University of Zurich[UZH]

Dark Matter produced in association with top quark pair

Deborah Pinna

on behalf of the CMS Collaboration

50th Rencontres de Moriond EW: YSF

La Thuile, March 14th - 21st 2015

Introduction

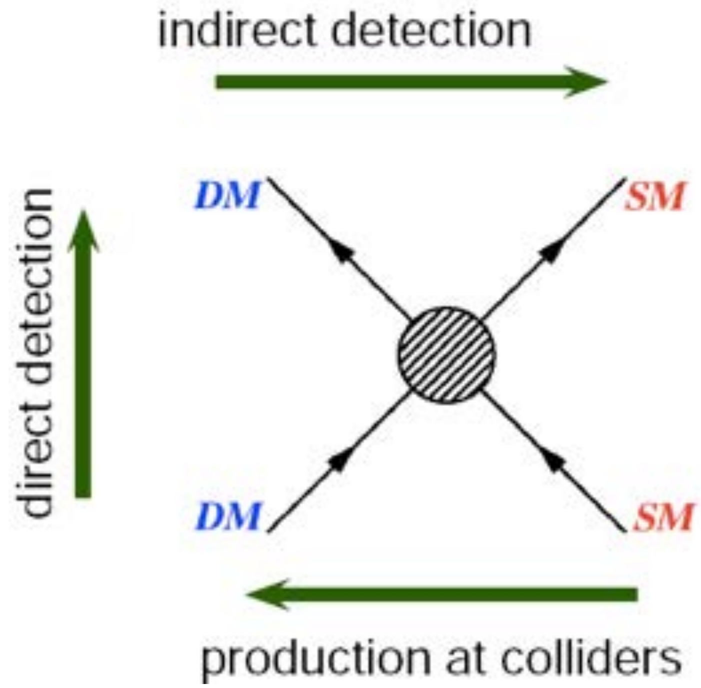
- Dark Matter (DM) empirical evidence for new physics beyond Standard Model (SM)
  - large variety of DM candidates: WIMP mostly studied
  - essential model-independent DM searches
    Effective Field Theory (EFT), interaction parametrized by effective operators
  - EFT approach valid when the momentum transferred Q_{tr} small cutoff scale M_*

$$Q_{tr} << M_*$$

G. Busoni et al., 1402.1275

- Discovery potential in different experiments:
  - direct and indirect searches
  - searches for production of DM at colliders

See C. Doglioni's talks



Effective Field Theory

- Assuming DM is a Dirac fermion χ, example of SM-DM effective operators

J. Goodman et al., 1008.1783

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M^3}\bar{\chi}\chi\bar{q}q$

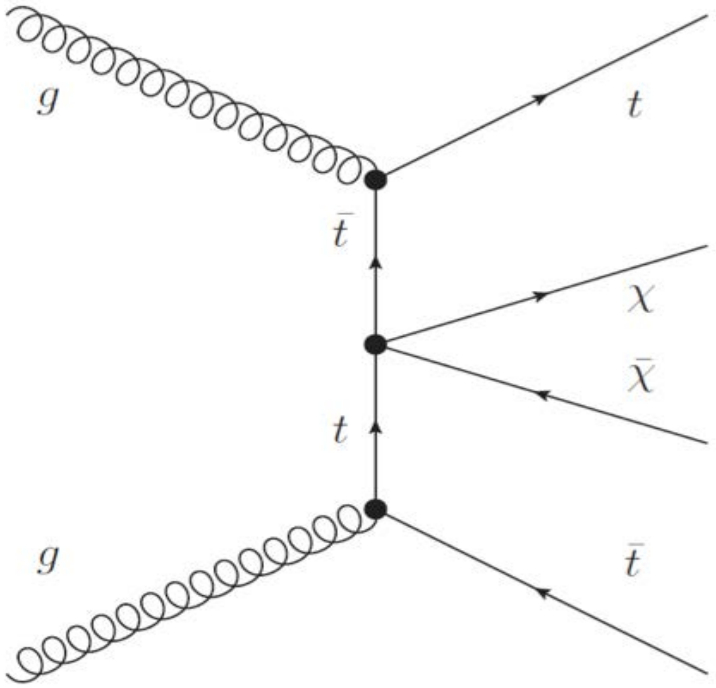
- Scalar interaction T. Lin et al., 1303.6638

proportional to quark mass, better constraints when DM couples to heavy quarks

Study of production of DM in association with top quark pair

- Searches performed using data collected by CMS experiment during 2012, $\sqrt{s}$ = 8 TeV, 19.7 fb^{-1}:

DM+tt single-lepton channel CMS-PAS-B2G-14-004

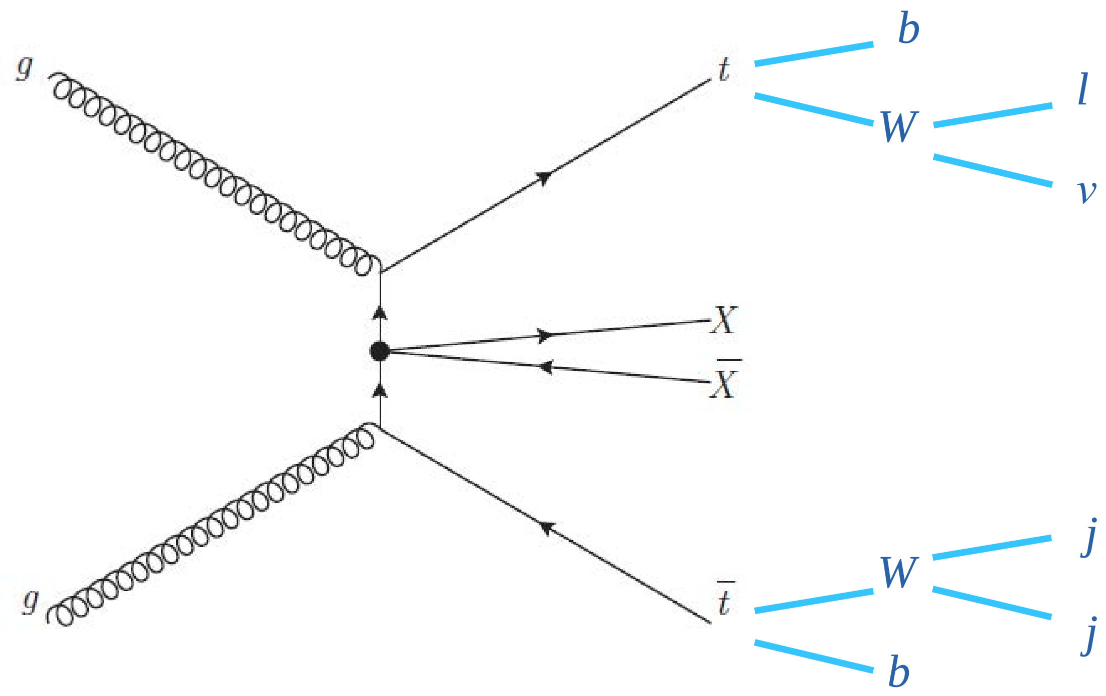


DM + tt ($\rightarrow b l \nu, bjj$): event selection

Analysis strategy

(1) Selection of topology

1 lepton, at least 3 jets, at least 1 b-tagged



(2) Rejection of background

(3) Extract normalization for background

tt+jets, W+jets: from data

Drell-Yan, single top, Di-boson: simulation

DM + tt ($\rightarrow blv, bjj$): event selection

Analysis strategy

(1) Selection of topology

1 lepton, at least 3 jets, at least 1 b-tagged

(2) Rejection of background

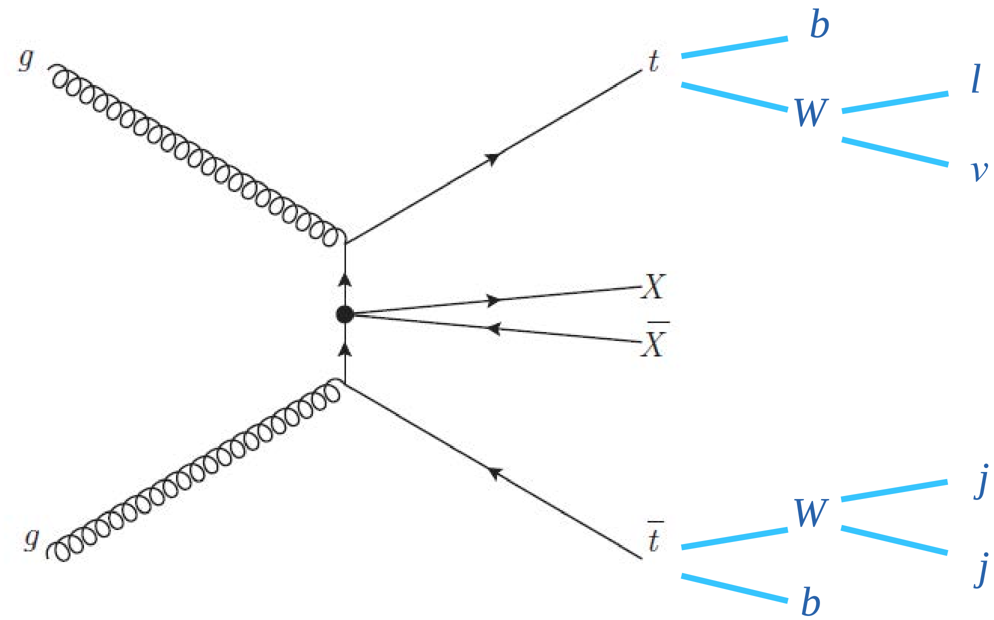
- signal has large MET from DM particles which escape detector

MET > 320 GeV

(3) Extract normalization for background

tt+jets, W+jets: from data

Drell-Yan, single top, Di-boson: simulation



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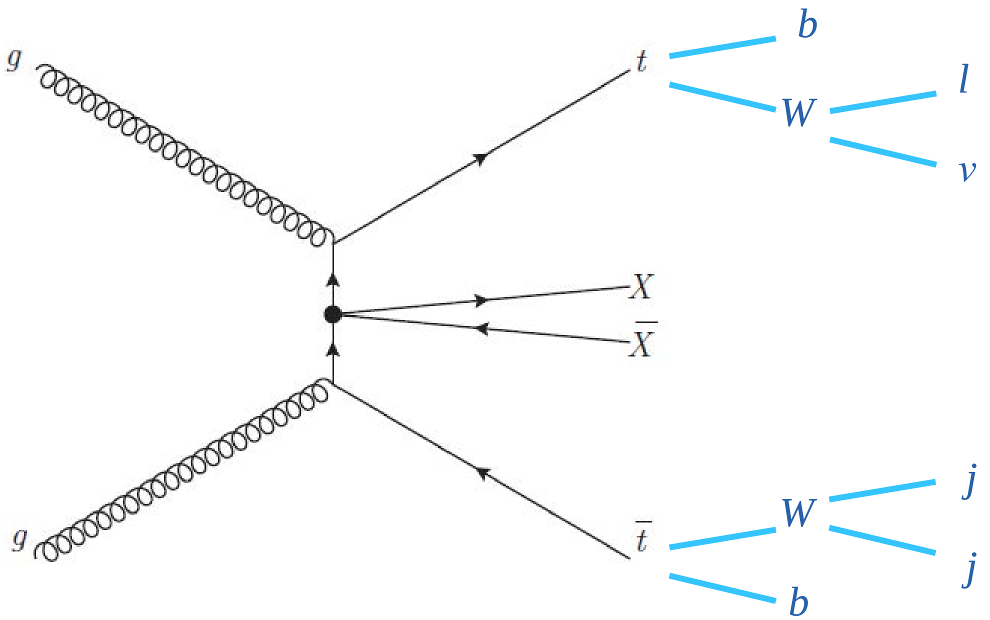


