Where is the New Physics ?

EXOTICA ?

EXOTICA at the CMS

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National Centre for Nuclear Research

NCBJ – Warsaw, Poland

Compact Muon Solenoid experiment at the CERN's LHC

2nd International Conference on New Frontiers in Physics

28 Aug - 5 Sep 2013

Kolymbari, Crete, Greece

EXOTICA at CMS

OUTLINE:

Short intro

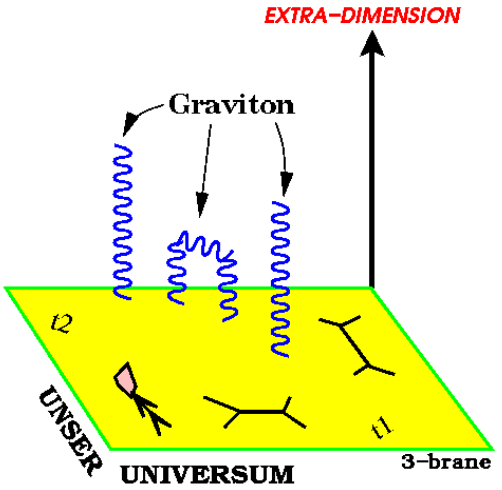
- What is EXOTICA at the CMS?
  - Beyond Standard Model physics
    & which is not a simple SUperSYmmetry
  - Unusual signatures

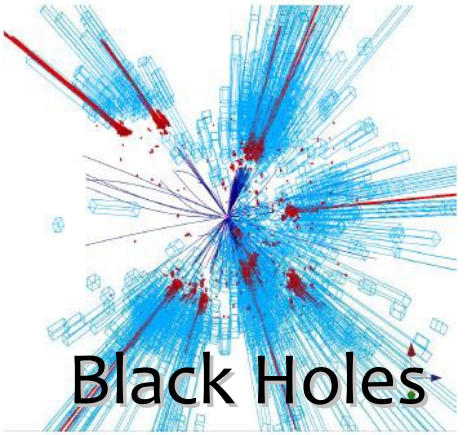
Main part

- Review of selected EXOTIC searches
  - EXO publications > 100 (2009-2013)
  - New results from CMS data collected in 2012 with **20/fb at 8 TeV**

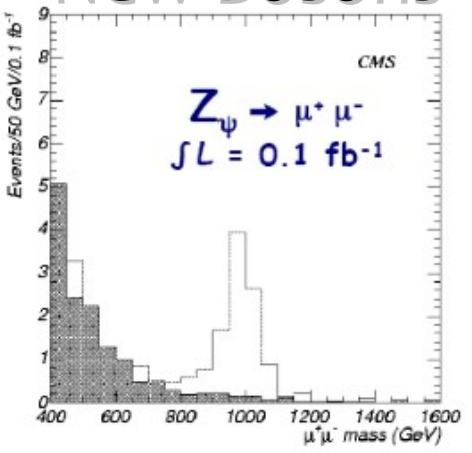
Exotic New Physics

- Extra dimensions
- New Gauge Bosons
- LeptoQuarks
- Black Holes
- Little Higgs theories
- Dark Matter
- Split SUSY, GMSB
- Hidden Valley
- . . .

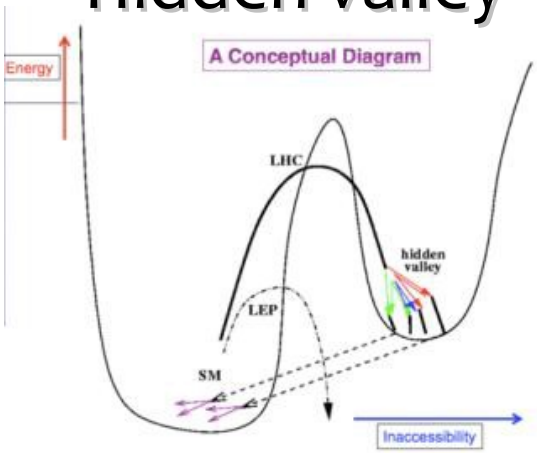




New Bosons

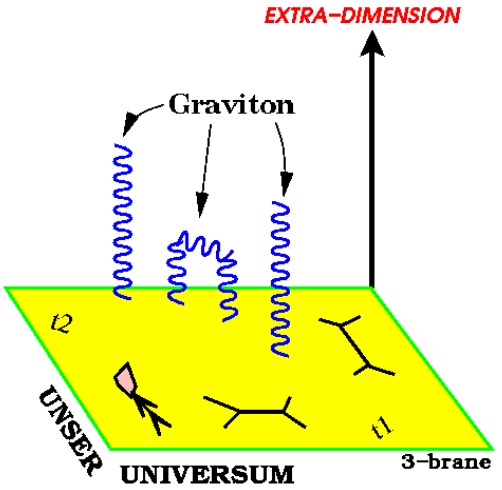


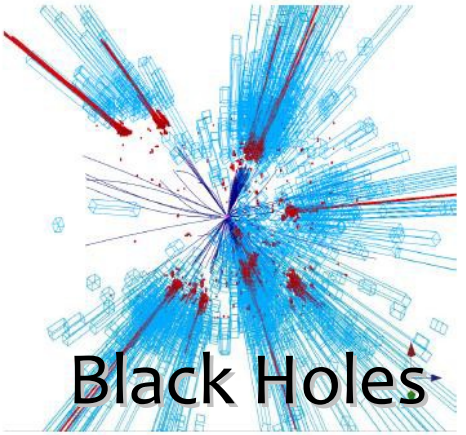
Hidden valley



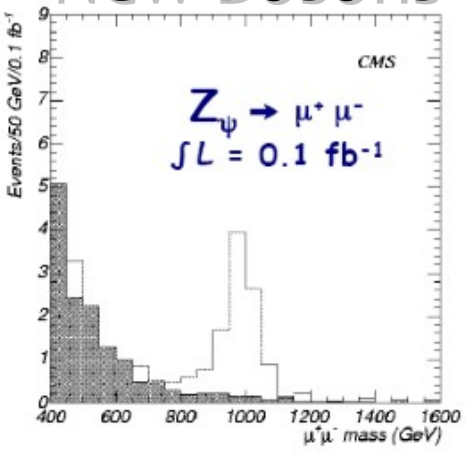
Signatures of Exotic New Physics

- **Resonances**
  - Di-lepton, di-jet
- **Di-bosons**
- **Multi-jets**
- **Mono-jet/γ, -lepton**
- **Top-like BSM**
- **Long-lived particles**
  - Delayed, displaced, kink tracks
- **. . .**

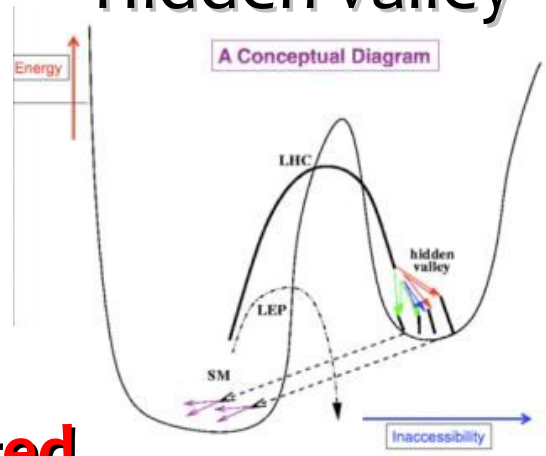




New Bosons



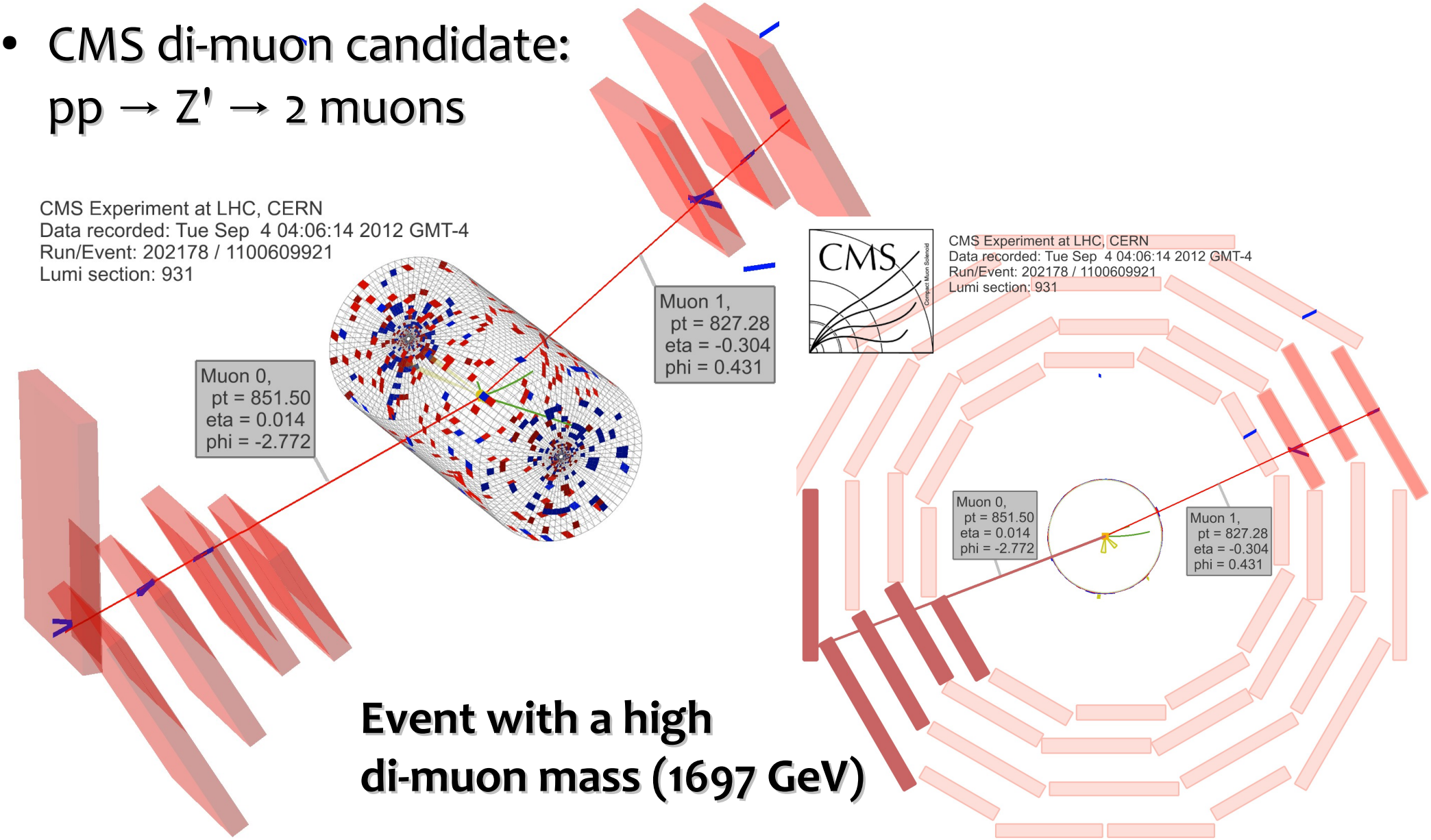
Hidden valley



→ **Only a few analysis can be presented**

Di-lepton Resonances

- CMS di-muon candidate:
  pp → Z′ → 2 muons



Event with a high di-muon mass (1697 GeV)

Di-lepton Resonances

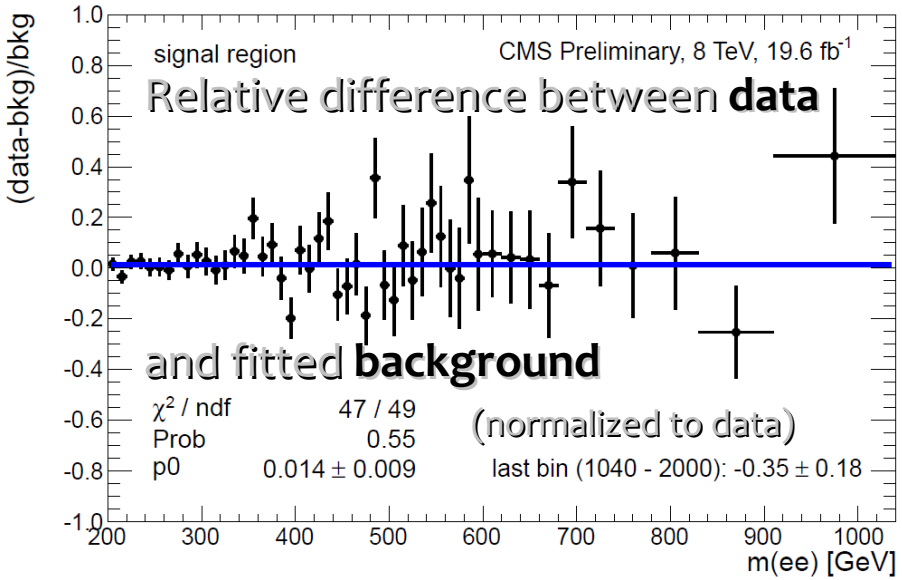
- **Many BSM models predict narrow *di-lep* resonances:**
  - **Grand Unified Theory** – heavy spin 1 boson Z' from broken SO(10)
    - Z'_{ψ} (Γ=14 GeV @ M=2.5 TeV)
  - **Sequential Standard Model** – Z'_{SSM} (Γ=80 GeV @ M=2.5 TeV)
  - **Little Higgs** – heavy gauge bosons Z'
  - **Extra Dimensions** – spin 2 Randall-Sundrum gravitons G*
    and many other models
- **Experimental challenge:**
  - **Reconstruction** of **very high-pT leptons**
    - 1 TeV scale, tails of SM distributions
  - Understand detector effects (efficiencies, uncertainty, trigger)
  - **BUT: clean signal expected**

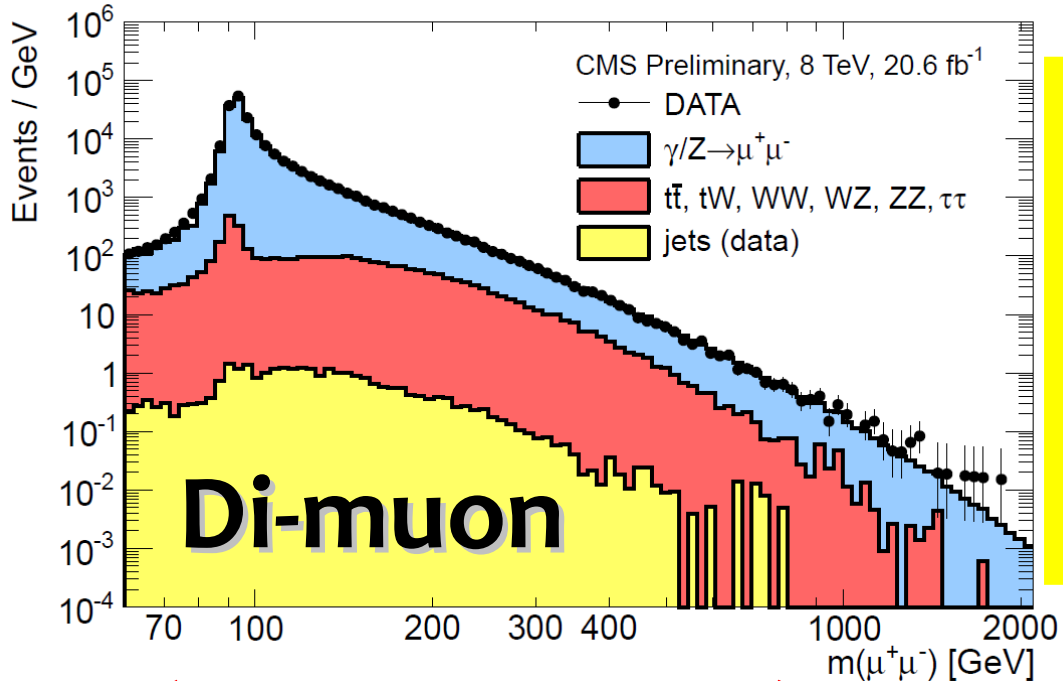
Di-lepton RESULTS

Event selection:

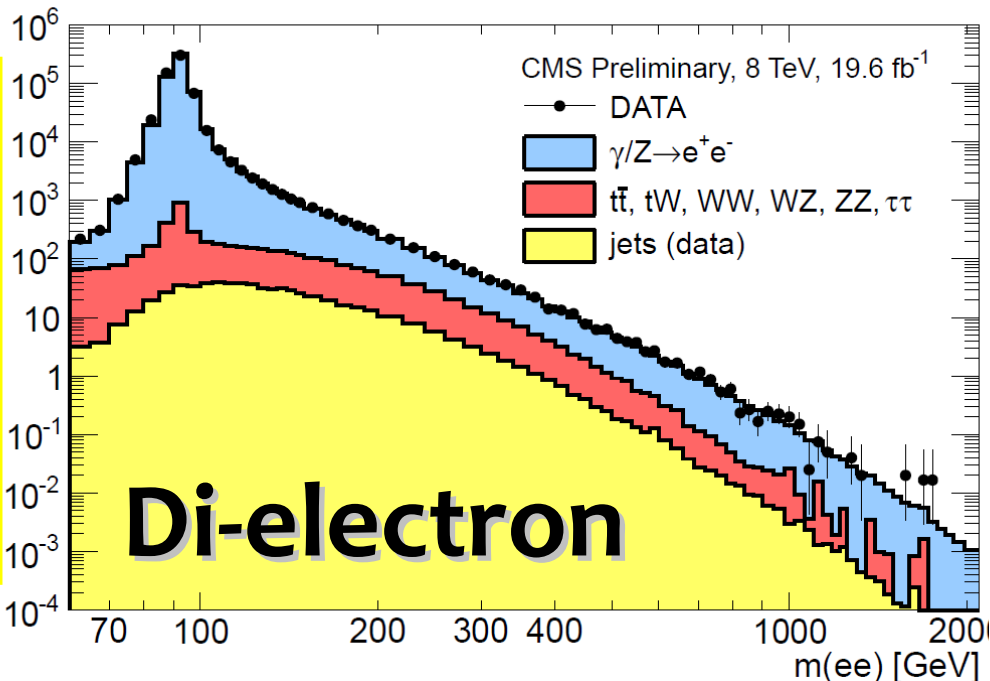
- Double lepton trigger
- isolated electron and muons
  (pT>35 GeV pT>45GeV)

