University of Zurich

Searching for Dark Matter at the LHC

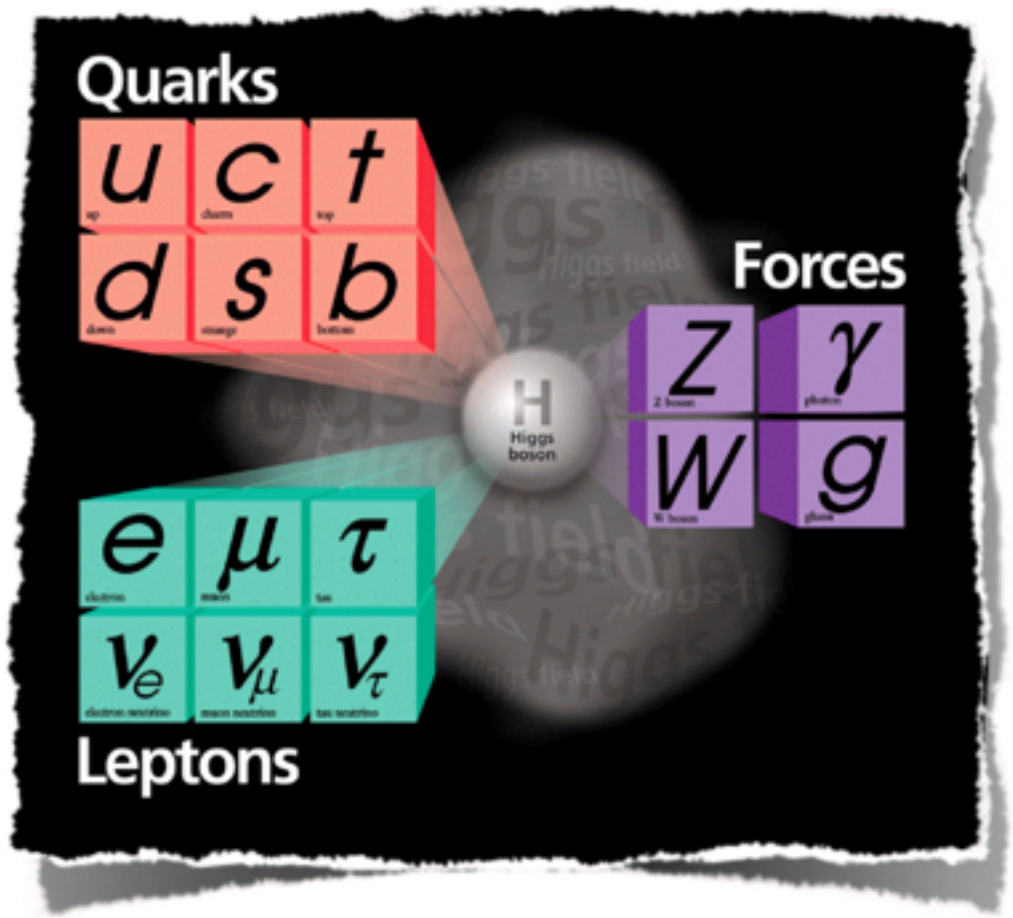
Annapaola de Cosa (University of Zurich)

May 2nd 2016

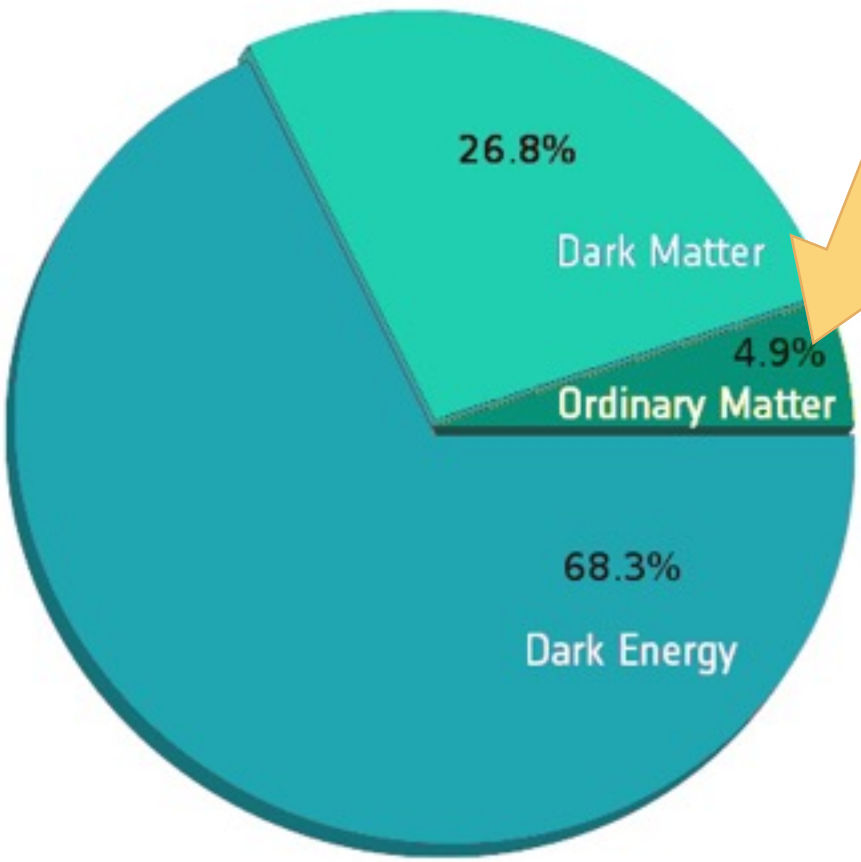
Università degli Studi di Napoli, "Federico II"

Going beyond the Standard Model

- **Great success of the Standard Model of particle physics in the last decades**
  - Accurate description of elementary particles and their interactions
- **2012: Discovery of the Higgs boson**
  - Last piece of the SM puzzle now in place



SM ~ 5%



But...What about Dark Matter?

- **Compelling proof of DM existence from astrophysical measurements**
- **SM does not predict DM**
- **Strong evidence for new physics**

First Hints of Dark Matter: 30s

1933: Zwicky measured galaxies velocity in the Coma Cluster

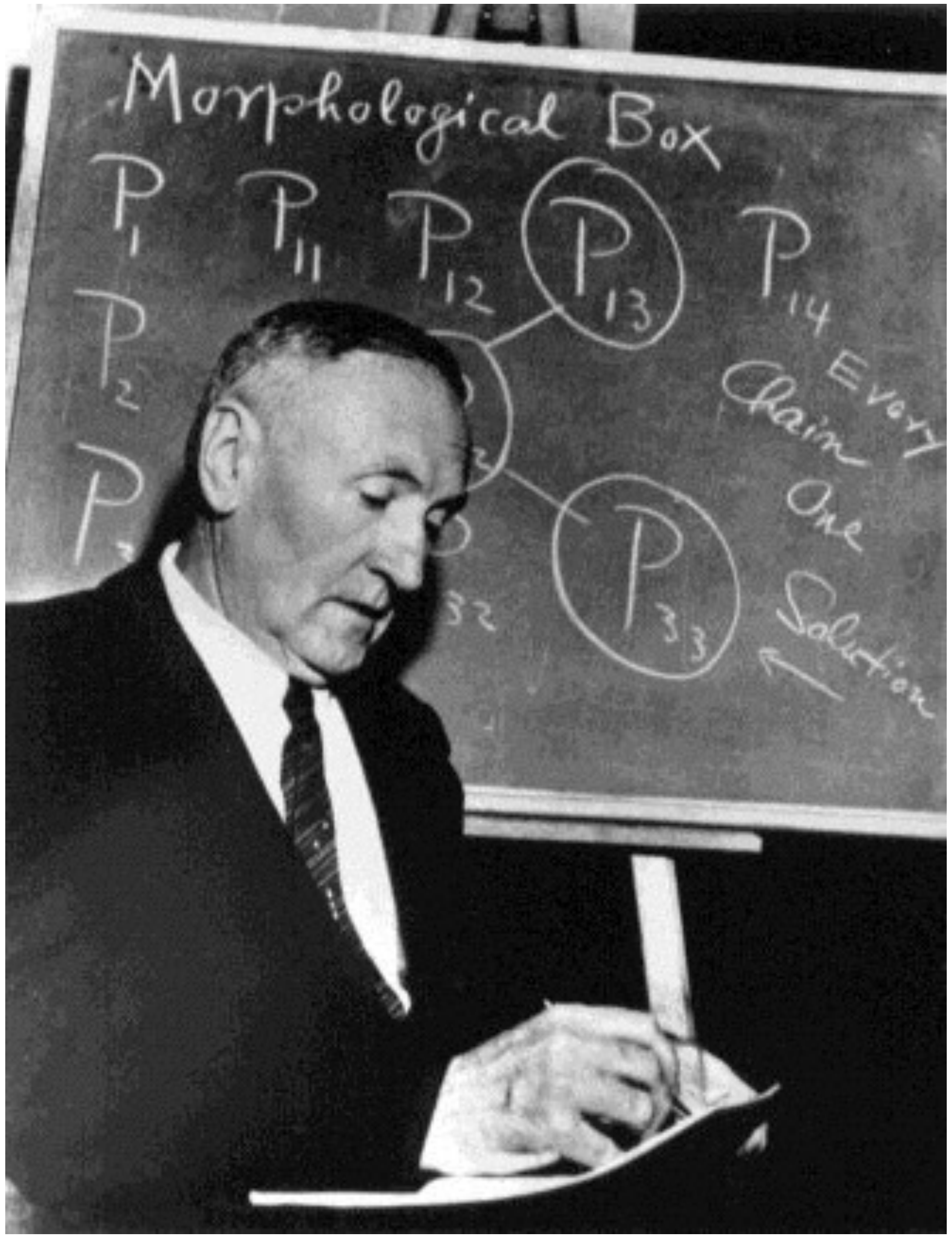
Virial Theorem: $2K = -U$

where:

$$k = \frac{1}{2} M \langle v \rangle^2 \qquad U = \frac{G\ M}{R}$$

Excess in direct mass measurement observed wrt luminosity-based measurements: M~10 M_L

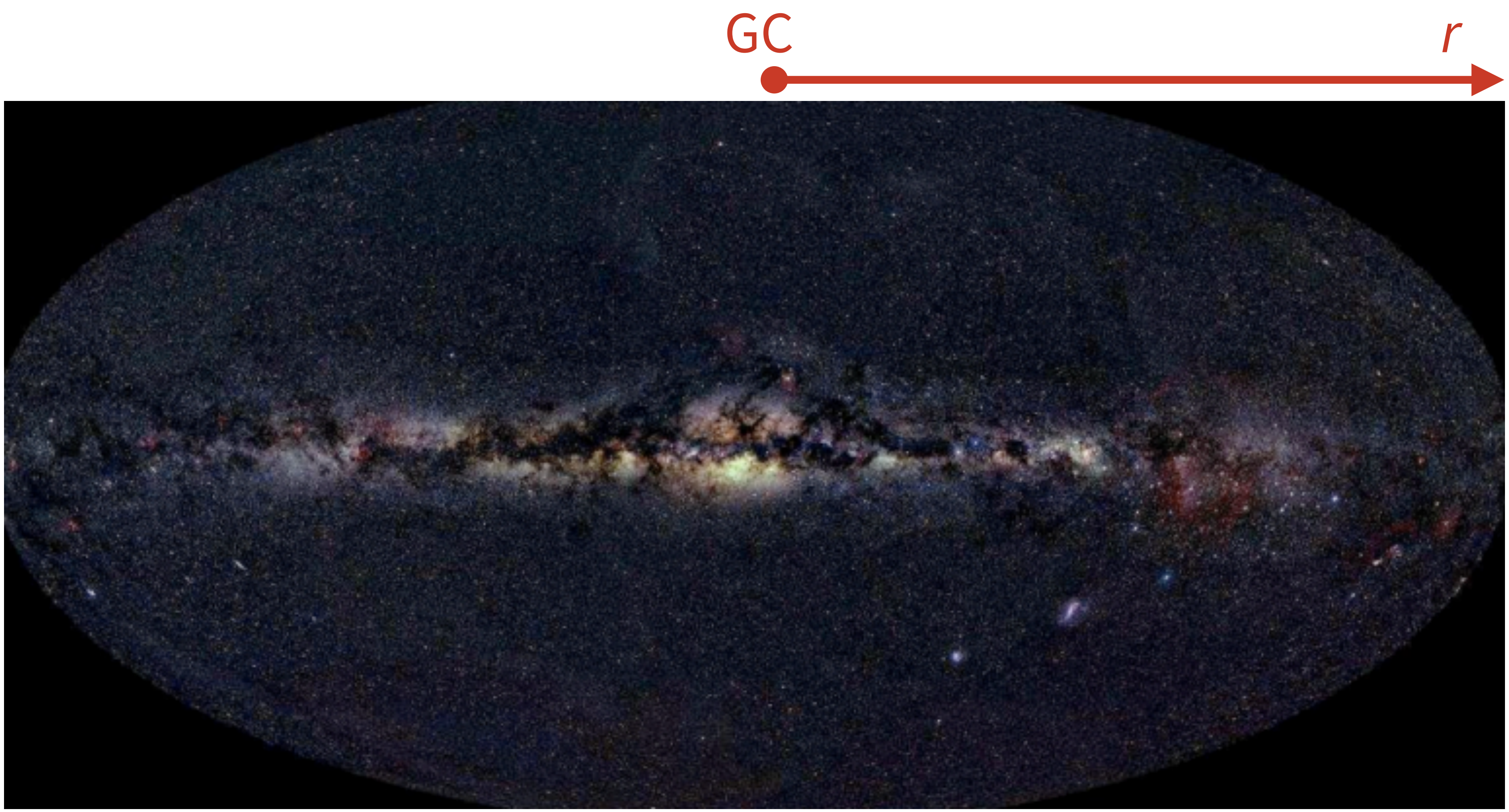
Bulk of matter is DARK



First hints of Dark Matter: 70s/80s

Galactic Rotation Curve: Starts and gas movement within a galaxy depends on the distance r to the Galactic Centre (GC)

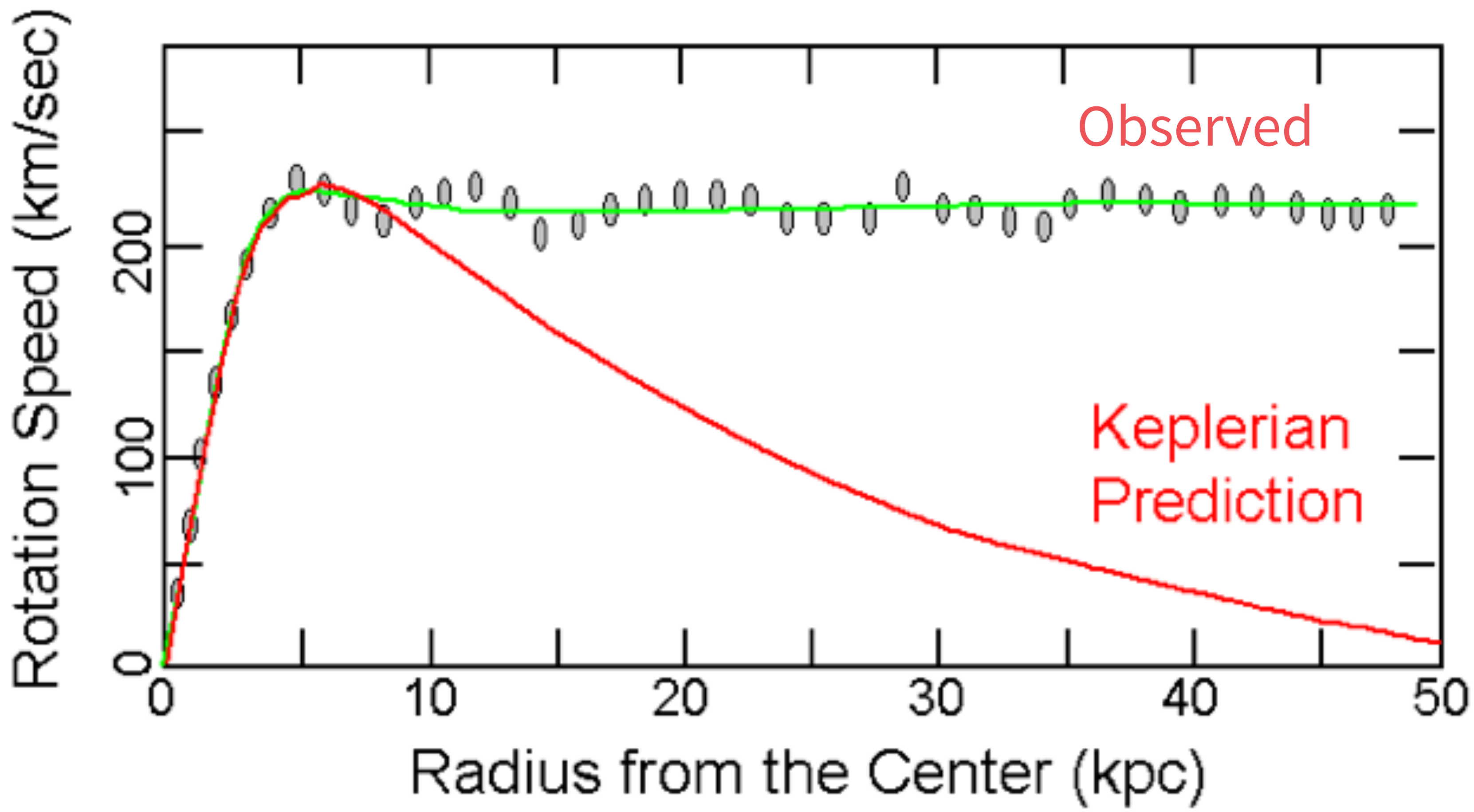
Expected behaviour: $v_r(r) \propto 1/\sqrt(r)$



First hints of Dark Matter: 70s/80s

Galactic Rotation Curve: Starts and gas movement within a galaxy depends on the distance r to the Galactic Centre (GC)

Observed behaviour: $v_r(r \geq R_0) \sim \mathrm{const}$

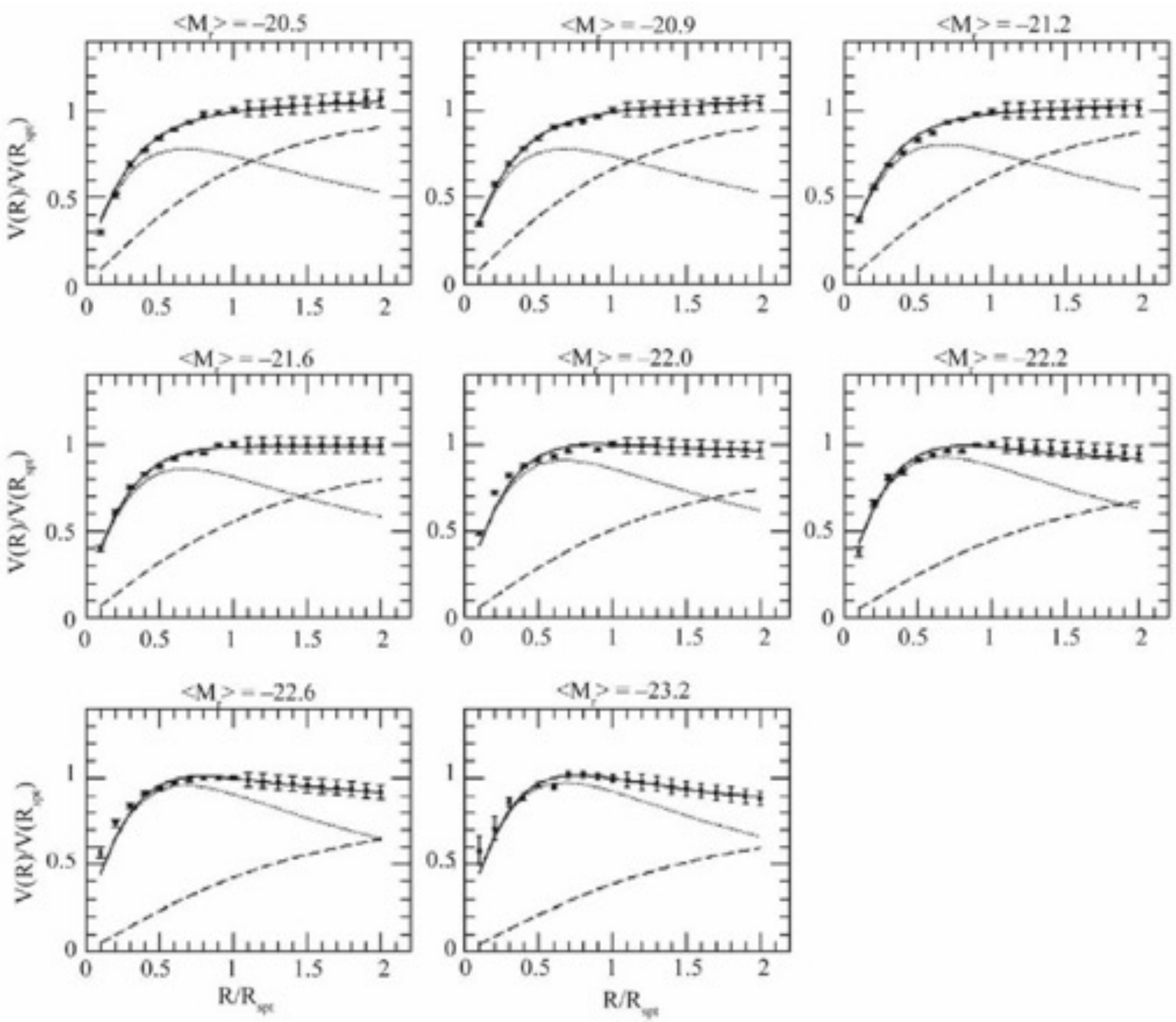


Non-visible mass component which increases with r must exist

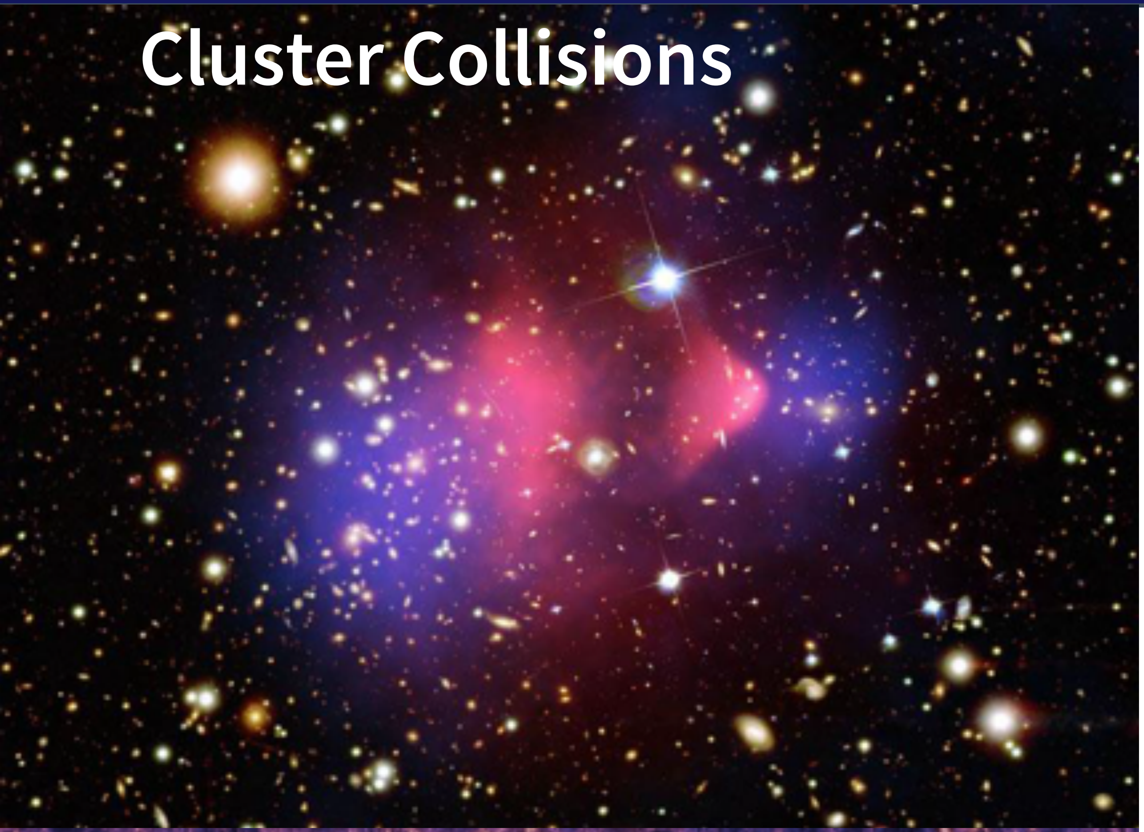
$M(r) \propto R$

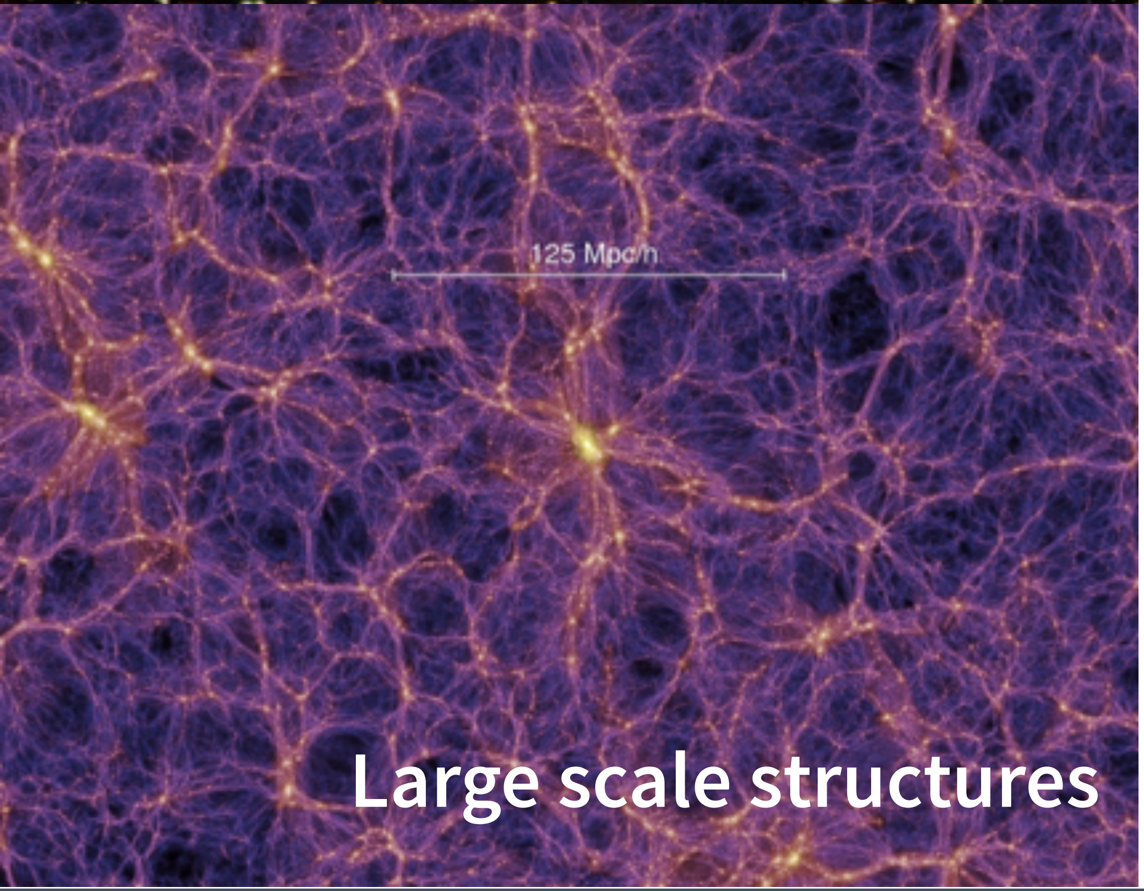
First hints of Dark Matter: 70s/80s

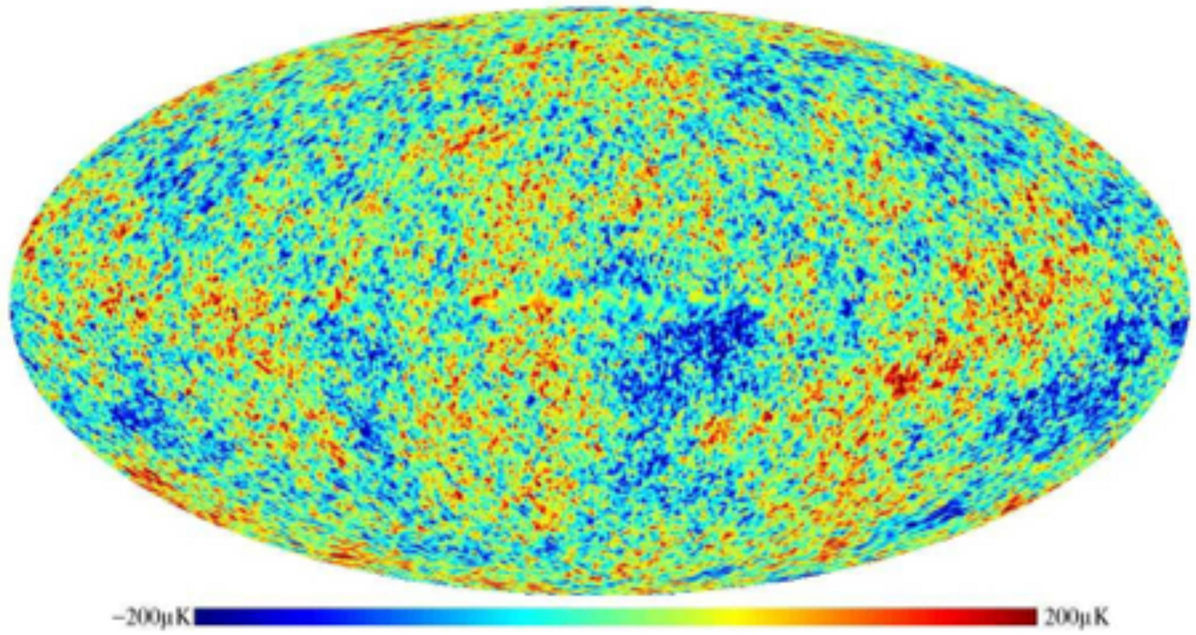
- **Some of the first measurements performed already in 40s by Babcock followed by further studies carried out in 70s/80s by Rubin and her team**
- **Rotation curves measured for many thousands of galaxies**
  - Same flat behaviour observed moving far from the GC



Other evidences following...





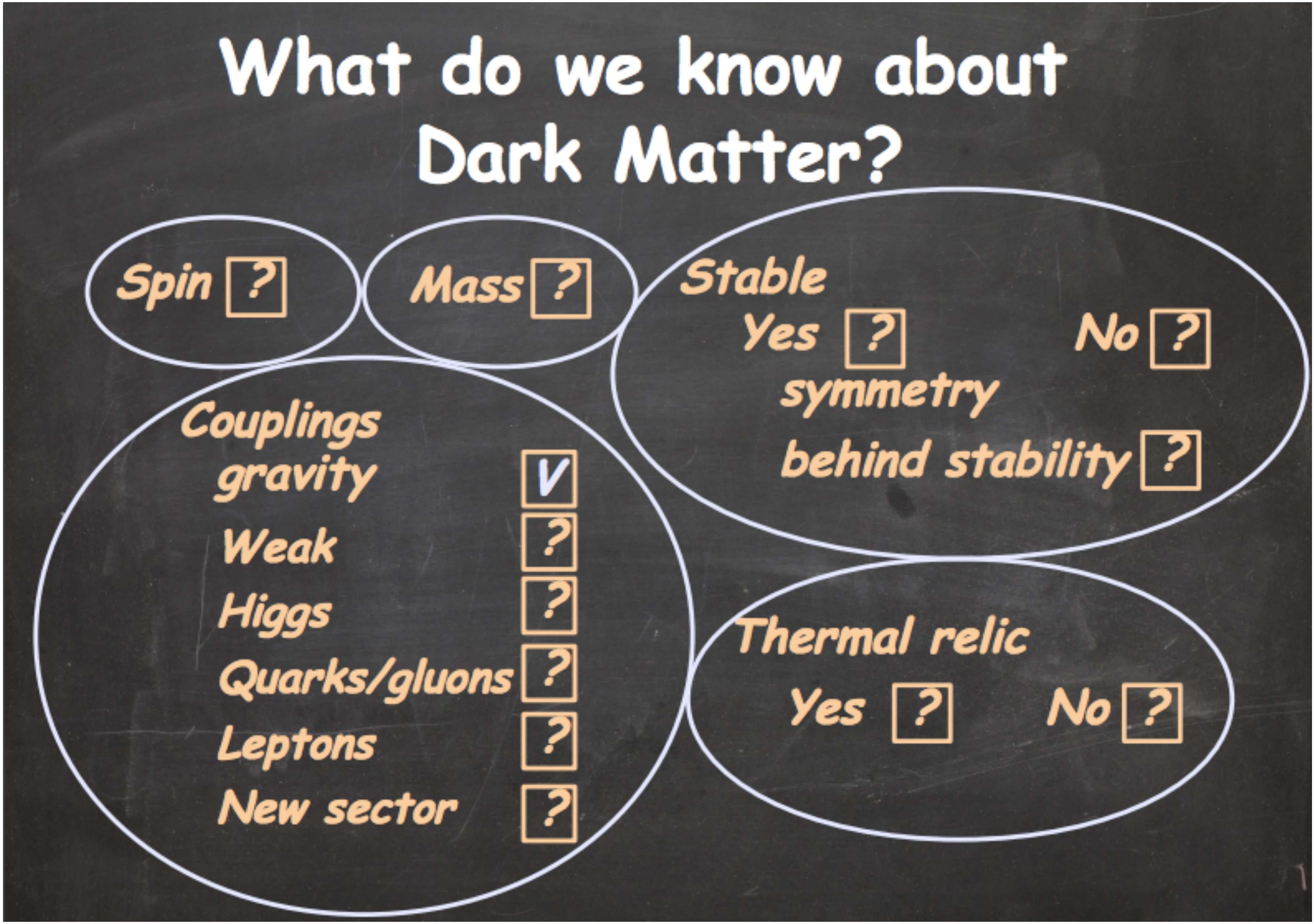


CMB anisotropies

Dark Matter is there outside

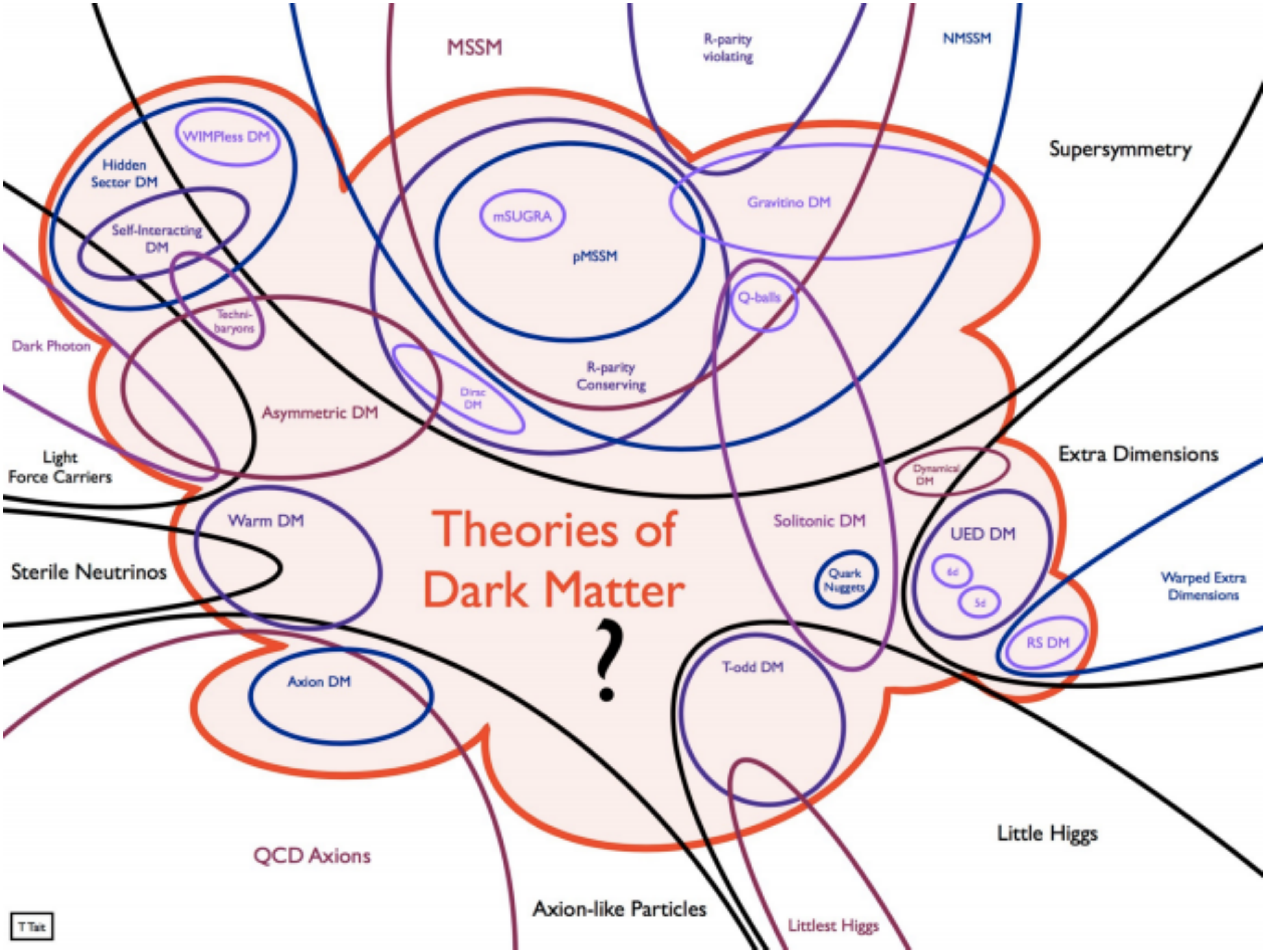
What about its nature?

