Dark matter search in the mono-lepton channel with CMS

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On behalf of the CMS Collaboration

RWTH Aachen III Phys. Inst. A

CMS-PAS-EXO-13-004
20. September 2013

Outline

Introduction

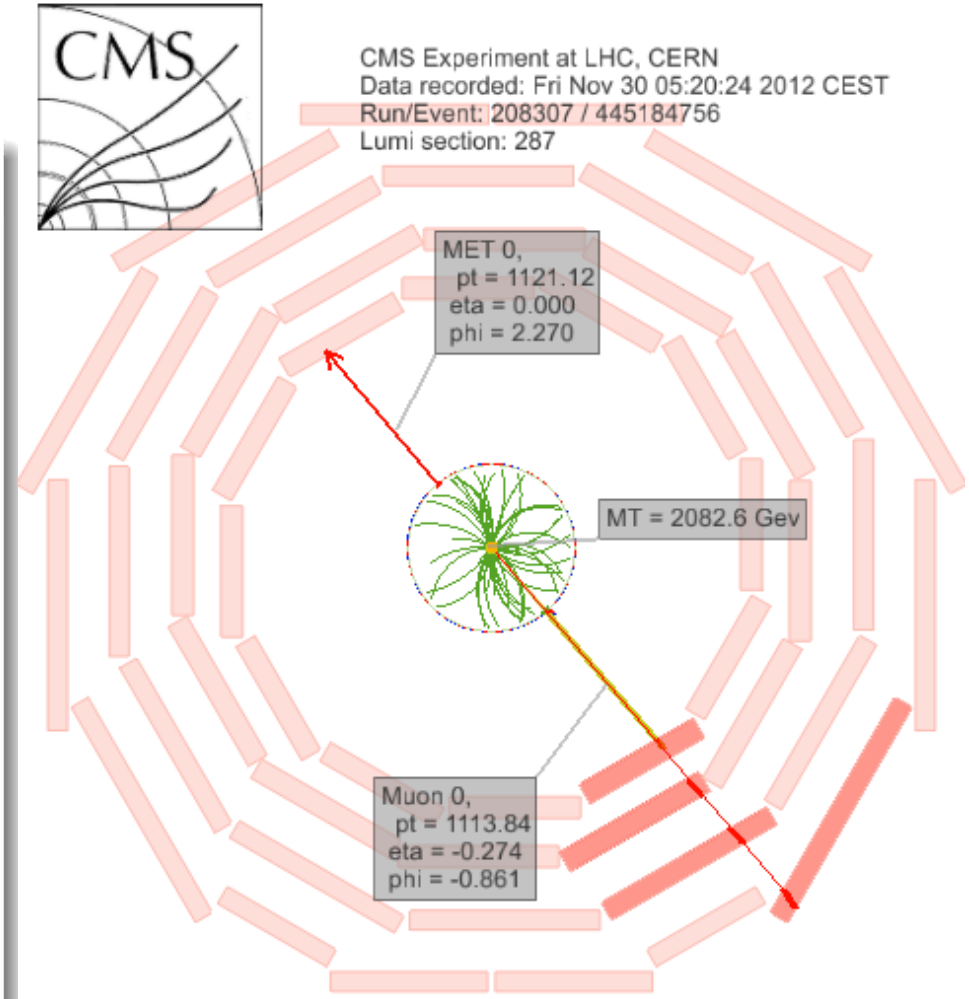
Origin of the mono-lepton DM search

- Analysis started out as W' search with muons and electrons CMS-PAS-EXO-12-060
- Reinterpretation of W' in terms of DM by T. Tait, Y. Bai (arXiv:1208.4361)
- Results are summarized in CMS-PAS-EXO-13-004

Motivation

Why mono-lepton?

- Experimental point of view:
  - Good trigger for mono-lepton events
  - Clean, well simulated background
  - Low systematic uncertainties from the detector
- Theoretical point of view:
  - Higher production cross section than mono-Z
  - Quark sensitive interference effects



Event with the highest M_T in the muon channel

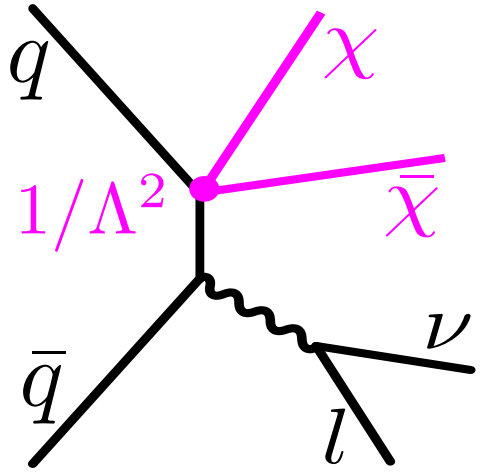
Theory

DM- Effective theory

Model following
arXiv:1008.1783
J. Goodman, et al.

General

- Effective Field Theory (EFT)
- Pair produced fermionic DM (χ)
- A reduction to 3 model parameters possible:
  - Effective Energy scale $\Lambda = (\frac{M_{messenger}}{\sqrt{g_\chi g_q}})$
  - Dark matter mass M_χ
  - Relative coupling to the quarks ξ



Concrete Implementation:

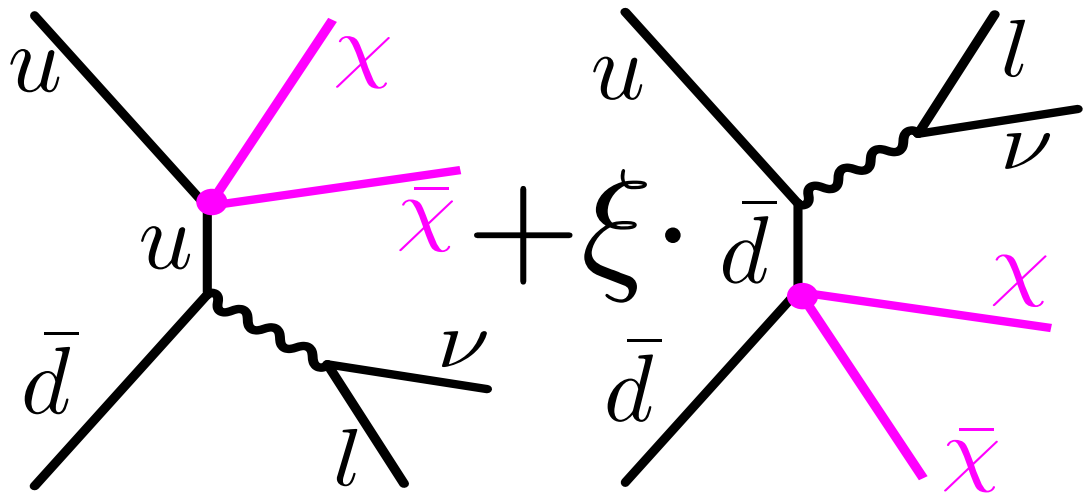
The most interesting and actively used couplings:

Vector (V): $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad \xi_i\bar{q}_i\gamma_\mu q_i$ spin-independent

Axial-Vector (AV): $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad \xi_i\bar{q}_i\gamma_\mu\gamma^5 q_i$ spin-dependent

Interference

At the production two initial states can interfere. Reduction of the quark state to a single relative factor:



Interference not visible in mono-jet/ mono-photon events

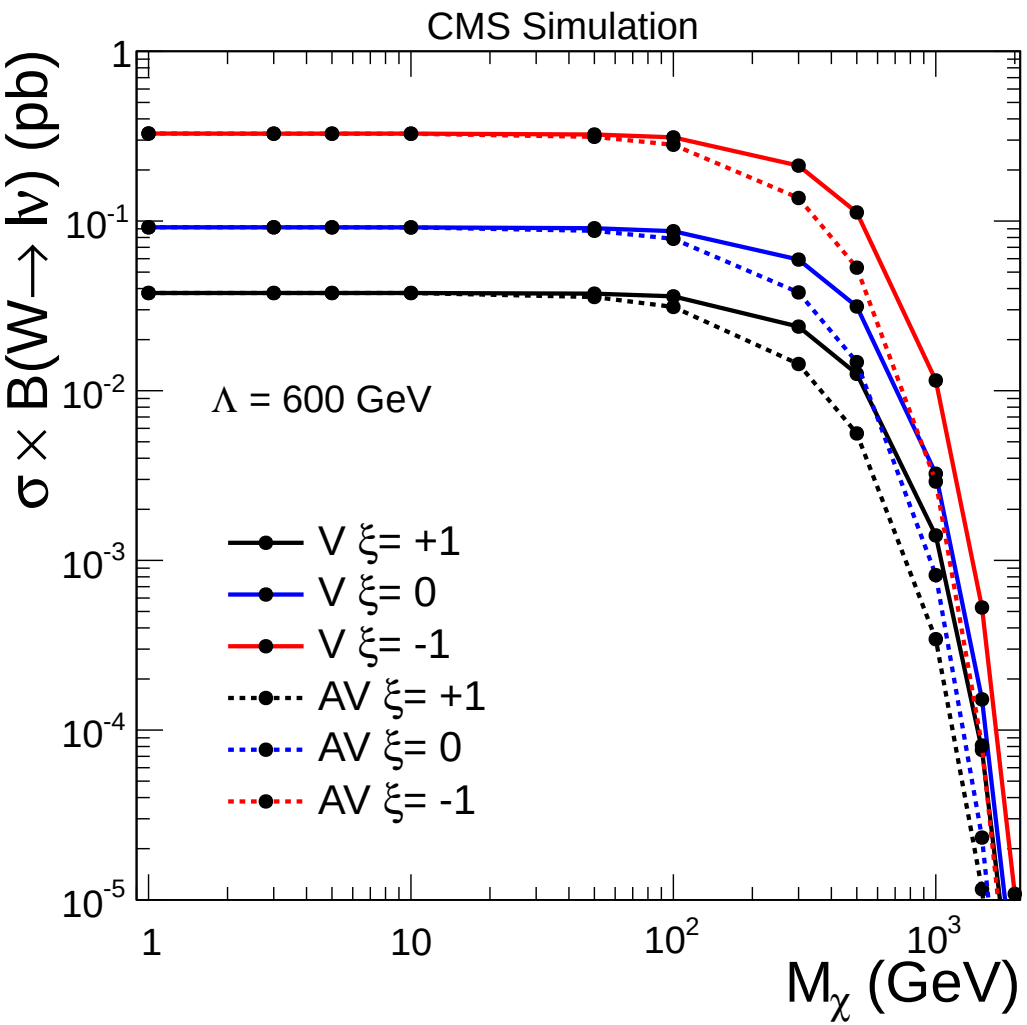
$$\text{V: } \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad (\bar{u}\gamma^\mu u + \xi\bar{d}\gamma_\mu d)$$

$$\text{AV: } \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad (\bar{u}\gamma^\mu\gamma_5 u + \xi\bar{d}\gamma^\mu\gamma_5 d)$$

The interference is described by a relative ξ between up- and down-type quarks. The interesting values are $\xi = -1, 0, +1$.

Signal Cross Section

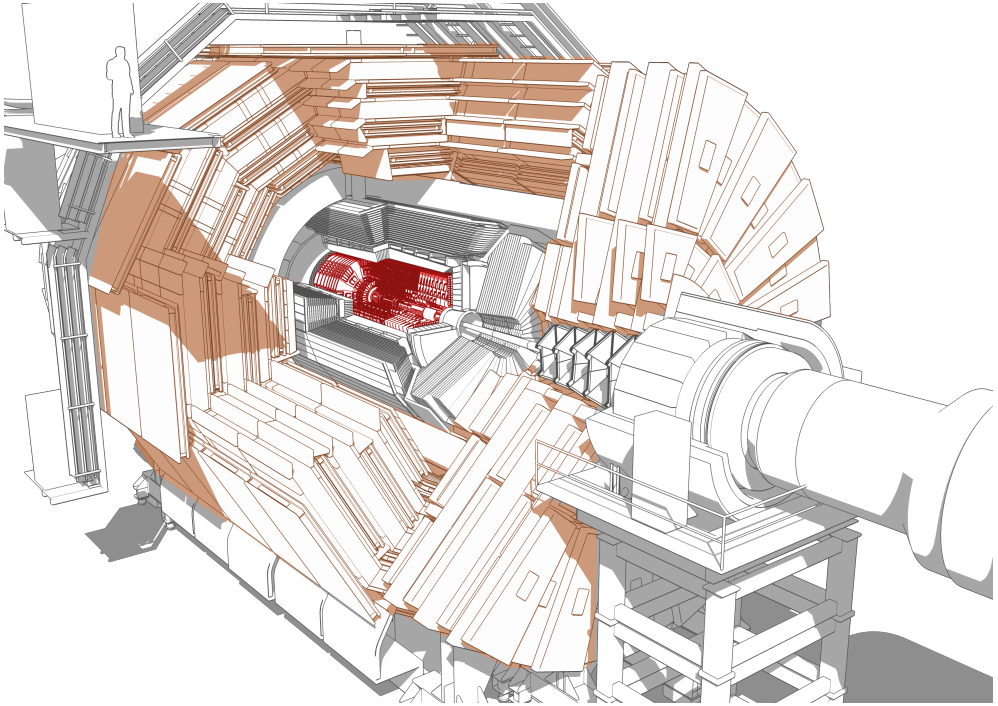
- Cross section flat vs M_χ up to 100 GeV
- Sharp drop at high M_χ
- Strong dependence on $\xi = 0, \pm 1$
- Small difference between AV and V
- Λ scales the cross section (no change in the kinematics)

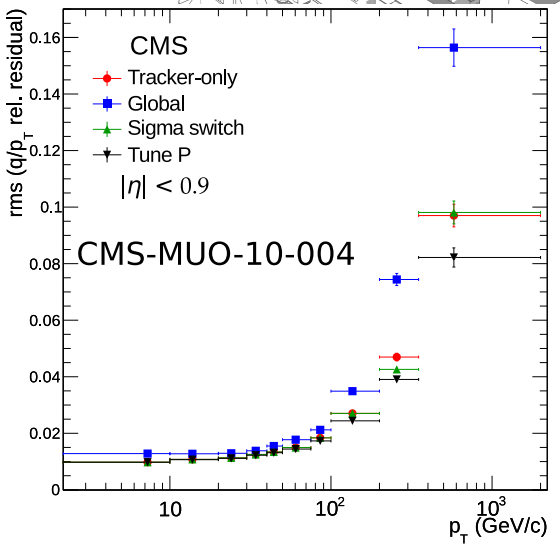


More interference later!