- **Background: (DY, Di-bosons, jets) estimation** from data or MC-based



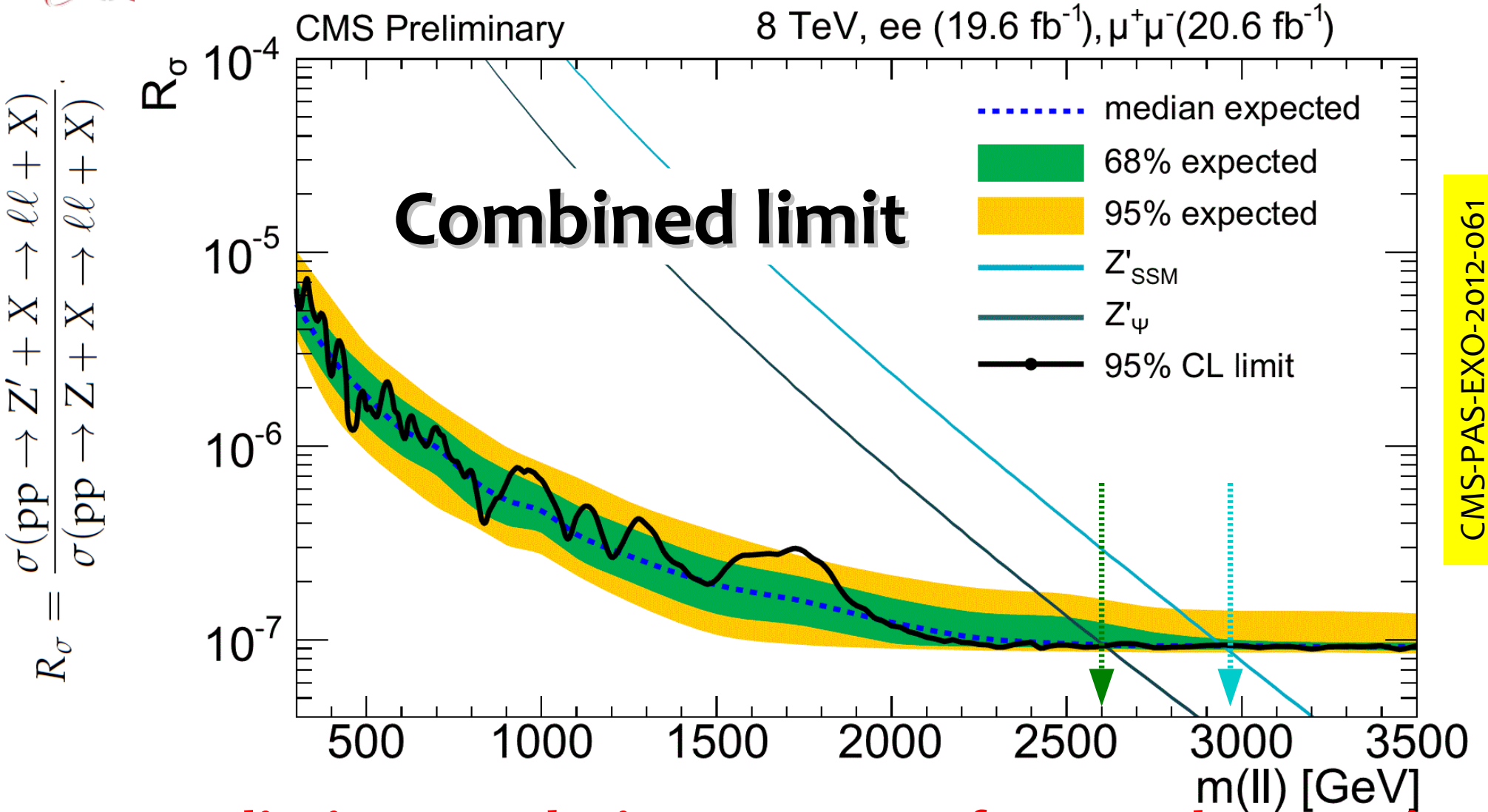


CMS-PAS-EXO-2012-061



NO (statistically significant) excess at high mass, especially at tails of data

LIMITS on Z' from di-leptons



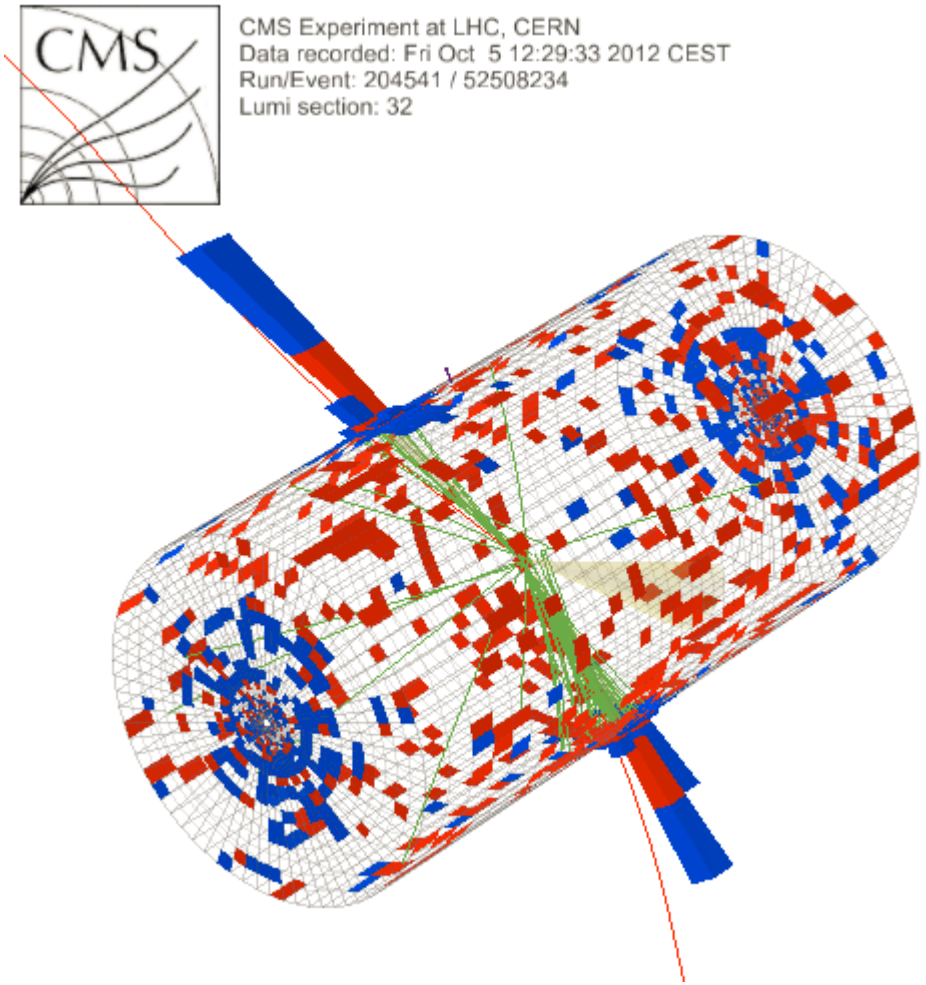
CMS-PAS-EXO-2012-061

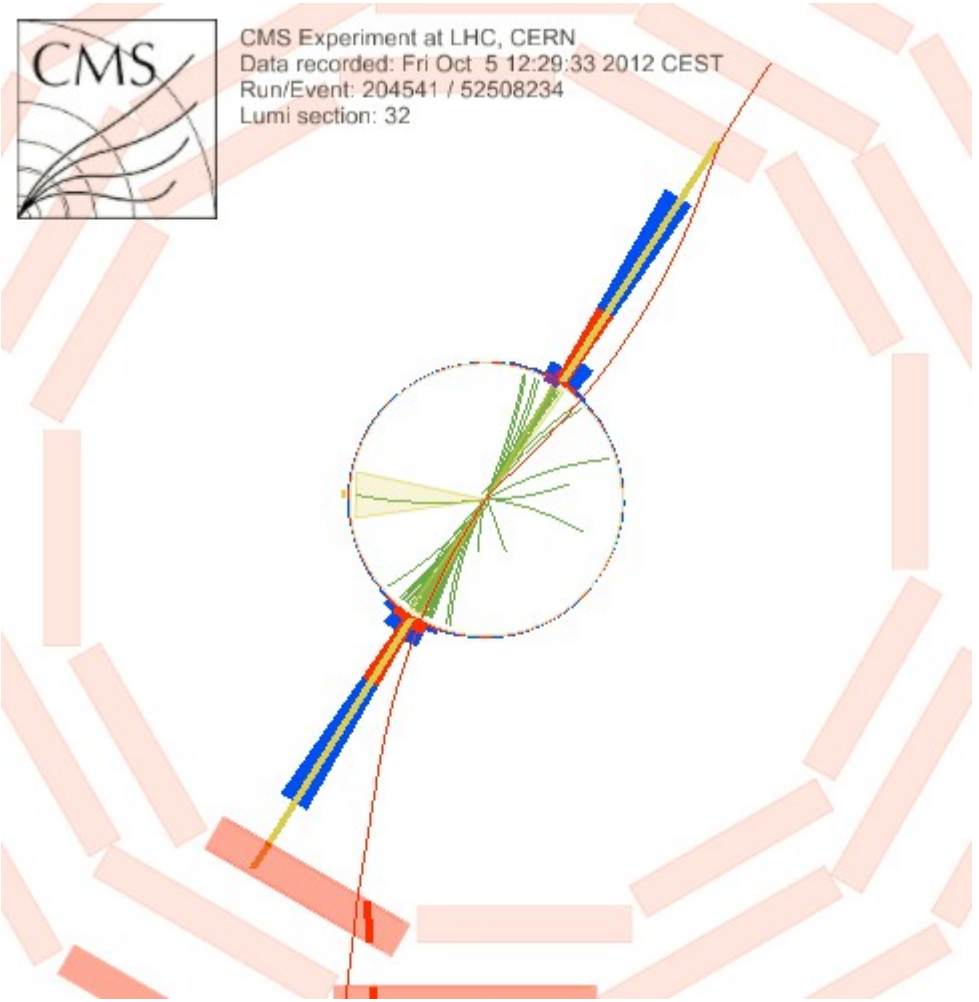
Upper limits on relative x-sec×BR for new boson Z'

m (Z'$_\psi$) > 2.60 TeV and **m (Z'$_{SSM}$) > 2.96 TeV**

Di-jet Resonances

- CMS event with the **highest di-jet mass** (5.15 TeV) in the data pp → X → 2 jets





Di-jet Resonances

CMS-PAS-EXO-2012-059

- Many models of New Physics predict resonances decaying into pairs of **quarks**, **gluons** or **quark-gluon**

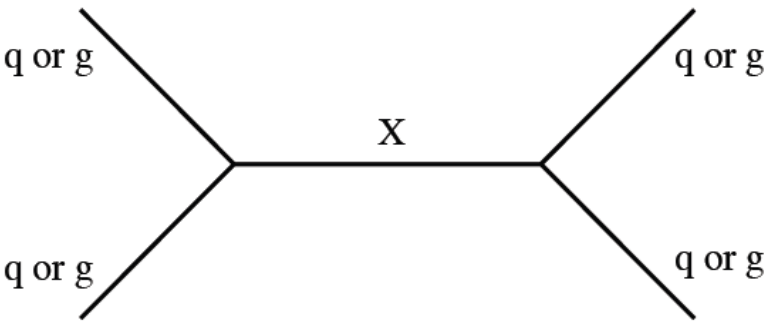
Models	X
Excited quark	q*
E_6 Diquark	D
Axigluon	A
Coloron	C
RS Graviton	G
Heavy W	W'
Heavy Z	Z'
String	S

Trigger:

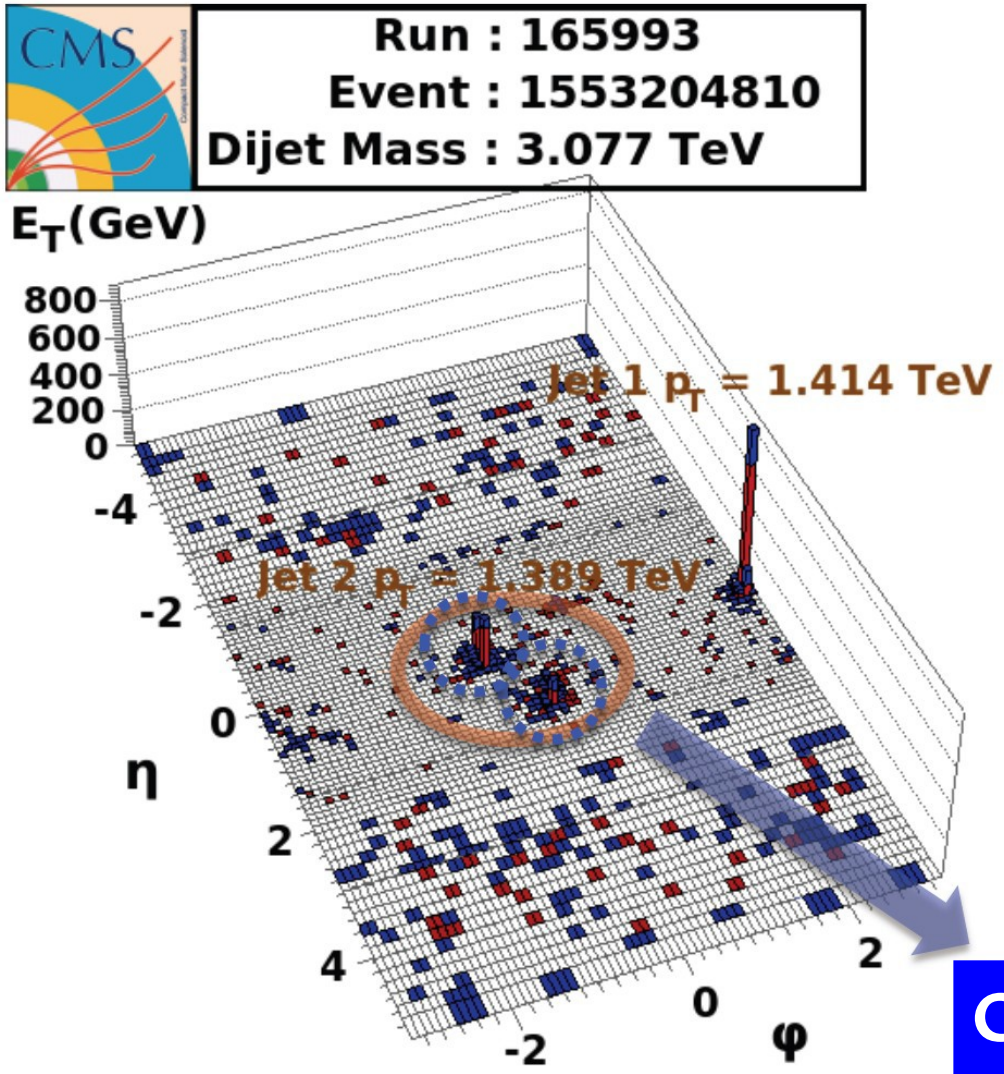
- **Trigger** based on $H_T = \sum_{i=1}^{N_{jet}} E_T$ > 650 GeV

Event selection:

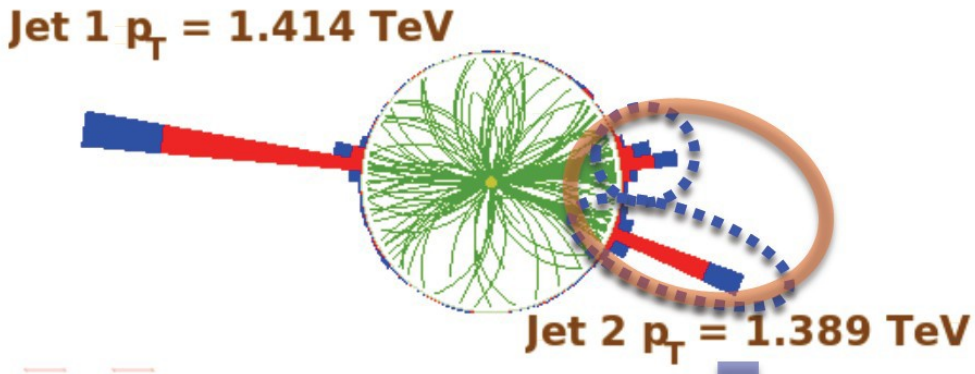
- **At least 2 jets** with $|\eta| < 2.5$ & $pT > 30$ GeV & $\Delta\eta 12 < 1.3$
- **Final selection:** events with di-jet invariant mass **Mjj > 890 GeV**
- **Special jet algo: WIDE JET** implemented
  - Standard anti-kT algo jets with cone 0.5 and 0.7 used for cross- checks



Wide Jet Technique



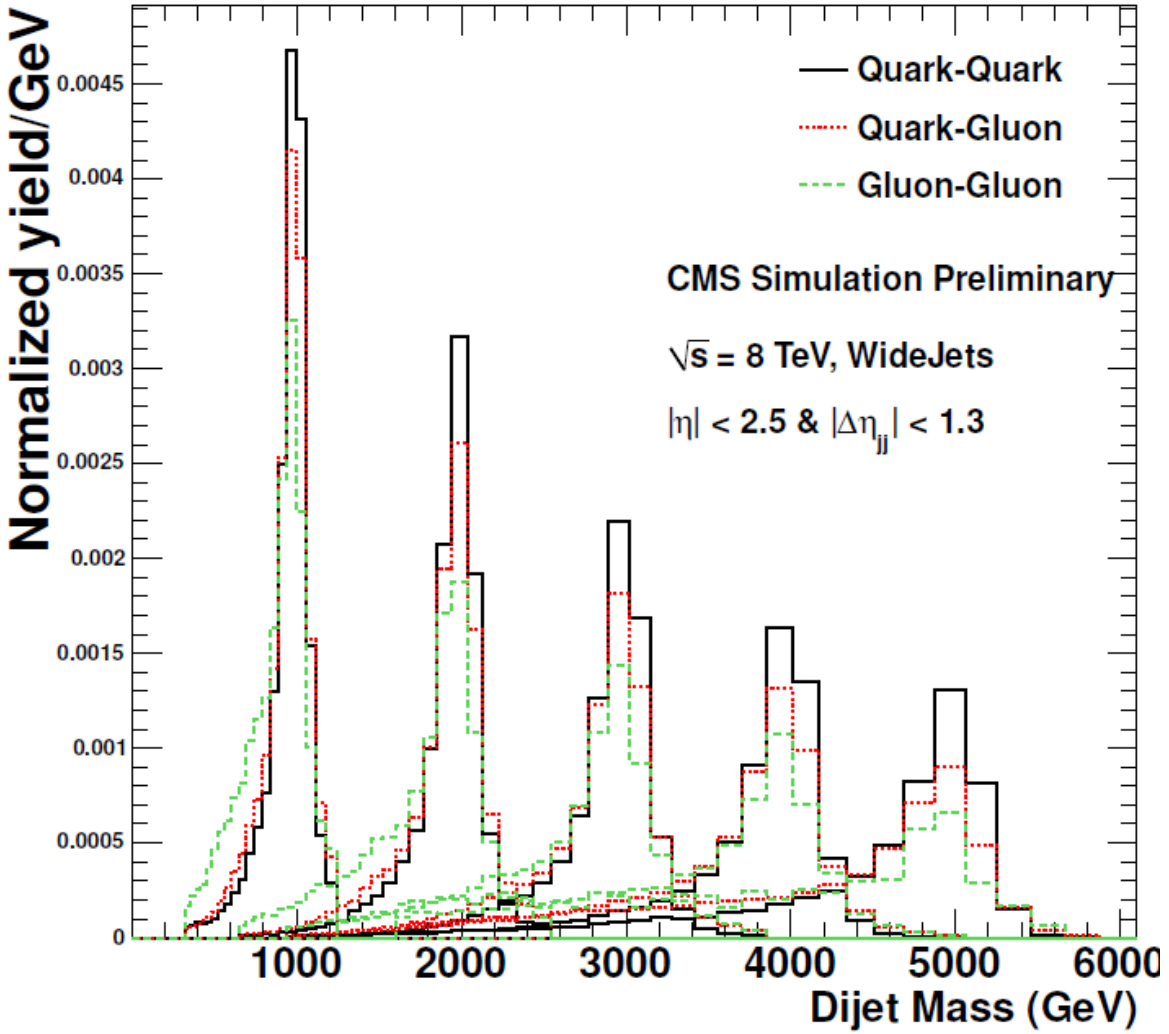
WIDE JETs optimize di-jet resonance mass resolution by recombining FSR into the two leading jets



Combined into one WIDE JET

Di-jet Mass Distributions

CMS-PAS-EXO-2012-059



Resonance shapes from CMS simulation:

- Resonance decaying to **qq**, **qg**, **gg**

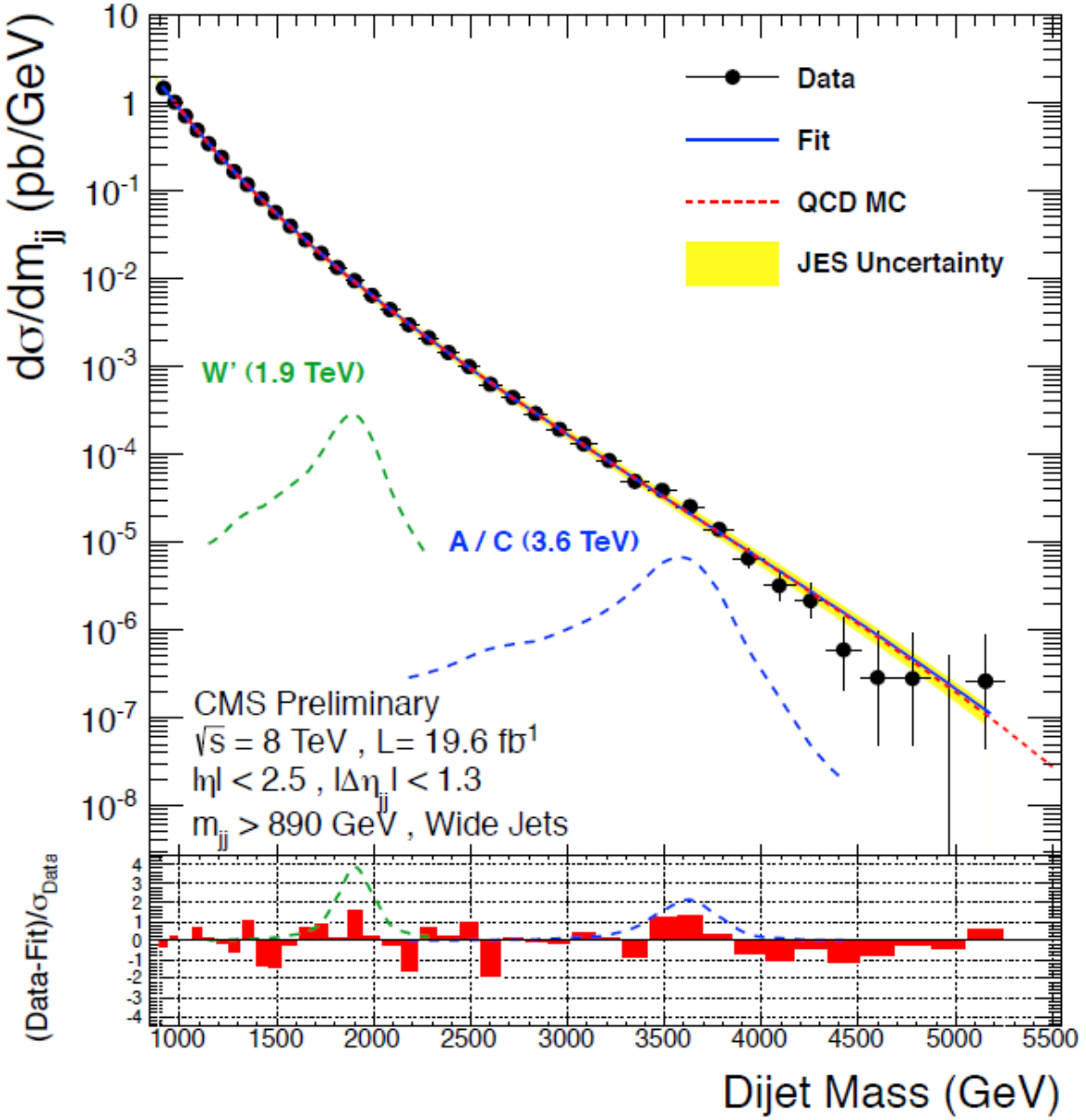
  → **Width increases** with number of gluons due to FSR

