Course on Physics at the LHC

Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV

A. M. Sirunyan *et al.* [CMS Collaboration], JHEP **1903** (2019) 141

[arXiv: 1901.01553 [hep-ex]]

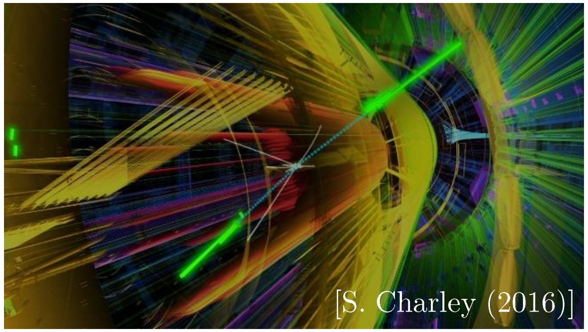
Débora Barreiros

June 28, 2019

Outline

[D. Clowe *et al.* (2006)]

[M. Hoch, M. Brice, CERN]



[S. Charley (2016)]

Introduction

- Particle Dark Matter candidates
- WIMP detection
- Collider searches

Search theoretical framework

CMS detector

Event reconstruction

Data sample and simulation

Event selection

Systematic uncertainties

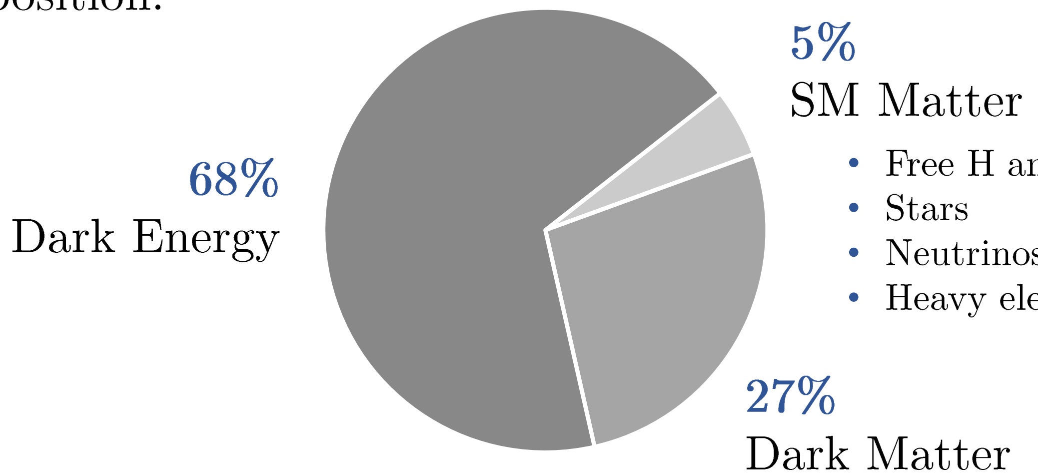
Signal extraction

Results

Summary

Dark Matter

Universe composition:



- Free H and He
- Stars
- Neutrinos
- Heavy elements

Dark Matter

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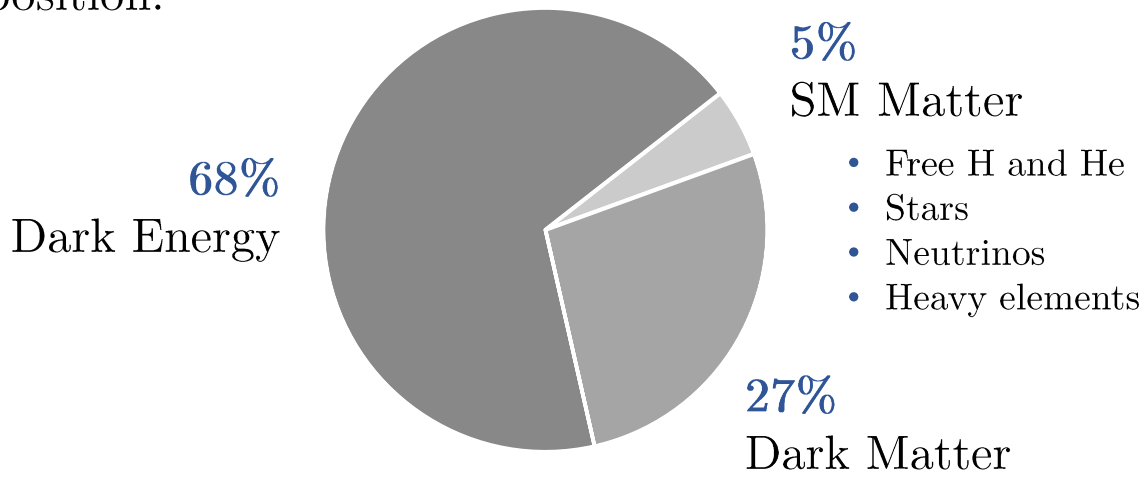

What do we know?

Stable, non-baryonic, cold/warm, collisionless, not charged under strong or electromagnetic forces, interacts weakly or very weakly with SM particles, has a relic abundance of $\Omega_{\rm DM} h^2 = 0.1186$

Dark Matter

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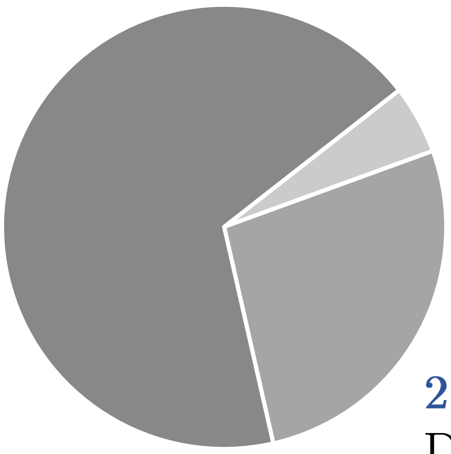

68%
Dark Energy

5%
SM Matter

- Free H and He
- Stars
- Neutrinos
- Heavy elements

27%
Dark Matter

Astrophysical observations →

- Galactic rotation curves
- Gravitational lensing
- LSS formation
- BBN data
- CMB radiation

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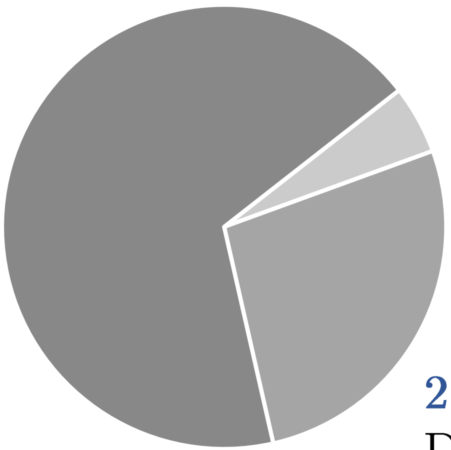

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What is missing?

Dark Matter nature

Dark Matter

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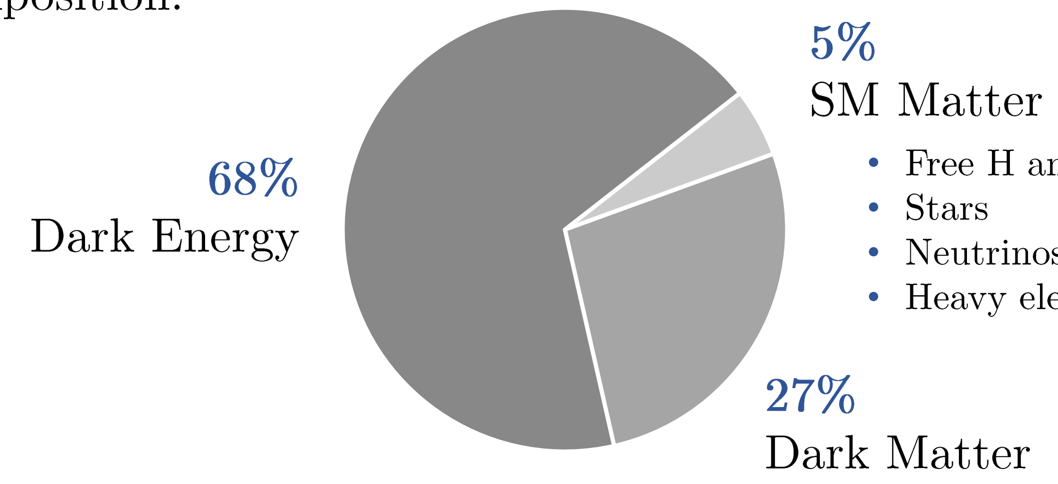

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Astrophysical observations → **What do we know?**

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$$\Omega_{\mathrm{DM}} h^2 = 0.1186$$

Direct detection
Indirect detection
Collider searches → **What is missing?**

Dark Matter nature

Particle Dark Matter candidates

Constraints for DM particle candidates: [G. Arcadi *et al.* (2018)]

- Must be non-baryonic
- Reproduce the correct relic abundance
- Should be cold ($v < 0.1c$) or warm ($0.1c < v < 0.95c$) DM
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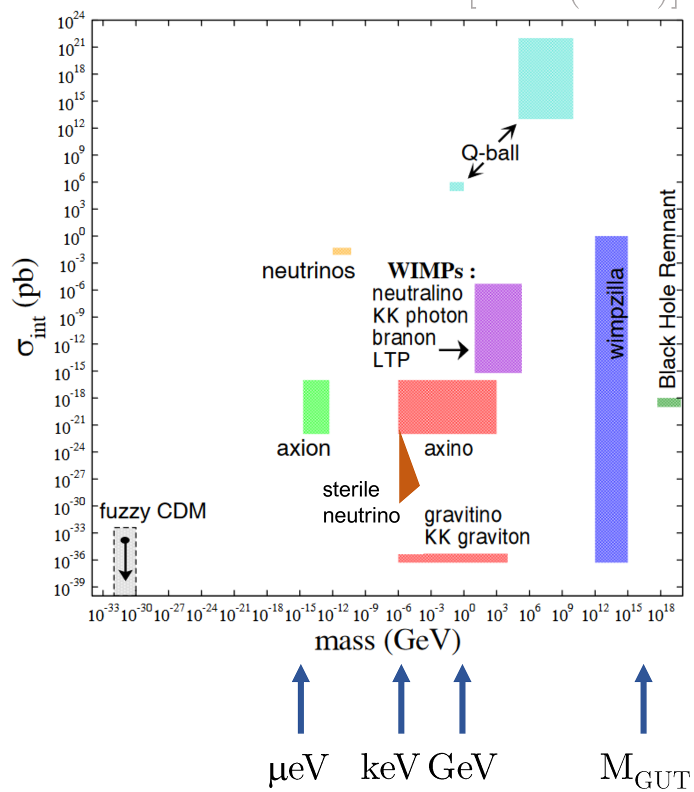
Popular candidates:

SM neutrinos	thermal relic (HDM)
Sterile neutrinos	thermal relic (WDM)
Axions	nonthermal relic
Gravitinos	thermal relic (WDM)
Solitons (Q-balls, B-balls,...)	nonthermal relic
Wimpzillas	nonthermal relic
Weakly Interacting Massive Particles	thermal relic (CDM)

[Park (2007)]



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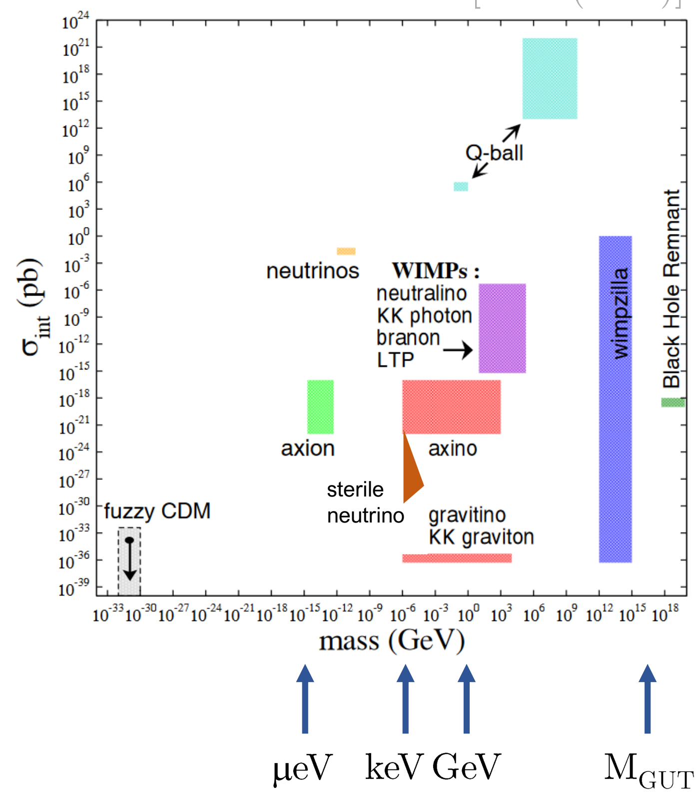

