Search for Heavy Resonances Using LHC Run 2 Data

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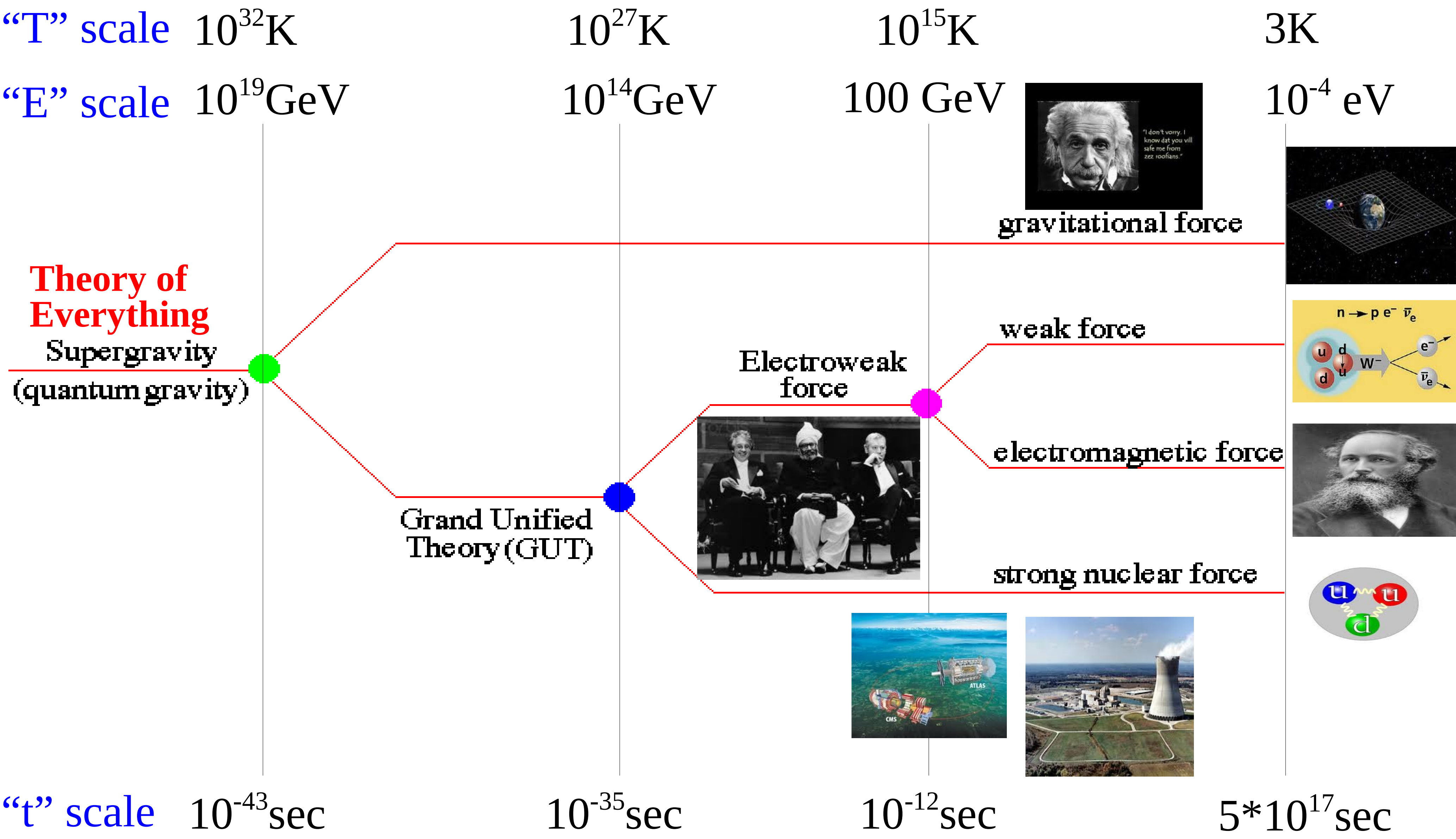
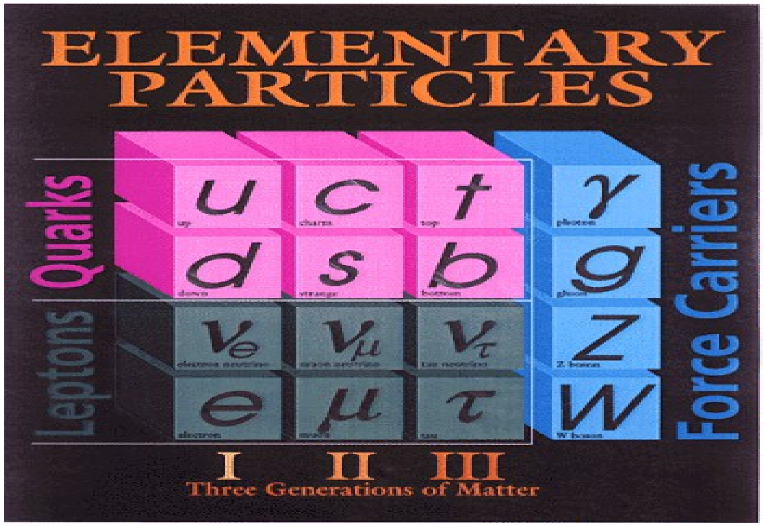
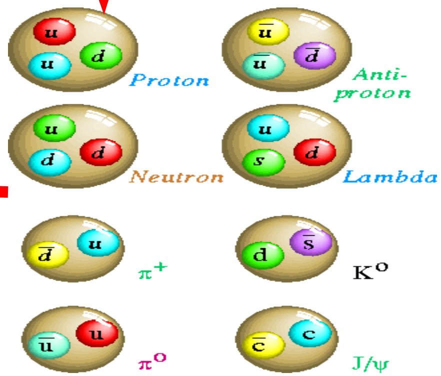
The 6th Egyptian School of High Energy Physics (BUE, 6 Dec 2016)

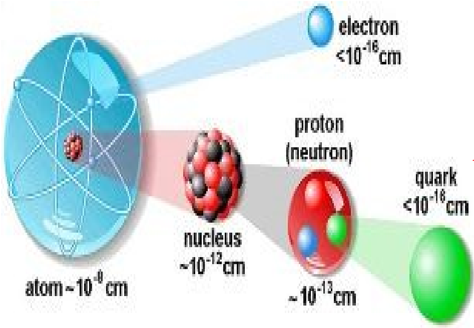
Fields & Unification



The Origin of Matter

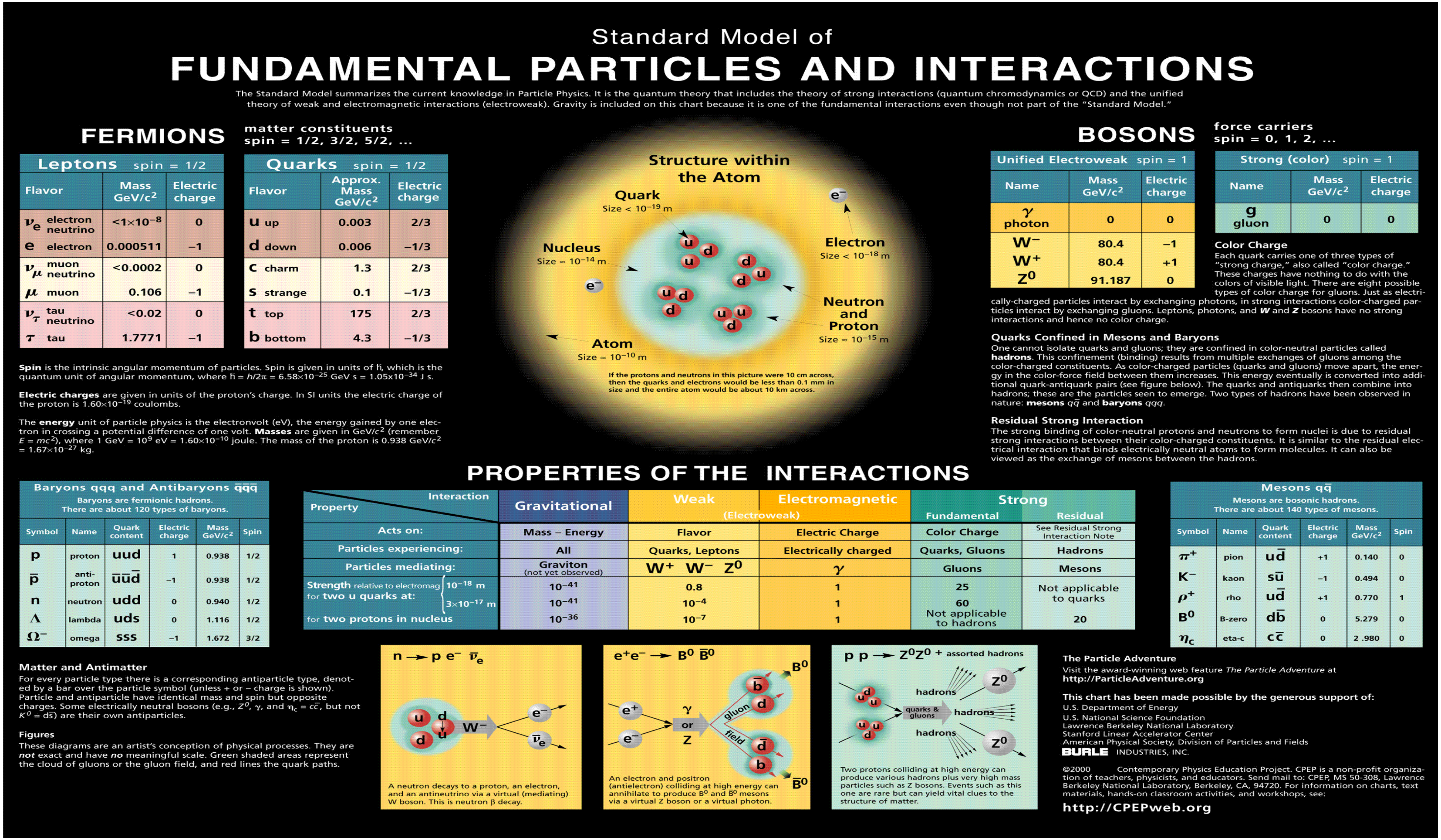






Standard Model of Particle Physics

$$L^{SM} = L_o + L_{FB} + L_{FH} + L_{BB} + L_{BH} + L_{HH}$$



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

Why BSM are needed?

Standard Model of Particle Physics could not give answers to many Physical phenomenons in Nature

[1] What is the origin of Dark Matter in the universe?

[2] Do we live in universe with more than 4 dimensions?

