DARK MATTER SEARCHES IN CMS

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23 August 2014

Kubec 2014 Workshop

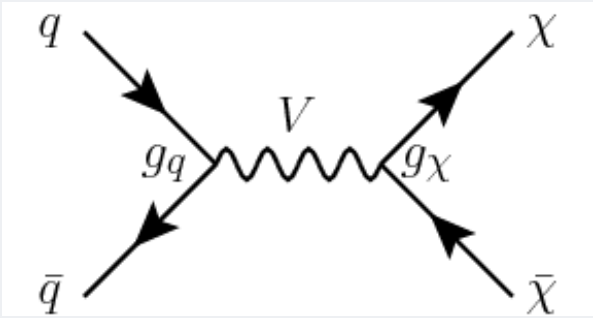
OUTLINE

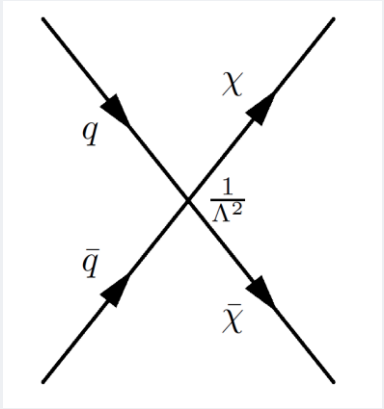
- ✧ DM Models & Signatures in CMS searches
- ✧ Analyzing CMS data
- ✧ MonoJet, MonoLepton, MonoPhoton, MonoTop, Top pairs, Higgs portal
- ✧ Perspectives for LHC Run 2

DM models in CMS searches

✧ Most of the CMS DM searches use **Effective Field Theories** :

⇒ ***MonoJet, MonoLepton, MonoPhoton, Top pair***





$$\Lambda = \frac{M_V}{\sqrt{g_c g_q}}$$

Perturbative
$g_{\chi,q} < 4\pi$

- **Validity** : M_V > Qtr = invariant mass of input partons / output DM
- **Search parameters** : cut-off scale Λ ; DM mass m_χ
- **Operators** : scalar pseudo-scalar γ^5 vector γ^μ axial-vector $\gamma^\mu\gamma^5$
  - probe spin-independent/dependent interactions
- **Translate** to elastic DM-Nucleon cross section:
  μ = reduced mass of the (χ, N) system
  see doi:10.1007/JHEP12(2010)048

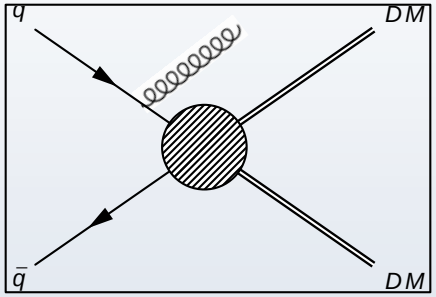
$$\sigma(cN \to cN) \propto \frac{m_\mu^2}{\Lambda^4}$$

Signatures

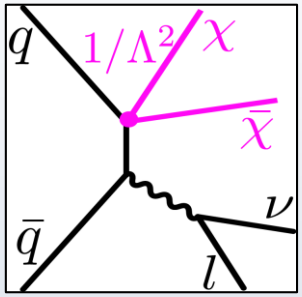
✧ DM weakly interacting ⇒ no detection
⇒ large **transverse momentum imbalance (MET)**

✧ Need particular **topologies** to **tag** the event (trigger+signal extraction)

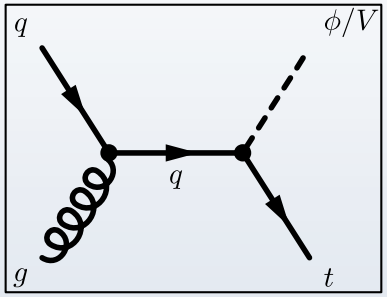
ISR jet/photon

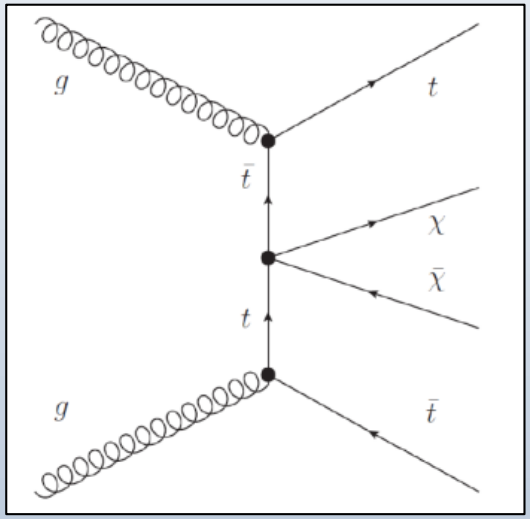


Recoiling W

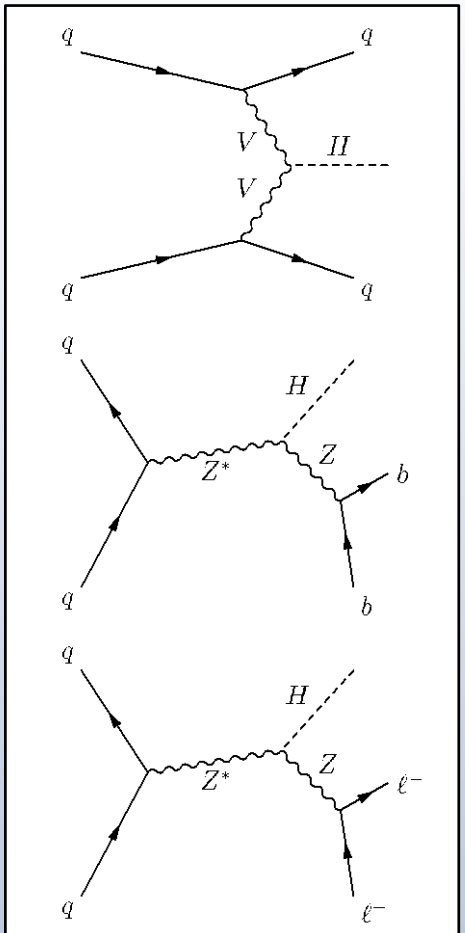


Single top

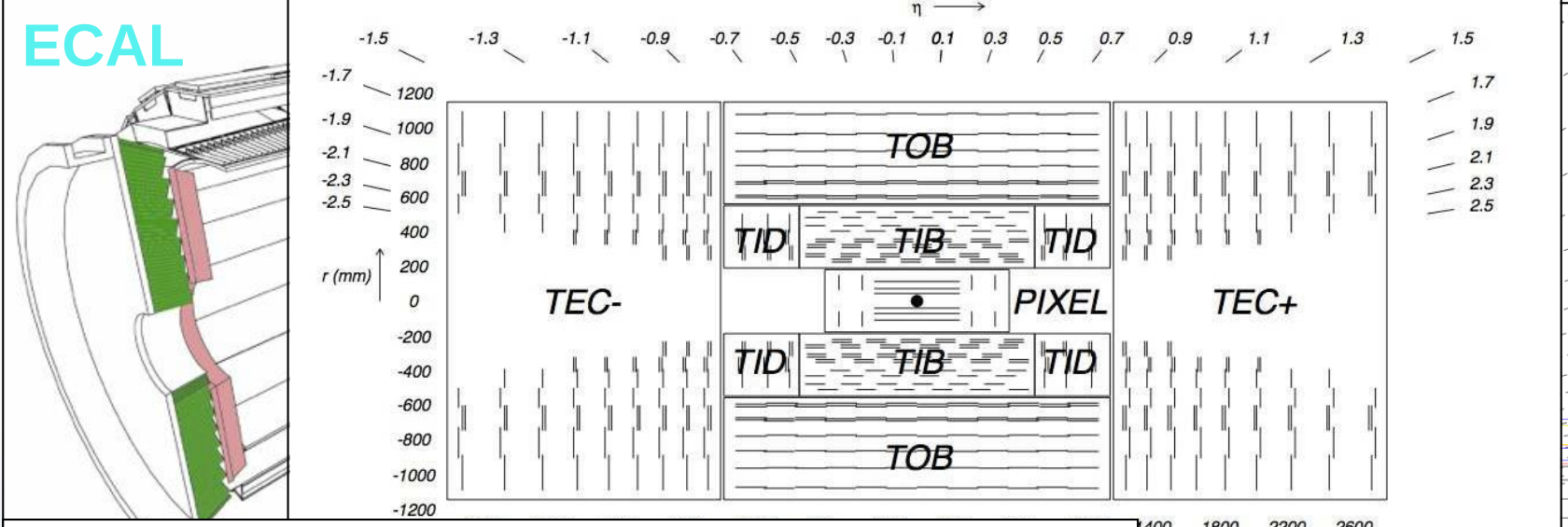


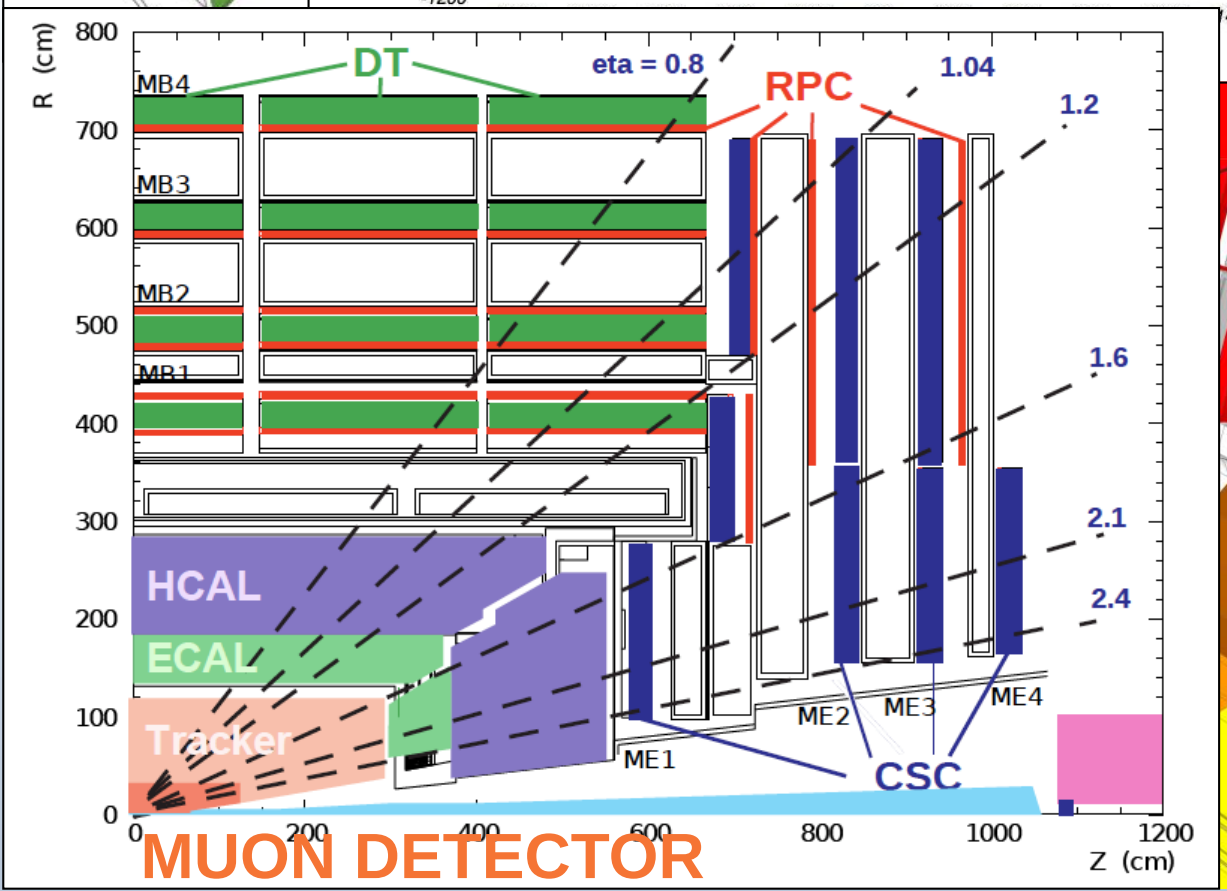


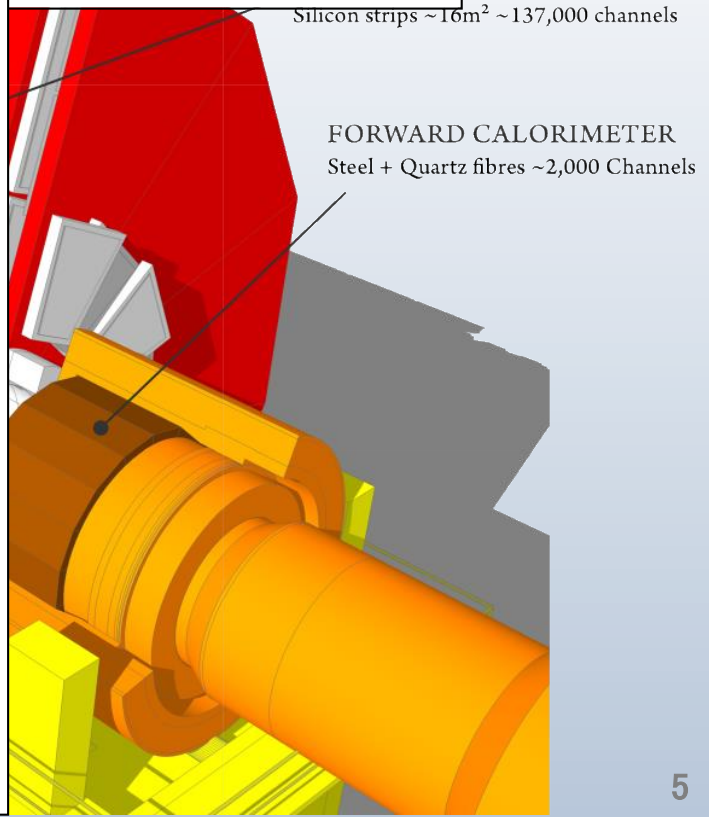
Associated production with Top pair



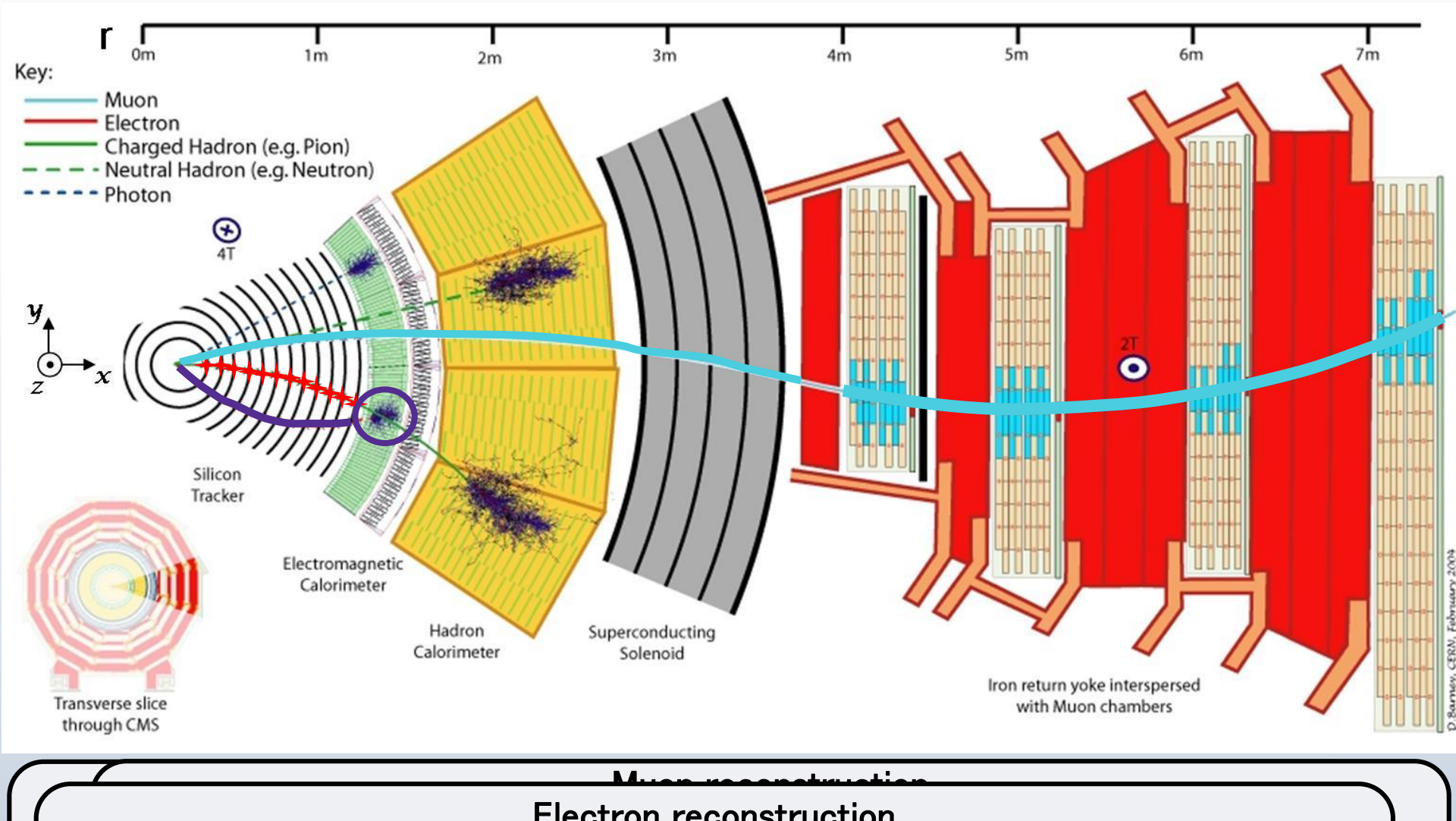
SM Higgs production


ECAL
η
-1.5 -1.3 -1.1 -0.9 -0.7 -0.5 -0.3 -0.1 0.1 0.3 0.5 0.7 0.9 1.1 1.3 1.5
-1.7 -1.9 -2.1 -2.3 -2.5
1.7 1.9 2.1 2.3 2.5
r (mm)
1200 1000 800 600 400 200 0 -200 -400 -600 -800 -1000 -1200
TOB
TID
TIB
TID
TEC-
PIXEL
TEC+
TID
TIB
TID
TOB
400 1800 2200 2600
z (mm)
HCAL
1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3.0
HF