  → Mass peak **shitfed towards** lower masses

  → Weaker limits expected for **gg**

Di-jet RESULTS

CMS-PAS-EXO-2012-059



Inclusive dijet mass spectrum from wide jets compared to a smooth fit and **predictions** for **QCD** and hypothetical **W'** and axigluon/coloron **(A/C)**

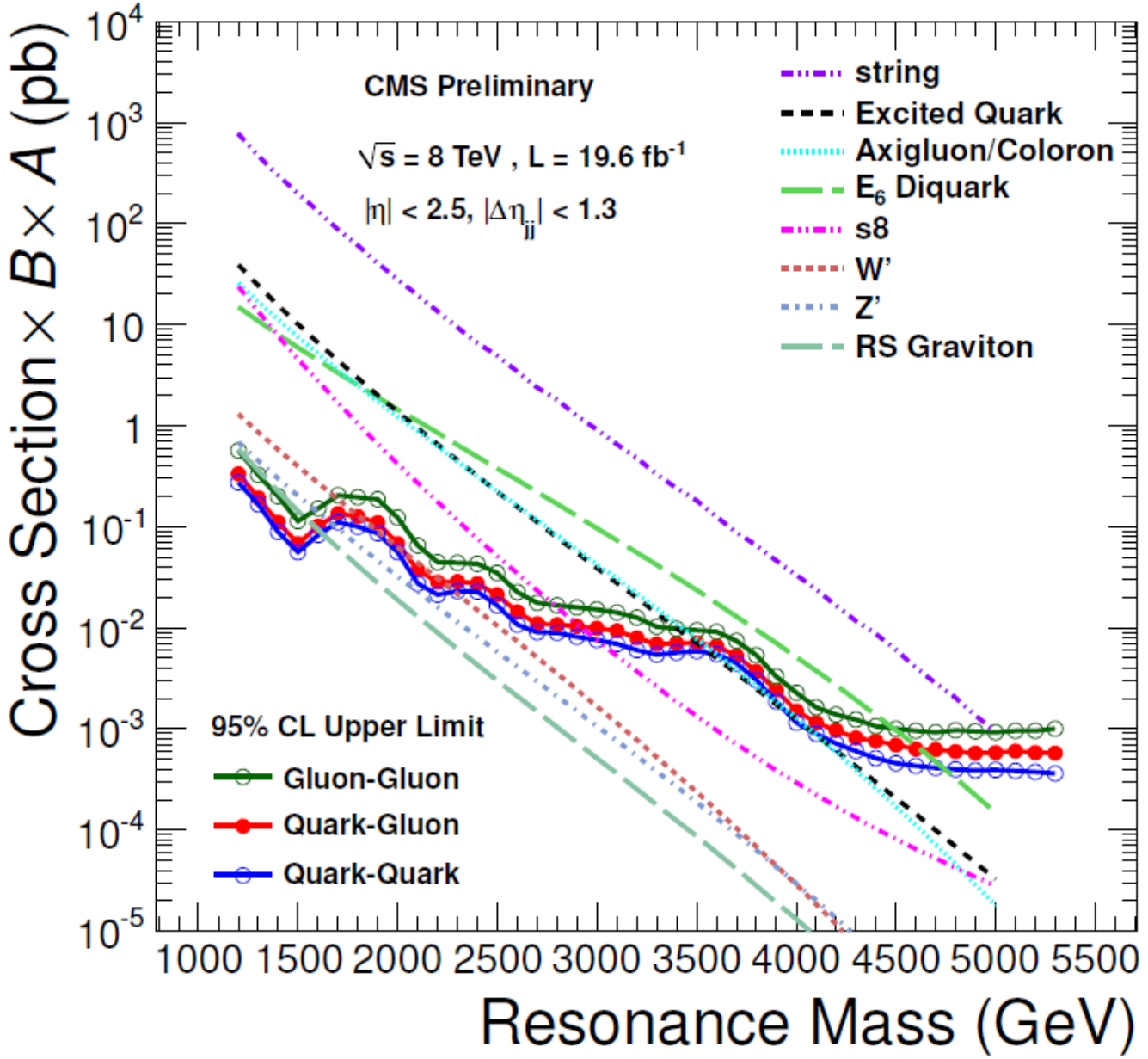
No evidence!

Data fitted with parametrization used also by CDF and ATLAS

$$\frac{d\sigma}{dm} = \frac{P_0(1-m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3\ln(m/\sqrt{s})}}$$

Di-jet Resonance LIMITS

CMS-PAS-EXO-2012-059



Final State	Obs. Mass Excl. [TeV]
qg	[1.20,5.08]
qg	[1.20,3.50]
qq	[1.20,4.75]
$q\bar{q}$	[1.20,3.60] + [3.90,4.08]
gg	[1.20,2.79]
$q\bar{q}$	[1.20,2.29]
$q\bar{q}$	[1.20,1.68]
$q\bar{q}$+gg	[1.20,1.58]

Observed **95% CL** upper limits on **σ× Branching Ratio × Acceptance** for di-jet resonances of type **qq**, **qg**, **gg** compared to theoretical predictions

(N-jet) Black Holes

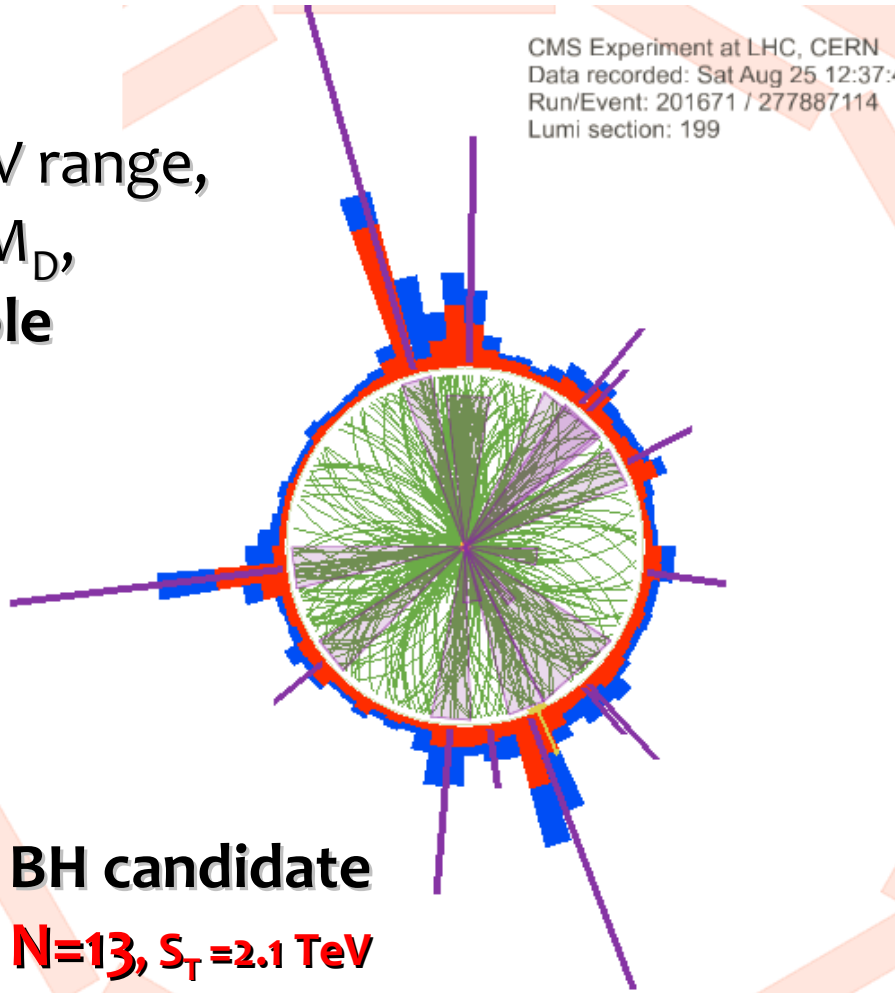
ADD ED, [Arkani-Hamed, Dimopoulos, Dvali,
Phys. Lett. B 429, 263 & Phys. Rev. D59,086004]

- The possibility of production of microscopic black holes in particle collisions has been predicted in models with low scale gravity

- If the "true" Planck scale M_D is in the 1 TeV range, partons colliding with energy exceeding M_D, may **collapse into a Microscopic Black Hole**

- Once produced, the **BH evaporate** almost instantaneously by **emitting energetic particles**

- **Multi-particle signature highly energetic**
  N objects (jets,leptons,photons)



BH candidate

N=13, S_T =2.1 TeV

Black Holes Search

CMS Analysis strategy: Select events with large total transverse energy and check the presence of multiple energetic jets, leptons, and photons

- **Multiplicity (N)**
  Number of objects (jet,lep,γ) with pT>50 GeV in an event, excluding MET

- **S_T Scalar**
  p_T sum of all objects with ET>50 GeV + MET (if greater >50 GeV)
  S_T is almost independent of the final state multiplicity N
  → QCD bkg. estimation

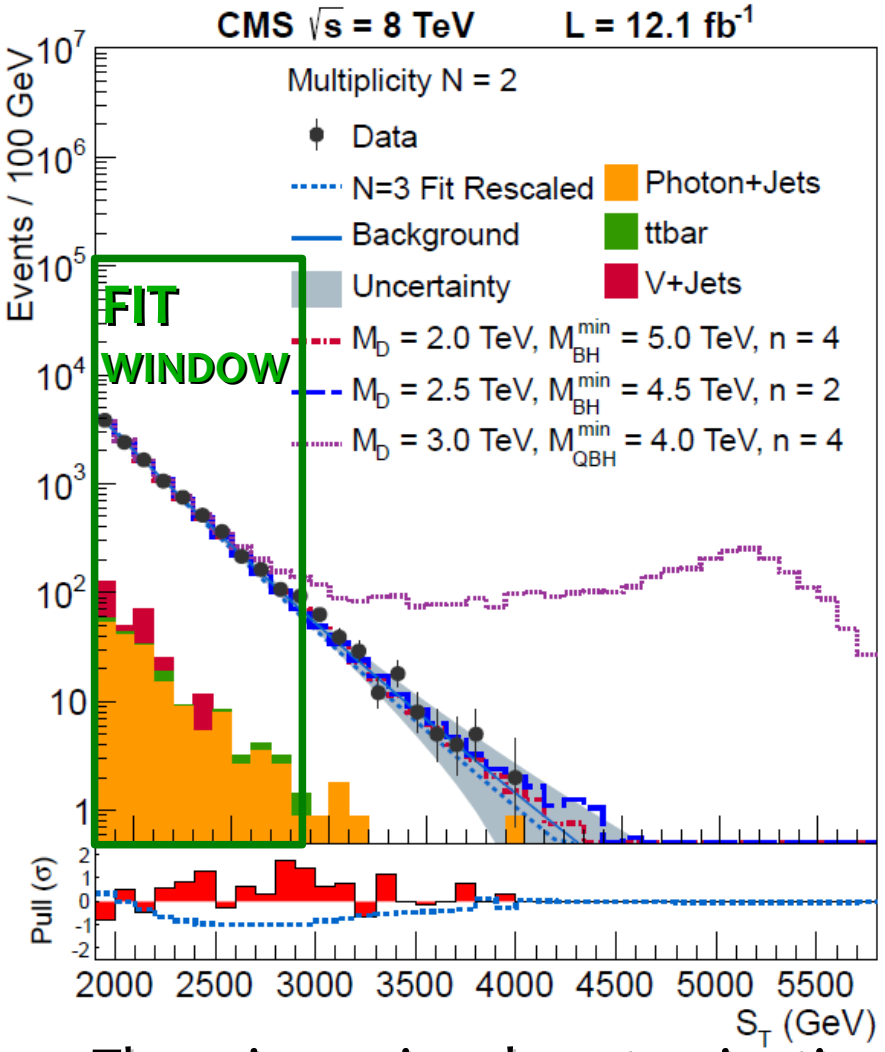
- **Separation**
  ΔR (jet, lep/γ) > 0.5 and ΔR (lep/γ, lep/γ) > 0.3

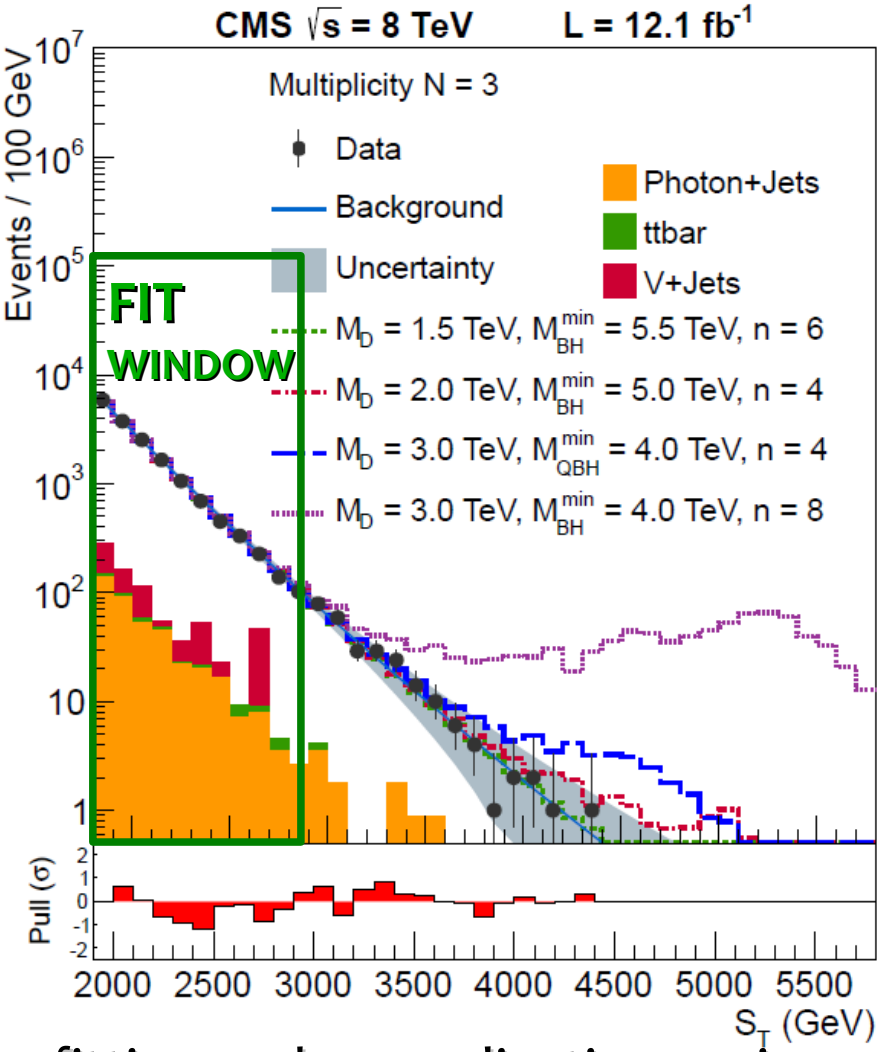
- **Trigger** on total jet activity H_T in 350 - 550 GeV

100% eff for S_T > 700 GeV

Background in BH Search

Exclusive multiplicities for bkg. estimation



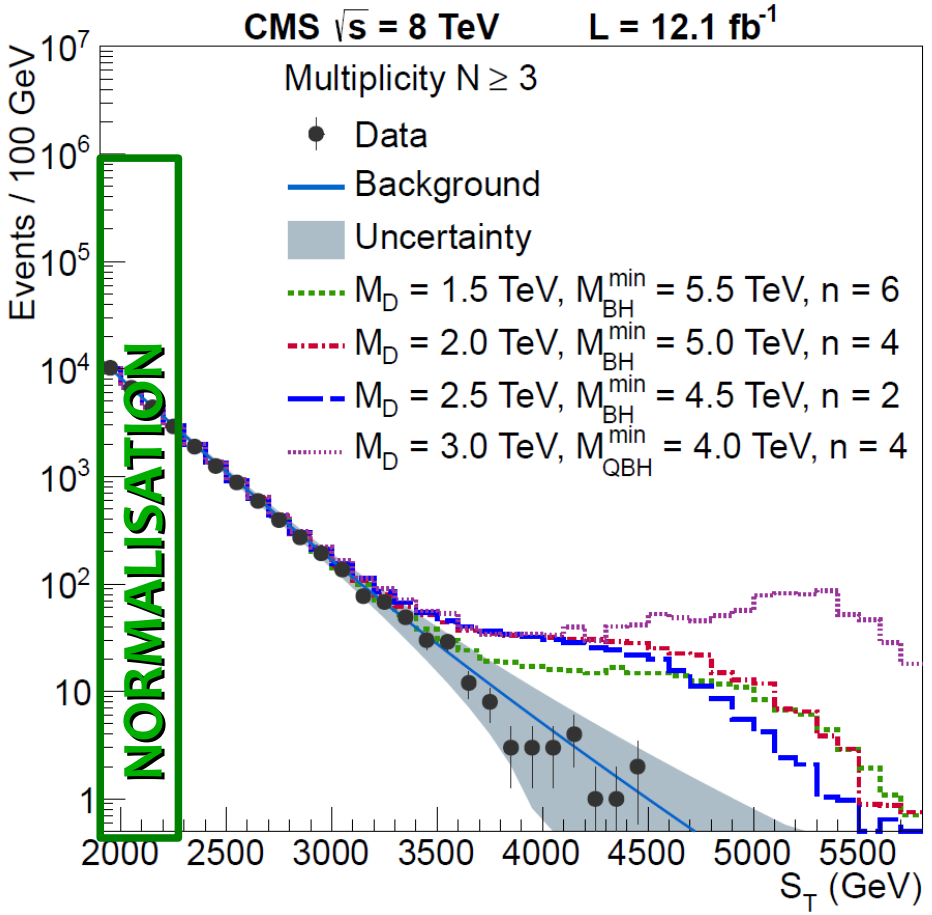


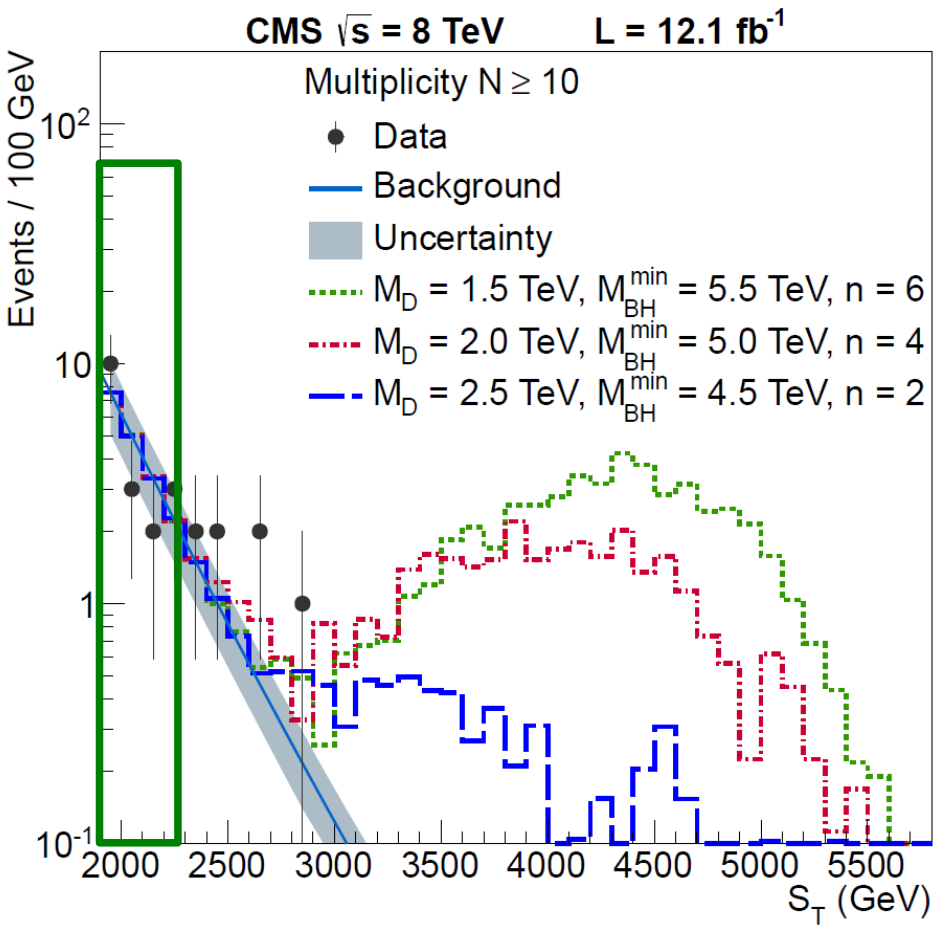
CMS-PAS-EXO-2012-009, JHEP07(2013)178

- There is no signal contamination in the fitting and normalization region
- Data-driven bkg. describes data consistently with data

Black Holes Events!