Dark Matter ID



From A.Belyaev @ Moriond2016

A theory of Dark Matter?



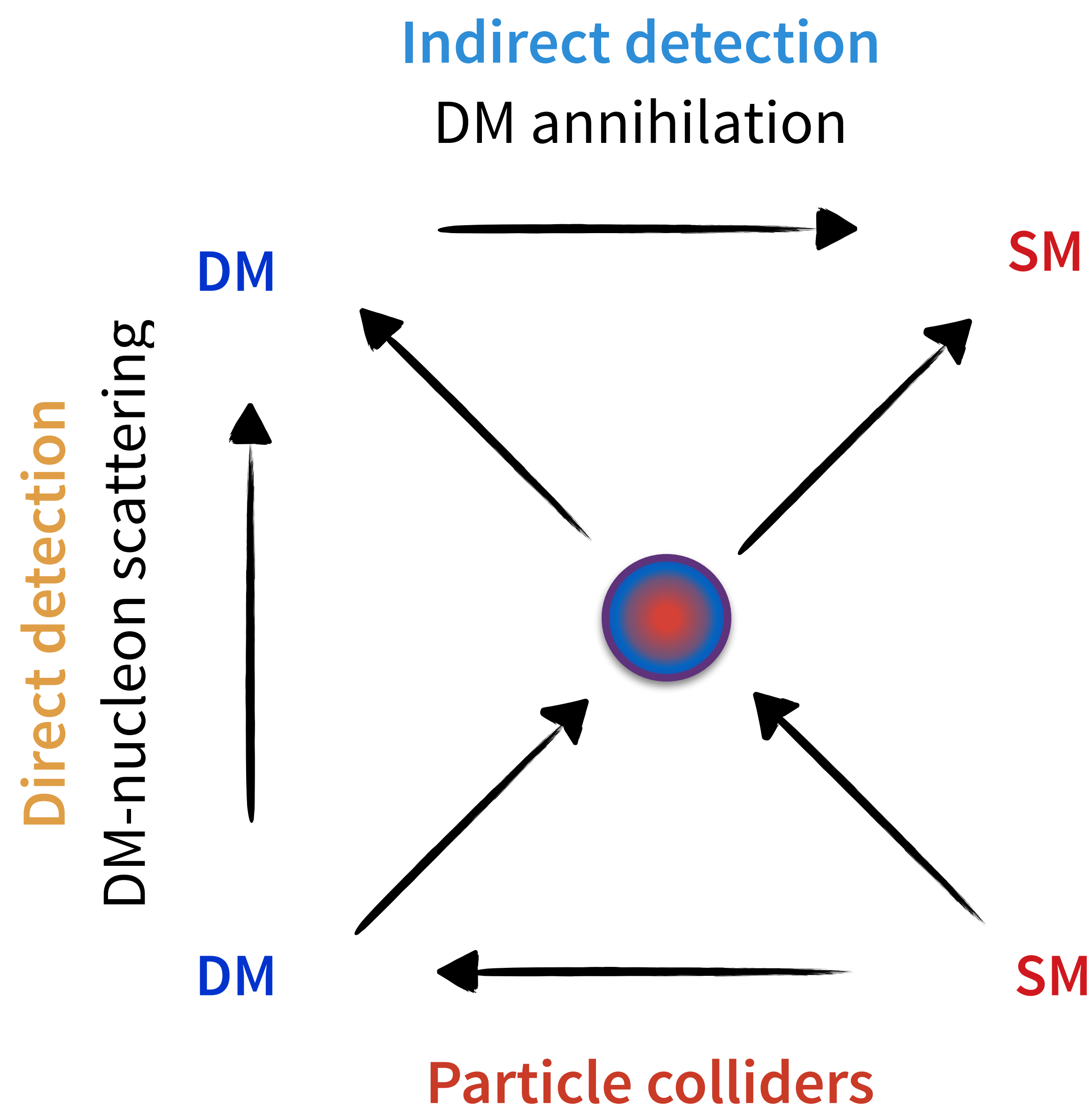
Tim Tait

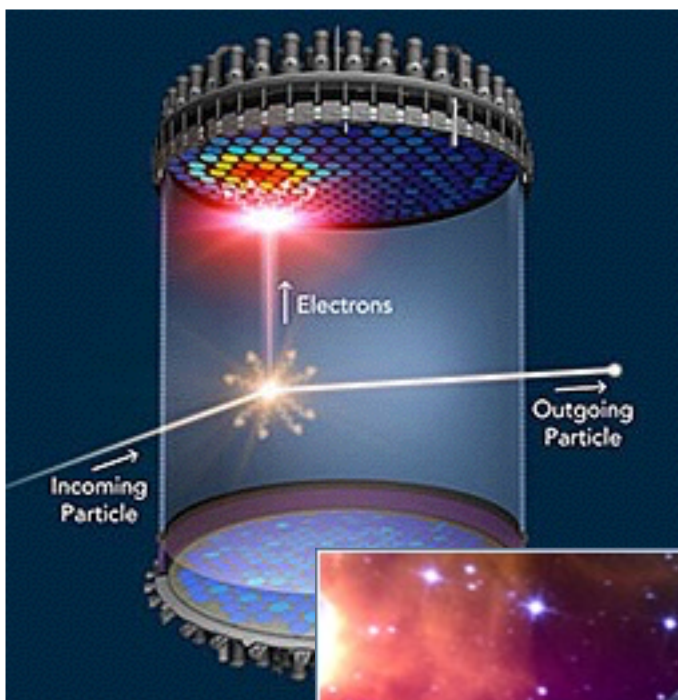
WIMPs

- **Huge variety of hypotheses about DM nature**
  - WIMPs (Weakly Interacting Dark Matter Particles) are the promising candidates:
    - Massive, neutral, stable particles
    - Weakly interacting with SM particles ($\sigma < 10^{-6}$ pb)
- **WIMPs nicely fit matter density in the Universe**

Probing Dark Matter

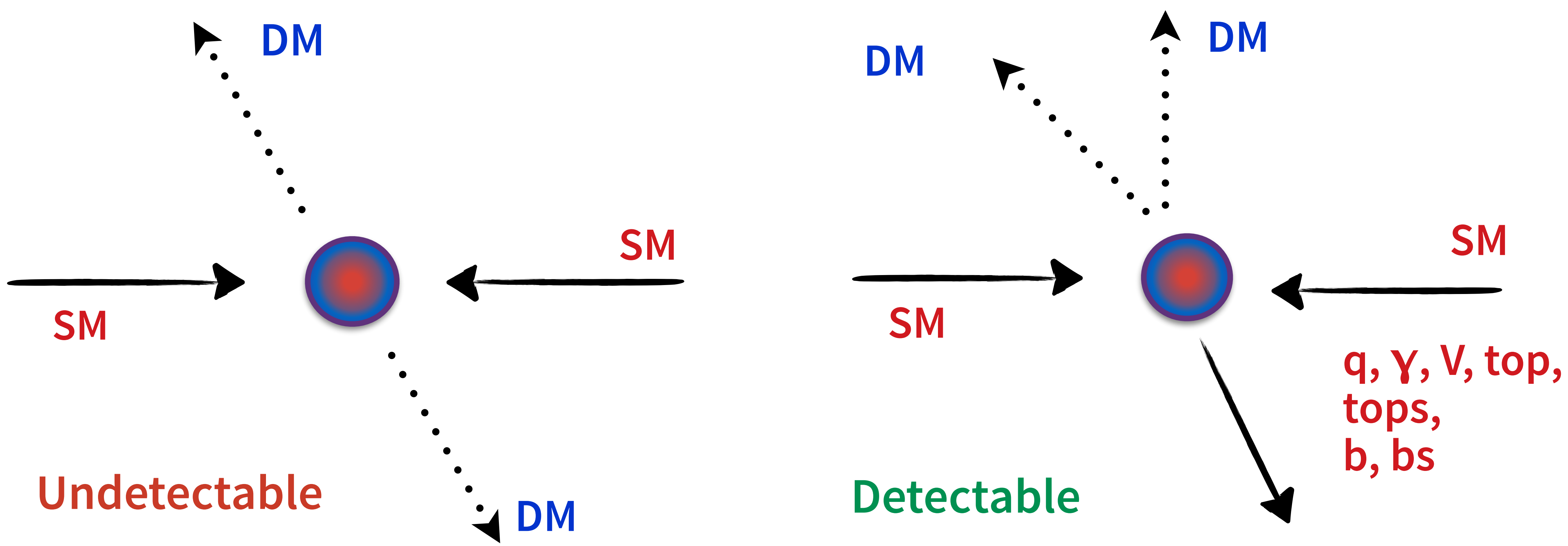
- **Three main strategies to search for weakly interacting DM**
  - Direct detection
  - Indirect detection
  - Production at particle colliders





Producing DM at particle colliders

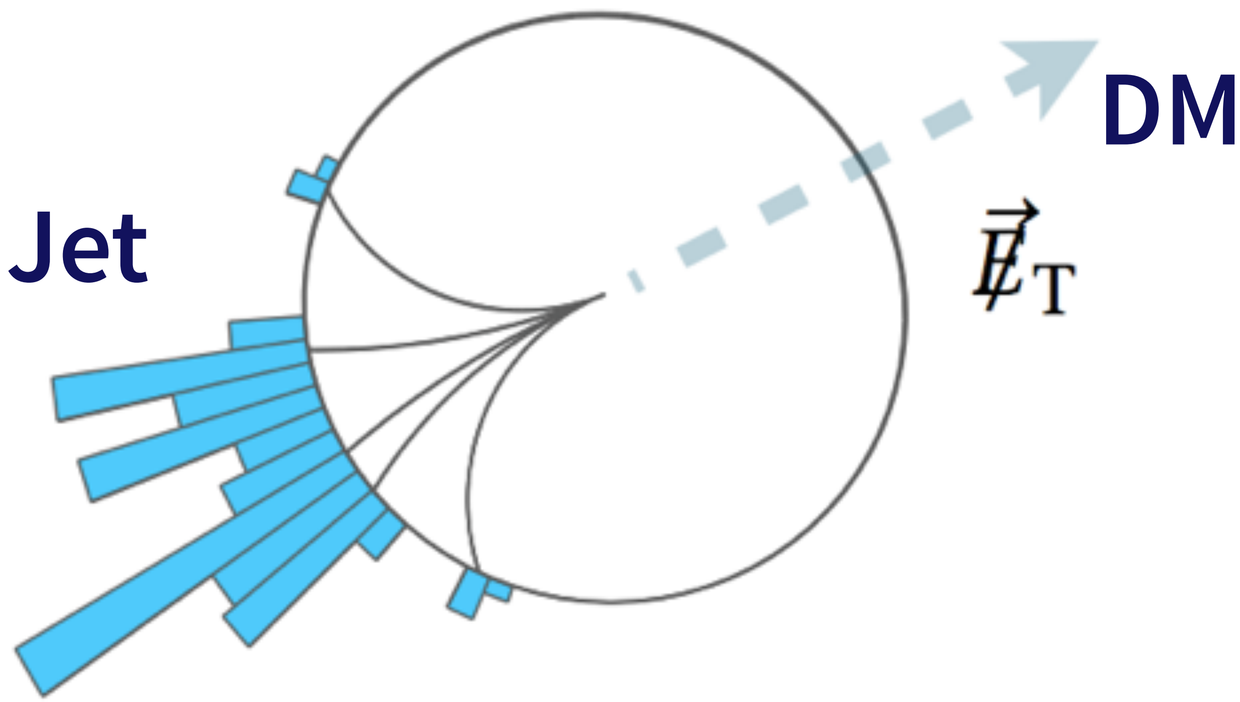
Dark Matter pair production at particle colliders



Dark Matter particles *invisible* to the detector

Visible objects used to flag DM production

Missing transverse momentum



$$E_T^{miss} = -\sum_i {p_T}^i$$

- **Missing transverse momentum** (E_T^{miss}) is defined as *the negative sum of the transverse momenta of all reconstructed particles*
- E_T^{miss} quantifies the energy imbalance due to **invisible particle production**

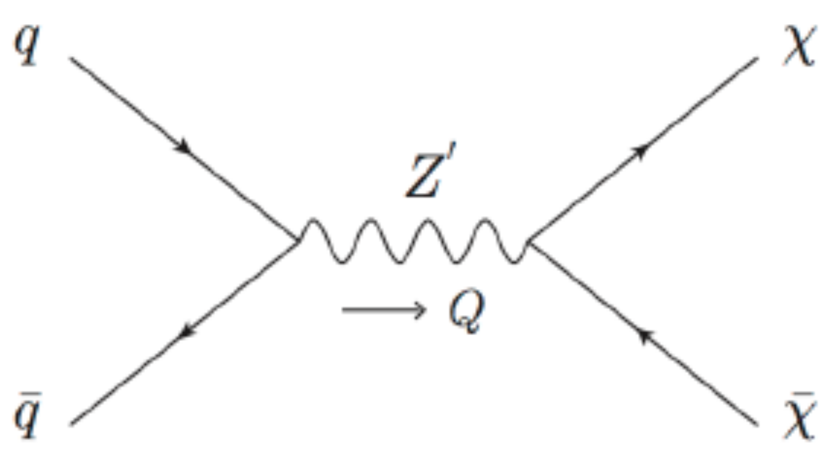
All DM searches at colliders rely on large amount of E_T^{miss}

Outline

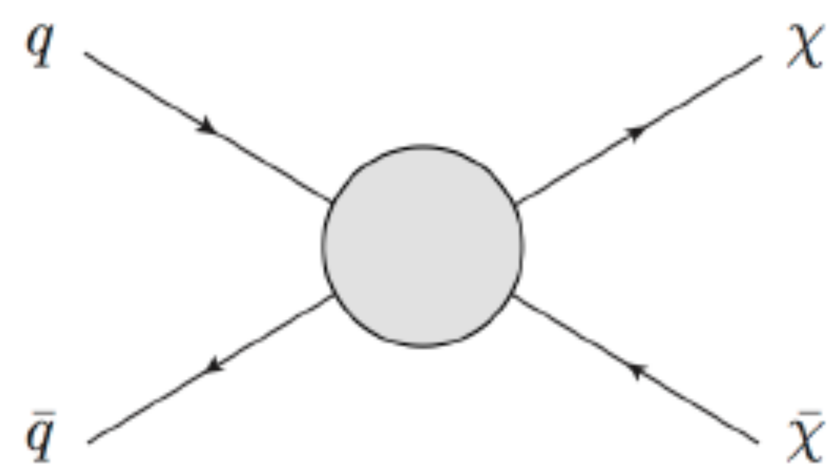
- **Interpretation of Dark Matter searches at LHC**
  - Effective Field Theory framework
  - Simplified Models
  - Interplay of direct searches and searches at colliders
- **DM searches at CMS and ATLAS**
  - Signal identification and background estimation techniques
  - DM detection channels
    - DM + ISR jet/s
    - DM + Vector bosons
    - DM + Heavy Flavour quarks
  - Results from LHC Run-II
- **Conclusions**

Effective Field Theory

Interpret the search in terms of Effective Field Theory (EFT)



if $Q \ll M_{Z'}$



2 theory parameters

- Dark Matter particle mass m_χ
- Interaction scale $M^* = M_{med}/\sqrt{(g_\chi g_q)}$

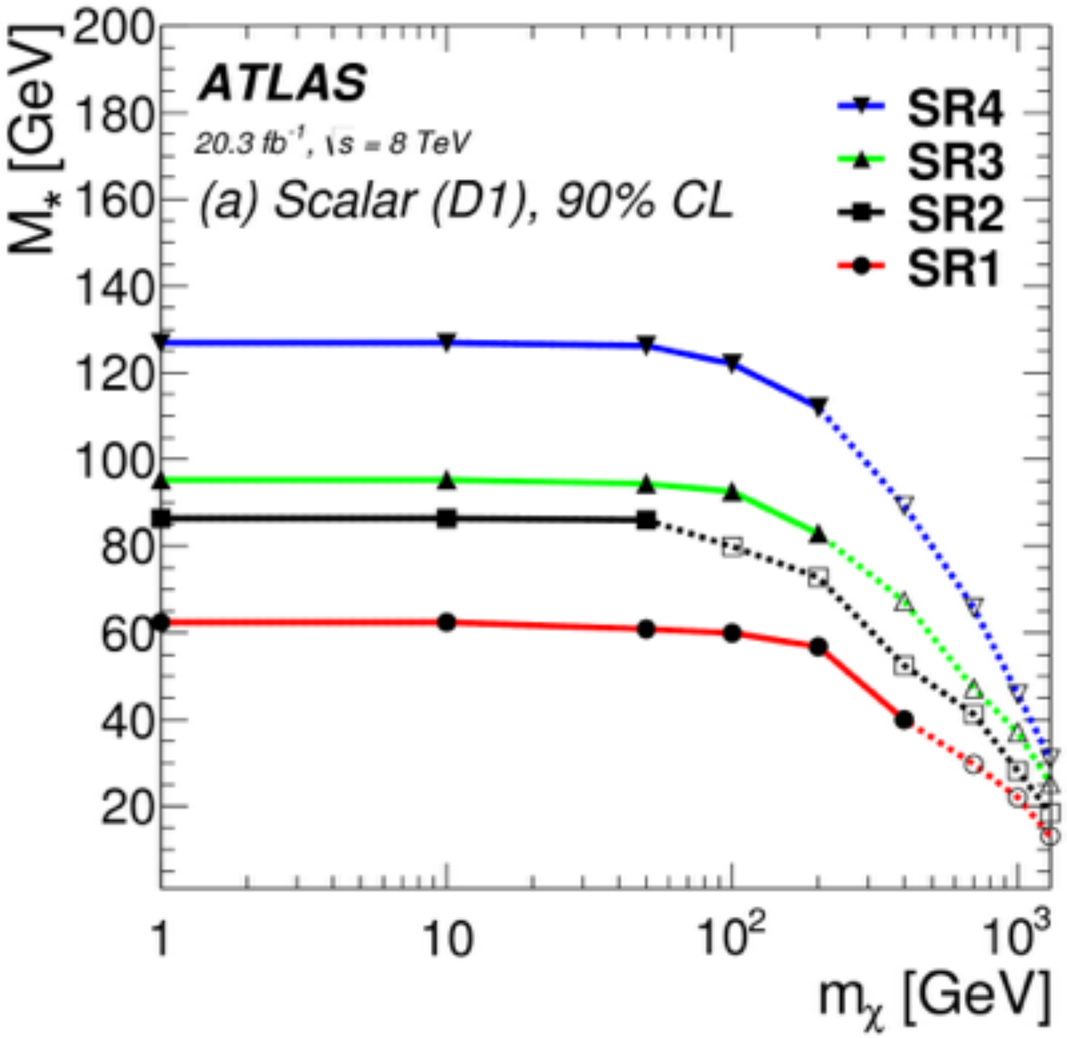
Plus interaction nature

Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

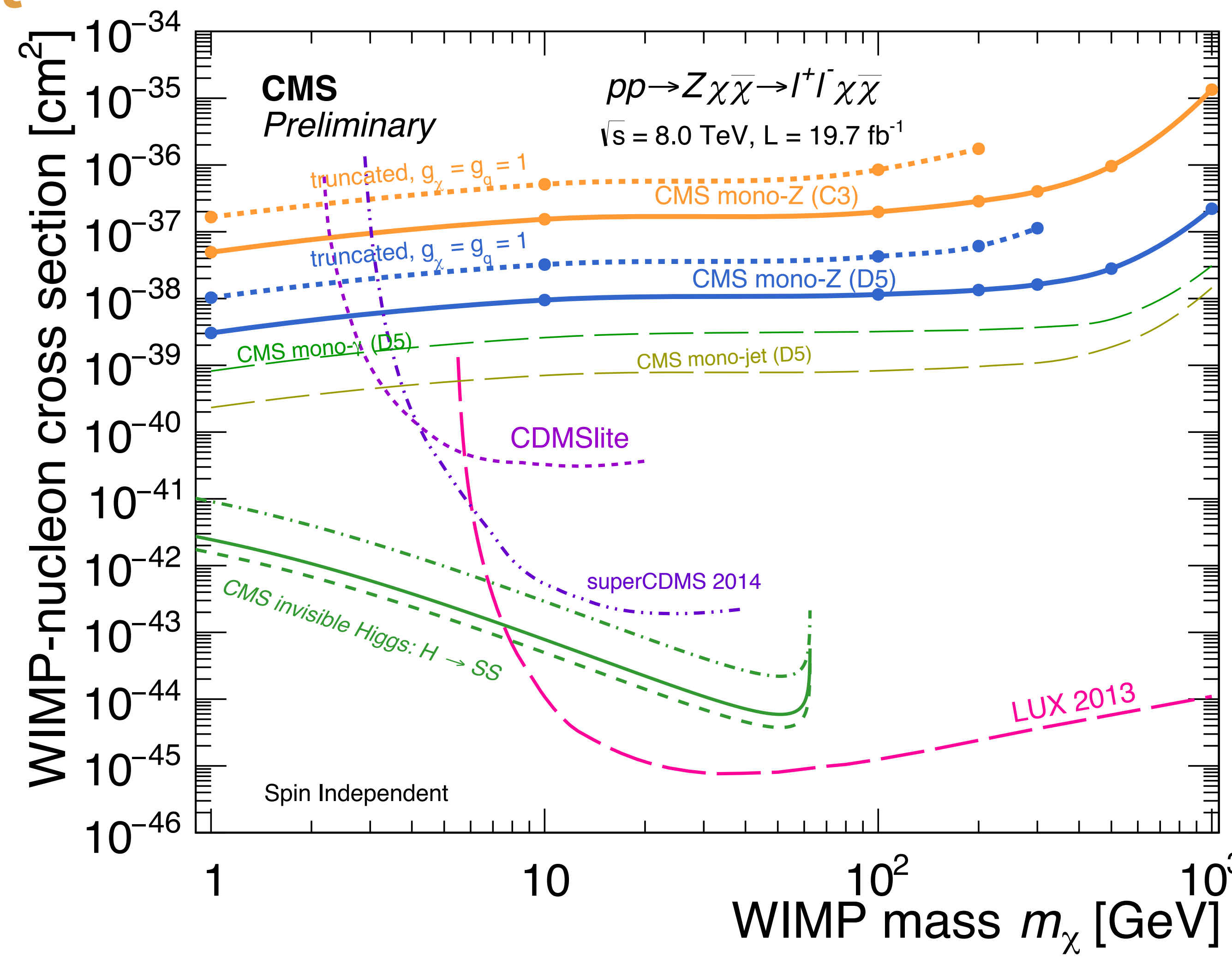
Comparison to DD experiments

EFT allow a comparison to direct detection searches

Constraint on M*



Constraint on σ_{DM-n}



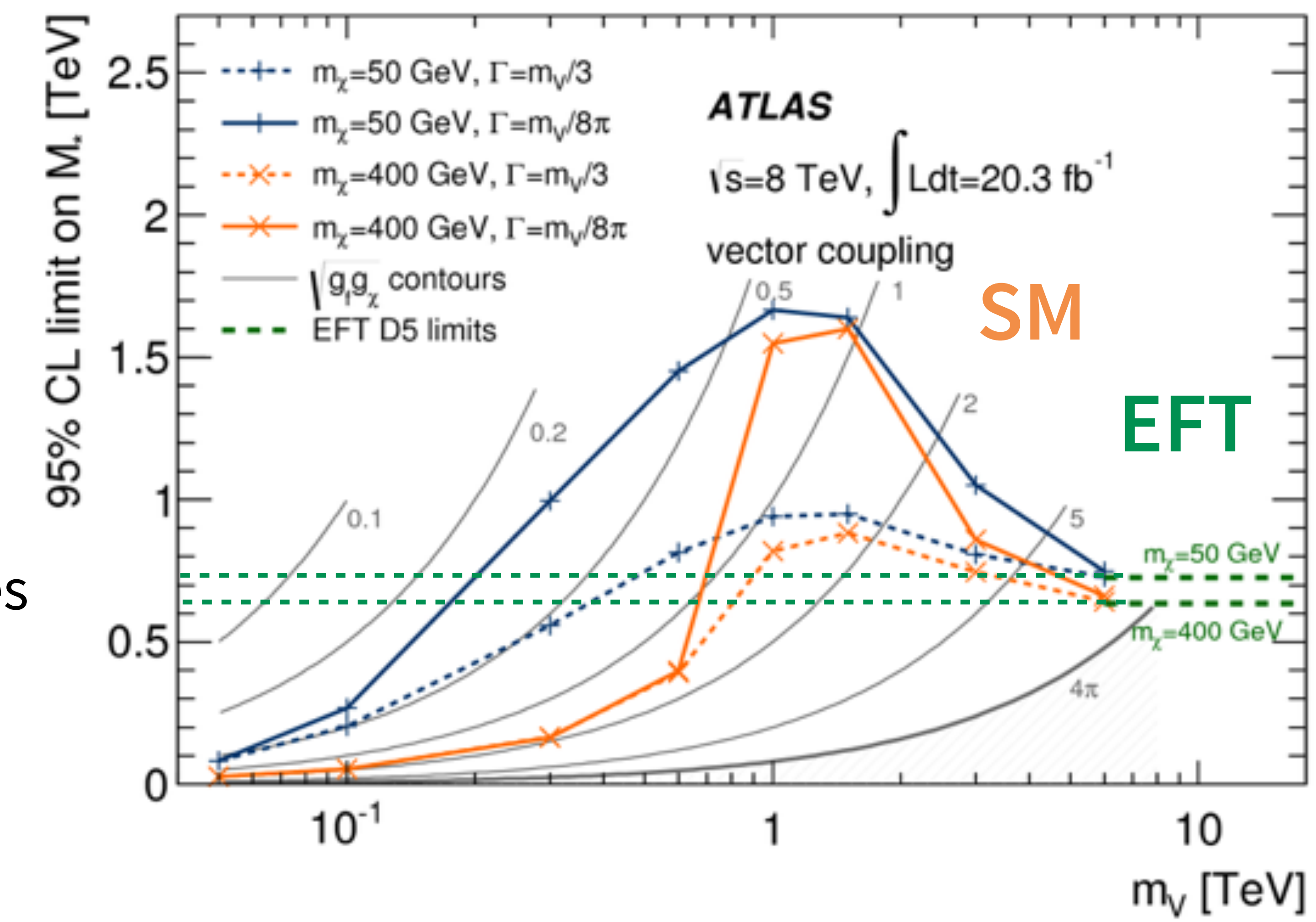
Collider searches sensitive to low DM mass region

Complementarity to DD experiments

EFT limitations

EFT doesn't correctly accounts for kinematics and is not valid for $Q < m_{MED}$

- **High m_{Med}:**
  - EFT consistent with SM
- **Intermediate m_{Med}:**
  - On-shell production increases σ
  - EFT limits too weak
- **Low m_{Med}:**
  - Off-shell production → σ decreases
  - Events are softer
  - EFT limits too strong



EFT not an appropriate approach to reach a comprehensive interpretation of DM searches

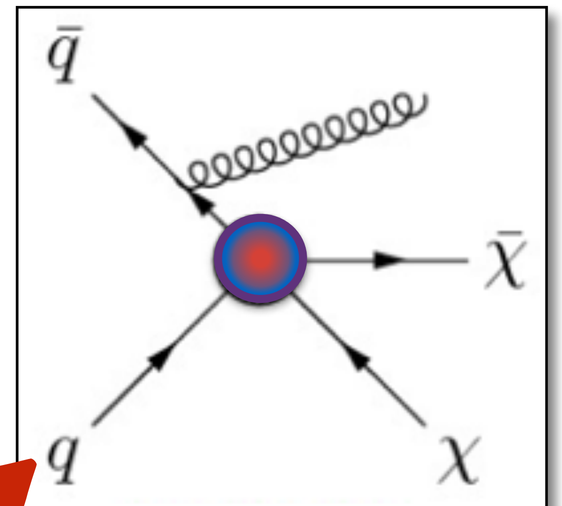
Beyond EFT: Simplified models

EFT validity issue [if Q > M_{med}]

Critical at high energies

$$\sigma \propto \frac{1}{M^{*4}}$$

[M*, m_χ]