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WIMP detection

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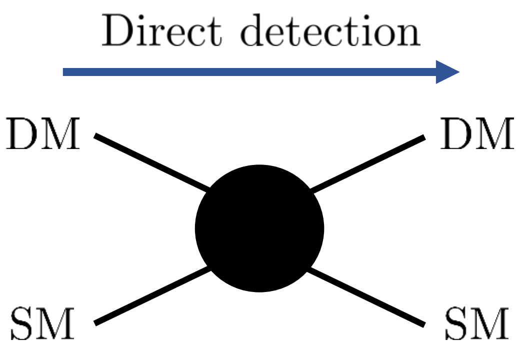


measure WIMP-nucleon scattering cross-section

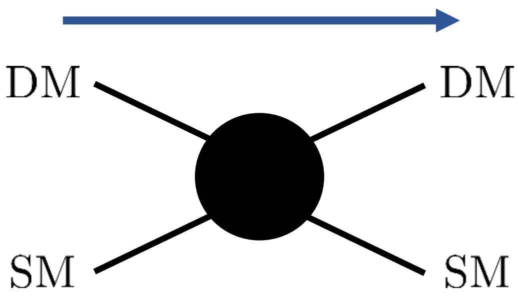
↓

Interaction of WIMPS with detector matter on Earth

- DAMA: "observed signal"
- CDMS, CRESST, EDELWEISS
- XENON100, LUX, PICO, PandaX

WIMP detection

Direct detection



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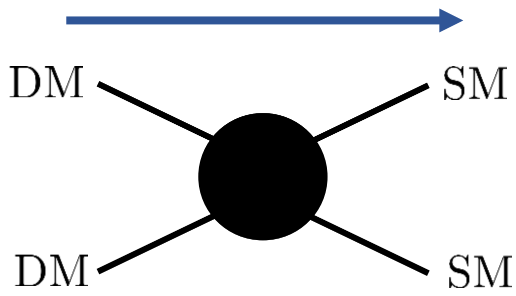


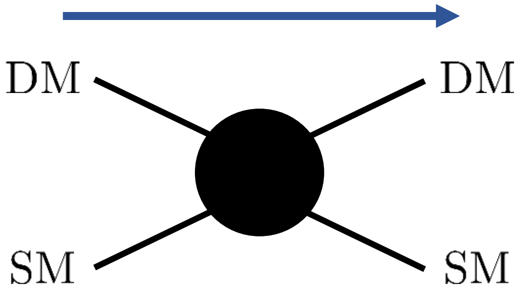
measure WIMP annihilation scattering cross-section

Search for radiation produced in WIMP annihilation

- Fermi-LAT, HESS, VERITAS, MAGIC
- AMS-02, PAMELA
- Antares, SuperK, IceCube, BAKSAN

WIMP detection

Direct detection



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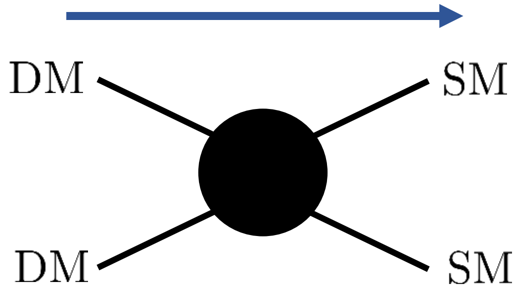

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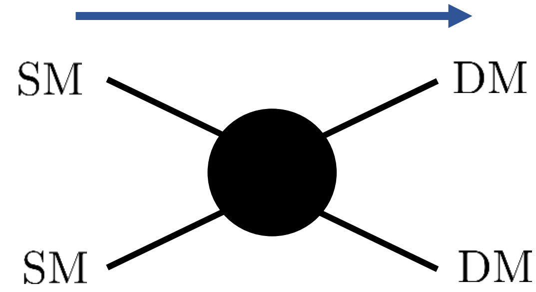
Collider searches



measure WIMP production cross-section at colliders

↓

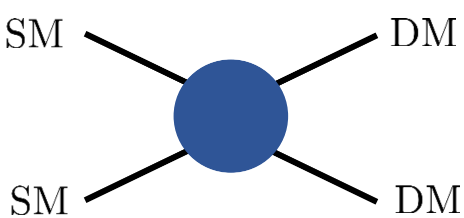
Find neutral stable particles whose signature is large missing energy

- LHC (ATLAS, CMS)

Collider searches

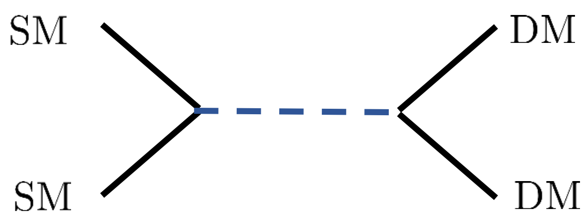
Rely on the choice of a theoretical framework for WIMP production

Effective Field Theories



- Interaction is described by non-renormalizable operators
- Model-independent, few parameters
- Only viable for mediators with masses above the TeV scale

Simplified Models



- Interaction is described by simple renormalizable Lagrangian
- Has a larger number of parameters (WIMP/mediator masses, couplings)
- Look at a single production channel

Complete Models

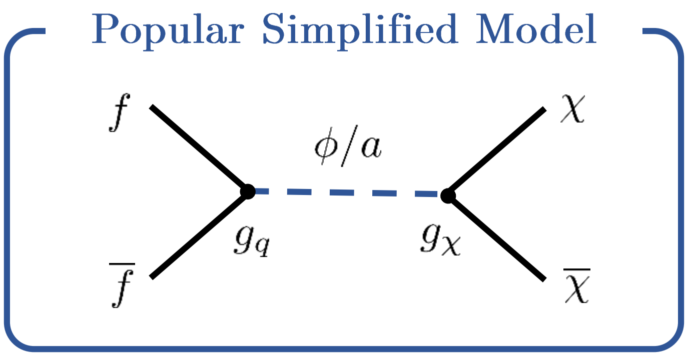
SUSY, 2HDM, UED, ...

- Interaction is included in a complete model
- Important correlations between observables are taken into account
- Too many parameters

Collider energy →

Search framework

Search for DM produced in association with **single top quark** or **top quark pair** in proton-proton collisions at $\sqrt{s} = 13$ TeV



may be easily embedded in models with extended scalar sector (e.g. 2HDM)

scalar mediator:

$$\mathcal{L}_\phi \supset g_\chi \phi \bar{\chi}\chi + \frac{g_q}{\sqrt{2}} \phi \sum_f y_f \bar{f} f$$

pseudoscalar mediator:

$$\mathcal{L}_a \supset i g_\chi a \bar{\chi}\gamma^5\chi + \frac{i g_q}{\sqrt{2}} a \sum_f y_f \bar{f}\gamma^5 f$$

$(y_f = \sqrt{2} m_f / v)$

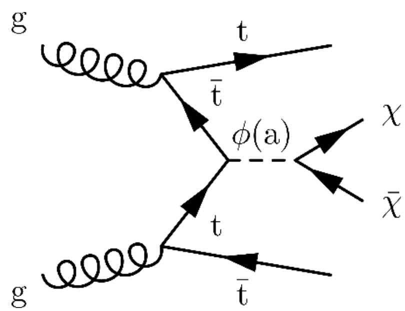
Assume:

- Dirac fermion DM
- Minimal flavour violation: mediators couple preferably to third generation quarks
- No mixing between the new scalar mediator and the Higgs

DM production channels

Associated production with top quark pair

$t\bar{t}$ + DM



Several previous searches (ATLAS and CMS):

- 8 TeV (EFT)
- 13 TeV (simplified models)

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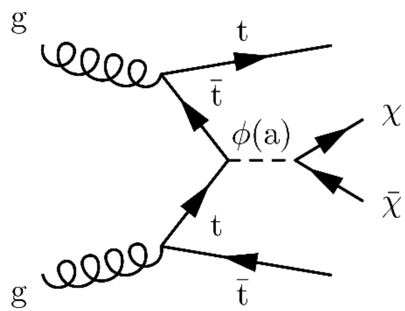

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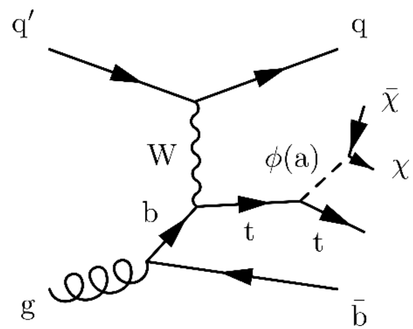
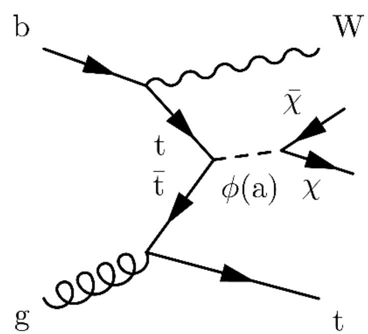
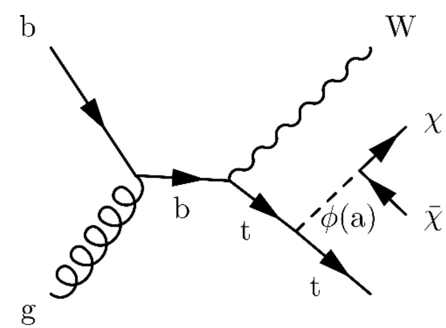




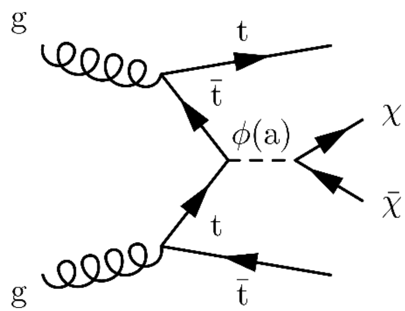


t-channel W boson production

associated tW production

DM production channels

Associated production
with top quark pair
$t\bar{t}$ + DM



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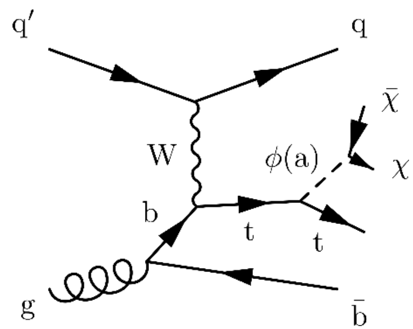

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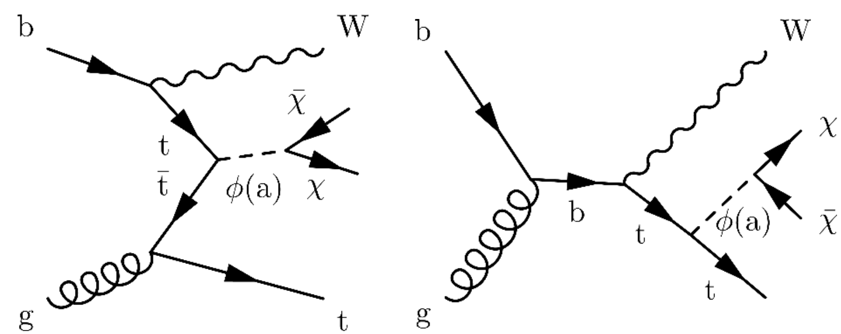

associated tW
production

New!

