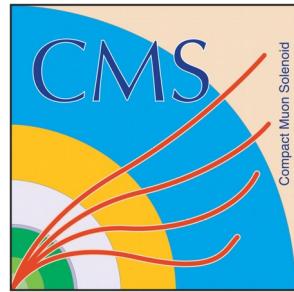


Dark Matter searches at CMS

ICHEP 2018



Andreas Albert
on behalf of the CMS collaboration



III. Physikalisches
Institut A

RWTHAACHEN
UNIVERSITY

Dark Matter at the LHC: Single-slide primer

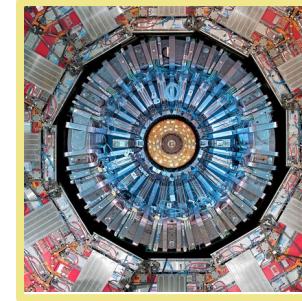
LHC:

Provides proton-proton collisions at $\sqrt{s} = 13$ TeV

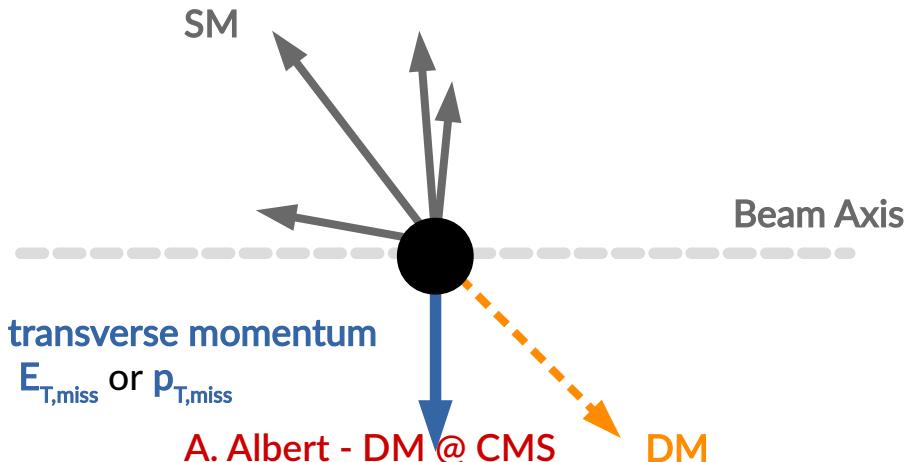


CMS:

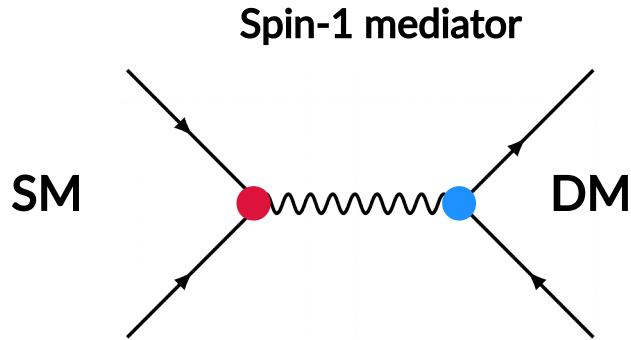
Records collisions, identifies outgoing particles



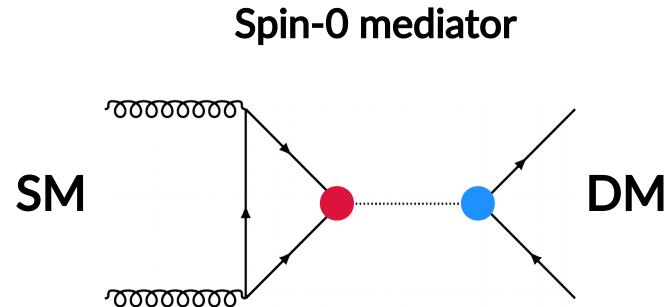
Non-interacting particles cause momentum imbalance in plane transverse to beam axis



Interpretation: Simplified models

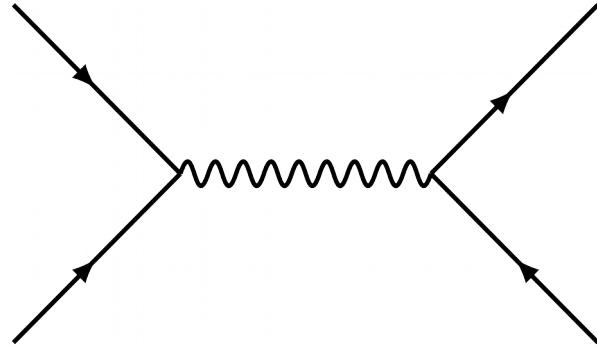


$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q$$



$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi} \chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q$$

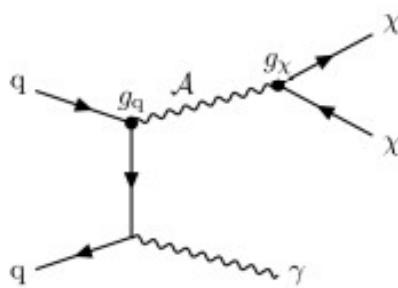
Simplified models with few free parameters:
 m_{med} , m_{DM} , **mediator-quark coupling**, **mediator-DM coupling**
 minimal flavour violation
 Benchmarks defined by LHC Dark Matter working group



Spin 1

Minimal flavour violation → Same coupling strength to all quarks

Search for DM produced with a high-pT photon



Select

$$p_T(\gamma) > 175 \text{ GeV}$$

$$E_{T,\text{miss}} > 170 \text{ GeV}$$

Main backgrounds:

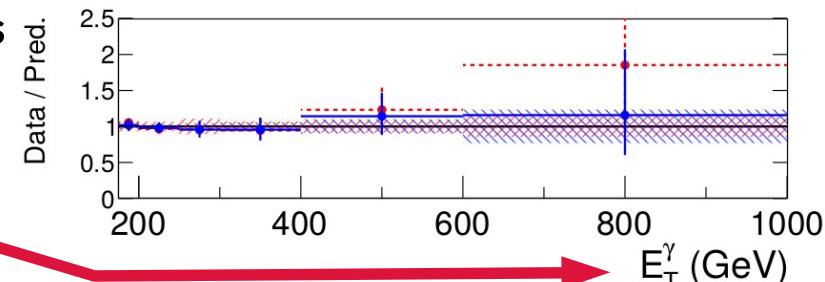
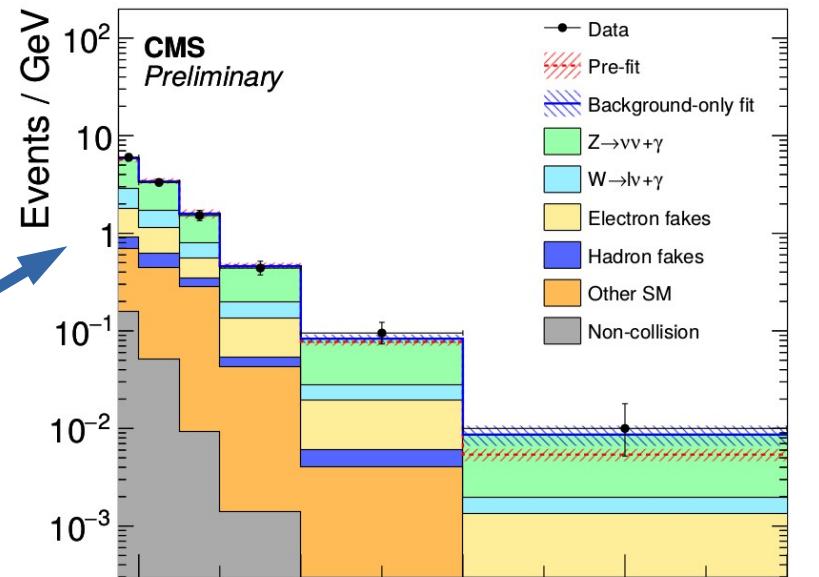
$$Z(vv) + \gamma$$

$$W(lv) + \gamma \text{ (Lost lepton)}$$

Fakes and Non-collision backgrounds
small because well-controlled

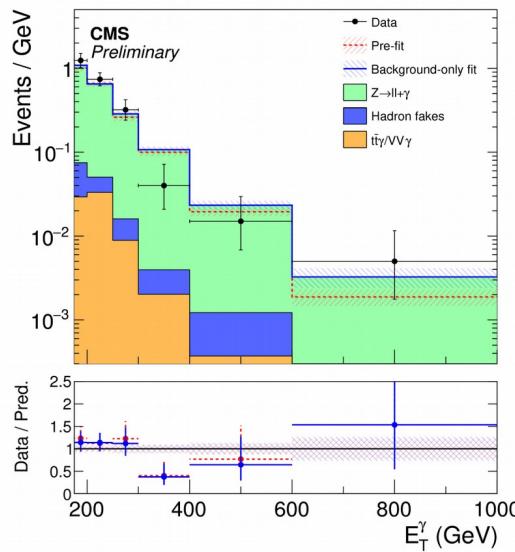
Signal extraction in E_T^γ

35.9 fb^{-1} (13 TeV)

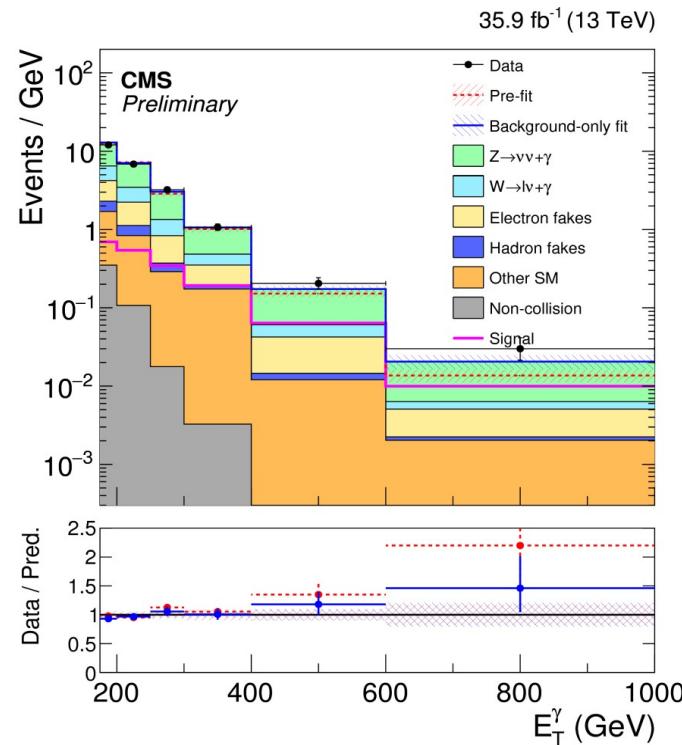


Use simultaneous maximum likelihood fit to determine backgrounds and extract signal
 Only process ratios from simulation → partial cancellation of uncertainties!

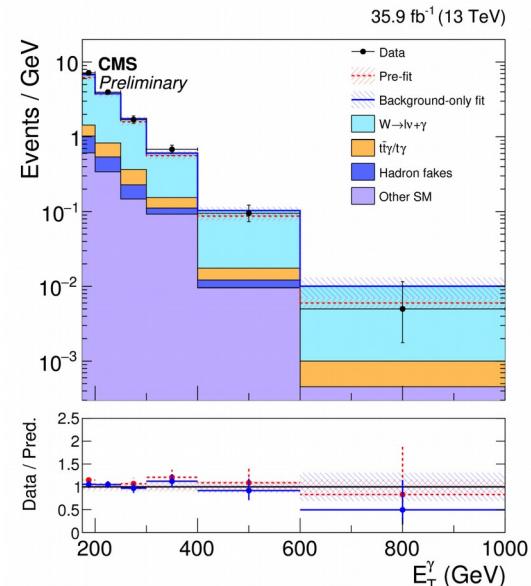
Z γ Control region
 $\gamma + 2$ leptons



Signal region
 $\gamma + 0$ leptons



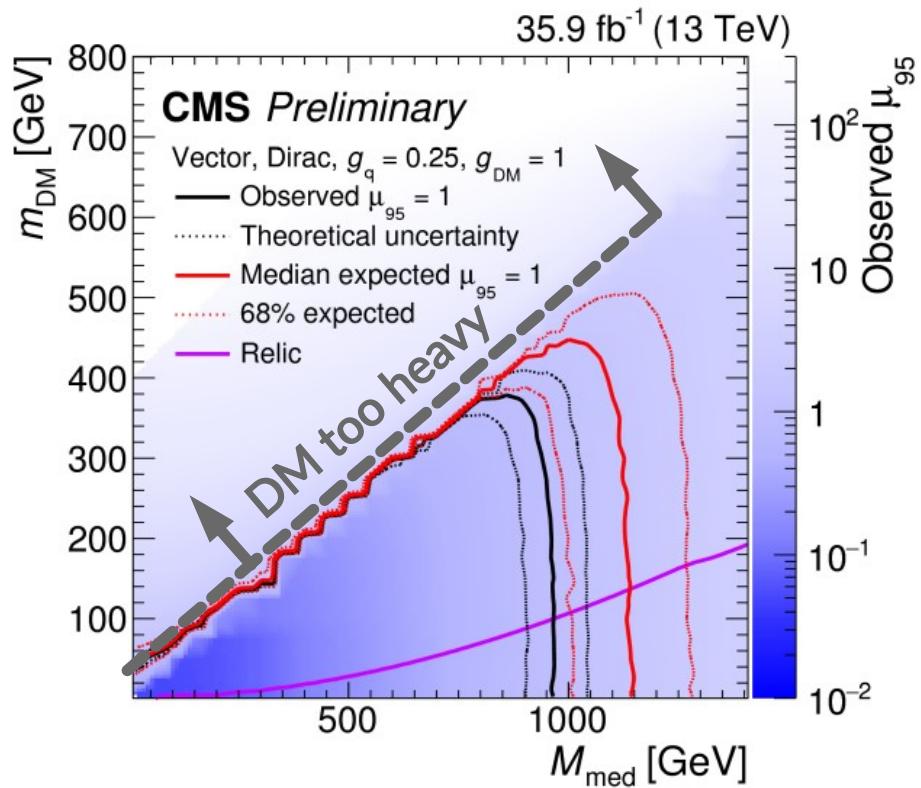
W γ Control region
 $\gamma + 1$ leptons



Monophoton exclusion reach

EXO-16-053

- Formulate exclusion in $m_{\text{med}} - m_{\text{DM}}$ plane
- m_{med} is main driver for sensitivity
 - Sensitive for $m_{\text{DM}} < m_{\text{med}} / 2$
 - Reach up to $m_{\text{med}} \approx 950$ GeV



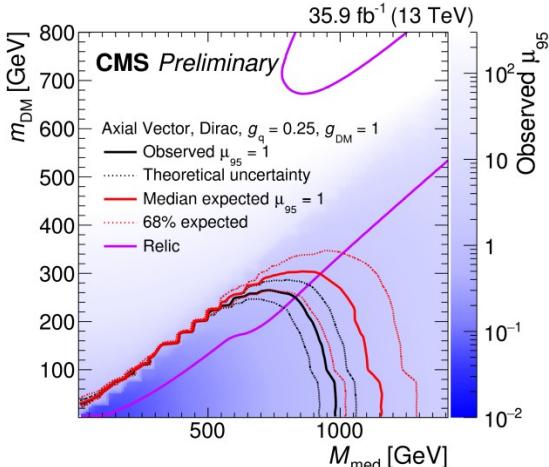
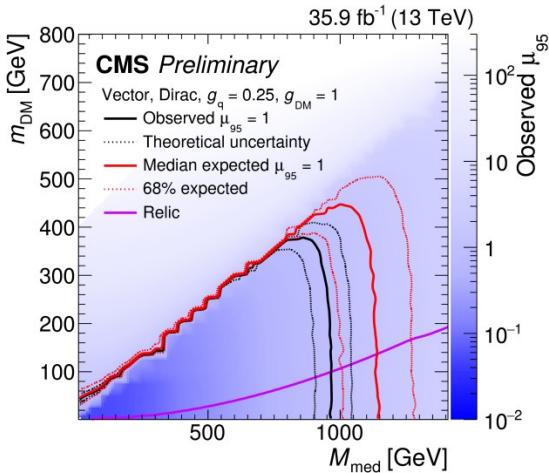
Monophoton exclusion reach