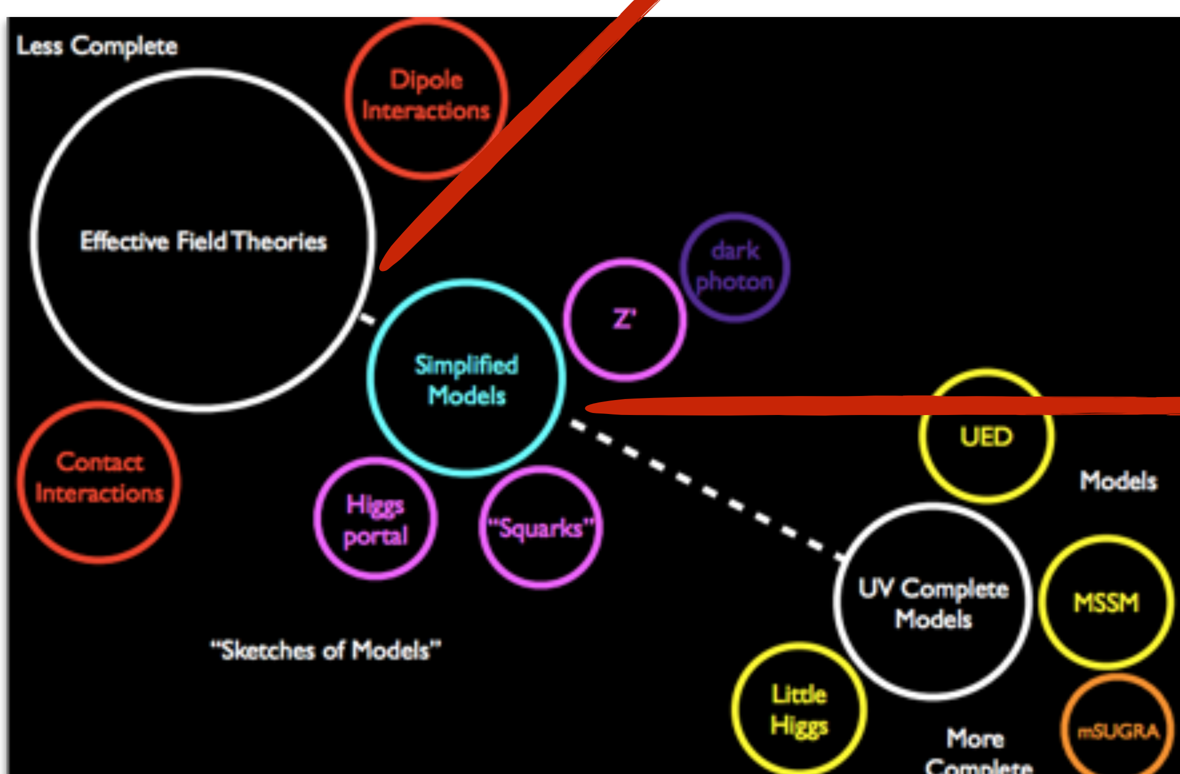
Simplified Models

Overcome EFT validity issue

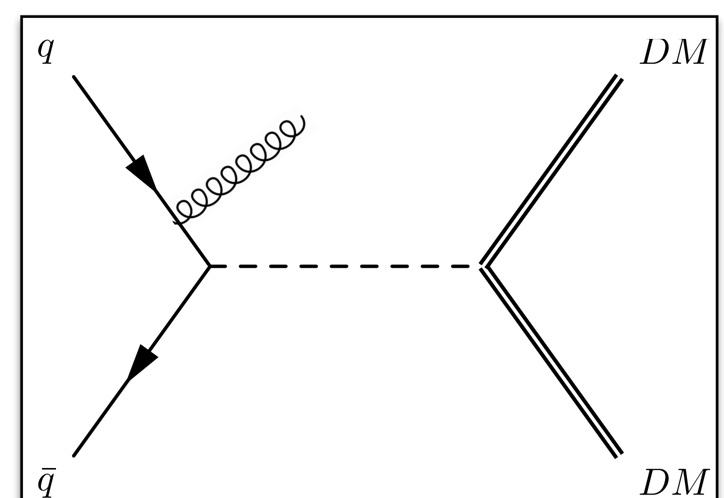
Direct access to the mediator

$$\sigma \propto \frac{g_{SM}^2 g_{DM}^2}{M_{med}^4}$$

Tim Tait, DM@LHC 2013

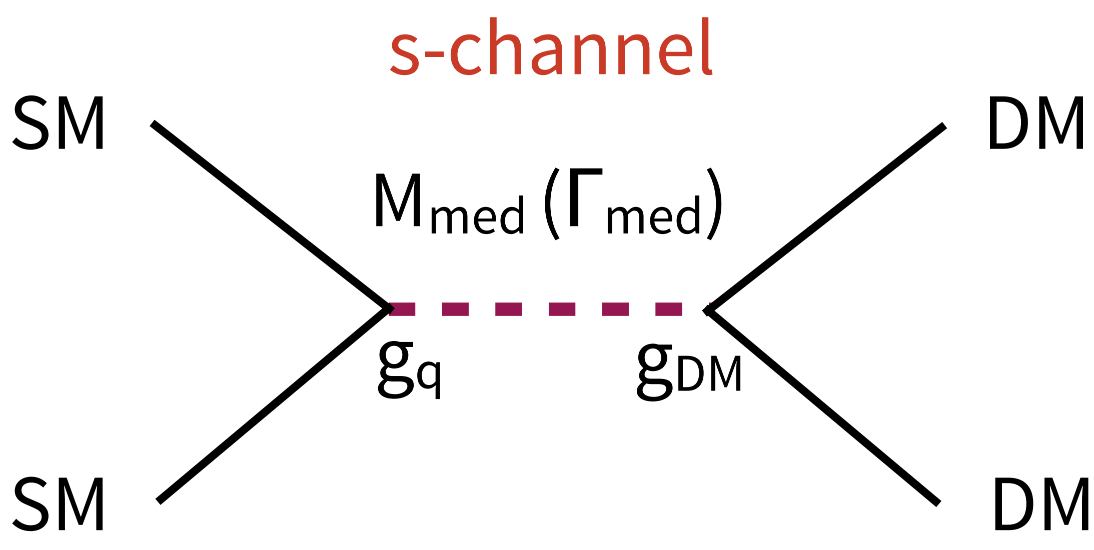


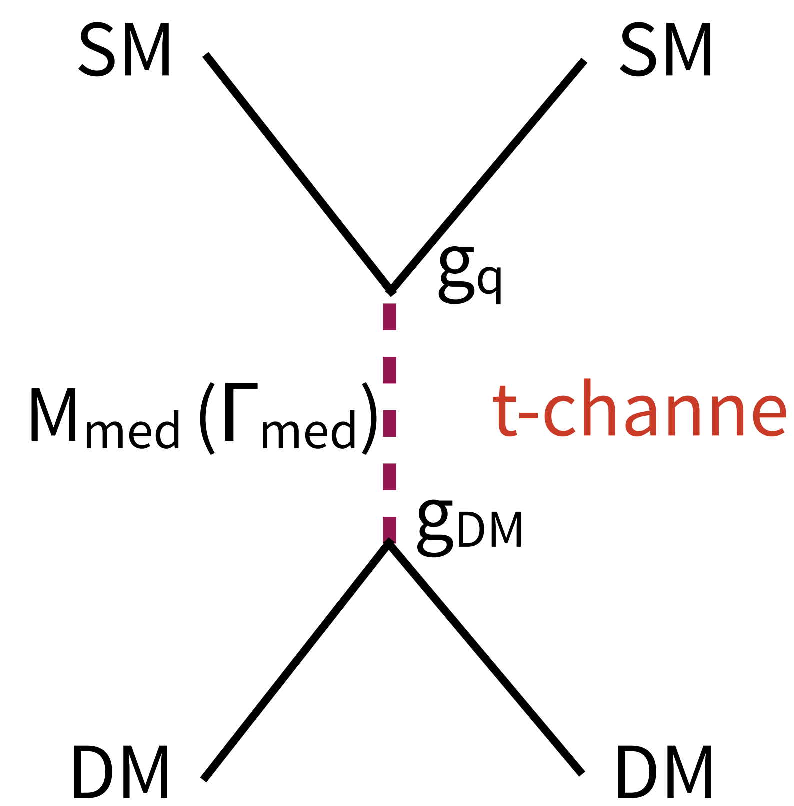
[M_{med}, Γ_{min}, m_χ, g_{SM}, g_{DM}]



Simplified Models

DM production characterised by a small set of parameters





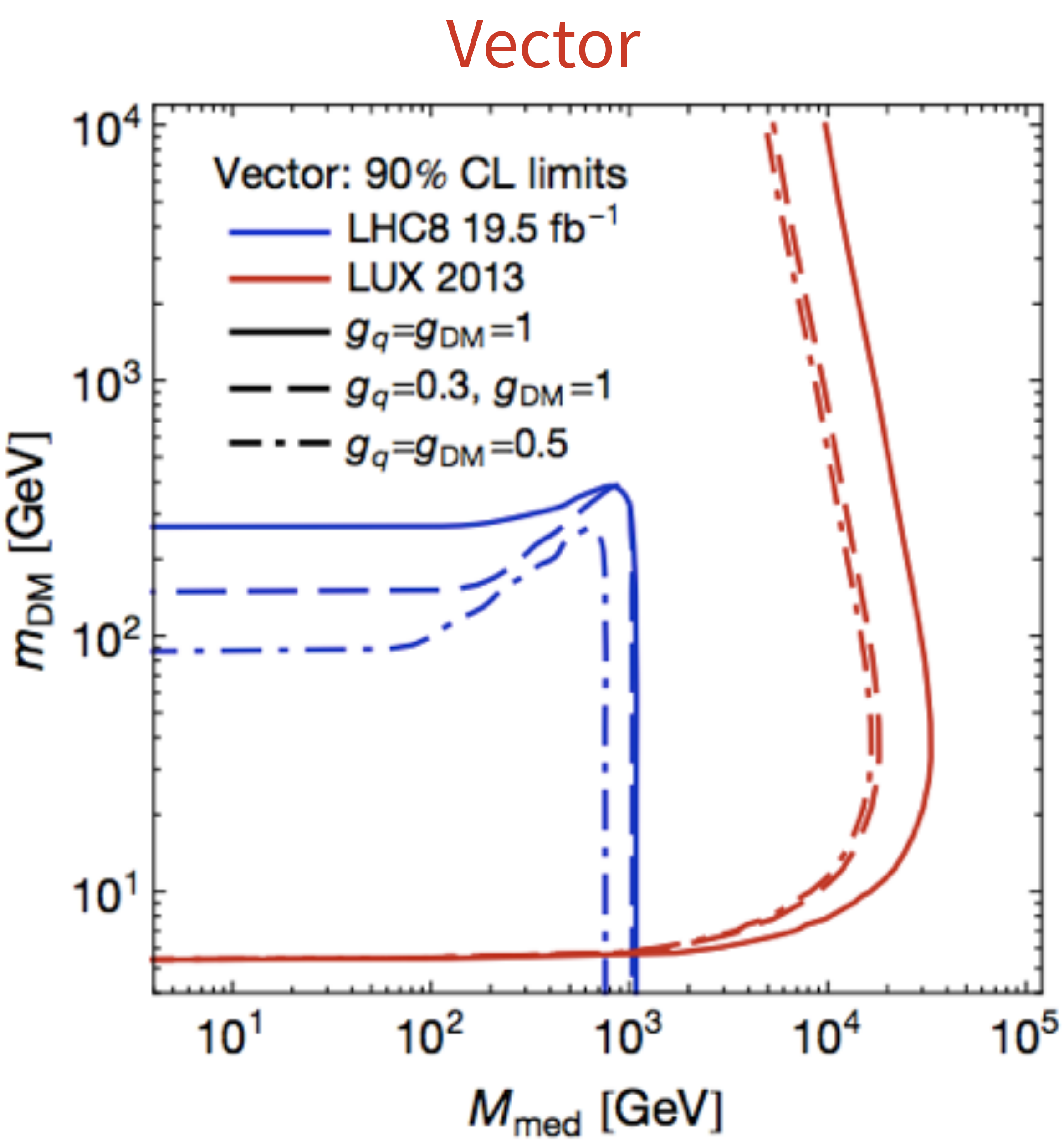
4 parameters	
m_{DM}	M_{med}
g_q	g_{DM}

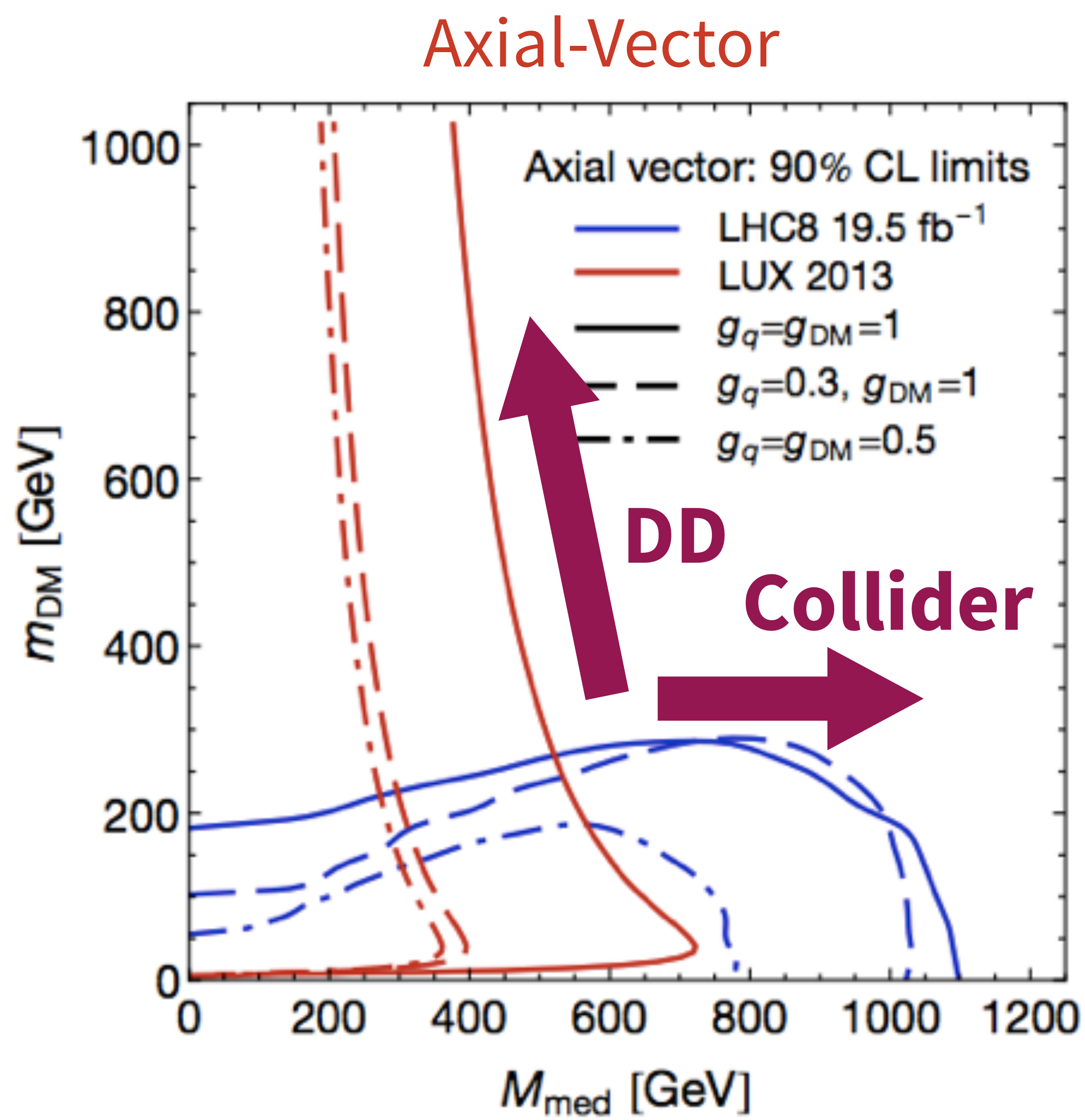
Mediators	
Vector	Axial-Vector
Scalar	Pseudo-Scalar

Dirac fermion DM particle

LHC DM Forum: arXiv:1507.00966

Collider vs Direct Detection

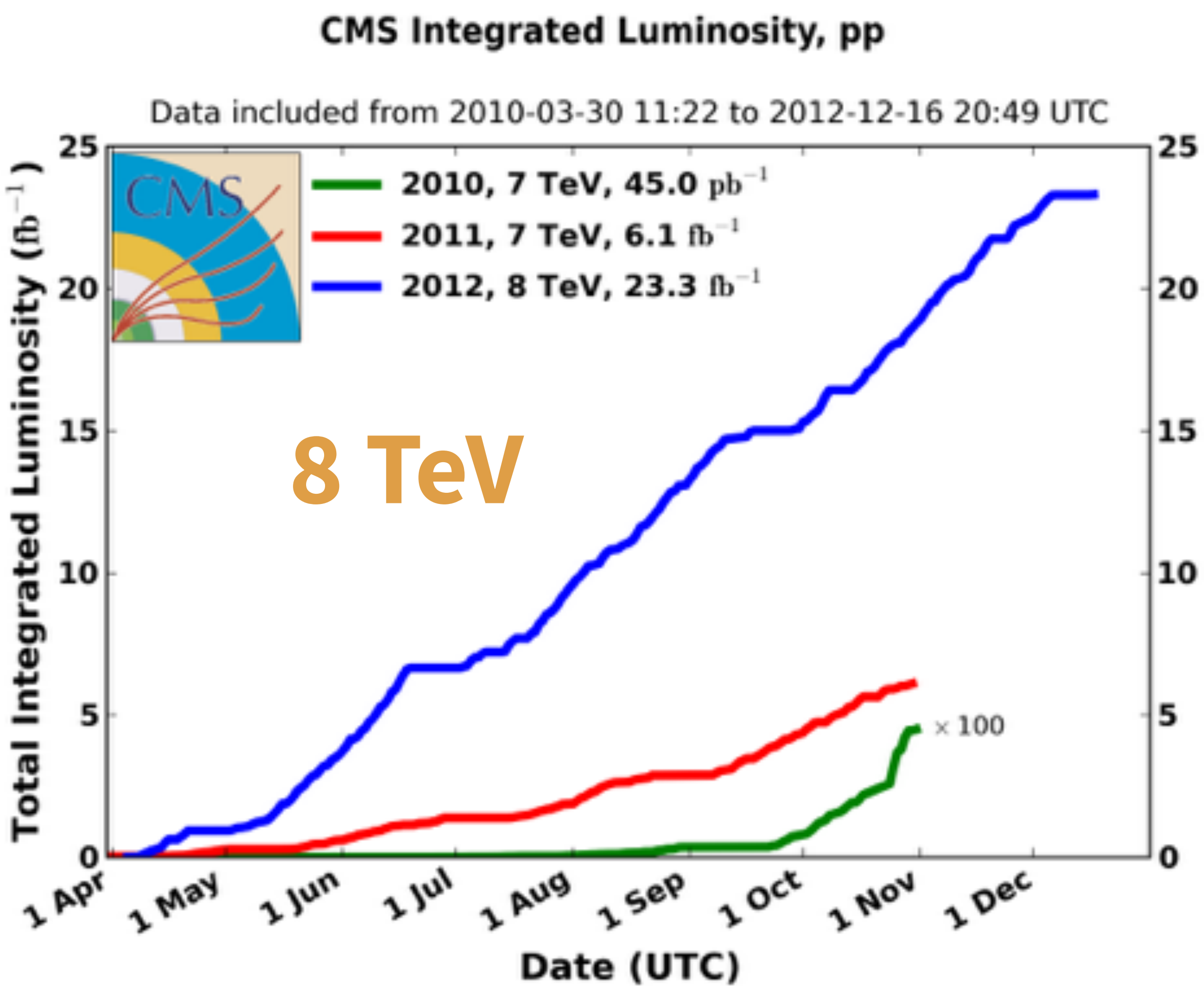


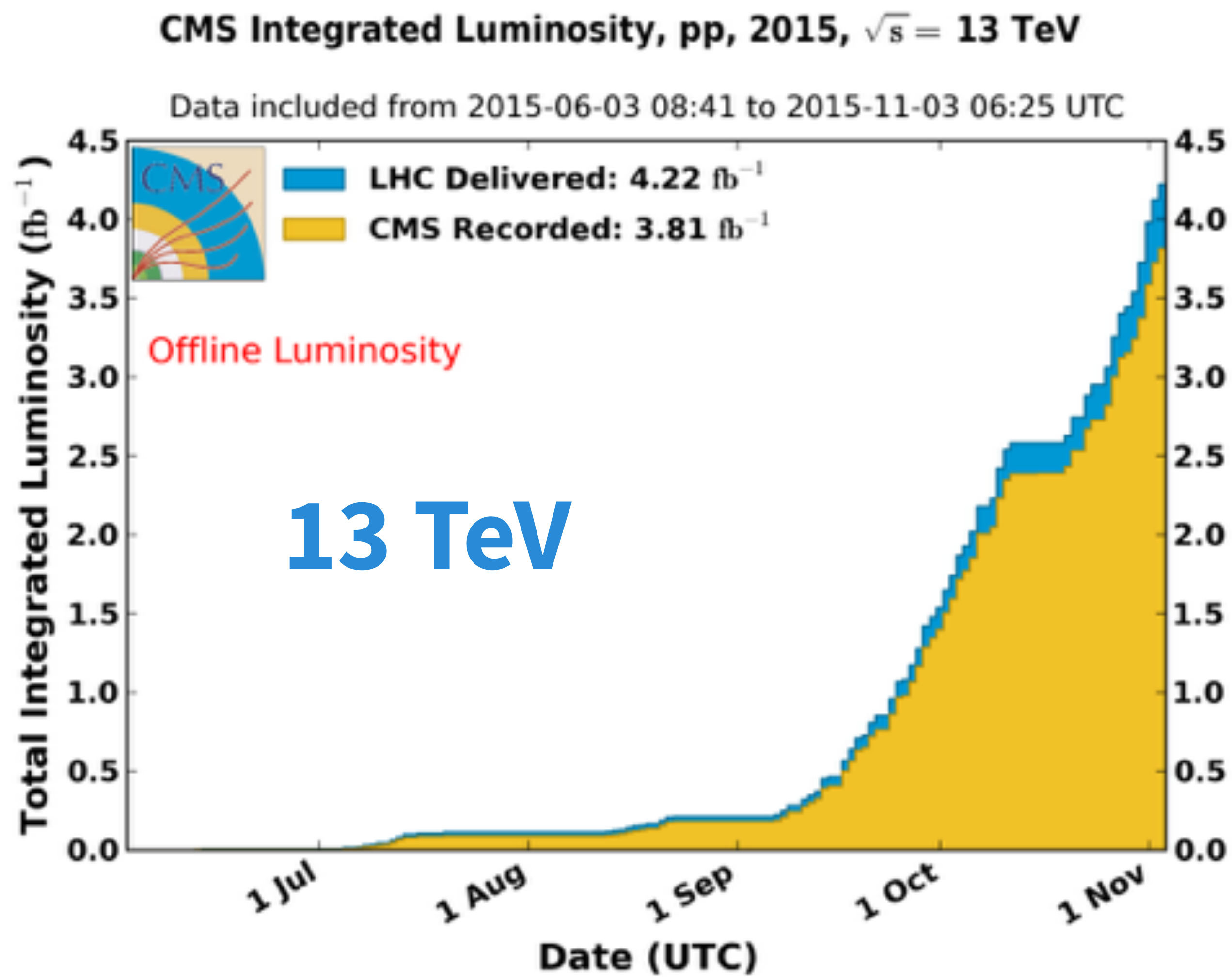


Direct detection limited at m_{DM} ~ 6 GeV

LHC p-p collision harvest

~25 fb^{-1} of p-p data delivered by LHC @ 8 TeV in 2012



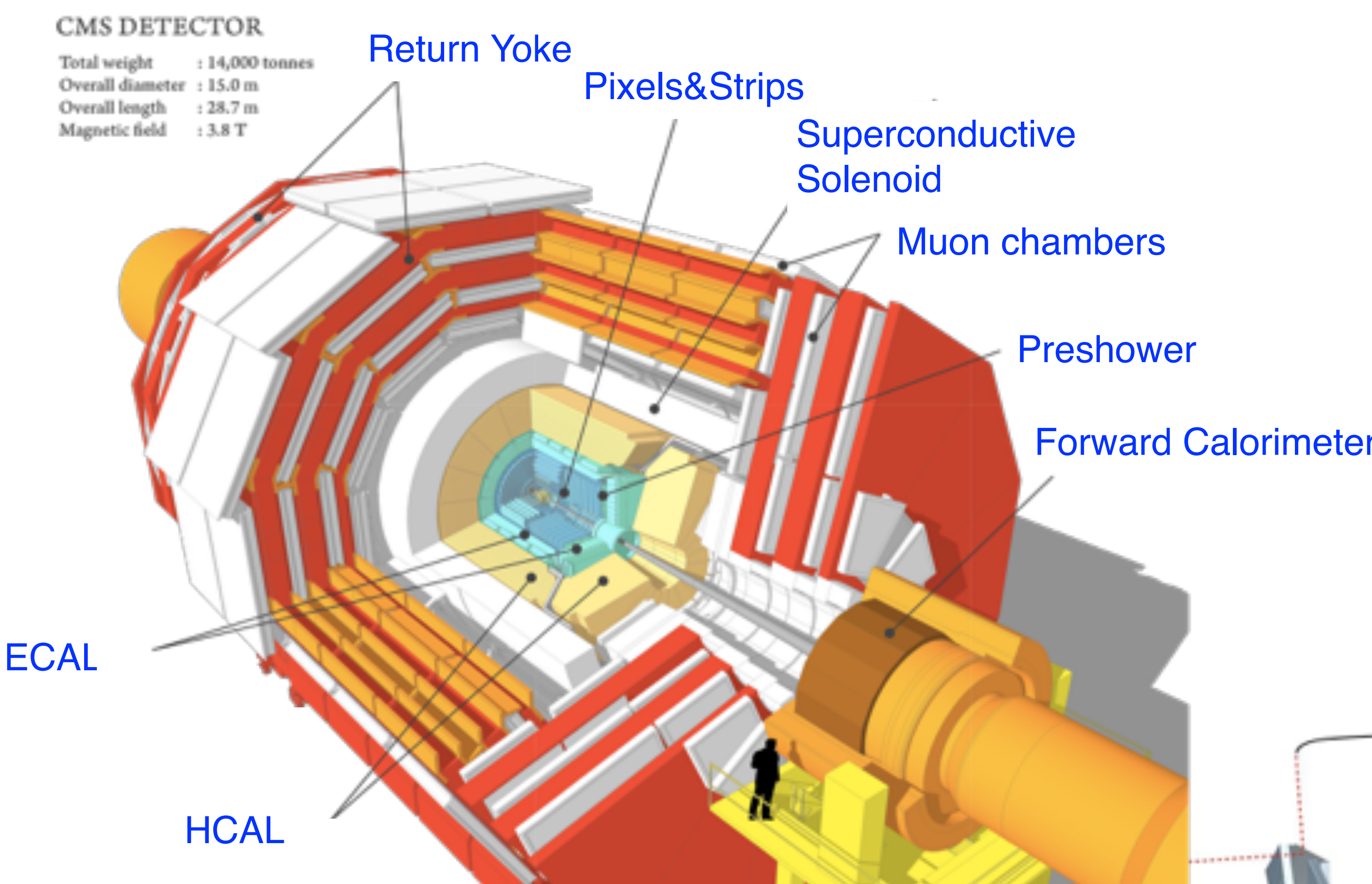


2015 → centre-of-mass energy raised up to **13 TeV**

~4 fb^{-1} of p-p data delivered in 2015

~ 25 fb^{-1} expected in 2016

ATLAS and CMS

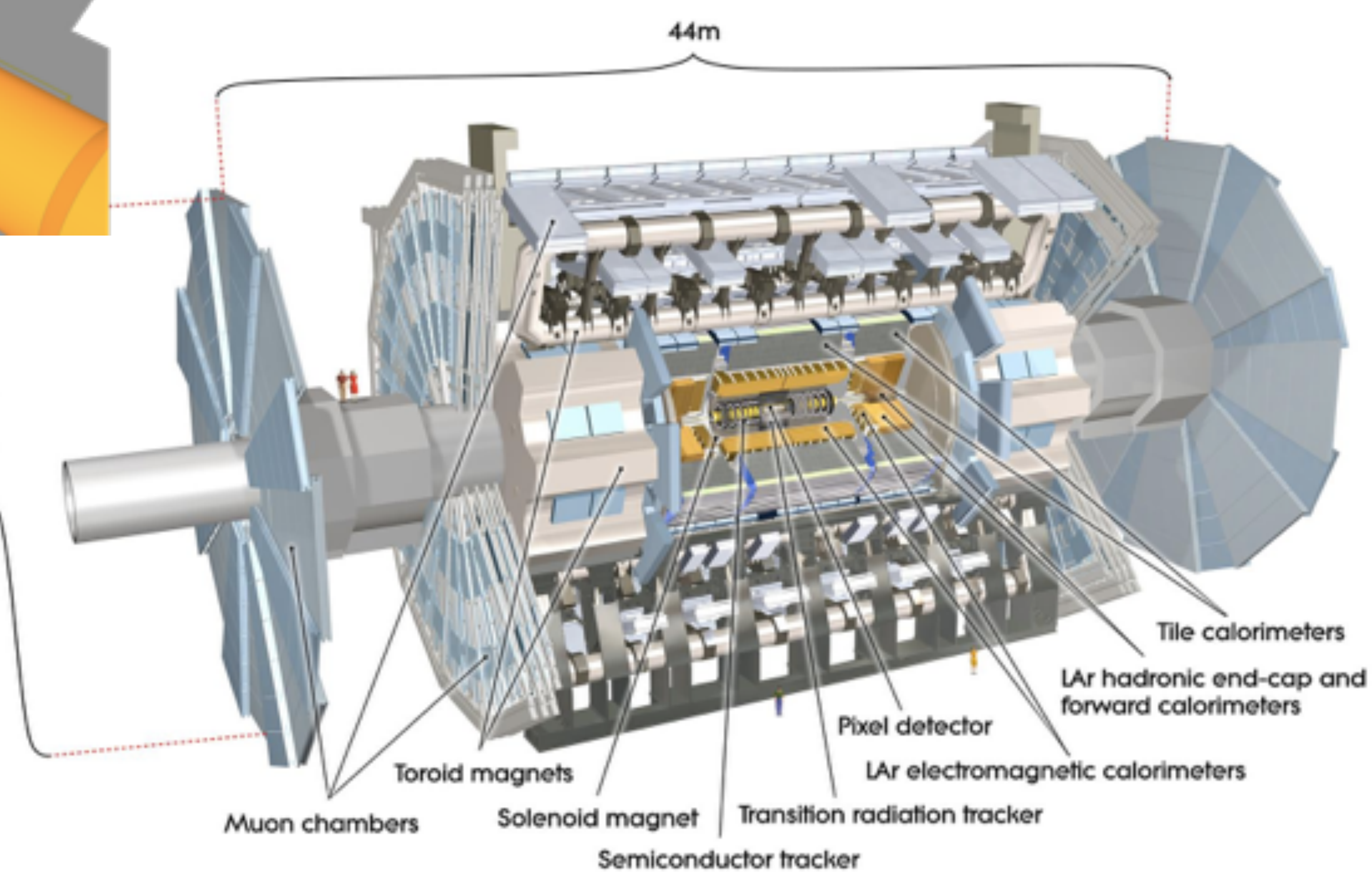


CMS

- Tracker: $\sigma(p_T)/p_T \sim 1.5 \cdot 10^{-4} p_T + 0.005$
- ECAL: $\sigma_E/E \sim 3\%/\sqrt{E}$ [GeV] $\oplus$ 0.5%
- HCAL: $\sigma_E/E \sim 100\%/\sqrt{E}$ [GeV] $\oplus$ 5%
- Trk+Mu: 1%÷10% [50 GeV-1 TeV]

ATLAS

- Tracker: $\sigma(p_T)/p_T \sim 5 \cdot 10^{-4} p_T + 0.01$
- ECAL: $\sigma_E/E \sim 10\%/\sqrt{E}$ [GeV] $\oplus$ 0.7%
- HCAL: $\sigma_E/E \sim 50\%/\sqrt{E}$ [GeV] $\oplus$ 3%
- Trk+Mu: 2%÷10% [50 GeV-1 TeV]



Experimental Approach to DM searches

Select events with large amount of missing momentum

Indicates production of WIMPs

↓

Reconstruct visible objects to flag DM production

Jet/s from ISR, Vector bosons (W, Z, γ), top or bottom quarks

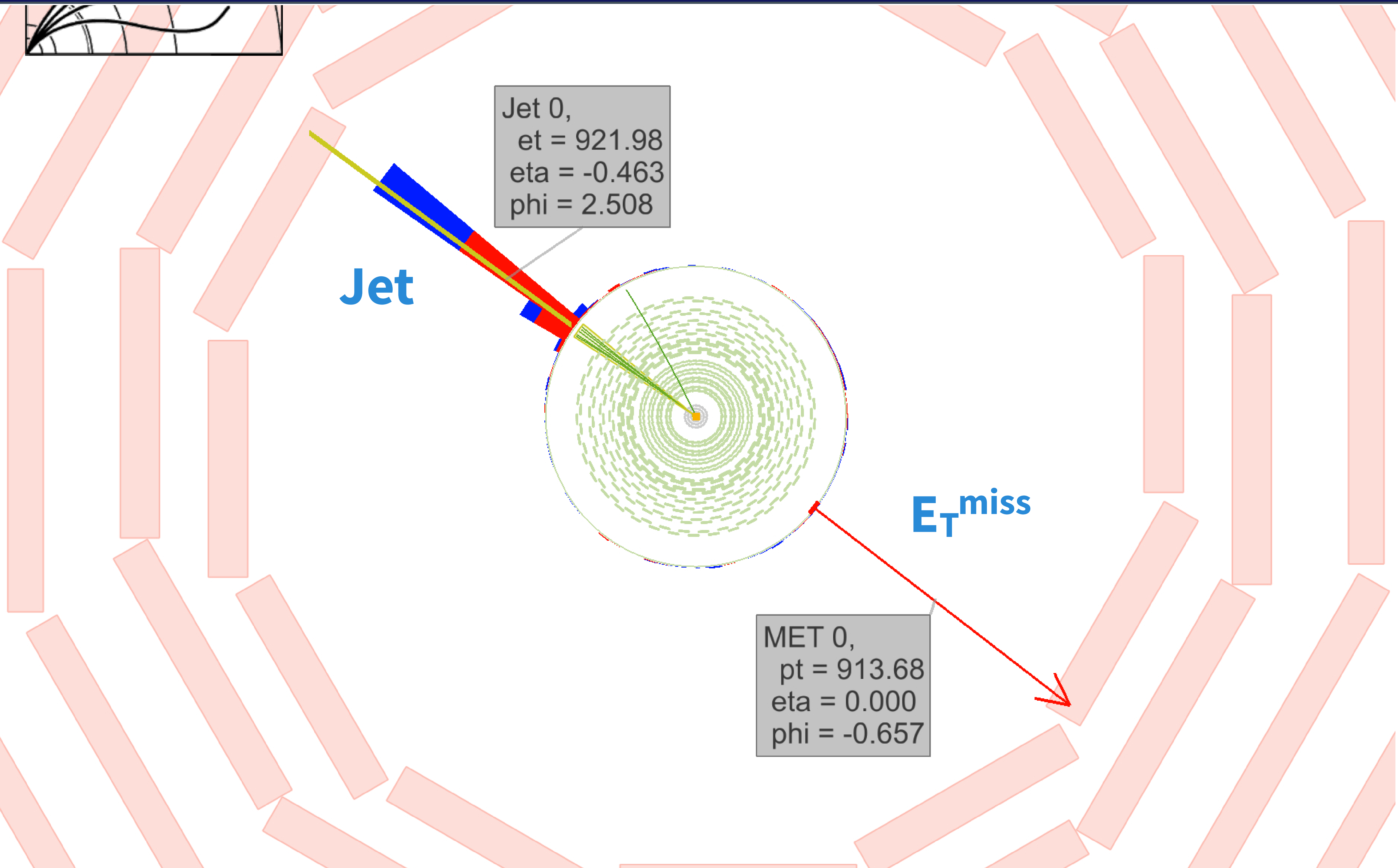
↓

Estimate backgrounds from data

↓

Interpret search results

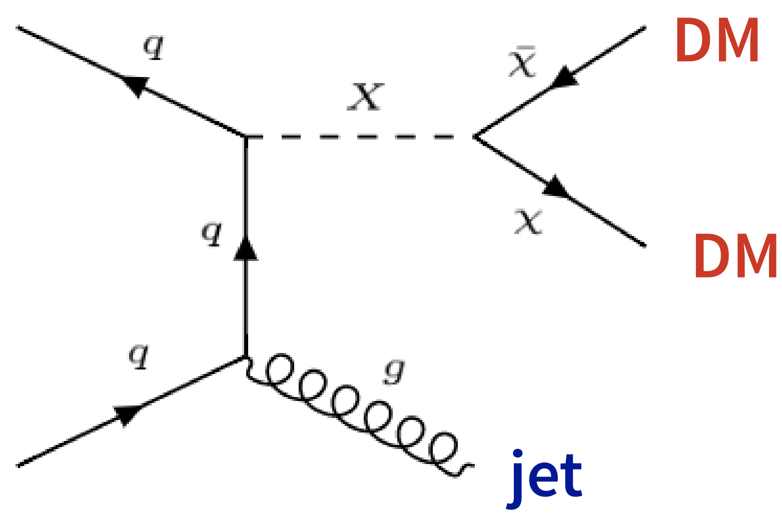
Monojet event display



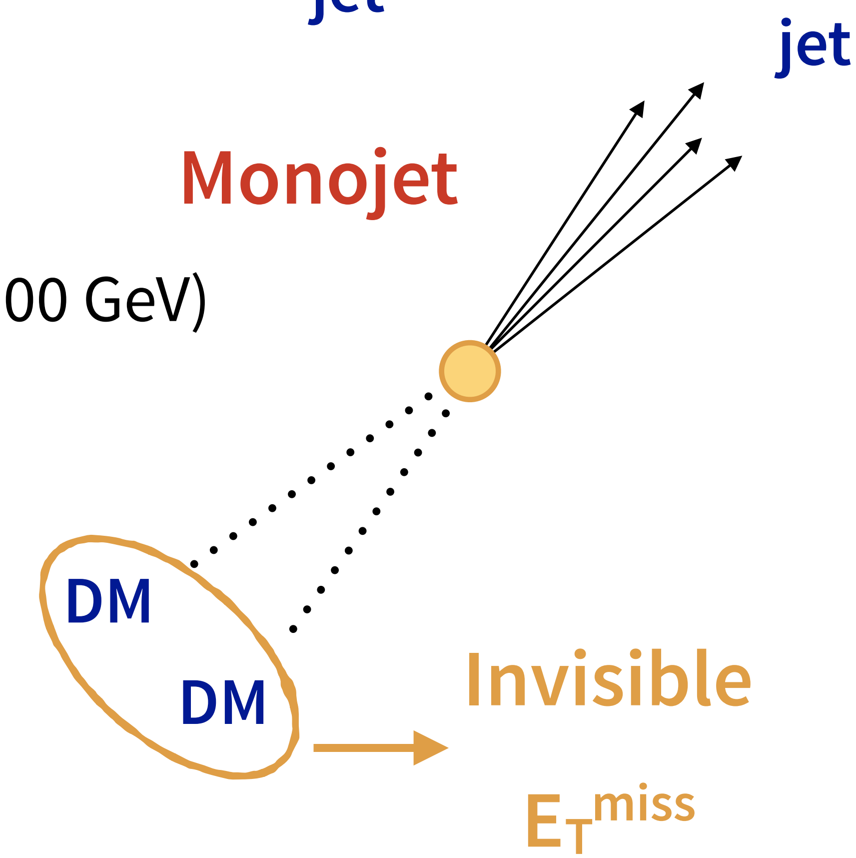
Looking for DM in Monojet events

CMS PAS EXO-15-003

Hard jet/s from initial state radiation (ISR) produced in association to a pair of DM particles



