Searches for Large Extra Dimensions at CMS

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On behalf of the CMS Collaboration

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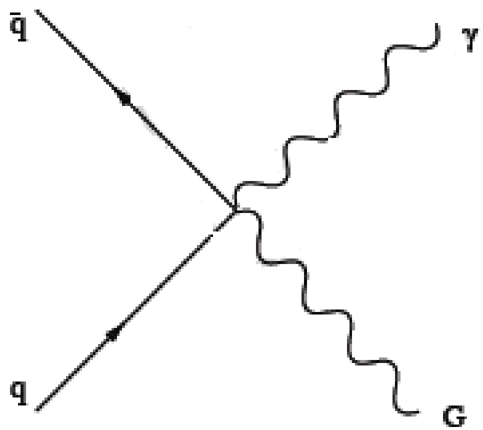
Outline

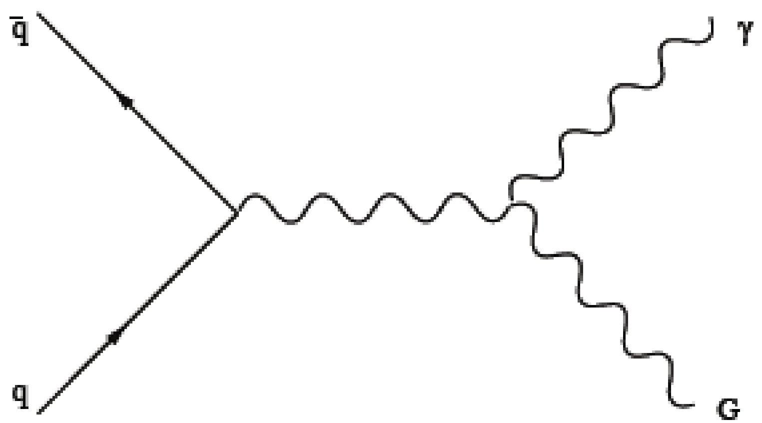
- **Searches for Extra Dimensions (ED) at CMS:**
  - ADD model – solution to the hierarchy problem
- **Analyses:**
  - Large ED in monophoton and monojet final state
  - LED and Randall-Sundrum gravitons in diphoton final state
  - LED in dimuon and dielectron final state
  - Microscopic black holes
- **Conclusions**

Search for Large Extra Dimensions in Monophoton Final State

CMS PAS EXO-11-096

- **Data and event selection:**
  - Data are collected with single photon triggers
  - One isolated (tracker and calorimeter) photon with $|\eta| < 1.44$ and $E_T > 145$ GeV, no track match
  - MET > 130 GeV
  - within 3 ns in time with collision
  - no jets with $p_T > 40$ GeV and no tracks with $p_T > 20$ GeV; muon tracks veto





- **Signal:** Pythia8, scaled to NLO

Backgrounds

4.7 fb^{-1}

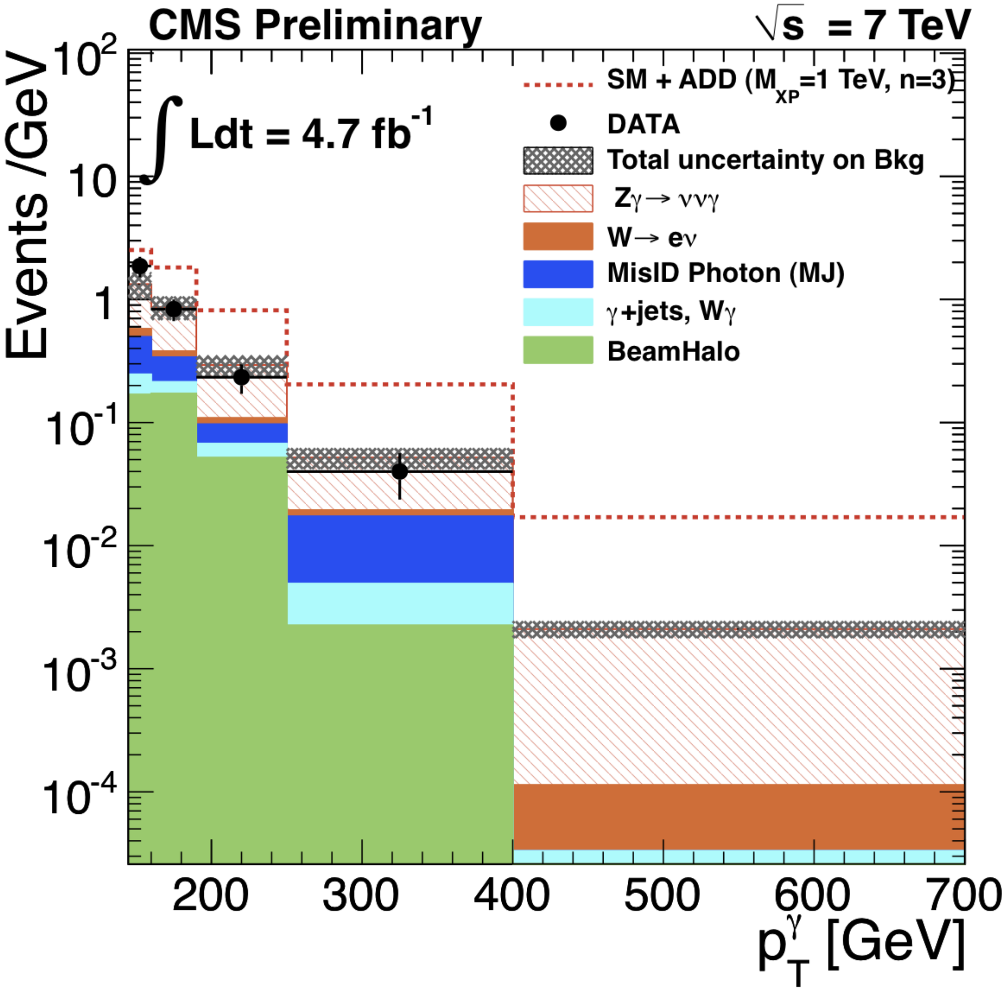
- **Simulated backgrounds:**
  - Main $Z(\nu\nu)\gamma$ – from Pythia6, scaled to NLO
  - $W(l\nu)\gamma$ – MadGraph and NLO corrected (MCFM)
  - γ+jet and diphoton – Pythia6

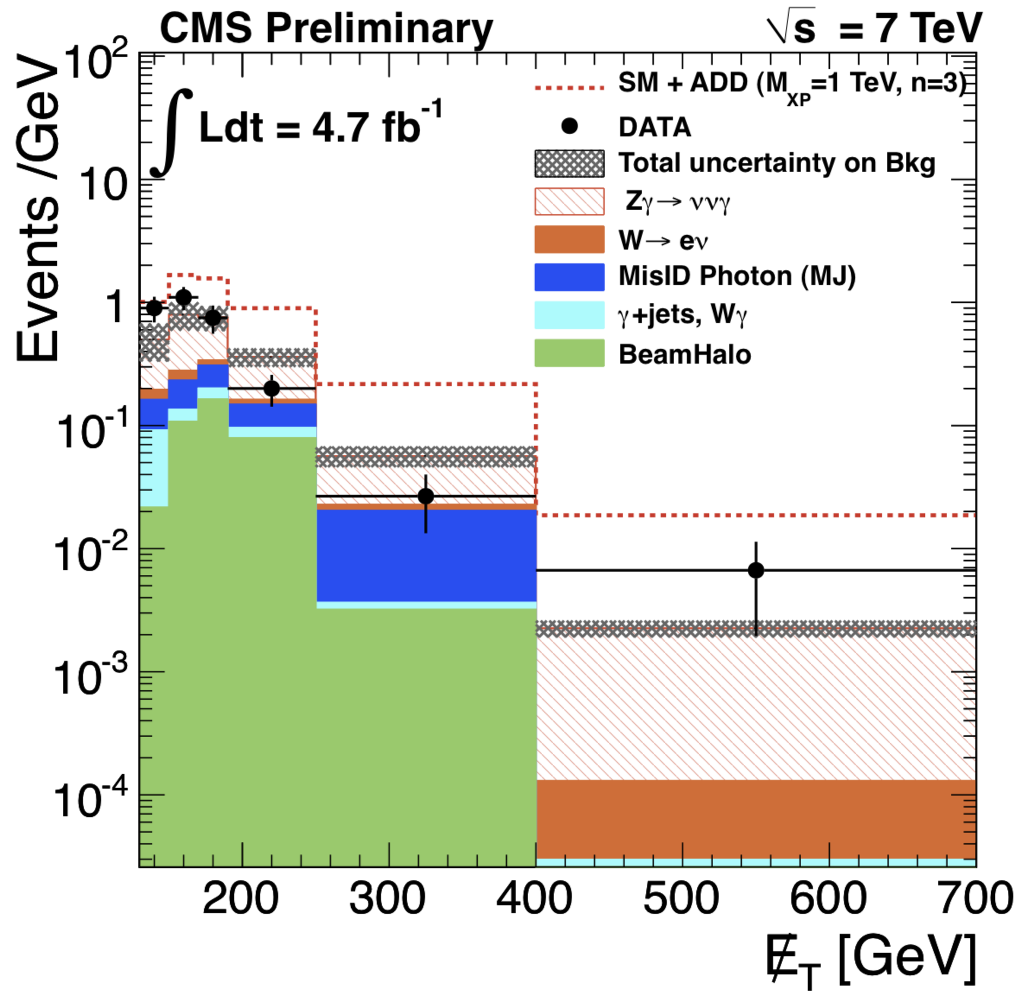
Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	2.8 ± 0.9
γ+jet	0.5 ± 0.2
$\gamma\gamma$	0.5 ± 0.3
$Z(\nu\bar{\nu})\gamma$	42.4 ± 6.3
Total Background	71.9 ± 9.1
Total Observed Candidates	73

- **Estimated from data:**
  - Out-of-time – templates are fit to data with no timing requirement
  - Jets misidentified as photons
  - Electrons faking photons – electron control sample scaled by $(1-\varepsilon)/\varepsilon$ (efficiency of matching a pixel seed to calorimeter cluster $\varepsilon = 0.994$)

Distributions

Transverse momentum and MET spectra

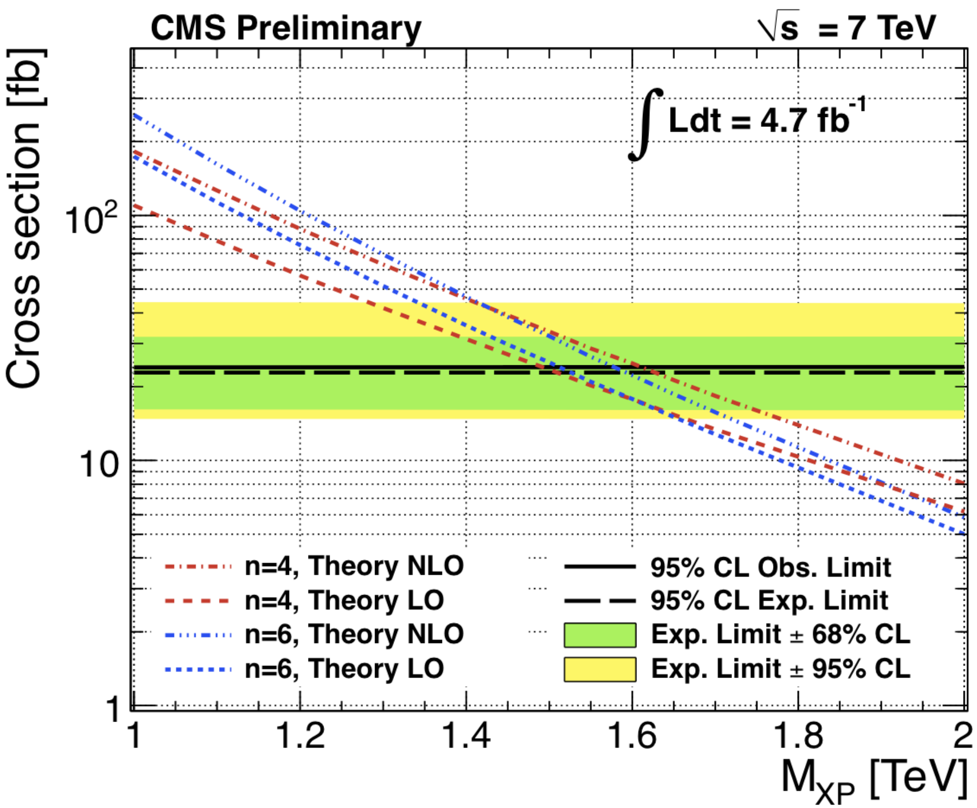




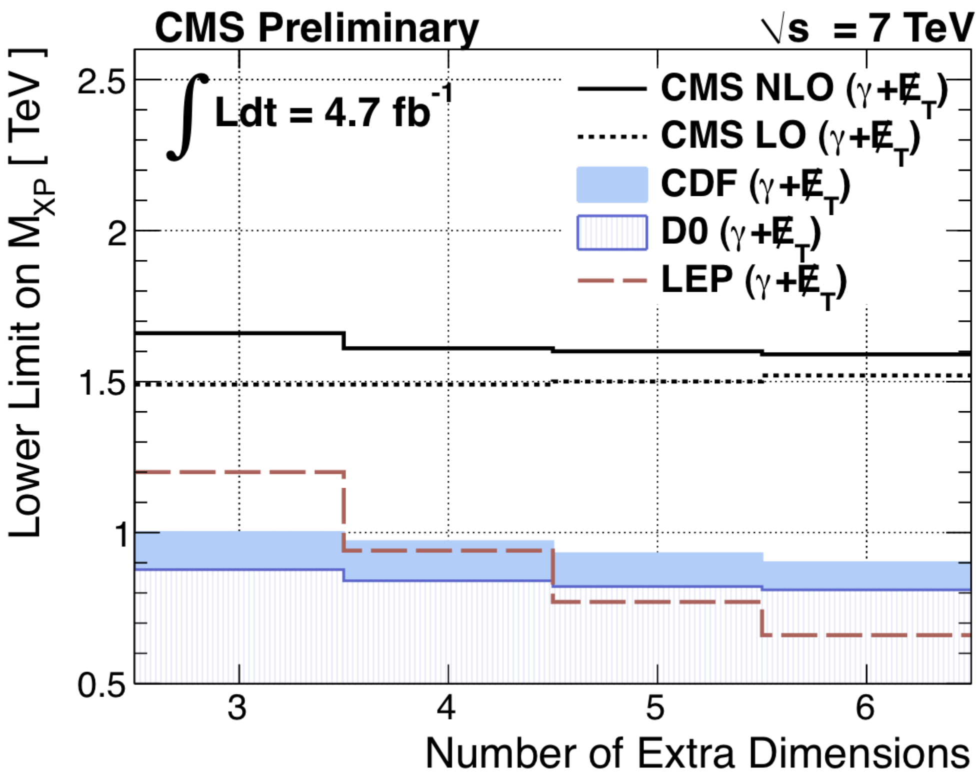
- **Good agreement between data and expected background**
- **Same spectra can be searched for Dark Matter**

95% CL Limits

Upper limits on cross section



Limits on M_{XP} as a function of n



M_{XP} limits:

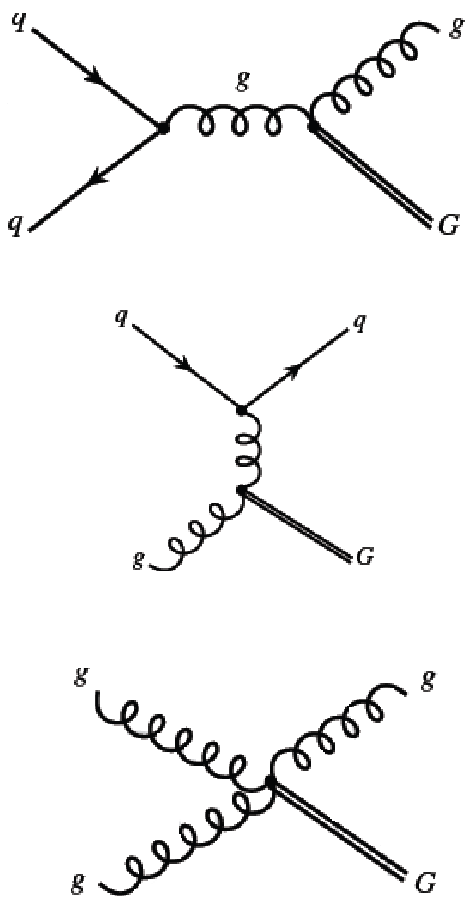
n	k-factor	Exp. Limit [TeV]	Obs. Limit, [TeV]
3	1.5 (1.0)	1.68 (1.51)	1.66 (1.49)
4	1.4 (1.0)	1.63 (1.51)	1.61 (1.49)
5	1.3 (1.0)	1.61 (1.52)	1.60 (1.50)
6	1.2 (1.0)	1.60 (1.53)	1.59 (1.52)

Search for Large Extra Dimensions in Monojet Final State

Searches for Monojets

CMS PAS EXO-11-059

- **Data and event selection:**
  - Data are collected with jet ($p_T > 80$) + MET ($E_T > 80$ or 95 GeV) triggers
  - $N \leq 2$ particle flow jets with $p_T > 30$ GeV, $p_T(j_1) > 110$ GeV, $|\eta(j_1)| < 2.4$, $\Delta\varphi(j_1,j_2) < 2.5$
  - MET > 200 GeV
  - veto events with isolated leptons or tracks with $p_T > 10$ GeV

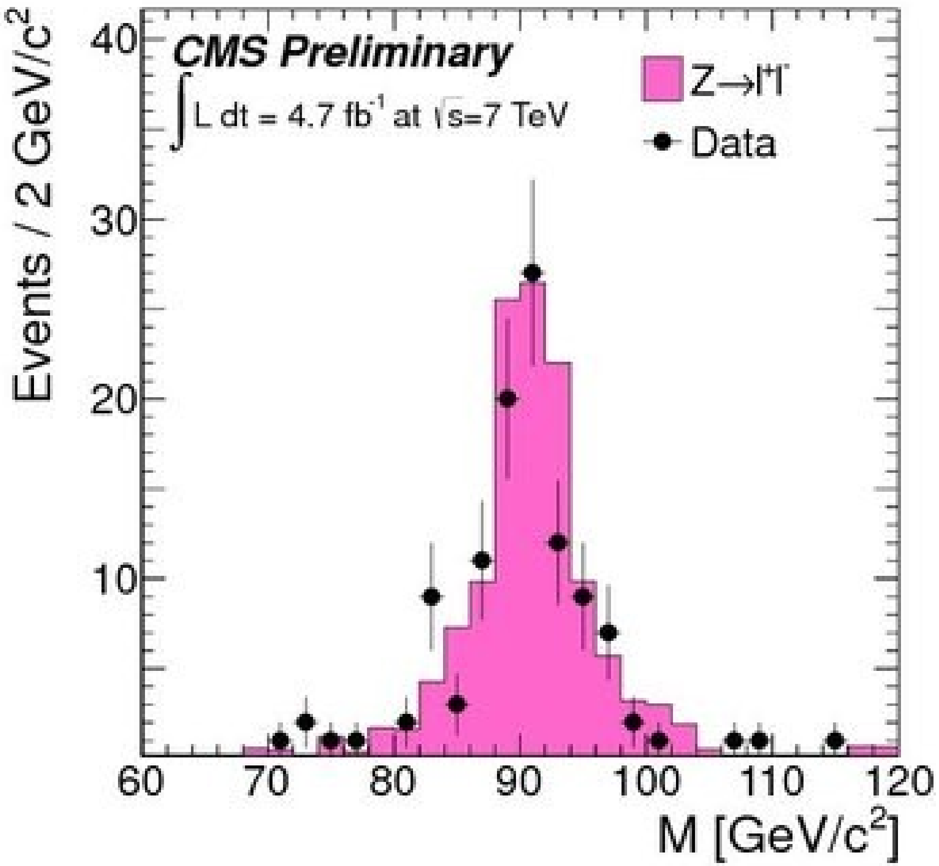


- **Signal:** Pythia8, scaled to NLO (order of 1.4 – 1.5), optimized MET > 350 GeV