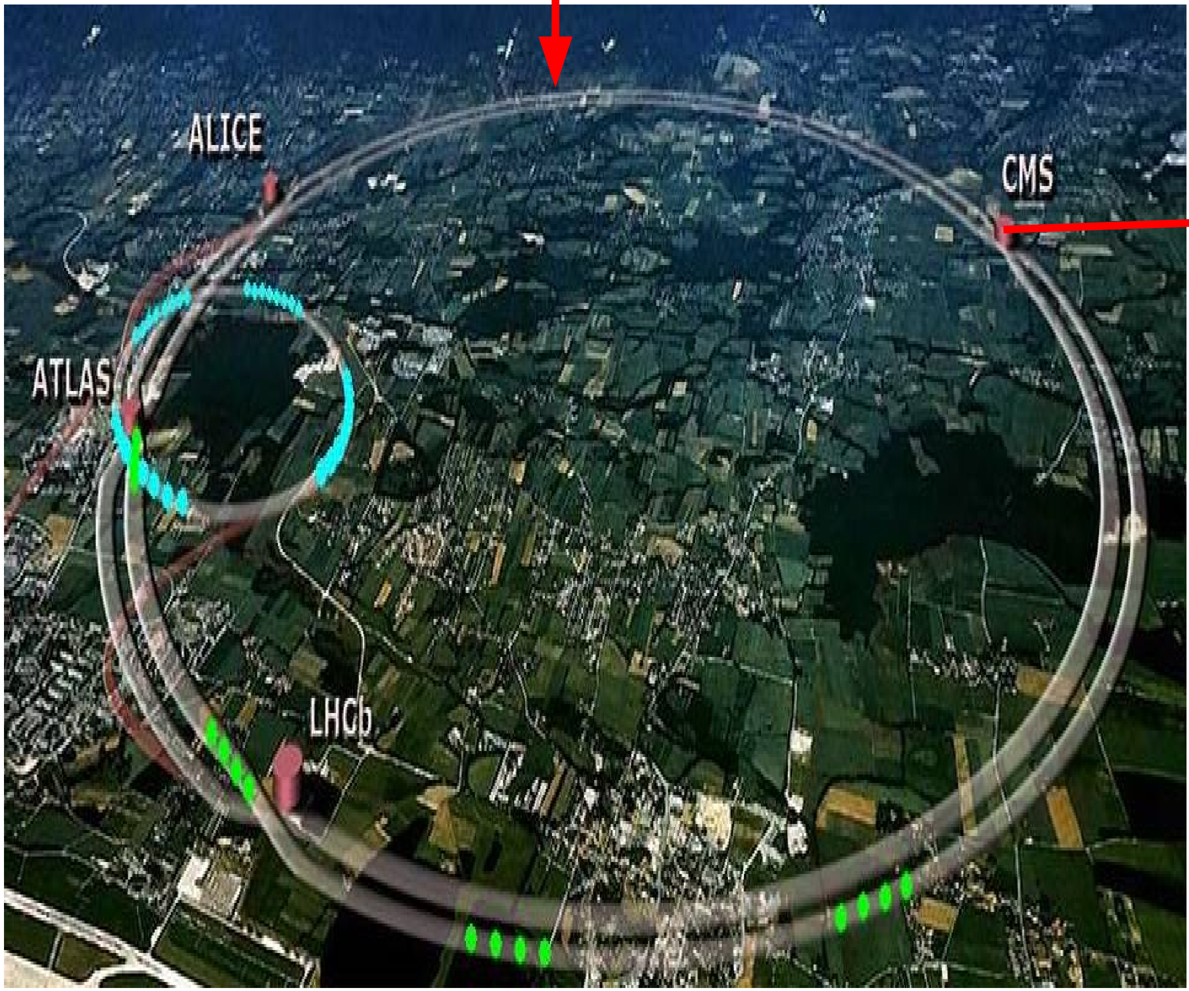
[3] Is the right handed neutrino “heavy” exist

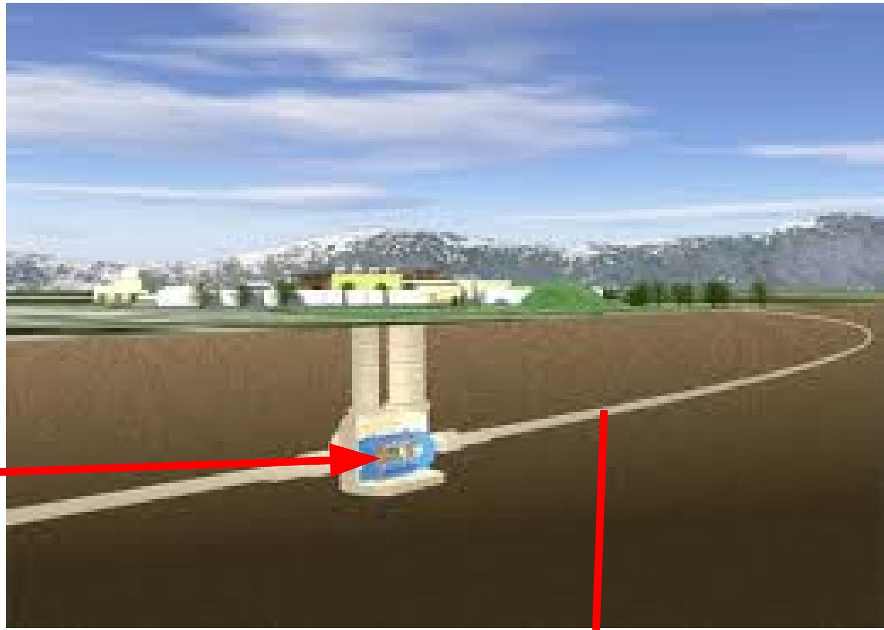
[4] Unification of Gravity with EM, WI and SI

[5] ...

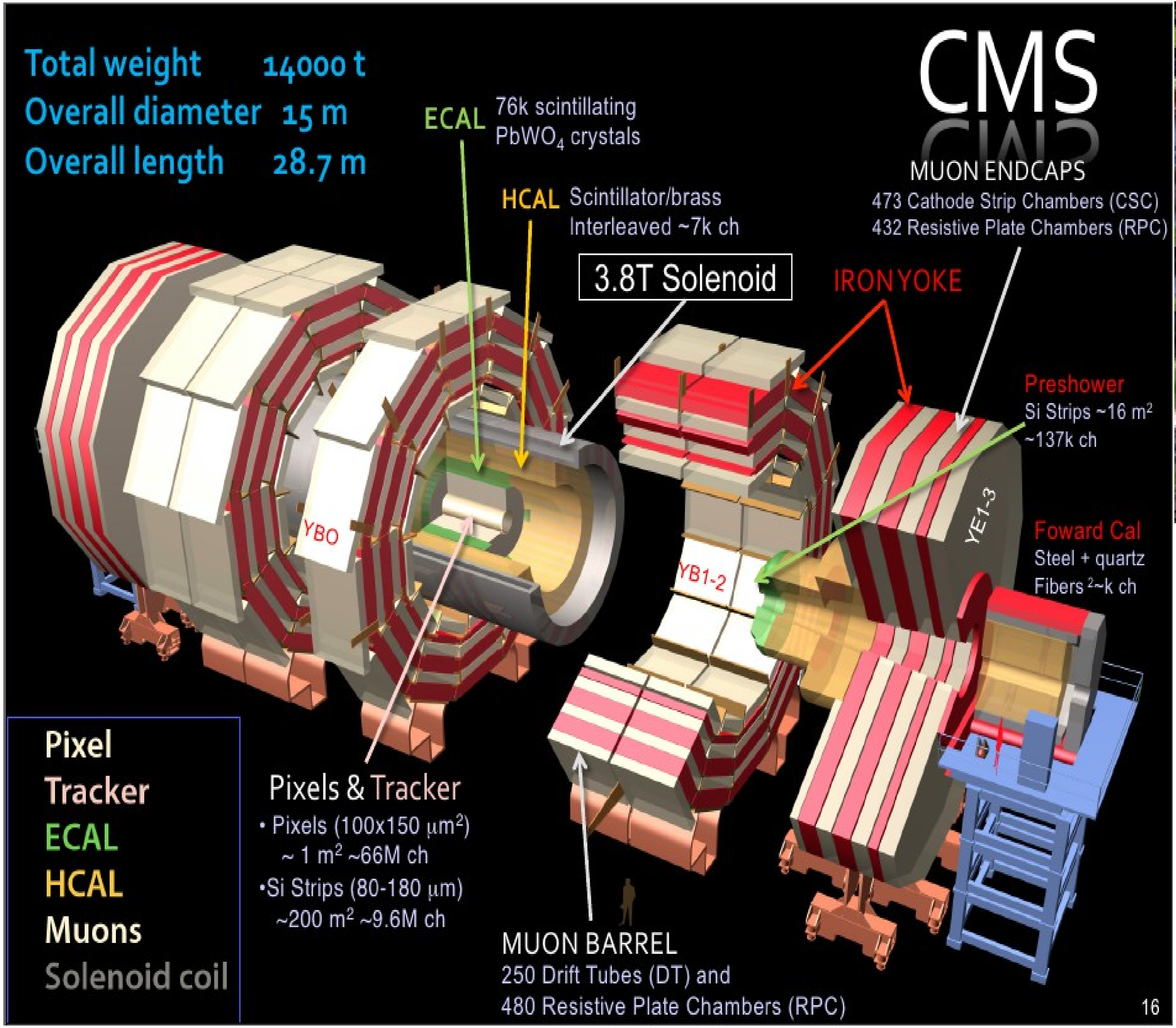
The LHC

CERN **Large Hadron Collider** (LHC)





Compact Muon Solenoid (CMS) Detector



Search for,

***Higgs boson** ☺

***Extra-dimensions**

*** particle that can make dark matter**

Physics Beyond Standard Model

Super-String E6 Model (Z' & W')

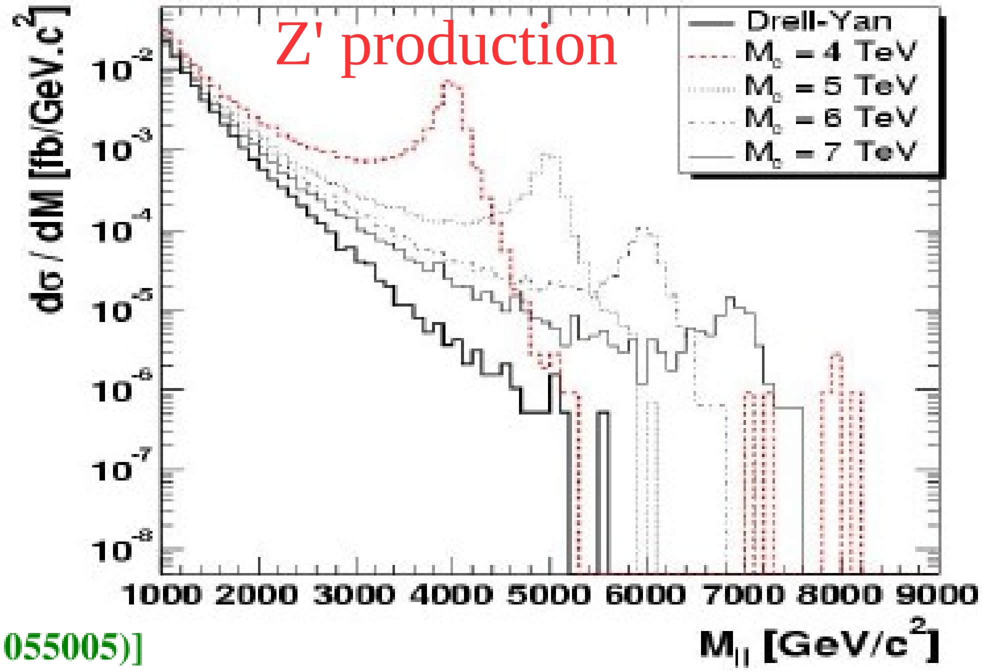
E_6 is GUT group of rank 6:

$$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$$
$$\to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)' , \qquad (2.2)$$