EXO-16-053

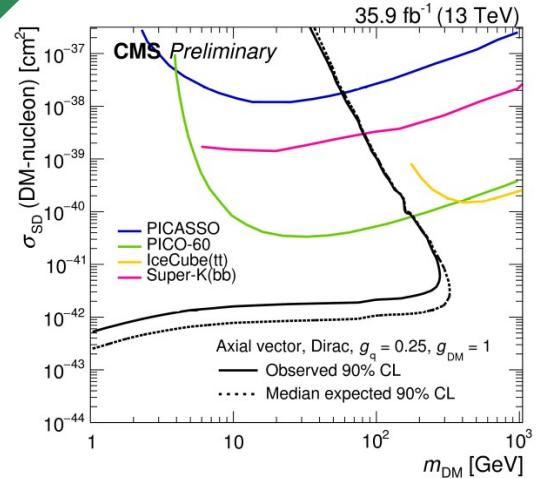
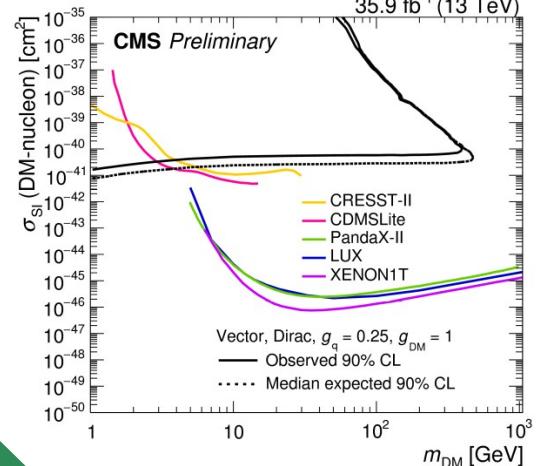
Vector Mediator

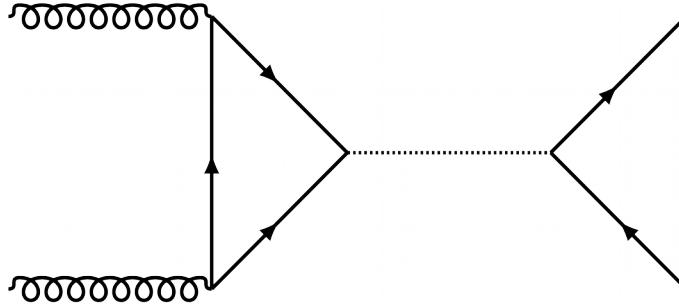
Probe different coupling structures
&
Compare to direct detection

Axial-Vector Mediator



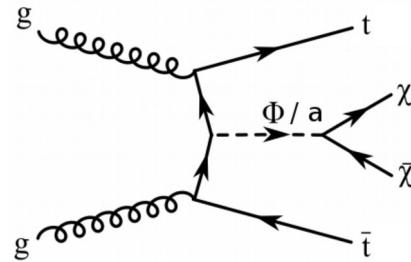
Model dependent!





Spin 0

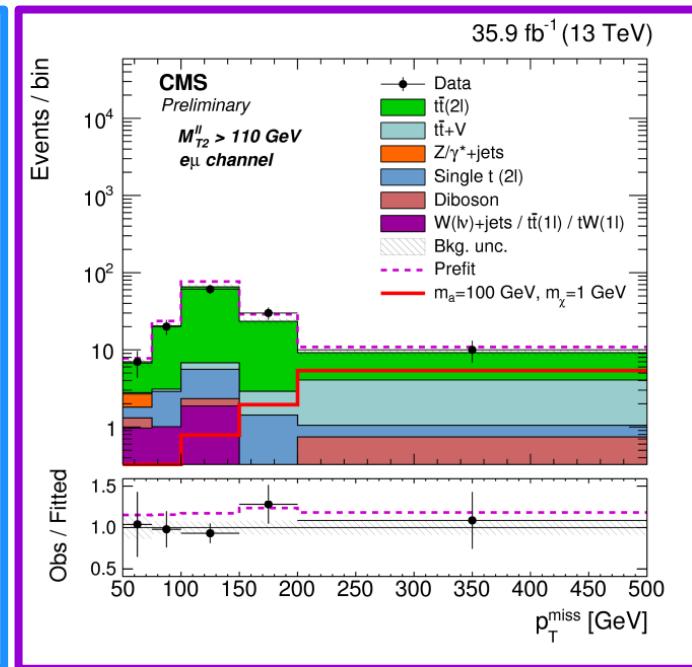
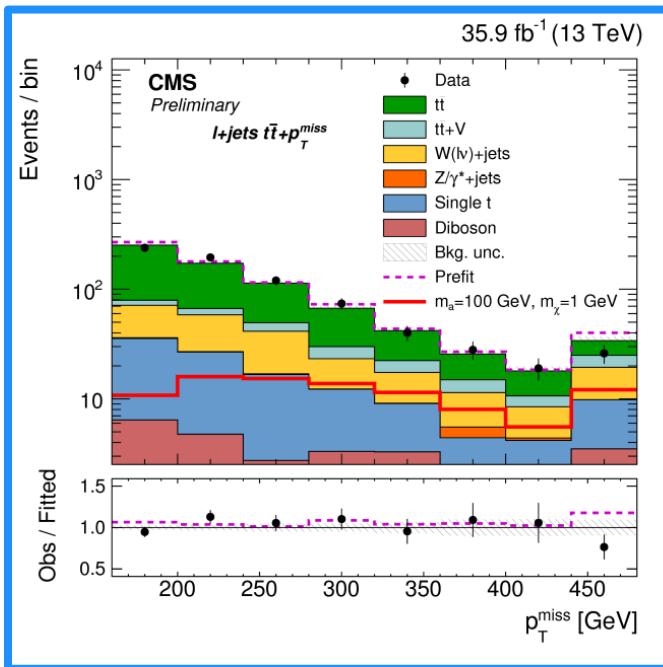
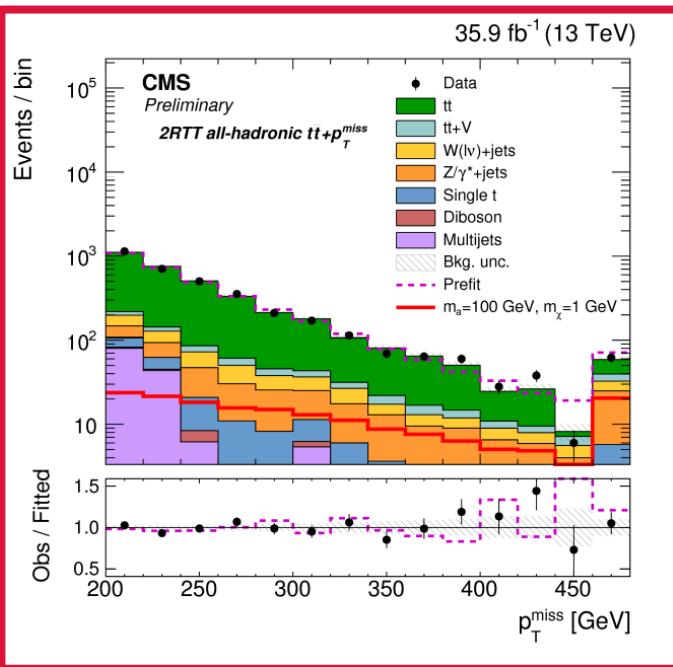
Minimal flavour violation → Quark coupling proportional to quark mass



Combined search in all top pair decay combinations:

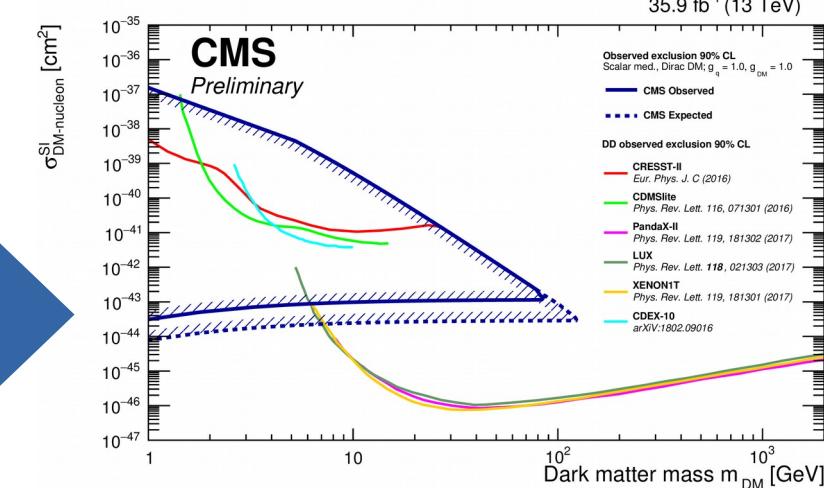
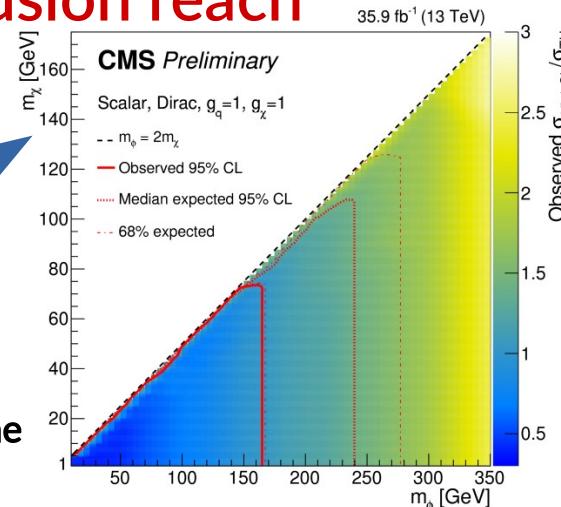
Fully hadronic, semi-leptonic, Fully leptonic

- 2-4 jets, ≥ 1 b jet, 0-2 leptons
- Further categorization based on top kinematics
- Signal extraction: fit $p_{T,\text{miss}}$ distribution



DM + Top pair exclusion reach

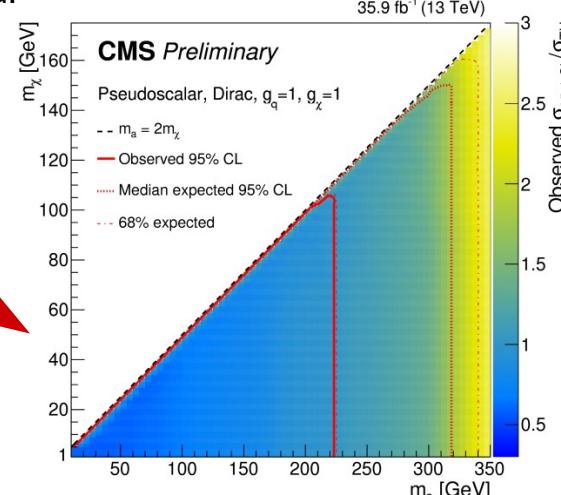
Scalar Mediator



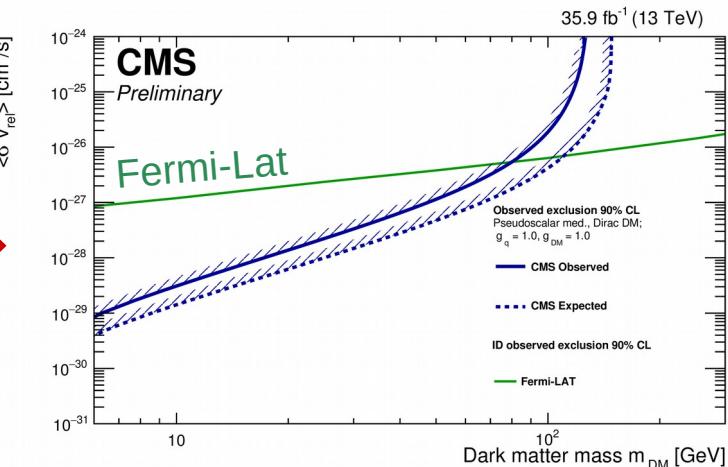
Formulate exclusion in $m_{\text{med}} - m_{\text{DM}}$ plane

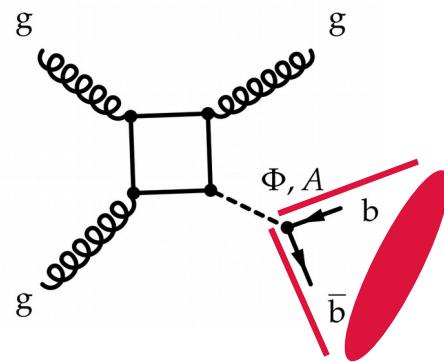
- Reach up to $m_{\text{med}} \approx 160 / 225$ GeV
- No DD constraints for pseudoscalar

Pseudoscalar Mediator



Model dependent!



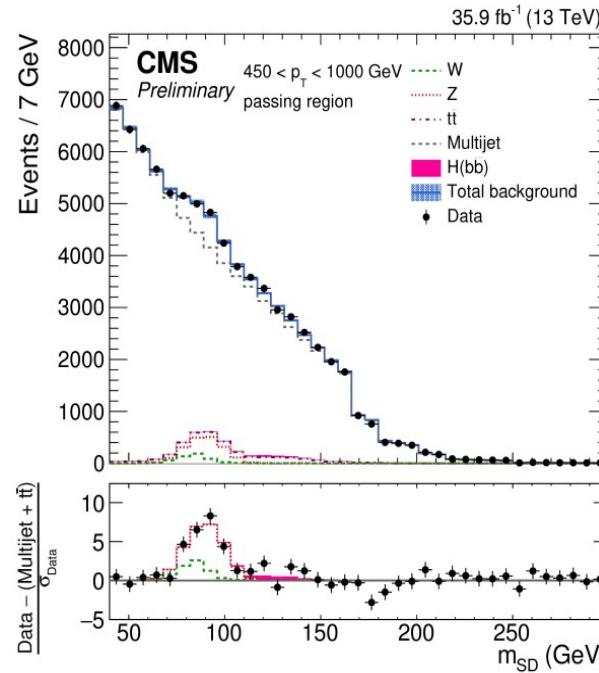


Large boost needed for triggering!
 p_T (leading jet) > 450 / 500 GeV

Use Double b tagging

- multivariate analysis of jet constituents
- Developed for $H \rightarrow bb$ discrimination against QCD background

