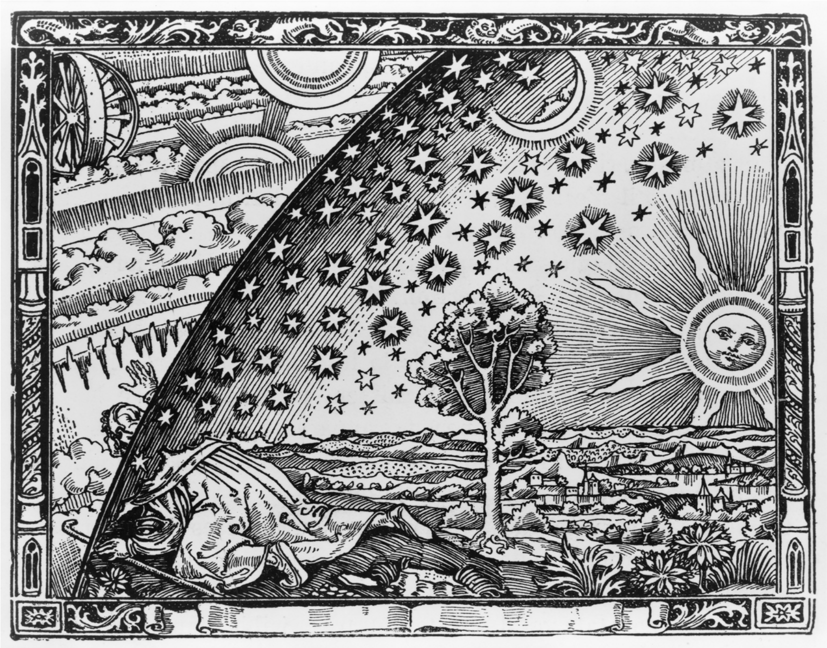
Beyond the Standard Model

Hamburg International Summer School
14 – 25 July 2025

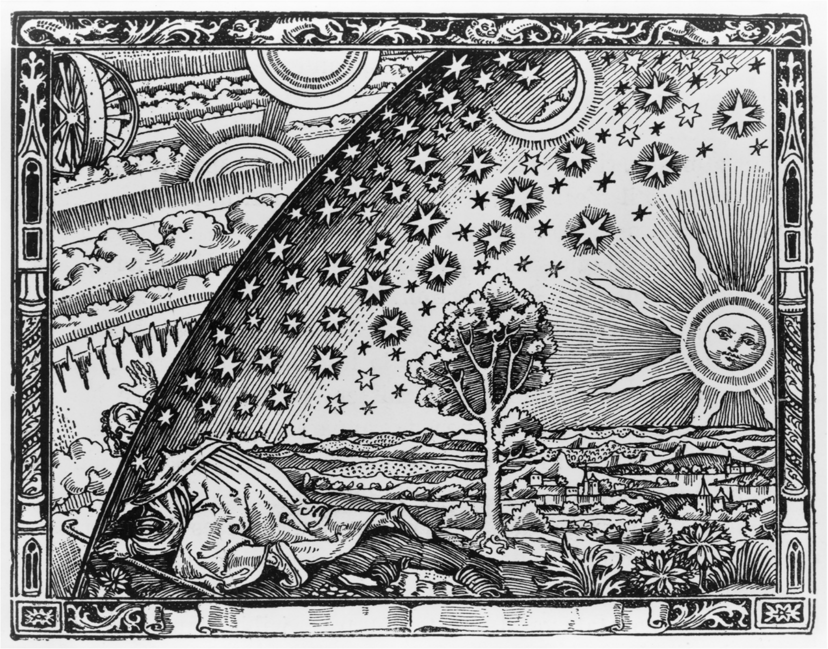


Katharina Behr

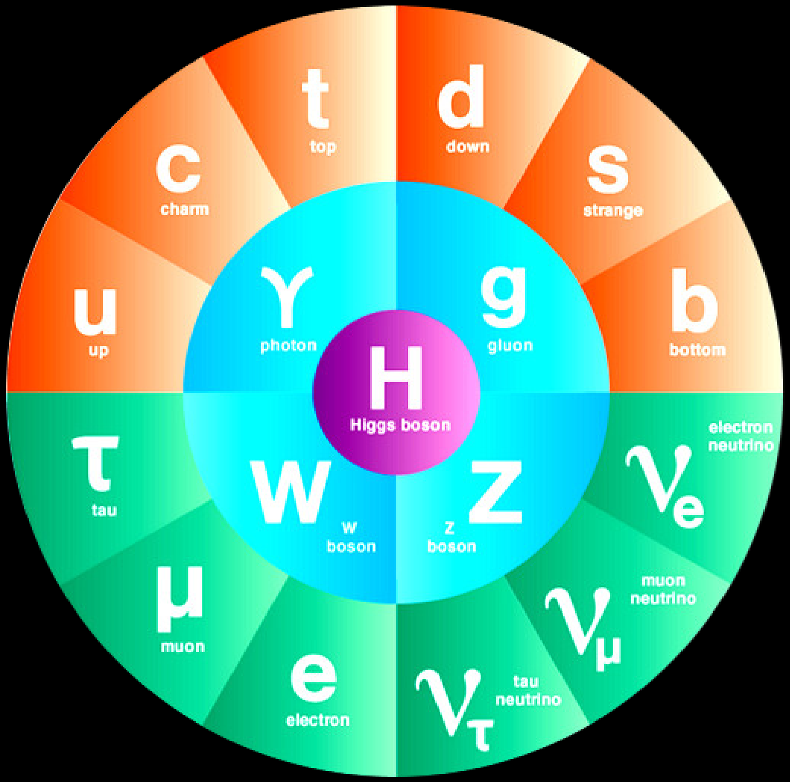
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
ATLAS EXPERIMENT
DESY.

Outline

- **Part 1:**
  - What motivates us to look beyond the Standard Model?
  - Experimental techniques
- **Part 2:**
  - Example: dark matter
    - WIMP searches at the LHC
    - Axion detectors at DESY
  - Outlook: the future of the LHC and beyond



85% dark matter

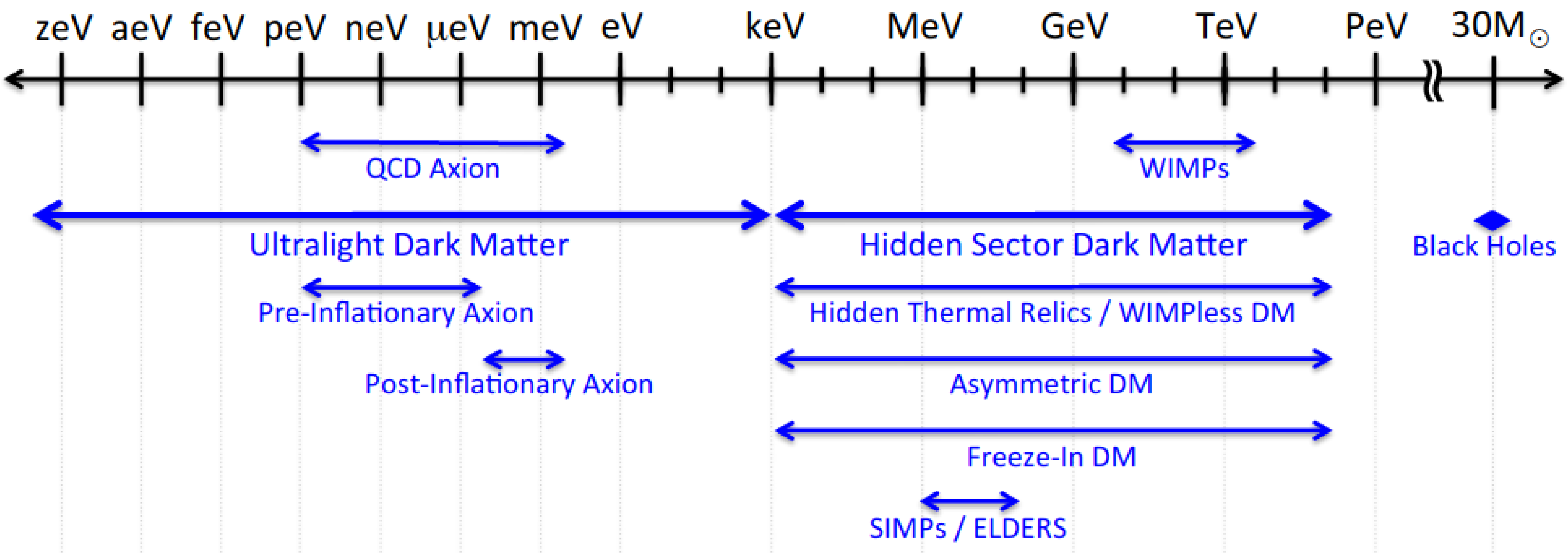


15% known matter

What should we be looking for?

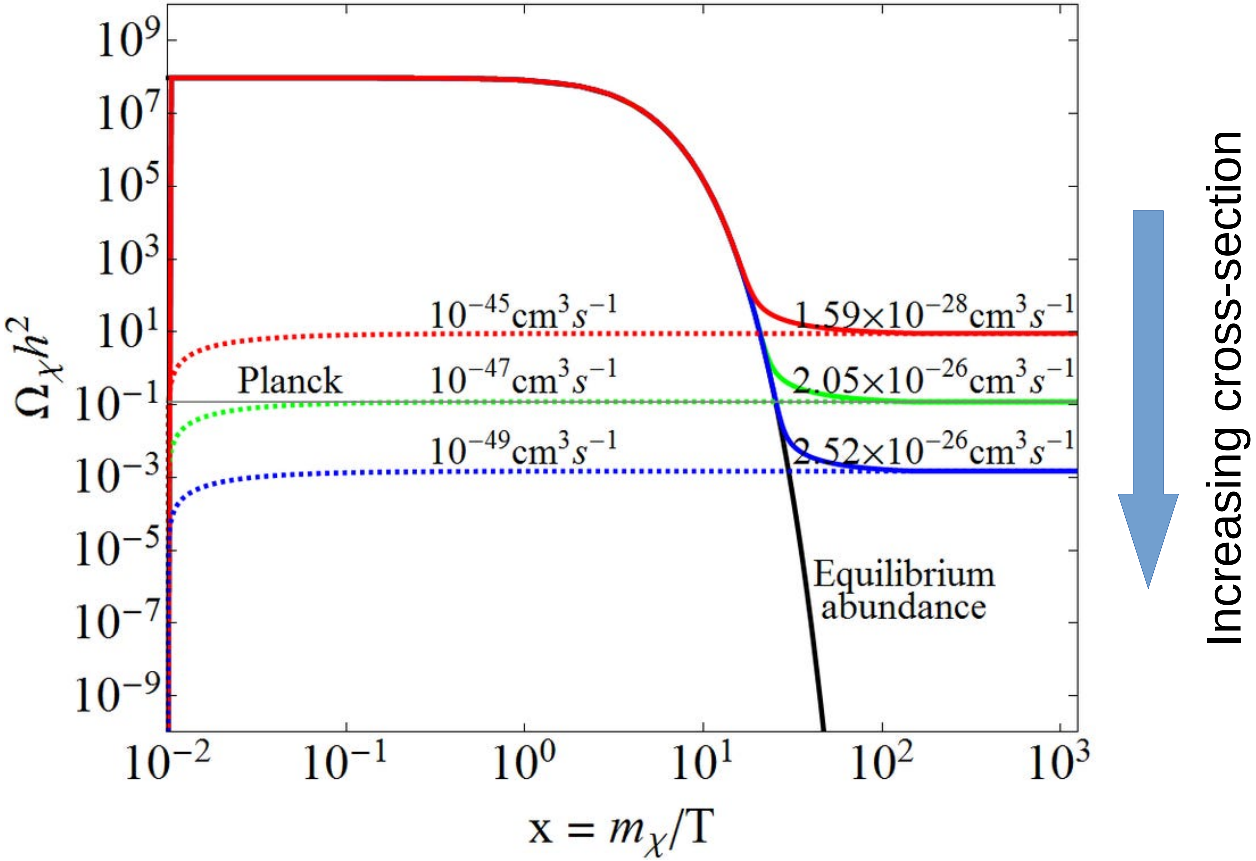
> Astrophysical and cosmological evidence:
  - DM must weakly interacting (no strong and EM interactions)
  - DM is cold (i.e. not neutrinos)
  - DM relic density in the Universe is known (see next slide)

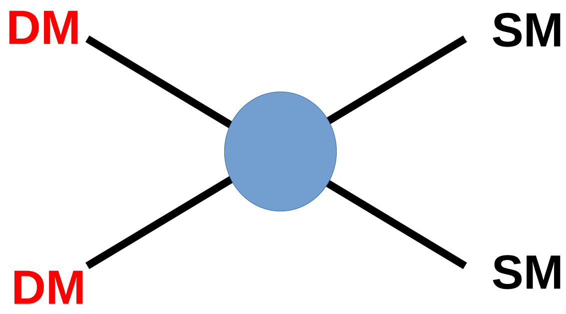
> Possible DM masses could vary across 80 (!!) orders of magnitude



Relic density

- Assume DM was produced at the Big Bang
- Relic density emerged when DM annihilation and production fell out of equilibrium during cooling





Cross-section depends on mass and coupling

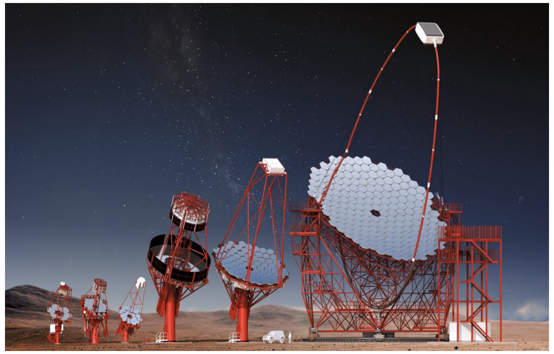
Weakly interacting massive particles (WIMPs)

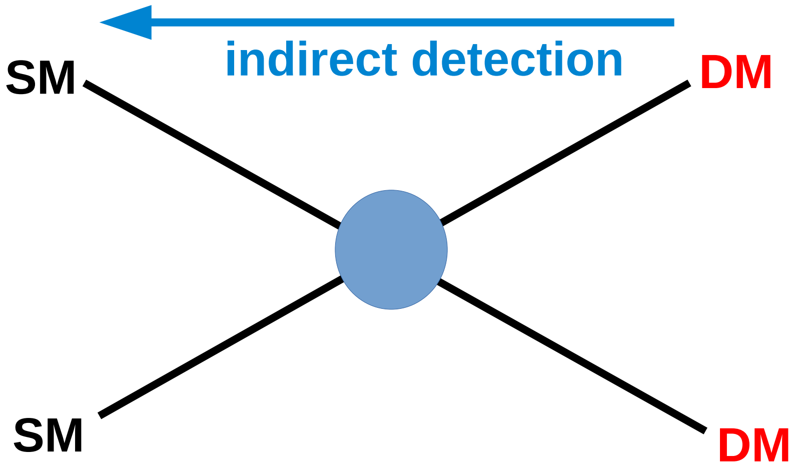
- Predicted by various BSM models addressing the hierarchy problem
  - E.g. lightest supersymmetric particle (LSP) is a WIMP
- Coupling: O(200 GeV), comparable to weak force
- Mass: O(100 GeV) – O(1 TeV), close to scale of EWSB
- Cross-section and relic density:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- Obtain observed relic density for WIMP with above properties
- Remarkable coincidence?! WIMP miracle!

How can we search for WIMPs?





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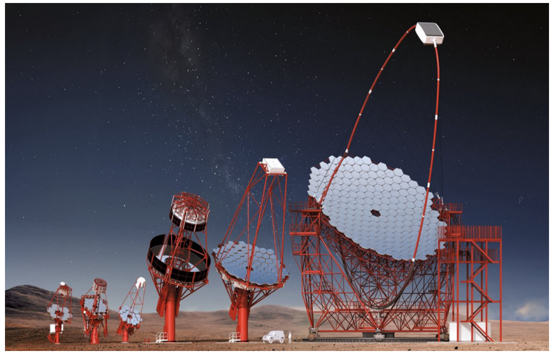

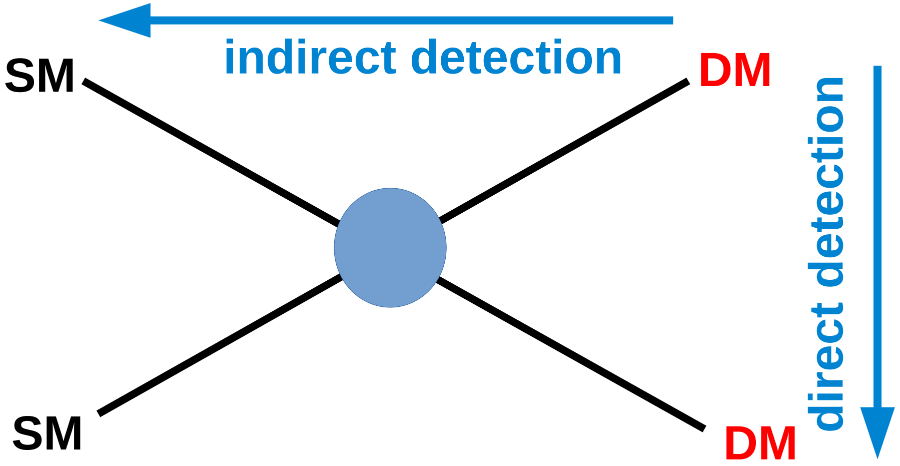

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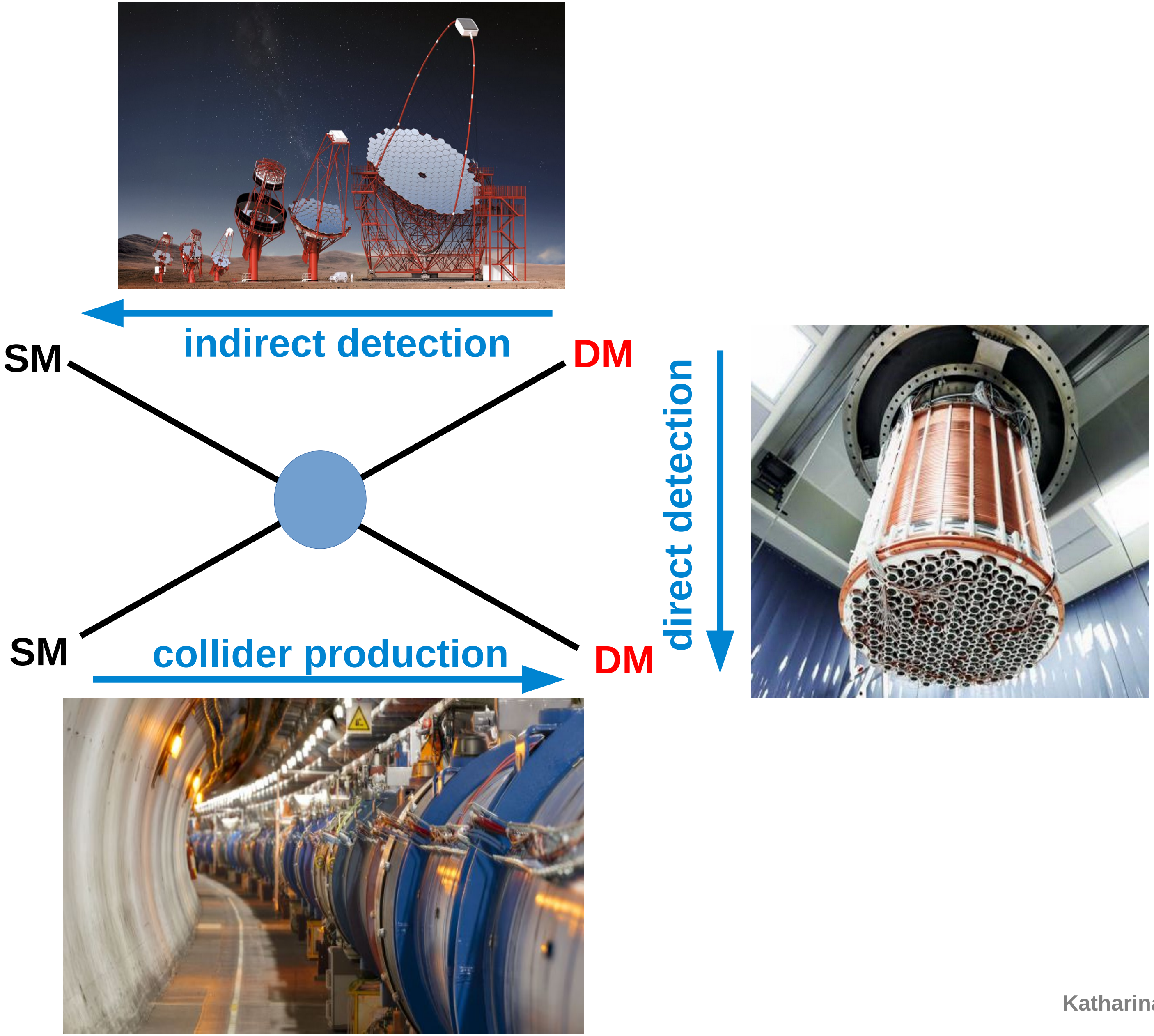
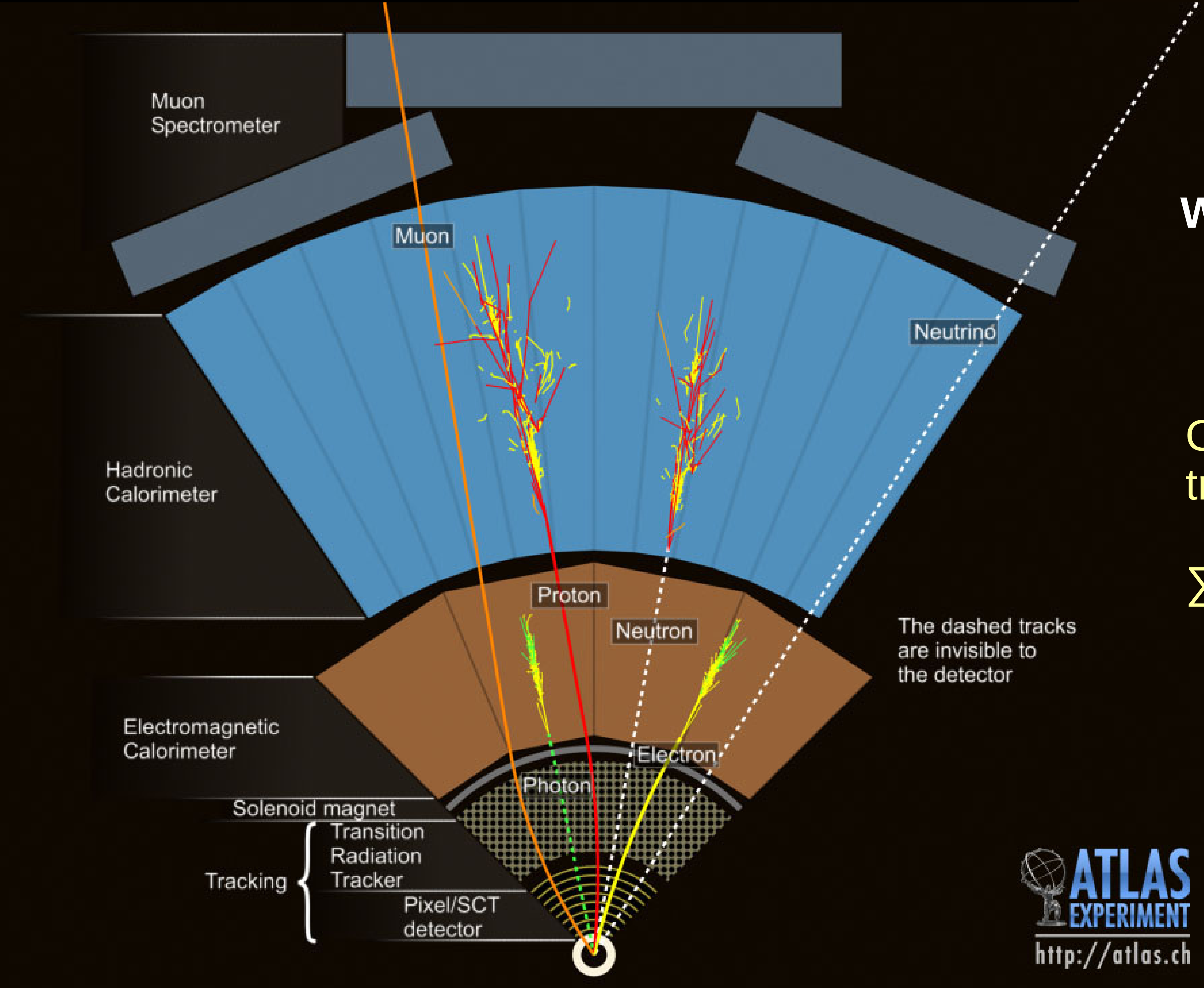


What about dark matter?