where $U(1)'$ is a linear compination of $U(1)_\chi$ and $U(1)_\psi$, thus

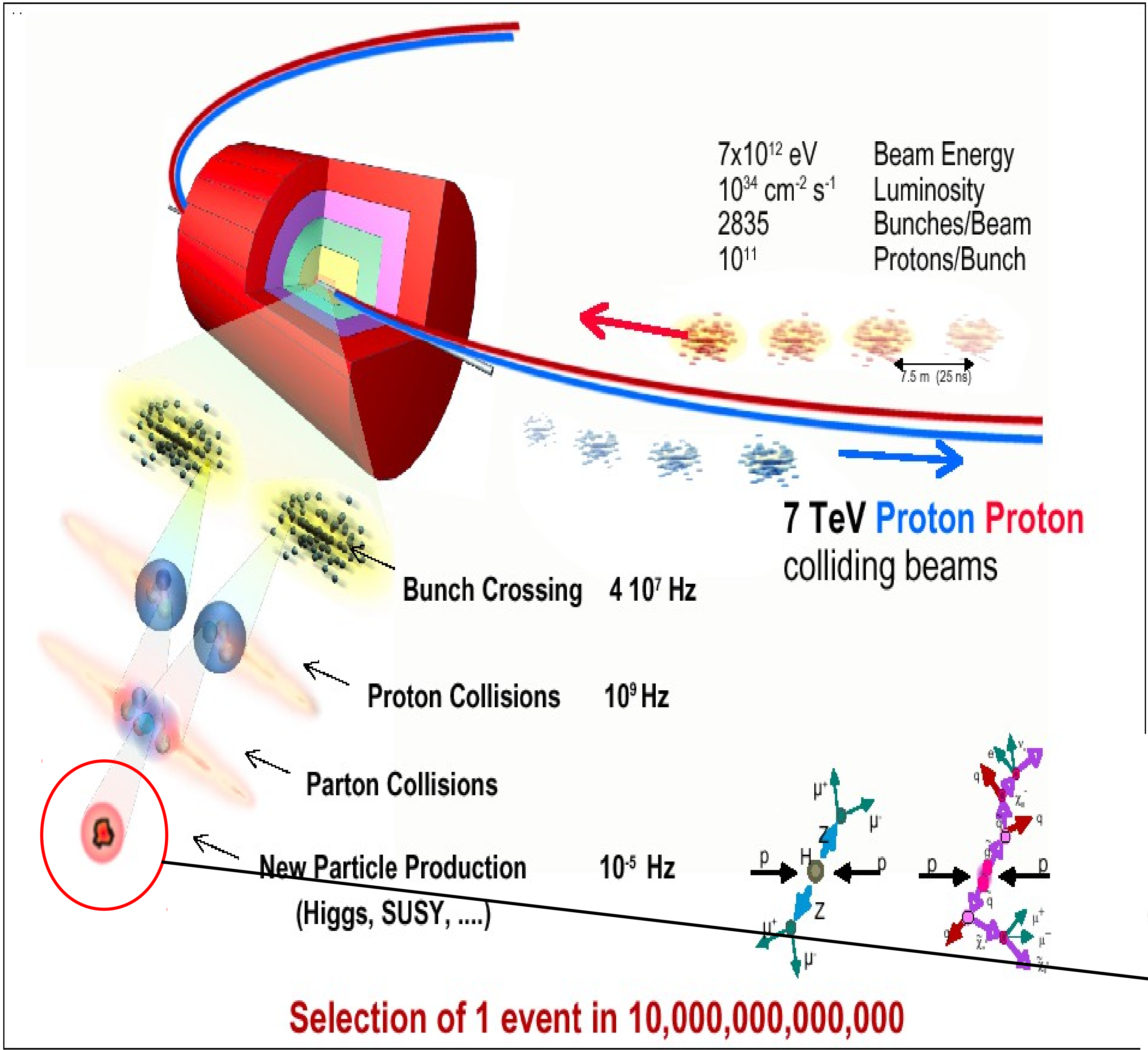
$$U(1)' = U(1)_\chi \cos(\theta) + U(1)_\psi \sin(\theta) , \qquad (2.3)$$

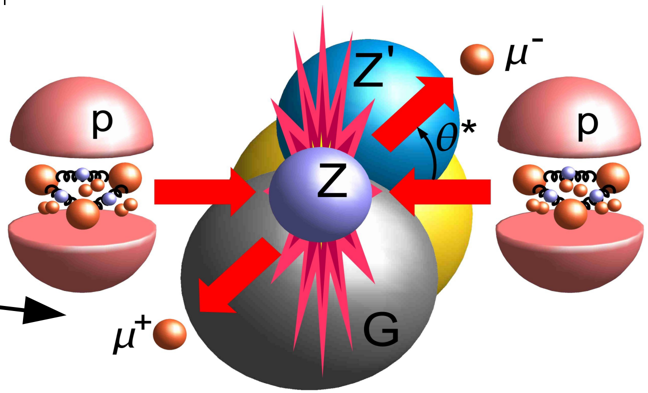
where θ, for E_6, is a free parameter [17]; if $\theta = 0$, one extra gauge boson Z'_χ exists from $SO(10)$, while for $\theta = \pi/2$ only Z'_ψ from E_6 is obtained. Finally, $U(1)_\eta$ is a particular combination of $U(1)_\chi$ and $U(1)_\psi$, i.e., $\theta = 2\pi - \tan^{-1}\sqrt{5/3}$, which produces Z'_η [17]. The additional neutral Z boson is more massive than the SM



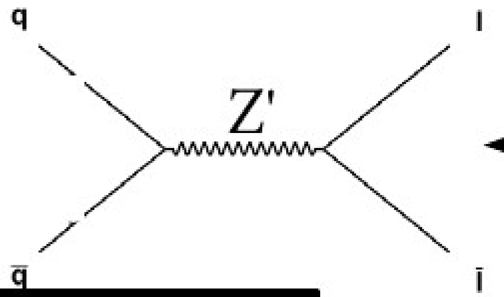
[Rizzo, PRD61(2000) 055005)]

How we perform the Z' analysis



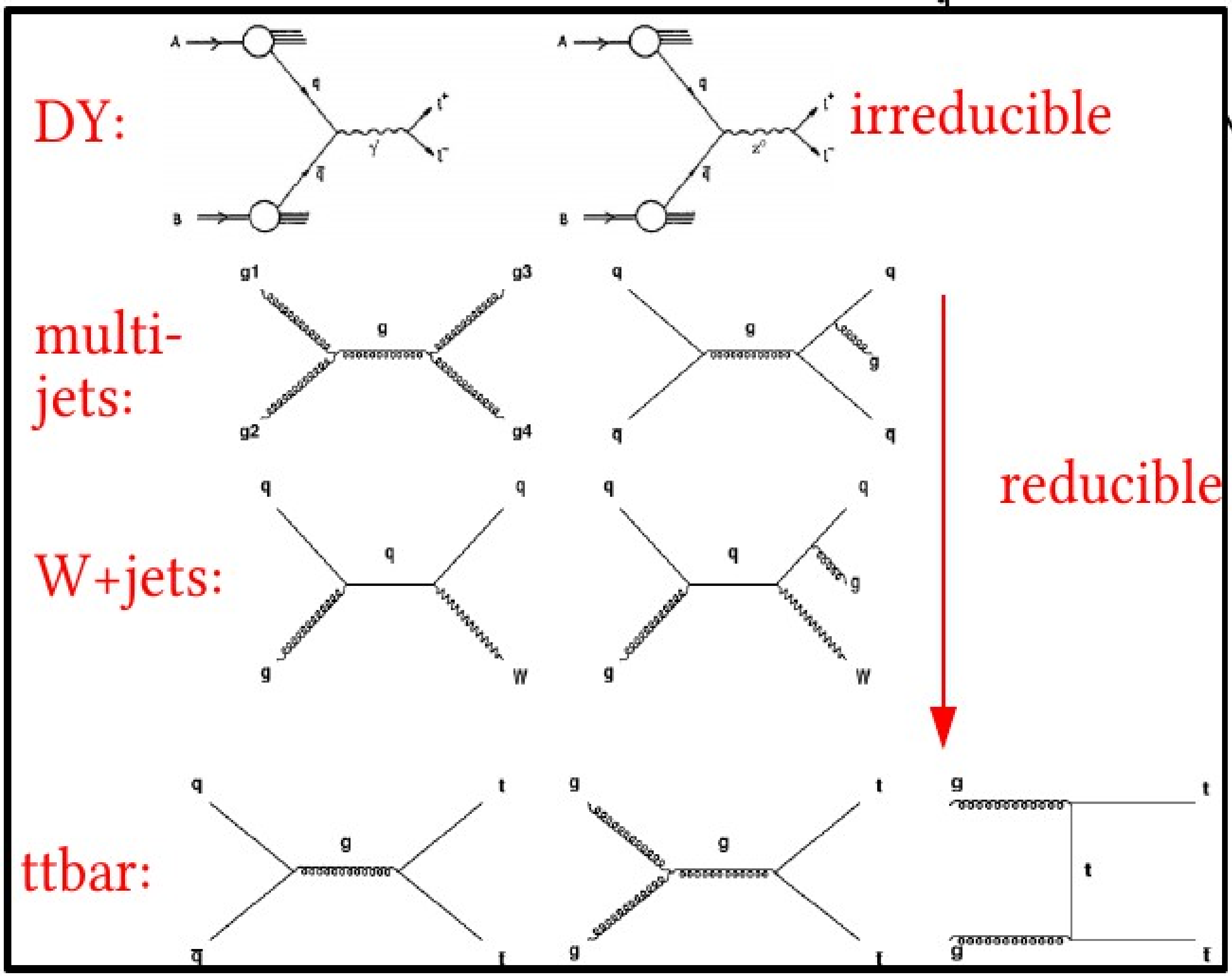


Physics we are interested in



Signal

Backgrounds



15 petabytes

CMS Triggers

* The LHC bunch crossing rate is 40 MHz, which leads to 10^9 interactions/s.

* Only a bout 10^2 interactions/s can be written to archival media.

* The trigger system has been designed to reject factor of 10^7.