Signal: Events **passing double b tag**



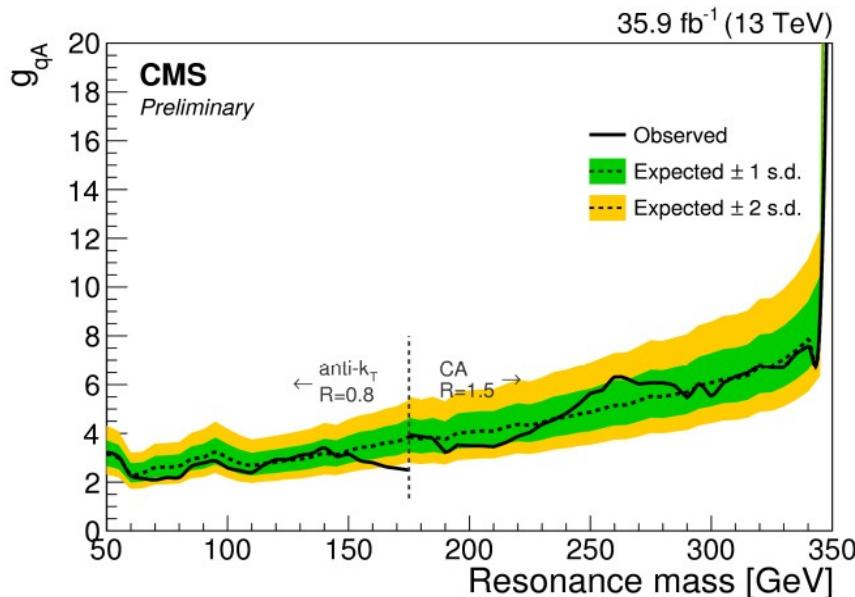
Search signal in jet mass spectrum

QCD background determined from events **failing** double b tag

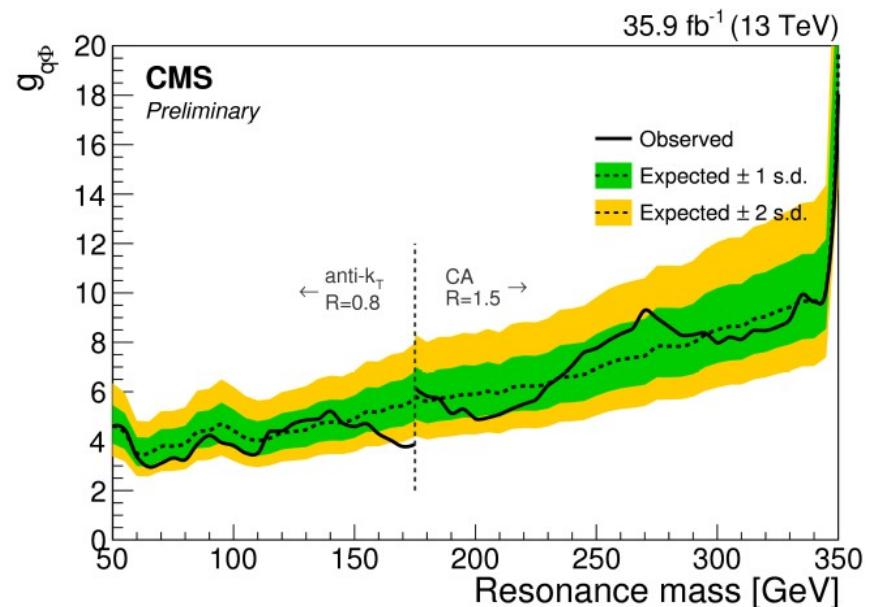
Spin-0 mediator \rightarrow bb: sensitivity

Set limits on coupling modifier assuming h(125)-like coupling values

Pseudoscalar mediator



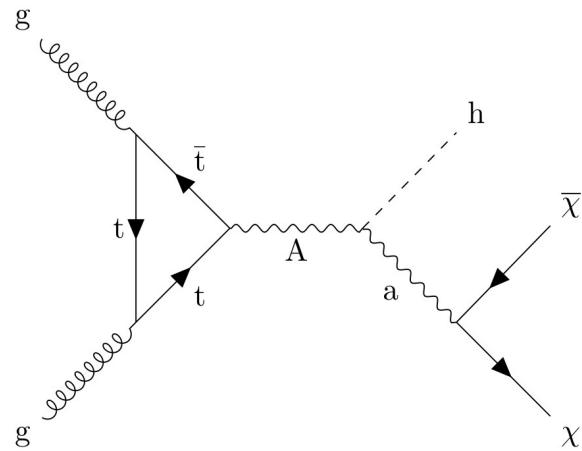
Scalar mediator



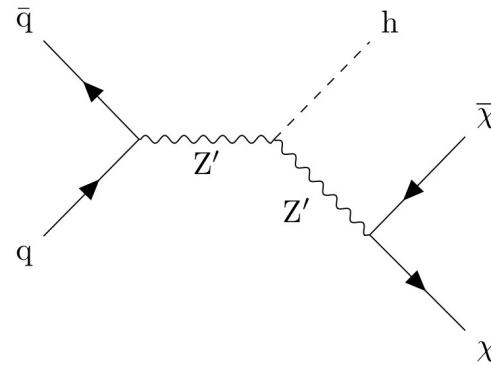
Target $m_{\text{DM}} > m_{\text{med}} / 2 \rightarrow$ Complimentary to $p_{T,\text{miss}}$ -based searches!

Non-minimal scenarios

Mono-Higgs signatures arise from simplified models with BSM boson dynamics



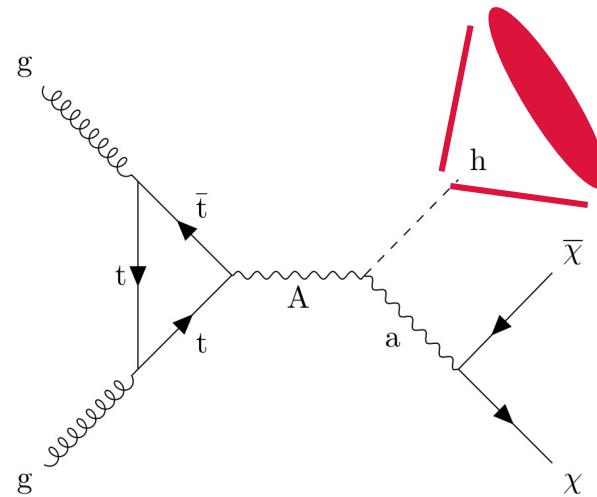
Pseudoscalar + 2HDM



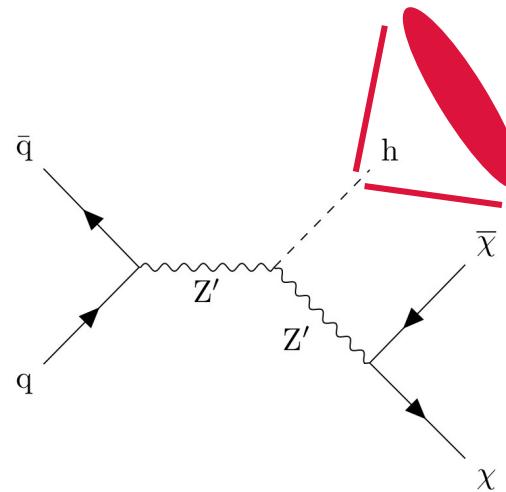
Baryonic Z'
(+ others)

Search for signal in SM Higgs decay channels: $\gamma\gamma$, bb , $\tau\tau$...

Mono-Higgs signatures arise from simplified models with BSM boson dynamics



Pseudoscalar + 2HDM



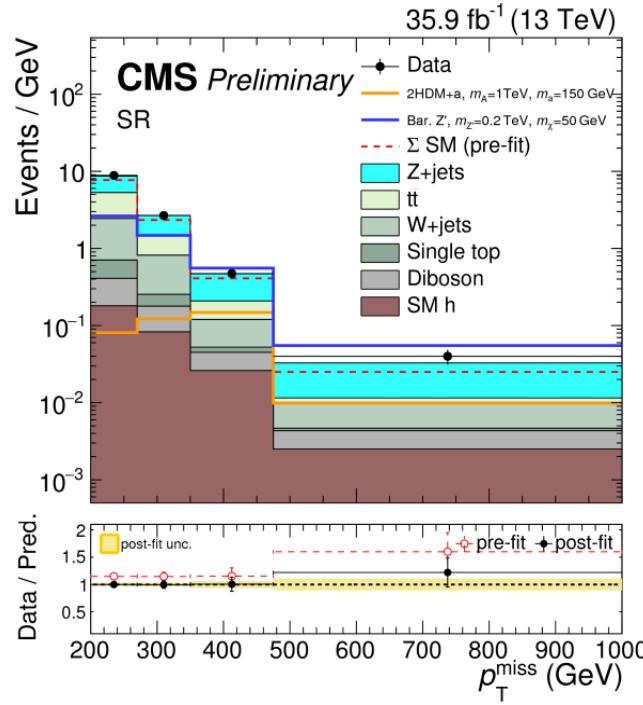
Baryonic Z'

(+ others)

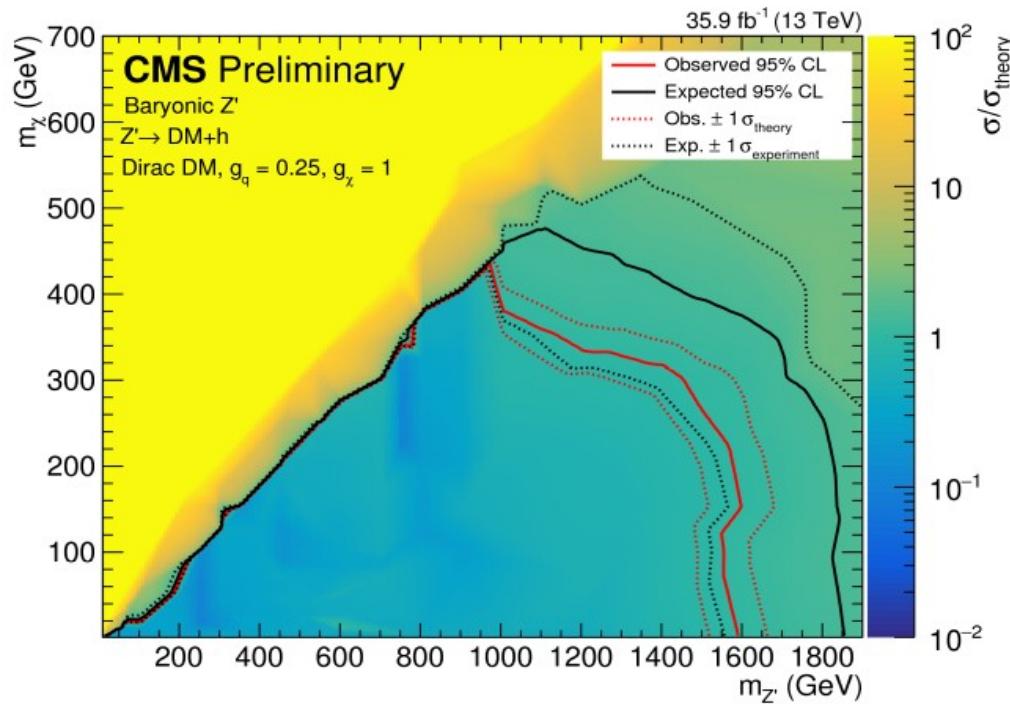
For $h \rightarrow bb$: similar strategy as in mediator search
double b tagged fat jet with $100 < \text{jet mass} < 150 \text{ GeV}$

Extract signal from Etmiss distribution

$pT(\text{jet}) > 200 \text{ GeV}$, $\text{Etmiss} > 200 \text{ GeV}$



Powerful exclusion reach!
Here: Baryonic Z' model

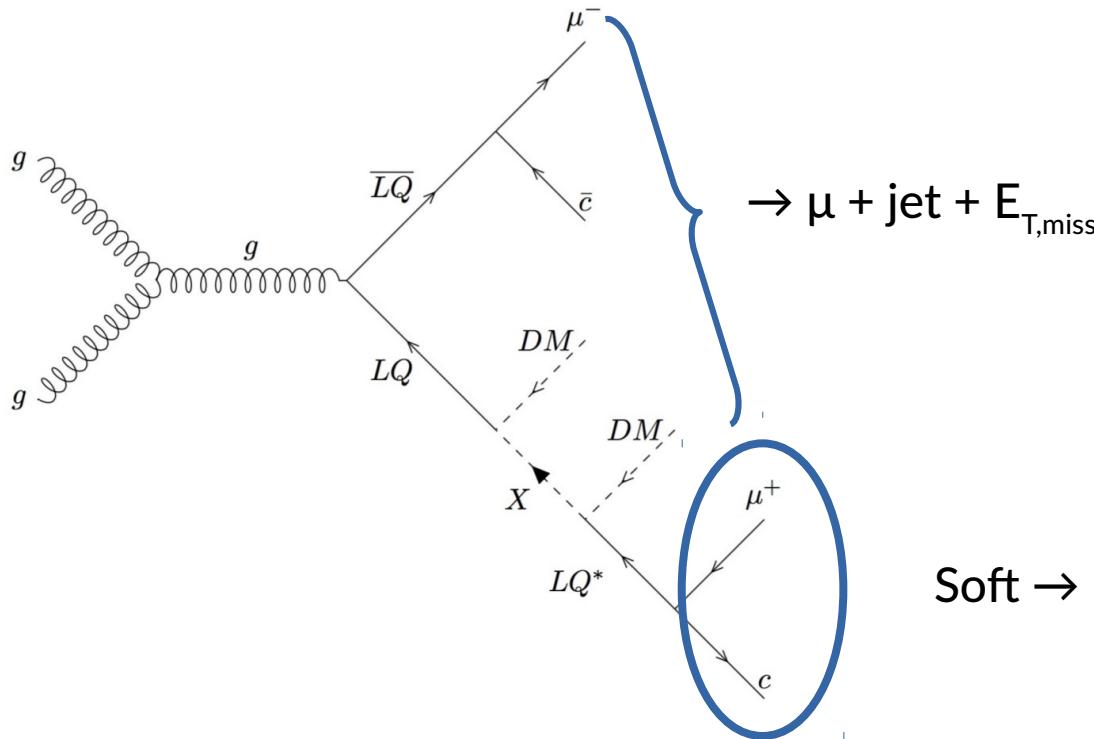


Main backgrounds constrained with total of 12 CR

E.g. $Z \rightarrow vv$: Use $Z \rightarrow ee, \mu\mu$ with/without double b tag

Dark Matter from leptoquark decay

EXO-17-015

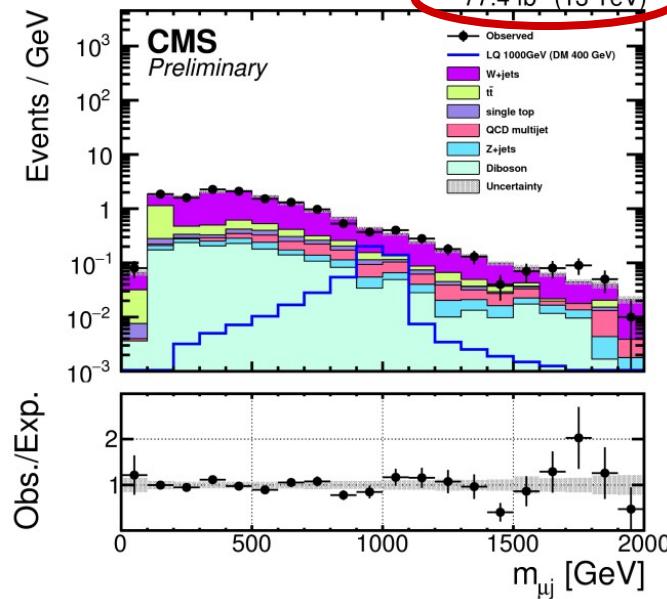


- Explore less conventional signatures
- Co-annihilation between Majorana DM + Dirac X drives relic density
- Consider small mass splitting $m_X / m_{\text{DM}} - 1 \approx 10\%$