Inclusive multiplicities for searches from N >=3 to 10



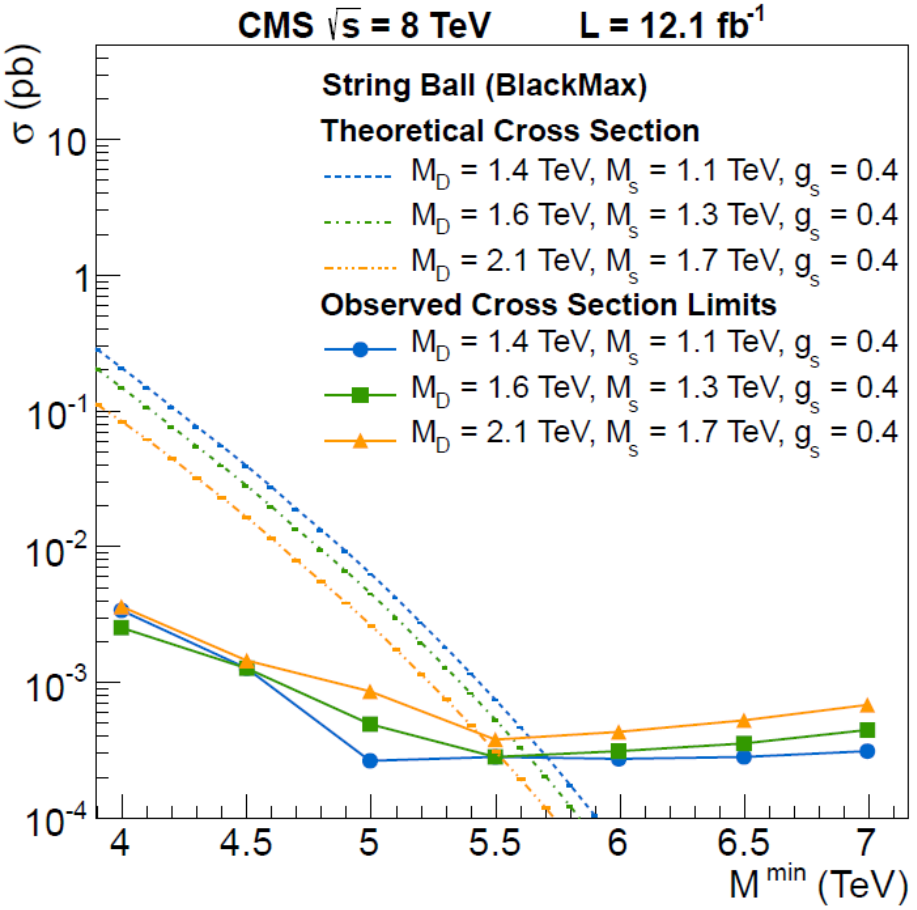


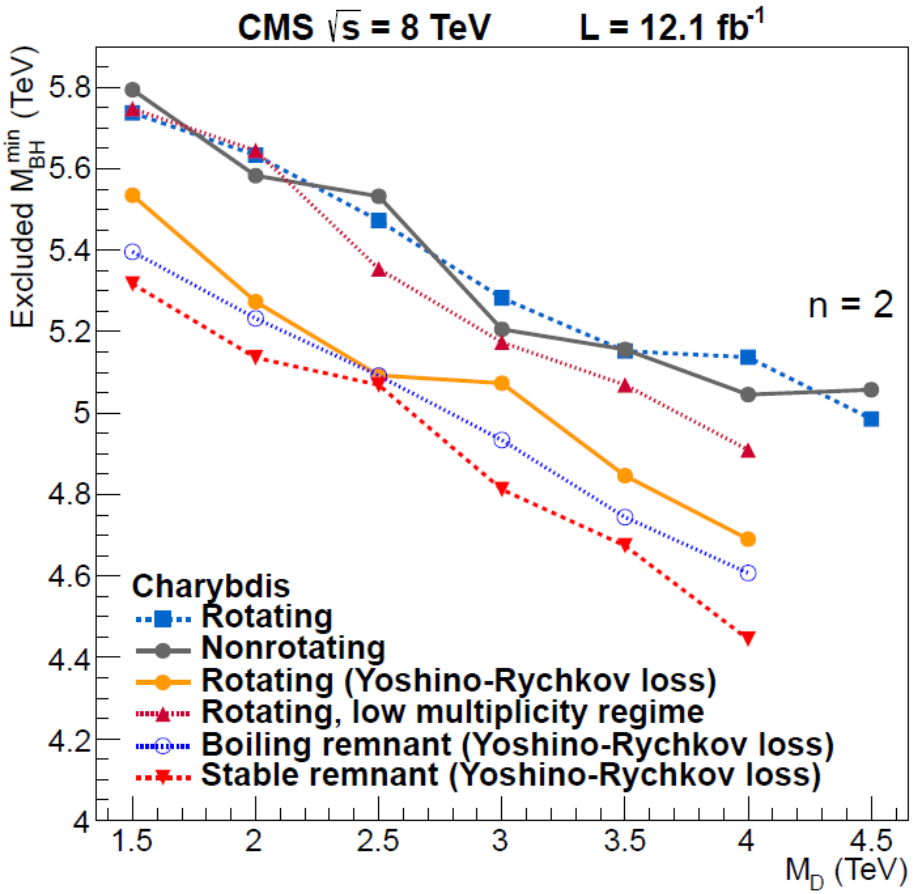
CMS-PAS-EXO-2012-009, JHEP07(2013)178

- No excess in the signal regions !

Microscopic Black Holes LIMITS

- Many limits can be set



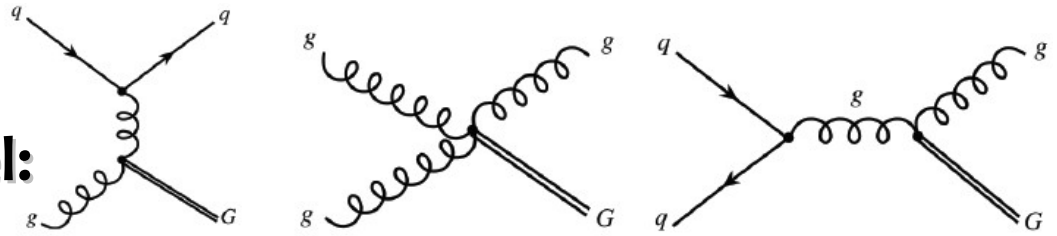


CMS-PAS-EXO-2012-009, JHEP07(2013)178

The 95% confidence level limits on the **black hole mass** as a function of the **multi-dimensional Planck scale MD** for various Charybdis black hole models with number of ED =2. The area below each curve is excluded by this search.

Black Hole mass limits 5.7, 5.6, 5.45 TeV

Mono-Jet / Photon

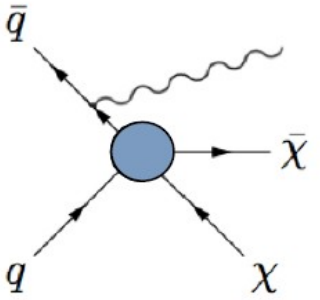


Large Extra-Dimension (ADD) model:

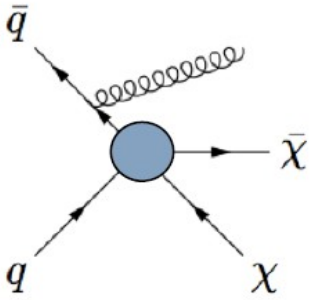
- δ extra dimensions compactified over a torus with radius R

Dark Matter particles WIMPs (χ)

- assume Dirac fermions
- relate production at LHC to χ nucleon interactions



monophoton +MET



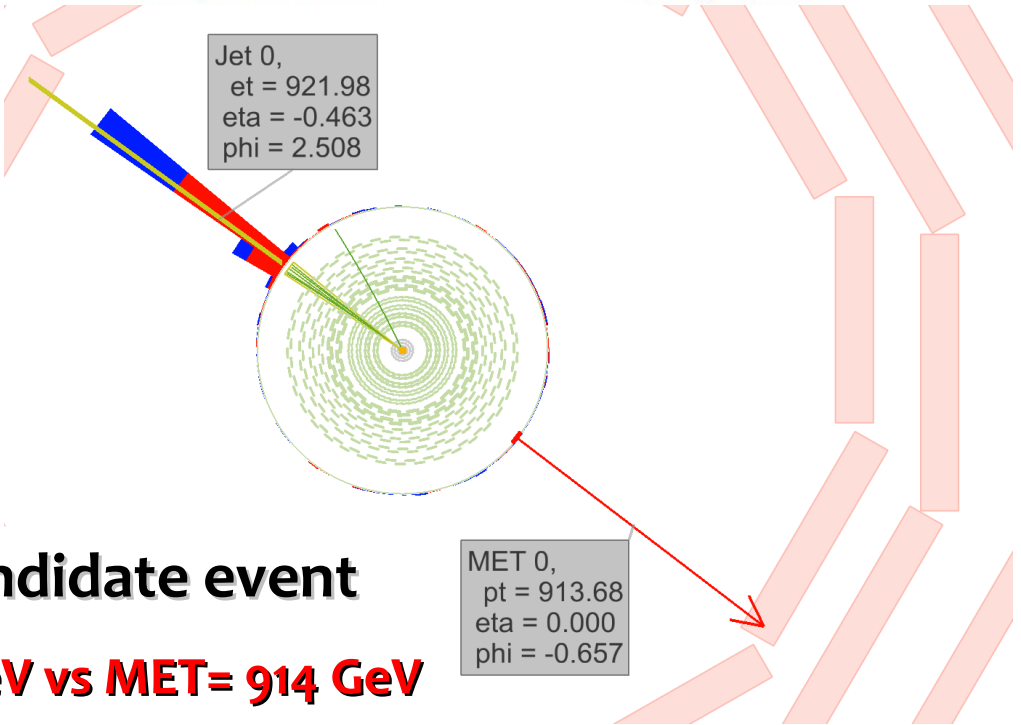
monojet +MET

Mono- signature:

- **One high pT jet** (~hundred GeV)
  in the central region, although 2nd
  less energetic jet is allowed
- **Large MET** (from Graviton or WIMP);
  same magnitude as jet, typically back-to-back

Background:

- from Z(νν)+jets, W+jets



Mono-jet candidate event

JET ET=922 GeV vs MET= 914 GeV

Mono-jets

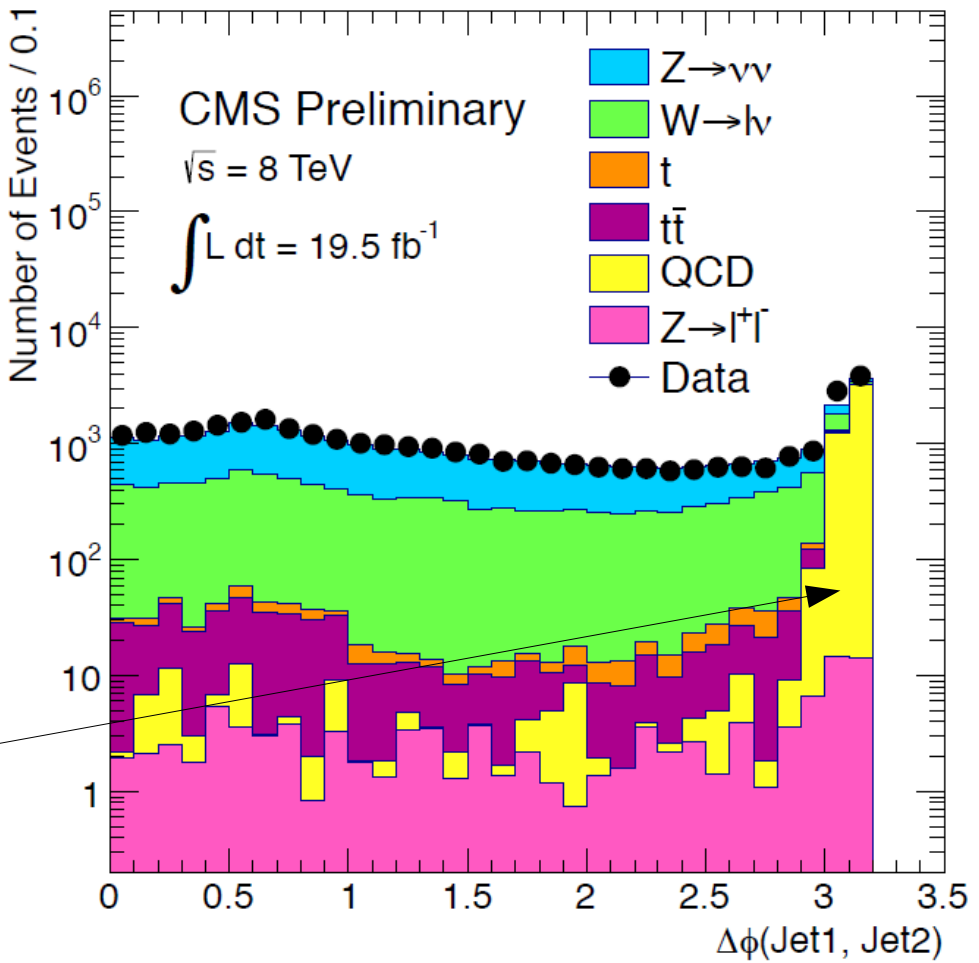
CMS-PAS-EXO-2012-048

Trigger:

- MET > 120 GeV
- jet pT > 80 GeV & MET > 105 GeV

Event Selection:

- Search for single jet recoiling against MET>250 GeV
- Leading jet pT>110 GeV (|η|<2.0)
- The second jet allowed with pT>30 GeV if Dφ (j1, j2) < 2.5 **to reject QCD**
- Events with isolated lepton (e,mu,tau) rejected **to remove EWK bkg**



Background: Data- Driven or MC, eg. :

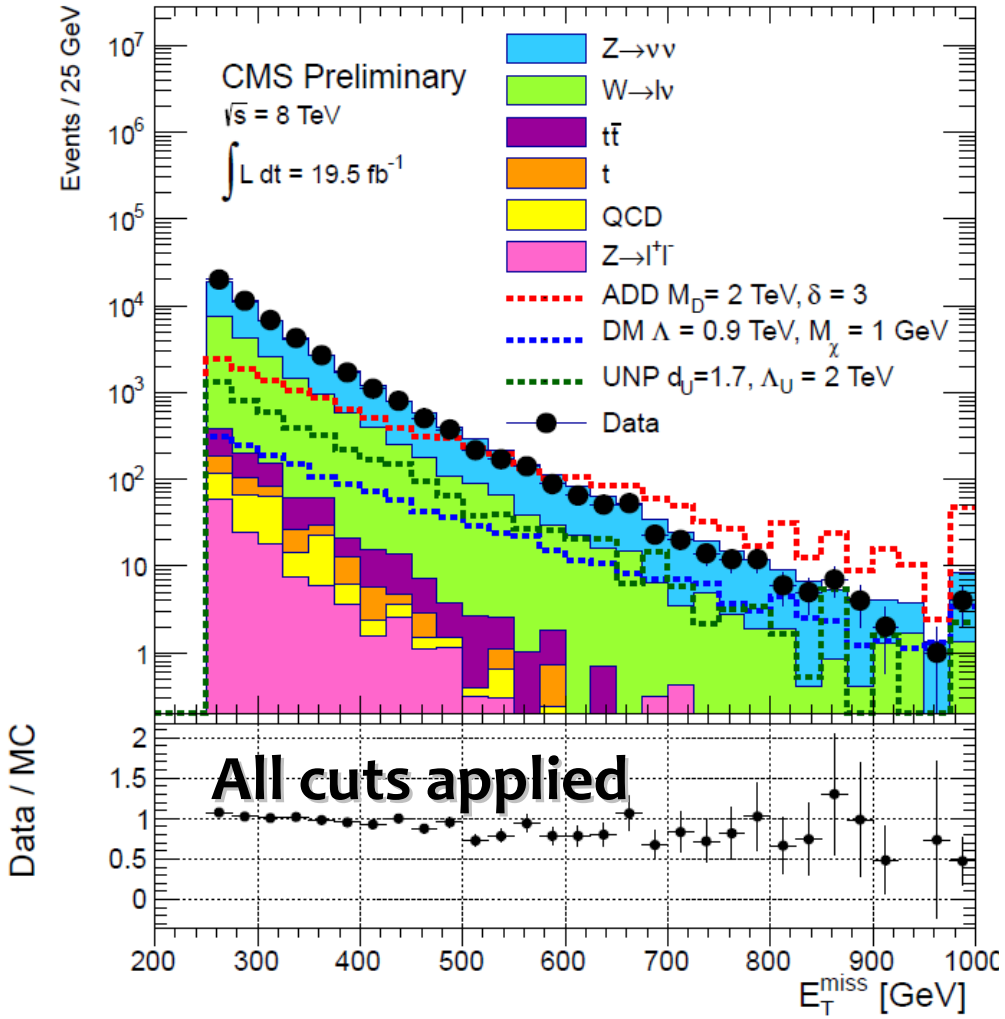
- **Z + jets** (measured) predicts **Z(νν) + jets**

All cuts applied besides Dφ (j1, j2)

