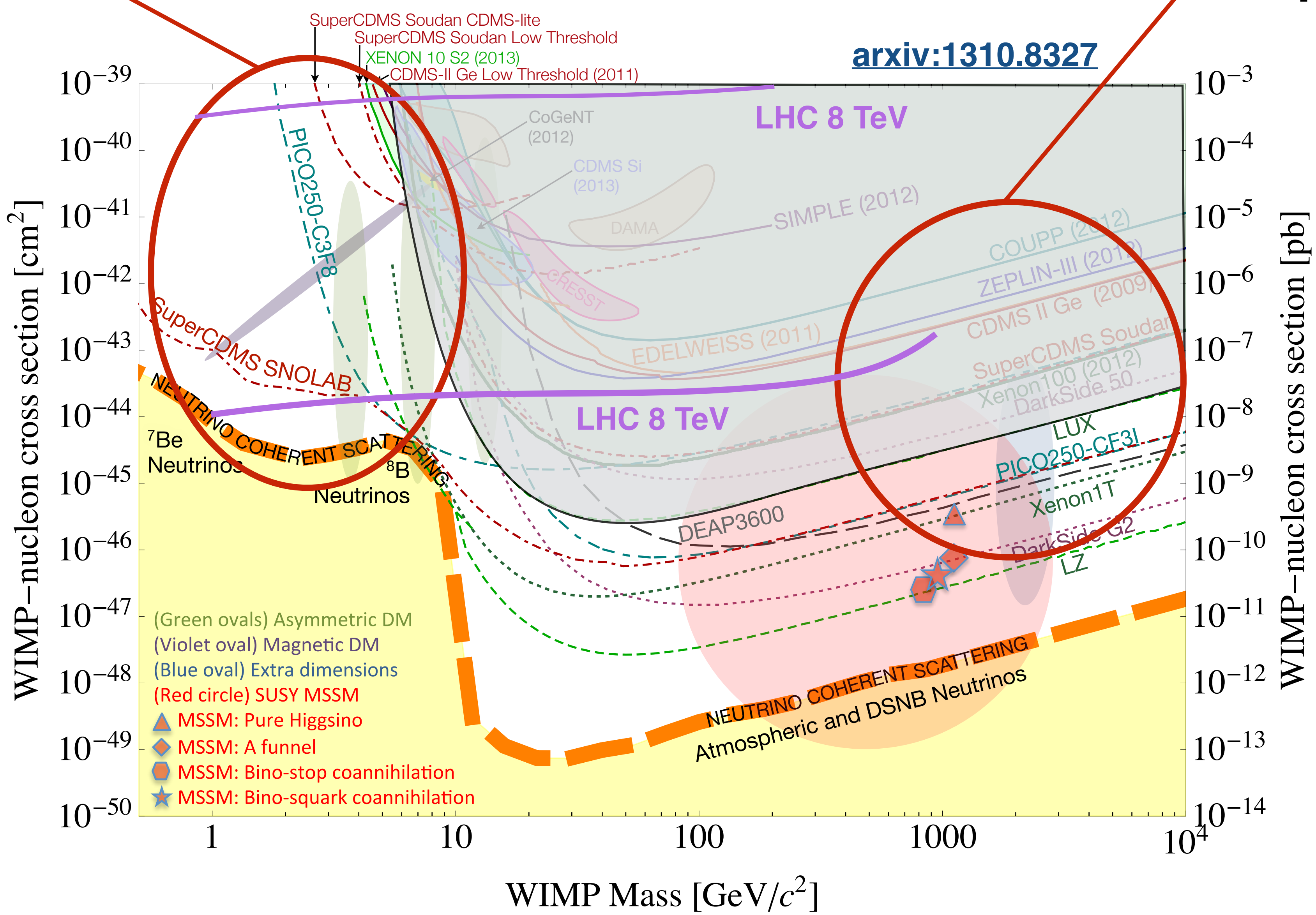

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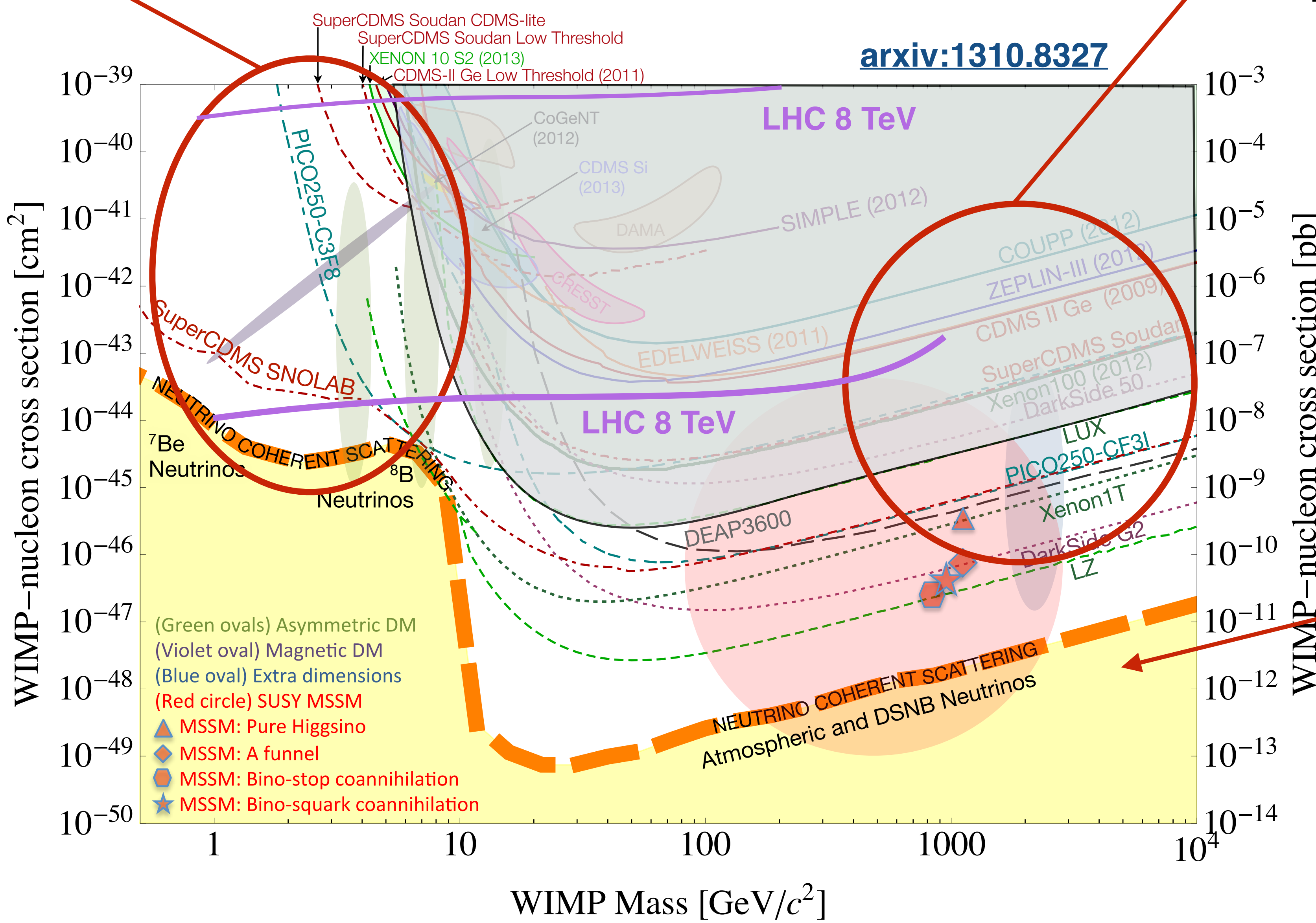

about to reach "neutrino floor"

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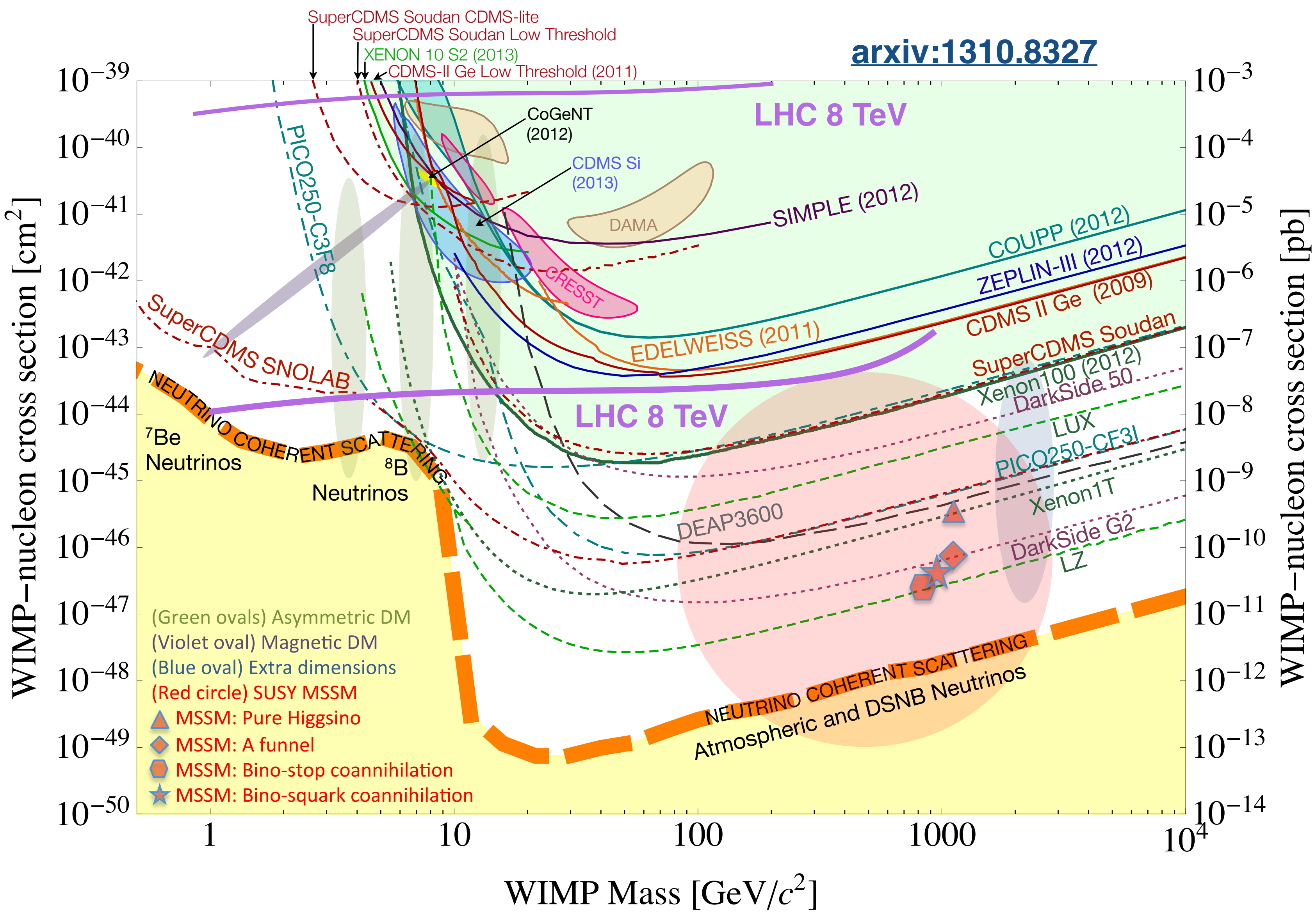

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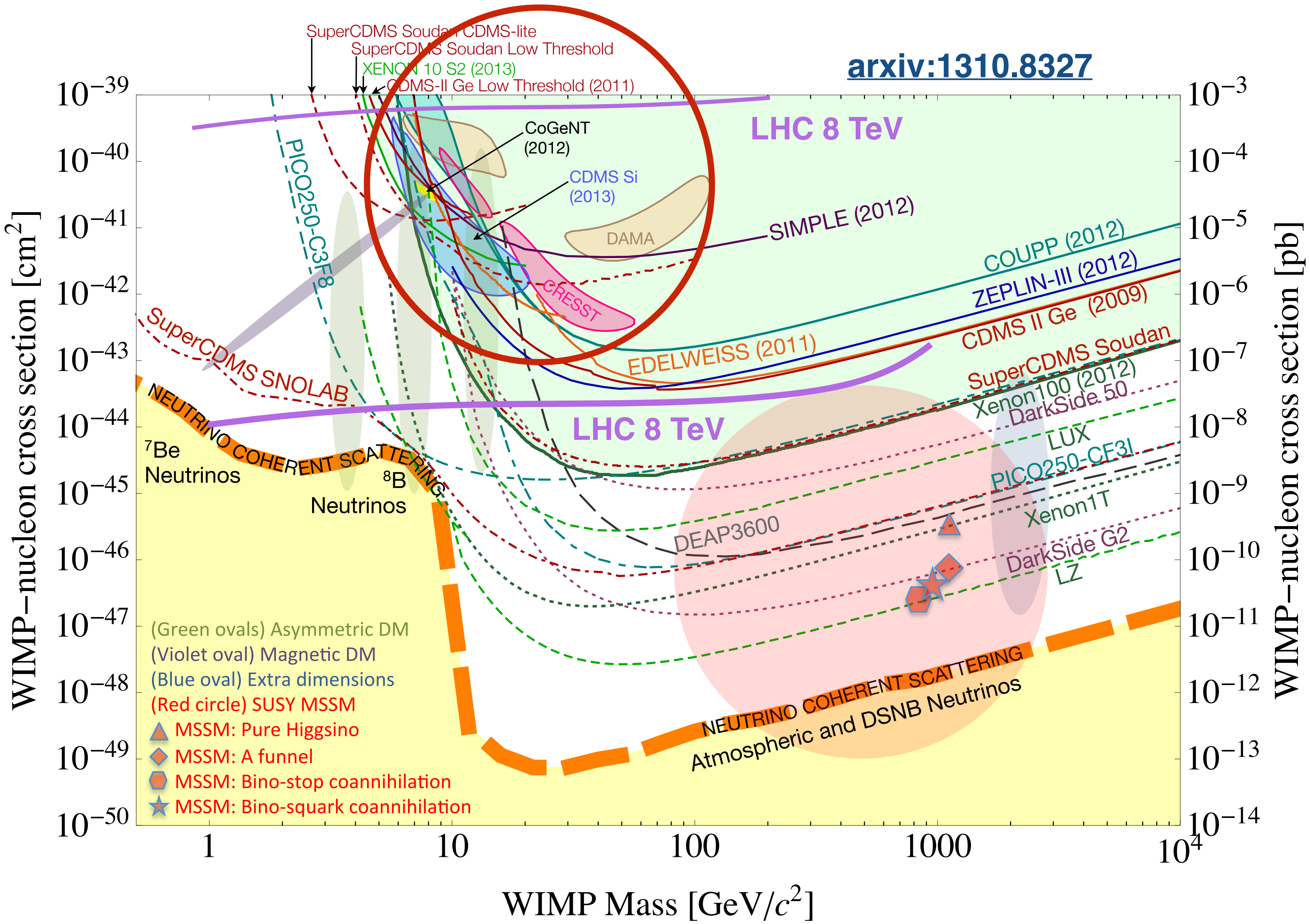
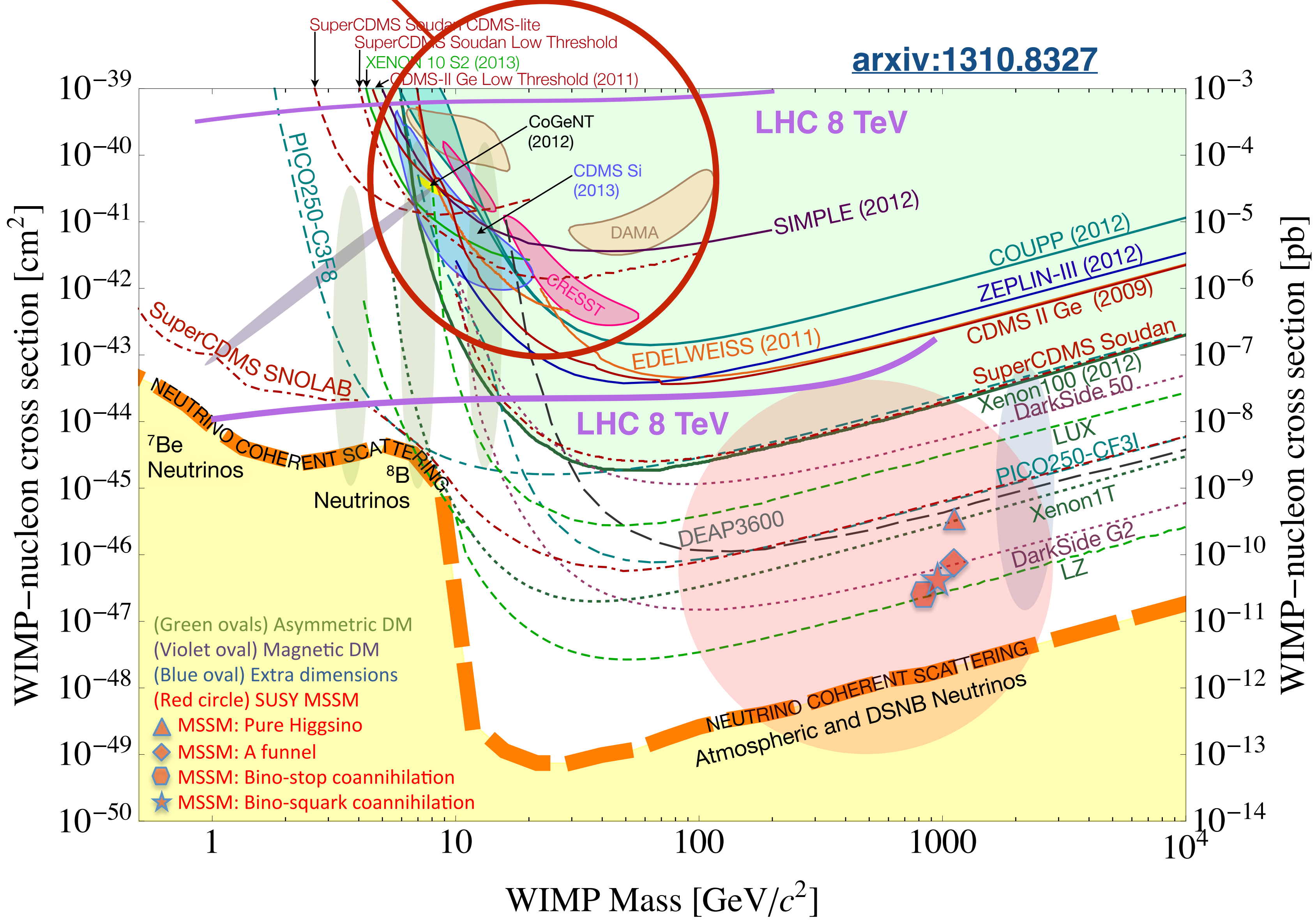


claims of **positive** signals

tension between results



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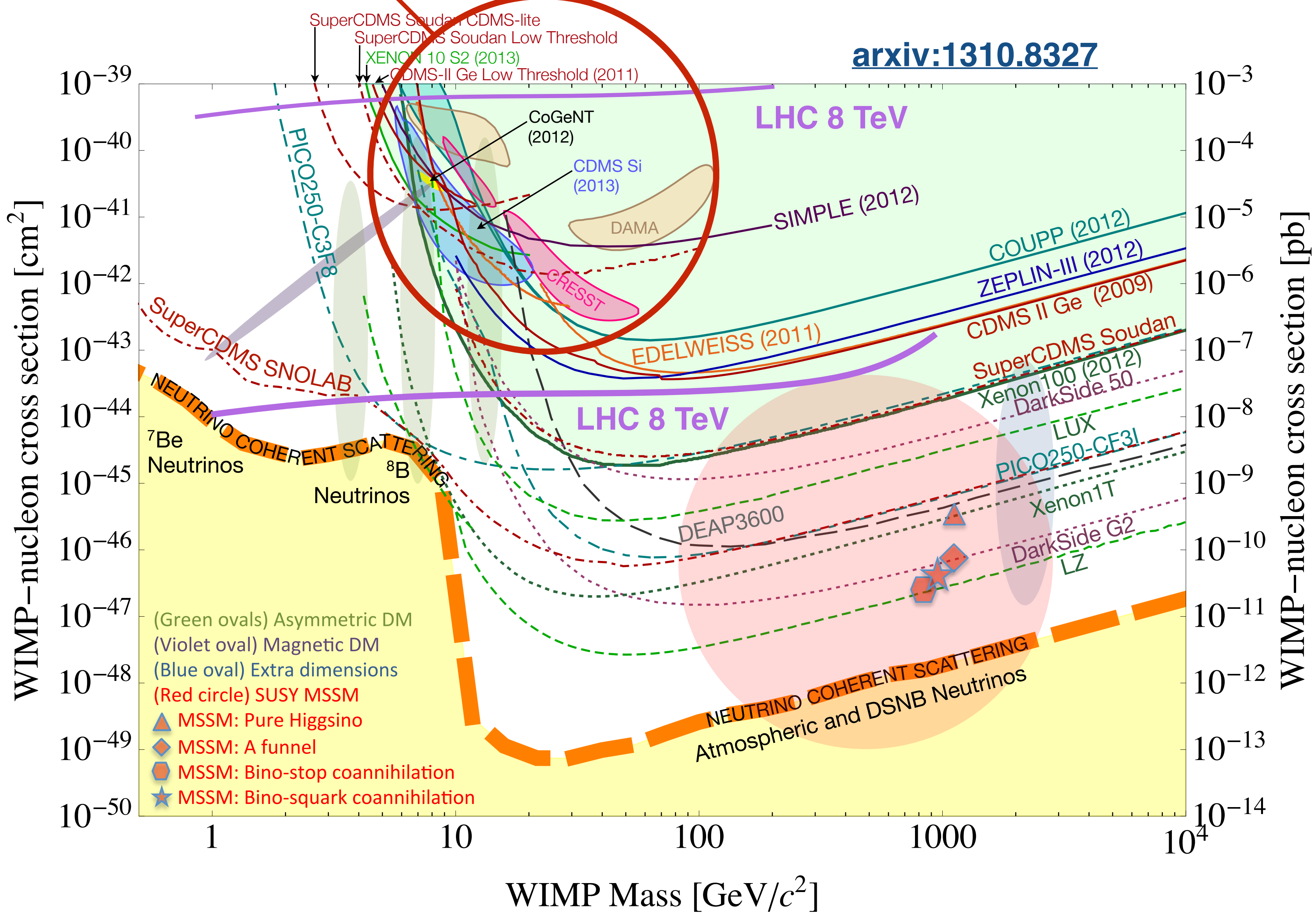


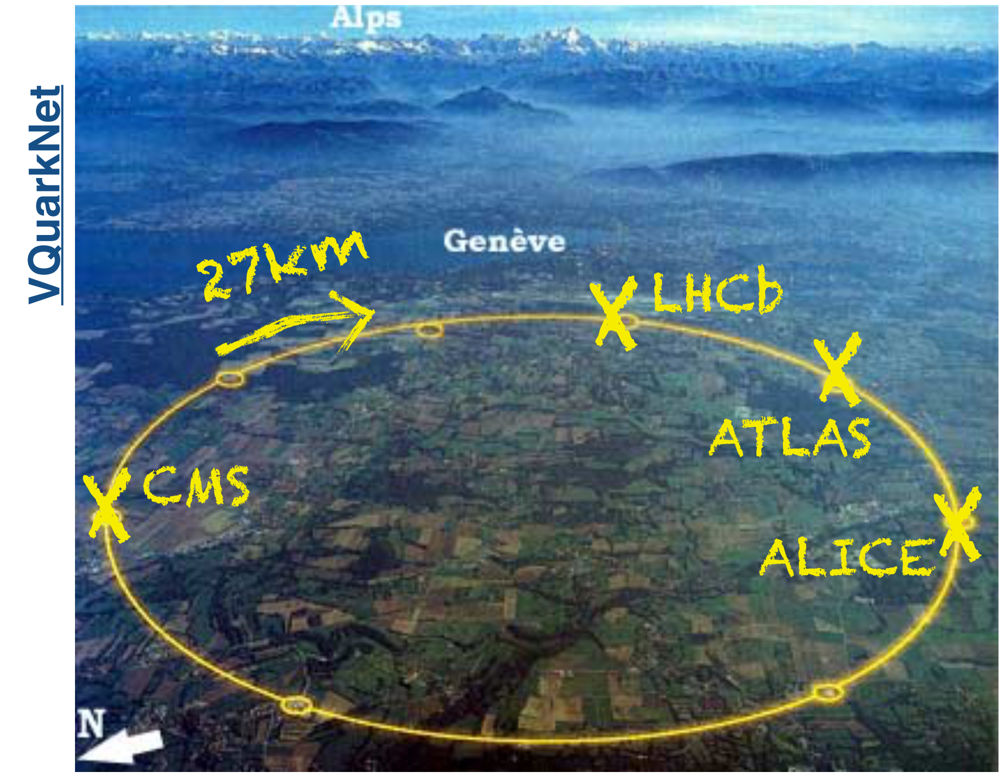
@collider: production in this mass range possible!
no astrophysical uncertainties!