(2) Rejection of background

- Most W+jets and tt+jets semi-leptonic events $M_T < M_W$. Signal events distribution peaks at higher values

$$M_T = \sqrt{2p_T^{lep}E_T^{miss}(1-\cos(\Delta\phi))} > 160 \text{ GeV}$$

(3) Extract normalization for background

tt+jets, W+jets: from data

Drell-Yan, single top, Di-boson: simulation

DM + tt (⟶*blv*,*bjj*): event selection

Analysis strategy

(1) Selection of topology

1 lepton, at least 3 jets, at least 1 b-tagged

(2) Rejection of background

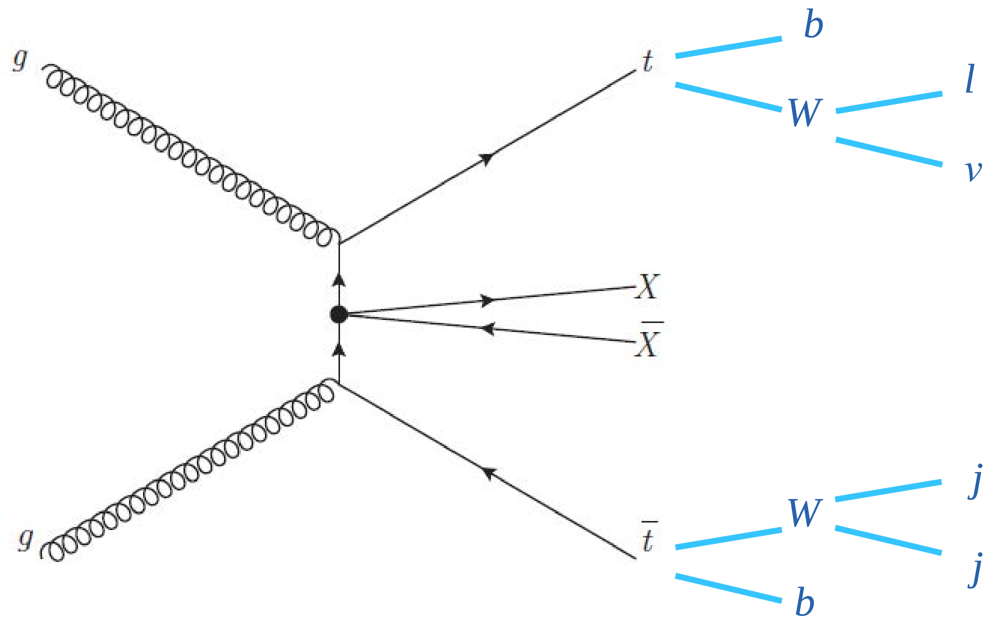
- The jets and the MET tends to be more separated in Φ in signal events than in tt and in single top events

min($\Delta\Phi_{j1,MET}$, $\Delta\Phi_{j2,MET}$) > 1.2 GeV

(3) Extract normalization for background

tt+jets, W+jets: from data

Drell-Yan, single top, Di-boson: simulation



DM + tt (⟶blv,bjj): event selection

Analysis strategy

(1) Selection of topology

1 lepton, at least 3 jets, at least 1 b-tagged

(2) Rejection of background

- For most tt+jets di-leptonic events M_{T2W} < M_{top}. Signal events distribution shows higher tails

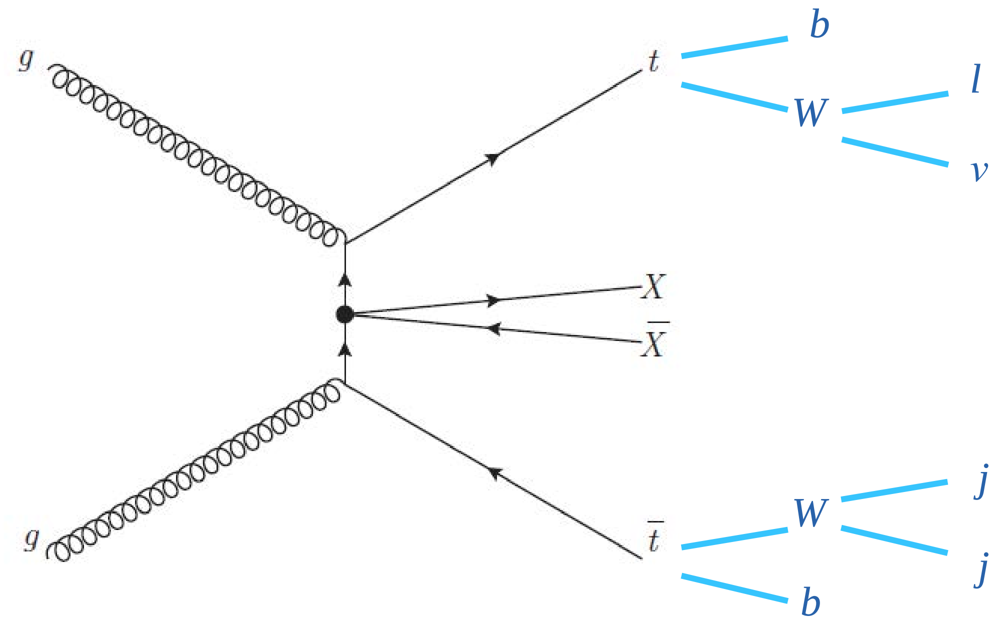
M_{T2W} > 200 GeV

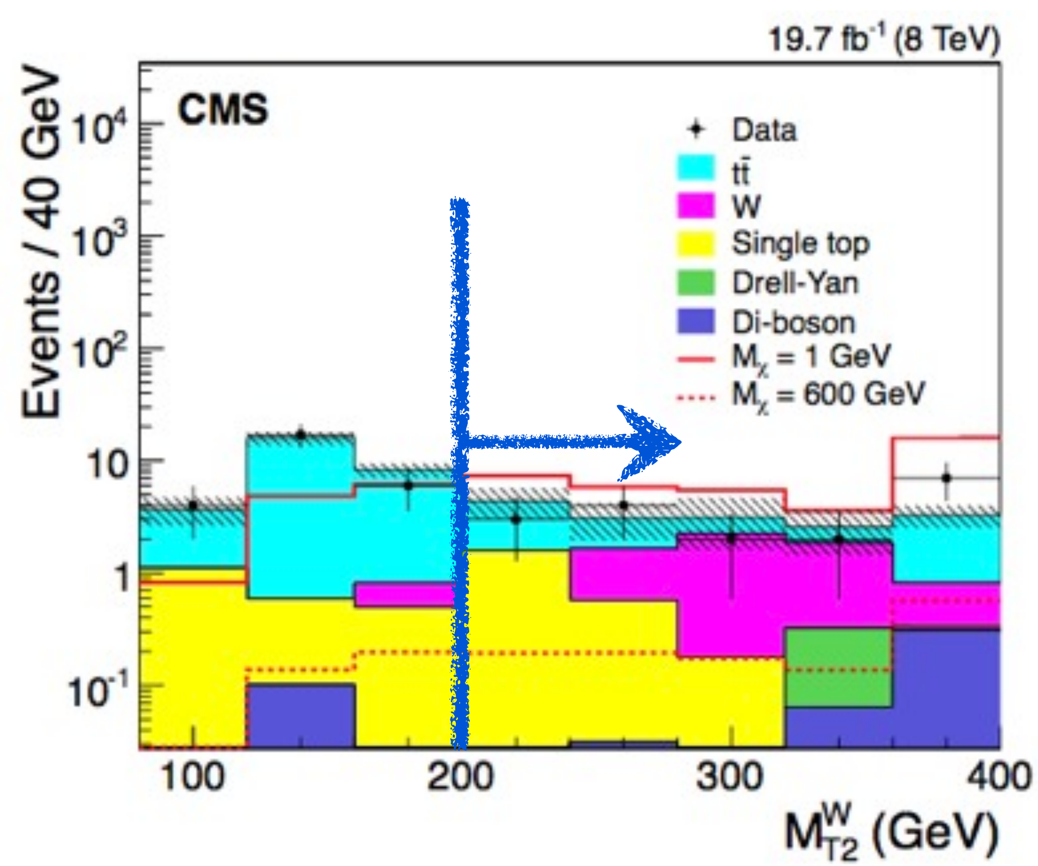
(see slide 20)