R (cm)
800 700 600 500 400 300 200 100 0
DT
MB4
MB3
MB2
MB1
eta = 0.8
RPC
1.04
1.2
1.6
2.1
2.4
HCAL
ECAL
Tracker
ME1
ME2
ME3
ME4
CSC
0 200 400 600 800 1000 1200
Z (cm)
MUON DETECTOR


Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

Event reconstruction : tracks, e, μ, γ



Muon reconstruction

Electron reconstruction

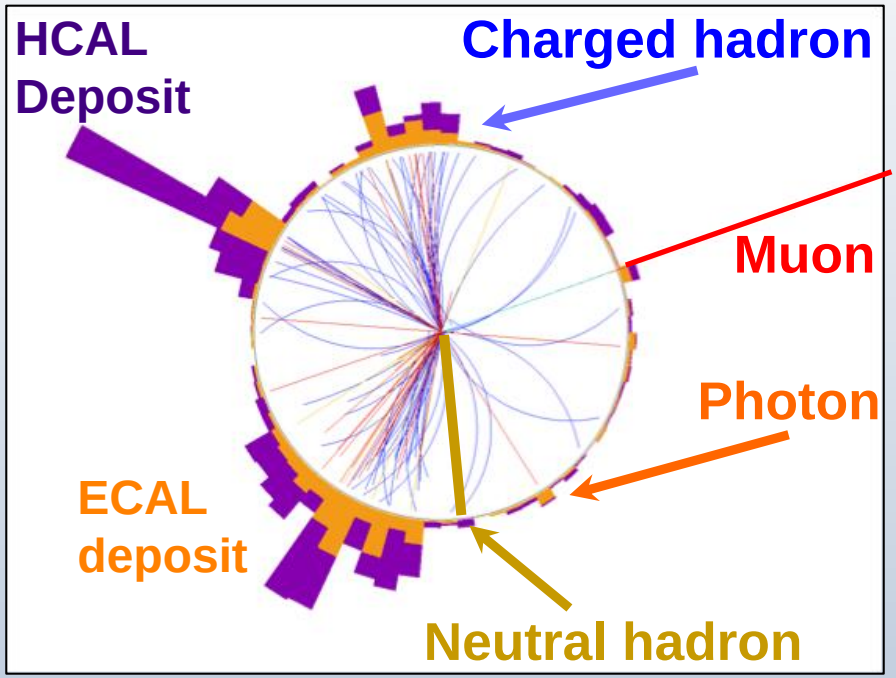
Photon reconstruction

- SuperCluster in ECAL not matched to a track
- ID : single tower H/E, SC shape, charged/neutral had & photon isolation

The Particle Flow algorithm

Reconstructs individual particles

- tracker : excellent resolution, esp. at low momentum
- ECAL : excellent resolution, esp. at high energy + position measurement
- HCAL : hadron identification and position
- muon detector : excellent resolution, esp. at high momentum



- ✧ Build input elements
  - clusters of ECAL crystals
  - clusters of HCAL towers
  - tracks in the tracker
  - standalone muons
- ✧ Match elements by pairs

  ⇒ geometrical compatibility

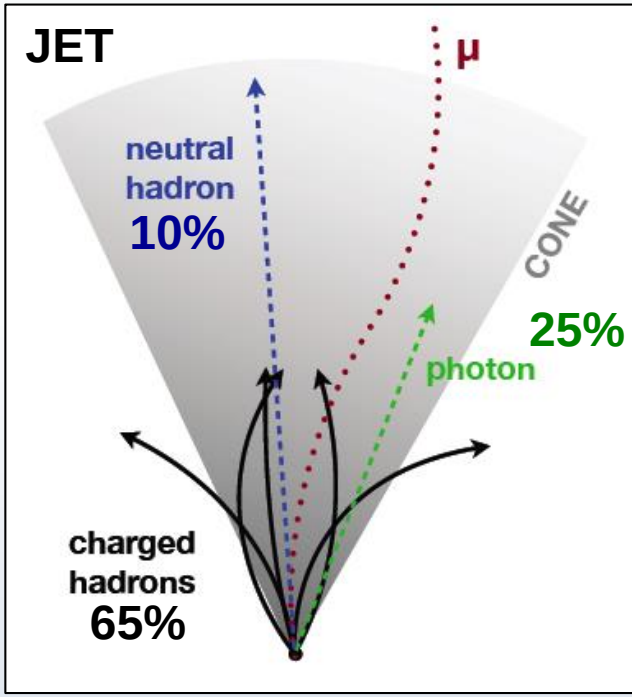
PF Jets, MET, Isolation

✧ Jet reco : PF particles □anti-kT
+ PU $h^{\pm,0}$ + energy corrections (detector effects)

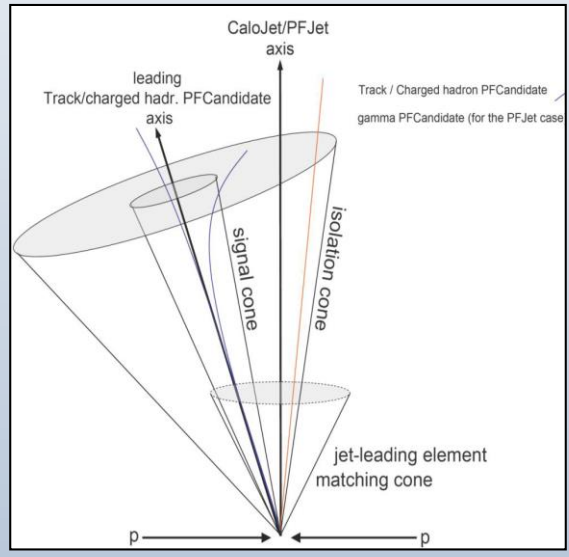
✧ Jet ID : charged/neutral em/had components
+ PU ID : BDT(components pT, position, multiplicities, PV)

✧ τ_h : reconstructs hadronic tau decay modes

✧ b : Likelihood(tracks impact parameters, 2nd vertices)



✧ MET : $\vec{p}_T^{\,M} = -\sum_{\text{PFparticles i}} \vec{p}_T^{\,i}$



✧ Isolation : process all PF particles btw 2 cones

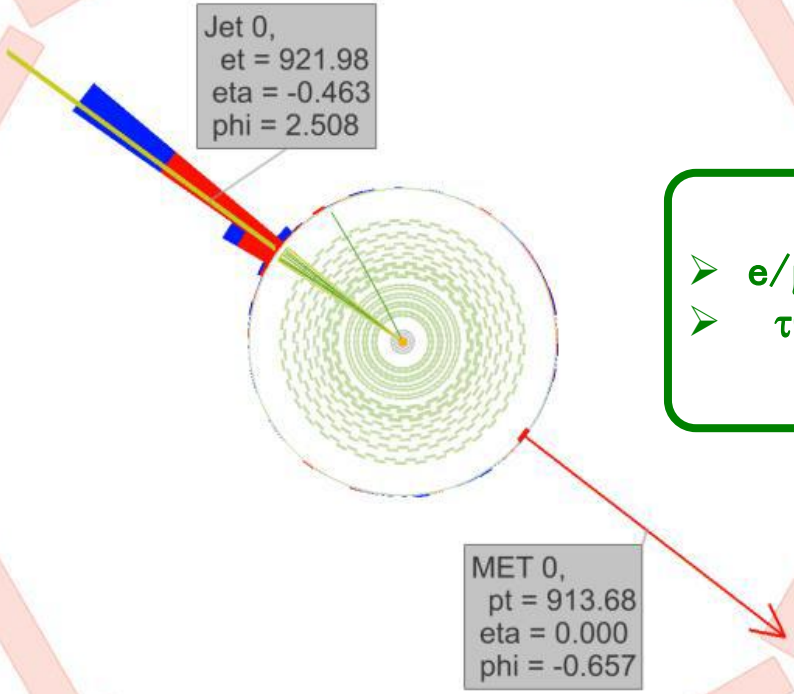
$$R_{\text{Iso}}^{\ell} \equiv \left(\sum_{\text{charged}} p_{\text{T}} + \text{MAX}\left[0, \sum_{\text{neutral}} p_{\text{T}} + \sum_{\gamma} p_{\text{T}} - 0.5 \sum_{\text{charged,PU}} p_{\text{T}} \right] \right) / p_{\text{T}}^{\ell}$$

CHARGED + NEUTRAL - NEUTRAL PU

MonoJet : event selection

- Jet $p_T>110$ $|\eta|<2.4$
- p_T fractions : ch. had. ≥ 20% neutr. had. ≤ 70% photons ≤ 70%
- Accept 2nd jet ($p_T>30$ $|\eta|<4.5$ $\Delta\phi_{J1J2}<2.5$)
- Veto 3rd jet (p_T, h)

Kill QCD, ttbar



Lepton veto :

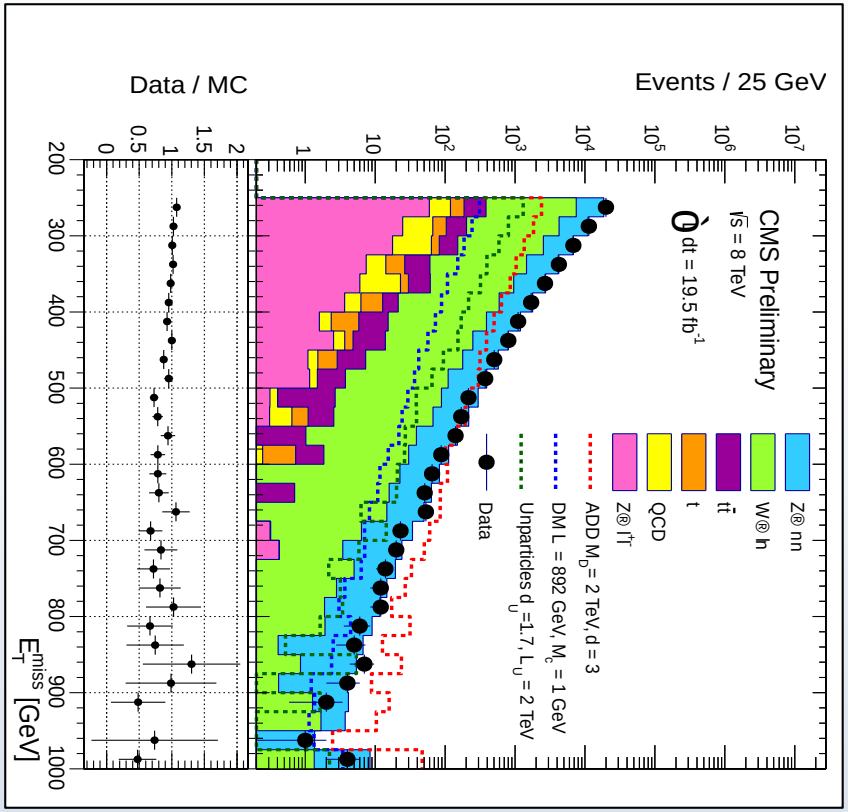
- e/μ($p_T>10$ $R_{iso}<0.2$)
- τ($p_T>20$ $|\eta|<2.3$)

Kill V, VV, top

- MET ≡ MET without μ
- 7 MET Regions : MET > {250, 300, 350, 400, 450, 500, 550} GeV

Ref : CMS-PAS-EXO-12-048

MonoJet : signal extraction



Single-bin counting after optimal MET cut

$$Z(\nu\nu) = \frac{Z(\mu\mu)^{Sgn}_{Data} - Bkg^{Sgn}_{MC}}{A_{MC} \times \epsilon_{MC} \times SF^{Data}_{MC}} \times \frac{BR(Z \to \nu\nu)}{BR(Z \to \mu\mu)}$$

$$W(\mu\nu) = \frac{W(\mu\nu)_{Data} - Bkg_{MC}}{A^{\mu}_{MC} \cdot \epsilon^{\mu}_{MC} \cdot SF^{\mu}} \cdot \left(1 - A^{\mu}_{MC} \cdot \epsilon^{\mu}_{MC} \cdot SF^{\mu}\right)$$

$$W(e\nu) = W(\mu\nu) \cdot \frac{W(e\nu)_{MC}}{W(\mu\nu)_{MC}} \cdot \frac{1 - A^{e}_{MC} \cdot \epsilon^{e}_{MC} \cdot SF^{e}}{1 - A^{\mu}_{MC} \cdot \epsilon^{\mu}_{MC} \cdot SF^{\mu}}$$

$$QCD = QCD^{Sgn}_{MC} \times \frac{QCD^{Ctrl}_{Data}}{QCD^{Ctrl}_{MC}}, \text{Ctrl}=\{\text{relax } N_J ; \Delta f_{J1J2} < 0.3\}$$

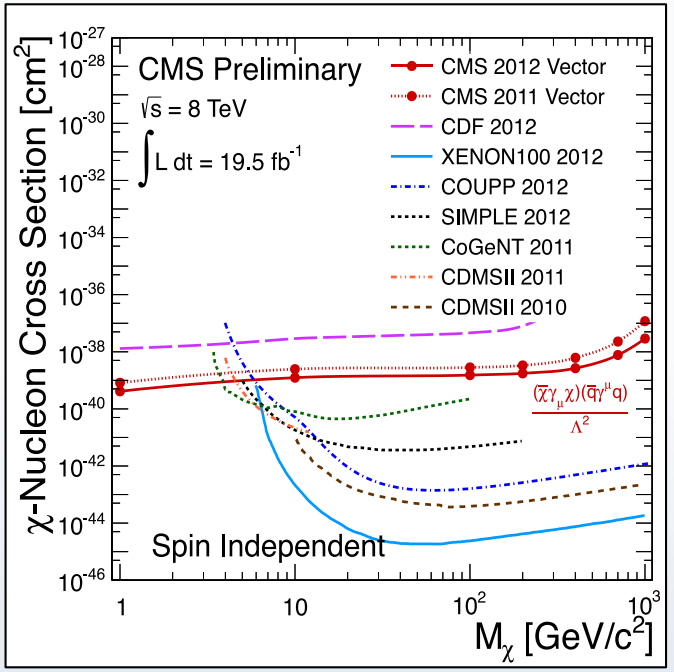
E_T^{miss} (GeV) →	> 250	> 300	> 350	> 400	> 450	> 500	> 550
$Z(\nu\nu)$+jets	30600 ± 1493	12119 ± 640	5286 ± 323	2569 ± 188	1394 ± 127	671 ± 81	370 ± 58
W+jets	17625 ± 681	6042 ± 236	2457 ± 102	1044 ± 51	516 ± 31	269 ± 20	128 ± 13
$t\bar{t}$	470 ± 235	175 ± 87.5	72 ± 36	32 ± 16	13 ± 6.5	6 ± 3.0	3 ± 1.5
$Z(\ell\ell)$+jets	127 ± 63.5	43 ± 21.5	18 ± 9.0	8 ± 4.0	4 ± 2.0	2 ± 1.0	1 ± 0.5
Single t	156 ± 78.0	52 ± 26.0	20 ± 10.0	7 ± 3.5	2 ± 1.0	1 ± 0.5	0 ± 0
QCD Multijets	177 ±88.5	76 ±38.0	23 ±11.5	3 ±1.5	2 ±1.0	1 ± 0.5	0 ± 0
Total SM	49154 ± 1663	18506 ± 690	7875 ± 341	3663 ± 196	1931 ± 131	949 ± 83	501 ± 59
Data	50419	19108	8056	3677	1772	894	508
Exp. upper limit	3580	1500	773	424	229	165	125
Obs. upper limit	4695	2035	882	434	157	135	131