Backgrounds

- **W+jets – from μ+jets events in control data sample:**
  - 50 GeV < M_T(μMET) < 100 GeV
  - Scaled by acceptance, efficiency
- **Z+jets – μμ+jets events:**
  - 60 GeV < M(μμ) < 120 GeV
  - For invisible Z decay, rescale by:
    - BR(Z → νν)/BR(Z → μμ)
    - Efficiency of lepton veto (MC)
    - MC acceptance and efficiencies
- **Top, ttbar, QCD, Z+jets – from MC, insignificant after selection cuts**

M(μμ) in Z control sample



Backgrounds

- **W+jets – from μ+jets events in control data sample:**
  - 50 GeV < M_T(μMET) < 100 GeV
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- **Z+jets – μμ+jets events:**
  - 60 GeV < M(μμ) < 120 GeV
  - For invisible Z decay, rescale by:
    - BR(Z → νν)/BR(Z → μμ)
    - Efficiency of lepton veto (MC)
    - MC acceptance and efficiencies

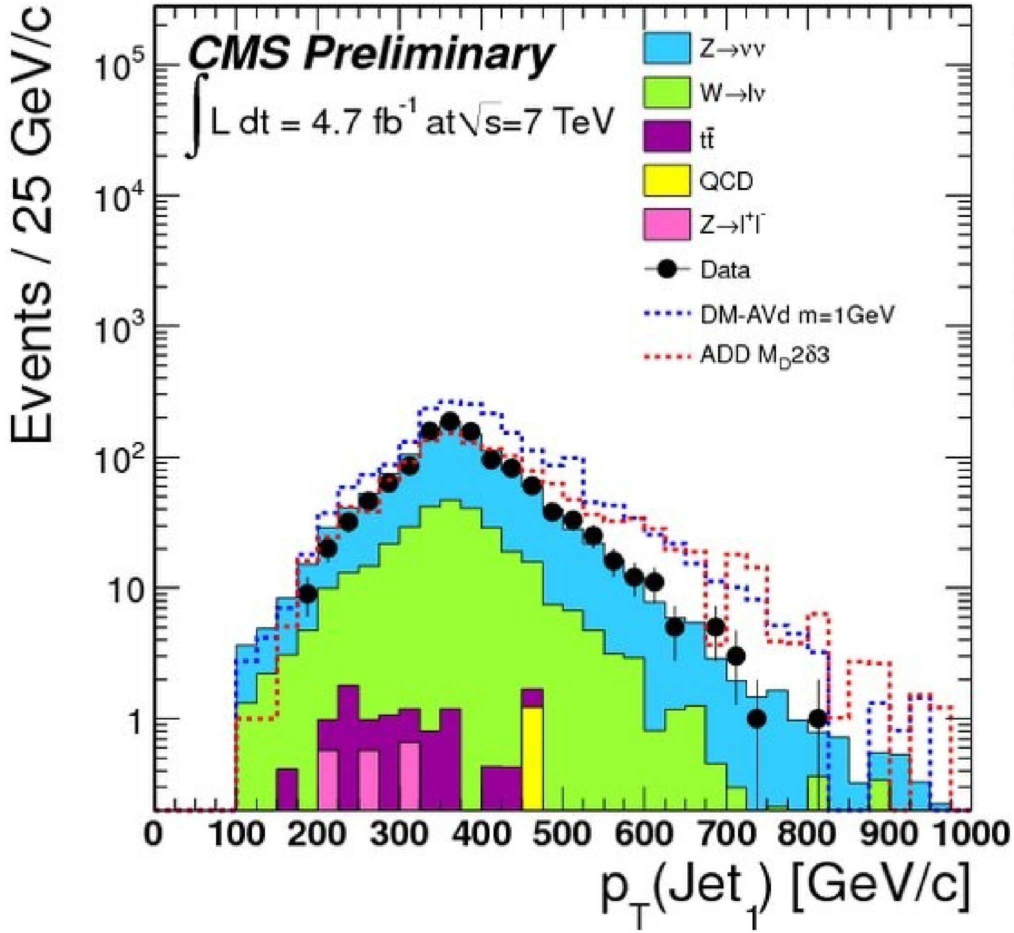
Background process	Events
$Z \to \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142

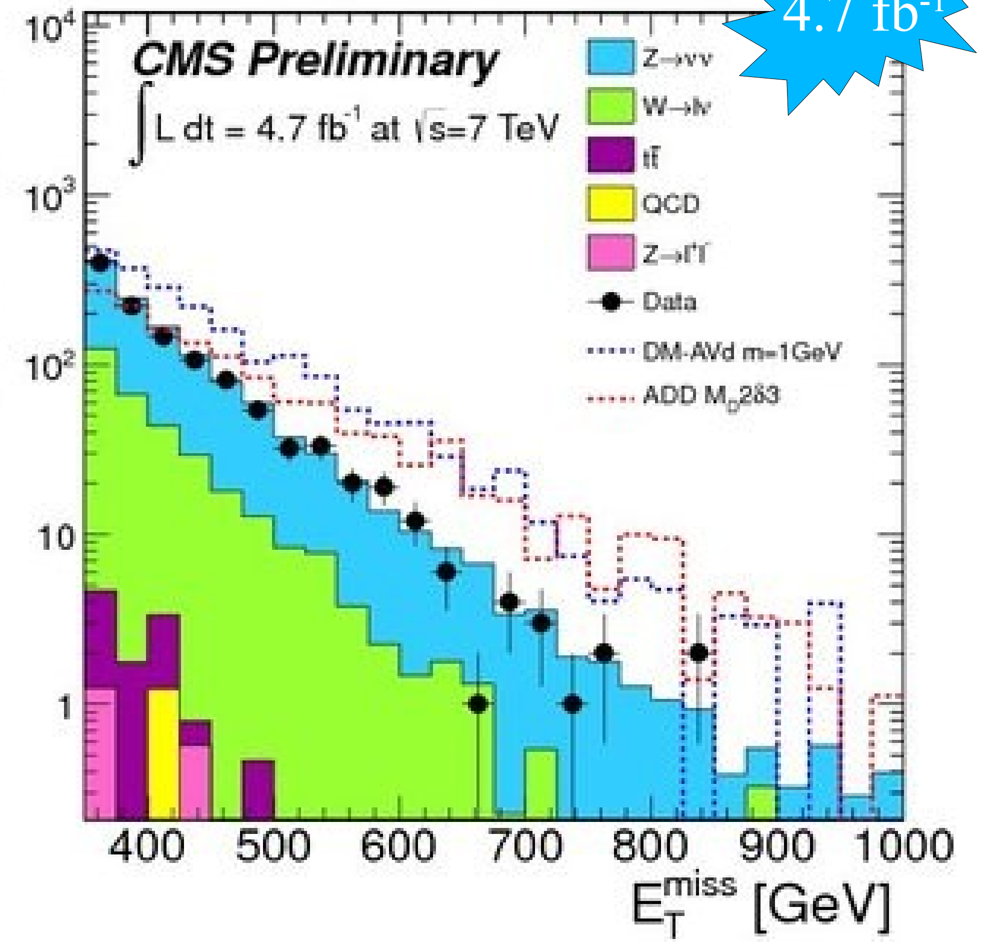
- **Top, ttbar, QCD, Z+jets – from MC, insignificant after selection cuts**

Distributions

Transverse momentum and MET spectra

4.7 fb^{-1}

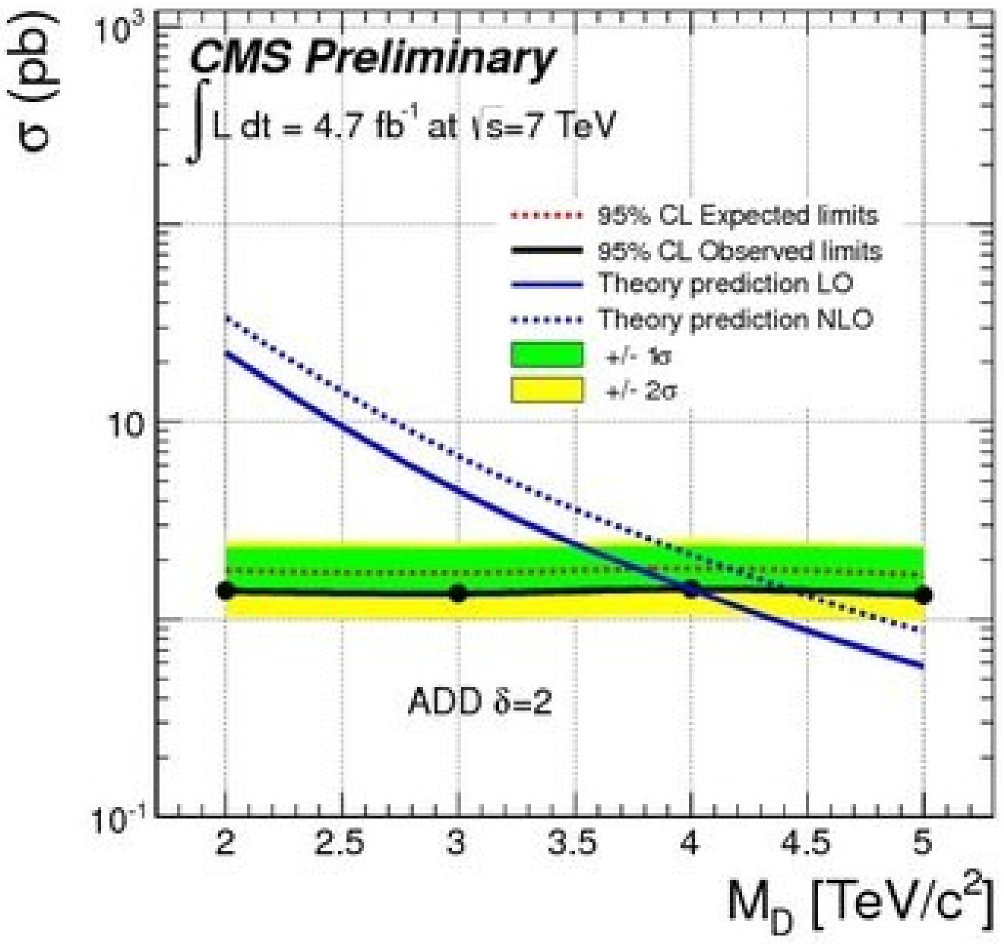


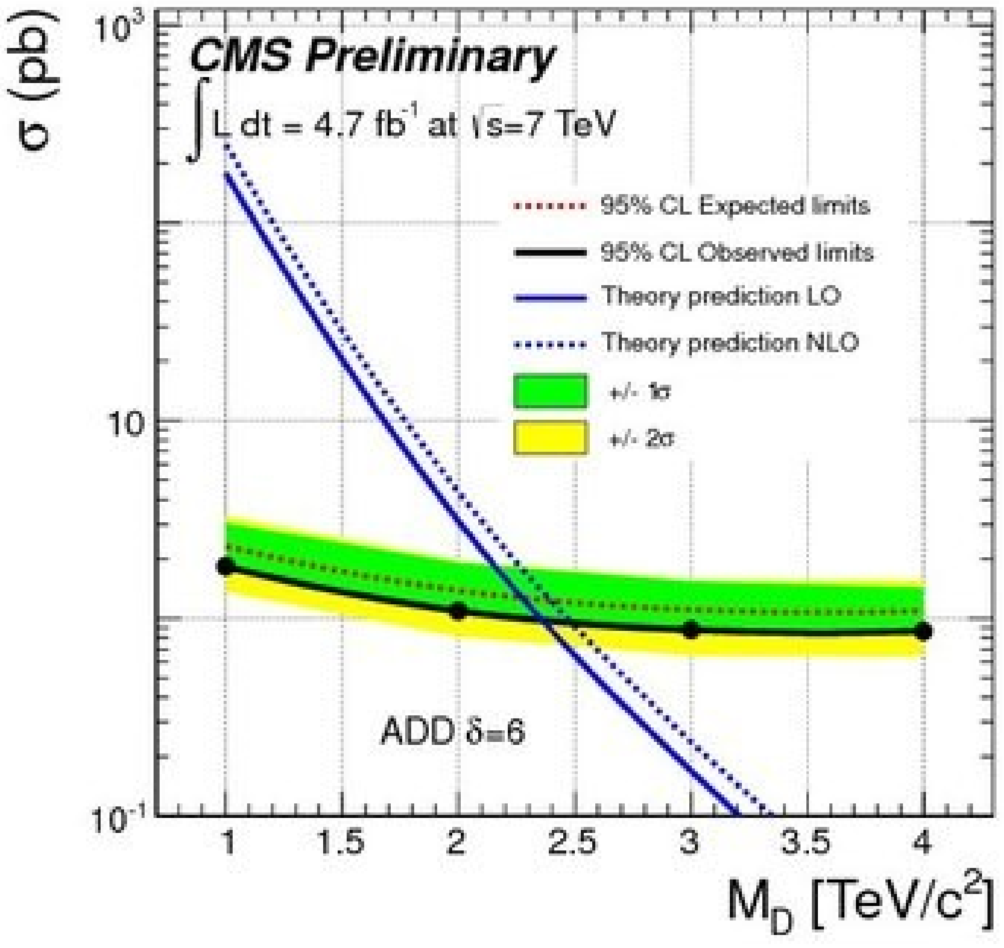


- **Good agreement between observed data and expected background**

95% CL Limits

95% CL limits as a function of M_D for $\delta = 2$ and 6





95% CL Limits

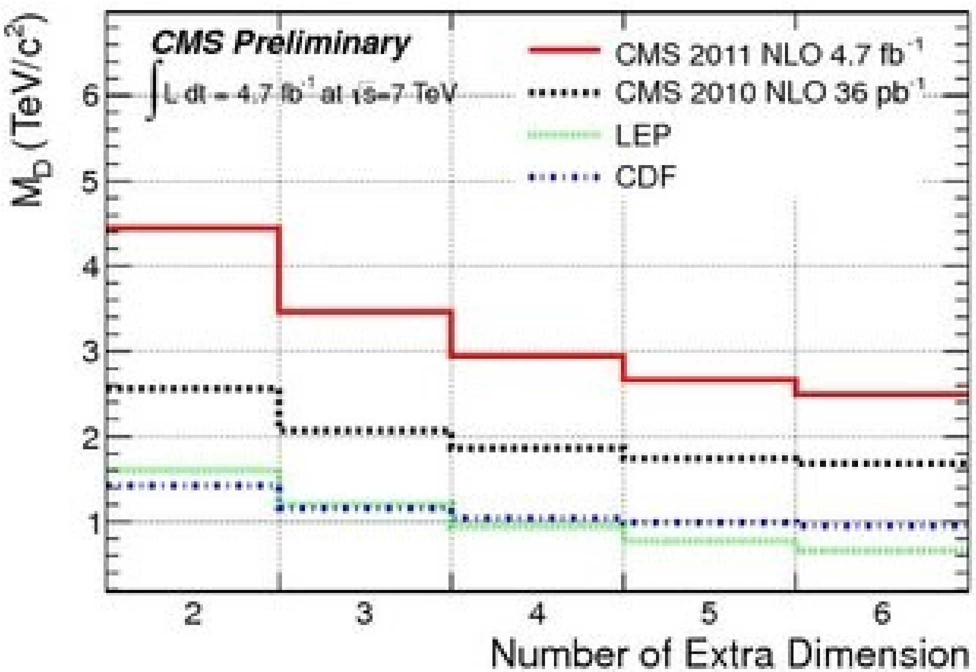
- **ATLAS monojet, 33 pb^{-1} (arXiv:1106.5327):**
  - $M_D > 1.85 - 2.3$ TeV for n = 4 to 2
- **CMS monojet, 36 fb^{-1} (PRL 107 (2011), 201804):**
  - $M_S > 1.68 - 2.56$ TeV for n = 6 to 2
- **This result:**

K-factor = 1.4 - 1.5

	LO		NLO	
δ	Exp. Limit	Obs. Limit	Exp. Limit	Obs. Limit
2	3.76	4.00	4.16	4.44
3	3.04	3.18	3.29	3.46
4	2.68	2.78	2.83	2.94
5	2.42	2.52	2.56	2.66
6	2.27	2.37	2.39	2.49

M_D limits

95% CL limits as a function of δ

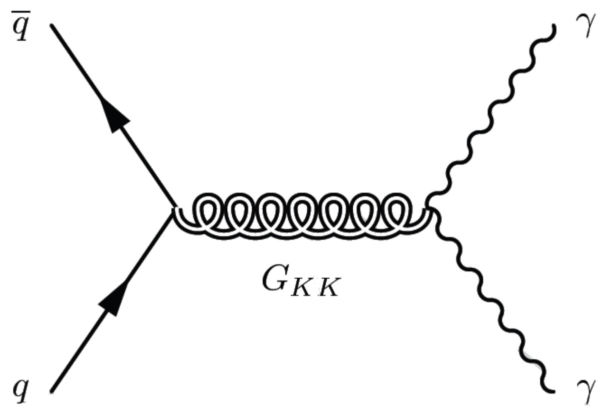


Search for Large Extra Dimensions in Diphoton Final State

ADD and RS1 in Diphotons

PRL 108 (2012), 111801

- **Data and event selection:**
  - Data are collected with diphoton triggers with individual photon $p_T > 33 - 60$ GeV
  - Two isolated photons with $|\eta| < 1.44$ and $p_T > 70$ GeV, no track match
  - $M(\gamma\gamma) > 140$ GeV