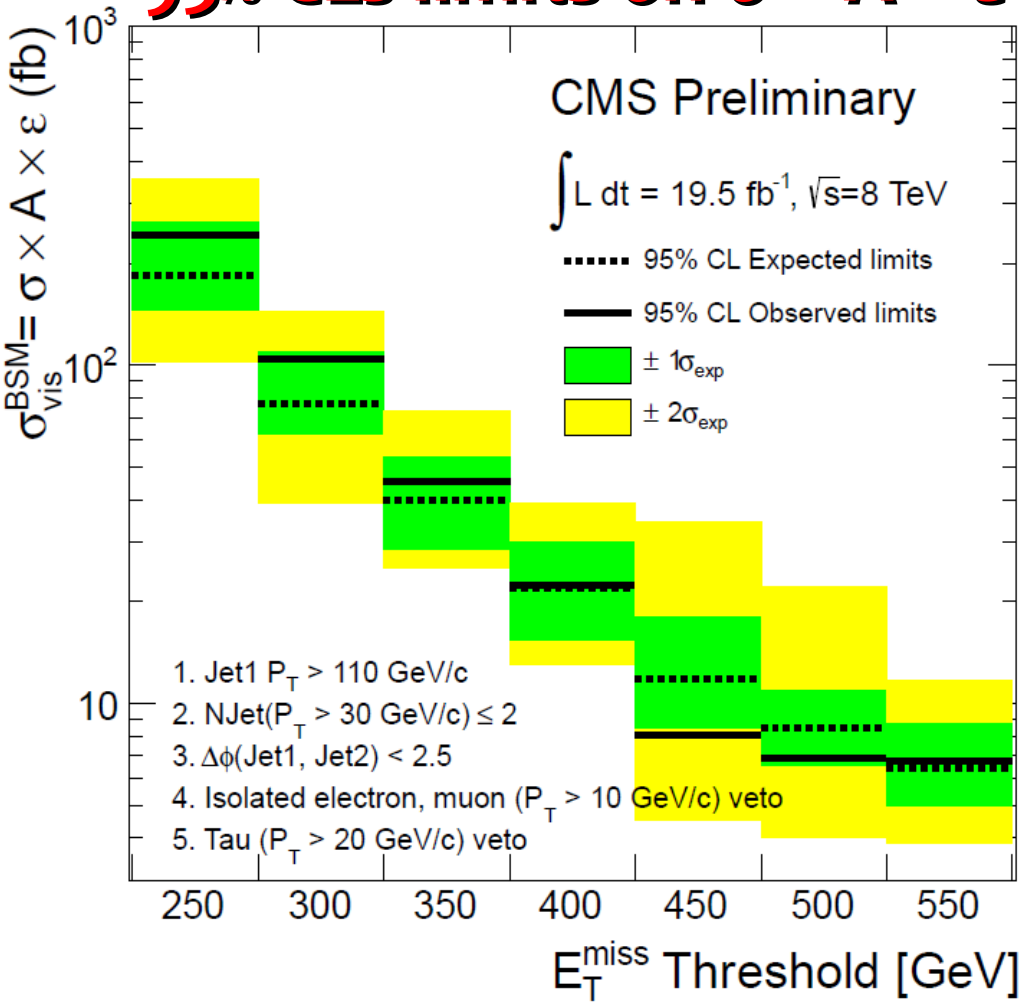
Mono-jet RESULTS

CMS-PAS-EXO-2012-048

- Search performed in 7 bins of MET



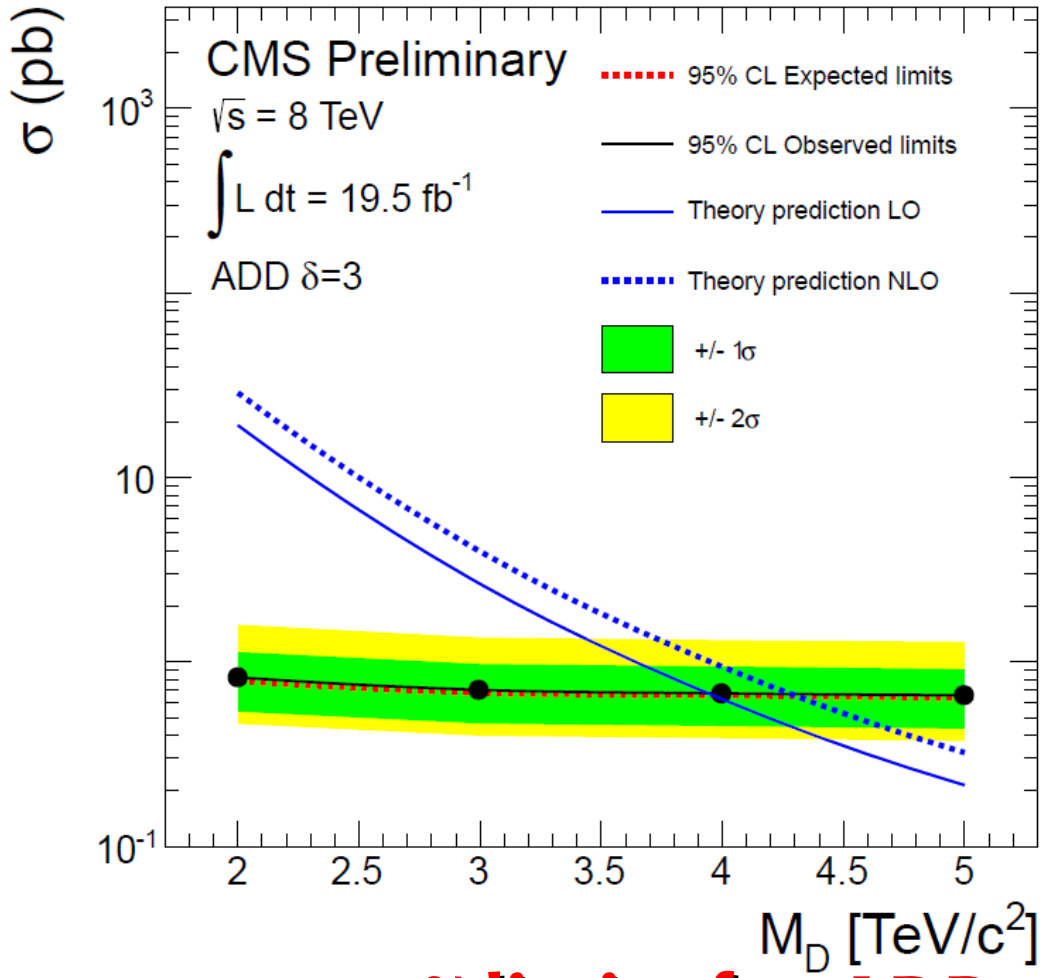
95% CLs limits on σ × A × ε

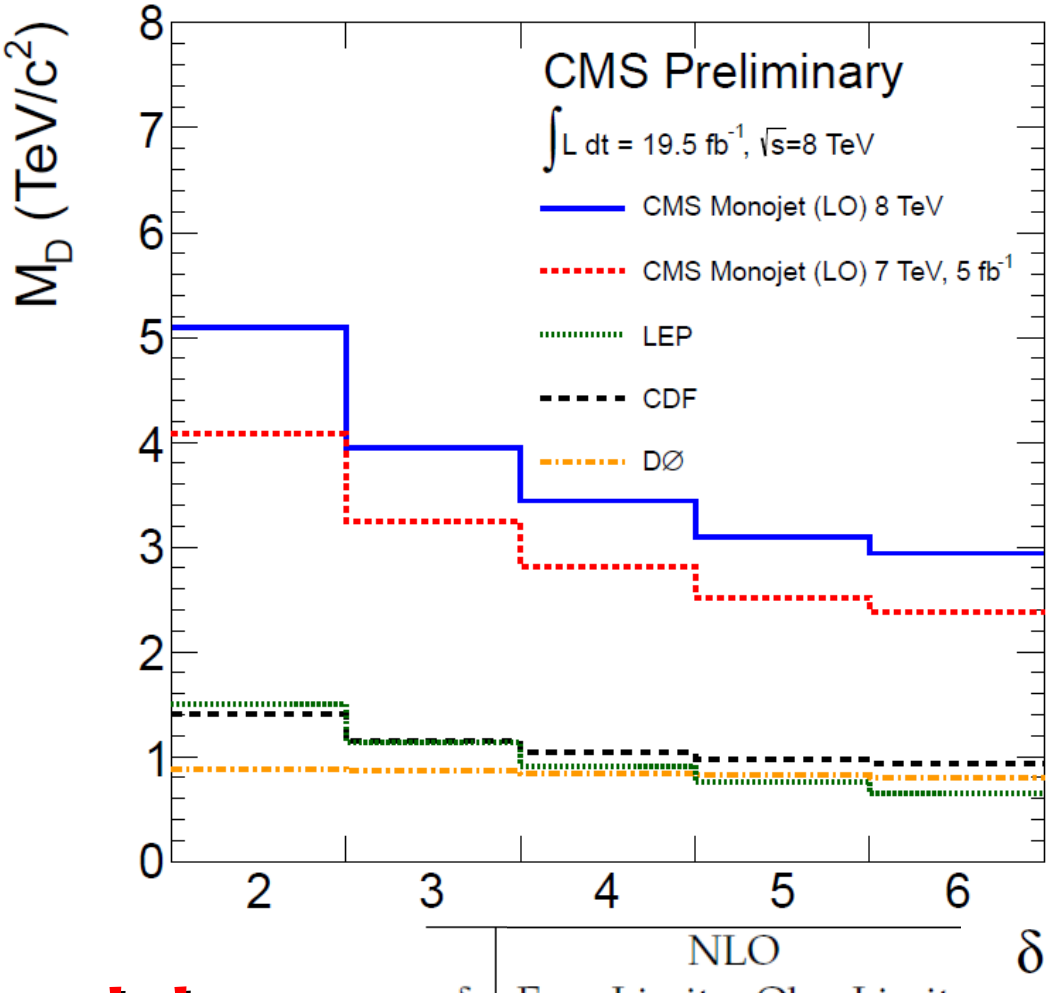


Data consistent with expectations !

Large Ex-Dim Interpretation

CMS-PAS-EXO-2012-048





95% limits for ADD model

$$M_{Pl}{}^2 \approx M_D{}^{\delta+2} R^{\delta}$$

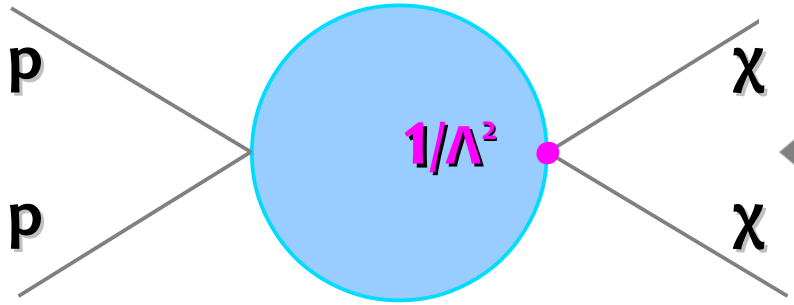
MPL - four-dimensional Planck scale
MD - fundamental 4+δ dimensional Planck scale
Number **δ** of extra spatial dimensions
compactified over torus of radius **R**

	NLO	
δ	Exp. Limit	Obs. Limit
2	5.70	5.67
3	4.31	4.29
4	3.72	3.71
5	3.32	3.31
6	3.13	3.12

Dark Matter Interpretation

CMS-PAS-EXO-2012-048

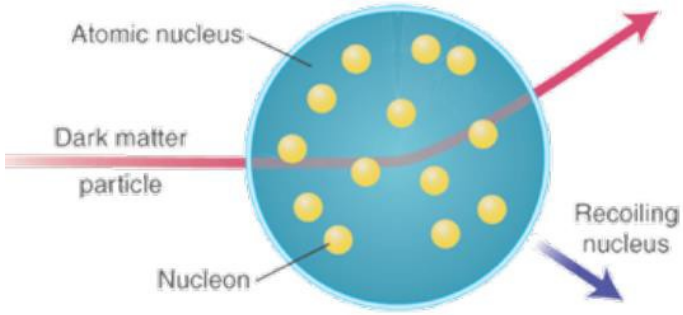
χ – Dirac fermion



$$\sigma^N_{SD} = \frac{3\mu^2}{\pi} \cdot \left(\sum_q \frac{\Delta^N_q}{\Lambda^2}\right)^2$$

$$\sigma^N_{SI} = \frac{\mu^2}{\pi} \cdot \left(\sum_q \frac{f^N_q}{\Lambda^2}\right)^2,$$

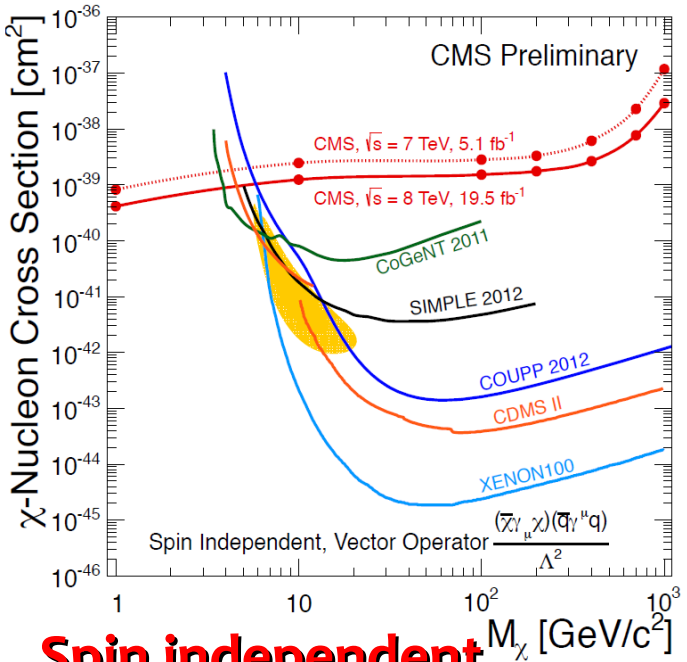
Dark Matter-nucleon scattering



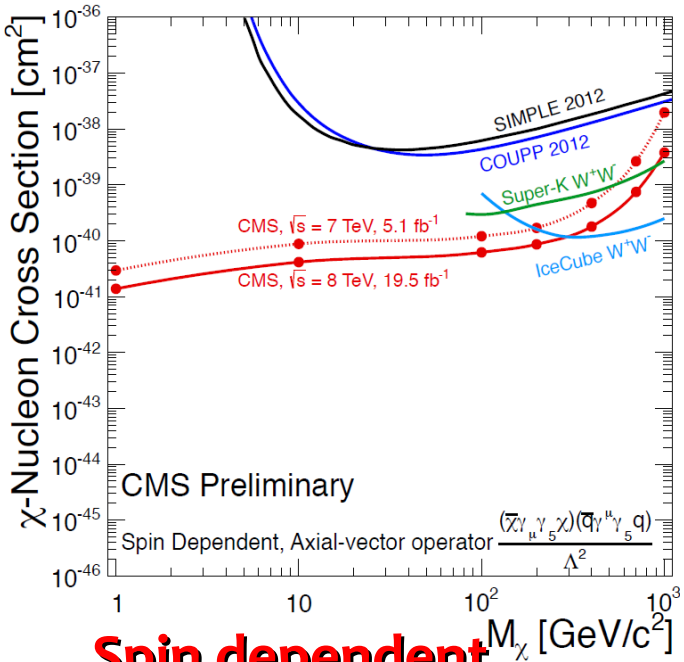
Pair production of DM (χ) characterized by a contact interaction effective theory

Vector and **scalar** interactions → **spin-independent (SI)** DM-nucleon interactions

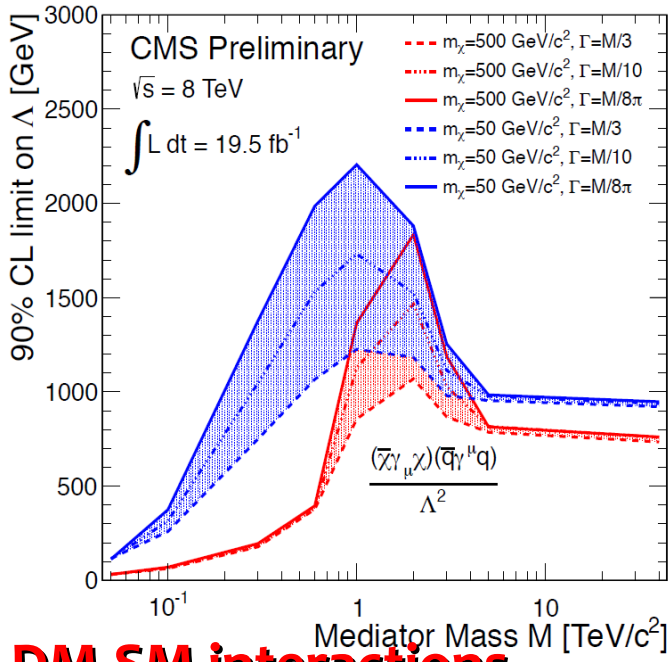
Axial-vector interactions → **spin-dependent (SD)** DM-nucleon interactions



Spin independent



Spin dependent

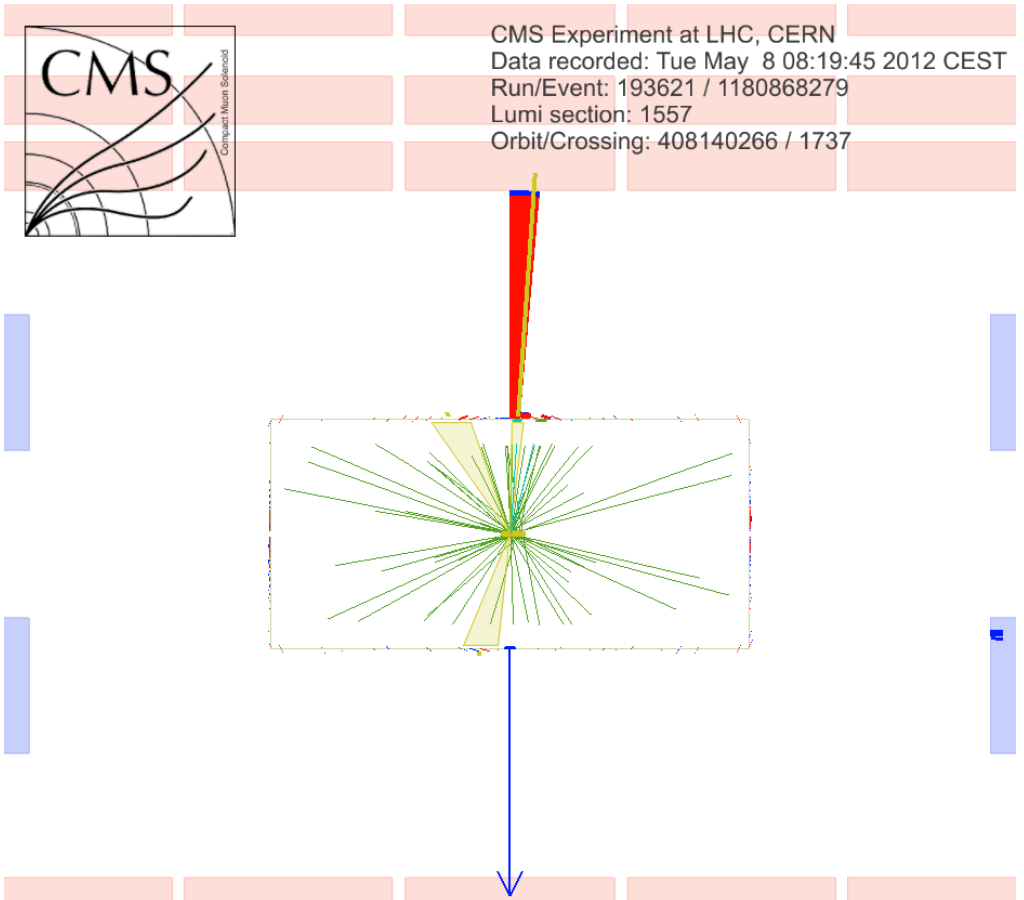


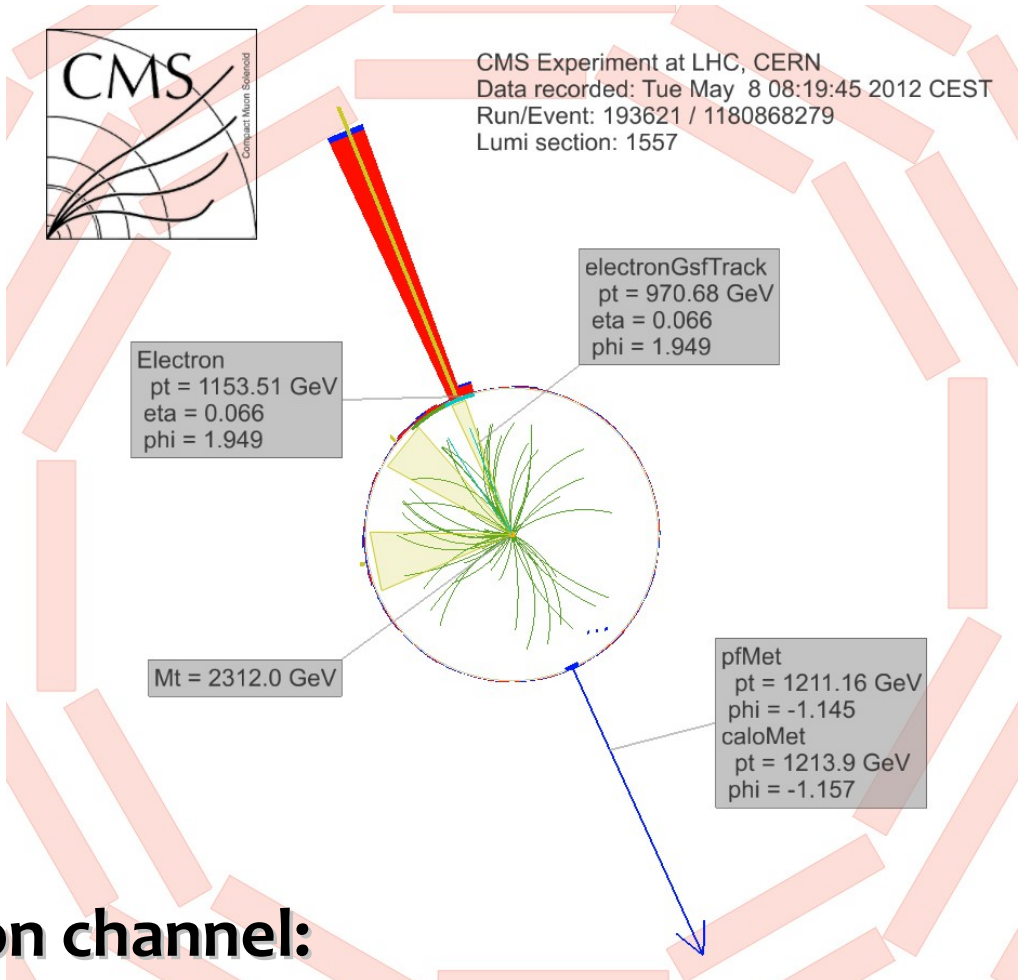
DM-SM interactions mediated by heavy particle

