Dark matter searches at accelerators

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(University of Wisconsin-Madison, LPC Distinguished Researcher)

on behalf of the *ATLAS, CMS, LHCb Collaborations*

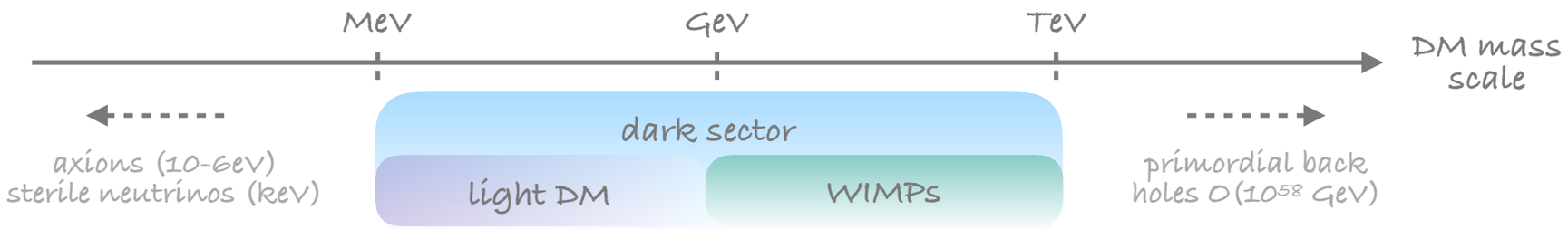
TAUP 2023

Vienna, 28 Aug - 1 Sept

What do we know about dark matter?

DM evidence

- Empirical evidence of DM from astrophysical observations at different scales
  - interacts gravitationally, long lived and neutral
  - no information about its nature (what DM could be?)
  - only measured quantitative property is its mass abundance
    - very large set of possible DM masses can account for observed final relic density



*thermal production

DM production

* explain its production and prerequisite for detection

- Thermal DM must have some non-gravitational interactions with SM particles

MeV-GeV:
- avoid DM overproduction with new mediator below weak scale
- new state must have suff. small SM coupling for consistency with collider searches

GeV-TeV:
- WIMP models, DM itself can have small couplings to SM particles
- most minimal scenario, no other new particles or interactions required

- dark sector: DM and mediator part of a separate "dark SM" with portal link to SM, can be fairly minimal or with composite dark sectors

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assume interactions with SM

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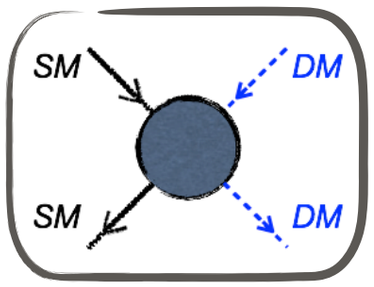

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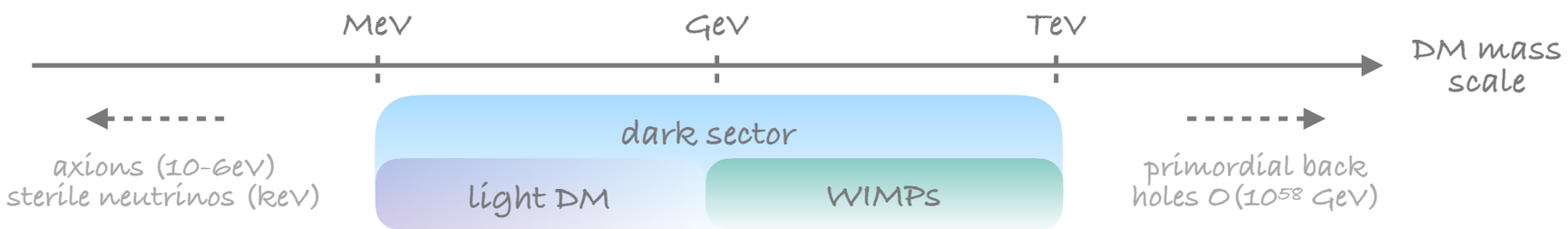

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How can we study DM interactions with SM?

- Where and how to look?

  MeV-GeV:

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  - → high-intensities

  GeV-TeV:

  - extensions of the SM at the GeV-TeV scale
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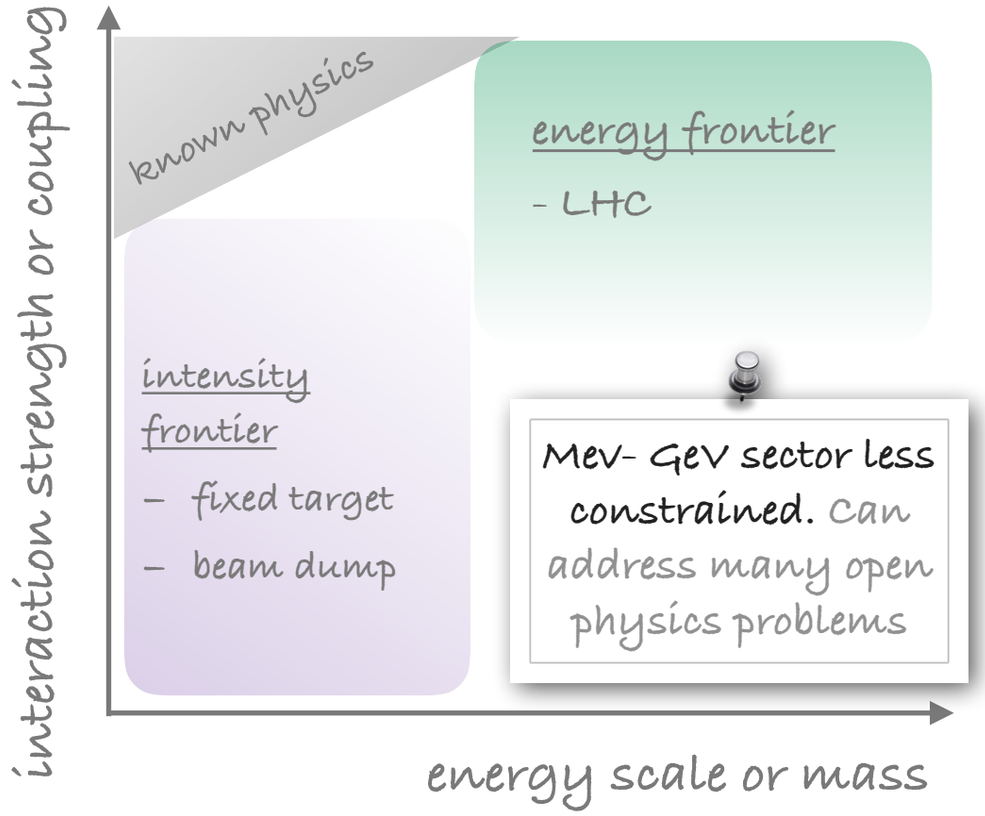
- dark sector mediators could be heavy, light, and/or long-lived

* can have rich connections and complementarity between type of experiments



- Assuming DM-SM interactions enables different searches:

  - indirect detection, products from DM annihilation
  - direct detection, nuclear recoils from DM-nuclei scattering
  - colliders: DM production

* Complementarity essential: eg. info about lifetime in case of DM discovery at colliders (~10^{-7}s), particle properties compared with cosmological constraints

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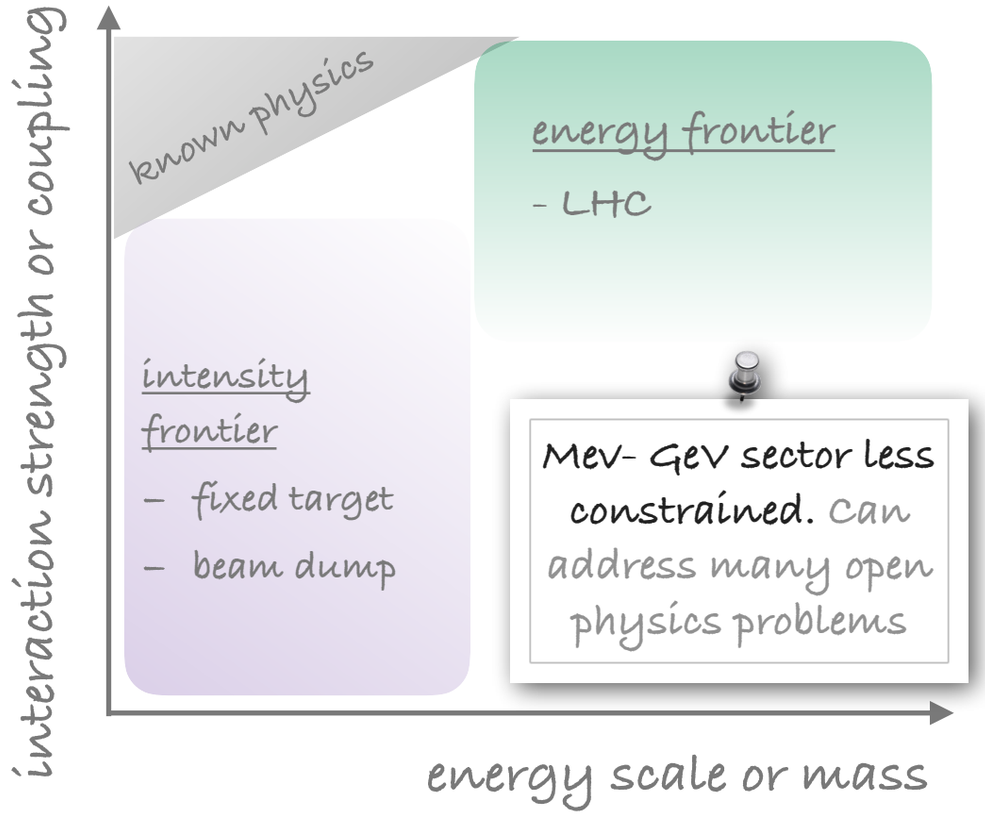

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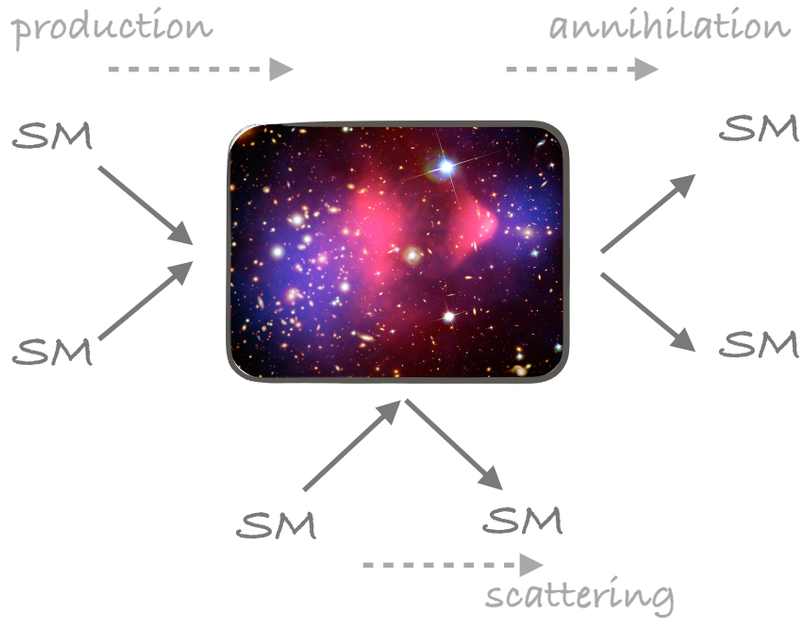

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Dark matter phenomenology

Intensity frontiers: MeV- GeV

- dark sector's small couplings to SM makes it challenging to detect, but … guides towards allowed relevant interactions:

  * **vector:** mediated by a dark vector boson (dark photon) that mixes with SM photon

  * **scalar:** mediated by a new scalar dark Higgs mixing with the SM Higgs boson, which leads to couplings to fermions.

  * **fermion:** mediated by a heavy neutral lepton (HNL) that can mix with SM neutrinos

  * **pseudo-scalar:** a axion-like particle can have couplings to SM fermions or gauge bosons

Energy frontiers: GeV, TeV

Simplified models

- one new mediator (spin-1 or spin-0), one DM particle
- limited parameters set (m_{DM}, m_{med}, g_q, g_{DM})

	vector	axial-vector
spin-1	$g_{DM}\sum_q V_\mu \bar{q}\gamma^\mu q$	$g_{DM}\sum_q A_\mu \bar{q}\gamma^\mu\gamma^5 q$
	scalar	pseudoscalar
spin-0	$g_{DM}\frac{\phi}{\sqrt{2}}\sum_f \bar{f}f$	$g_{DM}\frac{iA}{\sqrt{2}}\sum_f \bar{f}\gamma^5 f$

* interaction type define most sensitive signatures

- Higgs boson could be the SM-DM mediator

Signatures:

- *invisible*: production of DM through the decay of a portal/SM particles
- *visible*: dark mediator particles can decay back to SM particles (especially if sector's lightest state)
- *displaced (long-lived)*: production of dark sector particle with significant lifetime that decays visibly to SM

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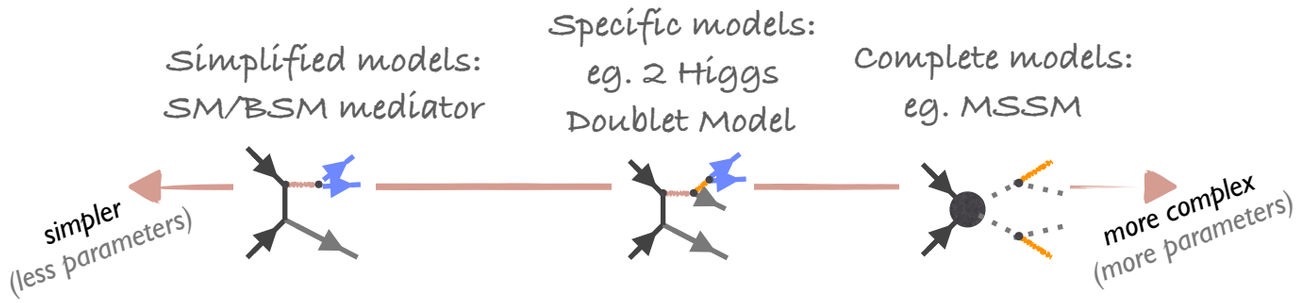

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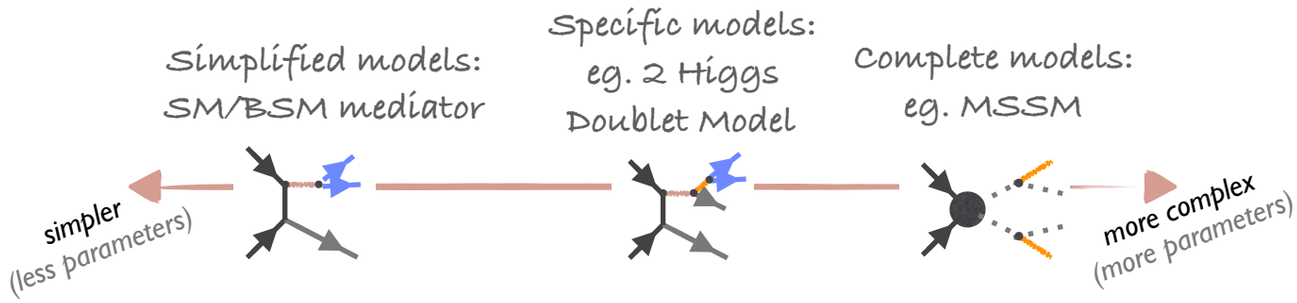

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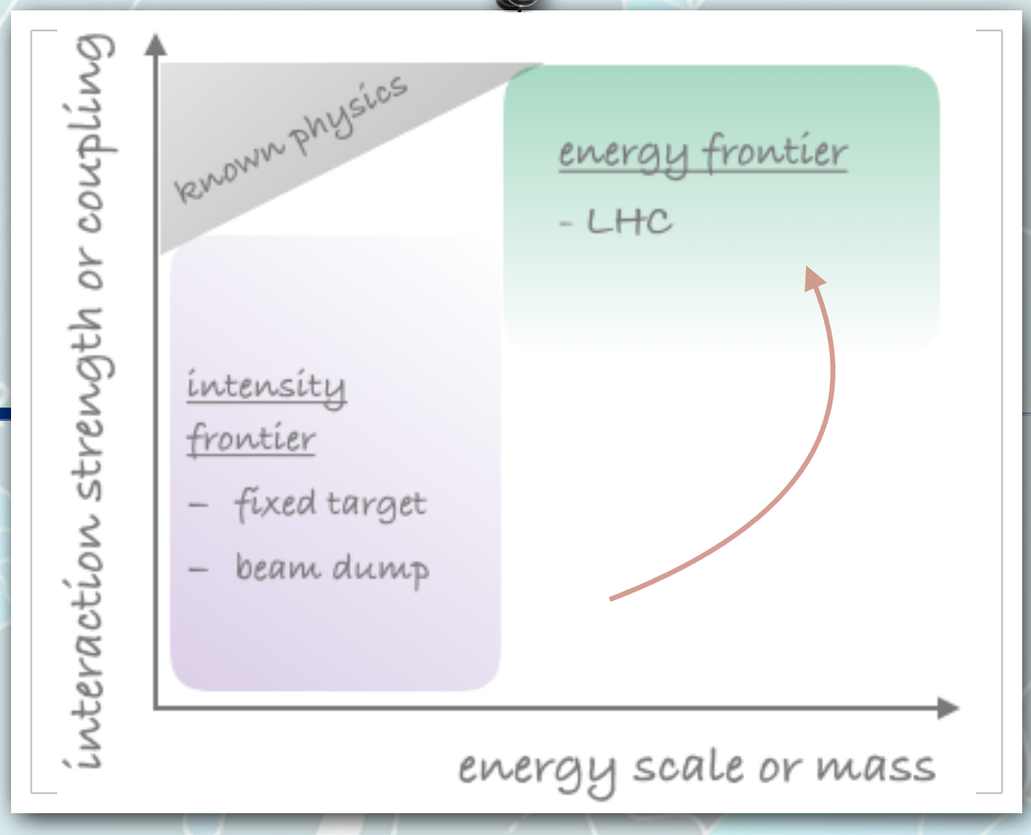
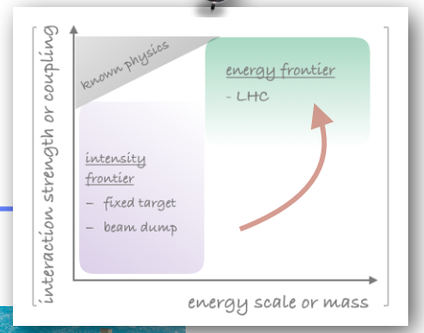
The energy frontier



Collider experiments: ATLAS, CMS, LHCb



ATLAS and CMS multipurpose detectors at LHC

- goals: precision test of SM, search for new physics
- particle identification, energy and momenta measurements
- trigger system: select events interesting for physics analysis
- pp collisions
  - Run2: 13 TeV, ~140 fb^{-1} | Run3: 13.6 TeV, already collected ~70fb^{-1}
  - more than 8.5 million Higgs boson produced!
- DM could be produced at colliders (rare process):
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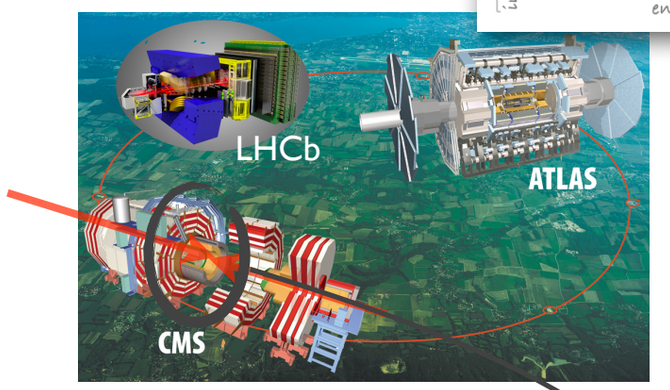
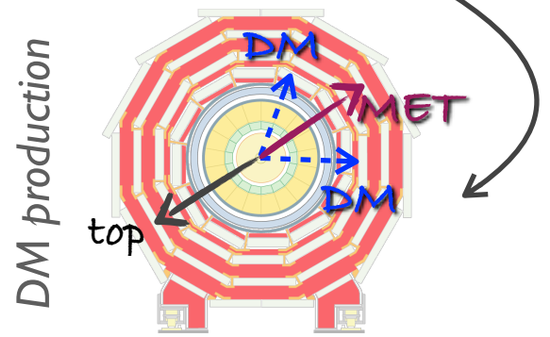
    - can be inferred from p_T imbalance (***MET***)
    - need visible particle to which DM particle recoils against "mono-X"





LHCb at LHC

- single-arm spectrometer originally devoted to heavy flavour physics, now a general purpose experiment
  - triggers with low p_T thresholds, probes rapidity region only partially accessible to other LHC experiments
  - excellent vertex, mass and lifetime resolution, particle identification
  - can operate in collider and fixed target mode
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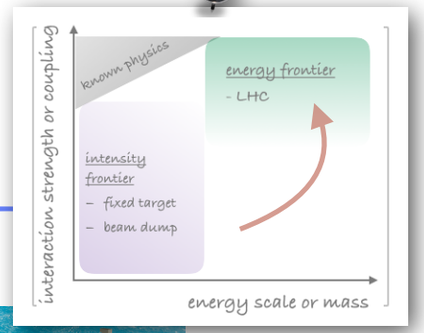

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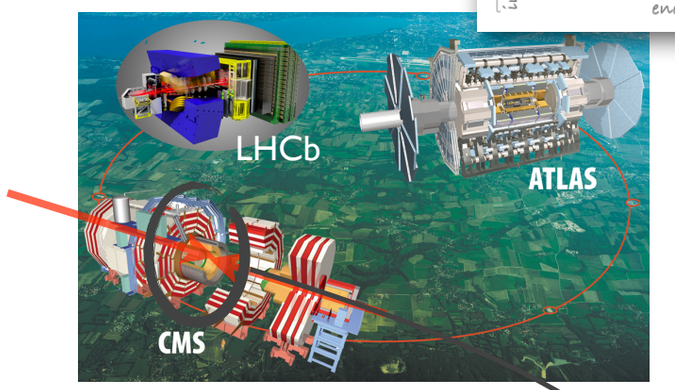

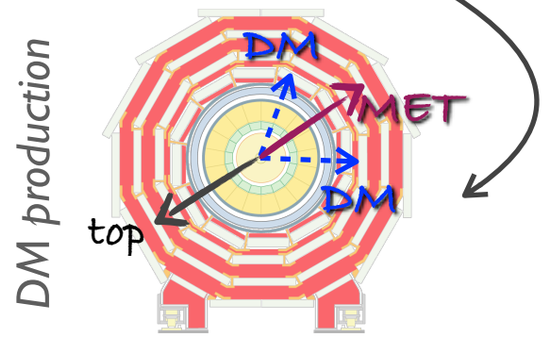

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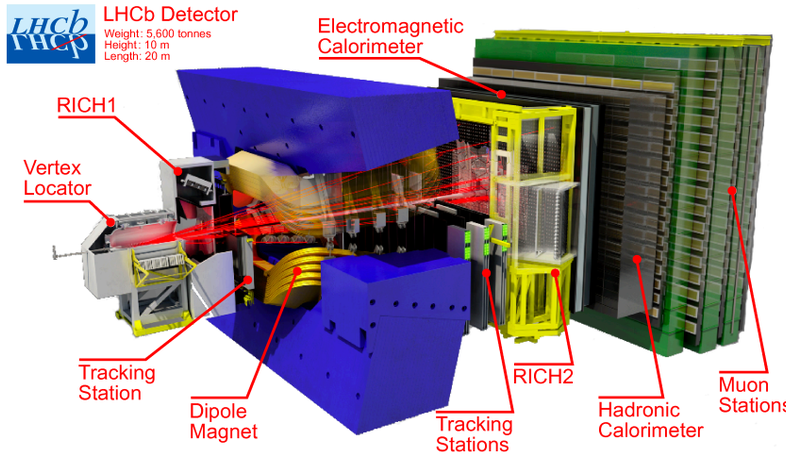


How do we search for DM at colliders?