Mono-Leptons in CMS

Muons in CMS





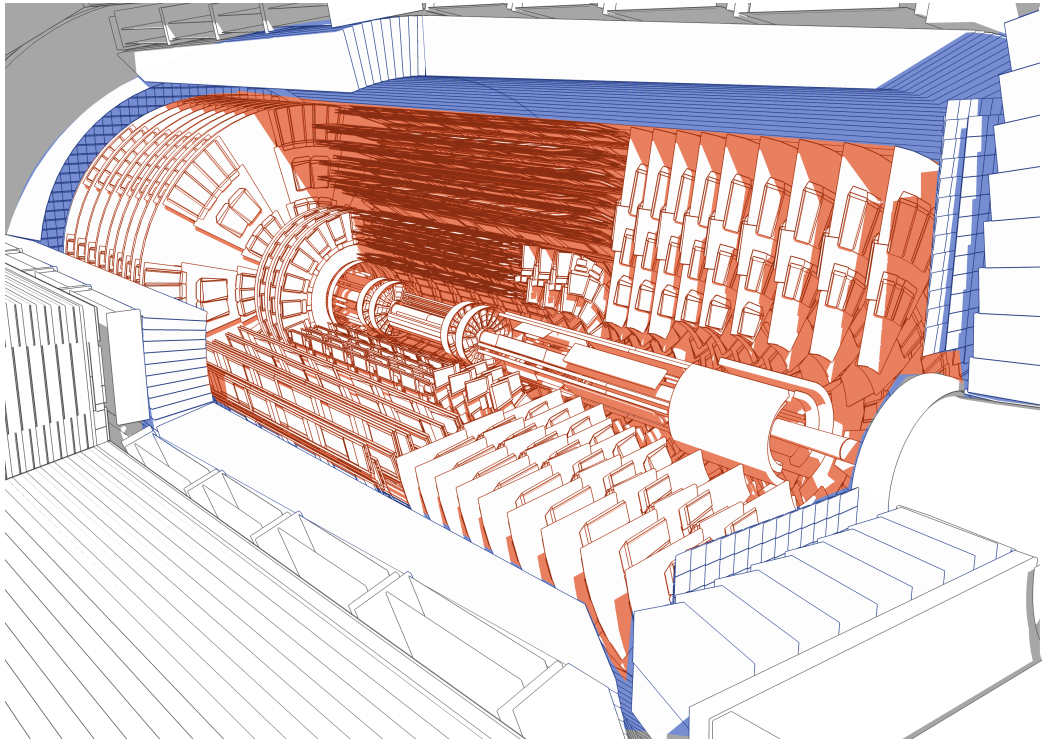
Muon Reconstruction

- Tracker + Muon System
- Triggering all non isolated muons with p_T >40 GeV
- Resolution 1–1.5% at 10 GeV, ∼8% at 1 TeV
- Overall efficiency (Barrel/End-cap) (Trigger x Reco x ID) ∼ 90%/78%

Analysis Requirements

- $p_T > 45$ GeV
- $|\eta| < 2.1$
- ID optimized for high p_T

Electrons in CMS



Electron Reconstruction

- Tracker + ECAL
- Triggering all electrons with E_T >80 GeV and a loose ID
- Resolution better than 1% for E_T >100 GeV
- Overall efficiency (Barrel/End-cap) (Trigger x Reco x ID) $\sim$ 84%/80%

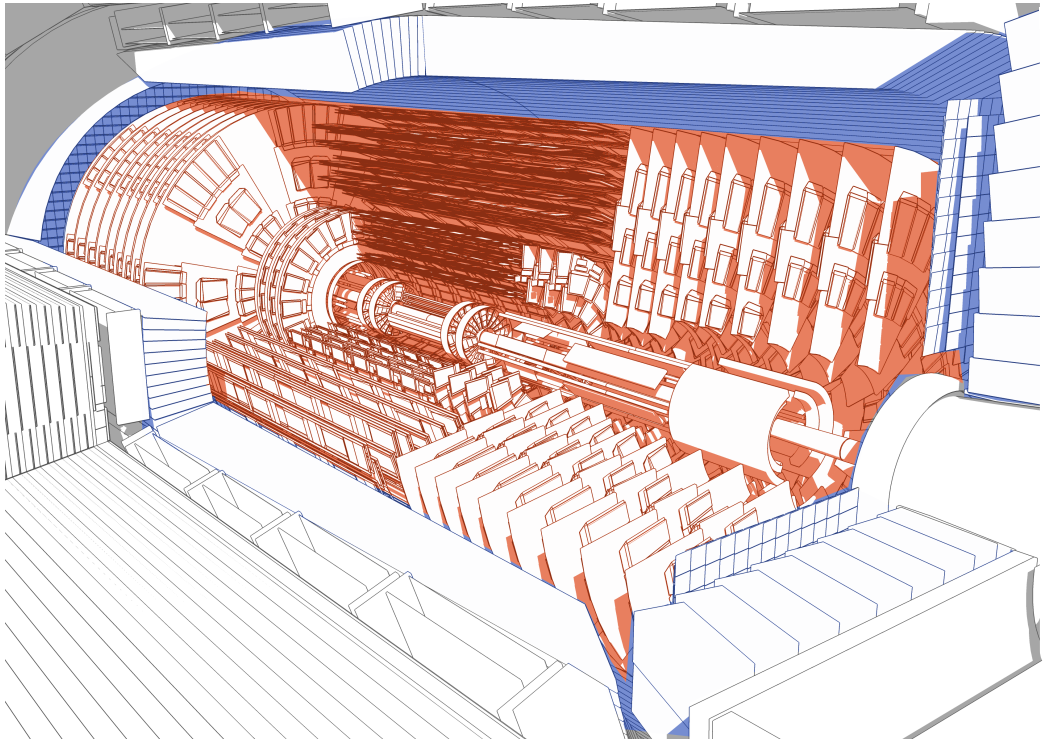
Analysis Requirements

- $E_T > 100$ GeV
- $|\eta| < 2.5$
- Shower shape and track requirements optimized for high E_T

Missing Transverse Energy

Particle Flow $\not{E}_T$ used, dominated by the reconstructed lepton.

Electrons in CMS



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Analysis

Analysis Selection

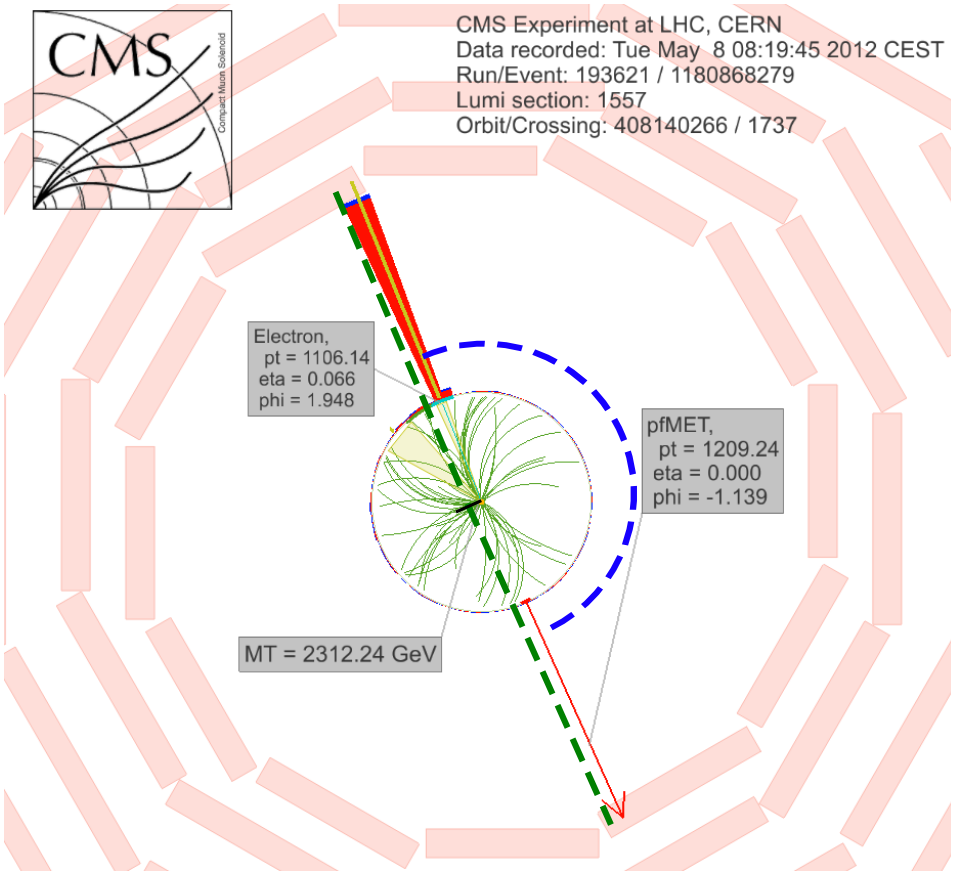
The main value to identify signal events is M_T:

$$M_T = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot \not{E}_{\mathrm{T}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

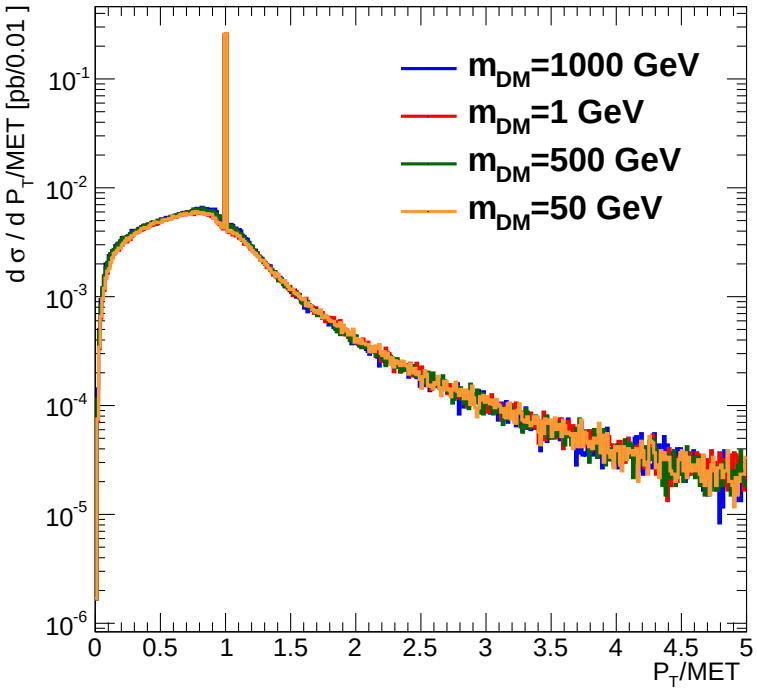
To reduce the background two kinematic selections are used:

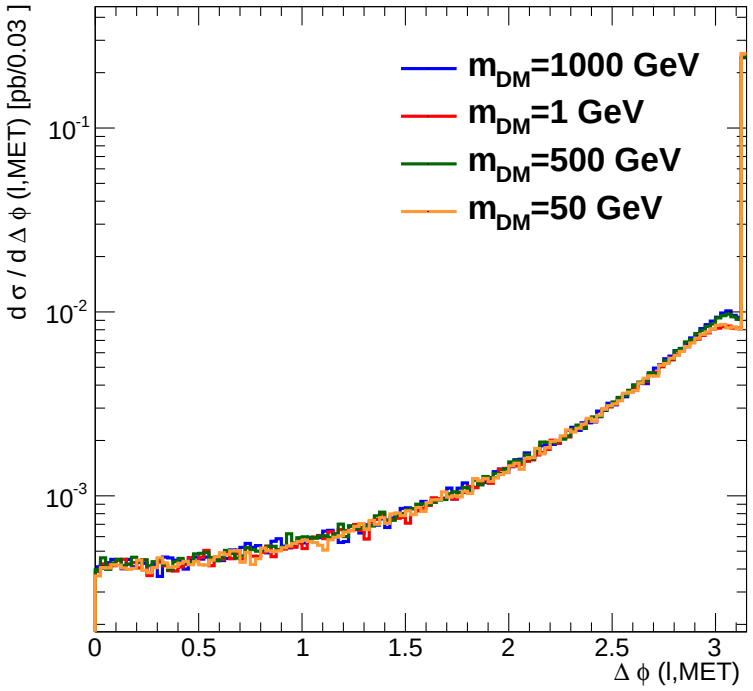
$$\Delta\phi(\mathrm{l}, \not{E}_{\mathrm{T}}) > 2.5$$

$$0.4 < p_{\mathrm{T}}/\not{E}_{\mathrm{T}} < 1.5$$

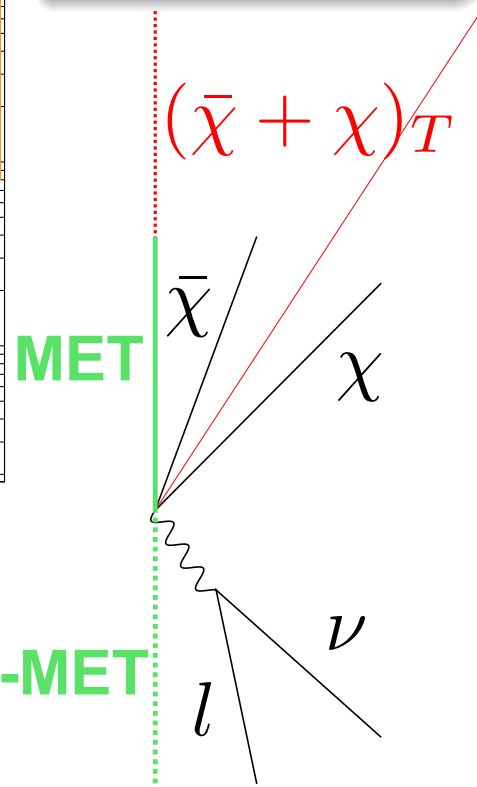


Reco level kinematics





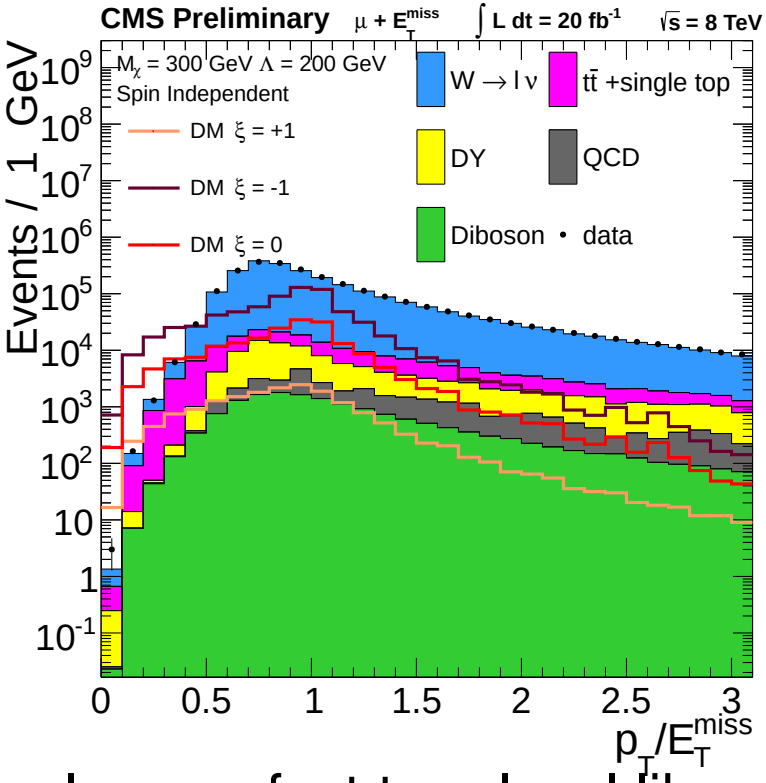
MADGRAPH 5
Model from T.Tait
arXiv:1008.1783

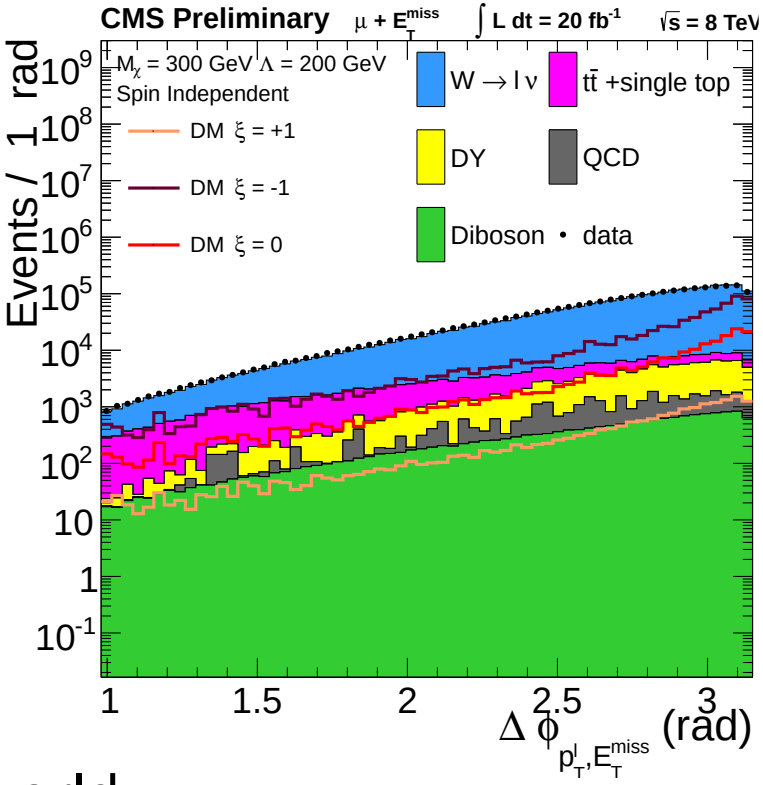


In a perfect tree level like world:
$p_T^l/\not{E}_T = 1$ and $\Delta\phi(p_T^l, \not{E}_T) = \pi$:

$$p_T^l + p_T^\nu = p_T^{\bar{\chi}} + p_T^{\chi}$$
$$\rightarrow p_T^l = p_T^{\bar{\chi}} + p_T^{\chi} - p_T^\nu$$

Reco level kinematics





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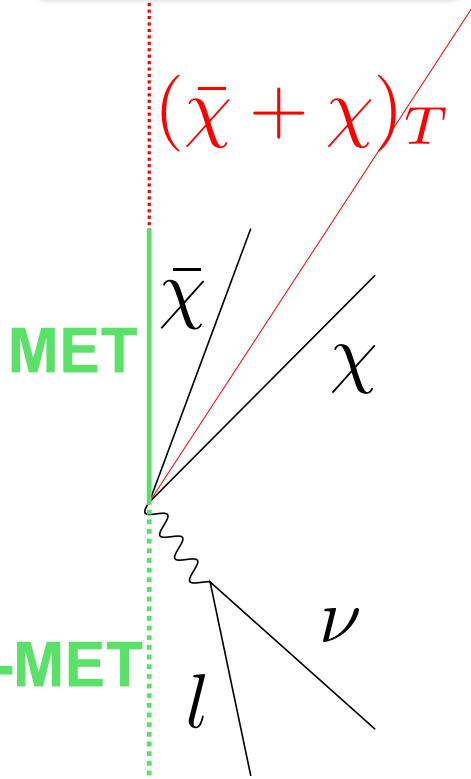

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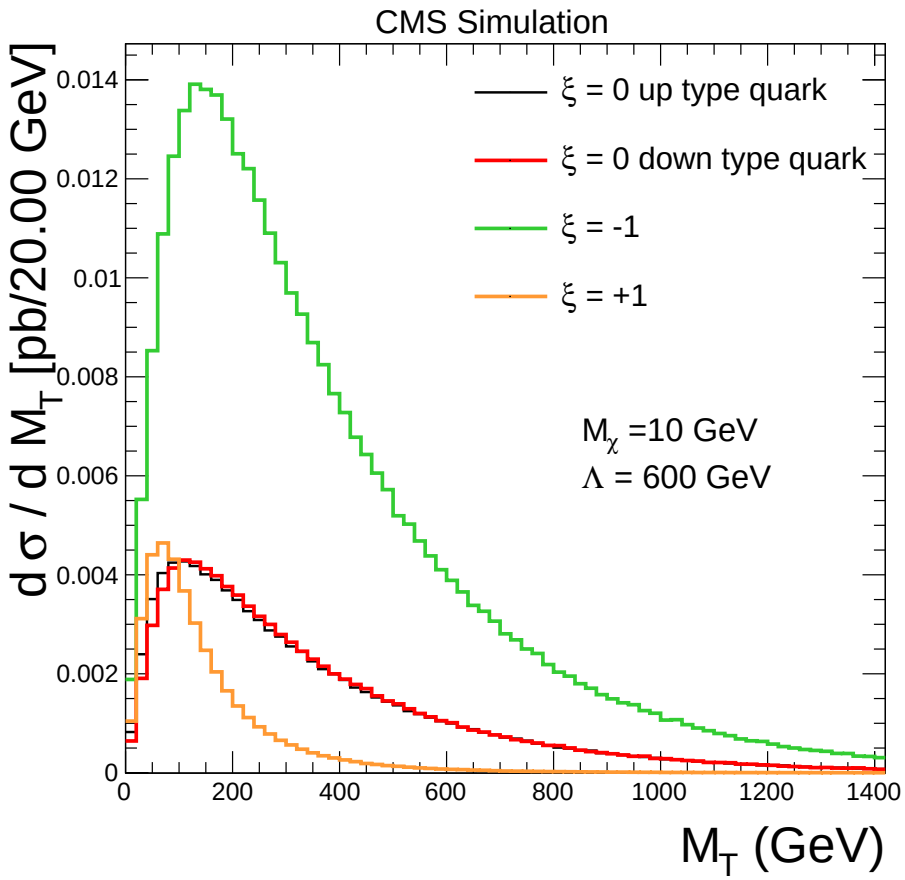
$$p_T^l + p_T^\nu = p_T^{\bar{\chi}} + p_T^{\chi}$$