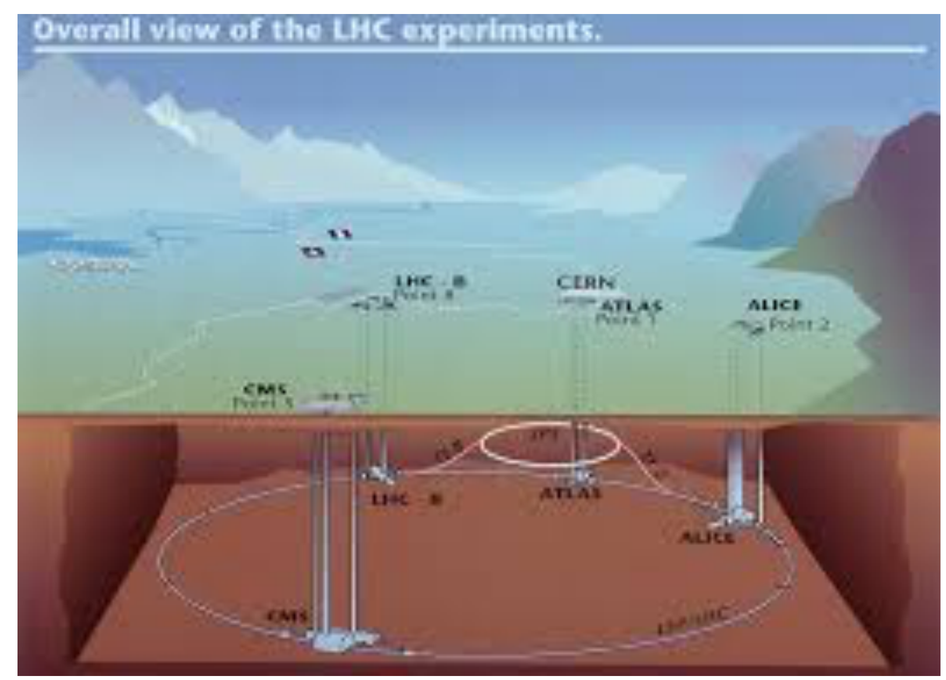
Large Hadron Collider (LHC)

- hadrons: particles built from (2 or 3) quarks
  - e.g. proton ("uud"), neutron ("ddu")
- 1232 superconducting dipole magnets
  - cooled by liquid He (1.9K)

- 392 quadrupole magnets
- collides protons, heavy ions or both
- collisions with intervals as short as 25ns
- centre-of-mass energies up to 14 TeV

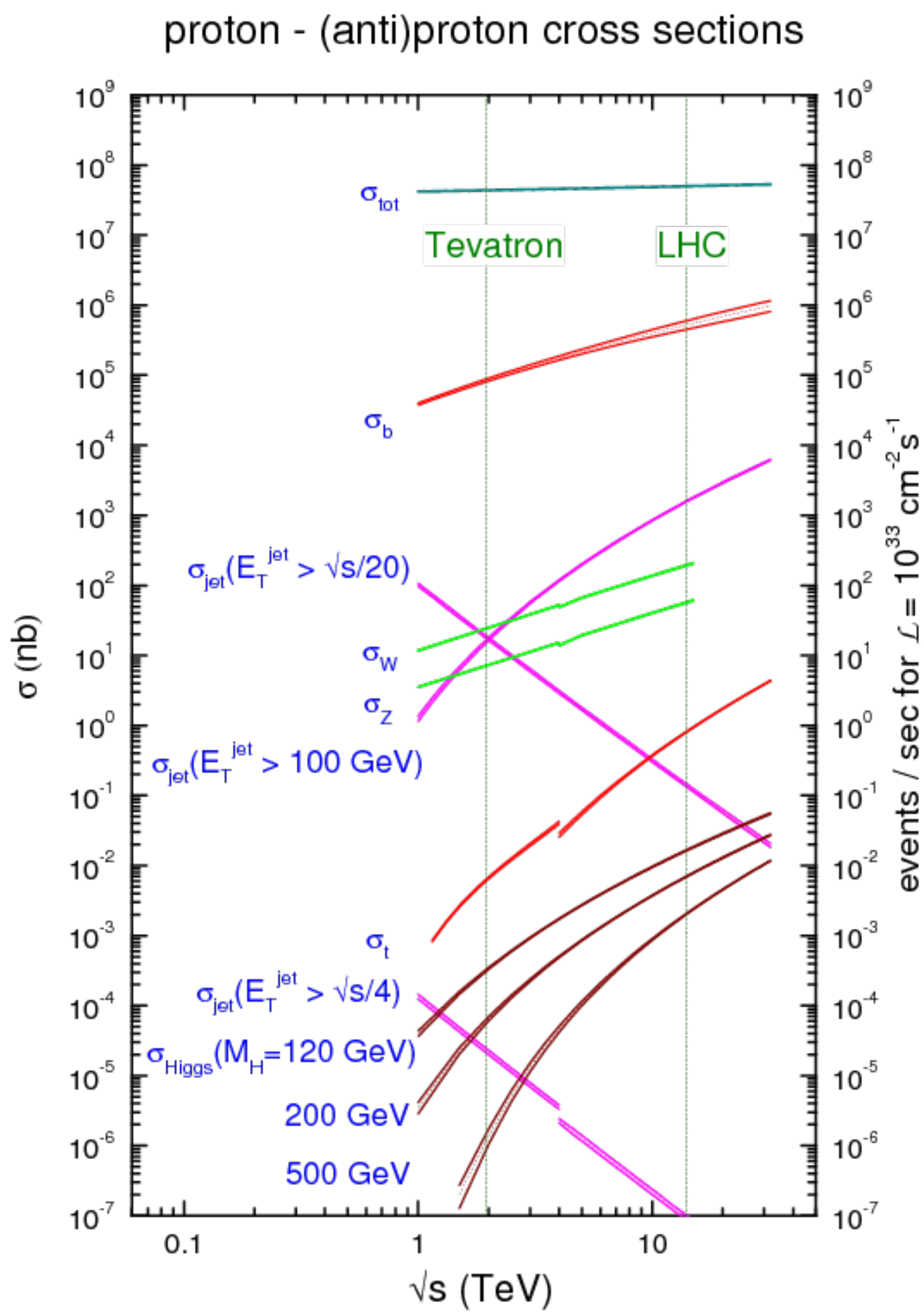
- 27km, 100m underground





The Background Challenge

- direct detection: “background free” searches
- collider searches: not exactly…



W.J. Stirling, private communication

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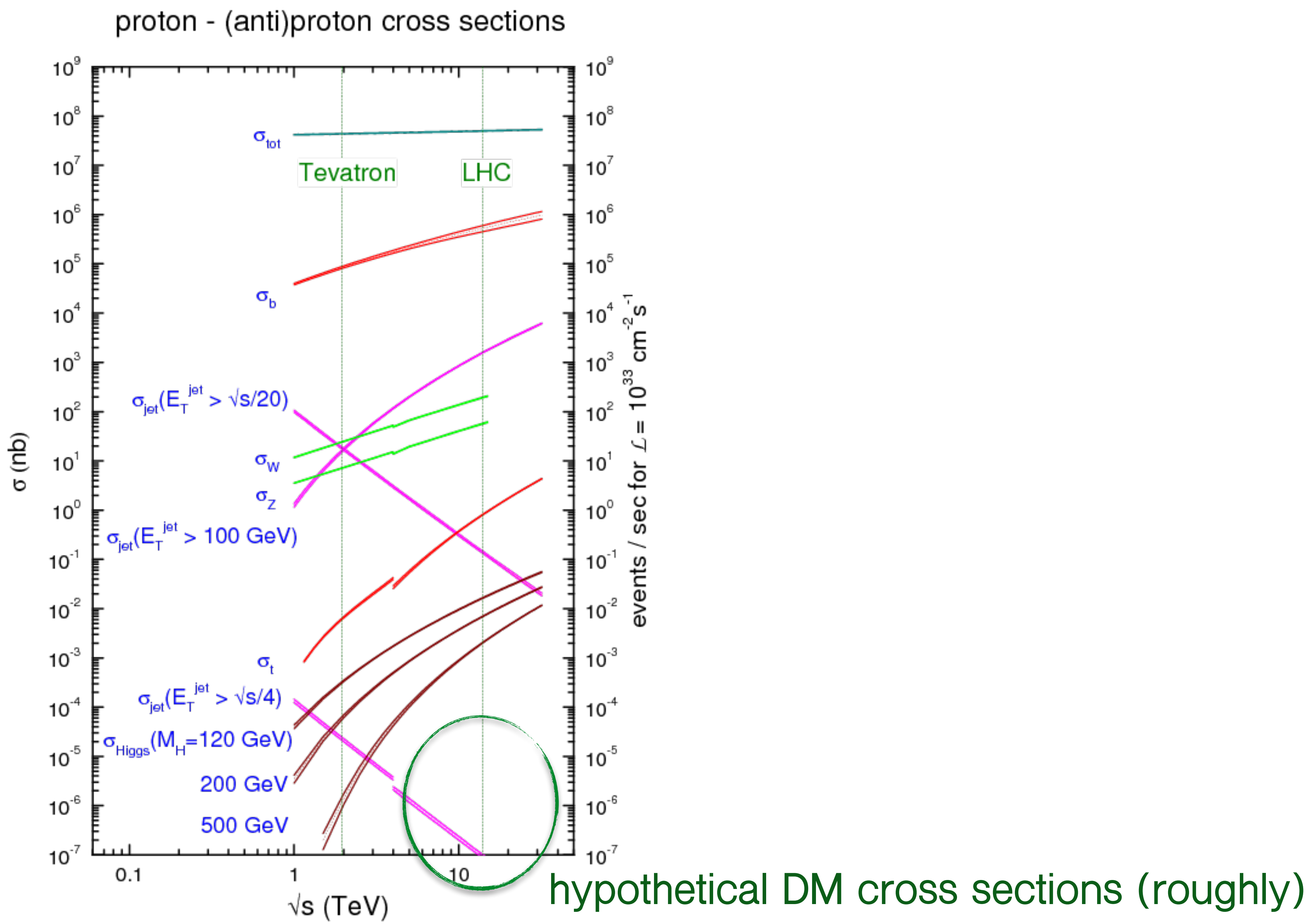
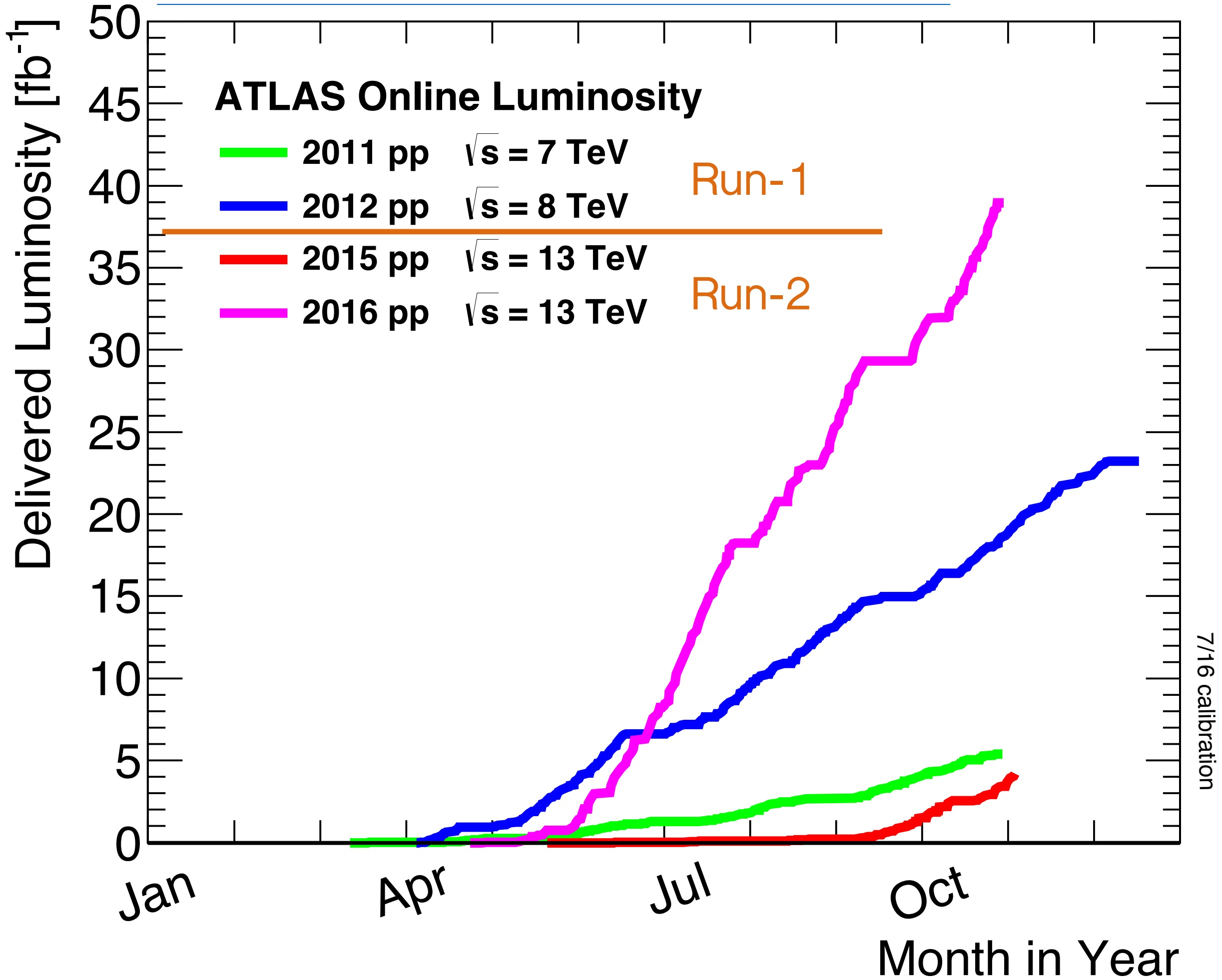


W.J. Stirling, private communication

Datasets and Future Milestones

- important figure of merit: integrated **luminosity** L —> amount of data
  - measured in 1/fb

AtlasPublic/LuminosityPublicResultsRun2



- more to come:

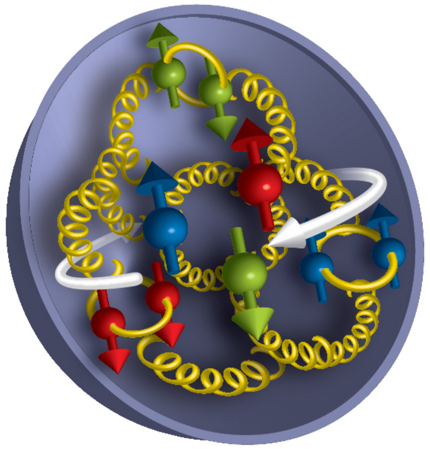
  ~100/fb by end of run-2 (2018)

  shutdown until 2021

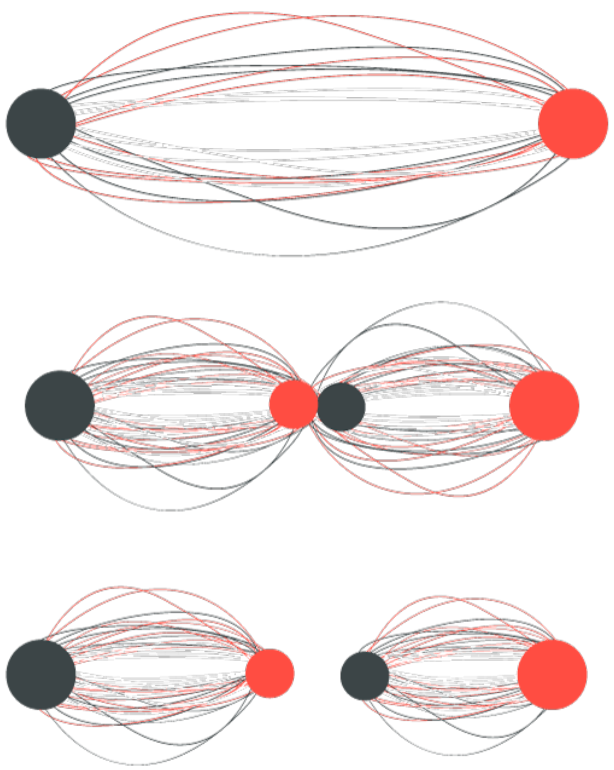
  ~300/fb by end of run-3 (2023)

Inside the proton

- protons are **not fundamental** particles!
  - made up of **3 valence quarks** + "sea quarks" & gluons
    - collectively: **partons**



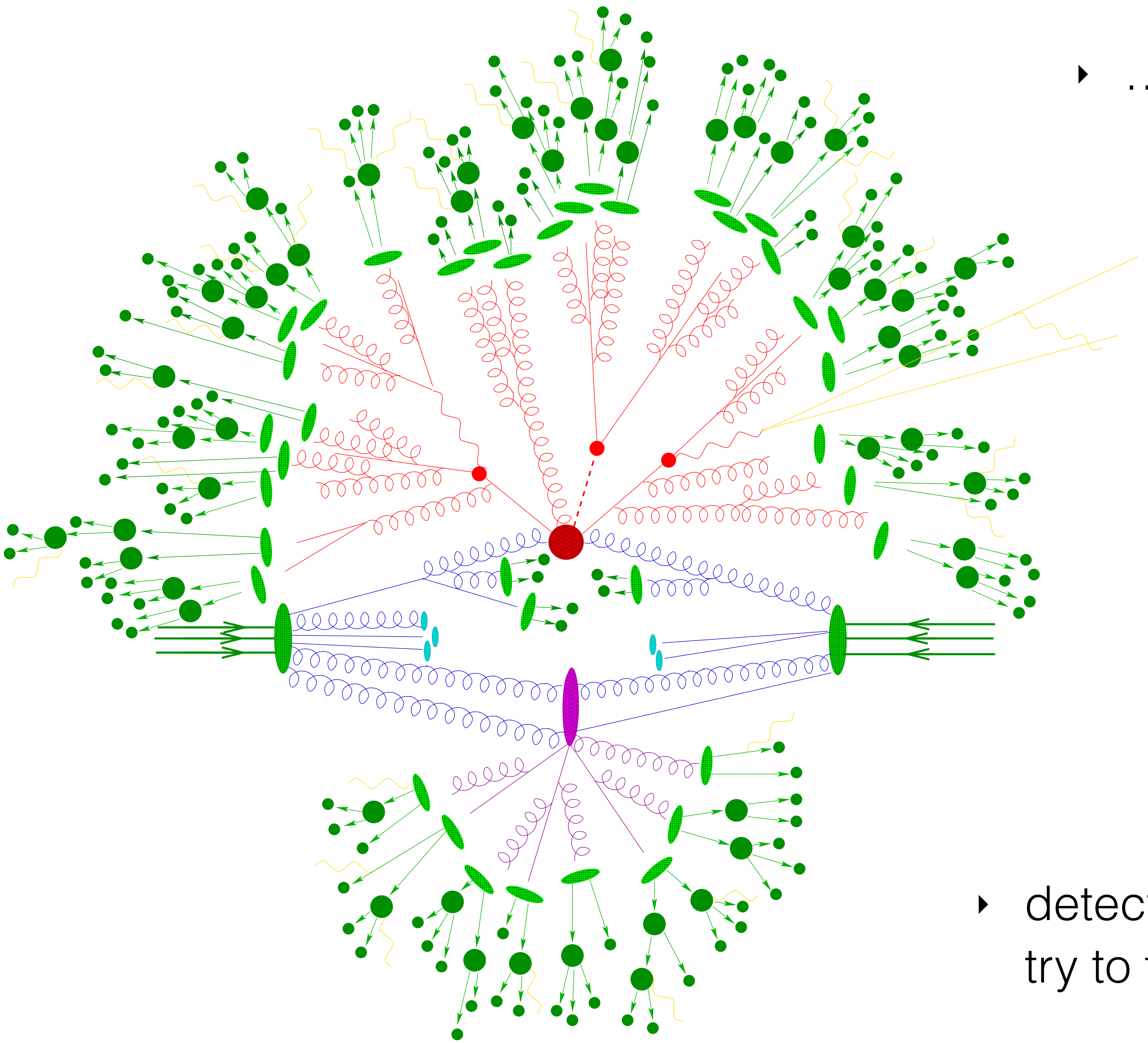
- special feature of strong interaction:



- gets **stronger** at larger distance!
  - like a rubber band pulled apart
- at some point, energy large enough to form new quarks ($E=mc^2$)
- hadrons are formed => "**jets**"
- **confinement** of quarks in hadrons, i.e. there are **no free quarks**

Proton-Proton Collisions

- proton-proton collisions are actually parton-parton collisions

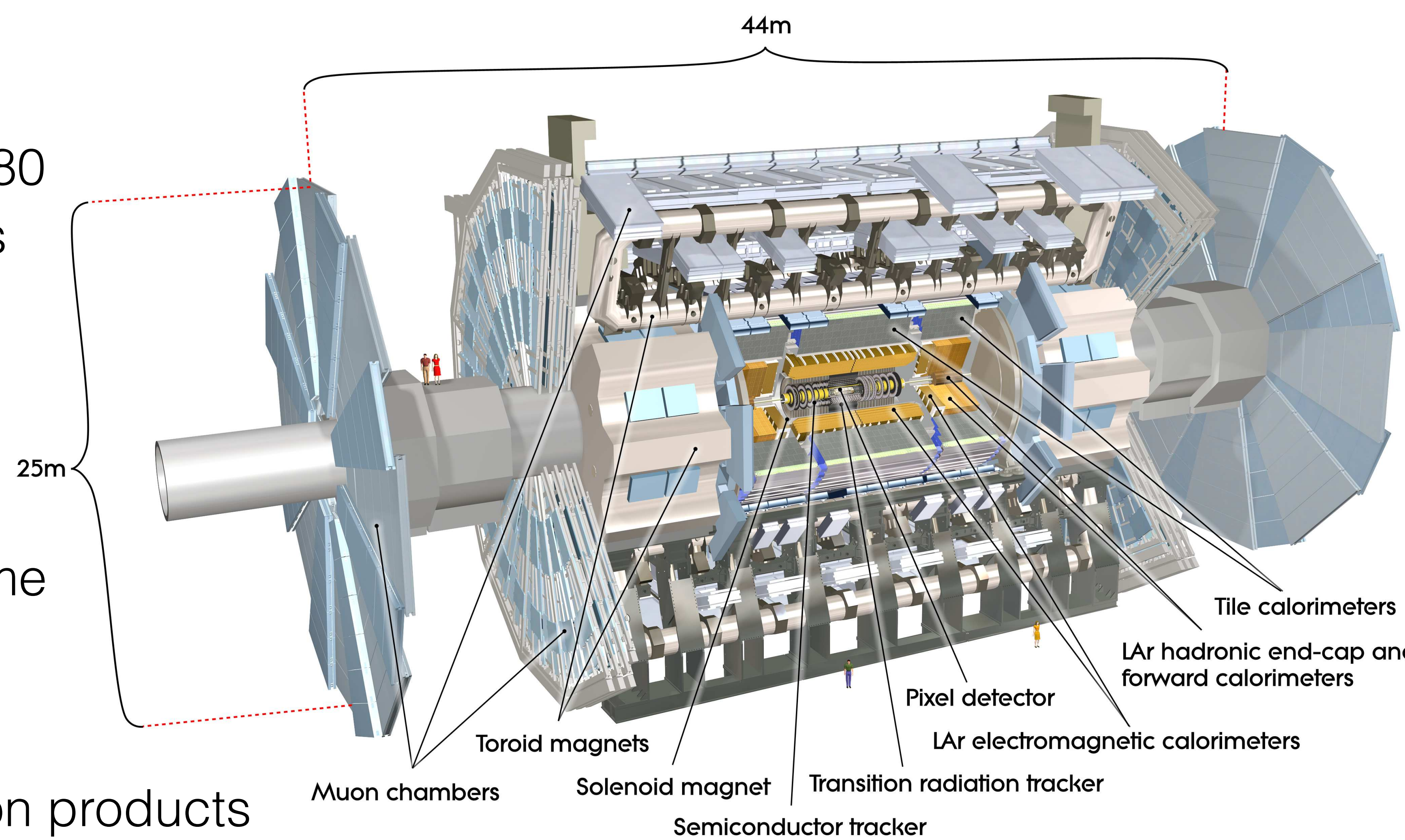


- … and they are messy

- detectors collect the debris and try to find interesting signatures

ATLAS

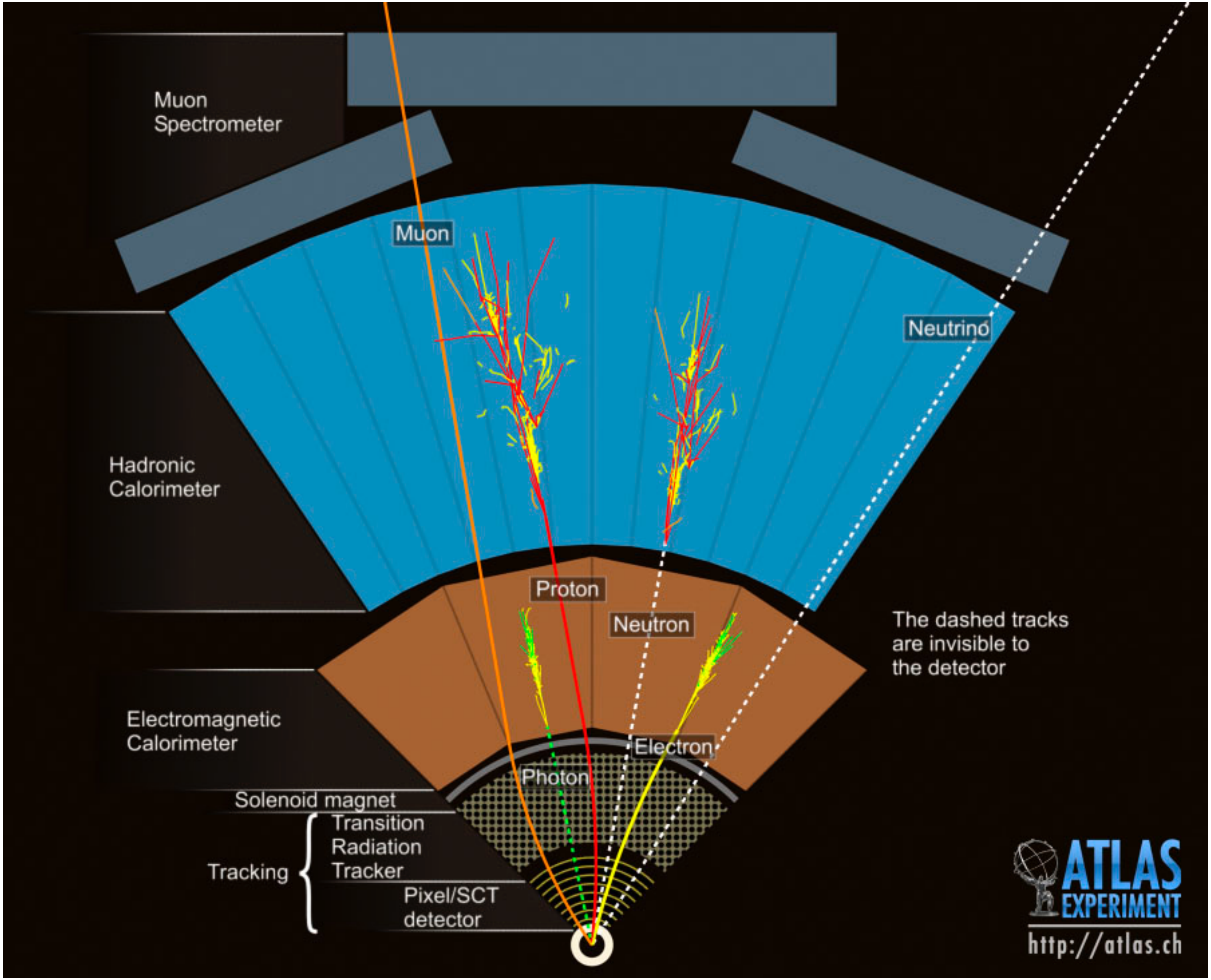
- large collaboration
  - ~5000 scientists from 180 institutes in 38 countries
- **general-purpose** detector
  - broad physics programme
- **precisely measure** collision products (energies, momenta, position, charge…)



https://cds.cern.ch/record/1095924

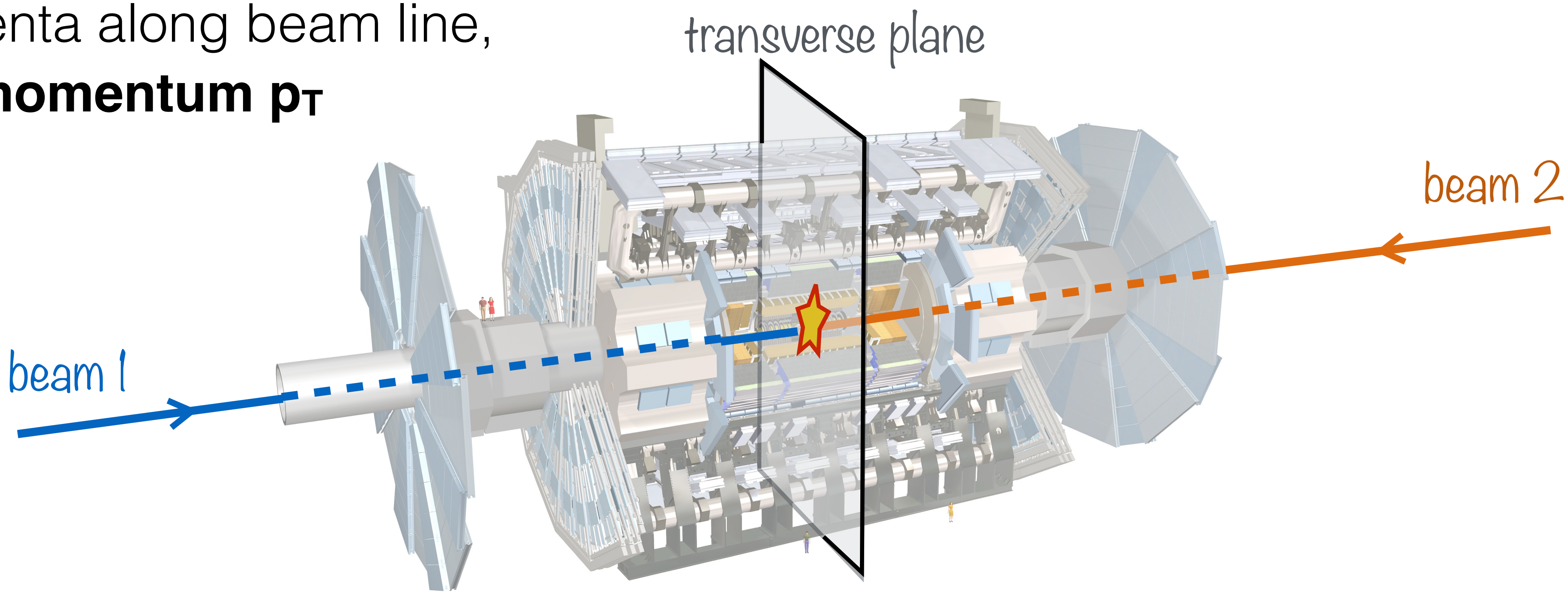
- **reconstruct** physics objects (electrons, photons, jets…)
- non-interacting particles “carry away” energy (part of many new physics signals)
  - **missing transverse energy** (**E_T^{miss}**) calculated from all measured momenta

Particle Detection



The Invisible

- initially: all momenta along beam line, **no transverse momentum p_T**



  - vector sum of transverse momenta after collision has to **sum up to 0**!

