High Energy Scattering and Search for Extra Dimensions at the LHC

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Outline

INTRODUCTION

- **Main tasks for LHC**

  Higgs, Susy, extra-dimensions

- **Reasons to think about extra dimensions**
  - Kaluza-Klein,
  - Strings
  - D-branes
  - TeV-gravity scenario

- **Possible manifestations of Extra Dimensions**
  - **KK modes** → **Extra heavy particles**
  - **Black Hole/Wormhole production** → **Thermal Hawking radiation**
  - **Signs of strong quantum gravity** → **Change of scattering amplitudes Lost momentum**

INTRODUCTION. Main tasks for LHC

- **Higgs.**

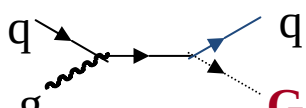
  Search for Higgs bosons is one of the first priority tasks of CMS and ATLAS Physics program

- **Extensive searches for physics beyond the SM**

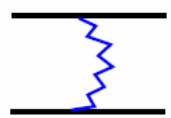
- **Susy**
- **Extra-dimensions. Different models: flat(ADD), warped(RS)**

- **KK modes** real emission of KK gravitons, virtual graviton exchange

Missing transverse energy (ATLAS)



For recent review: Kong,Matchev,Servant, 1001.4801

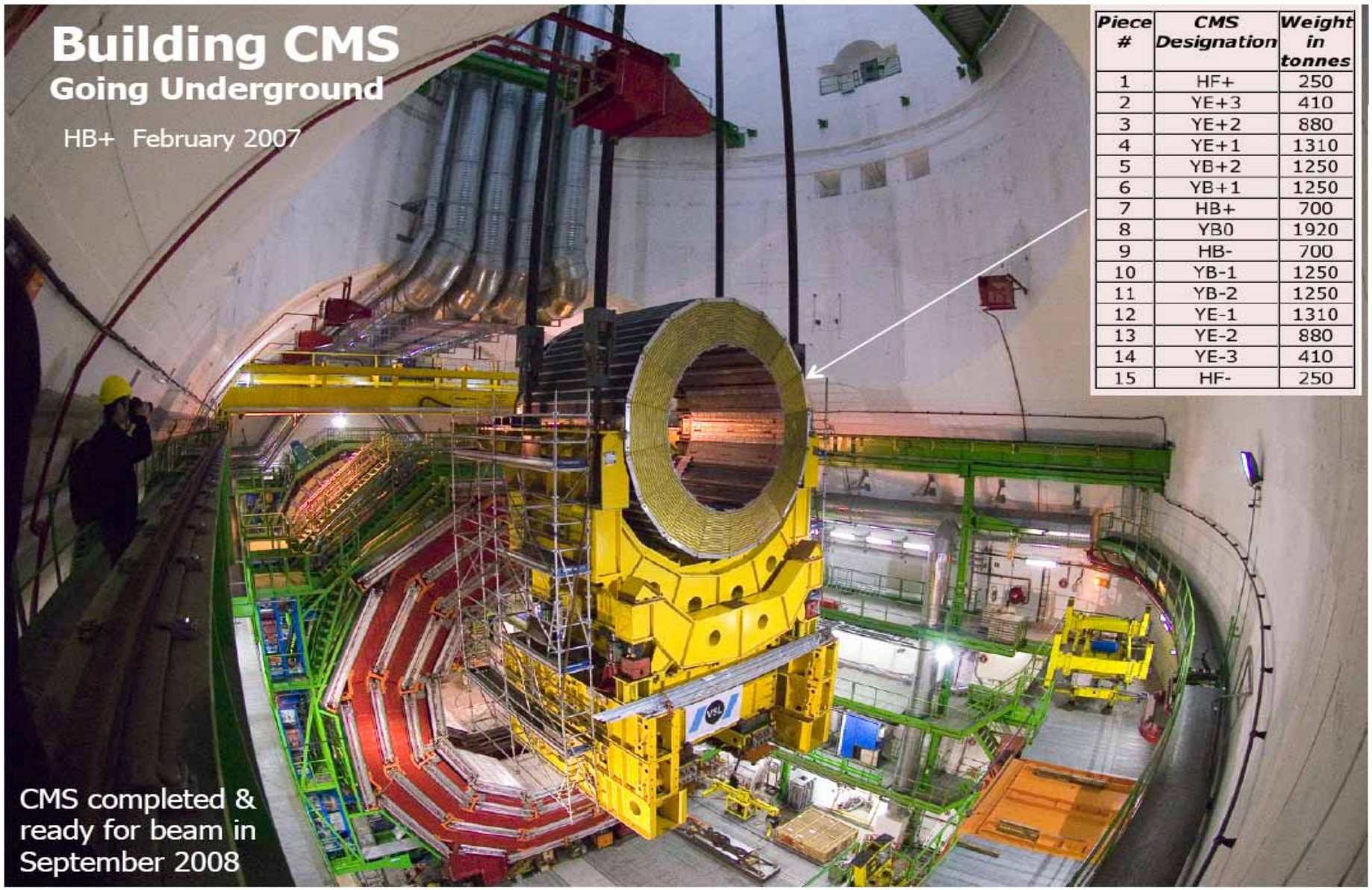


Guidice, Rattazzi,Well, hep-ph/0112161, ADD contributions to the Drell-Yan, Hewett, PRL,1999

- **BH production** (ATLAS collaboration)