<u>The CMS trigger and data acquisition system consists of 4 parts:</u>

[1] the detector electronics,

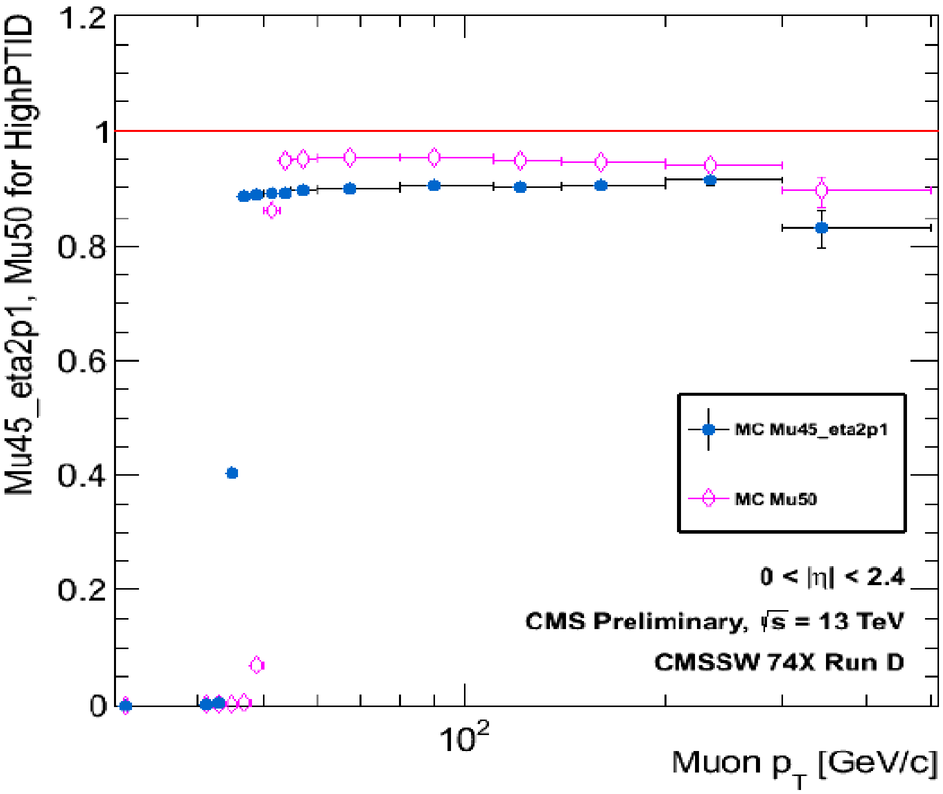
[2] the read-out network system (Trigger Primitives),

[3] the Level-1 trigger processors (L1 trigger),

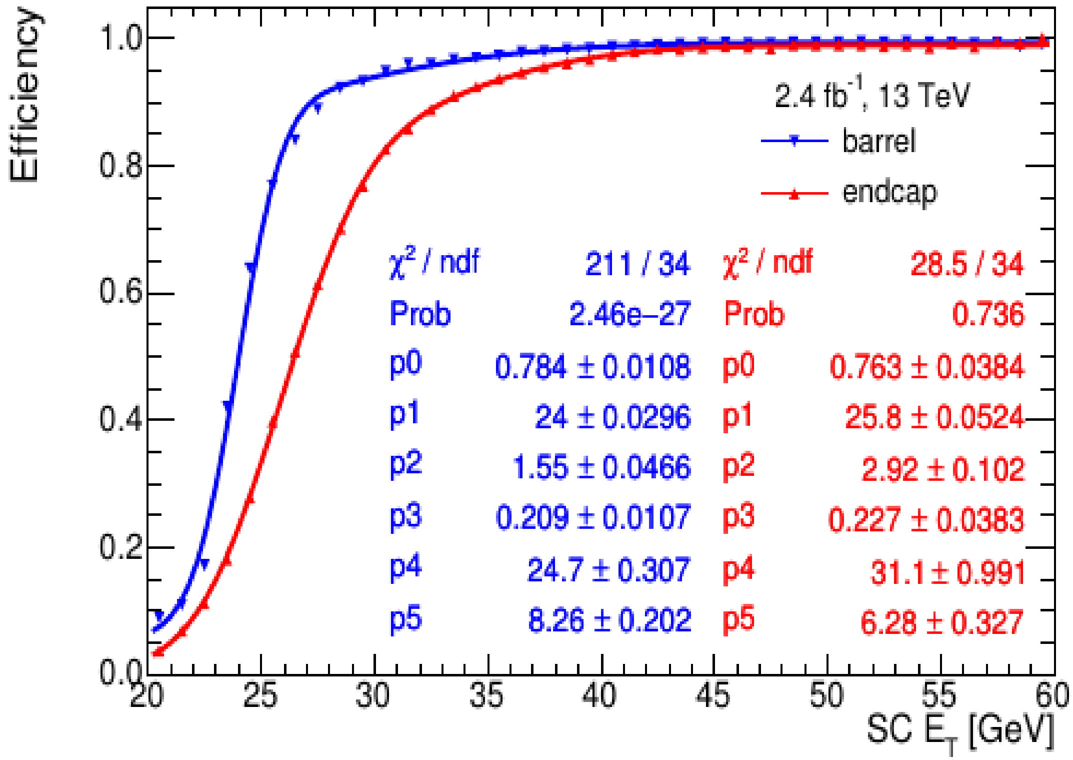
[4] the on-line event filter system (processor farm that executes the CMSSW for HLT)

Electron & Muon Triggers performance

HLT_Mu40_eta2p1



HLT_DoubleEle33_CaloIdL_GsfTrkIdVL.



BUE

High pt Muon Selection

[1] Muon must be reco as global muon
[2] pt > 45.0 GeV
[3] Error on pt/pt < 0.3
[4] Number Of Valid Muon Hits> 0
[5] Number Of Matched Stations > 1
[6] Number Of Valid Pixel Hits > 0
[7] Number Of Tracker Layers With Measurement > 5
[8] |dxy| < 0.2
[9] Σtrack pt/pt(inner track) < 0.10

High pt muon ID in

Extra cuts applied

[1] 2 muons with opposite charge

[2] 3D angle between two muons' momenta <= pi-0.02

[3] v.totalChiSquared()/v.NDF*() <= 10

[4] mass is computed from vertex fit

BUE

High Et Electron Positron Selection

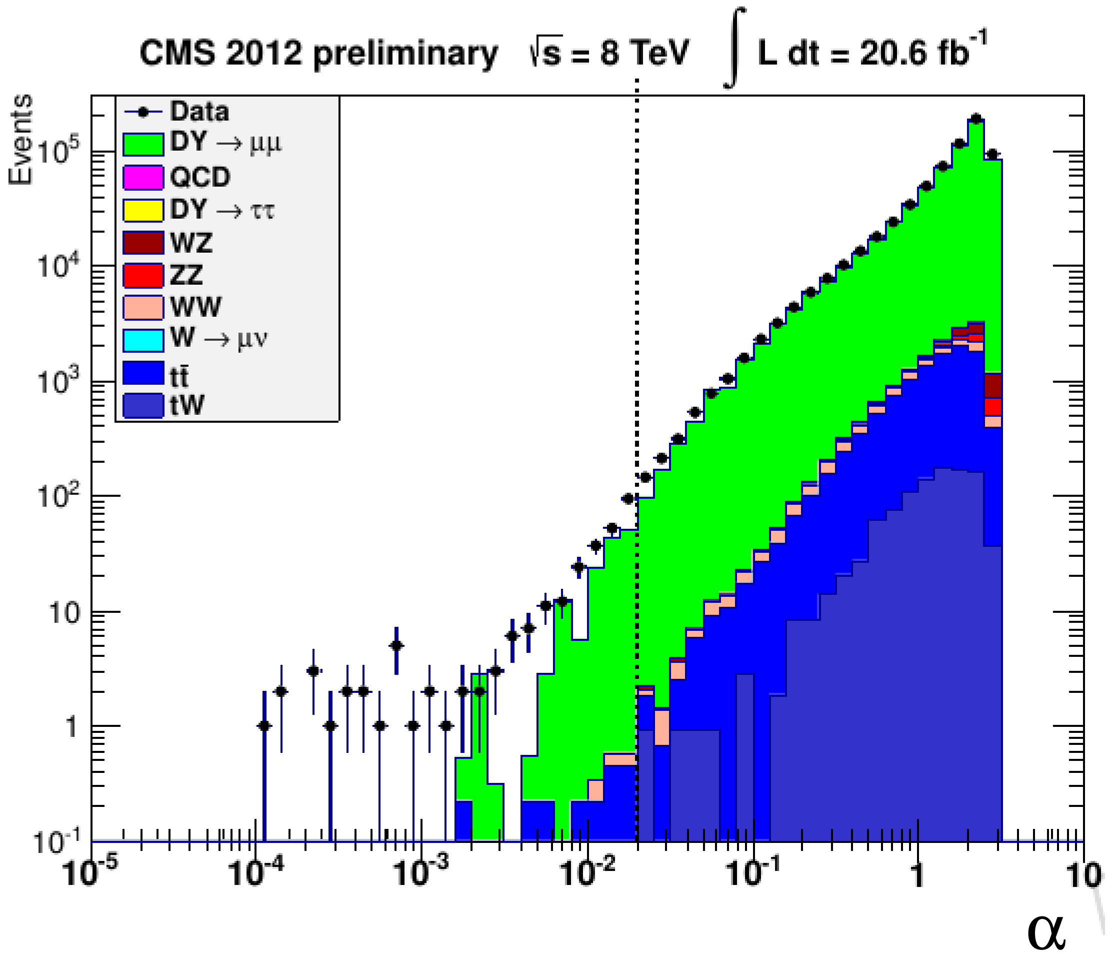
4.1 HEEP ID V6.0

The HEEP ID has evolved since 2012 from ID V4.1 to ID V6.0. Details of the evolution can be found in AN-15-058. The current HEEP ID V6.0 selections are shown in table 7. For the current study, where only the `Run2015D` dataset is used, the $\Delta\eta_{in}^{seed}$ and $\Delta\phi_{in}$ selections are applied. However, when including `Run2015B` and `Run2015C` datasets it will be necessary to take the misalignment in the endcaps into account.

Variable	Barrel	Endcap
	Acceptance selections	
E_T	$E_T > 35\,\text{GeV}$	$E_T > 35\,\text{GeV}$
η	$\lvert\eta_{SC}\rvert < 1.4442$	$1.566 < \lvert\eta_{SC}\rvert < 2.5$
	Identification selections	
`isEcalDriven`	true	true
$\Delta\eta_{in}^{seed}$	$\lvert\Delta\eta_{in}^{seed}\rvert < 0.004$	$\lvert\Delta\eta_{in}^{seed}\rvert < 0.006$
$\Delta\phi_{in}$	$\lvert\Delta\phi_{in}\rvert < 0.06$	$\lvert\Delta\phi_{in}\rvert < 0.06$
H/E	$H/E < 1/E + 0.05$	$H/E < 5/E + 0.05$
$\sigma_{i\eta i\eta}$	-	$\sigma_{i\eta i\eta} < 0.03$
$E_{1\times5}, E_{2\times5}$	$E_{1\times5} > 0.83$ or $E_{2\times5} > 0.94$	-
Inner lost layer hits	lost hits ≤ 1	lost hits ≤ 1
Impact parameter, d_{xy}	$\lvert d_{xy}\rvert < 0.02$	$\lvert d_{xy}\rvert < 0.05$
	Isolation selections	
EM + had depth 1 isolation, iso	$iso < 2 + 0.03E_T + 0.28\rho$	$iso < 2.5 + 0.28\rho$ ($E_T < 50\,\text{GeV}$) else $iso < 2.5 + 0.03(E_T - 50\,\text{GeV}) + 0.28\rho$
p_T isolation, $isopt$	$isopt < 5\,\text{GeV}$	$isopt < 5\,\text{GeV}$

Table 7: Definitions of HEEP ID V6.0 selections.