Only indirectly as missing transverse momentum

$\sum p_T(\text{vis}) + p_T(\text{miss}) = 0$

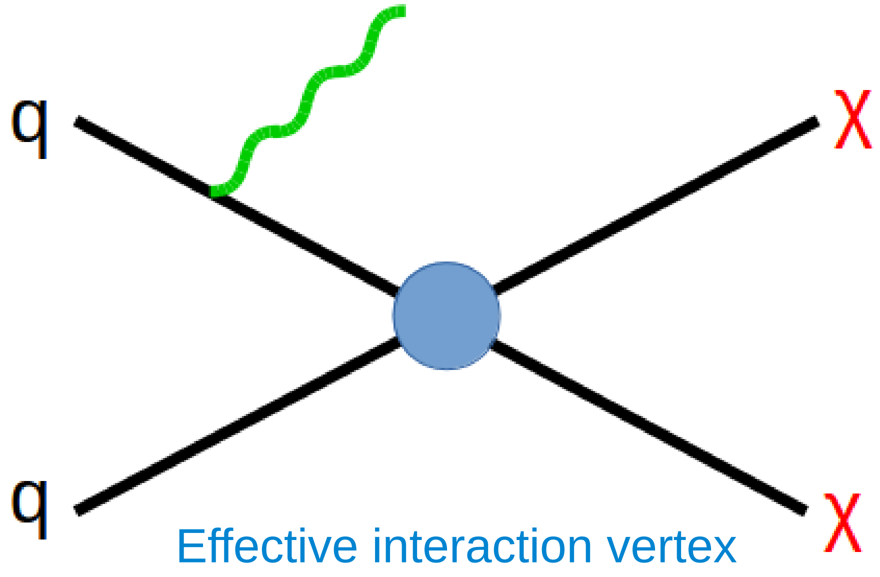
Dark matter production @ LHC

> Problem: Need a hard object to trigger on the event

> Solution: **initial-state radiation (ISR)**

   – Jet

   – ...

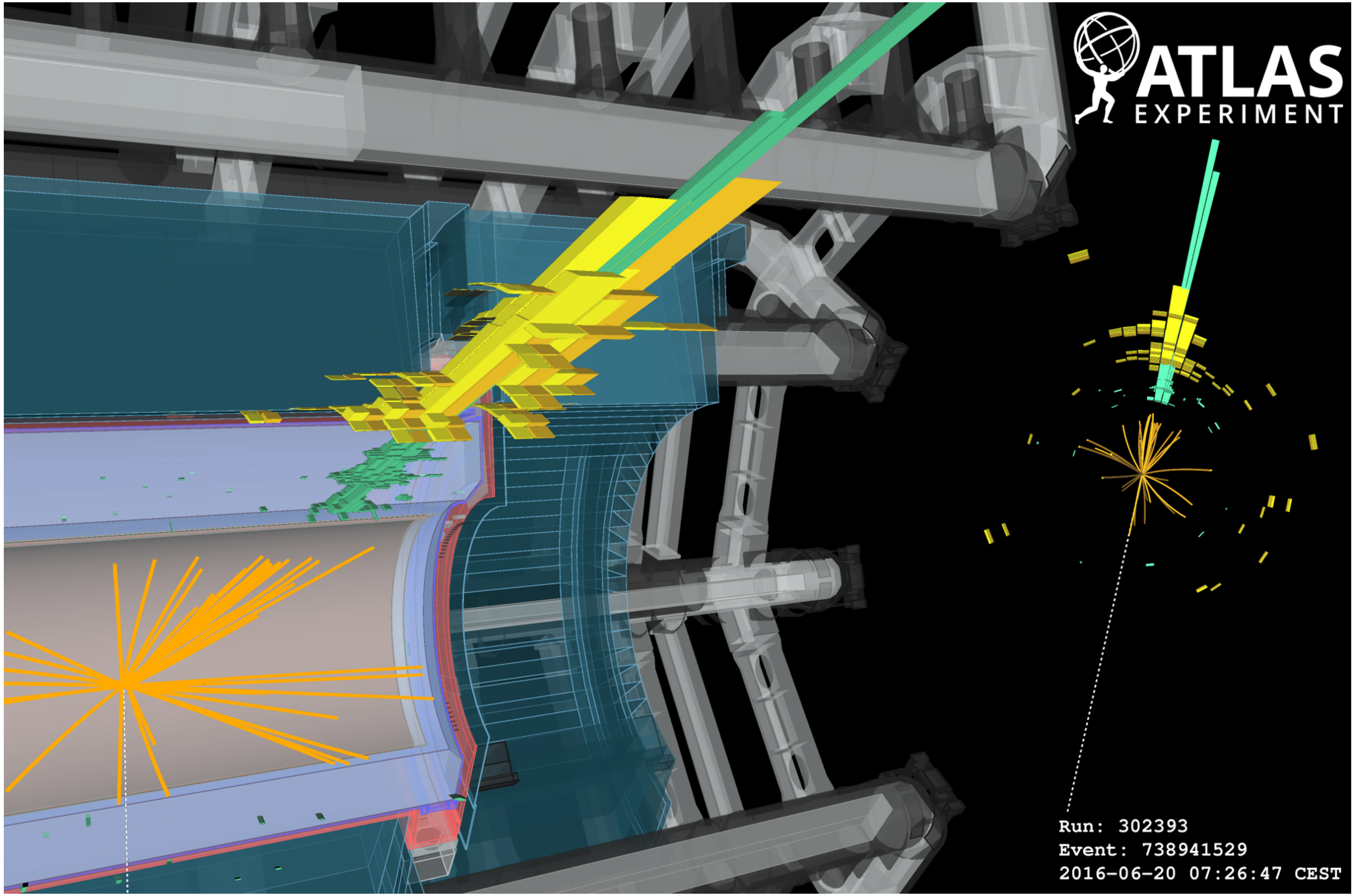


Signatures

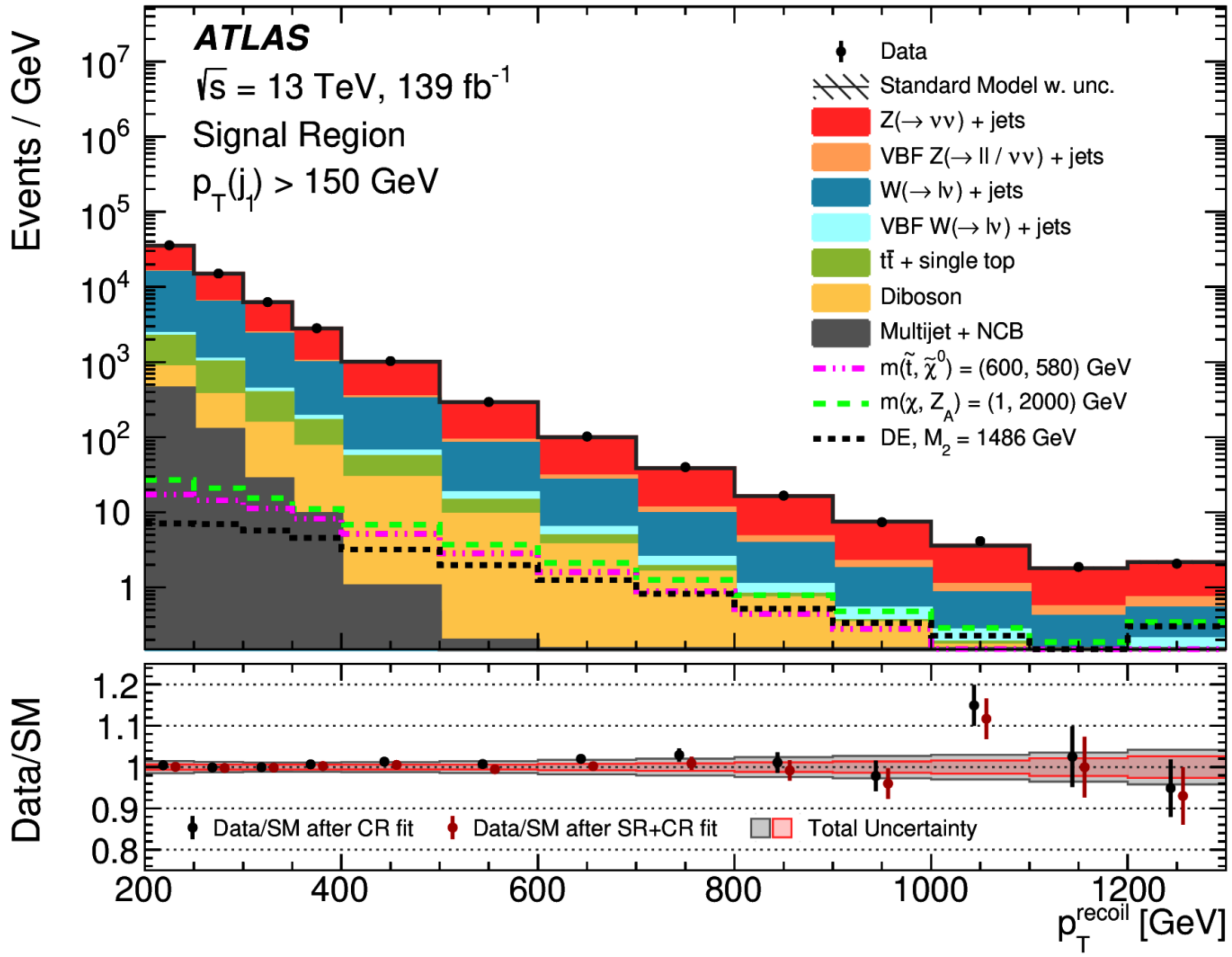
Mono-jet

...

A mono-jet event in 2016

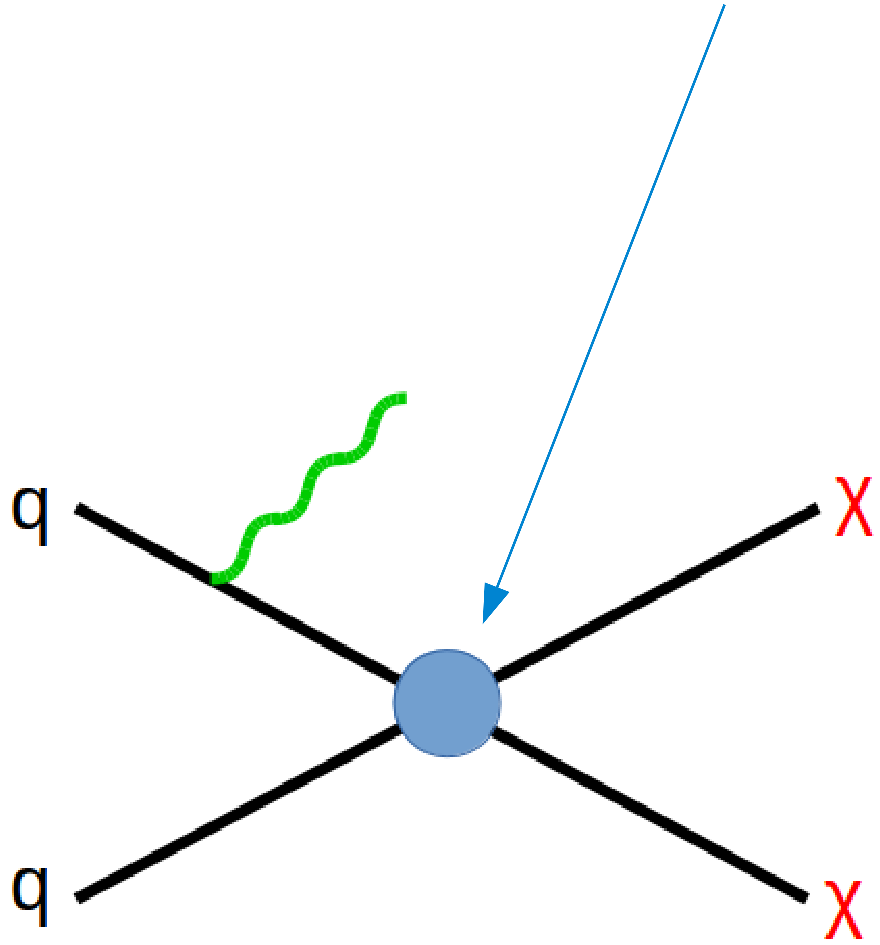


Tail hunt in MET spectrum

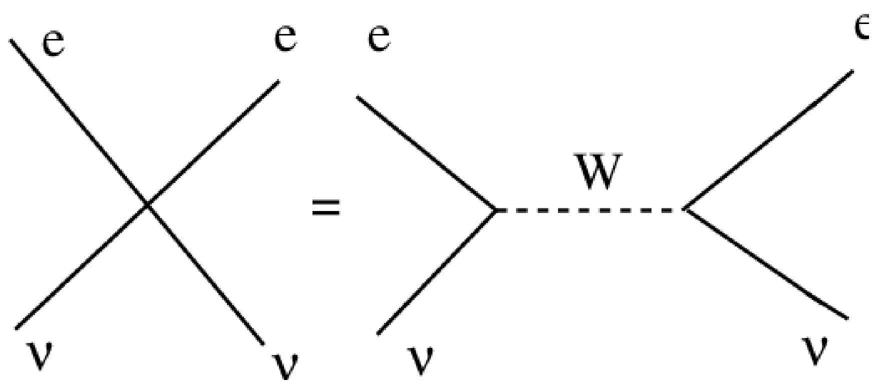


Probing the SM - DM interaction

Can we resolved this effective vertex at the LHC?

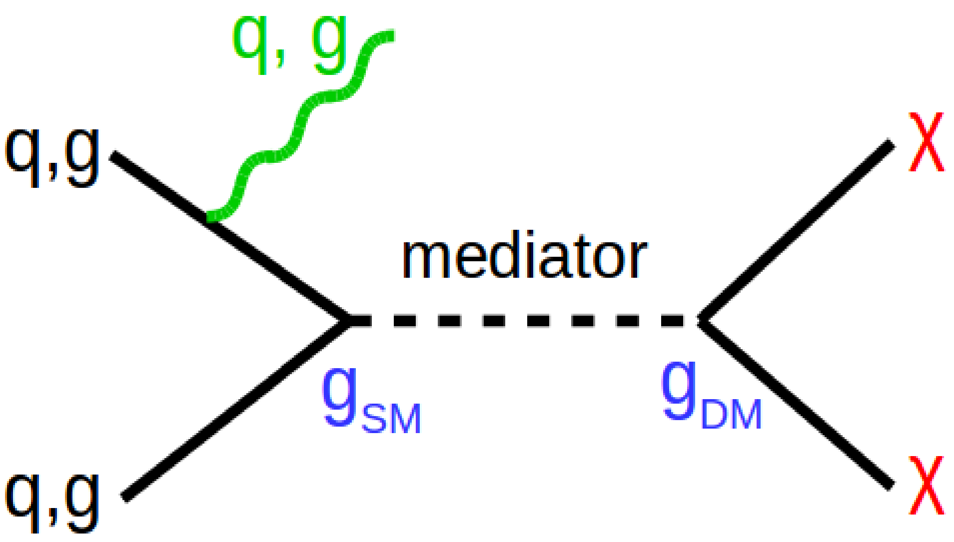


Analogy: Fermi's 4-point interaction



Probing the SM - DM interaction

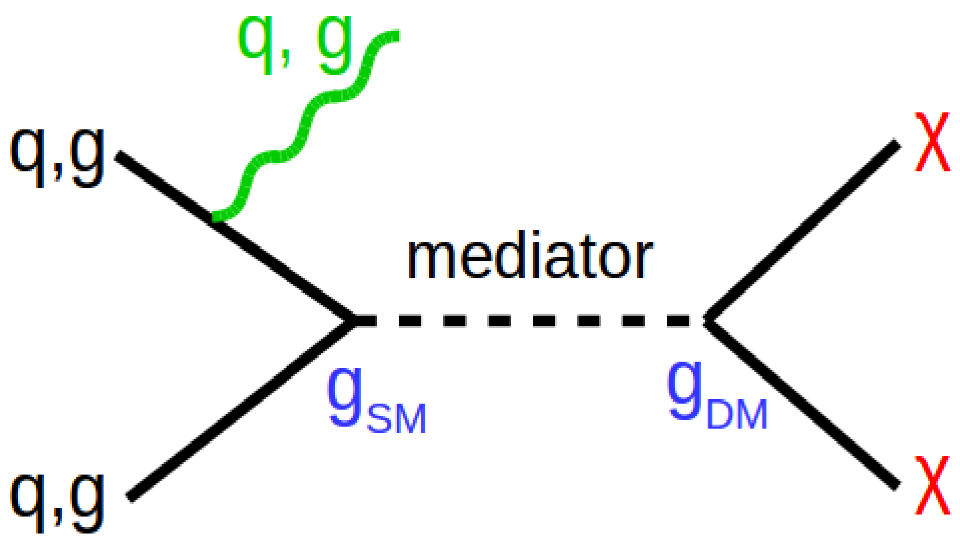
> Interaction mediated by a new particle (**mediator**)

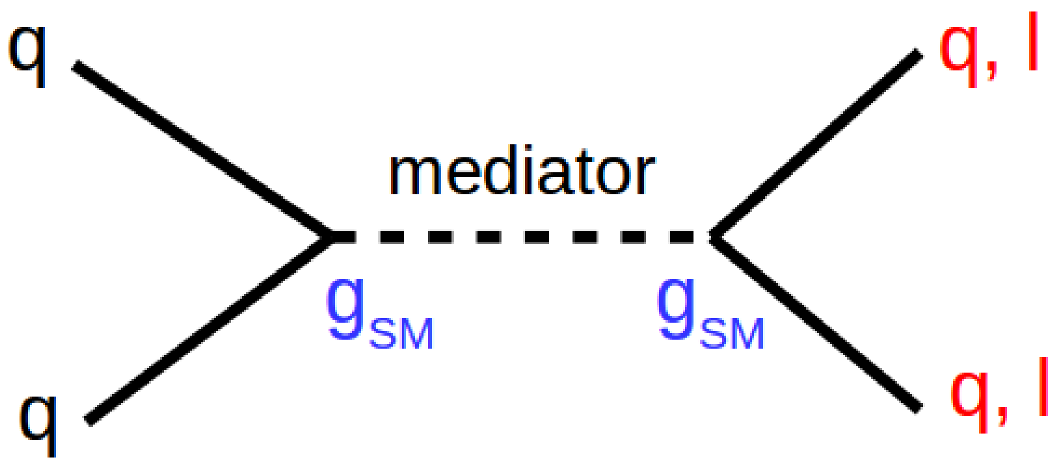


Probing the SM - DM interaction

- Interaction mediated by a new particle (**mediator**)
- Mediators can decay back into (visible) SM fermions

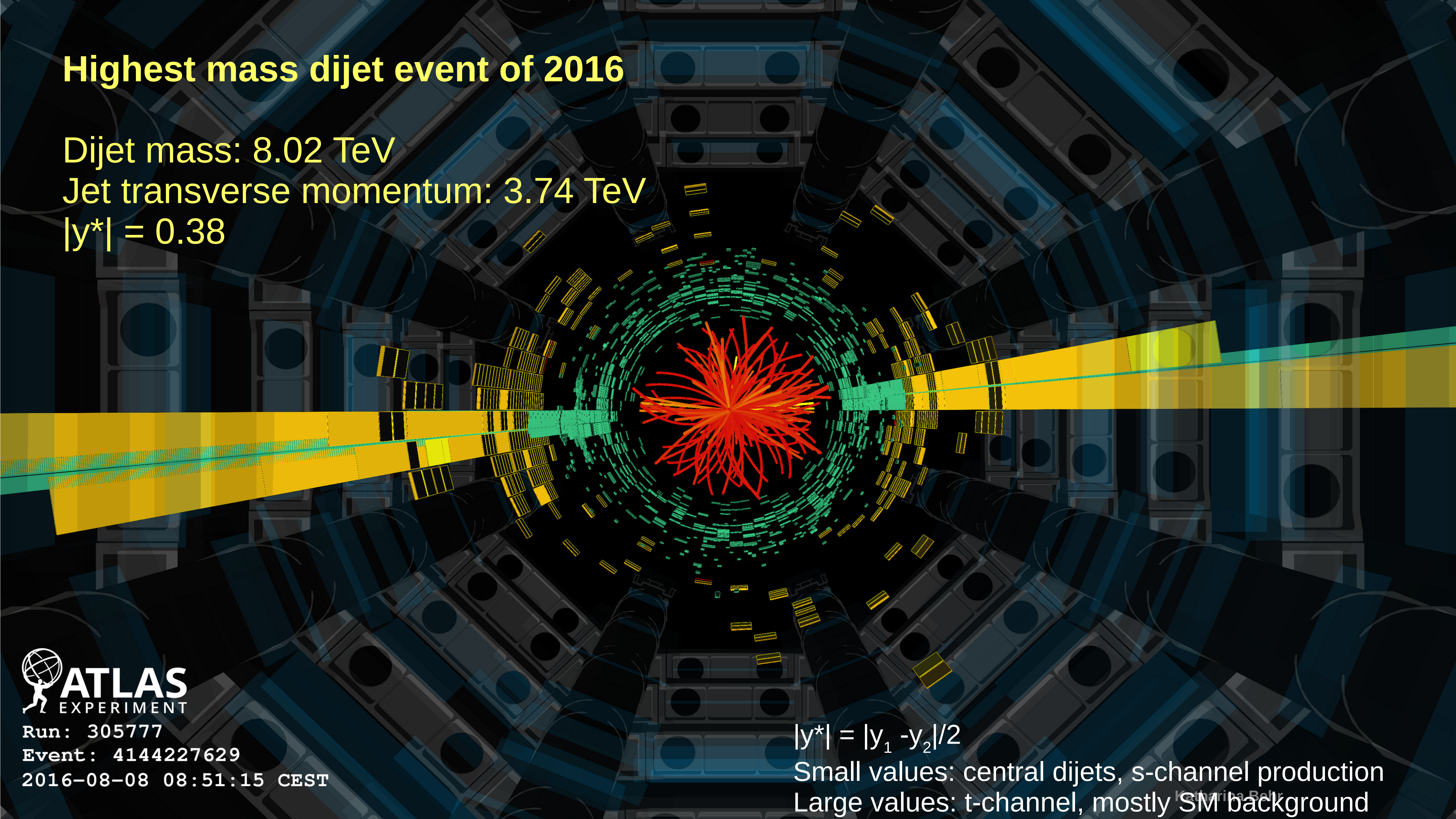
Two complementary search strategies at the LHC!