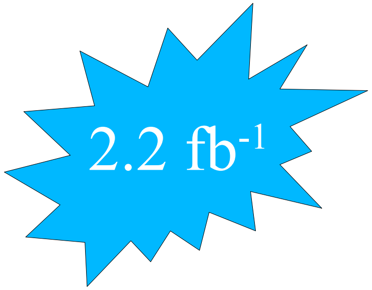


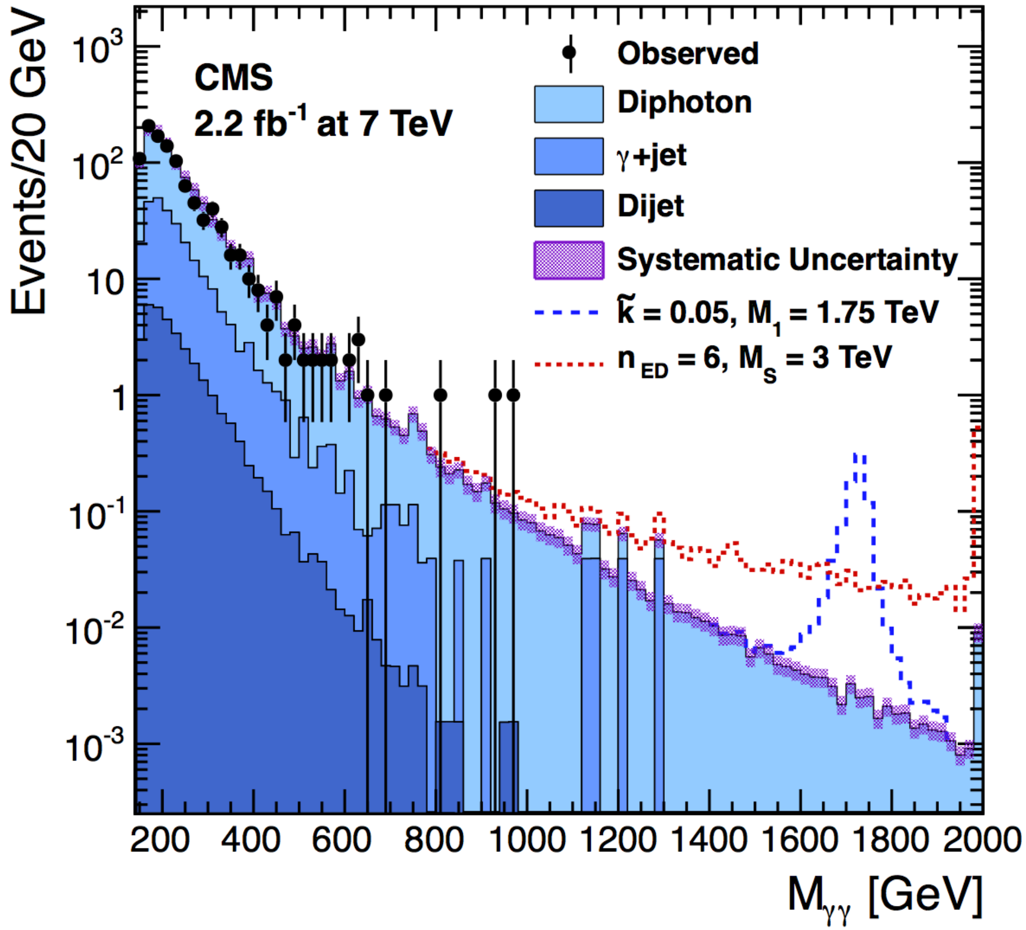
- **Signal:**
  - ADD $\gamma\gamma$ is simulated with Sherpa; NLO K-factor = 1.6 ± 0.1. Use signal MC to optimize $M(\gamma\gamma) > 900$ GeV cut
  - RS $\gamma\gamma$ is simulated with Pythia, NLO K-factor = $f(M(\gamma\gamma)) = 1.6 - 1.8$. Windows around each M_1 containing 96 – 97% of signal acceptance

- **Backgrounds highlights:**
  - Dominant irreducible SM diphoton production is estimated with Pythia, NLO K-factor = 1.7 – 1.1 (DIPHOX); 15% systematics from K-factor variation with M(γγ)
  - Data-driven method to estimate jet-γ fake rate: 7 – 2% at 70 – 120 GeV
  - Fake rate is applied to low-mass background-dominated samples to estimate multijet and jet+photon backgrounds (small in signal region)
- **Systematic uncertainties:**

	Value	**Rel. Uncertainty**
Int. Luminosity	**2.2 fb^{-1}**	**4.5%**
Signal Eff.	**76.4%**	**12.6%**
Signal K-factor	**1.6 – 1.8**	**6%**
Bkg. K-factor	**1.7 – 1.1**	**15%**

Data Yields

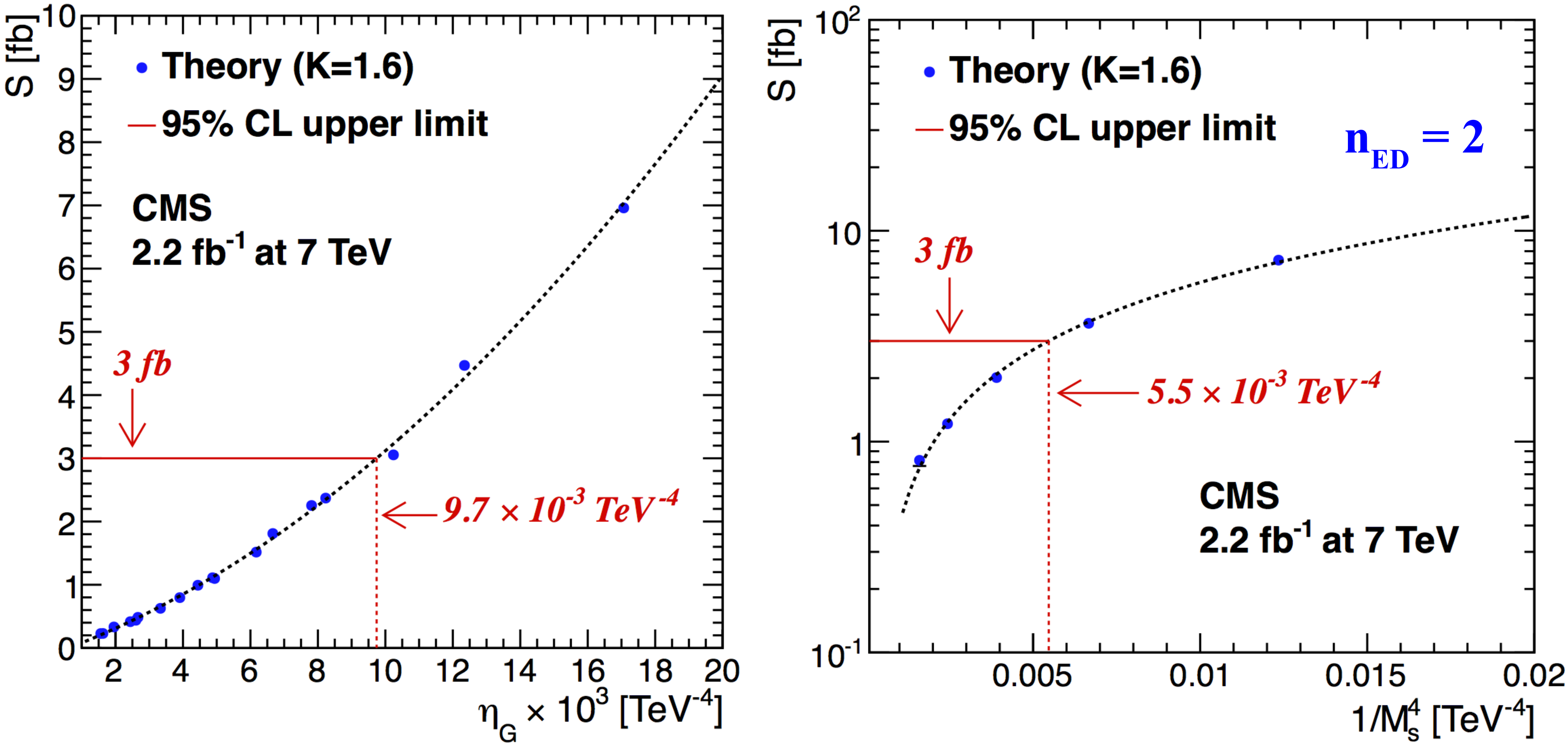




Process	Diphoton Invariant Mass Range [TeV]			
	[0.14, 0.2]	[0.2, 0.5]	[0.5, 0.9]	> 0.9
Multijet	15 ± 6	17 ± 7	0.2 ± 0.1	0.003 ± 0.001
$\gamma + \text{jet}$	102 ± 15	124 ± 18	2.5 ± 0.4	0.19 ± 0.04
Diphoton	372 ± 70	414 ± 78	16.9 ± 3.2	1.3 ± 0.3
Backgrounds	489 ± 73	555 ± 81	19.6 ± 3.2	1.5 ± 0.3
Observed	484	517	16	2

Signal Cross Section Parameterization

Signal cross section (S) parameterization as a function of η_G and $1/M_S^4$



- **Upper 95% CL limit on S = 3 fb**

95% CL Limits on ADD

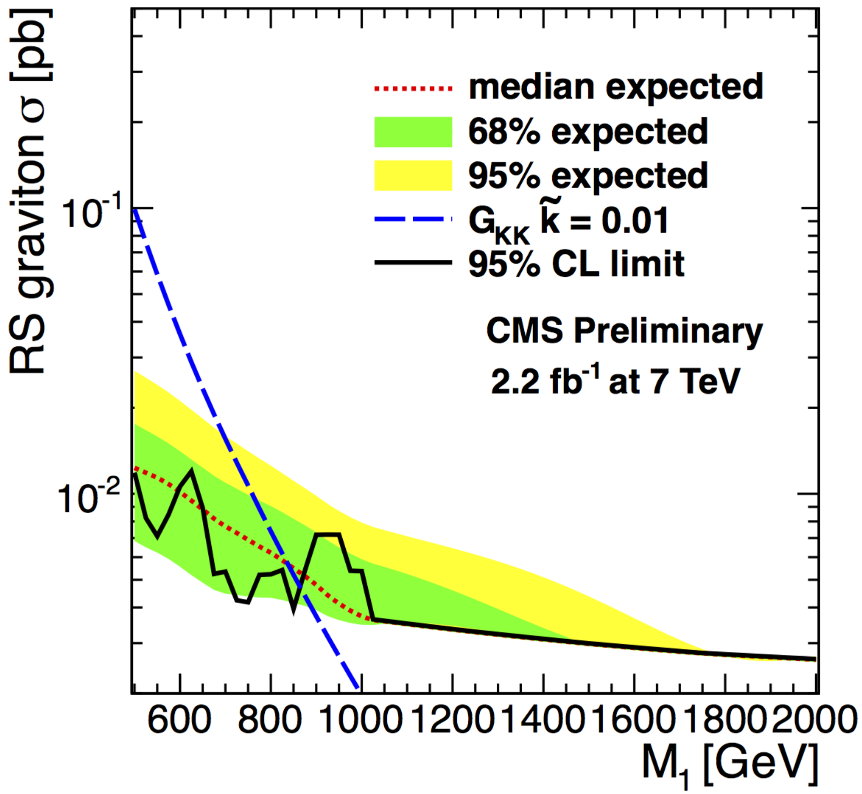
- **CMS diphotons, 36 pb^{-1} (JHEP 5 (2011), 85):**
  - M_S > 1.31 – 2.23 TeV for n = 7 to 3
- **D0 diphotons+dielectrons, 1.05 fb^{-1} (PRL 102 (2009), 051601):**
  - M_S > 2.09 for n = 2
- **This result (PRL 108 (2012), 111801):**

K factor	GRW	Hewett		HLZ					
		pos.	neg.	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
1.6	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53

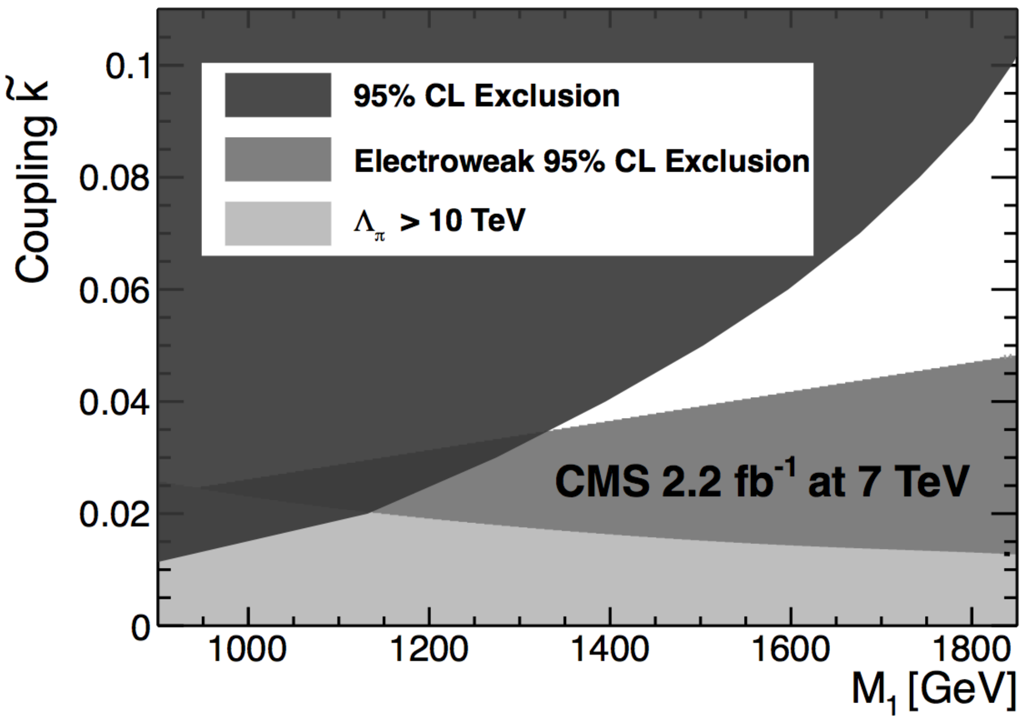
95% CL Limits on RS1

- **Previous: ATLAS dileptons, 1.08 and 1.21 fb^{-1} (arXiv:1108.1582):**
  - $M_1 > 1.63$ for $k/M_{Pl} = 0.1$

Limits on cross section for $k/M_{Pl} = 0.01$



Exclusion region for RS1 model

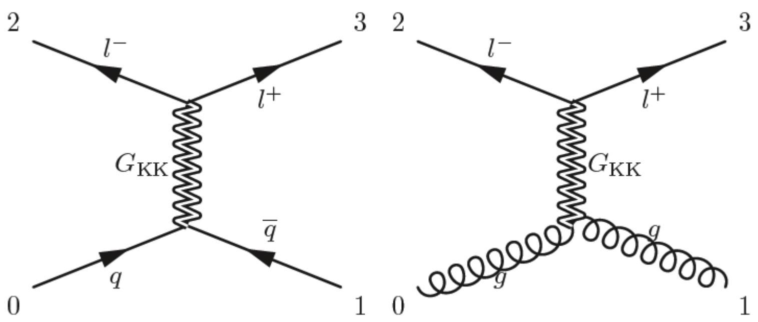


$\tilde{k}$	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
M_1 [TeV]	0.86	1.13	1.27	1.39	1.50	1.59	1.67	1.74	1.80	1.84	1.88

Search for Large Extra Dimensions in Dilepton Final State

arXiv:1202.3827v1/hep-ex
Submitted to PLB

Data and event selection:



- Data are collected with single muon (p_T > 15 – 40 GeV) or dielectron/diphoton (p_T > 33 GeV) triggers
- Two isolated muons with $|\eta| < 2.1$ and p_T > 45 GeV, with hits in both tracker and muon chambers, not exactly back-to-back
- Two isolated (in tracker and calorimeter) electrons with p_T > 35 (40) GeV in barrel (endcap), track matched to calorimeter cluster
- Using signal MC, optimized dilepton mass M(ll) > 1.1 TeV in both electron and muon channels

Backgrounds/Signal/Systematic Uncertainties

- **Backgrounds:**
  - Dominant irreducible SM Drell-Yan.
    - Muons: MC@NLO with NNLO QCD (FEWZ) corrections = 1.03 ± 0.03.
    - Electrons: Pythia6, normalized to Z peak in data.
    - Both: NLO EWK (Horace) corrected (0.90 or 0.92 ± 0.06)
  - Smaller ttbar, tW, diboson: from MadGraph and Pythia6 (cross-checked with background-dominated control sample in data)
- **Signal – Pythia6, corrected for NLO (K-factor 1.3)**
- **Systematic uncertainties:**

Systematic uncertainty	Uncertainty on signal (%)	Uncertainty on background (%)
Integrated luminosity	4.5	4.5
Trigger and reconstruction efficiency	4 ($\mu\mu$), 3 (ee)	3 ($\mu\mu$), 3 (ee)
Muon momentum resolution	1	5
Electron energy scale	1 – 3	1 – 3
Drell–Yan PDF uncertainties	—	13
Drell–Yan higher order corrections	—	10

Data Yields

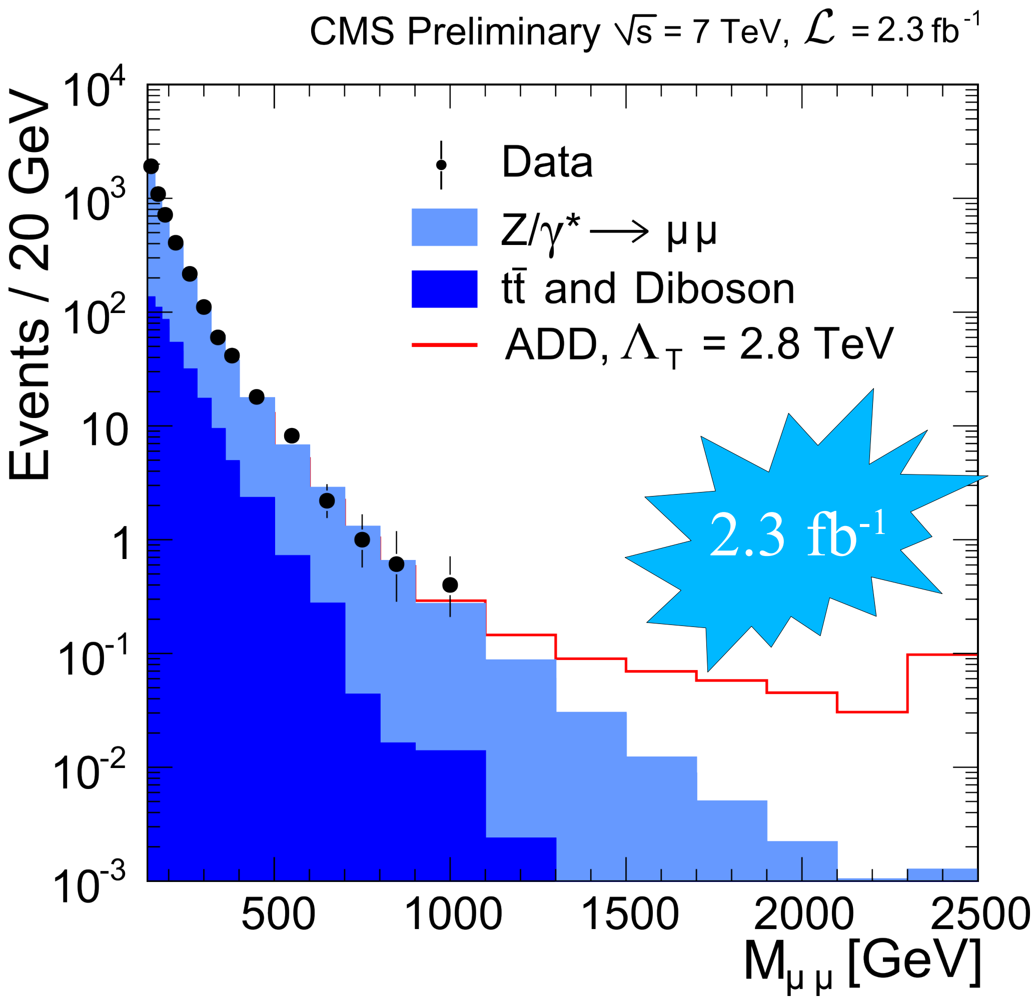
Observed and expected N events comparison
ADD signal K-factor set to 1.0 here