- **Signs of strong quantum gravity**

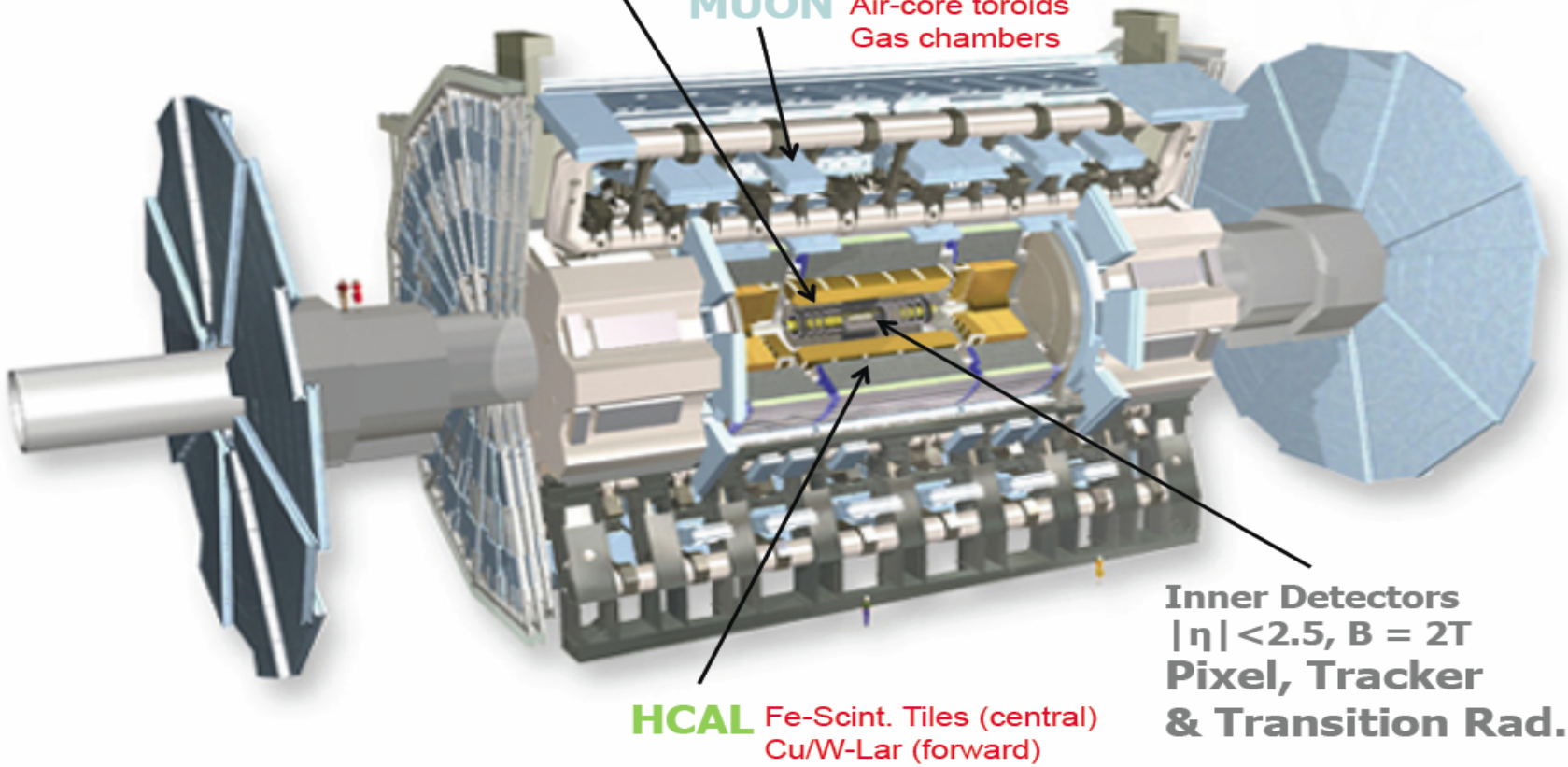
The CMS Muon Detector



Piece #	CMS Designation	Weight in tonnes
1	HF+	250
2	YE+3	410
3	YE+2	880
4	YE+1	1310
5	YB+2	1250
6	YB+1	1250
7	HB+	700
8	YB0	1920
9	HB-	700
10	YB-1	1250
11	YB-2	1250
12	YE-1	1310
13	YE-2	880
14	YE-3	410
15	HF-	250

Total weight	7000 t
Overall diameter	25 m
Overall length	44 m

ATLAS



ATLAS: 7.7 × CMS in volume / 0.56 × CMS in weight

INTRODUCTION. Reasons to think about extra dimensions

- Kaluza-Klein
- Strings
- D-branes
- TeV-gravity scenario (an alternative to SUSY in addressing the hierarchy problem)

INTRODUCTION. Raisons to think about extra dimensions.

TeV-gravity scenario

N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, I. Antoniadis, 1998

$$M_{SM} \approx 1\,TeV$$

$$M_{Pl} \approx 1.2 \cdot 10^{16}\,TeV$$

$$\boxed{M_D \approx 1\,TeV}$$

$$\boxed{S = M_D^{D-2} \int d^D x \sqrt{-g}\, R(g)}$$