Highest mass dijet event of 2016

Dijet mass: 8.02 TeV
Jet transverse momentum: 3.74 TeV
$|y^*| = 0.38$



ATLAS EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST

$|y^*| = |y_1 - y_2|/2$
Small values: central dijets, s-channel production
Large values: t-channel, mostly SM background

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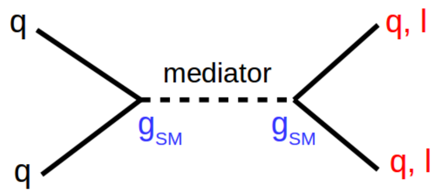
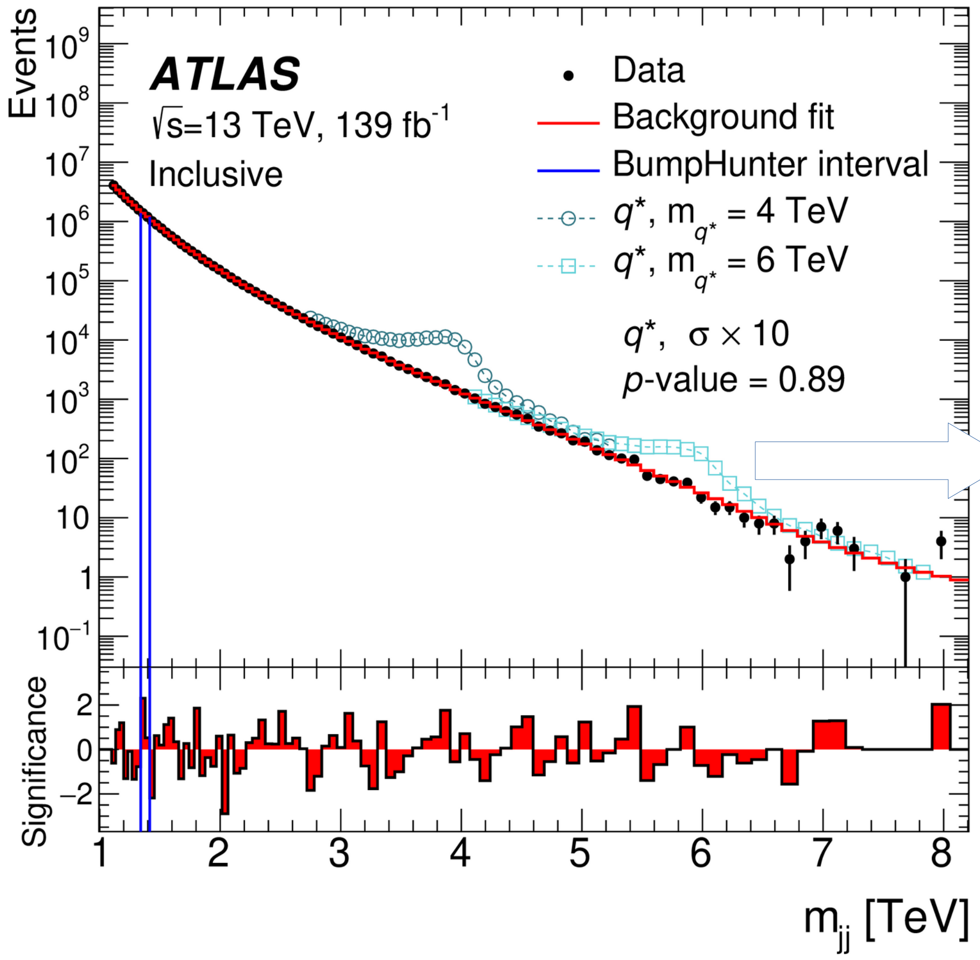
Bump hunt in the dijet mass spectrum

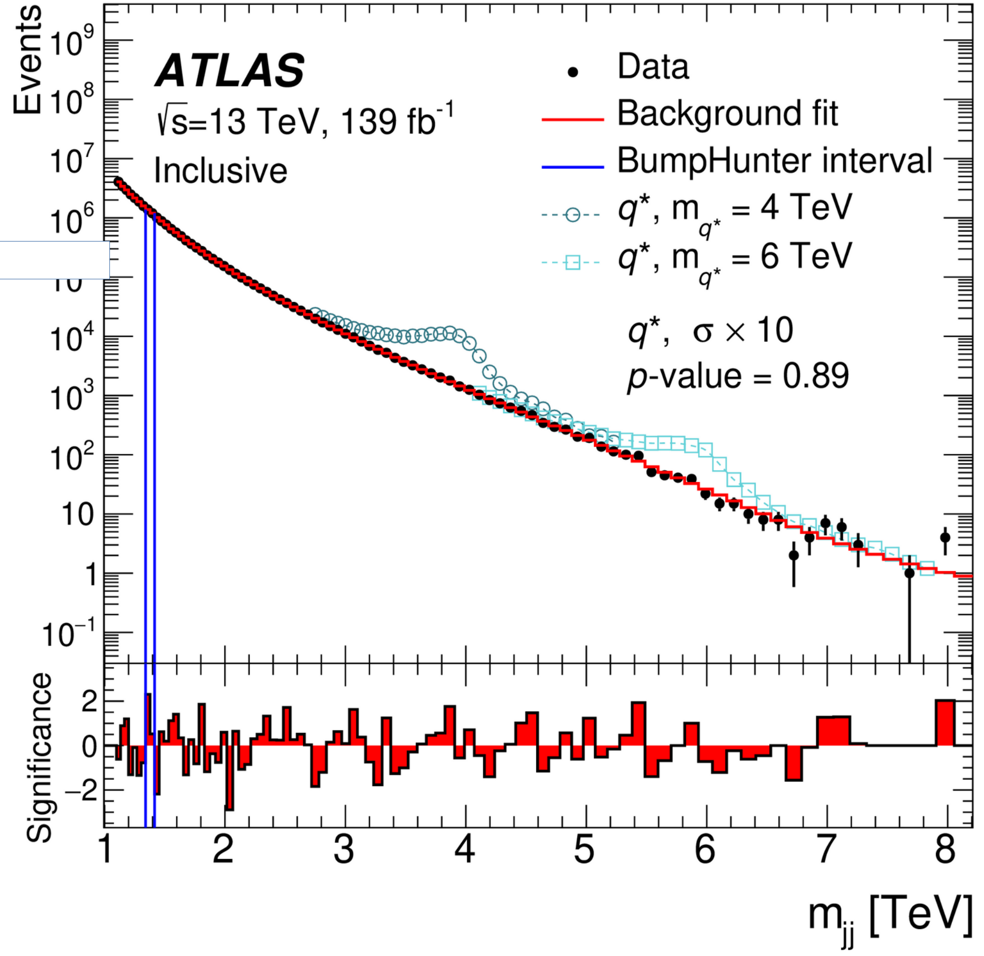


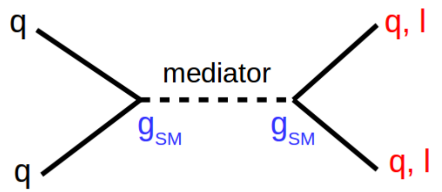


Early LHC days:
main focus on high-mass range
(accessible for the first time)

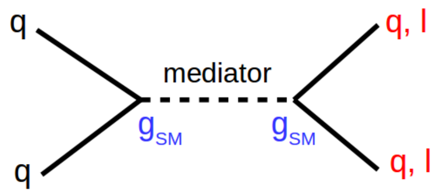
Bump hunt in the dijet mass spectrum

LHC Run-2:
Increasing focus on more low-mass range
(and smaller couplings)





Bump hunt in the dijet mass spectrum



LHC Run-2:
Increasing focus on more
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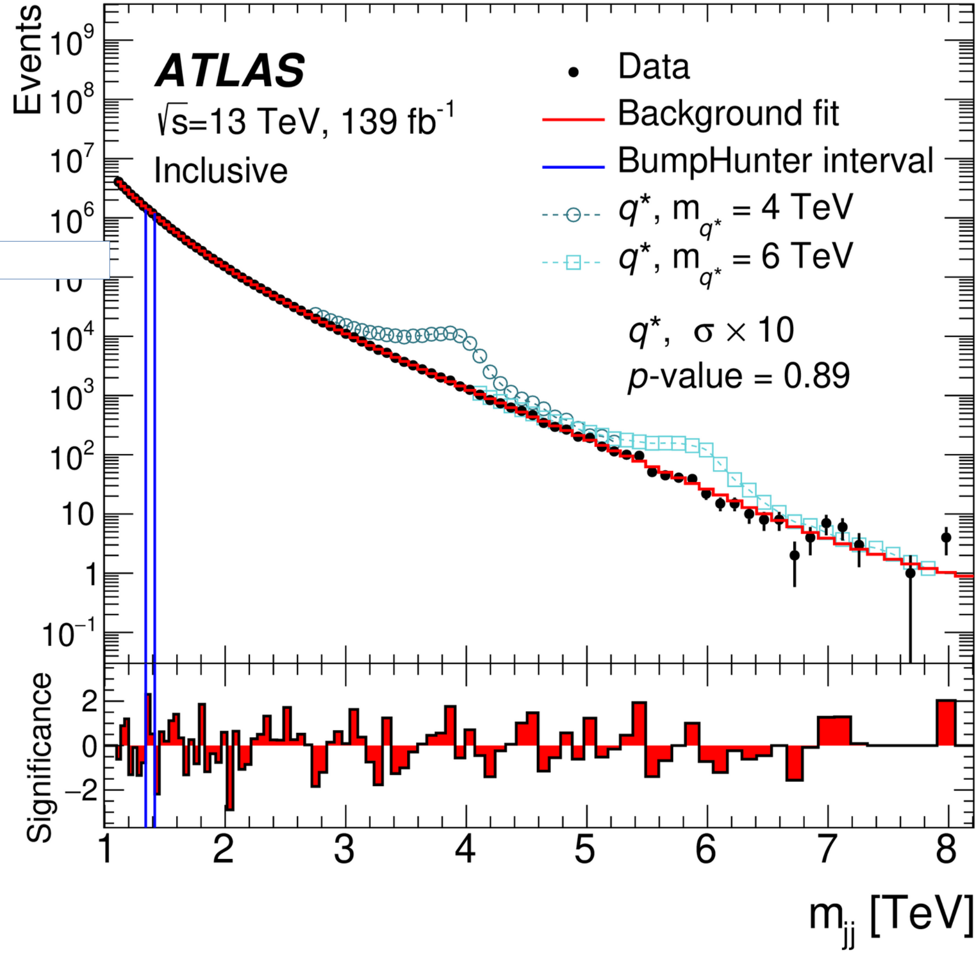
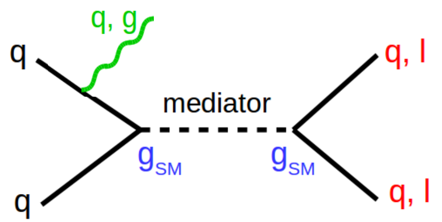
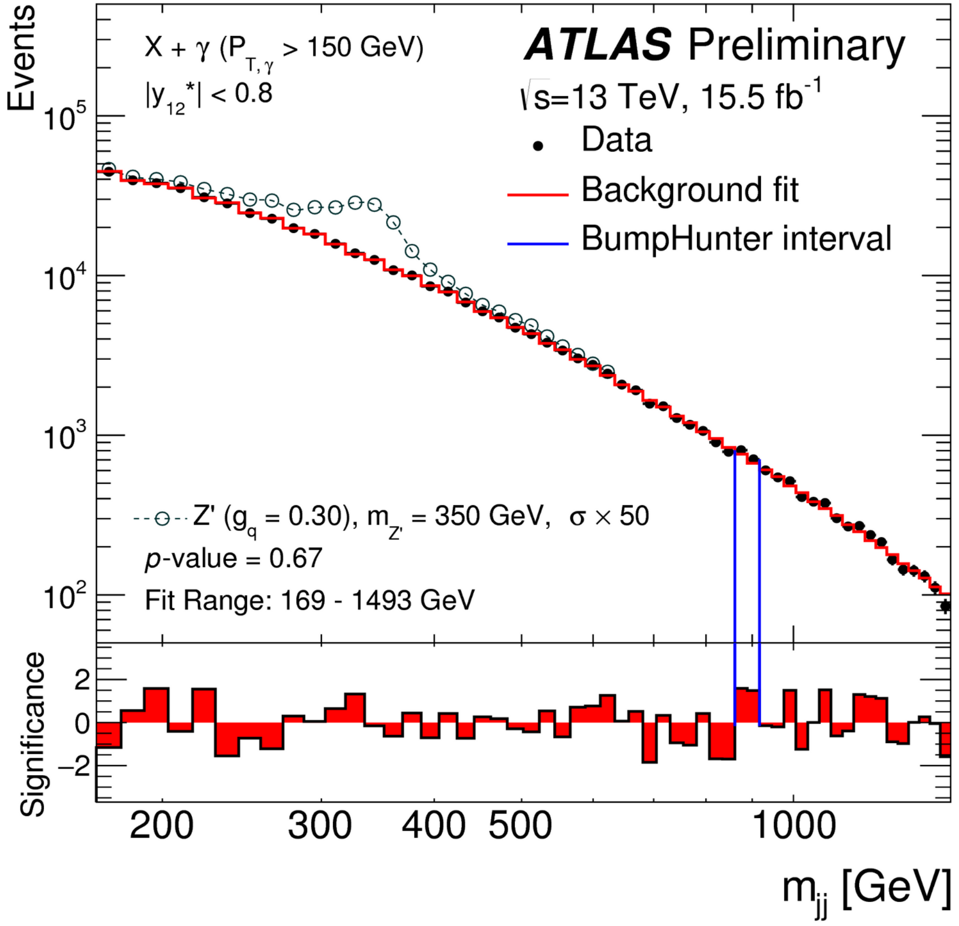


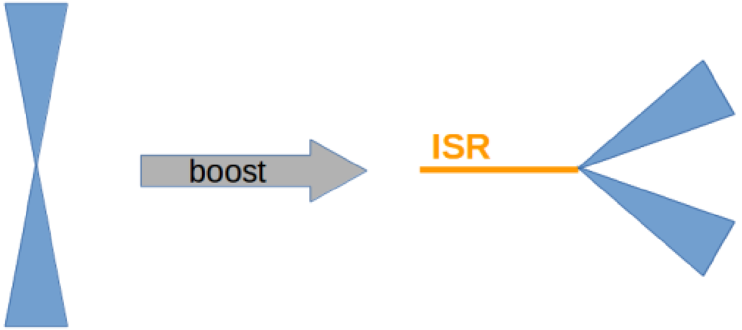
- → More challenging due to higher background rates!
- → Conventional dijet searches limited by trigger thresholds
- → Trigger typically requires jet p_T > 500 GeV
- → Limits search to m_{jj} > 1 TeV
- → Need smart ideas to go lower!

Smart idea 1: trigger on ISR

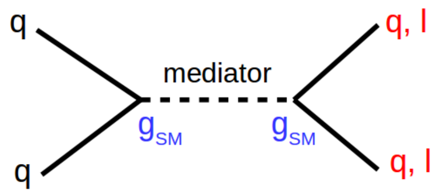
> Trigger on hard ISR rather than soft final-state jets from low-mass resonance
> Similar idea as for MET+X searches





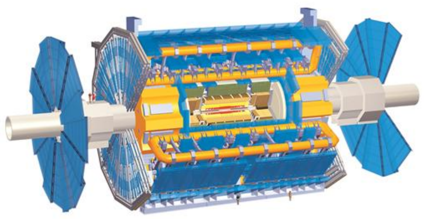


Smart idea 2: trigger-level analysis (TLA)



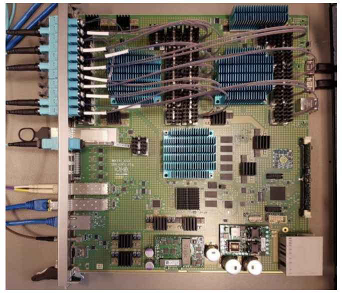
- Key idea: dijet searches rely on very little event information
  - Jet 4-vectors, some calorimeter variables
- No need for full offline reconstruction!
- Write out separate datastream with only HLT event information
  - HLT event size ~0.5% of full offline event
  - Can afford higher acceptance rates

LHC collisions



40 MHz

L1 hardware trigger



1 kHz

HLT software trigger

1 kHz → Full event info for offline reconstruction

~6 kHz → HLT event info for TLA

Smart idea 2: trigger-level analysis (TLA)

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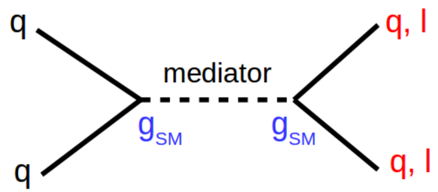
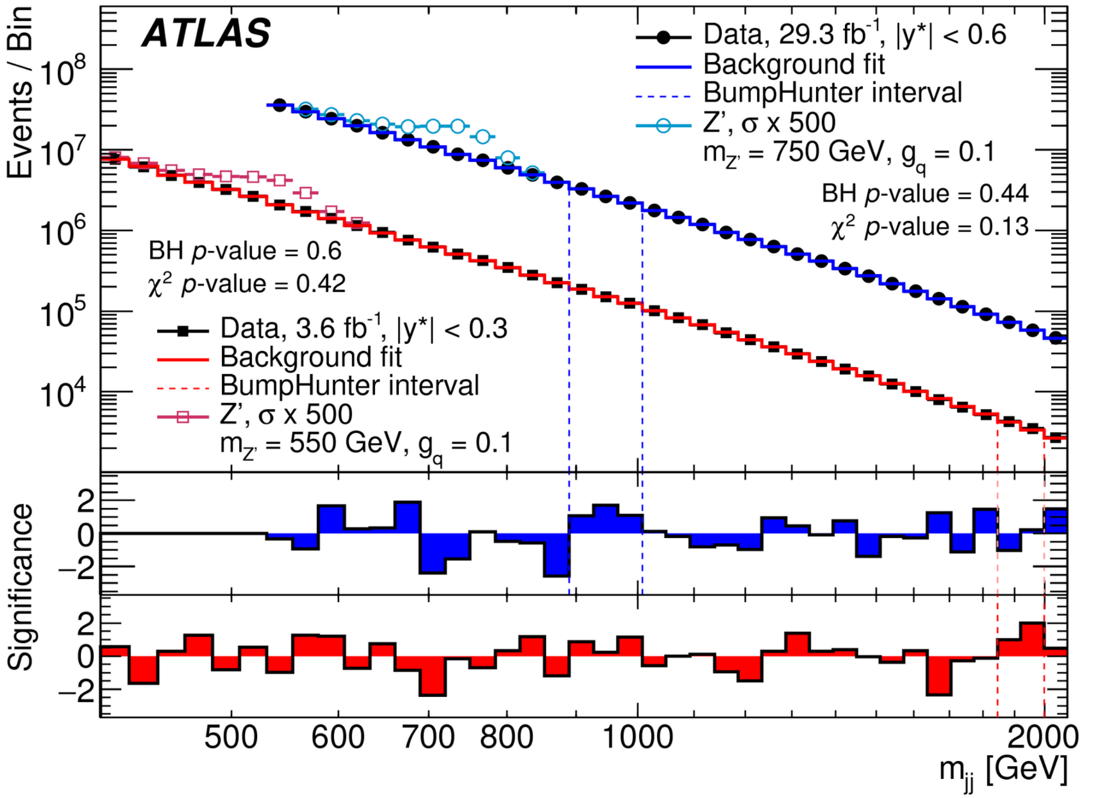
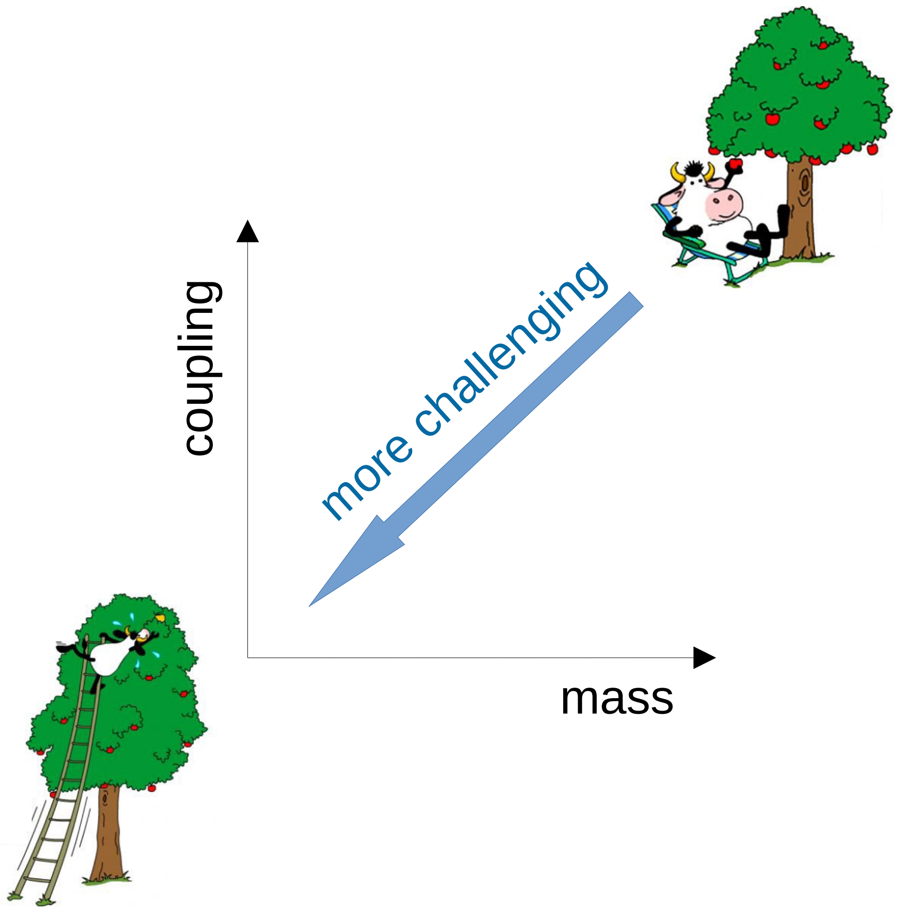
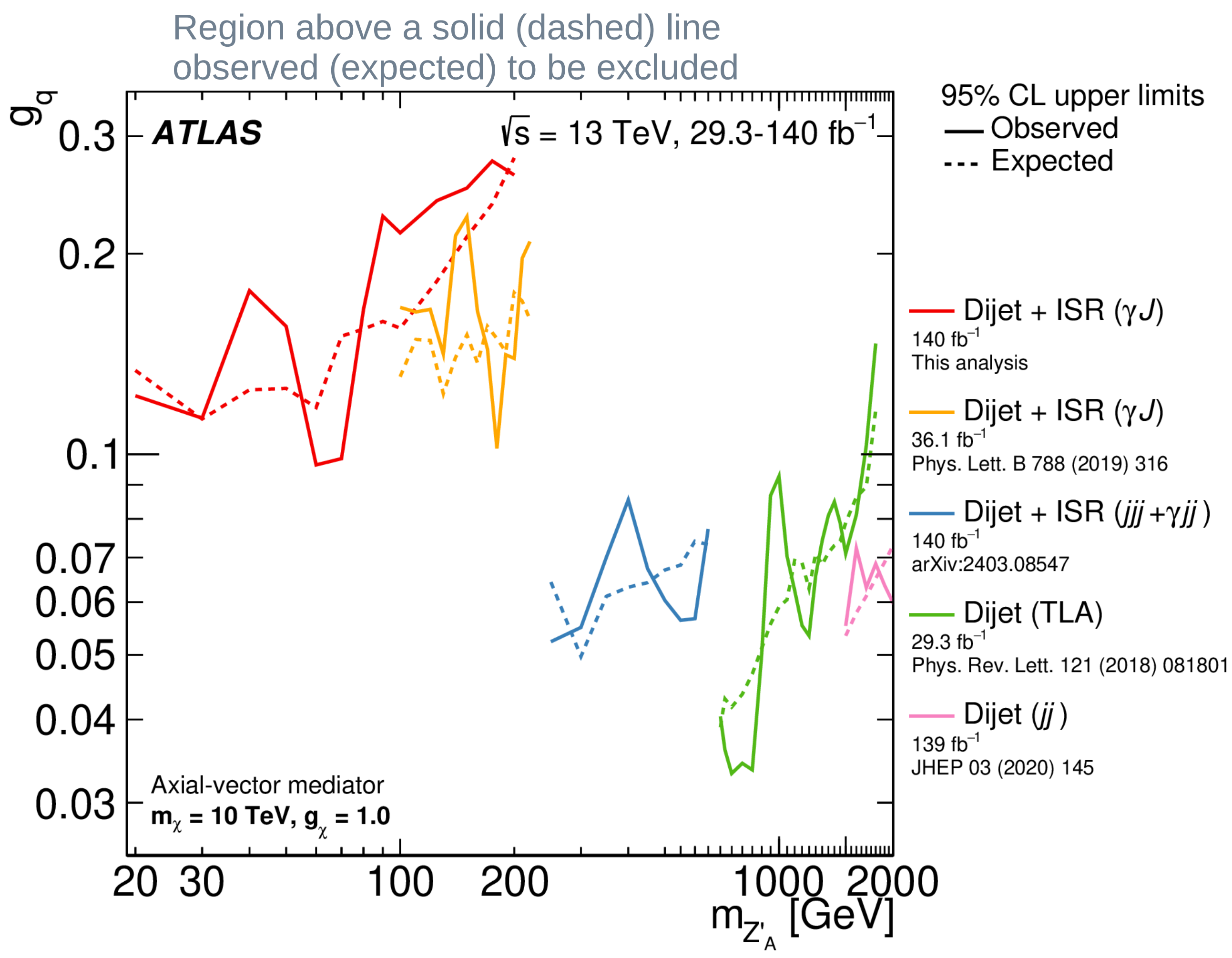