Importance of t/$\bar{t}$ + DM

[D. Pinna *et al.* (2017), arXiv: 1701.05195]

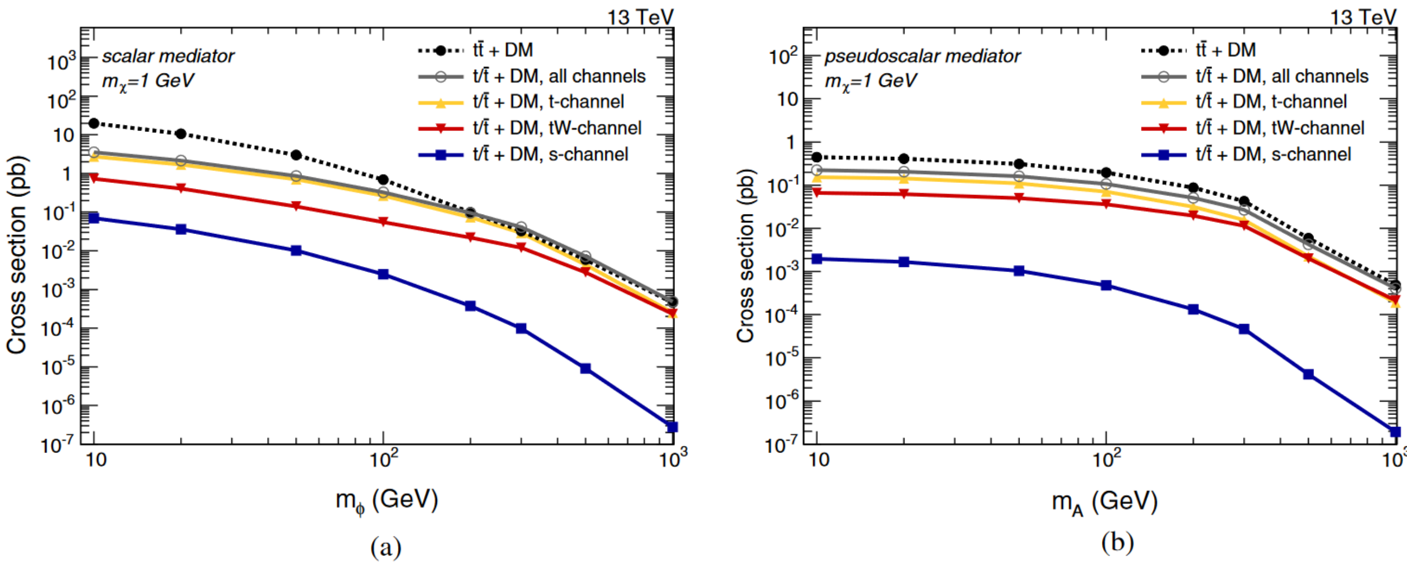

FIG. 2. Cross sections of the $t/\bar{t}$ + DM and $t\bar{t}$ + DM processes for the scalar (a) or pseudoscalar (b) hypothesis assuming different mediator masses m_φ and $m_\chi = 1$ GeV. The $t/\bar{t}$ + DM processes are split by production mode (t–, s–, and tW channels). The sum of the three channels is also shown.

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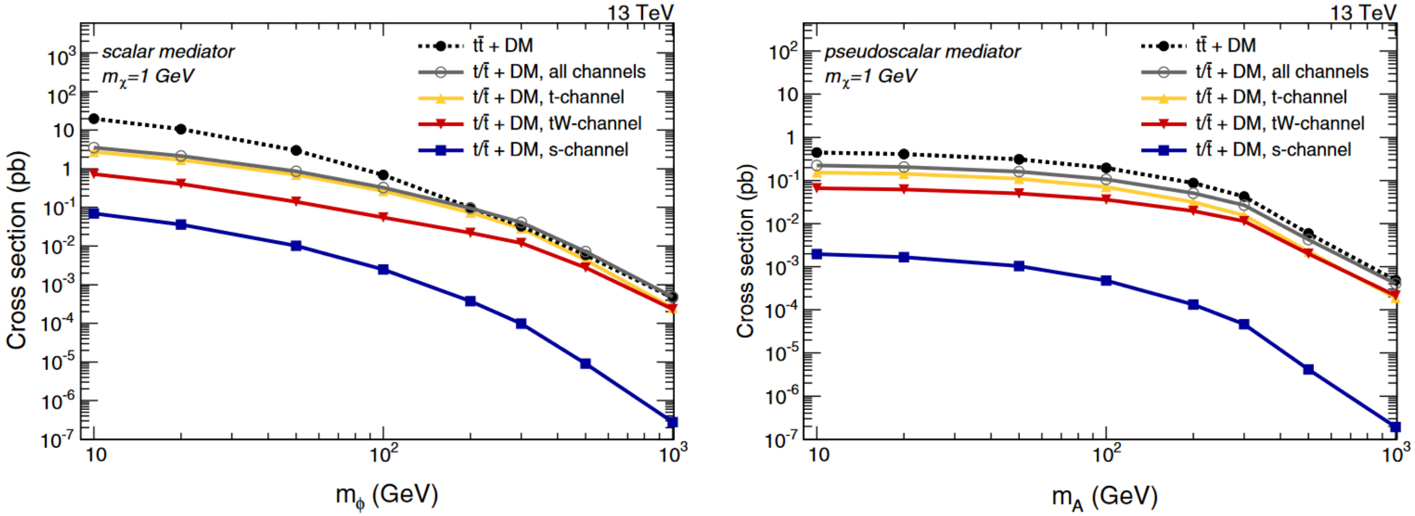

(a) (b)

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- Exclusion limit set by the LHC searches for dark matter can be improved by 30% up to a factor of two, depending on the mass assumed for the mediator particle

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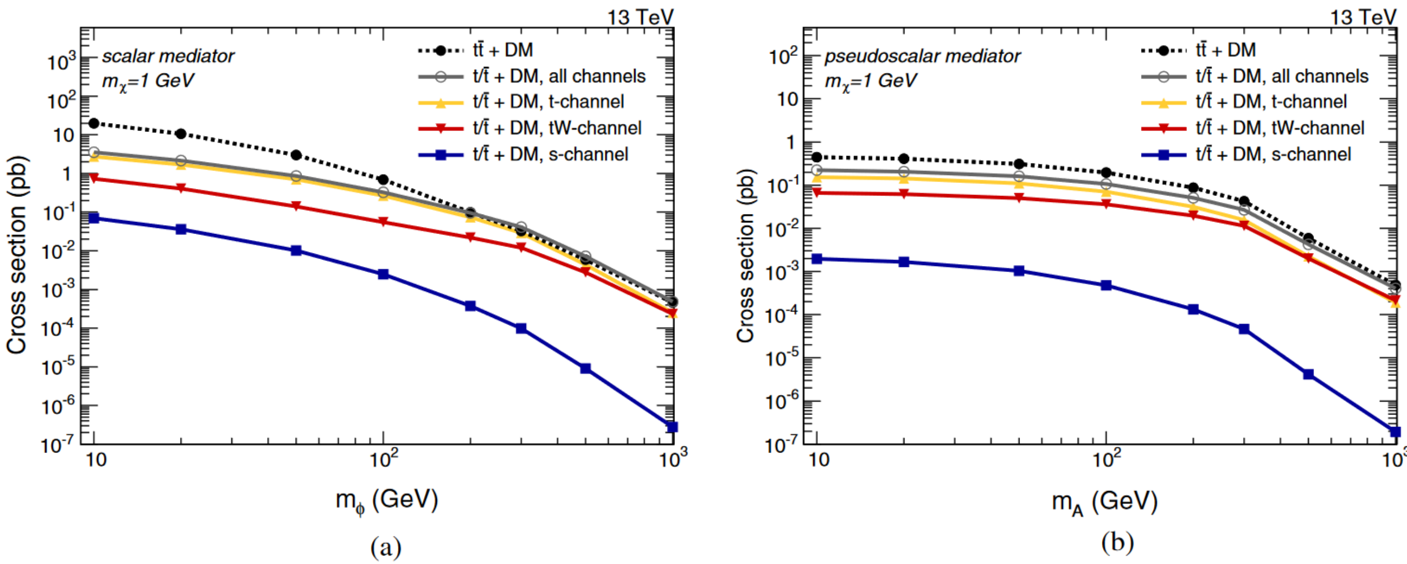

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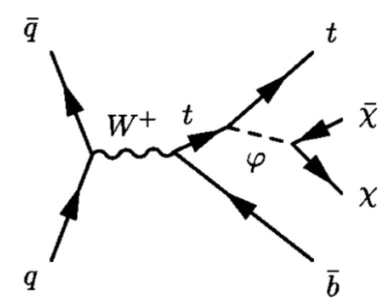
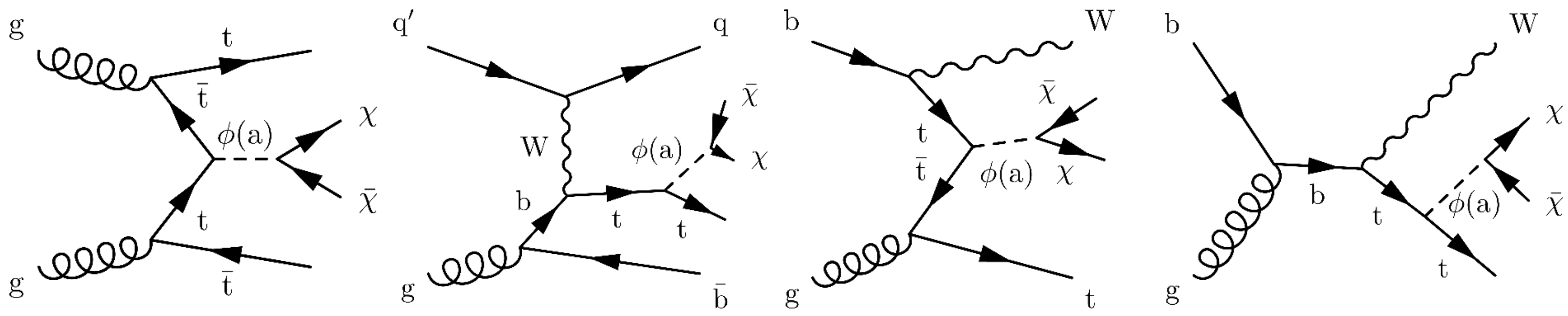
- Exclusion limit set by the LHC searches for dark matter can be improved by 30% up to a factor of two, depending on the mass assumed for the mediator particle
- s-channel W production has much smaller contribution (not considered in this search)



Search framework

Simplified model:



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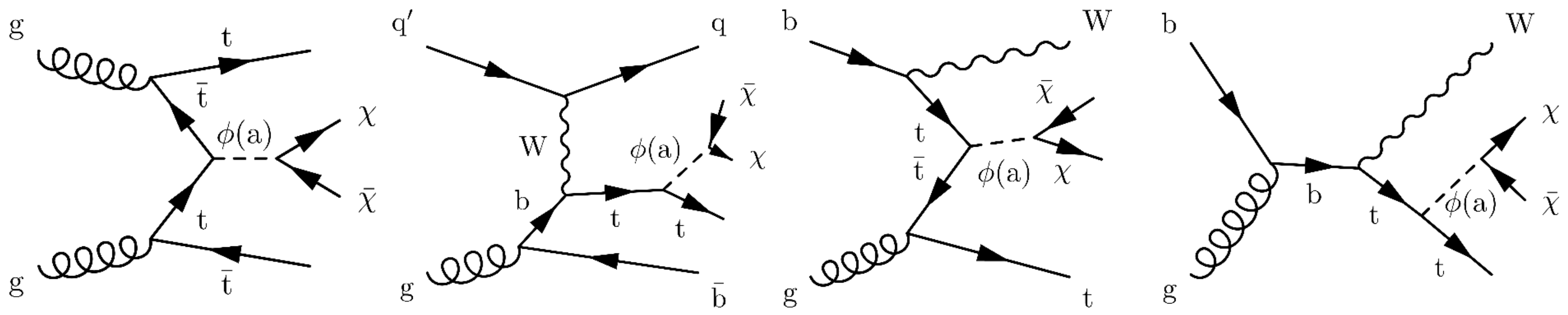

knowing that

$$\mathrm{BR}(t \to Wb) \sim 100\%$$

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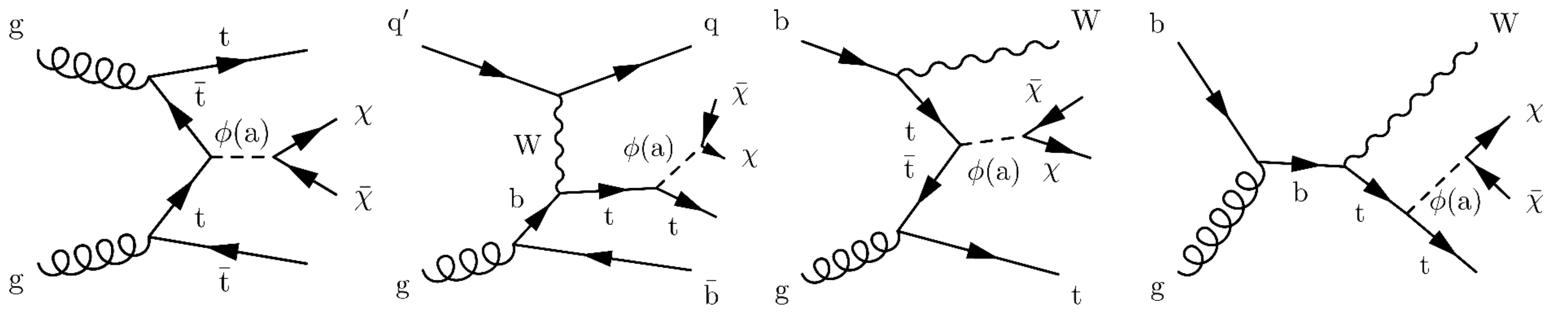