(3) Extract normalization for background

tt+jets, W+jets: from data

Drell-Yan, single top, Di-boson: simulation





DM + tt (→*blv*,*bjj*): event selection

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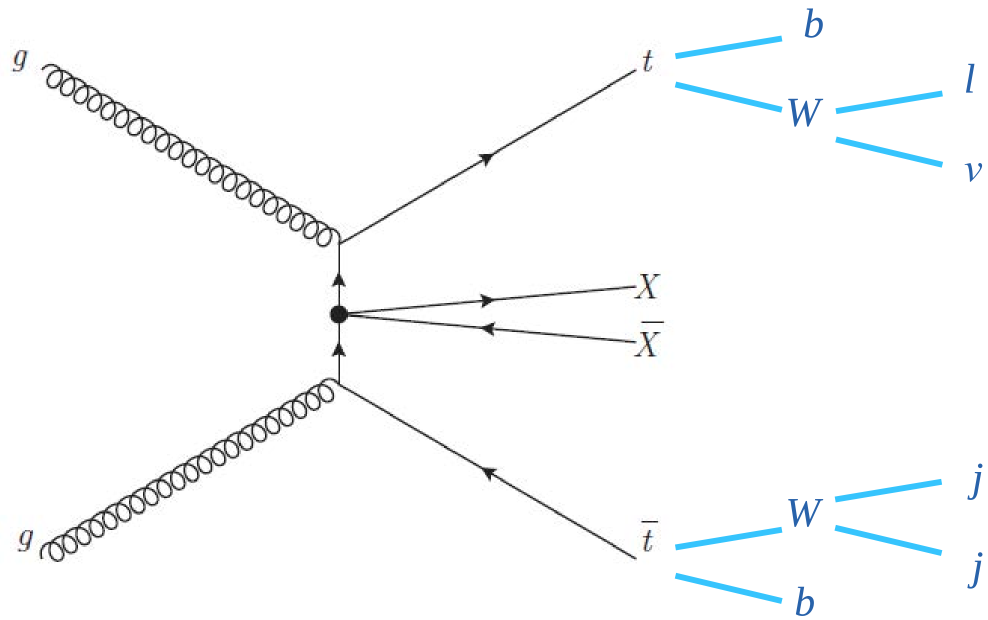
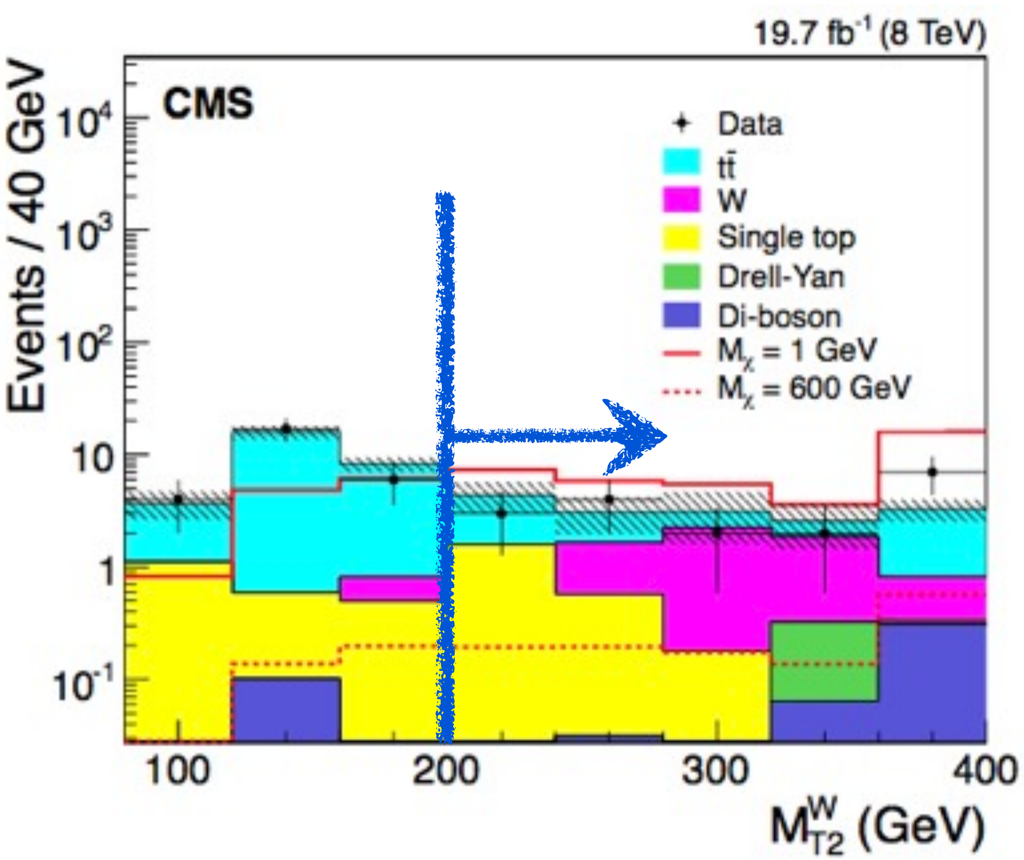


(2) Rejection of background

Variable	Cut
MET	> 320 GeV
$M_T = \sqrt{2p_T^{lep}E_T^{miss}(1-\cos(\Delta\phi))}$	> 160 GeV
$\min(\Delta\Phi_{j1,MET}, \Delta\Phi_{j2,MET})$	> 1.2
M_{t2W}	> 200 GeV



(3) Extract normalization for background

tt+jets, W+jets: from data

Drell-Yan, single top, Di-boson: simulation

DM + tt (→*blν,bjj*): results

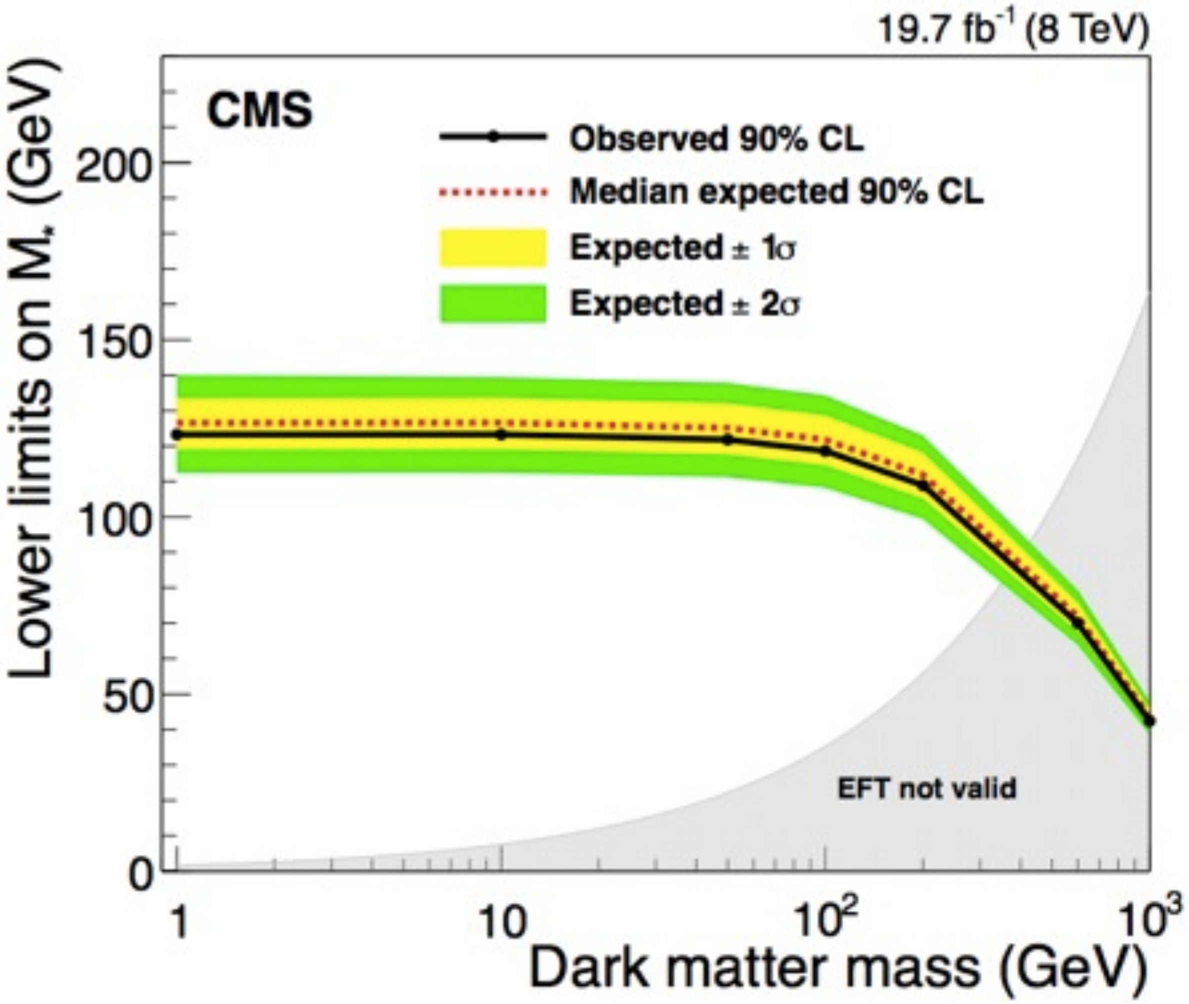
(4) Final yields

Mχ=1GeV M*=100 GeV

Source	Yield (± stat. ± syst. unc.)
Data	18
Signal	$38.3 \pm 0.7 \pm 2.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.7$
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.7 \pm 0.6$
Single top	$2.3 \pm 1.1 \pm 1.1$
Di-boson	$0.5 \pm 0.2 \pm 0.2$
Drell-Yan	$0.3 \pm 0.3 \pm 0.1$

main systematics on total background

13% from background estimation



(5) Results

- 90% CL **lower limits on interaction scale M*** for scalar interaction

→ Assuming 100 GeV mass DM particle, M* below 118 GeV is excluded

- 90% CL upper limits on tt+DM production cross section

→ Cross sections higher than 55 fb for 1 GeV and higher than 20 fb for 1 TeV DM mass are excluded

DM + tt (⟶*blν,bjj*): results

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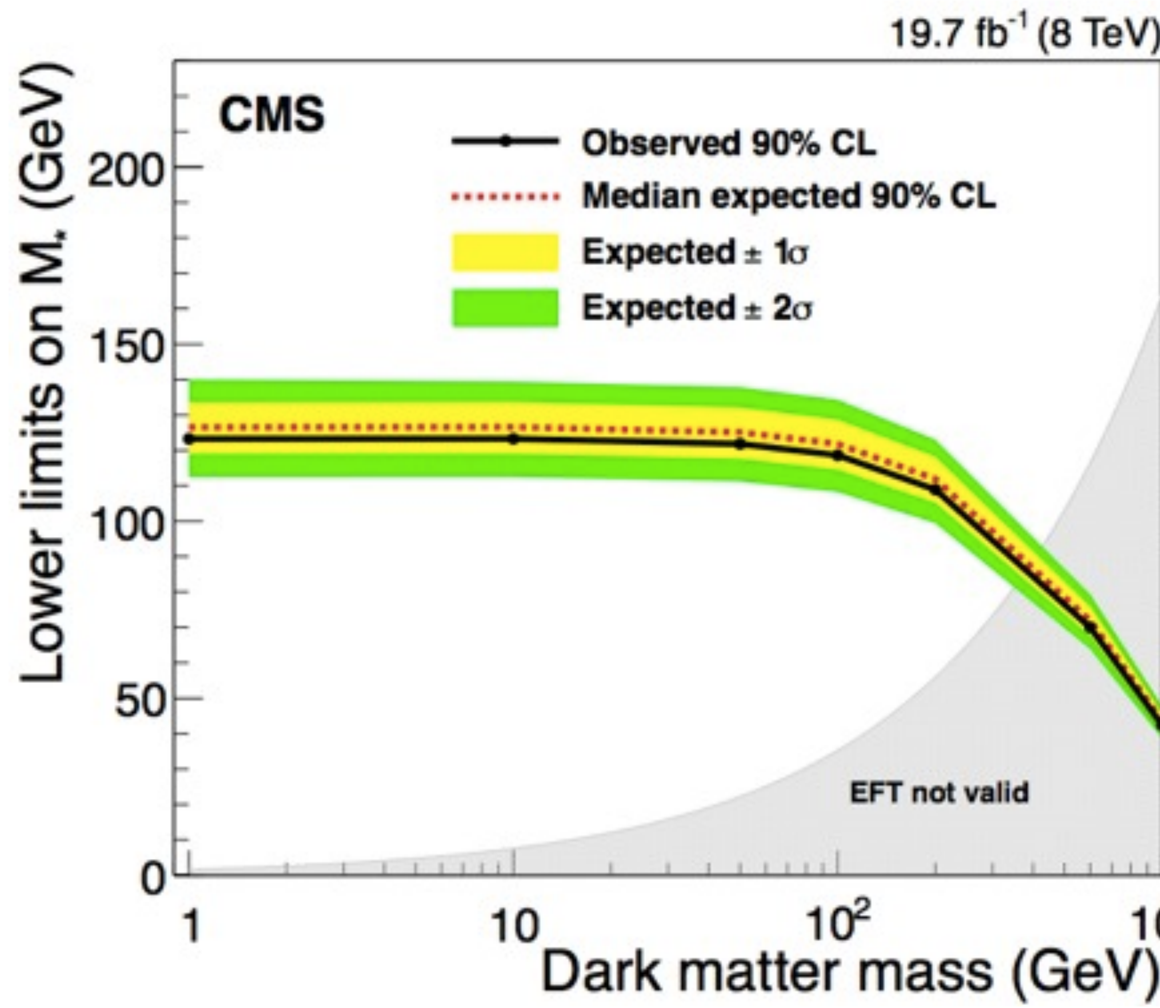