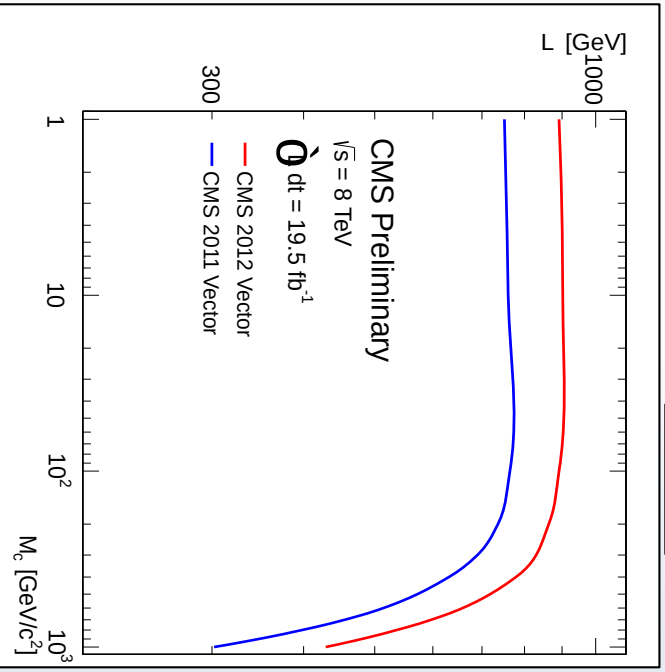
MonoJet : results

Vector coupling

Spin-independent interaction

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

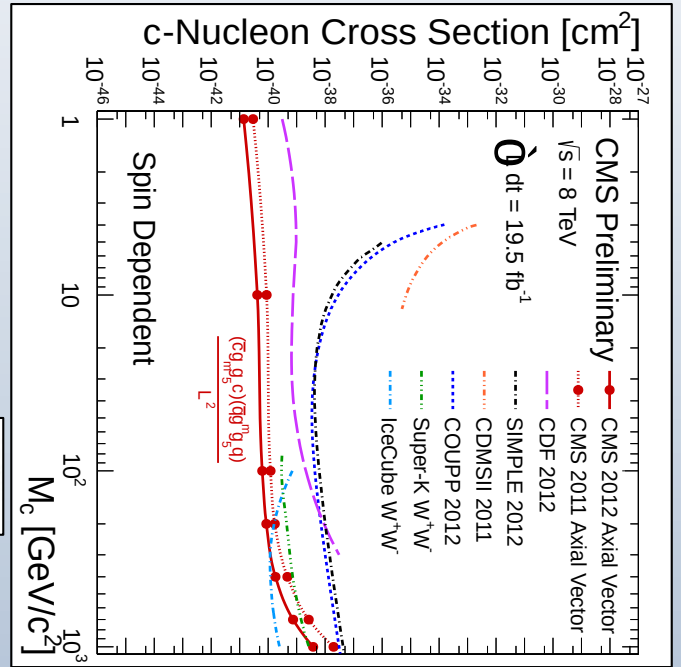


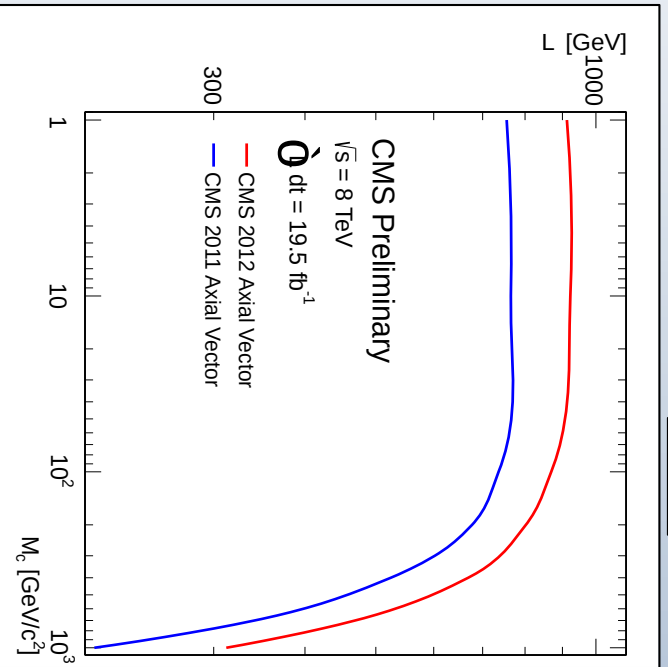


Axial-Vector coupling

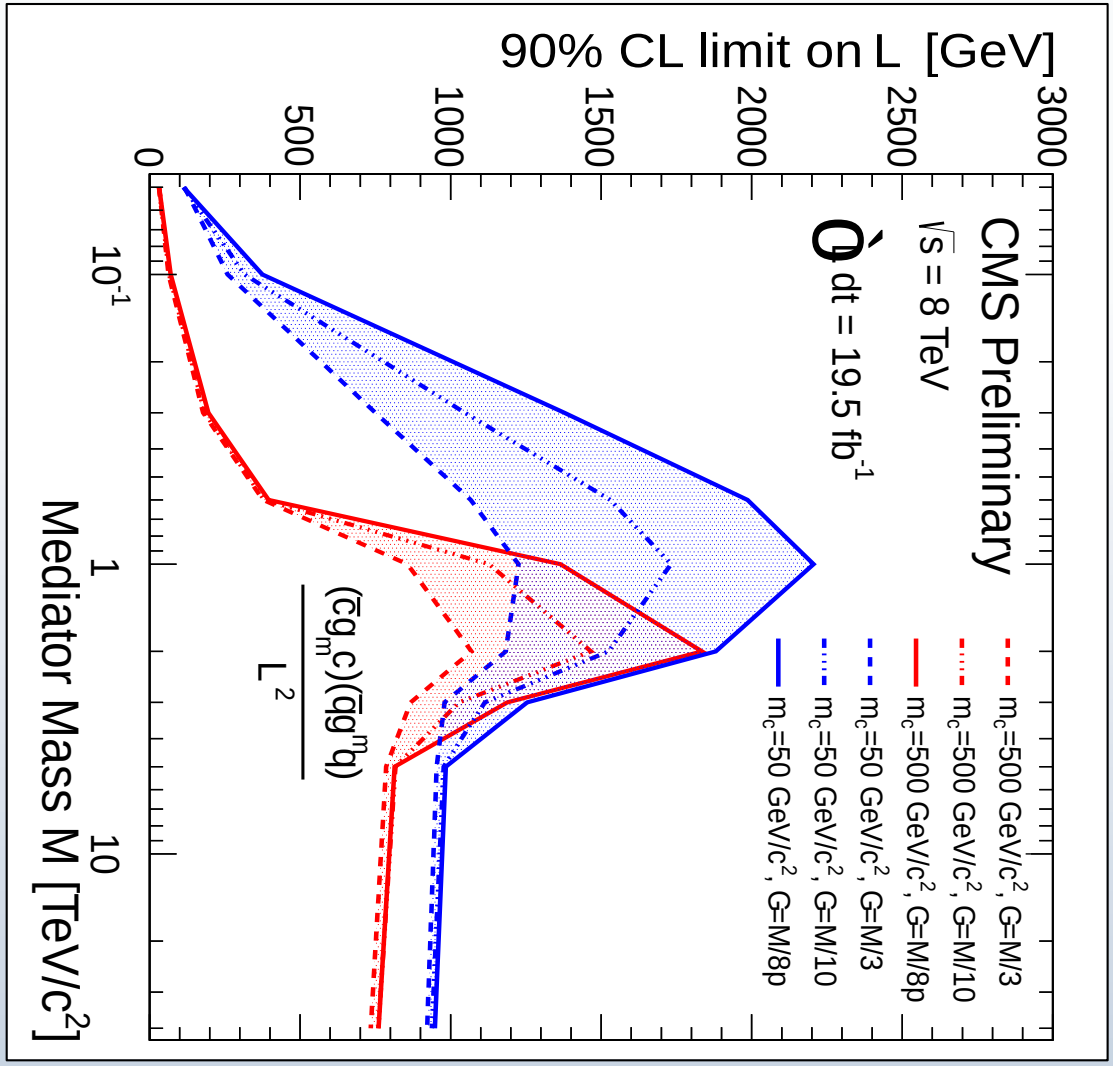
Spin-dependent interaction

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$





MonoJet : mediator mass scan



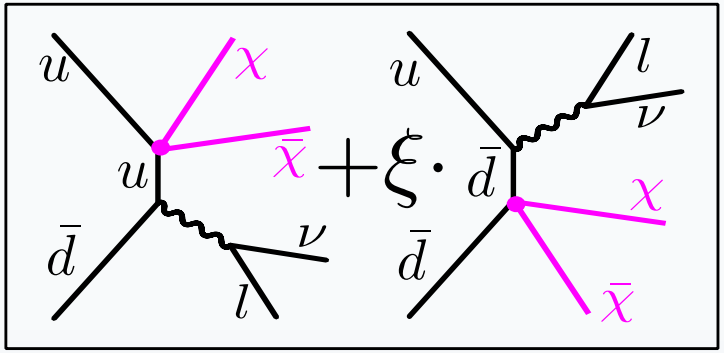
Light mediator
- can be produced @ LHC
- resonant behaviour

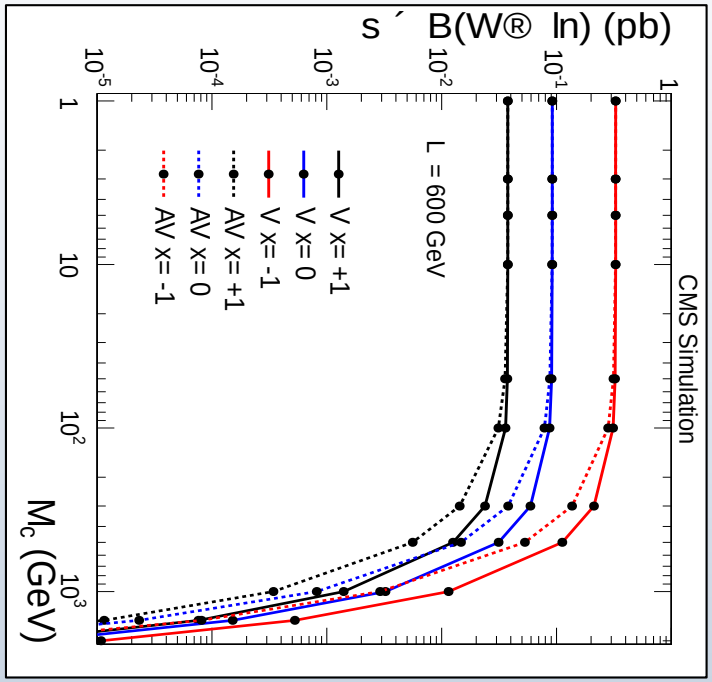
Vector interactions

LOWER LIMIT ON THE INTERACTION SCALE

MonoLepton

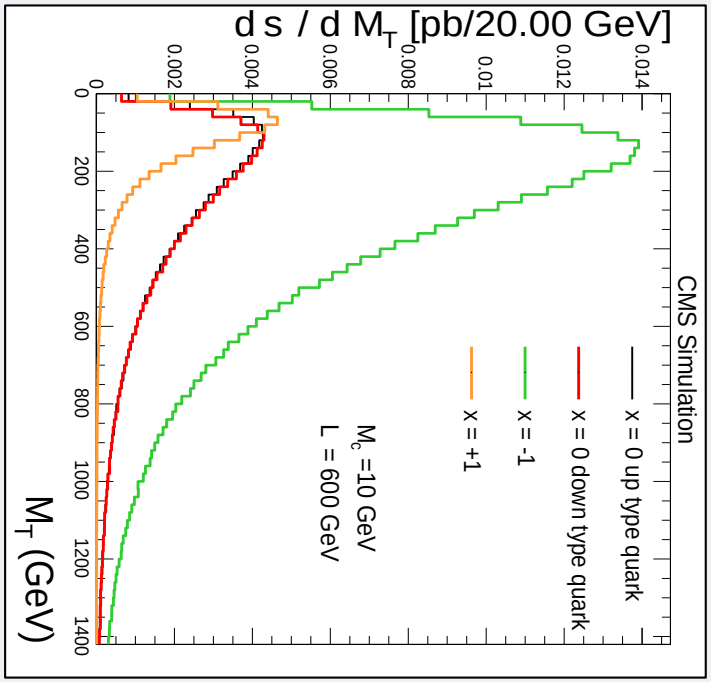
- Advantages : clean leptonic signature
  - less background @ LHC
  - easier to trigger than mono-jet/photon
- Interferences sensitive to different couplings for Up/Down type quarks





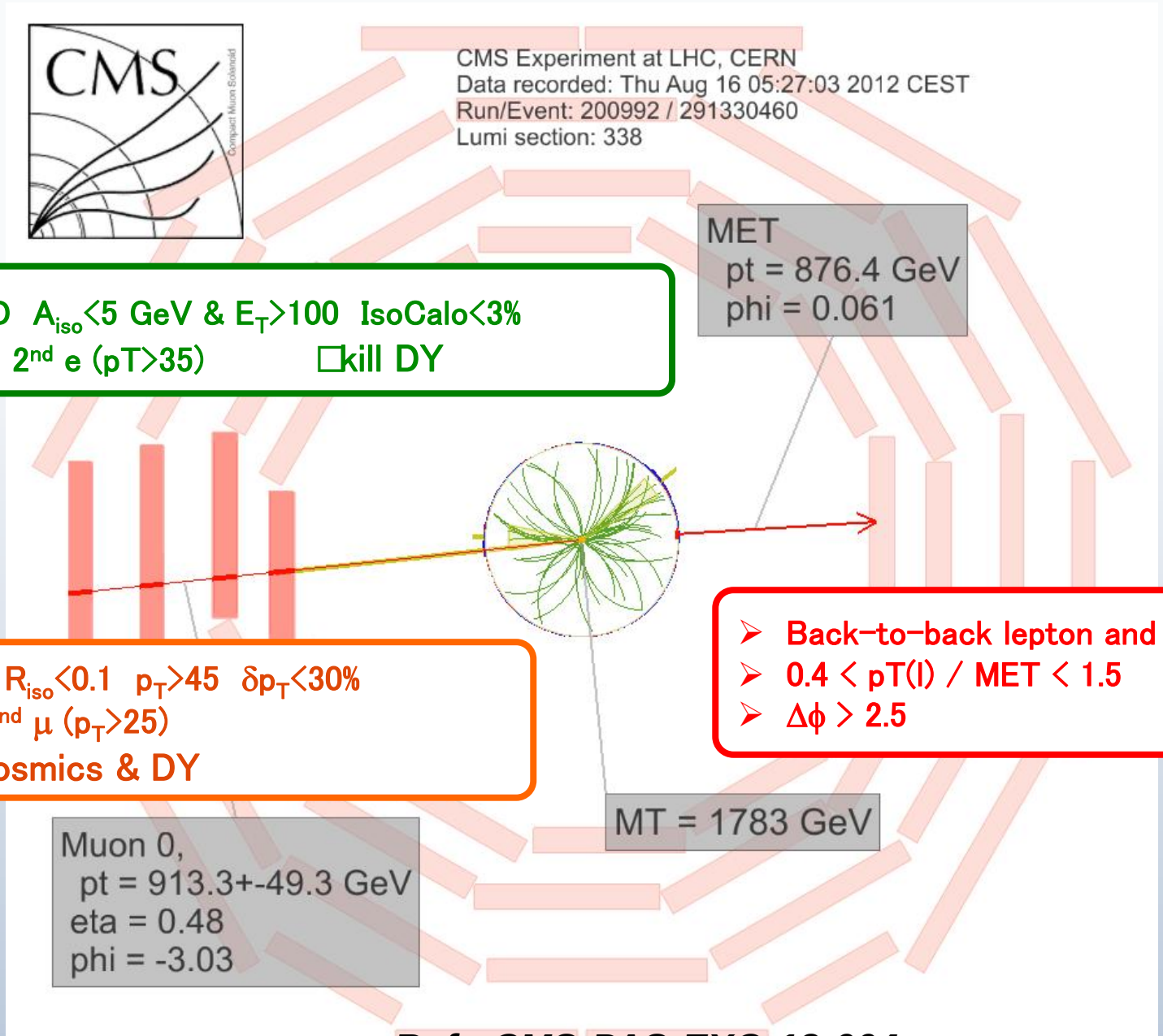
- Largest σ for ξ=−1
- Mχ > 100 GeV steep drop
- "edge" depends on ξ.

Master variable → transverse mass m_T



- Shape m_T depends on ξ !

MonoLepton : event selection



- e : ID A_{iso}<5 GeV & E_T>100 IsoCalo<3%
- Veto 2nd e (pT>35) ☐kill DY

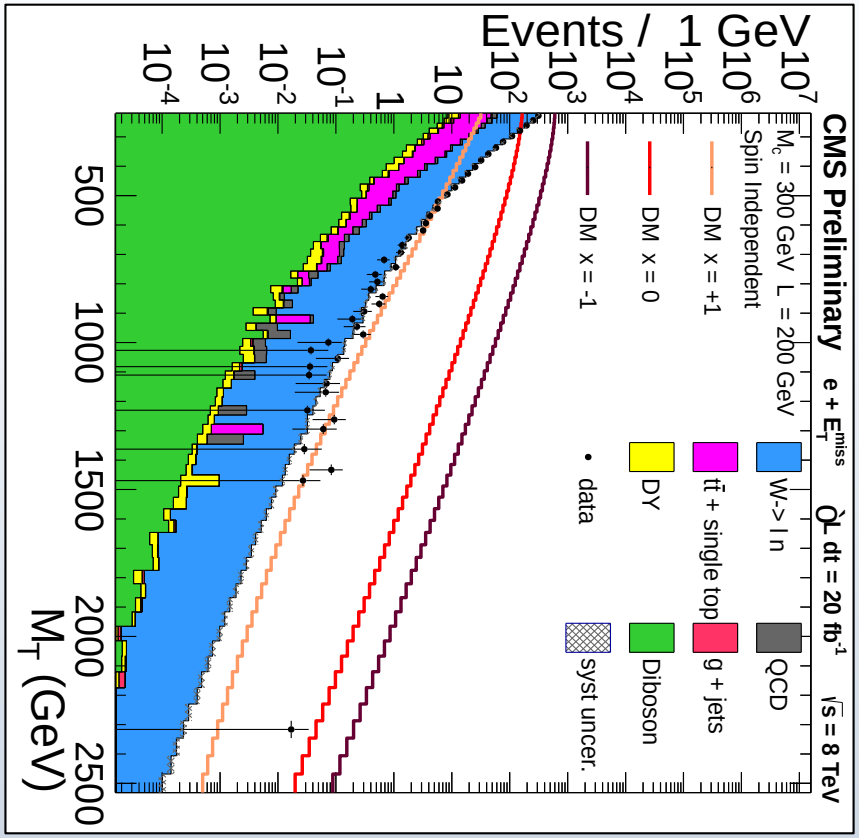
- μ : ID R_{iso}<0.1 p_T>45 δp_T<30%
- Veto 2nd μ (p_T>25)