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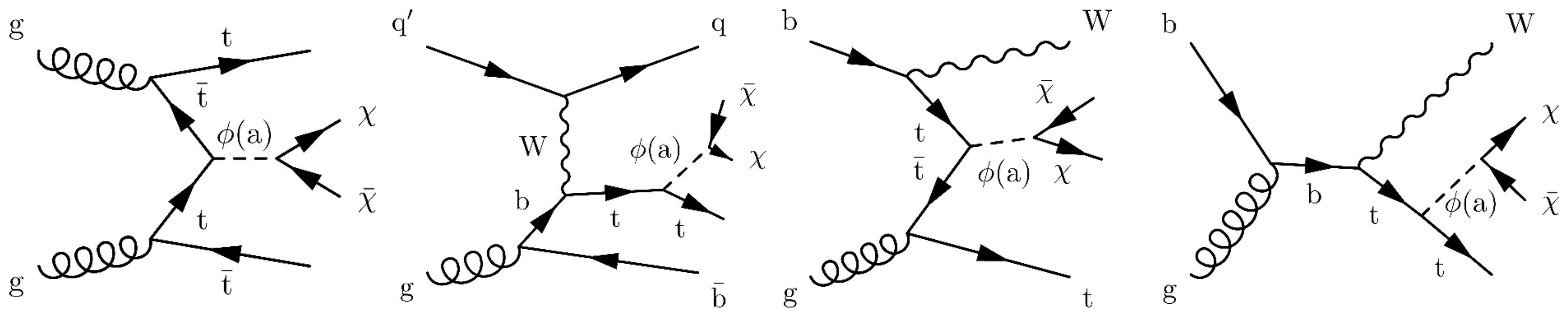

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What are we looking for?

Excess of events in the **missing transverse momentum** spectrum

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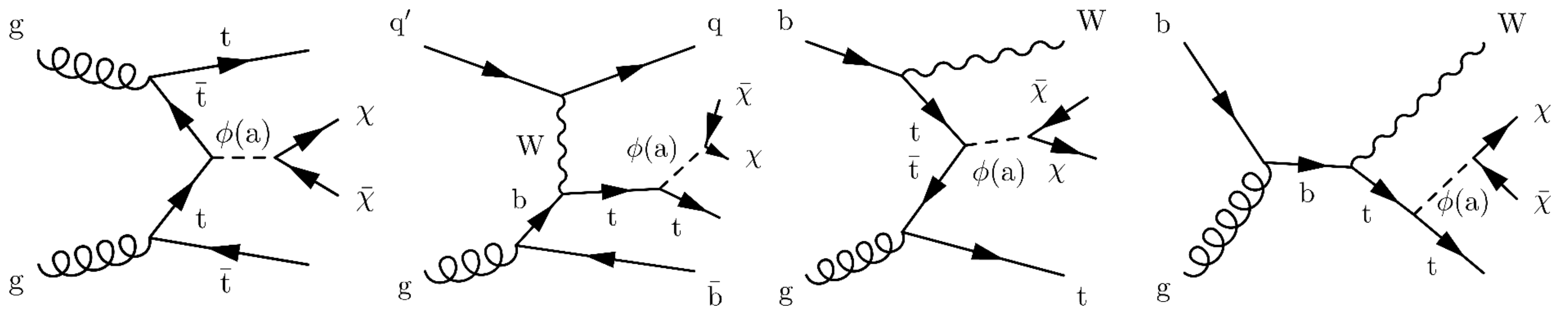

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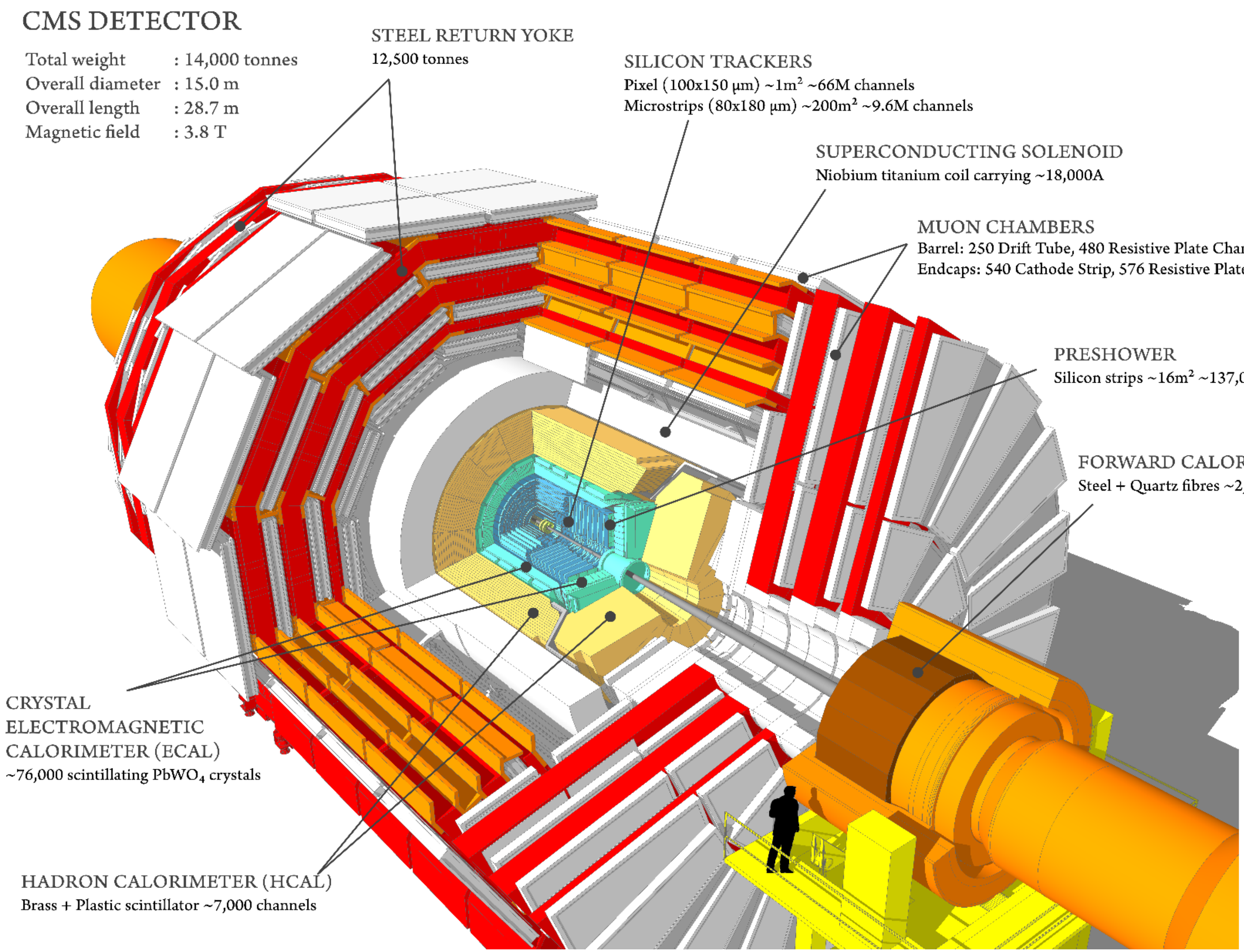
Events with

- exactly **one lepton** (e or μ): “single-lepton” (SL)
- **zero leptons**: “all-hadronic” (AH)

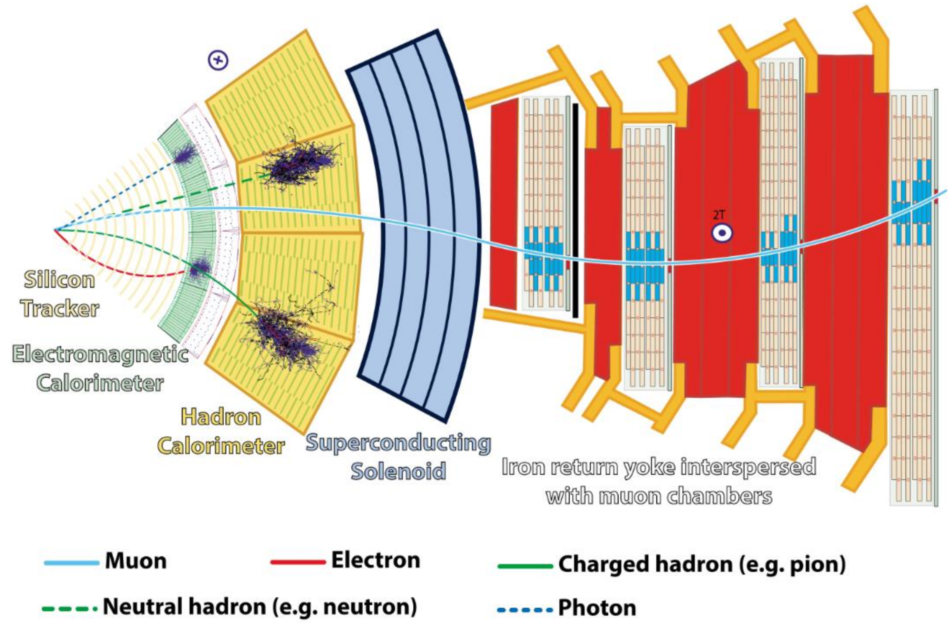
CMS detector



Event reconstruction

Trigger

- First level: selection rate of 100kHz
- Second level (high-level): reduces to 1 kHz



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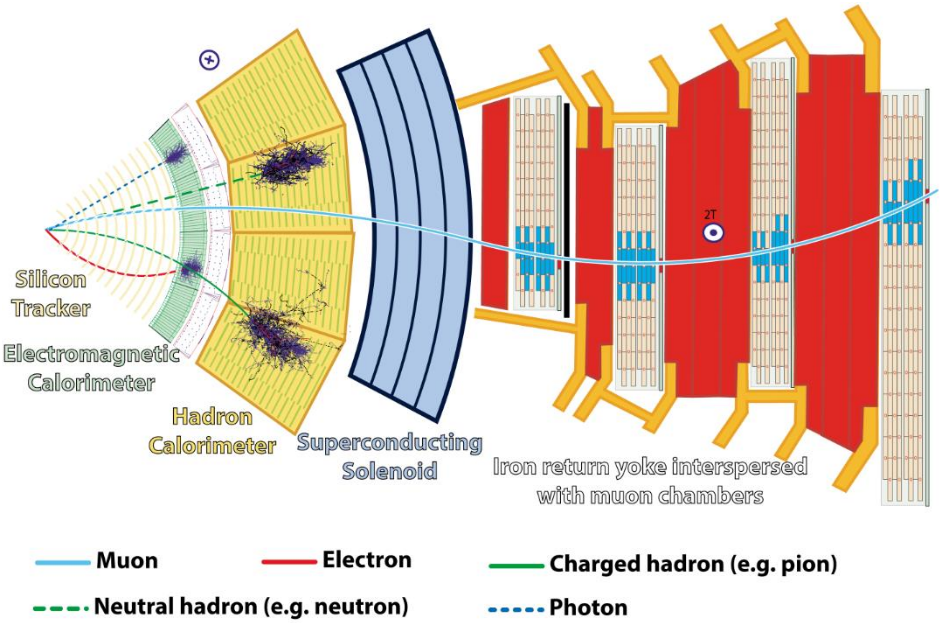
- Particles are categorized in mutually exclusive way into photons, electrons, muons, charged hadrons and neutral hadrons