(5) Results

- 90% CL **lower limits on interaction scale M*** for scalar interaction
  - ⟶ Assuming 100 GeV mass DM particle, M* below

What is next ?

cross section

  - ⟶ Cross sections higher than 55 fb for 1 GeV and higher than 20 fb for 1 TeV DM mass are excluded

DM + tt (⟶*blν,bjj*): results

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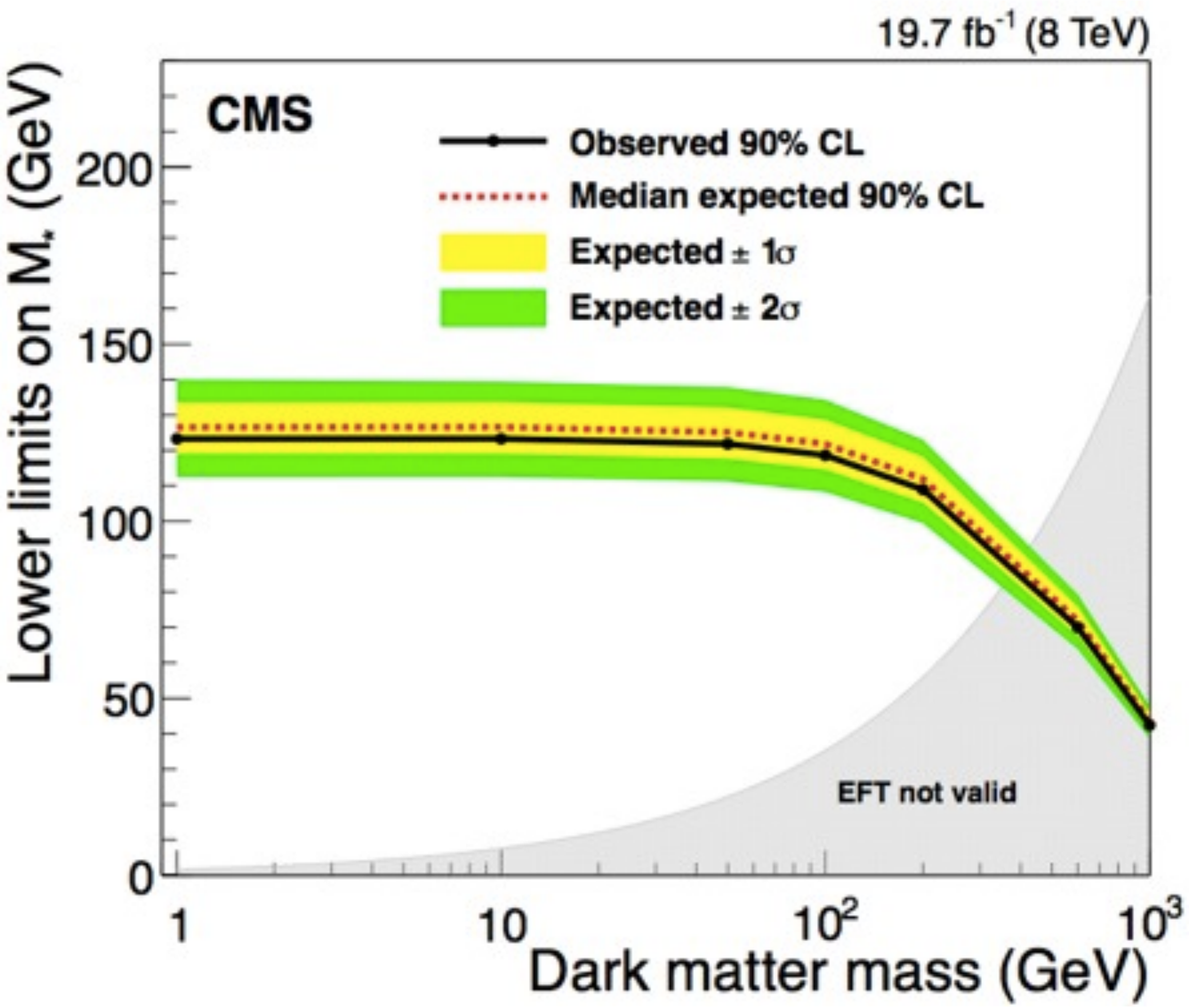

(6) Run 2

- Simplified models, EFT kept as benchmark

See C. Doglioni's and U. Haisch's talks

- Proton collisions from the LHC can shed light on the mysterious DM

DM + tt (→*blν*,*bjj*): results

(4) Final yields

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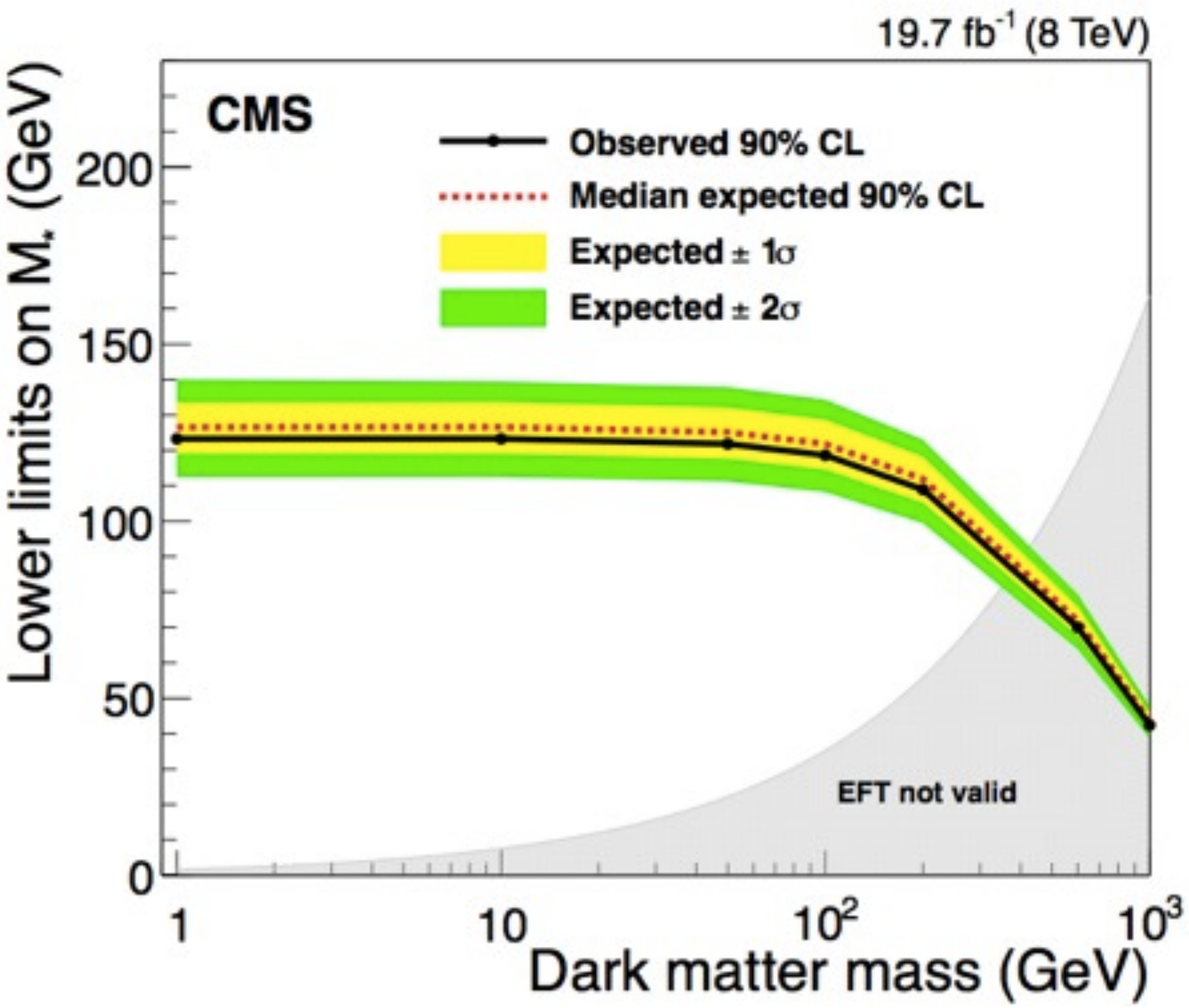

(6) Run 2

- Simplified models, EFT kept as benchmark

- Proton collisions from the LHC can shed light on the mysterious DM

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Thank you!