Cosmic Muon Rejection

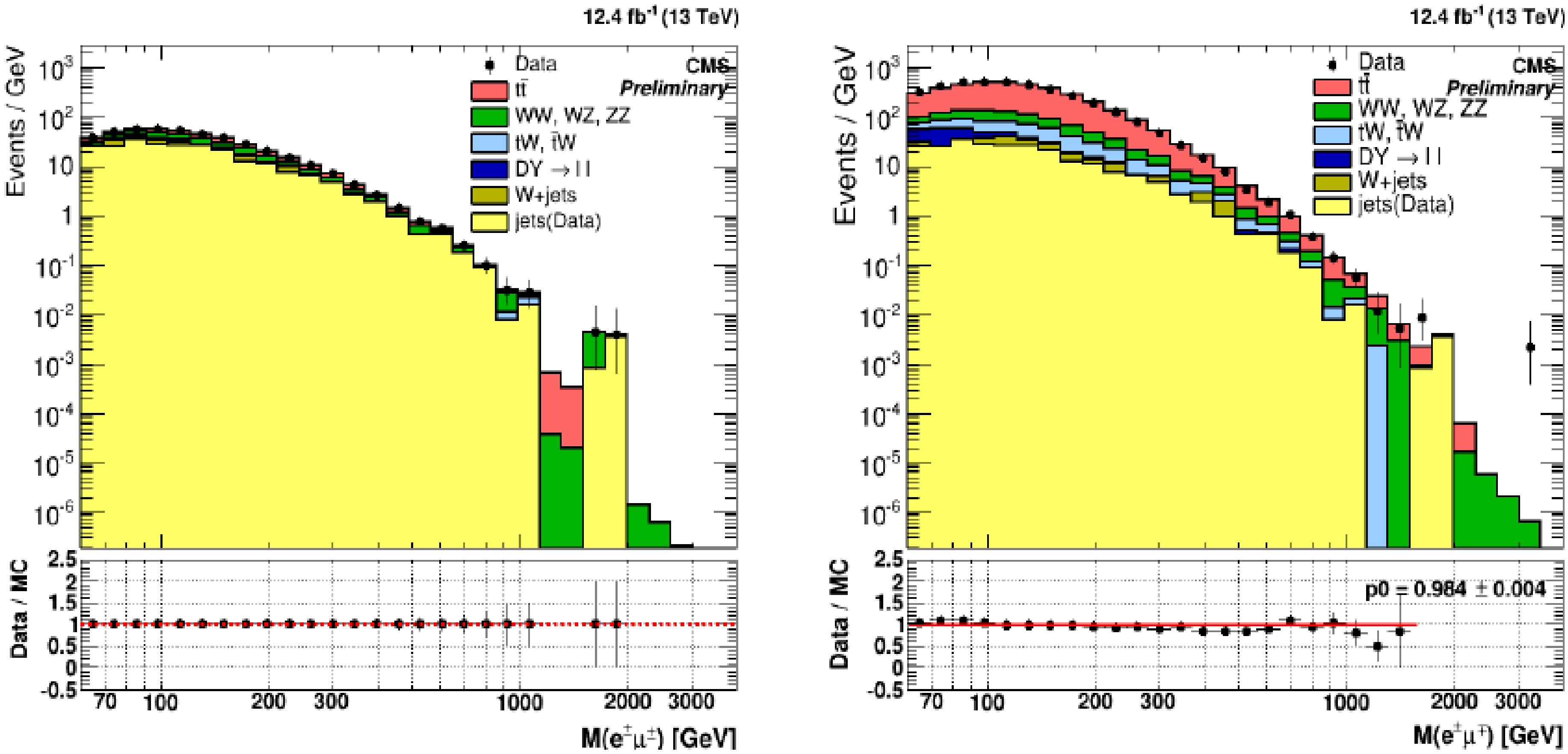


$\alpha = \pi -$ **"3D angle between two muons' momenta"**

$\alpha > 0.02$ (condition for cosmic muon rejection)

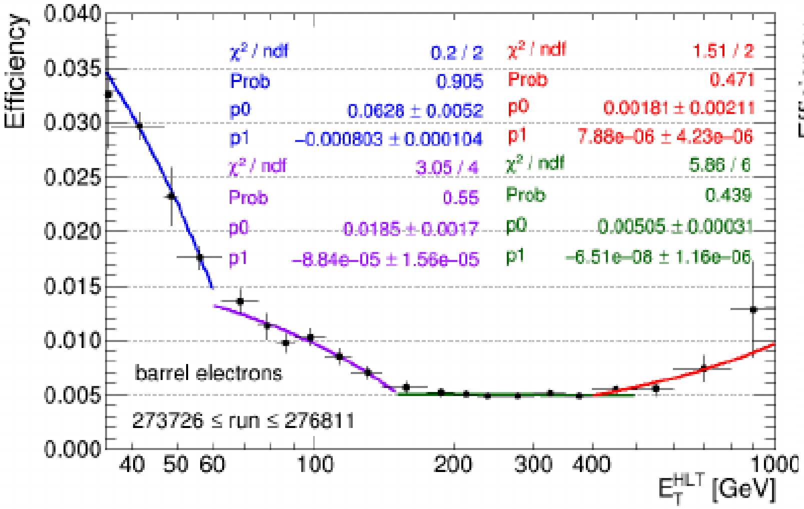
e-mu data Driven Method

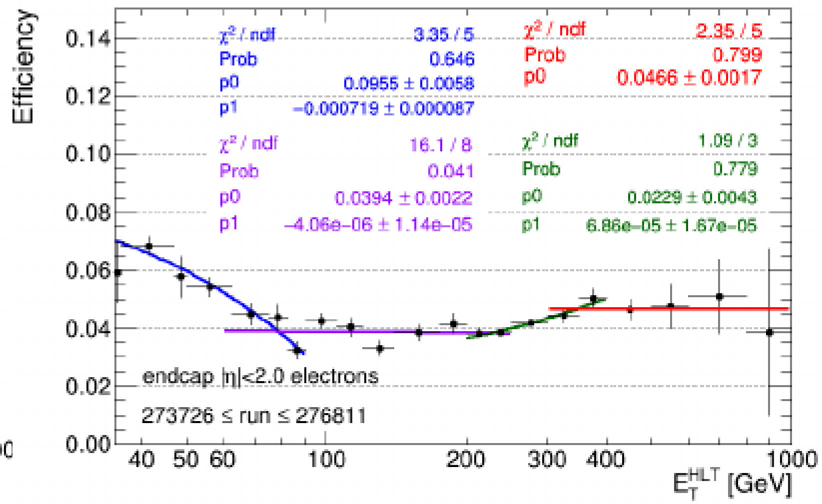
* **Data sample:** MuEG 2012 datasets
* **HLT:** HLT_Mu30_Electron30_CaloIdL
* **Events selection:** First object is a Muon passing high pt muon ID
  Second object is an Electron passing HEEP V6.0

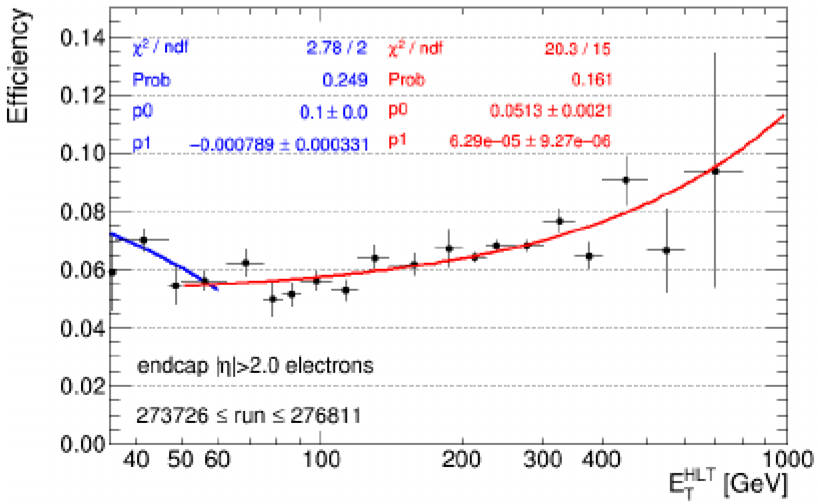


BUE Jet Bkg estimate "using Fake Rat Method"

(3) FR is $\frac{\text{(Nb. Of ele objects passing full high Et ele id+isolation)}}{\text{(Nb. of ele objects passing FR per-selection)}}$