☐kill cosmics & DY

- Back-to-back lepton and MET
- 0.4 < pT(l) / MET < 1.5
- Δϕ > 2.5

Ref : CMS-PAS-EXO-13-004

MonoLepton : signal extraction



m_T shape analysis : multi-bin counting

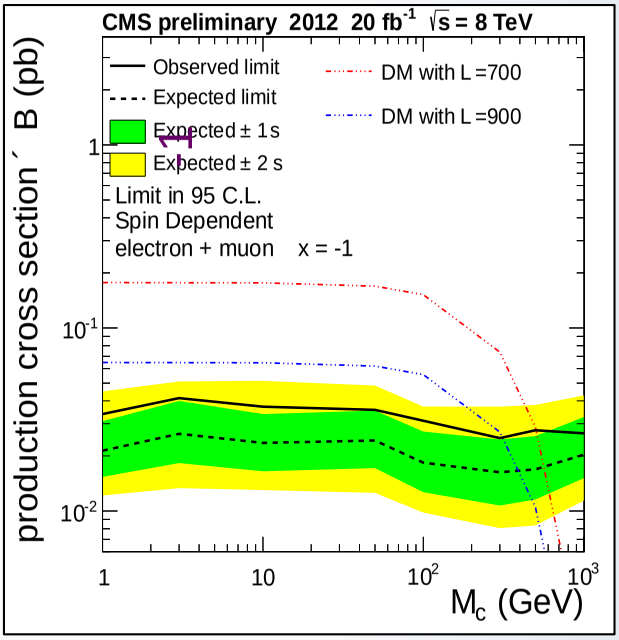
Major backgrounds = MC x SF from data

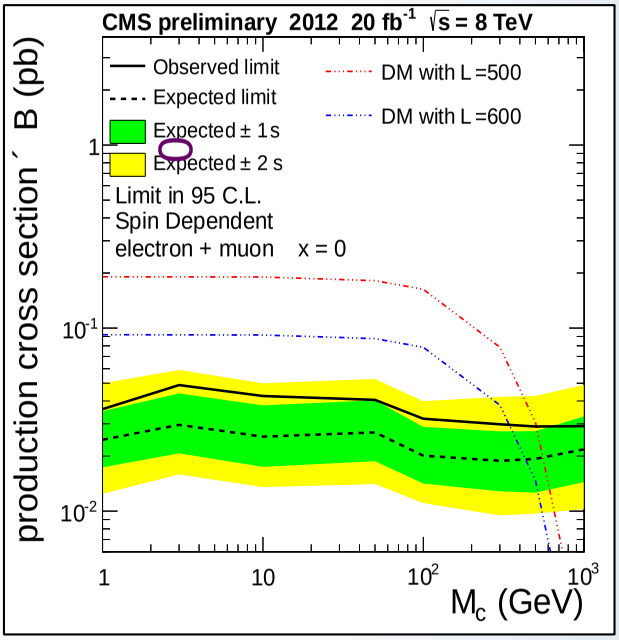
High m_T tail fit: $f(m_T) = e^{a+bm_T+cm_T^2} \cdot m_T^d$

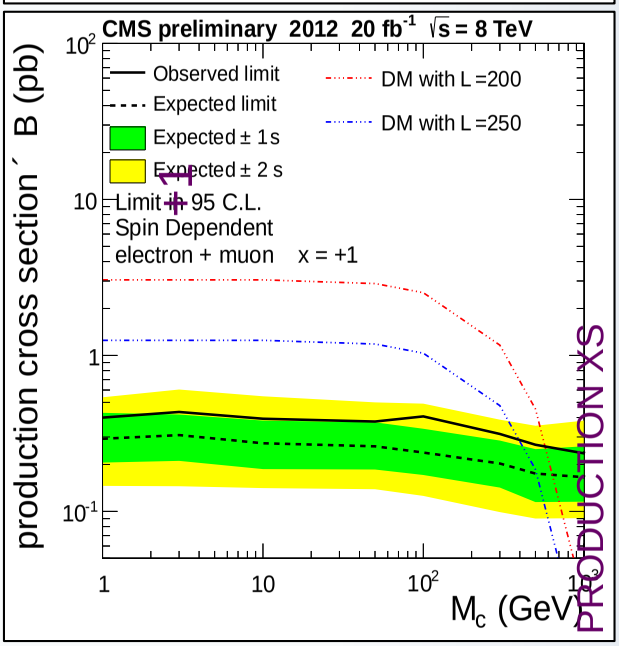
$$QCD = Data^{Sgn}_{\text{e fails iso}} \cdot \frac{r_{ttl}}{1 - r_{ttl}}, \; r_{ttl}(E_T^e, h^e) = \frac{Data^{Ctrl}_{\text{e pass iso}}}{Data^{Ctrl}}$$

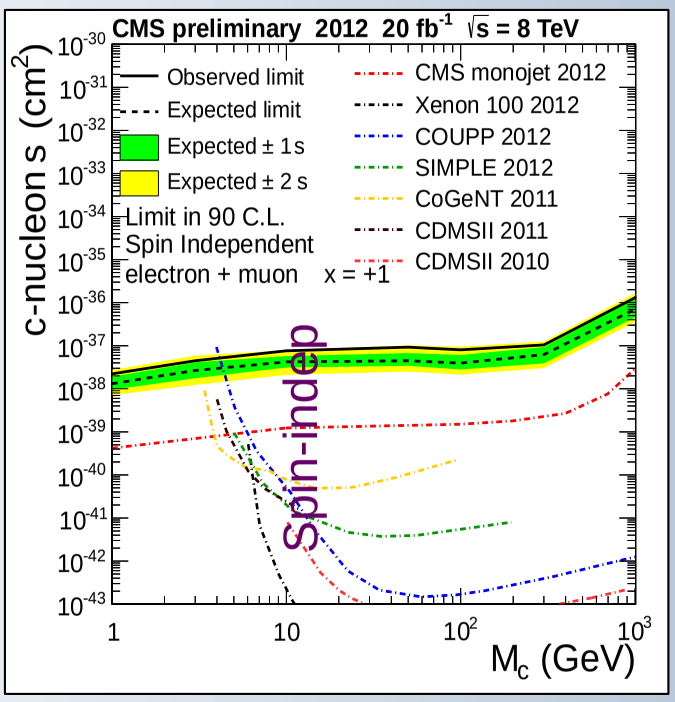
$$\text{Ctrl} = \{1.5 < \frac{E_T^e}{MET} < 10\}$$

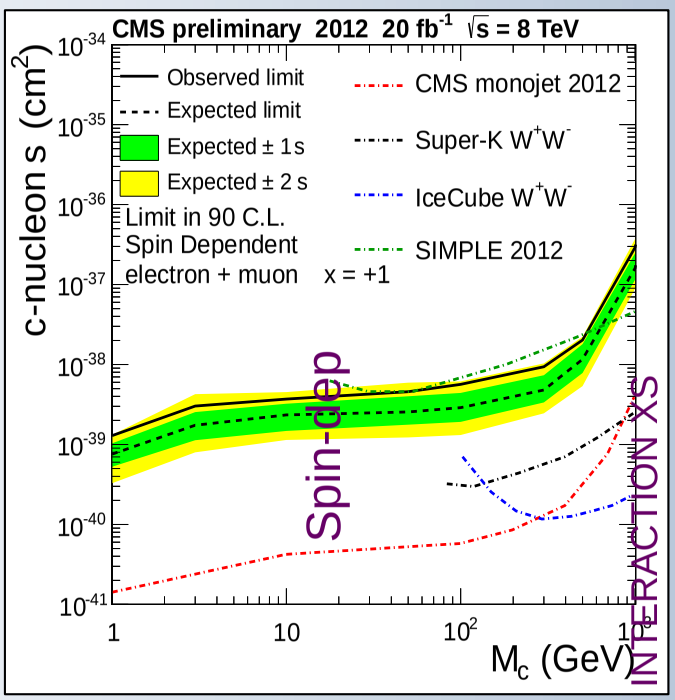
MonoLepton : results (e+μ)





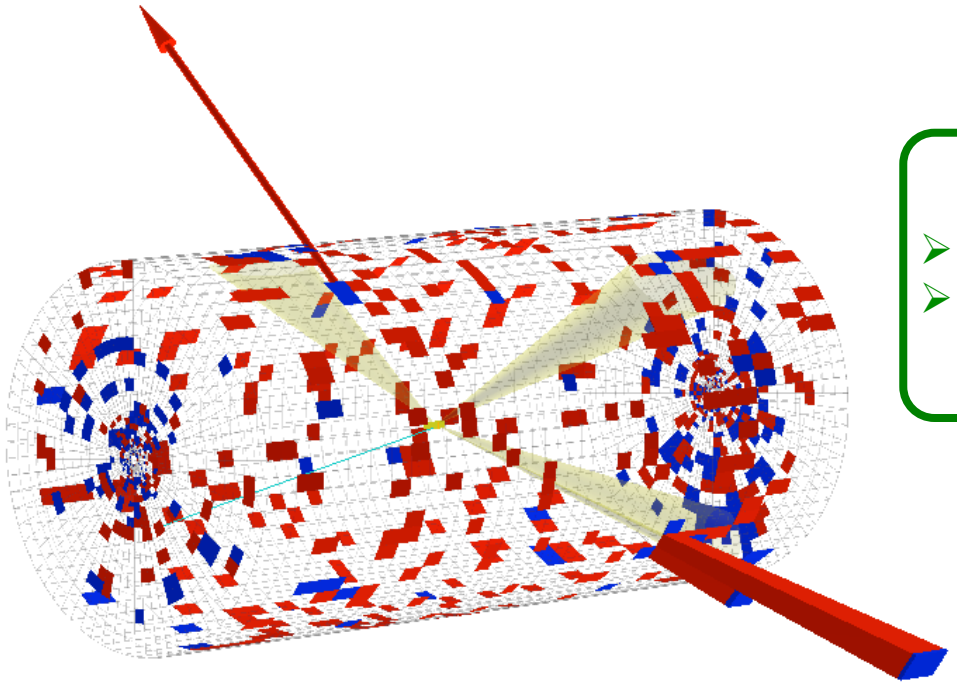






MonoPhoton : event selection

- MET > 140 — Kill γ+jet
- Δφ(MET, γ) > 2.0
- "MET ID" : χ^2 fit using unclustered energy
  - remove fake MET



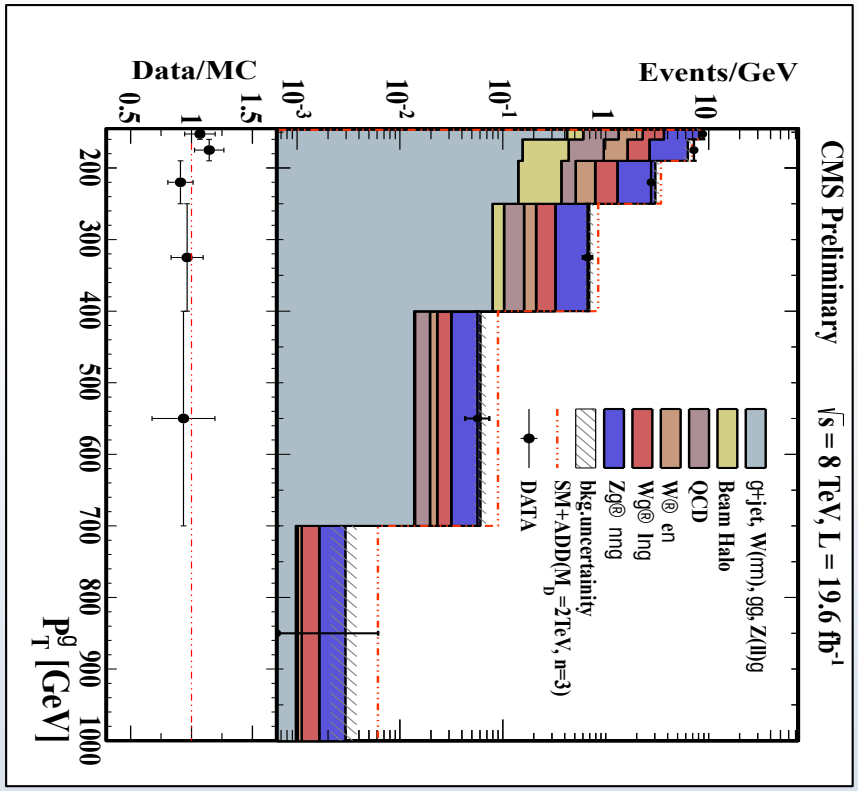
Lepton veto :
- ≥1 isolated lepton
- R_{iso} < 0.2 (e) / 0.1 (μ)

Kill W(lν)+γ

Photon
- E_T > 145 GeV — |η|<1.44 (purity)
- ID : H/E < 0.05 — ECAL cluster shape
- Anomalous signals removal, timing cut (BX±3ns)
- PF isolation : surrounding $h^{\pm,0}$ and photons
- Fake photons from electrons removed

Ref : CMS-PAS-EXO-12-047

MonoPhoton : signal extraction



Single-bin counting after $p_T(\gamma)$ cut

Major backgrounds = MC x SF from data

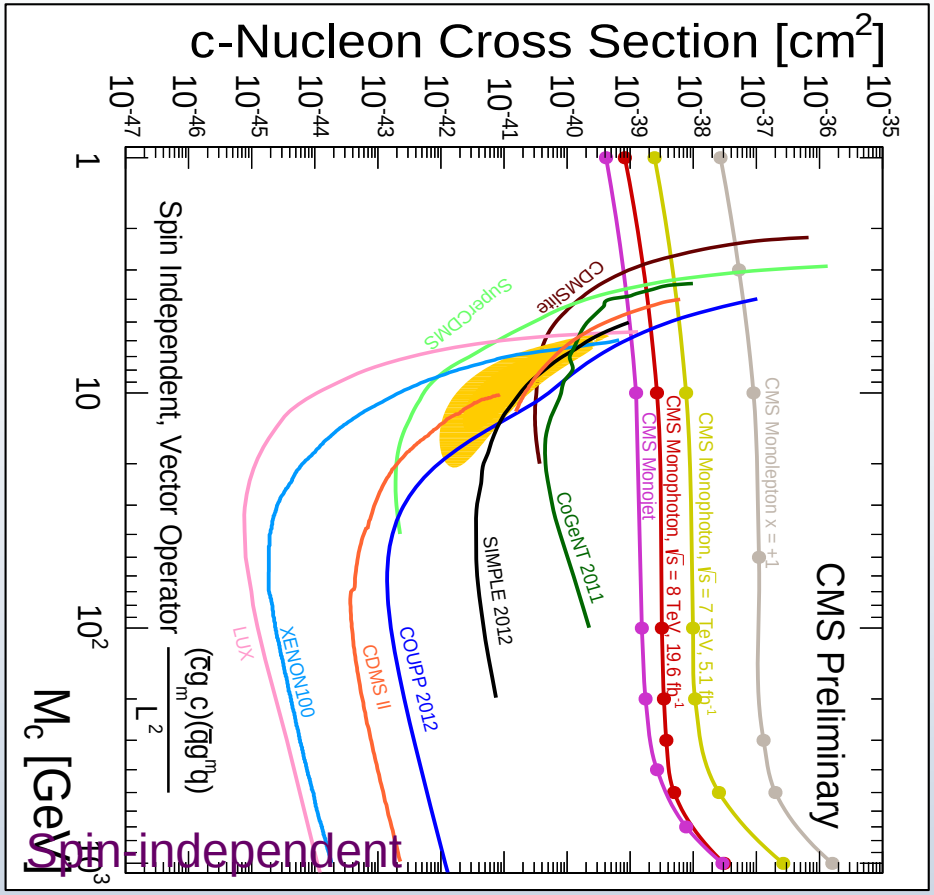
Beam halo □timing distribution in data

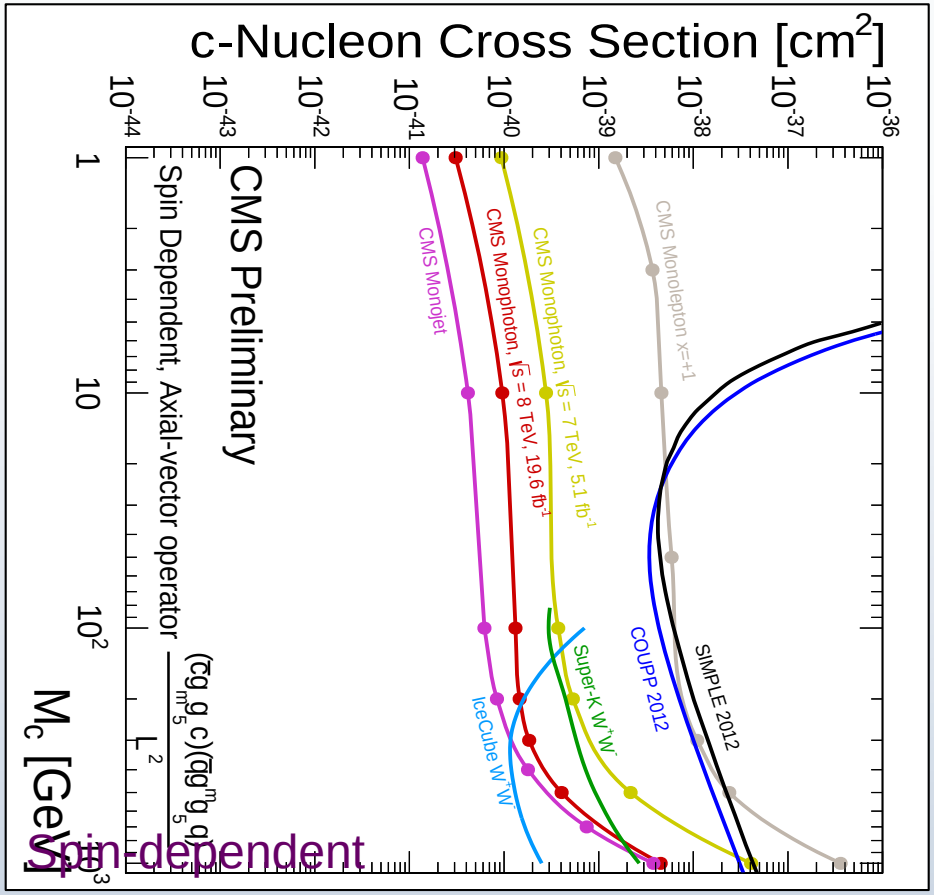
$$W(e\nu) = Data(\text{Sgn, PIX matching}) \times \frac{1 - \epsilon_{\text{Data}}^{\text{Match PIX}}}{\epsilon_{\text{Data}}^{\text{Match PIX}}}$$

$$QCD = Data^{Sgn,\gamma \text{ fails iso}} \times \frac{QCD_{Data}^{jet \text{ pass } \gamma \text{ ID}} - QCD_{MC}^{\text{real } \gamma}}{QCD_{Data}^{jet \text{ fail} \geq 1 \text{ iso cut}}}$$