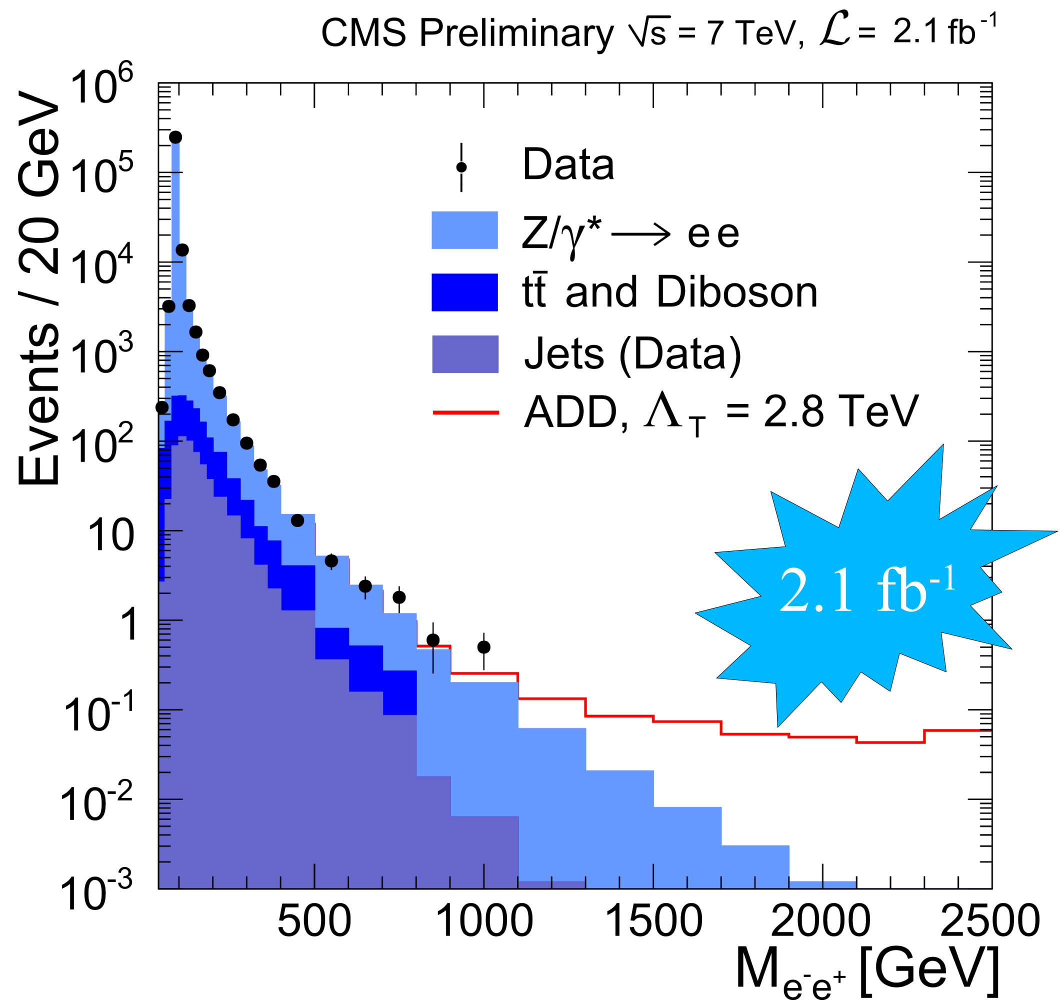
$\mu\mu$, $\mathcal{L} = 2.3\,\text{fb}^{-1}$				ee, $\mathcal{L} = 2.1\,\text{fb}^{-1}$			
Mass region [TeV]	N_{obs}	Background expectation	Signal exp. $\Lambda_T = 2.8$ TeV	Mass region [TeV]	N_{obs}	Background expectation	Signal exp. $\Lambda_T = 2.8$ TeV
Control regions				Control regions			
0.14–0.20	3723	3690±300	-	0.12–0.20	6592	6598±530	-
0.20–0.40	1674	1605±160	-	0.20–0.40	1413	1301±120	-
0.40–0.60	131	122±13	-	0.40–0.60	88	103±11	-
0.60–0.80	16	21±3	-	0.60–0.80	21	18±3	-
0.80–1.10	8	5±1	0.8	0.80–1.10	7	6±1	0.6
Signal region				Signal region			
> 1.10	0	1.0±0.2	3.2	> 1.10	0	1.3±0.2	2.7

- **Good agreement between data and simulation**
- **No events observed in signal region (> 1.1 TeV)**

Invariant Mass Distributions

Dielectron and dimuon invariant mass spectra

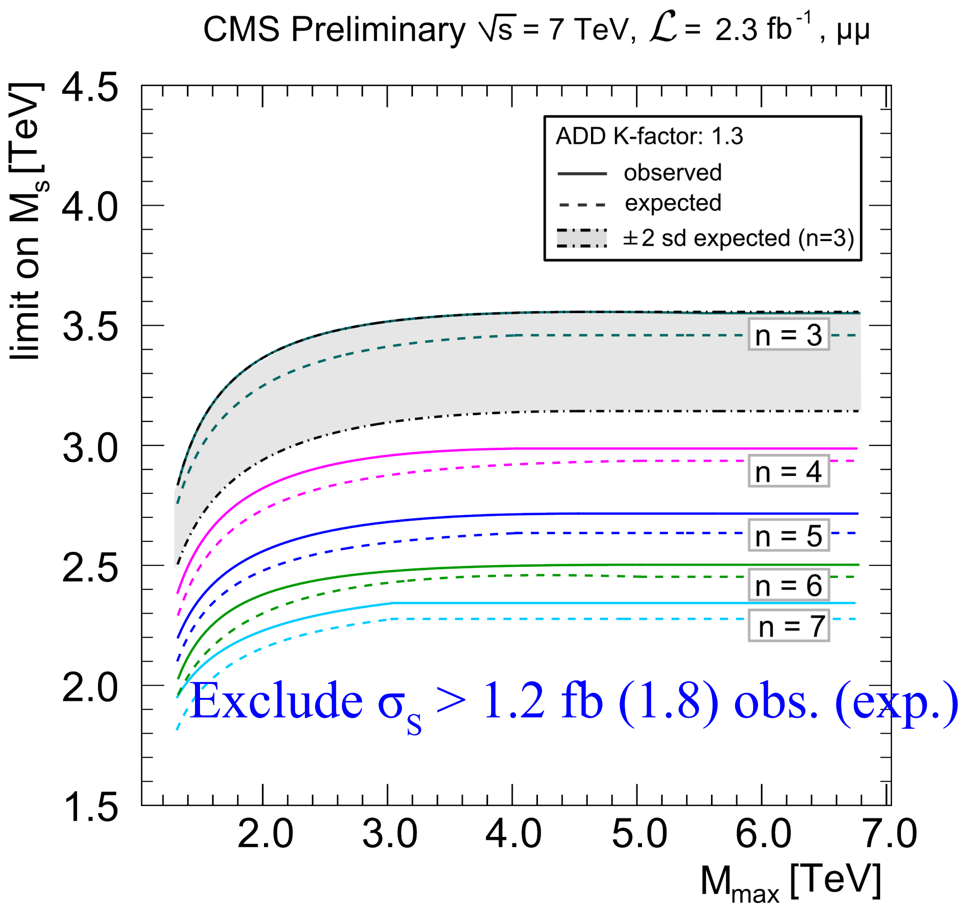


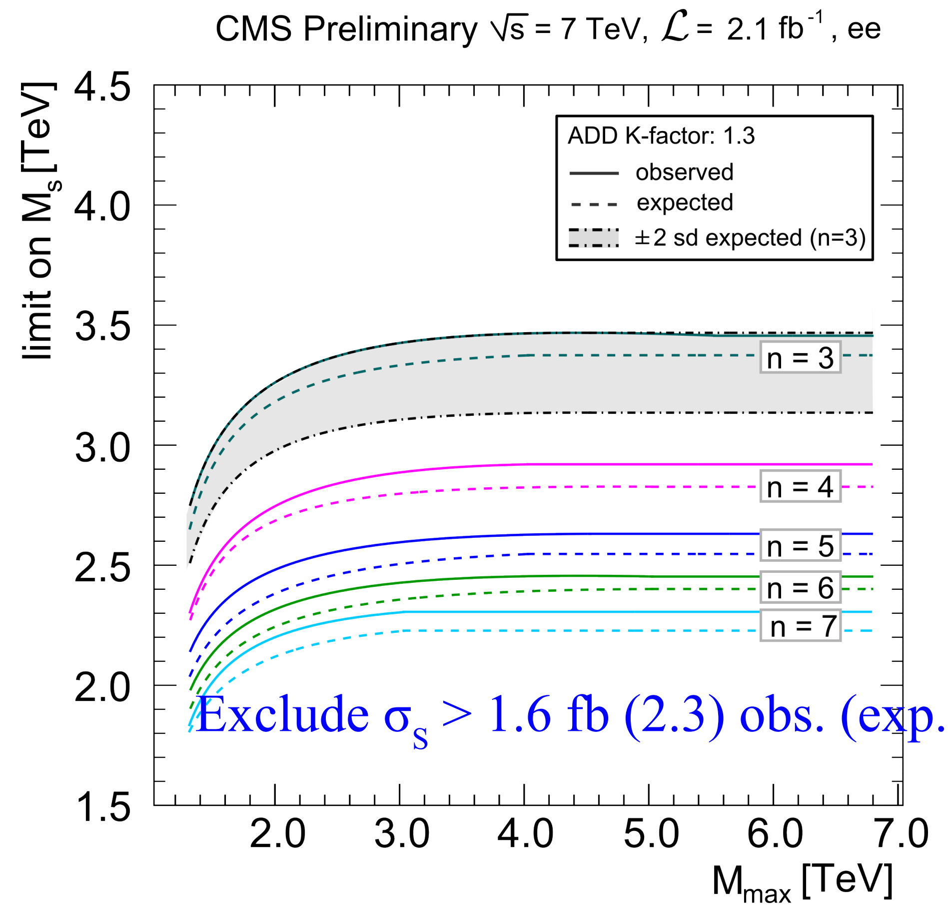


- **Good agreement between data and simulation**
- **No events observed in signal region (> 1.1 TeV)**

KK Gravitons in Dileptons – 95% CL Limits

Lower limits on M_s – individual channels

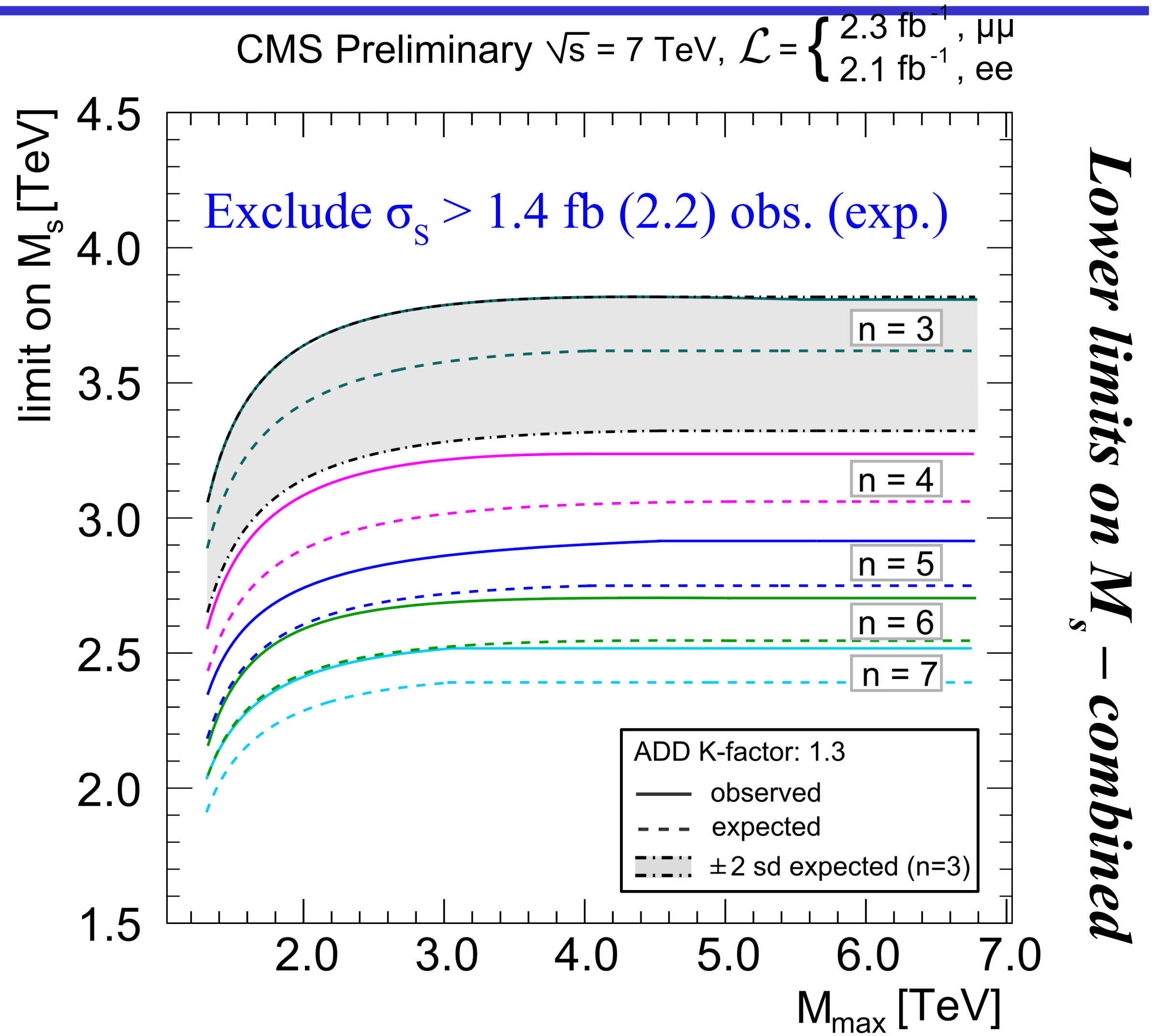




ADD K-factor	Λ_T [TeV] (GRW)	M_s [TeV] (HLZ) $n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
$\mu\mu$, $\sigma_{s,\mu\mu} <$ 1.2 fb (1.8 fb expected) at 95% CL							
1.0	2.8	3.0	3.4	2.8	2.5	2.3	2.2
1.3	3.0	3.2	3.5	3.0	2.7	2.4	2.3
ee, $\sigma_{s,ee} <$ 1.6 fb (2.3 fb expected) at 95% CL							
1.0	2.8	2.9	3.3	2.8	2.5	2.3	2.2
1.3	2.9	3.1	3.4	2.9	2.5	2.4	2.2

KK Gravitons in Dileptons – 95% CL Limits

- **D0 μμ, 246 pb^{-1} (PRL 95 (2005), 161602):**
  - $M_S > 0.85 - 1.27$ TeV
- **D0 ee+γγ, 1.05 fb^{-1} (PRL 102 (2009), 051601):**
  - $M_S > 1.3 - 2.1$ TeV
- **This result (submitted to PLB):**



Extra 0.1-0.3 TeV (obs.) improvement with diphotons

ADD K-factor	Λ_T [TeV] (GRW)	M_s [TeV] (HLZ) $n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
$\mu\mu$ and ee, $\sigma_{s,\mu\mu+ee} <$ 1.4 fb (2.2 fb expected) at 95% CL							
1.0	3.1	3.7	3.7	3.1	2.8	2.5	2.4
1.3	3.2	3.8	3.8	3.2	2.9	2.7	2.5

Search for Black Holes and String Balls in Energetic Multiparticle Final State

Event Selection

arXiv:1202.6396v1/hep-ex
Submitted to JHEP

- **Data and event selection:**
  - Data are collected with H_T ($H_T = \sum p^{jets}_T > 150 – 650$ GeV) triggers
  - Jets (akT5Calo) – energy deposits in ECAL/HCAL in $|\eta| < 2.6$, quality cuts to suppress noise, latest corrections applied; MET – Calo
  - Electrons/photons – isolated energy deposits in ECAL in $|\eta| < 2.4$, w/ (e) or w/o (γ) hits in silicon
  - Muons – matching tracks in silicon and muon chambers in $|\eta| < 2.1$; isolated in tracker
  - Construct S_T ($\sum p_T$ + MET) and Multiplicity (N, number of reco'ed objects, MET not included) for objects (and MET) with $p_T > 50$ GeV
  - Require S_T above trigger turn-on and N > 1 (mostly jets)

Signal Samples / Backgrounds

- **Signal samples (more than 700 points total):**

Table 1: Signal Monte Carlo samples and generators used in the analysis.