Pushing the limits of sensitivity

> Many other smart ideas: push sensitivity to lower couplings and masses

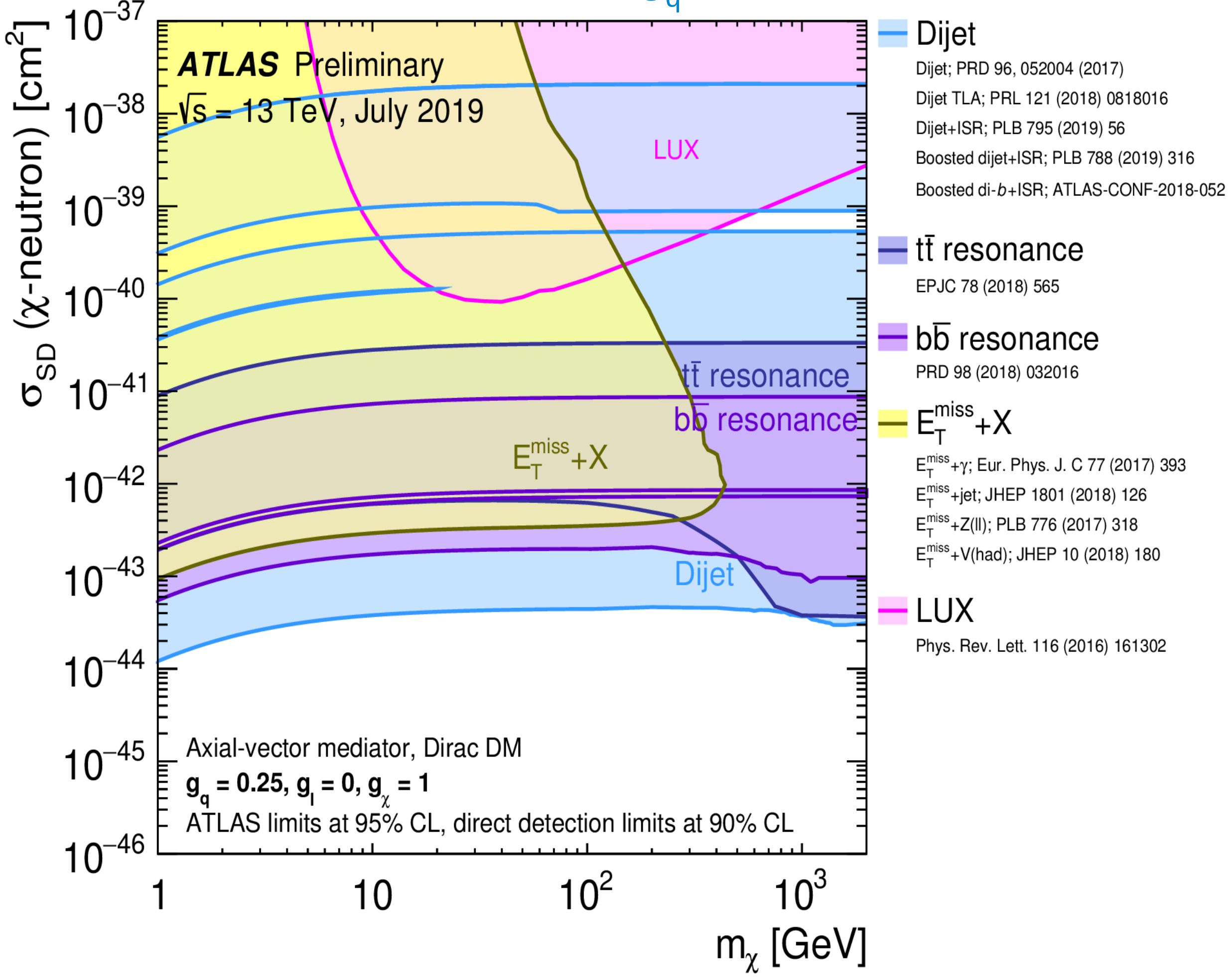




LHC vs Direct Detection

Relative sensitivities are model dependent!

Axialvector mediator, $g_q = 0.25$



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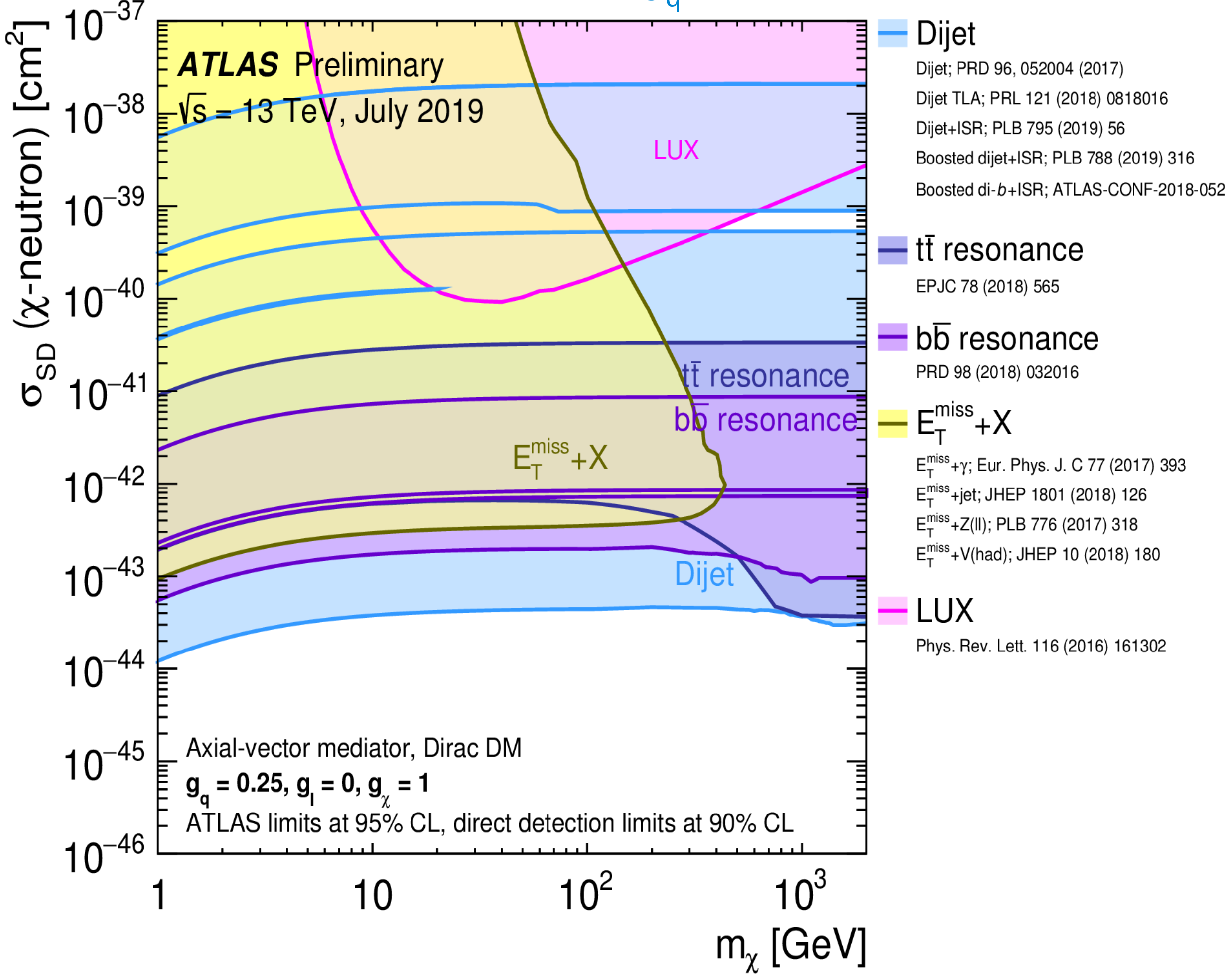
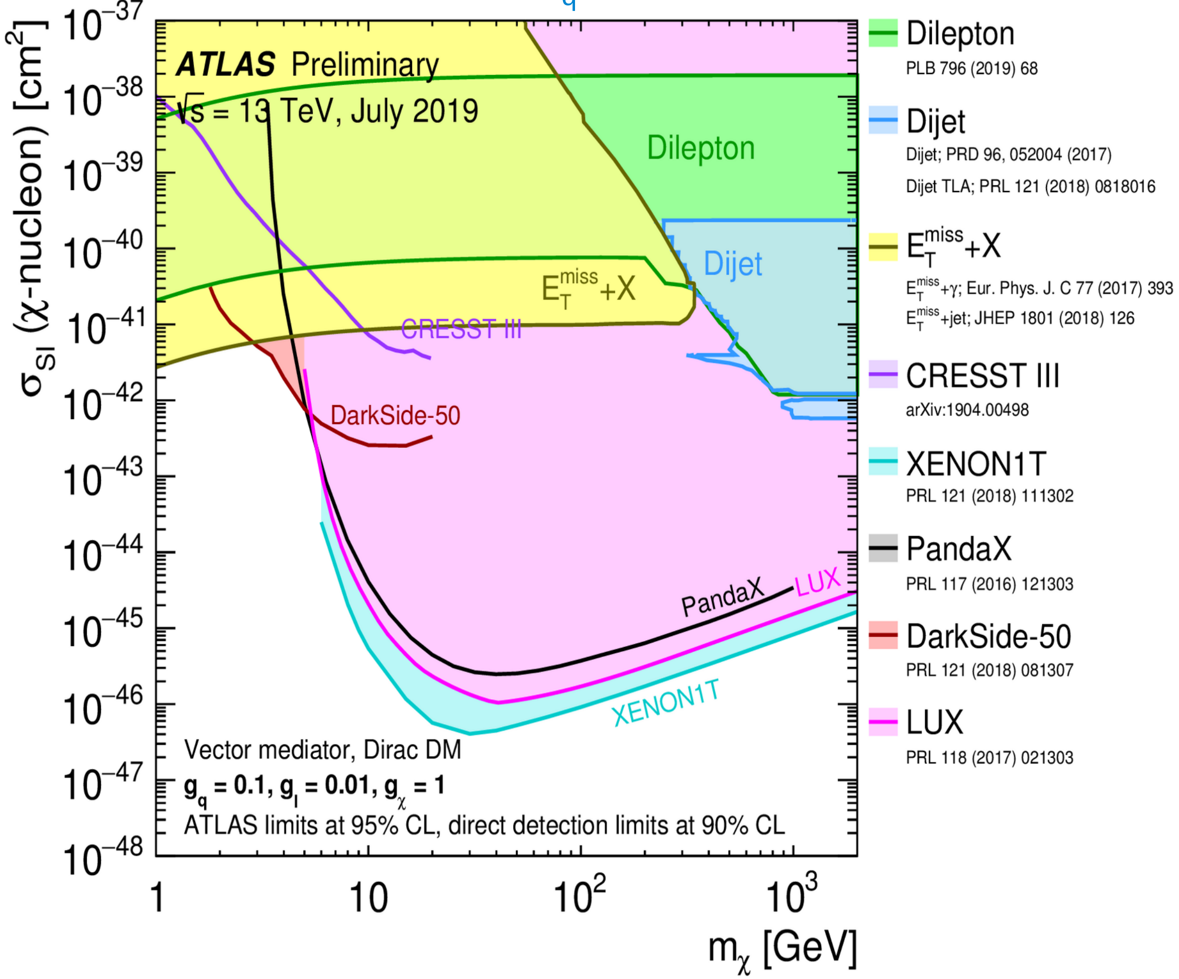


Vector mediator, $g_q = 0.1$

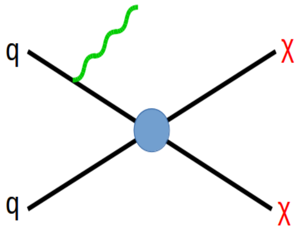


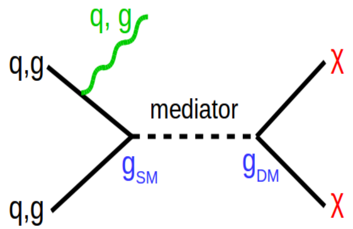
Evolution of dark-matter models at the LHC

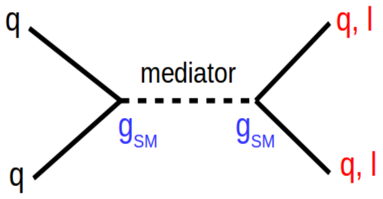
Effective field theories

Simplified models

model-independent,
limited validity



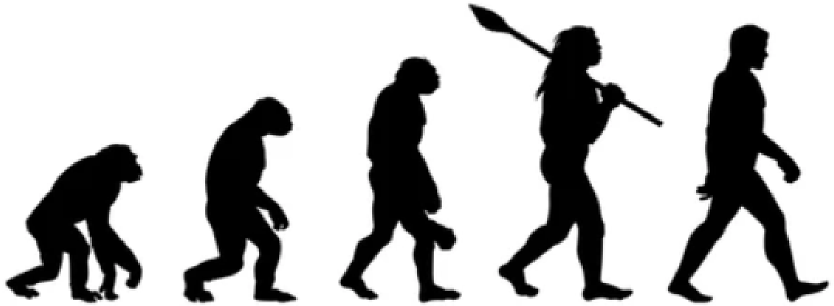




Are we missing any interesting signatures by looking at too simplistic models?

Early Run 1

Run 1 + Run 2

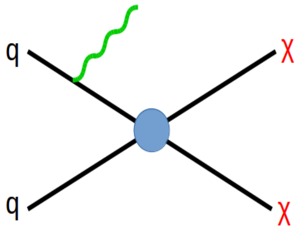


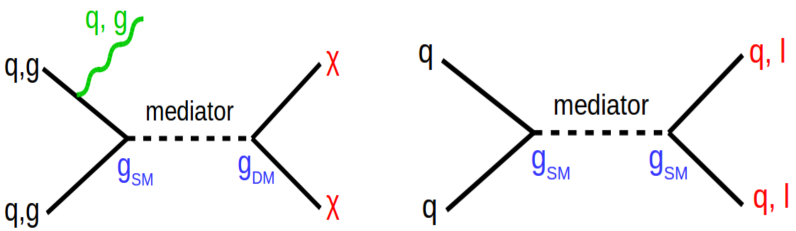
Evolution of dark-matter models at the LHC

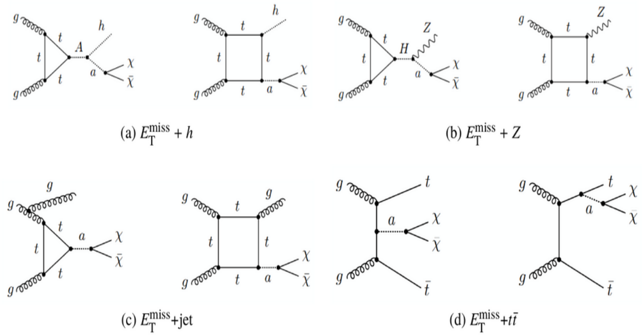
Effective field theories | Simplified models | UV-complete theories

model-independent,
limited validity

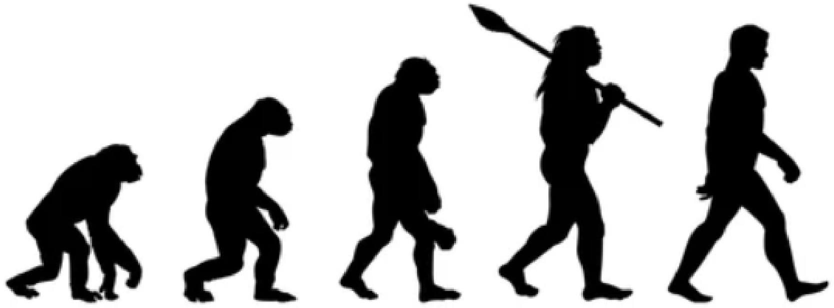
model-dependent,
rich phenomenology







Early Run 1 | Run 1 + Run 2 | Late Run 2 + Run 3



Example: 2HDM+a

> Extend simplified model with pseudo-scalar mediator

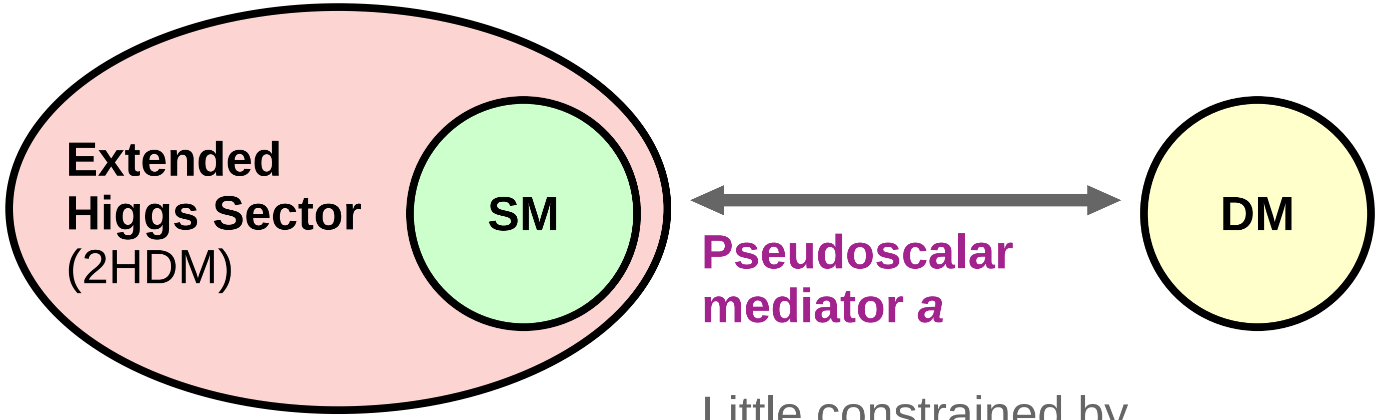
Little constrained by direct detection experiments

Example: 2HDM+a

> Extend simplified model with pseudo-scalar mediator by extending the Higgs sector to 2HDM

> Minimal, UV-complete extension of pseudo-scalar simplified models

> Common benchmark model developed in close collaboration of theorists and experimentalists



- Scalars: h, H,
- Pseudoscalar: A,
- Charged Higgs: $H^{\pm}$

Little constrained by direct detection experiments

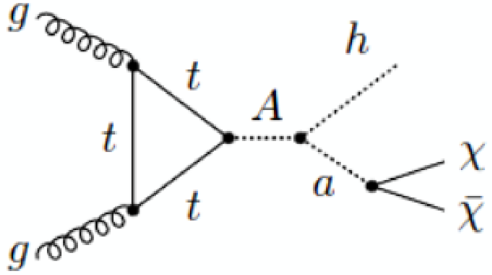
LHC Dark Matter Working Group: Phys. Dark Univ. 27 (2020) 100351

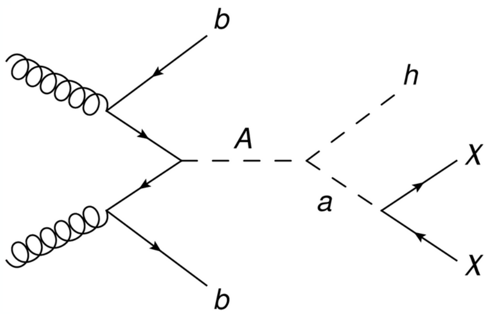
Bauer, Haisch, Kahlhoefer: JHEP05(2017) 138

Example: 2HDM+a

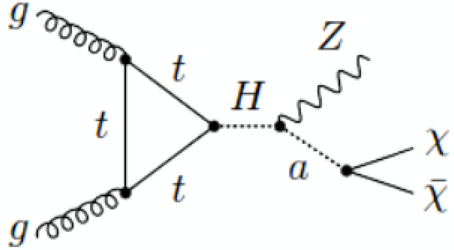
> Rich collider phenomenology!