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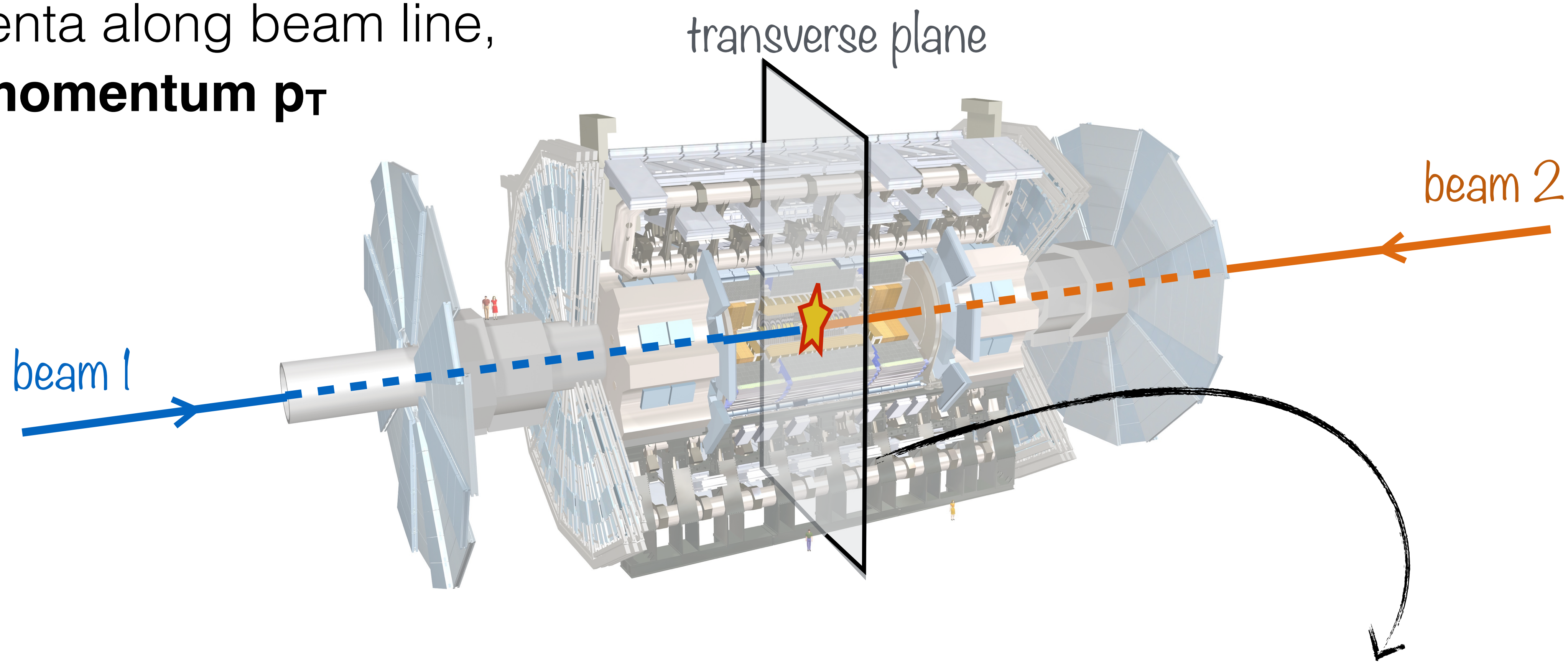

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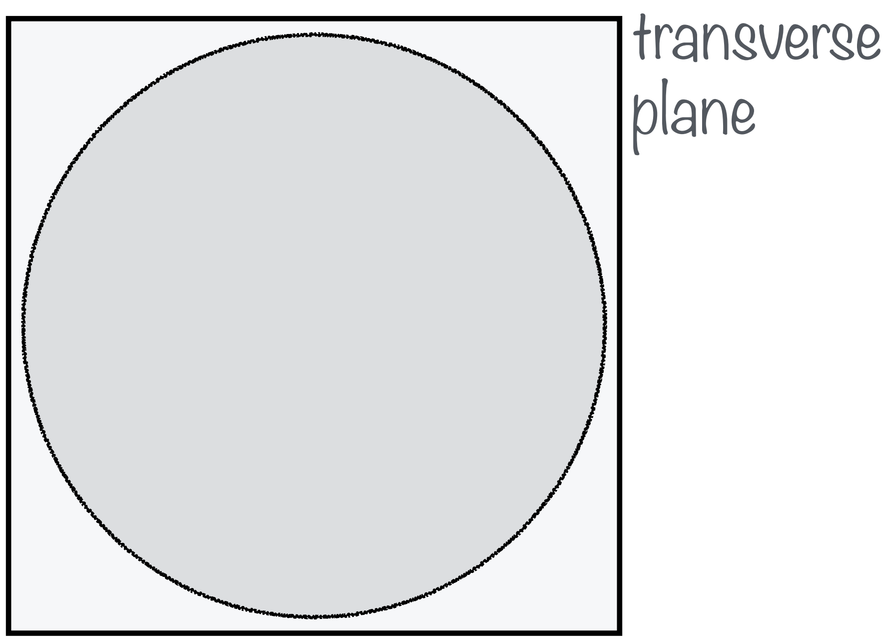

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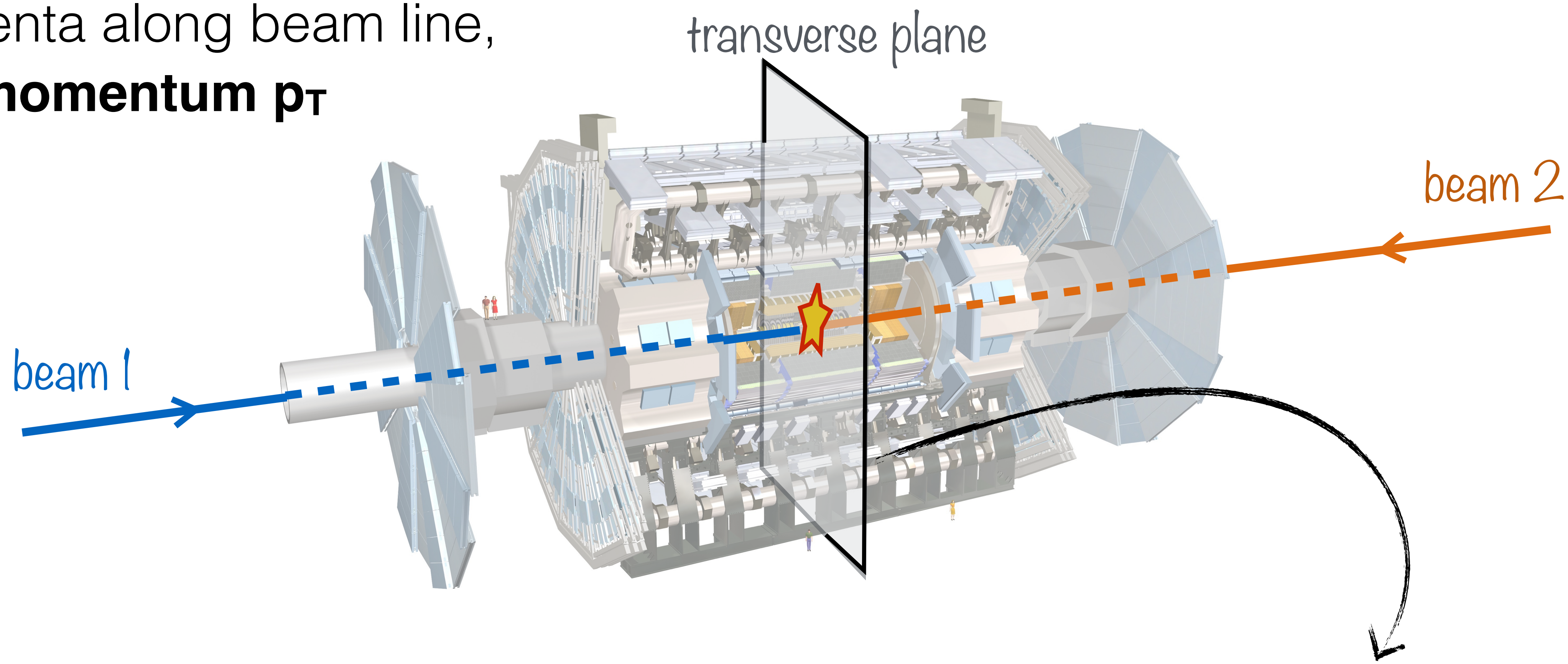

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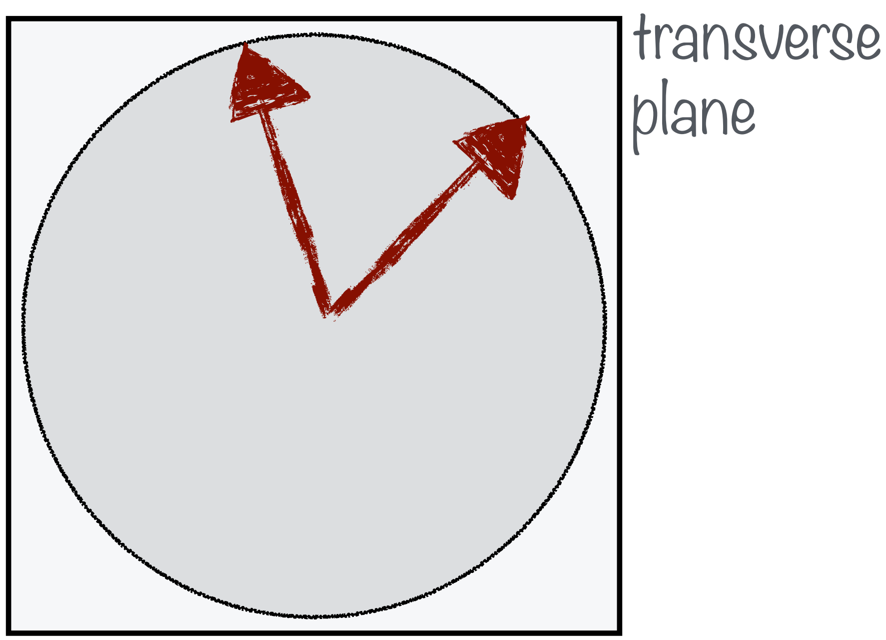

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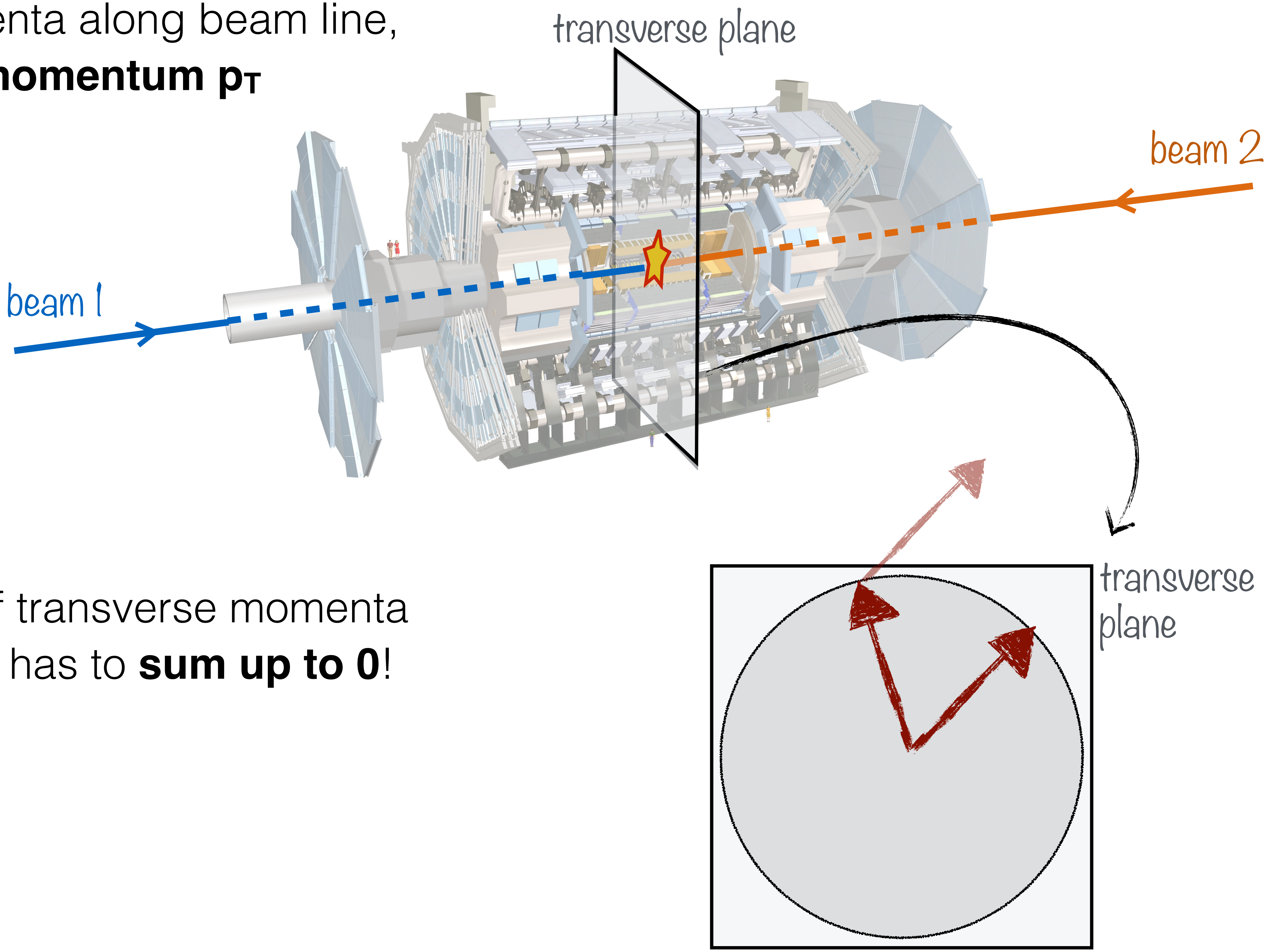

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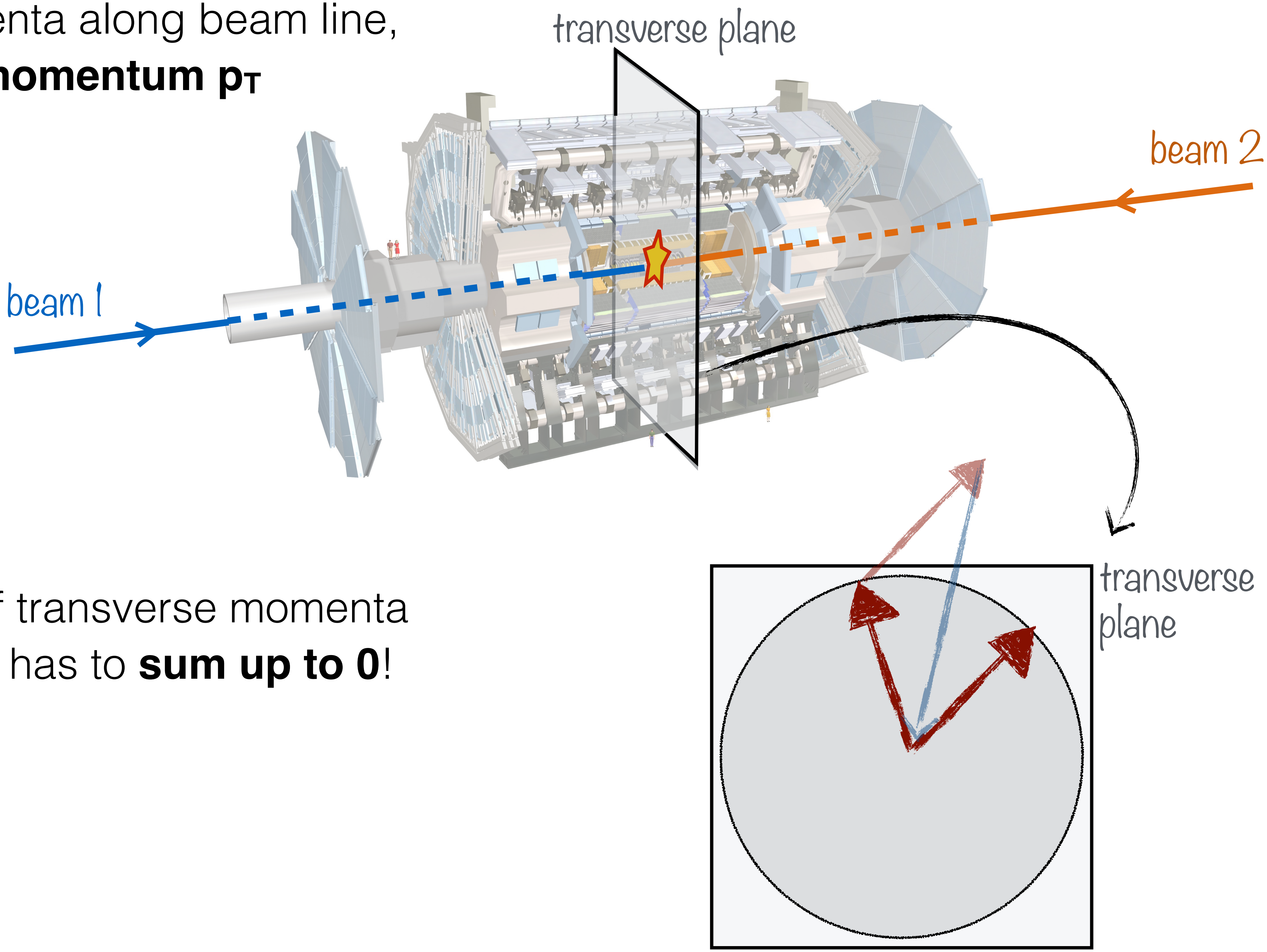

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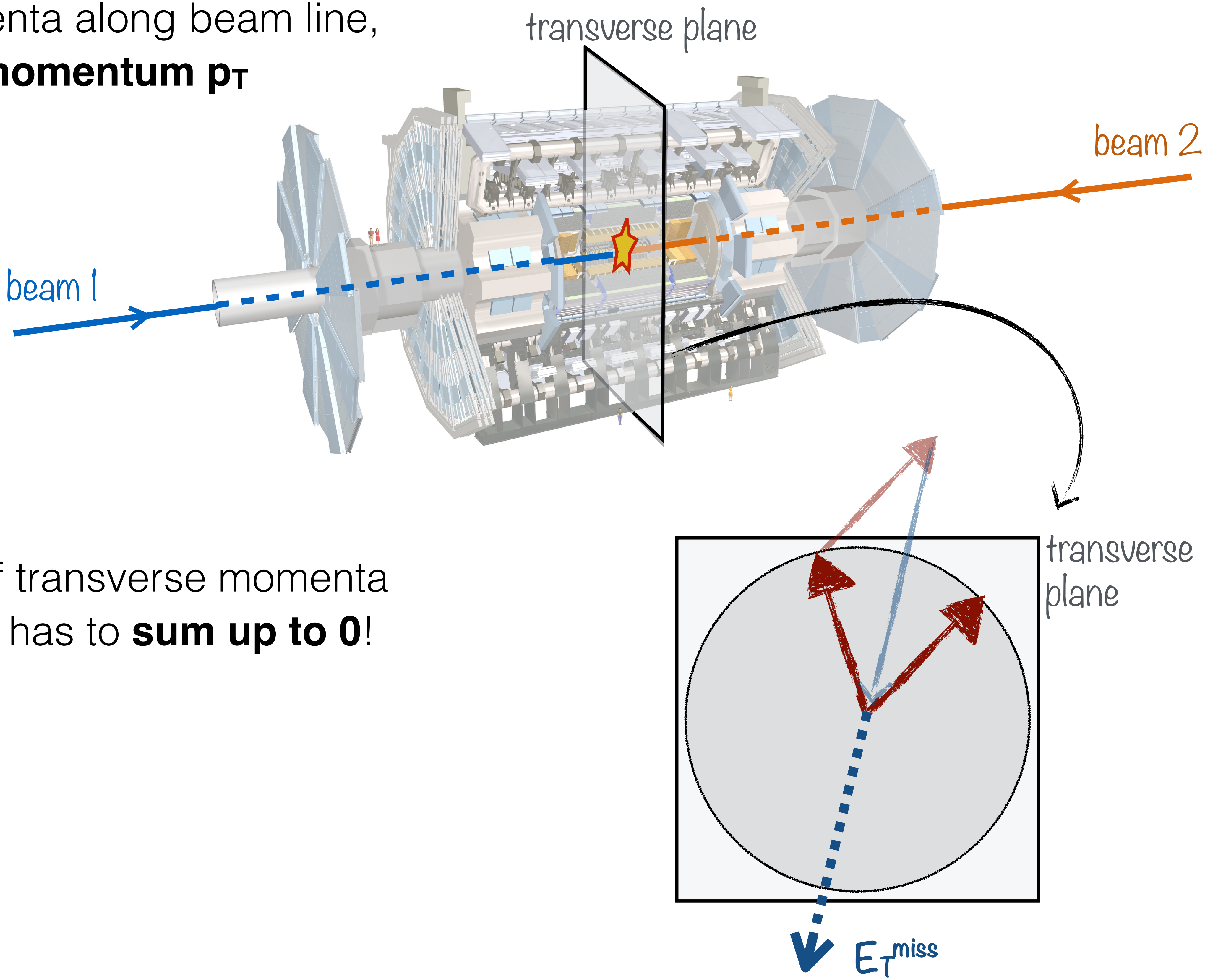

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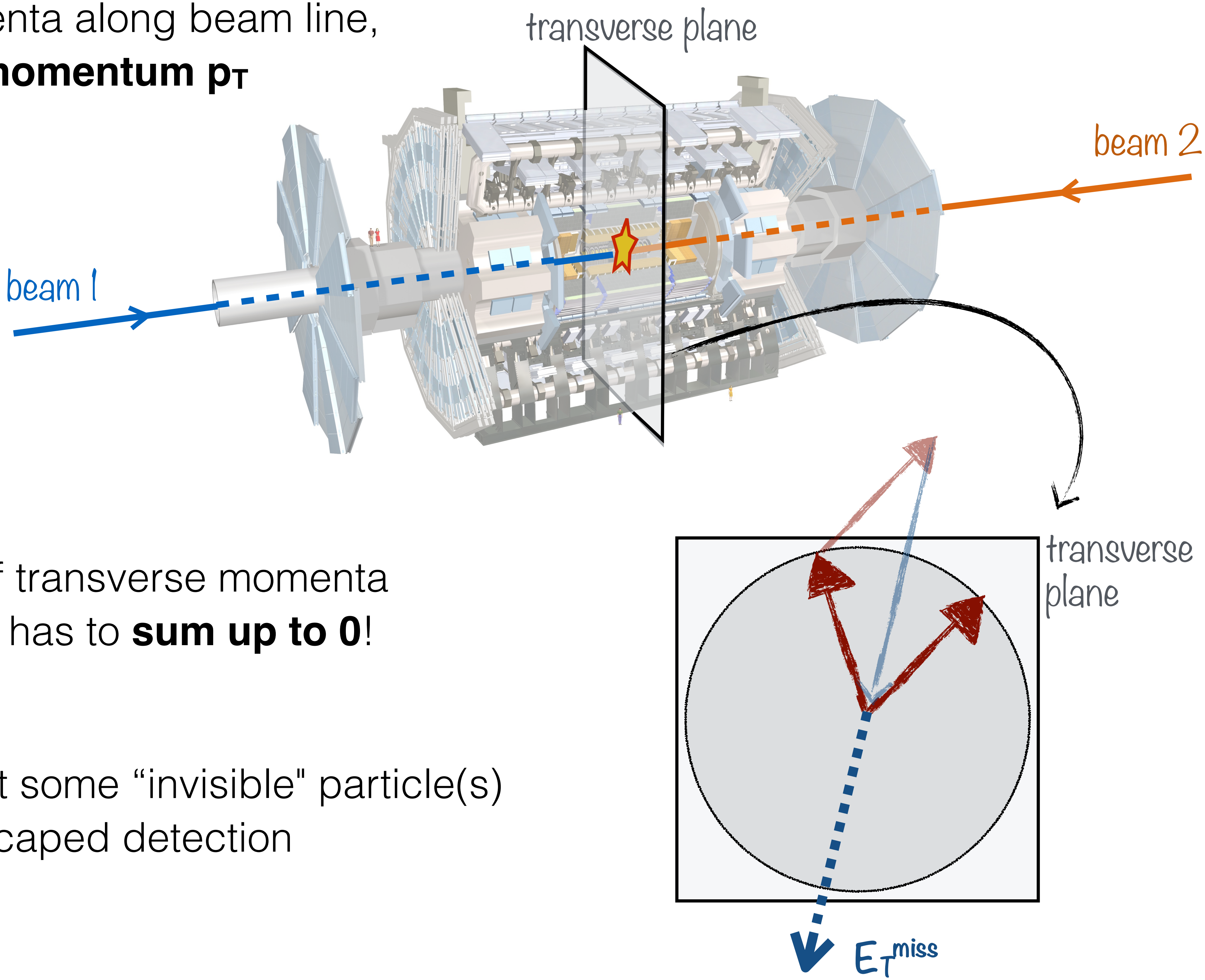


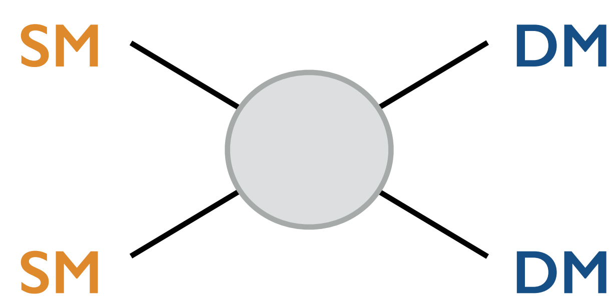
- vector sum of transverse momenta after collision has to **sum up to 0**!
  - infer that some “invisible" particle(s) have escaped detection

Collider WIMP Signature

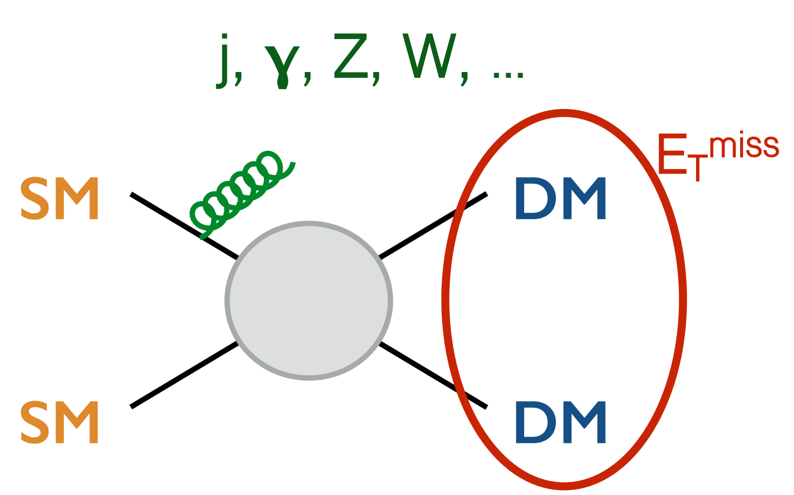
- **WIMPs:**
  - **massive** —> can account for relic density
  - **interacting** = interacting non-gravitationally
  - **weakly** interacting

    —> escape collider experiment **undetected**
    - **additional** (high pT) object to trigger on
      - missing transverse energy from recoiling WIMPs