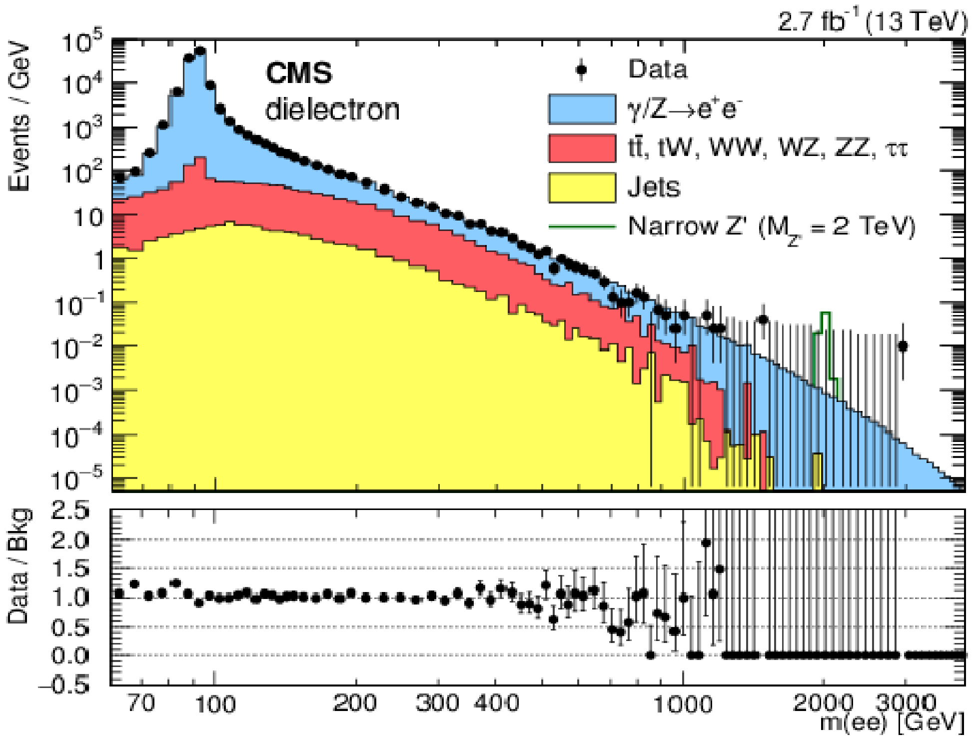


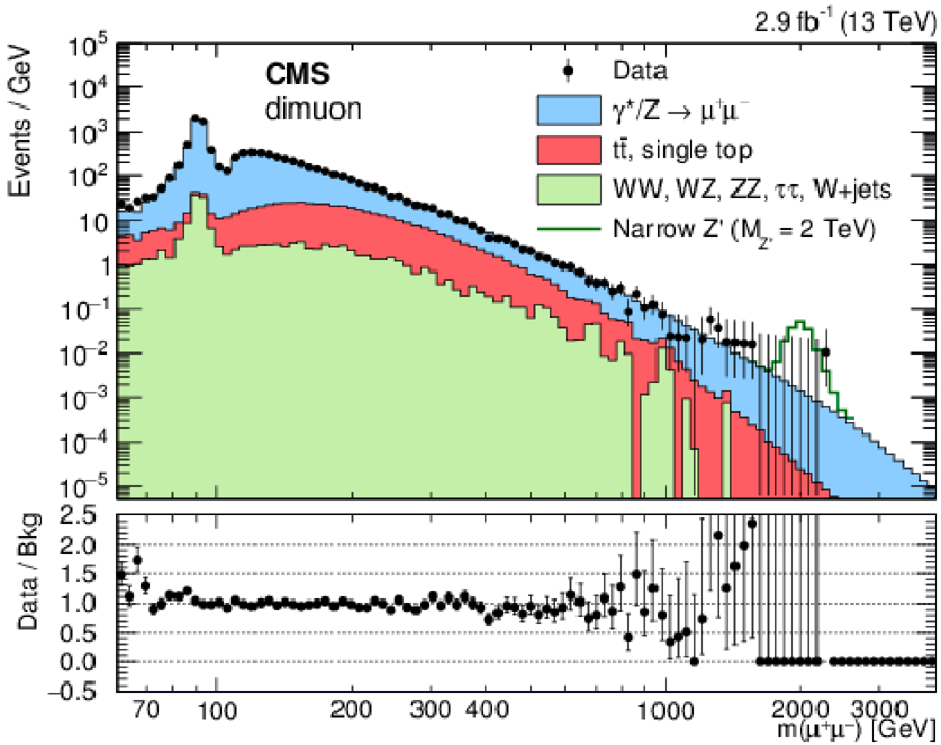


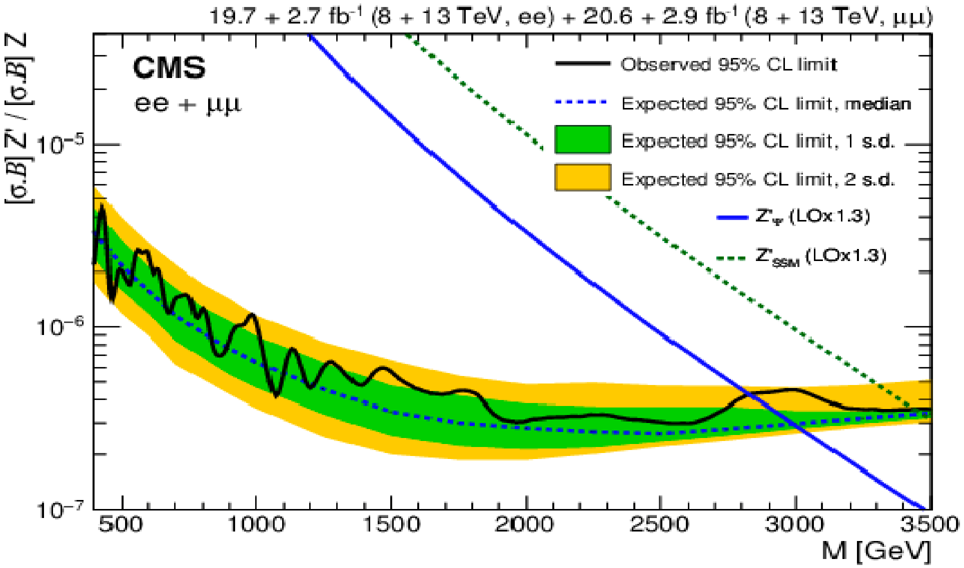
Fate Rate Preselection

variable	barrel	endcap
$\sigma_{i\eta i\eta}$	<0.013	<0.034
H/E	<0.15	<0.15
nr. missing hits	<= 1	<= 1
$\lvert dxy \rvert$	< 0.02	< 0.05

Di-Lepton Invariant mas Spectra



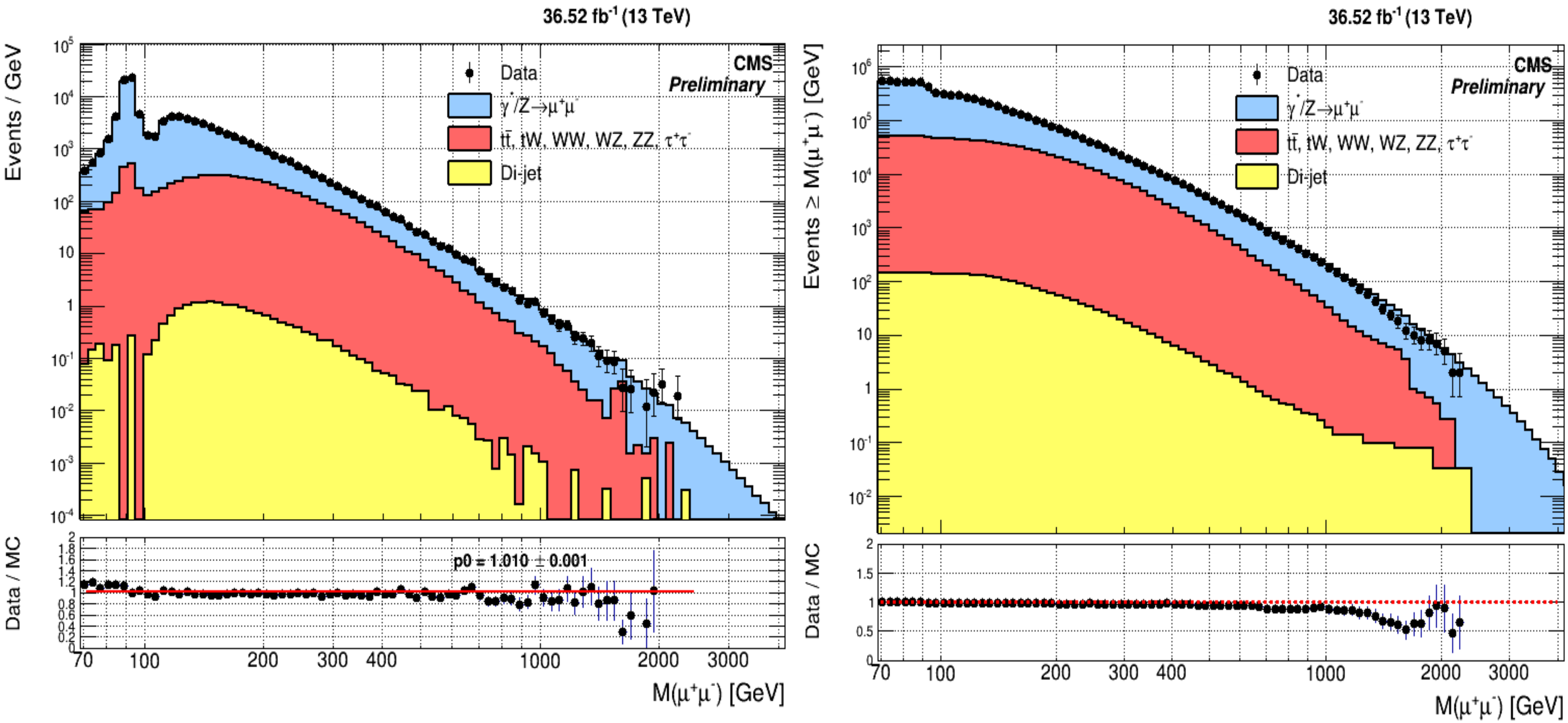




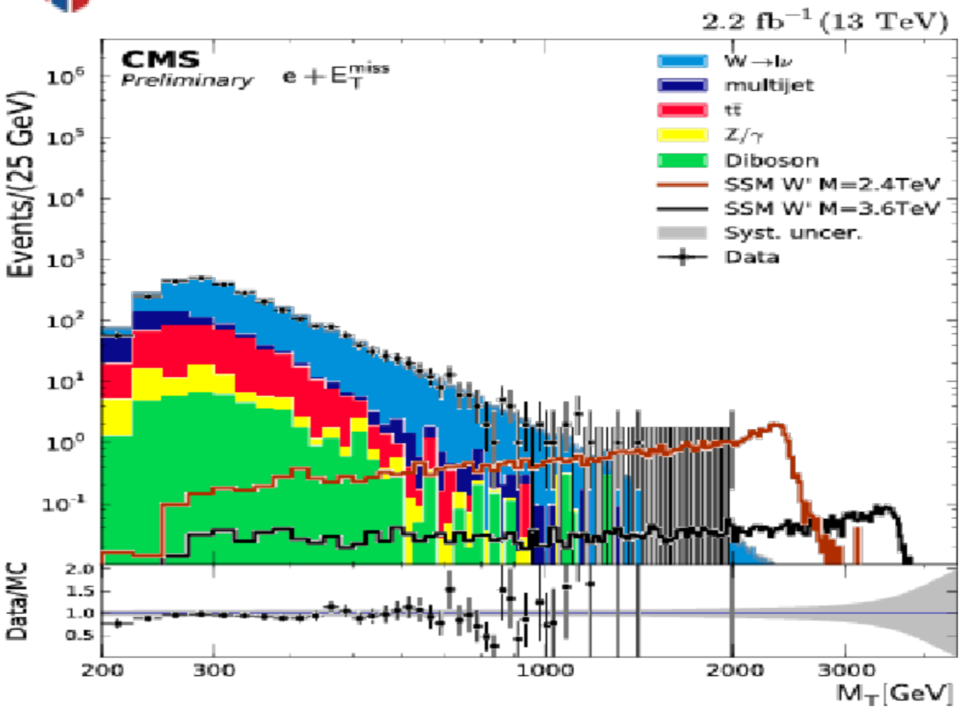
Exclude Z'(SSM) up to 3.5 TeV

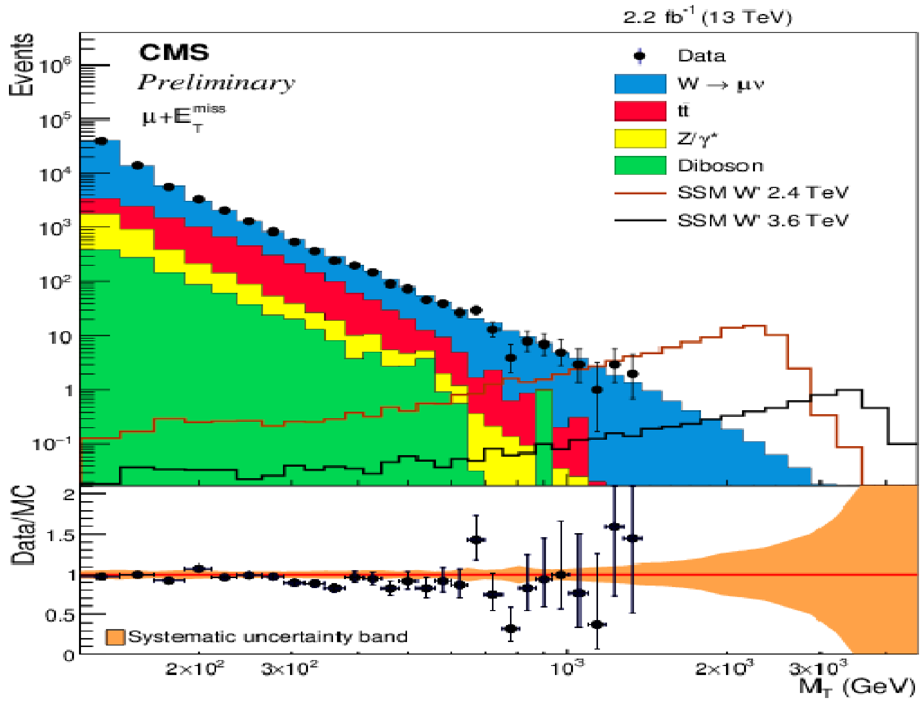
Exclude Z'(psi) up to 2.8 TeV

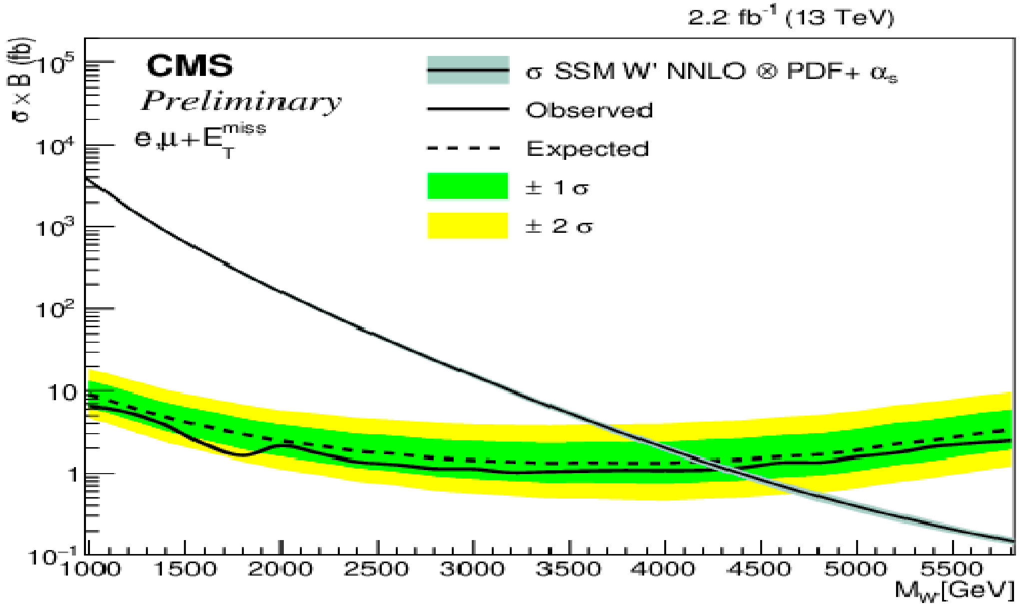
Di-Lepton Invariant mas Spectra full stat.