- Resonantly enhanced production of MET+h and MET+Z signatures
- Additional Higgs bosons
- Processes not predicted by simplified models
  - Inspires new searches, e.g. MET+tW search (**ATLAS:** CERN-EP-2020-184, see backup slides)

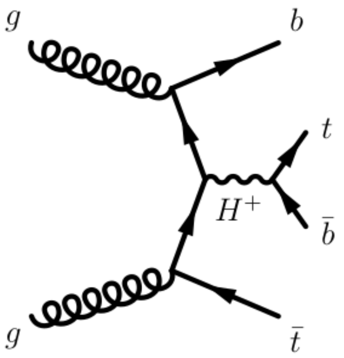




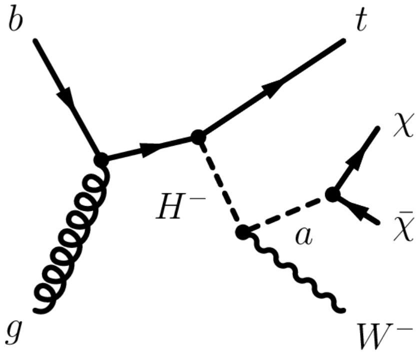
MET+h



MET+Z



tb H±(tb)



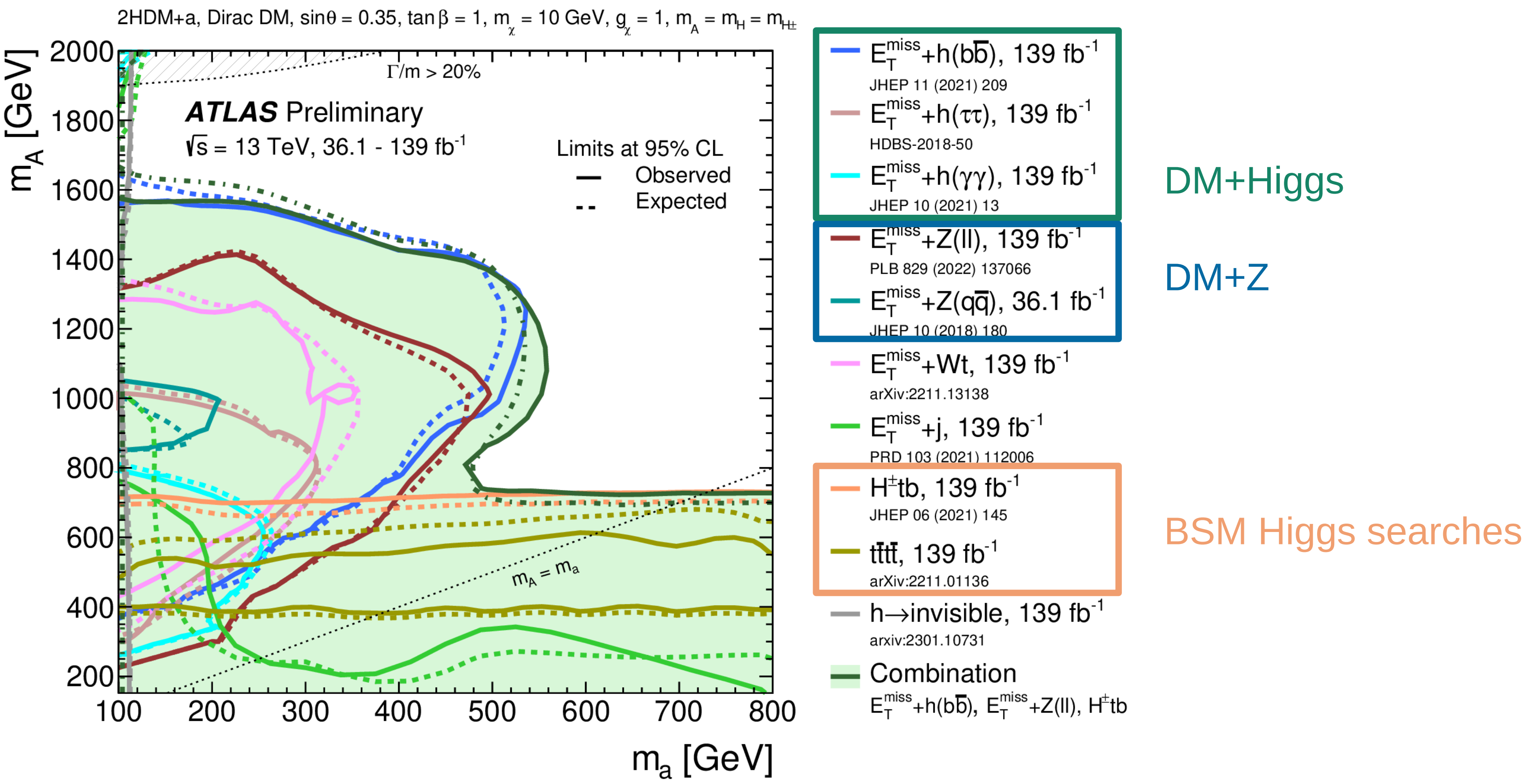
MET+tW

Example: 2HDM+a

arxiv:2306.00641

> Combine searches sensitive to different parameter regions

> Here: just one selected benchmark scenario where we vary mediator and neutral Higgs masses



A philosophical view of collider searches

Top down approach: searches guided by **benchmark models**

Optimise searches

Identify missing signatures

Compare experiments

A philosophical view of collider searches

Top down approach: searches guided by **benchmark models**

Optimise searches

Identify missing signatures

Compare experiments

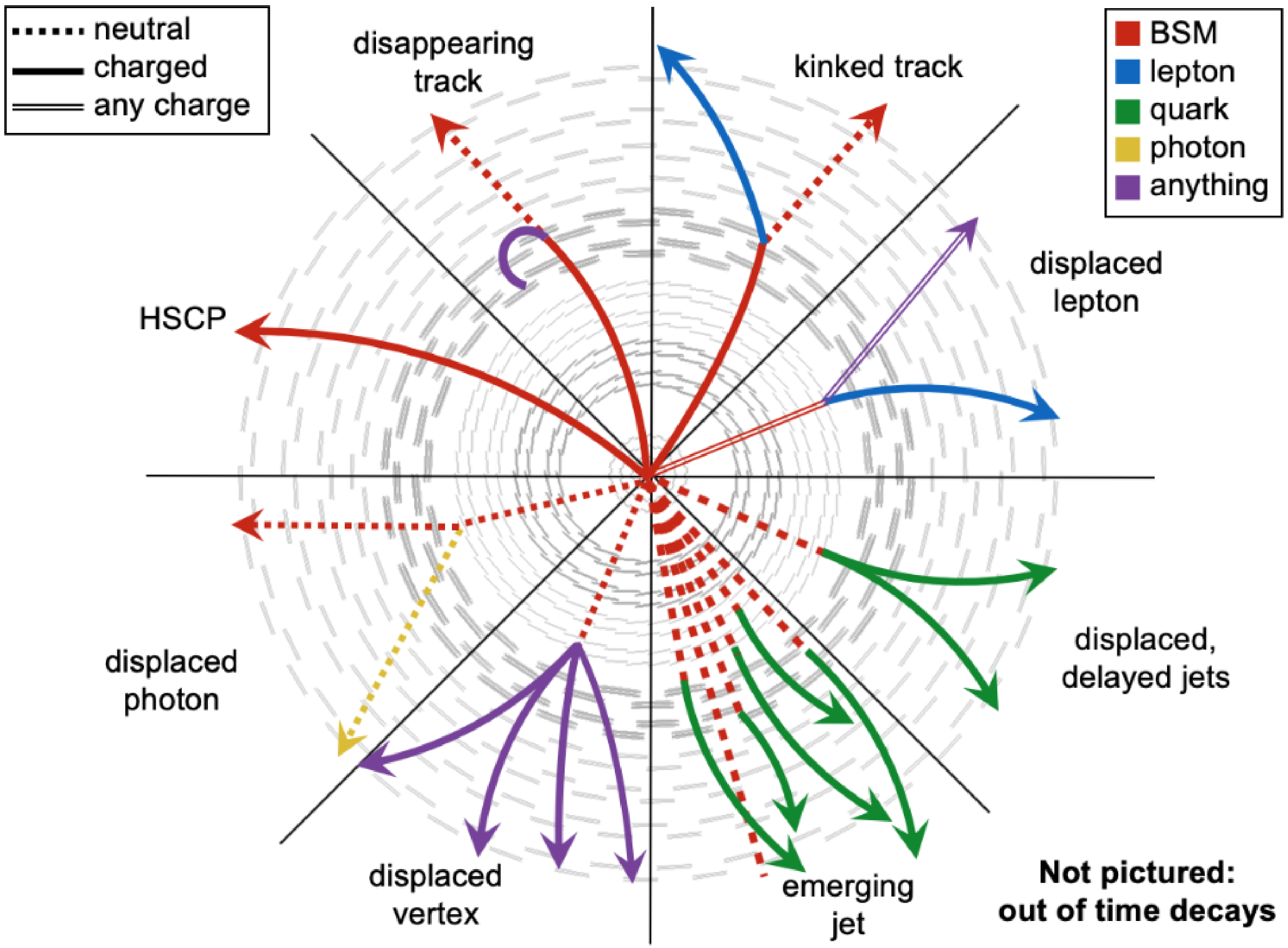
Probe new kinematic regions and signatures

Get the most out of our data

“because we can”

Bottom up approach: searches guided by **new experimental techniques**

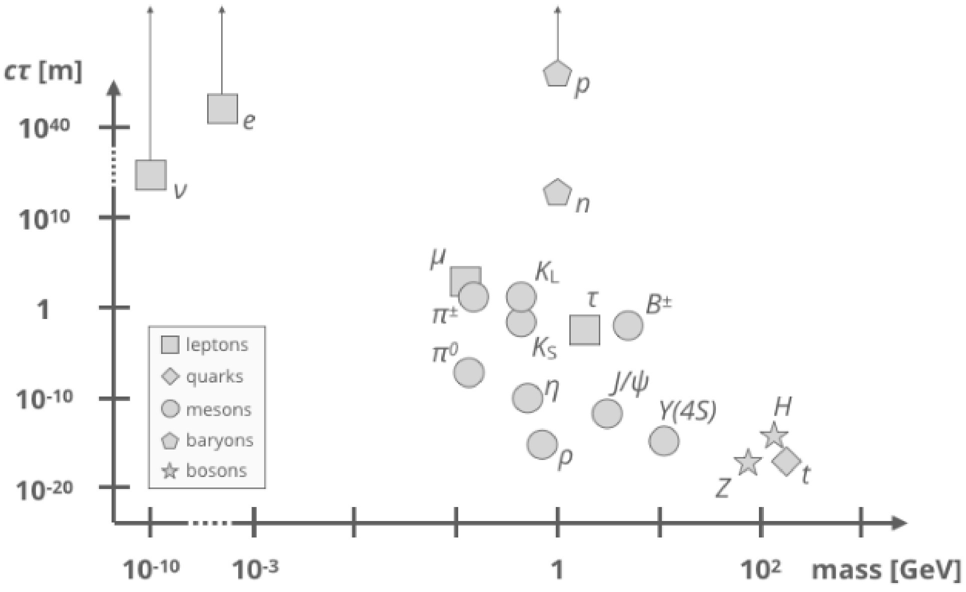
Unconventional signatures



Not pictured: out of time decays

Long-lived particles

- Implicit assumption of all previous benchmarks: all reactions happen at the interaction point
- Many SM particles have longer lifetimes...

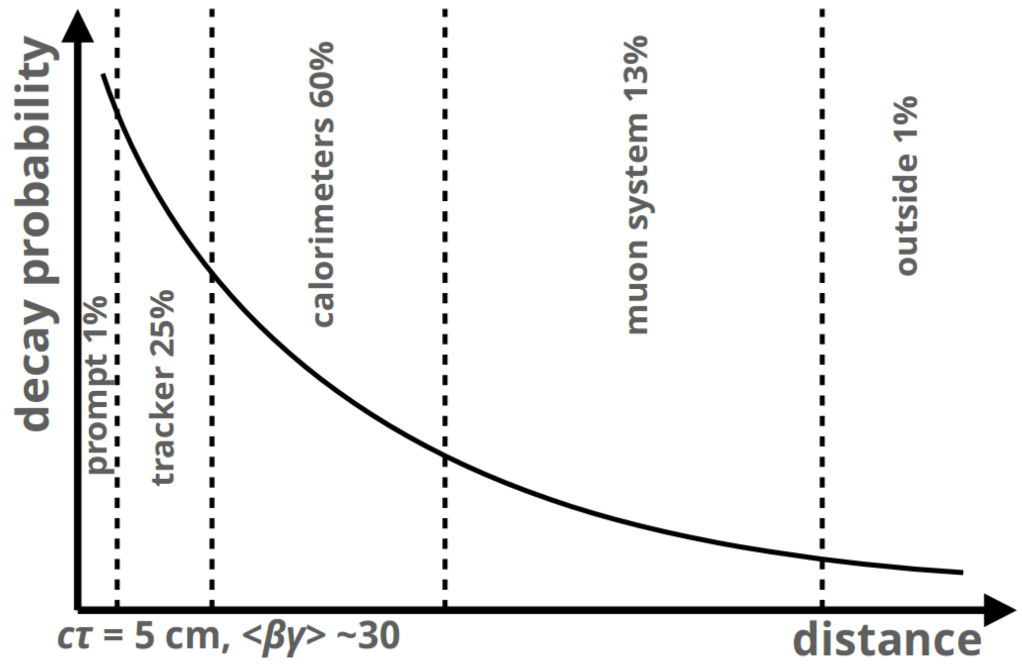


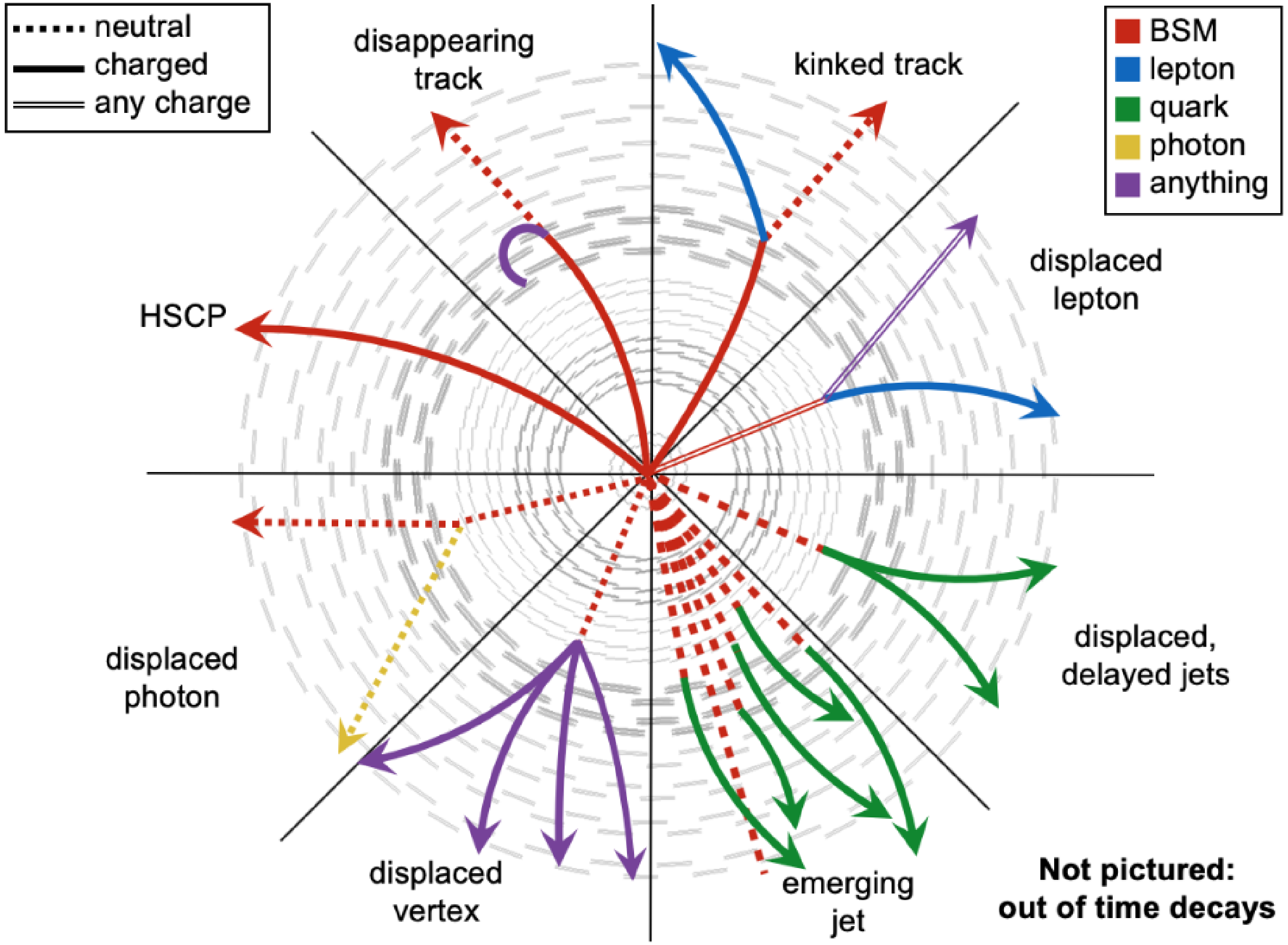
- ... so, long-lived BSM particles?
  - (nearly) mass-degenerate spectra
  - small couplings
  - highly virtual intermediate states
  - (almost) conserved quantum number

Image credits: S. Mehlhase

Unconventional detector signatures

- Plethora of (often little explored) unconventional signature
- 1 new particle = different possible signatures
- **Caveat**: often suppressed by standard reconstruction algorithms

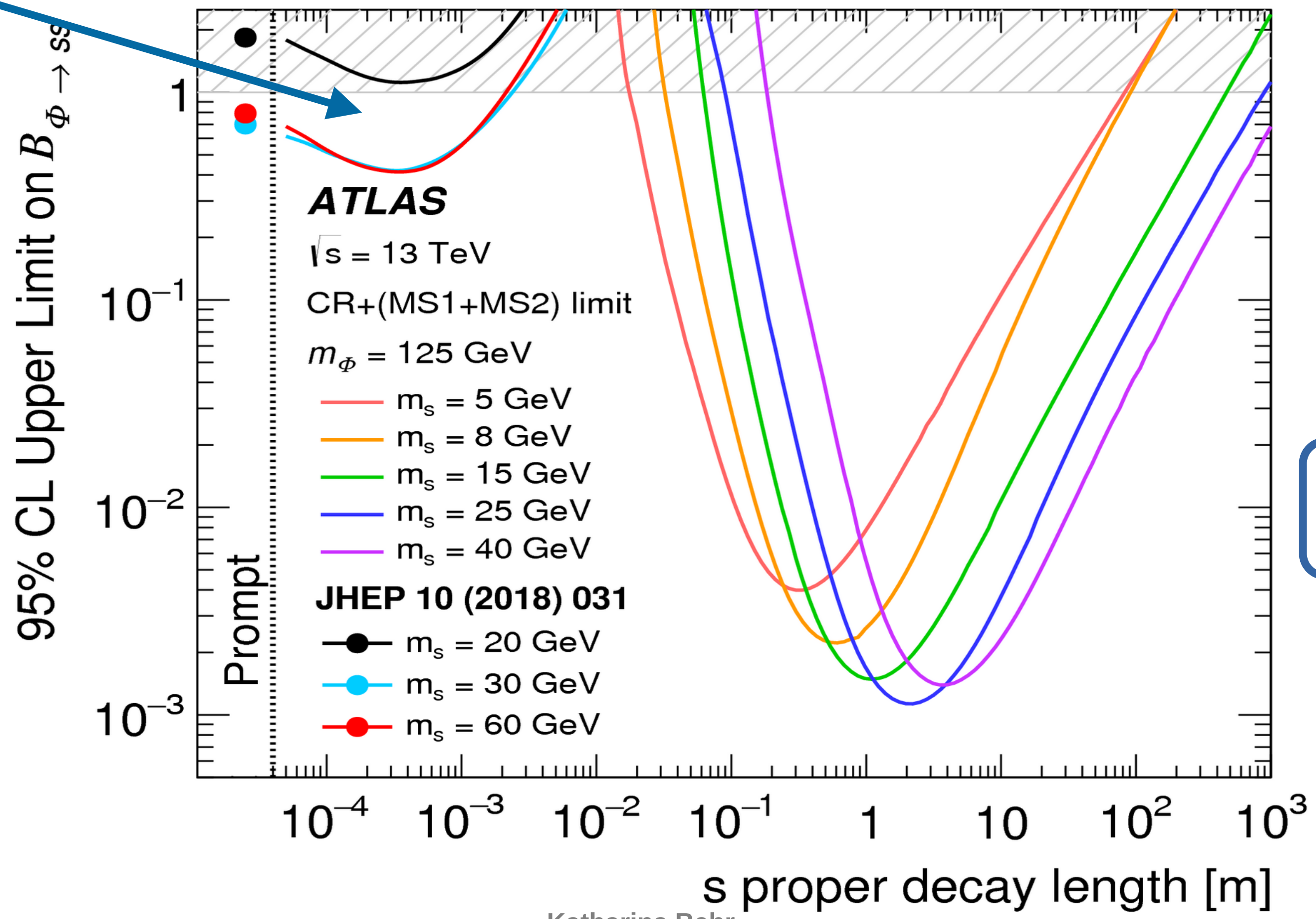


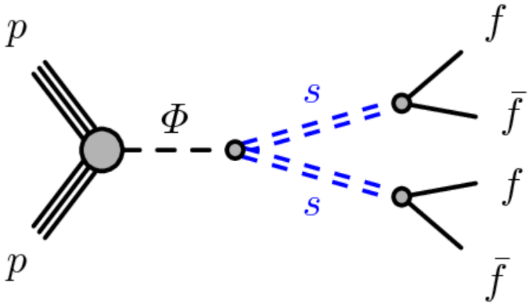


Example: Hidden Sector searches

> Exotic Higgs boson decays into a pair of long-lived “dark” Higgs bosons *s* decaying to SM fermions