Mono-leptons DM

CMS-PAS-EXO-2013-004

- First limits on DM with mono-leptons





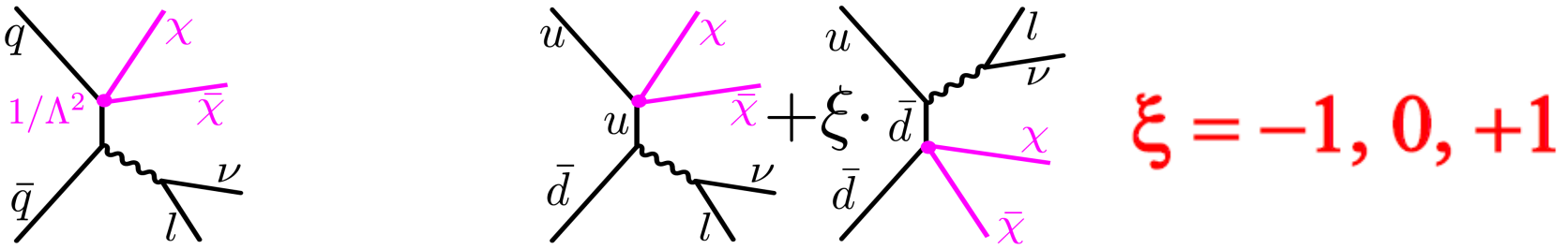
the highest MT event in the electron channel: MT=2.3 TeV, well reconstructed

$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

Mono-leptons

CMS-PAS-EXO-2013-004

- Dark Matter radiation and interference W^+



$\xi = -1, 0, +1$

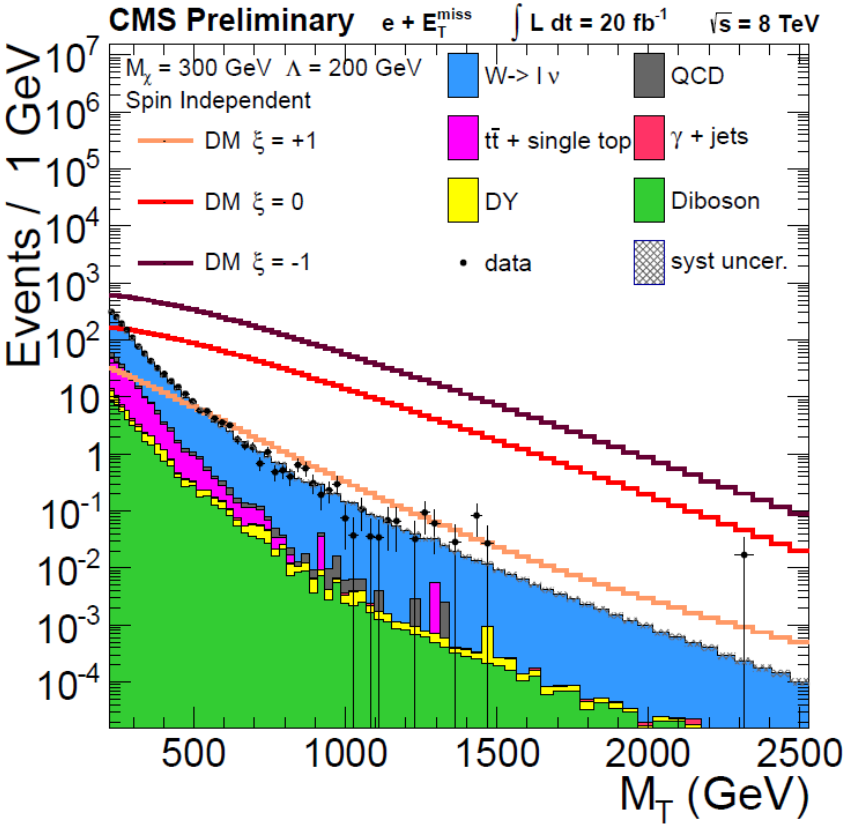
- Model is characterized by scale $\Lambda = \frac{M_{messenger}}{\sqrt{g_\chi g_q}}$

Event selection:

- Single electron(muon) trigger with pT>85(40) GeV
- Lepton ID optimized for high pT
- Kinematical selections: 0.4 < pT / MET < 2
- Δφ (lep pT, MET) < 0.8

Background:

- Main: W→ lν
- Contributions derived from MC



Mono-leptons LIMITS

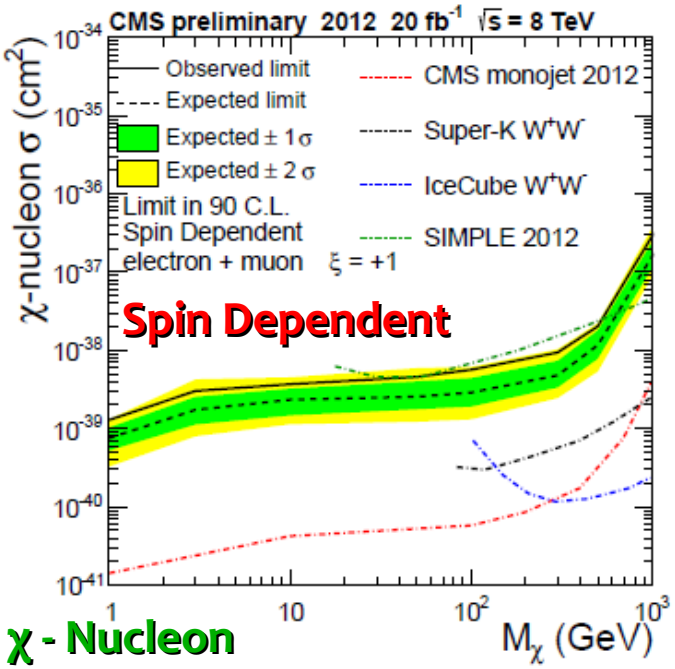
CMS-PAS-EXO-2013-004

Excluded **nucleon-** and **proton- Dark Matter cross section** for the combination of electron and muon channels

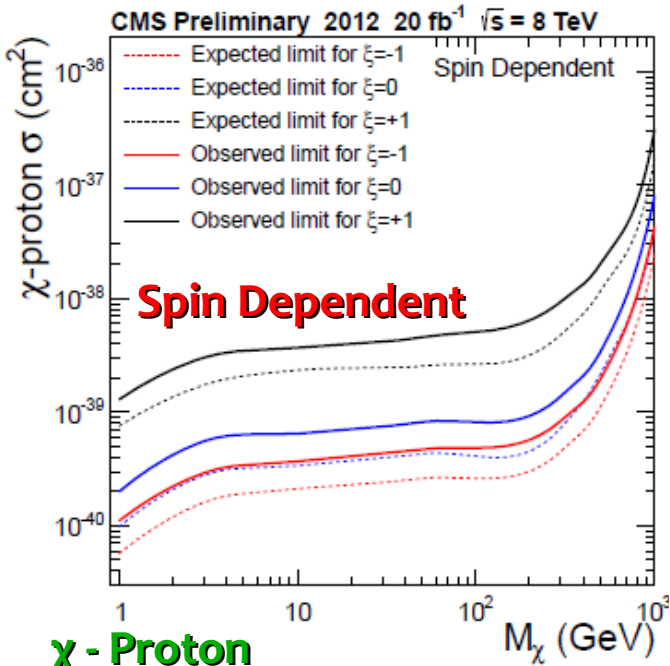
The χ-proton cross section has to be small than:

$4\times10^{-40}\mathrm{cm}^2$, $7\times10^{-40}\mathrm{cm}^2$, $5\times10^{-39}\mathrm{cm}^2$
$(1\times10^{-40}\mathrm{cm}^2\ 2\times10^{-39}\mathrm{cm}^2\ 9\times10^{-38}\mathrm{cm}^2)$

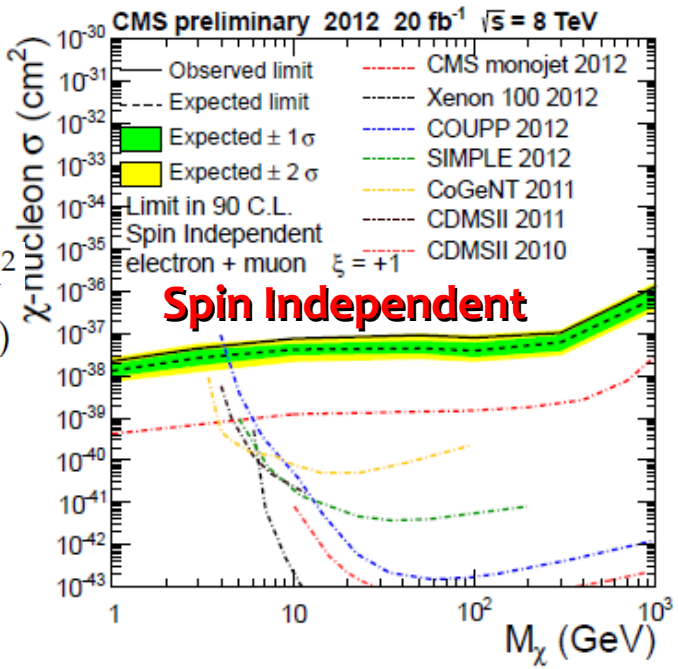
for axial-vector (vector) coupling for **ξ =-1/0/+1**

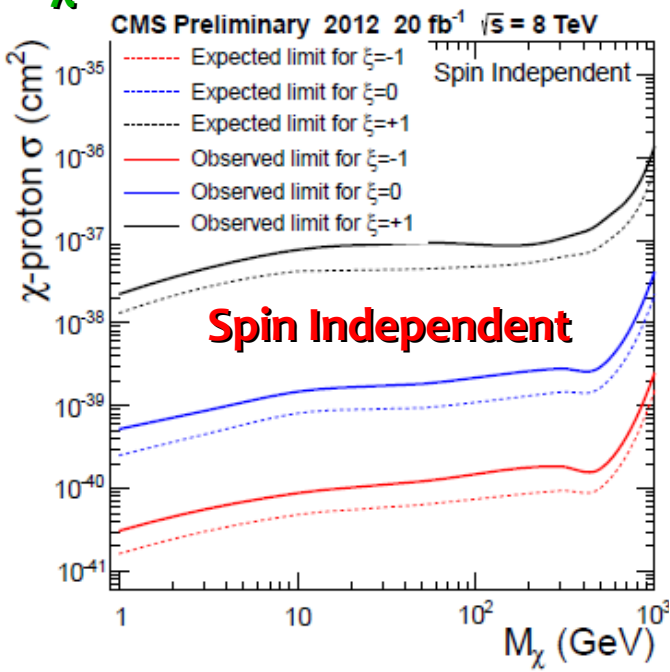


χ - Nucleon



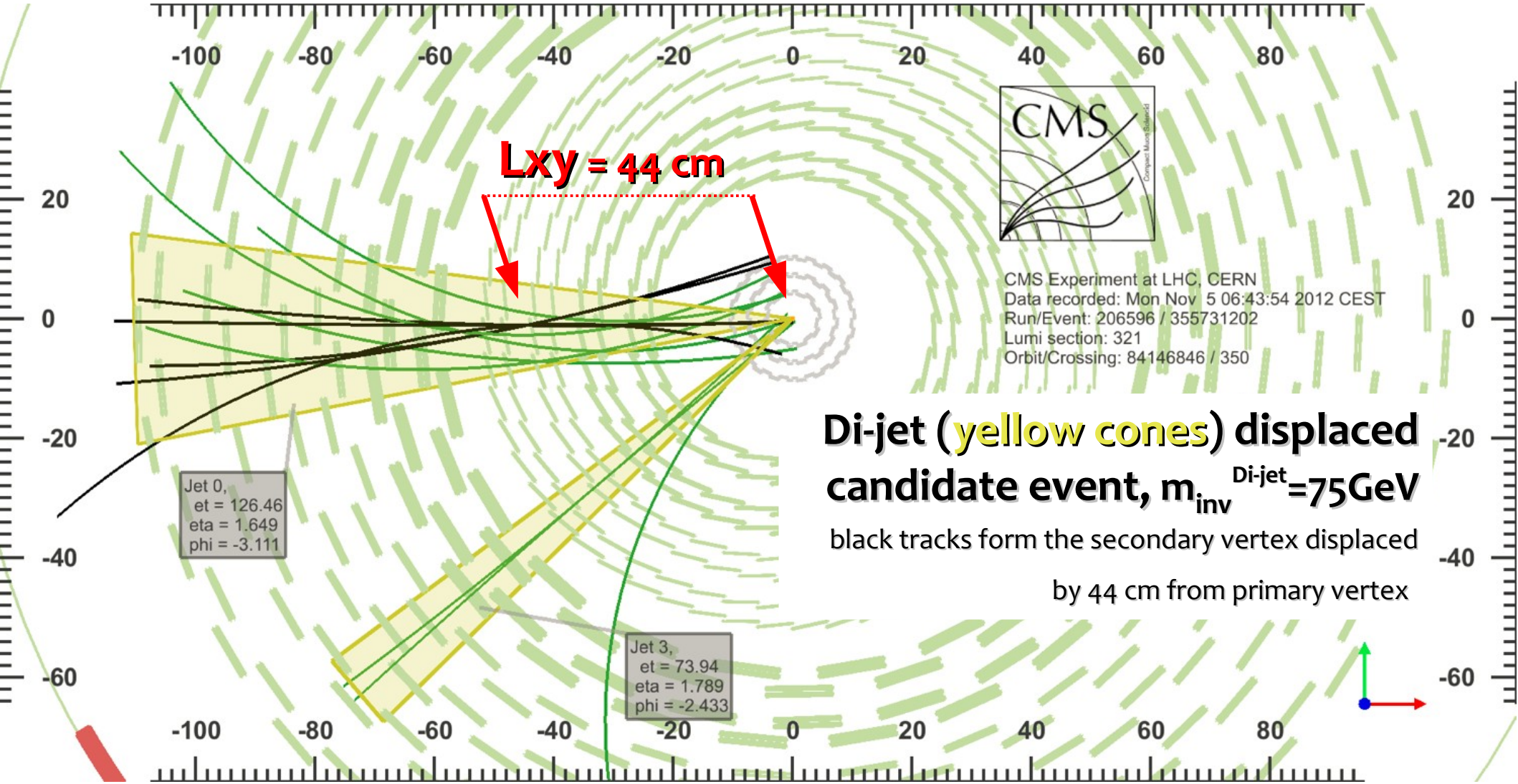
χ - Proton





Displaced Jets

- Long-lived massive neutral particles decaying to quark-antiquark pairs
- Distinctive topology of a pair of jets originating at a secondary vertex



Di-jet (yellow cones) displaced candidate event, $m_{inv}^{Di\text{-}jet}$=75GeV

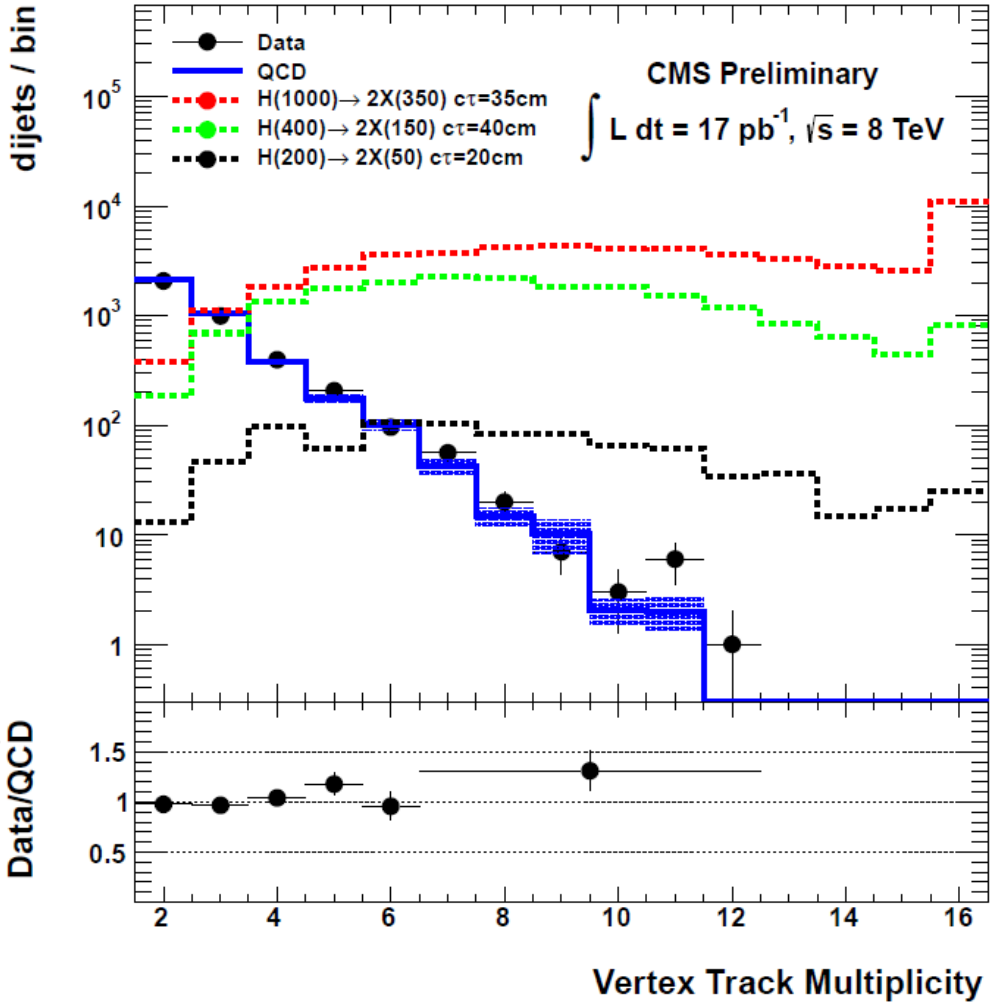
black tracks form the secondary vertex displaced by 44 cm from primary vertex

Displaced Jets

CMS-PAS-EXO-2012-038

Signal: gg → (non-SM) H → 2X, X → qq

- originating from Hidden Valley model, Split SUSY, RPV SUSY, GMSB, etc.
- Benchmark points
  M_H = [200, 400, 1000] GeV,
  M_X = [50,150,350] GeV,
  $c\tau_X$ = [3,20,35,40,300] cm



Event selection:

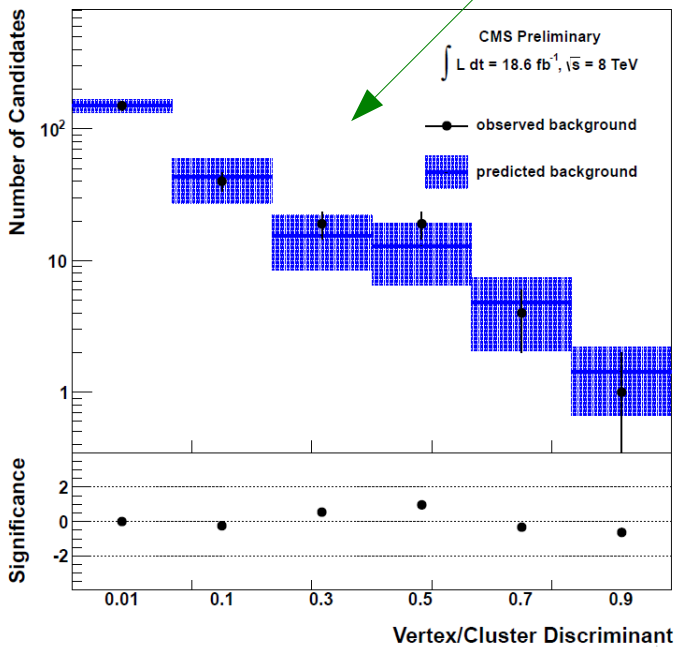
- Trigger: **HT >300 GeV** and **> 1 jets** with small fraction of prompt tracks
- **Multivariate discriminant** based on vertex track multiplicity, fraction of tracks with positive d0, and variables from a dedicated track cluster algorithm