Process	Estimate
$Z(\to \nu\bar{\nu}) + \gamma$	344.8 ± 42.5
$W(\to \ell\nu) + \gamma$	102.5 ± 20.6
$W \to e\nu$	59.5 ± 5.5
jet $\to \gamma$ fakes	45.4 ± 13.9
Beam halo	24.7 ± 6.2
Others	35.7 ± 3.1
Total background	612.6 ± 63.0
Data	630.0

MonoPhoton : results





MonoLepton (+1)
MonoPhoton 7 TeV
MonoPhoton 8 TeV
MonoJet 8 TeV

Top Pairs & MonoTop

➢ Top pairs

✧ Heavy quarks enhance sensitivity to scalar interactions

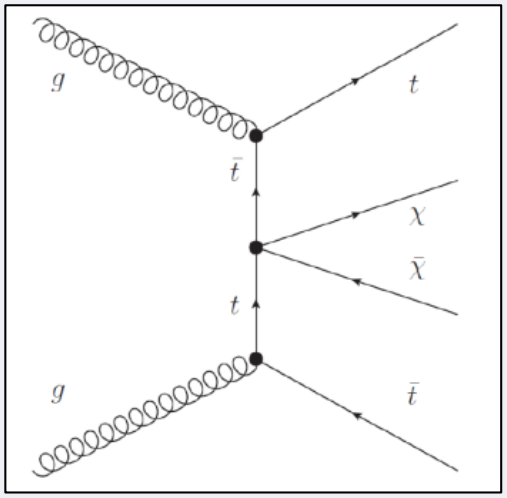
$$L_{\text{int}} = \frac{m_q}{\Lambda^3} q\bar{q}\, c\bar{c}$$

✧ Two possible final states : $tt \to bb + ll / ljj$

✧ Signatures:

➢ 1. Large MET + 2 leptons + ≥2 Jets @low pT

➢ 2. Large MET + 1 lepton + 3 Jets +



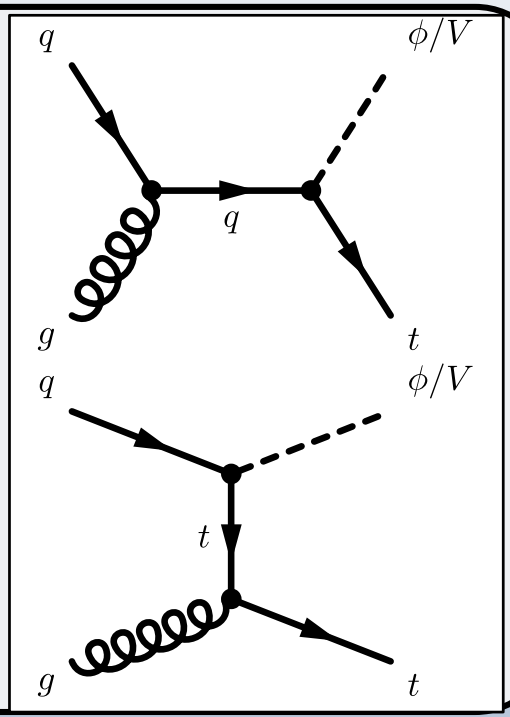
➢ MonoTop

✧ Probe couplings that favor heavy quarks

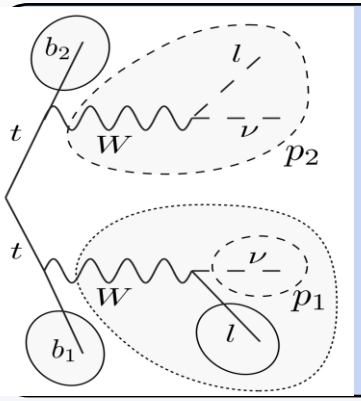
✧ FCNC diagrams with new particle in the final state

✧ Search for scalar & vector DM particle

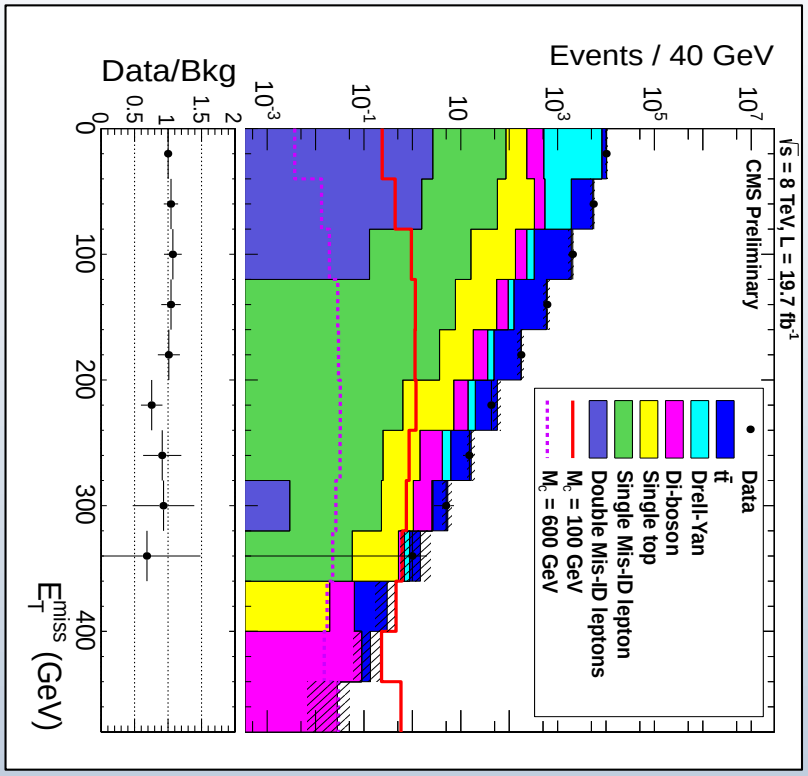
✧ Signature : t → bW(qq) → 1 b-jet + 2 jets + MET



Top Pairs dileptonic



- Leptons : R_{iso}<0.12(μ) 0.1(e) p_T>20 |η|<2.4(μ) 2.5(e)
- Leptons : m_{L1L2}>20 $m_{ll} = m_Z \pm 15$ GeV scalar pT sum > 120 Δφ<2
- Jets : ≥2 Jets pT>30 |η|<5 loose ID
- Jets : scalar pT sum < 400
- MET > 320



Fit (S,B) to data

- Irreducible bkg = MC x SF from data
  - tt, t, DY, VV

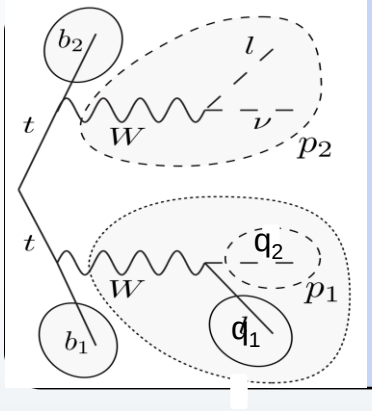
- Fakes : 1 or 2 mis-ID lepton(s)

$$Fake_{Data}^{NL} = Data^{\text{1 Lepton fails Tight but passes Loose}}_{\text{1 Lepton passes Tight ID}} \times \frac{e_{Data}^{\text{Nloose L passes tight ID}}}{1 - e_{Data}^{\text{Nloose L passes tight ID}}}$$

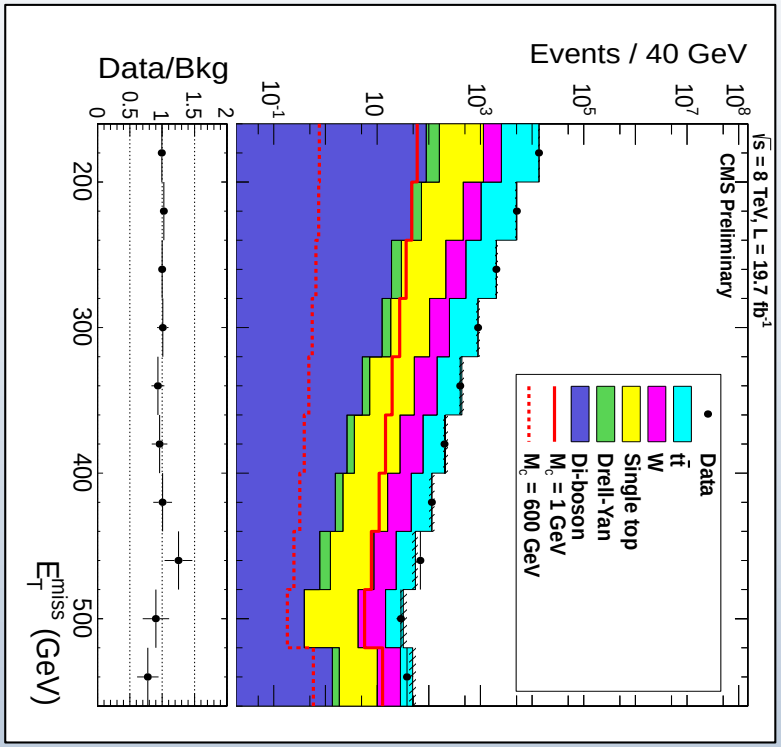
Background Source	Yield
$t\bar{t}$	$0.87 \pm 0.18 \pm 0.27$
Single top	$0.48 \pm 0.46 \pm 0.09$
Di-boson	$0.32 \pm 0.09 \pm 0.05$
Drell-Yan	$0.19 \pm 0.14 \pm 0.03$
One Mis-ID lepton	$0.02 \pm 0.07 \pm 0.02$
Double Mis-ID leptons	$0.00 \pm 0.00 \pm 0.00$
Total Bkg	$1.89 \pm 0.53 \pm 0.39$
Data	1
Signal	$1.88 \pm 0.11 \pm 0.07$

Ref : CMS-PAS-B2G-13-004

Top Pairs semileptonic



- 1 Lepton : R_{iso}<0.12(μ) 0.1(e) p_T>30 |η|<2.1(μ) 2.5(e)
- Jets : ≥3 Jets pT>30 |η|<4 loose ID ≥1 b-jet
- Jets/MET : Δϕ(Jet1+Jet2 , MET) > 1.2
- MET>320 GeV m_T>160 GeV m_{T2}^W (W decay kinematics)>200 GeV



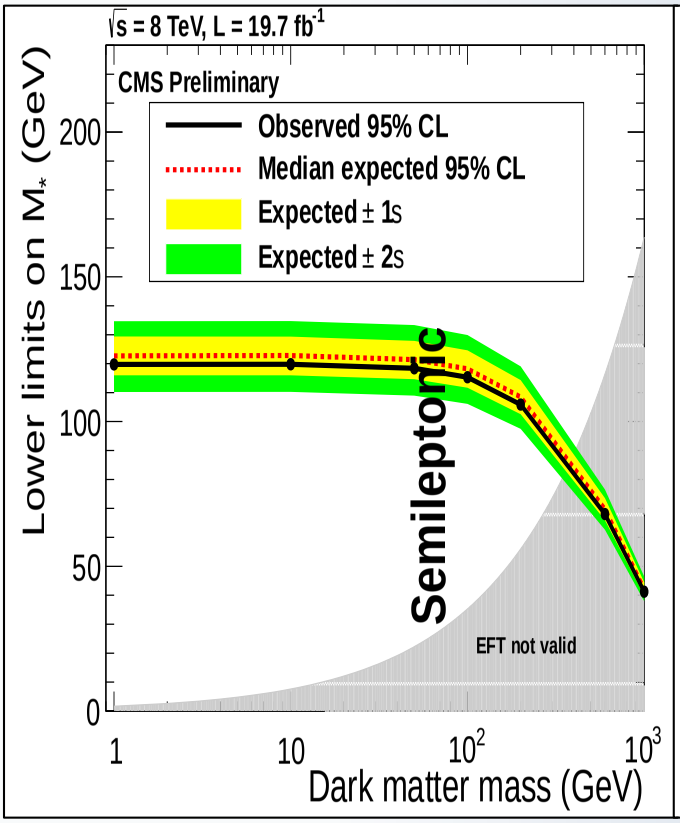
Fit (S,B) to data

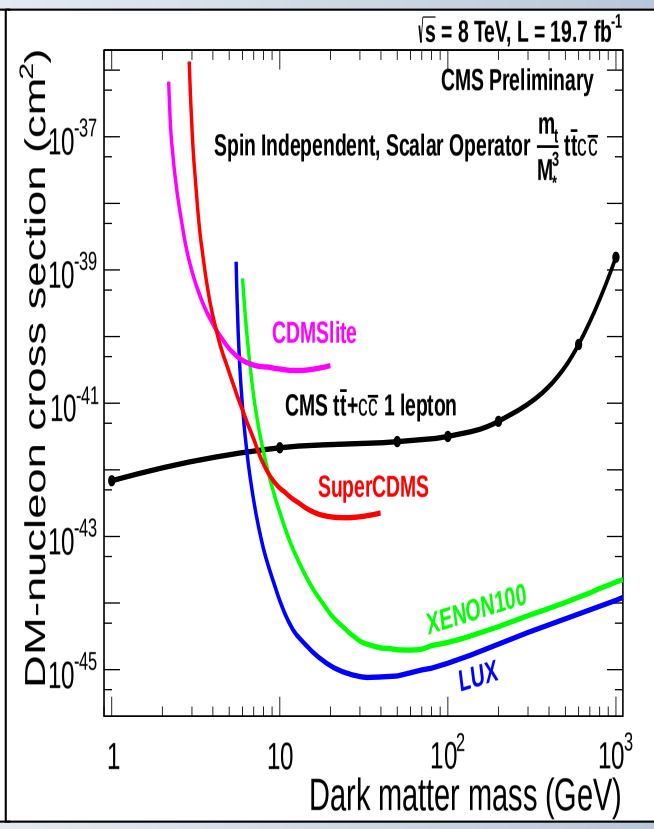
- All backgrounds = MC x SF from data

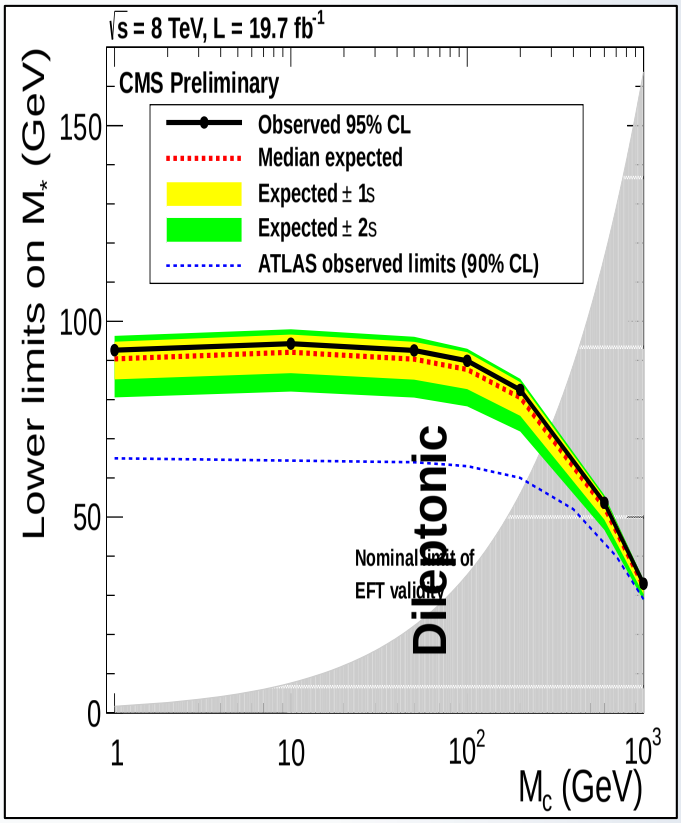
Background Source	Yield
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.7 \pm 0.6$
Single top	$2.3 \pm 1.1 \pm 1.1$
Di-boson	$0.5 \pm 0.2 \pm 0.2$
Drell-Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.7$
Data	18
Signal	$38.3 \pm 0.7 \pm 2.1$