DM from leptoquark decay

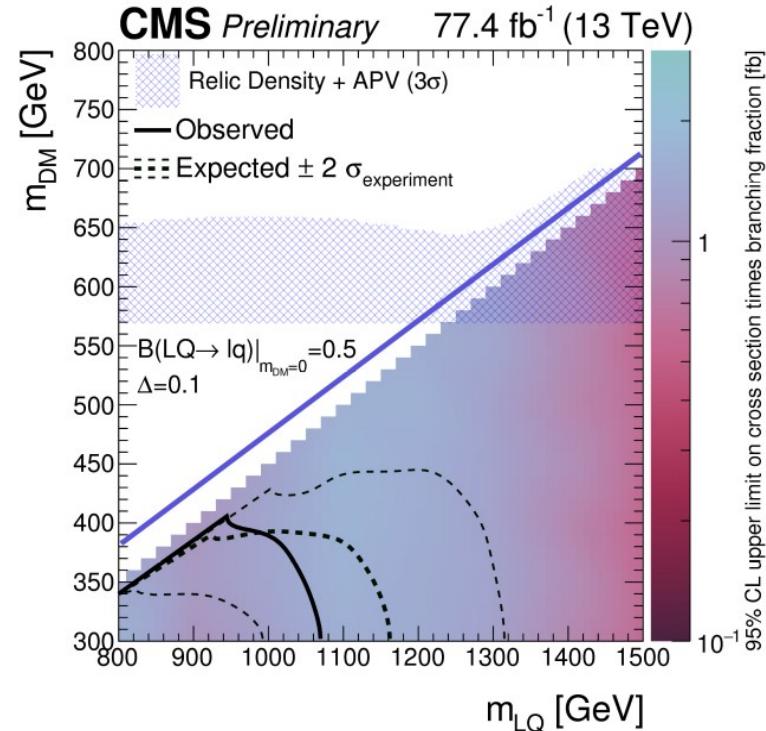
EXO-17-015

- $M_T(\mu, E_{T,\text{miss}}) > 500 \text{ GeV}$
- Search for bump in mass of μ -jet system
- Perform analysis on combined 2016+2017 dataset



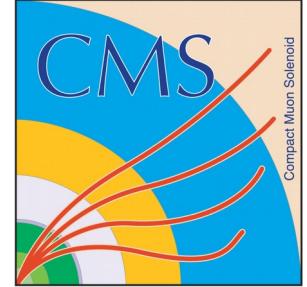
Main BG: W and top

Shape from simulation, norm. from data



- Probe LQ masses up to **1.15 TeV**, DM up to **420 GeV**
- Strong constraints from direct LQ search for $m_{\text{LQ}} < 800 \text{ GeV}$

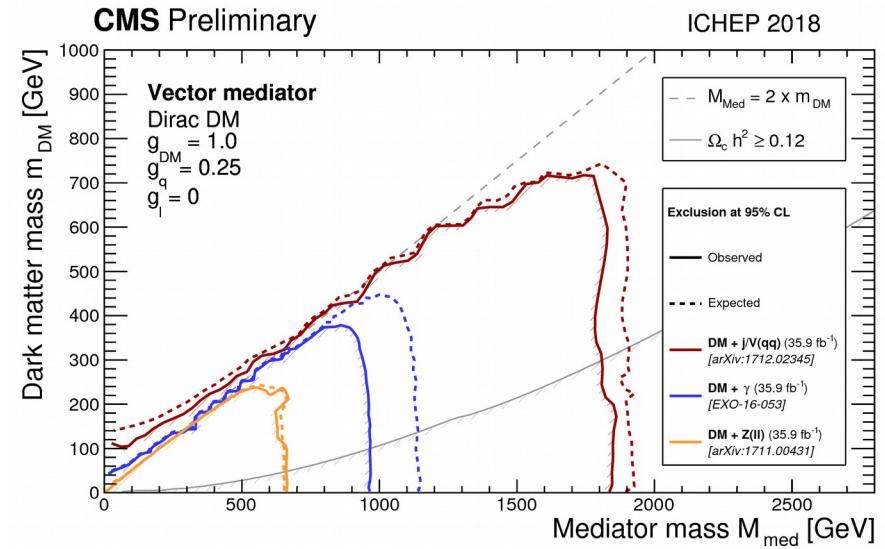
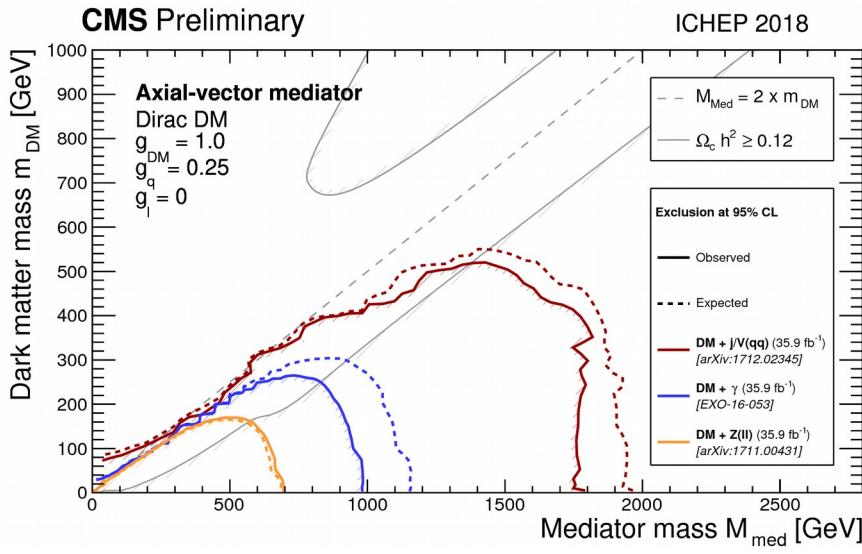
Summary and conclusions



- CMS has a rich search program for DM particles
- Presented a small subset, focus on **new results**:
 - Monophoton (EXO-16-053)
 - DM + Top pair (EXO-16-049)
 - Boosted mediator → bb (EXO-17-024)
 - Mono-H → bb (EXO-16-050)
 - Mono-Leptoquark (EXO-17-015)
- For more, **ask me or go to**:
 - Preliminary results:
 - <https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/>
 - Publications:
 - <https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/DM.html>

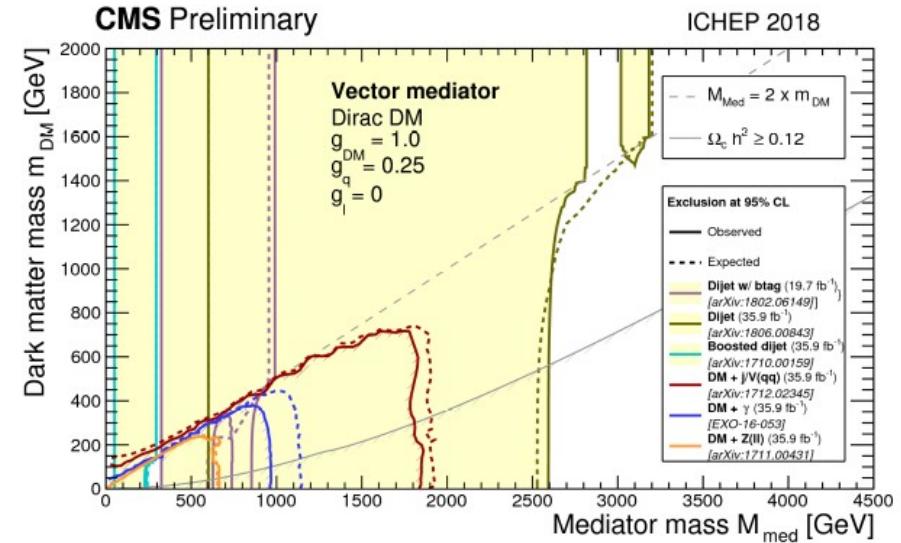
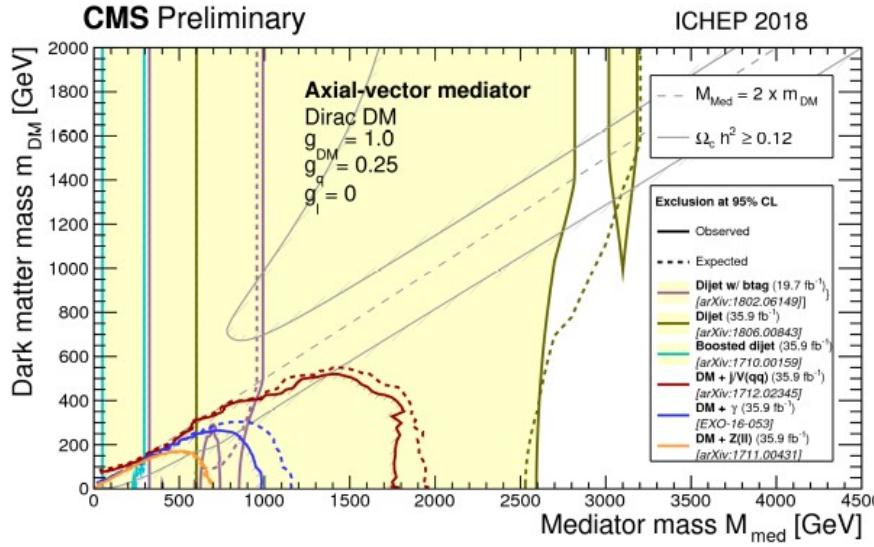
Backup: Summary plots

Summary plots: Spin-1 mediator via MET-based searches



Summary plots: Spin-1 mediator via MET-based and direct searches

Strong constraints from dijet search for mediator

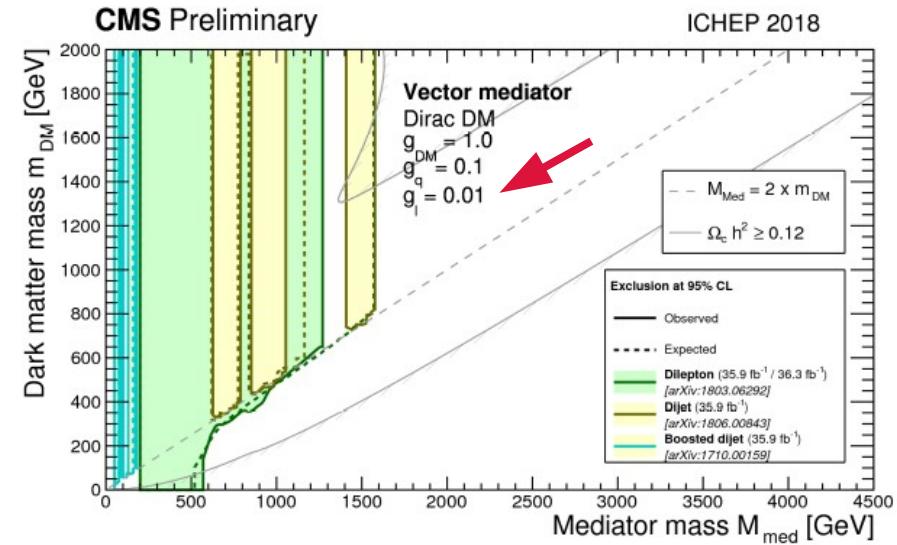
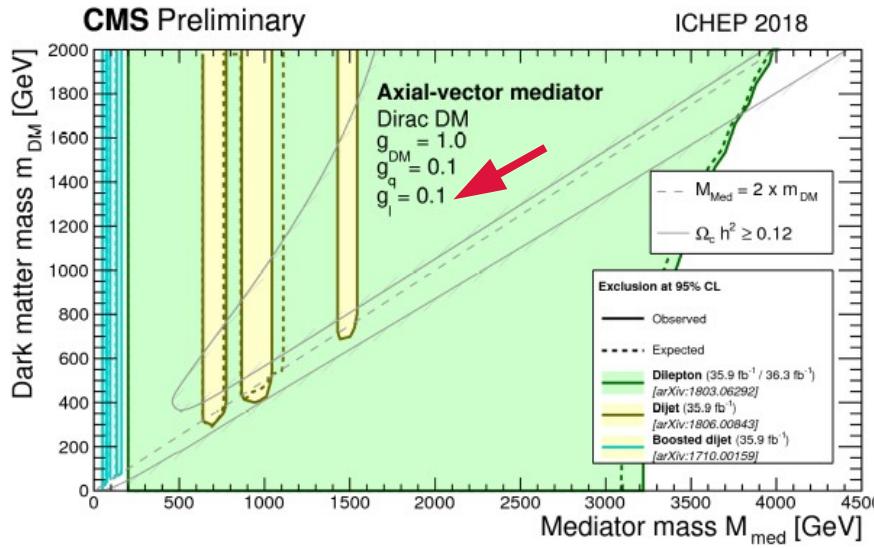


Can probe also $m_{\text{DM}} > m_{\text{med}} / 2$

But: strong dependence on choice of g_q

Summary plots: Spin-1 mediator via MET-based and direct searches

For $g_{q\bar{q}} = 0.1$, dijet is only relevant if DM too heavy

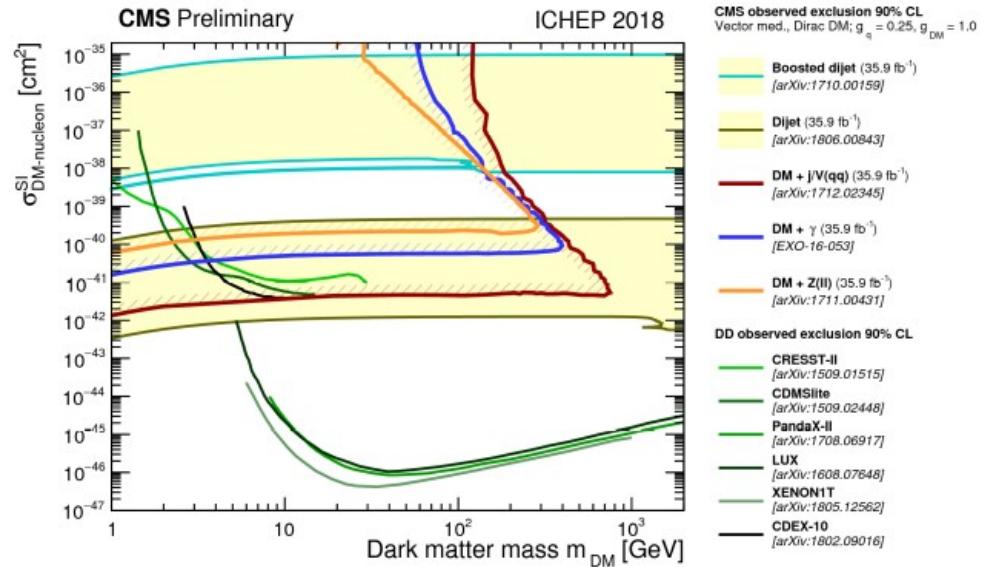
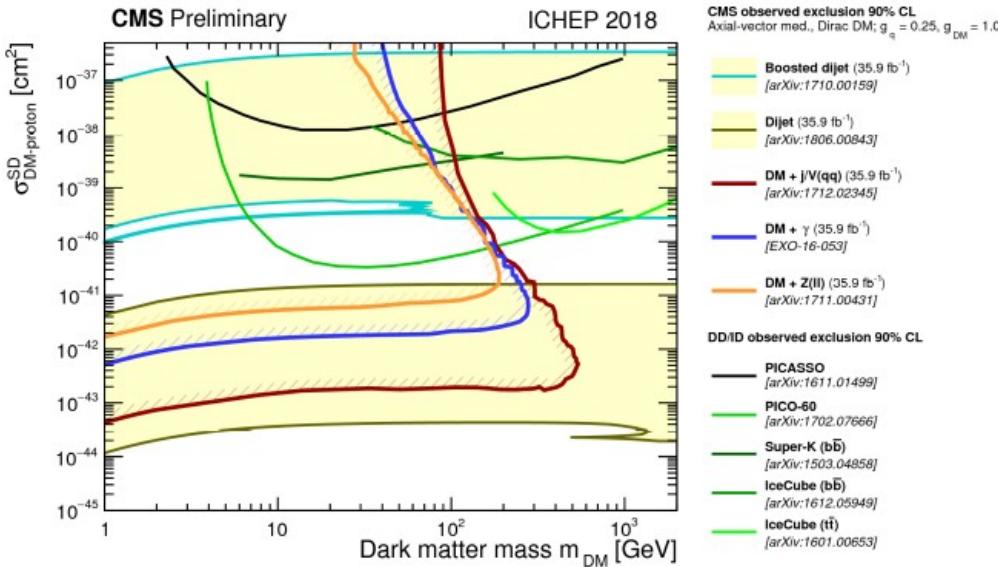


Mediator now narrow enough to be constrained with dilepton search!