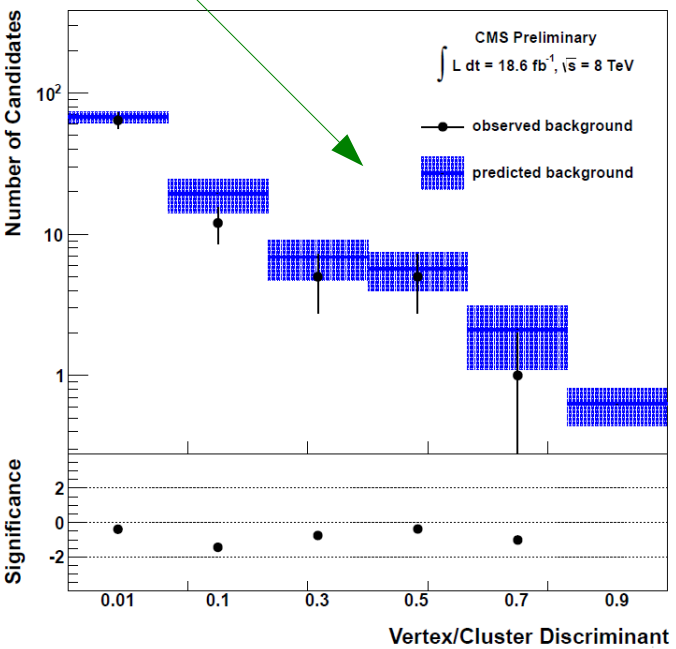
Displaced Jets RESULTS & LIMITS

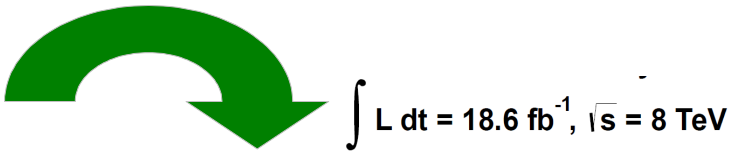
CMS-PAS-EXO-2012-038

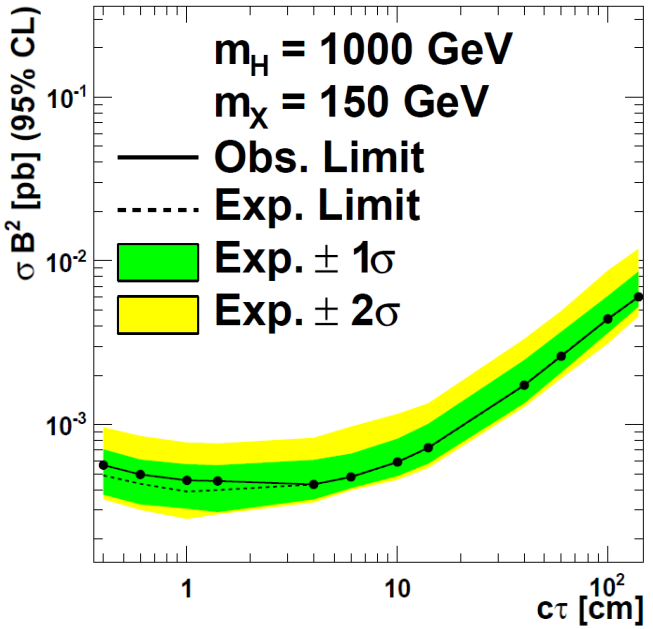
- **Background**: ABCD prediction using jet variables and vertices infos
- Search optimised for two regions Lxy < 20 or Lxy > 20 cm
- For X mean lifetimes of **0.1 to 200 cm**, the upper **cross-section x B^2** ($X \rightarrow qq$) limits are typically **0.3-300 fb**

L_{xy}	< 20 cm(low)	> 20 cm(high)
prompt tracks	≤ 1	≤ 1
prompt energy fraction	< 0.15	< 0.09
vertex/cluster disc.	> 0.9	> 0.8
expected background	$1.60 \pm 0.26(stat.) \pm 0.51(syst.)$	$1.14 \pm 0.15(stat.) \pm 0.52(syst.)$
observed	**2**	**1**





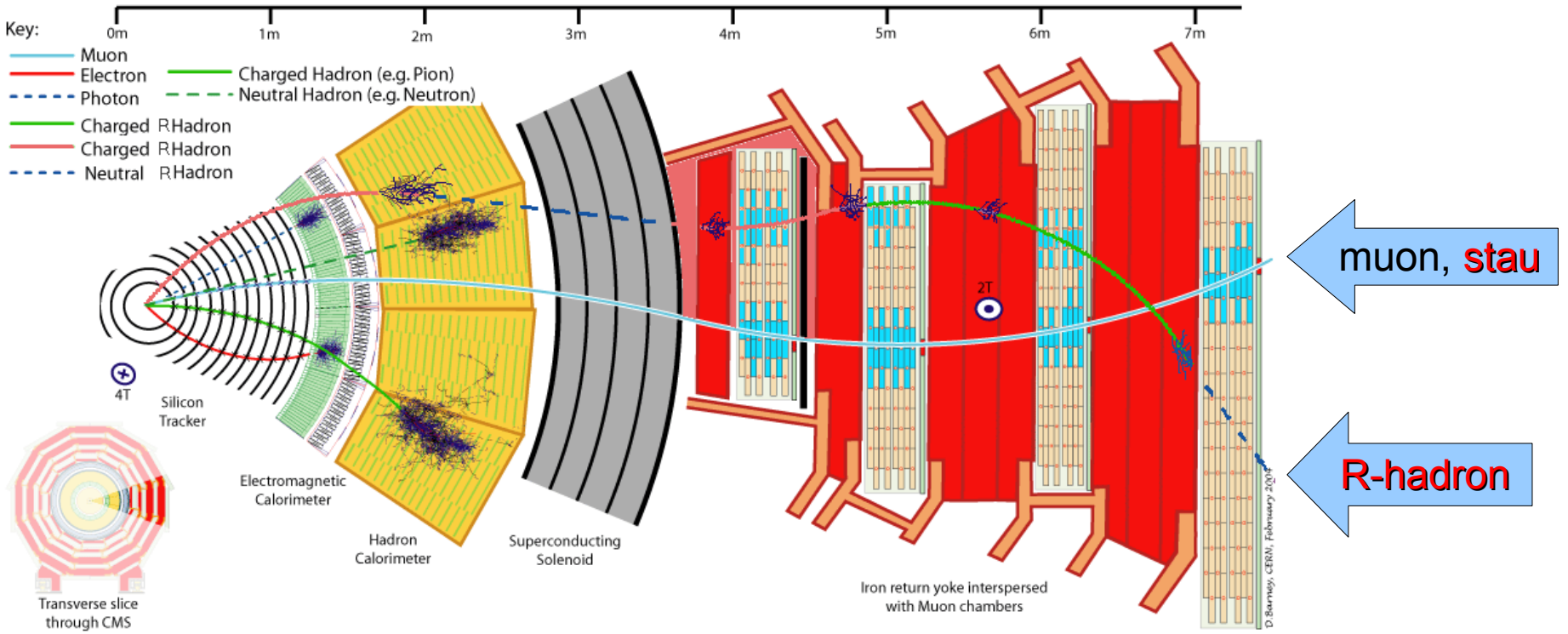




Heavy QUASI Stable Charged Particles

Signal: Long-Lived Particles from GMSB, Split SUSY and others:

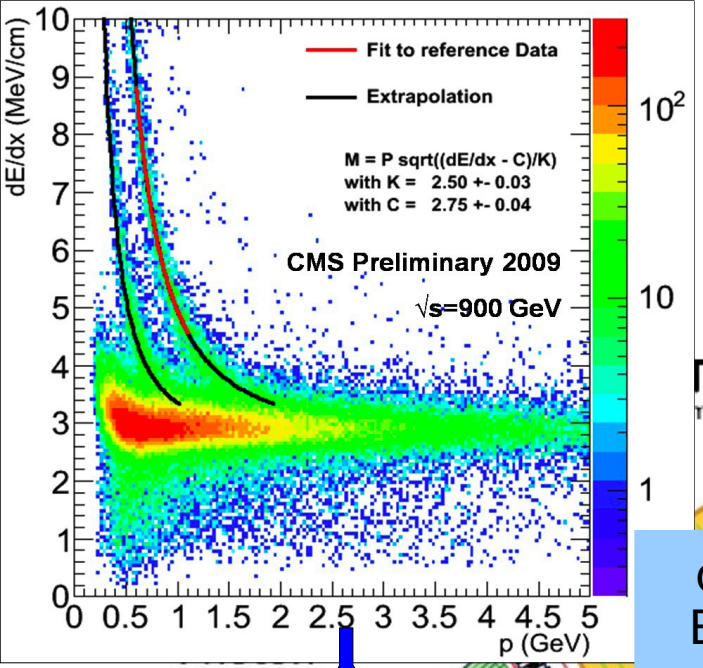
- **lepton like** (stau)
  - fractional charge $(Q = n \cdot 1/3e)$
  - mulitple charge $(Q = n \cdot e)$
- **R-hadrons** formed from **gluino** or **stop**
  - charge can flip while crossing particle interacting with detector



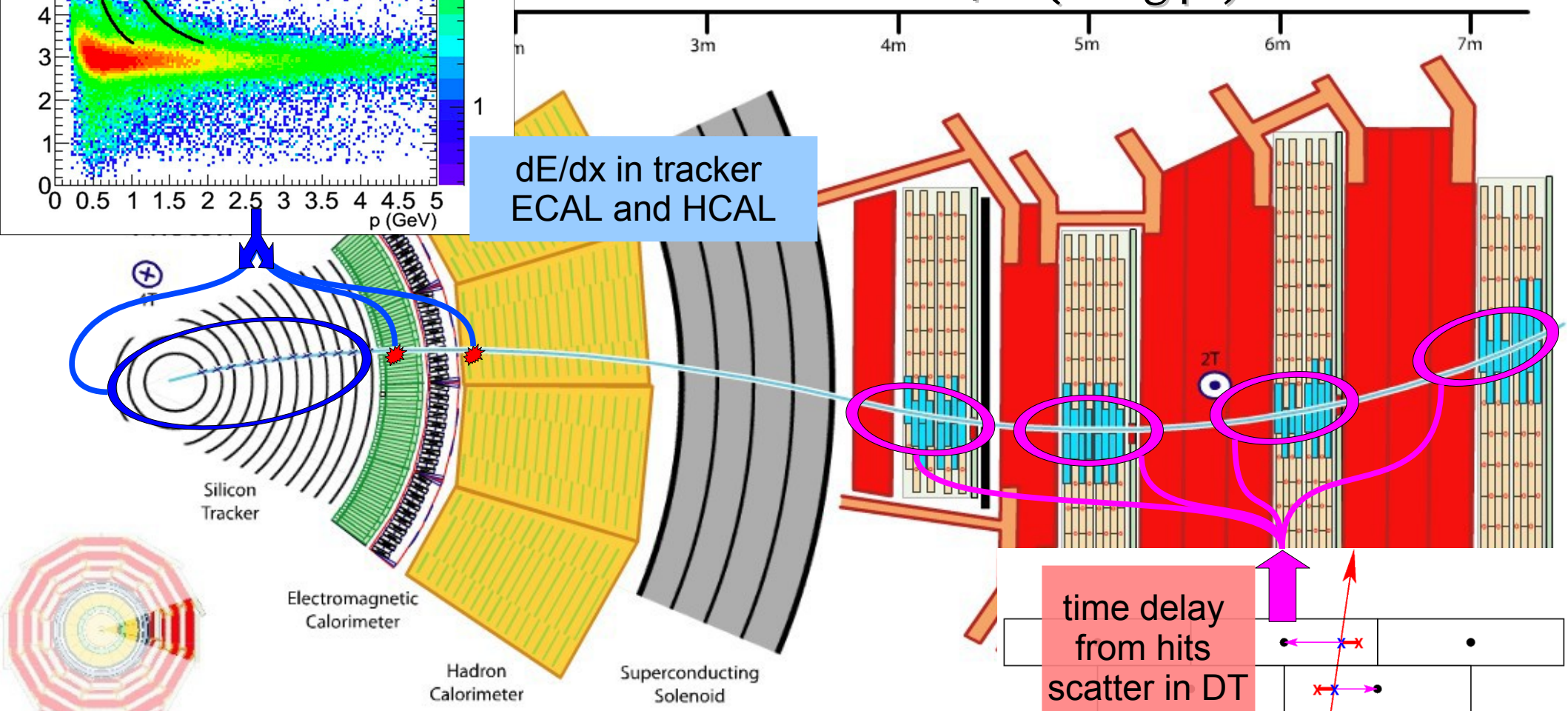
Idea of HSCP Search

Tracker: Mass determination from dE/dx (using pt)

$$I_h = K\frac{m^2}{p^2} + C$$

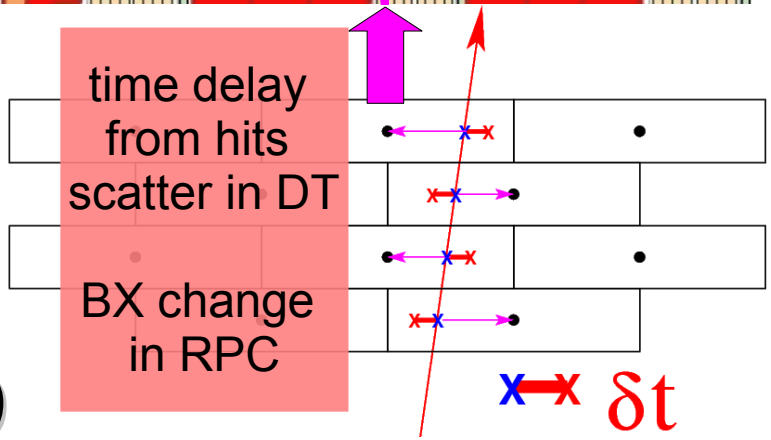


dE/dx in tracker ECAL and HCAL



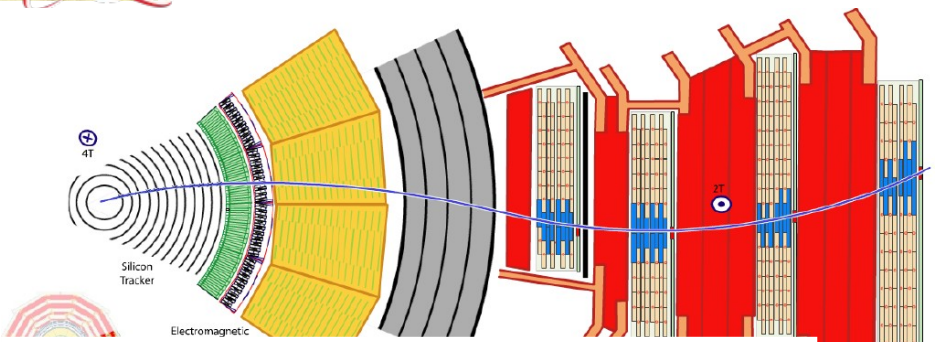
time delay from hits scatter in DT

BX change in RPC

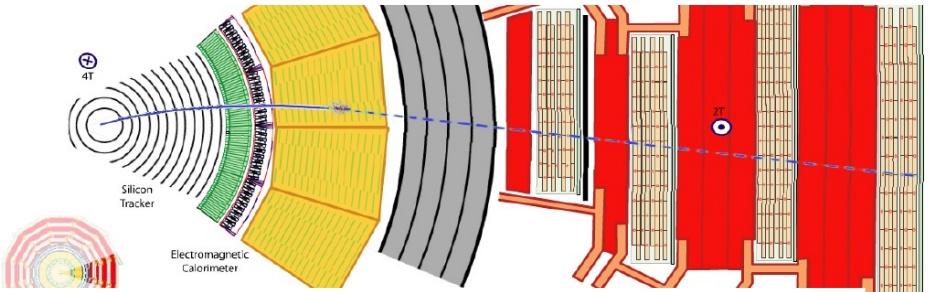


TOF: HSCP velocity (β) measurement from DT, CSC, (RPC for triggering)

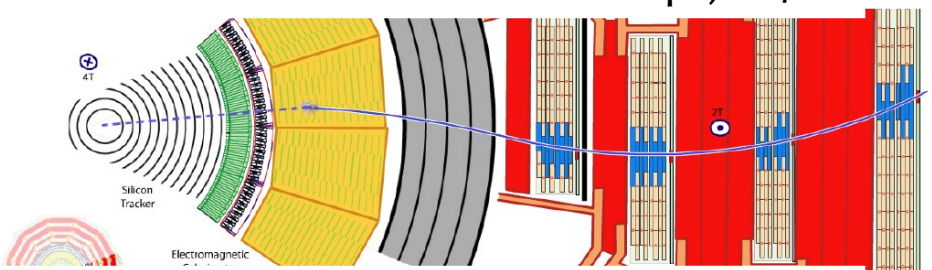
Five HSCP Search Paths



HSCP unchanged – **Tracker+TOF** uses: pt, dE/dx TOF



HSCP becoming neutral – **Tracker-only** uses: pt, dE/dx

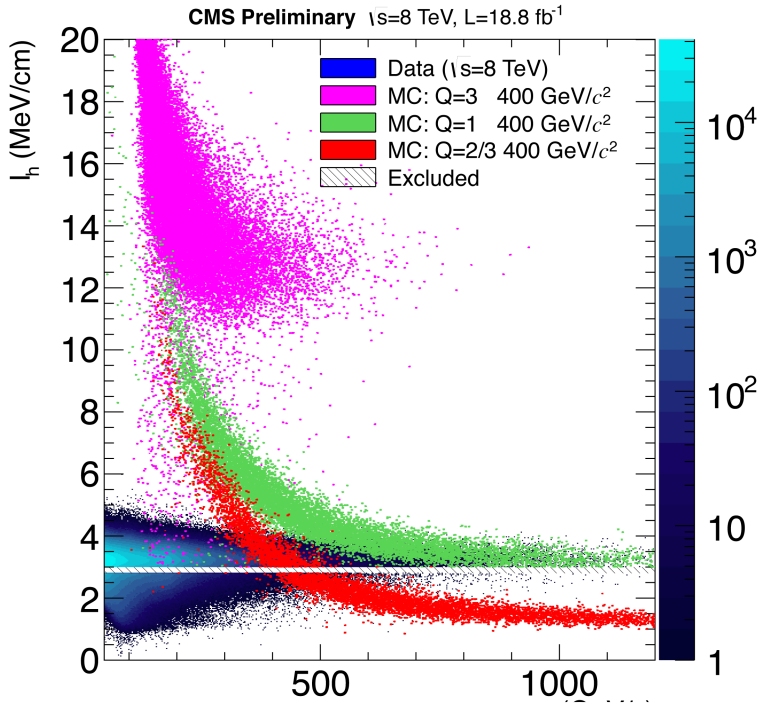


HSCP neutral in tracker, becoming charged – **Muon-only** uses: pt, TOF

HSCP with Q = n · *e*

Mutiply Charged Particles

uses: dE/dx TOF, **do not use pt,** because reco pt ~ true pt/Q



HSCP with Q = n · 1/3*e*

Fractionaly Charged Particles

uses: pt, dE/dx, no TOF to be inclusive

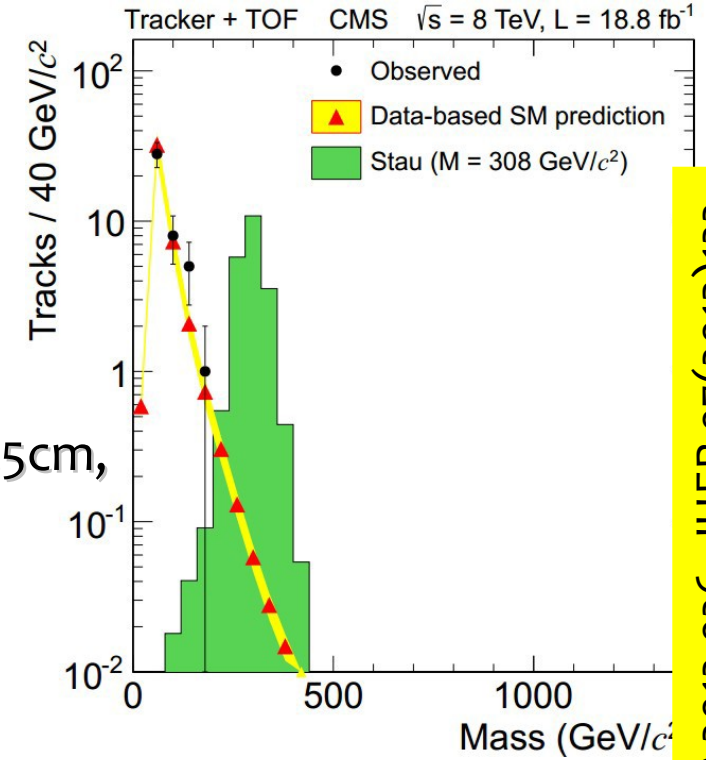
CMS-PAS-EXO-2012-026, JHEP 07(2013)122

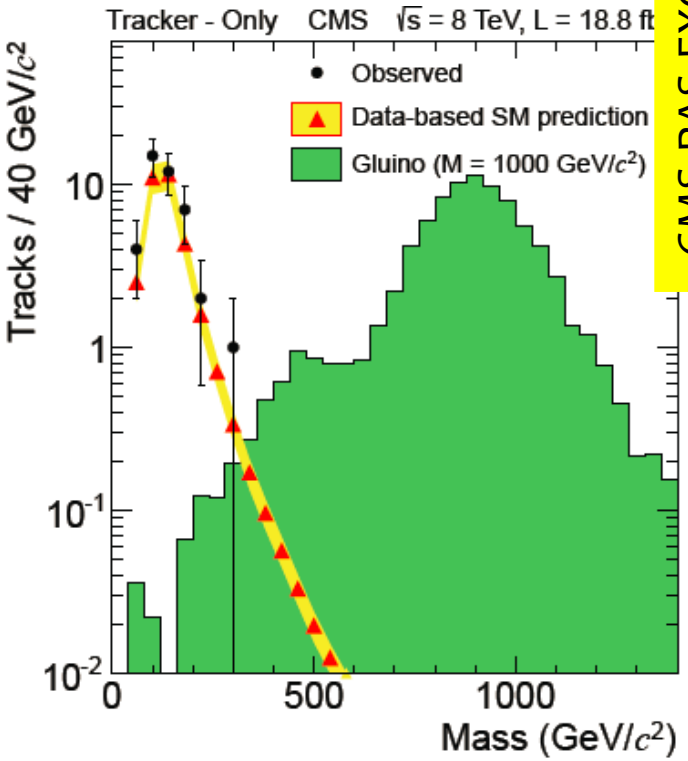
HSCP RESULTS

Event selection:

- **Trigger:** muon (pT>40 GeV) or MET > 150 GeV or mu pt> 60 GeV & MET > 65 GeV
- **Basic pre-selection:** pT>45GeV, |η|<2.1, |dxy| and |dz|<0.5cm, #Hits>7, very loose isolation, cosmic veto, etc
- **Selection optimised** to for the best discovery reach for each class of models using **track pT, Muon 1/β, Track I_{as}** (dE/dx discriminator)
- **Background** from ABCD method

	Selection criteria				Number of events $\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV	
	p_T (GeV/c)	$I_{as}^{(\prime)}$	$1/\beta$	Mass (GeV/c^2)	Pred.	Obs.	Pred.	Obs.
Tracker-only	>70	>0.4	–	>0	7.1 ± 1.5	8	33 ± 7	41
				>100	6.0 ± 1.3	7	26 ± 5	29
				>200	0.65 ± 0.14	0	3.1 ± 0.6	3
				>300	0.11 ± 0.02	0	0.55 ± 0.11	1
				>400	0.030 ± 0.006	0	0.15 ± 0.03	0
Tracker+TOF	>70	>0.125	>1.225	>0	8.5 ± 1.7	7	44 ± 9	42
				>100	1.0 ± 0.2	3	5.6 ± 1.1	7
				>200	0.11 ± 0.02	1	0.56 ± 0.11	0
				>300	0.020 ± 0.004	0	0.090 ± 0.02	0
Muon-only	>230	–	>1.40	–	–	–	6 ± 3	3
$\|Q\| > 1e$	–	>0.500	>1.200	–	0.15 ± 0.04	0	0.52 ± 0.11	1
$\|Q\| < 1e$	>125	>0.275	–	–	0.12 ± 0.07	0	1.0 ± 0.2	0





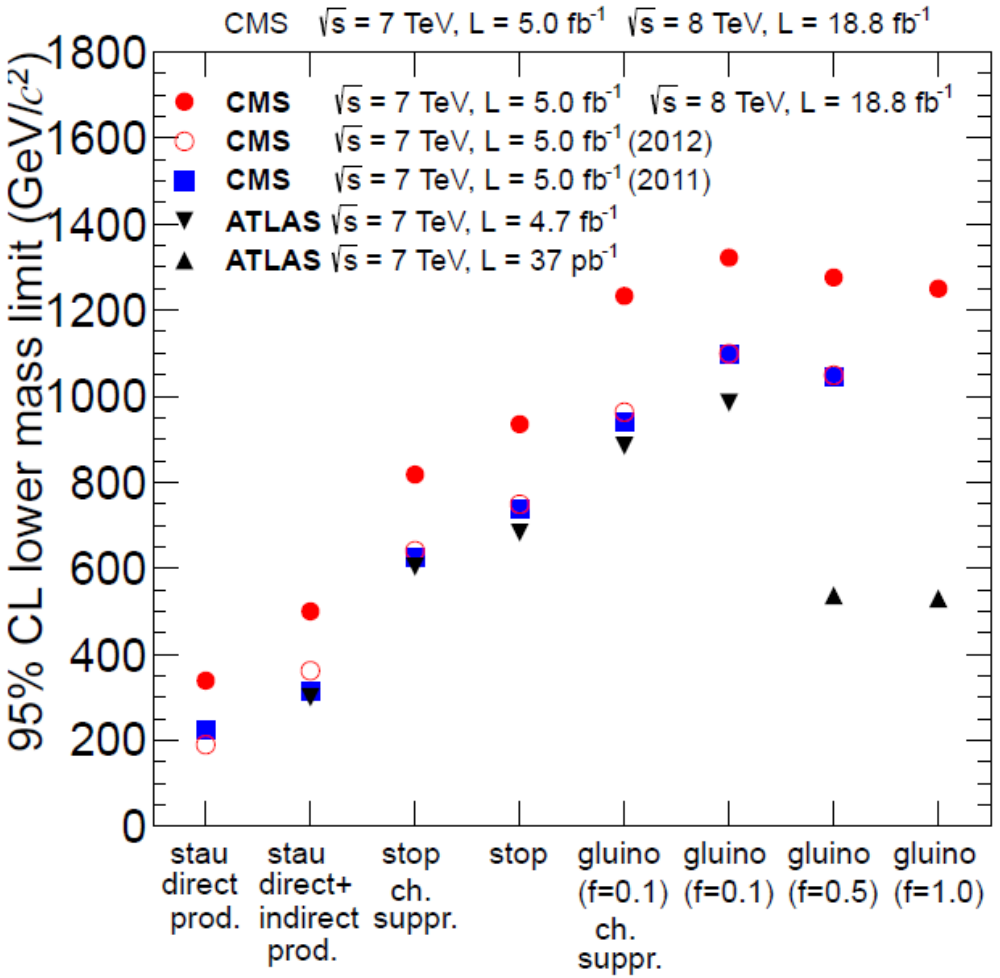
CMS-PAS-EXO-2012-026, JHEP 07(2013)122

HSCP LIMITS

CMS-PAS-EXO-2012-026, JHEP 07(2013)122

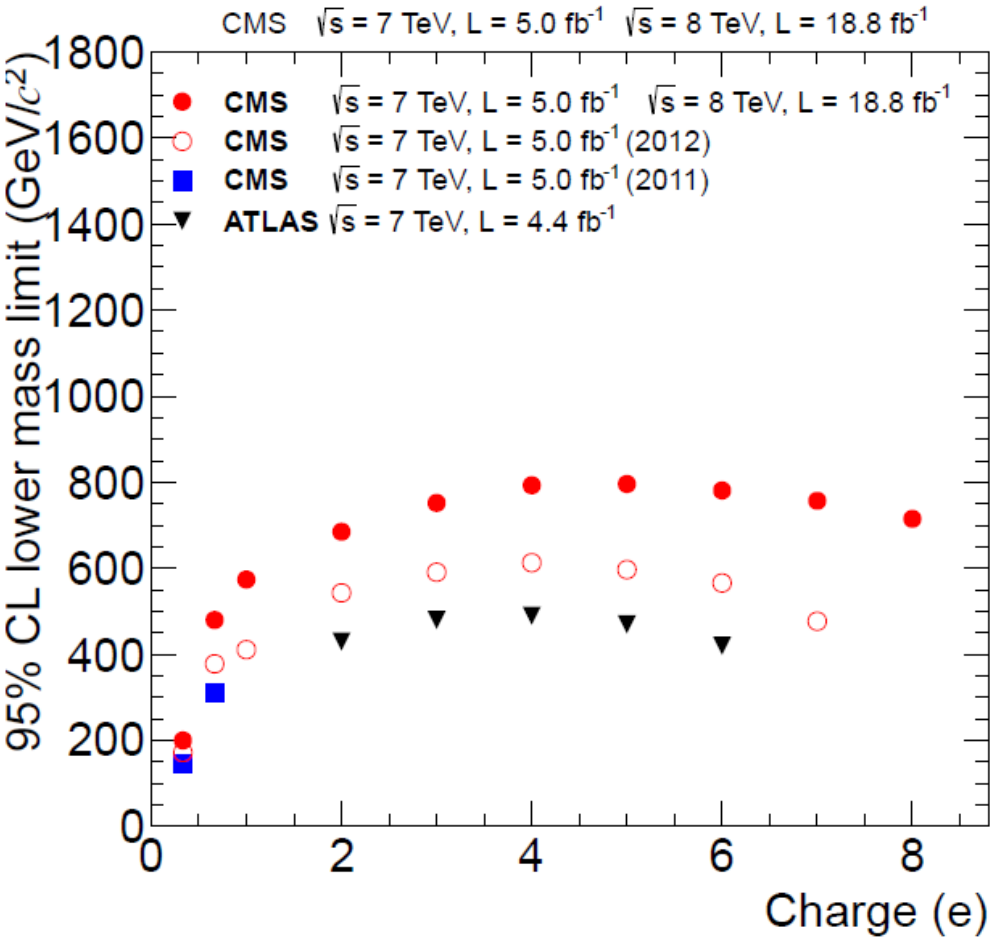
Stau

R-hadrons (stop, gluino)



Mutiply Charged Particles

Fractionaly Charged Particles



EXOTICA @ CMS

Summary (a kind of)

- We have searched for (almost) everything

EXOTICA @ CMS

Summary (a kind of)

- We have searched for (almost) everything
- We have found nothing
- We will keep searching

"Exotic island" not have seen yet

EXOTICA @ CMS

Summary (a kind of)

- We have searched for (almost) everything
- We have found nothing
- We will keep searching

"Exotic island" not have seen yet

- CMS performed a **large set of inclusive and exclusive searches** with different signatures and methods
  - No evidence of new physics so far →
  - Mass, cross-section limits are set in context of considered models
- **Let's be patient**
  - More sophisticated analyses with 2012 8 TeV data on the way
  - We have about one year to get ready (plan and improve techniques) for collisions at 13 TeV

References:

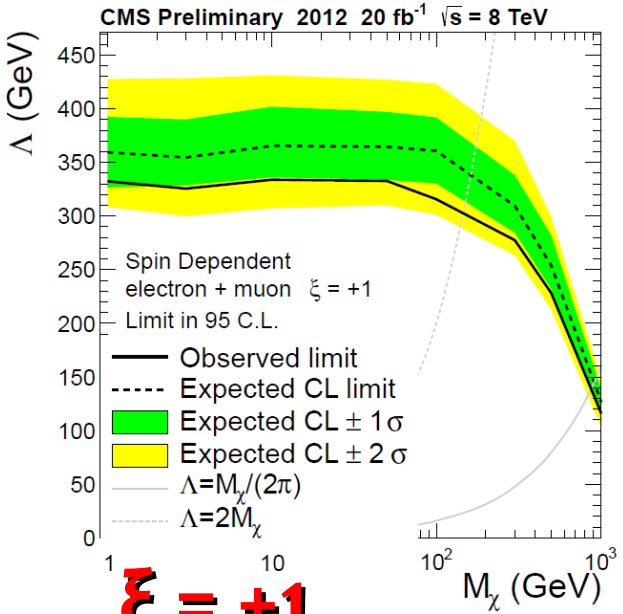
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

List of included publications

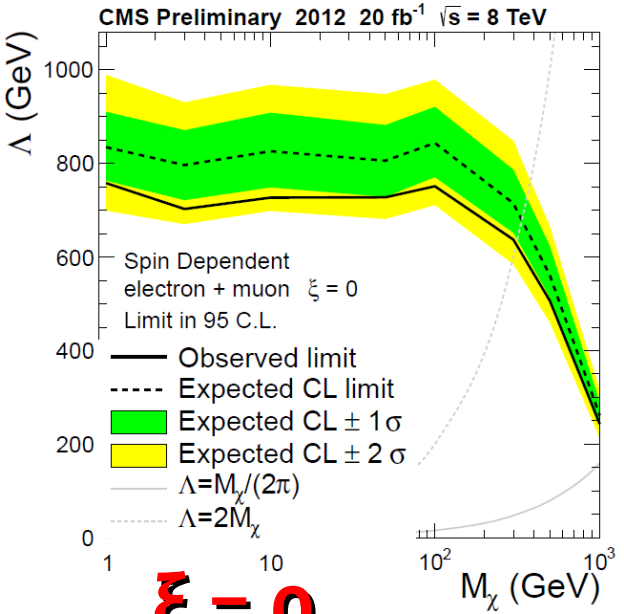
- 12-061 Di-lep; Z'
- 12-059 Di-wide-jets; q*,A,D,C,Z',W',S
- 12-009 Multi-jet; Black Holes
- 12-048 Mono-jets; ADD, DM
- 13-004 Mono-lep; DM
- 12-038 Displaced jets; Hidden Valley
- 12-026 HSCP; stau, R-hadron

Mono-leptons

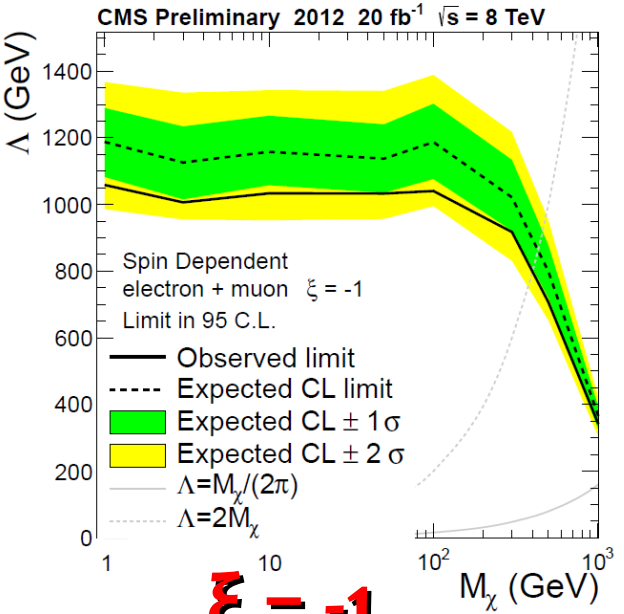
CMS-PAS-EXO-2013-004



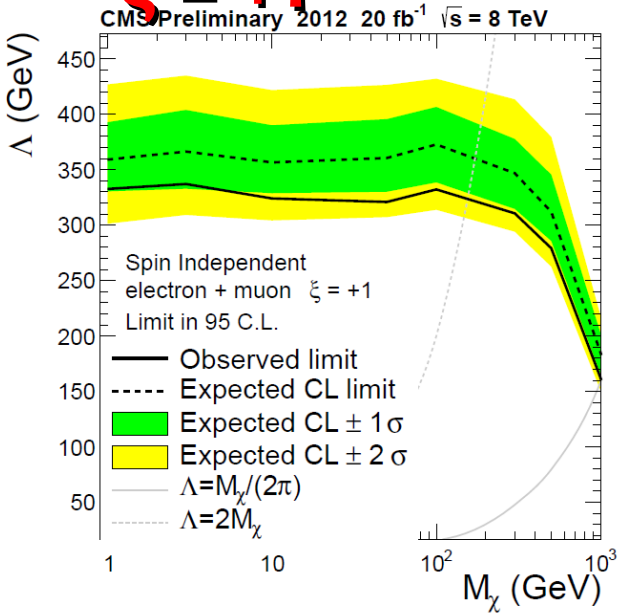
ξ = +1

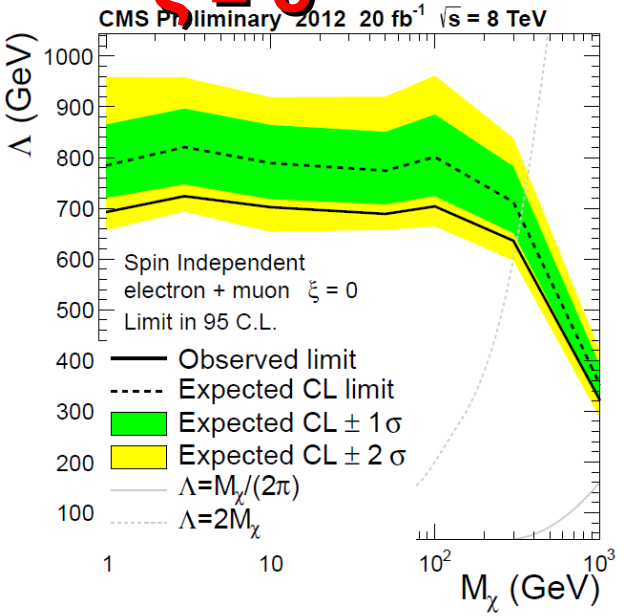


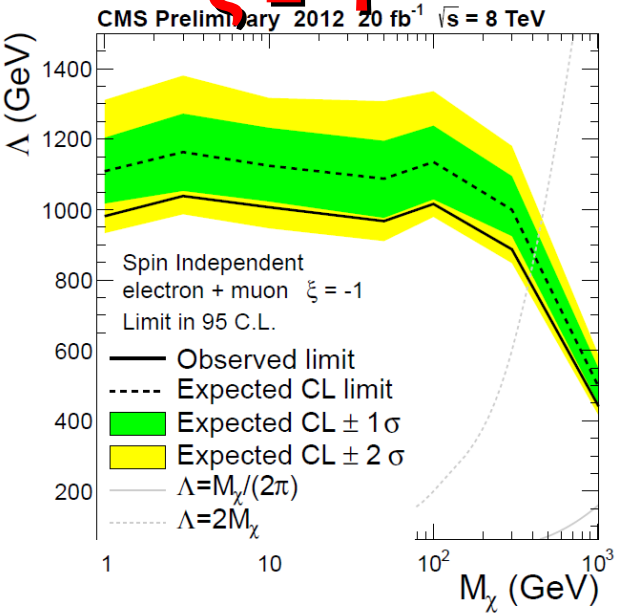
ξ = 0



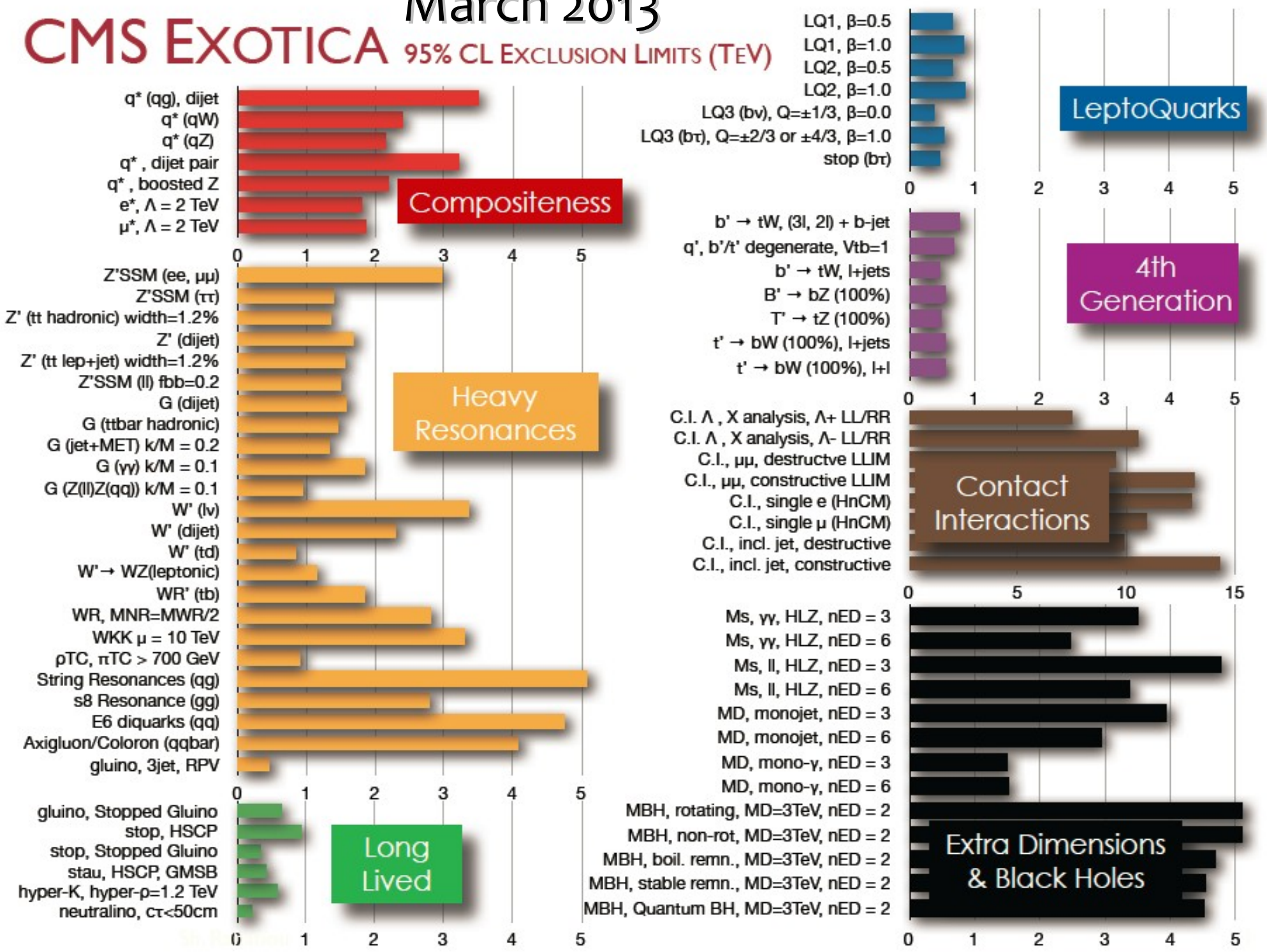
ξ = -1







March 2013


CMS EXOTICA
95% CL EXCLUSION LIMITS (TEV)
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Heavy Resonances
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
Long Lived
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
LeptoQuarks
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
4th Generation
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Contact Interactions
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
Extra Dimensions & Black Holes