Search for W' in lepton + MET channel





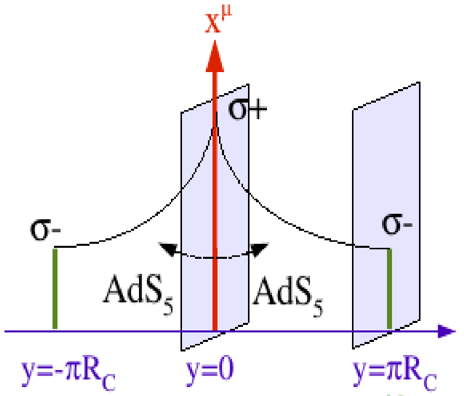


"RS" Model of Extra-Dimensions

[Phys.Rev.Lett. 83 (1999) 3370 - hep-ph/9905221]

1 ED compactified, constant and negative curvature space (AdS_5):

bounded by 2 branes: Planck brane (y=0) and TeV or SM brane ($y=\pm\pi R_C$)



$$m \rightarrow m e^{-\pi k R_c}$$

metric: (non factorizable)

$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$$

$$R_5 = -20\, k^2$$

Gauss law: relates M_D to M_{Pl}:

$$\overline{M}_{Pl}^2 = \frac{M_D^3}{k}(1 - e^{-2\pi k R_c})$$

The scale of phys. phen. as realized by 4D flat metric ⊥ to 5^{th} dim:

$\sim 10^{18}$ GeV → 1 TeV need $kR_C \sim 11$

→ $R_C \sim 10^{-32}$ m (very small)

$$\Lambda_\pi = \overline{M}_{Pl}\, e^{-k\pi R_c}$$

No hierarchy: $k \sim M_D \sim M_{Pl}$

consistency SM:

$k < M_D$ ($k <= 0.1 M_D$)

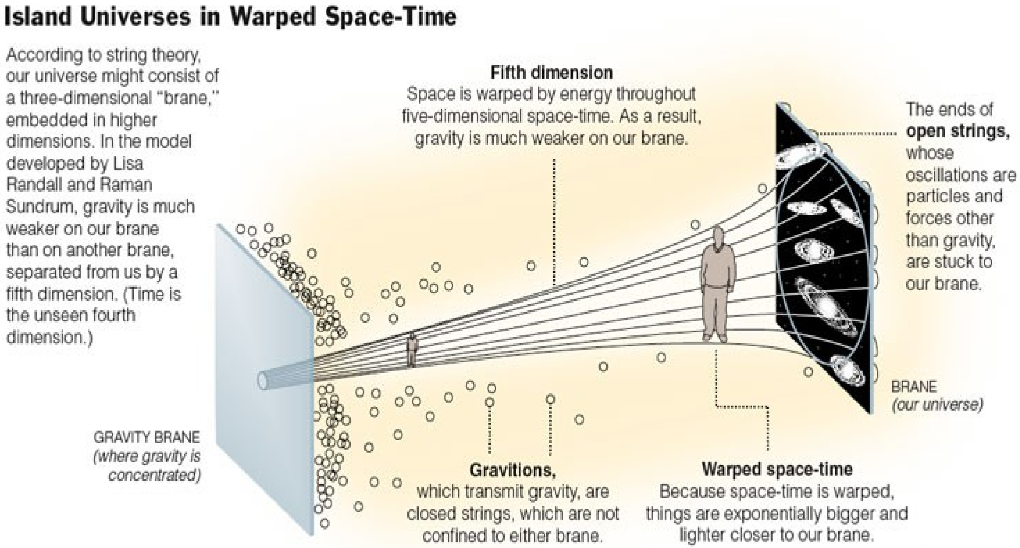
$k < 0.1 M_{Pl}$

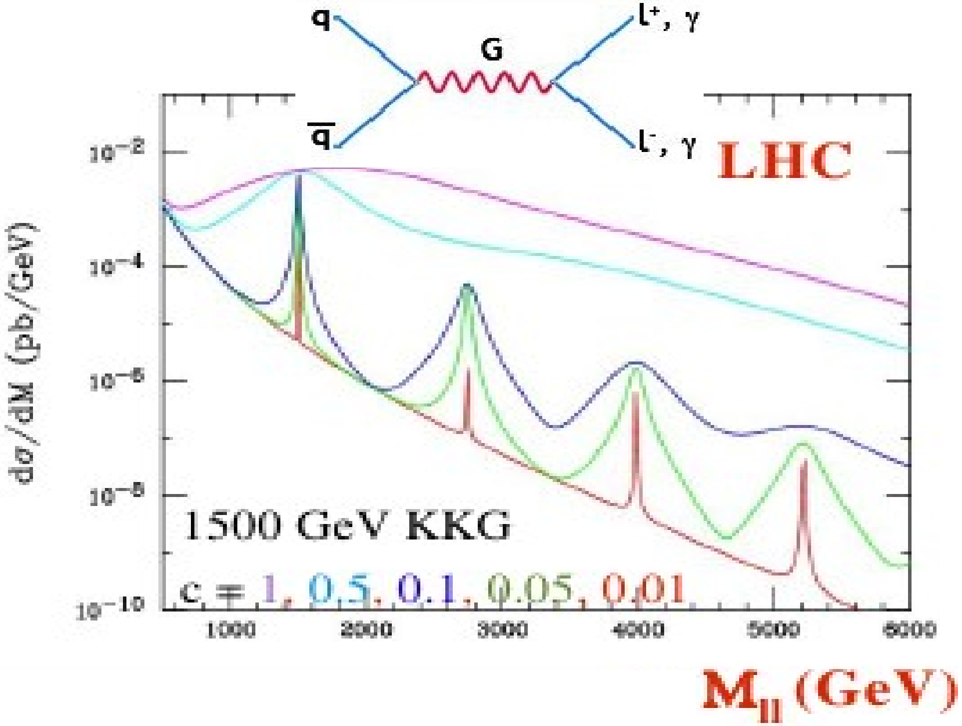
2 free parameters: m_1 or Λ_π and $k/M_{Pl} = c$

width: $\sim (k/M_{Pl})^2$

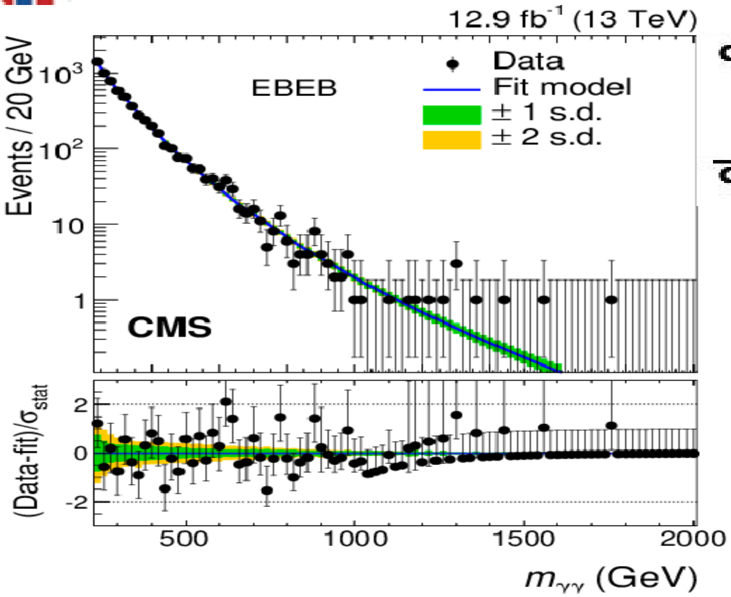
$\sim m_n^3$

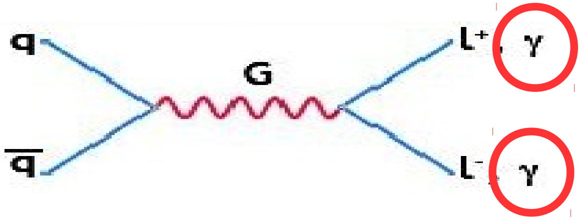
$$m_n = x_n k e^{-\pi k R_c} \qquad x_n : J_1(x_n) = 0$$