1- Selection: DM appears as excess of events in MET tail wrt SM (or peak)

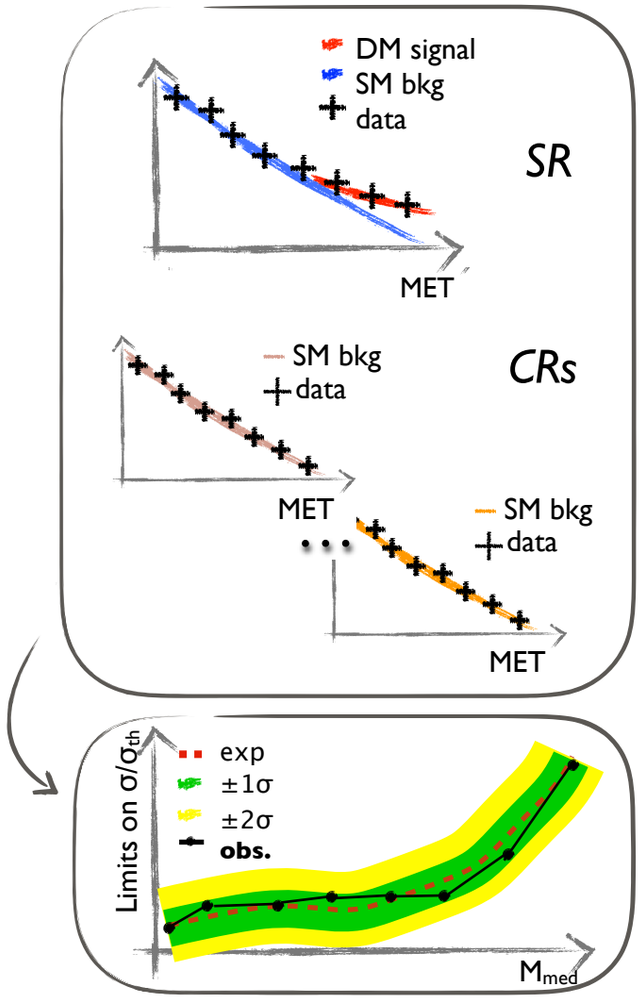
- *invisible*: no striking signature, eg. mass peak, m_T kinematic endpoint
- look for excess in region enriched in signal (signal region - SR)

2- Bkg: precise modeling, evaluation of SM processes in SR essential

- achieved through use of multiple control regions (CRs)

3- Results: Compare SM predictions with data

- *excess of events in data*. Did we find DM?
- *no excess*, interpret result in terms of theory model parameters



Experimental challenges for invisible signatures

- accurate *E* calibration/resolution of visible objects (*"fake" MET from mis-measured jets*)
- precise particle reconstruction and identification
- mitigate effects from additional *pp* collisions (pile-up)
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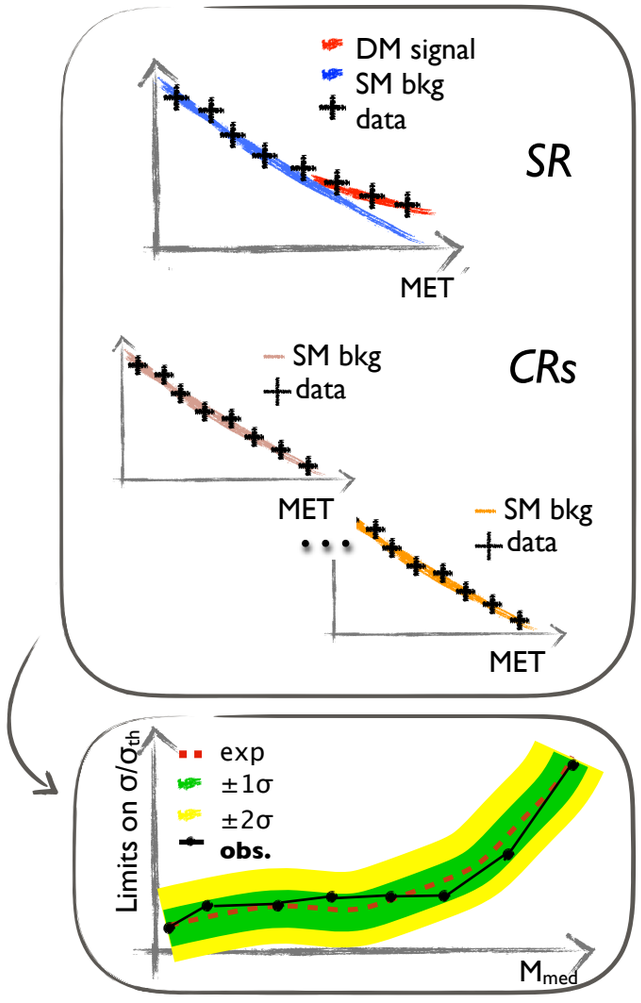

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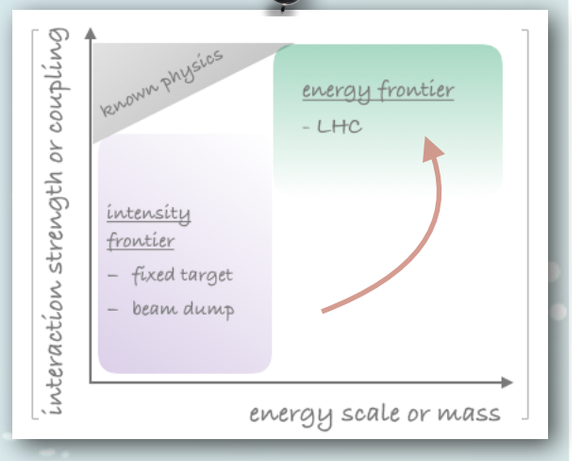


Simplified models and extensions

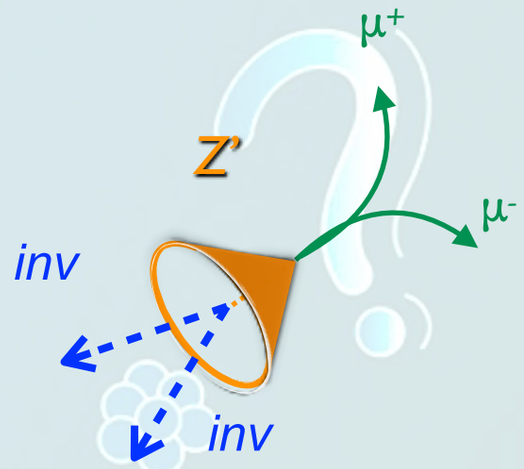
Signature: large MET (recoil) and ≥1 high-p_T visible particle

mono-Z'

* *ATLAS: CONF-2023-045*

mono-WW

* *CMS: EXO-21-012*



* *Belle II: PRL130(2023)*

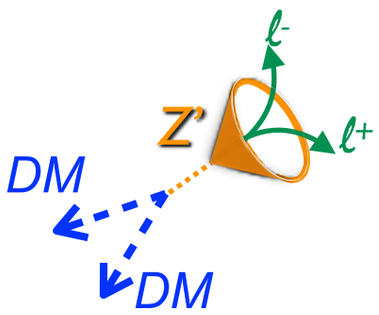
* *ATLAS: PLB842(2023)*
* *CMS: HIG-21-007*

* *selected recent results*

DM+Z' search

ATLAS: CONF-2023-045

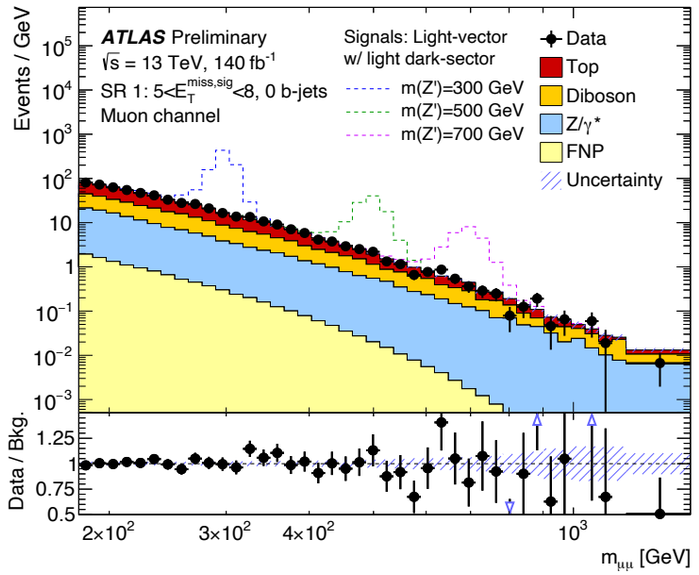
1- Selection:



- 1 opposite-sign ee/μμ pair
- 0 b-tagged jets, MET > 55 GeV
- $m_{\ell\ell}$ above Z peak
- events categorized on MET significance values

2- Bkg:

- ***tt, Z+jets,***
  VV *main bkg, from CRs*



3- Results: combined fit of SRs and CRs (systematic unc. included as nuisance parameters)

- interpretation in terms of DM model: upper limits at 95% CL on cross section

Dark-Higgs model

- h_D and DM dark-sector particles
- h_D radiated from Z', decays in DM

Light-vector model

- X_1 *and* X_2 dark-sector
- Z' off-diagonal coupling to X_1, X_2

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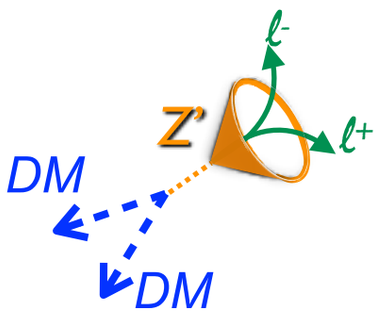

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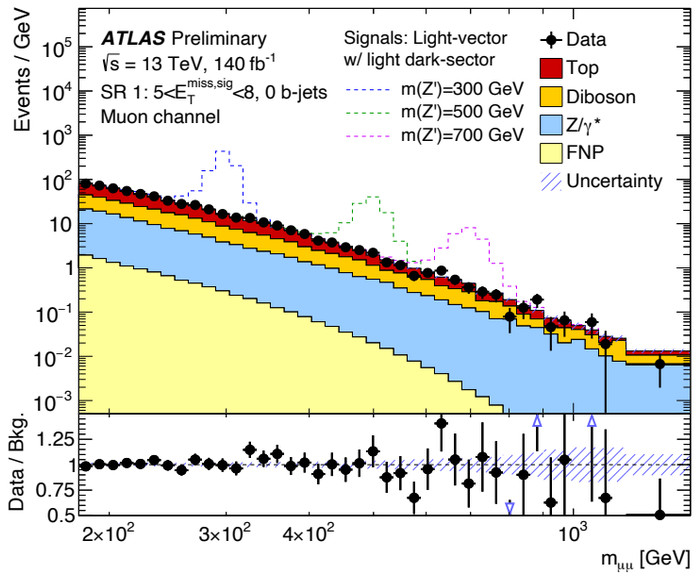

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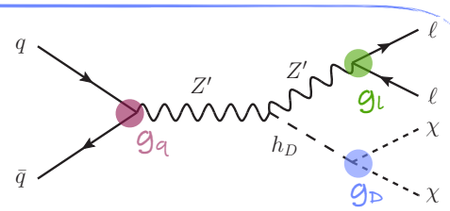

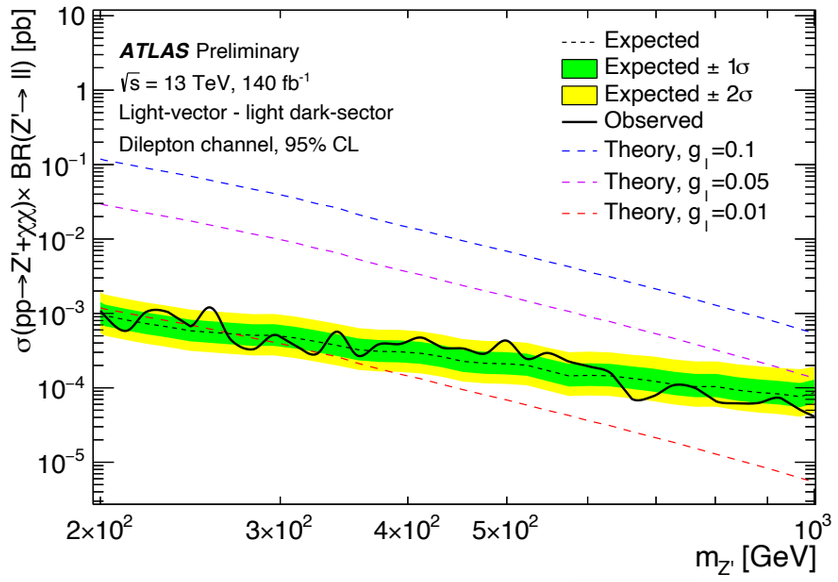

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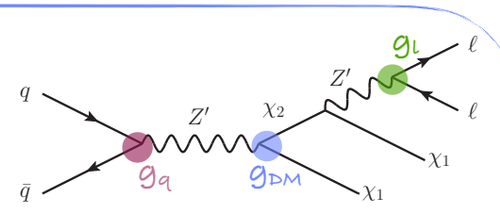

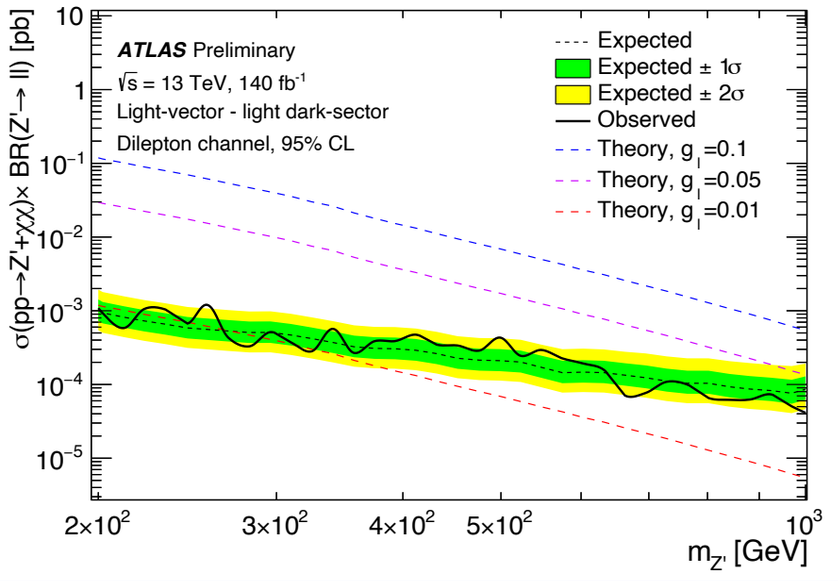

DM+WW search

CMS: EXO-21-012

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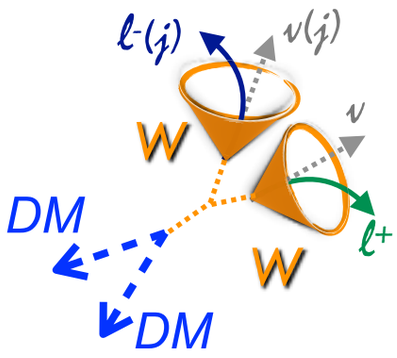
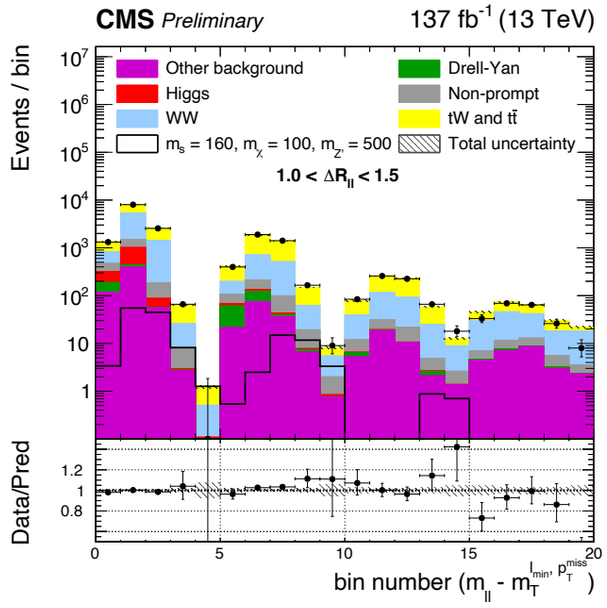


1ℓ
- 1 lepton, ≥ 2 jets (m_{jj} ~ W mass)
- 0 b-tagged jets, MET > 60 GeV
- MVA techniques to recover sensitivity

2ℓ
- 1 opposite-charge ℓℓ pair
- 0 b-tagged jets, MET > 20 GeV
- events categ. on dark-H boost

- 2- Bkg:

- ***tt, tW, W+jets (1ℓ), Z+jets, WW*** *(2ℓ) main bkg, from CRs*



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- *s* can be lighter than DM, observed relic can be attained

(*) first CMS result on dark-Higgs model

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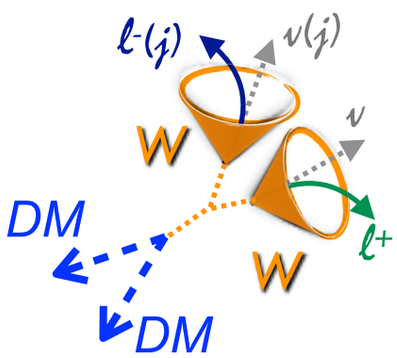

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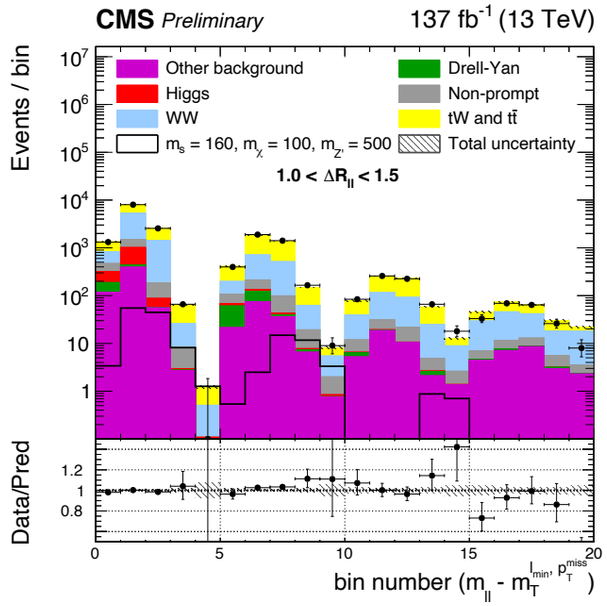
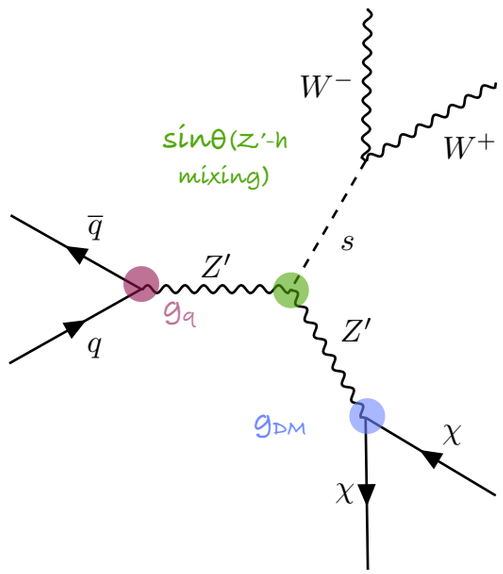
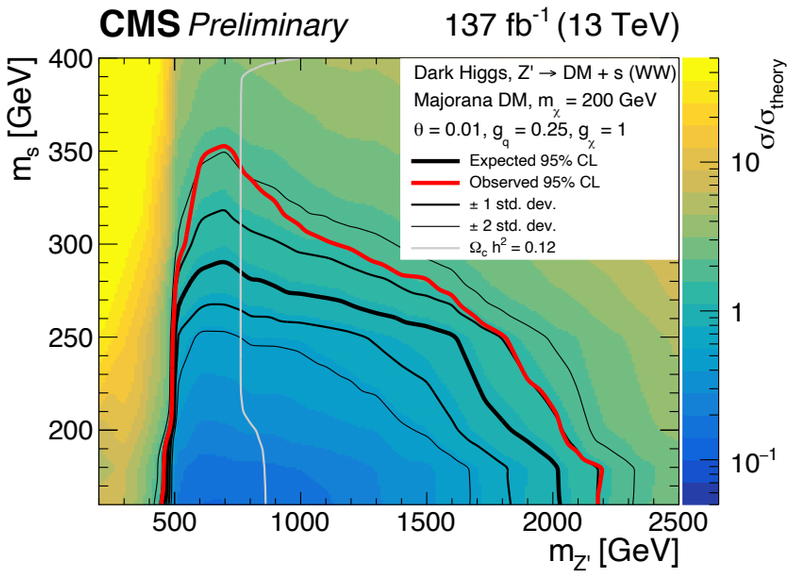


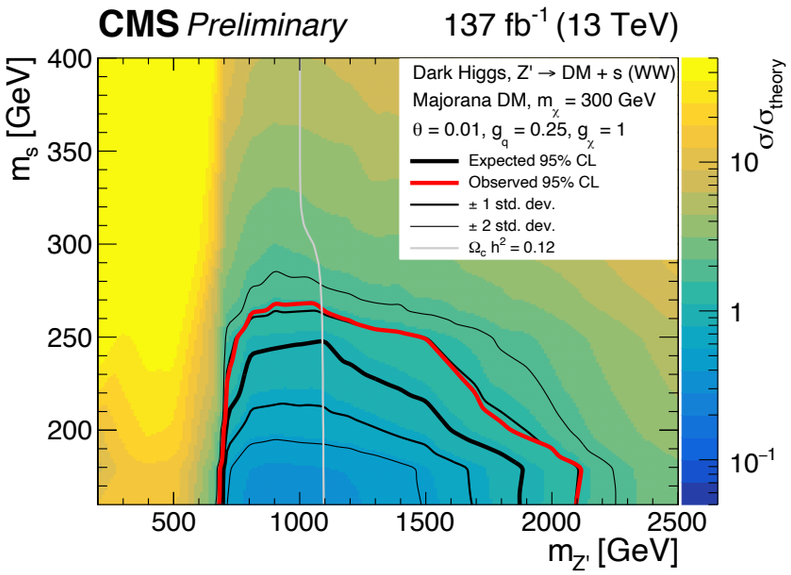
- **3- Results:** combined fit of SRs and CRs (systematic unc. included as nuisance parameters)
  - interpretation in terms of DM model: upper limits at 95% CL on cross section

Dark-Higgs model

- dark Higgs (*s*) can be lighter than DM, observed relic can be attained





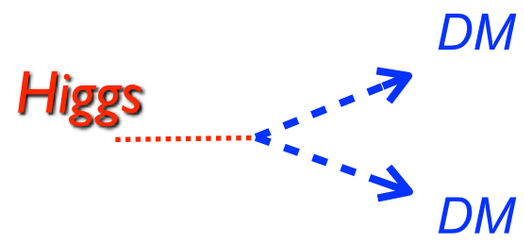


(*) first CMS result on dark-Higgs model

Higgs: a portal to the invisible?