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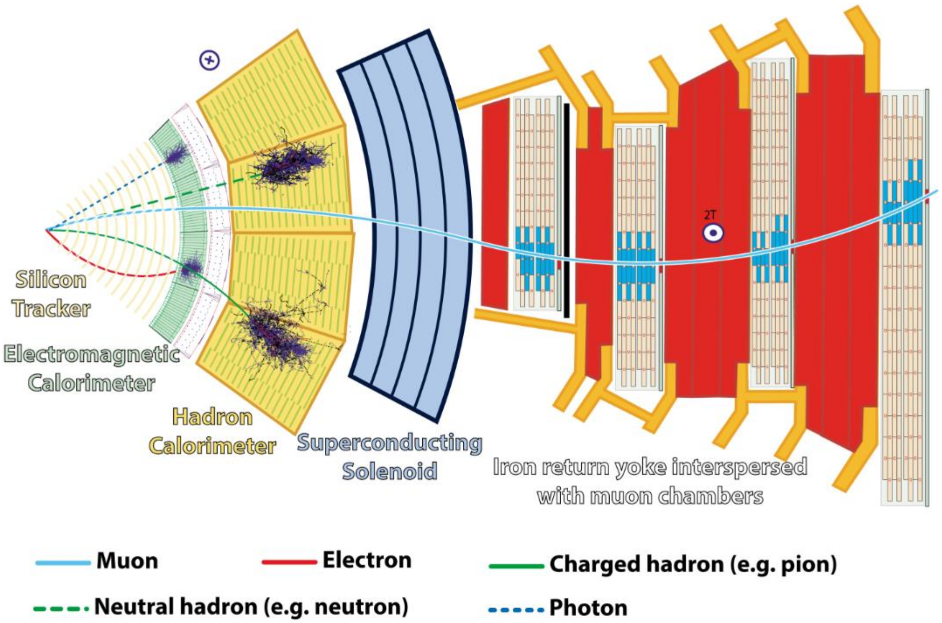
- Jet momentum is the vectorial sum of all particle momenta in the jet



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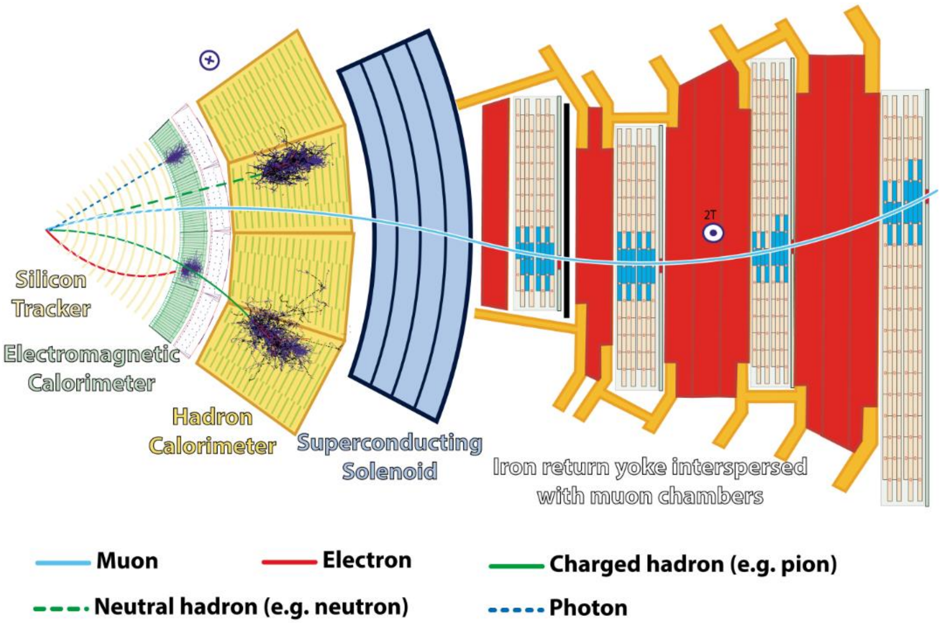
CSVv2 algorithm

- Identifies jets coming from hadronization of b quarks
- b-tagging efficiency in tt events ~ 80%



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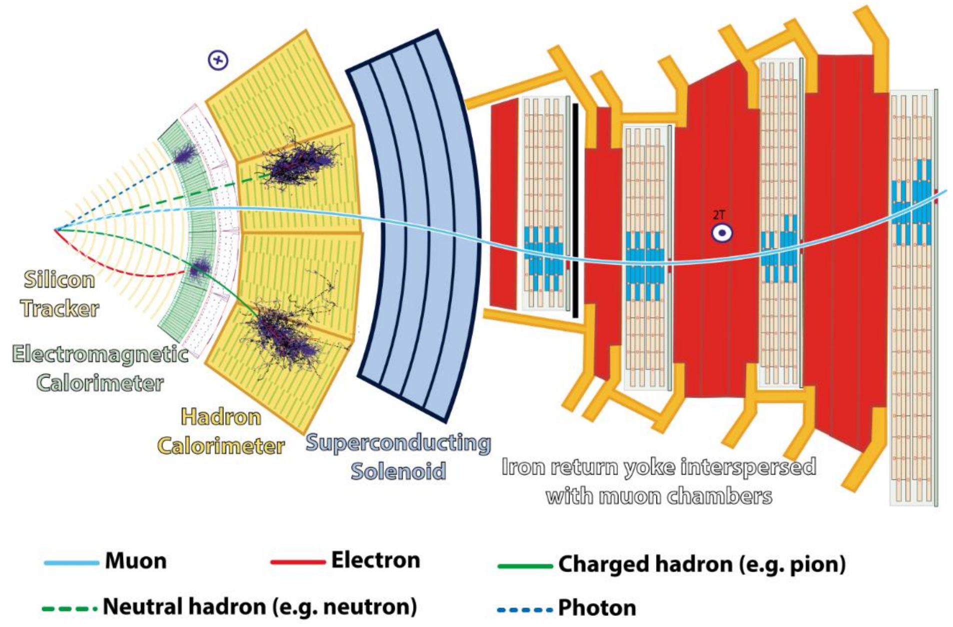

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Missing transverse momentum

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{\mathrm{PF}} \vec{p}_{\mathrm{T}}$$

Calculated using all PF particles originating from the primary vertex (with the largest momentum sum) and taking into account jet corrections

Data sample and simulation

Data sample and simulation

- Data recorded by CMS in **2016** corresponding to **35.9 fb^{-1}** at $\sqrt{s}$ = 13 TeV

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	Simulator
$t\bar{t}$+jets	POWHEG v2 (NLO)
single top	POWHEG v1 (NLO)
Z+jets, W+jets, QCD multijets	MADGRAPH5_aMC@NLO (LO)
$t\bar{t}$+W, $t\bar{t}$+Z	MADGRAPH5_aMC@NLO and FxFx (NLO)
WW, WZ, ZZ, WH, ZH	MADGRAPH5_aMC@NLO or POWHEG v2 (NLO)
$t\bar{t}$+DM, t/$\bar{t}$+DM	MADGRAPH5_aMC@NLO v2.4.2 (LO)
parton showering and hadronization	PYTHIA 8.205 (LO or NLO)
CMS detector	GEANT4

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	CMS detector	GEANT4

Signal ↓ Benchmark

$g_\chi = g_q = 1$

$m_\chi = 1$ GeV (production cross section is almost independent of the DM mass for on-shell mediators)

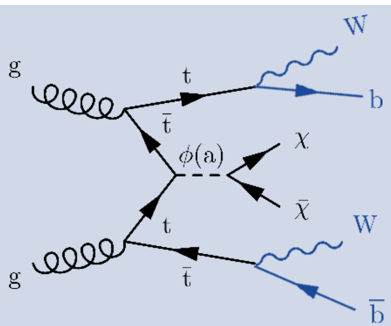
Event selection

Selection criteria:

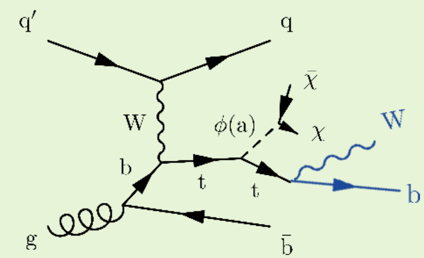
- Jets: $p_{\mathrm{T}} > 30$ GeV (central jet: $|\eta| < 2.4$, forward jet: $2.4 < |\eta| < 4.0$)
- b-tagged jets: $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.4$
- Electrons and muons: $p_{\mathrm{T}} > 30$ GeV, $|\eta| < 2.1$, $\Delta R_e < 0.3$ and $\Delta R_\mu < 0.4$

Signal regions: # of b-tagged jets, # of forward jets

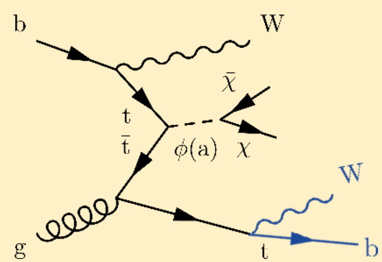
two or more b-tagged jets
$\mathrm{t\bar{t}}$ + DM

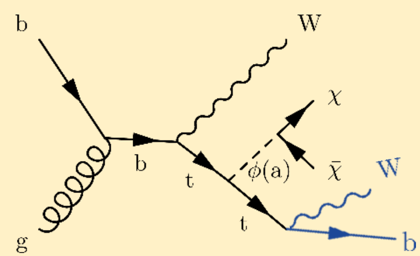


exactly one b-tagged jet + one or more forward jets
$\mathrm{t}/\bar{\mathrm{t}}$ + DM (t-channel)



exactly one b-tagged jet + exactly zero forward jets
$\mathrm{t}/\bar{\mathrm{t}}$ + DM (tW-channel)





Control regions: orthogonal to signal regions, where SM background dominates

Signal and control regions

Signal regions

	Single-lepton SRs			All-hadronic SRs		
	1ℓ, 1 b-tag, 0 FJ	1ℓ, 1 b-tag, 1FJ	1ℓ, 2 b-tag	0ℓ, 1 b-tag, 0 FJ	0ℓ,1 b-tag, 1 FJ	0ℓ, 2 b-tag
Forward jets	$=0$	≥1	—	$=0$	≥1	—
n_{b}	$=1$	$=1$	≥2	$=1$	$=1$	≥2
n_{lep}	$=1$	$=1$	$=1$	$=0$	$=0$	$=0$
$p_{\mathrm{T}}(\mathrm{j}_1)/H_{\mathrm{T}}$		—			—	<0.5
n_{jet}		≥2			≥3	
$p_{\mathrm{T}}^{\mathrm{miss}}$		>160 GeV			>250 GeV	
m_{T}		>160 GeV			—	
$m_{\mathrm{T2}}^{\mathrm{W}}$		>200 GeV			—	
$\min\Delta\phi(\mathrm{j}_{1,2},\vec{p}_{\mathrm{T}}^{\mathrm{miss}})$		>1.2 rad.			>1.0 rad.	
$m_{\mathrm{T}}^{\mathrm{b}}$		>180 GeV			>180 GeV	

Signal and control regions

Signal regions

exactly one lepton with $p_T > 30$ GeV

	Single-lepton SRs			All-hadronic SRs		
	1ℓ, 1 b-tag, 0 FJ	1ℓ, 1 b-tag, 1FJ	1ℓ, 2 b-tag	0ℓ, 1 b-tag, 0 FJ	0ℓ,1 b-tag, 1 FJ	0ℓ, 2 b-tag
Forward jets	=0	≥1	—	= 0	≥1	—
n_b	=1	=1	≥2	= 1	=1	≥2
n_{lep}	=1	=1	=1	= 0	=0	=0
$p_T(j_1)/H_T$		—			—	<0.5
n_{jet}		≥2			≥3	
p_T^{miss}		>160 GeV			>250 GeV	
m_T		>160 GeV			—	
m_{T2}^W		>200 GeV			—	
$\min\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$		>1.2 rad.			>1.0 rad.	
m_T^b		>180 GeV			>180 GeV	

Signal and control regions

Signal regions

	exactly one lepton with $p_T > 30$ GeV			exactly zero leptons with $p_T > 10$ GeV		
	Single-lepton SRs			All-hadronic SRs		
	1ℓ, 1 b-tag, 0 FJ	1ℓ, 1 b-tag, 1FJ	1ℓ, 2 b-tag	0ℓ, 1 b-tag, 0 FJ	0ℓ,1 b-tag, 1 FJ	0ℓ, 2 b-tag
Forward jets	=0	≥1	—	= 0	≥1	—
n_b	=1	=1	≥2	= 1	=1	≥2
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n_b	=1	=1	≥2	= 1	=1	≥2
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Background mainly from $t\bar{t}(2\ell)$ and W+jets

Signal and control regions

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But how can we estimate the SM background in these different regions?