Sample description	BLACKMAX	CHARYBDIS	QBH
nonrotating BH	YES	YES	NO
Rotating BH	YES	YES	NO
Rotating BH with mass and angular momentum loss	YES (10% loss)	YES (18 – 30% loss)	NO
Rotating BH, low multiplicity regime	NO	YES	NO
Boiling remnant	NO	YES	NO
Stable remnant	NO	YES	NO
String balls	YES	NO	NO
Quantum BH	NO	NO	YES

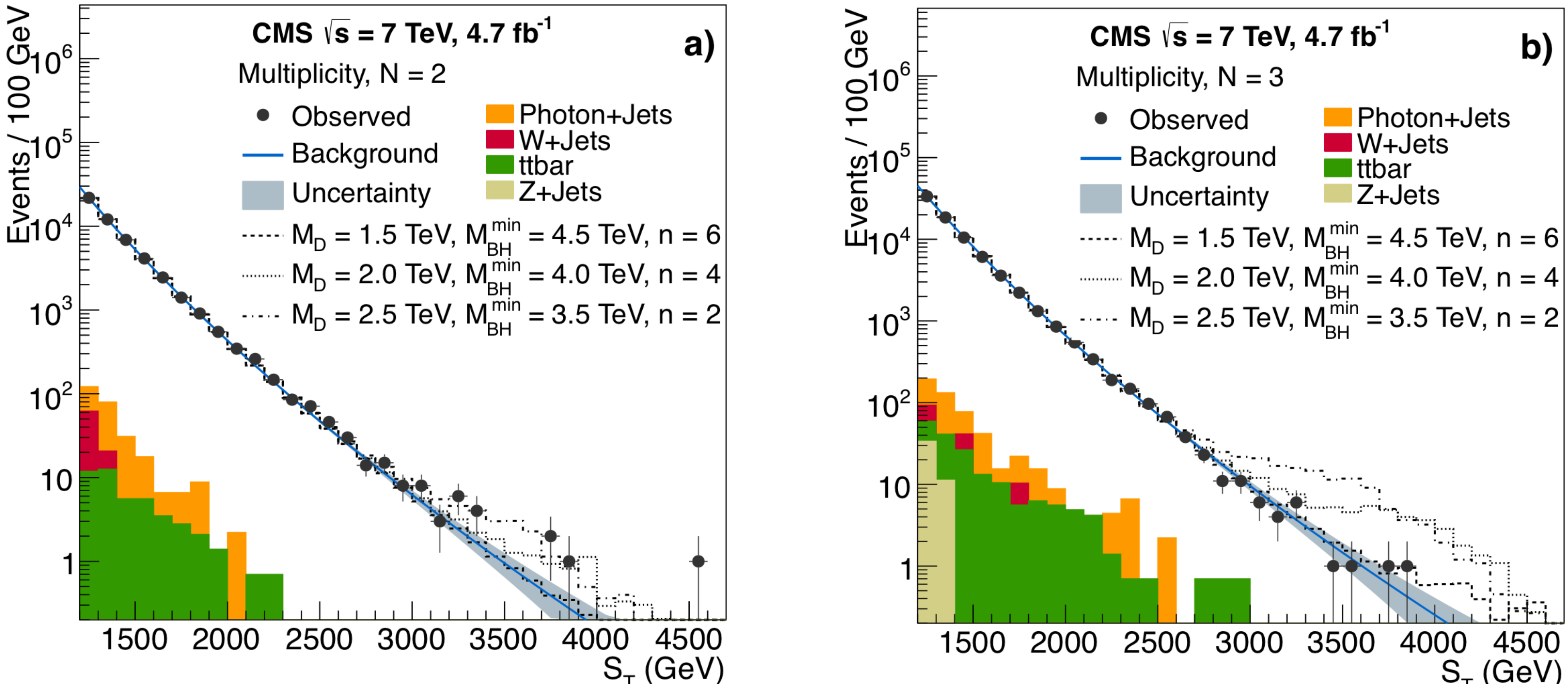
- **Backgrounds:**
  - Dominant – multijet QCD
  - ttbar, γ/W/Z+jets – negligible after selection cuts

Backgrounds

- **QCD background – data-driven method**
  - Extract S_T shape from N = 2 and 3 data samples
  - Scale to higher multiplicities (exclusive and inclusive)

4.7 fb^{-1}

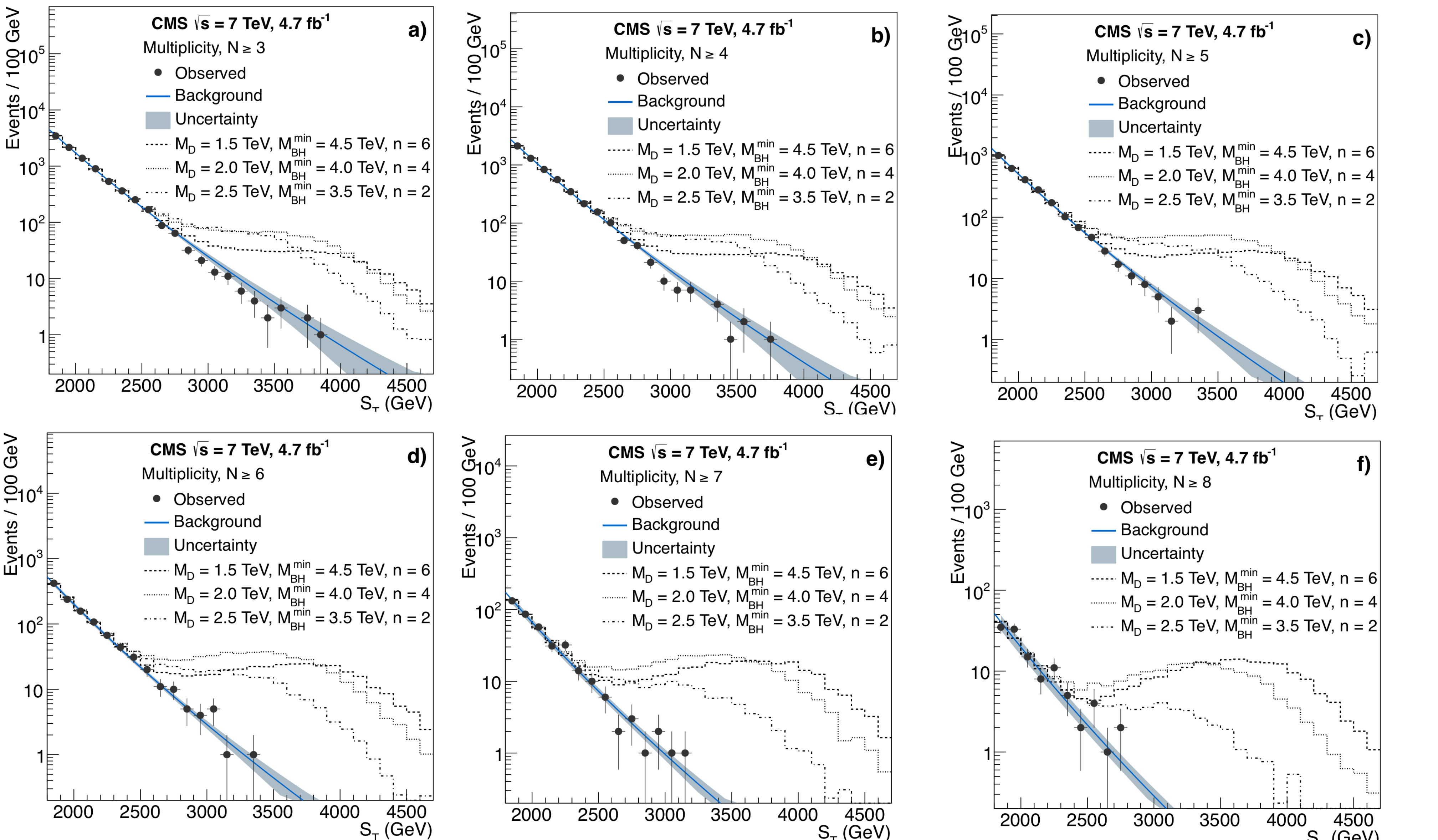
S_T in low exclusive multiplicity data



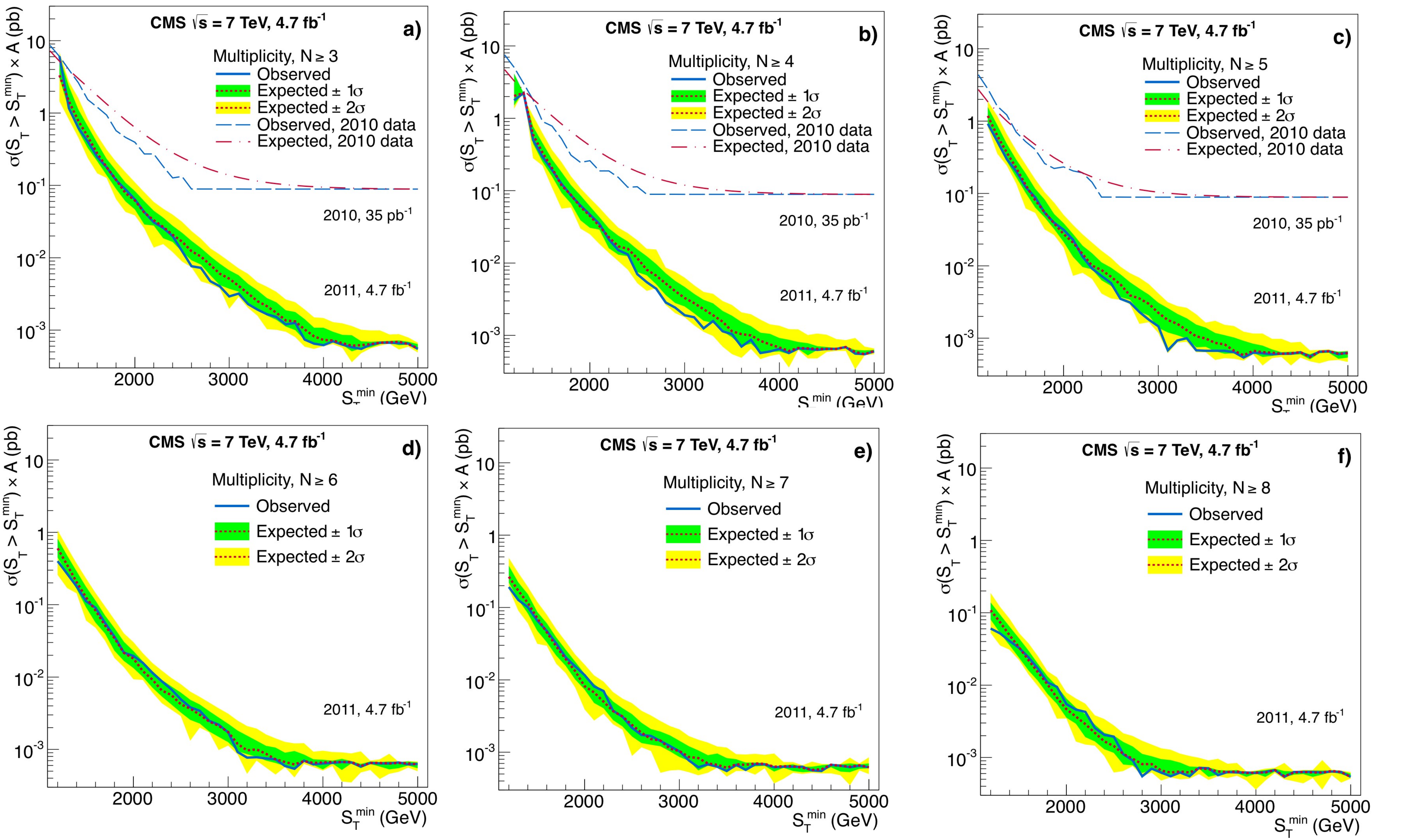
- **Non-multijet backgrounds contribution is < 1%**
- **Very little signal leakage to low multiplicity bins**

S_T Distributions (Inclusive Multiplicities)

S_T in inclusive multiplicities bins



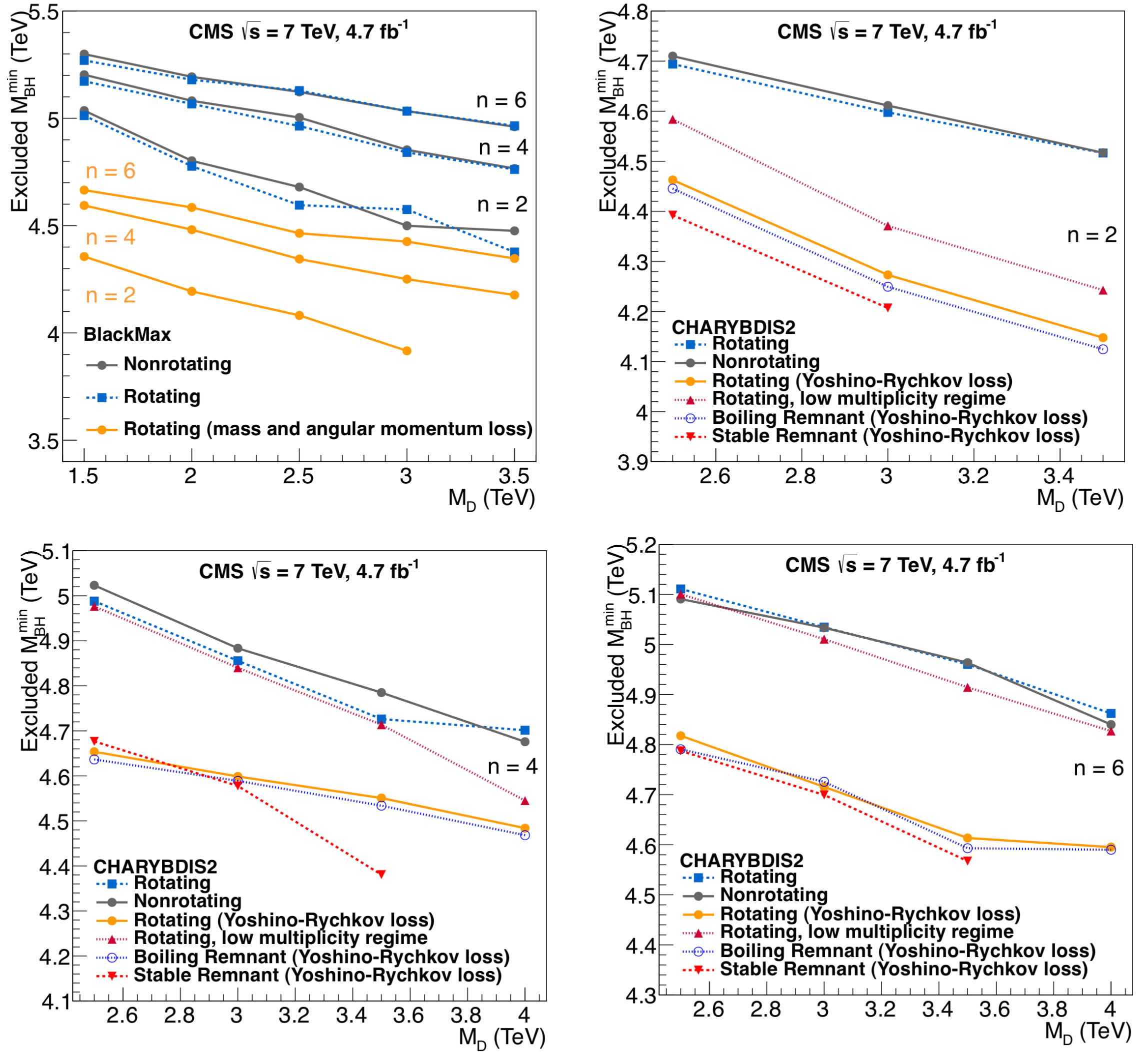
Model-Independent Limits



- **High-S_T limits approach 0.6 fb (×130 better than 2010 pub.)**

95% CL Limits: Semiclassical Black Holes

95% CL lower limits on BH masses



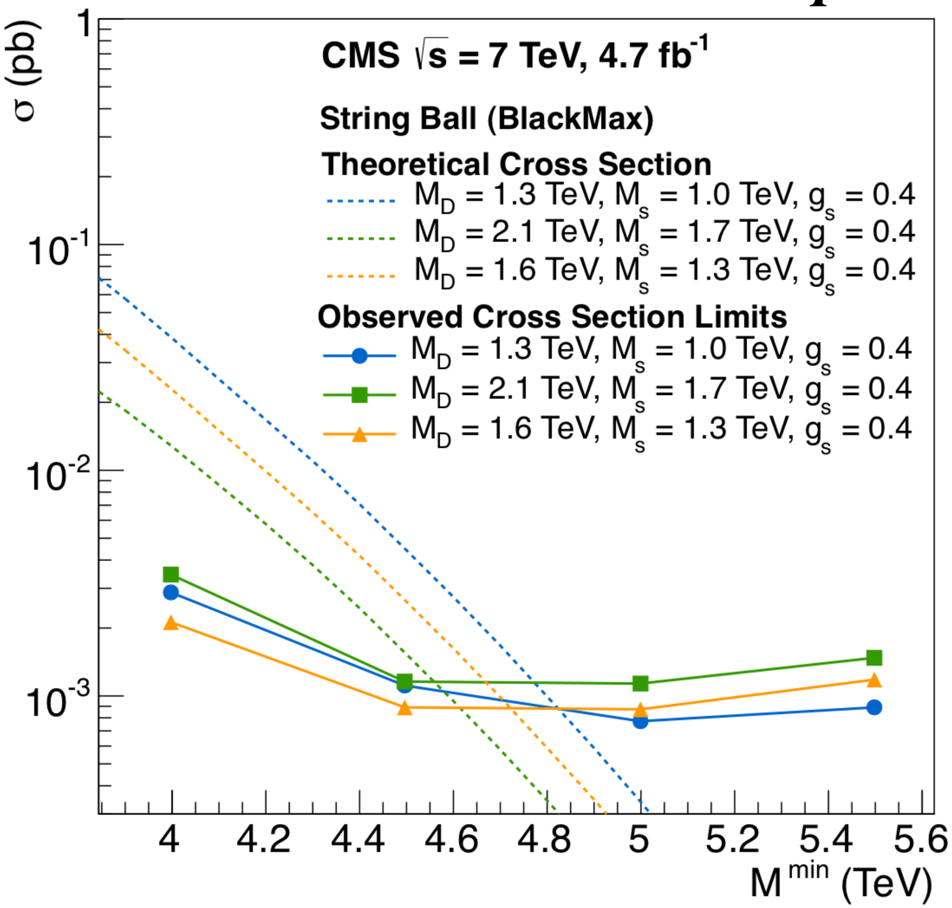
- **In terms of ADD parameters and BlackMax and Charybdis frameworks:**

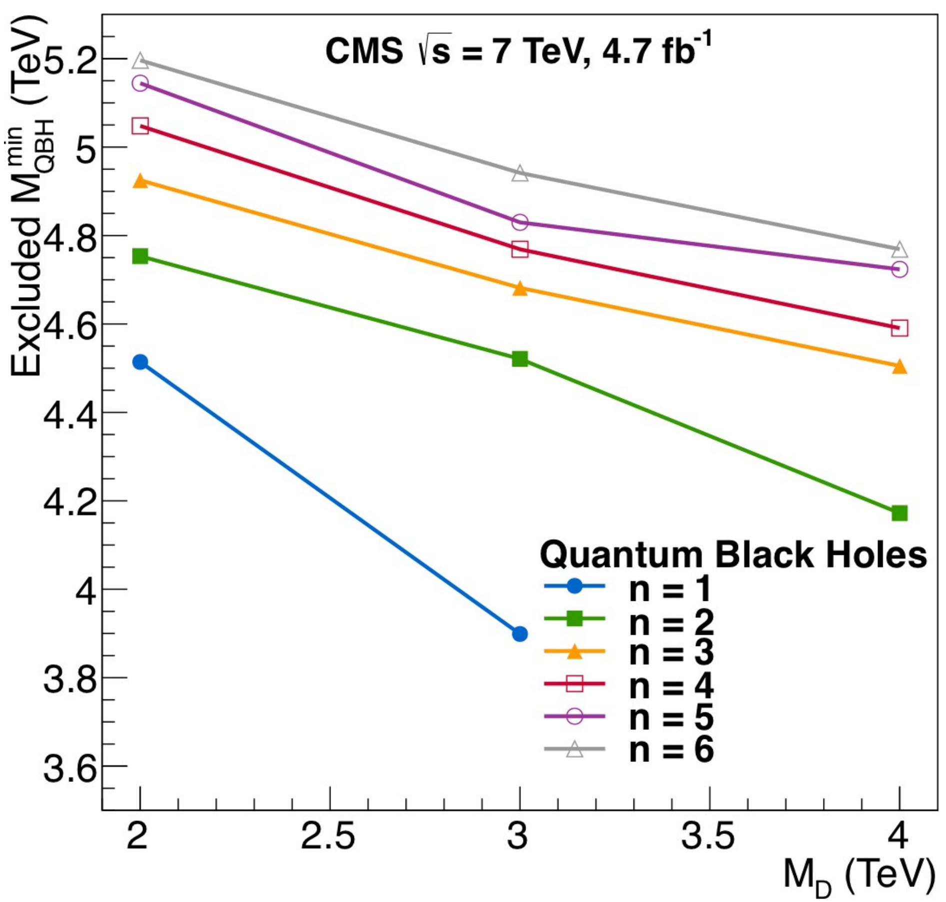
exclude BH with M_{min} = 3.9 – 5.3 TeV for M_D = 1.5 – 4 TeV and n = 2 – 6