ATLAS: PLB842(2023)137963
CMS: HIG-21-007

- DM-SM interactions mediated by Higgs boson: coupling to DM enhance H invisible decays (SM ~0.1%)
- Higgs production as in SM
  - gluon fusion (MET+j)
  - associated VH (MET+V), ttH (MET+tt)
  - vector-boson fusion (MET+2jets)



- 3- Results: combination of results from various Higgs production,
  translated into a spin-independent DM-nucleon elastic scattering xsec limit:
  - $m_{DM} < m_H/2$, interaction between DM and nucleus mediated by H exchange

LHC searches complementary to direct detection

BR(H→inv) <0.15(0.08) obs(exp.)

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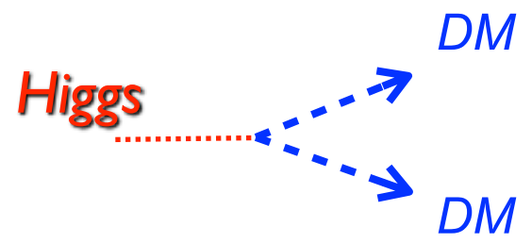

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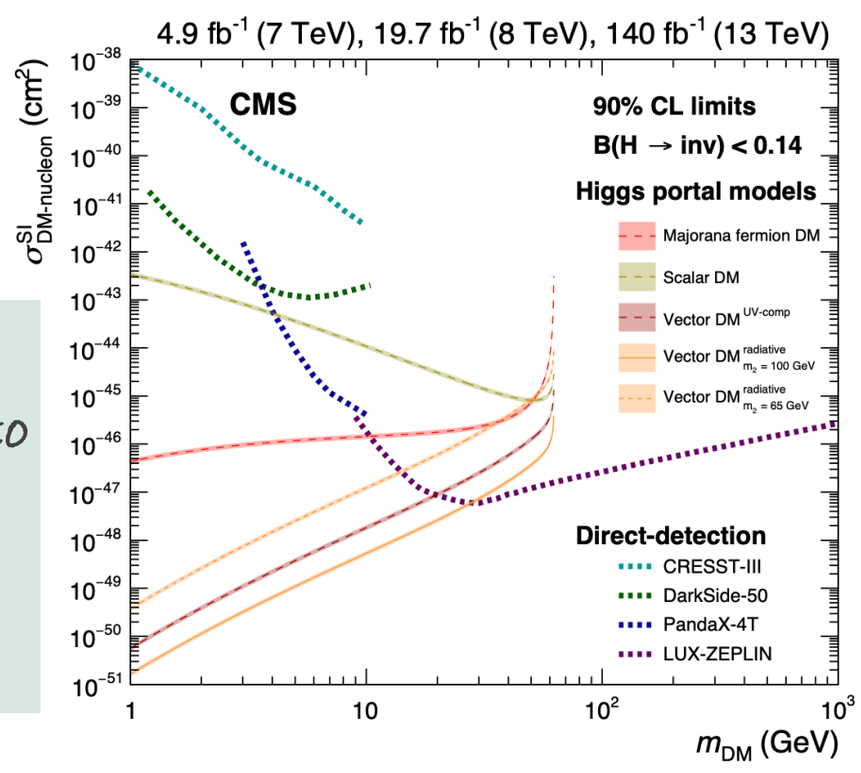

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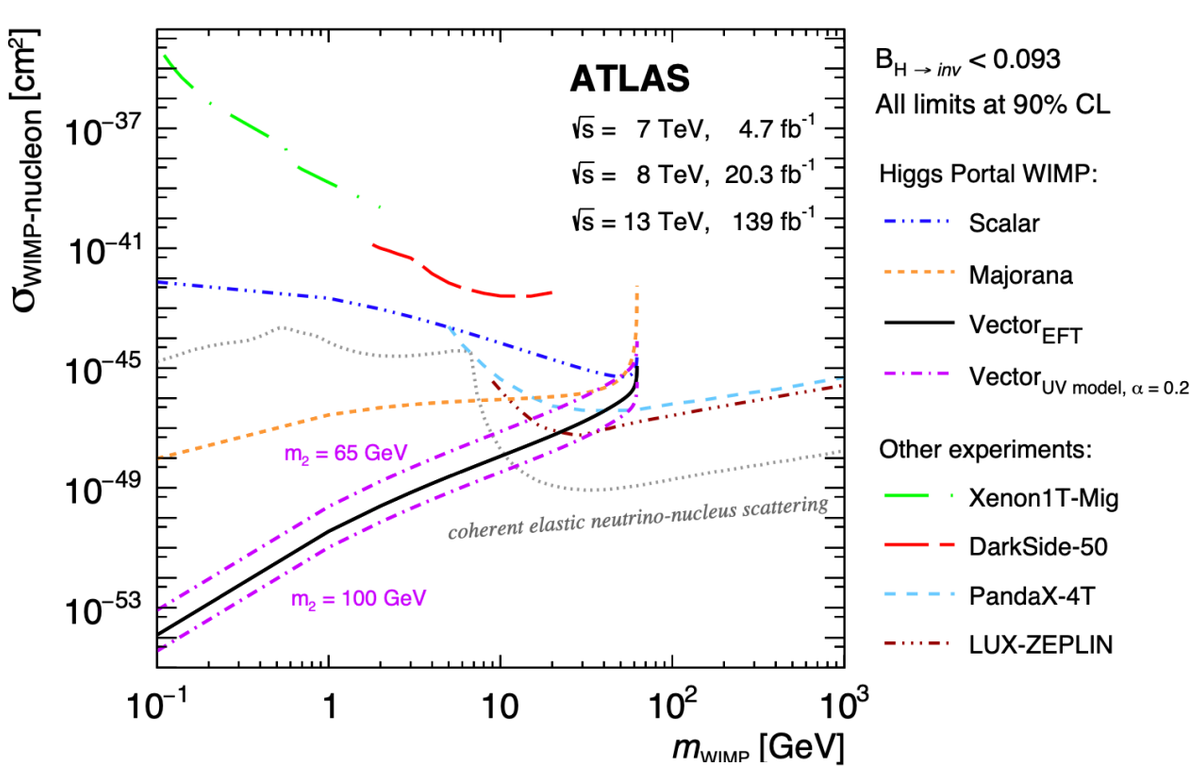

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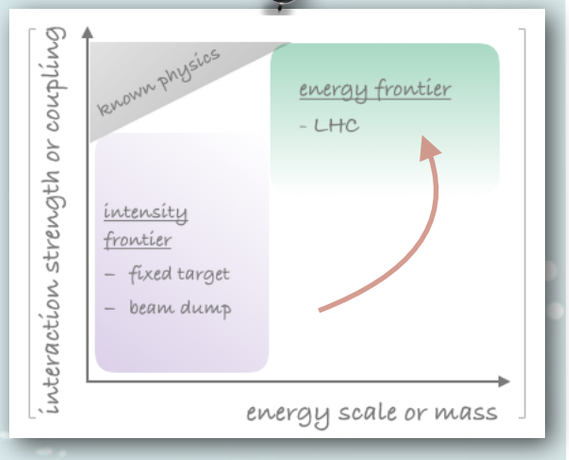
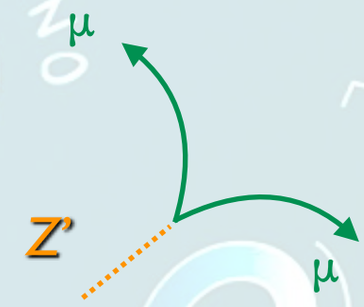


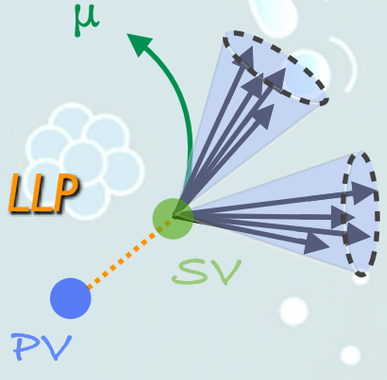
Looking for the mediator

Signature:

- di-muon resonances:
  - ✱ CMS: EXO-21-005
  - ✱ ATLAS: JHEP07(2023)090



- massive long-lived particles:
  - ✱ LHCb: EPJC373(2022)



✱ selected recent results

Di-muon low-mass resonances

CMS: EXO-21-005

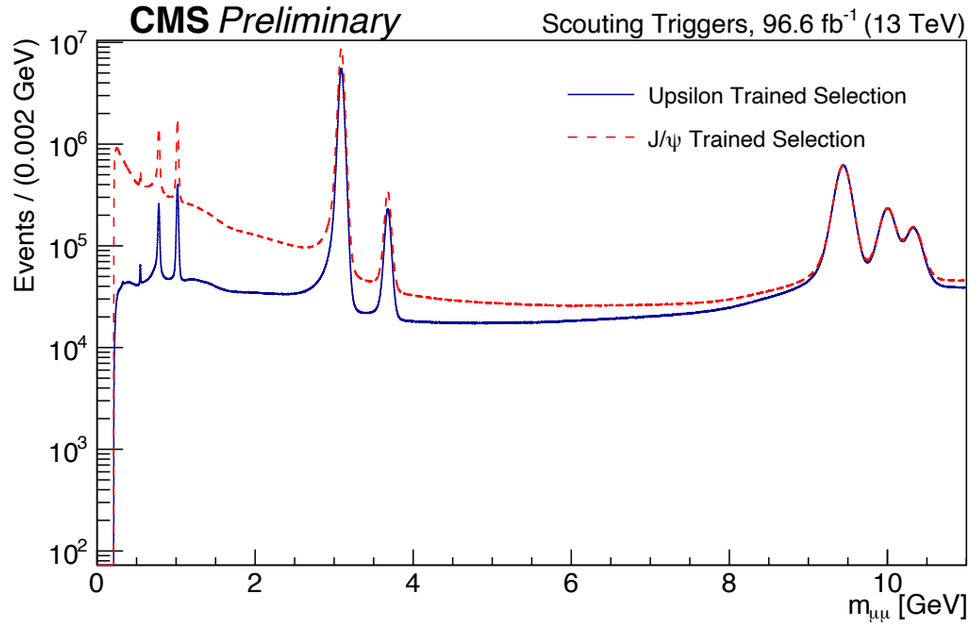
1 - Selection: resonance appears as peak wrt SM invariant mass

- 1 opp.-sign μ pair, categories on $p_T(\mu\mu)$
  - dedicated $\mu\mu$ trigger: low p_T thresholds, high rate, retain only 4-momentum, isolation, track information
  - muon identification based on MVA techniques

2 - Bkg:

- known resonances, D meson decays to kaons (from CR)

3- Results: fit to $\mu\mu$ invariant mass, upper limits at 90% CL on mixing coefficient ε



Dark photon

- dark/SM sectors interaction through dark photon Z_D, with kinetic mixing ε

Higher sensitivity at low masses

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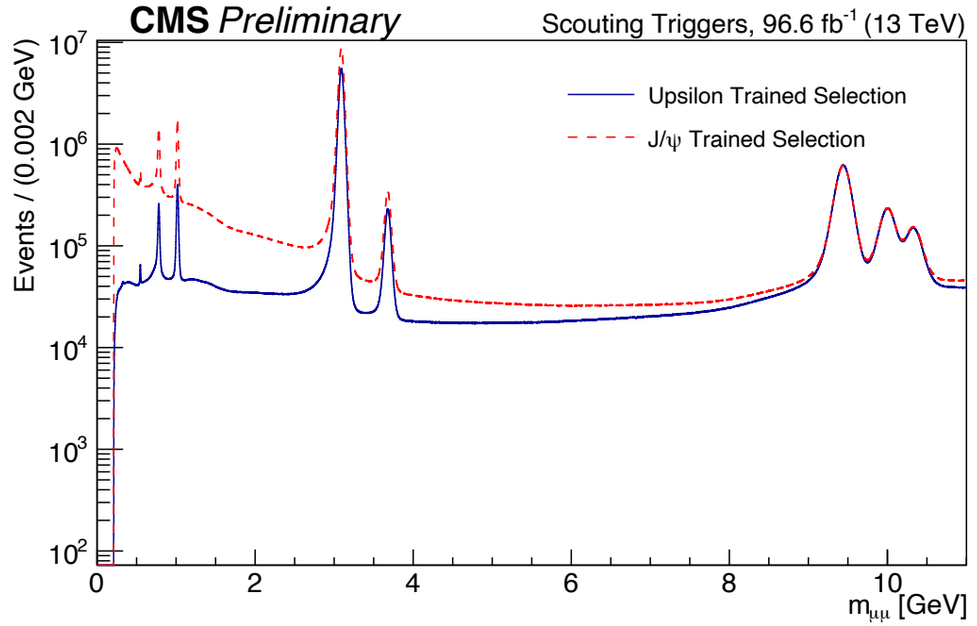

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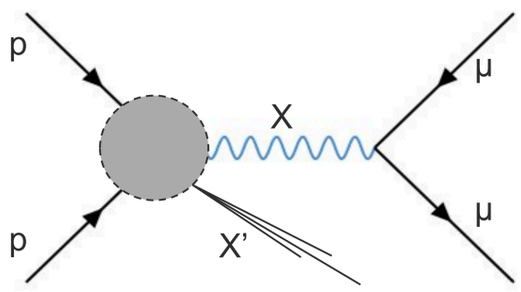

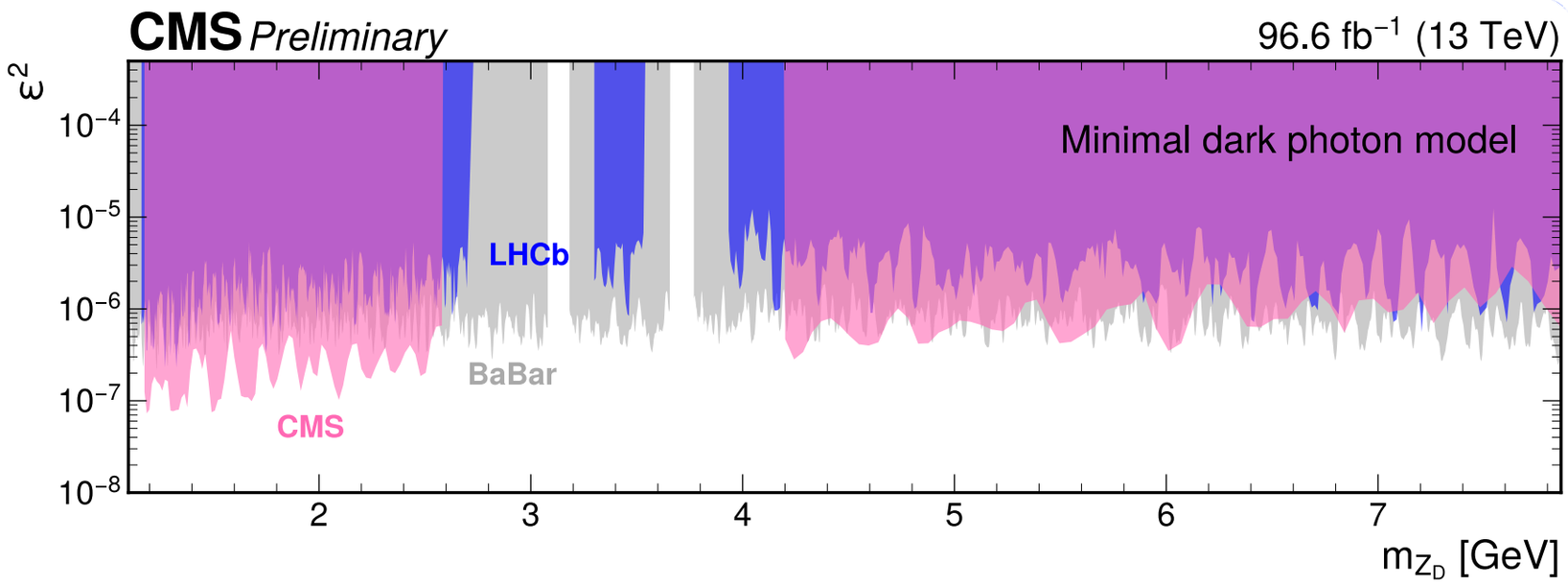

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Z' vector boson in 4μ signatures

ATLAS: JHEP07(2023)090

1- Selection: signal events appears as peak wrt SM invariant mass spectrum

- at least 4μ, 1st pair with mass closest to m_Z, 2nd with highest mass
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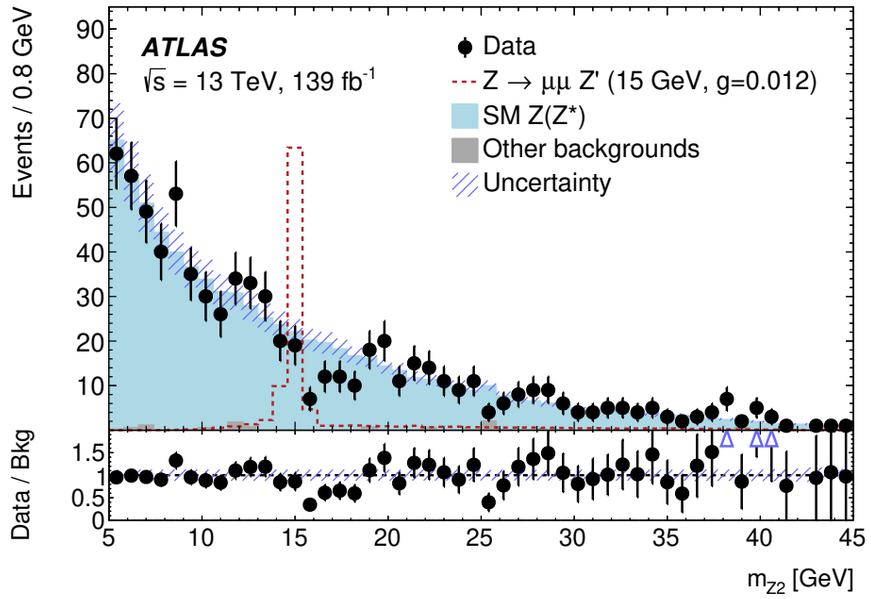

2- Bkg:

- ***Z+jets, tt, WZ*** *main bkg, normalized from CR*

3- Results: fit to *μμ* invariant mass (systematic unc. included as nuisance parameters)

$L_\mu - L_\tau$ model

- new gauge boson Z' interacts only the 2nd and 3rd gen. leptons
- can address observed g-2 and rare B decays anomalies

(mZ',g) not strongly constrained in experiments, Z' does not couple to electron or quarks (no direct probe from e+e- and pp beams)

gap is now largely excluded by this analysis

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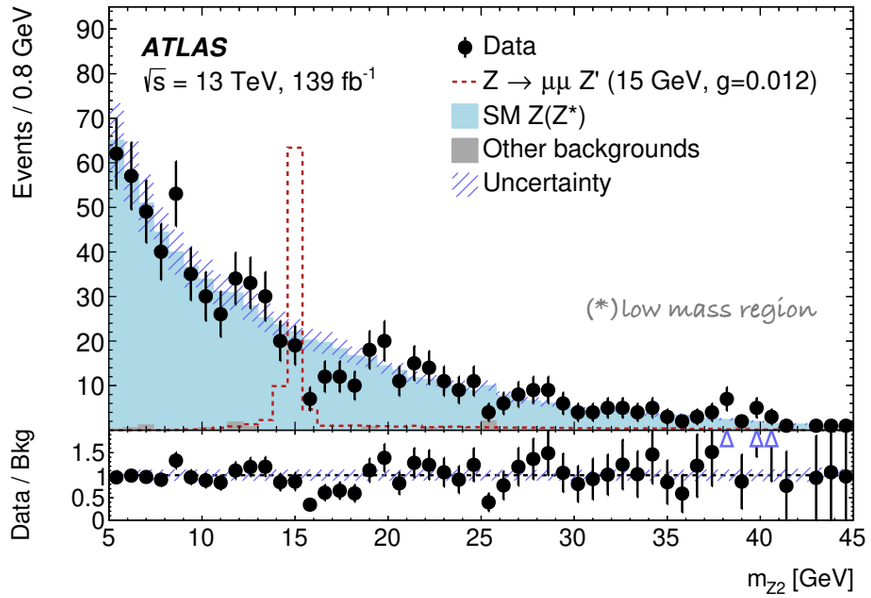

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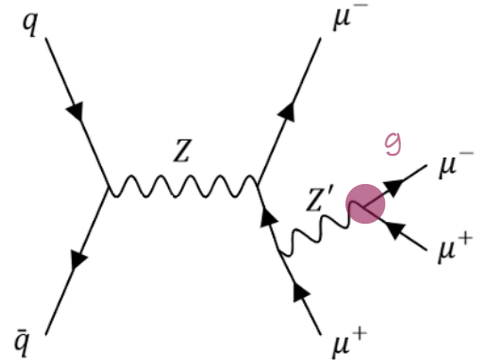

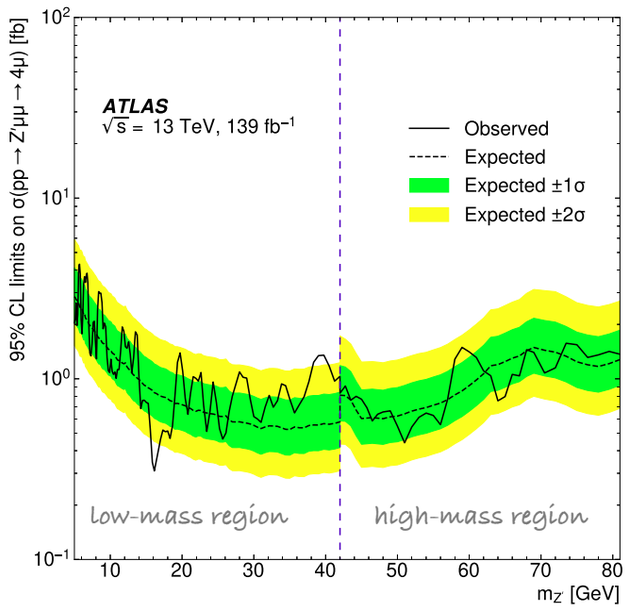

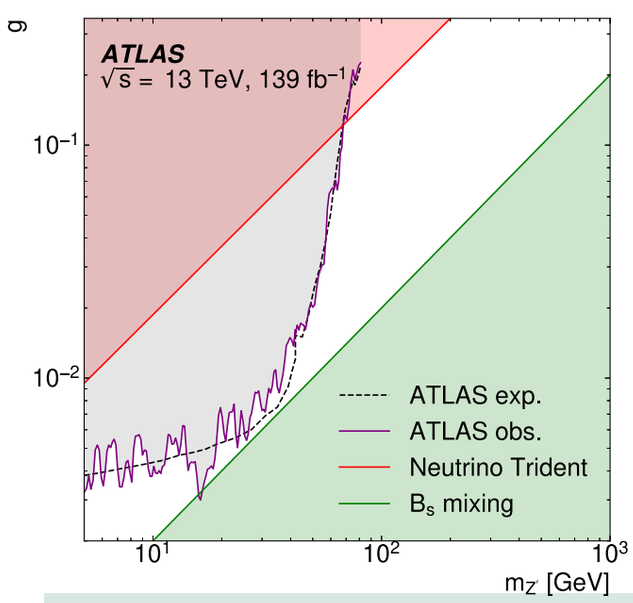

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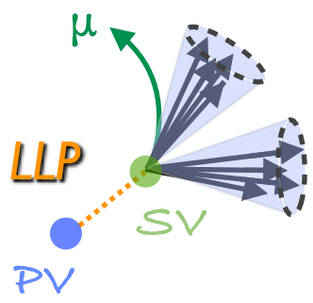
Search for LLPs → μ+jets