=> "X+E_T^{miss}" searches

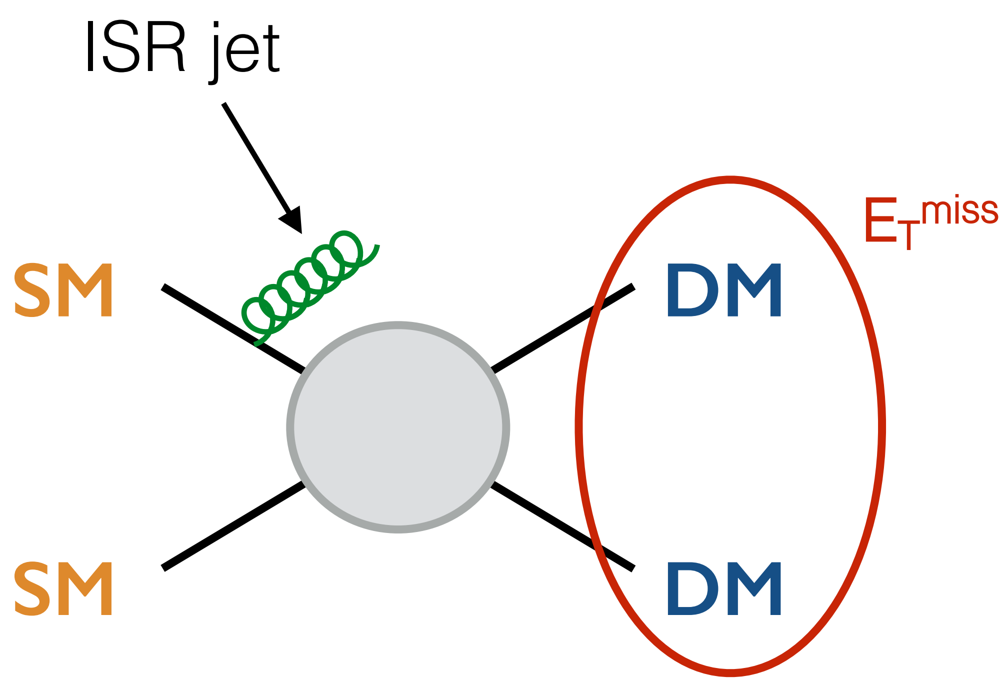


e.g. "initial state radiation" (ISR)



The Workhorse: jet+E_T^{miss} ("Mono-jet")

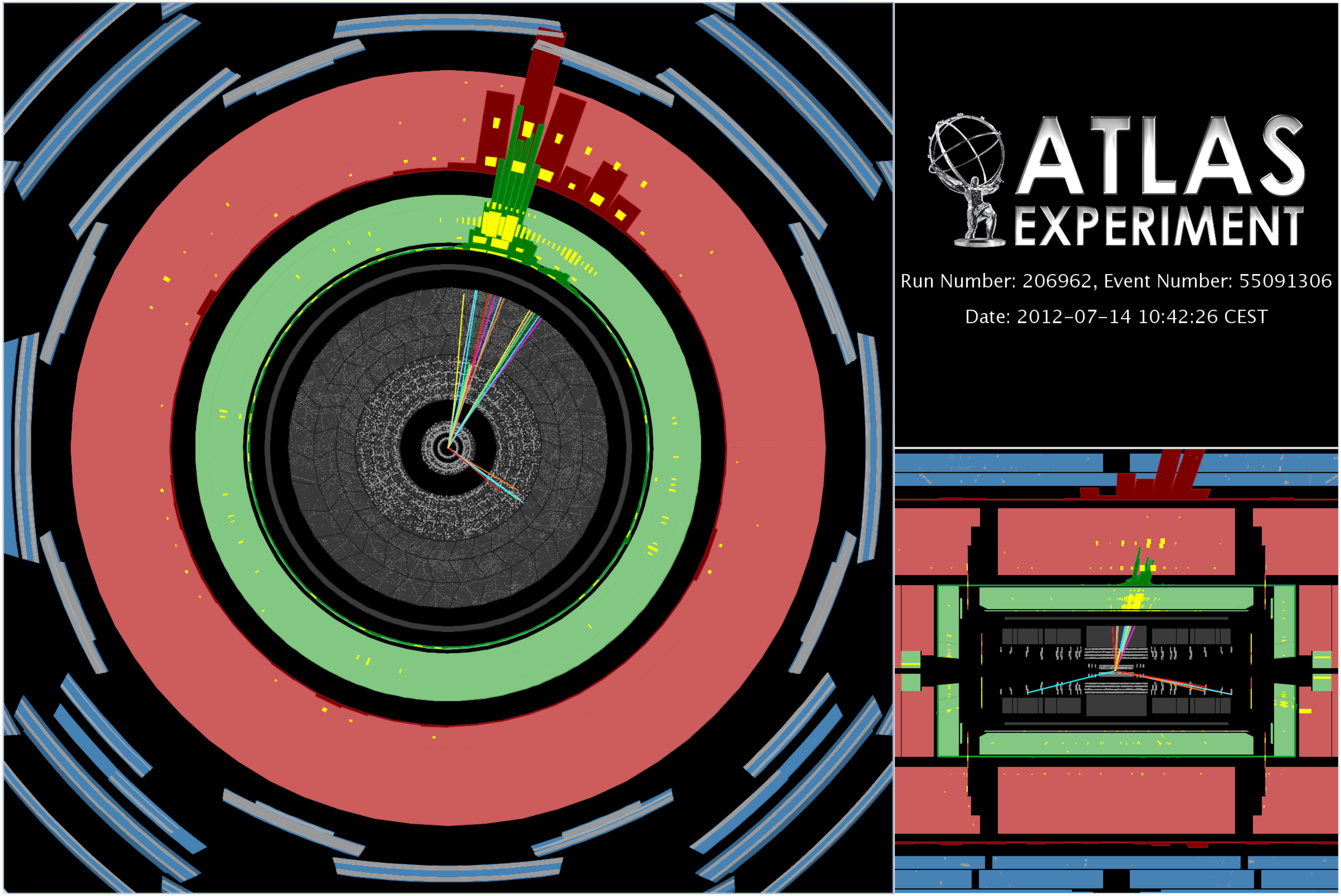
- large cross sections for jet production at hadron collider



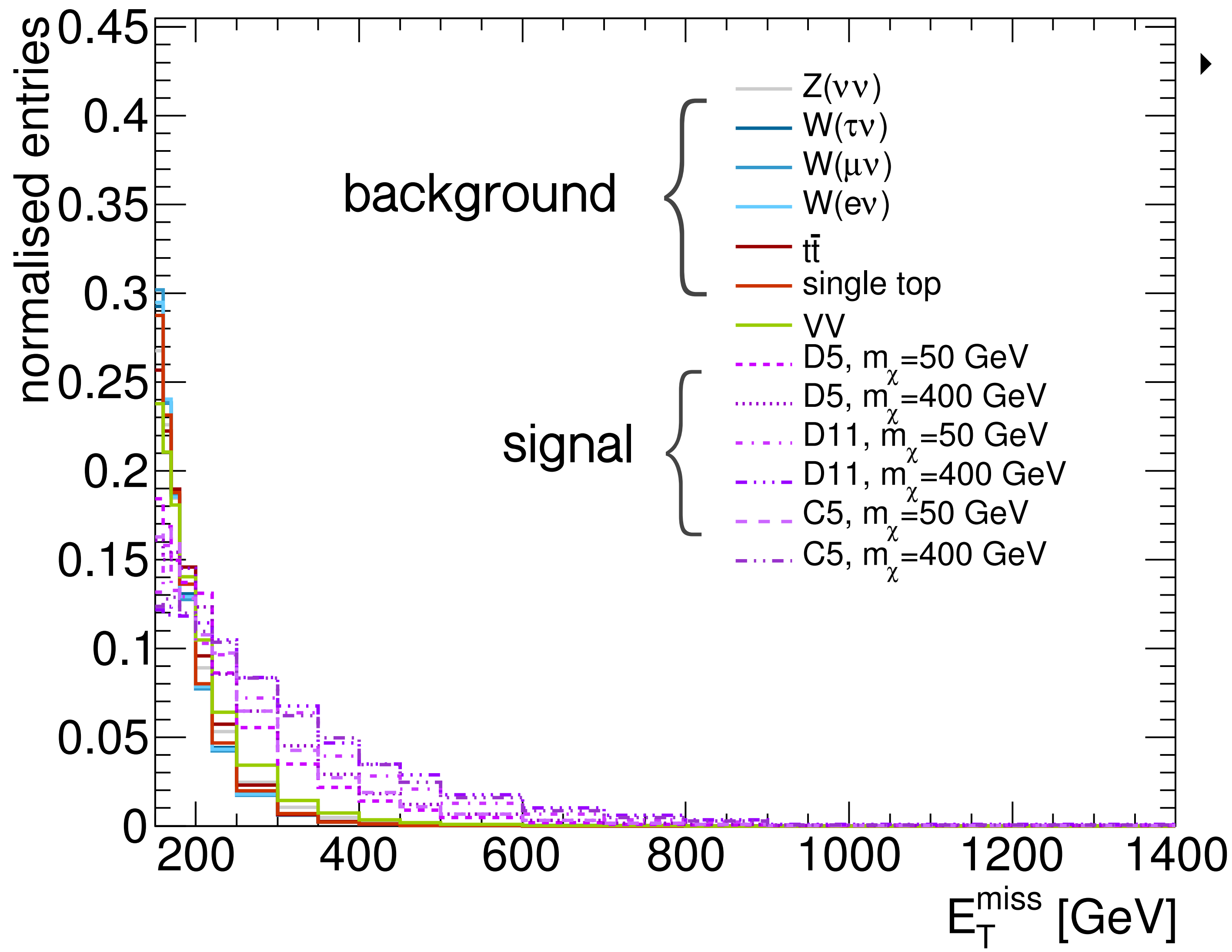
- highly energetic **jet**
  + large **missing E_T**

Real Life Event Display

ATLAS-CONF-2012-147



Discrimination

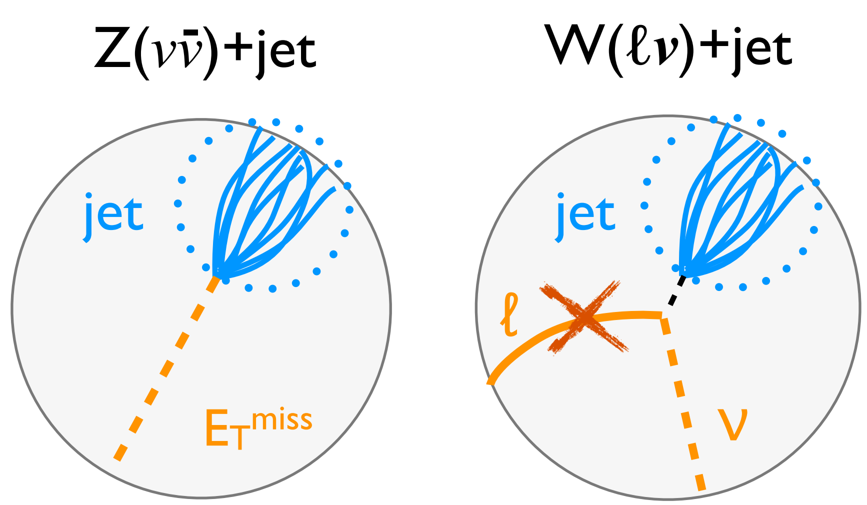


- Monte Carlo (MC) simulation
  - larger WIMP mass => higher E_T^{miss}
  - missing E_T as discriminant variable

=> search for excess over SM prediction at high E_T^{miss}

Background Estimation

- main challenge: **estimation of irreducible/dominant backgrounds**
  - e.g. jet+E_T^{miss}:



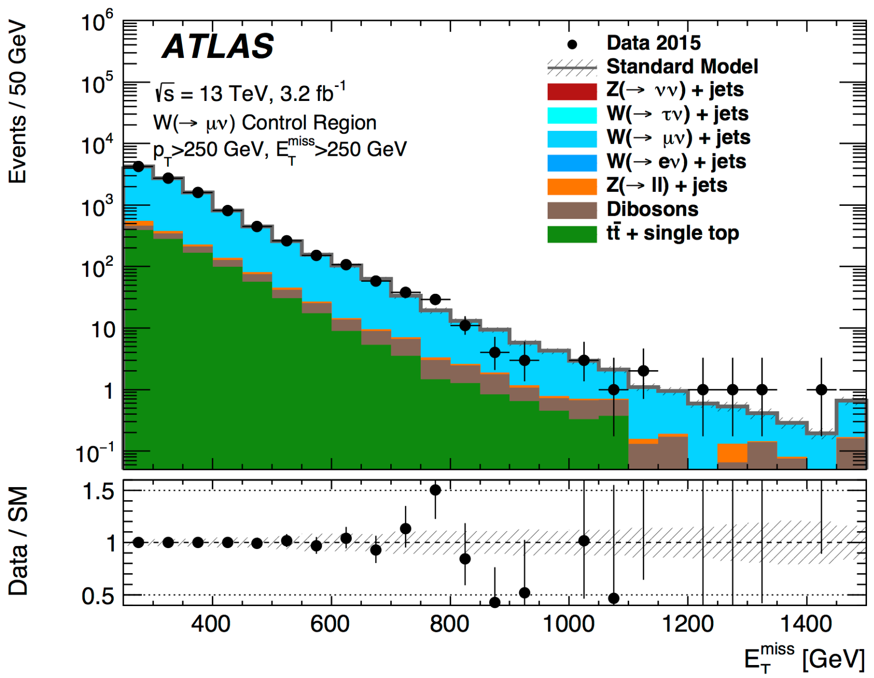
- simulation constrained using **data** in **control regions** (CR)
  - **non-overlapping** with signal region (SR)
    - e.g. jet+E_T^{miss}
      - **CRs**: select Z($\ell\ell$)/W($\ell\nu$) events (i.e. explicitly **select leptons**)
      - **SR**: **veto** leptons
- typically "global fit" to all CRs simultaneously
  - constrain normalisation/shapes

Example: jet+E_T^{miss}

[Phys. Rev. D 94, 032005]

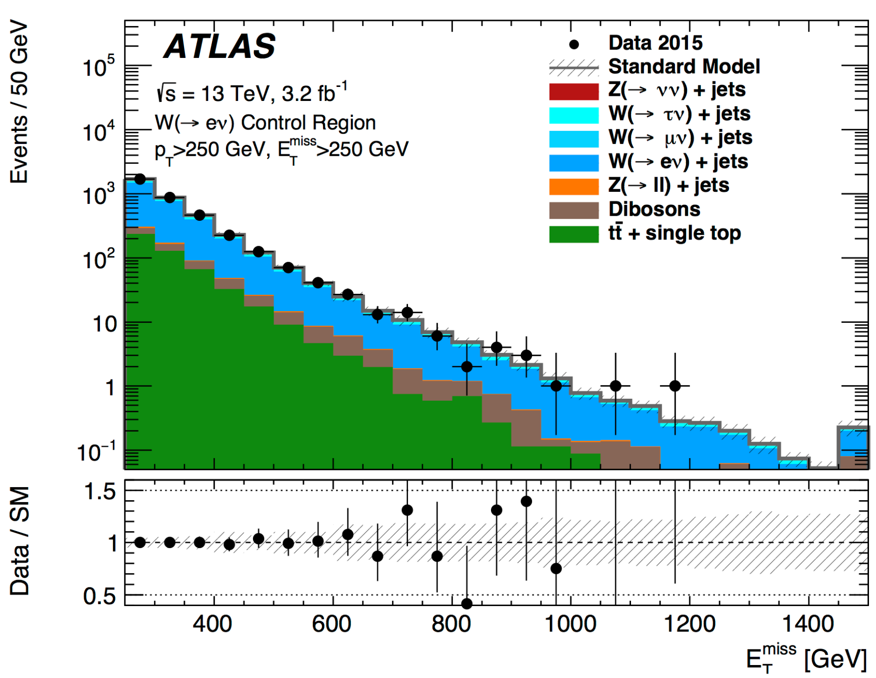
W($\mu\nu$)+jets CR

- 1 muon, 0 electrons
- m_T in [30,100] GeV



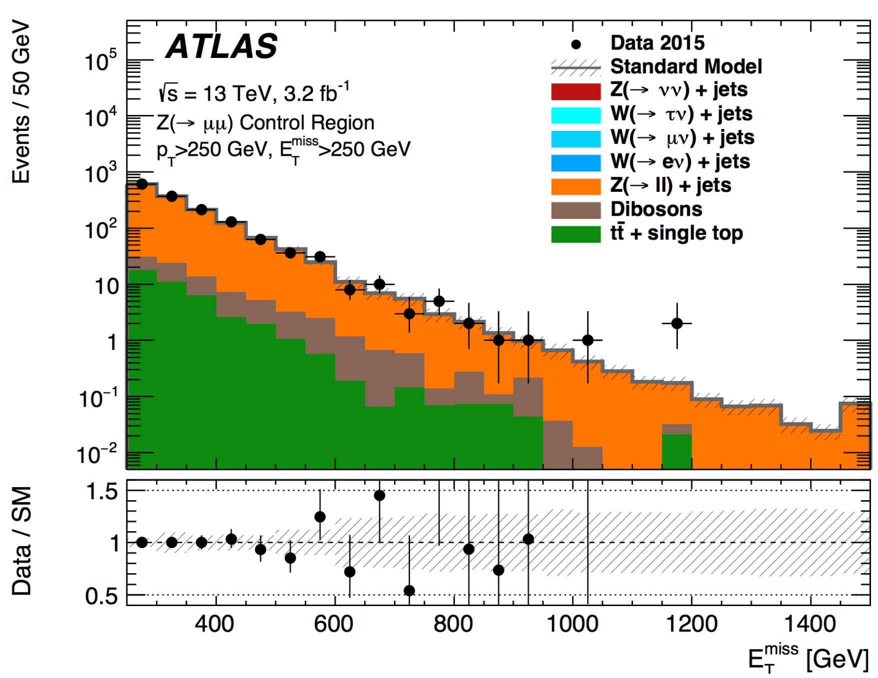
W(eν)+jets CR

- 1 electron, 0 muons



Z($\mu\mu$)+jets CR

- 2 muons
- m_{ll} in [66,116] GeV



$m_T=\sqrt{(2p_T^{\ell}E_T^{miss}(1-\cos(\Delta\phi(\ell,E_T^{miss}))))}$

Example: jet+E_T^{miss}

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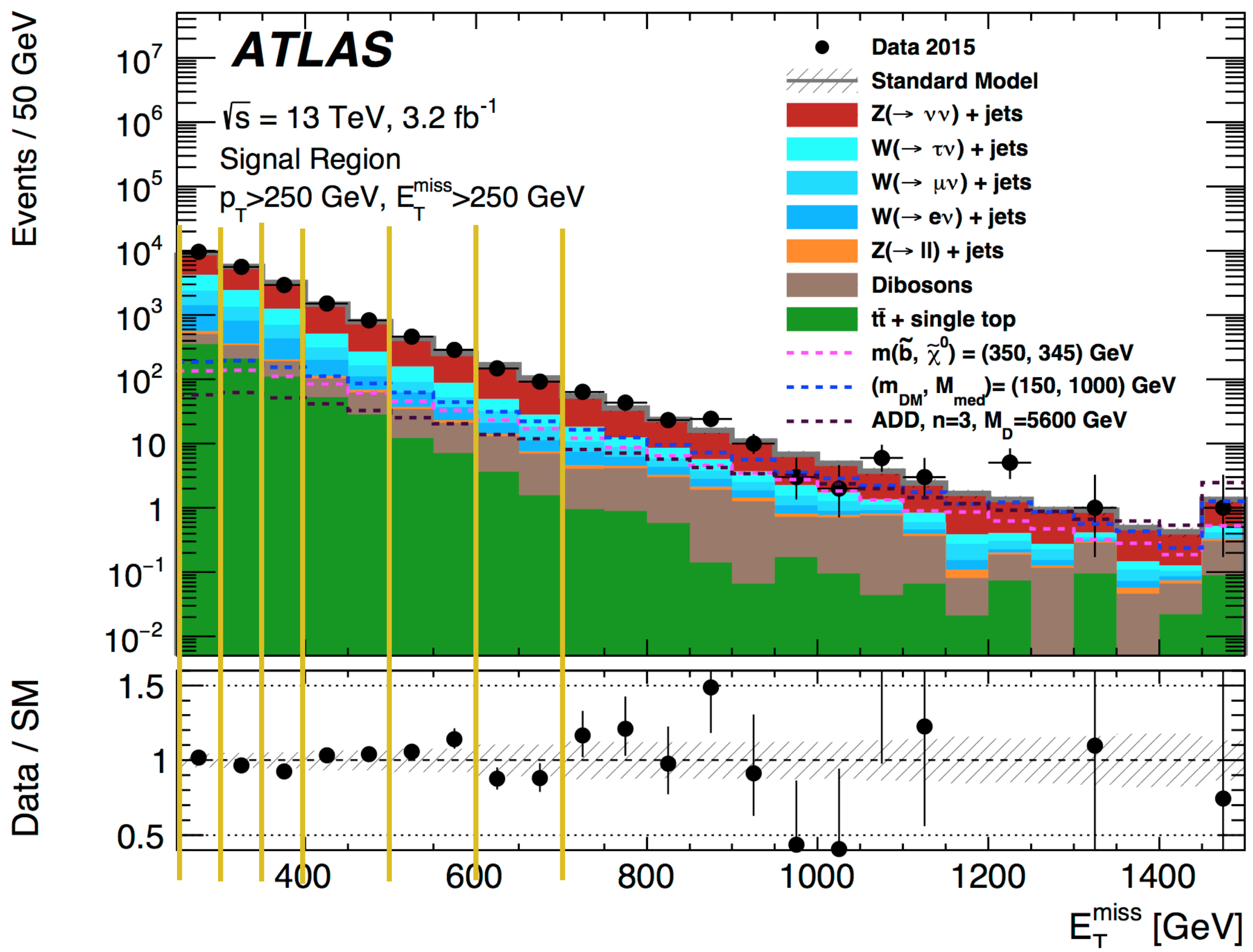
- **SRs**: muon and electron **veto**
  - inclusive and exclusive in E_T^{miss}

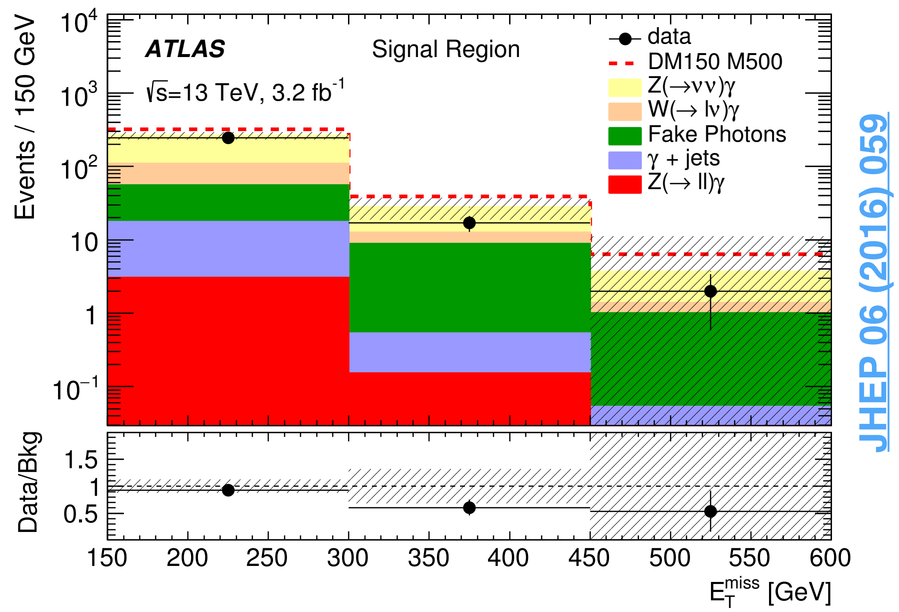


- largest uncertainties:
  - W/Z transfer: 2-4%
  - data statistics in CRs: up to 10%
  - theory uncertainties on top: 3%