Ref : CMS-PAS-B2G-14-004

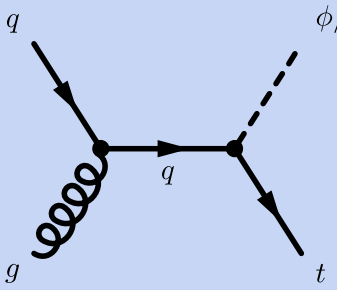
Top Pairs : results



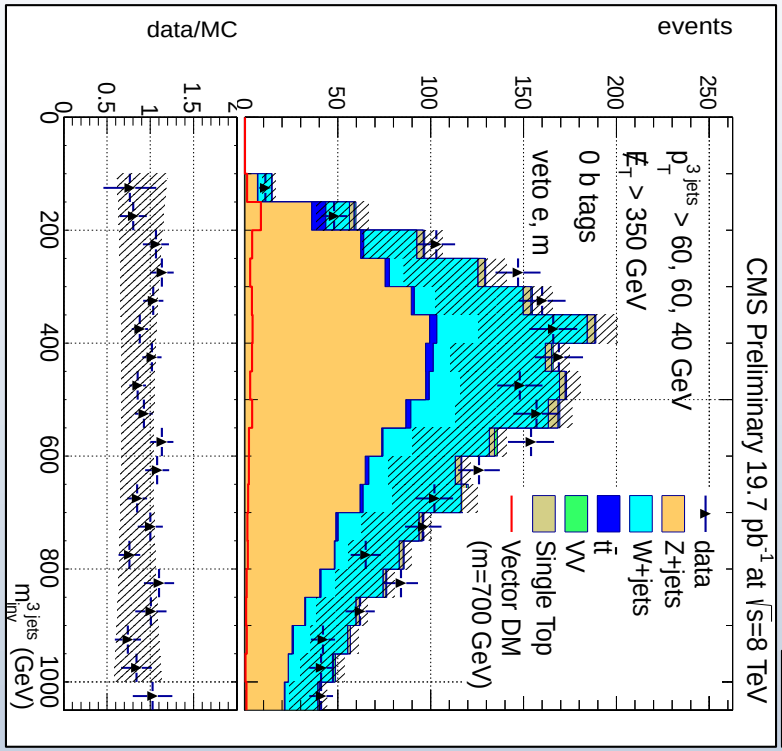




MonoTop : event selection



- 3 jets : pT>60,60,40 GeV m_{3J}<250 GeV 1 b-jet $|\eta|$<2.4
- 4th jet veto : pT > 35 GeV
- Lepton veto : pT>10(μ) 20(e) $|\eta|$<2.4(2.5) μ(e) ; $R_{iso} \leq 2$
- MET > 350



$$Z(\nu\nu) = \frac{Z(\mu\mu + 3Jets)^{Sgn}_{\text{Data}} - Bkg^{Sgn}_{MC}}{A_{\text{MC}} \times \epsilon_{\text{MC}} \times \text{SF}^{\text{Data}}_{\text{MC}}} \times \frac{BR(Z \to \nu\nu)}{BR(Z \to \mu\mu)}$$

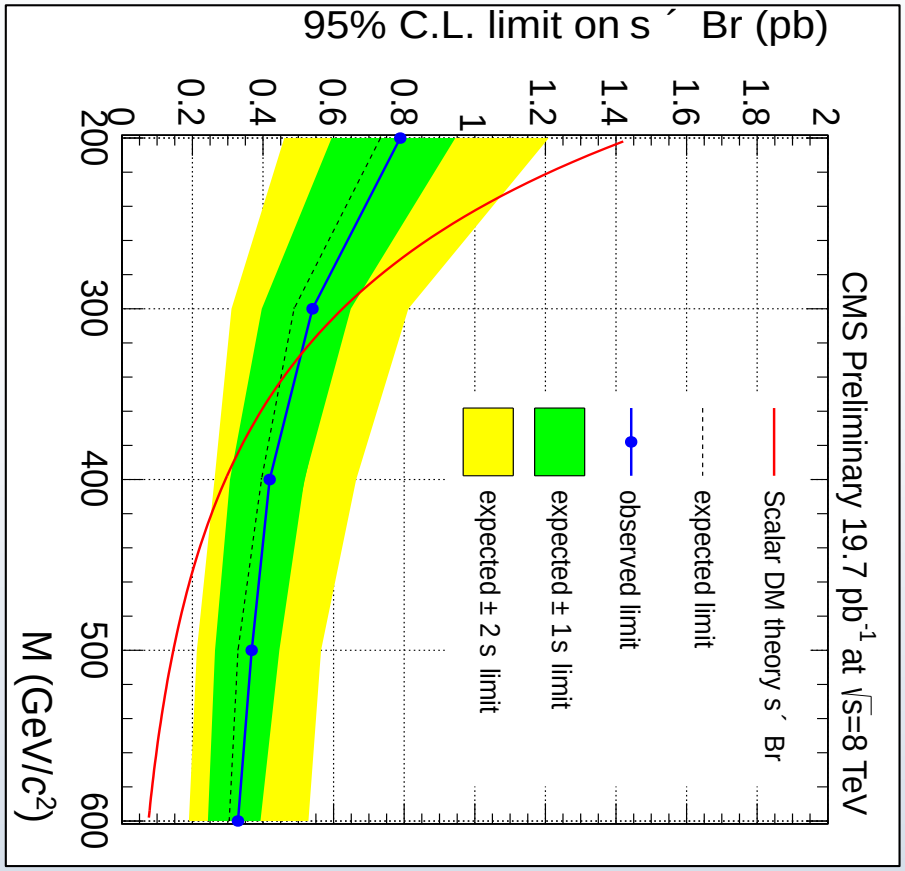
$$W(l\nu) = \frac{W(l\nu + 3J)^{\text{Sgn}}_{\text{Data}} - Bkg^{\text{Sgn}}_{MC}}{A^{\mu}_{\text{MC}} \times \epsilon^{\mu}_{\text{MC}} \times \text{SF}(\mu)} \times \sum_{l=e,\mu t_h} p(\text{lost l}) \times p_{MC}(b\text{-}tag)$$

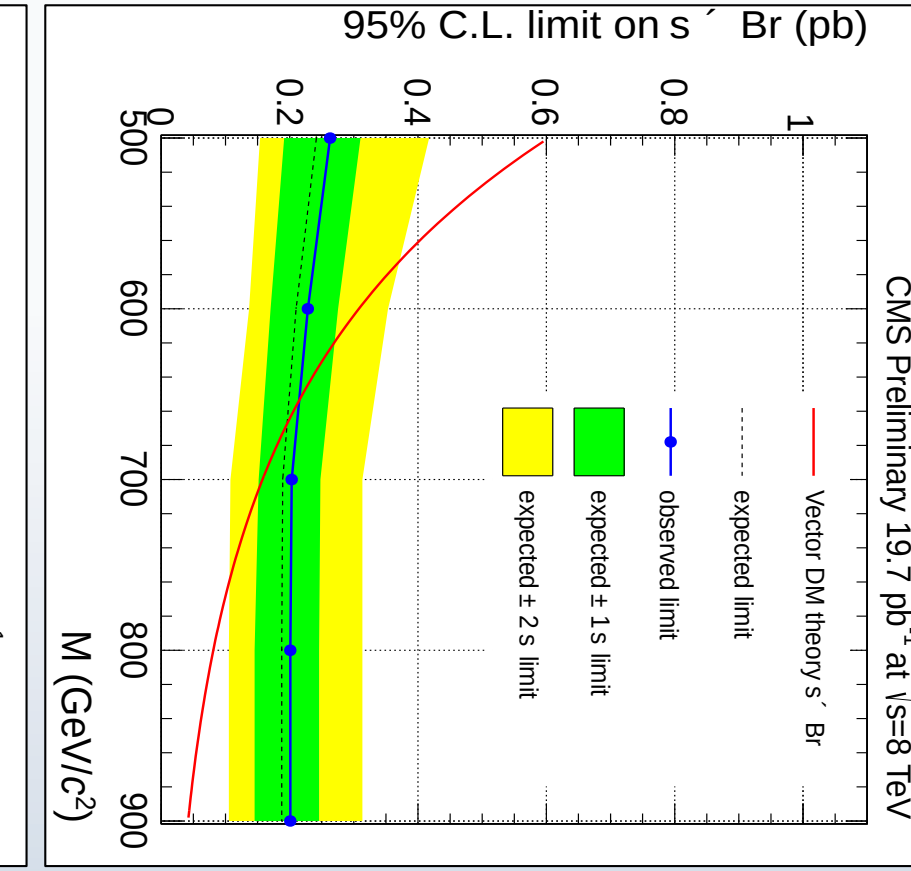
$$\begin{cases} N^{0b} = p^{0b}_{sig} \cdot N_{sig} + p^{0b}_{QCD} \cdot N_{QCD} + N^{0b}_{other\ bg} \\ N^{1b} = p^{1b}_{sig} \cdot N_{sig} + p^{1b}_{QCD} \cdot N_{QCD} + N^{1b}_{other\ bg} \end{cases}$$

$$\mathcal{L}_{\text{S+B}}(\sigma_{sig}, \nu) = Poisson\left(N^{0b}_{observed} | N^{0b}\right) \times Poisson\left(N^{1b}_{observed} | N^{1b}\right)$$

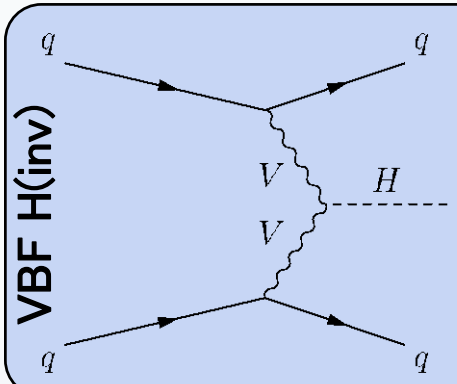
Ref : CMS-PAS-B2G-12-022

MonoTop : results

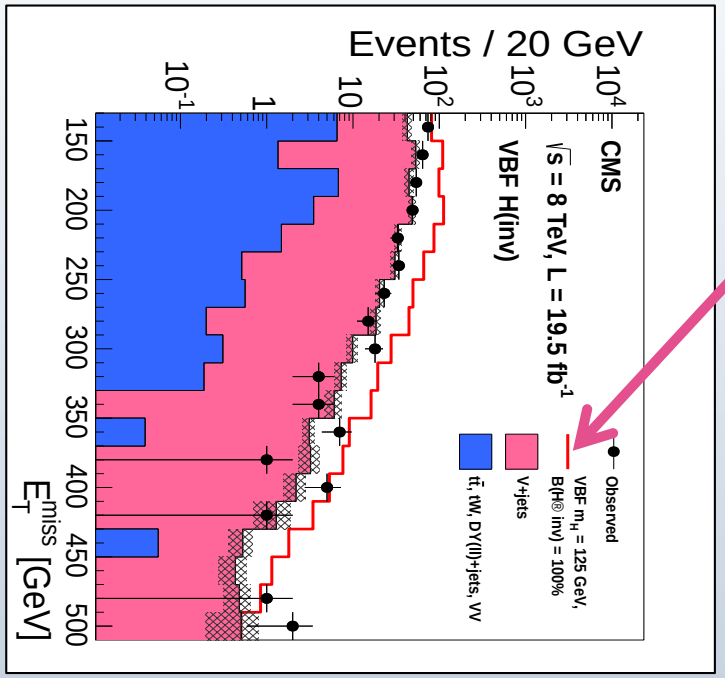




Higgs portal : VBF H(inv)



- 2 leading jets p_T>50 $|\eta|$<4.7 $\eta_1\eta_2$<0 $\Delta\eta$>4 m>1100
- Central Jet Veto ($\eta_{j1} < \eta_j < \eta_{j2}$) $\Delta\phi_{jj}$<1 □kill QCD
- Veto events with ≥1 lepton (ID & p_T>10) □kill W, Z
- MET > 130 GeV
- Optimize cuts □ikelihood based on signal significance



Single-bin counting experiment

$$Z(\nu\nu) = \left[Z(\mu\mu)^{Ctrl}_{\text{Data}} - Bkg^{Ctrl}_{MC} \right] \times \frac{BR(Z \to \nu\nu)}{BR(Z \to \mu\mu)} \times \frac{\epsilon^{Sgn}_{\text{Z MC}}}{\epsilon^{Ctrl}_{\text{Z MC}}}$$

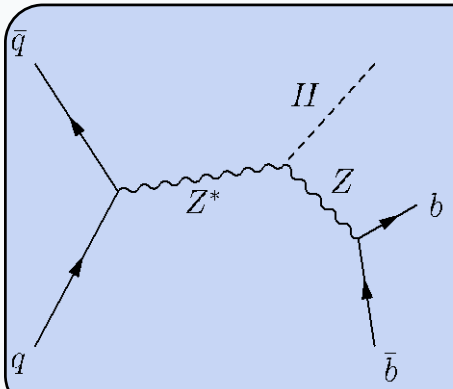
$$W(l\nu) = \left(W(l\nu)^{Ctrl}_{\text{Data}} - Bkg^{Ctrl}_{MC} \right) \times \frac{W^{Sgn}_{\text{MC}}}{W^{Ctrl}_{\text{MC}}}$$

$$QCD = \frac{N^{Sgn}_{\text{Data}}(\text{pass MET, fail CJV}) \times N^{Sgn}_{\text{Data}}(\text{fail MET, pass CJV})}{N^{Sgn}_{\text{Data}}(\text{fail MET, fail CJV})}, \quad N_{\text{Data}} - = \text{EWK}_{\text{MC}}$$

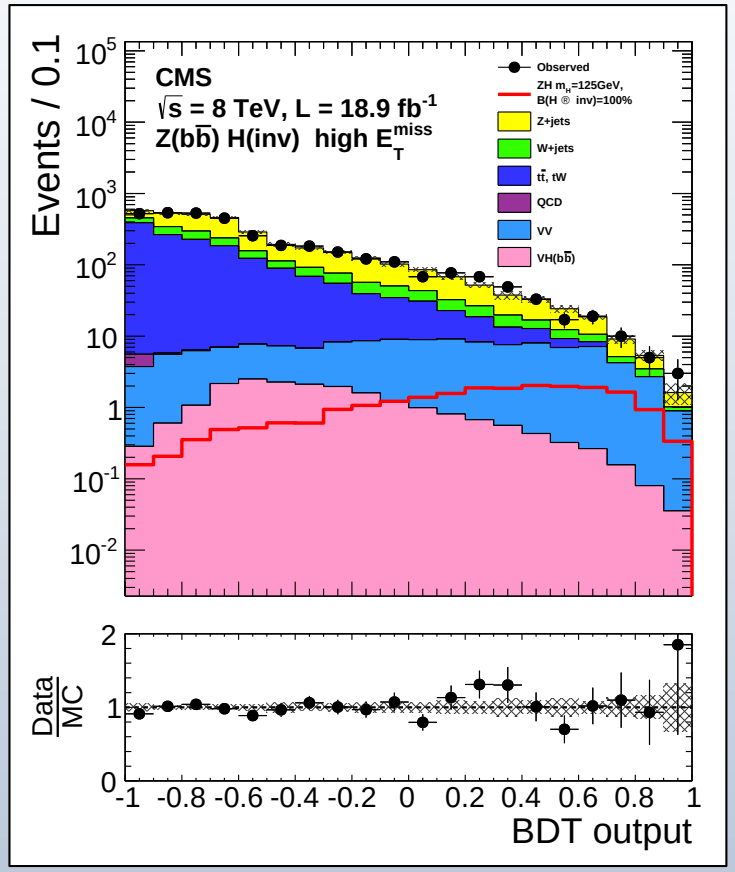
Process	Event yields
$Z(\nu\nu)$+jets	99 ± 29 (stat) ± 25 (syst)
$W(\mu\nu)$+jets	67 ± 5 (stat) ± 16 (syst)
$W(e\nu)$+jets	63 ± 9 (stat) ± 18 (syst)
$W(\tau_h\nu)$+jets	53 ± 18 (stat) ± 18 (syst)
QCD multijet	31 ± 5 (stat) ± 23 (syst)
Sum ($t\bar{t}$, single top quark, VV, DY)	20.0 ± 8.2 (syst)
Total background	332 ± 36 (stat) ± 45 (syst)
VBF H(inv.)	210 ± 29 (syst)
ggF H(inv.)	14 ± 10 (syst)
Observed data	390
S/B	70%

Ref : CMS-HIG-13-030

Higgs portal : Z(bb) H(inv)



- Categories : 3 MET regions [100, 130] [130, 170] [170, ∞]
- Topology : $p_{T,J1(J2)}$>60(30) $p_{T,JJ}$>130 Δφ(Z,H)>2.0 boosted H
- b tagging ☐kill V+Jets, VV
- Lepton veto (p_T>15) ☐kill WZ, ttbar
- Third jet veto (low-MET)
- Fake MET veto: Δφ(MET, J)>0.7 Δφ(MET, MET±)<0.5 ☐kill QCD

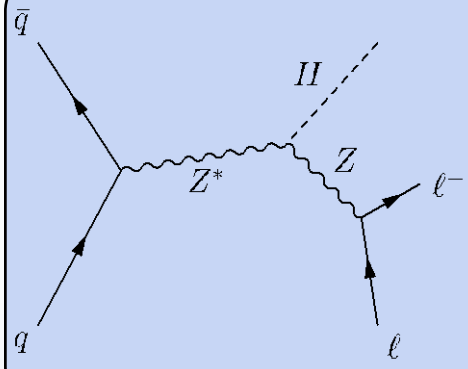


Fit BDT(topology) for Sgn and Bkg on Data

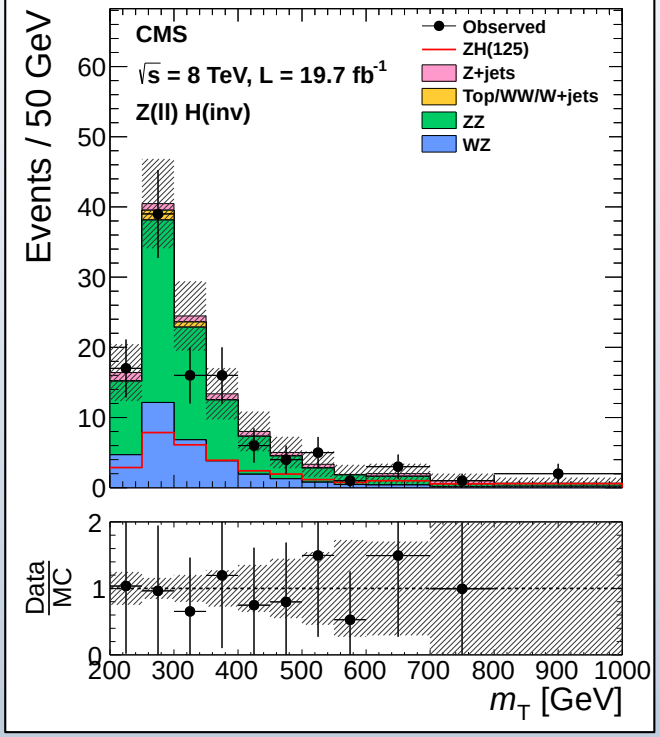
- All backgrounds : MC + scale factors from Data