- **DM signal recoiling against QCD ISR**
- **Channel highly sensitive to DM production**
  - High gluon production cross-section
- **Signal events signature:**
  - At least 1 high p_T jet (p_T > 100 GeV)
  - Large energy imbalance in transverse plane (E_T^{miss} > 200 GeV)
  - No leptons or photons
- **Key variable**
  - Missing transverse energy spectrum, E_T^{miss}

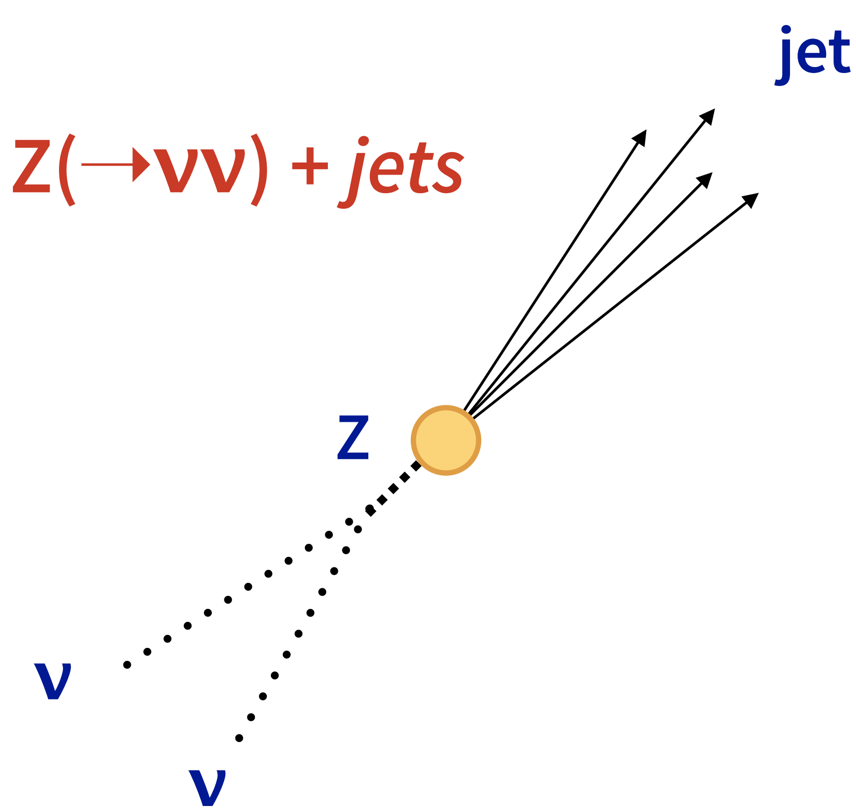


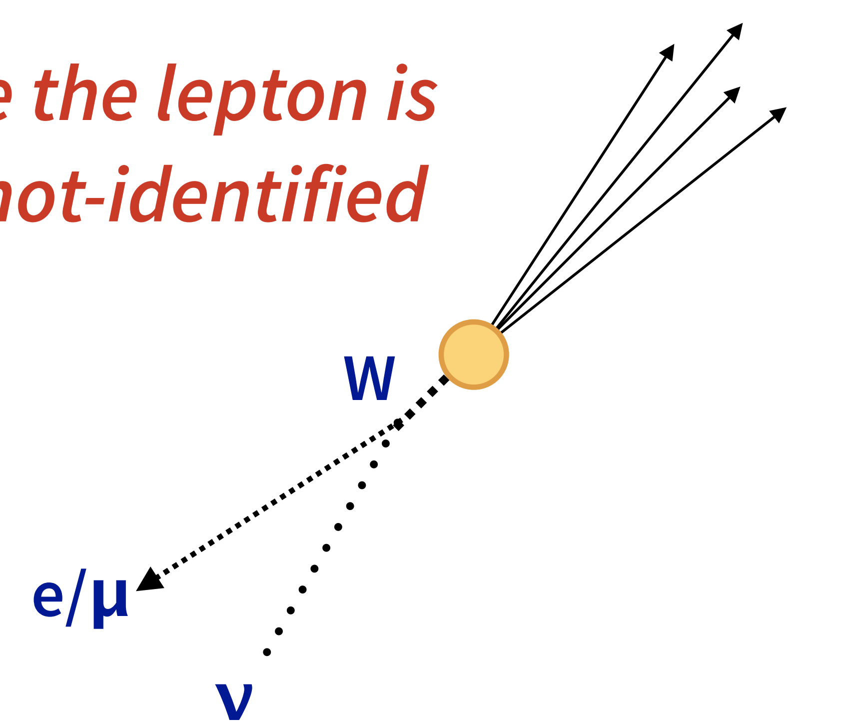
Analysis performed on 13 TeV and 8 TeV data

EWK backgrounds

Dominant backgrounds from EWK processes:

- Z(→νν) + jets
- W(→lν) + jets

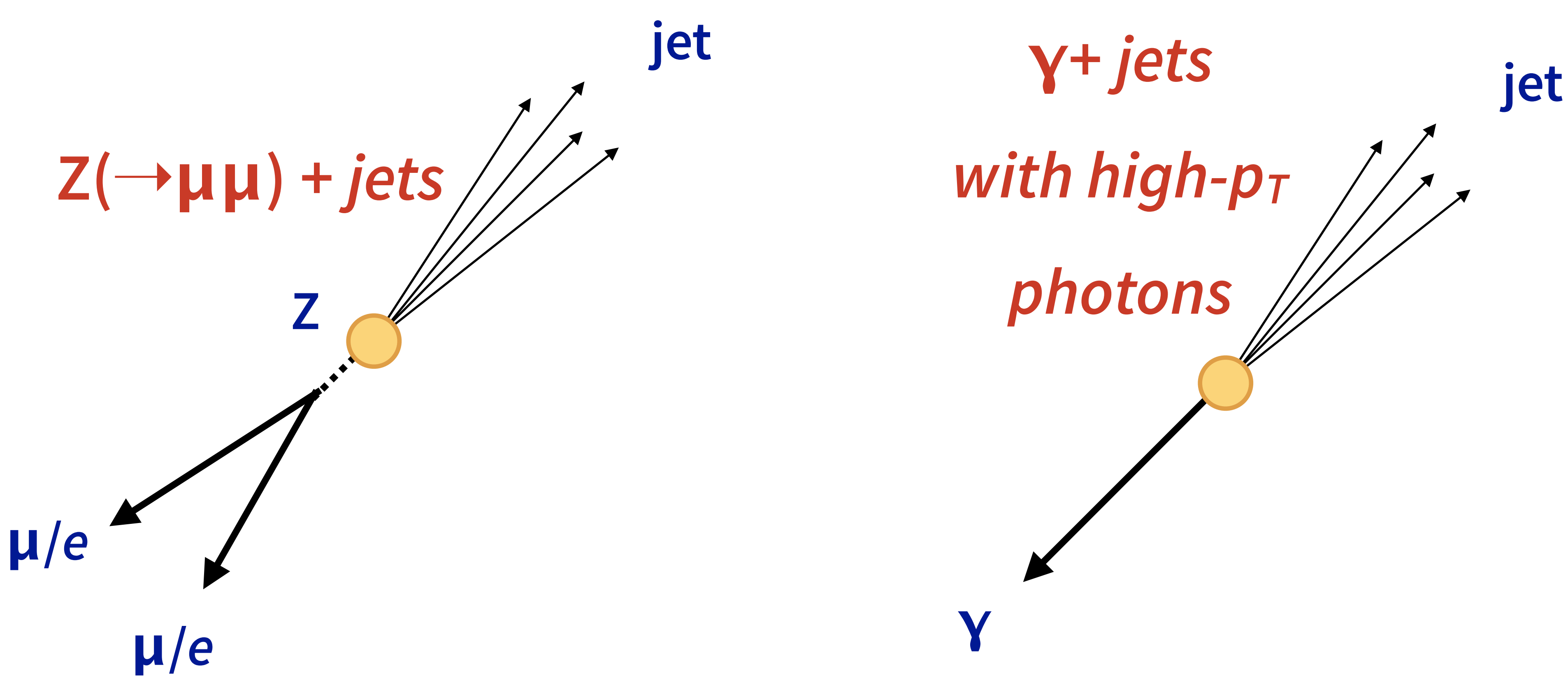




Looking at similar processes?

Background expectation can be determined from data

- **Looking at similar final states**
  - **Z(→νν) + *jets***: **Z(→μμ/ee) + *jets*** and **γ+*jets***



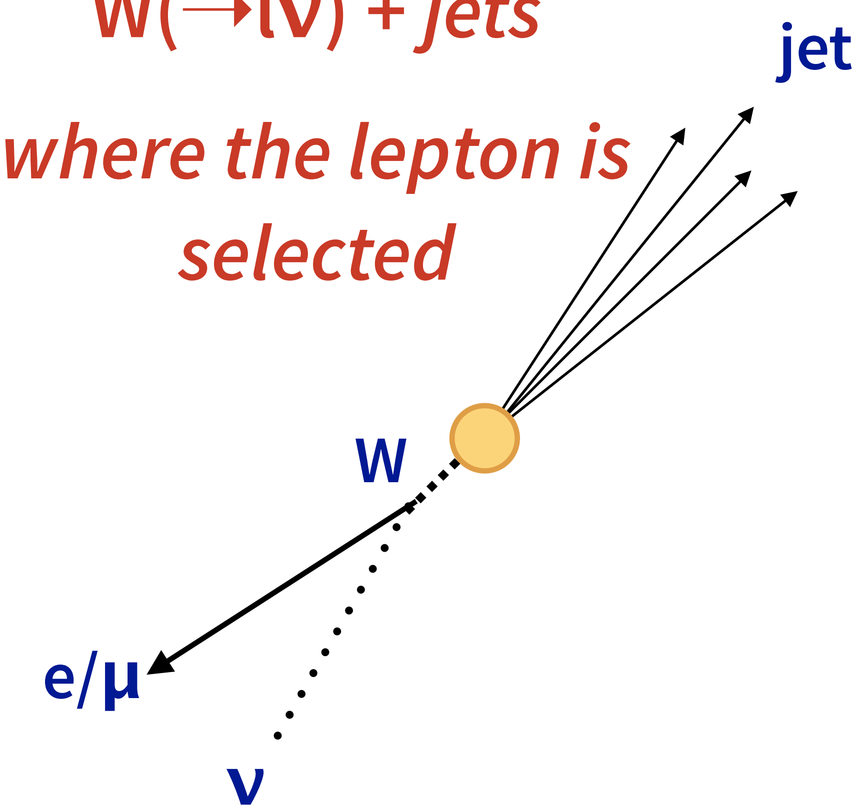
Looking at similar processes?

Background expectation can be determined from data

- **Looking at similar final states**
  - **Z(→νν) + *jets***: **Z(→μμ/ee) + *jets***, **W(→μ/e ν) + *jets*** and **γ+*jets***
  - **W(→μ/e ν) + *jets***: **W(→μ/e ν) + *jets*** with visible lepton

W(→lν) + *jets*

where the lepton is selected



EWK Background Estimation Procedure

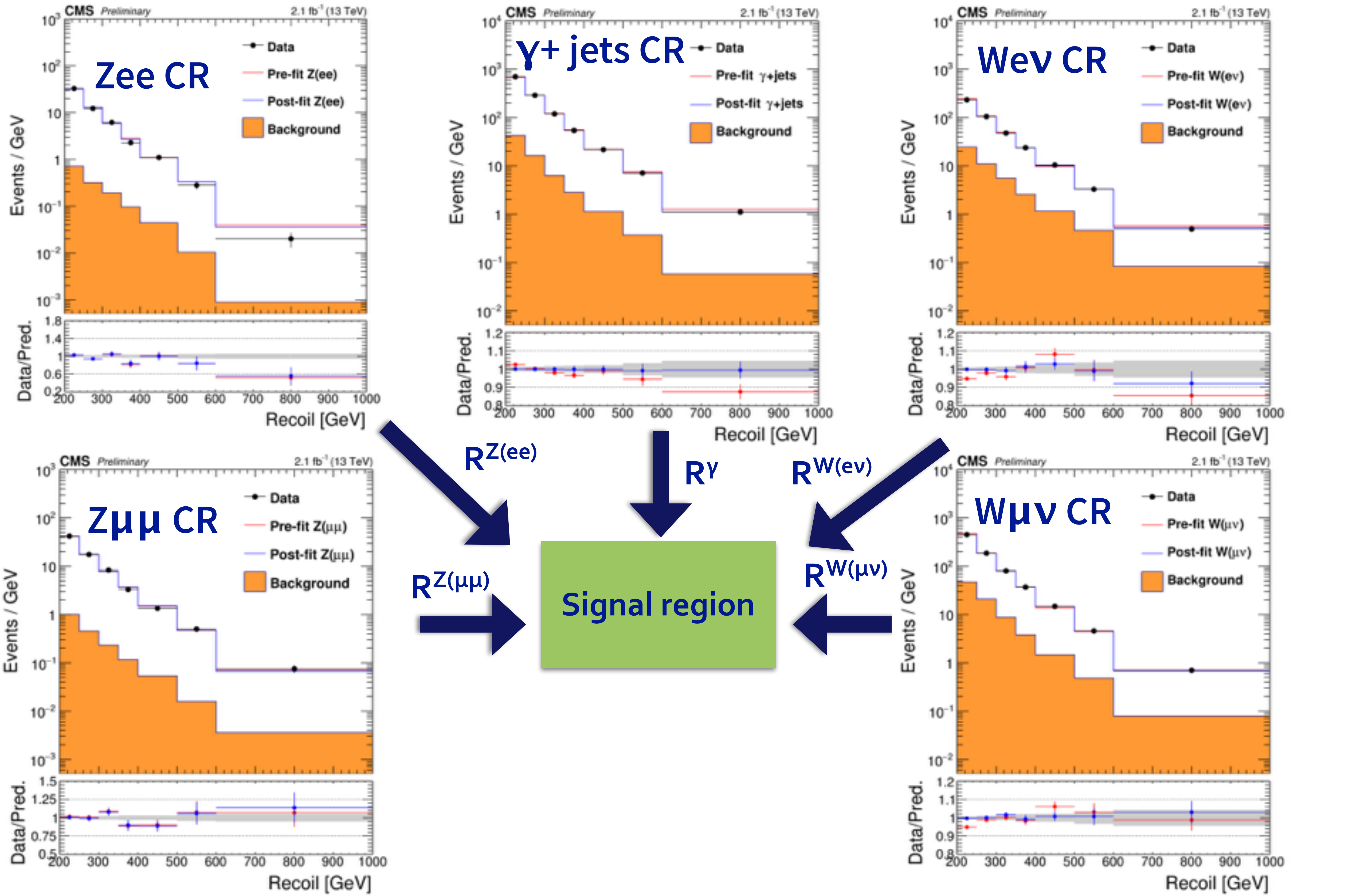
Want to estimate EWK background in the *signal region* (SR)

- Using data-driven techniques to reduce uncertainties

1. **Definition of control samples (CR) enriched in events from similar processes**
   - Same selection as in SR except lepton/photon veto is inverted
   - Double and single lepton CRs plus photon CR: 5 CRs
2. **Consider boson recoil (W/Z/γ p_T) to mimic E_T^{miss} in SR**
   - Z(→ll) + *jets:* $p_T^Z = p_T^{l1} + p_T^{l2}$
   - W(→lν) + *jets:* $p_T^W = p_T^l + p_T^\nu$
   - γ+*jets:* p_T^γ
3. **Relate CR and SR using bin-by-bin transfer factors "R" from simulation**
   - $N_i^{Z(SR)} = N_i^{Z(ll)} \times \mathbf{R^{Z(ll)}}$
   - $N_i^{Z(SR)} = N_i^{\gamma} \times \mathbf{R^{\gamma}}$
   - $N_i^{W(SR)} = N_i^{W(l\nu)} \times \mathbf{R^{W(l\nu)}}$

R accounts for cross-section ratio and for efficiency and acceptance of leptons/photons in CRs

Control regions



Fit to signal and control regions

Combined maximum likelihood fit to CRs and SR to estimate E_T^{miss} shape and normalisation of EWK backgrounds

signal

$$\mathcal{L}(\mu, \mu^{Z\to\nu\nu}, \mu^{W\to l\nu}, \theta) = \prod_i \mathrm{Poisson}\left(d_i | B_i(\theta) + \mu_i^{W\to l\nu} + \mu_i^{Z\to\nu\nu} + \mu S_i(\theta)\right)$$

$$\times \prod_i \mathrm{Poisson}\left(d_i^Z | B_i^Z(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^Z(\theta)}\right)$$ *dilepton*

$$\times \prod_i \mathrm{Poisson}\left(d_i^\gamma | B_i^\gamma(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^\gamma(\theta)}\right)$$ *photon*

$$\times \prod_i \mathrm{Poisson}\left(d_i^W | B_i^W(\theta) + \frac{\mu_i^{W\to l\nu}}{R_i^W(\theta)}\right)$$ *single lepton*

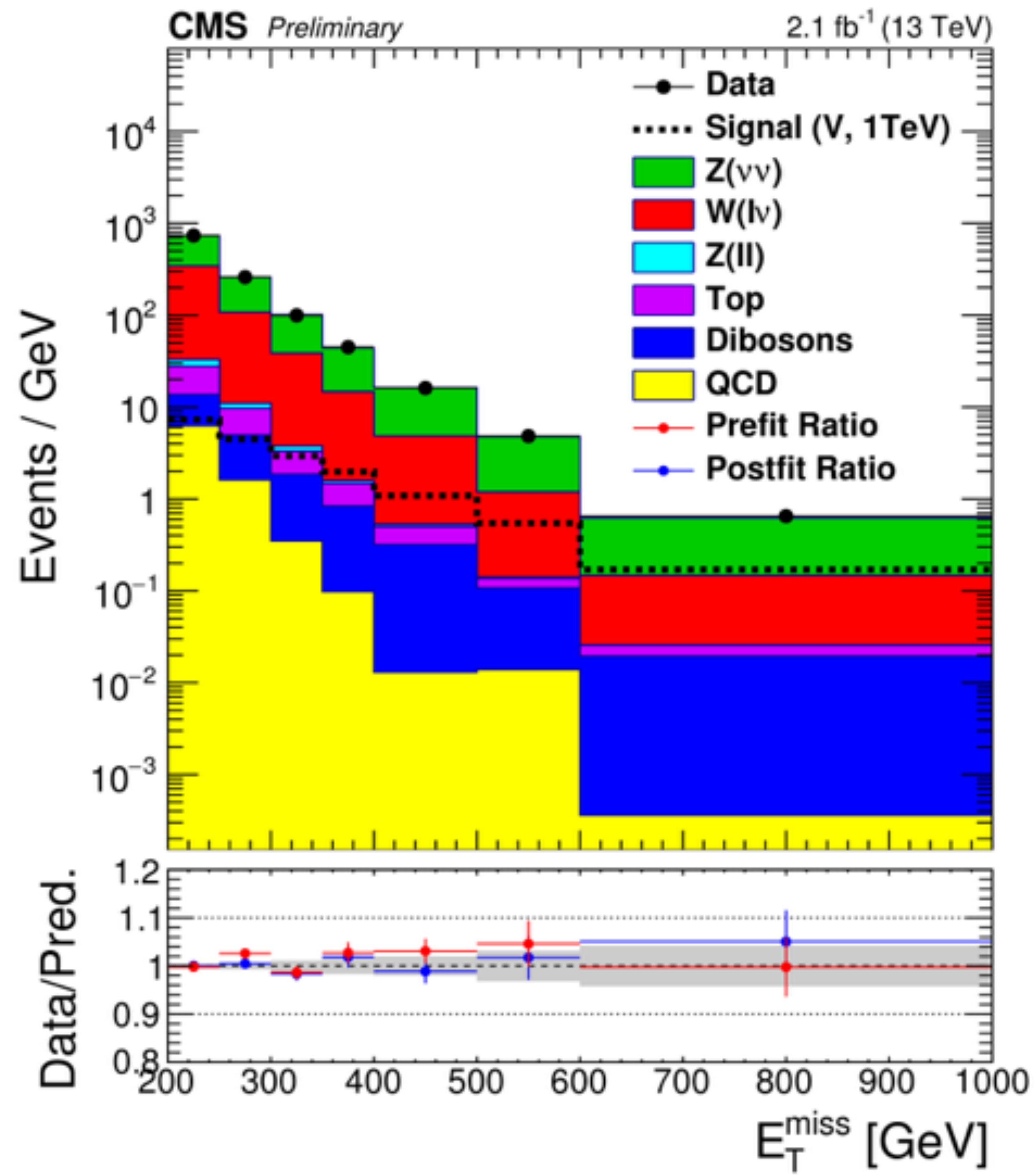
Z(→νν) + jets and W(→μ/e ν) + jets estimates further constrained by Z/W cross-section ratio

$$\mu^{W\to l\nu} \to f_i(\theta) \cdot \mu^{Z\to\nu\nu}$$

E_T^{miss} distribution in signal region

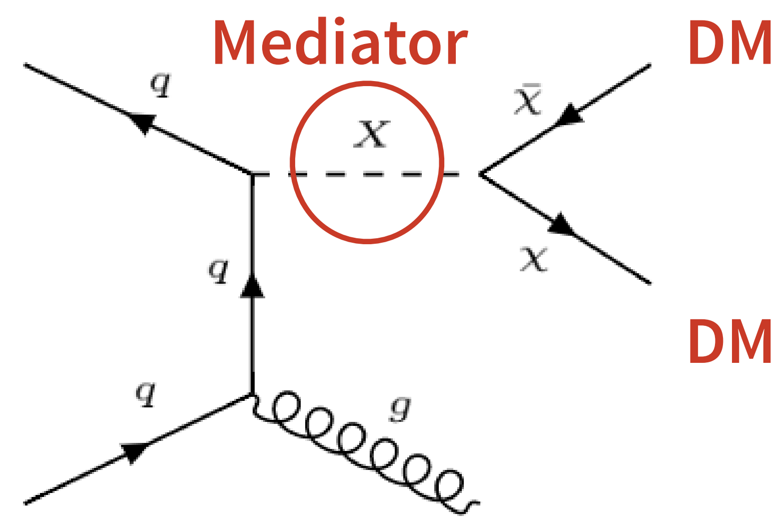
CMS PAS EXO-15-003

- **Subdominant background contributions from**
  - Top, diboson and QCD multijet events
  - Estimated from simulation
- **Overall good agreement post fit (blue dots)**
- **Uncertainties get constrained from data in control regions as well as in signal region**

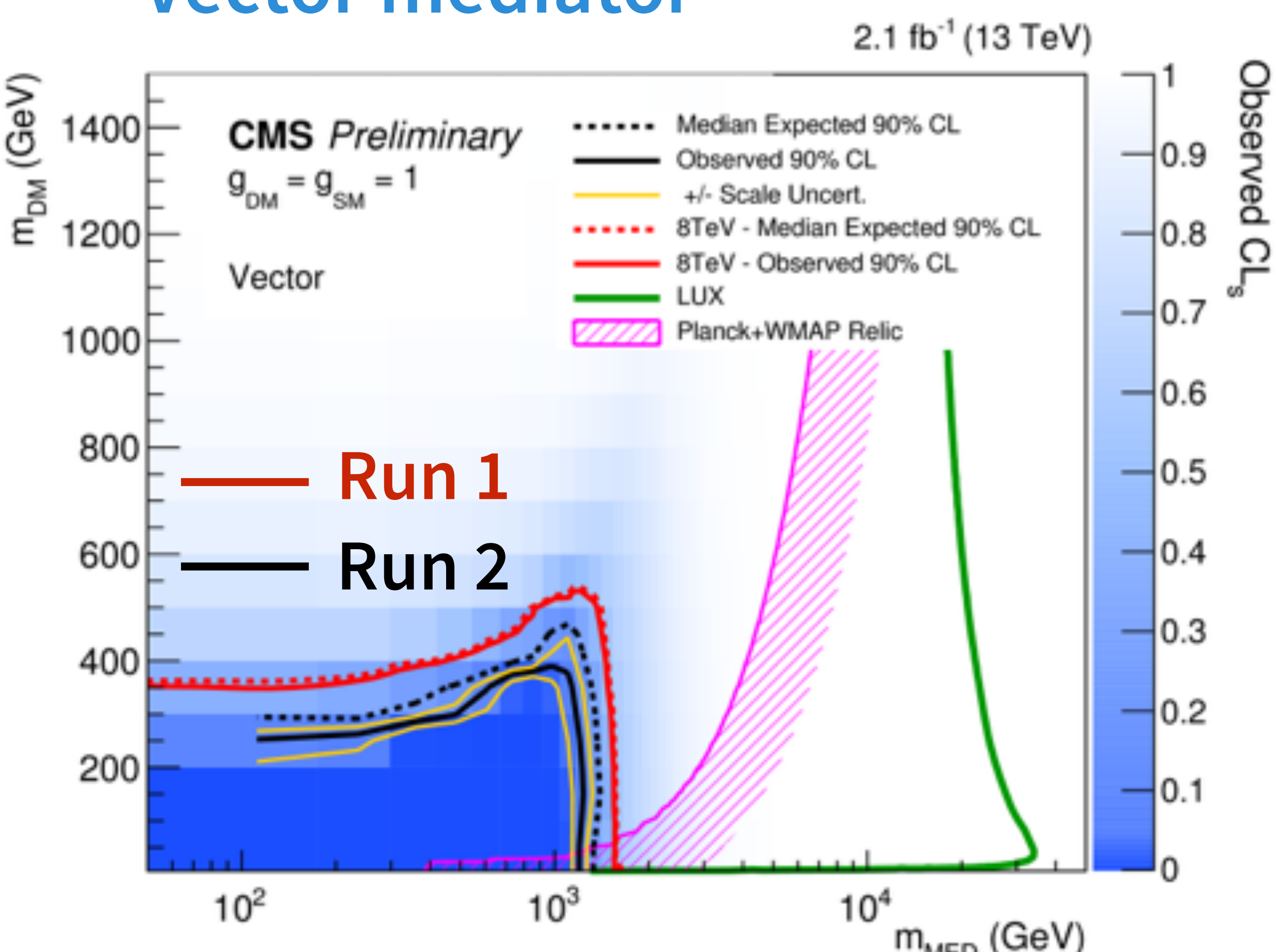


Interpretation

- **Interpretation in terms of simplified models:**
  - Limits on production σ set as a function of:
    - m_{DM} and m_{MED}