$$\boxed{S = M_{Pl}^2 \int d^4 x \sqrt{-g}\, R(g)}$$

$$\boxed{G_D = \frac{1}{M_D{}^{D-2}}}$$

$$M_{Pl}^2 = M_D^2 \left(\frac{M_D}{M_c}\right)^n$$

$$If \quad \frac{M_D}{M_c} >> 1 \quad \Rightarrow M_D^2 << M_{Pl}^2$$

$$M_{Pl}^2 = M_D^2 (\frac{M_D}{M_c})^n$$

$$L_c = \frac{1}{M_c}$$

$$L_c = M_D^{-1} (\frac{M_{Pl}}{M_D})^{2/n}$$

$$M_{Pl} \approx 10^{16} TeV$$

$$M_D \approx TeV$$

$$n = 2, \quad L_c \approx 10^{-1} cm$$

$$n = 4, \quad L_c \approx 10^{-9} cm$$

$$n = 6, \quad L_c \approx 10^{-12} cm$$

$$L_{Pl} \approx 10^{-33} cm, \quad L_{SM} \approx 2 \cdot 10^{-17} cm,$$

INTRODUCTION. Raisons to think about extra dimensions.
TeV-gravity scenario. Modification of the Newton law

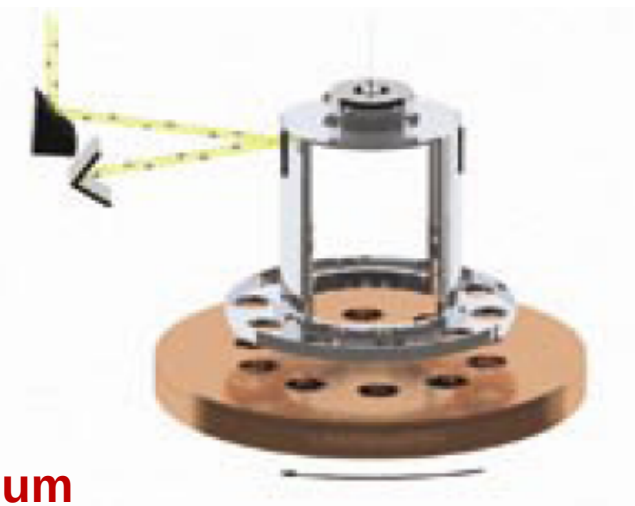
$$F = \frac{G_{Newton}}{r^2} m_1 m_2 \quad \Rightarrow \quad F = \frac{G_{Newton}}{r^2} m_1 m_2 \qquad for\ r \geq L_c$$

$$F = \frac{V_n}{r^n} \frac{G_{Newton}}{r^2} m_1 m_2 \qquad for\ r \leq L_c$$

Tabletop experiments:

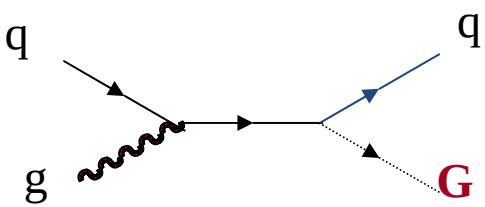
Schematic drawing of the Eöt-Wash group's search for deviations from Newton's Law of Gravitation.

Image: Eöt-Wash group, University of Washington



Cavendish-type experiments using torsion pendulum

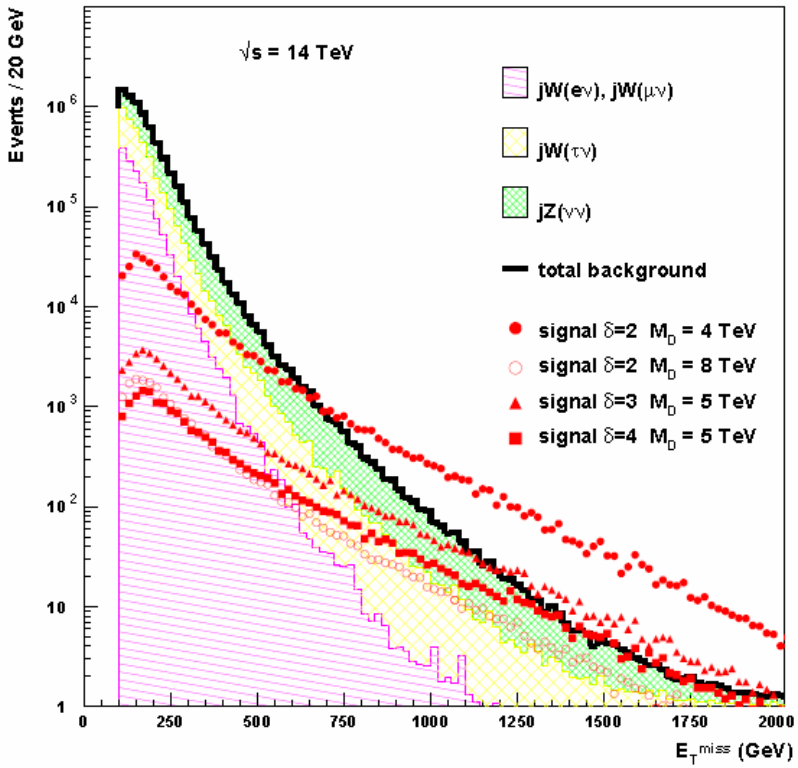
Possible manifestations of Extra Dimensions.
Kaluza-Klein modes. Missed energies



Direct graviton production analysis (ATLAS)

Directly produced KK gravitons interact weakly with ordinary matter and go undetected

Signature is large E_{tr} from undetected graviton + a high P_{tr} jet /photon



$$\delta = n \equiv D - 4$$

Missing transverse energy, from
Vacavant, Hinchliffe, J.Phys.G, 27,2001,1839

Possible manifestations of Extra Dimensions.

High Energy Scattering. Transplanckian energy

Transplanckian energy

$$M_{Pl,D} < E$$

$$M_{Pl} = \sqrt{\frac{\hbar c}{G_{Newton}}}$$

$$c = 1, \quad \hbar = 1$$

D=4

$$M_{Pl,4} \cong 10^{19} Gev$$

$$G_4 \equiv G_{Newton}$$

D > 4

$$M_{Pl,D} \approx 1\,TeV$$

$$G_D = \frac{1}{M_D^{D-2}}$$

Possible manifestations of Extra Dimensions.