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Control regions

	Single-lepton CRs		All-hadronic CRs		
	CR $t\bar{t}(2\ell)$	CR $W(\ell\nu)$	CR $t\bar{t}(1\ell)$	CR $W(\ell\nu)$	CR $Z(\ell\ell)$
n_b	≥1	=0	≥1	=0	=0
n_{lep}	=2	=1	=1	=1	=2
n_{jet}	≥2	≥2	≥3	≥3	≥3
p_T^{miss}	>160 GeV	>160 GeV	>250 GeV	>250 GeV	>250 GeV
m_T	—	>160 GeV	<160 GeV	<160 GeV	—
$\min\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$	—	—	>1.0 rad.	—	—
$m_{\ell\ell}$	—	—	—	—	[60, 120] GeV

Systematic uncertainties

- Consequences for either the **simulation of background processes** or the underlying **theoretical modelling**
- All uncertainties are included in the global simultaneous fit
- Uncertainties in b-tagging scale factor and limited statistics on the dilepton tt CR have the largest impacts on final result

Sources of uncertainties

only affect the normalization of the p_T spectrum	**also affect the shape of the p_T^{miss} distribution**
Lepton reconstruction, selection and trigger (2.2% for e and 1% for μ)	Jet energy scale
p_T^{miss} trigger (2%)	PDF uncertainties
b-tagging efficiency scale factors	W/Z+heavy-flavor fraction
Forward jets (2 - 7%)	Electroweak and QCD K factors
Pileup modeling (4.6%)	Top quark p_T reweighting
Luminosity (2.5%)	Factorization and renormalization scales
QCD multijet background normalization (100%)	Simulation sample size
Single top quark background normalization (20%)	
ECAL mistiming (10%)	

Signal Extraction

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- DM signal is extracted from a **simultaneous fit** to the missing transverse momentum distribution in the various **signal and control regions**, taking into account all the **uncertainties** (RooStats statistical package, combining both SL and AH regions)

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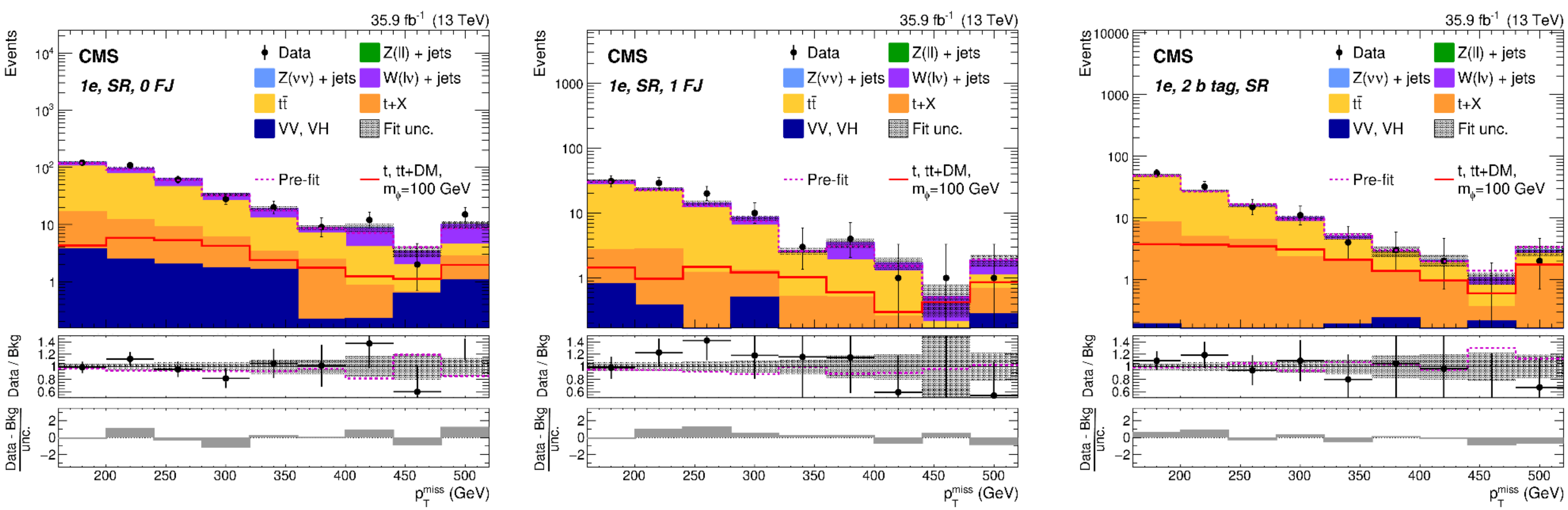
- No significant excess at high missing transverse momentum is observed in any of the SRs

Example: background-only post-fit distribution for the SRs of the single-lepton selection (electron case)



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- Potential DM signal contributions scaled by **signal strength modifier** ($\mu = \sigma/\sigma_{\mathrm{th}}$)
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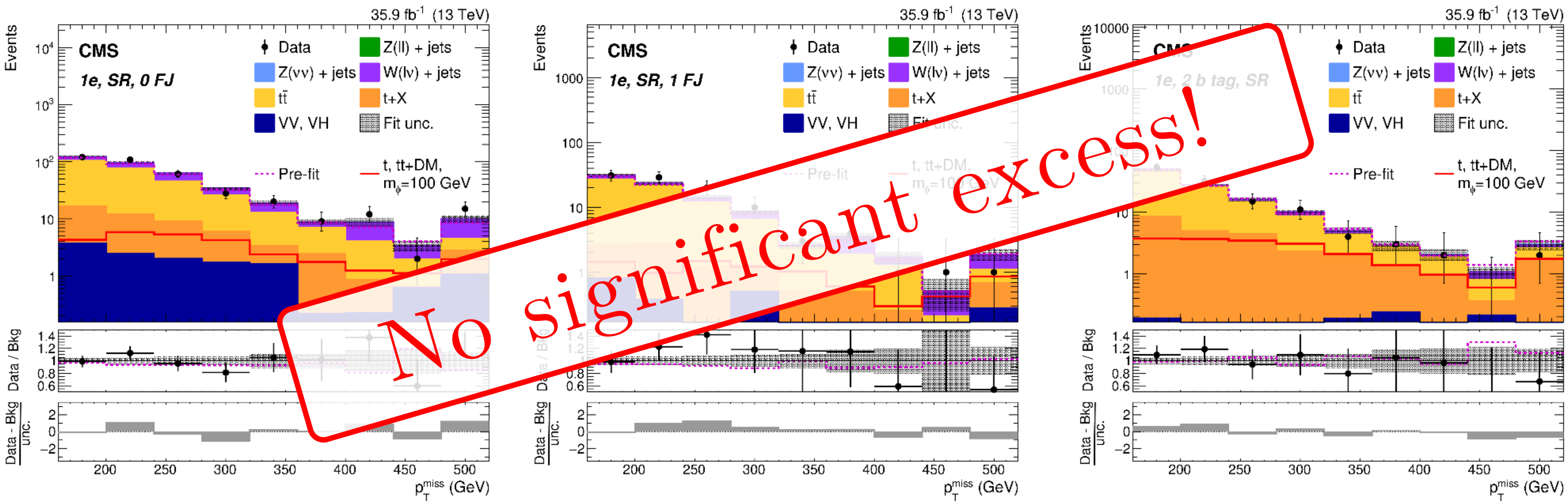
- No significant excess at high missing transverse momentum is observed in any of the SRs

Example: background-only post-fit distribution for the SRs of the single-lepton selection (electron case)



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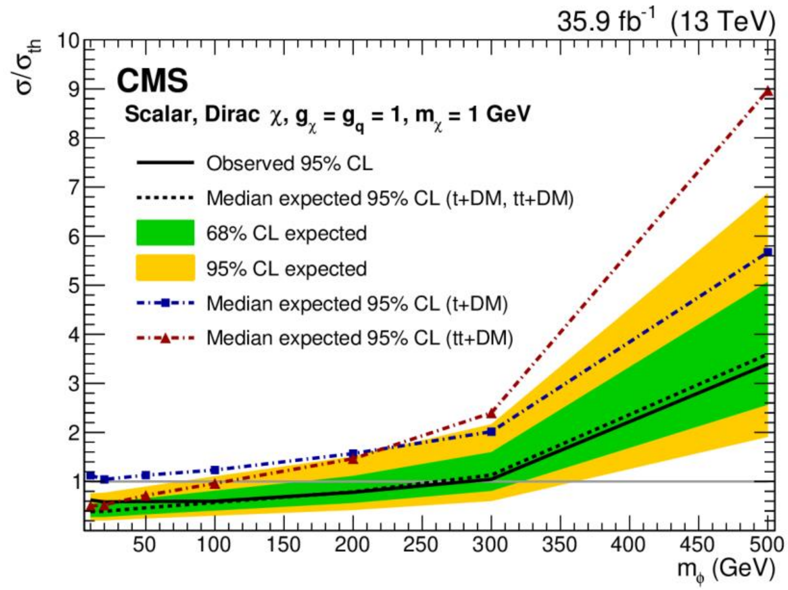

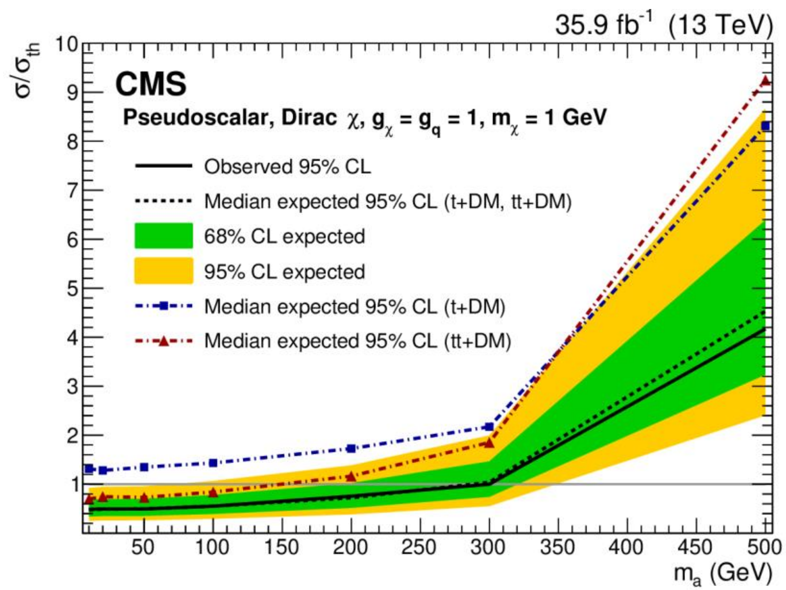

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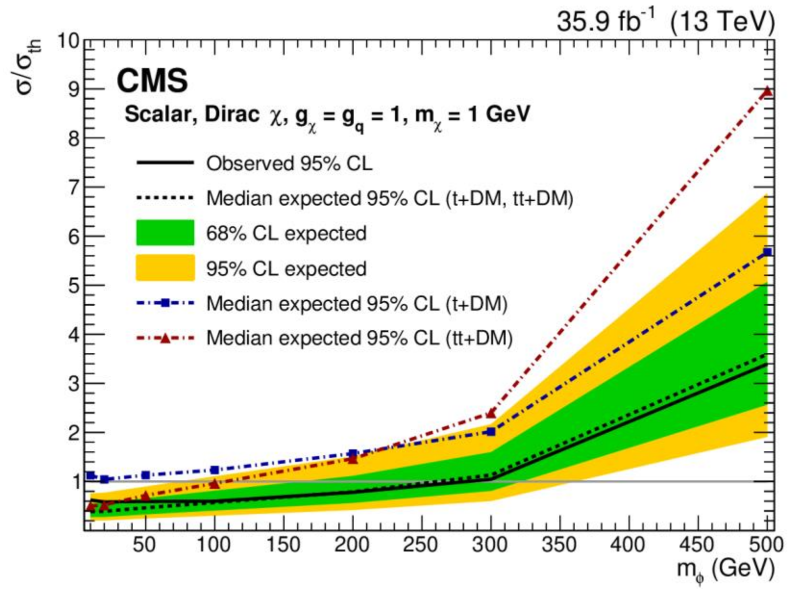