$$\rightarrow p_T^l = p_T^{\bar{\chi}} + p_T^{\chi} - p_T^\nu$$

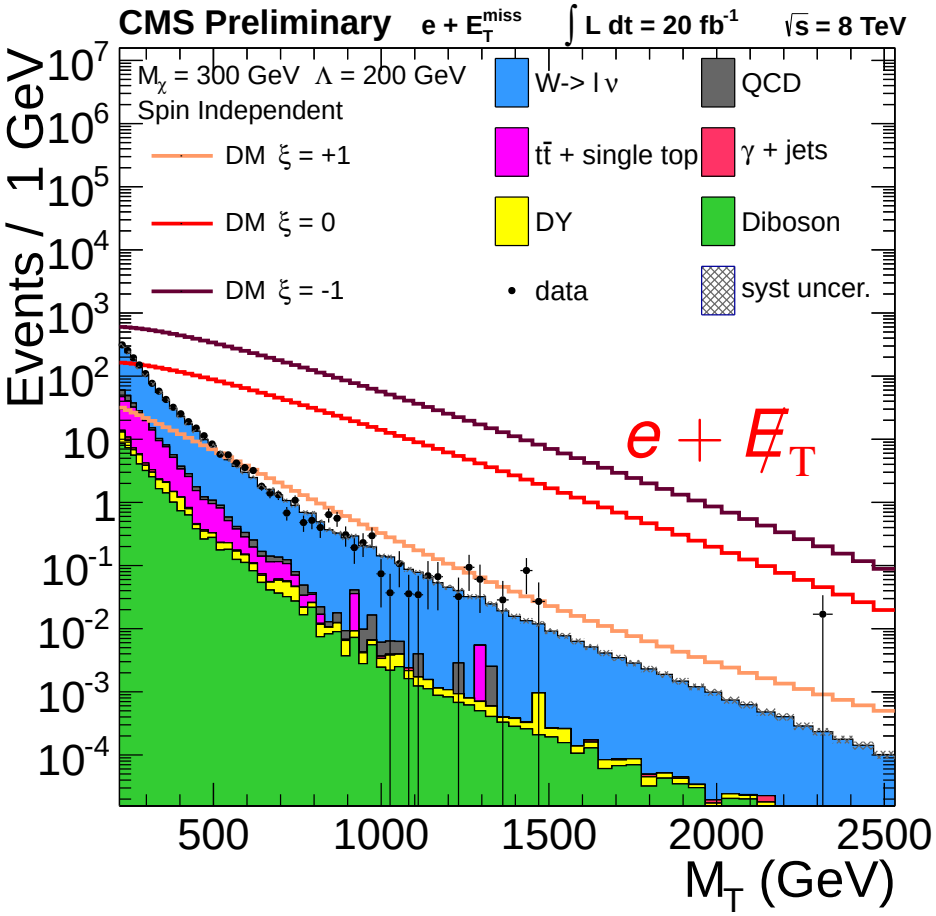
Signal Shape

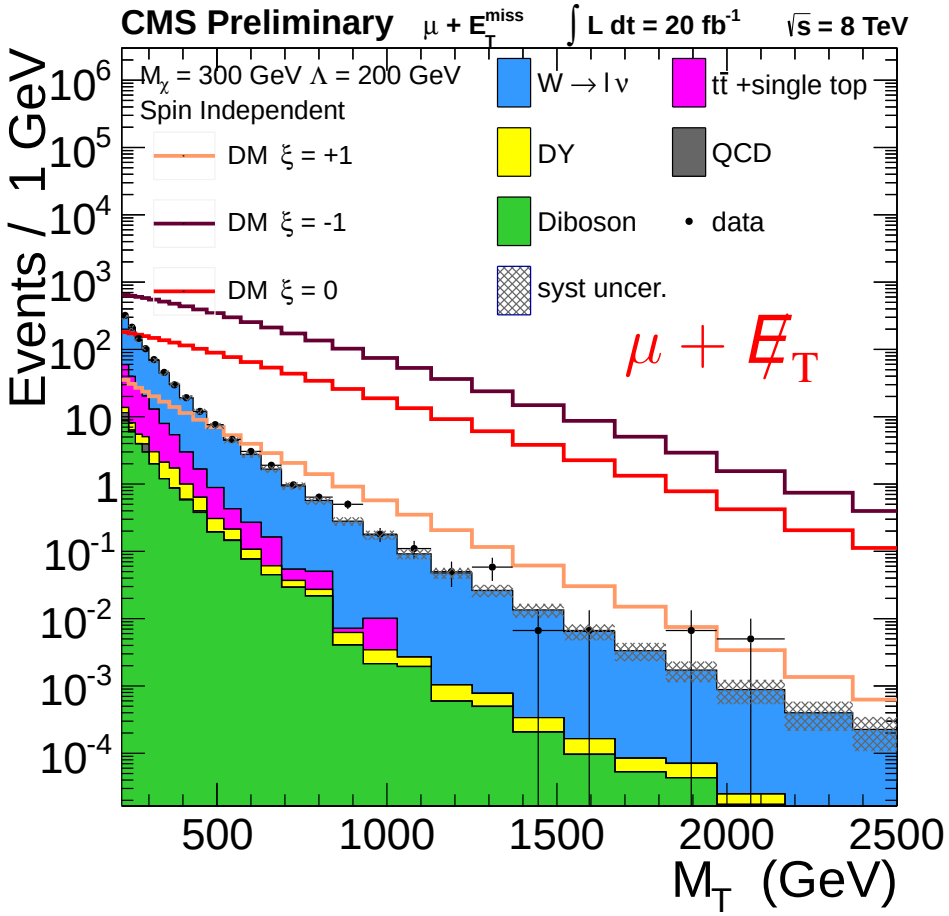
- No difference between only up or only down type quarks
- This is the only channel that is sensitive to the interference.
- Heavier quarks (c,s) production also contributes

signal shape for different ξ



M_T distribution





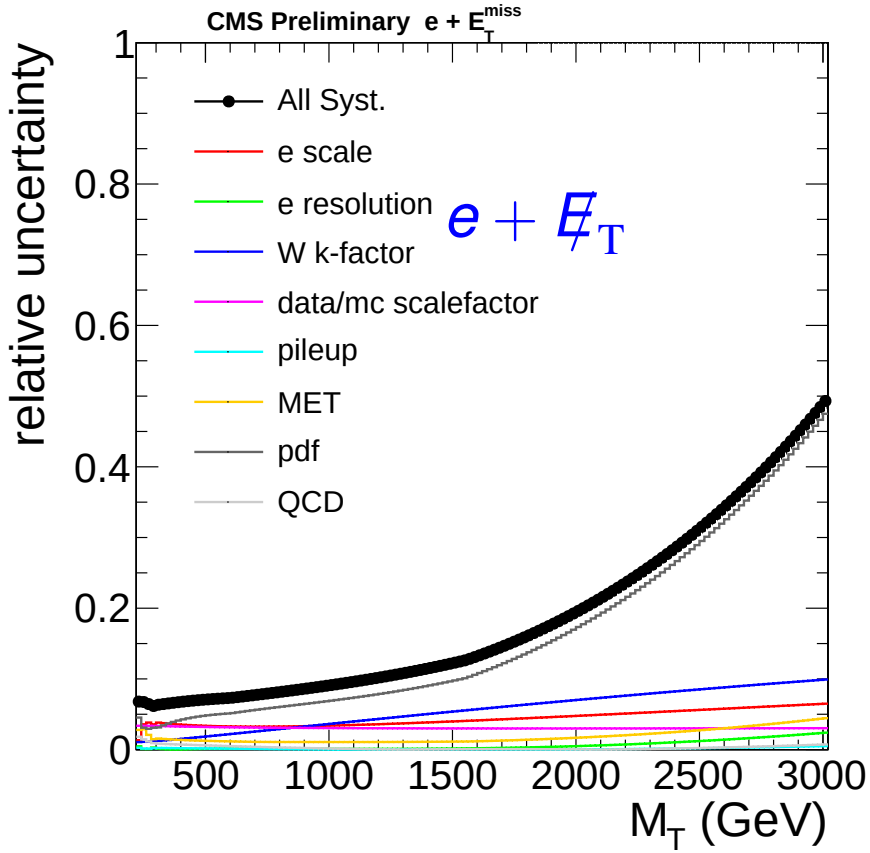
Challenges for mono-lepton

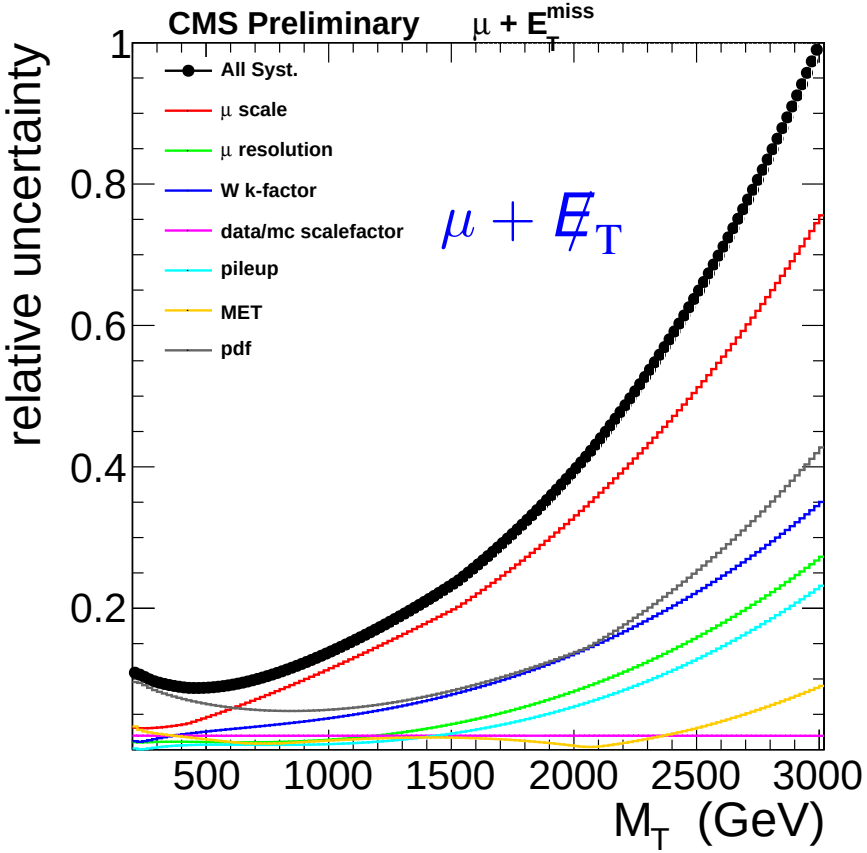
- electron channel benefits from the high ECAL resolution
- Signal would change the steepness
- Low M_T region more sensitive

Limits

Limit calculation

- Multi-bin limit over the hole M_T range
- Bayesian approach
  - Uniform prior for parameter of interest
  - Log-normal priors for systematic uncertainties





Limit calculation

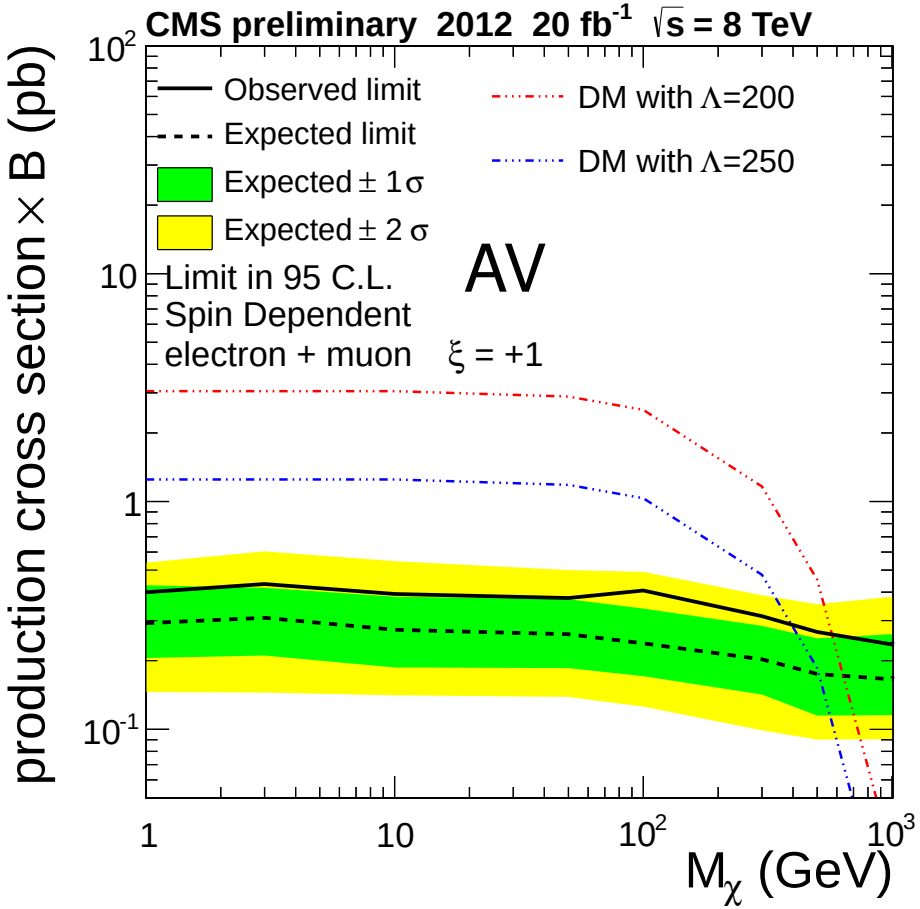
Model parameters:

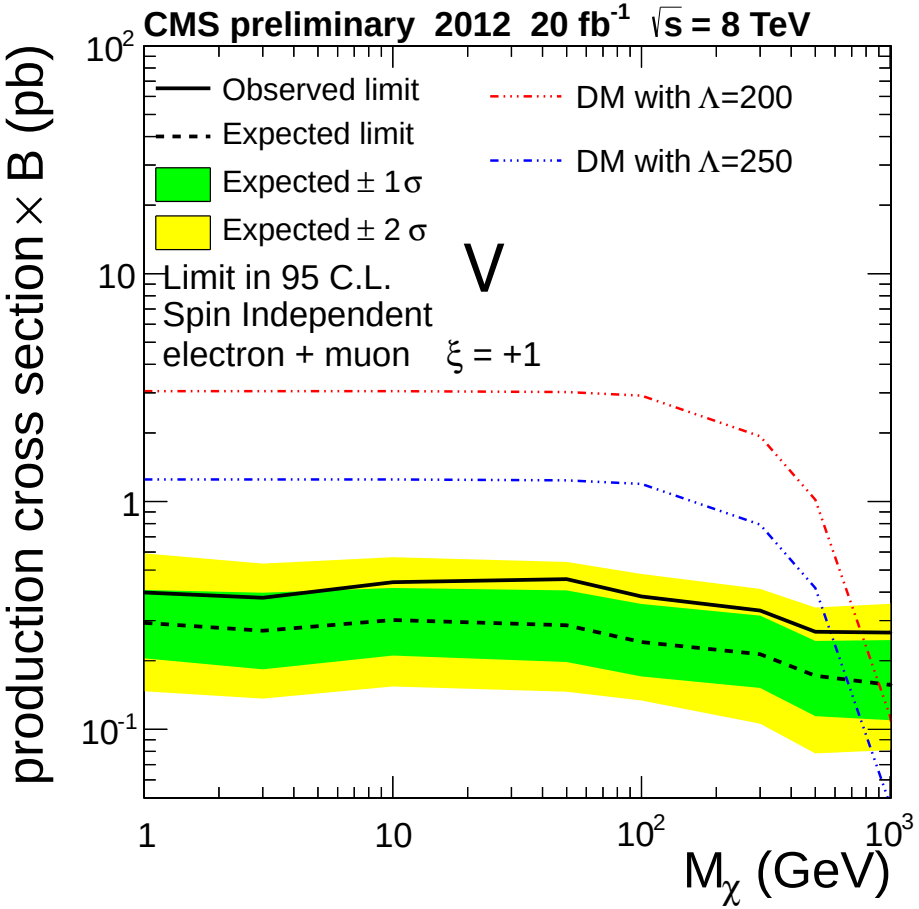
- Coupling: V or AV
- Mass M_χ
- Interaction scale Λ
- Interference parameter ξ