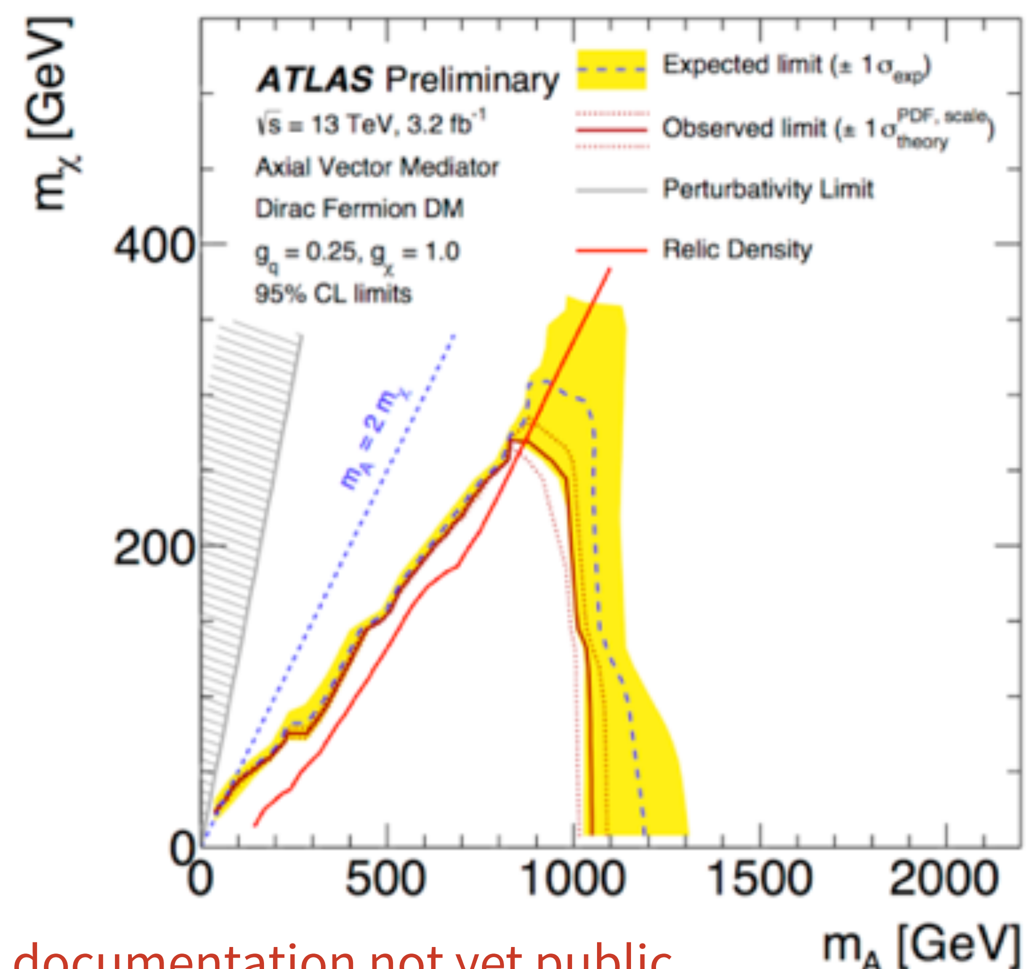


Vector mediator



CMS PAS EXO-15-003

Axial-Vector mediator

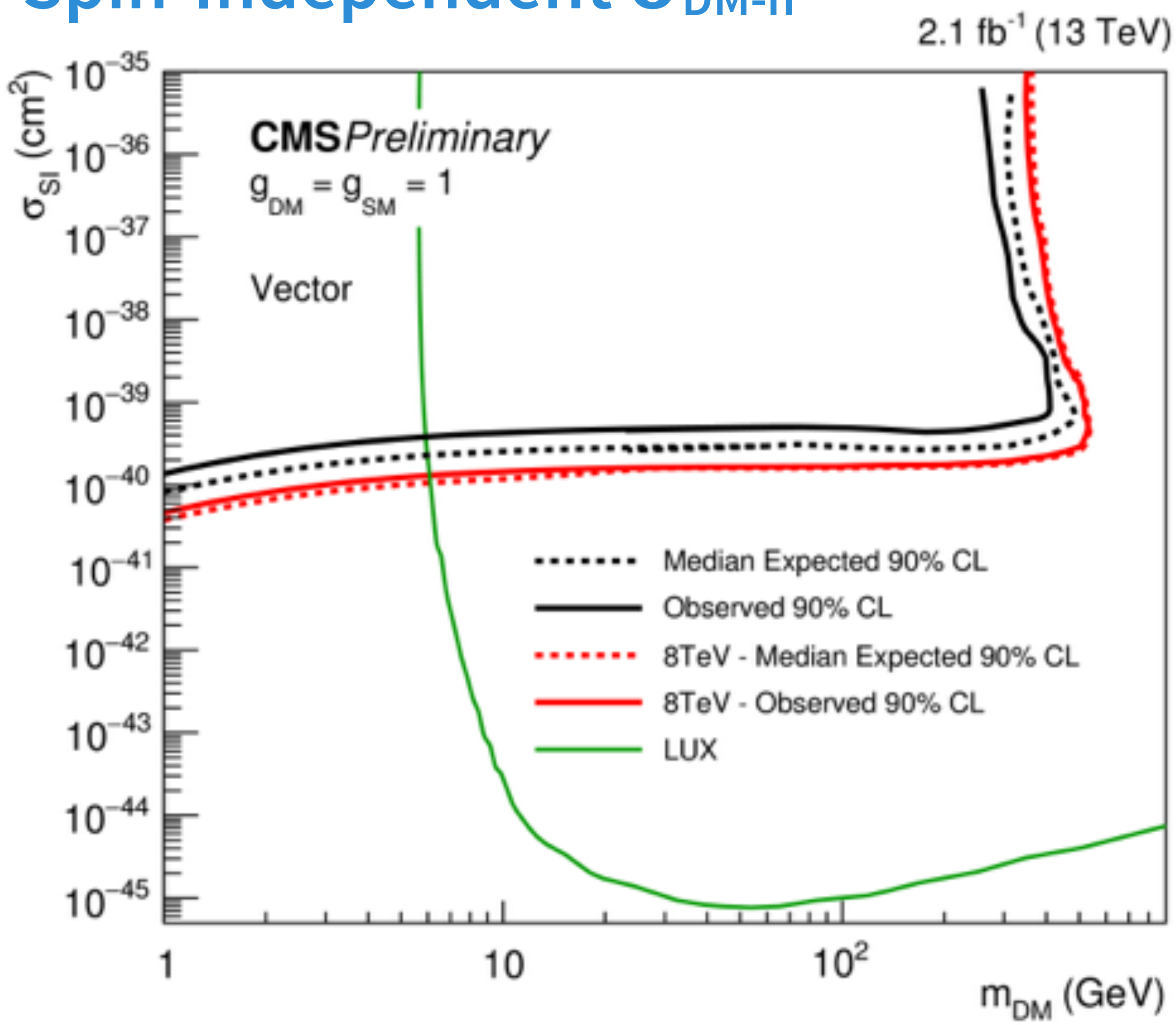


ATLAS documentation not yet public

Interpretation

Limits recast in terms of DM-nucleon cross section

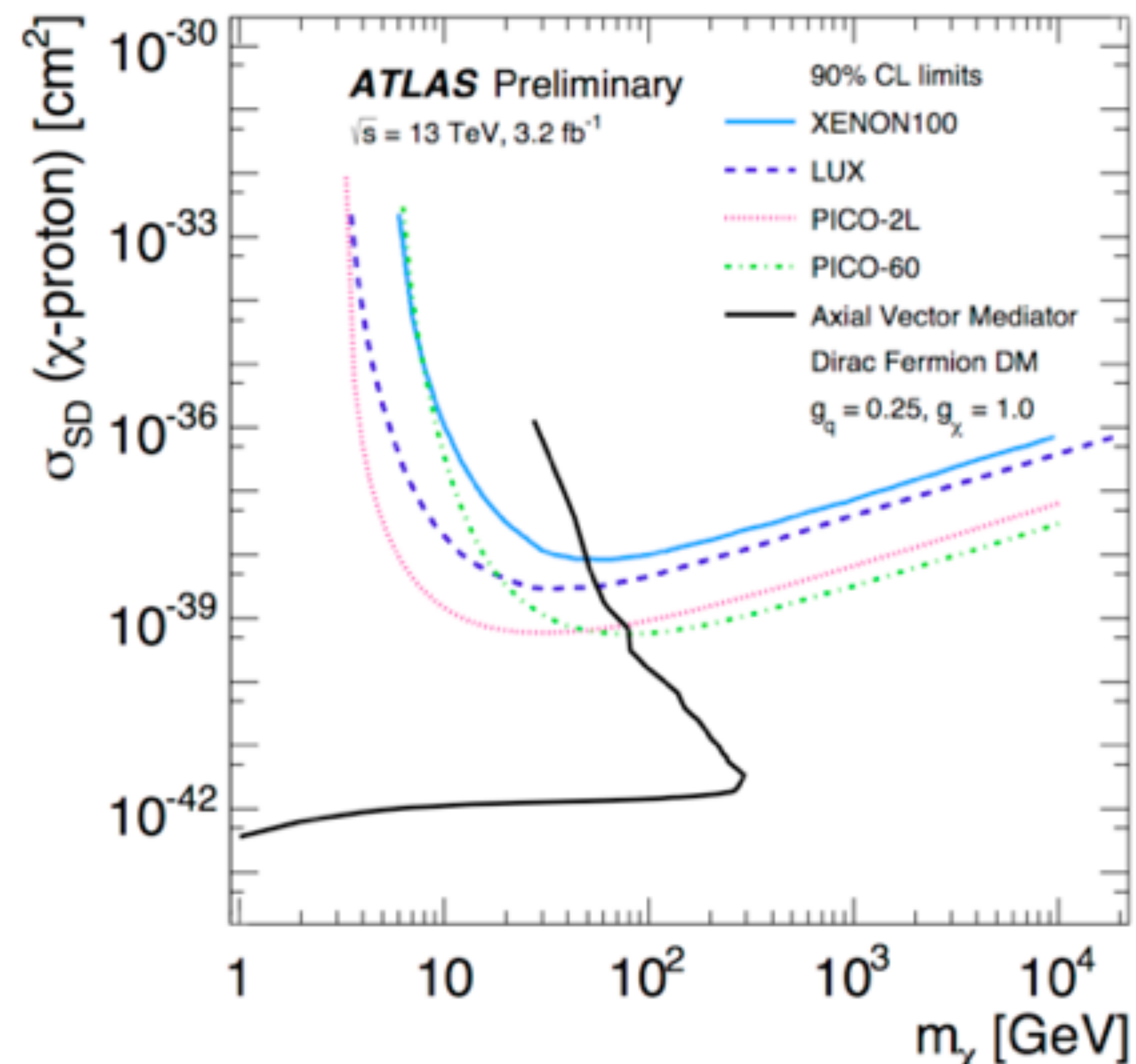
Spin-Independent $\sigma_{DM\text{-}n}$



Excluded $\sigma_{DM\text{-}n} > 10^{-41} cm^2$ for low m_{DM}

CMS PAS EXO-15-003

Spin-Dependent $\sigma_{DM\text{-}n}$



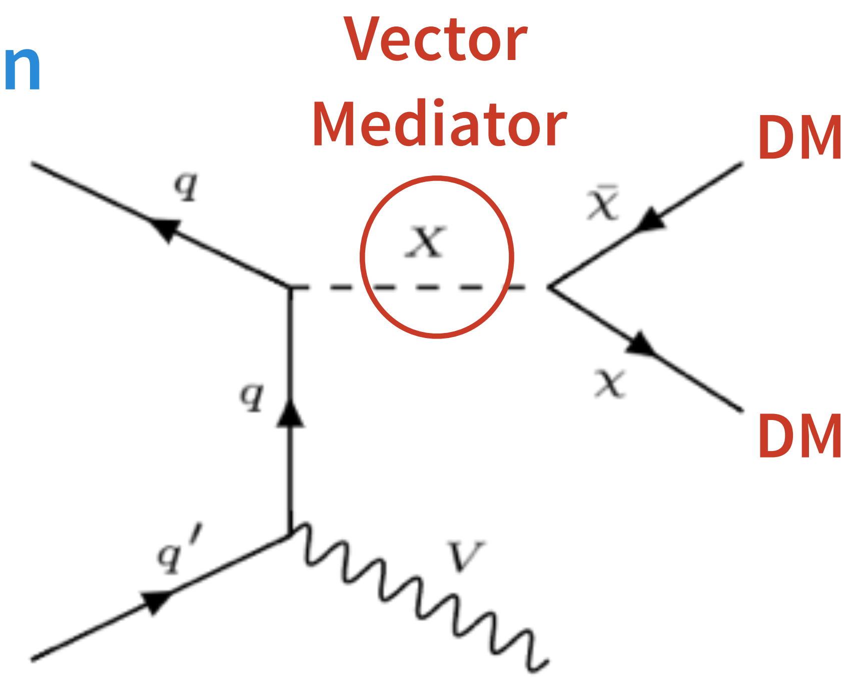
Excluded $\sigma_{DM\text{-}n} > 10^{-42} cm^2$ for low m_{DM}

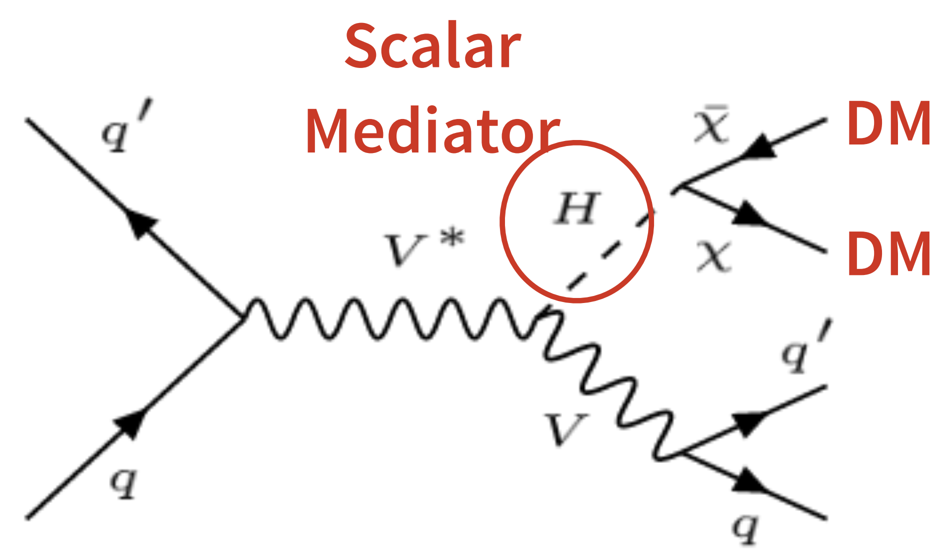
ATLAS documentation not yet public

What about V + DM?

DM can be produced in association to a W/Z boson

- **Lower σ but also lower backgrounds wrt Jet + E_T^{miss}**
- **V boson recoiling against high E_T^{miss}**
- **2 possible decay channels:**
  - Leptonic and Hadronic
- **Search strategy based on V reconstruction**
  - Strongly depends on decay channel
    - Leptonic V reconstruction from leptons
    - Hadronic V reconstruction from jets in low/high p_T regime
- **Backgrounds estimation**
  - From data similarly to Monojet





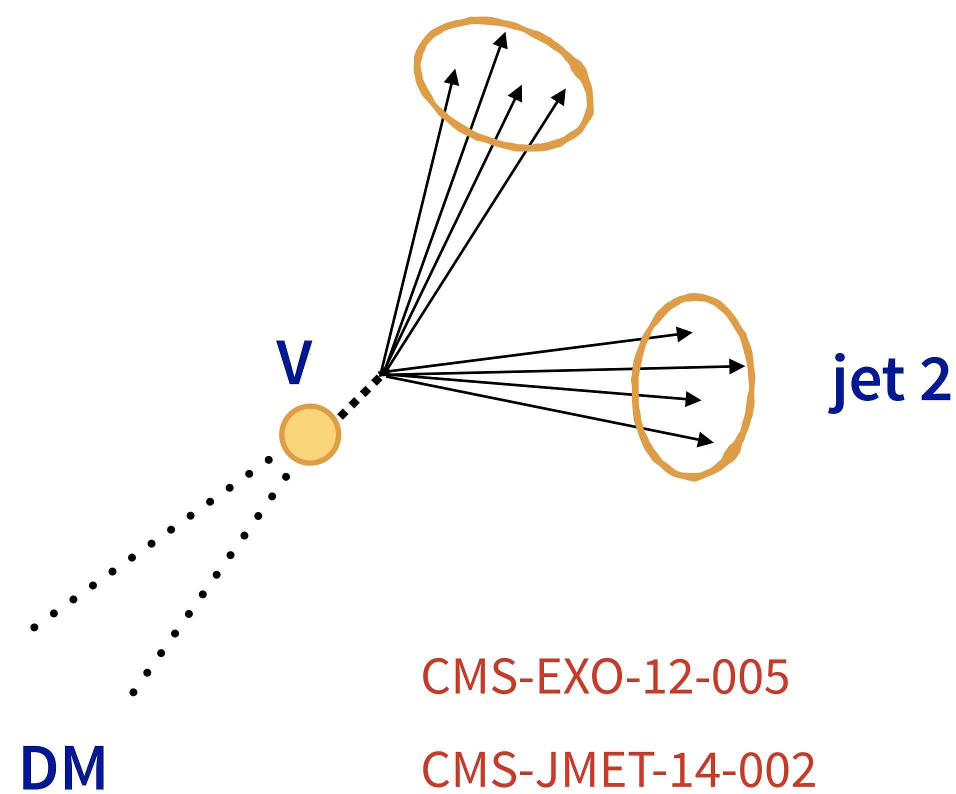
SM Higgs-stralung with invisible Higgs decay mode

Low p_T V (hadronic decay)

Low V p_T: V→jj decay fully reconstrcuted

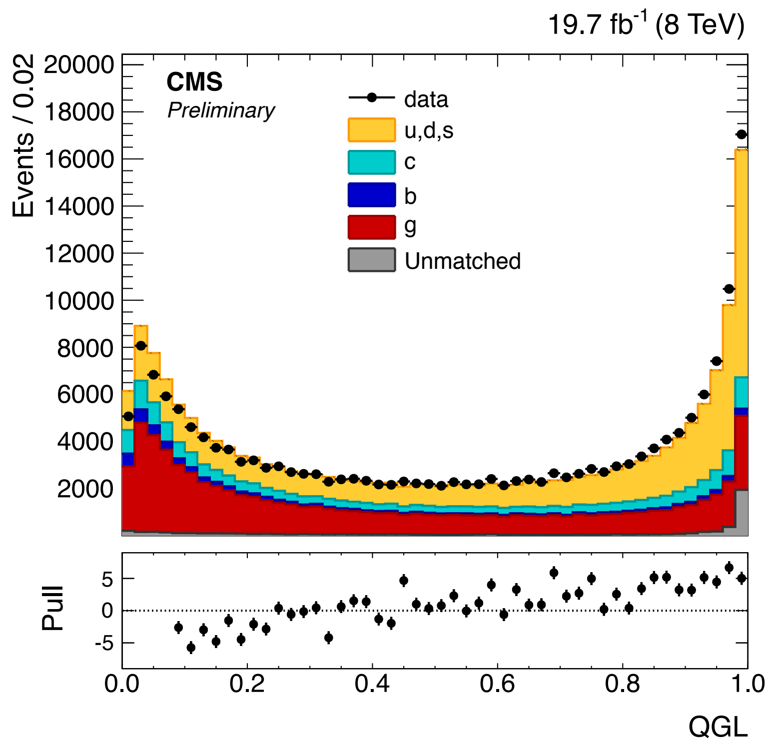
- V decay products emerged as two distinct jets
- Multivariate discriminator based on jet and di-jet properties, e.g:
  - m_{jj} consistent with V boson mass
  - Jet Quark-Gluon likelihood (QGL)
  - Color flow

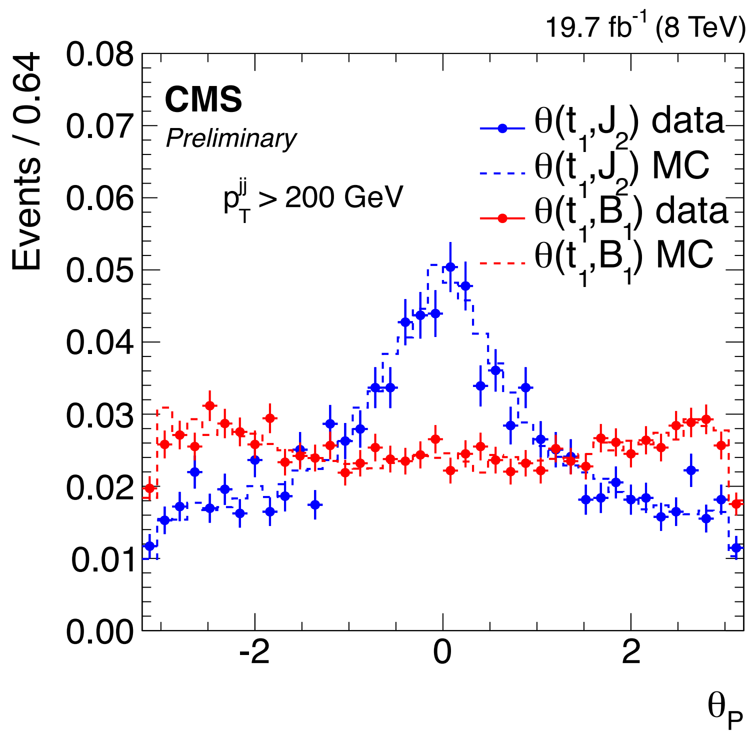
V tagging



CMS-EXO-12-005

CMS-JMET-14-002





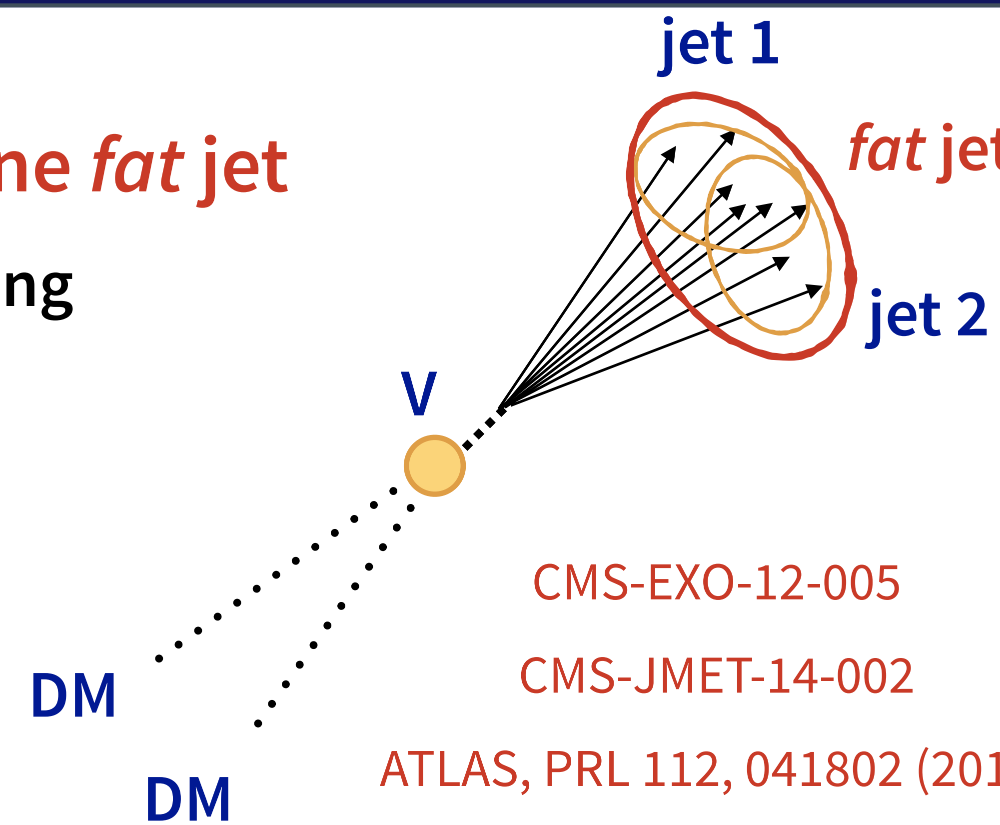
Bkg jets

Signal jets

High p_T V (hadronic decay)

High V p_T: V→jj decay products merged in one *fat* jet

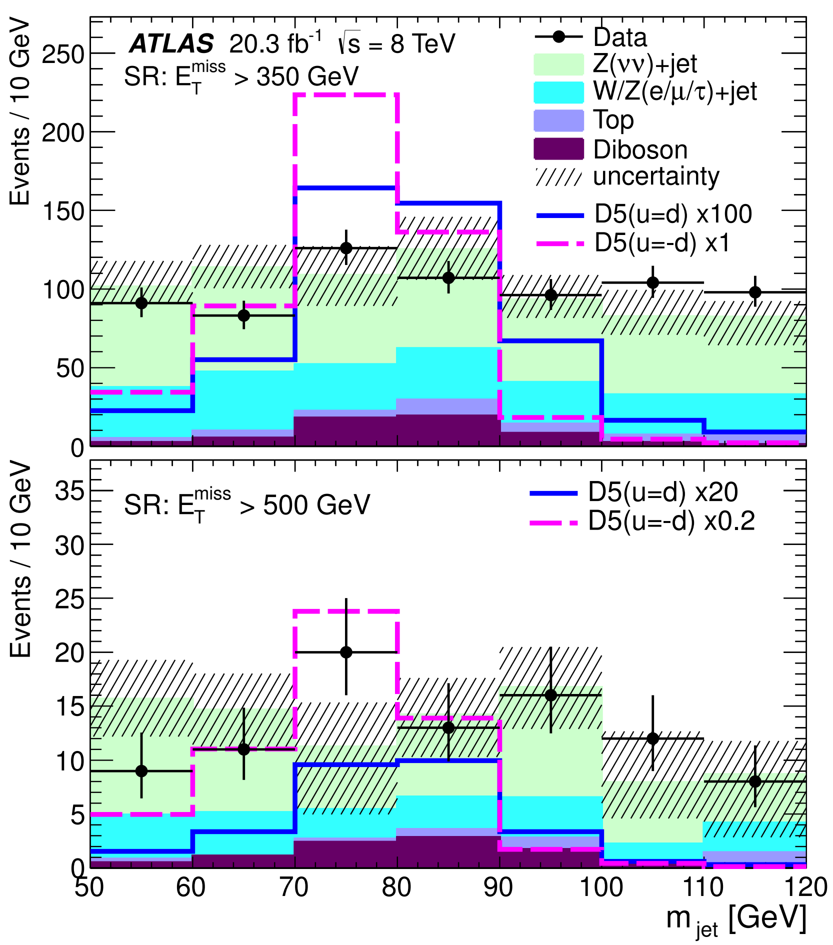
- **Substructure techniques employed: V boson tagging**
  - 1 central, high p_T fat jet with m_j compatible with V boson mass [ATLAS & CMS]
  - Fat jet likely to be originated from 2 jets, N-subjettiness [CMS]

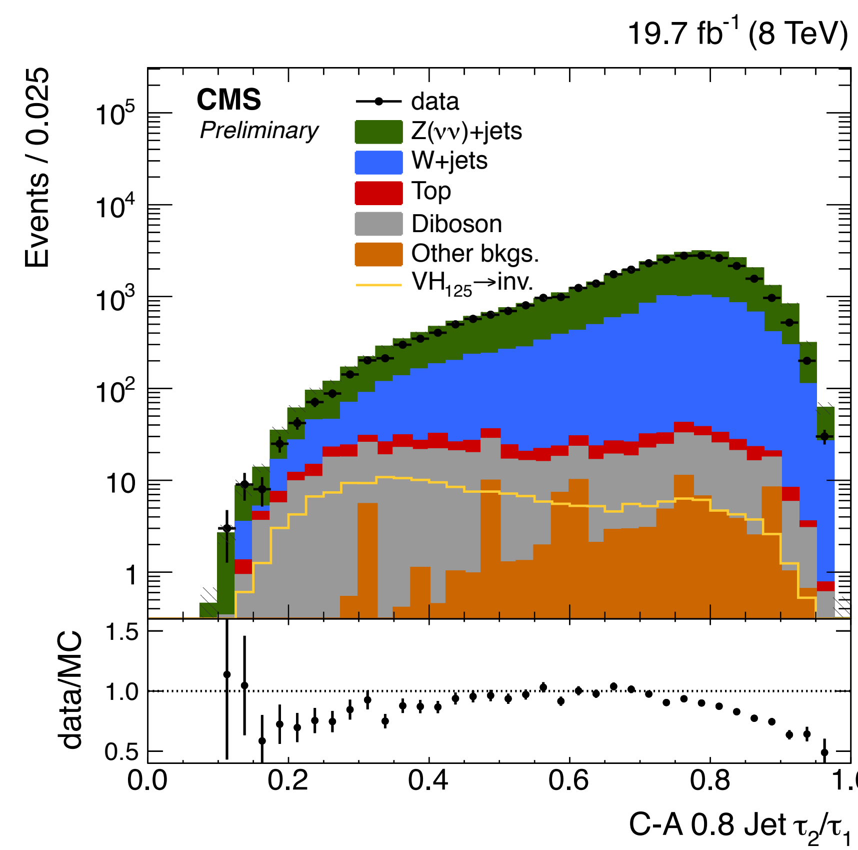


CMS-EXO-12-005

CMS-JMET-14-002

ATLAS, PRL 112, 041802 (2014)





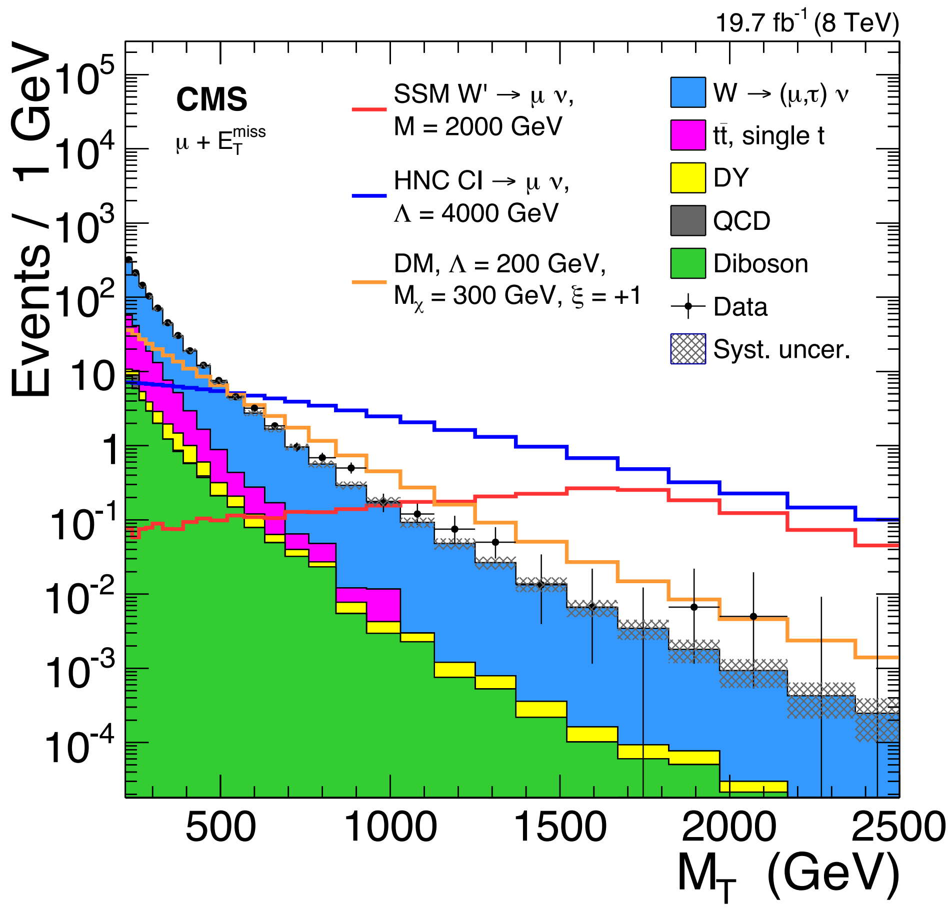
What about leptonic V?

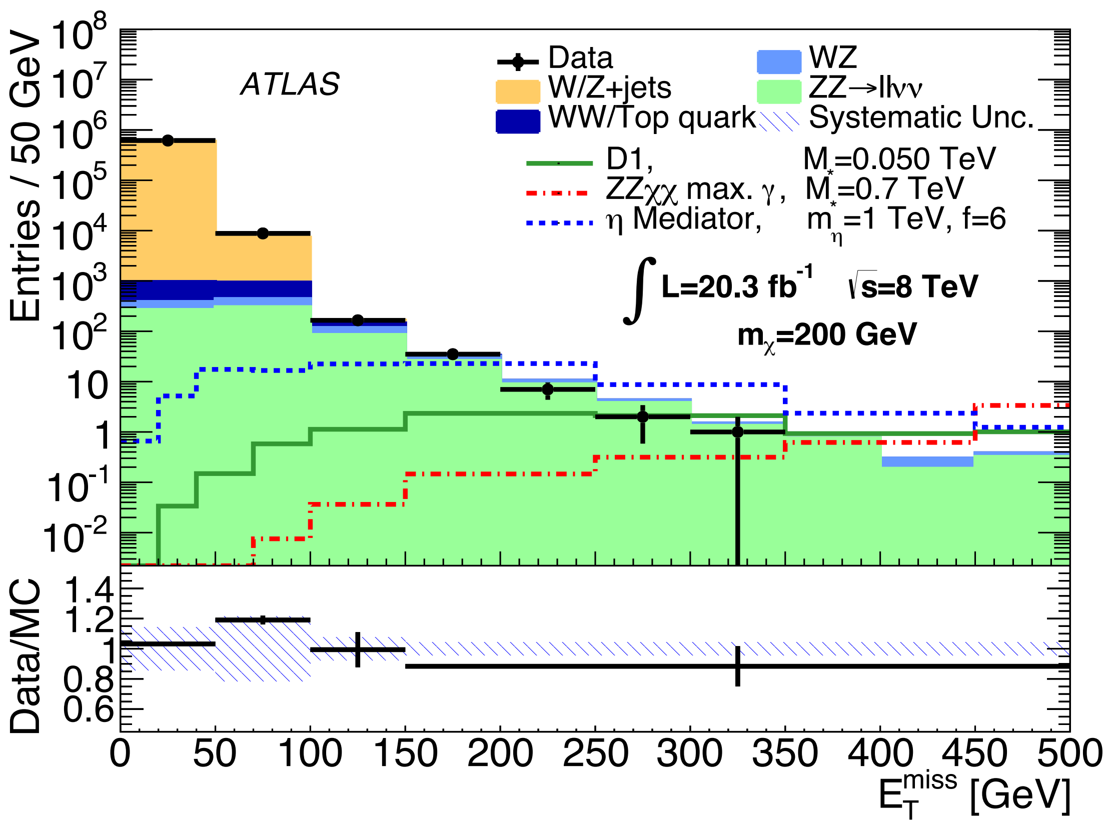
W(→l ν) + DM

- 1 isolated, high p_T lepton and high E_T^{miss}
- W not fully reconstructable
  - Transverse mass, M_T

$$M_T = \sqrt{2 p_T^{lep} E_T^{miss} (1 - \cos(\Delta\phi))}$$

CMS, PRD 91, 092005 (2015) / ATLAS, JHEP 09 (2014) 037





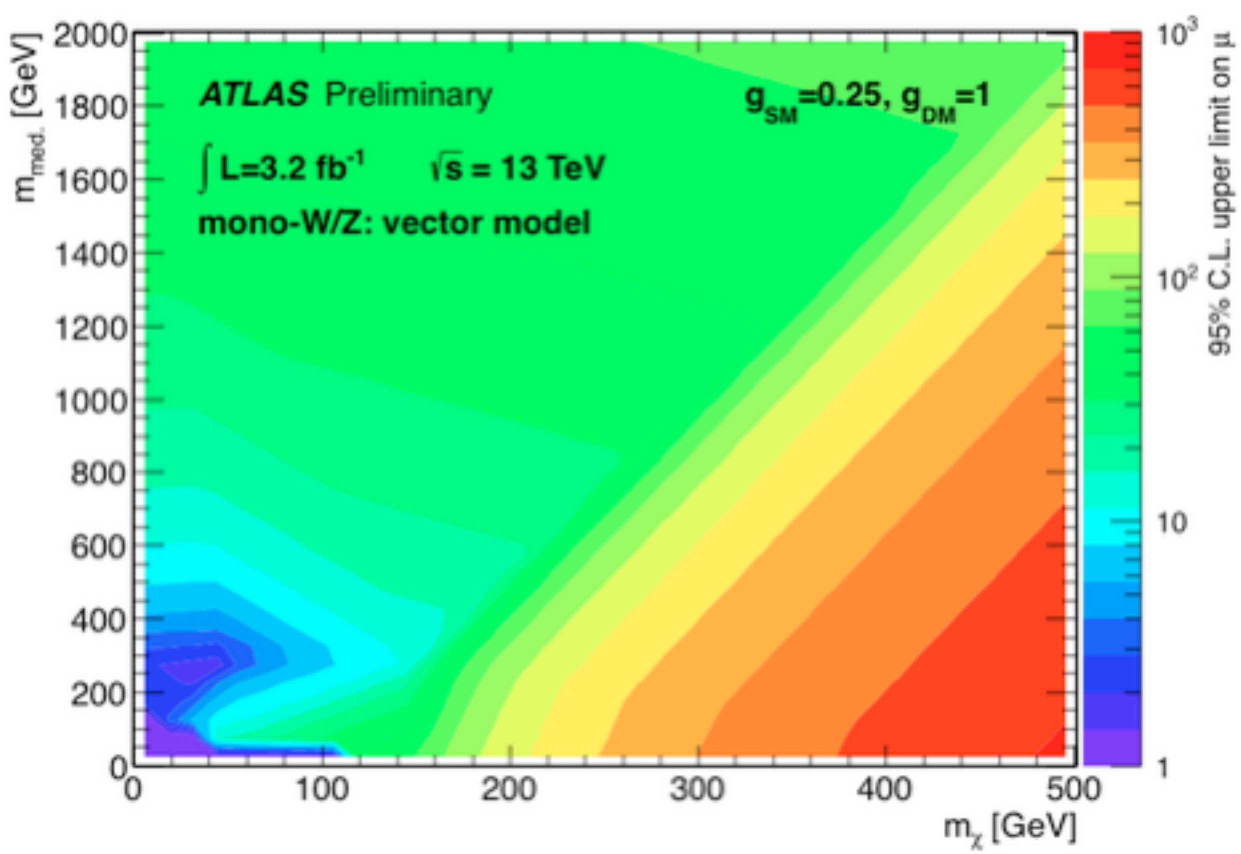
Z(→l l) + DM

- Z reconstructed from 2 opposite-charge same-flavour leptons
- ATLAS looks for signal events in the tails of E_T^{miss} spectrum, CMS looks at M_T

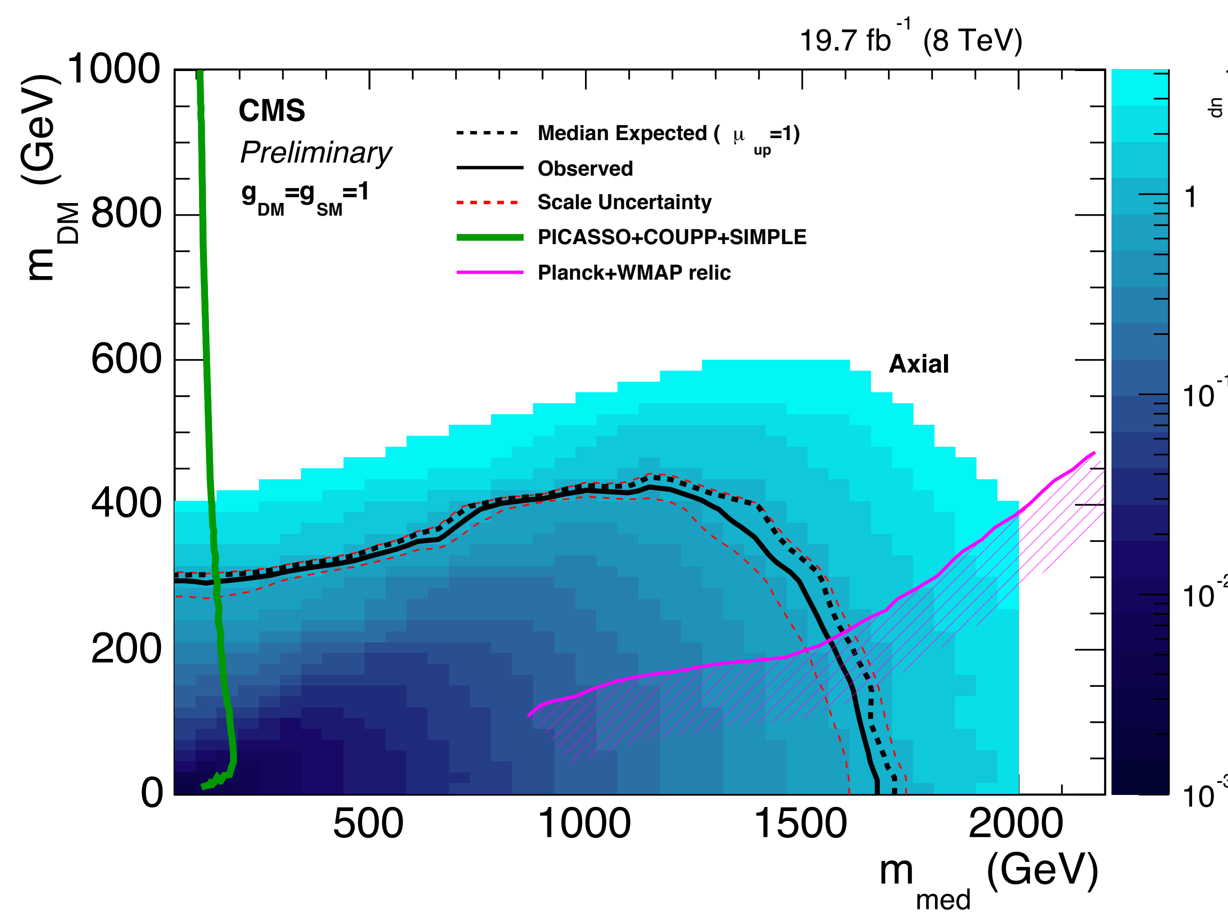
CMS-EXO-12-054 / ATLAS, PRD 90, 012004 (2014)