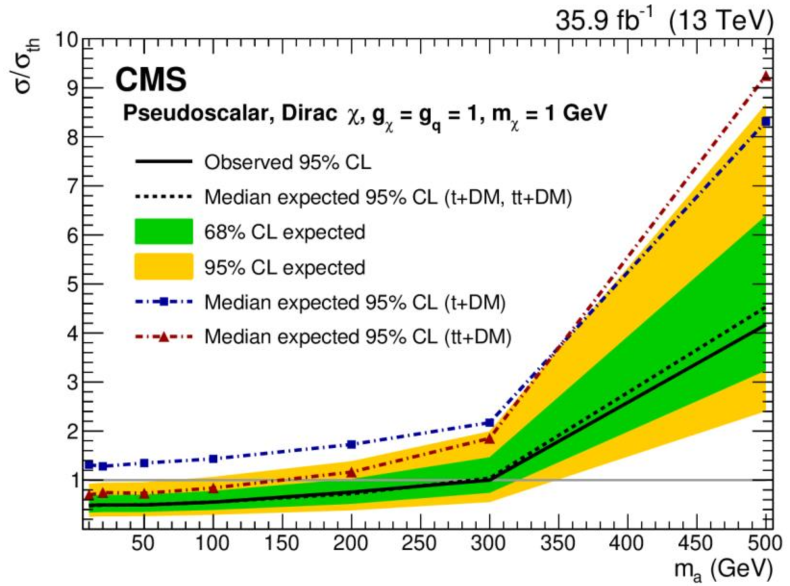

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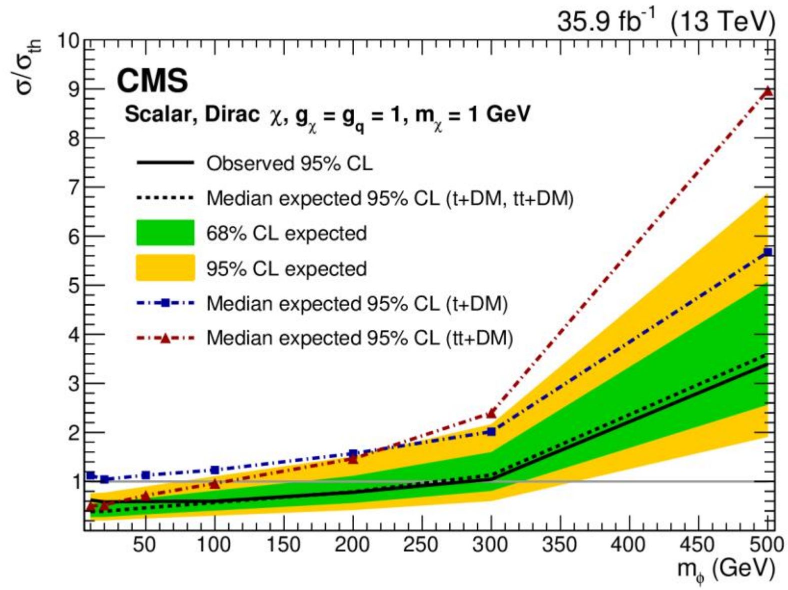

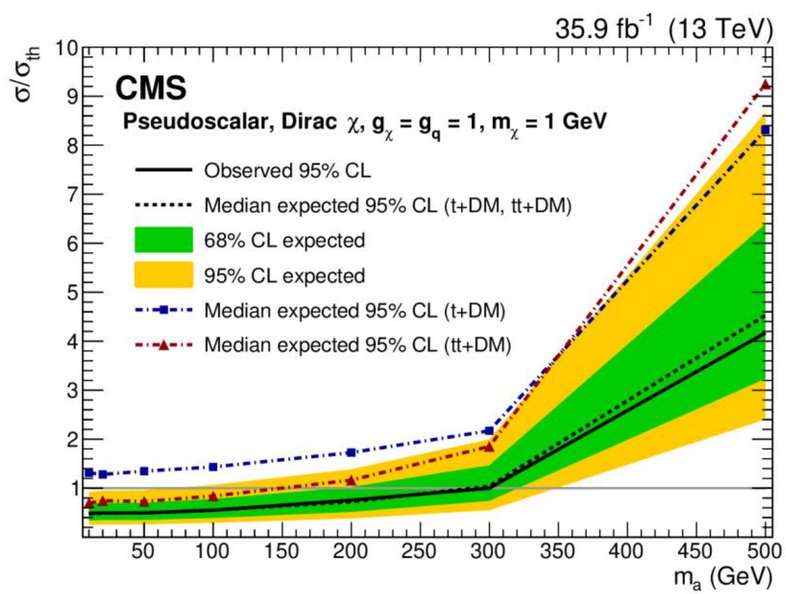

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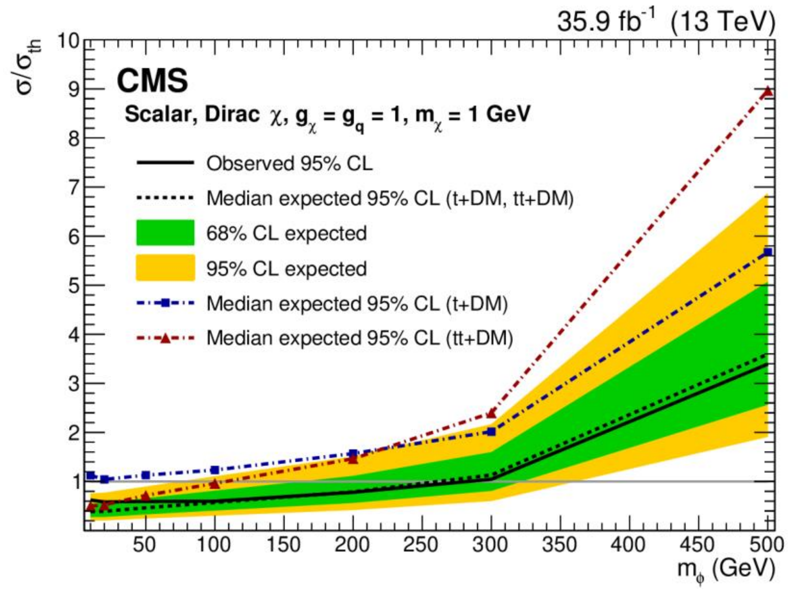

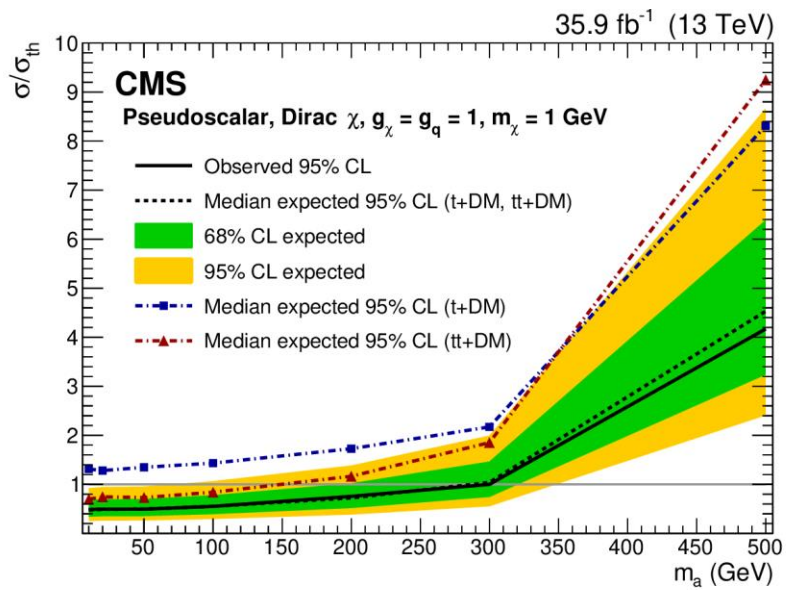

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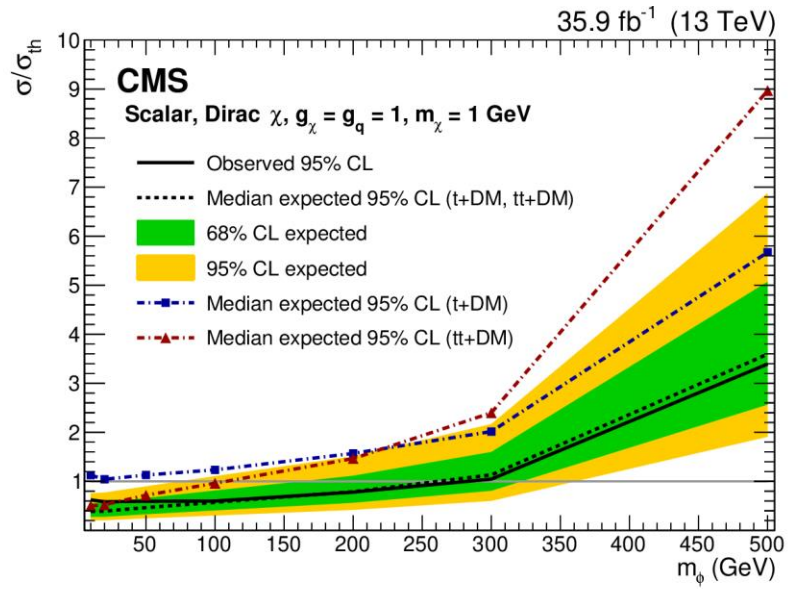

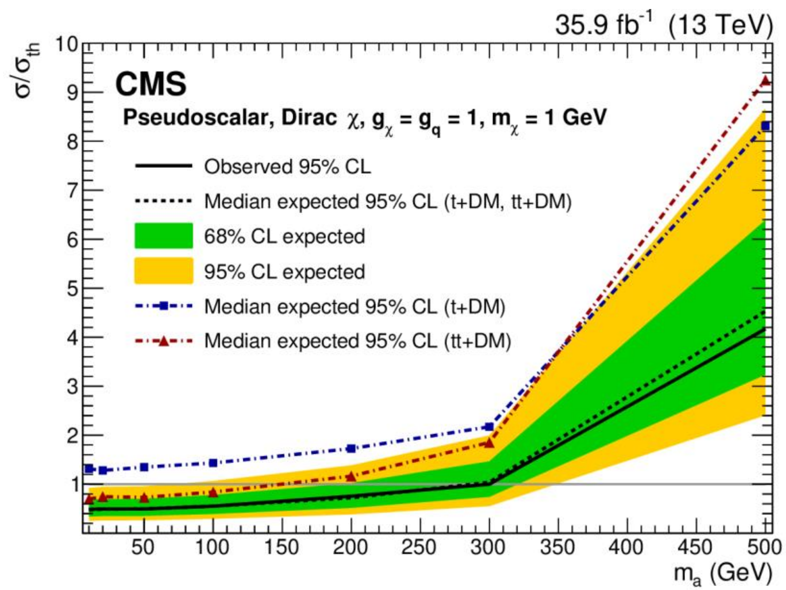

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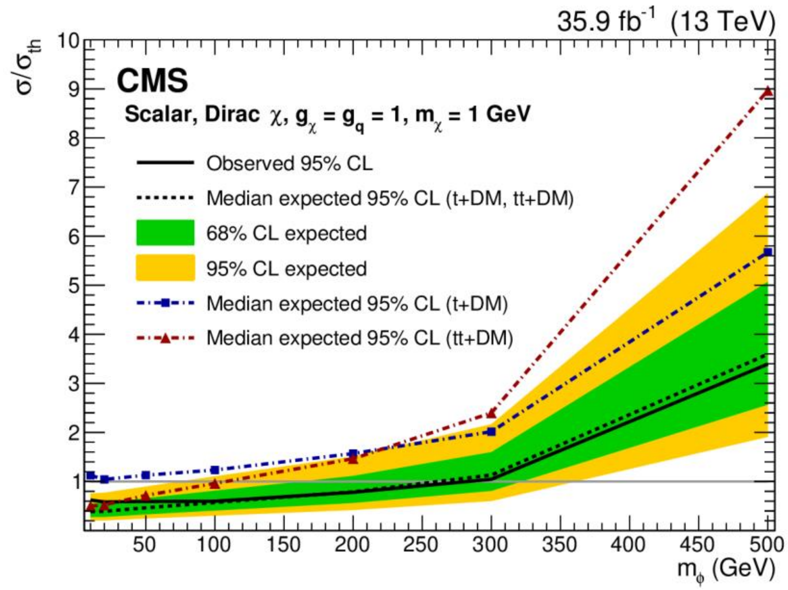