Backup slides

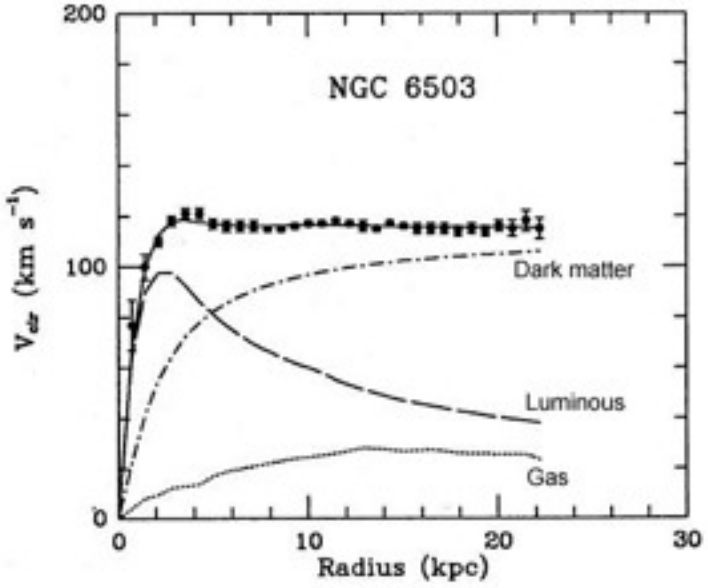
Introduction

- Evidence at different observable length scales for Dark Matter (DM)
  - dispersion velocity of galaxies in galactic cluster too large to be explained by luminous matter
  - rotation curves on singular galaxies constant beyond luminous region

    velocity is expected to go like r $^{-1/2}$

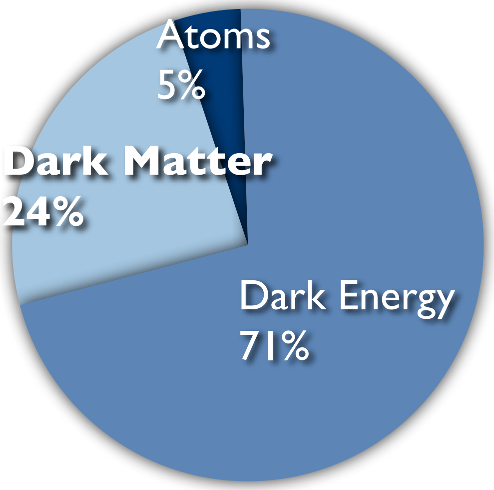
    differences explained by existence of dark matter

Begeman, K. G., et al., MNRAS (1991) Vol. 249 523-537



- Studies at different scales provide measurements that universe is composed mainly of non-baryonic matter

  Dark matter abundance ~24% of the universe, five times the amount of baryonic matter

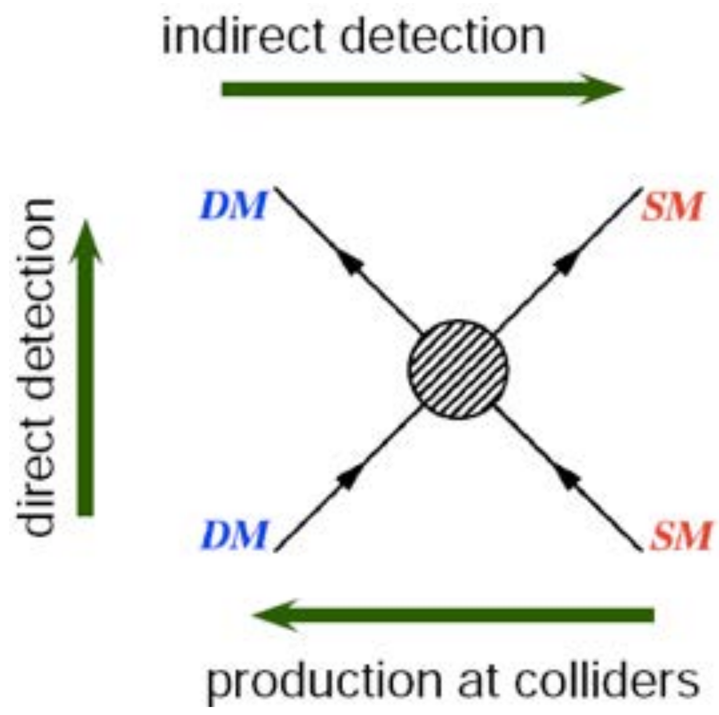


- Evidence based on gravitational interactions, no information of what is the nature of Dark Matter

Introduction

- Most studied DM candidate: **Weakly Interacting Massive Particle (WIMP)**
  - neutral particle
  - mass in the range ~10 GeV - TeV
  - weak interactions
  - correct relic density
  - may be detected in different ways

- Studies at largest and smallest observable length scales
  - indirect searches:
    products of DM annihilations or decays
  - direct searches:
    scattering DM-heavy nucleons
  - collider searches:
    signature of DM production



Dark Matter signatures at LHC

- In p-p collisions Dark Matter could be produced

  very stable weakly interacting particle which escape detector

  - Missing Transverse Energy (MET)

    Energy imbalance will be observed in the plane transverse to the colliding proton beams

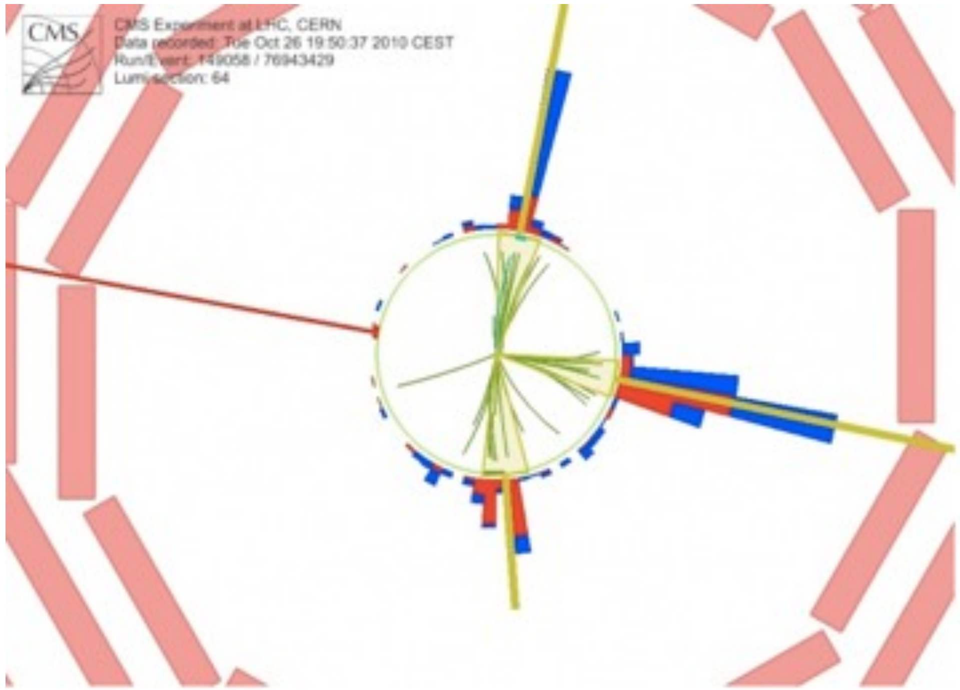
    initial transverse momenta of partons considered negligible, rules of conservations can be applied

$$\mathrm{MET} = \sqrt{\left(\sum_n E_x\right)^2 + \left(\sum_n E_y\right)^2}$$

  - Recoil

    searches for DM need also visible particles in the event to which DM particle recoil against

    searches classified depending on type of visible particles used to “tag” the event



DM+tt semi-leptonic backup

DM + tt ($\longrightarrow$*blν,bjj*): background

Dominant background (tt+jets, W+jets)

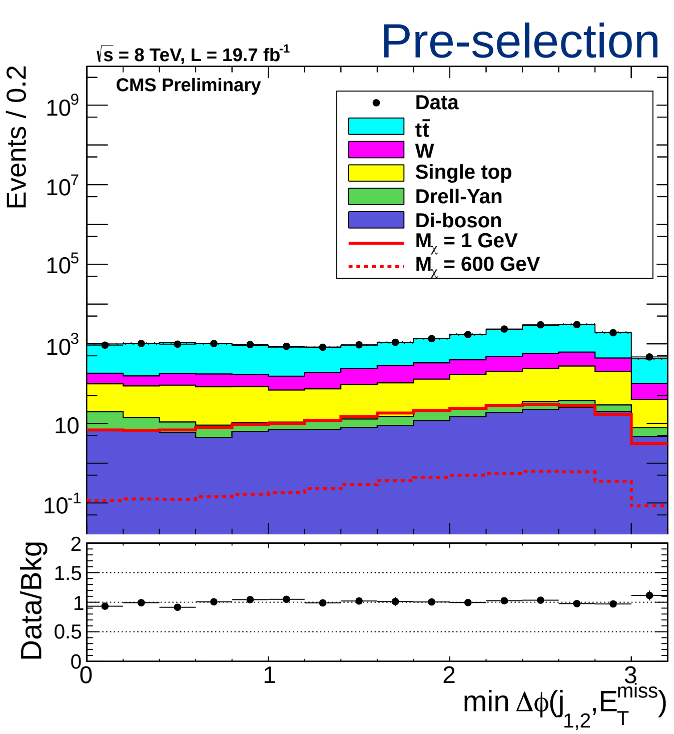
Scale Factors (SFs) extracted in CRs enriched in background composition and negligible signal contribution fitting simultaneously two simulated template distributions to data

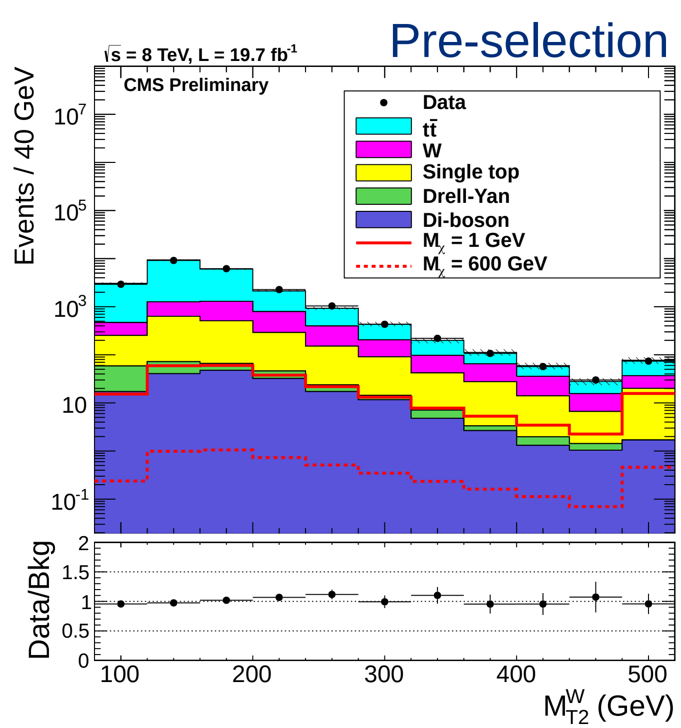
MET in W+jets enriched CR
(pre-selection + M_T>160 GeV)

M_T in tt+jets enriched CR
(pre-selection but 0 b-tag + M_T>160 GeV)

SF(tt+jets)	1.11 ± 0.02 (stat)
SF(W+jets)	1.26 ± 0.06 (stat)

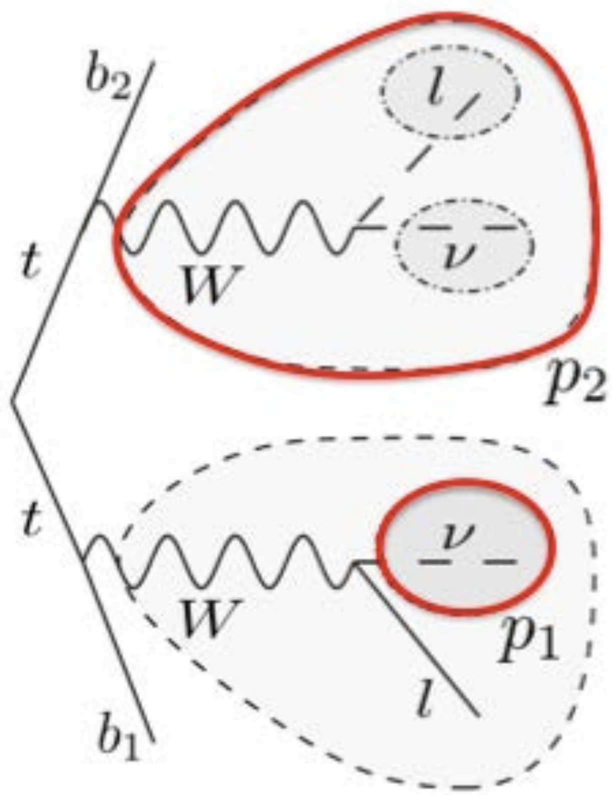
predicted background yields and uncertainties propagated from CR to SR