Displaced jets
Eur. Phys. J. C 79 (2019) 481





Displaced muons
PRD 99, 052005 (2019)

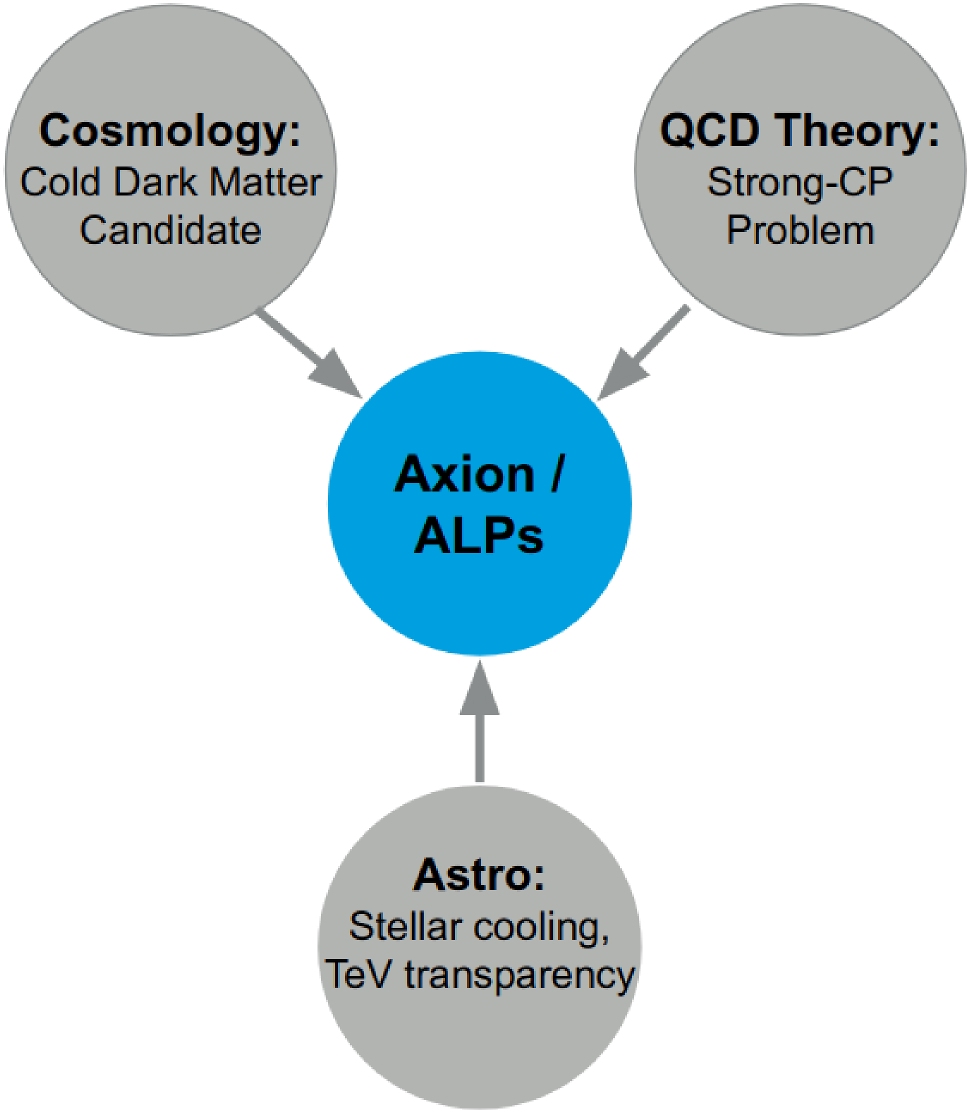
Axions and ALPs

> **Axions**

- First proposed for strong CP problem
- Feeble EM interaction (next slide)
- Coupling to EM fields depends on axion mass

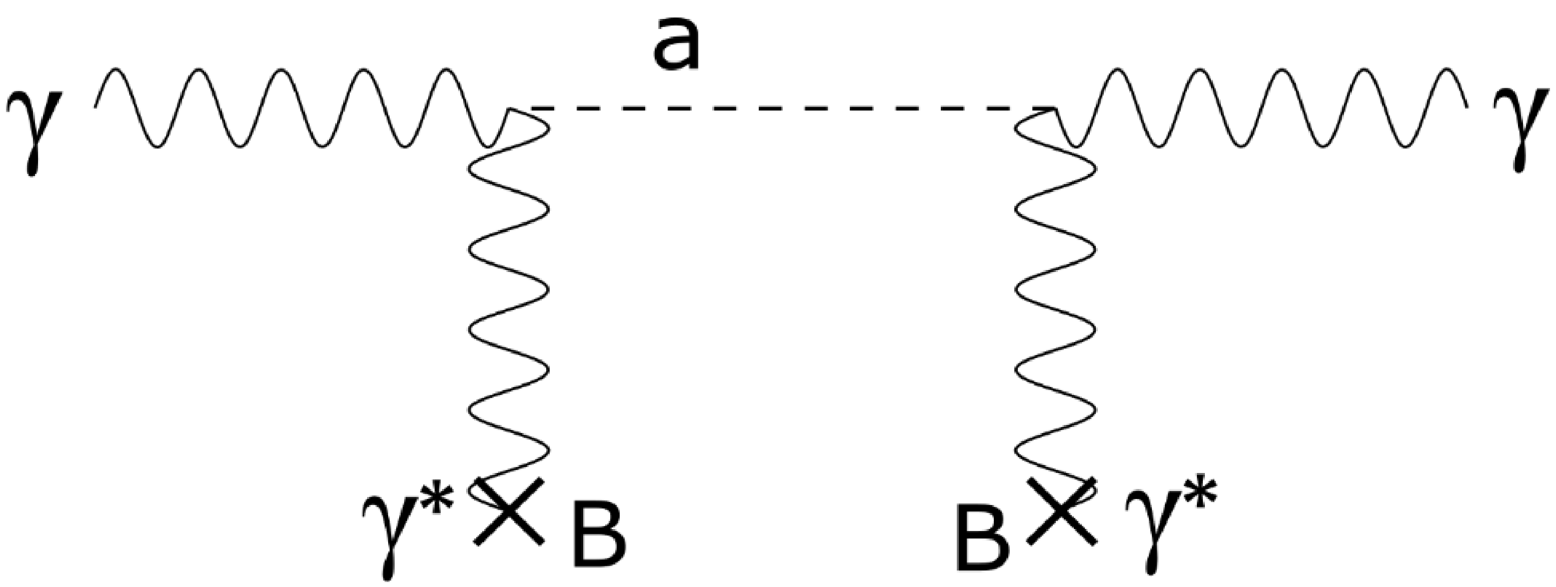
> **Axion-like particles (ALPs)**

- Family of sub-eV particles
- Properties similar to axions
- EM coupling independent of mass



EM interactions of ALPs

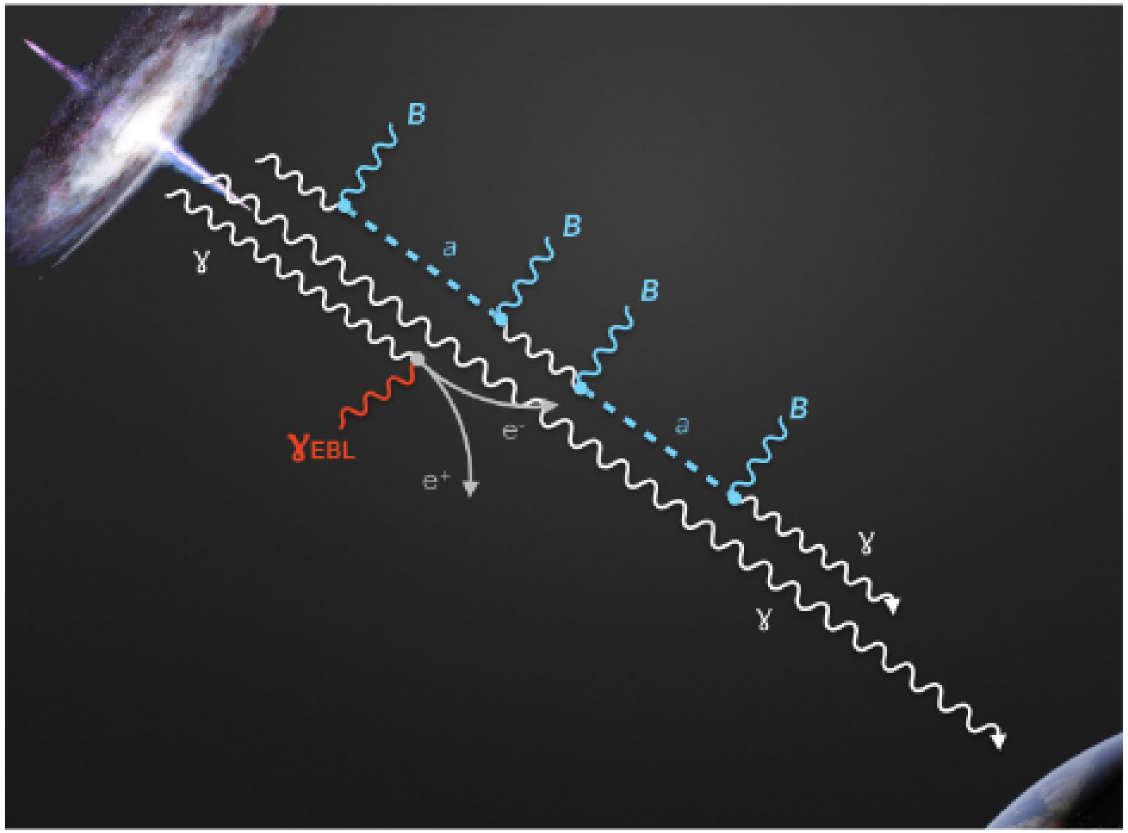
- Feeble EM interaction allows ALPs to convert to photons (and back) in a magnetic field
- Characterised by coupling $g_{a\gamma\gamma}$



$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

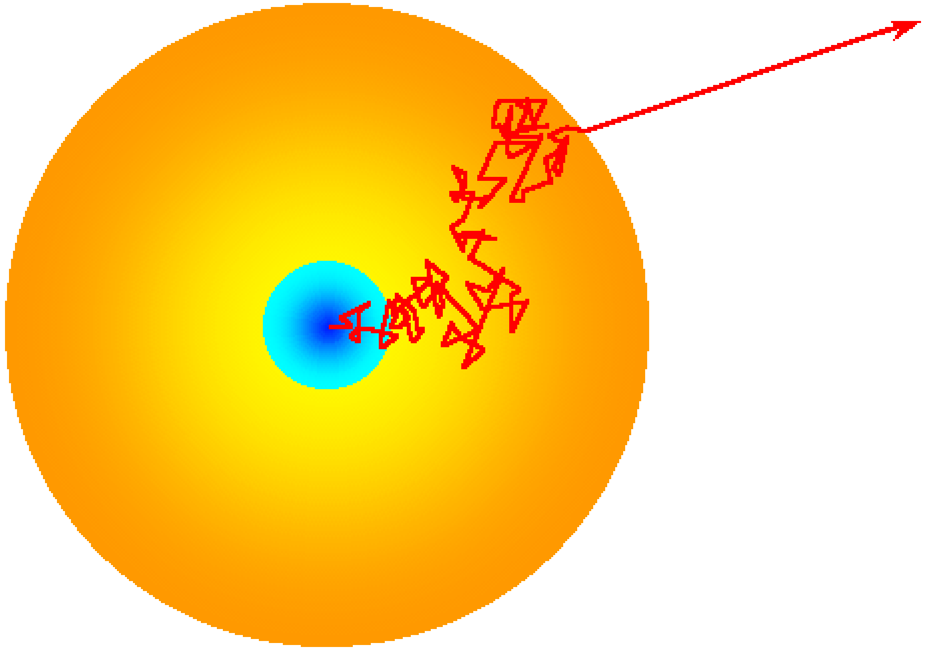
ALPs in Astrophysics

> **TeV transparency of the Universe**
  - Interstellar TeV photons lost through pair production
  - Excess of TeV photons from distant sources
  - Could be explained by conversion to ALPs

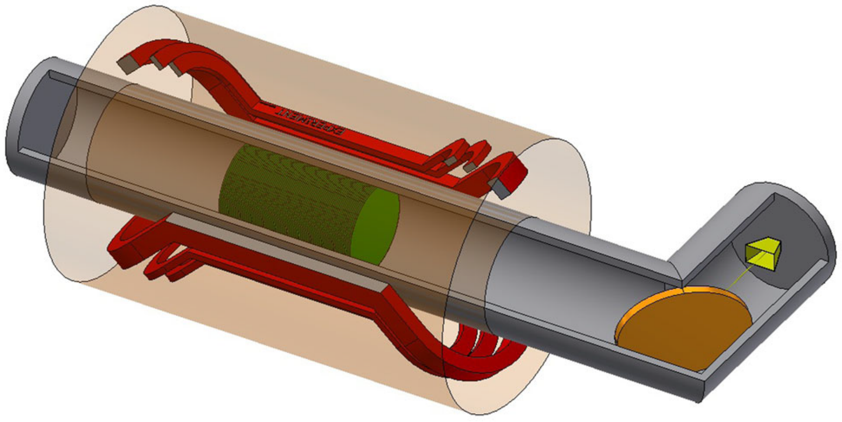


ALPs in Astrophysics

- **TeV transparency of the Universe**
  - Interstellar TeV photons lost through pair production
  - Excess of TeV photons from distant sources
  - Could be explained by conversion to ALPs
- **Stellar cooling**
  - Random walk of photons due to scattering
  - Takes O(1k)-O(1M) years for photon to leave sun
  - Excess cooling observed compared to solar SM
  - Could be explained by conversion to ALPs

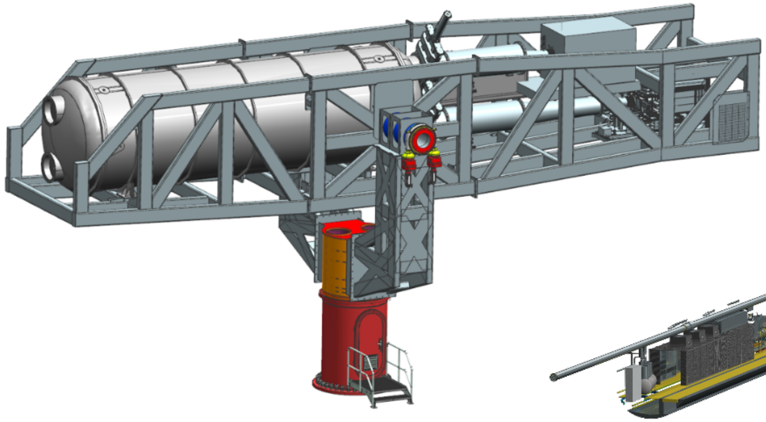


Axion Experiments @ DESY



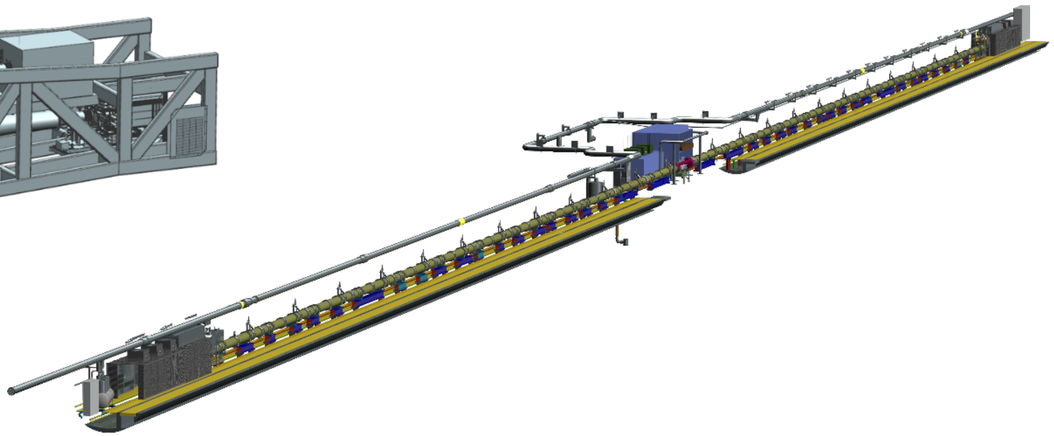
MADMAX
(Di-electric Axion Haloscope)
Dark Matter Axions & ALPs

Aim to finish prototype by 2027



BabyIAXO
(Axion Helioscope)
Solar Axions & ALPs

Planning stage



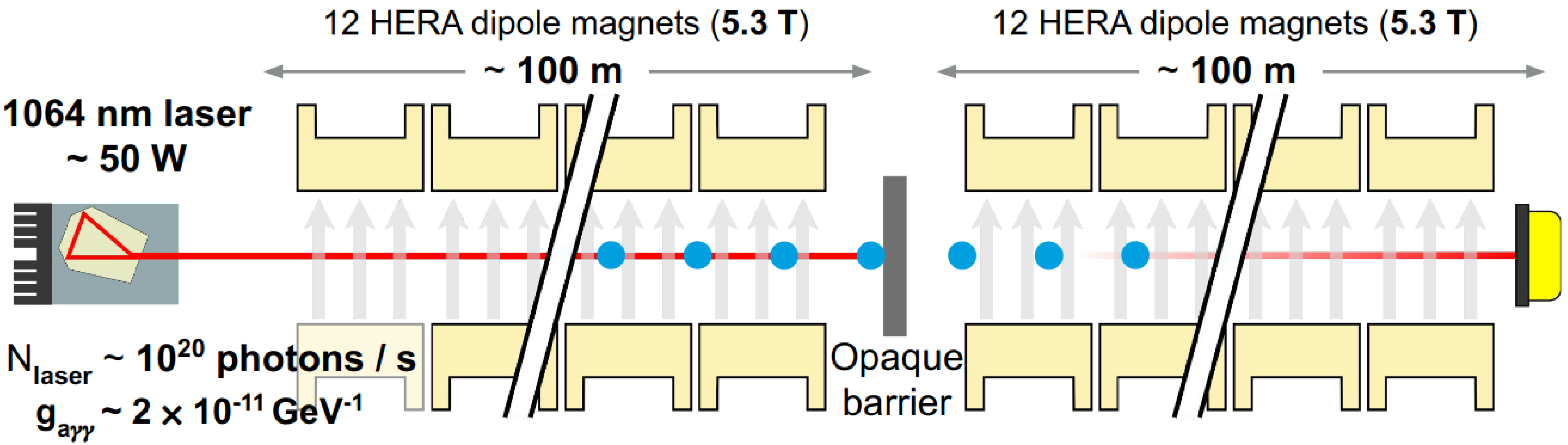
ALPS II
(Light-Shining-Through-Wall)
Laboratory ALPs

Data taking started in late 2022

All three utilize the conversion of axions to photons in strong magnetic fields

ALPS-II

> Light-shining-through-wall experiment (using old, straightened HERA magnets)



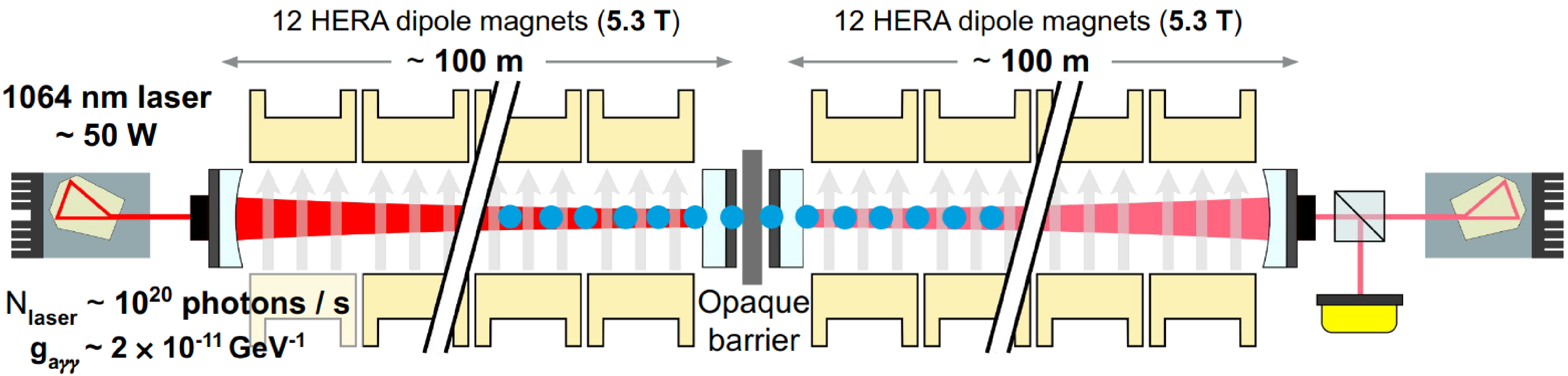
without optical cavities:

$$N_s = N_{laser} \frac{1}{16} \left(g_{\alpha\gamma\gamma} BL\right)^4$$

~photon / 150,000 yrs

ALPS-II

> Light-shining-through-wall experiment (using old, straightened HERA magnet)



without optical cavities:

$$N_s = N_{laser} \frac{1}{16} (g_{\alpha\gamma\gamma} BL)^4$$

~photon / 150,000 yrs

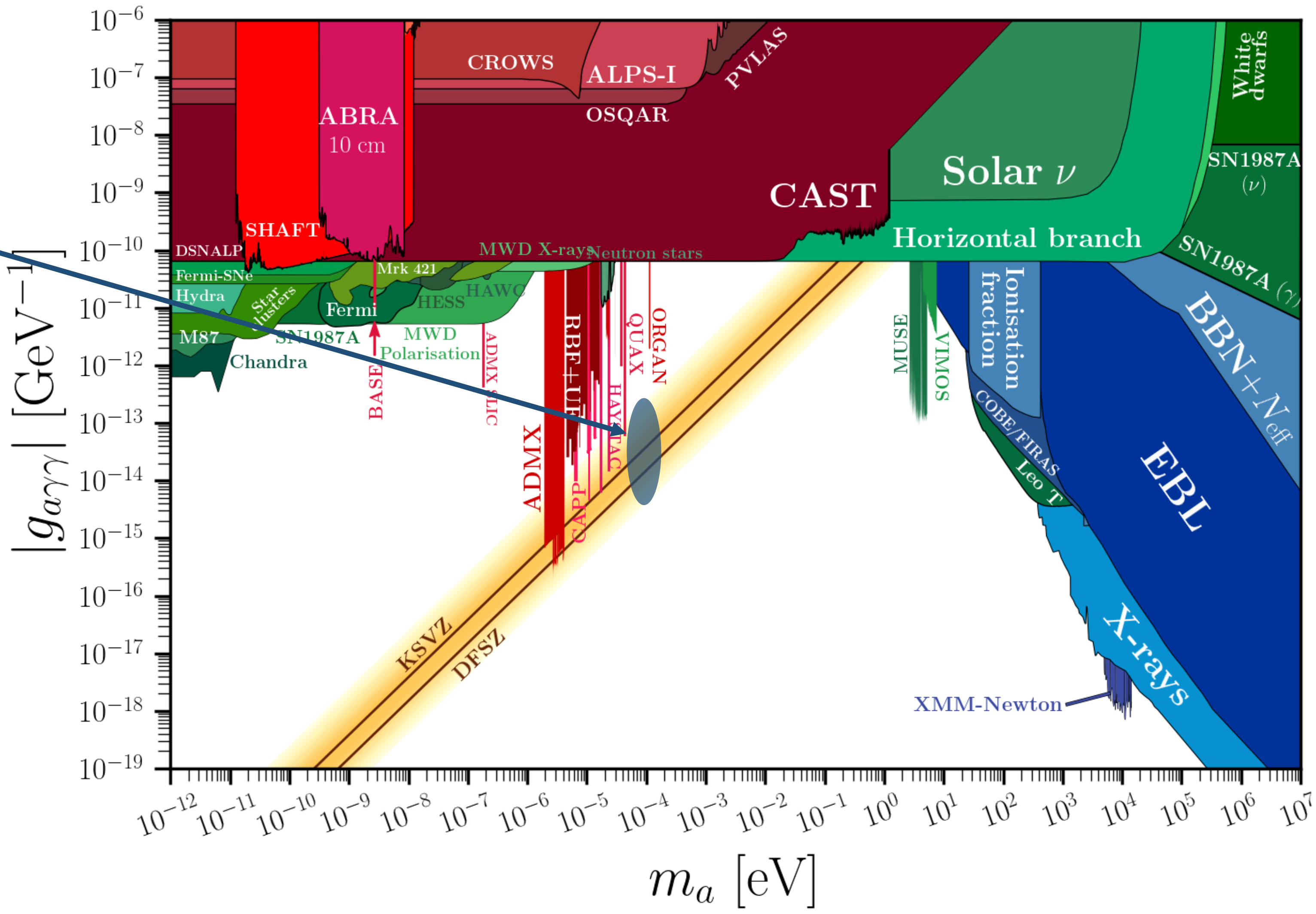
with optical cavities:

$$N_s = \eta^2 N_{PC} \beta_{RC} \frac{1}{16} (g_{\alpha\gamma\gamma} BL)^4$$

~photon / day!