LHCb: EPJC373(2022)

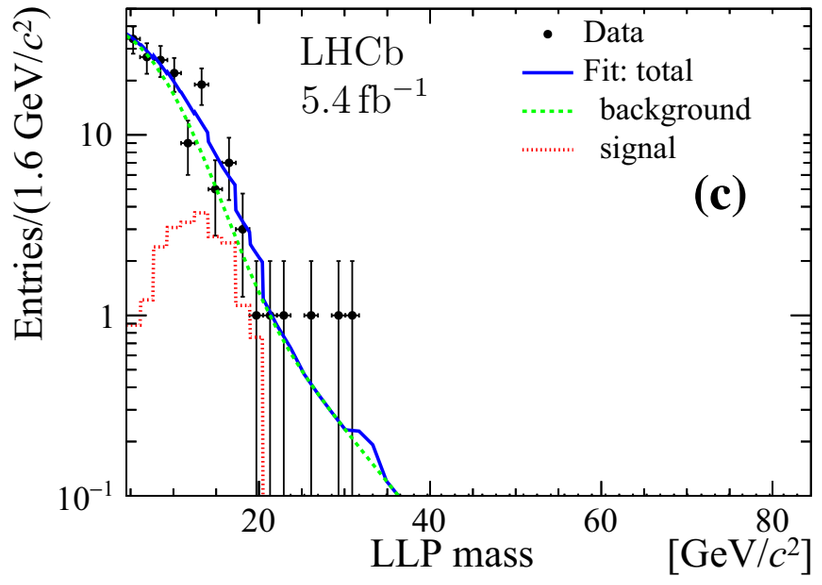
1- Selection:



- 1 displaced vertex from any PV containing 1μ
- ≥1 LLP candidates : ≥3 tracks (1μ) with inv mass above B resonances
- MVA techniques to recover sensitivity

2- Bkg:

- ***bb processes and material interactions***



3- Results: combined fit to LLP reconstructed mass in SRs and CRs

Upper limits at 95% CL on cross section

Massive long-lived particles (LLP)

- (a) Higgs-like particle h^0 produced by ggF, decays into two LLPs
- (b) direct LLP production from quark interactions

heavier particles → lower lifetime/boost

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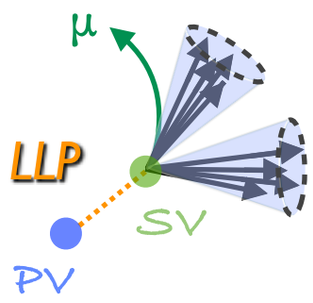

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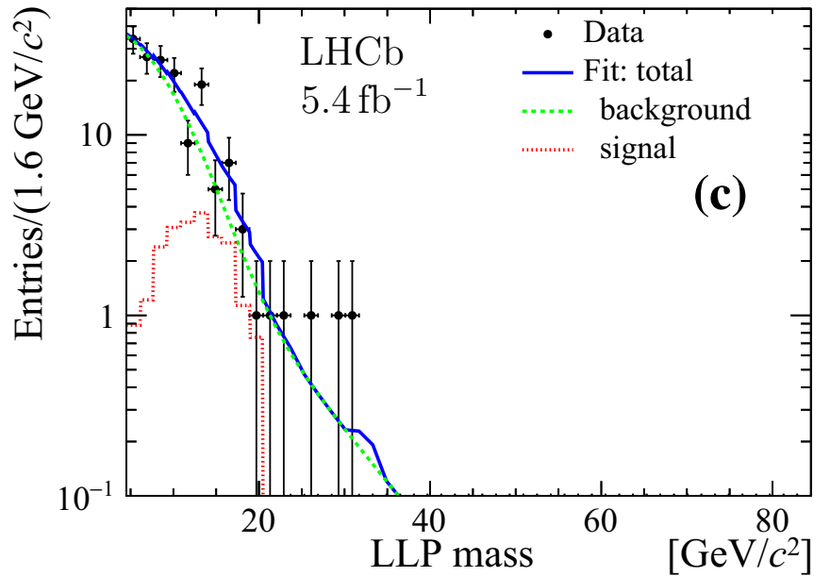

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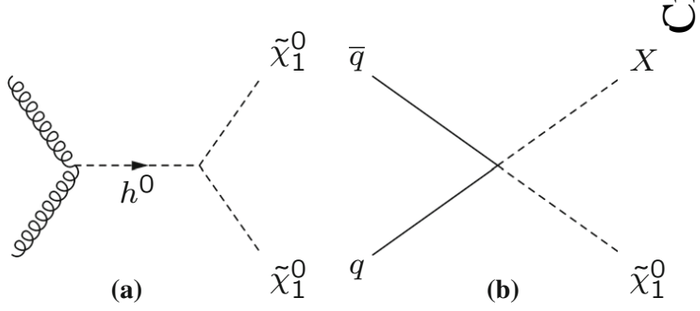

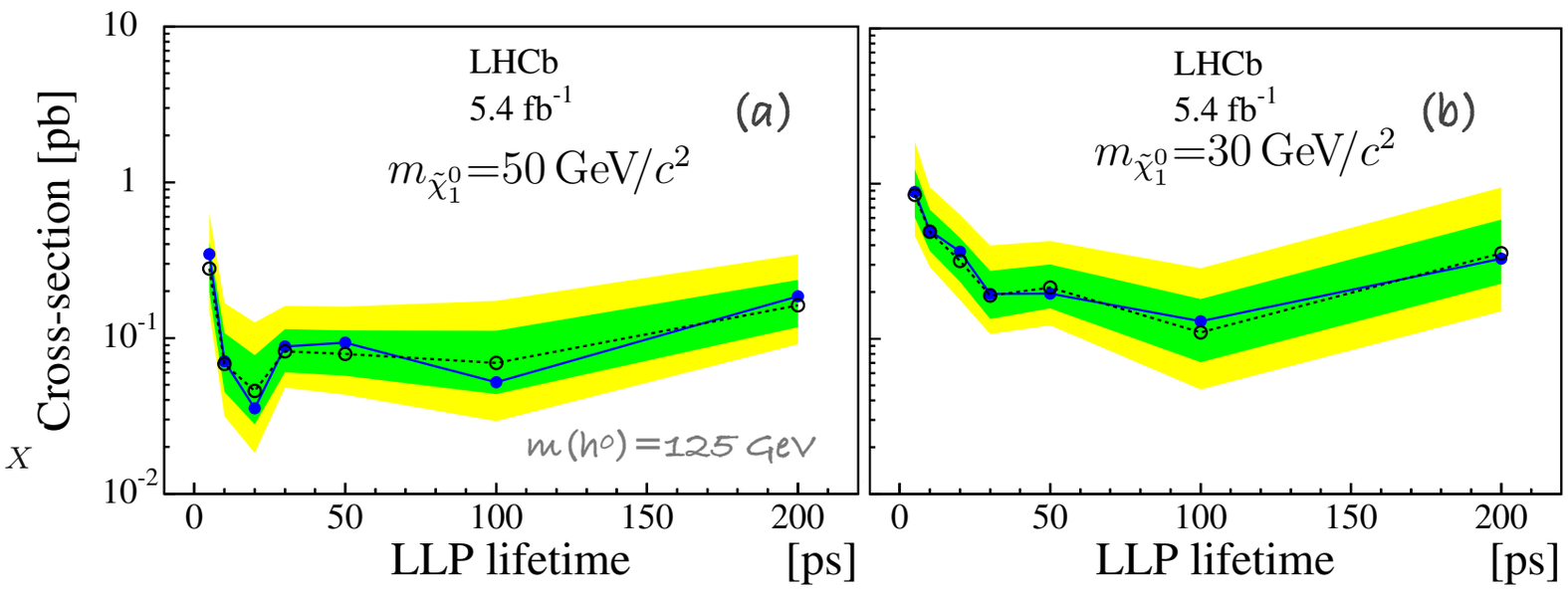

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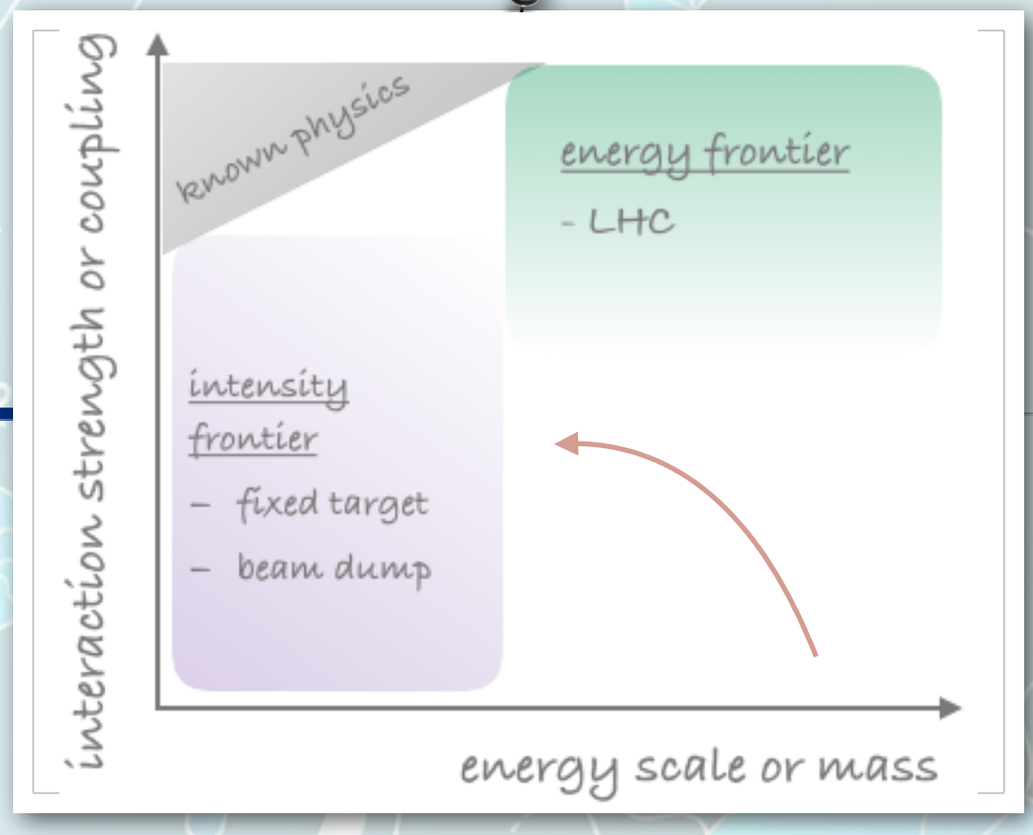
The intensity frontier



How do we search for light-DM at colliders?

MeV-GeV
- models of thermal light-DM rely on light force-carriers with suff. small SM couplings
- interactions too weak for detection at high-energy colliders, small kinetic energy for traditional direct detection

Solution
- intensity-frontier experiments essential to explore light dark-sector
- optimized for intensity, instrumentation precision, bkg rejection

Search strategies

* missing energy, momentum, or mass:
  - signature: exploit visible particles kinematics to infer invisible particles (energy and momentum conservation)
  - detector: e+e- annihilation, lepton-beam fixed-target experiments excellent forward hermiticity, good calorimetry

* re-scattering:
  - signature: detect DM produced from beam dump scattering off electron/proton in detector volume
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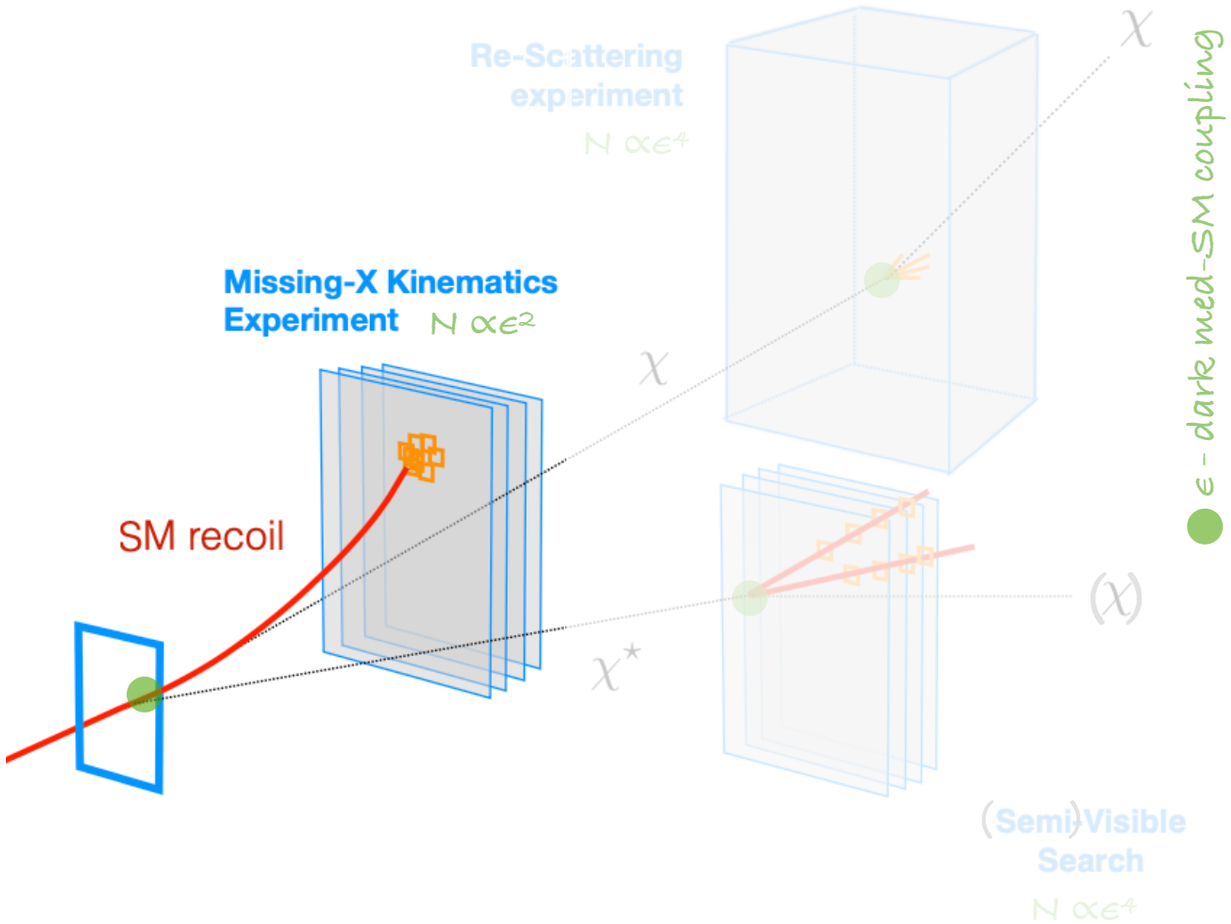

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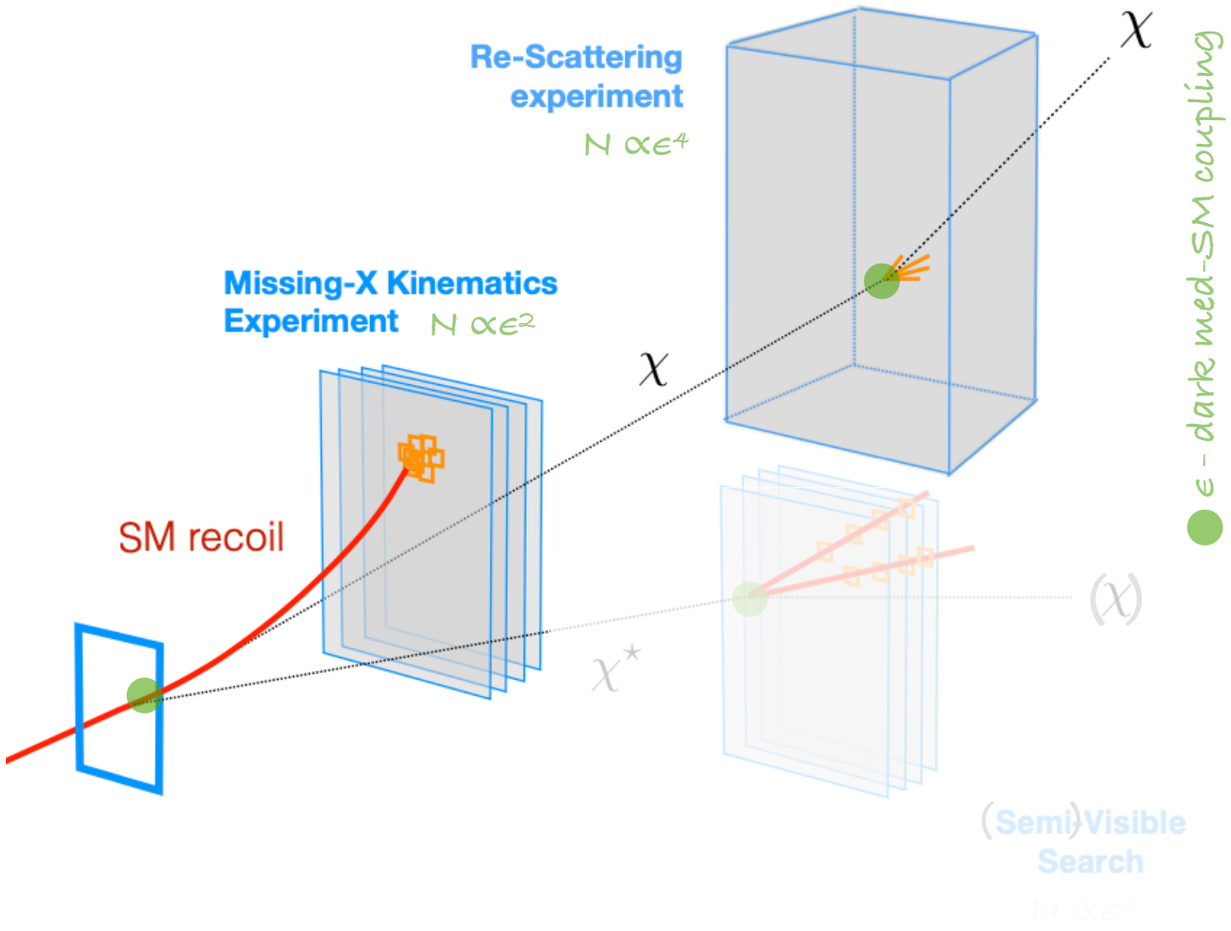

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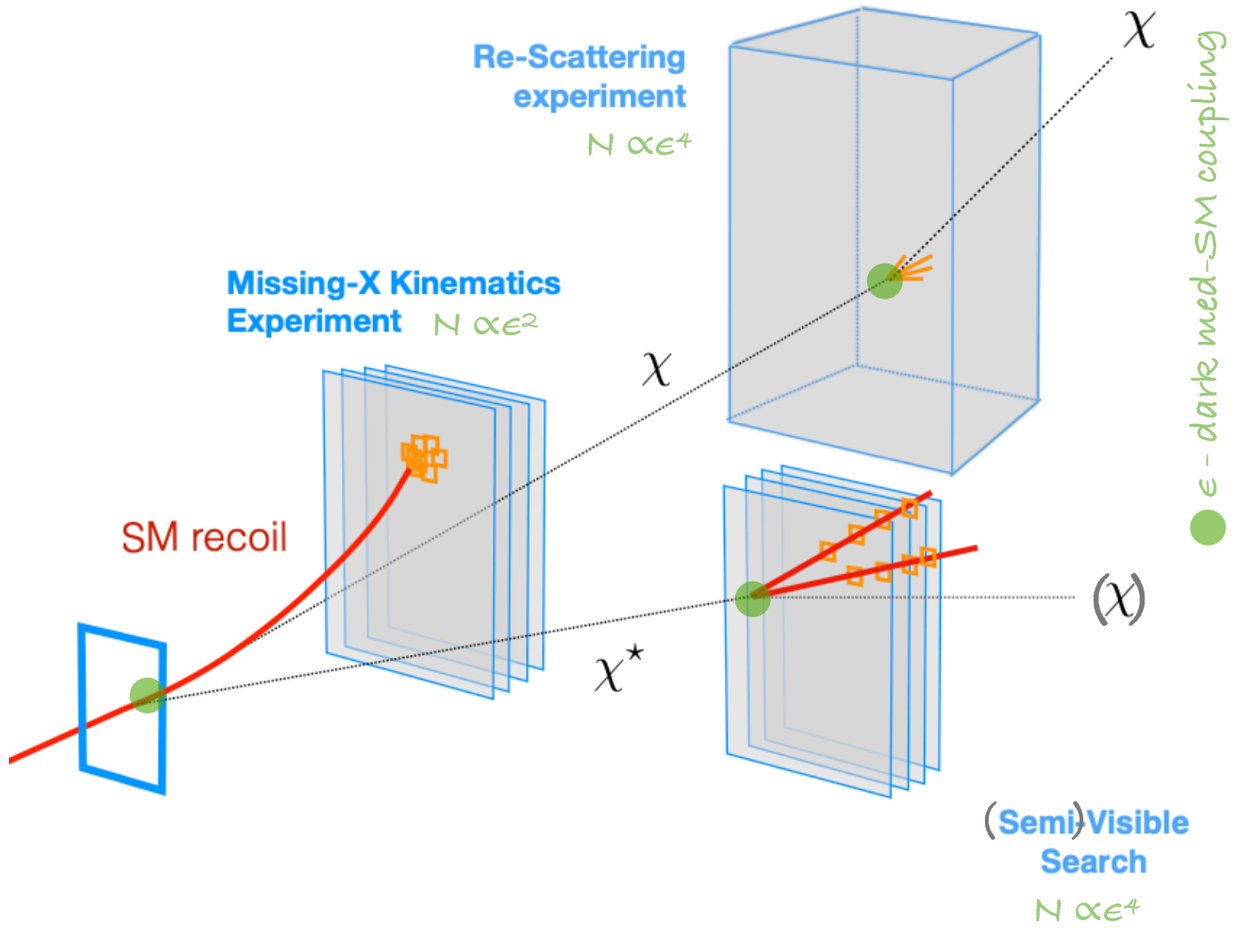

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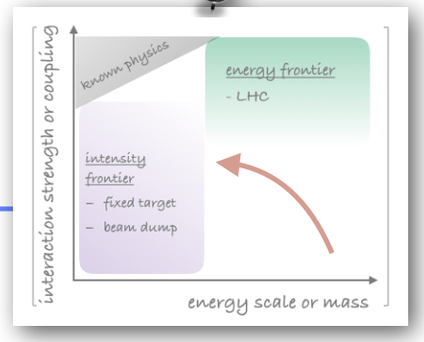
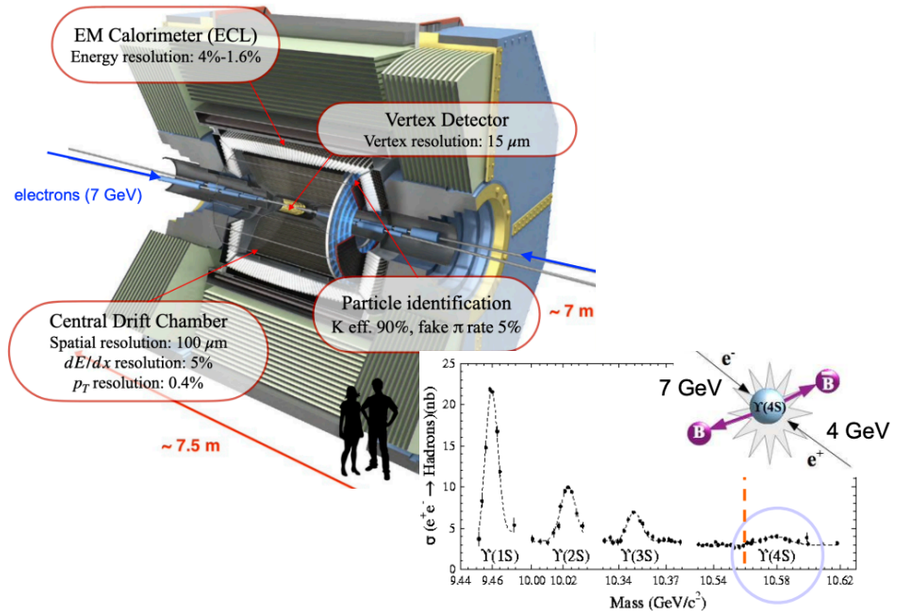
Collider experiments: NA64 and Belle II



- **missing energy, momentum, or mass:** lepton fixed-target experiments, e+e- annihilation excellent forward hermiticity, good calorimetry
  - many current and proposed exp., eg: positron fixed-target PADME (LNF), muon fixed-target dumps NA64μ (CERN), M³ (FNAL), ...