Good agreement between data and simulation is observed after SFs are applied

M_{T2W} as discriminating variable



Missing particles

Most irreducible background from tt di-leptonic

- Large MET can arise from neutrinos and missing lepton
- M_T higher than W mass because of additional missing particles

Transverse mass M_{T2} can be used to reject background event

- minimal mother particle mass compatible with assumed event topology and daughter particle mass

A variable where the intermediate W are considered on shell can be used

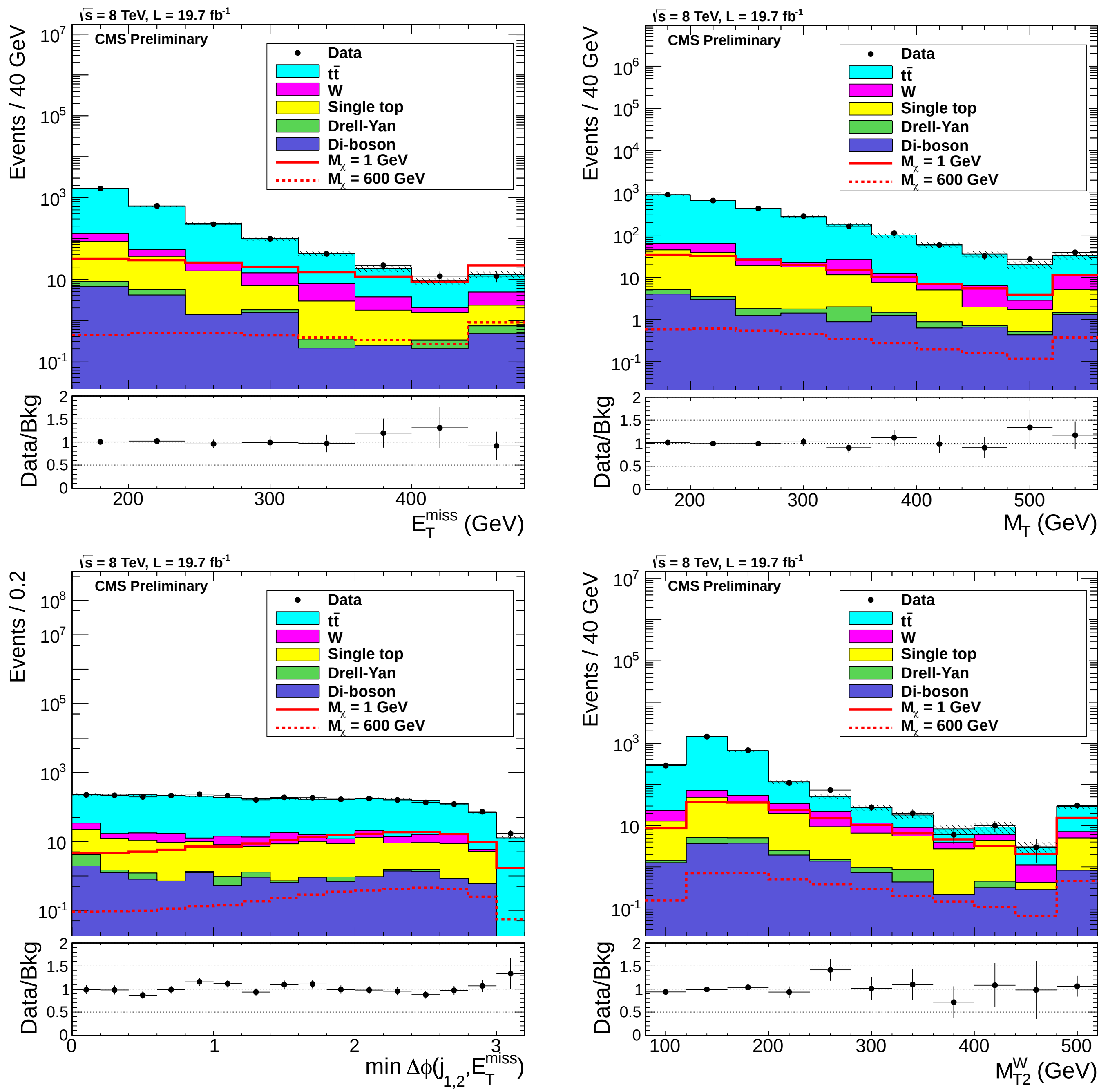
$$M_{T2}^W = \min\left\{ m_y \text{ consistent with: } \left[\begin{array}{c} \vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{\rm miss},\ p_1^2 = 0,\ (p_1+p_\ell)^2 = p_2^2 = M_W^2, \\ (p_1+p_\ell+p_{b_1})^2 = (p_2+p_{b_2})^2 = m_y^2 \end{array} \right] \right\}$$

it adds other kinematical info w.r.t to other M_{T2} variables

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

Data-simulation agreement

Agreement between data and MC samples is used to check the validity of this estimate

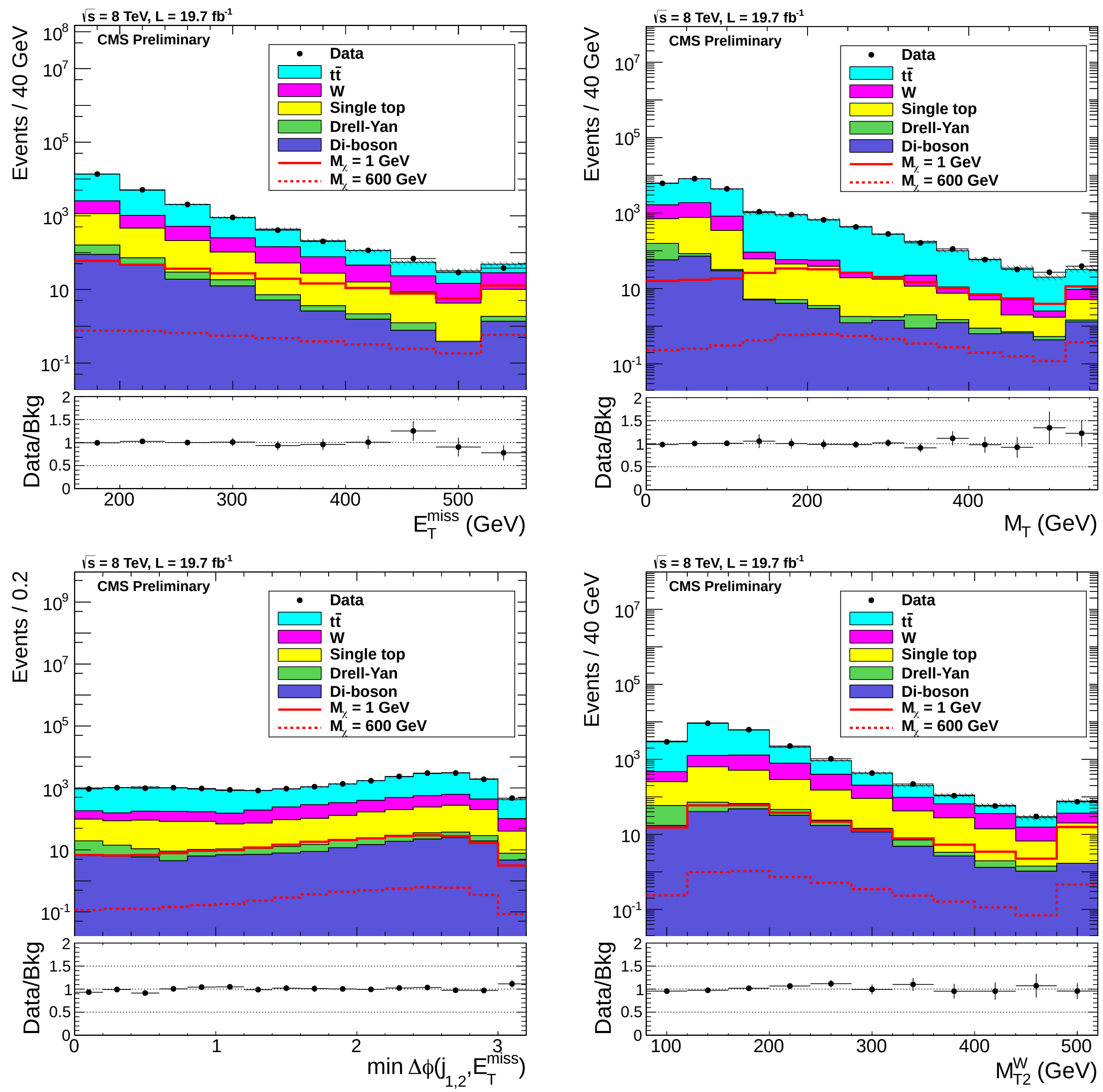


CR1 (tt enriched)

- In all distributions good agreement between data and background prediction is observed after SFs applied

Data-simulation agreement

Agreement between data and MC samples is used to check the validity of this estimate



PRE-SELECTION

- In all distributions good agreement between data and background prediction is observed after SFs applied

Systematic uncertainties

- **Uncertainties on backgrounds**

  normalization uncertainties covered by SFs
  shape uncertainties constrained in CRs and SFs propagated in SR