Reach depends on choice of lepton coupling g_i

Summary plots: Spin-1, comparison to DD

Collider searches especially relevant
for spin dependent couplings and at low $m_{DM} \approx 6$ GeV

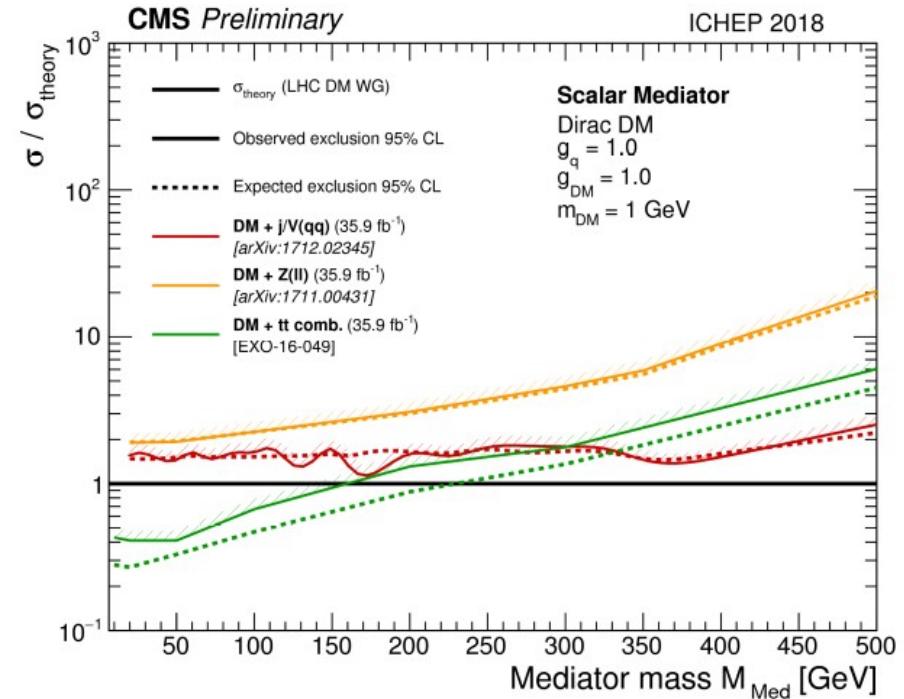
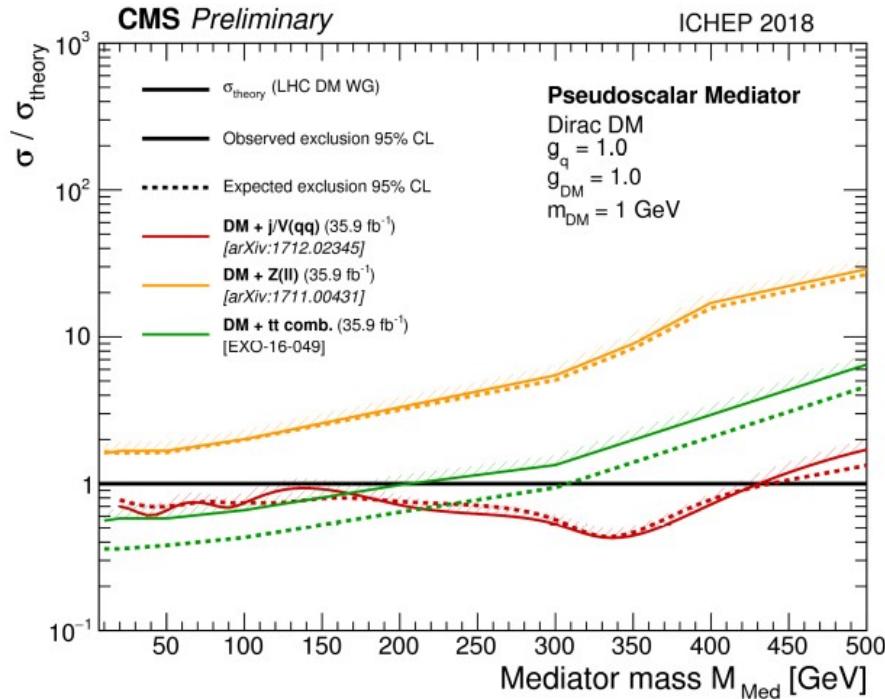


NB: Model dependent translation!

Y-axis is quantity of direct measurement for DD experiments,
derived quantity for collider

A. Albert - DM @ CMS

Summary plots: Spin-0

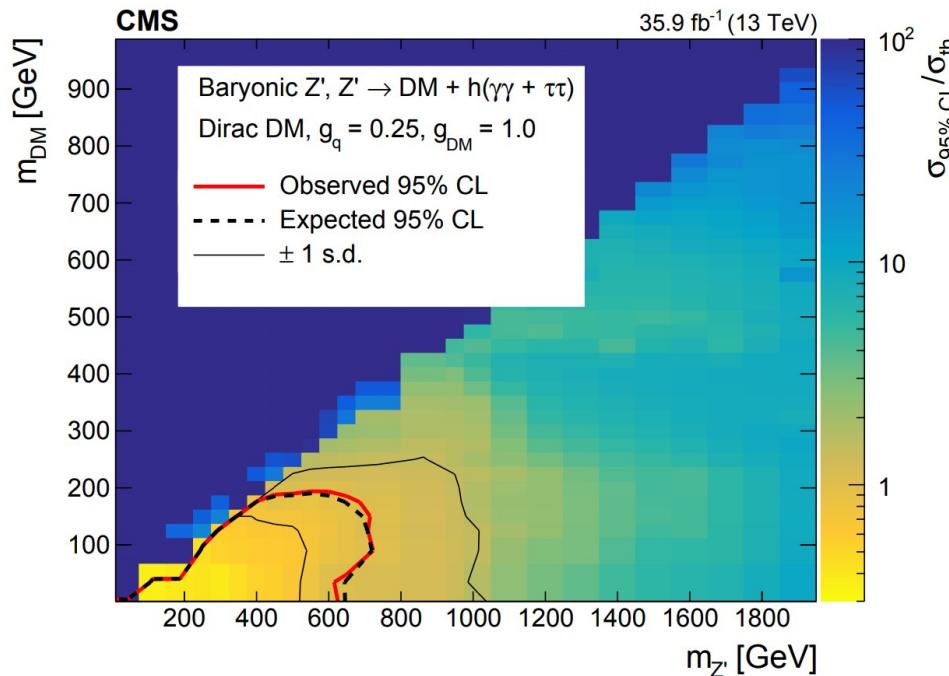


Strongest constraints from monojet / V and top pair + DM

Model does not have a Mediator-Z vertex → Mono-Z weaker

Mono-Higgs: Other decay channels

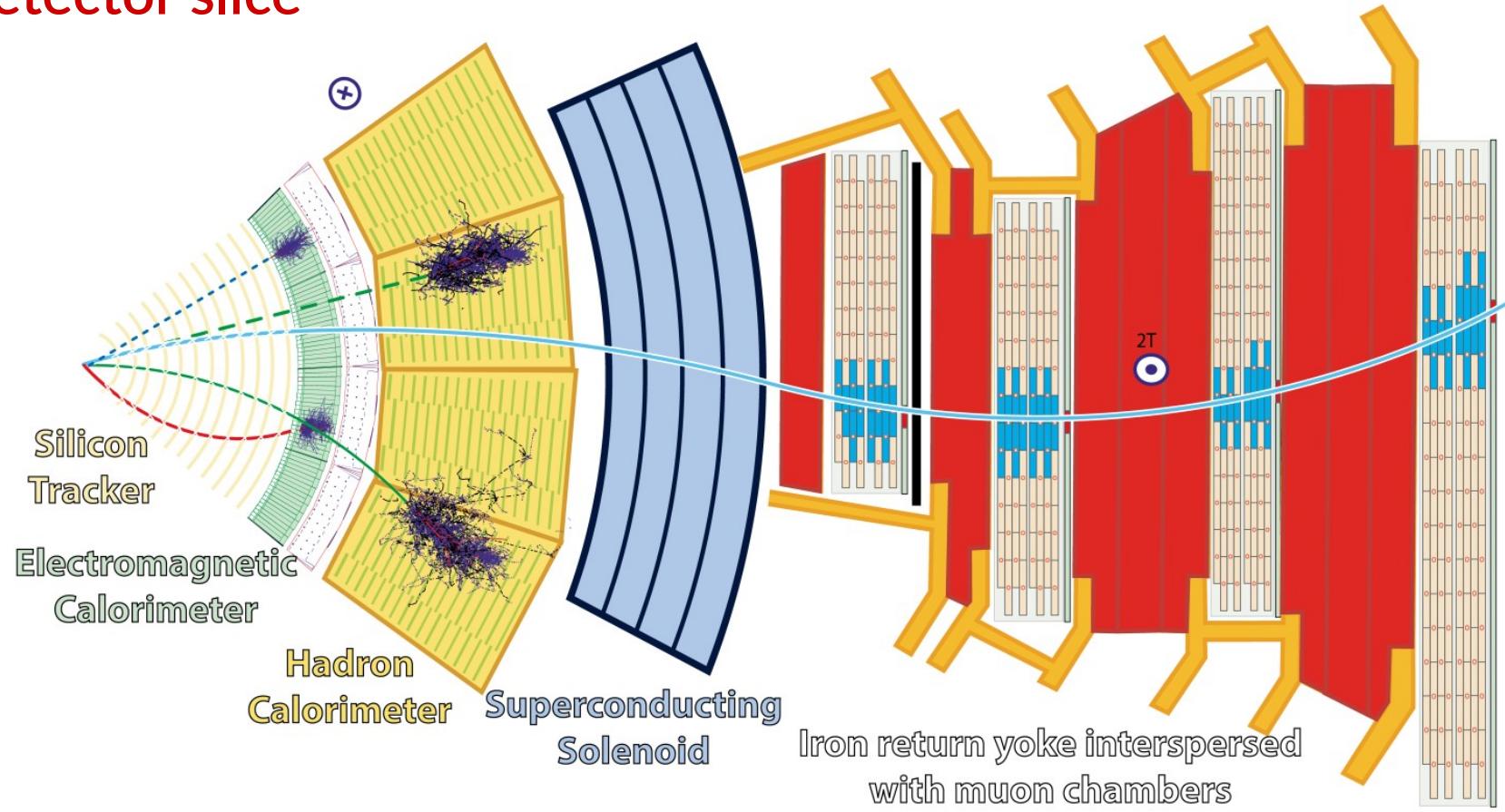
EXO-16-055



Mono-Higgs decay channels other than bb :
limited mass reach, but strong at low mass
Shown here: $\tau\tau + \gamma\gamma$ combination

Backup: CMS detector

CMS: Detector slice



Muon

Electron

Charged hadron (e.g. pion)

Neutral hadron (e.g. neutron)

Photon

Backup: Monophoton

Monophoton: Likelihood

Signal region yield:
 $W\gamma + Z\gamma = (1 + f) Z\gamma$

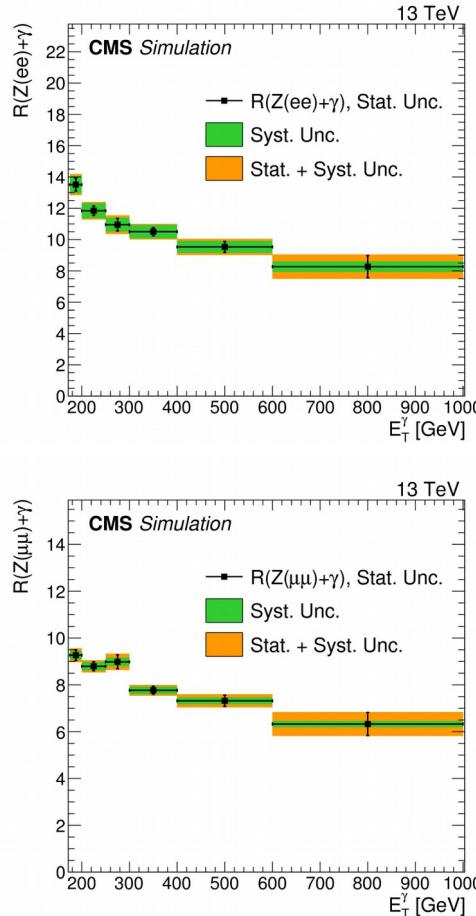
$$\mathcal{L} = \prod_i \left[\prod_{K=\text{horiz.,vert.}} \mathcal{P} \left(d_{K,i} \mid \left(1 + f_{Z\gamma,i}^{W\gamma}(\theta) \right) C_K N_i^{Z\gamma} + h n_{K,i}^{\text{halo}}(\theta) + b_{K,i}(\theta) \right) \right. \\ \cdot \prod_{K=e\gamma,\mu\gamma} \mathcal{P} \left(d_{K,i} \mid R_{K,i}^{W\gamma}(\theta) f_{Z\gamma,i}^{W\gamma}(\theta) N_i^{Z\gamma} + b_{K,i}(\theta) \right) \\ \cdot \prod_{K=ee\gamma,\mu\mu\gamma} \mathcal{P} \left(d_{K,i} \mid R_{K,i}^{Z\gamma}(\theta) N_i^{Z\gamma} + b_{K,i}(\theta) \right) \Big]$$

· $\prod_j \mathcal{N}(\theta_j)$,

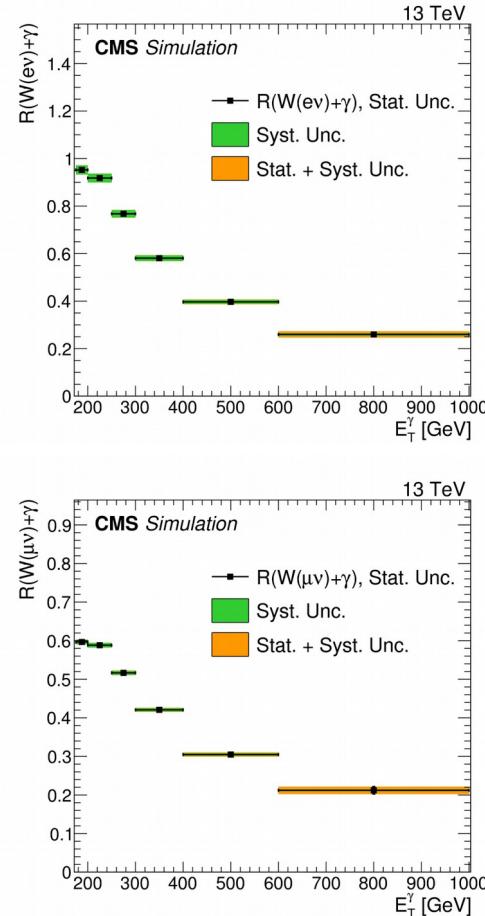
Transfer factors from control to signal regions

Monophoton: Ratios

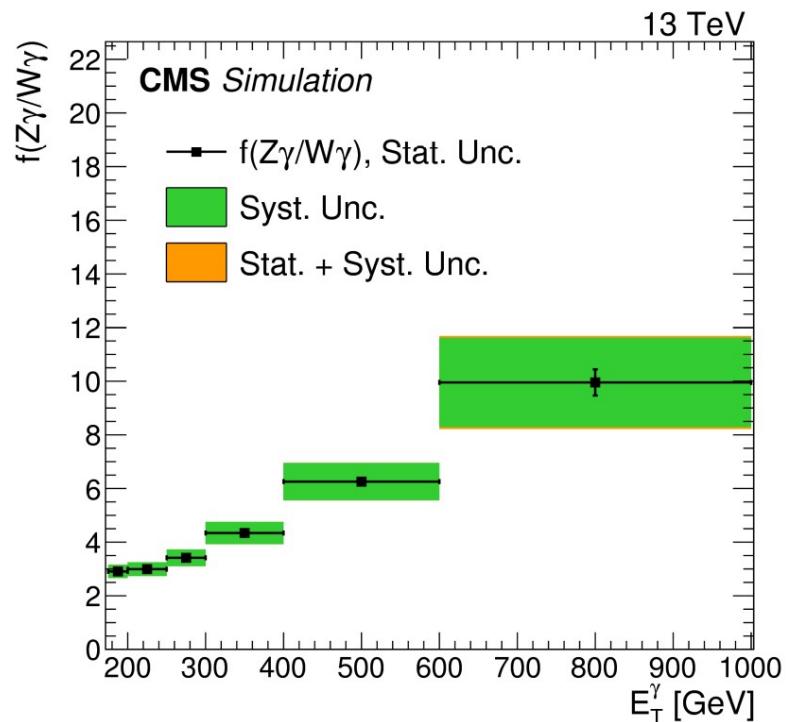
From Z(l_l) to Z(vv)