- Previous: CMS 36 pb^{-1} (PLB 697 (2011) 434): M = 3.5 – 4.5 TeV

Limits on String Balls and Quantum BH

95% CL limits on quantum BH and string ball masses





- **Limits on minimum SB mass are 4.6 – 4.8 TeV**
- **Limits on minimum QBH mass are 3.8 – 5.2 TeV**
  - Previous: ATLAS dijets, 36 pb^{-1} (arXiv:1103.3864): M = 0.75 – 3.67 TeV

Conclusions

- **All these searches made possible by the LHC – thanks for high-quality data!**
- **Searches for Extra Dimensions are ongoing**
  - No evidence of new physics yet
  - Many interesting results on 2011 data have been obtained
  - Most of them give best limits to date
  - Public pages:
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
- **Waiting for 8 TeV data – stay tuned!**

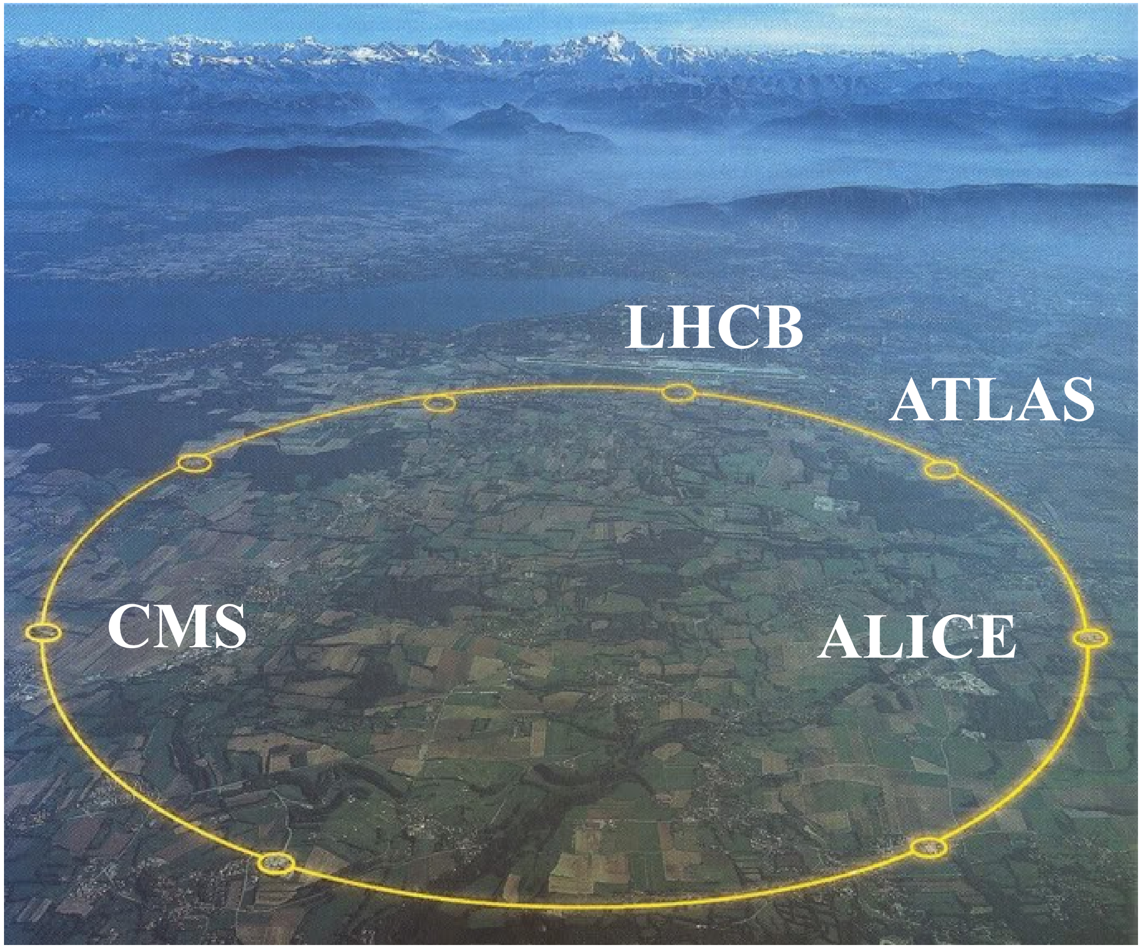
Thanks!

- **Thanks to my colleagues for the results I've shown today**

- **Thanks to SEARCH2012 Organizers!**

BACKUP

Large Hadron Collider



- **proton-proton collider with $\sqrt{s}$ = 7 TeV**
- **3.5e33 $cm^{-2}s^{-1}$ achieved integrated luminosity**
- **> 5 fb^{-1} delivered to experiments (Thanks LHC!!)**

BROWN

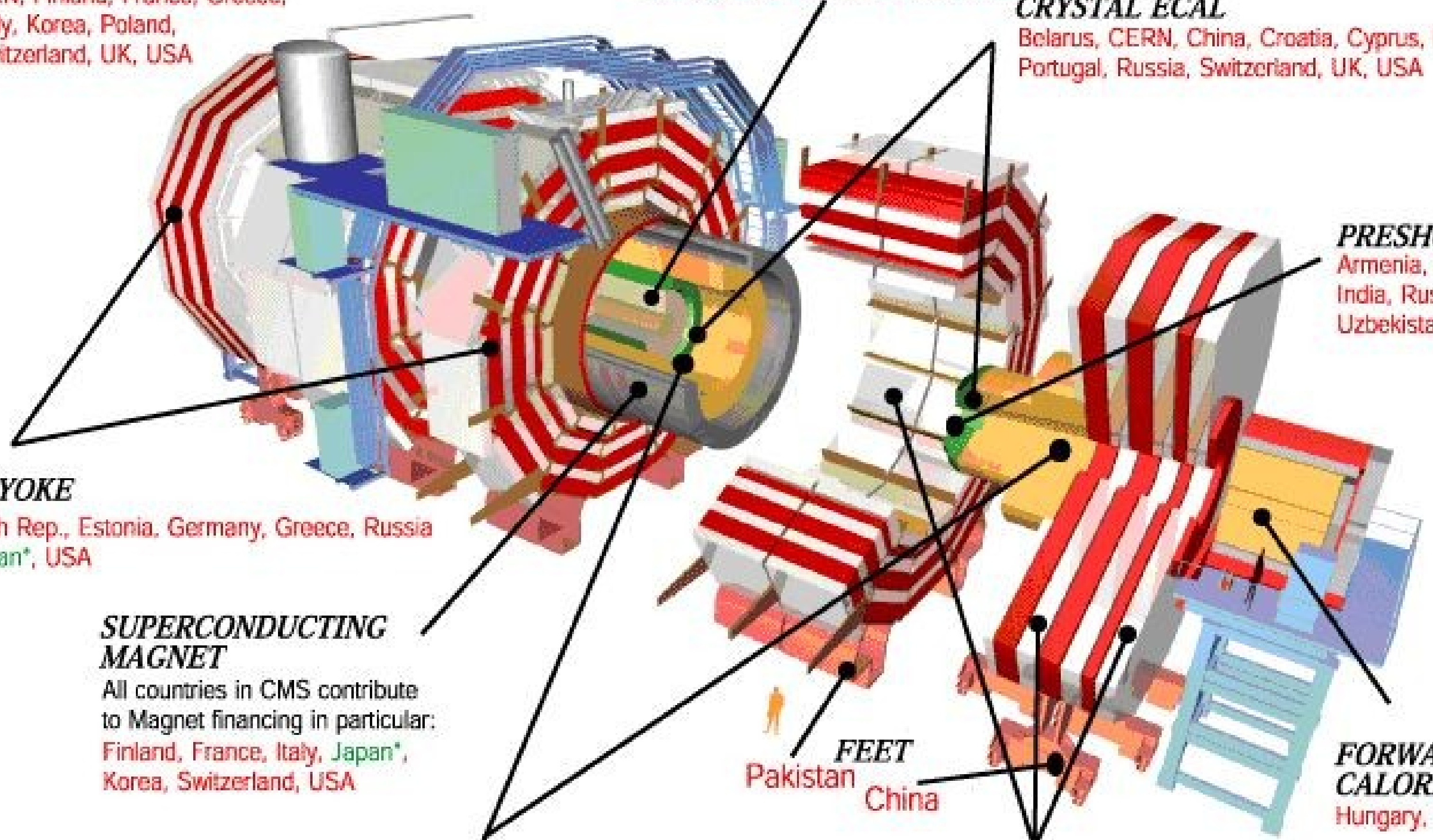
Compact Muon Solenoid

31 Nations, 150 Institutions, 1870 Scientists

TRIGGER & DATA ACQUISITION
Austria, CERN, Finland, France, Greece, Hungary, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

TRACKER
Austria, Belgium, CERN, Finland, France, Germany, Italy, Japan*, Switzerland, UK, USA

CRYSTAL ECAL
Belarus, CERN, China, Croatia, Cyprus, France, Italy, Japan*, Portugal, Russia, Switzerland, UK, USA



PRESHOWER
Armenia, Belarus, CERN, Greece, India, Russia, Taiwan (PC), Uzbekistan

RETURN YOKE
Barrel: Czech Rep., Estonia, Germany, Greece, Russia
Endcap: Japan*, USA

SUPERCONDUCTING MAGNET
All countries in CMS contribute to Magnet financing in particular:
Finland, France, Italy, Japan*, Korea, Switzerland, USA

FEET
Pakistan
China

FORWARD CALORIMETER
Hungary, Iran, Russia, Turkey, USA

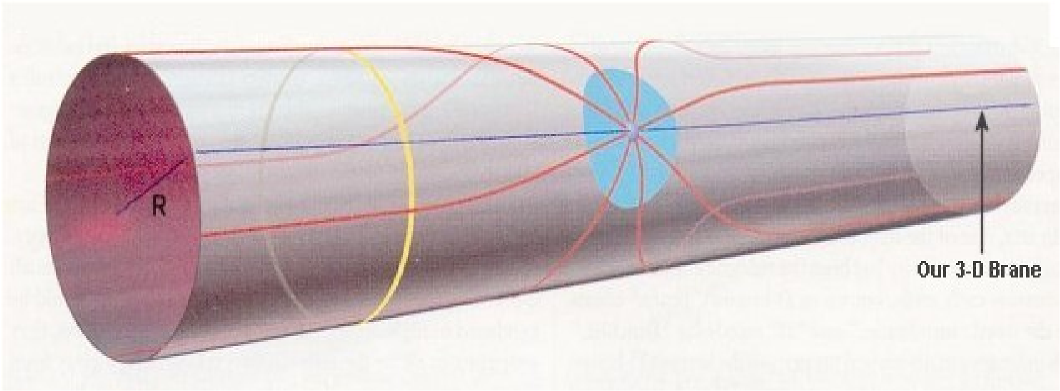
HCAL
Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Russia, Ukraine
HO: India

MUON CHAMBERS
Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain,
Endcap: Belarus, Bulgaria, China, Korea, Pakistan, Russia, USA

Total weight	:	**12500 T**
Overall diameter	:	**15.0 m**
Overall length	:	**21.5 m**
Magnetic field	:	**4 Tesla**

* Only through industrial contracts

Extra Dimensions – ADD



- **Universe is (3+1)-dim:**
  - Planck scale O(10^{16} TeV)
  - EWK scale O(0.1 - 1 TeV)
- **Hierarchy problem:**
  - Gravity is much weaker than EWK interactions
- **Possible solution – ADD extra dimensions (Arkani-Hamed, Dimopoulos, Dvali –** ***PLB 429 (1998) 263*****):**
  - Gauge interactions are localized on (3+1)-dim brane
  - Gravity (strong!) propagates in ***n*** flat extra-dimensions compactified on torus or sphere with radius ***r***

n	R
1	8×10^{12} m
2	0.7 mm
3	3 nm
4	6×10^{-12} m

- **True Planck scale (M_D):** M_D = O(TeV)

$$M_{\rm Pl}^2 = 8\pi M_D^{n+2} r^n$$

Kaluza-Klein (KK) graviton exchange:

- Gives raise to diphoton/dilepton cross section
- Non-resonant production – continuum spectrum of diphotons, dimuons, and dielectrons
- Sum of all KK diverges – need an UV cutoff M_S
- Virtual graviton effects parameterized by $\eta_G = \mathcal{F}/M_S^4$, where

$$\mathcal{F} = 1 \quad \text{(Guidice, Rattazzi, and Wells, GRW [5])},$$

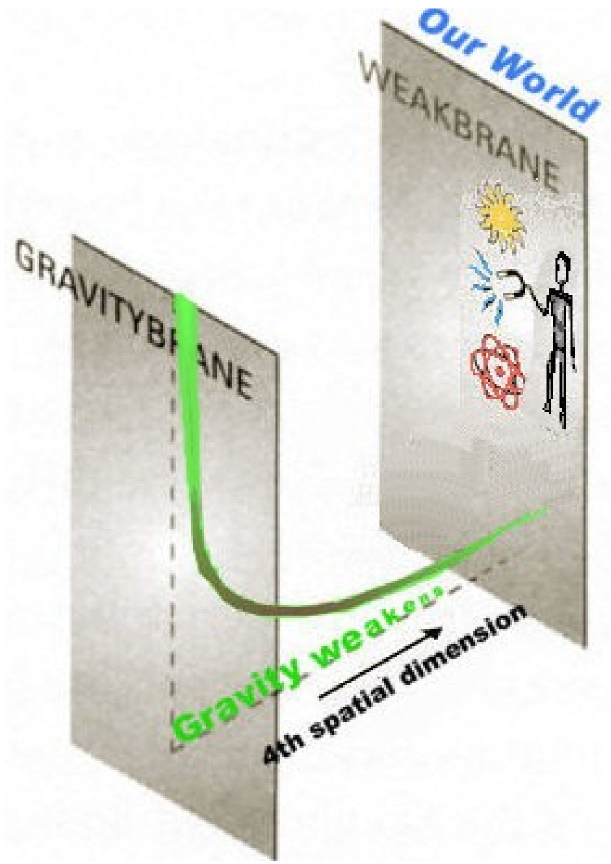
$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right) & \text{if } n_{ED} = 2 \\ \frac{2}{(n_{ED}-2)} & \text{if } n_{ED} > 2 \end{cases} \quad \text{(Han, Lykken, and Zhang, HLZ [6])},$$

$$\mathcal{F} = \pm\frac{2}{\pi} \quad \text{(Hewett [7])},$$

Extra Dimensions – Randall-Sundrum

- **Production of Randall-Sundrum (RS1) gravitons:**
  - Single warped ED (size r_C, k is curvature) exists, separating two branes
  - Apparent Planck scale

$$\Lambda_\pi = \overline{M}_{\rm Pl} e^{-kr_c\pi} = O(\text{TeV}) \text{ for } kr_C \sim 10$$



  - Gives raise to resonant diphoton cross section
  - Resonant production – towers of KK excitations
  - Model parameters: mass of the first excited

mode M_1 and dimensionless coupling

$$\tilde{k} \equiv k/\overline{M}_{\rm Pl} \quad (0.01 - 0.1)$$

A Microscopic Black Hole?

- **Strong gravity in extra dimensions allows for formation of micro black holes with size r_S:**

$$r_S = \frac{1}{\sqrt{\pi} M_D} \left[\frac{M_{BH}}{M_D} \frac{8\Gamma(\frac{n+3}{2})}{n+2} \right]^{\frac{1}{n+1}}$$

  - Thermal decay via Hawking radiation into all kinds of particles (75% quarks/gluons; 25% the rest, e.g. photons, leptons, gauge bosons, H)
  - Cross section (PDG definition) ~ πr_S^2, up to few hundred pb with extra dimensions
  - Semi-classical approximation: $M_{BH} > M_{min} > M_D$

Or a String Ball?

- **What if $M_s < M < M_{min} \sim M_s/g_s^2$?**
  - Proposed by Dimopoulos and Emparan (*PLB* ***526*** *(2002) 393*)
  - GR breaks – this is string theory now!
  - A string ball forms with cross section:

$$\sigma \sim \begin{cases} \dfrac{g_s^2 M_{SB}^2}{M_s^4} & M_s \ll M_{SB} \leq M_s/g_s\,, \\ \dfrac{1}{M_s^2} & M_s/g_s < M_{SB} \leq M_s/g_s^2 \\ \dfrac{1}{M_P^2}\left(\dfrac{M_{BH}}{M_P}\right)^{\frac{2}{n+1}} & M_s/g_s^2 < M_{BH}\,. \end{cases}$$

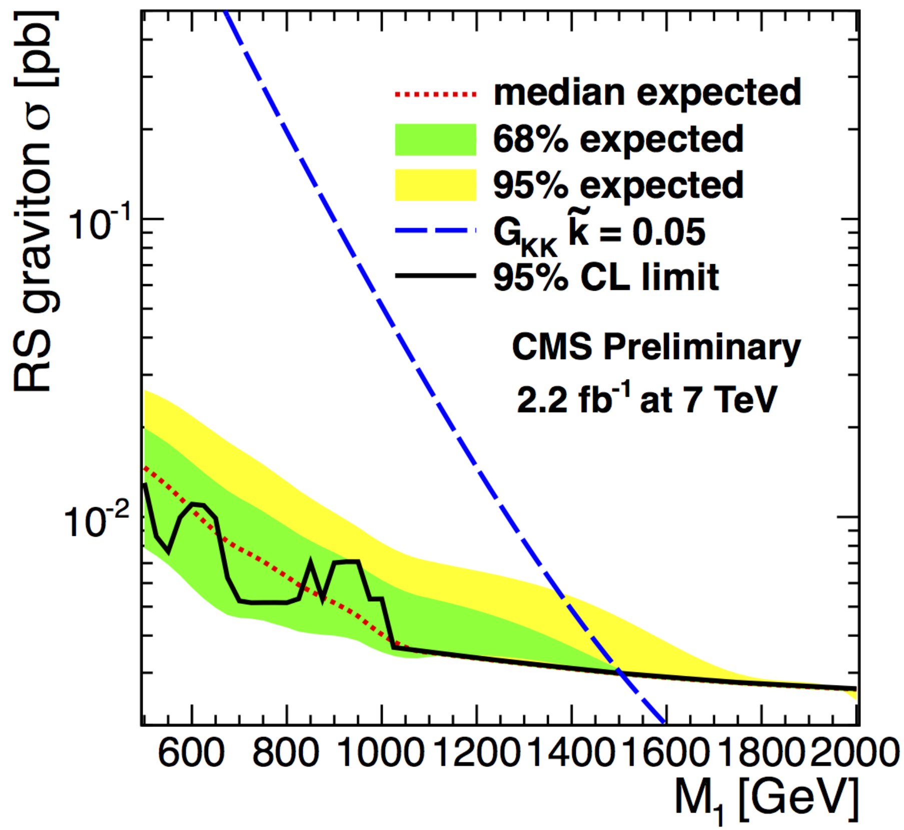
  - Properties are similar to semi-classical black hole
  - Search strategy for both: high-multiplicity (5 – 6 objects on average) energetic final state

Or a Quantum Black Hole?