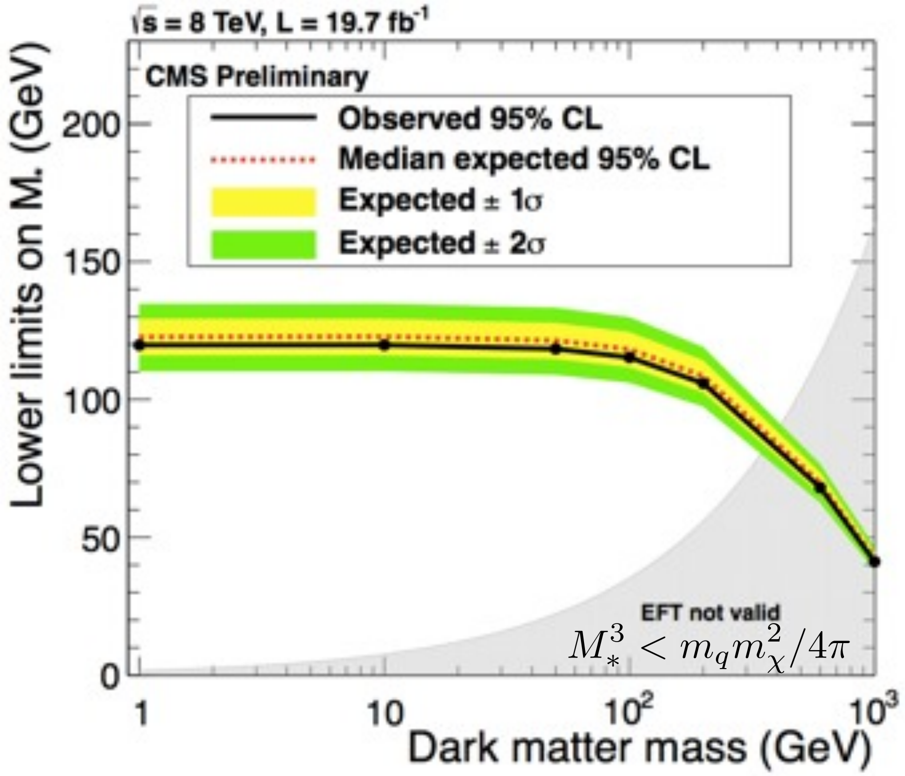
- **Uncertainties on signal**: 5-6%

Source of systematic uncertainties	Relative error on total background (%)
50% normalization error of other bkg in deriving SFs	10
Statistical error of SF_{W+jets}	1.5
$t\bar{t}$+jets jet-parton matching	8.2
$t\bar{t}$+jets Q^2	6.6
$t\bar{t}$+jets top p_T reweighting	3.9
Jet energy scale	4.0
Jet energy resolution	3.0
b-tagging correction factor (heavy flavor)	1.0
b-tagging correction factor (light flavor)	1.8
Pileup model	2.0

- Limits are calculated using the CL_S technique with ROOSTATS software package. Frequentist treatment of nuisance parameters

Results: lower limits on M*

M_χ GeV	Signal efficiency (%) ($\pm$ stat. $\pm$ syst. unc.)	$\sigma^{\text{lim}}_{\text{exp}}$ (fb)	$\sigma^{\text{lim}}_{\text{obs}}$ (fb)
1	$1.01 \pm 0.02 \pm 0.05$	47^{+21}_{-13}	55
10	$1.01 \pm 0.02 \pm 0.05$	46^{+21}_{-13}	54
50	$1.20 \pm 0.02 \pm 0.06$	38^{+18}_{-11}	45
100	$1.46 \pm 0.02 \pm 0.07$	32^{+15}_{-9}	37
200	$1.73 \pm 0.02 \pm 0.08$	27^{+12}_{-8}	32
600	$2.40 \pm 0.03 \pm 0.11$	19^{+9}_{-6}	23
1000	$2.76 \pm 0.04 \pm 0.13$	17^{+8}_{-5}	20



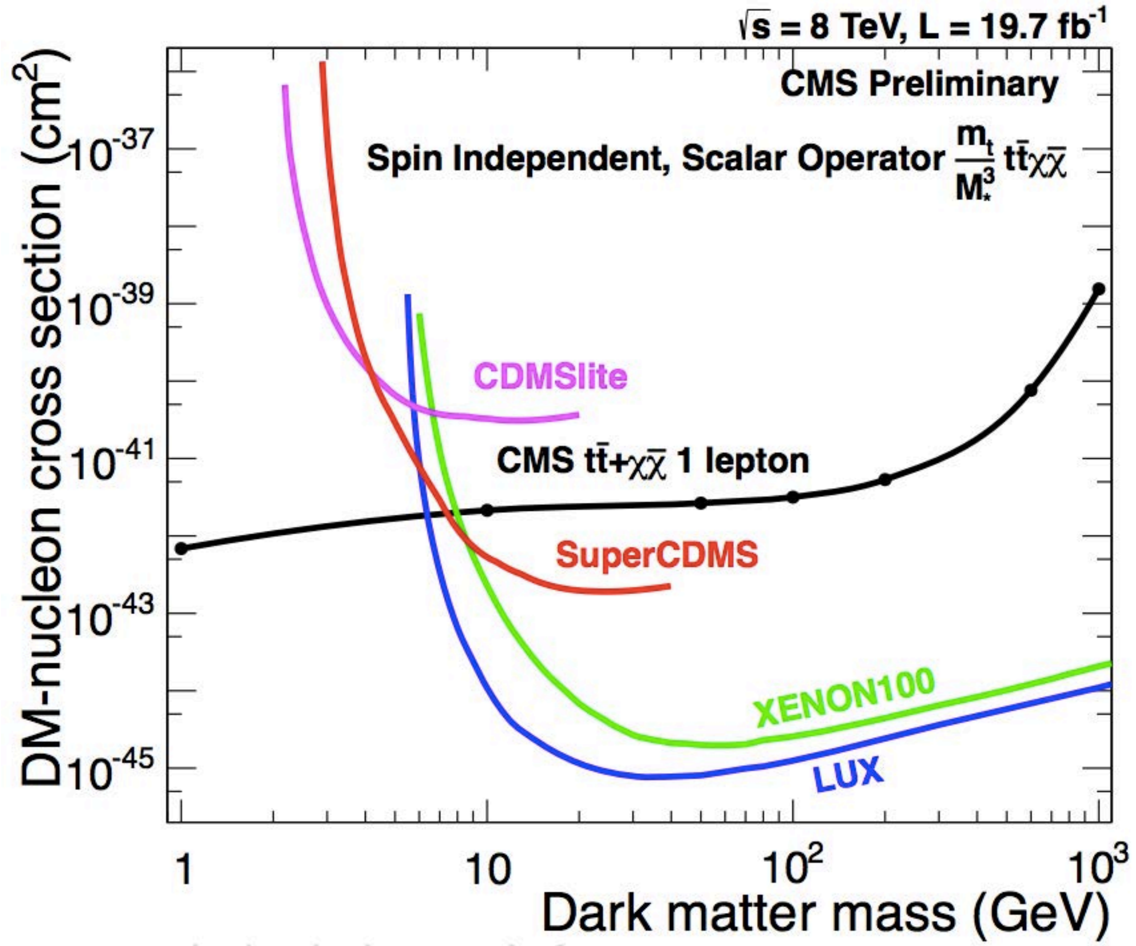
- Values below the observed limit are excluded
- The grey area represent only minimal requirement on M* for the EFT to be valid. There could be other areas on the plane where the EFT breaks down

Results: cross section limits

- Can be translated in upper limits on DM-nucleon cross section for comparison with results from direct detection experiment

$$\sigma_0^{D1} = 1.60 \times 10^{-37} \text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{20\text{GeV}}{M_*}\right)^6$$

μ_χ reduced mass DM-nucleon system



Excluded dark matter-nucleon cross sections higher than 1 − 2 × 10^{-42} cm^2 for DM masses from 1 to 6 GeV

Physics objects

- Trigger: single-lepton triggers: single-electron, single-muon with p_T > 24 and 27 GeV

	Electrons	Muons	Jets
Reconstruction	ECAL driven algorithm	Tracker and global muon algorithms	anti-k_T clustering algorithm with a cone size of $\Delta R = 0.5$
	standard muon identification criteria	standard muon identification criteria	
Selection	Loose $p_T \geq 30$ GeV, $\lvert\eta\rvert<2.5$	Tight $p_T \geq 30$ GeV, $\lvert\eta\rvert<2.1$	$p_T \geq 30$ GeV $\lvert\eta\rvert<4.0$
	$I_{rel}<0.1$ in $\Delta R=0.3$	$I_{rel}<0.12$ in $\Delta R=0.4$	b-tagging with medium working point CSV algorithm $\lvert\eta\rvert<2.4$

Physics objects

MUON IDENTIFICATION CUTS

Variables	cuts
isGlobalMuon	true
isPFMuon	true
χ^2/d.o.f.	< 10
Number of muon hits	> 0
Number of pixel hits	> 0
Number of matched stations	> 1
Number of tracker layers	> 5
d_{xy}(vtx)	< 0.2 cm
d_z(vtx)	< 0.5 cm
pfIso04/p_T, $\Delta\beta$ corr.	< 0.12

JET IDENTIFICATION CUTS

PF Jet ID	Cuts
Neutral hadron fraction	< 0.99
Neutral EM fraction	< 0.99
Number of constituent	> 1
Below for $\|\eta\| < 2.4$ only	
Charged hadron fraction	> 0
Charged multiplicity	> 0
Charged EM fraction	< 0.99

ELECTRON IDENTIFICATION CUTS

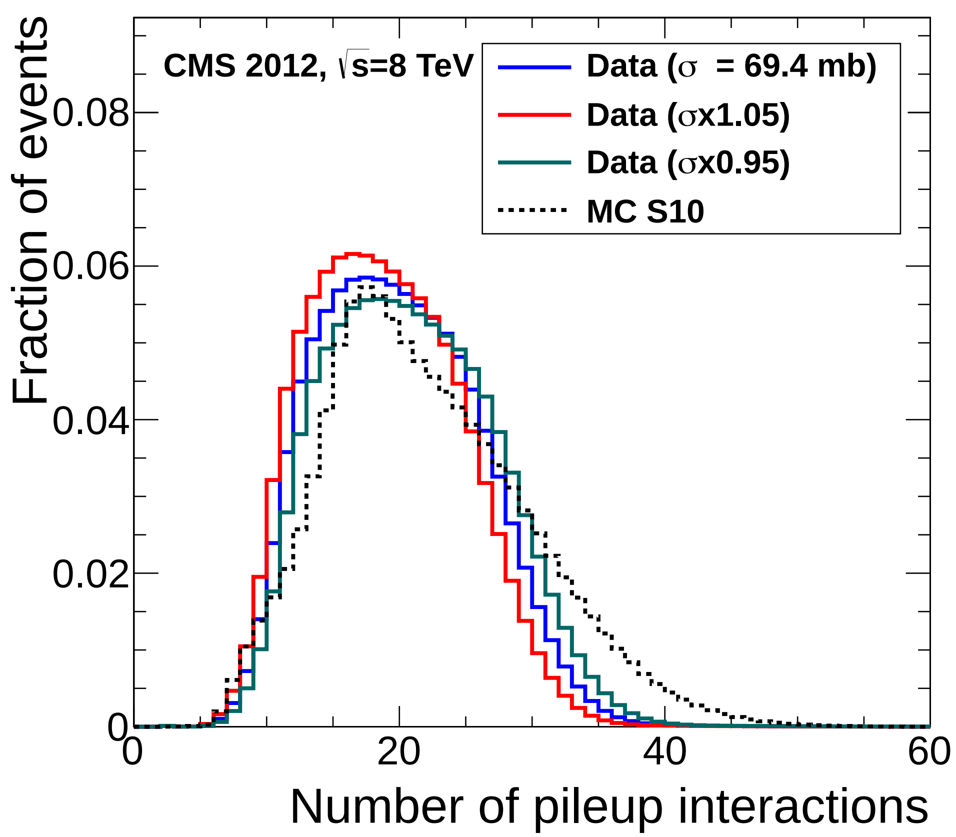
Variables	tight cuts
$\|d_0(\text{vtx})\|$	< 0.02 cm
$\|d_z(\text{vtx})\|$	< 0.1 cm
$\sigma_{i\eta i\eta}$	< 0.01(barrel), < 0.03(endcap)
$\|\Delta\eta_{\text{in}}\|$	< 0.004(barrel), < 0.005(endcap)
$\|\Delta\phi_{\text{in}}\|$	< 0.03(barrel), < 0.02(endcap)
H/E	< 0.12(barrel, < 0.10(endcap)
$\|1/E - 1/p\|$	< 0.05
pfIso03/p_T	< 0.1
Matched conversion?	false
Missing hits	0