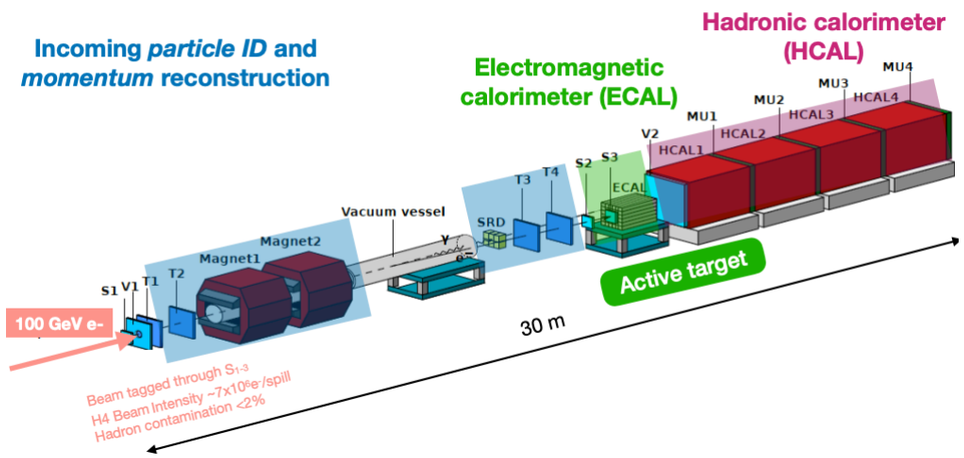
Belle II at SuperKEKB

- optimized for tracking and B vertex reconstruction, K-π identification
- good missing energy reconstruction
- potential to reconstruct displaced vertices
- e+e- collisions asymmetric-energy B factory (Υ(4S))
  - data taking start in 2019: ~430 fb^{-1}
  - recoil quantities from knowledge of initial-state total momentum

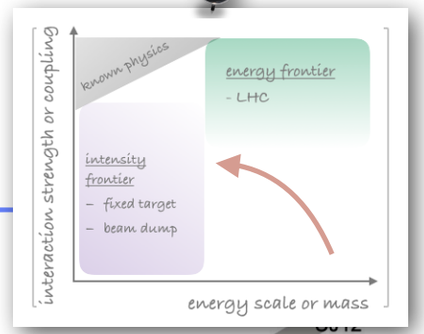


NA64 at LHC

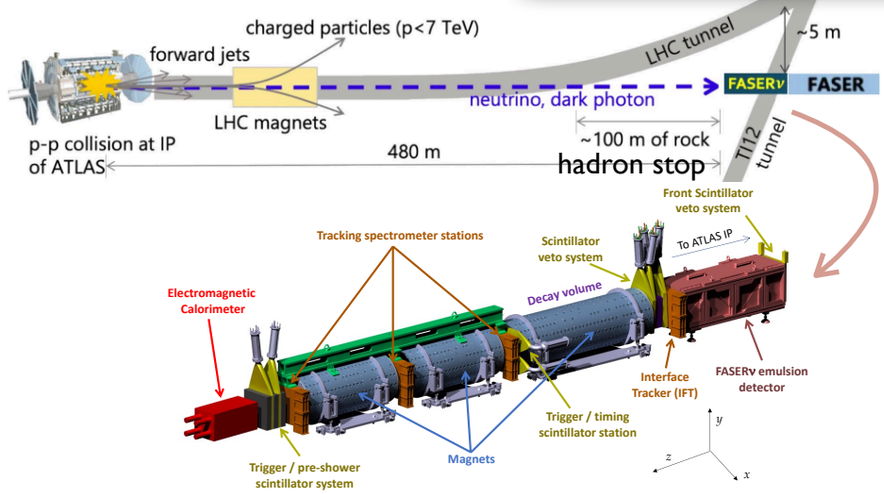
- 100 GeV electrons beam from SPS
- beam identification: magnetic spectrometer and synchrotron detector
- active target electromagnetic calorimeter (ECAL)
- plastic scintillator VETO, HCAL to veto muons or hadrons secondary production in the e-nuclei interactions in the target
- Successfully operated throughout 2016-2022



Collider experiments: FASER and μBooNE



- (semi-)visible: intense beams, long decay volumes, excellent tracking
  - many current and planned exp., eg: electron-beam dump NA64 (CERN), HPS and APEX (JLab), proton-beam dump DarkQuest (FNAL), SHiP (CERN), ...



FASER at LHC

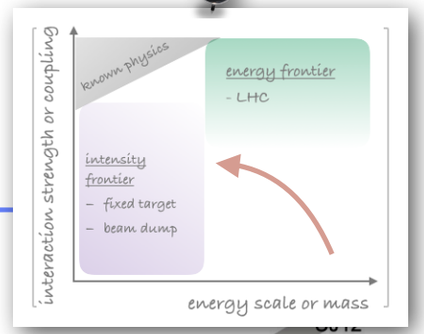
- designed for dark photons and long-lived BSM searches, detect high energy neutrinos produced in pp collisions
- located approximately 480 m from the ATLAS interaction point
- most SM particles bent away by LHC magnets or stopped by 100m rock
- Successfully operated throughout 2022: ~70 fb^{-1}

- re-scattering: intense beams or high-luminosity colliders
  - many current and planned exp., eg: electron-beam dumps BDX (JLAB), proton-beam dumps SBDN (FNAL)

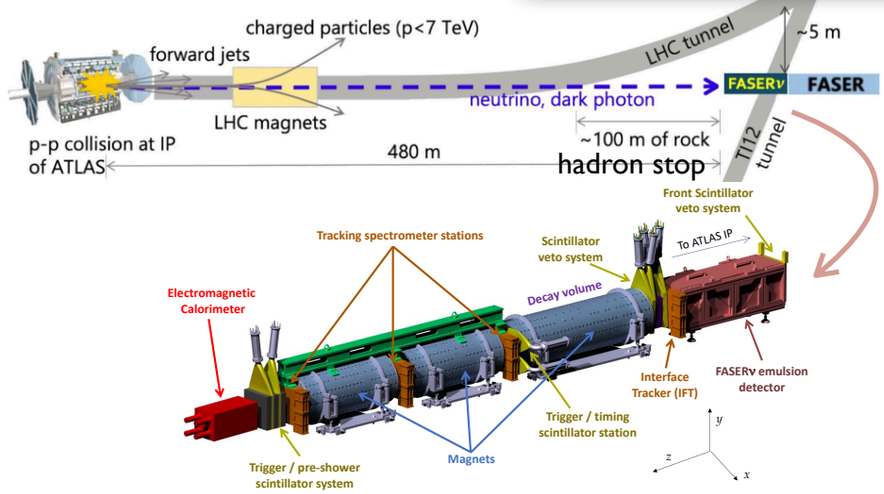
μBooNE at FNAL

- proton-beam dump, 85 ton liquid-argon Time Projection Chamber
- primarily designed for neutrino scattering measurements
- no p_T trigger limitations (reduced collider sensitivities to low masses)
- excellent particle identification
- Can target also visible decays of dark mediator
- Near future BSM prospect: search for DM produced from neutral meson decays in beams and its inelastic signatures (darkstrahlung)

Collider experiments: FASER and μBooNE



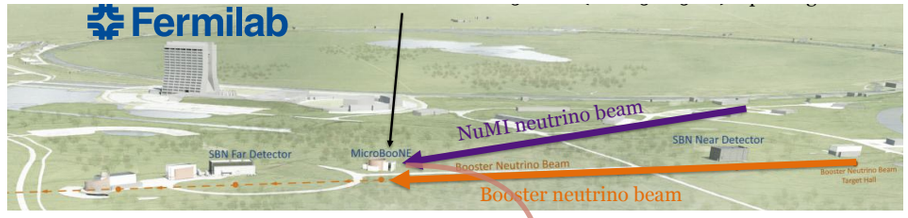
- (semi-)visible: intense beams, long decay volumes, excellent tracking
  - many current and planned exp., eg: electron-beam dump NA64 (CERN), HPS and APEX (JLab), proton-beam dump DarkQuest (FNAL), SHiP (CERN), ...



FASER at LHC

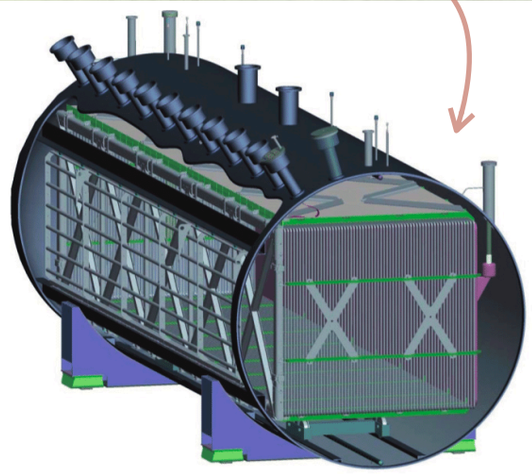
- designed for dark photons and long-lived BSM searches, detect high energy neutrinos produced in pp collisions
- located approximately 480 m from the ATLAS interaction point
- most SM particles bent away by LHC magnets or stopped by 100m rock
- Successfully operated throughout 2022: ~70 fb^{-1}

- re-scattering: intense beams or high-luminosity colliders
  - many current and planned exp., eg: electron-beam dumps BDX (JLAB), proton-beam dumps SBDN (FNAL), ...



μBooNE at FNAL

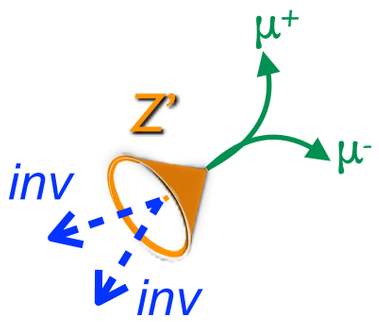
- proton-beam dump, 85 ton liquid-argon Time Projection Chamber
- primarily designed for neutrino scattering measurements
- no p_T trigger limitations (reduced collider sensitivities to low masses)
- excellent particle identification
- Can target also visible decays of dark mediator
- Near future BSM prospect: search for DM produced from neutral meson decays in beams and its inelastic signatures (darkstrahlung)



Z' (inv) with 2μ

Belle II: PRL 130(2023)

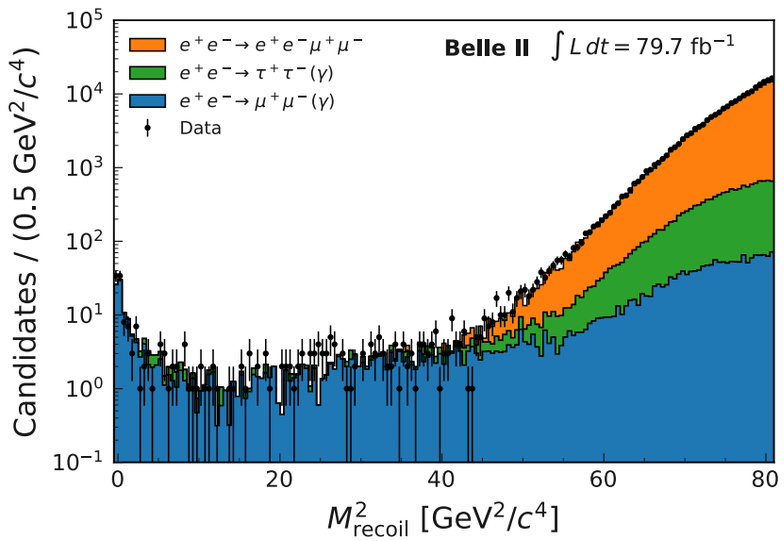
1- Selection:



- 1 opp.-sign μ pair
- negligible additional activity in the detector (eg. photon veto)
- MVA techniques to recover sensitivity
- recoil quantities from knowledge of initial-state total momentum

2- Bkg:

- ***processes with 2μ and missing energy,*** *eg.* $e^+e^- \to \mu^+\mu^-(\gamma)$, *main bkg*



3- Results: combined fit to M_{recoil}, θ_{recoil} wrt the detector axis

Upper limits at 90% CL on cross section/couplings

$L_\mu - L_\tau$ model

- new gauge boson Z' interacts only the 2nd and 3rd gen. leptons
- can address observed g-2 and rare B decays anomalies

first direct-search results excluding a fully invisible Z' as (g-2) anomaly explanation for $0.8 < M_{Z'} < 5.0$ GeV

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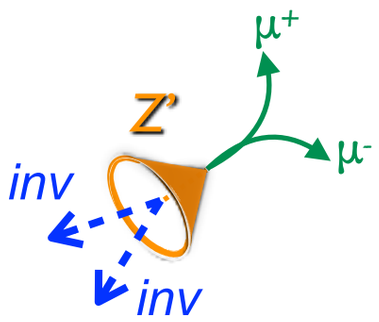

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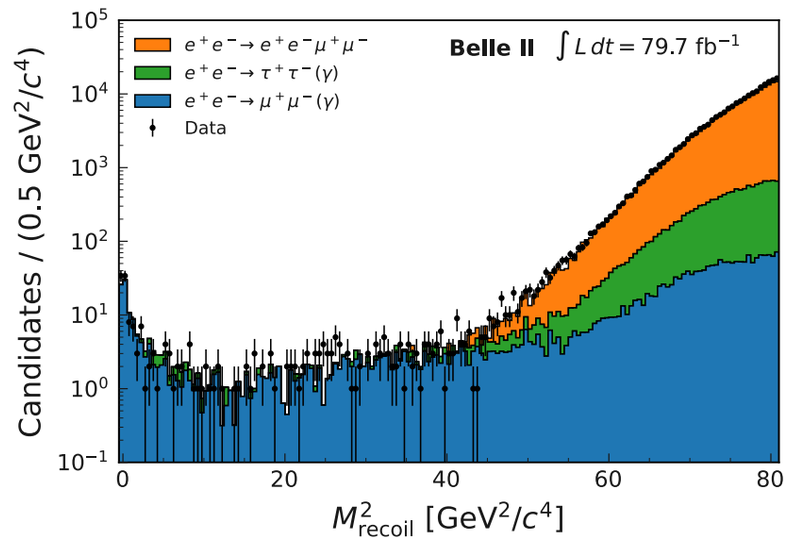

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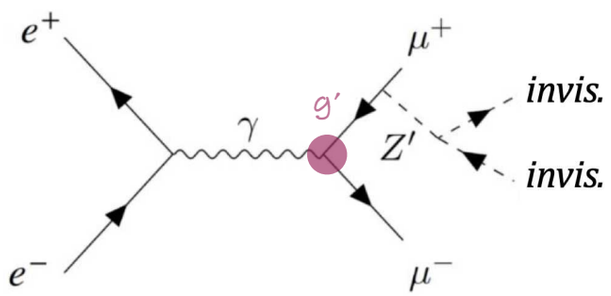
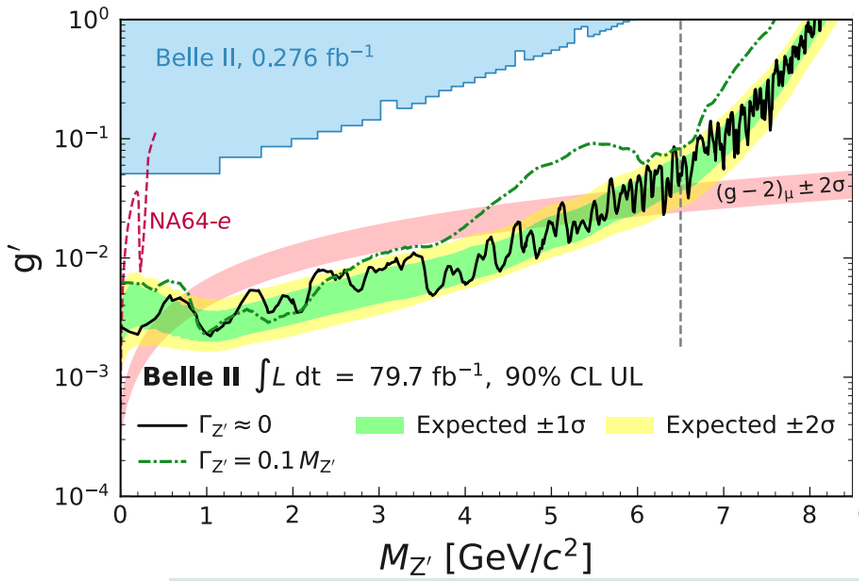
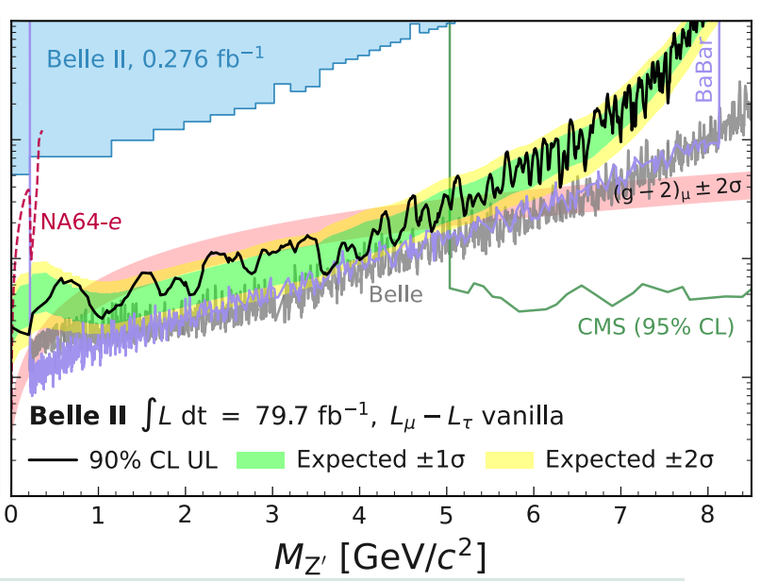


(*) fully invisible model (Z'→DMDM)



(*) vanilla model (Z'→νν)



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Search for dark photon→DM

NA64: arXiv:2307.02404

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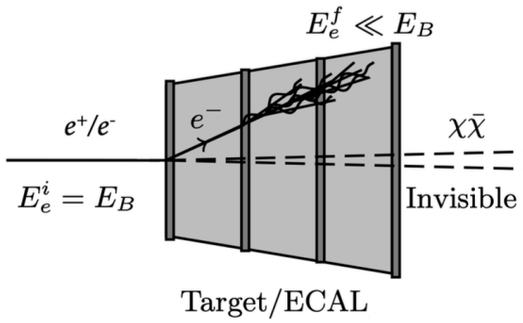
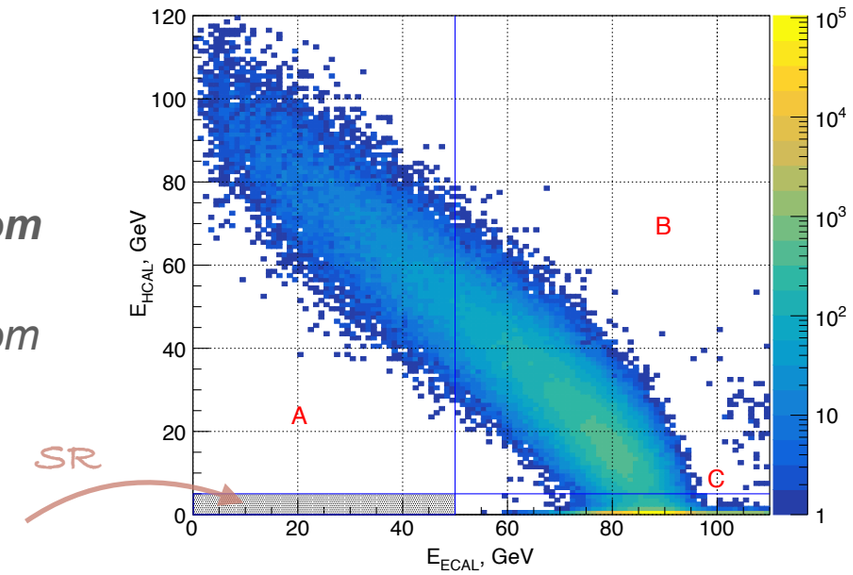


- incoming track with 100 GeV momentum
- no additional activity
- missing energy > 50GeV

2- Bkg:

- ***escaping large-angle neutrals from beam line***
  main bkg from CRs



3- Results: no data events after selection. Exclusion limits at 90% CL on dark photons mixing coefficient ε

Dark photon

- dark/SM sectors interaction through dark photon A', with kinetic mixing ε to SM and coupling α_D to DM

bremsstrahlung

annihilation

results already starting to probe the y, m_{DM} space predicted for α_D, $m_{DM}/m_{A'}$ benchmarks

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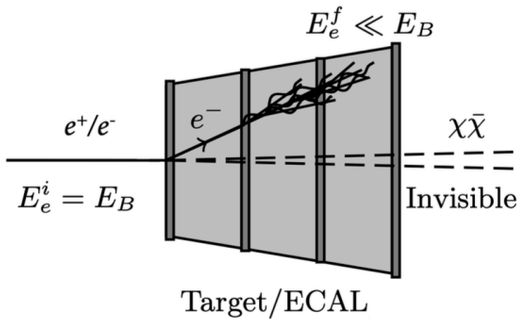