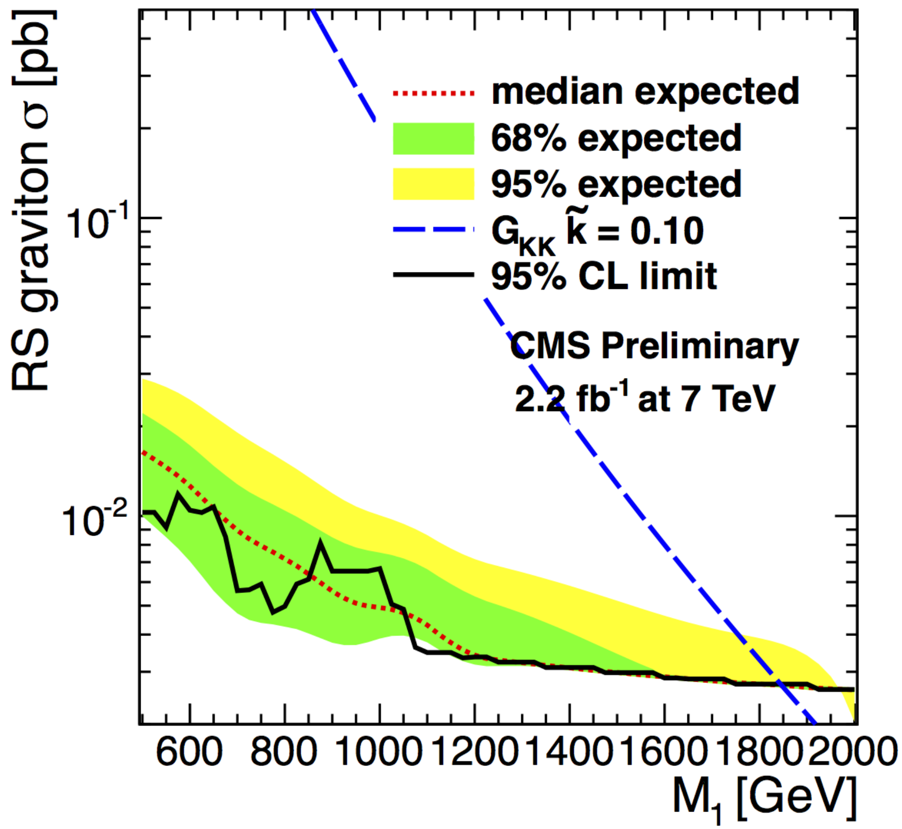
- **Quantum BH properties:**
  - Relatively light (typically, $M_D < M < 3M_D$)
  - QBH evaporates faster than it thermalizes
  - Result: non-thermal decay into a pair of jets
    - Low multiplicity energetic final state

Diphotons: RS1

Limits on cross section for $k/M_{Pl} = 0.05$

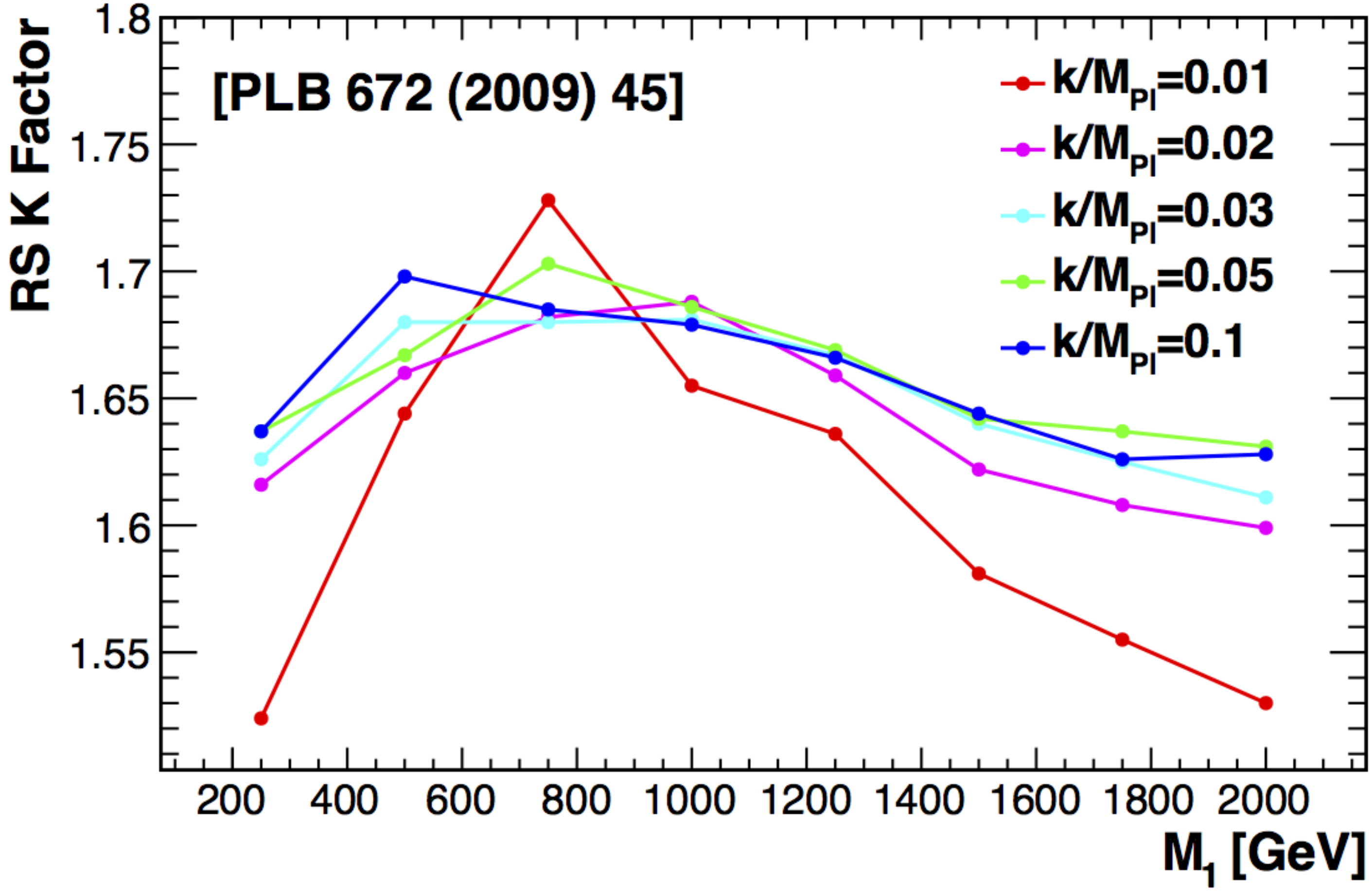


Limits on cross section for $k/M_{Pl} = 0.1$



Diphotons: RS1

RS1 signal K-factor variations with k/M_{Pl} and M_1



Dileptons

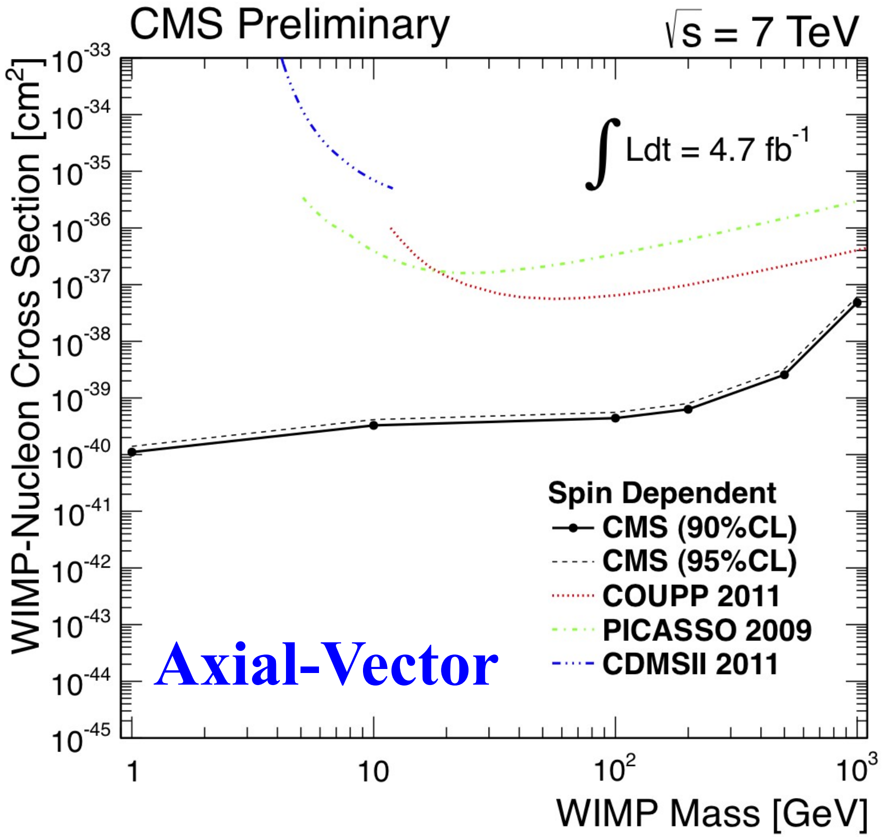
$\mu\mu$, $\mathcal{L} = 2.3\,\text{fb}^{-1}$			
Mass region [TeV]	N_{obs}	Background expectation	Signal exp. $\Lambda_T = 2.8$ TeV
Control regions			
0.14–0.20	3723	3690±300	-
0.20–0.40	1674	1605±160	-
0.40–0.60	131	122±13	-
0.60–0.80	16	21±3	-
0.80–1.10	8	5±1	0.8
Signal region			
> 1.10	0	1.0±0.2	3.2

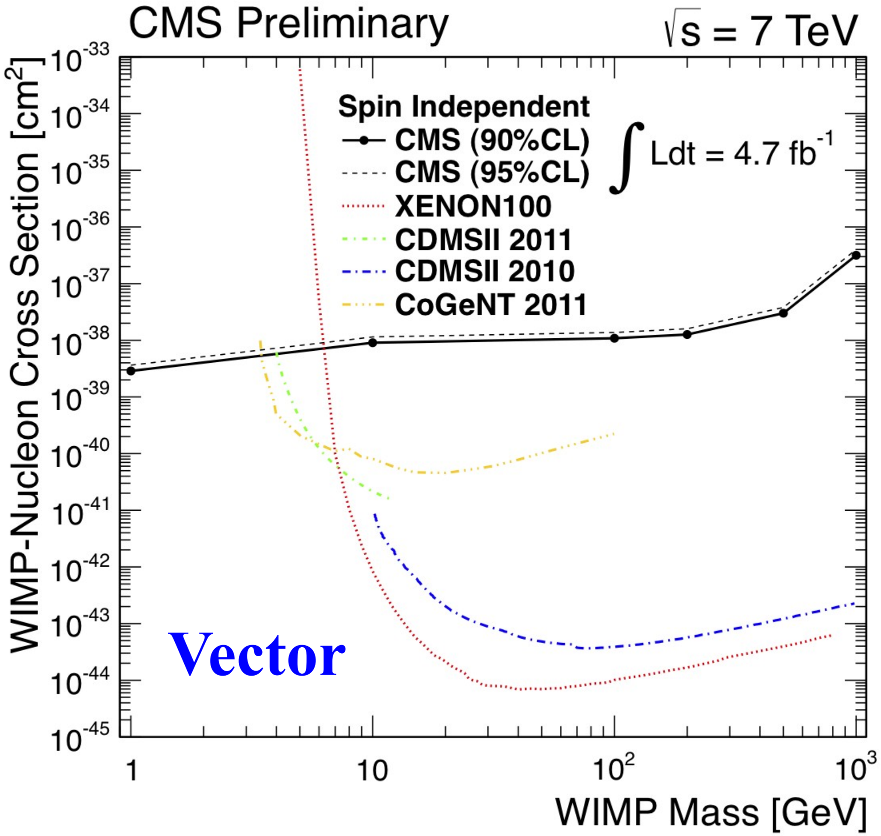
ee, $\mathcal{L} = 2.1\,\text{fb}^{-1}$			
Mass region [TeV]	N_{obs}	Background expectation	Signal exp. $\Lambda_T = 2.8$ TeV
Control regions			
0.12–0.20	6592	6598±530	-
0.20–0.40	1413	1301±120	-
0.40–0.60	88	103±11	-
0.60–0.80	21	18±3	-
0.80–1.10	7	6±1	0.6
Signal region			
> 1.10	0	1.3±0.2	2.7

ADD K-factor	Λ_T [TeV] (GRW)	M_s [TeV] (HLZ)					
		$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
$\mu\mu$, ee, and $\gamma\gamma$							
1.3 ($\mu\mu$ and ee), 1.6 ($\gamma\gamma$)	3.3	4.1	3.9	3.3	3.0	2.8	2.6

Monophotons: Dark Matter

Upper limits on the WIMP-nucleon cross section



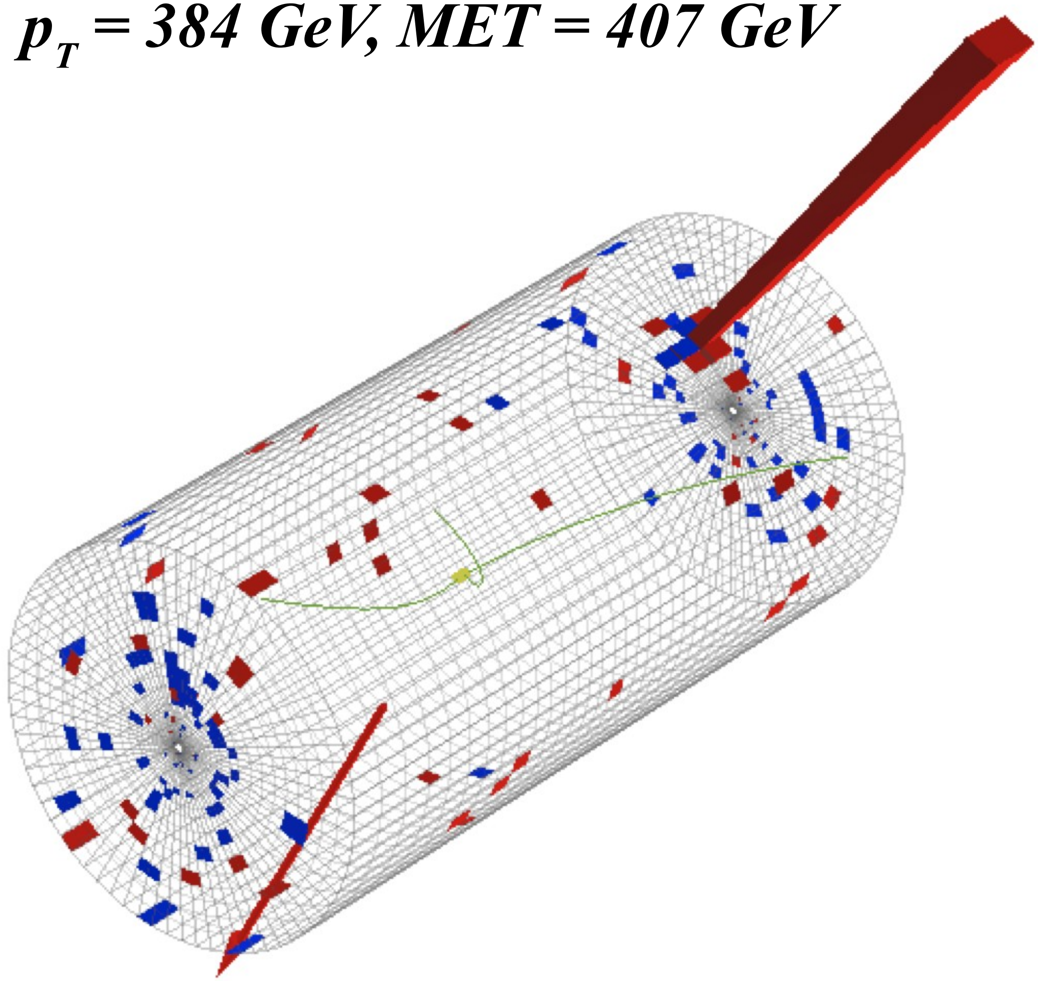


M_{DM} [GeV]	90% CL Limits		95% CL Limits	
	σ [fb]	Λ [GeV]	σ [fb]	Λ [GeV]
1	17.6 (17.1)	543 (546)	22.2 (20.3)	512 (523)
10	16.6 (16.1)	550 (554)	20.9 (19.2)	519 (531)
100	16.4 (15.9)	532 (536)	20.7 (18.9)	502 (513)
200	16.5 (16.1)	488 (491)	20.9 (19.1)	460 (470)
500	16.1 (15.7)	344 (346)	20.4 (18.6)	324 (332)
1000	16.4 (15.9)	165 (166)	20.7 (18.9)	156 (159)

M_{DM} [GeV]	90% CL Limits		95% CL Limits	
	σ[fb]	Λ[GeV]	σ[fb]	Λ[GeV]
1	16.8 (16.4)	549 (553)	21.3 (19.5)	518 (529)
10	16.8 (16.4)	549 (552)	21.3 (19.5)	517 (529)
100	16.8 (16.3)	546 (550)	21.2 (19.4)	515 (526)
200	16.8 (16.4)	527 (530)	21.3 (19.5)	497 (508)
500	16.1 (15.6)	425 (428)	20.3 (18.6)	401 (410)
1000	16.6 (16.1)	235 (237)	20.9 (19.2)	222 (227)

Candidate Event

$p_T = 384$ GeV, MET = 407 GeV



CMS Experiment at LHC, CERN
Data recorded: Sun Apr 24 22:57:52 2011 CDT
Run/Event: 163374 / 314736281
Lumi section: 604

Monojets

Table 4: Sources of systematic uncertainty and their contribution to the total uncertainty on the W+jets background.

Source of Uncertainty	Size(%)
Statistics (N_{obs})	2.9
Background (N_{bgd})	3.9
Acceptance (A)	7.7
Selection efficiency (ϵ)	6.8
Total	11.3

Table 2: Sources of systematic uncertainty and their fractional contributions to the total uncertainty on the $Z \rightarrow \nu\nu$ background.