Process	High E_T^{miss}	Intermediate E_T^{miss}	Low E_T^{miss}
$Z(\nu\bar{\nu})H(b\bar{b})$(SM)	2.0 ± 0.3	0.4 ± 0.1	0.1 ± 0.0
$W(\ell\nu)H(b\bar{b})$(SM)	0.5 ± 0.1	0.1 ± 0.0	0.1 ± 0.0
ZZ(bb)	27.7 ± 3.1	11.6 ± 1.3	5.5 ± 0.7
WZ(bb)	10.2 ± 1.6	7.3 ± 0.9	3.1 ± 0.5
VV(udscg)	5.3 ± 1.1	0.3 ± 0.2	0.1 ± 0.1
$Z+b\bar{b}$	61.8 ± 7.1	21.1 ± 2.4	13.2 ± 1.6
Z+b	16.7 ± 1.7	3.2 ± 1.4	0.7 ± 0.9
Z+udscg	7.1 ± 0.3	0.6 ± 0.4	3.1 ± 2.5
$W+b\bar{b}$	15.8 ± 2.2	5.8 ± 0.8	3.0 ± 1.4
W+b	4.7 ± 1.2	0.2 ± 0.3	0.0 ± 0.0
W+udscg	4.9 ± 0.2	1.1 ± 0.3	0.2 ± 0.3
$t\bar{t}$	20.4 ± 1.8	9.6 ± 1.0	8.9 ± 1.1
Single-top-quark	4.1 ± 2.4	3.5 ± 2.0	2.5 ± 0.7
QCD	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Total backgrounds	181.3 ± 9.8	64.8 ± 4.1	40.5 ± 4.1
$Z(b\bar{b})H$(inv)	12.6 ± 1.1	3.6 ± 0.3	1.6 ± 0.1
Observed data	204	61	48
S/B	6.9%	5.6%	3.9%

Higgs portal : Z(ll) H(inv)



- Categories : 0-jet 1-jet
- Lepton pair $e^+e^-/\mu^+\mu^-$ p_T>20 m = m_Z ± 15 GeV
- Third lepton veto (p_T>10) ☐kill W, Z
- Jet veto: N(jet pT>30) ≥ 2 ☐kill Z(ll)+jets (fake MET)
- b jet veto: $p_T(\mu)$>7 OR p_T(b-jet)>20 ☐kill top
- MET>120 $\Delta\phi_{ll}$>2.7 $|MET - p_T^{ll}| / p_T^{ll} < 0.25$ ☐kill Z(ll) t



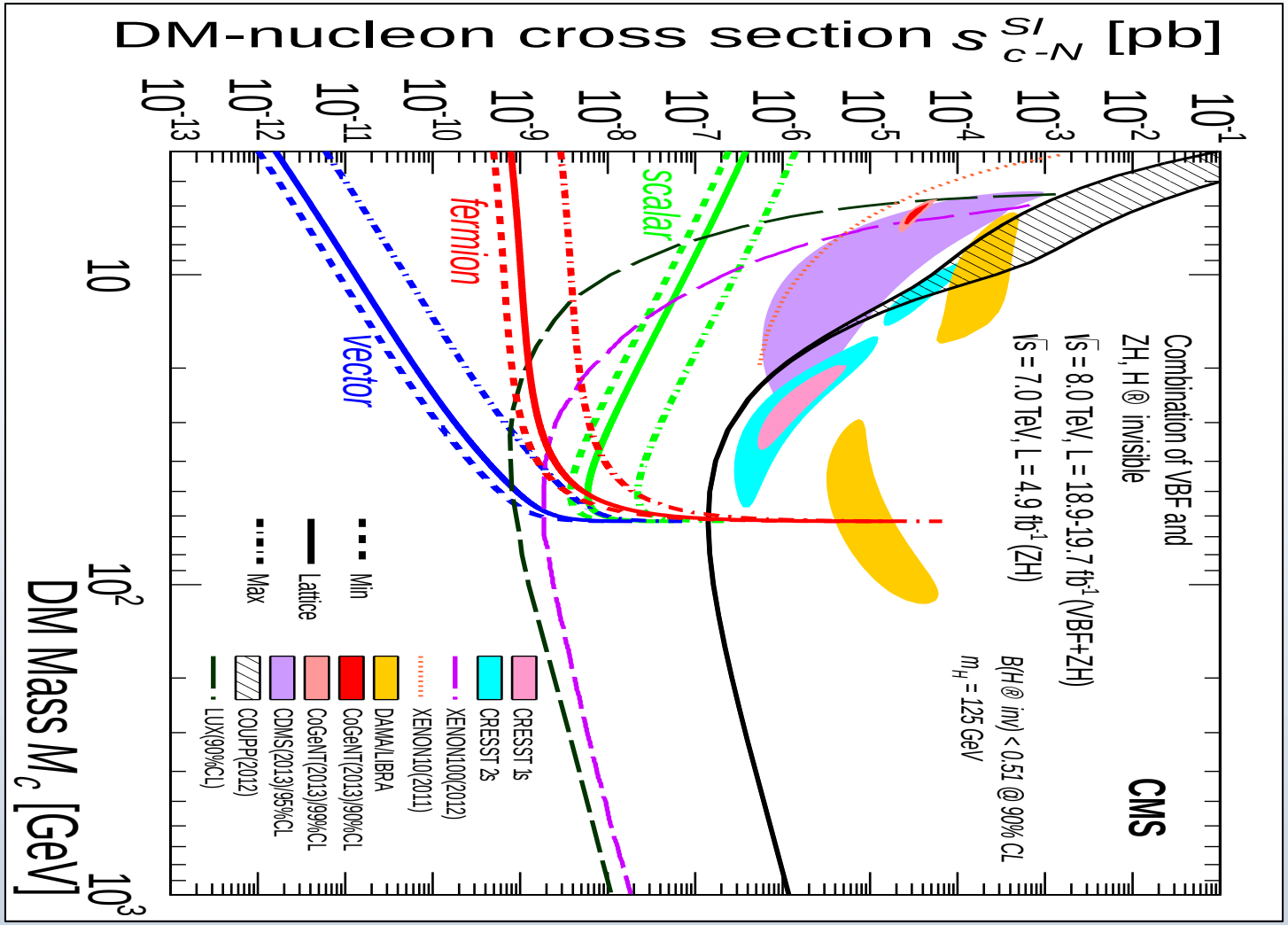
☐Max likelihood fit 2D : (m_T , $\Delta\phi_{ll}$)

$$Z(ll) = \left(g_{\text{Data}}^{Sgn} - Bkg_{MC}^{Sgn}\right) \times w_{\text{kinematics}}\left(p_T^Z\right) \times w_{\text{PU}}$$

$$h\left[\text{Top, WW, W+Jets, Z}(\tau\tau)\right] = \left[\text{Data}(\text{Sgn}, e^{\pm}\mu^{\mp}) - Bkg_{MC}^{Sgn}\right] \times \frac{N_{ll}^{Ctrl}}{N_{e\mu}^{Ctrl}}$$

Process	$\sqrt{s}=7$ TeV ee	$\sqrt{s}=7$ TeV $\mu\mu$	$\sqrt{s}=8$ TeV ee	$\sqrt{s}=8$ TeV $\mu\mu$
0 jet selection				
$Z/\gamma^* \to \ell^+\ell^-$	0.1 ± 0.1	0.2 ± 0.2	0.2 ± 0.3	0.9 ± 1.4
$WZ \to 3\ell\nu$	1.7 ± 0.2	2.0 ± 0.3	10.4 ± 1.6	14.1 ± 1.7
$ZZ \to 2\ell 2\nu$	5.8 ± 0.7	7.8 ± 0.9	26.4 ± 3.0	35.9 ± 3.6
$t\bar{t}$, Wt, WW & W+jets	1.1 ± 6.4	1.0 ± 3.1	0.4 ± 1.5	0.7 ± 2.1
Total backgrounds	8.7 ± 6.5	11.0 ± 3.3	37.4 ± 3.7	51.6 ± 4.8
ZH(125)	2.3 ± 0.2	3.1 ± 0.3	10.3 ± 1.2	14.7 ± 1.5
Observed data	9	10	36	46
S/B	26%	28%	28%	24%
1 jet selection				
$Z/\gamma^* \to \ell^+\ell^-$	0.2 ± 0.2	$0.0 \pm {}^{1.3}_{0.0}$	2.0 ± 3.8	3.0 ± 5.6
$WZ \to 3\ell\nu$	0.8 ± 0.1	0.9 ± 0.2	3.3 ± 0.4	3.8 ± 0.5
$ZZ \to 2\ell 2\nu$	1.1 ± 0.2	1.4 ± 0.2	4.8 ± 0.5	6.3 ± 0.7
$t\bar{t}$, Wt, WW & W+jets	0.5 ± 0.6	0.5 ± 0.8	0.4 ± 1.7	0.7 ± 1.3
Total backgrounds	2.6 ± 0.7	2.8 ± 0.9	10.6 ± 4.2	13.8 ± 5.8
ZH(125)	0.4 ± 0.1	0.5 ± 0.1	1.6 ± 0.2	2.5 ± 0.3
Observed data	1	4	11	17
S/B	15%	18%	15%	18%

Higgs portal : results

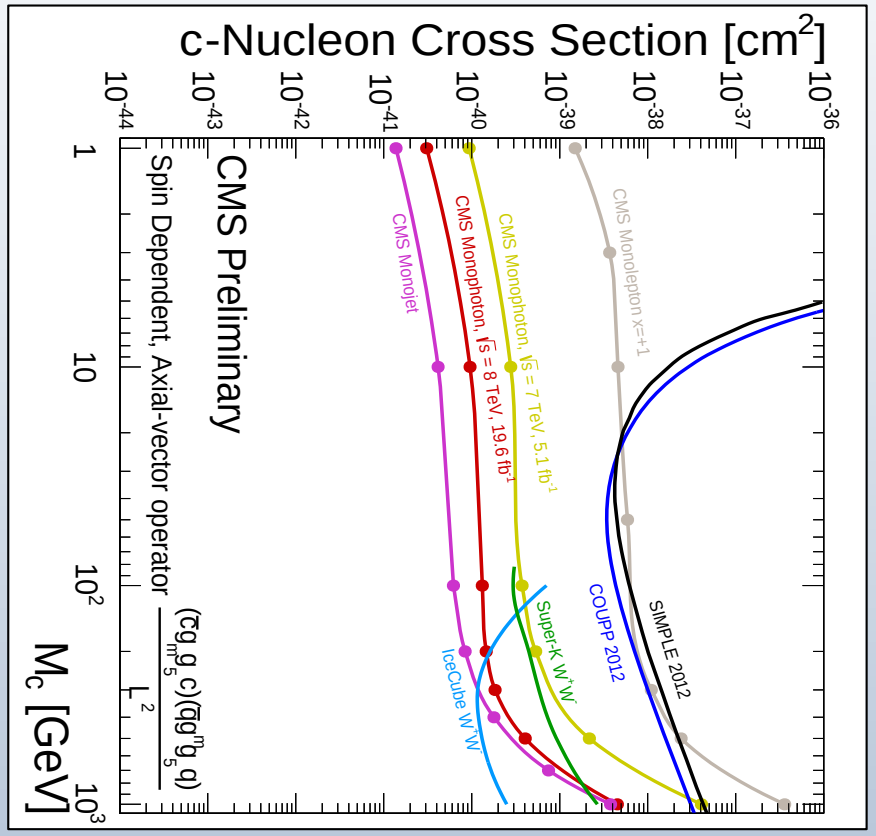


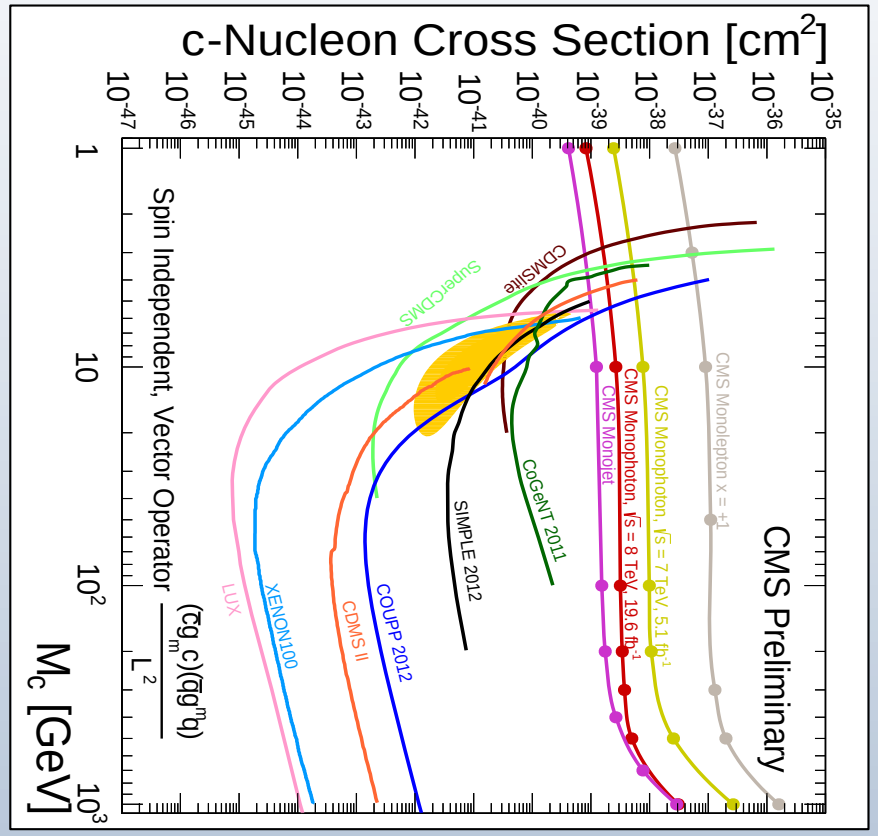
Summary

- ✧ CMS covers a broad panel of final states and scenarios

- ➢ Upper limits on production x-sections between 10^{-1} –10^{-2} pb
- ➢ Upper limits on χ-nucleon interaction x-sections between 10^{-38} –10^{-42} cm^2

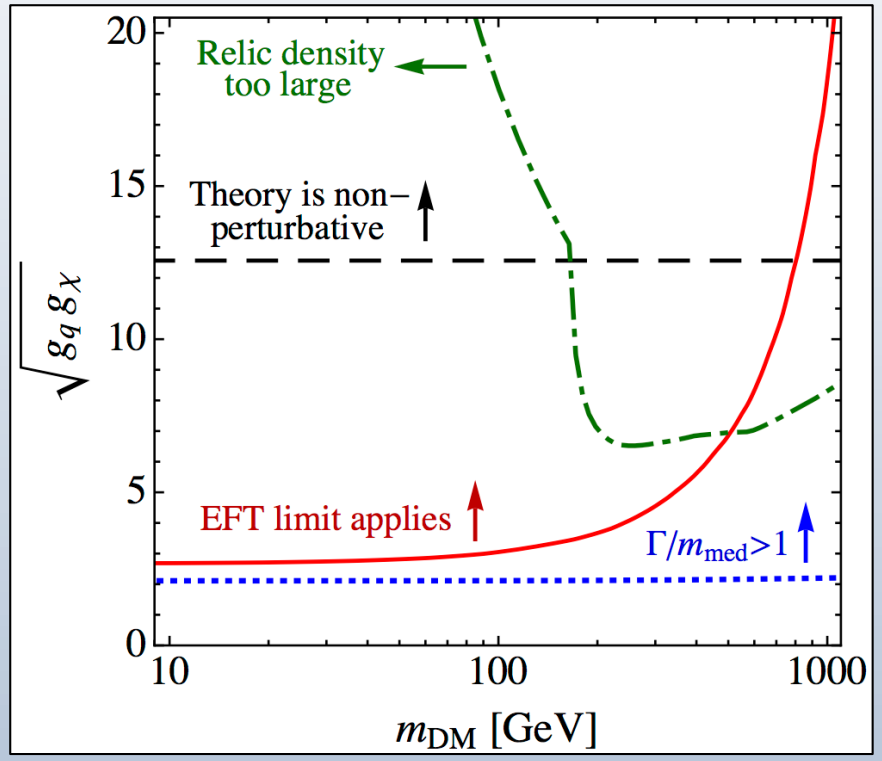
- ➢ Collider limits are the only limits available below $M\chi < O(1\ \text{GeV})$!!
- ➢ Cross-check direct detection experiments at higher masses.