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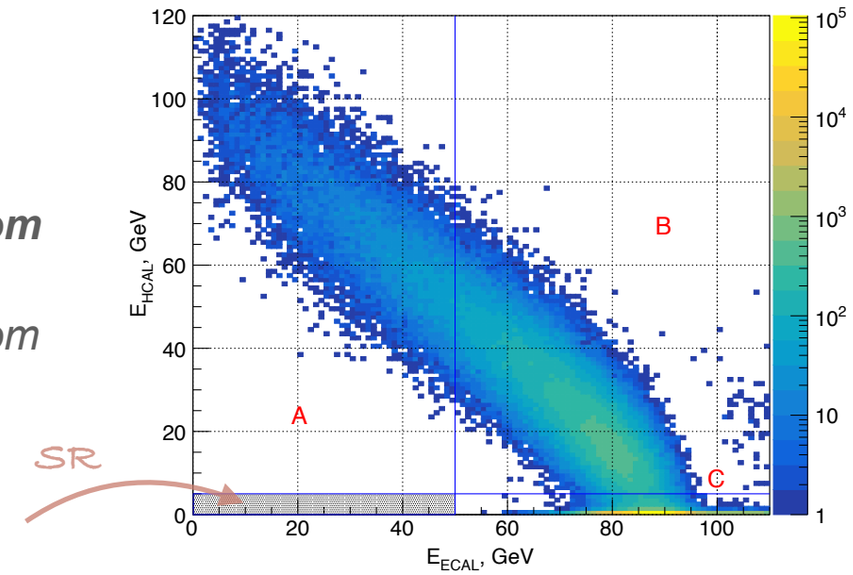

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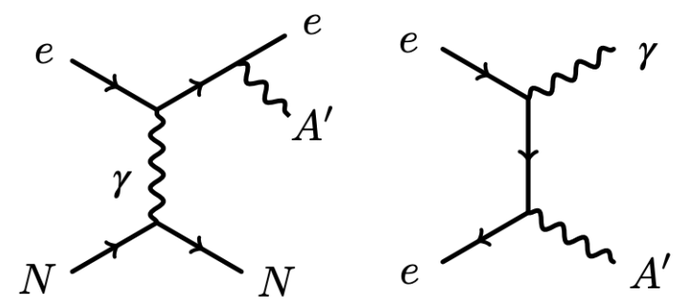

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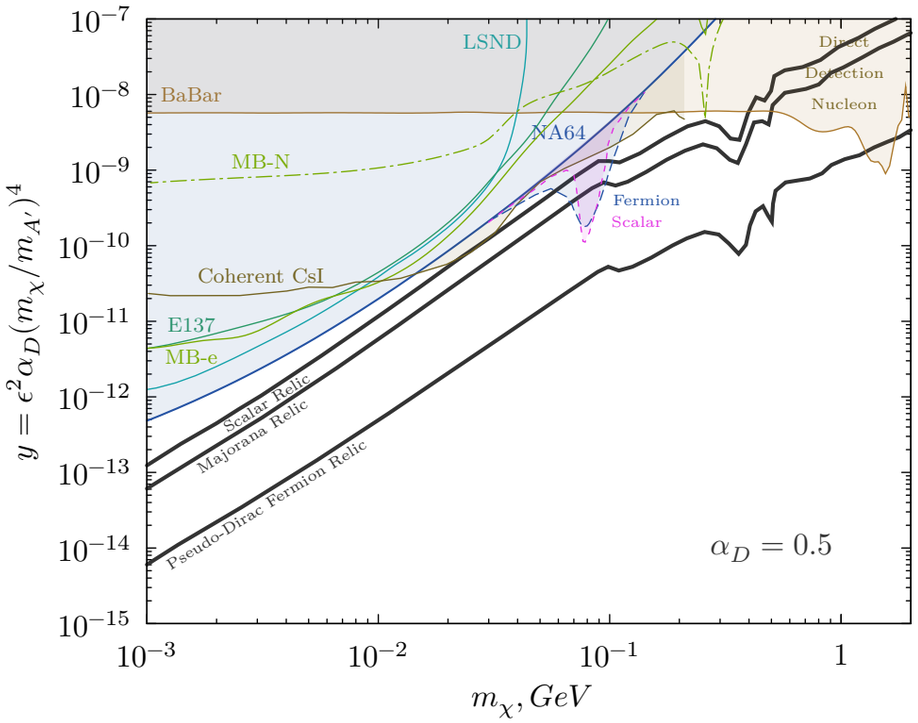

Search for dark photon → e^+e^-

FASER: arXiv:2305.08665

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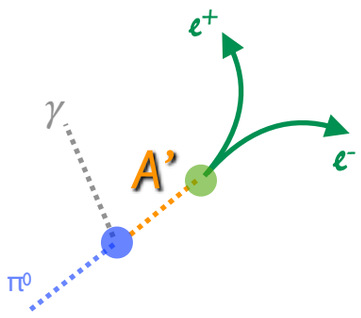
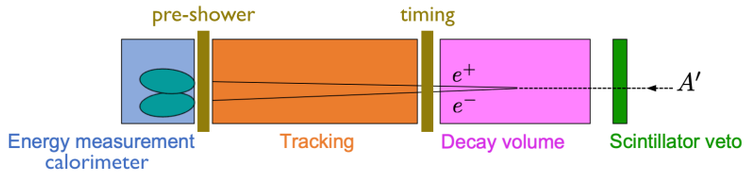
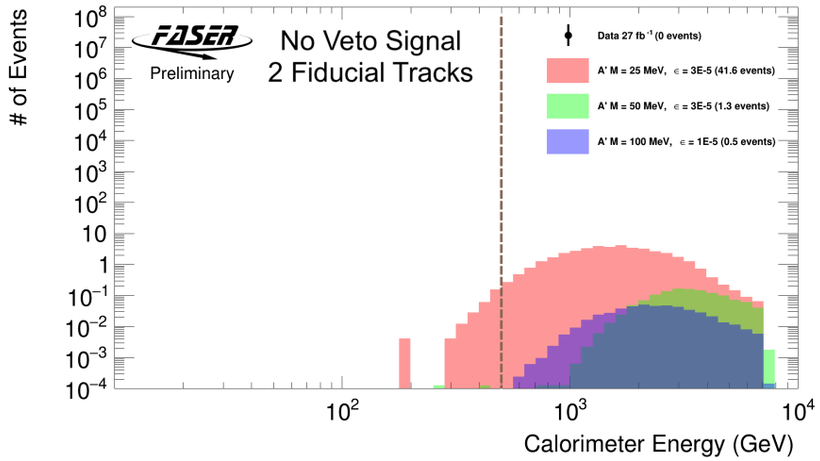


- no signal in veto scintillator
- 2 tracks in timing and pre-shower scintillators layer
- >500 GeV energy deposit in electromagnetic calorimeter



2- Bkg:

- ***ν interactions and neutral hadrons decays*** *main bkg from simulation*



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Dark photon

- dark/SM sectors interaction through dark photon A', with kinetic mixing ε

result from initial year of data-taking

FASER sensitive in cosmologically interesting region for dark photons coupling to complex scalar DM

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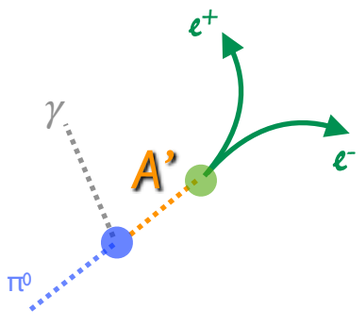

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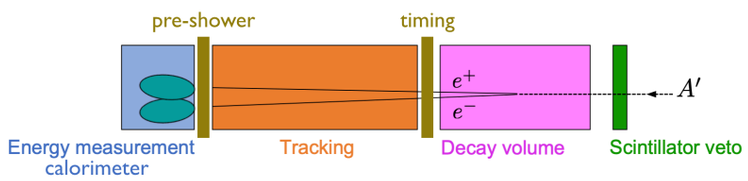

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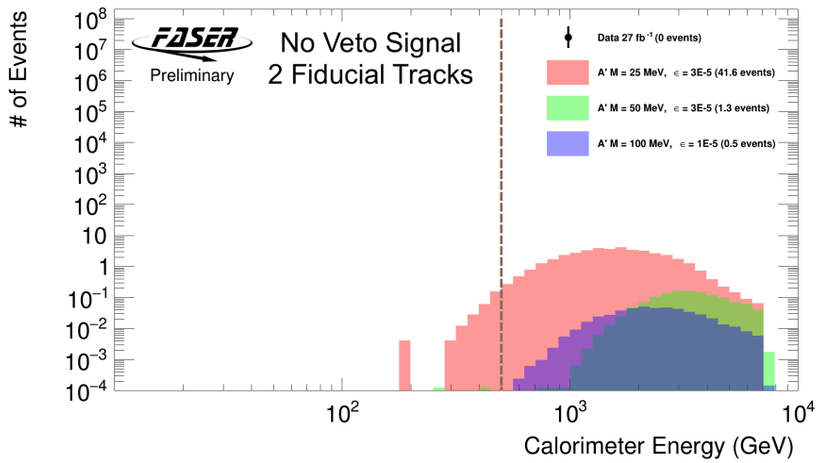

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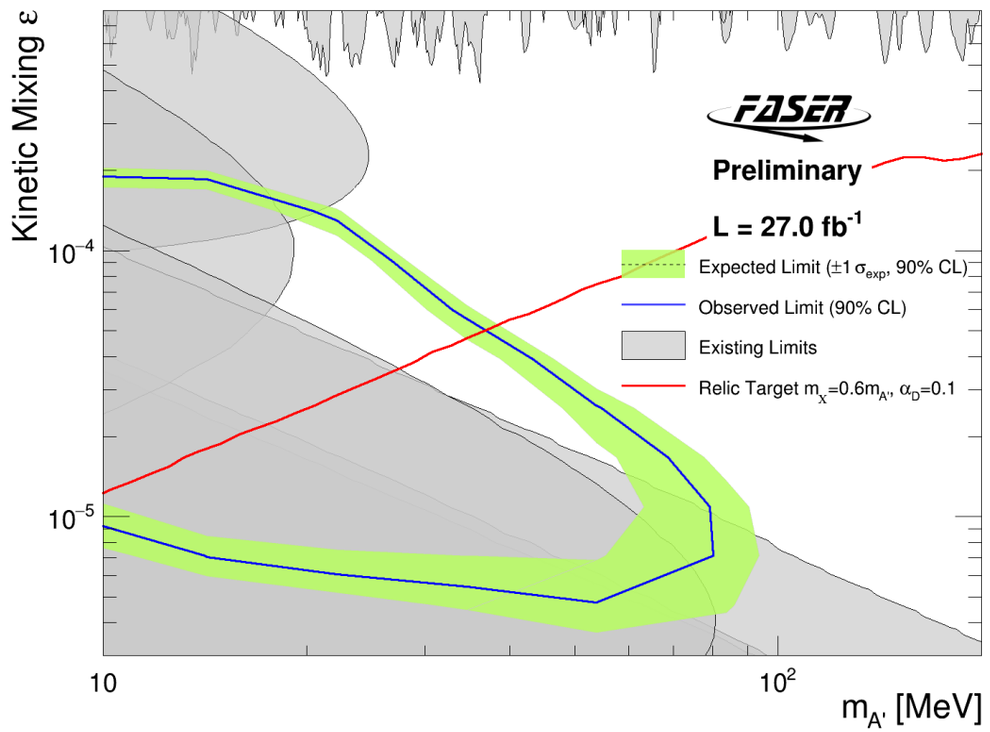

Dark Higgs → e^+e^-

μBooNE: PRL127.151803

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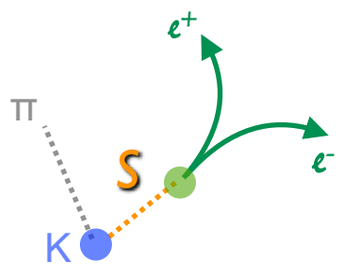
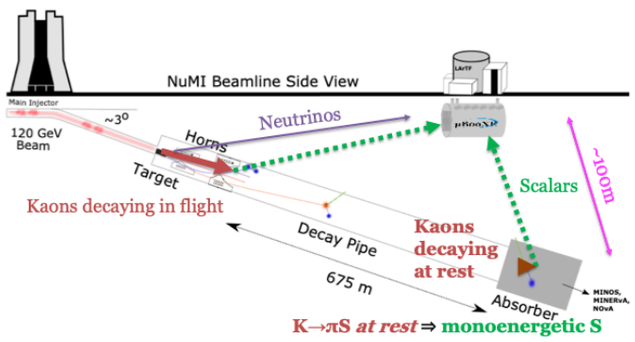


- e^+e^- pairs, with large opening angle, in time with beam
- MVA techniques for selection



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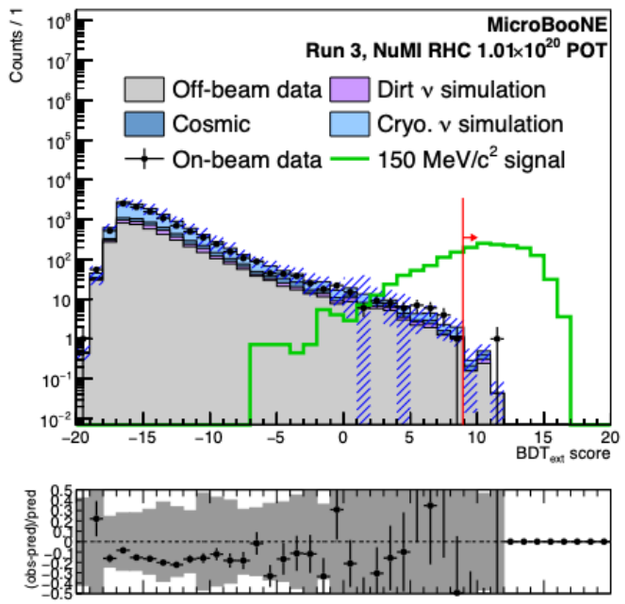

3- Results: counting experiment. Upper limits at 95% CL on Higgs portal couplings

Dark-Higgs model

- new scalar S mixes with Higgs boson with mixing angle θ
- if $2m_e<m_S<2m_\mu$, and $m_S<m_{DM}$ S decay to electron-positron

most constraining for m_S=[120-160] GeV

2015-2016 and 2017- 2018 dat-taking

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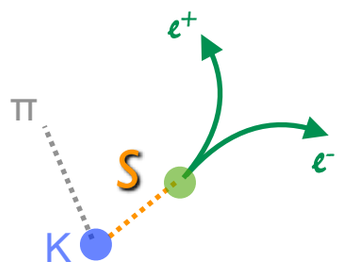

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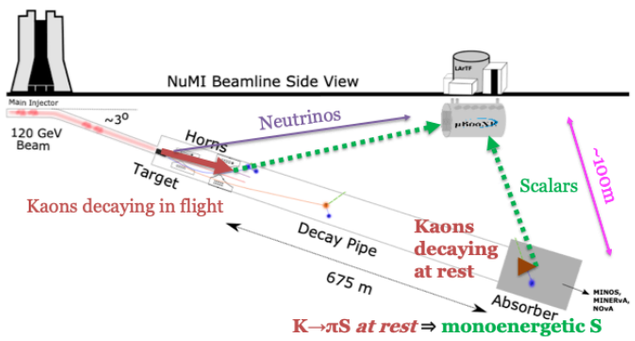

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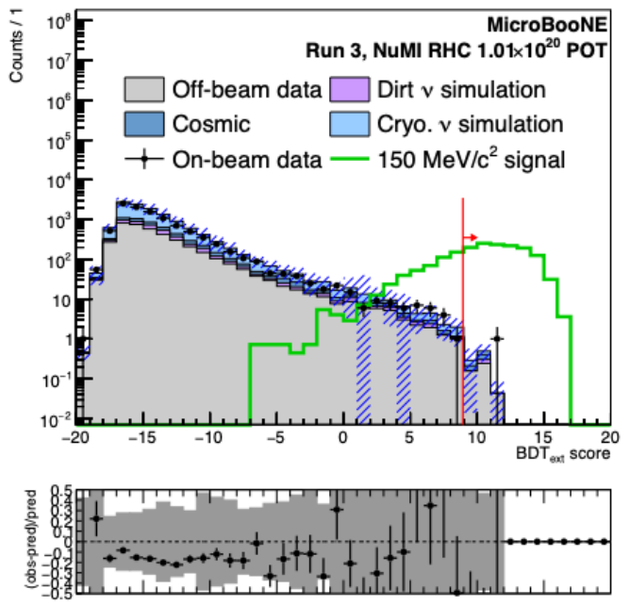

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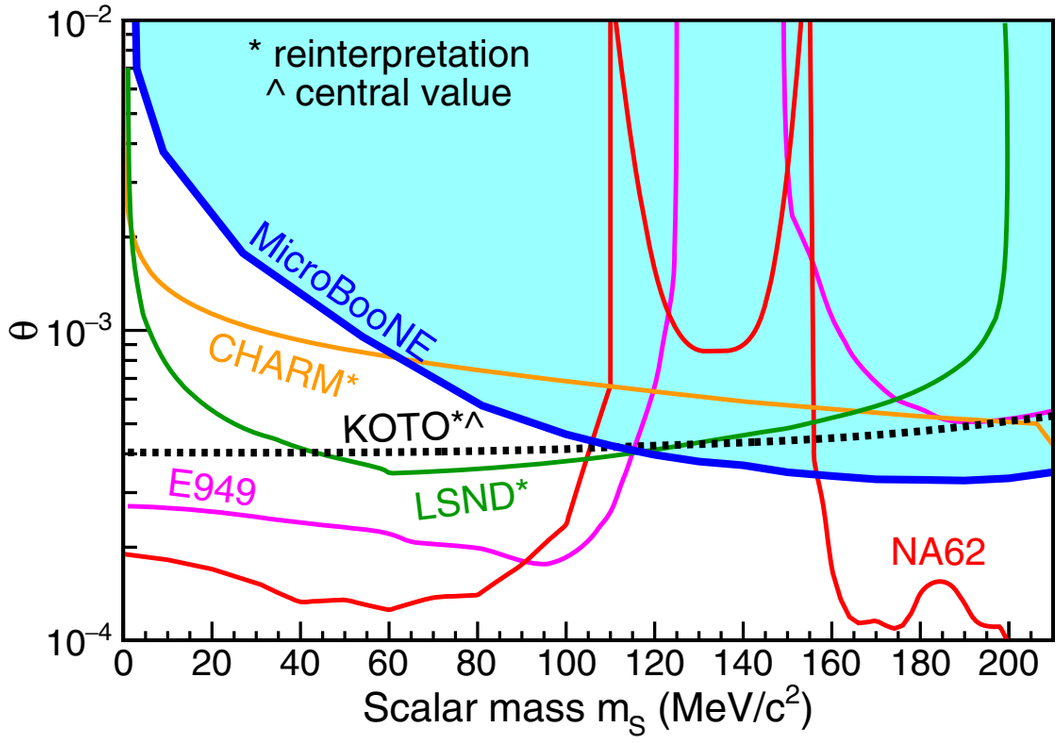
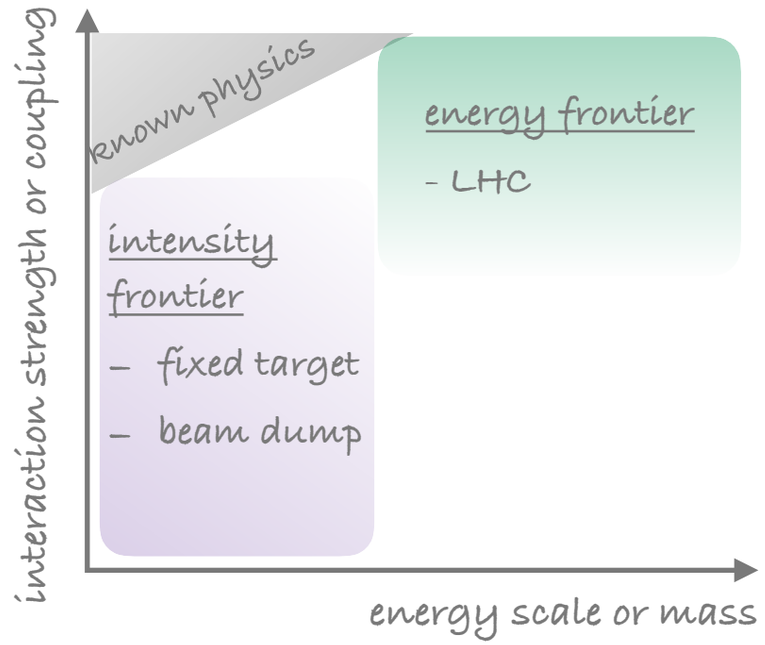


Complementarity to discover DM

- luminosity: determines size of coupling that can be probed
- energy: determines probed mass range
- invisible/visible: directly probe DM or explore mediator



- Complementarity:
  - results often presented in terms of different mediator masses, notation and model assumptions
  - concerted effort to align models, representation to exploit complementary between energy- and intensity-frontiers to discover DM/dark-sector

- Complementarity with direct-detection also essential:
  - accelerator-based directly characterize particle properties of produced DM, explore relativistic DM production
  - direct detection explores a combination of DM properties with their cosmological abundance, probe non-relativistic scattering

– different type of interactions can be suppressed or enhanced based on velocity → complementarity

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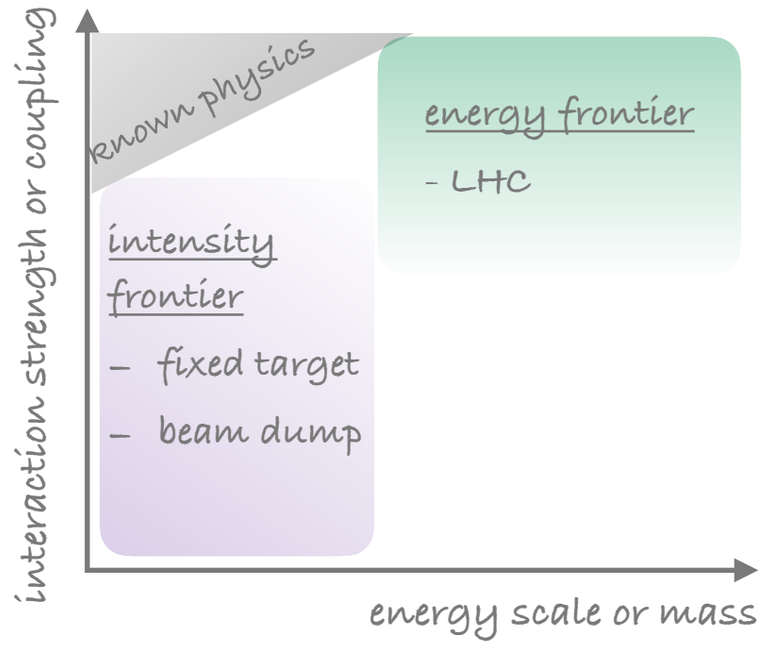