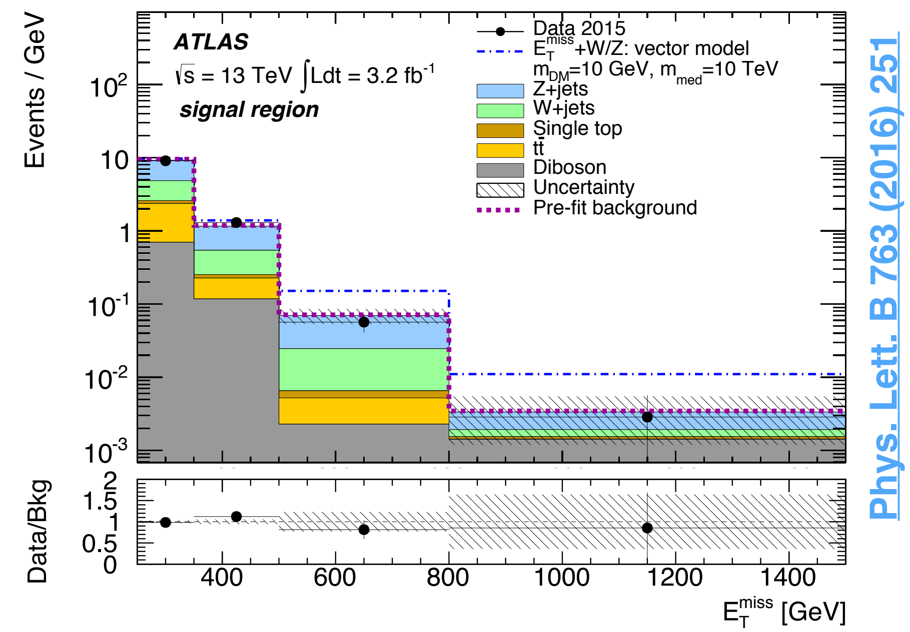
no significant excess

More X+E_T^{miss} Searches

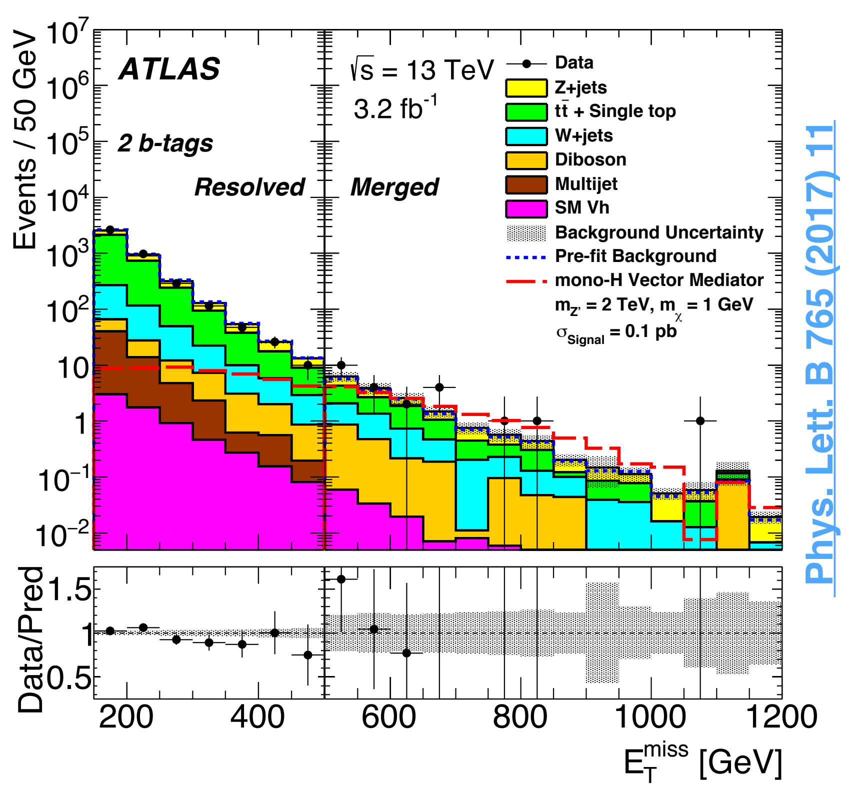
- X can also be…
  - a photon

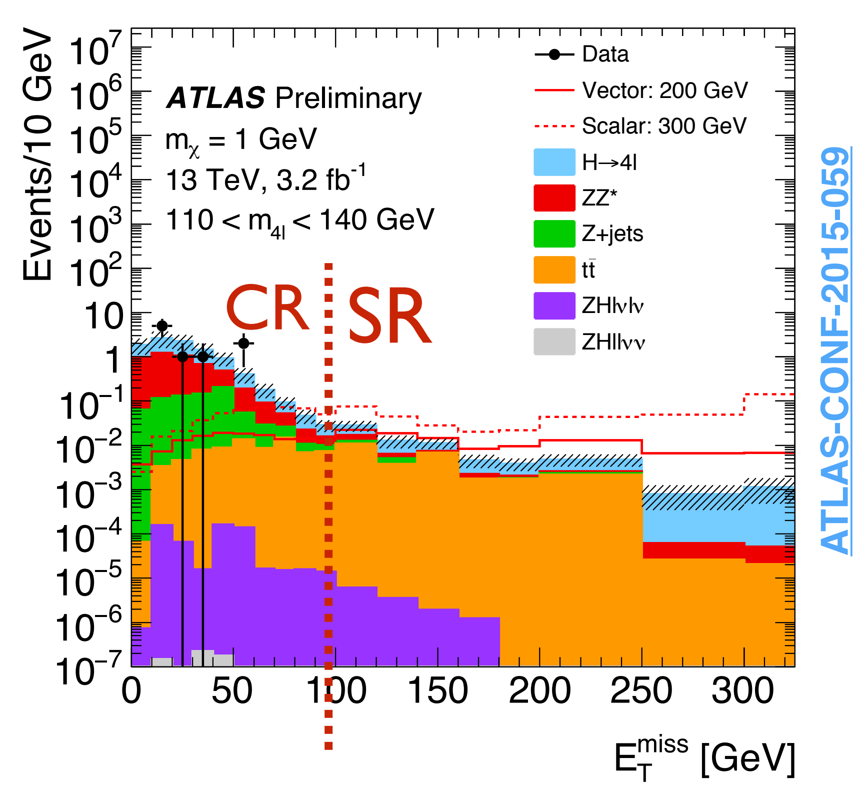


  - a heavy vector boson

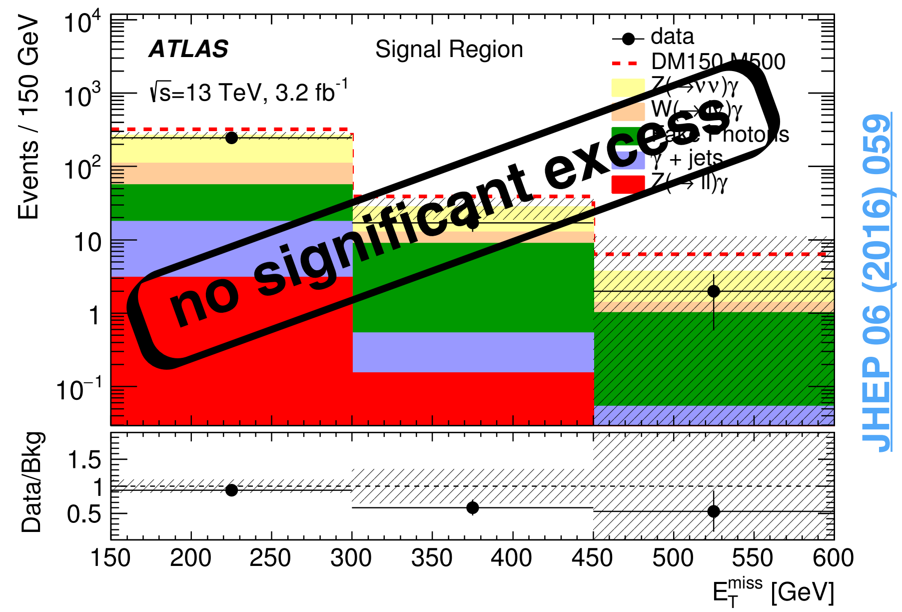


  - a Higgs boson

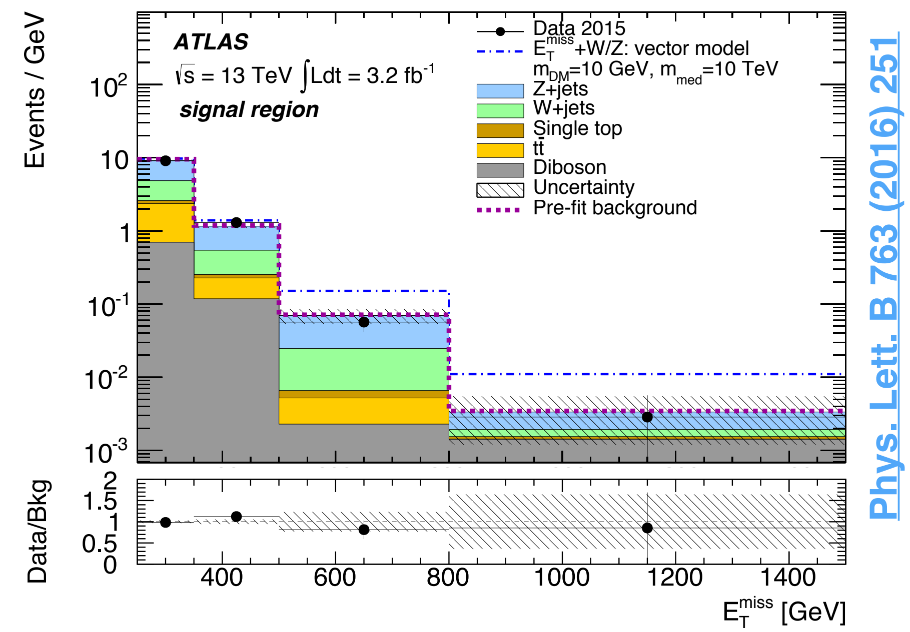




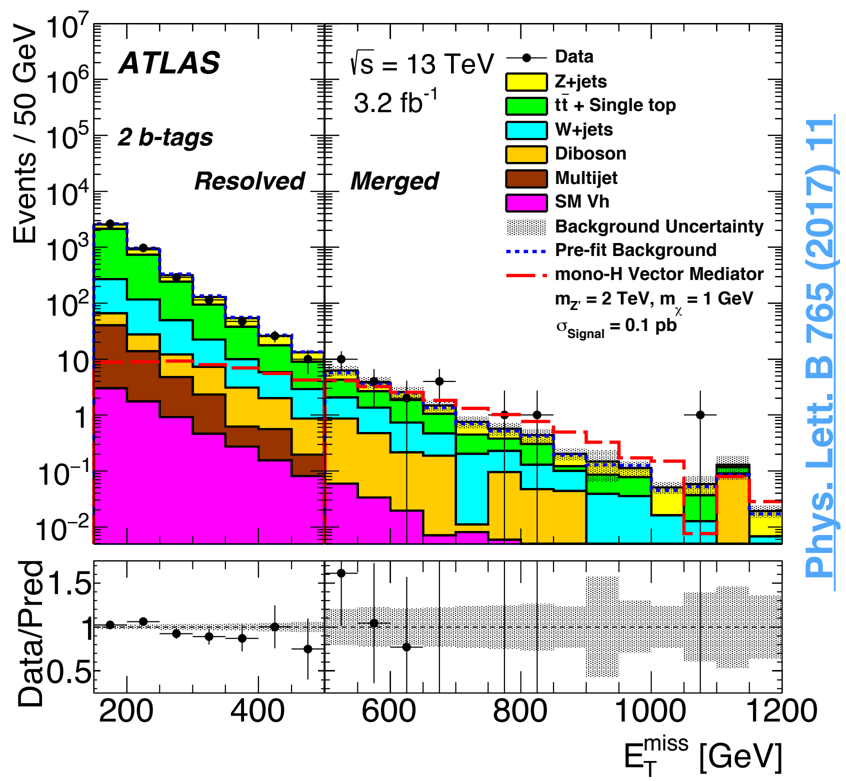
- X can also be…
  - a photon

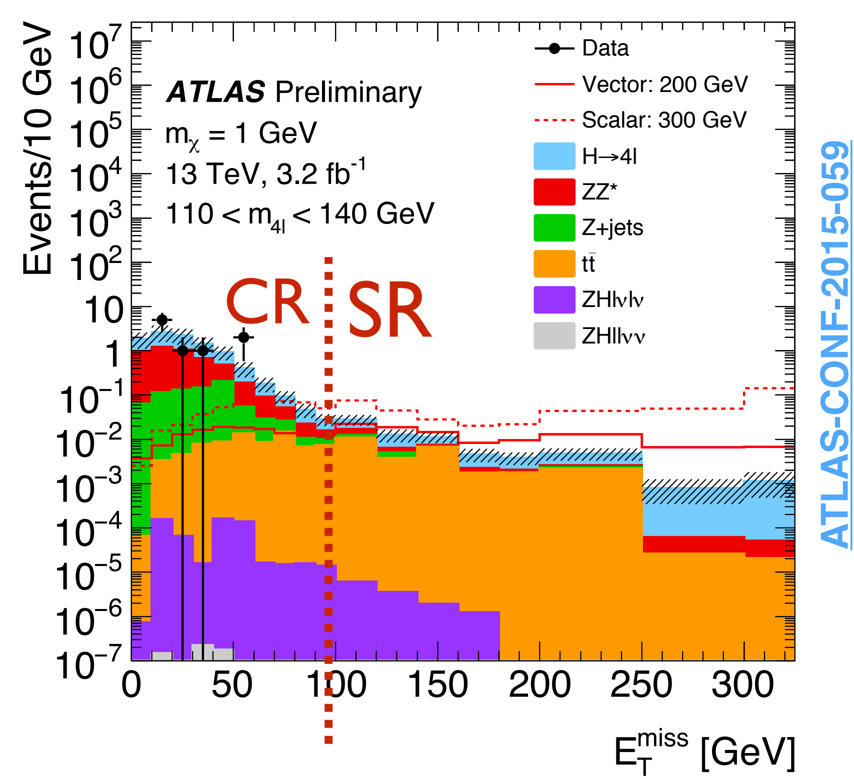


  - a heavy vector boson

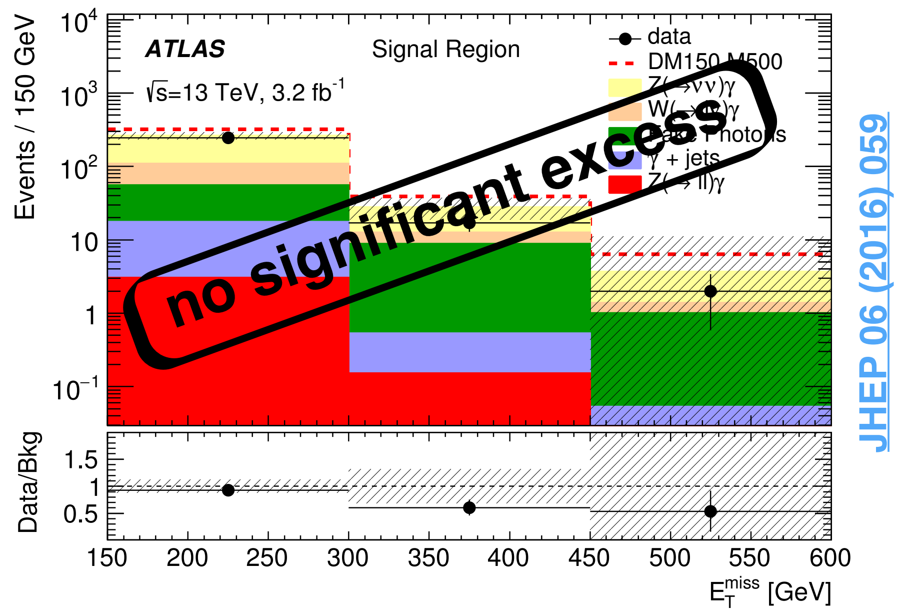


  - a Higgs boson

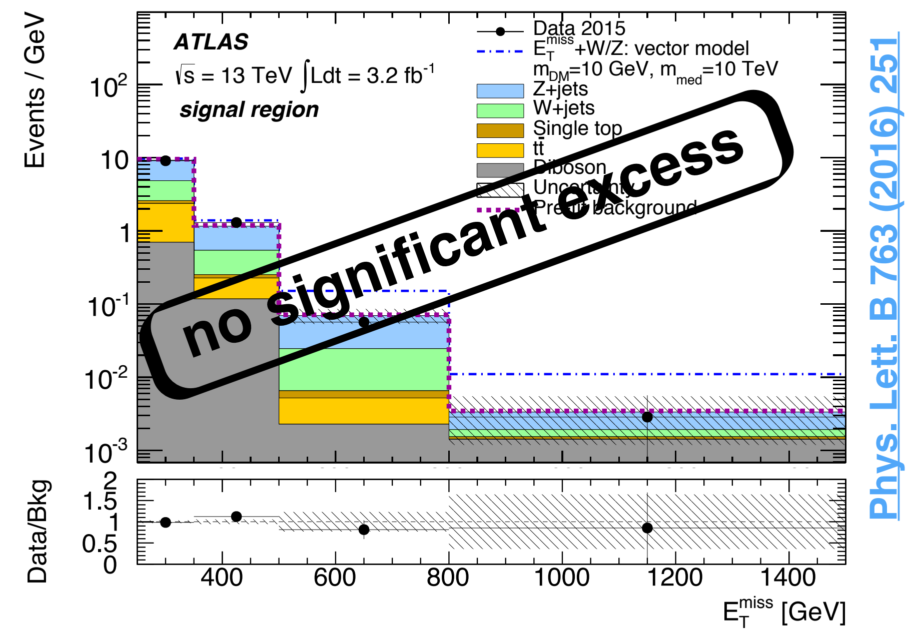




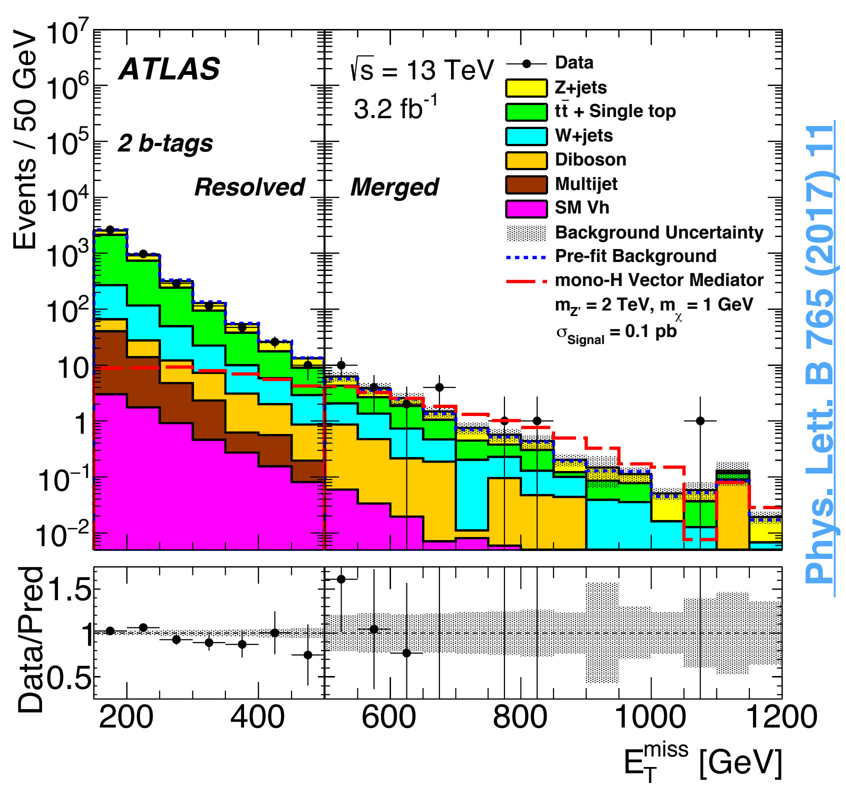
- X can also be…
  - a photon

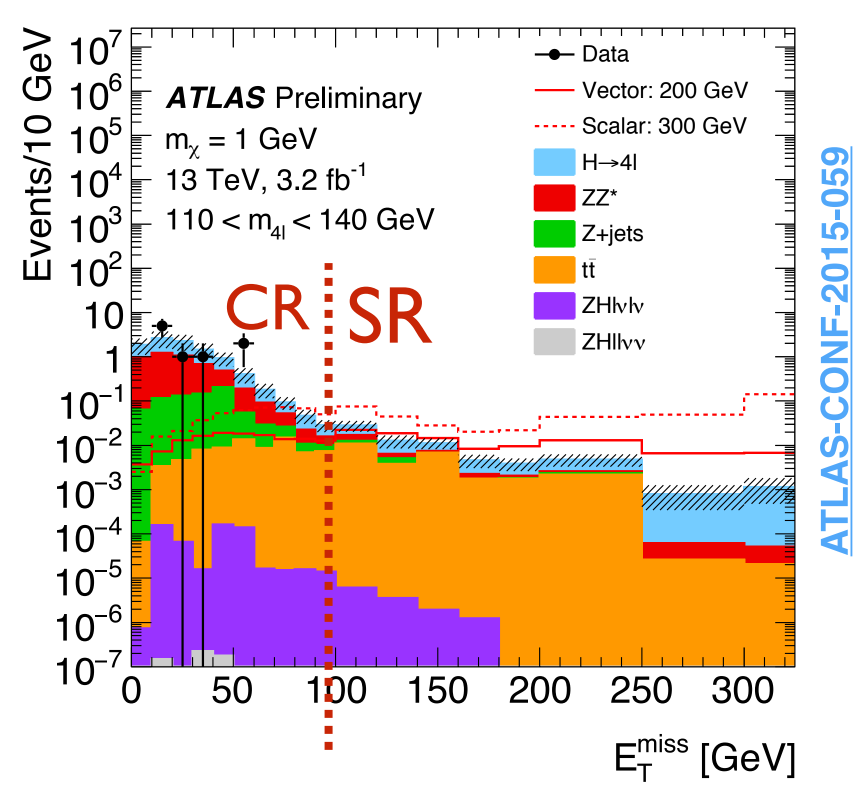


  - a heavy vector boson



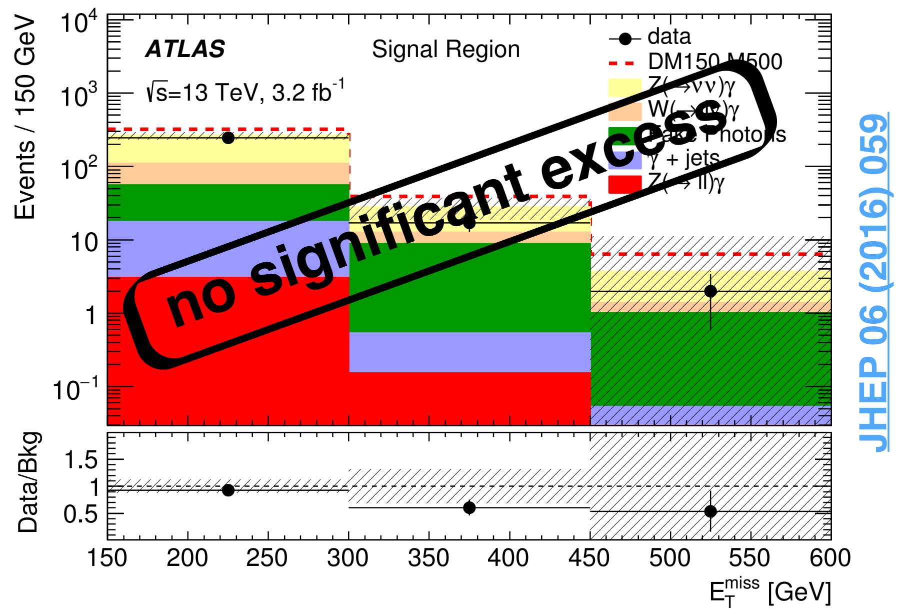
  - a Higgs boson



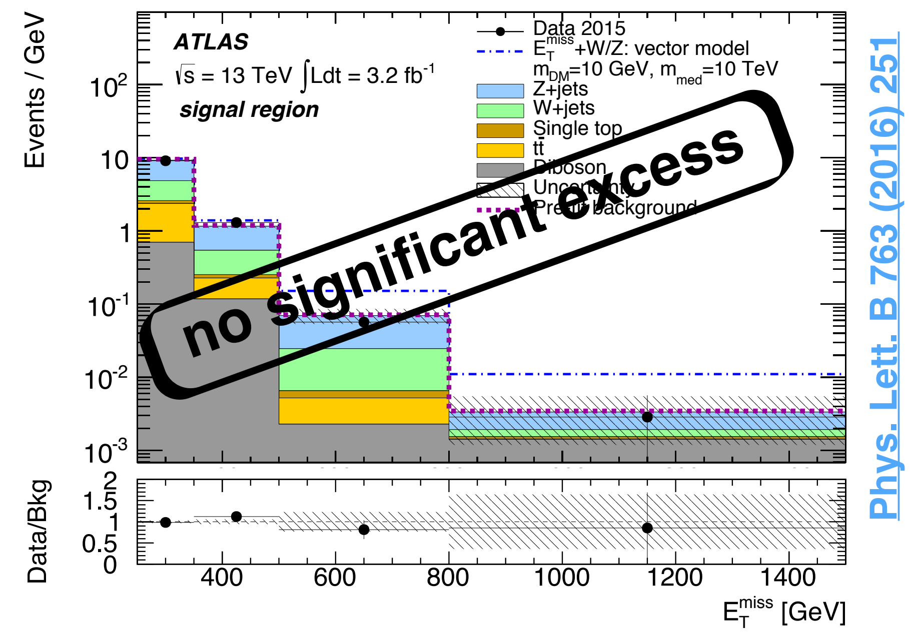


More X+E_T^{miss} Searches

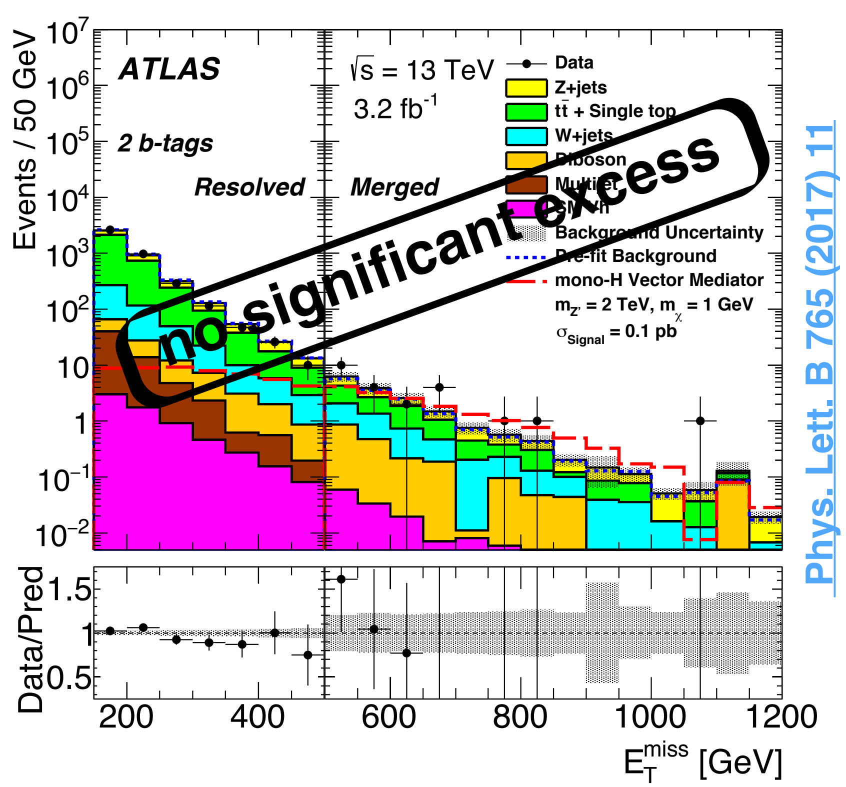
- X can also be…
  - a photon

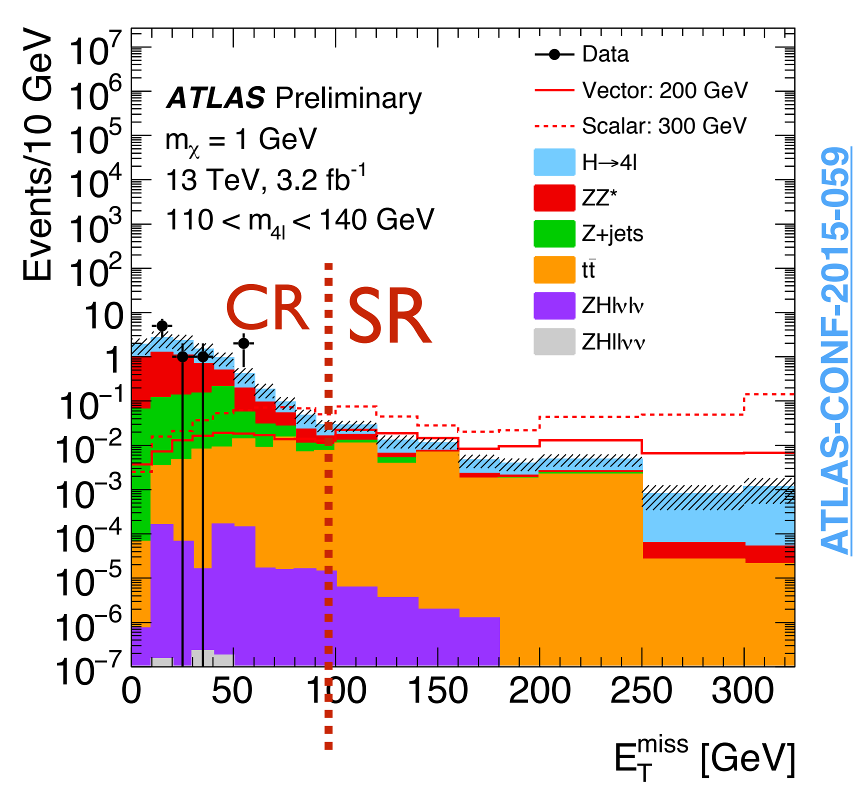


  - a heavy vector boson



  - a Higgs boson





More X+E_T^{miss} Searches

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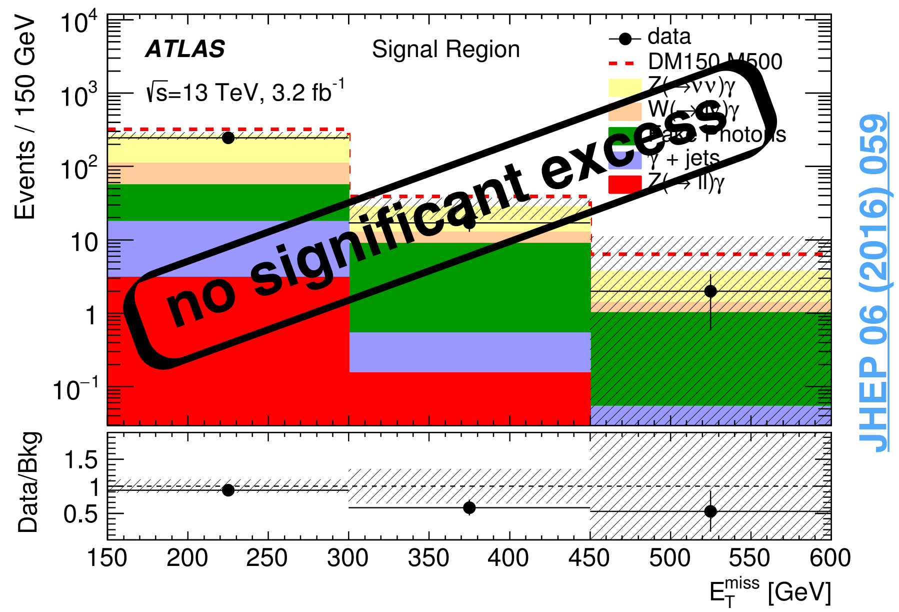
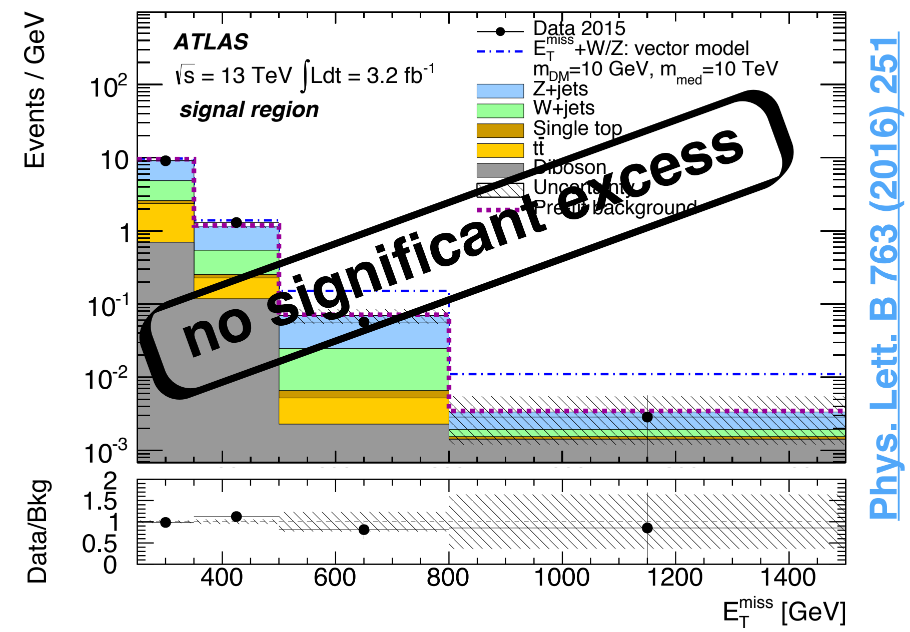
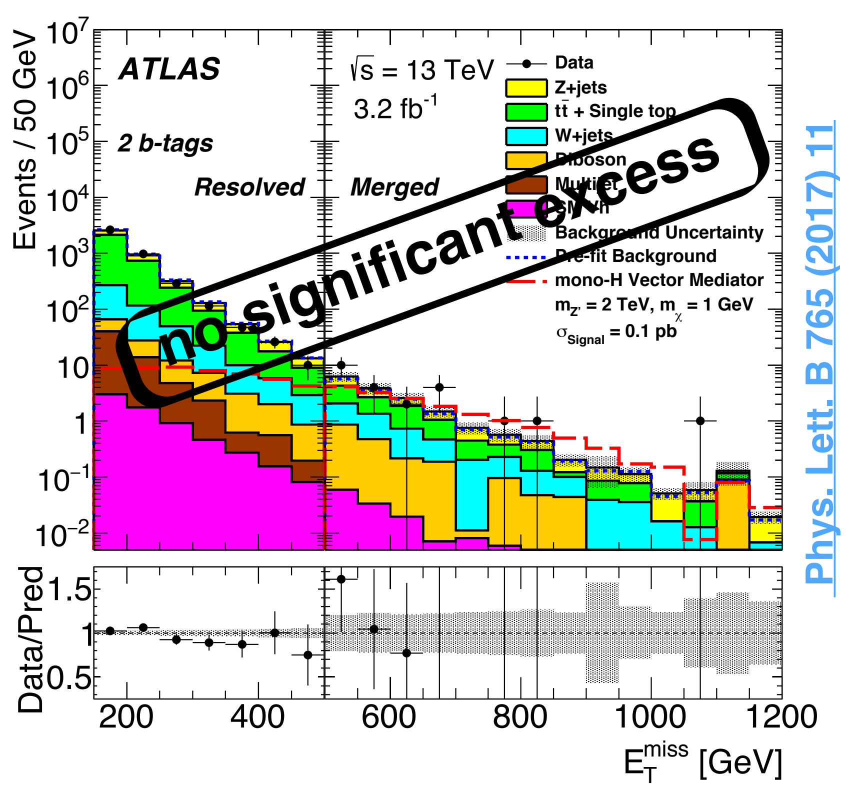
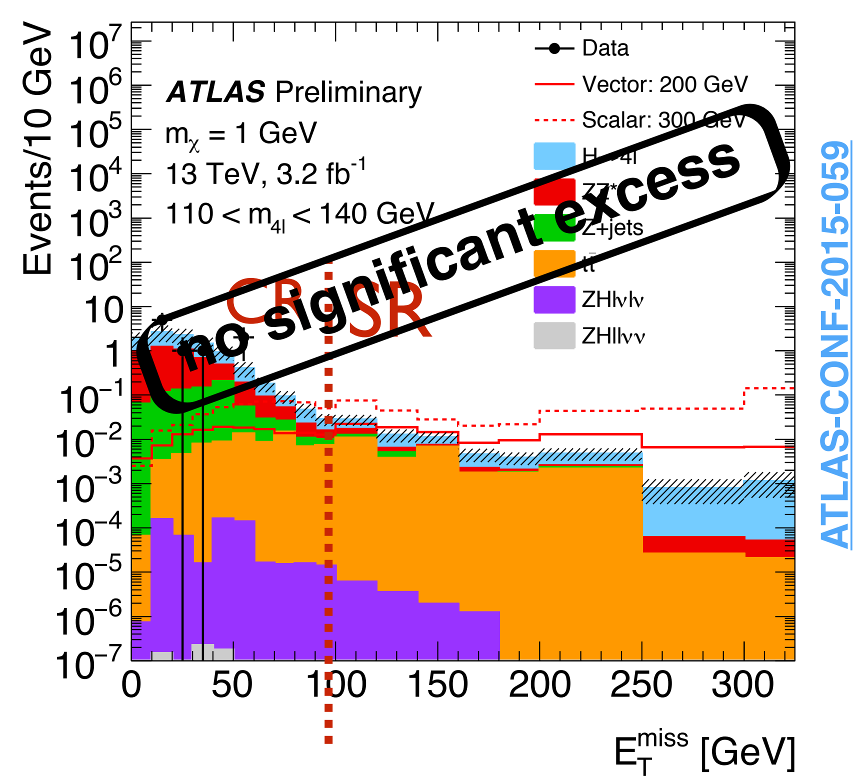


  - a heavy vector boson



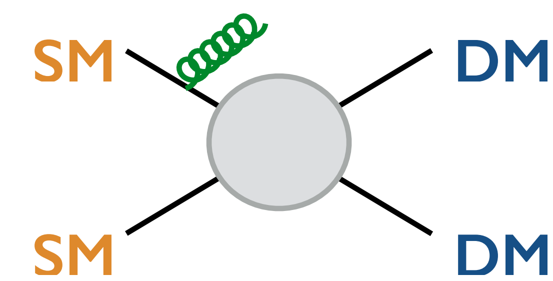
  - a Higgs boson



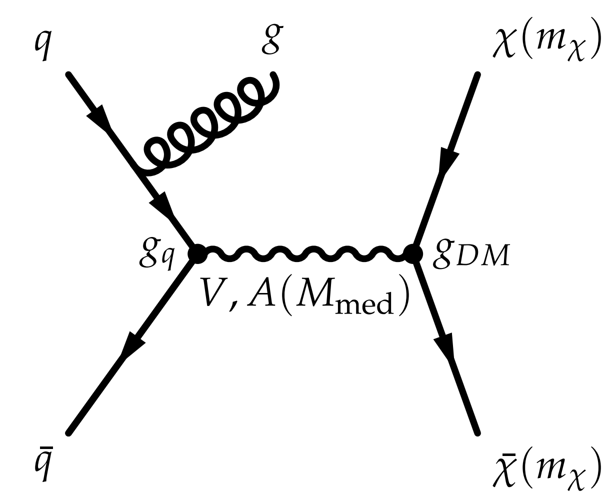


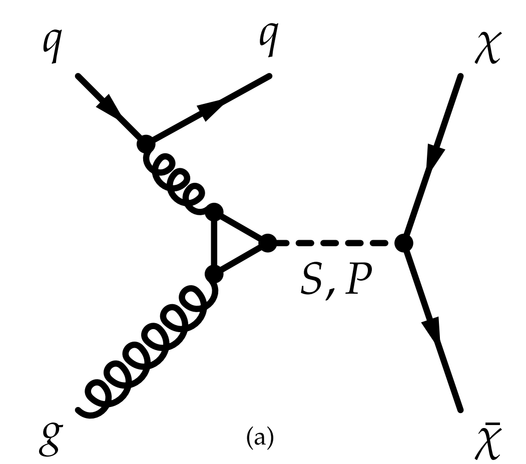
Interpretation

- Run-1: effective field theories (EFT) = low energy approximation