From W(lv) to W(lv)



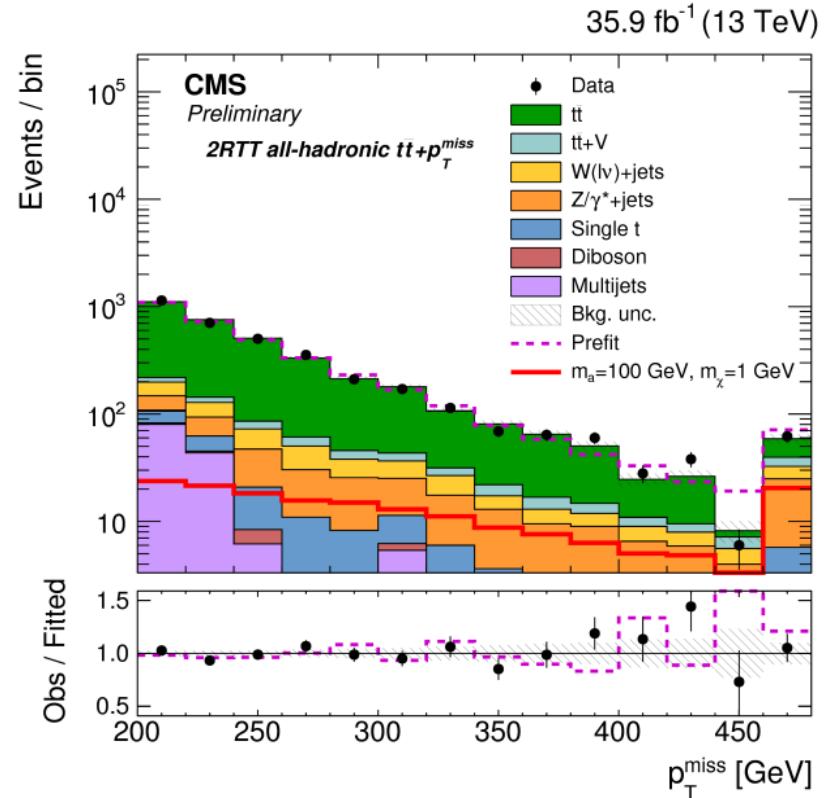
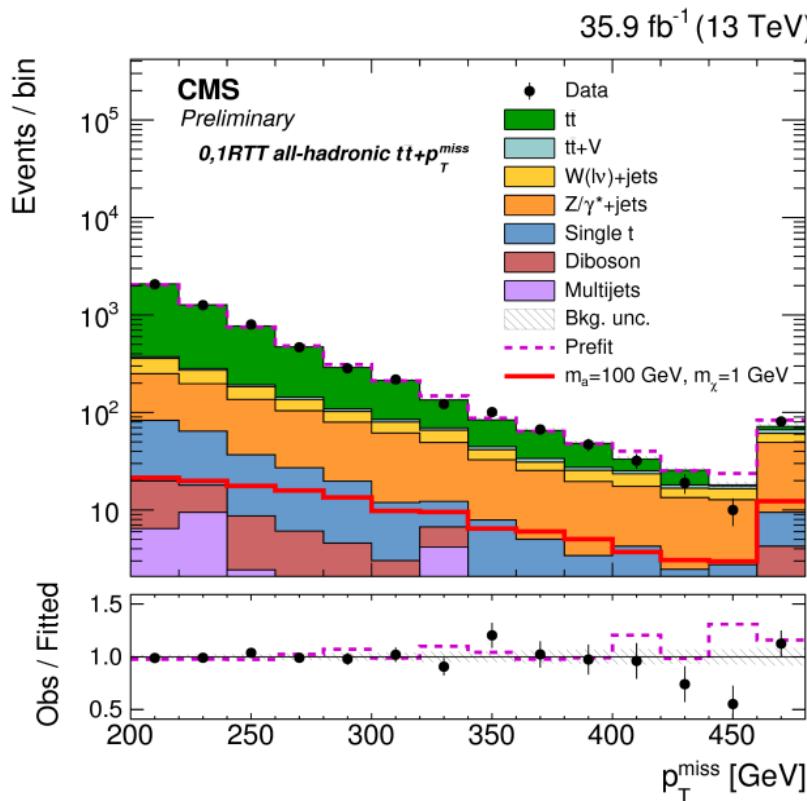
Overall $Z\gamma / W\gamma$ ratio



Backup: DM + Top pair

DM + Top pair: hadronic signal regions

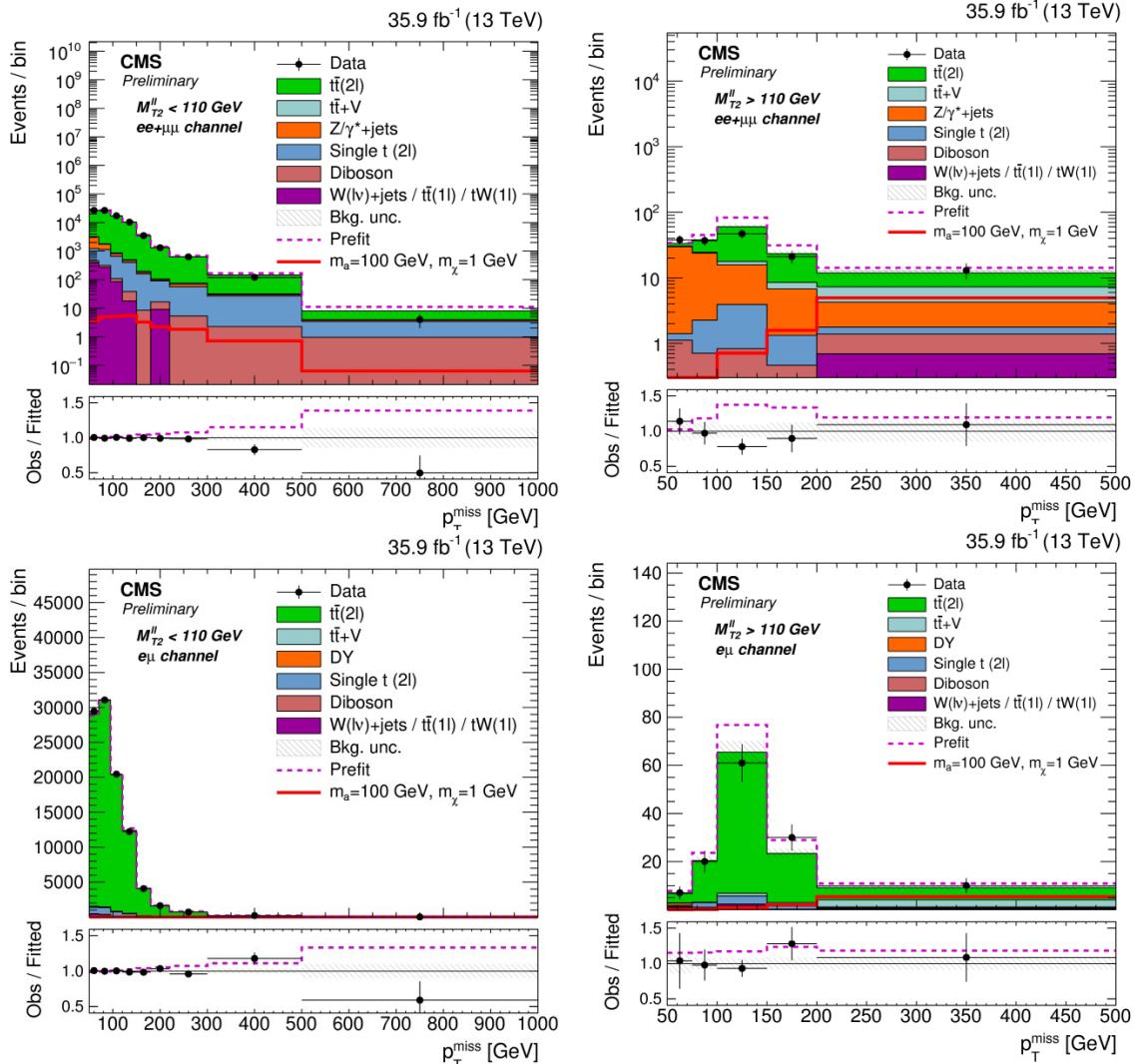
Signal regions divided by number of **Resolved Top Tags (RTT)**



DM + Top pair: leptonic signal regions

Divide by lepton flavour
 Same flavour (top)
 Opposite flavour (bottom)

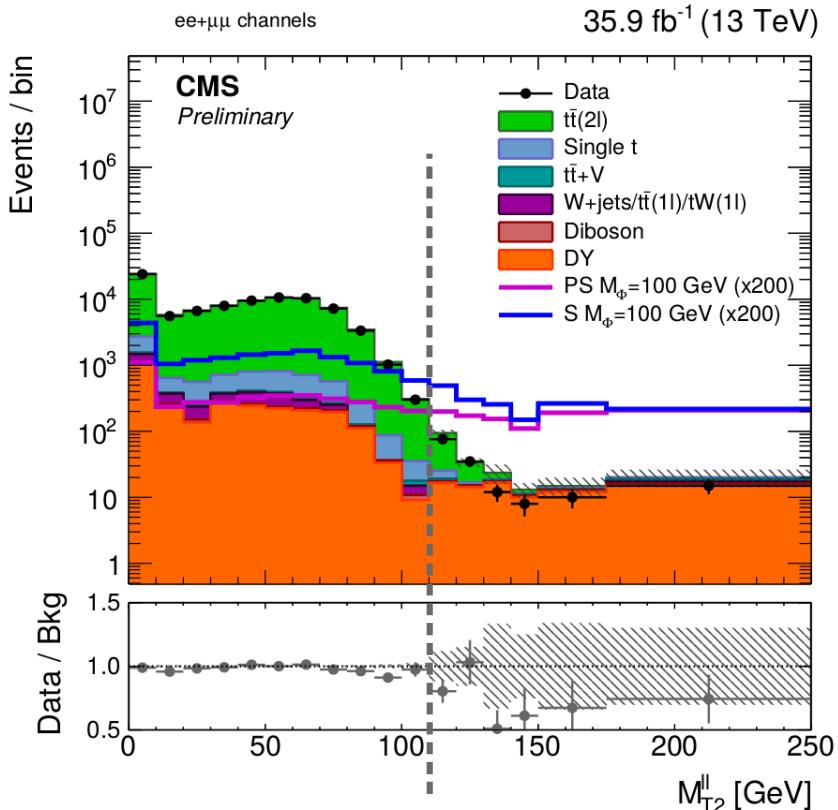
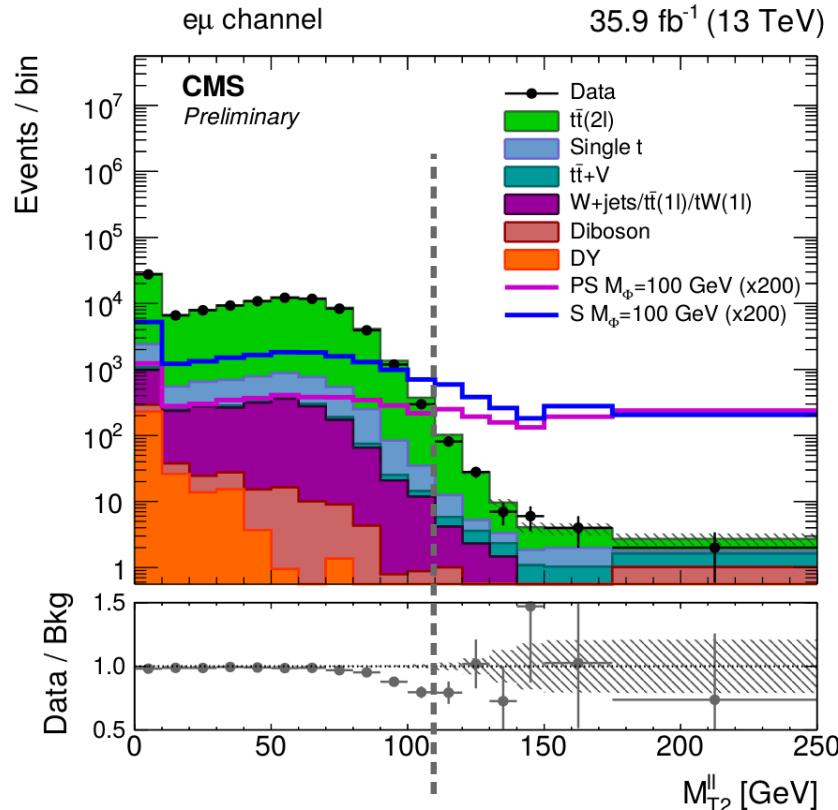
And MT2(II) value
 <110 (left)
 >110 right



DM + Top pair: M_{T2}^{\parallel}

$$M_{T2}^{\ell\ell} = \min_{\vec{p}_{T1}^{\text{miss}} + \vec{p}_{T2}^{\text{miss}} = \vec{p}_T^{\text{miss}}} \left(\max \left[M_T \left(\vec{p}_T^{\ell_1}, \vec{p}_{T1}^{\text{miss}} \right), M_T \left(\vec{p}_T^{\ell_2}, \vec{p}_{T2}^{\text{miss}} \right) \right] \right)$$

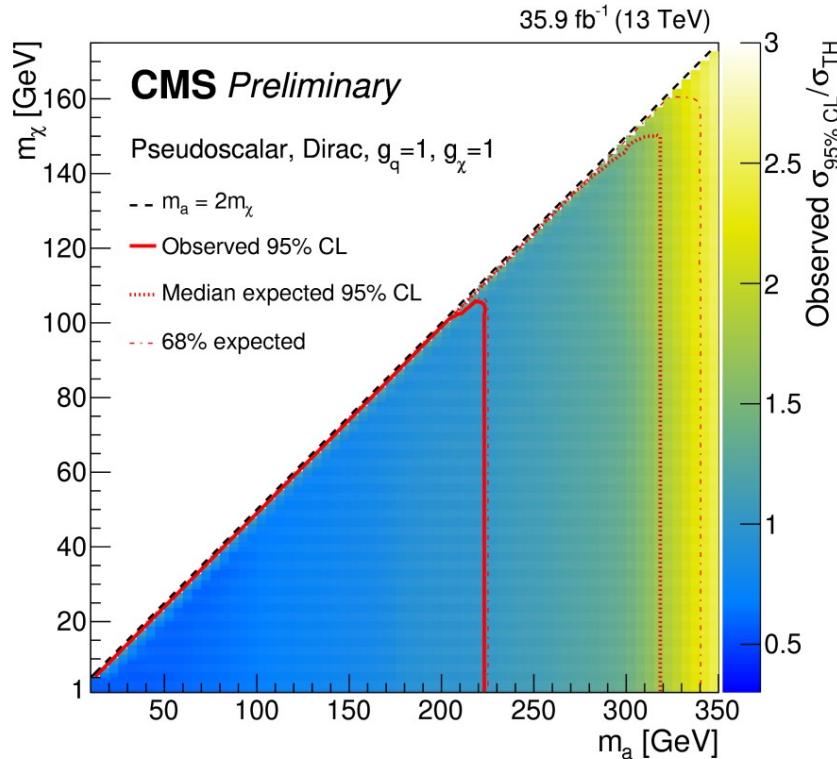
Spectrum shows characteristic drop-off for SM-like events
 Divide into high and low- M_{T2}^{\parallel} signal regions