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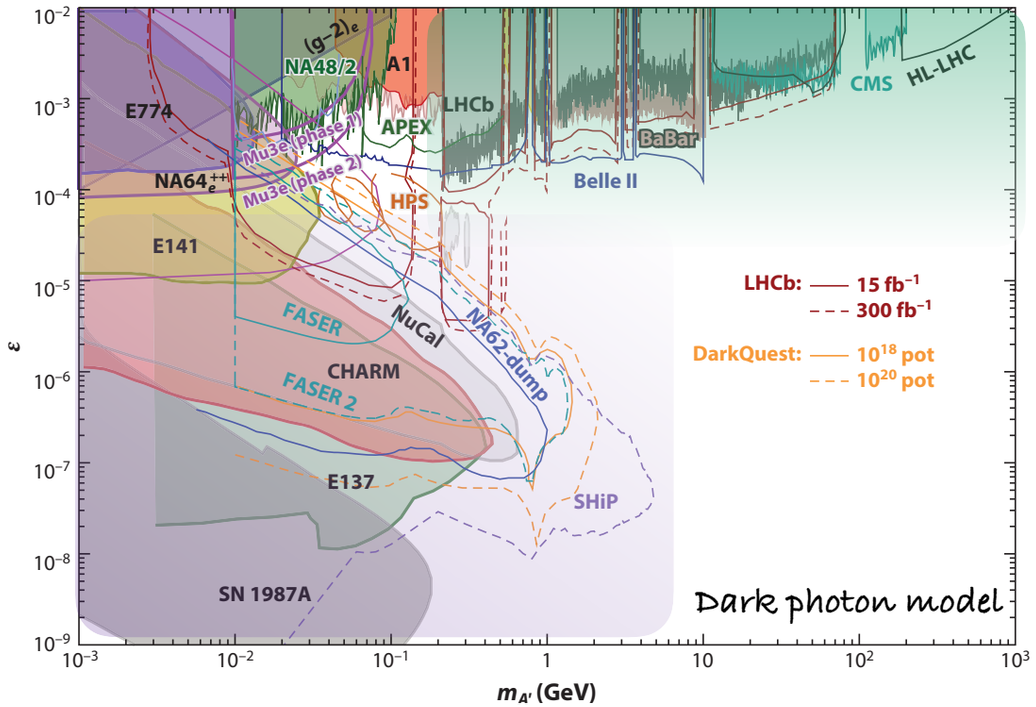

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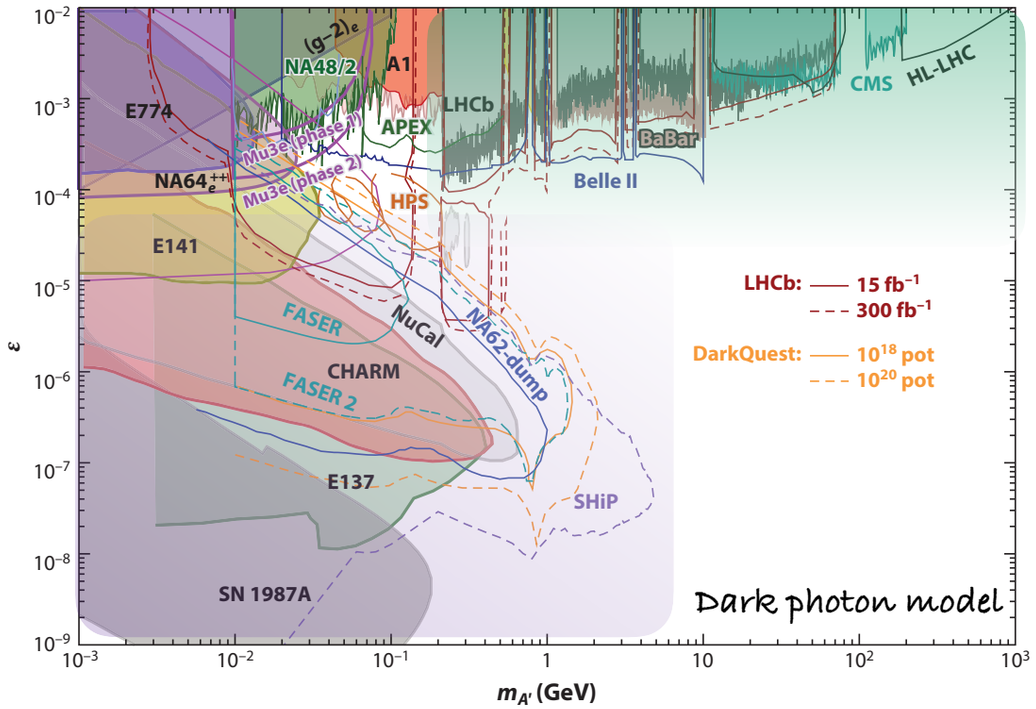

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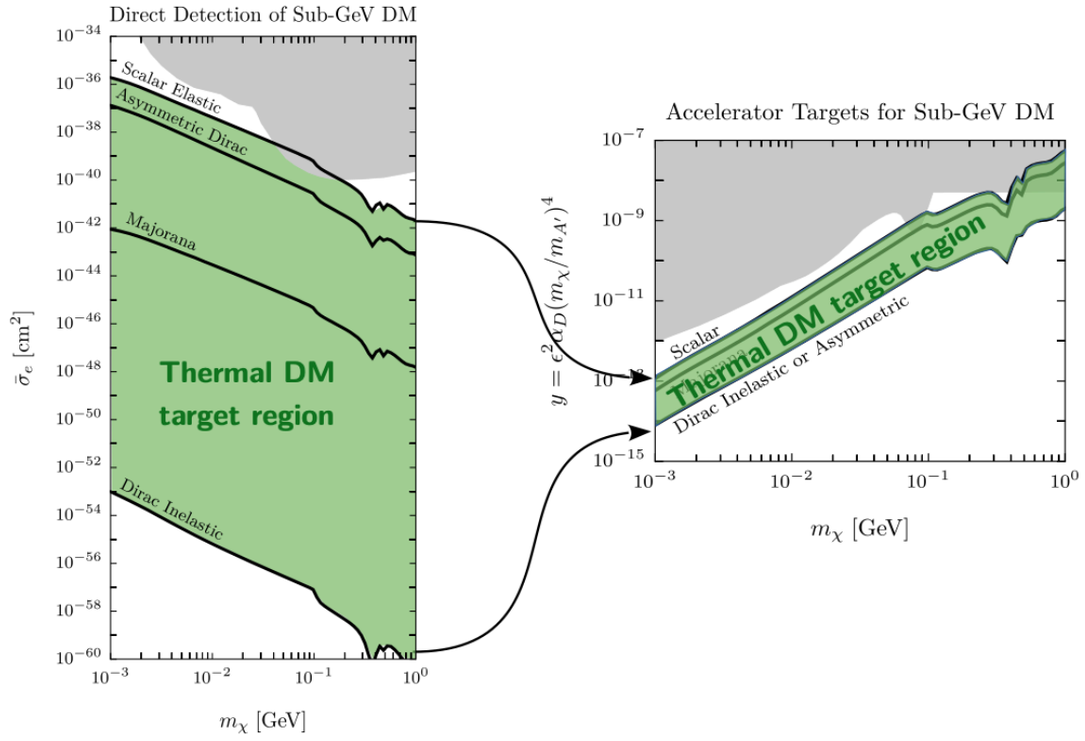

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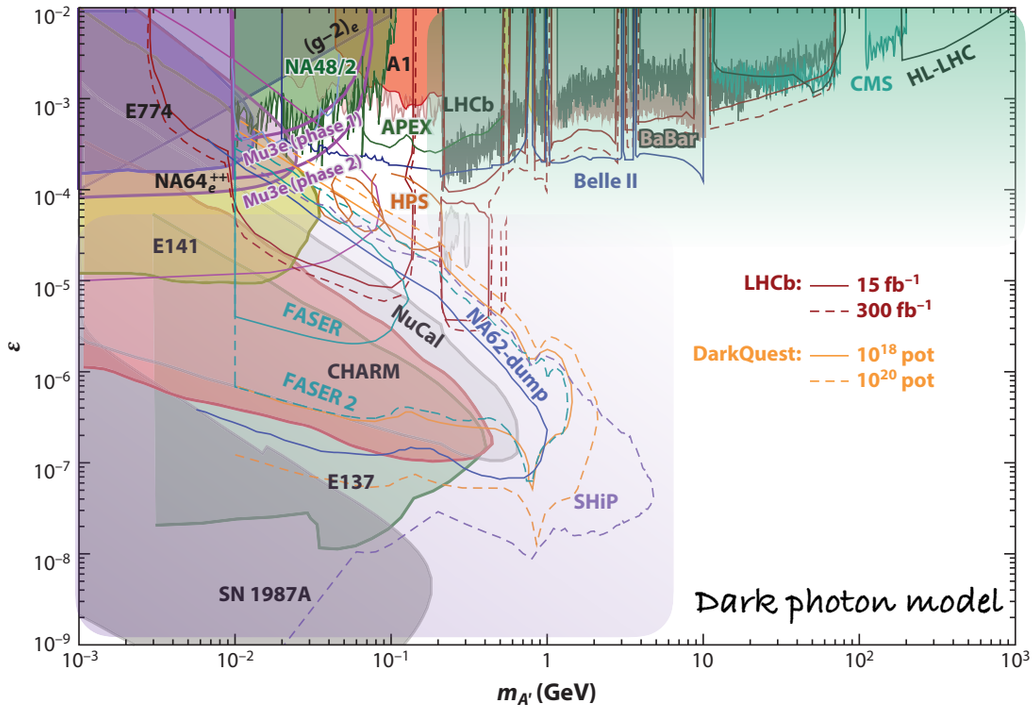

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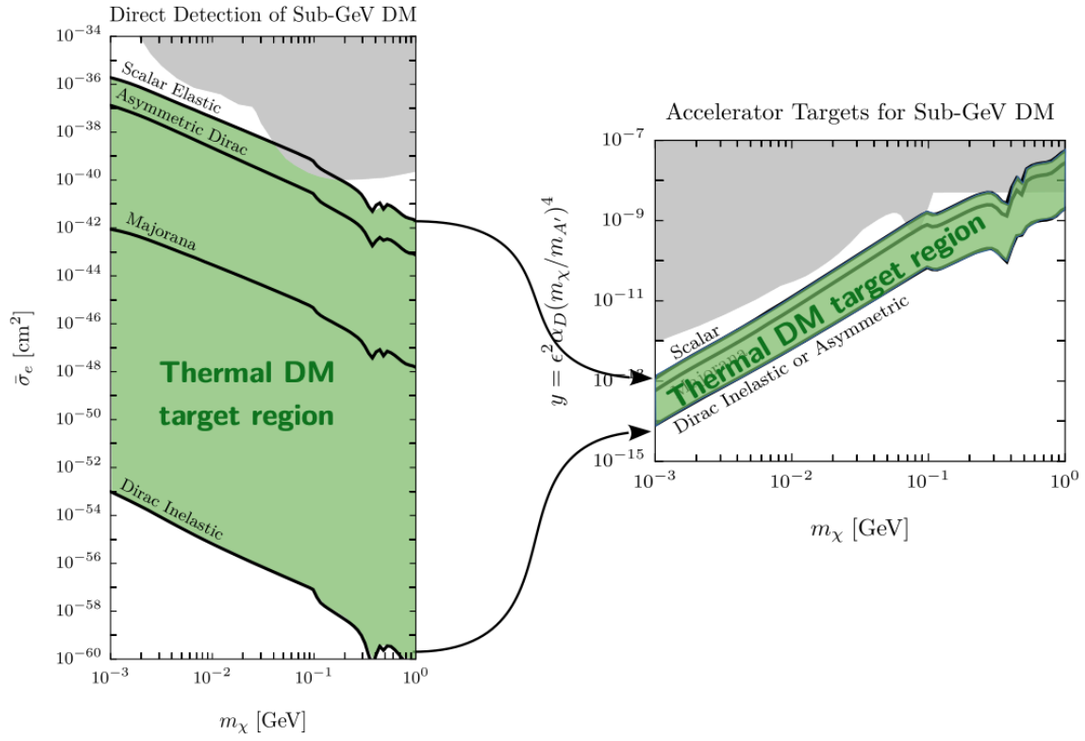

Important to identify common benchmarks to better exploit complementarity

Summary

assume interaction with SM

DM nature
(large region of parameter space of DM models excluded)

DM/dark-sector production

different interactions/signature investigated

benchmark models to interpret the results

- Rich DM physics program at high-energy and high-intensity experiments
  - essential complementarity among experiments and with non-collider searches
  - inputs from various signatures (mono-X, resonances, H→inv, visible, …)
- Many new results/experiments expected in the near future!

Summary

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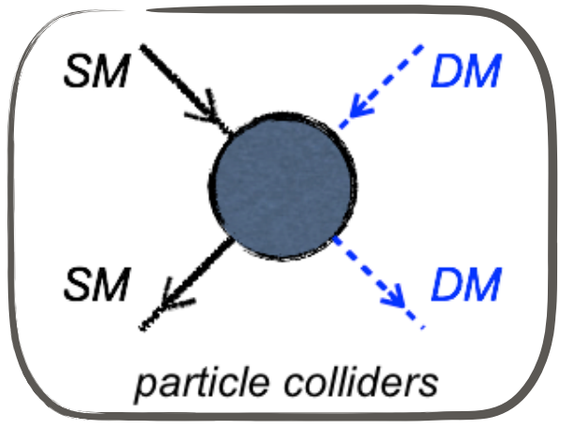
DM/dark-sector production



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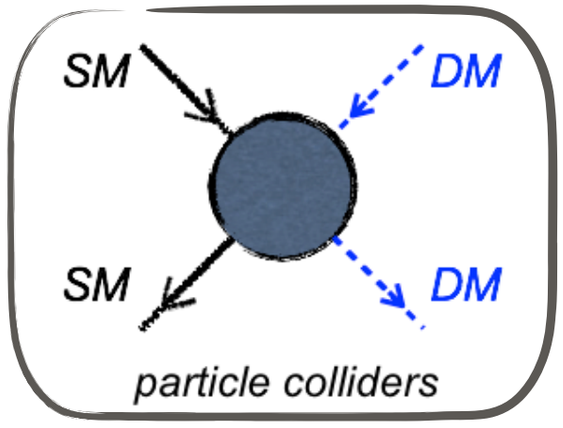

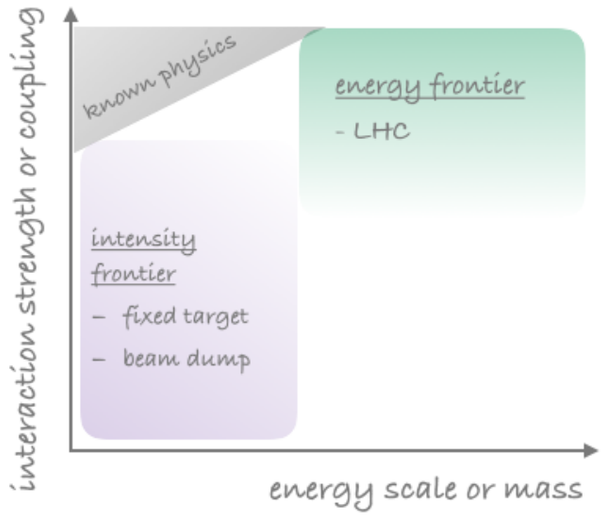

different interactions/signature investigated

benchmark models to interpret the results

- Rich DM physics program at high-energy and high-intensity experiments
  - essential complementarity among experiments and with non-collider searches
  - inputs from various signatures (mono-X, resonances, H→inv, visible, …)
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Summary

DM nature
(large region of parameter space of DM models excluded)

assume interaction with SM

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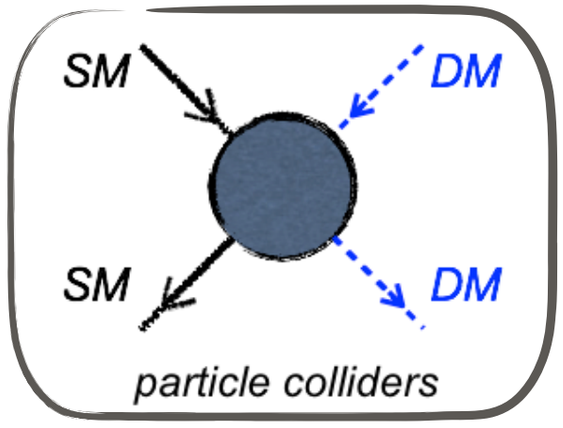

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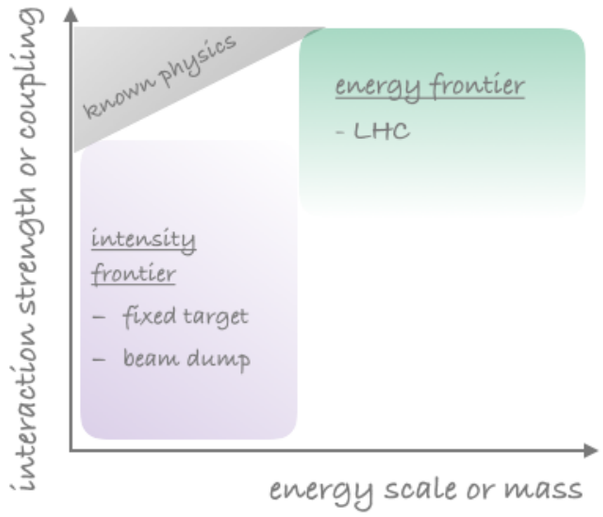

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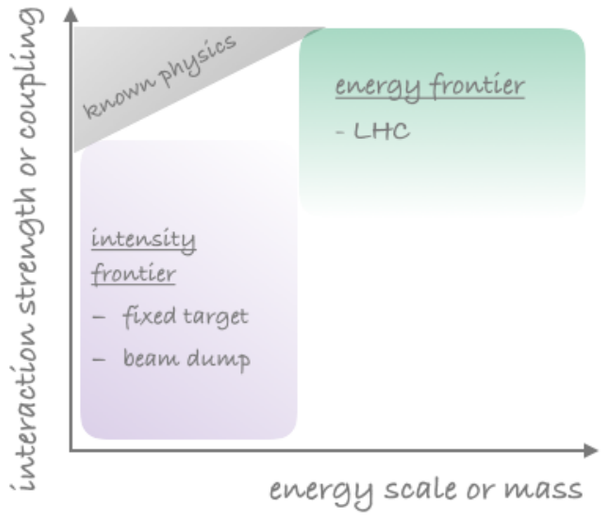

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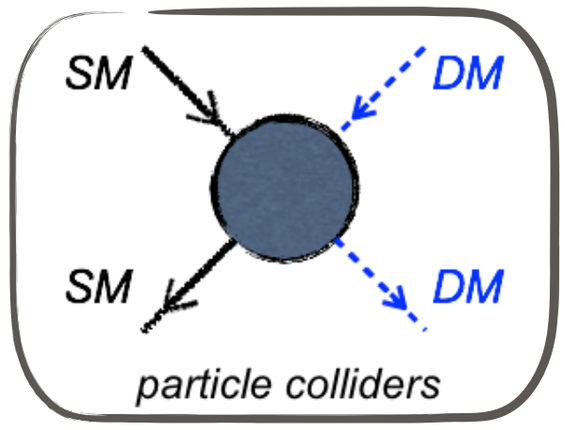

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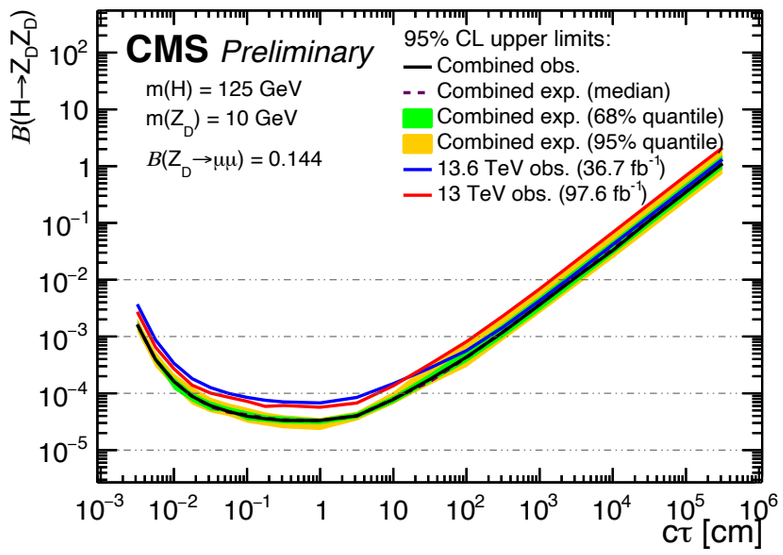
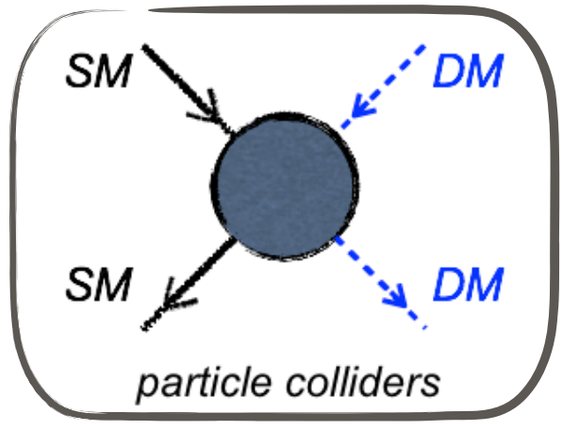


CMS new data result for LLP made in Vienna (HEPHY group) :)

DM/dark-sector production



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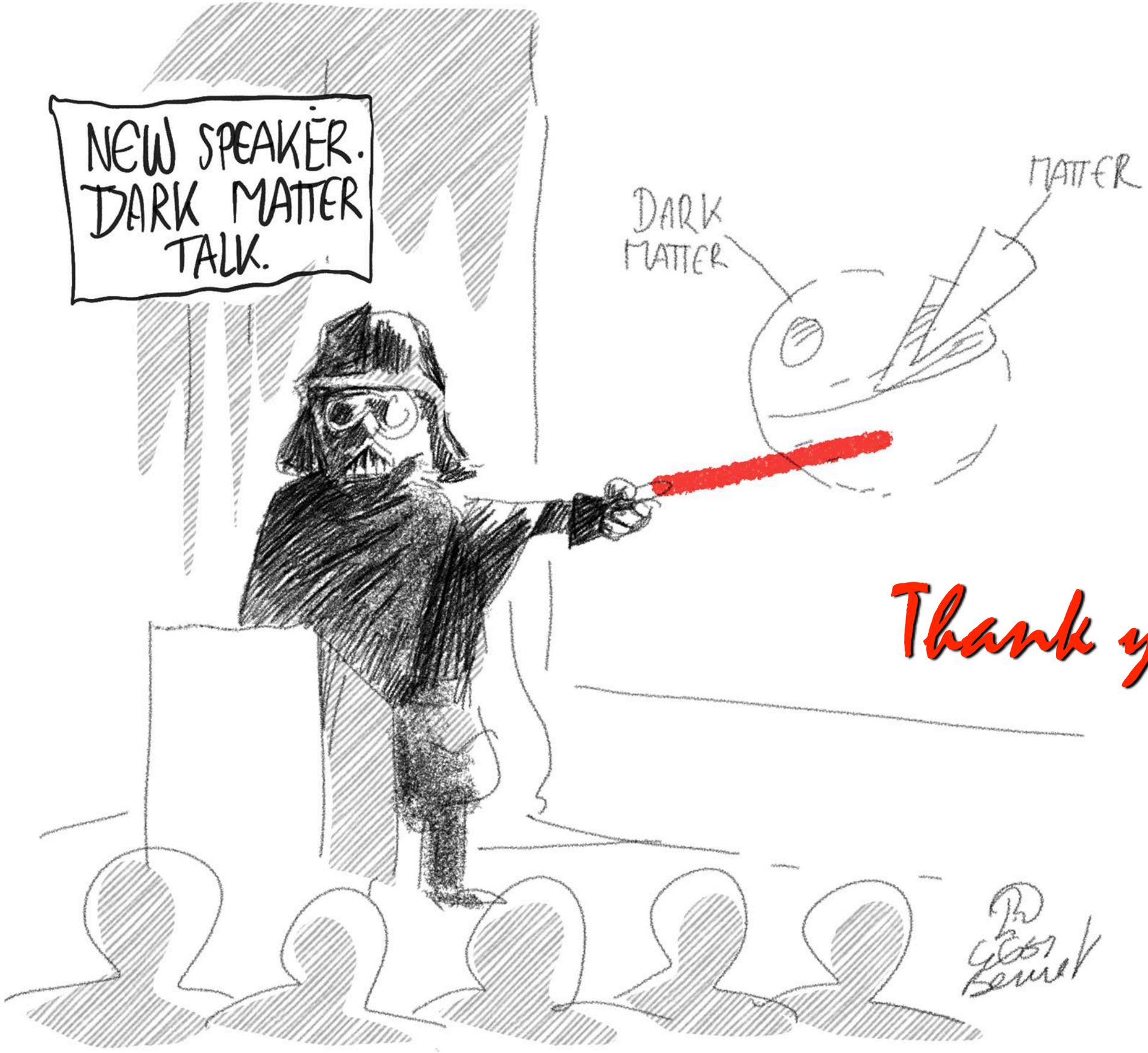
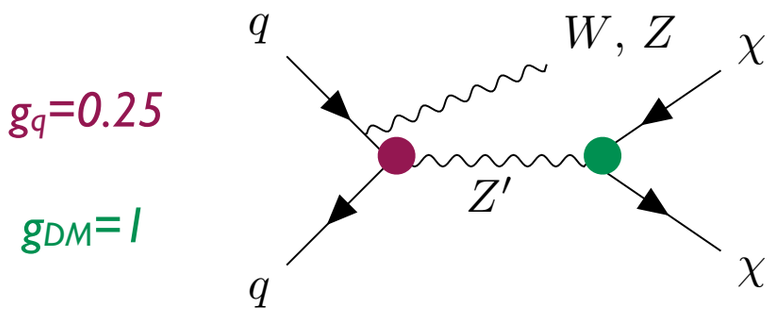


Thank you!