Possible Limits

- Cross section vs. M_χ (direct observable)
- Λ vs. M_χ (direct interpretation)
- Dark matter-nucleon cross section vs. M_χ (recalculation of Λ)

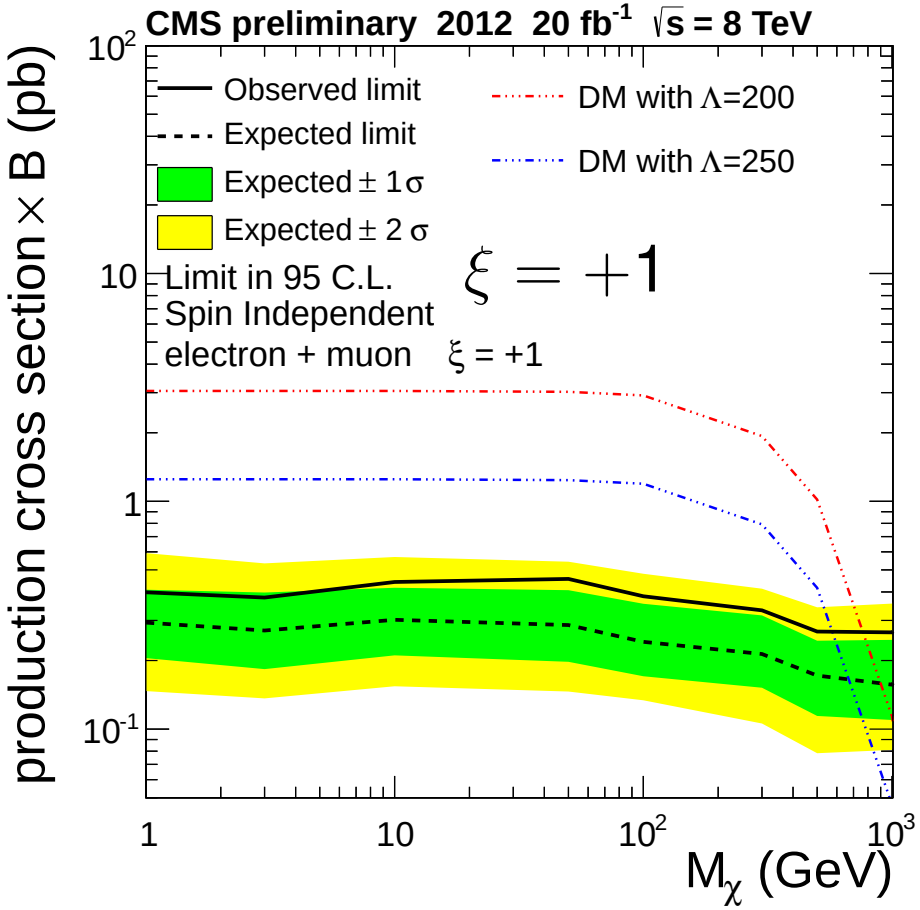
pp-cross section AV vs V

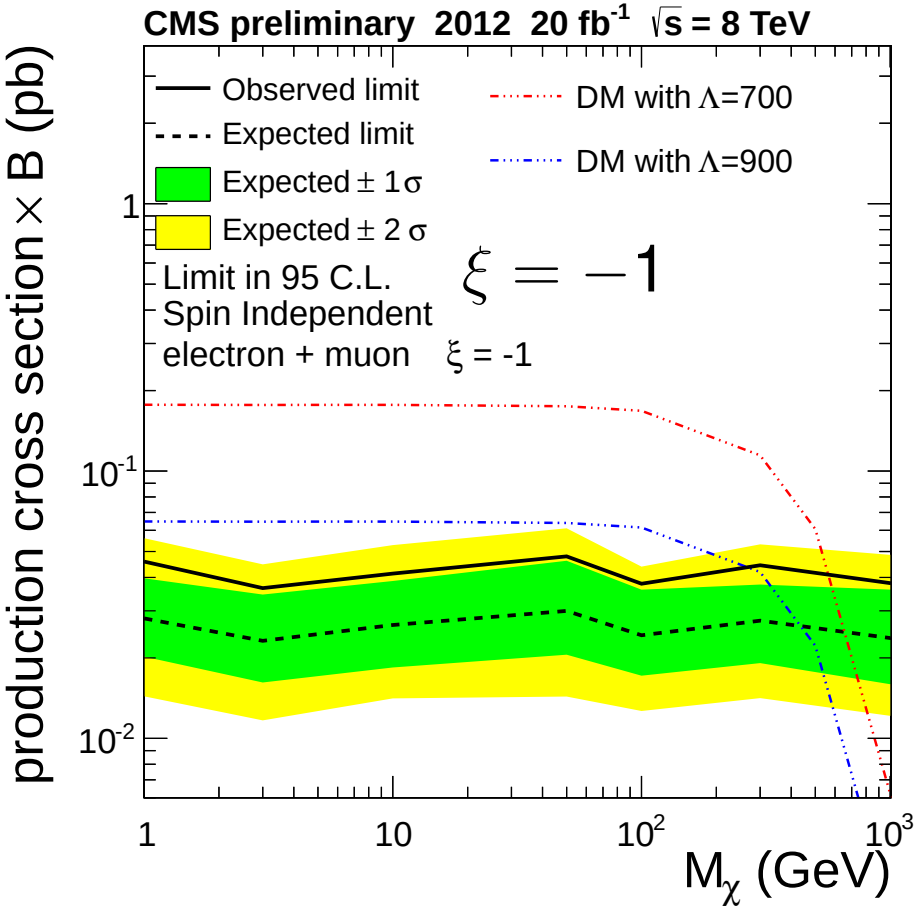




- 95% C.L. exclusion limit on the pp-cross section
- No dependence on M_χ or on the coupling (Vector vs. Axial-vector)

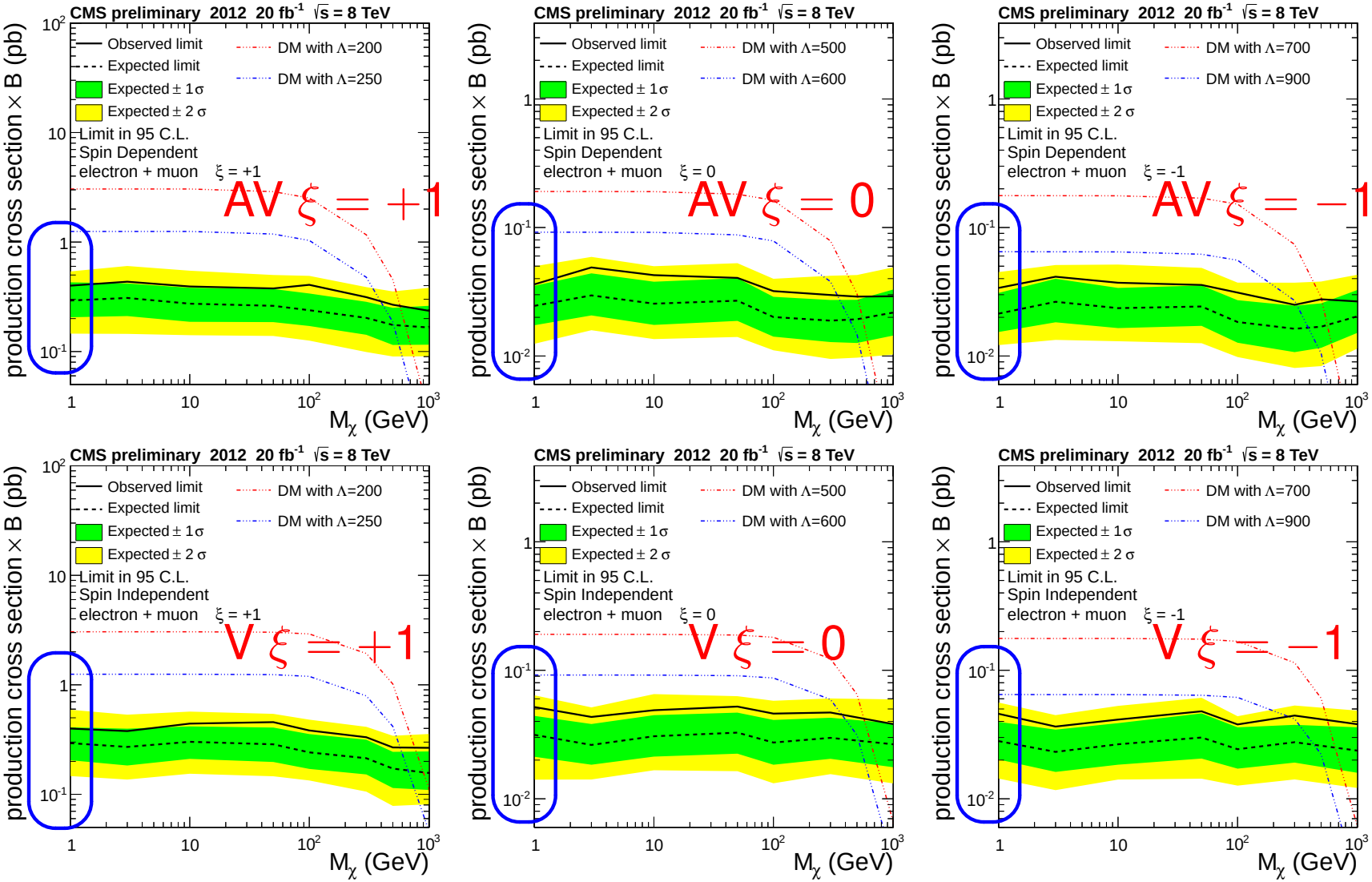
pp-cross section $\xi = -1$ vs $\xi = +1$





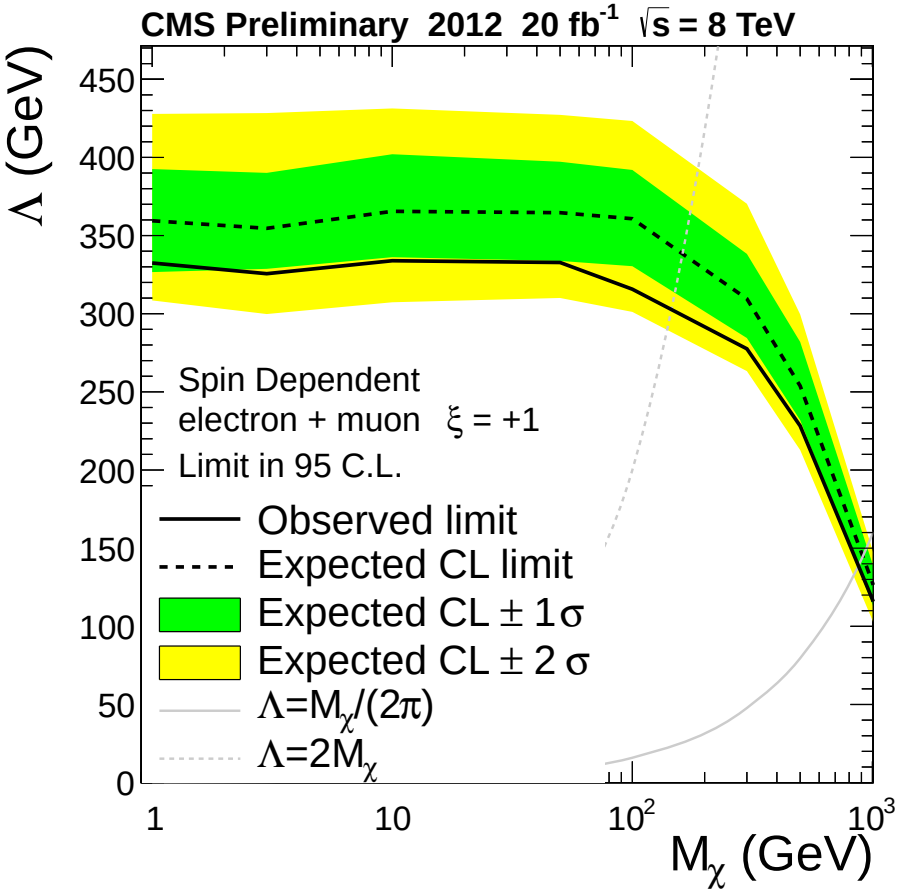
- The important M_T region changes with ξ
- Higher signal efficiency $\rightarrow$ high M_T important