Exclusion limits on signal strength μ in m_{DM}—m_{MED} plane

Vector



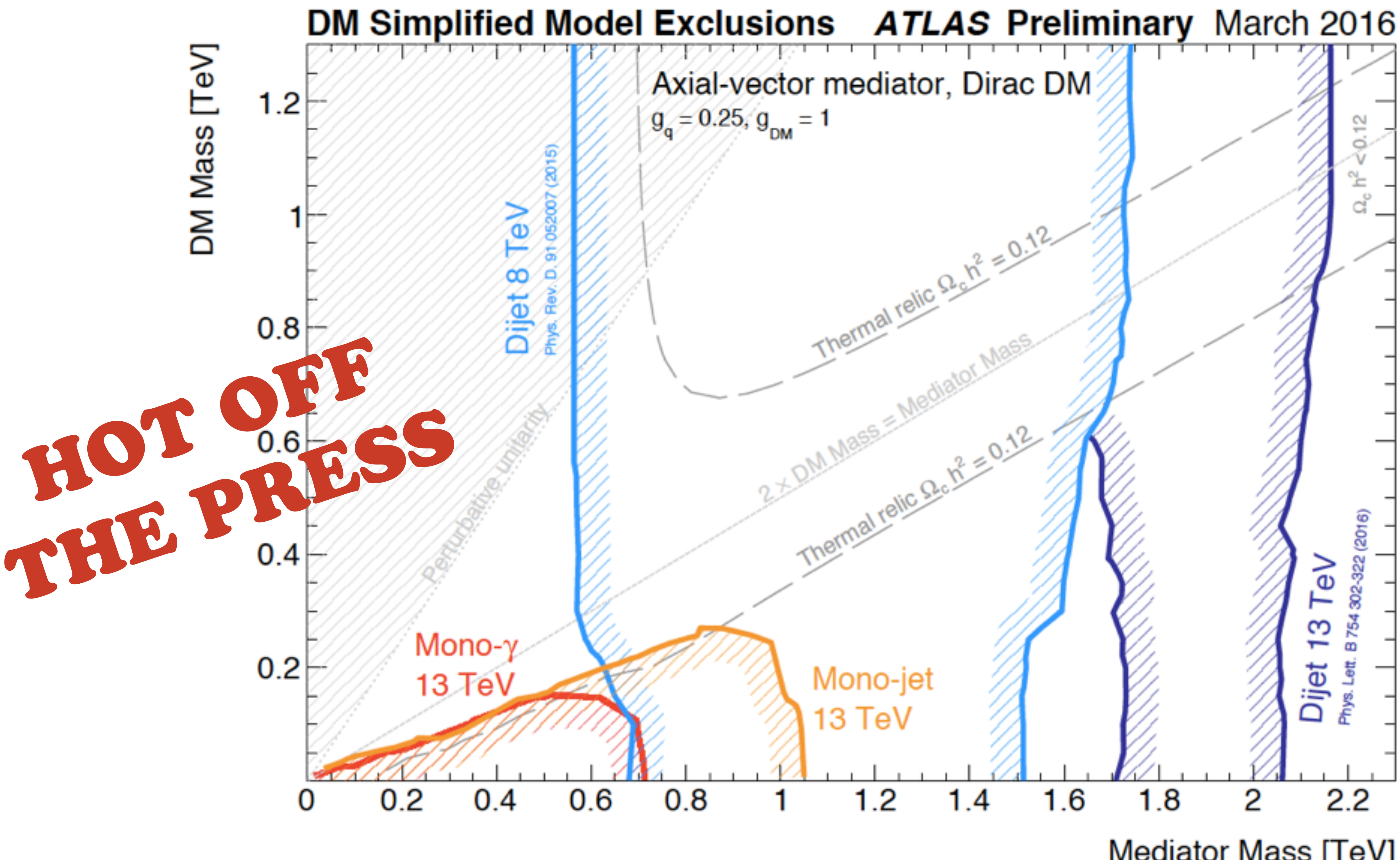
Axial-Vector



CMS-PAS-EXO-12-055

ATLAS documentation for 13 TeV not yet public

Constraints from di-jet searches



From S.Resconi - Moriond QCD 19-16 March

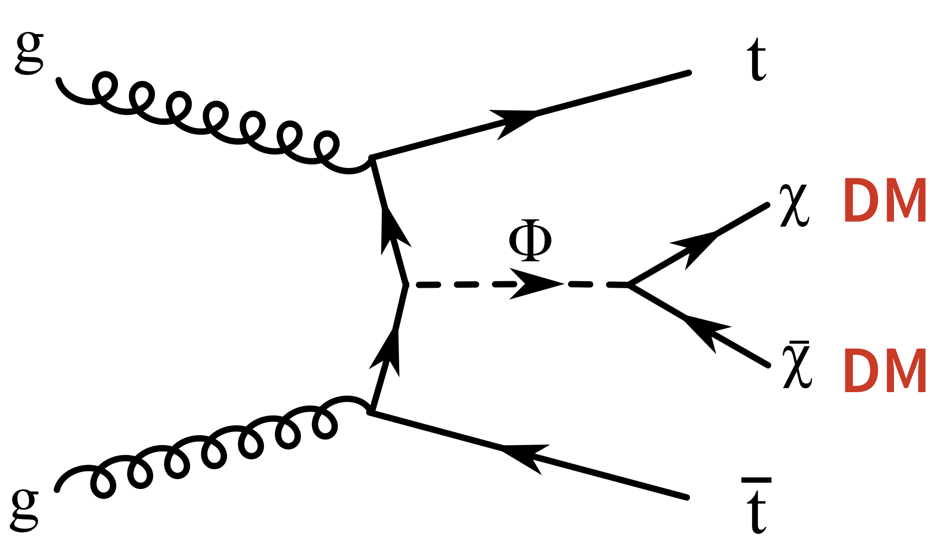
Documentation not yet public

Dark Matter and top quarks

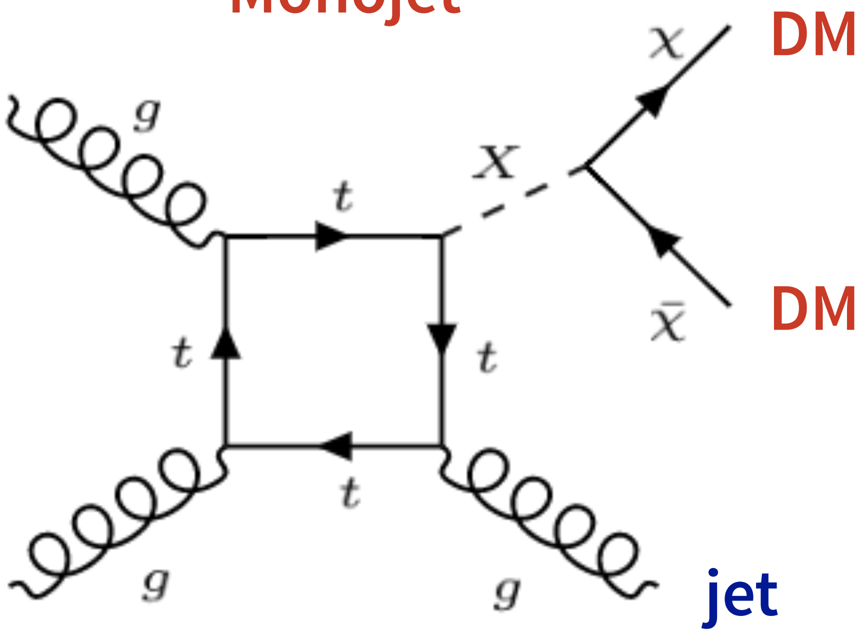
DM production in association to top quarks

- **Favoured in case of scalar/pseudoscalar mediator models**
  - Under the assumption of Yukawa-like coupling
    - HF coupling enhanced ($\propto$ m_q)
    - Loop-suppression for monojet process

DM + tt



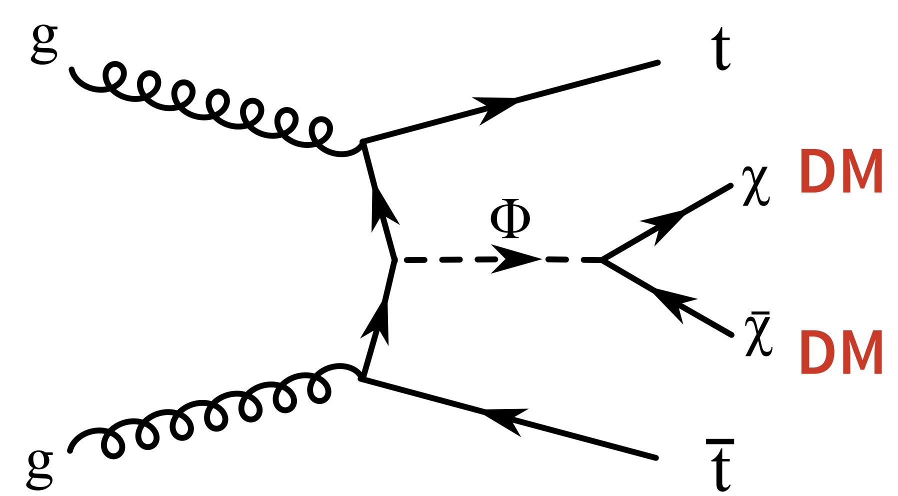
Monojet

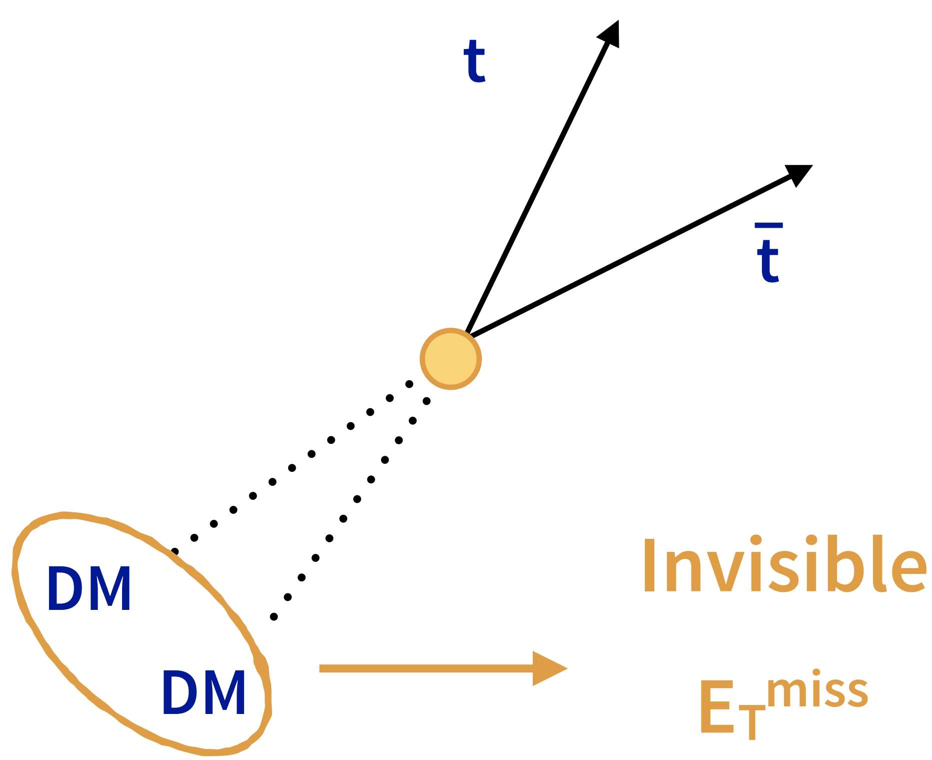


Dark Matter and top quarks

DM production in association to top quarks

- **Favoured in case of scalar/pseudoscalar mediator models**
  - Under the assumption of Yukawa-like coupling
    - HF coupling enhanced ($\propto$ m_q)
    - Loop-suppression for monojet process
- **Top-quark pair recoiling against DM particles**

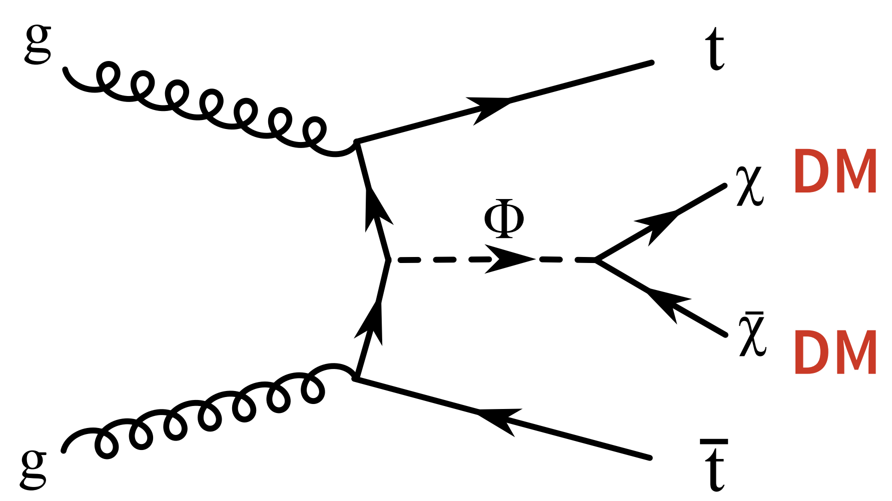




Dark Matter and top quarks

DM production in association to top quarks

- **Favoured in case of scalar/pseudoscalar mediator models**
  - Under the assumption of Yukawa-like coupling
    - HF coupling enhanced ($\propto$ m_q)
    - Loop-suppression for monojet process



- **Top-quark pair recoiling against DM particles**
- **Top decays almost exclusively to W b**
  - Two possible final states:

$$t \rightarrow W\ b \rightarrow l\ \nu\ b$$

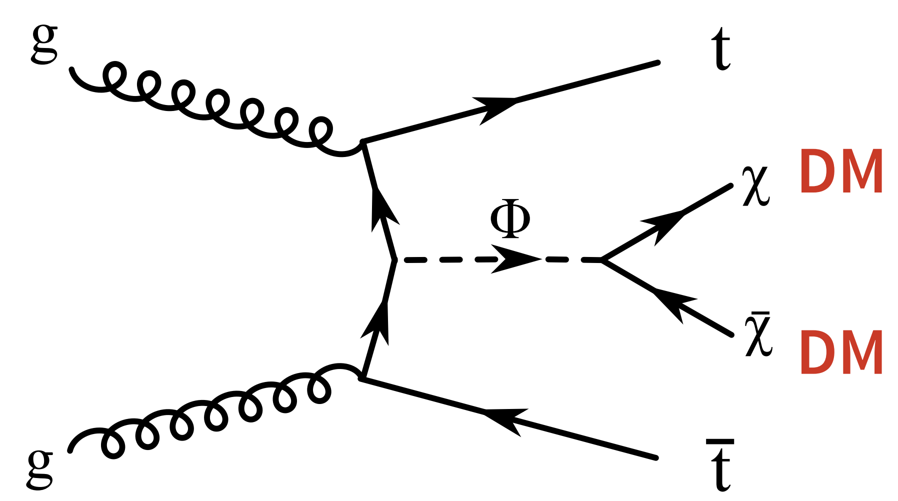
$$t \rightarrow W\ b \rightarrow q\ q'\ b$$

3 Combination for a tt decay:
- **Single lepton**
- **Dilepton**
- **Hadronic**

Dark Matter and top quarks

DM production in association to top quarks

- **Favoured in case of scalar/pseudoscalar mediator models**
  - Under the assumption of Yukawa-like coupling
    - HF coupling enhanced ($\propto$ m_q)
    - Loop-suppression for monojet process



- **Top-quark pair recoiling against DM particles**
- **Top decays almost exclusively to W b**
  - Two possible final states: **l ν b** *or* **q q' b**

Signal characterisation

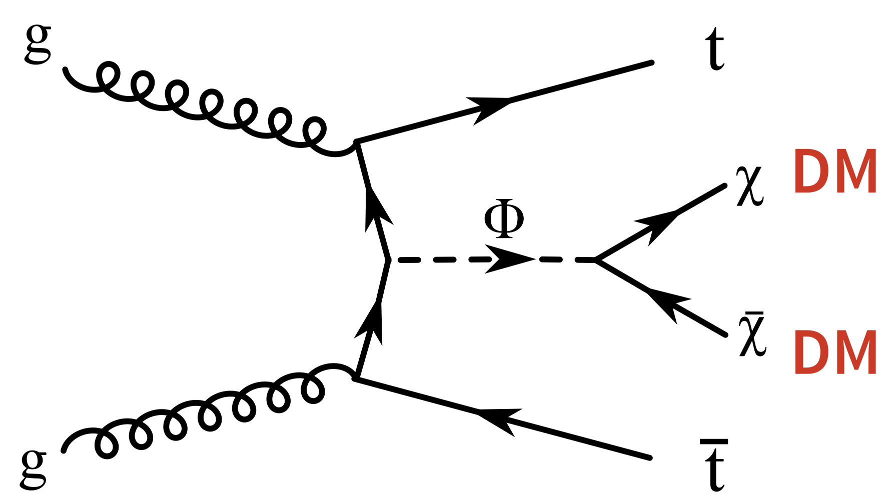
- **Large missing energy**
- **LF jets plus HF jets**
- **0/1/2 leptons depending on the final state**

3 Combination for a tt decay:
- **Single lepton**
- **Dilepton**
- **Hadronic**

Dark Matter and top quarks

DM production in association to top quarks

- **Favoured in case of scalar/pseudoscalar mediator models**
  - Under the assumption of Yukawa-like coupling
    - HF coupling enhanced ($\propto\ m_q$)
    - Loop-suppression for monojet process
- **Top-quark pair recoiling against DM particles**
- **Top decays almost exclusively to W b**
  - Two possible final states: **l ν b** *or* **q q' b**



Signal characterisation

- **Large missing energy**
- **LF jets plus HF jets**
- **0/1/2 leptons depending on the final state**

3 Combination for a tt decay:
- **Single lepton**
- **Dilepton**
- **Hadronic**

Analysis Strategy: Single-lepton channel

Signal selection

- **1 lepton and at least 3 jets**
  - out of which 1 b-tagged
- **E_T^{miss} > 160 GeV**

Background contamination

- **Dominant backgrounds from**
  - tt+jets (2l), W($\rightarrow$lν) + jets
- **Minor contributions from**
  - Z($\rightarrow$ll)+jets, SingleTop, Dibosons

Analysis Strategy: Single-lepton channel

Signal selection

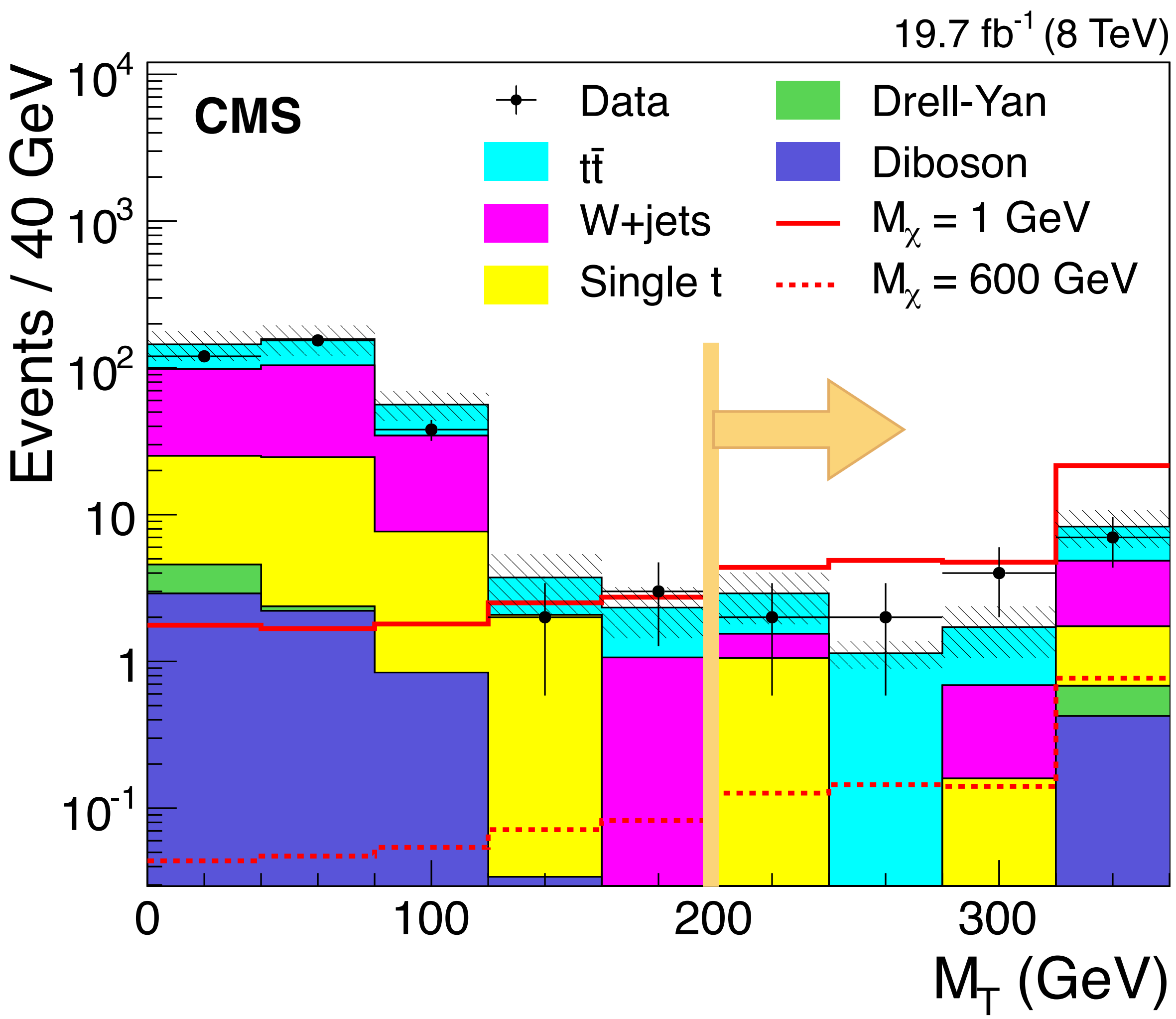
- **1 lepton and at least 3 jets**
  - out of which 1 b-tagged
- **E_T^{miss} > 160 GeV**

Background contamination

- **Dominant backgrounds from**
  - tt+jets (2l), W(→lν) + jets
- **Minor contributions from**
  - Z(→ll)+jets, SingleTop, Dibosons

W(→lν) + Jets suppression through selection on m_T^W

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



CMS, arXiv:1504.03198

Analysis Strategy: Single-lepton channel

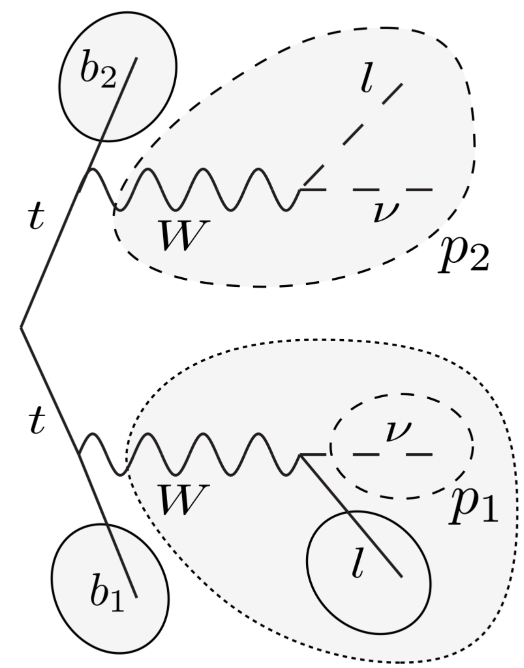
Signal selection

- **1 lepton and at least 3 jets**
  - out of which 1 b-tagged
- **E_T^{miss} > 160 GeV**

Background contamination

- **Dominant backgrounds from**
  - **tt+jets (2l)**, W(→lν) + jets
- **Minor contributions from**
  - Z(→ll)+jets, SingleTop, Dibosons

tt + Jets suppression through selection on m_{T2}^{W}



Dileptonic tt+jets with 1 lepton lost

m_{T2}^{W}: minimal mother particle mass compatible with t t → lνb lνb event topology and daughter particle mass

Dileptonic tt+jets event have lower values of m_{T2}^{W} with respect to signal

Analysis Strategy: Single-lepton channel

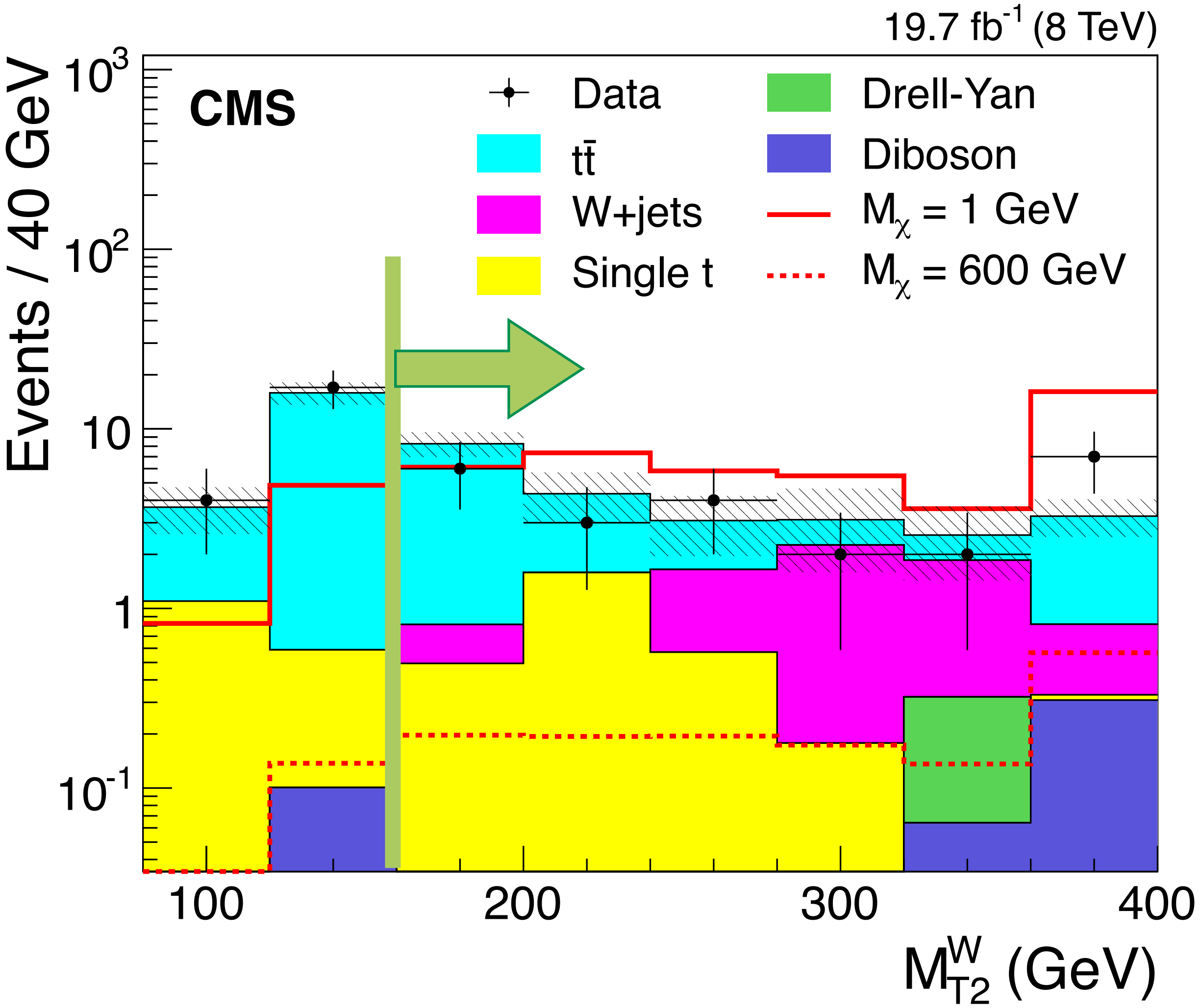
Signal selection

- **1 lepton and at least 3 jets**
  - out of which 1 b-tagged
- **E_T^{miss} > 160 GeV**

Background contamination

- **Dominant backgrounds from**
  - tt+jets (2l), W(→lν) + jets
- **Minor contributions from**
  - Z(→ll)+jets, SingleTop, Dibosons

tt + Jets suppression through selection on m_{T2}^W



CMS, arXiv:1504.03198

Analysis Strategy: Hadronic channel

Signal selection

- **At least 4 jets**
  - out of which 2 b-tagged
- **Veto on leptons**
- **Large E_T^{miss}**

Background contamination

- **Dominant backgrounds from**
  - tt+jets (1l), W(→lν)/Z(→νν) + jets
- **Minor contributions from**
  - SingleTop, Dibosons, QCD

Analysis Strategy: Hadronic channel

Signal selection

- **At least 4 jets**
  - out of which 2 b-tagged
- **Veto on leptons**
- **Large E_T^{miss}**

Background contamination

- **Dominant backgrounds from**
  - tt+jets (1l), W(→lν)/Z(→νν) + jets
- **Minor contributions from**
  - SingleTop, Dibosons, QCD

W(→lν) + Jets and Z(→νν) + jets reduced by request on b-tagging.

Remain source of irreducible bkgs

Analysis Strategy: Hadronic channel

Signal selection

- **At least 4 jets**
  - out of which 2 b-tagged
- **Veto on leptons**
- **Large E_T^{miss}**

Background contamination

- **Dominant backgrounds from**
  - **tt+jets (1l)**, W(→lν)/Z(→νν) + jets
- **Minor contributions from**
  - SingleTop, Dibosons, **QCD**

QCD and tt + jets suppression through selection on $\Delta\Phi(j, E_T^{miss})$

$\Delta\Phi(j, E_T^{miss})$ useful to reject dileptonic tt+jets events also in single-lepton channel

Analysis Strategy: Hadronic channel

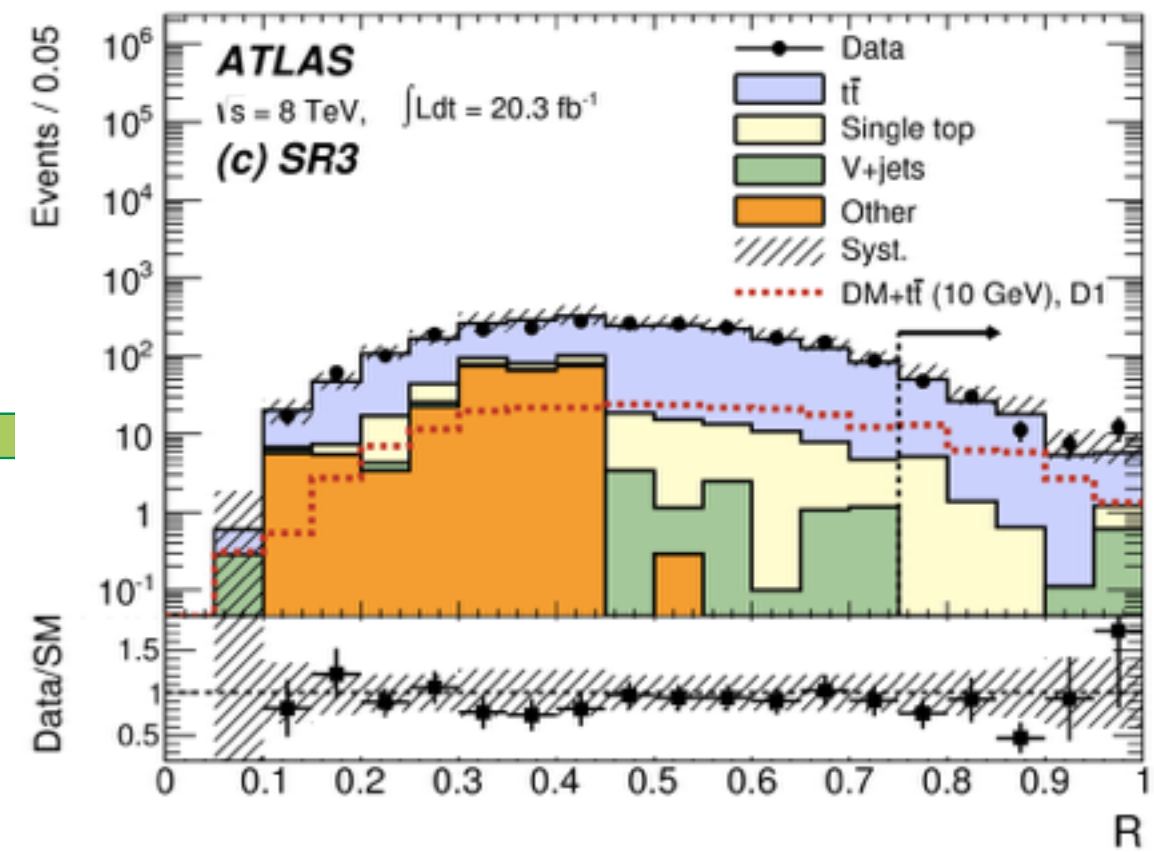
Signal selection

- **At least 4 jets**
  - out of which 2 b-tagged
- **Veto on leptons**
- **Large E_T^{miss}**

Background contamination

- **Dominant backgrounds from**
  - tt+jets (1l), W(→lν)/Z(→νν) + jets
- **Minor contributions from**
  - SingleTop, Dibosons, QCD

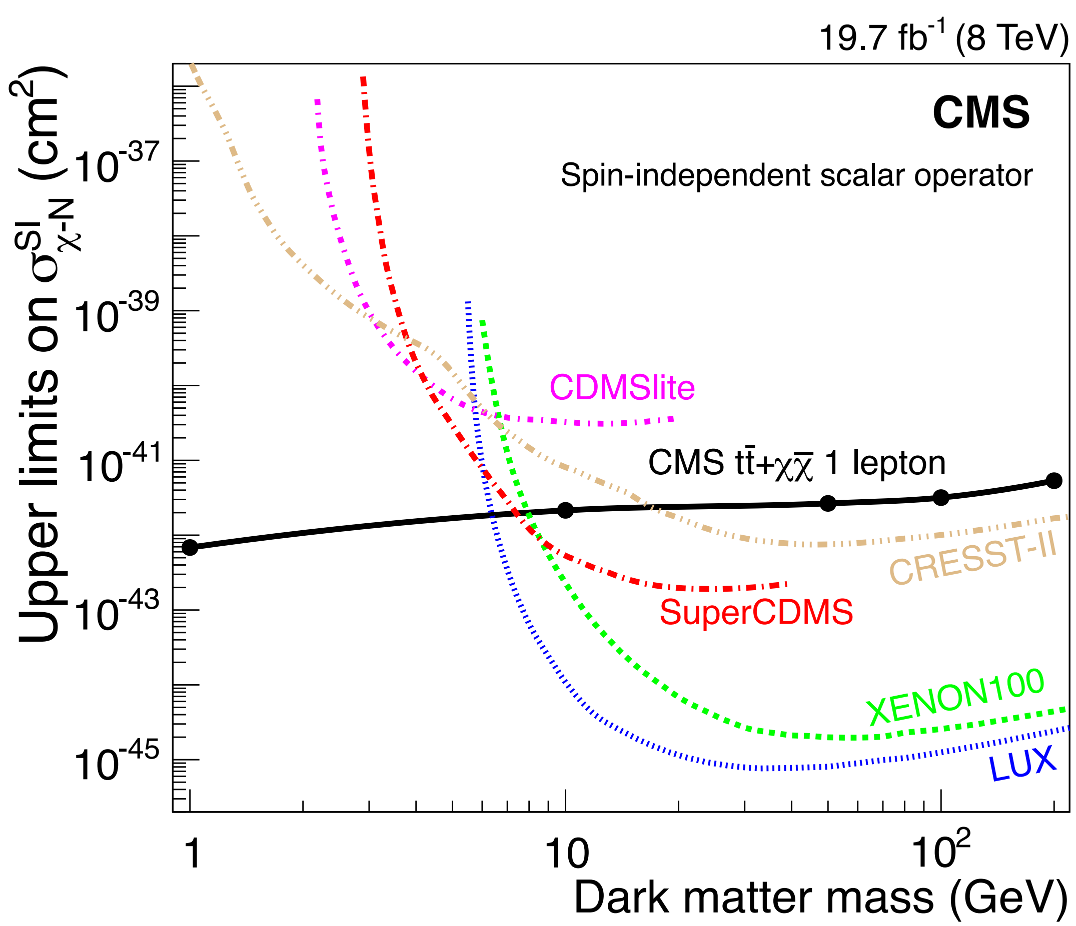
tt + jets suppression through selection on Razor variables