Backup

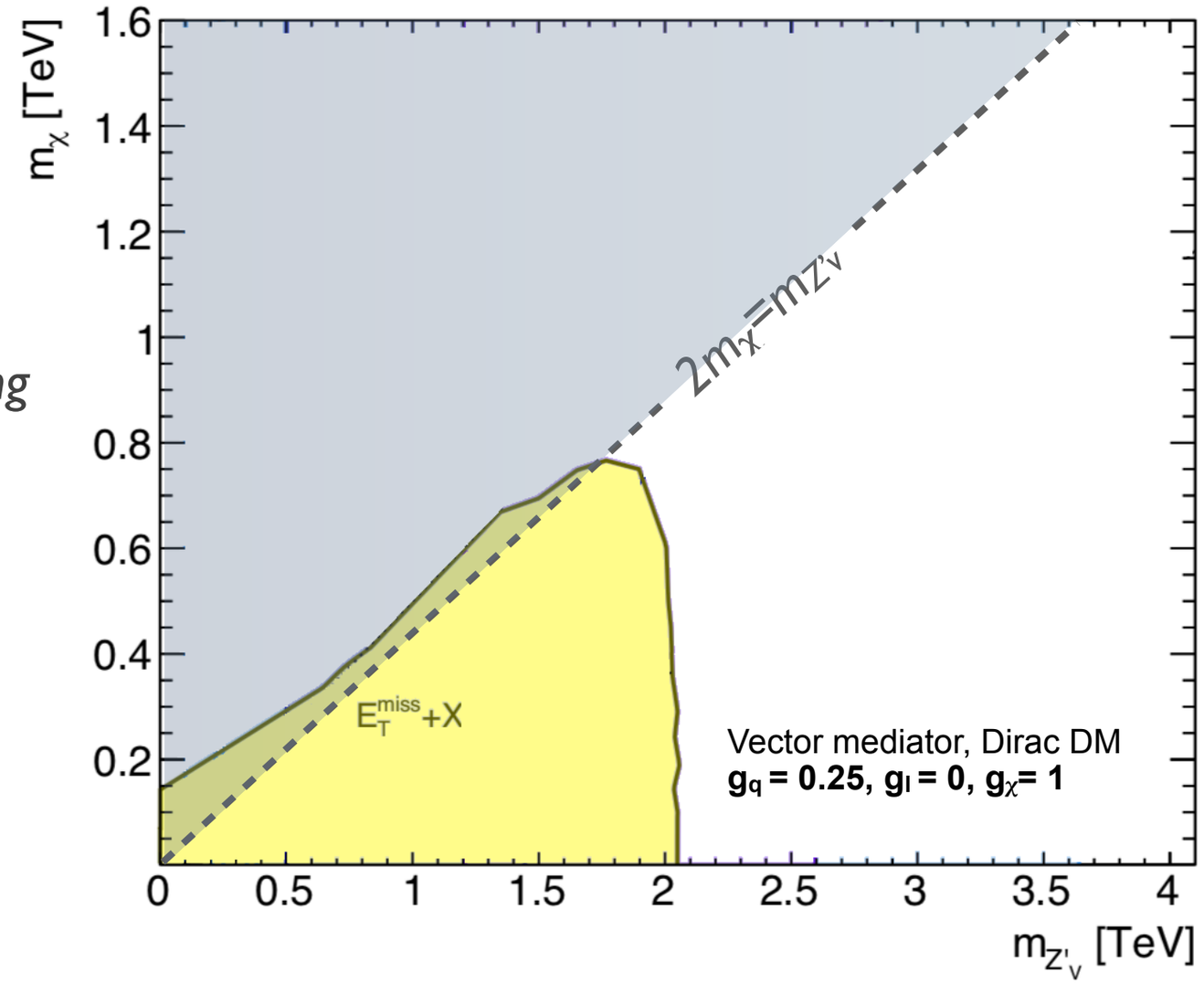
The invisible through the visible

Simplified vector model



- *low sensitivity to off-shell region due to strong reduction of production cross-section*
- *Can we recover the sensitivity?*

✱ *ATLAS:ATL-PHYS-PUB-2023-018*



✱ *also ATLAS 2HSM+a combination: arXiv:2306.00641*

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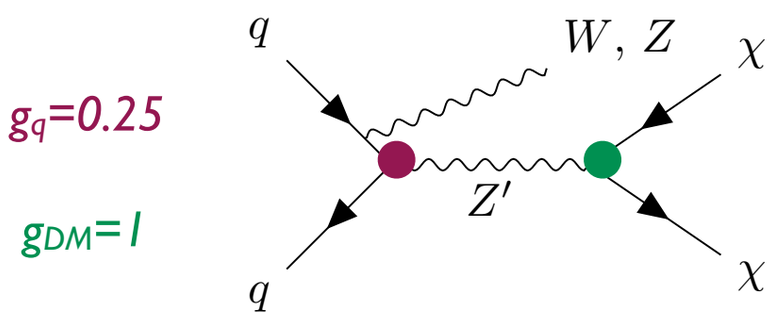

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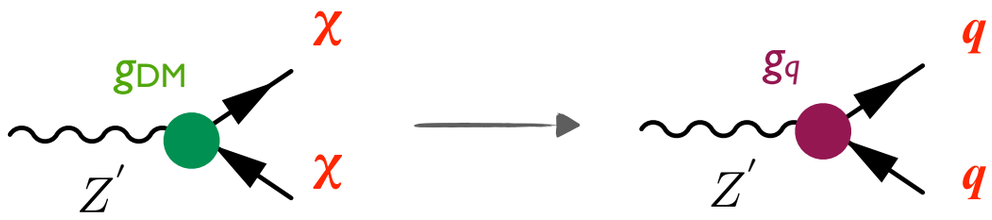
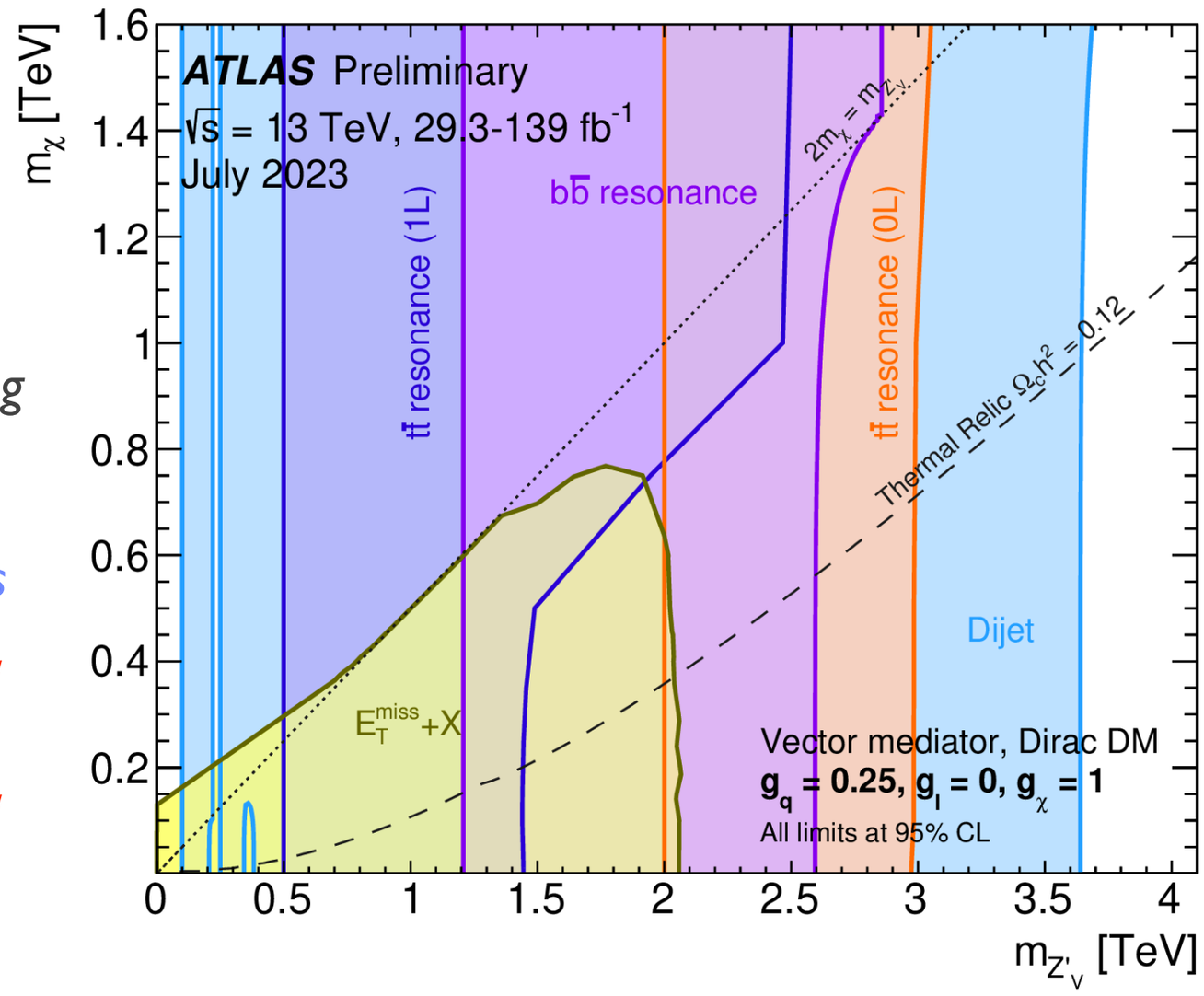


g_q=
- ✱ *mediator*
  - *narrow resonance*
  - *wide resonance*

✱ *ATLAS:ATL-PHYS-PUB-2023-018*

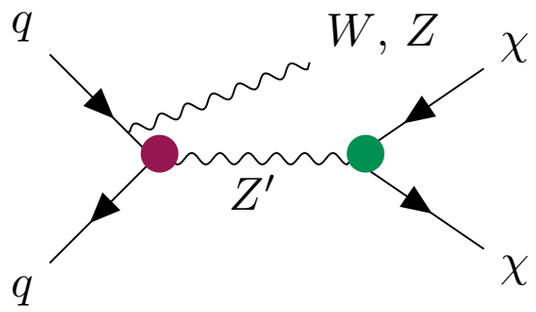


The invisible through the visible

Simplified vector model

g_q=0.25

g_{DM}= 1



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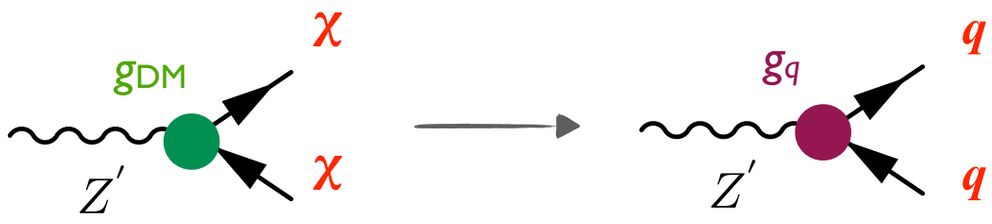
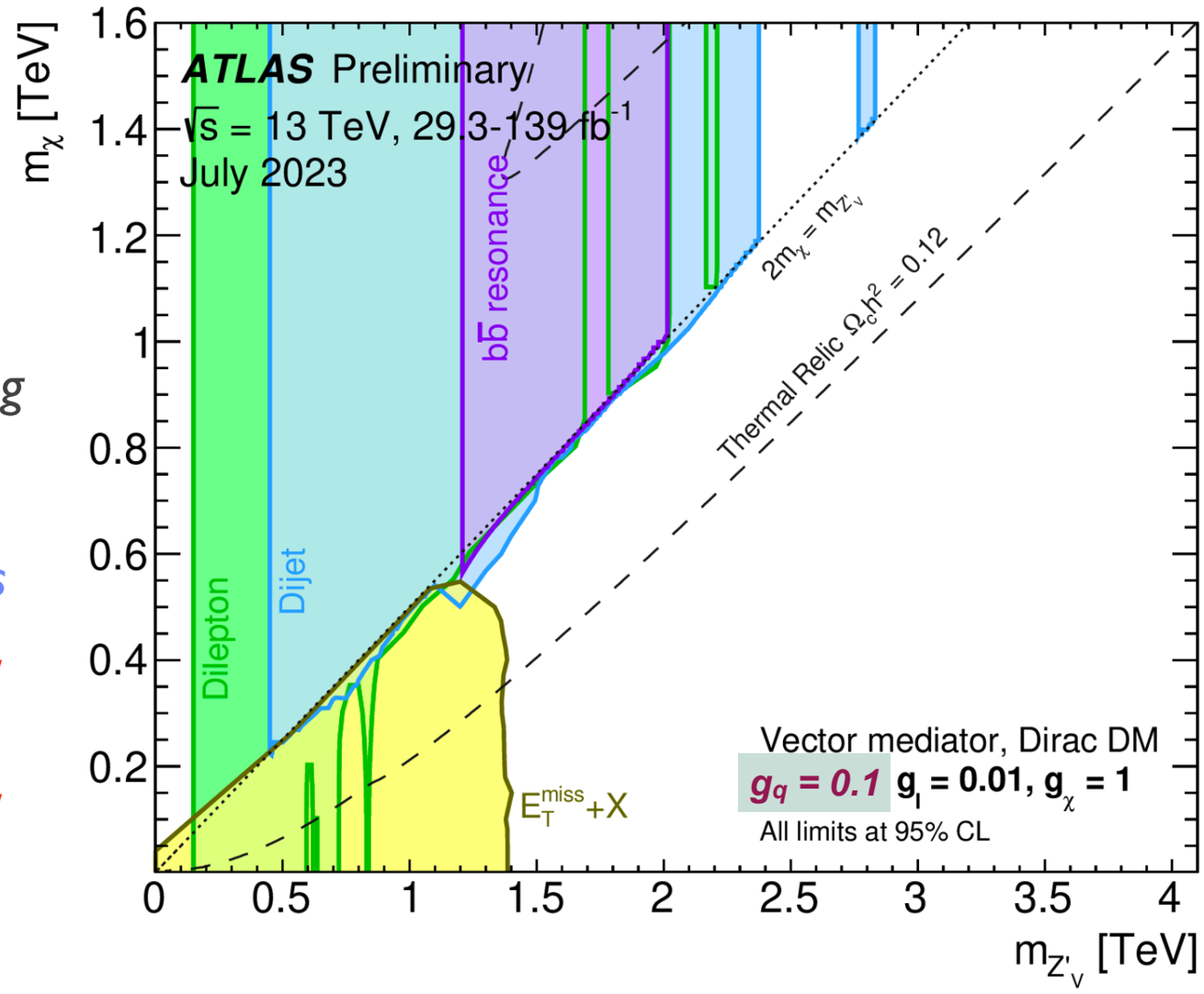


g_q=

- ✱ *mediator*
  - *narrow resonance*
  - *wide resonance*
- ✱ *interplay changes*

✱ ATLAS:ATL-PHYS-PUB-2023-018



Di-muon low-mass resonances

CMS: EXO-21-005

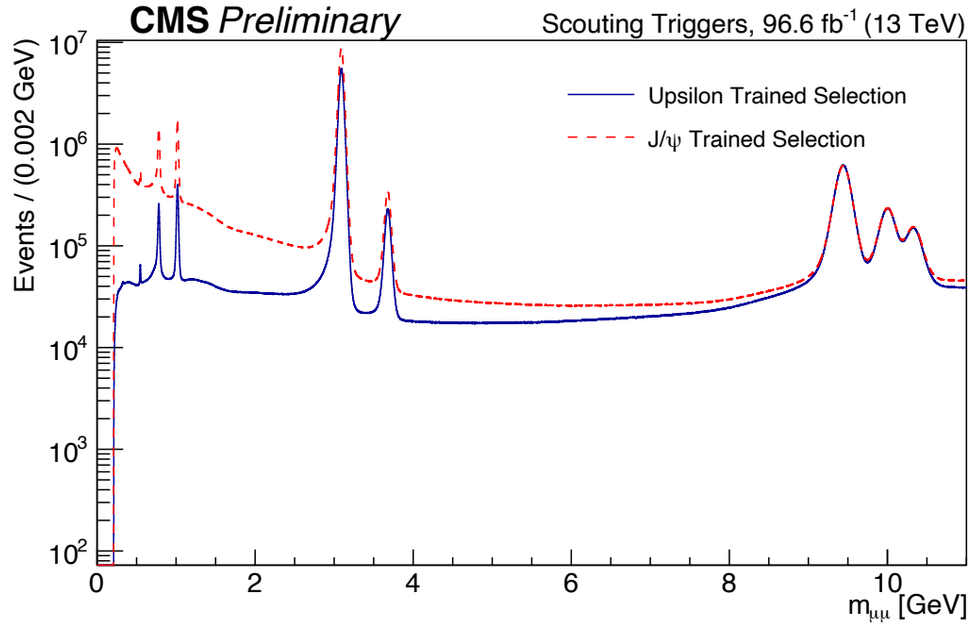
1 - Selection: resonance appears as peak wrt SM invariant mass

- 1 opp.-sign μ pair, categories on $p_T(\mu\mu)$
  - dedicated $\mu\mu$ trigger: low p_T thresholds, high rate, retain only 4-momentum, isolation, track information
  - muon identification based on MVA techniques

2 - Bkg:

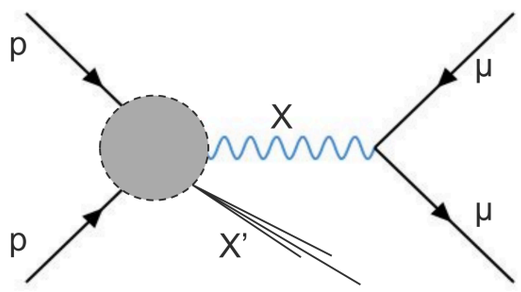
- known resonances, D meson decays to kaons (from CR)

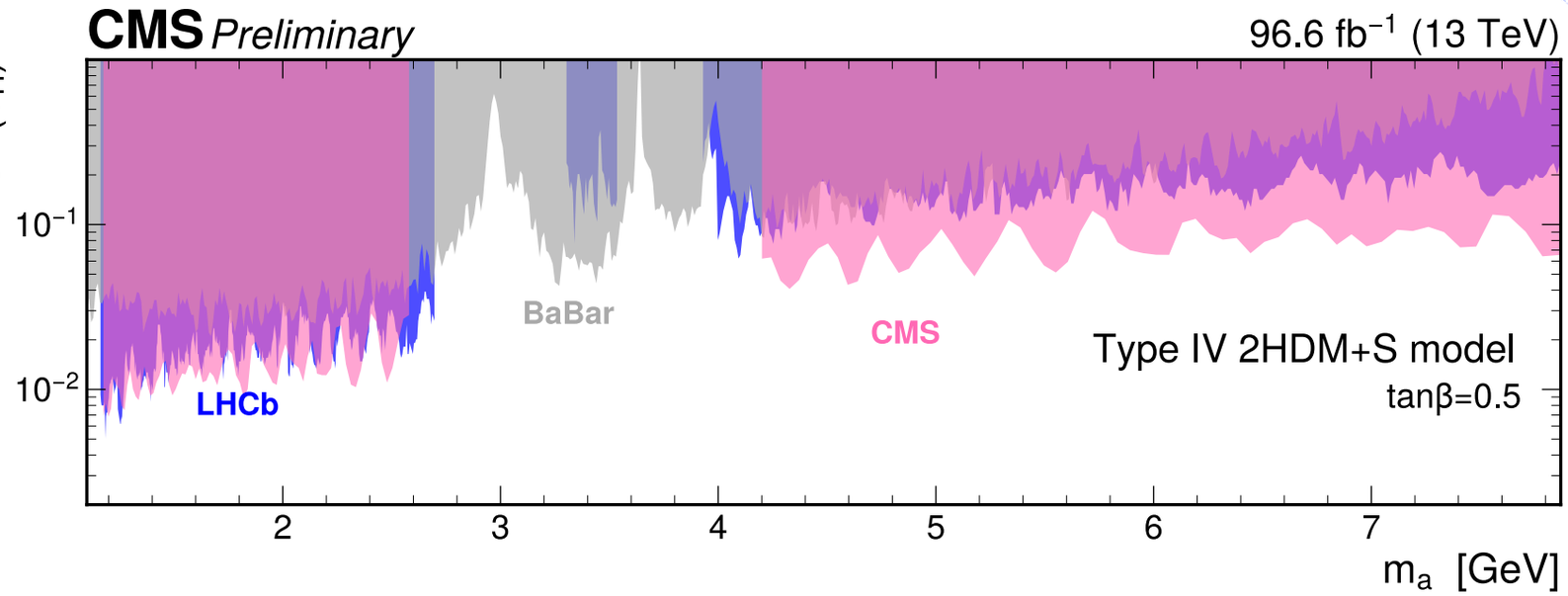
3- Results: fit to $\mu\mu$ invariant mass, upper limits at 90% CL on mixing coefficient ε



2HSM+a

- pseudoscalar a, couplings to SM through mixing with Higgs doublets (θ_H, tanβ)





Similar (higher) sensitivity as LHCb at low(high) masses