ALPs landscape

Recent calculations constrain axion mass for post-inflationary scenario between 40 and 180 μeV
M. Buschmann, J.W. Foster, A. Hook et al.,
Nat. Commun. **13,** 1049 (2022)
(https://doi.org/10.1038/s41467-022-28669-y)



ALPs landscape with DESY experiments

Recent calculations constrain axion mass for post-inflationary scenario between 40 and 180 µeV
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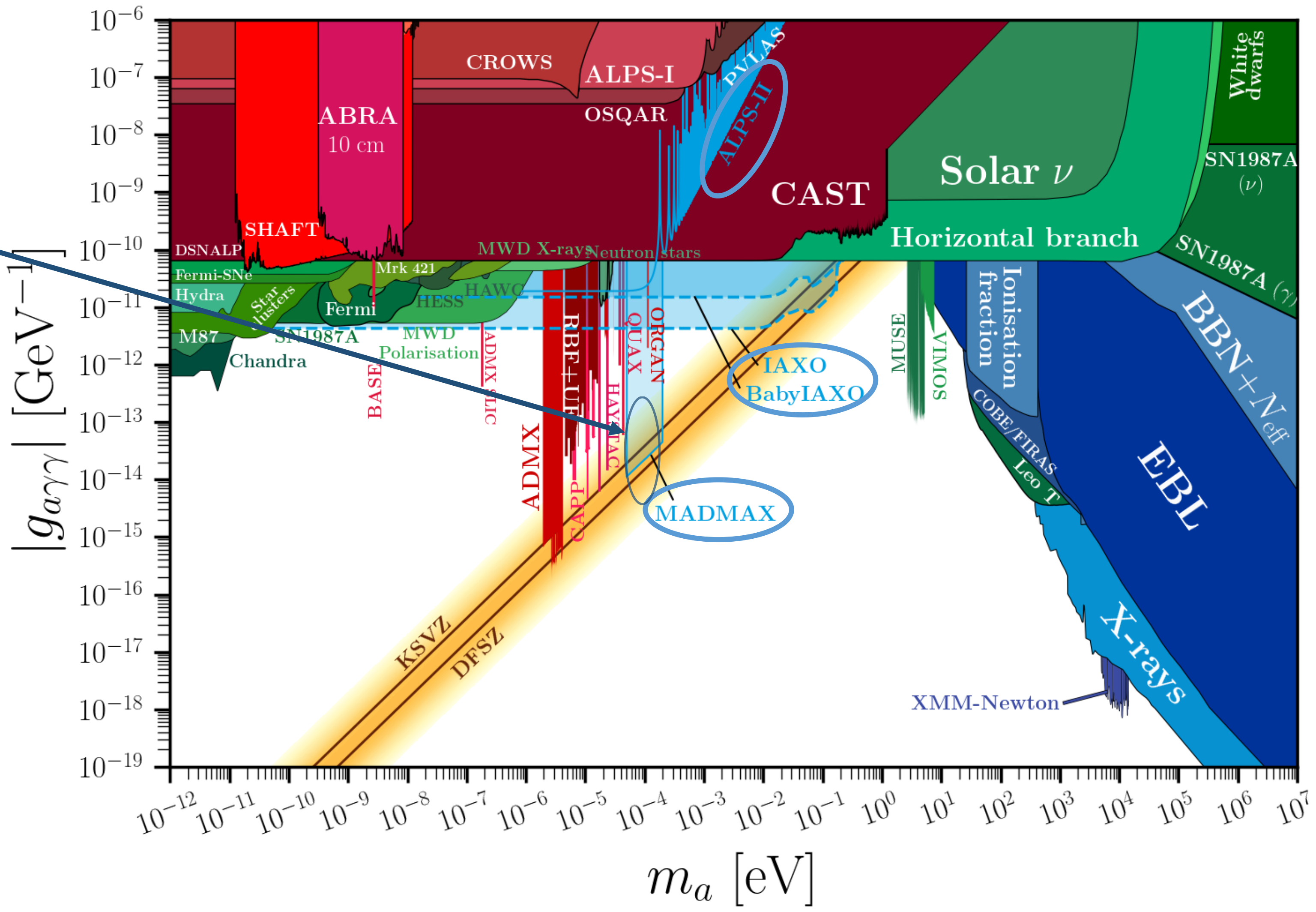


LHC reach

Take Aways

> Strong motivations to look for phenomena beyond the SM:
  - Dark matter, baryon asymmetry, hierarchy problem, ...

> LHC offers unprecedented sensitivity to search for new phenomena at the energy frontier

> Strong search programmes with the ATLAS and CMS general-purpose detectors
  - Dark-matter signatures, extra Higgs bosons, long-lived particles, ...

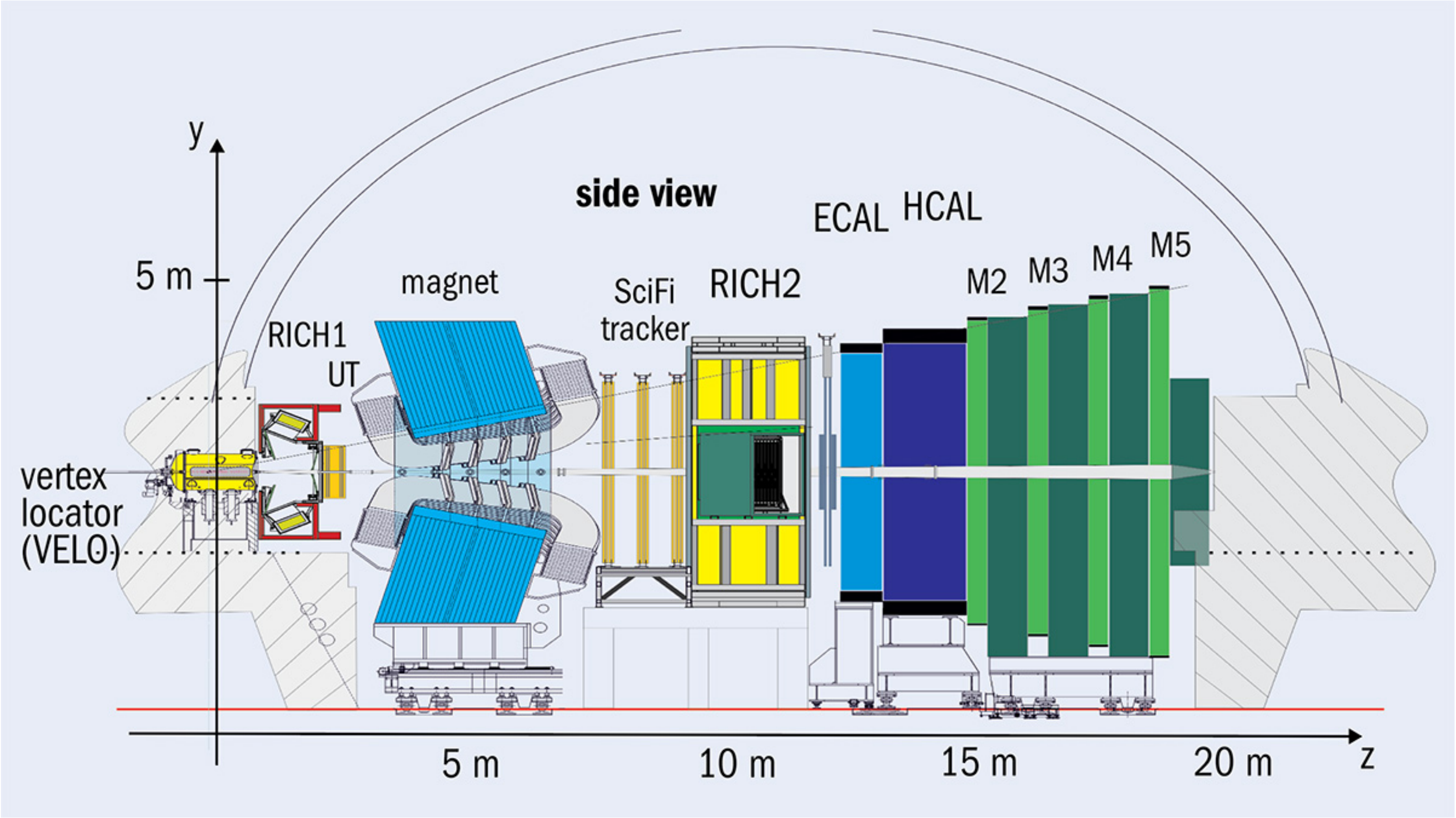
> Hinges on strong collaborations with theory groups, smart analysis techniques, and technological improvements

> YOUR smart ideas could be crucial for the next discovery!

BONUS SLIDES

Flavour anomalies: LHCb

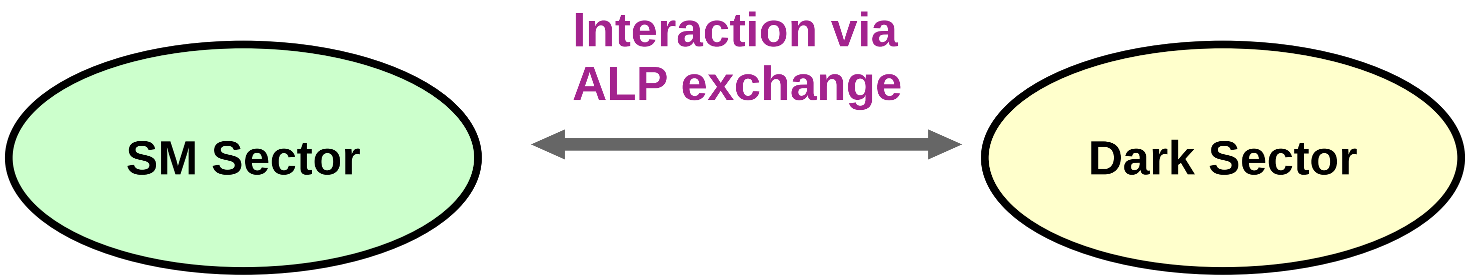
- Highly asymmetric detector design, specialised for heavy-flavour detection
- Various detector upgrades installed during recent LHC shutdown (2019 – 2021)



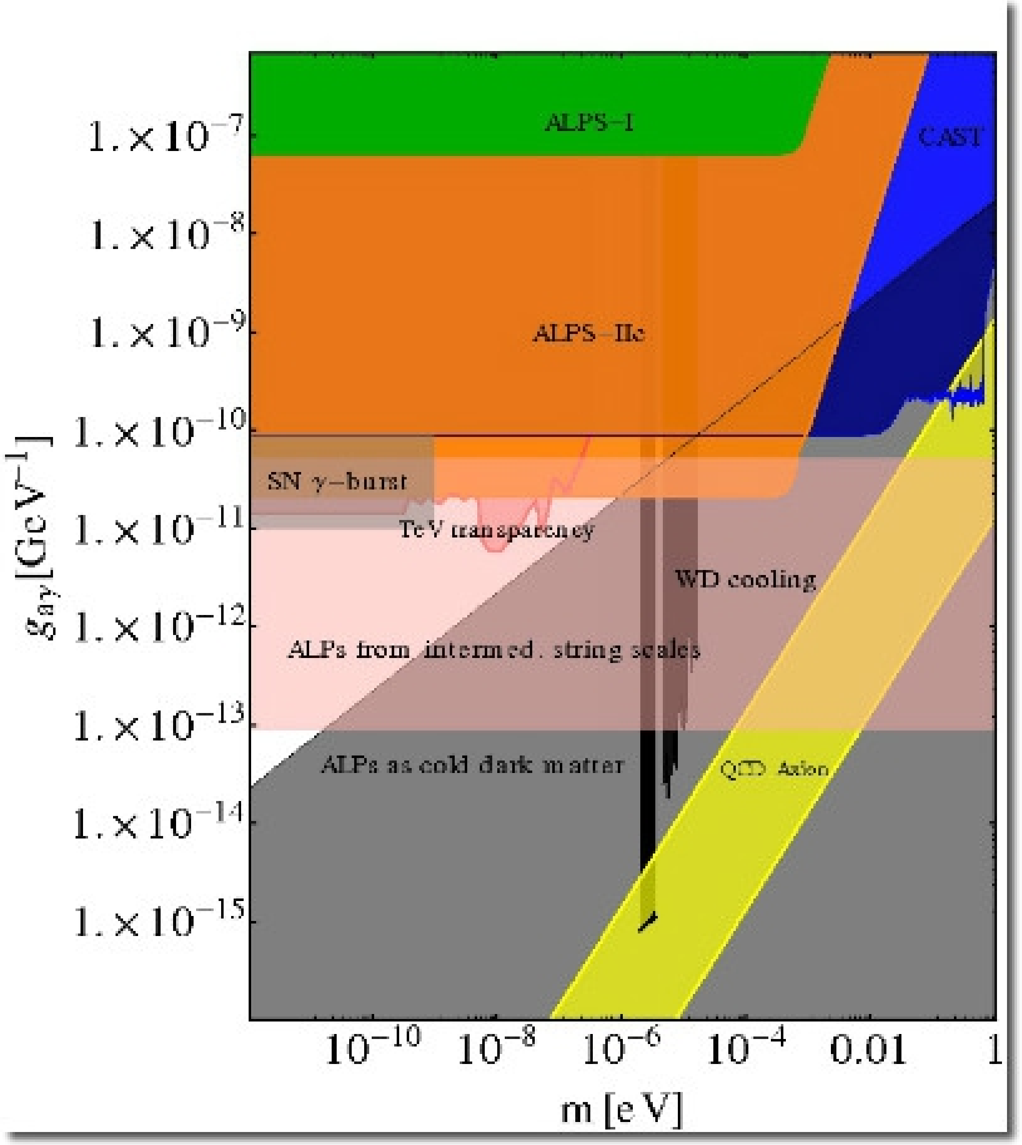
- E.g. SciFi tracker
  - Large-scale use of SiPMs
  - New coolant Novec-649 to reduce carbon footprint

ALPs at the GeV scale

> Motivated for example by dark sector models



ALPS-II

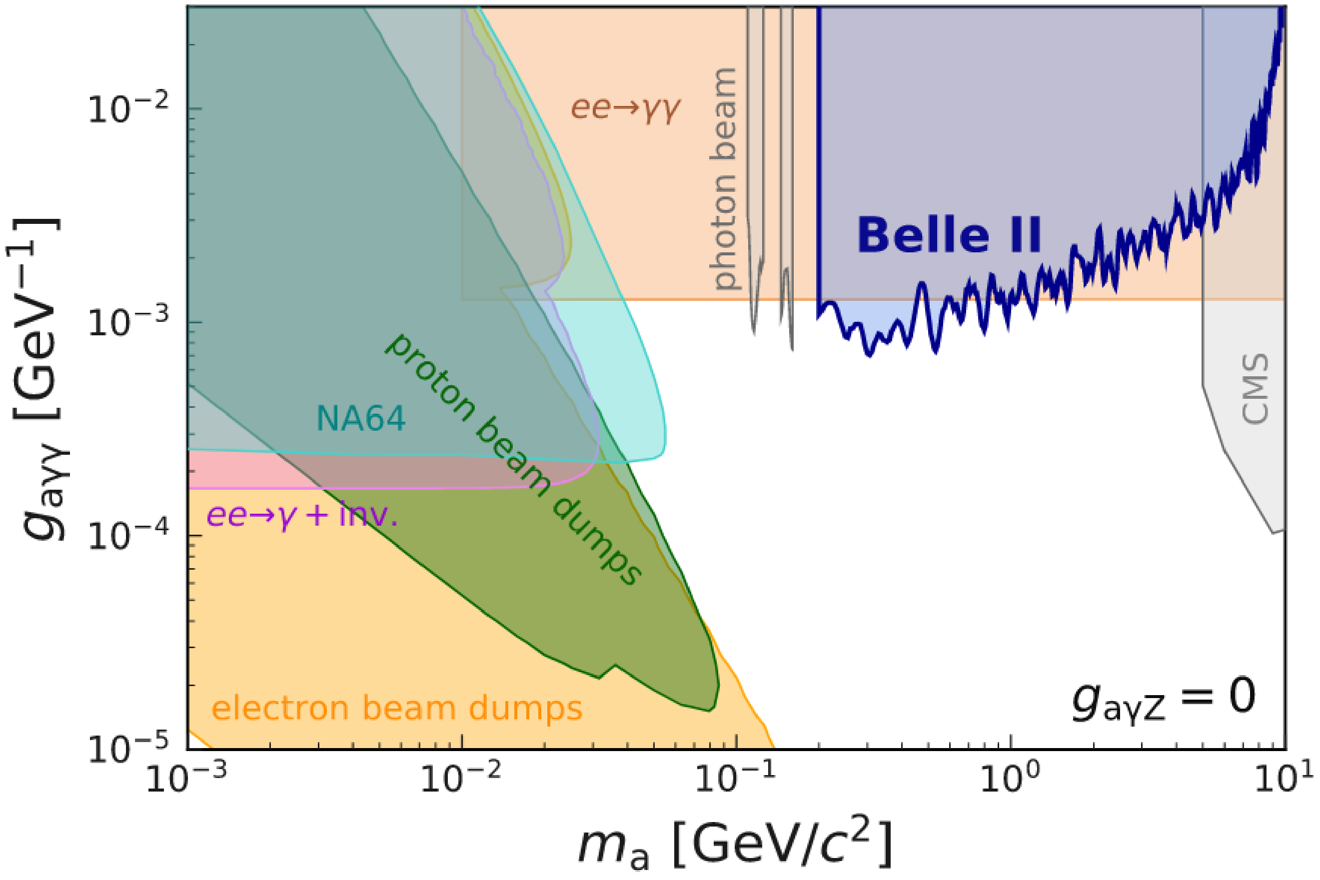


ALPS-I
CAST
ALPS-IIc
SN γ−burst
TeV transparency
WD cooling
ALPs from intermed. string scales
ALPs as cold dark matter
QCD Axion
$g_{a\gamma}$[GeV^{-1}]
$1.\times10^{-7}$
$1.\times10^{-8}$
$1.\times10^{-9}$
$1.\times10^{-10}$
$1.\times10^{-11}$
$1.\times10^{-12}$
$1.\times10^{-13}$
$1.\times10^{-14}$
$1.\times10^{-15}$
10^{-10}
10^{-8}
10^{-6}
10^{-4}
0.01
1
m [eV]

ALPs at the GeV scale

- Motivated for example by dark sector models
- On-going collider searches

- Belle-II experiment at Super-KEKB
- B-factory colliding e^+e^- @ up to 10 GeV
- First results on using small fraction of final dataset



Matter-antimatter imbalance

> Equal amounts of matter and antimatter created in the Big Bang (B=0)

> Observable universe completely dominated by matter (B>0)

> What caused this imbalance?

> **Sakharov conditions**

1. Baryon number violating processes
2. C and CP violation
3. Processes out of thermal equilibrium

- Possible in the SM and BSM models
  - E.g. supersymmetry
- Not observed yet
  - Proton decay would be the smoking gun

Matter-antimatter imbalance

- Equal amounts of matter and antimatter created in the Big Bang (B=0)
- Observable universe completely dominated by matter (B>0)
- What caused this imbalance?