Black Hole/Wormhole production. Transplanckian energy

- **TeV Gravity (1998)**
  N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali,
  I. Antoniadis, 1998

- **TeV Gravity can produce BH at Labs (1999)**
  Banks, Fischler, hep-th/9906038
  I.A., hep-th/9910269,
  Giuduce, Rattazzi, Wells, hep-ph/0112161
  Giddings, hep-ph/0106219
  Dimopolos, Landsberg, hep-ph/0106295,

  .....

4-dimensional Schwarzschild Solution

$$R_{\mu\nu} = 0$$

$$ds^2 = -\left(1 - \frac{R_S}{r}\right) dt^2 + \left(1 - \frac{R_S}{r}\right)^{-1} dr^2 + r^2 d\Omega_2{}^2$$

$$R_S = 2\, G_{Newton}\, M_{BH}$$

$$G_{Newton} = \frac{1}{M_{Pl}^2}$$

Possible manifestations of Extra Dimensions.

Black Hole/Wormhole production. Black Holes in GR

D-dimensional Schwarzschild Solution

$$R_{\mu\nu} = 0, \quad \mu,\nu = 0,1...D-1$$

$$ds^2 = -\left(1-(\frac{R_S}{r})^{D-3}\right)dt^2 + \left(1-(\frac{R_S}{r})^{D-3}\right)^{-1} dr^2 + r^2 d\Omega_{D-2}{}^2$$

$$R_S = \gamma_{BH}(D)\frac{1}{M_D}(\frac{M_{BH}}{M_D})^{\alpha_{BH}}$$

$$\alpha_{BH} = \frac{1}{D-3}$$

$$\gamma_{BH}(D) = \frac{1}{\sqrt{\pi}}\left(\frac{8\Gamma(D-1/2)}{D-2}\right)^{1/(D-3)}$$

$$G_D = \frac{1}{M_D{}^{D-2}}$$

$$G_4 \equiv G_{Newton}$$

Possible manifestations of Extra Dimensions.

Black Hole production in particles collisions

- In 1987 't Hooft and Amati, Ciafaloni and Veneziano conjectured that in string theory and in QG at energies much higher than the Planck mass BH emerges.

  Aichelburg-Sexl shock waves to describe particles,

  Shock Waves ------> BH

- Colliding plane gravitation waves to describe particles

  Plane Gr. Waves -----> BH

  I.A., Viswanathan, I.Volovich, Nucl.Phys., 1999

- Boson stars (solitons) to describe particles

  Boson stars ------> BH

  M.Choptuik and F.Pretorius, Phys.Rev.Lett, 2010

Possible manifestations of Extra Dimensions.

Black Hole production in particles collisions. BHs in Quantum Gravity

S Matrix and path integral

$$< h'', \varphi'', \Sigma'' \,|\, h', \varphi', \Sigma' >= \int\limits_{\text{Sum over topologies}} \exp\{\frac{i}{\hbar} S[g, \Phi]\}\, dg\, d\Phi,$$

$$\Sigma'' : h_{ij}'', \varphi'' \quad ; \quad \Sigma' : h_{ij}', \varphi',$$

$$g\,|_{\Sigma''} = h\,'', \Phi\,|_{\Sigma''} = \varphi''; \;\; g\,|_{\Sigma'} = h\,', \Phi\,|_{\Sigma'} = \varphi'$$

I.A., Viswanathan, I.Volovich, Nucl.Phys., 1995

By analogy with

I.A., L.D.Faddeev, A.A.Slavnov
***Generating Functional for the S Matrix in Gauge Theories*. TMP(1974)**

Possible manifestations of Extra Dimensions.

Black Hole production in particles collisions. Quantum Gravity

Quantum Gravity = summation over topologies

$$< h'', \Sigma'' \,|\, h', \Sigma' >= \int\limits_{\text{sum over topologies}} \exp\{\frac{i}{\hbar} S[g, .]\}\, dg\ ,$$

$$g\,|_{\Sigma''} = h\ ''; \;\; g\,|_{\Sigma'} = h\ '$$

No coupling constant to suppress-out channels with nontrivial topology

Theorem (Geroch, Tipler):

Topology-changing spacetimes must have CTC (closed timelike curve=time machine)

I.A., I.Volovich,

***Time Machine at the LHC*, 2007**