Perspectives for LHC Run 2

- ✧ Running conditions : 13 TeV, 25 ns, <PU> = 40 ☐expect rate x4
- ✧ Optimise X+MET triggers to cope with such conditions
- ✧ Refine background estimations and reduce associated uncertainties
- ✧ Physics models : EFT validity is an important limitation
  ☐switch to simplified models with extra search parameters

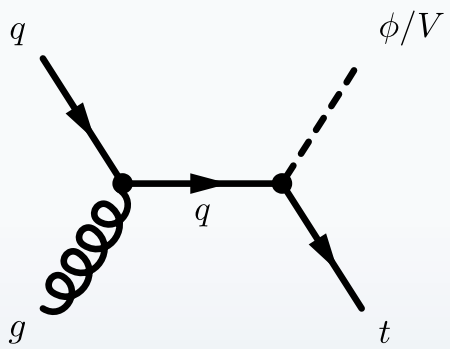


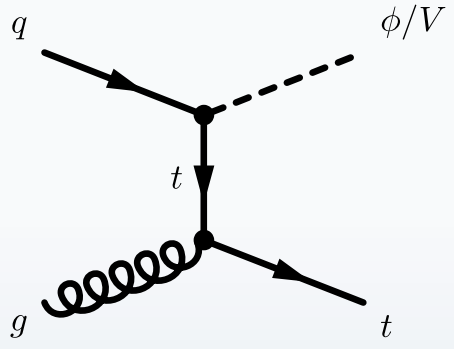
BACKUP

DM models in CMS searches

✧ **MonoTop** :

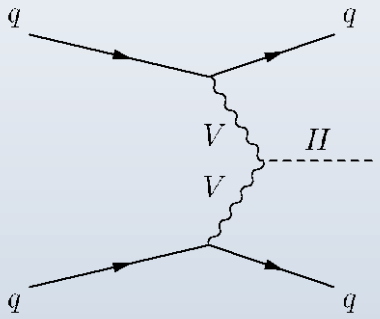
- explicit interaction lagrangian
- FCNC diagrams

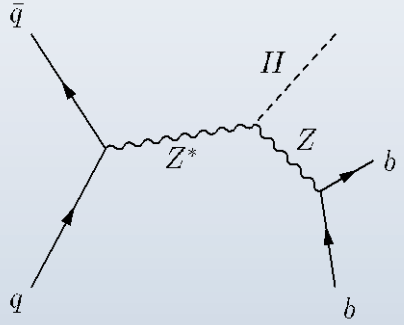


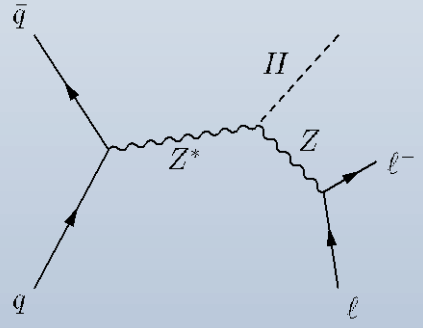


✧ **Higgs portal** :

- SM Higgs production
- search for invisible decays
- DM–nuclei interaction = exchange of Higgs bosons



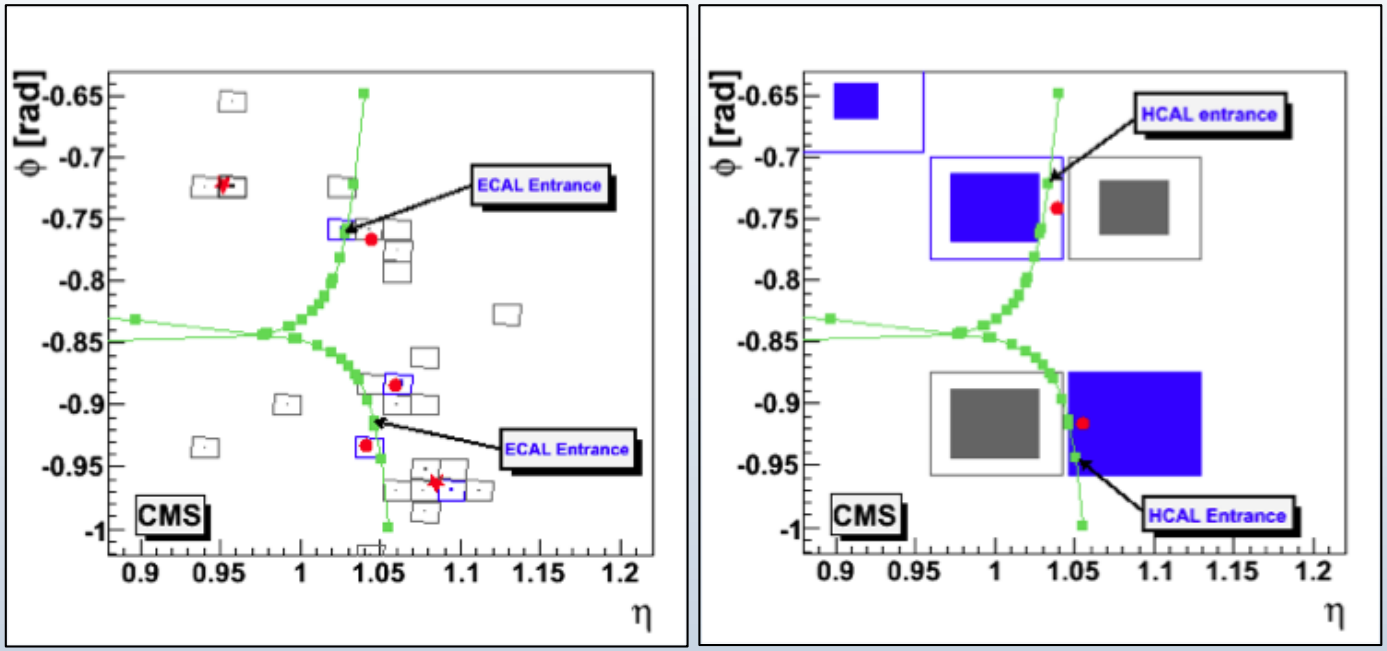




Particle Flow reconstruction

✧ Build input elements
- clusters of ECAL crystals / HCAL towers (topological algorithm)
- tracks in the tracker
- standalone muons

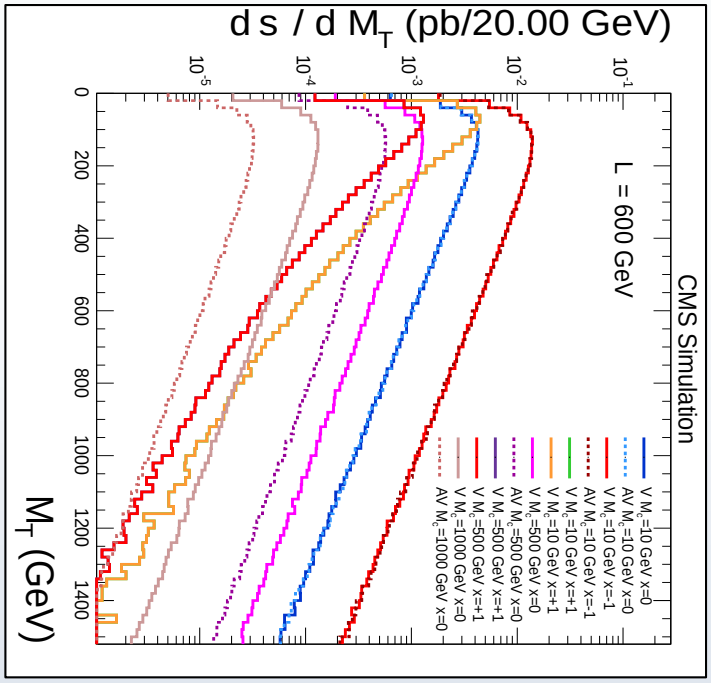
✧ Match elements by pairs (geometrical compatibility)



- 2 photons : ECAL clusters, no tracks

- 2 charged hadrons : h^+ and h^-

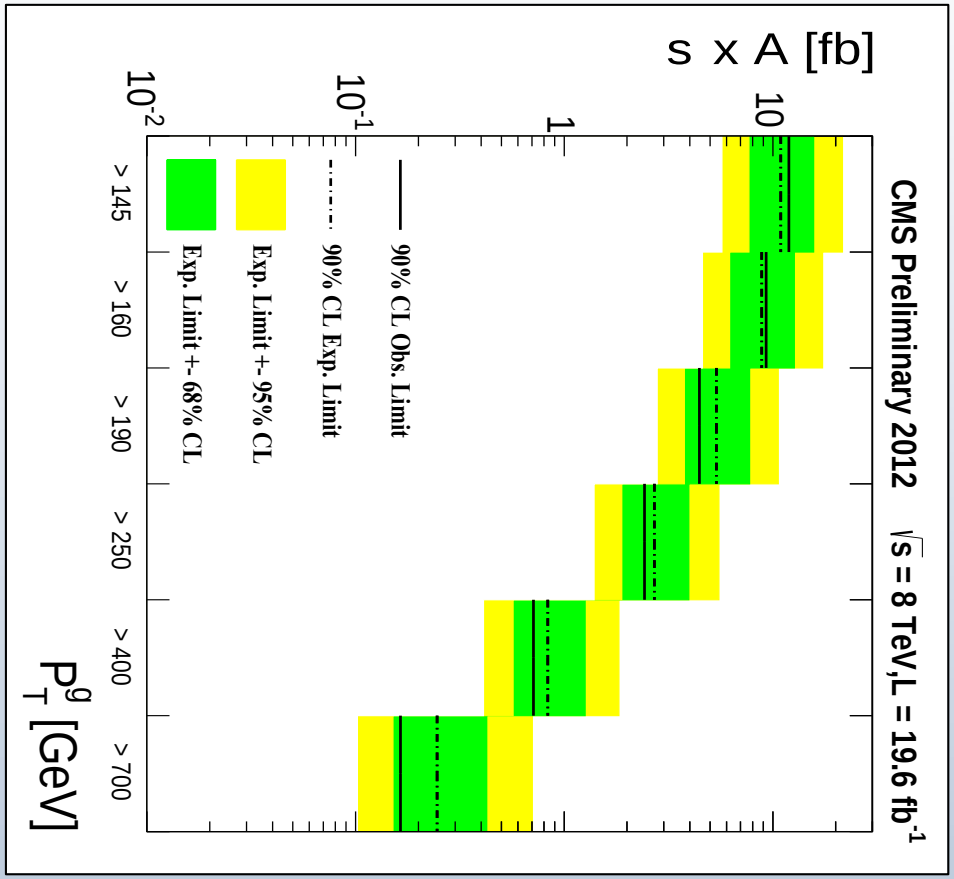
Backup 1


d s / d M_T (pb/20.00 GeV)
CMS Simulation
L = 600 GeV
V M_t=10 GeV x=0
AV M_t=10 GeV x=0
V M_t=10 GeV x=-1
AV M_t=10 GeV x=-1
V M_t=10 GeV x=+1
AV M_t=10 GeV x=+1
V M_t=500 GeV x=0
AV M_t=500 GeV x=0
V M_t=500 GeV x=+1
AV M_t=500 GeV x=+1
V M_t=1000 GeV x=0
AV M_t=1000 GeV x=0
M_T (GeV)

Monojet : uncertainties

E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 450	> 500	> 550
Statistics (N^{obs})	0.9	1.3	2.0	2.9	4.0	5.5	7.5
Background (N^{bgd})	2.5	2.3	1.9	2.1	2.1	1.9	2.4
Acceptance and efficiency	2.0	2.0	2.2	2.4	2.8	3.3	4.1
PDFs	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Total	3.9	3.9	4.1	4.9	6.0	7.6	10.1

Monophoton


CMS Preliminary 2012 √s = 8 TeV,L = 19.6 fb-1
s x A [fb]
10
1
10-1
10-2
90% CL Obs. Limit
90% CL Exp. Limit
Exp. Limit +- 95% CL
Exp. Limit +- 68% CL
> 145
> 160
> 190
> 250
> 400
> 700
PTg [GeV]

Higgs portal

Z(bb)H(inv) cuts

Variable	Selection		
	Low E_T^{miss}	Intermediate E_T^{miss}	High E_T^{miss}
E_T^{miss}	100–130 GeV	130–170 GeV	>170 GeV
p_T^{j1}	>60 GeV	>60 GeV	>60 GeV
p_T^{j2}	>30 GeV	>30 GeV	>30 GeV
p_T^{jj}	>100 GeV	>130 GeV	>130 GeV
M_{jj}	<250 GeV	<250 GeV	<250 GeV
CSV_{max}	>0.679	>0.679	>0.679
CSV_{min}	>0.244	>0.244	>0.244
N additional jets	<2	—	—
N leptons	=0	=0	=0
$\Delta\phi(Z,H)$	>2.0 radians	>2.0 radians	>2.0 radians
$\Delta\phi(E_T^{miss},j)$	>0.7 radians	>0.7 radians	>0.5 radians
$\Delta\phi(E_T^{miss},E_T^{miss}{}_{trk})$	<0.5 radians	<0.5 radians	<0.5 radians
E_T^{miss} significance	>3	not used	not used

Higgs portal

VBF syst

Source	Total background	Signal
Control region statistics	11%	—
MC statistics	11%	4%
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale/resolution	7%	13%
QCD background estimation	4%	—
Lepton efficiency	2%	—
Tau ID efficiency	1%	—
Luminosity	0.2%	2.6%
Cross sections	0.5–1%	—
PDFs	—	5%
Factorization/renormalization scale	—	4%
Gluon fusion signal modelling	—	4%
Total	18%	14%

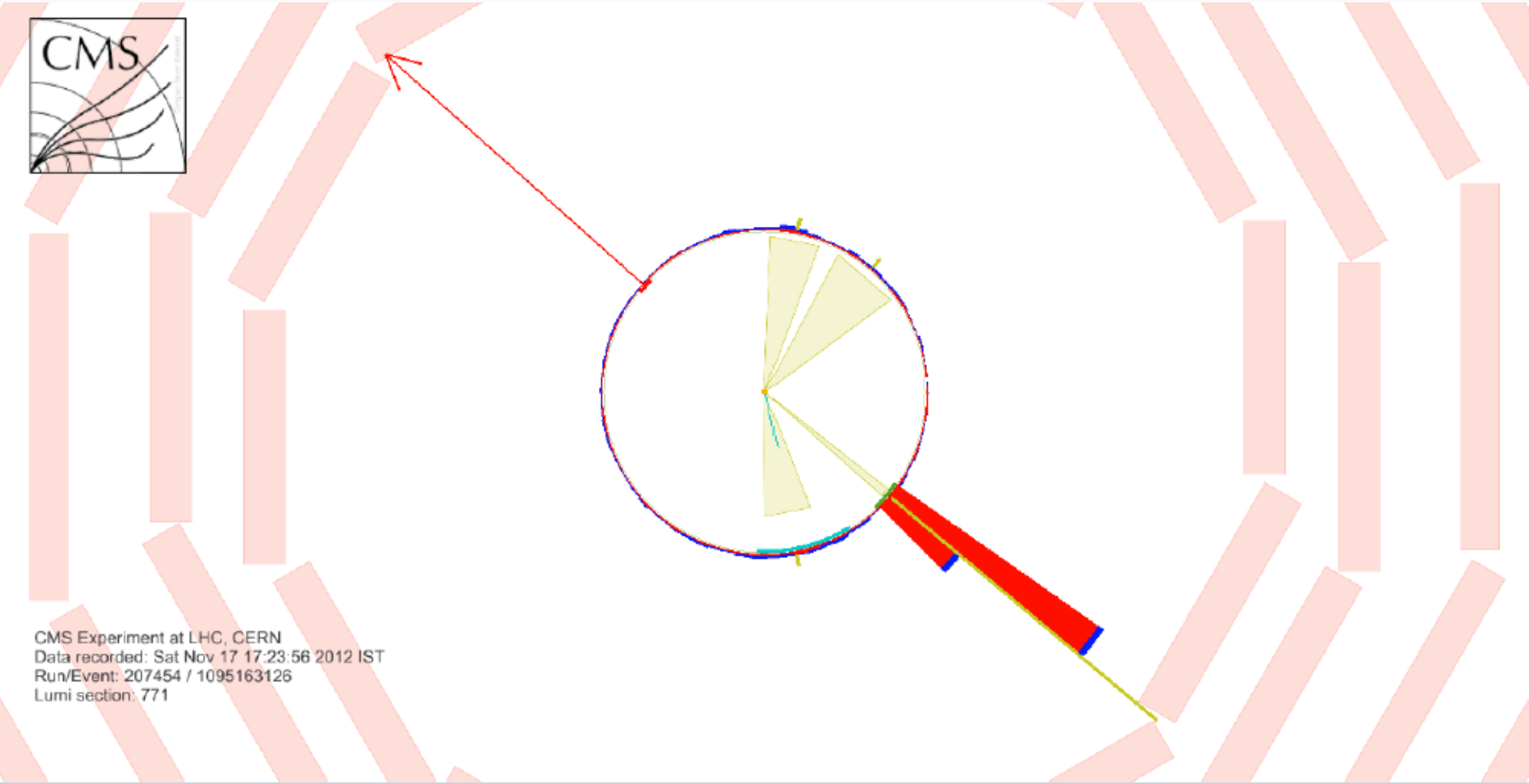
Z(ll)H(inv) syst

Type	Source	Background uncertainty(%)	Signal uncertainty(%
Norm.	PDFs	5.0	5.7
	Factorization/renormalization scale	6.4	7.0
	Luminosity	2.3	2.2–2.6
	Lepton trigger, reconstruction, isolation	2.7	3.0
	Drell–Yan normalization	4.8	—
	$t\bar{t}$, Wt, WW & W+jets normalization	1.0	—
Shape	MC statistics (ZH, ZZ, WZ)	1.8–3.8	3.0–4.0
	Control region statistics (DY($\ell\ell$)+jets)	0.6–1.2	—
	Control region statistics ($t\bar{t}$, Wt, WW & W+jets)	2.0-3.8	—
	Pile up	0.2	0.3
	b-tagging efficiency	0.2	0.2
	Lepton momentum scale	0.9	1.0
	Jet energy scale/resolution	2.4–3.1	2.6–3.2
	$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	1.7–2.9	1.4–2.3
	Total	11-12	11

Z(bb)H(inv) syst

Type	Source	Background uncertainty(%)	Signal uncertainty(%)
Norm.	Luminosity	0.9	2.6
	Factorization/renormalization scale and PDFs	—	7
	Signal p_{T} boost EW/QCD corrections	—	6
	Background data/MC scale factors	8	—
	Single-top-quark cross section	1	—
	Diboson cross section	4	—
Shape	Trigger	1	5
	Jet energy scale	4	3
	Jet energy resolution	3	3
	$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	1	2
	b tagging	7	5
	MC statistics	3	3
	MC modelling (V+jets and $t\bar{t}$)	3	—
	Total	12	11

Backup 1


CMS
CMS Experiment at LHC, CERN
Data recorded: Sat Nov 17 17:23:56 2012 IST
Run/Event: 207454 / 1095163126
Lumi section: 771

Models

✧ Statement 1

⇒ conclusion

✧ Statement 1

□conclusion

✧ Statement 1

□conclusion

Title

➢ sub-title statement

- ✧ Statement