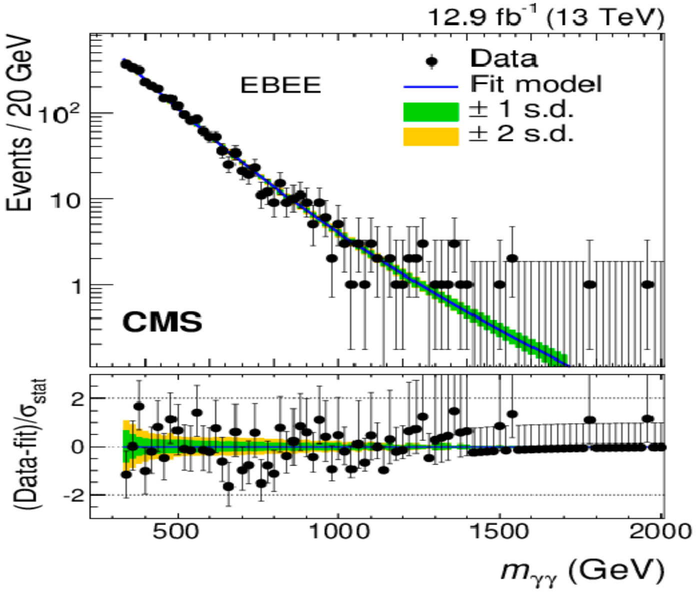


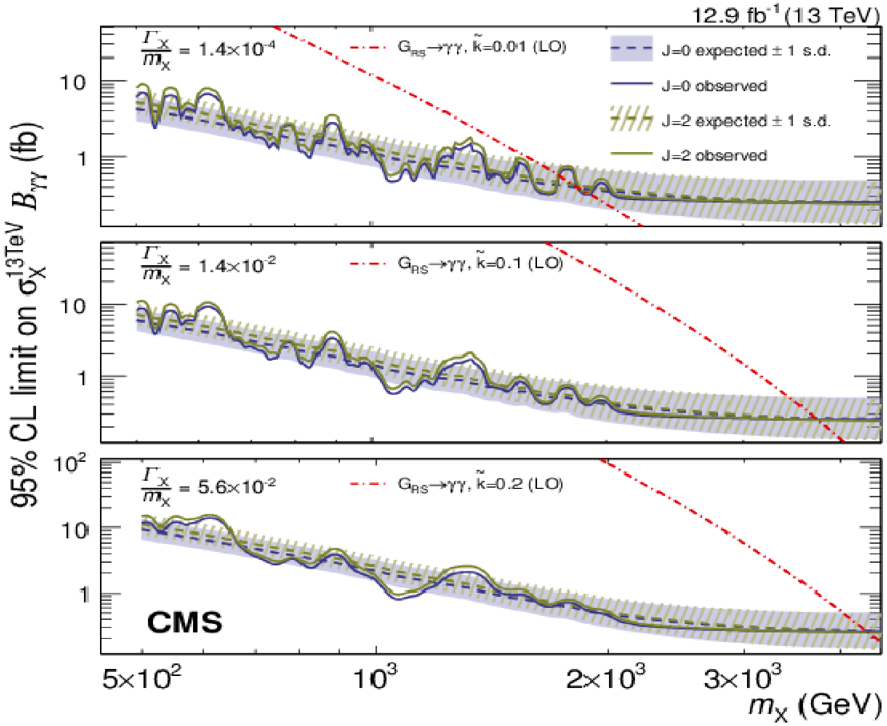


Search for ADD Model of Extra-Dimensions



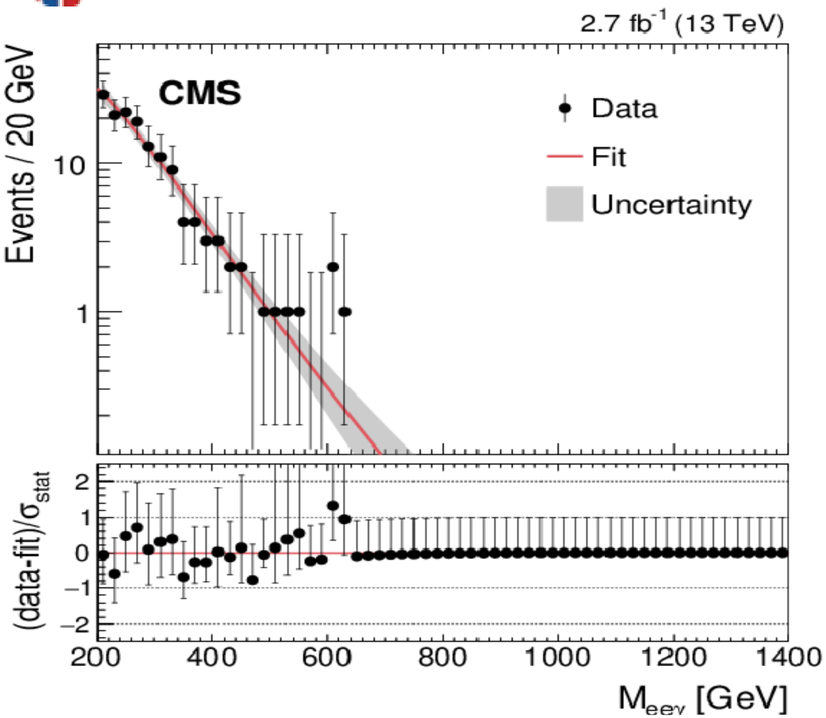


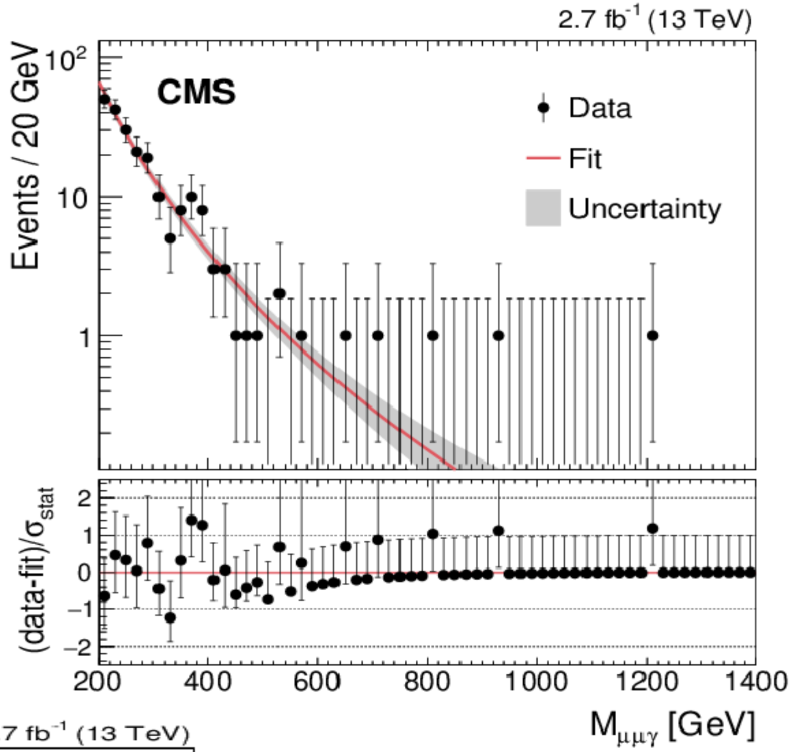


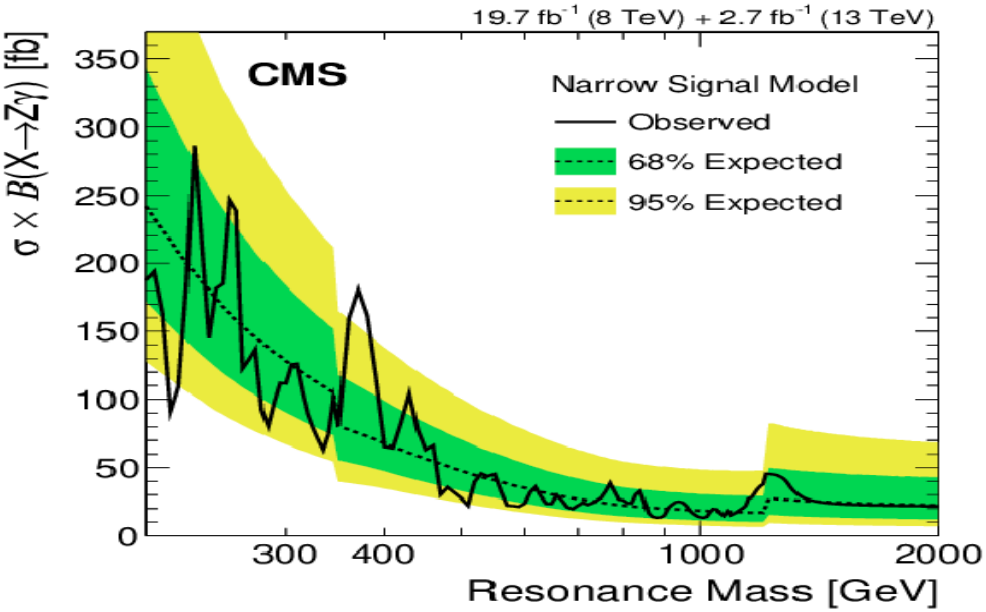


Search for high-mass Zγ resonances in e+e−γ and μ+μ−γ

X--->Zγ

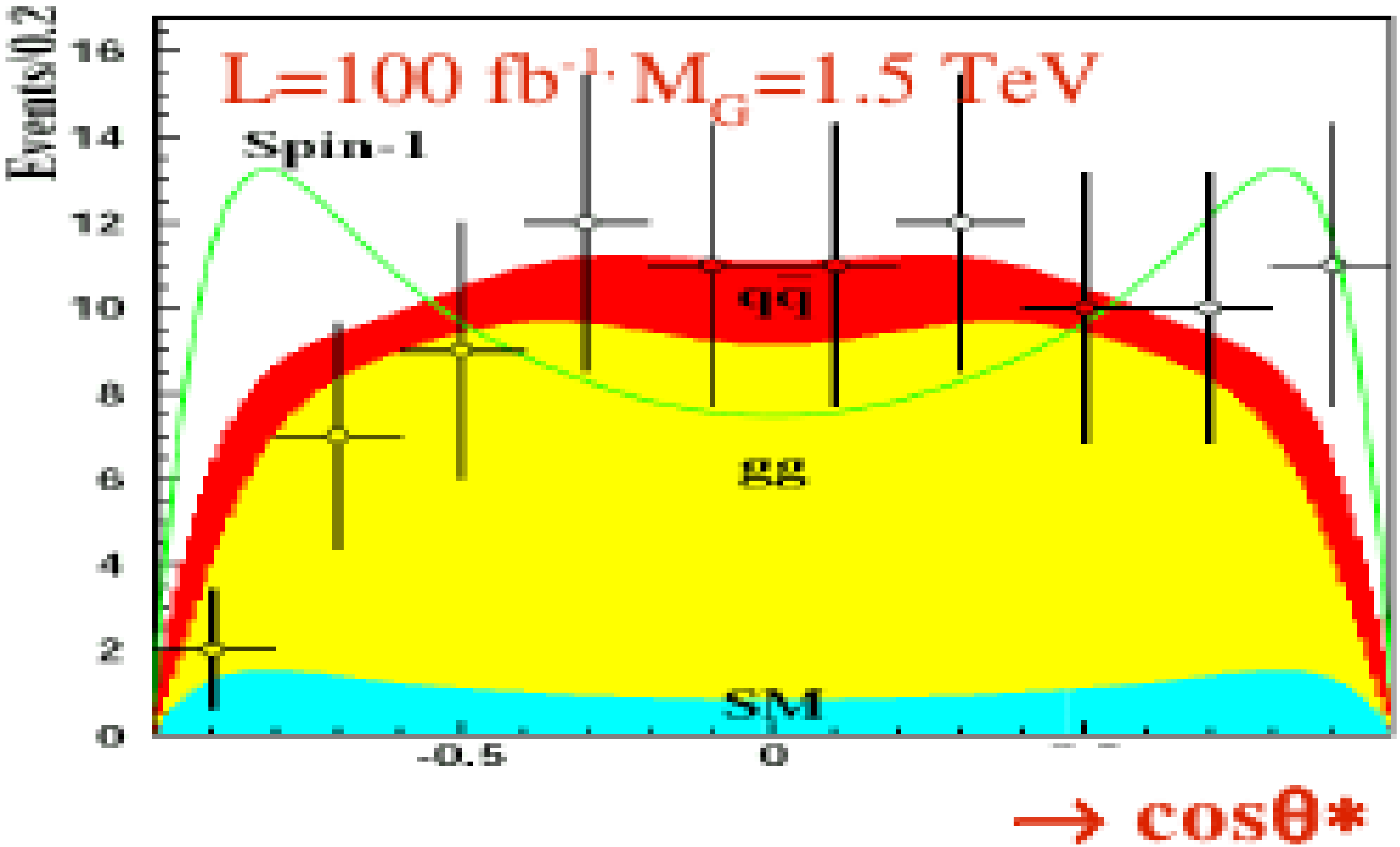






BUE

Angular Distribution "Spin of Bosons"




With LHC RUN2 is there a room for something new!
H
Z^0
$W^{+/-}$
?
?