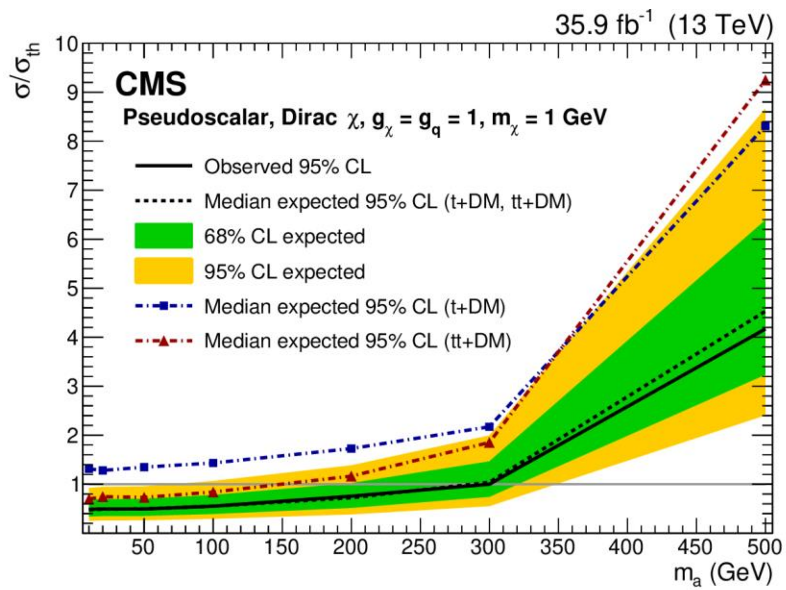

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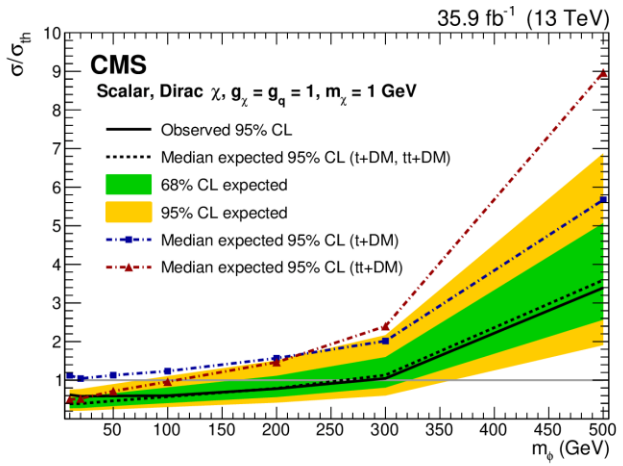

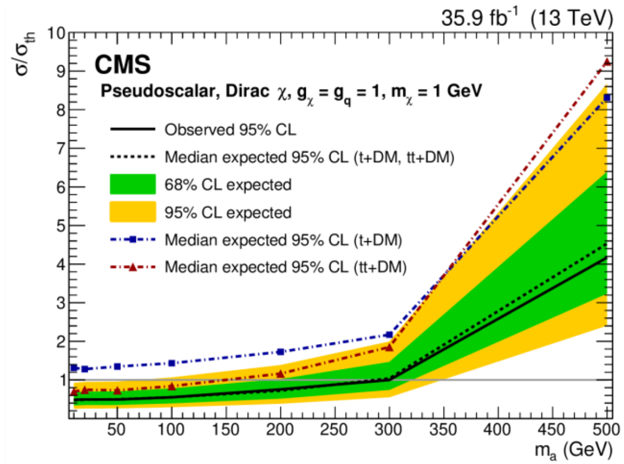

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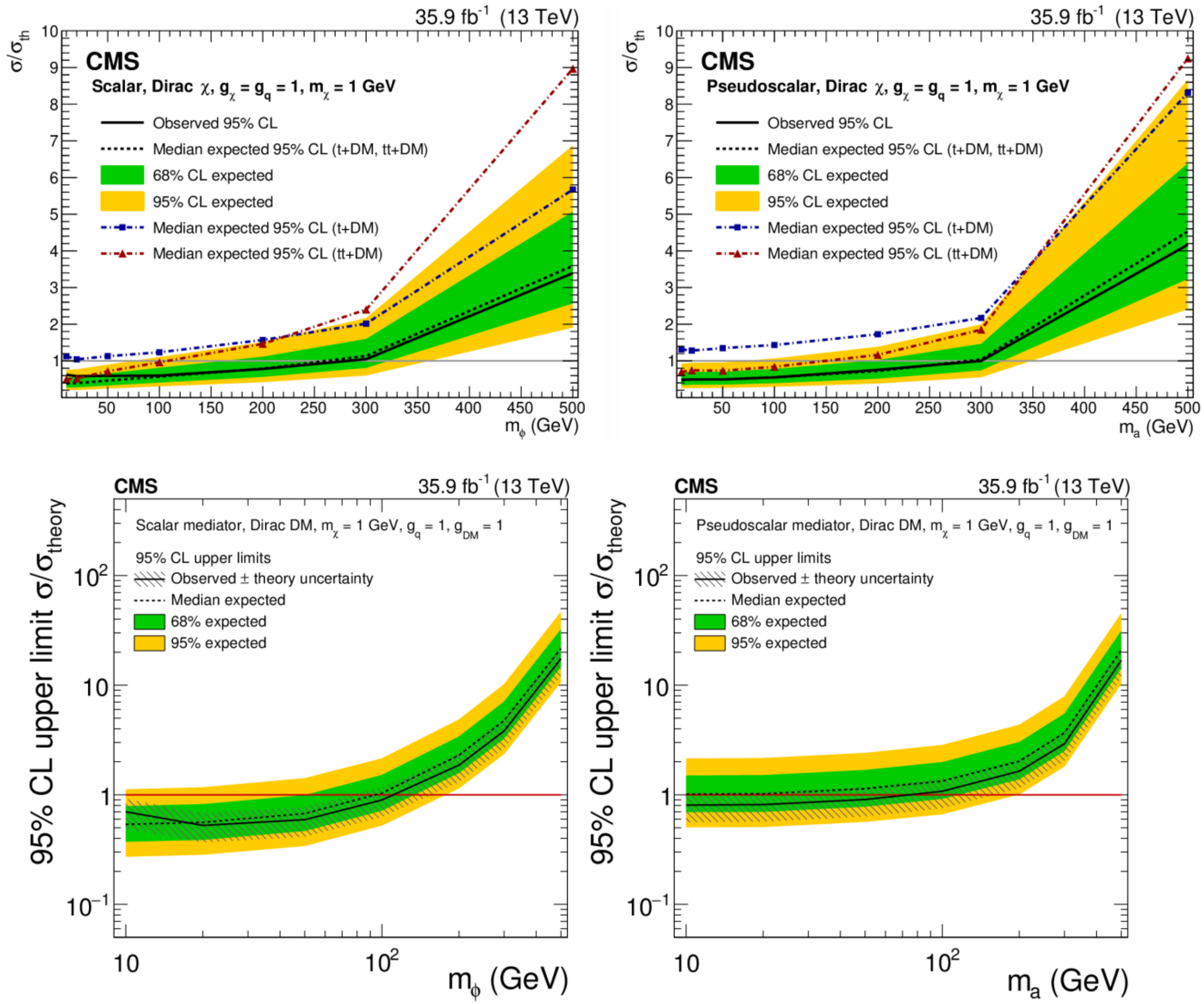

[A. M. Sirunyan *et al.*, CMS Collaboration (2018), arXiv: 1711.00752]

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Thank you!

Backup slides

Evidence for Dark Matter

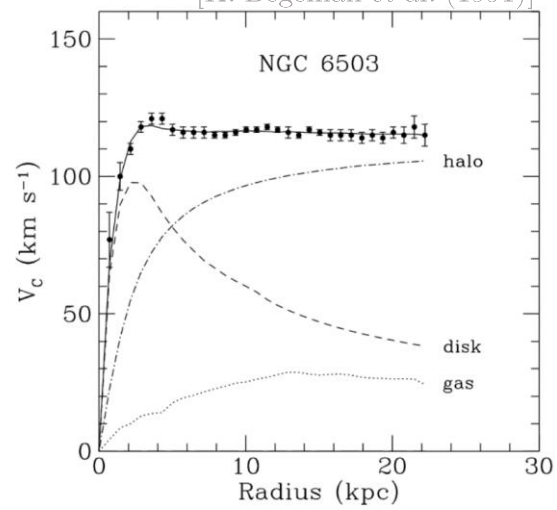
Existence of nonluminous matter:

Galactic rotation curves: stars in outer parts of spiral galaxies rotate far more quickly than would be expected if each galaxy consisted only of visible matter

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

- $M(r) \sim \text{const} \Rightarrow v(r) \propto 1/\sqrt{r}$
- $v(r) \sim \text{const} \Rightarrow M(r) \propto r$

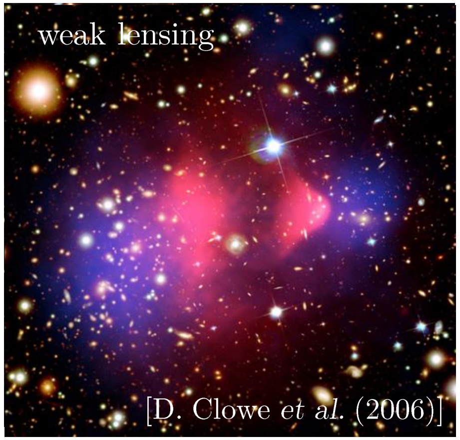
[K. Begeman *et al.* (1991)]



Gravitational lensing: the gravitational potential of a very massive body bends the light originating from an object behind it, allowing to probe its mass distribution

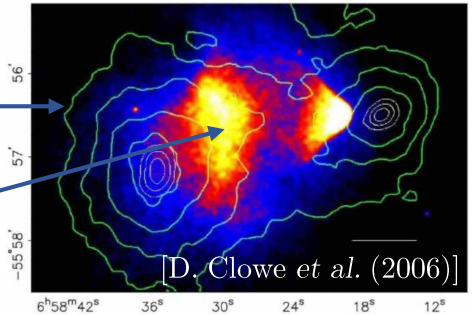
$$\delta\theta \simeq \frac{4GM}{b} \longrightarrow$$ allows to infer the mass of the heavy object

Bullet Cluster: system of two colliding clusters, where baryonic hot-gas clouds have been deaccelerated in the collision while the DM halos remain almost intact



[D. Clowe *et al.* (2006)]

Collisionless nature of DM
- mass distribution inferred from gravitational lensing
- X-ray distribution from baryonic matter



[D. Clowe *et al.* (2006)]

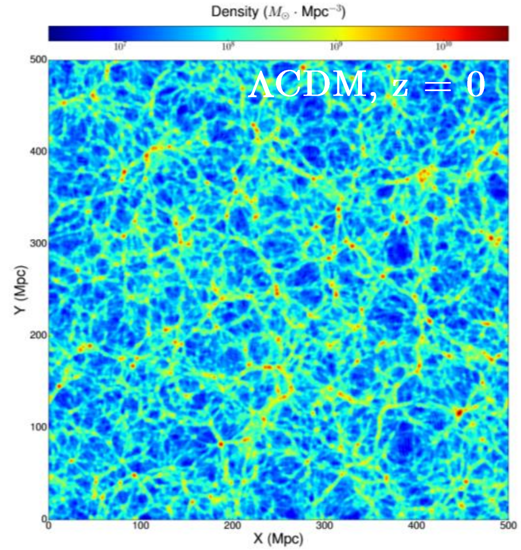
Evidence for Dark Matter

Proof of non-baryonic nature of DM:

LSS: reflects the history of gravitational clustering of matter since the Big Bang

- N-body simulations show that the observed LSS can only be formed in the presence of a large amount of non-dissipative CDM
- Allows to determine the total matter density of the Universe

$$\Omega_{\rm m} = 0.308$$



[A. Watts *et al.* (2017)]

BBN data: comparison between measurements of light element abundance and predictions of standard BBN

- Allows to determine the total baryon density of the Universe

$$0.021 \lesssim \Omega_{\rm b} h^2 \lesssim 0.024 \ (95\% \ \text{CL})$$

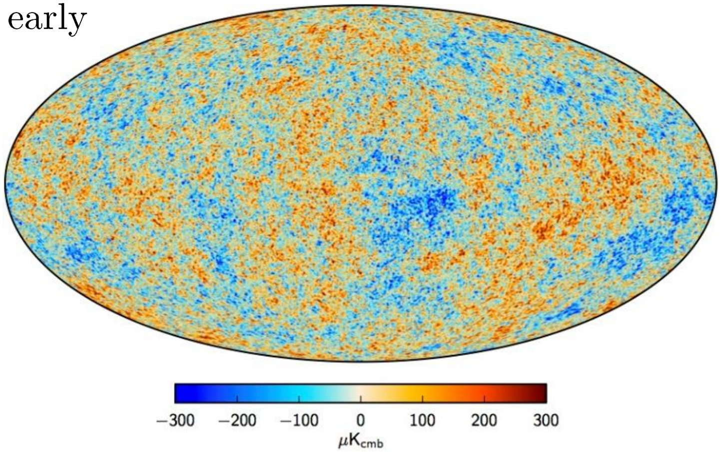
CMB radiation: comes from propagation of photons in the early Universe after decoupling from matter

- Small temperature anisotropies of the order of

$$\delta T/T \sim 10^{-5}$$

- CMB power spectrum is sensitive to the matter and baryon fractions, which allow to determine the non-baryonic DM contribution

$$\Omega_{\rm b} h^2 = 0.02226 \qquad \Omega_{\rm DM} h^2 = 0.1186$$



[R. Adam *et al.*, Planck Collaboration (2016)]

Dark Matter Candidates