  - questionable validity at LHC energies!



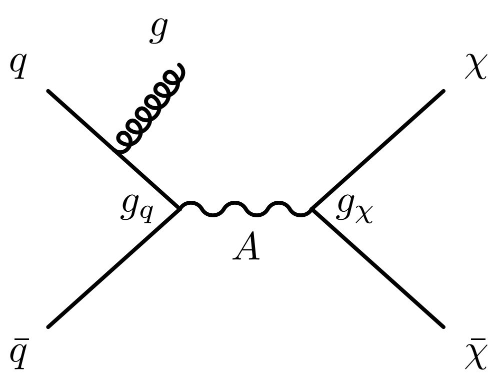
- for Run-2: benchmark **simplified models** (where possible)
  - provide basis for re-interpretations (distinct kinematics)
  - collected by **ATLAS/CMS DM forum** (now LHC DM working group)
  - Dirac-fermionic WIMPs
  - mostly 4 parameters:
    - mediator mass (M_{Med})
    - WIMP mass (m_χ)
    - 2 couplings (g_{DM} ,g_q), **typically (1, 0.25)**
  - different types of mediators, minimal width
  - UV complete, but less generic than EFT



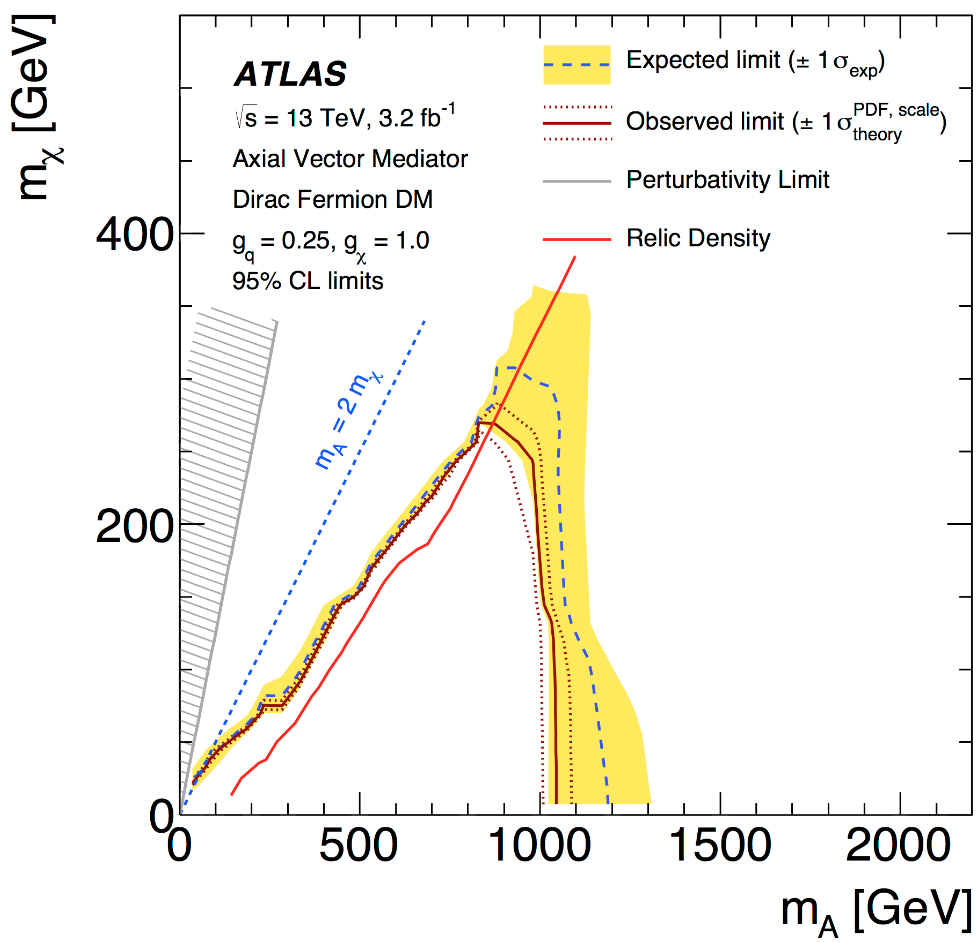


DM Forum report

Example: jet+E_T^{miss}



g_q=0.25, g_χ=1



Example: jet+E_T^{miss}

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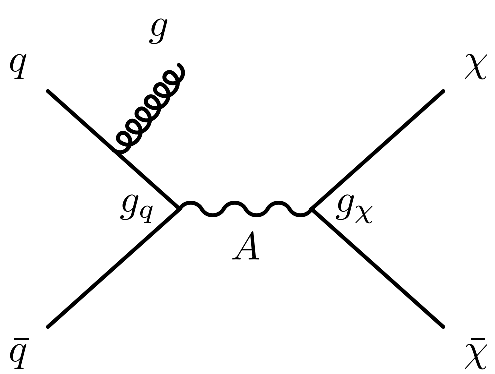
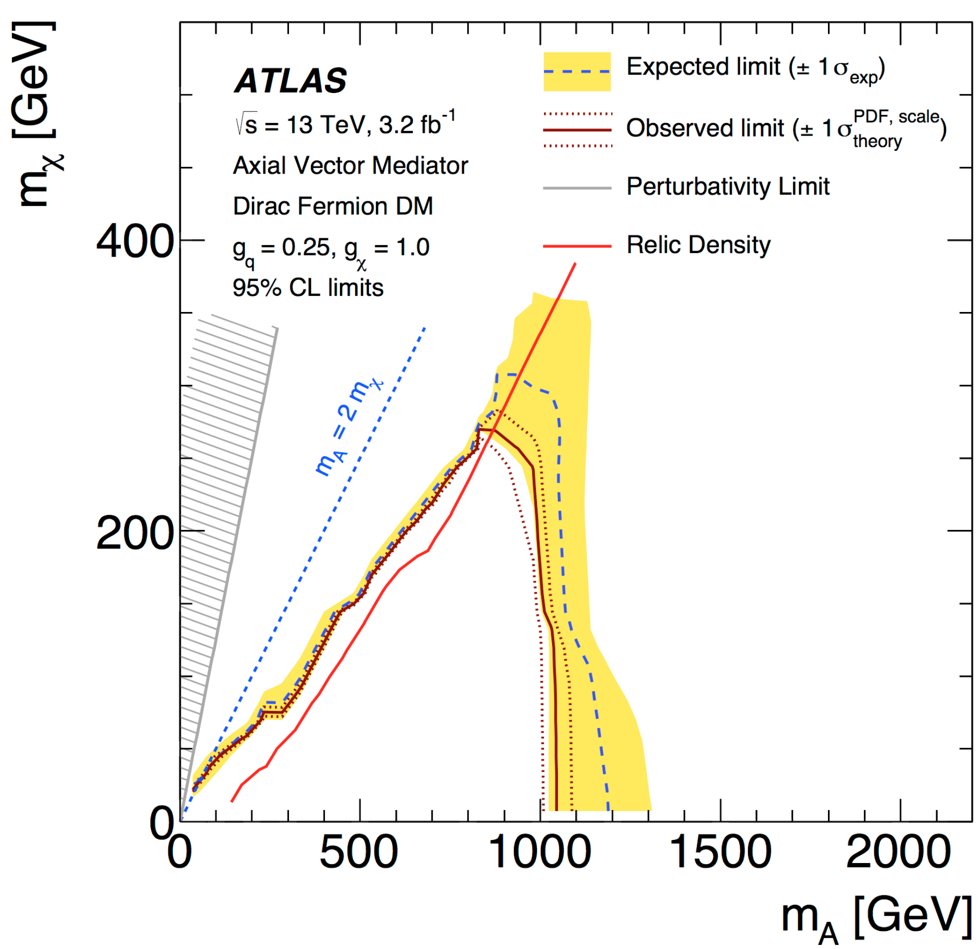
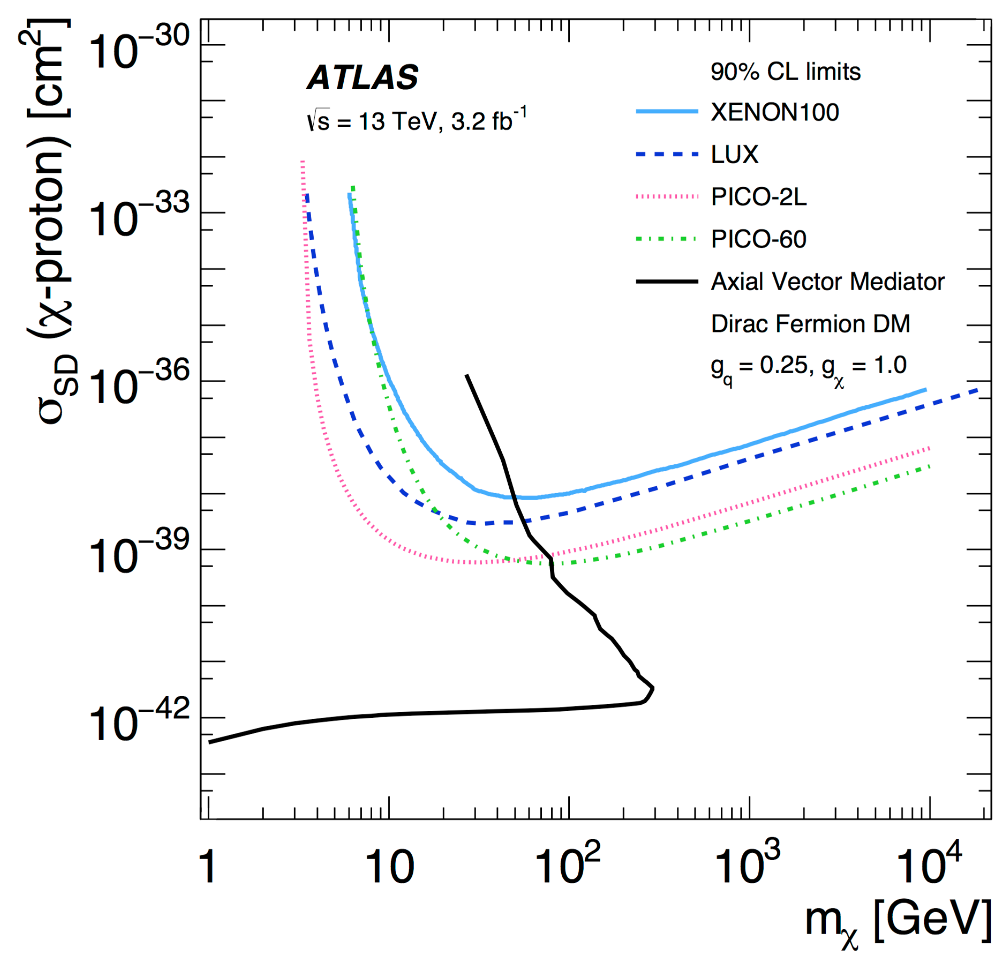


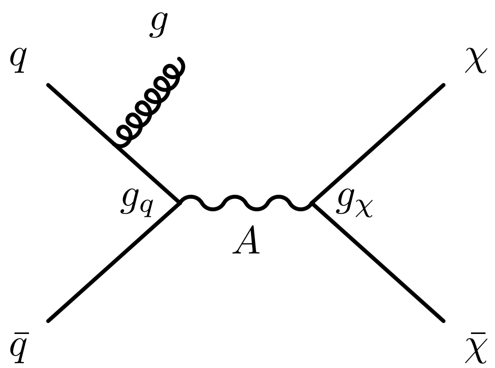
g_q=0.25, g_χ=1



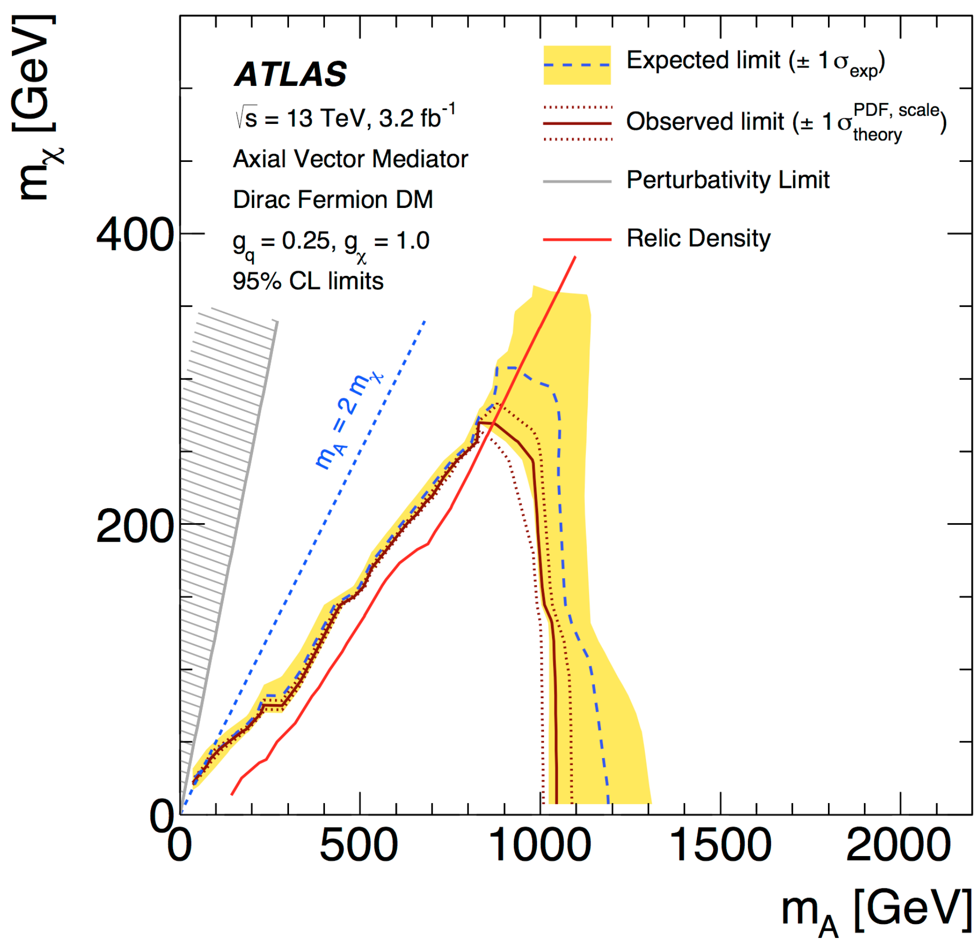


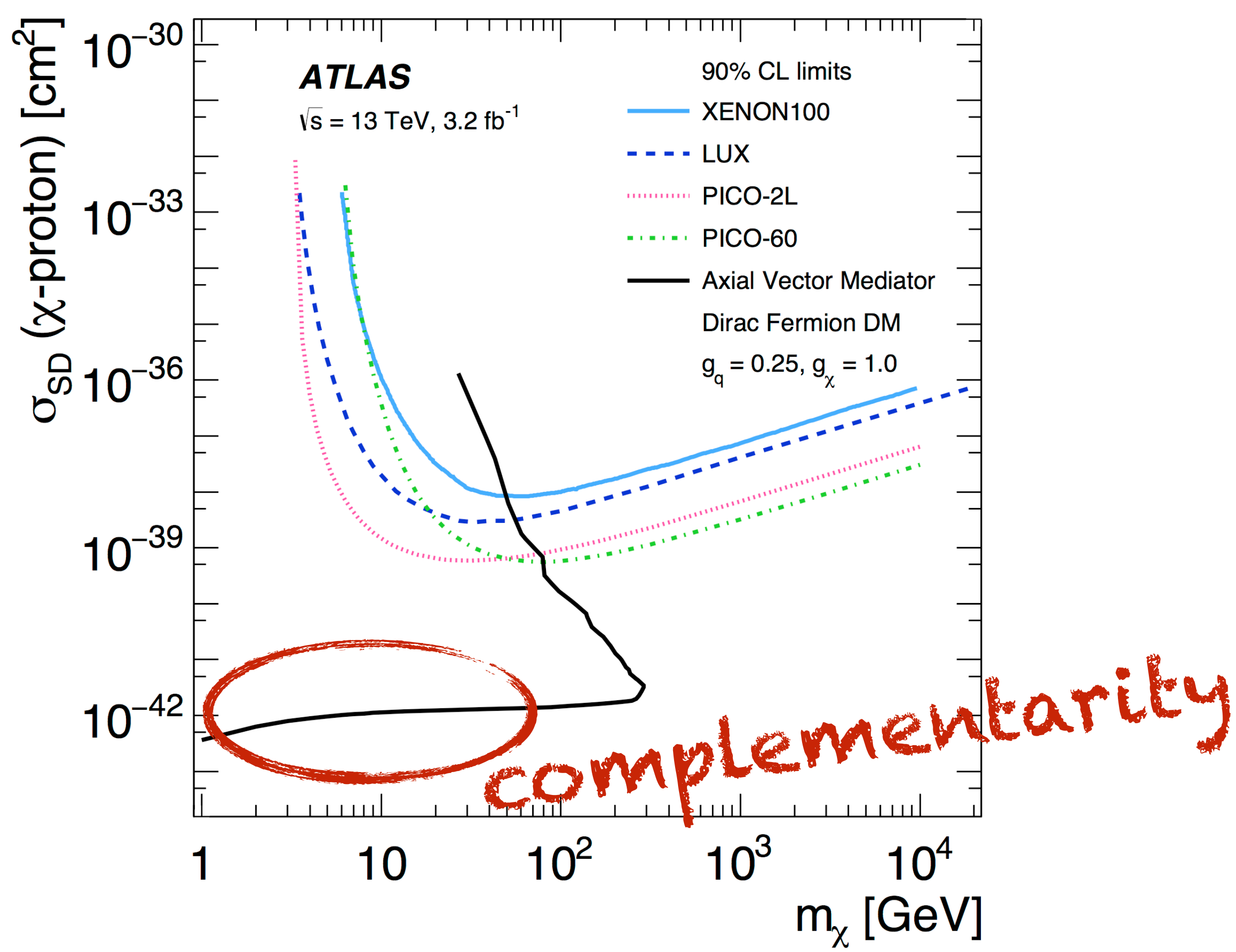
Example: jet+E_T^{miss}

[Phys. Rev. D 94, 032005](#)



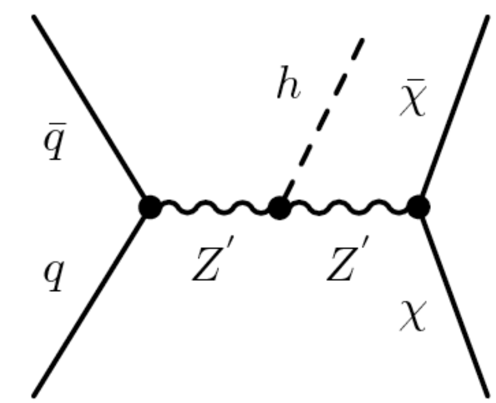
g_q=0.25, g_χ=1



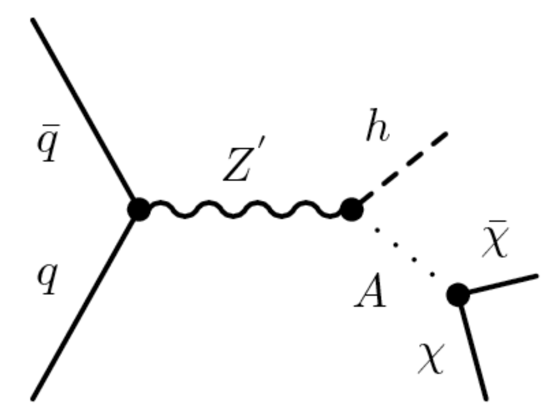


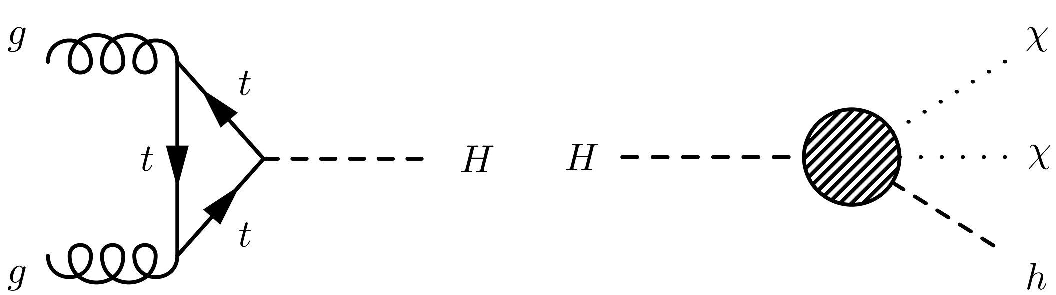
Higgs+E_T^{miss}: Models

- new after Higgs discovery
- **no ISR!** (small coupling)
- widely used simplified model:
  s-channel vector mediator radiating Higgs



- other models considered in some analyses:
  - s-channel scalar mediator radiating Higgs
  - Z'-2HD simplified model
  - scalar 2HD simplified model