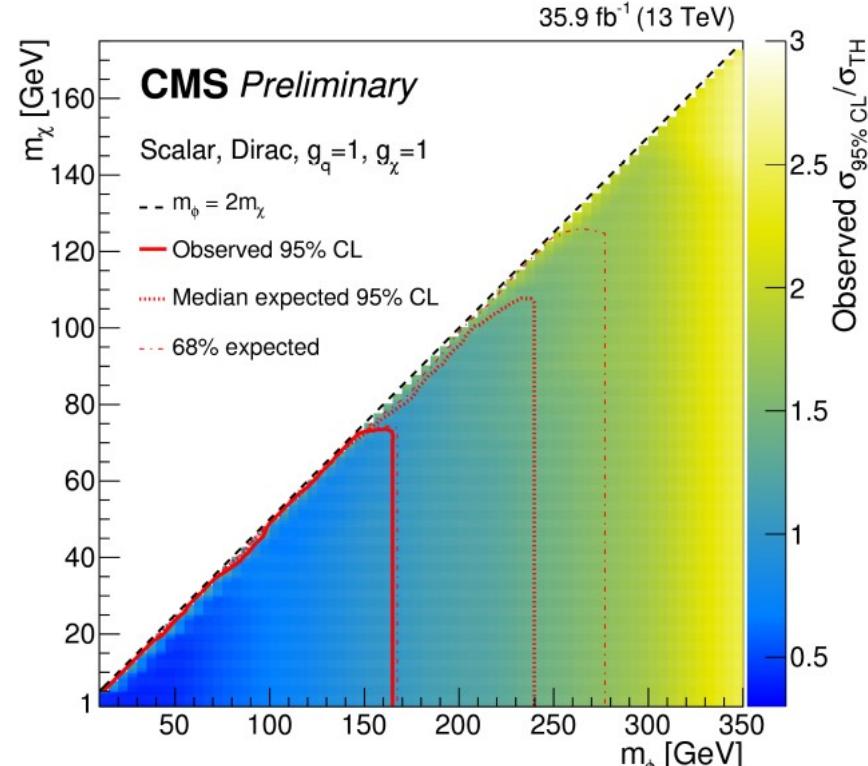
DM + Top pair: Exclusion reach

Exclusion in the plane of mediator and DM masses

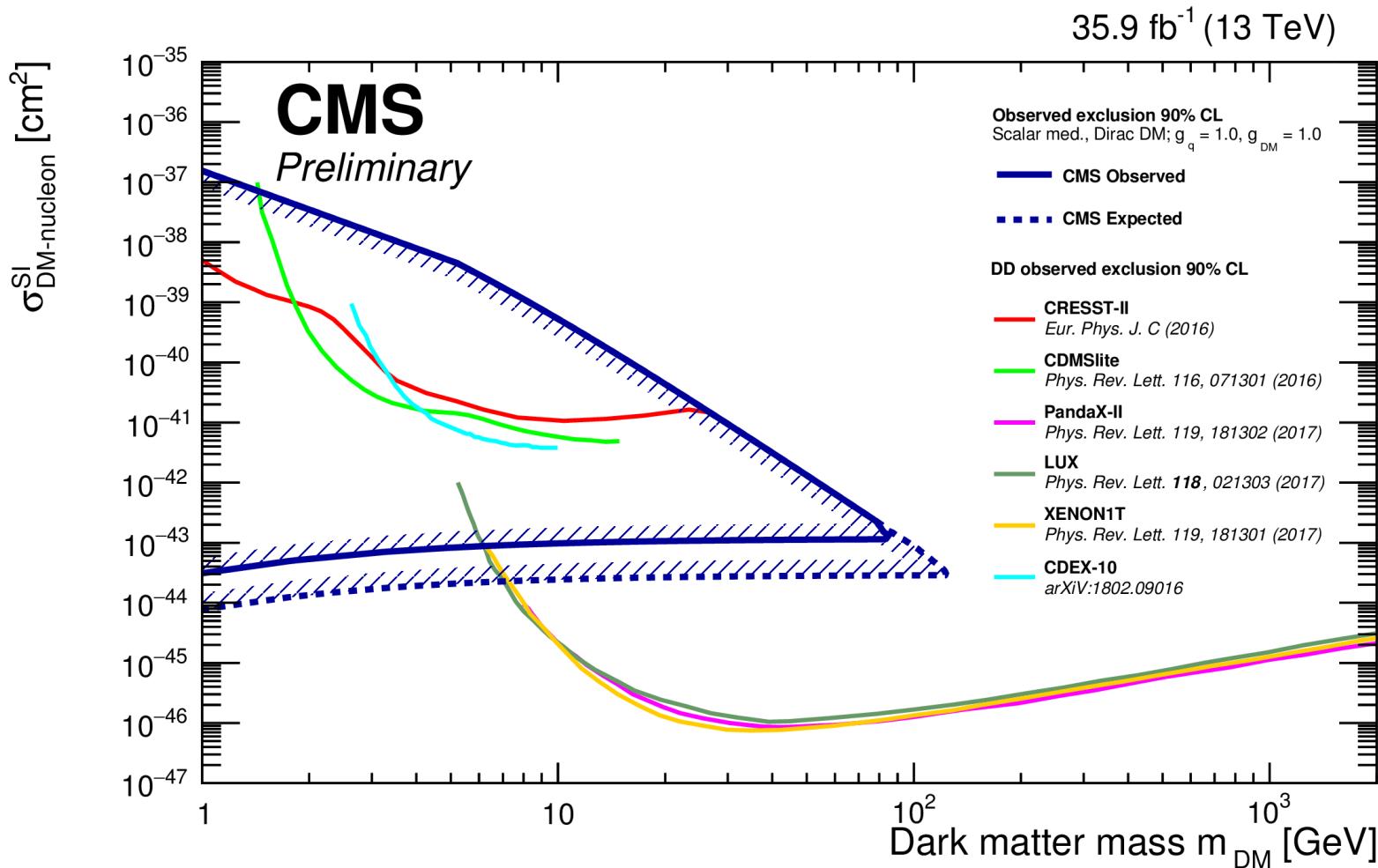
Pseudoscalar mediator



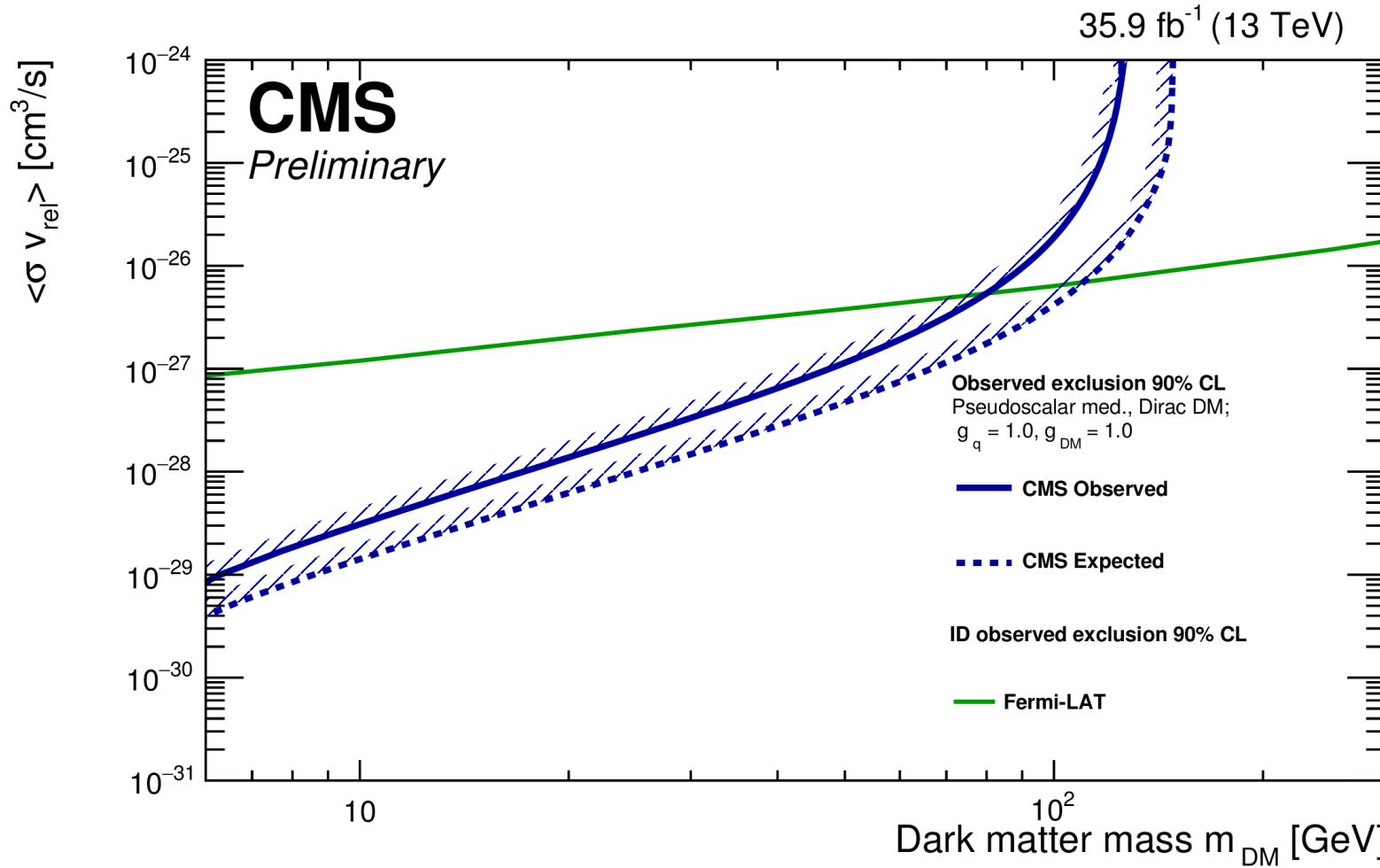
Scalar mediator



DM + Top pair: Scalar mediator, direct detection

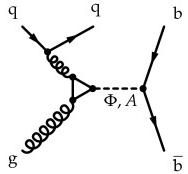


DM + Top pair: Pseudoscalar mediator, indirect detection



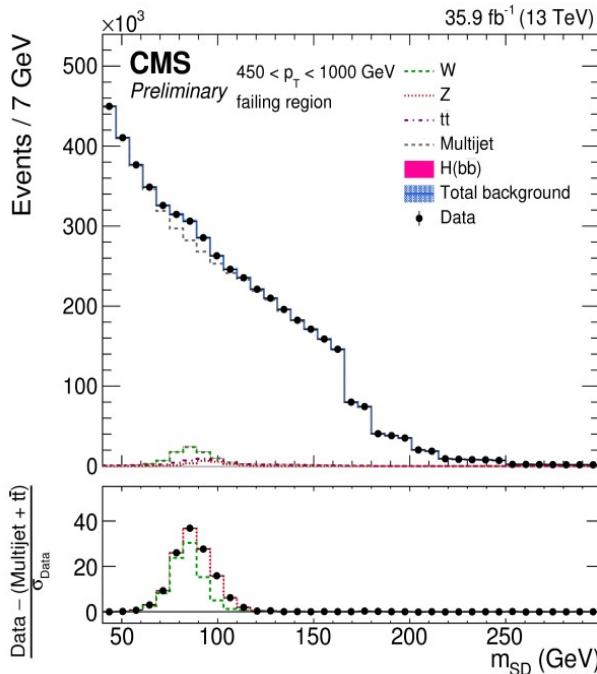
Backup: Boosted mediator → bb

Boosted spin-0 mediator → bb: Background estimation



Consider “soft drop mass” : Remove soft radiation from jet
Improved resolution of mediator mass

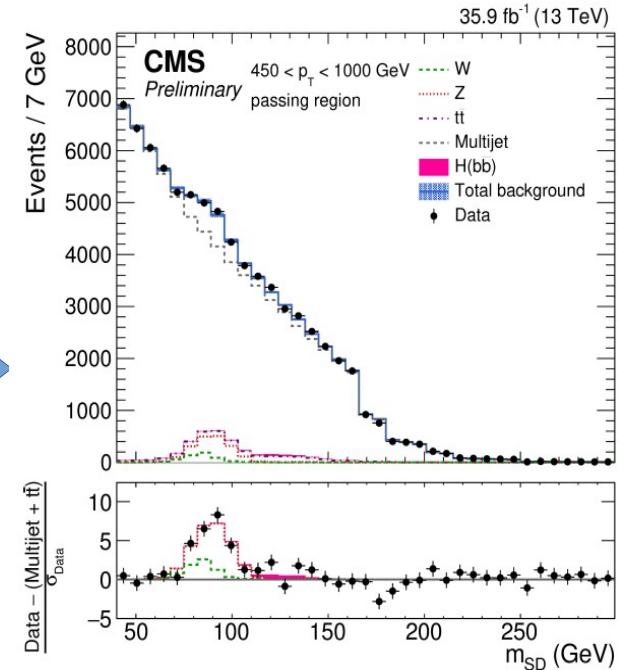
Control: Events **failing** double b tag



QCD:
Simultaneous fit of
transfer function



Signal: Events **passing** double b tag



Boosted spin-0 mediator → bb: Transfer function

Pass / Fail ratio not strongly dependent on jet mass and p_T

Residual differences accounted for with transfer function polynomial:

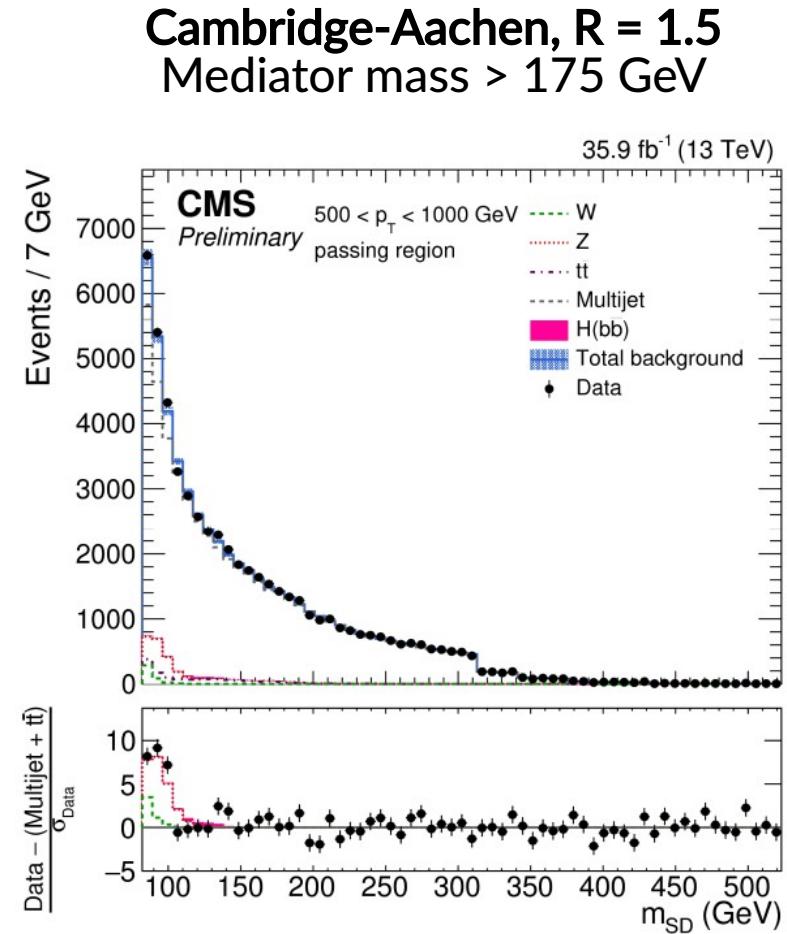
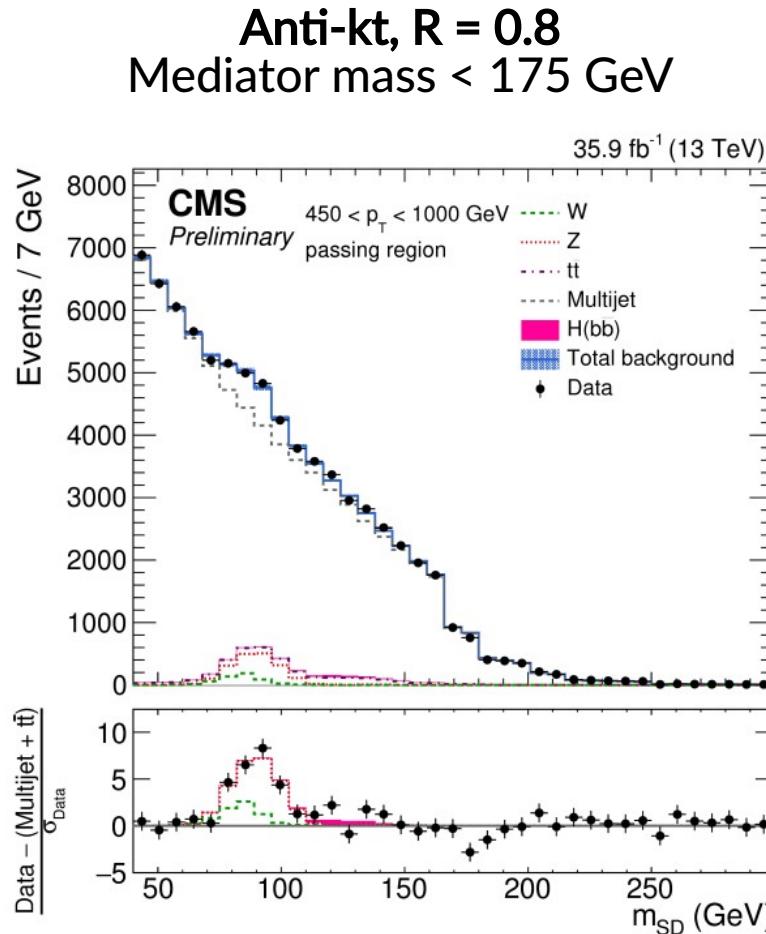
$$R_{p/f}(\rho, p_T) = \sum_{k,\ell} a_{k\ell} \rho^k p_T^\ell \quad \rho = \log(m_{SD}^2 / p_T^2)$$

Order of polynomial determined with Fisher F-Test

AK8 jets
 $k \leq 2$
 $\ell \leq 1$

CA15 jets
 $k \leq 5$
 $\ell \leq 1$

Boosted spin-0 mediator → bb: Jet algorithms

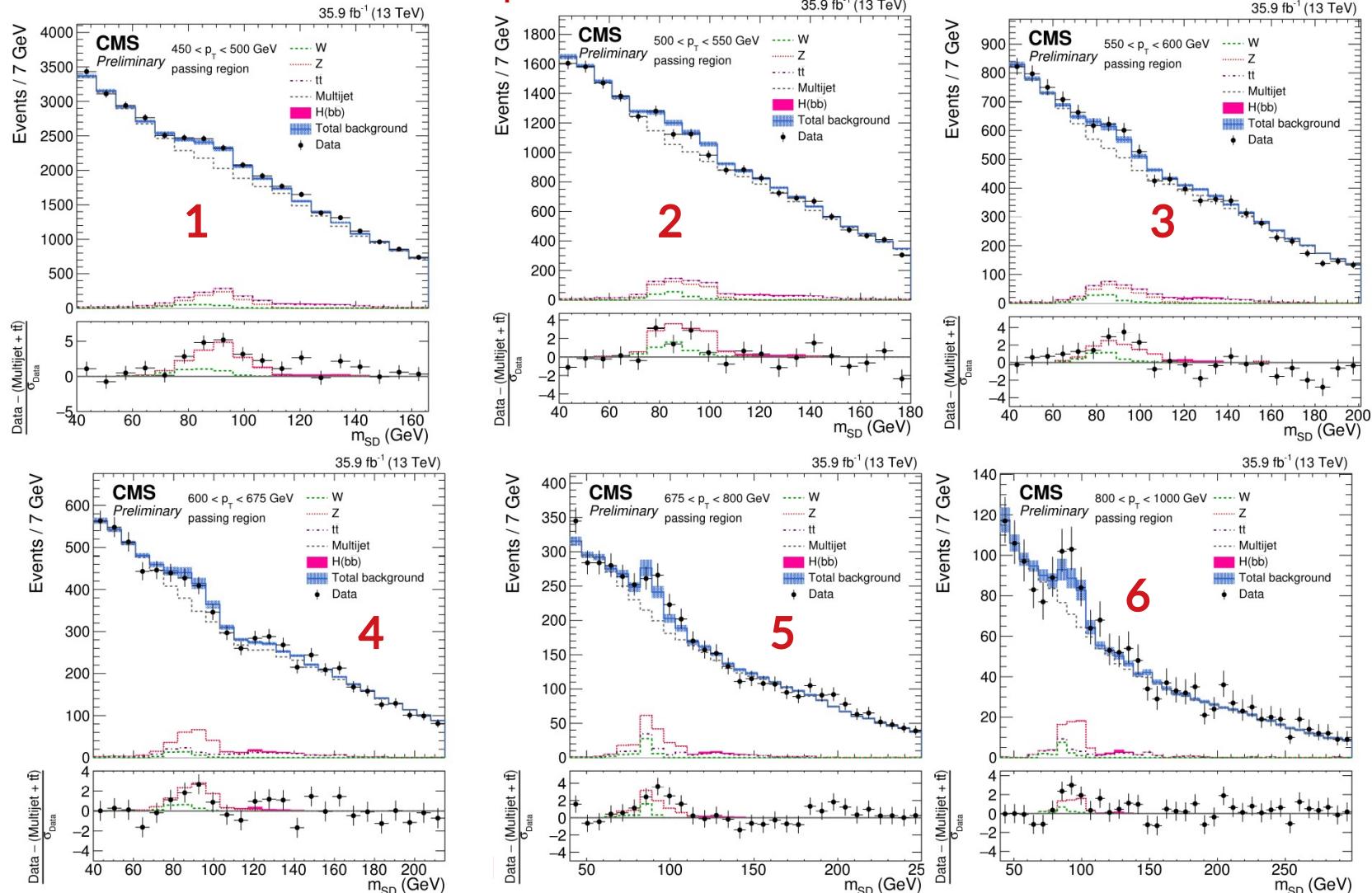


Boosted spin-0 mediator \rightarrow bb: p_T Categories, AK8

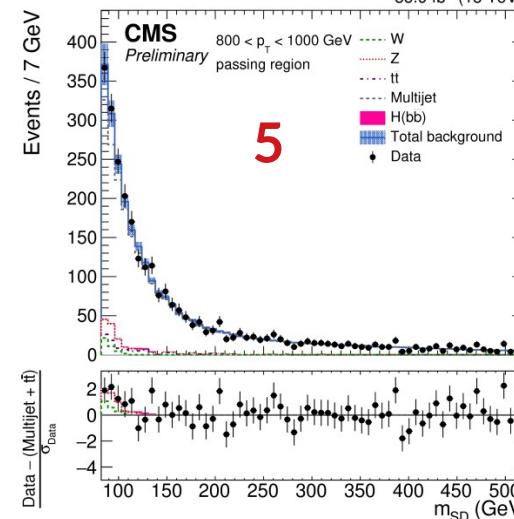
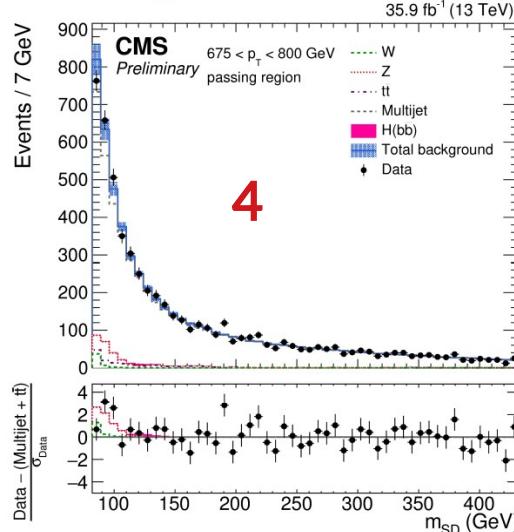
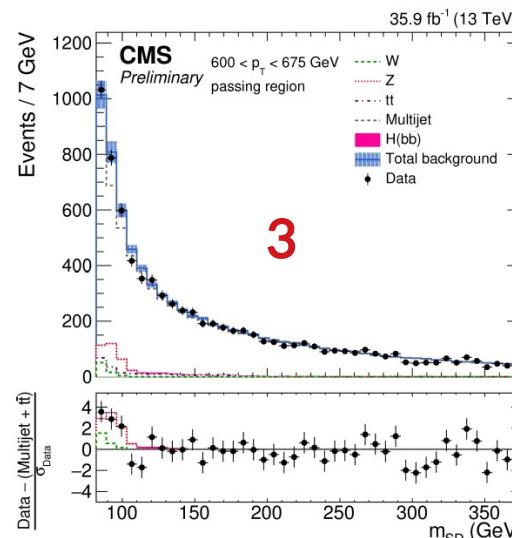
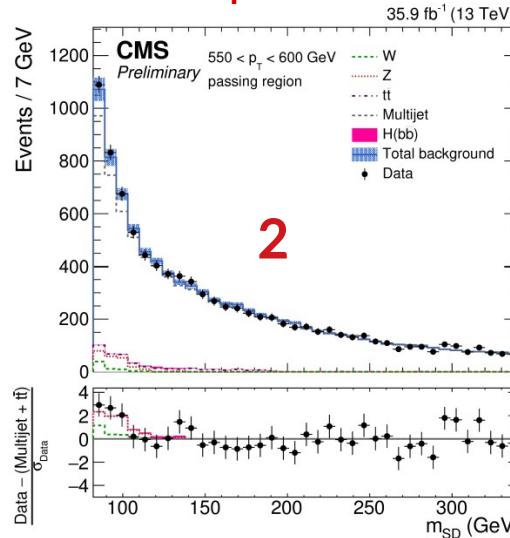
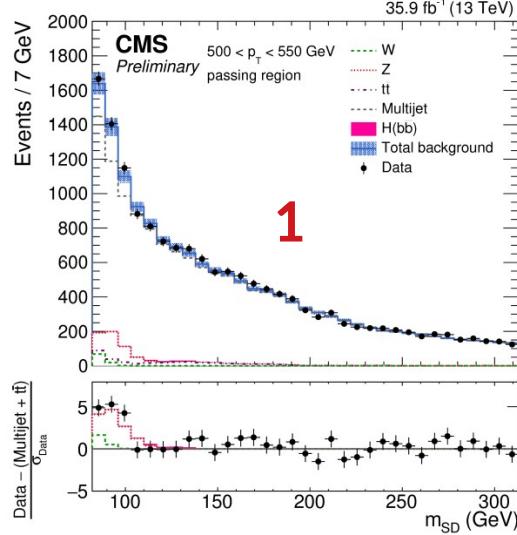
$$\rho = \log(m_{SD}^2 / p_T^2)$$

$$-6.0 < \rho < -2.1$$

04/07/18



Boosted spin-0 mediator → bb: p_T Categories, CA15



$$\rho = \log(m_{SD}^2 / p_T^2)$$

$$-4.7 < \rho < -1.0$$

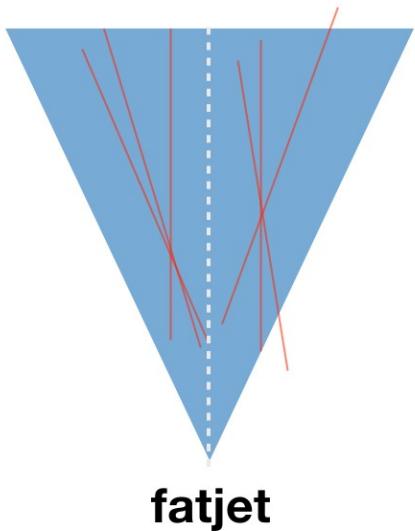
04/07/18

t - DM @ CMS

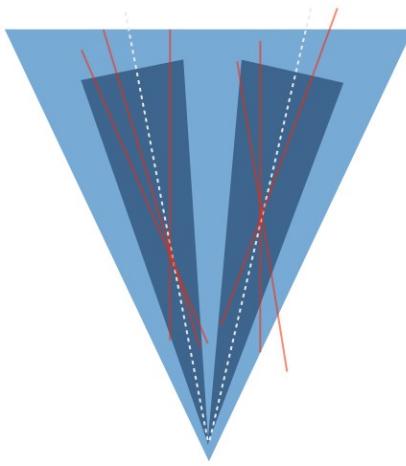
45

Boosted spin-0 mediator search: Double B Tagging

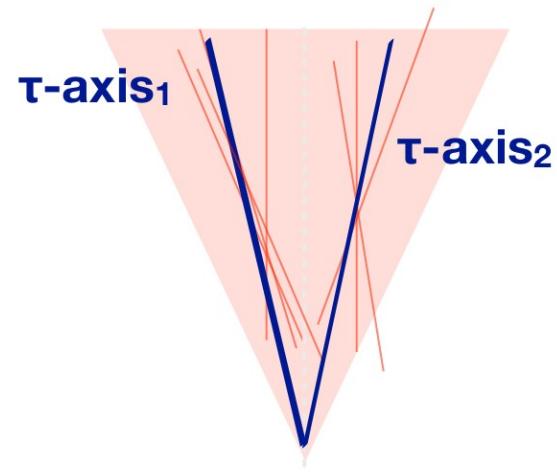
Not the same as subjet b tagging!



fatjet



subjets



double-b

CMS-BTV-15-002

Backup: Mono-H(bb)

Mono-H(bb): Region definition

Common preselection applied to all regions:

- exactly 1 CA15 jet
 - $pT > 200 \text{ GeV}$
 - $100 < mSD < 150 \text{ GeV}$
- $\text{MET} / U > 200 \text{ GeV}$
- $\Delta\phi(\text{jets}, \text{MET}) > 0.4$
- $< 2 \text{ AK4 jets w/o overlap with CA15 jet}$

Additional lepton, b jet multiplicites define regions:

Region	Main background process	Additional AK4 b tag	Leptons	Double-b tag
Signal	Z+jets, $t\bar{t}$, W+jets	0	0	pass
Single-lepton, b-tagged	$t\bar{t}$, W+jets	1	1	pass/fail
Single-lepton, anti-b-tagged	W+jets, $t\bar{t}$	0	1	pass/fail
Dilepton	Z+jets	0	2	pass/fail

Separate control regions for events failing double b tagger

Backup: DM from leptoquark decay

DM from leptoquark decay: Model

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The Coannihilation Codex

Michael J. Baker, Joachim Brod, Sonia El Hedri, Anna Kaminska, Joachim Kopp,
Jia Liu, Andrea Thamm, Maikel de Vries, Xiao-Ping Wang, Felix Yu, José Zurita*

PRISMA Cluster of Excellence & Mainz Institute for Theoretical Physics, Johannes Gutenberg
University, 55099 Mainz, Germany

Field	$(SU(3), SU(2), U(1))$	Spin assignment
DM	(1, 1, 0)	Majorana fermion
X	(3, 2, 7/3)	Dirac fermion
M_s	(3, 2, 7/3)	Scalar

Table 10. Field content, Standard Model gauge quantum numbers, and spin assignments for the case study ST11.

DM from leptoquark decay: Misc

Definition of transverse mass:

$$M_T = \sqrt{2 p_T^\ell \cdot p_T^{\text{miss}} (1 - \cos[\Delta\phi(\ell, \vec{p}_T^{\text{miss}})])}$$