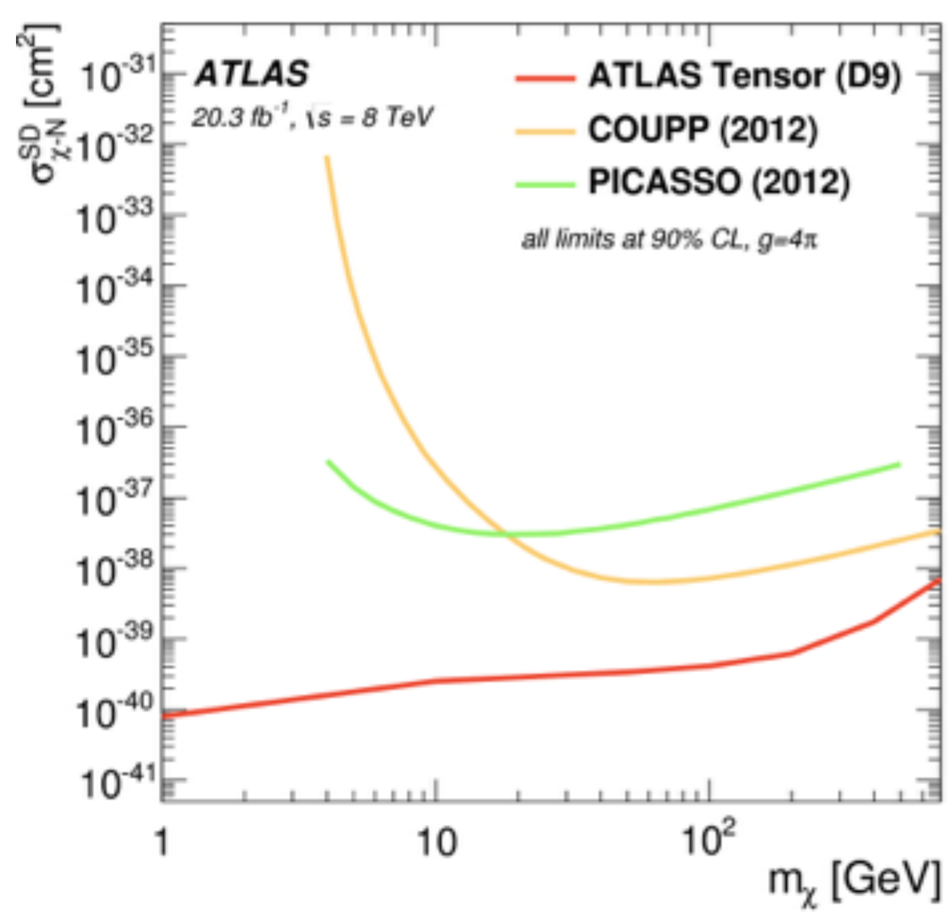


Razor variables use both transverse and longitudinal information about the event, to fully exploit the kinematics of the decay

Results from tt + DM search

- **Up so far: results from 8 TeV published by both collaborations**
  - Effective Field theory approach used for results interpretation
    - Major sensitivity to Scalar/Pseudoscalar interactions
  - Set limits on DM-nucleon elastic scattering cross section, as a function od M_{DM}
  - Collider searches more sensitive at low M_{DM}



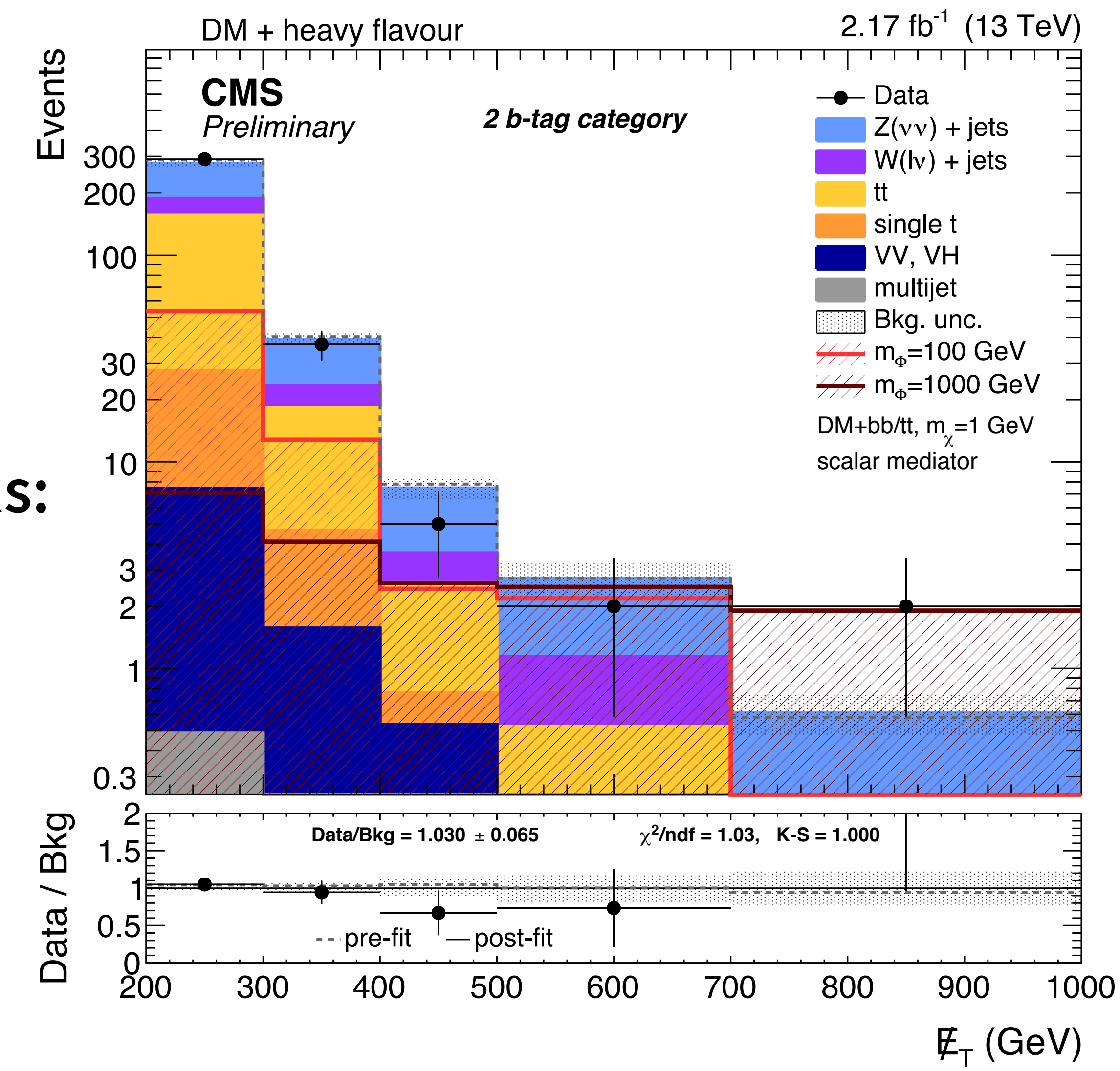


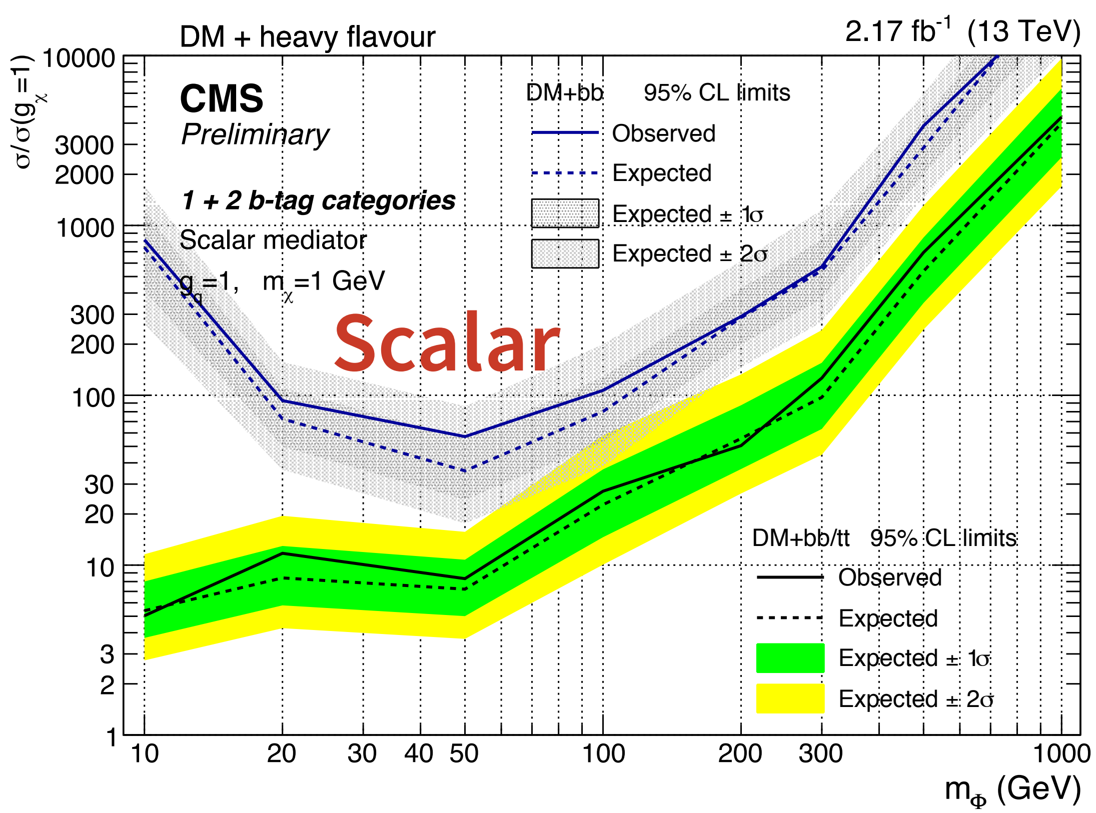
DM plus bottom quarks

CMS PAS B2G-15-007

DM production in association with b quarks

- **Signal characterisation :E_T^{miss} + b-quarks**
  - 2 categories of signal-like events:
    - based on jet and b-tag multiplicity
- **Signal extraction from E_T^{miss} distribution**
- **Main backgrounds derived from leptonic CRs:**
  - Z(→νν) + *jets*, W(→lν) + *jets*, ttbar



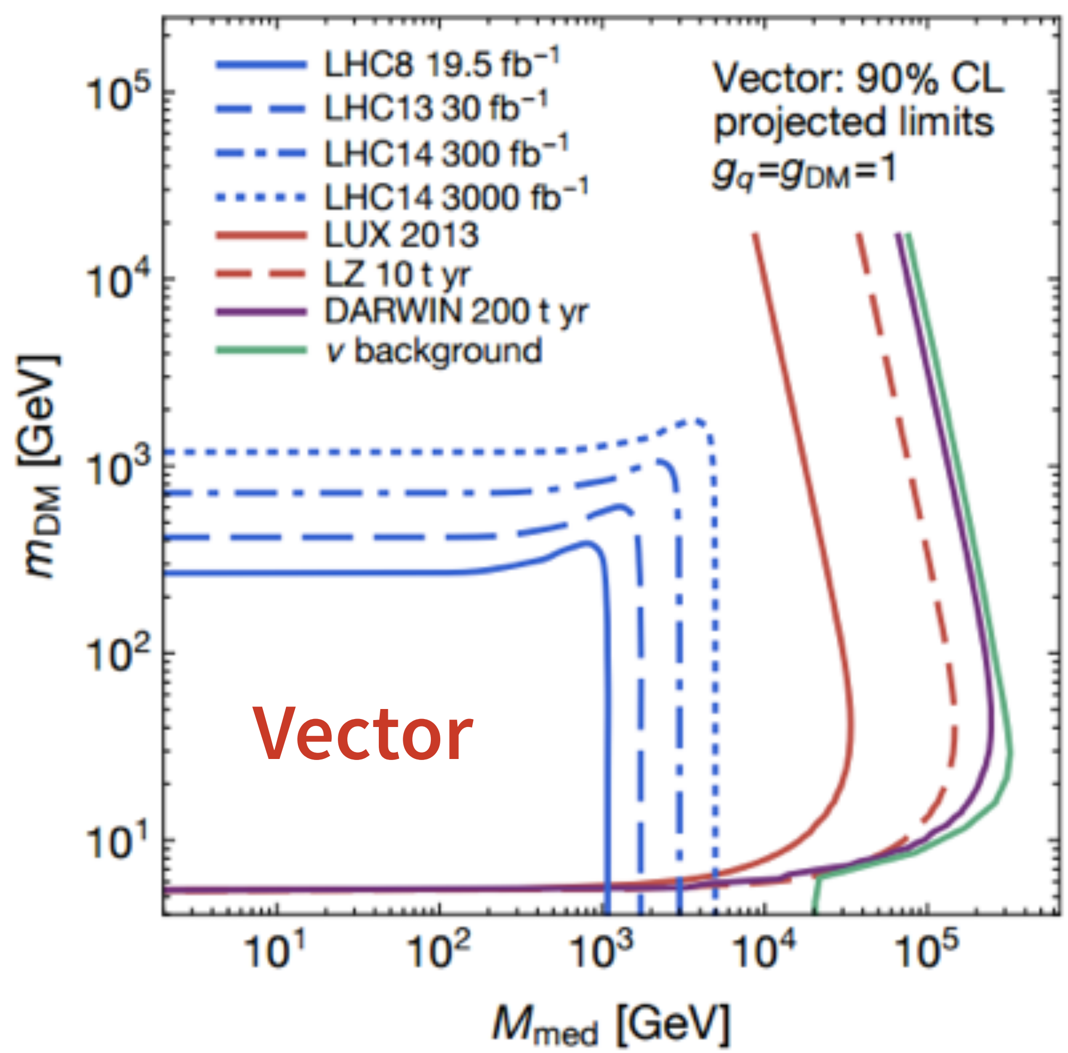


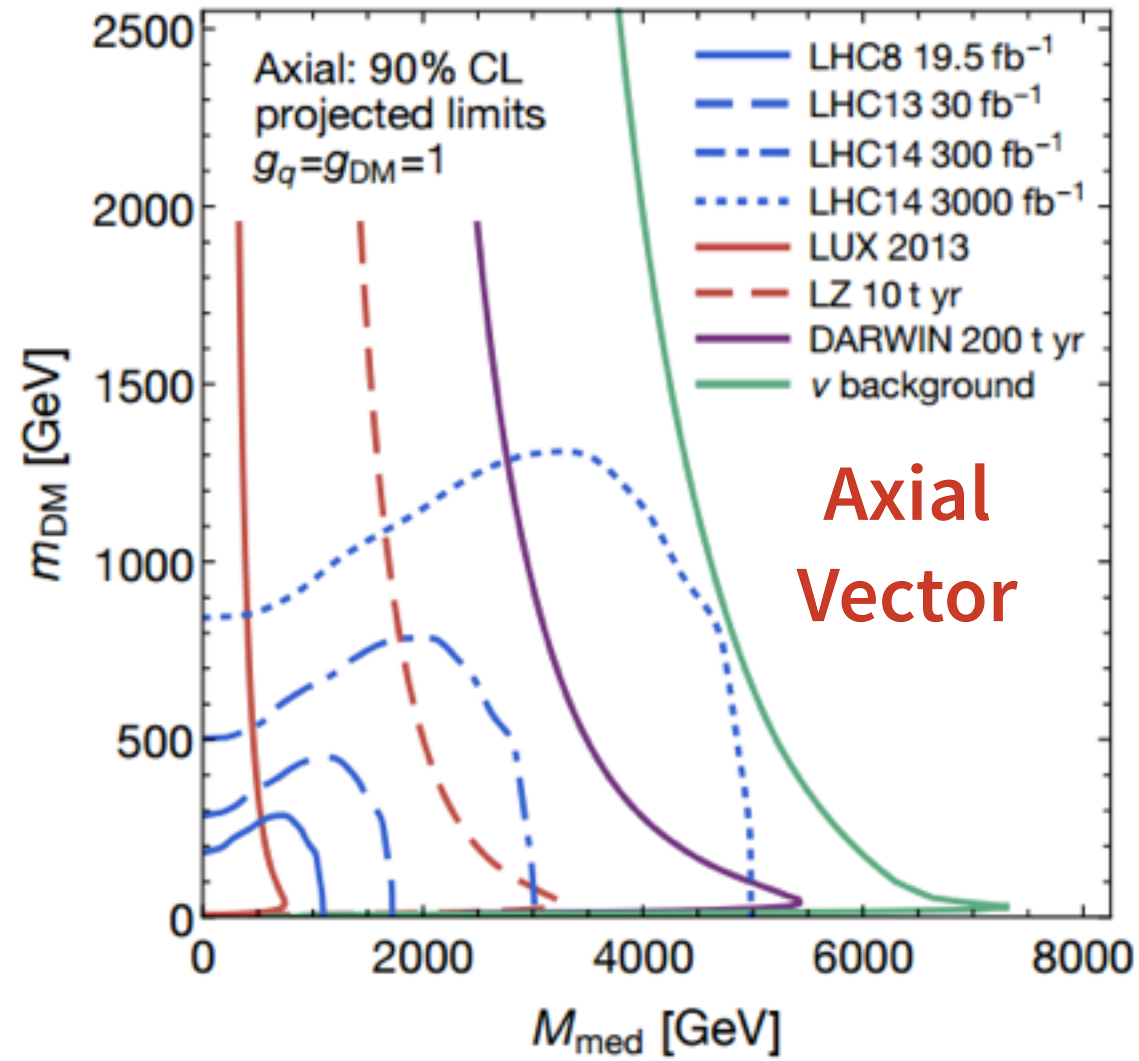
Complementary to DM + tt search

Sensitivity projections

Projections for

- Run-II: 30 fb^{-1} @ 13 TeV
- Run-III: 300 fb^{-1} @ 14 TeV
- HL-LHC: 3000 fb^{-1} @ 14 TeV





Expected limits for

- LUX-ZEPLIN: 10 tonne years exposure
- DARWIN 200 tonne years exposure

Conclusions

- **The Dark Matter problem stands out as one of the major challenges for modern physics**
  - LHC allow to probe DM at the frontiers of high energy physics in a variety of direct searches
- **Needs appropriate interpretation of the searches and careful comparison with other experiments**
  - Simplified models provide a more accurate interpretation framework with respect to EFT
  - Working closely with theorists to develop new models

LHC Run-II is just started and we are waiting for more data

Hopefully the discovery is just behind the corner!

Thank you
for your attention!

Additional Material

Monojet Systematic Uncertainties

- **Experimental uncertainties on transfer factors R**
  - Lepton efficiency: 1/2% (μ/e)
  - Lepton veto: 3%
  - Photon efficiency: 2%
  - Photon purity: 2%
- **Theoretical uncertainties on transfer factors R**
  - QCD scale, PDF uncertainties
  - EWK corrections
- **Systematic uncertainties on minor bkgs**
  - Top cross section: 10%
  - Diboson cross-section: 20%
  - Luminosity: 12%
  - MET: 4%
  - b-veto: 6%

Translating results on DD plane

Vector

$$\sigma^{V}_{\chi\mathrm{p}} = \frac{9}{\pi}\frac{g^2_{\mathrm{DM}} g^2_{\mathrm{SM}} \rho^2}{m^4_{\mathrm{MED}}}$$

Scalar

$$\sigma^{S}_{\chi\mathrm{p}} = \frac{\rho^2}{\pi}\left|\frac{m_p}{m_t}\frac{g_t y_t \; g_\chi y_\chi}{m^2_{\mathrm{MED}}}\frac{2}{27} f_{\mathrm{TG}}\right|^2$$

Axial-Vector

$$\sigma^{A}_{\chi\mathrm{p}} = \frac{3}{\pi}\frac{g^2_{\mathrm{DM}} g^2_{\mathrm{SM}} a^2 \rho^2}{m^4_{\mathrm{MED}}}$$

Pseudoscalar

$$\langle \sigma v \rangle^{P}_{\bar{b}b} = \frac{N_C}{2\pi}\frac{(y_b g_b)^2 (y_\chi g_\chi)^2 \, m^2_{\mathrm{DM}}}{(m^2_{\mathrm{MED}} - 4m^2_{\mathrm{DM}})^2 + m^2_{\mathrm{MED}}\Gamma^2_{\mathrm{MED}}}\sqrt{1 - \frac{m_b^2}{m^2_{DM}}}$$

hep-ph/1411.0535v2

hep-ph/1407.8257v2

tt+DM: Background estimation

- **Major backgrounds after selection are:**
  - Single-lepton: tt(2l), W(lν) +Jets
  - Hadronic: tt(1l), W(lν)+Jets, Z(νν)+jets
- **Dedicated background enriched CRs defined for single-lepton and hadronic channels :**

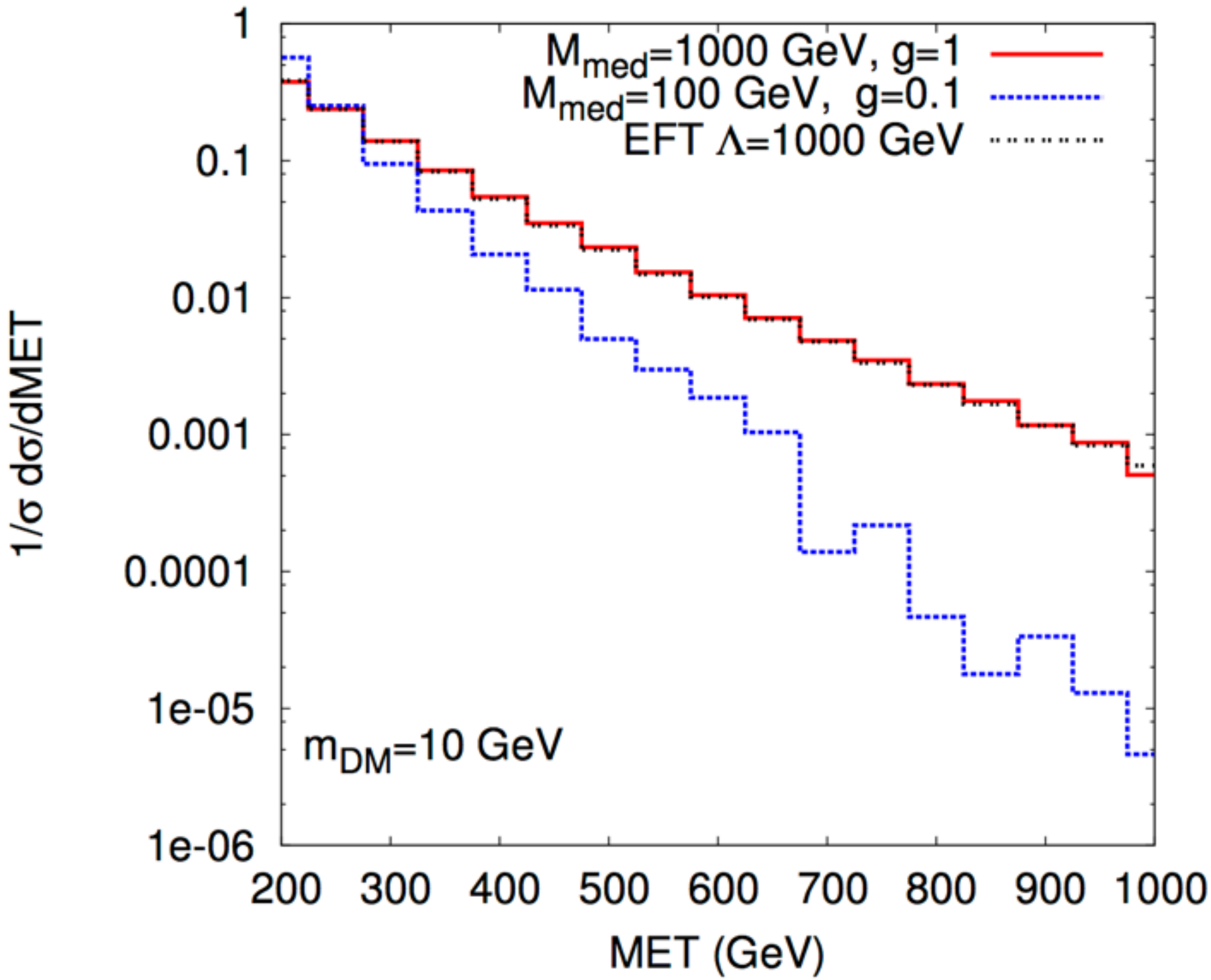
Single-lepton channel

Backgro	Control Region
tt(2l)	ee/μμ/eμ
V+ Jets	0 b jets M_T >160

Full-hadronic channel

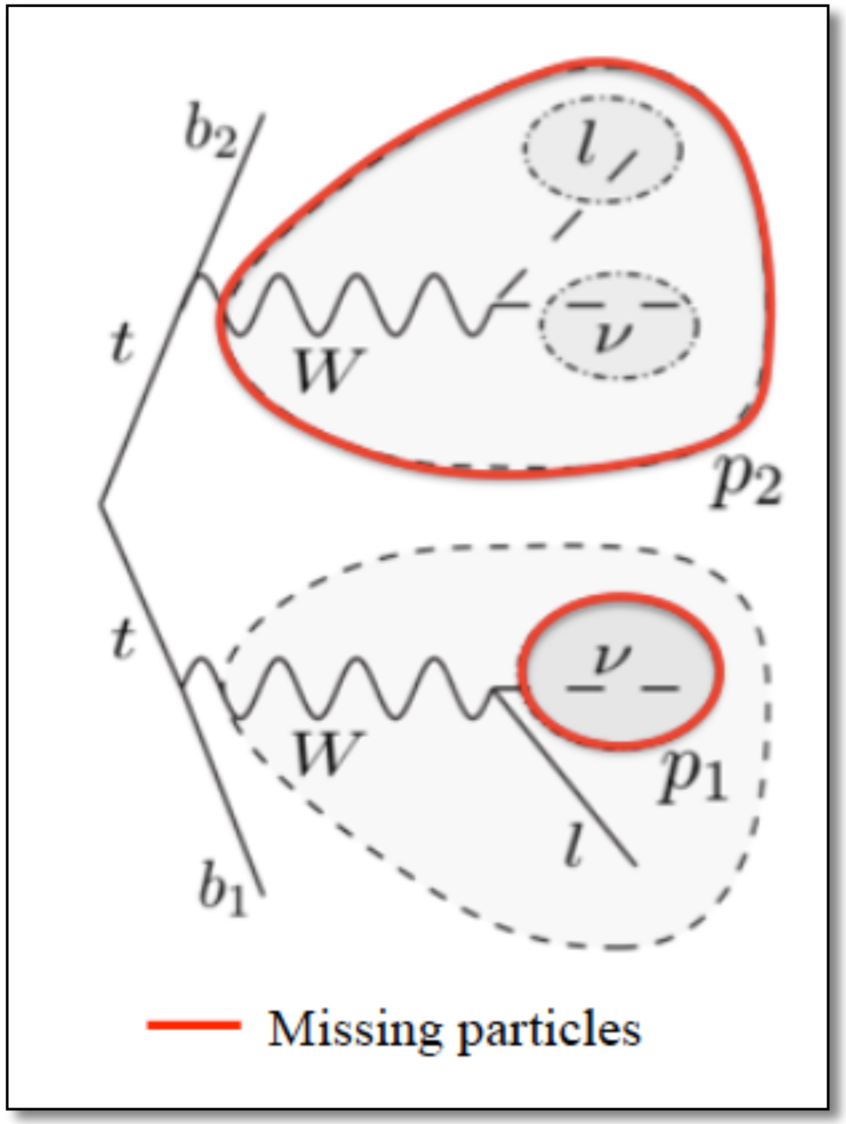
Backgroun	Control Region
tt(1l)	Single e/μ with M_T<160
V+ Jets	0 b jets
W(lν) + Jets	e/μ, 0 b jets & M_T<160
Z(νν) + Jets	ee/μμ, 0 b jets & M_{ll}<160

DM Kinematics



$M_{T2}{}^{W}$

- **tt di-leptonic**
  - irreducible background for tt+ DM semileptonic channel
- **Large E_T^{miss} from neutrino and missing lepton**
  - This implies higher M_T
- **Transverse mass M_{T2} can be used to reject such kind of background events**
  - $M_{T2}{}^{W}$ is the minimal mother particle mass compatible with assumed event topology and daughter particle mass



$$M_{T2}^{W} = \min\left\{ m_y \text{ consistent with: } \left[\begin{array}{c} \vec{p}_1^{\,T} + \vec{p}_2^{\,T} = \vec{E}_T^{\rm miss},\ p_1^2 = 0,\ (p_1 + p_\ell)^2 = p_2^2 = M_W^2, \\ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{array} \right] \right\}$$

Bai, Cheng, Gallichio, Gu JHEP 07 (2012) 110

Bounds on $\sigma_{\chi\text{-}N}$

[CMS, JHEP 06 (2015) 121]

- **Upper limits on σ_χ translated in lower limits on M* (interaction scale)**
  - Ex: scalar interaction $\propto (M^*)^{-3}$

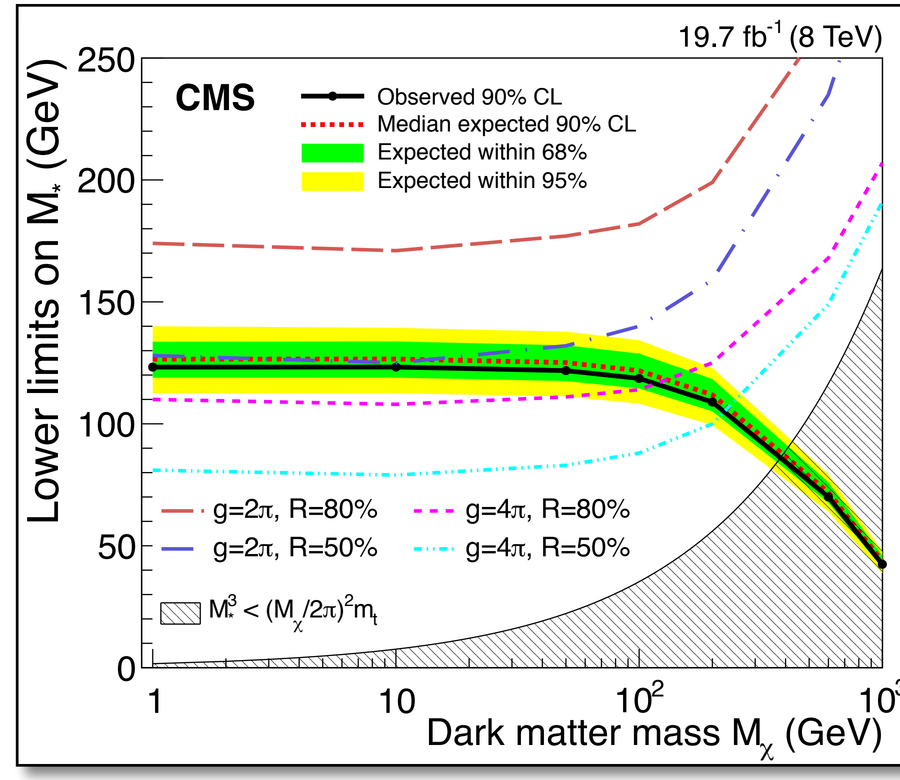
$$\mathcal{O} = \frac{m_q}{M_*^3}\bar{q}q\bar{X}X$$