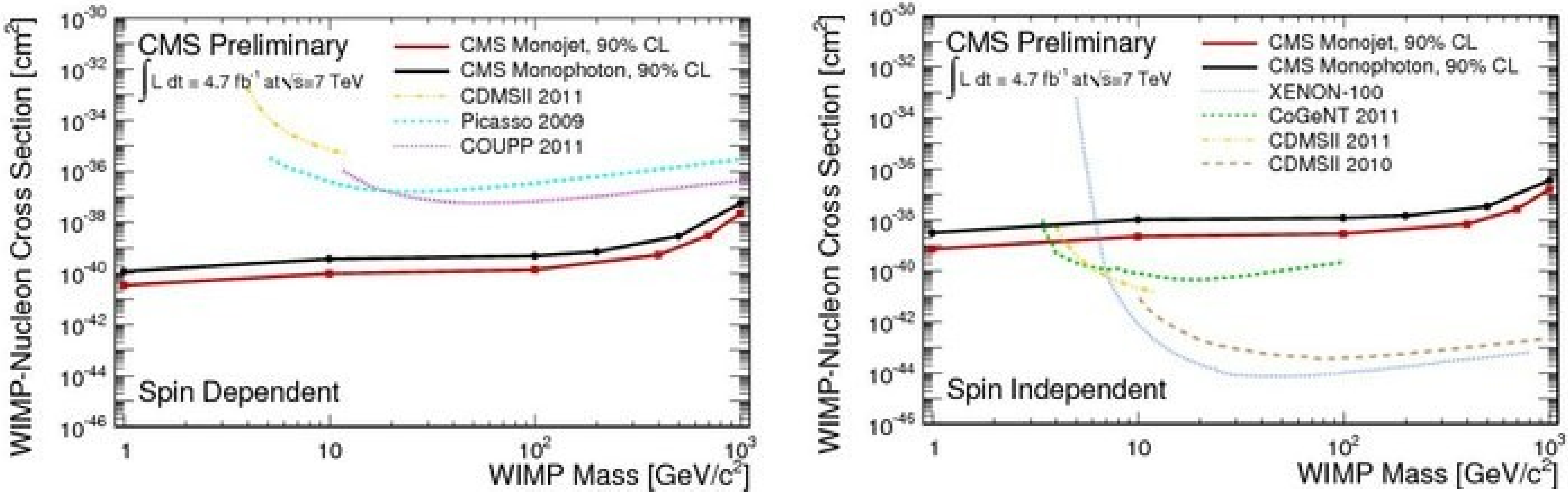
Source of Uncertainty	Size(%)
Statistics (N_{obs})	9.5
Acceptance (A)	3.7
Selection efficiency (ϵ)	2.1
Ratio (R)	0.3
Total	10.4

Major systematic uncertainties on signal

Jet energy scale	**10%**
PDF	**2 – 7%**
ISR/FSR in Pythia8	**2%**
Pileup	**3%**

Monojets: Dark Matter

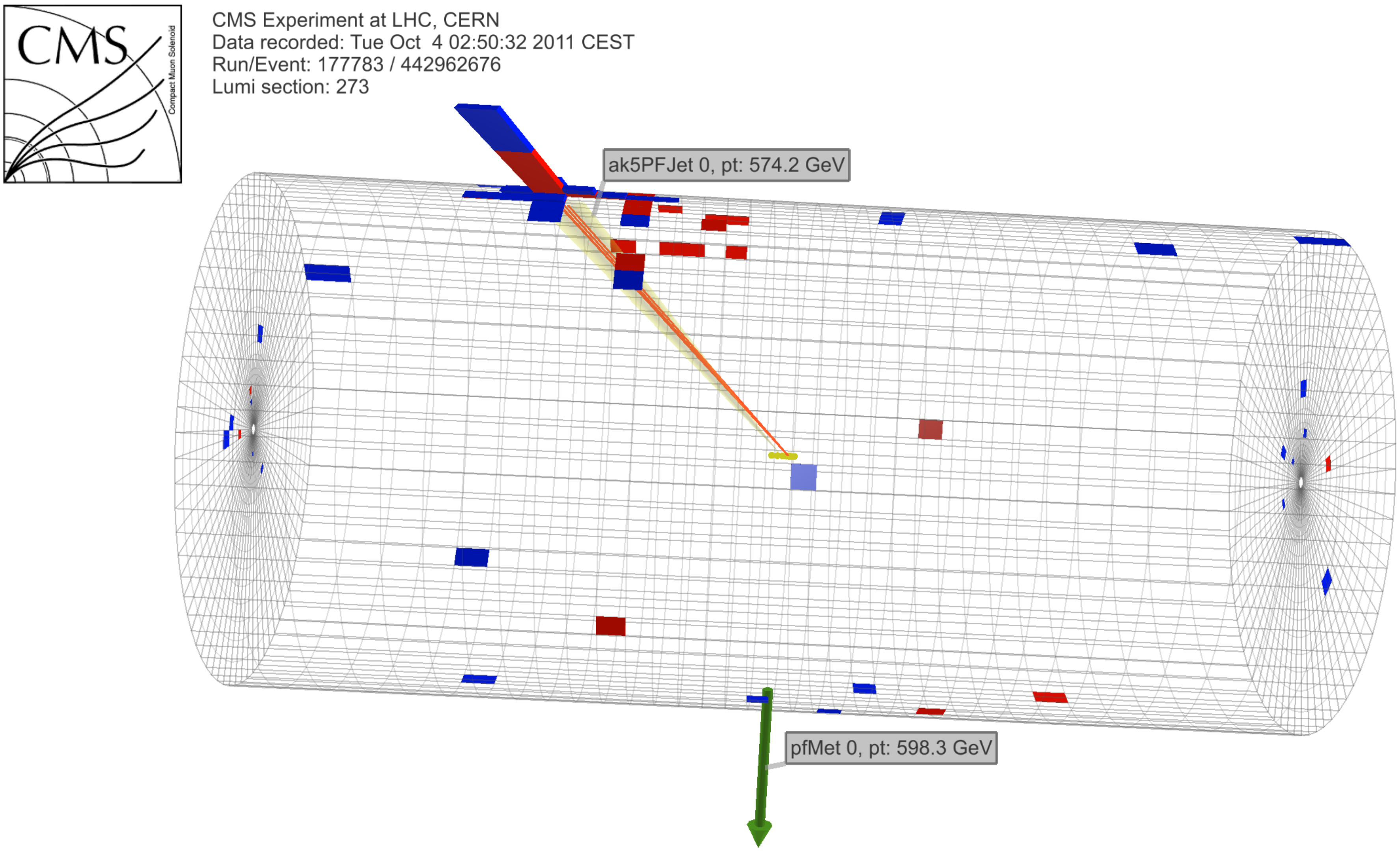
Upper limits on the dark matter-nucleon scattering cross section



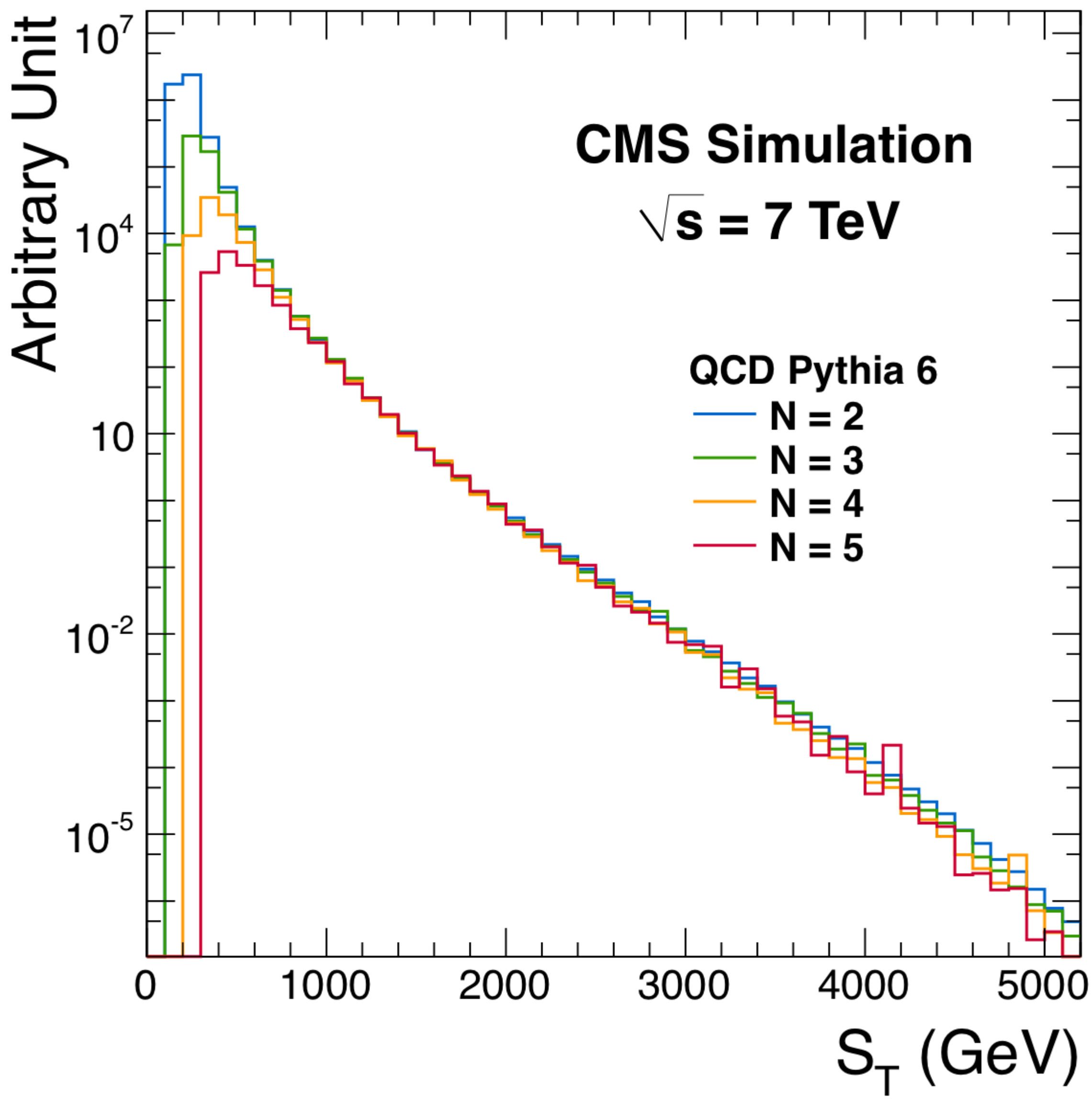
	Spin-dependent		Spin-independent	
M_χ (GeV/c^2)	σ(cm^2)	Λ(GeV)	σ(cm^2)	Λ(GeV)
1	3.37×10^{-41}	730	7.20×10^{-40}	776
10	9.83×10^{-41}	744	2.12×10^{-39}	789
100	1.33×10^{-40}	718	2.65×10^{-39}	776
400	5.14×10^{-40}	514	6.66×10^{-39}	619
700	2.95×10^{-39}	332	2.62×10^{-38}	440
1000	2.15×10^{-38}	202	1.57×10^{-37}	281

Candidate Event

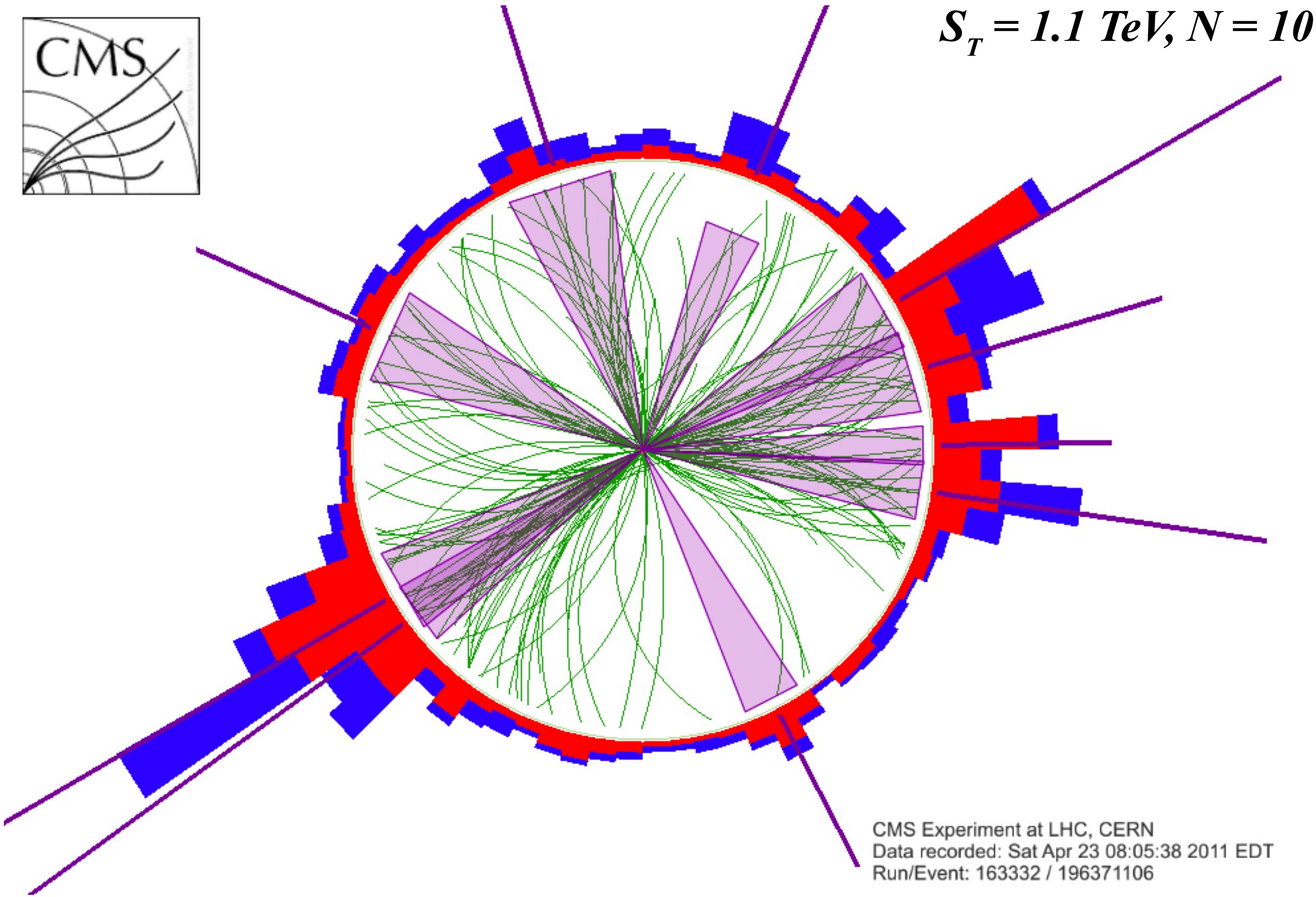
p_T = 574 GeV, MET = 598 GeV



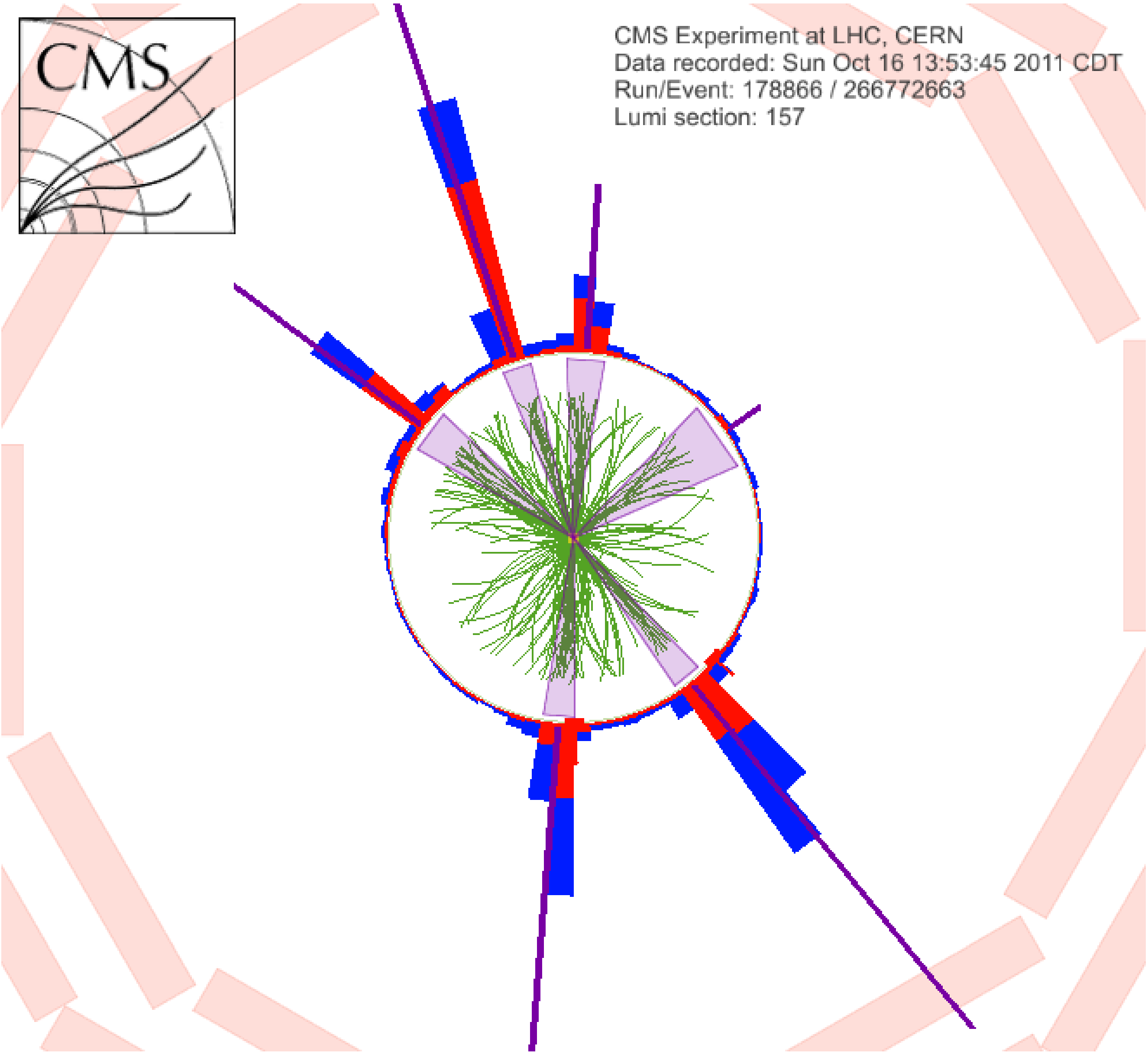
Independence of S_T shapes of final-state multiplicities



Black Holes


CMS
S_T = 1.1 TeV, N = 10
CMS Experiment at LHC, CERN
Data recorded: Sat Apr 23 08:05:38 2011 EDT
Run/Event: 163332 / 196371106

Black Holes



$S_T = 3.1\ TeV,\ N = 6$