- additional parameters, e.g. $g_{Z'Z'h}$, mixing angle…

Higgs+E_T^{miss}: Results

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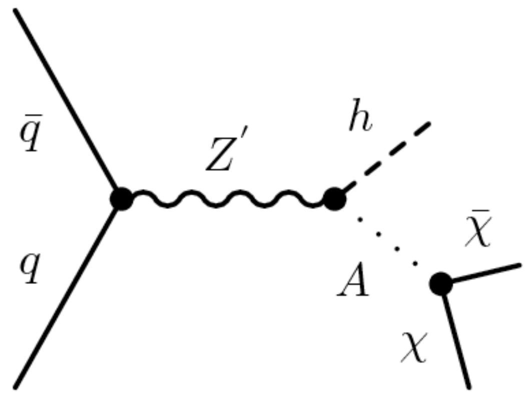
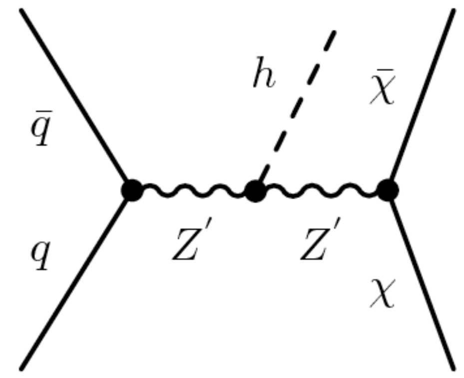
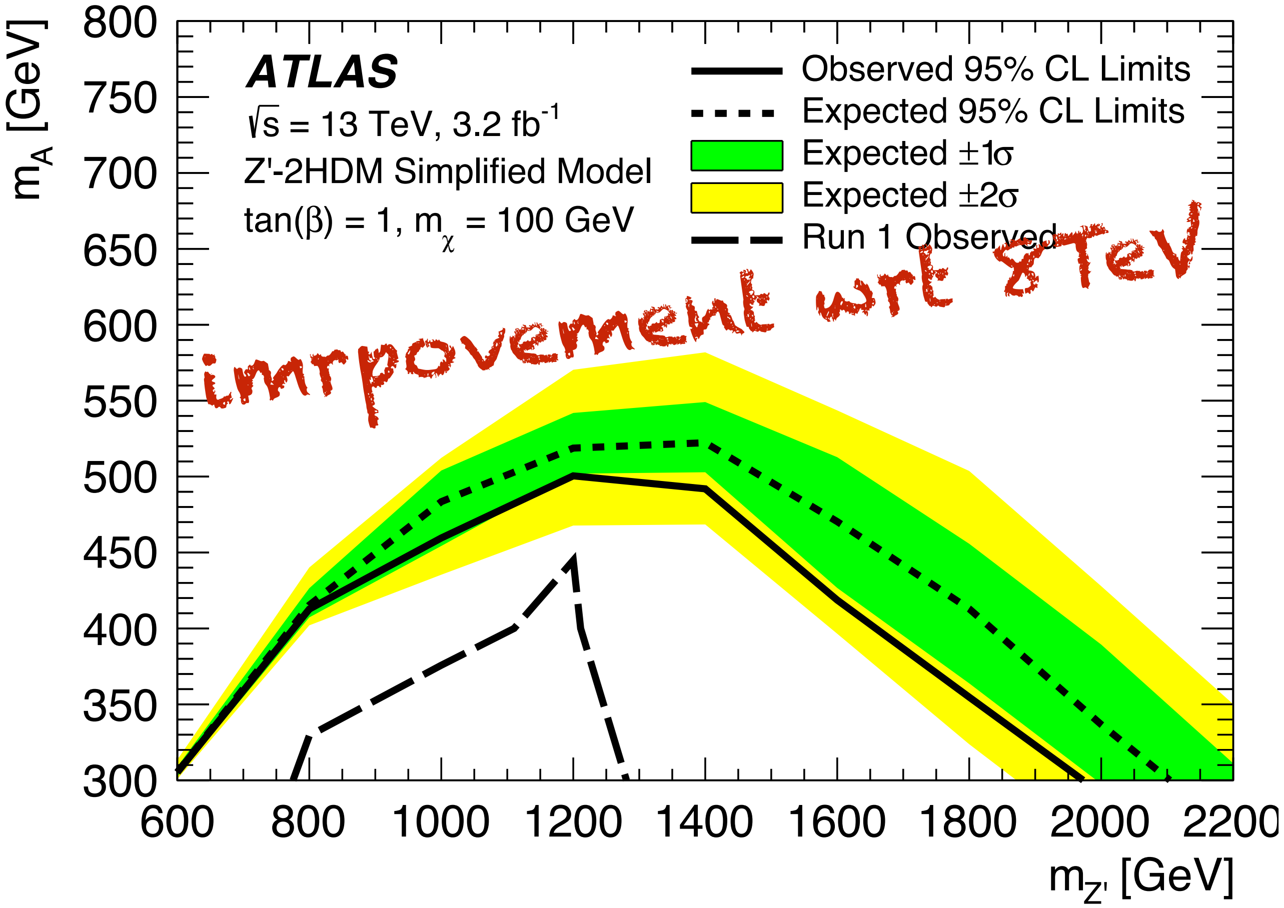
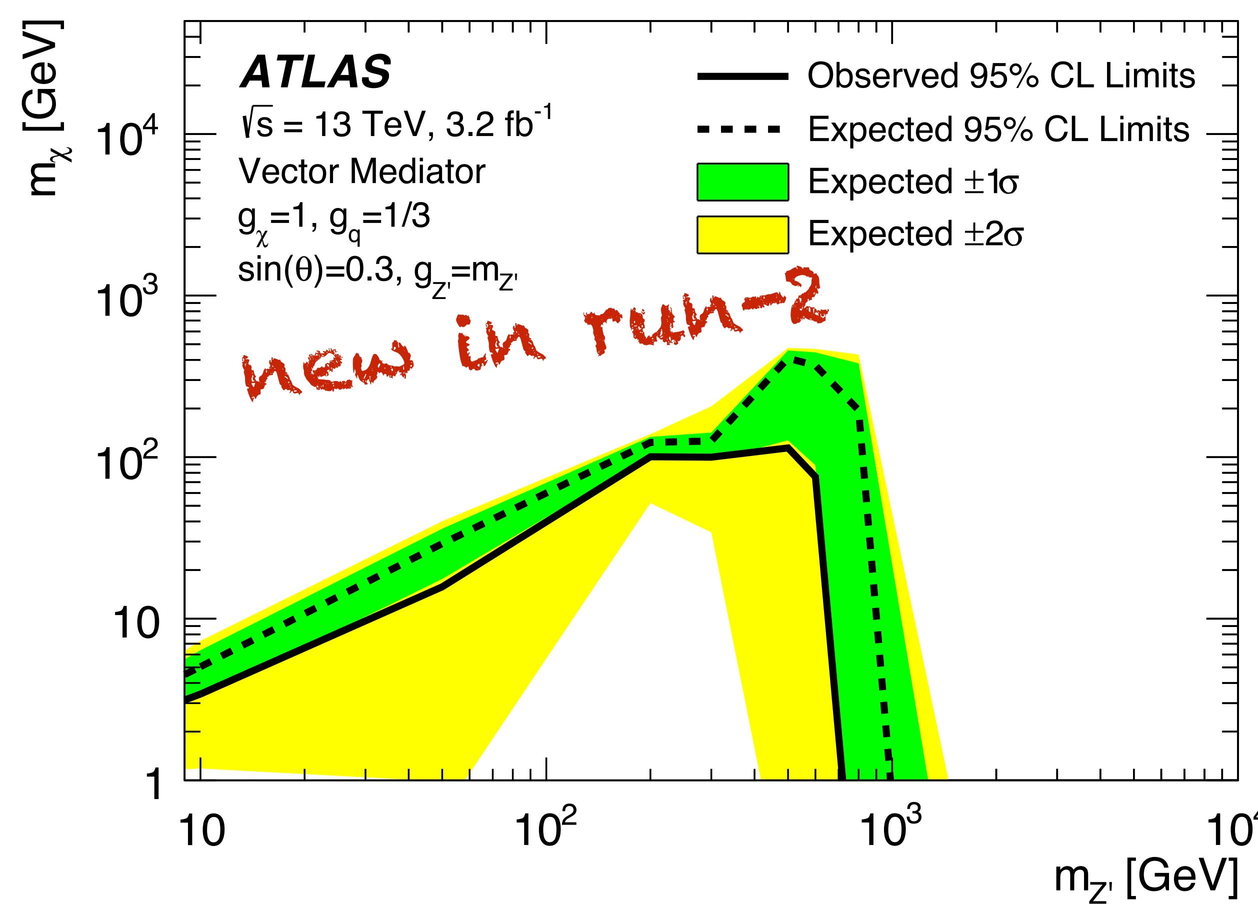




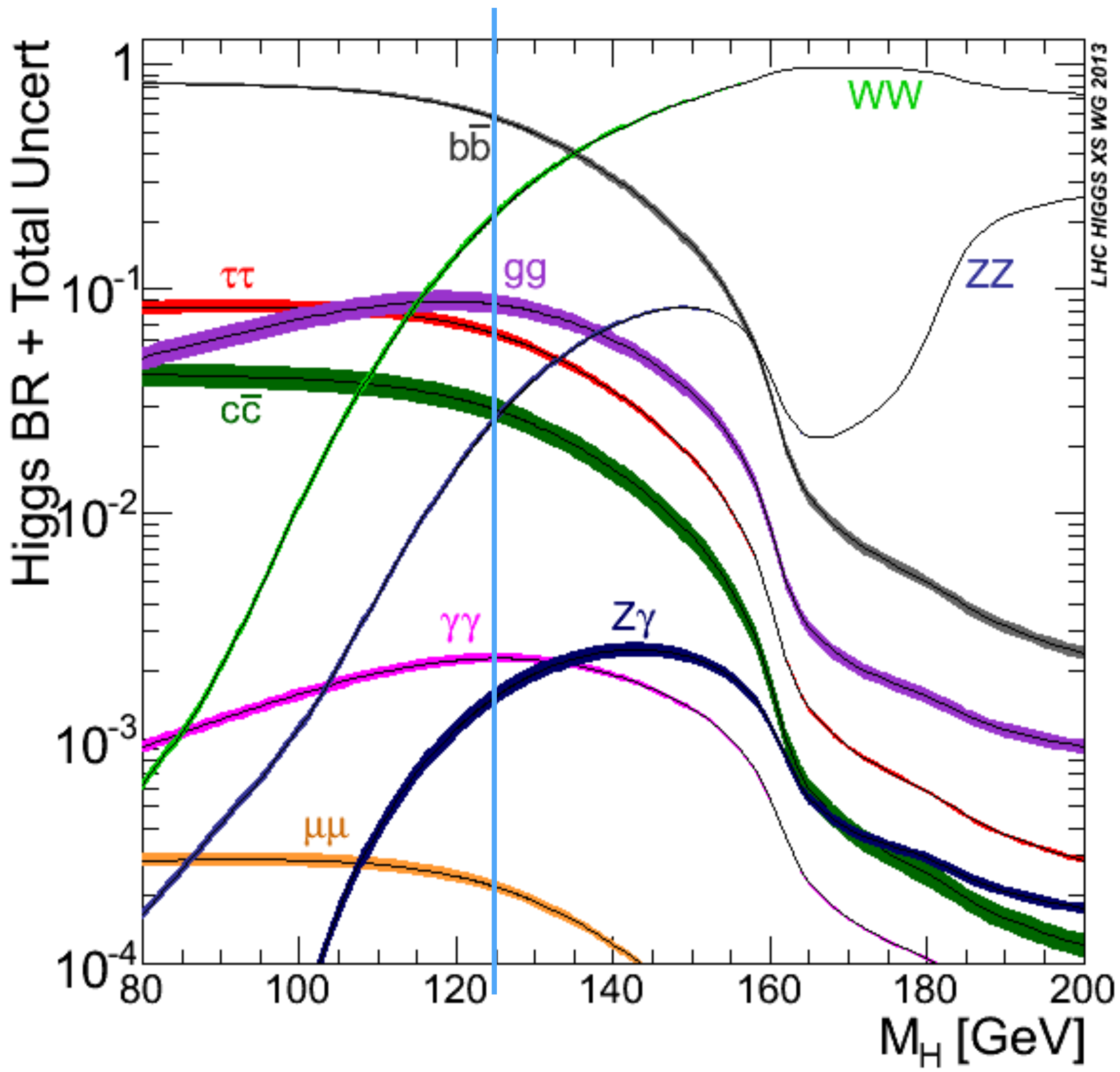




The Future

- more data (full run-2 and beyond)
- new window: Higgs+E_T^{miss} searches (more channels)
- more models
- consistent set of models/parameters with CMS
- combination
- comparisons with direct detection

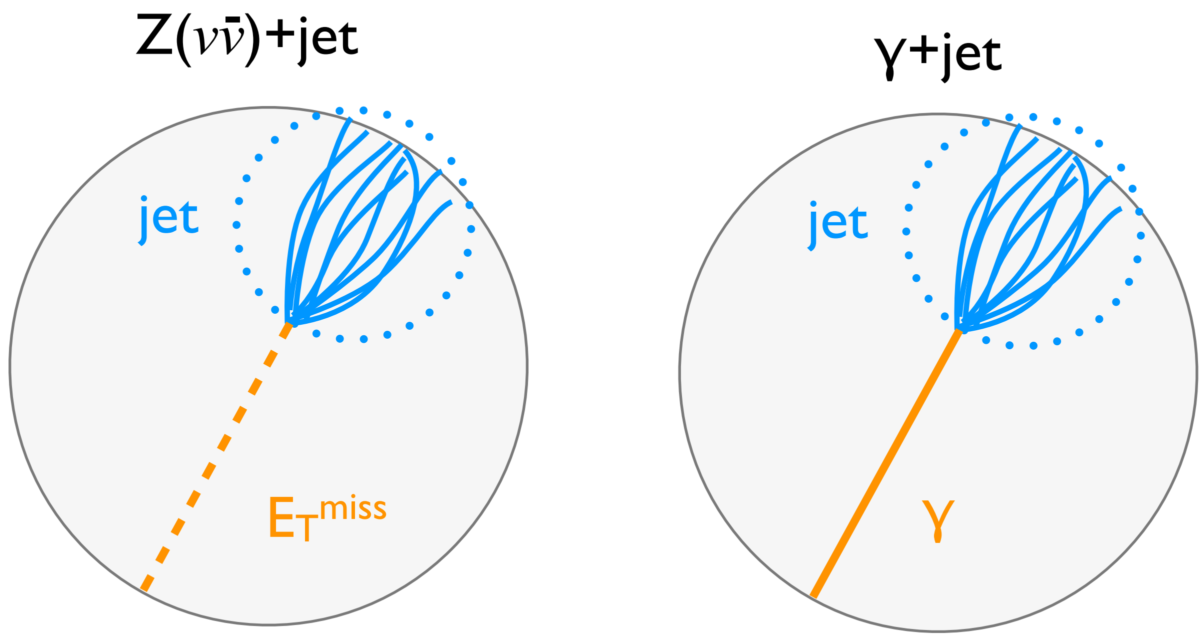
Higgs Boson Decays



- largest branching ratios: **$b\bar{b}$** and **WW**
  - BR($b\bar{b}$)~ 3 * BR(WW)

$H(b\bar{b})+E_T^{miss}$ - Background Estimation

- alternative method to estimate one of the main backgrounds: Z(νν)+jets
  - explore use of **photon(γ)+jets** events
    - very similar topology at high boson p_T
      - Z(νν)+jets: boson $p_T = E_T^{miss}$
      - γ p_T as proxy for E_T^{miss}



- γ well measurable!
- can select sample of γ+jets events with high purity

$H(b\bar{b})+E_T^{miss}$ - Background Estimation

- γ: electromagnetic interaction, Z: weak interaction
  - different coupling to quarks
  - theoretically well known

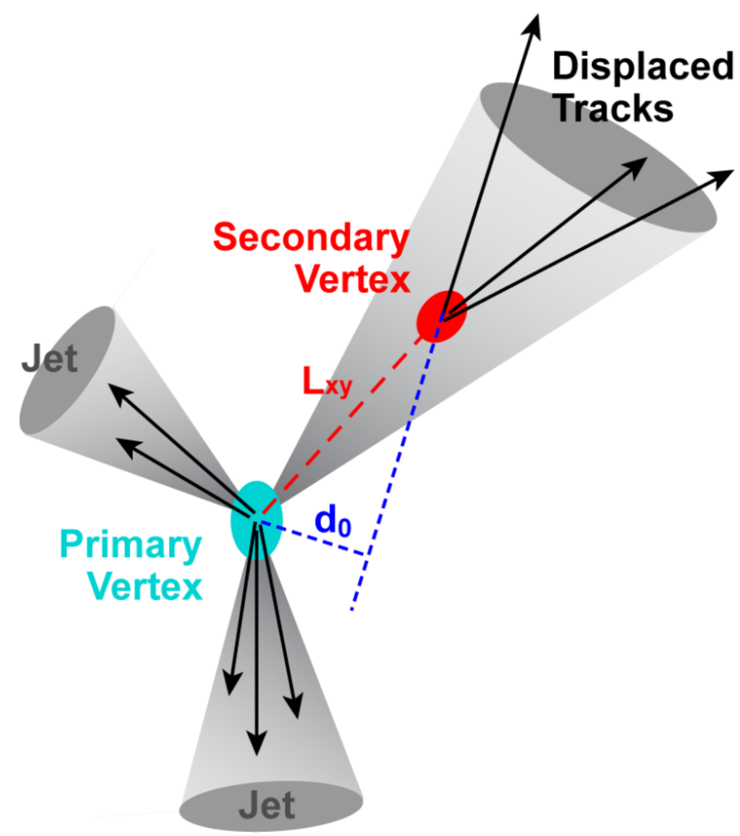
- use simulation to determine **ratio** Z(νν)/γ
  - (partial) cancellation of uncertainties
  - transfer factor $f_\mathrm{T} = \dfrac{N^{\mathrm{sim}}_{\mathrm{Z}(\nu\nu)+\mathrm{jets}}}{N^{\mathrm{sim}}_{\gamma+\mathrm{jets}}}$

- select pure γ+jets sample in **data**
  - **prediction** for Z(νν)+jets $N^{\mathrm{pred}}_{\mathrm{Z}(\nu\nu)+\mathrm{jets}} = f_\mathrm{T} \cdot N^{\mathrm{data}}_{\gamma+\mathrm{jets}}$

  - possible **reduction of uncertainties**
  - **independent cross check** of estimation

$H(b\bar{b})+E_T^{miss}$ - Finding b-Quarks

- analysis relies on identifying jets from b-quarks (**b-tagging**)
  - in the evolution of a collision event, quark combinations (hadrons) are formed
  - B-hadrons (containing b-quarks) have “visible" lifetimes
    - their “late" decay leads to secondary vertex

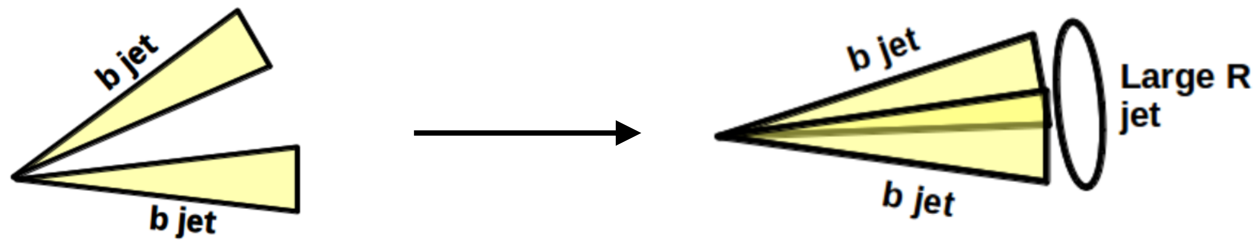


https://amva4newphysics.wordpress.com/2016/01/04/b-tagging-101/

    - resolved with excellent tracking resolution
  - multi variate techniques used to build a discriminator against light jets

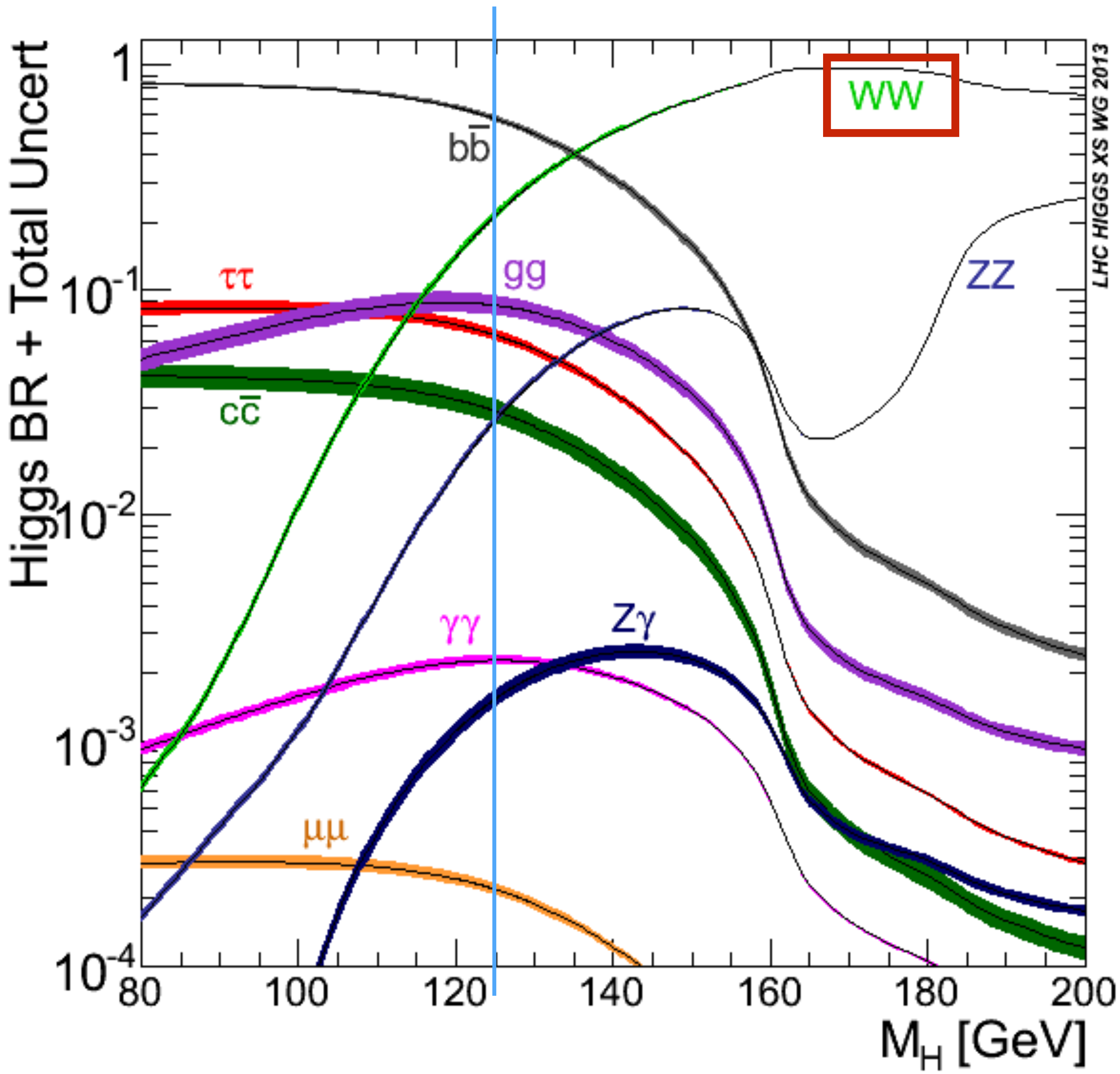
$H(b\bar{b})+E_T^{miss}$ - Finding b-Quarks

- at high E_T^{miss}: H is "boosted" —> b-jets *merge* into one



- use of **variable radius** (VR) jets can significantly **improve b-tagging efficiency**
  - jets become more narrow with higher p_T
    - adapt radius parameter used

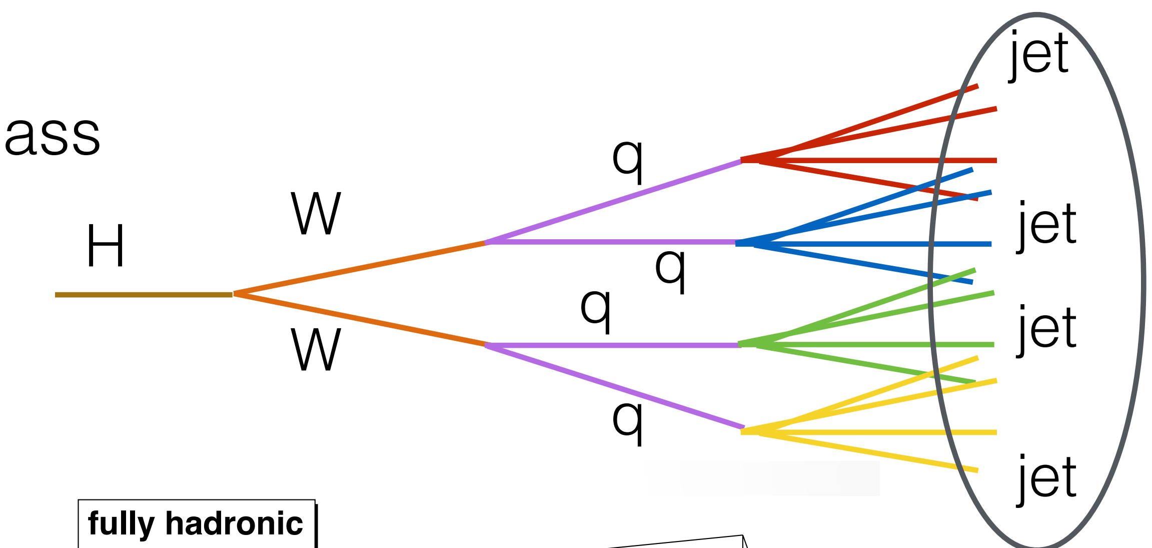
Reminder



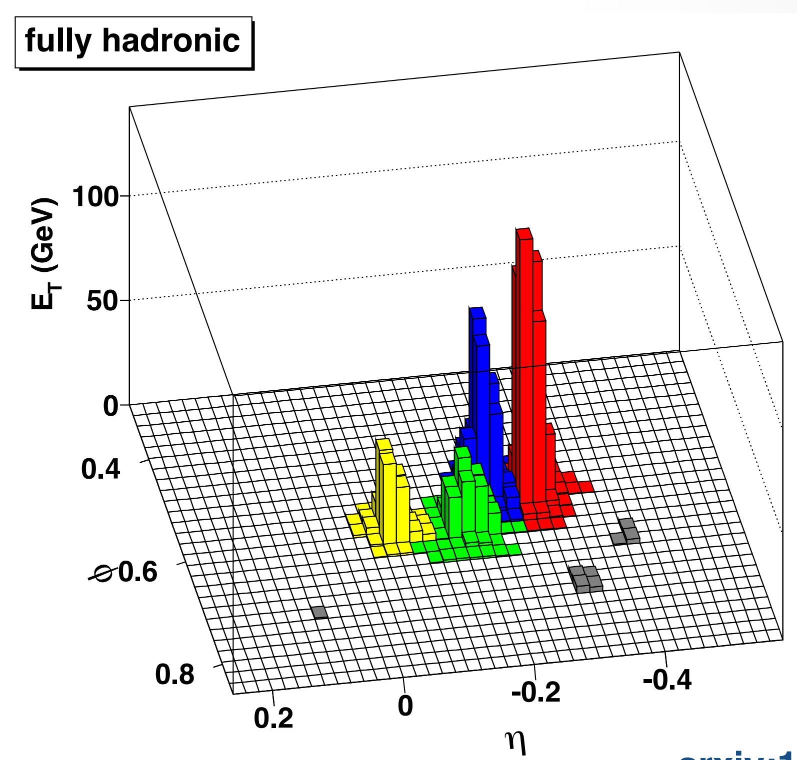
Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]
$b\bar{b}$
WW
ZZ
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
$\mu\mu$
LHC HIGGS XS WG 2013

H(WW)+E_T^{miss}

- not done yet
- most promising: decay of W bosons into pair of quarks
  - larger branching ratio
  - in W—>ℓν additional E_T^{miss} from neutrinos
    - complicates reconstruction of Higgs mass



- boosted regime: <u>one large jet</u>
  - four-prong substructure
  - “di-boson tagging”