- **Sakharov conditions**
  1. Baryon number violating processes
  2. C and CP violation
  3. Processes out of thermal equilibrium

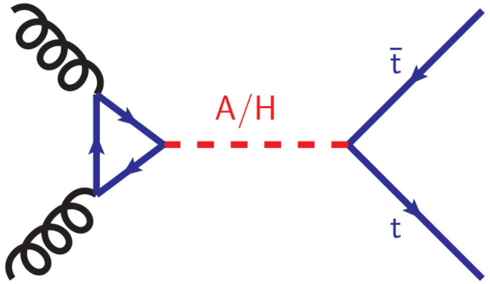
Conditions met in SM e.g. during EWSB

Searches for interference patterns

> Most prominent example: search for heavy Higgs bosons decaying to a top-quark pair

> Signal: loop induced resonant production of heavy scalar H or pseudoscalar A from gluons

  – Similar to SM Higgs production but $m_{A/H} > 2*m_{top}$



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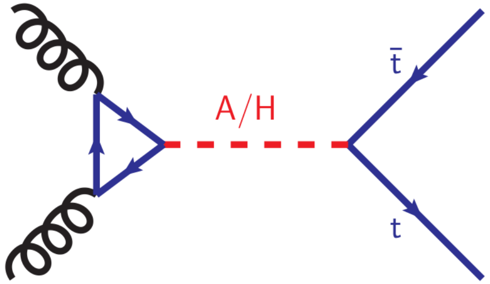
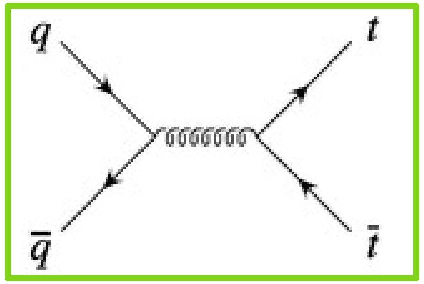
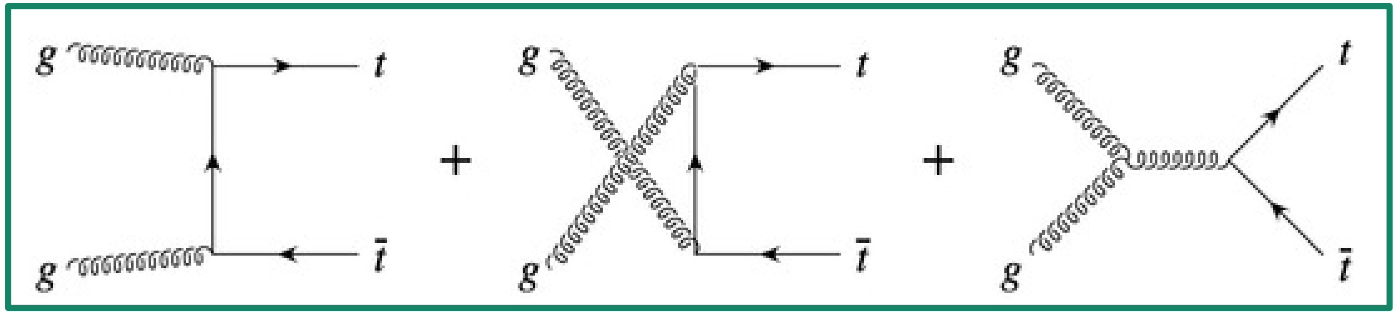
> Main, irreducible background: top quark pair production via the strong force



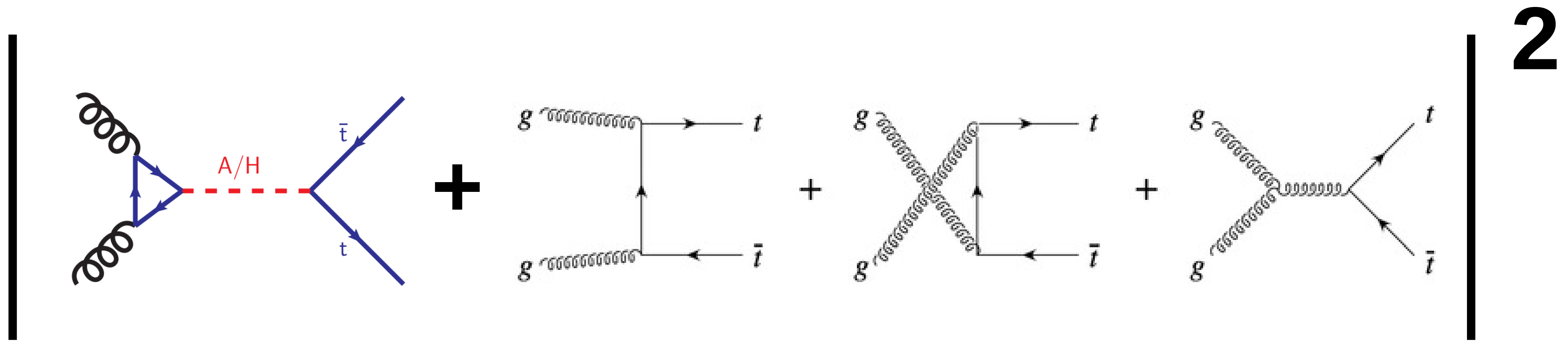




80% gg-initiated
20% qq-initiated

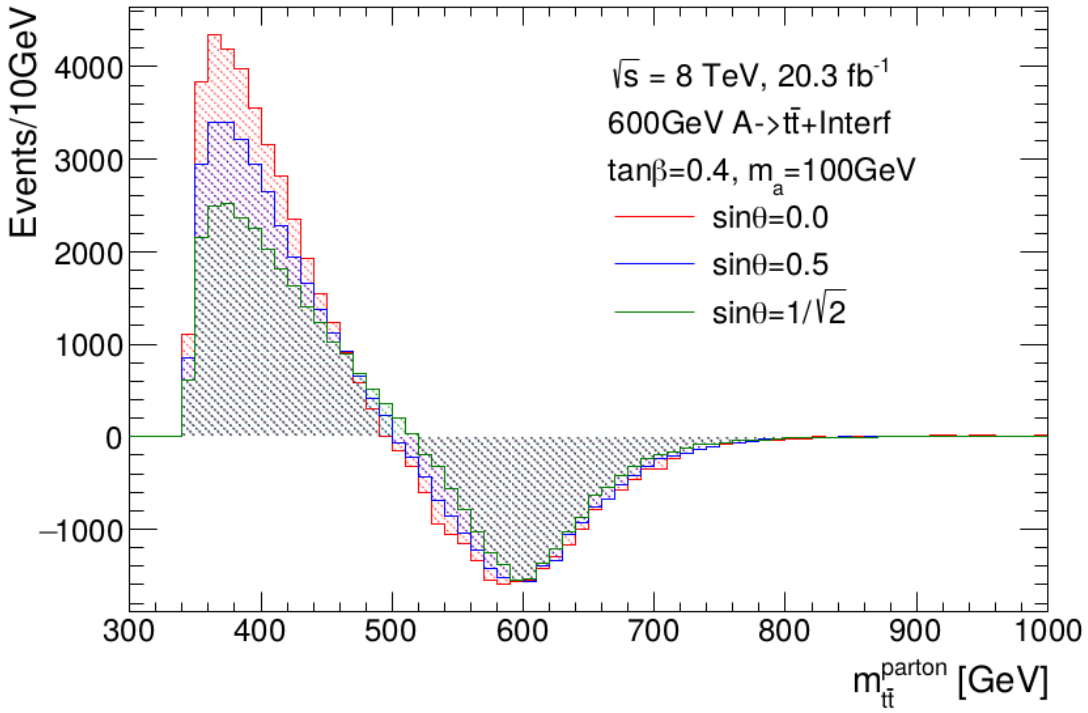
Searches for interference patterns

- Most prominent example: search for heavy Higgs bosons decaying to a top-quark pair
- Signal: loop induced resonant production of heavy scalar H or pseudoscalar A from gluons
  - Similar to SM Higgs production but $m_{A/H} > 2*m_{top}$
- Main, irreducible background: top quark pair production via the strong force (mostly from gluons)



Searches for interference patterns

- Most prominent example: search for heavy Higgs bosons decaying to a top-quark pair
- **Many challenges** compared to bump hunts
  - Interference pattern highly model dependent → many simulations needed!



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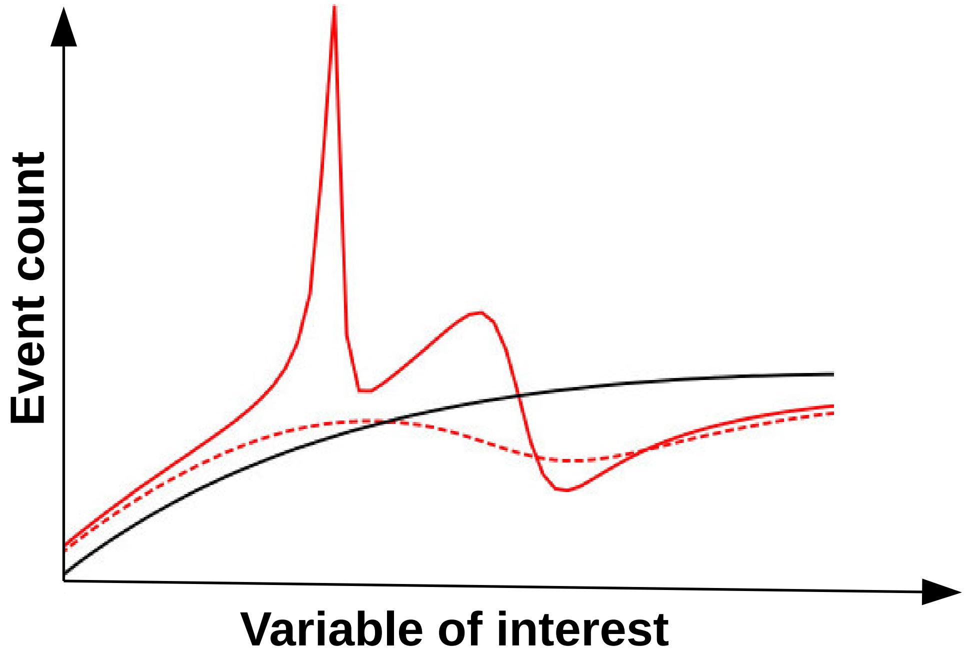


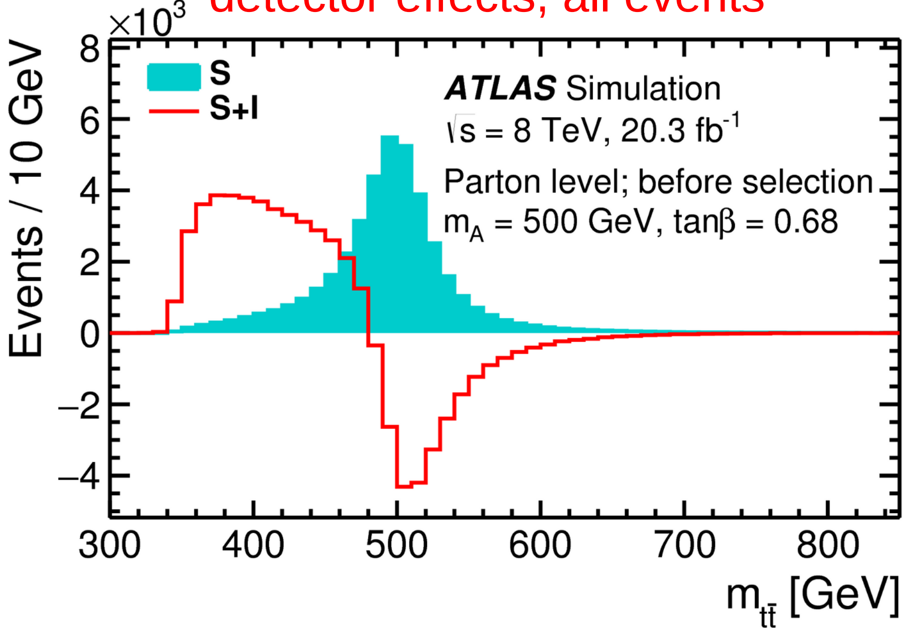
Searches for interference patterns

> Most prominent example: search for heavy Higgs bosons decaying to a top-quark pair

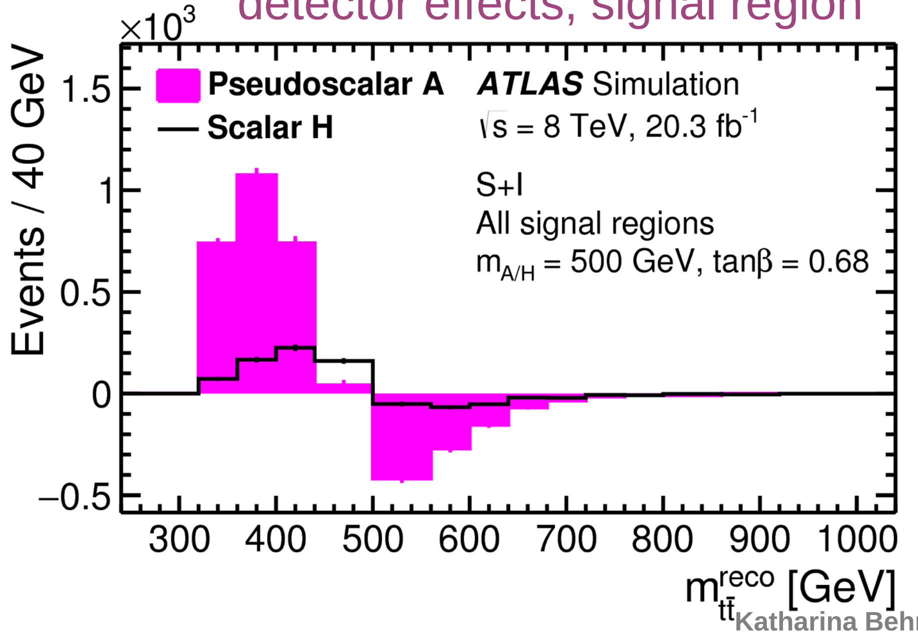
> **Many challenges** compared to bump hunts

- Interference pattern highly model dependent → many simulations needed!
- Very complex patterns, especially if there is more than one new particle
- Detector effects "wash out" details of pattern

Simulated pattern without detector effects, all events

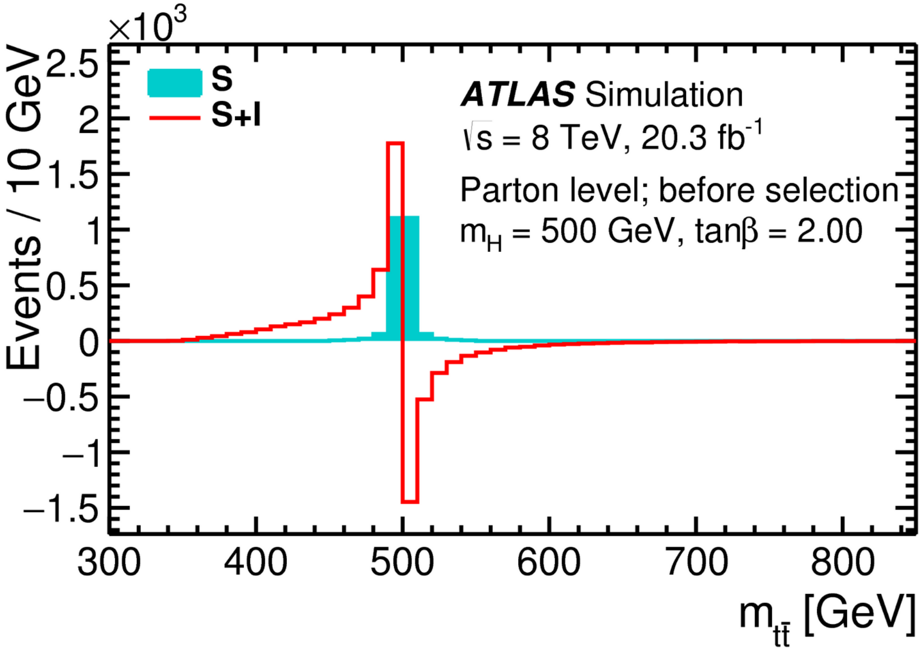


Simulated pattern with detector effects, signal region



Searches for interference patterns

- Most prominent example: search for heavy Higgs bosons decaying to a top-quark pair
- **Many challenges** compared to bump hunts
  - Interference pattern highly model dependent → many simulations needed!
  - Very complex patterns, especially if there is more than one new particle
  - Detector effects “wash out” details of pattern
  - Risk to miss narrow patterns
    - Peak and dip in the same bin cancel out
  - ...



The strong CP problem (1)

> QCD can in principle violate CP (assuming all quarks are massive)

> Example of a Yang-Mills theory with a single massive quark

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{\theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}} + \bar{\psi}(i\gamma^\mu D_\mu - \boxed{me^{i\theta'\gamma_5}})\psi.$$

Potentially CP violating, unless $\theta = -\theta'$
→ fine-tuning!

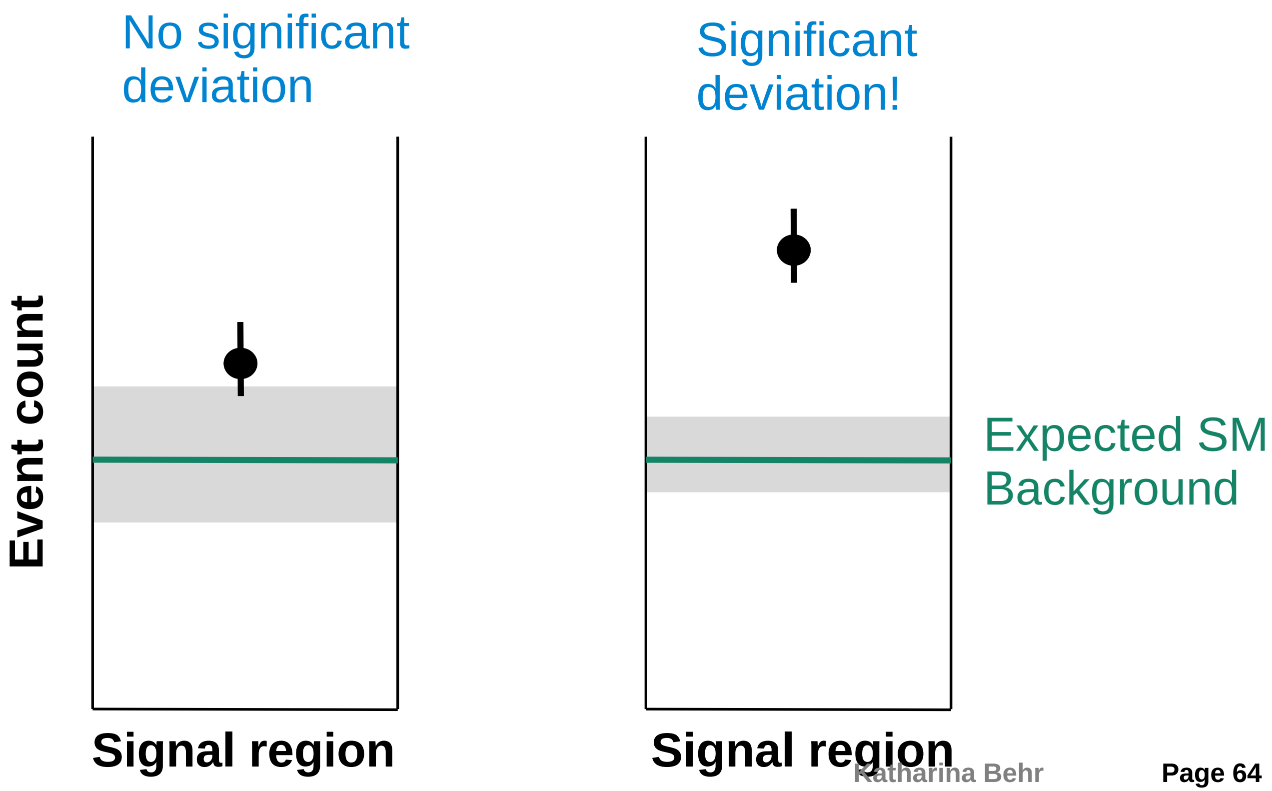
> Strong CP violation in SM QCD (6 massive quarks) via equivalent phase θ^*

> Would imply non-zero neutron electric dipole moment: $d_N = (5.2\ 10^{-16}\ e\ \text{cm})\ \theta^*$

> Measurements constrain dipole moment to $|d_N| < 10^{-26}\ e$ cm → $\theta^* < 10^{-10}$ → fine-tuning!

Cut-and-count method

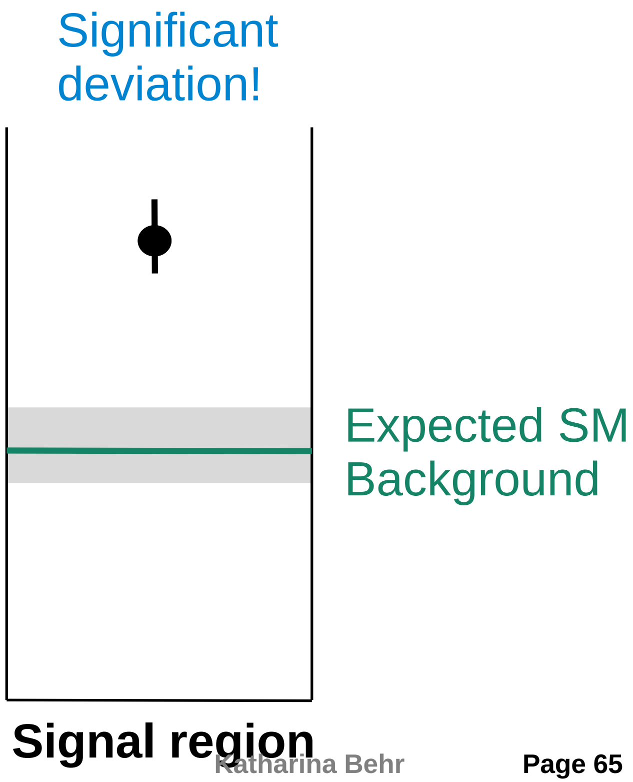
- Select (**cut**) events that you expect to be consistent with signal (signal region)
- **Count** data events in signal region and compare with number of expected SM events
- Calculate significance of deviation from SM prediction (accounting for uncertainties)



Cut-and-count method

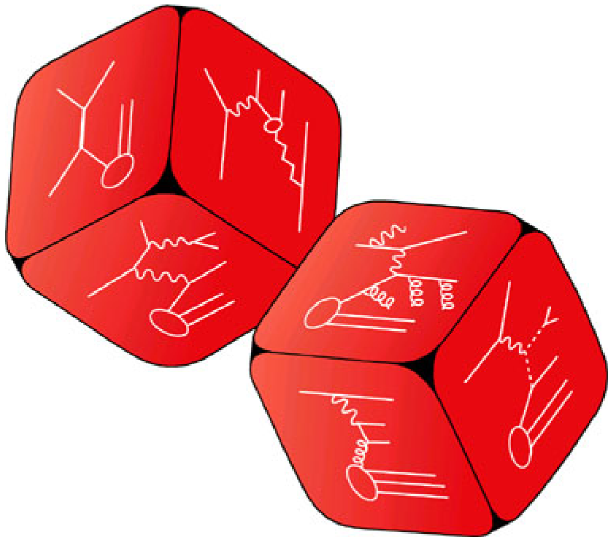
- Select (**cut**) events that you expect to be consistent with signal (signal region)
- **Count** data events in signal region and compare with number of expected SM events
- Calculate significance of deviation from SM prediction (accounting for uncertainties)

- **Advantage**: suited for low-stat regions, model agnostic
- **Disadvantage**: single bin → vulnerable to fluctuations → less sensitive



Monte Carlo event generators in a nutshell

- Quantum nature of elementary particle interactions: non-deterministic
  - Given initial state can lead to different final states with different probabilities
- **Idea:**
  - Calculate probability distribution for a given process (or sub-processes)
  - Random sampling to generate events with particle kinematics according to these distributions



Think outside the (black)box!

*“Questions were to be put to the **Pythia**, the ‘Priestess’ or ‘Prophetess’ of the Oracle. […] Seated on a tripod, she inhaled the obnoxious vapours that seeped up through a crevice in the ground. This brought her to a trance-like state, in which she would scream **seemingly random words and sounds**.*

*It was the **task of the professional priests** in Delphi to [...] edit them into the official Oracle prophecies, [...] these edited replies were **often less than easy to interpret**. The Pythic oracle acquired a reputation for **ambiguous answers**.”*

From the manual of the Pythia5 MC generator