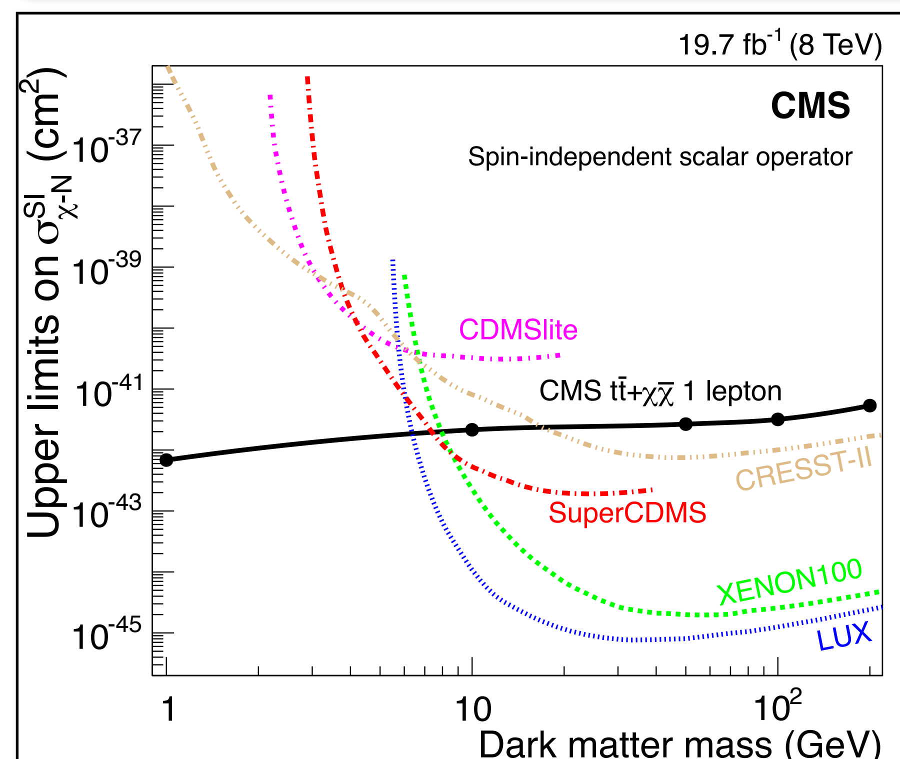
  - And $\sigma_\chi \propto (M^*)^{-6}$

$$M^* = M^*_{gen}\left(\frac{\sigma_{gen}}{\sigma_\chi}\right)^{(1/6)}$$

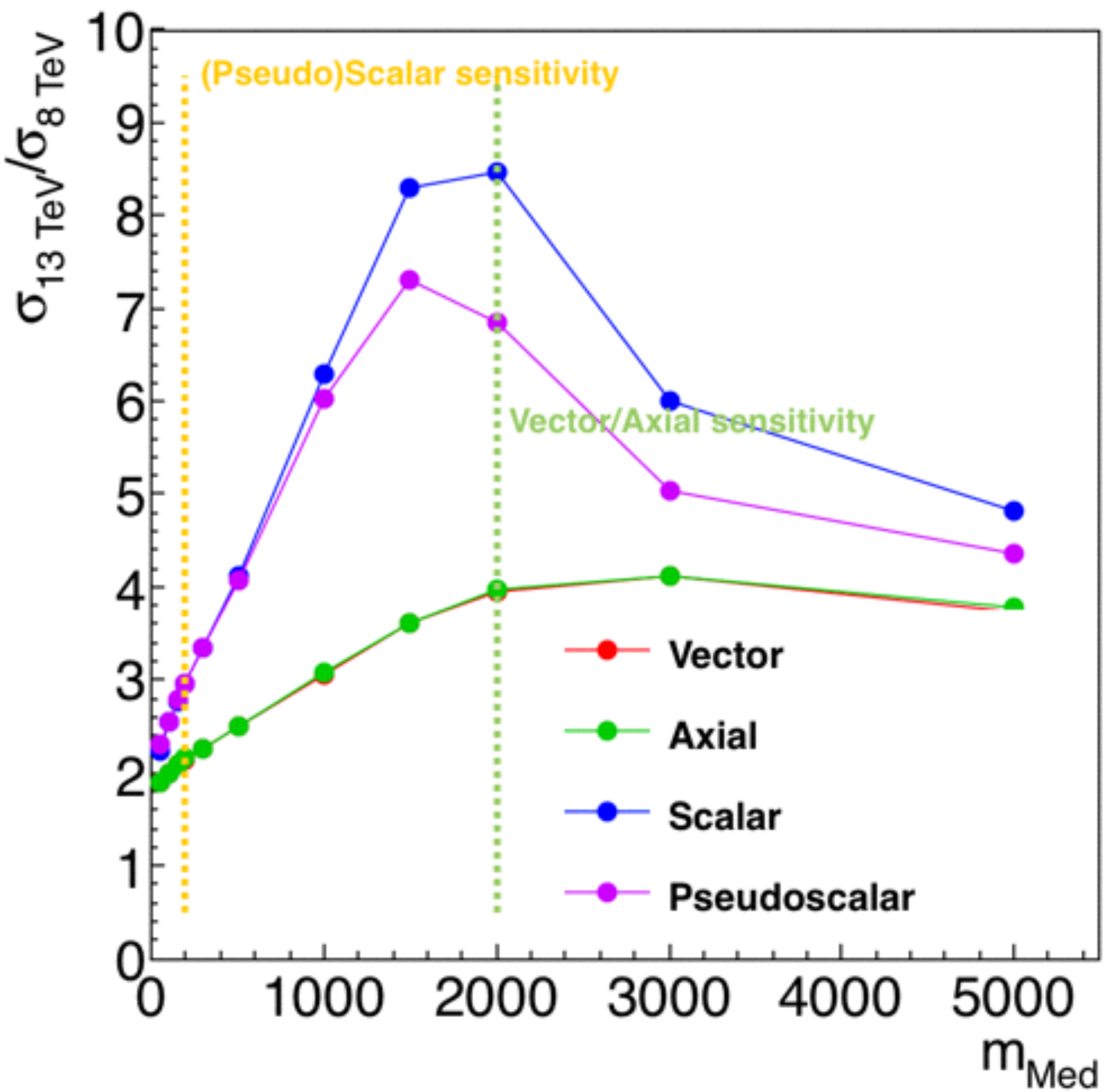
  - Translation of the constraints on M* in bounds on $\sigma_{\chi\text{-}N}$ (SI or SD according to the case)
    - Phys.Rev.D82:116010,2010

$$\sigma_0^{D1} = 1.60x10^{-37}\text{cm}^2\left(\frac{\mu_\chi}{1\text{ GeV}}\right)^2\left(\frac{20\text{ GeV}}{M^*}\right)^6$$





$\sigma_{13TeV}/\sigma_{8TeV}$ (monojet)



DM + b(b)

Scalar

$\sigma/\sigma(g_\chi, g_q = 1)$	m_Φ (GeV) 10	15	20	50	100	200	300	500	1000
m_χ (GeV) 1	824	-	93	57	107	291	572	$3.8 \cdot 10^3$	$2.3 \cdot 10^4$
10	$2.7 \cdot 10^3$	$1.8 \cdot 10^3$	-	54	61	-	-	-	-
50	-	-	-	$1.2 \cdot 10^4$	$7.1 \cdot 10^3$	-	-	-	-
100	-	-	-	-	-	-	-	-	-
150	-	-	-	-	-	$7.2 \cdot 10^4$	$2.7 \cdot 10^4$	$4.7 \cdot 10^3$	$2.8 \cdot 10^4$
500	$8.0 \cdot 10^6$	-	-	-	-	-	-	$5.0 \cdot 10^6$	$6.9 \cdot 10^5$

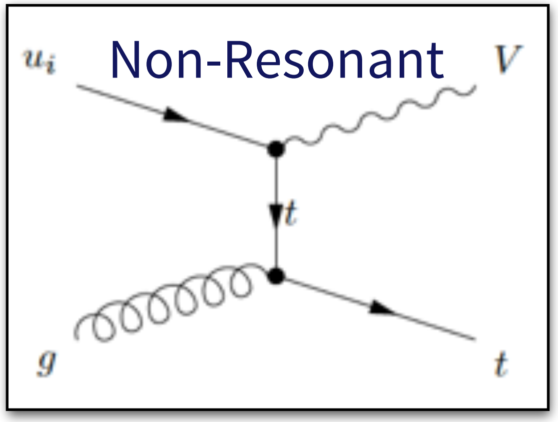
Pseudoscalar

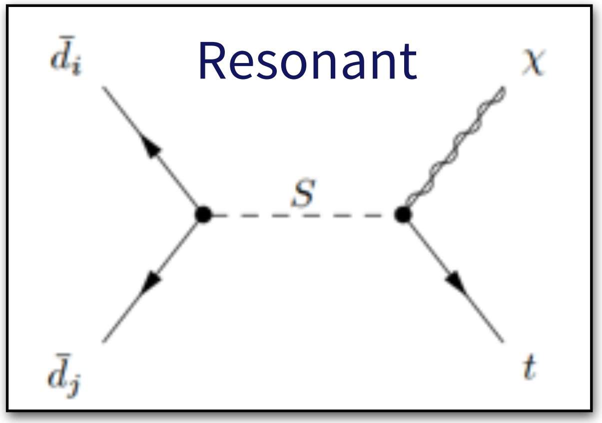
$\sigma/\sigma(g_\chi, g_q = 1)$	m_Φ (GeV) 10	15	20	50	100	200	300	500	1000
m_χ (GeV) 1	$1.0 \cdot 10^4$	-	143	96	117	268	671	$5.0 \cdot 10^3$	$3.1 \cdot 10^4$
10	-	340	-	74	60	-	-	-	-
50	$1.1 \cdot 10^4$	-	-	$7.0 \cdot 10^3$	$2.9 \cdot 10^3$	360	-	-	-
100	-	-	-	-	-	-	-	-	-
150	-	-	-	-	-	$2.8 \cdot 10^4$	$7.3 \cdot 10^3$	$5.9 \cdot 10^3$	$2.4 \cdot 10^4$
500	$3.3 \cdot 10^6$	-	-	-	-	-	-	-	-

Monotop @ 8 TeV

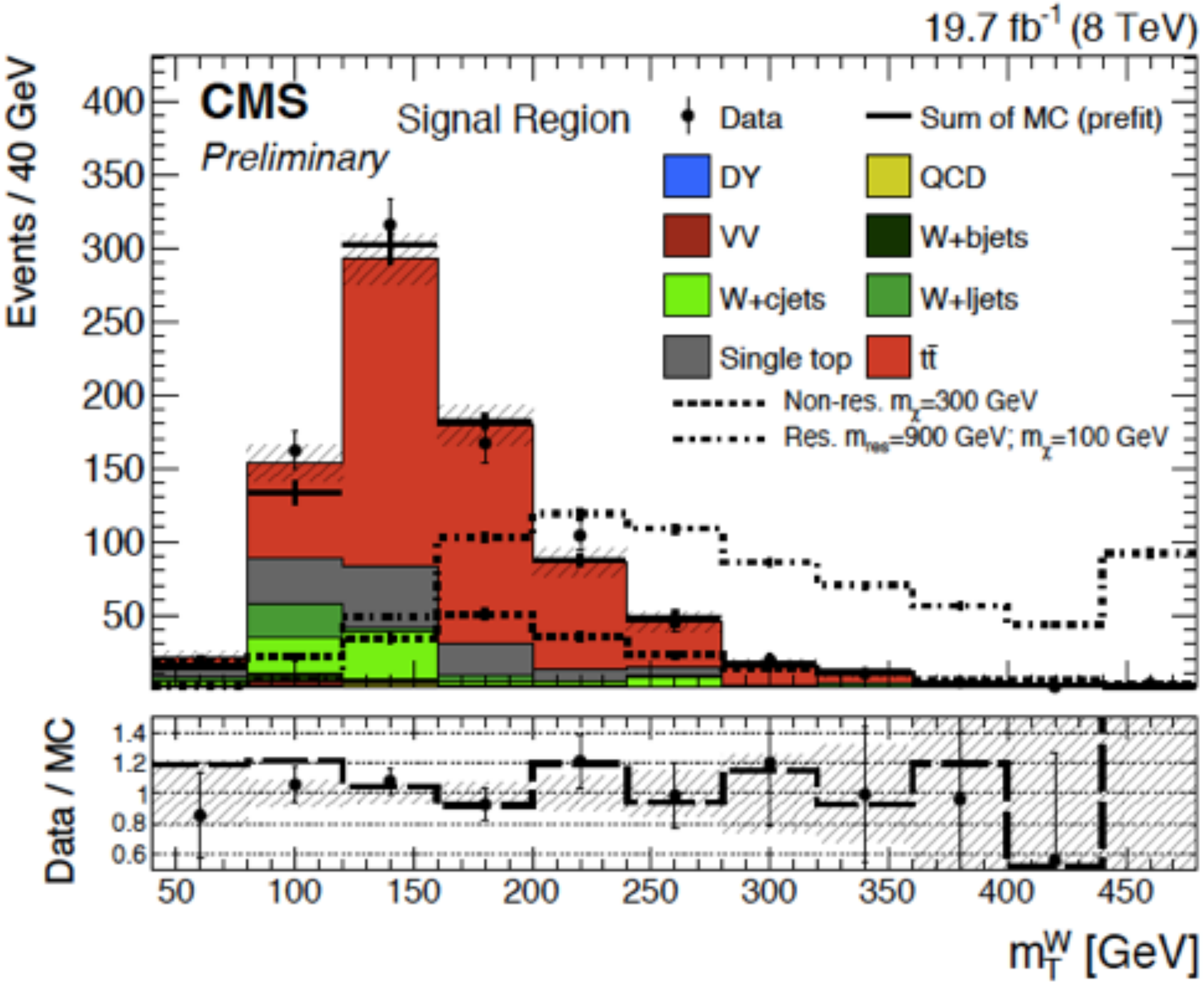
CMS PAS B2G-15-001

SM production of single top associated to large E_T^{miss} (monotop signature) suppressed





- **Two production modes BSM:**
  - FCNC interaction with an invisible Vector/Scalar DM particle
  - Resonant production of an invisible exotic state
- **Signal signature:**
  - 1 b-jet, 1 μ + E_T^{miss}
  - Excess of events in m_T^W tails

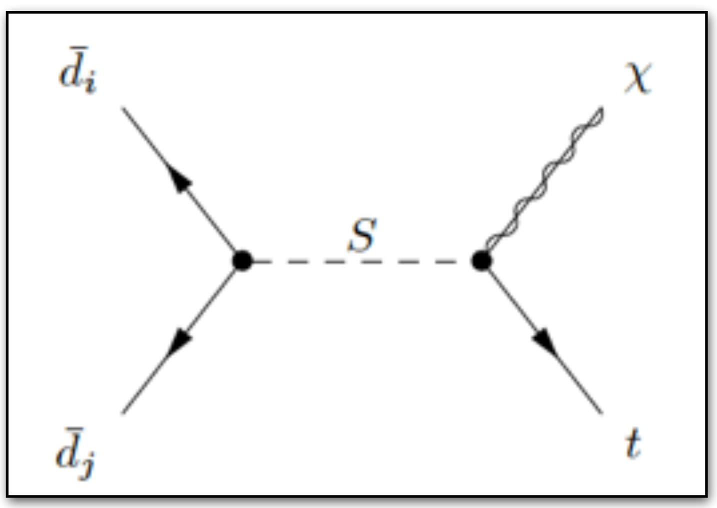


$$m_T^W = \sqrt{2p_T^{\mu}E_T^{miss}(1-\cos(\Delta\phi(\mu, E_T^{miss})))}$$

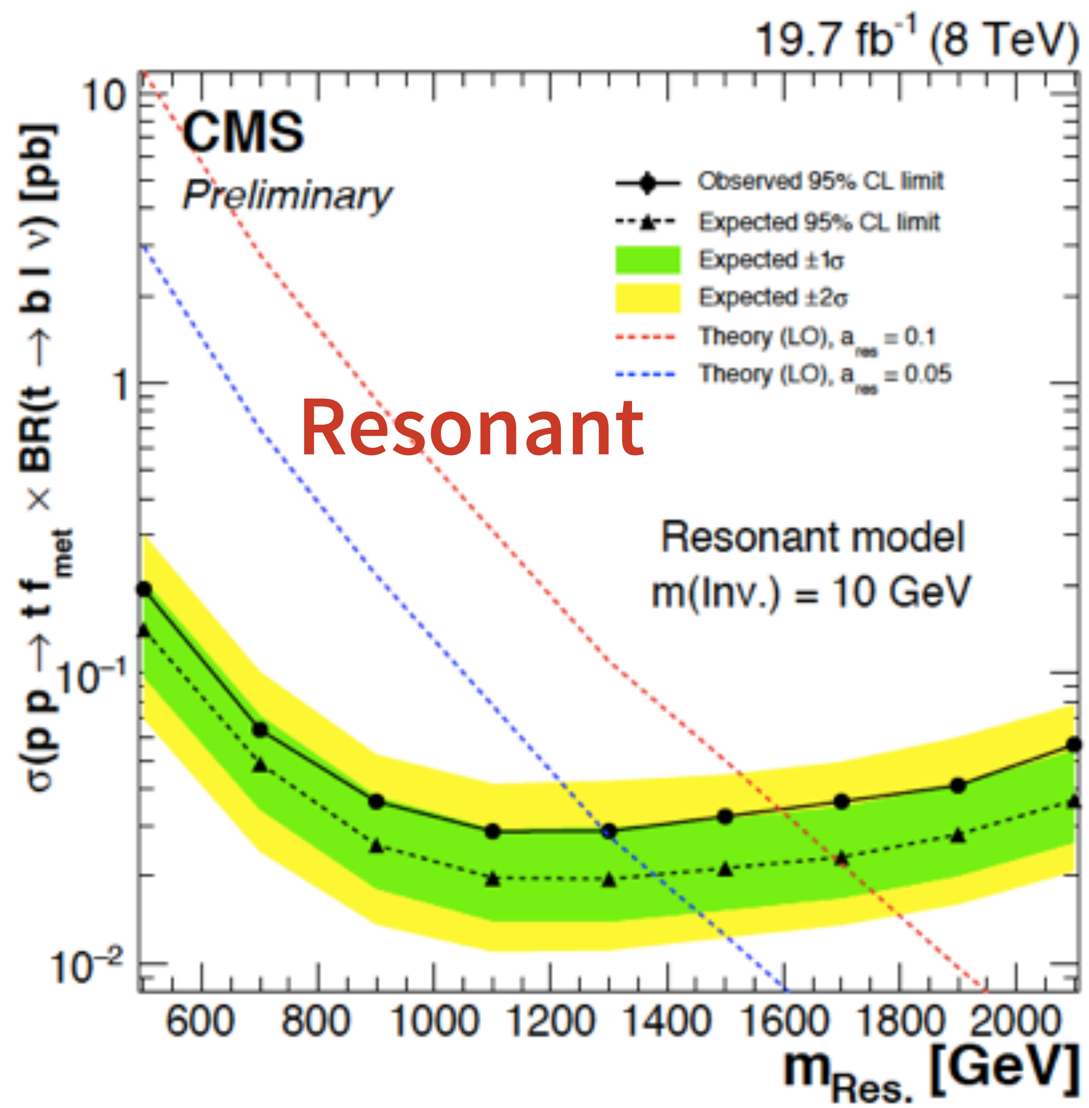
- Previous CMS search: hadronic decay

Monotop @ 8 TeV: Results

- **Main backgrounds, W+jets and ttbar, modelled from control samples**
  - W enriched CR (1j 0b)
  - ttbar enriched CR (2j 2b)
- **Template fit to m_T^W spectrum in signal and control samples**



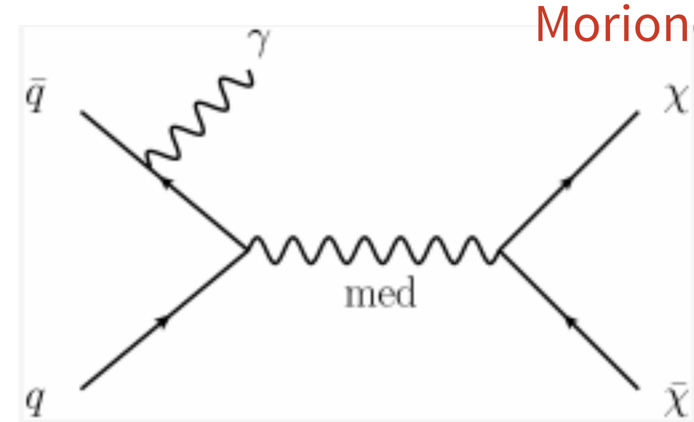
Resonant scenario excluded for resonant particle masses **up to 1610 GeV** (a_{res} = 0.1)

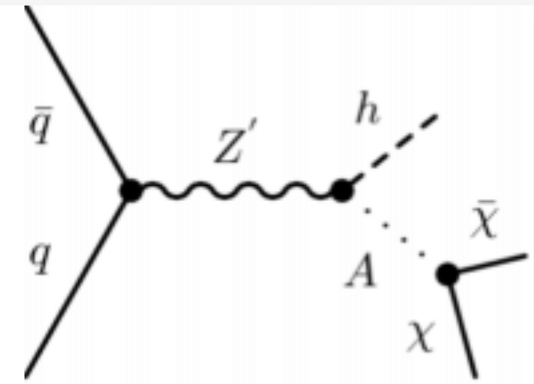


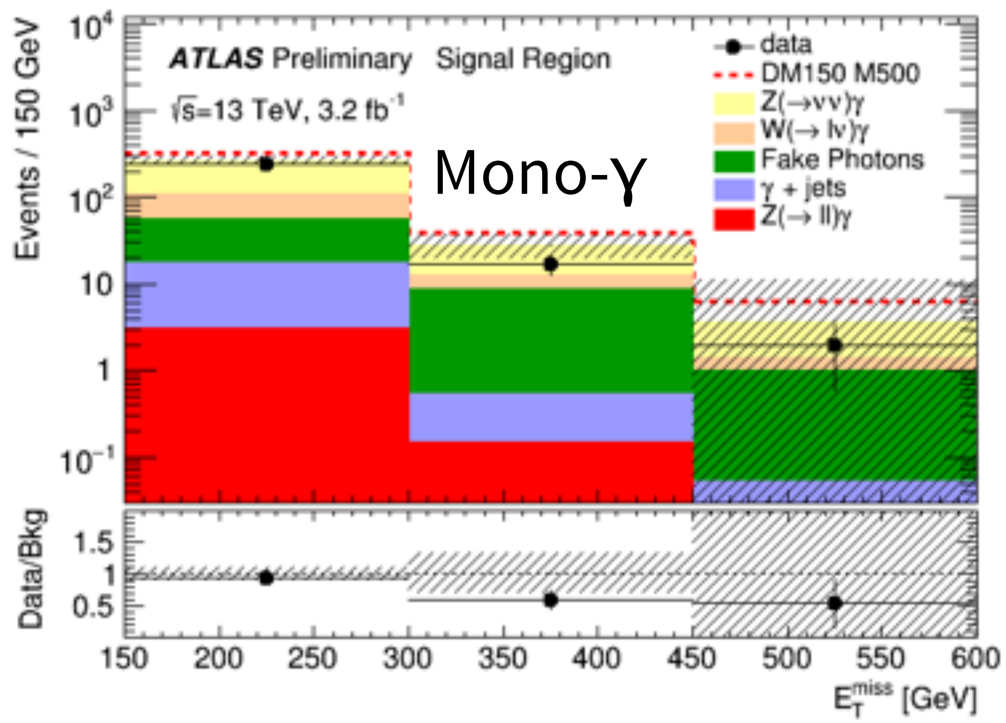
More mono-searches

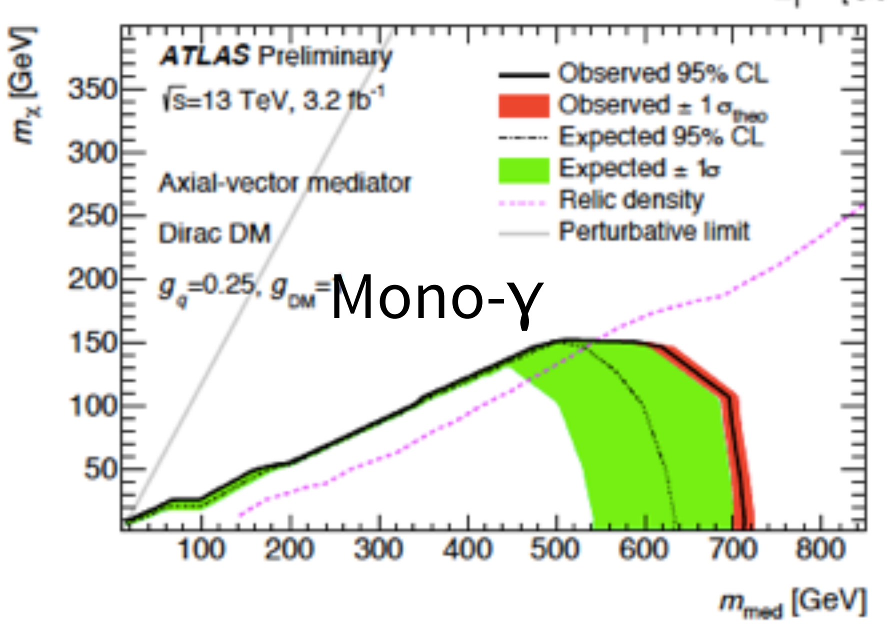
Moriond QCD 2016

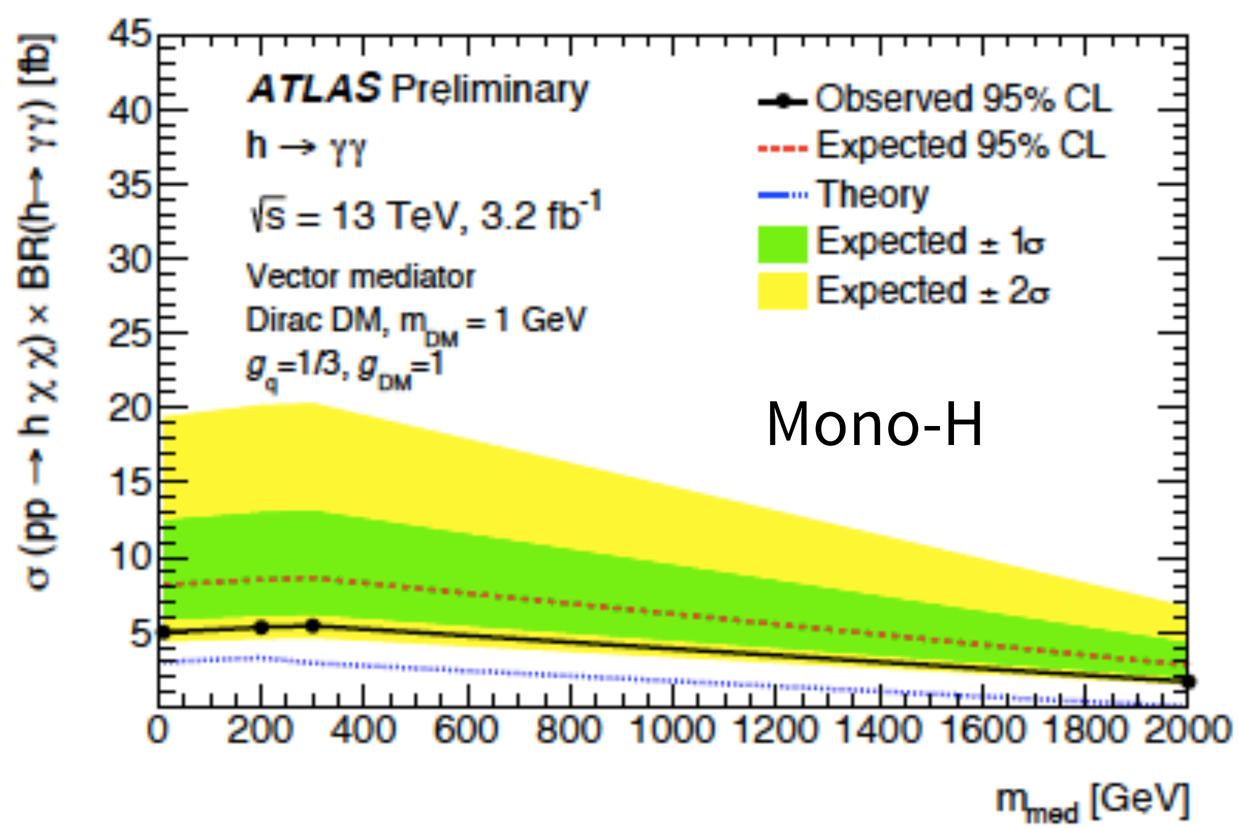
- **Mono-Photon: γ + DM**
  - Major uncertainties from photon fake rate
- **Mono-Higgs: H(γ γ/bb) + DM**





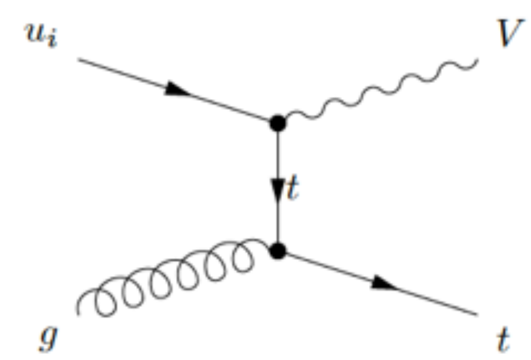


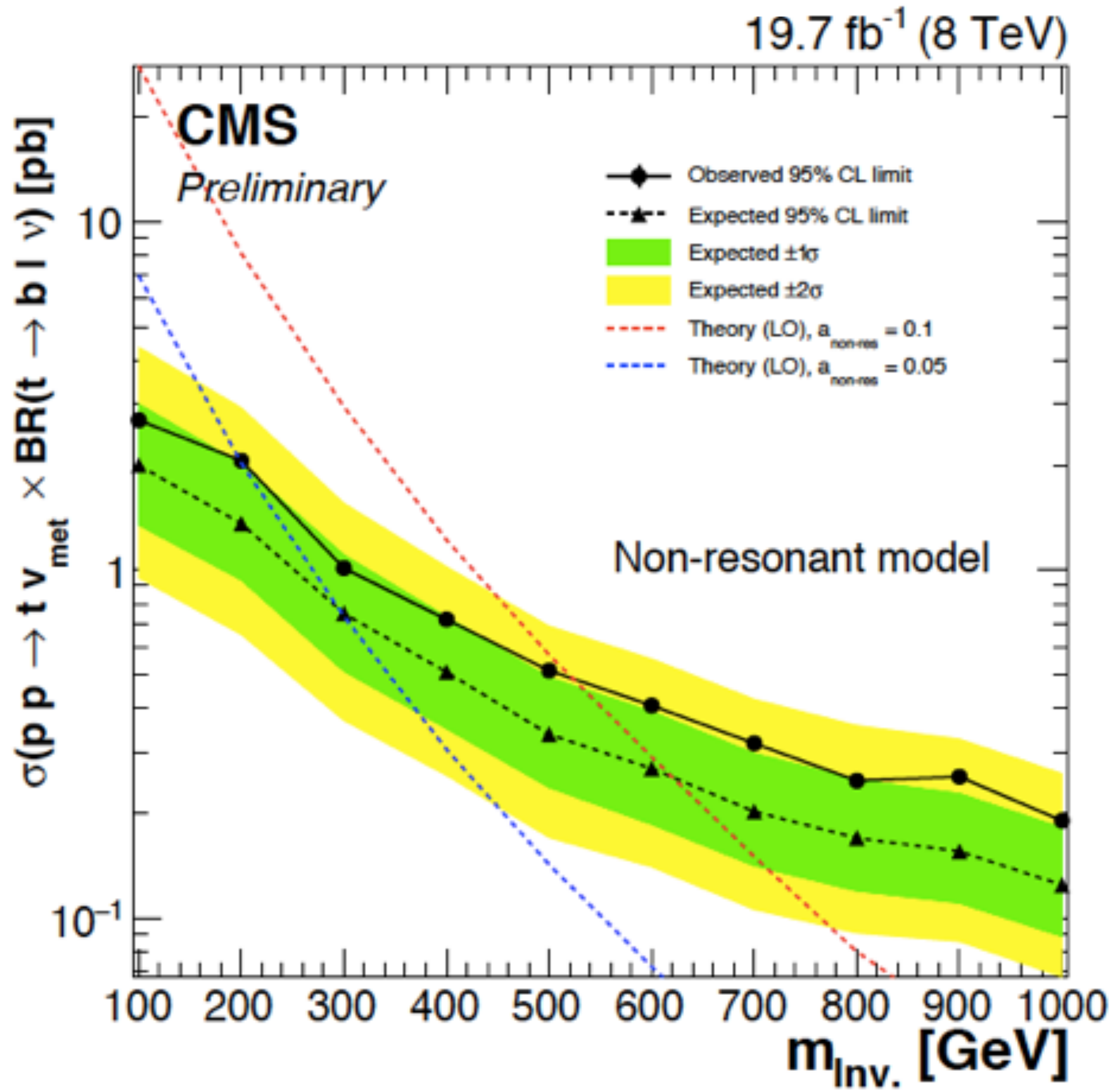




Monotop @ 8 TeV

- **Non-resonant scenario excluded for invisible particle masses up to 523 GeV**
- **Sensitivity close to hadronic channel**
  - Invisible vector particles excluded up to 650 GeV (CMS, arXiv:1410.1149v2])

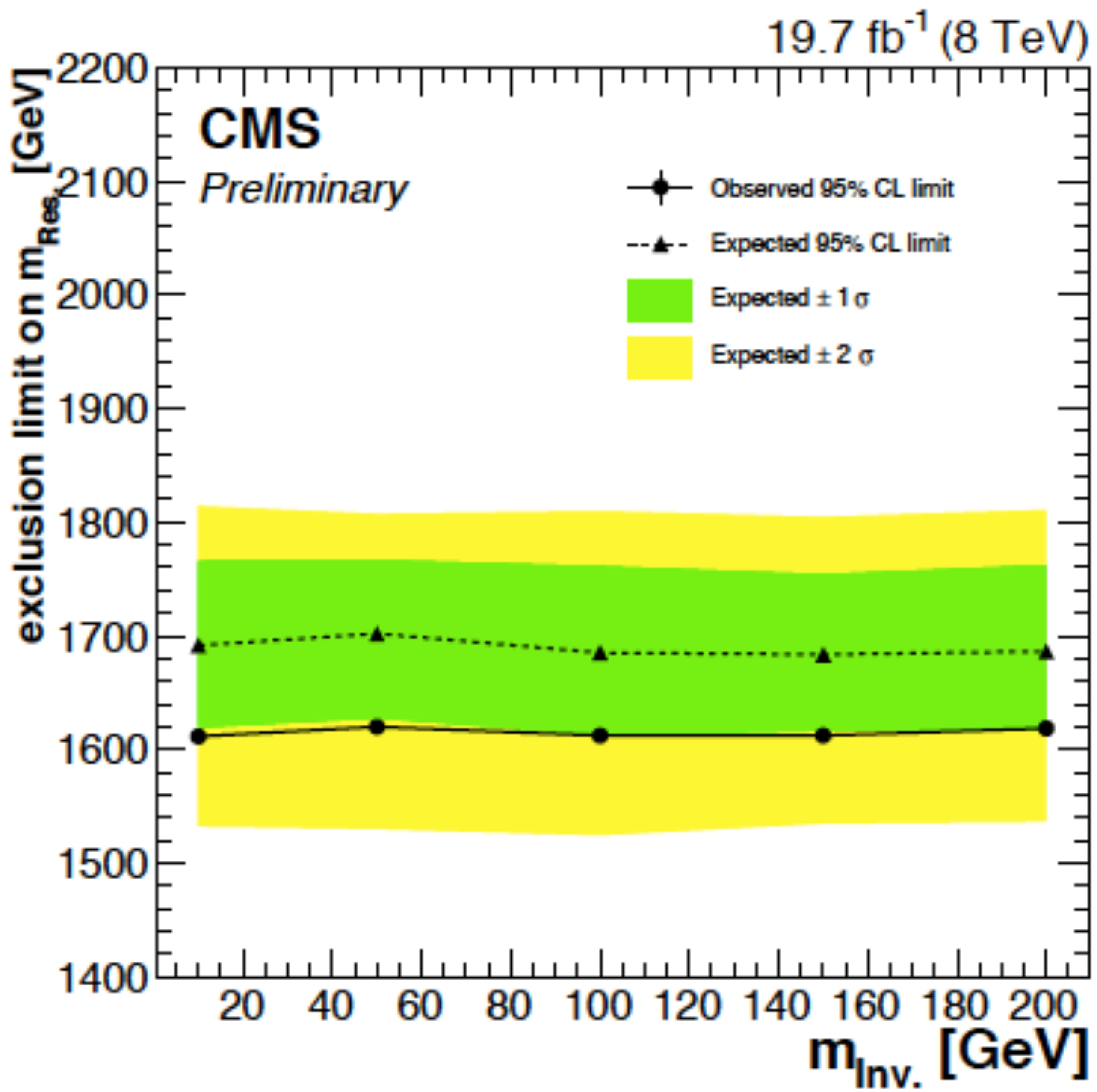




CMS PAS B2G-15-001

Monotop @ 8 TeV

Excluded resonant mass as a function of invisible mass (a = 0.1)



CMS PAS B2G-15-001