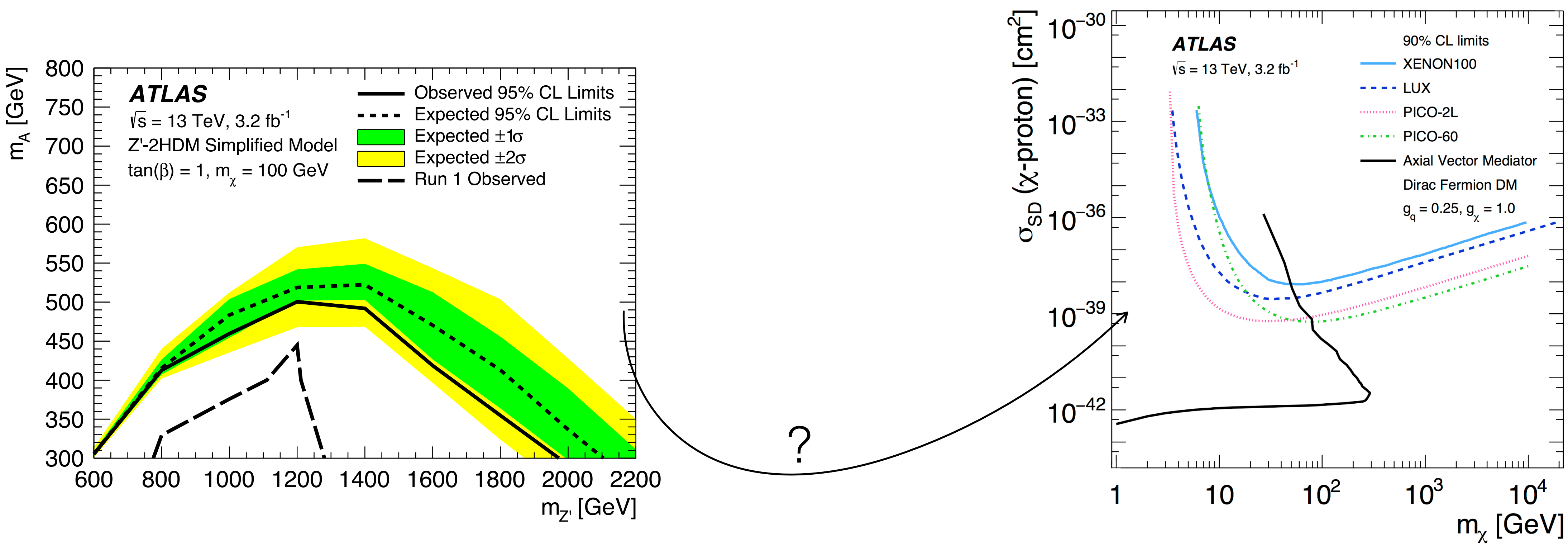


arxiv:1204.0525

- **new analysis** channel
  - different systematic effects
  - additional handle on DM

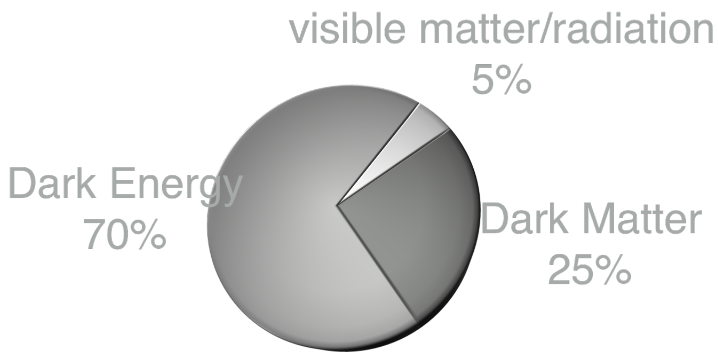
Interdisciplinary Interpretation

- H+E_T^{miss}: no comparisons to results of other searches so far

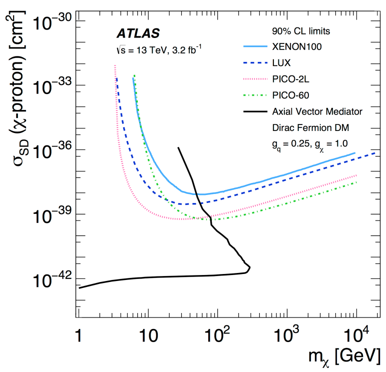


- need to develop ways to do that

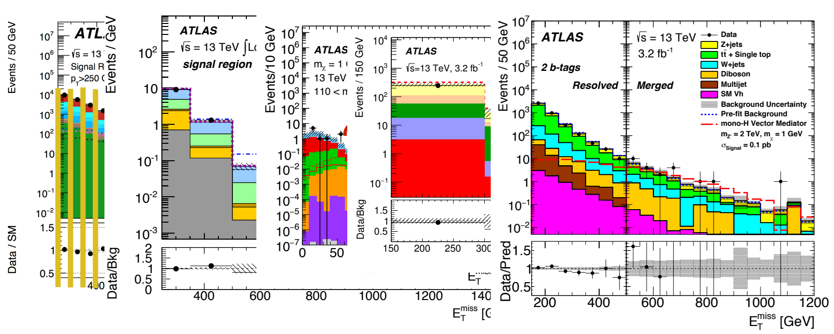
Summary



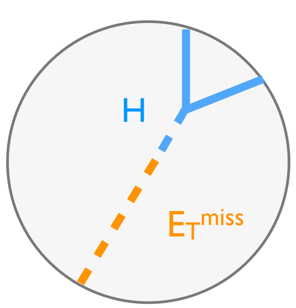
- **Dark Matter** one of the hottest topics of present day (astro)particle physics



- **complementarity** of colliders and direct detection



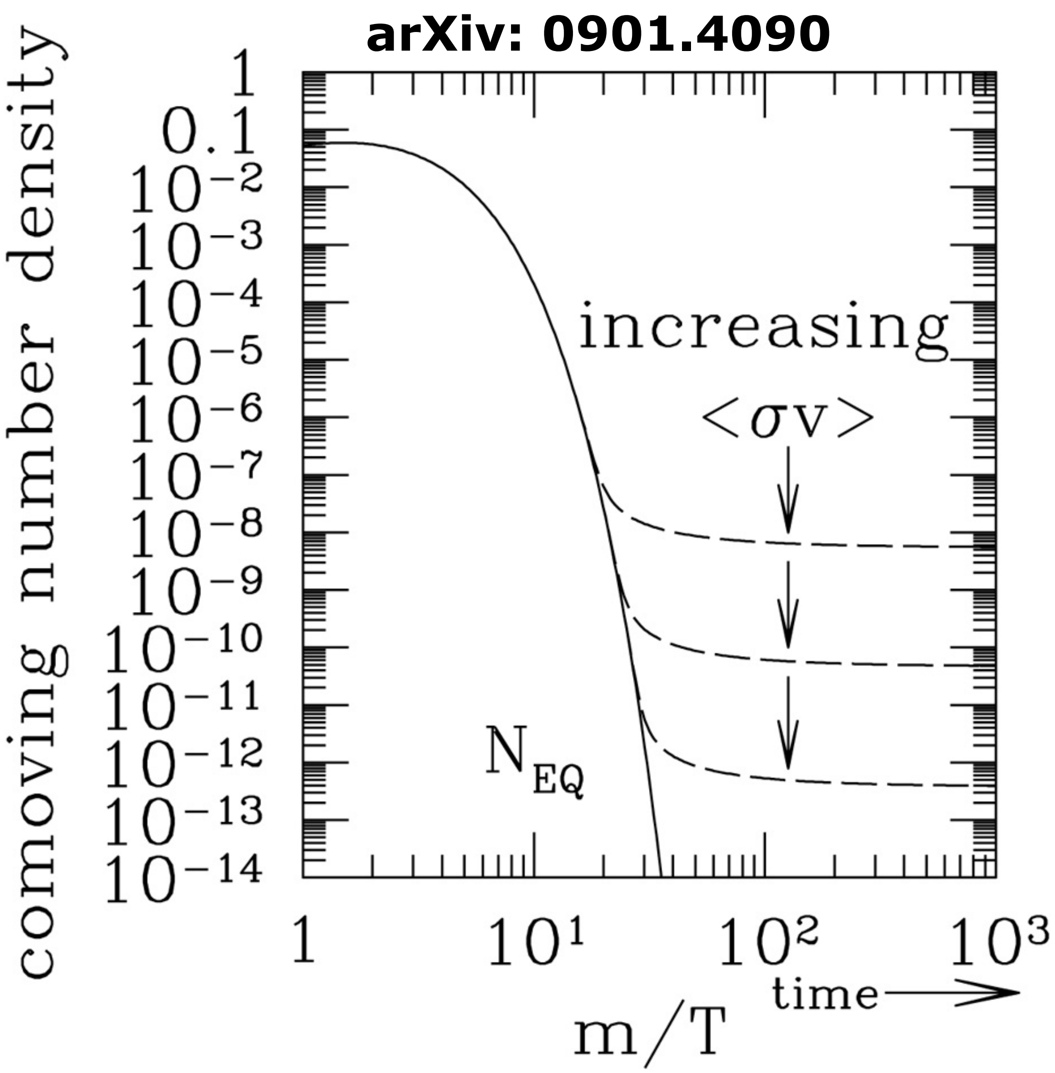
- whole suite of **X+E$_T$^{miss}** searches looking for DM at colliders



- **Higgs+E$_T$^{miss}** searches hold great potential for upcoming data

Additional Material

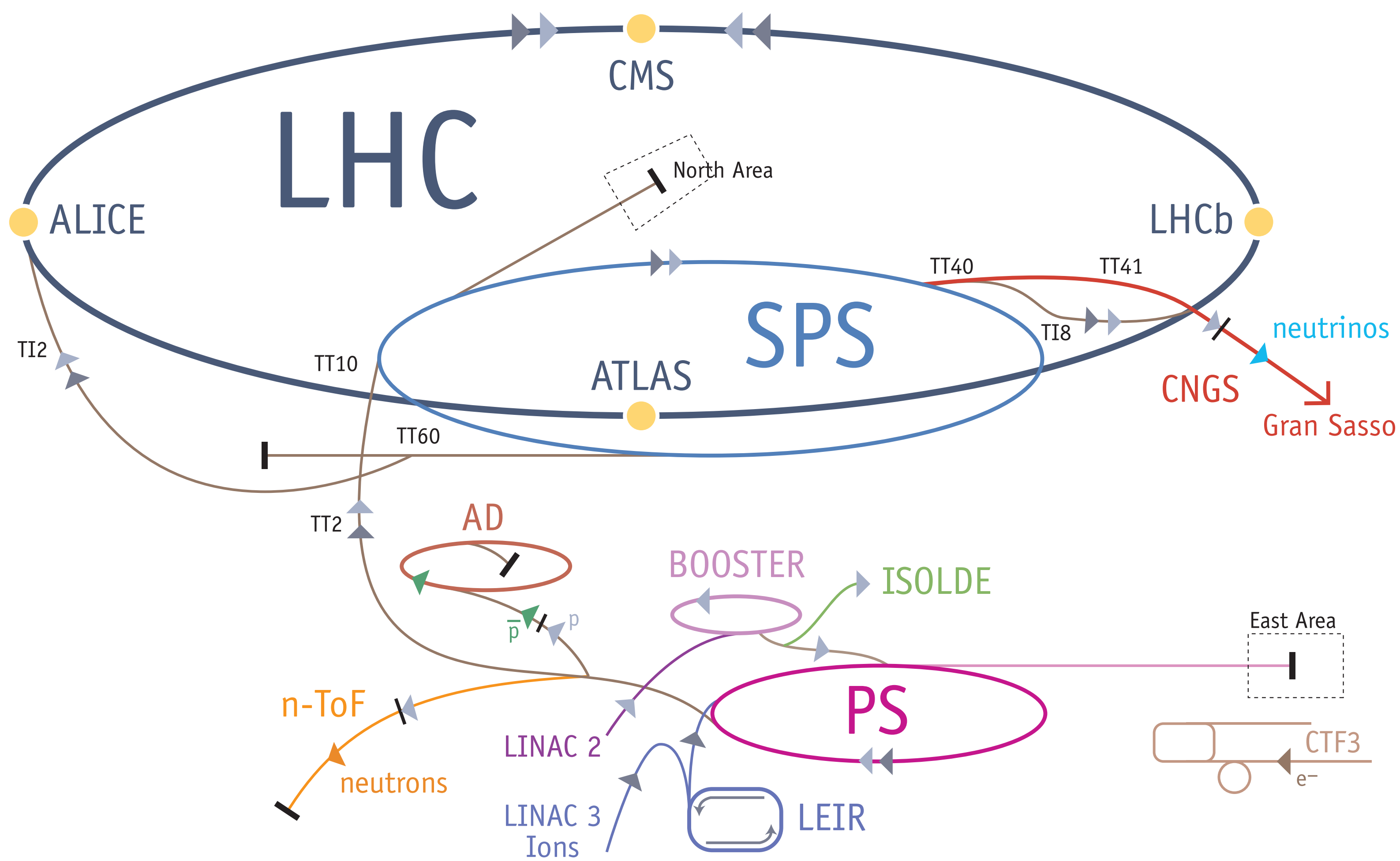
WIMPs, a thermal relic



- the larger the annihilation cross section, the later the freeze-out and the smaller the relic density
    - ‘survival of the weak'
    - present day abundance determined by annihilation cross section at time of freeze out

Accelerator Chain

- beams not continuous, but 2808 packets (“**bunches**”) with **10^{11}** protons each
- accelerated in **several stages**



- circulating in opposite directions in LHC
- brought to collision at the 4 interaction points

Interpretation, Run-1

- LHC Run-1: “traditional" effective field theory (**EFT**) approach
  - assume mediator too heavy to be produced
  - 2 parameters: WIMP mass ($\mathbf{m}_\chi$) & suppression scale (**M***)
  - comparison with direct detection

Interpretation, Run-1

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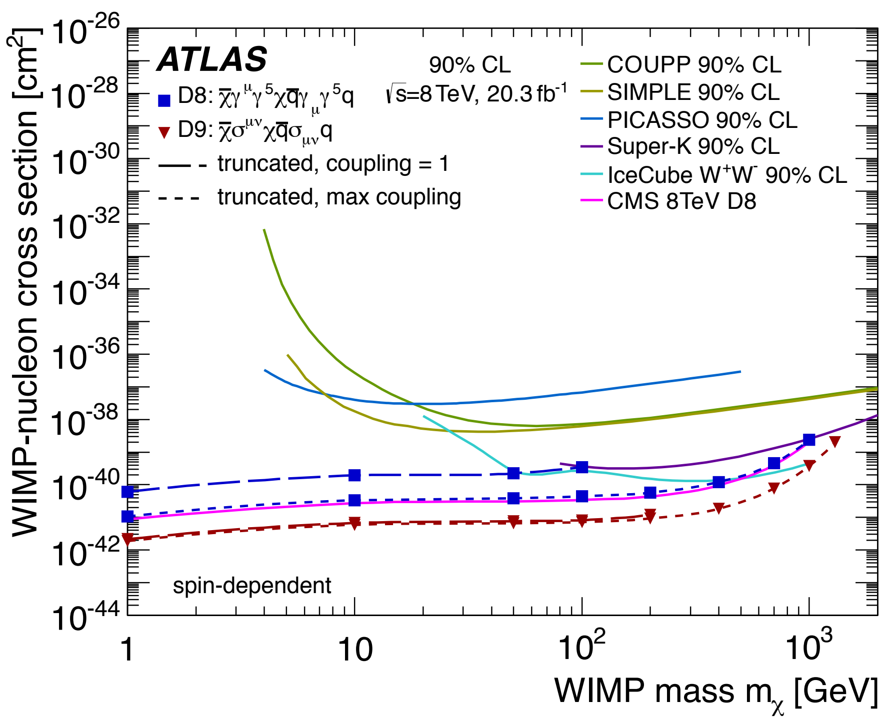
VALIDITY @LHC?

- LHC Run-1: “traditional" effective field theory (**EFT**) approach
  - assume mediator too heavy to be produced
  - 2 parameters: WIMP mass (**m**$_\chi$) & suppression scale (**M***)
  - comparison with direct detection

- truncation
  - for s-channel vector mediator $M_* = \frac{M_{Med}}{\sqrt{g_\chi g_{\rm SM}}}$
  - minimal validity requirement: $Q_{tr} < M_{Med}$

$M_* > \frac{Q_{tr}}{\sqrt{g_\chi g_{\rm SM}}}$.

- iteratively remove events that fail this



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- LHC Run-1: “traditional" effective field theory (**EFT**) approach
  - assume mediator too heavy to be produced
  - 2 parameters: WIMP mass (**m**$_\chi$) & suspression scale (**M***)
  - comparison with direct detection

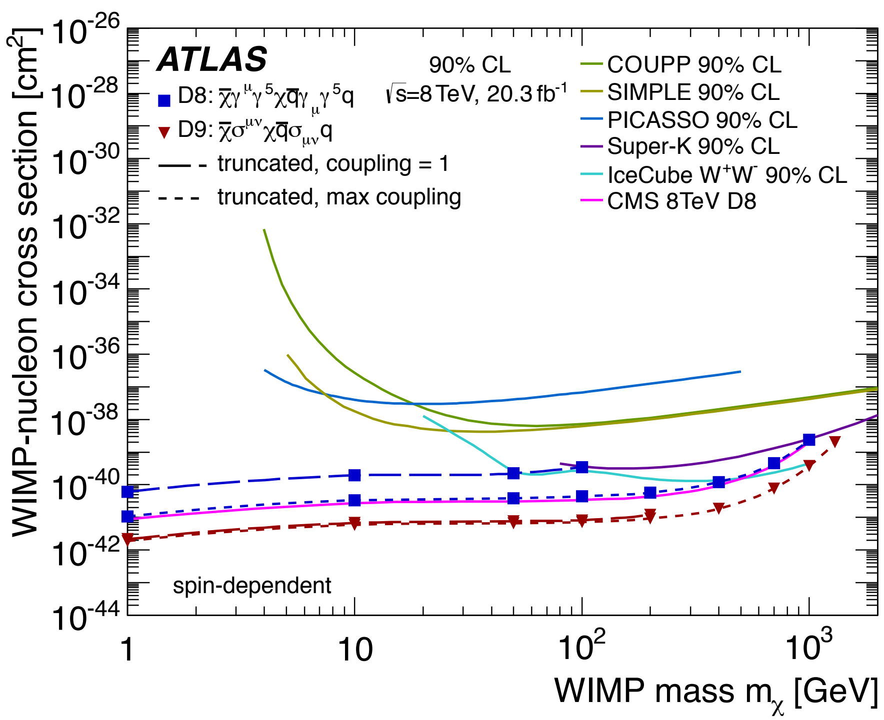
VALIDITY @LHC?

- truncation
  - for s-channel vector mediator $M_* = \frac{M_{Med}}{\sqrt{g_\chi g_{\mathrm{SM}}}}$
  - minimal validity requirement: $Q_{tr} < M_{Med}$

$M_* > \frac{Q_{tr}}{\sqrt{g_\chi g_{\mathrm{SM}}}}.$

  - iteratively remove events that fail this

- some comparisons to "simplified model"



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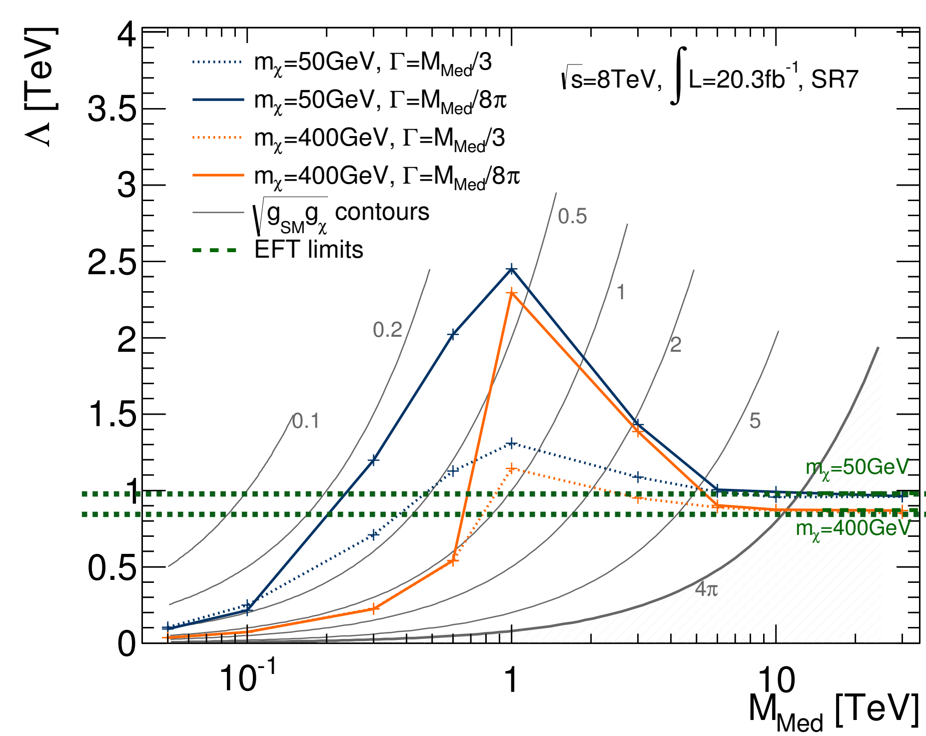

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Example: photon+E_T^{miss}

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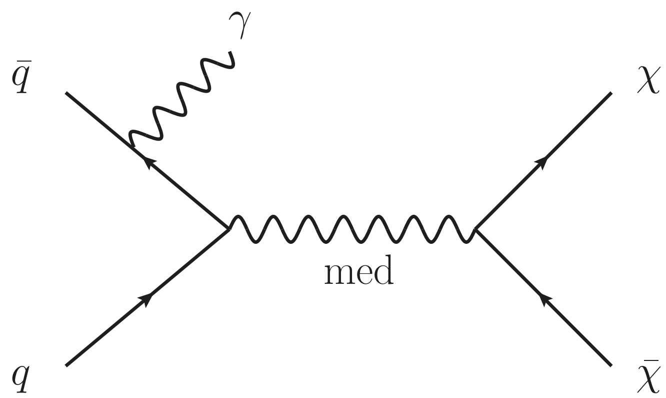
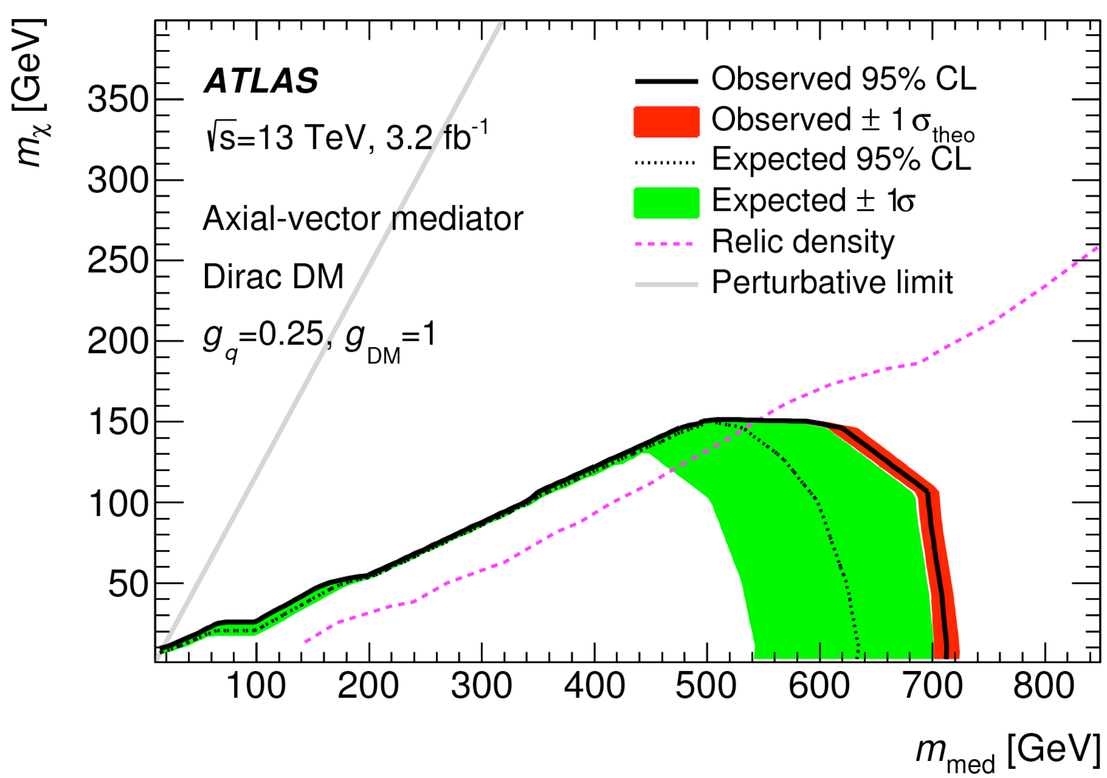
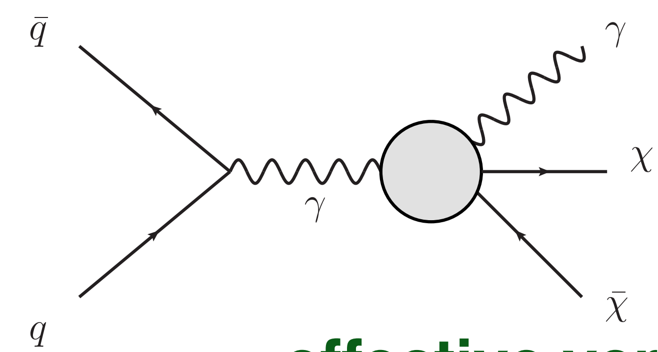
Simplified Model



g_q=0.25, g_χ=1

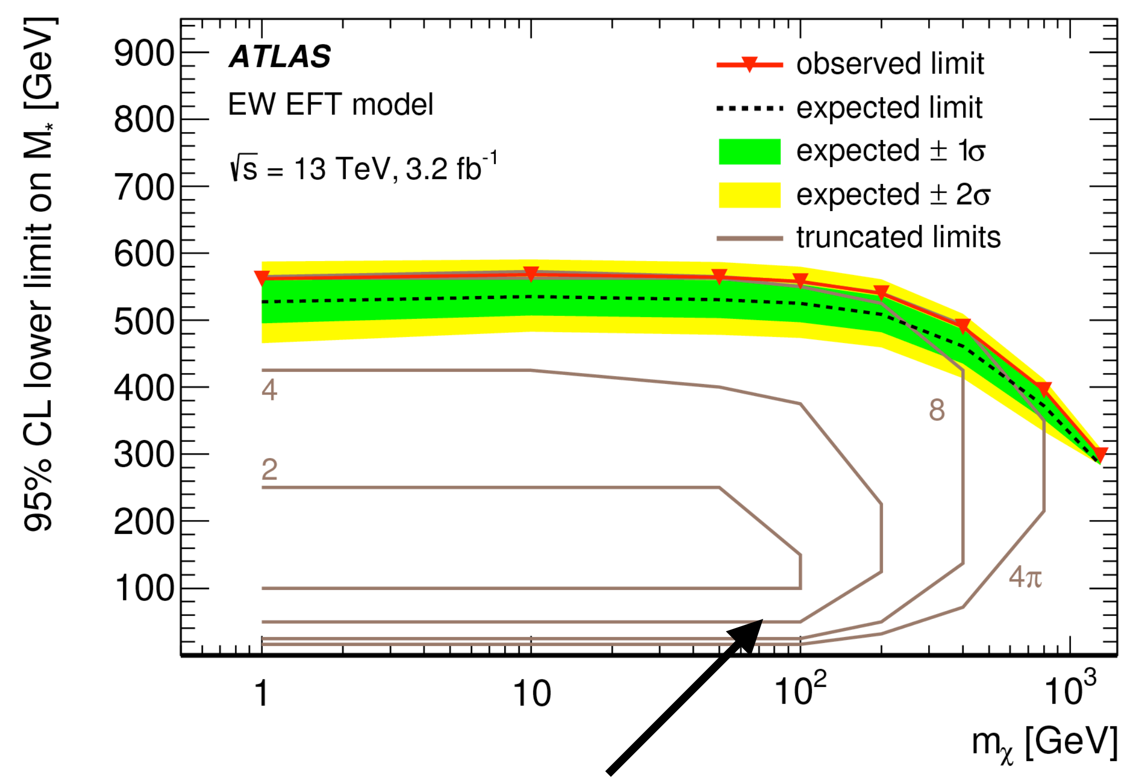


Effective Operator



no ISR!

effective vertex: $\gamma\gamma\chi\chi$



to address question of EFT validity: truncation, i.e. remove events with √s > gM* for various values of g