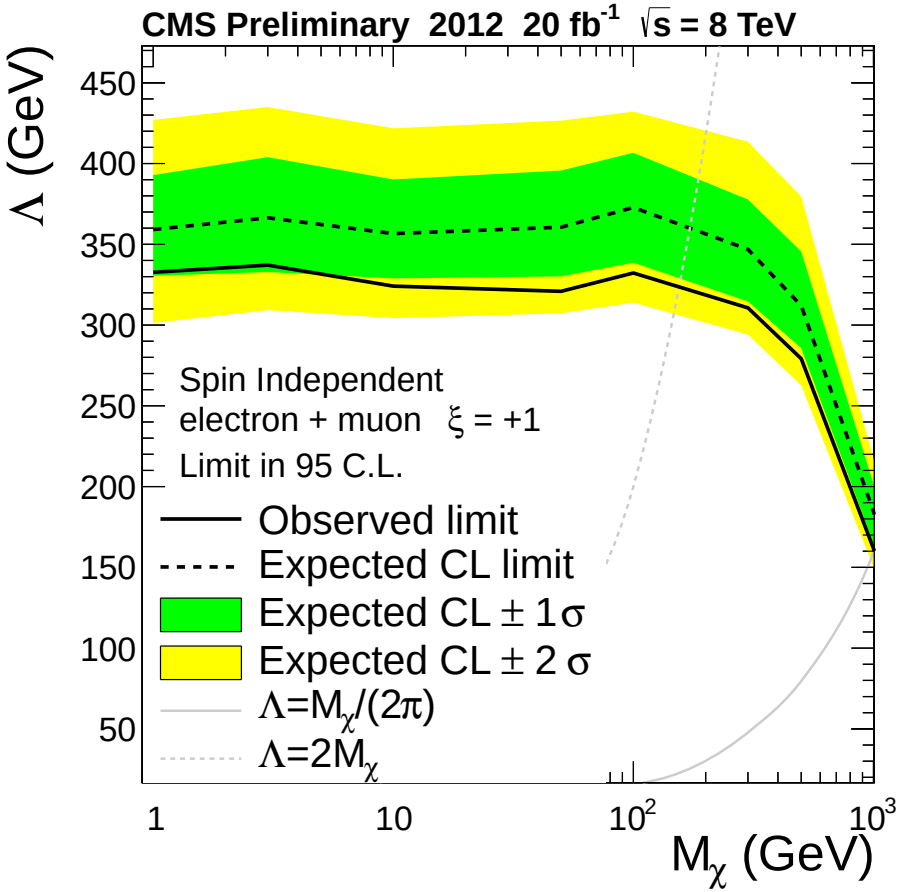
Comparison of all limits on pp-cross section



- limit dependence on ξ
- note the different cross section scales

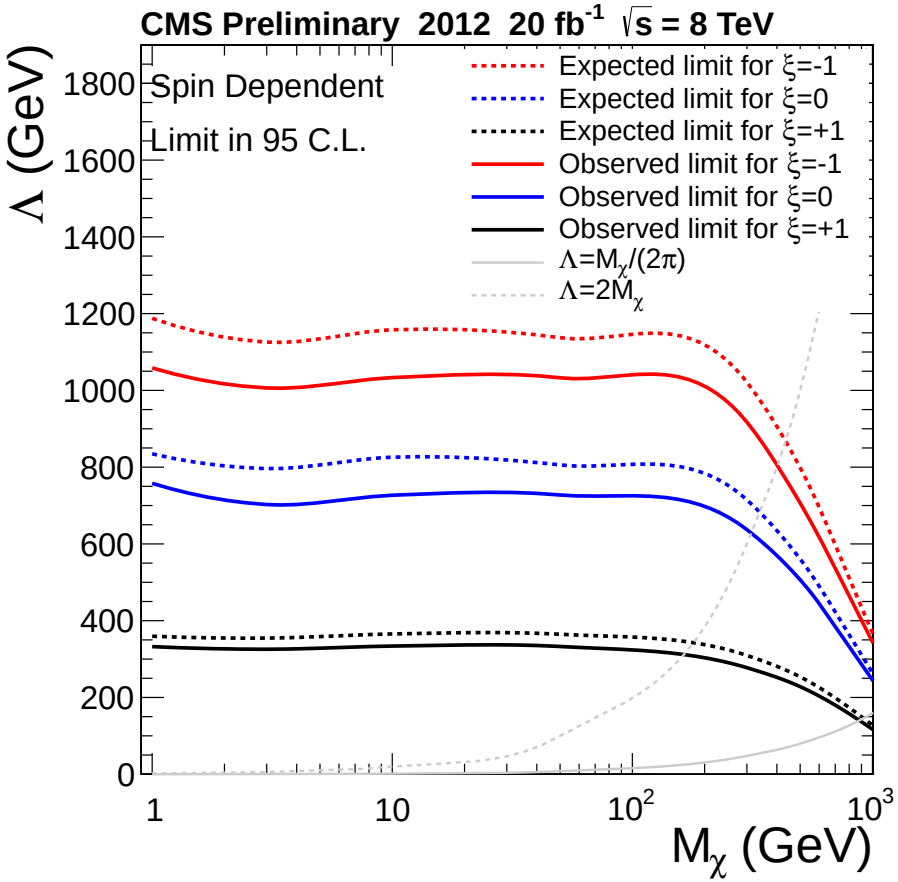
Reinterpretation of σ_{pp} in terms of Λ $\xi = +1$

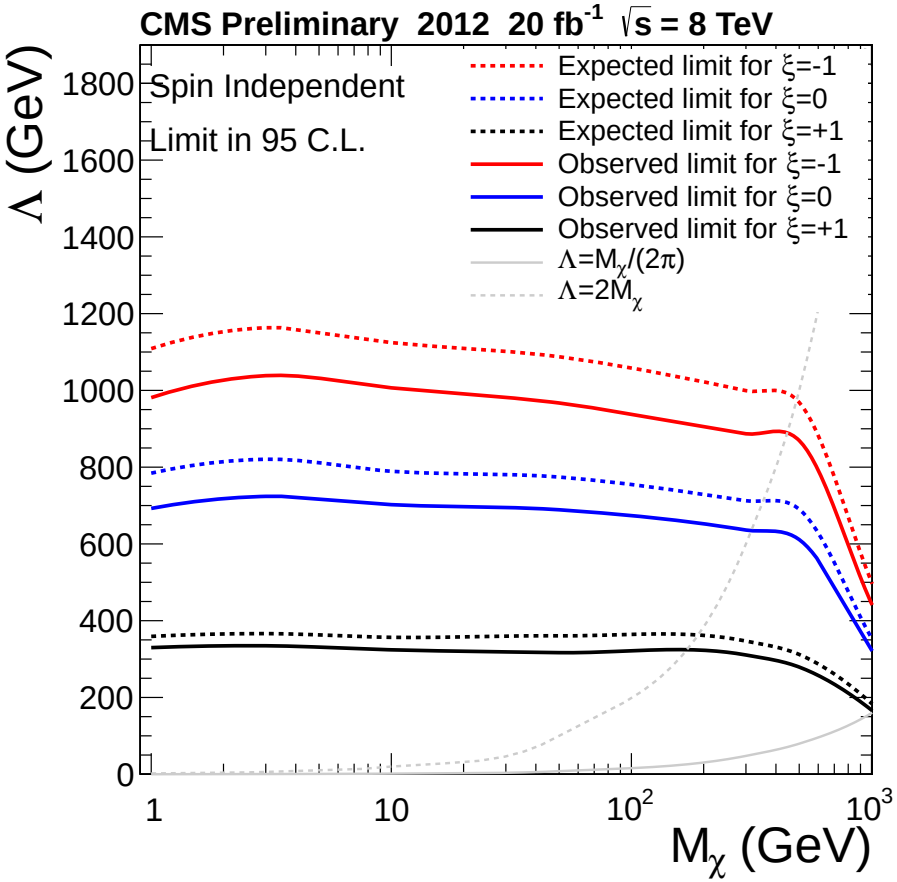




- Effective theory validity shown for $\Lambda \gtrsim 2M_\chi$ ($g_\chi g_q = 1$) and $\Lambda \gtrsim M_\chi/(2\pi)$ ($g_\chi g_q = (4\pi)^2$)
- M_χ dependence of Λ due to production σ
- No phase-space for high M_χ

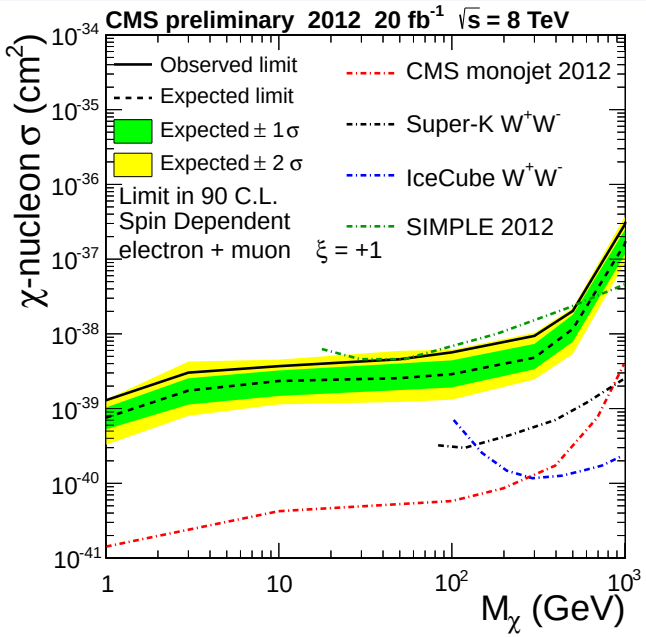
Λ limts

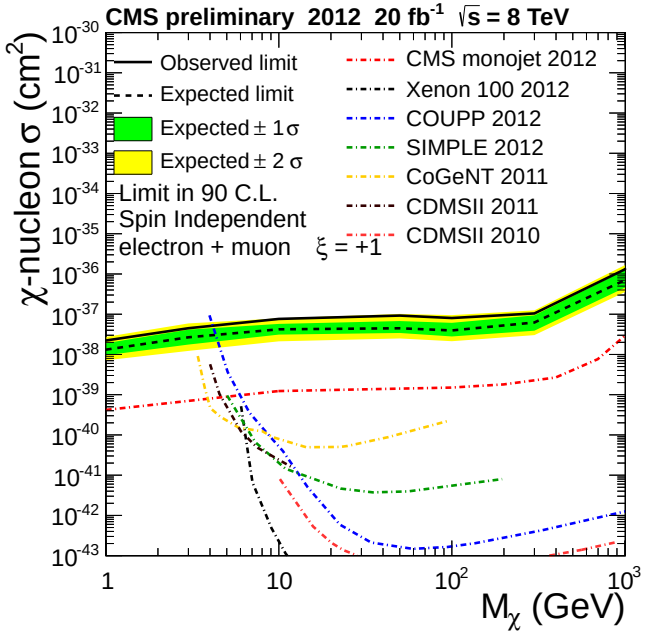




	$\xi=-1$	$\xi=0$	$\xi=+1$	$\xi=-1$	$\xi=0$	$\xi=+1$
M_χ	V Λ[TeV]			AV Λ[TeV]		
1	1.06	0.75	0.33	0.99	0.69	0.33
10	1.05	0.74	0.34	1.01	0.71	0.32
100	1.06	0.75	0.31	1.01	0.70	0.33
500	0.72	0.51	0.23	0.89	0.62	0.28

Limit on DM-proton cross section





- 90% C.L. on the DM-proton cross section
- Allows comparison with other DM experiments

$$\sigma_{SI}(\Lambda) = \frac{\mu^2}{\pi}\left(\sum_q \frac{\xi_q f_q^N}{\Lambda^2}\right)^2 \qquad \Lambda = \Lambda_d = \Lambda_u$$

$$\sigma_{SD}(\Lambda) = \frac{3\mu^2}{\pi}\left(\sum_q \frac{\xi_q \Delta_q^N}{\Lambda^2}\right)^2 \qquad \mu = \frac{M_\chi \cdot M_p}{M_\chi + M_p}$$