Pileup reweighting

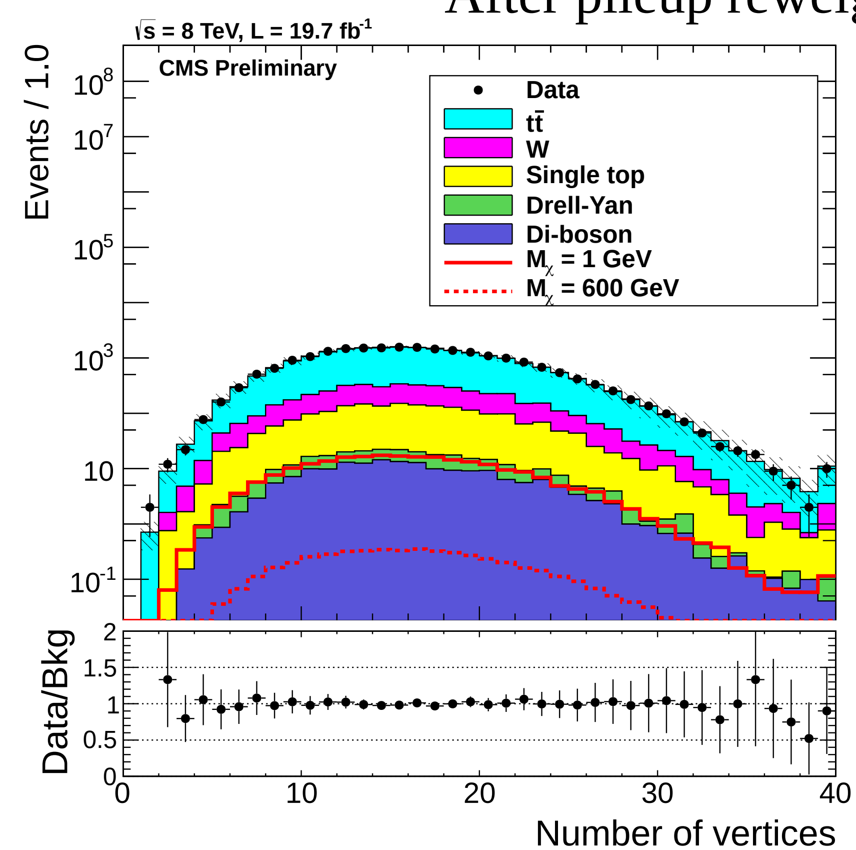
Pileup distribution different in MC w.r.t data

- MC number pileup reweighted to match data
- Data distribution re-calculated with ±5% variation on cross section to cover pileup mis-modeling syst. unc.

Good agreement data-MC after pileup reweighting



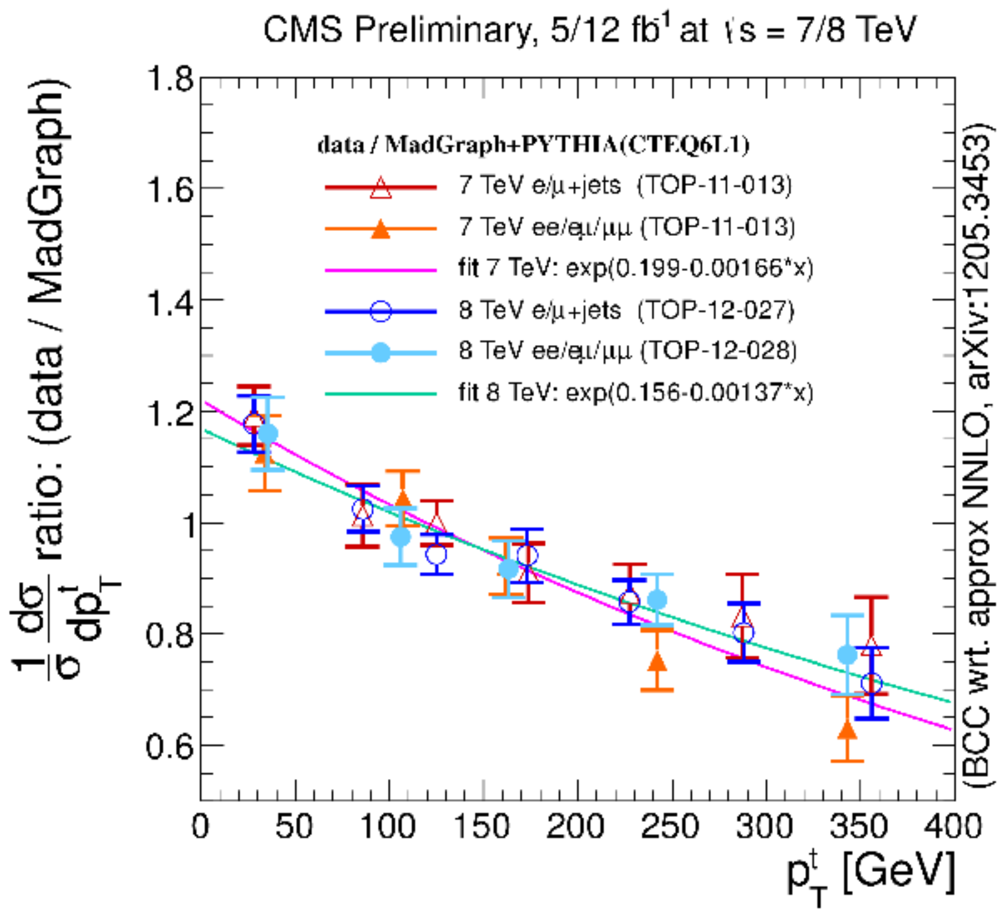
After pileup reweighting



Top p_T reweighting

p_T distribution of leptons and jets from tops softer in data w.r.t Madgraph simulation

- Top differential cross section measurement provide SFs for correction
- Each event weighted by geometric mean of SFs from 2 tops (assumed flat > 400 GeV)
- Syst. unc.: no SF, SF applied twice



$$SF = e^{0.156 - 0.00137 \times p_T}$$

Physics objects: b jets

b jets

b-tagging algorithm: **C**ombined **S**econdary **V**ertex (CSV)

- Standard CMS b-tagging algorithm
- Used to identify jets likely to come from b quarks fragmentation-adronization
- Exploits long lifetime of b hadrons

  large impact parameter and presence of a secondary vertex as input
- Continuous output: allows selection of optimal working points

Efficiencies, mis-tag rates

for CSV > 0.90 b quark tag: 50%
c quark tag: 6%
light quark tag: 0.15 %

for CSV > 0.50 b quark tag: 72%
c quark tag: 23%
light quark tag: 3 %

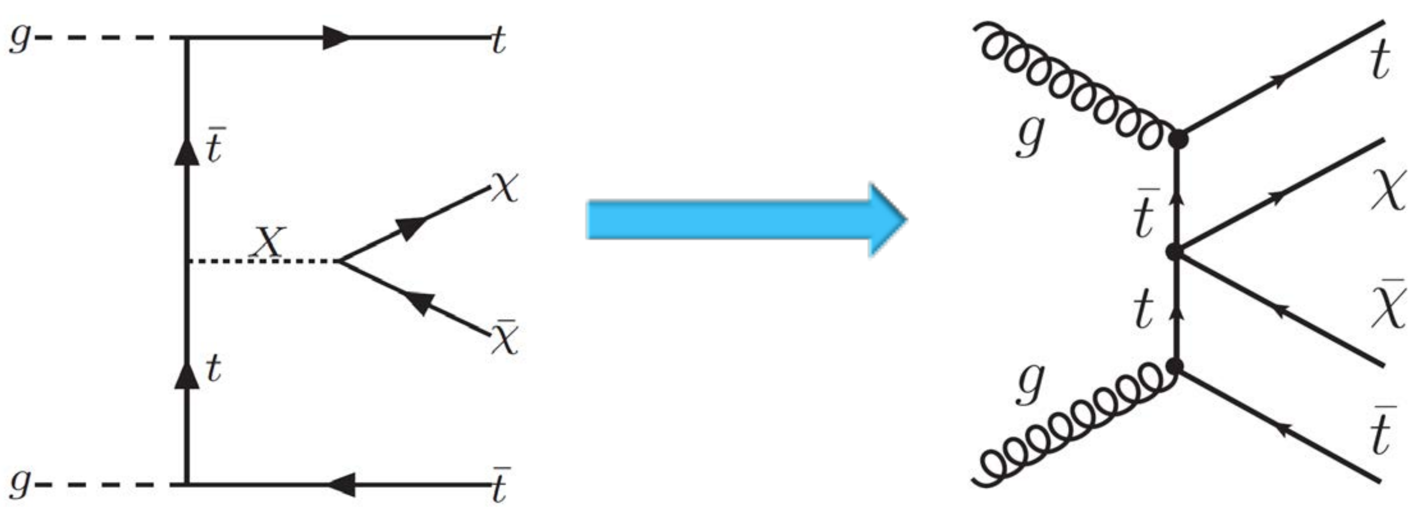
Effective Field Theory backup

Effective Field Theory

University of Zurich[UZH]

- Supposing a heavy mediator of mass M in the s-channel coupling to DM and SM with couplings g_1 g_2.

  Considering only the lowest order operators in the EFT approach is connected to the propagator expansion



$$\frac{g_1 g_2}{Q_{tr}^2 - M^2} = -\frac{g_1 g_2}{M^2}\left(1 + \frac{Q^2}{M^2} + \mathcal{O}\left(\frac{Q_{tr}^4}{M^4}\right)\right) \simeq -\frac{g_1 g_2}{M^2} \text{ for } Q_{tr}^2 << M^2$$

the coefficient of the effective operator should match to reproduce the UV theory, i.e. for D1

$$M_* = \left(\frac{m_q M^2}{g_1 g_2}\right)^{1/3}$$

Effective Field Theory

- In general the EFT field theory is valid when $Q_{tr} << M_*$

- The validity of the truncation of the propagator expansion requires

$$Q_{tr} < M$$

from the assumed UV details (heavy mediator, s-channel) $M_* = \left(\frac{m_q M^2}{g_1 g_2}\right)^{1/3}$

from kinematics $Q_{tr} > 2m_\chi$

assuming most strongly coupled scenario in the perturbative regime $\sqrt{g_1 g_2} < 4\pi$

$$\sqrt{\frac{M_*^3}{m_q}} > \frac{M_\chi}{2\pi}$$

- This is a very minimal requirement on M* and it depends on the details of the UV completion