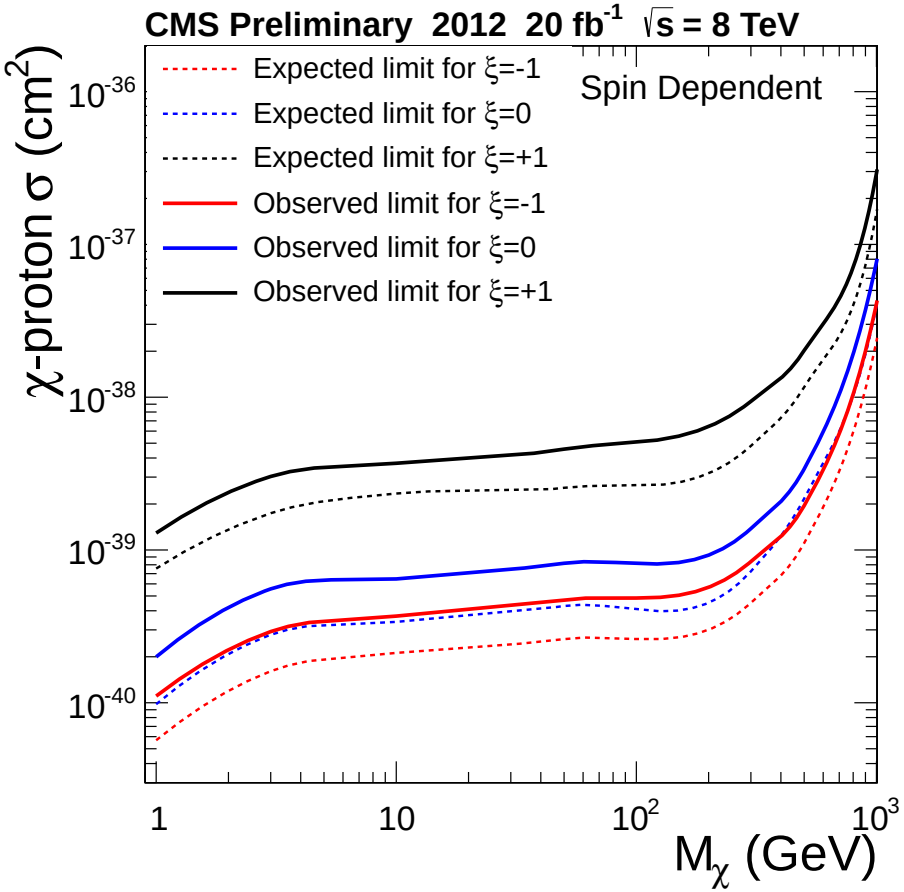
$f_u^p = f_d^n = 2, f_d^p = f_u^n = 1$ and $f = 0$ for other

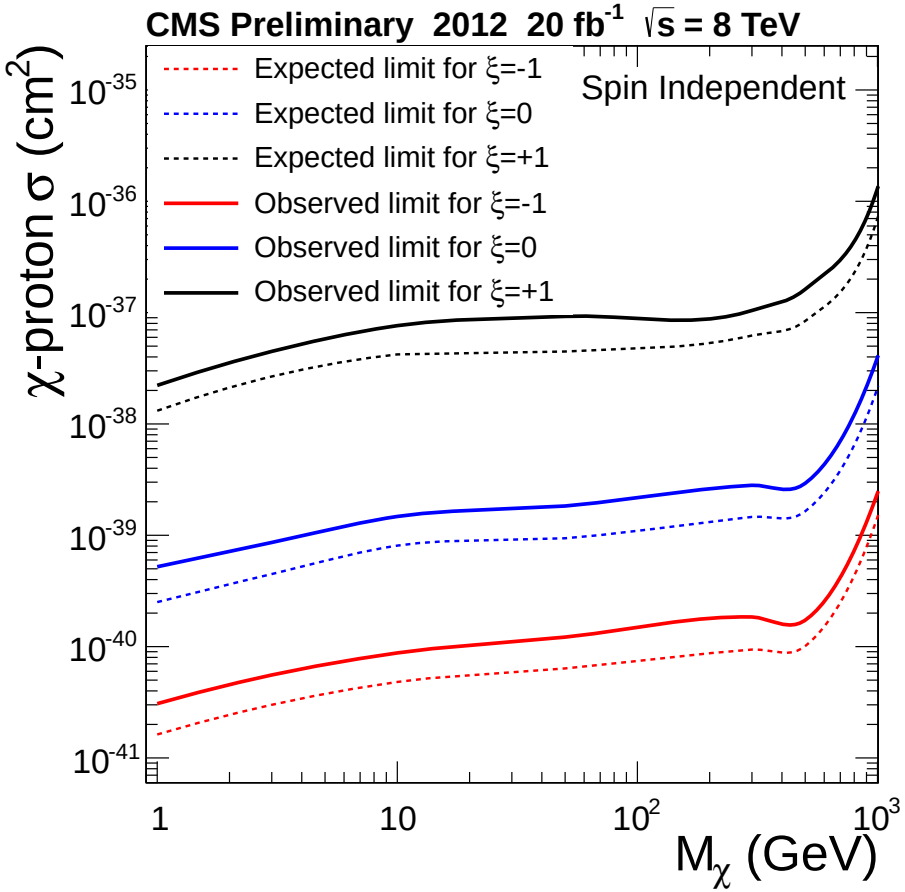
$\Delta_u^p = \Delta_d^n = 0.842 \pm 0.012$

$\Delta_d^p = \Delta_u^n = -0.427 \pm 0.013$

- Recalculation from Λ (not observable)
- direct detection much more sensitive on spin-independent coupling for M_χ>few GeV

Limits for DM-proton σ





	$\xi = -1$		$\xi = 0$		$\xi = +1$	
M_χ	Λ[TeV]	$\sigma_{p\chi}$[cm^2]	Λ[TeV]	$\sigma_{p\chi}$[cm^2]	Λ[TeV]	$\sigma_{p\chi}$[cm^2]
1	0.95	3.5×10^{-41}	0.68	5.5×10^{-40}	0.31	2.7×10^{-38}
10	0.97	1.0×10^{-40}	0.68	1.7×10^{-39}	0.31	9.0×10^{-38}
300	0.86	1.9×10^{-40}	0.60	3.2×10^{-39}	0.30	1.3×10^{-37}

Summary

- Successfully investigated the mono-lepton dark matter interpretation
- Evaluation of the kinematics for mono-lepton events
- Studied the effect of interference
- No observation of dark matter
- Limits for various scenarios

Backup

Electron selection

Trigger

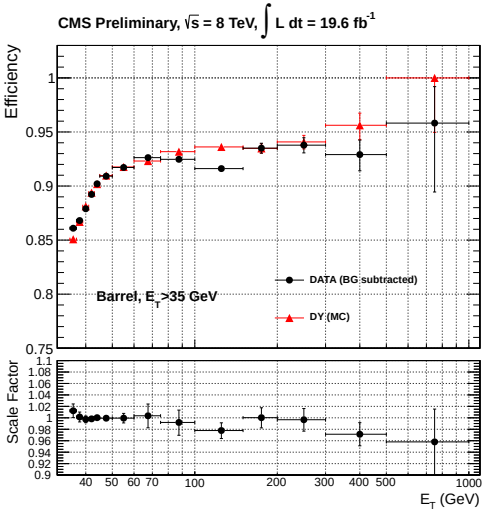
HLT_Ele80_CaloIdVT_TrkIdT, HLT_Ele80_CaloIdVT_GsfTrkIdT,

Exactly one good electron. To avoid turn-on: $E_T > 100$ GeV.

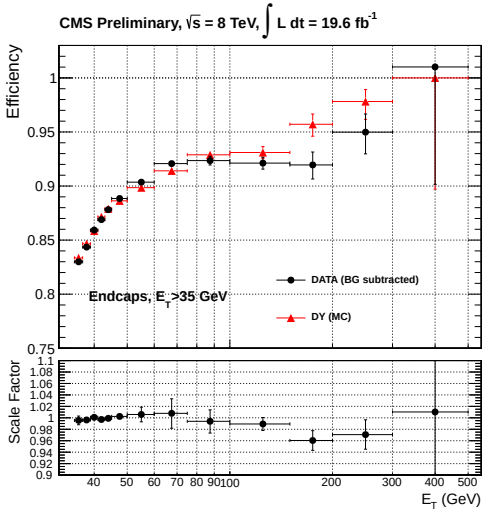
Quantity	HEEP v4.1	
	EB ($0 < \|\eta\| < 1.442$)	EE ($1.56 < \|\eta\| < 2.5$)
SC E_T	35 GeV	35 GeV
$\|\Delta\eta\|$	0.005	0.007
$\|\Delta\phi\|$	0.06	0.06
H/E	0.05	0.05
$\sigma_{i\eta i\eta}$	-	0.03
E^{2x5}/E^{5x5}	>0.94 or E1x5/E5x5 > 0.83	-
EM + Had Depth 1 Iso	$< \rho$*0.28 + 2+ 0.03*Et	$< \rho$*0.28 + 1+ 0.03*Et (p_T>50 GeV) $< \rho$*0.28 + 2.5 (p_T<50)
Tracker Isolation	5 GeV	5 GeV
Inner Layer Lost Hits	≤ 1	≤ 1
$\|d_{xy}\|$	< 0.02 cm	< 0.05 cm

Electron Performance in CMS

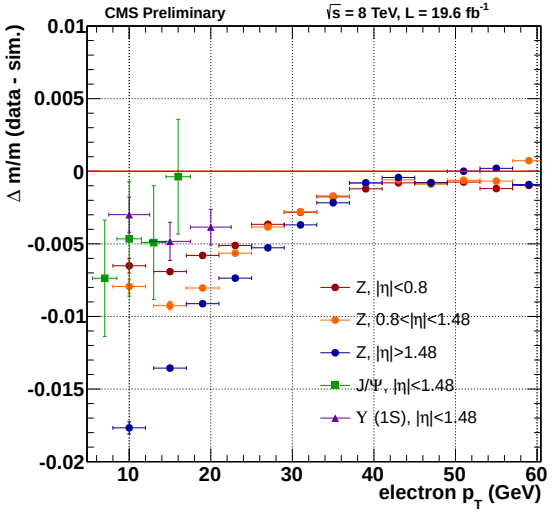
Barrel HEEP ID



Endcap HEEP ID



Electron Resolution



- Good data-mc agreement for the HEEP ID
- Identification easier for high p_T
- Electron resolution well simulated for in the accessible region

Muon selection

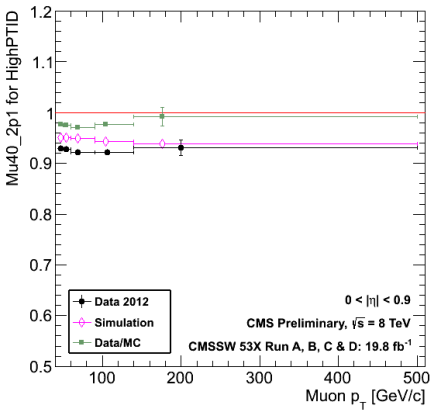
Trigger

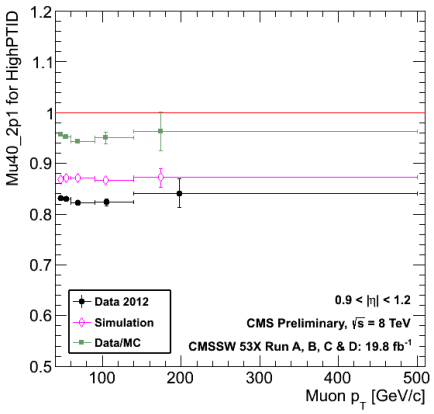
HLT_Mu40_eta2p1

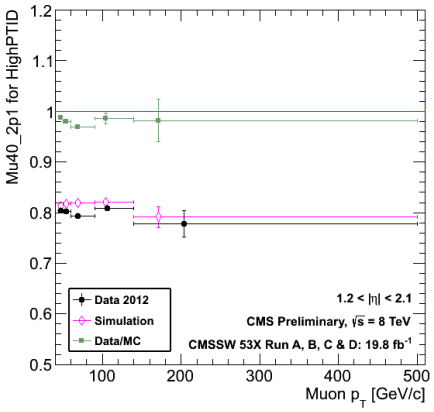
Require exactly one good muon. The muon has to be a global muon and a tracker muon at the same time, with

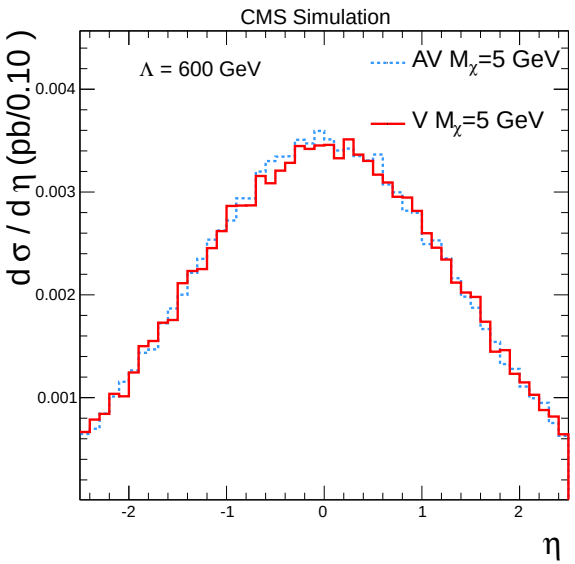
- at least one hit from the muon detector in the global track,
- at least one hit from the pixel detector from the global track, and
- muon segments in at least two muon stations.
- the transverse impact parameter with respect to the beamspot of less than 0.2 mm in order to further reduce cosmic background.
- the longitudinal distance of the tracker track wrt. the primary vertex is d_z <5 mm.
- to guarantee a good p_{T} measurement more than five tracker layers with hit(s) are required.
- $\Delta p_{\mathrm{T}}/p_{\mathrm{T}} < 0.3$, to suppress muons with an uncertain p_{T}.

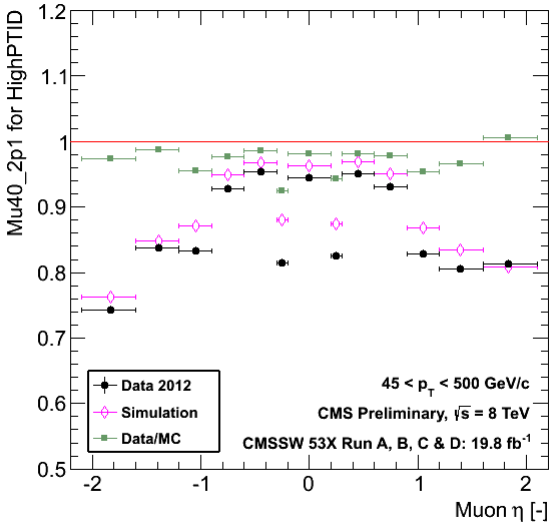
Muon Performance in CMS











- Strong η dependence of the single muon trigger
- Signal produced in the central region
- Flat efficiency for high p_{T}

possible couplings

The focus of recent papers was on the vector, axial vector like coupling:

$$\text{Vector: } \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad \bar{q}\gamma_\mu q$$

$$\text{Axial-Vector: } \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad \bar{q}\gamma_\mu\gamma^5 q$$

For a detailed study look at paper Beltran et al. (arXiv:0808.3384).

Scalar like

$$\frac{m_q}{\Lambda^3}\bar{\chi}\chi \quad \bar{q}q$$

$$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi \quad \bar{q}q$$

$$\frac{m_q}{\Lambda^3}\bar{\chi}\chi \quad \bar{q}\gamma^5 q$$

$$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi \quad \bar{q}\gamma^5 q$$

Vector like

$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad \bar{q}\gamma_\mu q$$

$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad \bar{q}\gamma_\mu q$$

$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad \bar{q}\gamma_\mu\gamma^5 q$$

$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad \bar{q}\gamma_\mu\gamma^5 q$$

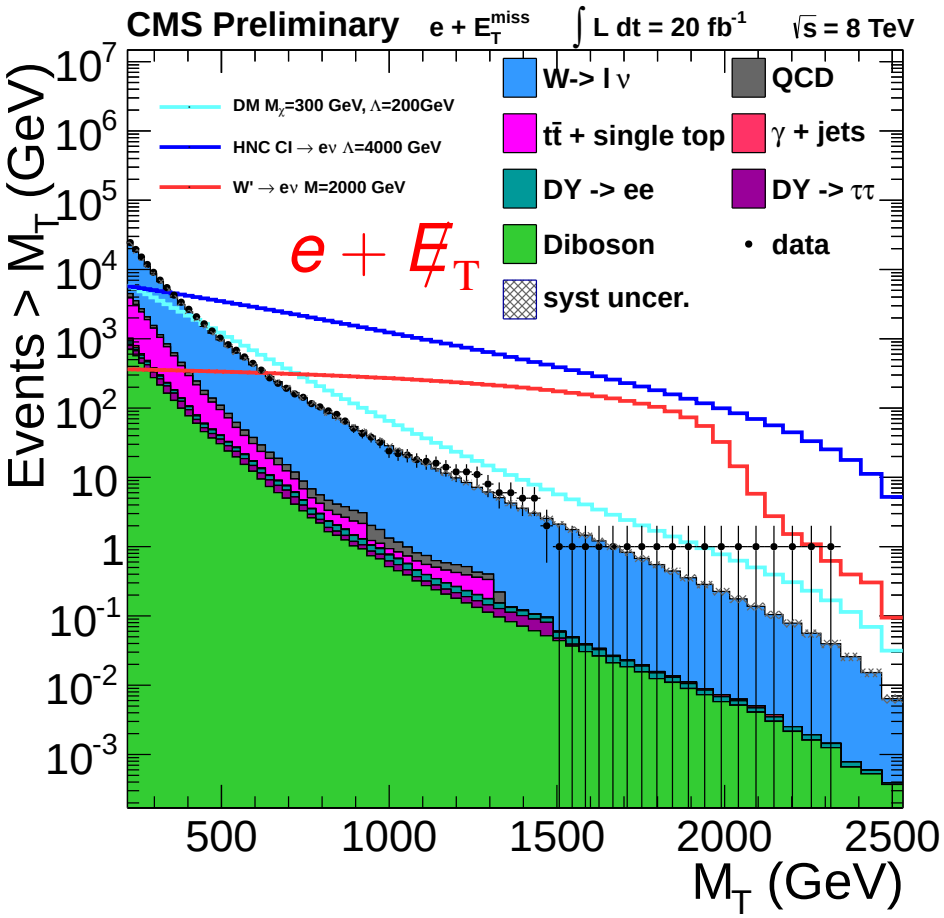
Tensor like

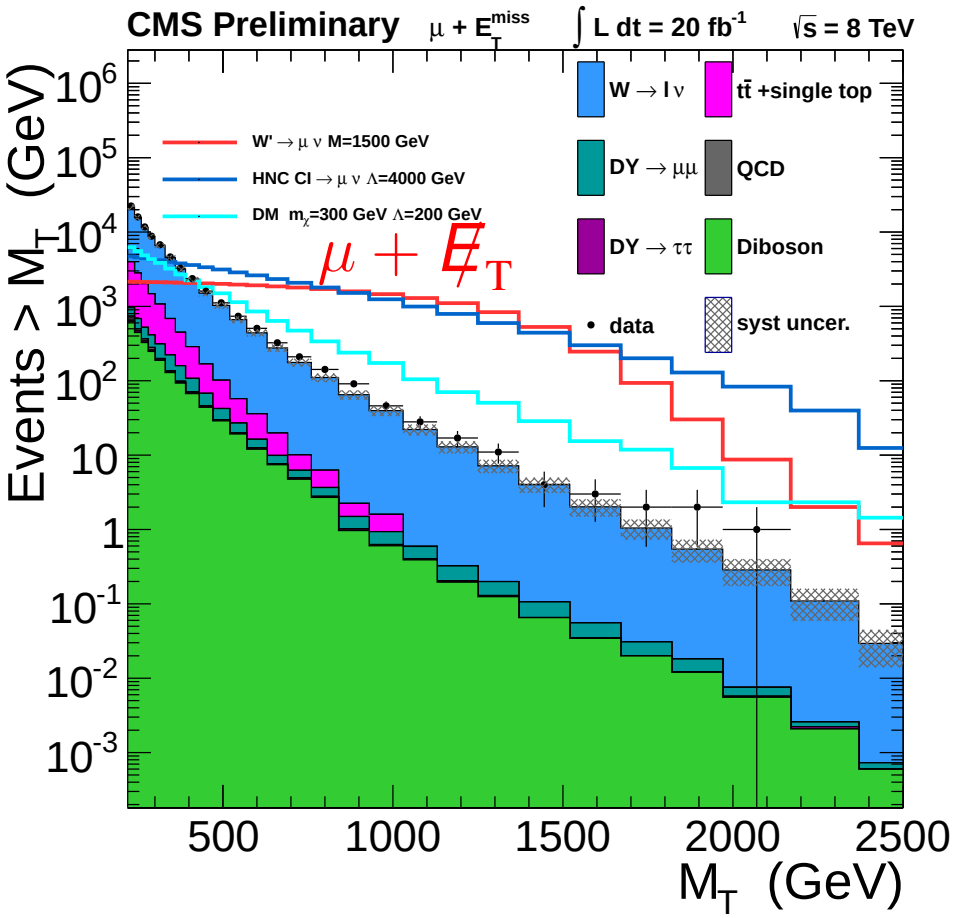
$$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi \quad \bar{q}\sigma_{\mu\nu} q$$

$$\frac{1}{\Lambda^2}\epsilon^{\mu\nu\alpha\beta}\bar{\chi}\sigma^{\mu\nu}\chi \quad \bar{q}\sigma_{\alpha\beta} q$$

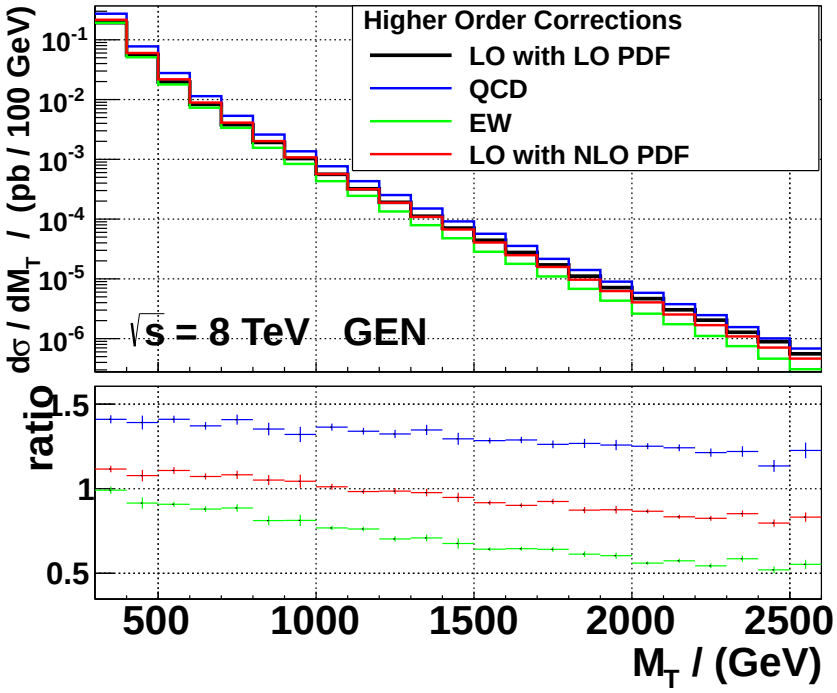
strong gluon Coupling

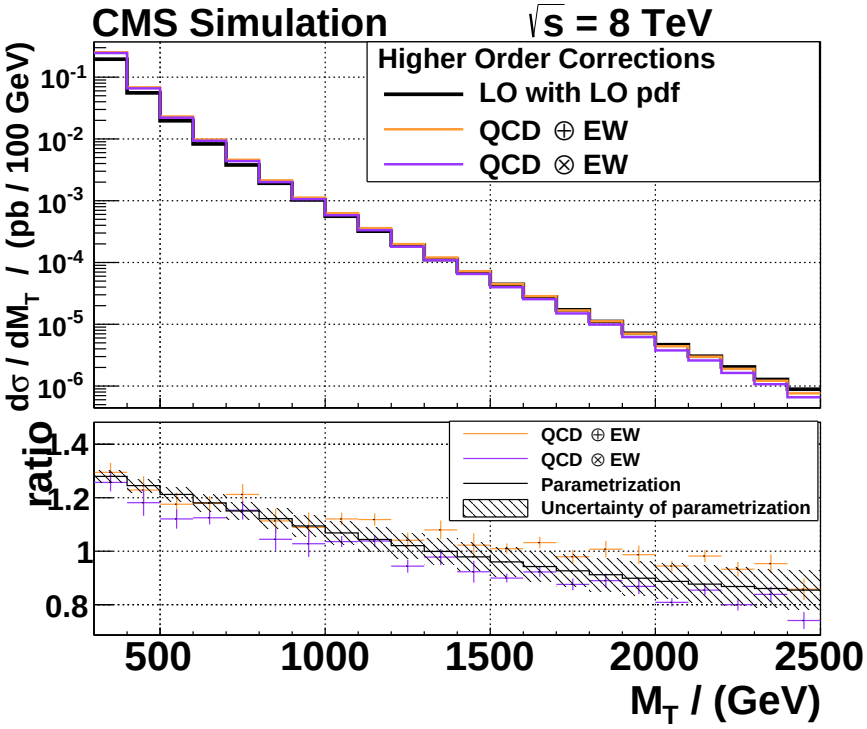
Cumulative M_T distribution





NLO Corrections W





- NLO QCD with MCatNLO
- NLO EW with HORACE
- $k(M_T) = \frac{\Delta\sigma(\mathrm{NLO})/\Delta M_T}{\Delta\sigma(\mathrm{LO})/\Delta M_T}$
- combination additive and multiplicative

Interference

vector-coupling:
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad (\bar{u}\gamma^\mu u + \xi\bar{d}\gamma_\mu d)$
simplified:
$|(a+\xi b)|^2$
$= |a|^2 + |\xi b|^2 - 2\Re(\xi \cdot a \cdot b)$
$= |a|^2 + |\xi b|^2 - 2 \cdot \xi \cdot a \cdot b$
for $\xi = -1$
$\implies |a|^2 + |b|^2 + 2 \cdot a \cdot b$ (constructive interference)
for $\xi = 0$
$\implies |a|^2$ (no interference)
for $\xi = +1$
$\implies |a|^2 + |b|^2 - 2 \cdot a \cdot b$ (destructive interference)